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# UNIFORM $C^{1,\alpha}$ -REGULARITY FOR ALMOST-MINIMIZERS OF SOME NONLOCAL PERTURBATIONS OF THE PERIMETER

M. GOLDMAN, B. MERLET, AND M. PEGON

ABSTRACT. In this paper, we establish a  $C^{1,\alpha}$ -regularity theorem for almost-minimizers of a functional  $\mathcal{F}_{\varepsilon,\gamma} = P - \gamma P_\varepsilon$ , where  $\gamma \in (0, 1)$  and  $P_\varepsilon$  is a nonlocal energy converging to the perimeter as  $\varepsilon$  vanishes. Our theorem provides a criterion for  $C^{1,\alpha}$ -regularity at a point of the boundary, which is *uniform* as the parameter  $\varepsilon$  goes to 0. Building upon previous work by the last two authors, as an application of this theorem we obtain that volume-constrained global minimizers of  $\mathcal{F}_{\varepsilon,\gamma}$  are balls for any  $\varepsilon$  small enough. For small  $\varepsilon$ , this minimization problem corresponds to the large mass regime for a Gamow-type problem where the nonlocal repulsive term is given by an integrable kernel  $G$  with sufficiently fast decay at infinity.

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## 1. INTRODUCTION

Motivated by the study of Gamow's liquid drop model in the large mass regime for general kernels which decay sufficiently fast at infinity, we are interested in the minimization problem

$$\min \left\{ \mathcal{F}_{\gamma,\varepsilon}(E) := P(E) - \gamma P_\varepsilon(E) : E \subseteq \mathbb{R}^n \text{ measurable such that } |E| = |B_1| \right\}, \quad (\mathcal{P})$$

where  $n \geq 2$ ,  $\gamma \in (0, 1)$ , and  $P_\varepsilon$  is a nonlocal perimeter functional such that  $P_\varepsilon \rightarrow P$  as  $\varepsilon \rightarrow 0$ . More precisely, given a measurable radial function  $G : \mathbb{R}^n \mapsto (0, \infty)$  we define the rescaled kernels  $G_\varepsilon$  by  $G_\varepsilon(x) := \varepsilon^{-(n+1)}G(\varepsilon^{-1}x)$  for all  $x \in \mathbb{R}^n$  and the nonlocal perimeter  $P_\varepsilon$  by

$$P_\varepsilon(E) := \int_{\mathbb{R}^n \times \mathbb{R}^n} |\mathbf{1}_E(x) - \mathbf{1}_E(y)| G_\varepsilon(x - y) dx dy = 2 \int_{E \times E^c} G_\varepsilon(x - y) dx dy$$

for every measurable set  $E \subseteq \mathbb{R}^n$ . We will elaborate further below on the link with Gamow's model when the kernel  $G$  is integrable.

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The main contribution of this paper is a  $C^{1,\alpha}$ -regularity theorem for almost-minimizers of  $\mathcal{F}_{\varepsilon,\gamma}$  (whose meaning is given in [Definition 1.1](#) just below) which is *uniform* as  $\varepsilon$  goes to 0, under suitable assumptions on  $G$ . As a consequence, we obtain the following characterization of minimizers of  $(\mathcal{P})$  for small  $\varepsilon$ .

**Theorem A** (Minimality of the unit ball). *Assume  $n \geq 2$ ,  $\gamma \in (0,1)$  and that  $G$  satisfies [\(H1\)](#) to [\(H5\)](#) (see below). Then there exists  $\varepsilon_{\text{ball}} = \varepsilon_{\text{ball}}(n, G, \gamma) > 0$ , such that, for every  $\varepsilon \leq \varepsilon_{\text{ball}}$ , the unit ball is the unique minimizer of  $(\mathcal{P})$ , up to translations and Lebesgue-negligible sets.*

For our  $C^{1,\alpha}$ -regularity theorem, we work with a classical notion of almost-minimality for  $\mathcal{F}_{\varepsilon,\gamma}$ .

**Definition 1.1** (Almost-minimizers). Let  $\gamma \in (0,1)$  and  $\varepsilon > 0$ . For any positive constants  $\Lambda$  and  $r_0$ , we say that  $E$  is a  $(\Lambda, r_0)$ -minimizer of  $\mathcal{F}_{\varepsilon,\gamma}$  if for every set of finite perimeter  $F \subseteq \mathbb{R}^n$  such that  $E \Delta F \subset\subset B_r(x)$  with  $0 < r \leq r_0$  and  $x \in \mathbb{R}^n$ , we have

$$\mathcal{F}_{\varepsilon,\gamma}(E) \leq \mathcal{F}_{\varepsilon,\gamma}(F) + \Lambda |E \Delta F|.$$

As is standard for these types of variational problems (see e.g. [\[28, 17, 20, 12\]](#)), we will see that minimizers of  $(\mathcal{P})$  are  $(\Lambda, r_0)$ -minimizers of  $\mathcal{F}_{\varepsilon,\gamma}$  for any  $r_0$  and some constant  $\Lambda$ , not depending on  $\varepsilon$ .

*Remark 1.2.* We could generalize the above definition to an open subset  $\Omega \subseteq \mathbb{R}^n$ , imposing that competitors  $F$  differ from  $E$  only in balls  $B_r(x) \subseteq \Omega$ . Our arguments work just the same and yield uniform regularity of  $E$  in  $\Omega$ . This applies for instance to sets  $E$  which are prescribed outside  $\Omega$  and minimize  $\mathcal{F}_{\varepsilon,\gamma}$  locally in  $\Omega$ .

For  $k \in \mathbb{N}$  and a general kernel  $K$ , it will be convenient to introduce the  $k$ -th moment of  $K$ , which is defined by

$$I_K^k := \int_{\mathbb{R}^n} |z|^k |K(z)| \, dz. \quad (1.1)$$

In this work,  $G$  always satisfies the following hypotheses:

- (H1)  $G$  is a measurable, nonnegative, radial function, that is, there exists a measurable function  $g : (0, \infty) \rightarrow [0, \infty)$  such that  $G(x) = g(|x|)$  for every  $x \in \mathbb{R}^n \setminus \{0\}$ ;
- (H2)  $x \mapsto |x|G(x) \in L^1(\mathbb{R}^n)$  and the first moment is normalized by

$$I_G^1 = \frac{1}{\mathbb{K}_{1,n}}, \quad (1.2)$$

$$\text{where } \mathbb{K}_{1,n} := \int_{\mathbb{S}^{n-1}} |x_n| \, d\mathcal{H}^{n-1}.$$

We also set  $g_\varepsilon(r) := \varepsilon^{-(n+1)}g(\varepsilon^{-1}r)$  for every  $r > 0$ , so that  $G_\varepsilon(x) = g_\varepsilon(|x|)$  for every  $x \in \mathbb{R}^n \setminus \{0\}$ , and introduce the function  $Q : \mathbb{R}_+ \rightarrow \mathbb{R}_+$  defined by

$$Q(r) := \int_{\mathbb{R}^n \setminus B_r} |x|G(x) \, dx, \quad \forall r \in [0, \infty). \quad (1.3)$$

When necessary, we may use the following extra assumptions on  $G$ :

- (H3)  $G \in W_{\text{loc}}^{1,1}(\mathbb{R}^n \setminus \{0\})$ ,  $I_{|\nabla G|}^2 < \infty$ , and  $g'(r) = O(r^{-(n+1)})$  at infinity;
- (H4)  $\int_{B_1 \setminus B_r} G(x) \, dx \leq \frac{C}{r^{s_0}}$  for every  $r \in (0,1)$ , for some constants  $C > 0$  and  $s_0 \in (0,1)$ ;
- (H5)  $Q(r) \leq \frac{C}{r^{n-1+p_0}}$  for every  $r > 0$ , for some constants  $C > 0$  and  $p_0 > 0$ .

Let us briefly comment on these assumptions.

- (i) [\(H1\)](#) and [\(H2\)](#) are needed to ensure that  $P_\varepsilon$  is well-defined on sets of finite perimeter and that it converges to the standard perimeter. In particular, it is used to obtain existence of minimizers for small  $\varepsilon$  and convergence to the ball as  $\varepsilon$  vanishes. The need for extra assumptions [\(H3\)](#), [\(H4\)](#) and [\(H5\)](#) will be made clear further below when sketching the proof of our main result.
- (ii) With [\(H2\)](#), one can check that assumption [\(H5\)](#) is equivalent to  $I_G^{n+q_0} < \infty$  for some positive  $q_0$  (possibly different from  $p_0$ ).

- (iii) If  $G$  is a power law function near the origin, that is,  $G(x) = C|x|^{-a}$  for some  $C, a > 0$  in a neighborhood of 0, then (H4) states that  $a \leq n + s_0$ . Notice that in that particular example,  $|\cdot|^2 \nabla G$  is integrable near the origin, which is a part of (H3).
- (iv) If  $G$  is a power law function at infinity, that is  $G(x) = C|x|^{-b}$  whenever  $|x|$  is large enough, for some  $C, b > 0$ , (H5) states that  $b \geq 2n + p_0$ . In that particular example,  $|\cdot|^2 \nabla G$  is integrable at infinity, and  $g'(r) = O(r^{-(n+1)})$  when  $r \rightarrow \infty$ , which is the other part of (H3).
- (v) From the two previous points, we readily see that the kernel  $G$  defined by

$$G(x) := C \min(|x|^{-(n+s_0)}, |x|^{-(2n+p_0)})$$

with  $s_0 \in (0, 1)$ ,  $p_0 > 0$ , and  $C$  a normalizing constant, satisfies assumptions (H1) to (H5). Other admissible kernels are multiples of the Bessel kernels  $\mathcal{B}_{\alpha, \kappa}$ , defined for any  $\alpha > 0$  and  $\kappa > 0$  as the fundamental solution of the operator  $(\text{Id} - \kappa \Delta)^{\frac{\alpha}{2}}$ . Indeed, Bessel kernels are smooth away from zero, decay exponentially at infinity and, near the origin

$$\mathcal{B}_{\alpha, \kappa}(x) \propto \begin{cases} \frac{1}{|x|^{\alpha-n}} & \text{for } \alpha \in (0, n), \\ -\log(|x|) & \text{for } \alpha = n, \\ 1 & \text{for } \alpha > n. \end{cases}$$

Eventually, our paper covers the case of integrable compactly supported kernels (albeit with the extra assumption (H3)), which was studied in [28].

To state our  $C^{1, \alpha}$ -regularity theorem and sketch its proof, we need to introduce the notion of (spherical) excess, which measures the variation of the normal vector to the boundary of a set near a point.

For a set of finite perimeter  $E$ , we will always implicitly assume that  $E$  denotes a well-chosen representative such that its topological boundary  $\partial E$  satisfies (see e.g. [25, Proposition 12.19])

$$\partial E = \text{spt } |D\mathbf{1}_E| = \left\{ x \in \mathbb{R}^n : 0 < |E \cap B_r(x)| < |B_r(x)| \text{ for all } r > 0 \right\}.$$

We denote by  $\partial^* E$  the reduced boundary of  $E$ , and by  $\nu_E(x)$  the outer unit normal to  $\partial^* E$  at  $x$ .

**Definition 1.3** (Spherical excess). For any set of finite perimeter  $E \subseteq \mathbb{R}^n$  we define the spherical excess (or simply excess) of  $E$  in  $x \in \partial E$  at scale  $r > 0$  by

$$\mathbf{e}(E, x, r) := \inf_{\nu \in \mathbb{S}^{n-1}} \frac{1}{r^{n-1}} \int_{\partial^* E \cap B_r(x)} \frac{|\nu - \nu_E(y)|^2}{2} d\mathcal{H}_y^{n-1}.$$

We can now state the main theorem.

**Theorem B.** *Assume that  $G$  satisfies (H1) to (H5), and let  $\gamma \in (0, 1)$  and  $\Lambda > 0$ . Then there exist positive constants  $\tau_{\text{reg}}, \varepsilon_{\text{reg}}, \beta \in (0, 1)$ , and  $\alpha \in (0, 1)$  depending only on  $n, G$  and  $\gamma$  such that the following holds. If  $E$  is a  $(\Lambda, r_0)$ -minimizer of  $\mathcal{F}_{\varepsilon, \gamma}$  with  $\varepsilon \in (0, \varepsilon_{\text{reg}})$  satisfying, for some  $x \in \partial E$  and  $0 < r < r_0$*

$$\mathbf{e}(E, x_0, r) + \Lambda r \leq \tau_{\text{reg}}, \quad \text{and} \quad \varepsilon^{1-\beta} \leq r,$$

*then, up to a rotation,  $(\partial E - x_0) \cap (D_{r/2} \times (-\frac{r}{2}, \frac{r}{2}))$  coincides with the graph of a function  $u$  which satisfies*

$$\sup_{x', y' \in D_{r/2}} \frac{|\nabla u(x') - \nabla u(y')|}{|x' - y'|^\alpha} \leq C(n, G, \gamma, \Lambda).$$

*Here  $D_{r/2}$  denotes the  $(n-1)$ -dimensional open ball of radius  $r/2$  centered at the origin.*

This theorem falls into the category of “epsilon-regularity theorems” in the sense that it gives regularity of some object (here, the boundary of a set) in a region, provided its energy in a slightly larger region is below a critical threshold.

To the best of our knowledge, this is the first time such a uniform regularity theorem is obtained for a problem involving the competition of two local/nonlocal perimeters, when none of the terms is negligible in front of the other. One may compare our regularity result with the one of [5]. Therein, the authors establish a uniform  $C^{1, \alpha}$ -regularity result for local minimizers of the  $s$ -perimeter (when

$G(x) = |x|^{-(n+s)}$  which is uniform in  $s$  as  $s \rightarrow 1^-$ . However, due to the lack of a competing term, the problem and its analysis are rather different from the ones of the present work.

As stated above, the main motivation for this work is the characterization of minimizers of  $(\mathcal{P})$  for small  $\varepsilon$ . The study of this problem for kernels  $G$  satisfying (H1) and (H2) was started by the last author in [27], where the existence and convergence of minimizers (as well as their boundaries) to the ball was obtained. In [26], the last two authors proved [Theorem A](#) in the planar case, and in arbitrary dimension established that the unit ball is the unique minimizer, up to translations, among so-called ‘‘nearly spherical sets’’. Nearly spherical sets are sets whose boundaries are (small) Lipschitz perturbations of the unit sphere. Assumption (H3) is in particular required for this perturbative argument, where a Taylor expansion of the nonlocal perimeter around the unit ball was carried out. In a standard way, since [Theorem B](#) gives *uniform*  $C^{1,\alpha}$ -regularity estimates as  $\varepsilon \rightarrow 0$ , it can be used to bridge the gap between the Hausdorff convergence of the boundaries of minimizers and the fact that they are small Lipschitz perturbations of the unit sphere. Thus, by the aforementioned perturbative argument, minimizers can only be balls for small  $\varepsilon$ , which is precisely [Theorem A](#).

A first step for the proof of [Theorem B](#) is to observe that any  $(\Lambda, r_0)$ -minimizer  $E$  of  $\mathcal{F}_{\varepsilon,\gamma}$  satisfies in fact a weak quasi-minimality property of the form

$$P(E; B_r(x)) \leq CP(F; B_r(x))$$

for every set of finite  $F$  such that  $E \Delta F \subset\subset B_r(x)$ , for every  $x \in \mathbb{R}^n$  and  $0 < \Lambda r \leq 1 - \gamma$ , where  $C$  depends only on  $n$ ,  $G$  and  $\gamma$ . It is well-known that this kind of quasi-minimality only gives weak regularity properties on  $E$  (see [16, Theorem 5.6]; the original proof can be found in [7]). Namely, it ensures that the  $\mathcal{H}^{n-1}$ -density of  $\partial^* E$  (where  $\mathcal{H}^{n-1}$  is the  $(n-1)$ -dimensional Hausdorff measure) is bounded from below and from above (here, not depending of  $\varepsilon$ ). One can notice the analogy with the case of functions  $u \in H_{\text{loc}}^1(\mathbb{R}^n)$  satisfying, for some  $C \geq 1$  and some open set  $\Omega \subseteq \mathbb{R}^n$ , the quasi-minimality property with respect to the Dirichlet functional

$$\int_{\Omega} |\nabla u|^2 \leq C \int_{\Omega} |\nabla v|^2$$

for every function  $v \in H_{\text{loc}}^1(\Omega)$  such that  $\text{spt}(u - v) \subset\subset \Omega$ . This type of quasi-minimality ensures Hölder-regularity in  $\Omega$ , but not better in general for  $n \geq 2$  (see [18, Chapter 6] and references therein).

The main point of our work is to build upon this minimal regularity and obtain higher order regularity for  $(\Lambda, r_0)$ -minimizers of  $\mathcal{F}_{\varepsilon,\gamma}$ . The proof of our  $C^{1,\alpha}$ -regularity theorem is inspired by the usual strategy for almost-minimizers of the area functional developed in the literature by De Giorgi (see for example [9, 29, 19]), Almgren, Allard, Bombieri, Federer, Schoen, Simon (to name only the main figures). Here we follow the presentation of [25].

The key point in the standard strategy is to prove that if the excess in  $x \in \partial E$  is small enough at some scale  $r_0 > 0$ , then it decays as a power function at every scale smaller than  $r_0$ , i.e.,

$$\mathbf{e}(E, x, r) \lesssim \left(\frac{r}{r_0}\right)^{2\alpha} \mathbf{e}(E, x, r_0), \quad \forall r \in (0, r_0).$$

Since the excess measures the oscillation of the normal to the boundary at a given scale, it is well-known that such a power decay implies  $C^{1,\alpha}$ -regularity of the boundary by a Campanato-type argument.

To proceed, we distinguish between two scales, *small scales* when  $r \lesssim \varepsilon$ , and *large scales* when  $r \gg \varepsilon$ . If the excess is small enough at some large scale  $r \gg \varepsilon$ , then  $P_\varepsilon$  should be treated as the perimeter, so that, formally  $\mathcal{F}_{\varepsilon,\gamma} \simeq (1 - \gamma)P$ . In that regime, we are able to adapt the proofs in [25] to obtain power decay of the excess down to the scale  $\varepsilon^{1-\beta} \gg \varepsilon$  for any  $\beta > 0$  arbitrarily small, that is, down to any scale which remains much larger than  $\varepsilon$ .

Using the fact that the excess is now small at scale  $\varepsilon^{1-\beta}$ , the scaling property of the excess and (H5) allow us to jump to a smaller scale  $c\varepsilon$  for an arbitrary constant  $c > 0$ .

We now know that the excess is small at a small scale  $c\varepsilon$ , so we can use (H4) to treat the nonlocal perimeter as a *volume term*. The classical almost-minimality with respect to the perimeter functional then readily gives us that the excess decays as power function down to any smaller scale.

Since small scales can be treated in a standard way using the almost-minimality with respect to the perimeter, the major part of the work consists in handling the case of large scales. We follow the usual global strategy, but the nonlocal term needs to be treated with particular care, especially to obtain a Caccioppoli-type inequality.

Let us sketch the four main steps of this strategy, among which two differ substantially from the case of the perimeter functional. We first need to introduce the cylindrical excess and some more notation. Let

$$\mathbf{C}(x, r, \nu) = x + \left\{ y + t\nu : y \in \nu^\perp \text{ such that } |y| < r \text{ and } t \in (-r, r) \right\}$$

denote the (truncated) cylinder centered at  $x \in \mathbb{R}^n$  with direction  $\nu \in \mathbb{S}^{n-1}$ , basis radius  $r$  and height  $2r$ .

**Definition 1.4** (Cylindrical excess). For any set of finite perimeter  $E \subseteq \mathbb{R}^n$  and any cylinder  $\mathbf{C}(x, r, \nu)$  centered at  $x \in \partial E$  we define the cylindrical excess of  $E$  in  $\mathbf{C}(x, r, \nu)$  by

$$\mathbf{e}(E, x, r, \nu) := \frac{1}{r^{n-1}} \int_{\partial^* E \cap \mathbf{C}(x, r, \nu)} \frac{|\nu - \nu_E(y)|^2}{2} d\mathcal{H}_y^{n-1}.$$

We can now proceed with the sketch of the proof for large scales.

*Step 1.* We show that if the excess of a  $(\Lambda, r_0)$ -almost minimizer  $E$  of  $\mathcal{F}_{\varepsilon, \gamma}$  is small in a cylinder  $\mathbf{C}(x, 4r, \nu)$ , then  $\partial E \cap \mathbf{C}(x, 2r, \nu)$  is almost flat and almost entirely covered by the graph of a Lipschitz function  $u$ . The proof of this is standard. Indeed, thanks to the quasi-minimality property,  $E$  satisfies uniform lower and upper density estimates. Thus, plugging results from [25, 10], we see that almost-minimizers satisfy the so-called *height bound* property, which is the main tool needed for this step.

*Step 2.* We show that the function  $u$  “almost” satisfies an equation of the form  $(\Delta - \gamma \Delta_{G_\varepsilon})u = 0$  in  $\mathbf{C}(x, r, \nu)$ , where  $\Delta_{G_\varepsilon}$  is a nonlocal operator converging to the Laplacian as  $\varepsilon \rightarrow 0$ . For this part, we proceed as follows: 1. we write the Euler–Lagrange equation (actually, inequation) associated with deformations of  $E$  in the direction of  $\nu$ , 2. carefully discarding the negligible long-range interaction terms, we “localize” the equation to the cylinder  $\mathbf{C}(x, 2r, \nu)$ , 3. we pass the equation on  $\partial E$  to the graph of  $u$  using their proximity, 4. we linearize the equation.

Eventually, since  $r$  is much larger than  $\varepsilon$ , formally  $(\Delta - \gamma \Delta_{G_\varepsilon}) \simeq (1 - \gamma)\Delta$  in  $\mathbf{C}(x, r, \nu)$ , so that  $u$  is close to a harmonic function.

*Step 3.* Since  $u$  is close to a harmonic function, we show that the *flatness* of  $E$  (see Definition 4.1) at some smaller scale  $\lambda r$  is much smaller than the excess at scale  $4r$ , up to tilting the direction. This part is standard.

*Step 4.* By analogy with functions, one should think of the excess of  $E$  as the Dirichlet energy of  $u$ , and think of the flatness of  $E$  as the  $L^2$  norm of  $u$ . To transfer the smallness of the flatness at scale  $\lambda r$  to the excess, we prove a Caccioppoli-type inequality (or Reverse Poincaré), stating roughly

$$\mathbf{e}(E, x, \lambda r/2, \nu_0) \lesssim \mathbf{f}(E, x, \lambda r, \nu_0) + \left(\frac{\varepsilon}{\lambda r}\right)^\theta \mathbf{e}(E, x, \lambda r, \nu_0) + \text{“smaller terms”}$$

whenever  $\lambda r$  is still much larger than  $\varepsilon$ . Our proof of the Caccioppoli inequality relies on an improved quasi-minimality condition when the set  $E$  is already known to be sufficiently flat (see Proposition 4.2). To obtain this improved quasi-minimality, we heavily use the 1D slicing techniques already introduced in [26] and end up having to prove that the half-plane minimizes a quantity which can be interpreted as the average shadow of the boundary of a set obstructing a tube (see (4.18)).

Eventually, suitably iterating Steps 3 and 4, we obtain the needed power decay of the excess down to any scale  $\varepsilon^{1-\beta}$ .

### Motivation.

As mentioned at the beginning of the introduction, problem  $(\mathcal{P})$  is linked with Gamow’s liquid drop model for the atomic nucleus. More precisely, if  $G \in L^1(\mathbb{R}^n)$ , then the problem  $(\mathcal{P})$  actually corresponds to the Gamow-type problem

$$\min \left\{ P(F) + \int_{F \times F} \tilde{G}(x - y) dx dy : F \subseteq \mathbb{R}^n \text{ measurable such that } |F| = m \right\}, \quad (\mathcal{G})$$

where  $\tilde{G} := 2\gamma G$  and  $m := \frac{|B_1|}{\varepsilon^n}$ . Indeed, using the integrability of  $G$ , we have

$$\int_{F \times F} \tilde{G}(x - y) dx dy = 2\gamma m \|G\|_{L^1} - 2\gamma \int_{F \times F^c} G(x - y) dx dy,$$

so that  $(\mathcal{G})$  is equivalent to

$$\min \left\{ P(F) - 2\gamma \int_{F \times F^c} G(x-y) dx dy : F \subseteq \mathbb{R}^n \text{ measurable such that } |F| = m \right\}.$$

Setting  $E := \varepsilon F$ , where  $\varepsilon = \left(\frac{|B_1|}{m}\right)^{\frac{1}{n}}$ , by [Proposition 2.8](#) (with  $r = \varepsilon$ ) we then see that  $(\mathcal{G})$  is indeed equivalent to  $(\mathcal{P})$ . This is in particular the case for Bessel kernels or integrable compactly supported kernels.

As indicated by its name, problem  $(\mathcal{G})$  was introduced by Gamow in the 1920s as a simple model for the atomic nucleus in dimension  $n = 3$  with  $\tilde{G}(x) = \frac{1}{|x|}$  (see [\[6\]](#) for a short overview of this problem). This model gave a first qualitative explanation to the phenomenon a fission. Indeed, it was shown that there are two possibly equal critical masses  $0 < m_1 \leq m_2$  such that the problem admits a minimizer below  $m_1$  (and it is necessary the ball, up to translations), but existence is lost above  $m_2$  (which is interpreted as fission). This fact was rigorously proven much later and extended to arbitrary dimension in [\[22, 23\]](#). As a prototypical example of a model exhibiting a competition between short-range attractive forces and long-range repulsive ones, this model has been extensively studied and generalized the past decade. The case of Riesz kernels  $\mathcal{R}_\alpha(x) := \frac{1}{|x|^{n-\alpha}}$  has lead to many works, where the picture is similar to the 3-dimensional case with the Newton potential  $\frac{1}{|x|}$ : for every  $\alpha \in (0, n)$ , there exists a critical mass below which the ball is the unique minimizer (see [\[21, 4, 12\]](#)), and for every  $\alpha \in [n-2, n)$ , there exists a critical mass above which the problem admits no minimizer (see [\[4, 22, 23, 24, 13, 15, 14\]](#)).

If we consider a class of kernels which are integrable near the origin (to ensure that Gamow's problem rewrites as  $(\mathcal{P})$ ) and with a finite first moment, the nonlocal term can be regarded as a nonlocal perimeter. In that case, in contrast with Riesz kernels, the problem admits minimizers for any mass large enough whenever  $I_G^1 < \frac{2}{\mathbb{K}_{1,n}}$ , and after rescaling minimizers converge to the ball as the mass goes to infinity (see [\[27, 26\]](#)). Our work improves this result by establishing the following, which is a direct consequence of [Theorem A](#). If  $\tilde{G} \in L^1(\mathbb{R}^n)$ ,  $I_G^1 < \frac{2}{\mathbb{K}_{1,n}}$  and  $\tilde{G}$  satisfies [\(H1\)](#), [\(H3\)](#) and [\(H5\)](#), then there exists  $m_* > 0$  such that for every  $m \geq m_*$ , the ball of volume  $m$  is, up to translations, the unique minimizer of  $(\mathcal{G})$ .

It is worth mentioning that one can observe the same behavior (the ball is the unique minimizer for large masses) in the case of Riesz kernels by considering

$$\int_{\partial^* E} a(x) d\mathcal{H}_x^{n-1}$$

instead of the perimeter, where  $a$  is a density which grows sufficiently fast at infinity (see [\[1\]](#)).

**Outline of the paper.** The structure of the paper is as follows. In [Section 2](#), we recall and prove a few facts about nonlocal perimeters as well as some useful results from [\[27, 26\]](#) on minimizers of  $(\mathcal{P})$ . We then establish uniform density estimates for  $(\Lambda, r_0)$ -minimizers of  $\mathcal{F}_{\varepsilon, \gamma}$  and show that minimizers of  $(\mathcal{P})$  are almost-minimizers of  $\mathcal{F}_{\varepsilon, \gamma}$ . Eventually, we recall some basic properties of the excess and argue that such almost-minimizers satisfy the height bound property. In [Section 3](#) we prove the Lipschitz approximation theorem at scales which are much larger than  $\varepsilon$  ([Theorems 3.1](#) and [3.2](#)), which corresponds to the steps 2-3 sketched above. In [Section 4](#), we establish the Caccioppoli inequality for  $(\Lambda, r_0)$ -minimizers of  $\mathcal{F}_{\varepsilon, \gamma}$ . Finally, building upon [Sections 3](#) and [4](#), [Section 5](#) is devoted to establishing power decay of the excess from large scales down to arbitrarily small scales and consequently [Theorems A](#) and [B](#).

### Notation.

We write any point  $x \in \mathbb{R}^n$  as  $x = (x', x_n)$ . We denote by  $B_r(x) \subseteq \mathbb{R}^n$  the open ball of radius  $r$  in  $\mathbb{R}^n$  centered at  $x$ . When  $x = 0$  we simply write  $B_r$  for  $B_r(0)$ . For open balls in  $\mathbb{R}^{n-1}$ , we write  $D_r(x')$  and simply  $D_r$  when  $x' = 0$ . For any  $m \in \mathbb{N}$ ,  $\omega_m$  denotes the volume of the unit ball in  $\mathbb{R}^m$ , that is, its Lebesgue measure in  $\mathbb{R}^m$ .

For any set  $E \subseteq \mathbb{R}^n$ , we denote by  $E^c := \mathbb{R}^n \setminus E$  its complement, and write  $|E|$  for its volume whenever  $E$  is measurable. For any  $m \in \mathbb{N}$  we denote by  $\mathcal{H}^m$  the  $m$ -dimensional Hausdorff measure in  $\mathbb{R}^n$ . When integrating with respect to the measure  $\mathcal{H}^m$  in a variable  $x$ , we use the notation  $d\mathcal{H}_x^m$  instead of the standard but less compact notation  $d\mathcal{H}^m(x)$ . If  $A$  is of dimension  $m$  and  $f$  is  $\mathcal{H}^m$ -measurable, we often

use the convention

$$\int_A f := \int_A f(x) d\mathcal{H}_x^m.$$

Similarly, we will sometimes use the compact notation  $f_x := f(x)$ .

When  $\nu = e_n$  (the  $n$ -th vector of the canonical basis of  $\mathbb{R}^n$ ) we write  $\mathbf{C}_r(x)$  for the cylinder  $\mathbf{C}(x, r, \nu)$  and simply  $\mathbf{C}_r$  if in addition  $x = 0$ . We also write  $\mathbf{e}_n(E, x, r)$  for  $\mathbf{e}(E, x, r, e_n)$  and for  $x = 0$ ,  $\mathbf{e}_n(E, r) = \mathbf{e}_n(E, 0, r)$ . Moreover, when there is no risk of confusion we drop the explicit dependence on  $E$ .

## 2. PRELIMINARY

**2.1. Nonlocal perimeter and first variation.** In this section we recall a few basic properties of the nonlocal perimeter depending on our assumptions on  $G$ .

The following proposition is a consequence of [8] and our choice of  $I_G^1$ . It ensures that  $P_\varepsilon$  is well-defined on sets of finite perimeter and is bounded from above by the standard perimeter. We also state it for a general  $K$ , not necessarily normalized, since we will often use it with other kernels.

**Proposition 2.1** (Upper bound). *Assume that  $K : \mathbb{R}^n \rightarrow [0, \infty)$  satisfies (H1) and  $x \mapsto |x|K(x) \in L^1(\mathbb{R}^n)$ . Then, for every set of finite perimeter  $E$  in  $\mathbb{R}^n$ , we have*

$$P_K(E) \leq \mathbb{K}_{1,n} I_K^1 P(E). \quad (2.1)$$

In particular, for the kernels  $G_\varepsilon$ , we have

$$P_\varepsilon(E) \leq P(E), \quad \forall \varepsilon > 0. \quad (2.2)$$

Let us recall that  $P_\varepsilon$  is continuous with respect to the  $L^1$  topology along sequences with bounded perimeter.

**Lemma 2.2** (Continuity). *Assume that  $G$  satisfies (H1) and (H2). Let  $E_k$  be a sequence of sets of finite perimeter in  $\mathbb{R}^n$  and  $E \subseteq \mathbb{R}^n$  such that*

$$\sup_k (P(E_k) + |E_k|) < \infty \quad \text{and} \quad E_k \xrightarrow{L^1} E.$$

Then, for every  $\varepsilon > 0$ , we have

$$\lim_k P_\varepsilon(E_k) = P_\varepsilon(E).$$

*Proof.* Let  $C := \sup_k (P(E_k) + |E_k|) < \infty$ . Setting

$$u_k(z) := \int_{\mathbb{R}^n} |\mathbf{1}_{E_k}(x+z) - \mathbf{1}_{E_k}(x)| dx \quad \text{and} \quad u(z) := \int_{\mathbb{R}^n} |\mathbf{1}_E(x+z) - \mathbf{1}_E(x)| dx,$$

by the  $L^1$  convergence of  $E_k$  to  $E$ , for every  $z \in \mathbb{R}^n$ ,  $u_k(z)$  converges to  $u(z)$ . In addition, we have

$$P_\varepsilon(E_k) = \int_{\mathbb{R}^n} u_k(z) G_\varepsilon(z) dz$$

and

$$u_k(z) G_\varepsilon(z) \leq P(E_k) |z| G_\varepsilon(z) \leq C |z| G_\varepsilon(z) \in L^1(\mathbb{R}^n).$$

Hence by dominated convergence,  $\lim_k P_\varepsilon(E_k) = P_\varepsilon(E)$ .  $\square$

Depending on the integrability assumptions on  $G$ , we may estimate the difference  $P_\varepsilon(E) - P_\varepsilon(F)$  from above by a perimeter term, a volume term, or an interpolation of the two. This type of estimates is relatively standard in the context of nonlocal perimeters (see for instance [11, Lemma 5.3] for a similar statement in the case of  $s$ -perimeters). The last interpolation estimate will allow us to show a useful quasi-minimality property at small scales for  $(\Lambda, r_0)$ -minimizers of  $\mathcal{F}_{\varepsilon, \gamma}$  (see Proposition 2.12).

**Lemma 2.3.** *Let  $E, F \subseteq \mathbb{R}^n$  be two measurable sets, and let  $\varepsilon > 0$ . We have:*

(i) *if  $G$  satisfies (H1) and (H2), then*

$$P_\varepsilon(E) - P_\varepsilon(F) \leq P(E \Delta F); \quad (2.3)$$

(ii) *if  $G$  satisfies (H1) and  $G \in L^1(\mathbb{R}^n)$ , then*

$$P_\varepsilon(E) - P_\varepsilon(F) \leq \frac{2I_G^0}{\varepsilon} |E \Delta F|;$$



(iii) if  $G$  satisfies (H1), (H2) and (H4), then there exists  $C = C(n, G) > 0$  such that

$$P_\varepsilon(E) - P_\varepsilon(F) \leq C \left( \frac{|E\Delta F|}{\varepsilon} \right)^{1-s_0} P(E\Delta F)^{s_0}. \quad (2.4)$$

*Proof.* We decompose the proof in two steps.

*Step 1.* We establish  $P_\varepsilon(E) - P_\varepsilon(F) \leq P_\varepsilon(E\Delta F)$ . To this aim we note for  $A, B \subseteq \mathbb{R}^n$ ,

$$\Phi_\varepsilon(A, B) := \int_{A \times B} G_\varepsilon(x - y) \, dx \, dy$$

so that  $P_\varepsilon(E) = 2\Phi_\varepsilon(E, E^c)$ . It is readily checked that

$$\begin{aligned} \Phi_\varepsilon(E, E^c) - \Phi_\varepsilon(F, F^c) &= \Phi_\varepsilon(E \cap F, F \setminus E) + \Phi_\varepsilon(E \setminus F, E^c \cap F^c) - \Phi_\varepsilon(E \cap F, E \setminus F) \\ &\quad - \Phi_\varepsilon(F \setminus E, F^c \cap E^c) \\ &= \Phi_\varepsilon(E\Delta F, (E\Delta F)^c) - 2[\Phi_\varepsilon(E \cap F, E \setminus F) + \Phi_\varepsilon(F \setminus E, F^c \cap E^c)] \\ &\leq \Phi_\varepsilon(E\Delta F, (E\Delta F)^c). \end{aligned}$$

This concludes the first step.

*Step 2.* We deduce the different cases. Case (i) is direct consequence of Step 1 and (2.2). If  $G \in L^1(\mathbb{R}^n)$  then

$$P_\varepsilon(E) \leq 2\|G_\varepsilon\|_{L^1(\mathbb{R}^n)}|E|$$

which gives (ii). For (iii), let us write, for any  $R > 0$  and any  $E \subseteq \mathbb{R}^n$ ,

$$P_\varepsilon(E) = \int_{\mathbb{R}^n \setminus B_R} G_\varepsilon(z) \int_{\mathbb{R}^n} |\chi_E(x+z) - \chi_E(x)| \, dx \, dz + \int_{B_R} G_\varepsilon(z) \int_{\mathbb{R}^n} |\chi_E(x+z) - \chi_E(x)| \, dx \, dz.$$

Using

$$\int_{\mathbb{R}^n} |\chi_E(x+z) - \chi_E(x)| \, dx \leq 2|E|$$

and

$$\int_{\mathbb{R}^n} |\chi_E(x+z) - \chi_E(x)| \, dx \leq |z|P(E),$$

we deduce

$$\begin{aligned} P_\varepsilon(E) &\leq 2|E| \int_{\mathbb{R}^n \setminus B_R} G_\varepsilon(z) \, dz + P(E) \int_{B_R} |z|G_\varepsilon(z) \, dz \\ &= \frac{2|E|}{\varepsilon} \int_{\mathbb{R}^n \setminus B_{R/\varepsilon}} G(z) \, dz + P(E) \int_{B_{R/\varepsilon}} |z|G(z) \, dz. \end{aligned} \quad (2.5)$$

Next, we claim that (H4) implies

$$\int_{\mathbb{R}^n \setminus B_r} G(x) \, dx \leq \frac{C}{r^{s_0}}, \quad \forall r > 0 \quad (2.6)$$

and

$$\int_{B_r} |x|G(x) \, dx \leq Cr^{1-s_0}, \quad \forall r > 0, \quad (2.7)$$

for some  $C = C(n, G) > 0$ . It is of course enough to check these statements for either small or large  $r$ . We start with (2.6). Thanks to (H4), it holds for small  $r$ . If instead  $r \geq 1$ ,

$$\int_{\mathbb{R}^n \setminus B_r} G(x) \, dx \leq \frac{1}{r} \int_{\mathbb{R}^n \setminus B_r} |x|G(x) \, dx \leq \frac{I_G^1}{r} \leq \frac{C}{r^{s_0}}.$$

We now turn to (2.7). By (H2) it is enough to prove it for  $r \in (0, 1)$ . In this case, we have

$$\begin{aligned} \int_{B_r} |x|G(x) \, dx &= \sum_{k=0}^{\infty} \int_{B_{2^{-k}r} \setminus B_{2^{-(k+1)}r}} |x|G(x) \, dx \leq \sum_{k=0}^{\infty} \frac{r}{2^k} \int_{B_1 \setminus B_{2^{-(k+1)}r}} G(x) \, dx \\ &\stackrel{(2.6)}{\leq} C \sum_{k=0}^{\infty} \frac{r}{2^k} \left( \frac{2^k}{r} \right)^{s_0} = Cr^{1-s_0} \sum_{k=0}^{\infty} \frac{1}{2^{k(1-s_0)}} \leq Cr^{1-s_0}, \end{aligned}$$

proving (2.7).

Plugging (2.6) and (2.7) into (2.5) yields

$$P_\varepsilon(E) \leq C \left( \frac{|E|}{\varepsilon} \left( \frac{\varepsilon}{R} \right)^{s_0} + P(E) \left( \frac{R}{\varepsilon} \right)^{1-s_0} \right).$$

Finally choosing  $R = \frac{|E|}{P(E)}$ , we get

$$P_\varepsilon(E) \leq C \left( \frac{|E|}{\varepsilon} \right)^{1-s_0} P(E)^{s_0}.$$

This concludes the proof of (iii).  $\square$

We will use the following computation from [26, Lemma 2.3] to estimate the derivative of the nonlocal perimeter under rescaling.

**Lemma 2.4.** *Assume that  $G$  satisfies (H1), (H2) and (H3). Then for any set of finite perimeter  $E \subseteq \mathbb{R}^n$ , the function  $t \mapsto P_\varepsilon(tE)$  is locally Lipschitz continuous in  $(0, +\infty)$ , and for almost every  $t$ , we have*

$$\frac{d}{dt} [P_\varepsilon(tE)] = \frac{n}{t} P_\varepsilon(tE) - \frac{1}{t} \tilde{P}_\varepsilon(tE),$$

where  $\tilde{P}_\varepsilon(E)$  is defined by

$$\tilde{P}_\varepsilon(E) := 2 \int_E \int_{\partial^* E} G_\varepsilon(x-y) (y-x) \cdot \nu_E(y) d\mathcal{H}_y^{n-1} dx. \quad (2.8)$$

We now compute the first variation of the energy.

**Lemma 2.5.** *Assume that  $G$  satisfies (H1), (H2) and (H3). Let  $T \in C_c^1(\mathbb{R}^n; \mathbb{R}^n)$  a compactly supported vector field, and let us define  $f_t := \text{Id}_{\mathbb{R}^n} + tT$ . Then for any set of finite perimeter  $E \subseteq \mathbb{R}^n$ ,  $\varepsilon > 0$ ,  $\gamma \in (0, 1)$  and  $\Lambda \geq 0$ , the function  $t \mapsto \mathcal{F}_{\varepsilon, \gamma}(f_t(E))$  is differentiable at  $t = 0$  with  $\delta \mathcal{F}_{\varepsilon, \gamma}(E)[T] := \left[ \frac{d}{dt} \mathcal{F}_{\varepsilon, \gamma}(f_t(E)) \right]_{|t=0}$  given by*

$$\begin{aligned} \delta \mathcal{F}_{\varepsilon, \gamma}(E)[T] &= \int_{\partial^* E} \text{div}_E T d\mathcal{H}^{n-1} \\ &\quad - 2\gamma \left( \int_{E \times E^c} \text{div} T(x) G_\varepsilon(x-y) dx dy + \int_{\partial^* E} \int_E G_\varepsilon(x-y) (T(x) - T(y)) \cdot \nu_E(y) dx d\mathcal{H}_y^{n-1} \right) \end{aligned}$$

where  $\text{div}_E T$  is the boundary divergence of  $T$  on  $E$ , defined by

$$\text{div}_E T(x) := \text{div} T(x) - \nu_E(x) \cdot \nabla T(x) \nu_E(x), \quad \forall x \in \partial^* E.$$

*Proof.* Since the computation of the first variation of the perimeter is standard, see e.g. [25, Theorem 17.5], it is enough to compute the first variation of  $P_\varepsilon$ . We will show that (recall the notation  $T_x = T(x)$ )

$$\begin{aligned} \left[ \frac{d}{dt} P_\varepsilon(f_t(E)) \right]_{|t=0} &= 2 \int_{E \times E^c} \text{div} T(x) G_\varepsilon(x-y) dx dy \\ &\quad + 2 \int_{\partial^* E} \int_E G_\varepsilon(x-y) (T_x - T_y) \cdot \nu_E(y) dx d\mathcal{H}_y^{n-1}. \end{aligned}$$

Notice that using (2.2) and the fact that  $T$  is Lipschitz continuous, (H1) and (H2) imply that both terms on the right-hand side are well-defined. Since  $\varepsilon$  does not play any role we may assume without loss of generality that  $\varepsilon = 1$ . We set  $F_G(t) := \frac{1}{2} P_1(f_t(E))$ . Note that choosing  $t_0 \leq 1/\|\nabla T\|_{L^\infty}$ ,  $f_t$  is a diffeomorphism of  $\mathbb{R}^n$  for every  $t$  such that  $|t| \leq t_0$ . In particular  $f_t(E)$  is a set of finite perimeter (see e.g. [25, Proposition 17.1]). Thus,  $F_G(t)$  is well-defined for every  $t \in (-t_0, t_0)$ . We then set (for the moment this is just a notation)

$$F'_G(0) := \int_{E \times E^c} \text{div} T(x) G(x-y) dx dy + \int_{\partial^* E} \int_E G(x-y) (T_x - T_y) \cdot \nu_E(y) dx d\mathcal{H}_y^{n-1}.$$

We claim that as  $t \rightarrow 0$ ,

$$F_G(t) - F_G(0) - tF'_G(0) = o(t). \quad (2.9)$$

This would show that  $F_G$  is differentiable in 0 with derivative  $F'_G(0)$ , concluding the proof. Changing variables, for any  $t$  small enough we have

$$F_G(t) = \int_{E \times E^c} G(f_t(x) - f_t(y)) \det Df_t(x) \det Df_t(y) dx dy.$$

Since  $\det Df_t(x) = 1 + t \operatorname{div} T(x) + O(t^2)$ , we find

$$F_G(t) = \int_{E \times E^c} G(f_t(x) - f_t(y)) (1 + t \operatorname{div} T(x) + t \operatorname{div} T(y) + O(t^2)) dx dy.$$

Notice that by the reverse change of variables and (2.2),

$$\int_{E \times E^c} G(f_t(x) - f_t(y)) dx dy \leq C \int_{f_t(E) \times f_t(E)^c} G(x - y) dx dy \leq CP(f_t(E)) \leq CP(E).$$

Therefore

$$F_G(t) = \int_{E \times E^c} G(f_t(x) - f_t(y)) (1 + t \operatorname{div} T(x) + t \operatorname{div} T(y)) dx dy + O(t^2).$$

Now, using that

$$G(f_t(x) - f_t(y)) - G(x - y) = t \int_0^1 \nabla G(f_{st}(x) - f_{st}(y)) \cdot (T_x - T_y) ds$$

and the Lipschitz continuity of  $T$ , we have

$$\begin{aligned} & \left| \int_{E \times E^c} G(f_t(x) - f_t(y)) \operatorname{div} T(x) dx dy - \int_{E \times E^c} G(x - y) \operatorname{div} T(x) dx dy \right| \\ & \leq C|t| \int_0^1 \int_{E \times E^c} |\nabla G(f_{st}(x) - f_{st}(y))| |x - y| dx dy ds \\ & \leq C|t| \int_0^1 \int_{E \times E^c} |\nabla G(f_{st}(x) - f_{st}(y))| |f_{st}(x) - f_{st}(y)| dx dy ds \\ & \leq C|t| \int_0^1 \int_{f_{st}(E) \times (f_{st}(E))^c} |\nabla G(x - y)| |x - y| dx dy ds \\ & \leq CI_{|\nabla G|}^2 |t| \int_0^1 P(f_{st}(E)) ds \leq CI_{|\nabla G|}^2 |t|, \end{aligned}$$

where we used again (2.1) but for the kernel  $K = |\cdot| |\nabla G|$ . Since the same holds with  $\operatorname{div} T(x)$  replaced by  $\operatorname{div} T(y)$ , in order to prove (2.9) it is thus enough to show

$$\begin{aligned} & \int_{E \times E^c} G(f_t(x) - f_t(y)) dx dy - \int_{E \times E^c} G(x - y) dx dy \\ & + t \left( \int_{E \times E^c} G(x - y) \operatorname{div} T(y) dx dy - \int_{\partial^* E} \int_E G(x - y) (T_x - T_y) \cdot \nu_E(y) dx d\mathcal{H}_y^{n-1} \right) = o(t). \end{aligned}$$

Writing as above that

$$\begin{aligned} & \int_{E \times E^c} G(f_t(x) - f_t(y)) dx dy - \int_{E \times E^c} G(x - y) dx dy \\ & = t \int_0^1 \int_{E \times E^c} \nabla G(f_{st}(x) - f_{st}(y)) \cdot (T_x - T_y) dx dy ds \end{aligned}$$

we reduce it further to the proof of

$$\lim_{t \rightarrow 0} \int_0^1 \int_{E \times E^c} \nabla G(f_{st}(x) - f_{st}(y)) \cdot (T_x - T_y) dx dy ds = \int_{E \times E^c} \nabla G(x - y) \cdot (T_x - T_y) dx dy \quad (2.10)$$

together with the integration by parts formula

$$\begin{aligned} & \int_{E \times E^c} \nabla G(x - y) \cdot (T_x - T_y) + G(x - y) \operatorname{div} T(y) dx dy \\ & = \int_{\partial^* E} \int_E G(x - y) (T_x - T_y) \cdot \nu_E(y) dx d\mathcal{H}_y^{n-1}. \quad (2.11) \end{aligned}$$

Notice that this would be easy to prove if  $G$  was a smooth kernel with compact support. However, since our assumptions on  $G$  seem too weak to prove these directly we will argue by approximation. Let  $G_k$  be a sequence of smooth compactly supported radial kernels with

$$\lim_{k \rightarrow \infty} \int_{\mathbb{R}^n} |z| |G - G_k|(z) dz = 0 \quad \text{and} \quad \lim_{k \rightarrow \infty} \int_{\mathbb{R}^n} |z|^2 |\nabla[G - G_k](z)| dz = 0.$$

Since we assumed that  $I_G^1 + I_{|\nabla G|}^2 < \infty$  it is not difficult to construct such a sequence. We start with (2.10). For every fixed  $s \in [0, 1]$ , we have

$$\begin{aligned} & \left| \int_{E \times E^c} \nabla G(f_{st}(x) - f_{st}(y)) \cdot (T_x - T_y) dx dy - \int_{E \times E^c} \nabla G_k(f_{st}(x) - f_{st}(y)) \cdot (T_x - T_y) dx dy \right| \\ & \leq C \int_{E \times E^c} |[\nabla G - \nabla G_k](f_{st}(x) - f_{st}(y))| |x - y| dx dy \\ & \leq C \int_{f_{st}(E) \times f_{st}(E)^c} |\nabla[G - G_k](x - y)| |x - y| dx dy \\ & \leq C \left( \int_{\mathbb{R}^n} |z|^2 |\nabla[G - G_k](z)| dz \right) P(f_{st}(E)) \\ & \leq C \int_{\mathbb{R}^n} |z|^2 |\nabla[G - G_k](z)| dz, \end{aligned}$$

where we used (2.1) with  $K = |\cdot| |\nabla[G - G_k]|$  (which is radially symmetric). Integrating in  $s$  and using a simple diagonal argument, this proves (2.10). We now turn to (2.11). Since

$$-\operatorname{div}_y(G(x - y)(T_x - T_y)) = \nabla G(x - y) \cdot (T_x - T_y) + G(x - y) \operatorname{div} T(y),$$

the integration by parts formula (2.11) holds with  $G$  replaced by  $G_k$ . By the previous computations it is therefore enough to observe that on the one hand

$$\left| \int_{E \times E^c} G(x - y) \operatorname{div} T(y) dx dy - \int_{E \times E^c} G_k(x - y) \operatorname{div} T(y) dx dy \right| \leq CP(E) \int_{\mathbb{R}^n} |z| |G - G_k|(z) dz$$

and on the other hand,

$$\begin{aligned} & \left| \int_{\partial^* E} \int_E G(x - y) (T_x - T_y) \cdot \nu_E(y) dx d\mathcal{H}_y^{n-1} - \int_{\partial^* E} \int_E G_k(x - y) (T_x - T_y) \cdot \nu_E(y) dx d\mathcal{H}_y^{n-1} \right| \\ & \leq C \int_{\partial^* E} \int_E |x - y| |G - G_k|(x - y) dx d\mathcal{H}_y^{n-1} \leq CP(E) \int_{\mathbb{R}^n} |z| |G - G_k|(z) dz. \end{aligned}$$

□

**2.2. Perimeter quasi-minimizing properties of minimizers.** We recall from [27] that if  $G$  satisfies (H1) and (H2) minimizers of (P) exist for  $\varepsilon$  small enough (in [27] the extra hypothesis  $G \in L^1(\mathbb{R}^n)$  was imposed but as pointed out in [26, Theorem 2.7] it is not used in the proof).

**Proposition 2.6.** *Let  $\gamma \in (0, 1)$  and assume that  $G$  satisfies (H1) and (H2). Then there exists  $\varepsilon_{\text{ex}} > 0$  and a function  $\delta : (0, +\infty) \rightarrow (0, +\infty)$  vanishing in 0, both depending only on  $n, G$  and  $\gamma$  such that, for any  $\varepsilon \in (0, \varepsilon_{\text{ex}})$ , (P) admits a minimizer, and any minimizer  $E$  satisfies, up to a translation and a Lebesgue-negligible set,*

$$B_{1-\delta(\varepsilon)} \subseteq E_\varepsilon \subseteq B_{1+\delta(\varepsilon)}.$$

We also recall from [27, (4.2)] that using (2.2) it readily follows that if  $E$  satisfies  $\mathcal{F}_{\varepsilon, \gamma}(E) \leq \mathcal{F}_{\varepsilon, \gamma}(B_1)$ , then

$$P(E) \leq P(B_1) + \frac{\gamma}{1-\gamma} (P(B_1) - P_\varepsilon(B_1)) \leq \frac{1}{1-\gamma} P(B_1). \quad (2.12)$$

We now use the scaling properties given in Lemma 2.4 to prove the equivalence between (P) and the unconstrained minimization problem

$$\min \left\{ \mathcal{F}_{\varepsilon, \gamma}(E) + \Lambda ||E| - |B_1|| : E \subseteq \mathbb{R}^n \text{ measurable} \right\} \quad (\mathcal{P}')$$

if  $\Lambda$  is large enough, not depending on  $\varepsilon$ . As a consequence, minimizers of (P) are  $(\Lambda, r_0)$ -minimizers of  $\mathcal{F}_{\varepsilon, \gamma}$ .

**Proposition 2.7.** *Assume that  $G$  satisfies (H1) and (H2) and let  $\gamma \in (0, 1)$ . There exists  $C = C(n) > 0$  such that for every  $\gamma \in (0, 1)$ ,  $\varepsilon > 0$  and  $\Lambda \geq C/(1 - \gamma)$ , problems (P) and (P') are equivalent, in the sense that (P') admits a minimizer iff (P) does, and their minimizers coincide. In particular, any minimizer of (P) is a  $(\Lambda, r_0)$ -minimizer of  $\mathcal{F}_{\varepsilon, \gamma}$  for any  $\Lambda \geq C/(1 - \gamma)$  and any  $r_0 > 0$ .*

*Proof.* Let us set

$$\Lambda_0 := \frac{1}{1 - \gamma} \left( 1 + \left( n + \frac{2}{\mathbb{K}_{1,n}} \right) \right) \frac{P(B_1)}{|B_1|}.$$

Since

$$\inf_{|E|=|B_1|} \mathcal{F}_{\varepsilon, \gamma}(E) \geq \inf_E \mathcal{F}_{\varepsilon, \gamma, \Lambda}(E),$$

it is enough to prove that for  $\Lambda \geq \Lambda_0$ , the converse inequality holds and that any set minimizing  $\mathcal{F}_{\varepsilon, \gamma, \Lambda}$  must have measure equal to  $\omega_n$ . This in turn is equivalent to the claim that if  $E$  is such that

$$|E| \neq \omega_n \quad \text{and} \quad \mathcal{F}_{\varepsilon, \gamma, \Lambda}(E) \leq \inf_{|E|=|B_1|} \mathcal{F}_{\varepsilon, \gamma}(E)$$

then  $\Lambda < \Lambda_0$ . Let  $E$  be such a set. Recall that  $E$  satisfies (2.12). Let  $\lambda$  be such that  $|\lambda E| = |B_1|$ . We then have

$$P(E) - \gamma P_\varepsilon(E) + \Lambda(|E| - |B_1|) = \mathcal{F}_{\varepsilon, \gamma, \Lambda}(E) \leq \mathcal{F}_{\varepsilon, \gamma}(\lambda E) = \lambda^{n-1} P(E) - \gamma P_\varepsilon(\lambda E).$$

Reorganizing terms we find

$$\Lambda \omega_n |\lambda^n - 1| \leq (\lambda^{n-1} - 1) P(E) + \gamma |P_\varepsilon(E) - P_\varepsilon(\lambda E)|. \quad (2.13)$$

By Lemma 2.4 and (2.2), for any  $t > 0$  we have

$$\left| \frac{d}{dt} [P_\varepsilon(tE)] \right| \leq \frac{1}{t} \left( n P_\varepsilon(tE) + |\tilde{P}_{G_\varepsilon}(tE)| \right) \leq \frac{1}{t} \left( n P(tE) + 2P(tE) I_G^1 \right) \leq t^{n-2} \left( n + \frac{2}{\mathbb{K}_{1,n}} \right),$$

thus

$$|P_\varepsilon(E) - P_\varepsilon(\lambda E)| \leq \left| \int_\lambda^1 \frac{d}{dt} [P_\varepsilon(tE)] dt \right| \leq C_1 |\lambda^{n-1} - 1| P(E),$$

where  $C_1 := \left( n + \frac{2}{\mathbb{K}_{1,n}} \right)$ . Inserting this into (2.13) and using (2.12), this leads to

$$\Lambda \omega_n |\lambda^n - 1| \leq \frac{1}{1 - \gamma} (1 + C_1 \gamma) P(B_1) |\lambda^{n-1} - 1|.$$

Since  $|\lambda^{n-1} - 1| < |\lambda^n - 1|$  we conclude that  $\Lambda < \Lambda_0$ . □

To simplify the proofs, we will often rescale sets in order to assume cylinders are of unit length. This is justified by the following elementary scaling properties, which is given by a simple change of variables.

**Proposition 2.8.** *For any set of finite perimeter  $E$ , any  $\varepsilon > 0$  and any  $r > 0$  we have*

$$\mathcal{F}_{\varepsilon, \gamma}(E) = r^{n-1} \mathcal{F}_{\varepsilon/r, \gamma}(E/r).$$

*In particular  $E$  is a  $(\Lambda, r_0)$ -minimizer of  $\mathcal{F}_{\varepsilon, \gamma}$  if and only if  $E/r$  is a  $(\Lambda, \frac{r_0}{r})$ -minimizer of  $\mathcal{F}_{\varepsilon/r, \gamma}$ .*

We now prove that  $(\Lambda, r_0)$ -minimizers of  $\mathcal{F}_{\varepsilon, \gamma}$  are quasi-minimizers of the perimeter and thus have density bounds which are uniform in  $\varepsilon$ .

**Proposition 2.9** (Weak quasi-minimality). *Assume that  $G$  satisfies (H1) and (H2) and let  $\gamma \in (0, 1)$ ,  $\varepsilon > 0$ ,  $\Lambda > 0$  and  $r_0 > 0$  with  $\Lambda r_0 \leq 1 - \gamma$ . Then, for any  $(\Lambda, r_0)$ -minimizer  $E$  of  $\mathcal{F}_{\varepsilon, \gamma}$  and every set  $F$  with  $E \Delta F \subset \subset B_r(x)$  with  $0 < r \leq r_0$  we have*

$$P(E; B_r(x)) \leq \frac{4}{1 - \gamma} P(F; B_r(x)). \quad (2.14)$$

*As a consequence, there exists  $C = C(n) > 0$  such that for every  $x \in \partial E$  and every  $0 < r \leq r_0$ ,*

$$\left( \frac{1 - \gamma}{4} \right)^n \leq \frac{|E \cap B_r(x)|}{r^n} \leq 1 - \left( \frac{1 - \gamma}{4} \right)^n \quad \text{and} \quad \frac{(1 - \gamma)^{n-1}}{C} \leq \frac{P(E; B_r(x))}{r^{n-1}} \leq \frac{C}{1 - \gamma}. \quad (2.15)$$

*In particular, we have*

$$\mathcal{H}^{n-1}(\partial E \setminus \partial^* E) = 0. \quad (2.16)$$

*Proof.* We only prove (2.14) since it is standard that weak quasi-minimality implies density upper and lower bounds, which then imply (2.16). To obtain the correct scaling in  $\gamma$ , one can repeat the proof in [25, Theorem 21.11]. By scaling and translation, we may assume that  $r = 1$  and  $x = 0$ . Testing the  $(\Lambda, r_0)$ -minimality of  $E$  against  $F$ , we have

$$\begin{aligned} P(E; B_1) &\leq P(F; B_1) + \gamma(P_\varepsilon(E) - P_\varepsilon(F)) + \Lambda|E\Delta F| \\ &\stackrel{(2.3)\&(2.2)}{\leq} P(F; B_1) + \gamma P(E\Delta F) + \Lambda|E\Delta F|. \end{aligned}$$

We now argue as in [25, Remark 21.7], and use the isoperimetric inequality to infer

$$|E\Delta F| = |E\Delta F|^{\frac{1}{n}} |E\Delta F|^{1-\frac{1}{n}} \leq \frac{1}{n} P(E\Delta F).$$

We thus find

$$P(E; B_1) \leq P(F; B_1) + \left(\gamma + \frac{\Lambda}{n}\right) P(E\Delta F) \leq P(F; B_1) + \left(\gamma + \frac{\Lambda}{n}\right) (P(E; B_1) + P(F; B_1)).$$

Rearranging terms and using that  $\Lambda/n \leq (1-\gamma)/2$  yields (2.14).  $\square$

*Remark 2.10.* By Proposition 2.7 we can choose e.g.  $\Lambda := C/(1-\gamma)$  and  $r_0 := (1-\gamma)^2/C$ , so that minimizers of  $(\mathcal{P})$  are  $(\Lambda, r_0)$ -minimizers of  $\mathcal{F}_{\varepsilon, \gamma}$  with  $\Lambda r_0 \leq 1-\gamma$ .

*Remark 2.11.* Thanks to (2.16) if  $E$  is a  $(\Lambda, r_0)$ -minimizer of  $\mathcal{F}_{\varepsilon, \gamma}$  with  $\Lambda r_0 \leq 1-\gamma$ , we will not distinguish anymore between  $\partial E$  and  $\partial^* E$  when integrating.

Under hypothesis (H4) we prove that minimizers of  $(\mathcal{P}')$  are also almost-minimizers at scales which are small compared to  $\varepsilon$ .

**Proposition 2.12.** *Assume that  $G$  satisfies (H1), (H2) and (H4). Then there exists  $C = C(n, G, \gamma) > 0$  such that for every  $\gamma \in (0, 1)$ ,  $\varepsilon > 0$ ,  $\Lambda > 0$  and  $r_0 > 0$  with  $\Lambda r_0 \leq 1-\gamma$ , every  $(\Lambda, r_0)$ -minimizer  $E$  of  $\mathcal{F}_{\varepsilon, \gamma}$  and every set  $F$  with  $E\Delta F \subset\subset B_r(x)$  and  $r \leq r_0$ , we have*

$$P(E; B_r(x)) \leq P(F; B_r(x)) + \left(\frac{C}{\varepsilon^{1-s_0}}\right) r^{n-s_0} + \Lambda|E\Delta F|. \quad (2.17)$$

*Proof.* We may assume that  $P(F; B_r(x)) \leq P(E; B_r(x))$  otherwise there is nothing to prove. Arguing as above using the  $(\Lambda, r_0)$ -minimality of  $E$  we have

$$\begin{aligned} P(E; B_r(x)) &\leq P(F; B_r(x)) + \gamma(P_\varepsilon(E) - P_\varepsilon(F)) + \Lambda|E\Delta F| \\ &\stackrel{(2.4)}{\leq} P(F; B_r(x)) + C\gamma \left(\frac{|E\Delta F|}{\varepsilon}\right)^{1-s_0} P(E\Delta F)^{s_0} + \Lambda|E\Delta F| \\ &\stackrel{(2.15)}{\leq} P(F; B_r(x)) + \left(\frac{C}{\varepsilon^{1-s_0}}\right) r^{n-s_0} + \Lambda|E\Delta F|. \end{aligned}$$

$\square$

*Remark 2.13.* Proposition 2.12 indeed yields classical almost-minimality for the perimeter at scales smaller than  $\varepsilon$  since letting  $r = \varepsilon\hat{r}$  and  $E = x + \varepsilon\hat{E}$ , we find for every  $\hat{F}\Delta\hat{E} \subset\subset B_{\hat{r}}$ ,

$$P(\hat{E}; B_{\hat{r}}) \leq P(\hat{F}; B_{\hat{r}}) + C\hat{r}^{n-s_0} + \Lambda\varepsilon|\hat{E}\Delta\hat{F}|.$$

**2.3. Basic properties of the excess.** We recall two basic properties of the excess that we use extensively in the rest of the paper. The cylindrical excess and spherical excess are respectively defined in Definition 1.3 and Definition 1.4. We refer to [25, Chapter 22.1] for more details on the excess.

**Proposition 2.14** (Scaling properties). *Let  $E \subseteq \mathbb{R}^n$  be a set of finite perimeter,  $x \in \partial E$ ,  $\nu \in \mathbb{S}^{n-1}$  and  $0 < r < R$ . Then we have*

$$\mathbf{e}(E, x, r, \nu) \leq \left(\frac{R}{r}\right)^{n-1} \mathbf{e}(E, x, R, \nu) \quad \text{and}$$

*In addition, setting  $E_{x,r} := \frac{(E-x)}{r}$  we have*

$$\mathbf{e}(E_{x,r}, 0, 1, \nu) = \mathbf{e}(E, x, R, \nu).$$

Note that this property holds for the spherical excess as well.

**Proposition 2.15** (Changes of direction). *Let  $\gamma \in (0, 1)$  and  $\varepsilon > 0$ . There exists  $C = C(n, \gamma) > 0$  such that for every  $(\Lambda, r_0)$ -minimizer  $E$  of  $\mathcal{F}_{\varepsilon, \gamma}$  with  $\Lambda r_0 \leq 1 - \gamma$ , every  $\nu, \nu_0 \in \mathbb{S}^{n-1}$ ,  $x \in \partial E$  and  $r > 0$  such that  $\sqrt{2r} \leq r_0$ , we have*

$$\mathbf{e}(E, x, r, \nu) \leq C \left( \mathbf{e}(E, x, \sqrt{2r}, \nu_0) + |\nu - \nu_0|^2 \right).$$

The proof is identical to the one in [25, Proposition 22.5] and relies only on the density estimates for minimizers. Since it is very short, we write it for the reader's convenience.

*Proof.* Using the inequality  $|\nu - \nu_E(y)|^2 \leq 2|\nu - \nu_0|^2 + 2|\nu_0 - \nu_E(y)|^2$ , and the facts that  $\mathbf{C}(x, r, \nu) \subseteq \mathbf{C}(x, \sqrt{2r}, \nu_0)$  and  $\mathbf{C}(x, r, \nu) \subseteq B_{\sqrt{2r}}(x)$ , we have

$$\mathbf{e}(E, x, r, \nu) \leq \frac{2}{r^{n-1}} \int_{\partial E \cap \mathbf{C}(x, \sqrt{2r}, \nu_0)} \frac{|\nu_0 - \nu_E(y)|^2}{2} d\mathcal{H}_y^{n-1} + \frac{P(E; B_{\sqrt{2r}}(x))}{r^{n-1}} |\nu - \nu_0|^2.$$

The results follows from (2.15).  $\square$

**2.4. The height bound.** Thanks to the density estimates of Proposition 2.9,  $(\Lambda, r_0)$ -minimizers of  $\mathcal{F}_{\varepsilon, \gamma}$  satisfy the same ‘‘height bound’’ property as quasi-minimizers of the perimeter (see [25, Theorem 22.8]). This property is a crucial tool that we shall use very often to prove the Lipschitz approximation theorem and the Caccioppoli inequality.

**Proposition 2.16** (The height bound). *Let  $\varepsilon > 0$ ,  $\gamma \in (0, 1)$ ,  $\Lambda > 0$  and  $r_0 > 0$  with  $\Lambda r_0 \leq 1 - \gamma$ . There exist positive constants  $c(n, \gamma)$  and  $C(n, \gamma)$  such that the following holds. For every  $(\Lambda, r_0)$ -minimizer  $E$  of  $\mathcal{F}_{\varepsilon, \gamma}$ , every  $x \in \partial E$ ,  $\nu \in \mathbb{S}^{n-1}$  and  $r > 0$  with  $2r \leq r_0$ , if*

$$\mathbf{e}_n(x, 2r) < c,$$

then

$$\sup \left\{ |x_n - y_n| : (y', y_n) \in \partial E \cap \mathbf{C}_r(x) \right\} \leq Cr \mathbf{e}_n(x, 2r)^{\frac{1}{2(n-1)}}.$$

*Proof.* As recalled by F. MAGGI, the only step where the almost-minimality with respect to the perimeter is used in the proof of [25, Theorem 22.8] is to obtain the ‘‘small-excess position’’ of Lemma 22.10 therein. In fact, this lemma holds as long as we have density estimates on the perimeter for  $E$ , as is shown in [10, Lemma 7.2]. Hence, thanks to (2.15), the same height bound holds for  $(\Lambda, r_0)$ -minimizers of  $\mathcal{F}_{\varepsilon, \gamma}$ , whenever  $\Lambda r_0 \leq 1 - \gamma$  and  $2r \leq r_0$ .  $\square$

### 3. LIPSCHITZ APPROXIMATION THEOREM

This section is devoted to the proof of the Lipschitz approximation theorem for  $(\Lambda, r_0)$ -minimizers of  $\mathcal{F}_{\varepsilon, \gamma}$ , which can be divided into two parts. A first part states that a small excess of such an almost-minimizer  $E$  in a cylinder implies that the boundary of  $E$  in that cylinder is almost entirely covered by the graph of a Lipschitz function  $u$ . This part relies only on density estimates and on the height bound. A second step states that the aforementioned function  $u$  is close to a harmonic function as long as the scale is much larger than  $\varepsilon$ .

**3.1. Lipschitz approximation and harmonic comparison.** Since the first part of the Lipschitz approximation theorem relies only on standard properties on the excess, the density estimates and the height bound, by Propositions 2.9 and 2.16, the proof can be reproduced almost verbatim from Steps 1 to 4 of the proof of [25, Theorem 23.7]. Without loss of generality we state this first part for  $x = 0$ .

**Theorem 3.1** (Lipschitz approximation I). *Assume that  $G$  satisfies (H1), (H2) and (H3). Let  $\varepsilon > 0$ ,  $\gamma \in (0, 1)$ ,  $\Lambda > 0$  and  $r_0 > 0$  with  $\Lambda r_0 \leq 1 - \gamma$ . There exist positive constants  $\tau_{\text{lip}} = \tau_{\text{lip}}(n, \gamma)$ ,  $\delta_0 = \delta_0(n, \gamma)$  and  $C = C(n, \gamma)$  such that the following holds. If  $E$  is a  $(\Lambda, r_0)$ -minimizer of  $\mathcal{F}_{\varepsilon, \gamma}$  with  $0 \in \partial E$  and, for some  $r$  such that  $4\Lambda r \leq r_0$ ,*

$$\mathbf{e}_n(4r) \leq \tau_{\text{lip}},$$

then, setting

$$M := \partial E \cap \mathbf{C}_{2r},$$

and there exists a  $\frac{1}{2}$ -Lipschitz function  $u : \mathbb{R}^{n-1} \rightarrow \mathbb{R}$  such that:

$$(i) \|u\|_{L^\infty} \leq C r \mathbf{e}_n(4r)^{\frac{1}{2(n-1)}} < \frac{r}{4};$$

$$(ii) \mathcal{H}^{n-1}(M \Delta \Gamma_u) \leq C \mathbf{e}_n(4r) r^{n-1};$$

$$(iii) \frac{1}{r^{n-1}} \int_{D_{2r}} |\nabla u|^2 \leq C \mathbf{e}_n(4r).$$

We show that the function  $u$  in the conclusion of [Theorem 3.1](#) is “almost” a solution to a nonlocal linear equation of the form  $(\Delta - \gamma \Delta_{G_\varepsilon})u = 0$  in  $D_r$ .

**Theorem 3.2** (Lipschitz approximation II). *There exists  $C = C(n, \gamma, I_{\nabla G}^2) > 0$  such that under the same assumptions as [Theorem 3.1](#), the function  $u$  satisfies for every  $\varphi \in C_c^1(D_r)$ .*

$$\begin{aligned} \frac{1}{r^{n-1}} \left( \int_{D_r} \nabla u \cdot \nabla \varphi - \gamma \int_{D_{2r} \times D_{2r}} (u(x') - u(y'))(\varphi(x') - \varphi(y')) G_\varepsilon(x' - y', 0) dx' dy' \right) \\ \leq C \|\nabla \varphi\|_{L^\infty} \left( \mathbf{e}_n(4r) + Q \left( \frac{r}{4\varepsilon} \right) + \Lambda r \right). \end{aligned}$$

By scaling it is enough to prove [Theorem 3.2](#) for  $r = 1$ . Since the proof is quite long, we postpone it to the next section and show first how it leads to a harmonic approximation result.

**Proposition 3.3** (Harmonic approximation). *Let  $\gamma \in (0, 1)$  and assume that  $G$  satisfies [\(H1\)](#) and [\(H2\)](#). There exists  $\varepsilon_{\text{harm}} \in (0, 1)$  such that for every  $\tau > 0$ , there exists  $\sigma = \sigma(n, G, \gamma, \tau) > 0$  with the following property. If for some  $\varepsilon \in (0, \varepsilon_{\text{harm}})$ ,  $u \in H^1(D_2)$  satisfies*

$$\int_{D_2} |\nabla u|^2 \leq 1$$

and, for all  $\varphi \in C_c^1(D_1)$ ,

$$\left| \int_{D_1} \nabla u \cdot \nabla \varphi - 2\gamma \int_{D_2 \times D_2} (u(x') - u(y'))(\varphi(x') - \varphi(y')) G_\varepsilon(x' - y', 0) dx' dy' \right| \leq \|\nabla \varphi\|_{L^\infty} \sigma,$$

then there exists a harmonic function  $v$  on  $D_1$  such that

$$\int_{D_1} |\nabla v|^2 \leq 1 \quad \text{and} \quad \int_{D_1} |u - v|^2 \leq \tau.$$

*Proof.* As there is no risk for confusion, to simplify the notation we use  $x, y$  instead of  $x', y'$  for points in  $\mathbb{R}^{n-1}$ , and write  $G_\varepsilon(x)$  instead of  $G_\varepsilon(x', 0)$ . Arguing by contradiction, let us assume that there exist vanishing sequences  $(\varepsilon_k) \subseteq (0, 1)$  and  $(\sigma_k) \subseteq (0, 1)$ , a positive constant  $\tau > 0$  and a sequence  $(u_k) \subseteq H^1(D_2)$  such that the following holds:

$$(i) \int_{D_2} |\nabla u_k|^2 \leq 1 \text{ for all } k \in \mathbb{N};$$

(ii) for every  $\varphi \in C_c^\infty(D_1)$  we have

$$\left| \int_{D_1} \nabla u_k \cdot \nabla \varphi - 2\gamma \int_{D_2 \times D_2} (u_k(x) - u_k(y))(\varphi(x) - \varphi(y)) G_{\varepsilon_k}(x - y) dx dy \right| \leq \sigma_k \|\nabla \varphi\|_{L^\infty};$$

(iii) there is no harmonic function  $u$  on  $D_1$  such that

$$\int_{D_1} |\nabla u|^2 \leq 1 \quad \text{and} \quad \int_{D_1} |u_k - u|^2 \leq \tau.$$

Without loss of generality, up to adding a constant to each  $u_k$ , one may assume that  $\int_{D_2} u_k = 0$ , so that by Poincaré–Wirtinger inequality, we have

$$\int_{D_2} |u_k|^2 \leq C \int_{D_2} |\nabla u_k|^2 \leq C, \quad \forall k \in \mathbb{N}. \quad (3.1)$$

In particular,  $(u_k)$  is bounded in  $H^1(D_2)$ . Thus, up to extraction of a subsequence (not relabeled), there exists  $u \in H^1(D_2)$  such that  $u_k$  converges strongly to  $u$  in  $L^2(D_2)$  and  $\nabla u_k$  converges weakly to  $\nabla u$  in  $L^2(D_2; \mathbb{R}^{n-1})$ . We claim that for every  $\varphi \in C_c^\infty(D_1)$ ,

$$\lim_k \int_{D_2 \times D_2} (u_k(x) - u_k(y))(\varphi(x) - \varphi(y)) G_{\varepsilon_k}(x - y) dx dy = \frac{1}{2} \int_{D_1} \nabla u \cdot \nabla \varphi, \quad (3.2)$$



which we prove further below. By the weak convergence of  $\nabla u_k$  to  $\nabla u$ , the fact that  $\gamma \neq 1$  and (ii), this implies

$$\int_{D_1} \nabla u \cdot \nabla \varphi = 0, \quad \forall \varphi \in C_c^\infty(D_1);$$

in other words,  $u$  is harmonic. By (i) and lower semicontinuity with respect to the weak  $H^1$  convergence, we have

$$\int_{D_1} |\nabla u|^2 \leq 1, \tag{3.3}$$

and since  $u_k$  converges to  $u$  in  $L^2(D_1)$ , for any  $k$  large enough, we have

$$\int_{D_1} |u_k - u|^2 \leq \tau.$$

With (3.3), this contradicts (iii).

We now prove (3.2). Using the change of variable  $z = x - y$ , we have

$$\begin{aligned} & \int_{D_2 \times D_2} (u_k(x) - u_k(y))(\varphi(x) - \varphi(y))G_{\varepsilon_k}(x - y) dx dy \\ &= \int_0^1 \int_0^1 \int_{D_2 \times D_2} (\nabla u_k(x + t(y - x)) \cdot (x - y))(\nabla \varphi(x + s(y - x)) \cdot (x - y))G_{\varepsilon_k}(x - y) dx dy ds dt \\ &= \int_0^1 \int_0^1 \int_{\mathbb{R}^{n-1}} \int_{D_2} \mathbf{1}_{D_2}(x + z) (\nabla u_k(x + tz) \cdot z) (\nabla \varphi(x + sz) \cdot z) G_{\varepsilon_k}(z) dx dz ds dt. \end{aligned} \tag{3.4}$$

For each  $s, t \in (0, 1)$  and  $x \in D_2$ , using polar coordinates, we have

$$\begin{aligned} & \int_{\mathbb{R}^{n-1}} \mathbf{1}_{D_2}(x + z) (\nabla u_k(x + tz) \cdot z) (\nabla \varphi(x + sz) \cdot z) G_{\varepsilon_k}(z) dz \\ &= \int_0^4 r^n g_{\varepsilon_k}(r) \int_{\mathbb{S}^{n-2}} \mathbf{1}_{D_2}(x + r\sigma) (\nabla u_k(x + tr\sigma) \cdot \sigma) (\nabla \varphi(x + sr\sigma) \cdot \sigma) d\mathcal{H}_\sigma^{n-2} dr. \end{aligned} \tag{3.5}$$

Using the fact that for every  $s, t \in (0, 1)$  we have  $|\nabla \varphi(x + sr\sigma) - \nabla \varphi(x + tr\sigma)| \leq r \|D^2 \varphi\|_{L^\infty}$  and Cauchy–Schwarz inequality, we deduce that for every  $s, t \in (0, 1)$  and every  $\sigma \in \mathbb{S}^{n-2}$ ,

$$\begin{aligned} & \left| \int_0^4 r^n g_{\varepsilon_k}(r) \int_{D_2} \mathbf{1}_{D_2}(x + r\sigma) (\nabla u_k(x + tr\sigma) \cdot \sigma) (\nabla \varphi(x + sr\sigma) \cdot \sigma) dx dr \right. \\ & \quad \left. - \int_0^4 r^n g_{\varepsilon_k}(r) \int_{D_2} \mathbf{1}_{D_2}(x + r\sigma) (\nabla u_k(x + tr\sigma) \cdot \sigma) (\nabla \varphi(x + tr\sigma) \cdot \sigma) dx dr \right| \\ & \leq C \|D^2 \varphi\|_{L^\infty} \left( \int_0^4 r^{n+1} g_{\varepsilon_k}(r) dr \right) \left( \int_{D_2} |\nabla u|^2 \right)^{\frac{1}{2}}. \end{aligned}$$

Notice that

$$\lim_{k \rightarrow \infty} \int_0^4 r^{n+1} g_{\varepsilon_k}(r) dr = 0$$

since  $r \mapsto r^n g(r) \in L^1(\mathbb{R})$  and

$$\begin{aligned} \int_0^4 r^{n+1} g_{\varepsilon_k}(r) dr &= \int_0^{\frac{4}{\varepsilon_k}} (\varepsilon_k r) r^n g(r) dr \\ &= \int_0^{\frac{4}{\sqrt{\varepsilon_k}}} (\varepsilon_k r) r^n g(r) dr + \int_{\frac{4}{\sqrt{\varepsilon_k}}}^{\frac{4}{\varepsilon_k}} (\varepsilon_k r) r^n g(r) dr \\ &\leq 4\sqrt{\varepsilon_k} \int_0^\infty r^n g(r) dr + 4 \int_{\frac{4}{\sqrt{\varepsilon_k}}}^\infty r^n g(r) dr. \end{aligned}$$

Therefore, in view of (3.4) and (3.5), in order to prove (3.2), we only need to compute the limit of

$$\begin{aligned}
 & \int_0^1 \int_0^4 r^n g_{\varepsilon_k}(r) \int_{\mathbb{S}^{n-2}} \int_{D_2} \mathbf{1}_{D_2}(x+r\sigma) (\nabla u_k(x+t\sigma) \cdot \sigma) (\nabla \varphi(x+t\sigma) \cdot \sigma) dx d\mathcal{H}_\sigma^{n-2} dr dt \\
 &= \int_0^1 \int_0^4 r^n g_{\varepsilon_k}(r) \int_{\mathbb{S}^{n-2}} \int_{\mathbb{R}^{n-1}} \mathbf{1}_{D_2}(y-t\sigma) \mathbf{1}_{D_2}(y+(1-t)\sigma) (\nabla u_k(y) \cdot \sigma) (\nabla \varphi(y) \cdot \sigma) \\
 & \quad dy d\mathcal{H}_\sigma^{n-2} dr dt \\
 &= \int_0^1 \int_0^{\frac{4}{\varepsilon_k}} r^n g(r) \int_{\mathbb{S}^{n-2}} \int_{D_1} \mathbf{1}_{D_2}(y-t\varepsilon_k r\sigma) \mathbf{1}_{D_2}(y+(1-t)\varepsilon_k r\sigma) (\nabla u_k(y) \cdot \sigma) (\nabla \varphi(y) \cdot \sigma) \\
 & \quad dy d\mathcal{H}_\sigma^{n-2} dr dt, \tag{3.6}
 \end{aligned}$$

where we used a change of variables and the fact that  $\varphi \in C_c^\infty(D_1)$ . By the weak convergence of  $\nabla u_k$  to  $\nabla u$ , for any  $r > 0$ ,  $t \in (0, 1)$  and  $\sigma \in \mathbb{S}^{n-2}$ , we have

$$\lim_k \int_{D_1} (\nabla u_k \cdot \sigma) (\nabla \varphi \cdot \sigma) = \int_{D_1} (\nabla u \cdot \sigma) (\nabla \varphi \cdot \sigma)$$

and

$$\begin{aligned}
 & \left| \int_{D_1} \mathbf{1}_{D_2}(y-t\varepsilon_k r\sigma) \mathbf{1}_{D_2}(y+(1-t)\varepsilon_k r\sigma) (\nabla u_k(y) \cdot \sigma) (\nabla \varphi(y) \cdot \sigma) dy - \int_{D_1} (\nabla u_k \cdot \sigma) (\nabla \varphi \cdot \sigma) \right| \\
 & \leq \int_{D_1 \setminus (D_2(t\varepsilon_k r) \cup D_2((1-t)\varepsilon_k r))} |\nabla u_k| |\nabla \varphi| \\
 & \leq \|\nabla u_k\|_{L^2(D_1)} \left( \int_{D_1 \setminus (D_2(t\varepsilon_k r) \cup D_2((1-t)\varepsilon_k r))} |\nabla \varphi|^2 \right)^{\frac{1}{2}} \xrightarrow{k \rightarrow \infty} 0,
 \end{aligned}$$

where we used the inequality  $\|\nabla u_k\|_{L^2(D_1)} \leq 1$  to pass to the limit. Thus, for any  $r > 0$ ,  $t \in (0, 1)$  and  $\sigma \in \mathbb{S}^{n-2}$ , we have

$$\lim_k \int_{D_1} \mathbf{1}_{D_2}(y-t\varepsilon_k r\sigma) \mathbf{1}_{D_2}(y+(1-t)\varepsilon_k r\sigma) (\nabla u_k(y) \cdot \sigma) (\nabla \varphi(y) \cdot \sigma) dy = \int_{D_1} (\nabla u \cdot \sigma) (\nabla \varphi \cdot \sigma).$$

Hence, using once more  $\|\nabla u_k\|_{L^2(D_1)} \leq 1$  and Cauchy–Schwarz inequality, applying the dominated convergence theorem yields

$$\begin{aligned}
 & \lim_k \int_0^1 \int_0^{\frac{4}{\varepsilon_k}} r^n g(r) \int_{\mathbb{S}^{n-2}} \int_{D_1} \mathbf{1}_{D_2}(y-t\varepsilon_k r\sigma) \mathbf{1}_{D_2}(y+(1-t)\varepsilon_k r\sigma) (\nabla u_k(y) \cdot \sigma) (\nabla \varphi(y) \cdot \sigma) dy d\mathcal{H}_\sigma^{n-2} dr dt \\
 &= \int_0^\infty r^n g(r) \int_{\mathbb{S}^{n-2}} \int_{D_1} (\nabla u(y) \cdot \sigma) (\nabla \varphi(y) \cdot \sigma) dy d\mathcal{H}_\sigma^{n-2} dr. \tag{3.7}
 \end{aligned}$$

This concludes the proof of (3.2) in view of the normalization (1.2) and the fact that for every  $x, y \in \mathbb{R}^{n-1}$ ,

$$\begin{aligned}
 \int_{\mathbb{S}^{n-2}} (x \cdot \sigma) (y \cdot \sigma) d\mathcal{H}_\sigma^{n-2} &= x \cdot \left( \int_{\mathbb{S}^{n-2}} \sigma \otimes \sigma d\mathcal{H}_\sigma^{n-2} \right) y = \left( \int_{\mathbb{S}^{n-2}} |\sigma_1|^2 d\mathcal{H}_\sigma^{n-2} \right) x \cdot y \\
 &= \frac{1}{2} \left( \int_{\mathbb{S}^{n-1}} |\sigma_1| d\mathcal{H}_\sigma^{n-1} \right) x \cdot y, \tag{3.8}
 \end{aligned}$$

where the last equality comes from a direct computation (see [27, Lemma 3.13]).  $\square$

**3.2. Proof of Theorem 3.2.** We start by “localizing” the Euler–Lagrange inequation implied by the  $(\Lambda, r_0)$ -minimality condition and the first variation of  $\mathcal{F}_{\varepsilon, \gamma}$  given by Lemma 2.5.

**Lemma 3.4.** *Under the assumptions of [Theorem 3.1](#), there exists  $C = C(n, \gamma) > 0$  such that for every  $\varphi \in C_c^1(D_1)$  we have (with a slight abuse of notation we identify  $\varphi$  with a function of  $\mathbb{R}^n$ )*

$$\left| \int_{\partial E \cap \mathbf{C}_2} (\nabla \varphi \cdot \nu_E)(\nu_E \cdot e_n) + 2\gamma \int_{\partial E \cap \mathbf{C}_2} \int_{E \cap \mathbf{C}_2} G_\varepsilon(x-y)(\varphi(x) - \varphi(y))(\nu_E(y) \cdot e_n) dx d\mathcal{H}_y^{n-1} \right| \leq C \left( Q \left( \frac{1}{4\varepsilon} \right) + \Lambda \right) \|\nabla \varphi\|_{L^\infty}. \quad (3.9)$$

*Proof.* By [Proposition 2.16](#) we may choose  $\tau_{\text{lip}} = \tau_{\text{lip}}(n, \gamma)$  small enough so that

$$\left\{ x_n < -\frac{1}{4} \right\} \cap \mathbf{C}_2 \subseteq E \cap \mathbf{C}_2 \subseteq \left\{ x_n < \frac{1}{4} \right\} \cap \mathbf{C}_2. \quad (3.10)$$

To simplify notation we write  $\nu$  for  $\nu_E$  and recall the convention  $T_x$  for  $T(x)$ . We may assume without loss of generality that  $\|\nabla \varphi\|_{L^\infty} = 1$ . We start with the following simple observation. For every measure  $\mu$  and every sets  $A, B$  such that  $A \times B \subseteq \{(x, y) \in \mathbb{R}^n \times \mathbb{R}^n : |x - y| > 1/4\}$ ,

$$\int_{A \times B} G_\varepsilon(x-y) d\mu(x) dy \leq 4\mu(A) \int_{\mathbb{R}^n \setminus B_{\frac{1}{4}}} |z| G_\varepsilon(z) dz = 4\mu(A) Q \left( \frac{1}{4\varepsilon} \right). \quad (3.11)$$

Let now  $\alpha \in C_c^1((-\frac{1}{2}, 1); [0, 1])$  be such that  $\alpha \equiv 1$  in  $(-\frac{1}{2}, \frac{1}{2})$  and  $\|\alpha'\|_{L^\infty} \leq 4$ . We then consider the vector field  $T \in C_c^1(\mathbf{C}_1)$  defined by  $T(x) = \varphi(x')\alpha(x_n)e_n$  for all  $x \in \mathbb{R}^n$ . We first claim that

$$\left| \int_{\partial E} \nu \cdot (\nabla T \nu) + 2\gamma \int_{\partial E \cap \mathbf{C}_2} \int_{E \cap \mathbf{C}_2} G_\varepsilon(x-y)(T_x - T_y) \cdot \nu_y dx d\mathcal{H}_y^{n-1} \right| \leq C \left( Q \left( \frac{1}{4\varepsilon} \right) + \Lambda \right). \quad (3.12)$$

This would conclude the proof of [\(3.9\)](#) since  $T(x) = \varphi(x')e_n$  in  $D_2 \times (-\frac{1}{2}, \frac{1}{2})$  and

$$\left| \int_{\partial E \cap \mathbf{C}_2} \int_{E \cap (\mathbf{C}_2 \setminus (D_2 \times (-\frac{1}{2}, \frac{1}{2})))} G_\varepsilon(x-y)(T_x - \varphi(x')e_n) \cdot \nu_y dx d\mathcal{H}_y^{n-1} \right| \leq C \int_{\partial E \cap \mathbf{C}_2} \int_{E \cap (\mathbf{C}_2 \setminus (D_2 \times (-\frac{1}{2}, \frac{1}{2})))} G_\varepsilon(x-y) dx d\mathcal{H}_y^{n-1} \stackrel{(3.11)}{\leq} C Q \left( \frac{1}{4\varepsilon} \right),$$

where we used [\(3.11\)](#) with  $\mu = \mathcal{H}^{n-1} \llcorner \partial E$  and the fact that  $P(E; \mathbf{C}_2) \leq C$  by [\(2.15\)](#).

We thus prove [\(3.12\)](#). Notice that  $\text{div} T(x) = \varphi(x')\alpha'(x_n)$ . In particular, by [\(3.10\)](#),  $\text{div} T$  vanishes in

$$(\partial E \cap \mathbf{C}_1) \cup \left( E \cap \left\{ x_n \leq -1 \text{ or } x_n \geq -\frac{1}{2} \right\} \right).$$

By  $(\Lambda, r_0)$ -minimality of  $E$ , setting  $f_t(x) = x + tT(x)$  we have

$$\mathcal{F}_{\varepsilon, \gamma}(E) \leq \mathcal{F}_{\varepsilon, \gamma}(f_t(E)) + \Lambda |E \Delta f_t(E)|. \quad (3.13)$$

On the one hand, it is standard that for any  $|t|$  small enough

$$|E \Delta f_t(E)| \leq 2|t| \left| \int_{\partial E} T \cdot \nu \right| \stackrel{(2.15)}{\leq} C|t|.$$

On the other hand, for any  $|t|$  small enough, we have

$$\mathcal{F}_{\varepsilon, \gamma}(f_t(E)) \leq \mathcal{F}_{\varepsilon, \gamma}(E) + t(\delta \mathcal{F}_{\varepsilon, \gamma}(E)[T]) + o(t).$$

Hence, by [Lemma 2.5](#), [\(3.13\)](#) implies, for any  $|t|$  small enough

$$\begin{aligned} -t \left[ \int_{\partial^* E} \text{div}_E T d\mathcal{H}^{n-1} - 2\gamma \left( \int_{E \times E^c} \text{div} T(x) G_\varepsilon(x-y) dx dy \right. \right. \\ \left. \left. + \int_{\partial^* E} \int_E G_\varepsilon(x-y) (T(x) - T(y)) \cdot \nu_E(y) dx d\mathcal{H}_y^{n-1} \right) \right] \leq C|t|(\Lambda + o(1)). \end{aligned}$$

Since this holds for  $\pm t$  and for arbitrary small  $|t|$ , in terms of  $T$  this gives

$$\left| \int_{\partial E} \nu \cdot (\nabla T \nu) + 2\gamma \left( \int_{E \cap \mathbf{C}_1 \cap \{x_n \leq -\frac{1}{2}\}} \int_{E^c} \operatorname{div} T(x) G_\varepsilon(x-y) \, dy \, dx \right. \right. \\ \left. \left. + \int_{\partial E} \int_E G_\varepsilon(x-y) (T_x - T_y) \cdot \nu_y \, dx \, d\mathcal{H}_y^{n-1} \right) \right| \leq C\Lambda. \quad (3.14)$$

Using again that  $P(E; \mathbf{C}_2) \leq C$  by (2.15) and (3.11) with  $A = E \cap \mathbf{C}_1 \cap \{x_n \leq -\frac{1}{2}\}$ ,  $B = E^c$  and  $\mu$  the Lebesgue measure (recall that  $E^c \cap \mathbf{C}_2 \subseteq \{(x', x_n) : x_n \geq -\frac{1}{4}\}$ ) we see that in order to prove (3.12) it is enough to show that

$$\left| \int_{\partial E} \int_E G_\varepsilon(x-y) (T_x - T_y) \cdot \nu_y \, dx \, d\mathcal{H}_y^{n-1} \right. \\ \left. - \int_{\partial E \cap \mathbf{C}_2} \int_{E \cap \mathbf{C}_2} G_\varepsilon(x-y) (T_x - T_y) \cdot \nu_y \, dx \, d\mathcal{H}_y^{n-1} \right| \leq CQ \left( \frac{1}{4\varepsilon} \right). \quad (3.15)$$

Recalling that  $T = 0$  in  $\mathbf{C}_1^c$  we write

$$\int_{\partial E} \int_E G_\varepsilon(x-y) (T_x - T_y) \cdot \nu_y \, dx \, d\mathcal{H}_y^{n-1} - \int_{\partial E \cap \mathbf{C}_2} \int_{E \cap \mathbf{C}_2} G_\varepsilon(x-y) (T_x - T_y) \cdot \nu_y \, dx \, d\mathcal{H}_y^{n-1} \\ = - \int_{\partial E \cap \mathbf{C}_1} \int_{E \setminus \mathbf{C}_2} G_\varepsilon(x-y) T_y \cdot \nu_y \, dx \, d\mathcal{H}_y^{n-1} + \int_{\partial E \setminus \mathbf{C}_2} \int_{E \cap \mathbf{C}_1} G_\varepsilon(x-y) T_x \cdot \nu_y \, dx \, d\mathcal{H}_y^{n-1}.$$

Considering the last term on the right-hand side and using integration by parts we have

$$\int_{\partial E \setminus \mathbf{C}_2} \int_{E \cap \mathbf{C}_1} G_\varepsilon(x-y) T_x \cdot \nu_y \, dx \, d\mathcal{H}_y^{n-1} \\ = \int_{E \cap \partial \mathbf{C}_2} \int_{E \cap \mathbf{C}_1} G_\varepsilon(x-y) T_x \cdot \nu_{\mathbf{C}_2}(y) \, dx \, d\mathcal{H}_y^{n-1} - \int_{E \setminus \mathbf{C}_2} \int_{E \cap \mathbf{C}_1} \nabla G_\varepsilon(x-y) \cdot T_x \, dx \, dy.$$

Using Fubini's theorem and integration by parts again leads to

$$\int_{E \setminus \mathbf{C}_2} \int_{E \cap \mathbf{C}_1} \nabla G_\varepsilon(x-y) \cdot T_x \, dx \, dy \\ = \int_{E \cap \mathbf{C}_1} \int_{E \setminus \mathbf{C}_2} \nabla G_\varepsilon(x-y) \cdot T_x \, dy \, dx \\ = \int_{\partial E \cap \mathbf{C}_1} \int_{E \setminus \mathbf{C}_2} G_\varepsilon(x-y) T_x \cdot \nu_x \, dy \, d\mathcal{H}_x^{n-1} - \int_{E \cap \mathbf{C}_1} \int_{E \setminus \mathbf{C}_2} G_\varepsilon(x-y) \operatorname{div} T(x) \, dy \, dx.$$

Putting everything together we find

$$\int_{\partial E} \int_E G_\varepsilon(x-y) (T_x - T_y) \cdot \nu_y \, dx \, d\mathcal{H}_y^{n-1} - \int_{\partial E \cap \mathbf{C}_2} \int_{E \cap \mathbf{C}_2} G_\varepsilon(x-y) (T_x - T_y) \cdot \nu_y \, dx \, d\mathcal{H}_y^{n-1} \\ = -2 \int_{\partial E \cap \mathbf{C}_1} \int_{E \setminus \mathbf{C}_2} G_\varepsilon(x-y) T_y \cdot \nu_y \, dx \, d\mathcal{H}_y^{n-1} + \int_{E \cap \partial \mathbf{C}_2} \int_{E \cap \mathbf{C}_1} G_\varepsilon(x-y) T_x \cdot \nu_{\mathbf{C}_2}(y) \, dx \, d\mathcal{H}_y^{n-1} \\ + \int_{E \cap \mathbf{C}_1} \int_{E \setminus \mathbf{C}_2} G_\varepsilon(x-y) \operatorname{div} T(x) \, dy \, dx.$$

Using (3.11) with either  $A = \partial E \cap \mathbf{C}_1$ ,  $B = E \setminus \mathbf{C}_2$ ,  $\mu = \mathcal{H}^{n-1} \llcorner \partial E$  (and  $P(E; \mathbf{C}_1) \leq C$ ),  $A = E \cap \partial \mathbf{C}_2$ ,  $B = E \cap \mathbf{C}_1$ ,  $\mu = \mathcal{H}^{n-1} \llcorner \partial \mathbf{C}_2$  or  $A = E \cap \mathbf{C}_1$ ,  $B = E \setminus \mathbf{C}_2$  and  $\mu$  the Lebesgue measure we conclude the proof of (3.15).  $\square$

We now pass transfer this information to the graph of  $u$ .

**Lemma 3.5.** *Under the assumptions of [Theorem 3.1](#), there exists  $C = C(n, \gamma) > 0$  such that for every  $\varphi \in C_c^1(D_1)$  we have*

$$\begin{aligned} & \left| \int_{\Gamma_u} (\nabla\varphi \cdot \nu_{E_u})(\nu_{E_u} \cdot e_n) + 2\gamma \int_{\Gamma_u} \int_{E_u} G_\varepsilon(x-y)(\varphi(x) - \varphi(y))(\nu_{E_u}(y) \cdot e_n) dx d\mathcal{H}_y^{n-1} \right| \\ & \leq C \left( \mathbf{e}_n(4) + Q \left( \frac{1}{4\varepsilon} \right) \right), \end{aligned} \quad (3.16)$$

where

$$E_u := \left\{ (x', x_n) : x' \in D_2 \text{ and } x_n < u(x') \right\}.$$

*Proof.* As above we may assume without loss of generality that  $\|\nabla\varphi\|_{L^\infty} = 1$ . To simplify notation we write  $\nu$  for  $\nu_E$  and  $\nu^u$  for  $\nu_{E_u}$  and will use the convention  $T_x = T(x)$ . We recall that  $M = \partial E \cap \mathbf{C}_2$ . Since it is classical (see e.g. the proof of [\[25, Theorem 23.7\]](#)) that

$$\left| \int_{\Gamma_u} (\nabla\varphi \cdot \nu_{E_u})(\nu_{E_u} \cdot e_n) - \int_M (\nabla\varphi \cdot \nu_E)(\nu_E \cdot e_n) \right| \leq C \mathbf{e}_n(4),$$

from [\(3.9\)](#) it is enough to prove that

$$\begin{aligned} & \left| \int_{\Gamma_u} \int_{E_u} G_\varepsilon(x-y)(\varphi_x - \varphi_y)(\nu_y^u \cdot e_n) dx d\mathcal{H}_y^{n-1} - \int_M \int_{E \cap \mathbf{C}_2} G_\varepsilon(x-y)(\varphi_x - \varphi_y)(\nu_y \cdot e_n) dx d\mathcal{H}_y^{n-1} \right| \\ & \leq C \mathbf{e}_n(4) \|\nabla\varphi\|_{L^\infty}. \end{aligned} \quad (3.17)$$

To this aim we write

$$\begin{aligned} & \int_{\Gamma_u} \int_{E_u} G_\varepsilon(x-y)(\varphi_x - \varphi_y)(\nu_y^u \cdot e_n) dx d\mathcal{H}_y^{n-1} - \int_M \int_{E \cap \mathbf{C}_2} G_\varepsilon(x-y)(\varphi_x - \varphi_y)(\nu_y \cdot e_n) dx d\mathcal{H}_y^{n-1} \\ & = \int_{\Gamma_u} \left( \int_{E_u} G_\varepsilon(x-y)(\varphi_x - \varphi_y) dx - \int_{E \cap \mathbf{C}_2} G_\varepsilon(x-y)(\varphi_x - \varphi_y) dx \right) (\nu_y^u \cdot e_n) d\mathcal{H}_y^{n-1} \\ & \quad + \int_{\Gamma_u} \int_{E \cap \mathbf{C}_2} G_\varepsilon(x-y)(\varphi_x - \varphi_y)(\nu_y^u \cdot e_n) dx d\mathcal{H}_y^{n-1} \\ & \quad - \int_M \int_{E \cap \mathbf{C}_2} G_\varepsilon(x-y)(\varphi_x - \varphi_y)(\nu_y \cdot e_n) dx d\mathcal{H}_y^{n-1}. \end{aligned}$$

We claim that

$$\int_{\Gamma_u} \int_{E_u \Delta (E \cap \mathbf{C}_2)} G_\varepsilon(x-y) |\varphi_x - \varphi_y| dx d\mathcal{H}_y^{n-1} \leq C \mathbf{e}_n(4) \quad (3.18)$$

and

$$\begin{aligned} & \left| \int_{\Gamma_u} \int_{E \cap \mathbf{C}_2} G_\varepsilon(x-y)(\varphi_x - \varphi_y)(\nu_y^u \cdot e_n) dx d\mathcal{H}_y^{n-1} \right. \\ & \quad \left. - \int_M \int_{E \cap \mathbf{C}_2} G_\varepsilon(x-y)(\varphi_x - \varphi_y)(\nu_y \cdot e_n) dx d\mathcal{H}_y^{n-1} \right| \leq C \mathbf{e}_n(4), \end{aligned} \quad (3.19)$$

from which [\(3.17\)](#) would follow. We start with [\(3.18\)](#).

By [\(ii\)](#) of [Theorem 3.1](#), there exists a set  $A \subseteq D_2$  such that  $\mathcal{H}^{n-1}(A) \leq C \mathbf{e}_n(4)$  and

$$E \cap \{(x', t) : t \in (-2, 2)\} = E_u \cap \{(x', t) : t \in (-2, 2)\}, \quad \forall x' \in D_2 \setminus A,$$

since

$$\left\{ y' \in D_2 : \Pi_n^{-1}(\{y'\}) \cap E \cap \mathbf{C}_2 \neq \Pi_n^{-1}(\{y'\}) \cap \Gamma_u^- \cap \mathbf{C}_2 \right\} = \Pi_n(M \Delta \Gamma_u),$$

where  $\Pi_n : (y', y_n) \mapsto y_n$ . Thus, since  $\varphi$  and  $u$  are Lipschitz continuous we find

$$\begin{aligned} & \int_{\Gamma_u} \int_{E_u \Delta (E \cap \mathbf{C}_2)} G_\varepsilon(x-y) |\varphi_x - \varphi_y| dx d\mathcal{H}_y^{n-1} \\ & \leq \int_{\Gamma_u} \int_A \int_{-2}^2 G_\varepsilon((x', t) - y) |(x', t) - y| dt dx' d\mathcal{H}_y^{n-1} \\ & \leq C \int_A \int_{D_2} \int_{\mathbb{R}} G_\varepsilon((x', t) - u_{y'}) |(x', t) - u_{y'}| dt dy' dx' \\ & \leq C \mathcal{H}^{n-1}(A) \int_{\mathbb{R}^n} |z| G(z) dz \leq C \mathcal{H}^{n-1}(A). \end{aligned}$$

We now turn to (3.19). Notice that  $\mathcal{H}^{n-1}$ -a.e. on  $\Gamma_u \cap M$  we have  $\nu^u = \pm \nu$ . Moreover, setting  $\Gamma_1 := \Gamma_u \cap M \cap \{\nu^u = \nu\}$  and arguing exactly as in [25, (23.51)], we have  $\mathcal{H}^{n-1}((M \cap \Gamma_u) \setminus \Gamma_1) \leq C \mathbf{e}_n(4)$ . Recalling that by (ii) of Theorem 3.1,  $\mathcal{H}^{n-1}(M \Delta \Gamma_u) \leq C \mathbf{e}_n(4)$ , we find

$$\begin{aligned} & \left| \int_{\Gamma_u} \int_{E \cap \mathbf{C}_2} G_\varepsilon(x-y) (\varphi_x - \varphi_y) (\nu_y^u \cdot e_n) dx d\mathcal{H}_y^{n-1} \right. \\ & \quad \left. - \int_M \int_{E \cap \mathbf{C}_2} G_\varepsilon(x-y) (\varphi_x - \varphi_y) (\nu_y \cdot e_n) dx d\mathcal{H}_y^{n-1} \right| \\ & \leq \int_{(M \Delta \Gamma_u) \cup ((M \cap \Gamma_u) \setminus \Gamma_1)} \int_{E \cap \mathbf{C}_2} G_\varepsilon(x-y) |x-y| dx d\mathcal{H}_y^{n-1} \\ & \leq C \mathbf{e}_n(4) \int_{\mathbb{R}^n} |z| G_\varepsilon(z) dz \leq C \mathbf{e}_n(4). \end{aligned}$$

□

In order to conclude the proof of Theorem 3.2, we are left with the linearization of (3.16).

*Proof of Theorem 3.2.* Since arguing verbatim as in [25, Theorem 23.7] we have

$$\left| \int_{D_1} \nabla u \cdot \nabla \varphi - \int_{\Gamma_u} (\nabla \varphi \cdot \nu_{E_u}) (\nu_{E_u} \cdot e_n) \right| \leq C \mathbf{e}_n(4),$$

by Lemma 3.5 it is enough to prove that (recall the notation  $u_{x'} = u(x')$ )

$$\begin{aligned} & \left| \int_{D_2} \int_{D_2} \int_{-2}^{u_{x'}} G_\varepsilon(x' - y', t - u_{y'}) (\varphi_{x'} - \varphi_{y'}) dt dx' dy' \right. \\ & \quad \left. - \int_{D_2 \times D_2} (u_{x'} - u_{y'}) (\varphi_{x'} - \varphi_{y'}) G_\varepsilon(x' - y', 0) dx' dy' \right| \leq C \left( \mathbf{e}_n(4) + Q \left( \frac{1}{4\varepsilon} \right) \right). \end{aligned} \quad (3.20)$$

For  $x' \neq y'$  we have

$$\begin{aligned} & \int_{-2}^{u_{x'}} G_\varepsilon(x' - y', t - u_{y'}) dt = \int_{-2-u_{y'}}^{u_{x'}-u_{y'}} G_\varepsilon(x' - y', s) ds \\ & = \int_{-2-u_{y'}}^{-1} G_\varepsilon(x' - y', s) ds + \int_{-1}^0 G_\varepsilon(x' - y', s) ds + \int_0^{u_{x'}-u_{y'}} G_\varepsilon(x' - y', s) ds. \end{aligned} \quad (3.21)$$

On the one hand we observe that

$$\int_{D_2 \times D_2} (\varphi_{x'} - \varphi_{y'}) \int_{-1}^0 G_\varepsilon(x' - y', s) ds dx' dy' = 0. \quad (3.22)$$

On the other hand, since  $\|u\|_{L^\infty} \leq 1$ , for any  $y'$  we have  $-2 - u_{y'} < -1$ . Thus, using the fact that  $\varphi$  is 1-Lipschitz, we compute

$$\begin{aligned} & \left| \int_{D_2} \int_{D_2} \int_{-2-u_{y'}}^{-1} G_\varepsilon(x' - y', s) (\varphi_{x'} - \varphi_{y'}) dt dx' dy' \right| \\ & \leq \int_{D_2} \int_{-2-u_{y'}}^{-1} \int_{D_2} |x' - y'| G_\varepsilon(x' - y', s) dx' ds dy' \\ & \leq \int_{D_2} \int_{\mathbb{R}^n \setminus B_1} |z| G_\varepsilon(z) dz dy' \leq CQ \left( \frac{1}{4\varepsilon} \right). \end{aligned} \quad (3.23)$$

Combining (3.21), (3.22) and (3.23) yields

$$\begin{aligned} & \left| \int_{D_2} \int_{D_2} \int_{-2}^{u_{x'}} G_\varepsilon(x' - y', t - u_{y'}) (\varphi_{x'} - \varphi_{y'}) dt dx' dy' \right. \\ & \quad \left. - \int_{D_2 \times D_2} \int_0^{u_{x'} - u_{y'}} G_\varepsilon(x' - y', t) (\varphi_{x'} - \varphi_{y'}) dt dx' dy' \right| \leq CQ \left( \frac{1}{4\varepsilon} \right). \end{aligned} \quad (3.24)$$

Using again that  $\varphi$  is 1-Lipschitz and Fubini's theorem, we estimate

$$\begin{aligned} & \left| \int_{D_2 \times D_2} \int_0^{u_{x'} - u_{y'}} (G_\varepsilon(x' - y', t) - G_\varepsilon(x' - y', 0)) (\varphi_{x'} - \varphi_{y'}) dt dx' dy' \right| \\ & \leq \int_0^1 \int_{D_2 \times D_2} \int_0^{|u_{x'} - u_{y'}|} t |x' - y'| |\nabla G_\varepsilon(x' - y', st)| dt dx' dy' ds \\ & = \int_0^1 \int_0^1 t \int_{D_2 \times D_2} |u_{x'} - u_{y'}|^2 |x' - y'| |\nabla G_\varepsilon(x' - y', st |u_{x'} - u_{y'}|)| dx' dy' dt ds \\ & \leq \int_0^1 \int_0^1 \int_{D_2 \times D_2} |u_{x'} - u_{y'}|^2 |x' - y'| |\nabla G_\varepsilon(x' - y', st |u_{x'} - u_{y'}|)| dx' dy' dt ds. \end{aligned} \quad (3.25)$$

Set  $\tilde{G}_\varepsilon := \varepsilon^{-(n+1)} \tilde{G}(\cdot/\varepsilon)$  where  $\tilde{G} := |\cdot| |\nabla G|$  and  $\Phi_{stu}(x', y') := (x' - y', st(u_{x'} - u_{y'}))$ . Observing that  $|\Phi_{stu}(x', y')| \geq |x' - y'|$  we have for every fixed  $s, t$ ,

$$\begin{aligned} & \int_{D_2 \times D_2} |u_{x'} - u_{y'}|^2 |x' - y'| |\nabla G_\varepsilon(x' - y', st |u_{x'} - u_{y'}|)| dx' dy' \\ & \leq \int_{D_2 \times D_2} |u_{x'} - u_{y'}|^2 \tilde{G}_\varepsilon(|\Phi_{stu}(x', y')|) dx' dy'. \end{aligned}$$

Observing that  $I_G^1 = I_{|\nabla G|}^2$ , Lemma 3.6 below yields

$$\int_{D_2 \times D_2} |u_{x'} - u_{y'}|^2 \tilde{G}_\varepsilon(|\Phi_{stu}(x', y')|) dx' dy' \leq CI_{|\nabla G|}^2 \int_{D_2} |\nabla u|^2 \leq CI_{|\nabla G|}^2 \mathbf{e}_n(14),$$

where we used that by (iii) of Theorem 3.1,  $\int_{D_2} |\nabla u|^2 \leq C \mathbf{e}_n(4)$ . Combining this with (3.25) and (3.24) concludes the proof of (3.20).  $\square$

In the proof of Theorem 3.2 above, we used the following technical lemma.

**Lemma 3.6.** *Let  $G : \mathbb{R}^n \mapsto \mathbb{R}^+$  be a radial kernel such that (recall definition (1.1))  $I_G^1 < \infty$ . For  $u \in \text{Lip}(D_2)$ , we define the map  $\Phi_u : D_2 \times D_2 \rightarrow \mathbb{R}^{n-1} \times \mathbb{R}$  by*

$$\Phi_u(x', y') = (x' - y', u(x') - u(y')). \quad (3.26)$$

*There exists a constant  $C = C(n) > 0$  such that if  $\|\nabla u\|_{L^\infty(D_2)} \leq \frac{1}{2}$  then*

$$\int_{D_2 \times D_2} (u(x') - u(y'))^2 G(\Phi_u(x', y')) dx' dy' \leq CI_G^1 \int_{D_2} |\nabla u|^2. \quad (3.27)$$

*Proof.* We start by estimating

$$\begin{aligned}
& \int_{D_2 \times D_2} (u(x') - u(y'))^2 G(\Phi_u(x', y')) \, dx' \, dy' \\
& \leq \int_0^1 \int_{\mathbb{R}^{n-1} \times \mathbb{R}^{n-1}} \mathbf{1}_{D_2}(x') \mathbf{1}_{D_2}(y') |\nabla u(x' + t(y' - x'))|^2 |x' - y'|^2 G(\Phi_u(x', y')) \, dx' \, dy' \, dt \\
& = \int_0^1 \int_{\mathbb{R}^{n-1} \times \mathbb{R}^{n-1}} \mathbf{1}_{D_2}(\hat{x}' - tz') \mathbf{1}_{D_2}(\hat{x}' + (1-t)z') |\nabla u(\hat{x})|^2 |z'|^2 G(\Phi_u(\hat{x}' - tz', \hat{x}' + (1-t)z')) \\
& \hspace{25em} d\hat{x}' \, dz' \, dt \\
& \leq \int_0^1 \int_{D_2} |\nabla u(x')|^2 \left[ \int_{\mathbb{R}^{n-1}} |z'|^2 G(\Phi_u(x' - tz', x' + (1-t)z')) \, dz' \right] dx' \, dt,
\end{aligned}$$

where we made the change of variables  $z' = y' - x'$ ,  $\hat{x}' = x' + tz'$ , and used that by convexity of  $D_2$ ,  $D_2(tz') \cap D_2(-(1-t)z') \subseteq D_2$ . We finally claim that for every fixed  $t \in [0, 1]$  and  $x' \in D_2$ ,

$$\int_{\mathbb{R}^{n-1}} |z'|^2 G(\Phi_u(x' - tz', x' + (1-t)z')) \, dz' \leq CI_G^1, \quad (3.28)$$

which would conclude the proof of (3.27). For this we set  $G(z) = g(|z|)$  for some  $g : \mathbb{R}^+ \mapsto \mathbb{R}^+$ . and write using polar coordinates

$$\begin{aligned}
& \int_{\mathbb{R}^{n-1}} |z'|^2 G(\Phi_u(x' - tz', x' + (1-t)z')) \, dz' \\
& = \int_{\mathbb{S}^{n-2}} \int_0^\infty r^n g(\sqrt{r^2 + |u(x' - tr\sigma) - u(x' + (1-t)r\sigma)|^2}) \, dr \, d\mathcal{H}_\sigma^{n-2}. \quad (3.29)
\end{aligned}$$

We finally notice that for every fixed  $t \in [0, 1]$ ,  $x' \in D_2$  and  $\sigma \in \mathbb{S}^{n-2}$ , the function  $\Psi(r) := \sqrt{r^2 + |u(x' - tr\sigma) - u(x' + (1-t)r\sigma)|^2}$  is Lipschitz continuous with

$$\frac{\sqrt{5}}{2} r \geq \Psi(r) \geq r \quad \text{and} \quad \frac{5}{4} \geq \Psi'(r) \geq \frac{3}{2\sqrt{5}}$$

so that making the change of variables  $s = \Psi(r)$  we find

$$\int_{\mathbb{R}^{n-1}} |z'|^2 G(\Phi_u(x' - tz', x' + (1-t)z')) \, dz' \leq C \int_0^\infty s^n g(s) \, ds = CI_G^1.$$

This concludes the proof of (3.28).  $\square$

#### 4. CACCIOPOLI INEQUALITY

Let us first introduce the standard notion of *flatness* for sets of finite perimeter.

**Definition 4.1** (Flatness). For any set of finite perimeter  $E \subseteq \mathbb{R}^n$  we define the flatness of  $E$  in  $x \in \partial E$  at scale  $r > 0$  with respect to the direction  $\nu \in \mathbb{S}^{n-1}$  by

$$\mathbf{f}(E, x, r, \nu) := \inf_{c \in \mathbb{R}} \frac{1}{r^{n-1}} \int_{\partial^* E \cap \mathbf{C}(x, r, \nu)} \frac{|(y-x) \cdot \nu - c|^2}{r^2} \, d\mathcal{H}_y^{n-1}.$$

When  $\nu = e_n$ , we write  $\mathbf{f}_n(E, x, r)$  for  $\mathbf{f}(E, x, r, e_n)$ .

Using the harmonic approximation result given by Proposition 3.3, we will be able to show that  $\mathbf{f}(E, x, \alpha r, \nu) \lesssim \alpha^2 \mathbf{e}(E, x, r, \nu)$  for  $(\Lambda, r_0)$ -minimizers of  $\mathcal{F}_{\varepsilon, \gamma}$ , as long as  $r$  is much larger than  $\varepsilon$ . To pass this estimate to the excess at scale  $\alpha r/2$ , we prove in this section a Caccioppoli-type (or Reverse Poincaré) inequality. The key argument is to prove first that for sets which are sufficiently flat, the quasi-minimality condition (2.14) can be upgraded.

To that effect, we need to introduce some notation. For any  $t > 0$  and  $z \in \mathbb{R}^{n-1}$ , we define  $\mathbf{K}_t(z) := D_t(z) \times (-1, 1)$ , and we simply write  $\mathbf{K}_t$  when  $z = 0$ . For any cylinder  $\mathbf{K}_t(z)$ , any set of locally finite perimeter  $E$ , and any constant  $c \in \mathbb{R}$ , we define the quantities

$$\mathcal{F}(E, \mathbf{K}_t(z), c) := \int_{\mathbf{K}_t(z) \cap \partial^* E} \frac{(x_n - c)^2}{t^2} \, d\mathcal{H}^{n-1} \quad (4.1)$$



and

$$\mathcal{E}(E, \mathbf{K}_t(z)) := P(E; \mathbf{K}_t(z)) - \mathcal{H}^{n-1}(D_t(z)). \quad (4.2)$$

When  $z = 0$ , we make the abuse of notation  $\mathcal{E}(E, t) = \mathcal{E}(E, \mathbf{K}_t(z))$  and  $\mathcal{F}(E, t, c) = \mathcal{E}(E, \mathbf{K}_t(z), c)$ . Let us point out that these two quantities are respectively linked with the (non-scale-invariant) flatness and excess of  $E$  at scale  $t$  in the direction  $e_n$ . Indeed, if  $0 \in E$  and if for some  $h \in (0, t)$

$$\{(x', x_n) \in \mathbf{K}_t : x_n < -h\} \subseteq E \cap \mathbf{C}_t \subseteq \{(x', x_n) \in \mathbf{K}_t : x_n < h\},$$

then

$$\mathbf{f}_n(E, 0, t) = \inf_{c \in \mathbb{R}} \frac{1}{t^{n-1}} \mathcal{F}(E, t, c),$$

and

$$\mathcal{H}^{n-1}(D_t) = \int_{\partial^* E \cap \mathbf{C}_t} \nu_E \cdot e_n$$

(see [25, Lemma 22.11]), thus, for any  $t \in (0, 1)$ ,

$$\mathcal{E}(E, t) = \int_{\partial^* E \cap \mathbf{C}_t} (1 - \nu_E \cdot e_n) d\mathcal{H}^{n-1} = \frac{1}{2} \int_{\partial^* E \cap \mathbf{C}_t} |\nu_E - e_n|^2 d\mathcal{H}^{n-1} = \left( \frac{t^{n-1}}{2} \right) \mathbf{e}_n(E, t). \quad (4.3)$$

In particular, notice that  $\mathcal{E}(E, \cdot)$  is increasing in  $(0, 1)$ .

Eventually, recalling the definition of the function  $Q$  in (1.3), for any  $\theta \in [0, 1]$  we define the function  $Q_{1-\theta}$  by

$$Q_{1-\theta}(t) := Q(t^{1-\theta}), \quad \forall t > 0. \quad (4.4)$$

**4.1. A refined quasi-minimality condition.** We improve the quasi-minimality condition (2.14) for sets which are sufficiently flat. For any  $\varepsilon > 0$ , let us define the “critical” energy functional

$$\mathcal{F}_\varepsilon(E) := \mathcal{F}_{1,\varepsilon}(E) = (P - P_\varepsilon)(E).$$

**Proposition 4.2.** *Assume that  $G$  satisfies (H1) and (H2), and let  $\varepsilon \in (0, 1)$ ,  $\gamma \in (0, 1)$ ,  $\theta \in (0, 1]$  and  $\Lambda > 0$  with  $4\Lambda \leq 1 - \gamma$ . There exists  $C = C(n) > 0$  such that if  $E$  is a  $(\Lambda, 4)$ -minimizer of  $\mathcal{F}_{\varepsilon,\gamma}$  with*

$$\left\{ x_n < -\frac{1}{4} \right\} \cap \mathbf{K}_3 \subseteq E \cap \mathbf{K}_3 \subseteq \left\{ x_n < \frac{1}{4} \right\} \cap \mathbf{K}_3,$$

then the following holds. If  $t \in (0, 2)$  is such that  $\mathcal{H}^{n-1}(\partial \mathbf{K}_t \cap \partial E) = 0$  then for any set  $F$  of finite perimeter such that  $E \Delta F \subseteq \mathbf{K}_t$  and any set of and

$$\left\{ x_n < -\frac{1}{4} \right\} \cap \mathbf{K}_t \subseteq F \cap \mathbf{K}_t \subseteq \left\{ x_n < \frac{1}{4} \right\} \cap \mathbf{K}_t,$$

we have

$$\begin{aligned} \mathcal{E}(E, t) &\leq \left( \frac{1+\gamma}{1-\gamma} \right) \mathcal{E}(F, t) + \frac{2\gamma}{(1-\gamma)} [\mathcal{E}(E, t + \varepsilon^\theta) - \mathcal{E}(E, t)] \\ &\quad + \frac{C}{(1-\gamma)} Q_{1-\theta} \left( \frac{1}{\varepsilon} \right) + \frac{\Lambda}{(1-\gamma)} |E \Delta F| + \frac{1+3\gamma}{(1-\gamma)} \mathcal{H}^{n-1}(\partial^* F \cap \partial \mathbf{K}_t). \end{aligned} \quad (4.5)$$

*Proof.* To simplify a bit notation set  $\eta := \mathcal{H}^{n-1}(\partial^* F \cap \partial \mathbf{K}_t)$ . Since  $\mathcal{H}^{n-1}(\partial \mathbf{K}_t \cap \partial E) = 0$  and  $E \Delta F \subseteq \mathbf{K}_t$  we have

$$P(E) - P(F) = P(E; \mathbf{K}_t) - P(F; \mathbf{K}_t) - \eta. \quad (4.6)$$

By  $(\Lambda, 4)$ -minimality of  $E$  we find

$$(1-\gamma)P(E; \mathbf{K}_t) \leq (1-\gamma)P(F; \mathbf{K}_t) + \gamma[\mathcal{F}_\varepsilon(F) - \mathcal{F}_\varepsilon(E)] + \Lambda|E \Delta F| + (1-\gamma)\eta. \quad (4.7)$$

In the next two steps we prove that

$$\mathcal{F}_\varepsilon(F) - \mathcal{F}_\varepsilon(E) \leq 2\mathcal{E}(F, t + \varepsilon^\theta) + CQ_{1-\theta} \left( \frac{1}{\varepsilon} \right). \quad (4.8)$$

*Step 1.* In this first step we localize the estimate. Setting for simplicity

$$\tilde{D}_t := D_{t+\varepsilon^\theta}, \quad \tilde{\mathbf{K}}_t := \mathbf{K}_{t+\varepsilon^\theta}$$

and defining the “localized” functional

$$\mathcal{F}_\varepsilon^{\text{loc}}(E) := P(E; \tilde{\mathbf{K}}_t) - \int_{(E \cap \tilde{\mathbf{K}}_t) \times (E^c \cap \tilde{\mathbf{K}}_t)} G_\varepsilon(x-y) dx dy,$$

we claim that

$$\mathcal{F}_\varepsilon(F) - \mathcal{F}_\varepsilon(E) \leq \mathcal{F}_\varepsilon^{\text{loc}}(F) - \mathcal{F}_\varepsilon^{\text{loc}}(E) + CQ_{1-\theta}(\varepsilon^{-1}). \quad (4.9)$$

Since  $E \Delta F \subseteq \mathbf{K}_t \subset \tilde{\mathbf{K}}_t$ ,  $P(E) - P(F) = P(E; \tilde{\mathbf{K}}_t) - P(F; \tilde{\mathbf{K}}_t)$  and thus in order to prove (4.9), we just need to consider the nonlocal part. Setting  $\Phi(A, B) = \int_{A \times B} G_\varepsilon(x - y) dx dy$  and using that  $E \Delta F \subseteq \mathbf{K}_t$  we have

$$\begin{aligned} P_\varepsilon(E) - P_\varepsilon(F) &= \Phi(E, E^c) - \Phi(F, F^c) \\ &= \left[ \Phi(E \cap \tilde{\mathbf{K}}_t, E^c \cap \tilde{\mathbf{K}}_t) - \Phi(F \cap \tilde{\mathbf{K}}_t, F^c \cap \tilde{\mathbf{K}}_t) \right] + \Phi(E \cap \mathbf{K}_t, E^c \setminus \tilde{\mathbf{K}}_t) - \Phi(F \cap \mathbf{K}_t, E^c \setminus \tilde{\mathbf{K}}_t) \\ &\quad + \Phi(E \setminus \tilde{\mathbf{K}}_t, E^c \cap \mathbf{K}_t) - \Phi(E \setminus \tilde{\mathbf{K}}_t, F^c \cap \mathbf{K}_t) \\ &\leq \left[ \Phi(E \cap \tilde{\mathbf{K}}_t, E^c \cap \tilde{\mathbf{K}}_t) - \Phi(F \cap \tilde{\mathbf{K}}_t, F^c \cap \tilde{\mathbf{K}}_t) \right] + \Phi(E \cap \mathbf{K}_t, E^c \setminus \tilde{\mathbf{K}}_t) + \Phi(E \setminus \tilde{\mathbf{K}}_t, E^c \cap \mathbf{K}_t) \\ &\leq \left[ \Phi(E \cap \tilde{\mathbf{K}}_t, E^c \cap \tilde{\mathbf{K}}_t) - \Phi(F \cap \tilde{\mathbf{K}}_t, F^c \cap \tilde{\mathbf{K}}_t) \right] + 2\Phi(\mathbf{K}_t, (\tilde{\mathbf{K}}_t)^c). \end{aligned}$$

In order to prove (4.9) it is thus enough to estimate  $\Phi(\mathbf{K}_t, (\tilde{\mathbf{K}}_t)^c)$ . For this we write that

$$\begin{aligned} \Phi(\mathbf{K}_t, (\tilde{\mathbf{K}}_t)^c) &= \int_{\mathbf{K}_t \times (\tilde{\mathbf{K}}_t)^c} G_\varepsilon(x - y) dx dy \\ &= \int_{\mathbb{R}^n \times \mathbb{R}^n} \mathbf{1}_{\mathbf{K}_t}(x) \mathbf{1}_{\tilde{\mathbf{K}}_t^c}(x + z) G_\varepsilon(z) dx dz \\ &= \int_{\mathbb{R}^n \times \mathbb{R}^n} \mathbf{1}_{\mathbf{K}_t}(x) \mathbf{1}_{\tilde{\mathbf{K}}_t^c}(x + z) \mathbf{1}_{\mathbb{R}^n \setminus B_{\varepsilon\theta}}(z) G_\varepsilon(z) dx dz \\ &\leq \int_{\mathbb{R}^n \times \mathbb{R}^n} \mathbf{1}_{\mathbf{K}_t}(x) \mathbf{1}_{\mathbf{K}_t^c}(x + z) \mathbf{1}_{\mathbb{R}^n \setminus B_{\varepsilon\theta}}(z) G_\varepsilon(z) dx dz \\ &\leq \frac{1}{2} \left( \int_{\mathbb{R}^n \setminus B_{\varepsilon\theta}} |z| G_\varepsilon(z) dz \right) P(\mathbf{K}_t) \\ &\leq CQ_{1-\theta}(\varepsilon^{-1}), \end{aligned}$$

where we used (2.1) with  $K = \mathbf{1}_{\mathbb{R}^n \setminus B_{\varepsilon\theta}} G_\varepsilon$ .

*Step 2.* In this step we show

$$\mathcal{F}_\varepsilon^{\text{loc}}(F) - \mathcal{F}_\varepsilon^{\text{loc}}(E) \leq 2\mathcal{E}(F, t + \varepsilon^\theta) + CQ_{1-\theta}(\varepsilon^{-1}). \quad (4.10)$$

Together with (4.9) this would conclude the proof of (4.8).

In this step, we will use the slicing techniques introduced in [26, Section 3], rewriting  $P$  and  $P_\varepsilon$  as an average over 1-dimensional slices. Let us set  $\rho(t) := \omega_{n-1}|t|^{n-1}g(|t|)$  and  $\rho_\varepsilon(t) := \varepsilon^{-2}\rho(\varepsilon^{-1}t)$  for  $t \in \mathbb{R} \setminus \{0\}$ . For every line segment  $L \subseteq \mathbb{R}^n$ , we define the one-dimensional nonlocal perimeter functional in  $L$

$$P_\varepsilon^{\text{1D}}(E; L) := \int_{L \times L} |\mathbf{1}_E(x) - \mathbf{1}_E(y)| \rho_\varepsilon(x - y) d\mathcal{H}_x^1 d\mathcal{H}_y^1 = 2 \int_{(E \cap L) \times (E^c \cap L)} \rho_\varepsilon(x - y) d\mathcal{H}_x^1 d\mathcal{H}_y^1$$

and the one-dimensional critical energy in  $L$  by

$$\mathcal{F}_\varepsilon^{\text{1D}}(E; L) := \mathcal{H}^0(\partial^* E \cap L) - P^{\text{1D}}(E; L).$$

Proceeding as in [26, Proposition 3.1 & Corollary 3.3] (the only difference is the restriction to  $\tilde{\mathbf{K}}_t$ ) we have

$$\mathcal{F}_\varepsilon^{\text{loc}}(E) = \frac{1}{2\omega_{n-1}} \int_{\mathbb{S}^{n-1}} \int_{\{\sigma\}^\perp} \mathcal{F}_\varepsilon^{\text{1D}}(E; \tilde{L}_{\sigma,x}) d\mathcal{H}_x^{n-1} d\mathcal{H}_\sigma^{n-1},$$

where we set

$$L_{\sigma,x} := x + \mathbb{R}\sigma, \quad \text{and} \quad \tilde{L}_{\sigma,x} := L_{\sigma,x} \cap \tilde{\mathbf{K}}_t.$$

In particular

$$\mathcal{F}_\varepsilon^{\text{loc}}(F) - \mathcal{F}_\varepsilon^{\text{loc}}(E) = \frac{1}{2\omega_{n-1}} \int_{\mathbb{S}^{n-1}} \int_{\{\sigma\}^\perp} (\mathcal{F}_\varepsilon^{\text{1D}}(F; \tilde{L}_{\sigma,x}) - \mathcal{F}_\varepsilon^{\text{1D}}(E; \tilde{L}_{\sigma,x})) dx d\mathcal{H}_\sigma^{n-1}. \quad (4.11)$$

*Step 2.1.* We claim that for every  $\sigma \in \mathbb{S}^{n-1}$  and  $\mathcal{H}^{n-1}$ -a.e  $x \in \{\sigma\}^\perp$ , we have

$$\begin{aligned} \mathcal{F}_\varepsilon^{1D}(F; \tilde{L}_{\sigma,x}) - \mathcal{F}_\varepsilon^{1D}(E; \tilde{L}_{\sigma,x}) \\ \leq \begin{cases} 0 & \text{it } \partial^* F \cap \tilde{L}_{\sigma,x} = \emptyset, \\ 2 \left( \mathcal{H}^0(\partial^* F \cap \tilde{L}_{\sigma,x}) - 1 \right) + CQ_{1-\theta}(\varepsilon^{-1}) & \text{otherwise.} \end{cases} \end{aligned} \quad (4.12)$$

By the standard properties of one-dimensional restrictions of sets of finite perimeter (see e.g. [3]), it is enough to prove (4.12) for  $E, F \subseteq \mathbb{R}$  and  $\tilde{L}_{\sigma,x} = L = (0, a)$  for some  $a > 0$ . Notice that since  $E$  and  $F$  are of finite perimeter in  $L$ , they are just a finite union of disjoint intervals.

By [26, Remark 3.2], for any set of finite perimeter  $E \subseteq \mathbb{R}$ , we have  $P_\varepsilon^{1D}(E; \mathbb{R}) \leq \mathcal{H}^0(\partial E)$ , which implies  $\mathcal{F}_\varepsilon^{1D}(E; L) \geq \mathcal{F}_\varepsilon^{1D}(E; \mathbb{R}) \geq 0$ . Thus, if  $\mathcal{H}^0(\partial F \cap L) = 0$  (that is,  $\partial F \cap L = \emptyset$ ), then  $\mathcal{F}_\varepsilon^{1D}(F; L) - \mathcal{F}_\varepsilon^{1D}(E; L) \leq \mathcal{F}_\varepsilon^{1D}(F; L) \leq -P_\varepsilon^{1D}(E; L) \leq 0$ . If  $\mathcal{H}^0(\partial F \cap L) \geq 2$ , then

$$\mathcal{F}_\varepsilon^{1D}(F; L) - \mathcal{F}_\varepsilon^{1D}(E; L) \leq \mathcal{F}_\varepsilon^{1D}(F; L) \leq \mathcal{H}^0(\partial F \cap L) \leq 2(\mathcal{H}^0(\partial F \cap L) - 1).$$

There remains to focus on the case where  $\mathcal{H}^0(\partial F \cap L) = 1$ . In this case we claim that

$$\mathcal{F}_\varepsilon^{1D}(F; L) - \mathcal{F}_\varepsilon^{1D}(E; L) \leq CQ_{1-\theta}(\varepsilon^{-1}). \quad (4.13)$$

Let  $t_F$  be such that  $L \cap \partial F = \{t_F\}$  then either  $F \cap L = (0, t_F)$  or  $F \cap L = (t_F, a)$ . Since both cases are similar, we treat only the case  $F \cap L = (0, t_F)$ . We distinguish two sub-cases.

*Case 1:*  $d(t_F, L^c) \geq \varepsilon^\theta$ . In this case we argue somewhat similarly to (4.9). Using the fact that

$$2 \int_{-\infty}^c \int_c^\infty \rho_\varepsilon(s-t) ds dt = 2 \int_0^\infty t \rho_\varepsilon(t) dt = 1, \quad \forall c \in \mathbb{R}, \quad (4.14)$$

we compute

$$\begin{aligned} \mathcal{F}_\varepsilon^{1D}(F; L) &= 1 - 2 \int_0^{t_F} \int_{t_F}^a \rho_\varepsilon(s-t) ds dt \\ &= 2 \int_{-\infty}^{t_F} \int_{t_F}^\infty \rho_\varepsilon(s-t) ds dt - 2 \int_0^{t_F} \int_{t_F}^a \rho_\varepsilon(s-t) ds dt \\ &= 2 \int_{-\infty}^{t_F} \int_a^\infty \rho_\varepsilon(s-t) ds dt + 2 \int_{-\infty}^0 \int_{t_F}^a \rho_\varepsilon(s-t) ds dt \\ &\leq 2 \int_{-\infty}^0 \left( \int_{a-t_F}^\infty \rho_\varepsilon(s-t) ds dt + \int_{t_F}^\infty \rho_\varepsilon(s-t) ds \right) dt \\ &\leq 4 \int_{-\infty}^0 \int_{\varepsilon^\theta}^\infty \rho_\varepsilon(s-t) ds dt \\ &= 4 \int_{\varepsilon^\theta}^\infty (t - \varepsilon^\theta) \rho_\varepsilon(t) dt, \end{aligned}$$

thus

$$\mathcal{F}_\varepsilon^{1D}(F; L) \leq C \int_{\mathbb{R}^n \setminus B_{\varepsilon^\theta}} |z| G_\varepsilon(z) dz = CQ_{1-\theta}(\varepsilon^{-1}),$$

proving (4.13) in this case.

*Case 2:*  $d(t_F, L^c) < \varepsilon^\theta$ . Either  $0 < t_F < \varepsilon^\theta < a$  or  $0 < a - \varepsilon^\theta < t_F < a$ . Since both cases are similar, we treat only the case  $0 < a - \varepsilon^\theta < t_F < a$ .

Notice that  $E \Delta F \subseteq \mathbf{K}_t$  implies  $t_F \in \partial E$  and

$$F^c \cap (a - \varepsilon^\theta, a) = E^c \cap (a - \varepsilon^\theta, a) = (a - \varepsilon^\theta, a). \quad (4.15)$$

Let us write  $E \cap (0, a) = \bigcup_{j=1}^k I_j$ , where  $k \geq 1$  and  $I_j \subseteq (0, a)$  are open intervals. Then let  $\{s_1, \dots, s_{k_1}, t_1, \dots, t_{k_2}\}$  be the elements of  $\partial E \cap (0, a)$  such that

- $s_1 < s_2 < \dots < s_{k_1}$  and  $t_1 < t_2 < \dots < t_{k_2} = t_F$ ;
- for each  $j$ ,  $s_j$  is a left endpoint of some  $I_i$ , and  $t_j$  is a right endpoint of some  $I_i$ .

Note that  $s_1$  may not be the left endpoint of  $I_1$  (if  $I_1 = (0, t_1)$ ), so that  $k_1$  may be different from  $k_2$  (see Figure 1). The fact that  $t_{k_2} = t_F$  is due to (4.15).

For  $1 \leq j \leq k_1$ , we denote by  $A_j$  the connected component of  $E^c \cap L$  which is immediately on the left side of  $s_j$  (that is, its right endpoint is  $s_j$ ), and by  $\tilde{B}_j$  the union of all the connected components of  $E \cap L$  on the right side of  $s_j$ . Similarly, for  $1 \leq j \leq k_2$ , we denote by  $B_j$  the connected component of



FIGURE 1. Two examples of the situation in Step 2.1, Case 2 in the proof of [Proposition 4.2](#). On the left,  $k_1 = 2$  and  $k_2 = 3$ , and on the right,  $k_1 = k_2 = 3$ . The thick segments represent the set  $E \cap (0, a)$ .

$E \cap L$  which is immediately on the left side of  $t_j$ , and by  $\tilde{A}_j$  the union of all the connected components of  $E^c \cap L$  on the right side of  $t_j$ . See [Figure 2](#).

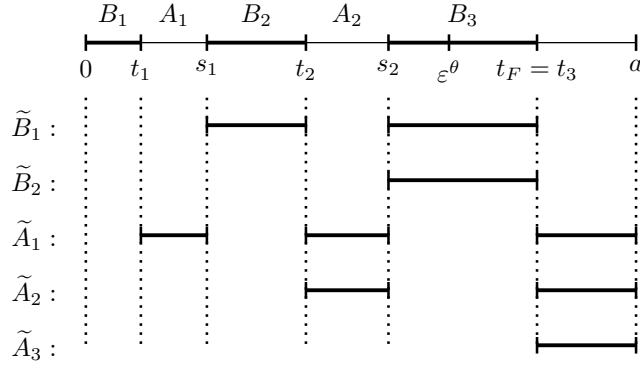


FIGURE 2. An example of the situation in Step 2.1, Case 2 in the proof of [Proposition 4.2](#), when  $k_1 = 2$  and  $k_2 = 3$ , with the representation of the  $\tilde{A}_j$  and the  $\tilde{B}_j$ .

Then using that  $\mathcal{H}^0(\partial E \cap L) = k_1 + k_2$  and decomposing the domain of integration of  $P_\varepsilon^{\text{1D}}(E; L)$  we see that

$$\mathcal{F}_\varepsilon^{\text{1D}}(E; L) = \sum_{j=1}^{k_1} \left[ 1 - 2 \int_{A_j \times \tilde{B}_j} \rho_\varepsilon(s-t) ds dt \right] + \sum_{j=1}^{k_2} \left[ 1 - 2 \int_{B_j \times \tilde{A}_j} \rho_\varepsilon(s-t) ds dt \right].$$

Each term of each sum is nonnegative by [\(4.14\)](#), and since  $\tilde{A}_{k_2} = (t_F, a)$  by [\(4.15\)](#) and  $B_{k_2} \subseteq (0, t_F)$  this implies in particular

$$\mathcal{F}_\varepsilon^{\text{1D}}(E; L) \geq 1 - 2 \int_{(0, t_F) \times (t_F, a)} \rho_\varepsilon(s-t) ds dt = \mathcal{F}_\varepsilon^{\text{1D}}(F; L),$$

concluding the proof of [\(4.13\)](#) in this case as well.

*Step 2.2.* For  $\sigma \in \mathbb{S}^{n-1}$  we define  $\pi_\sigma$  as the projection on  $\{\sigma\}^\perp$ . We then set

$$\begin{aligned} \text{Sh}(F; \tilde{\mathbf{K}}_t) &:= \int_{\mathbb{S}^{n-1}} \mathcal{H}^{n-1}(\pi_{\sigma^\perp}(\partial^* F \cap \tilde{\mathbf{K}}_t)) d\mathcal{H}_\sigma^{n-1} \\ &= \int_{\mathbb{S}^{n-1}} \int_{\{\sigma\}^\perp} \mathbf{1}_{\{\tilde{L}_{\sigma,x} \cap \partial^* F \neq \emptyset\}} d\mathcal{H}_x^{n-1} d\mathcal{H}_\sigma^{n-1}. \end{aligned}$$

Since

$$P(F; \Omega) = \frac{1}{2\omega_{n-1}} \int_{\mathbb{S}^{n-1}} \int_{\{\sigma\}^\perp} \mathcal{H}^0(\partial^* F \cap L_{\sigma,x} \cap \Omega) d\mathcal{H}_x^{n-1} d\mathcal{H}_\sigma^{n-1}.$$

we have

$$\begin{aligned} P(F; \tilde{\mathbf{K}}_t) &= \int_{\mathbb{S}^{n-1}} \int_{\{\sigma\}^\perp} \mathcal{H}^0(\partial^* F \cap \tilde{L}_{\sigma,x}) d\mathcal{H}_x^{n-1} d\mathcal{H}_\sigma^{n-1} \\ &\geq \int_{\mathbb{S}^{n-1}} \int_{\{\sigma\}^\perp} \mathbf{1}_{\{\tilde{L}_{\sigma,x} \cap \partial^* F \neq \emptyset\}} d\mathcal{H}_x^{n-1} d\mathcal{H}_\sigma^{n-1}. \end{aligned} \tag{4.16}$$

Thus, inserting (4.12) into (4.11) and using the fact that

$$\int_{\mathbb{S}^{n-1}} \int_{\{\sigma\}^\perp} \mathbf{1}_{\{\tilde{L}_{\sigma,x} \neq \emptyset\}} d\mathcal{H}_x^{n-1} d\mathcal{H}_\sigma^{n-1} \leq C$$

gives

$$\mathcal{F}_\varepsilon^{\text{loc}}(F) - \mathcal{F}_\varepsilon^{\text{loc}}(E) \leq 2(P(F; \tilde{\mathbf{K}}_t) - \text{Sh}(F; \tilde{\mathbf{K}}_t)) + CQ_{1-\theta}(\varepsilon^{-1}). \quad (4.17)$$

By Lemma 4.3 below,  $\text{Sh}$  is minimal when  $F \cap \tilde{\mathbf{K}}_t = \mathbb{R}_+^n \cap \tilde{\mathbf{K}}_t$ , which gives

$$\text{Sh}(F; \tilde{\mathbf{K}}_t) \geq \mathcal{H}^{n-1}(\tilde{D}_t).$$

In view of (4.17), this concludes the proof of (4.10).

*Step 3.* We may now conclude the proof of (4.5). By (4.8) and (4.7), we find

$$(1 - \gamma)P(E; \mathbf{K}_t) \leq (1 - \gamma)P(F; \mathbf{K}_t) + \gamma [2\mathcal{E}(F, t + \varepsilon^\theta) + CQ_{1-\theta}(\varepsilon^{-1})] + \Lambda|E\Delta F| + (1 - \gamma)\eta.$$

Subtracting  $(1 - \gamma)\mathcal{H}^{n-1}(D_t)$  from the previous inequality and using that by (4.6)

$$\mathcal{E}(F, t + \varepsilon^\theta) - \mathcal{E}(F, t) = \mathcal{E}(E, t + \varepsilon^\theta) - \mathcal{E}(E, t) + \eta,$$

yields

$$\begin{aligned} (1 - \gamma)\mathcal{E}(E, t) &\leq (1 - \gamma)\mathcal{E}(F, t) + 2\gamma\mathcal{E}(F, t + \varepsilon^\theta) + C\gamma Q_{1-\theta}(\varepsilon^{-1}) + \Lambda|E\Delta F| + (1 + \gamma)\eta \\ &= (1 + \gamma)\mathcal{E}(F, t) + 2\gamma[\mathcal{E}(F, t + \varepsilon^\theta) - \mathcal{E}(F, t)] + \Lambda|E\Delta F| + (1 + \gamma)\eta \\ &= (1 + \gamma)\mathcal{E}(F, t) + 2\gamma[\mathcal{E}(E, t + \varepsilon^\theta) - \mathcal{E}(E, t)] + \Lambda|E\Delta F| + (1 + 3\gamma)\eta. \end{aligned}$$

Dividing by  $(1 - \gamma)$  concludes the proof of (4.5).  $\square$

Let  $\pi_V$  denote the orthogonal projection on a vector space  $V \subseteq \mathbb{R}^n$ . We now prove that among sufficiently flat sets, the quantity

$$\text{Sh}(E; \mathbf{K}_t) = \frac{1}{2\omega_{n-1}} \int_{\mathbb{S}^{n-1}} \mathcal{H}^{n-1}(\pi_{\sigma^\perp}(\partial^* E \cap \mathbf{K}_t)) d\mathcal{H}_\sigma^{n-1} \quad (4.18)$$

is minimal when  $E$  is flat.

**Lemma 4.3.** *For any  $t > 0$ , and any set of finite perimeter  $E \subseteq \mathbb{R}^n$  such that*

$$\{x_n < -1/4\} \cap \mathbf{K}_t \subseteq E \cap \mathbf{K}_t \subseteq \{x_n < 1/4\} \cap \mathbf{K}_t, \quad (4.19)$$

*we have*

$$\text{Sh}(E; \mathbf{K}_t) \geq \text{Sh}(D_t \times (-1, 0); \mathbf{K}_t) = \mathcal{H}^{n-1}(D_t). \quad (4.20)$$

Notice that the equality  $\text{Sh}(D_t \times (-1, 0); \mathbf{K}_t) = \mathcal{H}^{n-1}(D_t)$  follows arguing as for (4.16).

*Proof of Lemma 4.3.* We start by fixing some notation. We denote by  $S : \mathbb{R}^n \rightarrow \mathbb{R}^n$  the symmetry with respect to the vertical line  $\{0_{\mathbb{R}^{n-1}}\} \times \mathbb{R}$ , that is, for  $\xi = (\xi', \xi_n)$ ,

$$S\xi := (-\xi', \xi_n).$$

We write

$$\text{Sh}(E; \mathbf{K}_t) = \frac{1}{4\omega_{n-1}} \int_{\mathbb{S}^{n-1}} [\mathcal{H}^{n-1}(\pi_{\sigma^\perp}(\partial^* E \cap \mathbf{K}_t)) + \mathcal{H}^{n-1}(\pi_{(S\sigma)^\perp}(\partial^* E \cap \mathbf{K}_t))] d\mathcal{H}_\sigma^{n-1}. \quad (4.21)$$

We claim that for every  $\sigma \in \mathbb{S}^{n-1}$ , the integrand is minimal when  $\partial^* E$  is horizontal in  $\mathbf{K}_t$ , that is,

$$\mathcal{H}^{n-1}(\pi_{\sigma^\perp}(\partial^* E \cap \mathbf{K}_t)) + \mathcal{H}^{n-1}(\pi_{(S\sigma)^\perp}(\partial^* E \cap \mathbf{K}_t)) \geq \mathcal{H}^{n-1}(\pi_{\sigma^\perp}(D_t)) + \mathcal{H}^{n-1}(\pi_{(S\sigma)^\perp}(D_t)). \quad (4.22)$$

After integration this would conclude the proof of (4.20). The proof of (4.22) is done in two steps. In the first step we prove it for  $n = 2$  and in the second step we use slicing to reduce ourselves to the two-dimensional situation.

*Step 1.* We first prove (4.22) for  $n = 2$ .

*Step 1.1.* By [2], we may decompose the set of finite perimeter  $\tilde{E} := E \cap \mathbf{K}_t$  into its (measure theoretic) connected components. By assumption (4.19) one of these components denoted  $\tilde{E}_1$  contains  $(-t, t) \times (-1, -\frac{1}{4})$ . Its external boundary is a Jordan curve  $\gamma \in C^0([0, 1], [-t, t] \times [-1, \frac{1}{4}])$  and we have  $\gamma([0, 1]) \subseteq \partial^M \tilde{E}_1 \subseteq \partial E$  up to a  $\mathcal{H}^1$ -negligible set, where  $\partial^M \tilde{E}_1$  is the essential boundary and  $\partial \tilde{E}_1$  the usual topological boundary of  $\tilde{E}_1$ . Moreover, by (4.19) we may assume up to a reparameterization that

$\gamma|_{[0, \frac{1}{2}]}$  is a parameterization of the broken line made of the three oriented segments joining  $(-t, -\frac{1}{4})$  to  $(-t, -1)$ , then  $(-t, -1)$  to  $(t, -1)$  and  $(t, -1)$  to  $(t, -\frac{1}{4})$ .

Denoting

$$\begin{aligned} s_1 &:= \max\{s \in [\frac{1}{2}, 1) : \gamma(s) \in \{t\} \times \mathbb{R}\}, \\ s_2 &:= \min\{s \in (s_1, 1) : \gamma(s) \in \{-t\} \times \mathbb{R}\}, \end{aligned}$$

we obtain the parameterization of an arc  $\gamma : [s_1, s_2] \rightarrow [-t, t] \times [-\frac{1}{4}, \frac{1}{4}]$  with

$$\gamma(s_1) \in \{t\} \times \mathbb{R}, \quad \gamma(s_2) \in \{-t\} \times \mathbb{R}, \quad \gamma([s_1, s_2]) \subseteq (-t, t) \times [-\frac{1}{4}, \frac{1}{4}].$$

Let  $I$  be the segment  $[\gamma(s_1), \gamma(s_2)]$ . Obviously, any straight line intersecting  $I$  also intersects the arc  $\gamma([s_1, s_2])$ , hence for every  $\sigma \in \mathbb{S}^1$ ,  $\pi_{\sigma^\perp}(\gamma([s_1, s_2]))$  contains  $\pi_{\sigma^\perp}(I)$ , so that

$$\mathcal{H}^1(\pi_{\sigma^\perp}(I)) \leq \mathcal{H}^1(\pi_{\sigma^\perp}(\gamma([s_1, s_2]))) \leq \mathcal{H}^1(\pi_{\sigma^\perp}(\partial^M E \cap \mathbf{K}_t)) = \mathcal{H}^1(\pi_{\sigma^\perp}(\partial^* E \cap \mathbf{K}_t)). \quad (4.23)$$

*Step 1.2.* For  $\sigma \in \mathbb{S}^1$ , let  $\theta \in [0, \frac{\pi}{2}]$  be such that

$$\{\mathbb{R}\sigma, \mathbb{R}(S\sigma)\} = \left\{ \mathbb{R} \begin{pmatrix} \cos \theta \\ \sin \theta \end{pmatrix}, \mathbb{R} \begin{pmatrix} -\cos \theta \\ \sin \theta \end{pmatrix} \right\}$$

and  $\varphi \in (-\frac{\pi}{2}, \frac{\pi}{2})$  be such that  $I$  has direction  $\begin{pmatrix} \cos \varphi \\ \sin \varphi \end{pmatrix}$ . We compute

$$\begin{aligned} \mathcal{H}^1(\pi_{\sigma^\perp}(I)) + \mathcal{H}^1(\pi_{(S\sigma)^\perp}(I)) &= \frac{2t}{\cos \varphi} (|\sin(\theta - \varphi)| + |\sin(\theta + \varphi)|) \\ &= \begin{cases} 4t|\tan \varphi| \cos \theta & \text{if } 0 \leq \theta \leq |\varphi| < \frac{\pi}{2}, \\ 4t \sin \theta & \text{if } |\varphi| < \theta \leq \frac{\pi}{2}. \end{cases} \end{aligned}$$

Since  $\tan \varphi$  is increasing in  $(\theta, \frac{\pi}{2})$  we have  $|\tan \varphi| \cos \theta \geq \sin \theta$  if  $\theta \leq |\varphi| < \frac{\pi}{2}$  and thus

$$\mathcal{H}^1(\pi_{\sigma^\perp}(I)) + \mathcal{H}^1(\pi_{(S\sigma)^\perp}(I)) \geq 4t \sin \theta = \mathcal{H}^1(\pi_{\sigma^\perp}(I_t)) + \mathcal{H}^1(\pi_{(S\sigma)^\perp}(I_t)).$$

Together with (4.23) applied both to  $\sigma$  and  $S\sigma$ , this proves the (4.22) when  $n = 2$ .

*Step 2.* The case  $n > 2$ . There exists  $e \in \mathbb{S}^{n-1} \cap [\mathbb{R}^{n-1} \times \{0\}] \sim \mathbb{S}^{n-2}$  such that

$$\sigma = (\sigma \cdot e)e + \sigma_n e_n, \quad S\sigma = -(\sigma \cdot e)e + \sigma_n e_n.$$

Denoting  $P := \text{Span}\{e, e_n\}$ ,  $V := P^\perp$  and  $P_y := y + P$  for  $y \in V$ , we have

$$\mathcal{H}^{n-1}(\pi_{\sigma^\perp}(\partial^* E \cap \mathbf{K}_t)) = \int_{V \cap B_t} \mathcal{H}^1(\pi_{\sigma^\perp}(\partial^* E \cap \mathbf{K}_t \cap P_y)) d\mathcal{H}_y^{n-2}, \quad (4.24)$$

$$\mathcal{H}^{n-1}(\pi_{(S\sigma)^\perp}(\partial^* E \cap \mathbf{K}_t)) = \int_{V \cap B_t} \mathcal{H}^1(\pi_{(S\sigma)^\perp}(\partial^* E \cap \mathbf{K}_t \cap P_y)) d\mathcal{H}_y^{n-2}. \quad (4.25)$$

Next, for almost every  $y \in V$ ,  $E \cap P_y$  is a set with finite perimeter in the plane  $P_y$  and up to a  $\mathcal{H}^1$ -negligible set,  $\partial_{P_y}^*(E \cap P_y) = (\partial_{\mathbb{R}^n}^* E) \cap P_y$ .

Noticing that for  $|y| \geq t$ ,  $\mathbf{K}_t \cap P_y = \emptyset$  and that for  $|y| < t$ ,  $\mathbf{K}_t \cap P_y = y + \{x_1 e + x_2 e_n : |x_1| < \sqrt{t^2 - |y|^2}, |x_2| < 1\} \sim (-\sqrt{t^2 - |y|^2}, \sqrt{t^2 - |y|^2}) \times (-1, 1)$  and using *Step 1* in  $\mathbf{K}_t \cap P_y$  concludes the proof.  $\square$

*Remark 4.4.* In [Proposition 4.2](#), we introduced a parameter  $\theta \in (0, 1]$  to find a proper balance between the terms

$$[\mathcal{E}(E, t + \varepsilon^\theta) - \mathcal{E}(E, t)] \quad \text{and} \quad Q_{1-\theta} \left( \frac{1}{\varepsilon} \right).$$

As we will see, through an averaging argument, we can roughly estimate

$$[\mathcal{E}(E, t + \varepsilon^\theta) - \mathcal{E}(E, t)] \lesssim \varepsilon^\theta \mathbf{e}(E, 2t) \quad (4.26)$$

se the first quantity gets smaller the closer  $\theta$  is to 1. However,  $Q_{1-\theta}(\varepsilon^{-1})$  gets larger as  $\theta$  goes to 1. In particular when  $\theta = 1$ ,  $Q_{1-\theta}(r/\varepsilon) = Q(1)$  is a constant (non-zero unless  $G$  is compactly supported in  $B_1$ ), which would prevent us to obtain a decay of the excess through iteration. We can choose later  $\theta$  small enough so that  $Q_{1-\theta}(r/\varepsilon)$  stays sufficiently small down to any scale  $\varepsilon^{1-\beta}$  with  $\beta \in (0, 1)$ . As long as  $\theta$  is non-zero, (4.26) will be sufficient to proceed with the iteration.

**4.2. A Caccioppoli-type inequality.** From the improved quasi-minimality condition given by Proposition 4.2, we first obtain an intermediate weaker form of a Caccioppoli inequality. We refer to (4.1), (4.2) and (4.4) for the definitions of  $\mathcal{F}$ ,  $\mathcal{E}$  and  $Q_{1-\theta}$ .

**Proposition 4.5.** *Assume that  $G$  satisfies (H1) and (H2), and let  $\varepsilon \in (0, 1)$ ,  $\gamma \in (0, 1)$ ,  $\theta \in (0, 1]$  and  $\Lambda > 0$  such that  $\varepsilon^\theta \in (0, \frac{1}{4})$  and  $4\Lambda \leq 1 - \gamma$ . Then for every  $(\Lambda, 4)$ -minimizer  $E$  of  $\mathcal{F}_{\varepsilon, \gamma}$  with*

$$\left\{x_n < -\frac{1}{8}\right\} \cap \mathbf{K}_3 \subseteq E \cap \mathbf{K}_3 \subseteq \left\{x_n < \frac{1}{8}\right\} \cap \mathbf{K}_3,$$

the following holds. For every  $c \in \mathbb{R}$  such that  $|c| < \frac{1}{4}$  and every  $t \in (4\varepsilon^\theta, 1)$ , we have

$$\mathcal{E}(E, t/2) \leq C \left( (\mathcal{E}(E, t)\mathcal{F}(E, t, c))^{\frac{1}{2}} + \left(\frac{\varepsilon^\theta}{t}\right) \mathcal{E}(E, t) + Q_{1-\theta}(\varepsilon^{-1}) + \Lambda t^{n-1} \right), \quad (4.27)$$

where  $C$  depends only on  $n$  and  $\gamma$ .

*Proof.* For almost every  $t \in (4\varepsilon^\theta, 1)$ , we have

$$\mathcal{H}^{n-1}(\partial \mathbf{K}_t \cap \partial E) = 0. \quad (4.28)$$

Let us fix such a  $t$ . If  $\mathcal{F}(E, t, c) \geq \frac{1}{16}\mathcal{E}(E, t)$ , then using the fact that  $\mathcal{E}(E, \cdot)$  is nondecreasing, we have

$$\mathcal{E}(E, t/2) \leq \mathcal{E}(E, t) \leq \sqrt{\mathcal{E}(E, t)}\sqrt{\mathcal{E}(E, t)} \leq 4(\mathcal{E}(E, t)\mathcal{F}(E, t, c))^{\frac{1}{2}}$$

thus (4.27) holds. Hence, we now assume  $\mathcal{F}(E, t, c) < \frac{1}{16}\mathcal{E}(E, t)$ , and set  $\lambda := \sqrt{\frac{\mathcal{F}(E, t, c)}{\mathcal{E}(E, t)}} \in (0, \frac{1}{4})$ . As in [25, Lemma 24.9] we want to use for  $s \in (0, 1)$  the construction of [25, Lemma 24.6] as competitor inside  $\mathbf{K}_{st}$  for Proposition 4.2. To this aim using for instance [25, Theorem 13.8], we approximate  $E$  by smooth sets  $E_k$  with  $|E \Delta E_k| \rightarrow 0$ ,  $P(E_k) \rightarrow P(E)$  and

$$\left\{x_n < -\frac{1}{4}\right\} \cap \mathbf{K}_3 \subseteq E_k \cap \mathbf{K}_3 \subseteq \left\{x_n < \frac{1}{4}\right\} \cap \mathbf{K}_3. \quad (4.29)$$

By the Morse–Sard lemma, for almost every  $s \in (0, 1)$ ,

$$\partial \mathbf{K}_{st} \cap \partial E_k \text{ is a } (n-2)\text{-dimensional hypersurface.} \quad (4.30)$$

For every such  $s$  we may apply [25, Lemma 24.6] with  $a = (1-\lambda)st$  and  $b = st$ , and use the inequalities  $\sqrt{1+t^2} \leq 1+t^2$  and  $1-(1-\lambda)^{n-1} \leq (n-1)\lambda$ , to construct an open set of finite perimeter  $F_s$  such that (4.29) holds for  $F_s$ ,

$$F_s \cap \partial \mathbf{K}_{st} = E_k \cap \partial \mathbf{K}_{st}, \quad (4.31)$$

and

$$\mathcal{E}(F_s, st) \leq C \left( \lambda st V_{\mathcal{E}}(st) + \frac{1}{\lambda st} V_{\mathcal{F}}(st) \right), \quad (4.32)$$

where we have set

$$V_{\mathcal{E}}(a) := \frac{d}{da}(\mathcal{E}(E_k, a)) = \mathcal{H}^{n-2}(\partial \mathbf{K}_a \cap \partial E_k) - \mathcal{H}^{n-2}(\partial D_a)$$

and

$$V_{\mathcal{F}}(a) := \frac{d}{da}(a^2 \mathcal{F}(E_k, a, c)) = \int_{\partial \mathbf{K}_a \cap \partial E_k} (x_n - c)^2 d\mathcal{H}^{n-2}.$$

Applying Proposition 4.2 with  $F = (F_s \cap \mathbf{K}_{st}) \cup (E \setminus \mathbf{K}_{st})$  and noticing that by (4.31) and [25, Theorem 16.16], for a.e.  $s$ ,  $\mathcal{H}^{n-1}(\partial^* F_s \cap \partial \mathbf{K}_{st}) = \mathcal{H}^{n-1}((E \Delta E_k) \cap \partial \mathbf{K}_{st})$  we find for such  $s$ ,

$$\begin{aligned} \mathcal{E}(E, st) &\leq C \left( \mathcal{E}(F_s, st) + [\mathcal{E}(E, st + \varepsilon^\theta) - \mathcal{E}(E, st)] + \Lambda |\mathbf{K}_{st}| + Q_{1-\theta}(\varepsilon^{-1}) \right. \\ &\quad \left. + \mathcal{H}^{n-1}((E \Delta E_k) \cap \partial \mathbf{K}_{st}) \right) \\ &\stackrel{(4.32)}{\leq} C \left( \lambda st V_{\mathcal{E}}(st) + \frac{1}{\lambda st} V_{\mathcal{F}}(st) + [\mathcal{E}(E, st + \varepsilon^\theta) - \mathcal{E}(E, st)] + \Lambda t^{n-1} + Q_{1-\theta}(\varepsilon^{-1}) \right. \\ &\quad \left. + \mathcal{H}^{n-1}((E \Delta E_k) \cap \partial \mathbf{K}_{st}) \right). \end{aligned} \quad (4.33)$$

We now integrate (4.33) for  $s$  between  $1/2$  and  $3/4$ . First, since  $\mathcal{E}(E, \cdot)$  is nondecreasing, we have

$$\frac{1}{4}\mathcal{E}(E, t/2) \leq \int_{\frac{1}{2}}^{\frac{3}{4}} \mathcal{E}(E, st) ds. \quad (4.34)$$

Second, we compute

$$\begin{aligned} \int_{\frac{1}{2}}^{\frac{3}{4}} [\mathcal{E}(E, st + \varepsilon) - \mathcal{E}(E, st)] ds &= \frac{1}{t} \int_{\frac{t}{2}}^{\frac{3t}{4}} [\mathcal{E}(E, a + \varepsilon^\theta) - \mathcal{E}(E, a)] da \\ &= \frac{1}{t} \left( \int_{\frac{t}{2} + \varepsilon^\theta}^{\frac{3t}{4} + \varepsilon^\theta} \mathcal{E}(E, a) da - \int_{\frac{t}{2}}^{\frac{3t}{4}} \mathcal{E}(E, a) da \right) \leq \frac{1}{t} \int_{\frac{3t}{4}}^{\frac{3t}{4} + \varepsilon^\theta} \mathcal{E}(E, a) da \leq \left( \frac{\varepsilon^\theta}{t} \right) \mathcal{E}(E, t), \end{aligned} \quad (4.35)$$

where we used the fact that  $\mathcal{E}(E, \cdot)$  is nondecreasing for the last inequality. Third,

$$\int_{\frac{1}{2}}^{\frac{3}{4}} stV_{\mathcal{E}}(st) ds \leq \frac{3}{4} \int_{\frac{t}{2}}^{\frac{3t}{4}} V_{\mathcal{E}}(a) da = \frac{3}{4} \left( \mathcal{E} \left( E_k, \frac{3t}{4} \right) - \mathcal{E} \left( E_k, \frac{t}{2} \right) \right) \leq \frac{3}{4} \mathcal{E}(E_k, t). \quad (4.36)$$

Finally, with a similar argument using that  $a \mapsto a^2 \mathcal{F}(E_k, a, c)$  is nondecreasing, we have

$$\int_{\frac{1}{2}}^{\frac{3}{4}} \frac{1}{st} V_{\mathcal{F}}(st) ds \leq 2\mathcal{F}(E_k, t, c). \quad (4.37)$$

Inserting (4.34), (4.35), (4.36) and (4.37) into (4.33) yields

$$\mathcal{E}(E, t/2) \leq C \left[ \lambda \mathcal{E}(E_k, t) + \frac{1}{\lambda} \mathcal{F}(E_k, t, c) + \left( \frac{\varepsilon^\theta}{t} \right) \mathcal{E}(E, t) + \Lambda t^{n-1} + Q_{1-\theta}(\varepsilon^{-1}) + |E \Delta E_k| \right]. \quad (4.38)$$

By (4.28) we can send  $k \rightarrow \infty$  to obtain

$$\mathcal{E}(E, t/2) \leq C \left[ \lambda \mathcal{E}(E, t) + \frac{1}{\lambda} \mathcal{F}(E, t, c) + \left( \frac{\varepsilon^\theta}{t} \right) \mathcal{E}(E, t) + \Lambda t^{n-1} + Q_{1-\theta}(\varepsilon^{-1}) \right].$$

Recalling that  $\lambda = \sqrt{\frac{\mathcal{F}(E, t, c)}{\mathcal{E}(E, t)}}$  concludes the proof of (4.27) for a.e.  $t \in (4\varepsilon^\theta, 1)$ . By the left-continuity of  $\mathcal{E}(E, \cdot)$  and  $\mathcal{F}(E, \cdot, c)$  this actually holds for every  $t \in (4\varepsilon^\theta, 1)$ .  $\square$

We now postprocess (4.27) to obtain the desired stronger Caccioppoli inequality. The main difference with [25, Theorem 24.1] is that in our case we cannot apply (4.27) at scales which are smaller than  $\varepsilon^\theta$ .

**Proposition 4.6** (Caccioppoli inequality). *Assume that  $G$  satisfies (H1) and (H2), and let  $\varepsilon \in (0, 1)$ ,  $\gamma \in (0, 1)$ ,  $\Lambda > 0$  and  $r_0 > 0$  with  $\Lambda r_0 \leq 1 - \gamma$ . There exist a constant  $\tau_{\text{cac}} = \tau_{\text{cac}}(n) > 0$  and universal constants  $\sigma_{\text{cac}} > 0$  and  $M_{\text{cac}} > 1$  such that the following holds. If  $E$  is a  $(\Lambda, r_0)$ -minimizer of  $\mathcal{F}_{\varepsilon, \gamma}$  satisfying, for some  $x \in \partial E$ ,  $\nu \in \mathbb{S}^{n-1}$ ,  $r > 0$  and  $\theta \in (0, 1]$ ,*

$$\mathbf{e}(E, x, M_{\text{cac}}r, \nu) \leq \tau_{\text{cac}}, \quad M_{\text{cac}}r < r_0, \quad \left( \frac{\varepsilon}{r} \right)^\theta \leq \sigma_{\text{cac}},$$

then

$$\mathbf{e}(E, x, r/2, \nu) \leq C \left( \mathbf{f}(E, x, r, \nu) + \left( \frac{\varepsilon}{r} \right)^\theta \mathbf{e}(E, x, r, \nu) + \Lambda r + Q_{1-\theta} \left( \frac{r}{\varepsilon} \right) \right), \quad (4.39)$$

where  $C = C(n, G, \gamma)$ .

*Proof.* Up to a translation and a rotation, we assume  $x = 0$  and  $\nu = e_n$ . Up to rescaling, we may assume that  $r = 1$ ,  $\varepsilon^\theta \leq \sigma_{\text{cac}}$  and  $E$  is a  $(\Lambda, \frac{r_0}{r})$ -minimizer of  $\mathcal{F}_{\varepsilon, \gamma}$  with  $\Lambda \left( \frac{r_0}{r} \right) \leq 1 - \gamma$ . Up to choosing  $M_{\text{cac}}$  large enough and  $\sigma_{\text{cac}}$  small enough, we may assume that  $E$  is a  $(\Lambda, 4)$ -minimizer of  $\mathcal{F}_{\varepsilon, \gamma}$  with  $4\Lambda \leq 1 - \gamma$  and  $16\varepsilon^\theta < 1$ . Thus, (4.39) amounts to proving

$$\mathbf{e}_n(E, \frac{1}{2}) \leq C \left( \mathbf{f}_n(E, 1) + \varepsilon^\theta \mathbf{e}_n(E, 1) + \Lambda + Q_{1-\theta} \left( \frac{1}{\varepsilon} \right) \right). \quad (4.40)$$

By Proposition 2.16, choosing  $M_{\text{cac}}$  even larger if necessary and  $\tau_{\text{cac}} = \tau_{\text{cac}}(n)$  small enough, we have

$$\left\{ (x', x_n) \in \mathbf{C}_4 : x_n < -\frac{1}{8} \right\} \subseteq E \cap \mathbf{C}_4 \subseteq \left\{ (x', x_n) \in \mathbf{C}_4 : x_n < \frac{1}{8} \right\}. \quad (4.41)$$



Thus for every  $z \in D_1$ , we have

$$\left\{ (x', x_n) \in \mathbf{K}_3(z) : x_n < -\frac{1}{8} \right\} \subseteq E \cap \mathbf{K}_3(z) \subseteq \left\{ (x', x_n) \in \mathbf{K}_3(z) : x_n < \frac{1}{8} \right\},$$

so we can apply [Proposition 4.5](#) to  $E + (z, 0)$  with  $2s$  for every  $s \in (2\varepsilon^\theta, \frac{1}{2})$ . Thus, for every  $s \in (2\varepsilon^\theta, \frac{1}{2})$  such that  $D_{2s}(z) \subseteq D_1$ , we have

$$\mathcal{E}(E, \mathbf{K}_s(z)) \leq C \left( (\mathcal{E}(E, \mathbf{K}_{2s}(z)) \mathcal{F}(E, \mathbf{K}_{2s}(z), c))^{\frac{1}{2}} + \left(\frac{\varepsilon}{s}\right)^\theta \mathcal{E}(E, \mathbf{K}_{2s}(z)) + Q_{1-\theta} \left(\frac{1}{\varepsilon}\right) + \Lambda s^{n-1} \right). \quad (4.42)$$

Setting

$$h := \inf_{|c| < \frac{1}{4}} \int_{\mathbf{C}_1 \cap \partial^* E} (x_n - c)^2 d\mathcal{H}^{n-1}$$

multiplying [\(4.42\)](#) by  $s^2$  and taking the infimum over  $|c| < \frac{1}{4}$ , using the fact that

$$s^2 \mathcal{F}(E, \mathbf{K}_{2s}(z), c) \leq \frac{\mathcal{F}(E, \mathbf{K}_1, c)}{4} \leq \frac{h}{4}$$

for every  $s \in (2\varepsilon^\theta, \frac{1}{2})$  with  $D_{2s}(z) \subseteq D_1$ , we find

$$s^2 \mathcal{E}(E, \mathbf{K}_s(z)) \leq C \left( (s^2 \mathcal{E}(E, \mathbf{K}_{2s}(z)) h)^{\frac{1}{2}} + \varepsilon^\theta \mathcal{E}(E, \mathbf{K}_{2s}(z)) + s^2 Q_{1-\theta} \left(\frac{1}{\varepsilon}\right) + \Lambda \right). \quad (4.43)$$

Set

$$\Psi := \sup \left\{ s^2 \mathcal{E}(E, \mathbf{K}_s(z)) : D_{2s}(z) \subseteq D_1 \text{ and } s \in \left(4\varepsilon^\theta, \frac{1}{2}\right) \right\}.$$

If

$$\Psi = \sup \left\{ s^2 \mathcal{E}(E, \mathbf{K}_s(z)) : D_{2s}(z) \subseteq D_1 \text{ and } s \in (4\varepsilon^\theta, 8\varepsilon^\theta) \right\}$$

then [\(4.40\)](#) holds. Indeed, using the left-continuity of  $t \mapsto \mathcal{E}(E, \mathbf{K}_t)$  and the fact that  $\mathcal{E}(E, \mathbf{K}_s(z)) \leq \mathcal{E}(E, \mathbf{K}_1)$  whenever  $D_{2s}(z) \subseteq D_1$ , in that case we find

$$\mathcal{E}(E, \mathbf{K}_{\frac{1}{2}}) \leq \frac{\Psi}{4} \leq C \varepsilon^{2\theta} \mathcal{E}(E, \mathbf{K}_1),$$

which gives [\(4.40\)](#) recalling that  $\mathbf{e}_n(E, \frac{1}{2}) = 2\mathcal{E}(E, \mathbf{K}_{\frac{1}{2}})$  (see [\(4.3\)](#)). We can thus take the supremum over  $s > 4\varepsilon^\theta$  or  $s > 8\varepsilon^\theta$  for  $\Psi$ . For any  $z$  and  $s$  such that  $D_{2s}(z) \subseteq D_1$  and  $s \in (8\varepsilon^\theta, \frac{1}{2})$ , we cover  $D_s(z)$  by  $N = N(n)$  balls  $D_{\frac{s}{4}}(z_k)$  with centers  $z_k \in D_s(z)$ . Then since  $\frac{s}{4} > 2\varepsilon^\theta$  and  $D_{\frac{s}{2}}(z_k) \subseteq D_1$ , we can apply [\(4.43\)](#) to each  $(\frac{s}{4})^2 \mathcal{E}(E, \mathbf{K}_{\frac{s}{4}}(z_k))$ . Thus, by the subadditivity of  $\mathcal{E}$ , and by definition of  $\Psi$ , for such  $z$  and  $s \in (8\varepsilon^\theta, \frac{1}{2})$ , we deduce

$$\begin{aligned} s^2 \mathcal{E}(E, \mathbf{K}_s(z)) &\leq \frac{1}{16} \sum_{k=1}^N \left(\frac{s}{4}\right)^2 \mathcal{E}(E, \mathbf{K}_{\frac{s}{4}}(z_k)) \\ &\leq C \sum_{k=1}^N \left( (s^2 \mathcal{E}(E, \mathbf{K}_{\frac{s}{2}}(z_k)) h)^{\frac{1}{2}} + \varepsilon^\theta \mathcal{E}(E, \mathbf{K}_{\frac{s}{2}}(z_k)) + s^2 Q_{1-\theta} \left(\frac{1}{\varepsilon}\right) + \Lambda \right) \\ &\leq C \left( \sqrt{\Psi h} + \varepsilon^\theta \Psi + Q_{1-\theta} \left(\frac{1}{\varepsilon}\right) + \Lambda \right). \end{aligned} \quad (4.44)$$

Recall that  $\Psi$  is in fact obtained by taking the supremum over the  $s, z$  such that  $D_{2s}(z) \subseteq D_1$  and  $s \in (8\varepsilon^\theta, \frac{1}{2})$  by the above discussion, thus, [\(4.44\)](#) yields

$$\Psi \leq C \left( \sqrt{\Psi h} + \varepsilon^\theta \Psi + Q_{1-\theta} \left(\frac{1}{\varepsilon}\right) + \Lambda \right). \quad (4.45)$$

If

$$\varepsilon^\theta \Psi + Q_{1-\theta} \left(\frac{1}{\varepsilon}\right) + \Lambda < \sqrt{\Psi h},$$

then [\(4.45\)](#) implies  $\Psi \leq Ch$ . Otherwise, [\(4.45\)](#) implies

$$\Psi \leq C \left( \varepsilon^\theta \Psi + Q_{1-\theta} \left(\frac{1}{\varepsilon}\right) + \Lambda \right) \leq C \left( \varepsilon^\theta \mathcal{E}(E, \mathbf{K}_1) + Q_{1-\theta} \left(\frac{1}{\varepsilon}\right) + \Lambda \right).$$

Recalling  $\mathbf{e}_n(E, \frac{1}{2}) = 2\mathcal{E}(E, \mathbf{K}_{\frac{1}{2}})$ , the left-continuity of  $t \mapsto \mathcal{E}(E, \mathbf{K}_t)$  and the definition of  $h$ , combining the different cases yields (4.40). This concludes the proof.  $\square$

## 5. UNIFORM REGULARITY

**5.1. Excess decay for  $r \lesssim \varepsilon$ .** If  $G$  satisfies assumptions (H1), (H2) and (H4), by Proposition 2.12 and Remark 2.13, it is standard to obtain power decay of the excess starting from a scale comparable to  $\varepsilon$ . One can for example apply the regularity theory of [29] for sets  $E$  satisfying the almost-minimality property

$$P(E; B_r(x)) \leq P(F; B_r(x)) + \omega(r), \quad \text{with} \quad \omega(r) := \Lambda r^{n-1+s_0},$$

for any competitor  $F$  such that  $E \Delta F \subset\subset B_r(x)$  with  $r < r_0$  and  $x \in \mathbb{R}^n$ .

As a consequence, we have the following power decay of the excess for small scales.

**Proposition 5.1** (Excess decay at small scales). *Assume that  $G$  satisfies (H1), (H2) and (H4), and let  $\gamma \in (0, 1)$ ,  $\varepsilon > 0$ ,  $\Lambda > 0$  and  $r_0 > 0$  with  $\Lambda r_0 \leq 1 - \gamma$ . Then for every  $\alpha \in (0, \frac{1-s_0}{2})$ , there exist positive constants  $\tau_{\text{dec}}^s = \tau_{\text{dec}}^s(n, G, \gamma, \alpha)$  and  $C = C(n, G, \gamma, \alpha)$  such that the following holds. If  $E$  is a  $(\Lambda, r_0)$ -minimizer of  $\mathcal{F}_{\varepsilon, \gamma}$  which satisfies, for some  $x \in \partial E$ ,  $R > 0$  with  $4R < r_0$  and  $\nu \in \mathbb{S}^{n-1}$ ,*

$$\mathbf{e}(E, x, 4R, \nu) + \Lambda \left( \frac{R}{\varepsilon} \right) \leq \tau_{\text{dec}}^s, \quad (5.1)$$

then we have

$$\mathbf{e}(E, x, r) \leq C \left( \frac{r}{R} \right)^{2\alpha} \mathbf{e}(E, x, 4R, \nu), \quad \forall r \in (0, R).$$

**5.2. Excess decay for  $r \gg \varepsilon$ .** Starting with a small excess at a given scale much larger than  $\varepsilon$ , we show that the excess is smaller at a smaller scale, up to tilting the direction.

**Lemma 5.2** (Tilt lemma). *Assume that  $G$  satisfies (H1), (H2) and (H3), and let  $\gamma \in (0, 1)$ ,  $\varepsilon > 0$ ,  $\Lambda > 0$  and  $r_0 > 0$  with  $\Lambda r_0 \leq 1 - \gamma$ . Then there exists a positive constant  $\lambda_{\text{tilt}}$  such that for every  $\lambda \in (0, \lambda_{\text{tilt}})$ , there exists  $\tau_{\text{tilt}}$  depending only on  $n, G, \gamma$  and  $\lambda$  such that the following holds. If  $E$  is a  $(\Lambda, r_0)$ -minimizer of  $\mathcal{F}_{\varepsilon, \gamma}$  which satisfies, for some  $x \in \partial E$ ,  $\nu \in \mathbb{S}^{n-1}$ ,  $0 < r < r_0$  and  $\theta \in (0, 1]$ ,*

$$\mathbf{e}(E, x, r, \nu) + \Lambda r + \left( \frac{\varepsilon}{r} \right)^\theta \leq \tau_{\text{tilt}},$$

then there exists  $\nu_0 \in \mathbb{S}^{n-1}$  such that

$$\mathbf{e}(E, x, \lambda r, \nu_0) \leq C(\lambda^2 \mathbf{e}(E, x, r, \nu) + \lambda \Lambda r) + C Q_{1-\theta} \left( \frac{\lambda r}{\varepsilon} \right), \quad (5.2)$$

where  $C = C(n, G, \gamma)$ .

*Proof.* We follow relatively closely the proof of [25, Theorem 25.3]. Let  $\lambda \in (0, \lambda_{\text{tilt}})$ , with  $\lambda_{\text{tilt}}$  and  $\tau_{\text{tilt}}$  to be chosen later. Up to a translation and a rotation, we assume  $x = 0$  and  $\nu = \mathbf{e}_n$ . Up to rescaling, we may assume that  $r = 4$ ,  $\mathbf{e}_n(E, 4) + 4\Lambda \leq \tau_{\text{tilt}}$ ,  $\varepsilon^\theta \leq \tau_{\text{tilt}}$  and  $E$  is a  $(\Lambda, \frac{4r_0}{r})$ -minimizer of  $\mathcal{F}_{\varepsilon, \gamma}$  with  $\Lambda \left( \frac{4r_0}{r} \right) \leq 1 - \gamma$ . In particular  $E$  is a  $(\Lambda, 4)$ -minimizer of  $\mathcal{F}_{\varepsilon, \gamma}$  with  $4\Lambda \leq 1 - \gamma$ . In the rest of the proof, we shall write  $\mathbf{e}_n(r)$  for  $\mathbf{e}_n(E, 0, r)$  and  $\mathbf{f}(r, \nu)$  for  $\mathbf{f}(E, 0, r, \nu)$ .

Assuming that  $\tau_{\text{tilt}} < \tau_{\text{lip}}$ , we can apply Theorem 3.1 with  $r = 1$ . Let  $C_1 = C_1(n, G, \gamma)$  be a large constant, and set

$$L := C_1 \left( \mathbf{e}_n(4) + Q \left( \frac{1}{\varepsilon} \right) + \Lambda \right).$$

We proceed in two steps.

*Step 1.* We claim that if

$$L \leq \min(\lambda^{(n-1)(n+3)}, \sigma^2), \quad (5.3)$$

where  $\sigma(n, G, \gamma, \lambda)$  is the constant given by Proposition 3.3 with  $\tau = \lambda^{n+3}$ , then there exists  $\nu_0 \in \mathbb{S}^{n-1}$  such that

$$\mathbf{f}(\lambda, \nu_0) \leq C \lambda^2 L, \quad (5.4)$$

where  $C = C(n, G, \gamma)$ . Let us assume that (5.3) holds, and let us set  $u_0 := \frac{u}{\sqrt{L}}$ . By Theorem 3.1,  $u_0$  satisfies

$$\int_{D_2} |\nabla u_0|^2 \leq 1$$

and, choosing  $C_1$  large enough, for all  $\varphi \in C_c^\infty(D_1)$ ,

$$\int_{D_1} \nabla u_0 \cdot \nabla \varphi - \gamma \int_{D_2 \times D_2} (u_0(x') - u_0(y'))(\varphi(x') - \varphi(y')) G_\varepsilon(x' - y', 0) dx' dy' \leq \sqrt{L} \|\nabla \varphi\|_{L^\infty}.$$

Assuming  $\tau_{\text{tilt}} \leq \varepsilon_{\text{harm}}$ , then since  $\sqrt{L} \leq \sigma$  by assumption, [Proposition 3.3](#) gives that there exists a harmonic function  $v_0 \in H^1(D_1)$  such that

$$\int_{D_1} |\nabla v_0|^2 \leq 1 \quad \text{and} \quad \int_{D_1} |u_0 - v_0|^2 \leq \lambda^{n+3}.$$

Setting  $v := \sqrt{L}v_0$ ,  $v$  is a harmonic function in  $D_1$  such that

$$\int_{D_1} |\nabla v|^2 \leq L \quad \text{and} \quad \int_{D_1} |u - v|^2 \leq \lambda^{n+3}L. \quad (5.5)$$

Consider  $w(z) := v(0) + \nabla v(0) \cdot z$  the tangent map of  $v$  at the origin. Then since  $v$  is harmonic, up to choosing  $\lambda_{\text{tilt}}$  small enough we have

$$\|v - w\|_{L^\infty(D_\lambda)}^2 \leq C(n)\lambda^4 \|\nabla v\|_{L^2(D_1)}^2 \leq C(n)\lambda^4 L,$$

thus with (5.5), this implies

$$\frac{1}{\lambda^{n+1}} \int_{D_\lambda} |u - w|^2 \leq C(n)\lambda^2 L. \quad (5.6)$$

Defining the new direction

$$\nu_0 := \frac{(-\nabla v(0), 1)}{\sqrt{1 + |\nabla v(0)|^2}},$$

using (5.5) and (5.6) and the consequences of [Theorem 3.1](#), proceeding exactly as in Step 1 of the proof of [\[25, Theorem 25.3, pp 343\]](#), we obtain the claim (5.4).

*Step 2.* For  $\lambda$  fixed, we can assume that  $\tau_{\text{tilt}}$  is chosen small enough depending on  $n, G, \gamma$  and  $\lambda$  to enforce (5.3). Then, a key observation is that with that choice of  $\nu_0$ , we have

$$|\nu_0 - e_n|^2 \leq C(n) \int_{D_1} |\nabla v|^2 \leq C(n)L.$$

Thus, since  $\mathbf{C}(0, r, \nu) \subseteq \mathbf{C}(0, \sqrt{2}r, e_n)$ , by [Propositions 2.14](#) and [2.15](#), if  $\lambda_{\text{tilt}}$  is small enough so that  $M_{\text{cac}}\sqrt{2}\lambda < 4$ ,

$$\mathbf{e}(M_{\text{cac}}\lambda, \nu_0) \leq C(n) \left( \mathbf{e}_n(M_{\text{cac}}\sqrt{2}\lambda) + |\nu_0 - e_n|^2 \right) \leq C(n) \left( \frac{1}{\lambda^{n-1}} \mathbf{e}_n(4) + L \right) \quad (5.7)$$

Whence, by (5.3), up to choosing  $\lambda_{\text{tilt}}$  even smaller if necessary

$$\mathbf{e}(M_{\text{cac}}\lambda, \nu_0) \leq C(n)\lambda^{(n-1)(n+2)} \leq \tau_{\text{cac}}.$$

As a consequence, we can apply [Proposition 4.6](#), which yields

$$\mathbf{e}(\lambda/2, \nu_0) \leq C_2 \left( \mathbf{f}(\lambda, \nu_0) + \left(\frac{\varepsilon}{\lambda}\right)^\theta \mathbf{e}(\lambda, \nu_0) + \lambda\Lambda + Q_{1-\theta} \left(\frac{\lambda}{\varepsilon}\right) \right), \quad (5.8)$$

where  $C_2 = C_2(n, G, \gamma)$ . Since  $\varepsilon^\theta \leq \tau_{\text{tilt}}$ , up to choosing  $\tau_{\text{tilt}}$  even smaller if necessary depending on  $\lambda$ , we have

$$C_2 \left(\frac{\varepsilon}{\lambda}\right)^\theta \mathbf{e}(\lambda, \nu_0) \leq C \left(\frac{\varepsilon}{\lambda}\right)^\theta \mathbf{e}(M_{\text{cac}}\lambda, \nu_0) \stackrel{(5.7)}{\leq} \frac{L\tau_{\text{tilt}}}{\lambda^{n-1+\theta}} \leq \lambda^2 L.$$

Thus, for  $\lambda_{\text{tilt}}$  small enough, (5.4) and (5.8) give

$$\mathbf{e}(\lambda/2, \nu_0) \leq C\lambda^2 L + C\lambda\Lambda + CQ_{1-\theta} \left(\frac{\lambda}{\varepsilon}\right).$$

Since  $Q$  is nonincreasing, this gives (5.2) with  $r = 4$  and  $\lambda/2$  in place of  $\lambda$ , which concludes the proof.  $\square$

As a corollary, iterating properly [Lemma 5.2](#), we get the following power decay of the excess down to scales  $\varepsilon^{1-\beta}$  for any arbitrary small  $\beta > 0$ .

**Proposition 5.3.** *Assume that  $G$  satisfies (H1), (H2), (H3) and (H5), and let  $\gamma \in (0, 1)$ ,  $\Lambda > 0$  and  $r_0 > 0$  with  $\Lambda r_0 \leq 1 - \gamma$ . Given any  $\alpha \in (0, \frac{1}{2})$ ,  $\theta \in (0, 1)$  and  $\beta \in (0, 1)$ , there exist positive constants  $\tau_{\text{dec}}^\ell = \tau_{\text{dec}}^\ell(n, G, \gamma, \alpha)$  and  $\varepsilon_* = \varepsilon_*(n, G, \gamma, \alpha, \beta, \theta) > 0$  such that the following holds. If  $E$  is a  $(\Lambda, r_0)$ -minimizer of  $\mathcal{F}_{\varepsilon, \gamma}$  with  $\varepsilon \in (0, \varepsilon_*)$  satisfying, for some  $x \in \partial E$  and  $0 < R < r_0$ ,*

$$\mathbf{e}(E, x, R) + \Lambda R \leq \tau_{\text{dec}}^\ell \quad \text{and} \quad \varepsilon^{1-\beta} \leq R,$$

then, for all  $r \in [\varepsilon^{1-\beta}, R]$ , we have

$$\begin{aligned} \mathbf{e}(E, x, r) &\leq C \left[ \left( \frac{r}{R} \right)^{2\alpha} (\mathbf{e}(E, x, R) + \Lambda R) + Q_{1-\theta} \left( \frac{r}{\lambda \varepsilon} \right) \right] \\ &\leq C \left[ \left( \frac{r}{R} \right)^{2\alpha} (\mathbf{e}(E, x, R) + \Lambda R) + r^{(n-1+p_0)(1-\theta)} \left( \frac{\beta}{1-\beta} \right) \right] \end{aligned} \quad (5.9)$$

where  $\lambda$  and  $C$  depend only on  $n, G, \gamma, \alpha$ .

*Proof.* Let  $\lambda = \lambda(n, G, \gamma, \alpha)$  to be chosen later small enough, and  $\tau_{\text{tilt}} = \tau_{\text{tilt}}(n, G, \gamma, \lambda)$  given by Lemma 5.2. Then let  $\varepsilon \in (0, \varepsilon_*)$  with  $\varepsilon_* = \varepsilon_*(n, G, \gamma, \lambda, \theta, \beta)$  to be chosen later as well. First, notice that by Proposition 2.14

$$\mathbf{e}(E, x, r) \leq 2^{n-1} \mathbf{e}(E, x, R) \leq C(n, \alpha) \left( \frac{r}{R} \right)^{2\alpha} \mathbf{e}(E, x, R), \quad \forall r \in \left( \frac{R}{2}, R \right).$$

Thus (5.9) holds for any  $r \in \left( \frac{R}{2}, R \right)$  and we may focus on  $r \in [\varepsilon^{1-\beta}, \frac{R}{2}]$ . By definition of the spherical excess, using the fact that  $\mathbf{C}(x, R/2, \nu_0) \subseteq B_R(x)$  and Proposition 2.14, there exists  $\nu_0 \in \mathbb{S}^{n-1}$  such that

$$\mathbf{e}(E, x, R/2, \nu_0) \leq C(n) \mathbf{e}(E, x, R) \leq C(n) \tau_{\text{dec}}^\ell.$$

Hence, up to redefining  $R$  and  $\tau_{\text{dec}}^\ell$ , we shall now assume

$$\mathbf{e}(E, x, R, \nu_0) \leq \tau_{\text{dec}}^\ell \quad (5.10)$$

and are lead to proving (5.9) for  $r \in [\varepsilon^{1-\beta}, R]$ . Let us choose  $\tau_{\text{dec}}^\ell := \frac{\tau_{\text{tilt}}}{4}$ . Next, we choose  $\varepsilon_* = \varepsilon_*(n, G, \gamma, \lambda, \beta, \theta)$  small enough so that

$$Q_{1-\theta} \left( \frac{r}{\varepsilon} \right) \leq Q_{1-\theta} (\varepsilon_*^{-\beta}) \leq \frac{\tau_{\text{tilt}}}{4C_1}, \quad \forall r \in [\varepsilon^{1-\beta}, R], \quad (5.11)$$

where  $C_1 = C_1(n, G, \gamma) \geq 1$  is chosen larger than the constant  $C$  of Lemma 5.2. Let  $k_0 \in \mathbb{N}$  be the largest integer so that

$$\lambda^{k_0} R \geq \varepsilon^{1-\beta}.$$

Thus by (5.11),

$$Q_{1-\theta} \left( \frac{\lambda^k R}{\varepsilon} \right) \leq \frac{\tau_{\text{tilt}}}{4C_1}, \quad \forall k \in \{0, \dots, k_0\}, \quad (5.12)$$

and up to choosing  $\varepsilon_*$  smaller if necessary, we also have

$$\left( \frac{\varepsilon}{\lambda^k R} \right)^\theta \leq \varepsilon_*^{\beta\theta} \leq \frac{\tau_{\text{tilt}}}{4}, \quad \forall k \in \{0, \dots, k_0\}. \quad (5.13)$$

Combining (5.10), (5.12) and (5.13) we have in particular

$$\mathbf{e}(E, x, R, \nu_0) + \Lambda R + \left( \frac{\varepsilon}{R} \right)^\theta \leq \tau_{\text{tilt}},$$

so we can apply Lemma 5.2 to obtain that there exists  $\nu_1 \in \mathbb{S}$  such that

$$\mathbf{e}(E, x, \lambda R, \nu_1) \leq C_1 (\lambda^2 \mathbf{e}(E, x, R, \nu_0) + \lambda \Lambda R) + C_1 Q_{1-\theta} \left( \frac{\lambda R}{\varepsilon} \right). \quad (5.14)$$

Defining the quantity

$$\tilde{\mathbf{e}}(t) := \left( \inf_{\nu \in \mathbb{S}^{n-1}} \mathbf{e}(E, x, t, \nu) \right) + \Lambda t,$$

since  $\alpha \in (0, \frac{1}{2})$  we can now choose  $\lambda$  small enough depending on  $C_1$  and  $\alpha$  so that (5.14) implies

$$\tilde{\mathbf{e}}(\lambda R) \leq \lambda^{2\alpha} (\mathbf{e}(E, x, R, \nu_0) + \Lambda R) + C_1 Q_{1-\theta} \left( \frac{\lambda R}{\varepsilon} \right). \quad (5.15)$$

If  $k_0 = 0$ , then  $\lambda R < \varepsilon^{1-\beta} \leq R$  and by scaling of the excess, we have

$$\mathbf{e}(E, x, r) \leq \frac{1}{\lambda^{n-1+2\alpha}} \left(\frac{r}{R}\right)^{2\alpha} \mathbf{e}(E, x, R), \quad \forall r \in [\varepsilon^{1-\beta}, R],$$

thus we now assume  $k_0 \geq 1$ . With (5.10), (5.11) and (5.13), by (5.15) we have  $\tilde{\mathbf{e}}(\lambda R) + \left(\frac{\varepsilon}{\lambda R}\right)^\theta \leq \left(\frac{3}{4}\right)\tau_{\text{tilt}}$ , so we can find yet another direction to apply Lemma 5.2. In fact, we see that we can apply Lemma 5.2 repeatedly  $k_0$ -times. We find the induction formula

$$\tilde{\mathbf{e}}(\lambda^k R) \leq \lambda^{2k\alpha} \tilde{\mathbf{e}}(\lambda^{k-1} R) + C_1 Q_{1-\theta} \left(\frac{\lambda^k R}{\varepsilon}\right), \quad \forall k \in \{1, \dots, k_0\}.$$

Iterating, using the fact that  $Q$  is nonincreasing we get, for all  $k \in \{1, \dots, k_0\}$ ,

$$\begin{aligned} \tilde{\mathbf{e}}(\lambda^k R) &\leq C \lambda^{2k\alpha} (\mathbf{e}(E, x, R) + \Lambda R) + C_1 \sum_{j=0}^{k-1} \lambda^{2j\alpha} Q_{1-\theta} (\lambda^{j+1} R \varepsilon^{-1}) \\ &\leq C \lambda^{2k\alpha} (\mathbf{e}(E, x, R) + \Lambda R) + 2C_1 Q_{1-\theta} (\lambda^k R \varepsilon^{-1}). \end{aligned} \quad (5.16)$$

Consider an arbitrary  $r \in [\varepsilon^{1-\beta}, R]$ . By definition of  $k_0$ , there exists  $k \in \{0, \dots, k_0\}$  such that  $\lambda^{k+1} R \leq r \leq \lambda^k R$ . By scaling of the excess, from (5.16) we deduce

$$\tilde{\mathbf{e}}(r) \leq \frac{1}{\lambda^{n-1}} \tilde{\mathbf{e}}(\lambda^k R) \leq \frac{C}{\lambda^{n-1+2\alpha}} \left[ \left(\frac{r}{R}\right)^{2\alpha} (\mathbf{e}(E, x, R) + \Lambda R) + Q_{1-\theta} \left(\frac{r}{\lambda \varepsilon}\right) \right] \quad (5.17)$$

where  $C = C(n, G, \gamma)$ . Recalling that  $\lambda = \lambda(n, G, \gamma, \alpha)$ , the fact that  $\mathbf{e}(E, x, r) \leq \tilde{\mathbf{e}}(E, x, R)$  and assumption (H5), this gives (5.9) and concludes the proof.  $\square$

**5.3.  $C^{1,\alpha}$ -regularity.** Eventually, combining Propositions 5.1 and 5.3 we obtain power decay of the excess down to arbitrary small scales.

**Theorem 5.4.** *Assume that  $G$  satisfies (H1) to (H5), and let  $\gamma \in (0, 1)$ ,  $\Lambda > 0$  and  $r_0 > 0$  with  $\Lambda r_0 \leq 1 - \gamma$ . Then for every  $\alpha \in \min(\frac{1-s_0}{2}, \frac{p_0}{n+p_0})$ , there exist  $\beta = \beta(n, G, \alpha)$ ,  $\tau_{\text{dec}} = \tau_{\text{dec}}(n, G, \gamma, \alpha)$  and  $\varepsilon_* = \varepsilon_*(n, G, \gamma, \alpha, \Lambda)$  such that the following holds. If  $E$  is a  $(\Lambda, r_0)$ -minimizer of  $\mathcal{F}_{\varepsilon, \gamma}$  with  $\varepsilon \in (0, \varepsilon_*)$  satisfying, for some  $x \in \partial E$  and  $0 < R < r_0$ ,*

$$\mathbf{e}(E, x, R) + \Lambda R \leq \tau_{\text{dec}} \quad \text{and} \quad \varepsilon^{1-\beta} \leq R,$$

then

$$\mathbf{e}(E, x, r) \leq C \left(\frac{r}{R}\right)^{2\alpha}, \quad \forall r \in (0, R), \quad (5.18)$$

where  $C = C(n, G, \gamma, \Lambda, \alpha)$ .

*Proof.* Let  $\alpha \in \min(\frac{1-s_0}{2}, \frac{p_0}{n+p_0})$ . Given  $p \in (0, p_0)$  to be chosen later, we choose  $\theta = \theta(n, G, p)$  such that

$$(n-1+p_0)(1-\theta) = (n-1+p).$$

Then notice that for every  $\beta < \frac{1}{n+p}$ , we have  $\tilde{\alpha} := (n-1+p) \left(\frac{\beta}{1-\beta}\right) / 2 < \frac{1}{2}$ . Let  $\beta$  to be chosen later as such and consider the corresponding  $\tilde{\alpha}$ . Eventually let  $\varepsilon_*$  and  $\tau_{\text{dec}}^\ell$  given by Proposition 5.3, depending on  $n, G, \gamma, \tilde{\alpha}$  and  $\theta$ , and set  $\tau_{\text{dec}} := \tau_{\text{dec}}^\ell$ . By Proposition 5.3, we thus have

$$\mathbf{e}(E, x, r) \leq C \left[ \left(\frac{r}{R}\right)^{2\tilde{\alpha}} + r^{(n-1+p) \left(\frac{\beta}{1-\beta}\right)} \right] \leq C \left(\frac{r}{R}\right)^{(n-1+p) \left(\frac{\beta}{1-\beta}\right)}, \quad \forall r \in [\varepsilon^{1-\beta}, R], \quad (5.19)$$

where  $C = C(n, G, \gamma, \Lambda, \tilde{\alpha})$  and the last inequality comes from our choice of  $\tilde{\alpha}$ . In particular, for  $r = \varepsilon^{1-\beta}$  we find

$$\mathbf{e}(E, x, \varepsilon^{1-\beta}) \leq C \varepsilon^{(n-1+p)\beta} \quad (5.20)$$

where  $C = C(n, G, \gamma, \Lambda, \tilde{\alpha})$ . Let  $\tau_{\text{dec}}^s = \tau_{\text{dec}}^s(n, G, \gamma, \alpha)$  given by Proposition 5.1. By scaling of the excess (see Proposition 2.14), (5.20) implies

$$\mathbf{e}(E, x, \left(\frac{4\tau_{\text{dec}}^s}{\Lambda}\right) \varepsilon, \nu_0) \leq \frac{C}{\varepsilon^{\beta(n-1)}} \mathbf{e}(E, x, \varepsilon^{1-\beta}) \leq C \varepsilon^{p\beta} \leq \tau_{\text{dec}}^s,$$

where for the last inequality we took  $\varepsilon_* = \varepsilon_*(n, G, \gamma, \alpha, \beta, \Lambda)$  even smaller if necessary. We can thus apply [Proposition 5.1](#) with  $R = \left(\frac{\tau_{\text{dec}}^s}{\Lambda}\right) \varepsilon$  so that

$$\mathbf{e}(E, x, r) \leq C \left(\frac{r}{\varepsilon}\right)^{2\alpha} \mathbf{e}(E, x, \left(\frac{4\tau_{\text{dec}}^s}{\Lambda}\right) \varepsilon, \nu_0) \leq C \left(\frac{r}{R}\right)^{2\alpha} \varepsilon^{p\beta-2\alpha} \quad \forall r \in (0, \left(\frac{\tau_{\text{dec}}^s}{\Lambda}\right) \varepsilon). \quad (5.21)$$

Recall that we can choose  $\beta$  arbitrarily close to  $1/(n+p)$ , making  $p\beta$  arbitrarily close to  $\frac{p}{n+p}$ . Since  $2\alpha < \frac{p_0}{n+p_0}$ , choosing  $p$  close enough to  $p_0$ , we have  $2\alpha \leq p\beta$ . Hence [\(5.21\)](#) gives

$$\mathbf{e}(E, x, r) \leq C \left(\frac{r}{R}\right)^{2\alpha} \quad \forall r \in (0, \left(\frac{\tau_{\text{dec}}^s}{\Lambda}\right) \varepsilon). \quad (5.22)$$

Then, for any  $r \in \left[\left(\frac{\tau_{\text{dec}}^s}{\Lambda}\right) \varepsilon, \varepsilon^{1-\beta}\right)$ , by scaling of the excess once again and using [\(5.20\)](#) we estimate

$$\mathbf{e}(E, x, r) \leq C \left(\frac{\varepsilon^{1-\beta}}{r}\right)^{n-1} \mathbf{e}(E, x, \varepsilon^{1-\beta}, \nu_0) \leq C \varepsilon^{p\beta} \leq C \left(\frac{r}{R}\right)^{p\beta}, \quad (5.23)$$

Since  $(n-1+p)\left(\frac{\beta}{1-\beta}\right) > p\beta \geq 2\alpha$ , combining [\(5.19\)](#), [\(5.22\)](#) and [\(5.23\)](#) yields [\(5.18\)](#).  $\square$

*Proof of [Theorem B](#).* Using that the spherical excess of a  $(\Lambda, r_0)$ -minimizer  $E$  of  $\mathcal{F}_{\varepsilon, \gamma}$  decays as a power function, it is then standard (we refer to [\[25\]](#) for this argument) to see that starting from a small cylindrical excess in a cylinder  $\mathbf{C}(x, r, \nu)$ , the boundary of  $E$  in fact coincides with the graph of a 1-Lipschitz function  $u$  in a smaller cylinder  $\mathbf{C}(x, r/2, \nu(x))$  (notice the possible tilt of direction), and the cylindrical excess with respect to  $\nu(x)$  decays as a power function. Rewriting the cylindrical excess in terms of  $u$ , this power decay implies that  $\nabla u$  meets Campanato's criterion for Hölder-continuous functions. In the end, we obtain the  $C^{1,\alpha}$ -regularity theorem, that is, [Theorem B](#).  $\square$

*Proof of [Theorem A](#).* Together with the lower semicontinuity of the excess, the uniform regularity criterion of [Theorem B](#) can be used in a standard way (see e.g. [\[25, Theorem 26.6\]](#)) to improve the Hausdorff convergence of  $\partial E$  to  $\partial B_1$ , which is given by [Proposition 2.6](#), and obtain uniform convergence of the outer unit normals. We deduce that  $E$  is a nearly spherical set, that is, its boundary is a Lipschitz perturbation of  $\partial B_1$  which vanishes as  $\varepsilon \rightarrow 0$ . Then, [Theorem A](#) is an immediate consequence of [\[26, Theorem 2\]](#).  $\square$

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