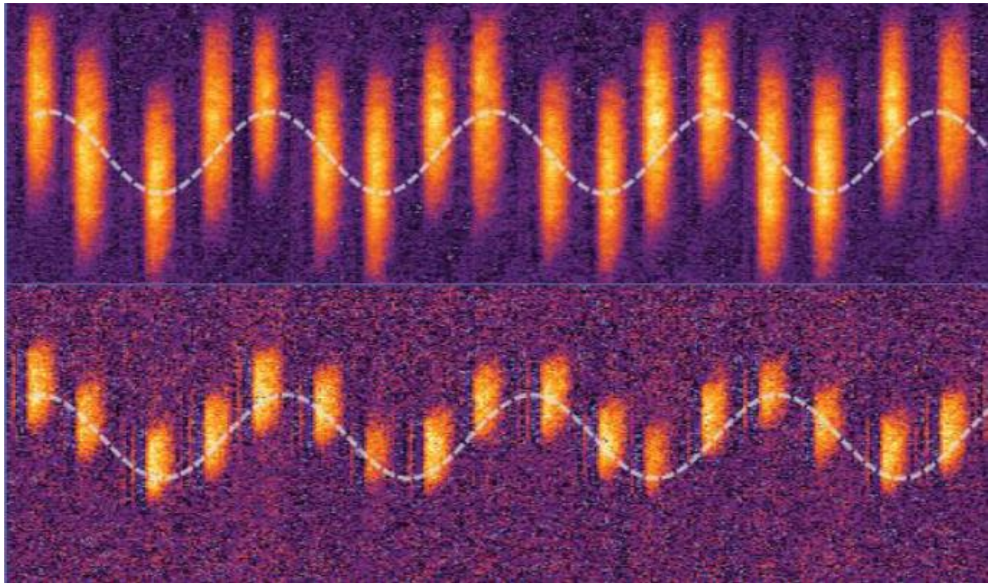
Imaging ultracold quantum gases



C. Salomon

Laboratoire Kastler Brossel
Physique quantique et applications

DPP-Fermions 2022, ENS Lyon
June 9, 2022

What can we learn from images of quantum gases ?

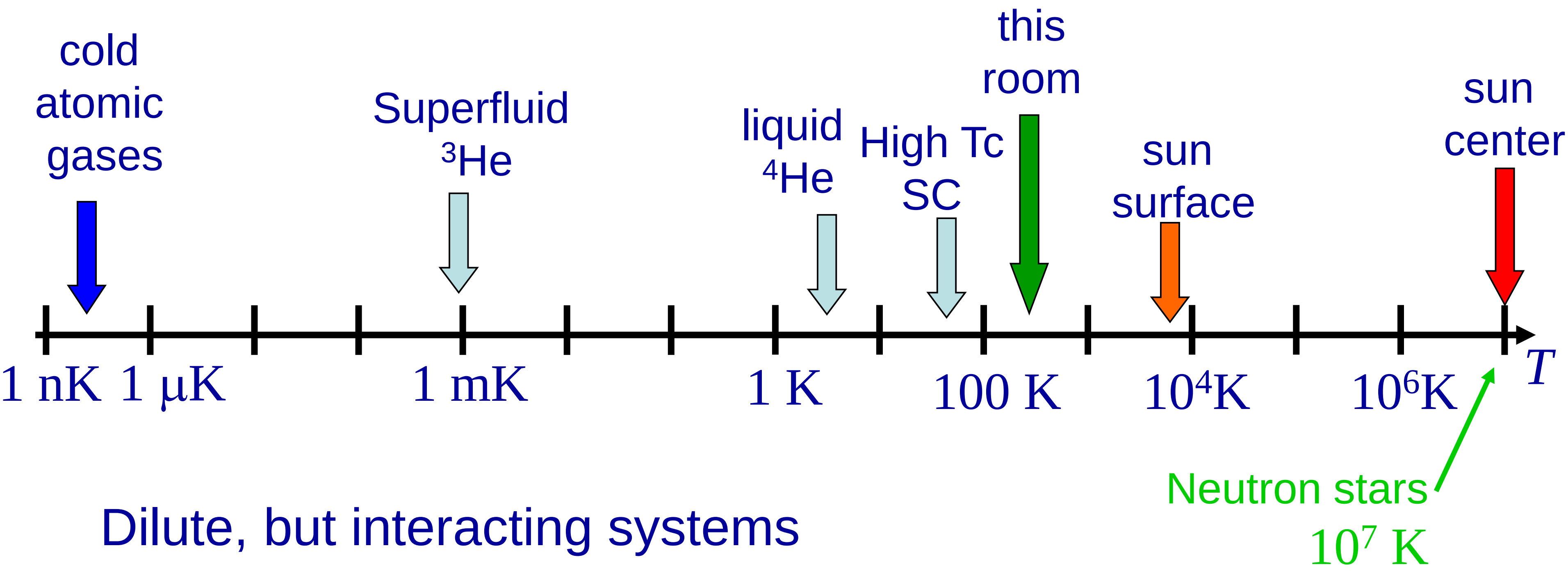
- Global thermodynamic properties: equation of state

- Exploring the link between fermionic superfluidity and Bose Einstein condensation

- Dual Bose-Fermi superfluid mixture: a surprise !

- Imaging fermions one by one:
  exploring the Fermi Hubbard model in 1 and 2 dimensions

Temperature scale of cold gases



Dilute, but interacting systems

Typical density: $\rho = 10^{13}$ to 10^{15} atoms/cm^3

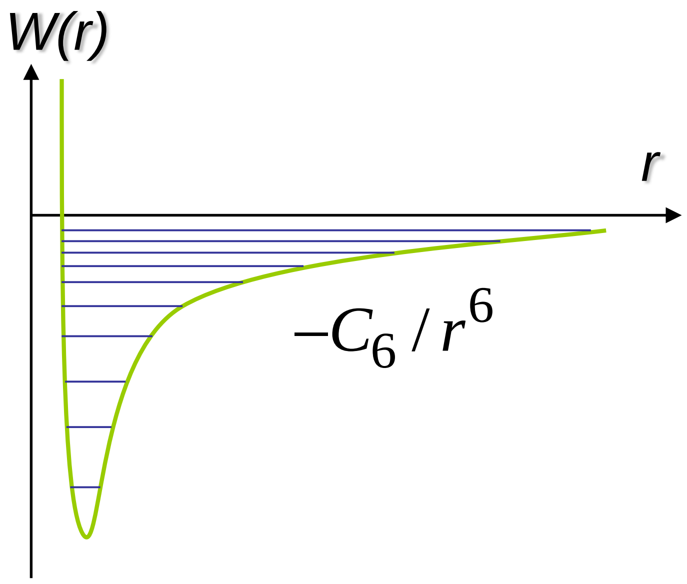
Interatomic distance 0.1 to $0.5\ \mu$m $\gg$ range of interatomic potentials

$E_{\text{int}} \gg \hbar\omega$ quantum of motion in the trap or box

$E_{\text{int}} \gg k_B T$ thermal energy

Equilibrium properties and dynamics are governed by interactions

Atom-atom interactions



At low temperature,
only s wave collisions, $l = 0$

$$\psi(\vec{r}) = e^{i\vec{k}.\vec{r}} - \frac{a}{r} e^{ikr}$$

$$a = -\lim_{k \to 0} \frac{\tan \delta_0(k)}{k}$$

The magnitude and sign of ***a*** depend sensitively on the detailed shape of long range potential
Importance of position of last bound state

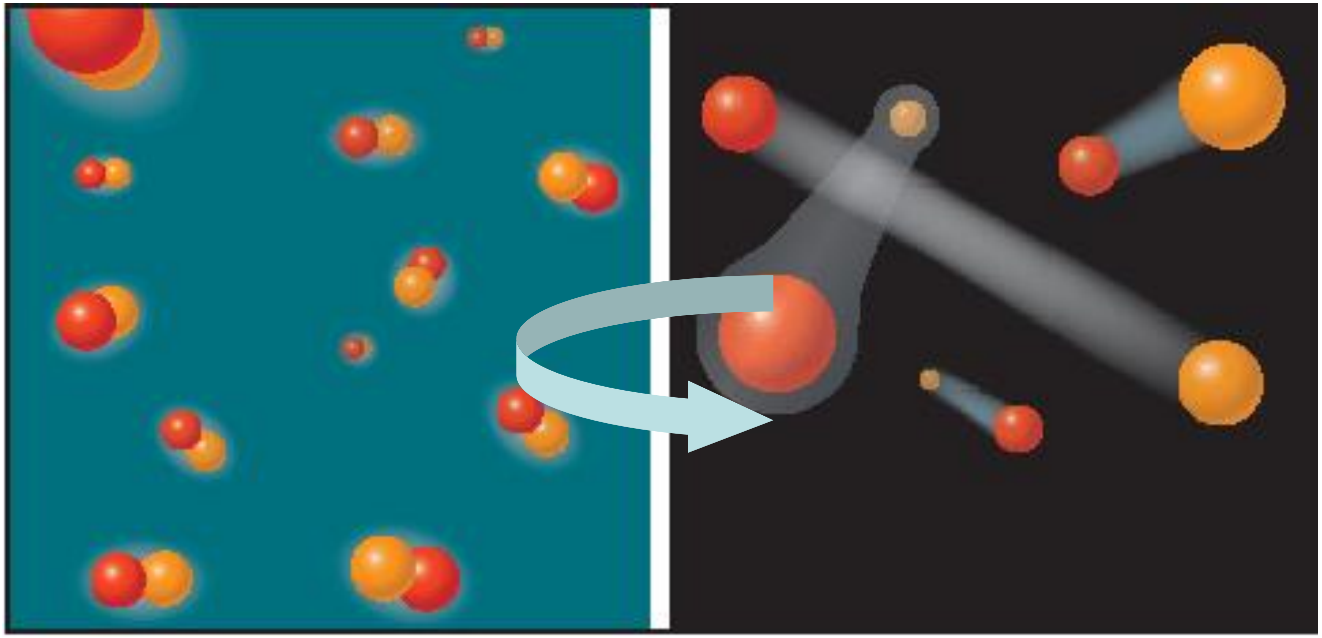
a: scattering length
|*a*|~1 to 10 nm

$$V(\vec{r}_1 - \vec{r}_2) = \frac{4\pi\hbar^2 a}{m} \delta(\vec{r}_1 - \vec{r}_2)$$

Tuning interactions via Fano-Feshbach resonance

a > 0 : effective repulsive interaction
a < 0 : effective attractive interaction

Fermions with two spin states with attractive interaction



$$T_c \approx T_F \, e^{-\pi/2k_F|a|}$$

BEC of molecules ⟵ BCS fermionic superfluid

Bound state   Interaction strength   No bound state

Equation of state in the BEC-BCS crossover

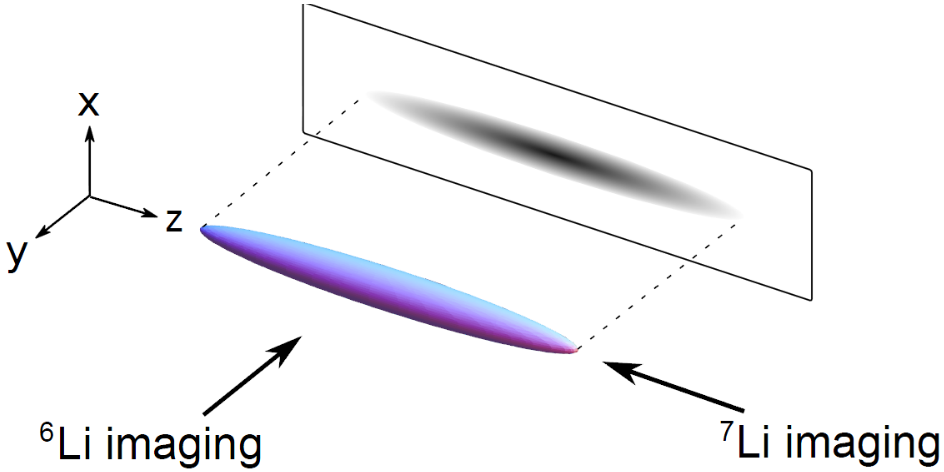
Spin 1/2 Fermi gas with tunable interaction

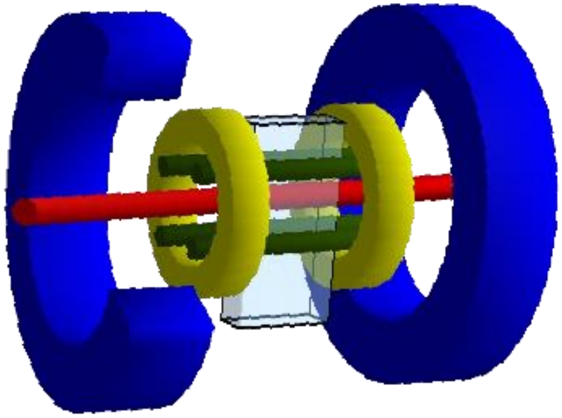
- Loading of ^{6}Lithium fermions in the optical trap

- Tune magnetic field to Feshbach resonance

- Evaporation of ^{6}Li to 30 nK

- Image of ^{6}Li ***in-situ***





The Equation of State of a cold Gas

Q. Zhou, T.L. Ho, Nature Physics, 09

C. Cheng, S.Yip, PRB (2007)

The pressure is obtained from *in situ* images

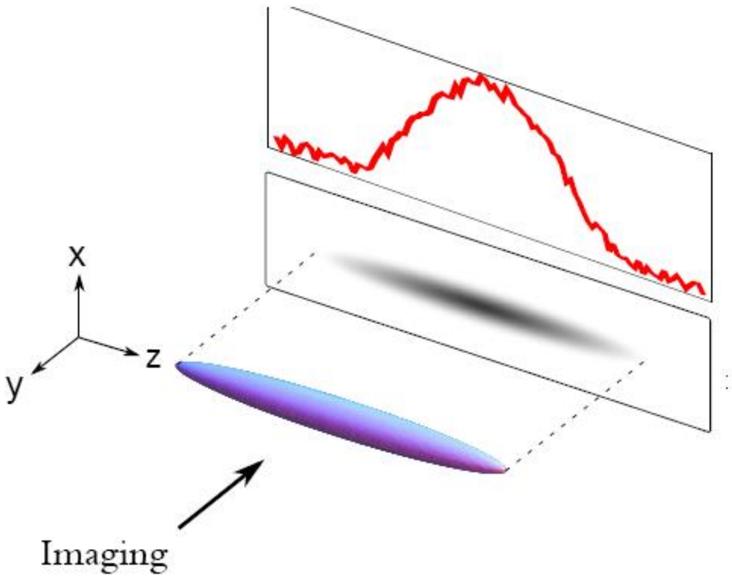
$$P(\mu_z, T) = \frac{m\omega_r^2}{2\pi}\bar{n}(z)$$

$$\bar{n}(z) = \int dxdy\, n(x, y, z)$$

Doubly-integrated density profile

Local density approx.

$$\mu(r) = \mu_0 - V(r)$$



$P(\mu_z, T)$ is an Equation of State of the locally homogeneous gas

Equation of State of Quantum Gases

Equilibrium properties given by thermodynamic potentials:

Grand potential $$\Omega = -PV = E - TS - \mu N$$

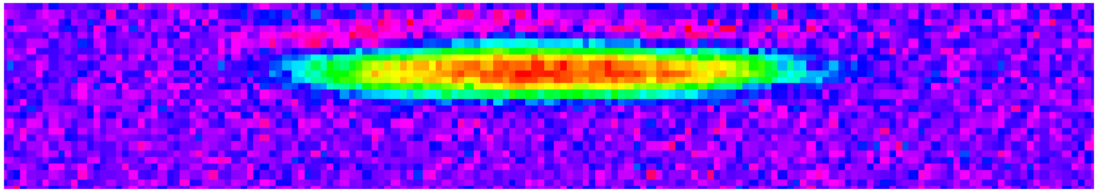
Pressure, Volume, Internal energy, Temperature, Entropy, Chemical potential, Atom number

We have measured the grand potential
of tunable Fermi and Bose gases

S. Nascimbène et al., Nature, **463**, 1057, (2010), temperature dependence
N. Navon et al., Science **328**, 729 (2010), ground state in crossover
N. Navon et al., PRL 2011, Lee-Huang-Yang quantum correction in Bose gas
S. Nascimbène et al., Fermi liquid behavior, PRL 2011
M. Horikoshi et al., Science, 327, (2010), M. Ku et al., Science, 335(2012)

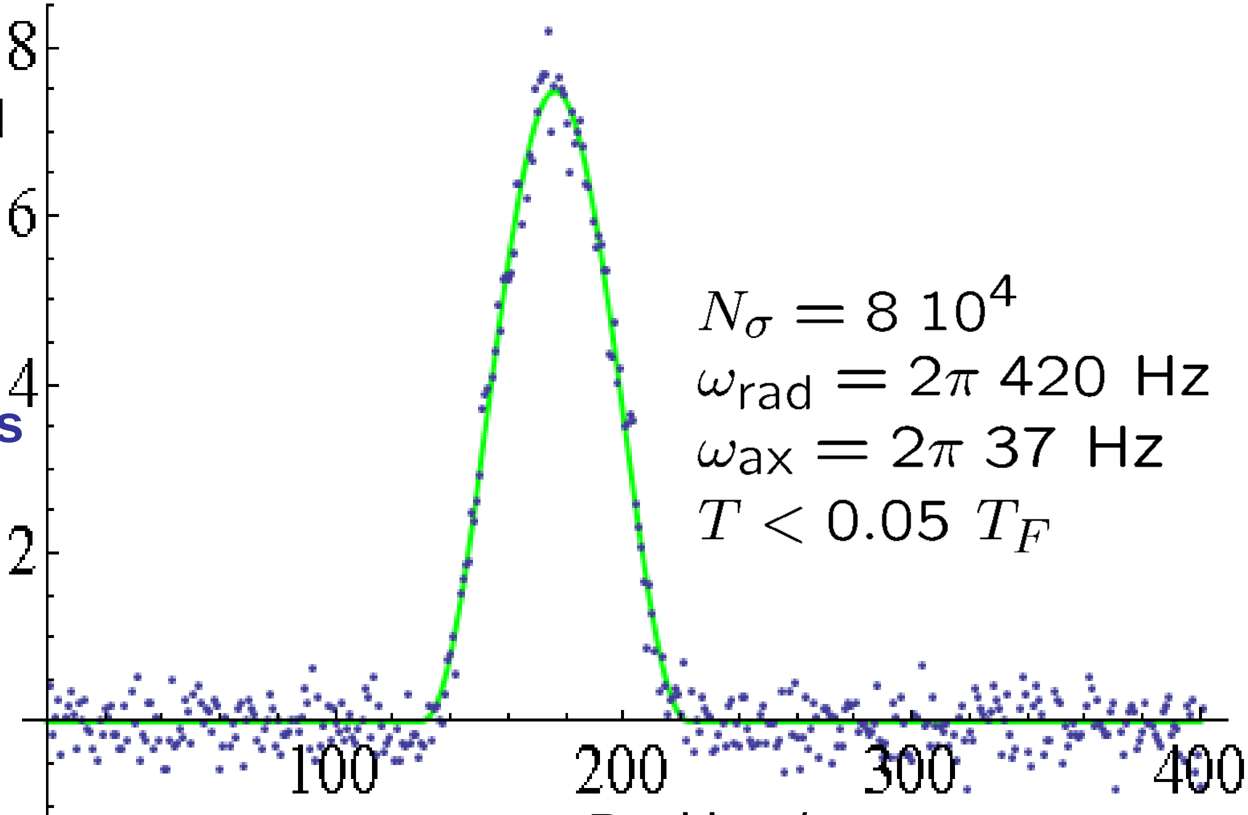
Unitary Fermi Gas

$$a = \infty$$



Doubly integrated Density

Pressure of the locally homogeneous gas



Position / **Chemical potential $\mu(z)$**

S. Nascimbène et al., Nature, **463**, 1057, (2010)

The Equation of State at unitarity: temperature dependence

$$1/k_F\, a = 0$$

Thermodynamics is universal

T.L. Ho, E. Mueller, '04

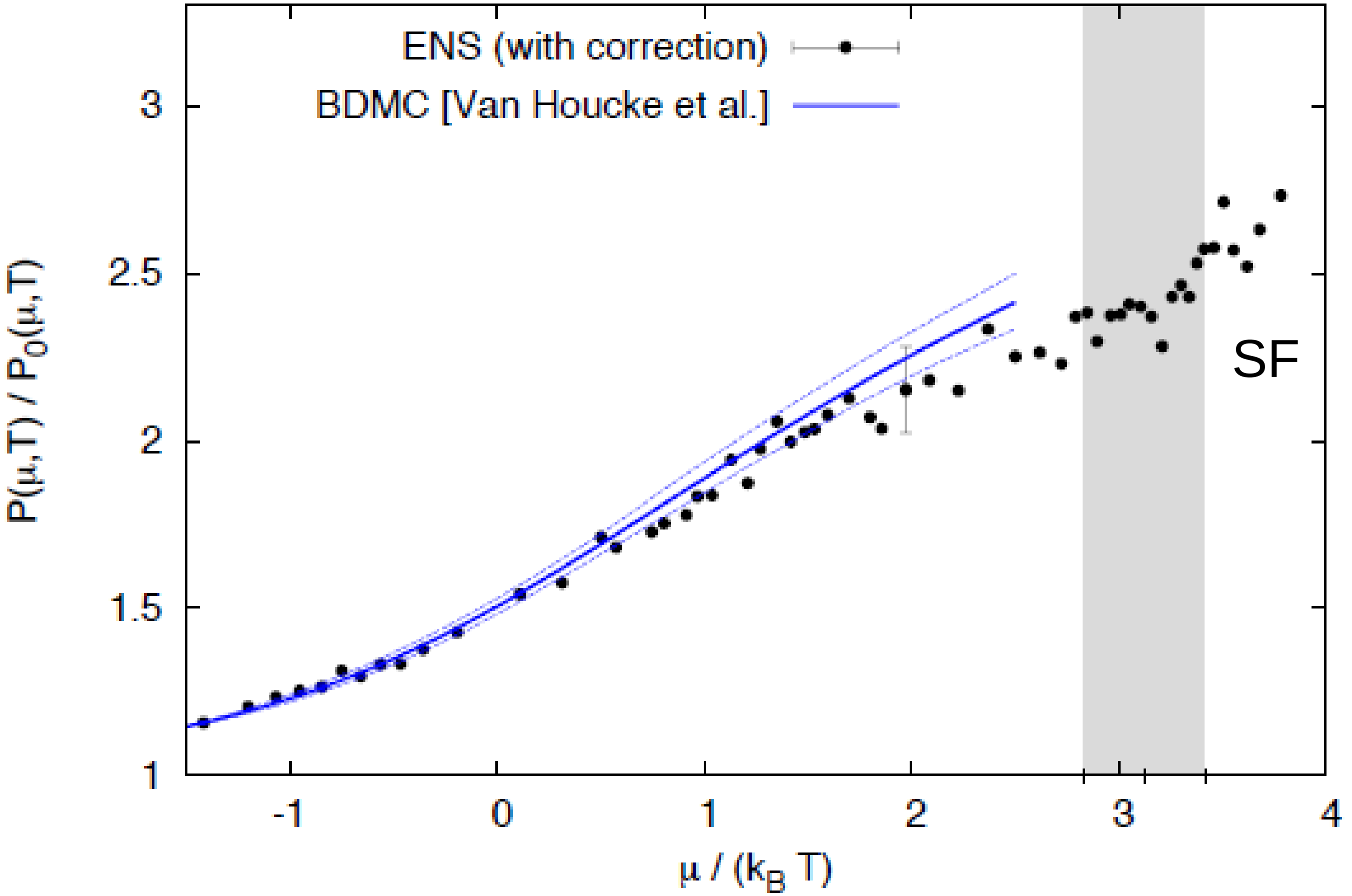
Continuous scale invariance

Pressure depends only on $\mu / k_B T$

S. Nascimbène et al., Nature, **463**, 1057, (2010)

$T_c = 0.16\ T_F$ *MIT 2012, Ku et al., Science*

Comparison with Bold Diagrammatic Monte-Carlo

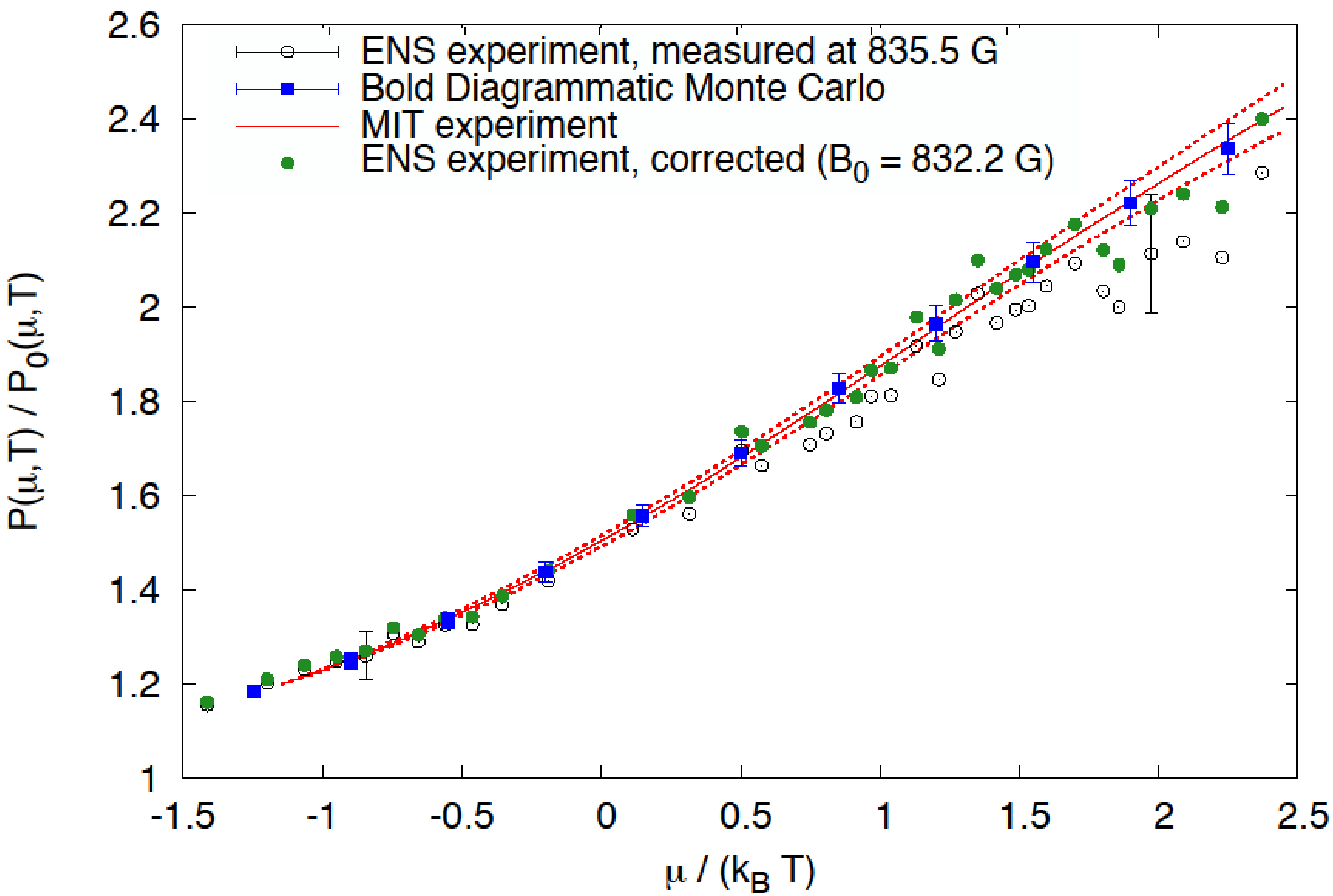


Theory:
Van Houcke,
et al.
Amherst
MIT
Nature Phys.,
2012

5% agreement with a Many-Body theory in strongly interacting regime

Universal Equation of State at Unitarity

Comparison with MIT 2012 and Bold diag MC simulation

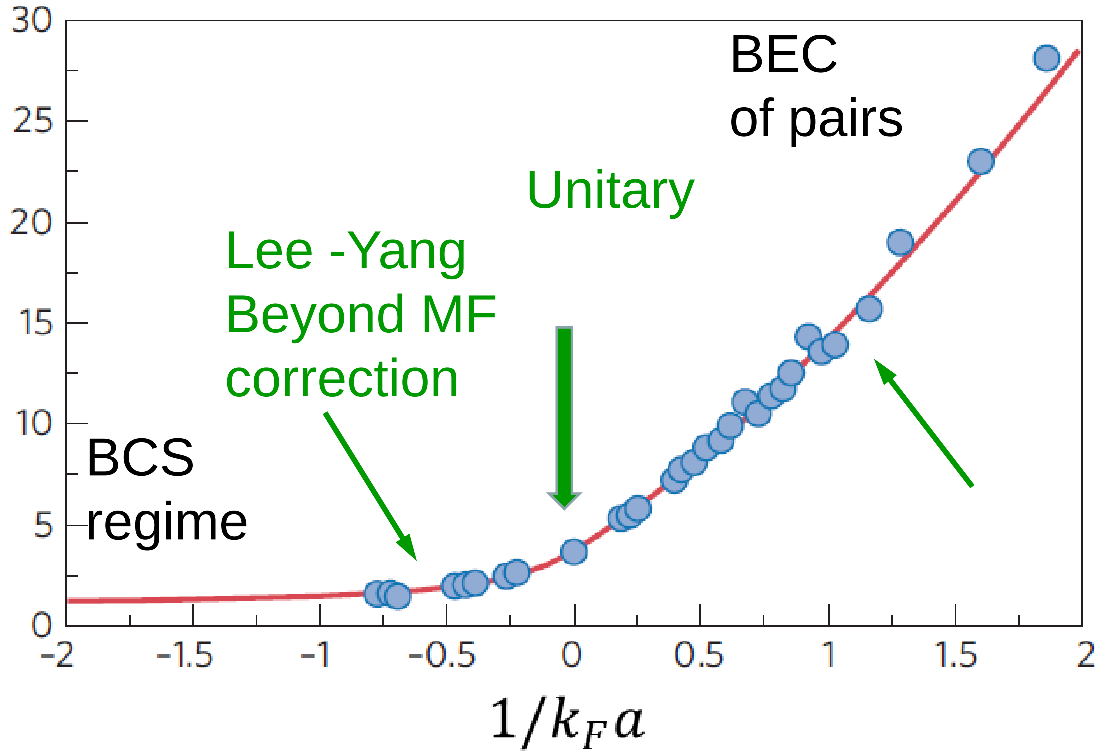


Theory:
Van Houcke,
Werner,
Kosik, Prokof'ev,
Svistunov,
Ku, Sommer
Cheuk, Schirotzek
Zwierlein
Nature Phys.,
2012

5% agreement with a Many-Body theory in strongly interacting regime

Equation of State of Fermi gas in the BEC-BCS crossover

Pressure equation of state $P/P_0 = f(1/k_F a)$

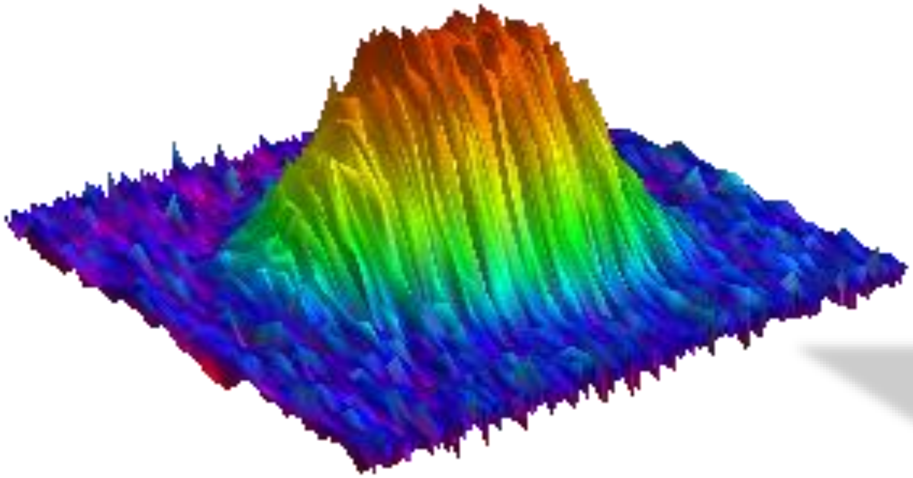


BCS-BEC crossover at T~0

An example of quantum simulation in the strongly correlated regime

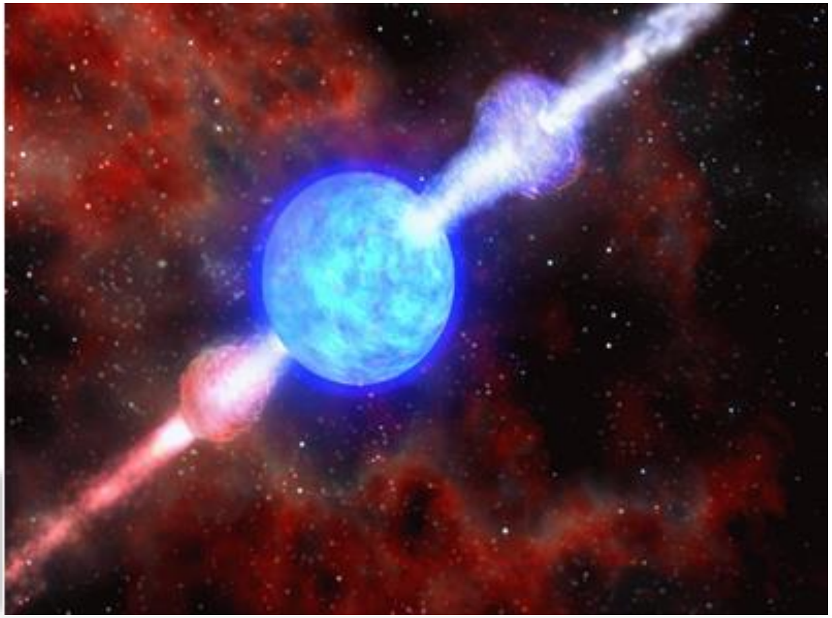
N. Navon, S. Nascimbène, F. Chevy, C. Salomon, *Science* **328**, 729-732 (2010)

Simulating the Eq. of State of neutron stars



lithium 6 atoms, spin ½,

n~ 10^{13} cm^{-3} , T=10^{-8} Kelvin
A superfluid 1 million times thinner than air !



Neutron star, Spin ½

a = -18.6 fm, n~2 10^{36}cm^{-3}

- $T_c=10^{10}$ K , $T=T_F/100$
- $k_F a$ ~ -4,-10,…

1000 billion times denser than Earth !

Baym, Carlson, Bertsch, Schwenk…

Second example

A novel system

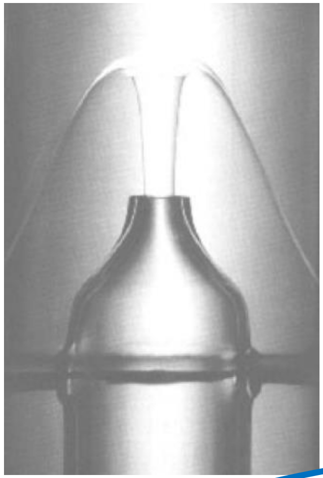
Bose-Fermi superfluid mixture

111 years of Quantum Fluids

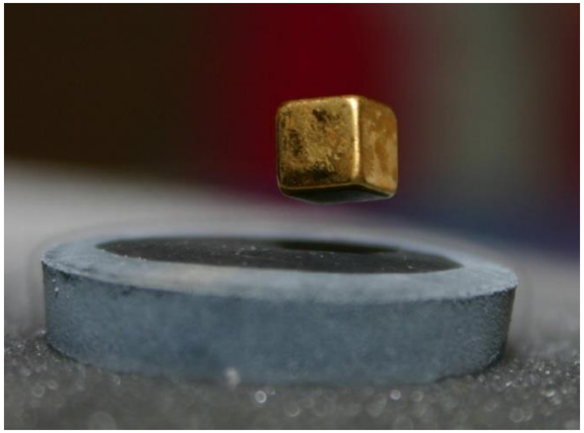
Bose Einstein condensate

Superconductivity

^4He

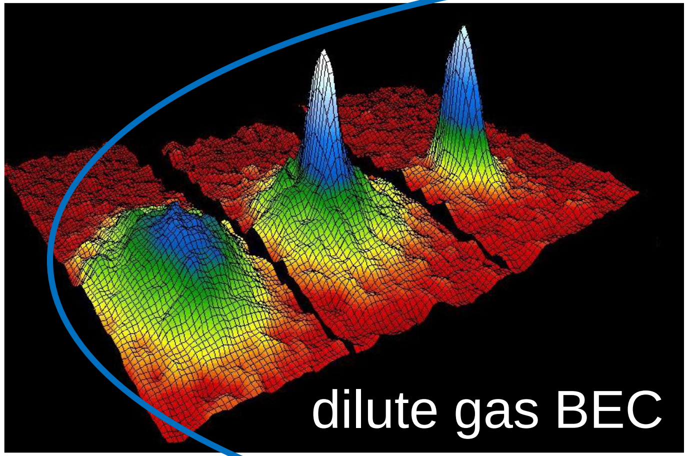


T~ 2.2 K

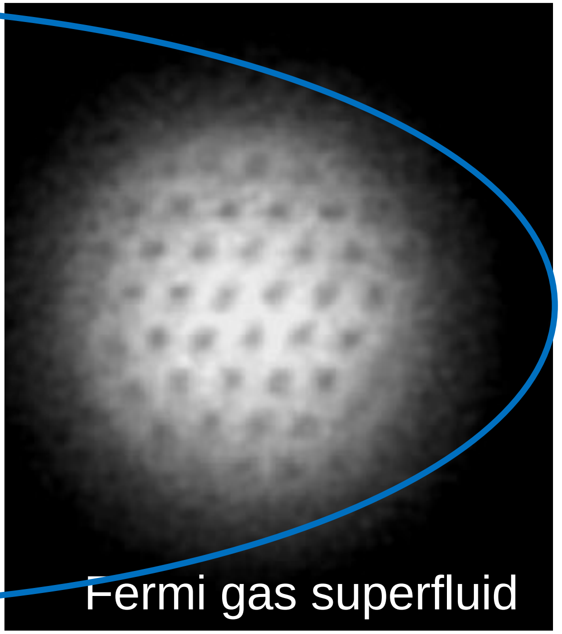


High T_c
77 K

^3He
2.5 mK

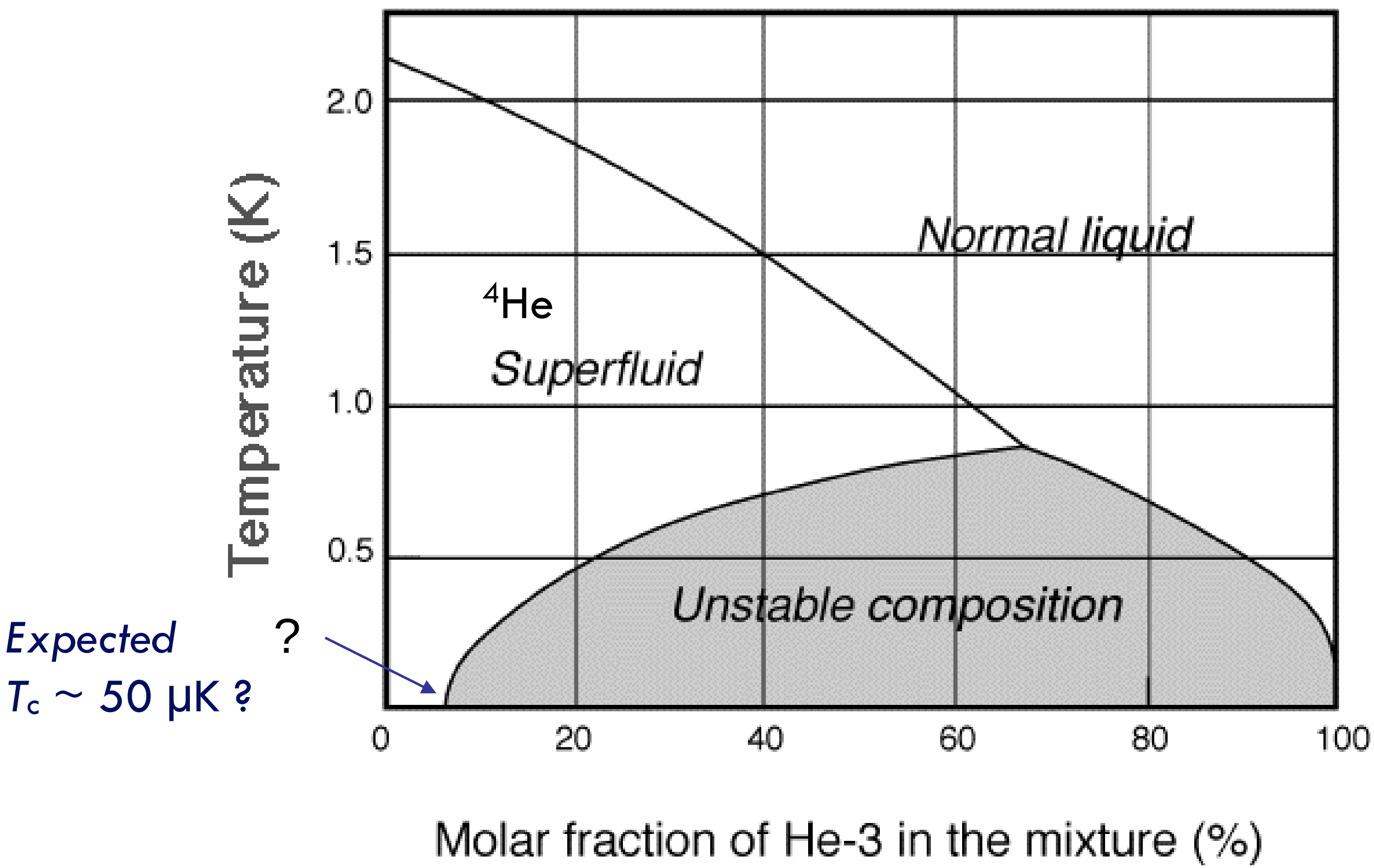


100 nK

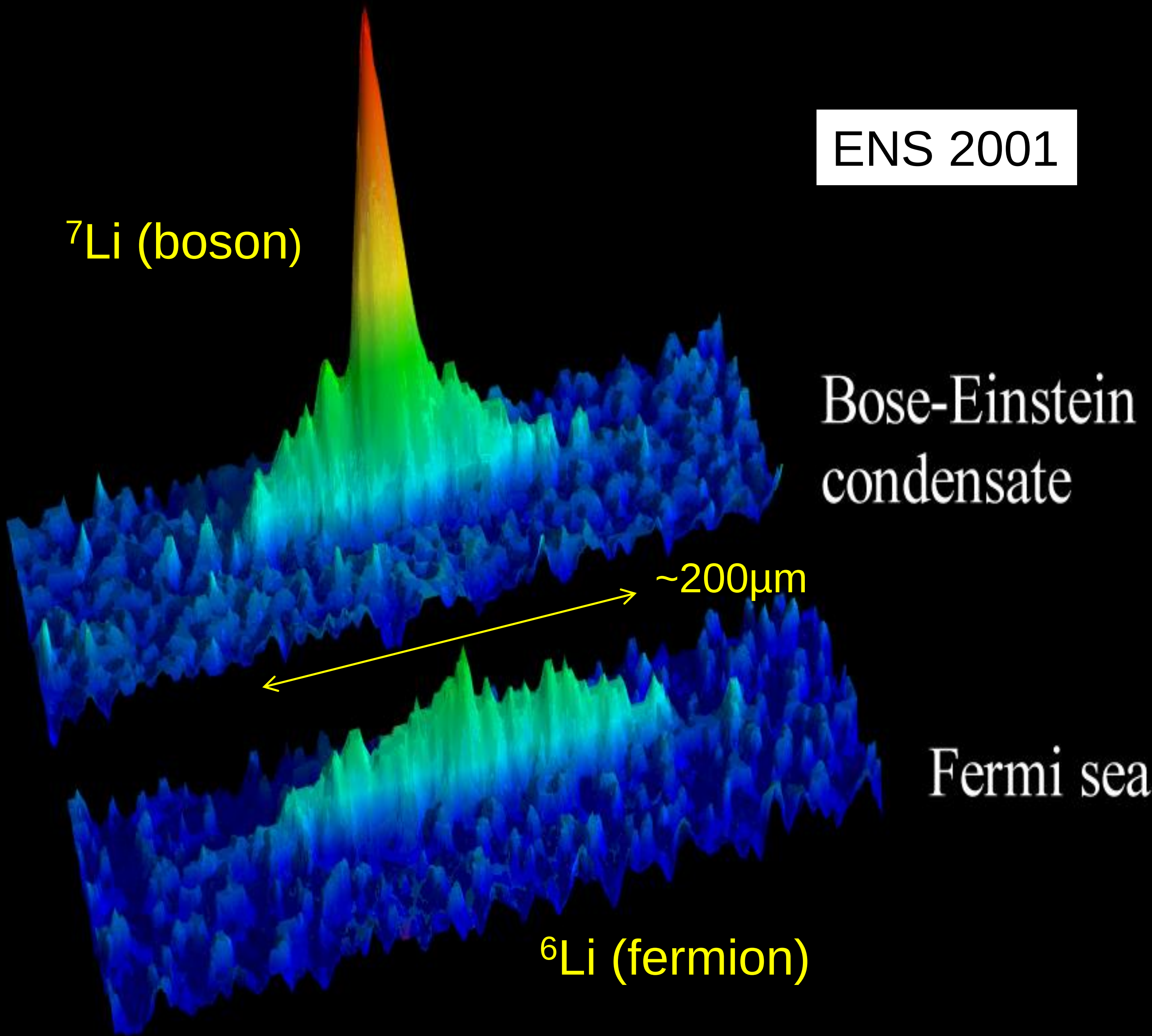


Also BEC of light (Bonn)
and exciton-polariton superfluids

Searching for superfluid Bose-Fermi systems: ^{4}He - ^{3}He mixture

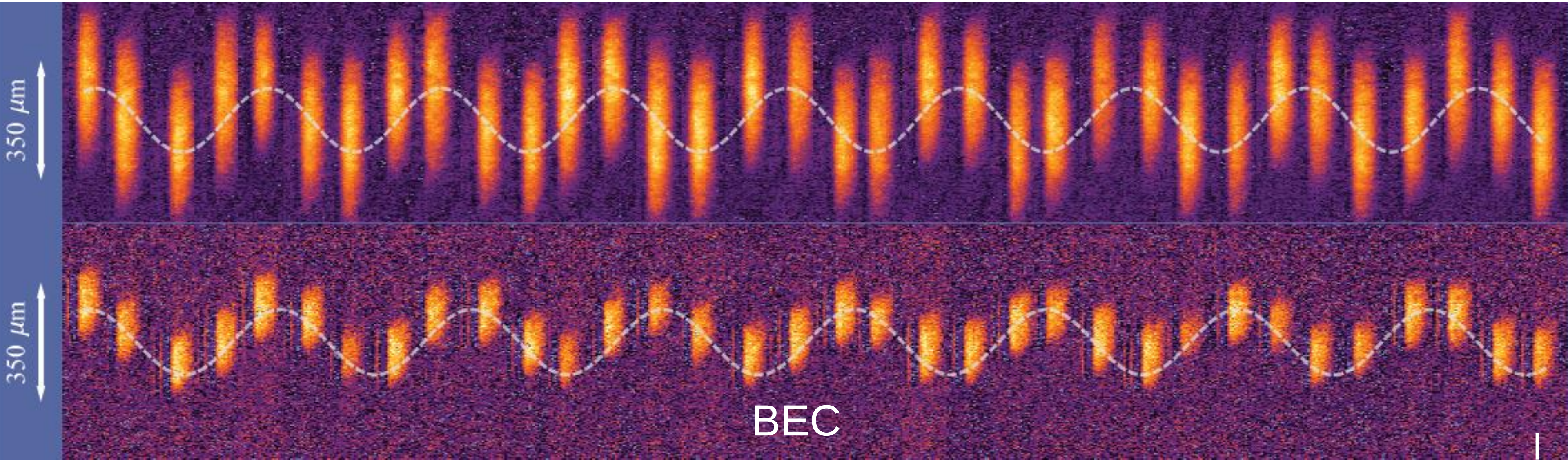


We use lithium 6 unitary Fermi gas mixed with lithium 7 bosons


ENS 2001
⁷Li (boson)
Bose-Einstein
condensate
~200μm
Fermi sea
⁶Li (fermion)

Long-lived Oscillations of Superfluid Counterflow

Fermi Superfluid



400 ms

time

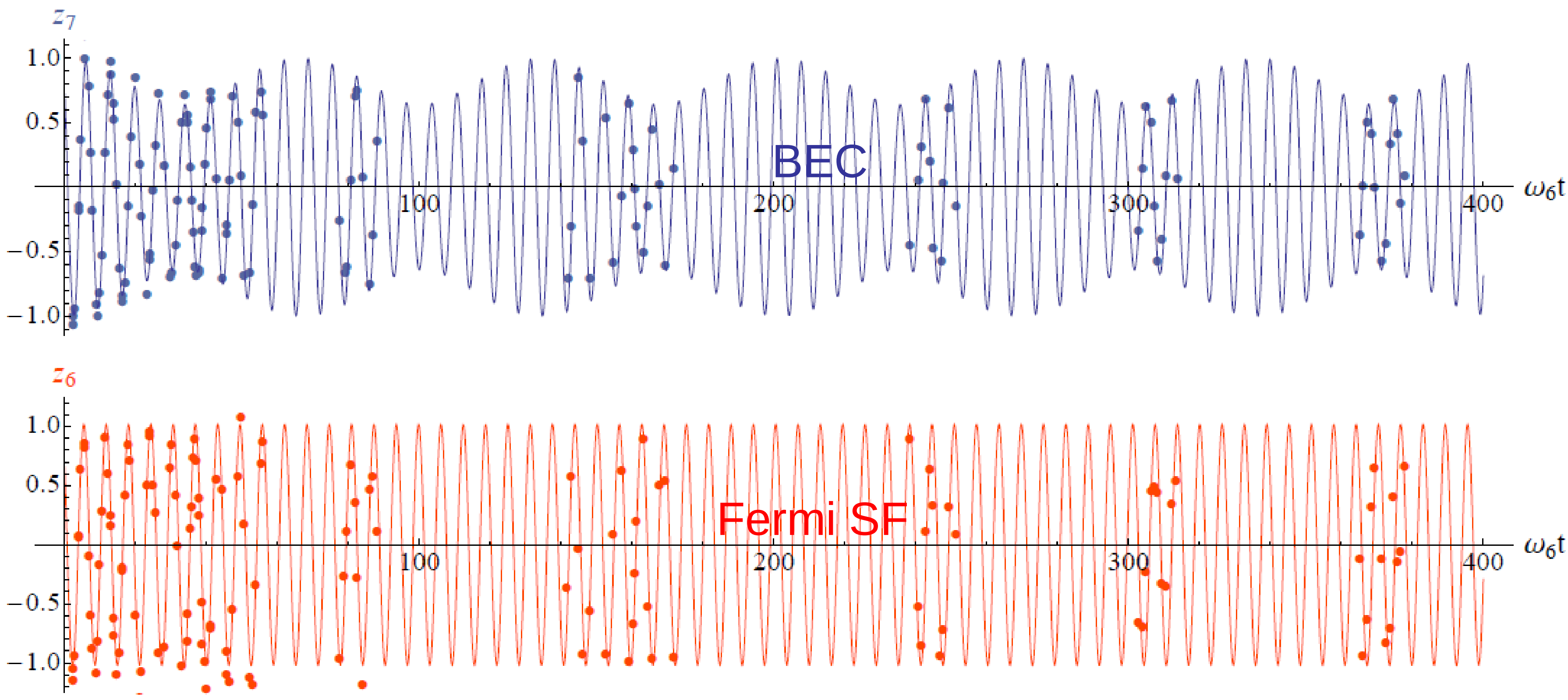
$$\tilde{\omega}_6 = 2\pi \times 17.06(1) Hz$$

$$\tilde{\omega}_7 = 2\pi \times 15.40(1) Hz$$

I. Ferrier-Barbut et al., Science, **345**, 1035, (2014)

Also, C. Hammer *et al* Phys. Rev. Lett. **106**, 065302 (2011) for boson-boson superfluid counterflow

Oscillations of both superfluids



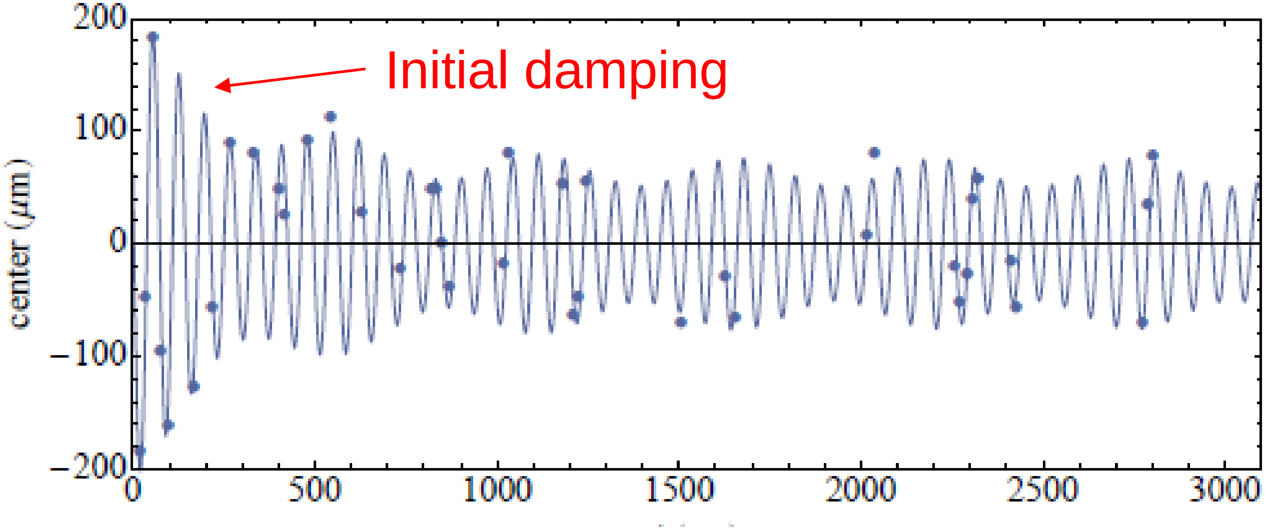
Very small damping: superfluid counterflow

Modulation of the ^{7}Li BEC amplitude by ~30% at $(\tilde{\omega}_6 - \tilde{\omega}_7)/2\pi$

Coherent energy exchange between the two oscillators

Frequencies can be measured very precisely !

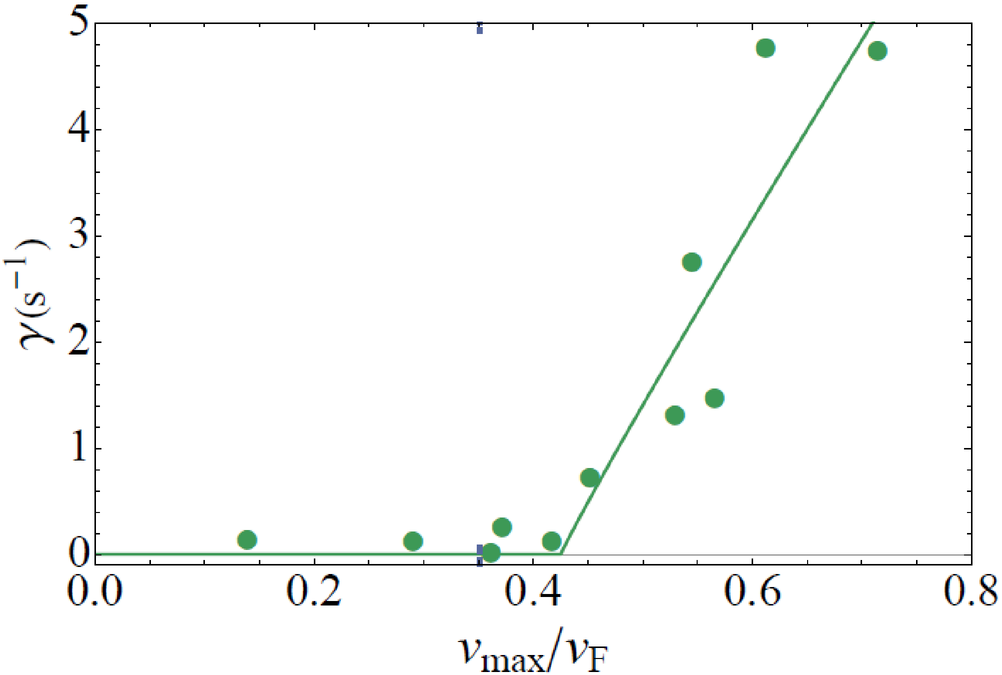
Critical velocity for superfluid counterflow



$$d = d_0 \exp(-\gamma t) + d'$$

$$\gamma = 3.1\, s^{-1}$$

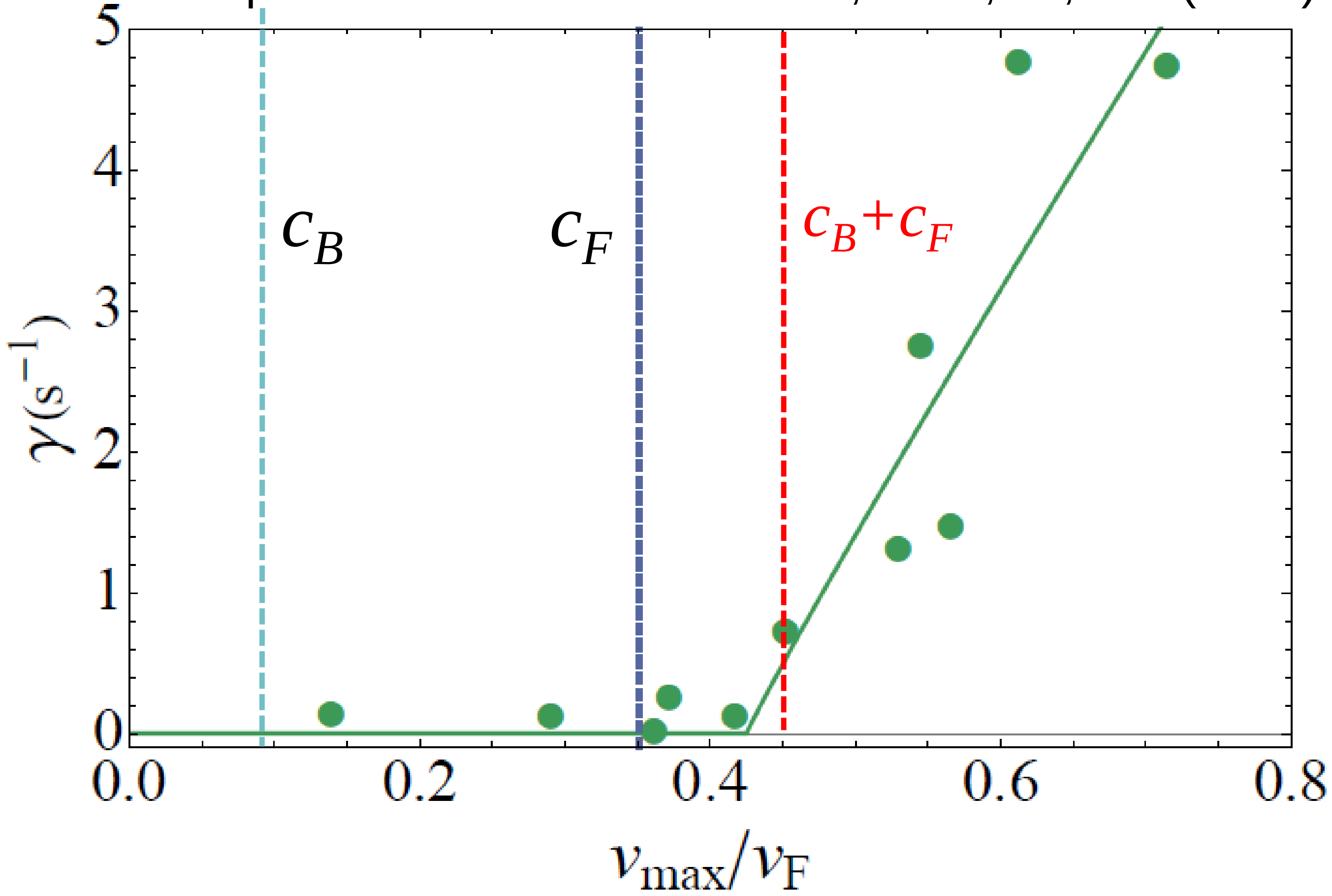
Time(ms)



V_c = 2 cm/s
is quite high !

Counter-flow critical velocity

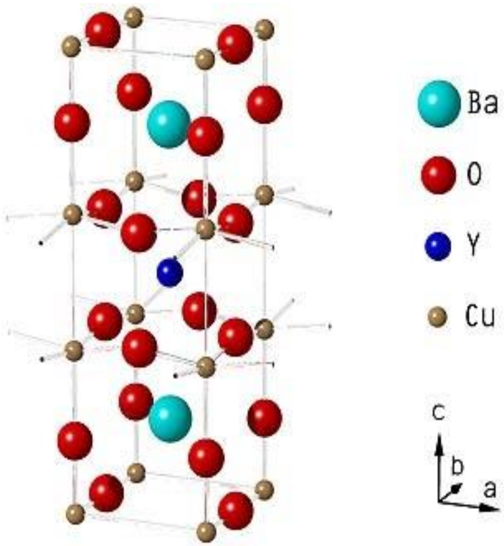
Y. Castin, I. Ferrier-Barbut and C. Salomon
Comptes-Rendus Acad. Sciences, Paris, **16**, 241 (2015)



M. Delehaye, S. Laurent, I. Ferrier-Barbut, S. Jin, F. Chevy, C. Salomon, PRL 2015

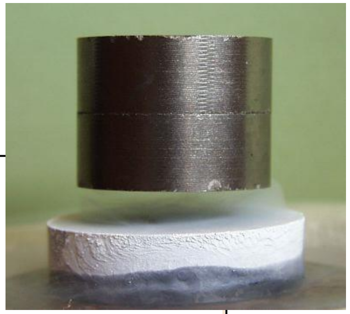
Related studies on Fermi gas at MIT, Miller PRL 2008, Hamburg, Weimer PRL 2015

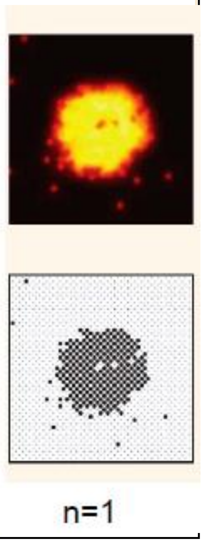
Quantum simulation with ultracold fermions observed one by one



$d \sim 0.4\ nm$

$YBa_2Cu_3O_7$
$d \sim 0.4\ nm$
$T_c = 92K$



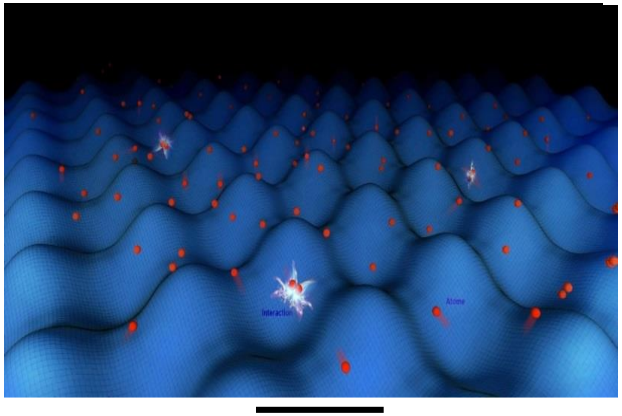


Mott insulator

$d \sim 0.5\ \mu m$

$T \sim 1\ \mu K$

Seing atoms one by one !

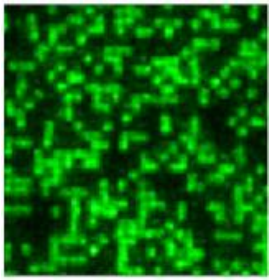


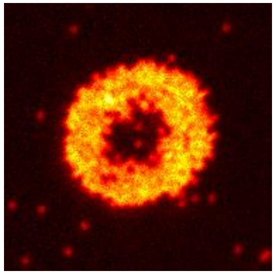
$0.5\ micron$

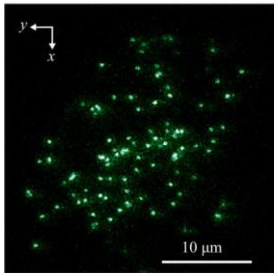
Bloch et al., MPQ 2010
Greiner et al., Harvard

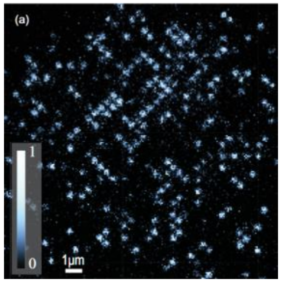
Quantum gas microscopy

- Boson microscopes: 2010



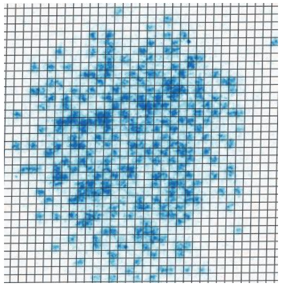


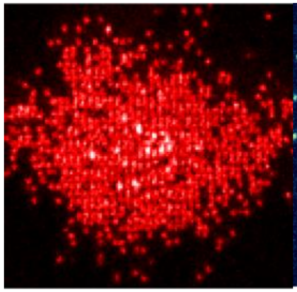


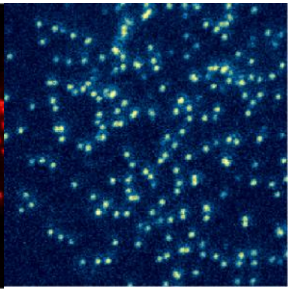


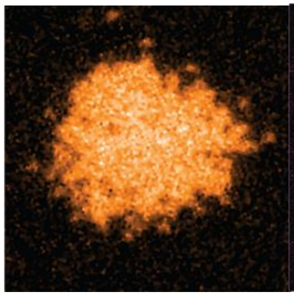
Harvard MPQ Kyoto Tokyo

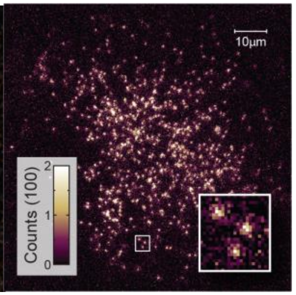
- Fermion microscopes: 2015

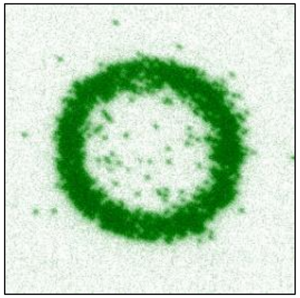






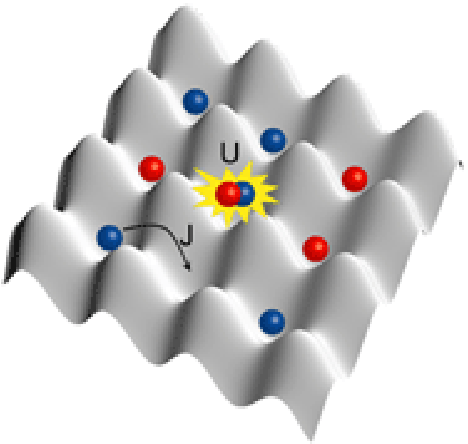






Harvard MPQ Strathclyde MIT Toronto Princeton

High Tc superconductivity and SU(2) Fermi Hubbard model

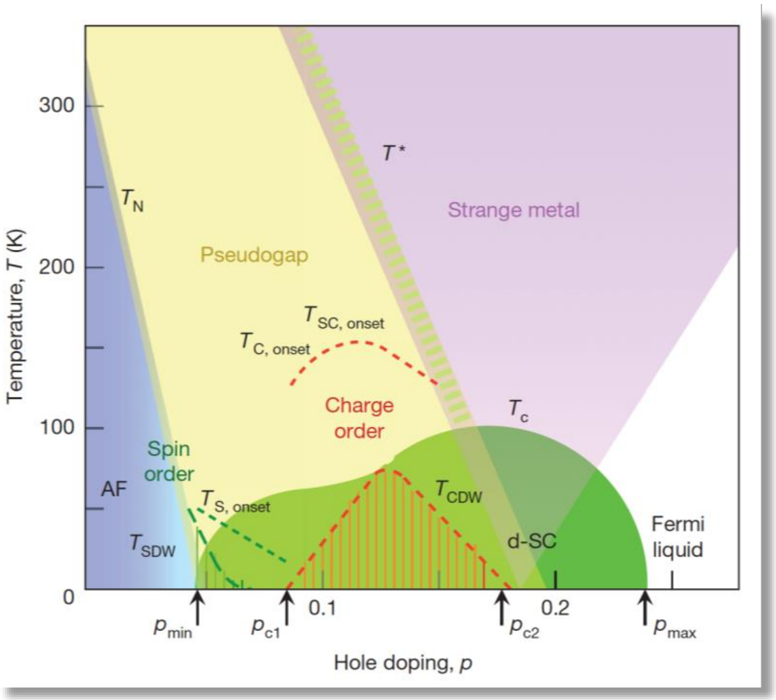


$$\mathcal{H} = -t \sum_{\langle ij \rangle, \sigma} \left(c^\dagger_{i,\sigma} c_{j,\sigma} + c^\dagger_{j,\sigma} c_{i,\sigma} \right) + U \sum_i n_{i,\uparrow} n_{i,\downarrow}$$

Realized naturally with cold atoms in optical lattices with fully tunable parameters.

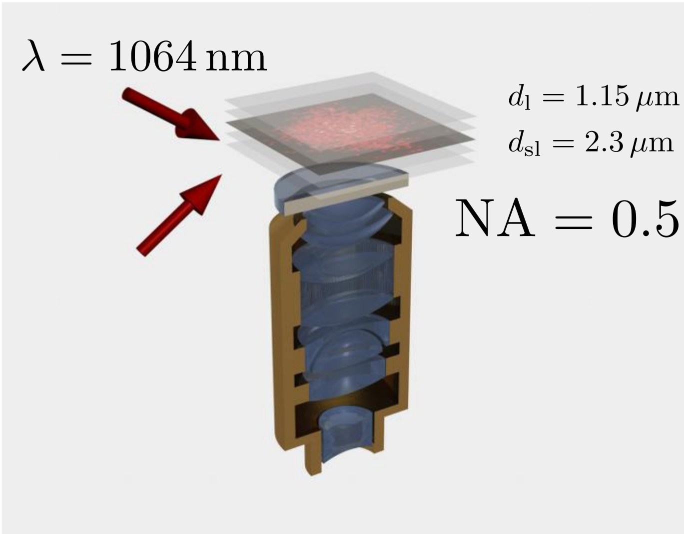
Rich phase diagram:

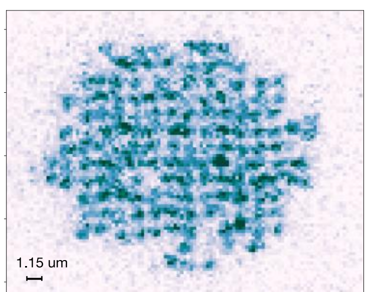
commensurate/ incommensurate AFM, pseudogap, strange metal, d-wave superconductivity…

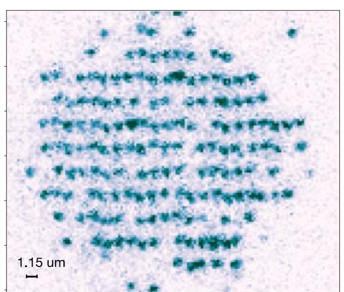


Keimer et al. *Nature* **518**, 179-186 (2015)

^{6}Li Quantum gas microscope in Munich



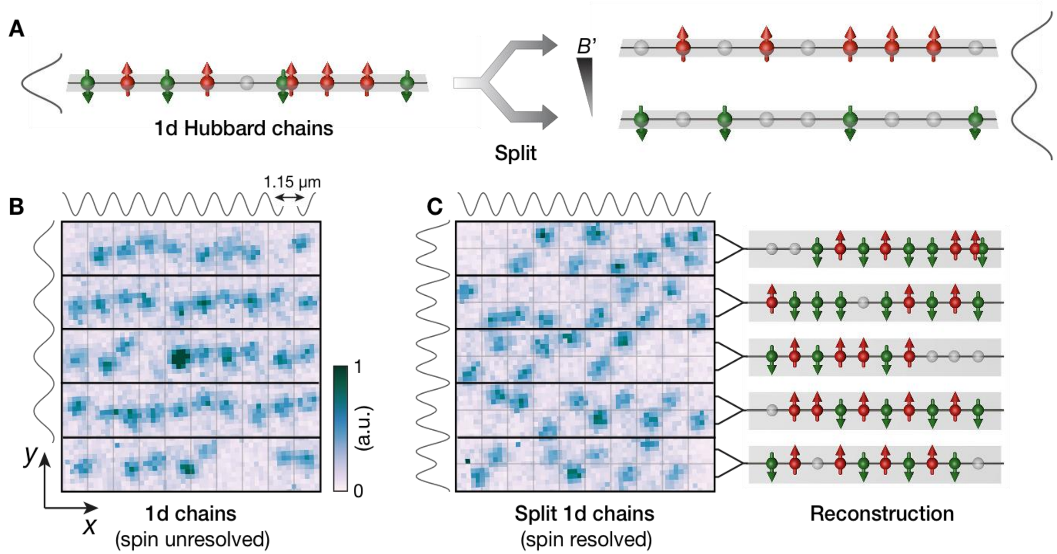




2D **1D**

Mott insulators

Spin resolved imaging



M. Boll, T. Hilker, G. Salomon *et al. Science* **353**, 6305 (2016)

Detection fidelity 98%

Direct access to spin, charge, holes and doublons

Measurement of arbitrary spin/density correlations

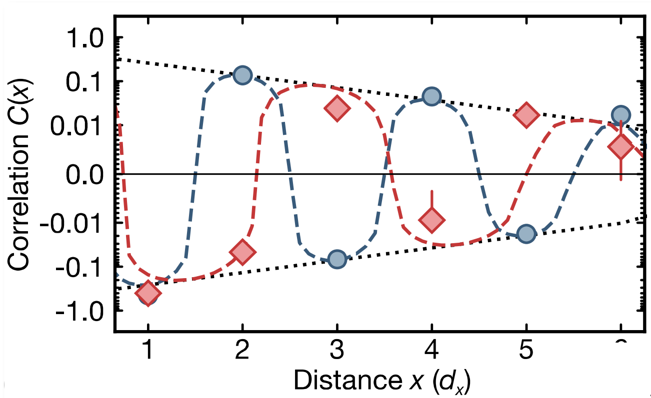
Influence of hole doping:

Commensurate-incommensurate magnetism

Influence of hole doping in 1D

G. Salomon et al., ***Nature*** (2018)
T. Hilker et al., ***Science*** (2017)
I. Bloch group, MPQ Garching

$$C(x) = 4\langle S_i^z S_{i+x}^z \rangle_{\bullet_i \bullet_{i+x}}$$



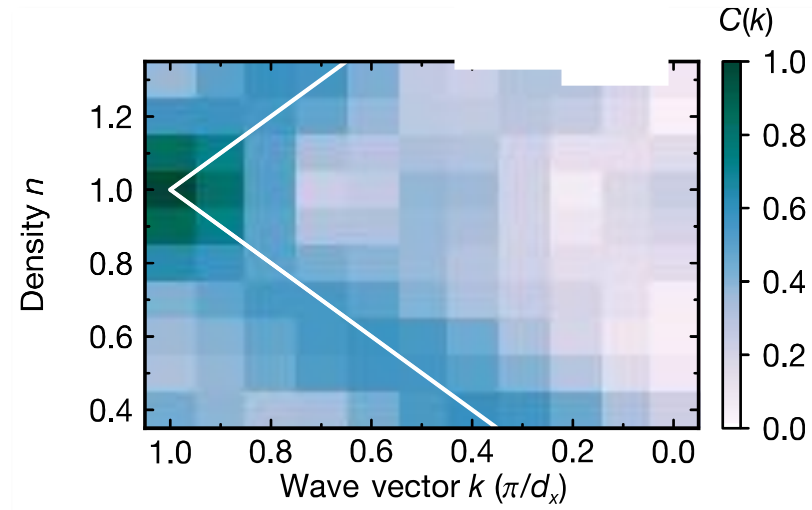
$\langle \hat{n} \rangle = 1$

$\langle \hat{n} \rangle = 0.7$

$t = 400\,\mathrm{Hz}$

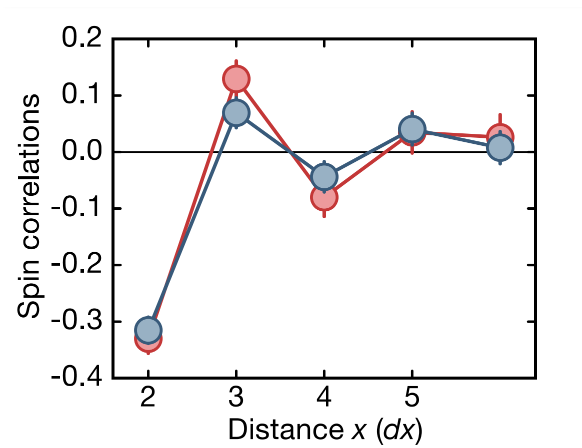
$U/t = 7$

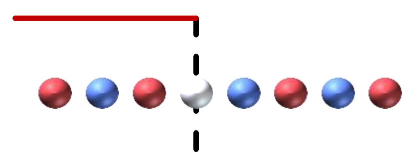
$T/t \simeq 0.29$

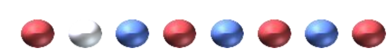


$$C_{SD/H}(x) = 4\langle S_i^z S_{i+x}^z \rangle_{\bullet_i, \circ_{i+1} \bullet_{i+x}}$$

- Agreement with Luttinger liquid theory







- No magnetic cost
- Holes / doublons = domain walls
- Equilibrium signature of spin charge separation

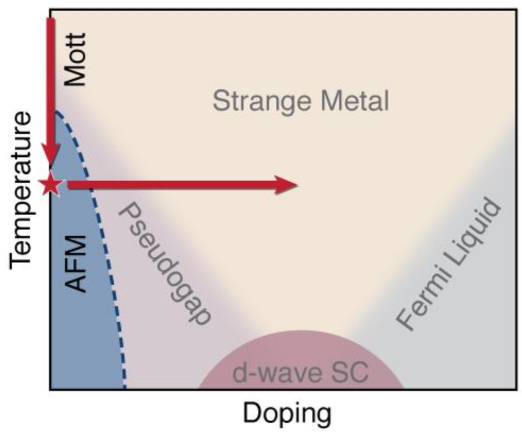
Also seen on the dynamics
MPQ and Rice

The Fermi Hubbard model in 2D

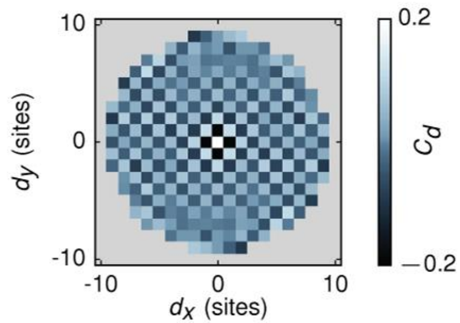
M. Greiner, Harvard, I. Bloch, MPQ
M. Koehl, Bonn, S. Kuhr, Glasgow
M. Zwierlein MIT, J. Thywissen, Toronto

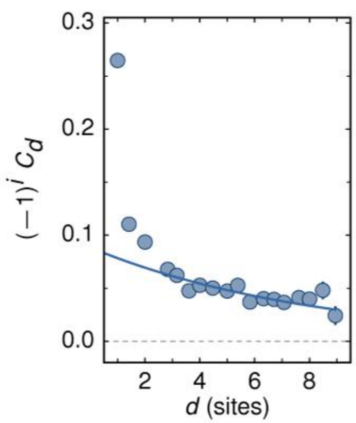
$$\hat{H} = -t \sum_{\sigma,\langle i,j\rangle \in \Omega} (\hat{c}^{\dagger}_{i,\sigma}\hat{c}_{j,\sigma} + h.c.) + U \sum_{i\in\Omega} \hat{n}_{i,\downarrow}\hat{n}_{i,\uparrow},$$

The Hubbard Model

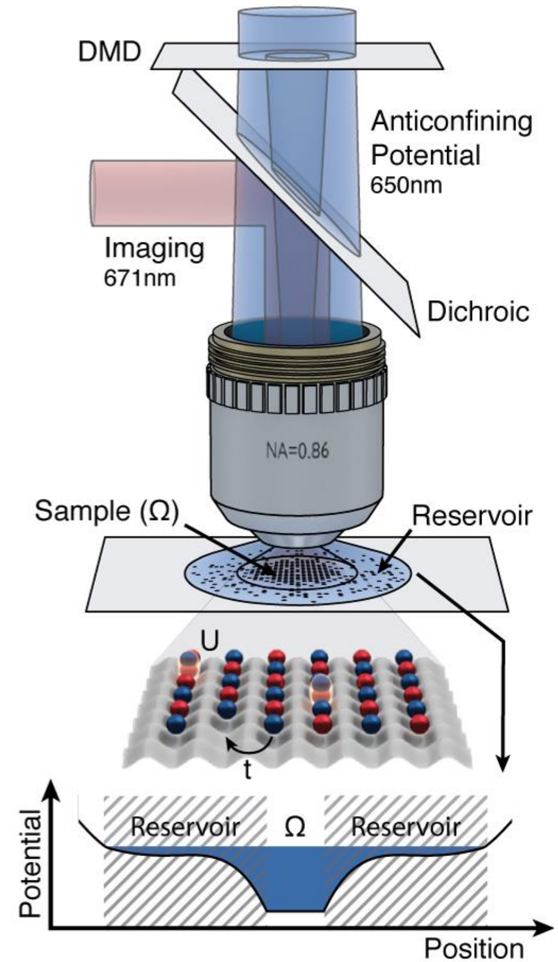


Spin Correlation Function

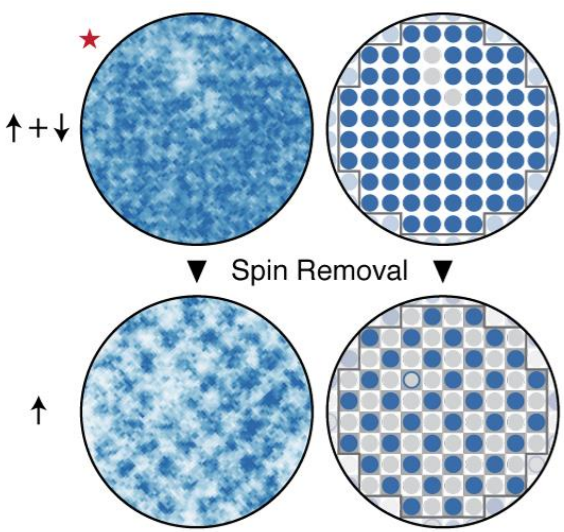




Entropy Redistribution



Long-range Antiferromagnet

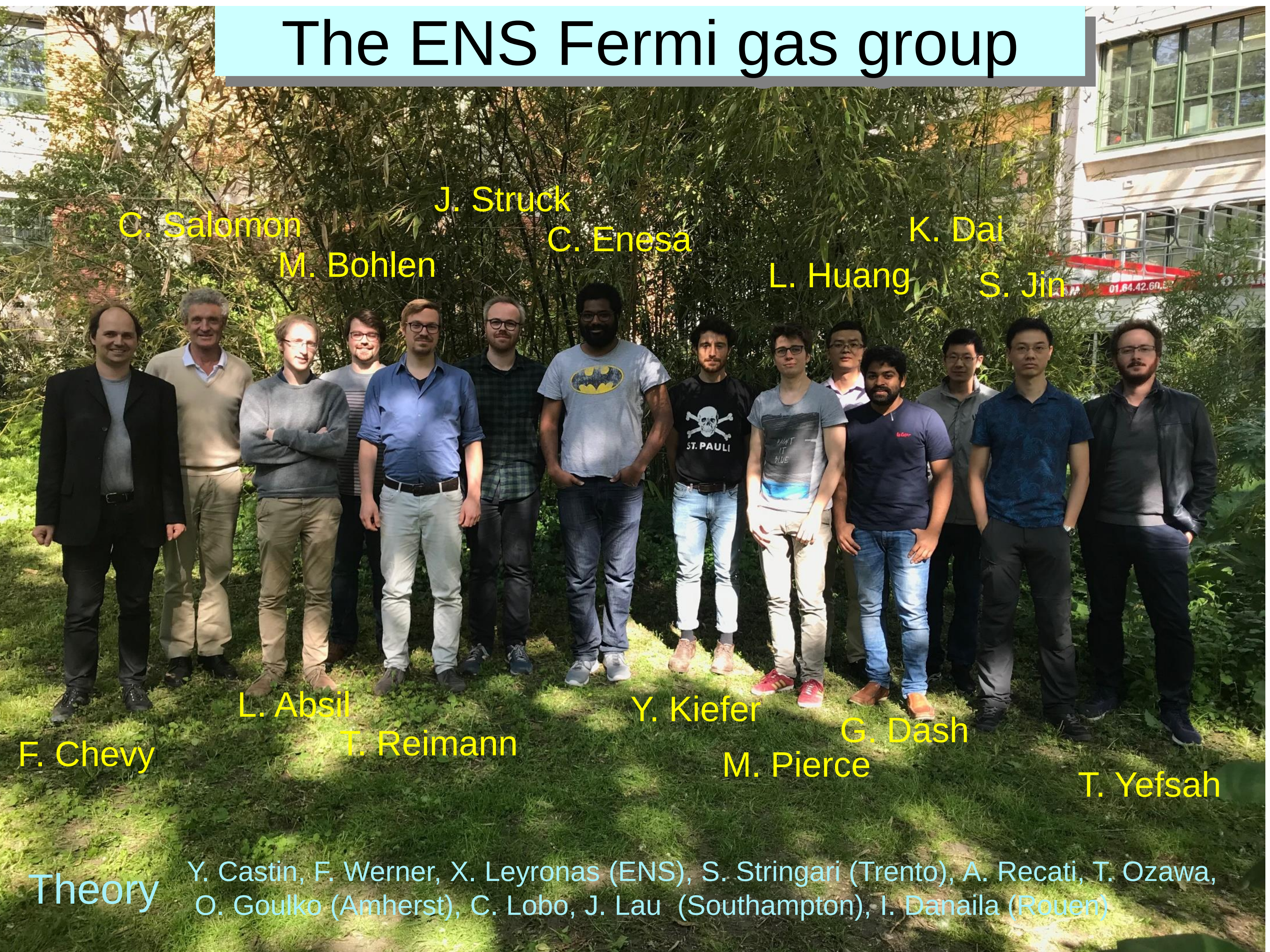


A. Mazurenko et al., Nature 2017

Summary

- 3 examples of quantum simulation with cold gases
- Explore further the cold atom-condensed matter interface: ex: spin polarization, FFLO phase
- Dynamics of quantum systems: time dependent Hamiltonian, Many-body localization, quantum quenches,…..
- Long range interactions: supersolids, dipole-dipole interaction
- Gauge fields and topological bands
- Spin-orbit coupling, integer quantum Hall states, and fractional QH.
- Mixed dimensions: 3D-2D, 3D-1D, 3D-0D.

The ENS Fermi gas group



Theory Y. Castin, F. Werner, X. Leyronas (ENS), S. Stringari (Trento), A. Recati, T. Ozawa, O. Goulko (Amherst), C. Lobo, J. Lau (Southampton), I. Danaila (Rouen)