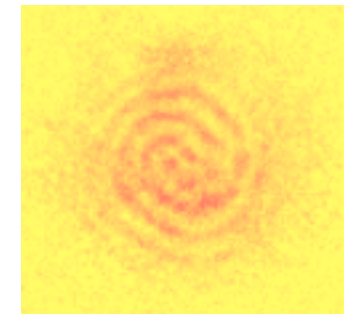
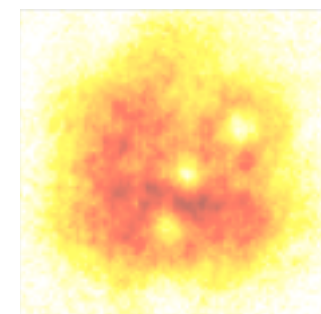
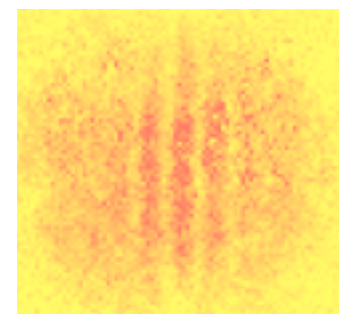
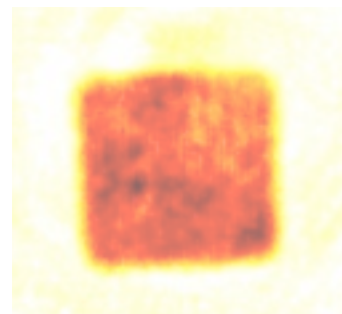
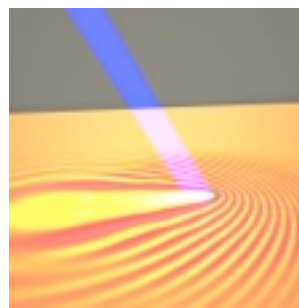
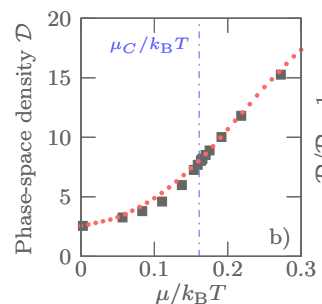
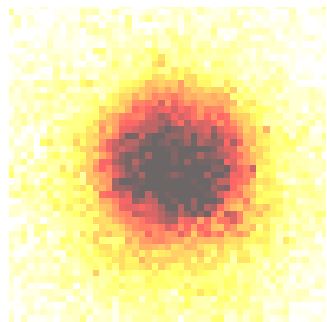


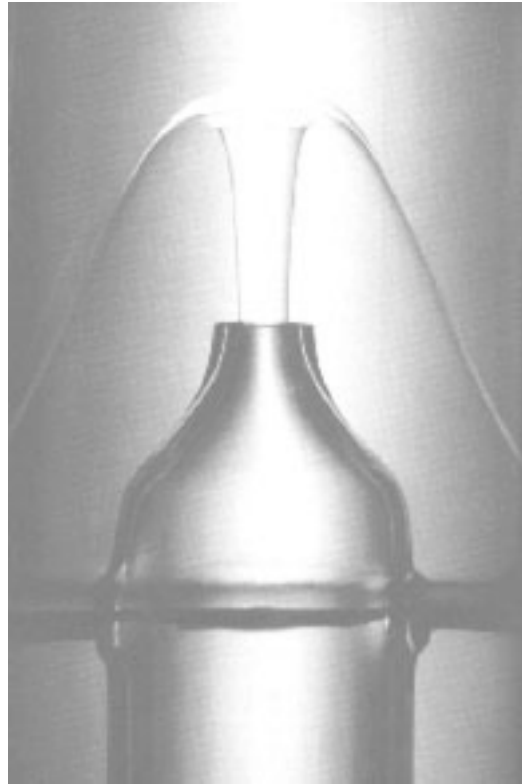
Superfluidity and coherence of Bose gases in reduced dimensions: from harmonic traps to uniform fluids



Lauriane Chomaz – PhD defense
November 10th, 2014

Macroscopic quantum phenomena.

Superfluidity

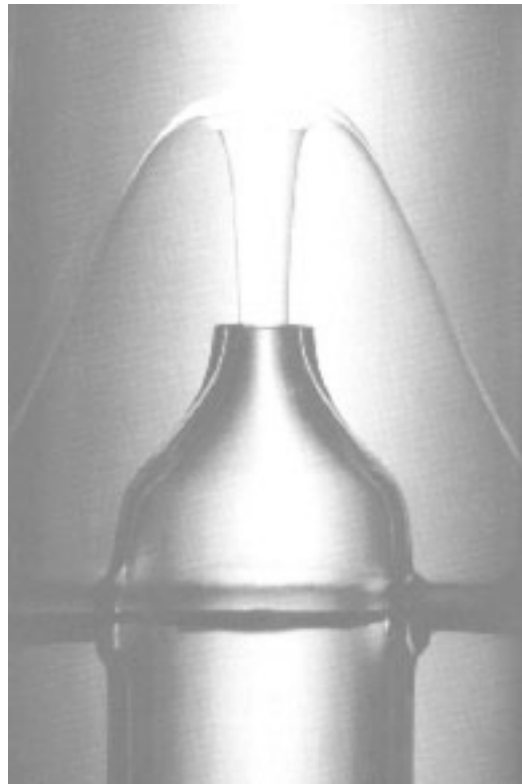


Superconductivity

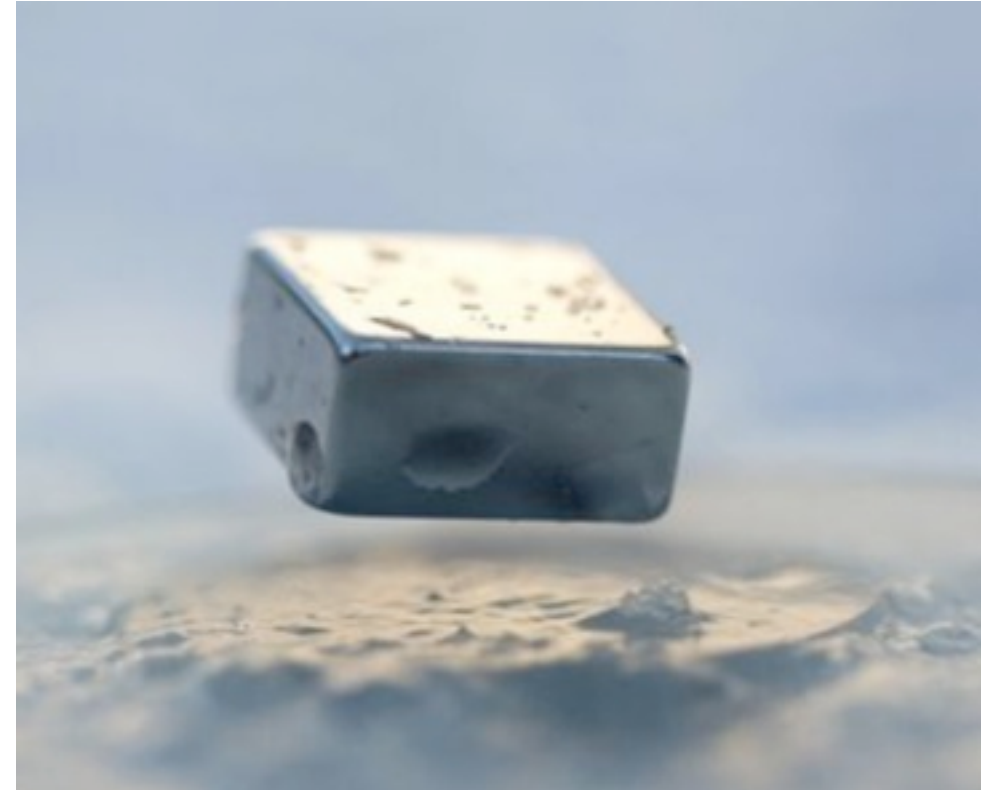


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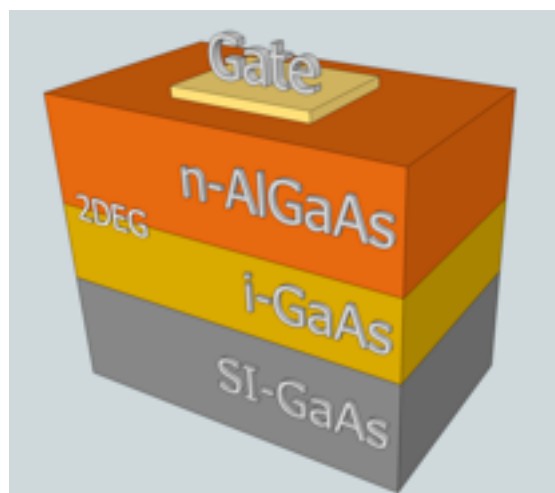
Superfluidity



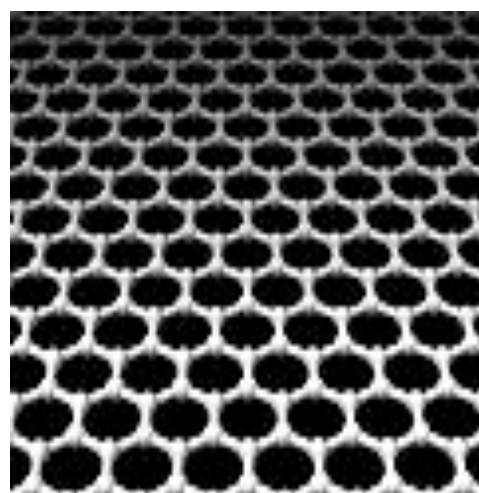
Superconductivity



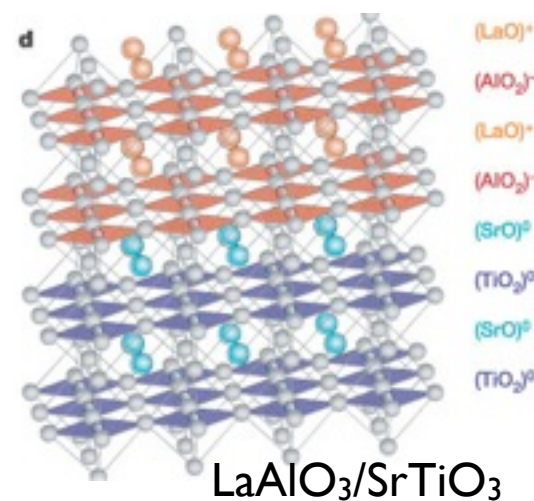
In 2D: special meaning. Important for understanding new material :



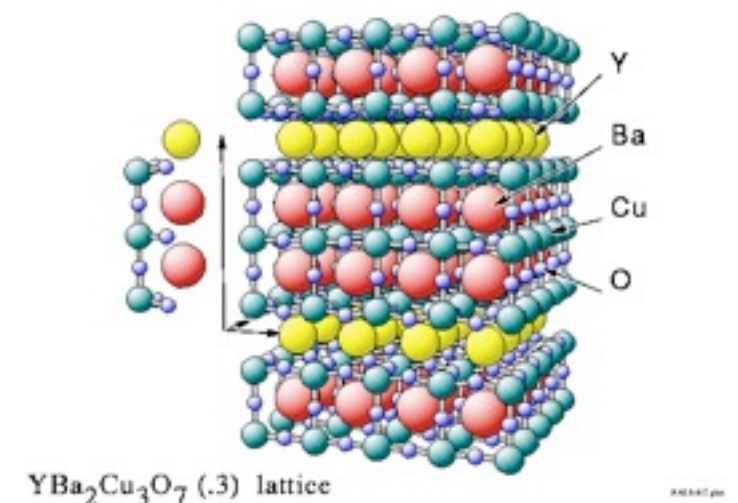
Semiconductors heterostructures



Graphene



Complex oxide heterostructures

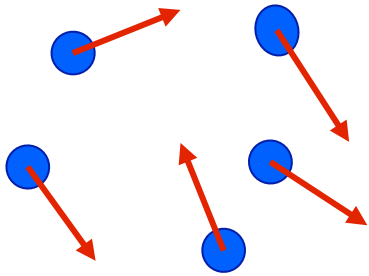


High-T_c superconductors

Quantum coherence.

Infinite uniform gas of non/weakly interacting Bosons at temperature T :

Classical world



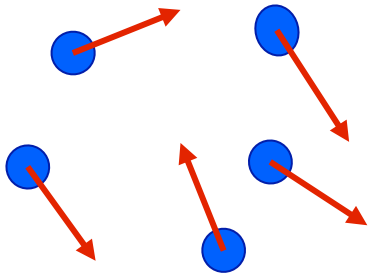
describe by trajectories

No coherence

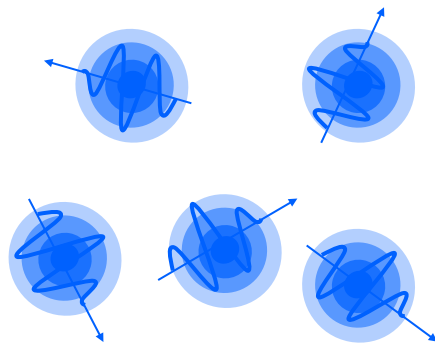
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Quantum world



Quantum field: $\hat{\psi}(\mathbf{r}) \equiv$ annihilates an atom in \mathbf{r}
 $\langle \hat{\psi}^\dagger(\mathbf{r}) \hat{\psi}(\mathbf{r}) \rangle =$ probability of finding an at. in \mathbf{r}
 $\langle . \rangle \equiv$ average over the thermal state of the gas

describe by trajectories

No coherence

describe by waves

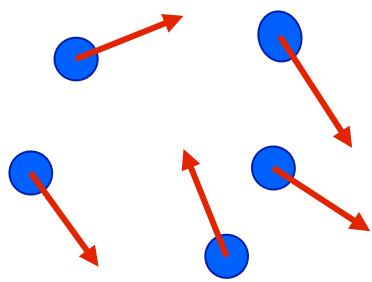
Coherence

$$G_1(\mathbf{r}) = \langle \hat{\psi}^\dagger(\mathbf{r}) \hat{\psi}(0) \rangle$$

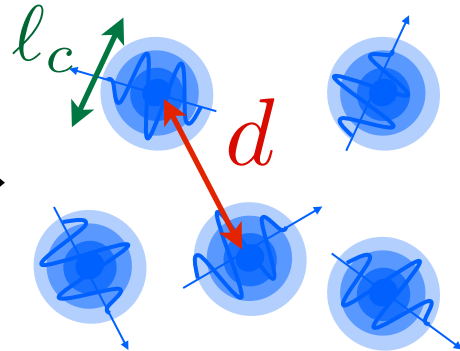
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Characteristic lengths in ideal quantum gases :

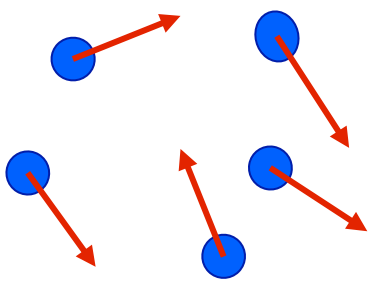
- ♣ Coherence length:
 $l_c \equiv$ charact. of decay of $G_1(r)$
- ♣ Thermal wavelength:

$$\lambda_T = \sqrt{2\pi\hbar^2 / mk_B T}$$
- ♣ Mean distance between particles: d

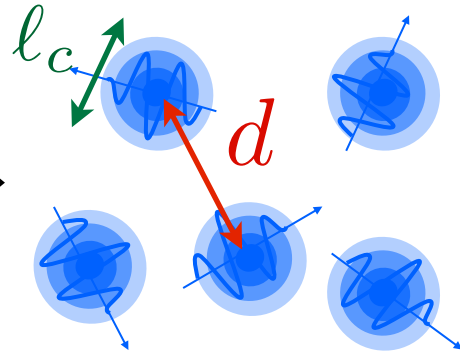
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high T

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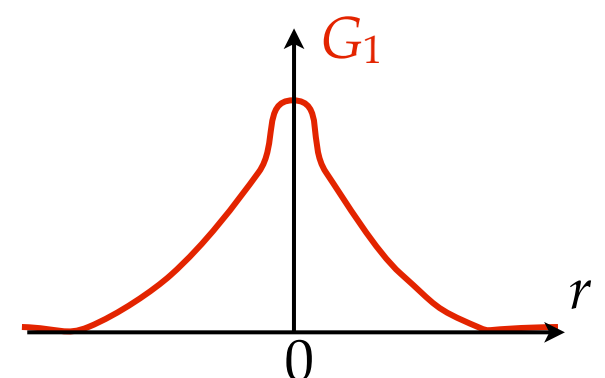
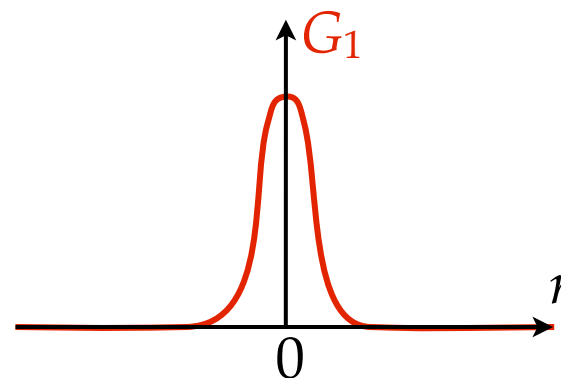
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~ Boltzmann statistics

Bose statistics

$$\lambda_T < d$$

$$\lambda_T > d$$



$$G_1(r) \propto \exp(-\pi r^2 / \lambda_T^2)$$

Modif. G_1 and $\uparrow l_c$.

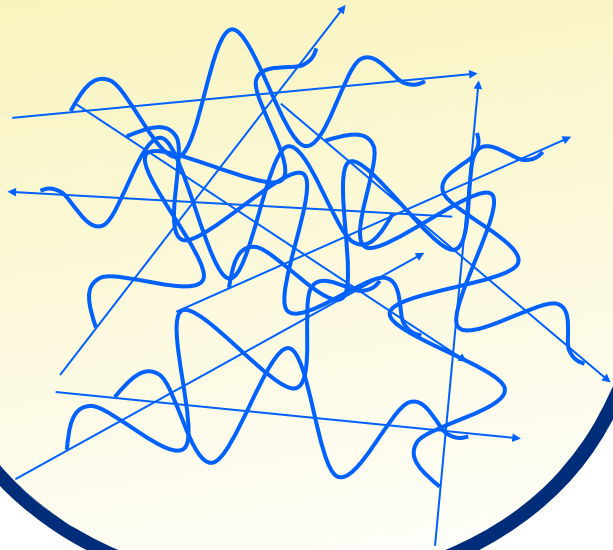
Coherence over $\sim \lambda_T$

depends on the dimension

Bose statistic in 3D.

3D ∞

ideal gas, $\lambda_T > d$

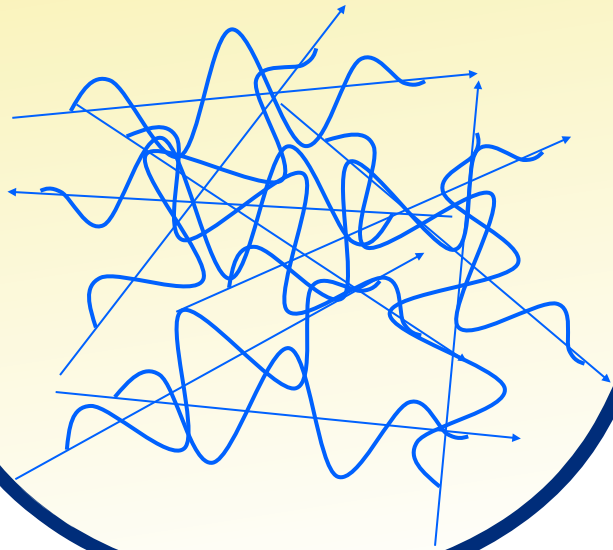


Bose-Einstein condensation (at $\lambda_T > C d$). $C = c^{\text{st}} \approx 1.38$ for 3D ∞ id.

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↔ **State of matter stemming from Bose stat.**

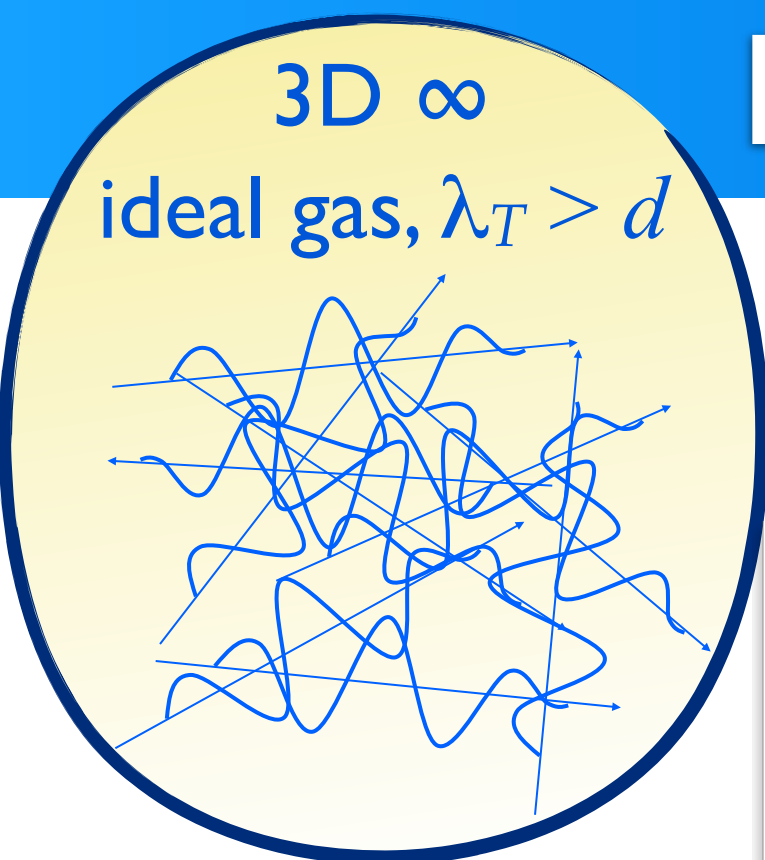
ideal gas

$$\hat{H} = \sum_{i \text{ atoms}} \hat{h}_i \left| \begin{array}{l} \text{single-part. Hamiltonian } \hat{h} = \frac{\hat{p}^2}{2m}. \\ \text{eigenstates} = |\varphi_{\mathbf{k}}\rangle, \mathbf{p} = \hbar\mathbf{k}. \end{array} \right.$$

➔ Saturation of the population in $k \neq 0$ at $\lambda_T = C d$.

↔ **Macroscopic occupation of a single-particle state $|\varphi_0\rangle$.**

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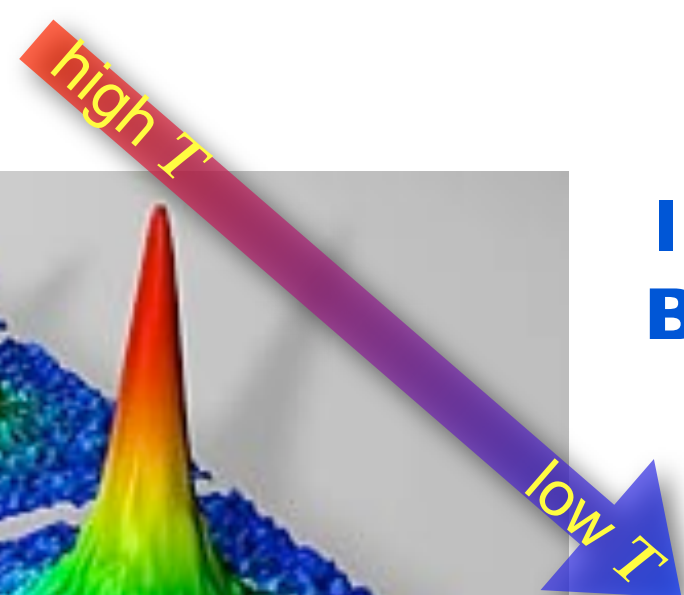
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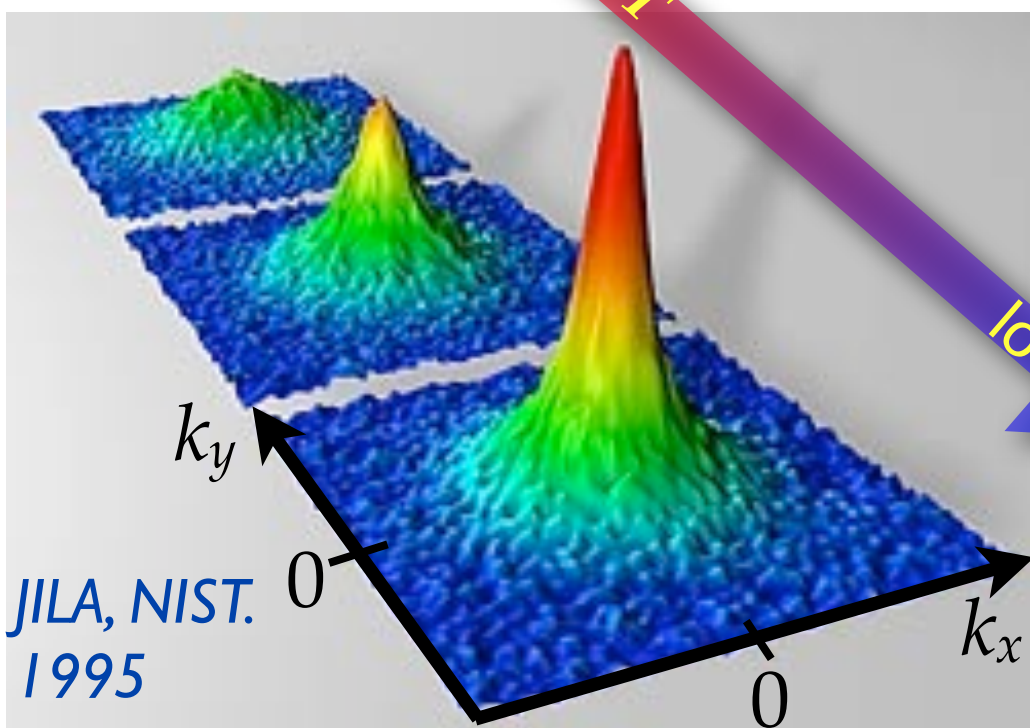
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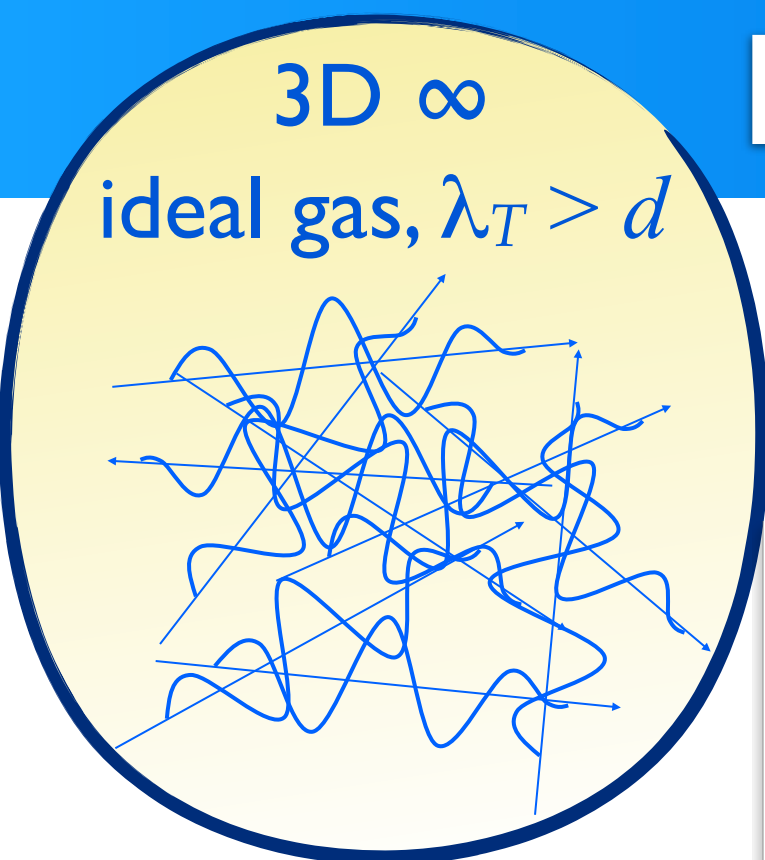
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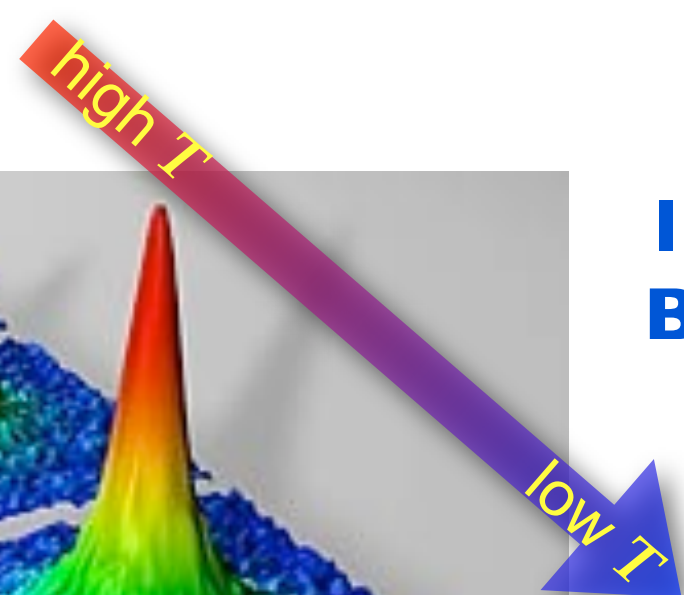
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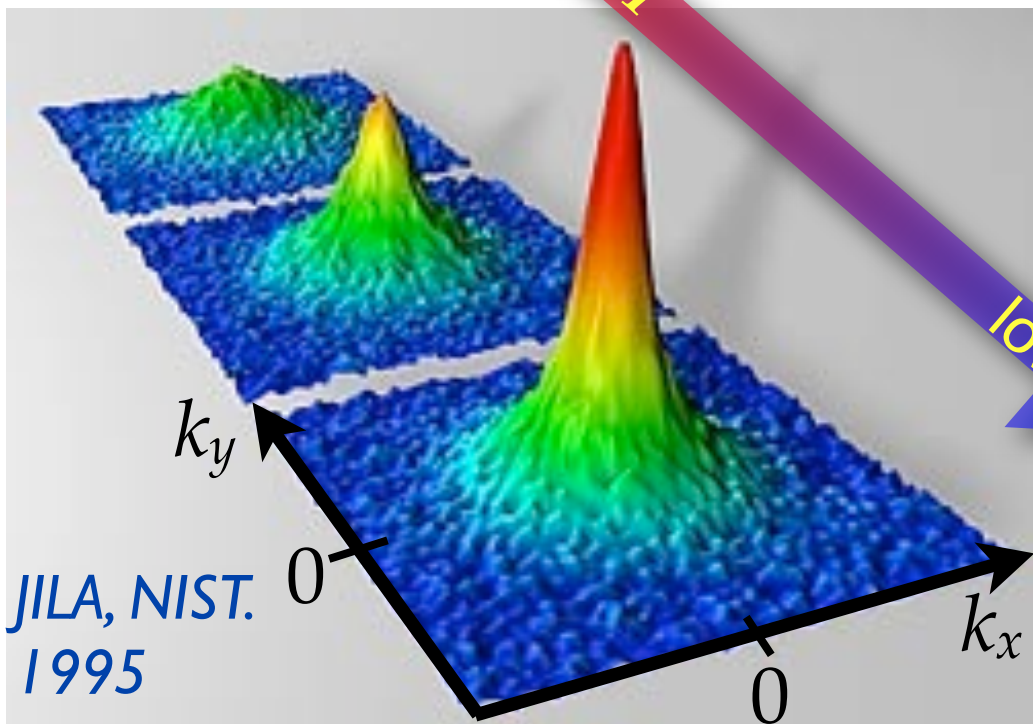
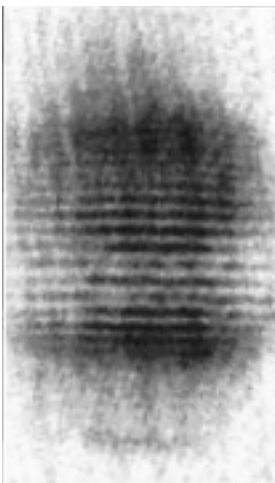


1995: Groundbreaking observation of BEC in dilute ultracold gases.

↔ **long-range phase coherence**

$$G_1(r) \xrightarrow{r \rightarrow \infty} n_0 \neq 0$$

$n_0 = \text{density in } |\varphi_0\rangle$



MIT.1997

Outline.

- ◆ Motivation: specificity of 2D and 3D-to-2D crossover.
- ◆ Motivation: from harmonic to uniform traps.
- ◆ Experimental setup: creating 2D uniform gases.
- ◆ Emergence of an extended phase coherence in 2D uniform gases at thermal equilibrium.
- ◆ Dynamics of the establishment of coherence along forced evaporative cooling in uniform fluids.

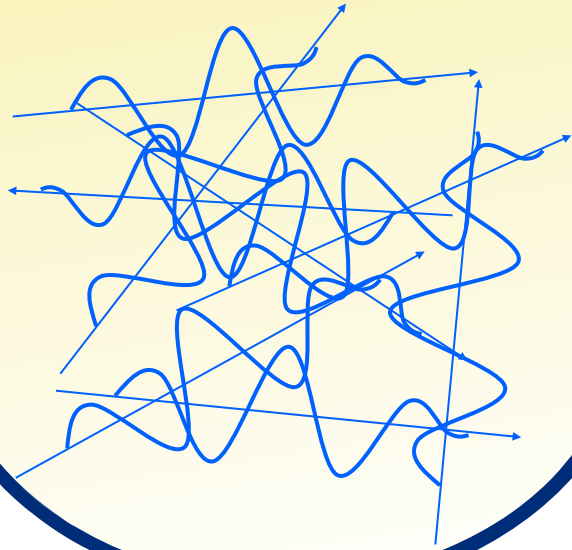
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Effect of bidimensionality.

2D ∞

ideal gas, $\lambda_T > d$



no BEC in an infinite 2D gas at $T \neq 0$

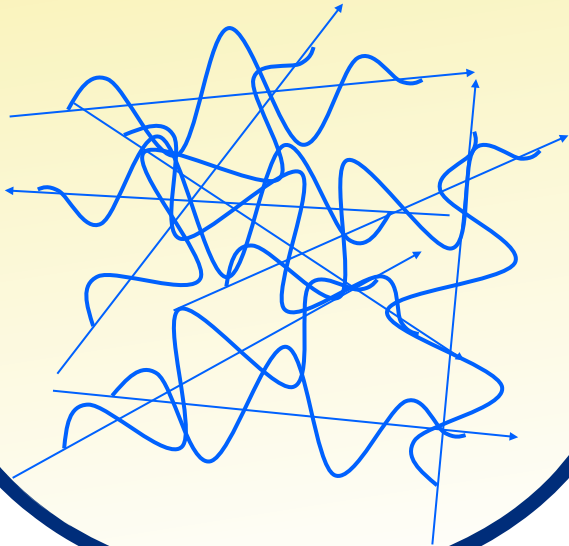
(Peierls - 1935, Mermin-Wagner-Hohenberg - 1966-67)

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high energy-states

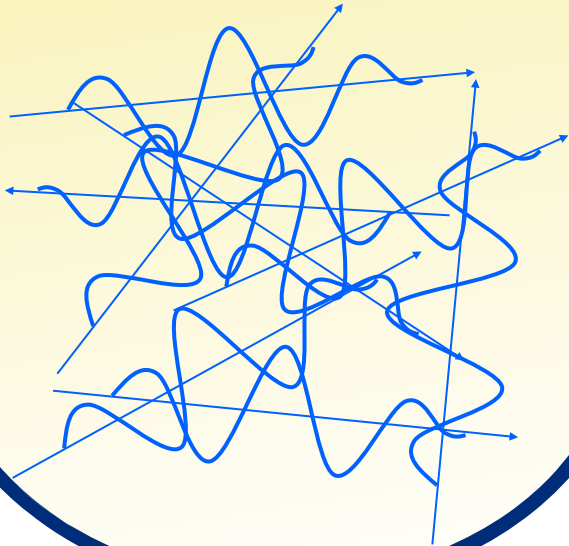
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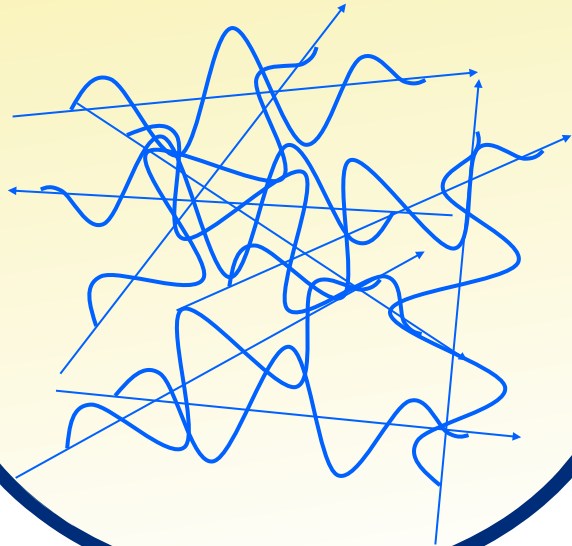
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\Rightarrow Fast increase of ℓ_c/λ_T when $\mathcal{D} \gtrsim 1$

ideal gas

Corrections for experimental 2D systems.



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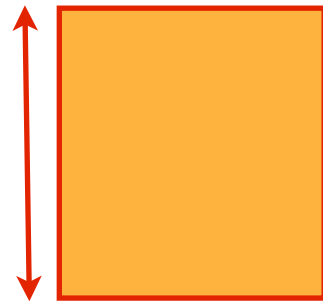
Finite size effect

Fast increase of ℓ_c with \mathcal{D}
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At $\mathcal{D} \geq \mathcal{D}_{\text{BEC}}$, $\ell_c \gtrsim L$

\Rightarrow recover BEC : L

$G_1(r) > 0 \forall r \in \text{gas.}$



$G_1(L) \Leftrightarrow$ condensed density

$\Rightarrow \mathcal{D}_{\text{BEC}} \sim 7-10$ (for typical L and T)

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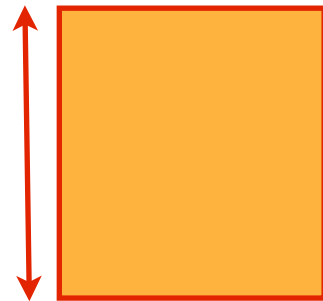
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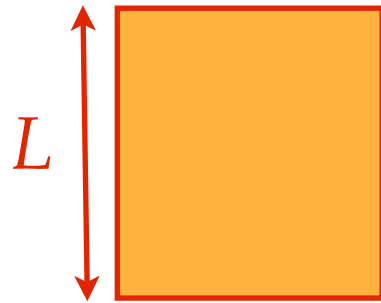
A distinct type of phase transition possible:
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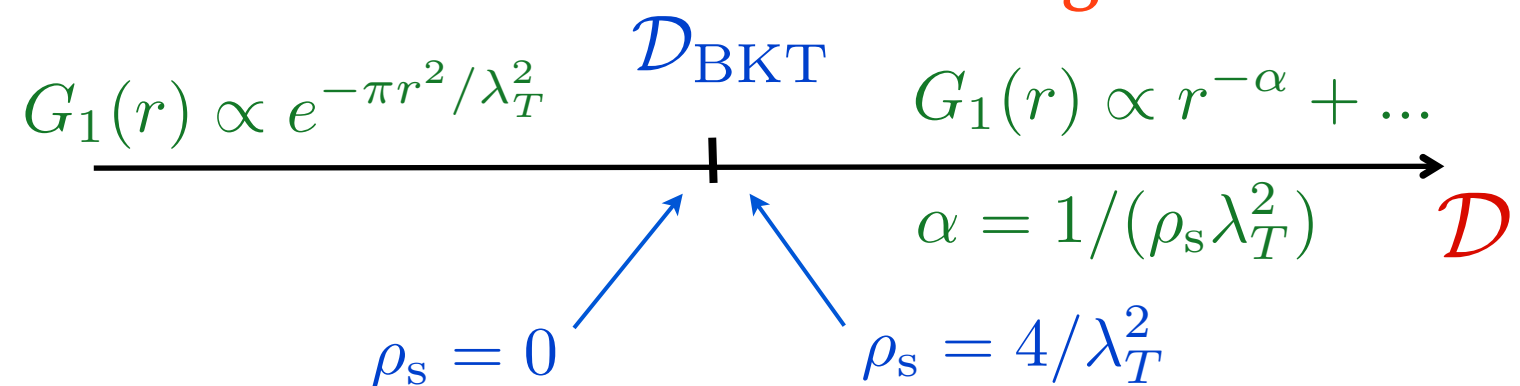
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**Quasi-long
range order**



Infinite order transition

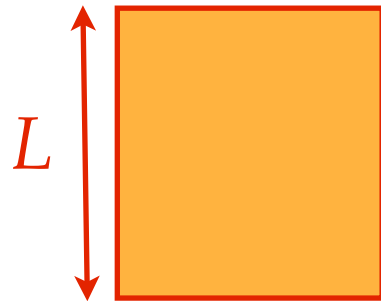
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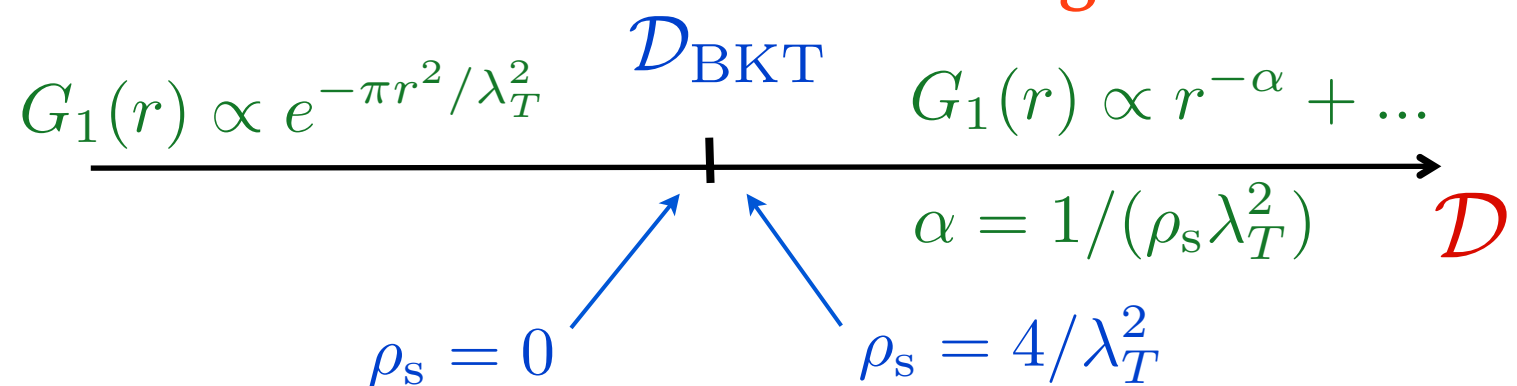
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Boltzmann

«Pre-superfluid» / «Quasi-condensate»

BEC/ Superfluid

\mathcal{D}

$$G_1(r) \propto e^{-\pi r^2 / \lambda_T^2} \approx 1$$

$$G_1(r) \propto \rho_0 e^{-r/\ell} + \dots$$

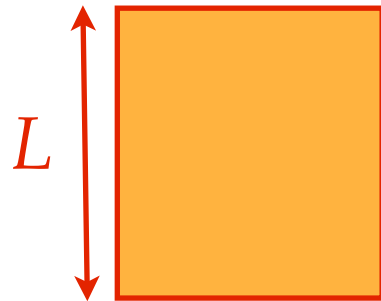
$$\approx 7-10 \quad G_1(r) > 0, \forall r \in \text{gas}$$

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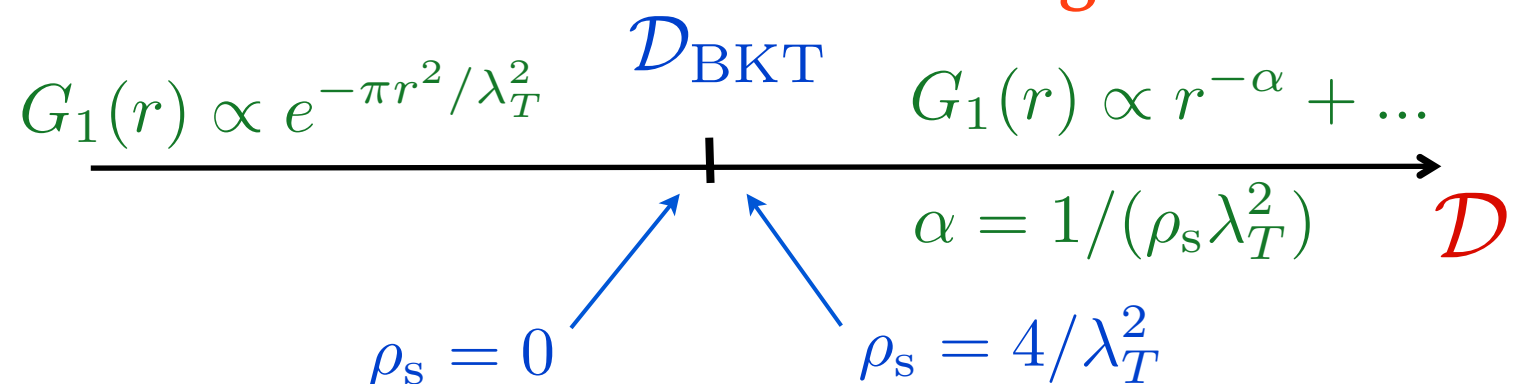
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NIST Gaithersburg, Boulder

Chicago, ENS, Seoul

Boltzmann

«Pre-superfluid» / «Quasi-condensate»

BEC/ Superfluid

\mathcal{D}

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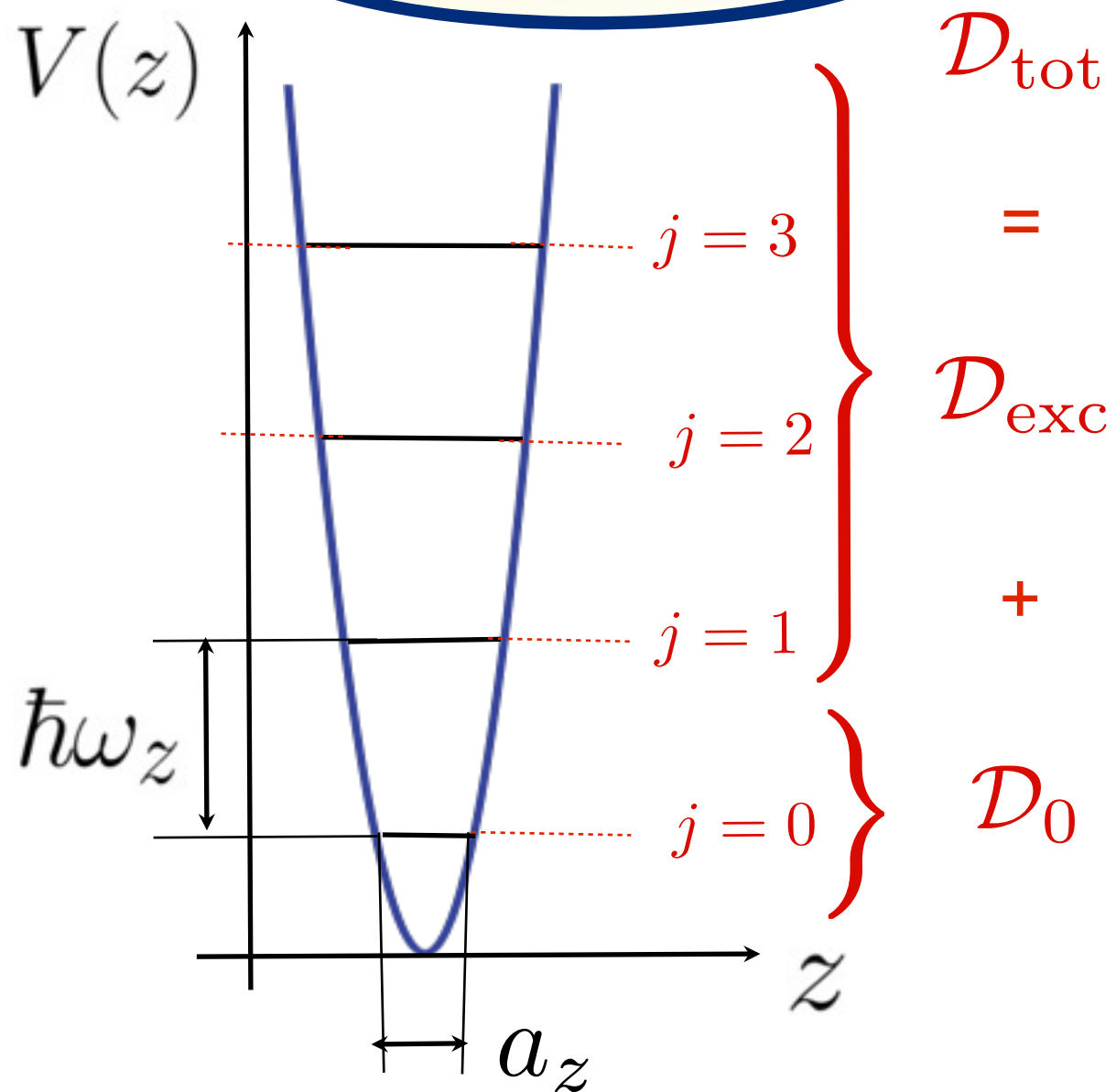
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3rd dim. in 2D experiments.

How to realize 2D systems in cold atoms experiments...

Along the 3rd direction z :
tight (harmonic) trap

$$\mathcal{D} \equiv \lambda_T^2 \rho \leftarrow \text{2D density}$$

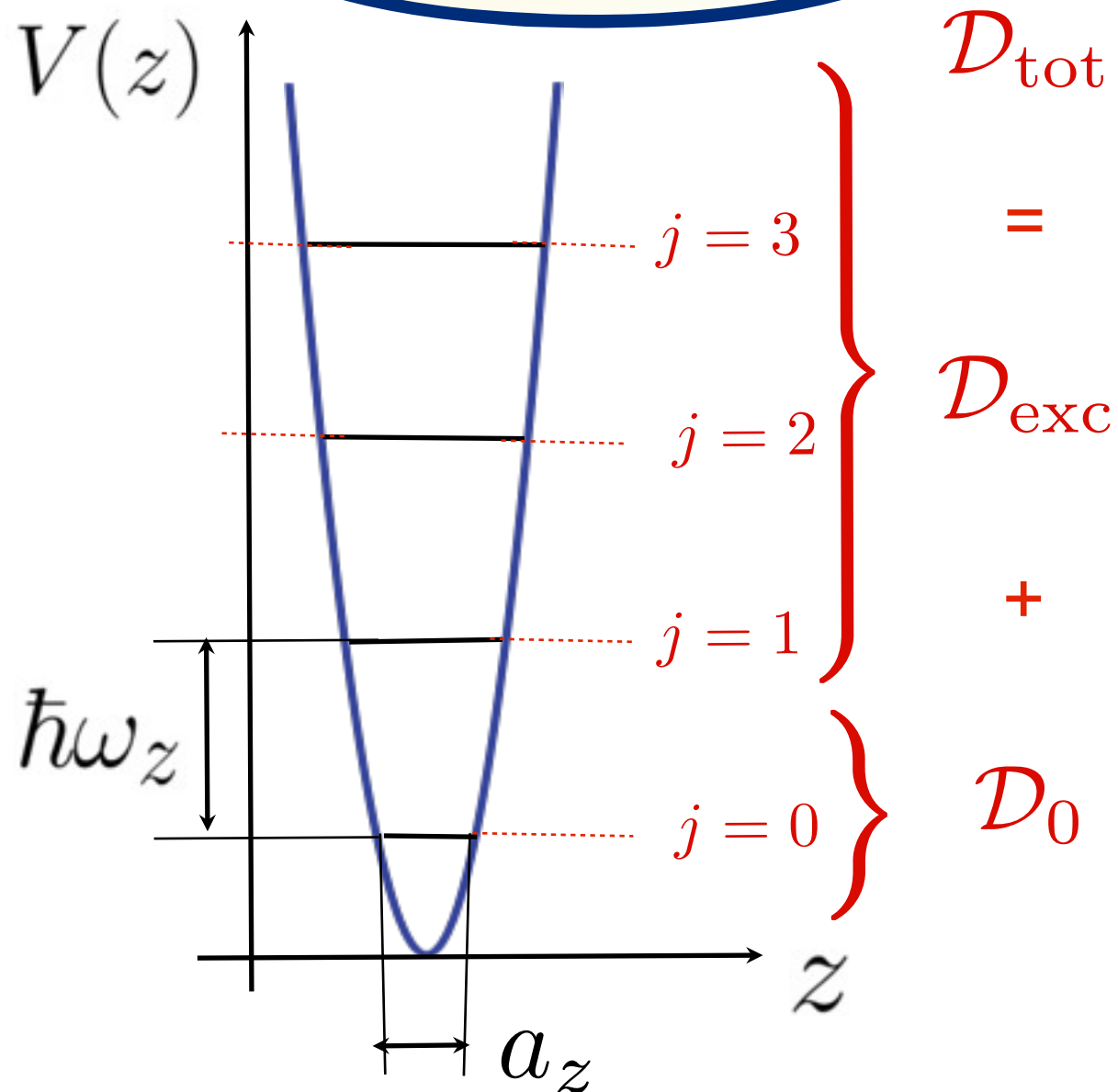


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♣ $k_B T \ll \hbar\omega_z$ thermally 2D, only $j=0$ populated:

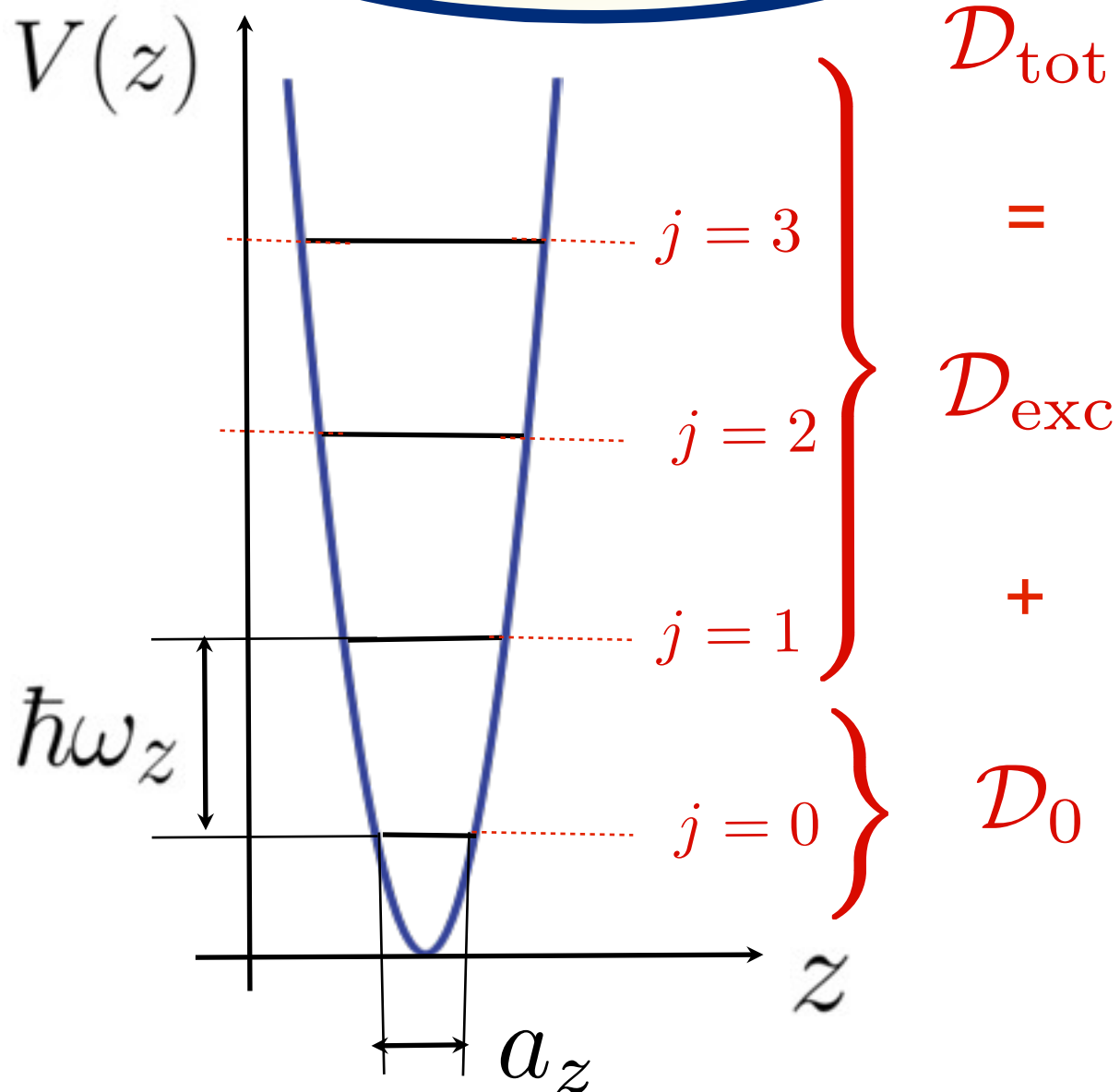
$$\mathcal{D}_{\text{tot}} \approx \mathcal{D}_0.$$

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Along the 3rd direction z :
tight (harmonic) trap

$$\mathcal{D} \equiv \lambda_T^2 \rho \leftarrow \text{2D density}$$



❖ $k_B T \ll \hbar\omega_z$ thermally 2D, only $j=0$ populated:

$$\mathcal{D}_{\text{tot}} \approx \mathcal{D}_0.$$

❖ $k_B T \gtrsim \hbar\omega_z$ all j 's must be accounted for.

$$\mathcal{D}_{\text{tot}} = \mathcal{D}_0 + \mathcal{D}_{\text{exc}}$$

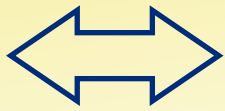
$$G_1(r) = \sum_{j=0}^{\infty} G_1^{(j)}(r)$$

$G_1^{(0)}(r) \equiv$ broadest contribution

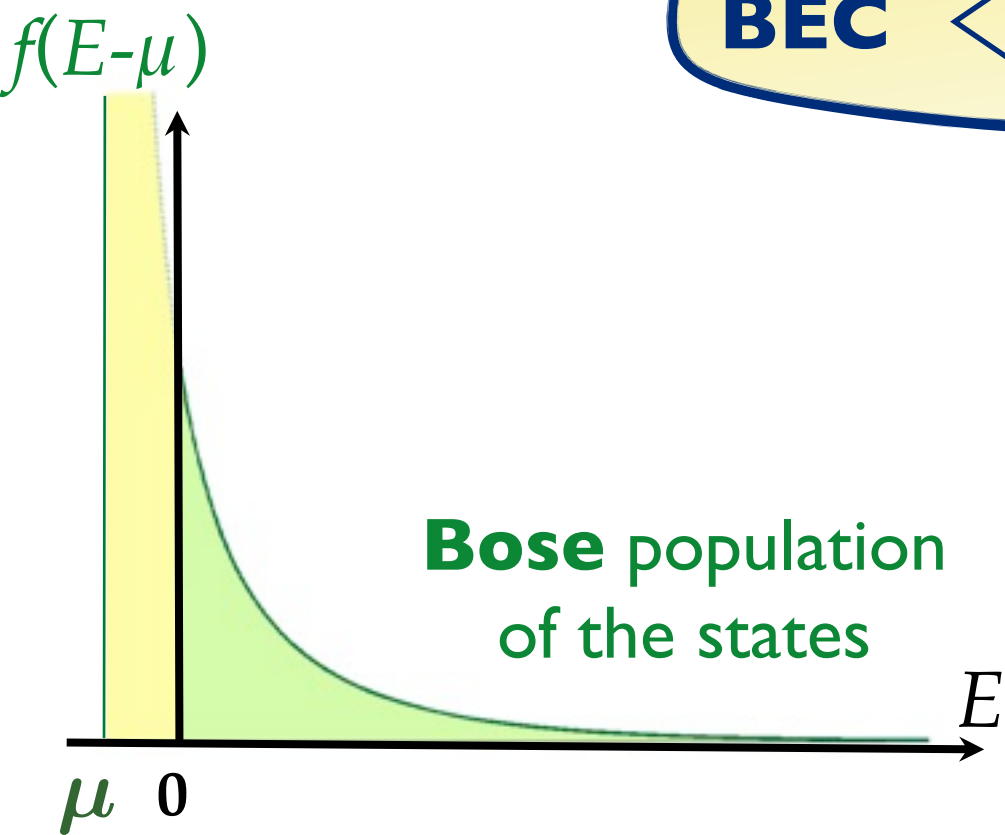
3rd dim.: Transverse condensation.

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BEC

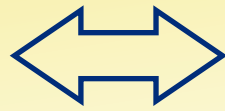


Saturation of the population of the quantum states in Bose statistics.

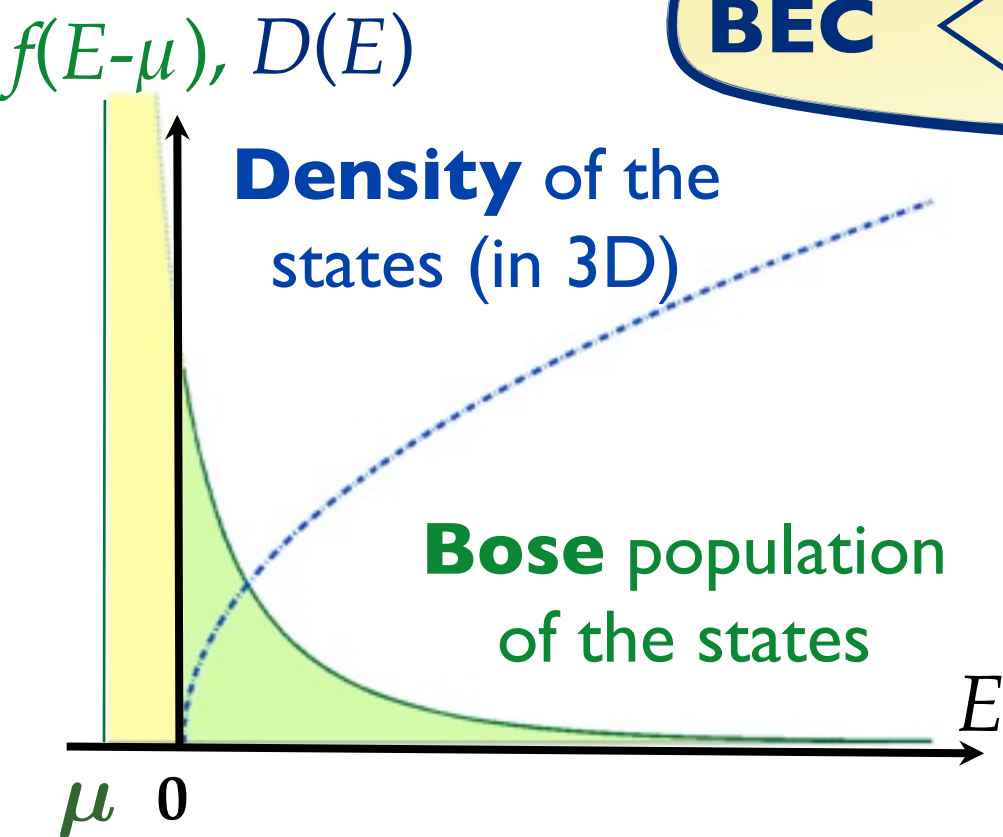


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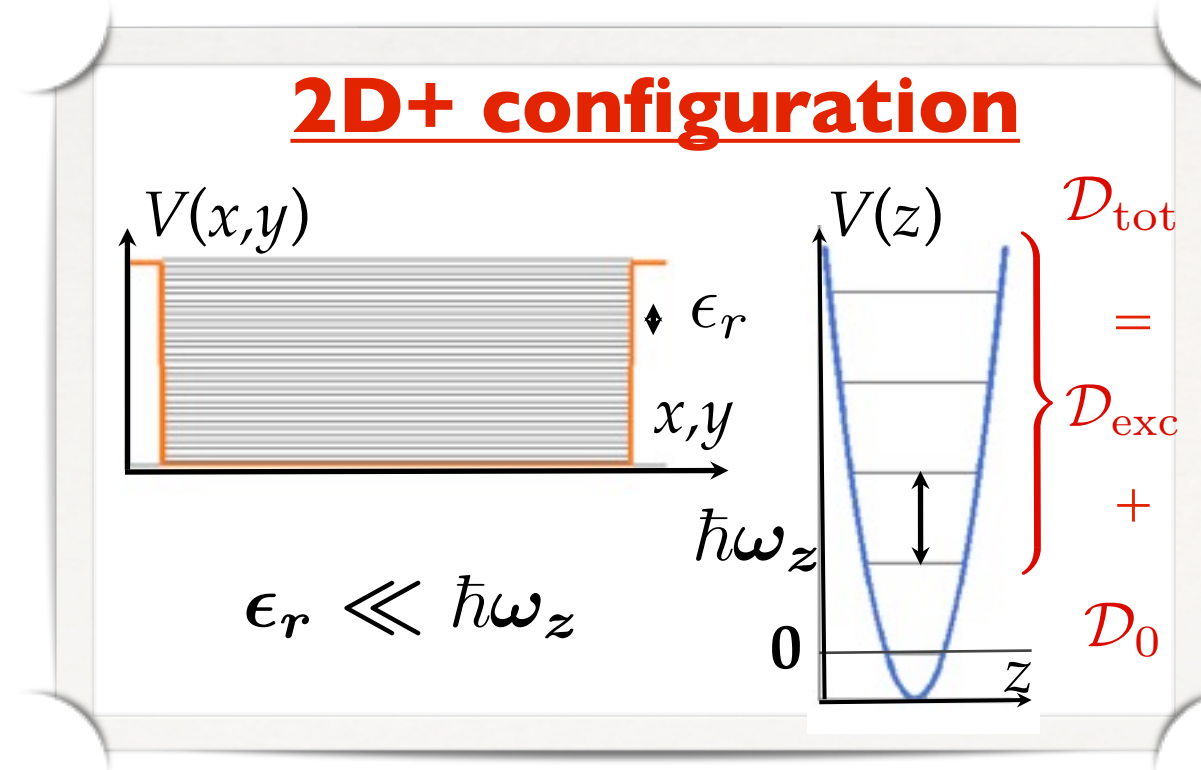
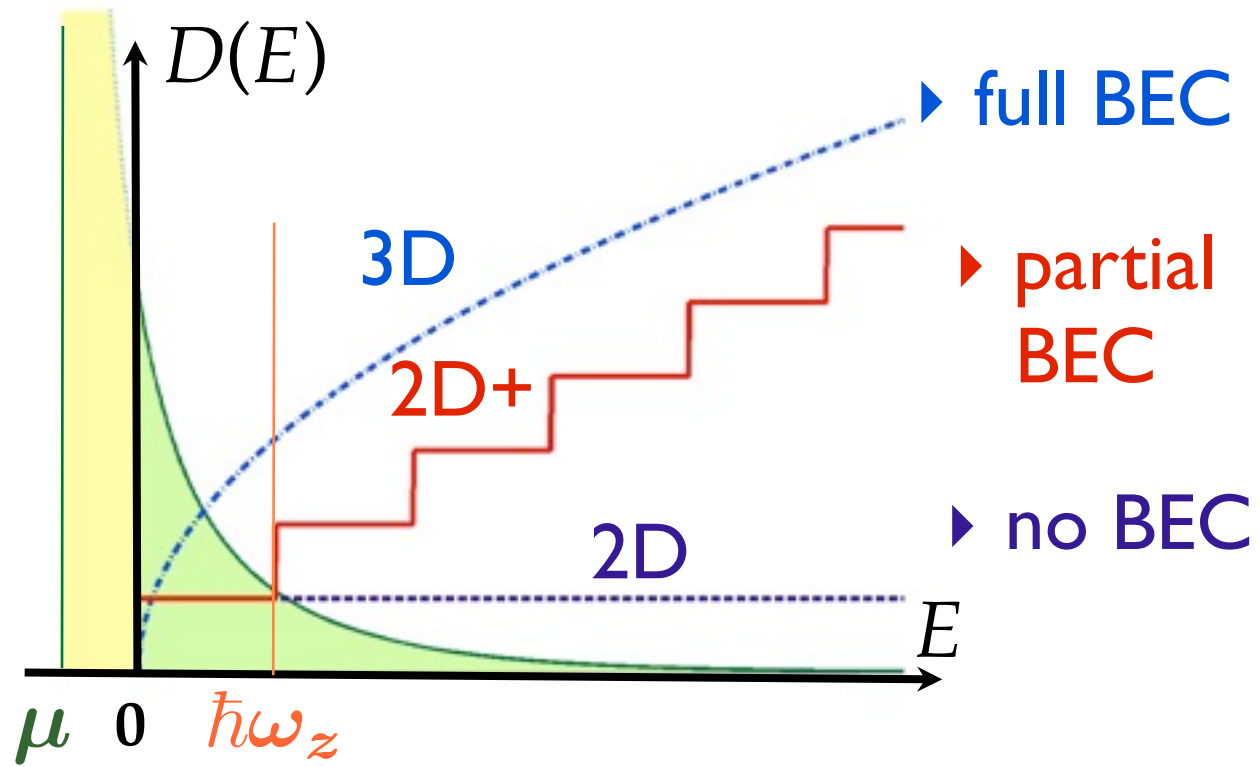
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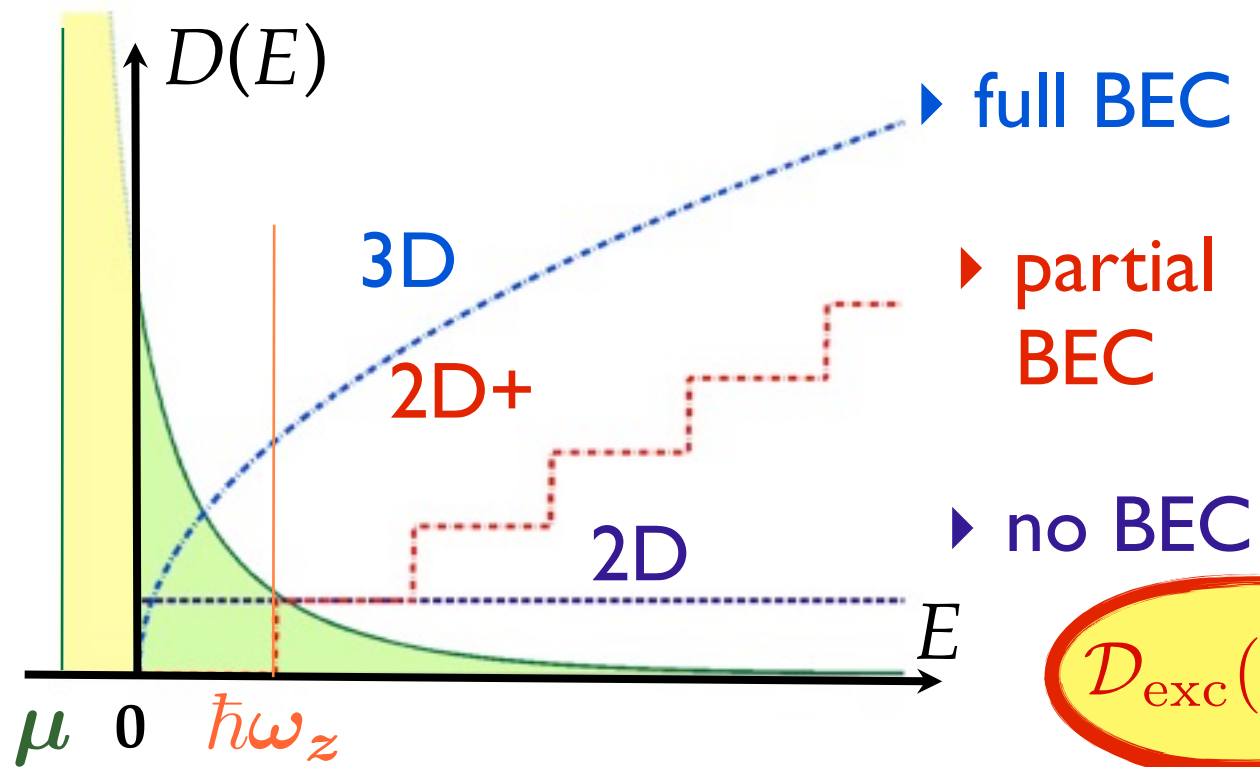
$$\mathcal{D}^{(D)}(\mu) = \left(\frac{\lambda_T}{L} \right)^D \int f(E - \mu) D(E) dE$$

$$\mathcal{D}^{(D)}(\mu) \xrightarrow{\mu \rightarrow 0} \begin{cases} \mathcal{D}_c & \Leftrightarrow \text{BEC} \\ \infty & \Leftrightarrow \text{no BEC} \end{cases}$$

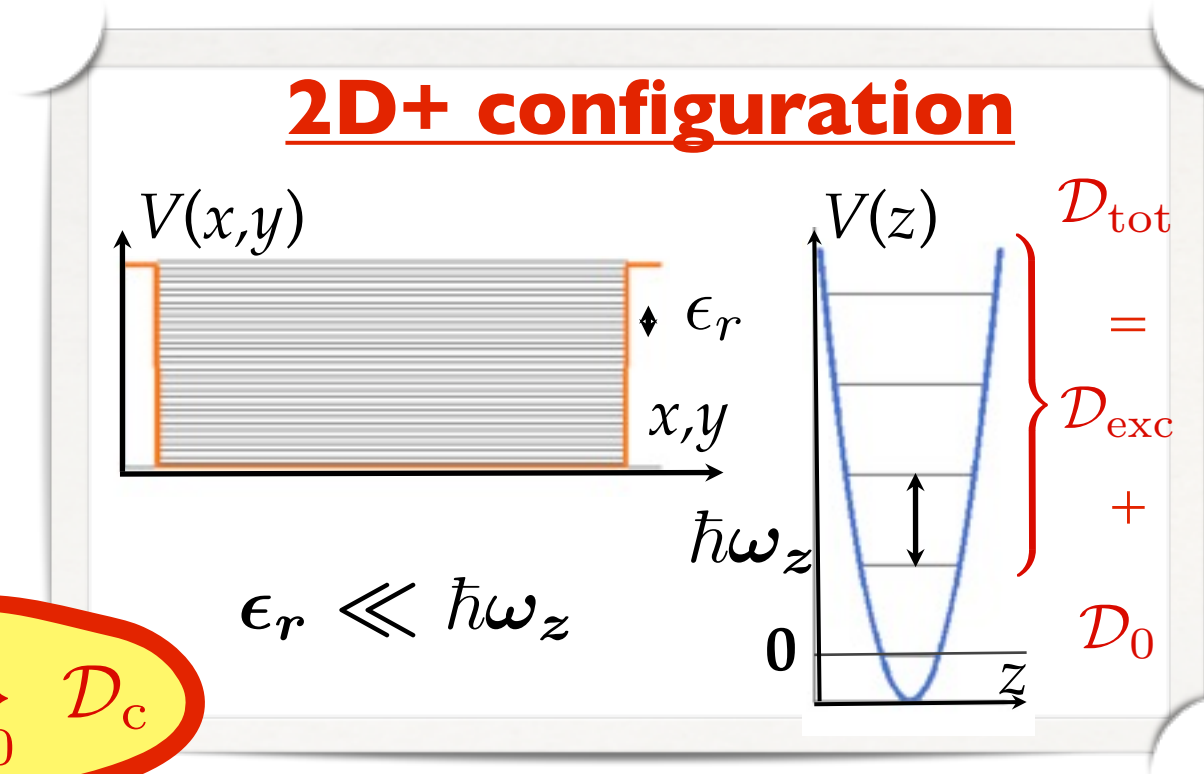
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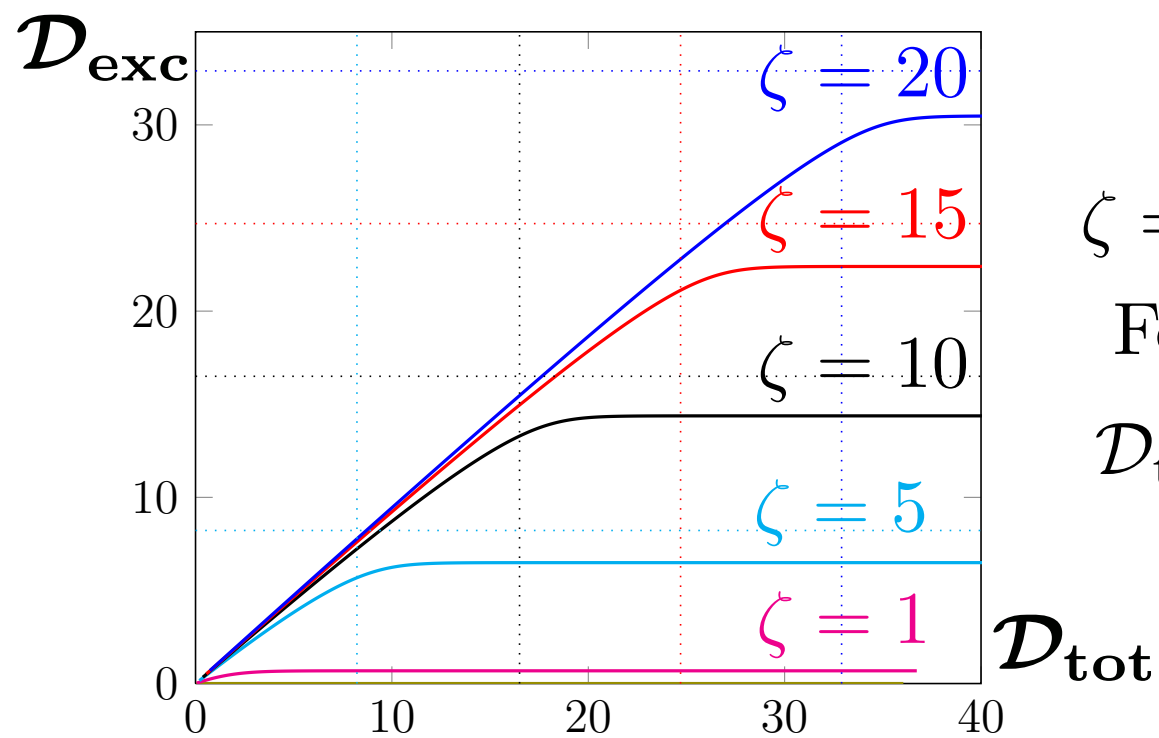
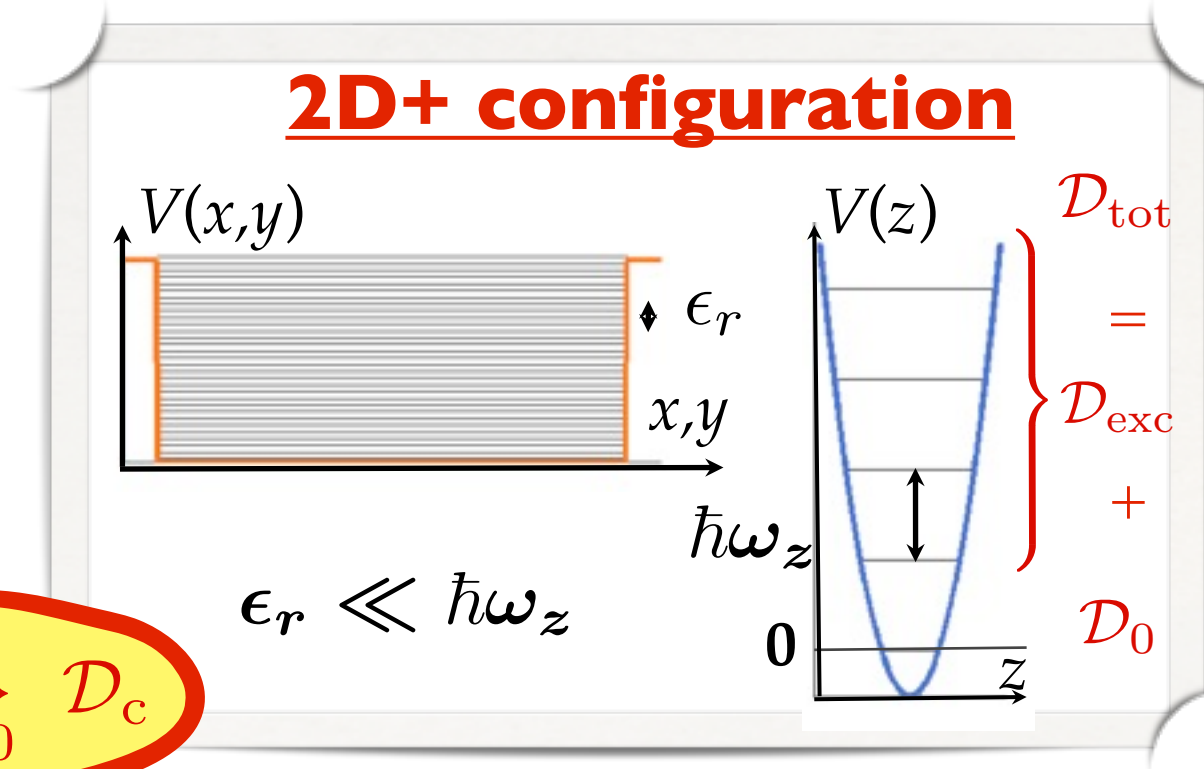
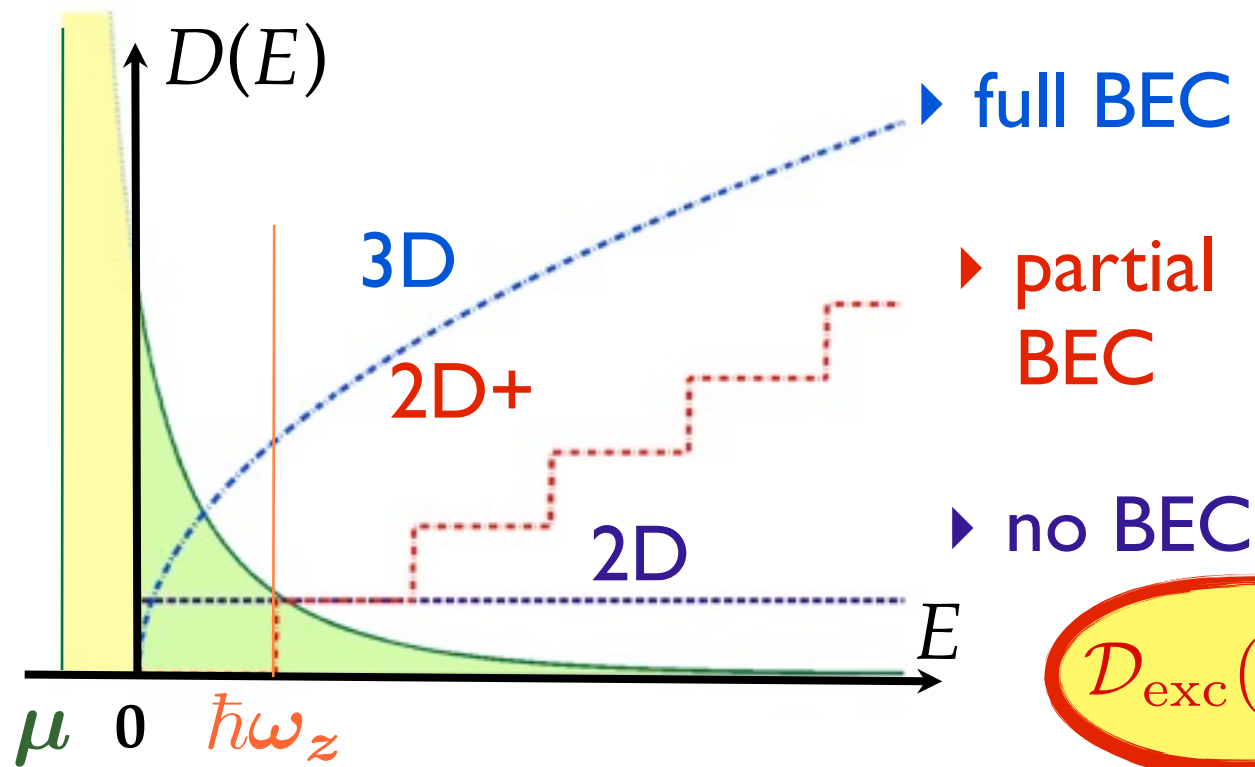
3rd dim.: Transverse condensation.



$$D_{\text{exc}}(\mu) \xrightarrow{\mu \rightarrow 0} D_c$$

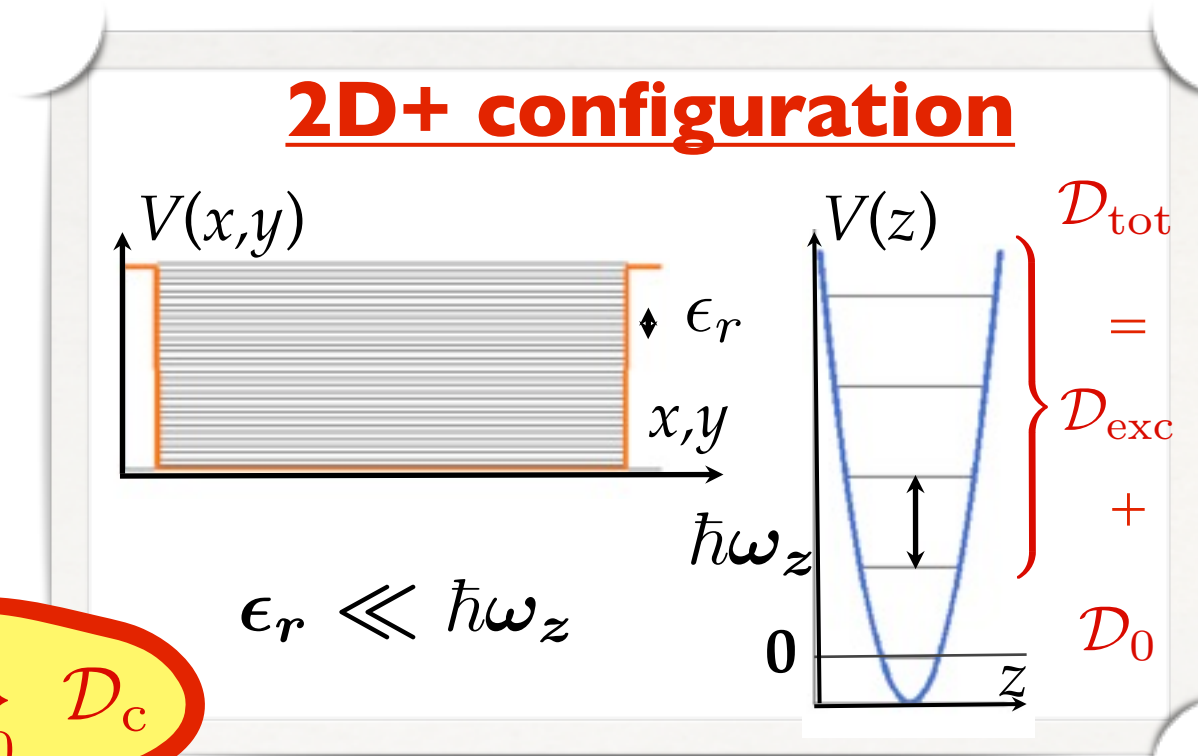
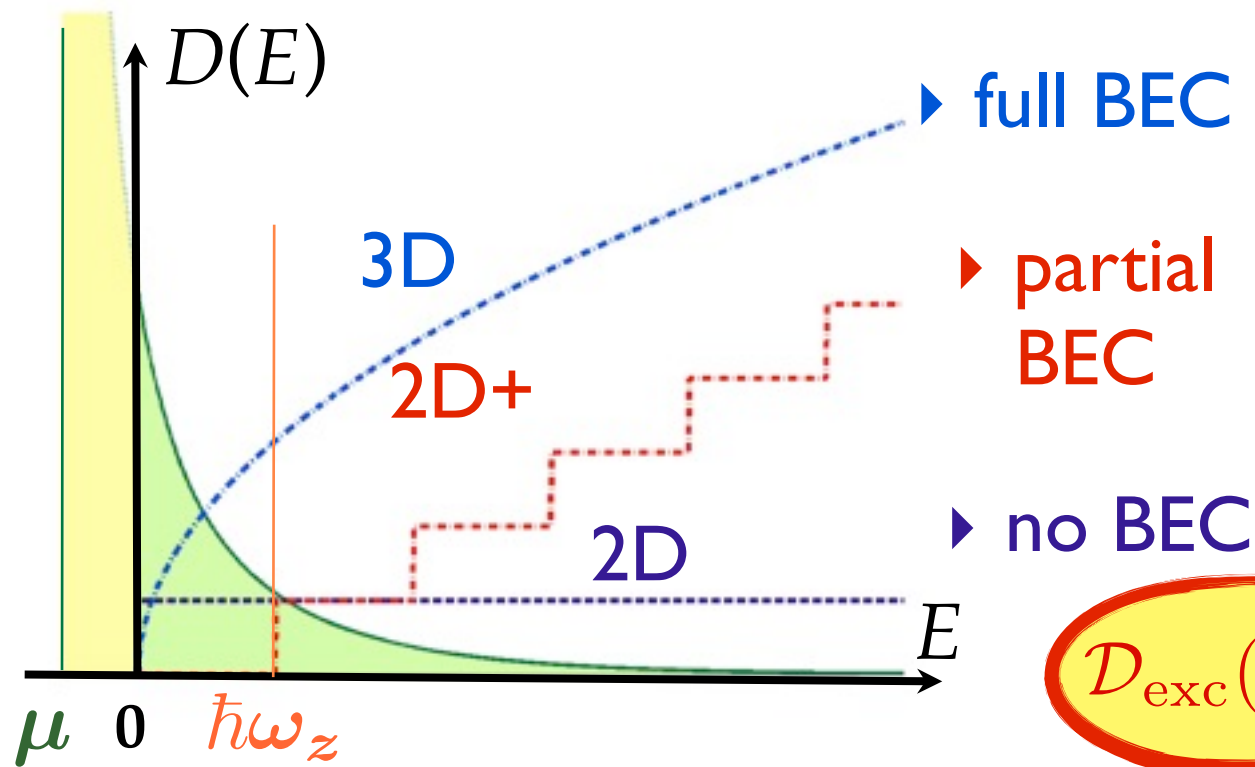


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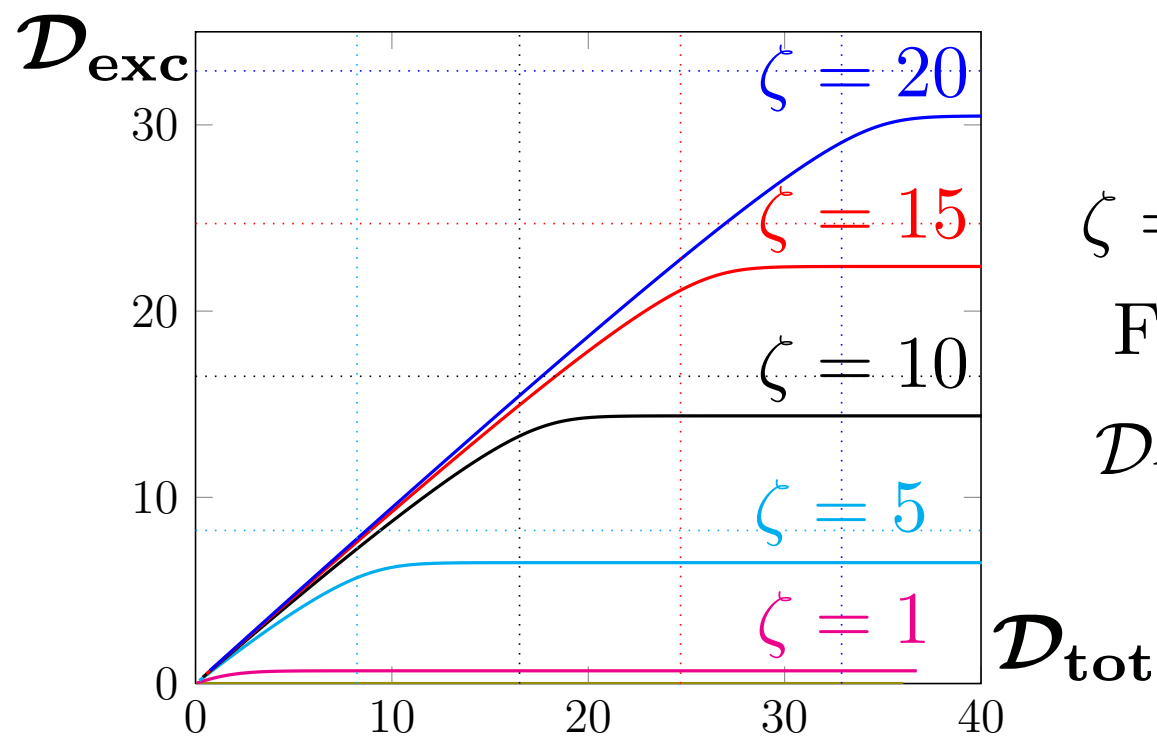
$\zeta = k_B T / \hbar\omega_z$
 For $\zeta \gg 1$:
 $\mathcal{D}_{\text{tot},c} = \frac{\pi^2}{6} \zeta$

3rd dim.: Transverse condensation.



$$D_{\text{exc}}(\mu) \xrightarrow{\mu \rightarrow 0} D_c$$

➔ When D_{tot} large enough, atoms accumulate in $j = 0$: $D_0 \sim D_{\text{tot}}$ even if $k_B T \gg \hbar\omega_z$.



$$\zeta = k_B T / \hbar\omega_z$$

For $\zeta \gg 1$:

$$D_{\text{tot},c} = \frac{\pi^2}{6} \zeta$$

Recover relevance for 2D physics!

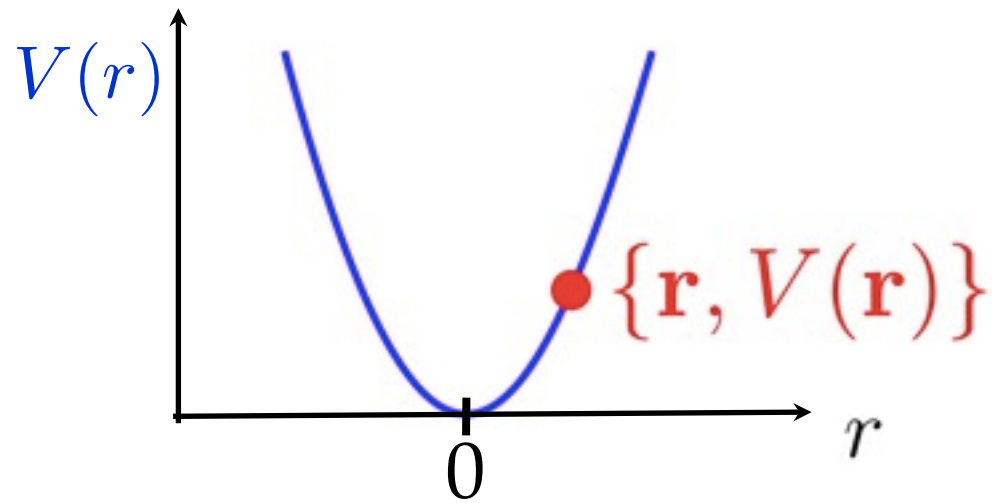
$$D \rightarrow D_0$$

$G_1^{(0)}(r)$ becomes dominant
 => enhanced coherence in plane!

Outline.

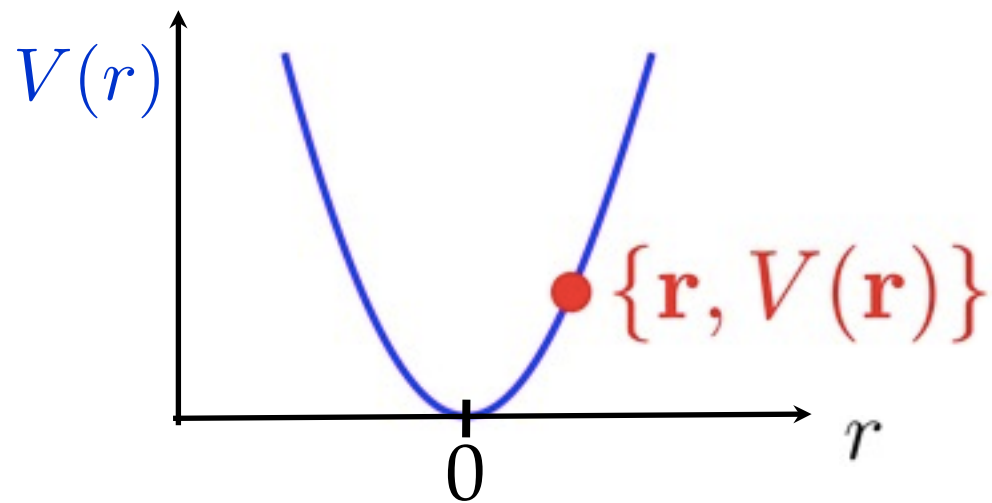
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Harmonic confinement and local probing



Trapping region :
extrema of magnetic field / light intensity.
 \Rightarrow typical dependance $V(r) \sim r^2$

Harmonic confinement and local probing



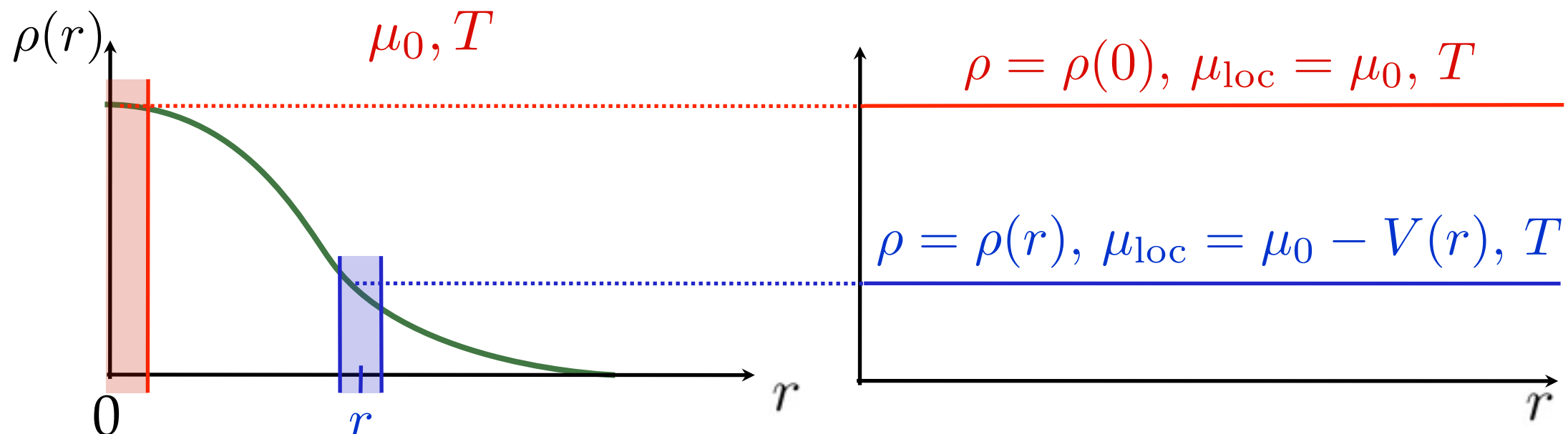
Trapping region :
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 \Rightarrow typical dependance $V(r) \sim r^2$

✿ Useful for exploring local properties : smooth variation \Rightarrow locally uniform.

Local Density Approximation

Trapped density profile

Homogeneous equivalent



Example of the Equation of State.

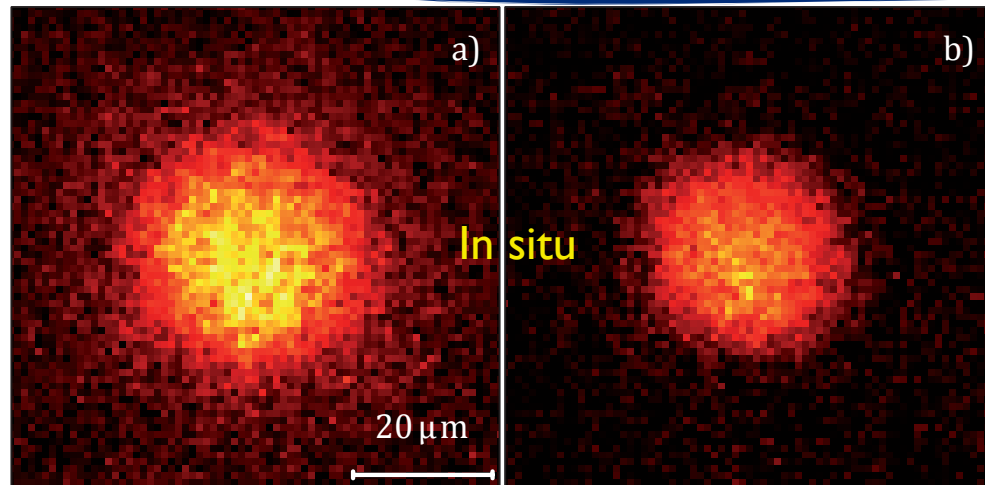
EoS = relation between dimensionless parameters.

=> dictates all thermodynamics properties. can deduce EoS for any variables.
In weakly interacting 2D gases: only **2** variables (approx. scale invariance).

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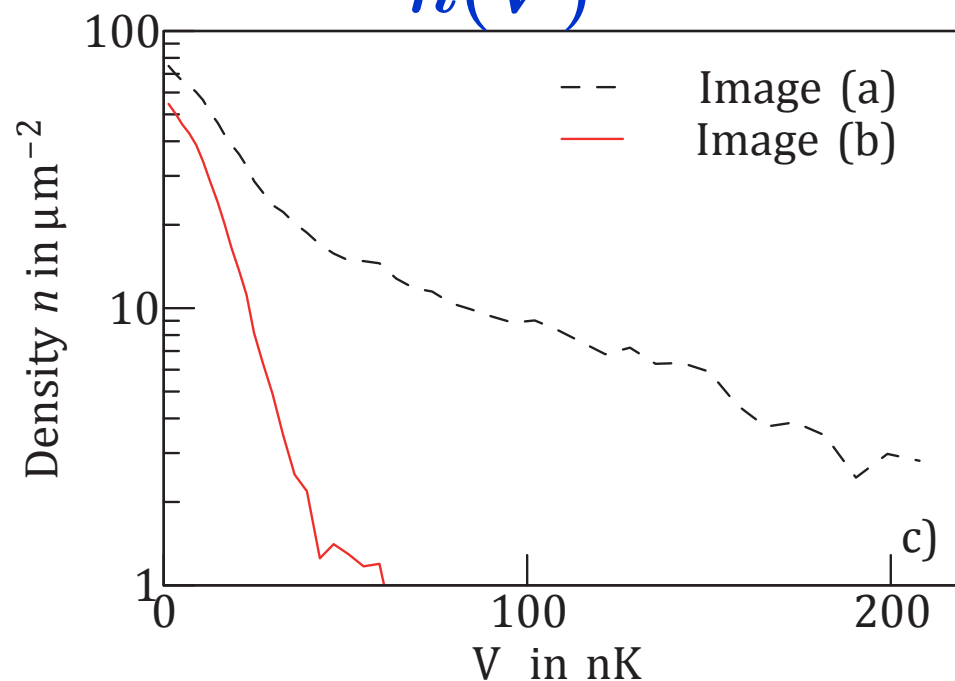
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$n(x, y)$



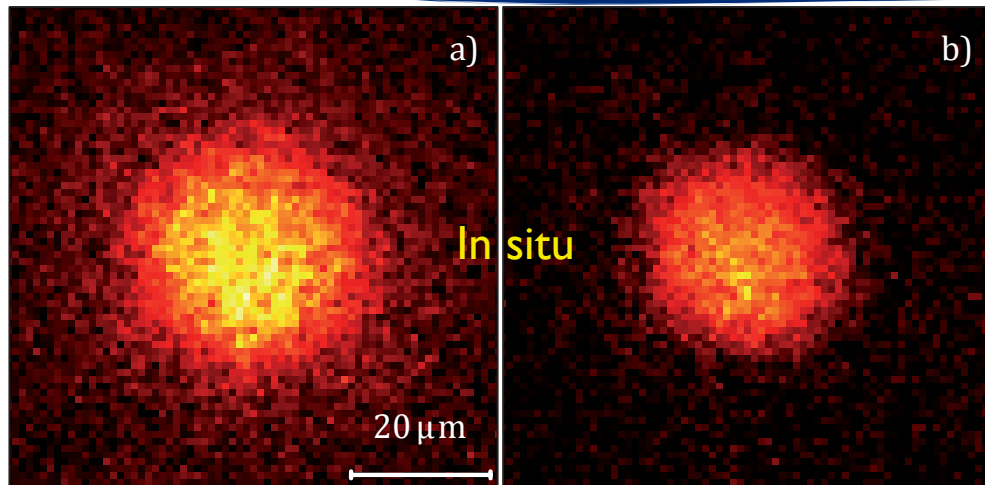
$n(V)$



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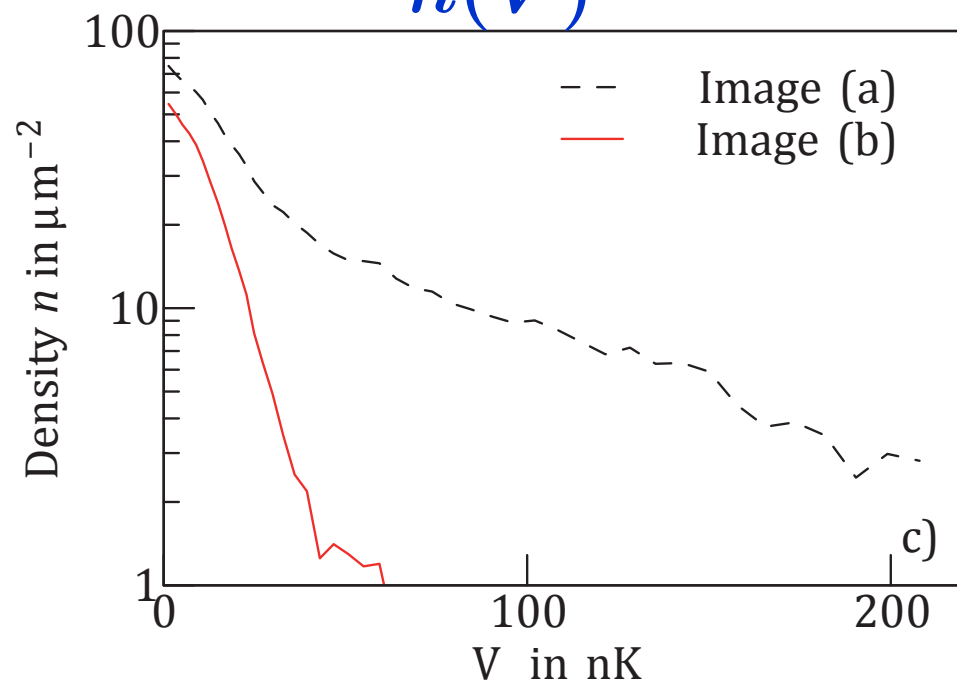
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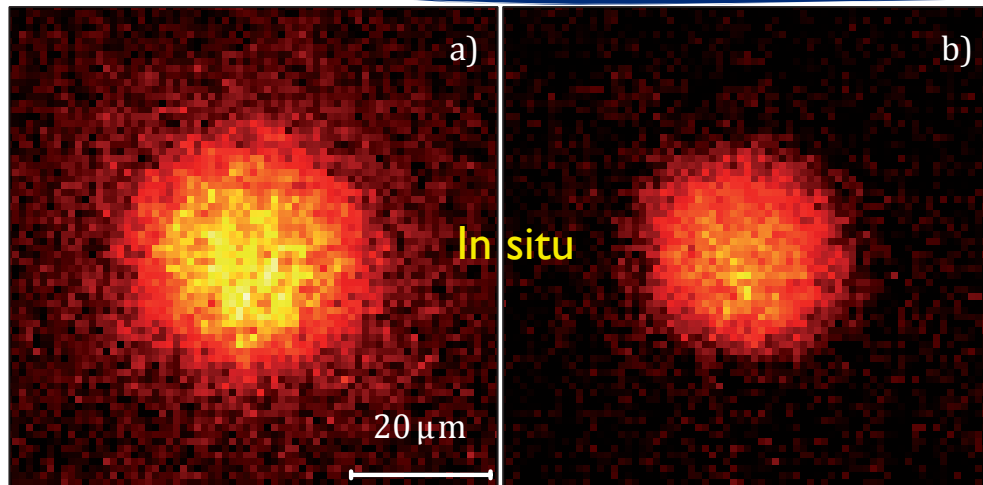


=> fit-free method for measuring the EoS by derivations/integrations of $E(V) = \frac{\hbar^2 n(V)}{m}$:

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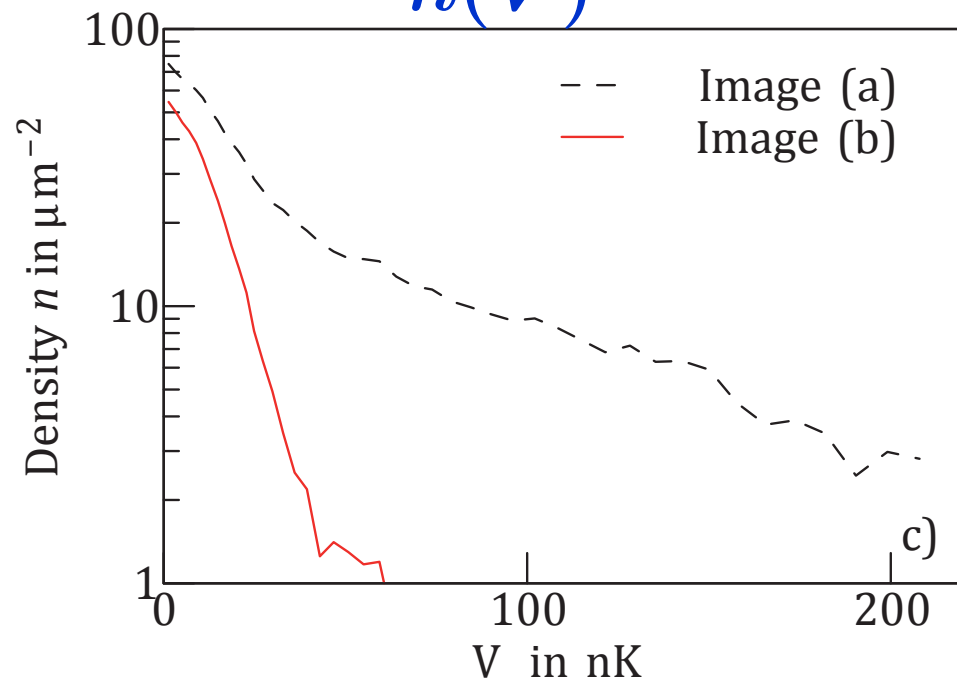
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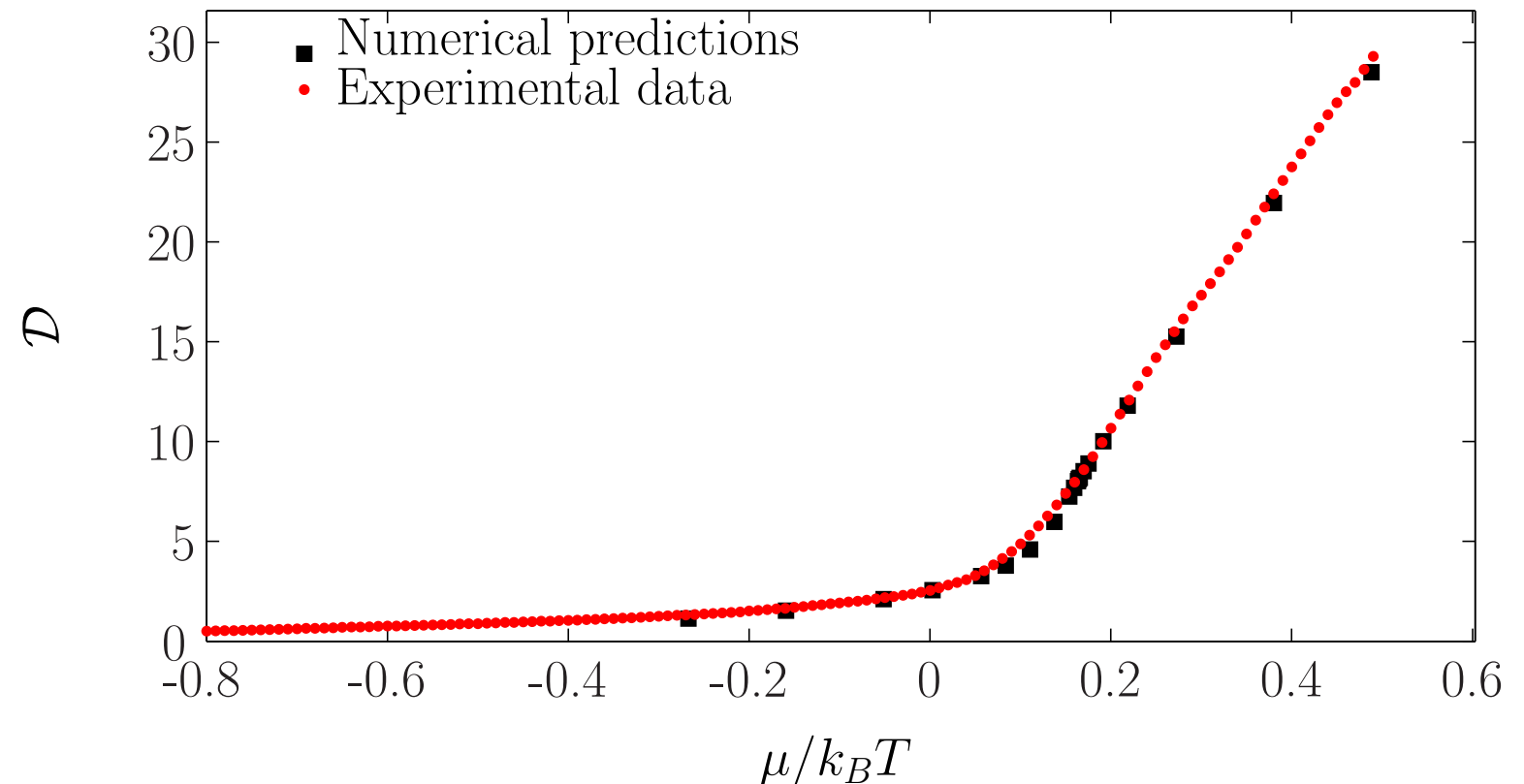
$n(V)$



=> fit-free method for measuring the EoS by derivations/integrations of $E(V) = \frac{\hbar^2 n(V)}{m}$:

check scale invariance

$\rightarrow (\mu/k_B T, \mathcal{D})$



Example of the superfluid behavior.

Superfluidity \Leftrightarrow frictionless response to a moving obstacle.

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Local probing :

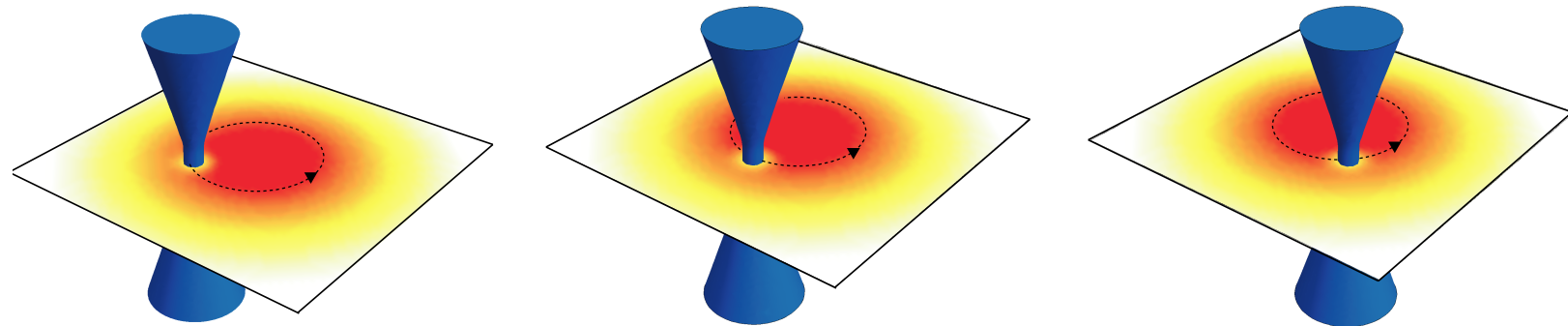
rotation of a tightly focused
laser beam

($w = 2 \mu\text{m} / R_{\text{TF}} = 20 \mu\text{m}$)

on "equi-potential" $r = c^{\text{st}}$

($\mu_{\text{loc}} = \mu_0 - V(r)$)

at velocity $v = c^{\text{st}}$.



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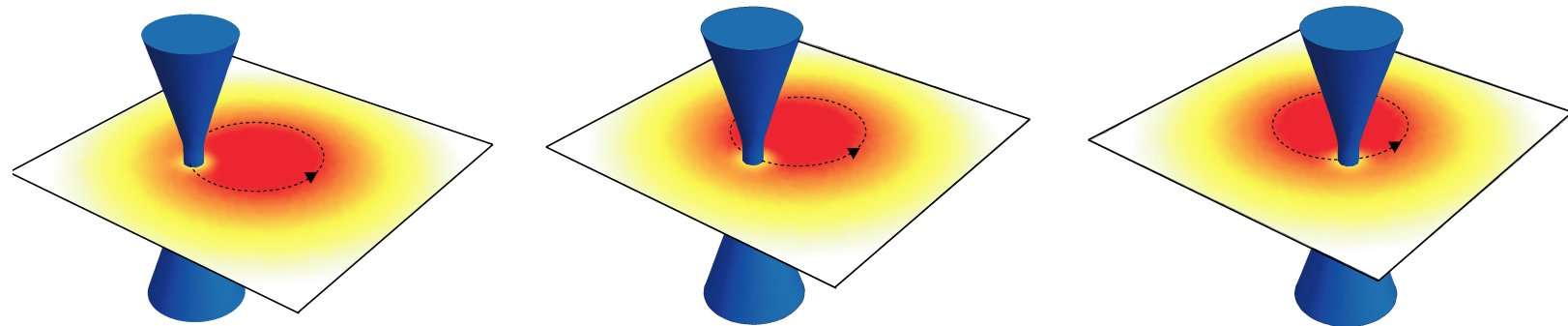
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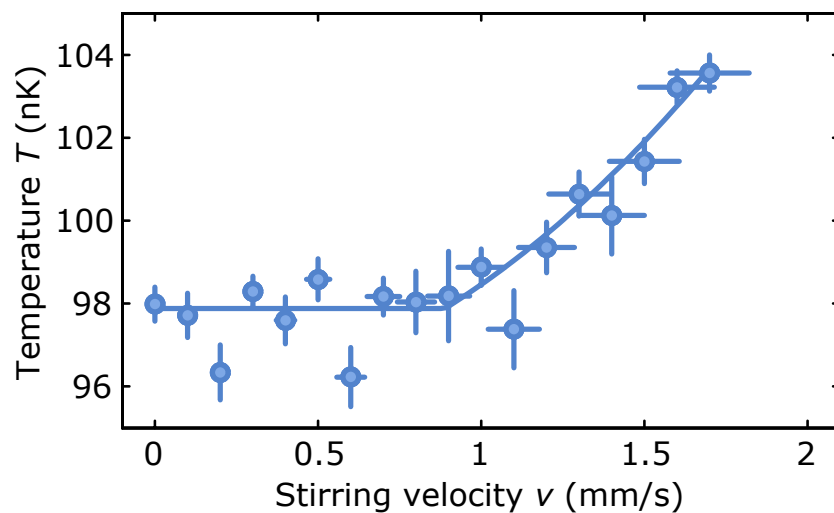
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Measure heating



$$T(v) = T_{v=0} + \kappa \tau \max [v^2 - v_c^2, 0]$$

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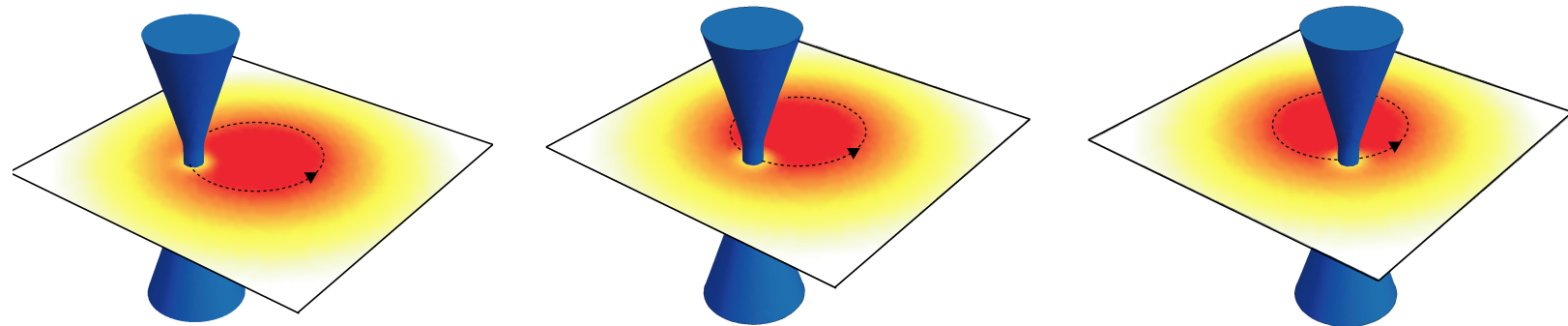
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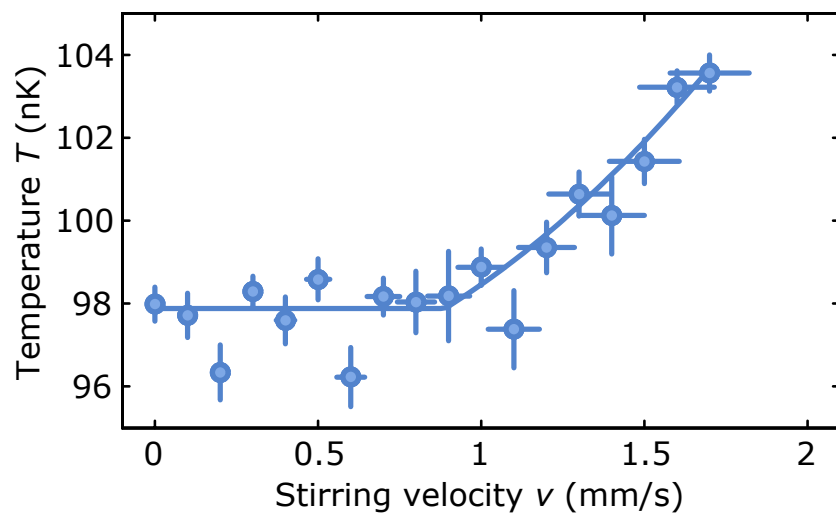
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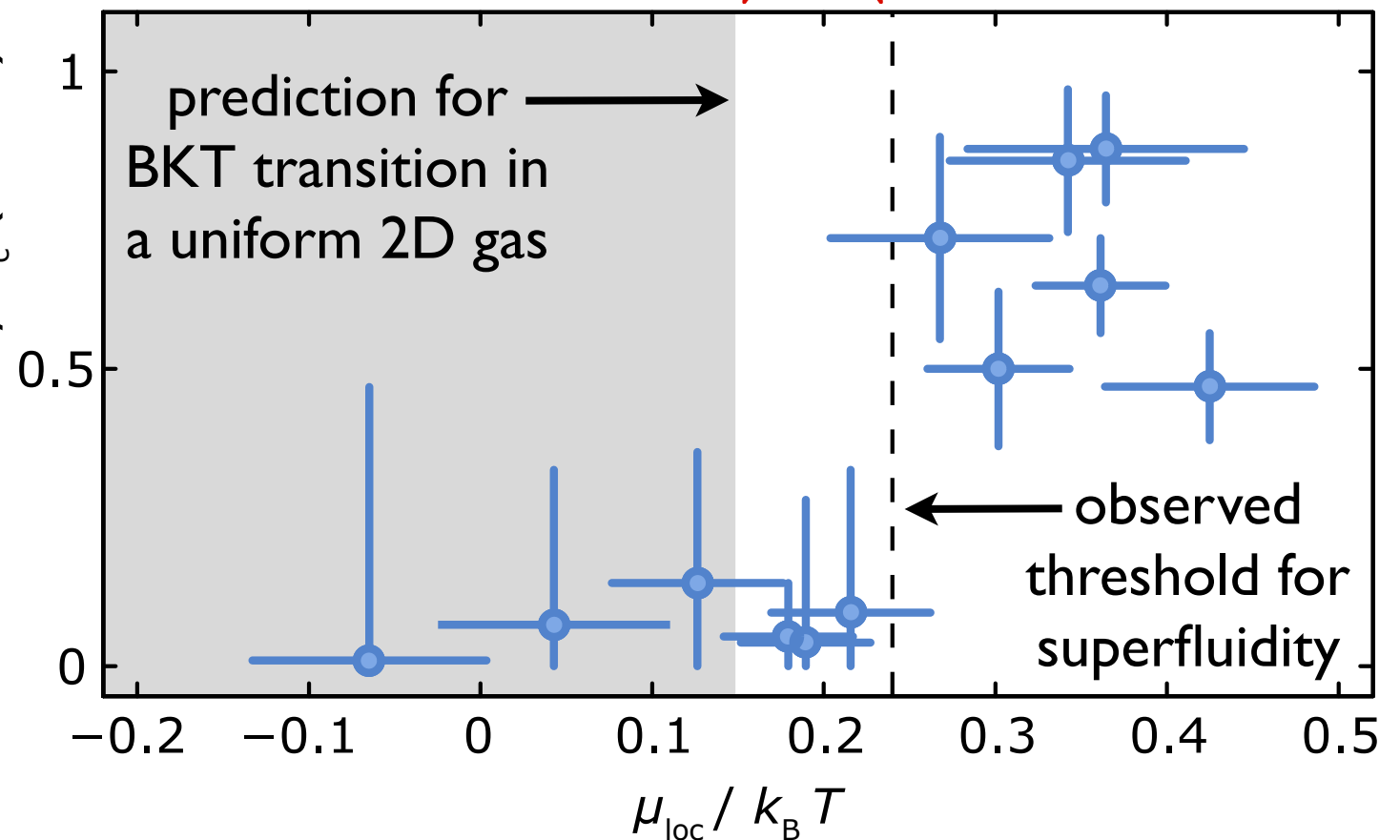
discrepancy (partly) due to $w \neq 0$

Measure heating



$$T(v) = T_{v=0} + \kappa \tau \max [v^2 - v_c^2, 0]$$

Critical velocity v_c (mm/s)



Limitations of harmonic confinement.

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❖ **Limiting for non-local measurements:**

- ▶ long-range properties
- ▶ coherence and correlation functions

❖ **In particular at vicinity of a transition point:**

- ▶ transitions become local phenomena
- ▶ divergences are smoothen

❖ **Entangles effects of interactions / Bose stat / dimensionality:**

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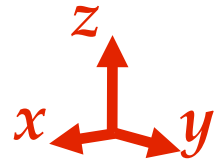
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➡ Toward uniform traps...

Outline.

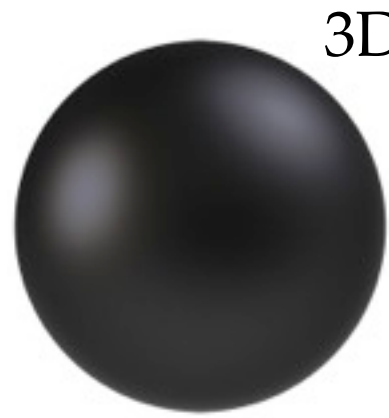
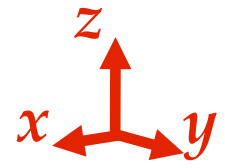
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Creating uniform 2D gases in experiments.



3D cold gas
of ^{87}Rb

Creating uniform 2D gases in experiments.



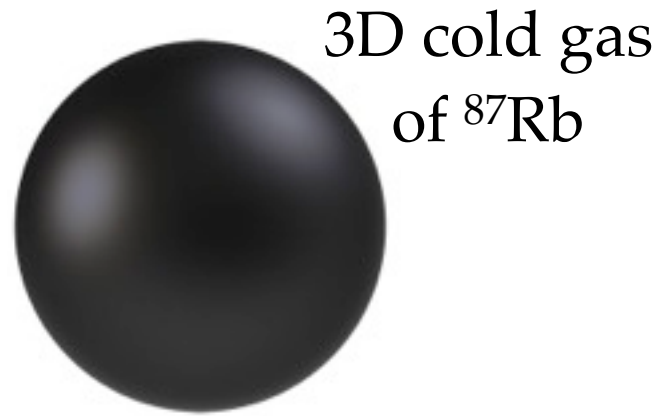
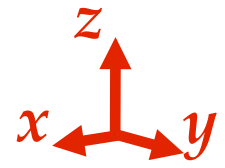
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Hermite-Gauss
beam = 2D conf.



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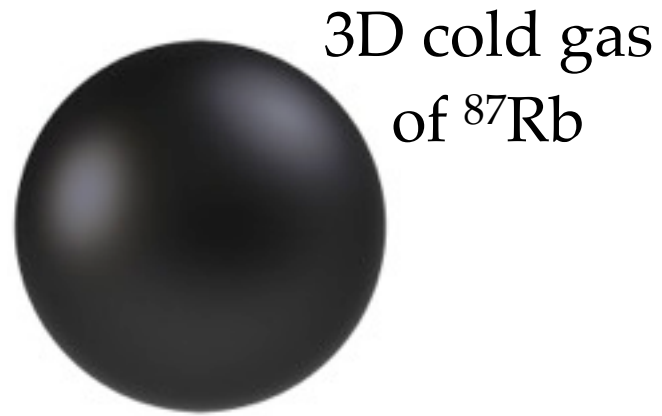
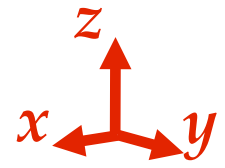
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Hollow beam
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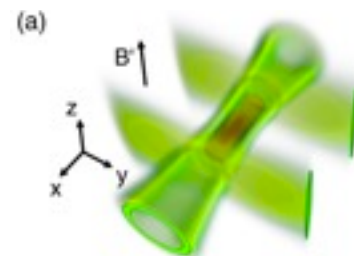
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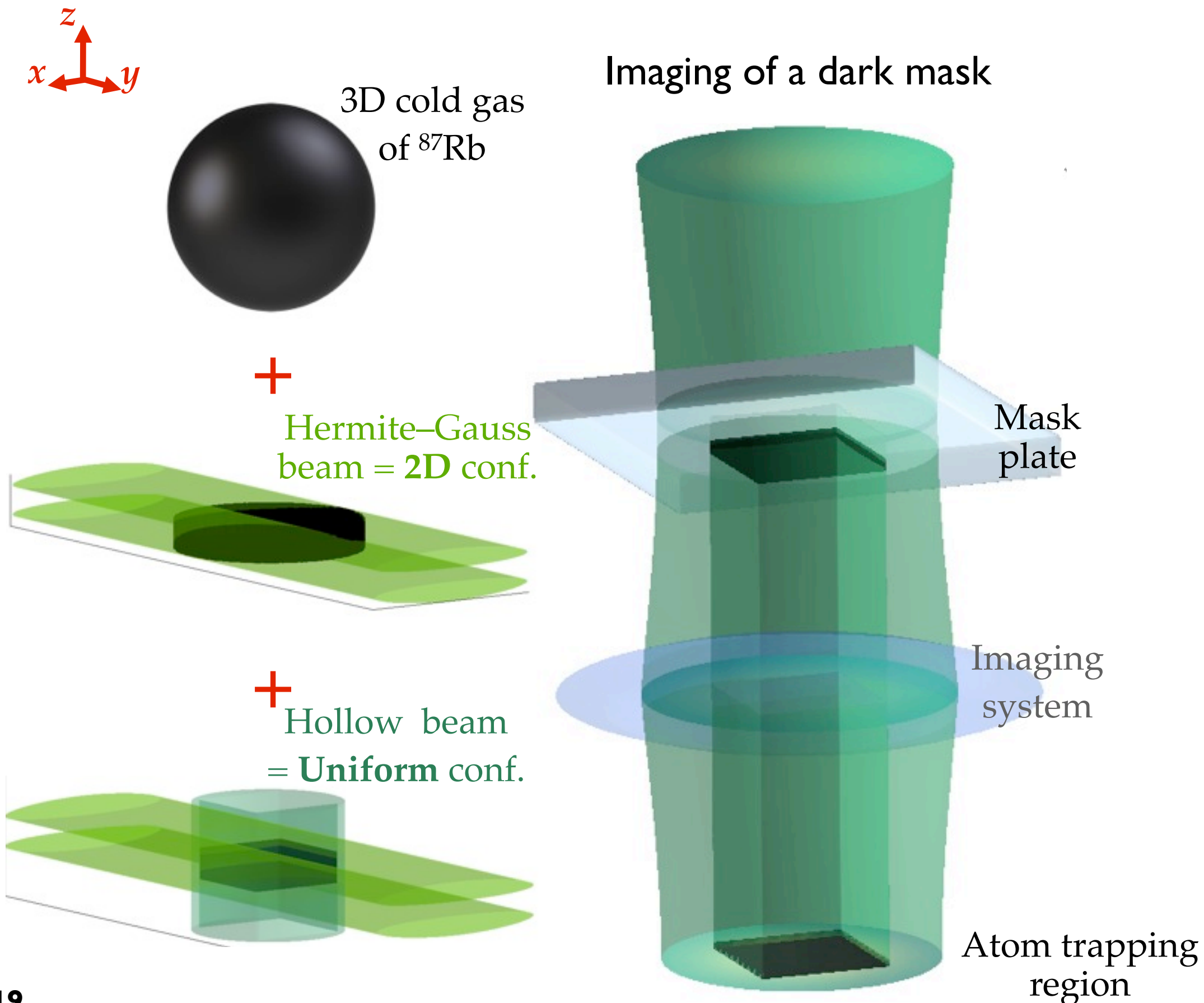
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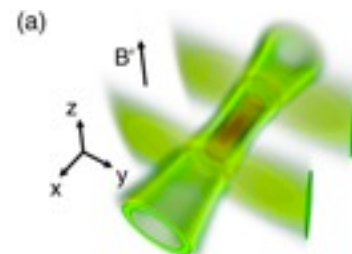
3D: Hadzibabic
group, 2013



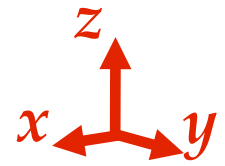
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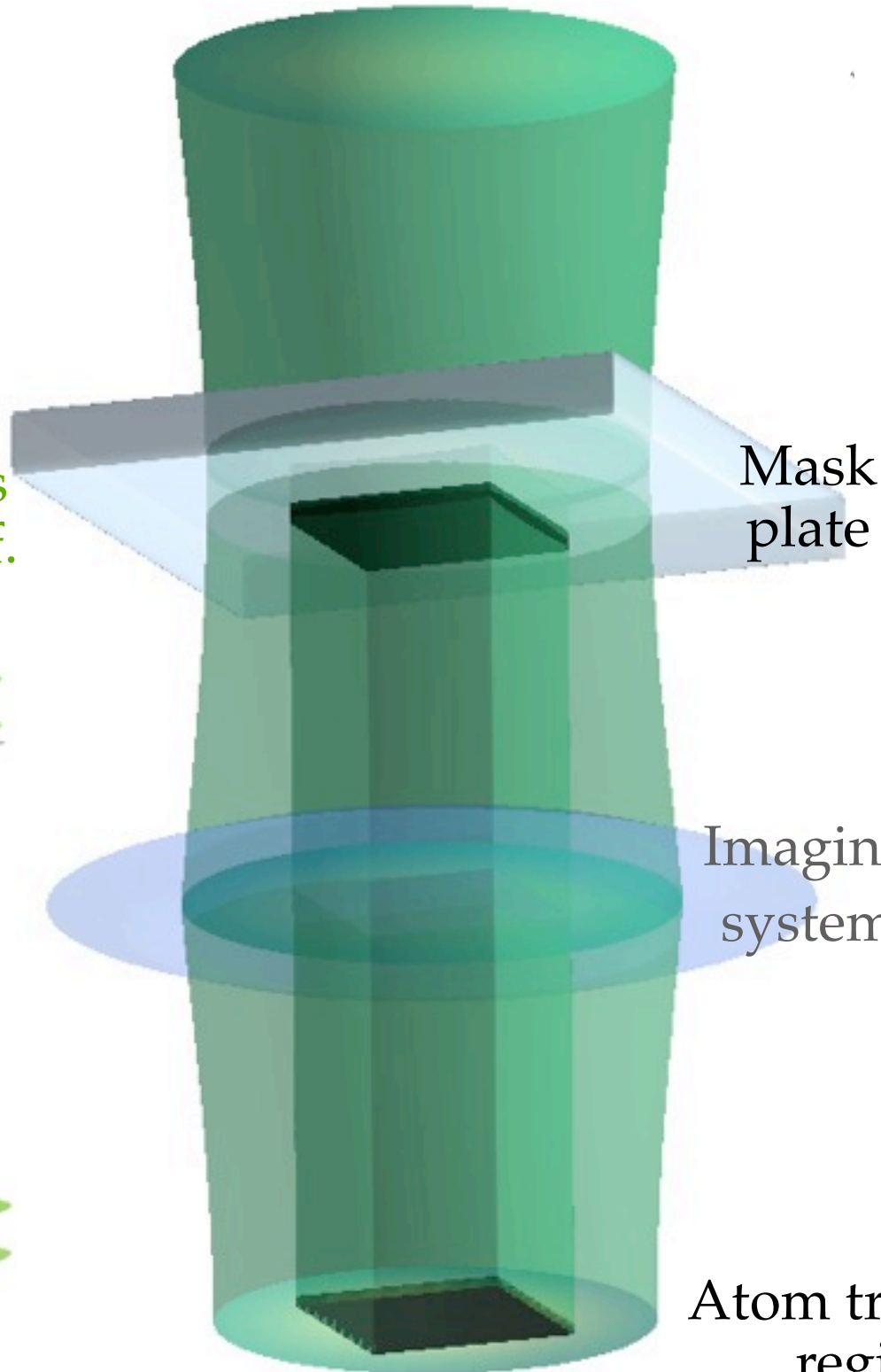


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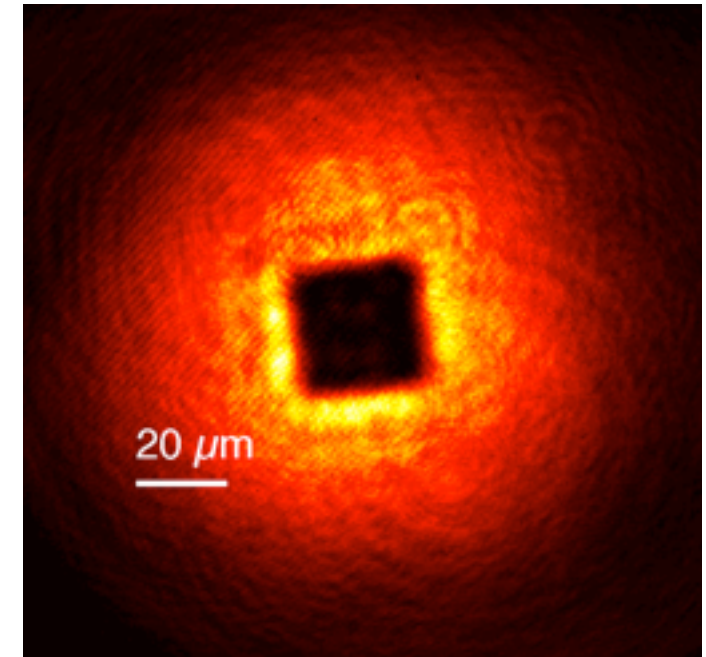
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Imaging of a dark mask

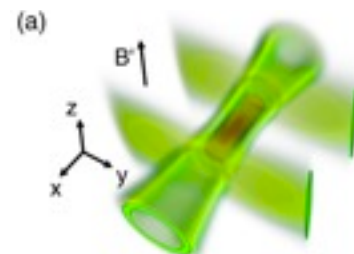


Uniformity characteristics

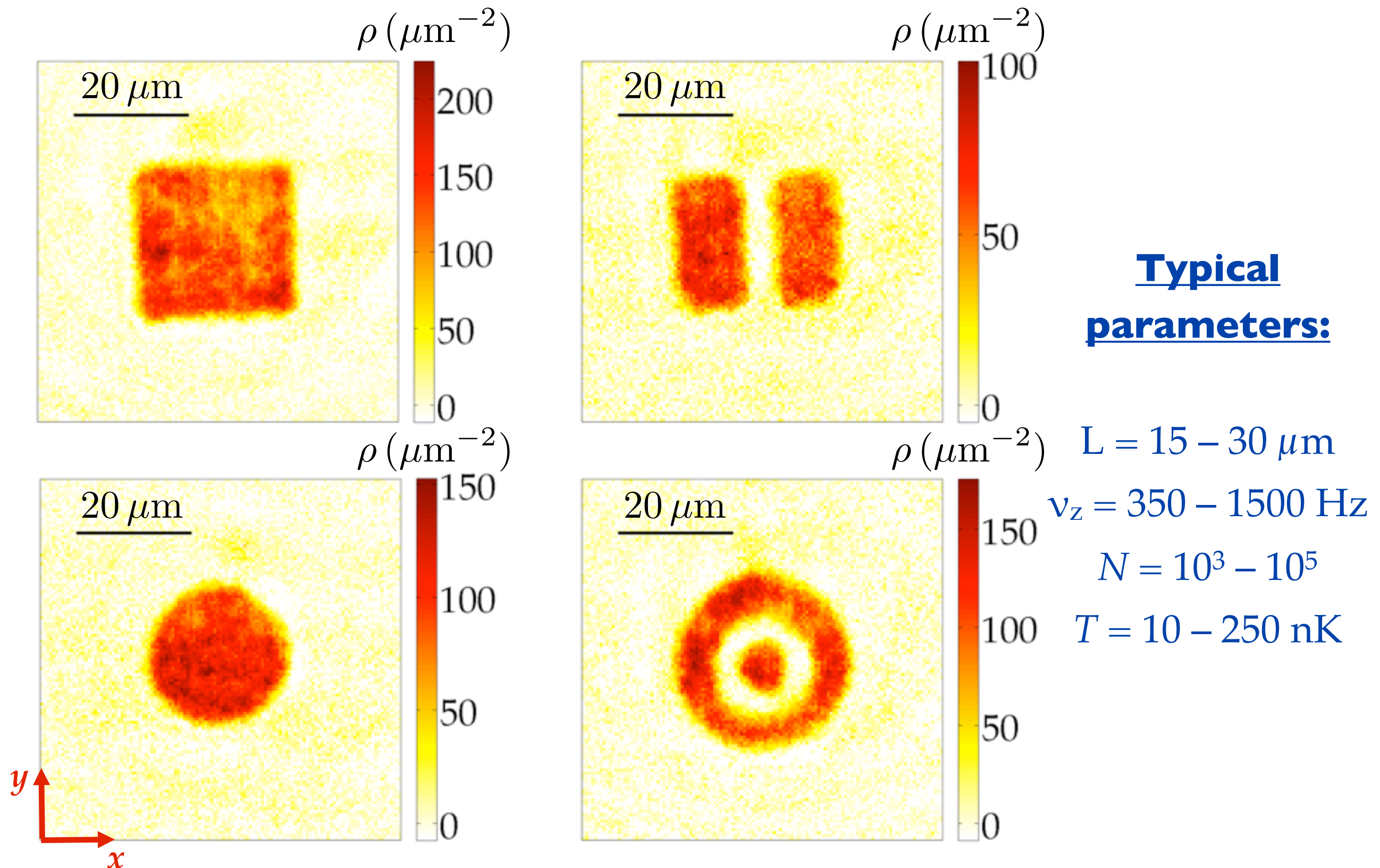


rugosity of trap bottom
 $\approx 3\%$ of barrier height

3D: Hadzibabic
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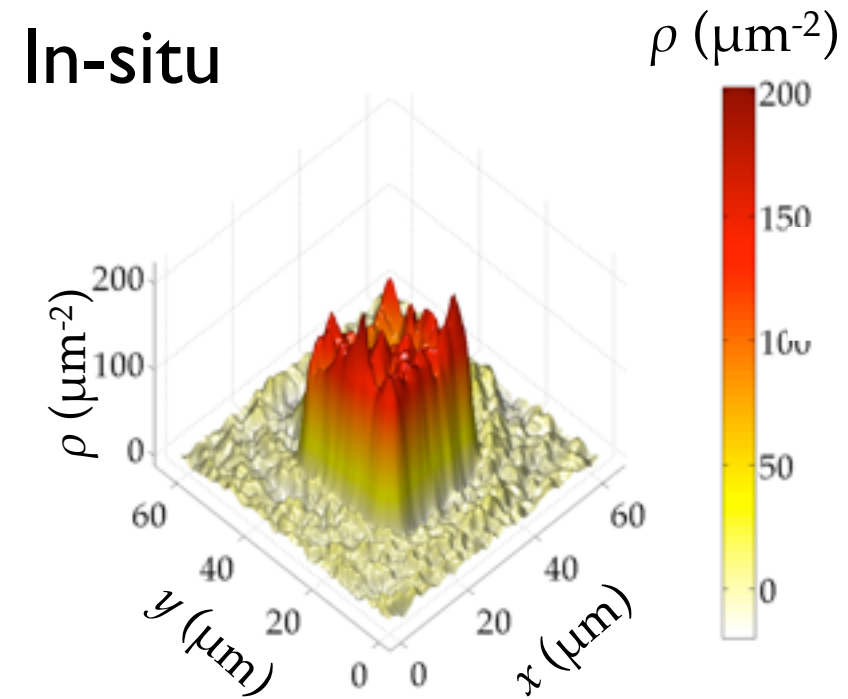
Quasi-2D gases in boxes.



Outline.

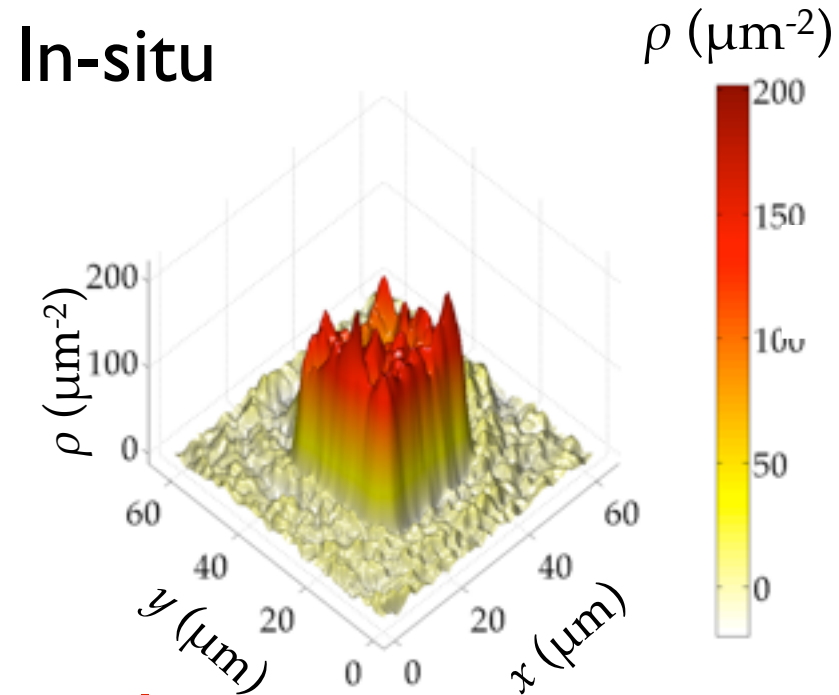
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Coherence in time-of-flight.



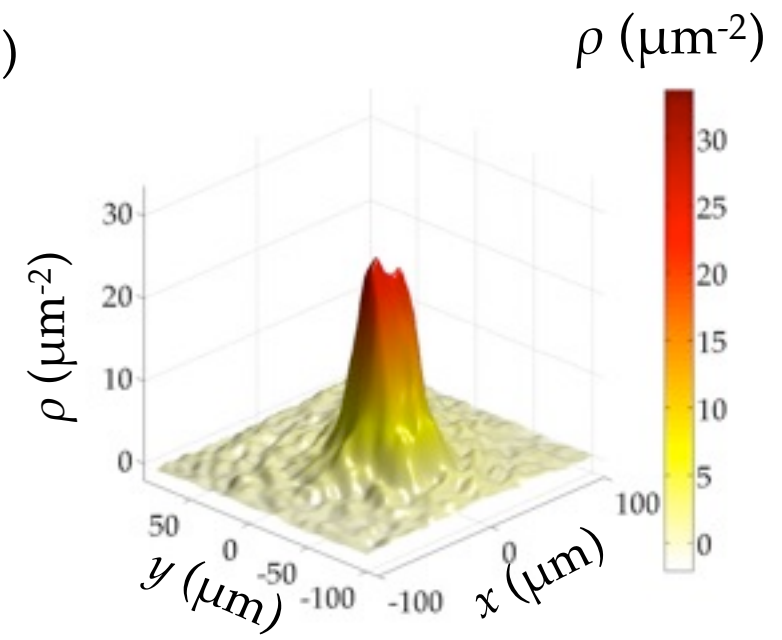
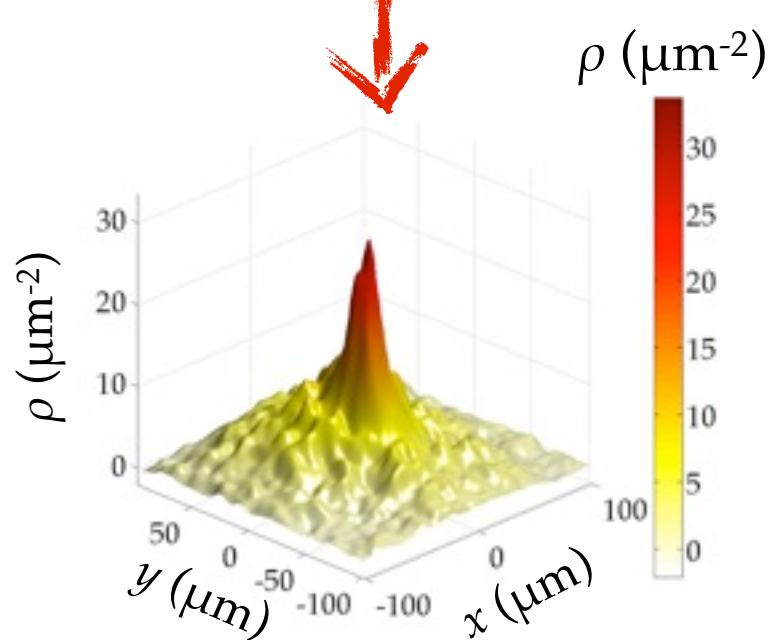
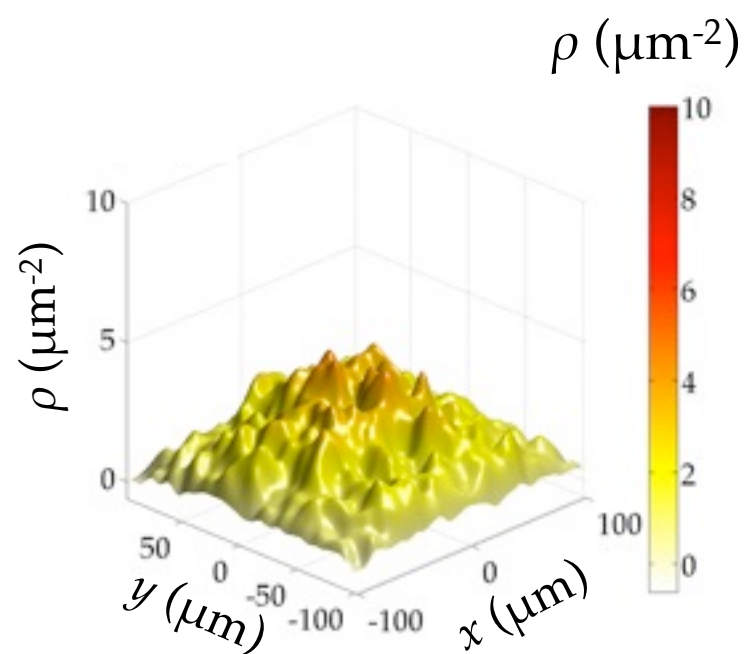
Coherence in time-of-flight.

3D ToF



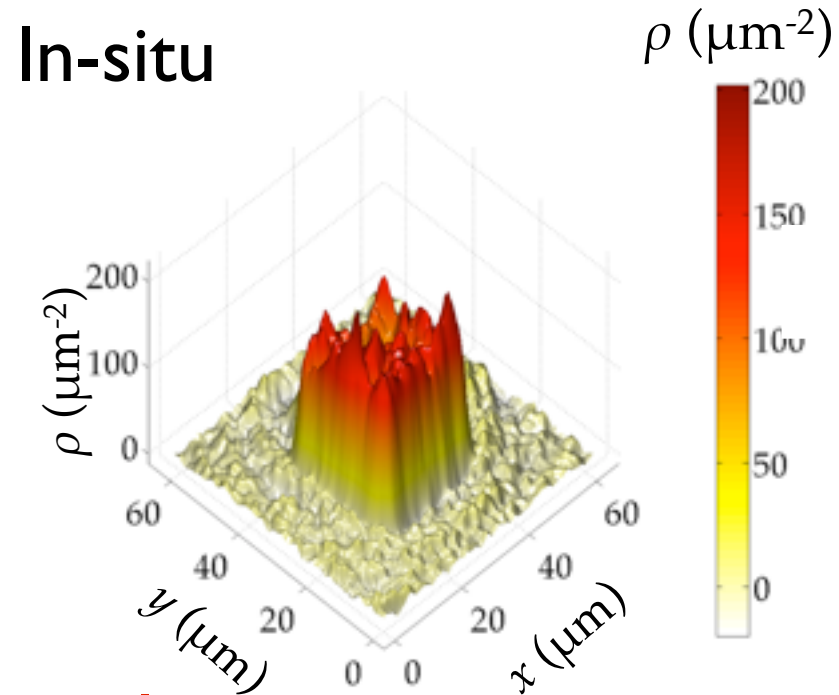
Release all trapping potential
and let expand for long τ :
access velocity distribution.

**velocity distribution =
Fourier transform of G_1**



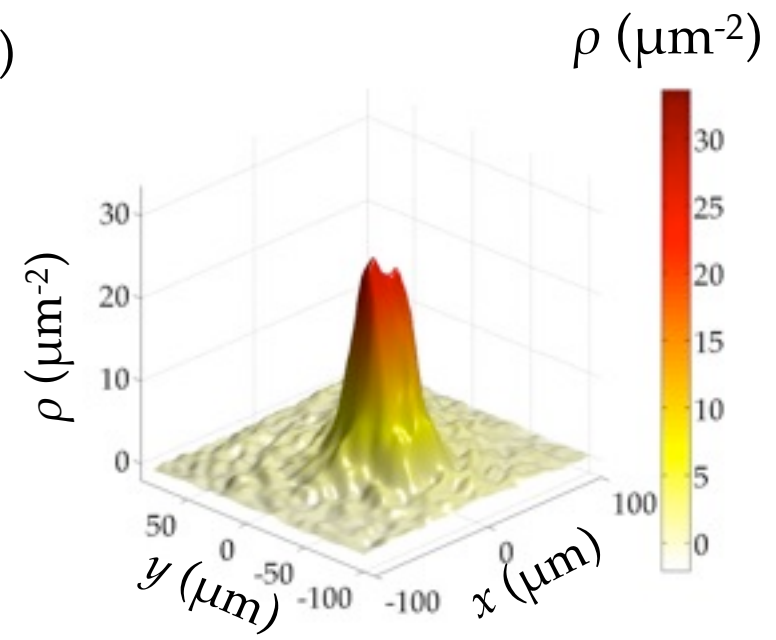
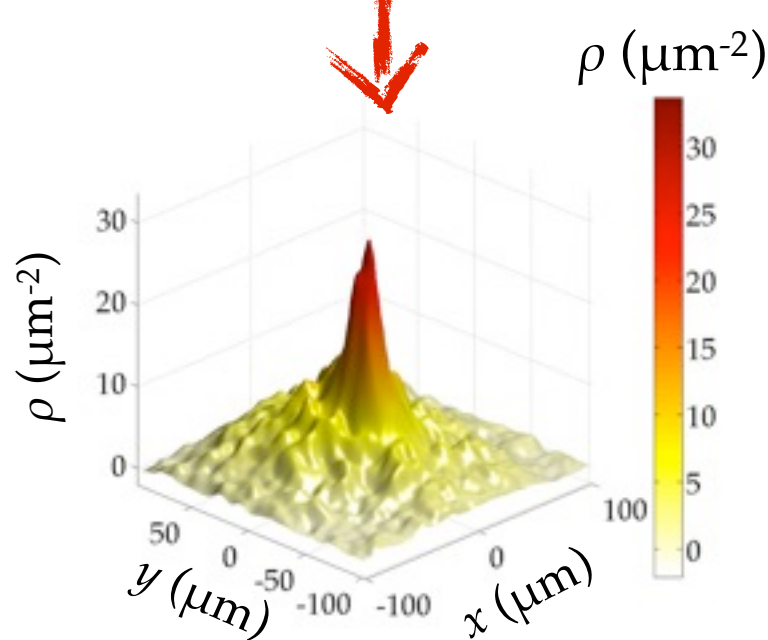
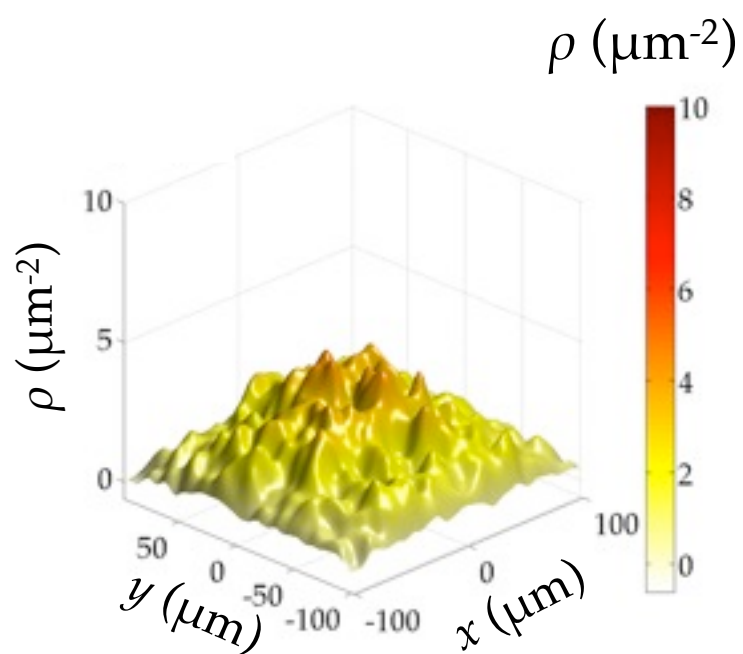
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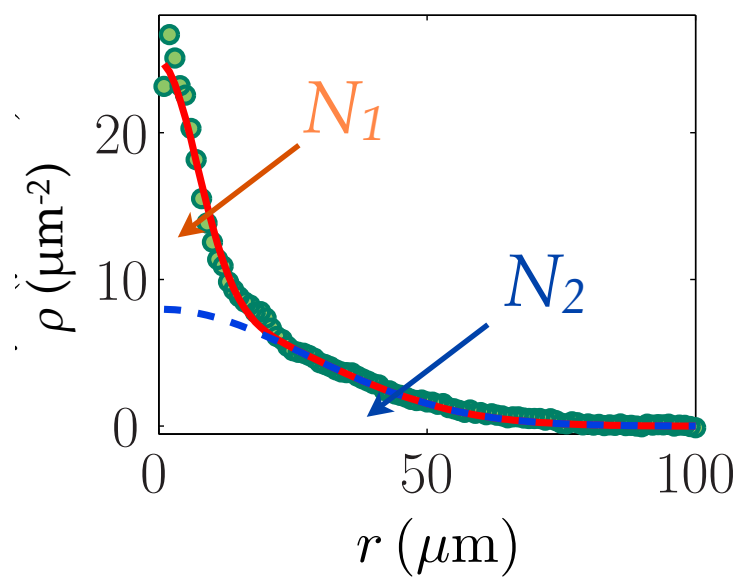
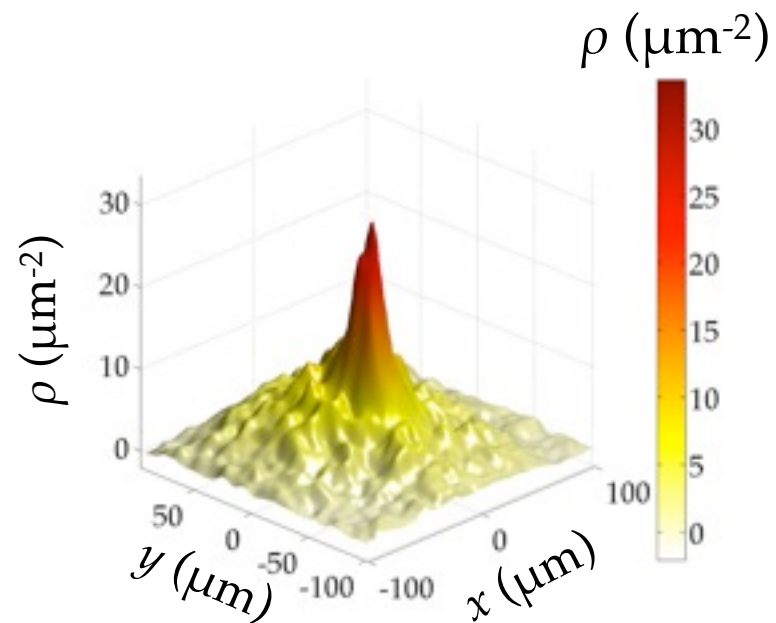


low \mathcal{D}

3 different atomic configurations (N, T)

high \mathcal{D}

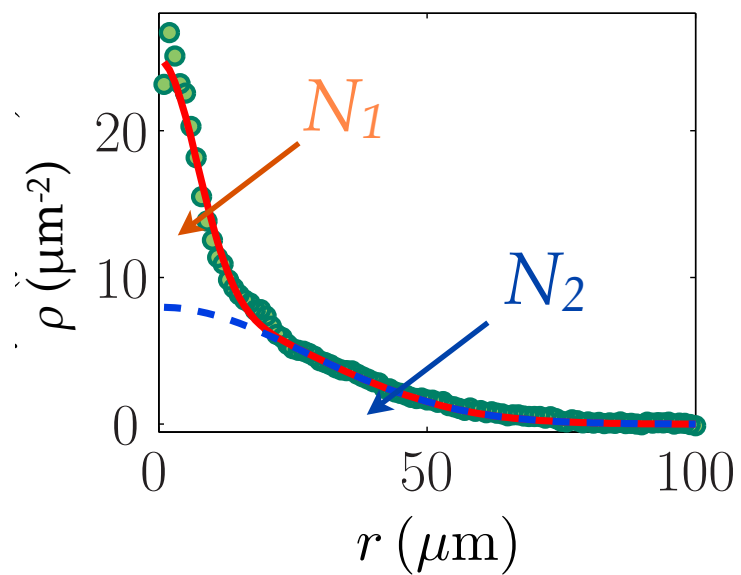
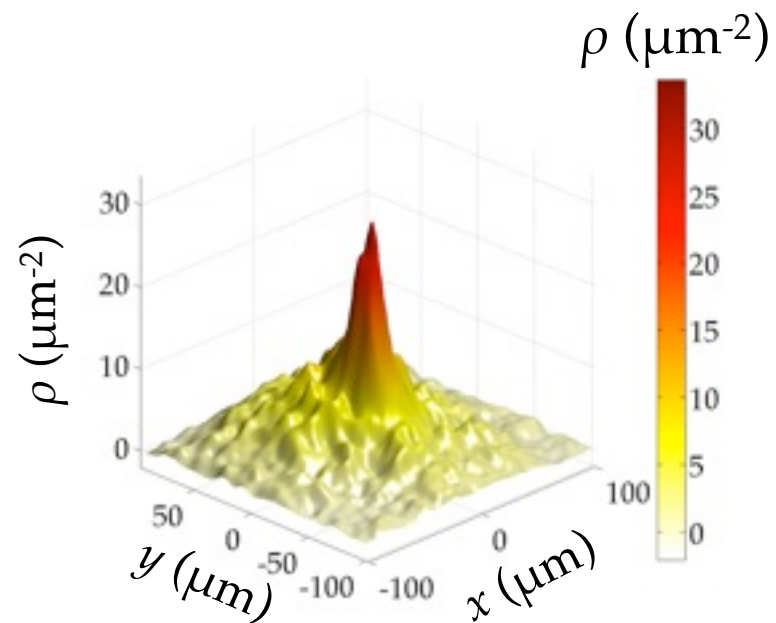
Bimodality of ToF density distribution.



fit by a sum of 2 Gaussians

$$N = N_1 + N_2$$

Bimodality of ToF density distribution.

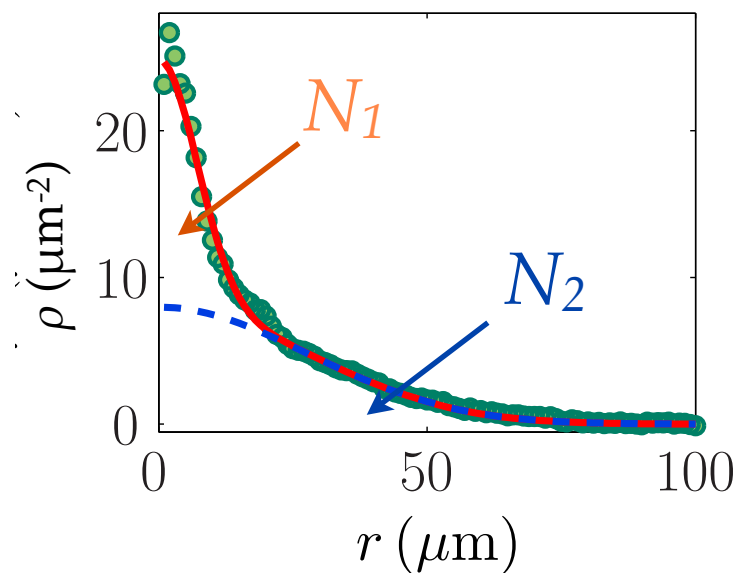
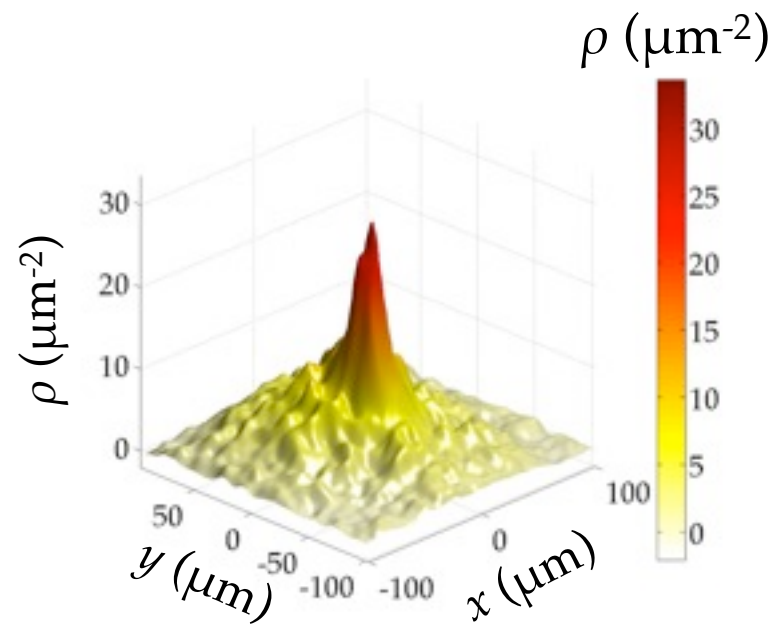


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bimodality parameter : $\Delta = N_1/N$

Bimodality of ToF density distribution.



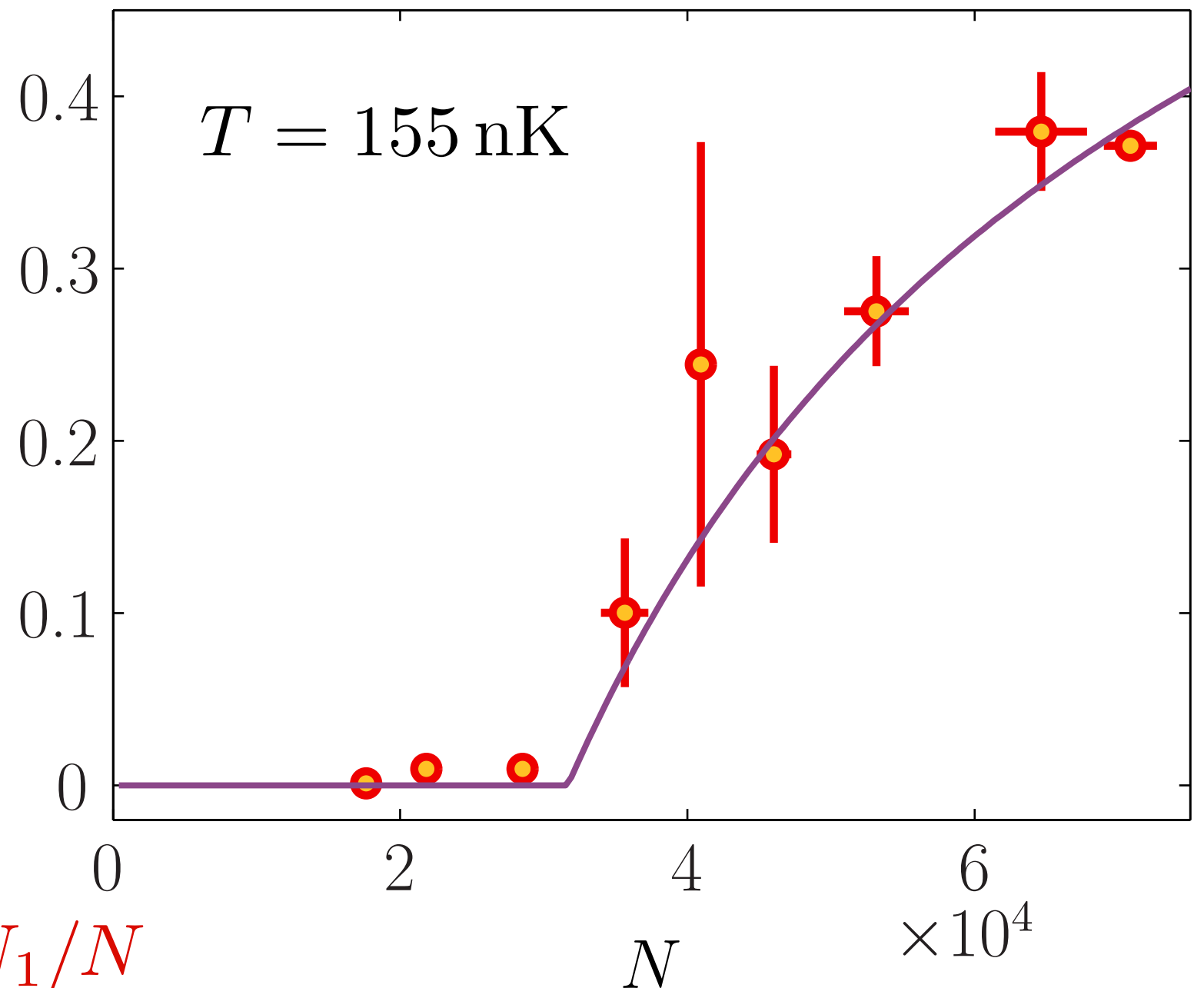
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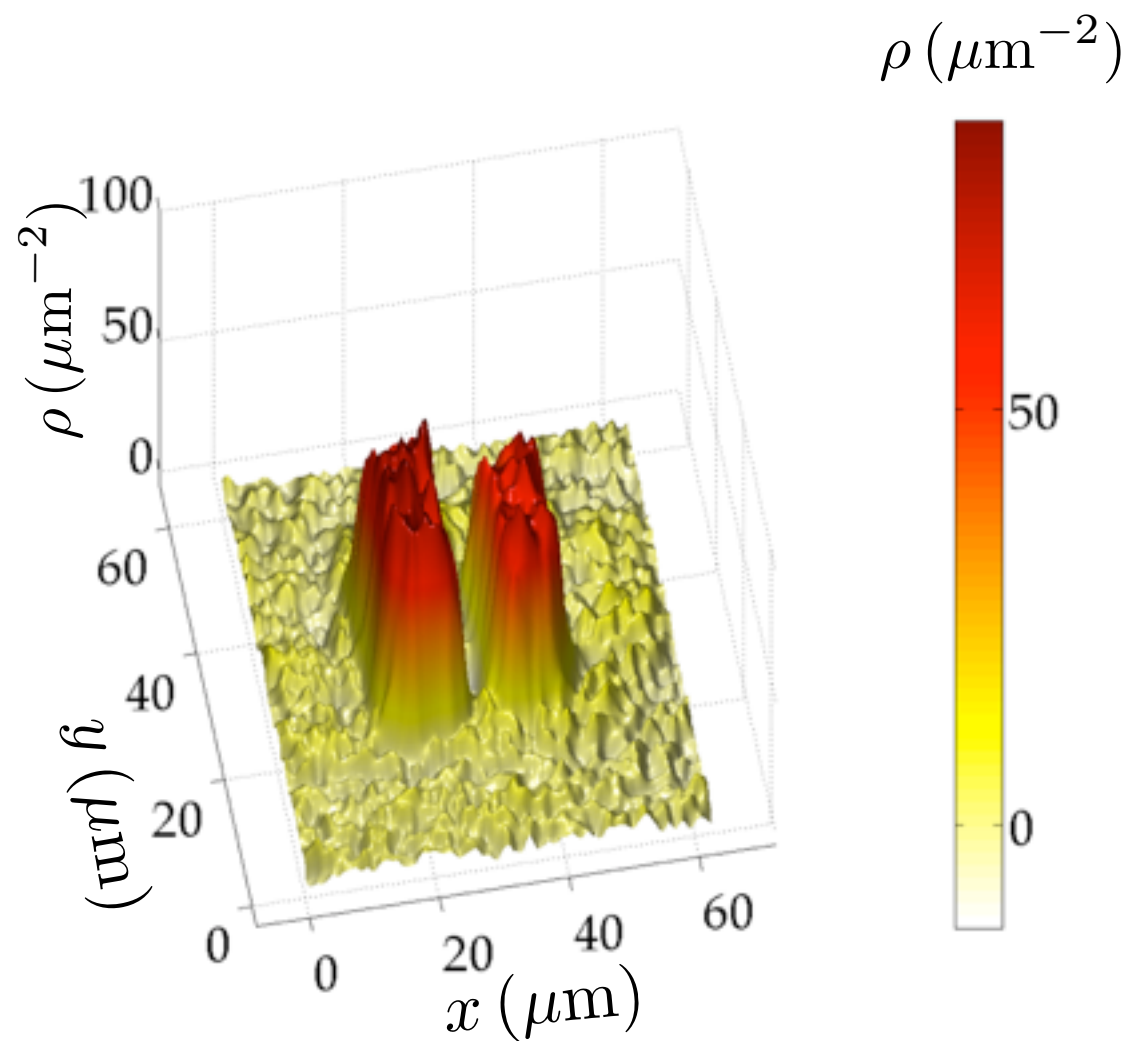
bimodality parameter : $\Delta = N_1/N$

For each T , fit $\Delta(N)$ by «heuristic»
threshold function:

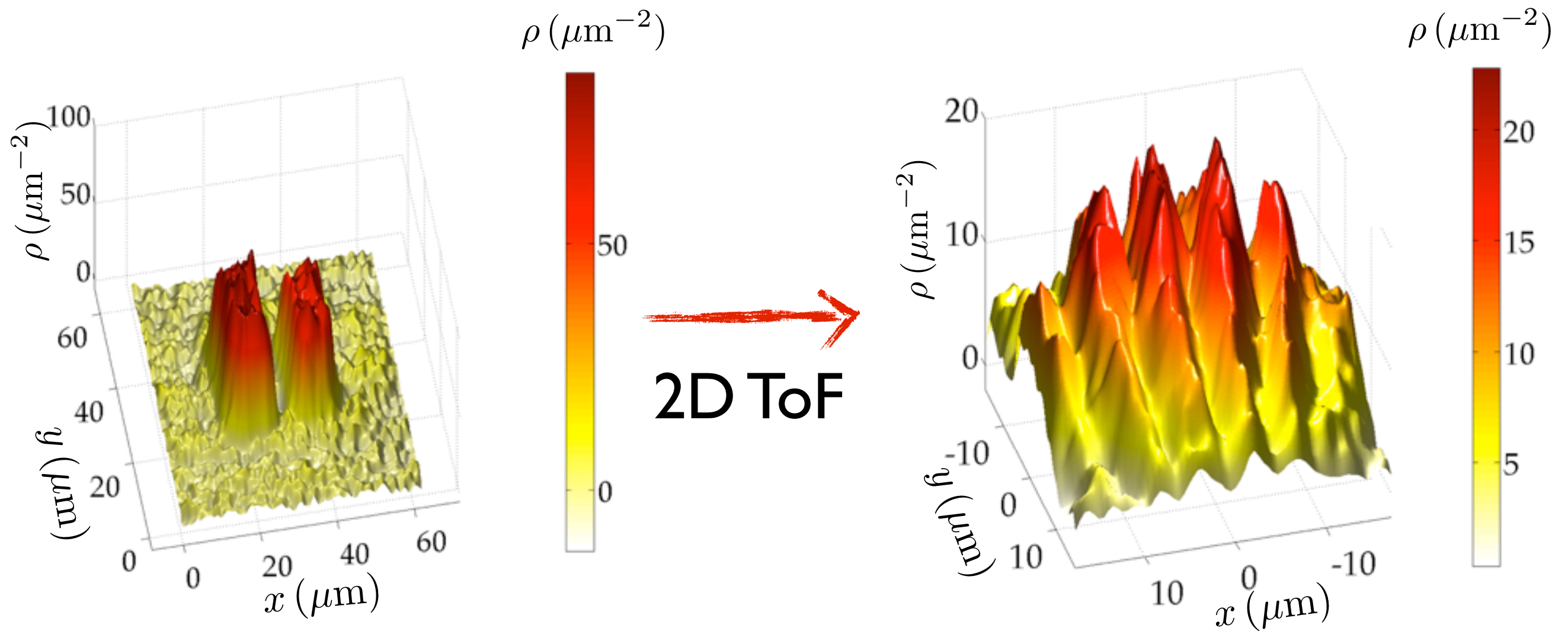
$$\Delta = \left(1 - (N_c/N)^{0.6}\right) \Theta(N > N_c)$$



Coherence via matter-wave interference.



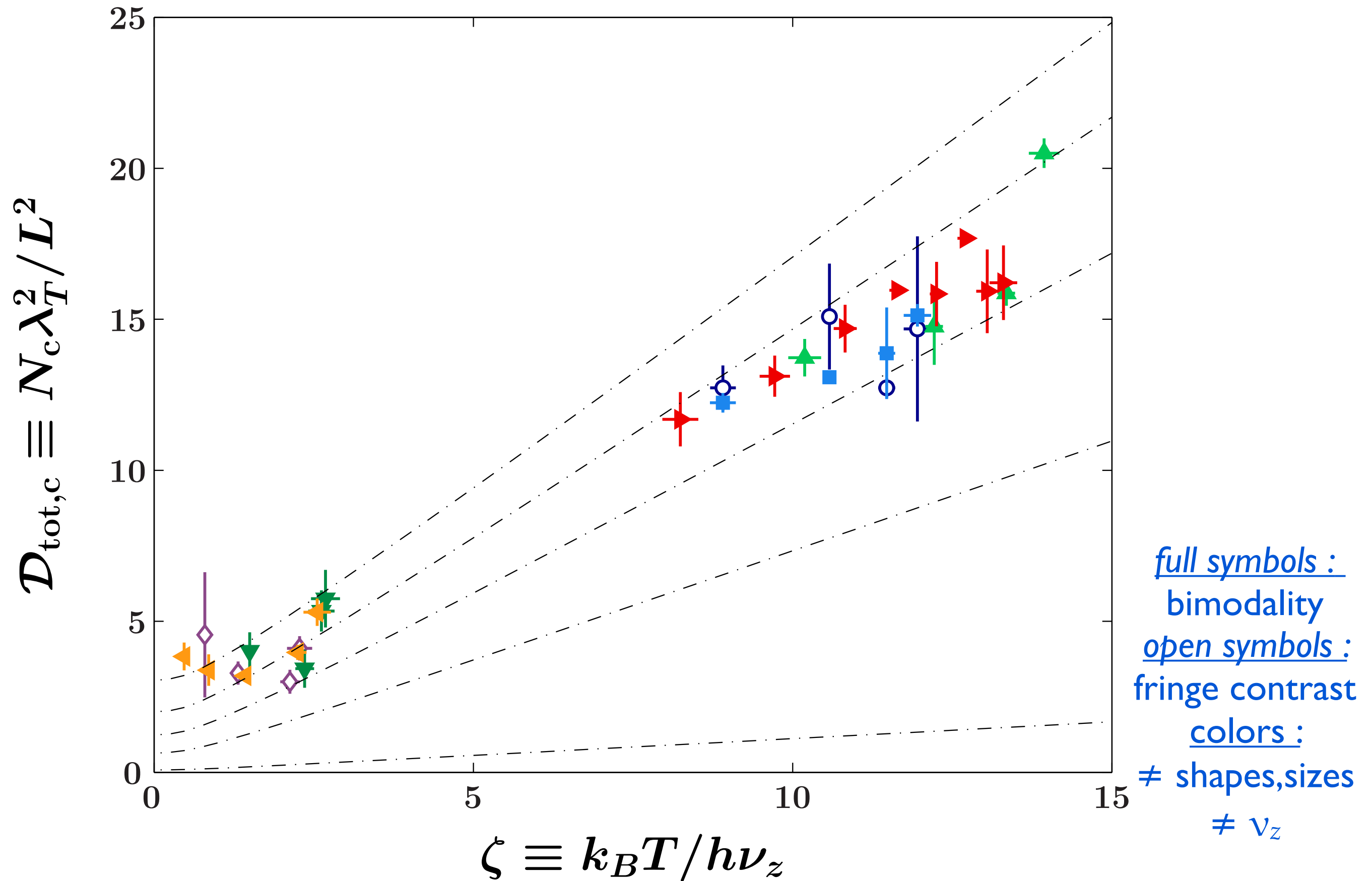
Coherence via matter-wave interference.



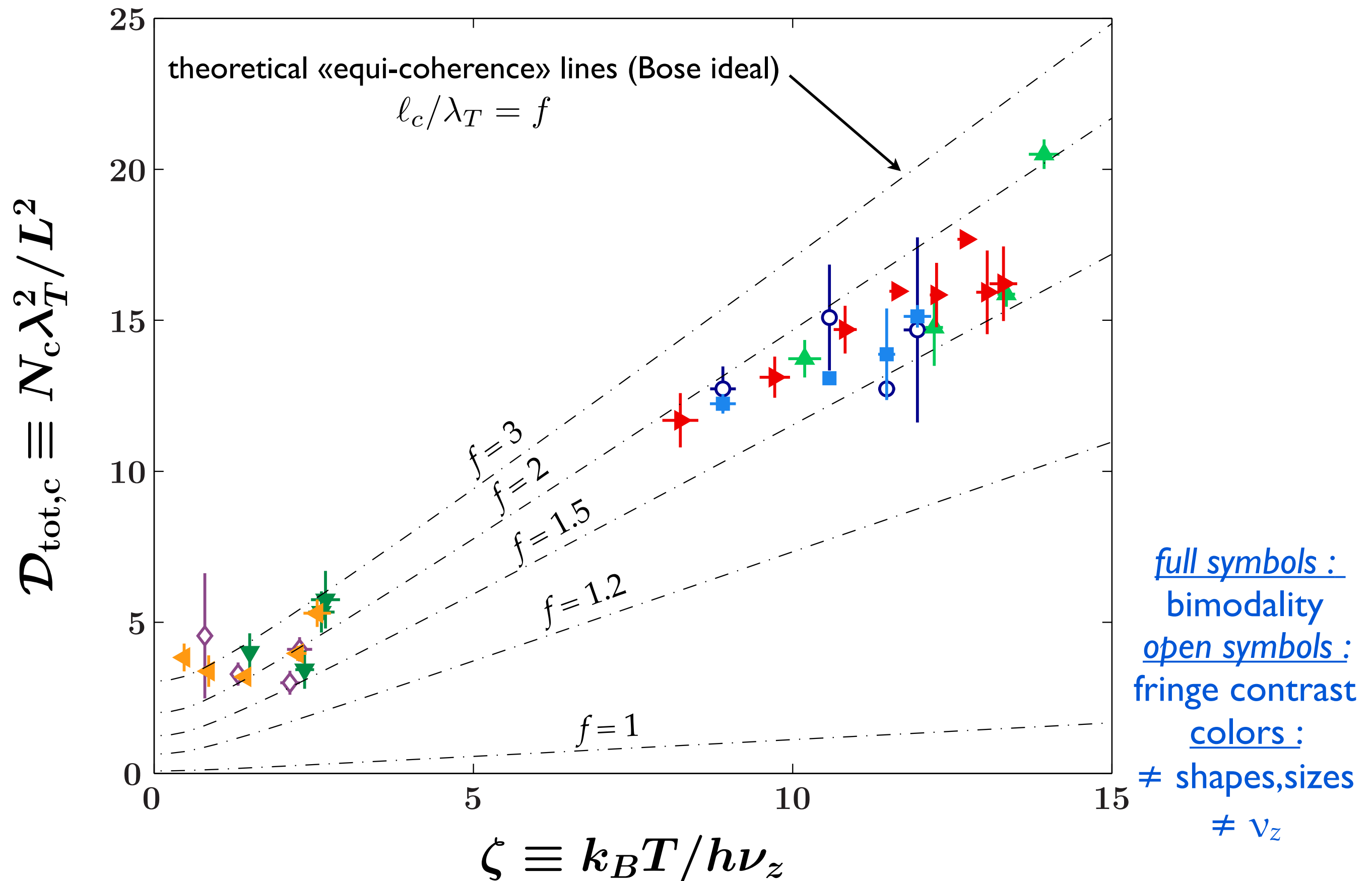
Release box confinement and let expand in-plane for τ such that the gases overlap

Visualize interferences in a unique plane.

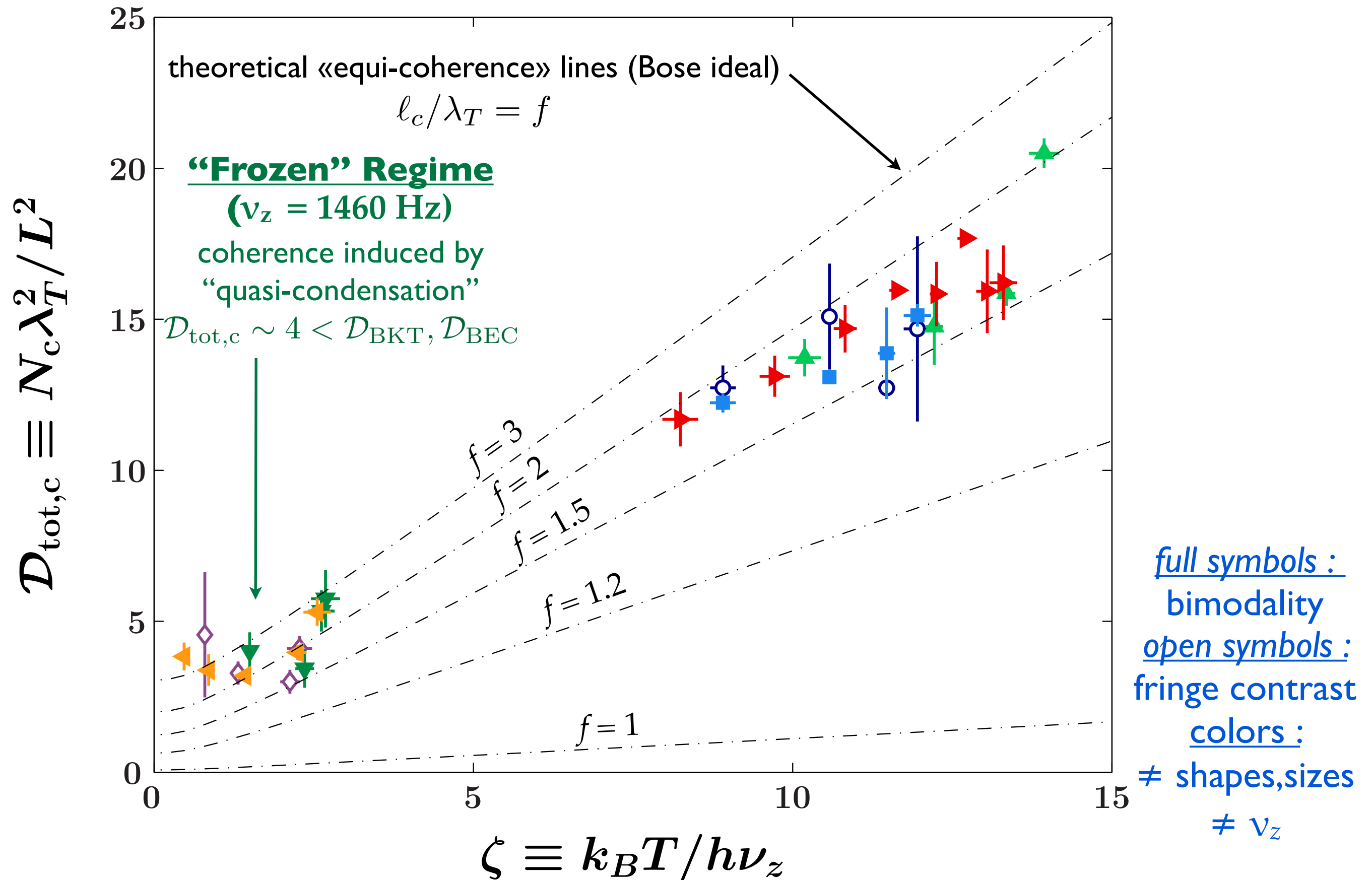
Universal behavior of the onset of coherence.



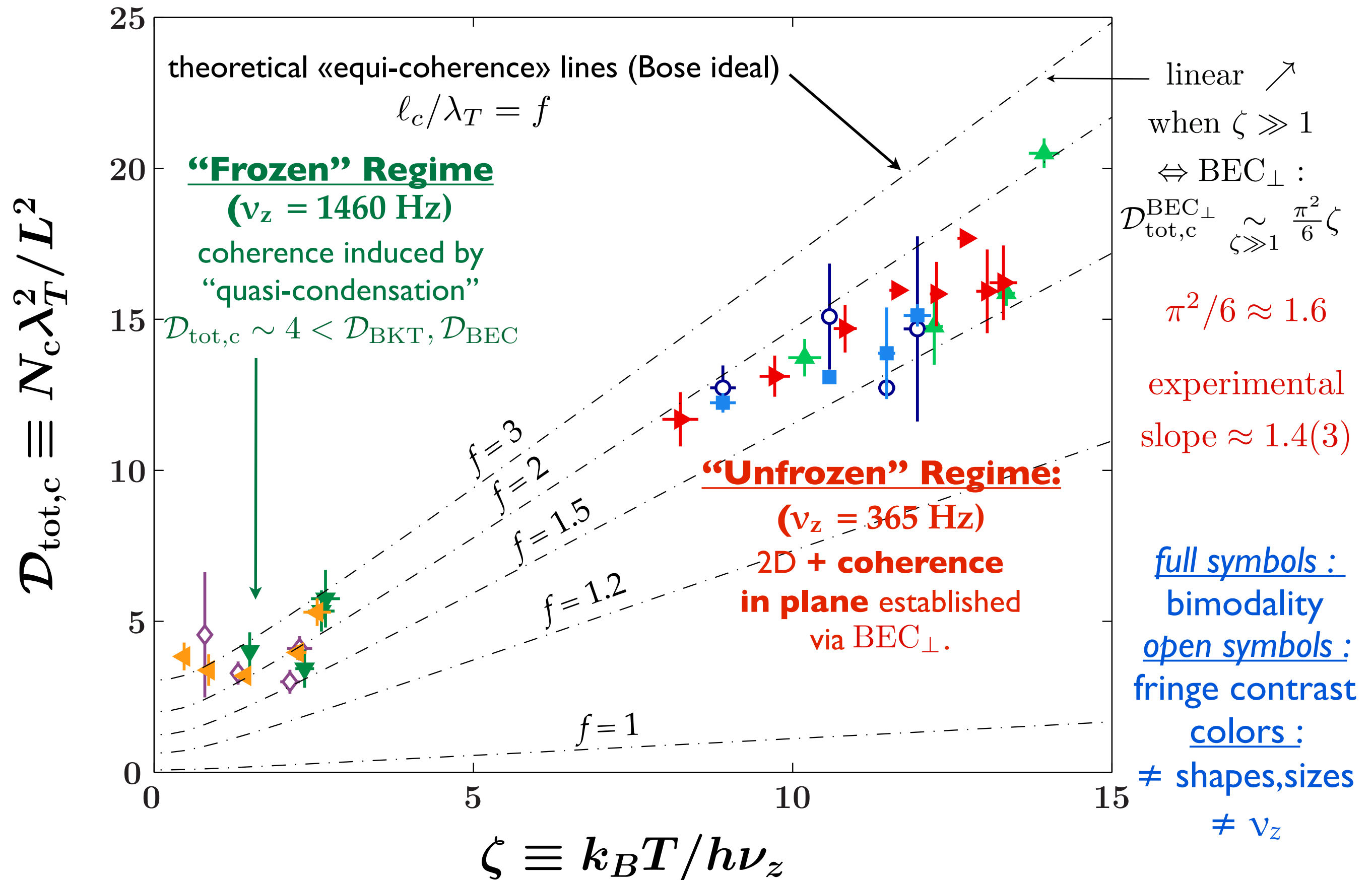
Universal behavior of the onset of coherence.



Universal behavior of the onset of coherence.



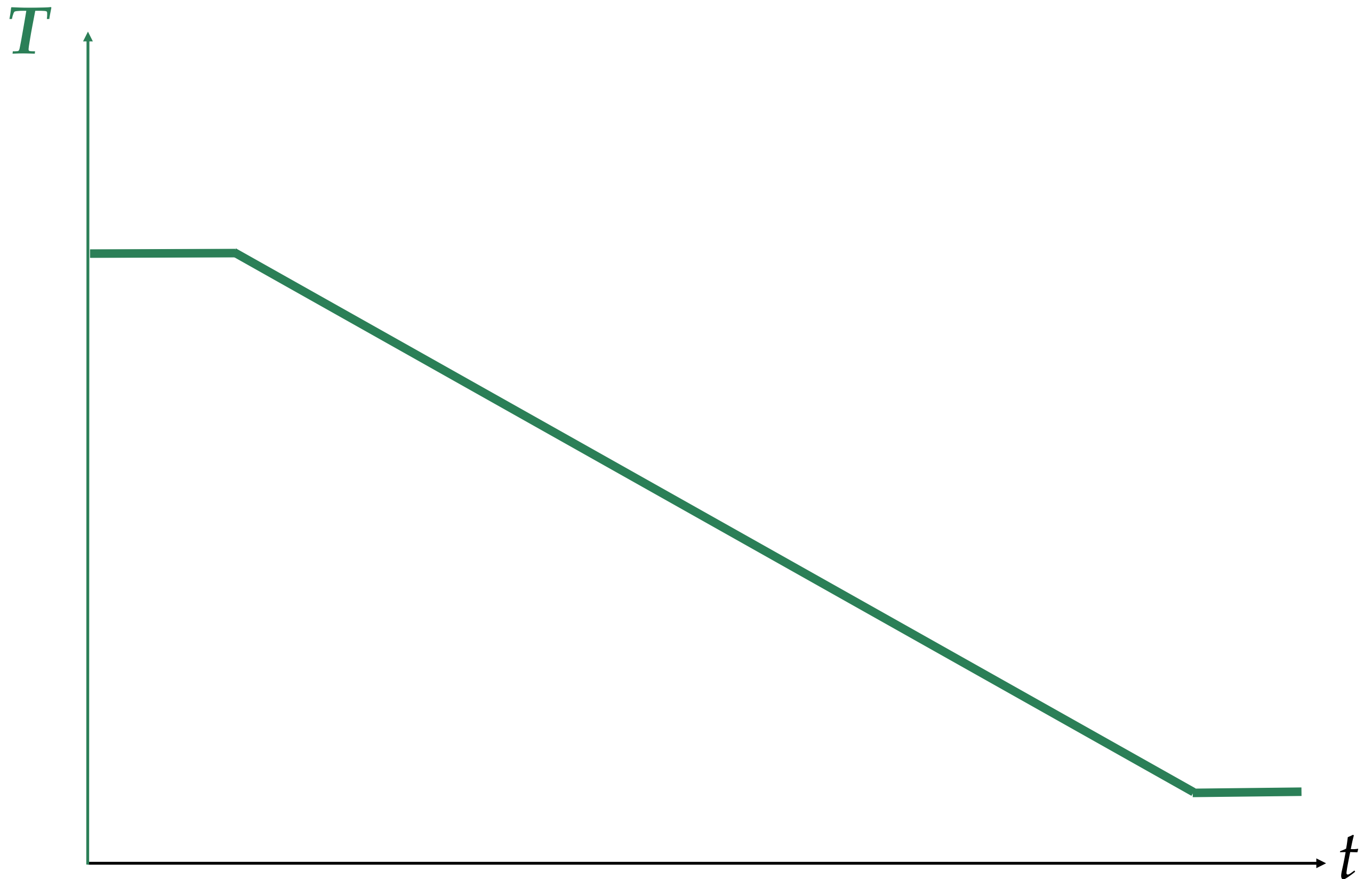
Universal behavior of the onset of coherence.



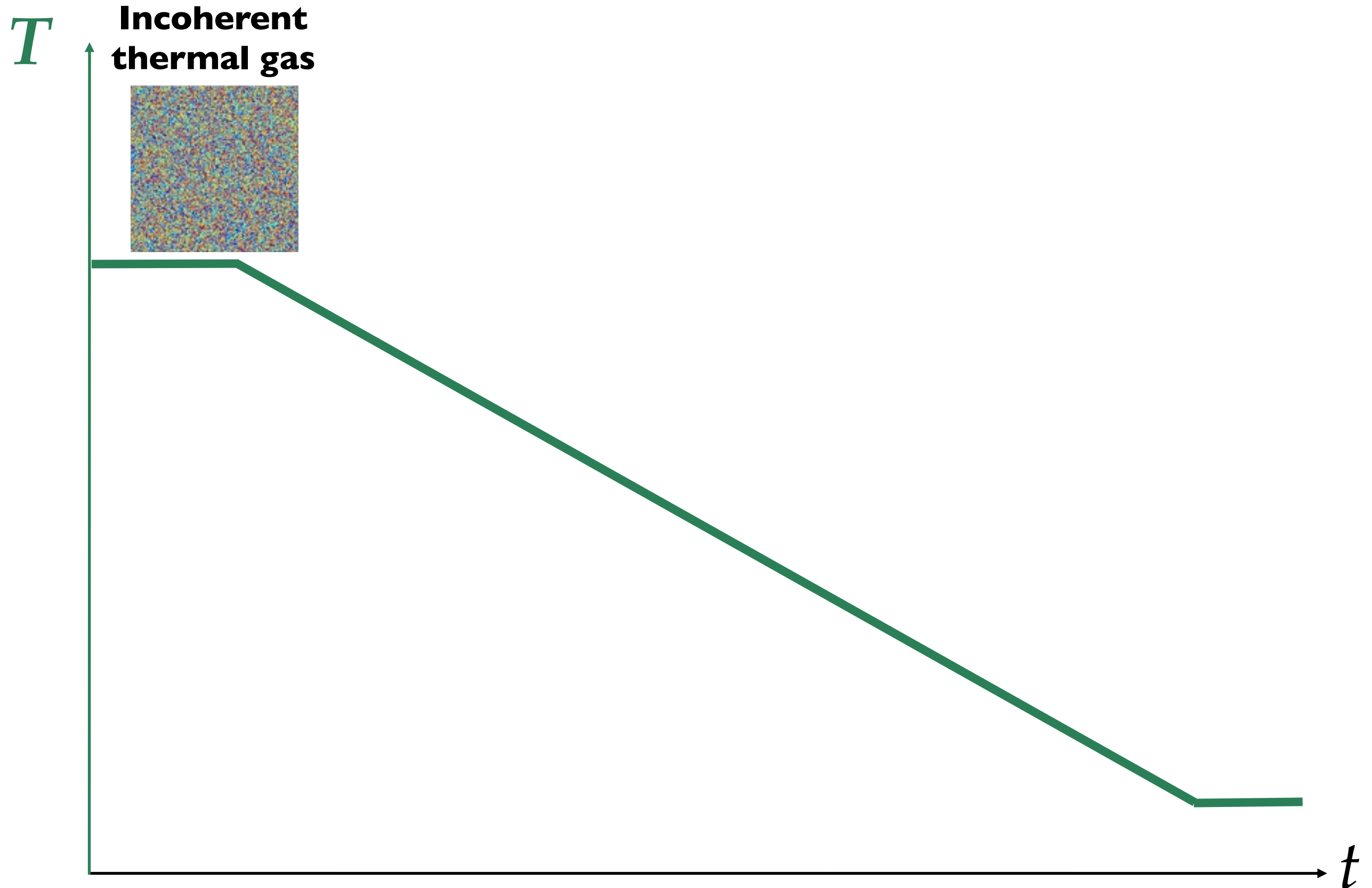
Outline.

- ◆ Motivation: specificity of 2D and 3D-to-2D crossover.
- ◆ Motivation: from harmonic to uniform traps.
- ◆ Experimental setup: creating 2D uniform gases.
- ◆ Emergence of an extended phase coherence in 2D uniform gases at thermal equilibrium.
- ◆ Dynamics of the establishment of coherence along forced evaporative cooling in uniform fluids.

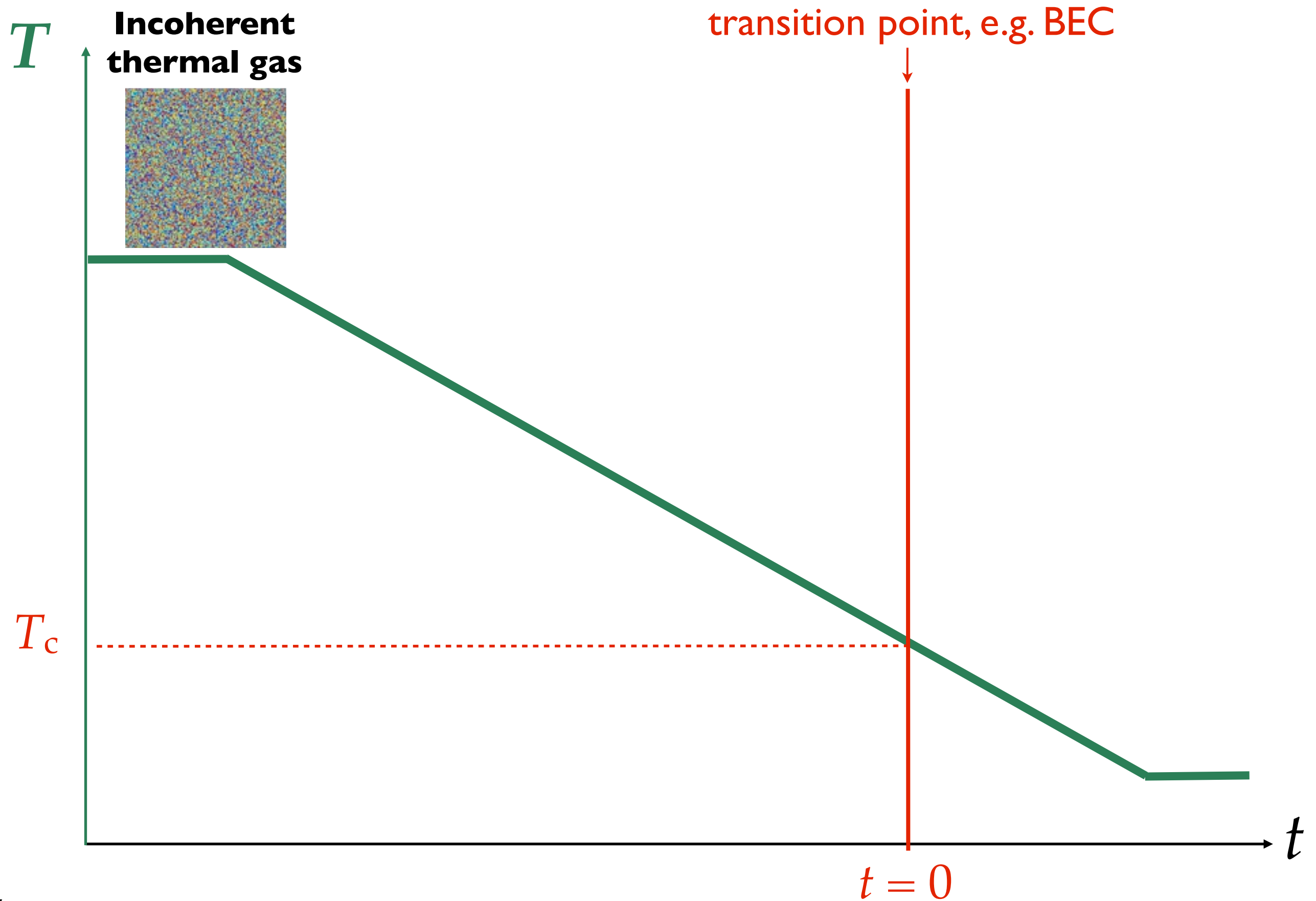
Kibble Zurek mechanism.



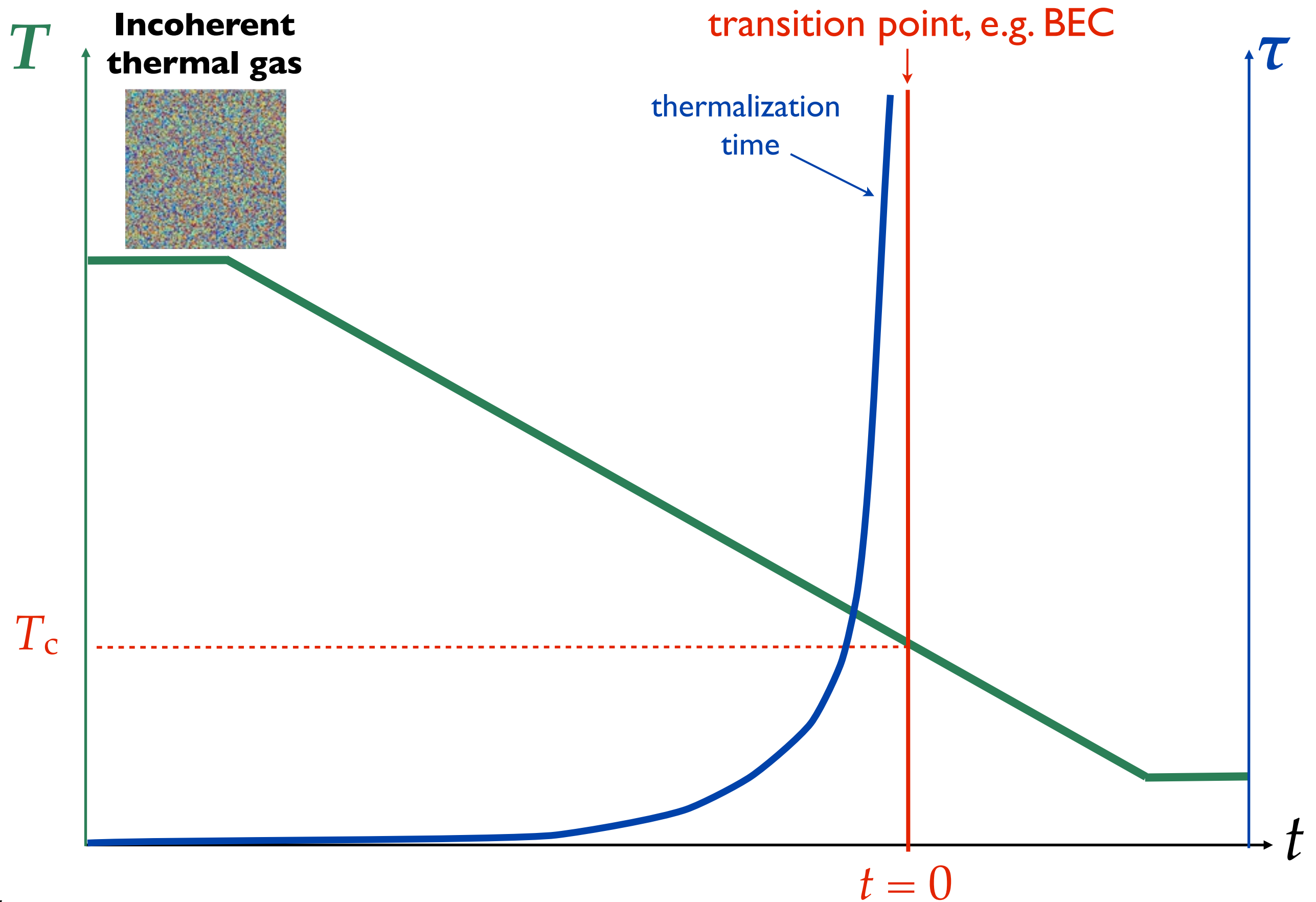
Kibble Zurek mechanism.



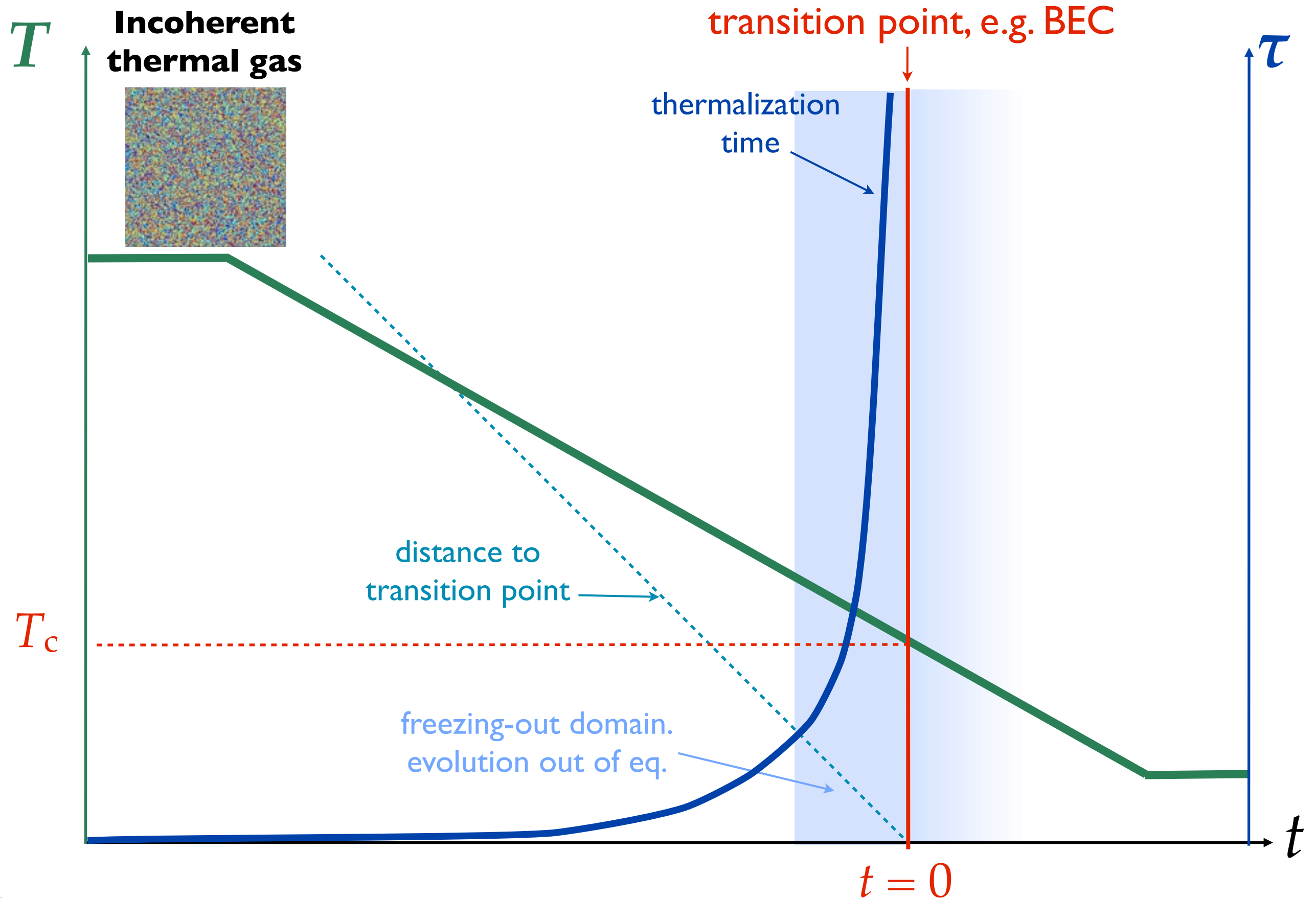
Kibble Zurek mechanism.



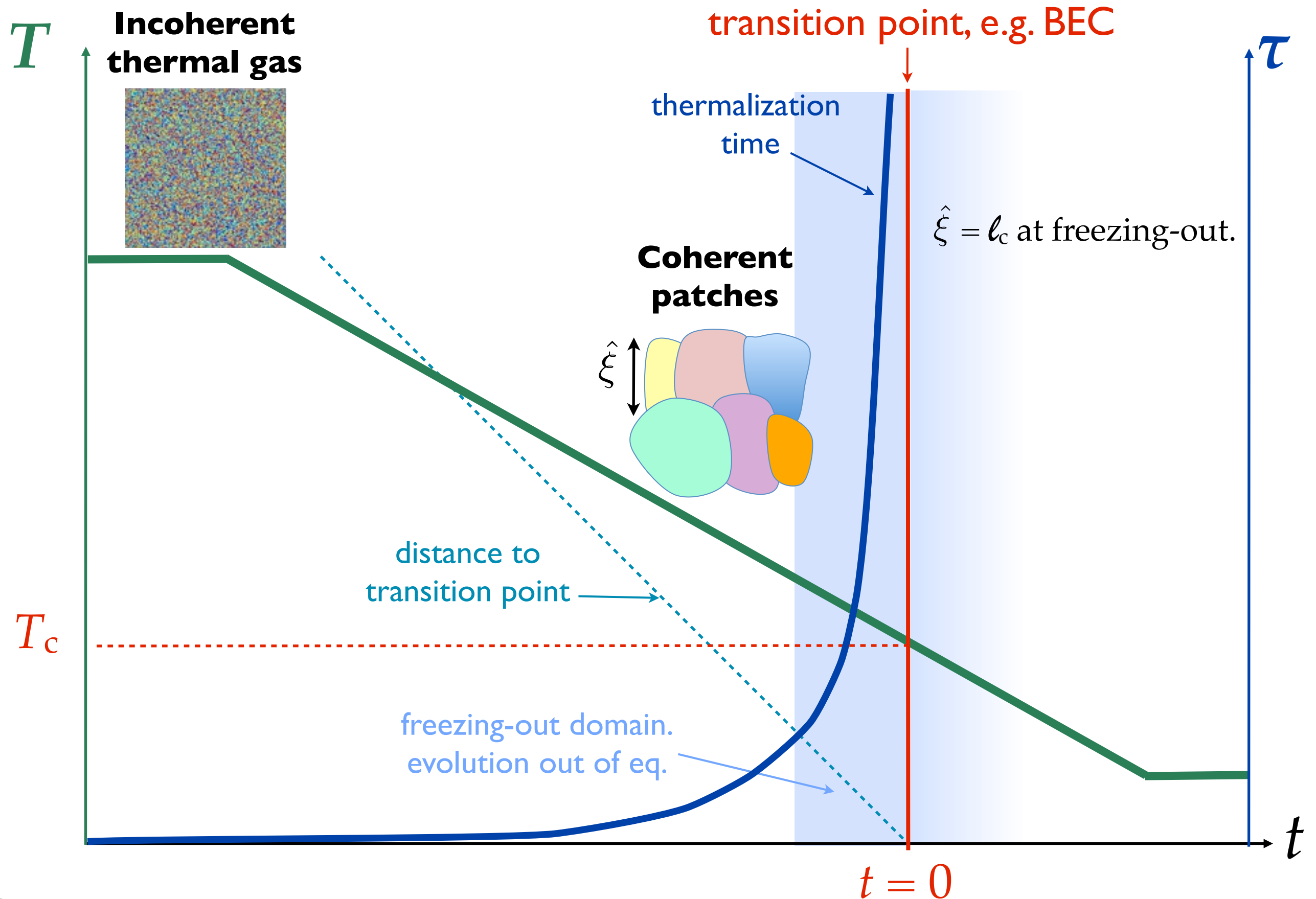
Kibble Zurek mechanism.



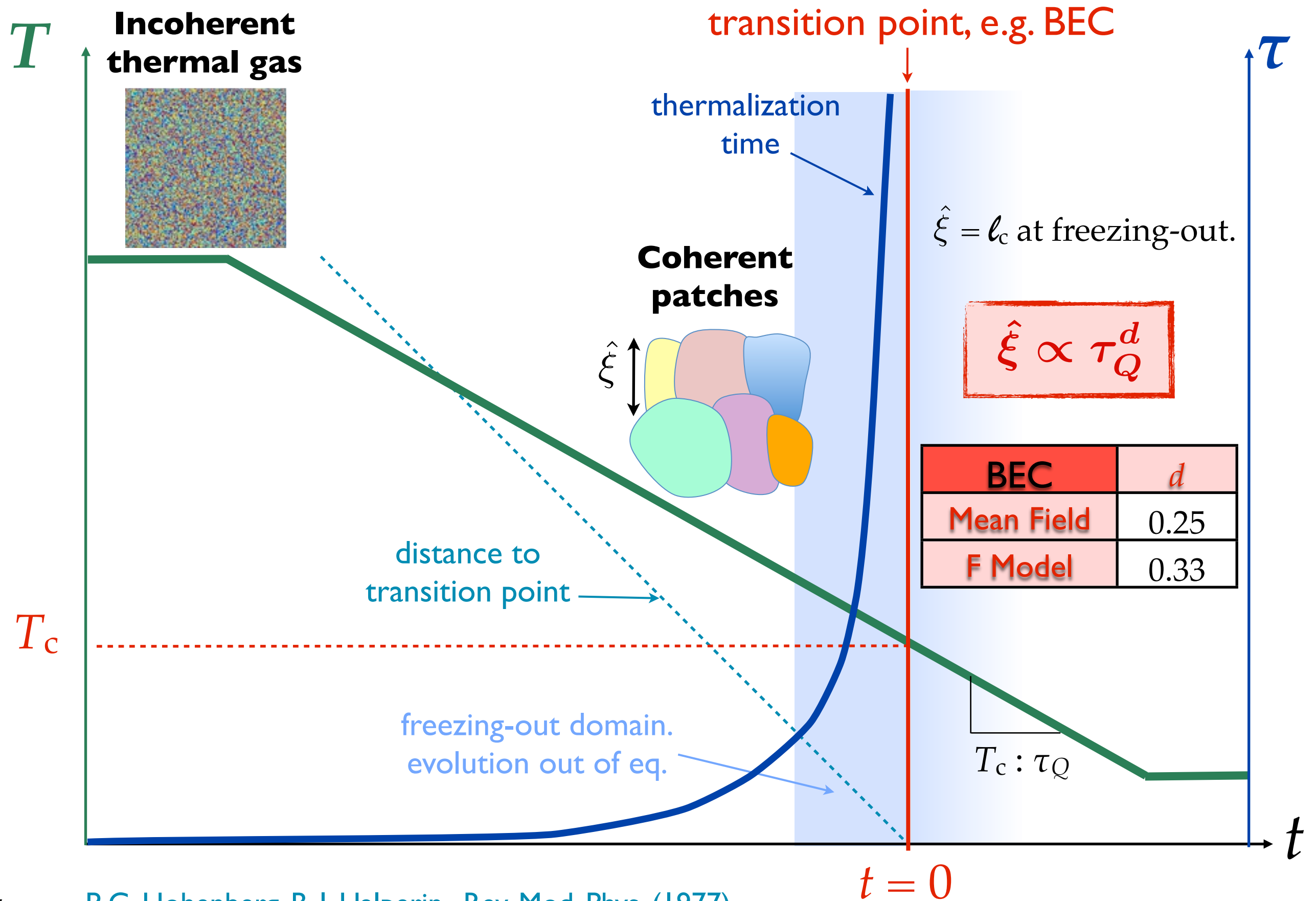
Kibble Zurek mechanism.



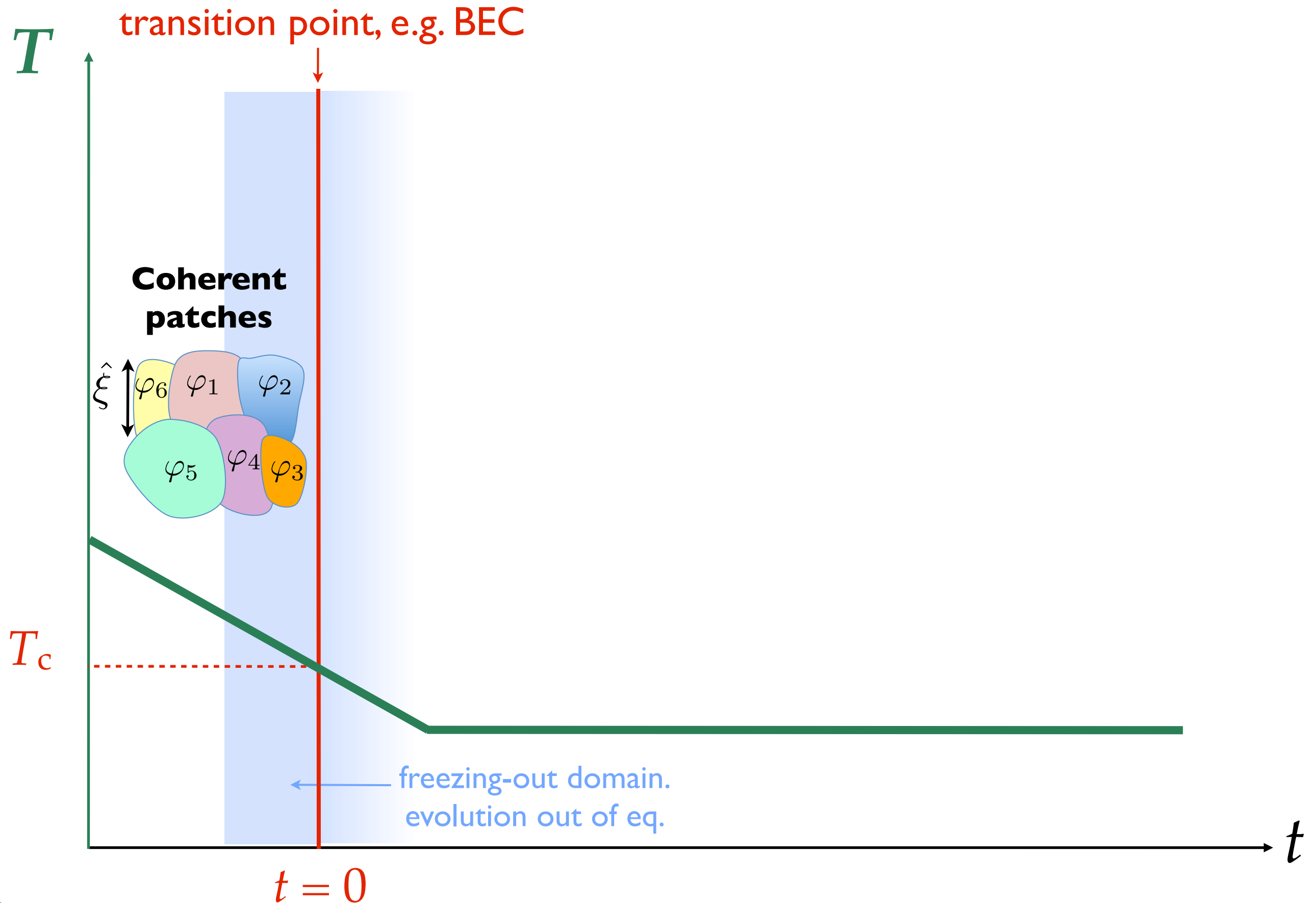
Kibble Zurek mechanism.



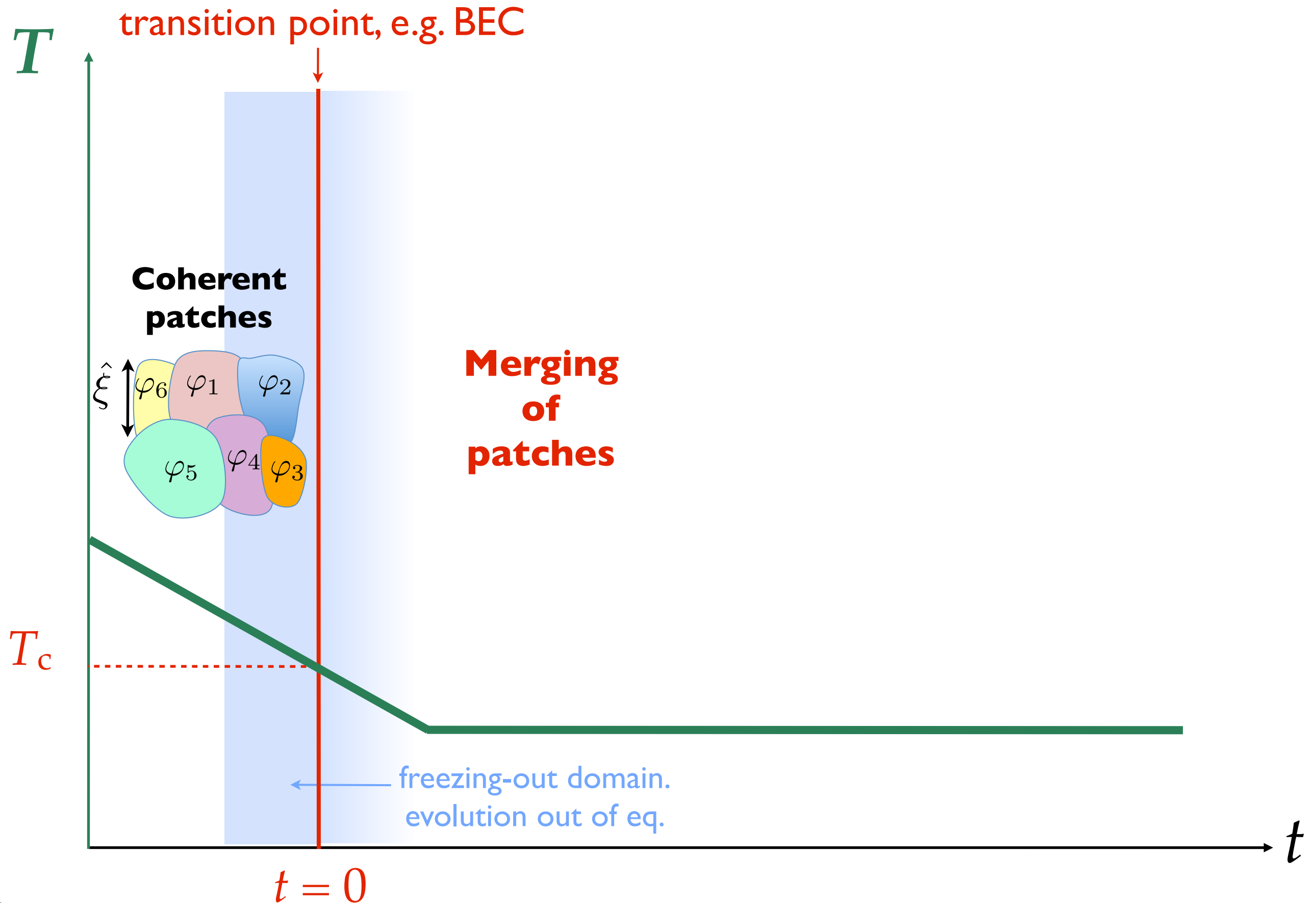
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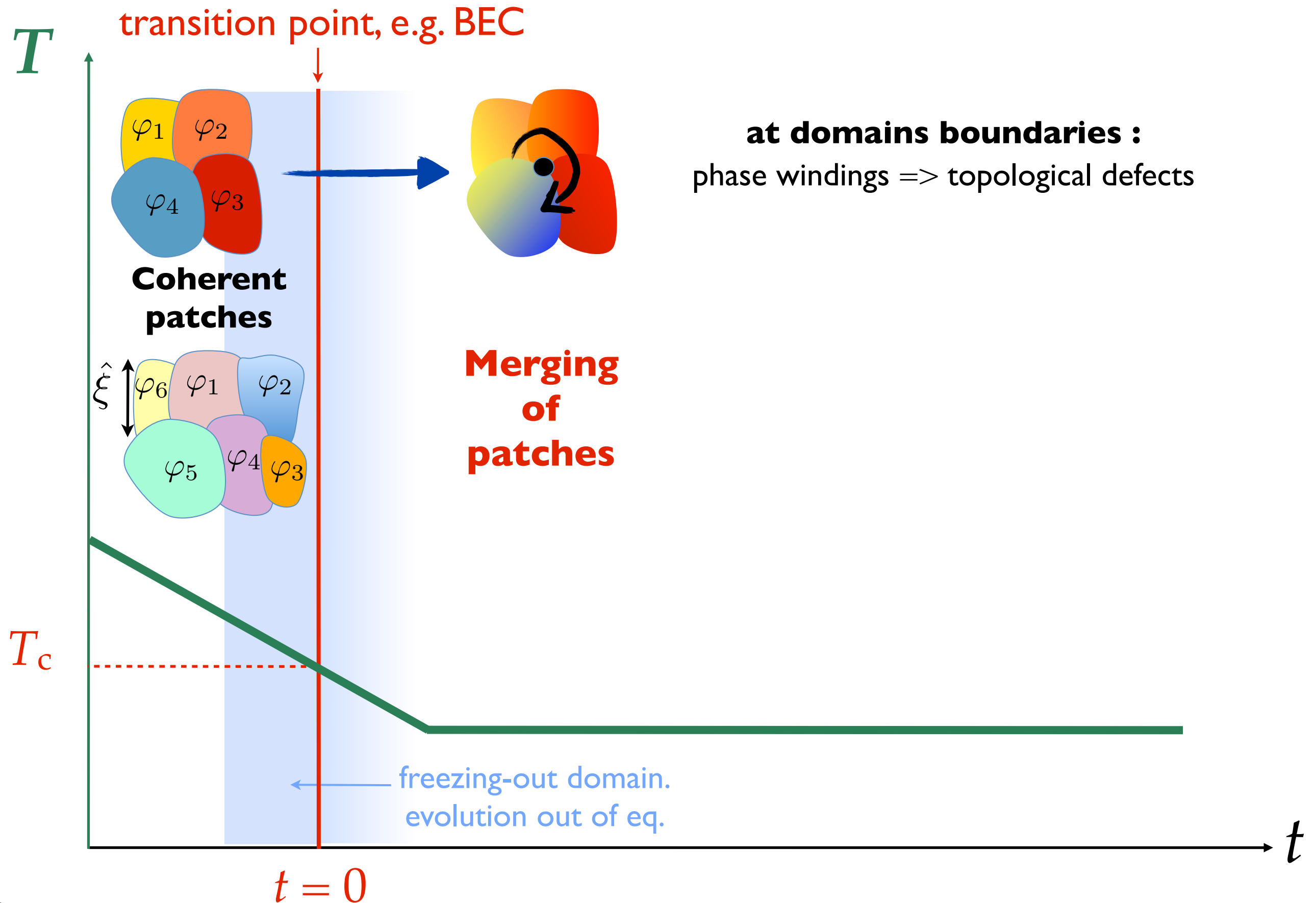
Topological defects from KZM.



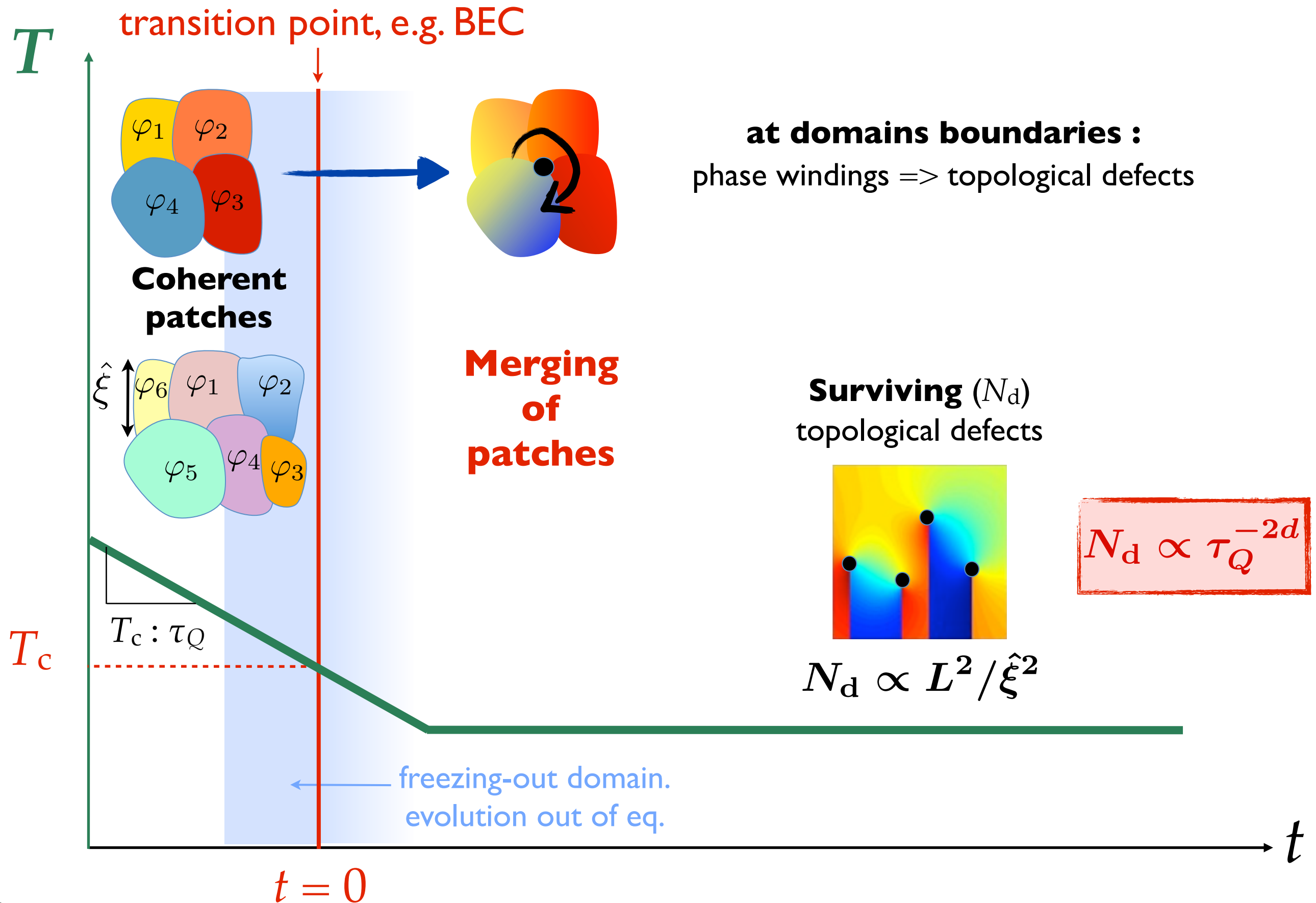
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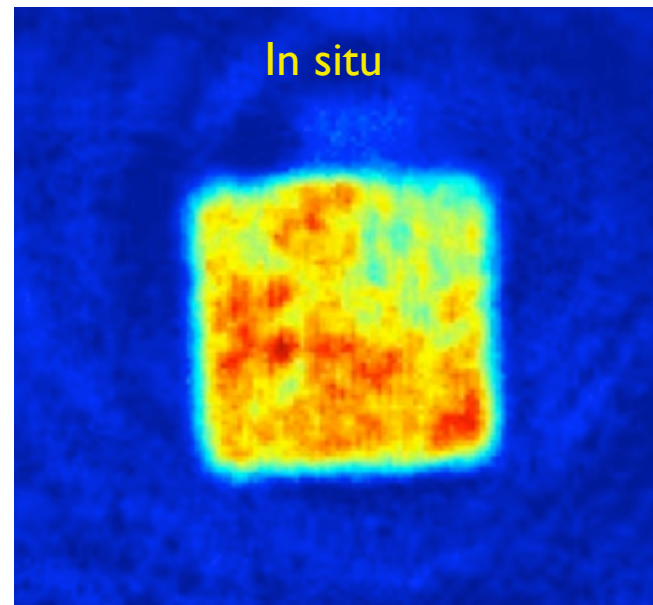
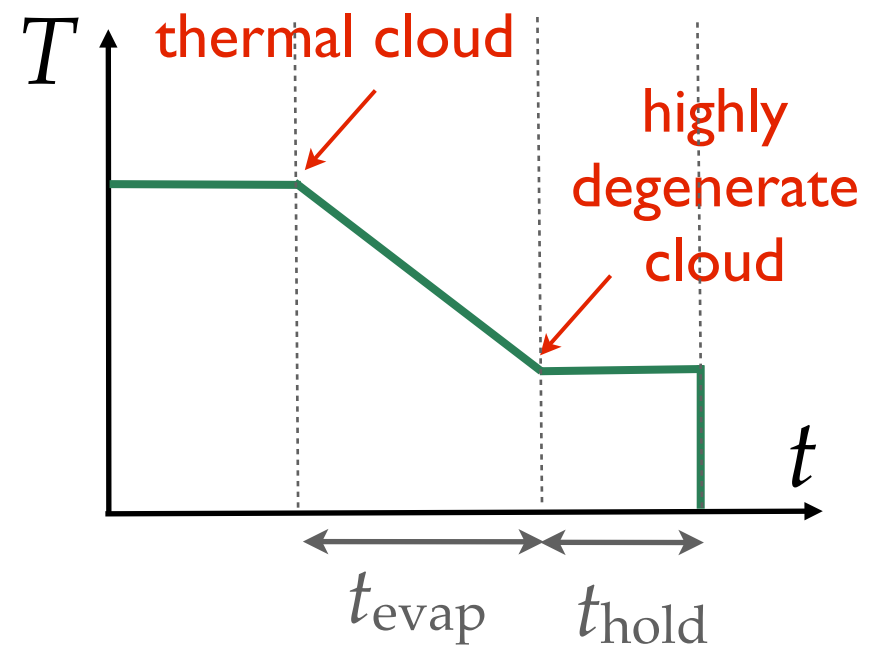
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Topological defects from KZM.



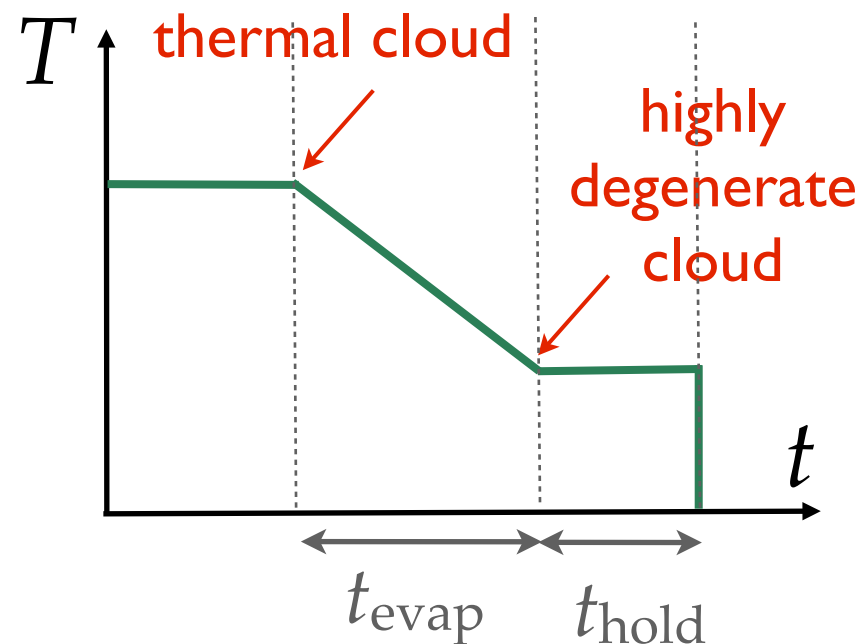
Direct observation of vortices.



$$\underline{v_z = 365 \text{ Hz:}}$$

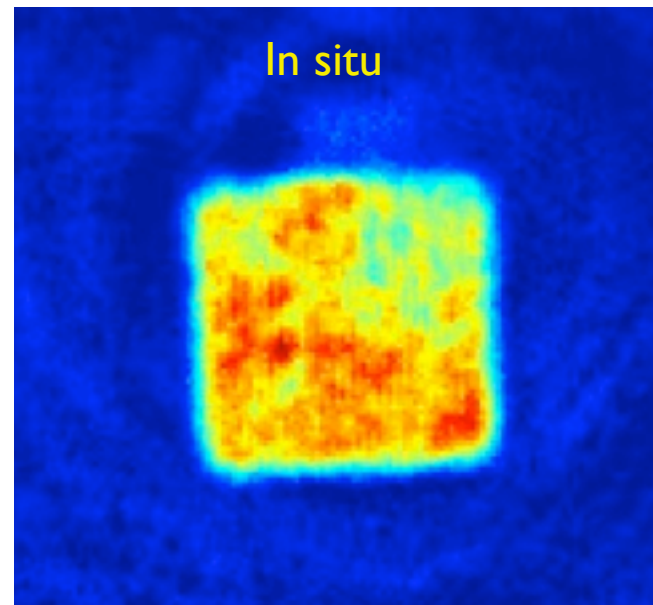
Coherence emerges
via BEC_\perp .

Direct observation of vortices.



$$\underline{v_z = 365 \text{ Hz:}}$$

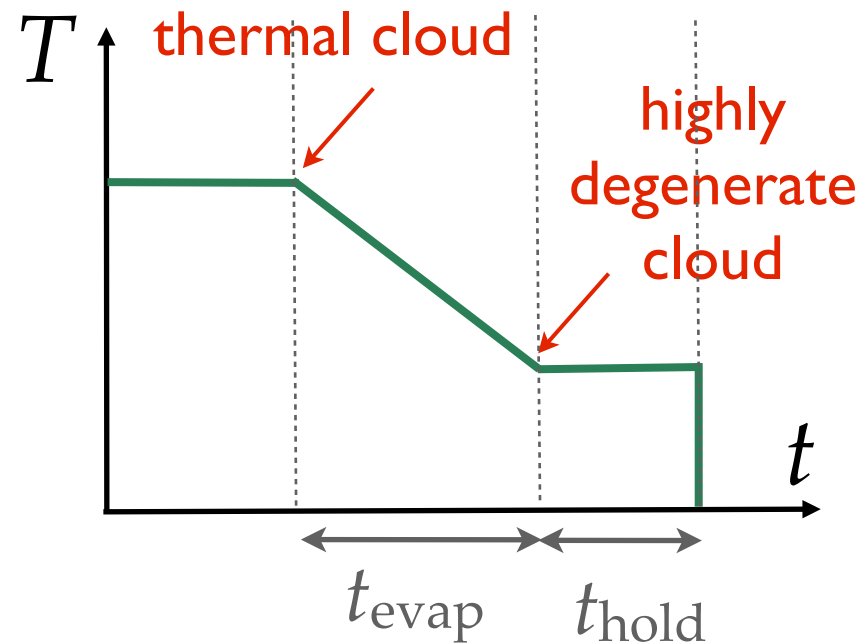
Coherence emerges
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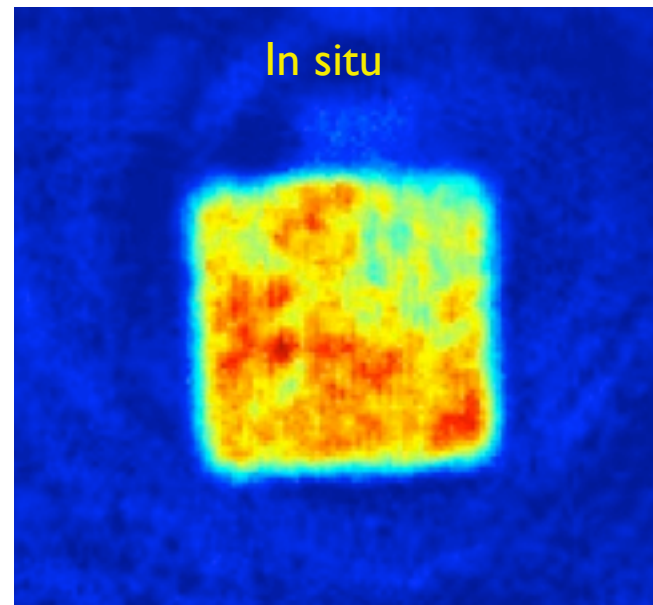
In situ images,
no excitation:

- Phonons = phase defects \Rightarrow not visible
- Vortices = too small (charact. size $\approx 0.6 \mu\text{m}$ / imaging res. $\approx 1\text{-}2 \mu\text{m}$)

Direct observation of vortices.



$\nu_z = 365$ Hz:
Coherence emerges
via BEC_{\perp} .

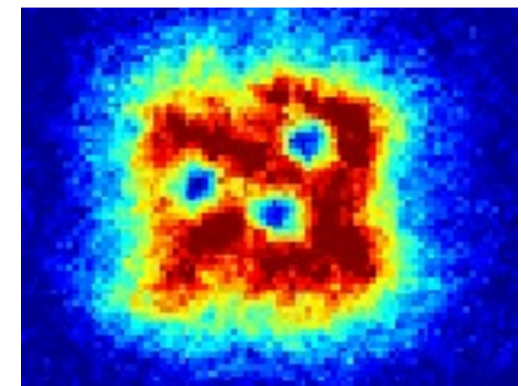
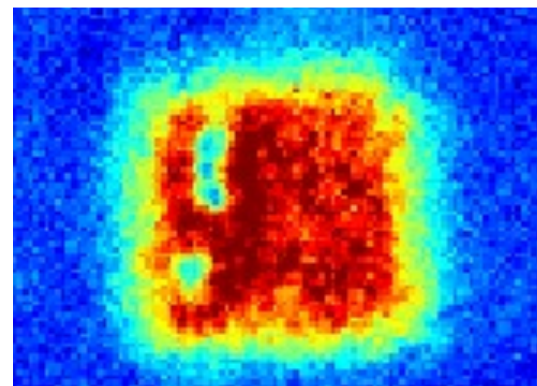
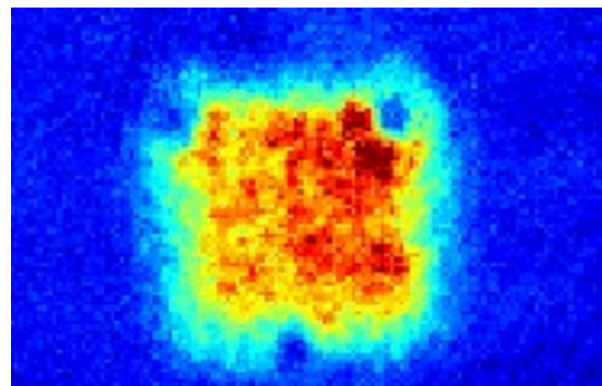


In situ images,
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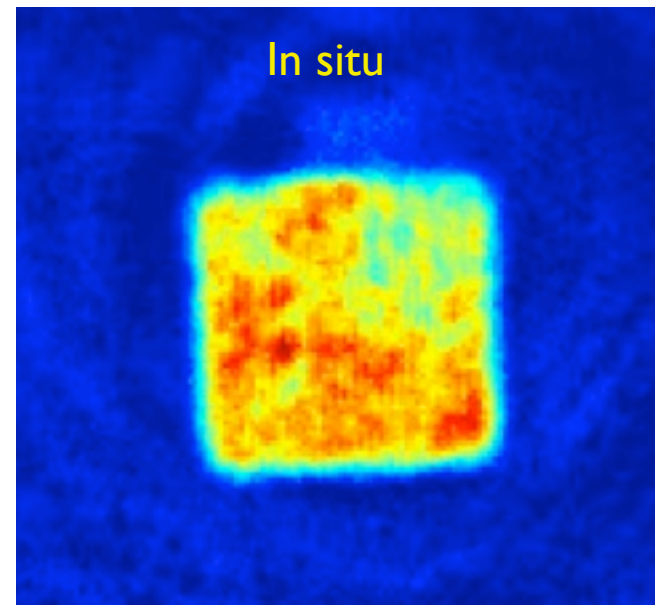
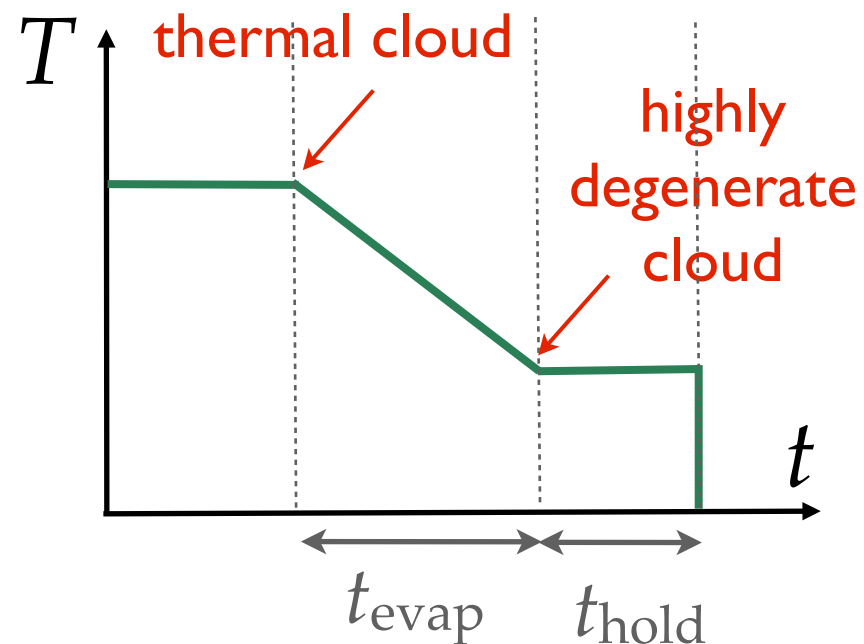


After 4 ms Release

«short» 3D TOF
reveals defects as
density holes...



Direct observation of vortices.



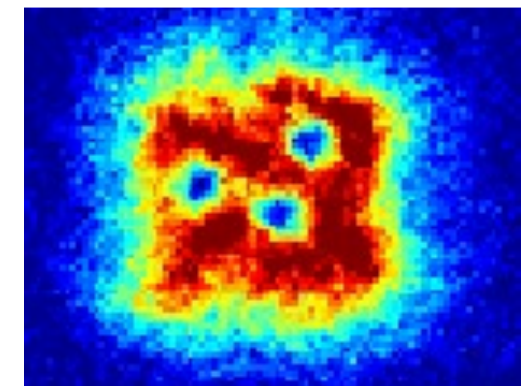
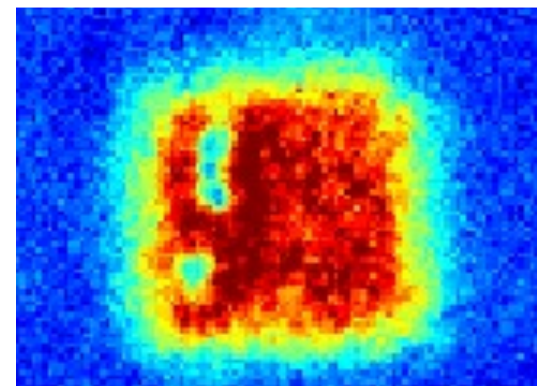
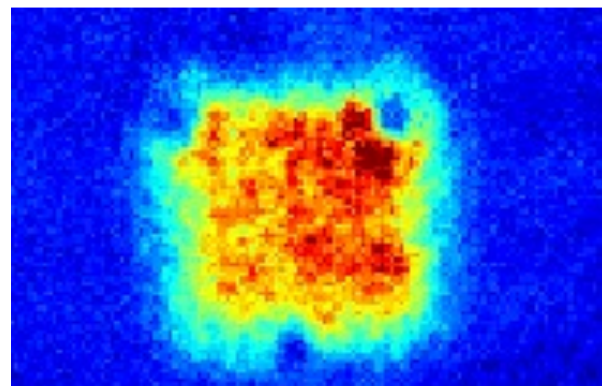
In situ images, no excitation:

- Phonons = phase defects \Rightarrow not visible
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$\nu_z = 365 \text{ Hz}$:
Coherence emerges via BEC_\perp .

«short» 3D TOF reveals defects as density holes...

After 4 ms Release



Analysis of holes properties (size, contrast) \Rightarrow single vortices (\neq phonons, \neq pairs)
Highly degenerate gas ($\text{PSD} > 100$) \Rightarrow no thermally activated vortices.

Transverse BEC as a candidate for KZM.

BEC_\perp similar to standard 3D BEC



BEC_\perp occurs at
 $n(z=0) = 2.612 \lambda_T^{-3}$



BEC in an ∞ 3D gas.

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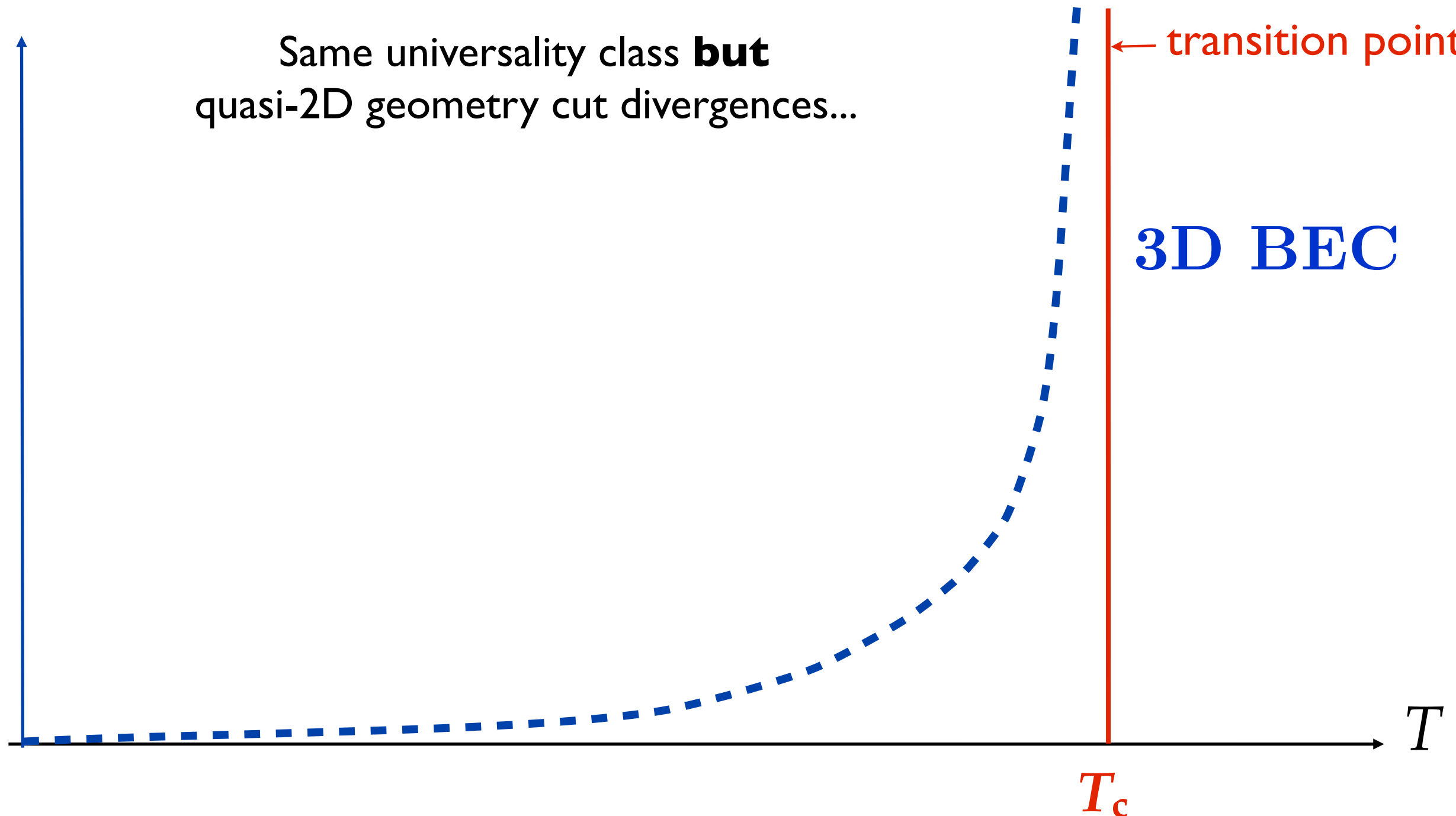
BEC in an ∞ 3D gas.

l_c

Same universality class **but**
quasi-2D geometry cut divergences...

← transition point

3D BEC



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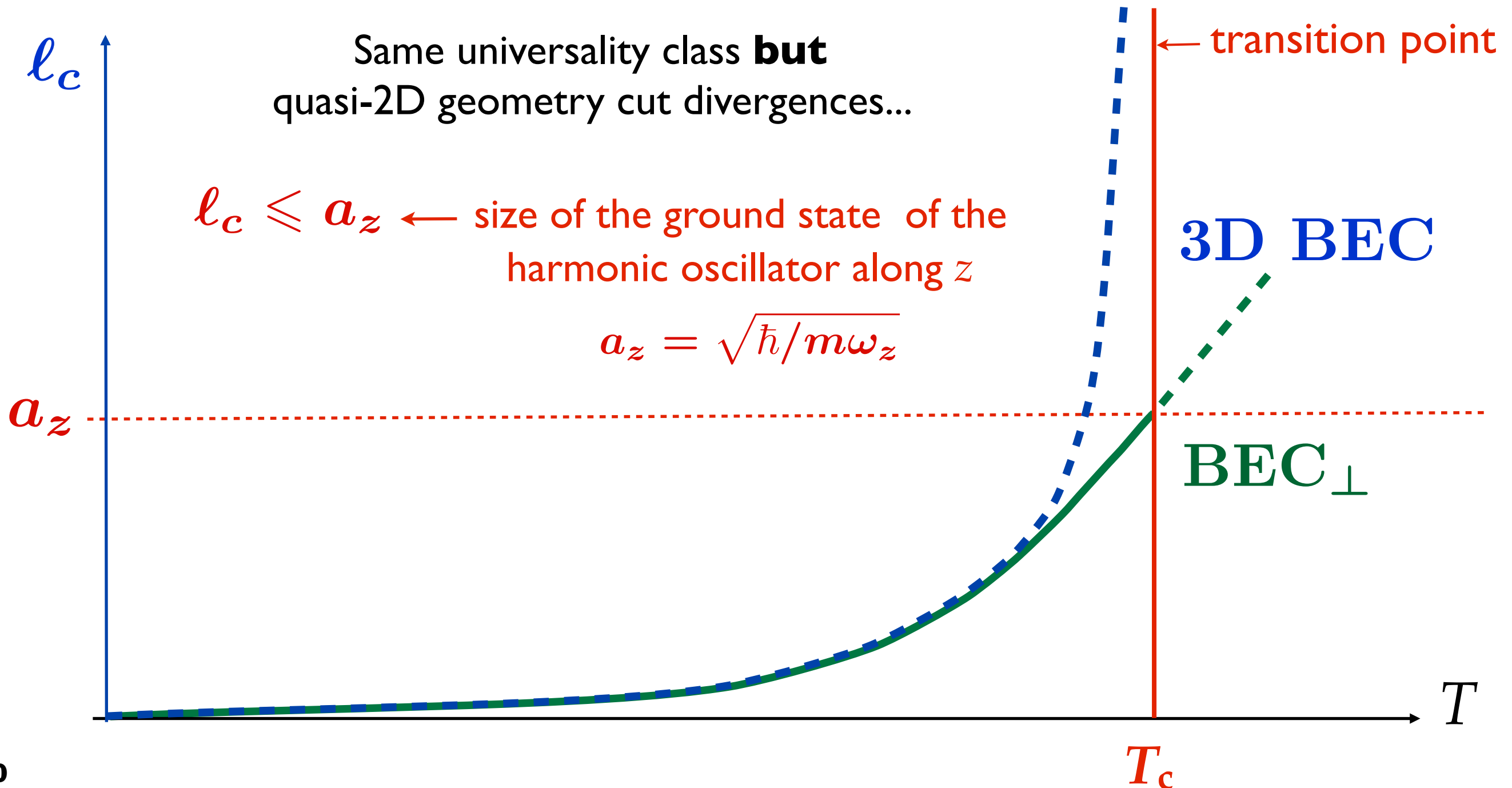


BEC in an ∞ 3D gas.

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$l_c \leq a_z$ ← size of the ground state of the
 harmonic oscillator along z

$$a_z = \sqrt{\hbar/m\omega_z}$$



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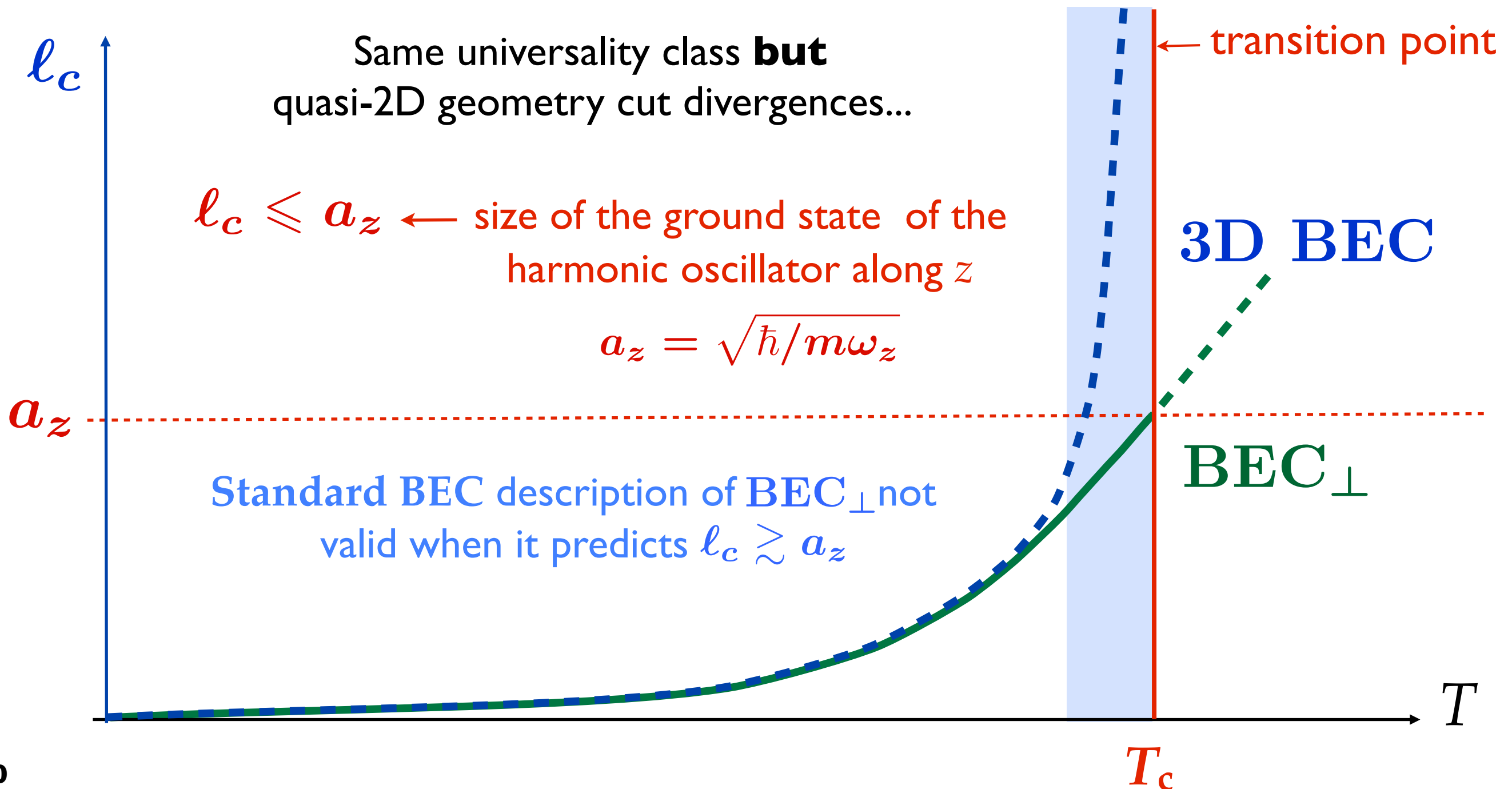
BEC in an ∞ 3D gas.

Same universality class **but**
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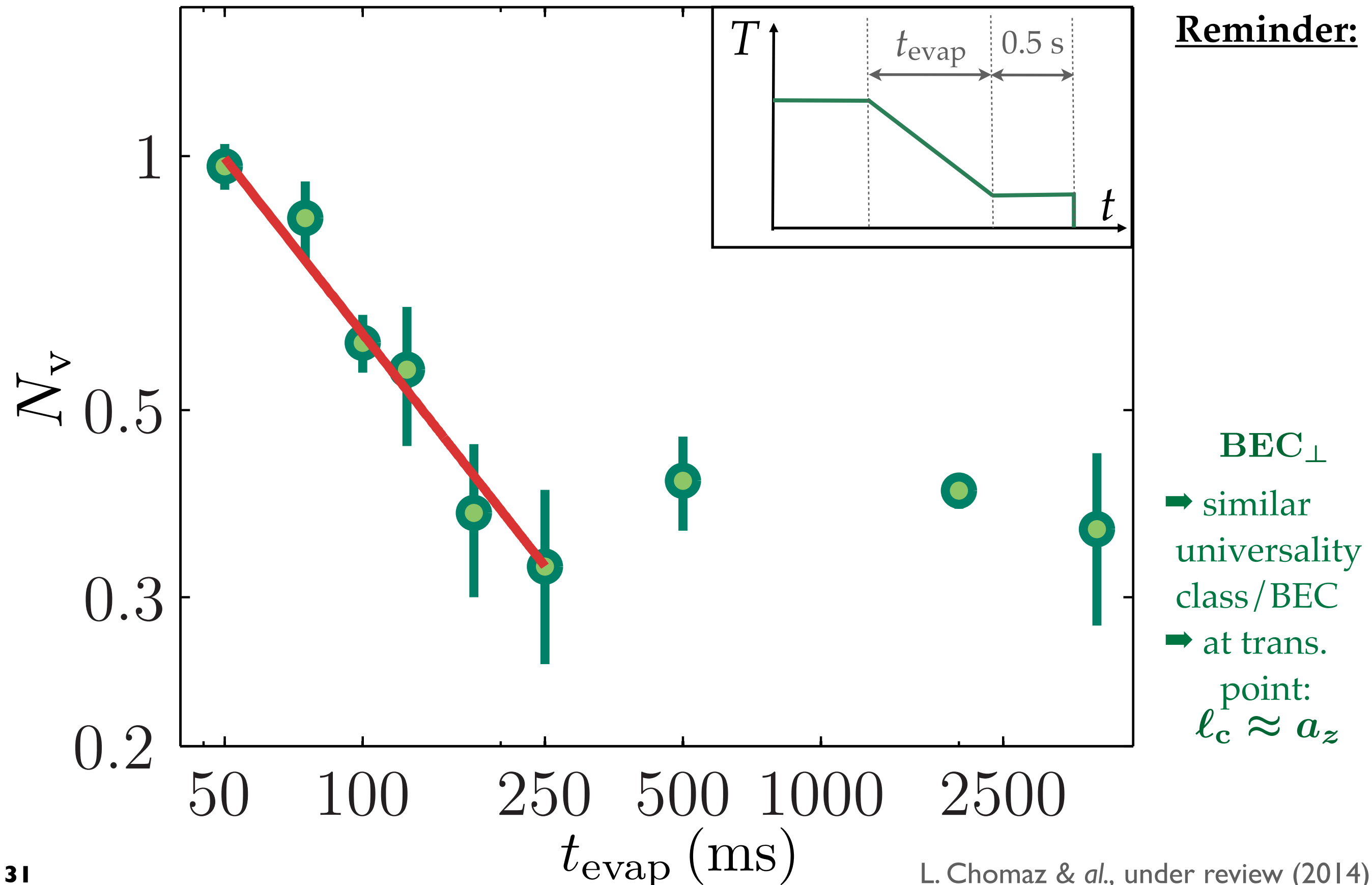
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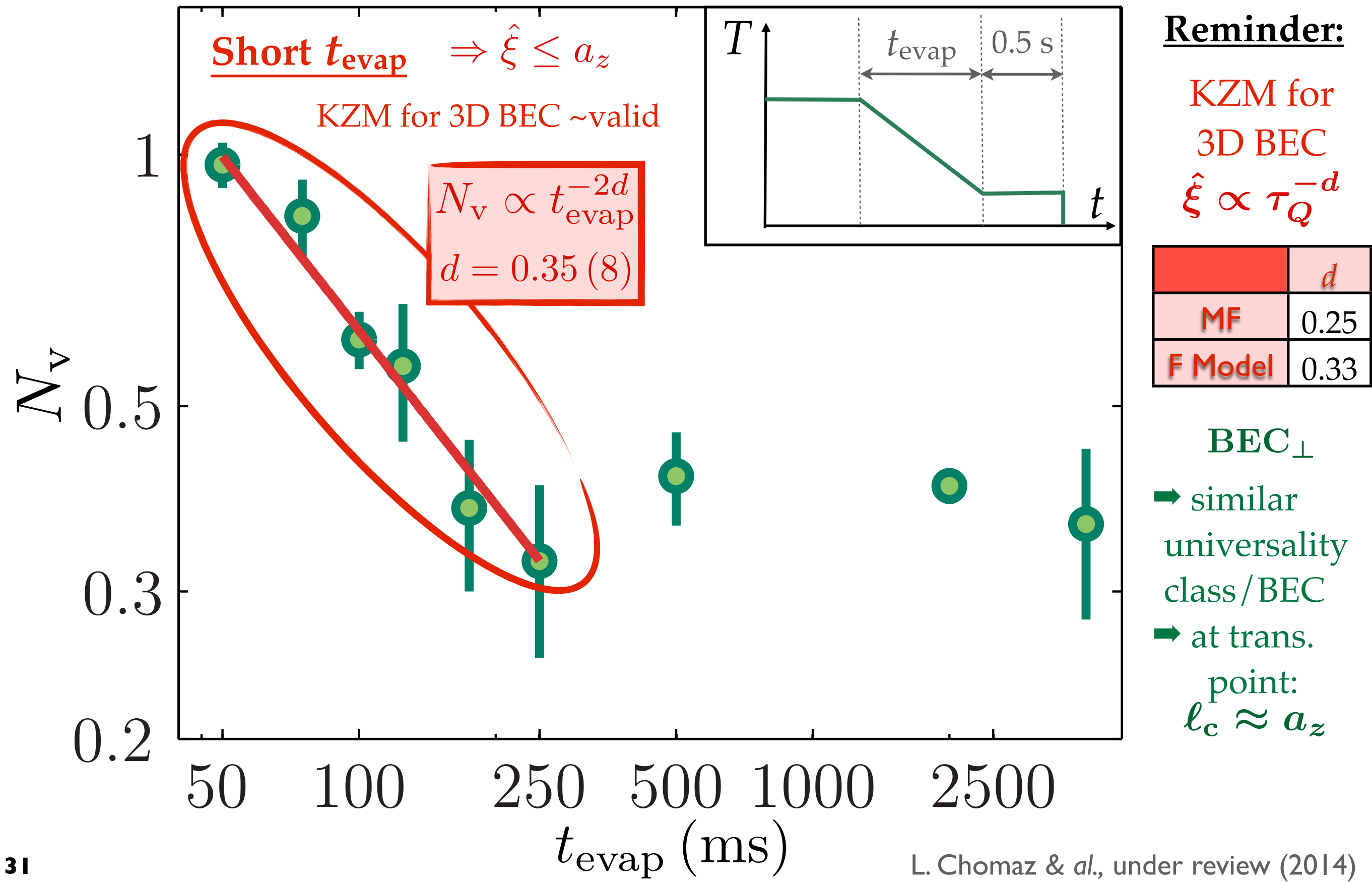
Standard BEC description of BEC_\perp not
 valid when it predicts $l_c \gtrsim a_z$



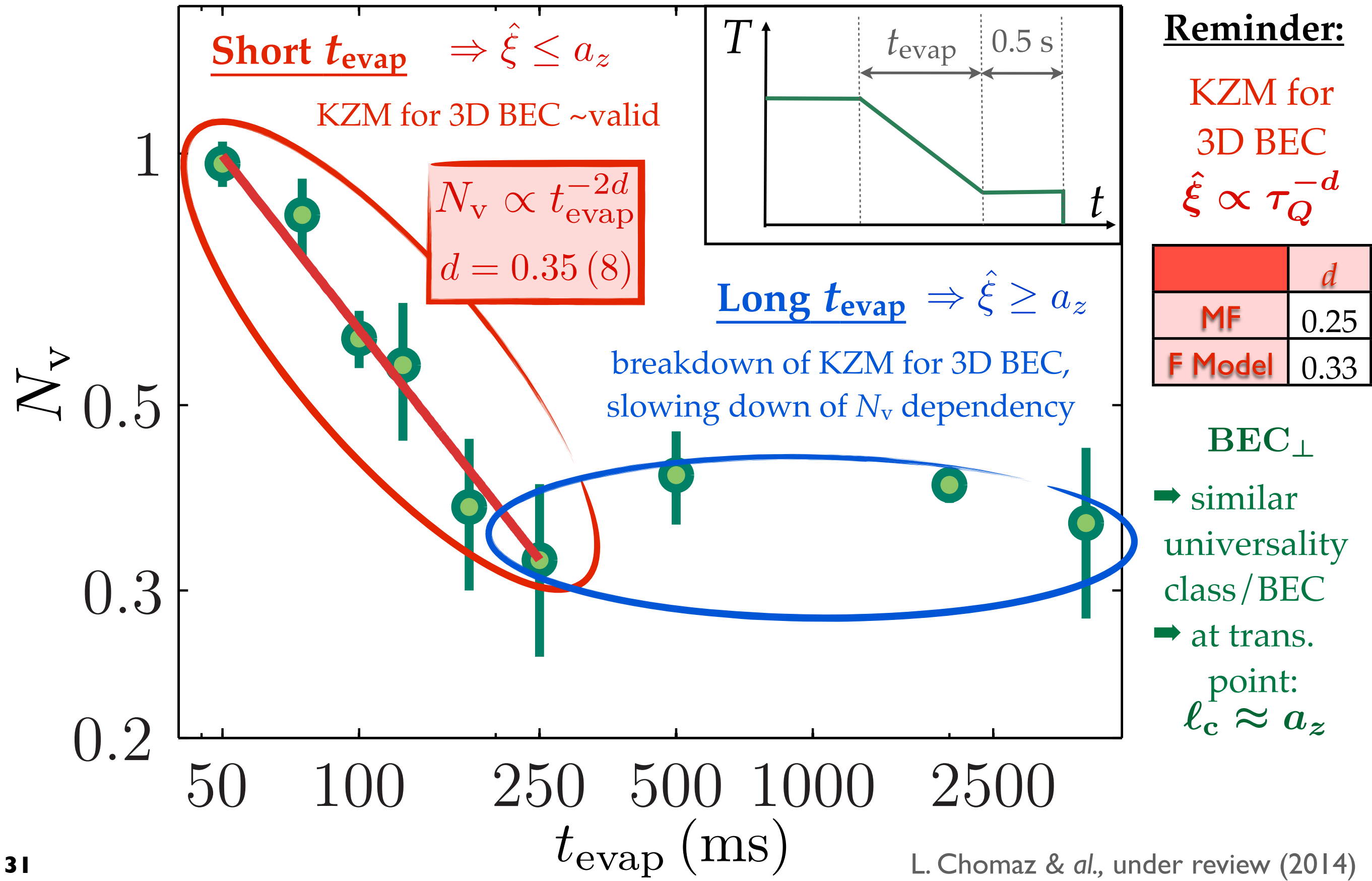
Quantitative test of KZM scaling.



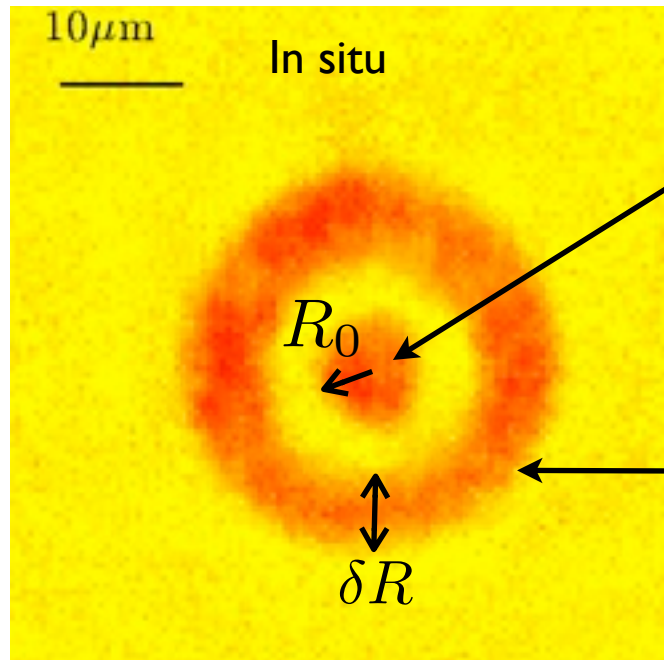
Quantitative test of KZM scaling.



Quantitative test of KZM scaling.



KZ supercurrents in an annulus.



small central disk
= phase reference

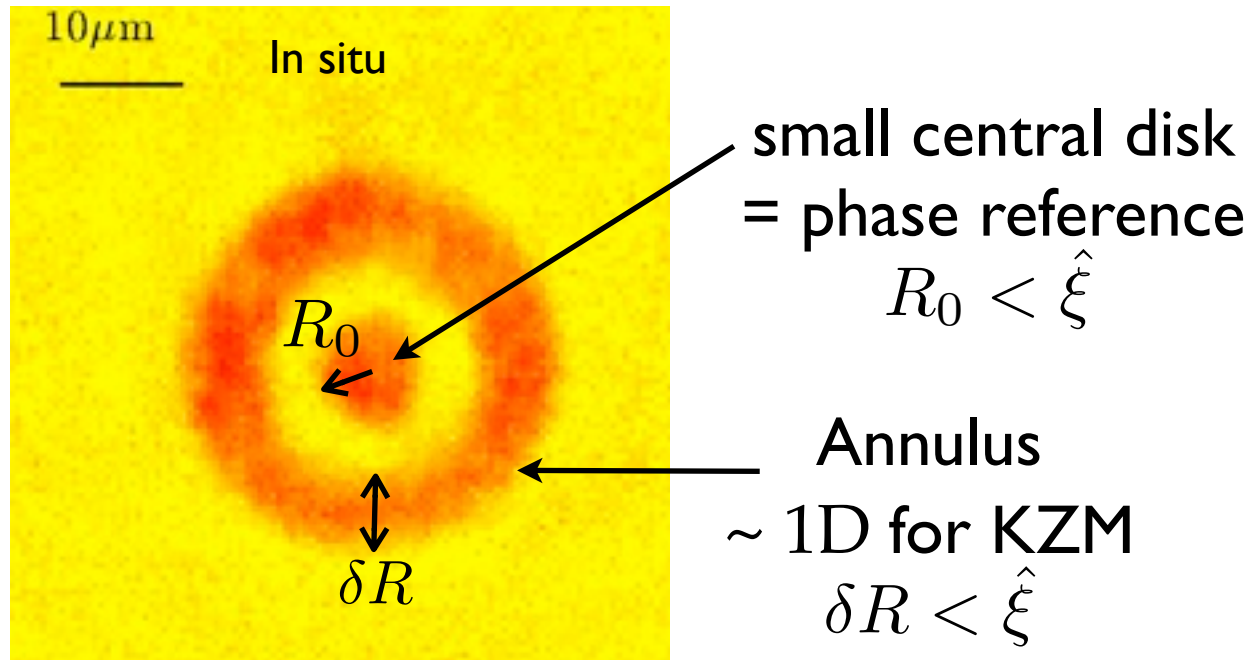
$$R_0 < \hat{\xi}$$

Annulus

$\sim 1D$ for KZM

$$\delta R < \hat{\xi}$$

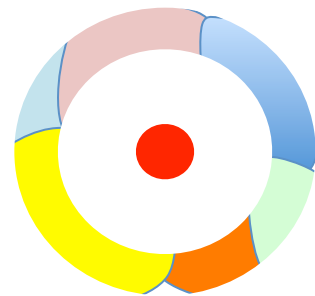
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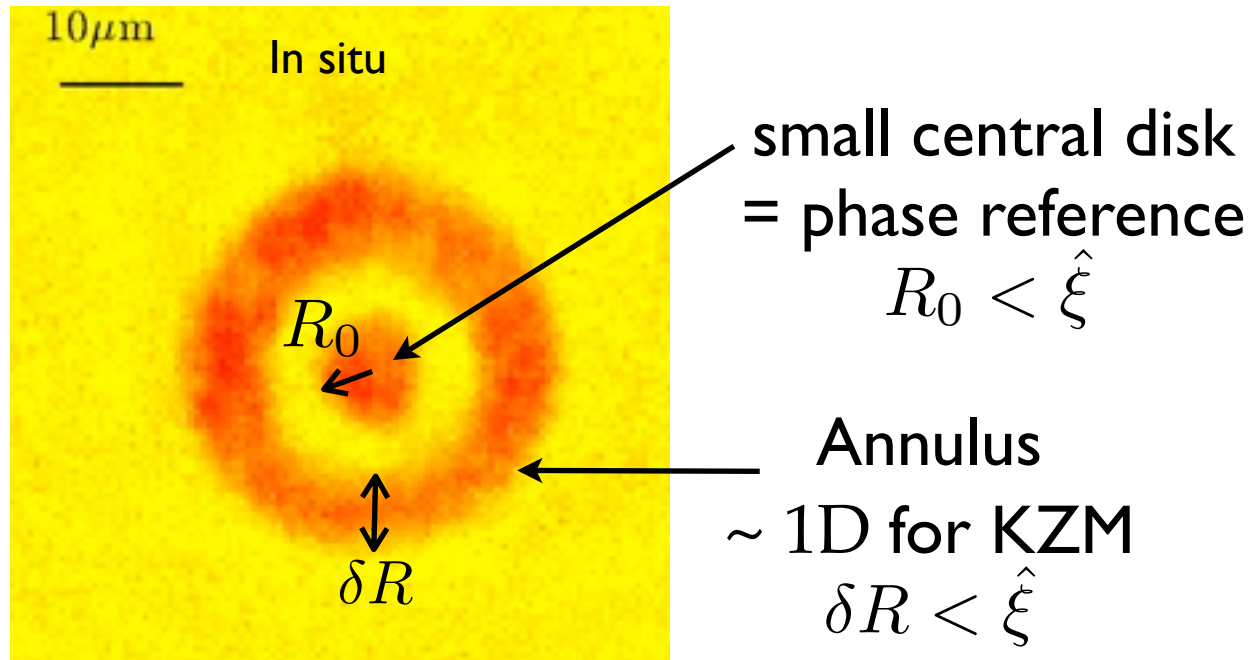
Similar quench through BEC_{\perp}

At freezing out:

- ♣ unique patch in the central disk
- ♣ 1D chain of phase patches in the annulus



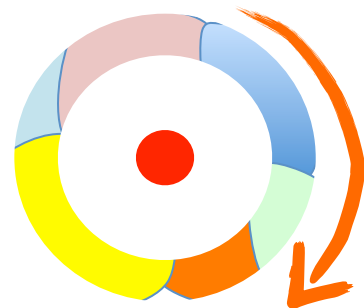
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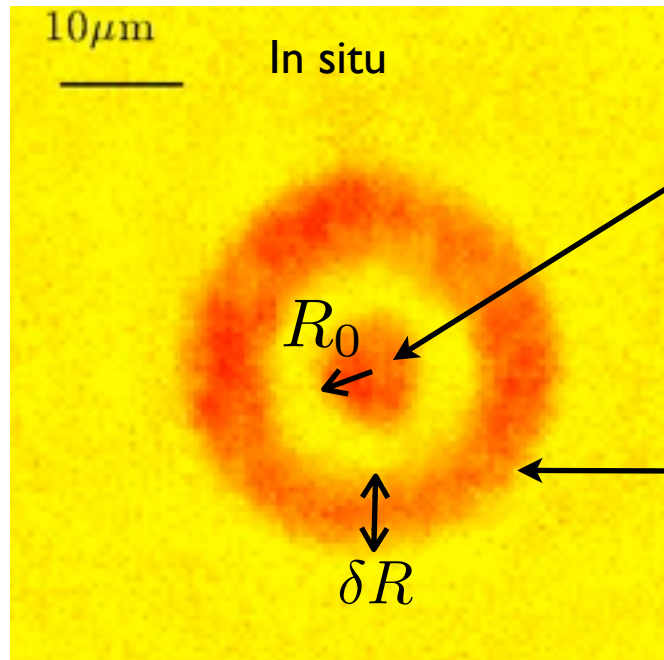


Merging of patches:

$\Rightarrow 2\pi n$ phase winding
= **Supercurrents**

$$n_w = \langle |n| \rangle \propto t_{\text{evap}}^{-d/2}$$

KZ supercurrents in an annulus.



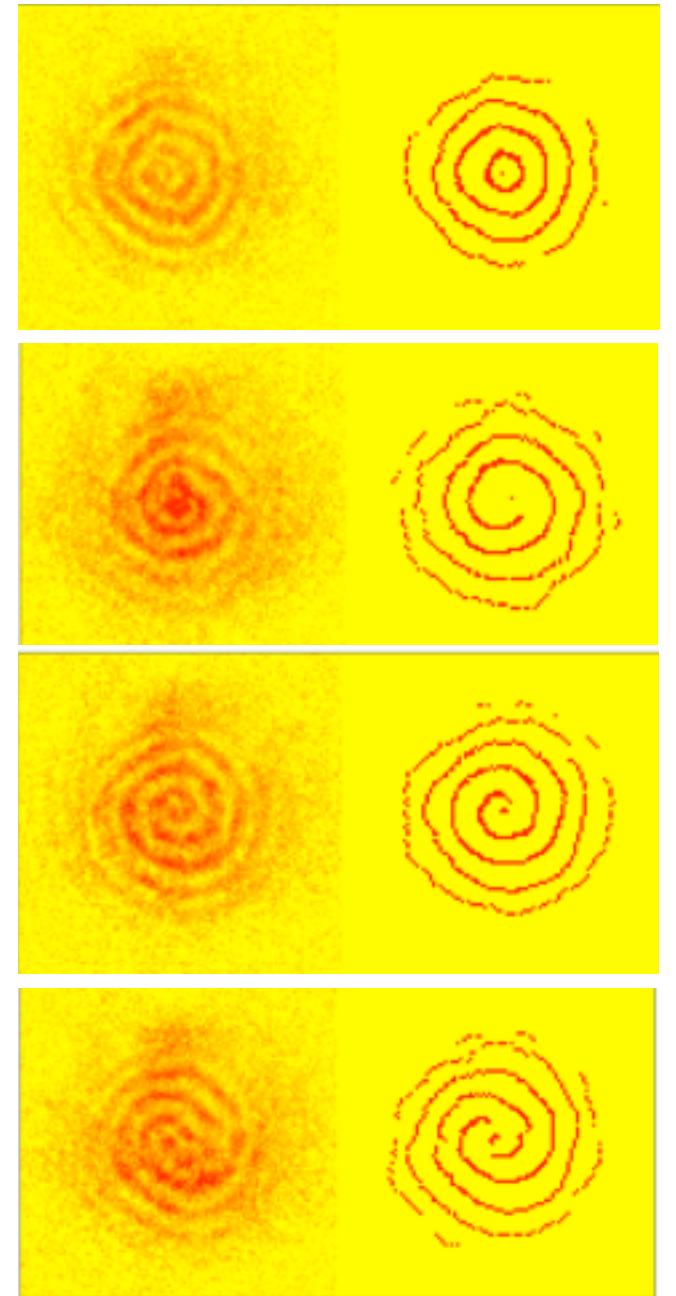
small central disk
= phase reference
 $R_0 < \hat{\xi}$

Annulus
 $\sim 1D$ for KZM
 $\delta R < \hat{\xi}$

2D TOF



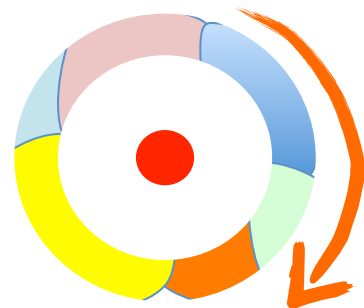
matter-wave
interference



Similar quench through BEC_{\perp}

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Merging of patches:

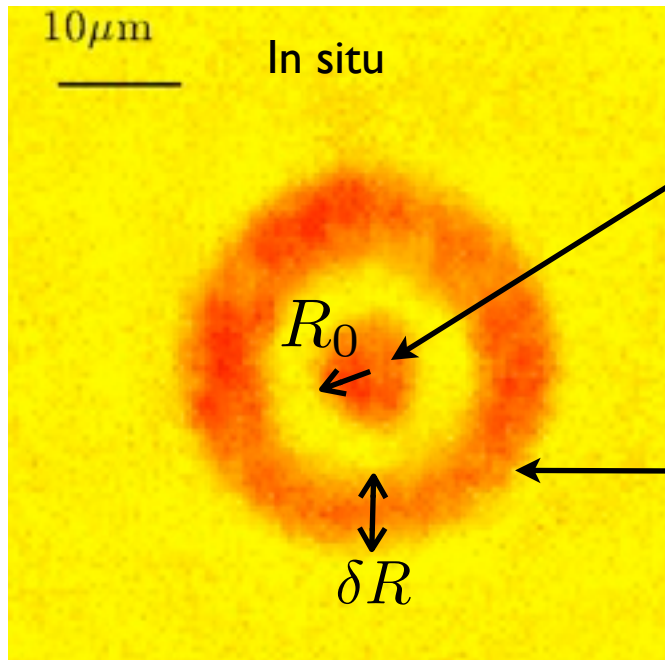
$\Rightarrow 2\pi n$ phase winding
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$$n_w = \langle |n| \rangle \propto t_{\text{evap}}^{-d/2}$$

Spiral pattern : $2n\pi$ phase winding in the annulus (+access to n)

KZ supercurrents in an annulus.

L. Corman, L. Chomaz & *al.*, PRL (2014)



small central disk
= phase reference

$$R_0 < \hat{\xi}$$

Annulus

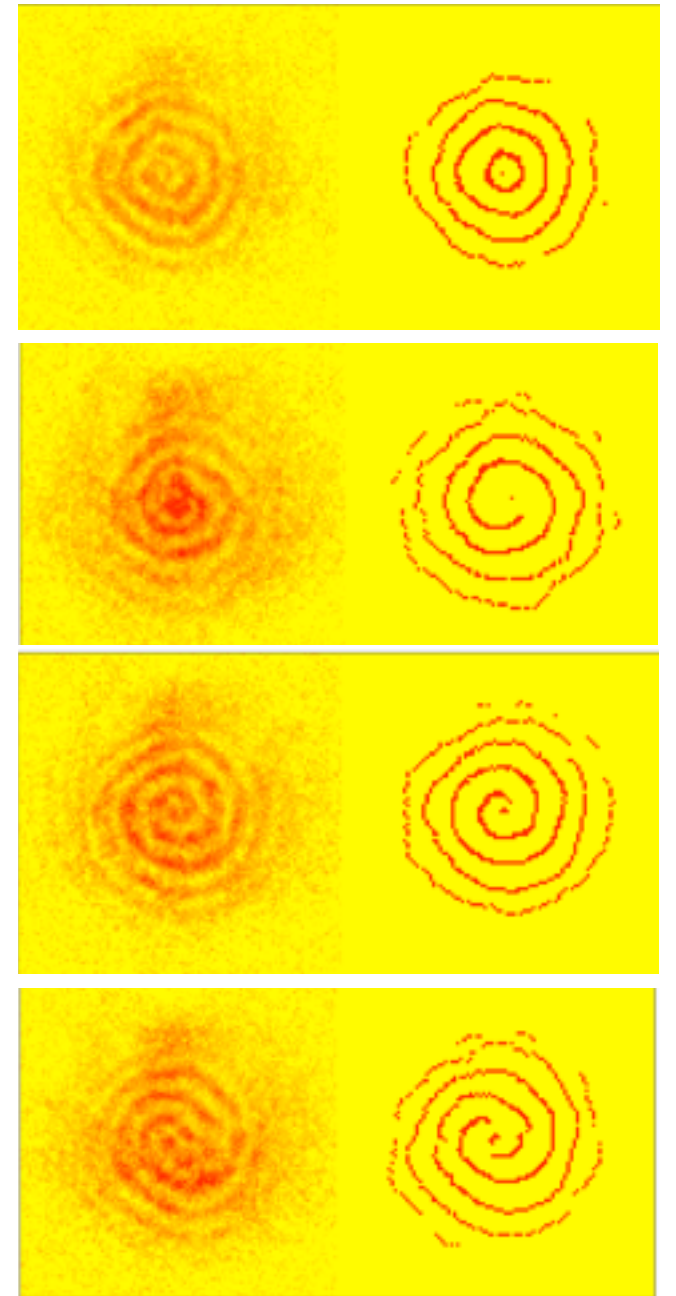
~ 1D for KZM

$$\delta R < \hat{\xi}$$

2D TOF



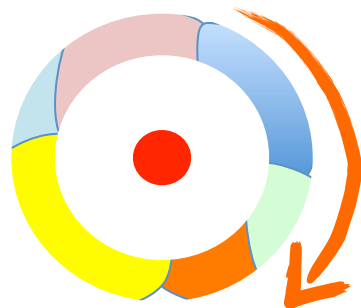
matter-wave
interference



Similar quench through BEC_\perp

At freezing out:

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- ♣ 1D chain of phase patches in the annulus



Merging of patches:

=> $2\pi n$ phase winding
= **Supercurrents**

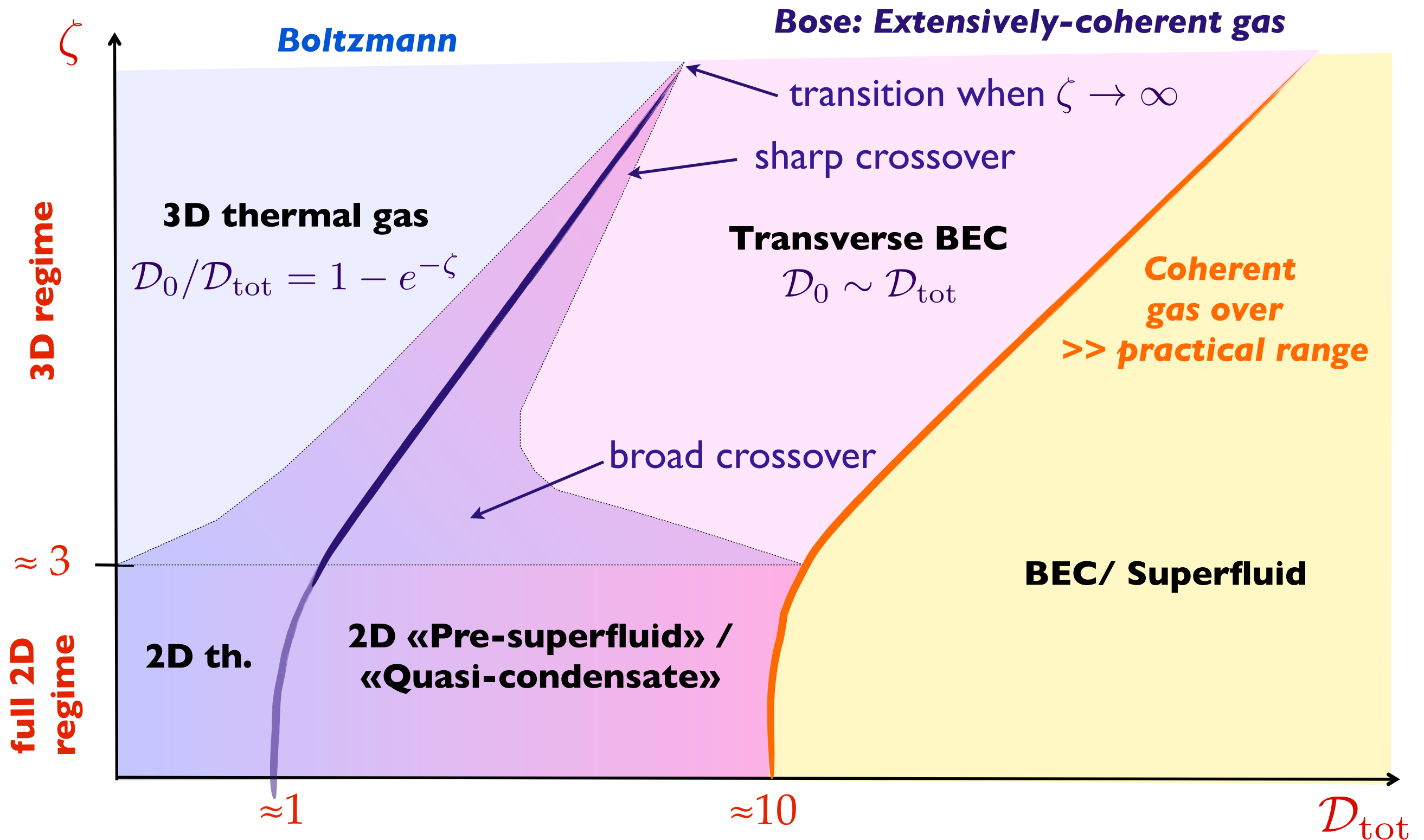
$$n_w = \langle |n| \rangle \propto t_{\text{evap}}^{-d/2}$$

Spiral pattern : $2n\pi$
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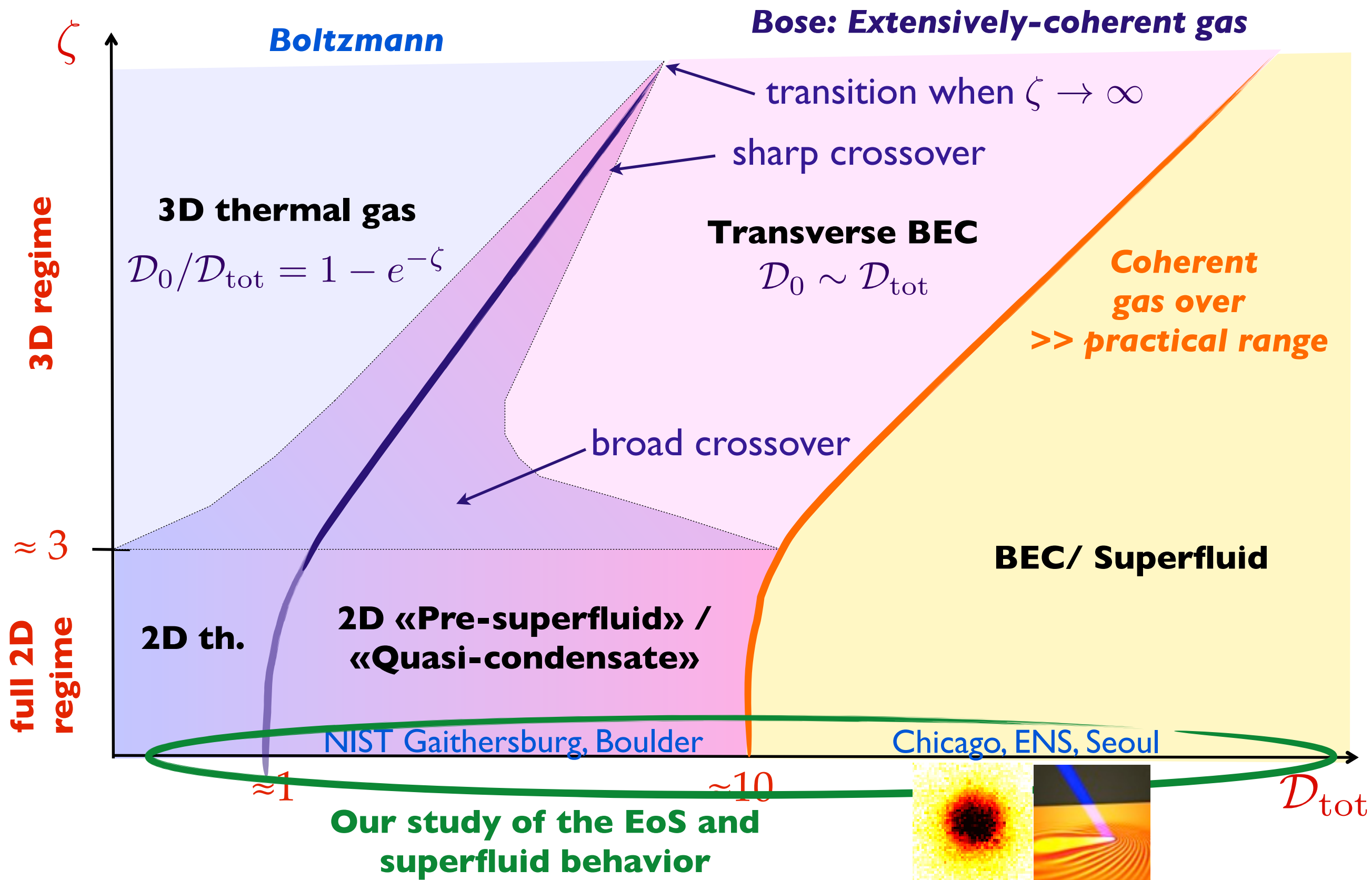
Experiments	d
Holes	0.35 (8)
Spirals	0.38 (12)

Theory, Model F: $d = 0.33$

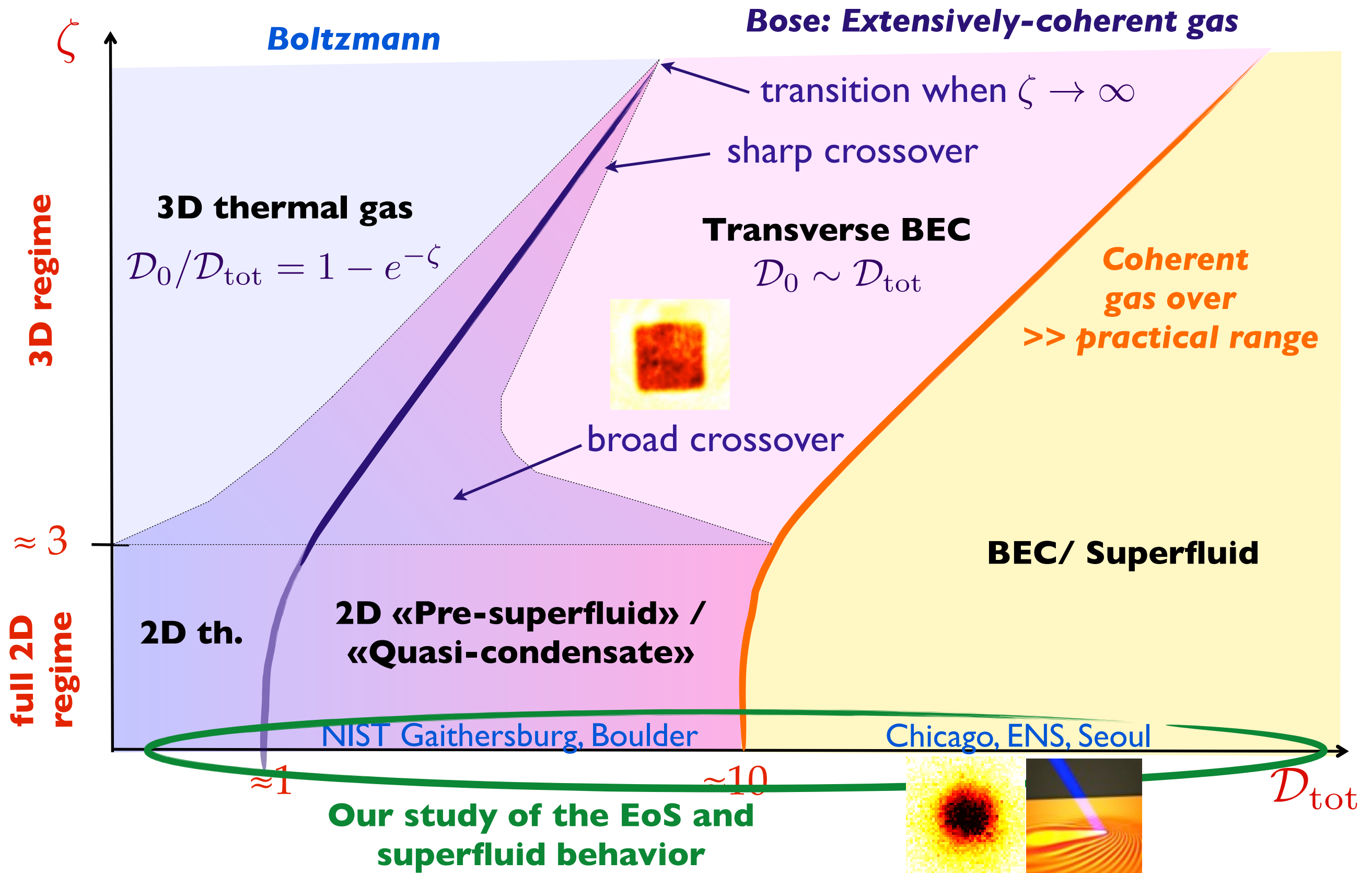
Summary



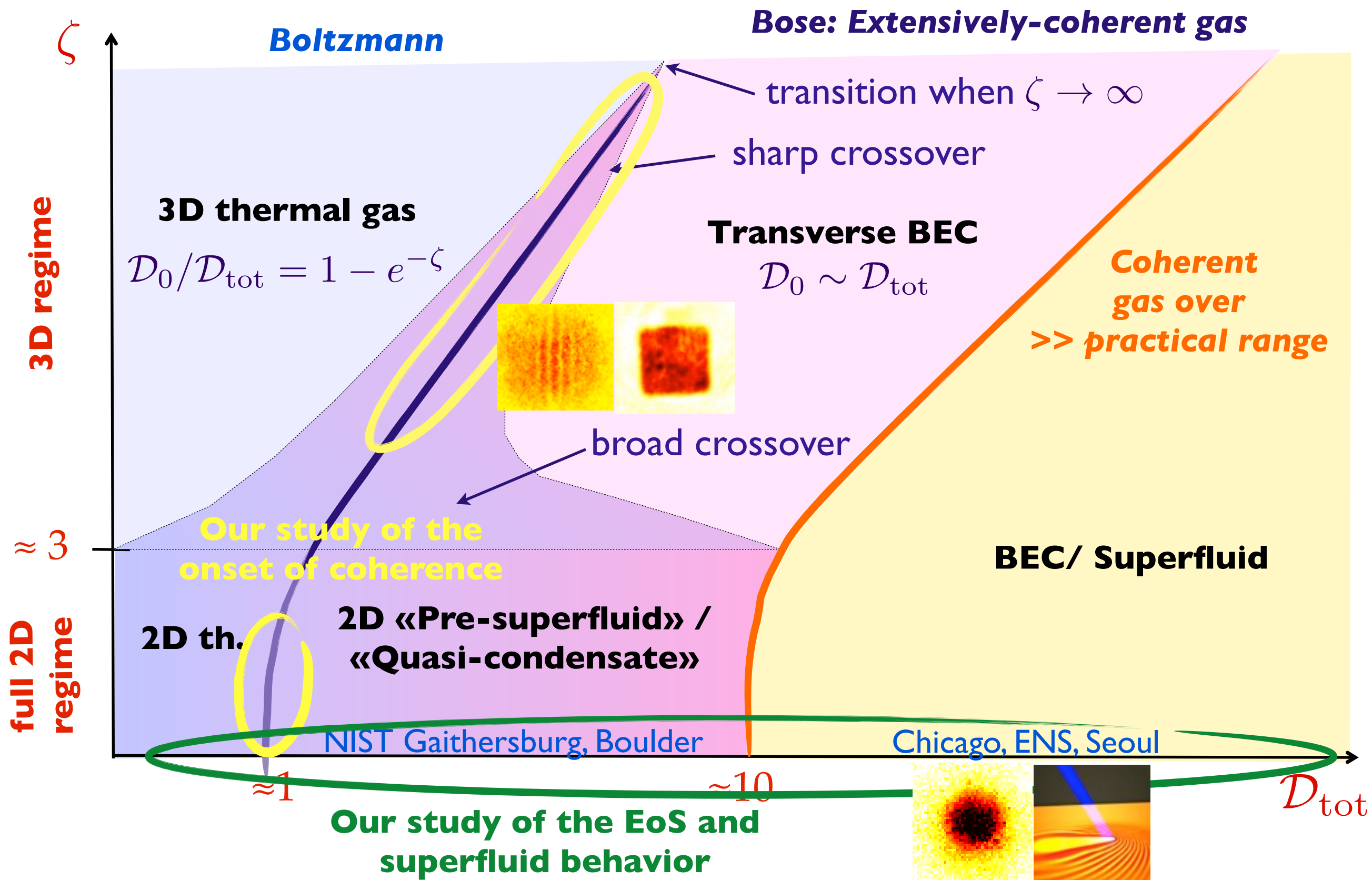
Summary



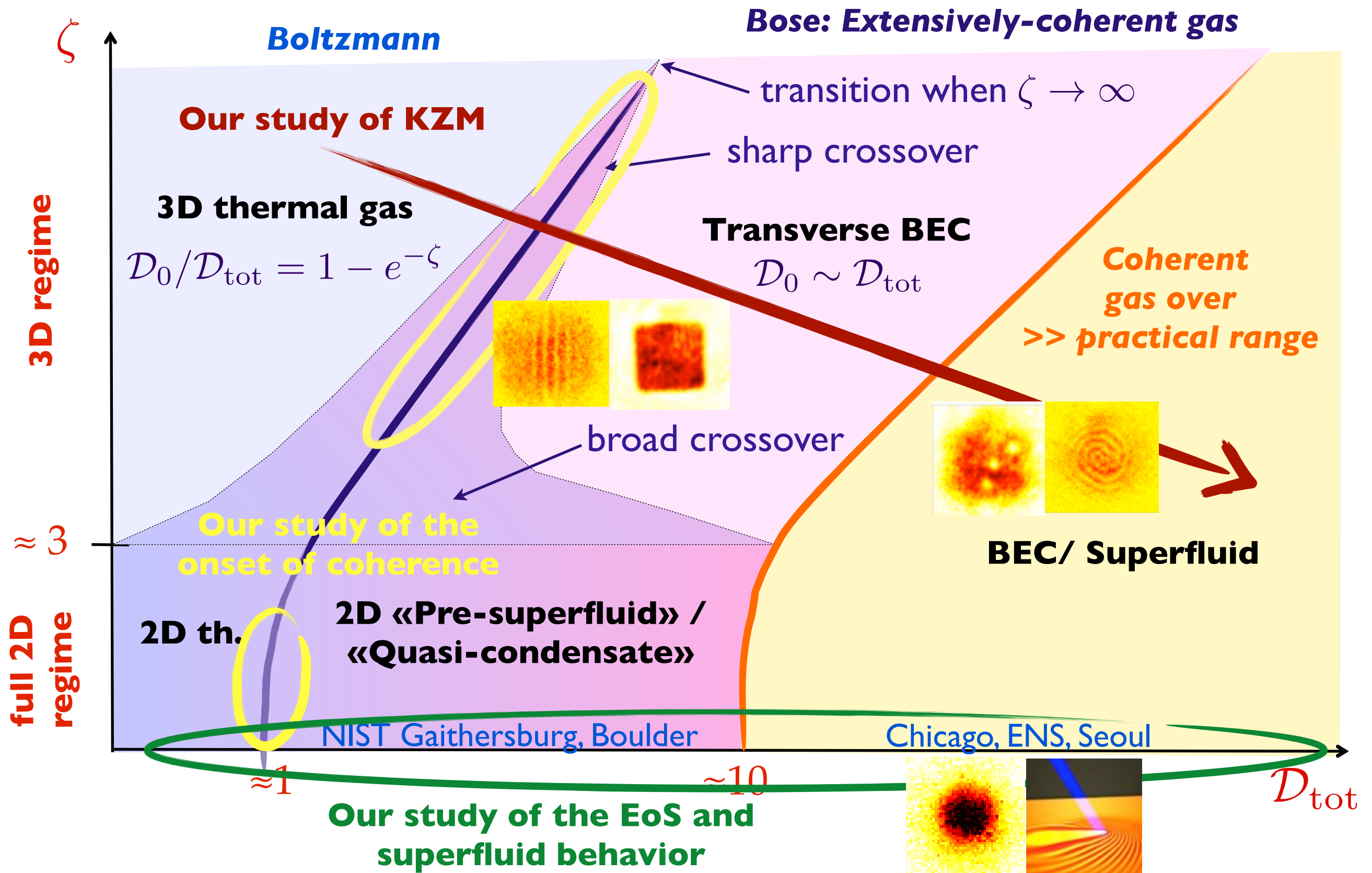
Summary



Summary



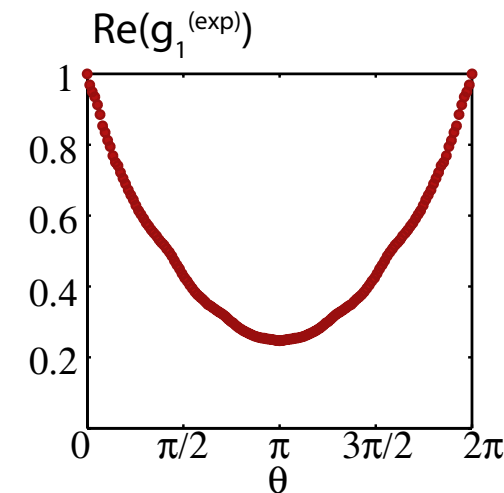
Summary



Outlook.

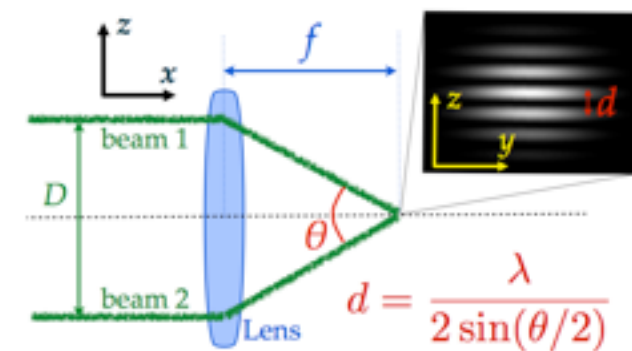
◆ Toward characterizing correlations and fluctuations:

- Characterization of G_1 : exponential vs. algebraic decay.
- Higher order correlation functions, e.g. G_2 (density fluctuations).



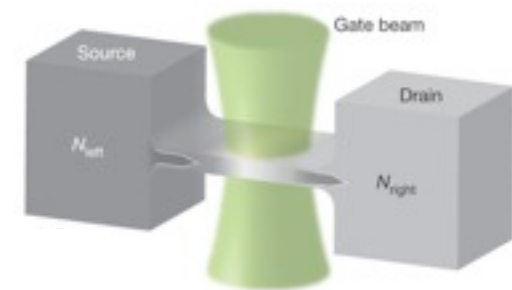
◆ Toward strongly interacting 2D gas in uniform geometry:

- Increase of ν_z : the accordion setup
- Regime where coherence established at BKT transition.
- New scaling expected from KZ mechanism.



◆ Toward other geometries, e.g. transport measurement:

- Two uniform reservoirs linked by a small channel.
- Study of superfluidity via transport measurement along the channel



Esslinger group

Thanks.

The Team:

Jean Dalibard
Jérôme Beugnon
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Kenneth J. Günter
Christof Weitenberg
Tom Bienaimé
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Rémi Desbuquois
Laura Corman
David Perconte
Benno Rem
Julian Leonard
Katharina Kleinlein
Jean-Loup Ville

The Group:

BEC:
Na, Yb, Dy
Gaz de Fermi:
Li, K-Li
+ The theory
...

The Lab

specially, the directors:
Paul Indelicato
Antoine Heidmann
+ its tutelles

L'X (teaching)

Linda Vary-Guevel

The technicians & administratives:

Mécanique, Electronique,
Matériaux, Magasin,
Secrétariats, Informatique,
Salle Blanche ...

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from ENS (Didier Courtiade)*

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for help in organizing*

The Jury:

Gabriele Ferrari
Bruno Laburthe-Tolra
Patrizia Vignolo
Chris Westbrook
JD & JB

The Family:

My parents
Pierrot & Lucile
Tonton Jean-Marc & Co.
Les Revels
Les Chomaz, Borel, Lopez

The Friends:

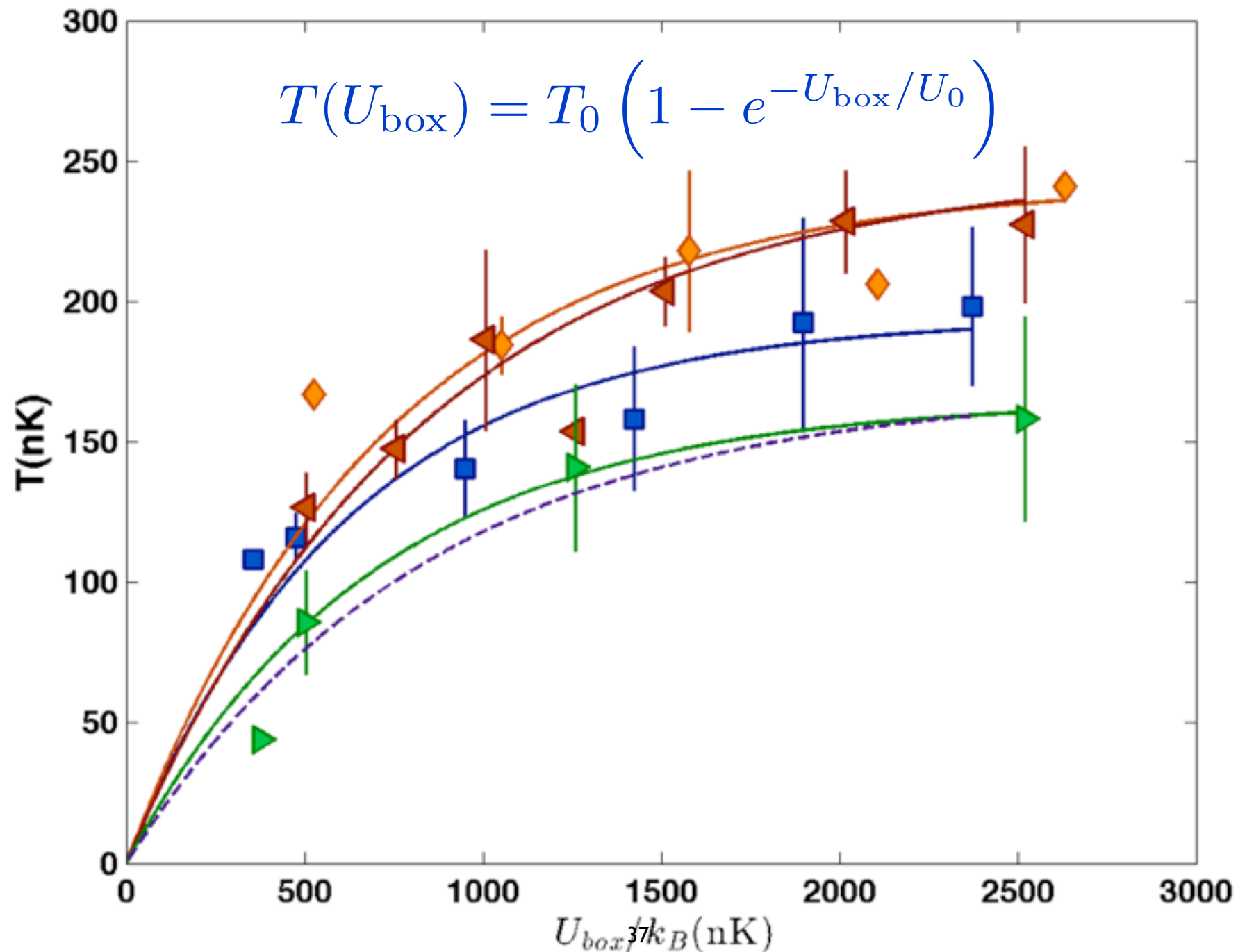
The atomic physicists
The Master «LKB»
The «Climbers» & co.
The «Caennais»
The unclassified
...

**To all the
people
present
today**



Temperature Measurement (I)

ToF measurement for very weakly gas configurations : N } $\xrightarrow[\text{Bose law ideal gas}]{\text{All quantum, 3D}}$ $\left\{ \begin{array}{l} Z = e^{\beta\mu} \\ T \end{array} \right.$
 Δv

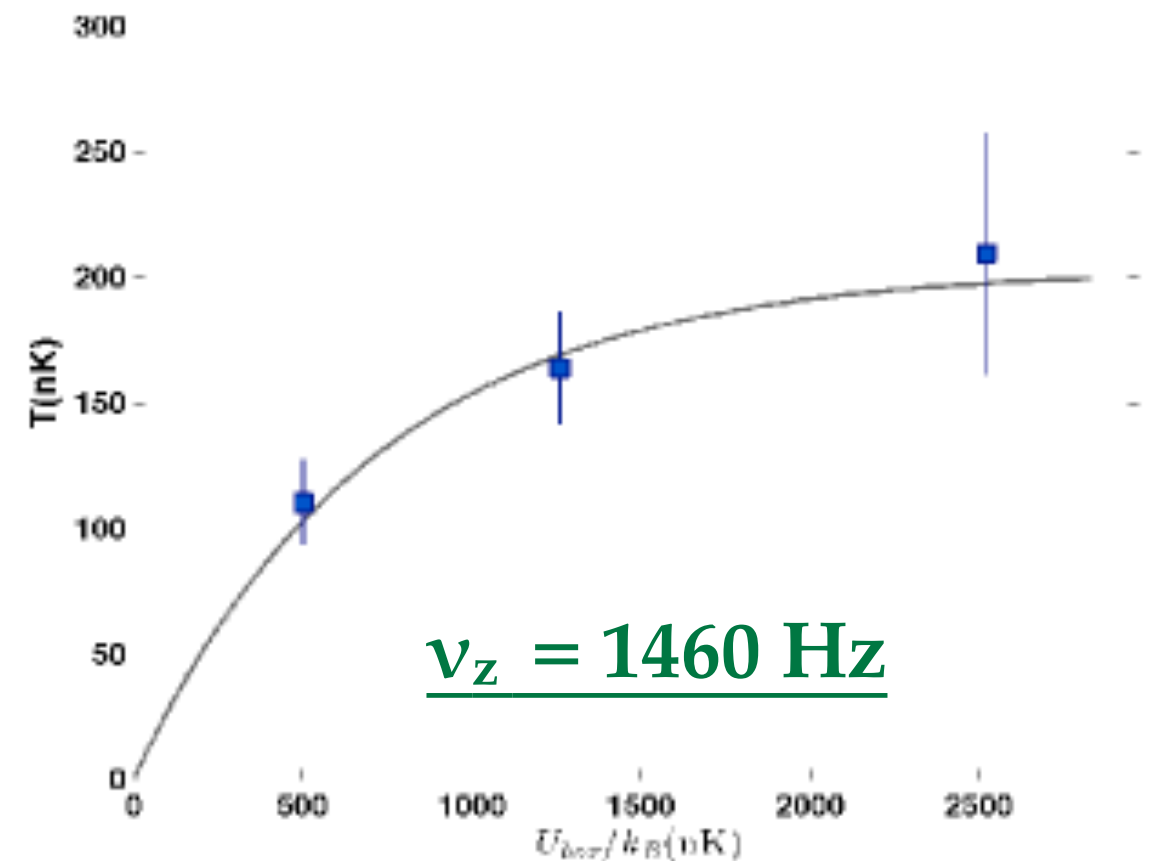
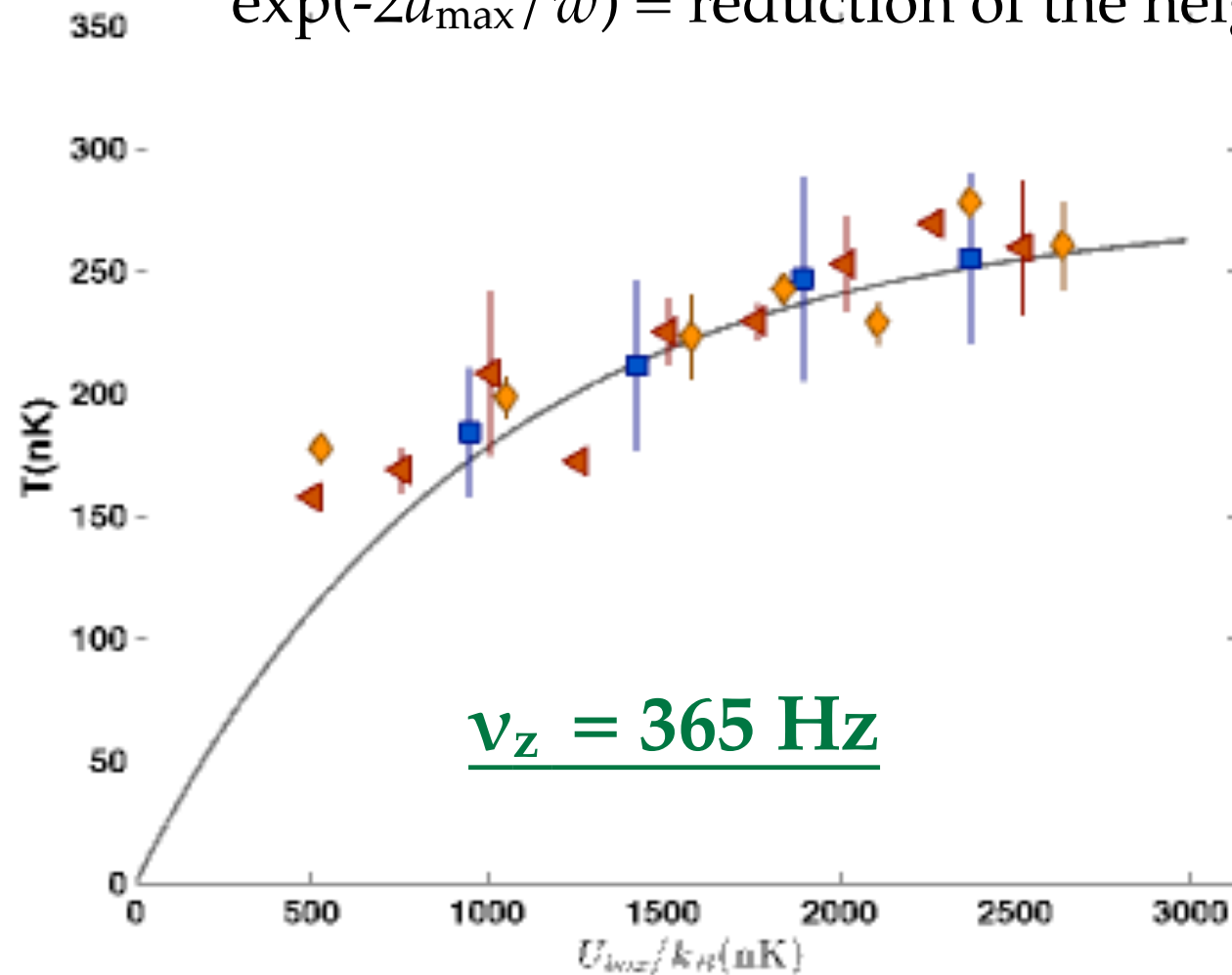


Temperature Measurement (II)

Renormalize all T and U by $\exp(2d_{\max}/w)$, d_{\max} = maximal distance to trap center:

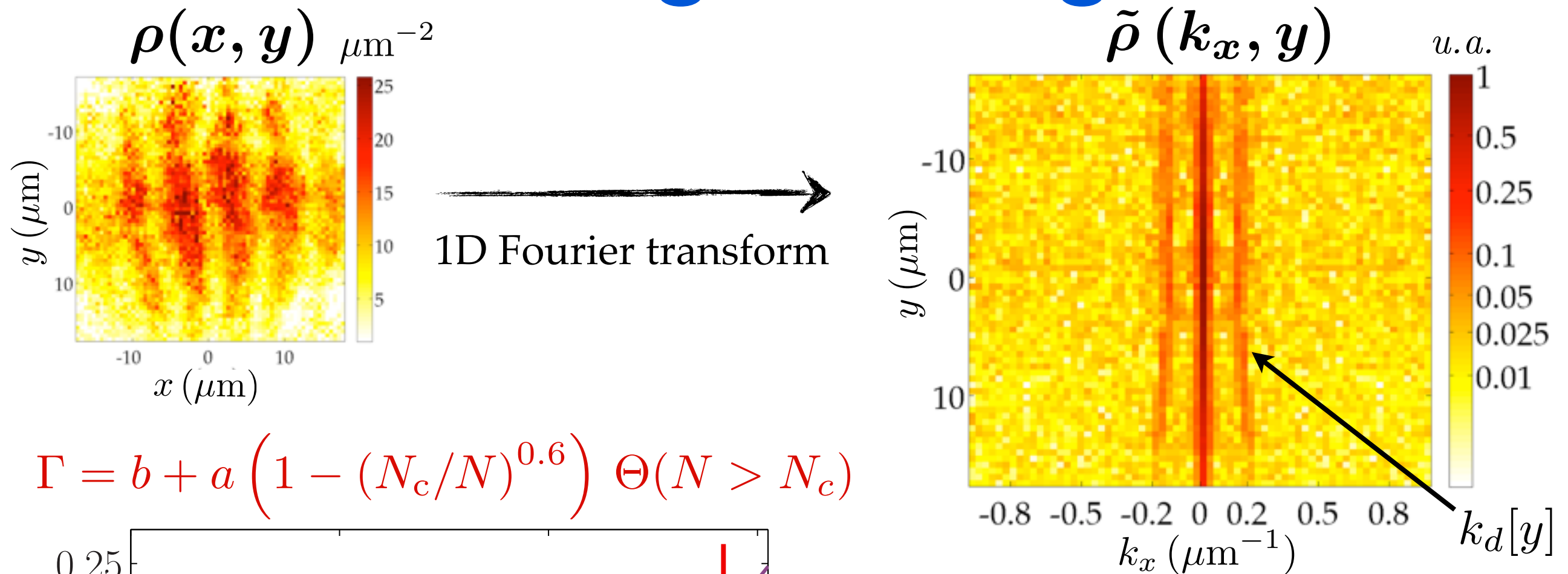
w = waist of the 2D trap beam (Hermite-Gauss and box trap)

$\exp(-2d_{\max}/w)$ = reduction of the heights of both traps compare to the center.

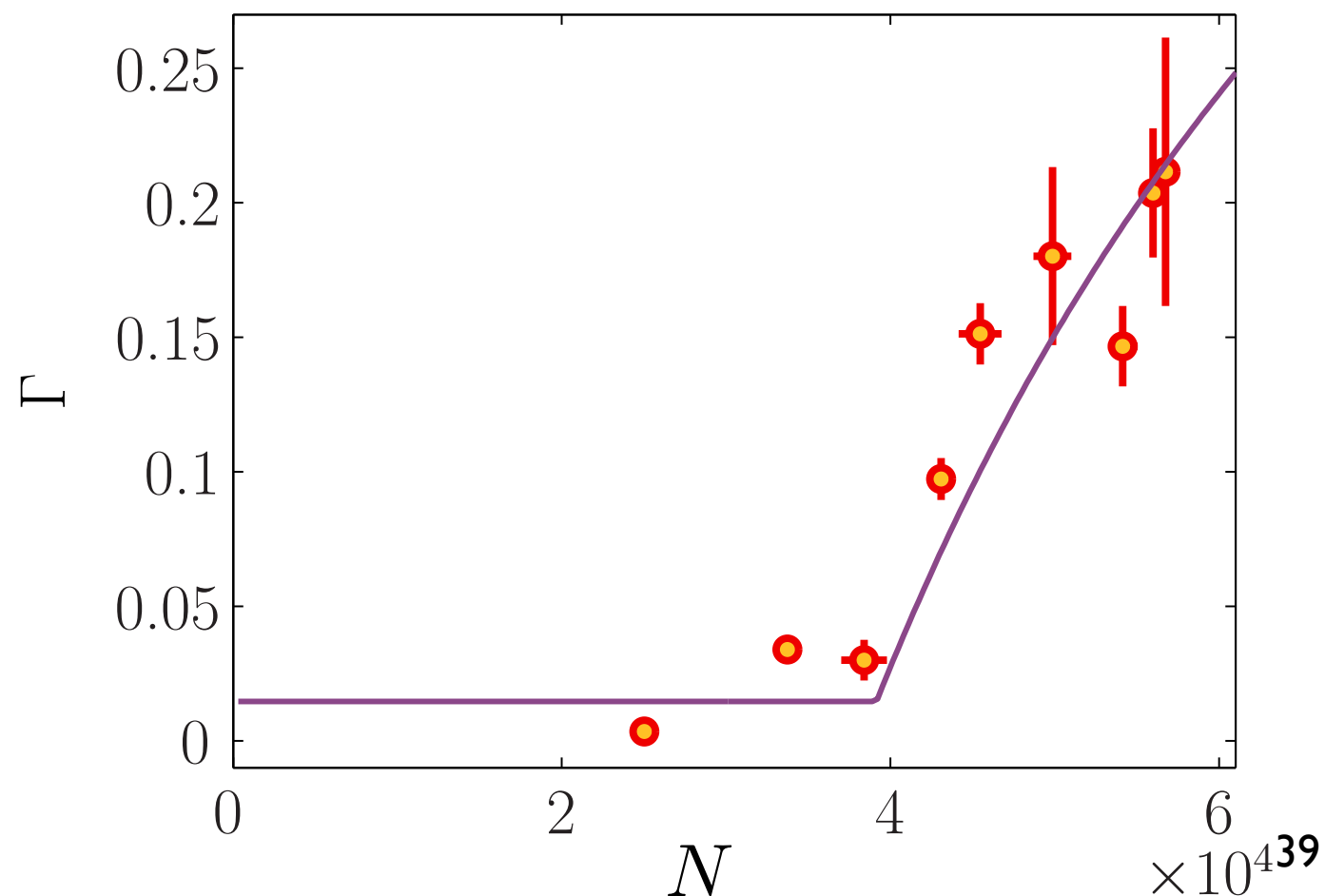


	U_0 / k_B	T_0	η
$\nu_z = 365 \text{ Hz}$	969 (75) nK	275 (8) nK	3.49 (25)
$\nu_z = 1460 \text{ Hz}$	712 [115] nK ₃₈	203 (18) nK	3.50[25]

Characterizing the fringe contrast



$$\Gamma = b + a \left(1 - (N_c/N)^{0.6} \right) \Theta(N > N_c)$$



❖ 1-Body corr. on complex fringe contrast:

$$\gamma(d) = | \langle \tilde{\rho}[k_p(y), y] \tilde{\rho}^*[k_p(y+d), y+d] \rangle |$$

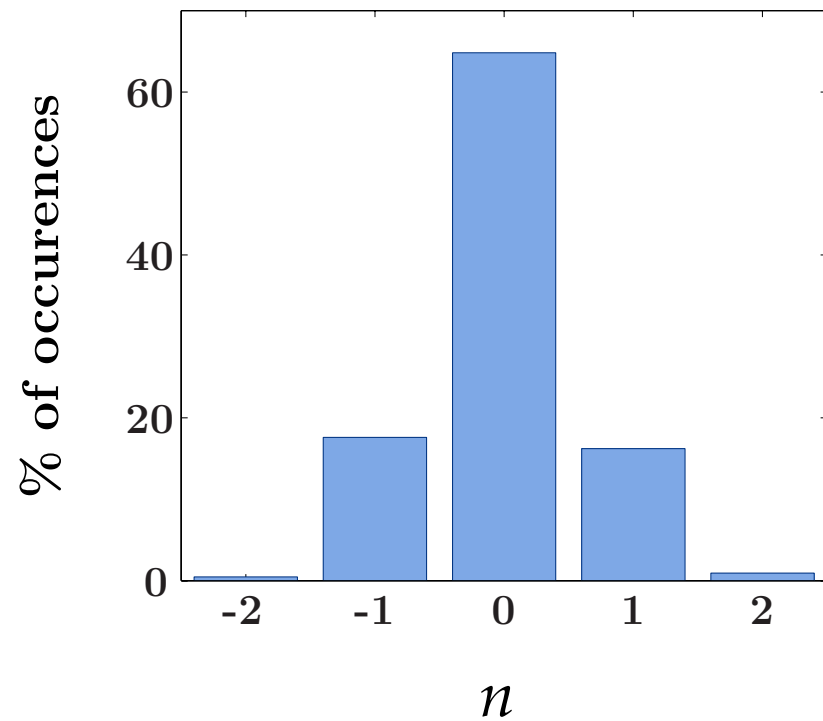
$$\infty \text{ 1D gases: } \gamma(d) = |G_1(d)|^2$$

❖ Look for extended coherence:

$$\Gamma = \langle \gamma(d) \rangle \quad 2 \mu\text{m} < d < 5 \mu\text{m}$$

$$[\text{sup}(\lambda_T) < 2 \mu\text{m}]$$

Kibble Zurek in an annulus



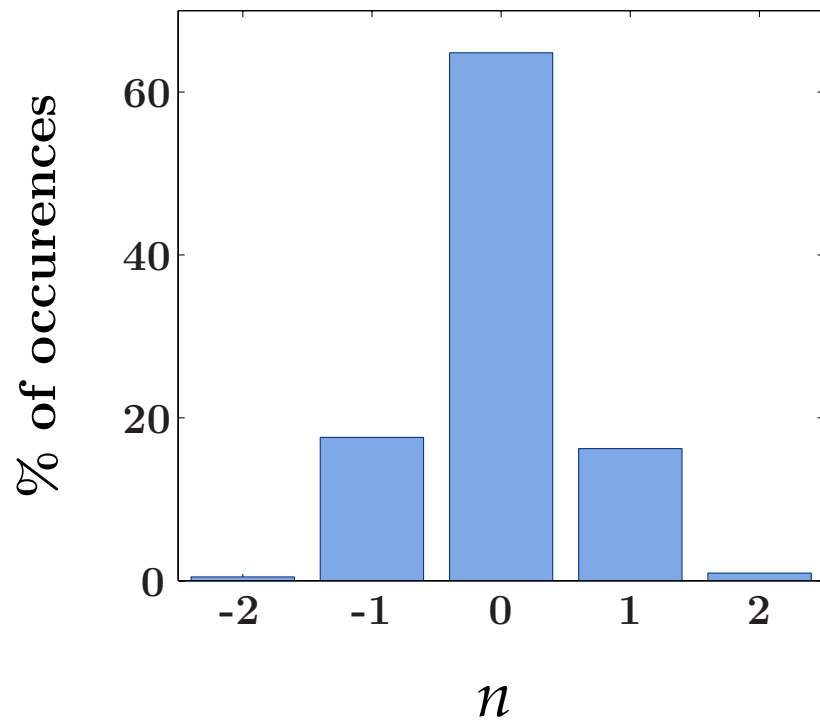
Stochastic origin:

random number of windings between -2 and 2
no bias on winding direction $\langle n \rangle = 0.001(12)$

Dynamic origin:

n_w not compatible with thermal predictions

Kibble Zurek in an annulus

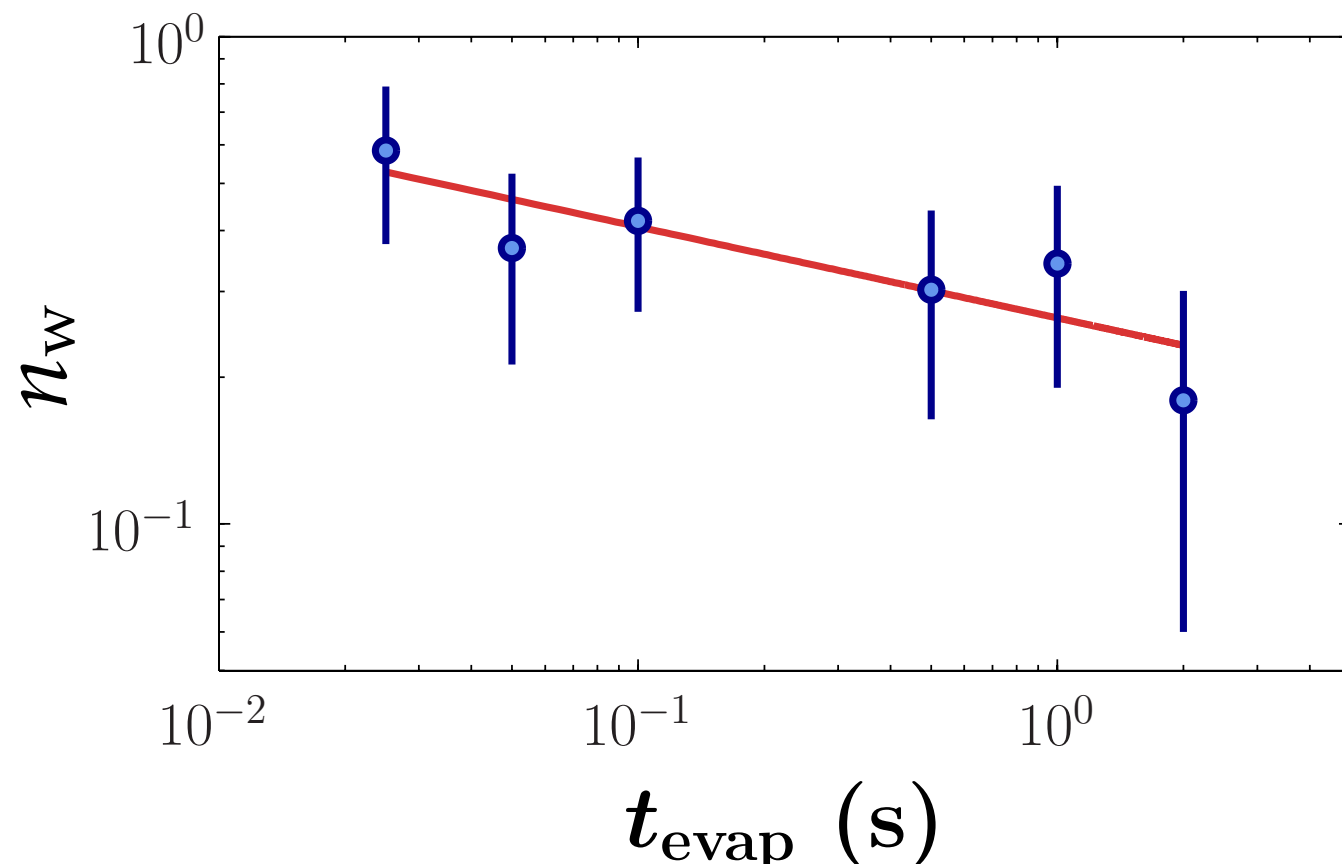


Stochastic origin:

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n_w not compatible with thermal predictions



$$n_w \propto t_{\text{evap}}^{-d/2}$$

$$d = 0.38(12)$$

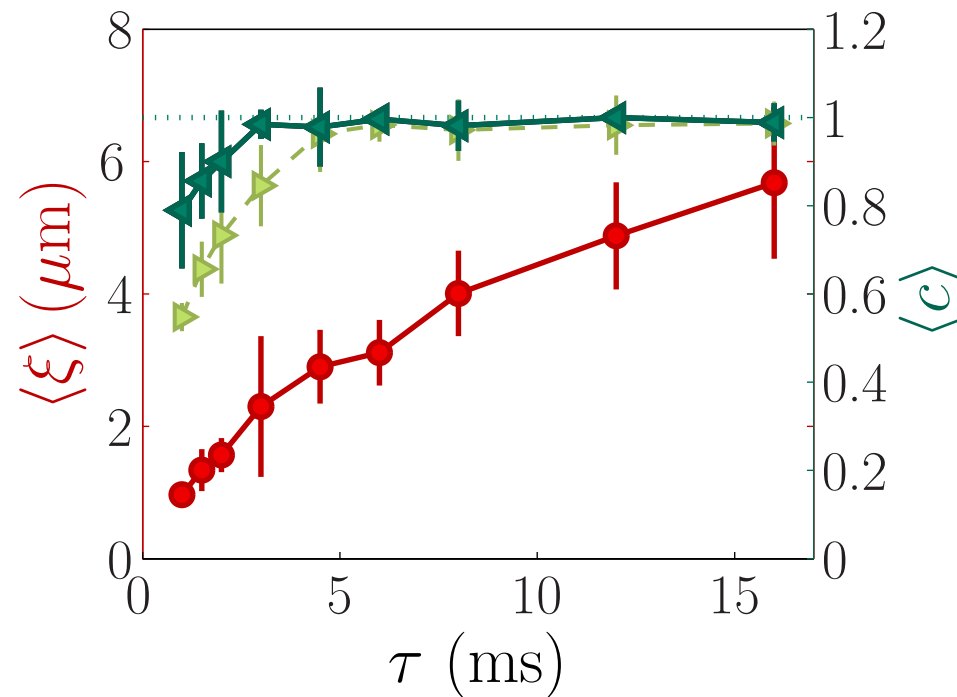
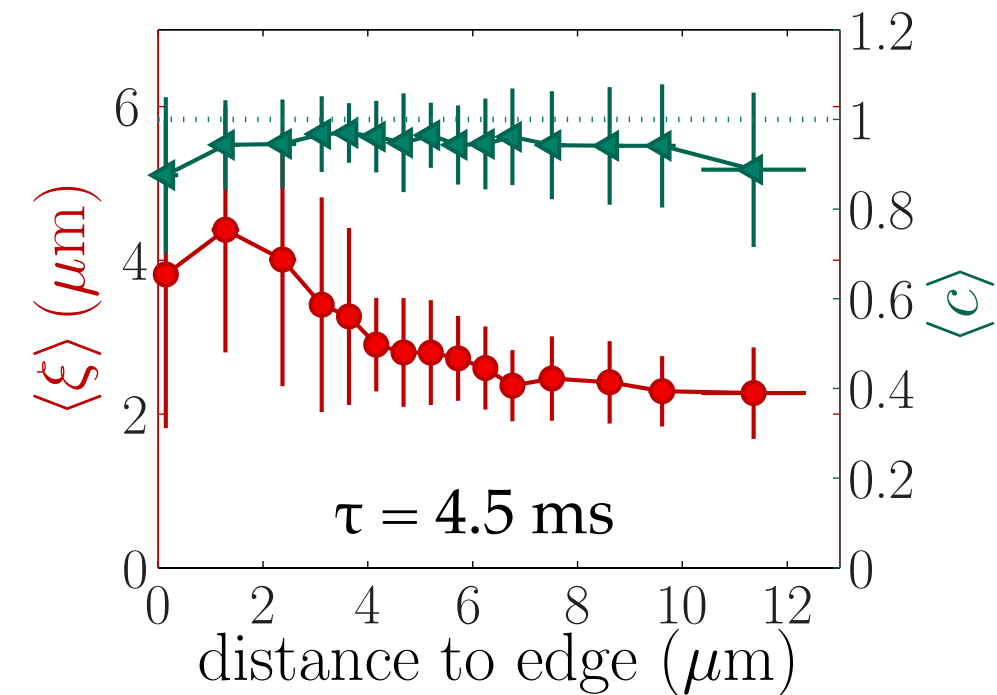
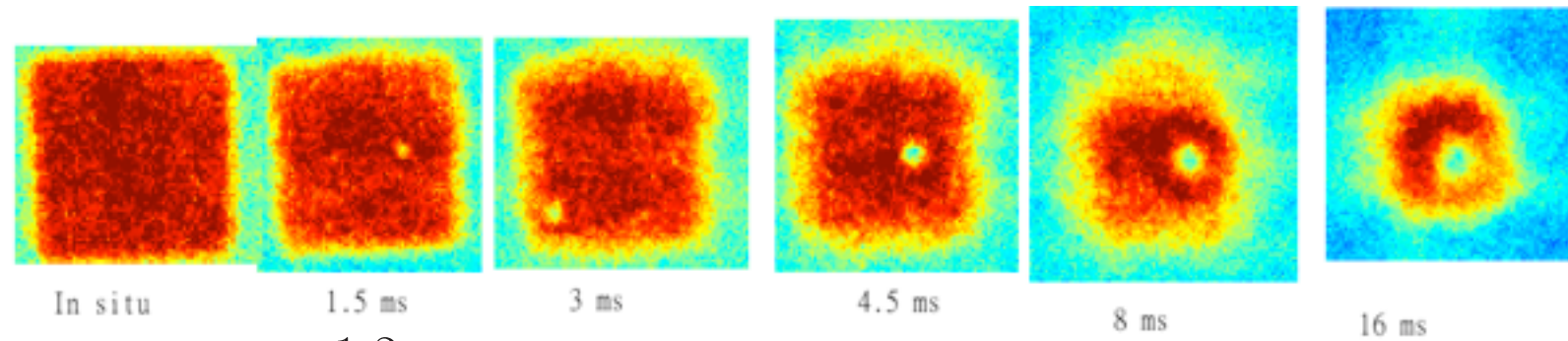
Reminder:

KZM for
3D BEC

	d
MF	0.25
F Model	0.33

no evidence for a breakdown
of KZM for 3D BEC (but no
counter-evidence either...) ₄₀

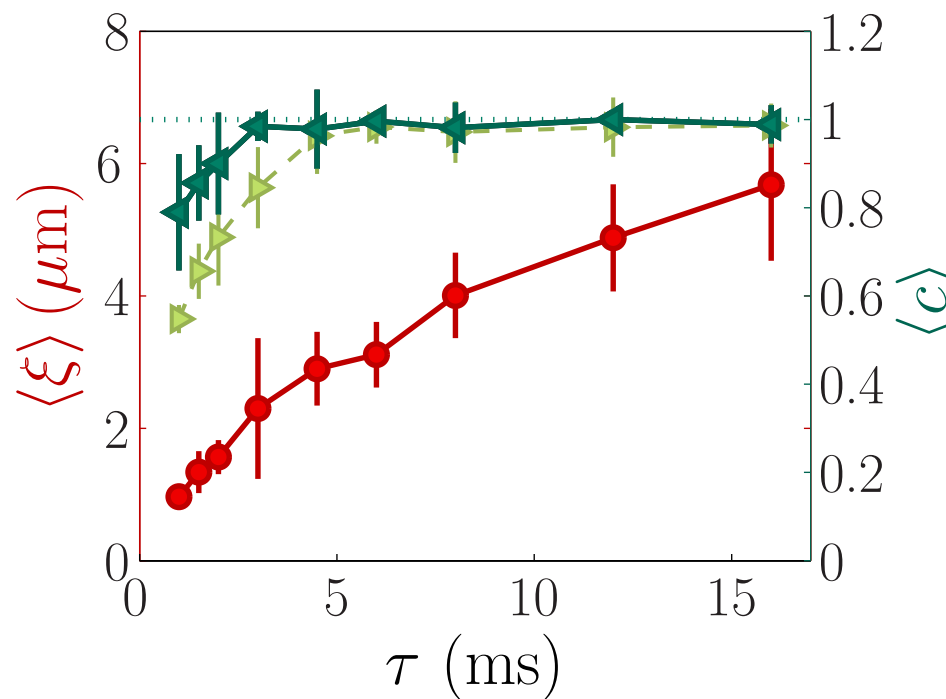
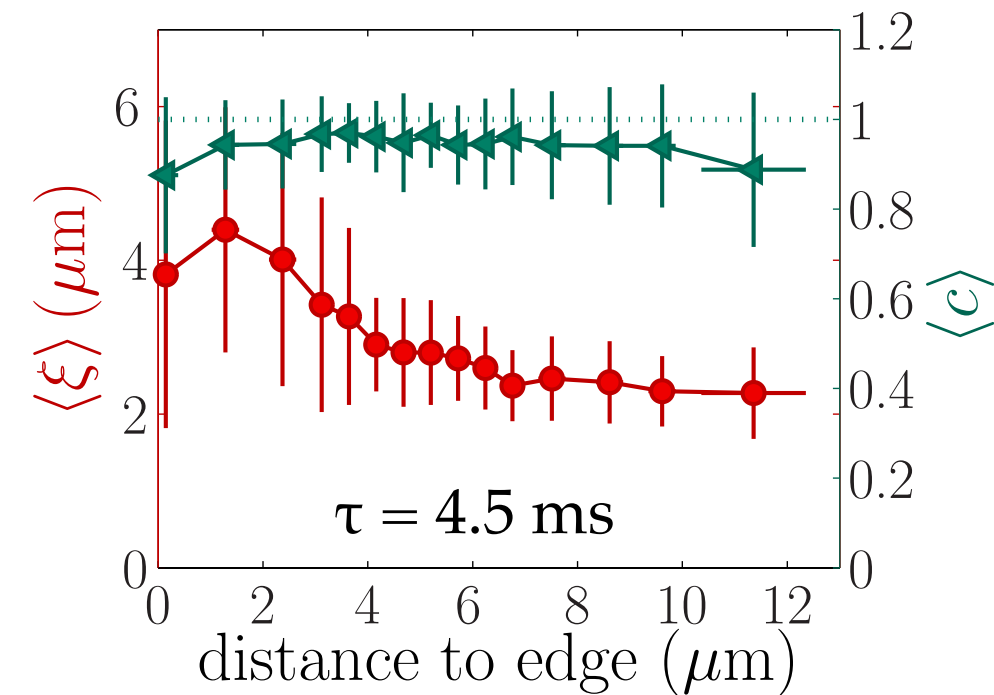
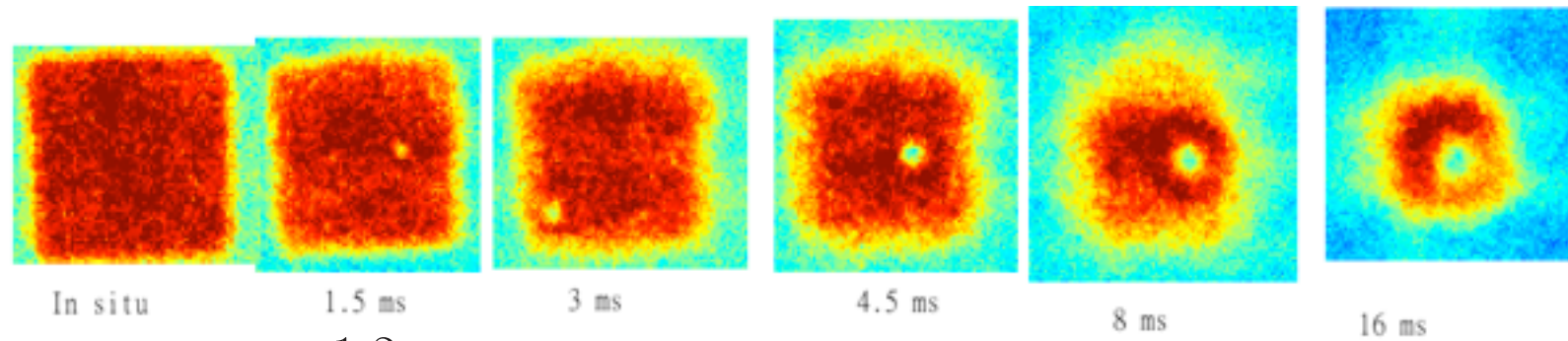
Direct Observation of vortices (II)



similar properties at a given τ
+ high contrast

constant contrast and
increasing size with τ

Direct Observation of vortices (II)

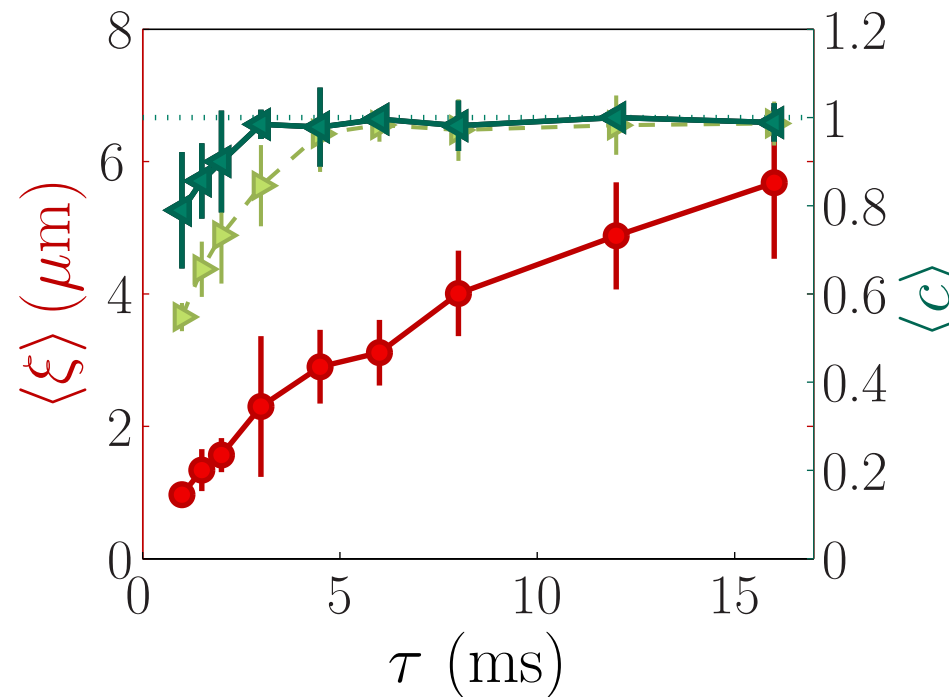
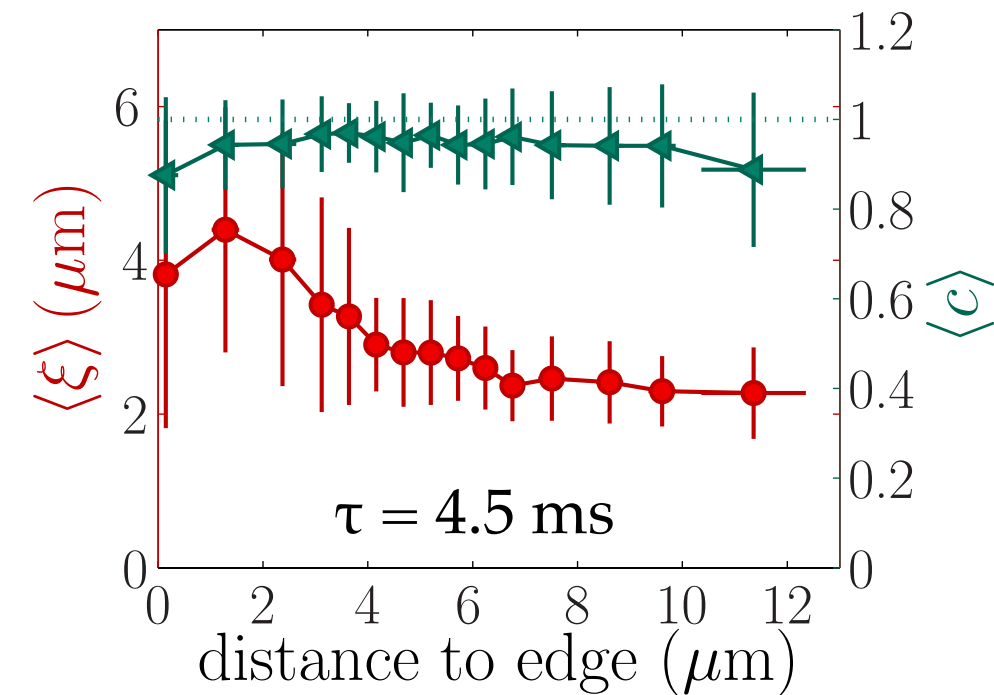
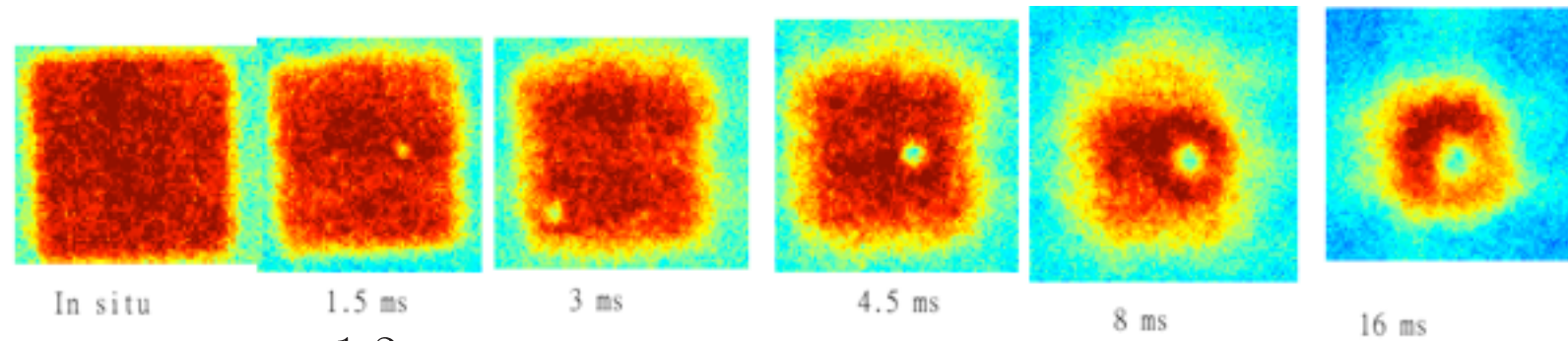


similar properties at a given τ
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constant contrast and
increasing size with τ

Hole Nature:
= single vortices
 \neq phonons
 \neq pairs of vortices

Direct Observation of vortices (II)



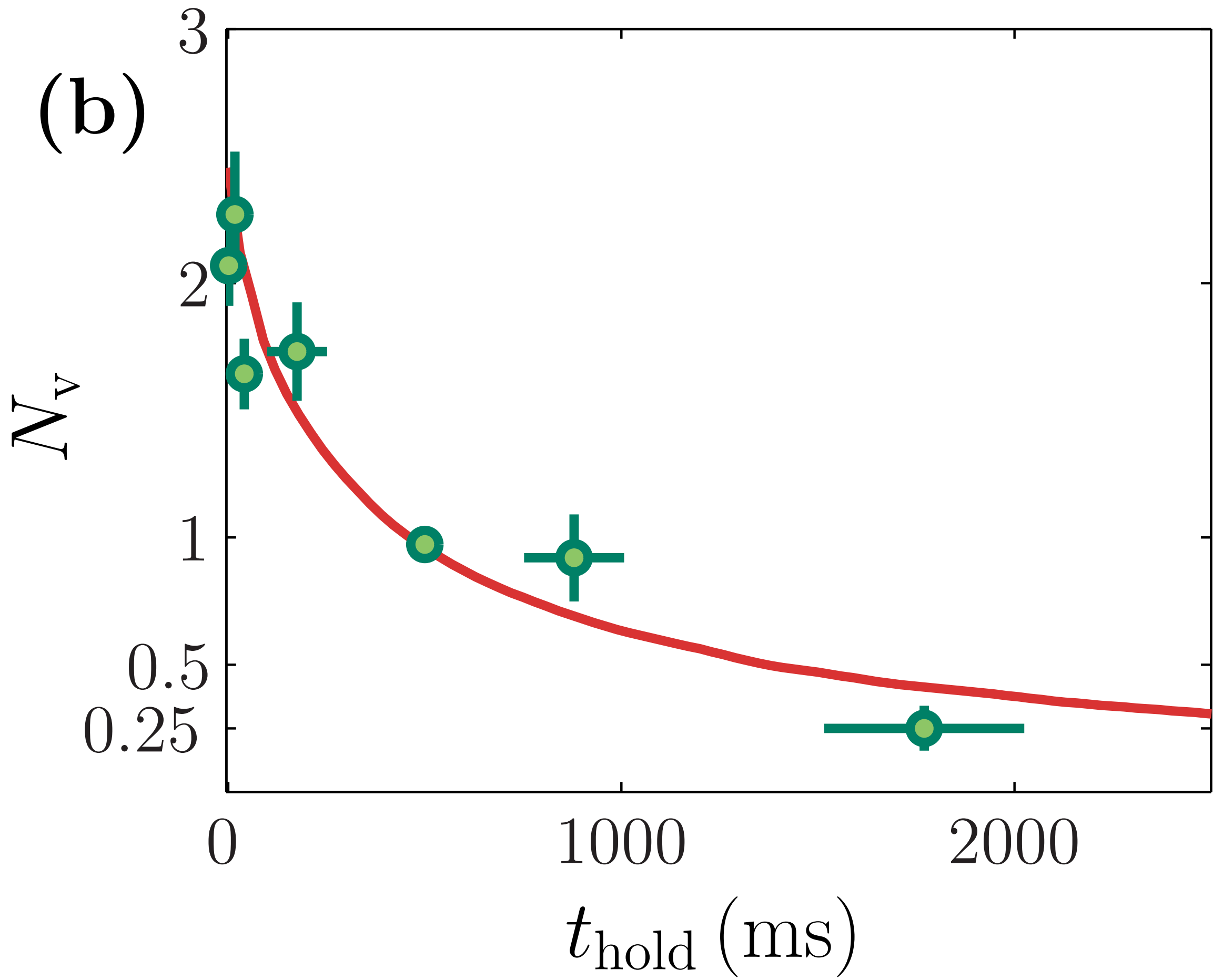
Hole Nature:
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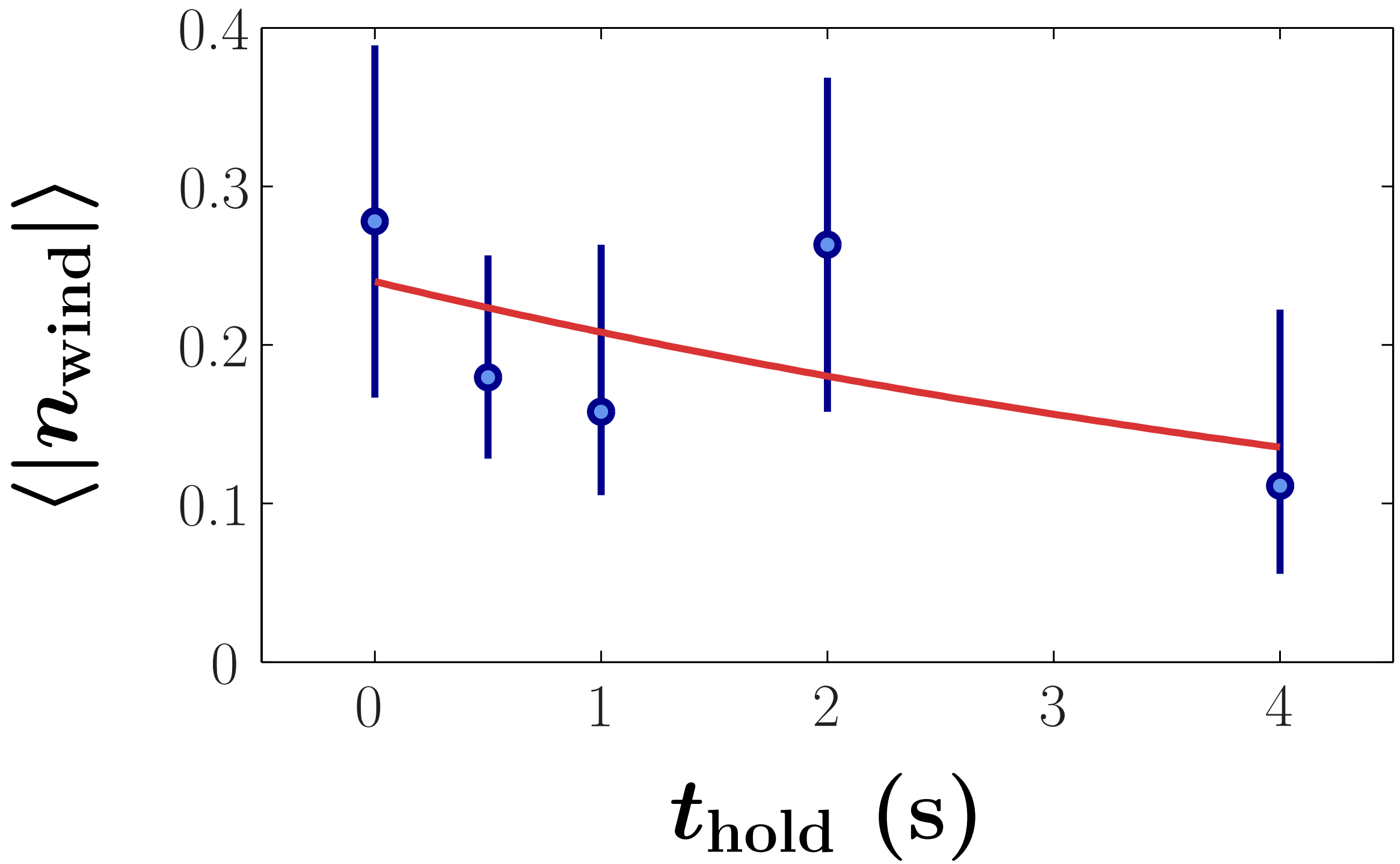
similar properties at a given τ
 + high contrast

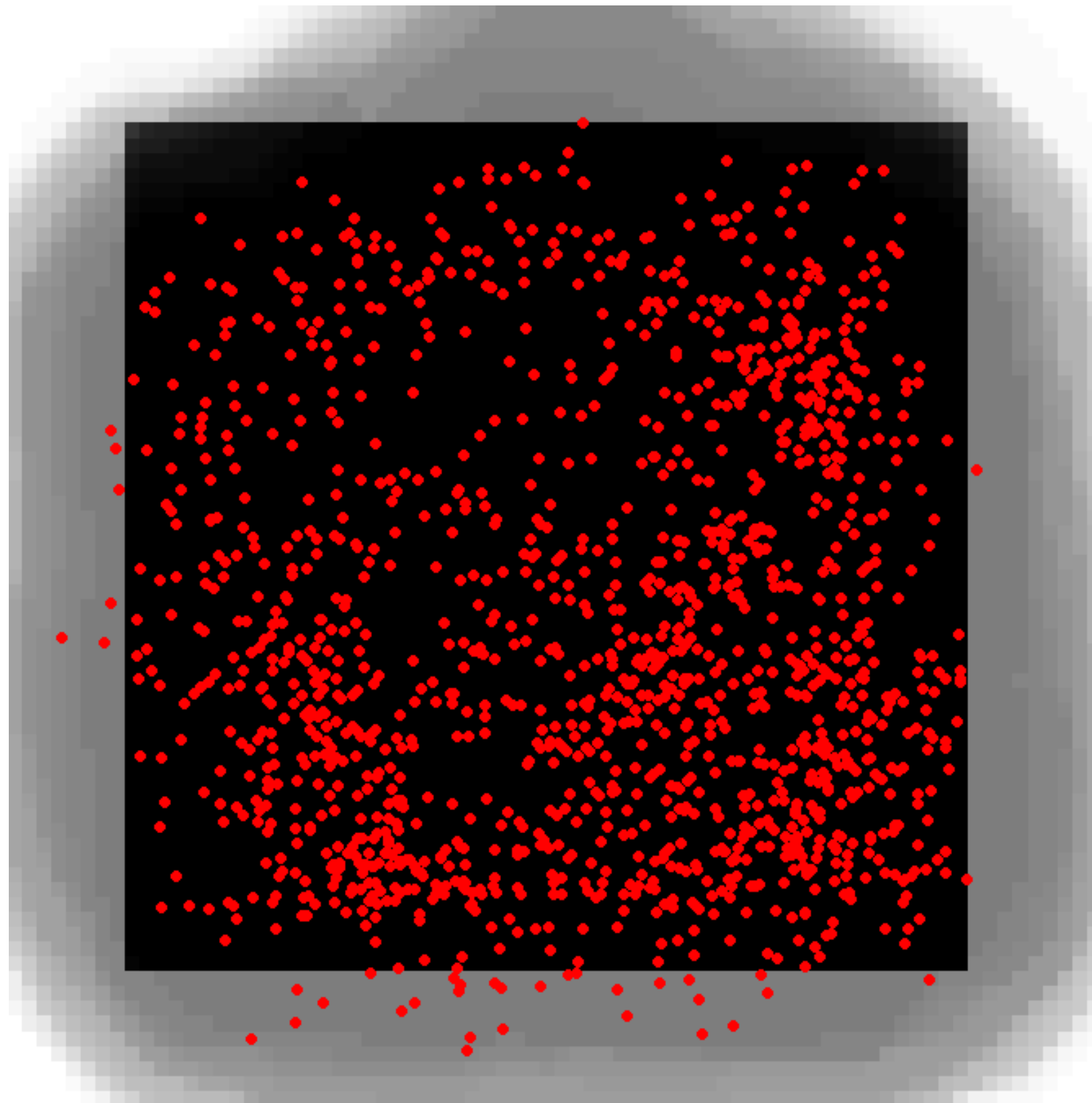
constant contrast and
 increasing size with τ

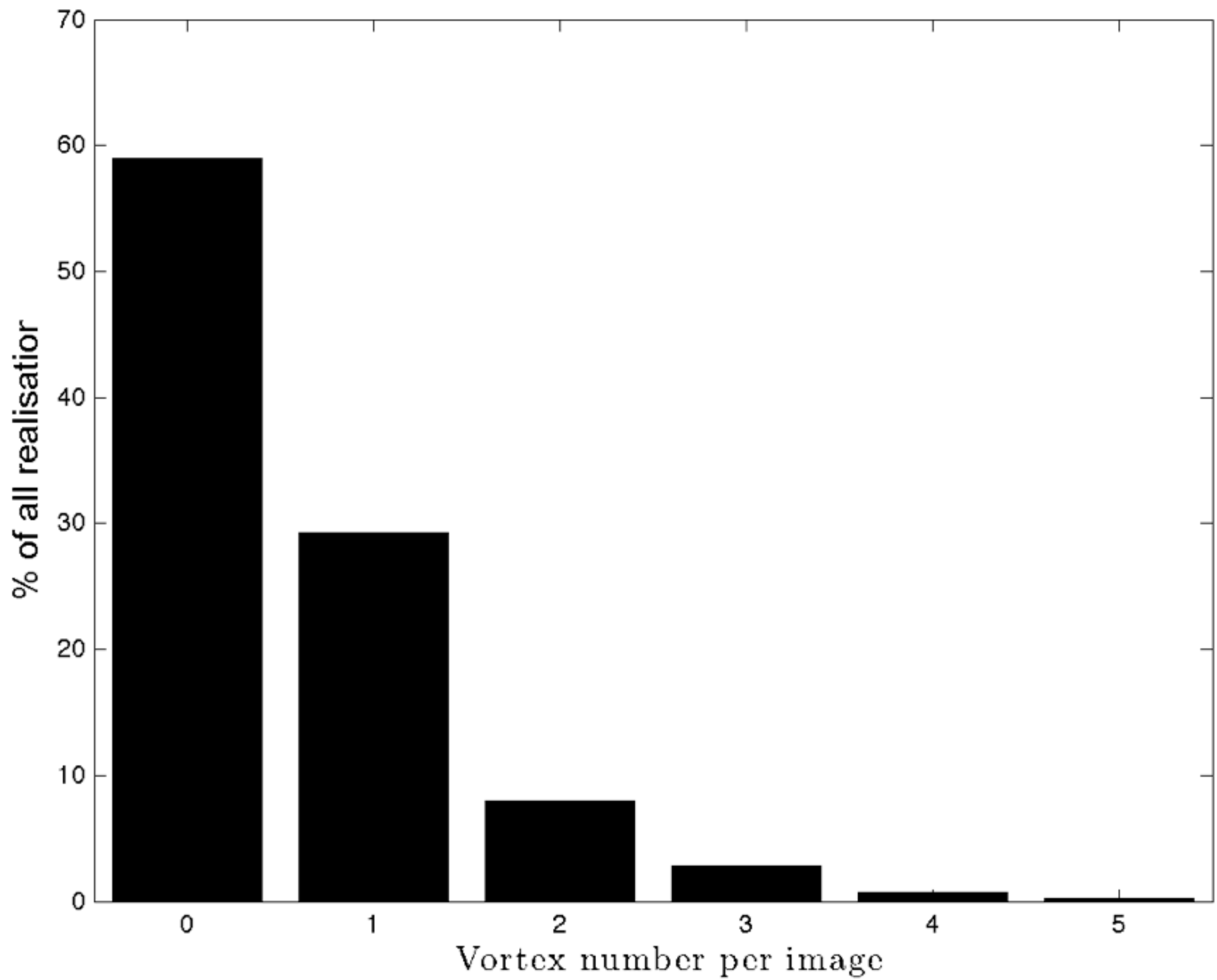
Dynamical origin:

- ❖ Equilibrium expectation at final PSD (> 100) = vanishingly small mean vortex number N_v . Experimentally $N_v \approx 0.6$
- ❖ BKT theory at final PSD = vortices must be tightly paired.
- ❖ Dissipative dynamic (variation of N_v) with a varying hold time \neq equilibrium.

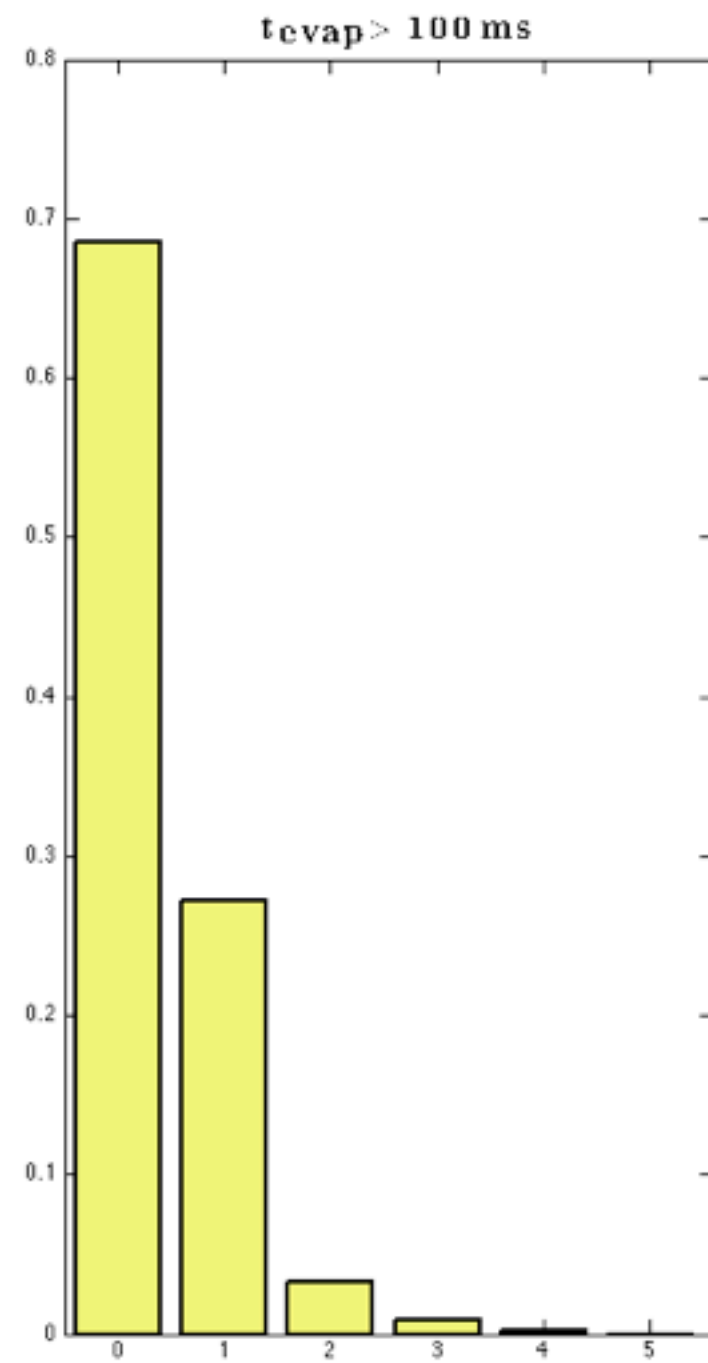
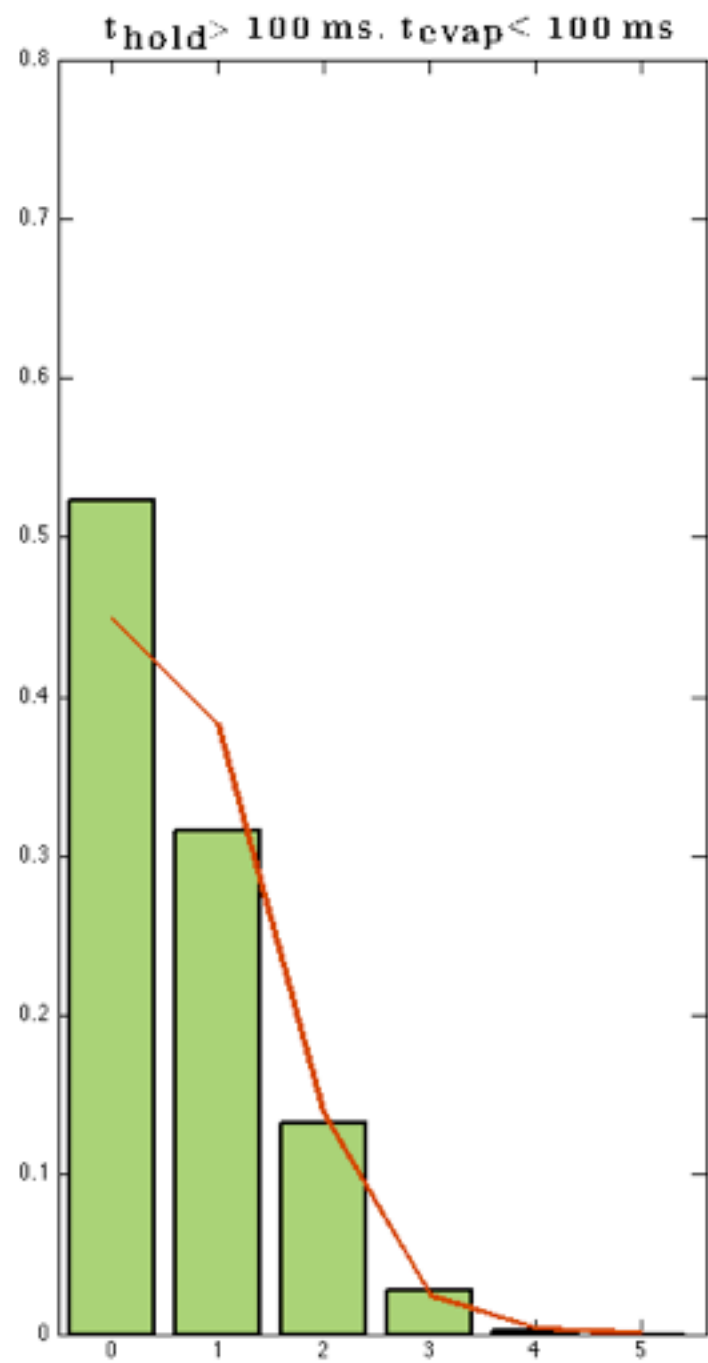
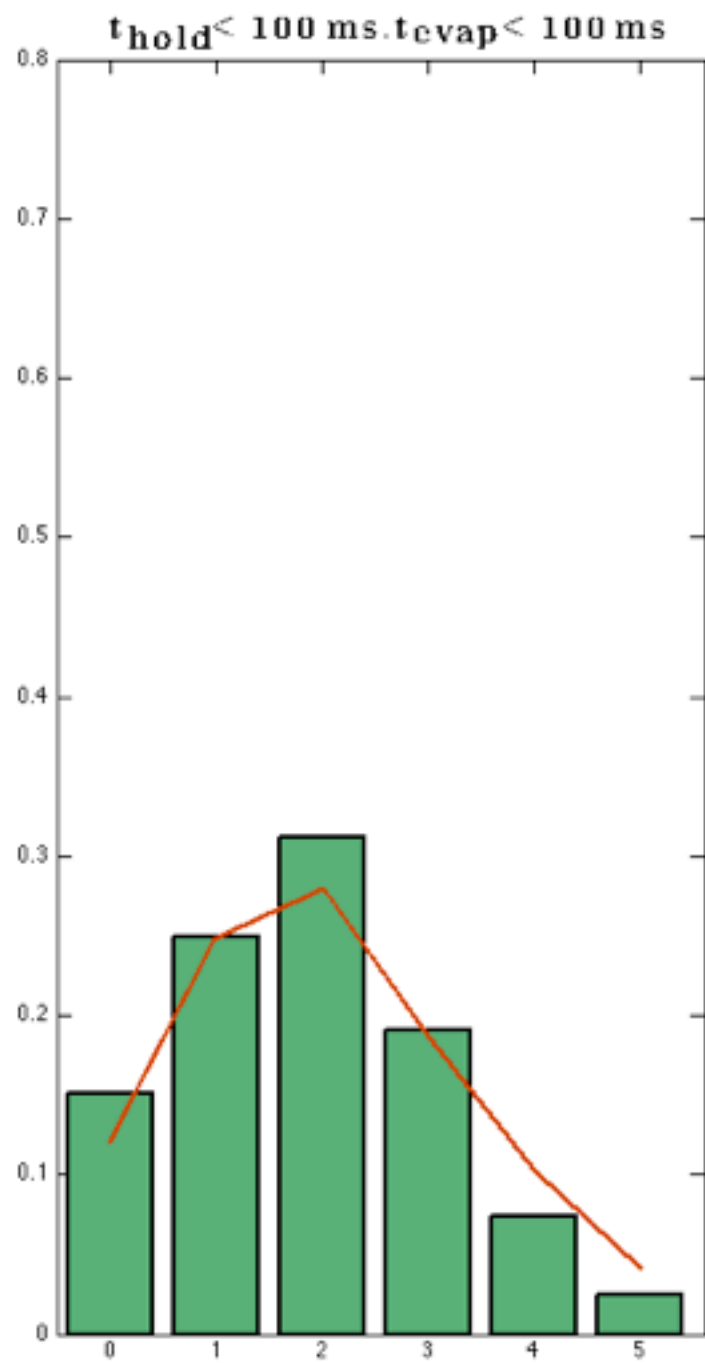








proportion of occurrences



vortex numbers

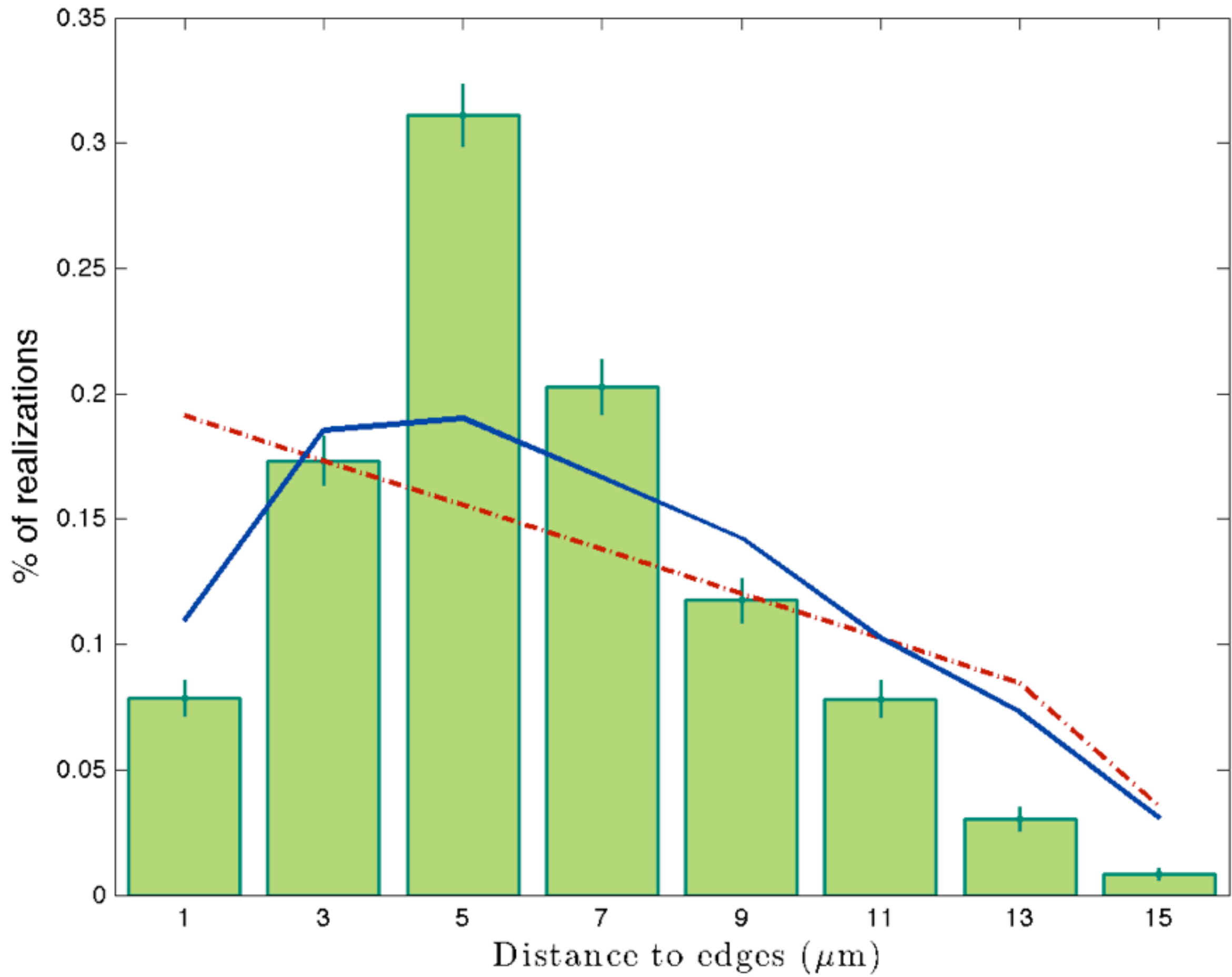
Active Research

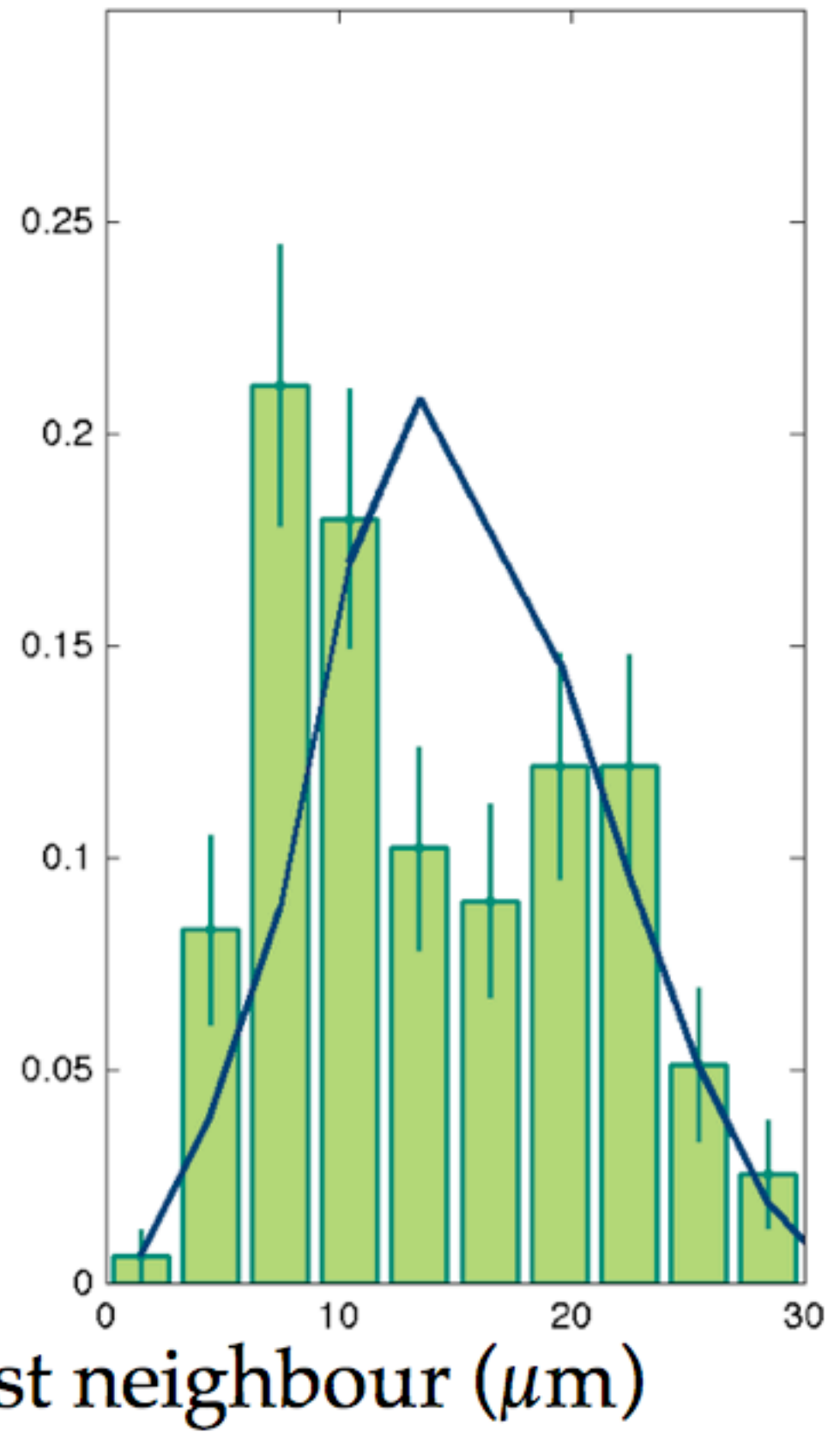
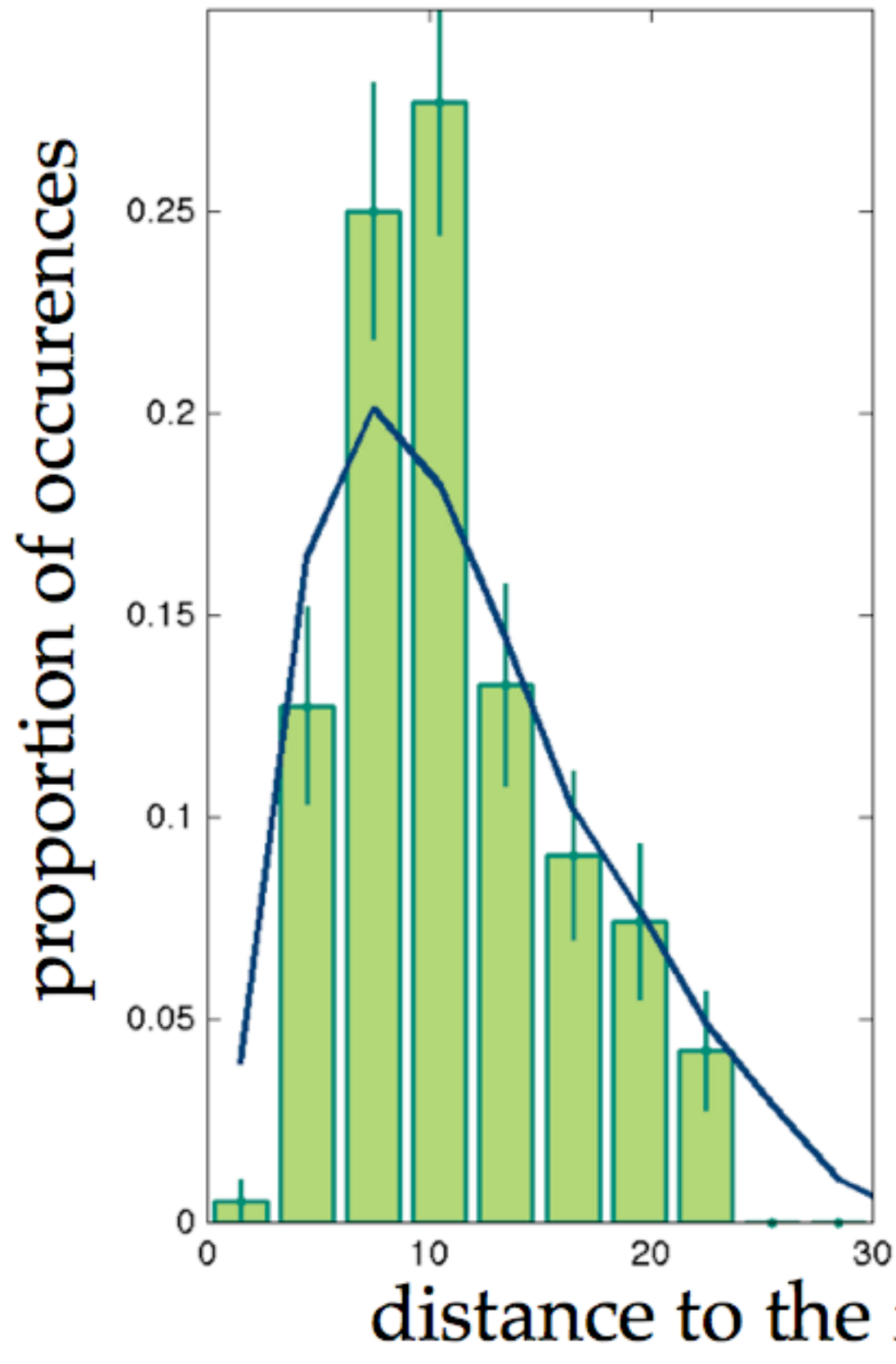
Steady state 2D Physics/ BKT Physics:

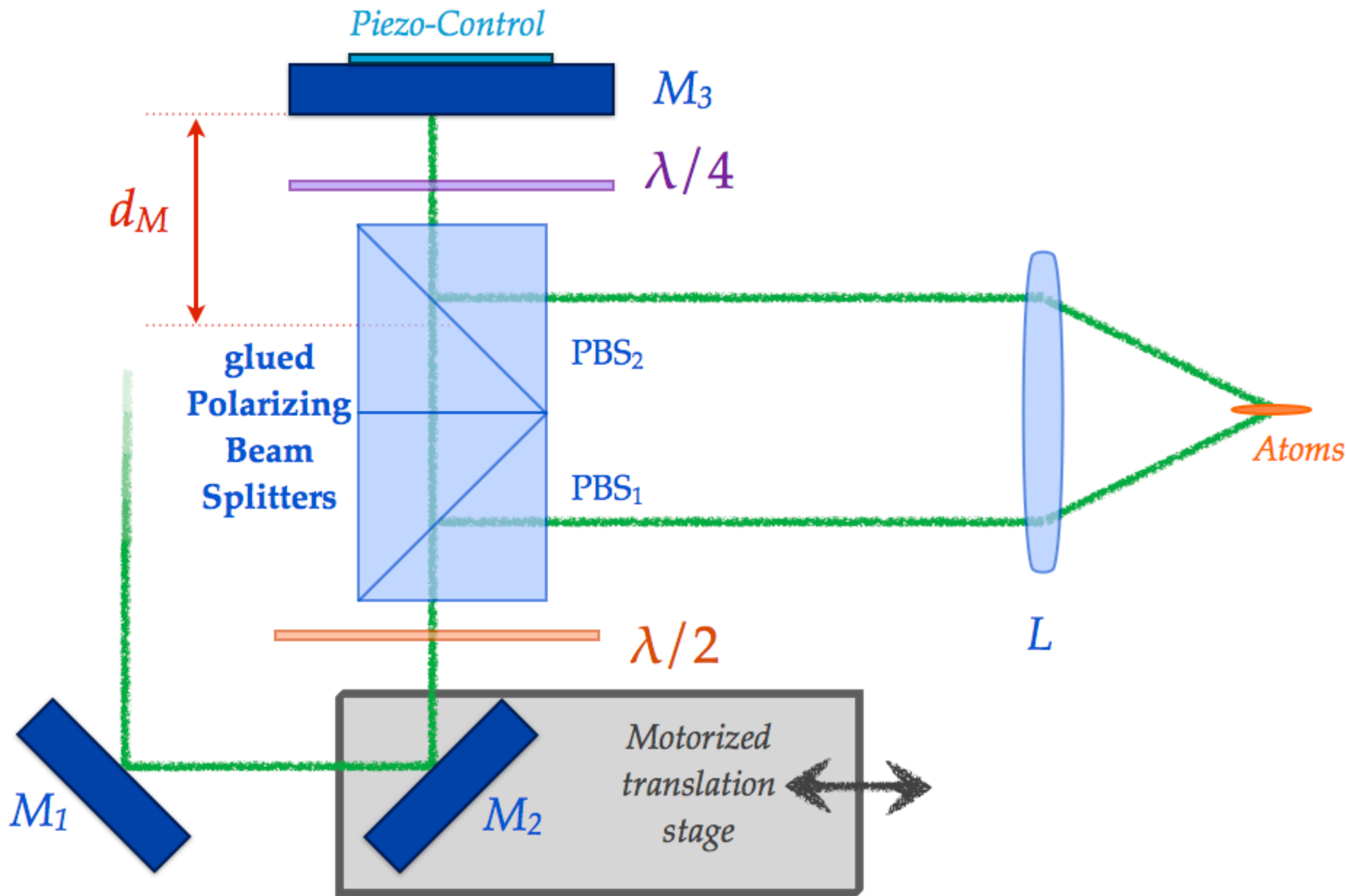
- ◆ Cheng Chin, Chicago, USA.
- ◆ Zoran Hadzibabic, Cambridge, UK.
- ◆ Yong-il Shin, Seoul, Korea.
- ◆ Bill Phillips, NIST, Maryland, USA.
- ◆ E.A. Cornell, JILA, Colorado, USA.
- ◆ Thomas Bourdel, Palaiseau, France.
- ◆ ...

Kibble Zurek mechanism with cold atoms

- ◆ B. P. Anderson, Tuscon, Arizona, USA.
- ◆ D. Stamper Kurn, Berkeley, California, USA.
- ◆ B. L. DeMarco, Urbana-Ch., Illinois, USA.
- ◆ Gabriele Ferrari, Trento, Italy.
- ◆ Immanuel Bloch, Munich, Germany.
- ◆ Zoran Hadzibabic, Cambridge, UK.
- ◆ ...



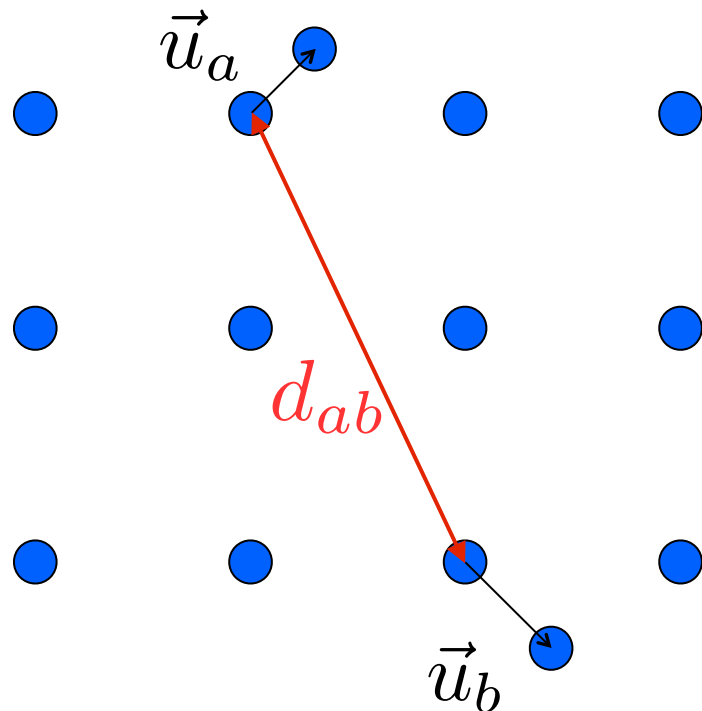




Symmetry Breaking in 2D

Peierls 1935

Crystalline order in 2D?



How do the fluctuations of the distance between two atoms vary with the distance itself?

$$\langle (\vec{u}_a - \vec{u}_b)^2 \rangle \propto \log(d_{ab})$$

Crystalline order destroyed by long wavelength phonons ($T \neq 0$)

Mermin-Wagner-Hohenberg theorem (1966-67)

No breaking of continuous symmetry in dimensions < 3 (+ short range interactions)

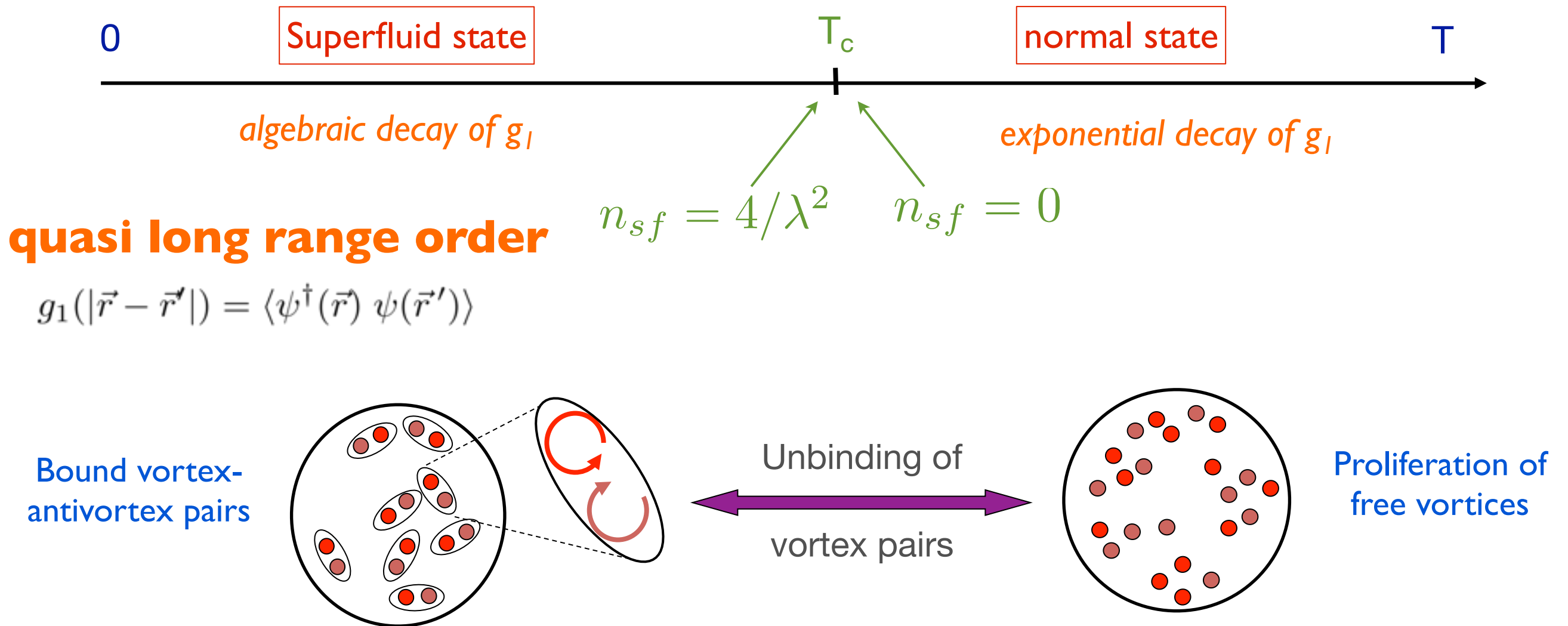
No BEC in an infinite, uniform 2D gas

$$g_1(r) = \langle \psi^\dagger(r) \psi(0) \rangle ; \lim_{r \rightarrow \infty} g_1(r) = 0$$

The superfluid transition in 2D

*Not all phase transitions are excluded in 2D,
only those due to symmetry breaking!*

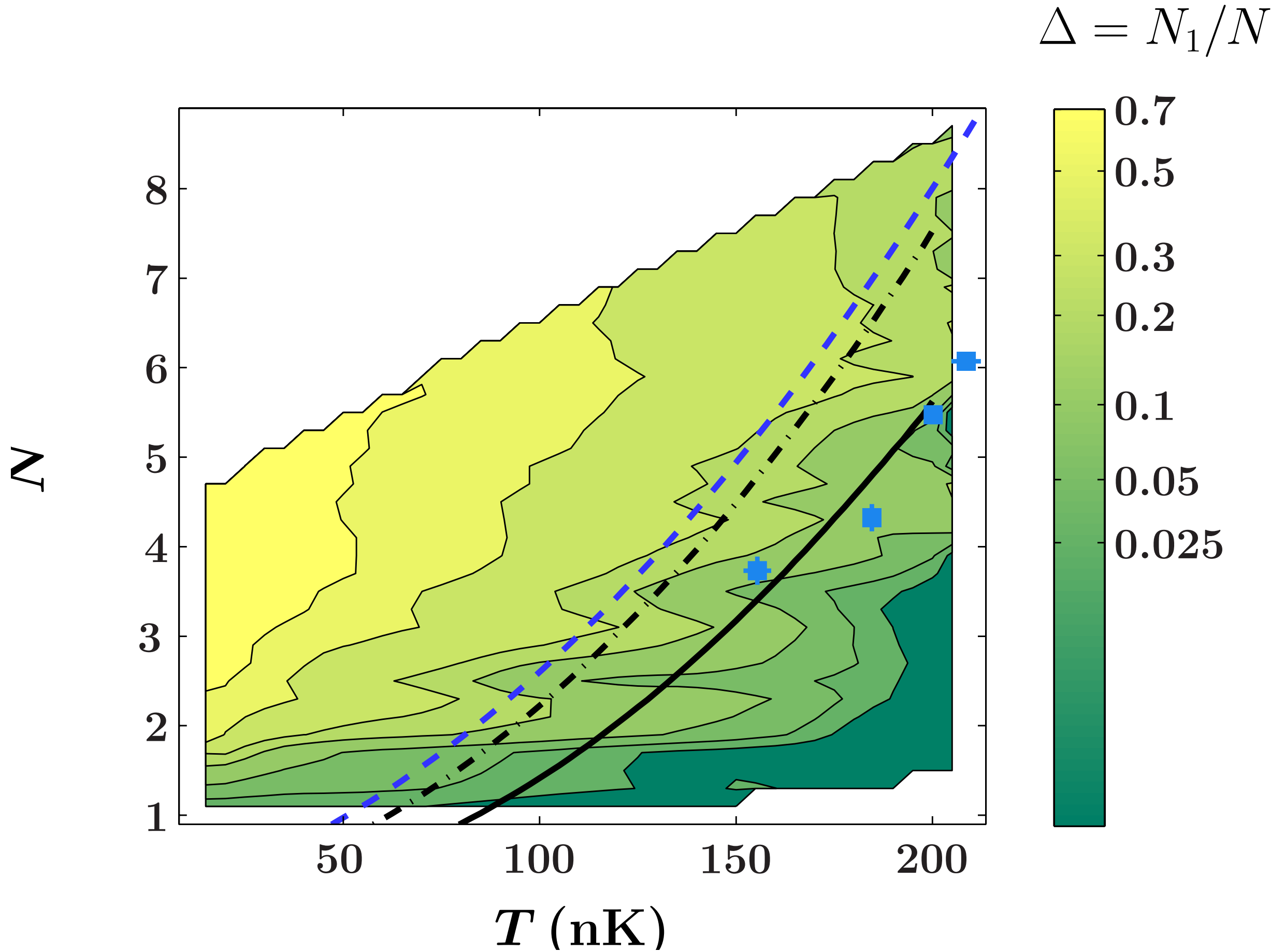
universal jump of superfluid density

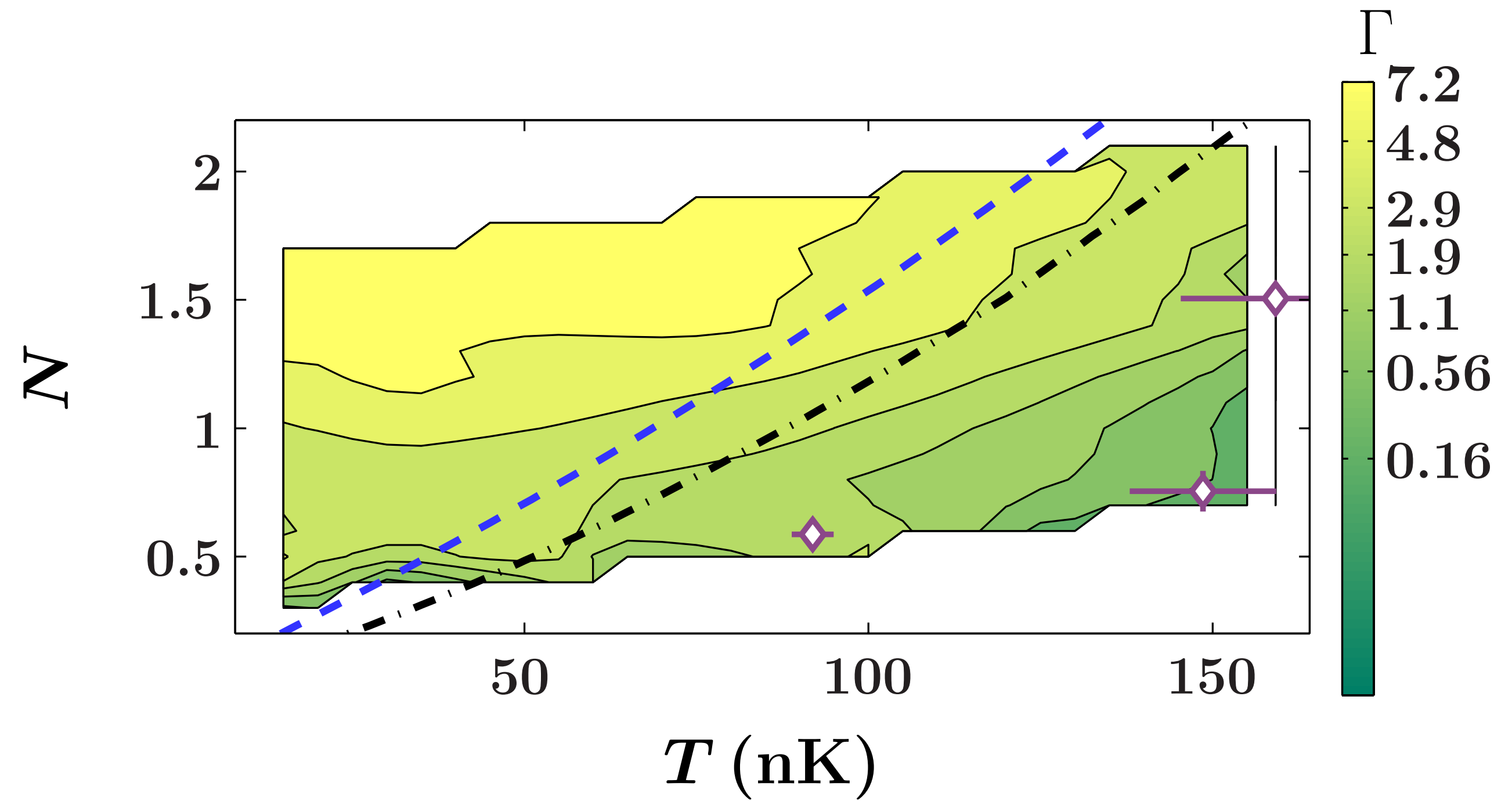


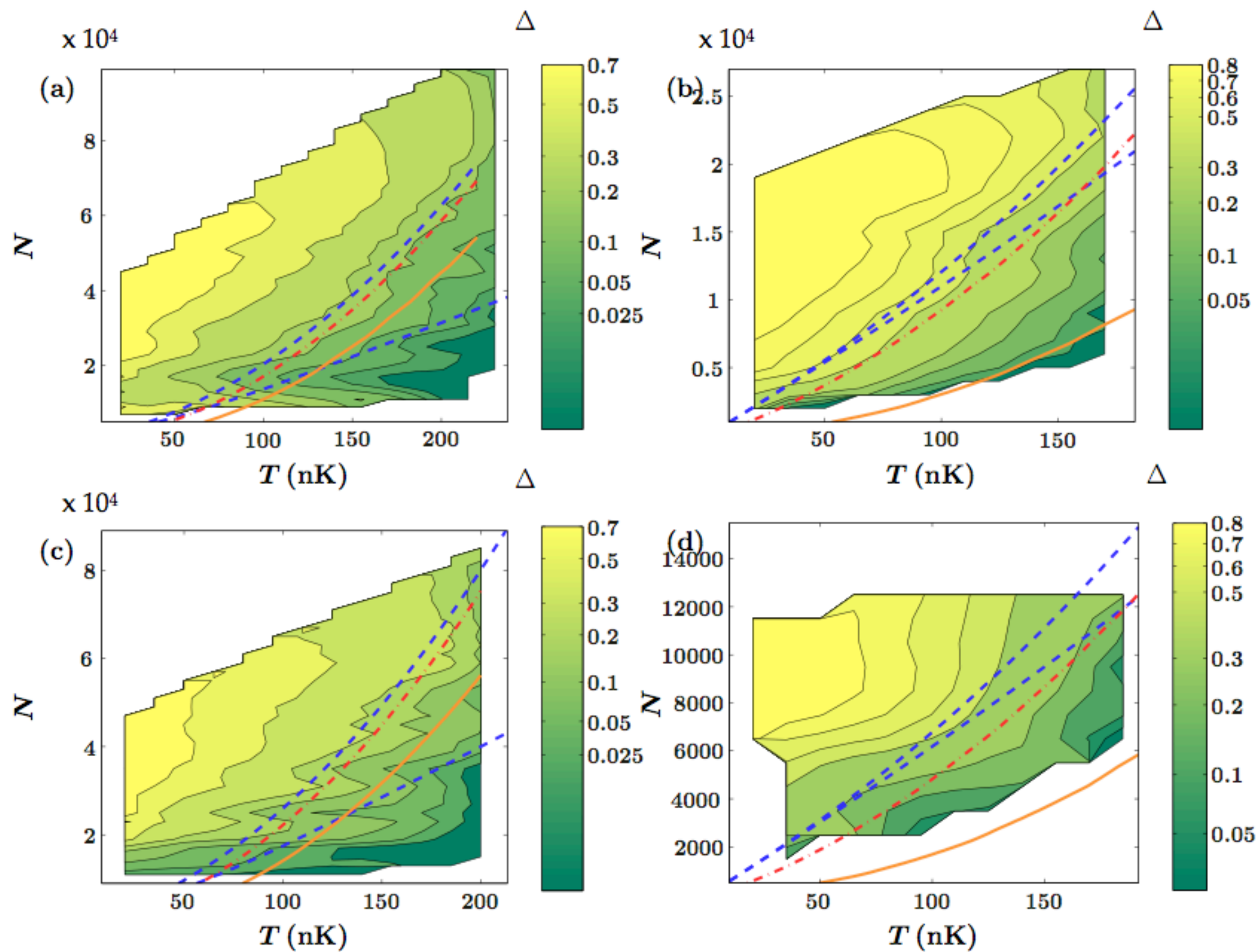
Coherence + microscopic nature of the transition : studied with cold atoms.

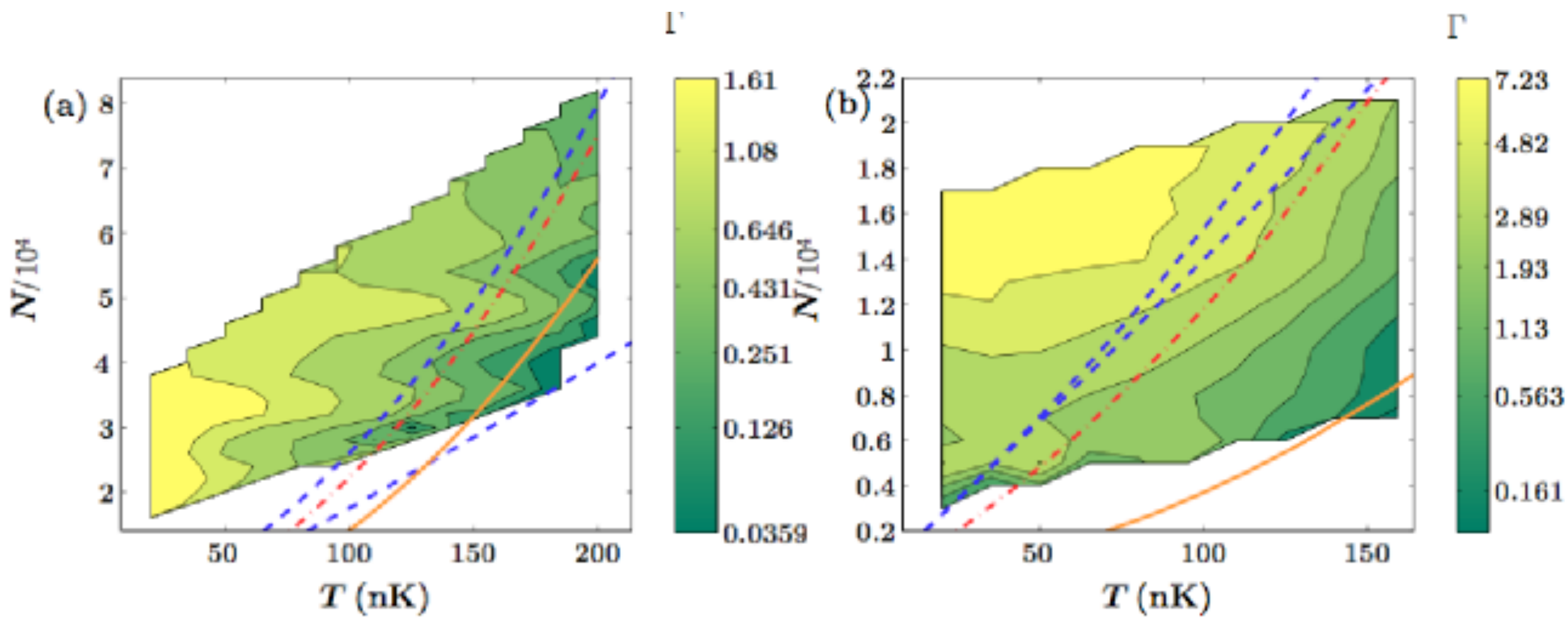
Previous studies with atomic gases and trapped ions:

- Kinks in ion chains: PTB (Mehlstäubler), Simon Fraser U. (Haljan), Mainz U. (Schmidt-Kaler), U. Freiburg (Schaetz)
- Quenched ferromagnetic spinor Bose-Einstein condensates: U. Berkeley (Stamper-Kurn)
- Formation of BEC in harmonic traps: U. Arizona (Anderson) & U. Queensland (Davis)
- Solitons in elongated BECs: U. Trento (Ferrari)
- Superfluid to Mott insulator: Munich (Bloch-Schneider)
- Formation of a 3D BEC in a box-like trap: U. Cambridge (Hadzibabic)









Kibble Zurek mechanism for a 3D Bose gas

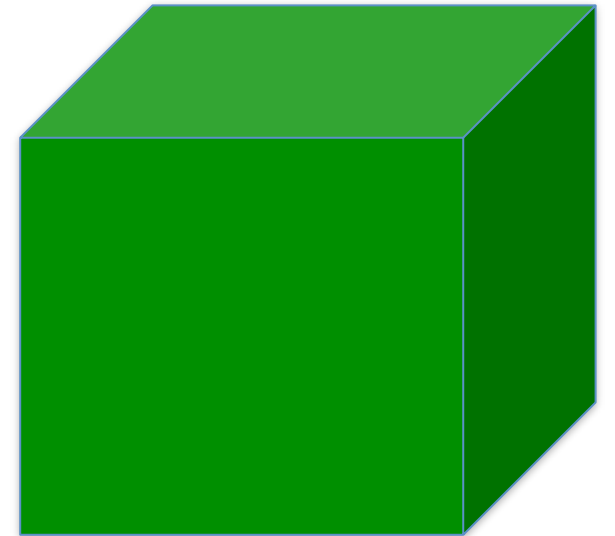
The static picture

Above the critical temperature, coherent patches of size d

For large T : $d \sim \lambda$ (thermal wavelength)

Approaching T_c : d diverges as $1/(T - T_c)^\nu$

Below T_c , full coherence: $d = \text{size of the box}$



Kibble Zurek mechanism for a 3D Bose gas

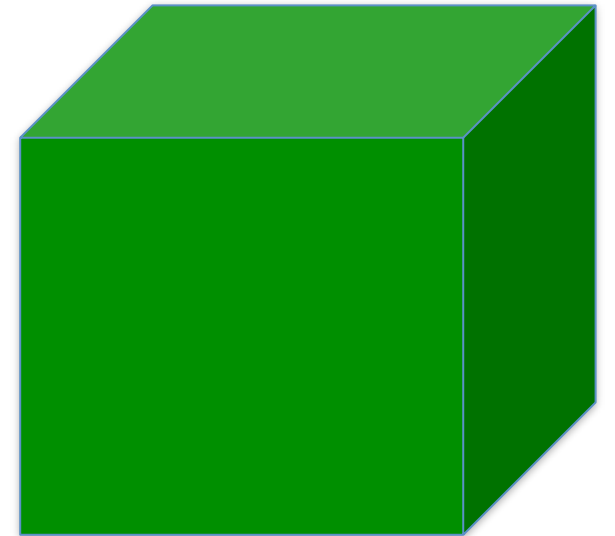
The static picture

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Below T_c , full coherence: $d = \text{size of the box}$



Dynamical aspects

For a finite cooling rate, this picture fails: coherence cannot be established fast enough

→ \dot{T} fixes the maximal size of phase-coherent patches: topological defects (vortex lines)

may appear at the border of the patches and survive to the subsequent

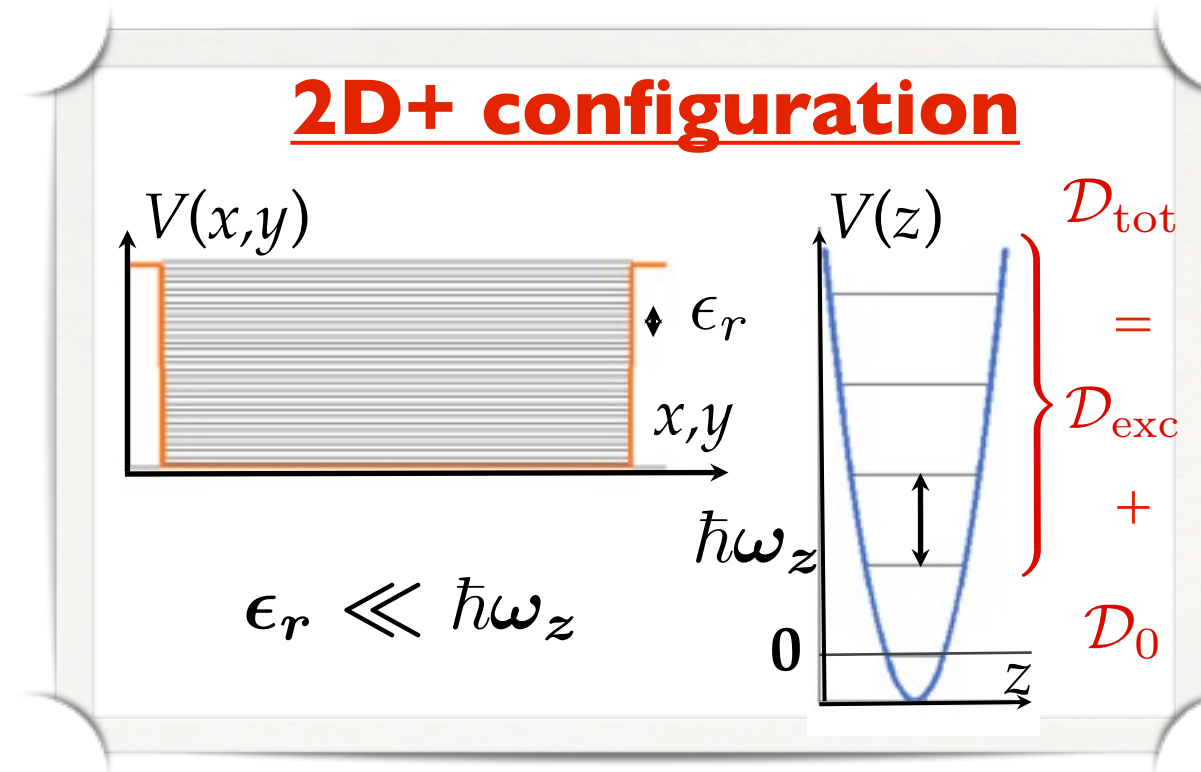
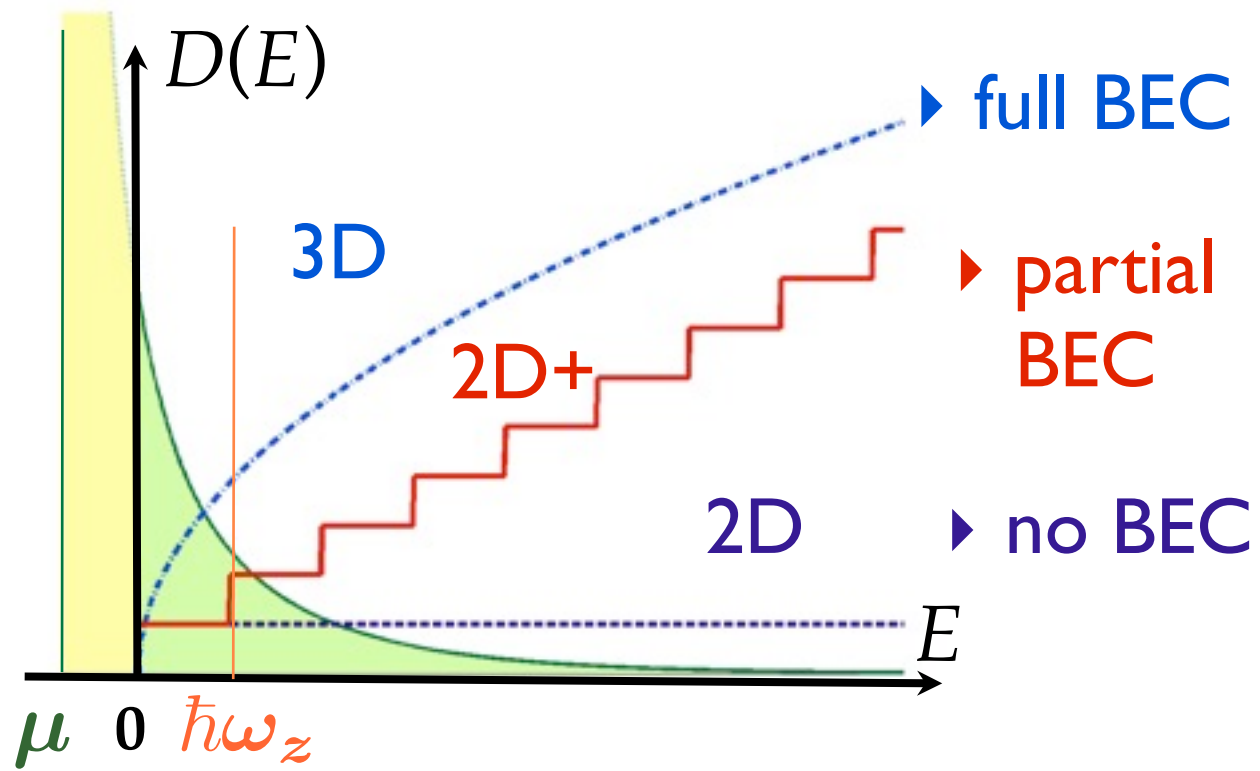
→ thermalization

$$N_t \propto (\dot{T}/T)^\alpha$$

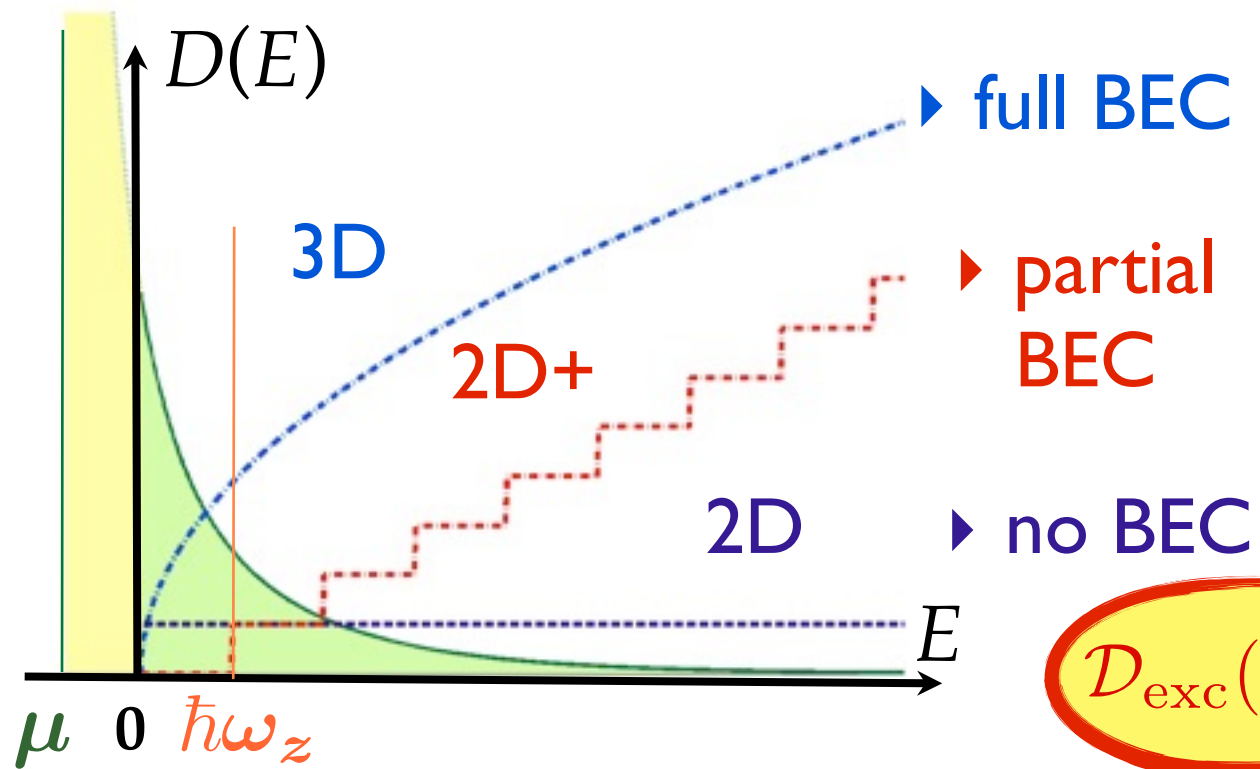
KZ theory relates the number of topological defects N_t to the cooling rate:

One can also look for other signatures than topological defects: Hadzibabic's talk

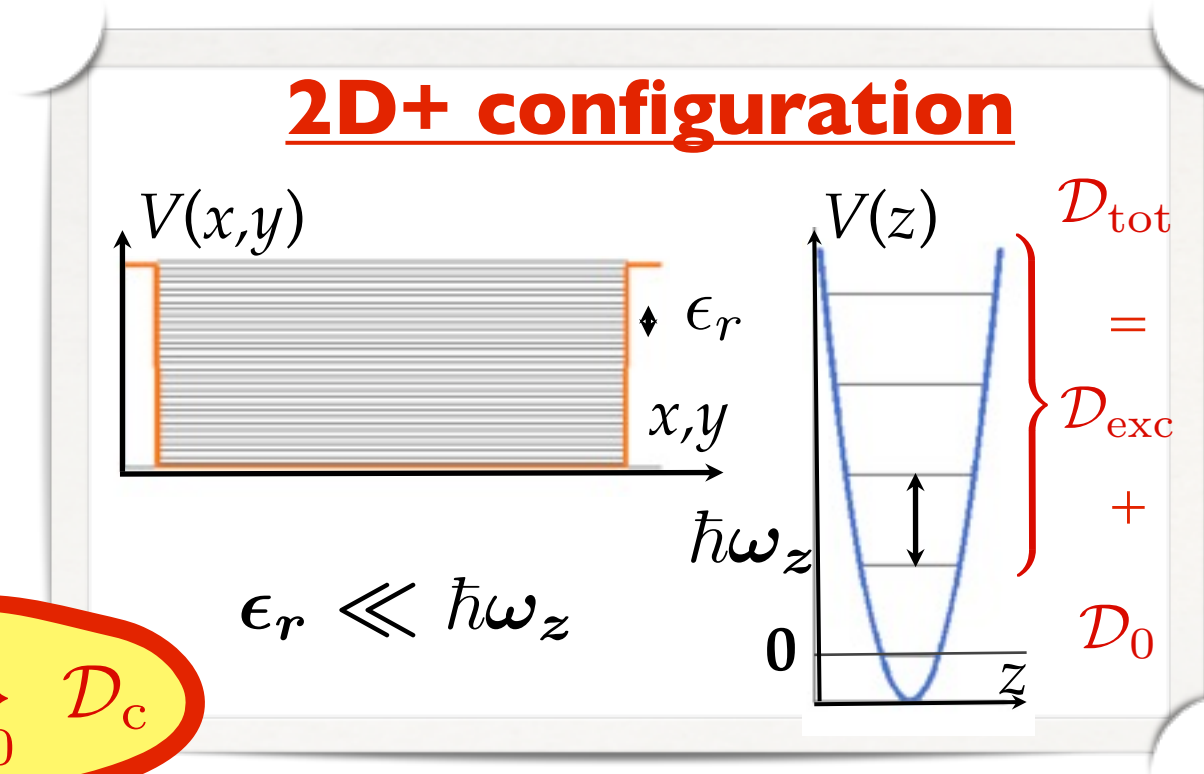
3rd dim.: Transverse condensation.



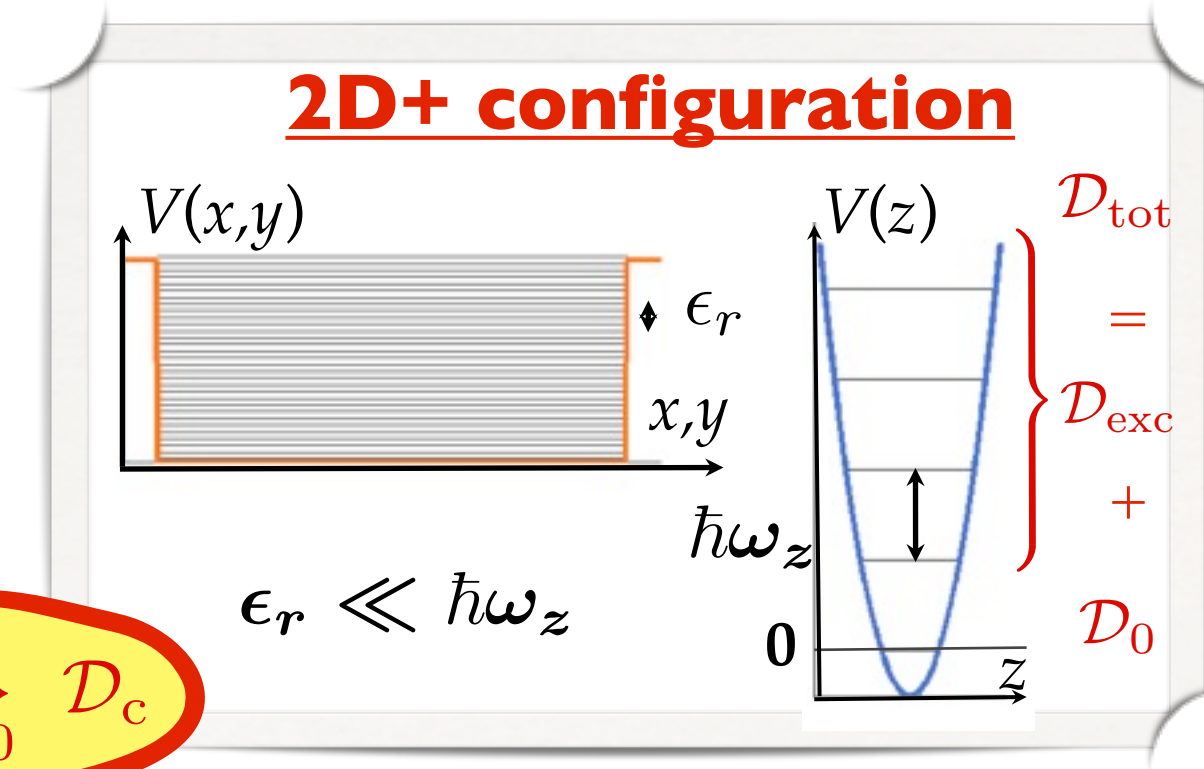
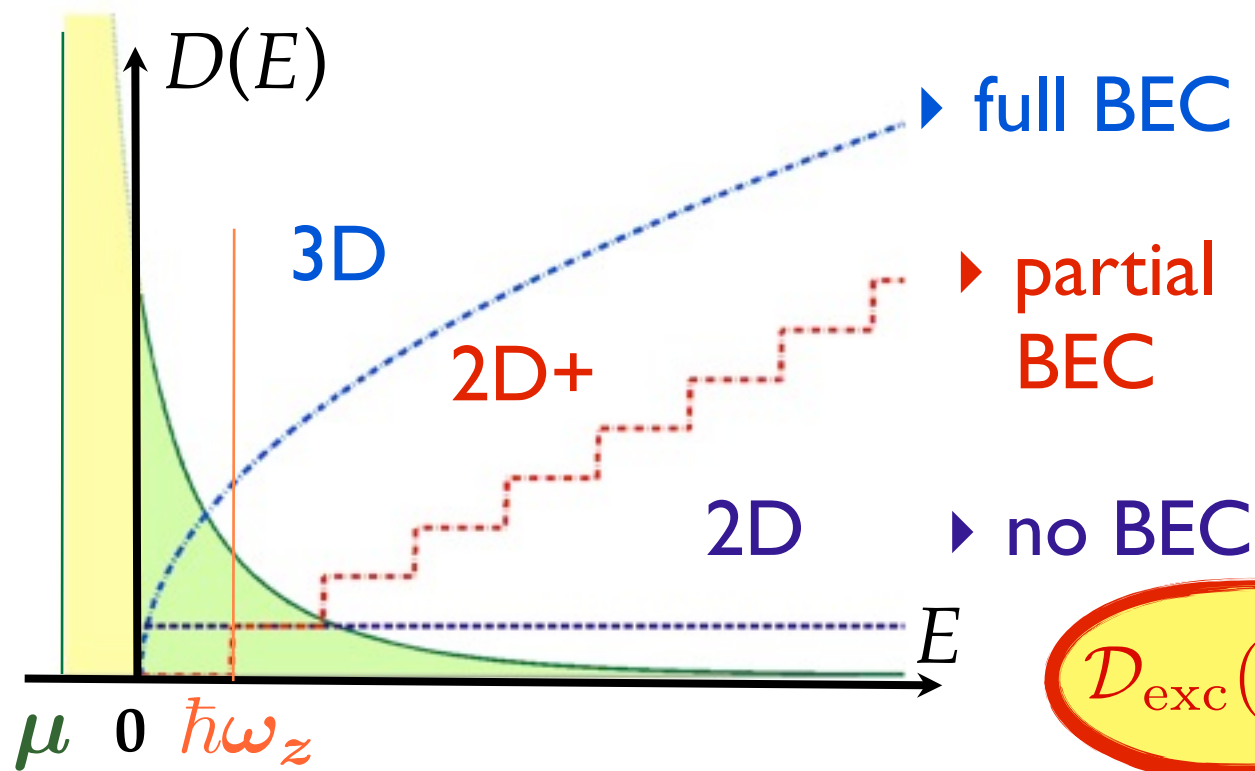
3rd dim.: Transverse condensation.



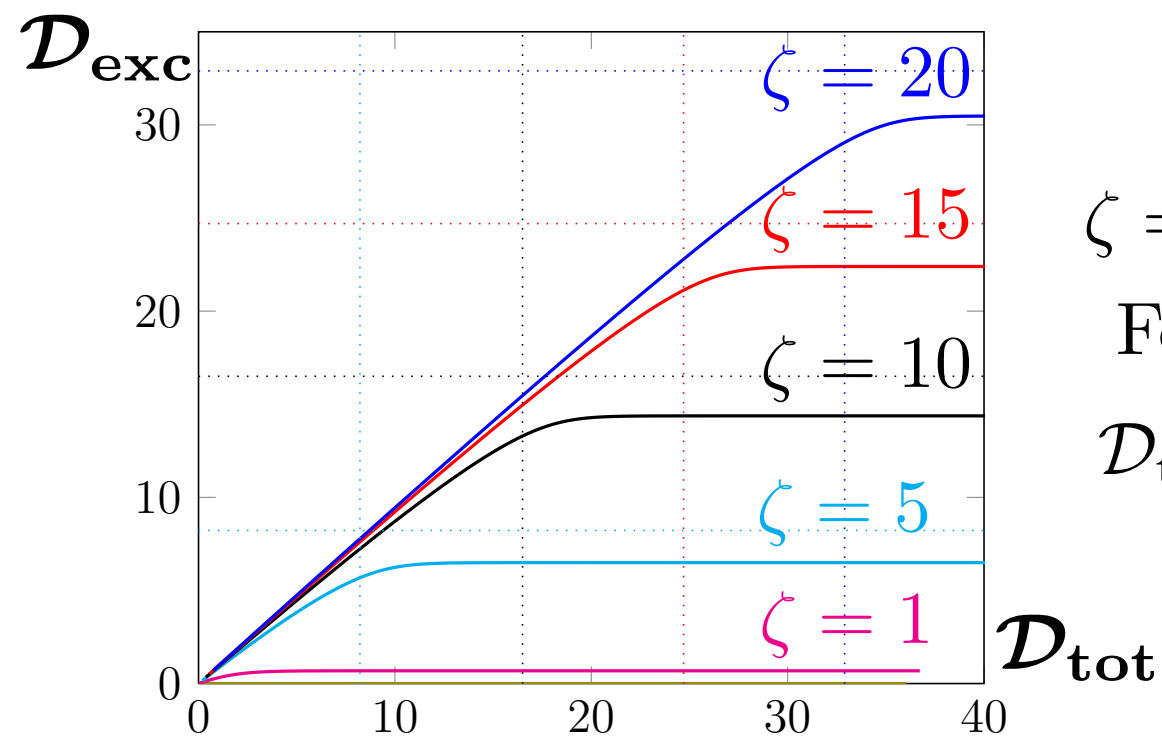
$$D_{\text{exc}}(\mu) \xrightarrow{\mu \rightarrow 0} D_c$$



3rd dim.: Transverse condensation.



$$\mathcal{D}_{\text{exc}}(\mu) \xrightarrow{\mu \rightarrow 0} \mathcal{D}_c$$

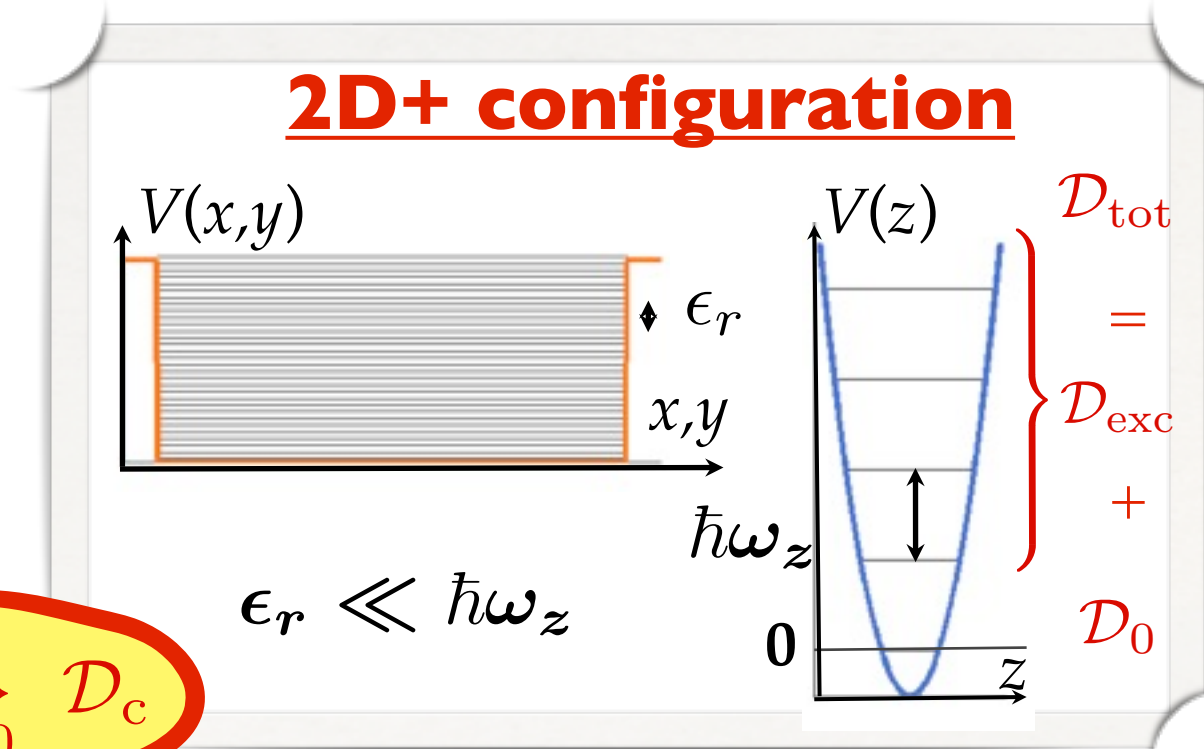
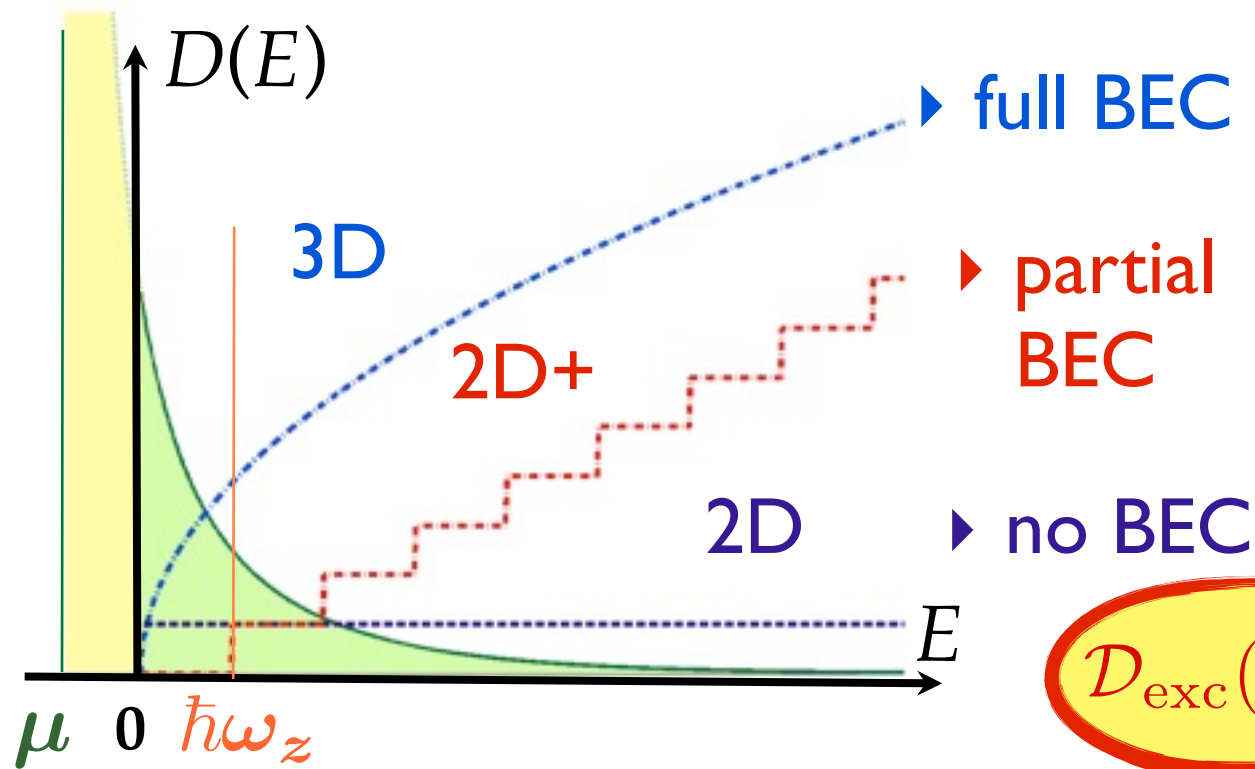


$$\zeta = k_B T / \hbar\omega_z$$

For $\zeta \gg 1$:

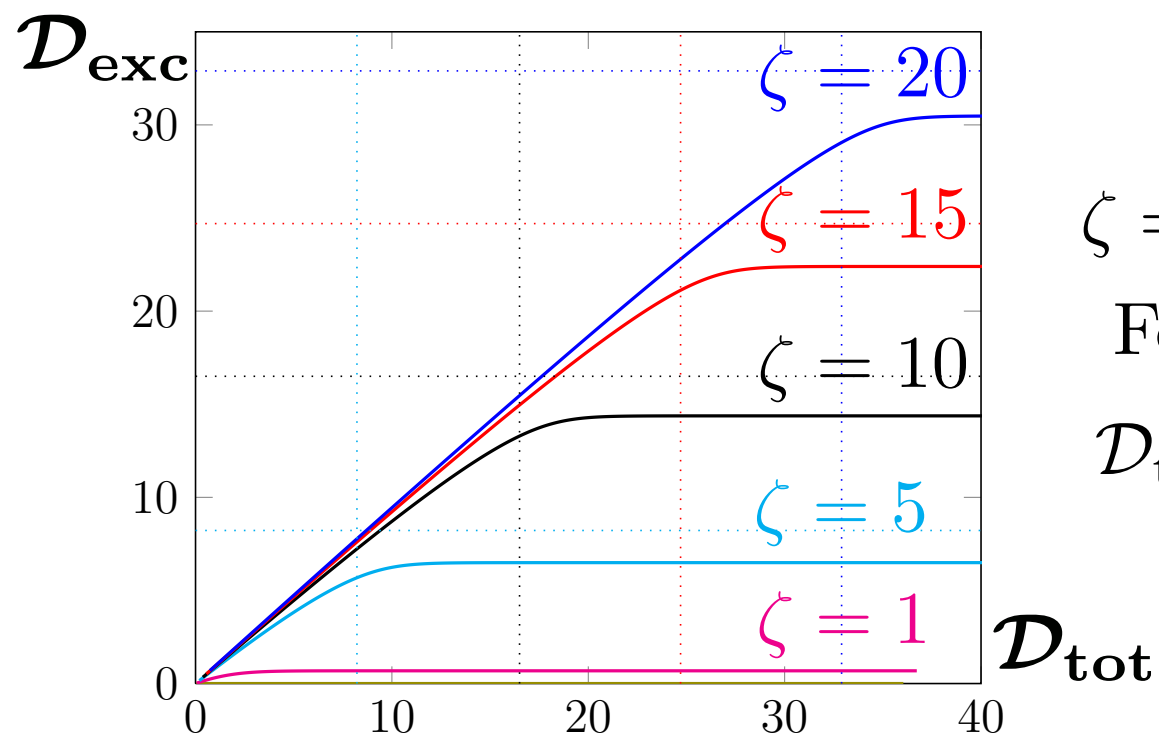
$$\mathcal{D}_{\text{tot},c} = \frac{\pi^2}{6} \zeta$$

3rd dim.: Transverse condensation.



$$D_{\text{exc}}(\mu) \xrightarrow{\mu \rightarrow 0} D_c$$

➔ When D_{tot} large enough, atoms accumulate in $j = 0$: $D_0 \sim D_{\text{tot}}$ even if $k_B T \gg \hbar\omega_z$.



$$\zeta = k_B T / \hbar\omega_z$$

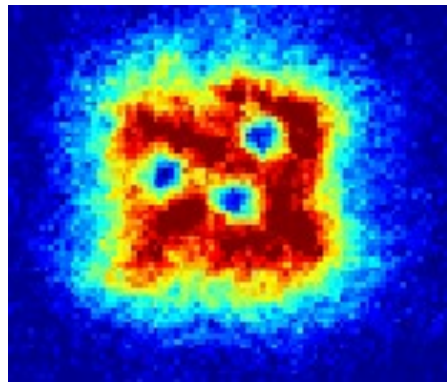
For $\zeta \gg 1$:

$$D_{\text{tot},c} = \frac{\pi^2}{6} \zeta$$

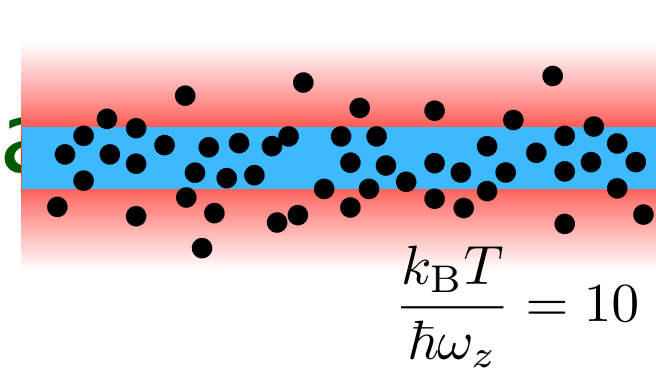
Recover relevance for 2D physics!

$$D \rightarrow D_0$$

$G_1^{(0)}(r)$ becomes dominant
 => enhanced coherence in plane!



Quench cooling of a thick 2D gas

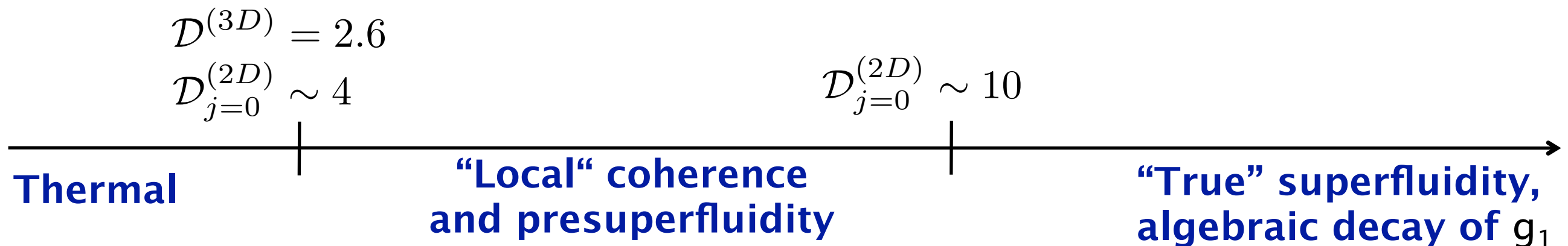


We cross two successive transitions:

T_1 : transverse BEC which occurs when the 3D phase-space density reaches 2.6

Atoms accumulate in the ground state $j = 0$ of the z motion, coherence $\sim a_{ho}$ length

T_2 : superfluid BKT // full BEC corresponding to quasi-full coherence over the sample



Tentative scenario:

- Formation of independent coherent phase domains during transition T_1
- Going up to the superfluid regime allows us to visualize the vortices