Thermal properties of quantum droplets

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NARODOWE CENTRUM NAUKI

Introduction

- ultracold quantum gas

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- behave like an incompressible liquid (self stabilization in the bulk at a well-defined density)

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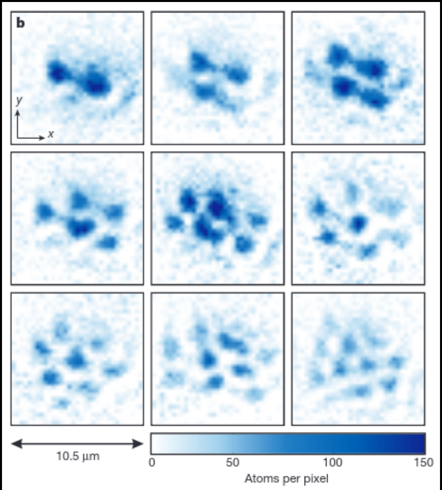
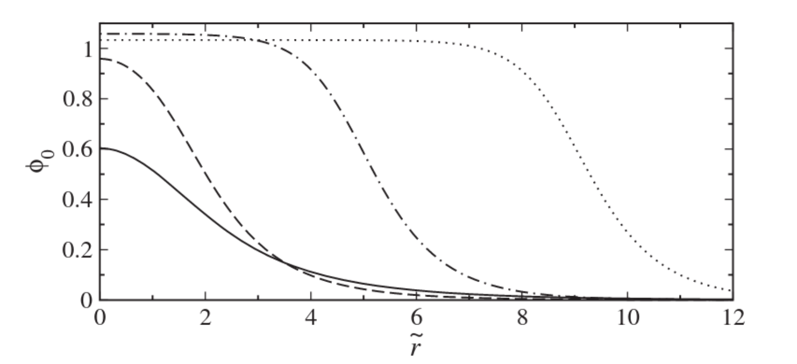
- behave like an incompressible liquid (self stabilization in the bulk at a well-defined density)
- self-bound without external trapping
- stabilized and dominated by quantum fluctuations (negligible in all other known dilute quantum matter)

Unexpected discovery



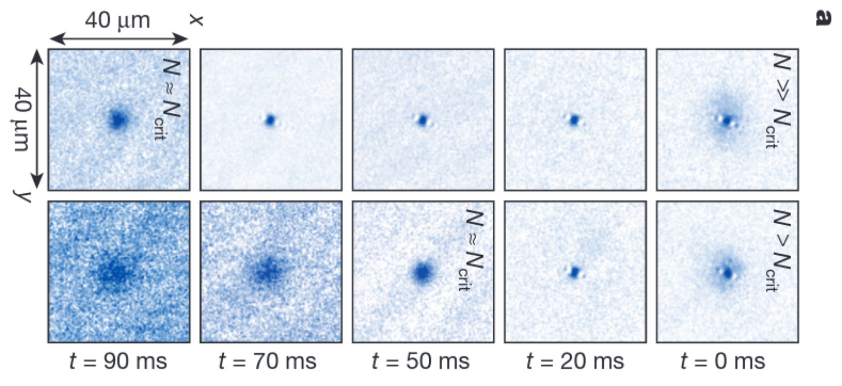
H. Kadau et al., Nature 530, 194 (2016)

Theoretical prediction



D. S. Petrov, Phys. Rev. Lett. 115, 155302 (2015)

Confirmation



M. Schmitt et al., Nature 539, 259 (2016)

2 components

2 component Bose-Bose mixture

$$E_{MF} = E_K + E_V + \frac{1}{2}\sum_{i,j} g_{ij} n_i n_j$$

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$g_{ii} > 0 \wedge g_{12}^2 < g_{11} g_{22} \implies$ stable (gas)

2 components

Beyond the MF: Bogoliubov spectrum in the LDA

$$E_{k,\pm} = \sqrt{\frac{\omega_1^2 + \omega_2^2}{2} \pm \sqrt{(\frac{\omega_1^2 - \omega_2^2}{2})^2 + \frac{g_{12}^2 n_1 n_2 k^4}{m_1 m_2}}}$$

$$\omega_i = \sqrt{\frac{k^2}{2m_i}(\frac{k^2}{2m_i} + 2g_{ii}n_i)}$$

$$E_{LHY} = \int \frac{d^3k}{2(2\pi)^3}(E_{k,+} + E_{k,-} - \frac{k^2}{2m_r} - g_{11}n_1 - g_{22}n_2 + \frac{m_1 g_{11}^2 n_1^2 m_2 g_{22}^2 n_2^2 + 4m_r g_{12}^2 n_1 n_2}{k^2})$$

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LHY significant when $g_{12} \approx -\sqrt{g_{11}g_{22}} \rightarrow$ protects the mixture from collapse

2 components

$$E_I = \frac{1}{2}\sum_{ij} g_{ij} n_i n_j = \sum_{\pm} \lambda_\pm n_\pm^2$$

$\delta g = g_{12} + \sqrt{g_{11} g_{22}}$

$$\lambda_+ \approx \frac{g_{11}+g_{22}}{2} \qquad \lambda_- \approx \frac{\delta g \sqrt{g_{11} g_{22}}}{g_{11}+g_{22}}$$
$$n_+ = \frac{n_1\sqrt{g_{11}} - n_2\sqrt{g_{22}}}{\sqrt{g_{11}+g_{22}}} \qquad n_- = \frac{n_1\sqrt{g_{22}} + n_2\sqrt{g_{11}}}{\sqrt{g_{11}+g_{22}}}$$

$+$ branch locks the equilibrium densities: $\frac{\bar{n}_1}{\bar{n}_2} = \frac{\sqrt{g_{22}}}{\sqrt{g_{11}}}$

LHY "beats" the $-$ branch

2 components

$$\delta g = g_{12} + \sqrt{g_{11} g_{22}}$$

$$\delta g < 0 \wedge g_{ii} > 0 \wedge |\delta g| \ll g_{ii}$$

$$\downarrow$$

Droplets!

Single component

$$i\partial_t\phi = (-\frac{\nabla^2}{2} - 3|\phi|^2 + \frac{5}{2}|\phi|^3 - \mu)\phi$$
$$\phi = \phi(x/\xi, t/\tau)$$

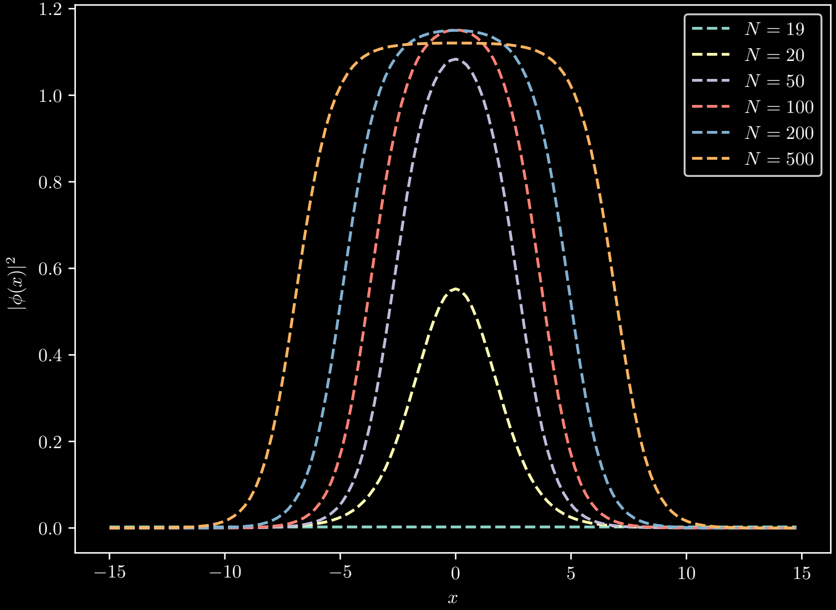
For ^{39}K atoms:
cooritinate units:

$$\xi \approx 2\mu m$$

time units:

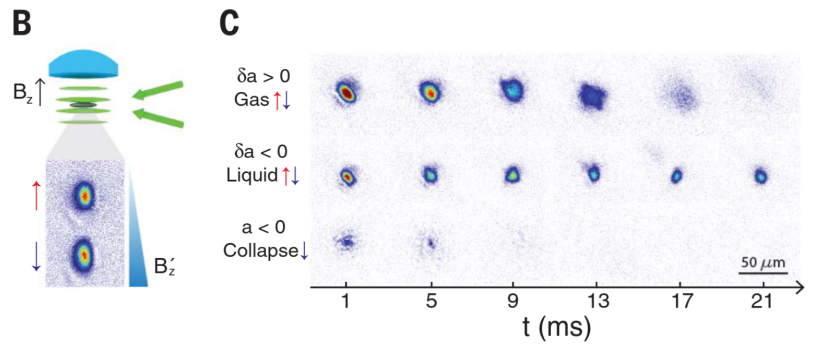
$$\tau \approx 2.5ms$$

3D droplets



$N = 19$
$N = 20$
$N = 50$
$N = 100$
$N = 200$
$N = 500$
$|\phi(x)|^2$
x
1.2
1.0
0.8
0.6
0.4
0.2
0.0
−15
−10
−5
0
5
10
15

Sausages and pancakes: an effective low dimensional description



C. R. Cabrera, L. Tanzi, J. Sanz, B. Naylor, P. Thomas, P. Cheiney, and L. Tarruell, Science 359, 301 (2018)

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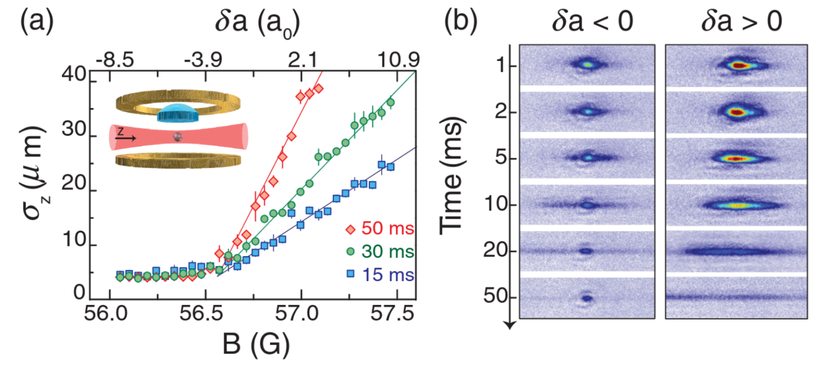

P. Cheiney et al., Phys. Rev. Lett. 120, 135301 (2018)

Sausages and pancakes: an effective low dimensional description

Most strict to least strict (quasi) low-D regimes:

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Strict 1D, 2D

D. S. Petrov and G. E. Astrakharchik, Phys. Rev. Lett. 117, 100401 (2016)

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$\downarrow$

Dimensional crossover

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Flattened/elongated 3D

this presentation

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Full 3D

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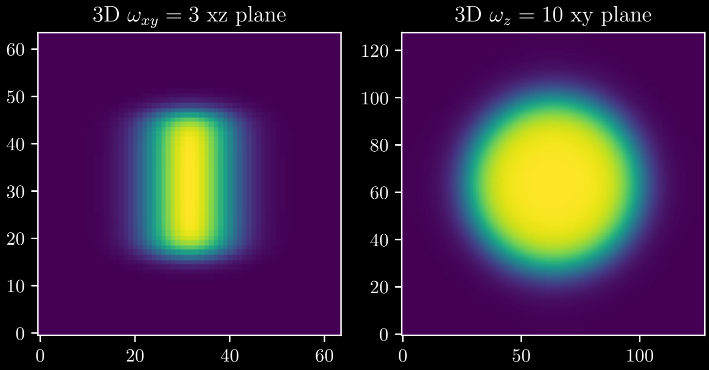


Sausages and pancakes: an effective low dimensional description

2D

$$\phi(x,y,z) = \phi_{\text{2D}}(x,y)\phi_{\text{gaussian}}(z)$$

1D

$$\phi(x,y,z) = \phi_{\text{gaussian}}(x,y)\phi_{\text{1D}}(z)$$

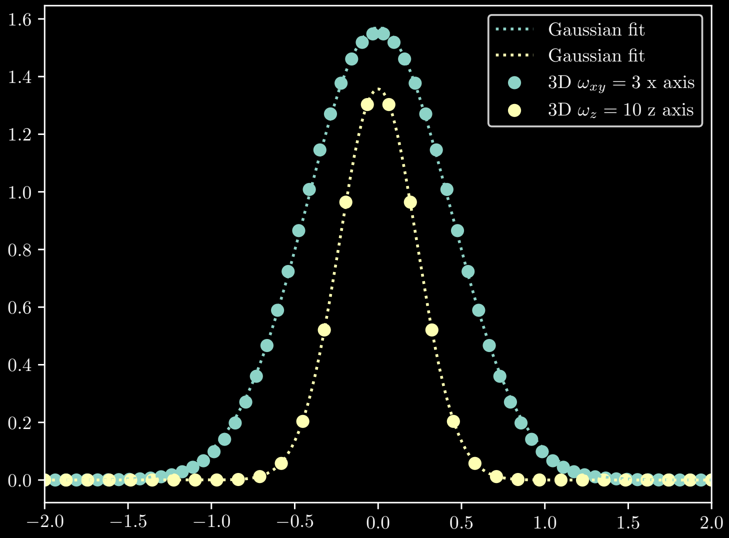
Sausages and pancakes: an effective low dimensional description

$$i\partial_t\phi = (-\frac{\nabla^2}{2} - 3|\phi|^2 + \frac{5}{2}|\phi|^3 - \mu)\phi$$

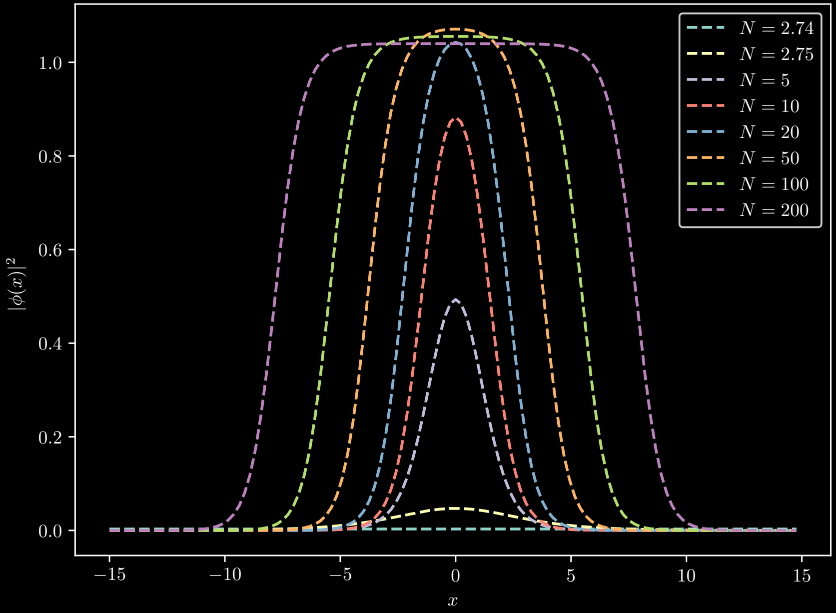
$$i\partial_t\phi_{2D} = (-\frac{\nabla^2}{2} - g_2(\omega)|\phi_{2D}|^2 + c_2(\omega)|\phi_{2D}|^3 - \mu)\phi_{2D}$$

$$i\partial_t\phi_{1D} = (-\frac{\nabla^2}{2} - g_1(\omega)|\phi_{1D}|^2 + c_1(\omega)|\phi_{1D}|^3 - \mu)\phi_{1D}$$

Sausages and pancakes: an effective low dimensional description



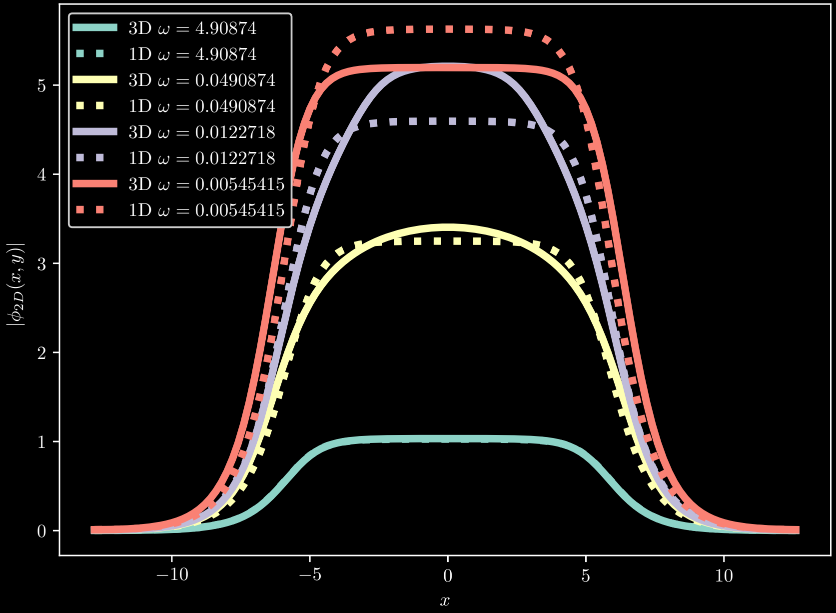
Effective 2D (flattened 3D)



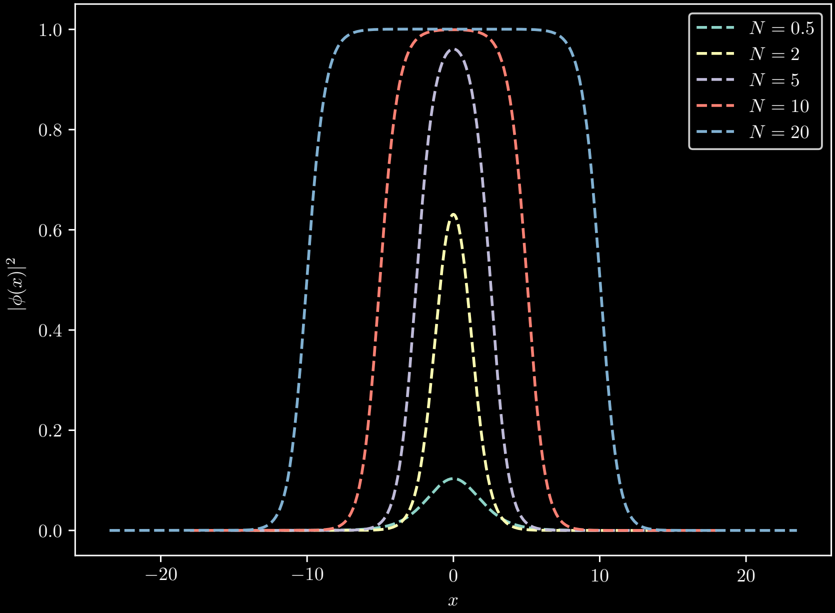
Effective 2D (flattened 3D)

$$2.74 < N_c < 2.75$$

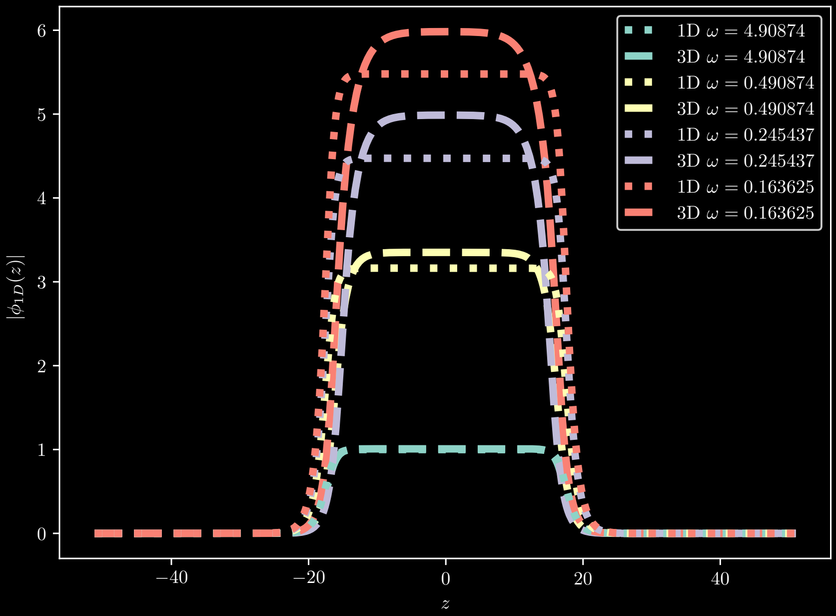
Effective 2D (flattened 3D)



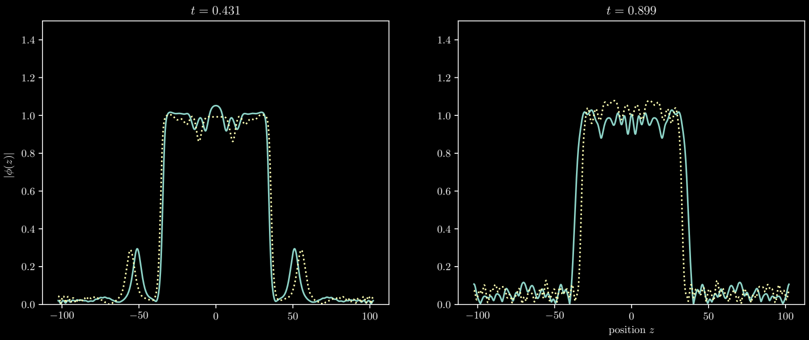
Effective 1D (elongated 3D)



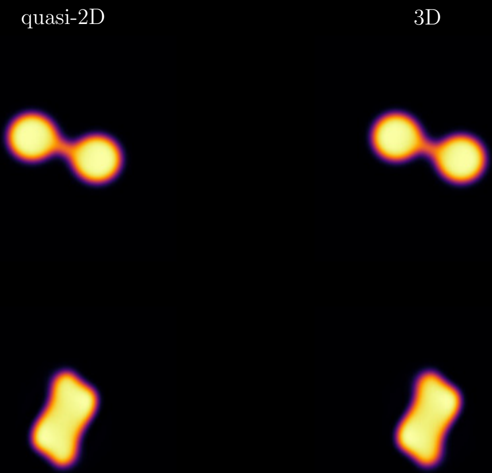
Effective 1D (elongated 3D)



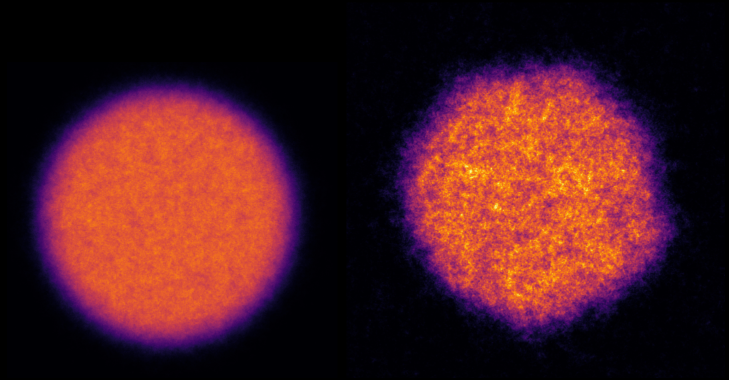
Effective 1D dynamics



Effective 2D dynamics



Thermal properties



Thermal properties

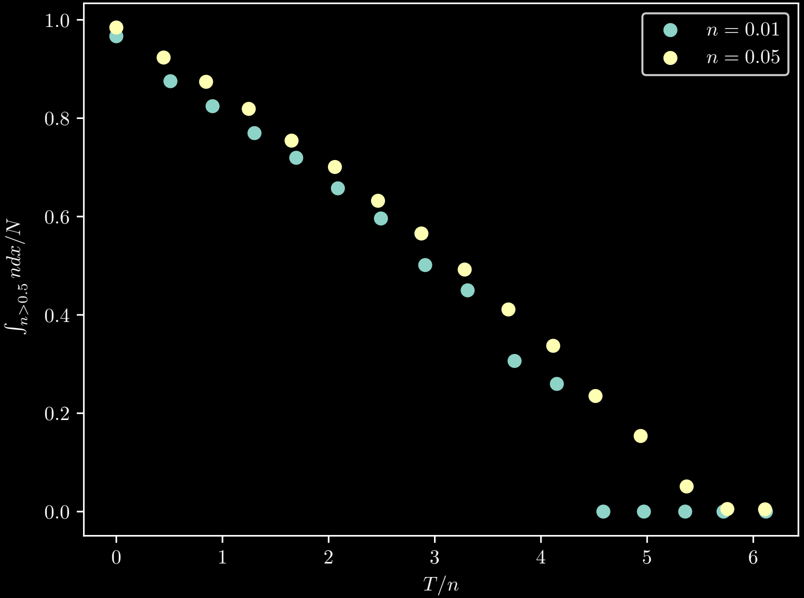
Modified Projected Stochastic GPE:

$$i\partial_t \phi = \mathcal{P}_C((1-i\gamma)(-\frac{\nabla^2}{2} - 3|\phi|^2 + \frac{5}{2}|\phi|^3 - \mu)\phi$$
$$- \frac{\gamma T}{\sigma^2}(N(\phi) - \bar{N})\phi$$
$$+ \sqrt{2\gamma T}\eta(x,t))$$

$$C = |\mu| + (\log 2)T$$

complex Gaussian noise: $\eta, \langle \eta^*(x,t)\eta(x',t'))\rangle = \delta(x-x')\delta(t-t')$

Thermal properties



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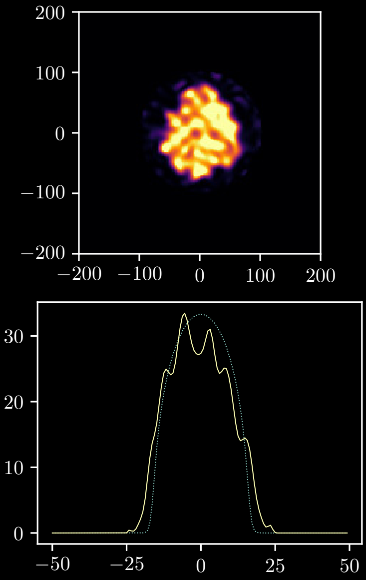

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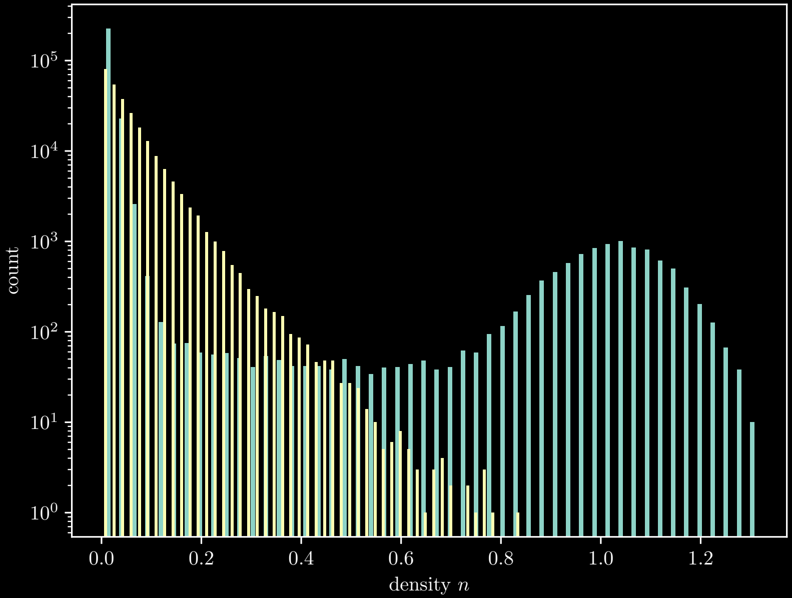

Thermal properties