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Julien Roth

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# NEW STABILITY RESULTS FOR SPHERES AND WULFF SHAPES 

JULIEN ROTH


#### Abstract

We prove that a closed convex hypersurface of the Euclidean space with almost constant anisotropic first and second mean curvatures in the $L^{p}$ sense is $W^{2, p}$-close (up to rescaling and translations) to the Wulff shape. We also obtain characterizations of geodesic hypersphere of space forms improving those of 10] and 11 .


## 1. Introduction

Let $F: \mathbb{S}^{n} \longrightarrow \mathbb{R}^{n+1}$ be a smooth function satisfying the following convexity assumption

$$
\text { (1) convexity } \quad A_{F}=\left(\nabla d F+F \operatorname{Id}_{\mid T_{x} \mathbb{S}^{n}}\right)_{x}>0,
$$

for all $x \in \mathbb{S}^{n}$, where $\nabla d F$ is the Hessian of $F$. Here, $>0$ means positive definite in the sense of quadratic forms. Now, we consider the following map

$$
\begin{aligned}
\phi: \mathbb{S}^{n} & \longrightarrow \mathbb{R}^{n+1} \\
x & \longmapsto F(x) x+\left(\operatorname{grad}_{\mid S^{n}} F\right)_{x}
\end{aligned}
$$

The image $\mathcal{W}_{F}=\phi\left(\mathbb{S}^{n}\right)$ is called the Wulff shape of $F$ and is a smooth convex hypersurface of $\mathbb{R}^{n+1}$ due to condition (1). Note that if $F=1$, the the Wulff shape is the sphere $\mathbb{S}^{n}$.

Now, let $\left(M^{n}, g\right)$ be a $n$-dimensional closed, connected and oriented Riemannian manifold, isometrically immersed into by $X$ into $\mathbb{R}^{n+1}$. We denote by $\nu$ a normal unit vector field globally defined on $M$, that is, we have $\nu: M \longrightarrow \mathbb{S}^{n}$. We set $S_{F}=A_{F} \circ \mathrm{~d} \nu$, where $A_{F}$ is defined in (1). The operator $S_{F}$ is called the $F$-Weingarten operator or anisotropic shape operator, and we can defined in this anisotrpic setting all the corresponding extrinsic quantities like anisotropic principal curvatures and anisotropic mean curvature and higher order mean curvature (see the preliminaries section for the precise definitions).

In the isotropic context, geodesic hyperspheres in Euclidean spaces can be characterized among closed hypersurfaces by various properties. In particular, it is well known that geodesic hyperspheres are the only totally umbilical closed connected hypersurfaces in Euclidean spaces. The question of the stability of this characterization has been intensively studied in the last years by many authors (see [1, 3, 8, 10, 11, 12, 13] and references therein for instance). In the anisotropic setting, the so-called Wulf shape plays the role of geodesic spheres and can be characterized by similar results (see [4, 7] for instance). Analogously to spheres, for a

[^0]given $F$, the Wulff shape $\mathcal{W}_{F}$ is, up to homotheties and translations, the only closed convex hypersurface with vanishing traceless anisotropic second fundamental form. Very recently, De Rosa and Gioffrè [2] studied the stability of this characterization. Namely, they proved that if the traceless part of the anisotropic second fundamental form is sufficiently small, then the hypersurface is closed to the Wulff shape. The aim of the present note is first to obtain a new stability result concerning the Wulff shape. Namely, we prove the following stability result.
 the convexity assumption (1), $h>0$ and $p>n$. Let $M$ a closed and oriented hypersurface of $\mathbb{R}^{n+1}$ bounding a convex domain. Assume that $\operatorname{Vol}(M)=\operatorname{Vol}\left(\mathcal{W}_{F}\right)$. Then, there exists $\varepsilon_{0}>0$ depending only on $n, p, h$ and $F$ such that if for $\varepsilon \leqslant \varepsilon_{0}$, we have

- $\left\|H^{F}-h\right\|_{p}<\varepsilon h$ and
- $\left\|H_{2}^{F}-h_{2}\right\|_{p}<\varepsilon h^{2}$ for a constant $h_{2}$,
then $M$ is closed to the Wulff shape in the following sense : there exists a smooth parametrisation $\psi: \mathcal{W}_{F} \longrightarrow M$, a vector $c_{0} \in \mathbb{R}^{n+1}$ and a constant $K$ depending on $n, p$ and $F$ so that

$$
\left\|\psi-\operatorname{Id}-c_{0}\right\|_{W^{2, p}(\mathcal{W})} \leqslant K h^{p} \varepsilon^{\frac{p}{2}} .
$$

Remark 1.2. - $\operatorname{Here} \operatorname{Vol}(M)$ is the volume of $M$ for the induced metric $g$.

- We recall that the extrinsic radius of $M$ is the radius of the smallest closed ball in $\mathbb{R}^{n+1}$ containing $M$.
- Note that the right-hand sides in both pinching conditions of the theorem are respectively $h \varepsilon$ and $h^{2} \varepsilon$ for some homogeneity reasons, since for the Wulff shape, we have $H_{2}^{F}=\left(H^{F}\right)^{2}$.
- As we will see in the proof (Lemma 3.1), the constant $h_{2}$ will be necessarily close to $h^{2}$.

This result is a generalization in the anisotropic context of the main result of [10], but not only since the hypothesis are that both first and second anisotropic mean curvatures are close to constants for the $L^{p}$-norm. We can also improve the results of [10] for space forms in the same way and obtain new characterizations of geodesic hyperspheres under weaker assumptions. We denote by $\mathbb{M}_{\delta}^{n+1}$ the simply connected real space form of constant curvature $\delta$. We prove the following result.
〈thm2〉 Theorem 1.3. Let $n \geqslant 2$ an integer, $h>0$ and $p>n$. Assume that $\left(M^{n}, g\right)$ is a closed connected hypersurface of $\mathbb{M}_{\delta}^{n+1}$ so that $\operatorname{Vol}(M)=\operatorname{Vol}\left(\mathbb{S}^{n}\right)$. If $\delta>0$, assume moreover that $M$ is contained in an open ball of radius $\frac{\pi}{4 \sqrt{\delta}}$. Then, there exist $\varepsilon_{0}(n, p, h)>0, K(n, p)$ and $\beta(n, p) \leqslant 1$ such that if for $\varepsilon \leqslant \varepsilon_{0}$, we have

- $\|H-h\|_{p}<\varepsilon h$ and
- $\left\|H_{2}-h_{2}\right\|_{p}<\varepsilon h^{2}$ for a constant $h_{2}$,
then $M$ is diffeomorphic and $K \varepsilon^{\beta}$-close to a geodesic hypersphere of radius $\frac{1}{\|H\|_{2}}$ in the following sense: there exists a diffeomorphism $F$ from $M$ to $\mathbb{S}^{n}\left(\frac{1}{\|H\|_{2}}\right)$ so that

$$
\left|\left|d_{x} F(u)\right|^{2}-1\right| \leqslant K \varepsilon^{\beta}
$$

for any $x \in M$ and any unit vector $u \in T_{x} M$.

Remark 1．4．－For more convenience，we wrote the above theorem with $H_{2}$ ， but due to the twice traced Gauss，formula，we have $n(n-1) H_{2}+\delta=$ Scal， we can reformulate equivalently the theorem with almost constant scalar curvature．
－This result is an improvement of a previous result of［10］since we assume $L^{p}$－norms instead of pointwise almost proximity to constant．Moreover，in the case where $\delta>0$ ，we assume that $M$ is contained in an opengeodesic ball of radius $\frac{\pi}{4 \sqrt{\delta}}$ ．We can remove the assumption with as counterpart， the fact that $C$ and $\varepsilon_{0}$ depend also on the extrinsic radius of $M$ ．We will develop this point in the proof．The same remark holds the the following two corollaries．

From the following theorem，we can obtain new characterizations of geodesic hyperspheres．

〈cor1〉 Corollary 1．5．Let $\left(M^{n}, g\right)$ be a closed and oriented Riemannian manifold，iso－ metrically immersed into $\mathbb{M}_{\delta}^{n+1}$ and $p>n$ ．If $\delta>0$ ，we assume that $M$ is contained in an open ball of radius $\frac{\pi}{4 \sqrt{\delta}}$ ．Let $h>0$ Then，there exists $\varepsilon(n, h, \delta)>0$ such that if $M$ has constant mean curvature $H=h$ ，and $\|$ Scal $-s \|_{p}<\varepsilon$ for a constant $s$ ， then $M$ is a geodesic sphere．
${ }^{\langle c o r 2\rangle}$ Corollary 1．6．Let $\left(M^{n}, g\right)$ be a closed and oriented Riemannian manifold，iso－ metrically immersed into $\mathbb{M}_{\delta}^{n+1}$ and $p>n$ ．If $\delta>0$ ，we assume that $M$ is contained in an open ball of radius $\frac{\pi}{4 \sqrt{\delta}}$ ．Let $s>0$ Then，there exists $\varepsilon(n, \delta)>0$ such that if $M$ has constant scalar curvature $\operatorname{Scal}=s$ ，and $\|H-h\|_{p}<\varepsilon$ for a constant $h$ ， then $M$ is a geodesic sphere．

When $p \in(1, n]$ ，one can not obtain similar result，since we use a pichning result for almost umbilical hypersurfaces for the $L^{p}$－norm with $p>n$ ．Nevertheless，we can obtain for the Euclidean space a stability result comparable to Theorem 1.1 ， with the assumption that the hypersurface is convex using a result by Gioffrè 3． Namely，we have the following for $p>1$ which can also be deduced form Theorem 1.1 for $F=1$ ．
？〈cor3〉？Corollary 1．7．Let $n \geqslant 2$ an integer，$h>0, p>1$ and $R>0$ ．Let $M a$ closed and oriented hypersurface of $\mathbb{R}^{n+1}$ bounding a convex domain．Assume that $\operatorname{Vol}(M)=\operatorname{Vol}\left(\mathbb{S}^{n}\right)$ and that the extrinsic radius of $M$ is smaller than $R$ ．Then， there exists $\varepsilon_{0}(n, p, h, R)>0$ such that if for $\varepsilon \leqslant \varepsilon_{0}$ ，we have
－$\|H-h\|_{p}<\varepsilon h$ and
－$\left\|H_{2}-h_{2}\right\|_{p}<\varepsilon h^{2}$ for a constant $h_{2}$ ，
then $M$ is closed to the unit sphere in the following sense ：there exists a smooth parametrisation $\psi: \mathbb{S}^{n} \longrightarrow M$ ，a vector $c_{0} \in \mathbb{R}^{n+1}$ and a constant $K$ depending on $n, p, h$ and $R$ so that

$$
\left\|\psi-\operatorname{Id}-c_{0}\right\|_{W^{2, p}(\mathcal{W})} \leqslant K \varepsilon^{\frac{p}{2}}
$$

Moreover，if $p \geqslant n-1$ ，then $\varepsilon_{0}$ does not depend on $R$ ．
Remark 1．8．Note that there is no interest here to obtain corollaries comparable to Corollaries 1.5 and 1．6．Indeed，if the hypersurface（which is supposed to bound a domain）has constant mean curvature，the Alexandrov theorem gives that $M$ is a sphere without need of the almost constancy of the scalar curvature．

Remark 1.9. In all the statements, we assume a normalization of the volume for a sake of simplicity, but be scaling, we can obtain statements with constants depending also on the volume.

## 2. Preliminaries

Let $\left(M^{n}, g\right)$ be a $n$-dimensional closed, connected and oriented Riemannian manifold isometrically immersed into the $(n+1)$-dimensional simply connected real space form $\mathbb{M}_{\delta}^{n+1}$ of constant curvature $\delta$. The (real-valued) second fundamental form $I I$ of the immersion is the bilinear symmetric form on $\Gamma(T M)$ defined for two vector fields $X, Y$ by

$$
I I(X, Y)=-g\left(\bar{\nabla}_{X} \nu, Y\right)
$$

where $\bar{\nabla}$ is the Riemannian connection on $\mathbb{M}_{\delta}^{n+1}$ and $\nu$ a normal unit vector field on $M$. When $M$ is embedded, we choose $\nu$ as the inner normal field.

From $I I$, we can define the mean curvature,

$$
H=\frac{1}{n} \operatorname{tr}(I I) .
$$

Now, we recall the Gauss formula. For $X, Y, Z, W \in \Gamma(T M)$,
(2) $\operatorname{gav}$ R $\$ X, Y, Z, W)=\bar{R}(X, Y, Z, W)+\langle S X, Z\rangle\langle S Y, W\rangle-\langle S Y, Z\rangle\langle S X, W\rangle$
where $R$ and $\bar{R}$ are respectively the curvature tensor of $M$ and $\mathbb{M}_{\delta}^{n+1}$, and $S$ is the Weingarten operator defined by $S X=-\bar{\nabla}_{X} \nu$.

By taking the trace and for $W=Y$, we get
(3) ? gausstra\&eit $(Y)=\overline{\operatorname{Ric}}(Y)-\bar{R}(\nu, Y, \nu, Y)+n H\langle S Y, Y\rangle-\left\langle S^{2} Y, Y\right\rangle$

Since, the ambient space is of constant sectional curvature $\delta$, by taking the trace a second time, we have
(4) ?gausstrace2?

$$
\text { Scal }=n(n-1) \delta+n^{2} H^{2}-\|S\|^{2},
$$

or equivalently
(5) ?gausstrace3?

$$
\text { Scal }=n(n-1)\left(H^{2}+\delta\right)-\|\tau\|^{2},
$$

where $\tau=S-H I d$ is the umbilicity tensor.
Now, we define the higher order mean curvatures, for $k \in\{1, \cdots, n\}$, by

$$
H_{k}=\frac{1}{\binom{n}{k}} \sigma_{k}\left(\kappa_{1}, \cdots, \kappa_{n}\right)
$$

where $\sigma_{k}$ is the $k$-th elementary symmetric polynomial and $\kappa_{1}, \cdots, \kappa_{n}$ are the principal curvatures of the immersion.

From the definition, it is obvious that $H_{1}$ is the mean curvature $H$. We also remark from the Gauss formula (2) that
(6) ? h2scal?

$$
H_{2}=\frac{1}{n(n-1)} \text { Scal }-\delta
$$

On the other hand, we have the well-known Hsiung-Minkowski formula
(7) hsiung1

$$
\int_{M}\left(H_{k+1}\langle Z, \nu\rangle+c_{\delta}(r) H_{k}\right)=0
$$

where $r(x)=d\left(p_{0}, x\right)$ is the distance function to a base point $p_{0}, Z$ is the position vector defined by $Z=s_{\delta}(r) \bar{\nabla} r$, and the functions $c_{\delta}$ and $s_{\delta}$ are defined by

$$
c_{\delta}(t)=\left\{\begin{array}{ll}
\cos (\sqrt{\delta} t) & \text { if } \delta>0 \\
1 & \text { if } \delta=0 \\
\cosh (\sqrt{-\delta} t) & \text { if } \delta<0
\end{array} \quad \text { and } \quad s_{\delta}(t)= \begin{cases}\frac{1}{\sqrt{\delta}} \sin (\sqrt{\delta} t) & \text { if } \delta>0 \\
t & \text { if } \delta=0 \\
\frac{1}{\sqrt{-\delta}} \sinh (\sqrt{-\delta} t) & \text { if } \delta<0\end{cases}\right.
$$

Finally, we define the function $t_{\delta}=\frac{s_{\delta}}{c_{\delta}}$.
On the other hand, let $F: \mathbb{S}^{n} \longrightarrow \mathbb{R}^{n+1}$ be a smooth function satisfying the following convexity assumption (1):

$$
A_{F}=\left(\nabla d F+F \operatorname{Id}_{\mid T_{x} \mathbb{S}^{n}}\right)_{x}>0
$$

for all $x \in \mathbb{S}^{n}$, where $\nabla d F$ is the Hessian of $F$. The Wullf shape is defined by $\mathcal{W}_{F}=\phi\left(\mathbb{S}^{n}\right)$ with

$$
\begin{aligned}
\phi: \mathbb{S}^{n} & \longrightarrow \mathbb{R}^{n+1} \\
x & \longmapsto F(x) x+\left(\operatorname{grad}_{\mid S^{n}} F\right)_{x}
\end{aligned}
$$

Now, let $\left(M^{n}, g\right)$ be a $n$-dimensional compact, connected, oriented manifold without boundary, isometrically immersed into by $X$ into $\mathbb{R}^{n+1}$. We denote by $\nu$ a normal unit vector field globally defined on $M$ and the $F$-Weingarten operator $S_{F}=A_{F} \circ S$, where $A_{F}$ is defined in (11). The eigenvalues of $A_{F}$ are the anisotropic principal curvatures that we will denote $\kappa_{1}^{F}, \kappa_{2}^{F}, \cdots, \kappa_{n}^{F}$. Finally, for $r \in\{1, \cdots, n\}$, the $r$-th anisotropic mean curvature is defined by

$$
H_{r}^{F}=\frac{1}{\binom{n}{r}} \sum_{i_{1}<\cdots<i_{r}} \kappa_{i_{1}}^{F} \cdots \kappa_{i_{r}}^{F}
$$

We also set $H_{0}^{F}=1$ for convenience. Note that the Wulff shape is $F$-umbilical, that is $S_{F}=H^{F}$ Id and all its anisotropic principal curvatures are equal to 1 and therefore, for any $r \in\{1, \cdots, n\}$, we have $H_{r}^{F}=1$.

We finally recall these integral forumlas proved by He and Li in 4 and which generalize the classical Hsiung-Minkowski formulas (7) in the anisotropic setting.
(8) hsiung

$$
\int_{M}\left(F(\nu) H_{r-1}^{F}+H_{r}^{F}<X, \nu>\right) d v_{g}=0
$$

We finish this section of preliminaries by the following results which give an upper bound of the diameter of a hypersurface in $\mathbb{M}_{\delta}^{n+1}$ in terms of its mean curvature and their consequence on the extrinsic radius. We have the following

Theorem 2.1. (Topping [14, Wu-Zheng [15]) Let $n \geqslant 1$ and ( $\left.M^{n}, g\right)$ be a closed〈Topping〉 connected Riemannian manifold isometrically immersed into a complete Riemannian manifold $\left(N^{n+p}, h\right)$ of curvature $K_{N}$ satisfying $K_{N} \leqslant b^{2}$ with $b$ a real or purely imaginary number. For any $0<\alpha<1$, if
(9) condsob1

$$
b^{2}(1-\alpha)^{-2 / n}\left(\omega_{n}^{-1} \operatorname{Vol}(M)\right)^{2 / n} \leqslant 1,
$$

condsob2

$$
\begin{equation*}
2 \rho_{0} \leqslant \operatorname{inj}_{M}(N) \tag{10}
\end{equation*}
$$

where $\operatorname{inj}_{M}(N)$ is the injectivity radius of $N$ restricted to $M, \omega_{n}=\operatorname{Vol}\left(\mathbb{S}^{n}\right)$ and $\rho_{0}$ is given by

$$
\rho_{0}= \begin{cases}b^{-1} \sin ^{-1}\left(b(1-\alpha)^{-1 / n}\left(\omega_{n}^{-1} \operatorname{Vol}(M)\right)^{1 / n}\right) & \text { if } b \text { is real } \\ (1-\alpha)^{-1 / n}\left(\omega_{n}^{-1} \operatorname{Vol}(M)\right)^{1 / n} & \text { if b is imaginary }\end{cases}
$$

then, we have the following

$$
\operatorname{diam}(M) \leqslant C(n, \alpha) \int_{M}|H|^{n-1} d v_{g}
$$

where $\operatorname{diam}(M)$ is the intrinsic diameter of $M$ and $H$ its mean curvature (for the immersion into $N$ ) and $C(n, \alpha)$ a constant depending only on $n$ and $\alpha$.

This result have be first proved by Topping if $N$ is the Euclidean space using the extrinsic Sobolev inequality of Michael and Simon 6. Then, it has been generalized by Wu and Zheng for arbitrary manifold with bounded curvature by using the general extrinsic Sobolev inequality of Hoffmann and Spruck [5]. This is the reason why assumptions (9) and (10) are neeeded. Note also that is $N$ is the Euclidean of hyperbolic space, then, both conditions (9) and (10) are trivially satisfied.

Finally, we recall that the extrinsic radius $R(M)$ of $M$ is defined by

$$
R(M)=\inf \left\{\rho>0 \mid \exists x \in \mathbb{M}^{n+1}(\delta) \text { s.t. } \phi(M) \subset B(x, r)\right\}
$$

where $\phi$ is the immersion of $M$ into $\mathbb{M}^{n+1}(\delta)$. By a slight abuse of notation, we denote it $R(M)$ but, this radius depends not only on $M$ but also on the immersion $\phi$. Since in this paper, the considered immersion will be fixed, this notation does not lead to any ambiguity.
The extrinsic radius is bounded from below by the mean curvature due to the following estimate (see [9])

$$
t_{\delta}(R(M)) \geqslant \frac{1}{\|H\|_{\infty}}
$$

with equality if and only if $M$ is a geodesic sphere. On the other hand, even if, this is not optimal at all, we remark obviously that $R(M) \leqslant \operatorname{diam}(M)$ and using Theorem 2.1. this implies that $R(M)$ is also bounded form above by in term of the mean curvature without any condition if $\delta \leqslant 0$. Now, we have the ingredients to prove the results.

## 3. KEy LEmmas

? 〈proof $\rangle$ ? First, using the integral formula (8), we are able to prove the following techincal lemma.
${ }^{\langle 1 \mathrm{em} 1\rangle}$ Lemma 3.1. Let $\left(M^{n}, g\right)$ be a closed Riemannian manifold, isometrically immersed into $\mathbb{R}^{n+1}$ and assume that the extrinsic radius of $M$ is smaller than $R$. Let $p>1$, $h$ and $h_{2}$ be two positive constants and $\varepsilon \in\left(0, \frac{1}{2}\right)$. If the first and second anisotropic mean curvatures satisfy

- $\left\|H^{F}-h\right\|_{p}<\varepsilon h$ and
- $\left\|H_{2}^{F}-h_{2}\right\|_{p}<\varepsilon h^{2}$,
for some positive $\varepsilon$, then

$$
\left|h^{2}-h_{2}\right| \leqslant A h^{2} \varepsilon
$$

where $A$ is an explicit positive constant depending on $n, h, R$ and $F$.
Moreover, if $p \geqslant n-1$ and $M$ is convex, then, $A$ does not depend on $R$.
Proof. The proof of this lemma is based on the Hisung-Minkowski formulas (8) for $r=1$ and $k=2$. Indeed, the Hisung-Minkowski formula for $r=2$ is the following
(11) ?hsiung2?

$$
\int_{M}\left(H_{2}^{F}\langle X, \nu\rangle+F(\nu) H^{F}\right) d v_{g}=0
$$

Then, we get

$$
\begin{aligned}
0= & \int_{M}\left(H_{2}^{F}\langle X, \nu\rangle+F(\nu) H\right) d v_{g} \\
= & \int_{M}\left(h_{2}\langle X, \nu\rangle+F(\nu) H\right) d v_{g}+\int_{M}\left(H_{2}^{F}-h_{2}\right)\langle X, \nu\rangle d v_{g} \\
= & \frac{h_{2}}{h} \int_{M} h\langle X, \nu\rangle+\int_{M} F(\nu) H^{F} d v_{g}+\int_{M}\left(H_{2}-h_{2}\right)\langle X, \nu\rangle d v_{g} \\
= & \frac{h_{2}}{h} \int_{M} H^{F}\langle X, \nu\rangle d v_{g}+\frac{h_{2}}{h} \int_{M}\left(h-H^{F}\right)\langle X, \nu\rangle d v_{g}+\int_{M} F(\nu) h d v_{g}+\int_{M} F(\nu)\left(H^{F}-h\right) d v_{g} \\
& +\int_{M}\left(H_{2}^{F}-h_{2}\right)\langle X, \nu\rangle d v_{g}
\end{aligned}
$$

Now, we use the Hsiung-Minkowski formula for $r=1$, that is
(12) ?hsiung0?

$$
\int_{M}\left(H^{F}\langle X, \nu\rangle+F(\nu)\right) d v_{g}=0
$$

to get

$$
\begin{aligned}
0= & -\frac{h_{2}}{h} \int_{M} F(\nu) d v_{g}+\frac{h_{2}}{h} \int_{M}\left(h-H^{F}\right)\langle X, \nu\rangle d v_{g}+\int_{M} F(\nu) h d v_{g}+\int_{M} F(\nu)\left(H^{F}-h\right) d v_{g} \\
& +\int_{M}\left(H_{2}^{F}-h_{2}\right)\langle X, \nu\rangle d v_{g} \\
= & \left(h-\frac{h_{2}}{h}\right) \int_{M} F(\nu) d v_{g}+\frac{h_{2}}{h} \int_{M}\left(h-H^{F}\right)\langle X, \nu\rangle d v_{g}+\int_{M} F(\nu)\left(H^{F}-h\right) d v_{g} \\
& +\int_{M}\left(H_{2}^{F}-h_{2}\right)\langle X, \nu\rangle d v_{g}
\end{aligned}
$$

Then, since $|\langle X, \nu\rangle| \leqslant R$, using the Hölder inequality and both conditions $\left\|H^{F}-h\right\|_{p}<\varepsilon h$ and $\left\|H_{2}^{F}-h_{2}\right\|_{p}<\varepsilon h^{2}$, we get

$$
\left|h-\frac{h_{2}}{h}\right| \int_{M} F(\nu) d v_{g} \leqslant h_{2} \varepsilon R \operatorname{Vol}(M)+\varepsilon h \sup (F) \operatorname{Vol}(M)+\varepsilon h^{2} R \operatorname{Vol}(M) .
$$

Using the fact that $\left|H_{2}^{F}\right| \leqslant\left(H^{F}\right)^{2}$, we deduce

$$
\left|h_{2}\right| \leqslant h^{2}+\left(H^{F}-h\right)^{2}+2 h\left(H^{F}-h\right)+\left(h_{2}-H_{2}^{F}\right)
$$

and so with the assumptions $\left\|H^{F}-h\right\|_{p}<\varepsilon h$ and $\left\|H_{2}^{F}-h_{2}\right\|_{p}<\varepsilon h^{2}$, we get

$$
\left|h_{2}\right| \leqslant 5 h^{2}
$$

Thus, we have

$$
\begin{aligned}
\left|h^{2}-h_{2}\right| \int_{M} F(\nu) d v_{g} & \leqslant \varepsilon h^{2} \sup (F) \operatorname{Vol}(M)+\left(h^{3}+h h_{2}\right) R \operatorname{Vol}(M) \varepsilon \\
& \leqslant \varepsilon h^{2} \sup (F) \operatorname{Vol}(M)+6 h^{3} R \operatorname{Vol}(M) \varepsilon
\end{aligned}
$$

and we obtain

$$
\begin{align*}
\left|h^{2}-h_{2}\right| & \leqslant\left(h^{2} \frac{\sup (F)}{\inf (F)}+\frac{6 h^{3} R}{\inf (F)}\right) \varepsilon  \tag{13}\\
& \leqslant h^{2} A(h, R, F) \varepsilon
\end{align*}
$$

which gives the wanted assertion.
Now assume that $p \geqslant n-1$ and $M$ is convex. We will show that $R$ can be controlled from above by $h$. First, as we have already mentionned, $R \leqslant \operatorname{diam}(M)$ and so, by Theorem 2.1, we have
(14) majR

$$
\begin{aligned}
R & \leqslant C(n) \int_{M}|H|^{n-1} d v_{g} \\
& \leqslant C(n) \operatorname{Vol}(M)\|H\|_{p}^{n-1}
\end{aligned}
$$

Now, let $\left\{e_{1}, \cdots, e_{n}\right\}$ an orthonormal basis diagonalizing $S_{F}$. Then, we have
(15) majHHF

$$
\begin{aligned}
H & =\sum_{i=1}^{n}\left\langle S e_{i}, e_{i}\right\rangle \\
& =\sum_{i=1}^{n}\left\langle A_{F}^{-1} \circ S_{F} e_{i}, e_{i}\right\rangle \\
& =\sum_{i=1}^{n} \kappa_{i}^{F}\left\langle A_{F}^{-1} e_{i}, e_{i}\right\rangle \\
& \leqslant\left\|A_{F}^{-1}\right\| \sum_{i=1}^{n} \kappa_{i}^{F}=\left\|A_{F}^{-1}\right\| H^{F}
\end{aligned}
$$

since all $\kappa_{i}^{F}$ are nonnegative by convexity of $M$. Moreover, from the assumption $\left\|H^{F}-h\right\|_{p}<\varepsilon h$ with $\varepsilon<\frac{1}{2}$, we get that

$$
\frac{h}{2} \leqslant(1-\varepsilon) h \leqslant\left\|H^{F}\right\|_{p} \leqslant(1+\varepsilon) h \leqslant 2 h
$$

Combining this with 14 and 15 , we obtain

$$
R \leqslant C(n) \operatorname{Vol}(M)\left(2 h\left\|A_{F}^{-1}\right\|\right)^{n-1}
$$

Finally, reporting this upper bound of $R$ into 13 , we get that $A$ can be choosen to be independent on $R$ if $p \geqslant n-1$ and $M$ is convex. This conludes the proof of the Lemma.

Now, we give this second lemma for hypersurfaces of spheres and hyperbolic spaces.
${ }^{\langle l e m 2\rangle}$ Lemma 3.2. Let $\left(M^{n}, g\right)$ be a closed Riemannian manifold, isometrically immersed into $\mathbb{M}_{\delta}^{n+1}$ and assume that the extrinsic radius of $M$ is smaller than $R$. Let $p>1$, $h$ and $h_{2}$ be two positive constants and $\varepsilon \in(0,1)$. If the first and second mean curvatures satisfy

- $\|H-h\|_{p}<\varepsilon h$ and
- $\left\|H_{2}-h_{2}\right\|_{p}<\varepsilon h^{2}$,
for some positive $\varepsilon$, then

$$
\left|h^{2}-h_{2}\right| \leqslant B h^{2} \varepsilon
$$

where $B$ is an explicit positive constant depending on $n, \delta, h$ and $R$.
Moreover, if $\delta \leqslant 0$ and $p \geqslant n-1$, or if $\delta>0$ and $M$ is contained in a geodesic ball of radius $\frac{\pi}{4 \sqrt{\delta}}$ then $B$ does not depend on $R$.

Proof: The proof is close to the proof of Lemma 3.1 with some slight differences. Proceeding as in the proof of Lemma 3.1 with the Hsiung-Minkowski (7) instead of the anisotropic one (8), we get

$$
\begin{aligned}
0= & \left(h-\frac{h_{2}}{h}\right) \int_{M} c_{\delta}(r) d v_{g}+\frac{h_{2}}{h} \int_{M}(h-H)\langle Z, \nu\rangle d v_{g}+\int_{M} c_{\delta}(r)(H-h) d v_{g} \\
& +\int_{M}\left(H_{2}-h_{2}\right)\langle Z, \nu\rangle d v_{g} .
\end{aligned}
$$

Then, since $|\langle Z, \nu\rangle| \leqslant s_{\delta}(R)$, using the Hölder inequality and both conditions $\|H-h\|_{p}<\varepsilon h$ and $\left\|H_{2}-h_{2}\right\|_{p}<\varepsilon h^{2}$, we get
$\left|h-\frac{h_{2}}{h}\right| \inf \left(c_{\delta}(r)\right) \operatorname{Vol}(M) \leqslant h_{2} \varepsilon s_{\delta}(R) \operatorname{Vol}(M)+\varepsilon h \sup \left(c_{\delta}(r)\right) \operatorname{Vol}(M)+\varepsilon h^{2} s_{\delta}(R) \operatorname{Vol}(M)$.
Using the fact that $\left|H_{2}\right| \leqslant(H)^{2}$, we deduce

$$
\left|h_{2}\right| \leqslant h^{2}+(H-h)^{2}+2 h(H-h)+\left(h_{2}-H_{2}\right)
$$

and so with the assumptions $\|H-h\|_{p}<\varepsilon h$ and $\left\|H_{2}-h_{2}\right\|_{p}<\varepsilon h^{2}$, we get

$$
\left|h_{2}\right| \leqslant 5 h^{2}
$$

Thus, we have

$$
\begin{aligned}
\left|h^{2}-h_{2}\right| \inf \left(c_{\delta}(r)\right) \operatorname{Vol}(M) & \leqslant \varepsilon h^{2} \sup \left(c_{\delta}(r)\right) \operatorname{Vol}(M)+\left(h^{3}+h h_{2}\right) s_{\delta}(R) \operatorname{Vol}(M) \varepsilon \\
& \leqslant \varepsilon h^{2} \sup \left(c_{\delta}(r)\right) \operatorname{Vol}(M)+6 h^{3} s_{\delta}(R) \operatorname{Vol}(M) \varepsilon
\end{aligned}
$$

and we obtain
(16) majh2h2

$$
\left|h^{2}-h_{2}\right| \leqslant\left(h^{2} \frac{\sup \left(c_{\delta}(r)\right)}{\inf \left(c_{\delta}(r)\right)}+\frac{6 h^{3} s_{\delta}(R)}{\inf \left(c_{\delta}(r)\right)}\right) \varepsilon
$$

If $\delta>0$, then $c_{\delta}(t)=\cos (\sqrt{\delta} t)$, so we deduce immediately that $c_{\delta}(R) \leqslant c_{\delta}(r) \leqslant 1$ and then

$$
h^{2} \frac{\sup \left(c_{\delta}(r)\right)}{\inf \left(c_{\delta}(r)\right)}+\frac{6 h^{3} s_{\delta}(R)}{\inf \left(c_{\delta}(r)\right)} \leqslant \frac{h^{2}}{c_{\delta}(R)}+\frac{6 h^{3} s_{\delta}(R)}{c_{\delta}(R)} .
$$

If $\delta=0$, then $c_{\delta}=1$ and so

$$
\left(h^{2} \frac{\sup \left(c_{\delta}(r)\right)}{\inf \left(c_{\delta}(r)\right)}+\frac{6 h^{3} s_{\delta}(R)}{\inf \left(c_{\delta}(r)\right)}\right)=h^{2}+6 h^{3} R .
$$

If $\delta<0$, then $c_{\delta}(t)=\cosh (\sqrt{-\delta} t)$ and thus $c_{\delta}(R) \geqslant c_{\delta}(r) \geqslant 1$ and then

$$
h^{2} \frac{\sup \left(c_{\delta}(r)\right)}{\inf \left(c_{\delta}(r)\right)}+\frac{6 h^{3} s_{\delta}(R)}{\inf \left(c_{\delta}(r)\right)} \leqslant h^{2} c_{\delta}(R)+6 h^{3} s_{\delta}(R)
$$

Then, in the three cases, we have $\left|h^{2}-h_{2}\right| \leqslant B h^{2} \varepsilon$, with $B$ a positive constant depending only on $\delta, h, F$ and $R$.
As in the proof of Lemma 3.1, if $p \geqslant n-1$, from Theorem 2.1, we can bound from above $R$ by $\|H\|_{n-1}$ and so therefore by $h$ due to the pinching condition $|H-h| \leqslant \varepsilon h$. Hence if $\delta \leqslant 0$, form its expression obtained in 16 , the constant $B$ can be choosen independent on $R$. Note that this can also been done if $\delta>0$ by with the two additional conditions $($ on $\operatorname{Vol}(M))$ needed to apply Theorem 2.1. But, if we assume that $M$ is contained in a geodesic ball of radius $\frac{\pi}{4 \sqrt{\delta}}$, then, we get that

$$
\frac{h^{2}}{c_{\delta}(R)}+\frac{6 h^{3} s_{\delta}(R)}{c_{\delta}(R)} \leqslant \sqrt{2} h^{2}+\frac{6 h^{3}}{\sqrt{\delta}}
$$

and $A$ does not depend on $R$. This concludes the proof of the lemma.

## 4. Proofs of the Theorems

Now, using this lemma together with appropriate result for almost umbilical hypersurfaces, we can prove the different theorems of this note.

Proof of Theorem 1.1. We begin with the proof of Theorem 1.1. For this, we first recall the main result of [2]. We will use this result together with Lemma 3.1] to conclude.
${ }^{?}\left\langle\right.$ thrm2 ${ }^{2}$ ? Theorem (De Rosa-Gioffrè [2]). Let $n>2, p \in(1, p)$ and $F: \mathbb{S}^{n} \longrightarrow \mathbb{R}^{+}$satisfying the convexity assumption (1). There exists a constant $\delta_{0}=\delta_{0}(n, p, F)>0$ such that if $\Sigma$ is closed convex hypersurface into $\mathbb{R}^{n+1}$ satisfying

$$
\operatorname{Vol}(M)=V\left(\mathcal{W}_{F}\right) \quad \text { and } \quad \int_{M}\left\|S_{F}-H^{F} \mathrm{Id}\right\|^{p} d v_{g} \leqslant \delta
$$

with $\delta \leqslant \delta_{0}$ then there exists a smooth parametrisation $\psi: \mathcal{W}_{F} \longrightarrow M$, a vector $c_{0} \in \mathbb{R}^{n+1}$ and a constant $C$ depending on $n, p$ and $F$ so that

$$
\left\|\psi-\mathrm{Id}-c_{0}\right\|_{W^{2, p}(\mathcal{W})} \leqslant C \delta
$$

Now, if $\left\|H^{F}-h\right\|<\varepsilon h$ and $\left\|H_{2}^{F}-h_{2}\right\|<\varepsilon h^{2}$, then from Lemma 3.1

$$
\left|h^{2}-h_{2}\right| \leqslant A h^{2} \varepsilon
$$

with $A$ a positive constant depending on $n, h$ and $F$. Thus, we deduce that

$$
\left(H^{F}\right)^{2}-H_{2}^{F} \leqslant\left(H^{F}-h\right)^{2}+2 h\left(H^{F}-h\right)+\left|h^{2}-h_{2}\right|+\left|h_{2}-H_{2}^{F}\right|
$$

and so

$$
\left\|\left(H^{F}\right)^{2}-H_{2}^{F}\right\|_{p} \leqslant\left(4 h^{2}+A h^{2}\right) \varepsilon=A^{\prime} \varepsilon
$$

where $A^{\prime}$ is a positive constant depending only on $n, h$ and $F$. On the other hand, we have

$$
\left(H^{F}\right)^{2}-H_{2}^{F}=\frac{1}{n^{2}(n-1)} \sum_{i, j=1}^{n}\left(\kappa_{i}-\kappa_{j}\right)^{2}
$$

so we get

$$
\left\|\sum_{i, j=1}^{n}\left(\kappa_{i}-\kappa_{j}\right)^{2}\right\|_{p} \leqslant A^{\prime \prime} \varepsilon
$$

where $A^{\prime \prime}=n^{2}(n-1) A^{\prime}$ is also a positive constant depending only on $h, n$ and $F$. Hence, $M$ has almost vanishing anisotropic second fundamental form. Indeed, we have at a point $x \in M$,

$$
\begin{aligned}
\left\|S_{F}-H^{F} \mathrm{Id}\right\|^{2} & =\sum_{i=1}^{n}\left(k_{i}-H^{F}\right)^{2} \\
& =\sum_{i=1}^{n}\left(\kappa_{i}-\frac{1}{n} \sum_{j=1}^{n} \kappa_{j}\right)^{2} \\
& =\frac{1}{n} \sum_{i, j=1}^{n}\left(\kappa_{i}-\kappa_{i}\right)^{2}
\end{aligned}
$$

which give after integration

$$
\left\|S_{F}-H^{F} \mathrm{Id}\right\|_{p}^{2} \leqslant \frac{1}{n} A^{\prime \prime} h^{2} \varepsilon
$$

Finally, we fix $p>n$ and set $\varepsilon_{0}=\inf \left\{1, \frac{n\left(\delta_{0} \operatorname{Vol}\left(\mathcal{W}_{F}\right)\right)^{\frac{2}{p}}}{A^{\prime \prime}}\right\}$ where $A^{\prime \prime}$ is the constant defined above and $\delta_{0}$ comes from Theorem 1.3 . Note that $\varepsilon_{0}$ depends on $n, p, h$ and $F$. Now, let $\varepsilon \leqslant \varepsilon_{0}$. We set $\delta=\frac{\left(A^{\prime \prime} \varepsilon\right)^{\frac{p}{2}}}{n^{\frac{p}{2}} V\left(\mathcal{W}_{F}\right)}$. Since $\varepsilon \leqslant \varepsilon_{0}$ and from the definiton of $\delta$, we have $\delta \leqslant \delta_{0}$ and

$$
\int_{M}\left\|S_{F}-H^{F} \mathrm{Id}\right\|^{p} d v_{g} \leqslant \delta
$$

Thus, since by assumption, we also have $\operatorname{Vol}(M)=\operatorname{Vol}\left(\mathcal{W}_{F}\right)$, we can apply Theorem 1.3 to obtain that there exists a smooth parametrisation $\psi: \mathcal{W}_{F} \longrightarrow M$ a vector $c_{0} \in \mathbb{R}^{n+1}$ and a constant $C$ depending on $n, p, h$ and $F$ so that

$$
\left\|\psi-\operatorname{Id}-c_{0}\right\|_{W^{2, p}(\mathcal{W})} \leqslant C \delta=K \varepsilon^{\frac{p}{2}}
$$

where $K=\frac{\left(n A^{\prime \prime}\right)^{\frac{p}{2}} C}{\operatorname{Vol}\left(\mathcal{W}_{F}\right)}$ is a positive constant depending only on $n, p, h$ and $F$ since $A^{\prime \prime}$ depends on $n, h$ and $F, \operatorname{Vol}\left(\mathcal{W}_{F}\right)$ depends on $n$ and $F$ and $C$ depends on $n, p$ and $F$. This concludes the proof of Theorem 1.1 .

Proof of Theorem 1.3. The proof of Theorem 1.3 is a combination of Lemma 3.2 and the main Theorem of 13 . We recall this result

Theorem (Roth-Scheuer [13]). Let $M \longrightarrow \mathbb{R}^{n+1}$ be a closed, connected, oriented and isometrically immersed hypersurface with $\operatorname{Vol}(M)=1$. Let $p>n \geq 2$. Then, there exist $\eta_{0}\left(n, p,\|A\|_{p}\right)>0, C\left(n, p,\|A\|_{p}\right)>0$ and $\alpha(n, p) \leqslant 1$ such that if for $\eta \leqslant \eta_{0}$,

$$
\|A-H \operatorname{Id}\|_{p} \leq\|H\|_{p} \eta
$$

holds, then $M$ is diffeomorphic and $C \eta^{\alpha}$-close to a geodesic hypersphere (of radius $\left.\frac{1}{\|H\|_{2}}\right)$.

First, if $\|H-h\|<\varepsilon h$ and $\left\|H_{2}-h_{2}\right\|<\varepsilon h^{2}$, then from Lemma 3.2

$$
\left|h^{2}-h_{2}\right| \leqslant B \varepsilon
$$

with $B$ a positive constant depending on $n, h$ and $\delta$. Thus, we deduce that

$$
H^{2}-H_{2} \leqslant(H-h)^{2}+2 h(H-h)+\left|h^{2}-h_{2}\right|+\left|h_{2}-H_{2}\right|
$$

and so after integration, we get immediately

$$
\left\|H^{2}-H_{2}\right\|_{p} \leqslant(4 h+B) \varepsilon=B^{\prime} \varepsilon
$$

with $B^{\prime}$ a positive constant depending only on $n, h$ and $\delta$. But, since

$$
\left\|H^{2}-H_{2}\right\|_{p}=n(n-1)\|A-H \operatorname{Id}\|_{p}^{2}
$$

we deduce that

$$
\|A-H \operatorname{Id}\|_{p} \leqslant\left(\frac{B^{\prime} \varepsilon}{n(n-1)}\right)^{\frac{1}{2}}=B^{\prime \prime} \varepsilon^{\frac{1}{2}}
$$

with $B$ depending on $n, h$ and $\delta$. Second, from the assumption $\|H-h\|_{p}<\varepsilon h$, we get immediately

$$
\frac{h}{2} \leqslant(1-\varepsilon) h \leqslant\|H\|_{p} \leqslant(1+\varepsilon) h \leqslant 2 h
$$

if we assume that $\varepsilon<\frac{1}{2}$. Hence, we deduce that

$$
\|A\|_{p} \leqslant B^{\prime \prime}+2 h \sqrt{n}
$$

So $\|A\|_{p}$ is bounded from above by a constant depending only on $n, h, R$ and $\delta$.
Now, we set $\varepsilon_{1}=\inf \left\{\frac{1}{2},\left(\frac{2 \eta_{1}}{B^{\prime \prime} h}\right)^{2}\right\}$. With this choice, if $\varepsilon<\varepsilon_{1}$, we get that $\eta=\frac{B^{\prime \prime}}{\|H\|_{p}} \varepsilon^{\frac{1}{2}} \leqslant \eta_{1}$ and

$$
\|A-H \operatorname{Id}\|_{p}^{p} \leqslant\|H\|_{p} \eta
$$

and we conclude that $M$ is diffeomorphic and $C \eta^{\alpha}$-close to a geodesic sphere of radius $\frac{1}{\|H\|_{2}}$. But, $C \eta^{\alpha}=C\left(\frac{B^{\prime \prime}}{\|H\|_{p}}\right)^{\alpha} \varepsilon^{\frac{\alpha}{2}} \leqslant C \eta^{\alpha}=C\left(\frac{2 B^{\prime \prime}}{h}\right)^{\alpha} \varepsilon^{\frac{\alpha}{2}}=K \varepsilon^{\beta}$, where $K$ is a constant depending only on $n, p, h$ and $\beta=\frac{\alpha}{2}$ depends only on $n$ and $p$.
In the case where the ambient space is the space form of constant curvature $\delta$, the proof is analogue using Theorem 3.1 of [13] for sphere and hyperbolic spaces obtain the Euclidean theorem with a conformal change of metric. In this case, the constants $C$, and so $K$ too, depend also on $\delta$. This conlcudes the proof.
4.1. Proof of Corollaries $\mathbf{1 . 5}$ and 1.6. Assume that $M$ has constant mean curvature $H=h$, and $\|$ Scal $-s \|_{p}<\varepsilon$ for a constant $s$. First, by the Gauss formula, we have clearly Scal $=n(n-1)\left(H_{2}+\delta\right)$ and so $\|$ Scal $-s \|_{p}<\varepsilon$ gives $\left\|H_{2}-h_{2}\right\|_{p} \varepsilon$ with $h_{2}=\frac{1}{n(n-1)}$ Scal $-\delta$ and we can apply Theorem 1.3 to conclude that $M$ is diffeomorphic to a geodesic hypersphere of radius $\rho$. But this diffeomorphism is explicitely given (see [10, 11]) by $F=\rho \frac{X}{|X|}$ where $X$ is the immersion of $M$ into $\mathbb{M}^{n+1}(\delta)$. Hence, $F$ is of the form $G \circ X$. Necessarily, $X$ is injective and so the immersion of $M$ is an embedding. By the Alexandrov theorem, we conclude that $M$ is a geodesic hypersphere.
If Scal is constant and $\|H-h\|_{p} \leqslant \varepsilon$, the proof is the same and we conclude by the Alexandrov theorem for $\mathrm{H}_{2}$.

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Laboratoire D'Analyse et de Mathématiques Appliquées, Université Paris-Est, 5, boulevard Descartes, Cité Descartes, 77454 Marne-la-Vallée cedex 2, France

E-mail address: julien.roth@u-pem.fr


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