A dipolar supersolid and a novel microscope to probe quantum gases

Tilman Pfau, Universität Stuttgart

IQ^ST Integrated Quantum Science and Technology

Universität Stuttgart
5. Physikalisches Institut

A pulsed ion microscope to probe quantum gases

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iRyd
Deutsche Forschungsgemeinschaft DFG
Carl Zeiss Stiftung

Christian Veit, Nicolas Zuber, Óscar A. Herrera-Sancho,
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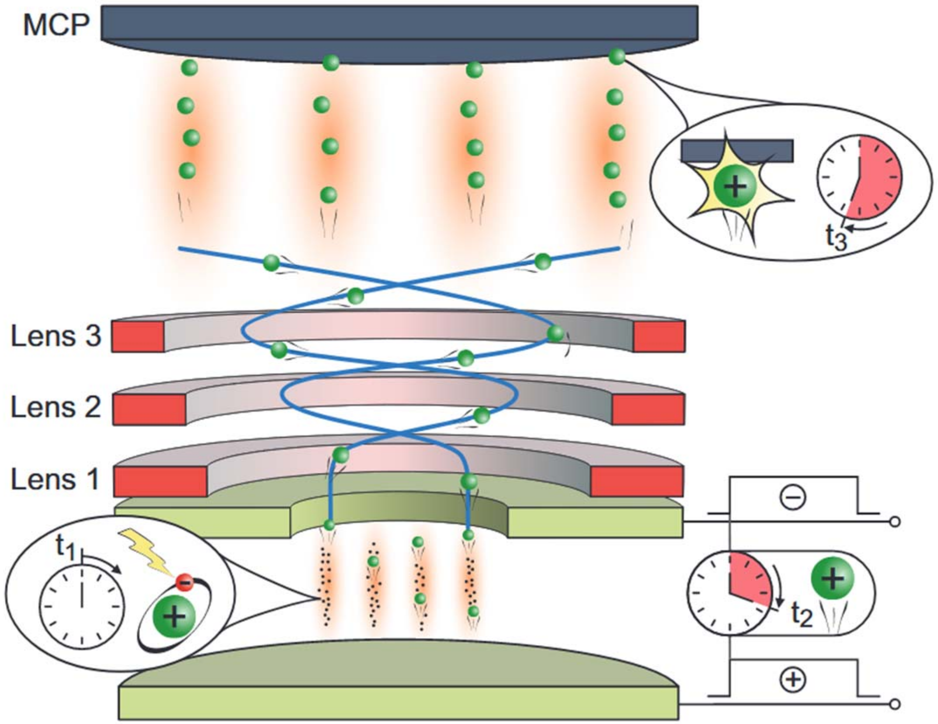


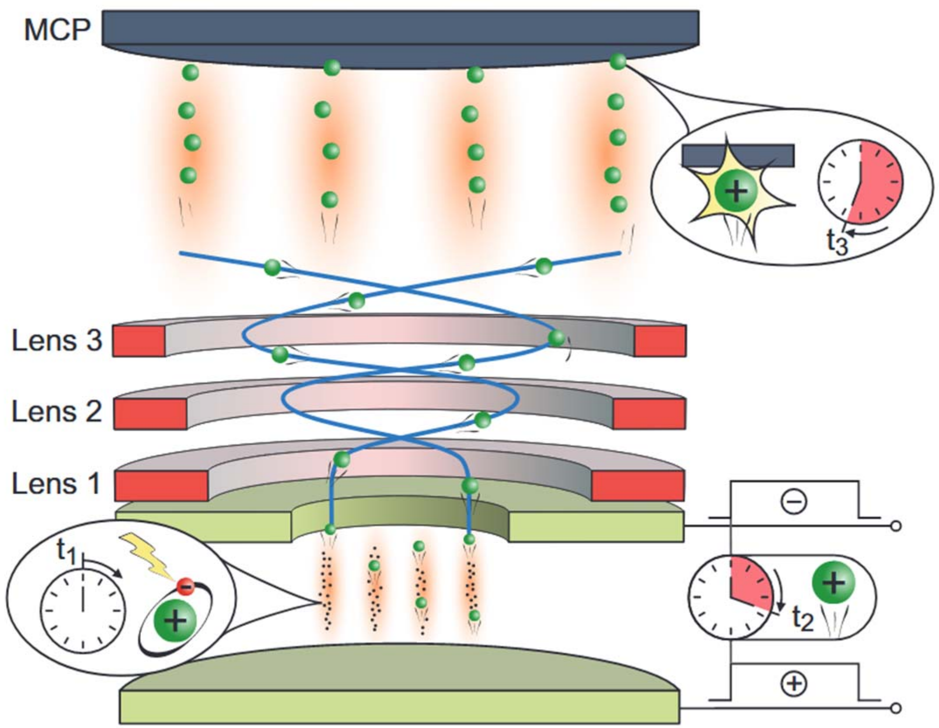
arxiv:2008.08512

A pulsed ion microscope to probe quantum gases

Benefits

- imaging of ground state atoms, Rydbergs & (ultracold) ionic impurities
- high resolution
- probing of dynamic processes
- 3D-imaging
- ...

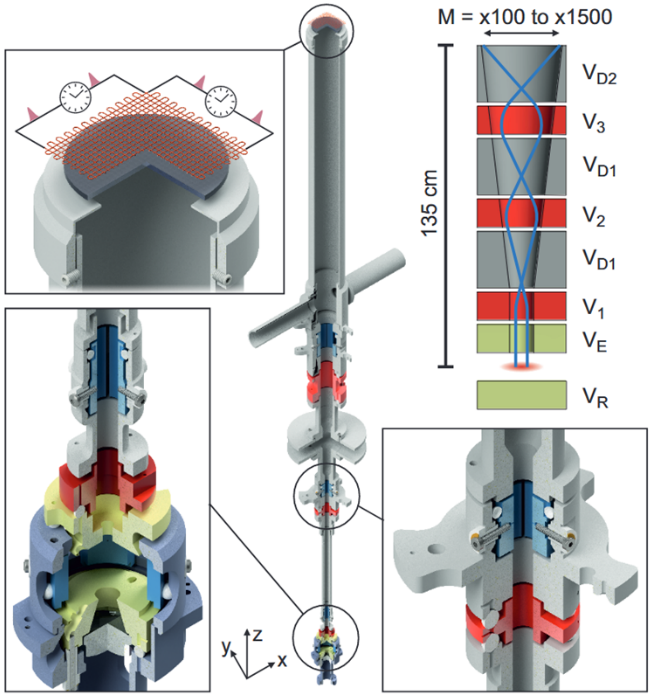
See also
Nat. Phys. **4**, 949 (2008, Ott)
Phys. Rev. Lett. **107**, 103001 (2011, Raithel)
New J. Phys. **19**, 043020 (2017, Fortágh/Günther)
arxiv:2008.08512 (2020)



arxiv:2008.08512

Ion optics

- E-field control + 3 electro-static lenses
- delay-line detector



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Ion optics

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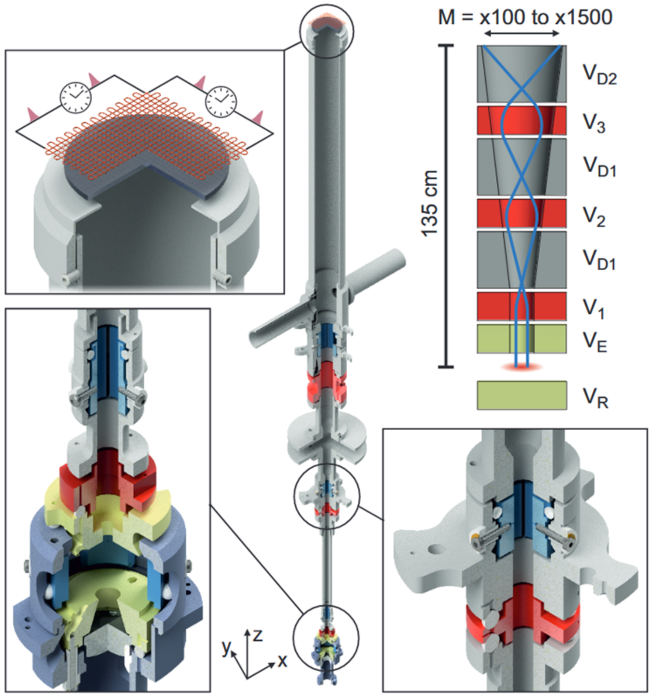
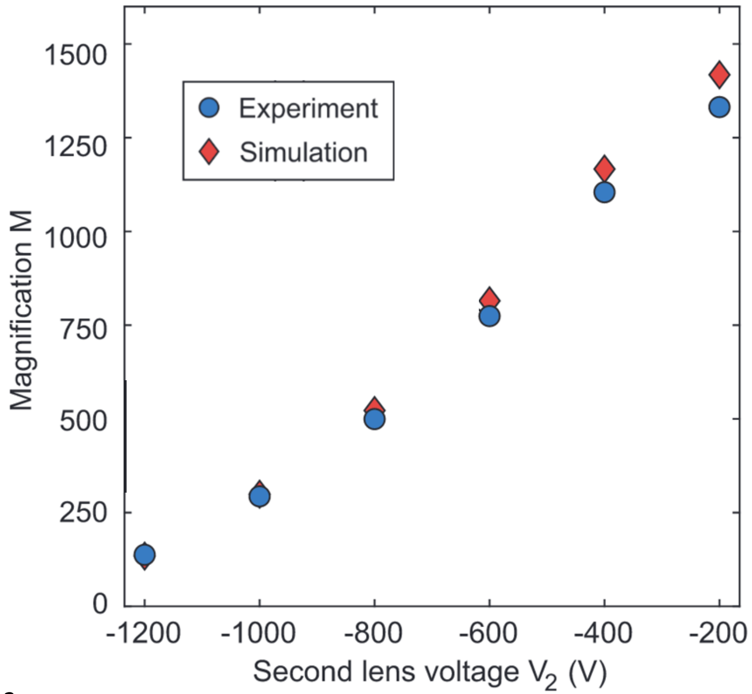


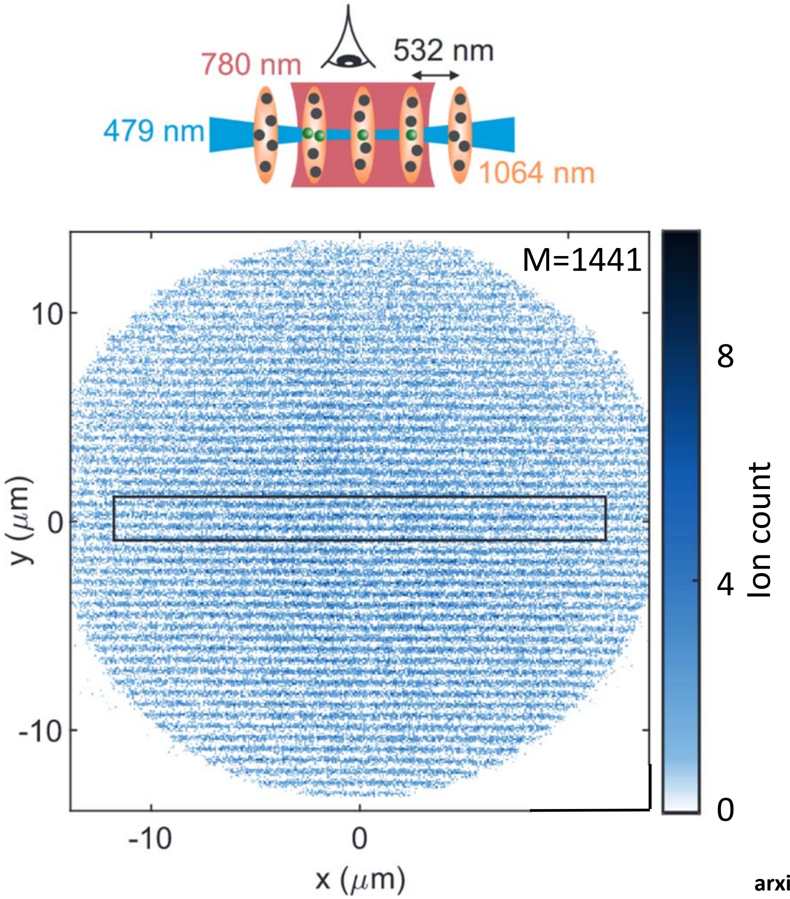
Magnification

- tuning of M via lens voltages
- both lower & higher M achievable



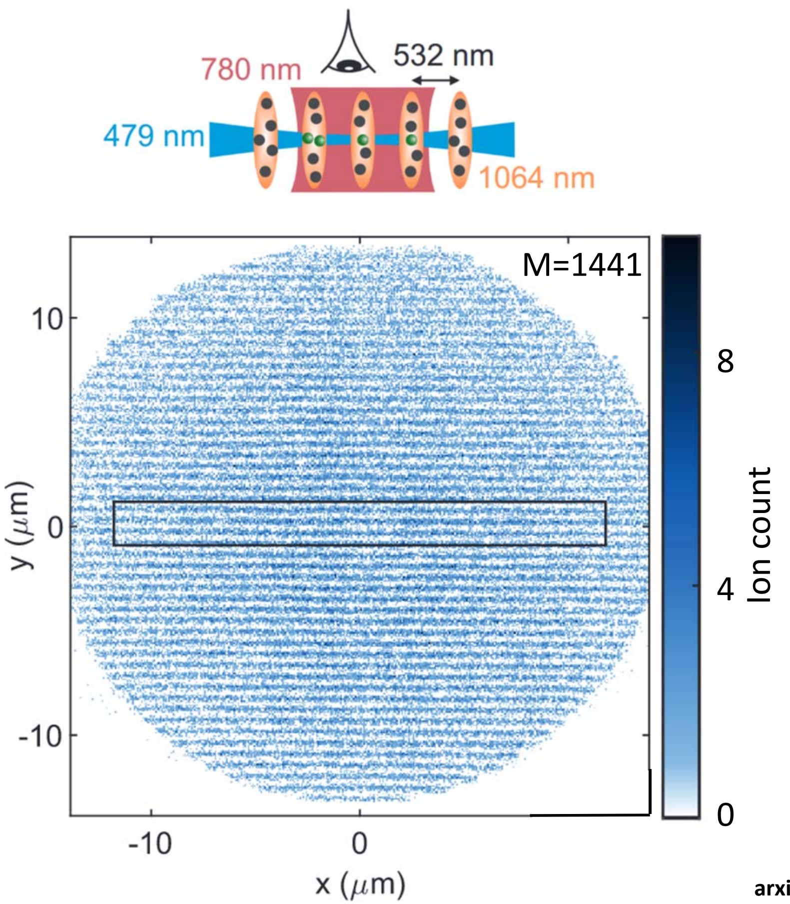
arxiv:2008.08512

Field of view

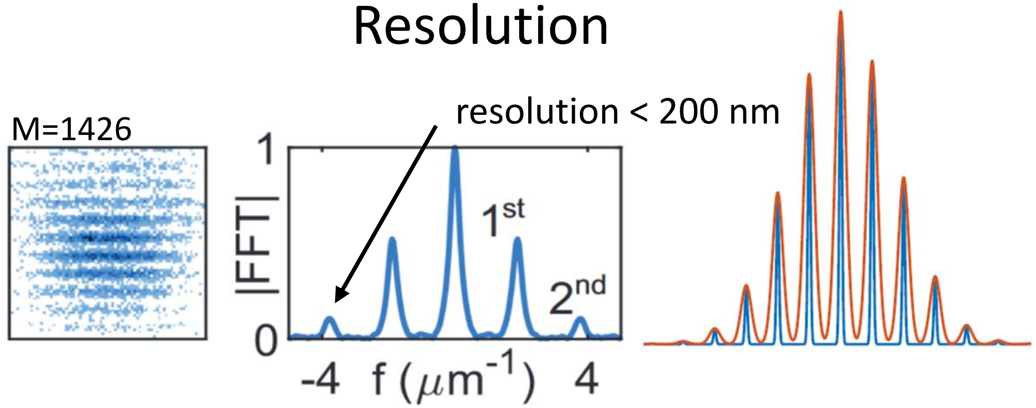


arxiv:2008.08512

Field of view

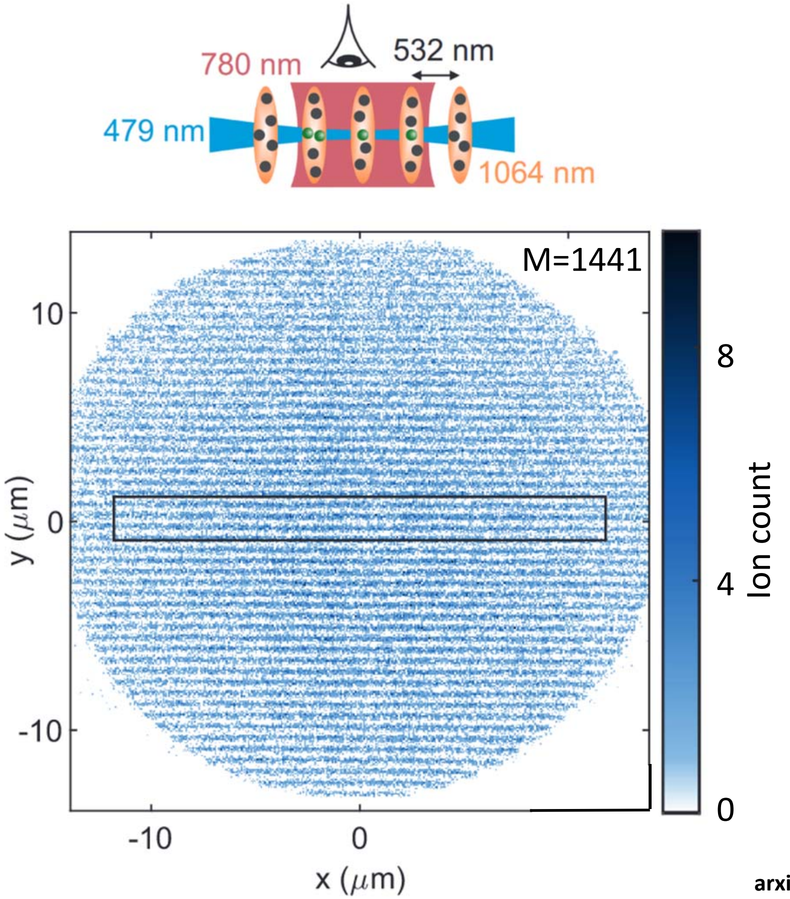


Resolution

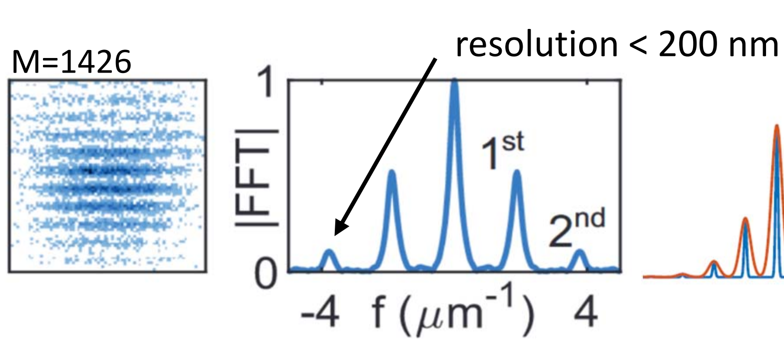


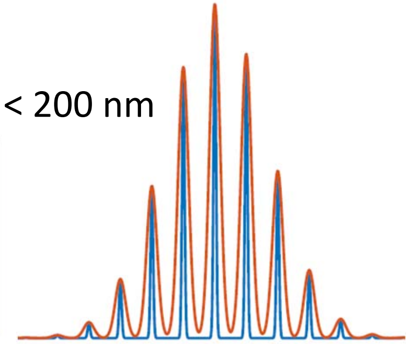
arxiv:2008.08512

Field of view

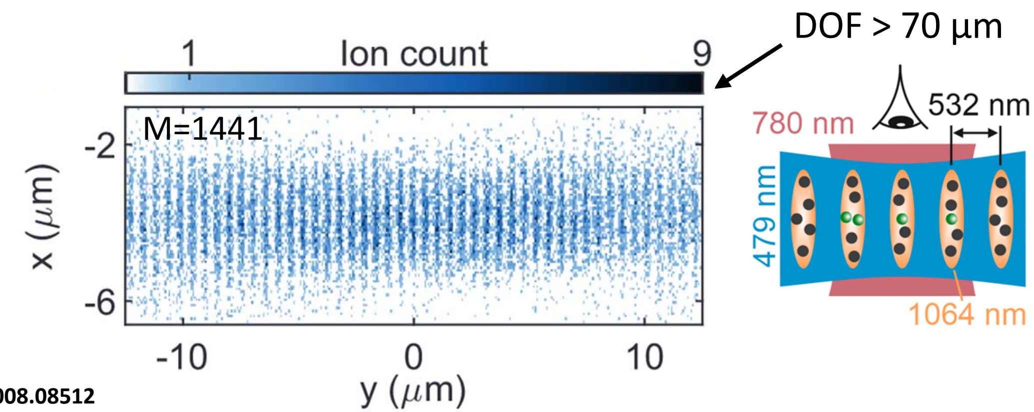


Resolution





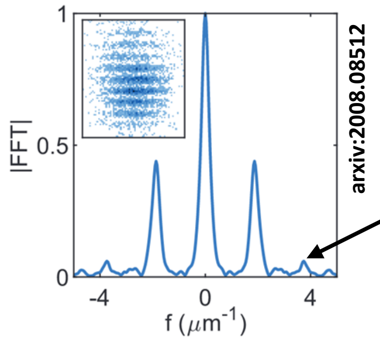
Depth of field



arxiv:2008.08512

Pulsed operation

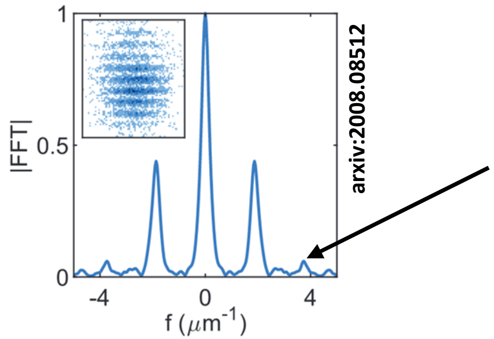
pulsed imaging (2D)



- enables Rydberg & ion imaging
- resolution ~250 nm
- enables 3D imaging

Pulsed operation

pulsed imaging (2D)



- enables Rydberg & ion imaging
- resolution ~250 nm
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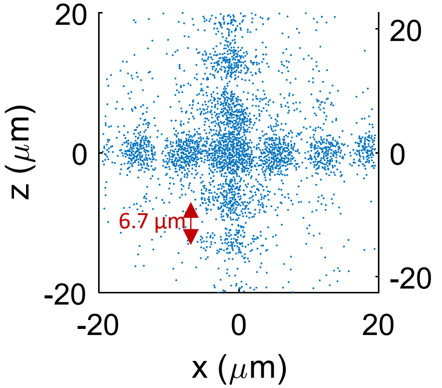
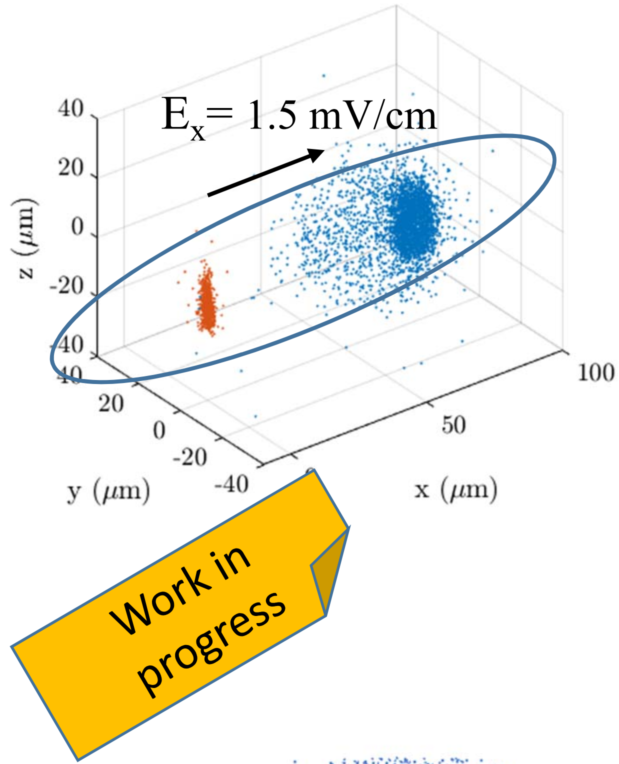
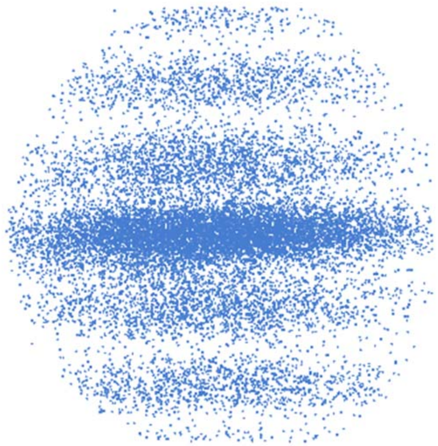
first 3D imaging result



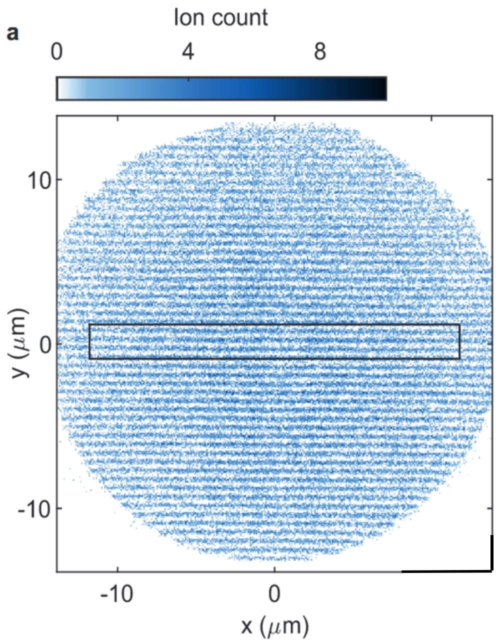
- 2D-diffraction pattern #
- expected achievable resolution <1µm

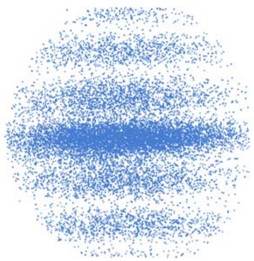




Short summary

pulsed ion microscope (3D)

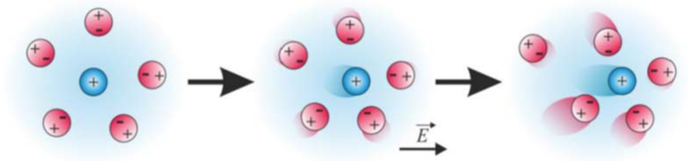




arxiv:2008.08512

Outlook

- ultracold ionic impurities in a degenerate quantum gas, polarons, transport etc.



- Friedel oscillations in e.g. ^{6}Li
- observation of ion-atom collisions in the quantum regime
  PRL**120**, 153401 (2018)
- Rydberg-Rydberg correlations in 3D
- ….

Questions, suggestions?

Interested?
We have open positions!

A dipolar supersolid and a novel microscope to probe quantum gases

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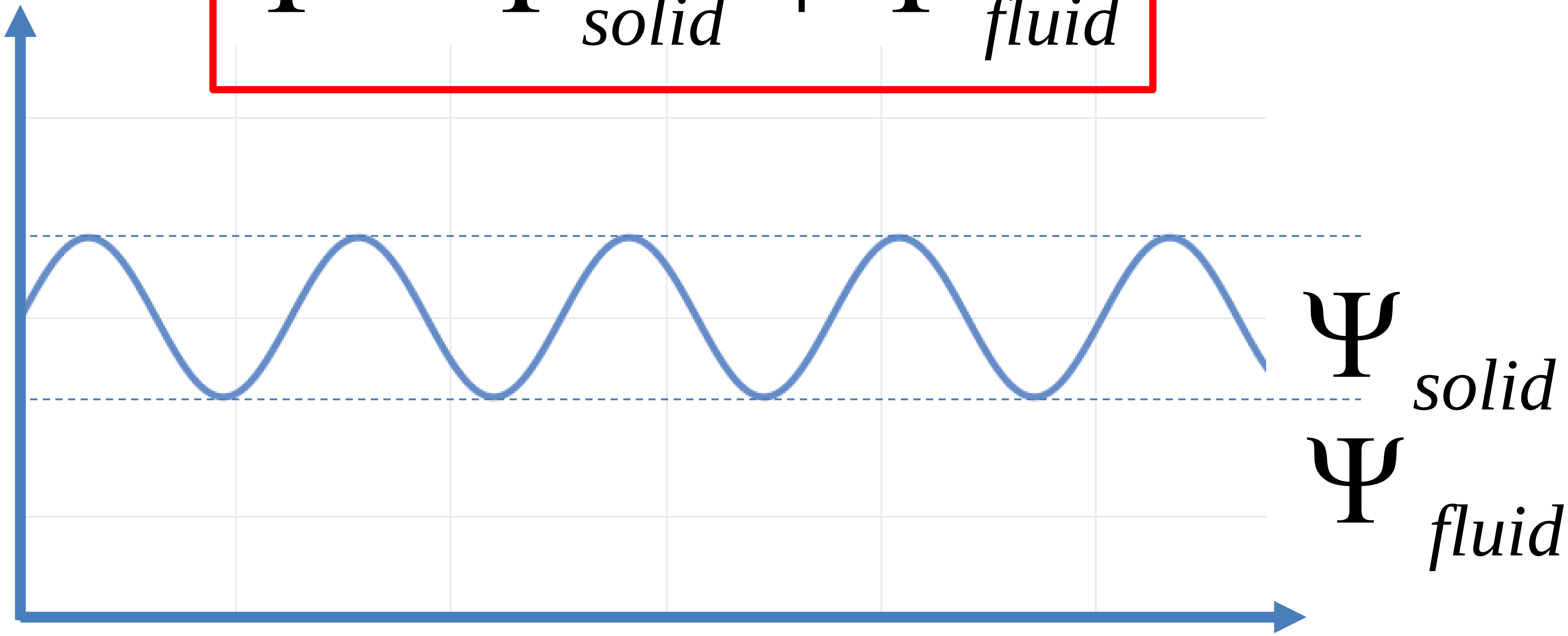
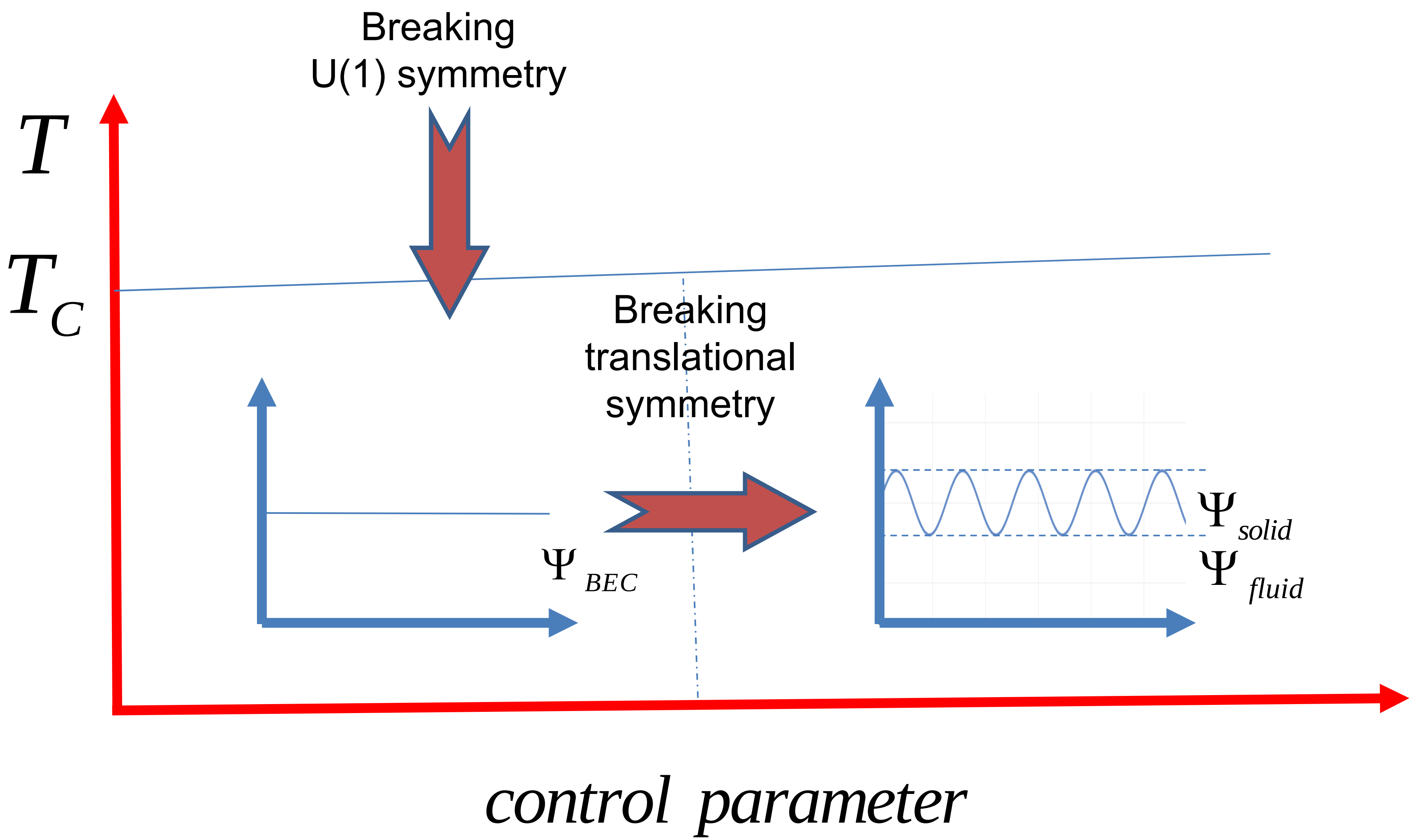
Imagine a Manybody ground state like this:

$$\Psi = \Psi_{solid} + \Psi_{fluid}$$



Supersolid state of matter!

Imagine a phase diagram like this:



Classical magnetic liquids

Rosensweig instability of a classical ferrofluid

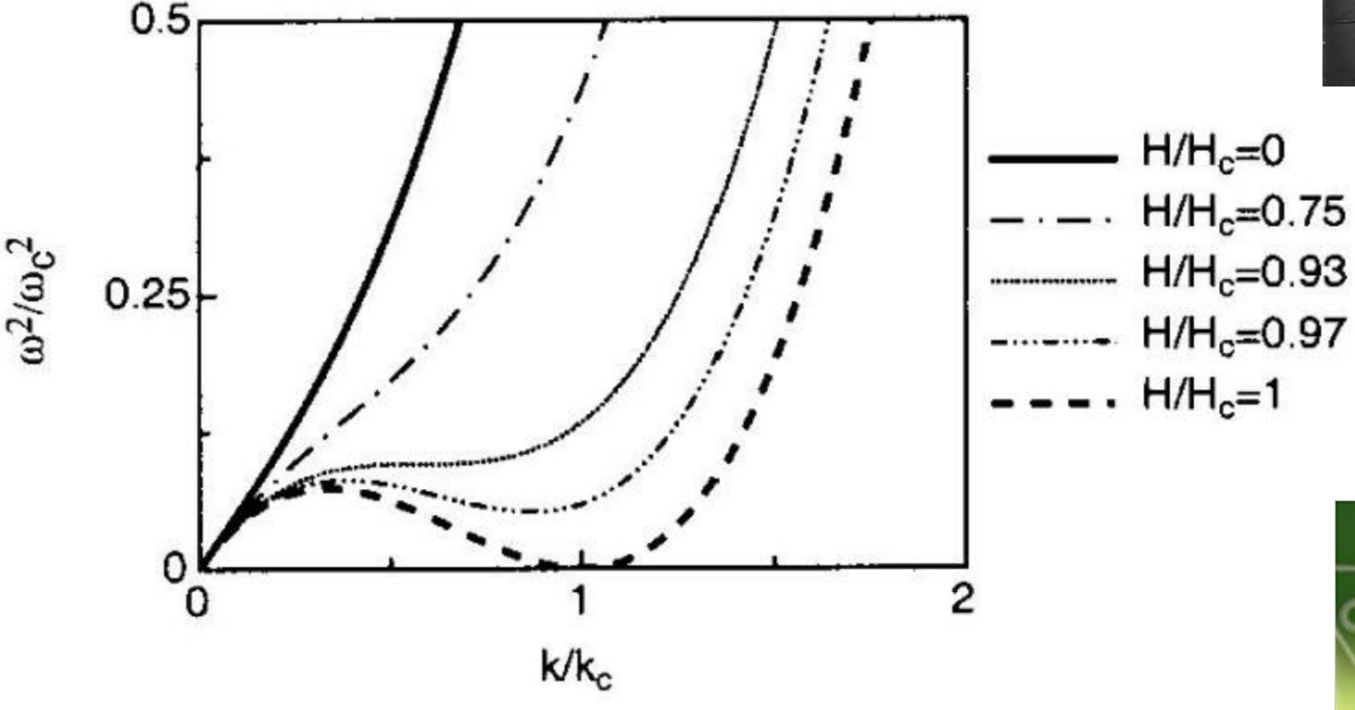
- Dipolar interaction (magnetization)
- Surface tension
- Gravity

Breaks the translational symmetry of the system!

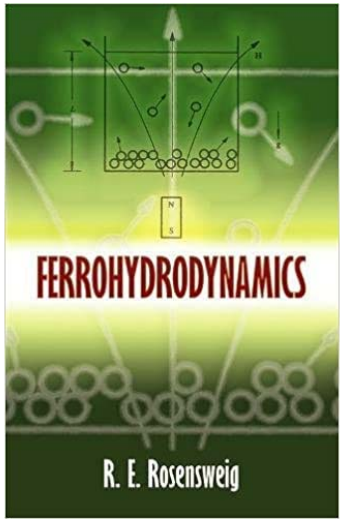
see e.g. Timonen et al., Science 341, 253 (2013)

Roton-like excitation spectrum in a ferrofluid

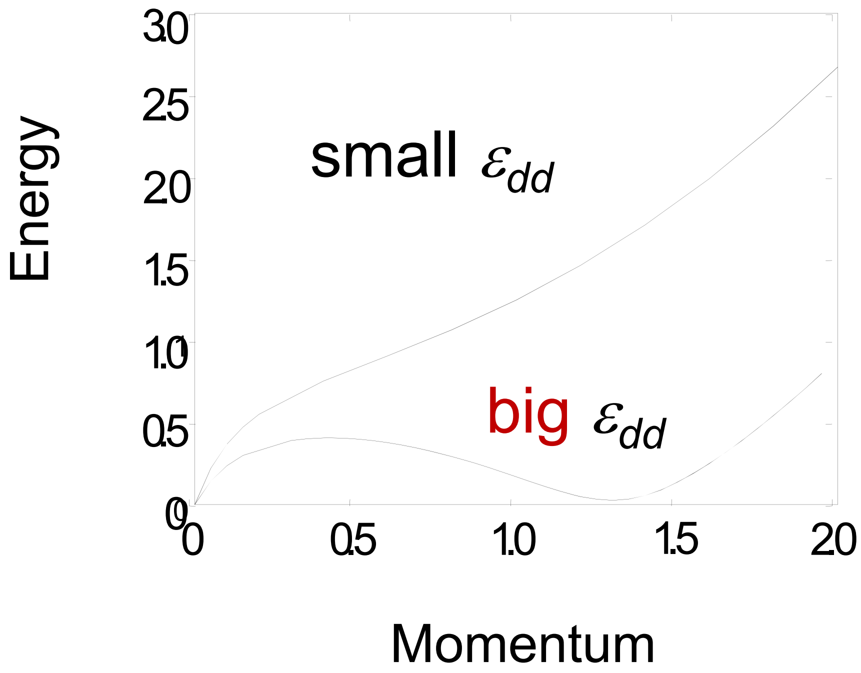
Dispersion relation of surface wave in ferrofluid



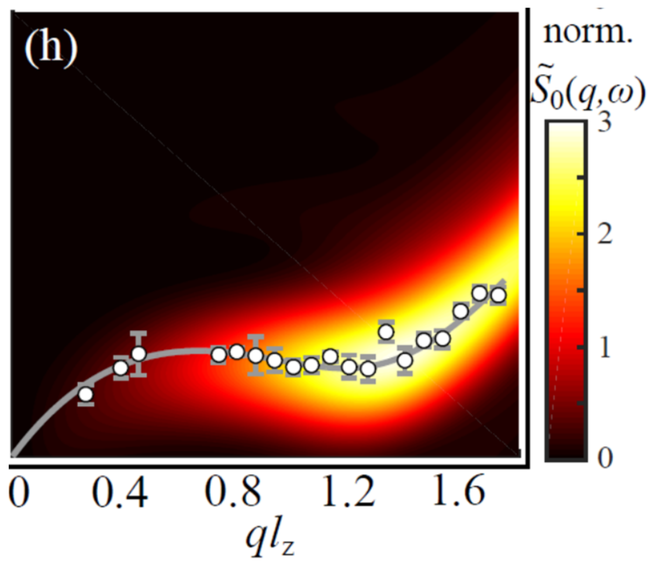
J. Browaeys et al., Braz. J. Phys. **31,** 447 (2001)
R. E. Rosensweig, Ferrohydrodynamics,
Dover Publications, Inc (1997), page 191



Selforganized structures in a dipolar BEC



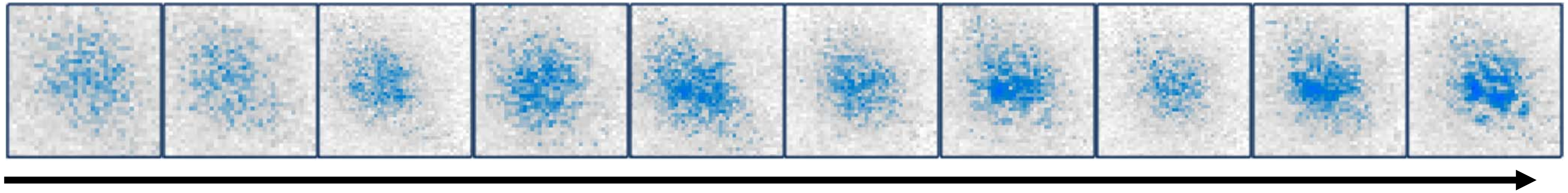
Santos, Shlyapnikov, and Lewenstein
PRL **90**, 250403 (2003)



D. Petter, et al. L. Chomaz, F. Ferlaino,
PRL **122**, 183401, (2019)

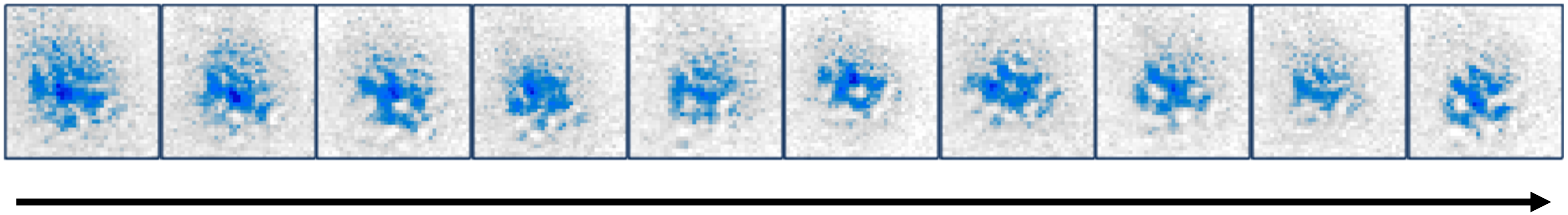
2015 surprise: no collapse….

direct evaporative cooling into droplet array



t = 0 ms

90 ms



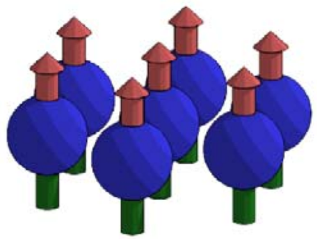
100 ms

190 ms

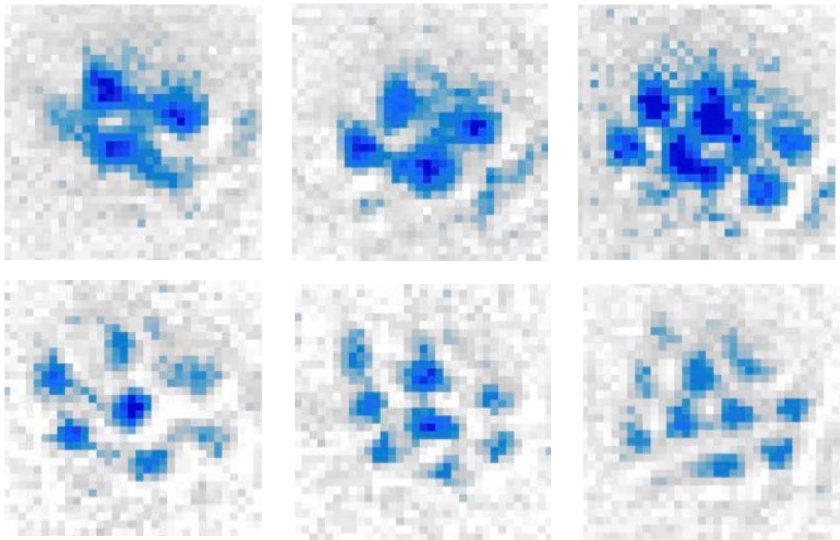
Wait time at constant trap depth away from Feshbach resonances.

Selforganized structure formation

- Rosensweig instability :



just like classical magnetic liquid !



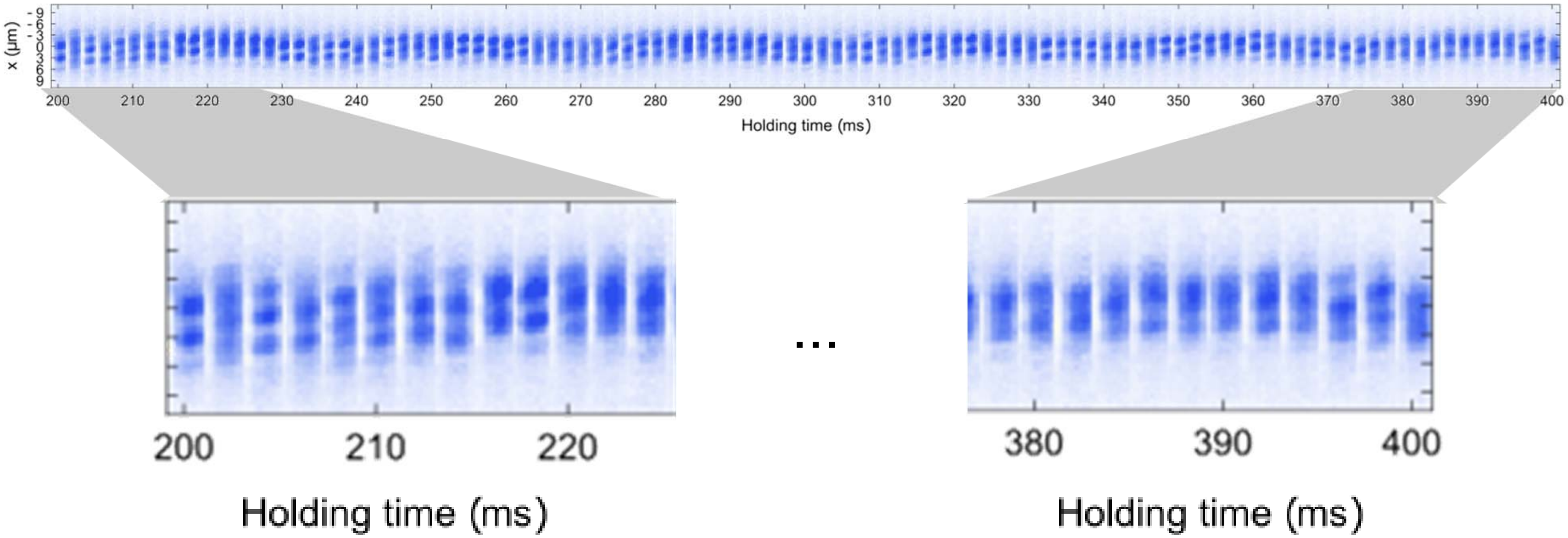
- Surprise: no collapse, but stable arrays of droplets in the trap.

But why is this state stable?

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

A long-lived ^{162}Dy supersolid

- long lifetimes:



- 1/e lifetime ~ 170ms, highly reproducible droplet arrays

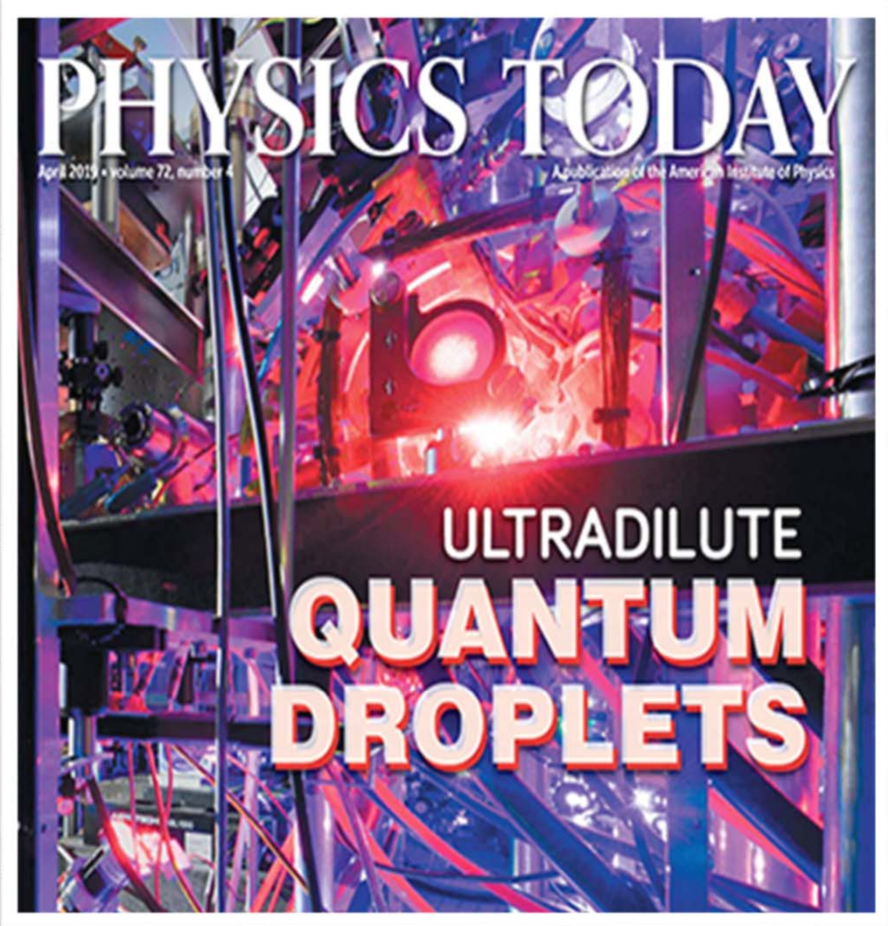
Quantum droplets

- Repulsive correction arrays in c
  I.Ferrier-Barbut, et

- Can be in Gross-Pita

  Theory by Petrov, Rzążewski …

- Ground st self-bound



I. Ferrier-Barbut, April 2019

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

LHY

C-MF

Schmitt et al., Nature **539**, 259 (2016)
Related work: Chomaz et al., PRX (2016)

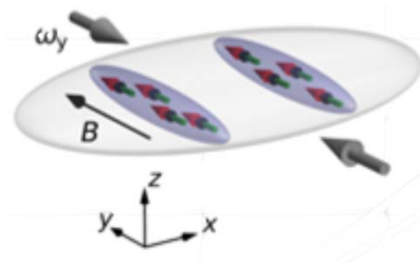
Petrov, *PRL* **115**, 155302 (2015)
L. Tarruell (ICFO)
M. Fattori group (Florence)
D.Wang group (CUHK)

Now a research topic in its own right!

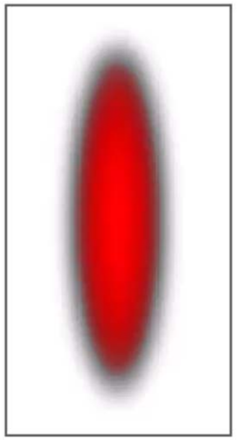
Connection to helium droplets, Bose-Bose mixtures, excitations …
Review: F. Böttcher *et al.*, arxiv:2007.06391 (2020)

Arrays of dipolar quantum droplets

Confinement induced arrays of quantum droplets

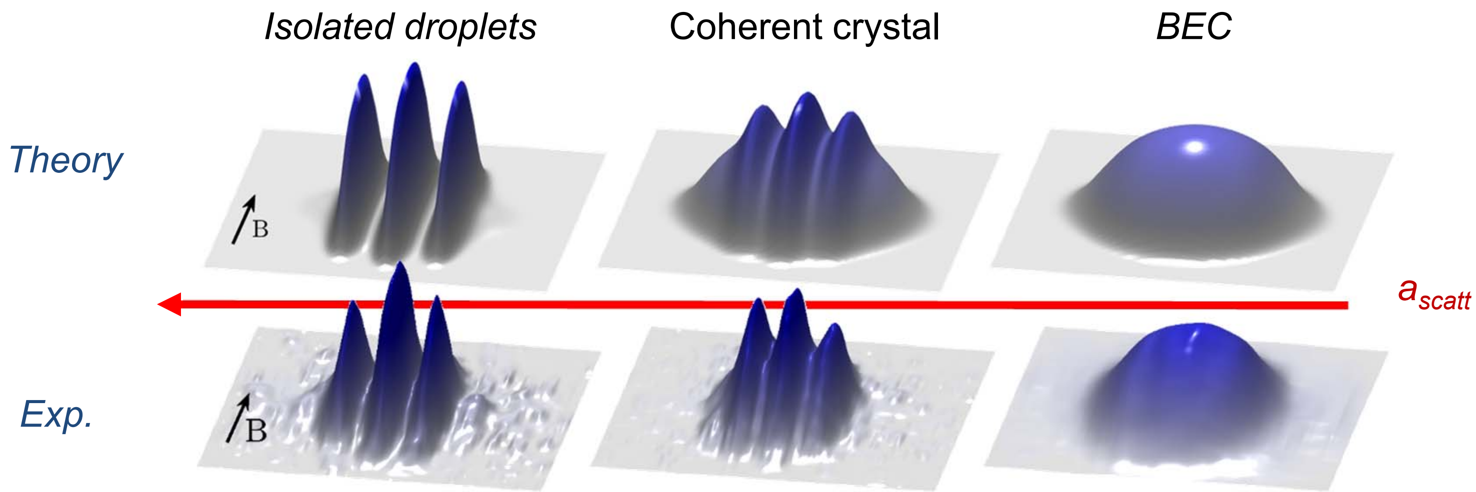


t = 0.00 ms

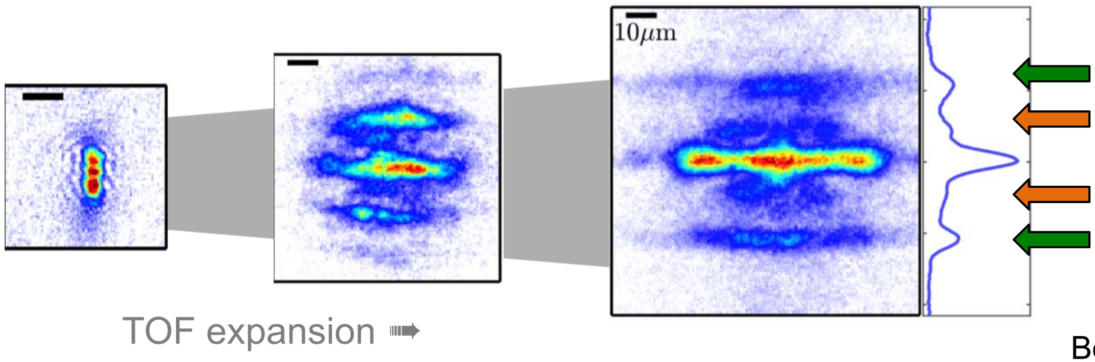


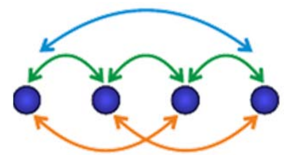
BEC-to-droplet-crystal transition

- Experimental observation of density modulation



- Probing coherence via time-of-flight interference



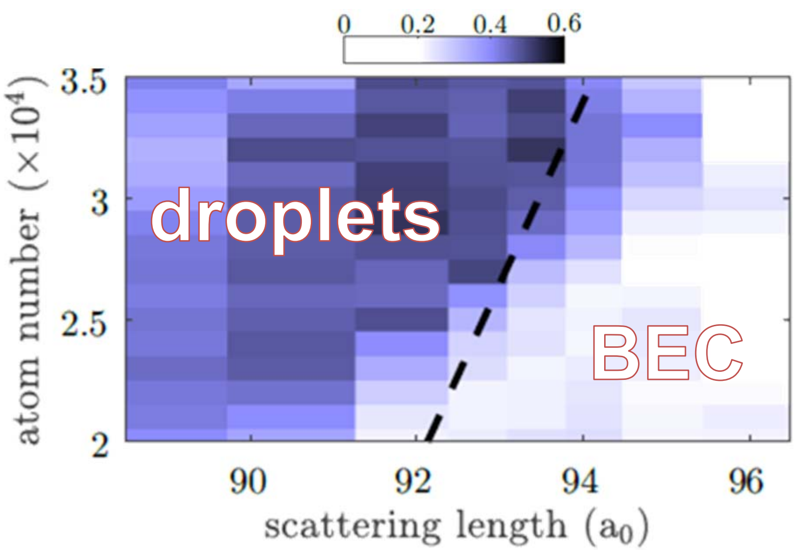


Individually resolve nearest- and next-nearest neighbor coherence

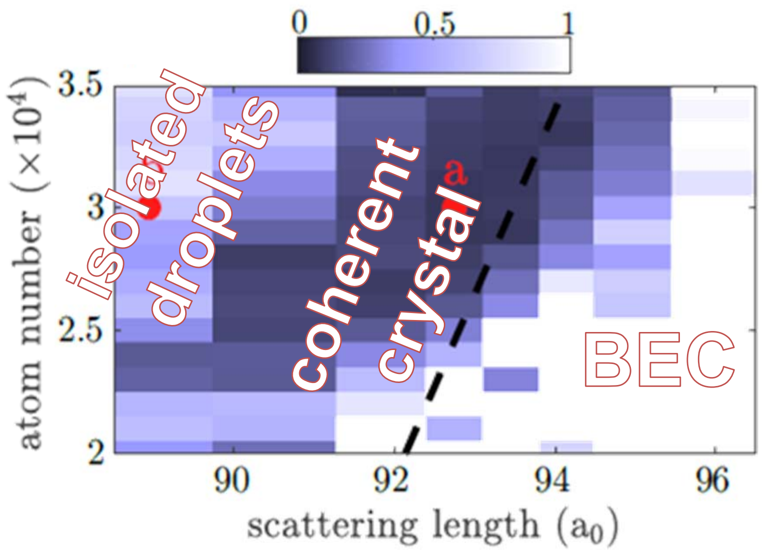
Böttcher *et al.*, PRX **9**, 011051 (2019)
related work by Pisa and Innsbruck group

Experimental phase diagram

In-situ density modulation



Nearest-neighbor coherence



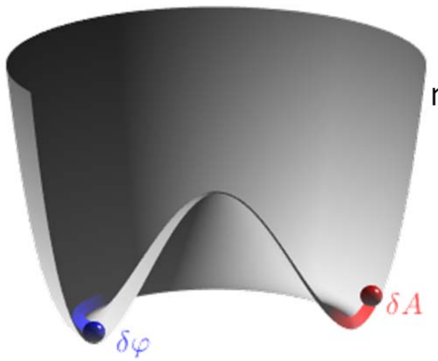
- Agrees very well with theory - strong evidence for supersolidity in dipolar quantum gases
- But is the state also superfluid? (In other words: Is there *phase rigidity* or *superfluid stiffness*?)

Böttcher *et al.*, PRX **9**, 011051 (2019)

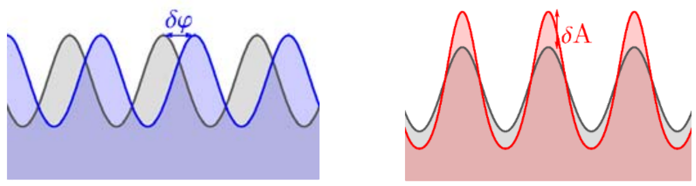
Goldstone and Higgs excitations

complex order parameter

$$\Phi = A\, e^{i\varphi}$$



mexican hat potential

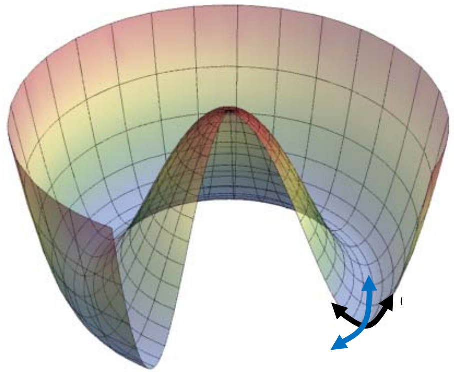


for a broken translational symmetry

D. Pekker & C. Varma, Annu. Rev. Condens. Matter Phys. **6,** 269-297 (2015)

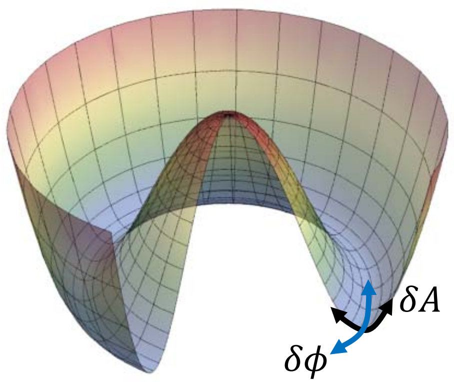
Supersolid: the thermodynamic limit

Superfluid

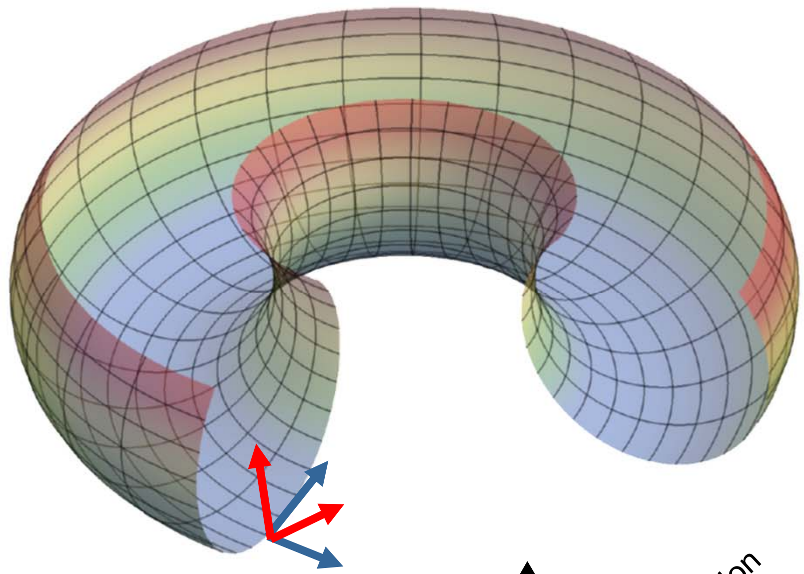


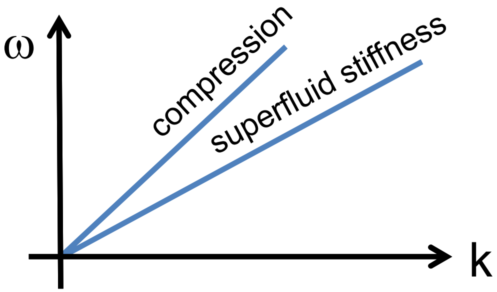
&

Crystal



Two new Goldstone modes





Compression phonons
(in phase BEC & crystal phonons)

Superfluid stiffness phonons
(out of phase BEC & crystal phonons)

See e.g. C. Josserand, Y. Pomeau, S. Rica
Eur. Phys. J. **146**, 47 (2007)

Spectrum of collective excitations

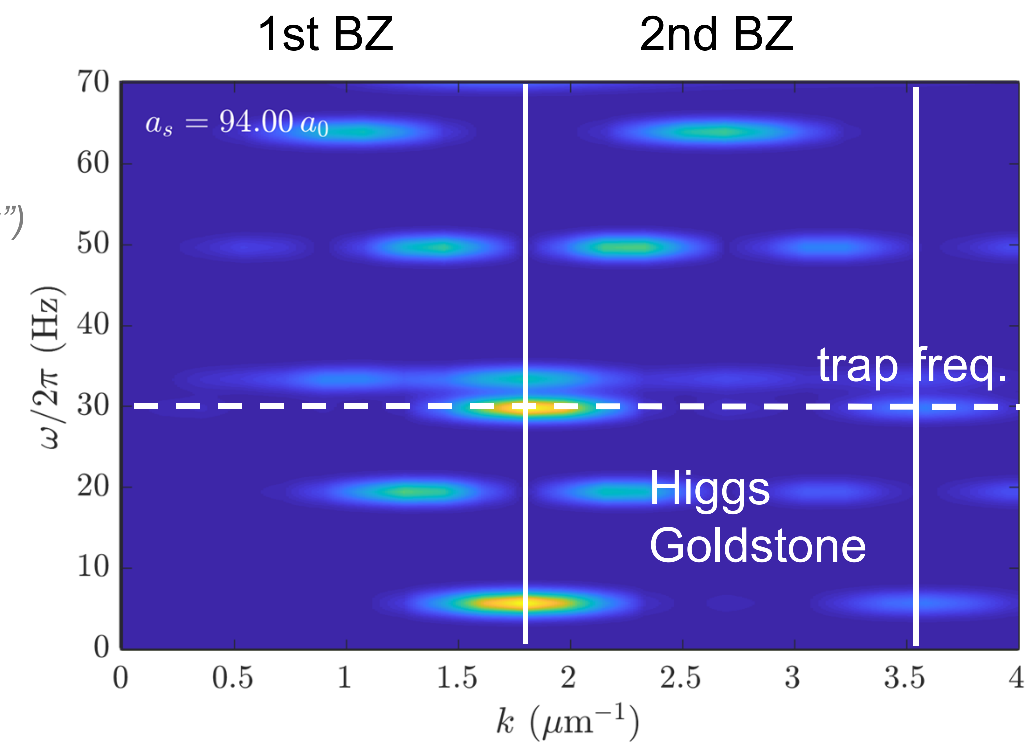
Calculate dispersion relation with Bogoliubov-de Gennes equations for our **finite, trapped system:**

- Discrete modes, shifted up to trap frequency

  Lowest excitation: dipole mode ("sloshing")

- Roton softening
- Higgs & Goldstone modes emerge at phase transition point
- Finally: periodicity of a crystal emerges

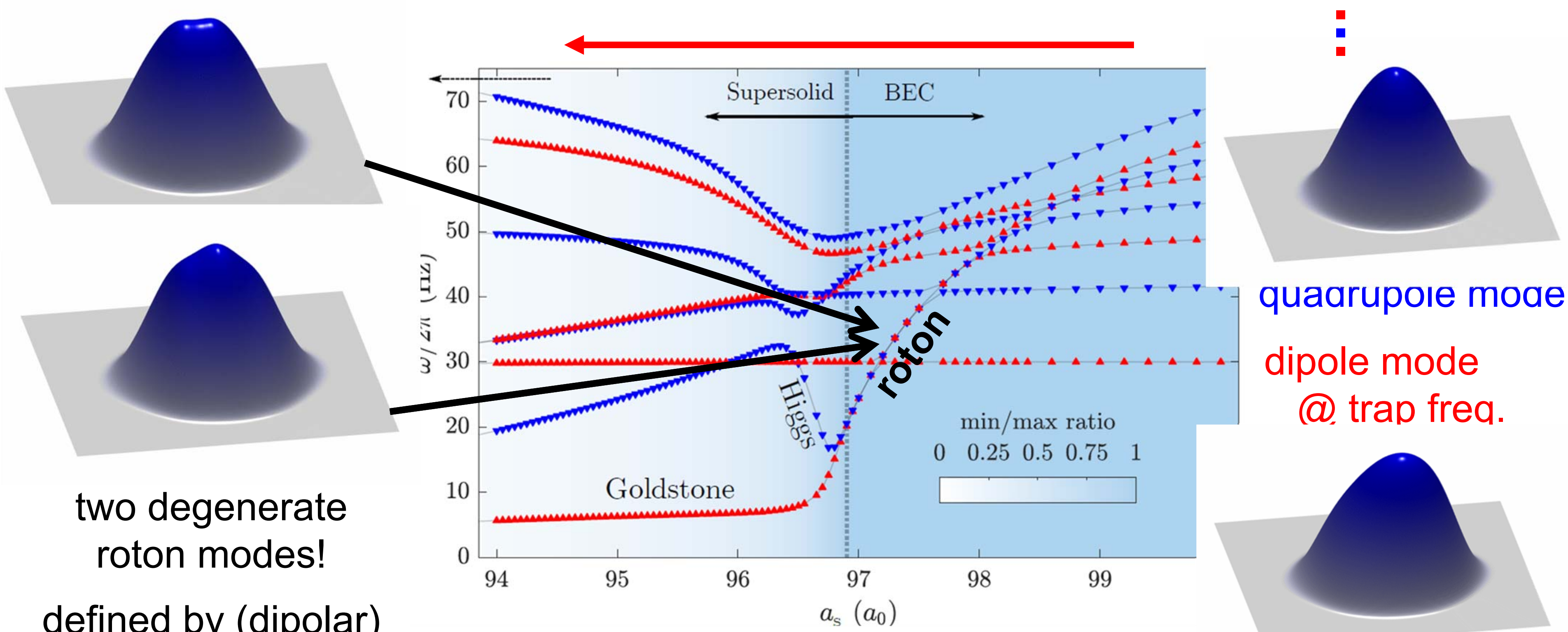
  Converges to infinite system result for large systems!



Hertkorn *et al.*, PRL **123**, 193002 (2019)

Spectrum of collective excitations

Dispersion relation calculated using Bogoliubov-de Gennes equations for our **finite, trapped system:**



defined by (dipolar) interactions

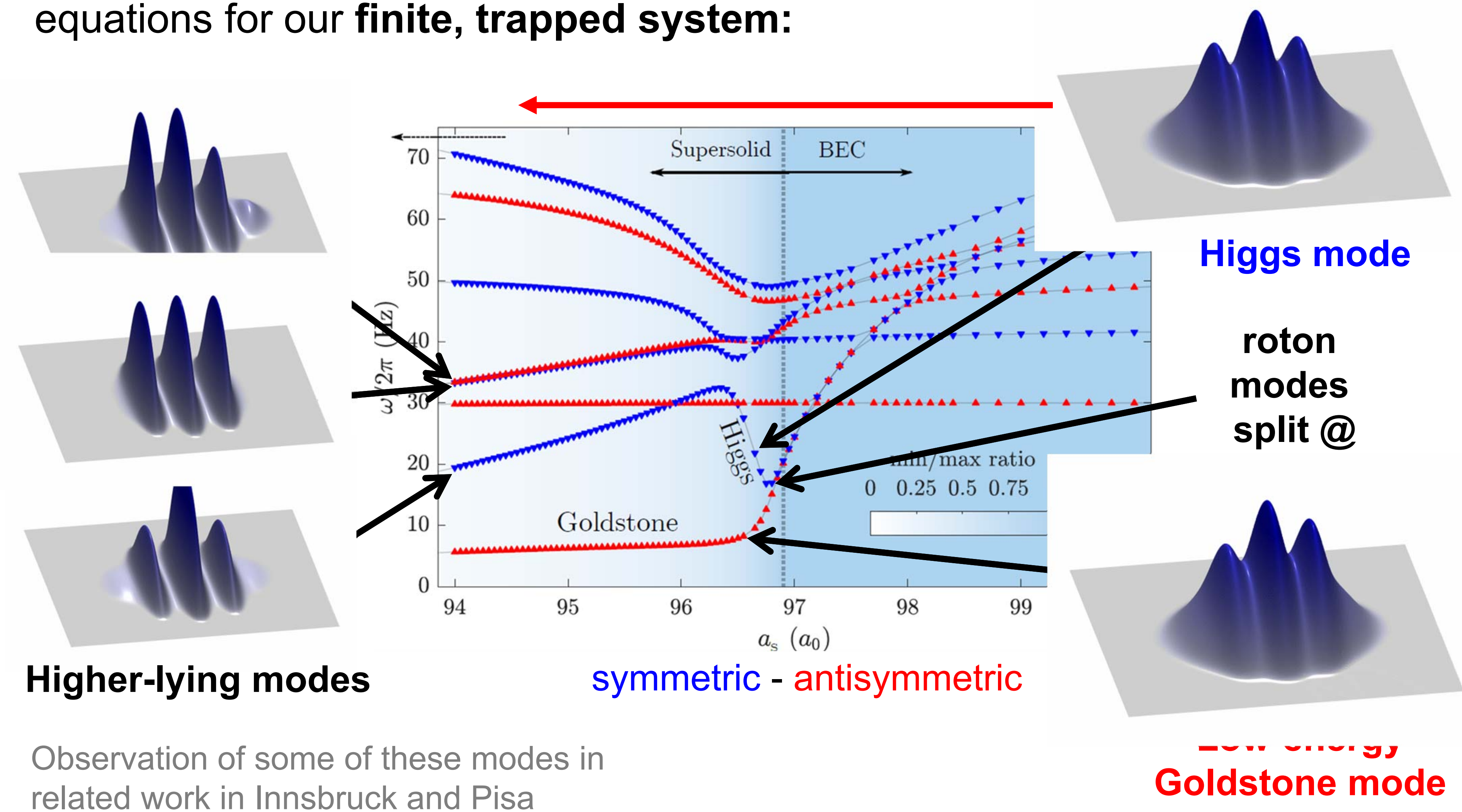
symmetric - antisymmetric

defined by the trap !

Hertkorn *et al.*, PRL **123**, 193002 (2019)

Spectrum of collective excitations

Dispersion relation calculated using Bogoliubov-de Ger
equations for our **finite, trapped system:**



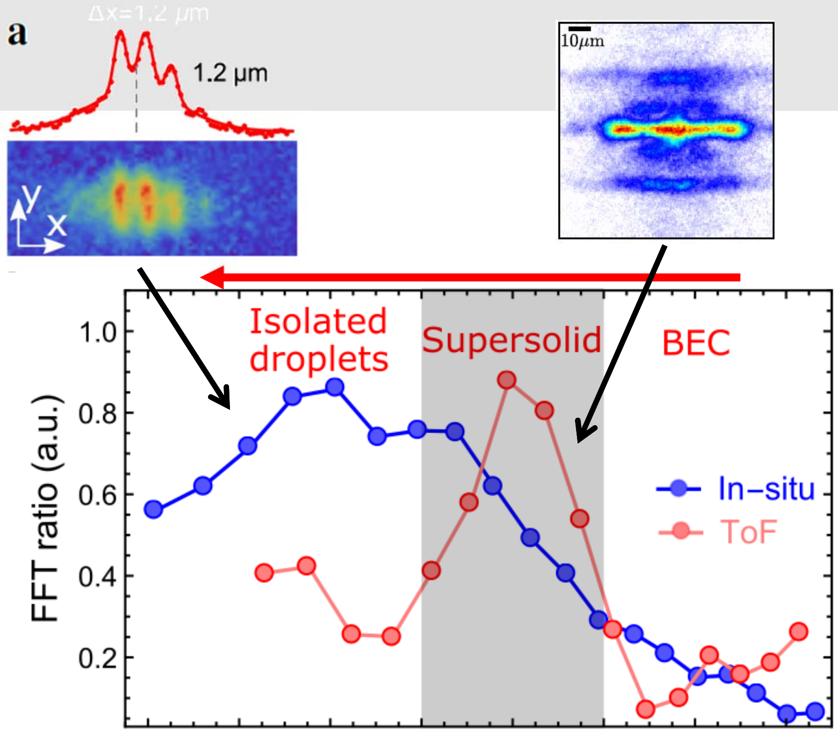
Observation of some of these modes in
related work in Innsbruck and Pisa

Hertkorn *et al.*, PRL **123**, 193002 (2019)

Experiment

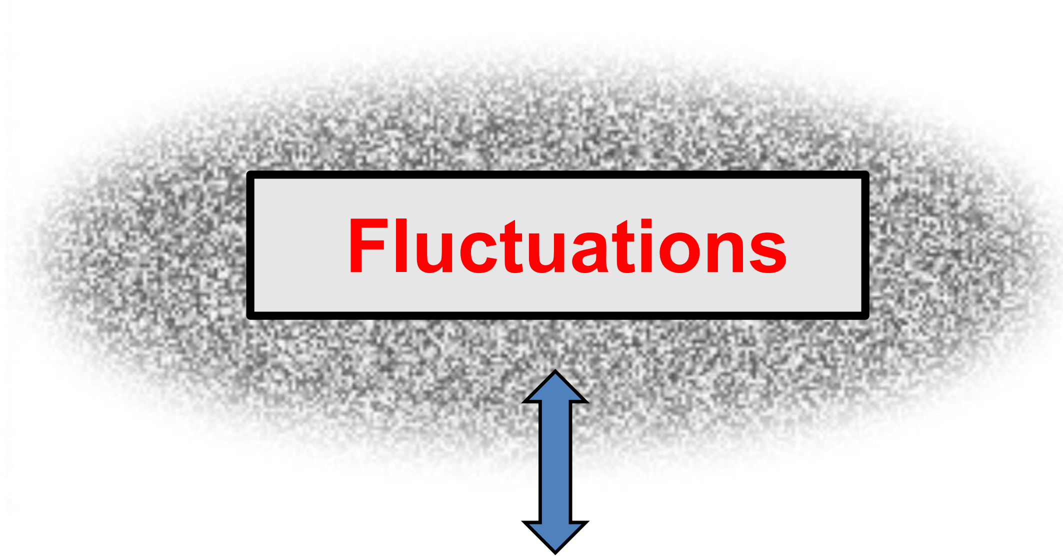
- Bringing together all hallmark features of a supersolid …

- in situ observation of modulation
- Phase coherence
- Low energy phonon mode



Guo *et al.*, Nature **574**, 386 (2019)

Density Fluctuations across the Superfluid-Supersolid Phase Transition



Characterize using

Structure factor

- Fourier transform of the density-density correlation function
- Historically important for superfluid He: neutron or X-ray scattering
- Well known in BECs, Fermi gases & dipolar BECs: Bragg spectroscopy

Hertkorn *et al.*, arxiv: 2009.08910 (2020)

e.g. MIT, Swinburne, IBK & Paris Nord + many others

Static structure factor

- Here: Extract directly from in situ density fluctuations / power spectrum

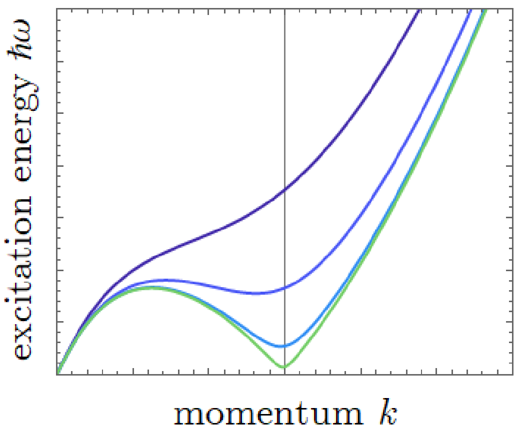
$$S(\boldsymbol{k}) = \langle|\delta n(\boldsymbol{k})|^2\rangle /N$$

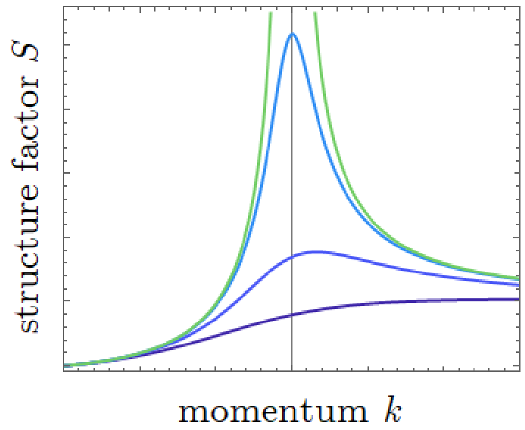
e.g. Pitaevskii & Stringari (2003)

- Simultaneous access to all momenta @ finite temperature
- Linked to excitation spectrum!

Famous *approximation*: Feynman-Bijl $S(\boldsymbol{k}) = \hbar^2\boldsymbol{k}^2/2m\varepsilon(\boldsymbol{k})$

e.g. Klawunn, Recati, Stringari, Pitaevskii, PRA (2011)



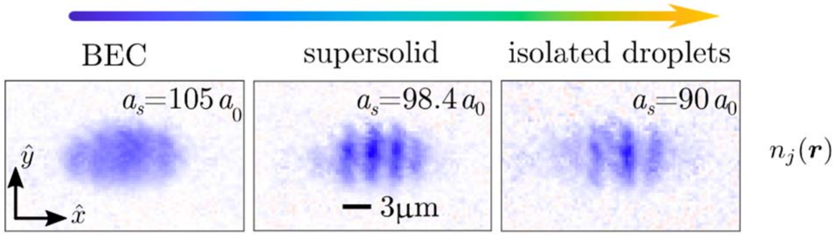


- As roton softens: fluctuations & structure factor dramatically enhanced
- Roton instability is the precursor to supersolid phase transition

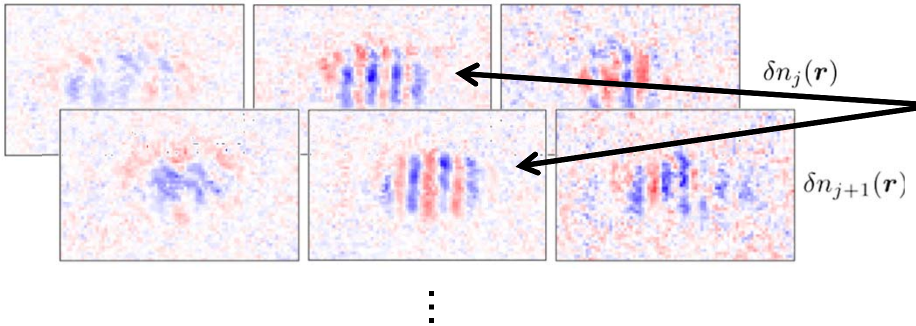
Hertkorn *et al.*, arxiv: 2009.08910 (2020)

Experiment

- Extract hundreds of images across the transition

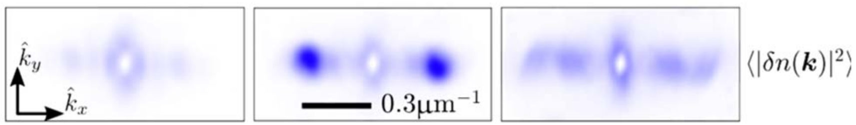


- Calculate mean image and fluctuations around the mean: $\delta n_j(\boldsymbol{r}) = n_j(\boldsymbol{r}) - \langle n(\boldsymbol{r}) \rangle$



Direct images of roton modes in single shots!

- Obtain mean power spectrum via Fourier transform and, hence, S(k)



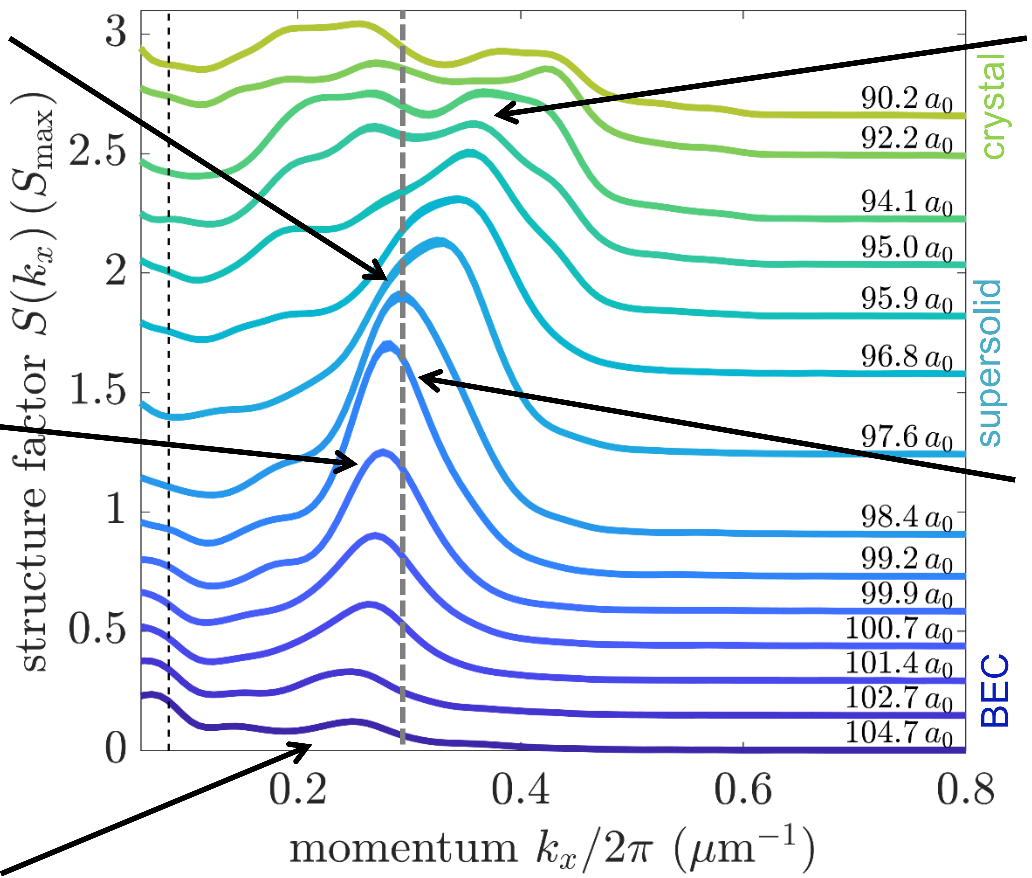
Hertkorn *et al.*, arxiv: 2009.08910 (2020)

Static structure factor

Phase transition:
inverse spacing and
roton momentum match

droplet spacing ~ 3 um

Splitting:
emerging phonon
modes of the crystal



Roton momentum shift
(in agreement with
variational approach)

Blakie et al., (2020)

Increasing amplitude
signals enhanced
fluctuations at transition:
$S_{\max} \sim T/\Delta^2_{\mathrm{rot}}$ ~ 260

Klawunn, Recati, Stringari, Pitaevskii, PRA (2011)

Temperature is important ! ($k_B T >> \Delta_{\mathrm{rot}}$)

Small roton population
already deep in BEC

Direct experimental data

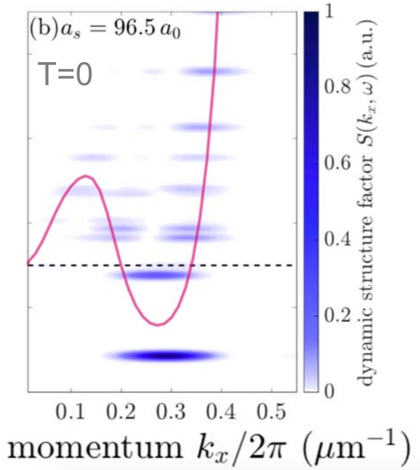
Hertkorn *et al.*, arxiv: 2009.08910 (2020)

Estimating the excitation spectrum

- Feynman-Bijl formula at finite temperature (weakly interacting gas, $na_s^3 \sim 10^{-5}$, $k_{rot}\,\xi < 1$!)

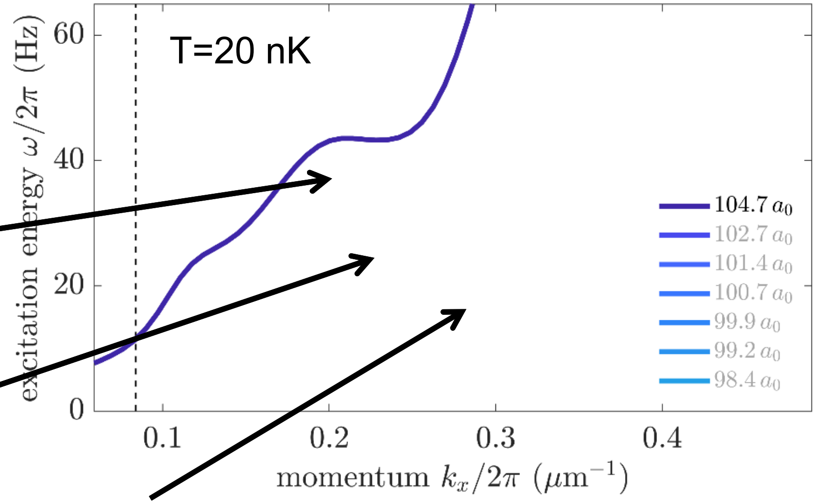
$$S(\boldsymbol{k}) = \frac{\hbar^2 \boldsymbol{k}^2}{2m\varepsilon(\boldsymbol{k})} \coth\left(\frac{\varepsilon(\boldsymbol{k})}{2k_B T}\right)$$

Klawunn *et al, PRA (2011)*
Hung *et al.*, NJP (2011)



- Invert to *estimate* the BEC excitation spectrum

Note: in crystal regime, band structure emerges, no longer single-mode, FB no longer applicable



Emergence of roton minimum

Closing of roton gap and shift of roton momentum

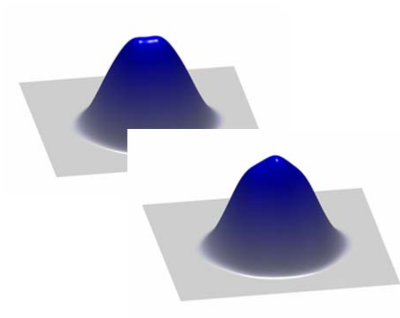
Lowest roton momentum at phase transition

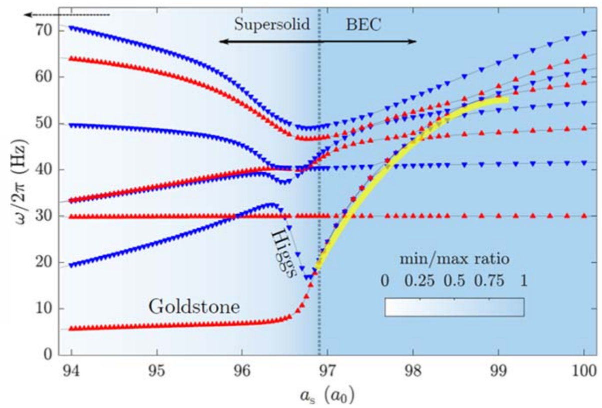
Everything here is model free

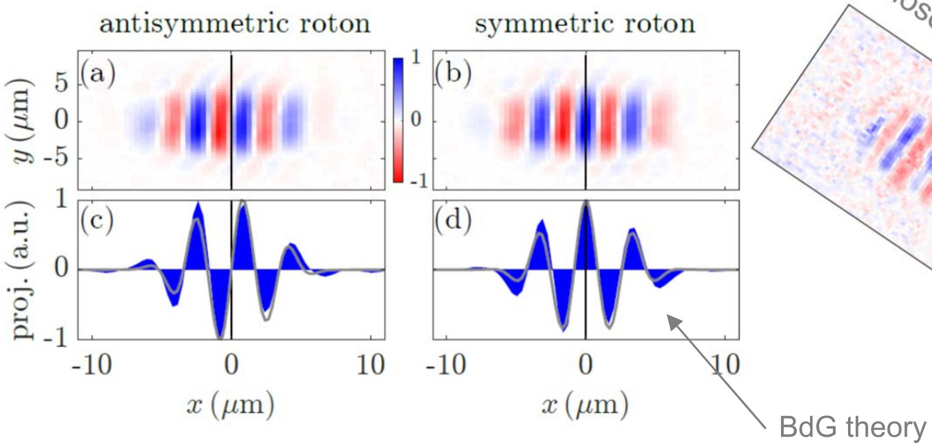
Hertkorn *et al.*, arxiv: 2009.08910 (2020)

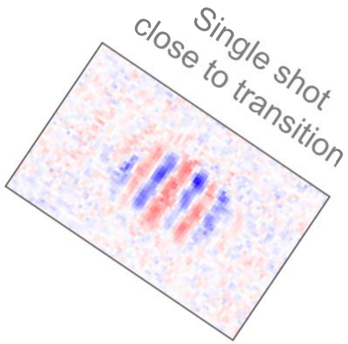
Principal component analysis: Rotons

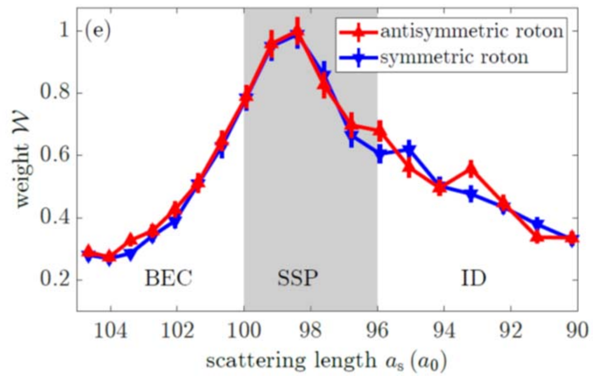
- Statistical analysis to find dominant fluctuation patterns over full dataset
- Results can be identified with BdG modes on BEC side   Debussy *et al.*, NJP (2014)
- Dominant modes are two degenerate roton modes
- Strong enhancement around the transition !
- See modes individually : (often) even in single shots









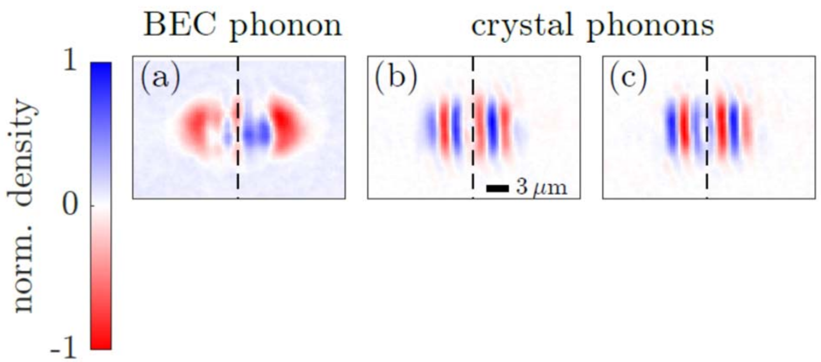


Hertkorn *et al.*, arxiv: 2009.08910 (2020)

Higher-order modes

Next-strongest modes:

- BEC quadrupole mode
- (anti-)symmetric crystal phonons



PCA

Fourier transform explains double peak structure in S(k)

- Splitting of excitations at the edge of the emerging Brillouin zone

Weights across the transition:

- BEC mode dominant in BEC
- Crystal phonons dominate from the transition

Supersolid region supports both BEC and crystal modes!

Hertkorn *et al.*, arxiv: 2009.08910 (2020)

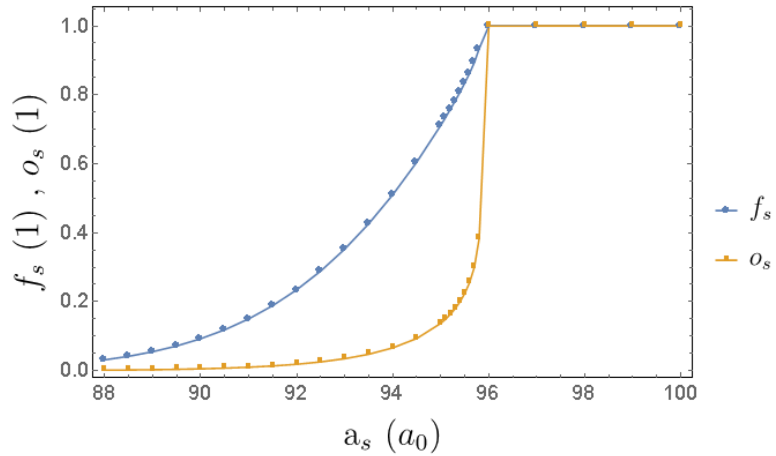
Outlook: 2D dipolar supersolid

Phase transition characterized by the superfluid fraction,[1]

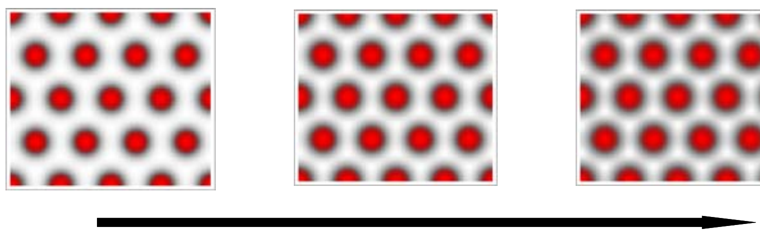
$$f_s = \min_\theta \left[\int \frac{(\int dx)^2}{\int |\psi(\bar{x}, \bar{y}, z)|^{-2} dx} dydz \right]$$

Where $\overline{x} = x\cos\theta - y\sin\theta \qquad \overline{y} = x\cos\theta + y\sin\theta$

alternatively: overlap $\qquad o_s = \frac{\min_x n(x)}{\max_x n(x)}$



(1) T. Pohl et al. , PRL **123**, 2019



Questions, suggestions?

Interested?
We have open positions!

Thank you!

Mingyang Guo,
Fabian Böttcher,
Jens Hertkorn,
Kevin Ng,
Jan-Niklas Schmidt,
Sean Graham,
Tim Langen,
Tilman Pfau
Hans Peter Büchler (Theory)
Martin Zwierlein (MIT)

FOR 2247

MARIE CURIE ACTIONS

QUANTERA

IQST

DFG

Alexander von Humboldt
Stiftung/Foundation