Superfluidity and Quasicrystals with non-local interactions

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Universidade Federal do Rio Grande do Norte

Trento, 16 September 2019

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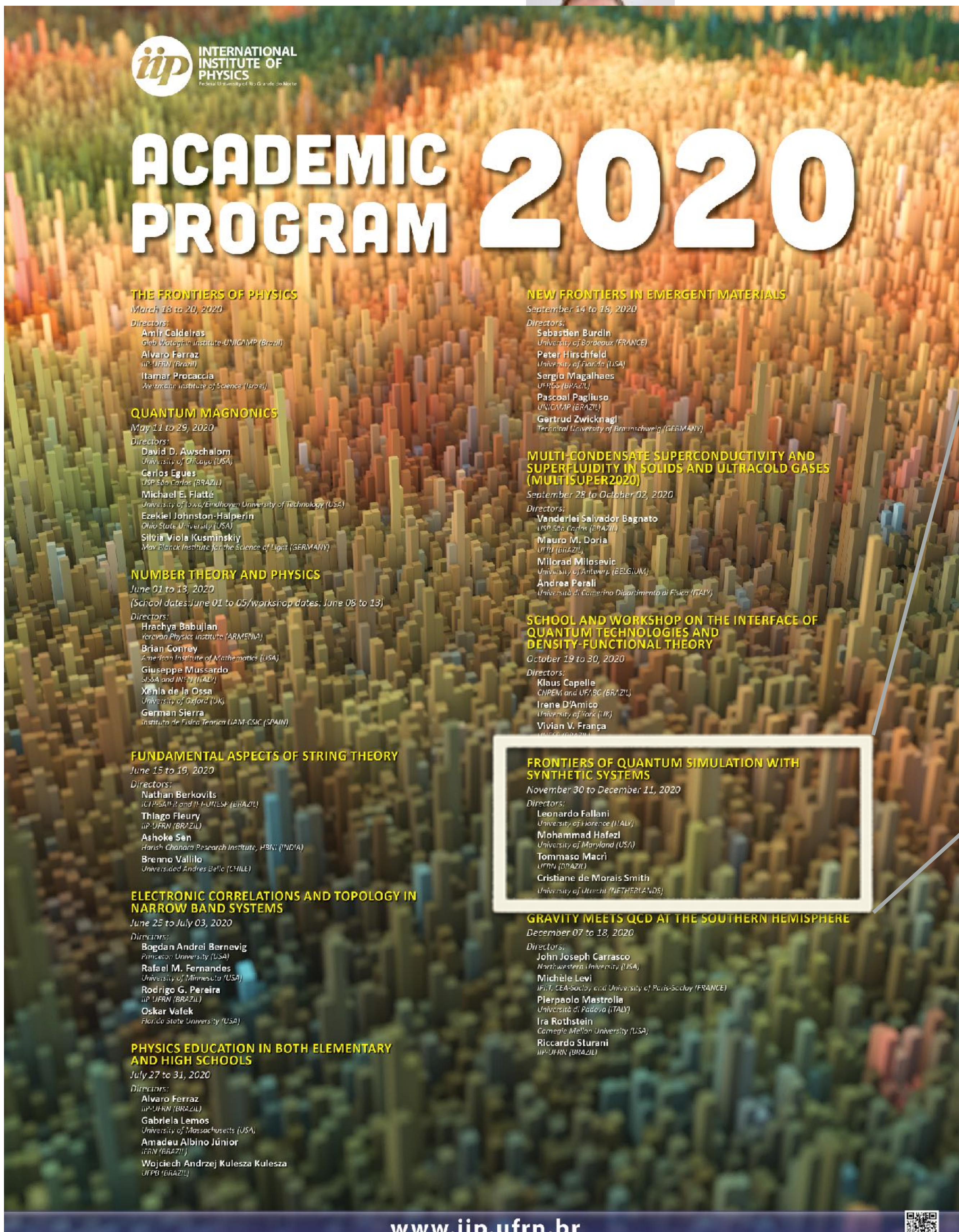
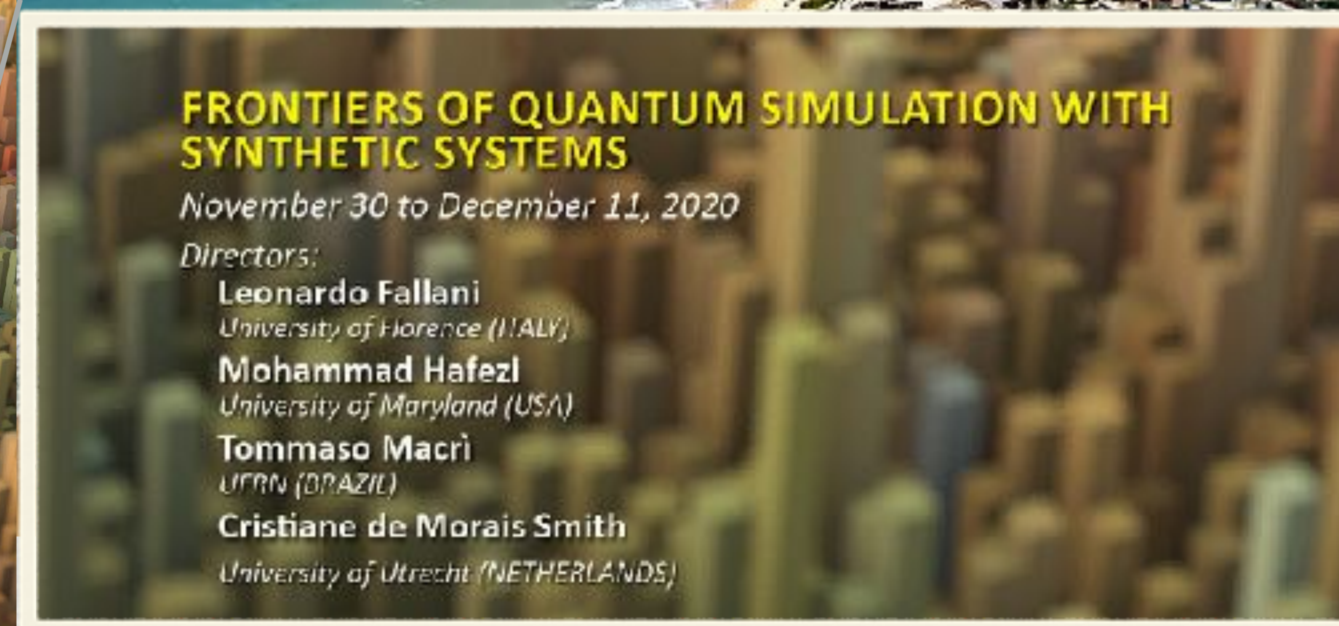
Quantum Simulation and Technology





60 ANOS

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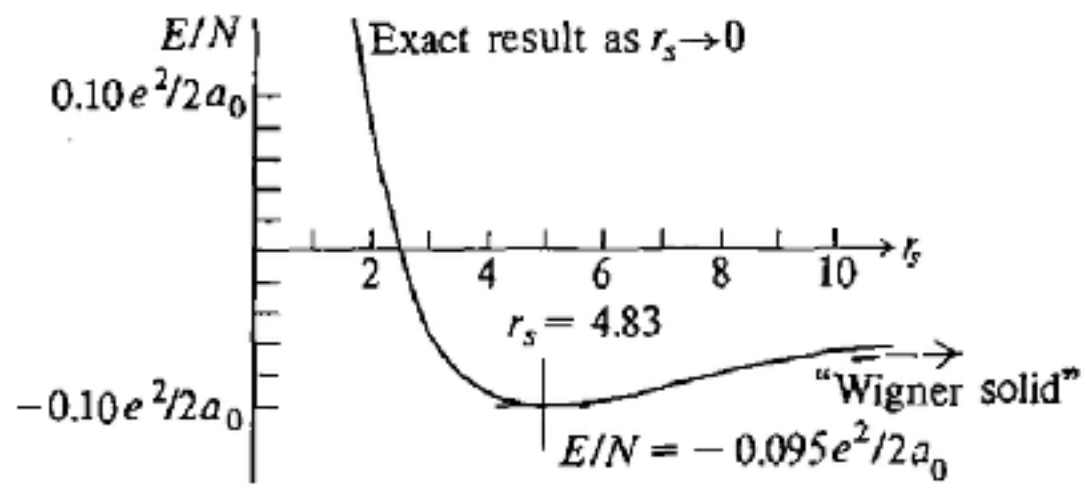
Crystallization in ultracold systems

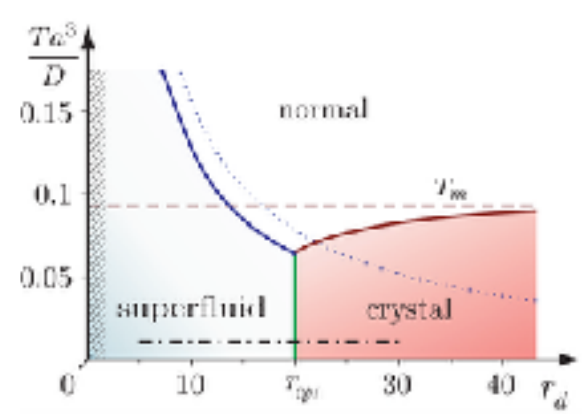
Crystallization: self-ordering of particles
into an array with regular geometry

Prototypical example:
Wigner crystal in
an electron gas in
uniform background
(Wigner 1934)



(Fetter and Walecka)

Polar molecules,
magnetic atoms



(Ye, Pfau, Ferlaino,
Büchler, Rey, Zoller…)

Atoms in cavities (Ritsch, Esslinger, …) Ions (Bollinger, Hennrich,..)

Spin-orbit coupled BECs (Spielmann, Stringari, Ketterle,…)

Rydberg atoms

- Hydrogen-like wave functions
- Quantum defects

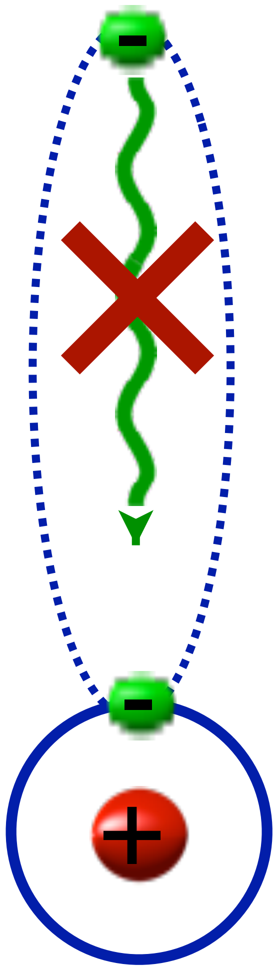
$$E_{nlj} = -\frac{\mathrm{Ry}}{[n - \delta_{lj}(n)]^2}$$

$^{87}\mathrm{Rb}\ \ 43\mathrm{S}_{1/2}$

$250\,\mathrm{nm}$

$^{87}\mathrm{Rb}\ \ 5\mathrm{S}_{1/2}$  $0.5\,\mathrm{nm}$

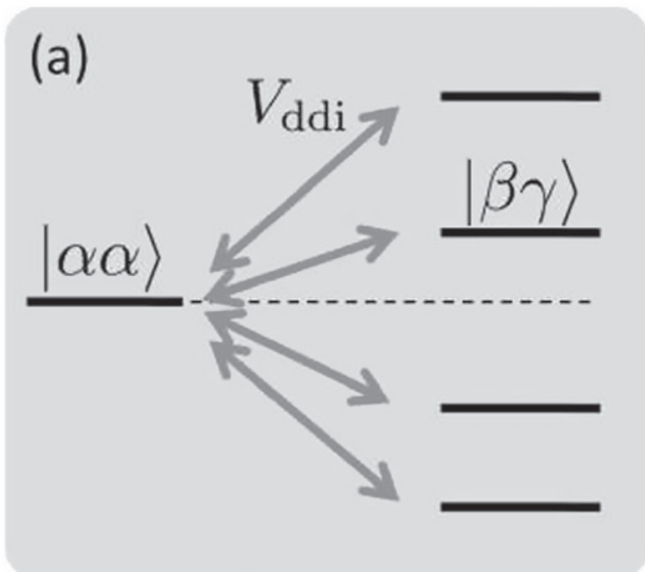
Property	Scaling	^{87}Rb 43S
Radius	$(n^*)^2$	$2400\ a_0 = 127$ nm
Lifetime	$(n^*)^3$	$45 \cdot 10^{-6}$ s
Van der Walls coefficient	$(n^*)^{11}$	$C6 = -1.7 \cdot 10^{-19}$ a.u.
Blockade radius (Rabi = 200 kHz)	$(n^*)^2$	$\sim 5 \cdot 10^{-6}$ m $a_{lat} = 532$ nm



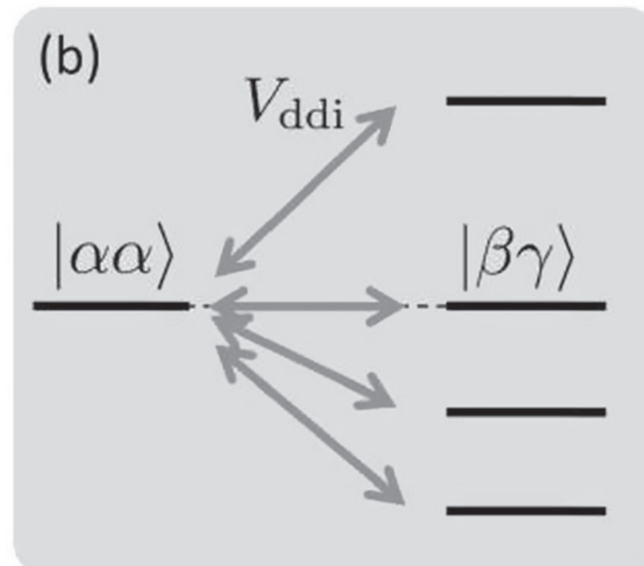
M. Saffman, T. G. Walker and K. Mølmer, Rev. Mod. Phys. (2010)

Long-range potentials from Rydberg atoms

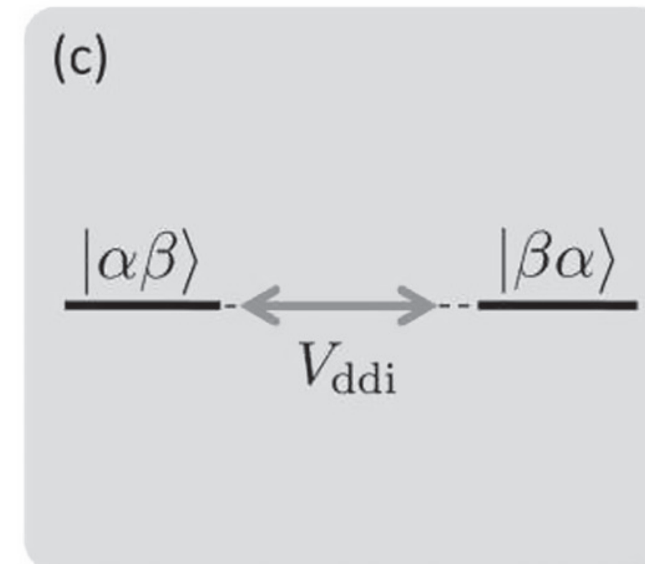
van der Walls



Förster resonance



resonant dipole-dipole



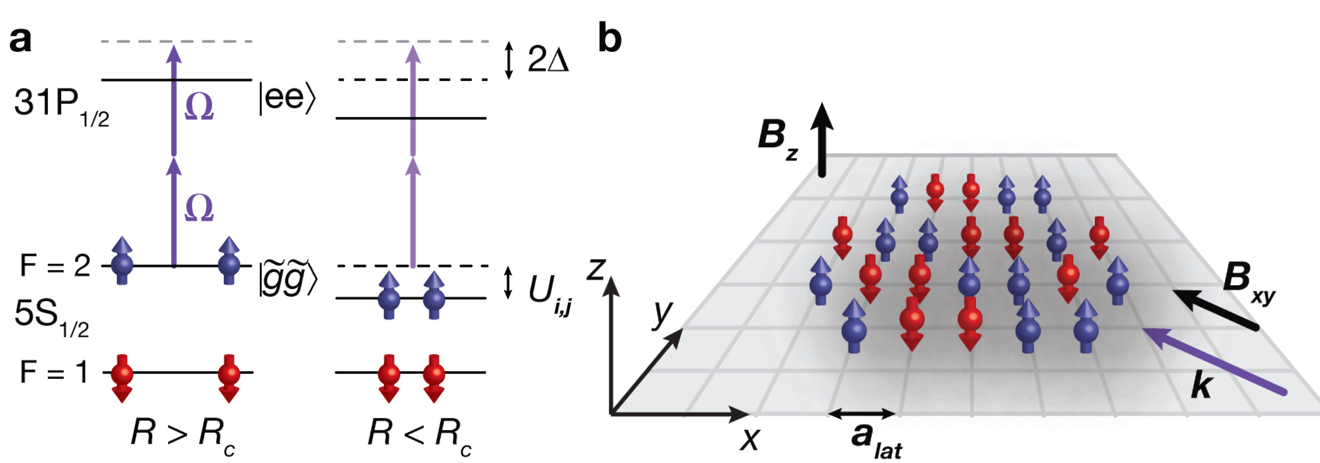
$$V_{\rm ddi} = \frac{1}{4\pi\varepsilon_0}\frac{\boldsymbol{d}_1\cdot\boldsymbol{d}_2 - 3(\boldsymbol{d}_1\cdot\boldsymbol{n})(\boldsymbol{d}_1\cdot\boldsymbol{n})}{R^3}$$

reviews: M. Saffman, T. G. Walker, K. Molmer, Rev. Mod. Phys. **82**, 2313 (2010)

A. Browaeys, D. Barredo, and T. Lahaye, J. Phys. B **49**, 152001 (2016)

P. Schauss, Quantum Sci. Technol. **3**, 023001 (2018)

Rydberg-dressing



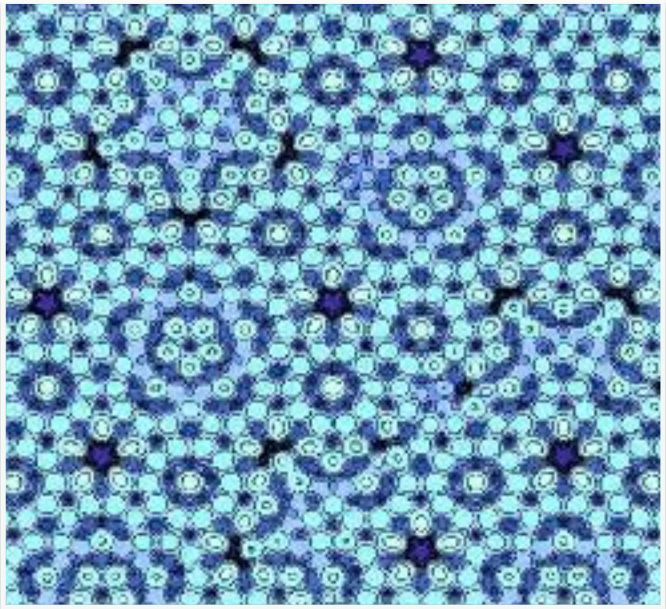
Applications to quantum simulation, quantum metrology, quantum information …

Experiments in Bloch group ('16-'18)

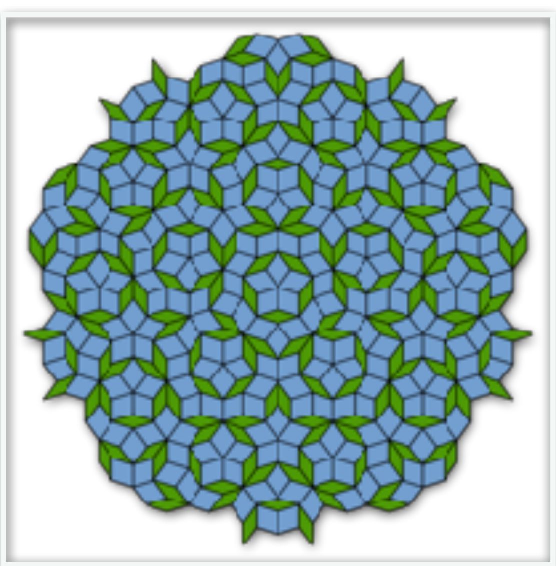
A. Glaetzle, M. Dalmonte, R. Nath, C. Gross, I. Bloch and P. Zoller, PRL **114**, 173002 (2014)

R. M. W. van Bijnen and T. Pohl, PRL **114**, 243002 (2015)

Quasicrystals

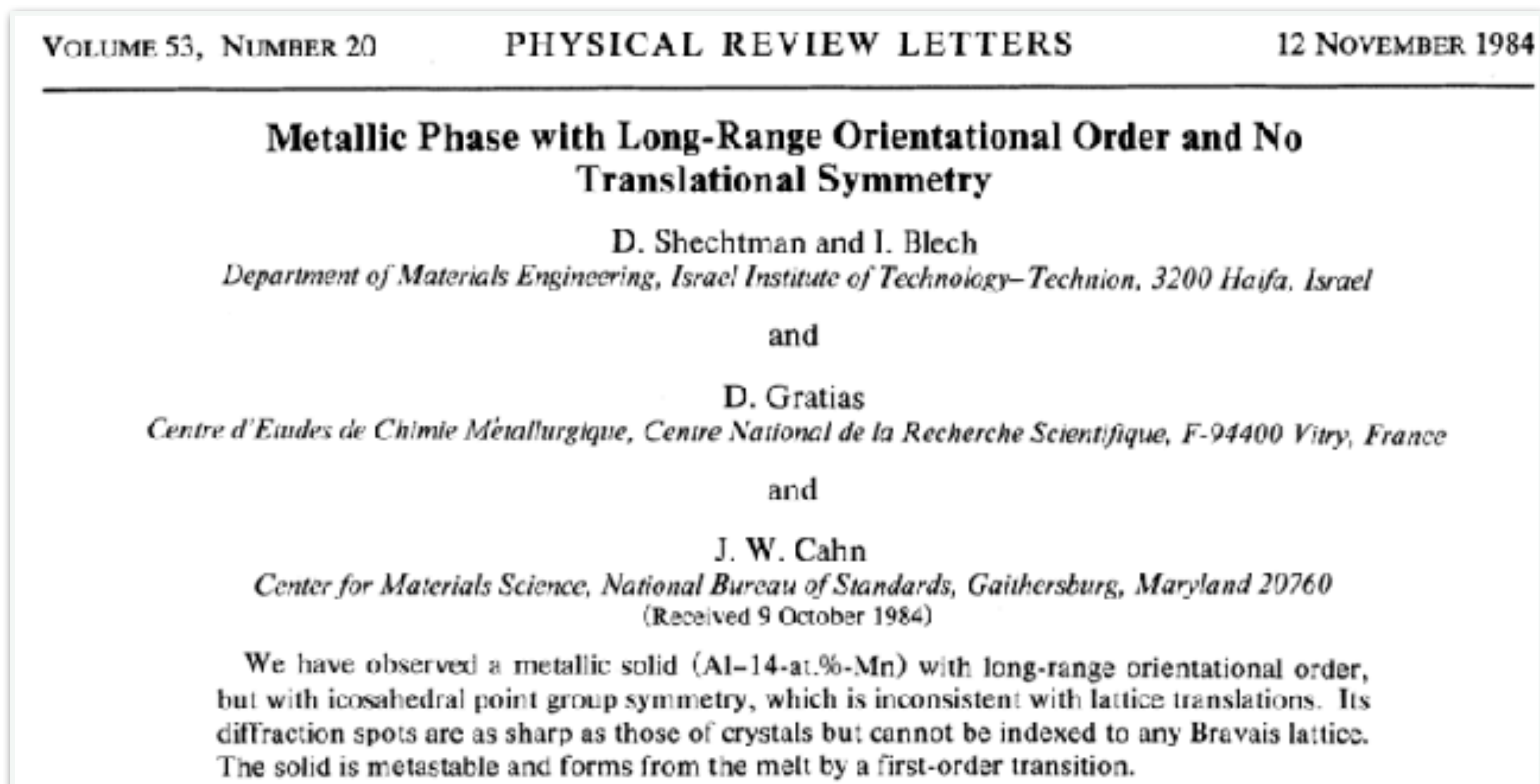


Silver depositing on Al-Pd-Mn quasicrystal surface



Math: Penrose tiling

- Symmetries in crystallography: 2-, 3-, 4- and 6-fold (from 2π to $2\pi/6$) symmetries are allowed
- But 5-, 7-fold and higher fold are forbidden
- Everything changed when Shechtman et al. observed an icosahedral single grain with a 5-fold symmetries…



VOLUME 53, NUMBER 20 PHYSICAL REVIEW LETTERS 12 NOVEMBER 1984

Metallic Phase with Long-Range Orientational Order and No Translational Symmetry

D. Shechtman and I. Blech
Department of Materials Engineering, Israel Institute of Technology–Technion, 3200 Haifa, Israel

and

D. Gratias
Centre d'Etudes de Chimie Métallurgique, Centre National de la Recherche Scientifique, F-94400 Vitry, France

and

J. W. Cahn
Center for Materials Science, National Bureau of Standards, Gaithersburg, Maryland 20760
(Received 9 October 1984)

We have observed a metallic solid (Al-14-at.%-Mn) with long-range orientational order, but with icosahedral point group symmetry, which is inconsistent with lattice translations. Its diffraction spots are as sharp as those of crystals but cannot be indexed to any Bravais lattice. The solid is metastable and forms from the melt by a first-order transition.

Combine quasicrystalline behavior and superfluidity from interactions?

Quasicrystals in Soft-matter

LETTER

doi:10.1038/nature12938

Mosaic two-lengthscale quasicrystals

T. Dotera[1], T. Oshiro[1] & P. Ziherl[2,3]

Over the past decade, quasicrystalline order[1] has been observed in many soft-matter systems: in dendritic micelles[2], in star[3] and tetrablock[4] terpolymer melts and in diblock copolymer[5] and surfactant micelles[6]. The formation of quasicrystals[7–9] from such a broad range of 'soft' macromolecular micelles suggests that they assemble by a generic mechanism rather than being dependent on the specific chemistry of each system. Indeed, micellar softness has been postulated[7] and shown to lead to quasicrystalline order[10]. Here we theoretically explore this link by studying two-dimensional hard disks decorated with step-like square-shoulder repulsion that mimics, for example, the soft alkyl shell around the aromatic core in dendritic micelles[2]. We find a family of quasicrystals with 10-, 12-, 18- and 24-fold bond orientational order which originate from mosaics of equilateral and isosceles triangles formed by particles arranged core-to-core and shoulder-to-shoulder. The pair interaction responsible for these phases highlights the role of local packing geometry in generating quasicrystallinity in soft matter, complementing the principles that lead to quasicrystal formation in hard tetrahedra[11,12]. Based on simple interparticle potentials, quasicrystalline mosaics may well find use in diverse applications ranging from improved image reproduction[13] to advanced photonic materials[14].

LETTERS

Stripe phases from isotropic repulsive interactions

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*e-mail: malescio@unime.it

Quasicrystals in BEC from complex external potentials

PHYSICAL REVIEW LETTERS **120,** 060407 (2018)

Superfluid-Quasicrystal in a Bose-Einstein Condensate

Junpeng Hou, Haiping Hu, Kuei Sun, and Chuanwei Zhang*
Department of Physics, The University of Texas at Dallas, Richardson, Texas 75080-3021, USA

(Received 1 September 2017; revised manuscript received 20 December 2017; published 8 February 2018)

A quasicrystal is a class of ordered structures defying conventional classification of solid crystals and may carry classically forbidden (e.g., fivefold) rotational symmetries. In view of long-sought supersolids, a natural question is whether a superfluid can spontaneously form quasicrystalline order that is not possessed by the underlying Hamiltonian, forming "superfluid-quasicrystals." Here we show that a superfluid-quasicrystal stripe state with the minimal fivefold rotational symmetry can be realized as the ground state of a Bose-Einstein condensate within a practical experimental scheme. There exists a rich phase diagram consisting of various superfluid-quasicrystal, supersolid, and plane-wave phases. Our scheme can be generalized for generating other higher-order (e.g., sevenfold) quasicrystal states, and provides a platform for investigating such new exotic quantum matter.

Quasicrystalline potentials

Featured in Physics   Editors' Suggestion

Matter-Wave Diffraction from a Quasicrystalline Optical Lattice

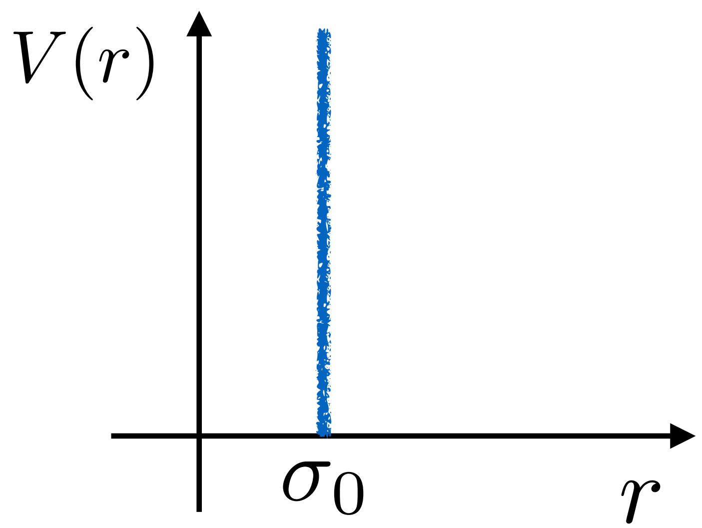
Konrad Viebahn, Matteo Sbroscia, Edward Carter, Jr-Chiun Yu, and Ulrich Schneider

Phys. Rev. Lett. **122**, 110404 – Published 20 March 2019

Physics See Viewpoint: A Quasicrystal for Quantum Simulations

B. Abreu, F. Cinti, T. Macrì, in preparation (2019)

Zoo of nonlocal interactions



- Hard-core potential (infinite repulsive barrier)
- Transition to crystal at $\rho\,\sigma^2 \approx 0.32$

Theoretical work in the dilute limit

M. Schick, PRA (1971)

S. Pilati et al. PRA (2005)

S. Pilati, S. Giorgini and N. Prokof'ev PRL (2008)

Numerical work on the structural transition

B. J. Alder et al. J. Chem. Phys. (1957)

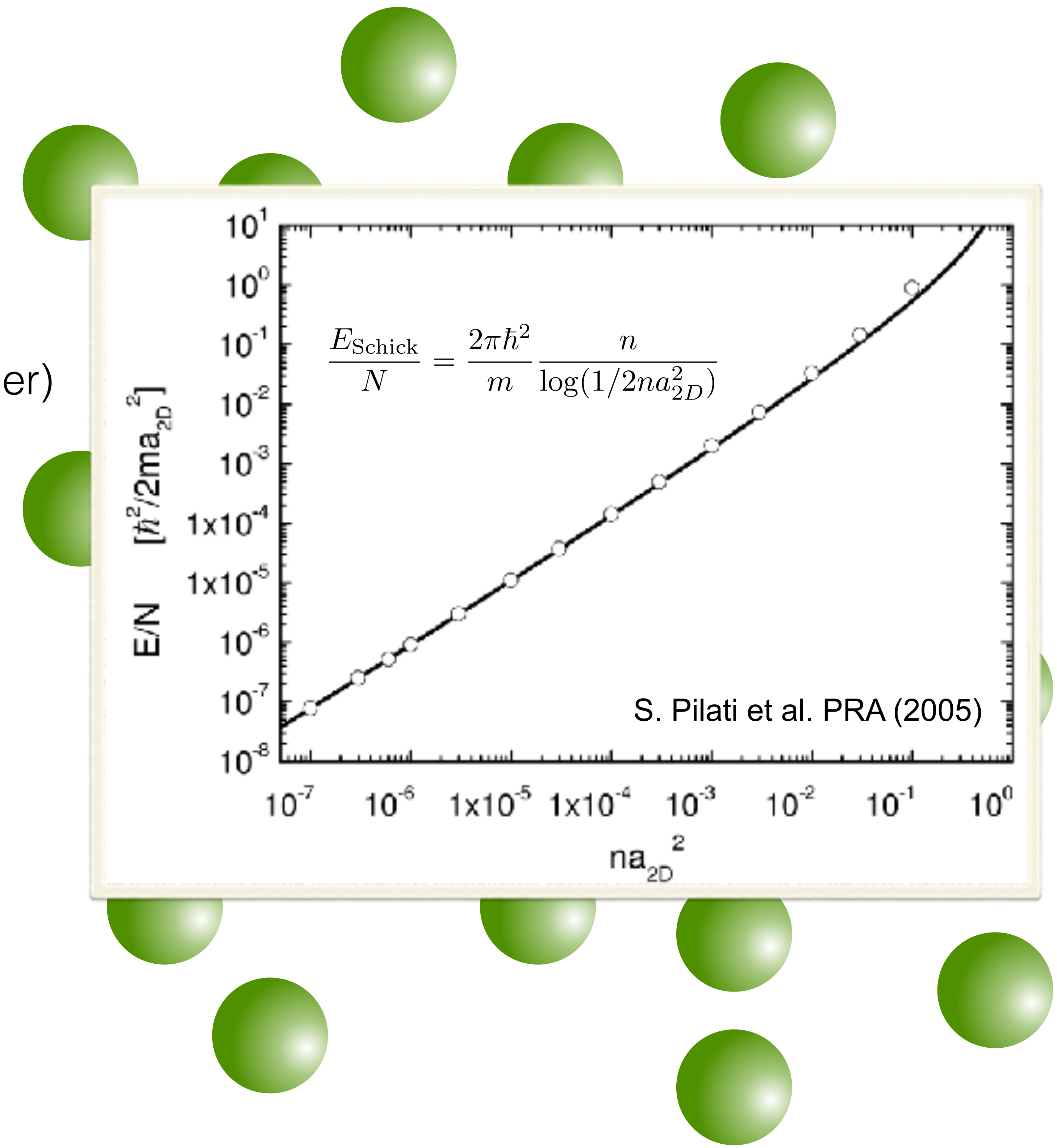
L. Xing, PRB (1990)

P. W. Leung and G. V. Chester PRB (1991)

T. Truskett et al. PRE (1998)

E. P. Bernard and W. Krauth PRL (2011)

A. Thorneywork et al. PRL (2017)



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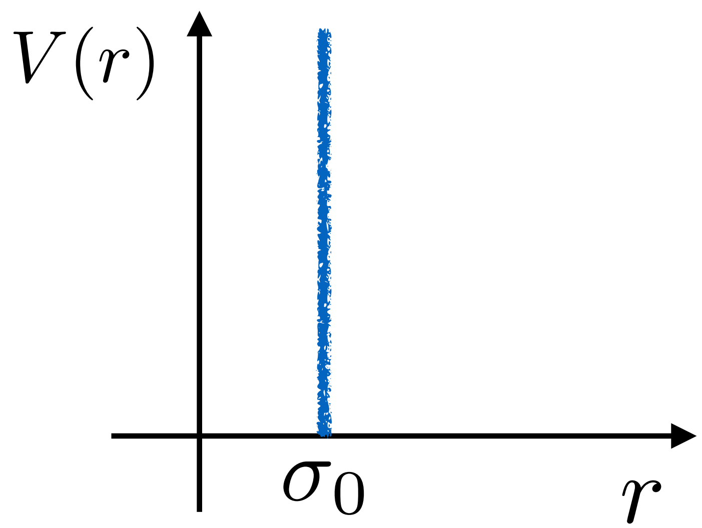

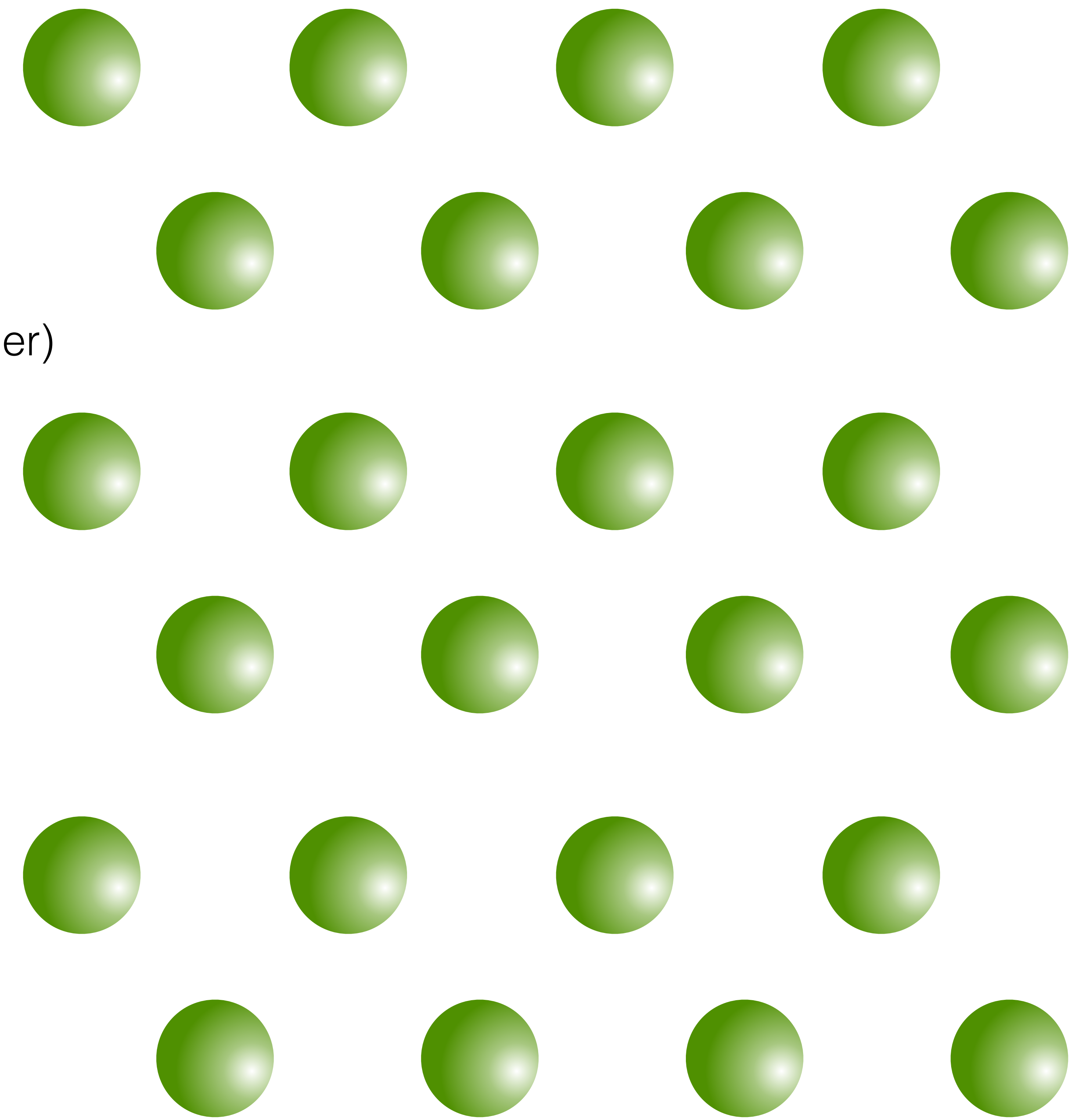

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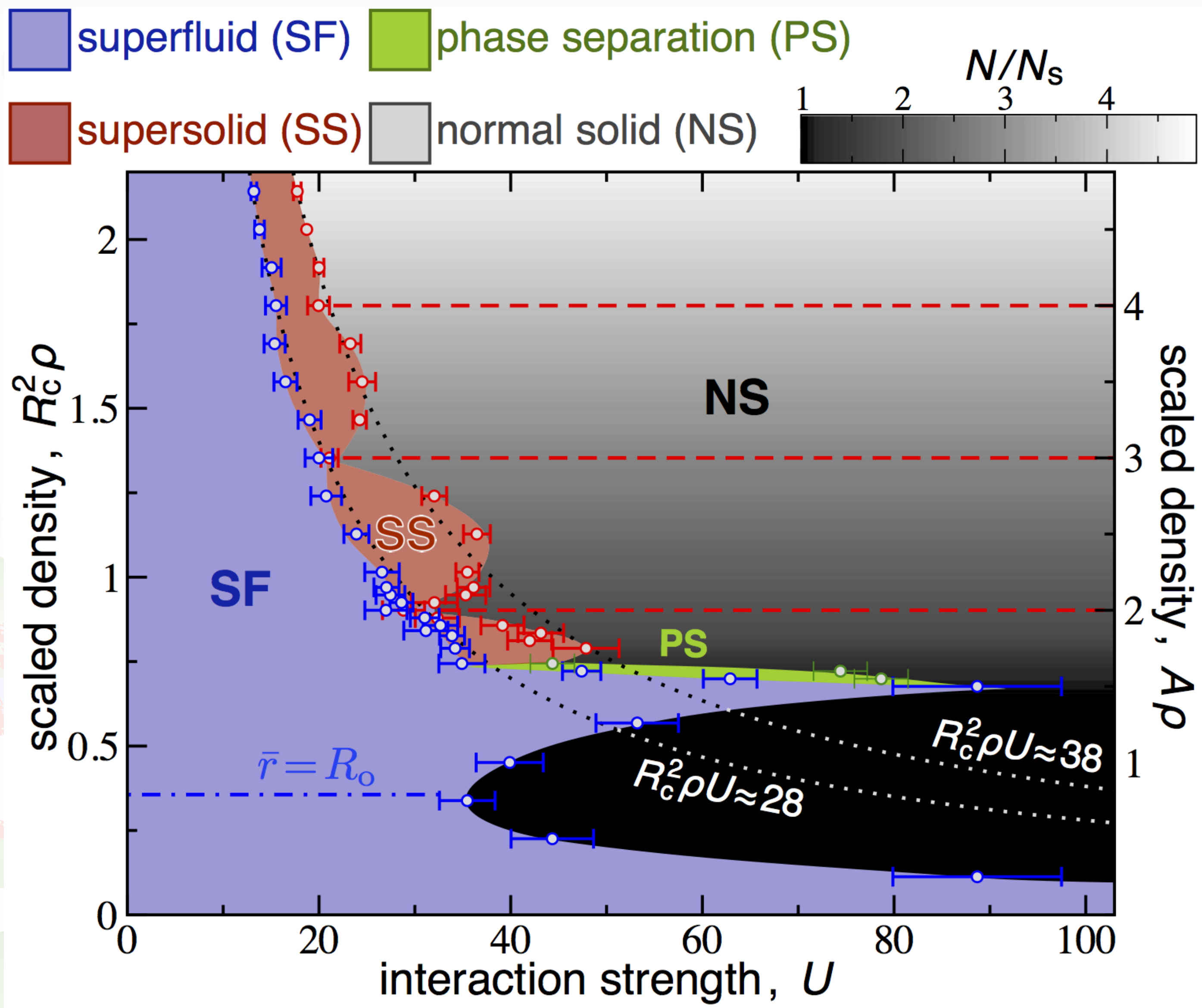
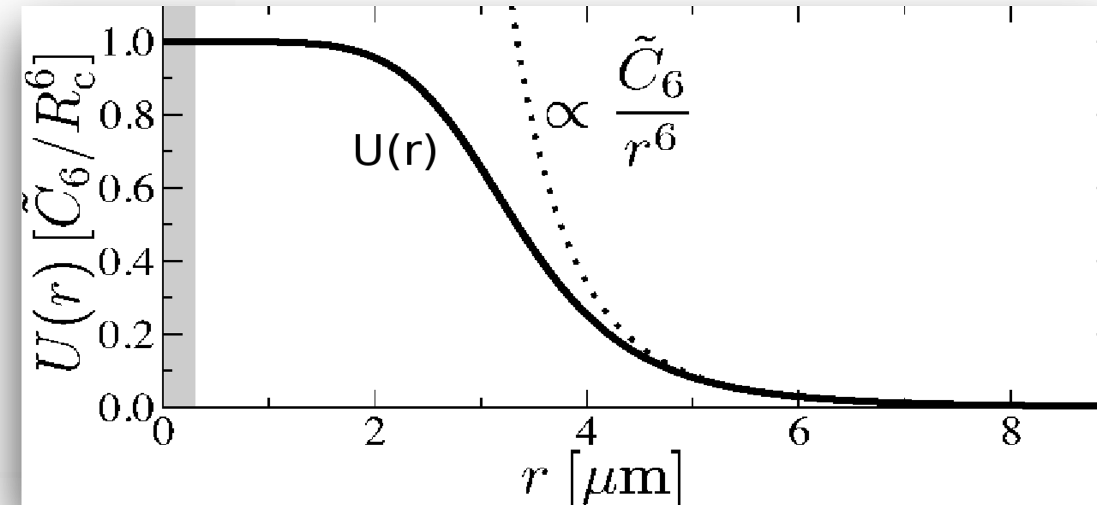
Zoo of nonlocal interactions

- Hard-core potential (infinite repulsive barrier)
- Transition to crystal at $\rho\,\sigma^2 \approx 0.32$
- Soft-core potential (finite repulsive)
- Rydberg atoms, **cluster supersolids**

Zoo of nonlocal interactions





$f_s = 1$

Superfluid

$0 < f_s < 1$

Supersolid

$f_s = 0$

Crystal

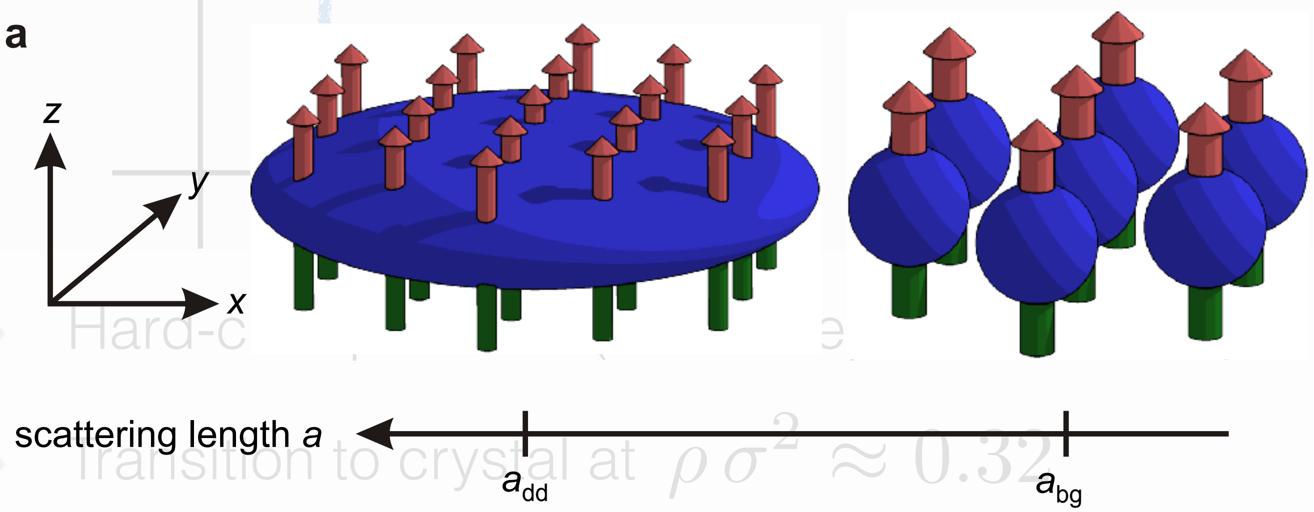
Applications to Quantum Technologies

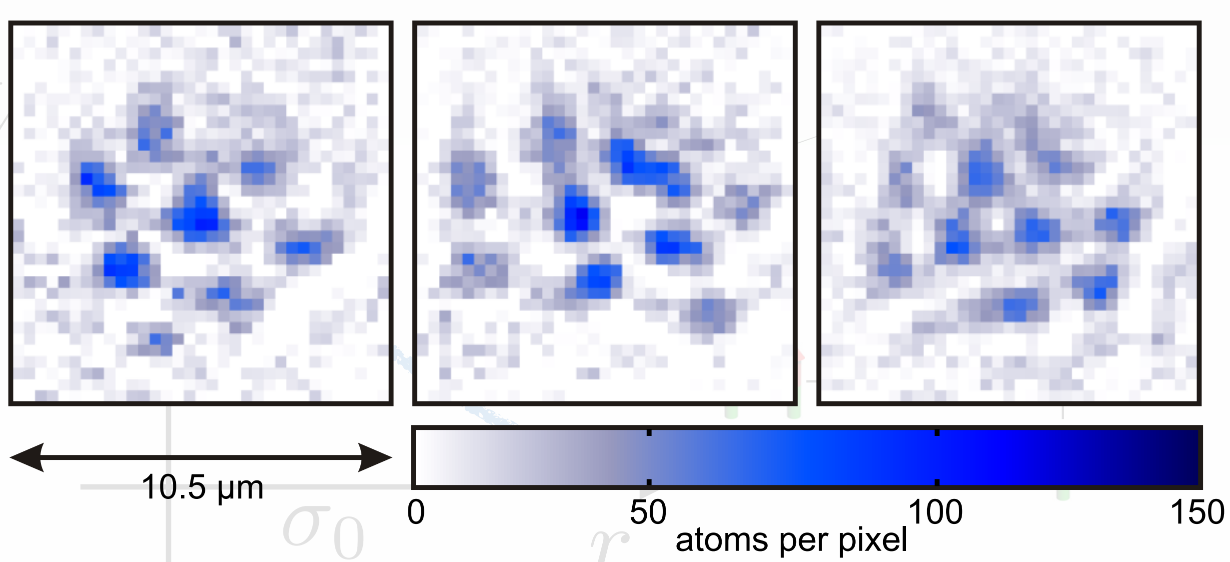
L. Gil et al. Rhys Rev Lett.112.103601 (2014)
T. Macrì, Smerzi and L. Pezzè PRA 94, 010101(R) (2016)
C. Gaul, et al. Phys. Rev. Lett. 116, 243001 (2015)
M. Khazali et al., Phys. Rev. A 94, 023408 (2016)
J. Balewski et al. New J. Phys. 16 (2014) 063012
A. Glätzle et al., PRX 4, 041037 (2015)
R. van Bijnen and T. Pohl, PhysRevLett.114.243002 (2016)

F. Cinti, T. Macrì, W. Lechner, G. Pupillo and T. Pohl, Nat. Comm. (2014)

Zoo of nonlocal interactions

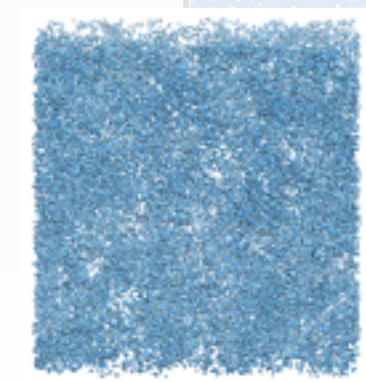
Quantum droplets and Supersolid in quasi-2D



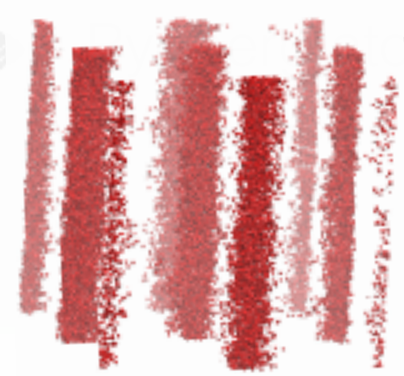


Dysprosium (Stuttgart, Pfau - Modugno, Pisa)
Erbium (Innsbruck - Ferlaino)

Quantum droplets and Filaments in 3D



Uniform superfluid phase with $f_s=1$

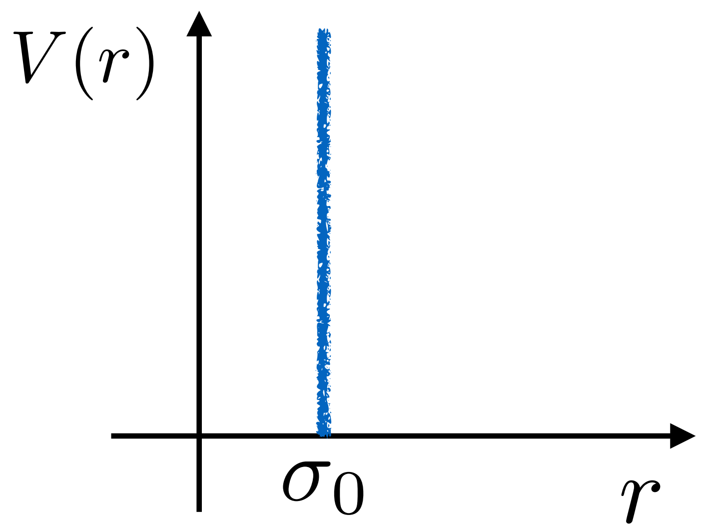


Filament phase (dipoles aligned vertically) with **anisotropic** superfluidity

Cluster phase - dipoles aligned vertically

F. Cinti, A. Cappellaro, L. Salasnich, T. M., Phys. Rev. Lett. **119**, 215302 (2017)

Zoo of nonlocal interactions



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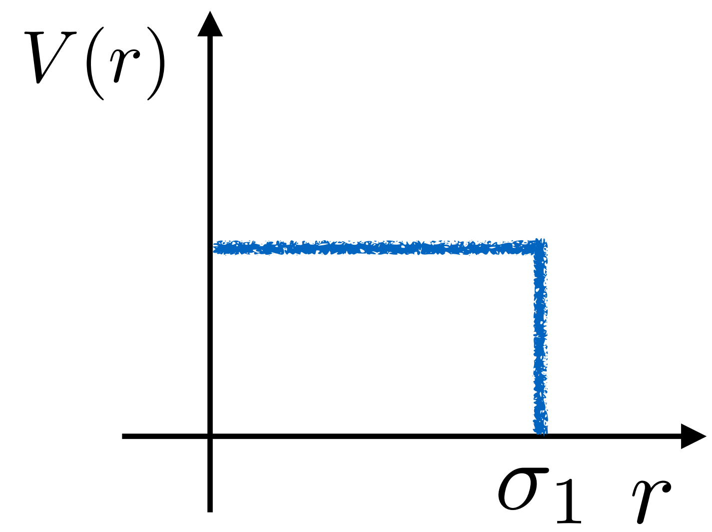
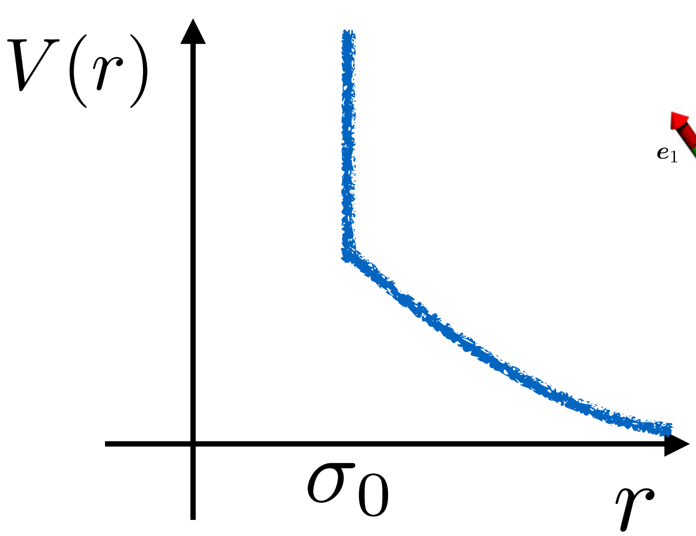
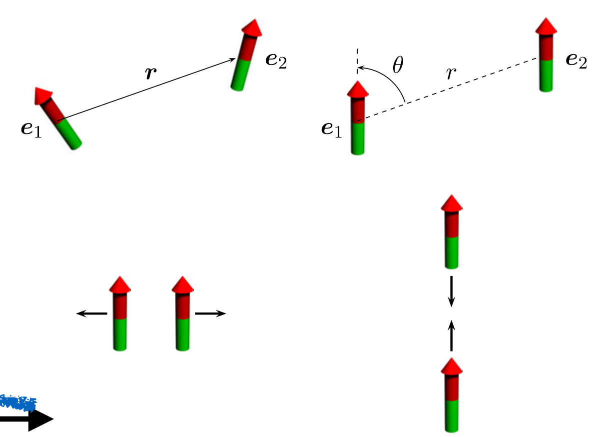
- Transition to crystal at $\rho\,\sigma^2 \approx 0.32$

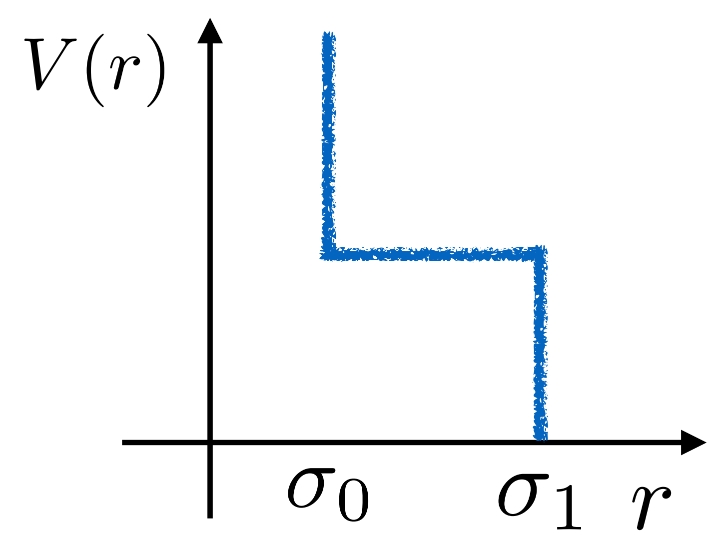


- Soft-core potential (finite repulsive)
- Rydberg atoms, **cluster supersolids**



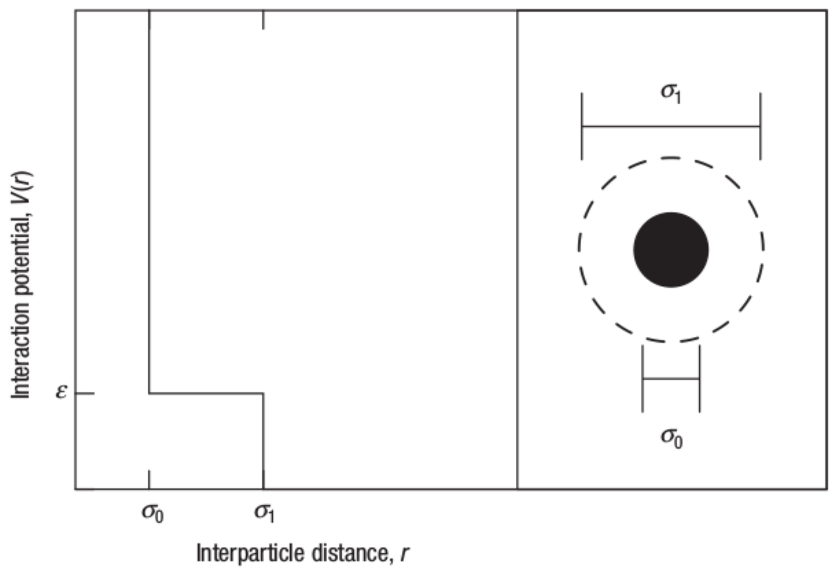


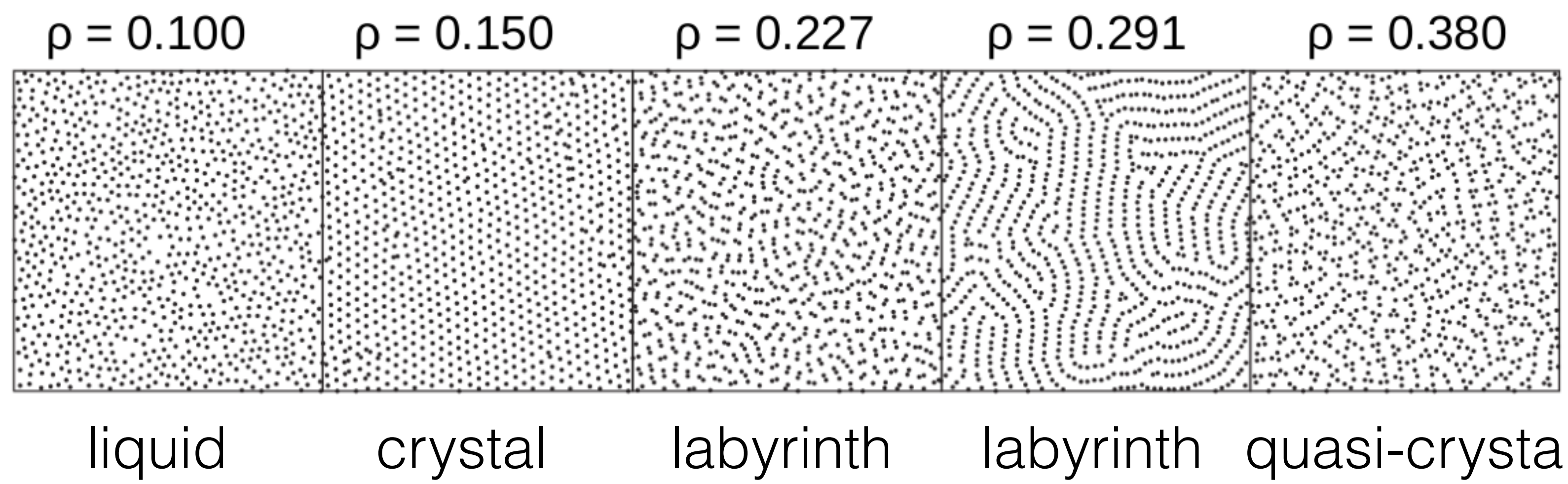
- Hard-core and dipolar (dipolar gases)
- Quantum droplets/superfluid filaments in 3D



- Hard-core and soft-core (finite repulsive)
- Rydberg atoms

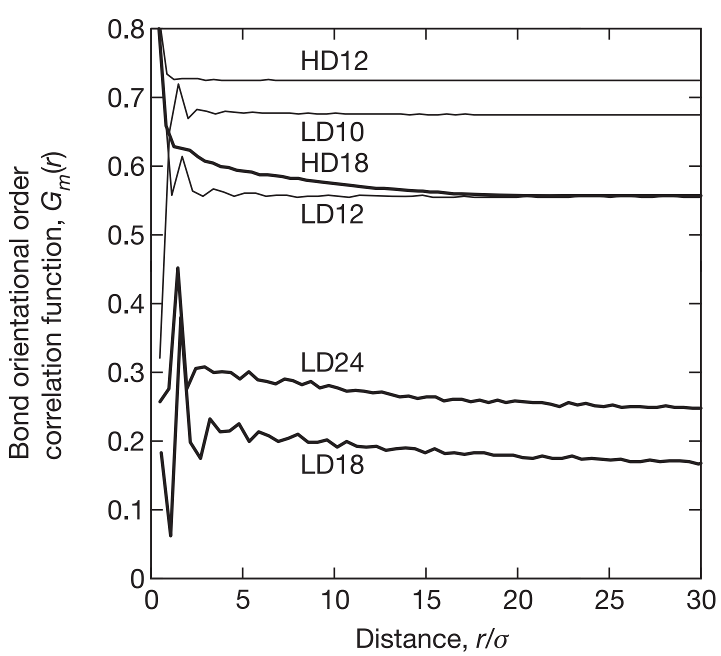
Classical Quasicrystals

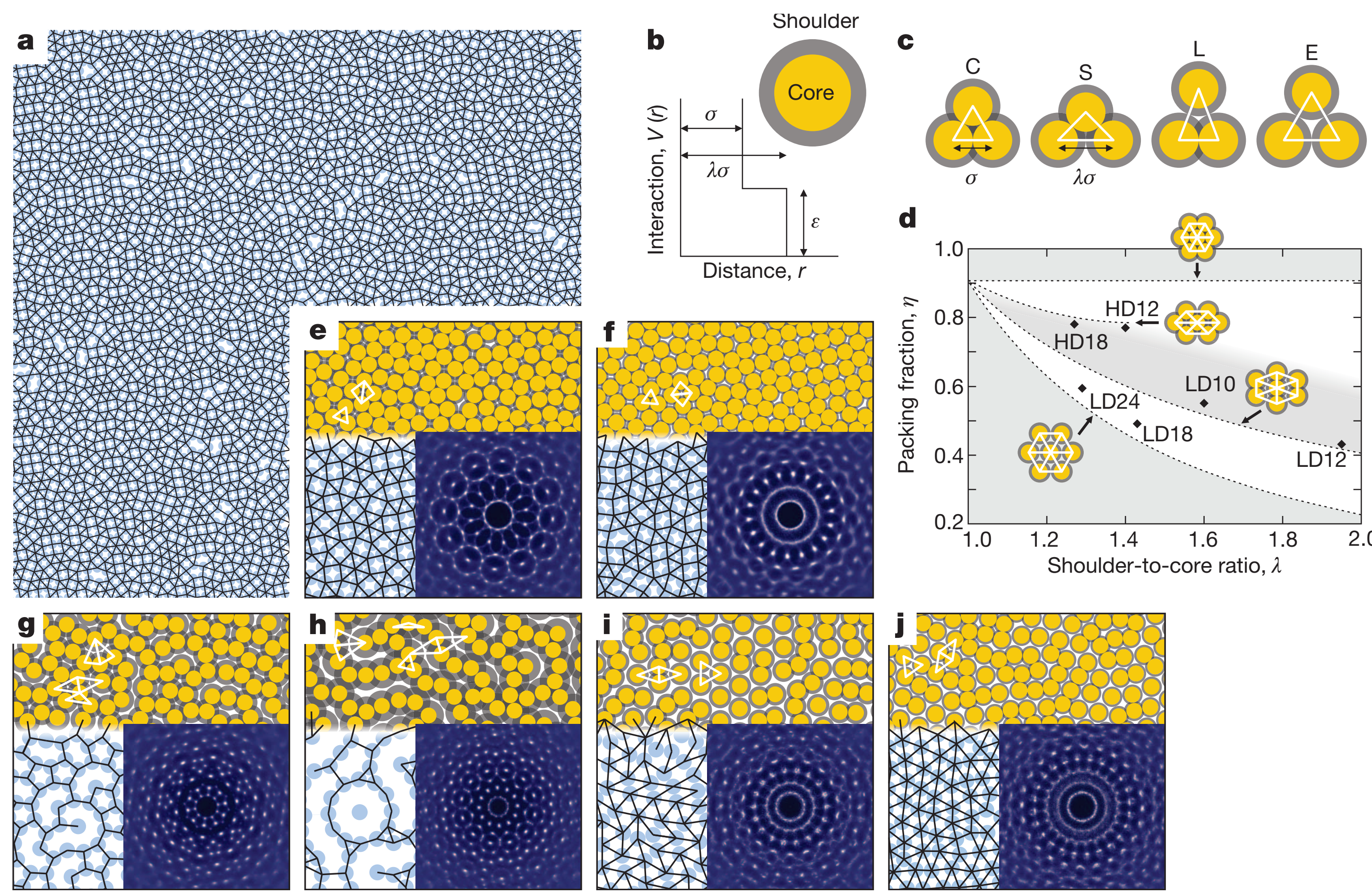




G. Malescio and G. Pellicane, Nature Materials (2003)

<u>classical</u> quasicrystals



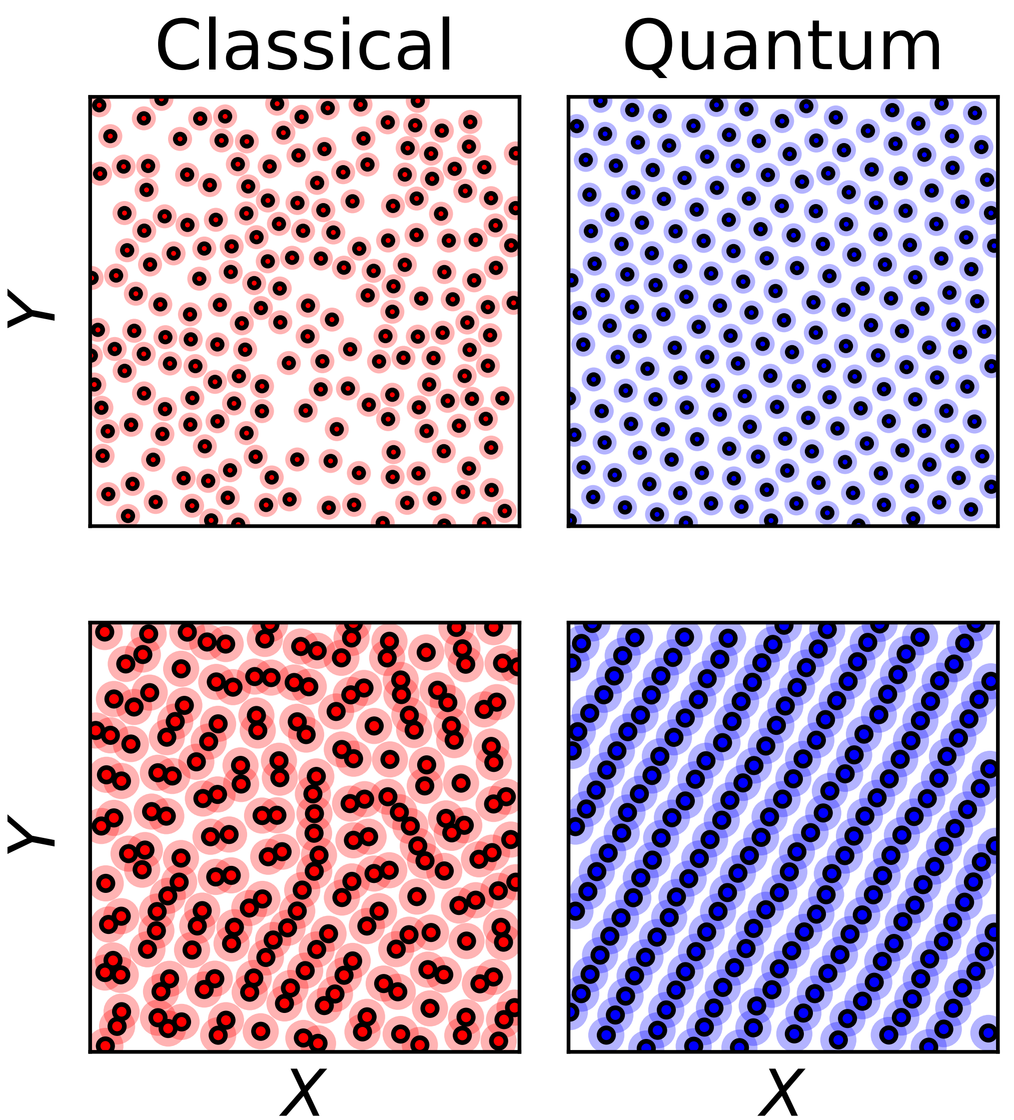


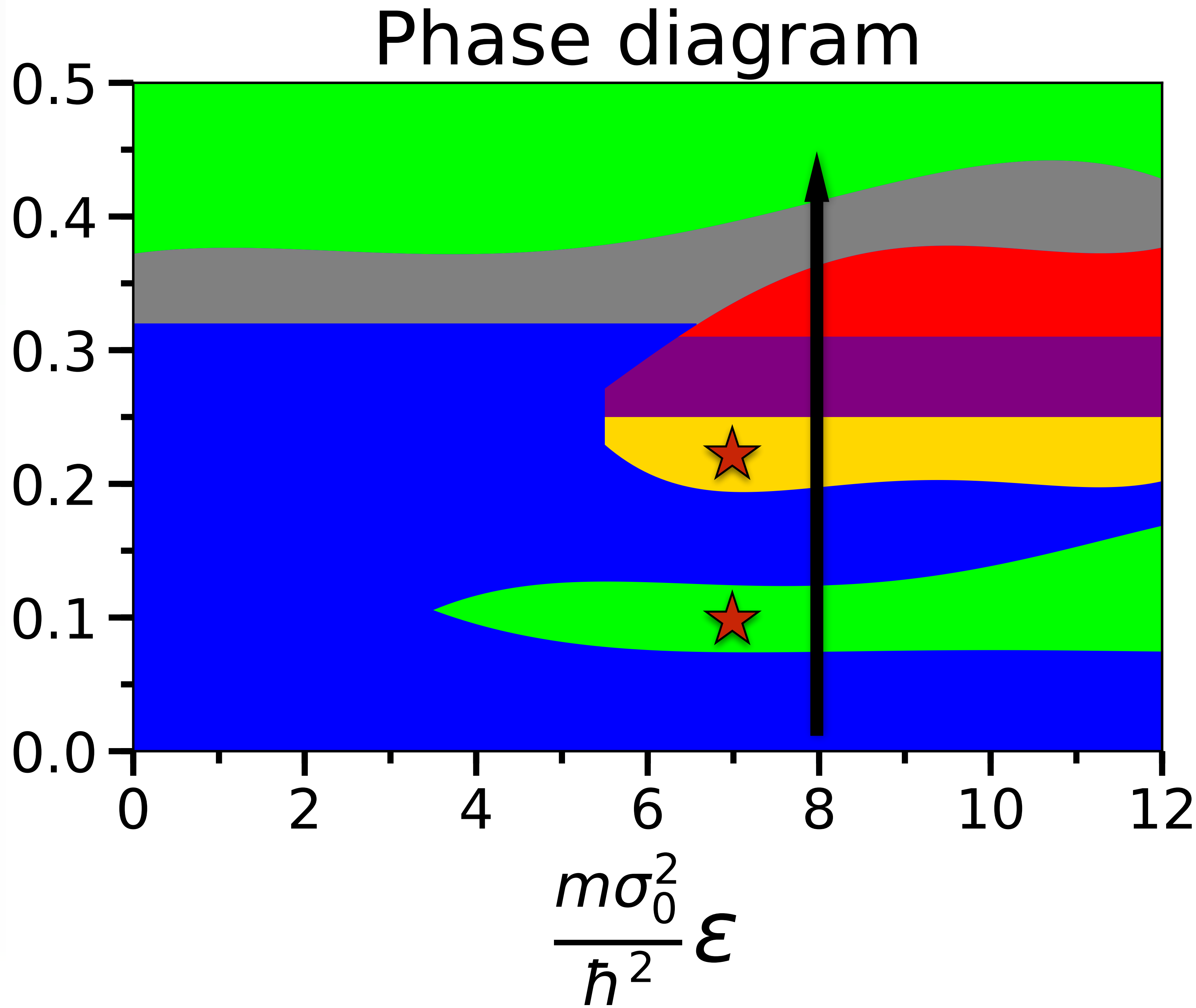
stable up to T=0? superfluid?

H. Pattabhiraman, A. P. Gantapara, and M. Dijkstra, J. Chem. Phys. (2015)

T. Dotera, T. Oshiro and P. Ziheri, Nature (2014)

Quantum Phases





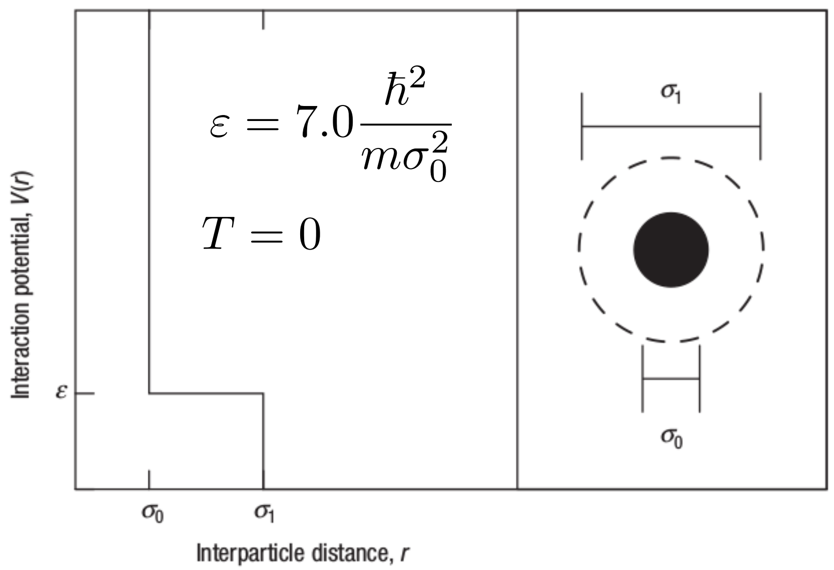
Labyrinth

Phase Coexistence

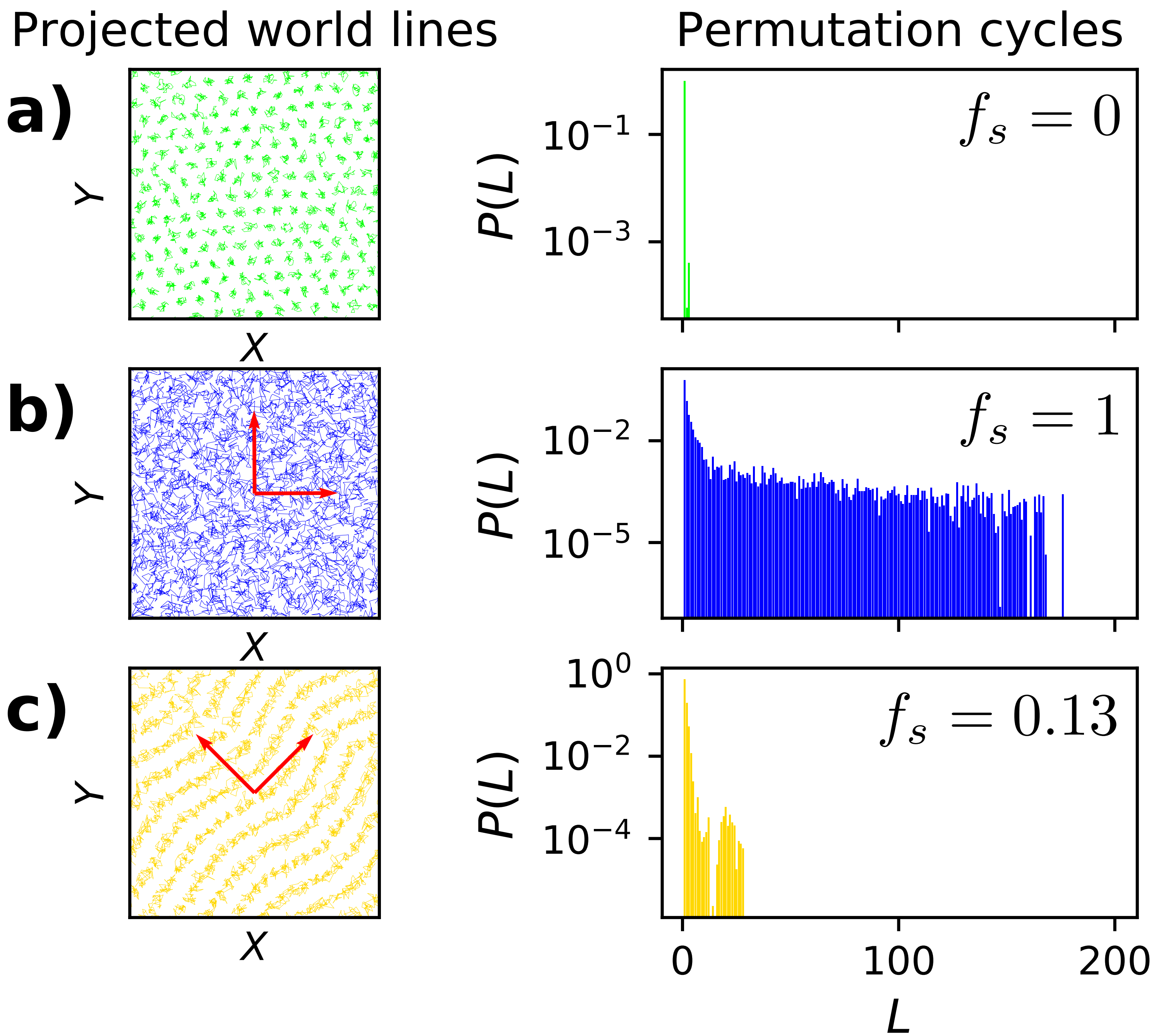
- PIMC method with the worm algorithm
- Few hundreds of particles

B. Abreu, F. Cinti, T.M. in preparation

Superfluidity



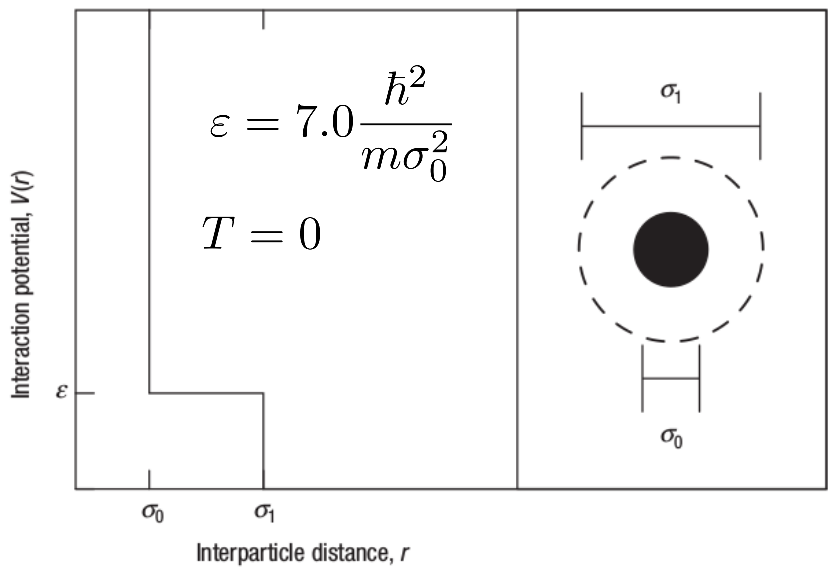
$$\sigma_1 = 2.5\sigma_0$$



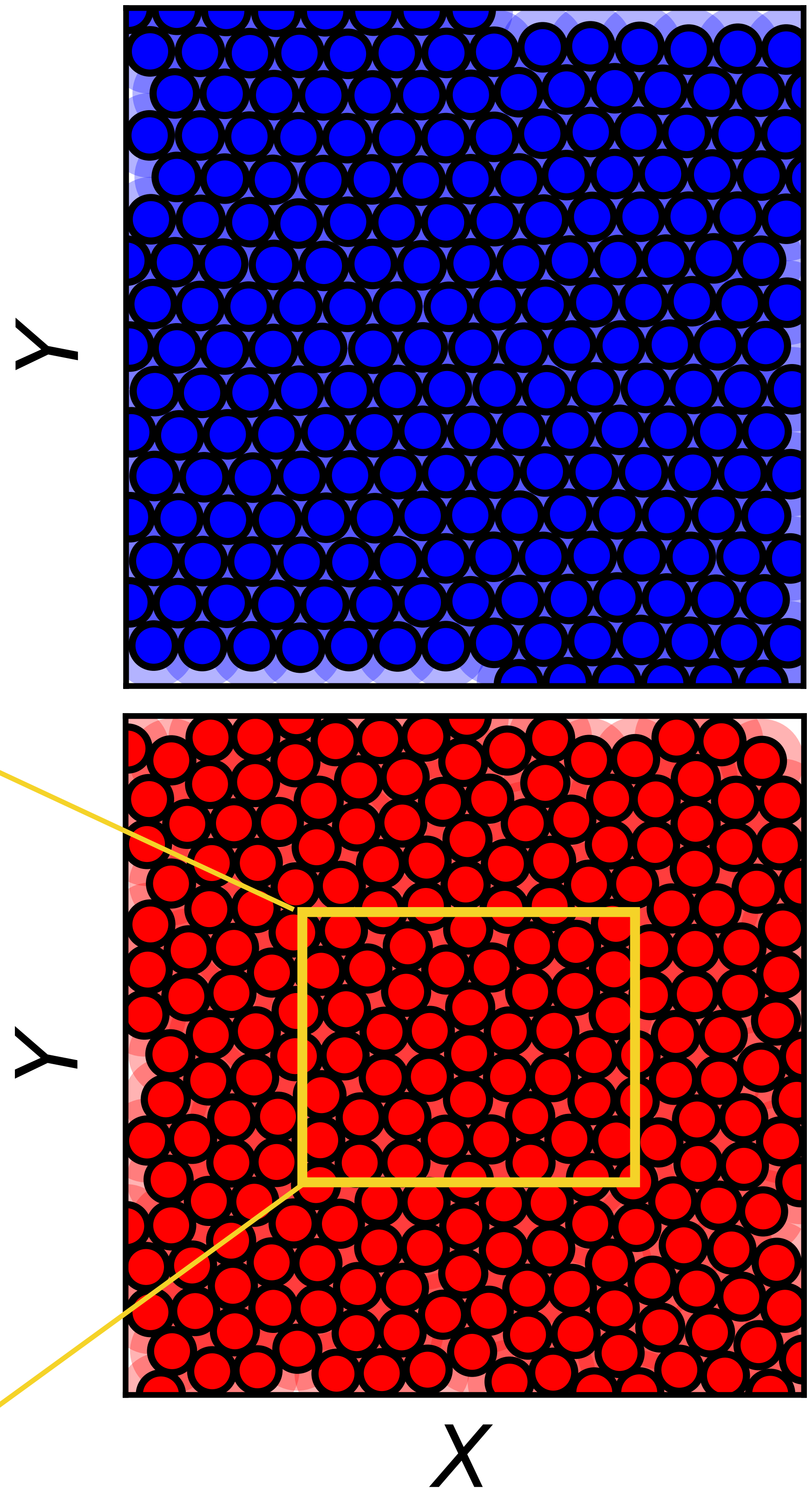
- Homogeneous superfluid
- Anisotropic superfluid tensor: Stripes nonuniform superfluids

B. Abreu, F. Cinti, T.M. in preparation

Quantum Quasicrystals



$$\sigma_1 = 1.95\sigma_0$$

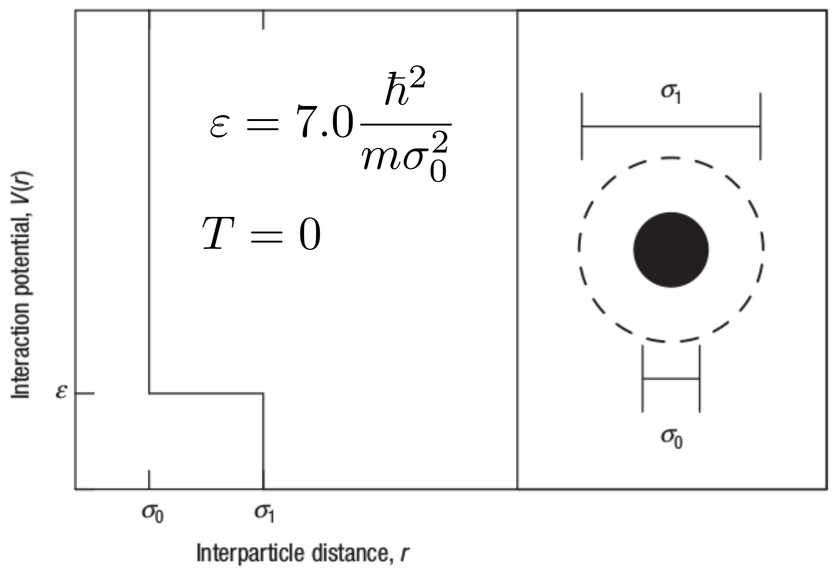


Triangular crystal

Square-triangle tiling

B. Abreu, F. Cinti, T.M. in preparation

Quantum Quasicrystals



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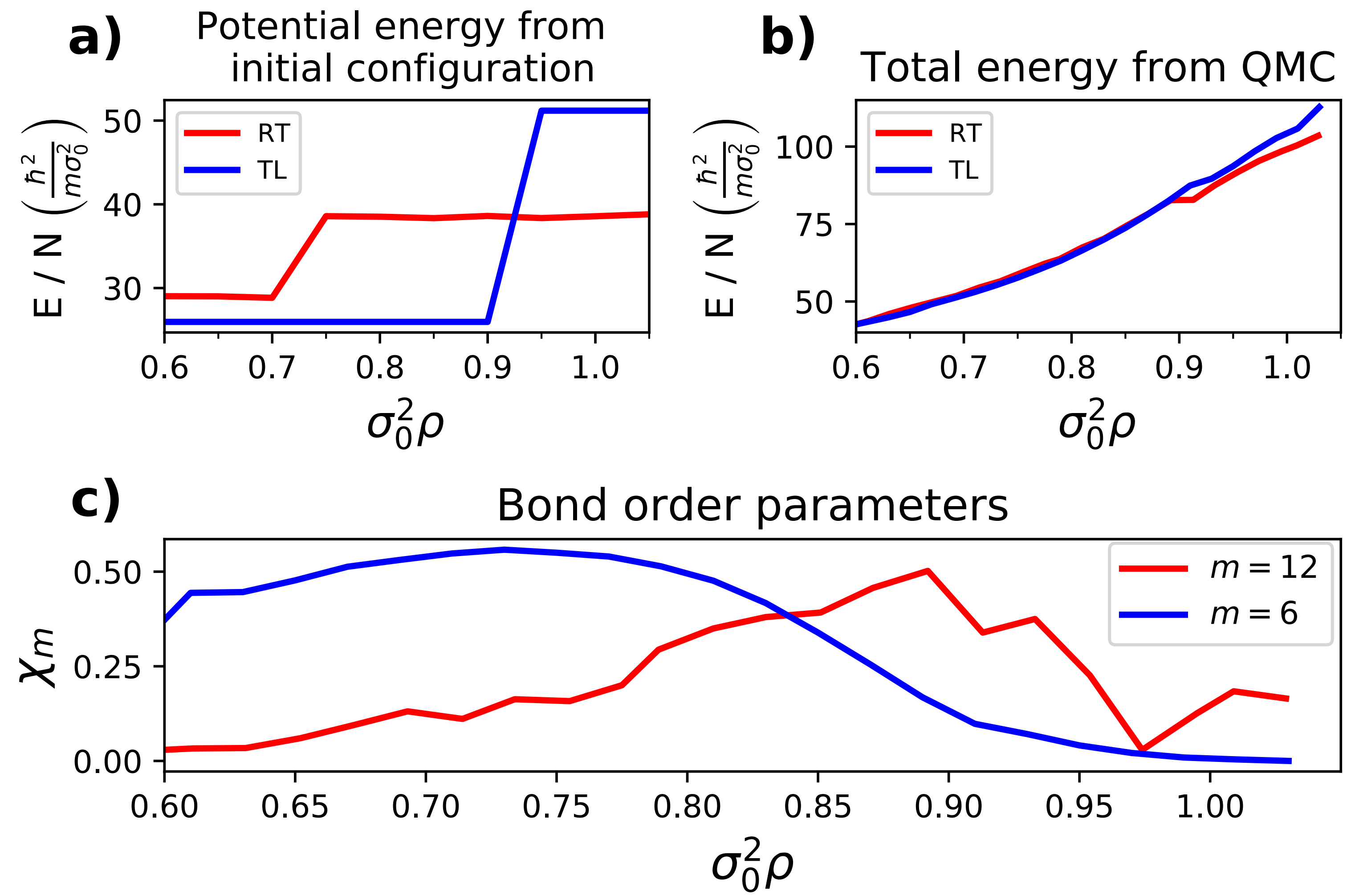
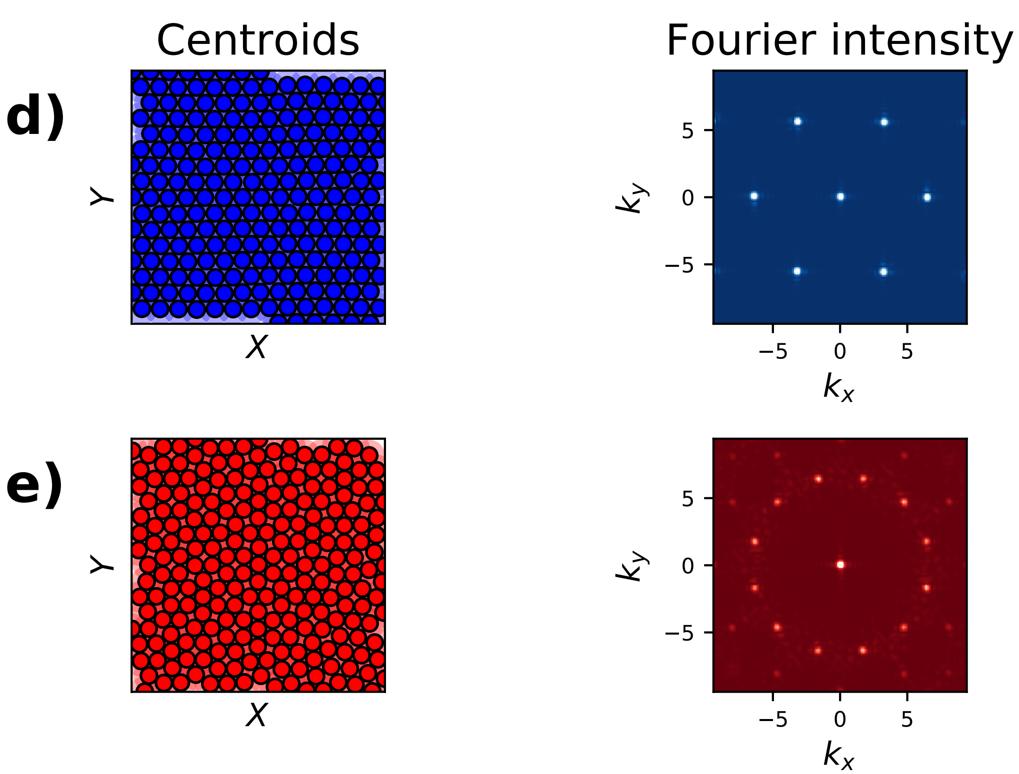




$$\chi_m = \left\langle \left| \frac{1}{N_b} \sum_b e^{im\theta_b} \right|^2 \right\rangle$$

- Competition of potential and kinetic energy (different from the soft-core)

B. Abreu, F. Cinti, T.M. in preparation

Quantum cluster quasicrystals

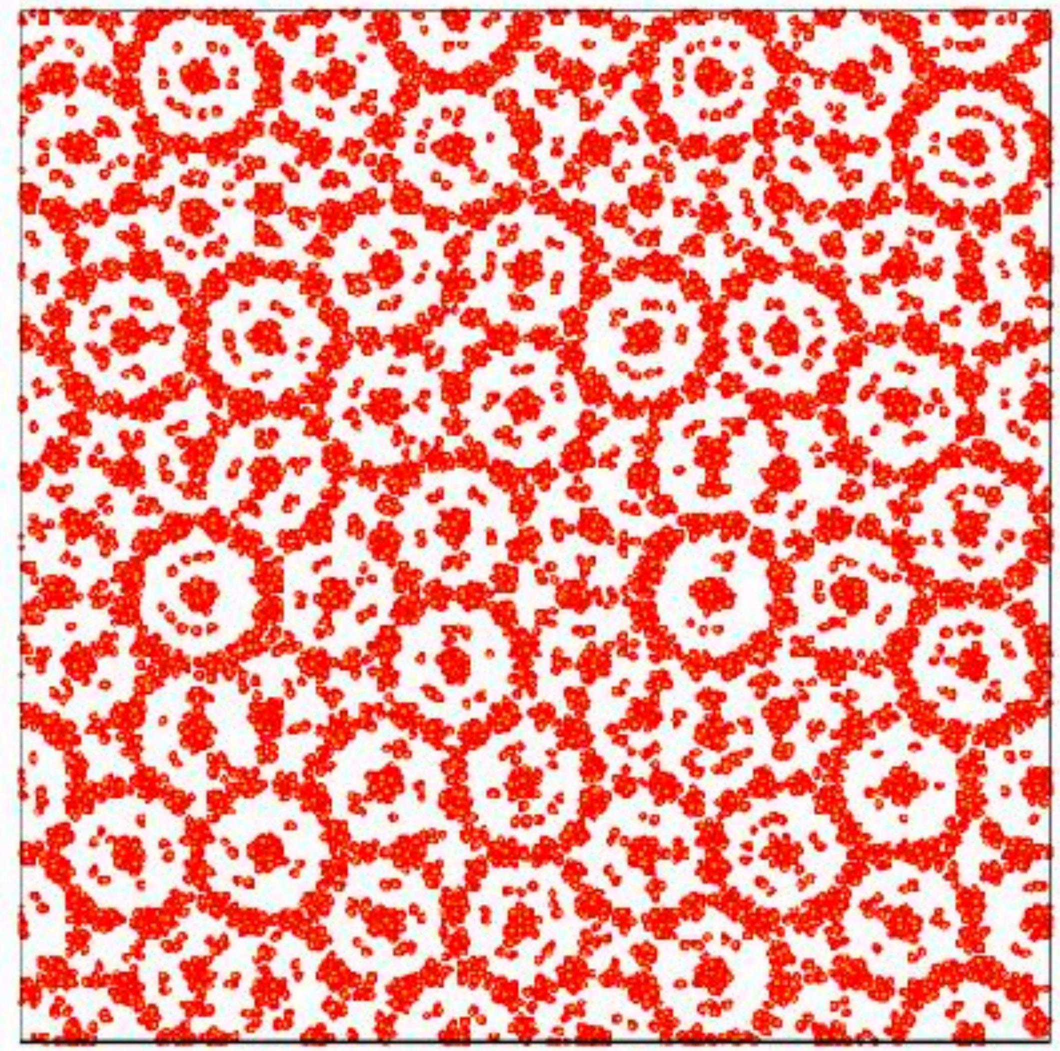
$$\hat{H} = -\frac{\hbar^2}{2m}\sum_{i=1}^{N}\nabla_i^2 + \sum_{i<j}^{N} V\left(r_{ij}\right)$$

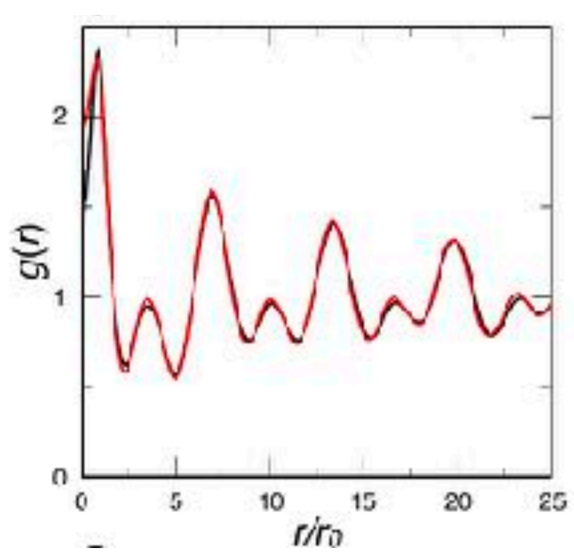
$$V(r) = \exp\left(-\sigma^2 r^2/2\right)\sum_{k=0}^{4} C_{2k}\, r^{2k}$$

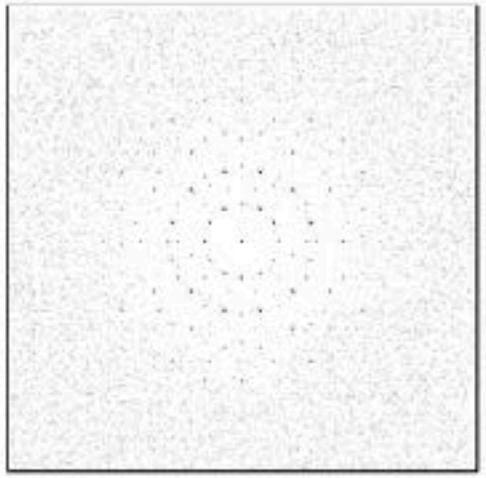
Fourier transform two equal-depth negative "incommensurate" minima

de Boer parameter $\Lambda = \sqrt{\frac{\hbar^2}{m r_0^2 V_0}}$

N=8192, t=0.03, ρr_0^2=0.8, Λ=0.1







Barkan, Engel and Lifshitz PRL 2014
Pupillo Ziherl and Cinti arxiv:1905.12073

Conclusions

- **Quantum fluctuations and crystallization**: hard-core and soft-core interactions.
- **Crystalline phases**: Triangular, superfluid stripes and quasicrystals.
- **Perspectives**: systematic characterization of the quantum phases with non-local potentials.

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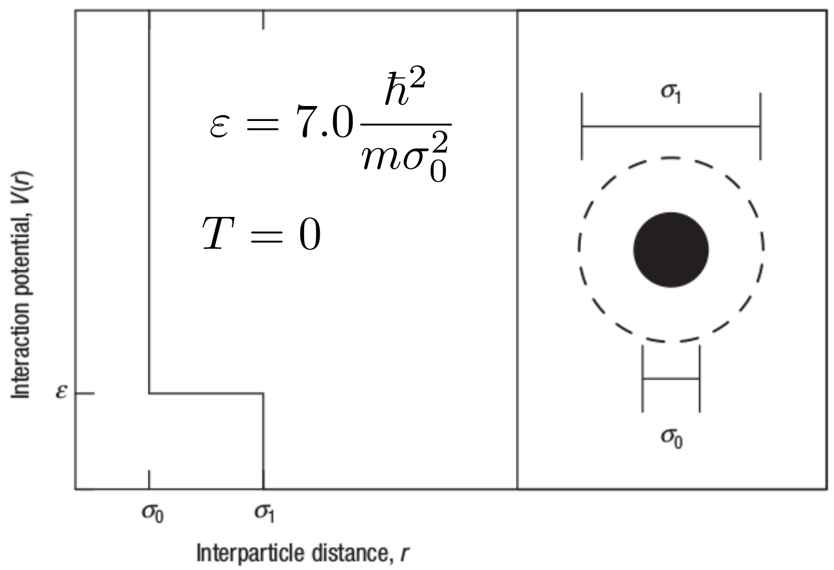

Cao-Berne approximation for the hard-core

See also S. Pilati & S. Giorgini

Semiclassical treatment of the soft-core potential

B. Abreu, F. Cinti, T.M. in preparation