Dipolar supersolids

Tim Langen

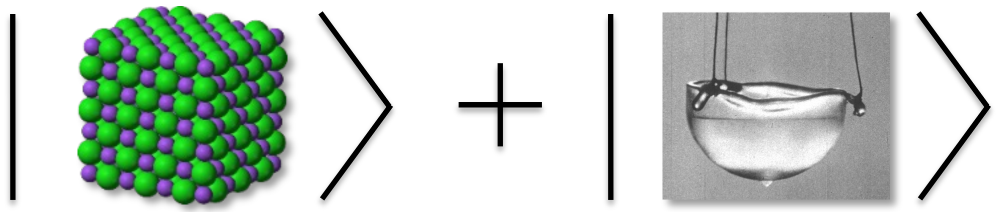
Picture: Manfred Mark

What is a supersolid?

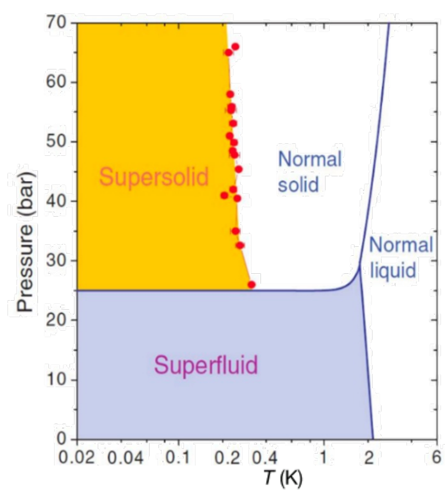
- Open question for > 60 years: **Can a Solid Be "Superfluid"?**

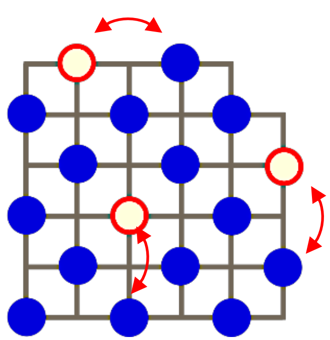
Penrose & Onsager, Andreev & Lifshitz, Gross, Thouless, Leggett + *many more*

- Counterintuitive: rigid structure of a solid + frictionless flow of a superfluid



- Prime candidate material: solid helium





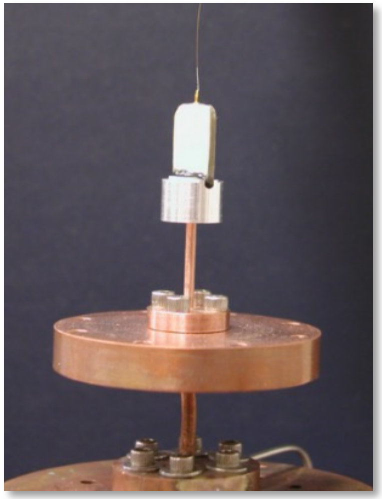
Finite superfluid fraction from Bose-condensed mobile vacancies

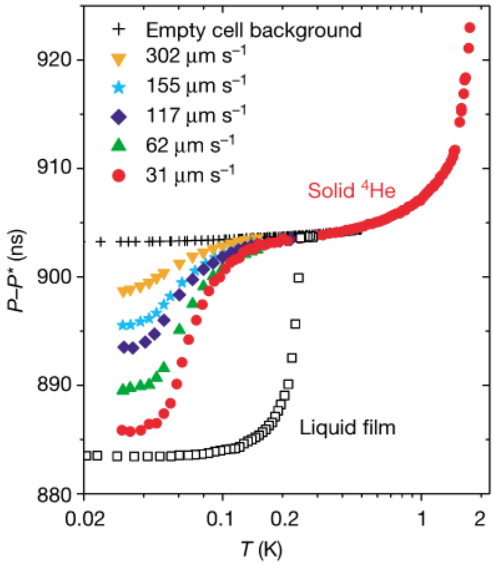
Boninsegni & Prokof'ev, Rev. Mod. Phys. **84**, 759 (2012)

Supersolidity in helium?

- Transition to supersolid should show up as change of **moment of inertia**

- Torsional oscillator: drop in resonance frequency below ~175 mK





Kim & Chan, Nature 427, 225 (2004)

- But: later shown to be related to unexpected change in **sheer modulus**!

Unclear if supersolidity exists (in helium)!

Other way round: Can a (super)fluid be solid?

Analogy: Rosensweig instability of a *classical* ferrofluid

- Nanoscale magnetic particles suspended in a liquid solvent
- Increase magnetization using external magnetic field
- Magnetization breaks the **translational symmetry** of the system!

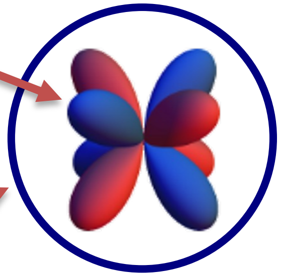
What if we add quantum mechanics?

Coherent superposition of fluid and crystal structure?

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

Quantum ferrofluids

- Ultracold dysprosium atoms:
  large magnetic moment $\mu \approx 10\ \mu_B$

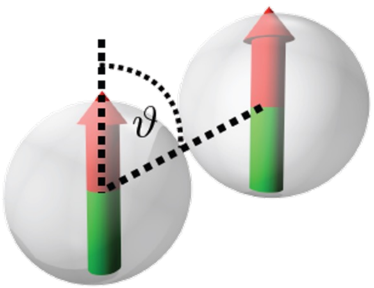


- Contact + Dipolar interactions

long-ranged and anisotropic

$$V_{\text{Born}} = \frac{4\pi\,\hbar^2\,a}{m}\delta(\boldsymbol{r}) + \frac{\mu_0\mu^2}{4\pi\,r^3}(1 - 3\cos^2(\theta))$$

tunable, short-ranged and isotropic

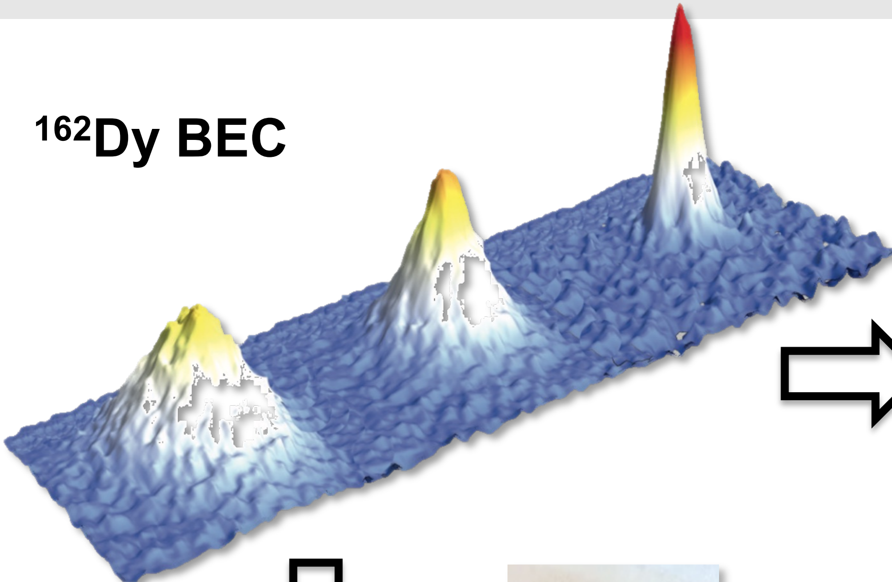


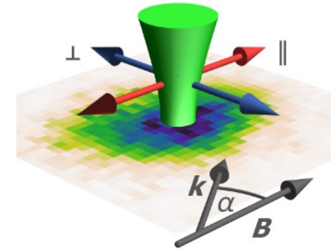
- Relative strength $\varepsilon_{dd} = \frac{a_{dd}}{a} \propto \frac{m\,\mu^2}{a}$ *dipolar* *contact*

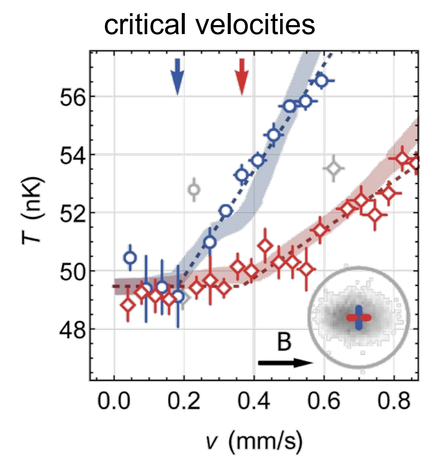
Significant dipolar interactions,
simple cooling and collisional stability!

Quantum ferrofluids

^{162}Dy BEC

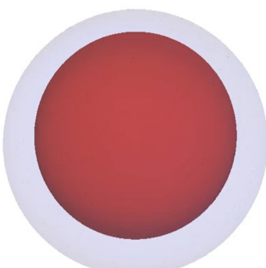






(Anisotropic) superfluid

Wenzel *et al.*, PRL **121**, 030401 (2018)



Spontaneously forms
crystal structures stabilized
by quantum flcutuations

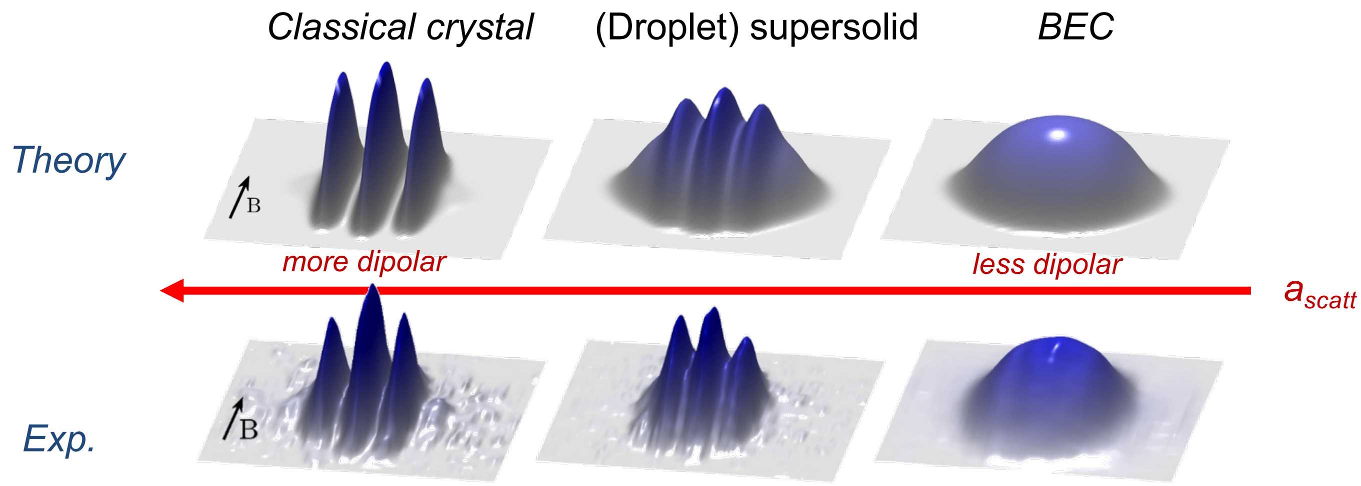
Kadau *et al.*, Nature **530**, 194 (2016)

Can this gas form a solid and be a superfluid at the same time?

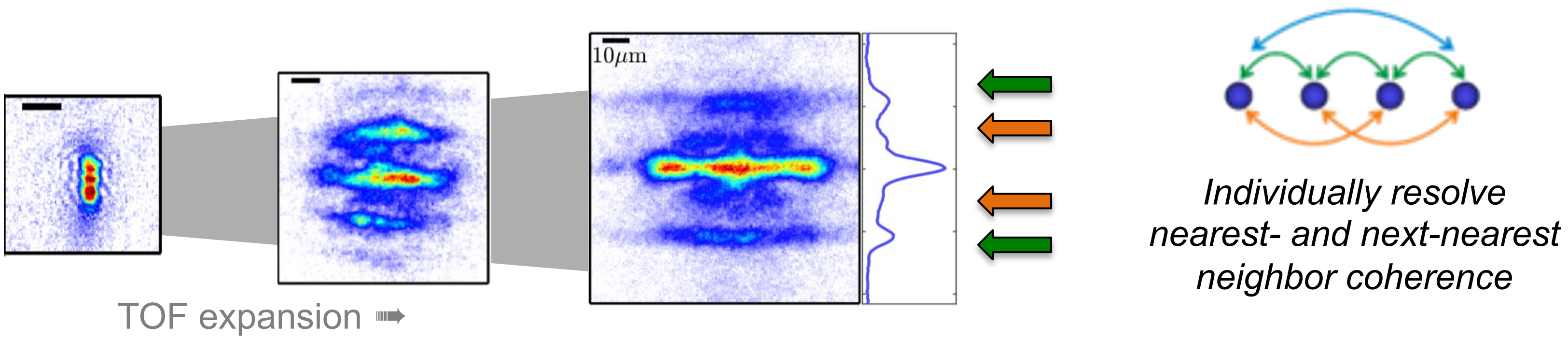
Can this gas form a supersolid?

BEC-to-crystal transition

- Experimental observation of 1D droplet crystals



- Probing supersolid coherence via time-of-flight interference



- Strong evidence for supersolidity, but can one “prove” the superfluid nature?

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

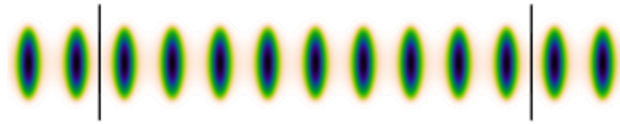
see also: Ferlaino & Modugno groups

Superfluidity and elementary excitations

Guo *et al.*, Nature **574**, 386 (2019)
Hertkorn *et al.*, PRL **123**, 193002 (2019)

Goldstone and amplitude ‘Higgs‘ modes

- **Infinite system**:



  Broken U(1) phase invariance
  Broken translational invariance

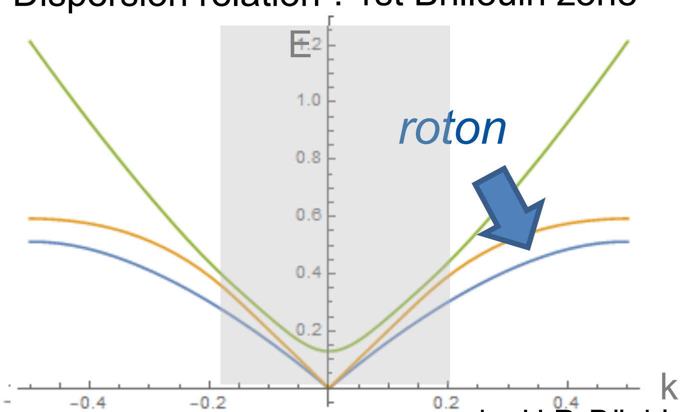
- **Two (gapless) Goldstone modes:**

  Phonon of the superfluid
  Phonon of the crystal *(self-assembled crystal!)*

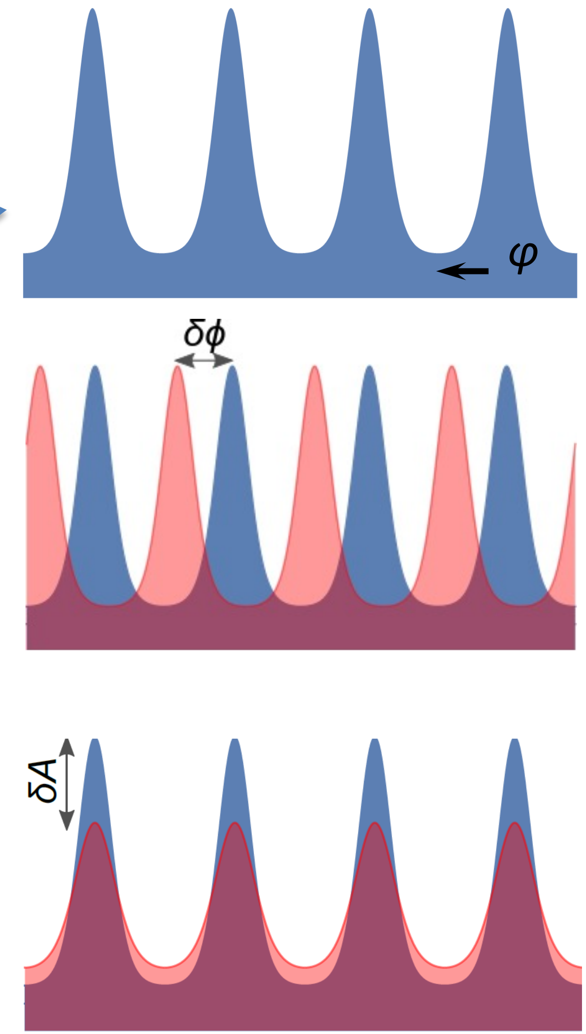
- **One (gapped) Higgs mode:**

  Oscillation between superfluid and crystal

Dispersion relation : 1st Brillouin zone



by H.P. Büchler

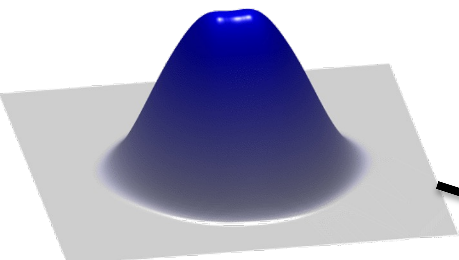


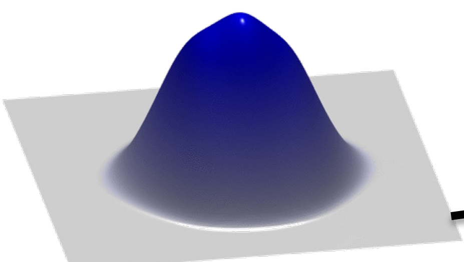
Hertkorn *et al.*, PRL **123**, 193002 (2019)

+Related work by Roccuzzo & Ancilotto PRA (2019)

Spectrum of collective excitations

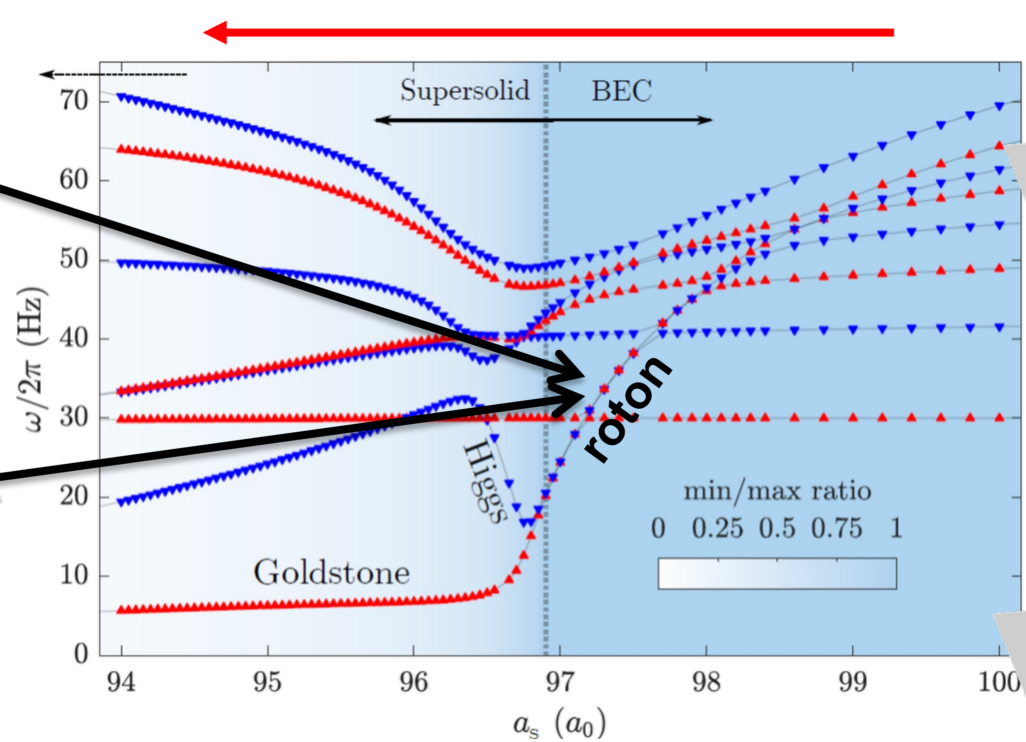
Dispersion relation calculated using Bogoliubov-de Gennes equations for our **finite, trapped system:**



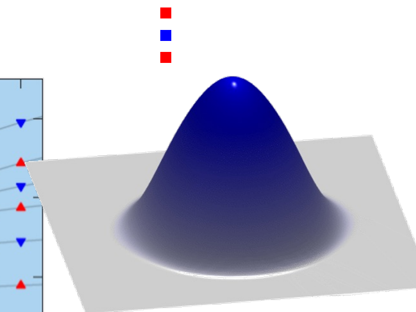


two degenerate roton modes!

defined by (dipolar) interactions

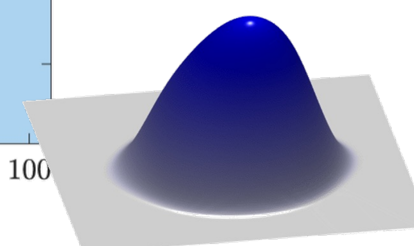


symmetric - antisymmetric



quadrupole mode

dipole mode @ trap freq.

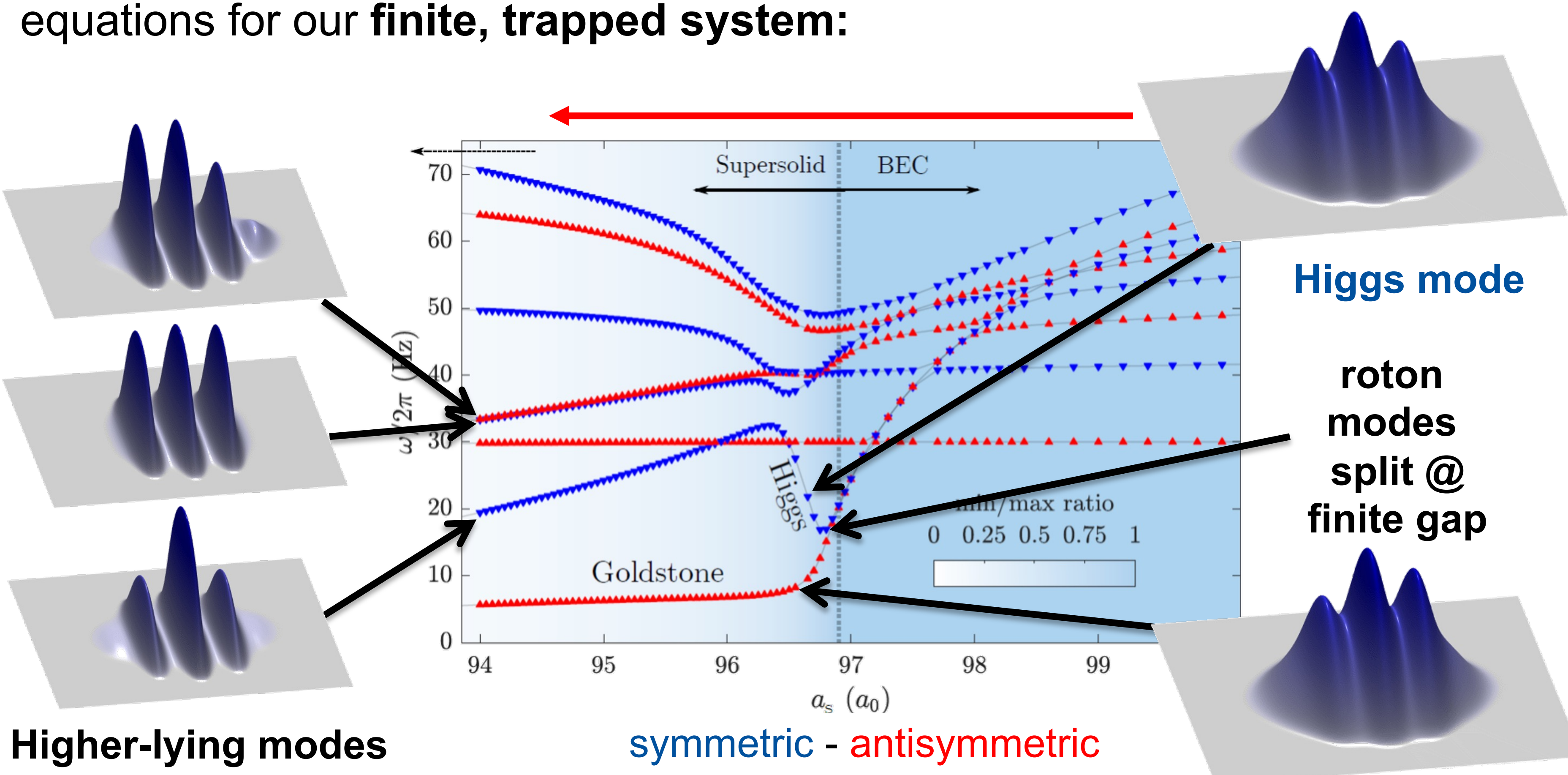


defined by the trap !

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

Spectrum of collective excitations

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



Higher-lying modes

symmetric - antisymmetric

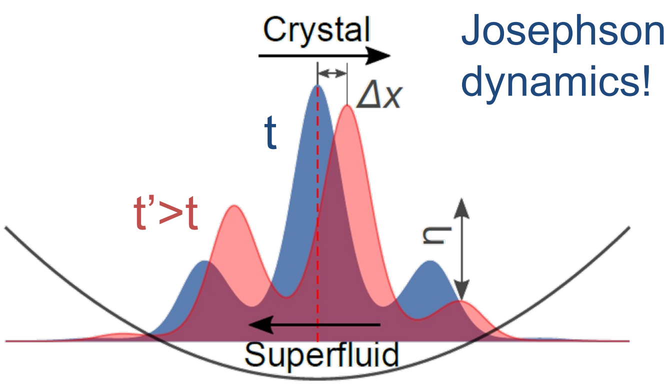
Low-energy Goldstone mode

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

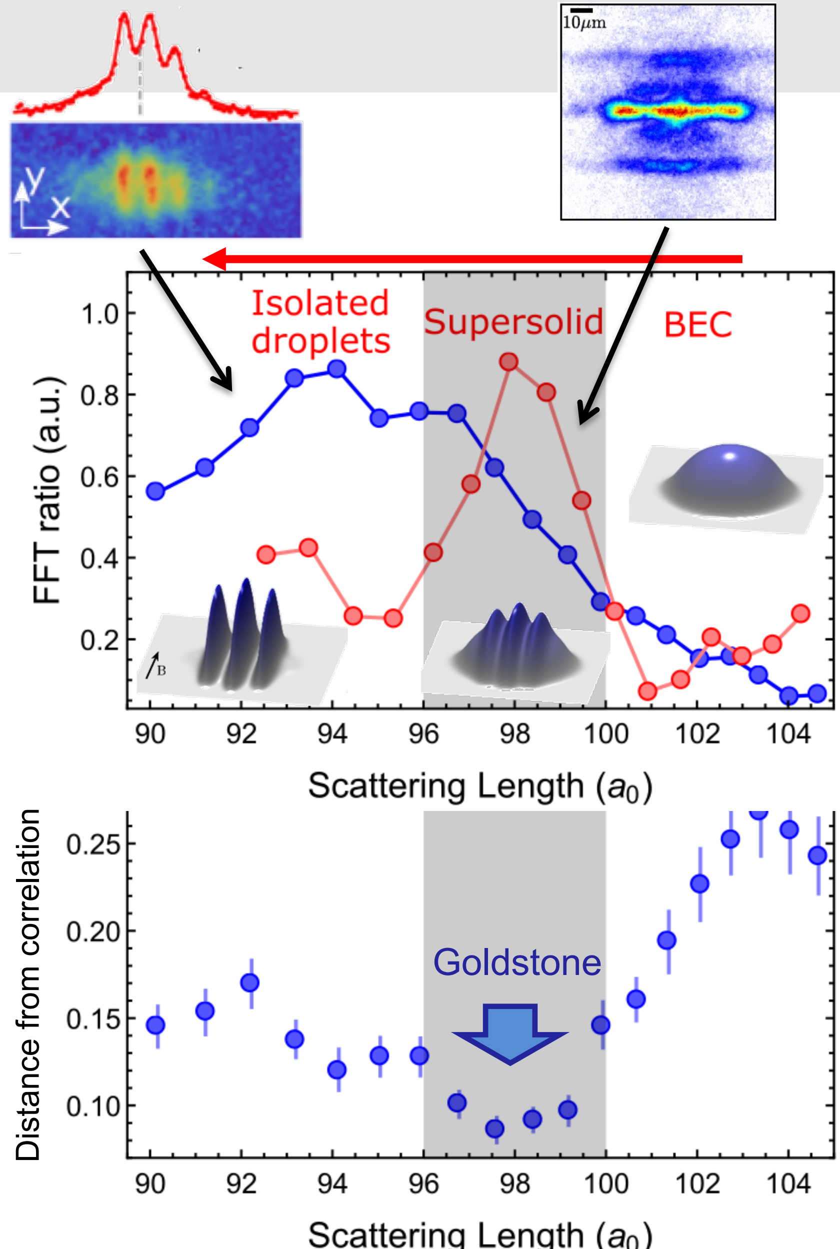
Hertkorn *et al.*, PRL **123**, 193002 (2019)

Goldstone mode

- All hallmark features of a supersolid in one experiment …
- Detect the Goldstone mode in coherent region using correlation analysis: superfluid crystal!



- Higgs mode can also be observed
- **The supersolid state of matter exists!**



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

Density fluctuations across the phase transition

Hertkorn *et al.*, Phys. Rev. X **11**, 011037 (2021)

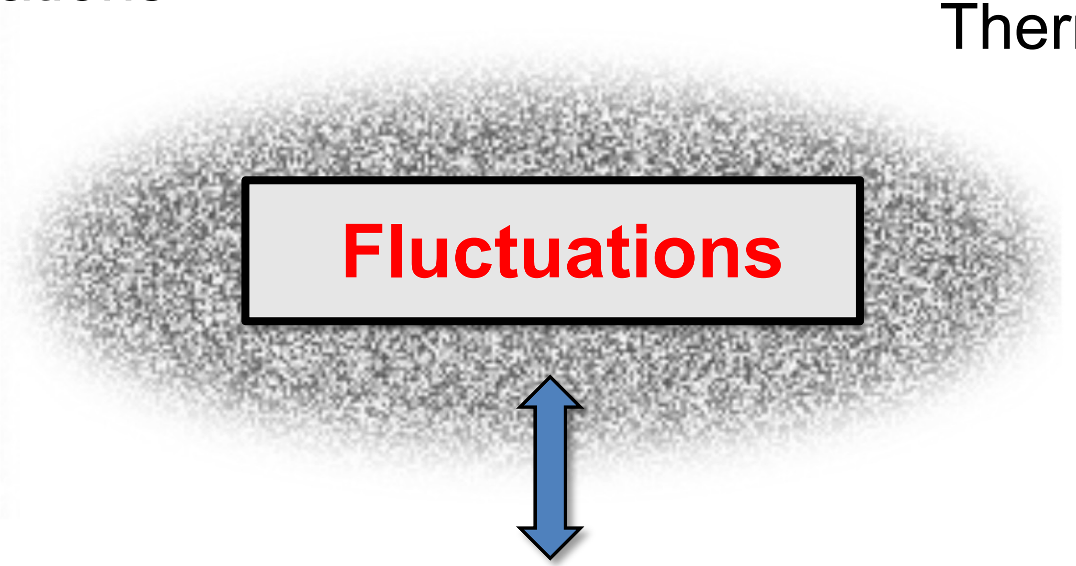
Something (not entirely) new ...

Phase transitions

Correlations

Thermodynamics

Excitation spectrum



(Dynamic) response

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

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

Static structure factor

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

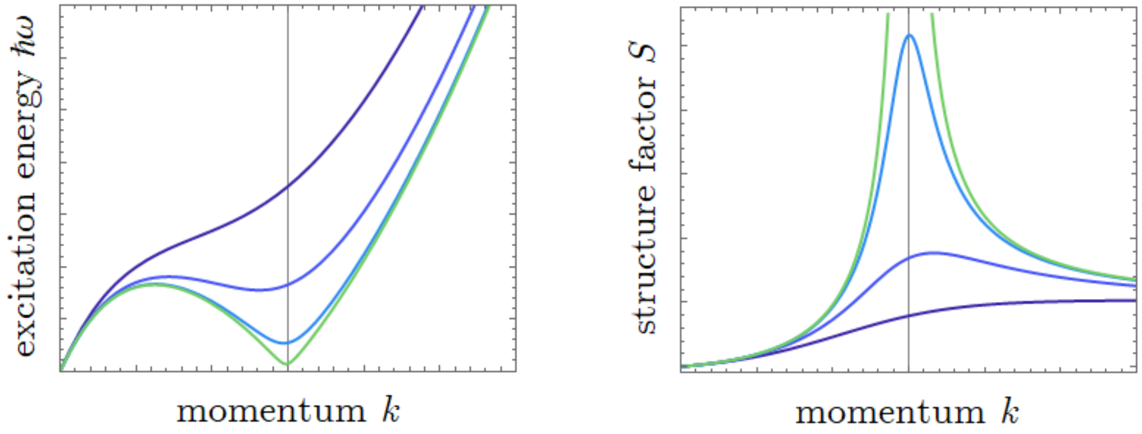
e.g. Pitaevskii & Stringari (2003)

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

- 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)

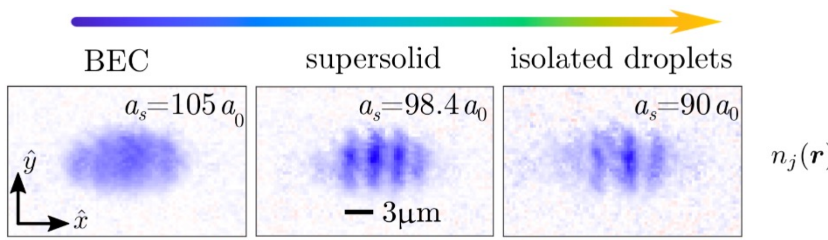


- As roton softens: fluctuations & structure factor dramatically enhanced

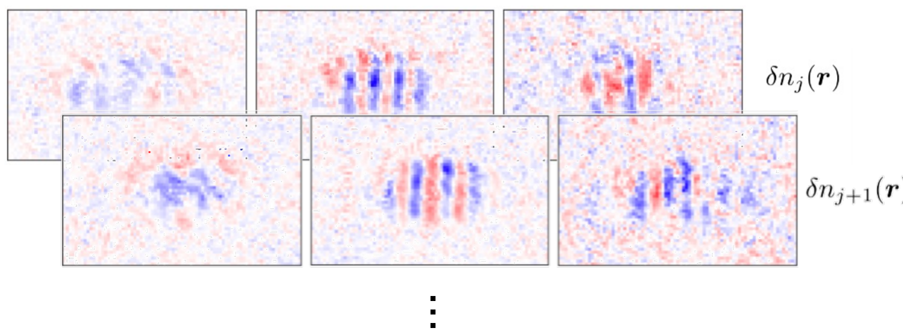
Hertkorn *et al.*, Phys. Rev. X **11**, 011037 (2021)

Experiment

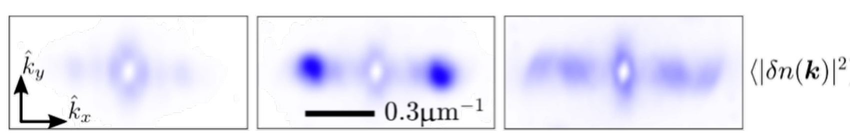
- Extract hundreds of images across the transition



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



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



Hertkorn *et al.*, Phys. Rev. X **11**, 011037 (2021)

Static structure factor

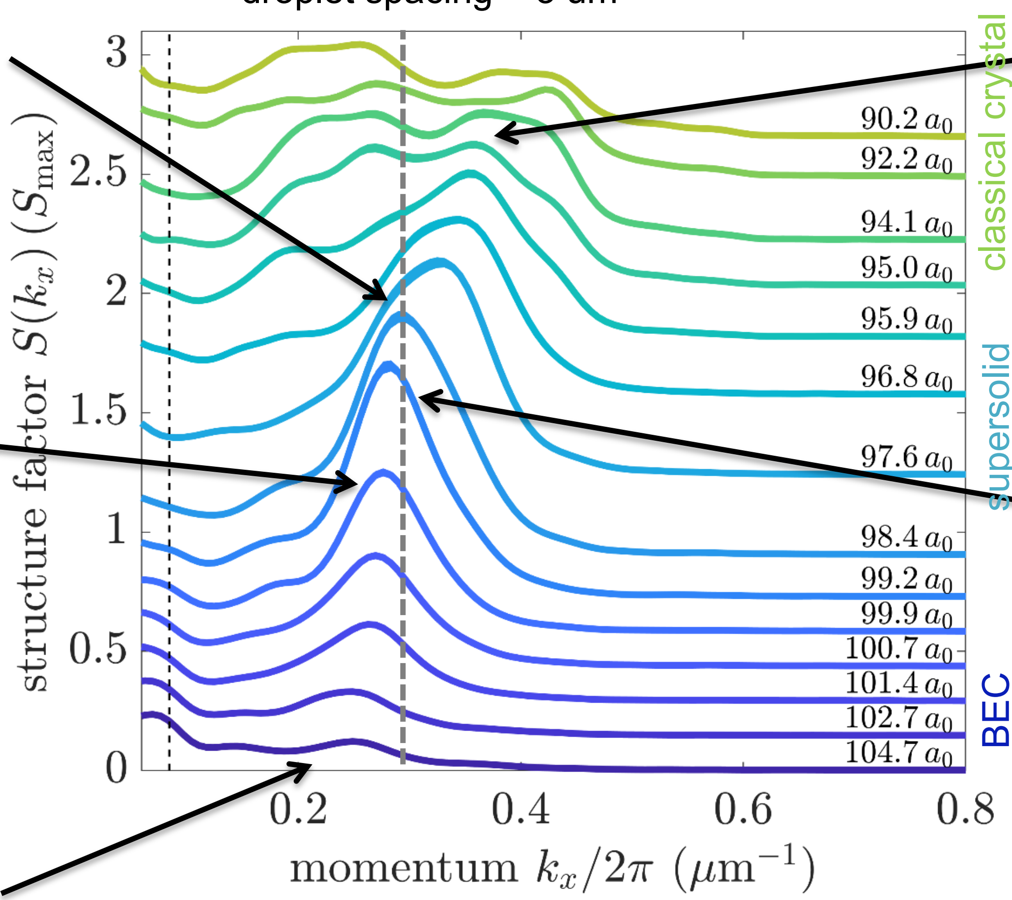
Phase transition:
inverse spacing and
roton momentum match

(That's why 1D is
so favorable!)

Roton momentum shift
(in agreement with
variational approach)

Blakie et al., (2020)

Small roton population
already deep in BEC



Splitting:
emerging phonon
modes of the crystal

Increasing amplitude
signals enhanced
fluctuations at transition:

$S_{\max} \sim T/\Delta^2_{\mathrm{rot}}$ ~ 260

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

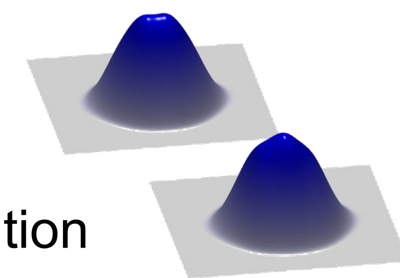
Temperature is
important ! ($k_B T >> \Delta_{rot}$)

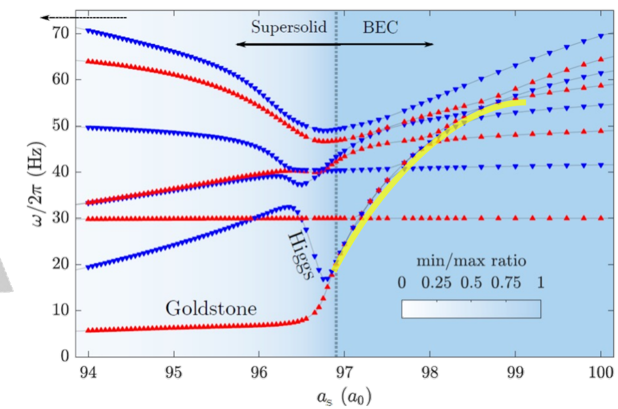
Direct experimental data!

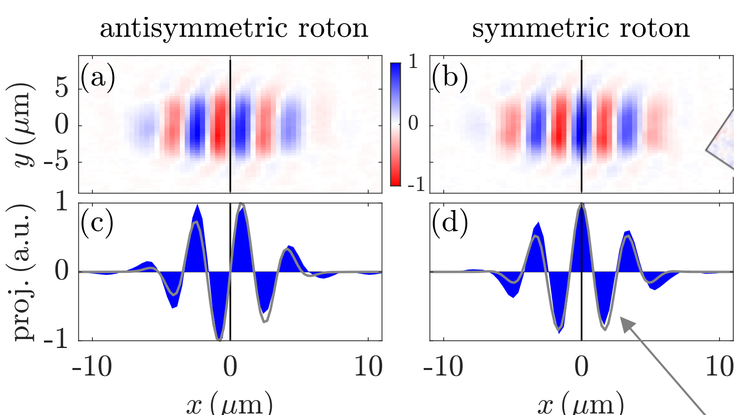
Note: No general finite temperature theory exists so far for these systems!

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
- Enhanced around the transition: precursor for transition
- See modes individually: (often) even in single shots

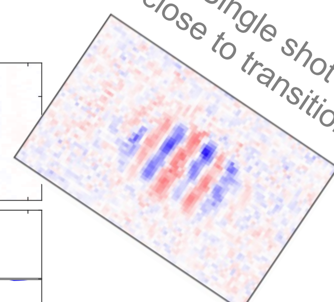


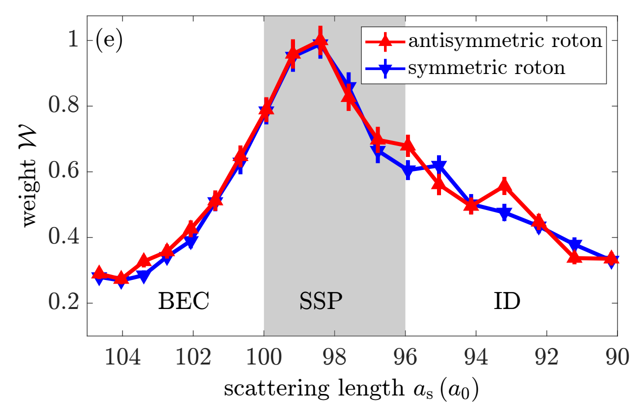




BdG theory!

Single shot close to transition





Hertkorn *et al.*, Phys. Rev. X **11**, 011037 (2021)

Higher-order modes

Next-strongest modes:

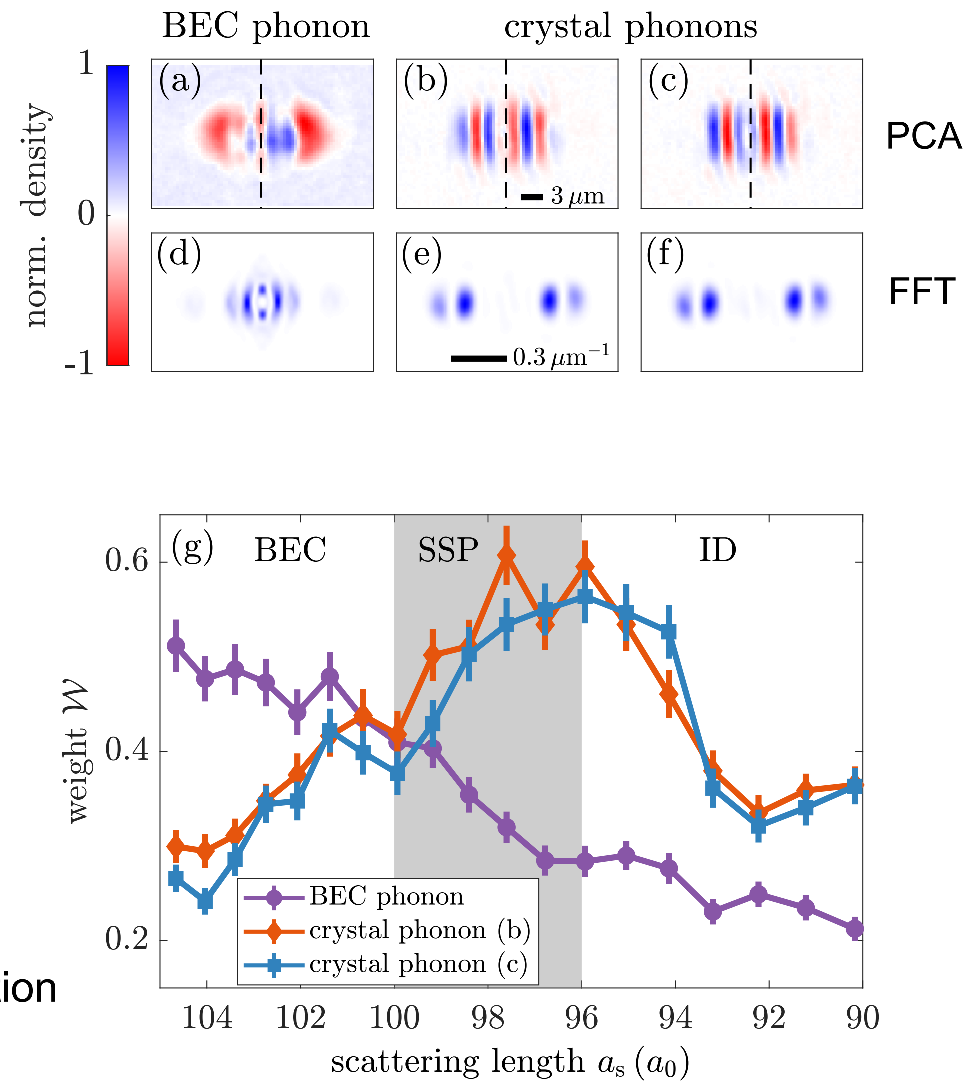
- BEC quadrupole mode
- (anti-)symmetric crystal phonons

Fourier transform explains double peak structure in S(k) !

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

Weights across the transition:

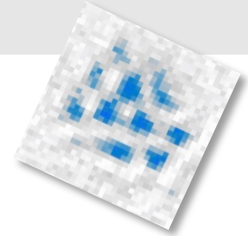
- BEC mode dominant in BEC
- Crystal phonons dominate from the transition



Supersolid region supports both BEC and crystal modes!

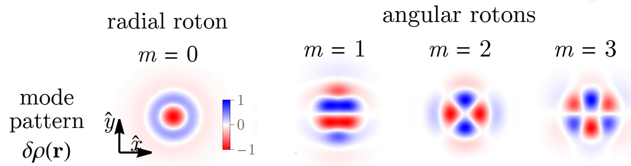
Hertkorn *et al.*, Phys. Rev. X **11**, 011037 (2021)

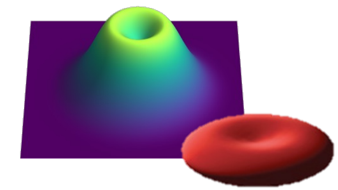
More dimensions, more modes!



How about “2D” pancake configurations?

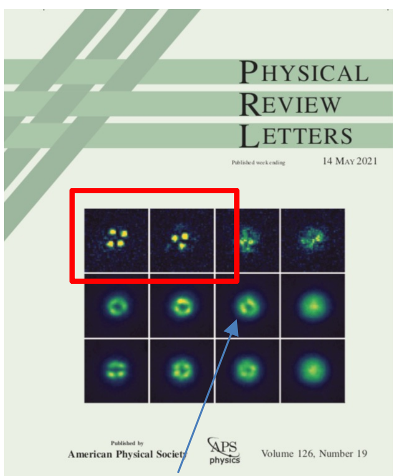
- Radial roton (~ same as 1D rotons)
- Angular rotons
- “Blood cell” ground states
  (more stable and abundant due to LHY!)



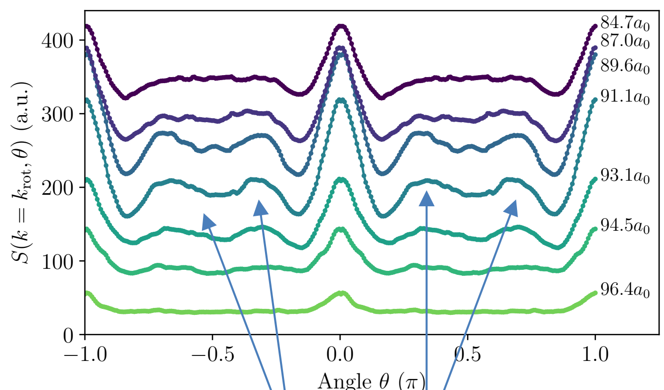


see also without LHY: Bohn group, PRL **98**, 030406 (2007)

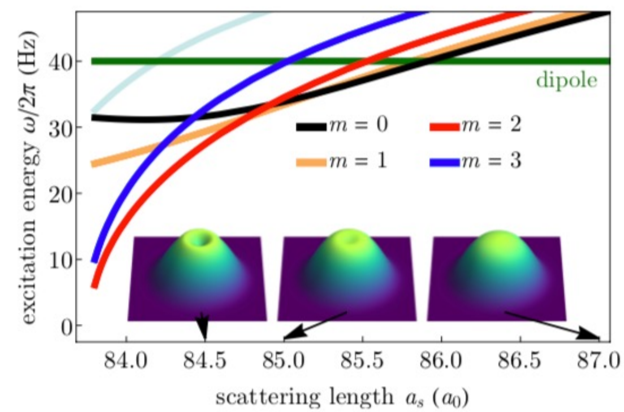
Repeat similar procedure as in 1D:



(Excited) blood cells



Softening m=2 and m=3 rotons



Mode competition: square vs. triangular

2D supersolidity? (Much) larger atom numbers to make m=3 dominant!

Non-equilibrium preparation? Ferlaino group, Nature (2021)

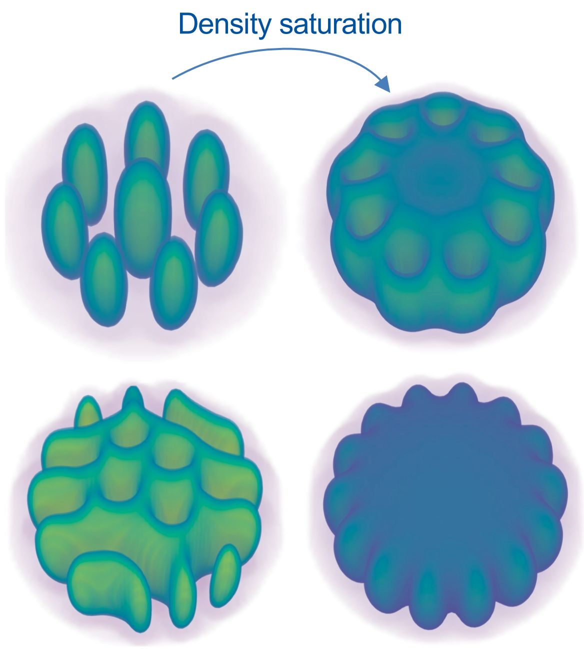
Schmidt *et al.*, PRL 126, 193002 (2021)
Hertkorn *et al.*, PRL 127, 155301 (2021)

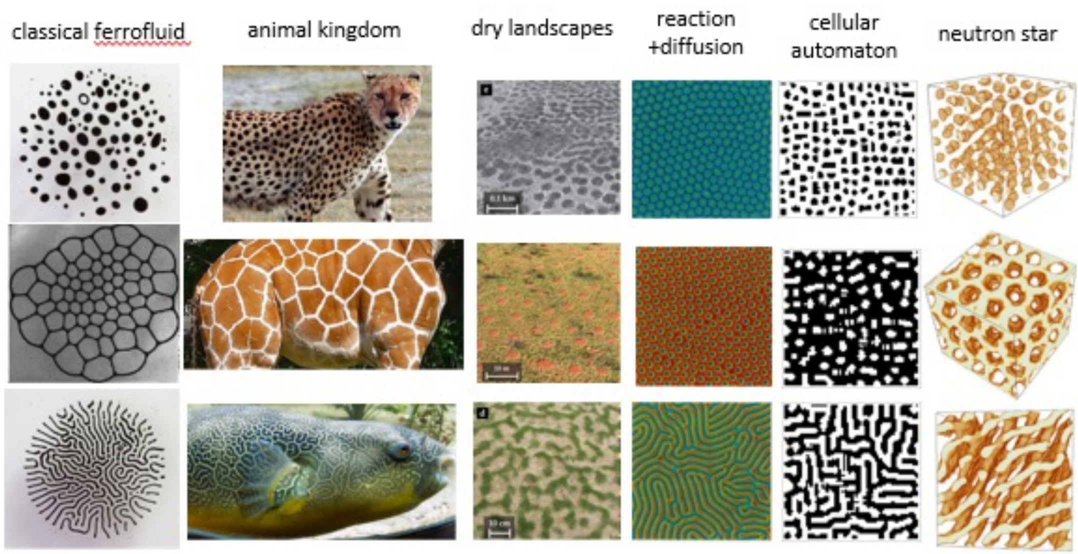
There's more than droplet crystals!

Hertkorn *et al.*, Phys. Rev. Research 3, 033125 (2021)
Schmidt *et al.*, Phys. Rev. Research 4, 013235 (2022)

Supersolid phase diagram in 2D

Not just supersolid droplets, but honeycomb, stripe, labyrinth, pumpkin/cogwheel patterns!





Cross & Hohenberg, RMP (1993)

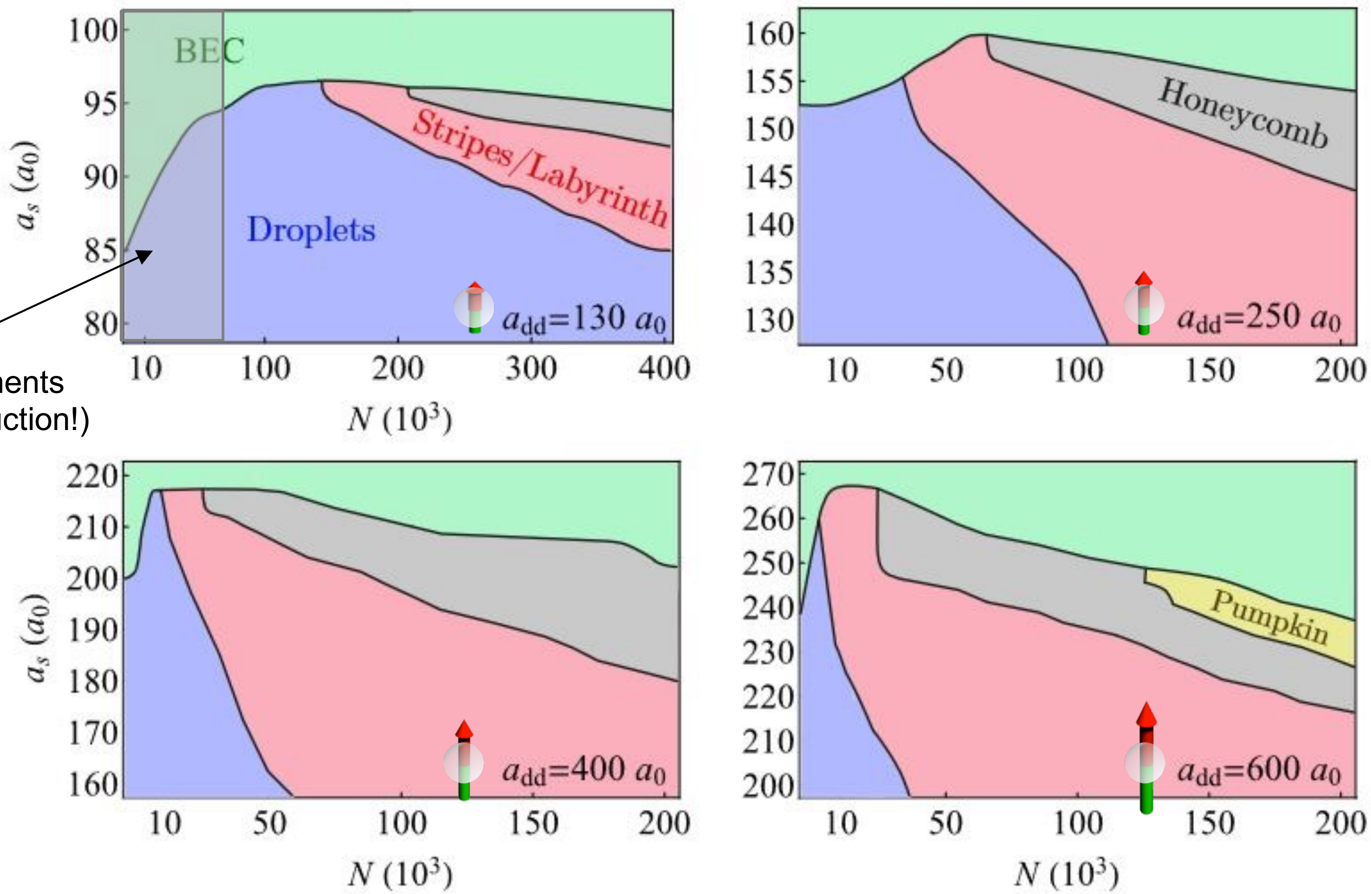
Analogy to patterns known on vastly different energy and length scales across all the sciences!

Hertkorn *et al.*, Phys. Rev. Research 3, 033125 (2021)
Related work by Pohl group

Supersolid phase diagram in 2D

How to realize this in experiment? Use larger dipoles!

Lower saturation density!

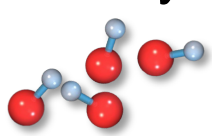


Typically accessible

(New experiments under construction!)

But: Magnetic moment already maxed out in dysprosium?

Use (electrically) dipolar molecules!



Schmidt *et al.*, Phys. Rev. Res. 4, 013235 (2022)

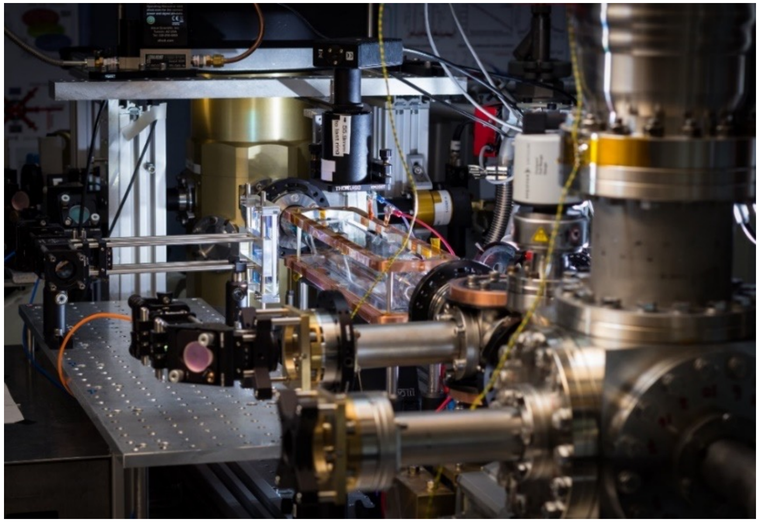
Towards molecular BECs

Direct laser cooling of

Heavy: Precision measurements

- Barium monofluoride (BaF)
- Calcium monofluoride (CaF)

BEC / many-body physics



Albrecht *et al.*, Phys. Rev. A **101**, 013413 (2020)
Kogel *et al.*, New J. Phys. **23**, 095003 (2021)

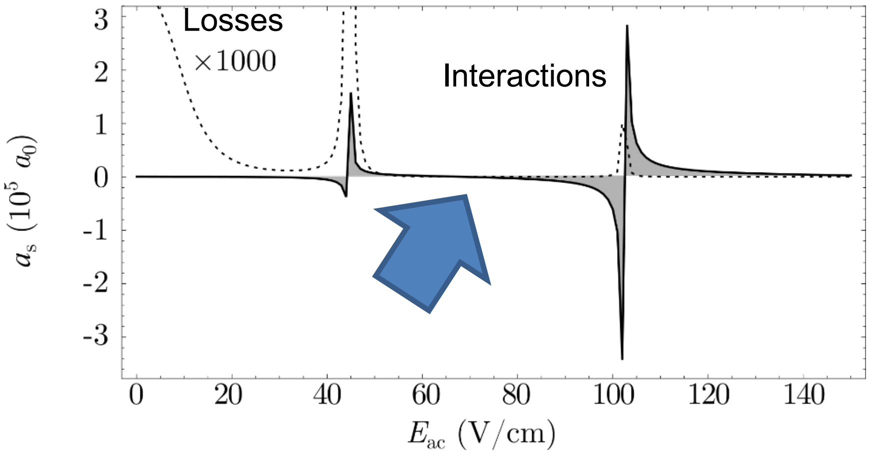
Electric dipole moment

- d ~ 3 Debye, tunable in lab frame
- Up to 10^4 x more dipolar than dysprosium!

Collisional stability and tunability via microwave dressing

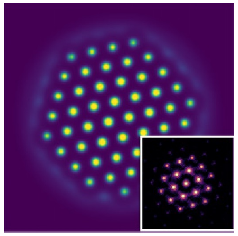
Doyle group, Science **373**, 779 (2021)
Bloch group, Nature **607**, 677 (2022) + several others

- Independent tuning of contact and dipolar interactions

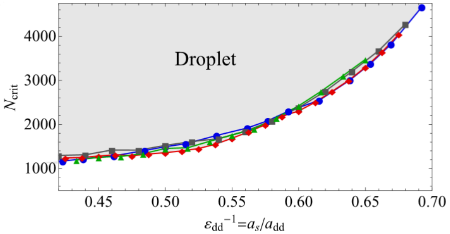


Schmidt *et al.*, Phys. Rev. Research **4**, 013235 (2022)

Many exciting experiments ahead!



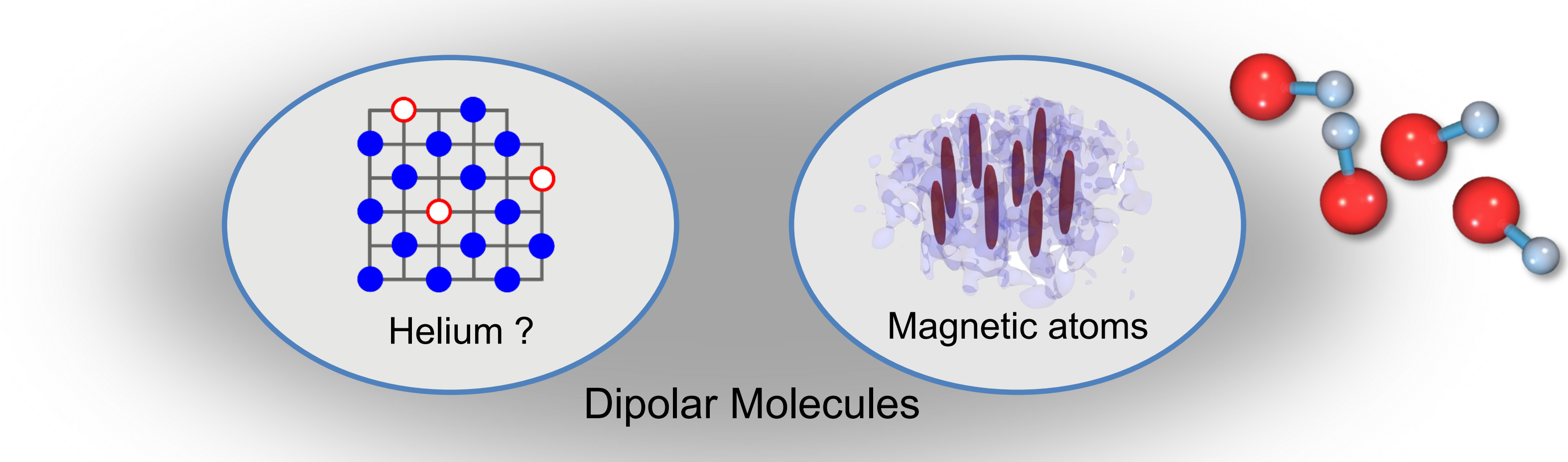
- Are supersolids only possible in fine-tuned dipolar atoms?
- What is the nature of the phase transition (less finite size)?
- Systematically check the beyond mean-field dipolar theories



- Connect vacancy-induced supersolids and droplet supersolids?

Lifshitz & Andreev (1970)

Gross (1957)



Leverage the tunability of interactions to find a universal picture!

Schmidt *et al.*, Phys. Rev. Research 4, 013235 (2022)

New magnetic atom quantum simulators

- Magnetic atoms still have many advantages, if only dipolar interactions were larger!

Fixed

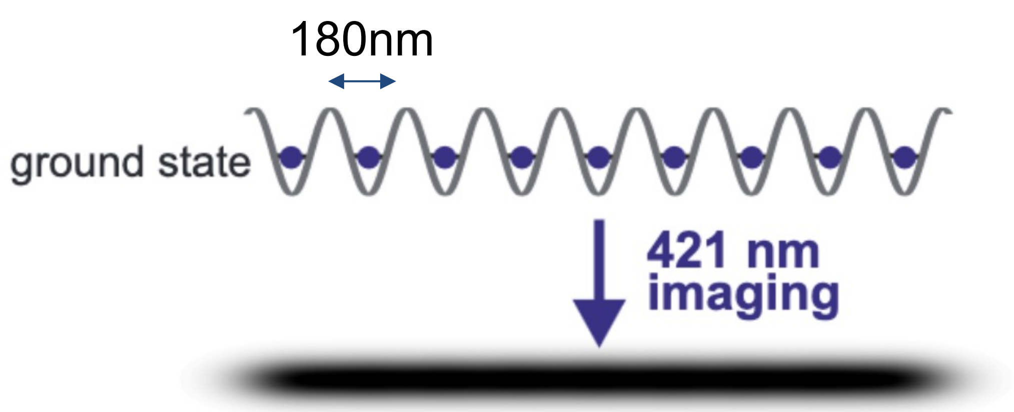
$$\frac{\mu_0 \boxed{\mu^2}}{4\pi \boxed{r^3}}(1 - 3\cos^2(\theta))$$

Not fixed

- Bring atoms closer together in UV lattice
  Coupling strength > KRb molecules

Microscope with 266nm spacing (Greiner)
Sub-wavelength-spaced 2D layers (Ketterle)

- Quantum gas microscopy is challenging



Fraxanet et al., PRL 128, 043402 (2022)

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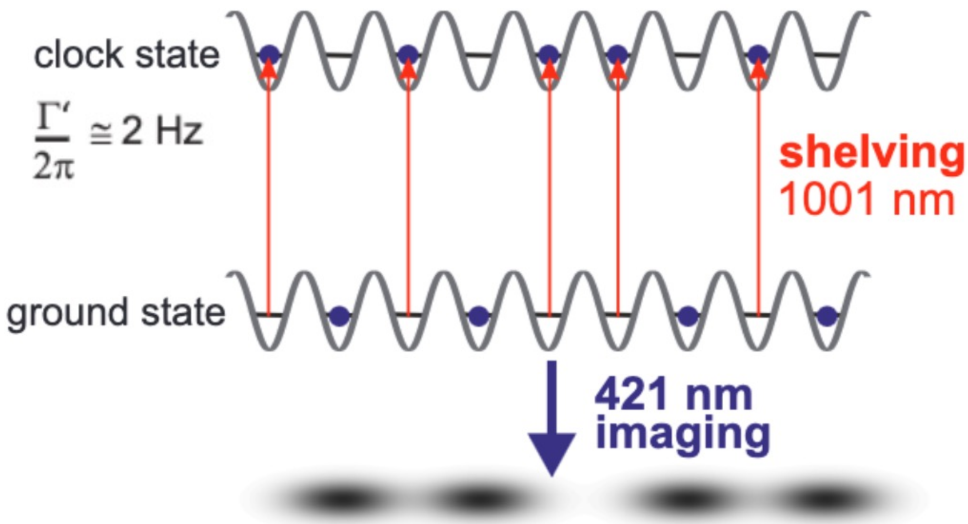

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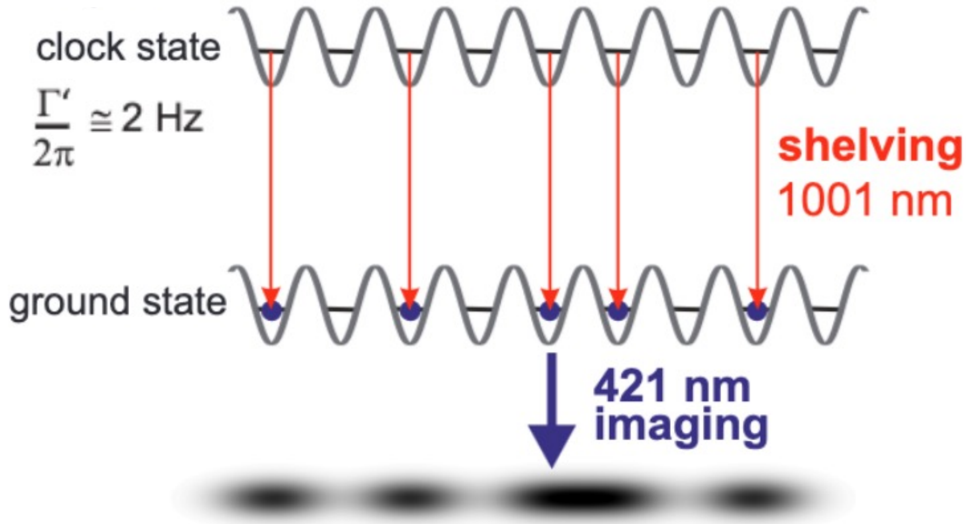

Fraxanet et al., PRL 128, 043402 (2022)

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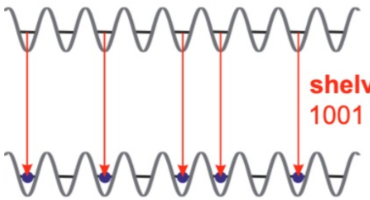
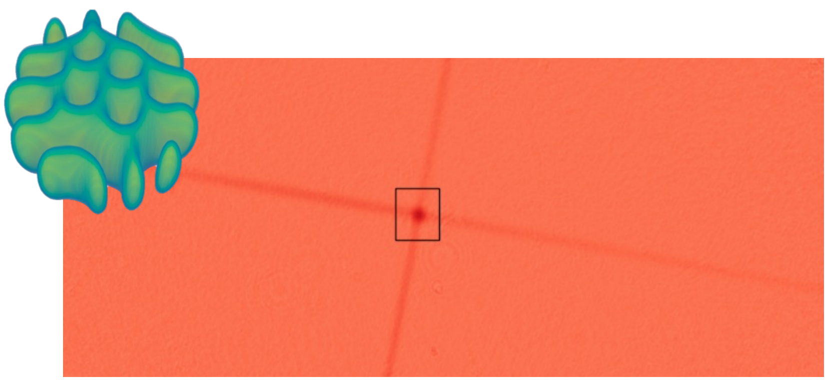


- Resolves: position, spin, energy …

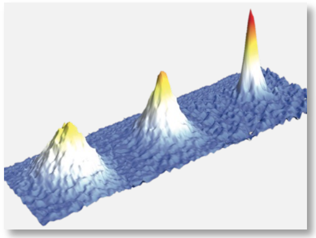
- New setup: currently evaporating to form large BECs – stay tuned

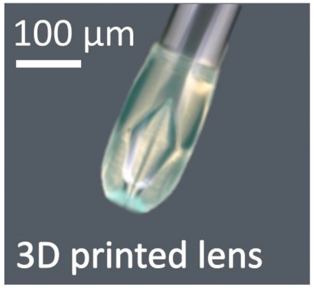


Fraxanet et al., PRL 128, 043402 (2022)

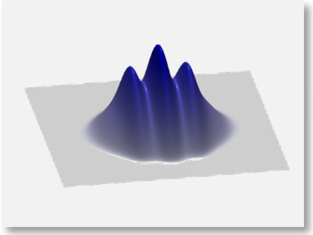
Conclusion

Also: 3D printed fiber tweezer traps

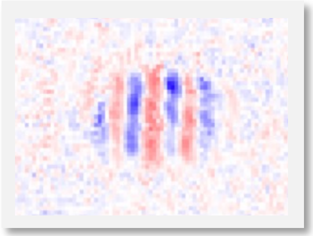




Experiments with **dipolar Bose-Einstein condensates** of dysprosium atoms



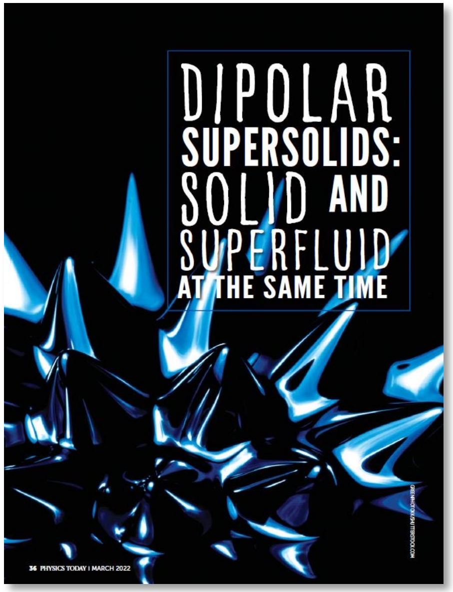
Formation of a **dipolar droplet supersolid** and observation of the **characteristic Goldstone modes**



Study **excitations** using measurements of fluctuations

Rich phase diagram featuring, e.g. **exotic pattern formation**

Realize using **molecular BECs**!



See also: Physics Today, March 2022

Thank you!

Max Mäusezahl: Poster 80, Thursday
“Hot Rydberg single photon source”

http://www.coldmolecules.de
http://www.pi5.uni-stuttgart.de

Dysprosium:
Mingyang Guo,
Jens Hertkorn,
Kevin Ng,
Jan-Niklas Schmidt,
Lucas Lavoine,
Ralf Klemt,
Hans Peter Büchler (Theory)
Martin Zwierlein (MIT)
Tim Langen (Co-PI)
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Alexandra Köpf
Tatsam Garg
Ole Prochnow
Philipp Groß
Tim Langen (PI)

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