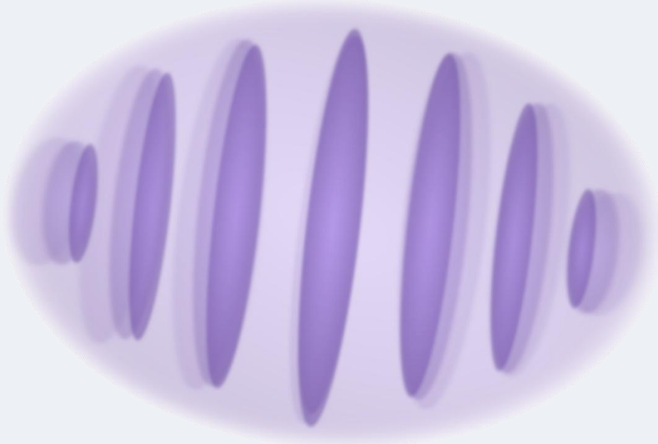
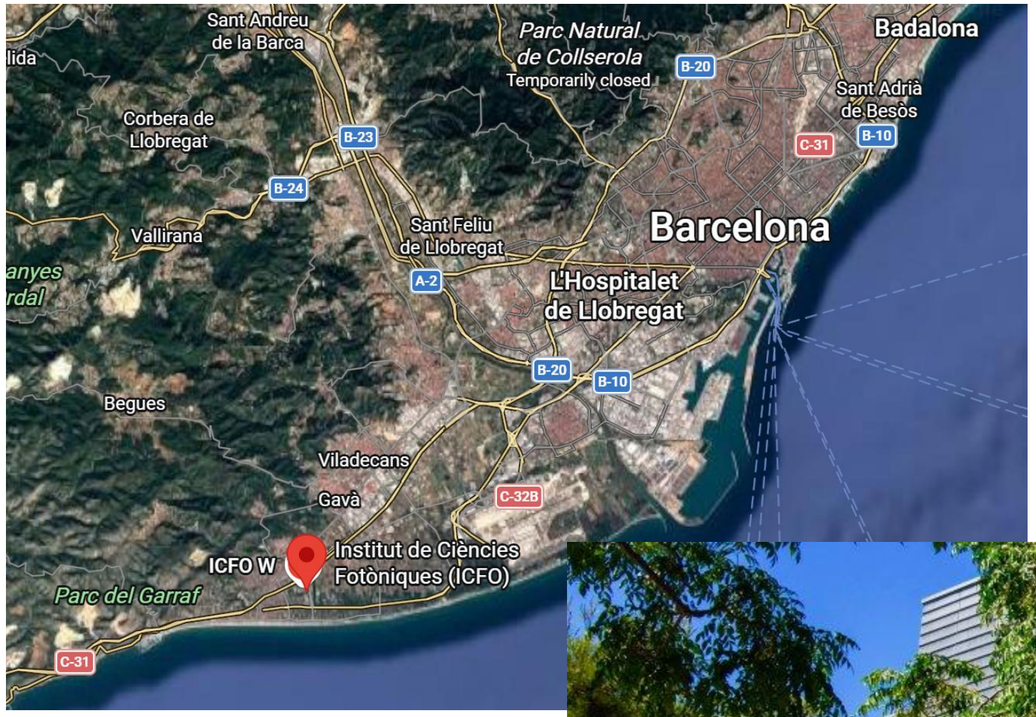
Engineering unconventional superfluids with ultracold bosonic mixtures

Sarah Hirthe
Group of Leticia Tarruell
ICFO (Barcelona, Spain)



Frontiers in Ultracold Quantum Gases
Maó 2026

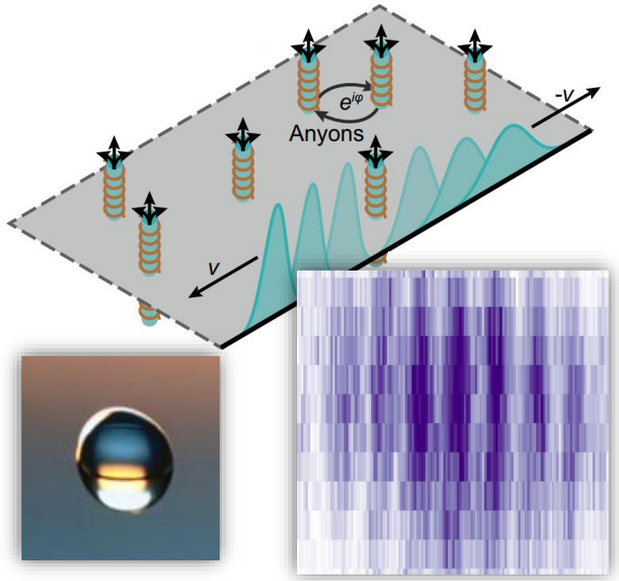
ICFO – The Institute of Photonic Sciences



Leticia
Tarruell

Ultracold Quantum Gases Group

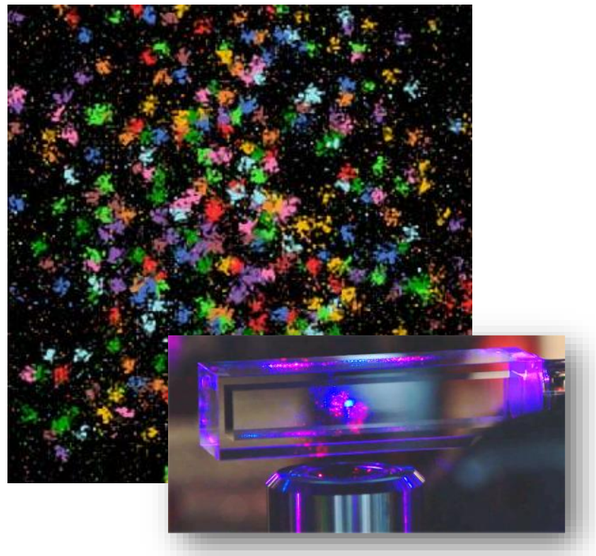
Potassium lab



Potassium spin mixtures

Cabrera et al., *Science* **359** (2018)
Frölian et al., *Nature* **608** (2022)
Chisholm et al., *Science* **391** (2026)
… and more

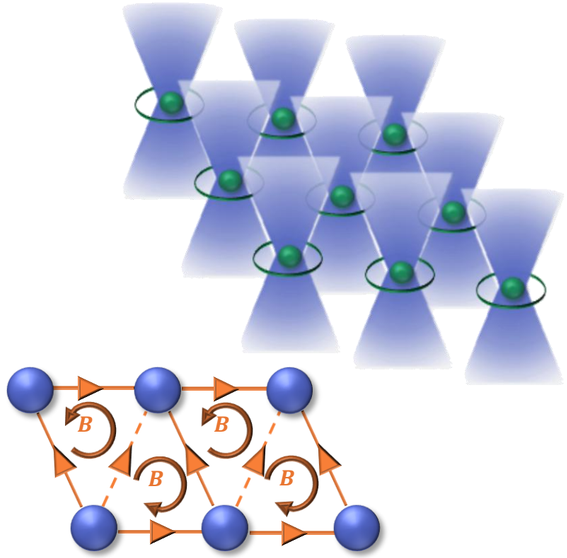
Strontium lab



Quantum gas microscope

Höschele et al., *PR Applied* ***19*** (2023)
Buob et al., *PRX Quantum* ***5*** (2024)
Gas-Ferrer et al., *arXiv:2603.05478*

Rydberg lab



Strontium Rydberg tweezers

Content

I. Bosonic mixtures with tunable interactions

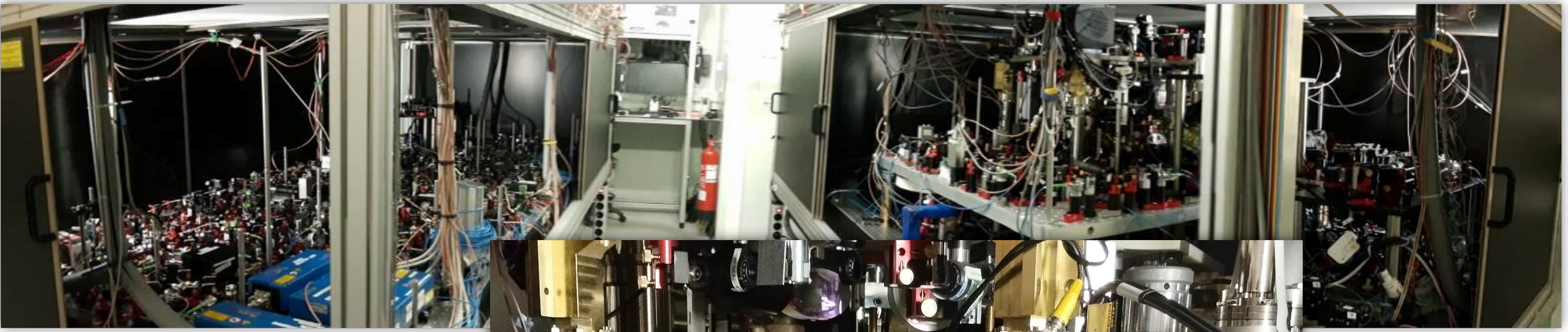
Quantum liquid droplets

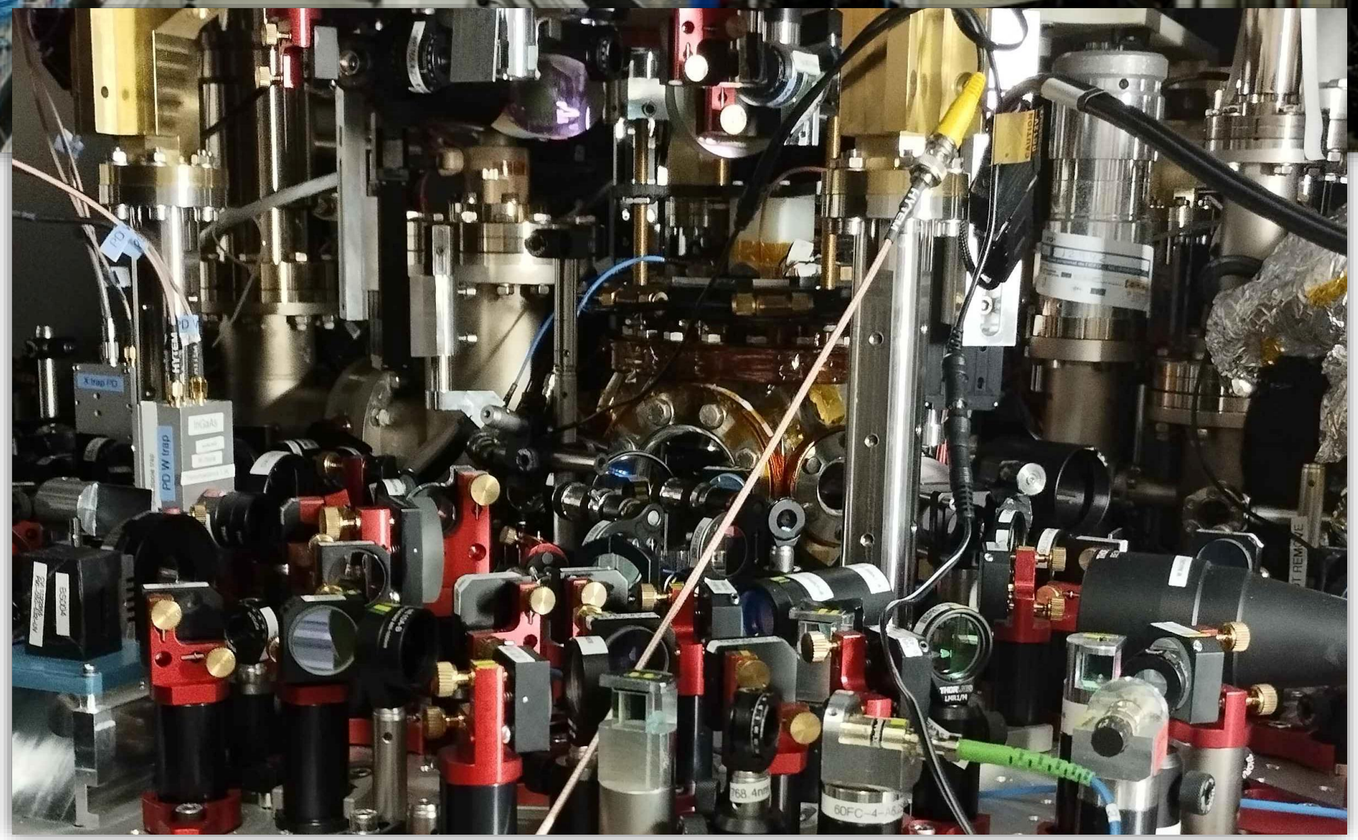
II. Raman-coupled mixtures

Supersolids

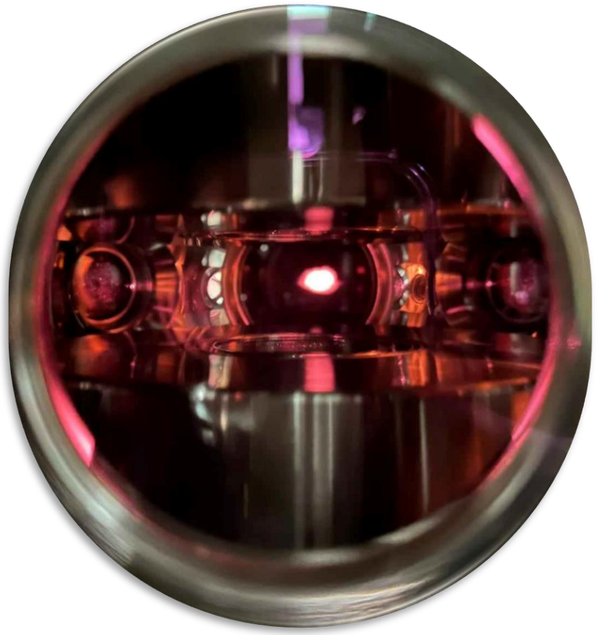
Chiral solitons

The lab

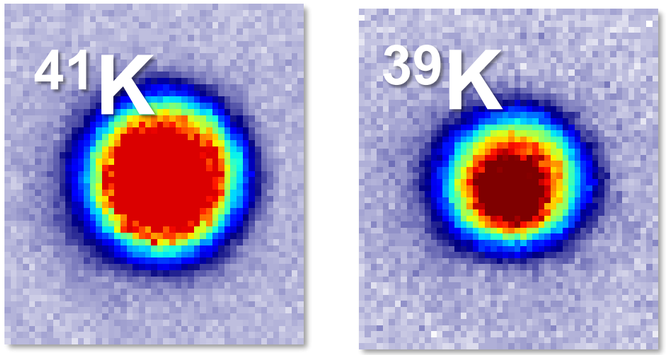




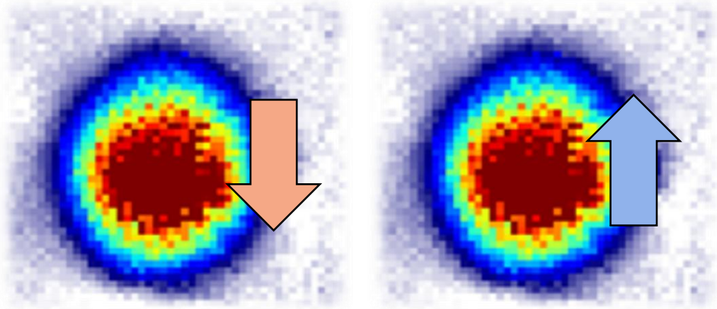
Mixtures of Bose-Einstein condensates

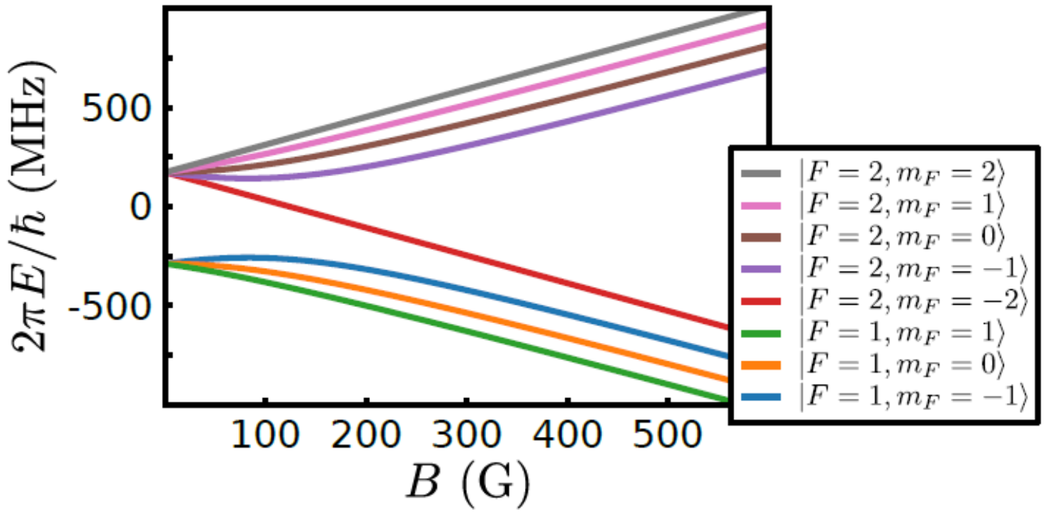


Two bosonic isotopes



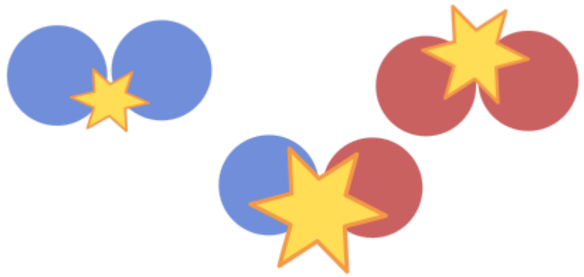
^{41}K spin mixtures

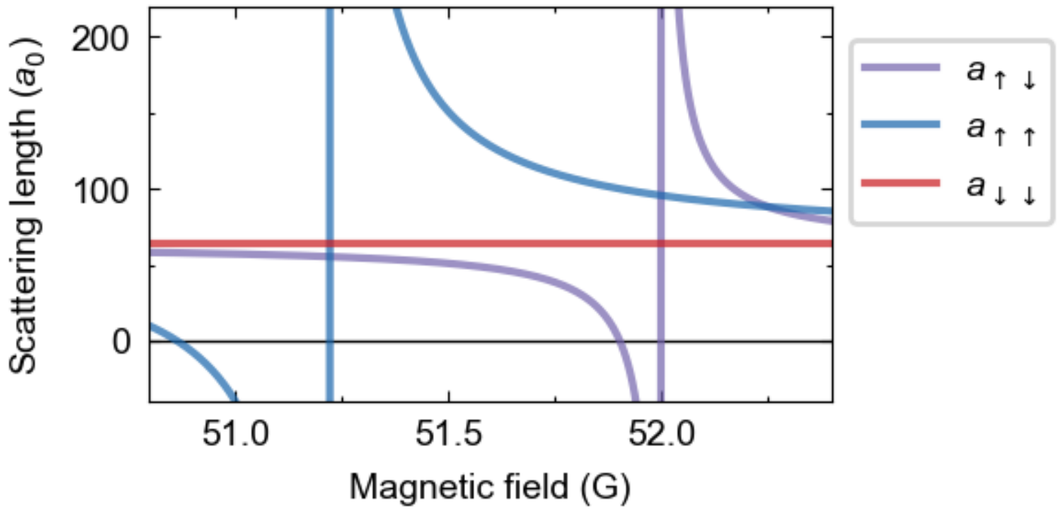




Mixtures of Bose-Einstein condensates

Tunable interactions





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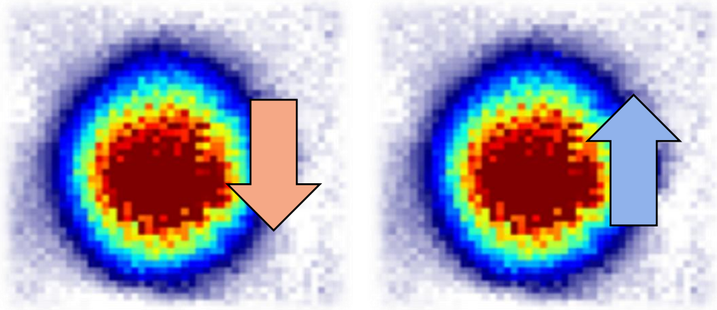
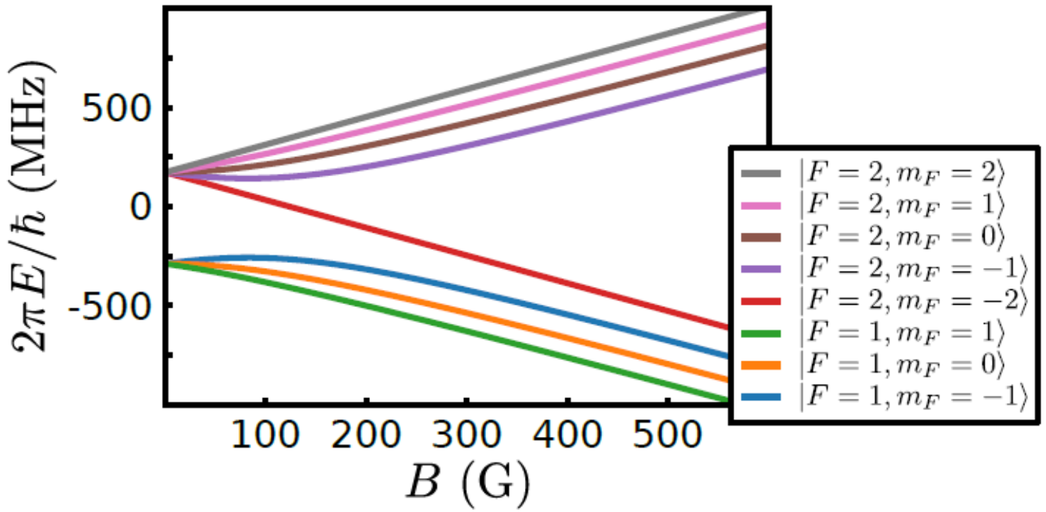
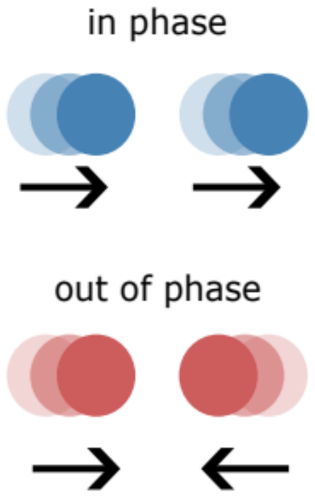


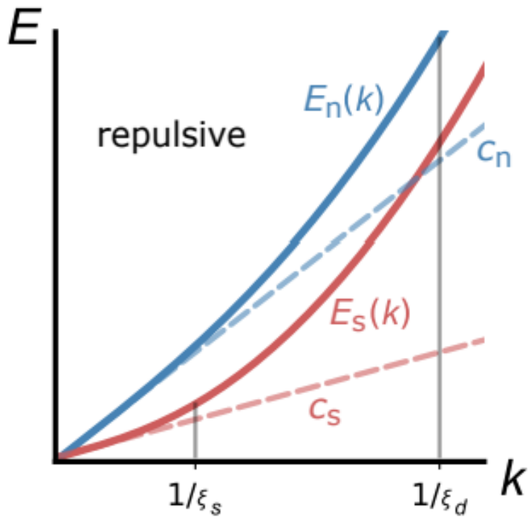


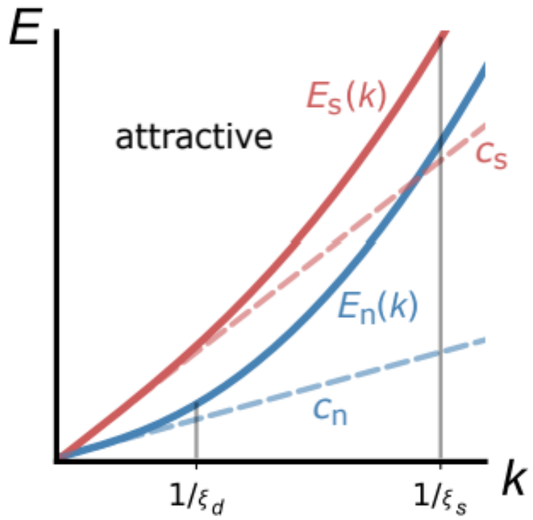
Bogoliubov excitation spectrum

$$g_{\uparrow\uparrow} = g_{\downarrow\downarrow} = \bar{g}$$

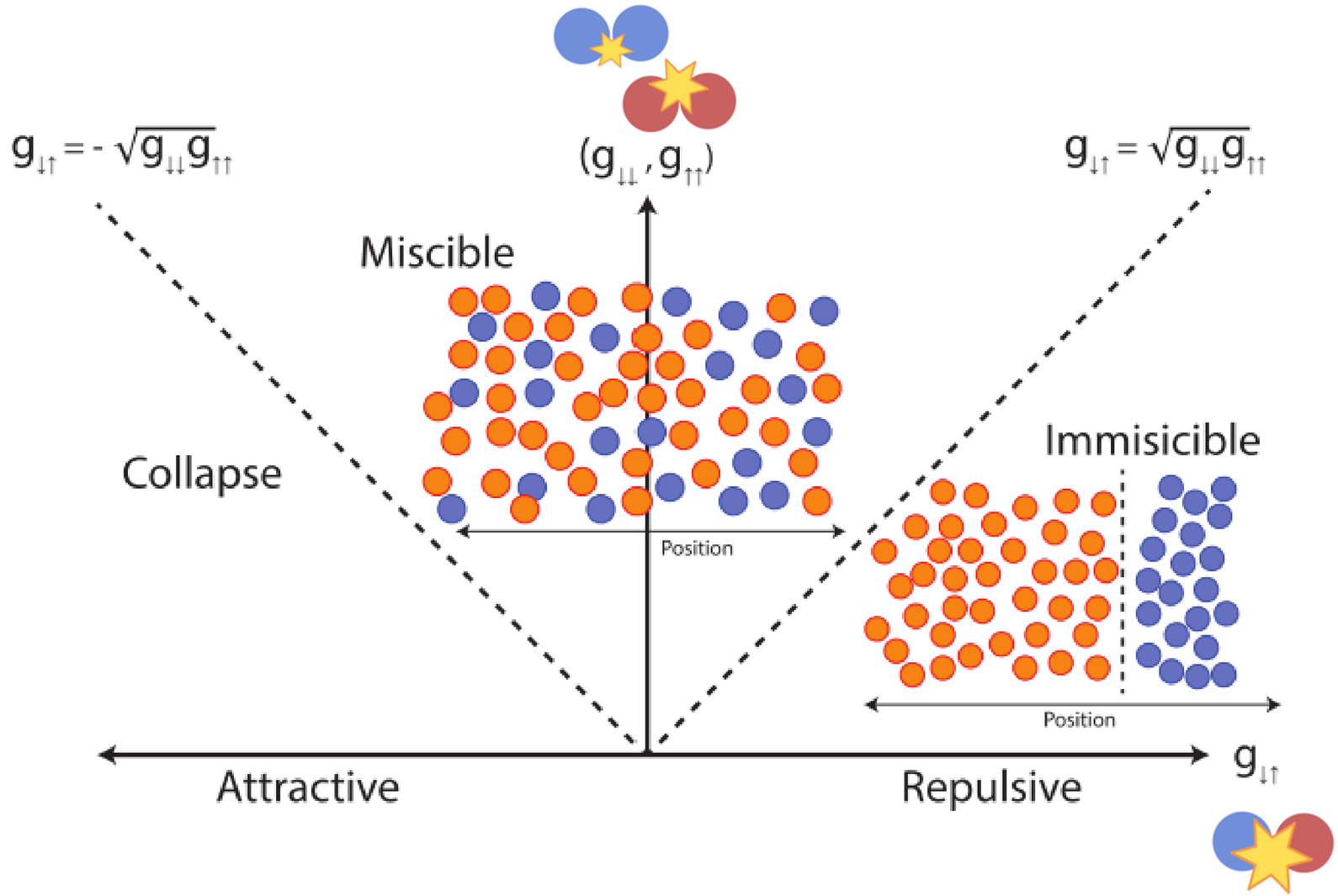
$$E(k)_{\pm} = \sqrt{\frac{\hbar^2 k^2}{2m}\left(\frac{\hbar^2 k^2}{2m} + 2mc_{\pm}^2\right)}, \qquad c_n = \sqrt{\frac{(\bar{g} + g_{\uparrow\downarrow})n}{2m}} \quad \text{and} \quad c_s = \sqrt{\frac{(\bar{g} - g_{\uparrow\downarrow})n}{2m}}$$





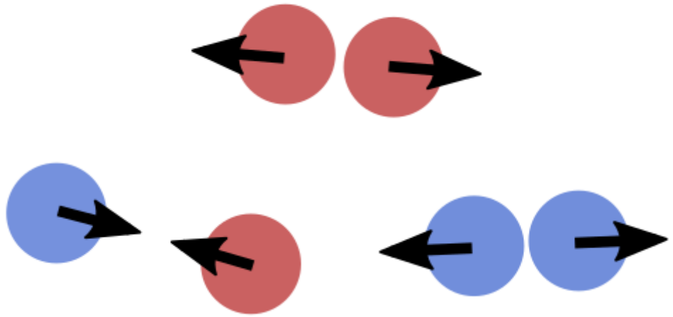


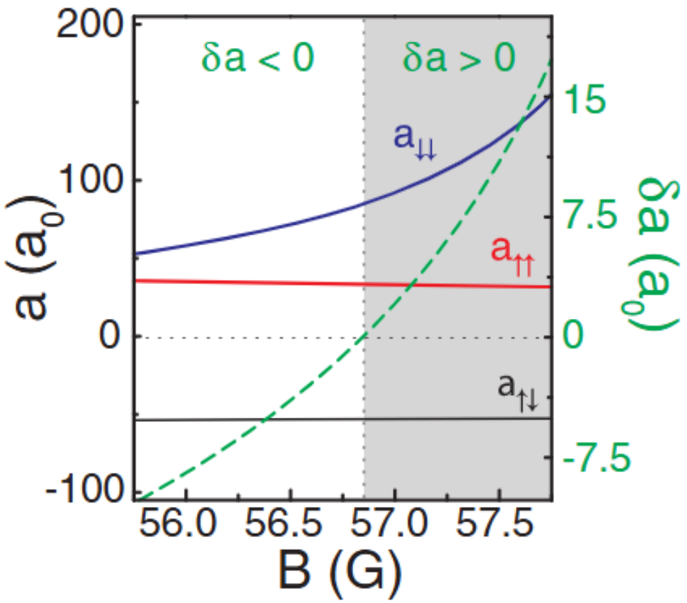
Mean field phase diagram



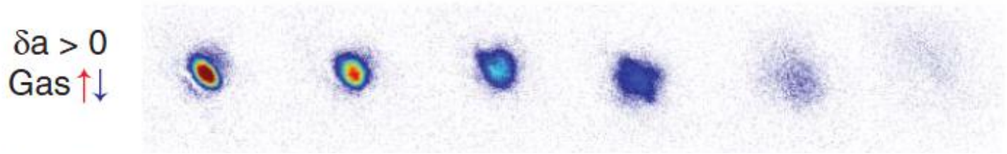
Cabrera, PhD thesis (2018)

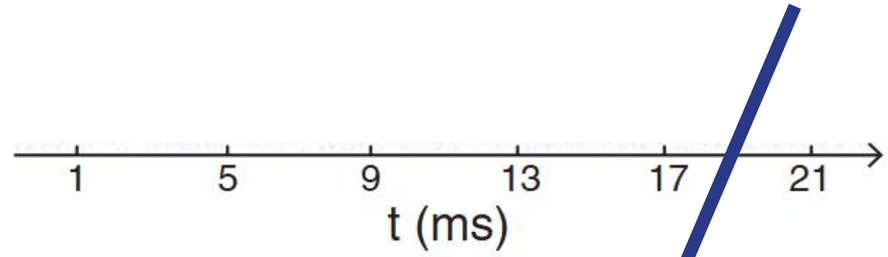
Quantum liquid droplets





$$\delta a = a_{\uparrow\downarrow} + \sqrt{a_{\uparrow\uparrow} a_{\downarrow\downarrow}}$$





Quantum liquid droplets!

Cabrera et al., *Science* **359** (2018)

Quantum liquid droplets

Beyond mean field effects!

Mean field energy basically cancels

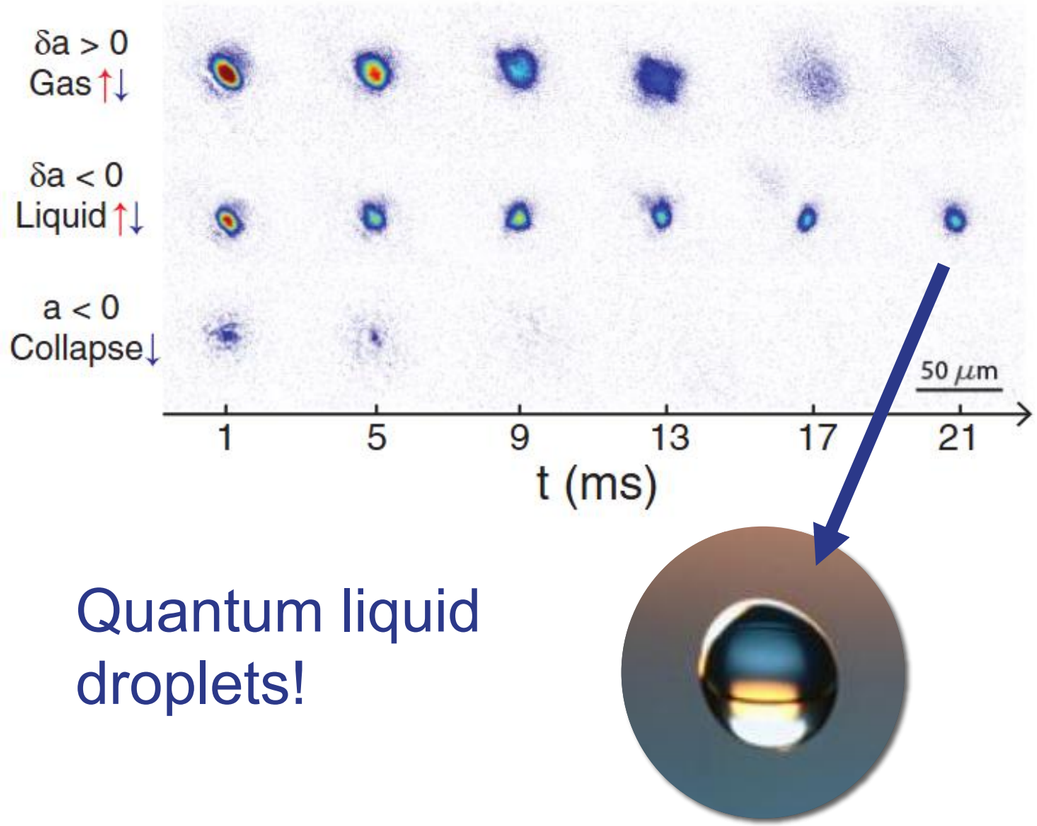
$$\mathcal{E}_{MF} = \frac{g + g_{\uparrow\downarrow}}{4} n^2 \qquad g_{\uparrow\uparrow} = g_{\downarrow\downarrow} = g$$

Beyond mean field term relevant!

$$\mathcal{E}_{LHY} = \frac{8m^{3/2}}{15\pi^2\hbar^3} \left(\frac{n}{2}\right)^{5/2} \left[(g + g_{\uparrow\downarrow})^{5/2} + (g - g_{\uparrow\downarrow})^{5/2}\right]$$

Lee-Huang-Yang term

Phase stabilized by quantum fluctuations



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Cabrera et al., *Science* **359** (2018)

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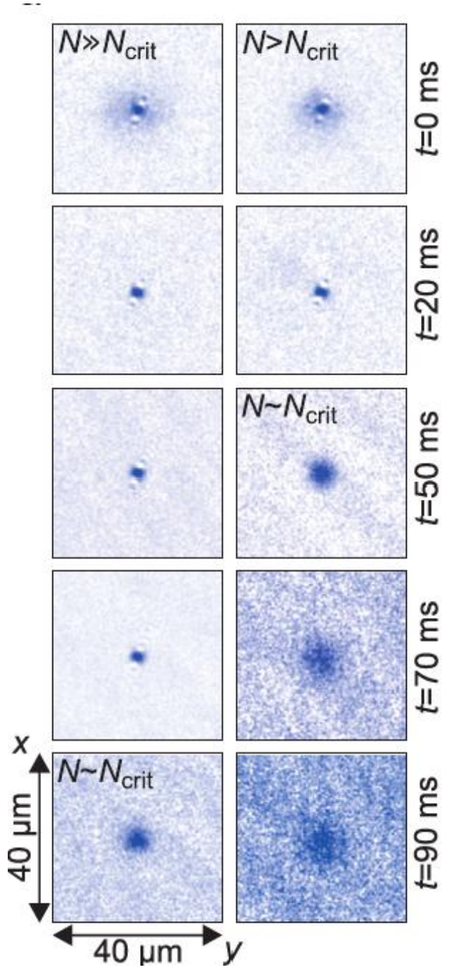
Lee-Huang-Yang term

Phase stabilized by quantum fluctuations

First prediction for Bose mixtures

Petrov, *Phys. Rev. Lett*. **115** (2015).



First observation in dipolar quantum gases

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

Content

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Quantum liquid droplets

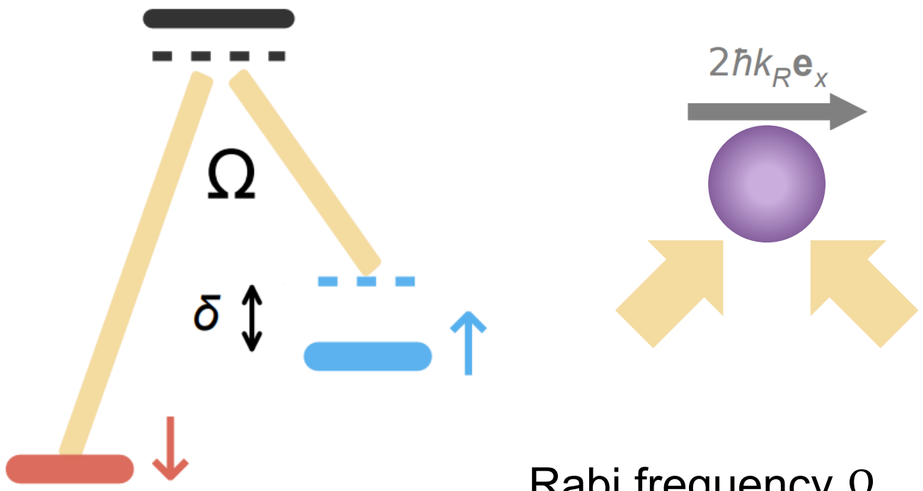
II. Raman-coupled mixtures

Supersolids

Chiral solitons

Raman coupling of potassium

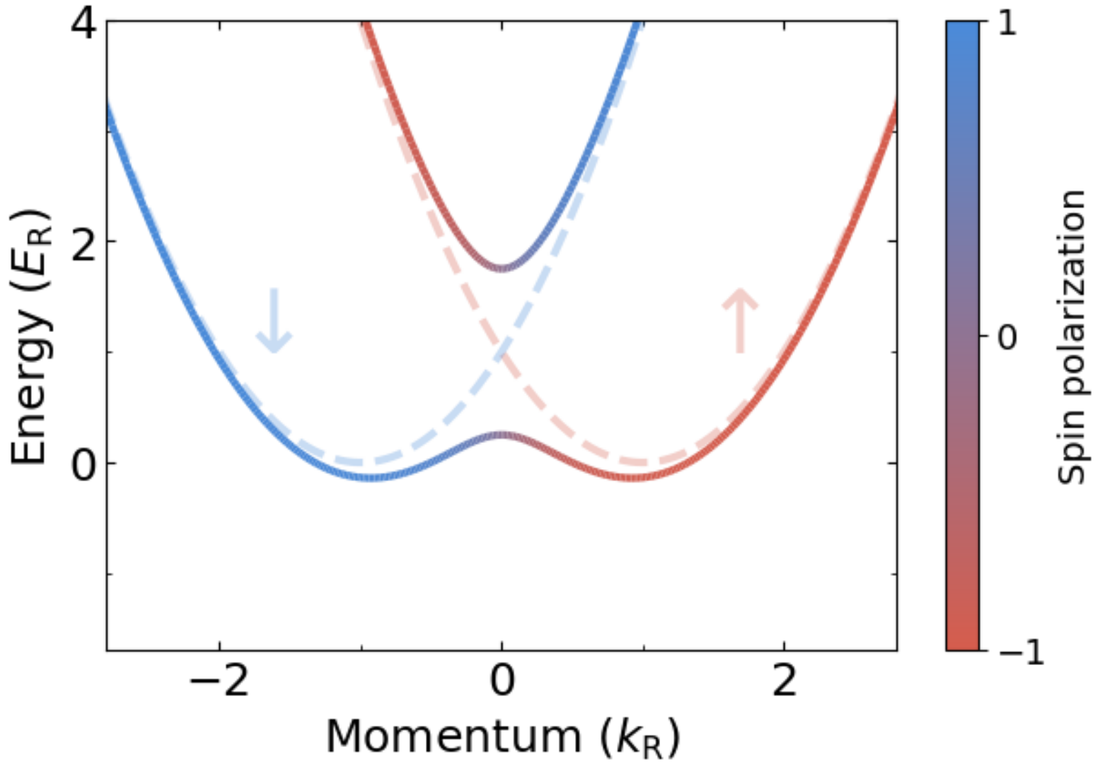
Raman coupling



Rabi frequency Ω
Two-photon detuning δ
Momentum transfer recoil k_R

Lin, Jiménez-García, and Spielman,
Nature **471**, 83 (2011)

Engineered dispersion relation

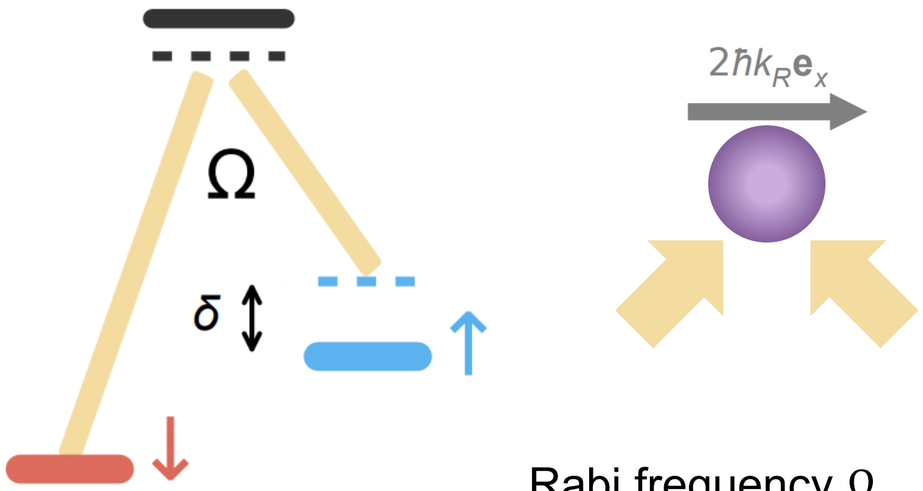


$$k_{\mathrm{R}} = \frac{2\pi}{\lambda_{\mathrm{R}}}\sin(\theta/2)$$

$$E_{\mathrm{R}} = \hbar^2 k_{\mathrm{R}}^2/2m$$

Raman coupling of potassium

Raman coupling



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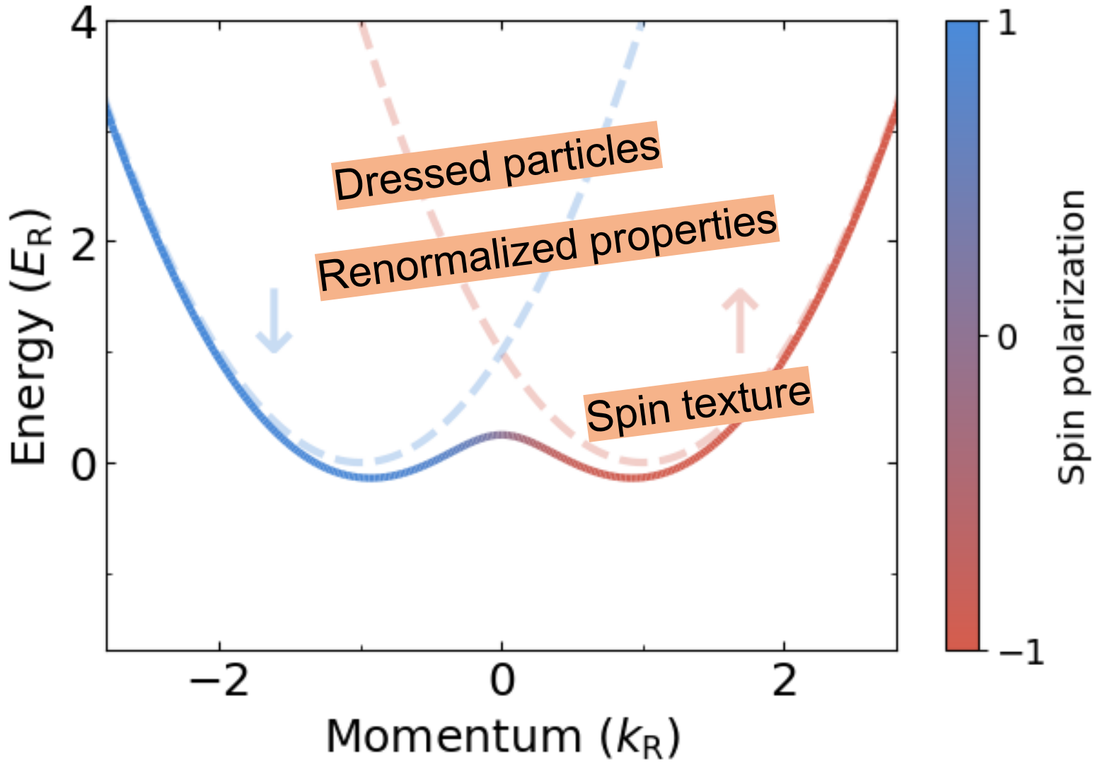

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Raman coupling of potassium

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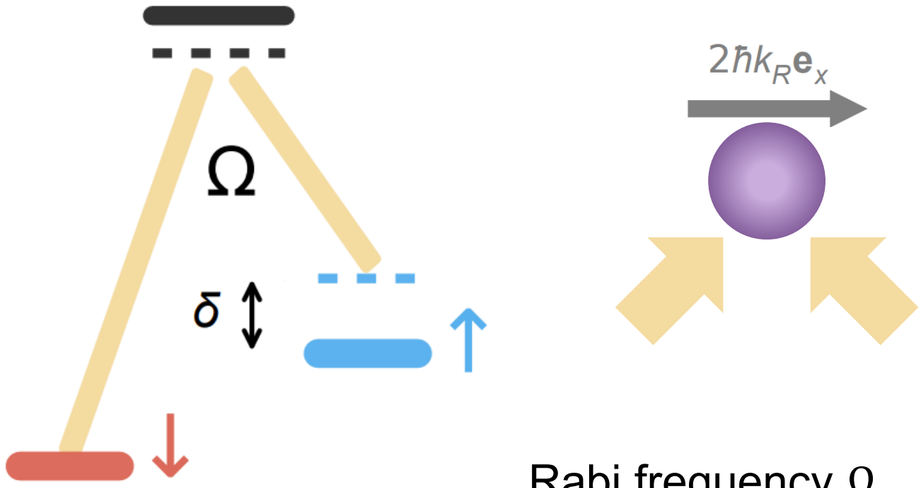

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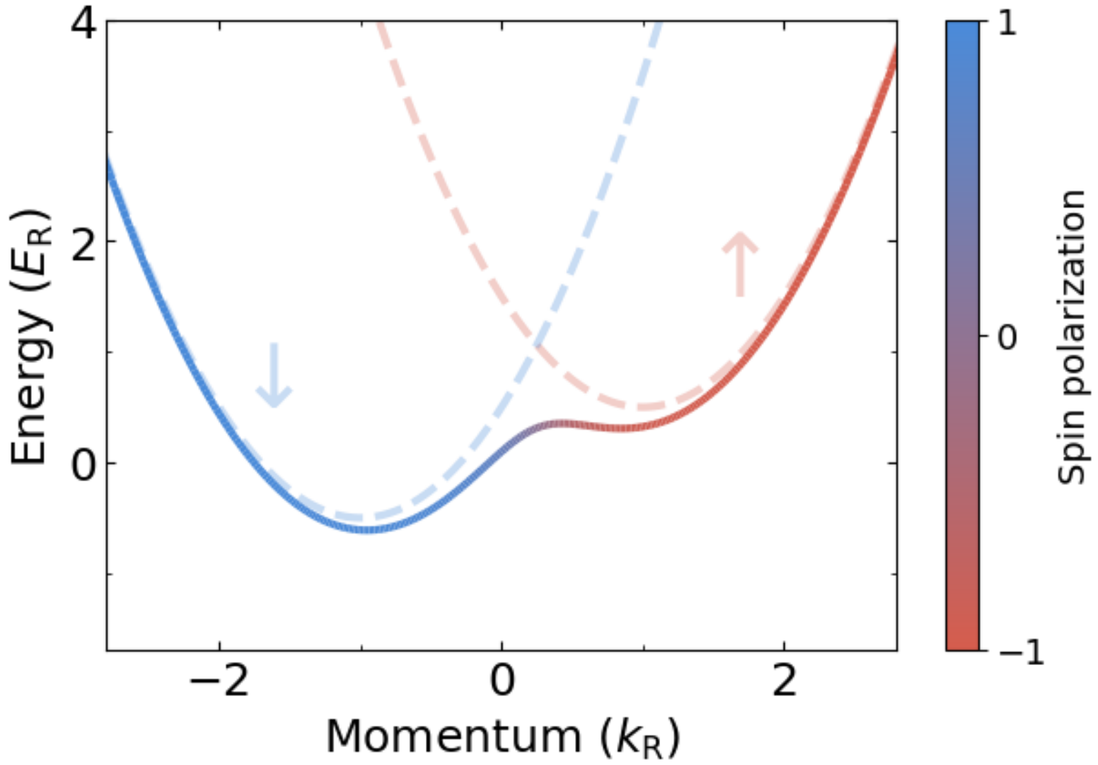

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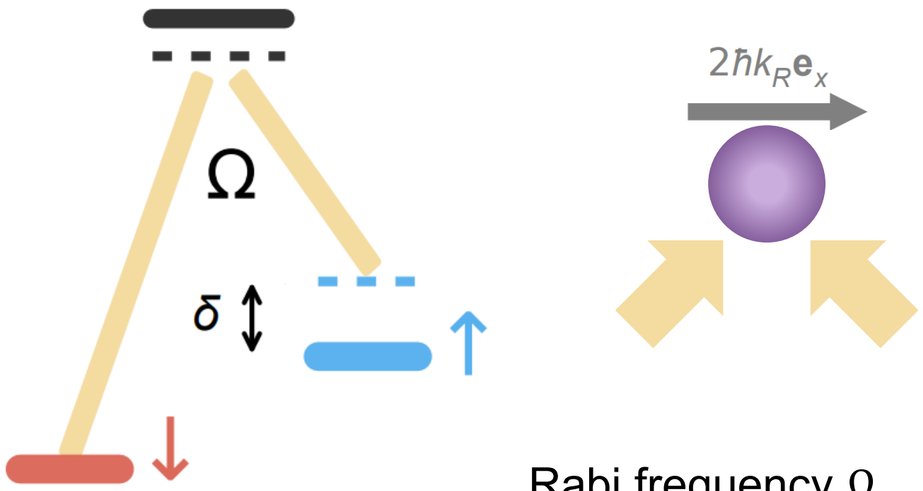

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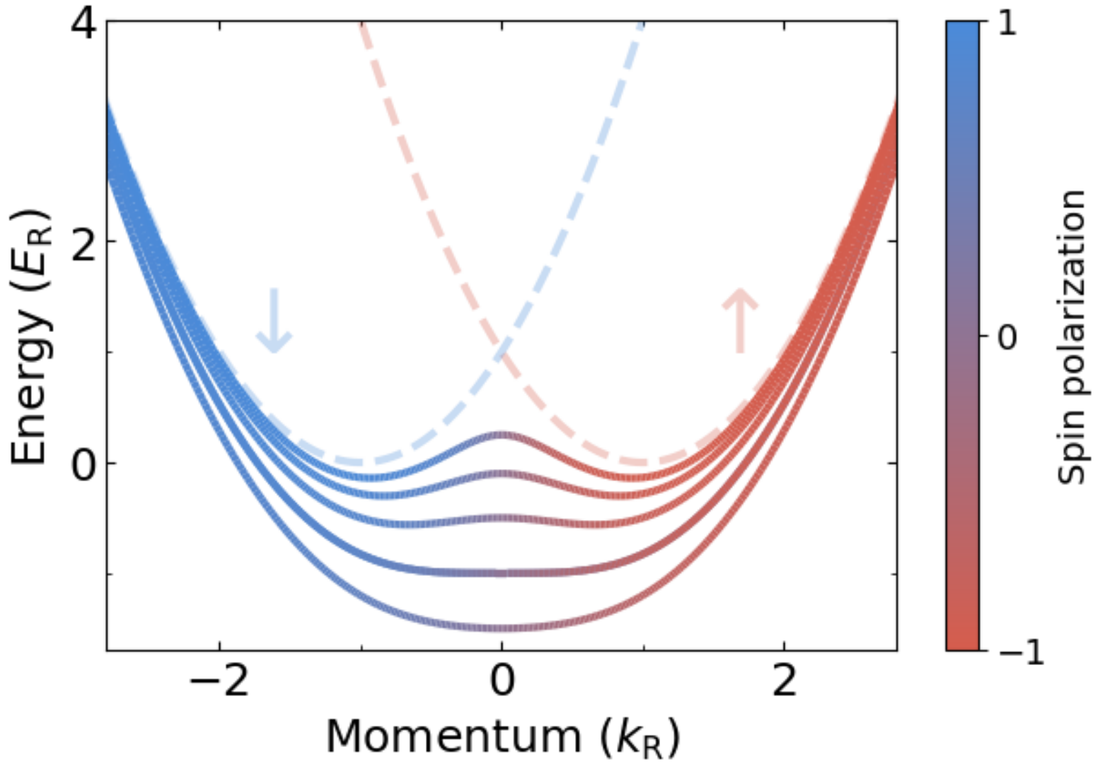
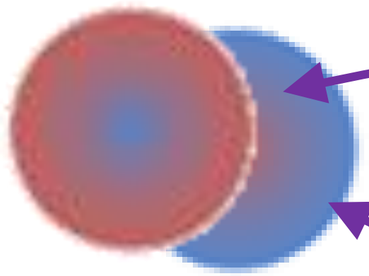


$$k_{\mathrm{R}} = \frac{2\pi}{\lambda_{\mathrm{R}}}\sin(\theta/2)$$

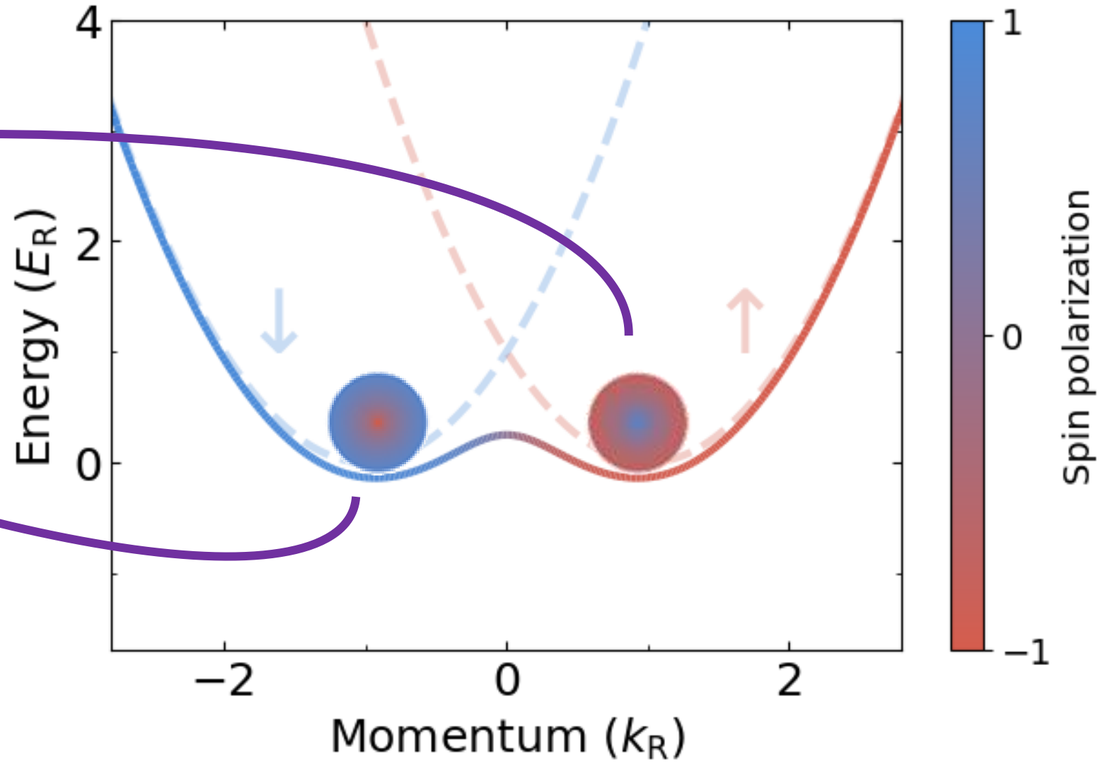
$$E_{\mathrm{R}} = \hbar^2 k_{\mathrm{R}}^2/2m$$

Spin-orbit coupling of potassium

Matter wave interference



Spin-orbit coupling



Spin-orbit coupling of potassium

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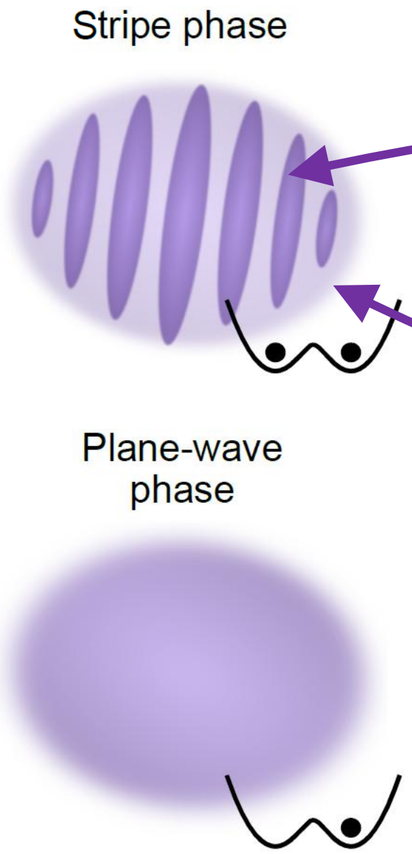
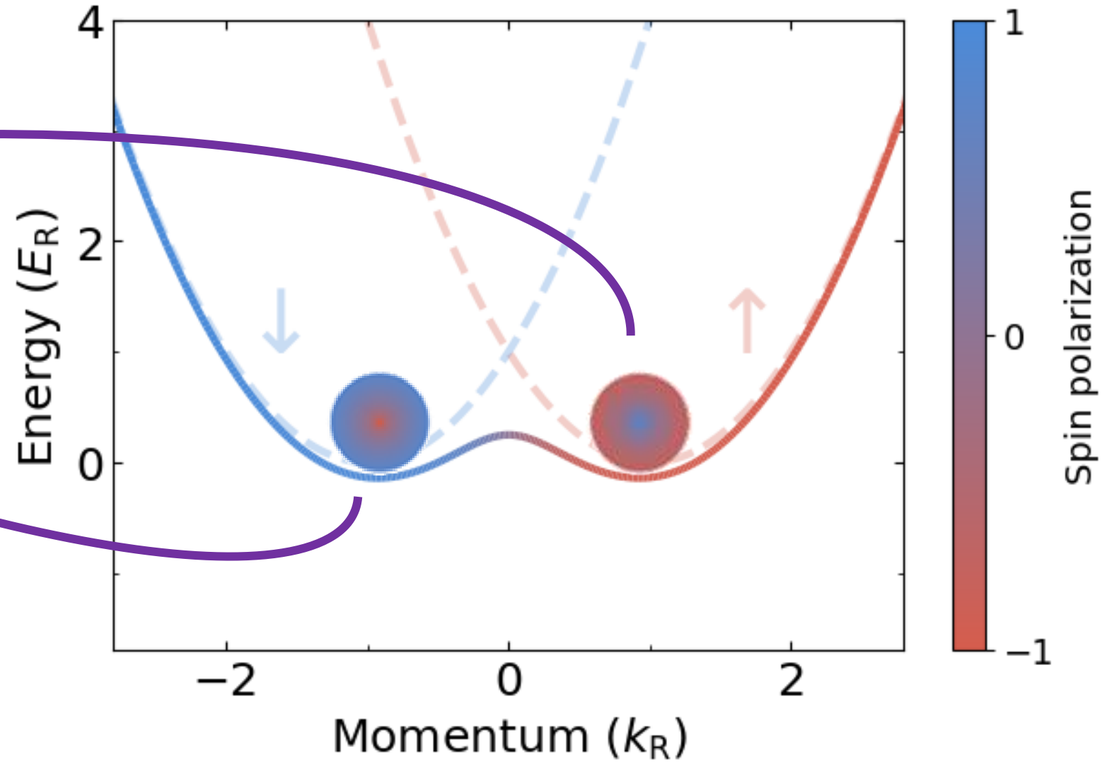


Spin-orbit coupling

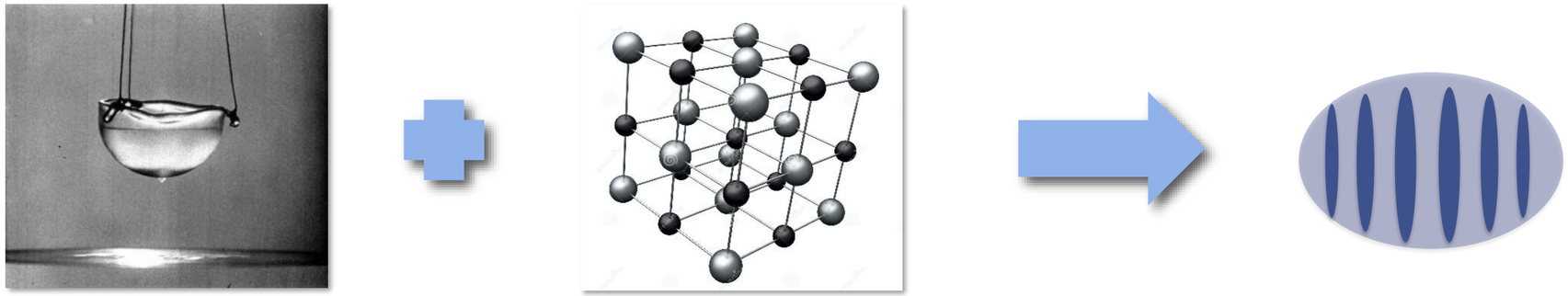


Supersolidity

Superfluid Spontaneous U(1) symmetry breaking

Solid Spontaneous translational symmetry breaking

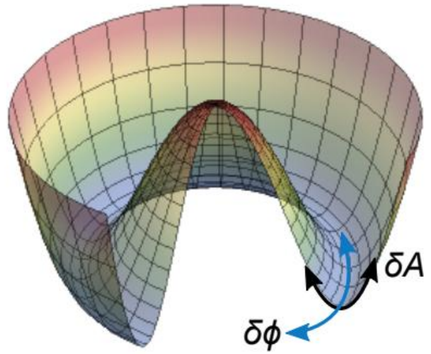
Supersolid both



Andreev and Lifshitz, *Sov. Phys. JETP* **29**, 1107 (1969)

Chester, *Phys. Rev. A* **2**, 256 (1970)

Leggett, *Phys. Rev. Lett* **25**, 1543 (1970)

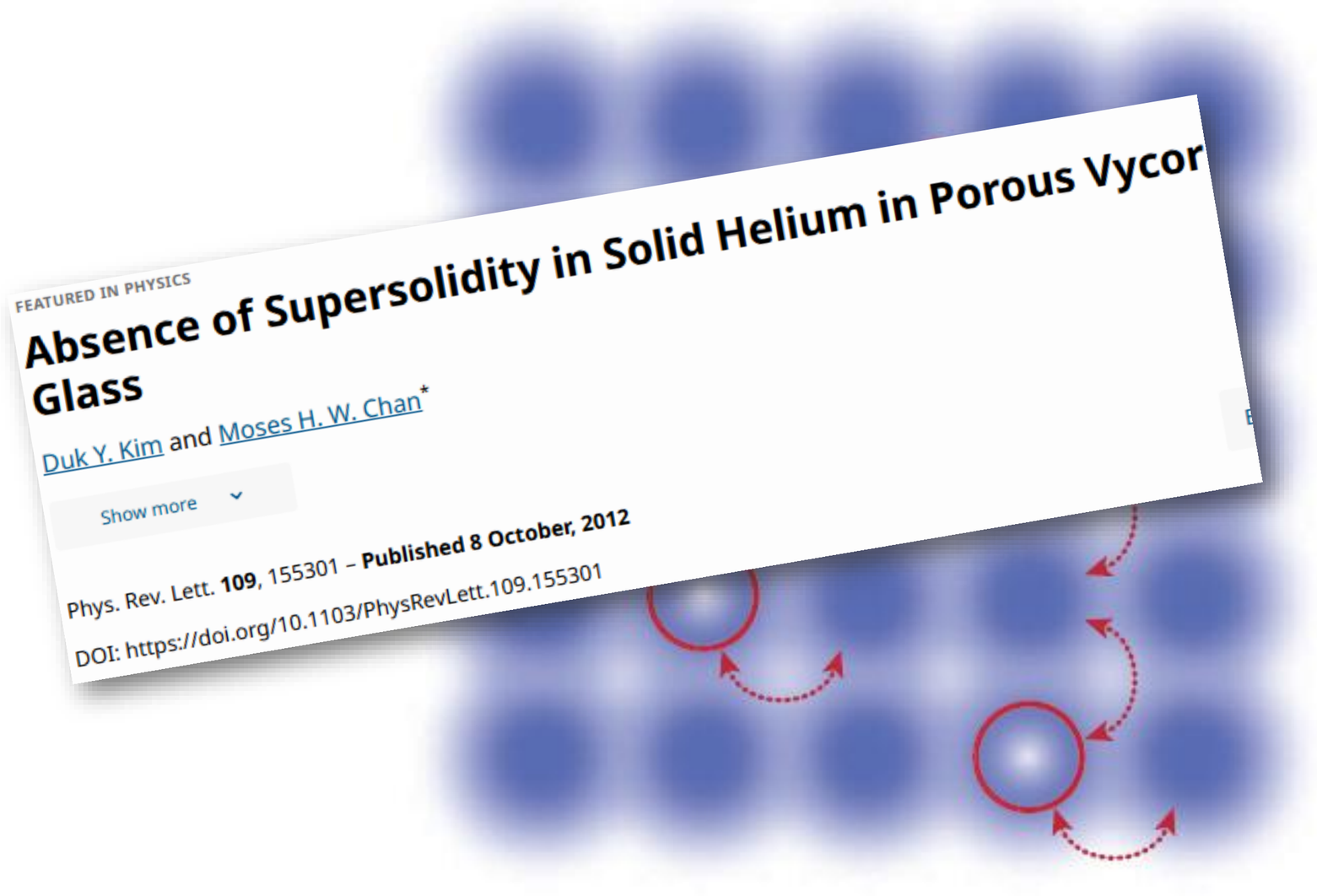


Guo et al. *Nature* **574**, 386 (2019)

two independent order parameters

- superfluid and crystal excitations

Supersolidity in ^{4}He

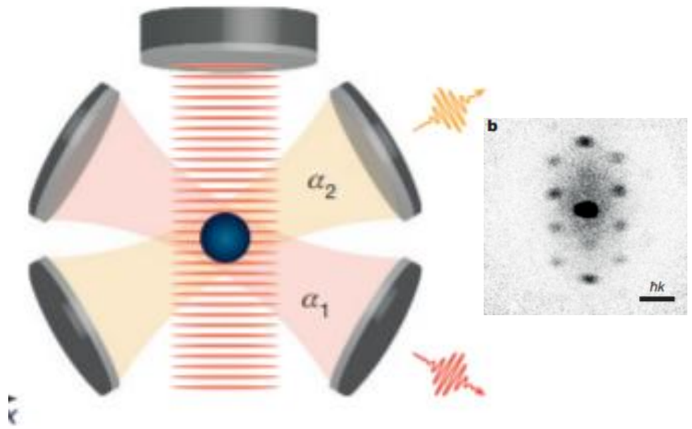


crystalline structure
&
phase coherence

Balibar, *Nature* **464**, 176 (2010)

Features of supersolidity in quantum gases

Cavity supersolids

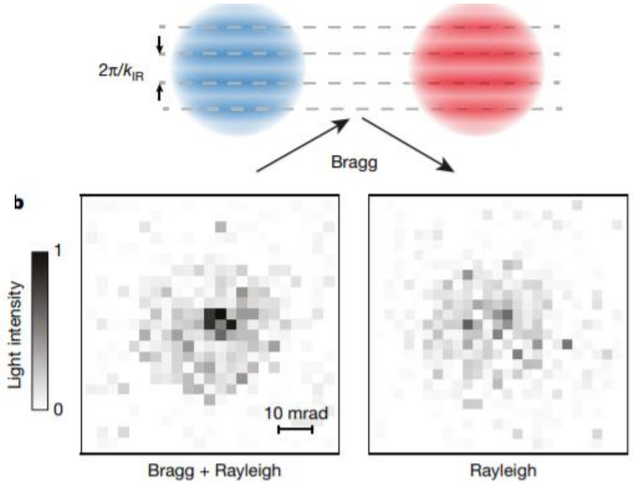


Léonard et al., *Nature* **543** (2017)
Léonard et al., *Science* **358** (2017)

Period fixed by light wavelength

Rigid crystal

Spin-orbit coupled BECs

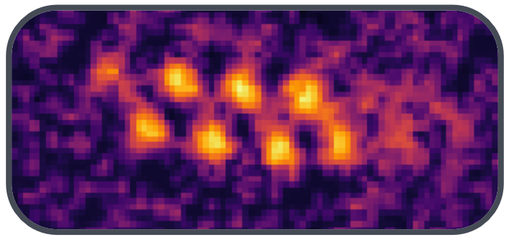


Li et al., *Nature* **543** (2017)
Putra et al., *PRL* **124** (2020)

Dynamics so far inaccessible

?

Dipolar supersolids



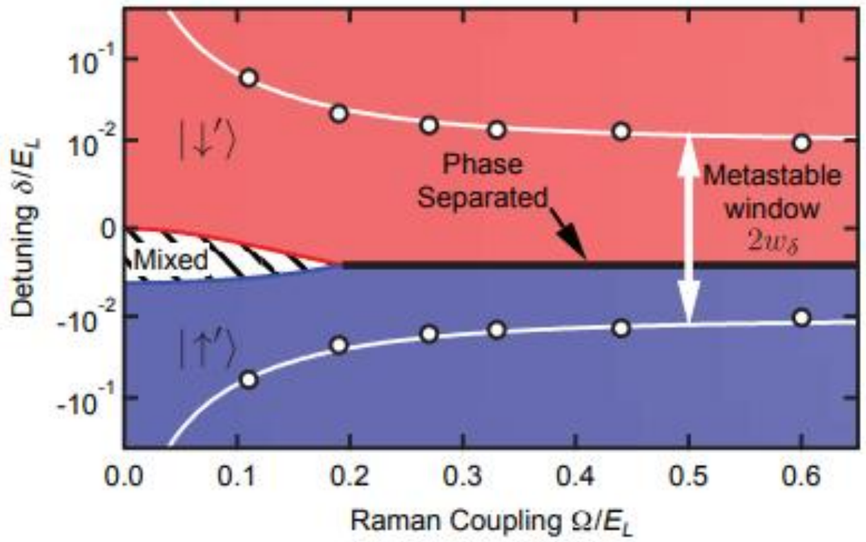
Norcia et al. Nature (2024)

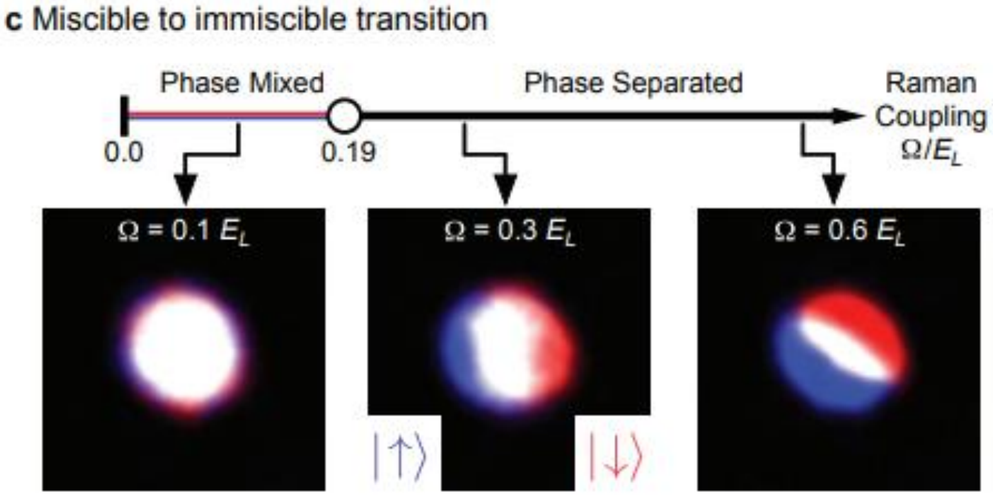
Tanzi et al., *PRL* **122** (2019)
Chomaz et al., *PRX* **9** (2019)
Böttcher et al., *PRX* **9** (2019)
…

Many excitation modes observed

Hosts phonon modes

Previous realizations





Lin et al. *Nature* **471** (2011)

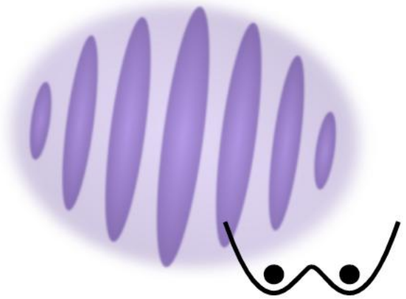
Problems:

- unstable stripe phase
- phase separation
- small modulation contrast $\mathcal{C} \sim \Omega$

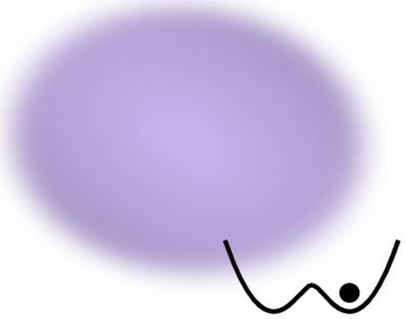
Spin-orbit-coupled Potassium

Matter wave interference

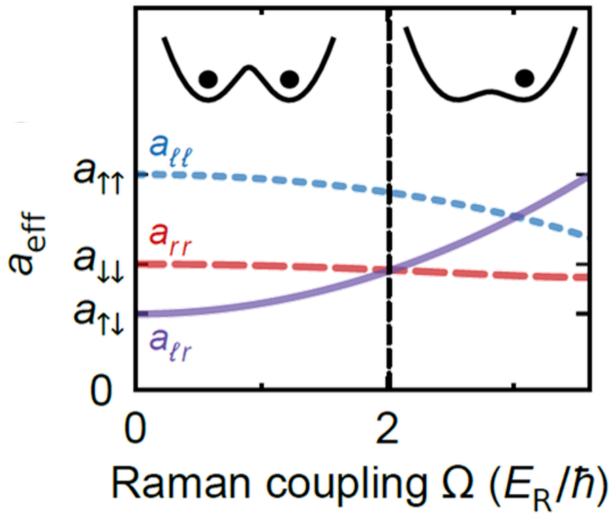
Supersolid
stripe phase

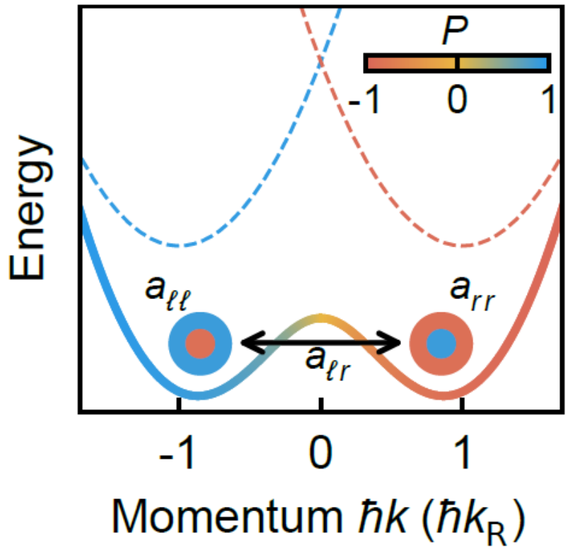


Plane-wave
phase



Phase diagram
determined by effective interactions

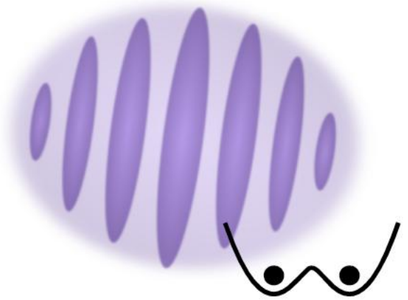




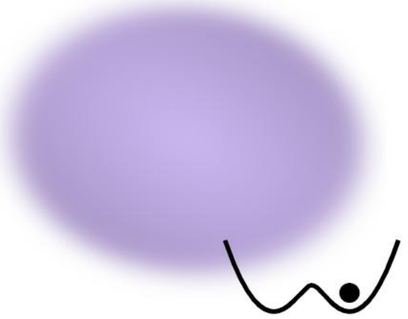
Spin-orbit-coupled Potassium

Matter wave interference

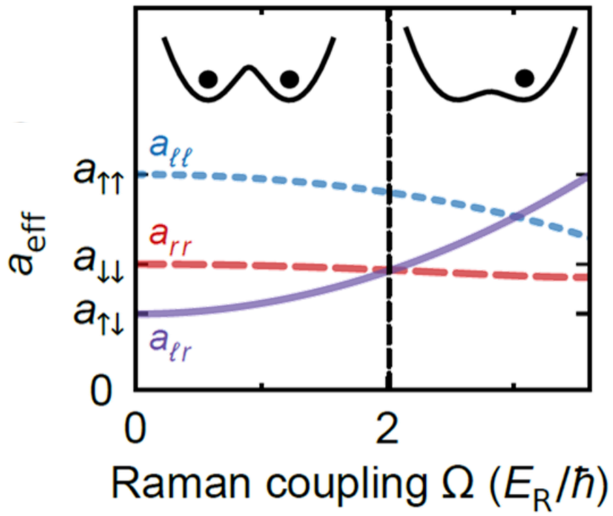
Supersolid
stripe phase

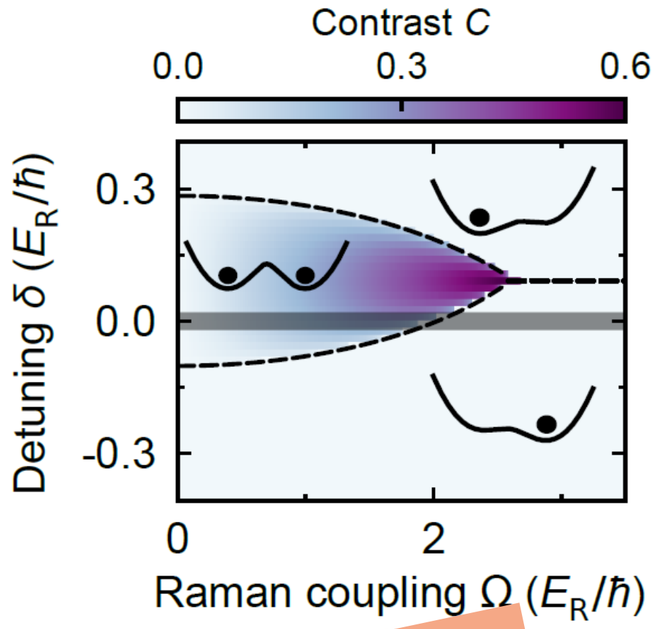


Plane-wave
phase



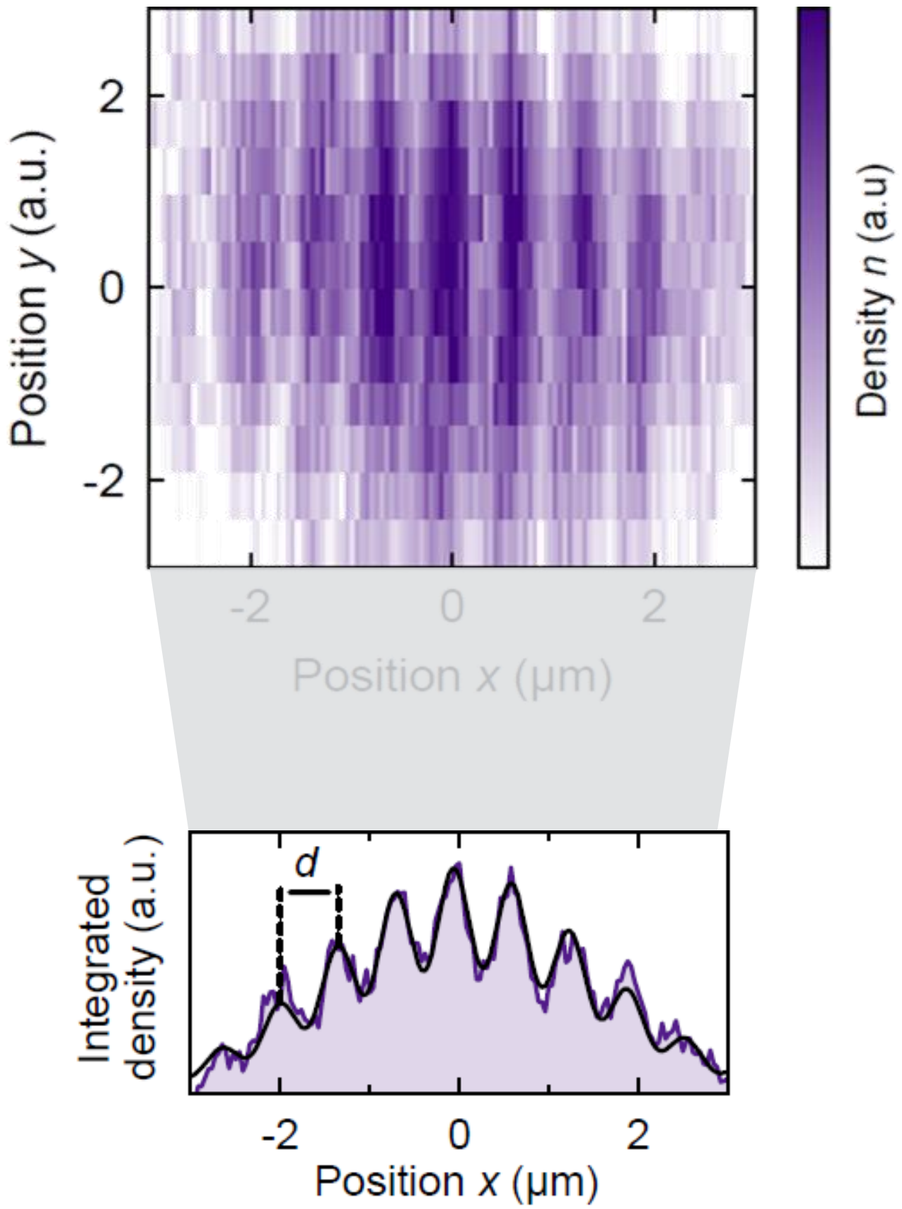
Phase diagram
determined by effective interactions



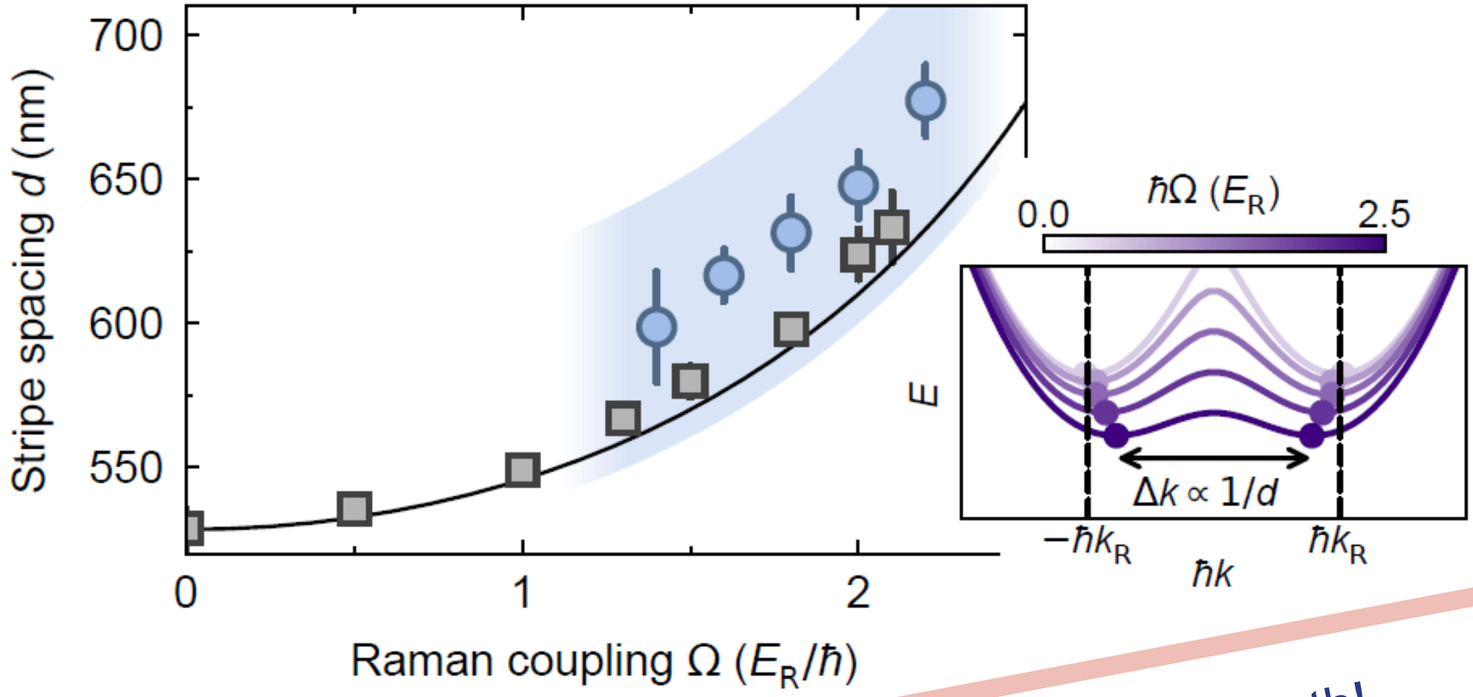


Stable stripe phase with high contrast

In-situ imaging of supersolid stripes



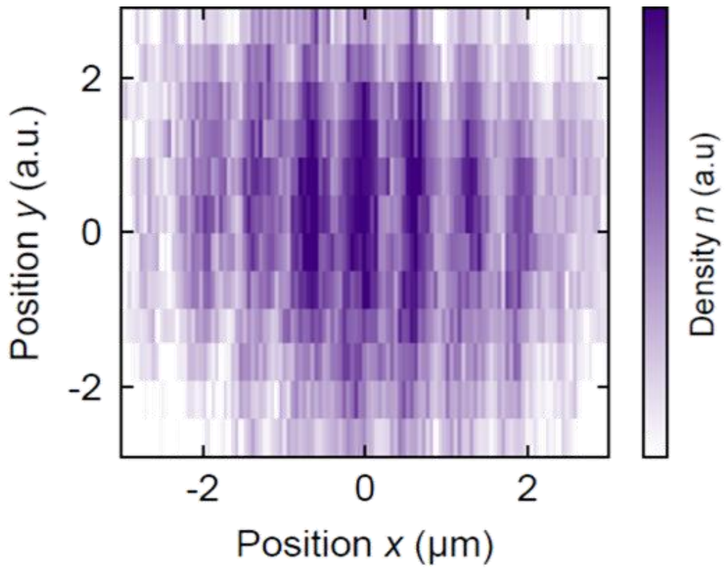
Modulation period is coupling dependent



not fixed by light wavelength!

Chisholm et al., *Science* **391** (2026)

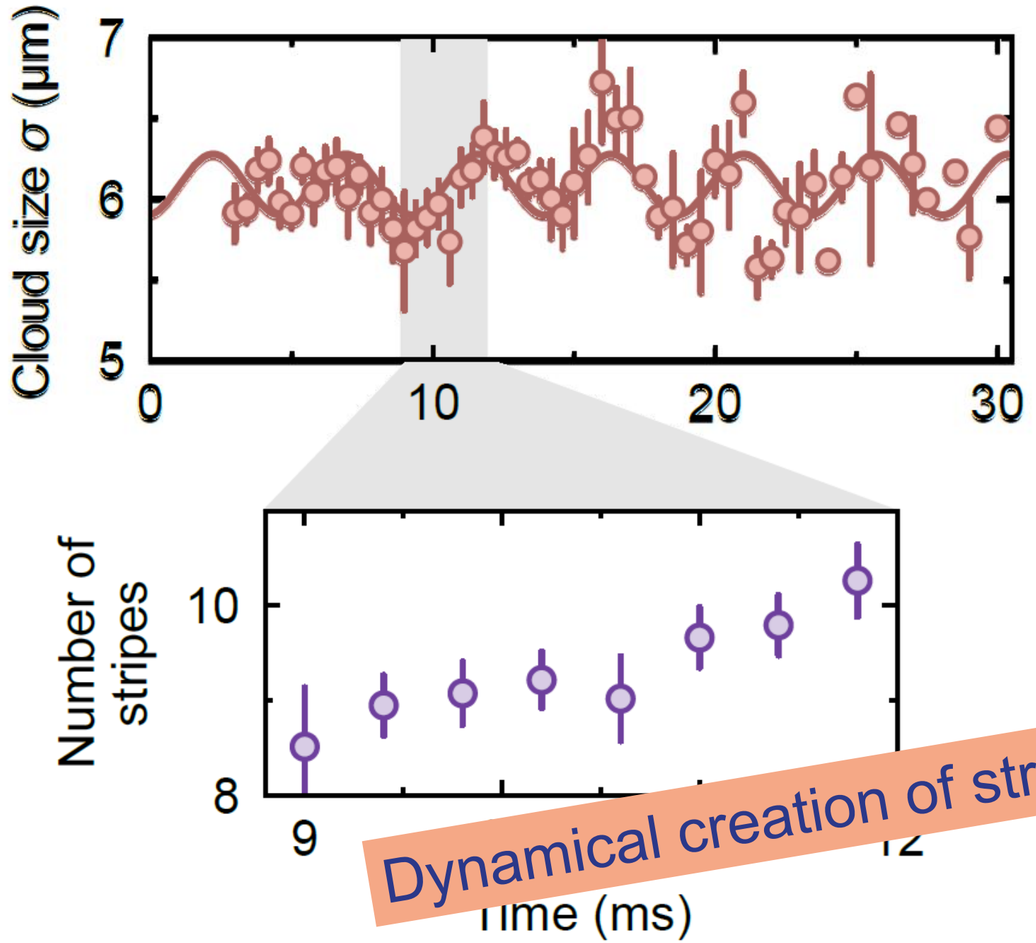
Collective modes of the superfluid



$$\frac{\omega_{\mathrm{breathing}}}{\omega_{\mathrm{dipole}}} = 1.5(1)$$

in good agreement with conventional BEC prediction

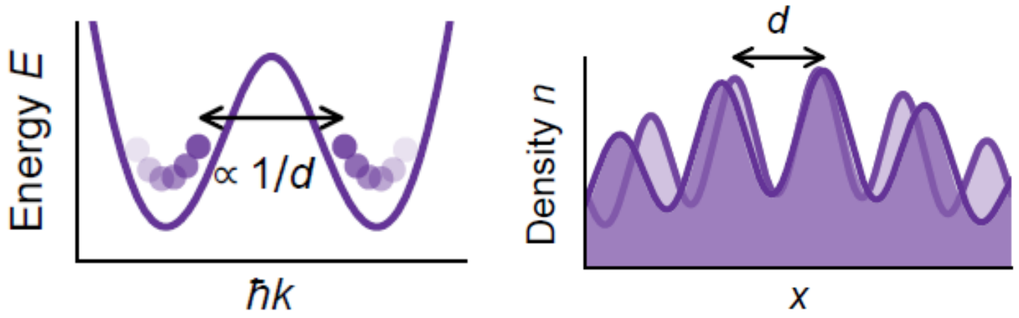
Superfluid breathing



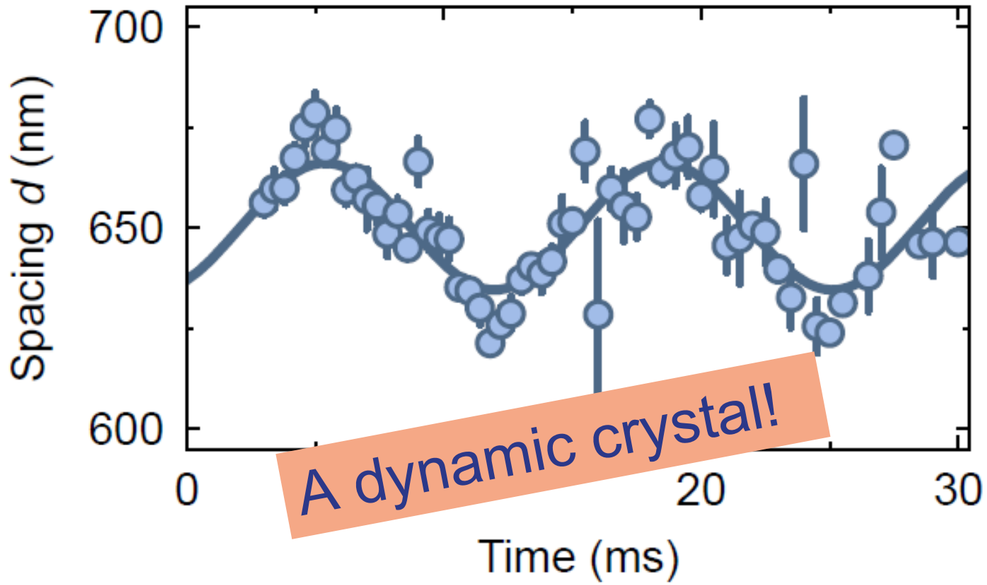
Chisholm et al., *Science* **391** (2026)

Observation of crystal compression

Stripe compression mode



Oscillation of the modulation period



Theory of collective modes in SOC supersolids:

- Geier et al., *PRL* **130** (2023)
- Geier et al. *PRL* **127** (2021)
- Martone and Stringari *SciPost Phys*. **11** (2021)
- Chen et al. *PRA* **98** (2017)

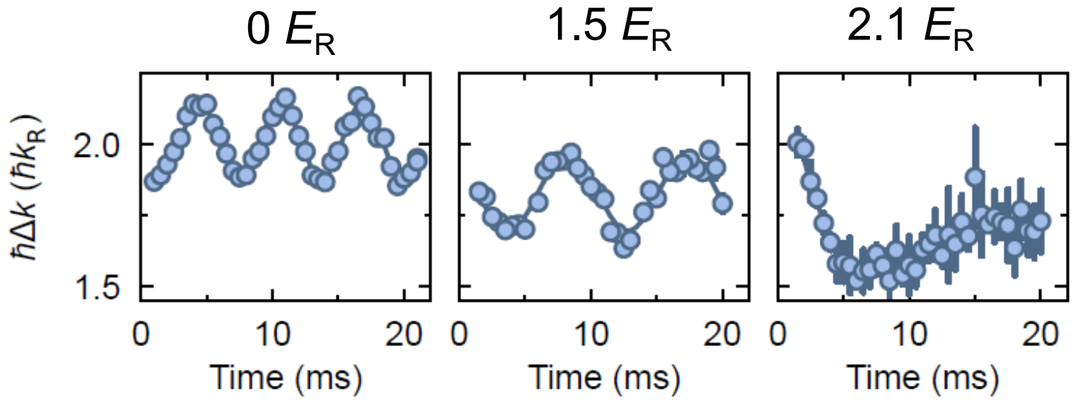
…

What happens at the transition?

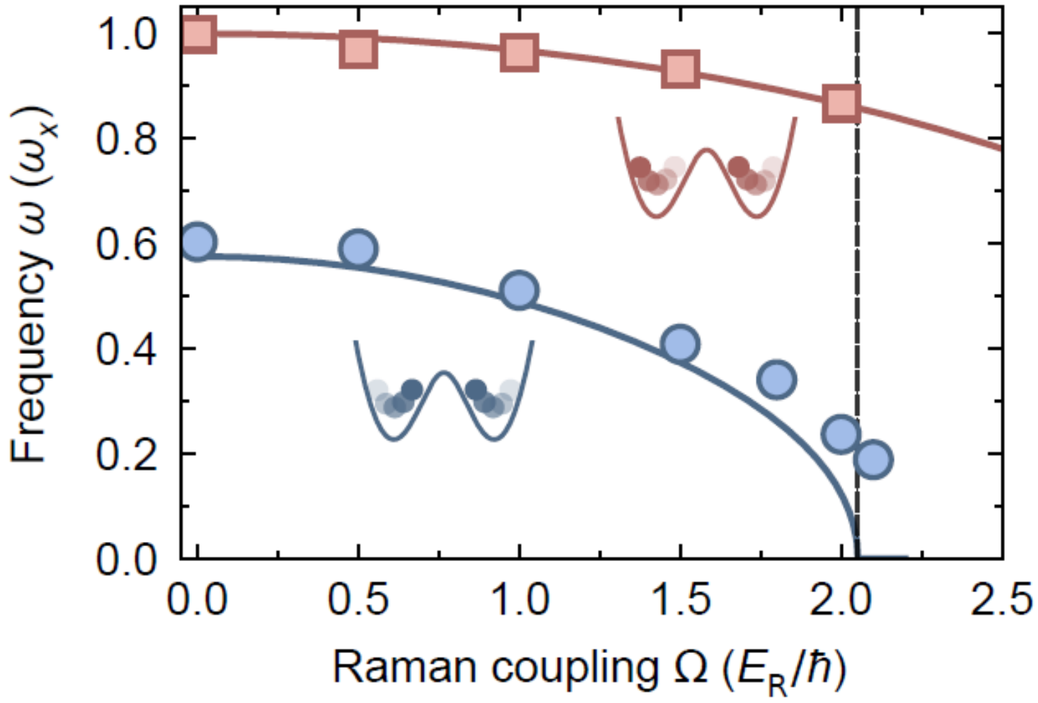
Chisholm et al., *Science* **391** (2026)

Softening of the compression mode

Frequency softening



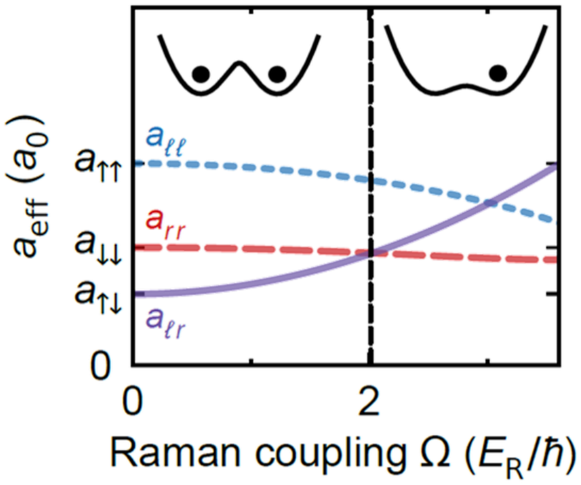
Compression mode softens at phase transition

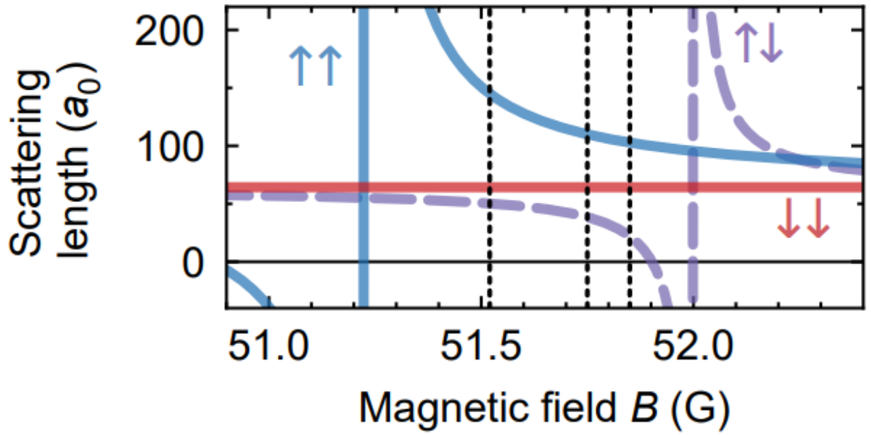


Chisholm et al., *Science* **391** (2026)

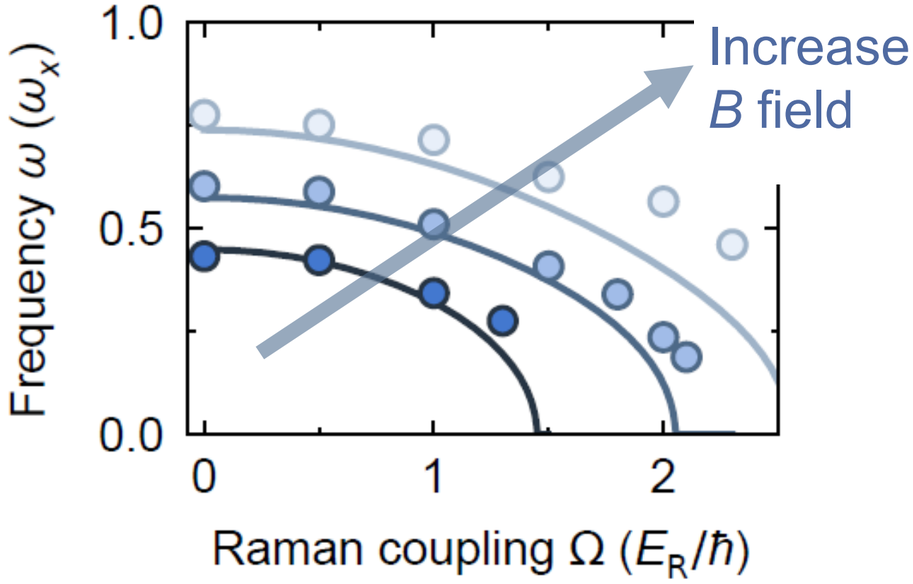
Probe phase transition

Tuning interacions





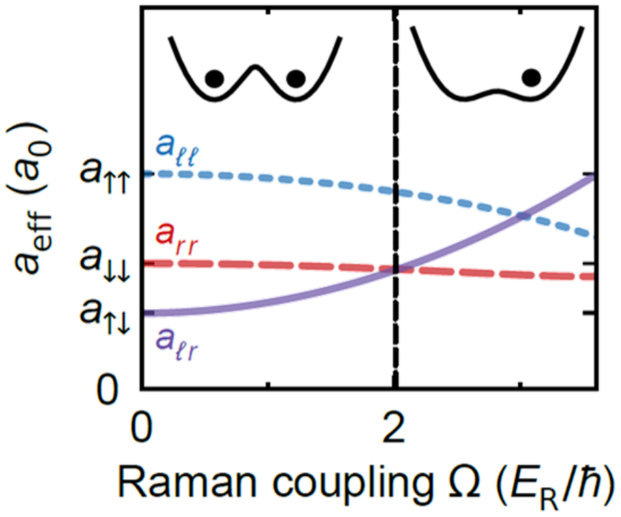
Tunable transition point



Chisholm et al., *Science* **391** (2026)

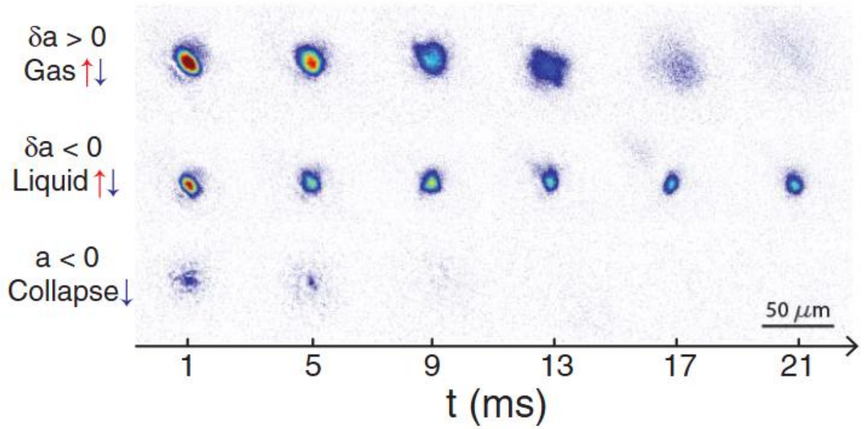
Outlook

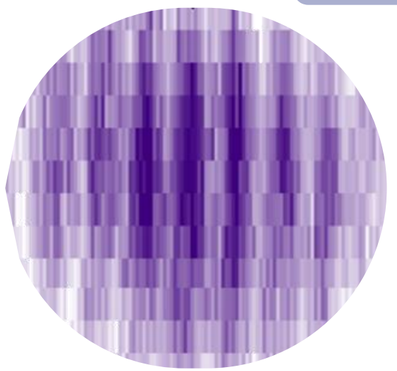
Spin-Orbit Coupling



+

Beyond-mean field effects





Self-bound supersolid

Sanchez-Baena, Boronat and Mazzanti, *Phys. Rev. A* **102** (2020)

Content

I. Bosonic mixtures with tunable interactions

Quantum liquid droplets

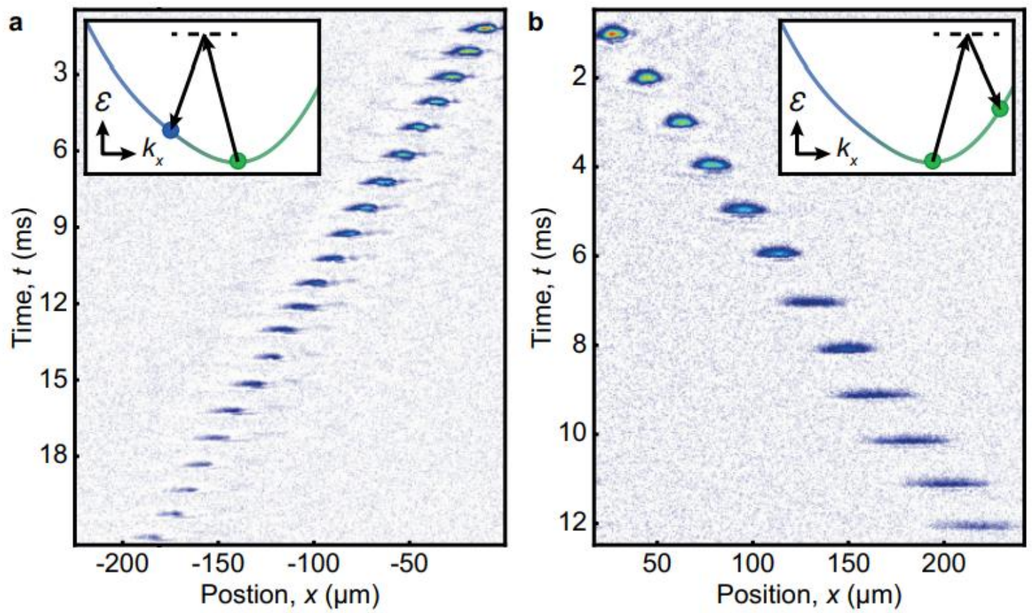
II. Raman-coupled mixtures

Supersolids

Chiral solitons

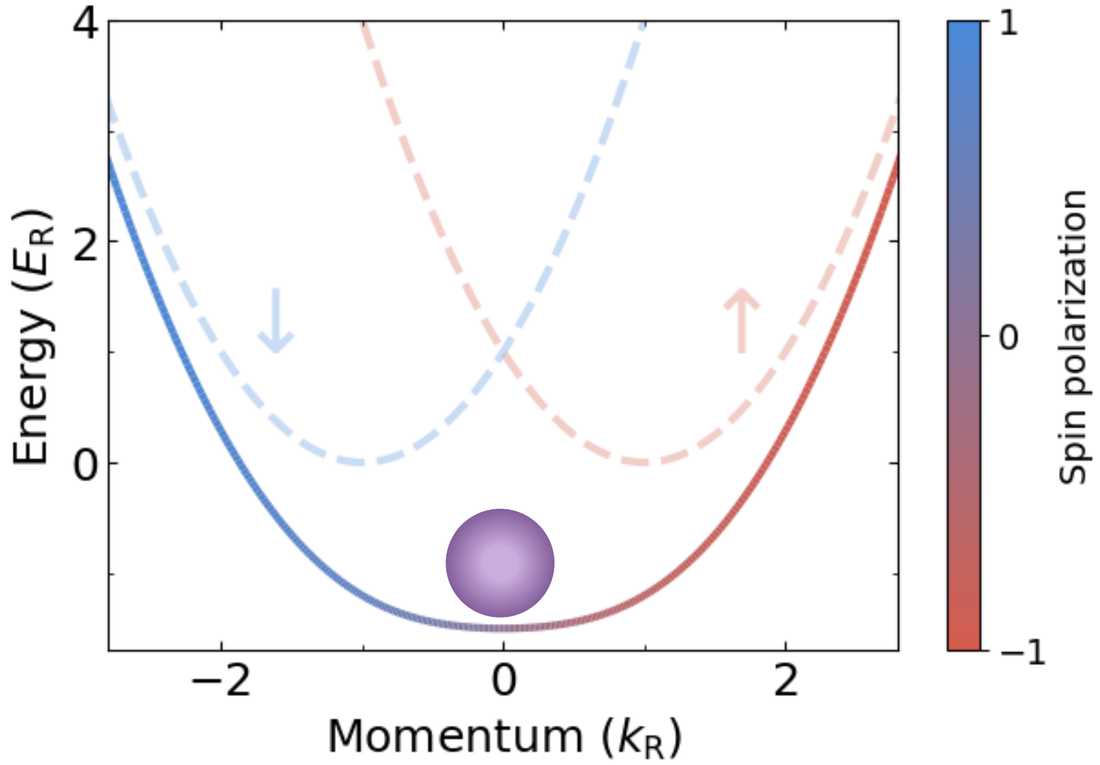
Raman coupling of potassium

Chiral solitons



Frölian et al., *Nature* **608**, 293 (2022)

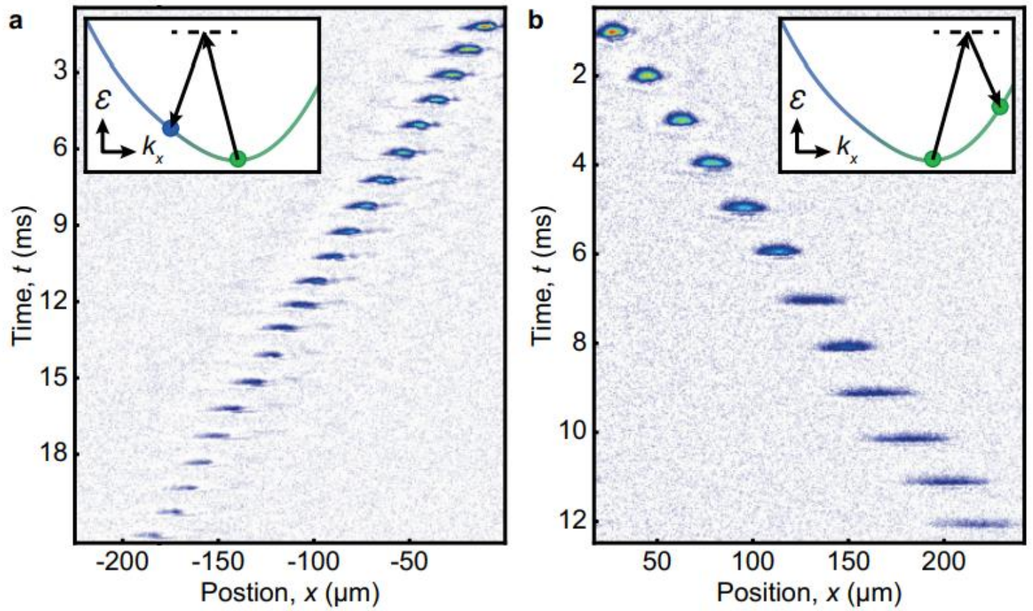
Engineered dispersion relation



$a_{\uparrow\uparrow}/a_0$	-4.9
$a_{\downarrow\downarrow}/a_0$	24.6
$a_{\uparrow\downarrow}/a_0$	-13.8

Raman coupling of potassium

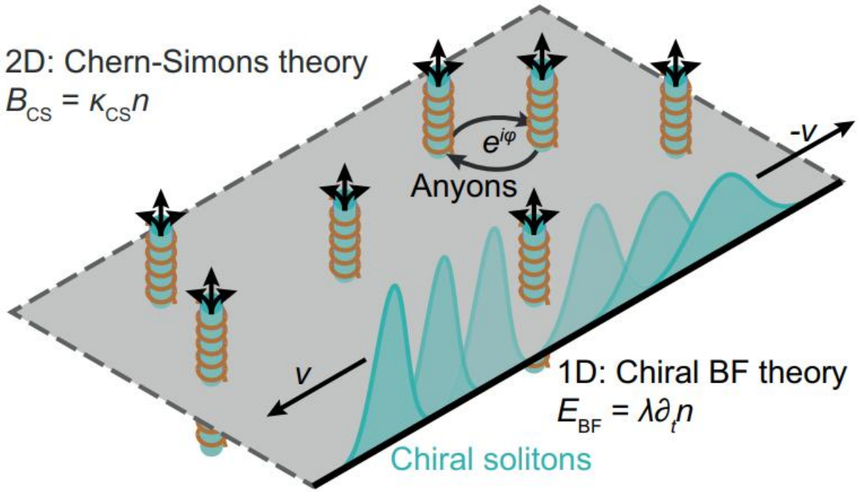
Chiral solitons



Frölian et al., *Nature* **608**, 293 (2022)

Simulation of a topological gauge theory

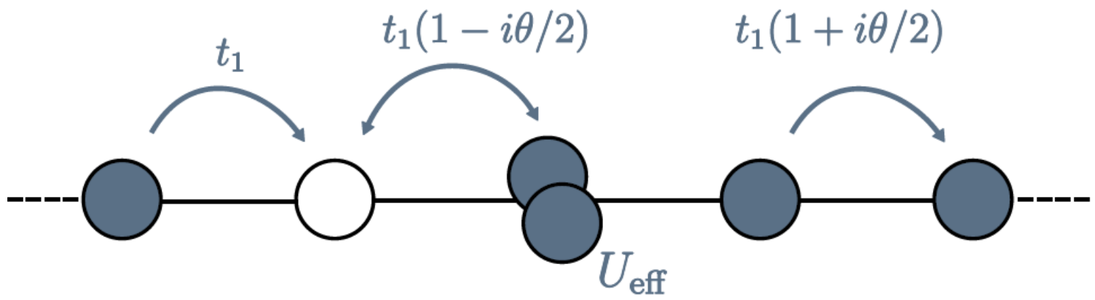
Chiral BF theory



$a_{\uparrow\uparrow}/a_0$	-4.9
$a_{\downarrow\downarrow}/a_0$	24.6
$a_{\uparrow\downarrow}/a_0$	-13.8

Outlook

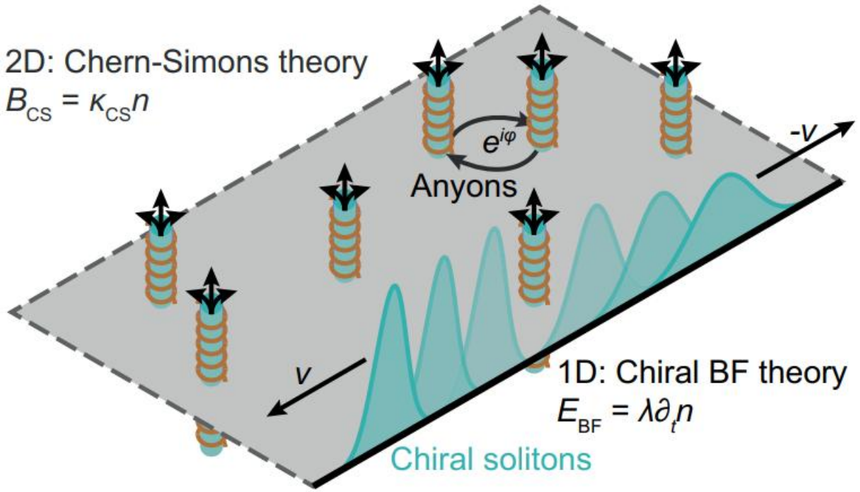
Linear anyons



$$H = -J\sum_j \left(b_j^\dagger e^{-in_j\theta} b_{j-1} + \text{h.c.}\right) + \frac{U}{2}\sum_j n_j(n_j-1)$$

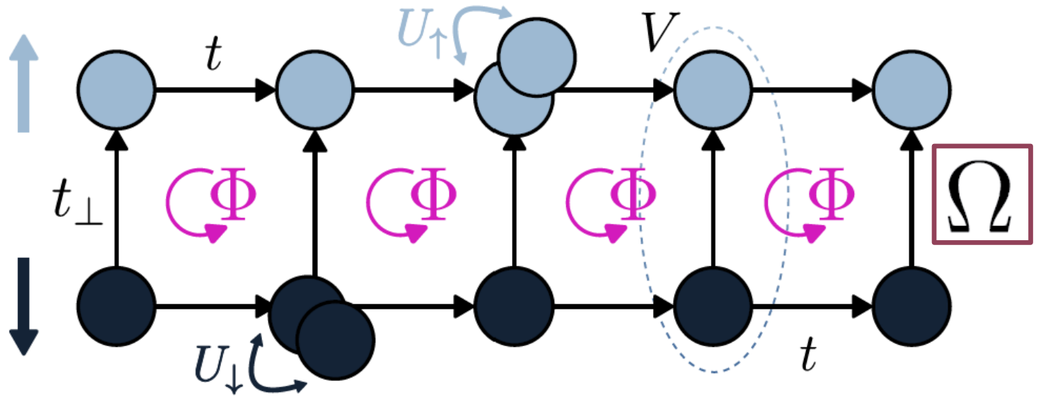
Cabedo et al. *In preparation*

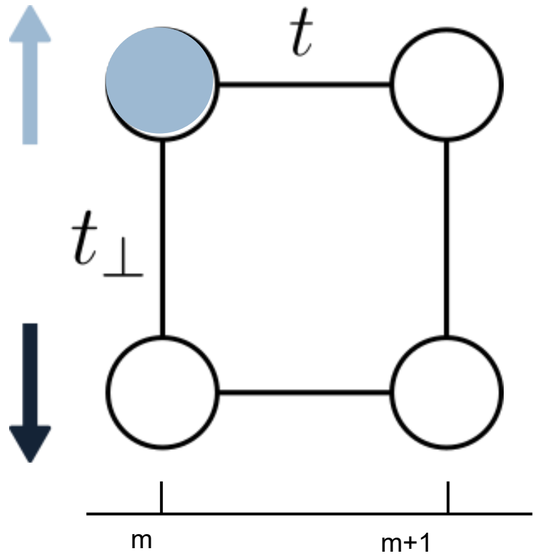
Chiral BF theory



Outlook: coupled mixtures in a lattice

Synthetic dimensions





N of flux quanta

$$\gamma = \sum \phi = 2k_R/d$$

$$\phi_{m,\uparrow\to m+1,\uparrow} = 0$$

$$\phi_{m+1,\uparrow\to m+1,\downarrow} = -2k_R(m+1)d$$

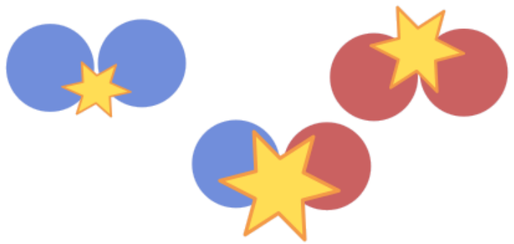
$$\phi_{m+1,\downarrow\to m,\downarrow} = 0$$

$$\phi_{m,\downarrow\to m,\uparrow} = 2k_R m d$$

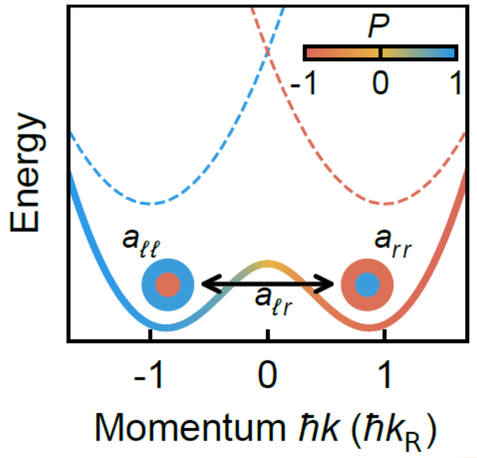
Celi et al., *PRL* **112** (2014)

Conclusion

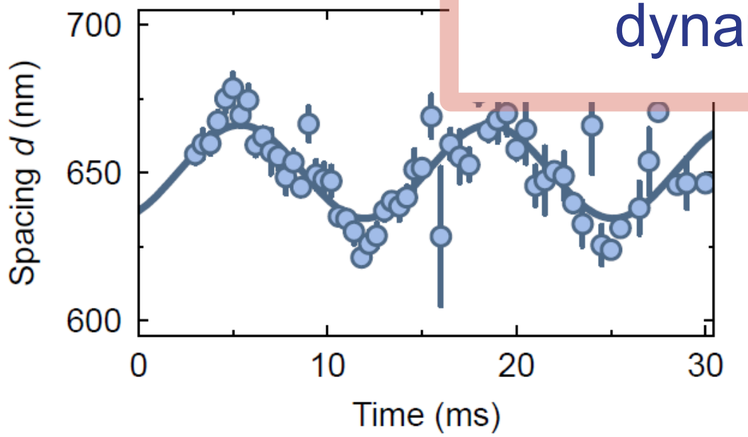
Tunable interactions



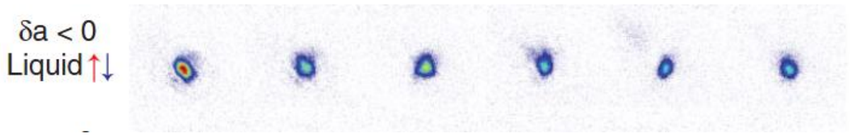
Raman coupling



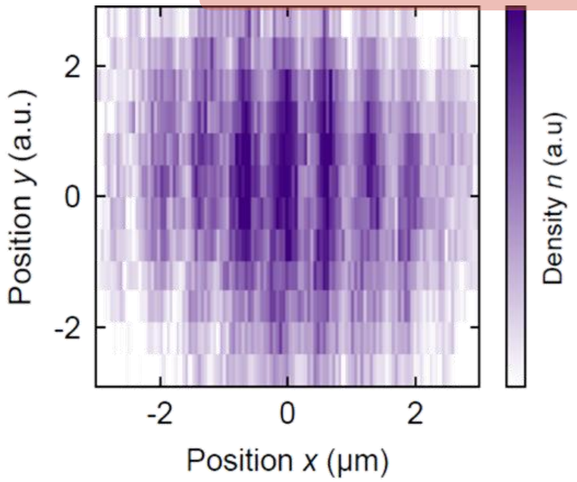
Supersolid dynamics



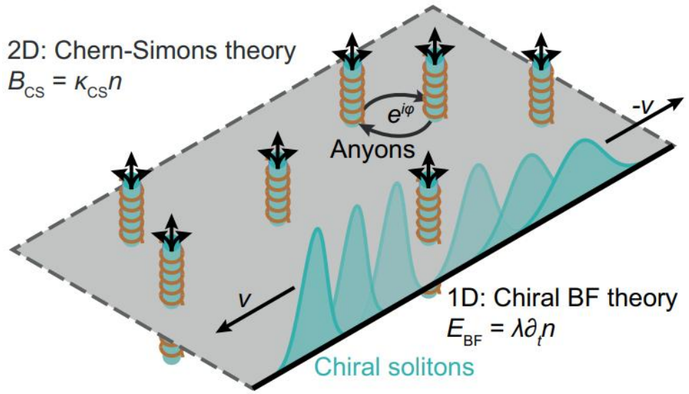
Droplets



Stripe phase



Chiral BF theory



Our group

Quantum Gases Experiment + Theory

Past and **present** potassium team

Leticia Tarruell
Cesar Cabrera
Pierrick Cheiney
Luca Tanzi
Julio Sanz
Bruno Naylor
Anika Frölian
Craig Chisholm
Elettra Neri
Ramón Ramos
Vasiliy Makhalov
Sarah Hirthe
Rémy Vatré
Ignacio Pérez
Andreas Meyer
Nicola Grani

GOBIERNO DE ESPAÑA
Generalitat de Catalunya
erc SuperComp
Fundació Privada MIR-PUIG
Fundació Privada CELLEX
Dynamite
Marie Skłodowska-Curie Actions
Epiquant
European Commission
AGAUR Agència de Gestió d'Ajuts Universitaris i de Recerca
UPC UNIVERSITAT POLITÈCNICA DE CATALUNYA BARCELONATECH
FOR 2414 DFG