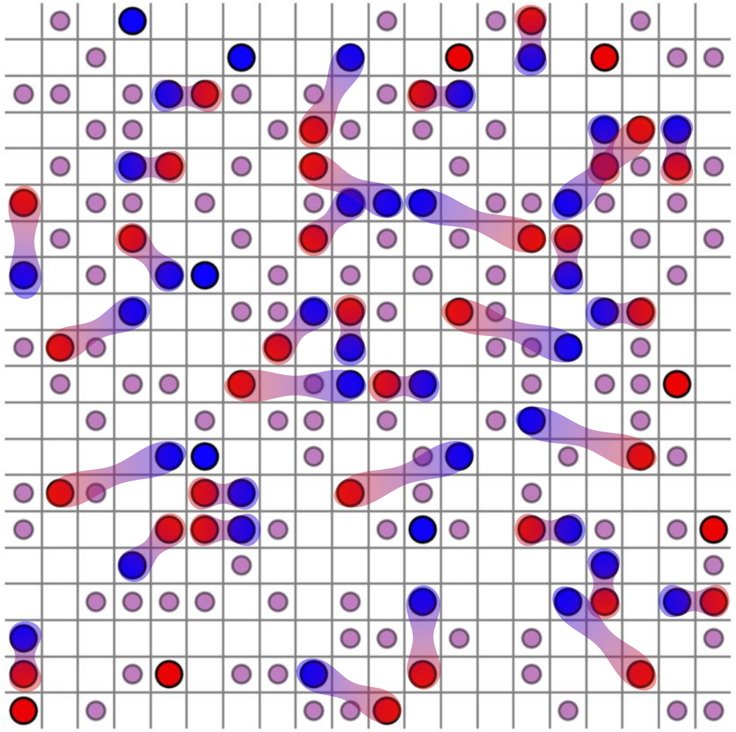
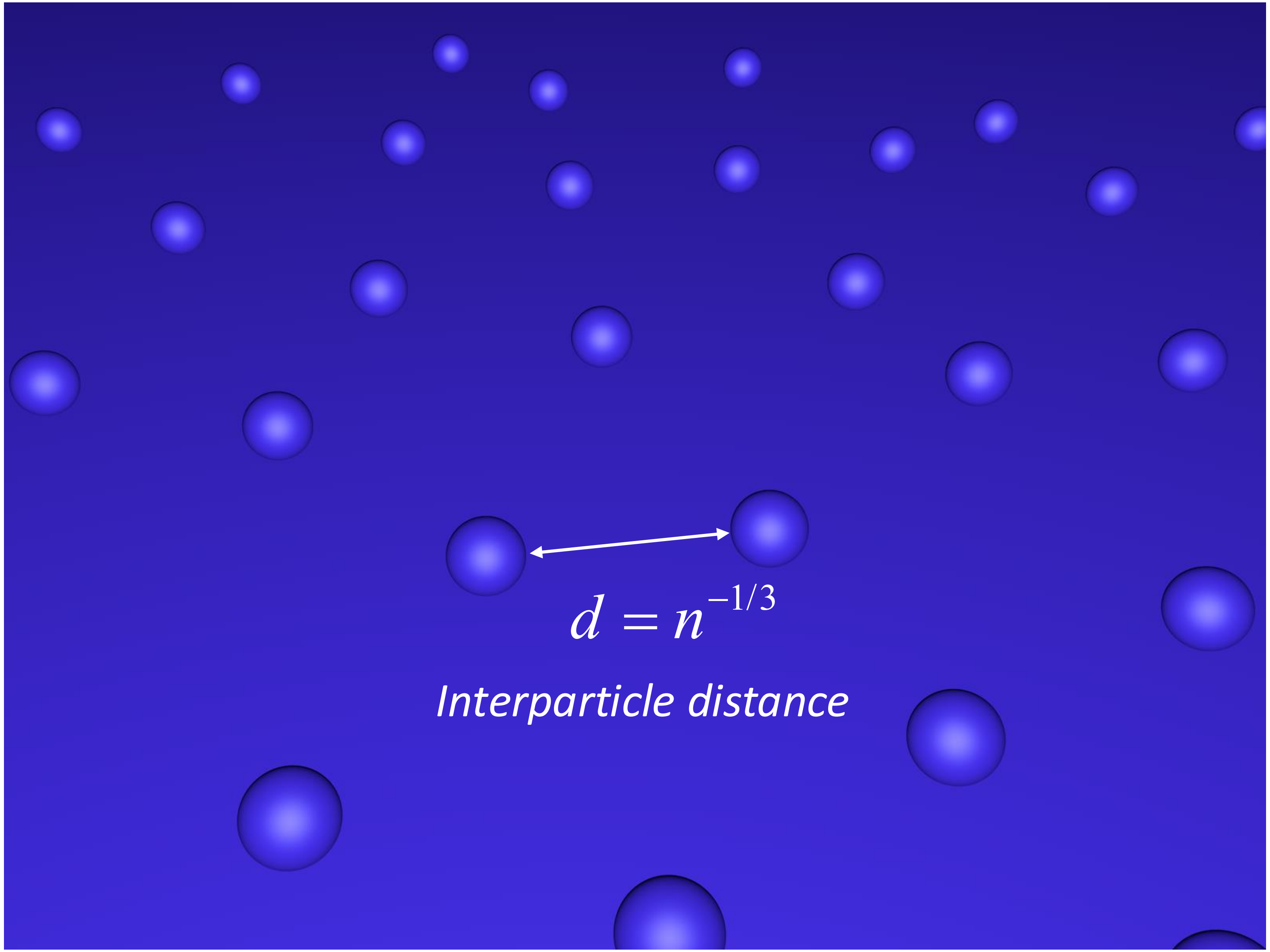
Fermi Legacy in Low-Temperature Physics, Accademia dei Lincei, Rome, Feb 5th 2026

Pairing and Superfluidity in Strongly Interacting Fermi Gases

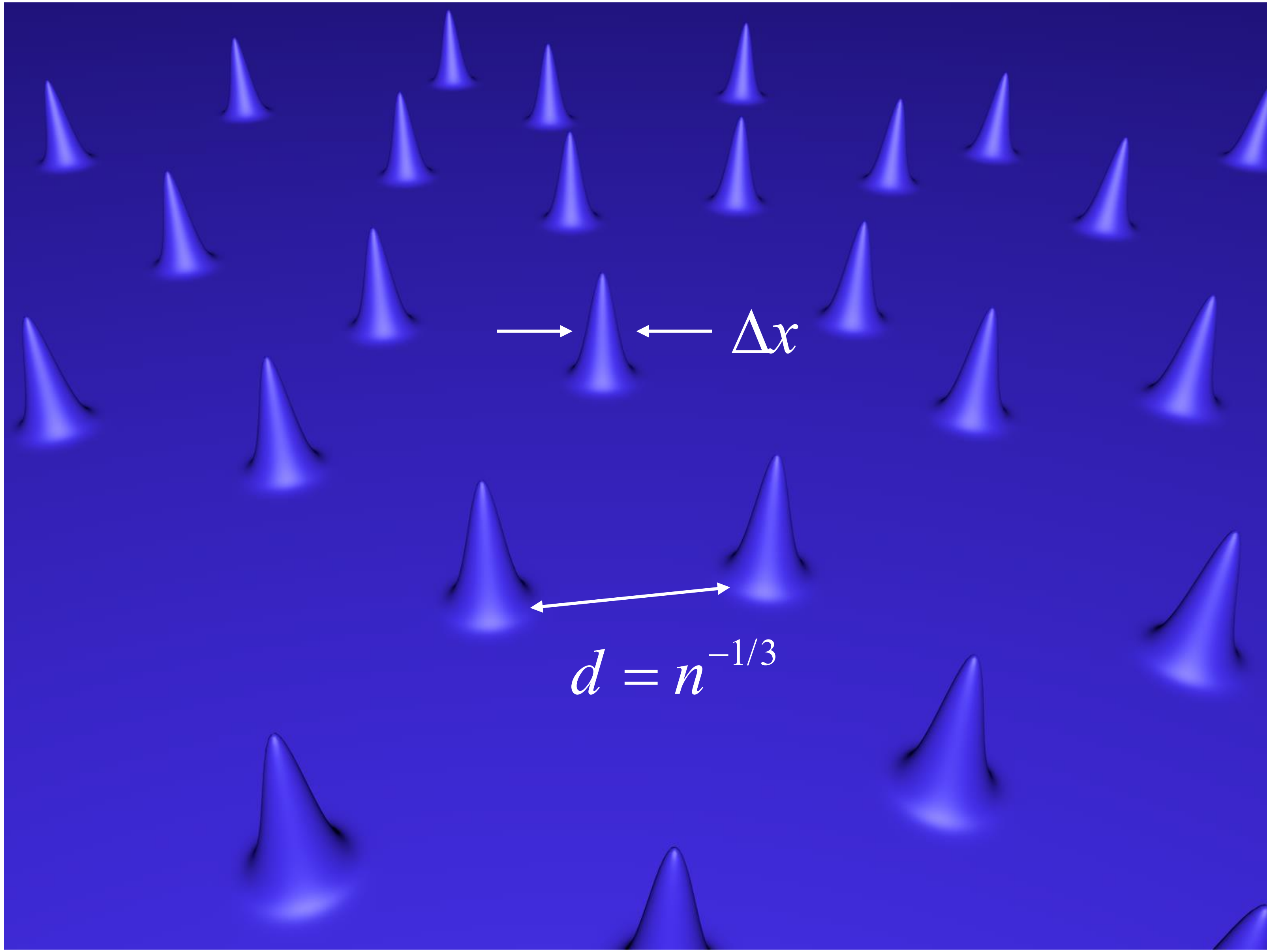
Martin Zwierlein
MIT, Center for Ultracold Atoms



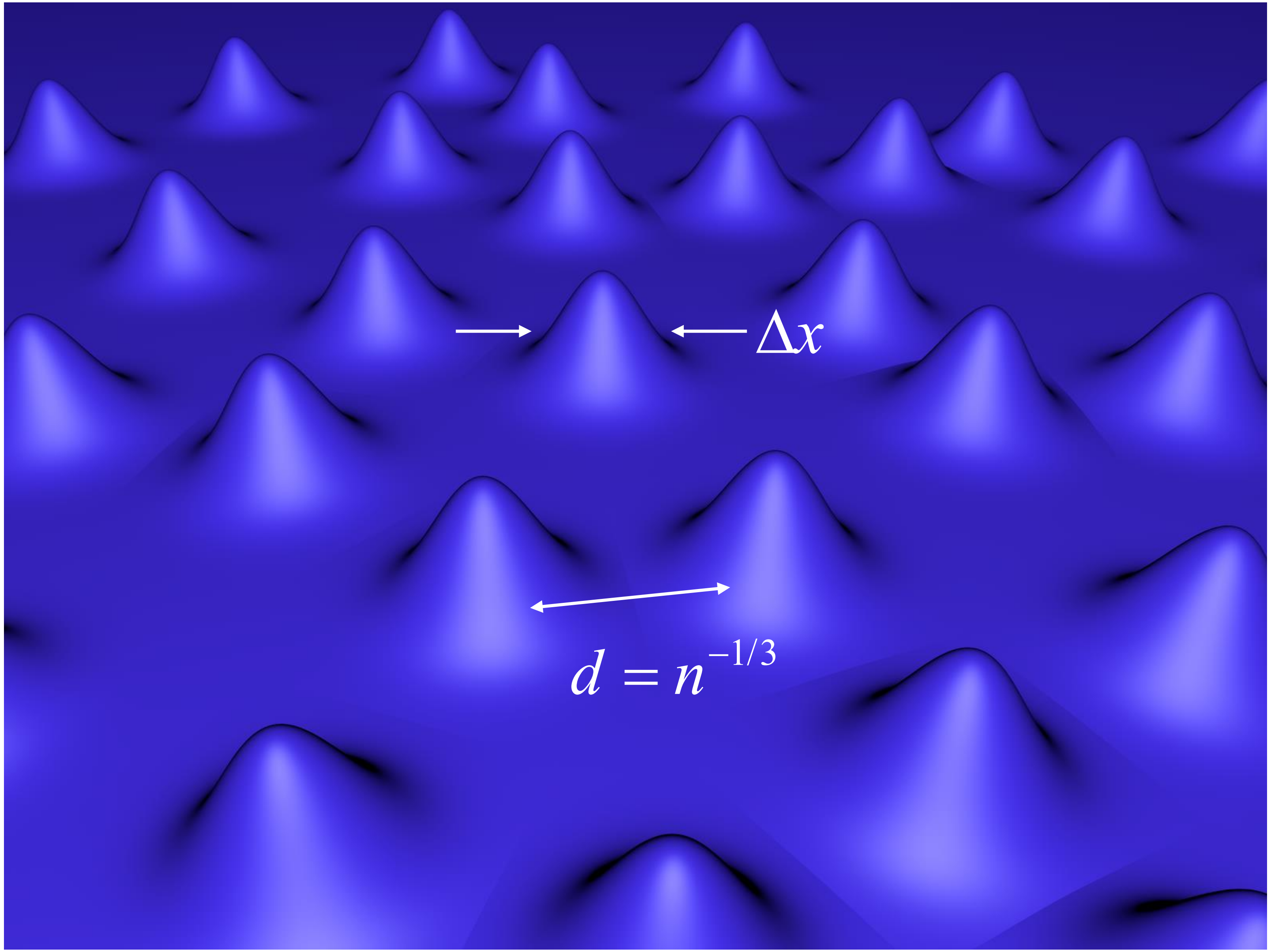
Particles...



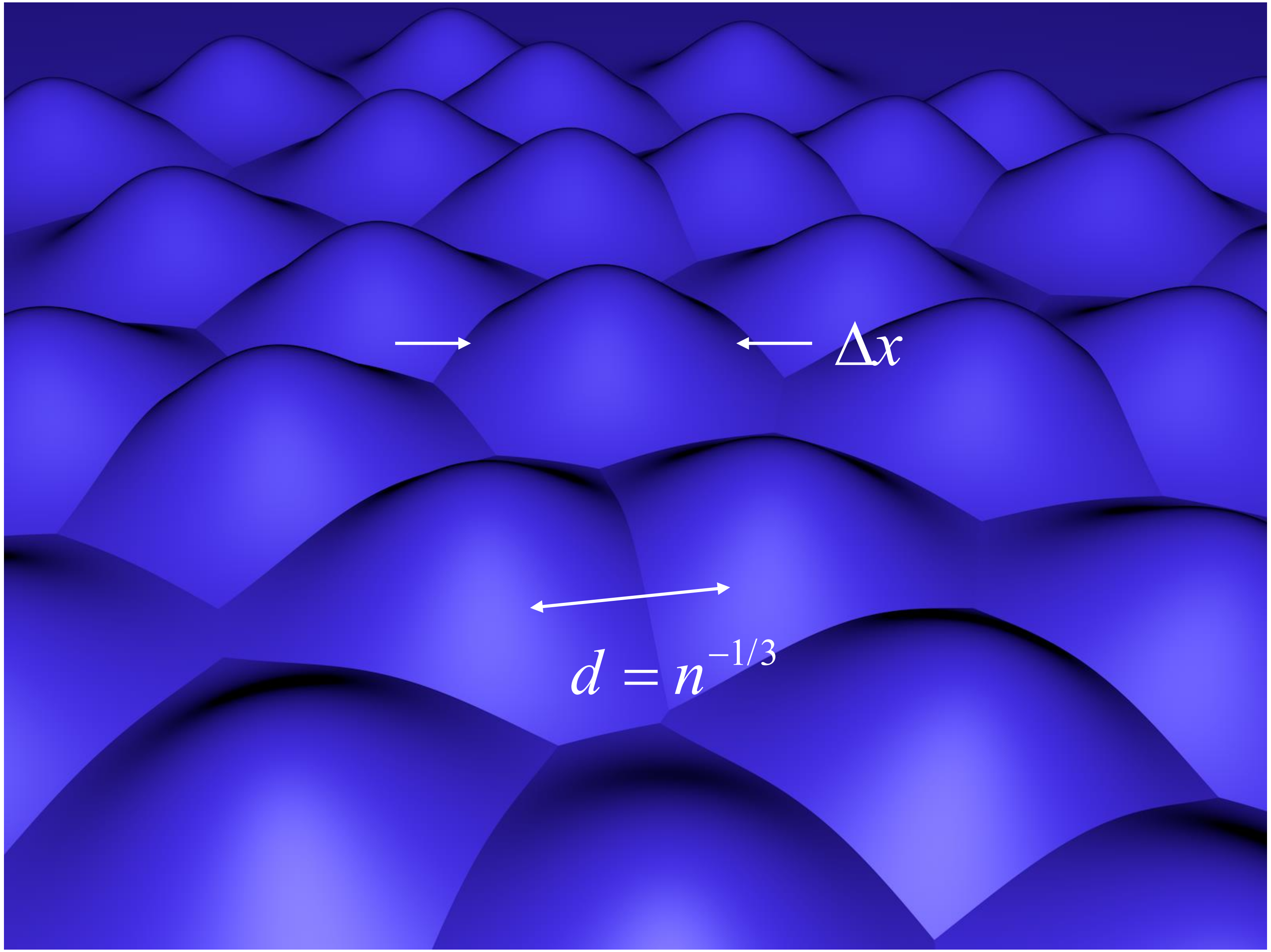
...behave as waves



When does wave mechanics matter?



When does wave mechanics matter?



Fermi's Paper

SULLA QUANTIZZAZIONE DEL GAS PERFETTO MONOATOMICO

« Rend. Lincei », 3, 145–149 (1926) (*).

- Applies Pauli's principle to motional states!
- Obtains the equation of state of the ideal gas under this constraint

$$p = \frac{2}{3} n \bar{L} = \frac{h^2 n^{5/3}}{2\pi m} P\left(\frac{2\pi m k T}{h^2 n^{2/3}}\right)$$

So that is $$p = \frac{2}{5} n E_F P\left(\frac{T}{T_F}\right)$$

with Fermi Energy

$$E_F = k_B T_F$$

Bosons versus Fermions

Fermions (unsociable):

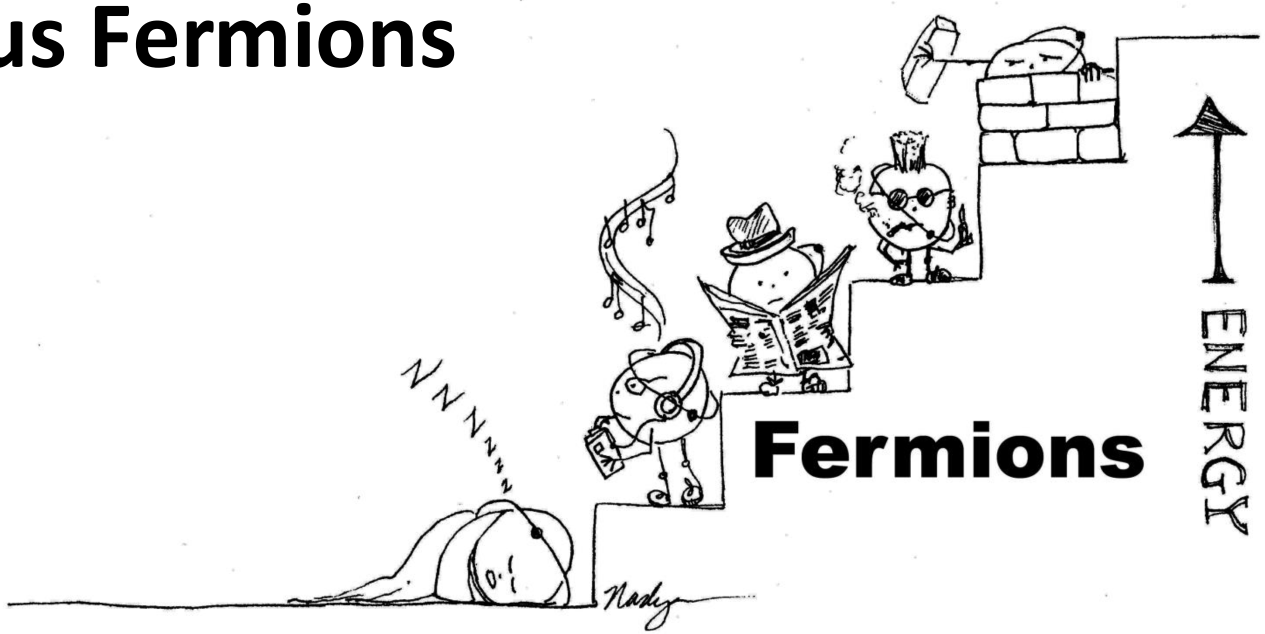
Half-Integer Spin

Pauli blocking → Form Fermi sea

No phase transition at low Temperature

Fermi Feb. 7, 1926

Dirac Oct. 1926



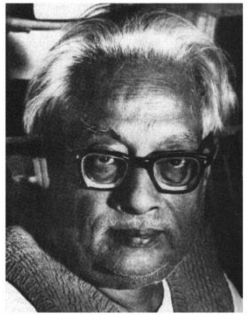
Bosons (sociable):

Integer Spin

Can share quantum states

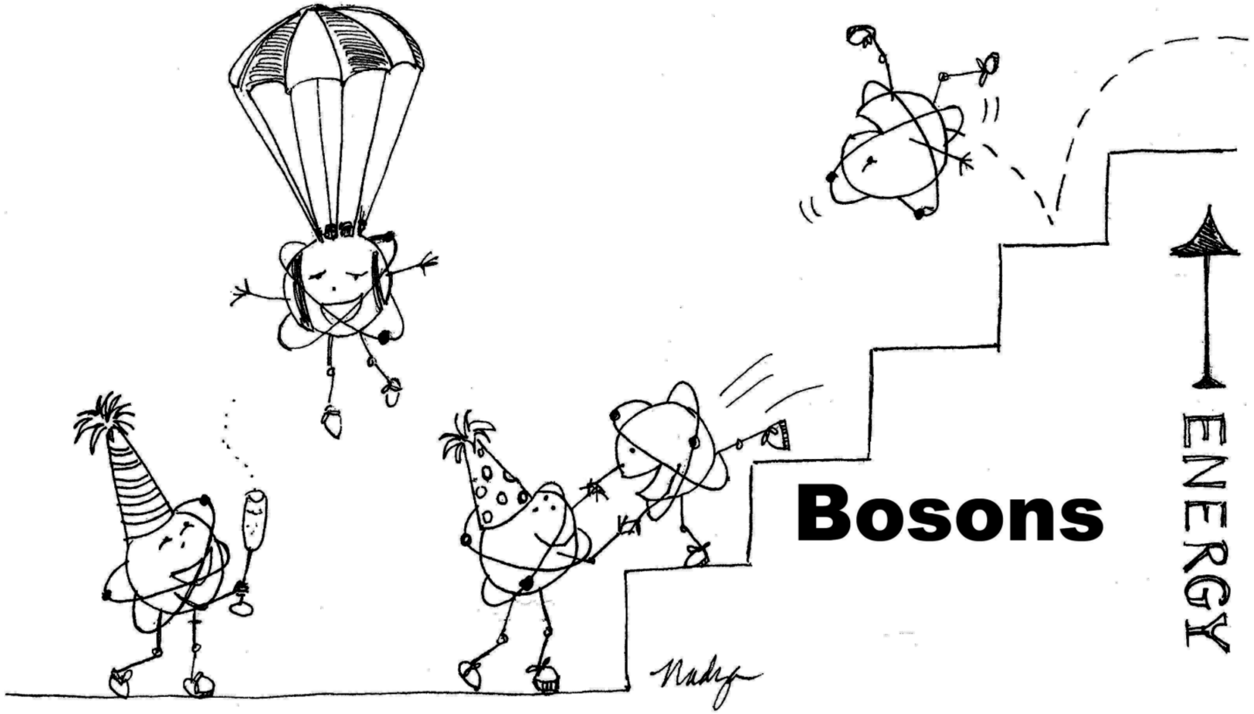
At low temperatures:

Bose-Einstein condensation

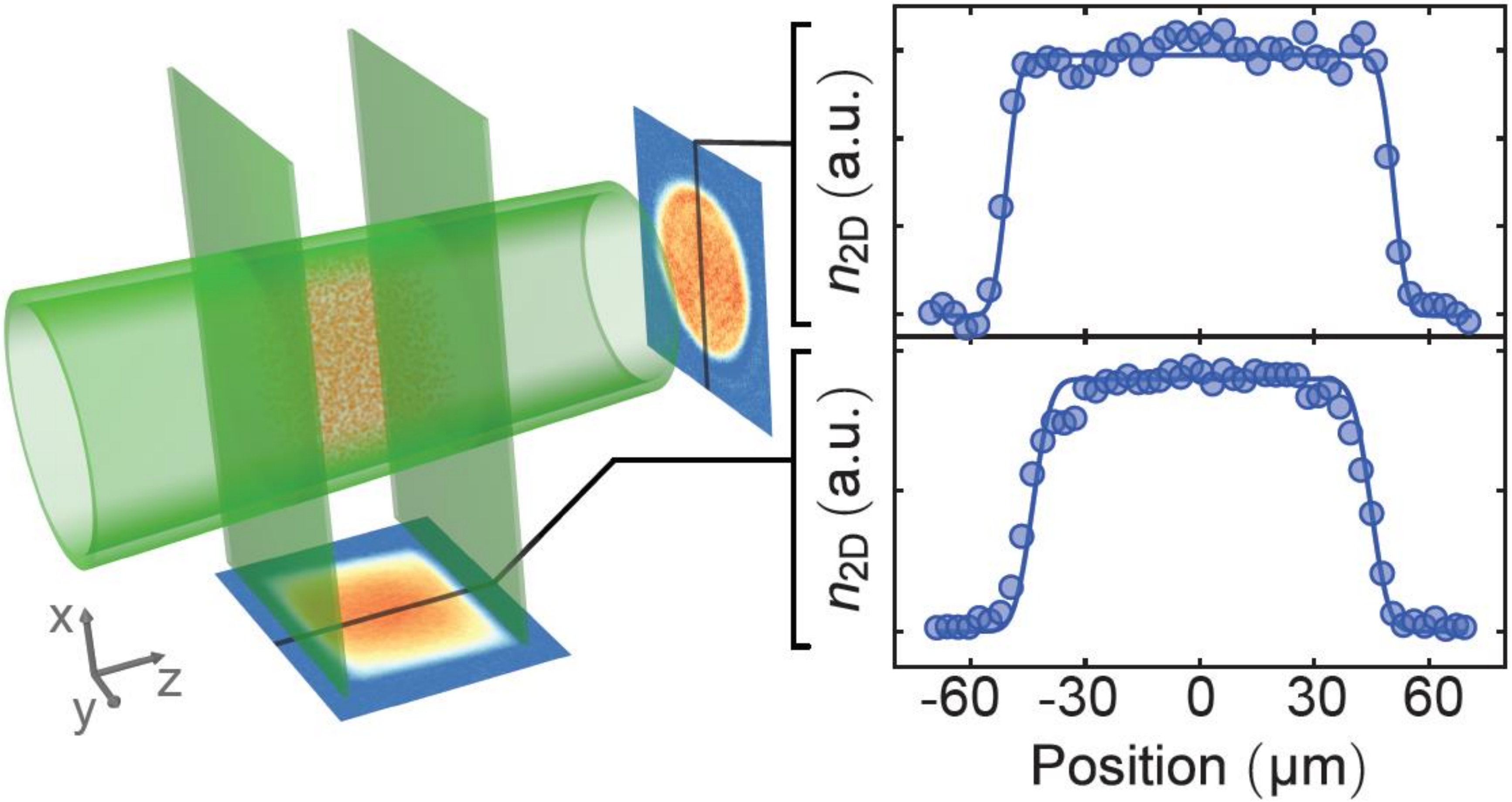


Bose 1924

Einstein 1924/25



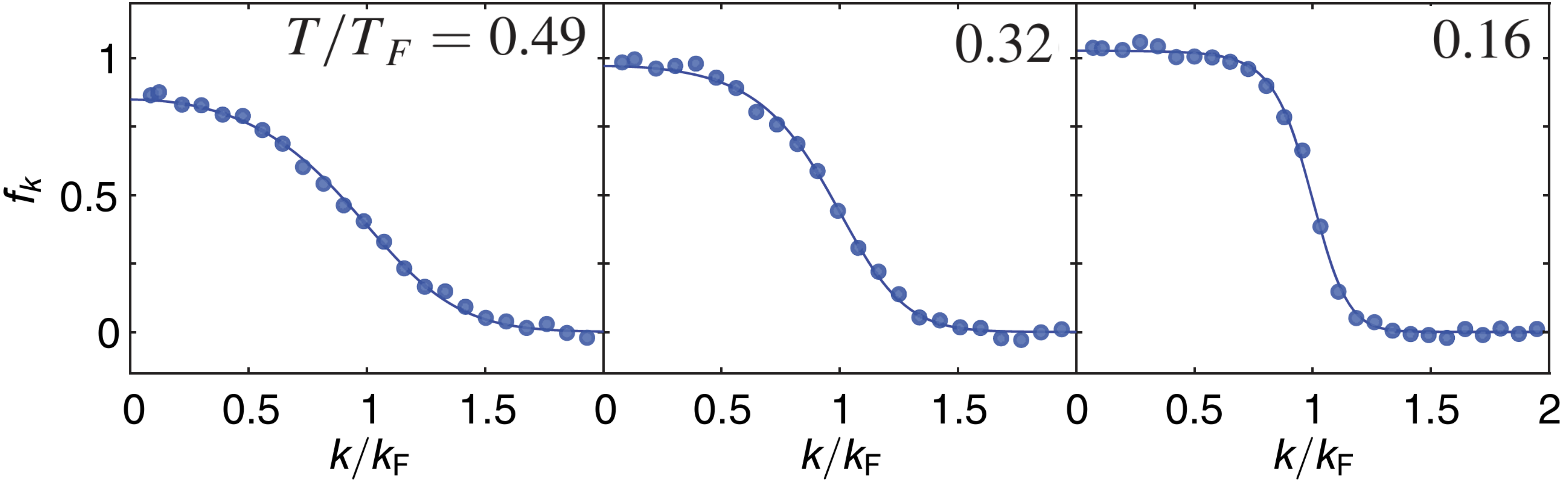
Fermions in a Box

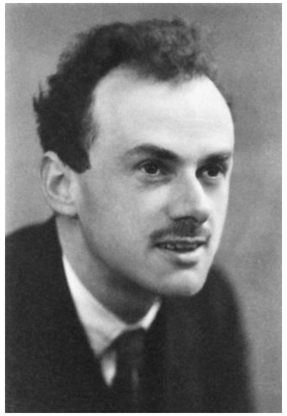


Time of Flight:

Z. Yan, P. Patel, B. Mukherjee, Z. Hadzibabic, T. Yefsah, J. Struck, MWZ, PRL 2017

Measuring the Fermi-Dirac distribution



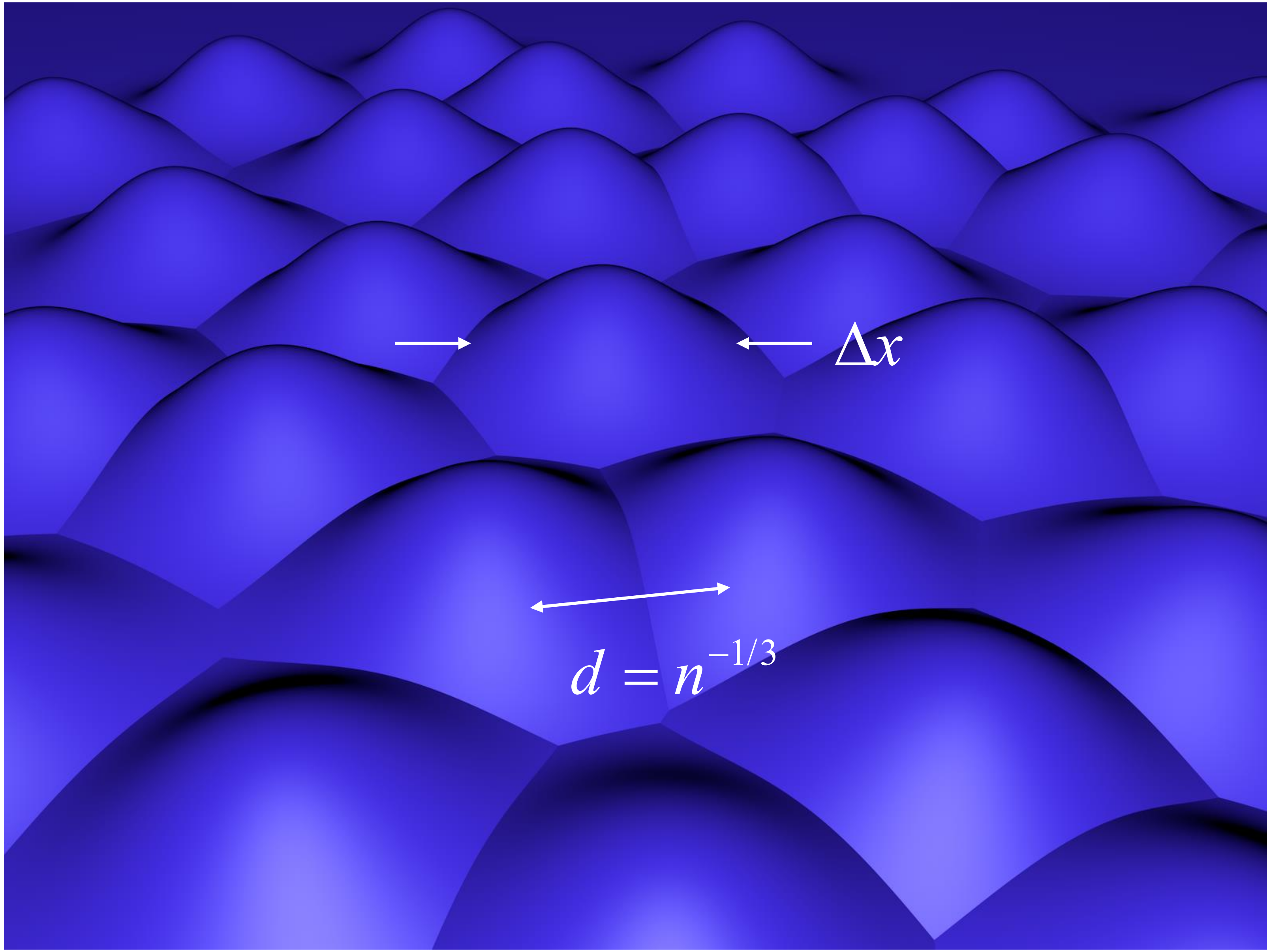


$$f_k = \frac{1}{e^{\beta(\epsilon_k - \mu)} + 1}$$

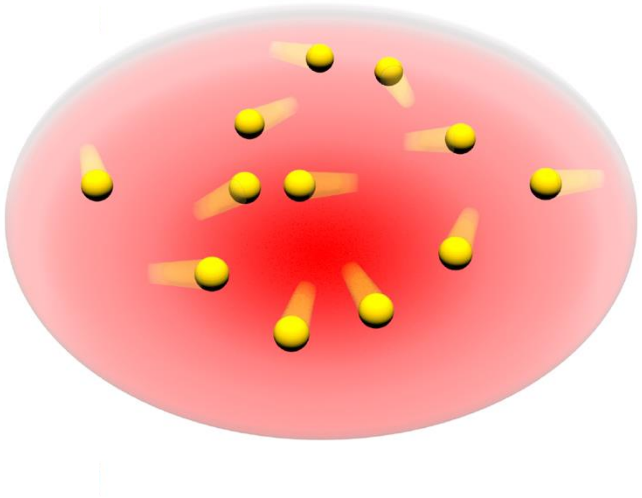
100th anniversary

Z. Yan, P. Patel, B. Mukherjee, Z. Hadzibabic, T. Yefsah, J. Struck, MZ, PRL 2017

Can one “see” the de Broglie waves in situ?



Build a “continuum” quantum gas microscope



R Yao, S Chi, M Wang, RJ Fletcher, MZ, PRL **134**, 183402 (2025);
see also: Fermions: Yefsah group, PRL **134**, 183403 (2025), Bosons: Ketterle group, PRL **134**, 183401 (2025)

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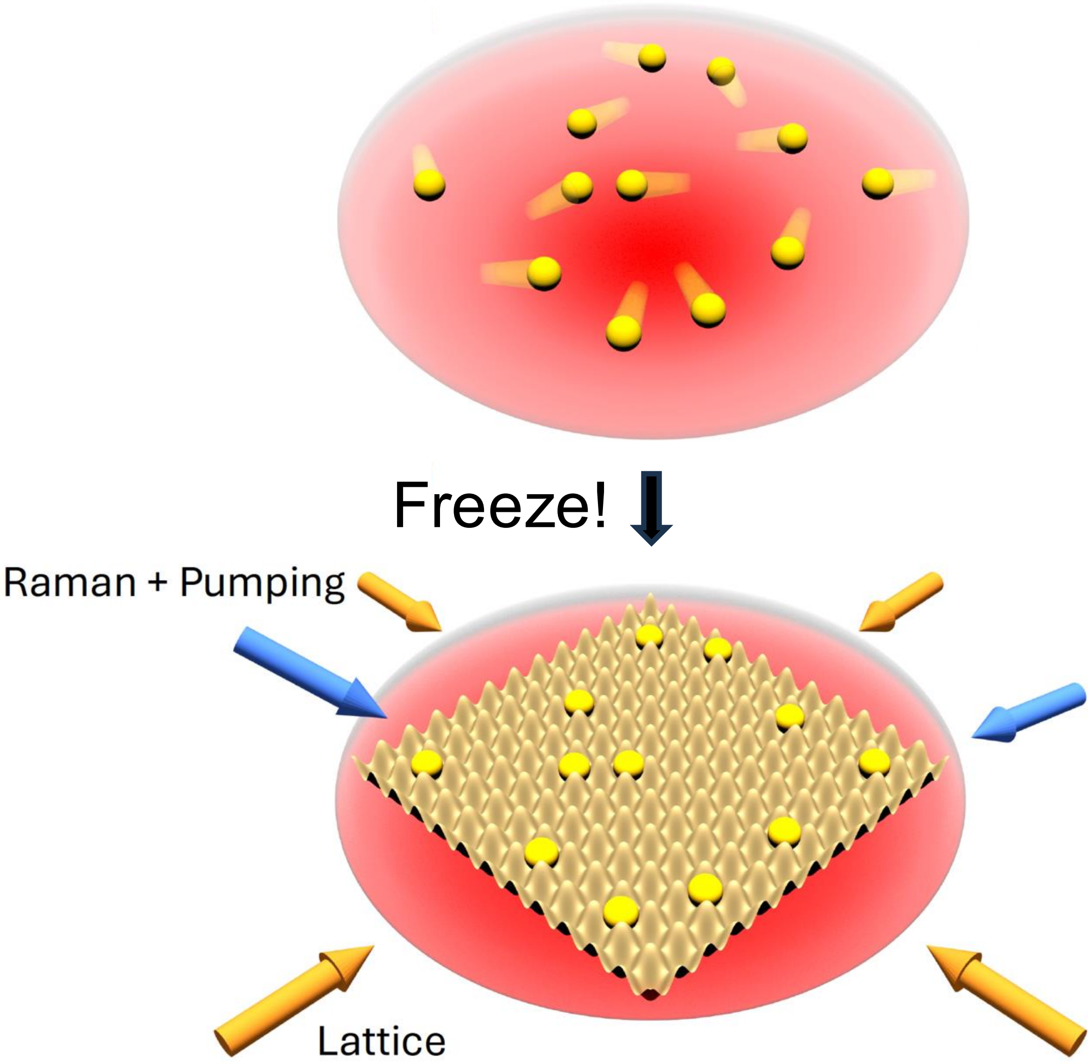

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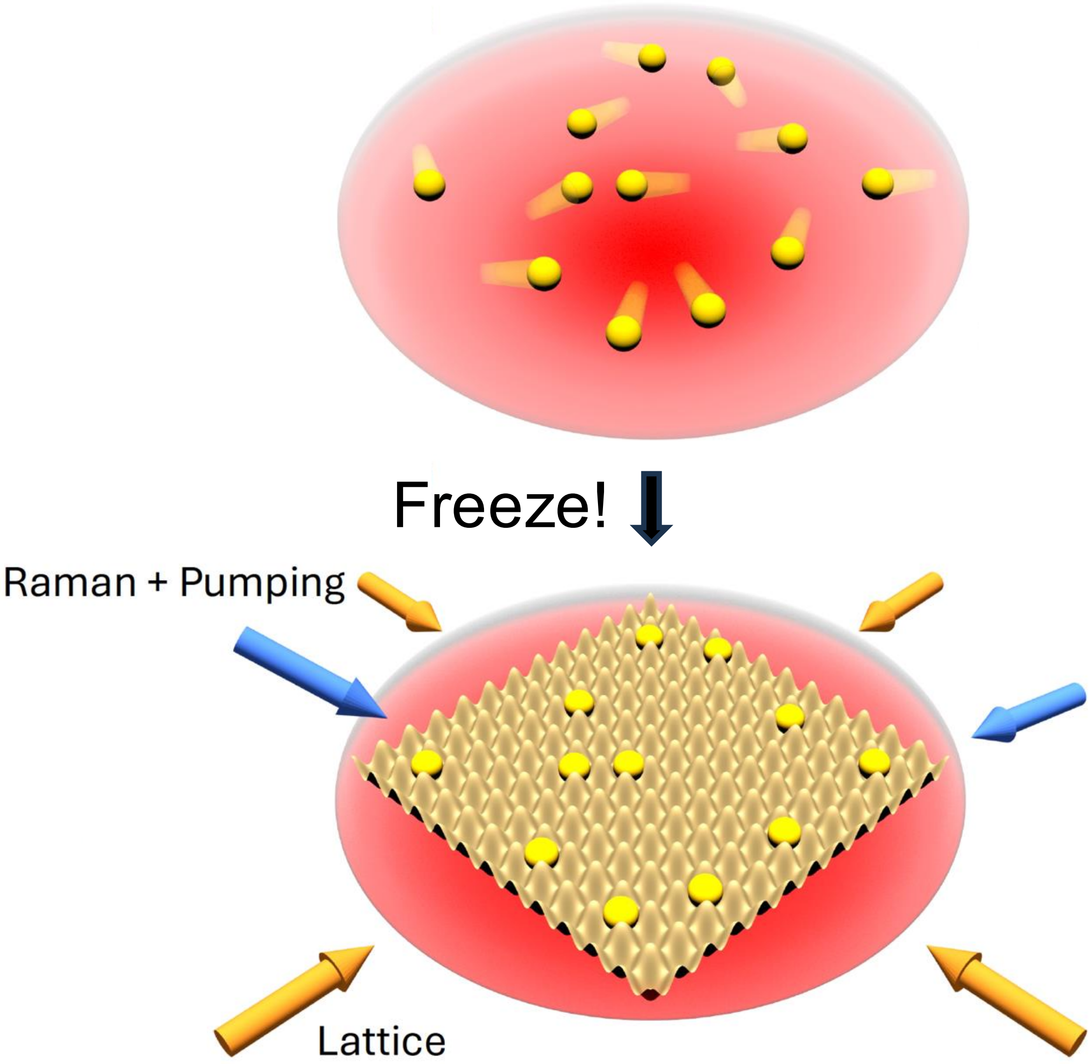
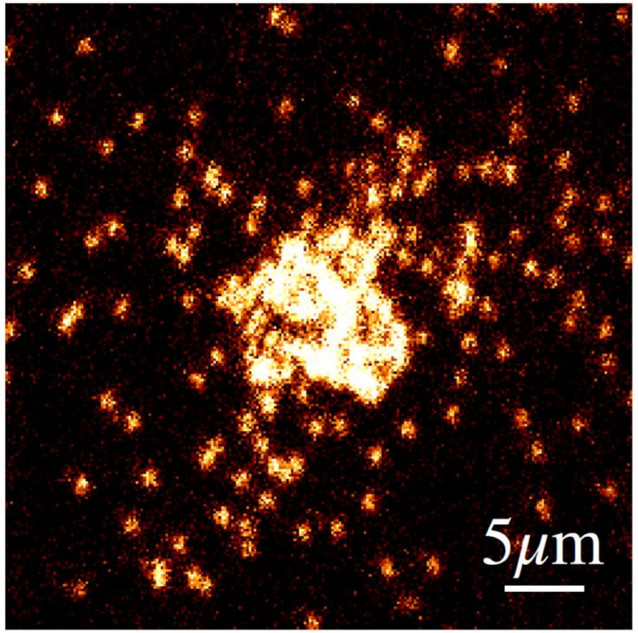


Bosons



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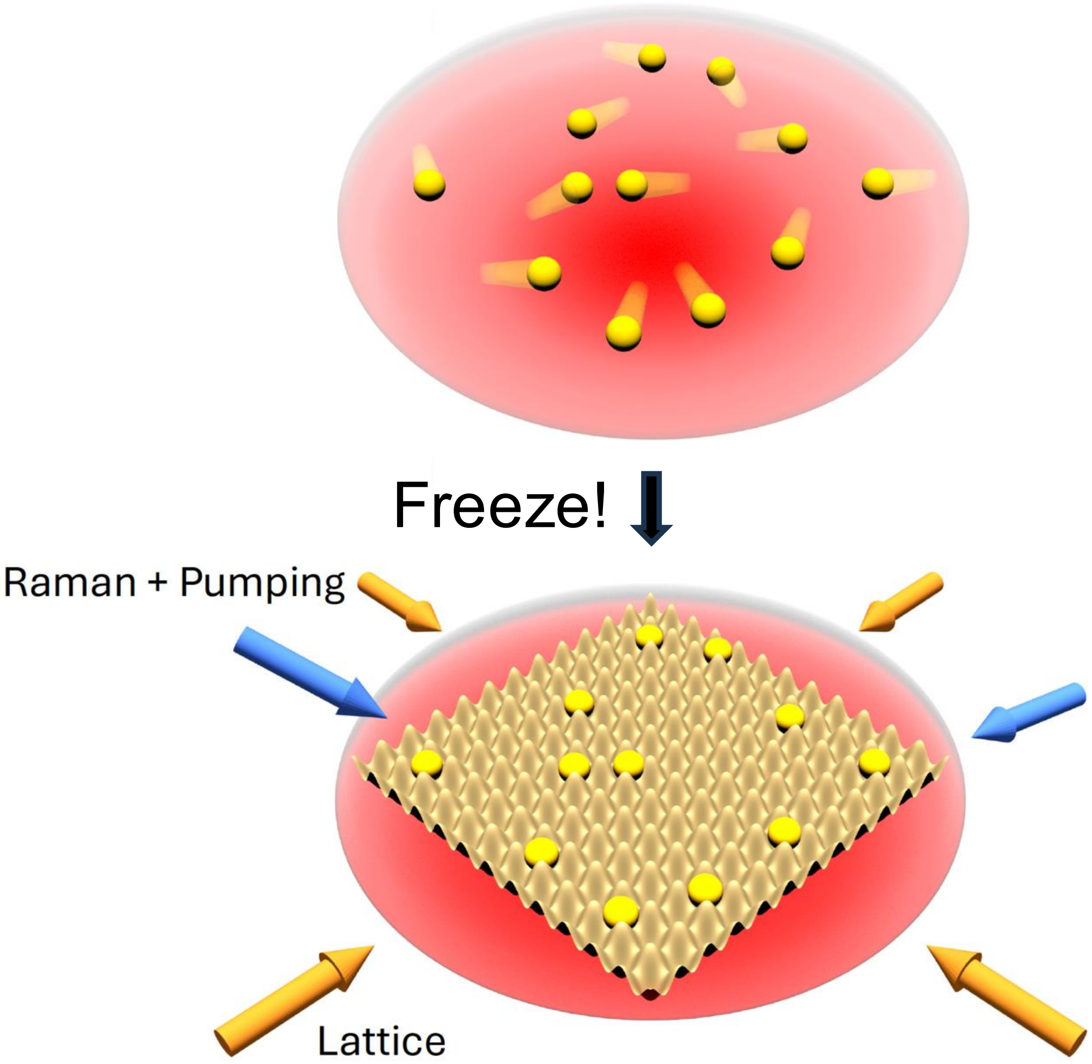
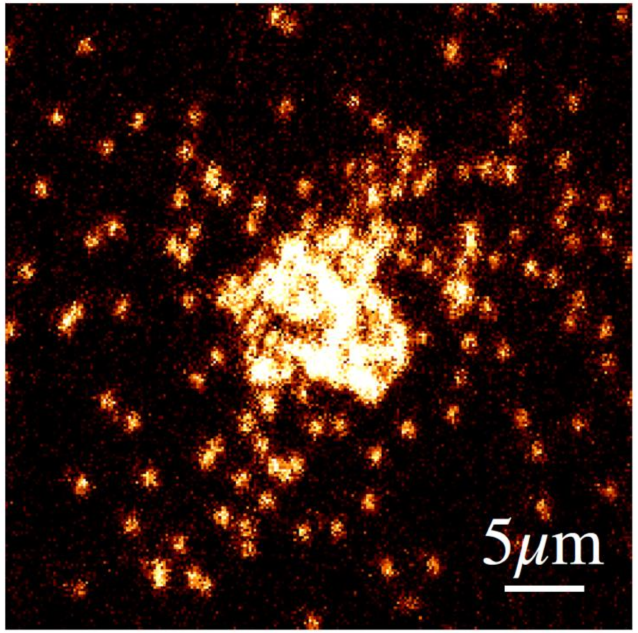
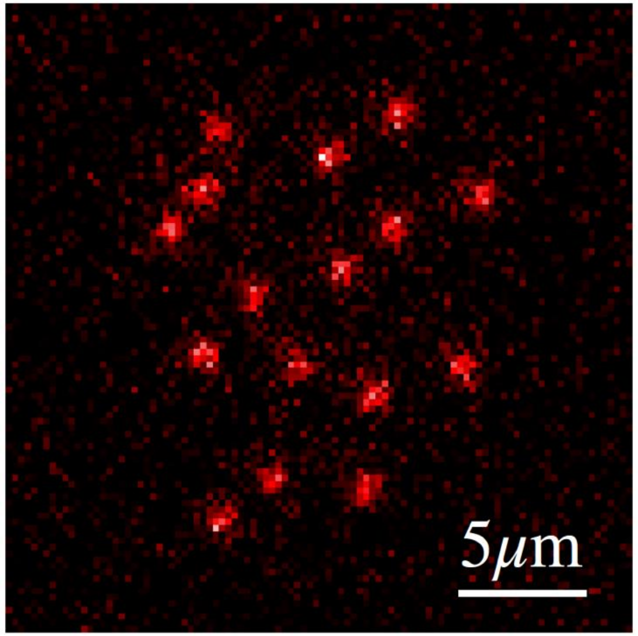


Bosons



Fermions



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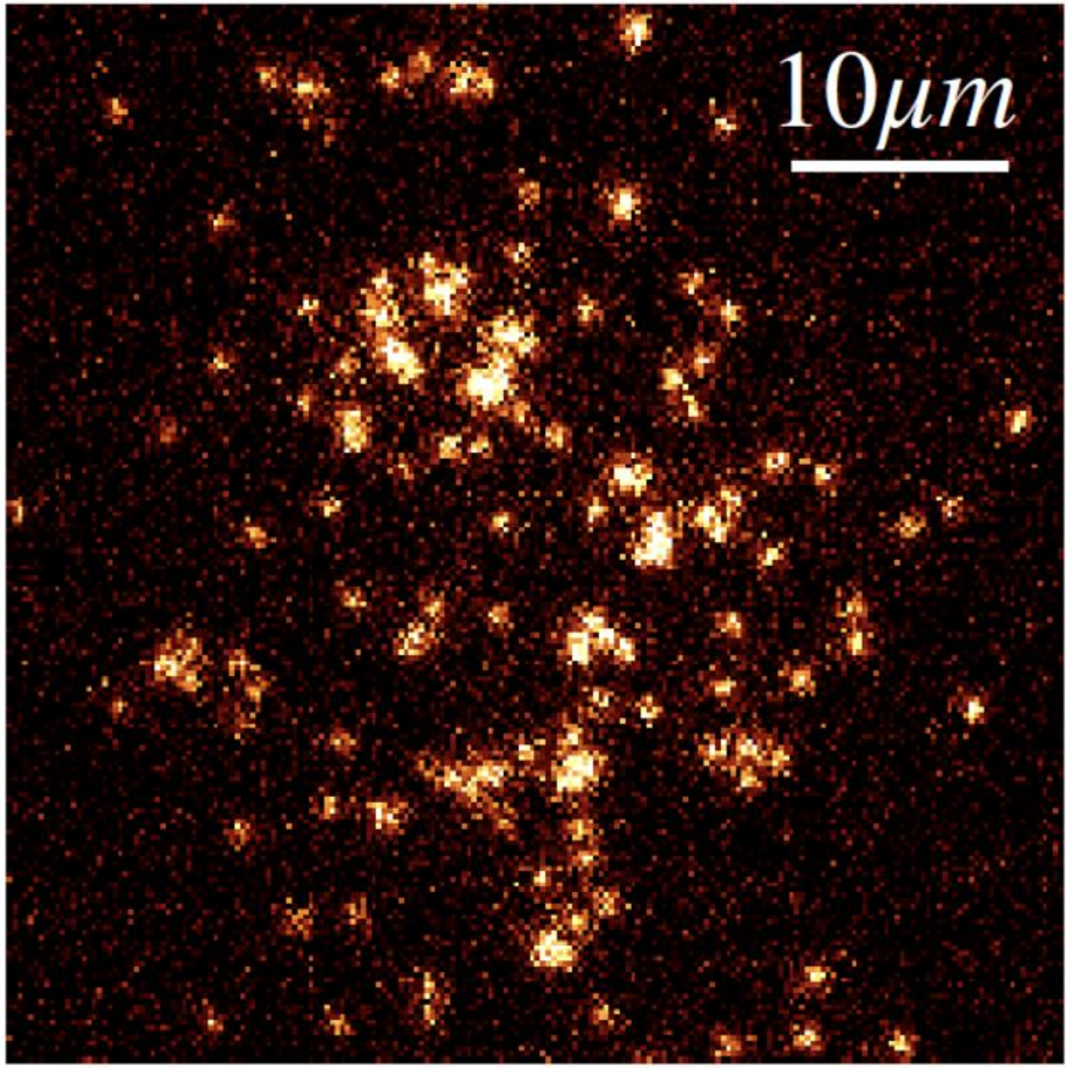
Fermions: Yefsah group, PRL **134**, 183403, Bosons: Ketterle group, PRL **134**, 183401

Pair correlation function $g^{(2)}(r)$

Thermal

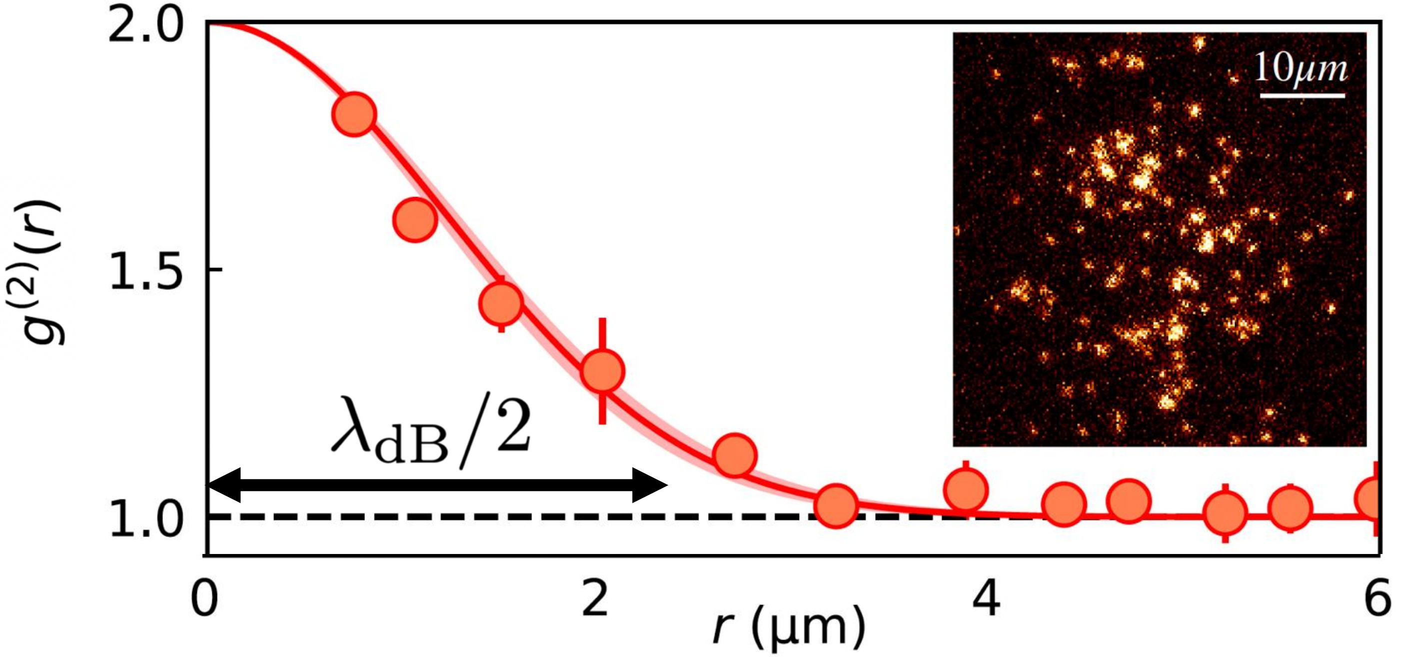
Bosons



R Yao, S Chi, M Wang,
RJ Fletcher, MZ, arXiv:2411.08780

Pair correlation function $g^{(2)}(r)$

Thermal
Bosons

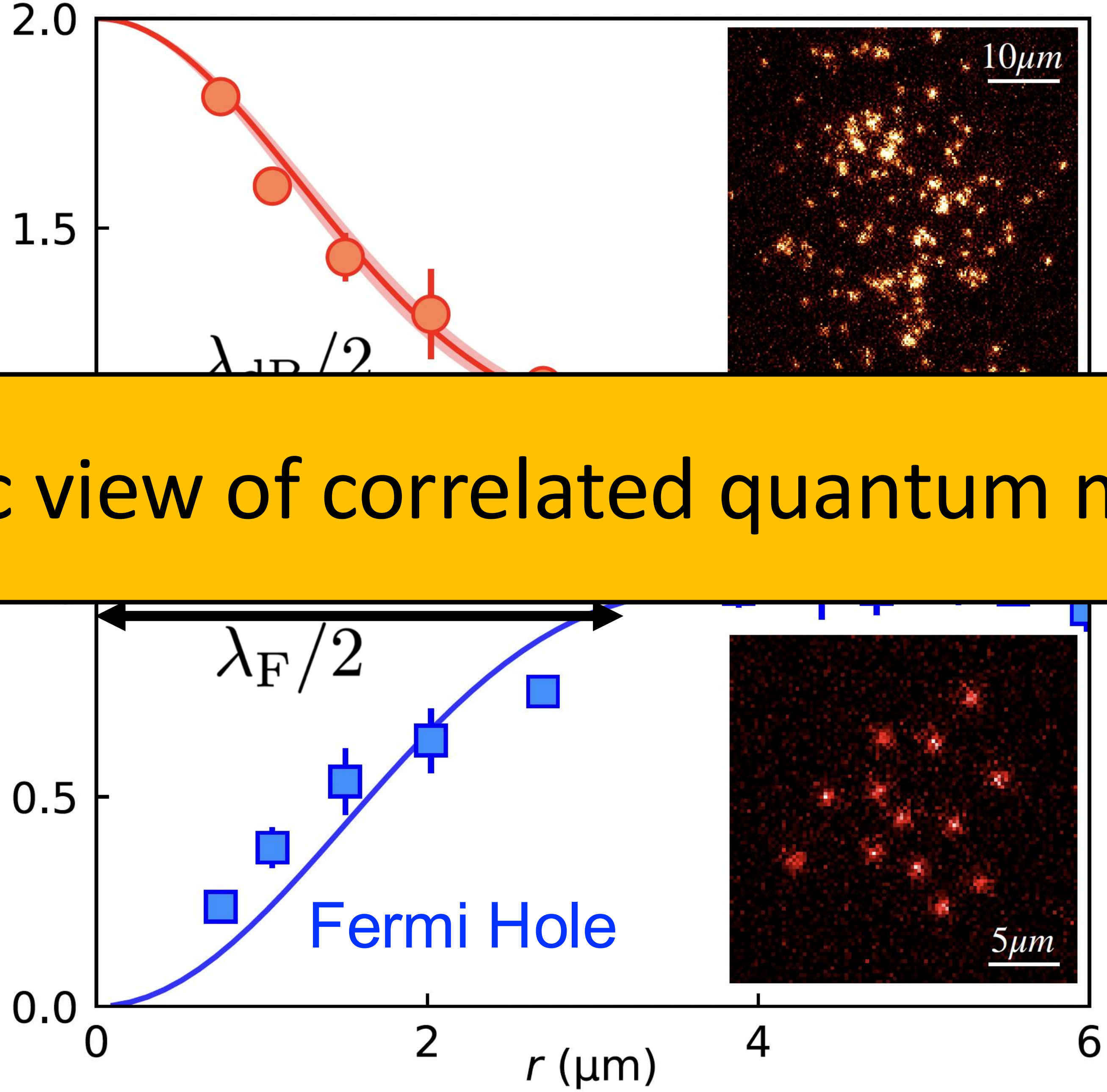


T = 6.9(3) nK

R Yao, S Chi, M Wang,
RJ Fletcher, MZ, arXiv:2411.08780

Pair correlation function $g^{(2)}(r)$

Thermal
Bosons



T = 6.9(3) nK

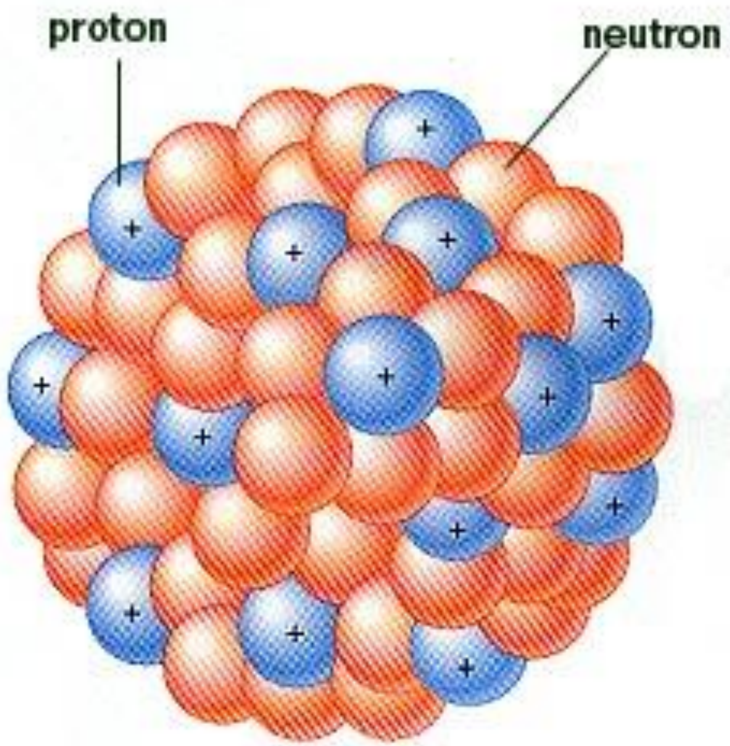
A microscopic view of correlated quantum matter

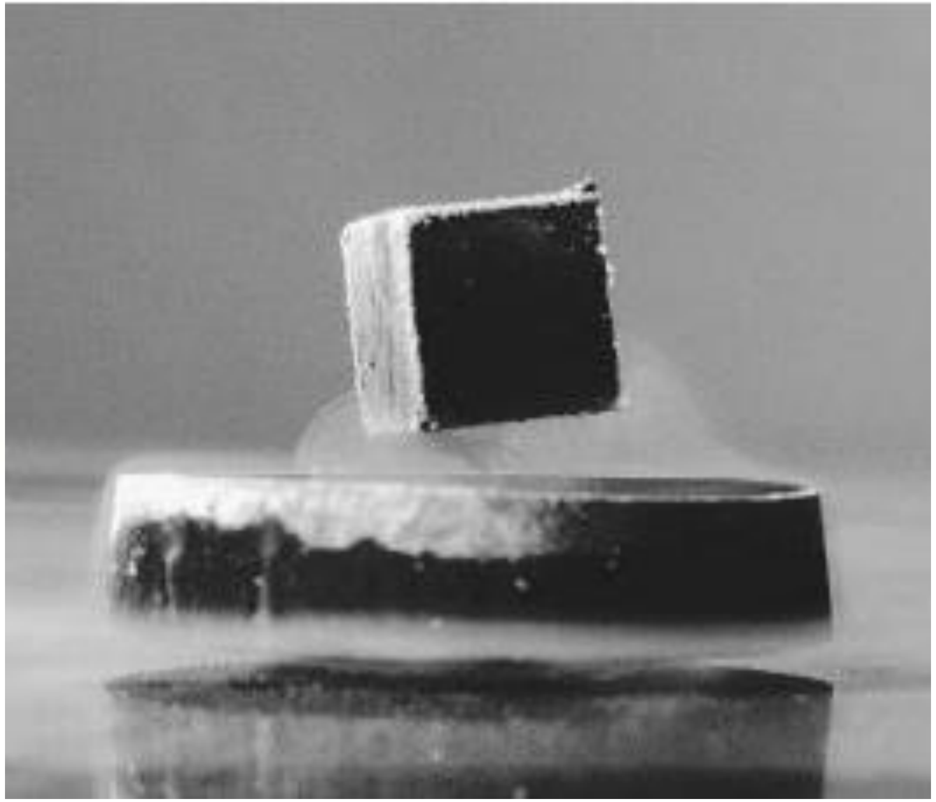
Fermions

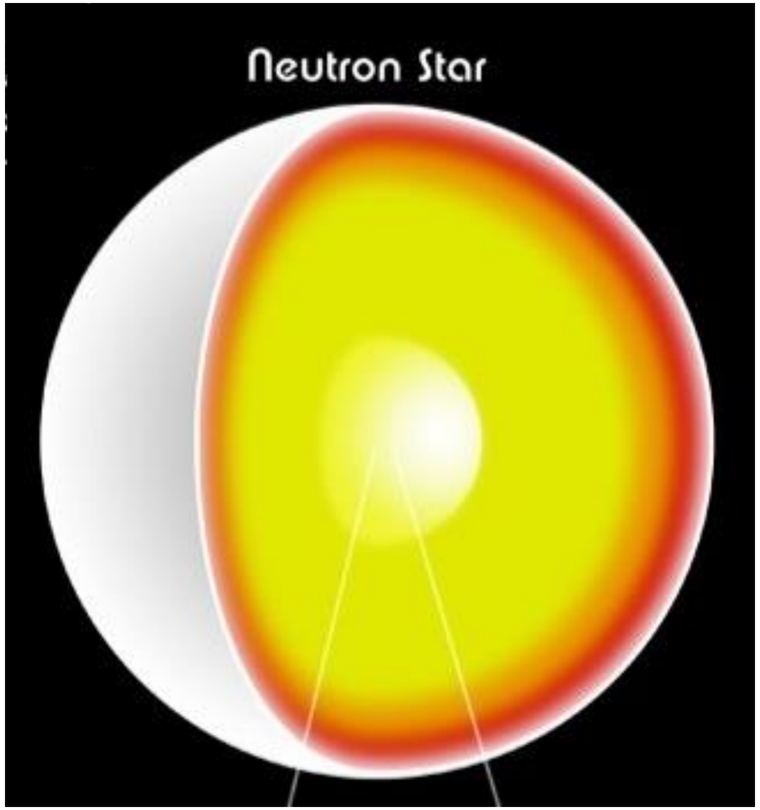
T = 3.7(3) nK
T_F= 45 nK
T/T_F=0.08

R Yao, S Chi, M Wang,
RJ Fletcher, MZ, arXiv:2411.08780

Matter is made of Fermions







Nuclei 10^{-15} m

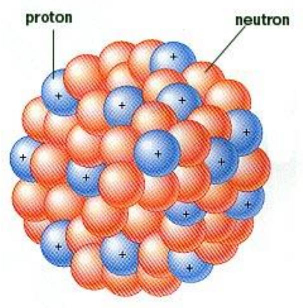
Superconductors 1 cm

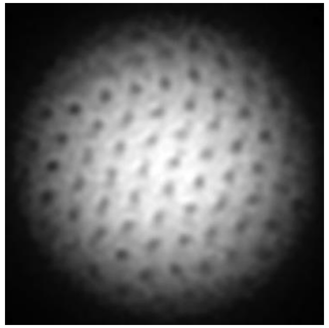
Neutron Stars 20 km

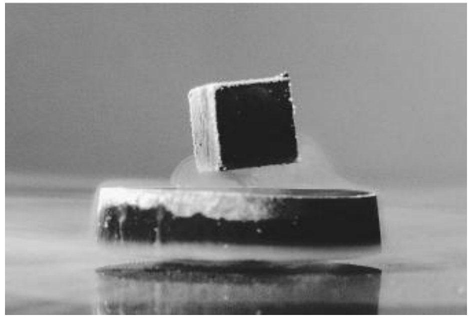
Strongly Correlated Fermi Systems

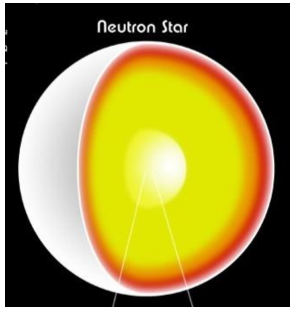
Length scales

10^{-15} m | 1 mm | 1 m | 10^4 m | 10^7 m









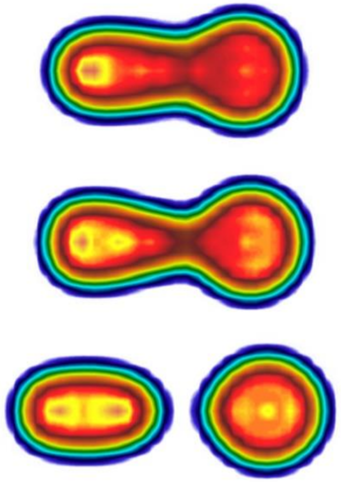
Nuclei

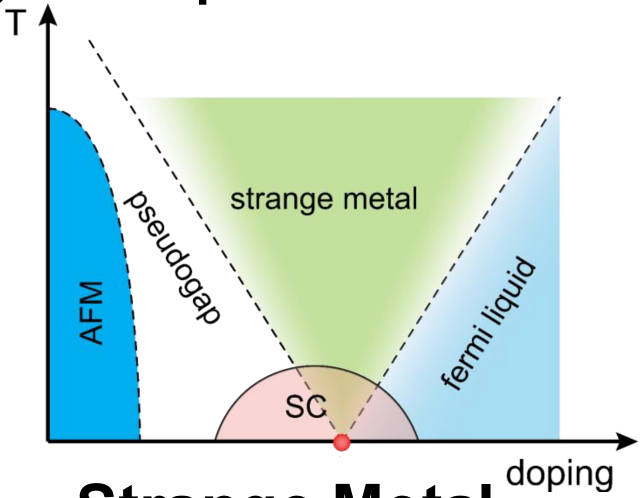
Ultracold Gases

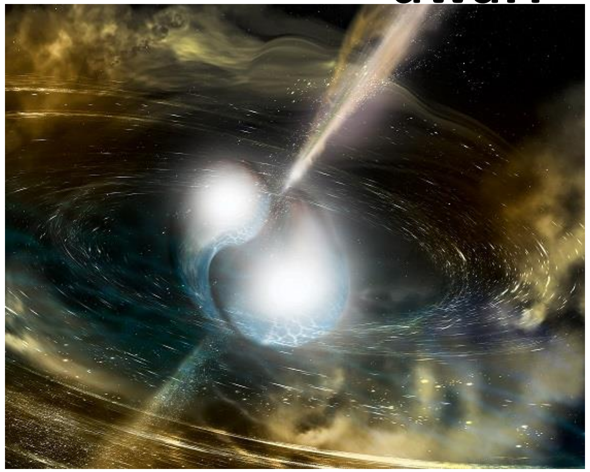
High-T_c Superconductors

Neutron Star

White dwarf







Nuclear Fission

Bulgac et al., PRL 116, 122504 (2016)

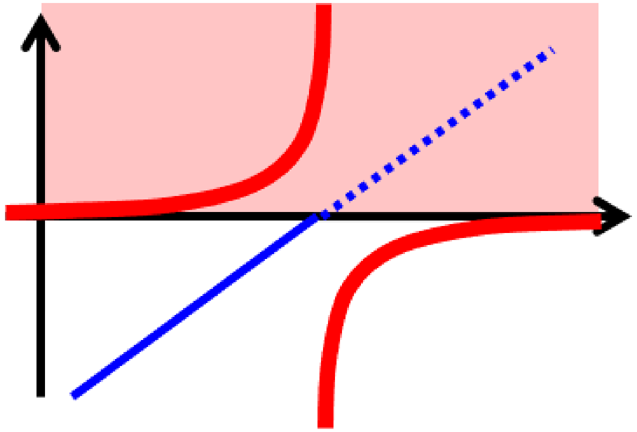
Strange Metal

Neutron Star Merger

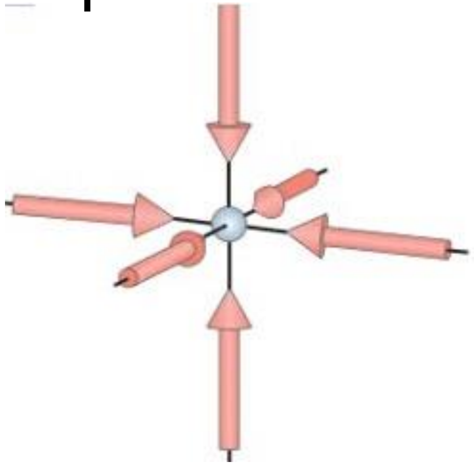
NSF/LIGO/Somona/A. Simonnet

Realizing strongly interacting Fermi systems

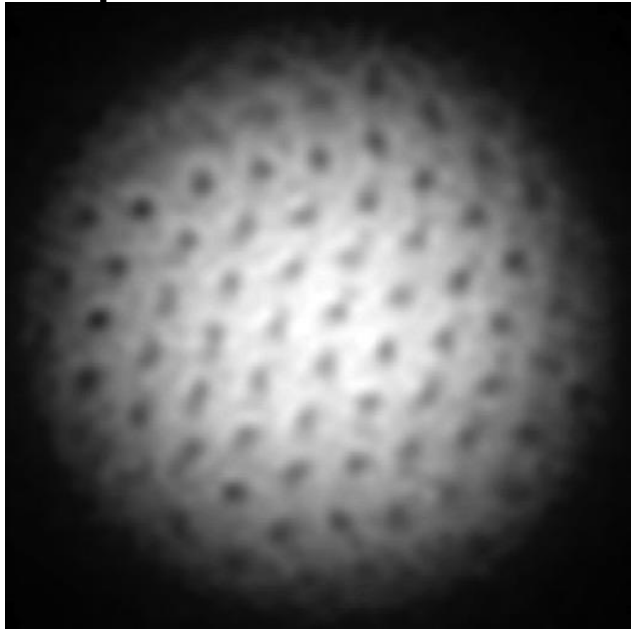
Feshbach Resonances



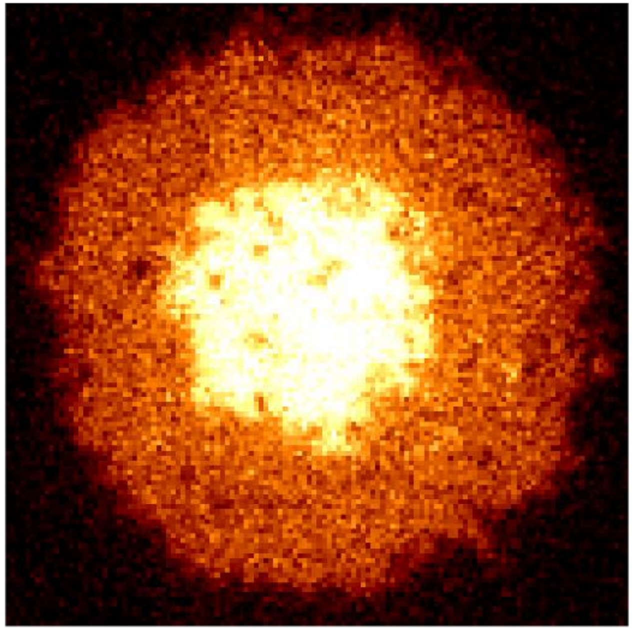
Optical Lattices



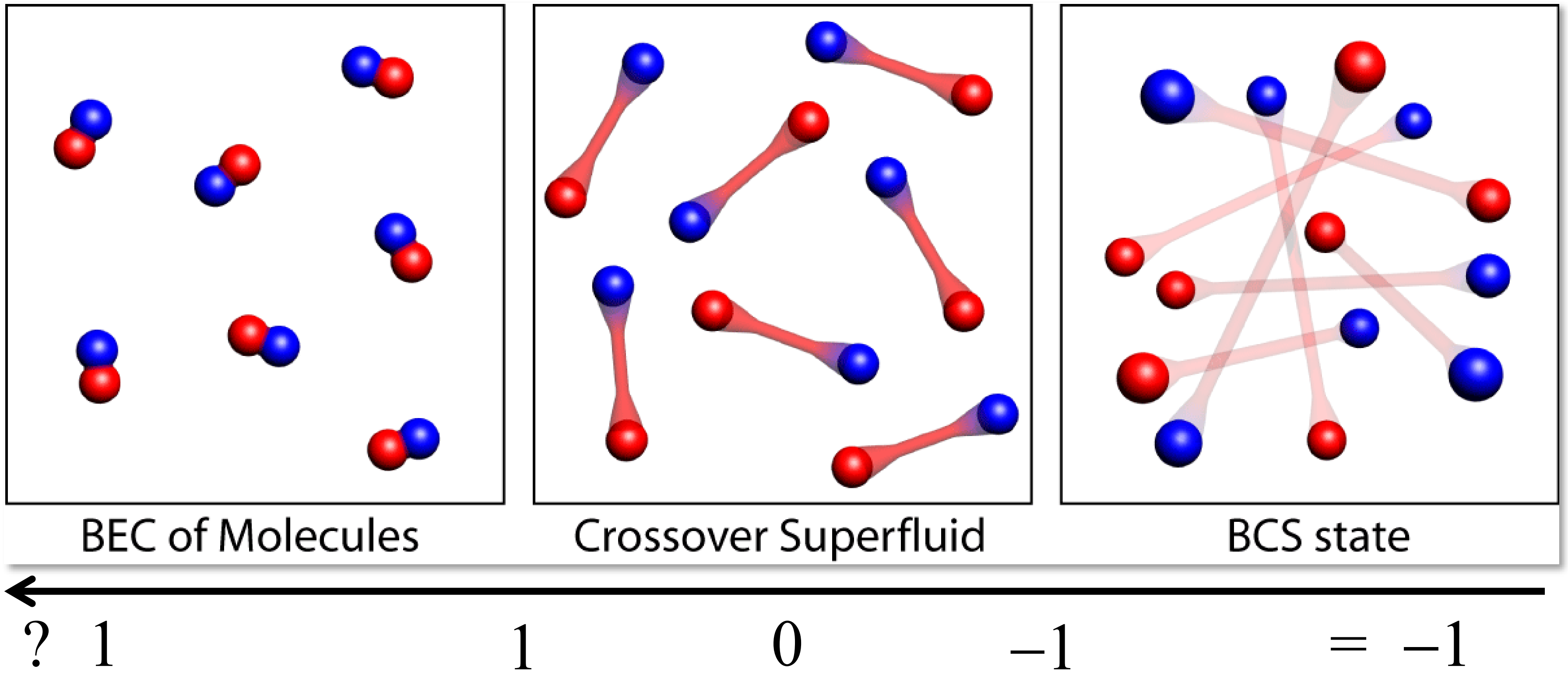
Superfluid Fermi Gas



Fermi-Hubbard Gas



Superfluid Fermi Gas – From BEC to BCS



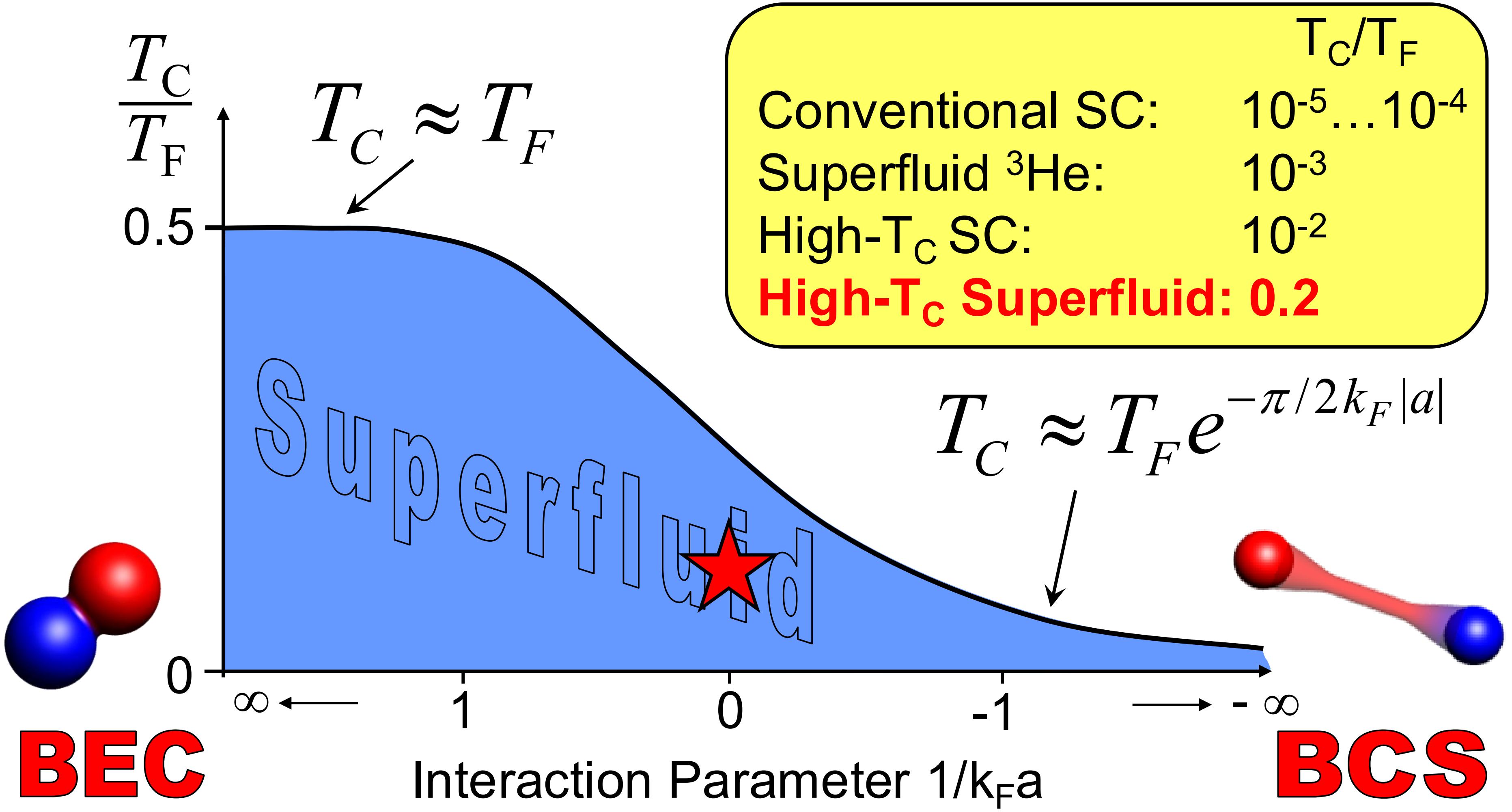
$$(k_F a)^{-1} = \frac{\text{Interparticle Distance}}{\text{Scattering Length}}$$

Theory: Eagles, Leggett, Nozières, Schmitt-Rink, Zwerger, Randeria, Timmermans, Holland, Strinati, Combescot, Griffin, Stoof, Levin, Giorgini, Stringari, Pitaevskii, ...

Early Experiments (2002-2006): Duke, JILA, MIT, Rice, Innsbruck, ENS

Reviews: Randeria, Zwerger, MZ, ed. W. Zwerger, (2012), MZ, in Novel Superfluids eds. Bennemann, Keterson (2015), Giorgini, Pitaevskii, Stringari, RMP 2008, Ketterle, MZ, Varenna 2008, Bloch, Dalibard, Zwerger, RMP 2008

Critical Temperature for Fermionic Superfluidity



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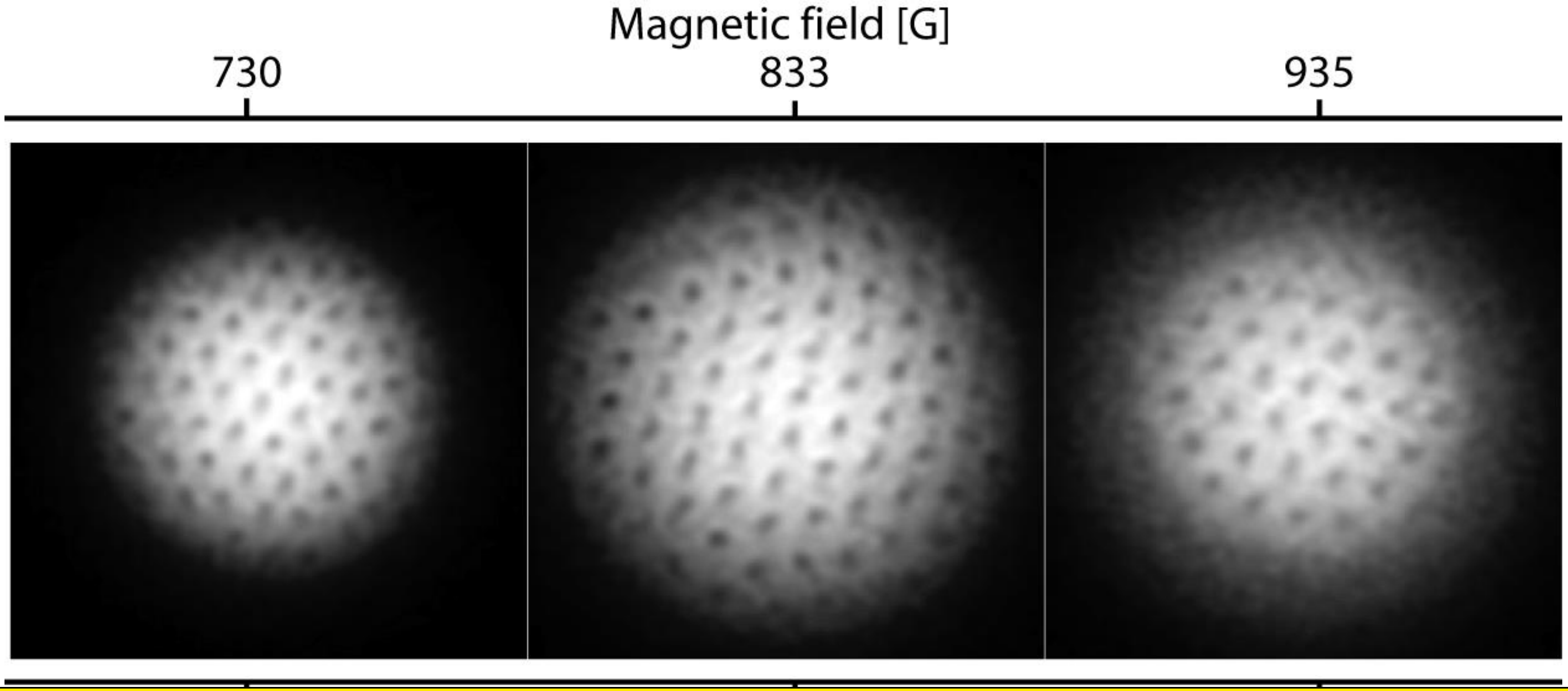
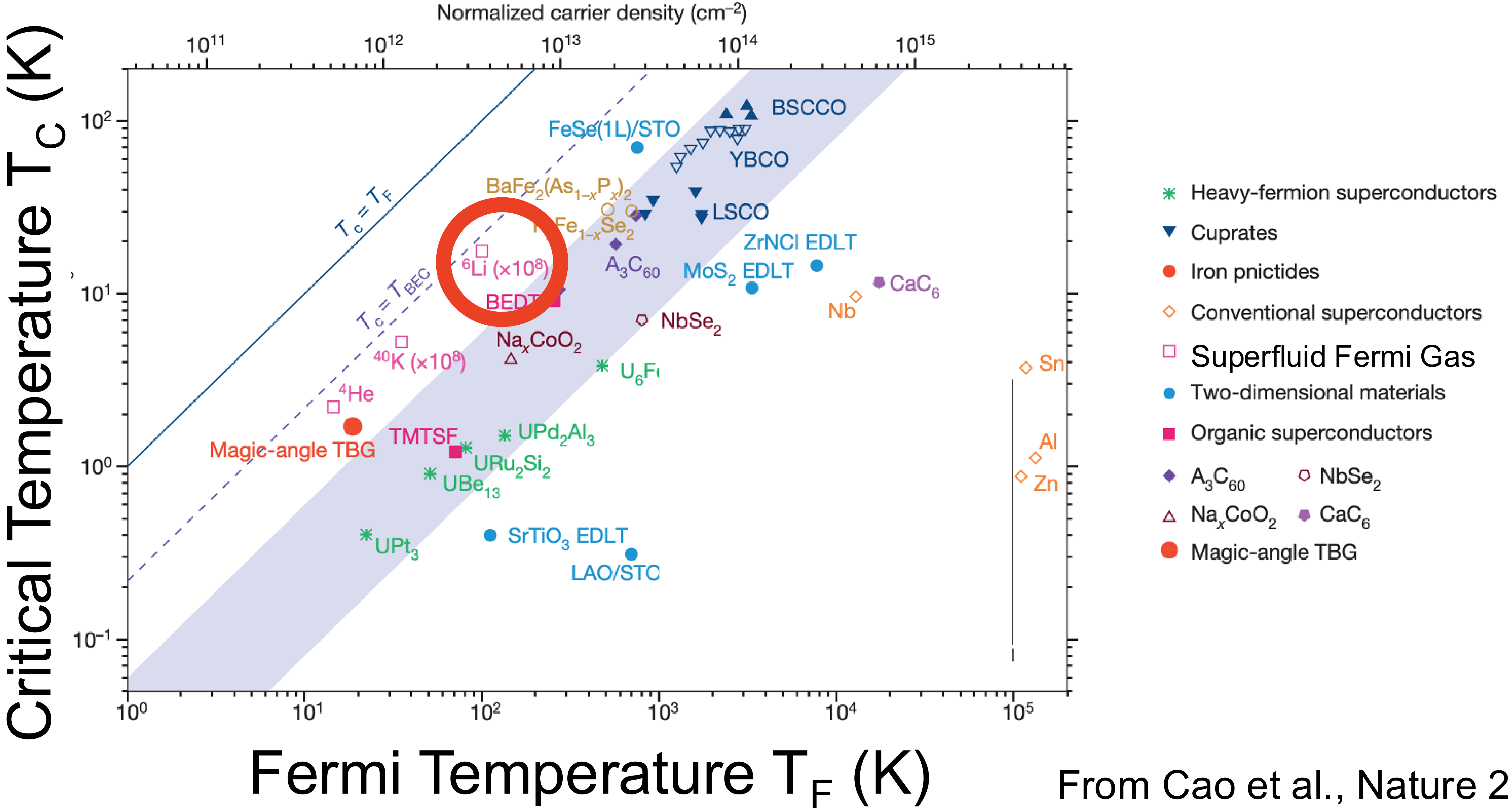
Vortex lattices in the BEC-BCS Crossover



Scaled to the density of electrons, superfluidity would occur far above room temperature

M.W. Zwierlein, J.R. Abo-Shaeer, A. Schirotzek, C.H. Schunck, W. Ketterle, Nature 435, 1047-1051 (2005)

Fermi Gas on the Uemura Plot

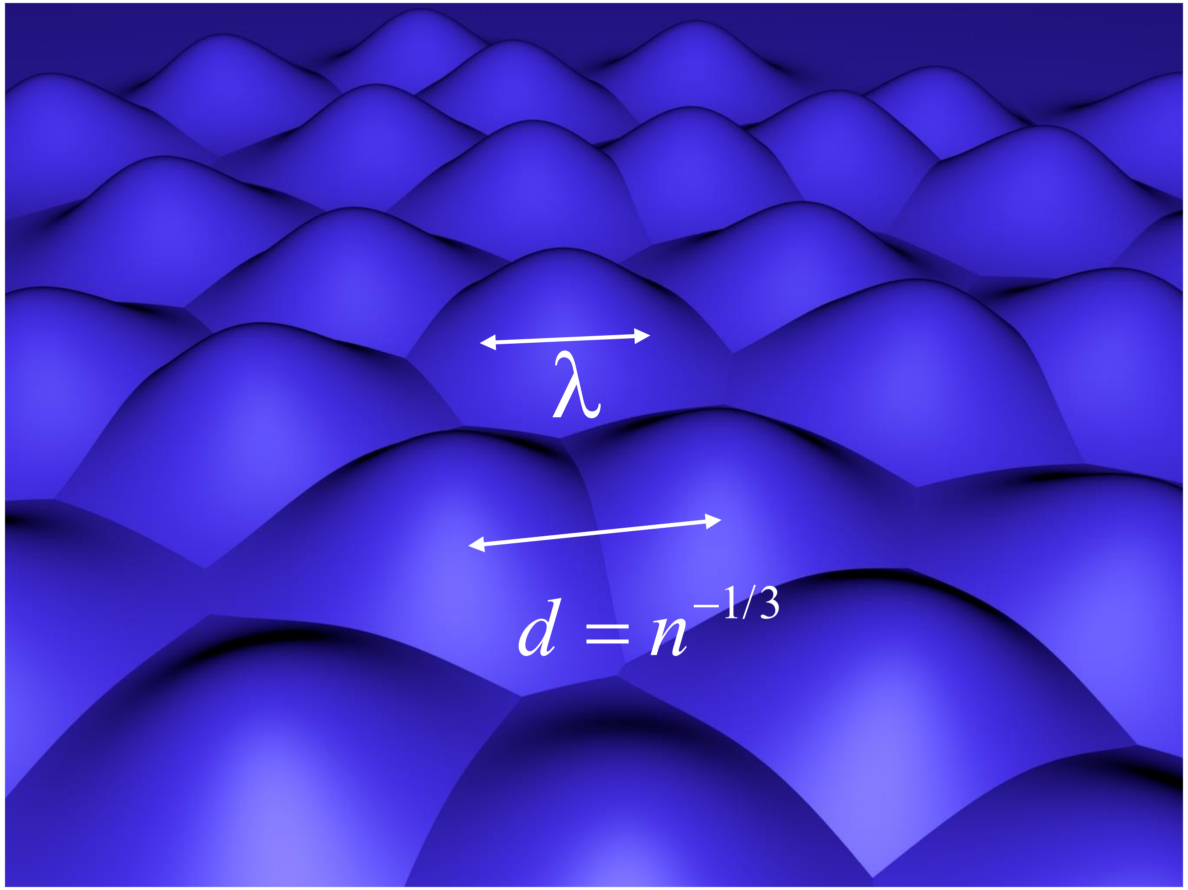


From Cao et al., Nature 2018

The Unitary Fermi Gas

Only two length scales:
Interparticle spacing $n^{-1/3}$
De Broglie wavelength λ_{dB}

Only two energy scales:
Fermi energy E_F
Temperature $k_{\mathrm{B}}T$



The Unitary Fermi Gas

Only two length scales:

Interparticle spacing $n^{-1/3}$

De Broglie wavelength λ_{dB}

Only two energy scales:

Fermi energy E_F

Temperature $k_{\mathrm{B}}T$

→ Universal equation of state

Duke/NC State, ENS, JILA, Innsbruck, Swinburne, MIT... also see: 2D Bose Gas: ENS, Cambridge

Again just like Fermi wrote:

--- only with different P(x)

$$p = \frac{2}{3} n \bar{L} = \frac{h^2 n^{5/3}}{2\pi m} P\left(\frac{2\pi m k T}{h^2 n^{2/3}}\right)$$

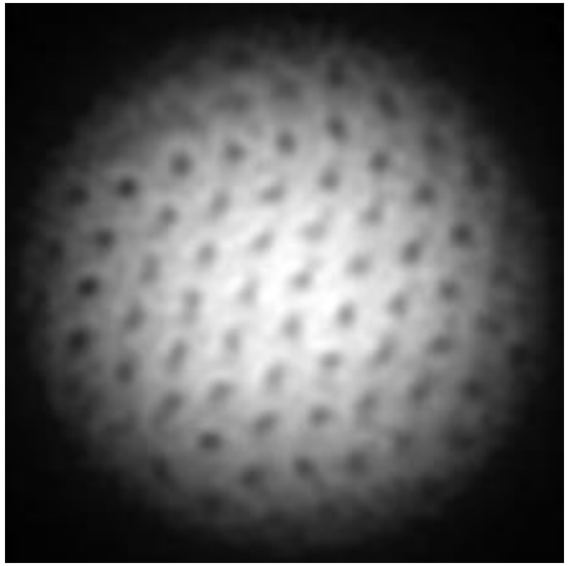
Ground-State Energy:

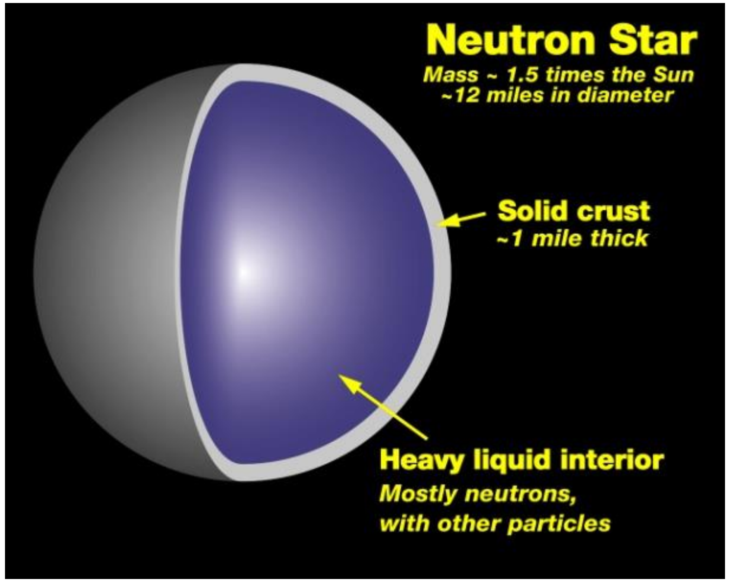
$$E = \xi \frac{3}{5} N E_F \qquad \xi_{\mathrm{Exp}} = 0.37(1)$$

Critical Temperature: $T_c = 0.17(1) T_F$

Mark Ku, Ariel Sommer, Lawrence Cheuk, MZ, Science **335**, 563-567 (2012)

Relation to equation of state of neutron matter





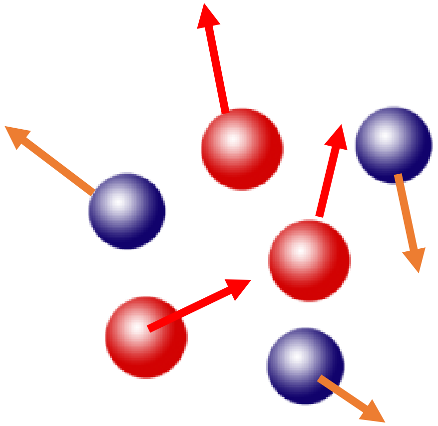
Property	Atoms	Neutrons
Spin	Pseudospin ½	Spin ½
Interparticle distance $n^{-1/3}$	1 μm	1 fm
Density	10^{13} cm^{-3}	10^{38} cm^{-3}
Fermi Energy	1 μK = 10^{-10} eV	10^{12} K = 150 MeV
Scattering length a	freely tunable	-19 fm

Both systems lie in universal regime: $a ? n^{-1/3}$

small print: neglecting effective range

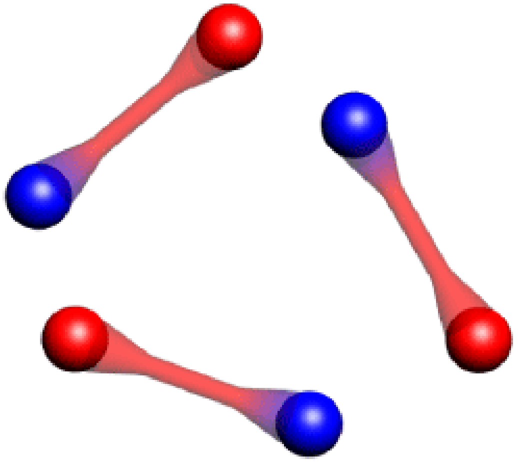
Classical gas Equation of State:

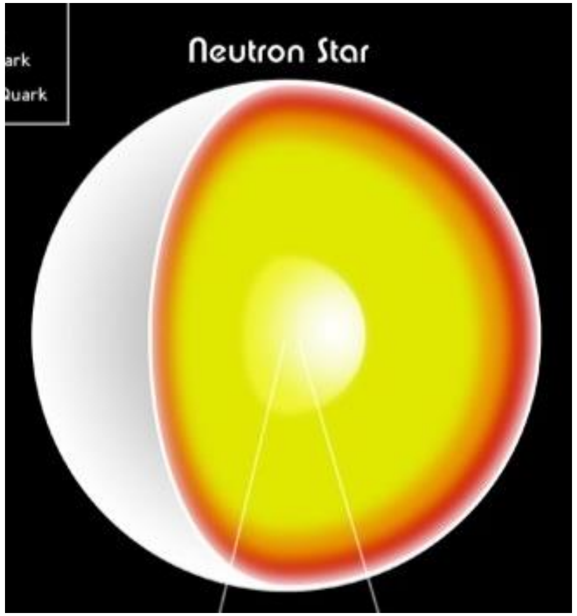
$$P = nk_BT$$



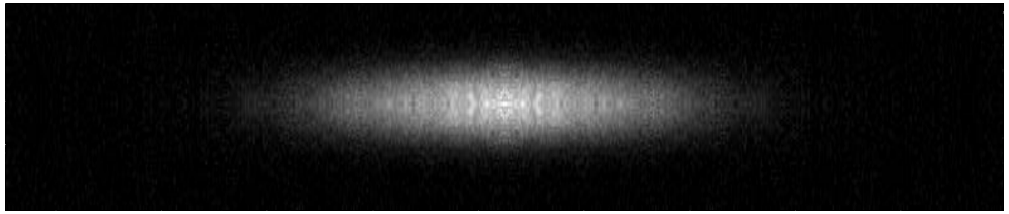
And for a strongly interacting Fermi gas?

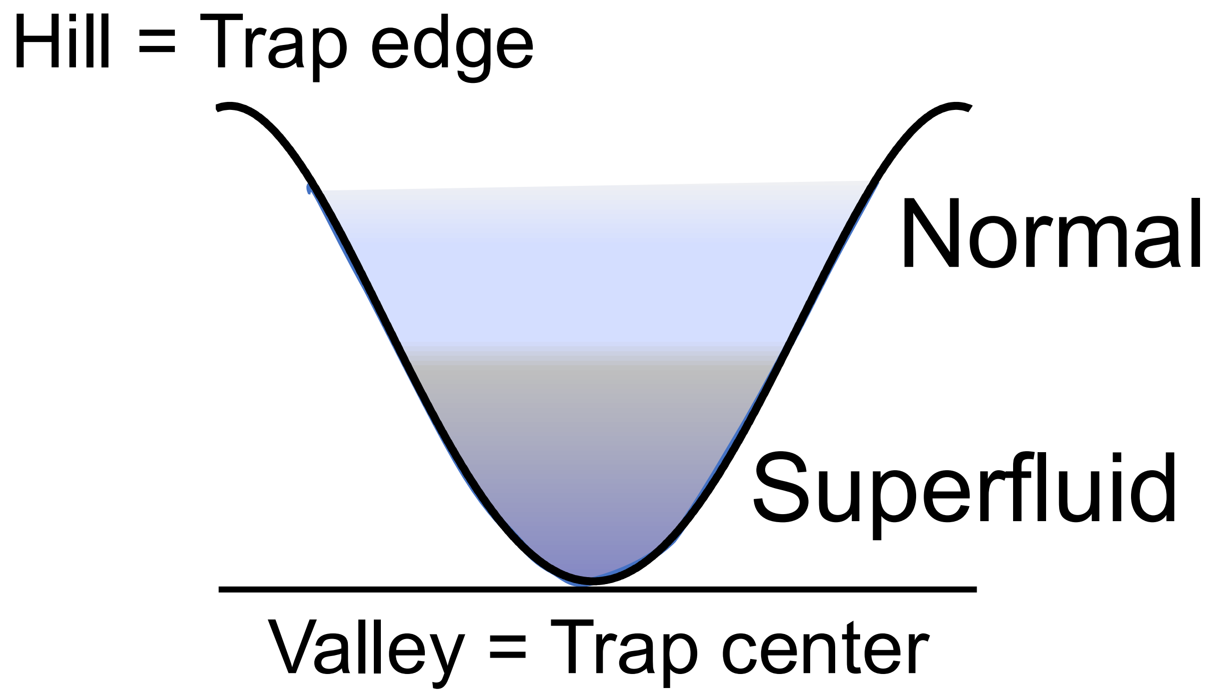
$$P(n,T) = ?$$

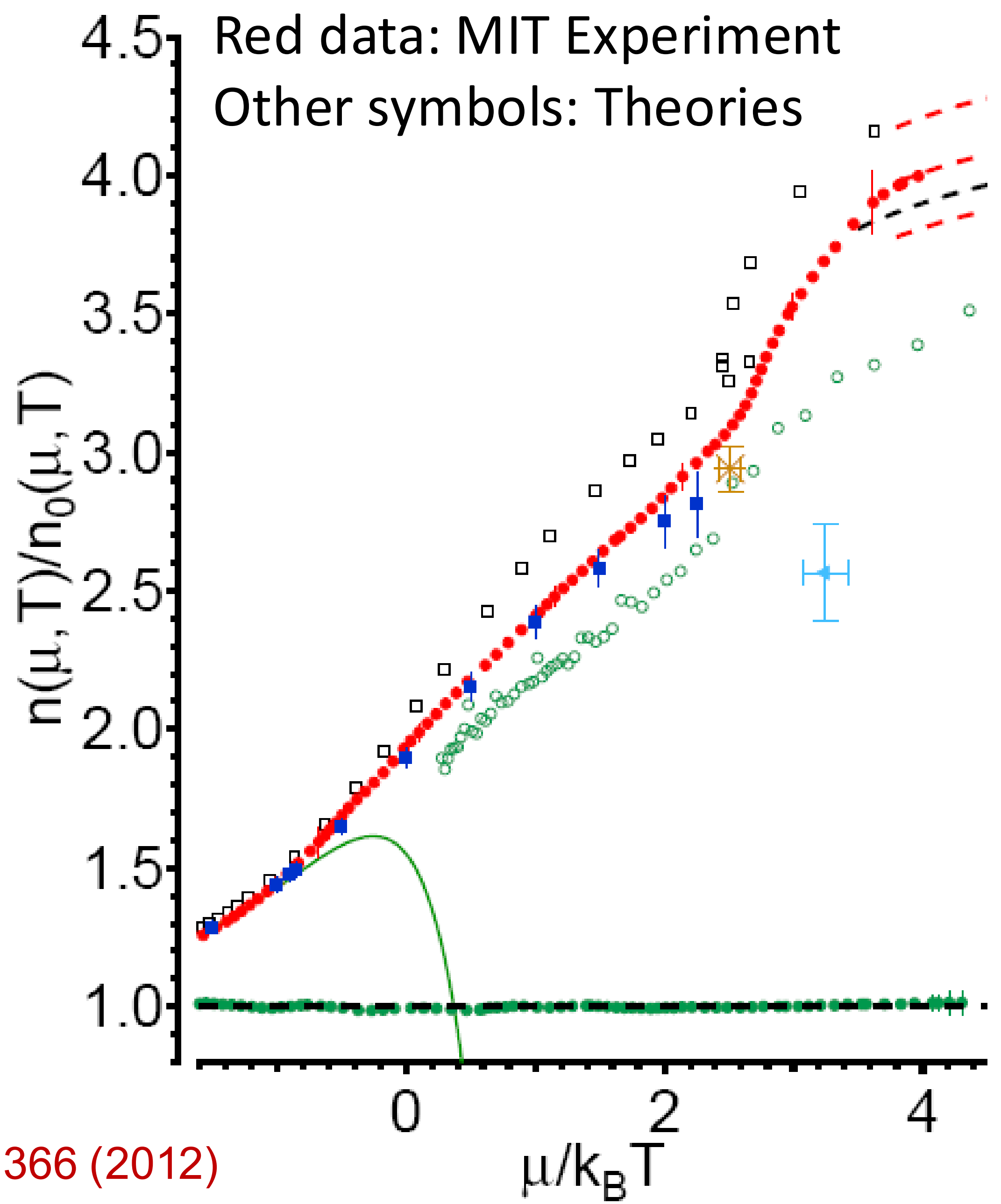




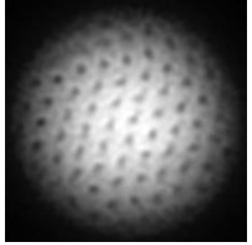
Measurement of the Equation of State





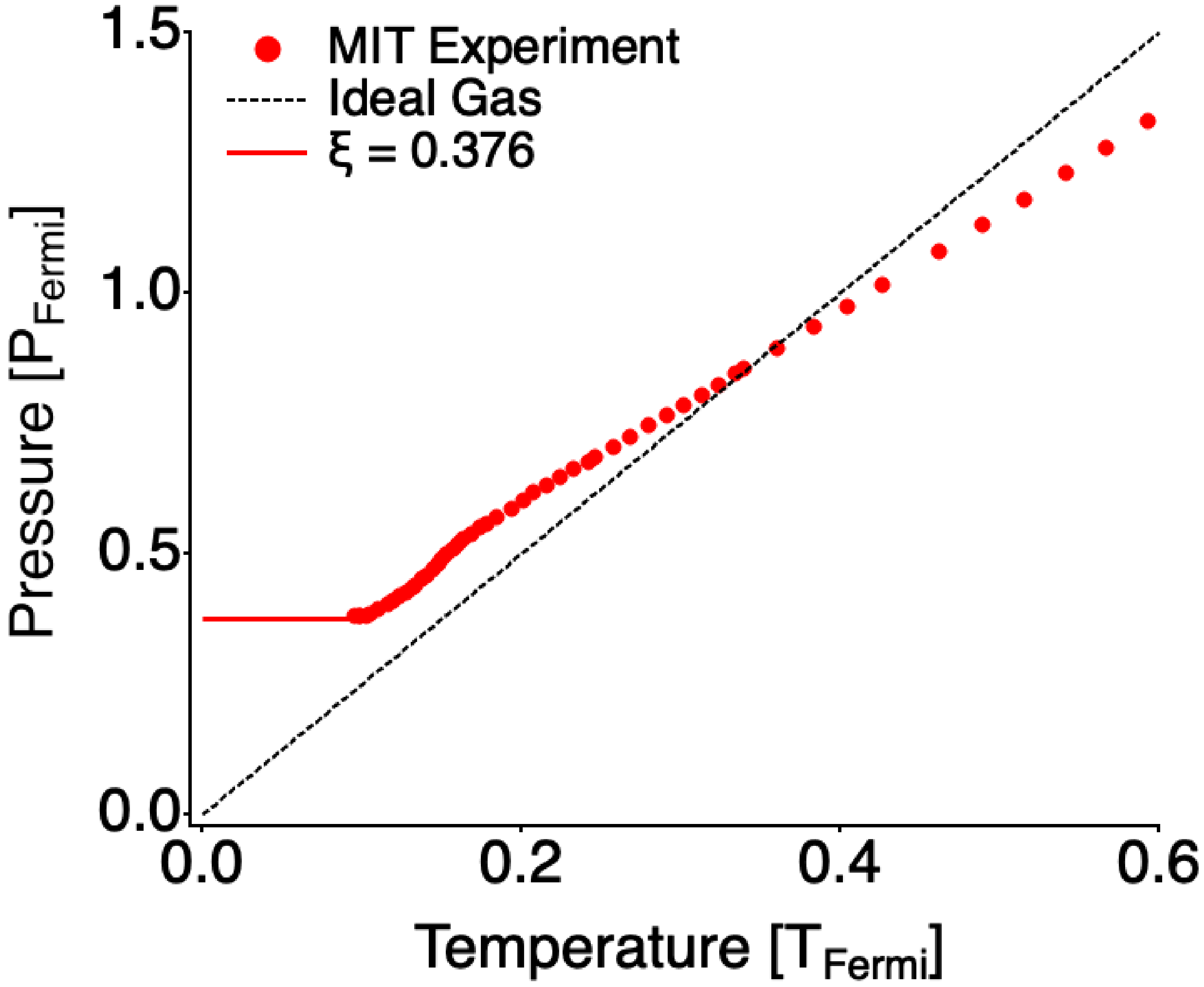


Mark Ku, Ariel Sommer, Lawrence Cheuk, MZ,
Science **335**, 563-567 (2012)
K. Van Houcke, F. Werner, E. Kozik, N. Prokofev, B. Svistunov,
M. Ku, A. Sommer, L. Cheuk, A. Schirotzek, MZ, Nature Physics **8**, 366 (2012)



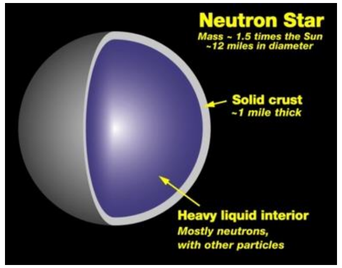
Ultracold Fermi Gas

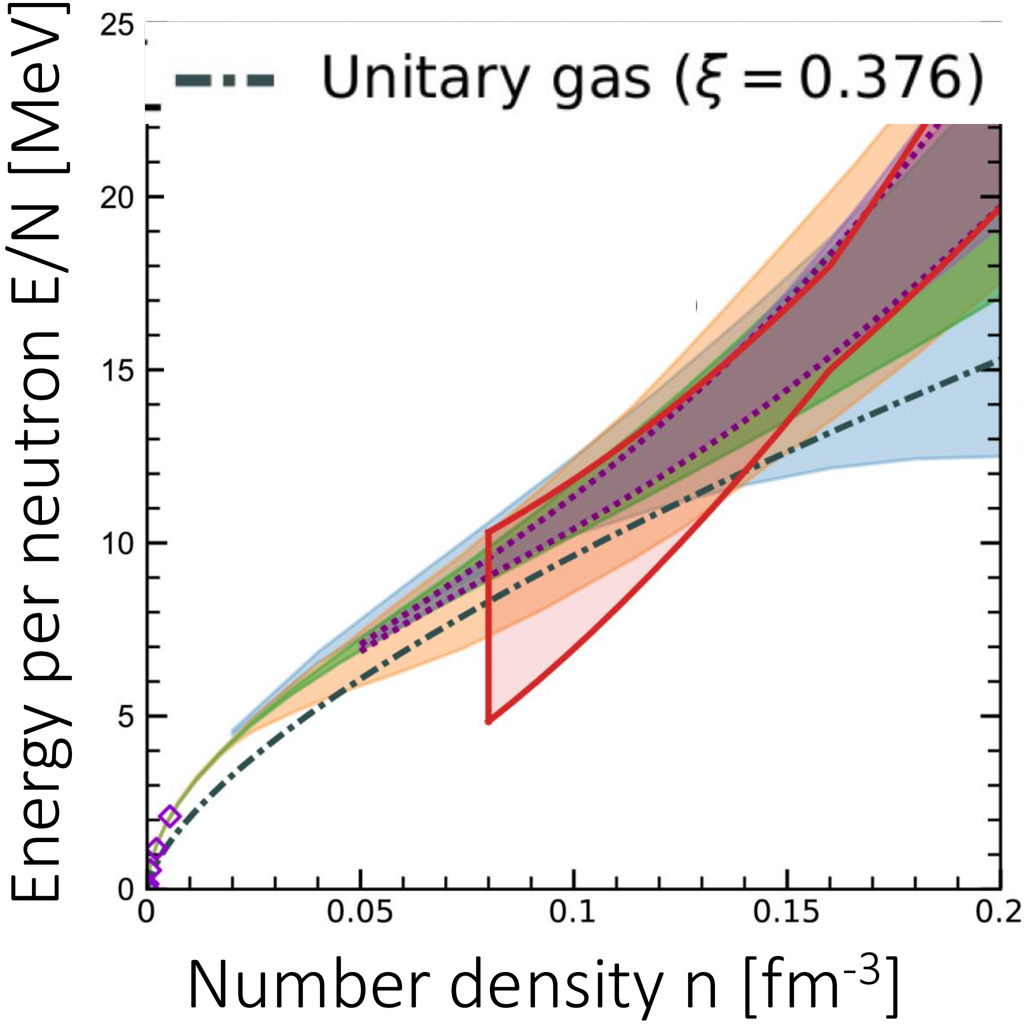
Ku, Sommer, Cheuk, Zwierlein, Science (2012)



Neutron Star

Huth et al., Nature (2021)

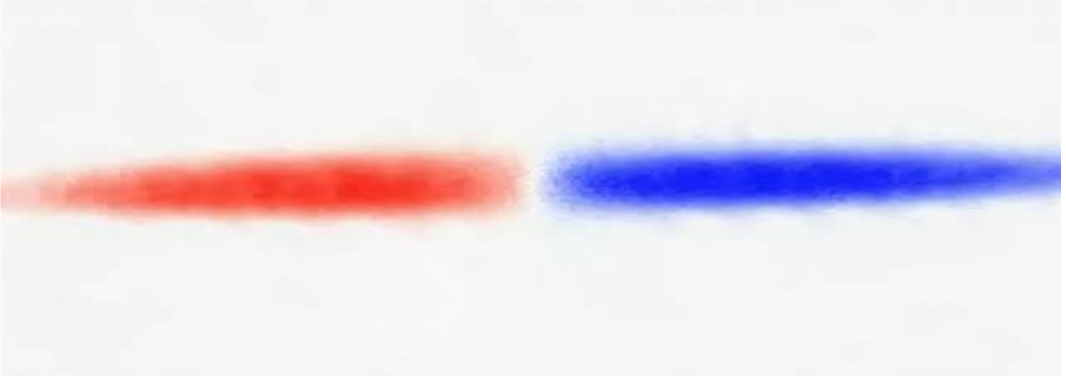




→ Ultracold Fermi gas constrains neutron star equation of state

Transport in the Unitary Fermi gas

e.g. Spin transport:



Mean free path ~ Interparticle spacing d

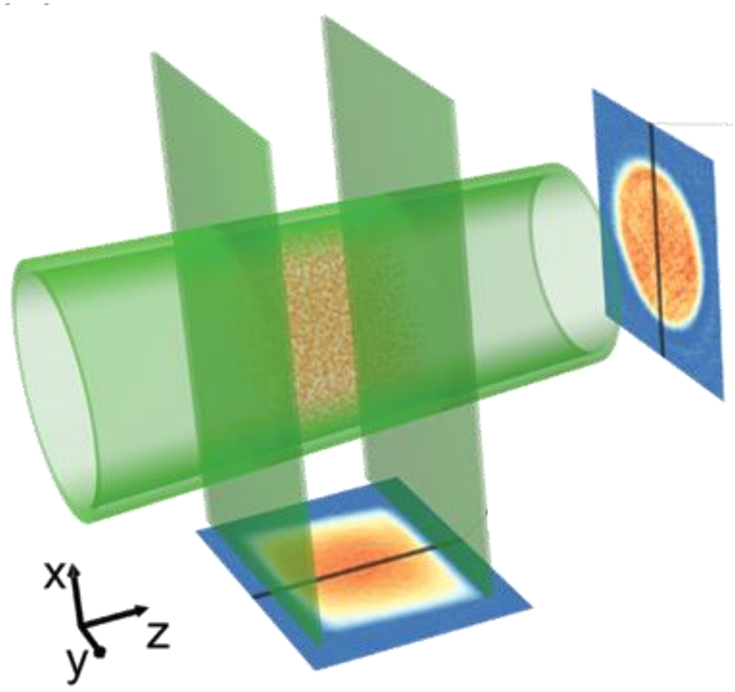
Average velocity $v : \frac{h}{md}$ Collision time $\tau : \frac{h}{E_F}$

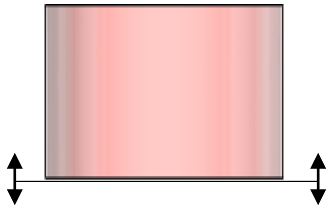
Diffusivity (charge, spin, momentum, thermal)

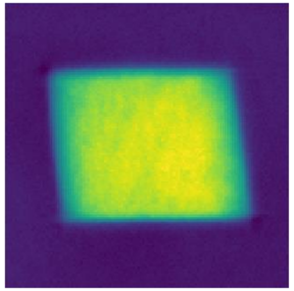
$$D : vl : \frac{h}{m}$$

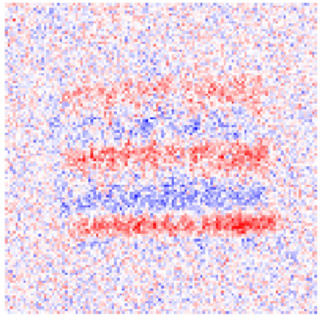
Spin Transport: A.T. Sommer, M.J.H. Ku, G. Roati, M.W. Zwierlein, Nature 472, 201 (2011)

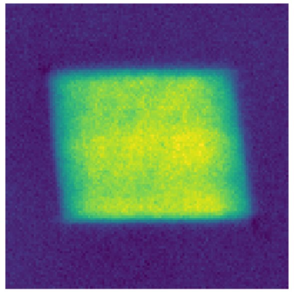
Creating Sound Waves in a Box of Fermions

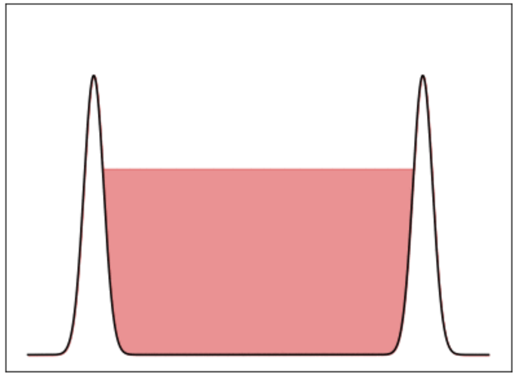


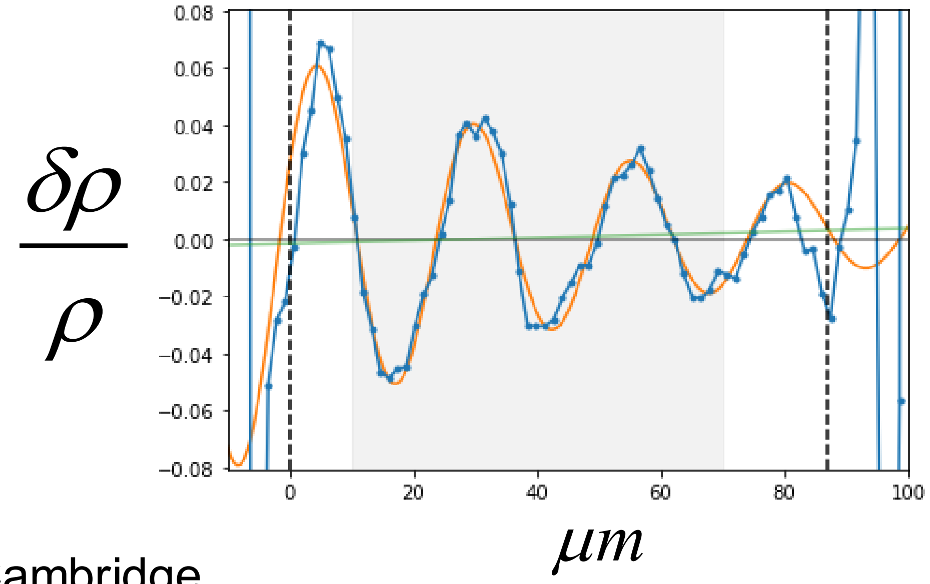












See also: 2D Bose gas, ENS, 2D+3D Cambridge
Fermi gas: NCState, Hamburg, Yale

Viscosity of Superfluid Helium-4

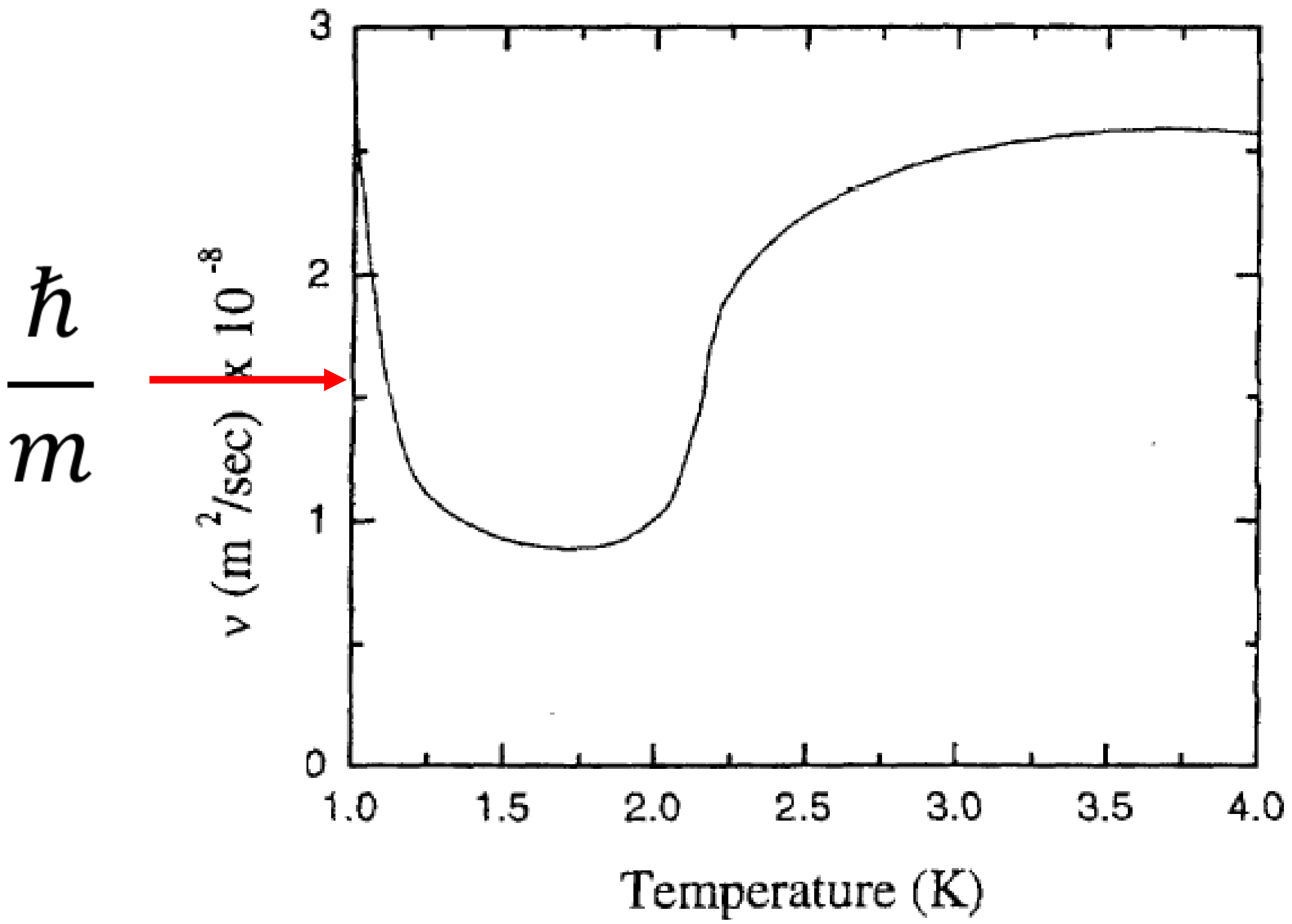
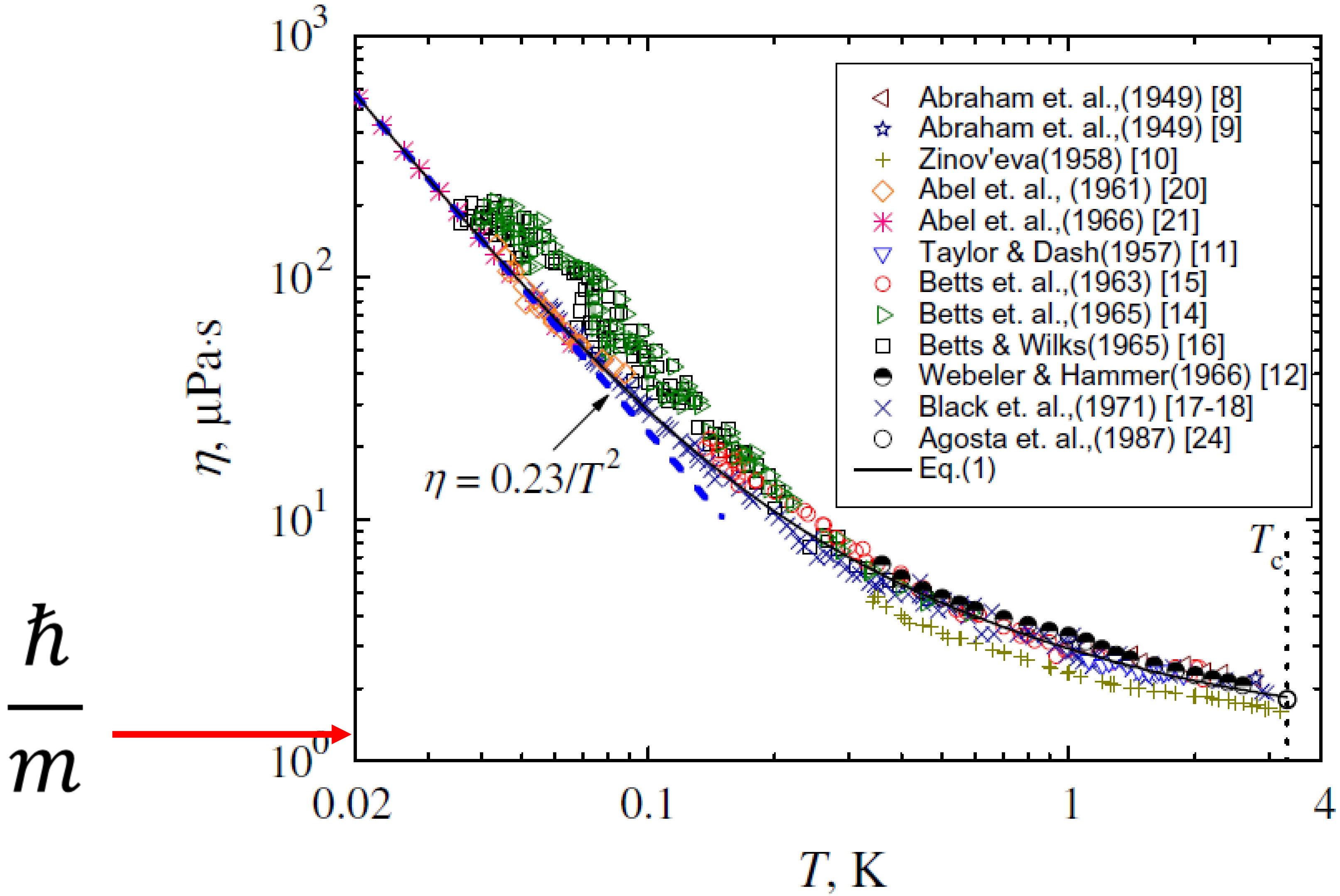


FIG. 12.3. The recommended values of the kinematic viscosity of liquid ^{4}He, $\nu = \eta/\rho$, as a function of temperature at the saturated vapor pressure.

From: Donnelly, Barenghi, JPC Reference Data, 1998

Viscosity of Superfluid Helium-3

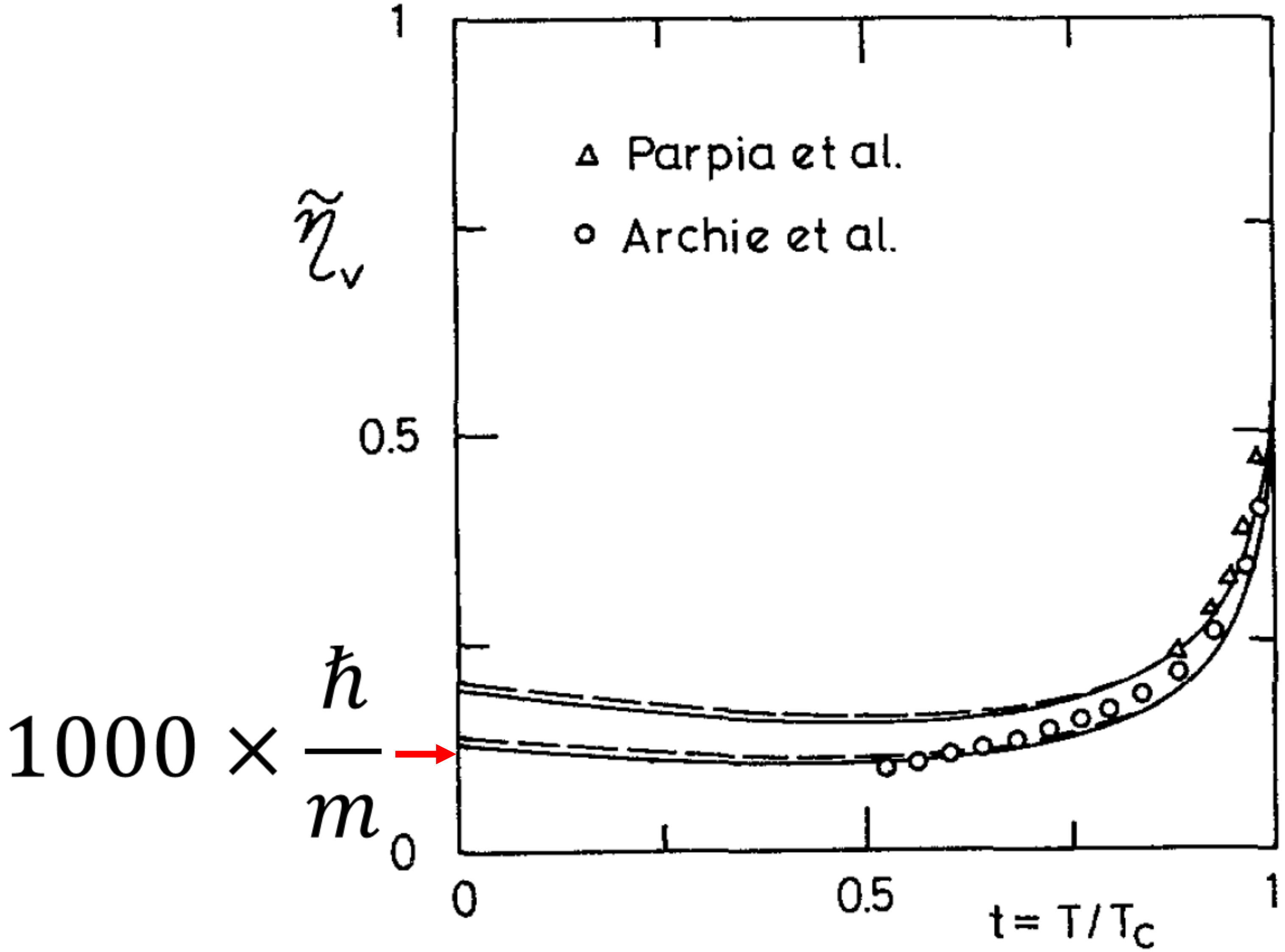
Helium-3 above T_c: Fermi Liquid behavior



Huang et al., Cryogenics 52, 538 (2012)

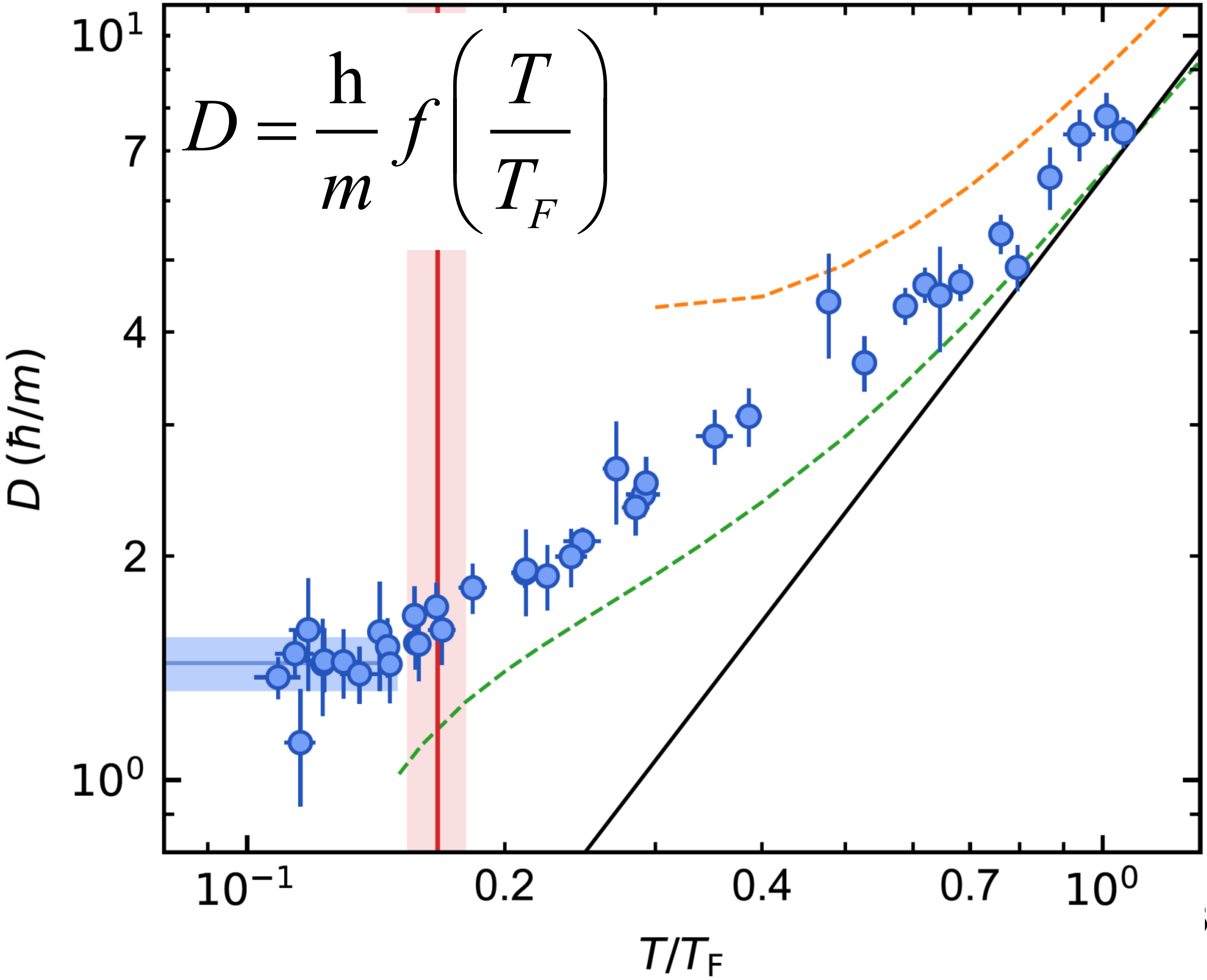
Viscosity of Superfluid Helium-3

Helium-3 below T_c: Sudden decrease, then constant



Ono et al.,
JLTP 48, 167
1982

Quantum Limited Sound Diffusion



Schäfer et al., PRA 2010

$$\left(\frac{4}{3}+\delta\right)\frac{\eta}{\rho}$$

High-T-Limit:

$$D \sim \frac{\hbar}{m}\left(\frac{T}{T_F}\right)^{3/2}$$

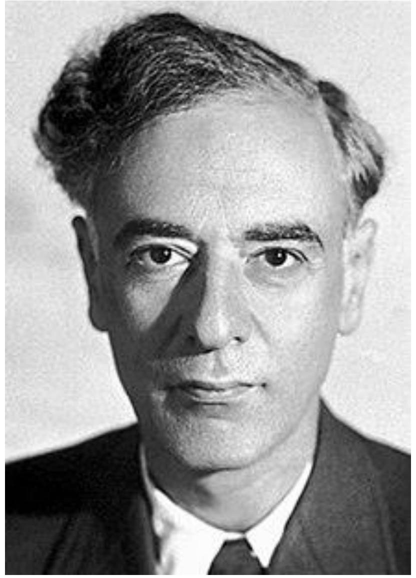
$$\frac{7}{3}\frac{\eta}{\rho}$$

η from Enss, Haussmann, Zwerger, Ann. Phys. (2011)

P. Patel, Z. Yan, B. Mukherjee, R. Fletcher, J. Struck, MZ, Science 370, 1222 (2020)

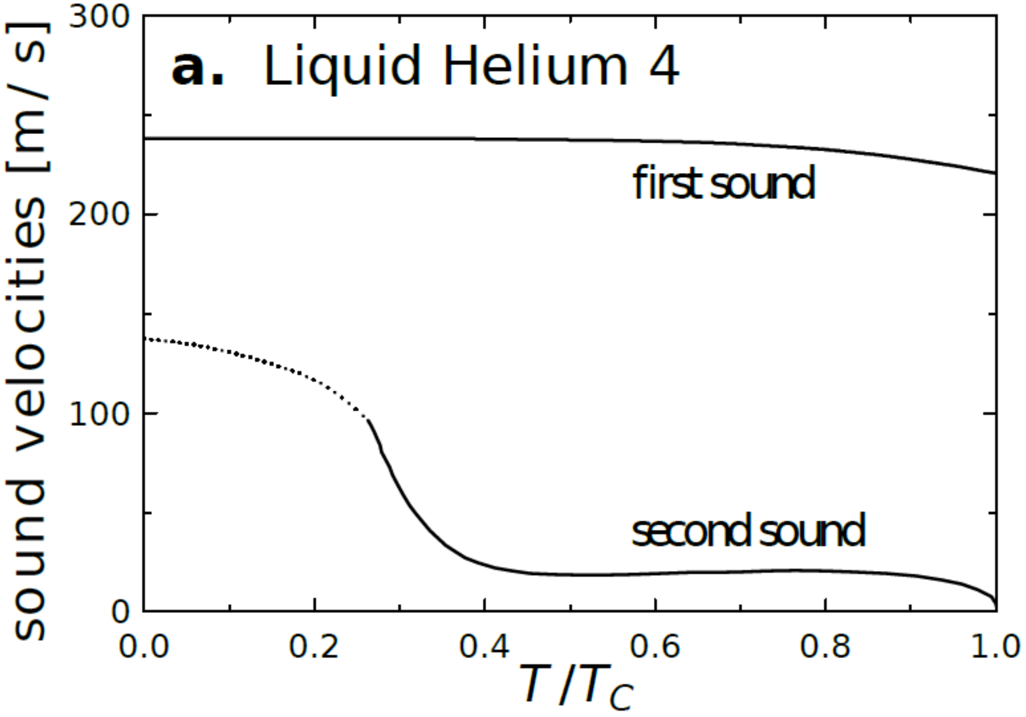
Two-Fluid Model for Superfluids

Laszlo Tisza



Lev Landau

Superfluid + Fluid of excitations
→ Two Sound Modes!

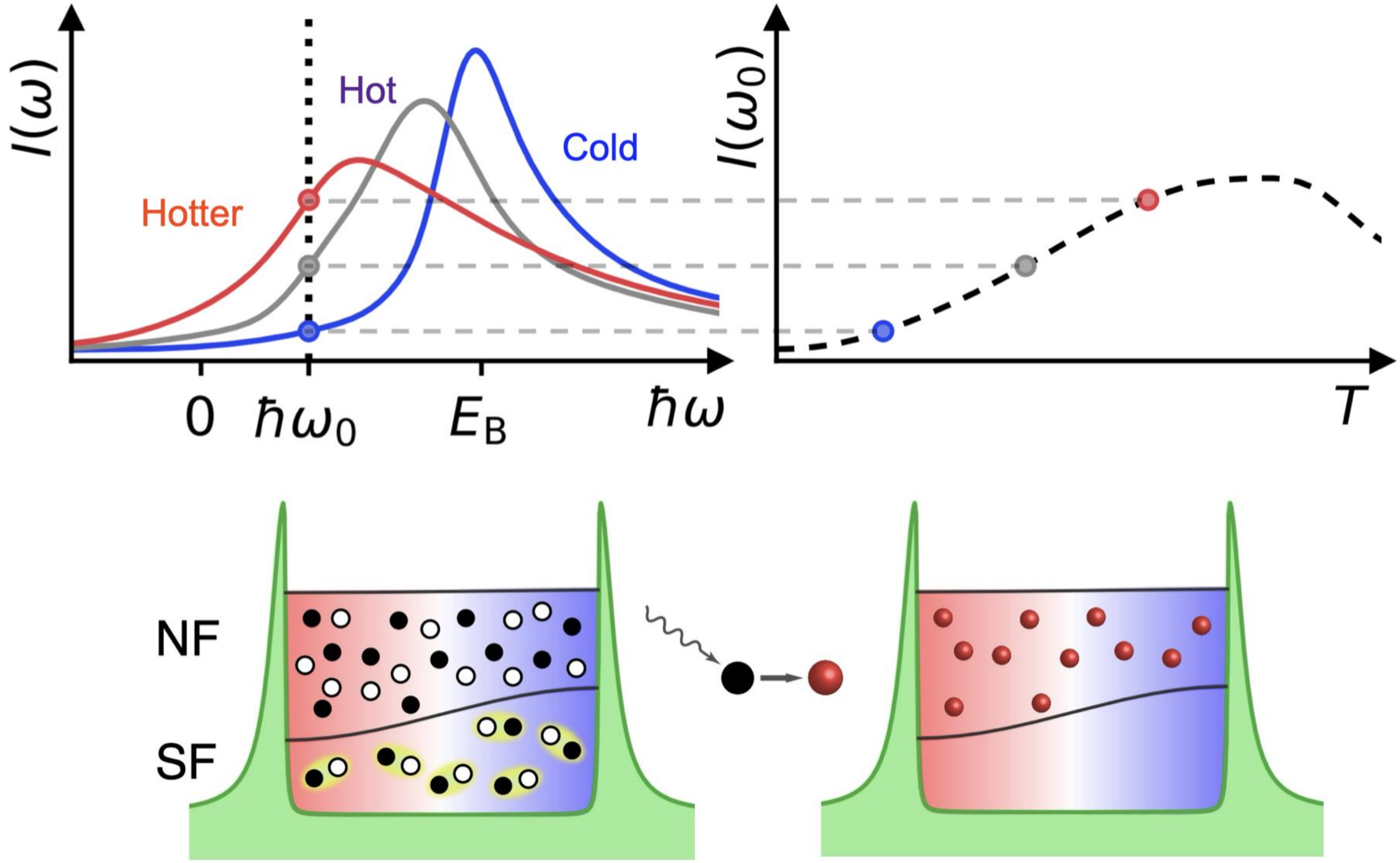


Observation of Second Sound in Quasi-1D geometry:
Sidorenkov et al., Grimm, Stringari&Piatevskii, Nature 2013

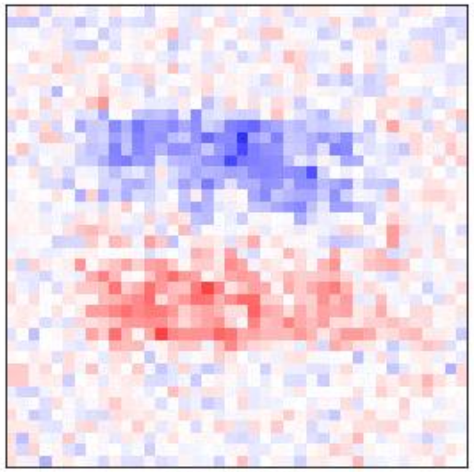
On bosons: weakly interacting situation: JILA, MIT
Hydrodynamic gas: van der Straten, 2D Bose Gas: Cambridge, ENS

A local thermometer for heat transport

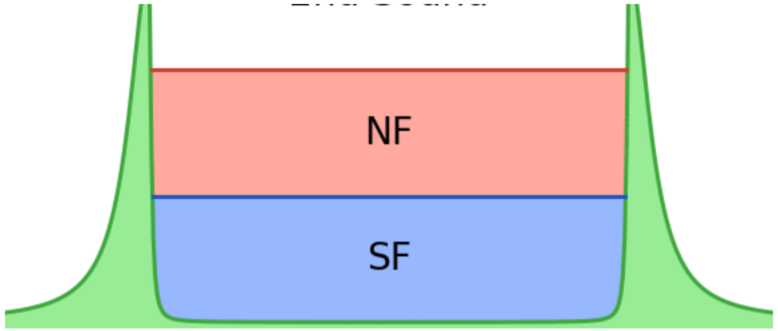
RF absorption spectra are temperature dependent



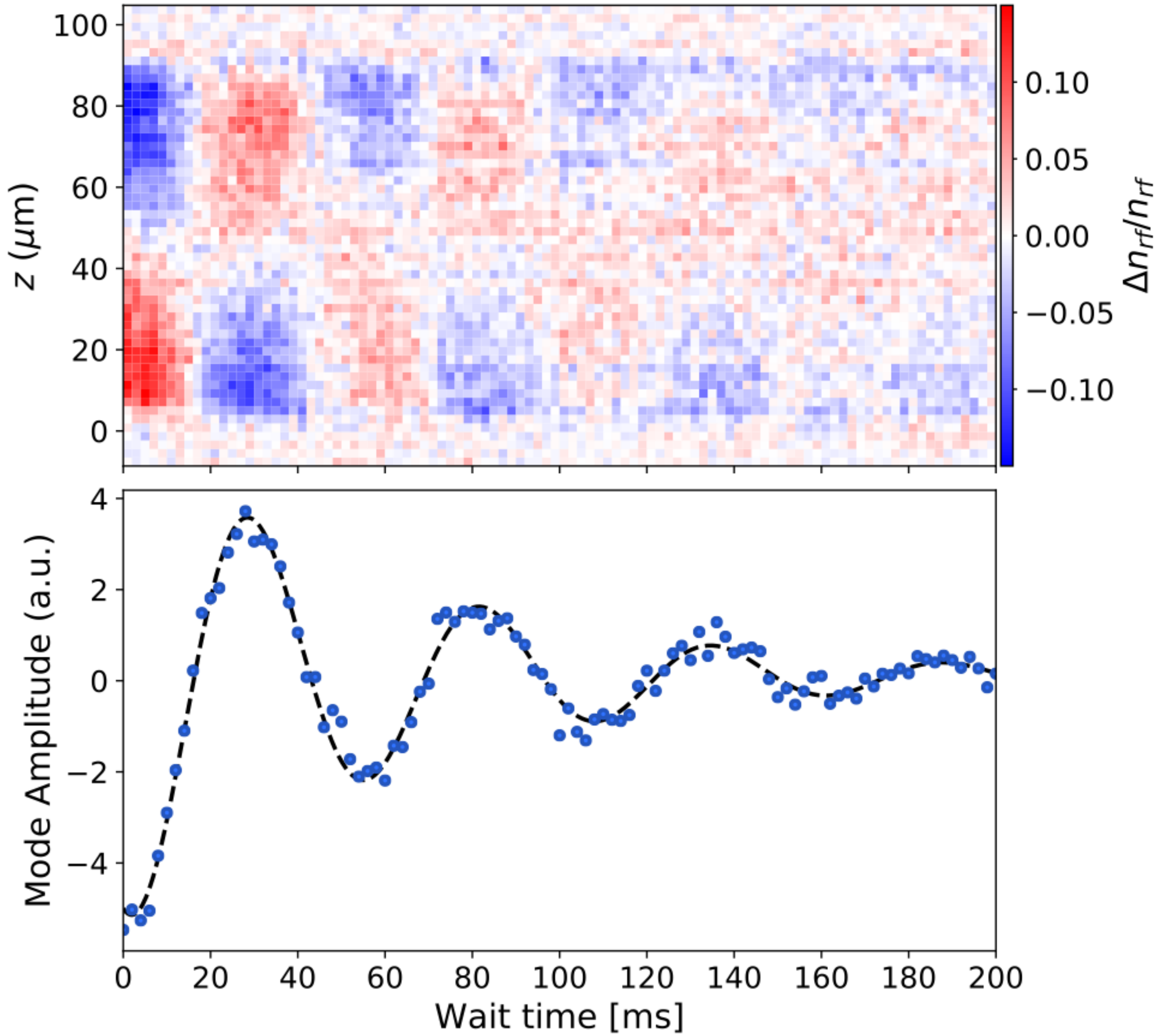
Second Sound



t= 0 ms

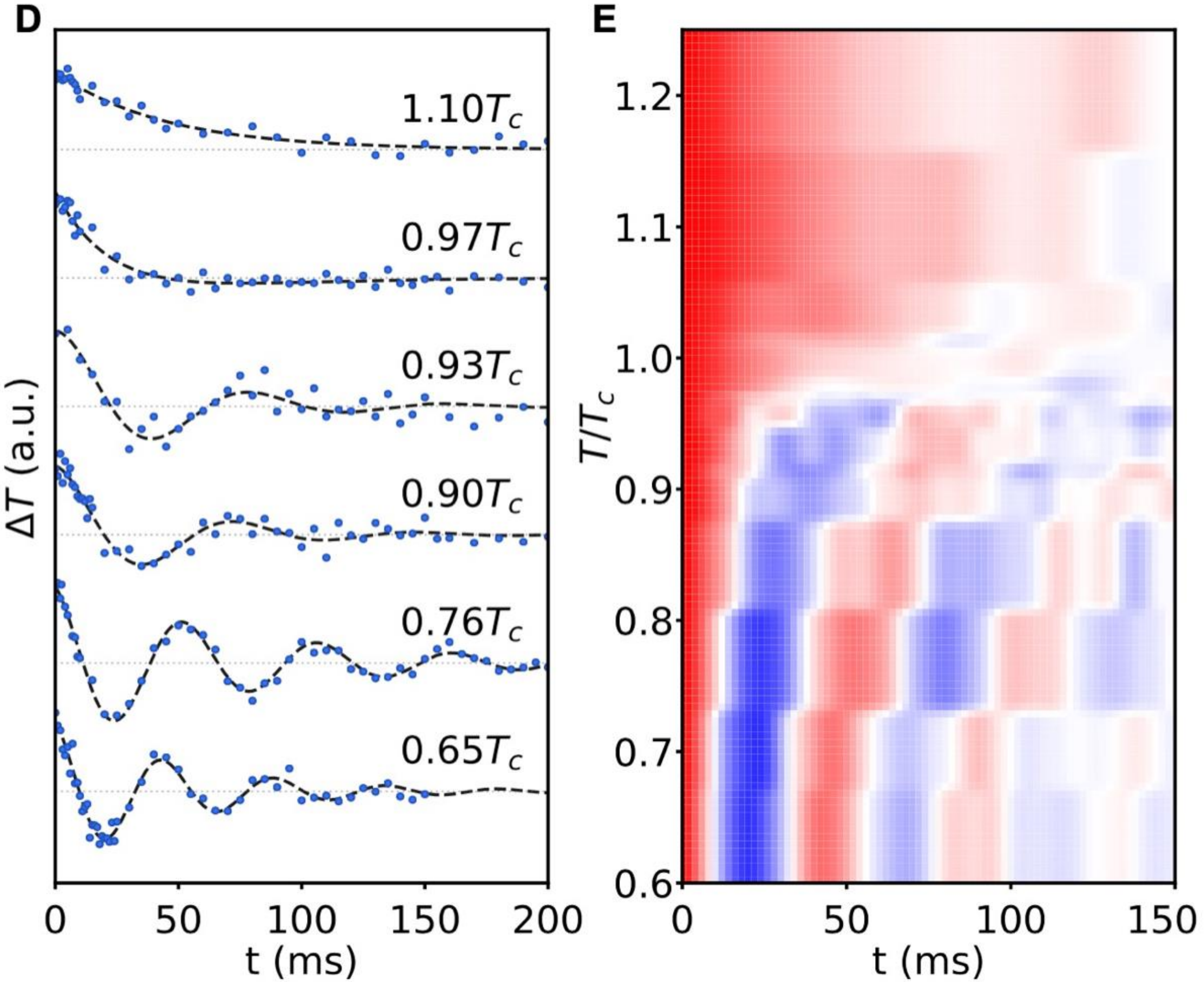


Temperature Probe

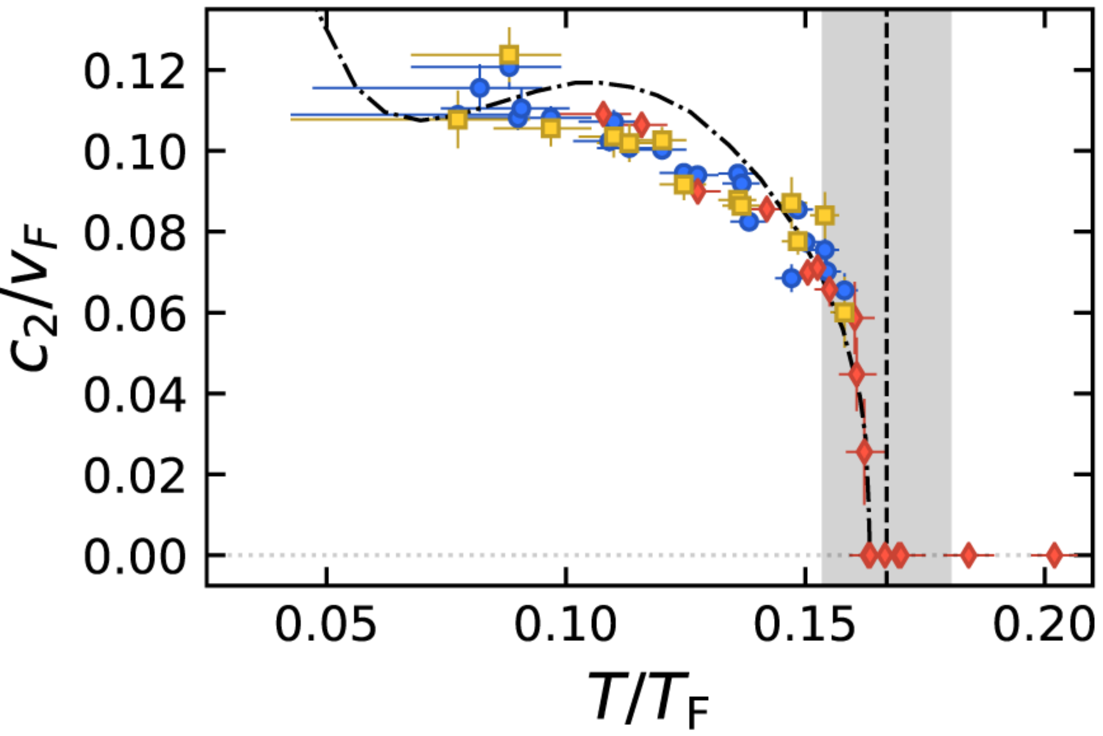


Yan, Patel, Mukherjee, Vale, Fletcher, MZ, Science 383, 629 (2024)

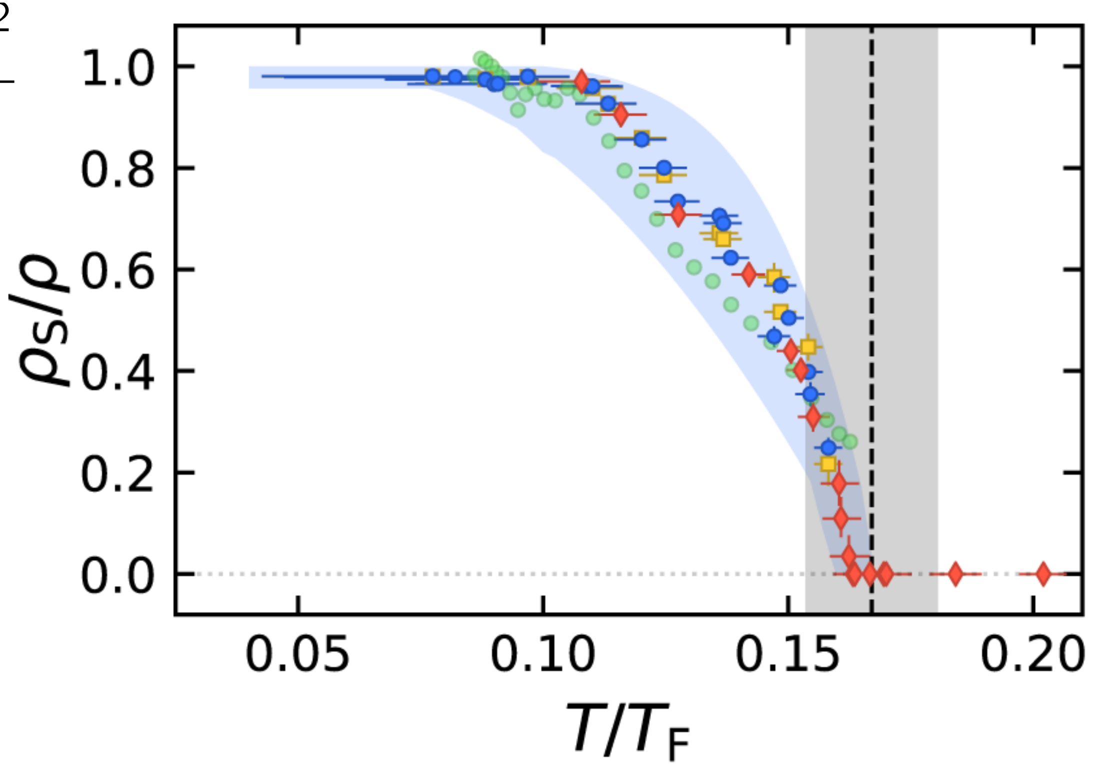
Transition from normal to superfluid



Superfluid Fraction from Second Sound



$$c_2^2 = \frac{\rho_S}{\rho_N}\frac{TS^2}{C_p}$$

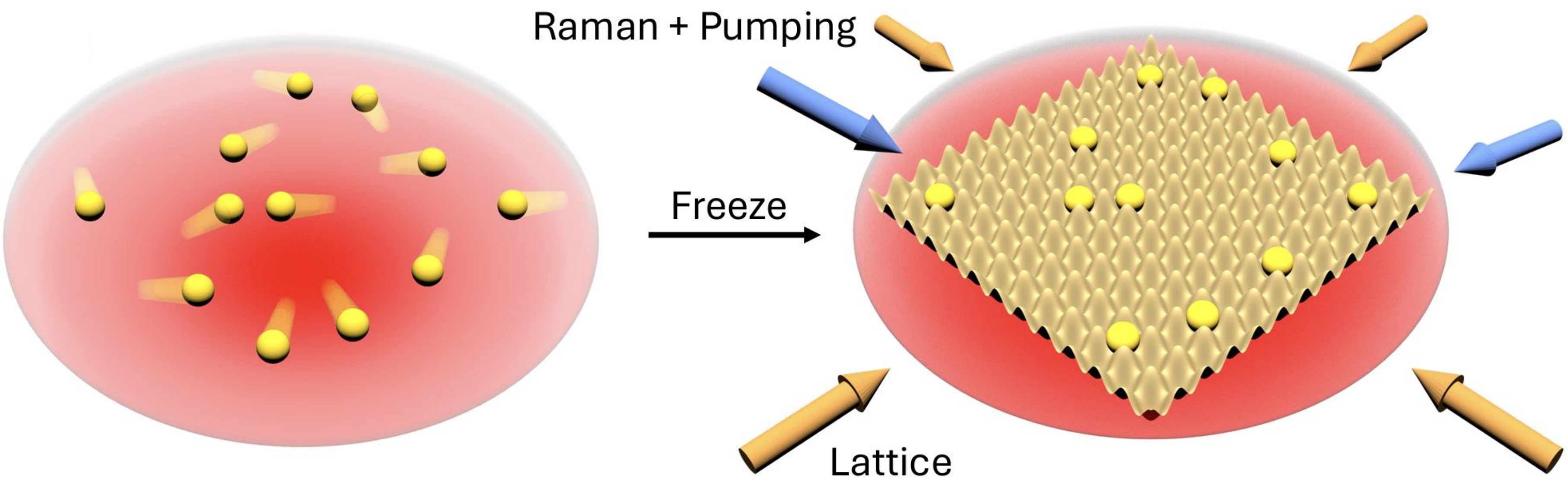


- Oscillation Frequency Scan
- Free evolution, resonant shaking
- Free evolution, local heater
- E. Taylor, et.al., Phys. Rev. A **80**, 053601 (2009).

- Second sound in quasi-1D Fermi gas
  L. Sidorenkov, *et al., Nature* **498,** 78–81 (2013).

A microscopic view of Fermion Pairs

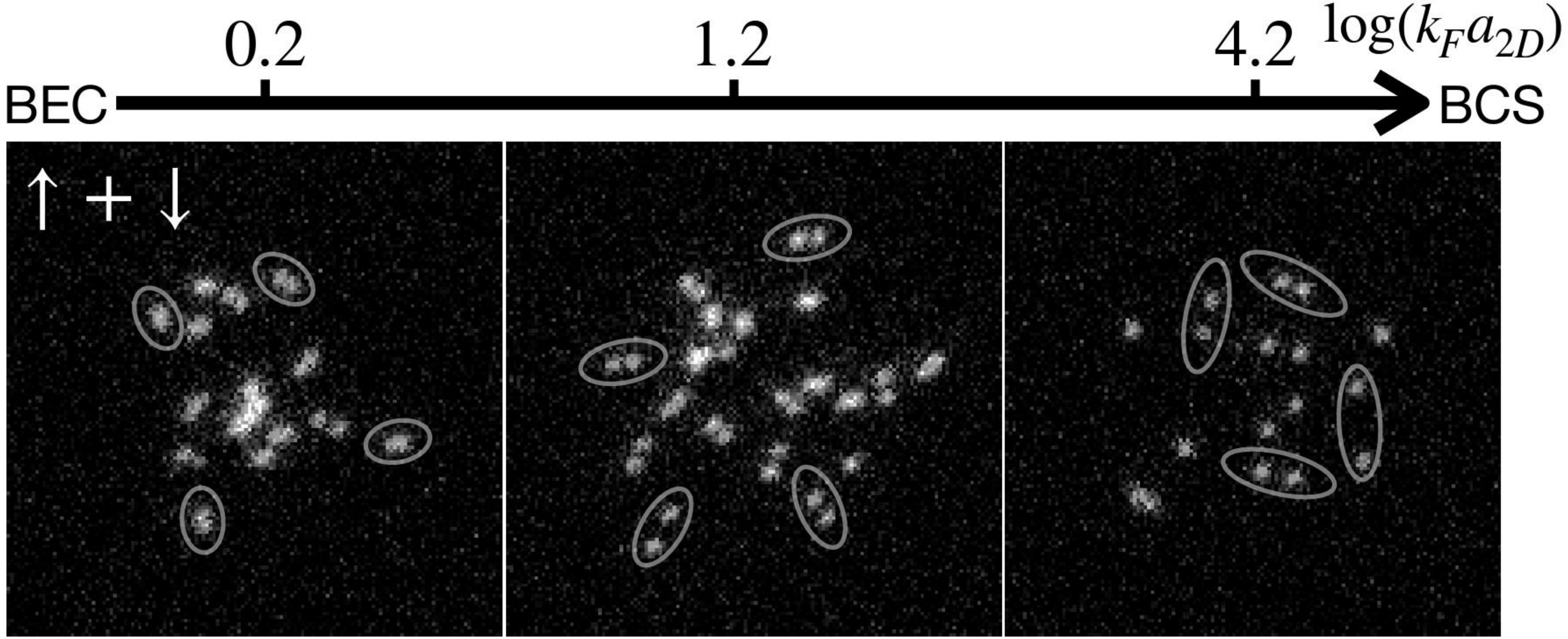
Apply the continuum gas microscope on a 2D Fermi gas in the BEC-BCS Crossover



R Yao, S Chi, M Wang,
RJ Fletcher, MZ, arXiv:2411.08780

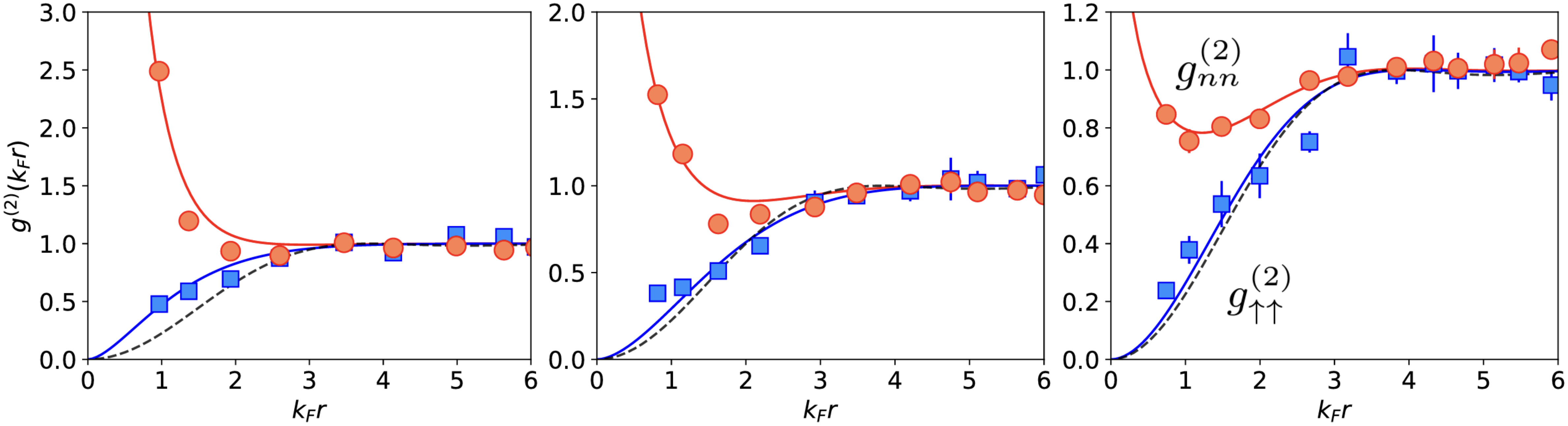
A microscopic view of Fermion Pairs

Apply the continuum gas microscope on a 2D Fermi gas in the BEC-BCS Crossover



R Yao, S Chi, M Wang, RJ Fletcher, MZ, PRL **134**, 183402 (2025),
also see Yefsah group: arXiv:2504.01885

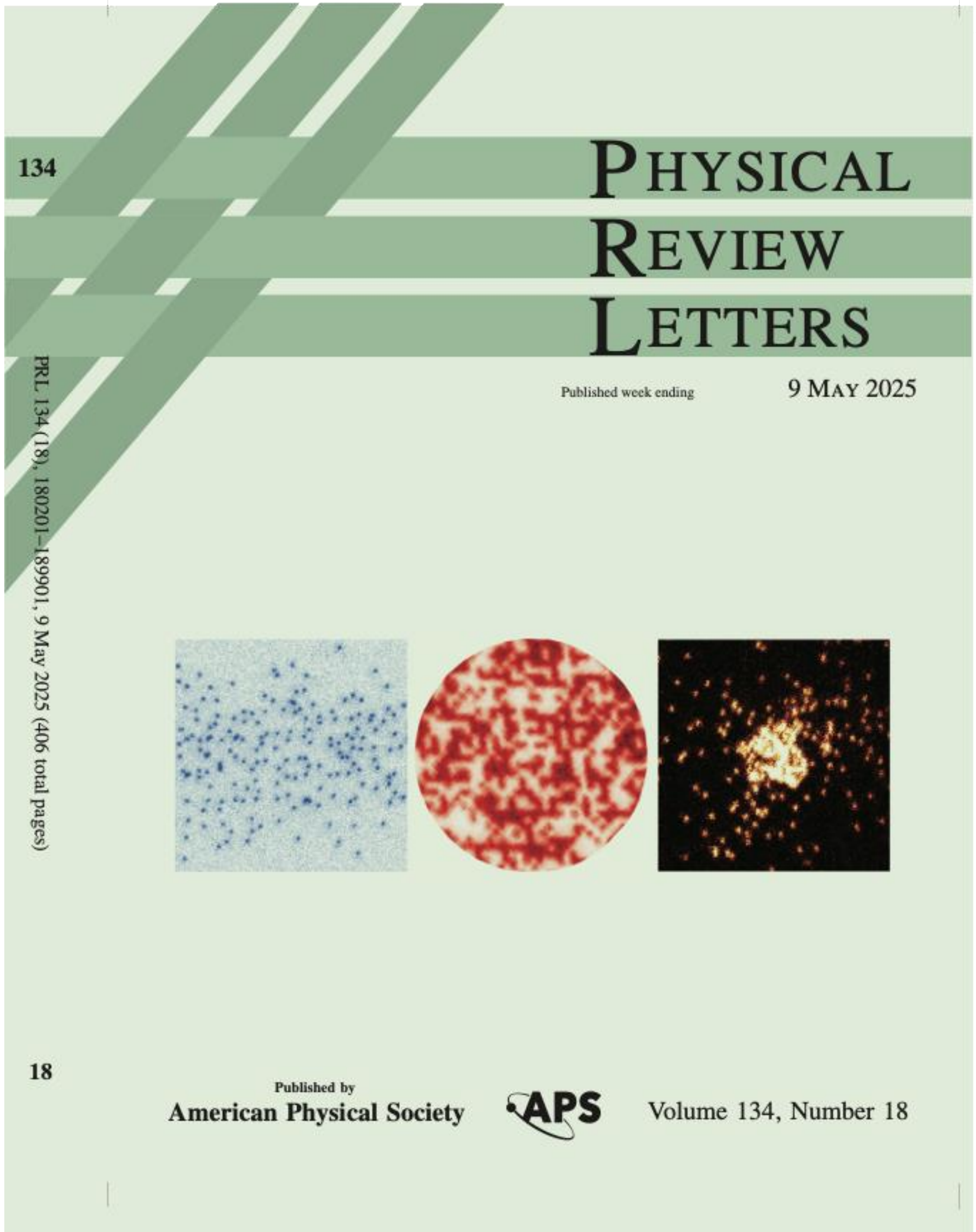
Pair correlation function $g^{(2)}(r)$



- Like fermions repel → Fermi Hole
- Unlike fermions attract → Contact+Pairing

Access to microscopic correlations in strongly interacting quantum gases

R Yao, S Chi, M Wang, RJ Fletcher, MZ, PRL **134**, 183402 (2025),
also see Yefsah group: arXiv:2504.01885

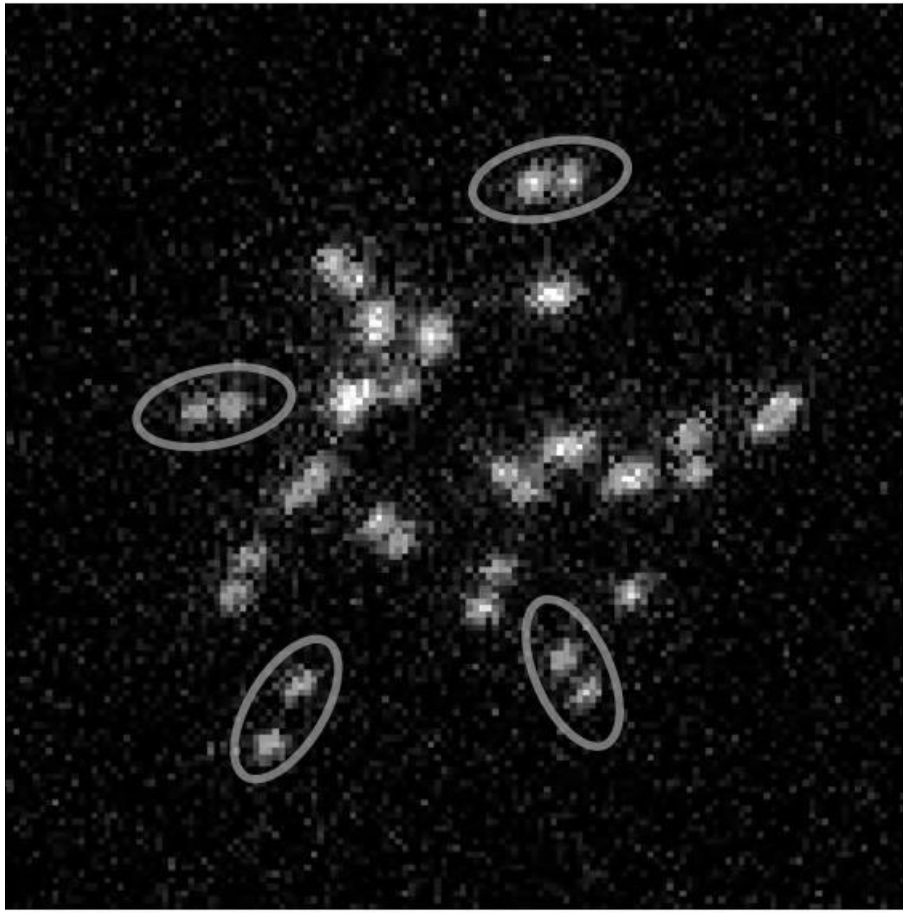


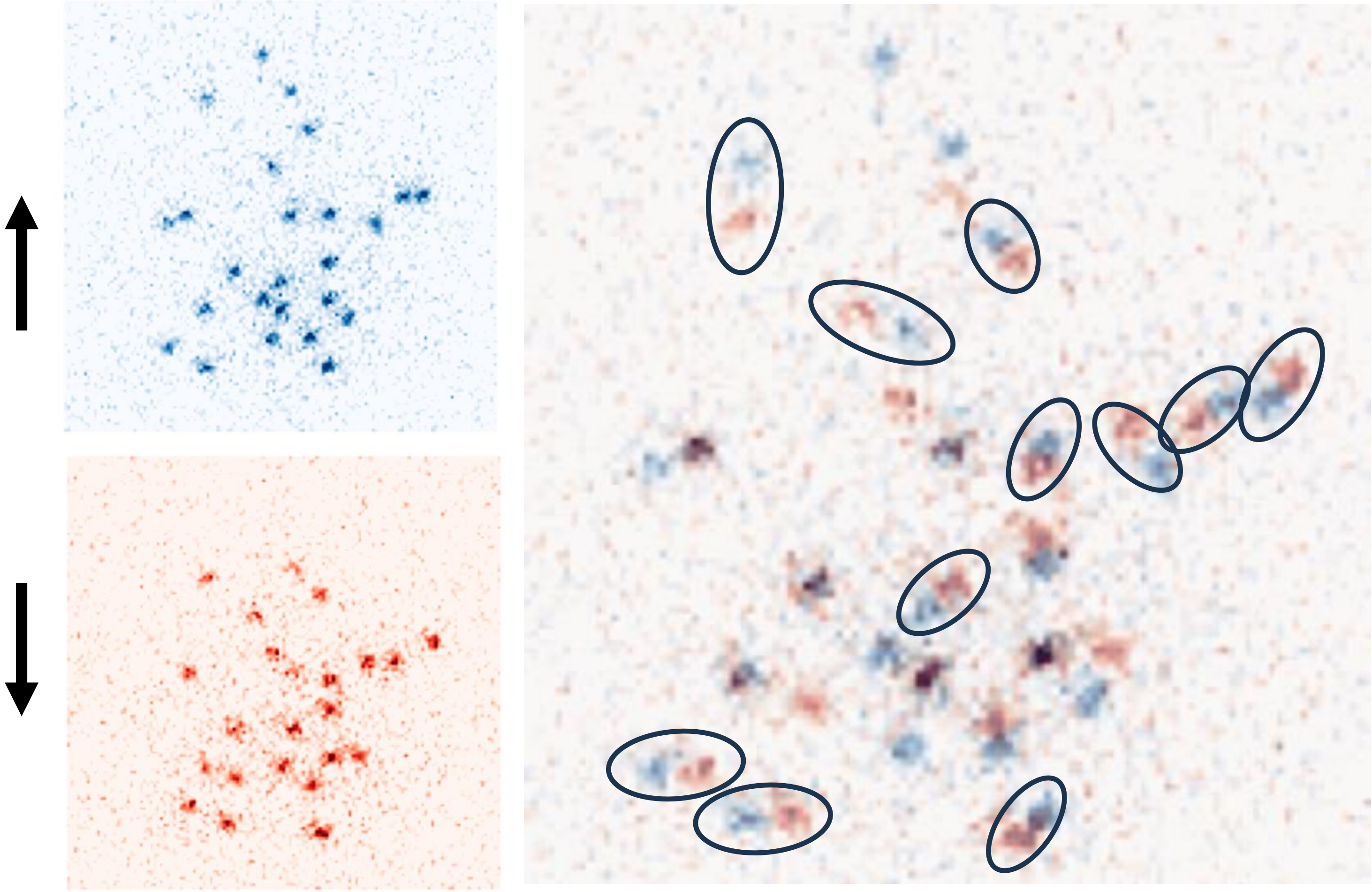
Yefsah group, PRL **134**, 183403 (2025) (free Fermions)
Ketterle group, PRL **134**, 183401 (2025) (Bosons)

R Yao, S Chi, M Wang, RJ Fletcher, MZ,
PRL **134**, 183402 (2025) (Bosons + Fermions)

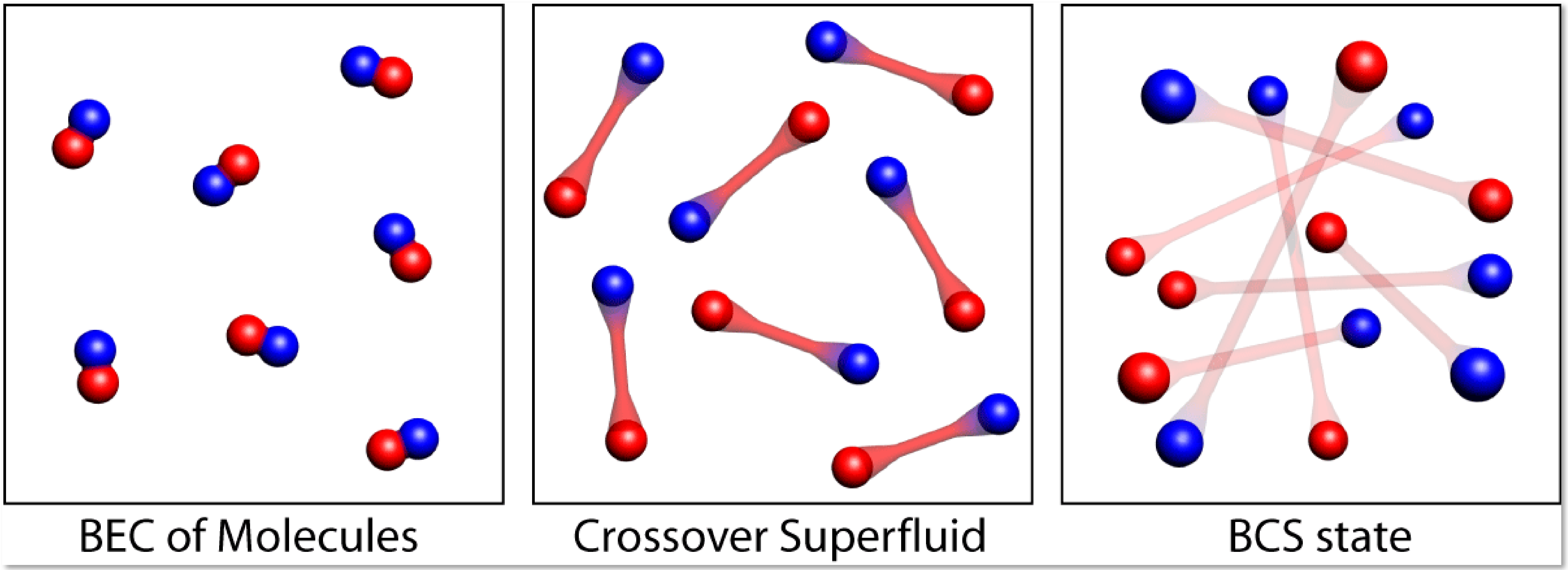
From black & white to color TV

A microscopic view of Fermion Pairs

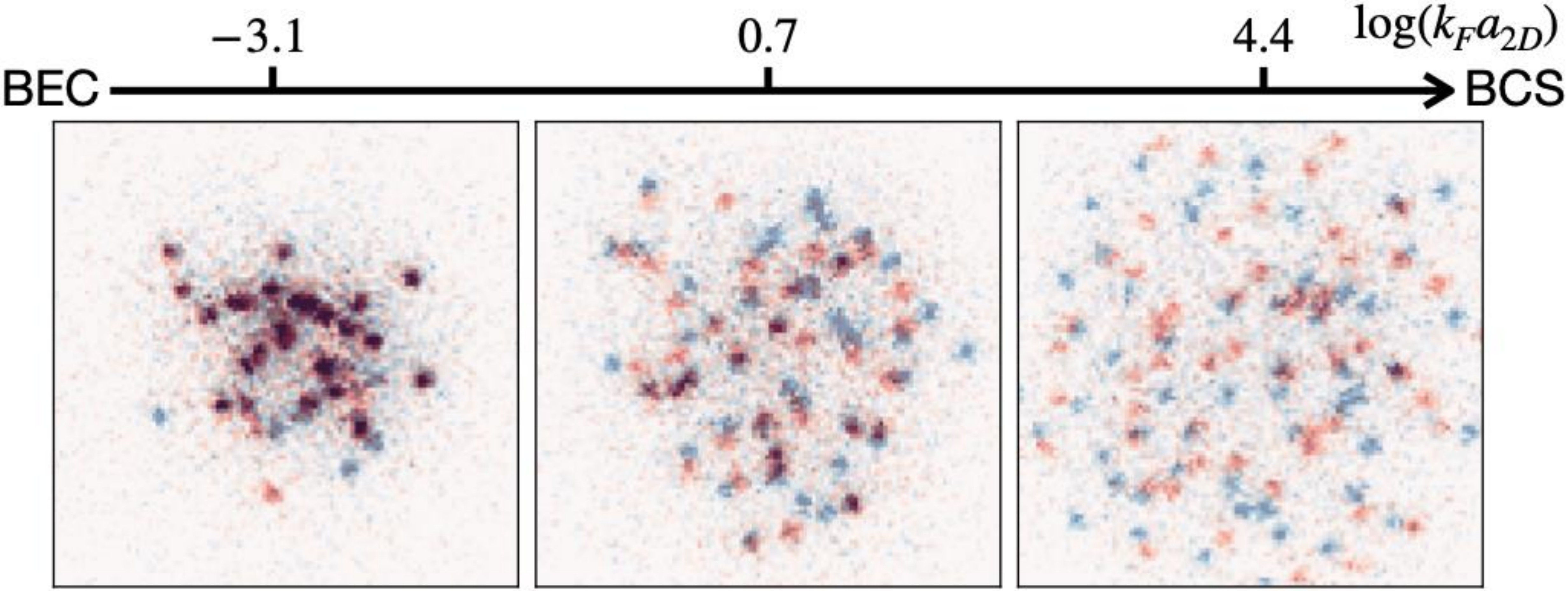




Fermion pairs in the BEC-BCS Crossover



Fermion pairs in the BEC-BCS Crossover



Ruixiao Yao, Sugnjae Chi, Kevin Wang, Richard Fletcher, MZ, in prep.

The contact

- Is a thermodynamic variable:
  measures change of energy with respect to interaction strength:

$$C = \frac{\Delta\ \mathrm{Energy}}{\Delta\ \mathrm{Interaction\ Strength}}$$

- measures the strength of short-range correlations:

$$C \sim \left\langle \psi_\uparrow^\dagger(0)\psi_\downarrow^\dagger(0)\psi_\downarrow(0)\psi_\uparrow(0) \right\rangle$$

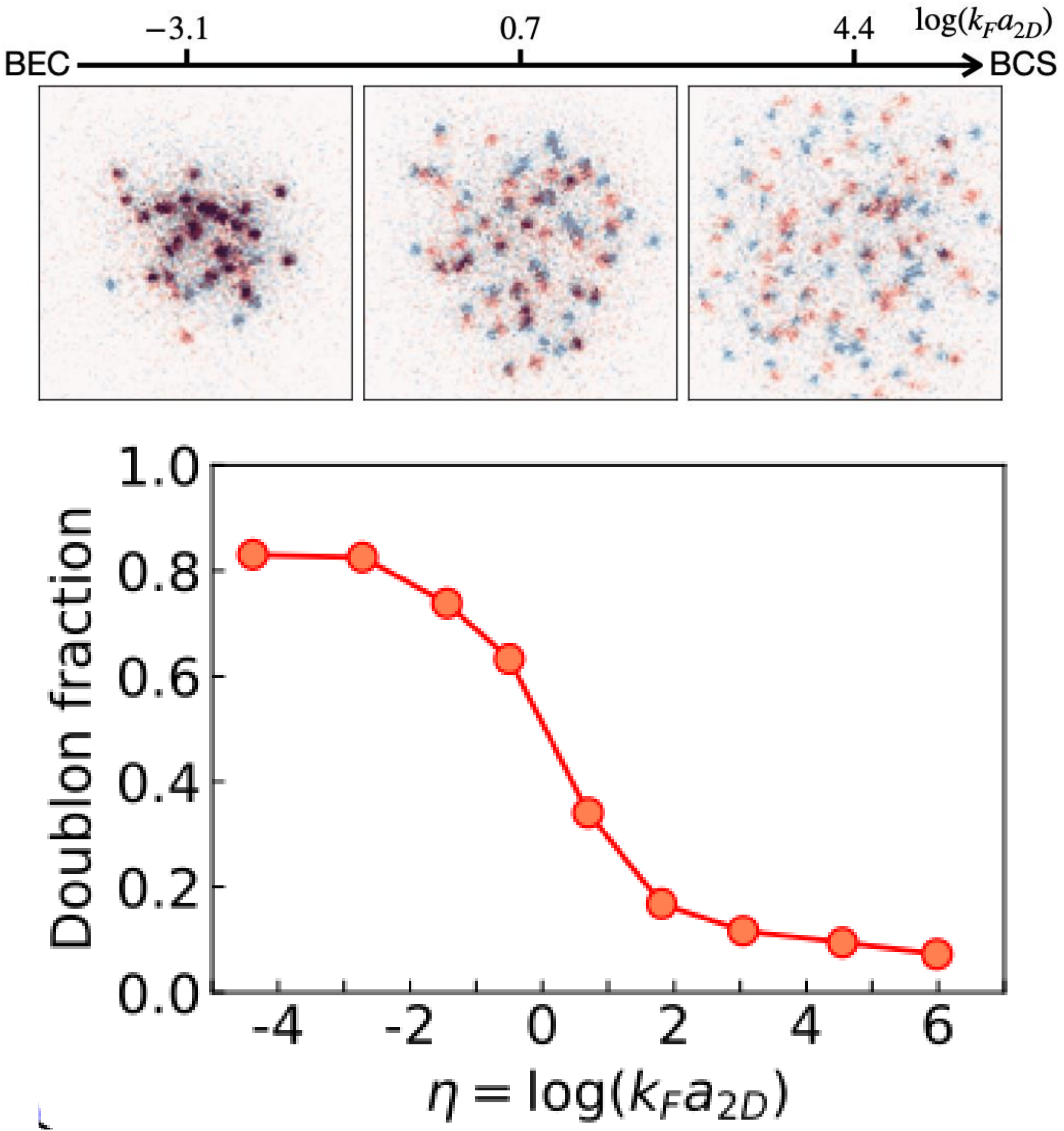
- governs the tail of the momentum distribution:

$$C = n(k)k^4 \quad \text{at large k}$$

- Controls e.g. the wings of RF spectra, photoassociation strength
- etc… (see Shina Tan 2005/2008, Baym et al. 2007, Werner Castin 2012, et al. mult.)

The contact

… can now just be read off from the number of doublons in the images!

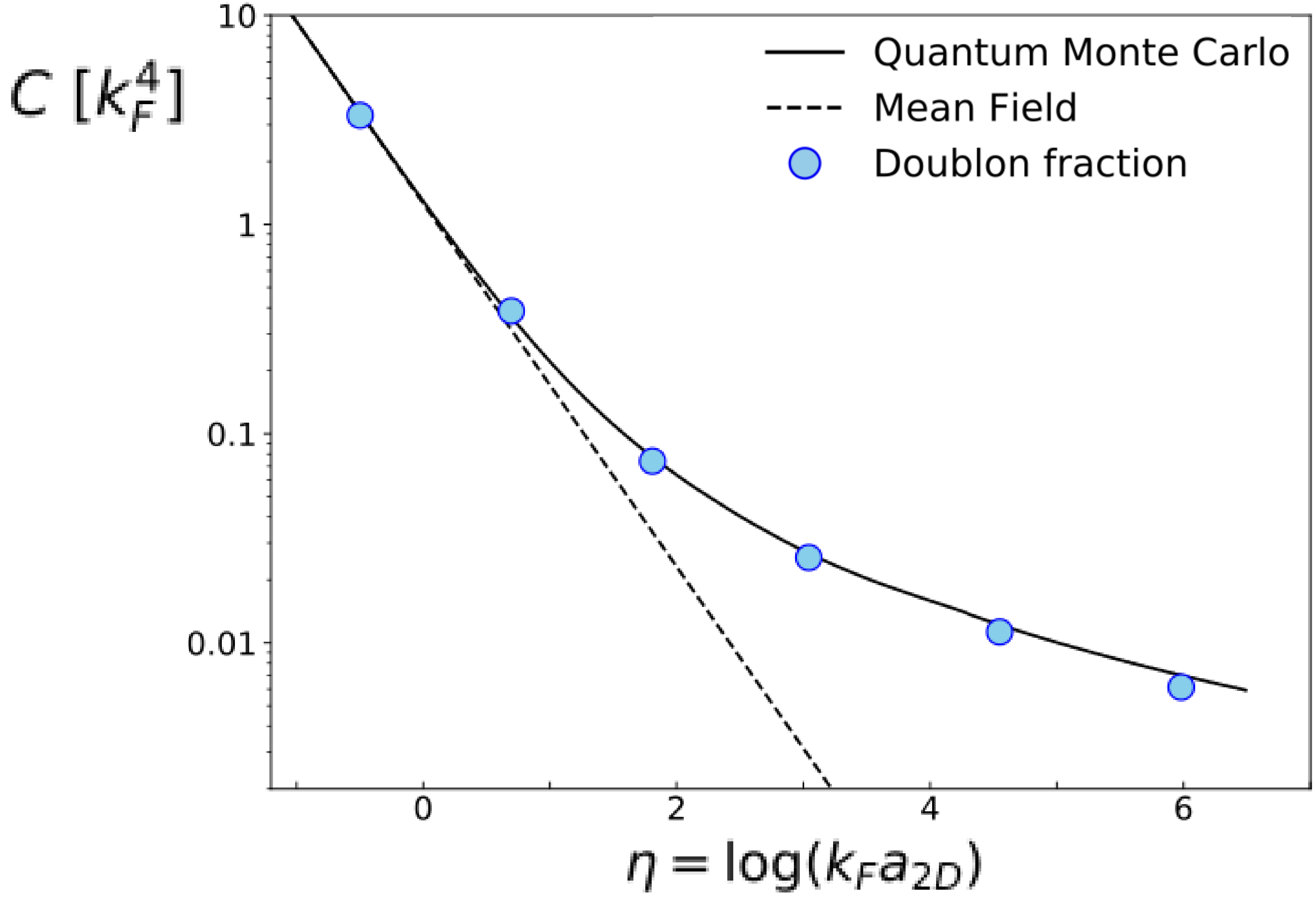


$g_{\uparrow\downarrow}(r) \sim C$ * two-body piece

→ By integration, the contact measures the number of pairs in a given region

→ Doublon fraction in a lattice cell gives contact

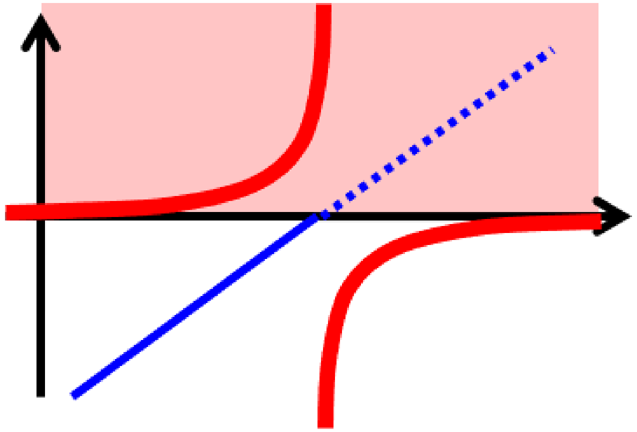
The contact



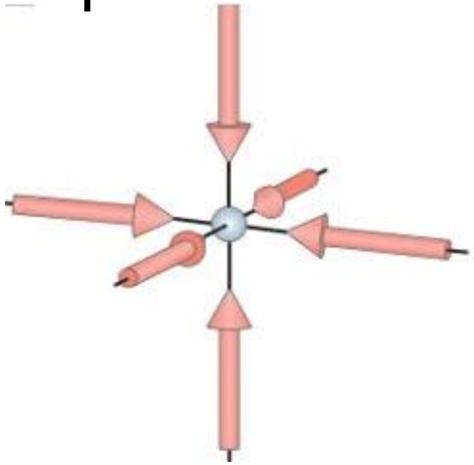
Alternatively: Use behavior of g2(r), Yao, Chi, Wang, Fletcher, MZ, PRL **134**, 183402 (2025)
Or use difference in total and spin-projected numbers: Yefsah group: arXiv:2504.01885

Realizing strongly interacting Fermi systems

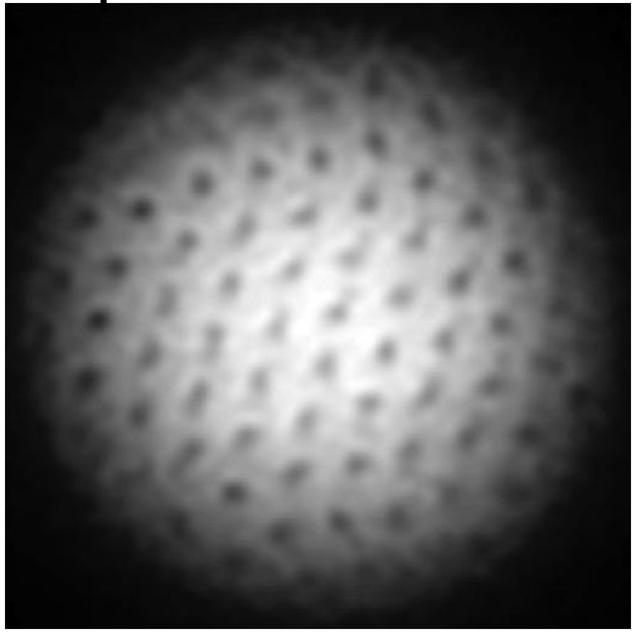
Feshbach Resonances



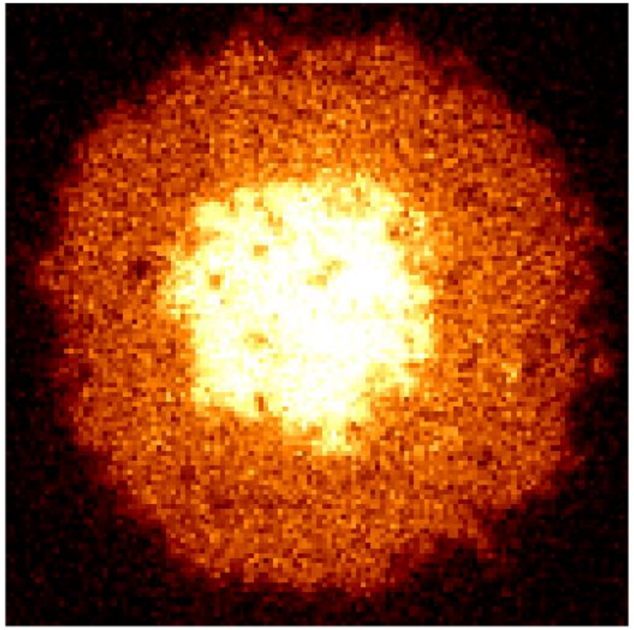
Optical Lattices



Superfluid Fermi Gas



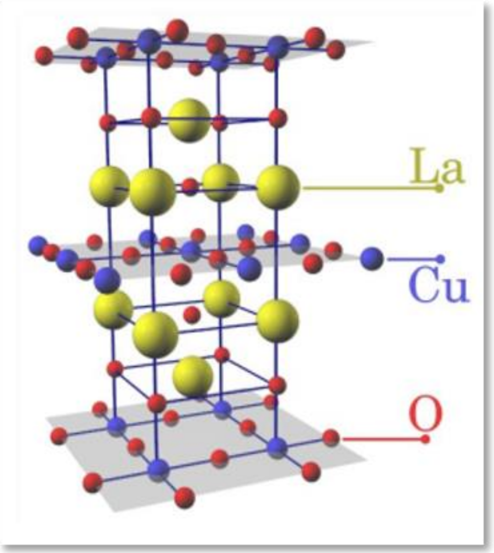
Fermi-Hubbard Gas

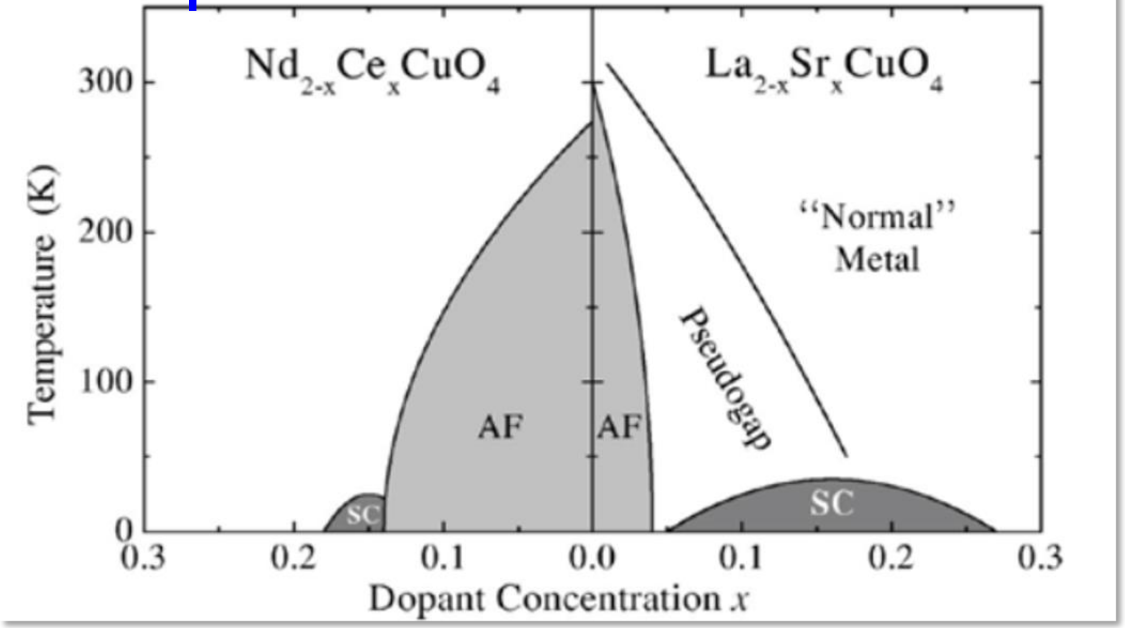


Quantum Simulation of the Fermi-Hubbard Model

$$H = -t \sum_{\langle i,j \rangle,\sigma} c_{i\sigma}^{\dagger} c_{j\sigma} + U \sum_{i} \hat{n}_{i\uparrow} \hat{n}_{i\downarrow}$$

Introduced to describe strongly correlated electrons
May contain essential features of
High-Temperature Superconductors



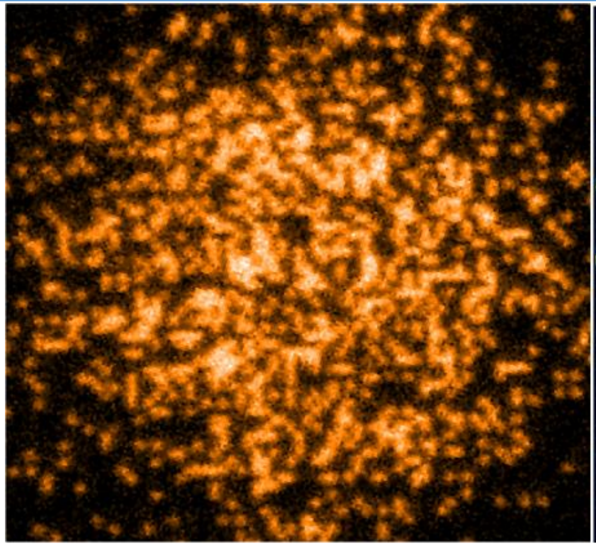


Damascelli et al., RMP 2003

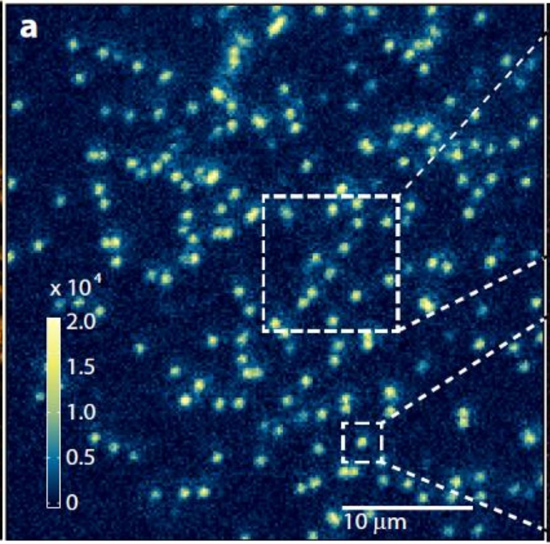
Many cold atom experiments: ETH, MPQ, Rice, MIT, Harvard, Florence, Bonn, Princeton, USTC, …

Fermi Lattice Gas Microscopes

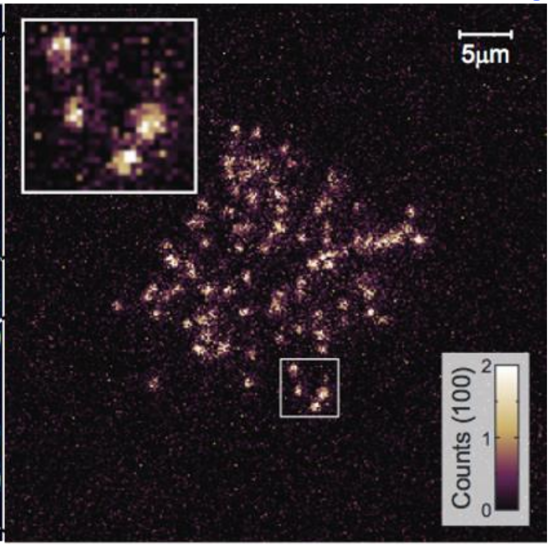
^{40}K



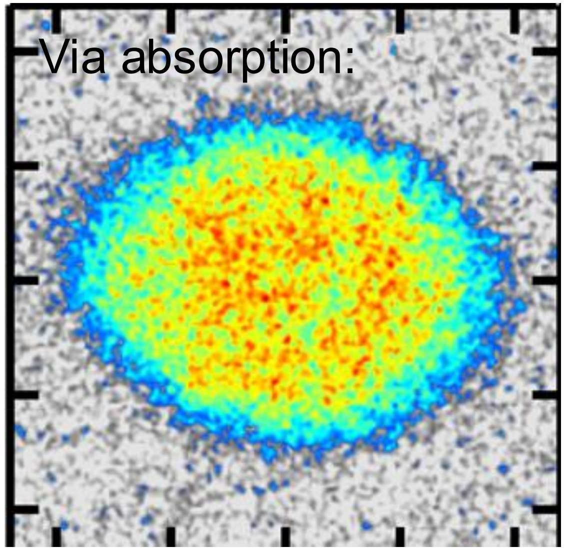
Zwierlein group, MIT
PRL **114**, 193001 (2015)



Kuhr group, Strathclyde
Nat. Phys. 11, 738 (2015)

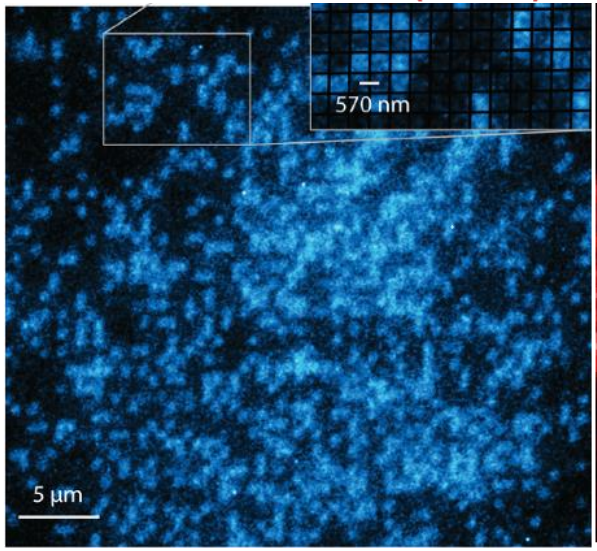


Thywissen group, Toronto,
PRA **92**, 063406 (2015)

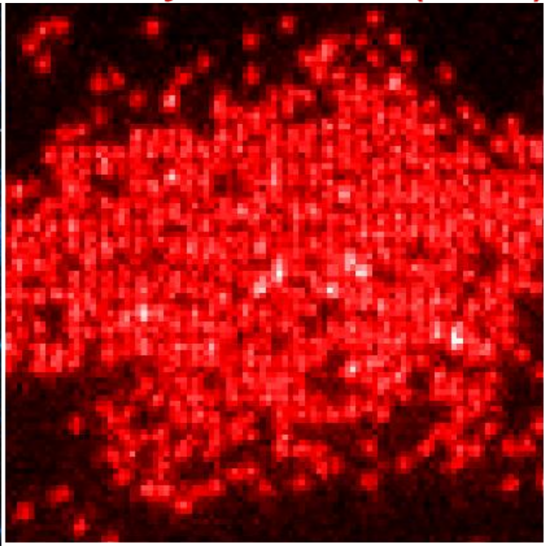


Köhl group, Bonn,
PRL 116, 175301 (2016)

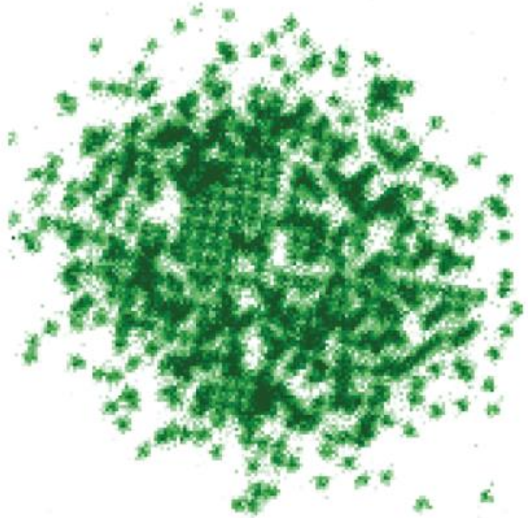
^{6}Li



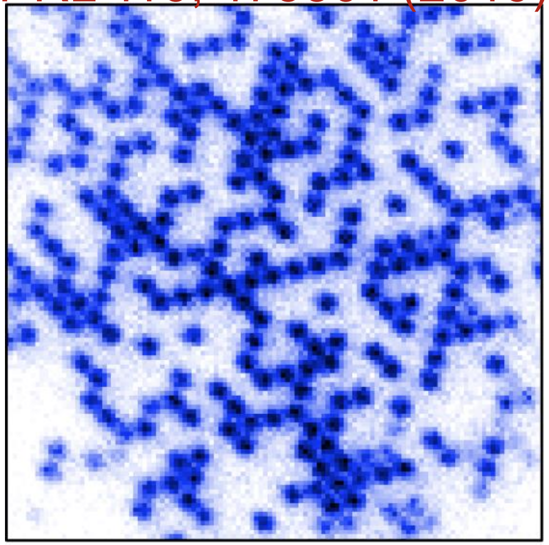
Greiner group, Harvard
PRL **114**, 213002 (2015)



Gross/Bloch group, MPQ
PRL **115**, 263001 (2015)



Bakr group, Princeton
Science, 357, 1385-1388 (2017)



Schauß group, Virginia
PRX Q 2, 020344 (2021)

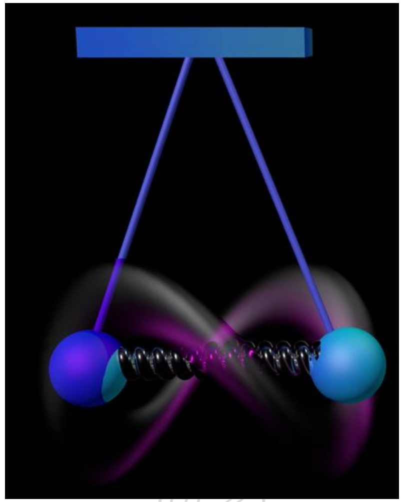
Thomas Hartke

Botond Oreg

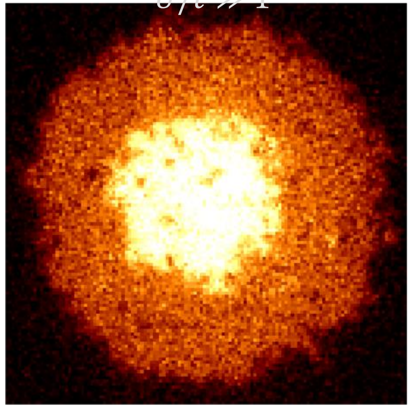
Carter Turnbaugh

Ningyuan Jia

Jens Hertkorn

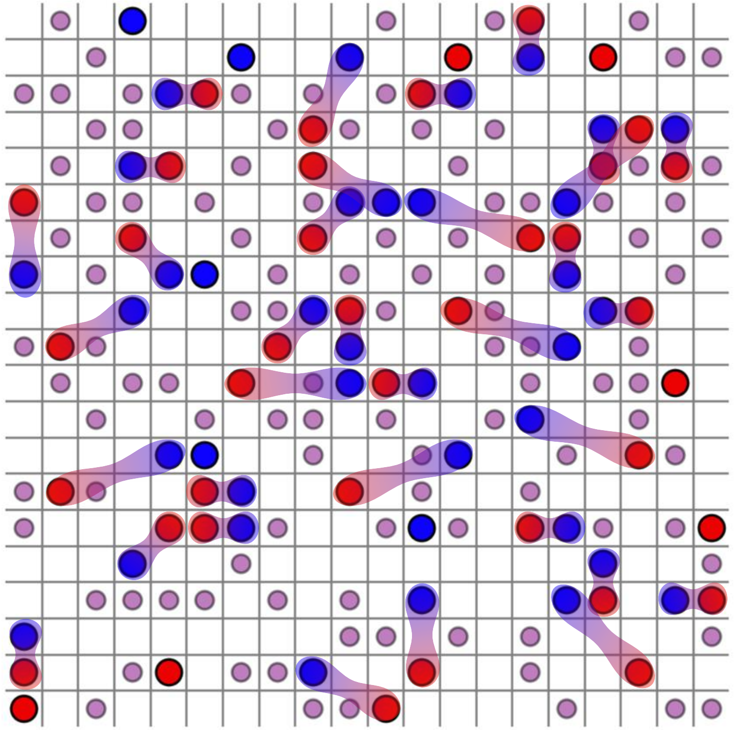


Quantum Register:
Nature 601, 537 (2022)



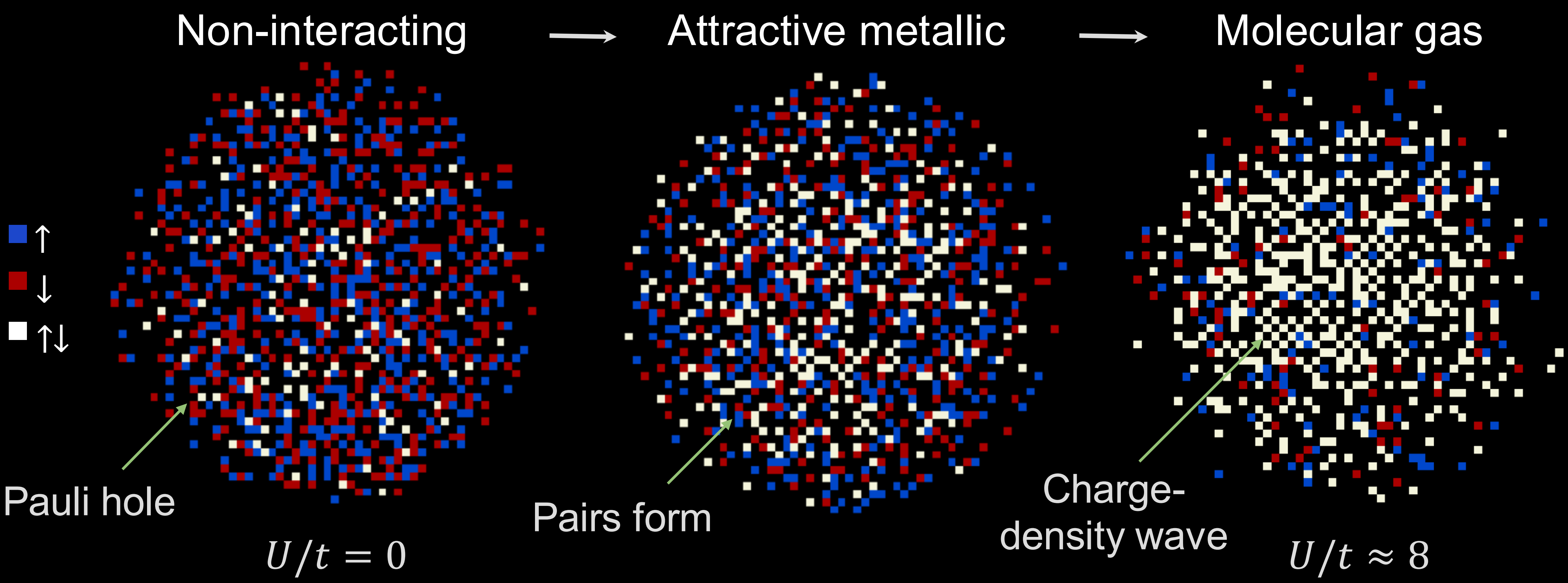
Doublon-Hole Correlations:
PRL 125, 113601 (2020)

Fermion Pairing:
Science 381, 82 (2023)



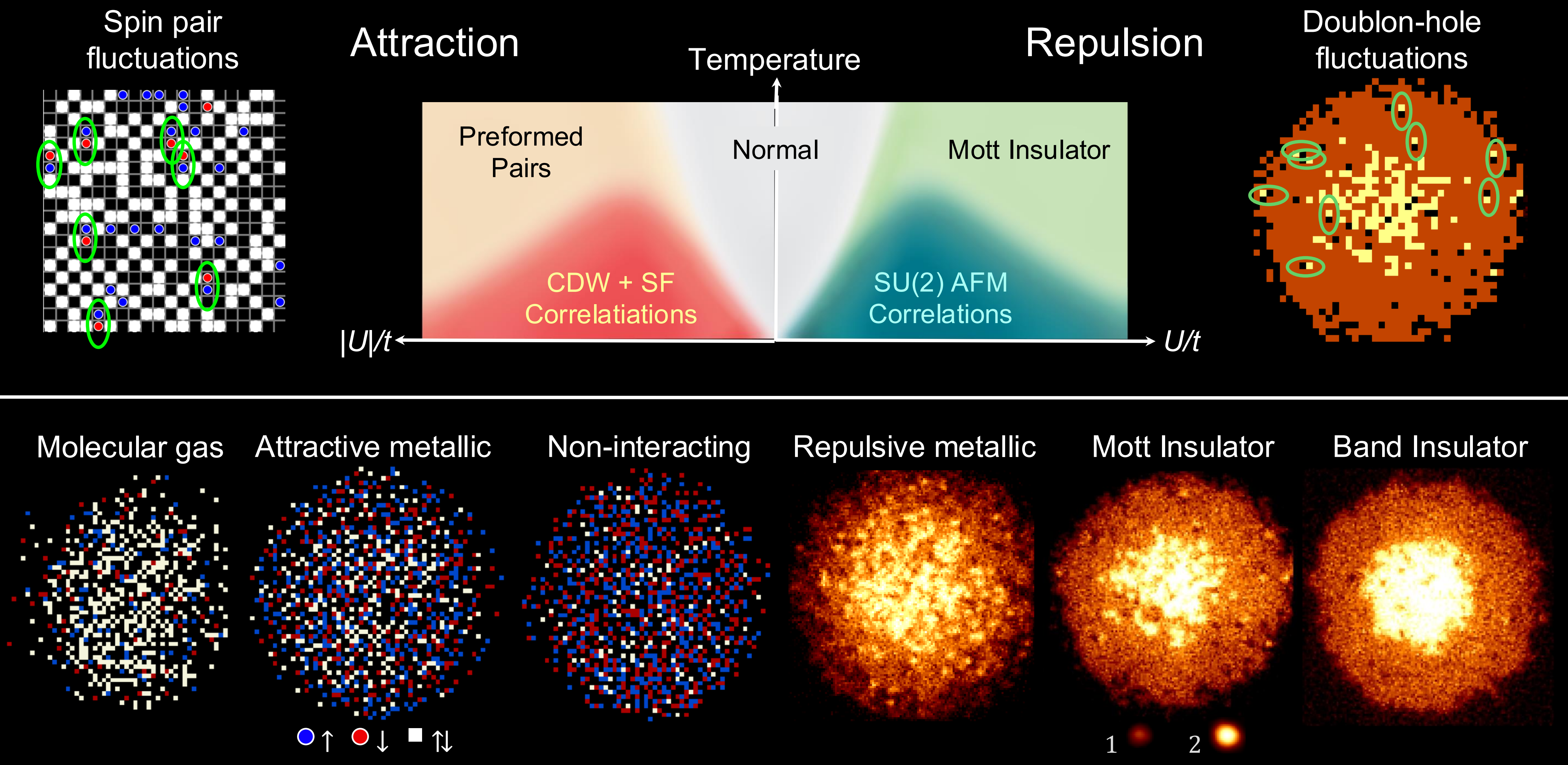
Spin Doping: arXiv:2511.10605 (2025)

Attractive Fermi-Hubbard

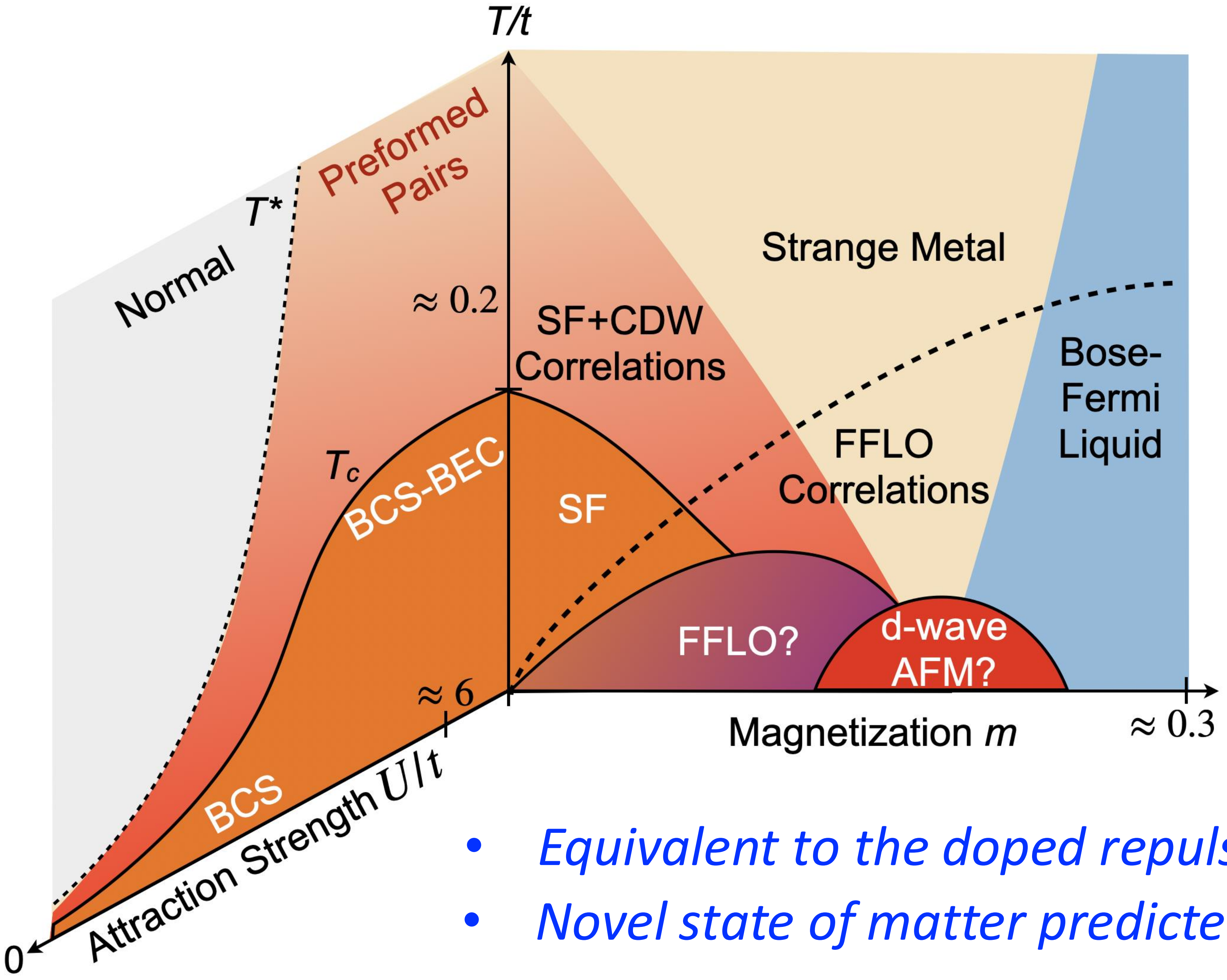


T. Hartke, B. Oreg, C. Turnbaugh, N. Jia, and M. Zwierlein, *Science*, 381, 82 (2023)

Phases of the Fermi-Hubbard Model



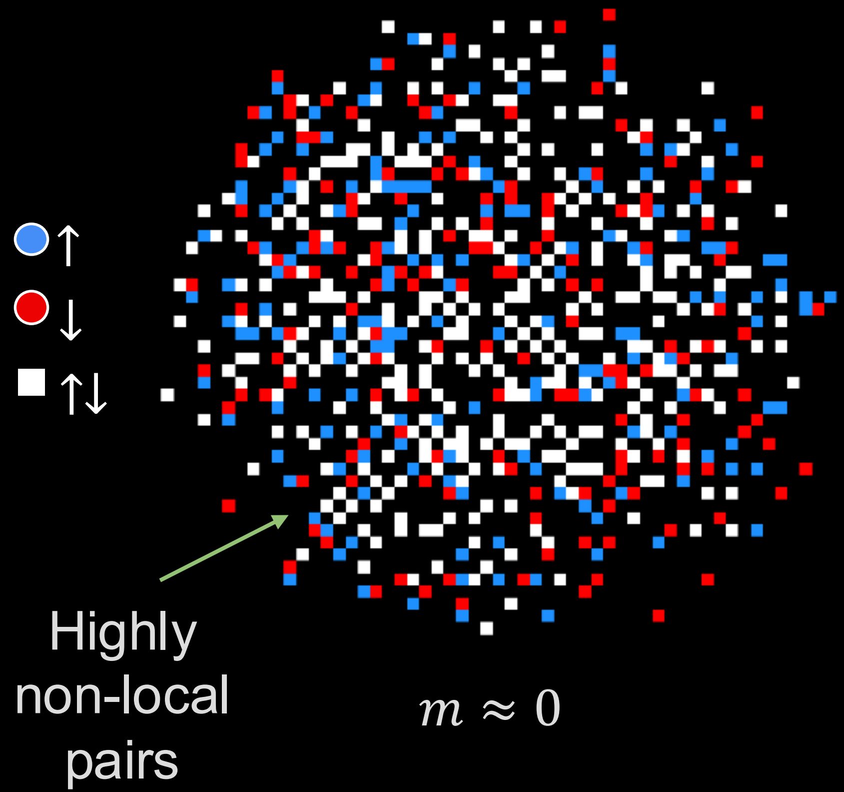
Adding loners: Spin-doped attractive Hubbard gas



- *Equivalent to the doped repulsive Hubbard gas*
- *Novel state of matter predicted: FFLO state*

Attractive Fermi-Hubbard

Spin-Balanced



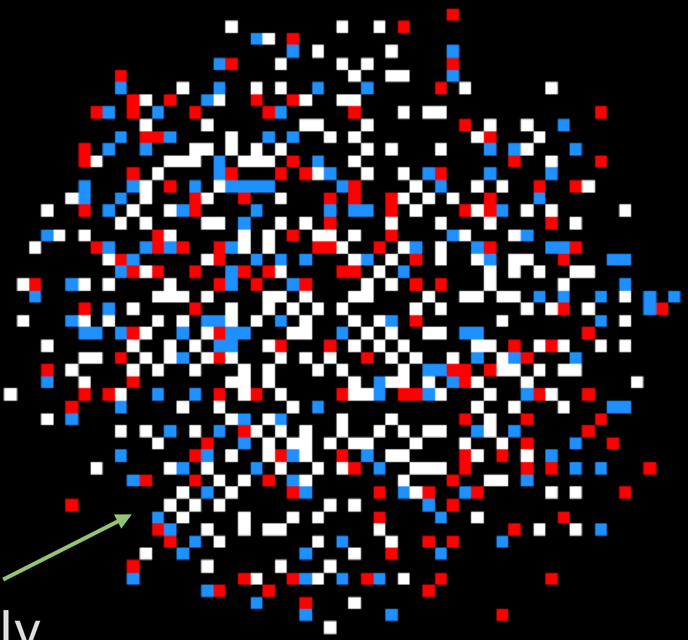
$m \approx 0$

Hartke, Oreg, Feng, Turnbaugh, Hertkorn, He, Jia, Khatami, Zhang, MZ, arXiv:2511.10605

Attractive Fermi-Hubbard + Spin Imbalance

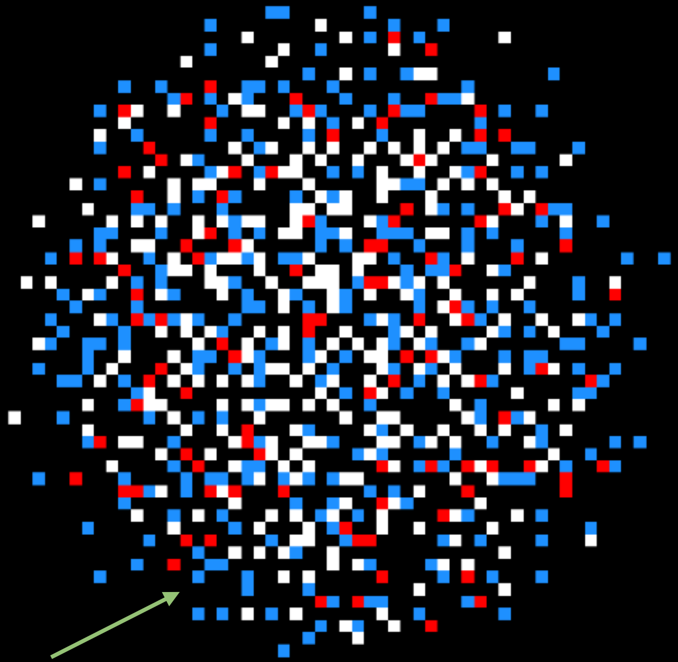
Spin-Balanced → A few additional spins

↑
↓
↑↓



Highly non-local pairs

$m \approx 0$

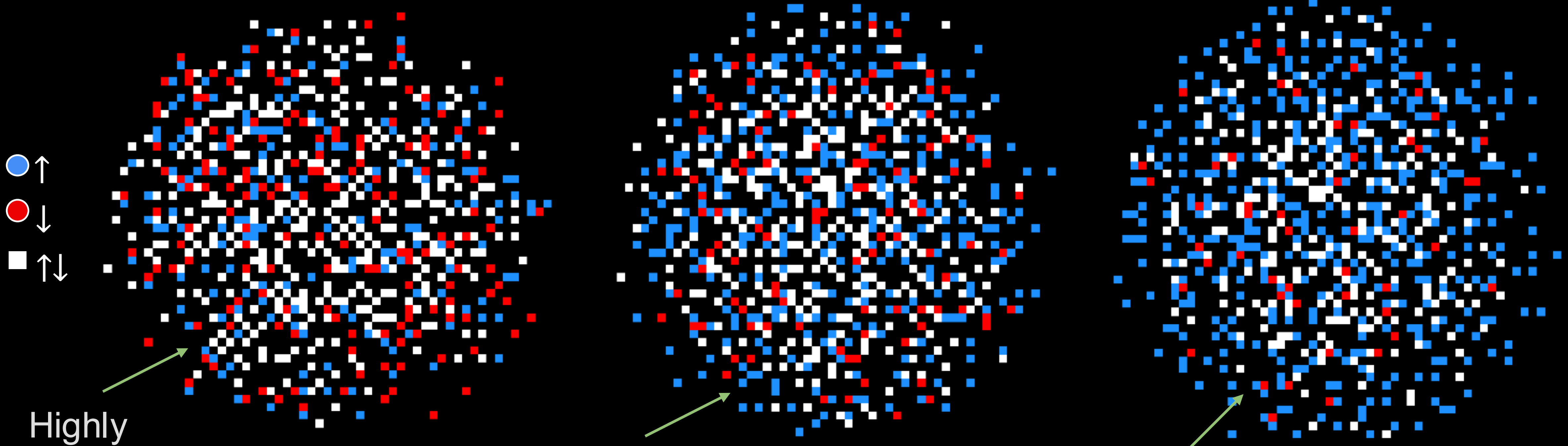


Stressed pairing

Hartke, Oreg, Feng, Turnbaugh, Hertkorn, He, Jia, Khatami, Zhang, MZ, arXiv:2511.10605

Attractive Fermi-Hubbard + Spin Imbalance

Spin-Balanced → A few additional spins → Spin-Imbalanced

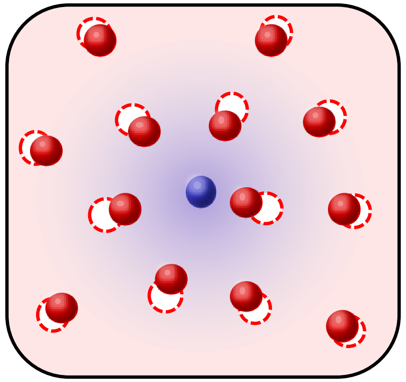


Hartke, Oreg, Feng, Turnbaugh, Hertkorn, He, Jia, Khatami, Zhang, MZ, arXiv:2511.10605

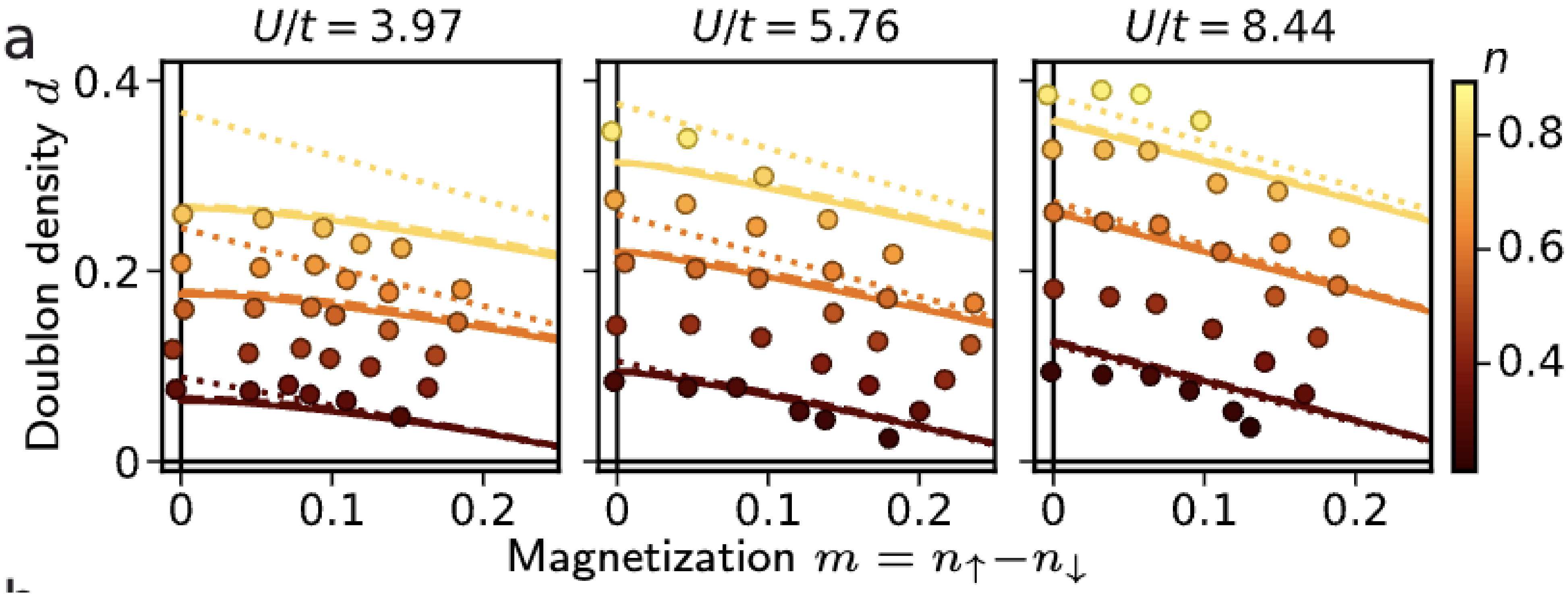
Fermi Polarons at large magnetization:

Fermi Polarons: Swimming in the Fermi Sea

Review: arXiv:2501.09618 (2025)

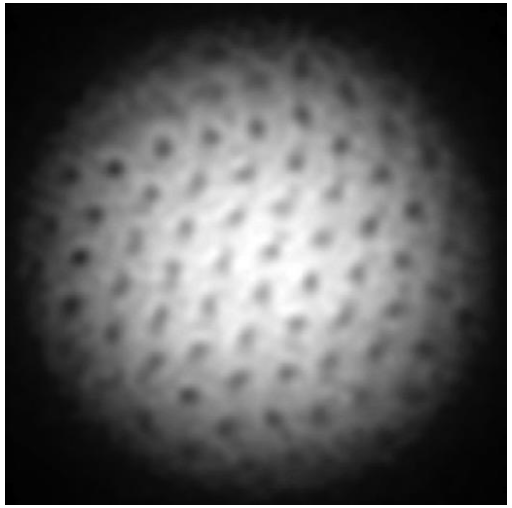


Doublon density:

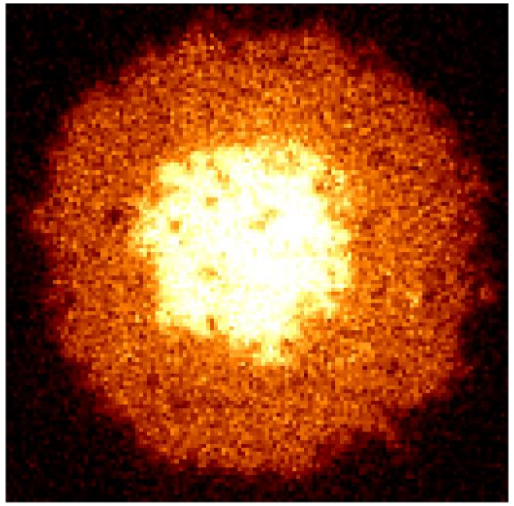


Dashed line: Fermi gas of polarons

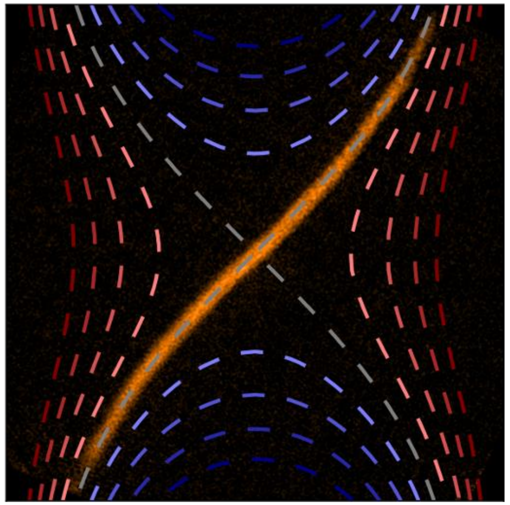
Quantum Many-Body Physics under the Microscope



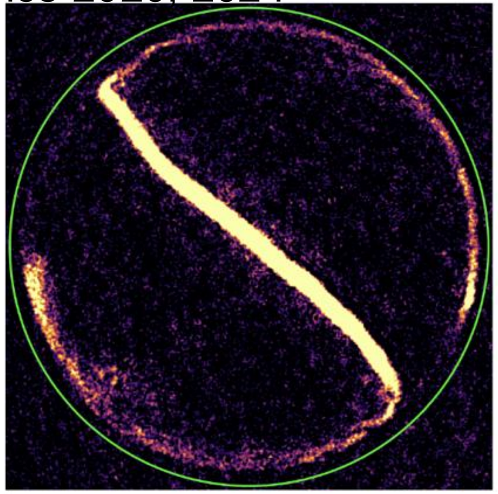
Superfluid Fermi Gas
Science 2020, 2024



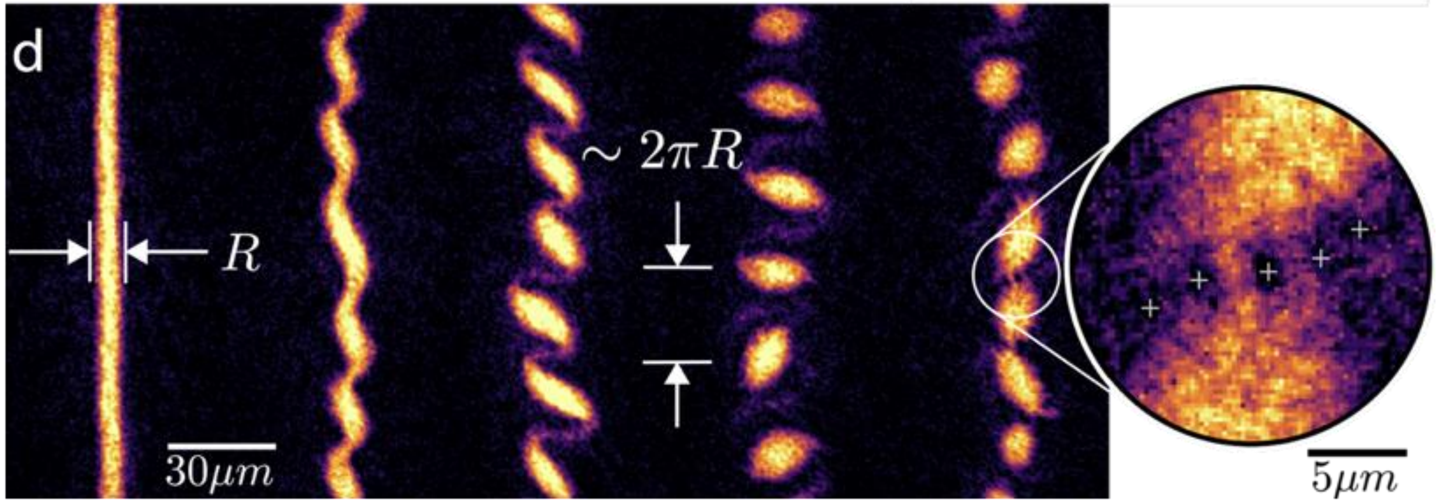
Fermi-Hubbard systems
Science 2023



Quantum Hall states
Science 2021

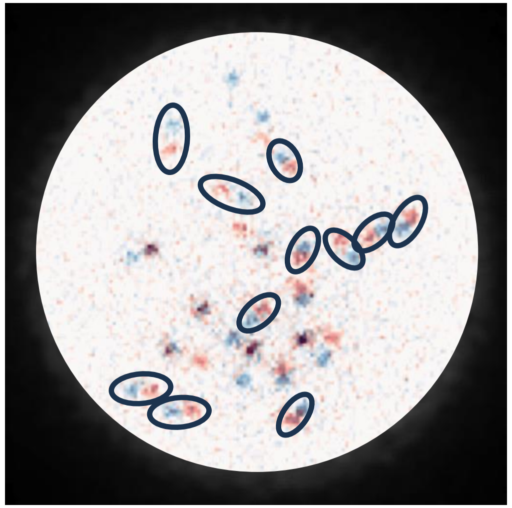


Topologically protected
Edge states Nat. Phys. 2024



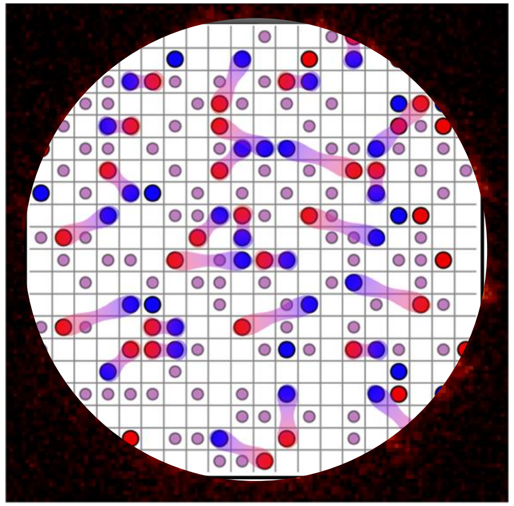
Non-Equilibrium Dynamics,
Quantum + Classical Turbulence
Nature 2022

Quantum Many-Body Physics under the Microscope



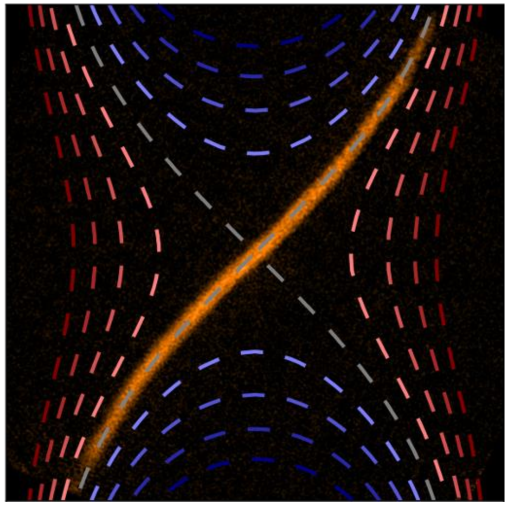
Superfluid Fermi Gas

Science 2020, 2024



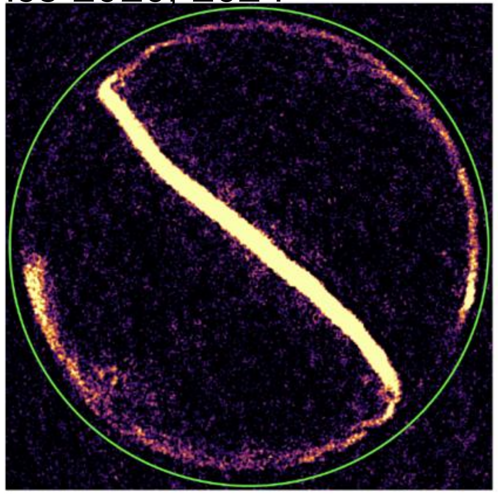
Fermi-Hubbard systems

Science 2023



Quantum Hall states

Science 2021



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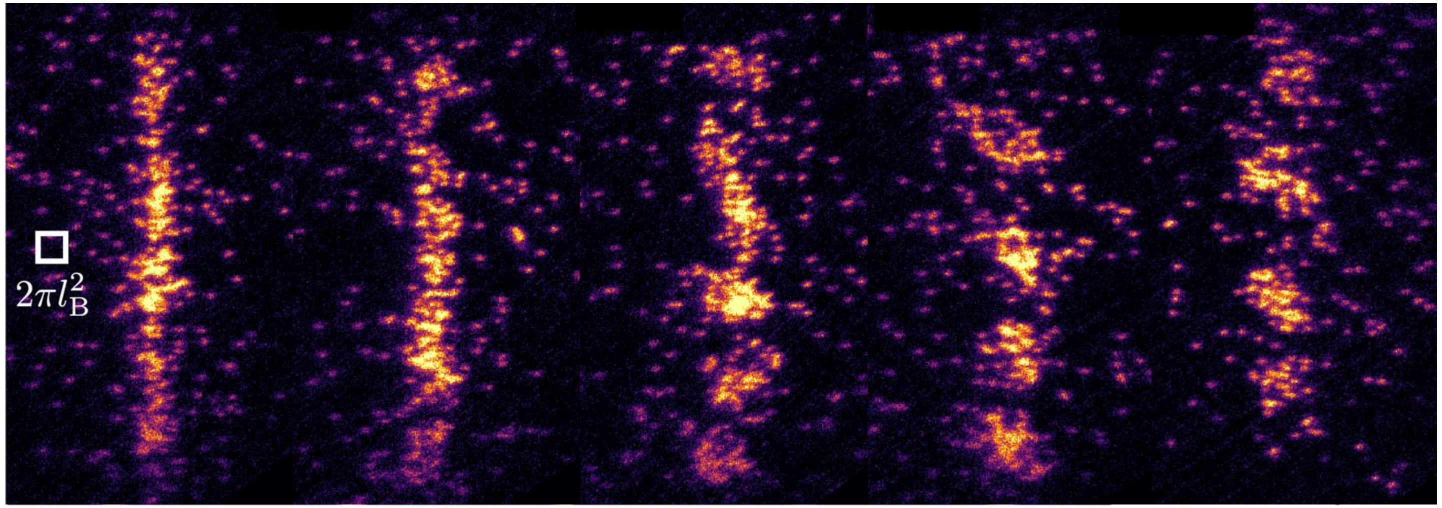


Non-Equilibrium Dynamics,
Quantum + Classical Turbulence

Nature 2022

Fermi's Legacy for the Future

- Think outside the box!
- Look for universality – transfer insights from low-energy (e.g. atomic) physics to high-energy (nuclei, quarks…)
- Combine Theory and Experiment – Complete Physics!

Some Future topics:

- Fulde-Ferrell-Larkin-Ovchinnikov phase
- Topological superfluids (e.g. p-wave with molecules?)
- Modeling the Standard Model: Gauge Theories
- Quantum Computation with Fermions

Bosons and Fermions

Bosons and Fermions

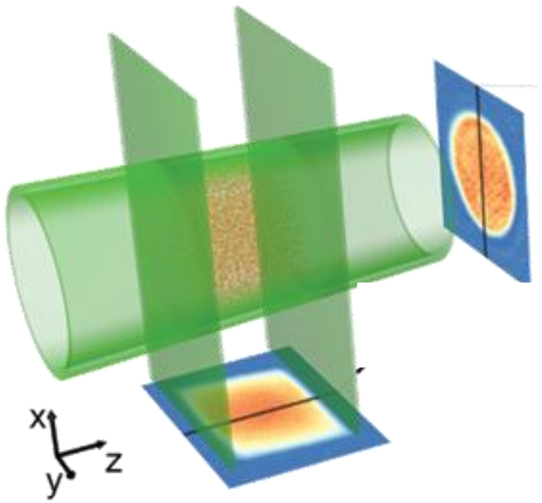
BEC 1/Fermi3

Fermional Superfluids

Eric Wolf

Recent Members:
Biswaroop Mukherjee
Parth Patel
Zhenjie Yan
Richard Fletcher
(→ MIT)

Recent Visitor:
Chris Vale

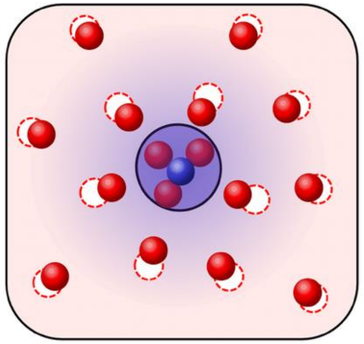


Fermi 1

NaK Dipolar Molecules

Huan Bui
Yiming Zhang
Jacob VanArsdale

Recent Members:
Alex Yu Chuang
Carsten Robens
Zoe Yan (→ Chicago)
Yiqi Ni
Theory collaborations:
Eugene Demler
Pavel Dolgirev
Kushal Seetharam
Arthur Christianen



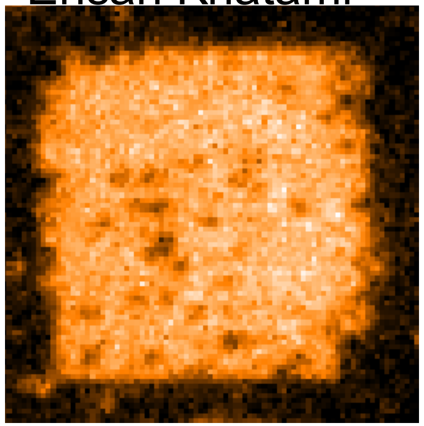
Fermi 2

Fermi Gas Microscope

Botond Oreg
Carter Turnbaugh
Zihan Xu
Jens Hertkorn

Recent Members:
Ningyuan Jia
Thomas Hartke

Theory collaborations:
Shiwei Zhang
Chunhan Feng
Ehsan Khatami



Fermi3

Rotating Superfluids

Ruixiao Yao
Sungjae Chi
Kevin Wang
in collaboration with
Richard Fletcher

Recent Members:
Airlia Shaffer-Moag
Cedric Wilson

Theory collaborations:
Valentin Crépel
Tapio Simula