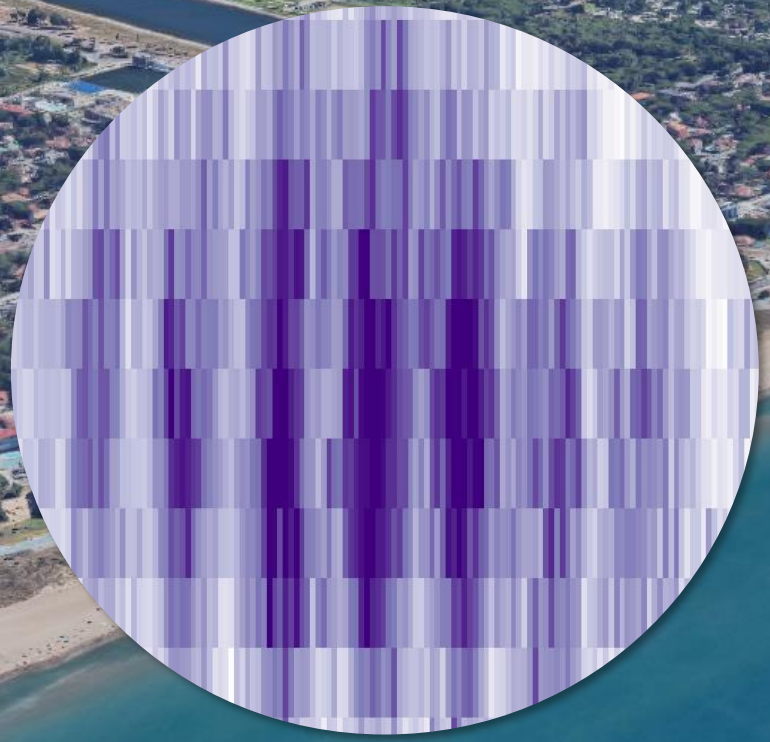
Probing supersolidity through excitations in a spin-orbit-coupled Bose-Einstein condensate



Leticia Tarruell

ICFO & ICREA

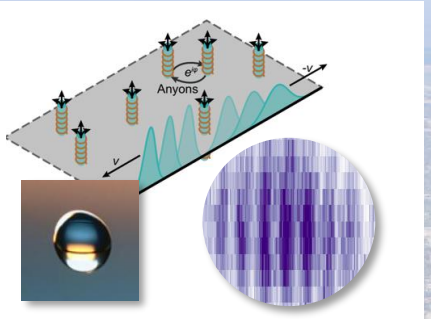
ICAP 2026

Wuhan, June 17th 2026

Potassium Lab

Mixtures of Bose-Einstein condensates

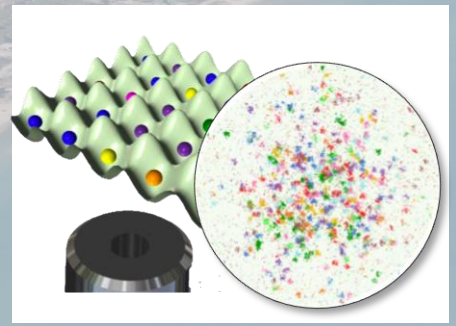
C. R. Cabrera *et al.*, Science **359**, 301 (2018)
A. Frölian *et al.*, Nature **608**, 293 (2022)
C. S. Chisholm *et al.*, Science **391**, 480 (2026)



Strontium Lab

Hubbard quantum-gas microscope

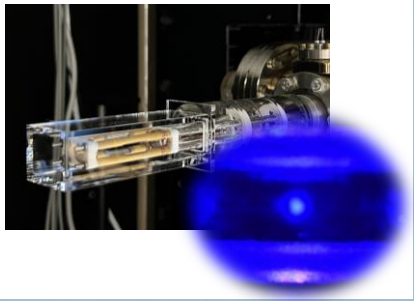
S. Buob *et al.*, PRX Quantum **5**, 020316 (2024)
C. Gas-Ferrer *et al.*, arXiv:2603.05478



Rydberg Lab

Rydberg atom arrays for 2D lattice gauge theories

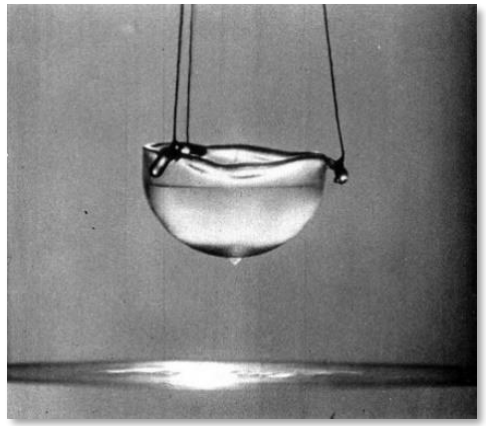
Under construction, loading tweezers!



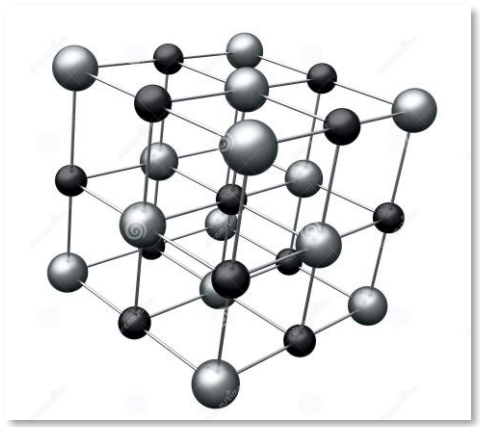
Supersolidity

Superfluid

U(1) symmetry breaking



Supersolid

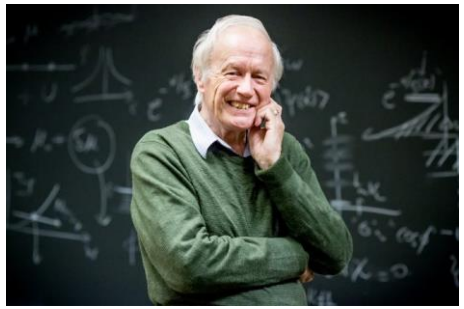


Solid

Translational symmetry breaking = crystallization

Spontaneous breaking of **both** symmetries!

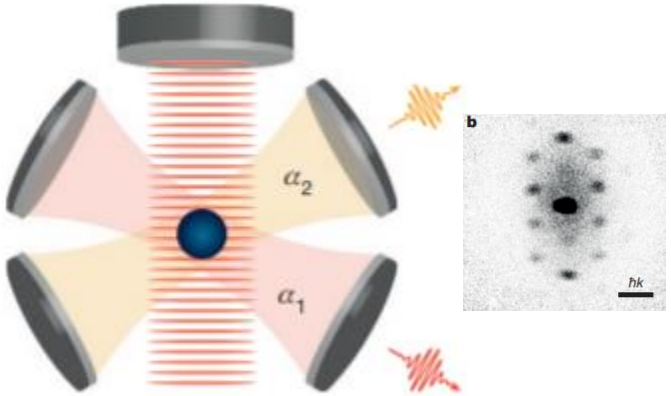
A. F. Andreev and I. Lifshitz, *Sov. Phys. JETP* **29**, 1107 (1969)
G. V. Chester, *Phys. Rev. A* **2**, 256 (1970)
A. J. Leggett, *Phys. Rev. Lett.* **25**, 1543 (1970)



Original proposal for solid helium, observed with quantum gases

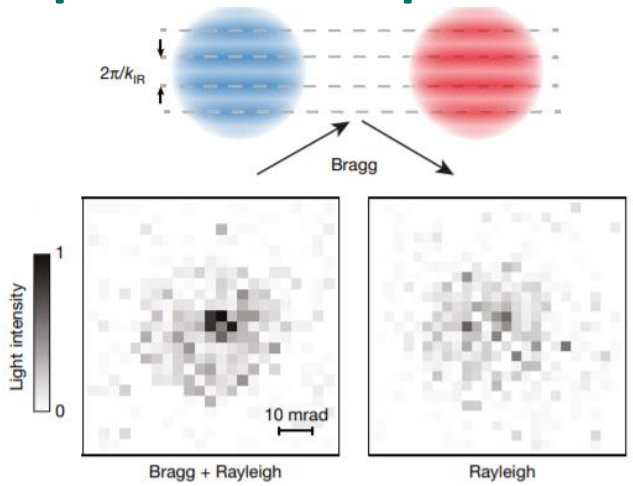
Supersolid phases in Bose-Einstein condensates

Cavity systems



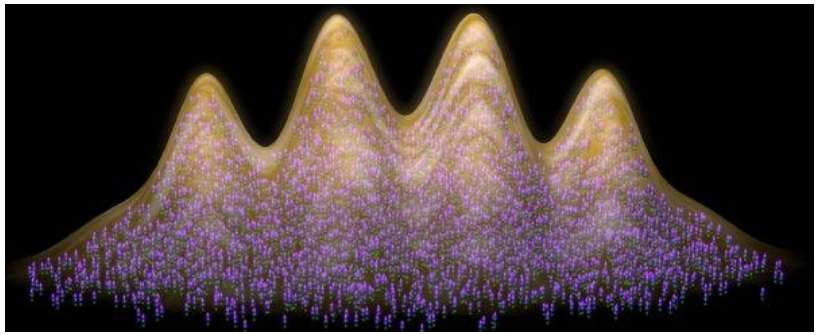
ETH, Tübingen, Stanford

Spin-orbit-coupled BECs



JQI, MIT, ICFO

Dipolar gases

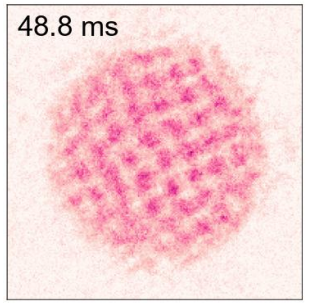


Pisa, Innsbruck, Stuttgart, Hong Kong/ Rice, Heidelberg

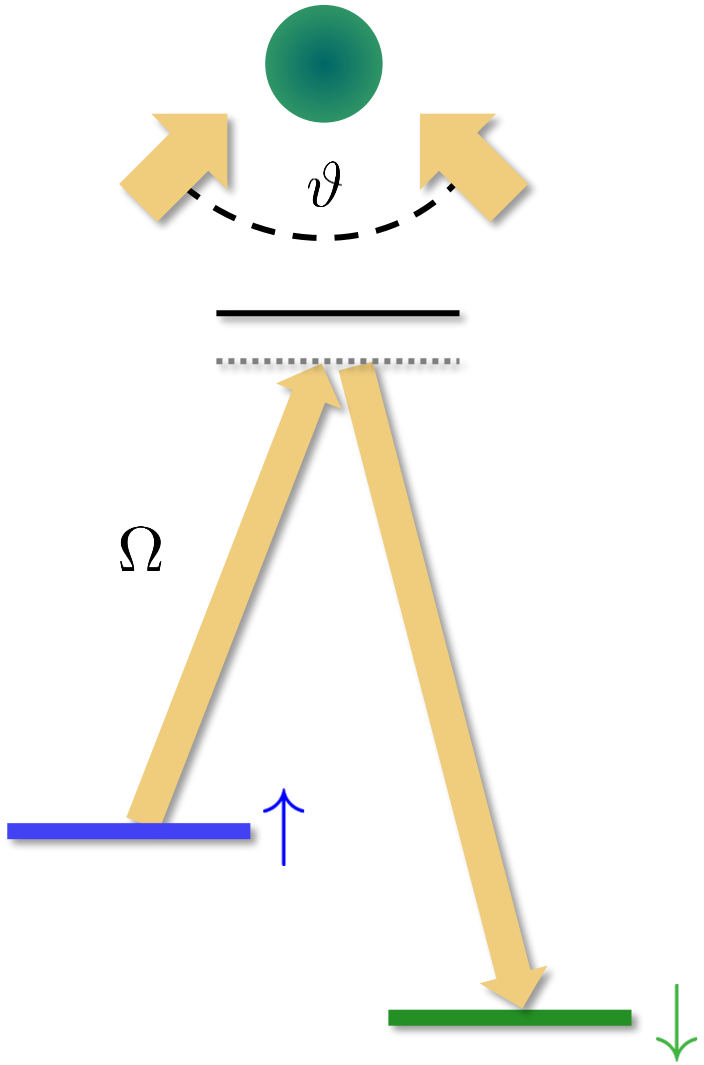
Crystalline structure and phase coherence

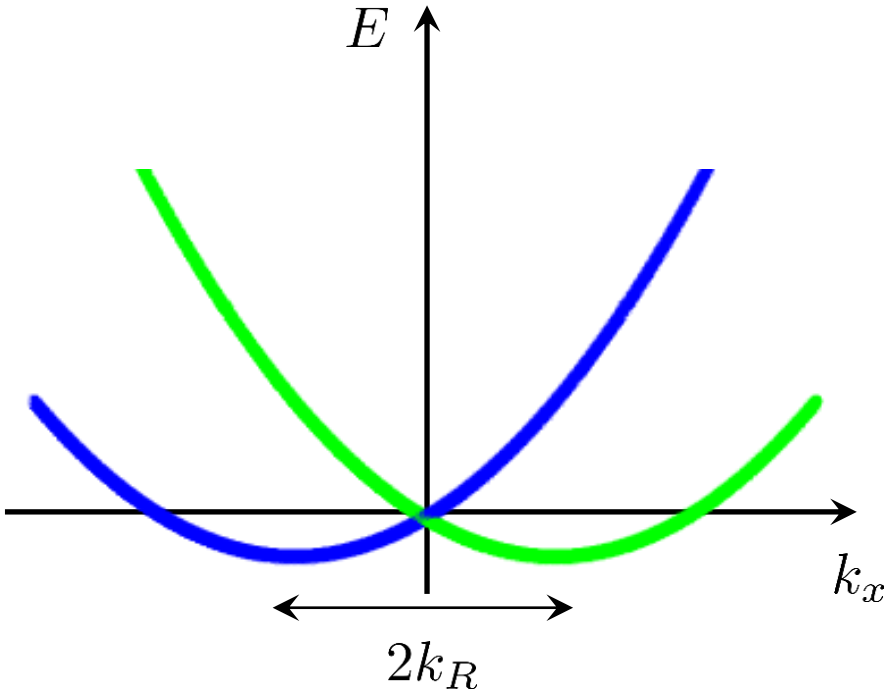
+ supersolid-like behavior in driven BECs

Heidelberg



Spin-orbit-coupled Bose-Einstein condensates



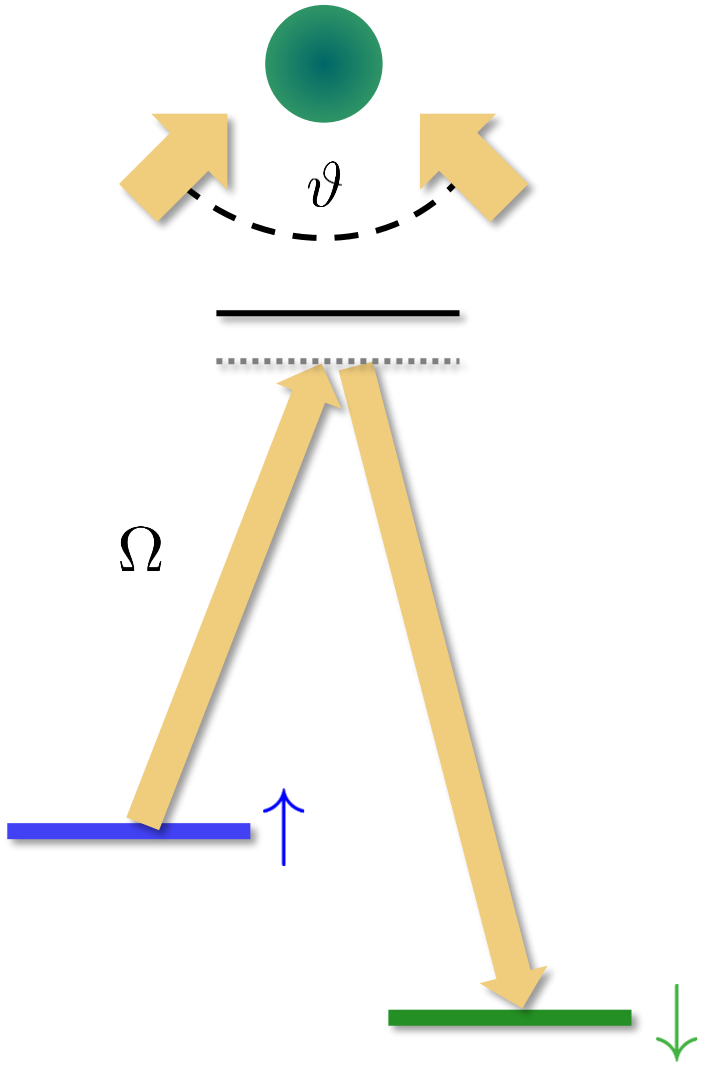


$$k_R = 2\pi \sin(\vartheta/2)/\lambda_R$$

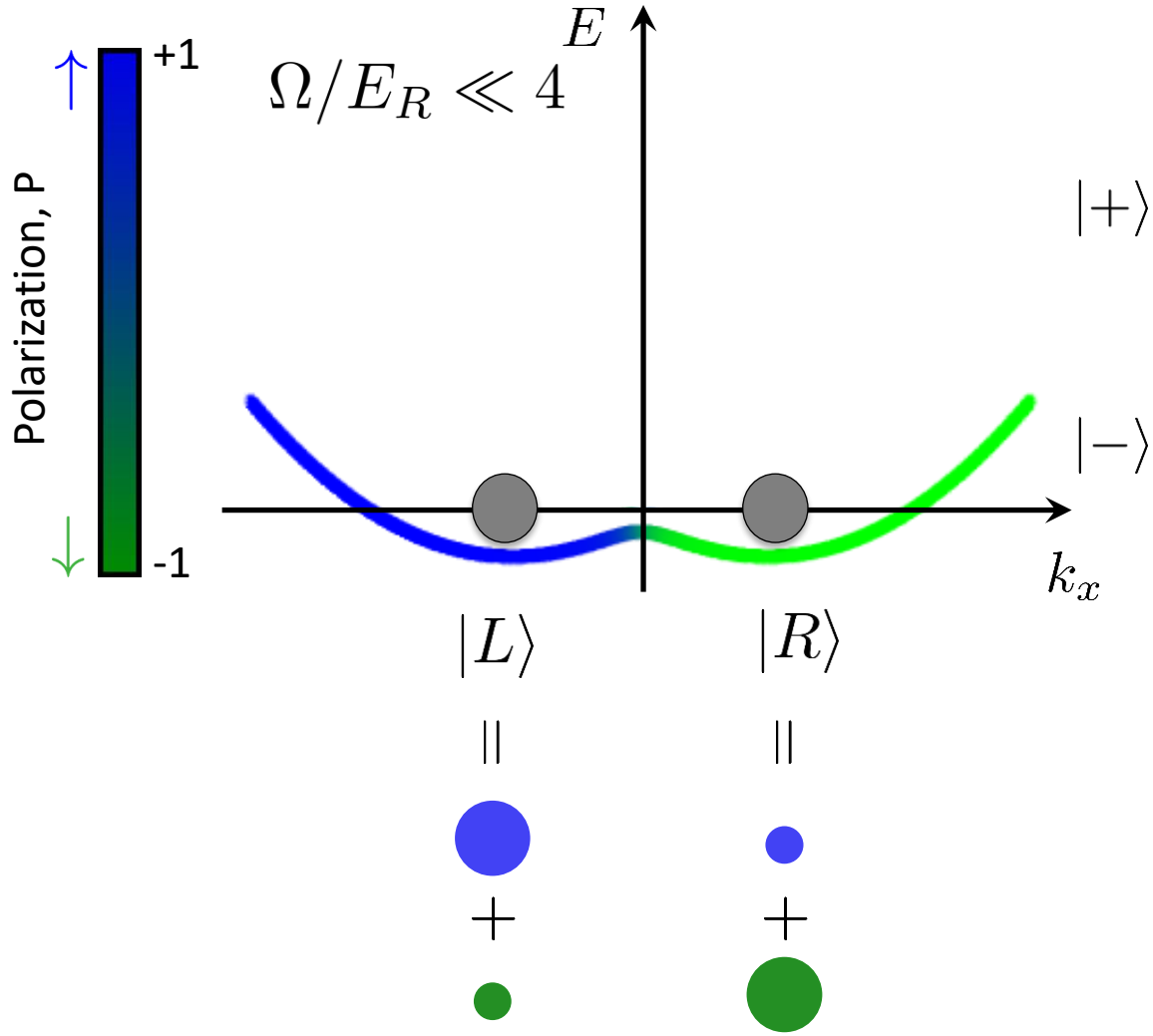
$$E_R = \hbar^2 k_R^2/2m$$

JQI, USTC, Shanxi, MIT, WSU, HKUST, Taipei, Wuhan, ICFO…

Spin-orbit-coupled Bose-Einstein condensates



JQI, USTC, Shanxi, MIT, WSU, HKUST, Taipei, Wuhan, ICFO…



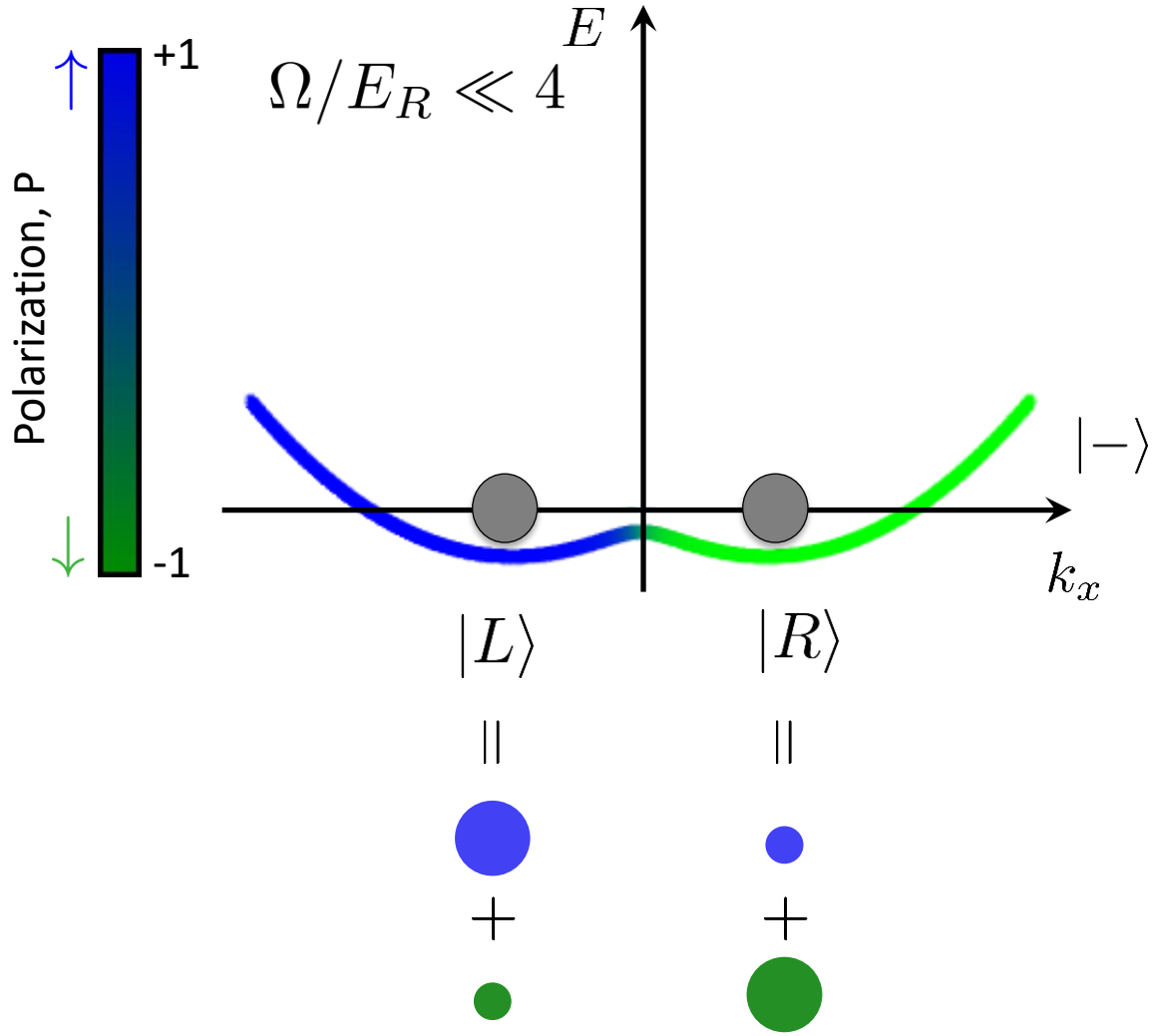
J. Higbie and D. M. Stamper-Kurn
Phys. Rev. A **69** 053605 (2004)

Spin-orbit-coupled Bose-Einstein condensates

Supersolid!

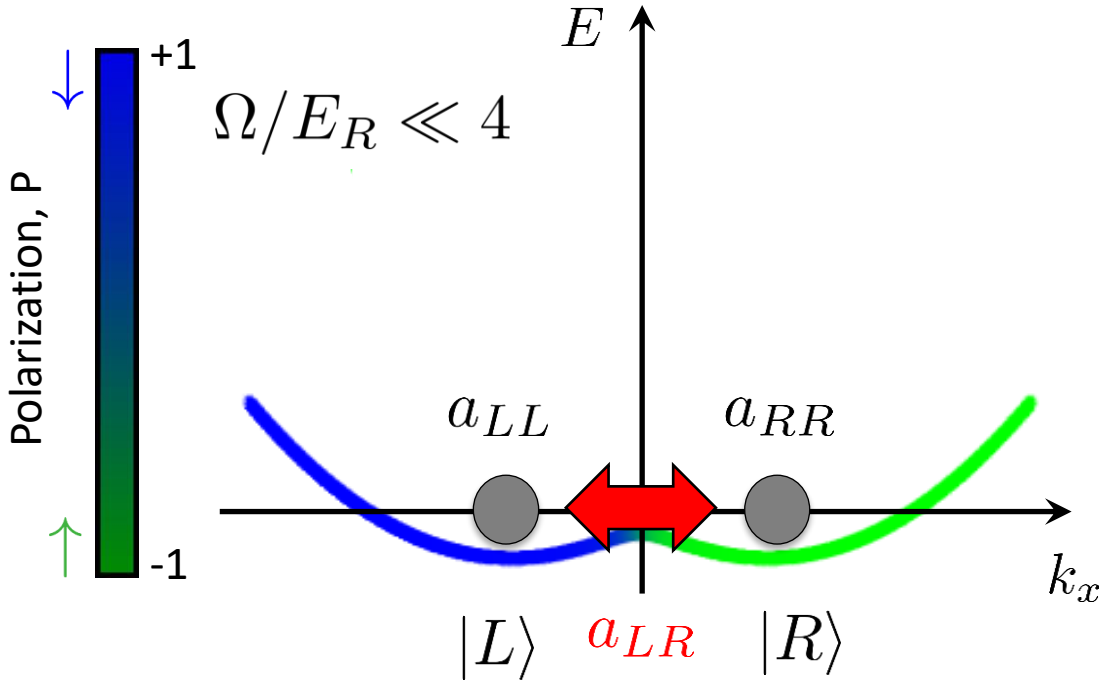
Density stripes

Theory: Ohio, Beijing, Trento
Experiments: JQI, MIT



J. Higbie and D. M. Stamper-Kurn
Phys. Rev. A **69** 053605 (2004)

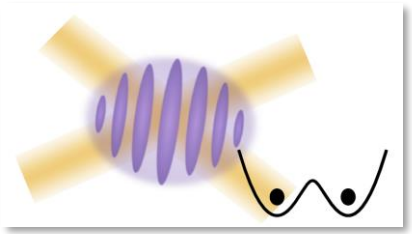
Where do the atoms condense?



Depends on dressed-state interactions

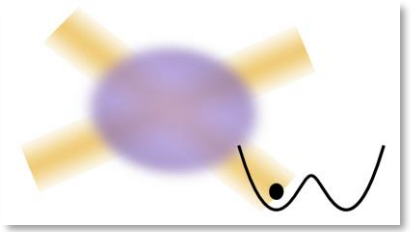
Supersolid-stripe phase

$$a_{LR}^2 < a_{LL}a_{RR}$$

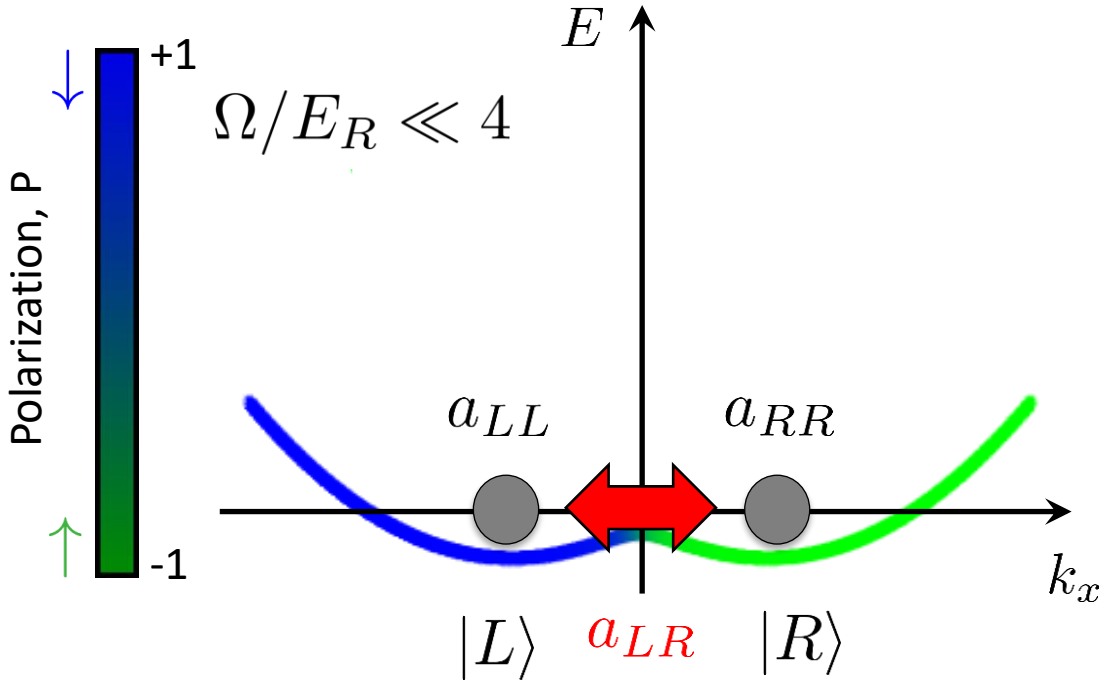


Plane-wave phase

$$a_{LR}^2 > a_{LL}a_{RR}$$

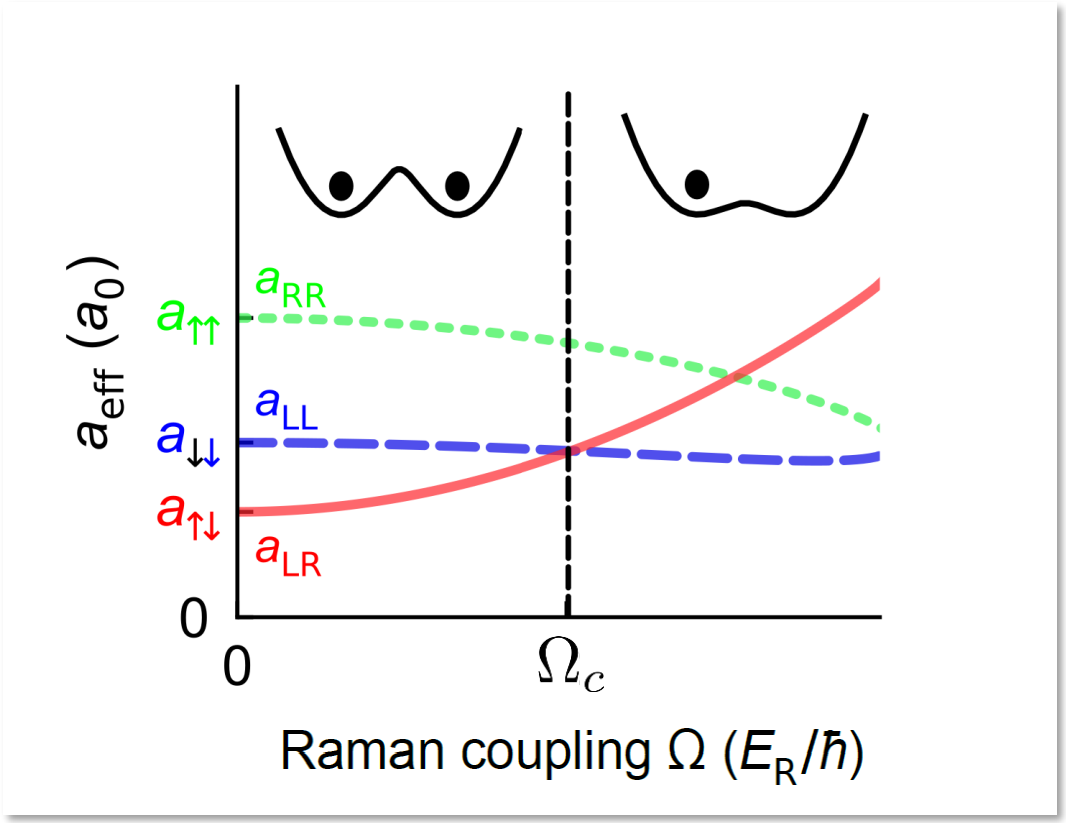


Effective interactions in spin-orbit-coupled BECs



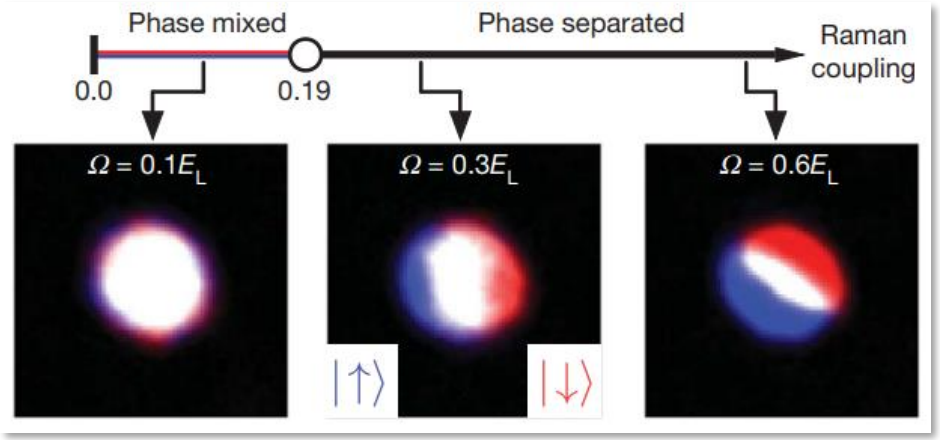
$$(g_{LL}, g_{RR}, g_{LR}) \neq (g_{\uparrow\uparrow}, g_{\downarrow\downarrow}, g_{\uparrow\downarrow})$$

Effective interactions given by polarization at the minima

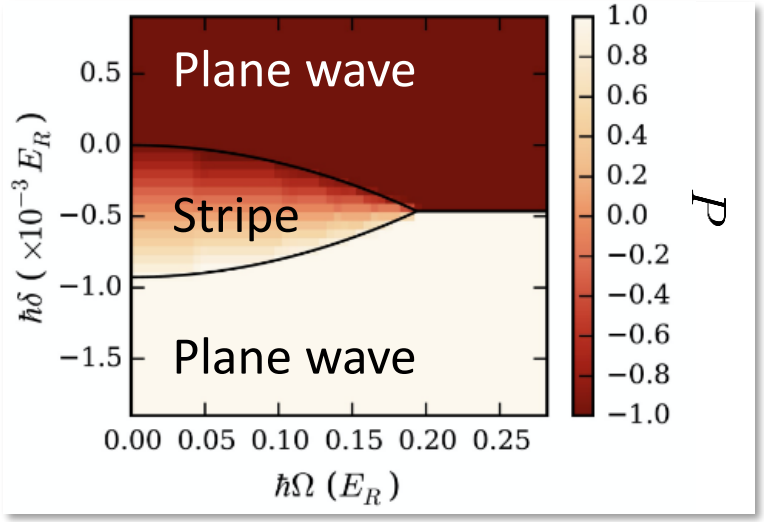


Miscibility controlled by Raman coupling Ω

Previous experiments with ^{87}Rb



Y. J. Lin *et al.*, *Nature* **471**, 83 (2011)



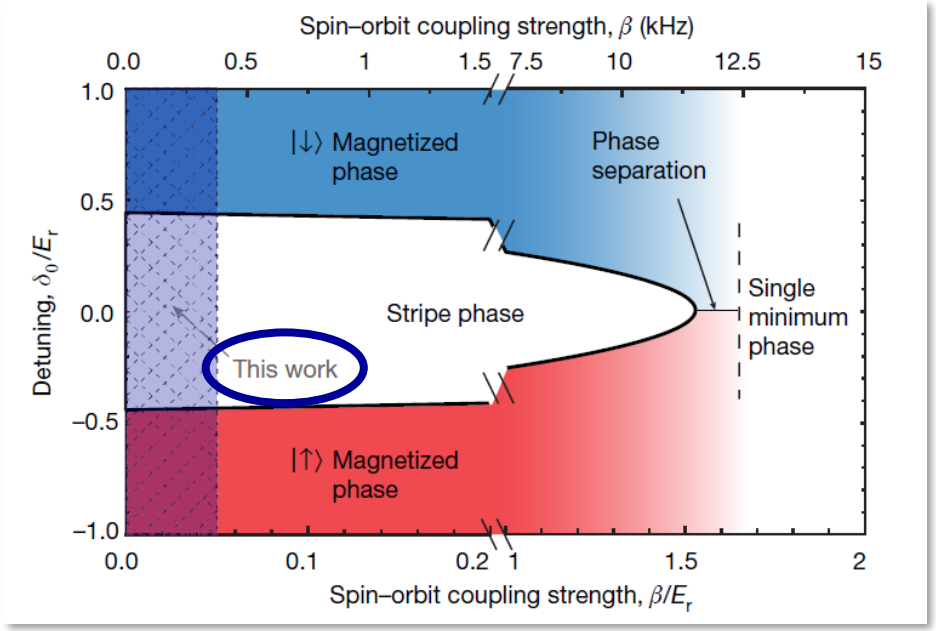
A. Putra, PhD thesis. University of Maryland (2018)
Theory as in Y. Li *et al.*, *Phys. Rev. Lett.* **108**, 225301 (2012)

Two major challenges:

- Very fragile supersolid-stripe phase ($a_{\uparrow\uparrow} \sim a_{\downarrow\downarrow} \sim a_{\uparrow\downarrow}$ and plane-wave phase dominates)
- Very small modulation contrast ($C \propto \Omega$ <5%)

How to make the stripe phase more stable?

MIT strategy: replace atomic spins by pseudospins (orbitals of a double-well lattice)

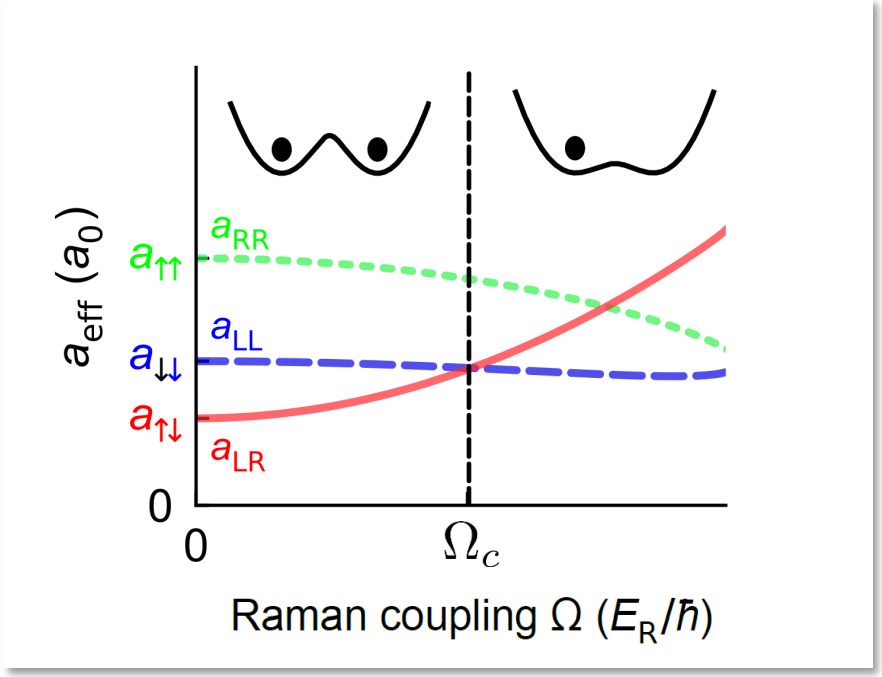


J.-R. Li *et al.*, *Nature* **543**, 91 (2017)

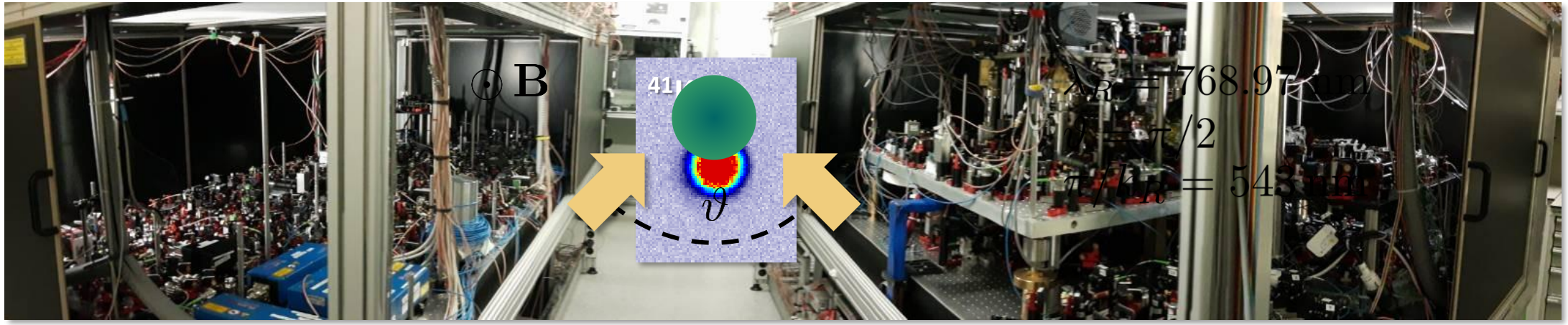
Enlarged phase diagram

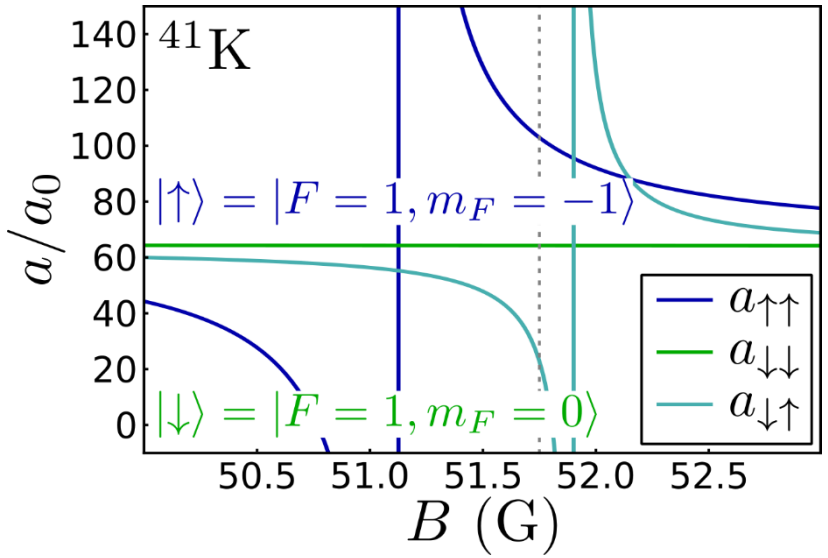
Still limited to small Ω (Floquet heating)

Our strategy: Reduce interspin interactions $a_{\uparrow\downarrow}$ with a Feshbach resonance



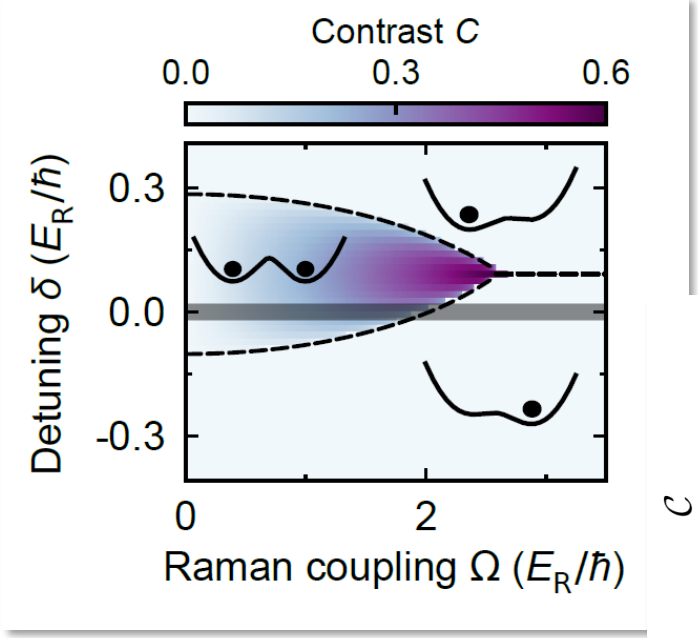
Potassium spin-orbit-coupled condensates

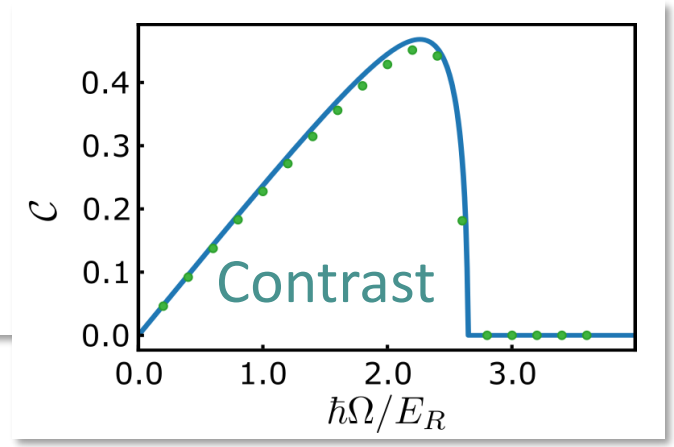




L. Tanzi *et al., Phys. Rev. A* **98**, 062712 (2018)

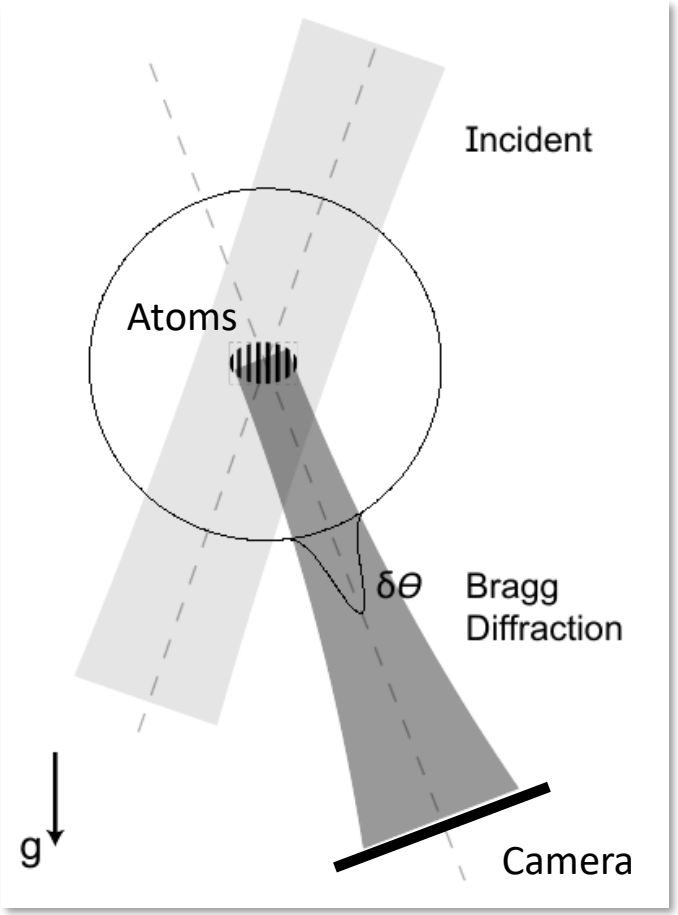
$(a_{\uparrow\uparrow}, a_{\downarrow\downarrow}, a_{\uparrow\downarrow}) = (115 \pm 10, 65 \pm 1, 40 \pm 8)\, a_0$



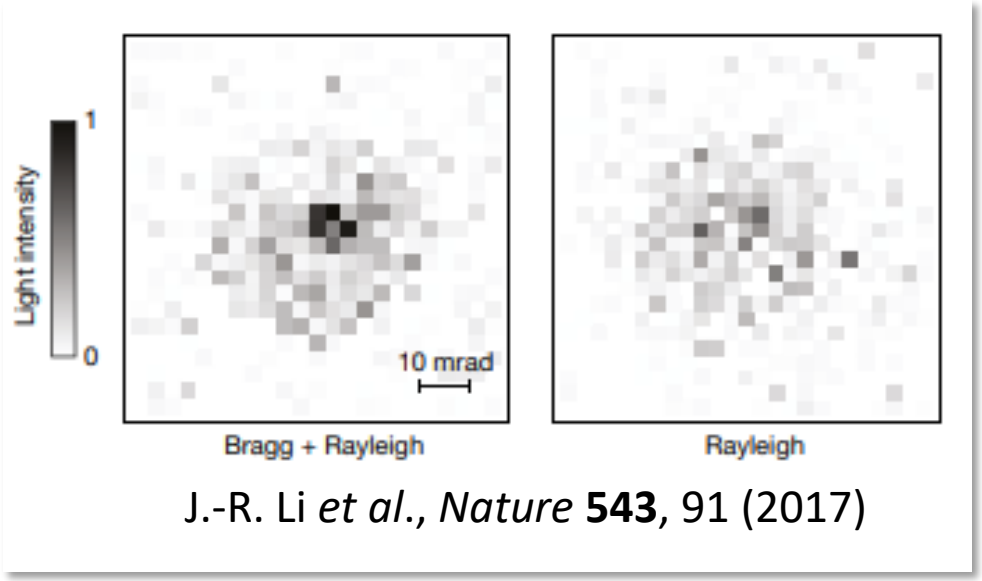


Detecting stripes below the imaging resolution

Previous experiments: Bragg scattering of light



J.-R. Li, PhD thesis, MIT (2019)



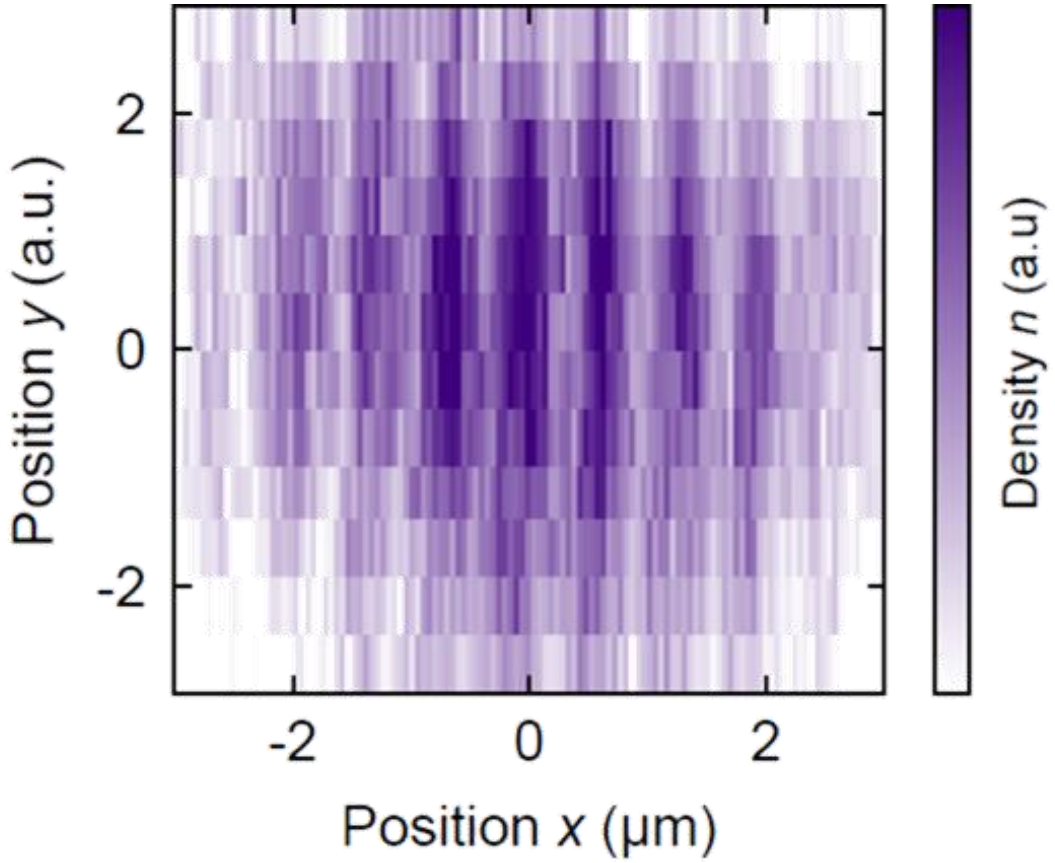
J.-R. Li *et al.*, *Nature* **543**, 91 (2017)

See also:
A. Putra *et al.*, *Phys. Rev. Lett.* **124**, 053605 (2020)

Our trick: use matter-wave optics to magnify the spatial distribution

L. Asteria *et al.*, *Nature* **599**, 571 (2021)

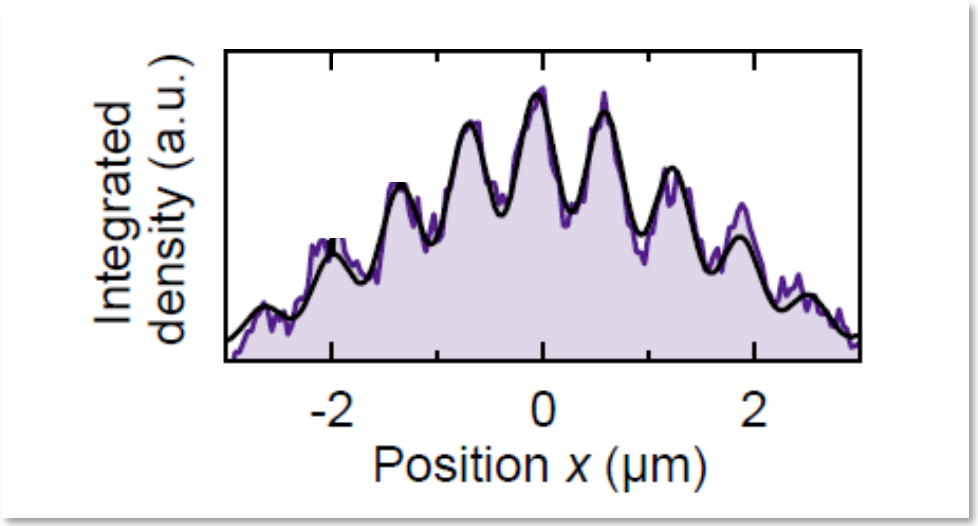
In situ observation of the supersolid-stripe phase



Imaging magnification x25

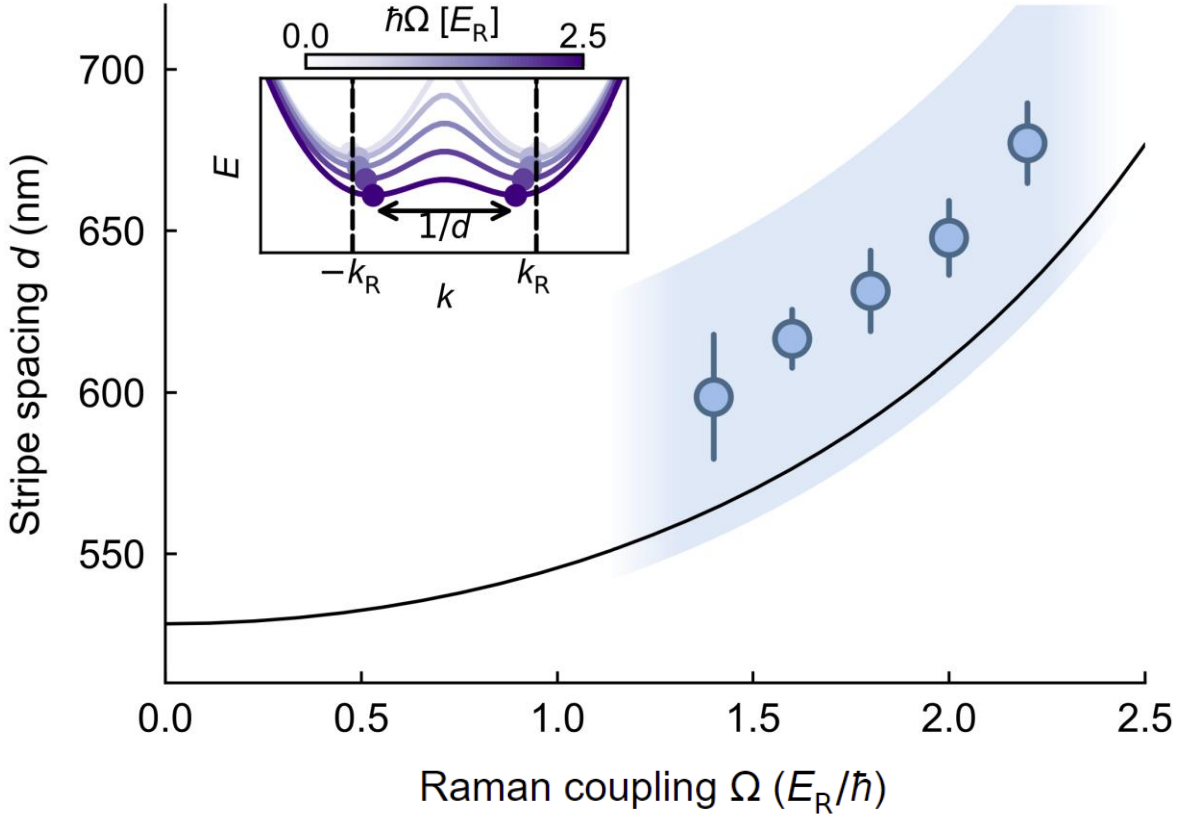
C. S. Chisholm*, S. Hirthe*, V. B. Makhalov*, R. Ramos*, R. Vatré*, J. Cabedo, A. Celi, and L. Tarruell, *Science* **391**, 480 (2026)

Measuring the crystal period



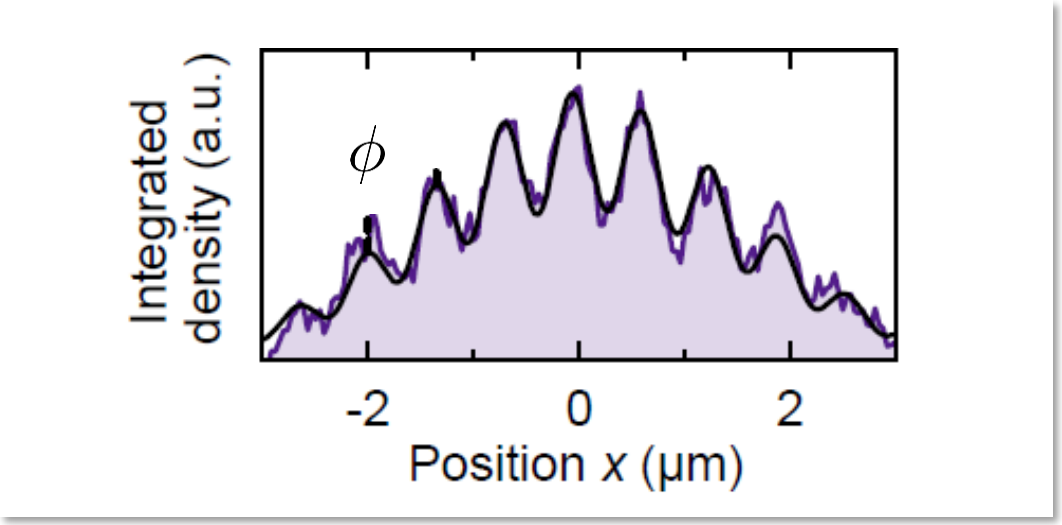
Crystal period not fixed by the Raman laser wavelength

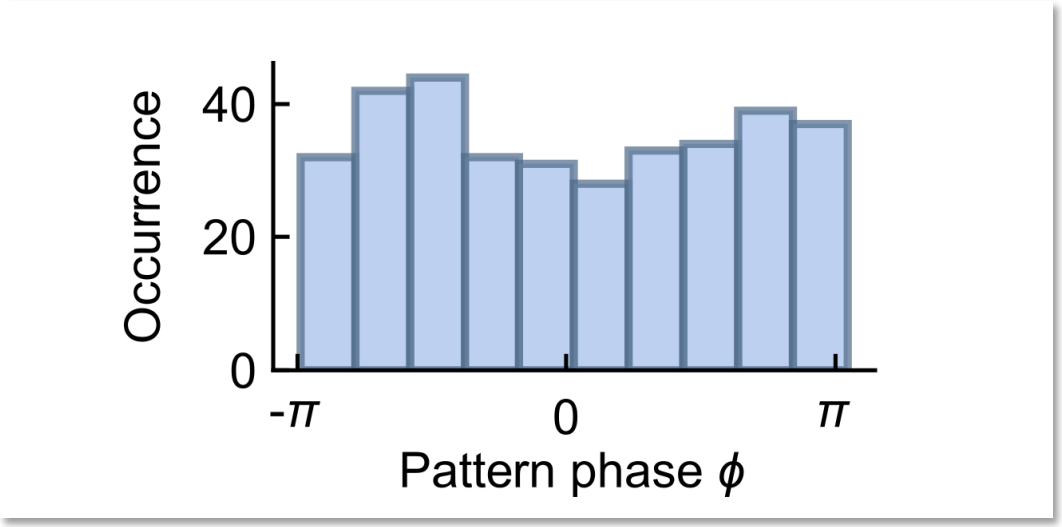
Tunable crystal period!



C. S. Chisholm*, S. Hirthe*, V. B. Makhalov*, R. Ramos*, R. Vatré*, J. Cabedo, A. Celi, and L. Tarruell, *Science* **391**, 480 (2026)

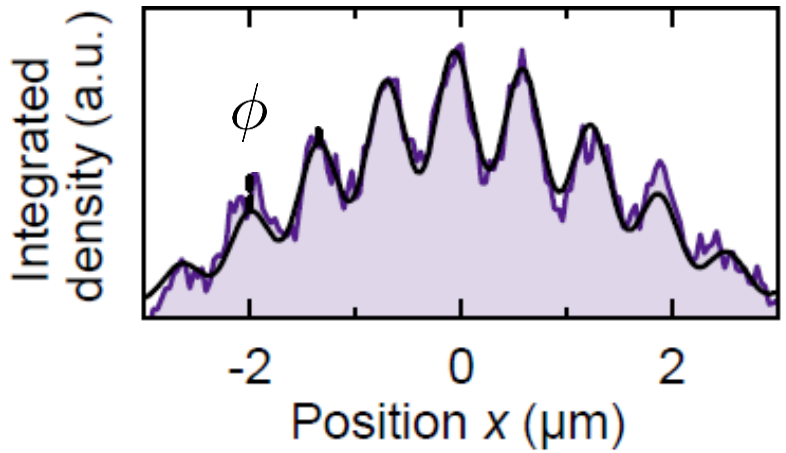
Spontaneous symmetry breaking

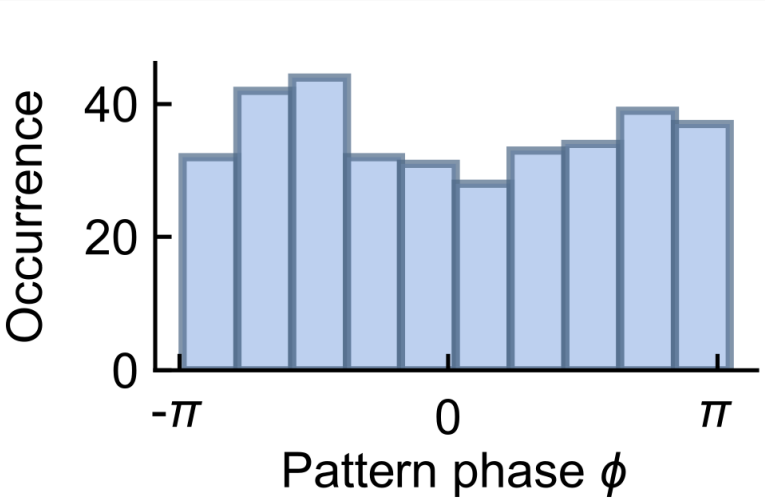




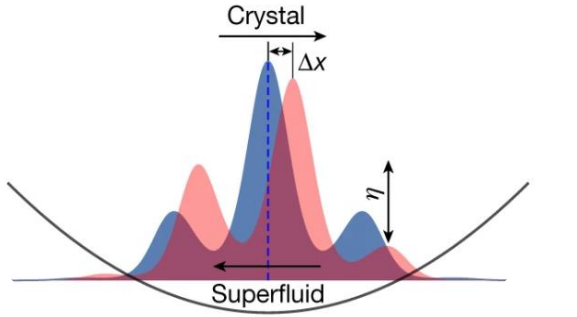
Random position of the stripe pattern

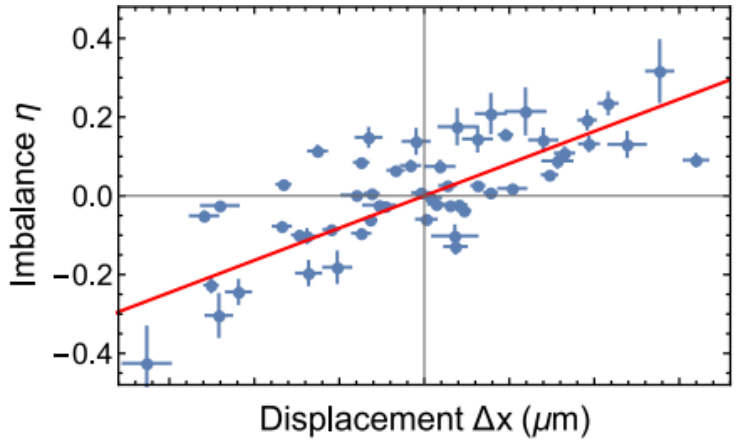
Crystal Goldstone mode





Dipolar supersolids





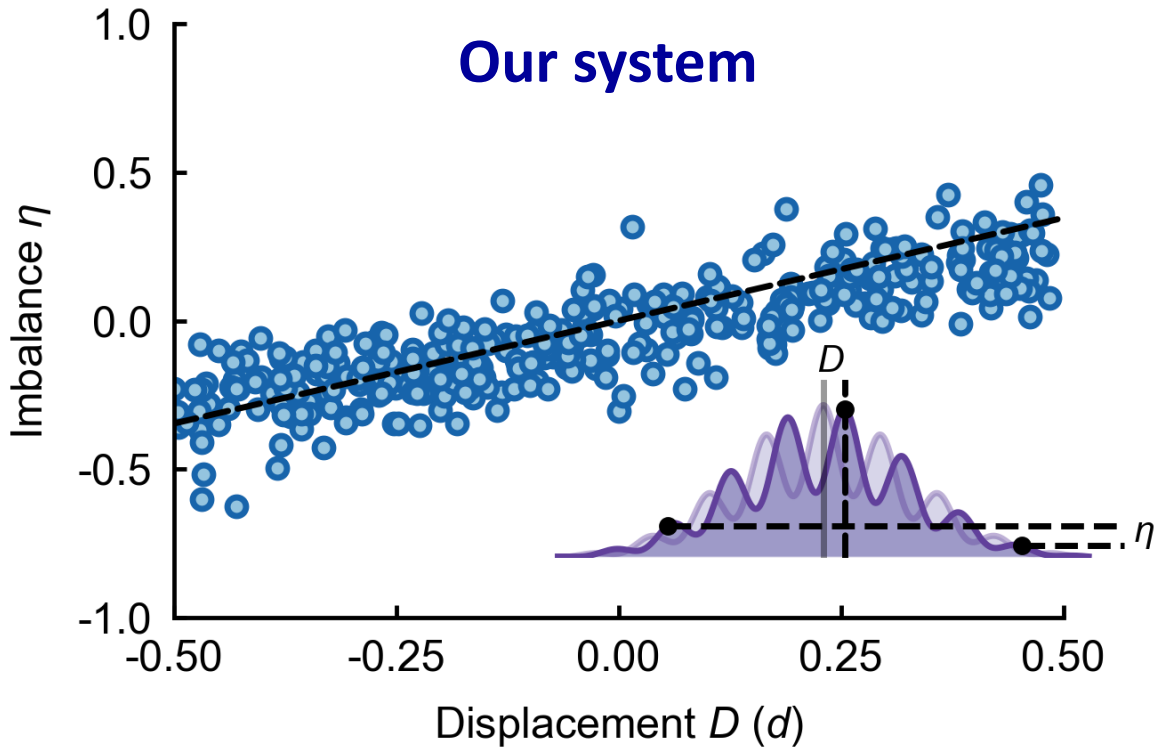
M. Guo *et al.*, *Nature* **574**, 386 (2019)

Random position of the stripe pattern

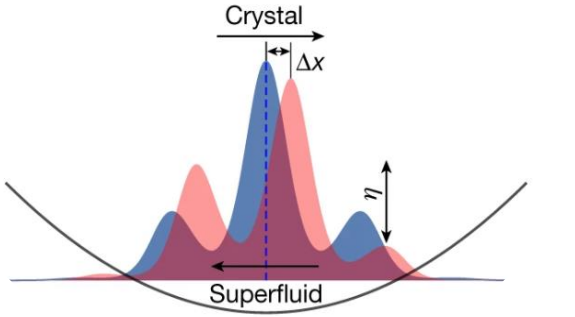
Crystal Goldstone mode

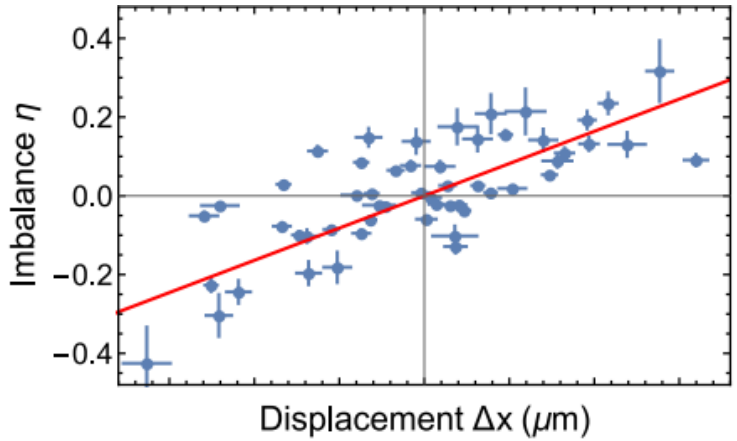
Sliding of the stripe pattern accompanied by particle flow

Our system



Dipolar supersolids



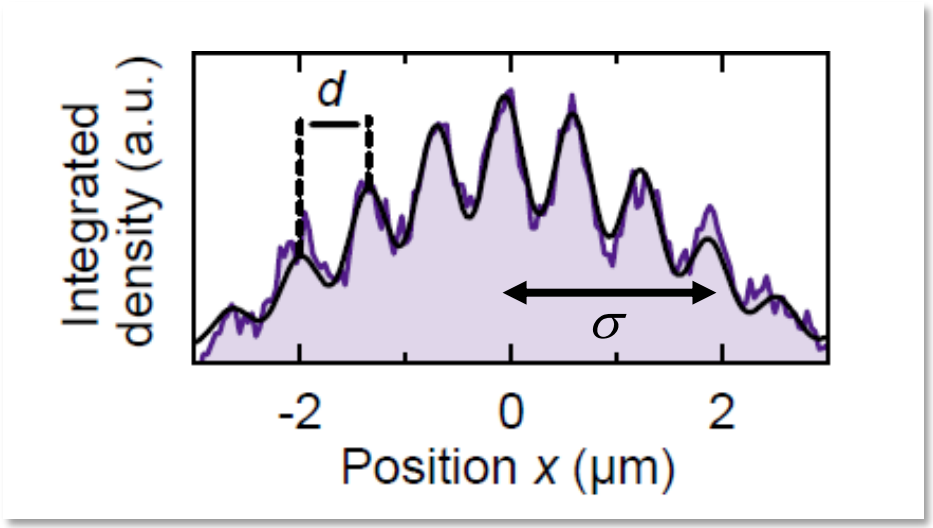


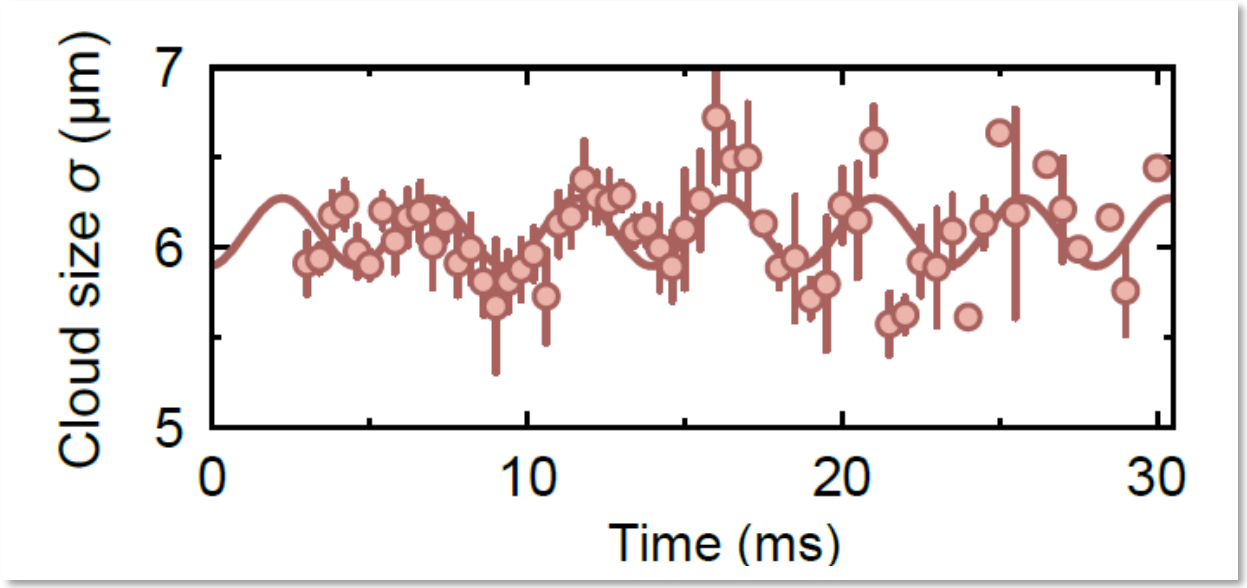
M. Guo *et al.*, *Nature* **574**, 386 (2019)

C. S. Chisholm*, S. Hirthe*, V. B. Makhalov*, R. Ramos*, R. Vatré*, J. Cabedo, A. Celi, and L. Tarruell, *Science* **391**, 480 (2026)

Superfluid breathing mode

Response to compression





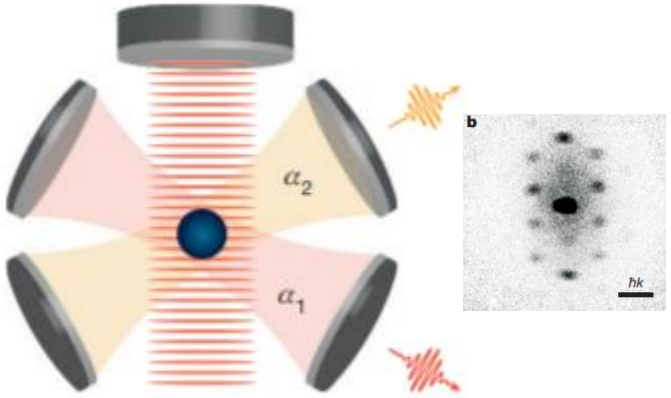
Measured breathing mode frequency indicates **superfluidity**

$$\omega_{\mathrm{B}} = 1.5(1)\omega_{\mathrm{D}} \simeq \sqrt{5/2}\omega_{\mathrm{D}}$$

C. S. Chisholm*, S. Hirthe*, V. B. Makhalov*, R. Ramos*, R. Vatré*, J. Cabedo, A. Celi, and L. Tarruell, *Science* **391**, 480 (2026)

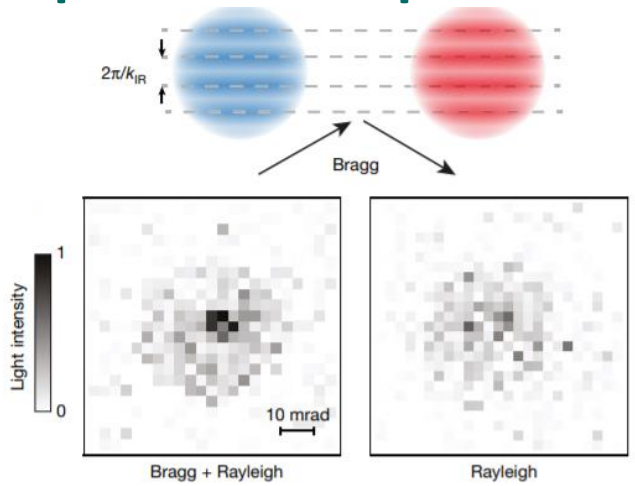
Supersolid phases in Bose-Einstein condensates

Cavity systems



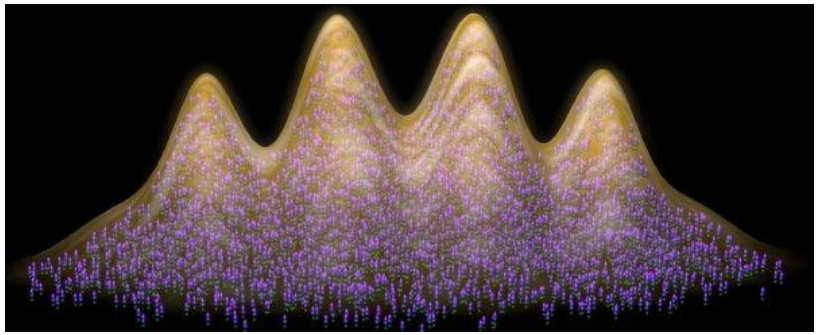
ETH, Tübingen, Stanford

Spin-orbit coupled BECs



JQI, MIT, ICFO

Dipolar gases



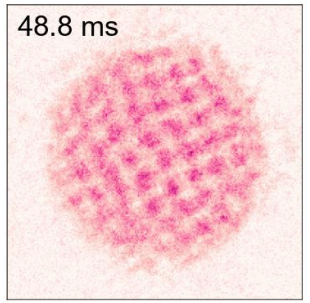
Pisa, Innsbruck, Stuttgart, Hong Kong/ Rice, Heidelberg

Crystalline structure and phase coherence

Do these systems host crystal compression modes (phonons)?

+ supersolid-like behavior in driven BECs

Heidelberg



Do spin-orbit coupled systems have phonons?

ICFO

Many experimentalists thought no…

context of ultracold atoms. The coexistence of phase coherence and density modulation has been reported in Bose-Einstein condensates (BECs) in optical cavities [6] and in the presence of synthetic spin-orbit coupling [7]. The modulation in these systems is, however, infinitely stiff since it is externally imposed.

L. Tanzi *et al.*, *Phys. Rev. Lett.* **122**, 130405 (2019)

provides far greater opportunity for control and observation. This new perspective has enabled supersolid properties to be observed in systems with spin–orbit coupling[33] or long-range cavity-mediated interactions[34], though in these cases the crystalline structure is externally imposed, yielding a state with a rigid lattice, and hence no phononic excitations. In contrast, dipolar quantum gases of highly magnetic

M. Norcia *et al.*, *Nature* **596**, 357 (2021)

cavity, and others use lasers to induce a spin–orbit coupling.[2] The result in both cases is the spontaneous emergence of a periodic crystal structure and properties of a supersolid, such as characteristic excitations and coherence. But the corresponding crystals have an infinitely stiff structure fixed by the external laser field. The atoms are thus always localized at the same distance from one another and only behave in that way because of an external influence. Both properties are funda-

T. Langen, *Physics Today* **75**, 36 (2022)

Theorists said yes…

PHYSICAL REVIEW LETTERS **130,** 156001 (2023)

Dynamics of Stripe Patterns in Supersolid Spin-Orbit-Coupled Bose Gases

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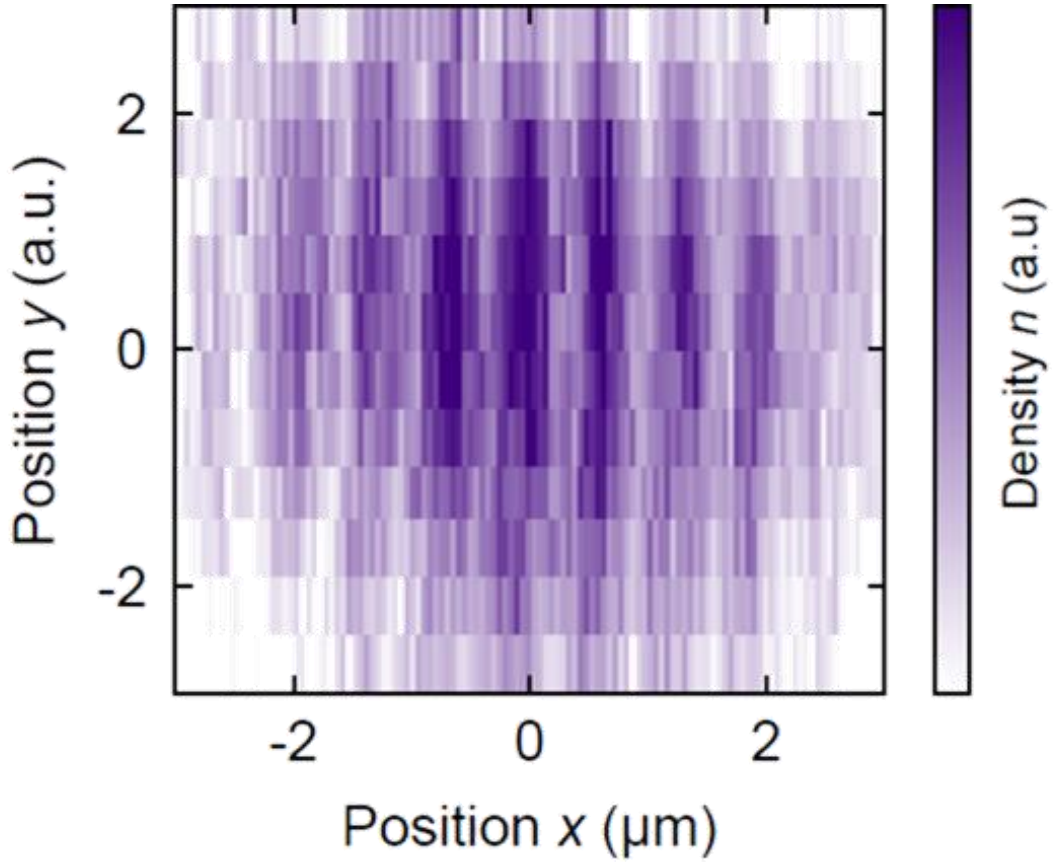
Despite ground-breaking observations of supersolidity in spin-orbit-coupled Bose-Einstein condensates, until now the dynamics of the emerging spatially periodic density modulations has been vastly unexplored. Here, we demonstrate the nonrigidity of the density stripes in such a supersolid condensate and explore

See also L. Chen *et al.*, *Phys. Rev. A* **95**, 033616 (2017);
K. T. Geier *et al.*, *Phys. Rev. Lett.* **127**, 115301 (2021);
G. I. Martone and S. Stringari, *SciPost Physics* **11**, 092 (2021)

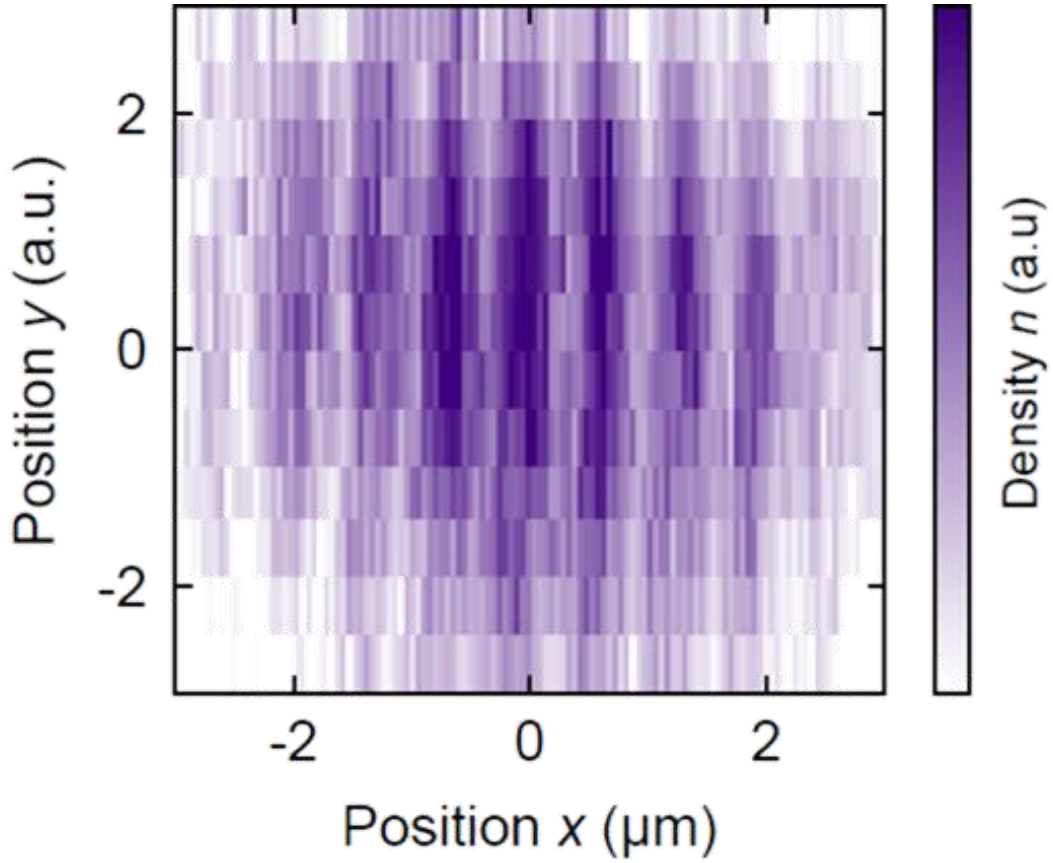
Many discussions at ICAP 2022 (Toronto)

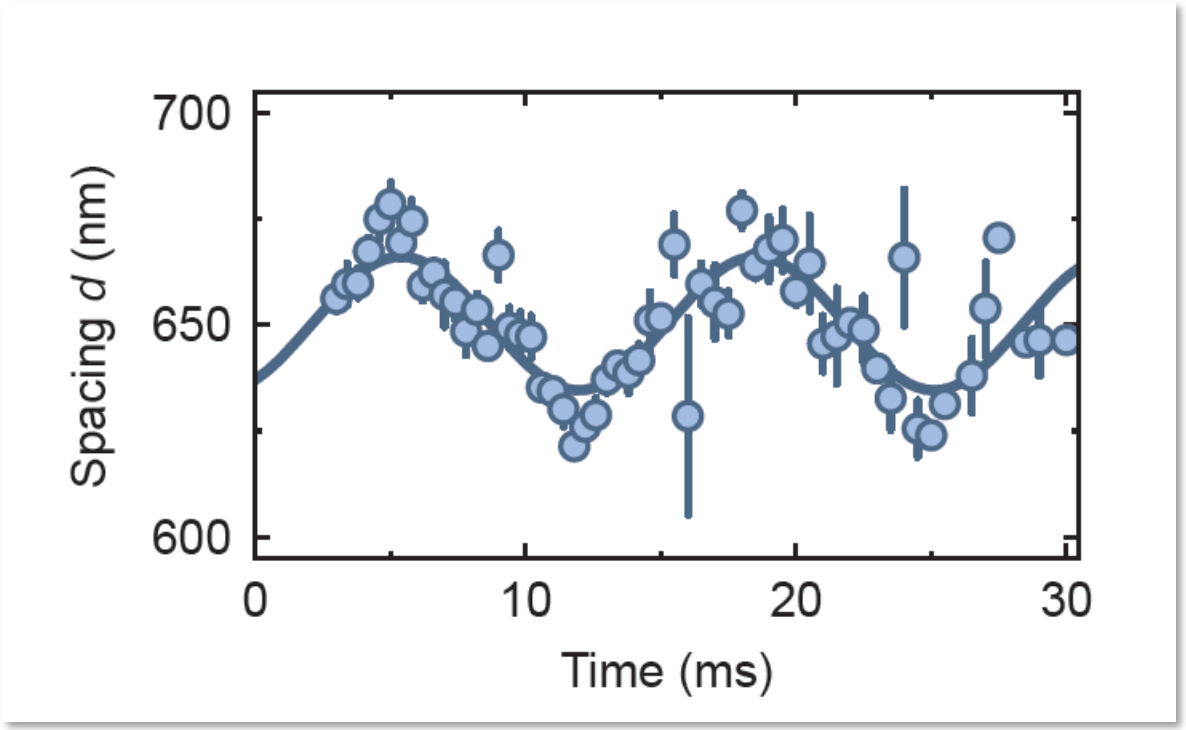
In situ observation of the supersolid-stripe phase

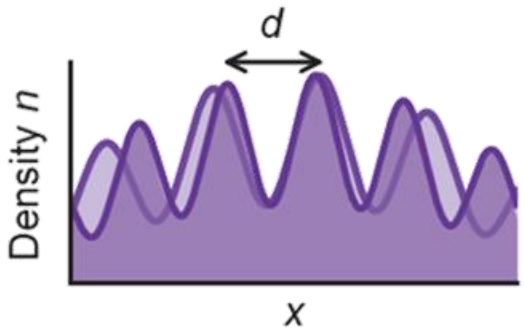


C. S. Chisholm*, S. Hirthe*, V. B. Makhalov*, R. Ramos*, R. Vatré*, J. Cabedo, A. Celi, and L. Tarruell, *Science* **391**, 480 (2026)

Observation of a stripe compression mode



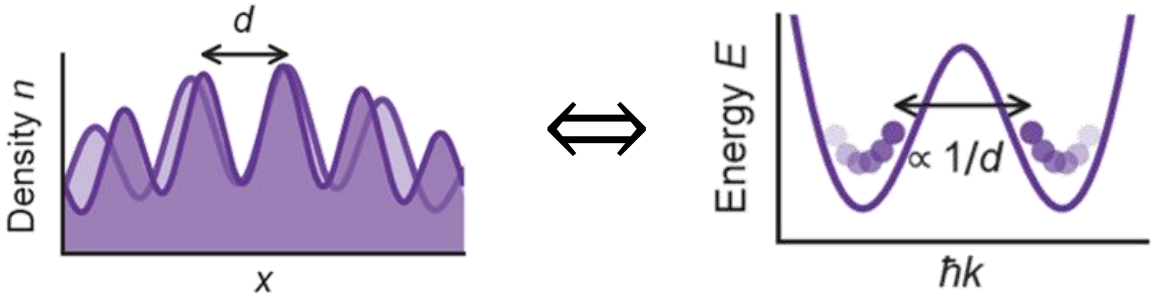




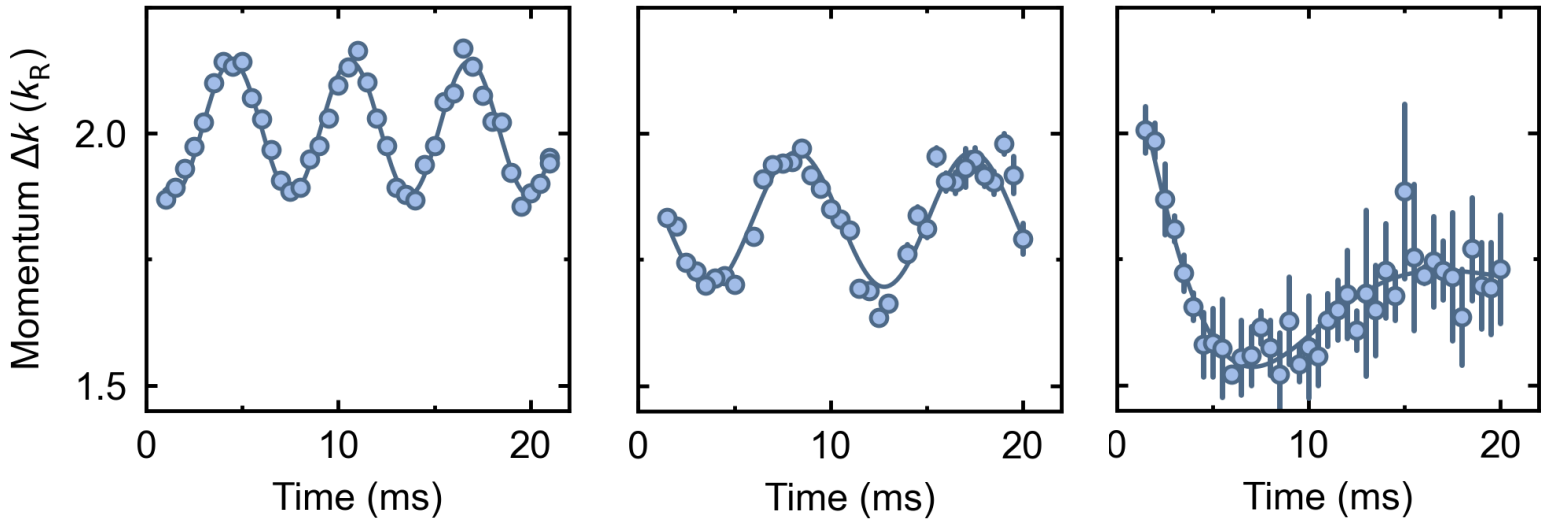
Phonons!

C. S. Chisholm*, S. Hirthe*, V. B. Makhalov*, R. Ramos*, R. Vatré*, J. Cabedo, A. Celi, and L. Tarruell, *Science* **391**, 480 (2026)

Measuring the mode frequency

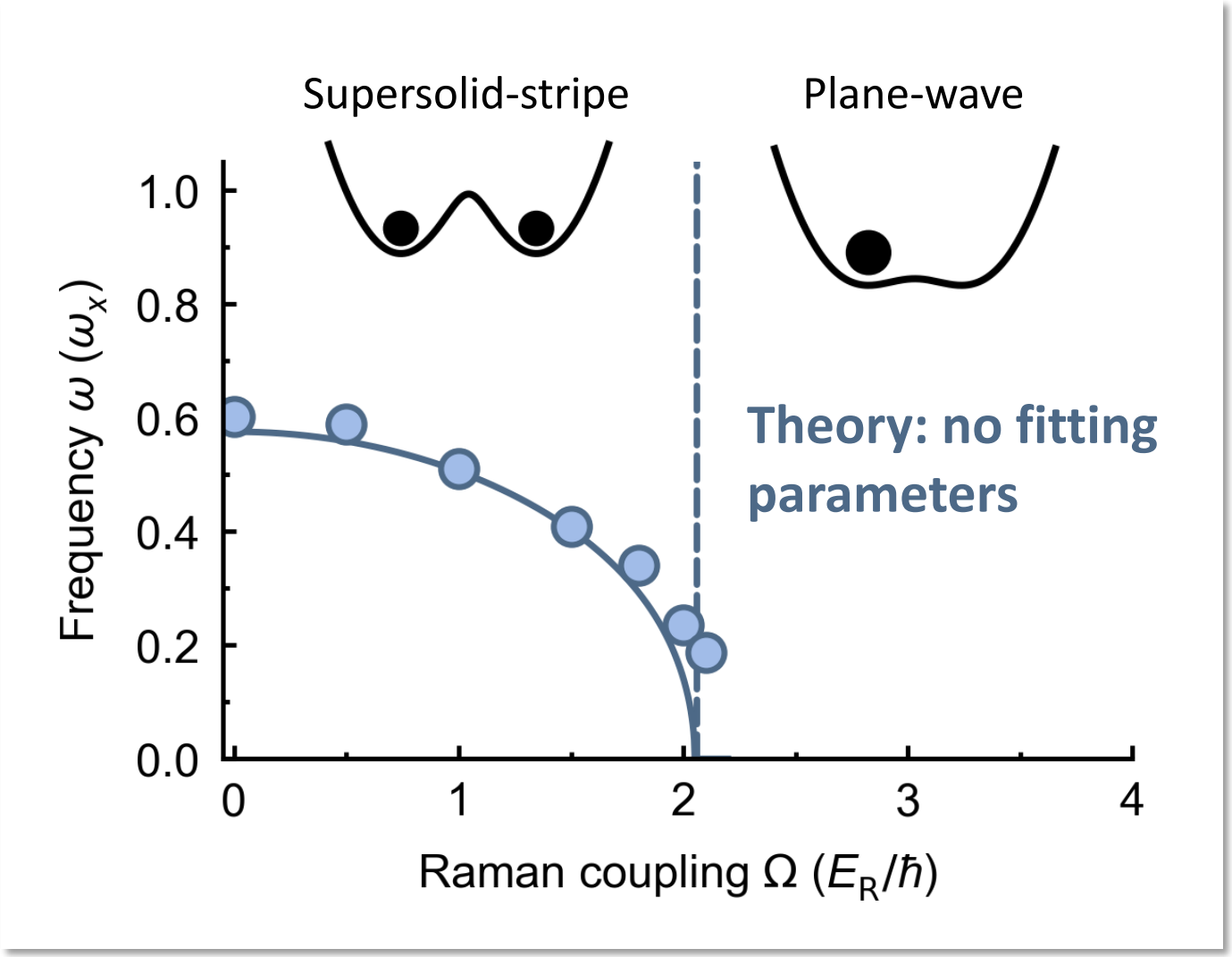


Crystal compression mode =
spin-dipole mode of dressed states



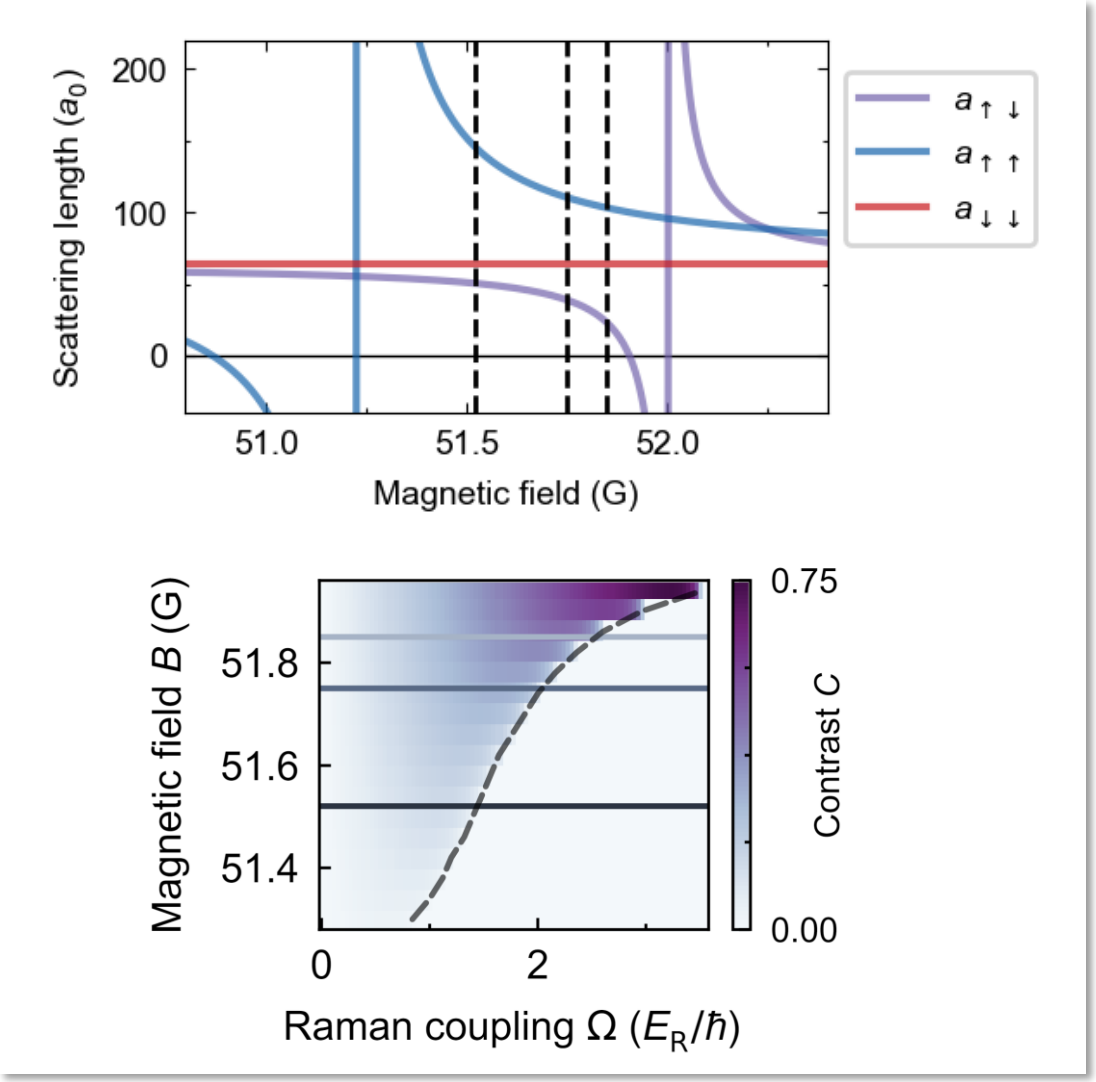
Increase Raman coupling Ω

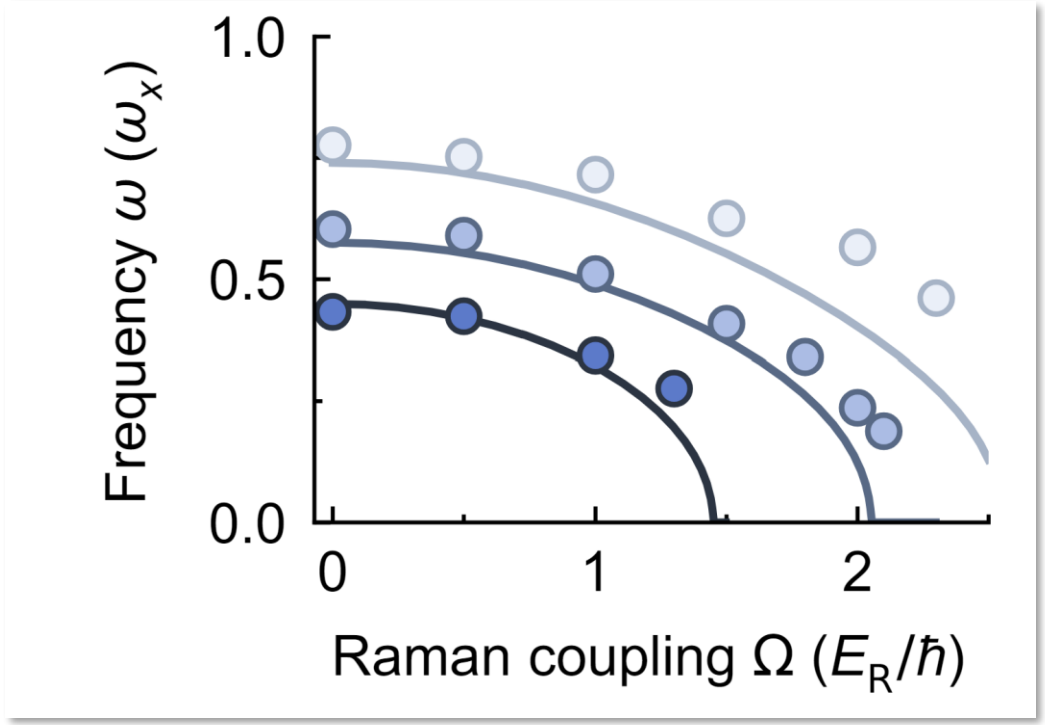
Probing mode softening at the phase transition



C. S. Chisholm*, S. Hirthe*, V. B. Makhalov*, R. Ramos*, R. Vatré*, J. Cabedo, A. Celi, and L. Tarruell, *Science* **391**, 480 (2026)

Tuning the phase transition point



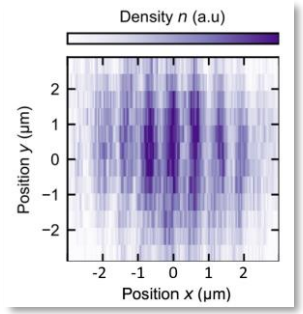


C. S. Chisholm*, S. Hirthe*, V. B. Makhalov*, R. Ramos*, R. Vatré*, J. Cabedo, A. Celi, and L. Tarruell, *Science* **391**, 480 (2026)

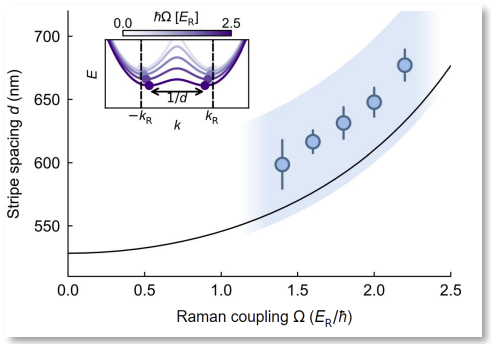
Summary and outlook

Robust supersolid-stripe phase in a spin-orbit-coupled ^{41}K BEC

In situ density modulation

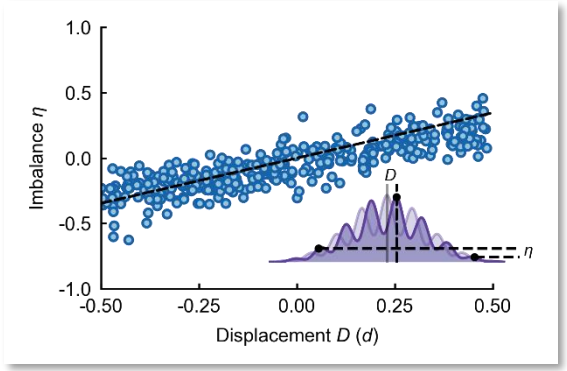


Tunable spacing

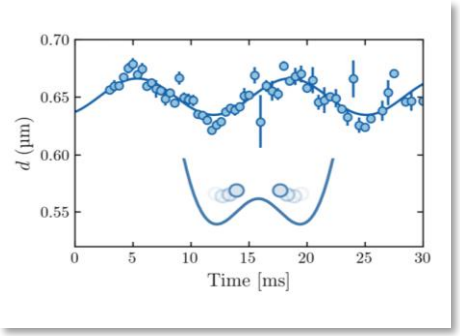


Probing supersolidity through excitations

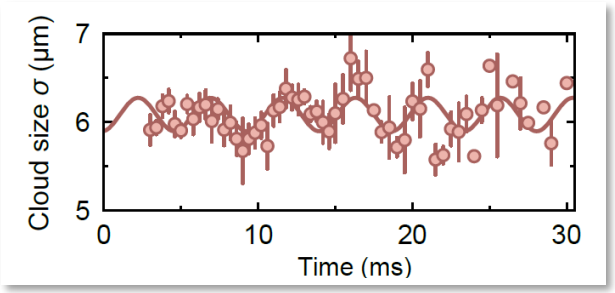
Goldstone mode



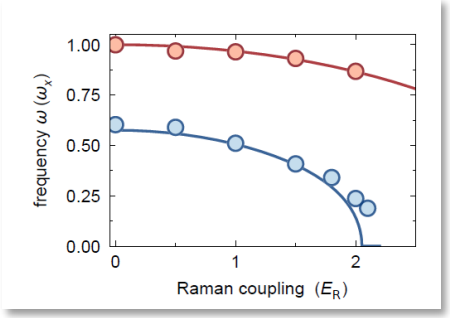
Crystal compression mode



Superfluidity



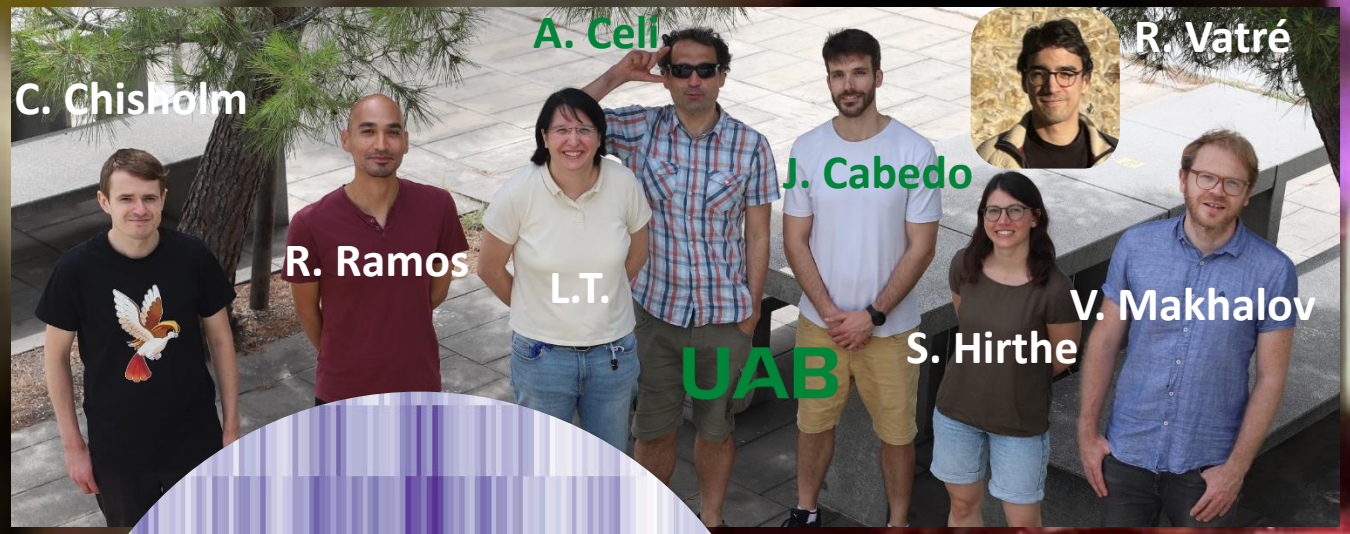
Mode softening

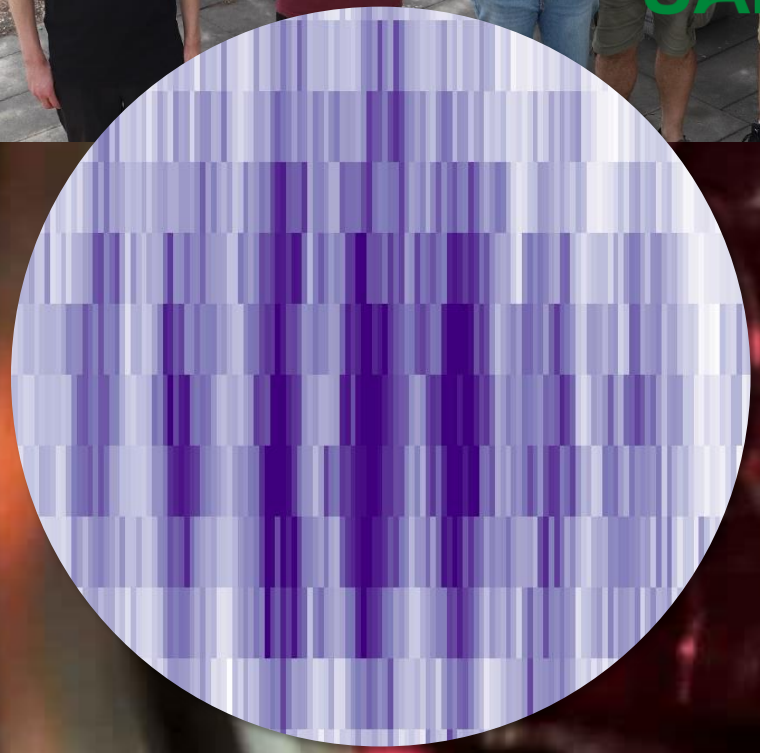


Next steps:

Investigation of other crystal modes, beyond mean-field effects (supersolid liquids)

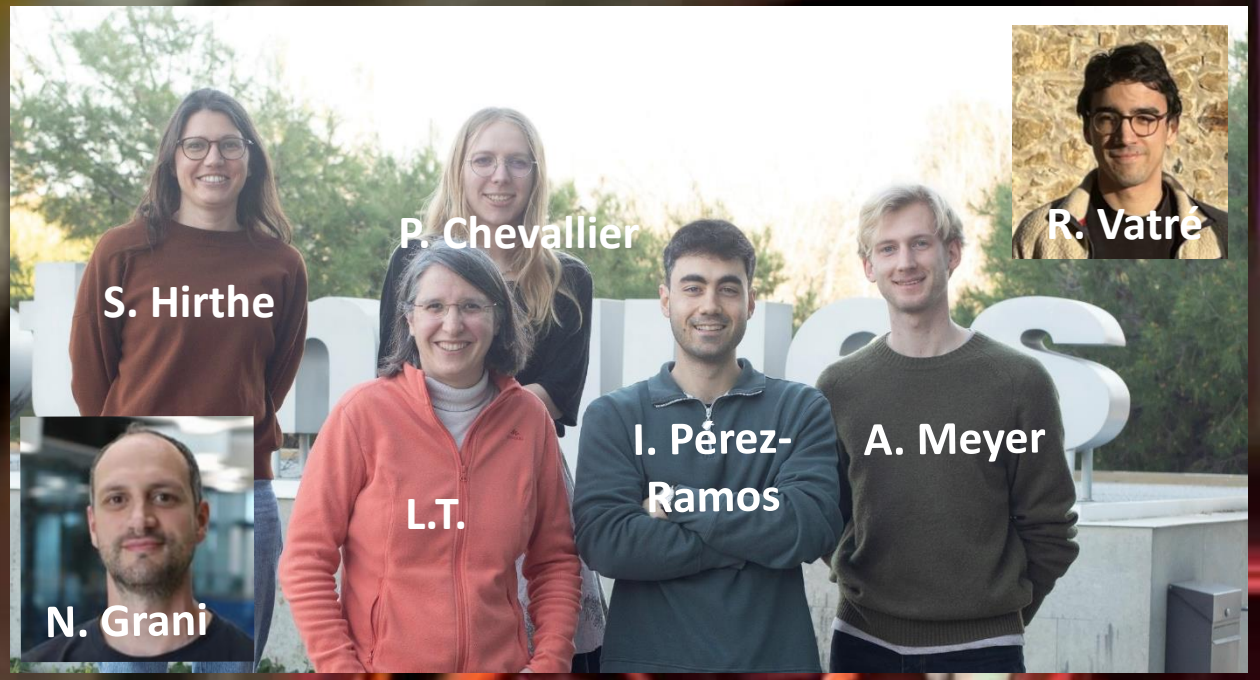
Interplay with external periodic potentials: bosonic Hofstadter ladders and 1D anyons





Probing supersolidity in a spin-orbit-coupled BEC

C. S. Chisholm*, S. Hirthe*, V. B. Makhalov*, R. Ramos*, R. Vatré*, J. Cabedo, A. Celi, and L. Tarruell, *Science* **391**, 480 (2026)

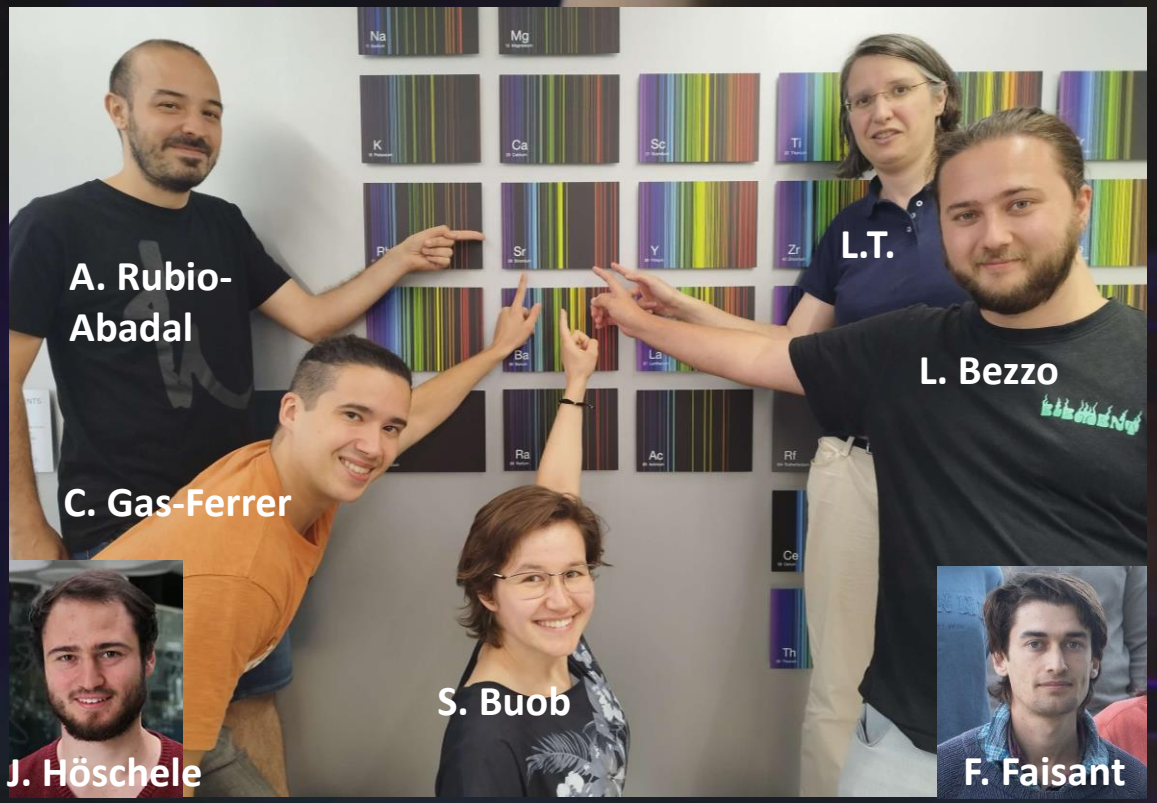


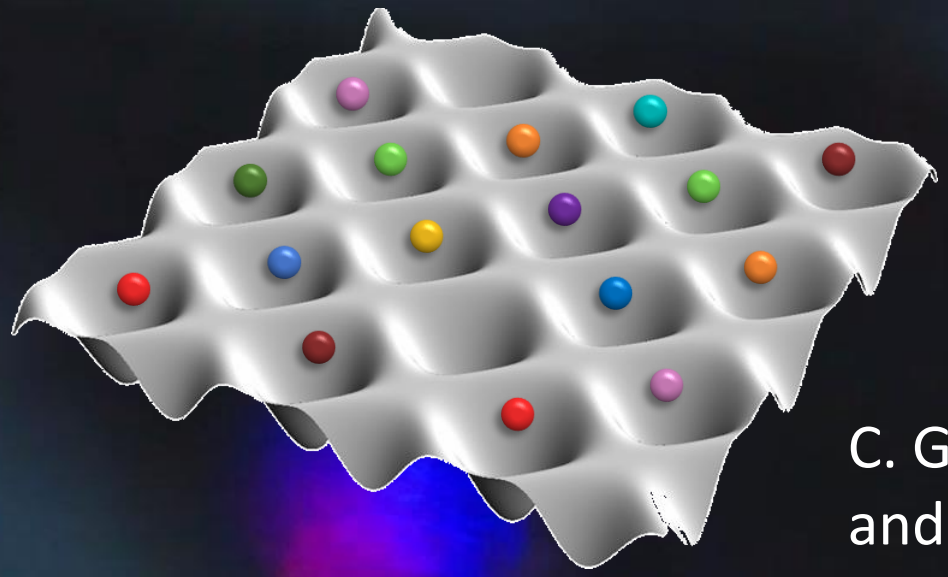
Potassium spin-orbit-coupling in a tunable-spacing optical lattice

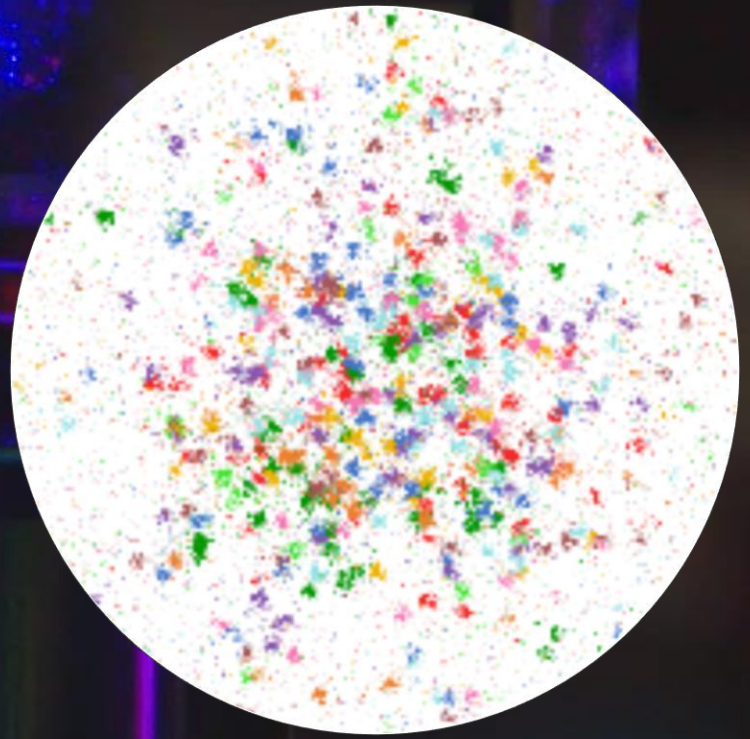
See A. Meyer’s poster tomorrow

Spin-resolved microscopy of an SU(10) Fermi-Hubbard system

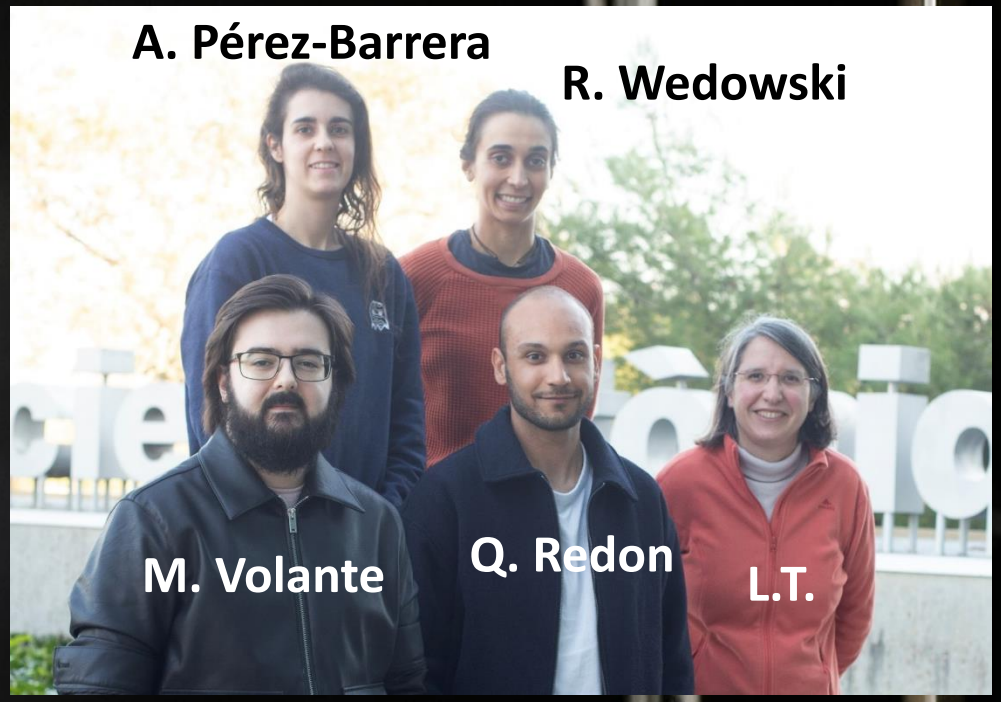
See C. Gas-Ferrer's poster tomorrow







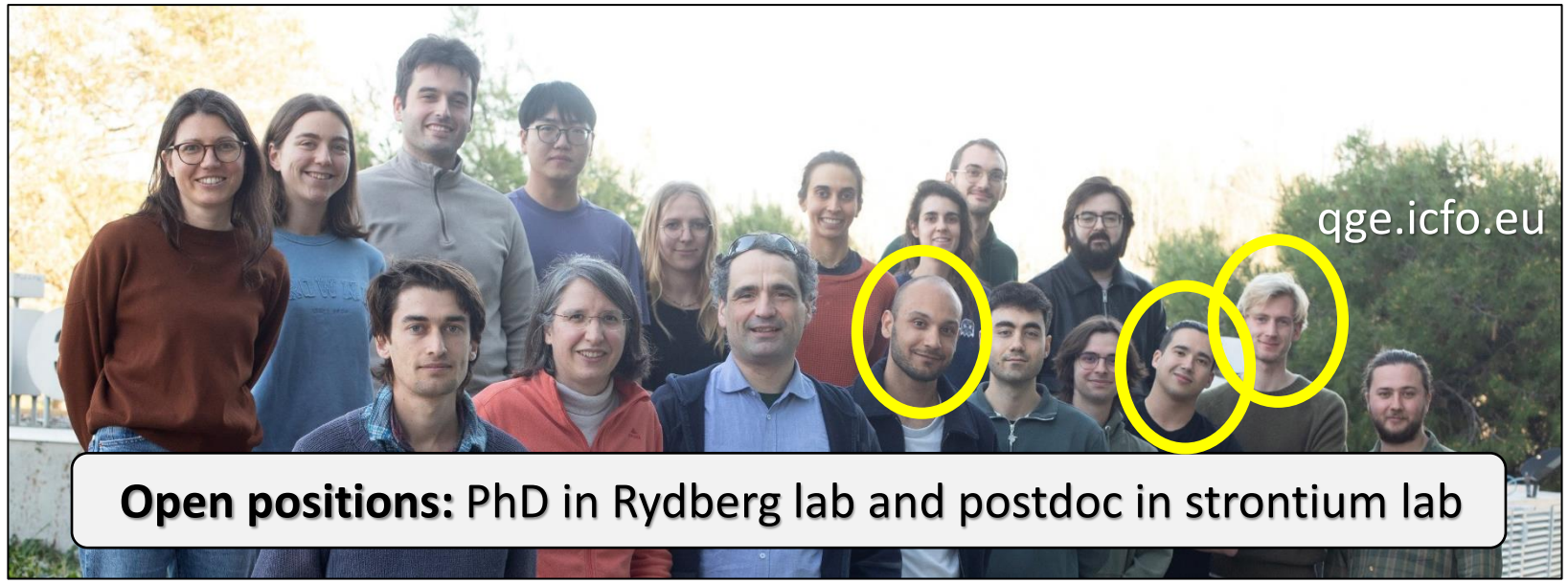
C. Gas-Ferrer*, A. Rubio-Abadal*, S. Buob, L. Bezzo, J. Höschele, and L. Tarruell, arXiv:2603.05478



A new Rydberg atom array platform for 2D lattice gauge theories

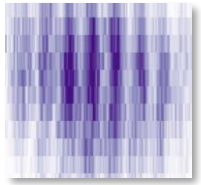
Discuss with Q. Redon (poster yesterday)

Thank you for your attention!

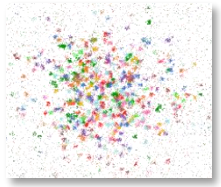


Open positions: PhD in Rydberg lab and postdoc in strontium lab

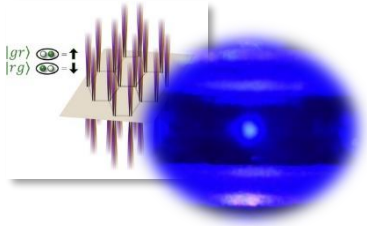
Potassium lab
Ignacio Pérez-Ramos
Andreas Meyer
Nicola Grani
Sarah Hirthe
Rémy Vatré → Paris Nord



Strontium lab
Carlos Gas-Ferrer
Leonardo Bezzo
Félix Faisant
Sandra Buob → IDEADED
Antonio Rubio-Abadal → UB



Rydberg lab
Ana Pérez-Barrera
Roxana Wedowski
Quentin Redon
Matías Volante



Theory (@UAB) - Alessio Celi
Claudio Iacovelli
Julia Bergmann
Marc Miranda-Riaza
Fengtao Pang
Josep Cabedo-Bru → Teaching
Pierpaolo Fontana

UAB

Former PhDs and postdocs: Jonatan Höschele (IDEADED), Vasiliy Makhalov (IGFAE), Craig Chisholm (OpenStar), Ramón Ramos (IDEADED), Anika Frölian (QuantumDiamonds), Elettra Neri (CareGlance), Cesar Cabrera (IGFAE), Julio Sanz (Quside), Bruno Naylor (teaching), Luca Tanzi (LENS), Pierrick Cheiney (exail)