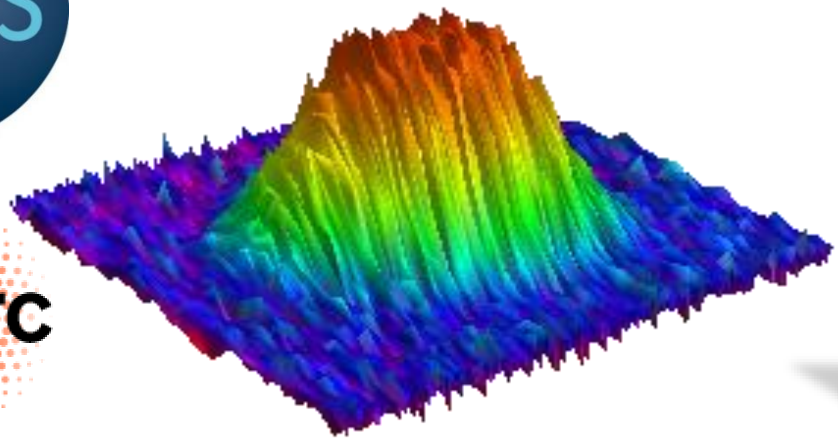
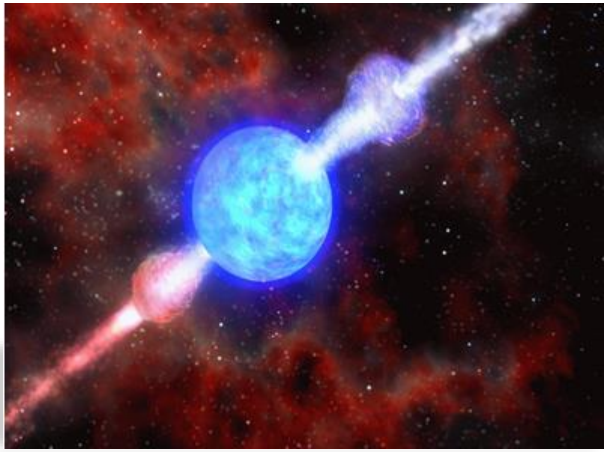
Ultracold Fermions
From Nuclear to Atomic Physics





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Laboratoire Kastler Brossel
Physique quantique et applications

QMBC- 2023, Orsay
March 23, 2023

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1530

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ANR

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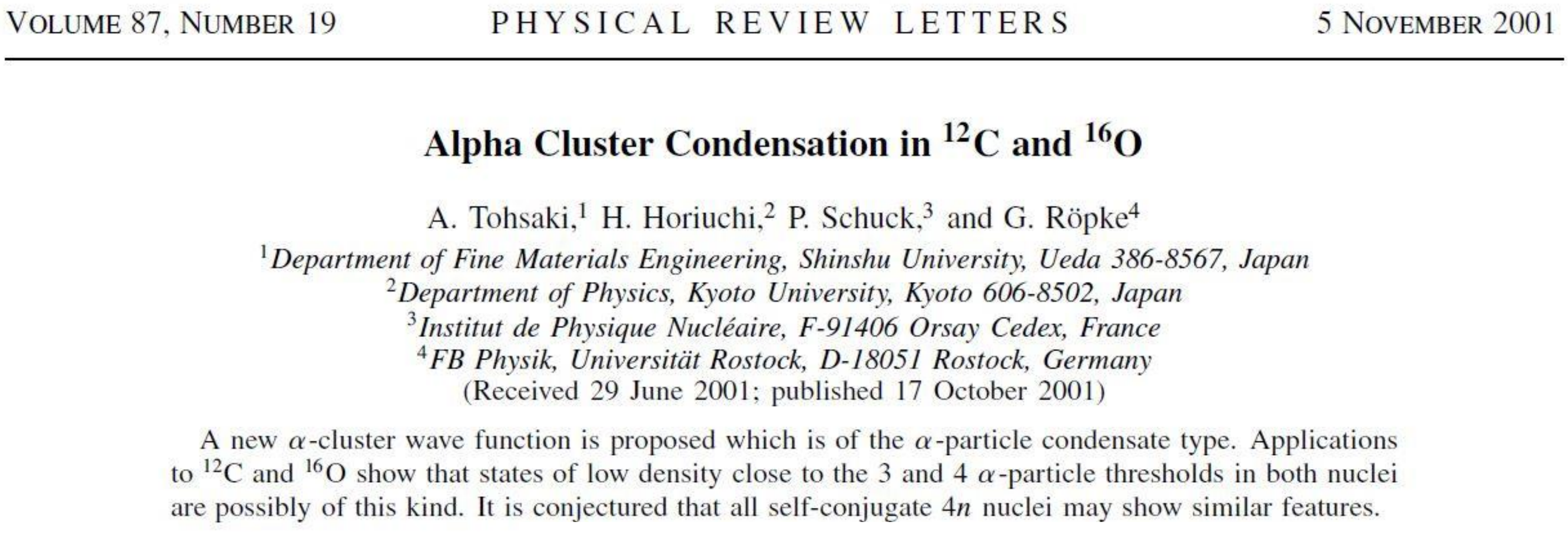
From nuclear matter to dilute gases



VOLUME 87, NUMBER 19 PHYSICAL REVIEW LETTERS 5 NOVEMBER 2001

Alpha Cluster Condensation in ^{12}C and ^{16}O

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(Received 29 June 2001; published 17 October 2001)

A new α-cluster wave function is proposed which is of the α-particle condensate type. Applications to ^{12}C and ^{16}O show that states of low density close to the 3 and 4 α-particle thresholds in both nuclei are possibly of this kind. It is conjectured that all self-conjugate $4n$ nuclei may show similar features.

DOI: 10.1103/PhysRevLett.87.19

There exists an intriguing problem w
ters as bound states of fermions are
Bose character of the composite clust
the fermionic properties of their consti
ample, we discuss the relevance of α
correlations in atomic nuclei. Special
such correlations which correspond to
sate in low-density symmetric nuclear m
Bose-Einstein condensation observed fo
bosonic atoms such as Rb or Na in trap

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Physics Reports

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The BCS–BEC crossover: From ultra-cold Fermi gases to nuclear systems

Giancarlo Calvanese Strinati [a,b,*], Pierbiagio Pieri [a,b], Gerd Röpke [c], Peter Schuck [d,e], Michael Urban [d]

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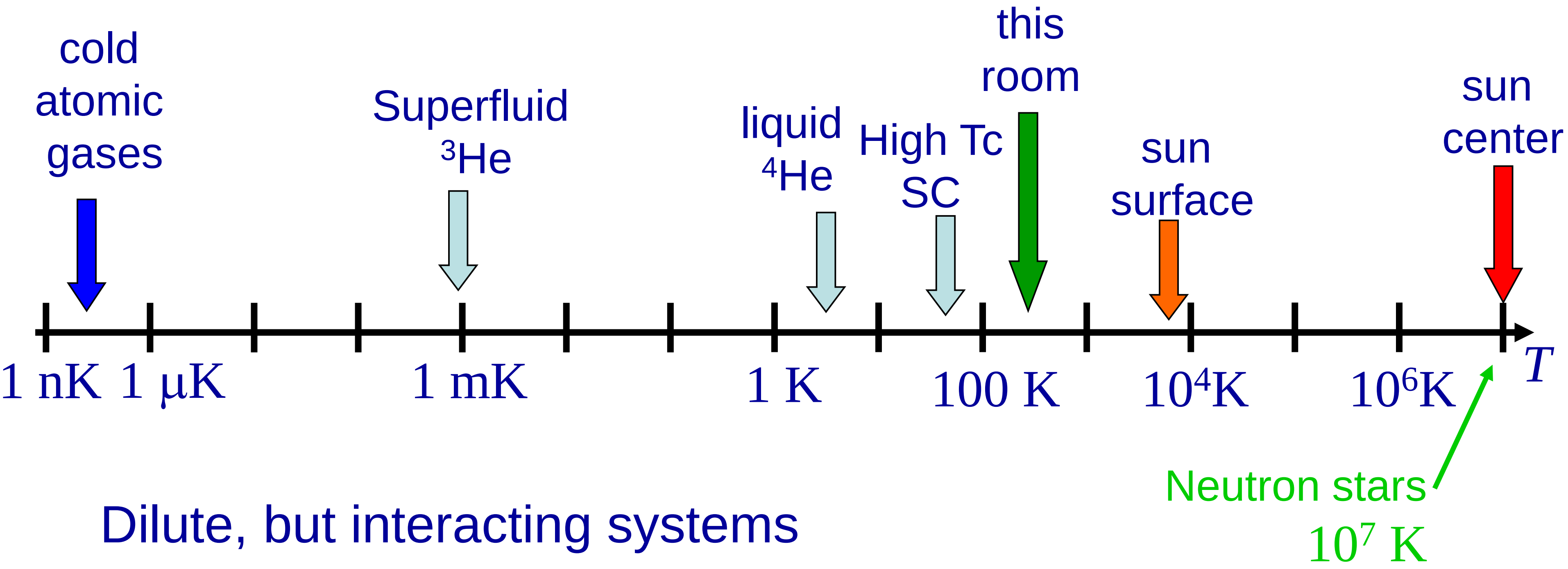
Ultracold quantum gases

- Dilute systems
- Tunable interaction + arbitrary trapping potentials
- Precision measurements through imaging
- Exploring the link between fermionic superfluidity and Bose Einstein condensation
- Global thermodynamic properties: equation of state
  link with nuclear matter
- Dual Bose-Fermi superfluid mixture: a surprise !

Temperature scale of cold gases



Dilute, but interacting systems

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

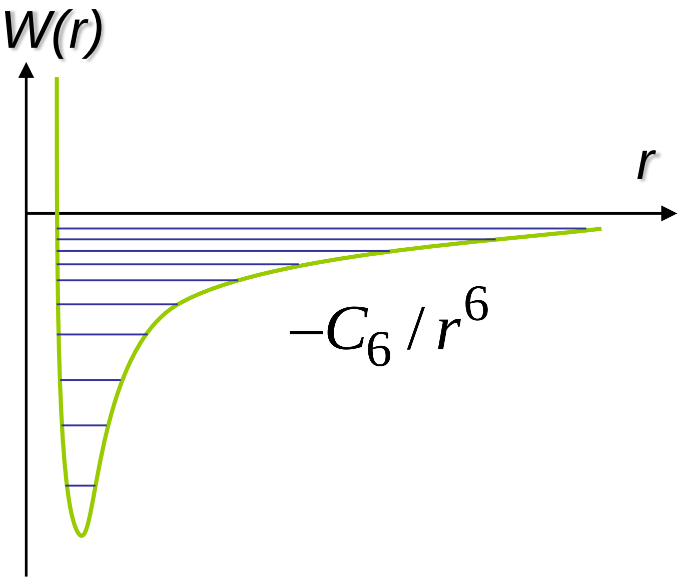
Interatomic distance 0.1 to $0.5\ \mu\text{m} \gg$ range of interatomic potentials

$E_{\text{int}} \gg \hbar\omega$ 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

$a_{VdW} << \lambda_{dB}$
$a_{vdW} << n^{-1/3}$

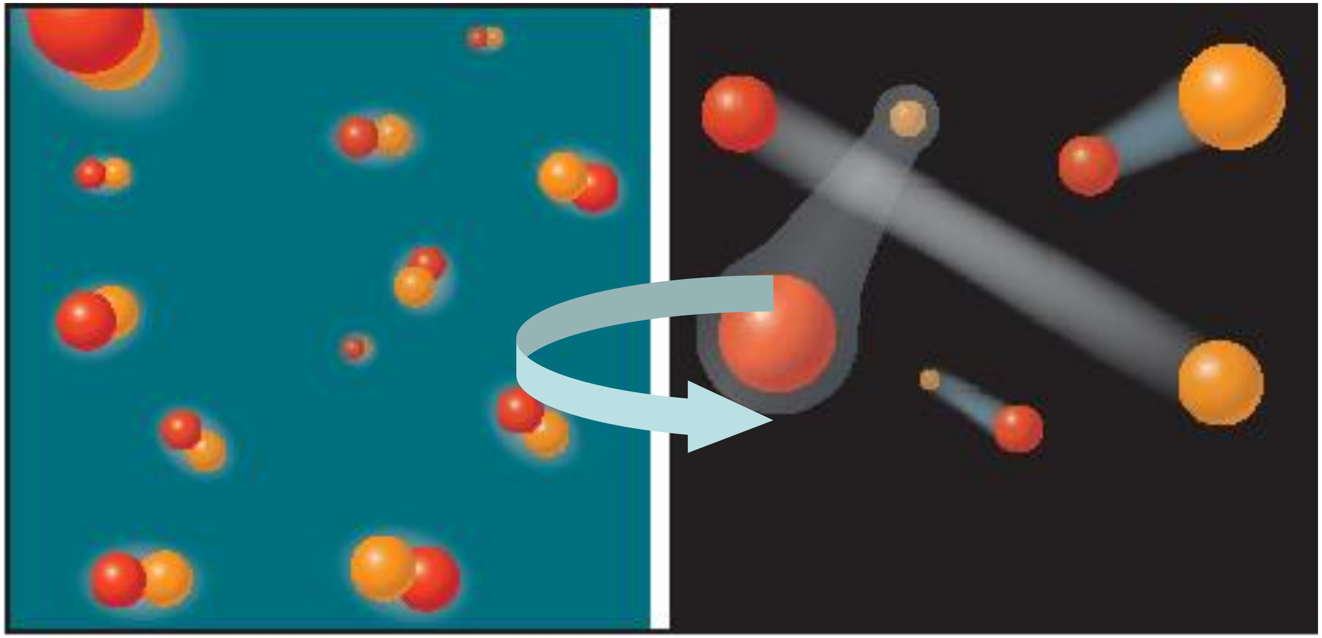
a: scattering length
$|a|\sim$1 to 10 nm

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

Tuning interactions via
Fano-Feshbach resonance

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

Fermions with two spin states with attractive interaction



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

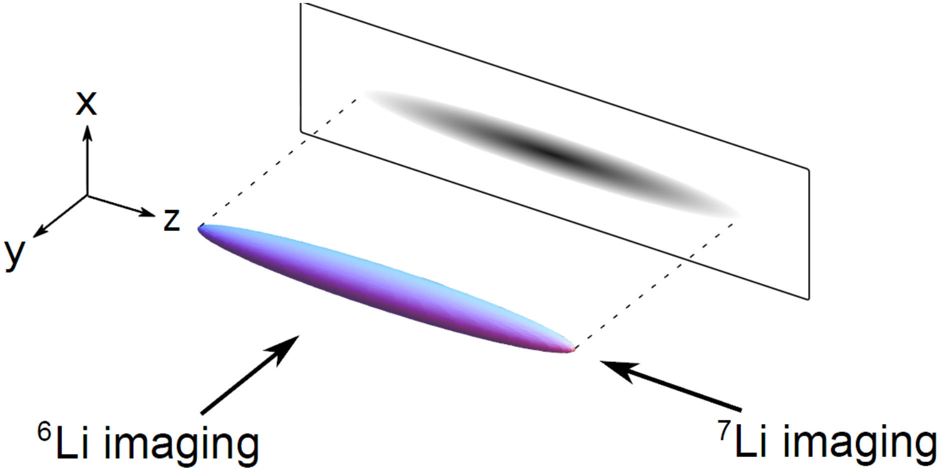
BEC of molecules ← BCS fermionic superfluid

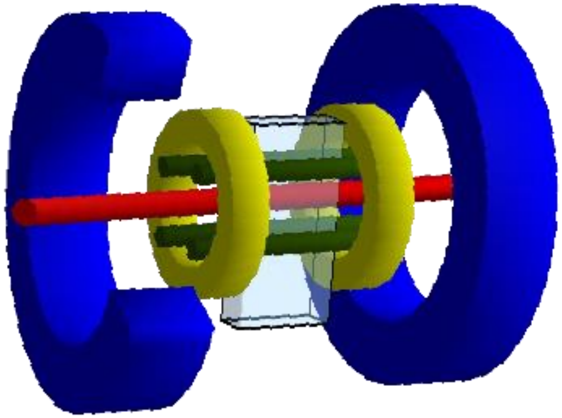
Bound state Interaction strength No bound state

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***





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), MIT

Equation of State of Quantum Gases

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

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

The pressure is obtained from *in situ* images

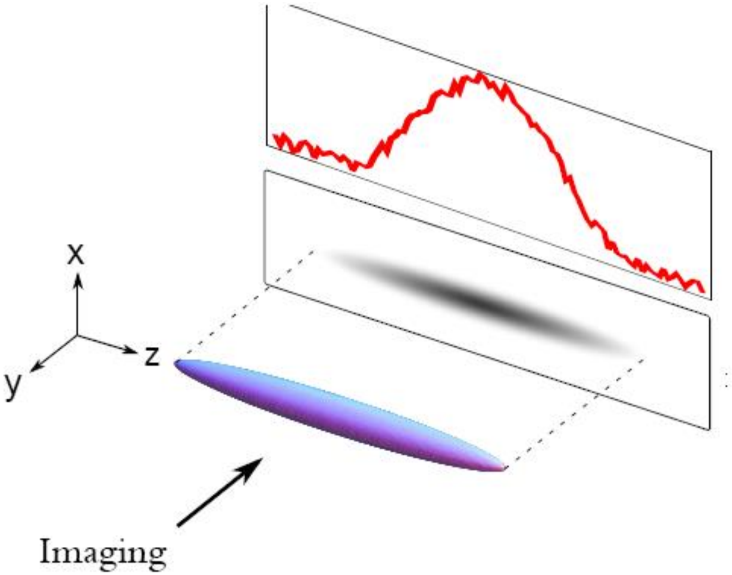
$$P(\mu_z, T) = \frac{m\omega_r^2}{2\pi}\bar{n}(z)$$

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

Doubly-integrated density profile

Local density approx.

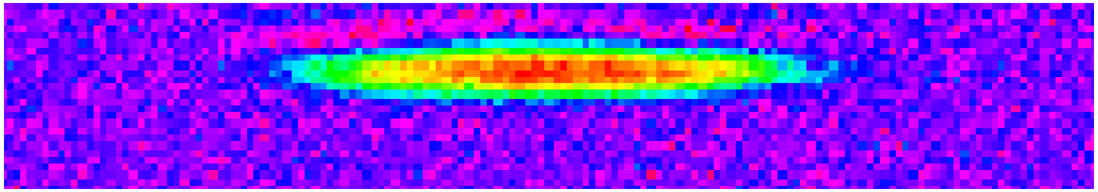
$$\mu(r) = \mu_0 - V(r)$$



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

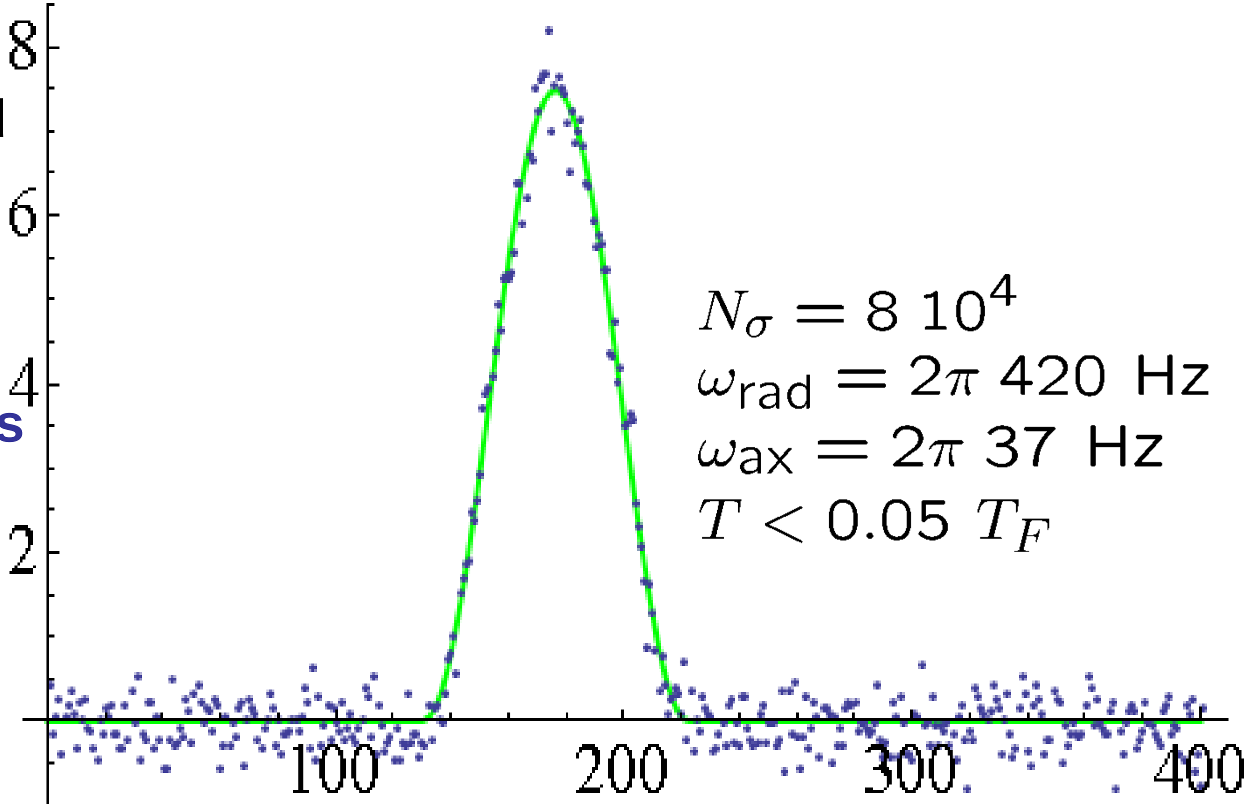
Unitary Fermi Gas

$$a = \infty$$



Doubly integrated Density

Pressure of the locally homogeneous gas



$N_\sigma = 8\ 10^4$

$\omega_{\text{rad}} = 2\pi\ 420\ \text{Hz}$

$\omega_{\text{ax}} = 2\pi\ 37\ \text{Hz}$

$T < 0.05\ T_F$

Position / **Chemical potential μ(z)**

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

The Equation of State at unitarity: temperature dependence

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

Continuous scale invariance
Thermodynamics is universal
T.L. Ho, E. Mueller, ’04

$\mu = 0.376(5)\ E_F$

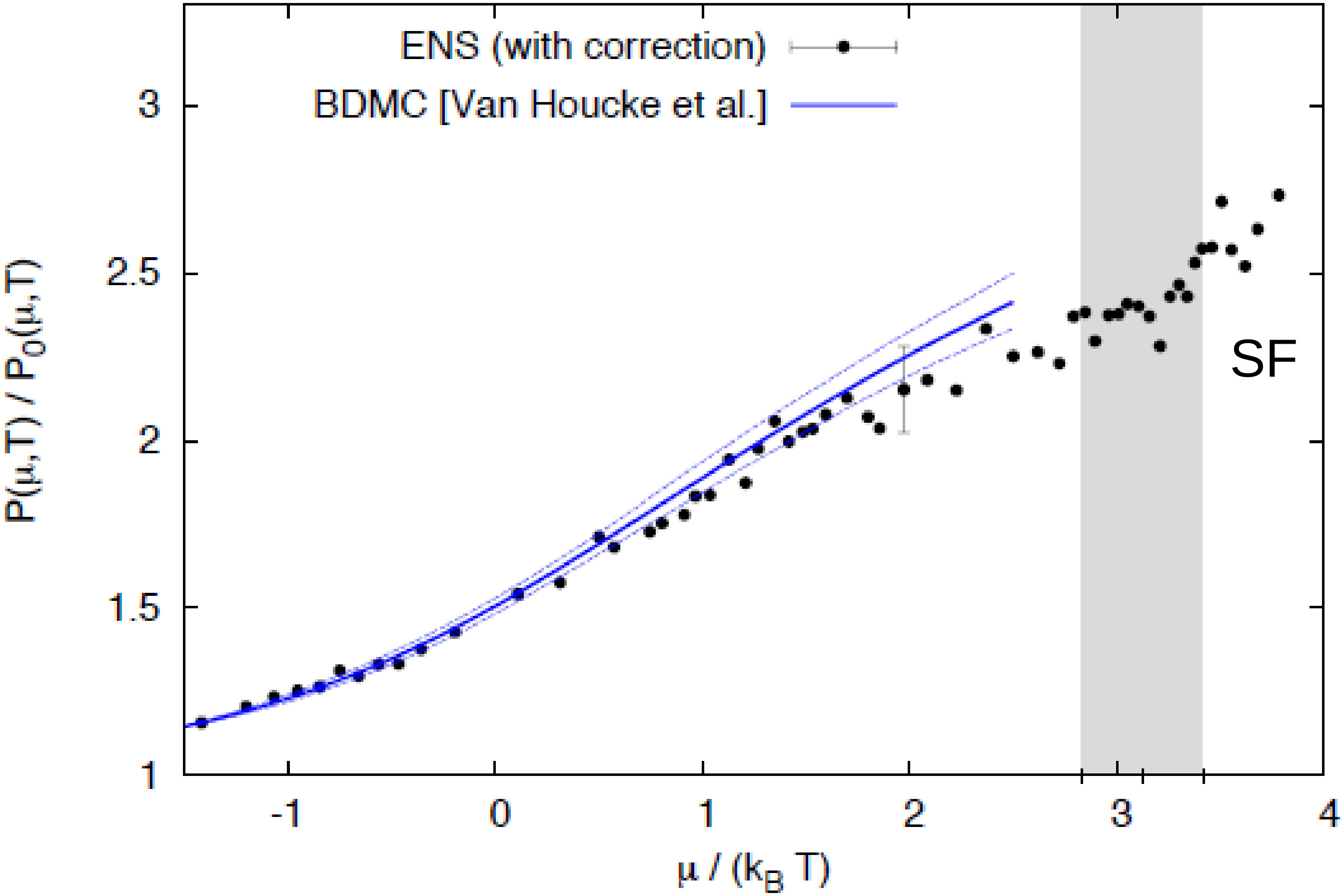
$T_c = 0.167(15)\ T_F$

MIT 2012, Ku et al.

Pressure depends only on $\boldsymbol{\mu / k_B T}$

Equation of State at unitarity & Comparison with Bold Diagrammatic Monte-Carlo

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

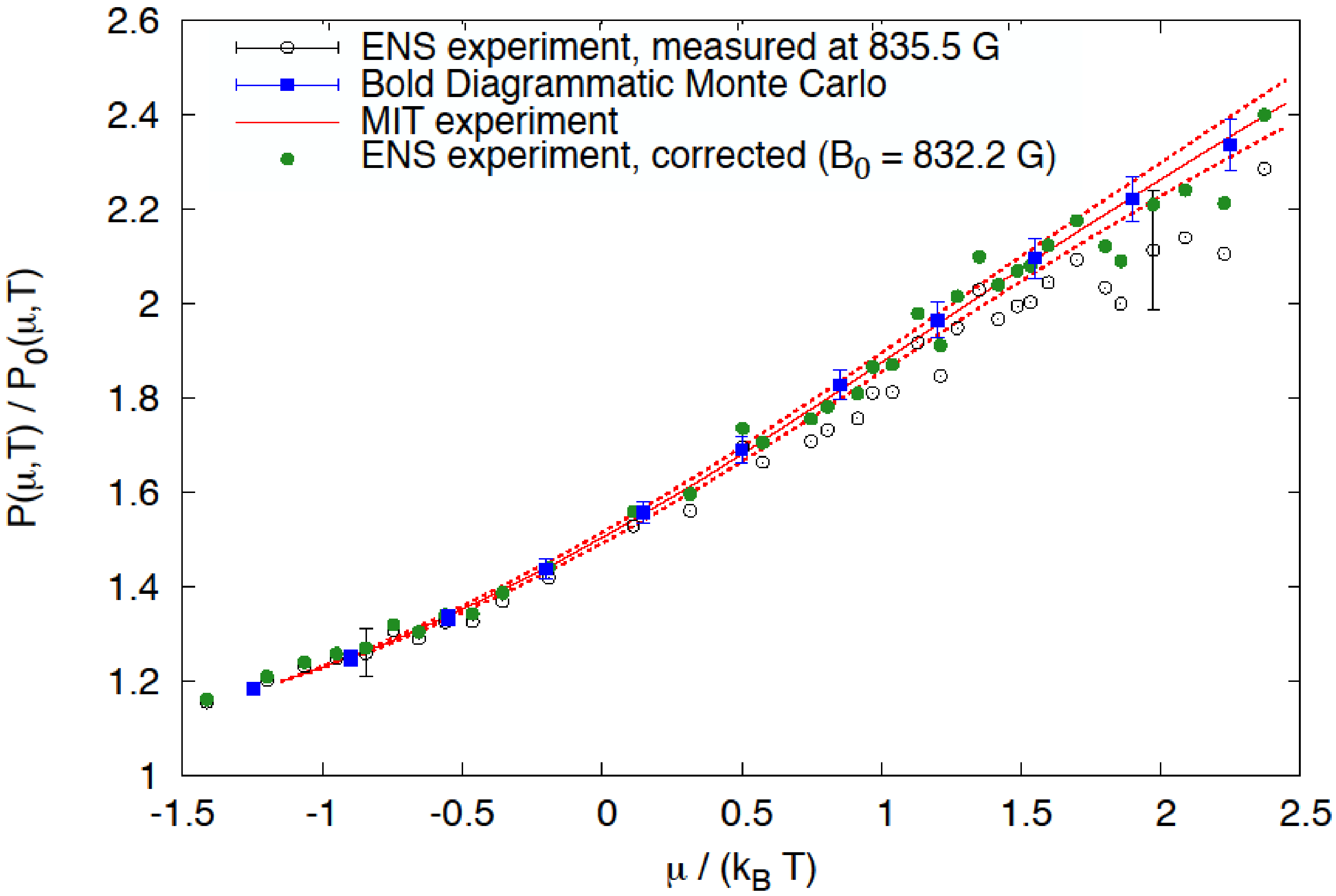


Theory:
Van Houcke, et al.
Amherst
MIT
Nature Phys., 2012

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

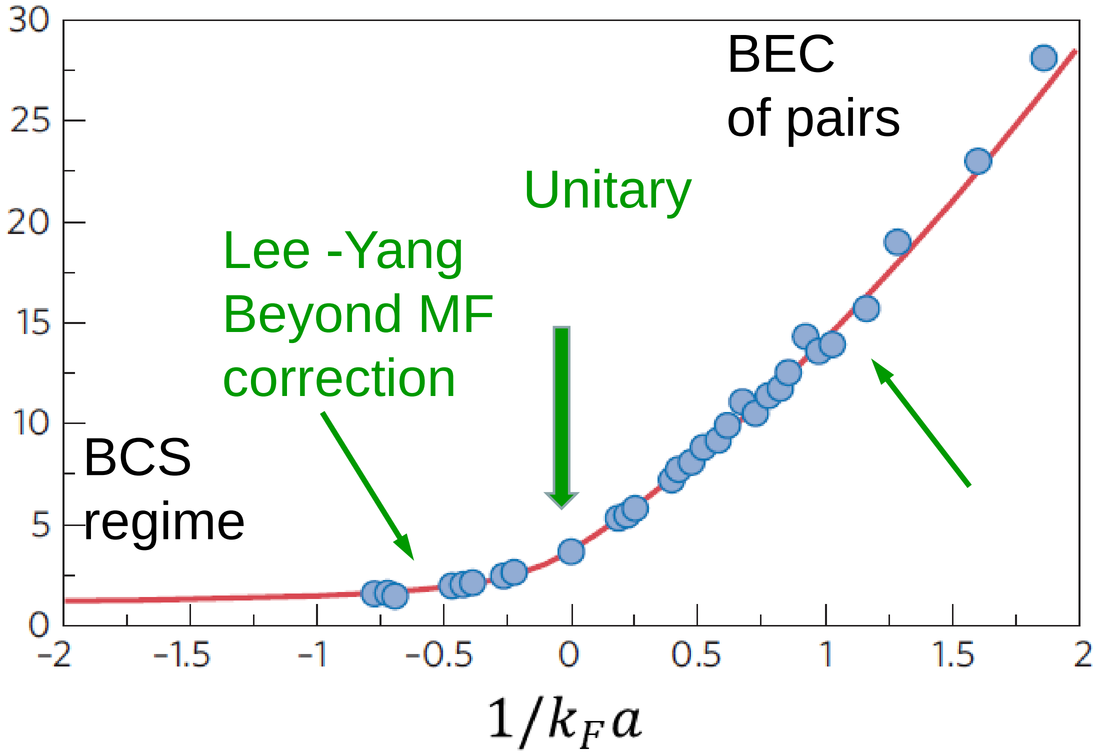


Theory:
Van Houcke,
Werner,
Kosik, Prokof’ev,
Svistunov,
Ku, Sommer
Cheuk, Schirotzek
Zwierlein
Nature Phys.,
2012

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 $P/P_0 = f(1/k_F a)$



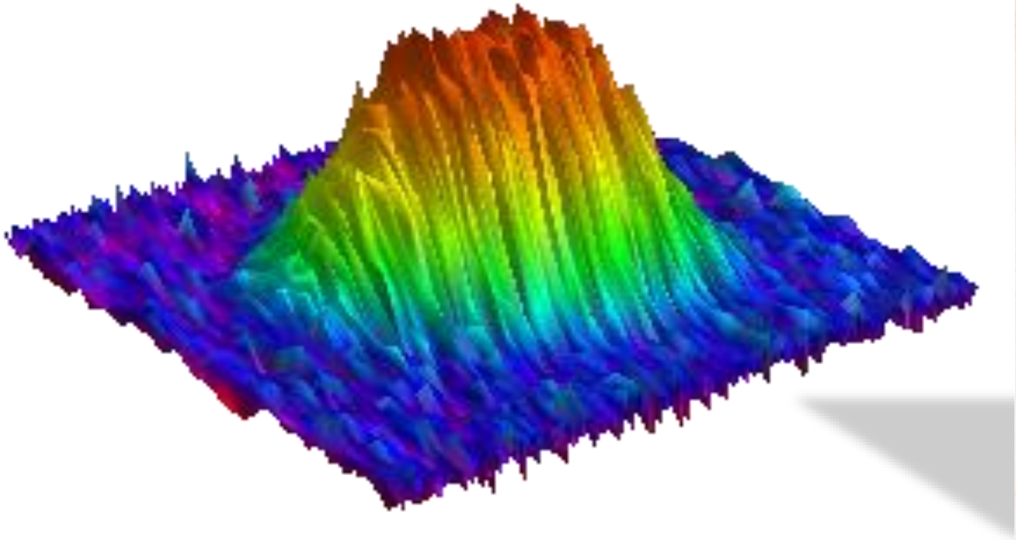
BCS-BEC crossover
at T~0

Lee-Huang-Yang
Beyond MF
correction

An example of quantum simulation in the strongly correlated regime

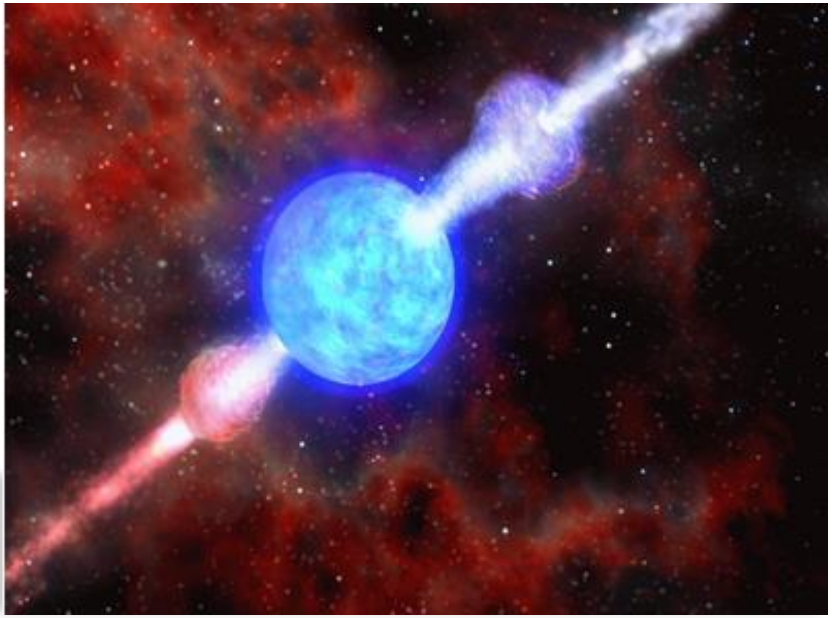
N. Navon, S. Nascimbène, F. Chevy, C. Salomon, *Science* **328**, 729-732 (2010)

Simulating the Eq. of State of neutron stars low density region



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,
Pethick, Schwenk…

Second example

A novel system

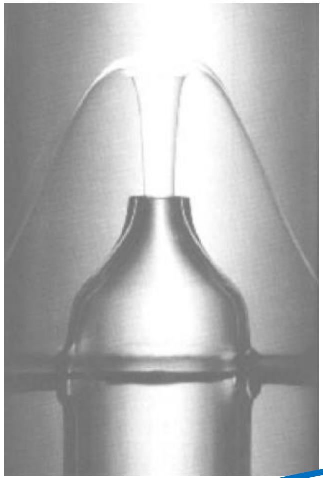
Bose-Fermi superfluid mixture

113 years of Quantum Fluids

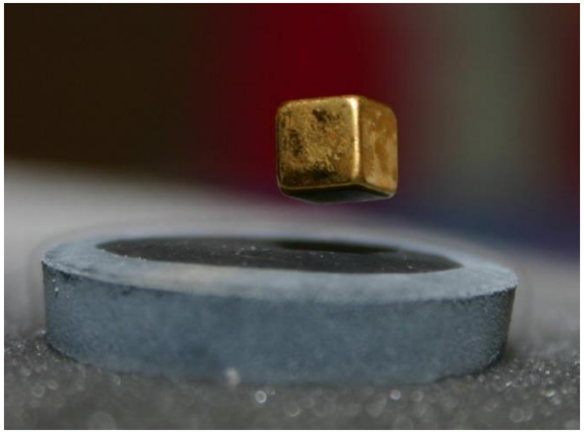
Bose Einstein condensate

Superconductors

^{4}He

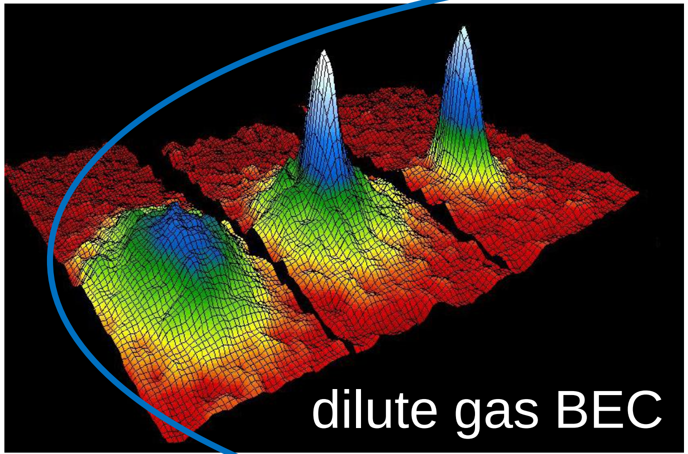


T~ 2.2 K



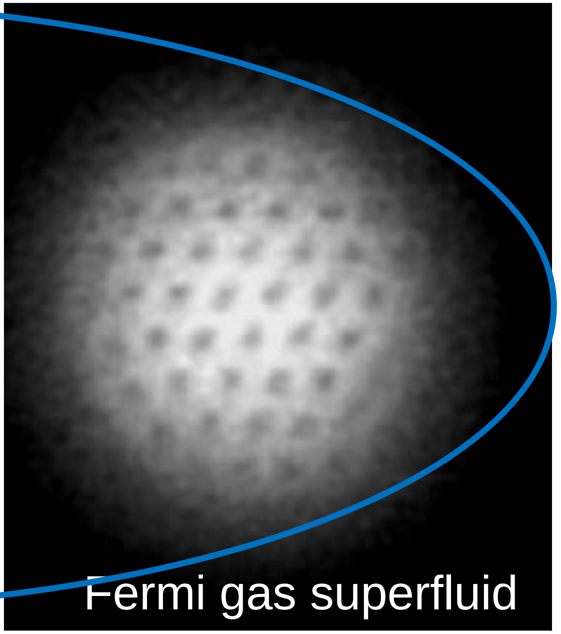
High T_c
77 K

^{3}He
2.5 mK



dilute gas BEC

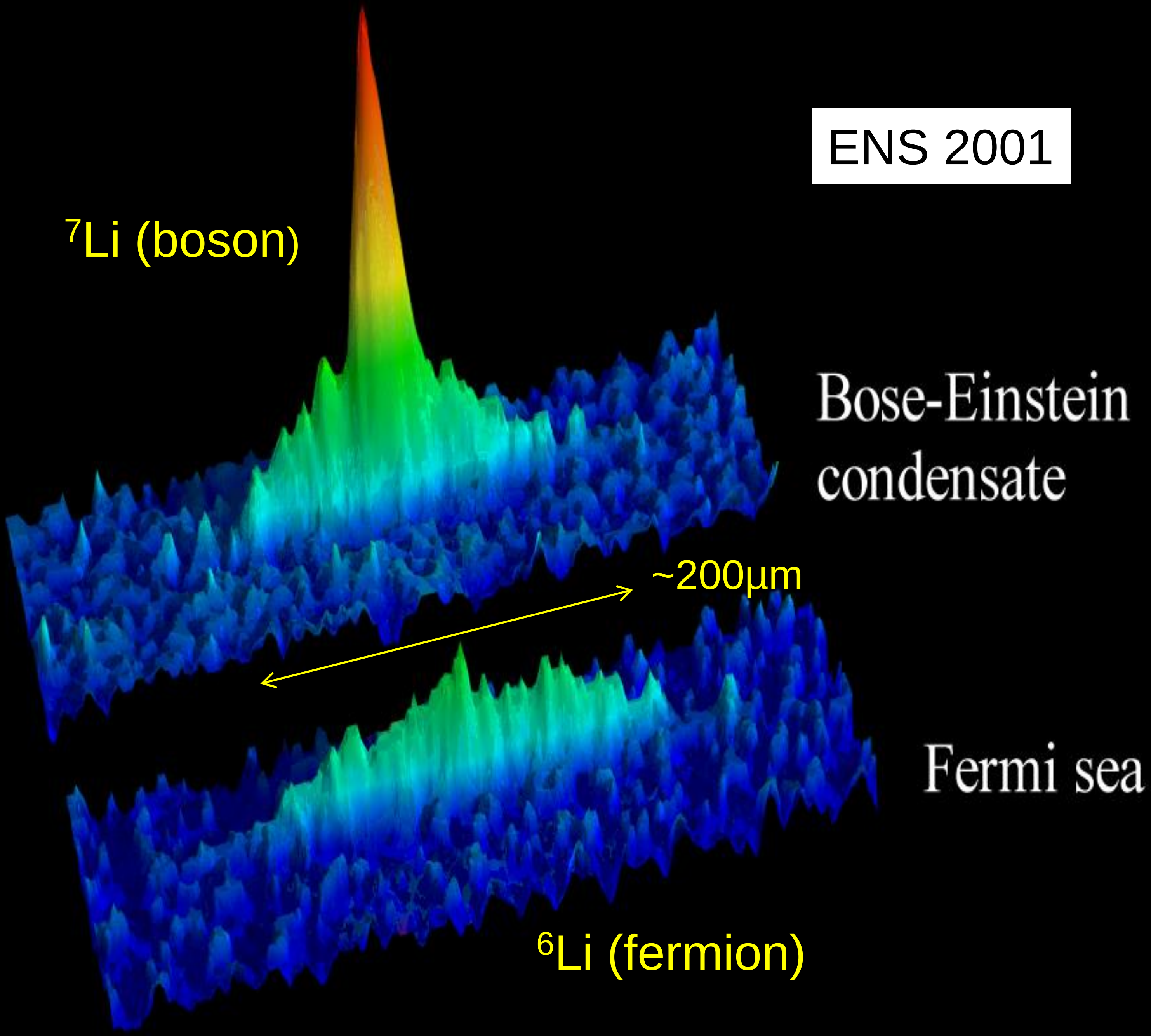
100 nK



Fermi gas superfluid

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

ENS 2001



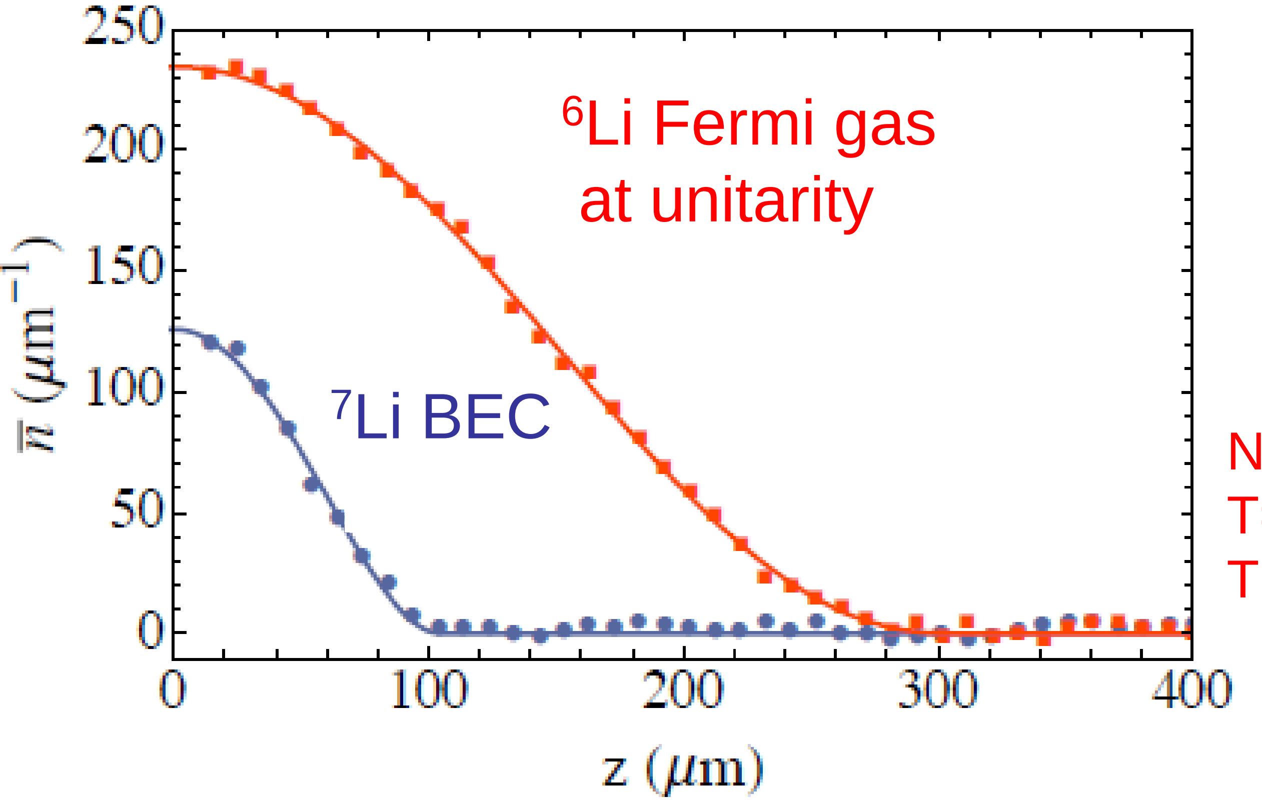
^{7}Li (boson)

~200µm

^{6}Li (fermion)

In situ density profiles

N_B= 2 10^4
T=80 nK
N_0/N_B> 80%
T<T_c/2



N_F= 2 10^5
T= 80 nK ~ T_c/2
T_F= 800 nK

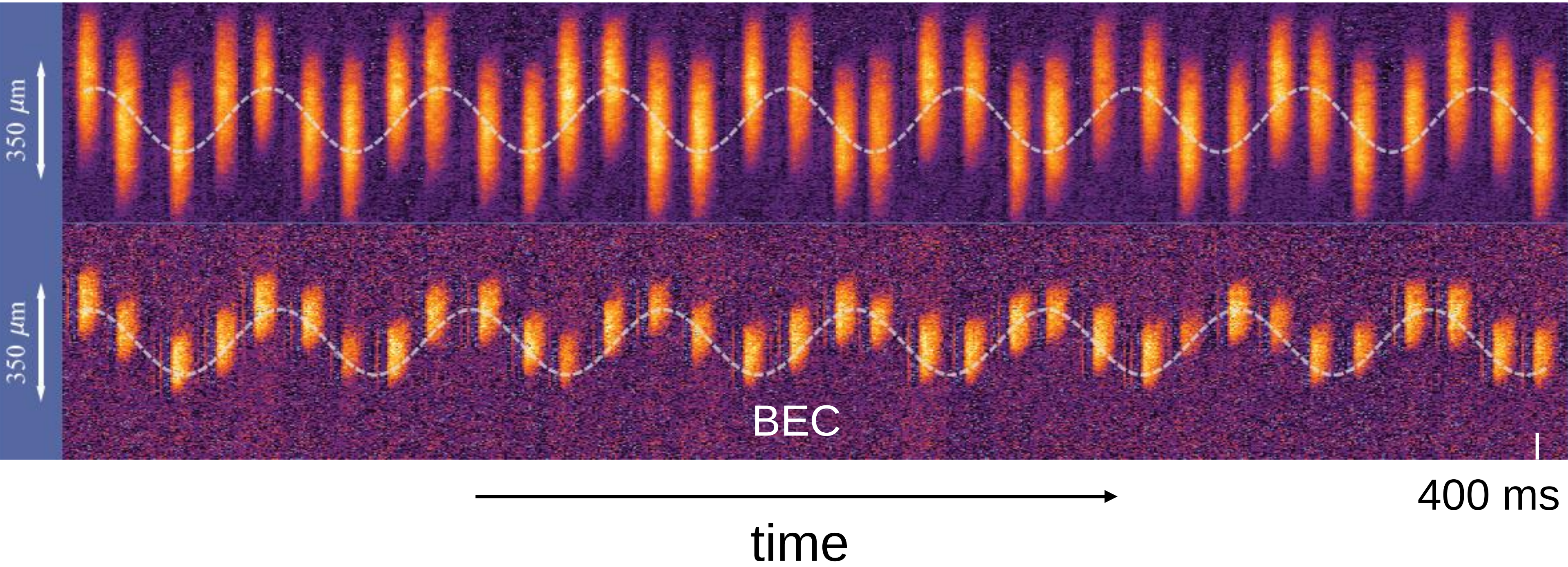
Trap frequencies: ν_z=15.6 Hz
for bosons, ν_{rad}= 440 Hz

Lifetime of mixture: 7s in shallowest trap

Unitary ^{6}Li Fermi gas can cool any species fulfilling the requirements to BEC
See also ^{6}Li-^{41}K, USTC, China, PRL ’16, and ^{6}Li-^{173}Yb, UWash, PRL’17

Long-lived Oscillations of Superfluid Counterflow

Fermi Superfluid



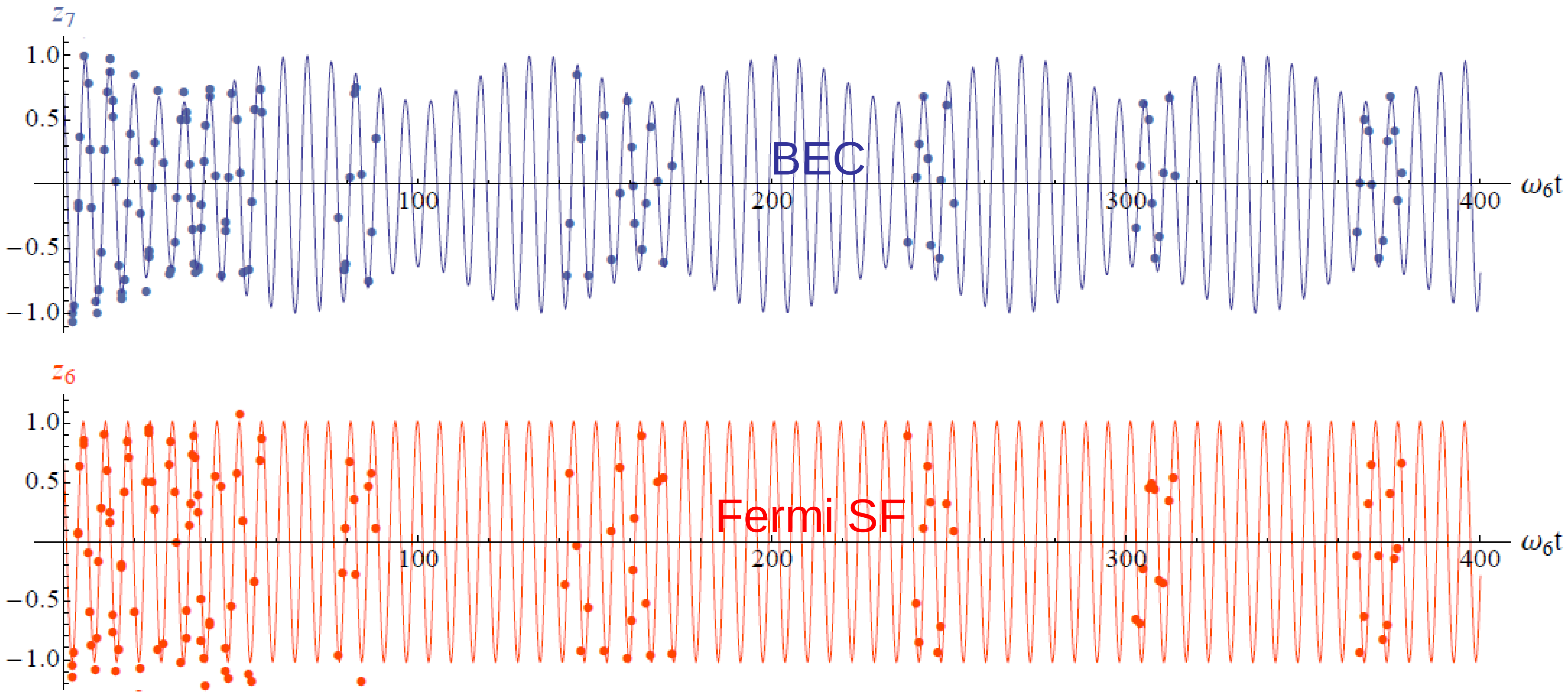
$$\tilde{\omega}_6 = 2\pi \times 17.06(1) Hz$$

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

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



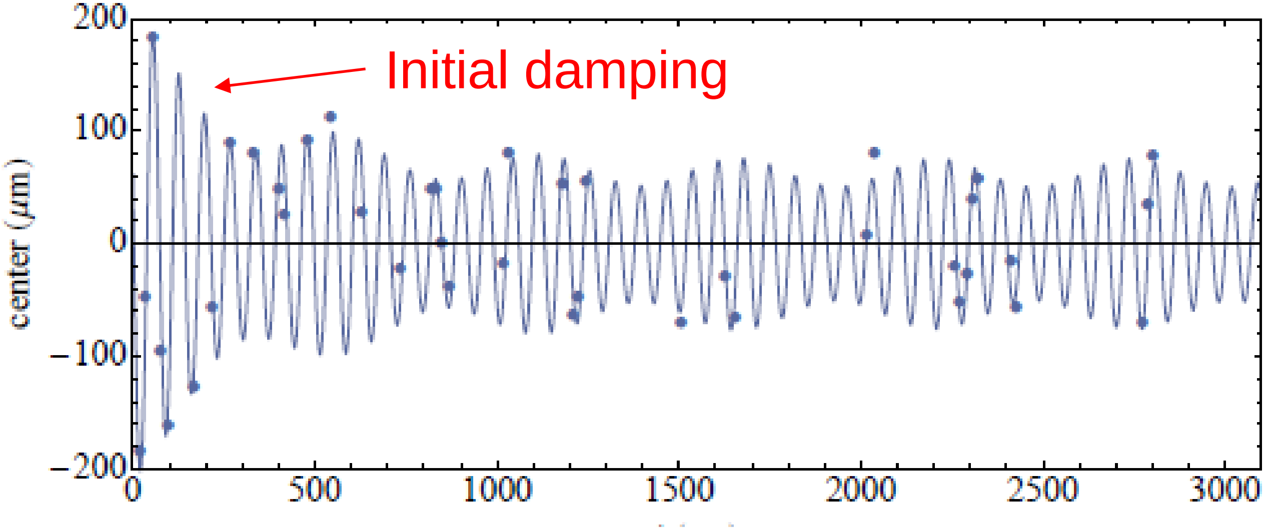
Very small damping: superfluid counterflow

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 !

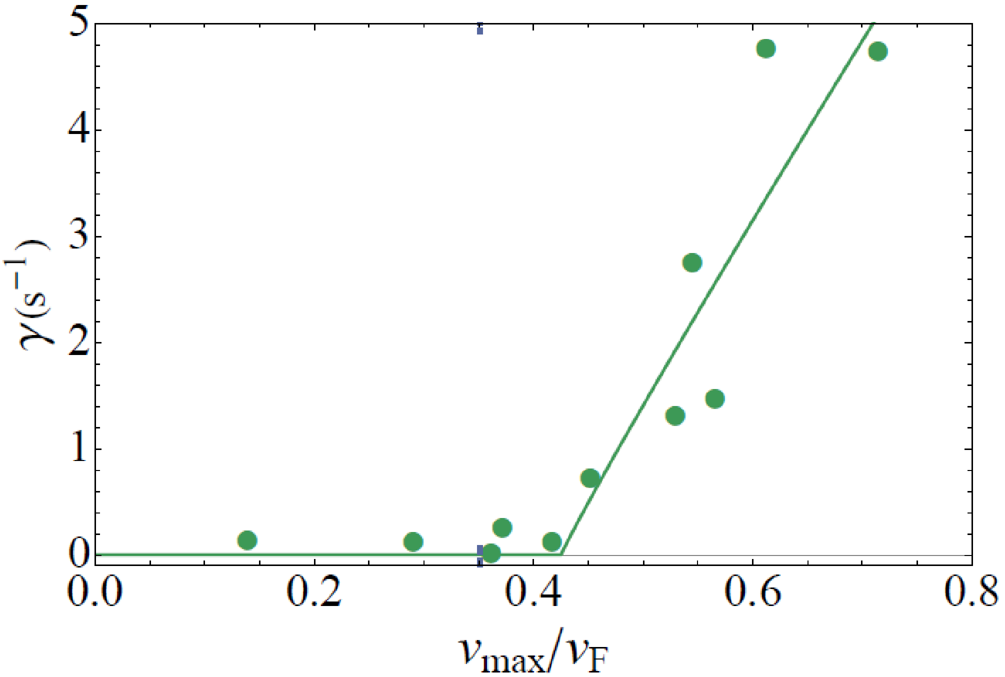
Critical velocity for superfluid counterflow



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

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

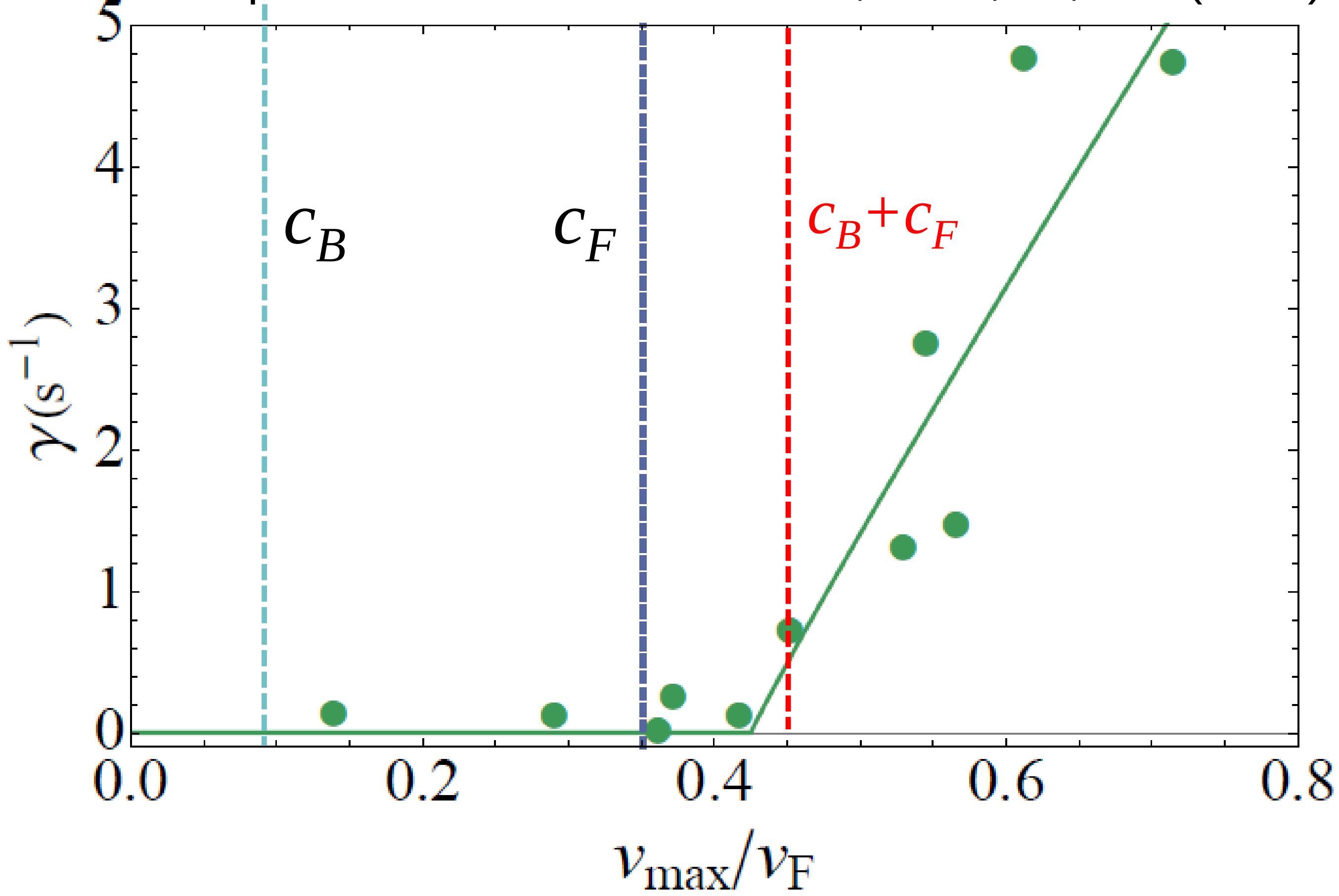
Time(ms)



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)



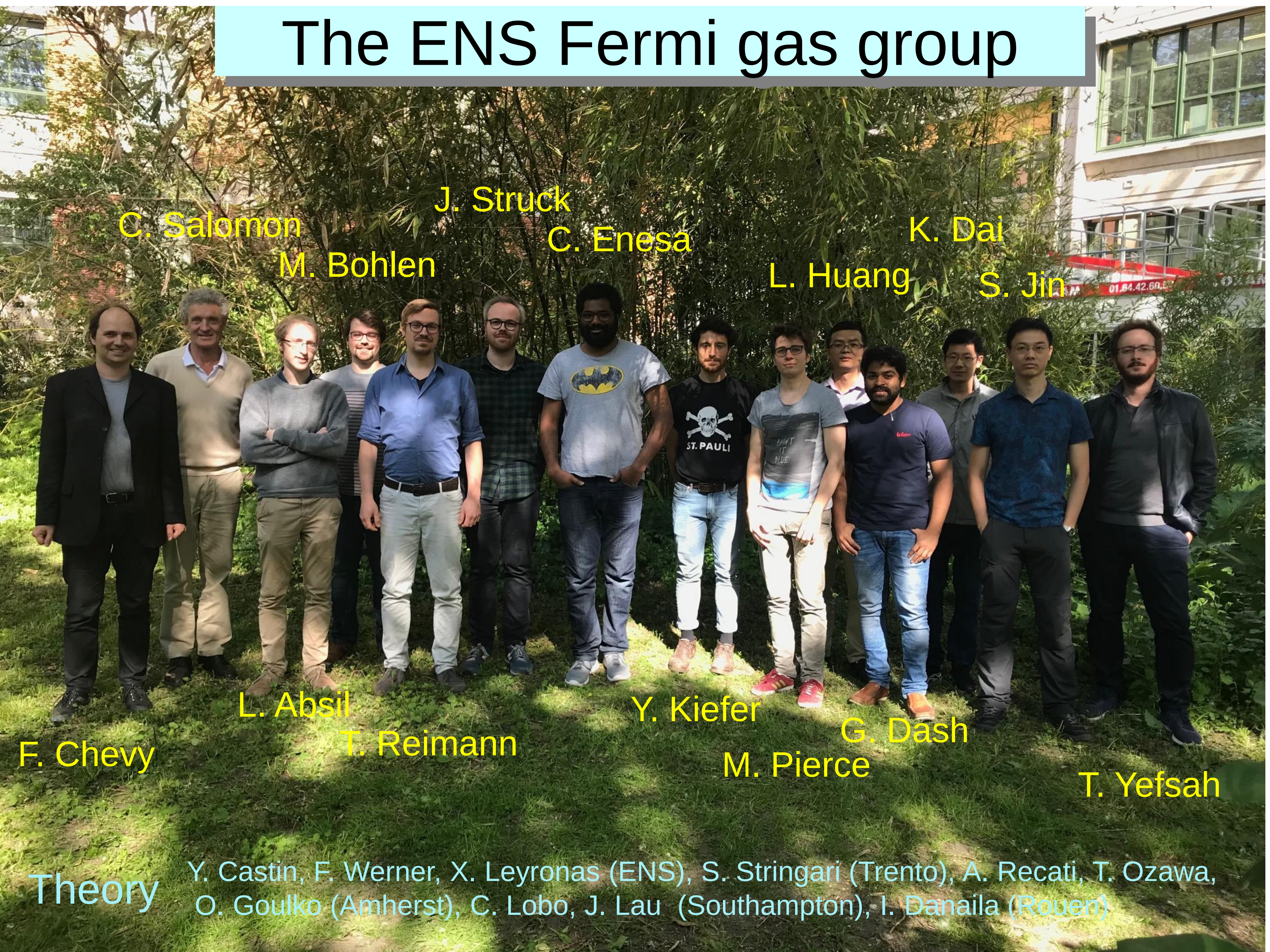
M. Delehaye, S. Laurent, I. Ferrier-Barbut, S. Jin, F. Chevy, C. Salomon, PRL 2015

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

Perspectives on quantum gases

- 2 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)