Dynamics of superfluid ^{6}Li gases through a thin barrier

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Area della ricerca CNR

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INO-CNR
ISTITUTO NAZIONALE DI OTTICA

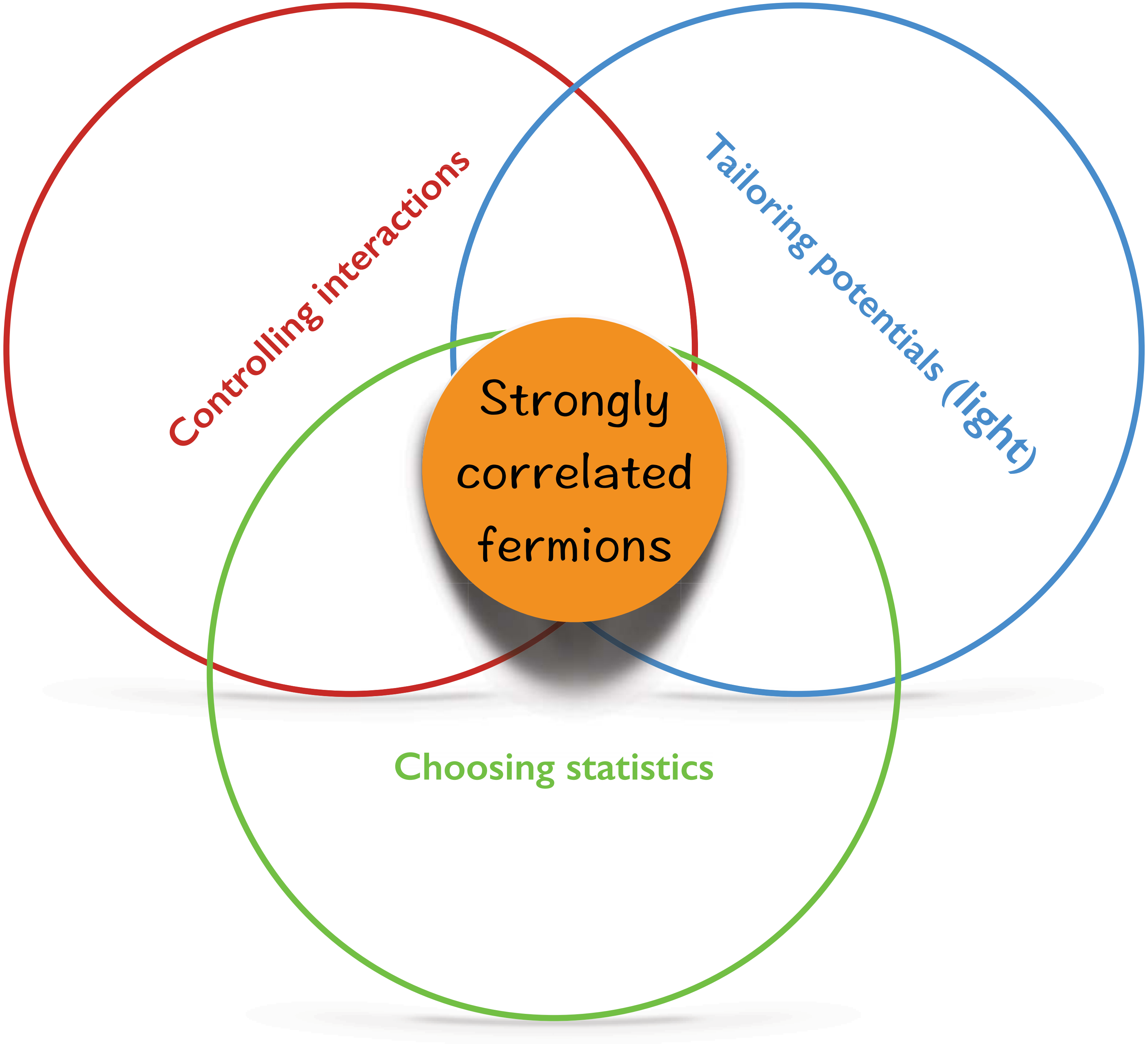
European Research Council

INTERNATIONAL YEAR OF LIGHT 2015

LENS
EUROPEAN LABORATORY FOR NON-LINEAR SPECTROSCOPY

OUTLINE

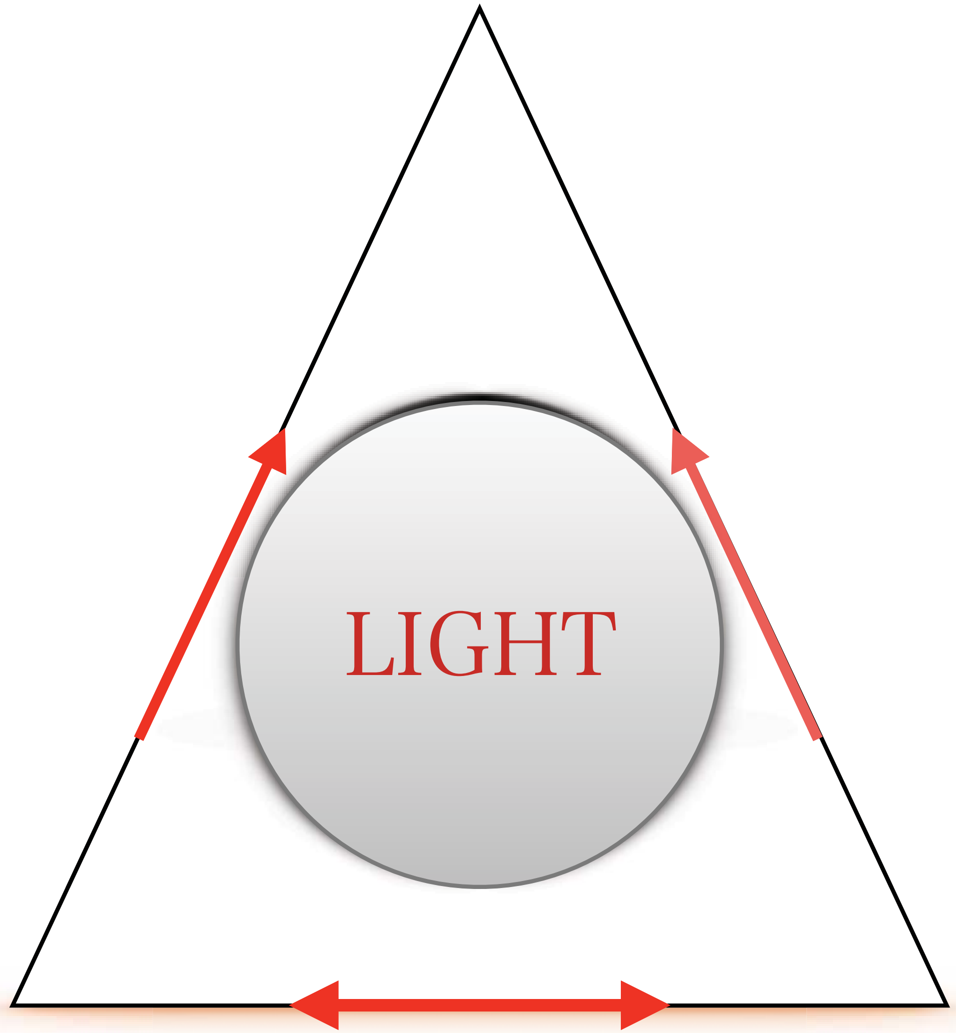
1. General motivations.
2. BEC-BCS crossover: strongly-correlated Fermi gases
3. Our experiments: tunneling of (strongly-correlated) fermions
4. Dynamics of superfluid Fermi gases across the BEC-BCS crossover: from coherent to dissipative dynamics
5. Spin diffusion across the BEC-BCS crossover: **work in progress.**
6. Conclusions



R. Feynman, International Journal of Theoretical Physics, **21**, (1982)

I. Bloch, et al., Rev. Mod. Phys., **80**, 885 (2008)

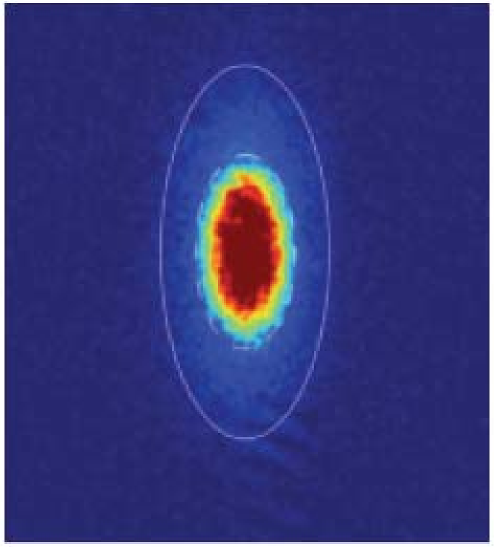
Real and new materials: technological impact



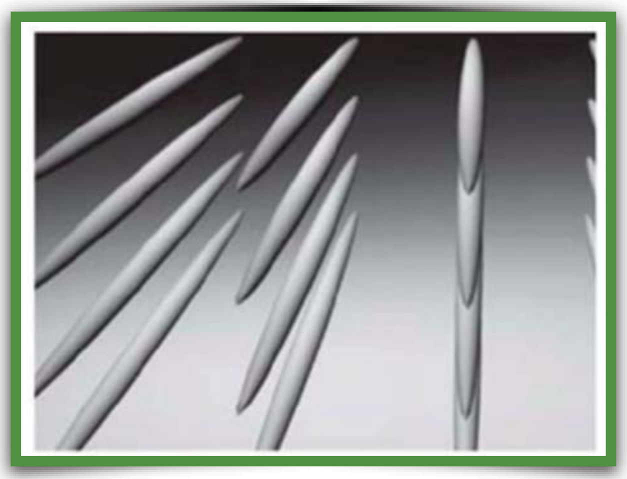
Quantum simulation: theory **Quantum simulation: experiments**

Simulating the electronic properties of materials long before they can be physically realised

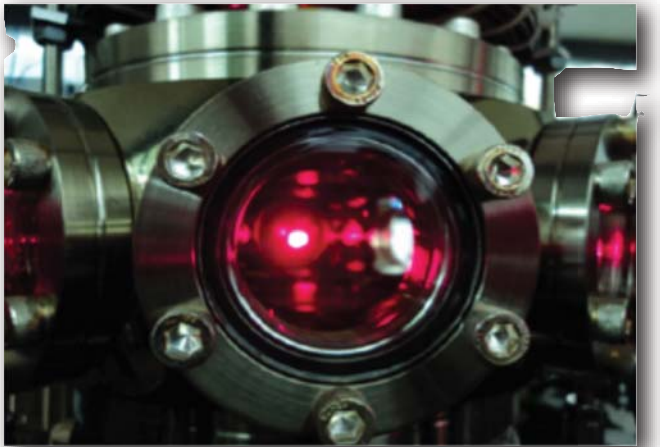
THE ESSENTIAL TOOL: light !!!



Imaging

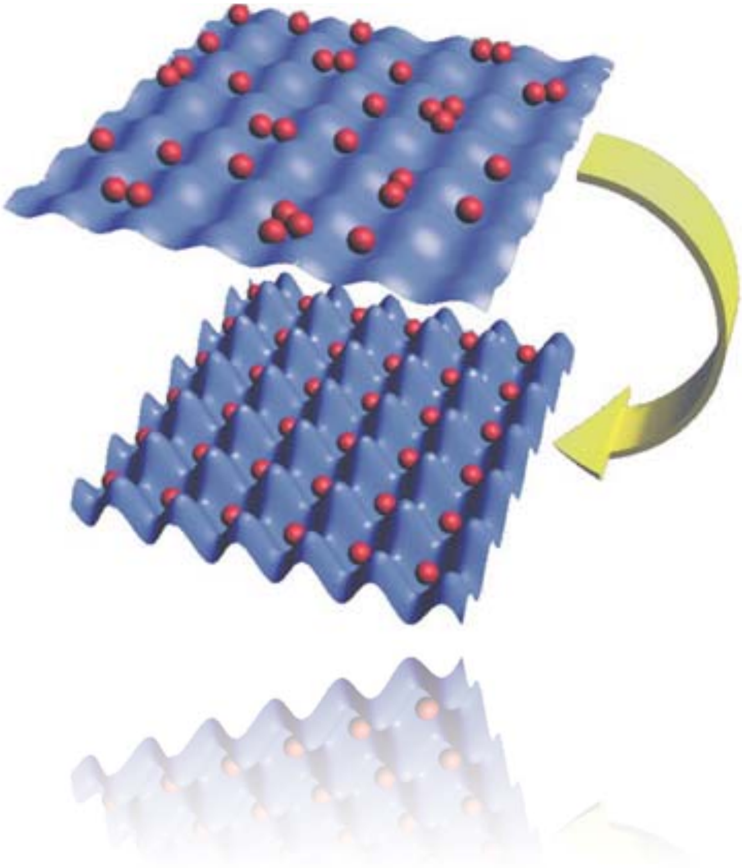


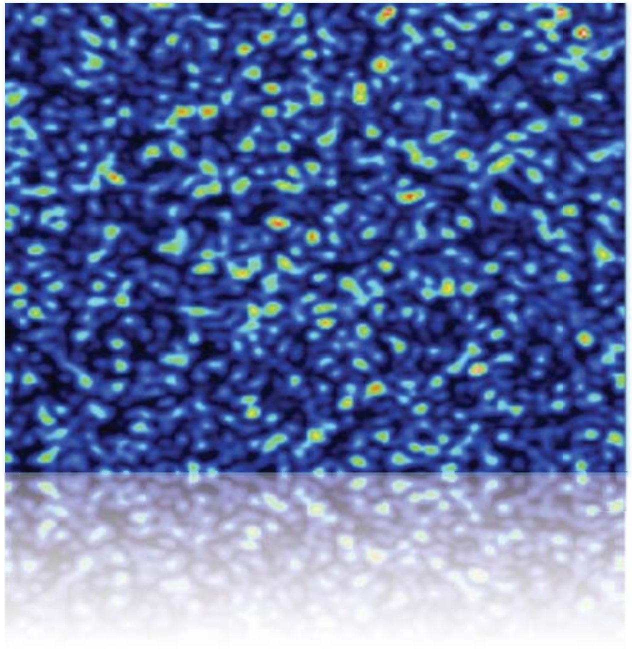
Trapping

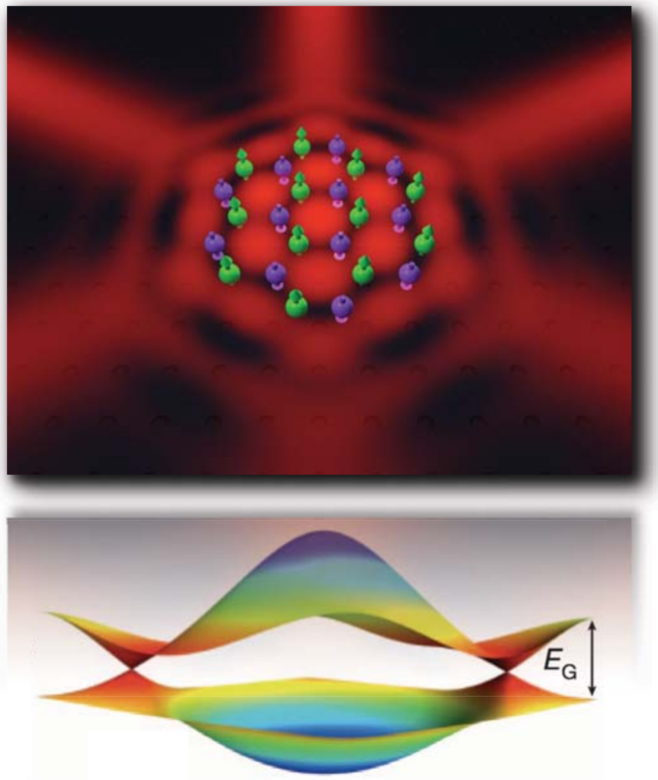


Cooling

THE ESSENTIAL TOOL: light !!!





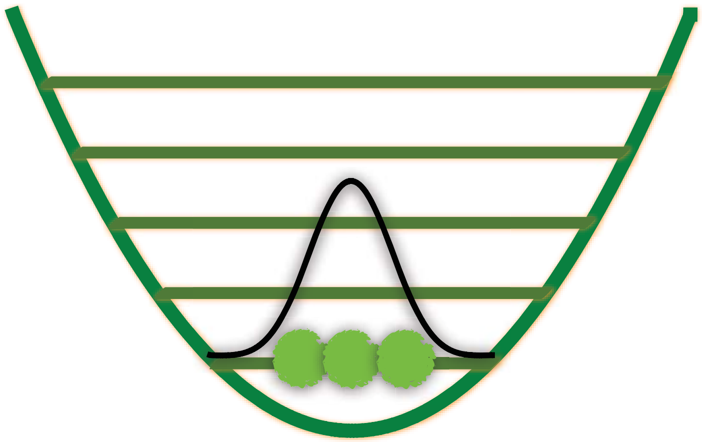


Engineering artificial “crystals” made by (laser) light

BEC-BCS crossover:

strongly-correlated (superfluid) fermions

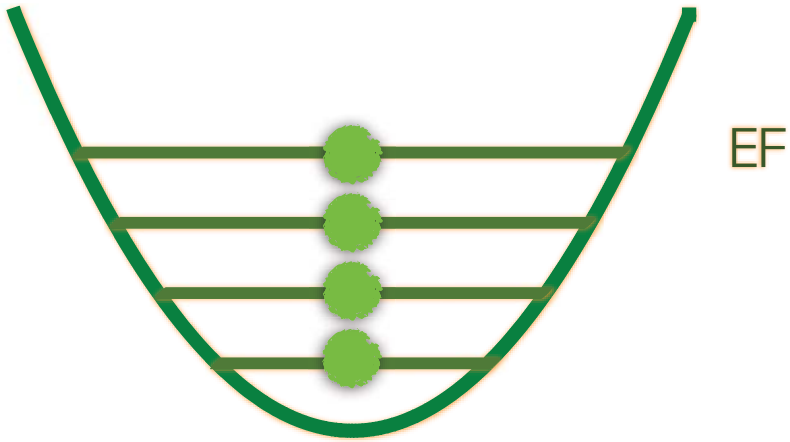
BOSONS (T=0)



Statistical "attraction" between the particles

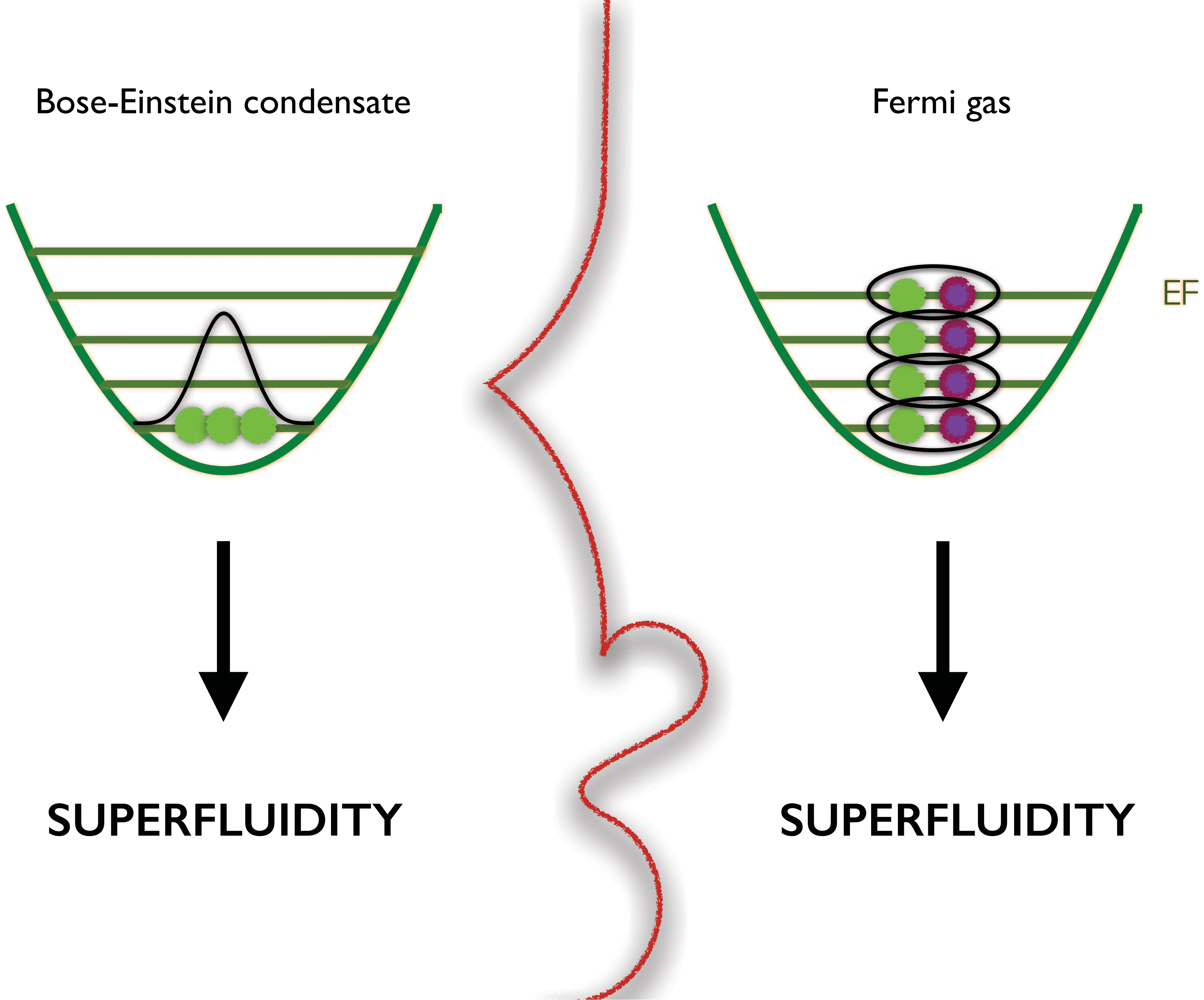
- Atomic gases
- Photons
- Phonons in crystal
- ^{4}He

FERMIONS (T=0)



Statistical "repulsion" between the particles

- Atomic gases
- Electrons and nuclei
- White Dwarf
- ^{3}He


Bose-Einstein condensate
Fermi gas
EF
SUPERFLUIDITY
SUPERFLUIDITY

Superfluidity is one of the most intriguing phenomenon in physics.

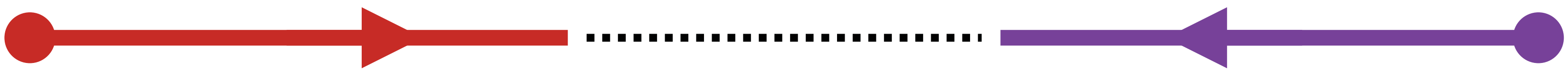
$$\Delta=|\Delta|e^{i\varphi}$$

Two paradigmatic "in principle disconnected" limits…

?

(Bosons)

(Fermions)

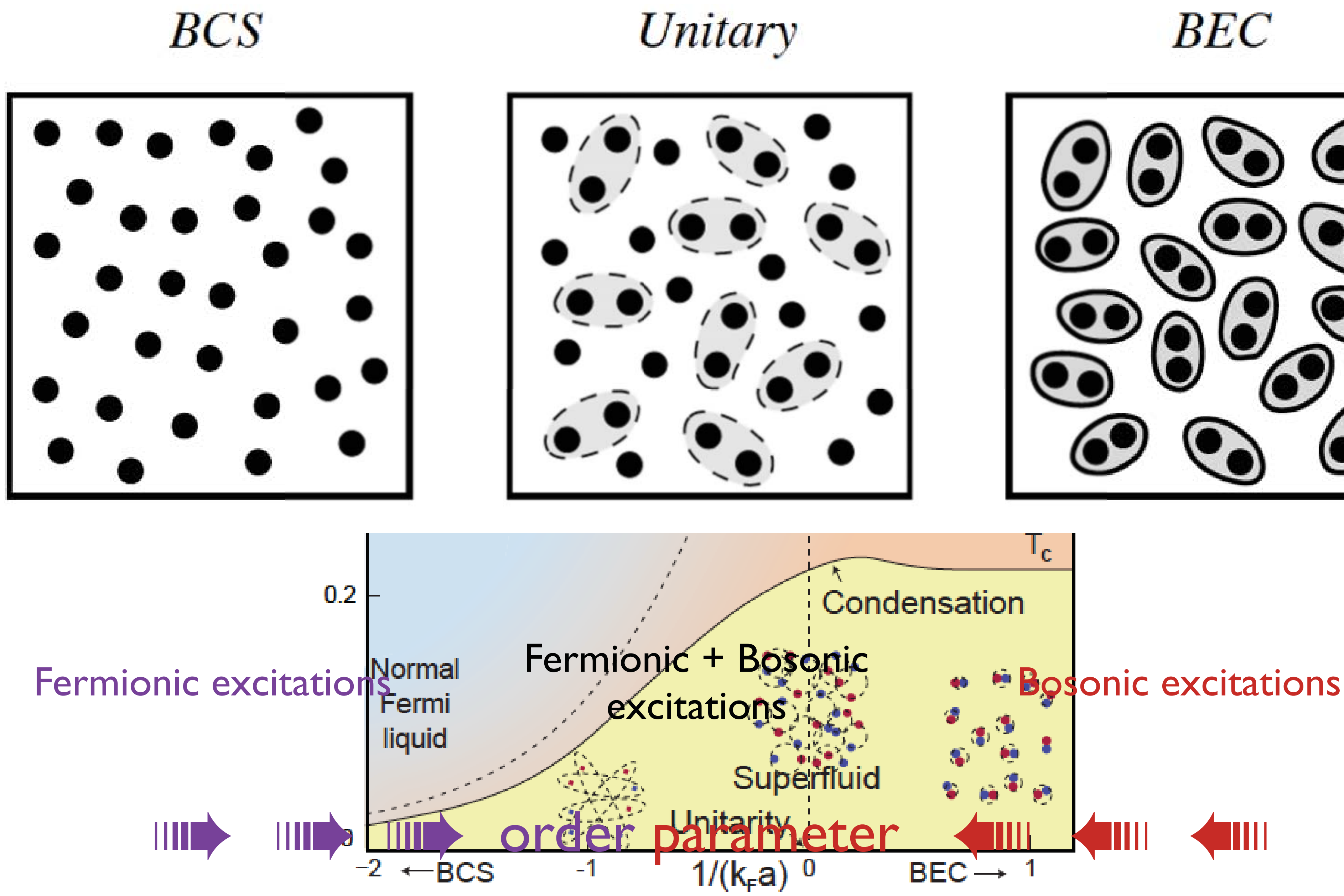


Bose-Einstein condensation

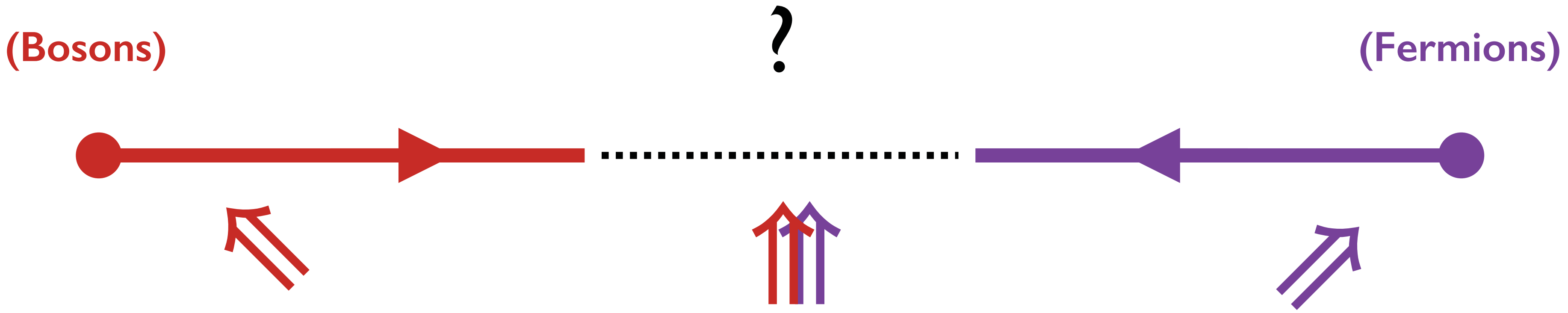
Helium 4
Atomic gases
Polaritons
Light

Bardeen-Schrieffer-Cooper pairing

Helium 3
Atomic gases
Superconductors
Nuclear matter



M. Randeria, Ultracold Fermi gases: pre-pairing for condensation, Nat. Phys. **6**, 561 (2010)

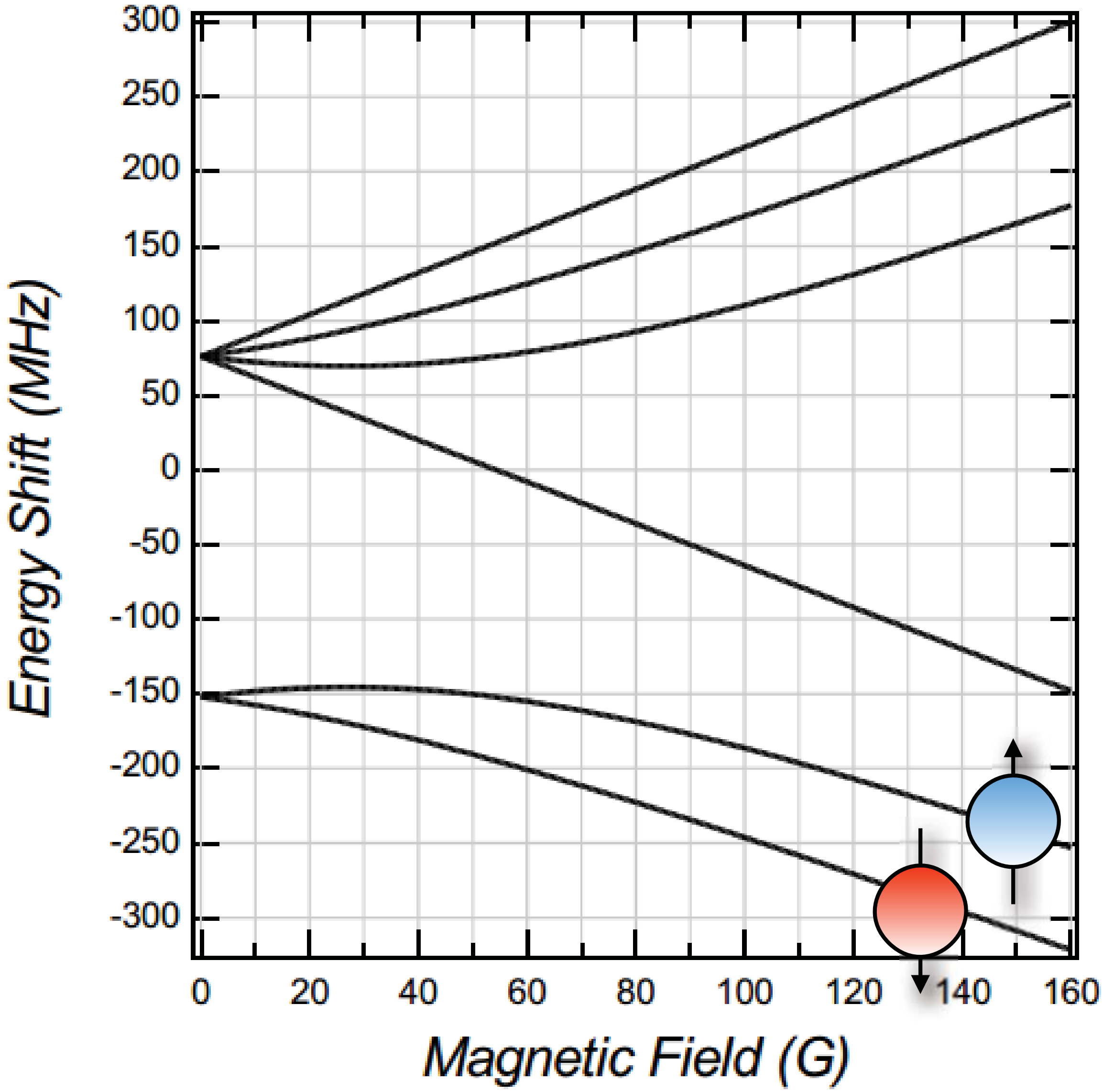


System	T_c	T_F	T_c/T_F
Metallic lithium at ambient pressure [110]	0.4 mK	55 000 K	10^{-8}
Metallic superconductors (typical)	10 K	100 000 K	10^{-4}
^{3}He	2.6 mK	5 K	5×10^{-4}
MgB_2	39 K	6 000 K	10^{-2}
High-T_c superconductors	100 K	5000 K	2×10^{-2}
Neutron stars	10^{10} K	10^{11} K	10^{-1}
Strongly interacting atomic Fermi gases	170 nK	1 μK	0.17

The **coldest** (nK) fermions in the universe but million times *thinner (10^{13} cm^{-3})* than air

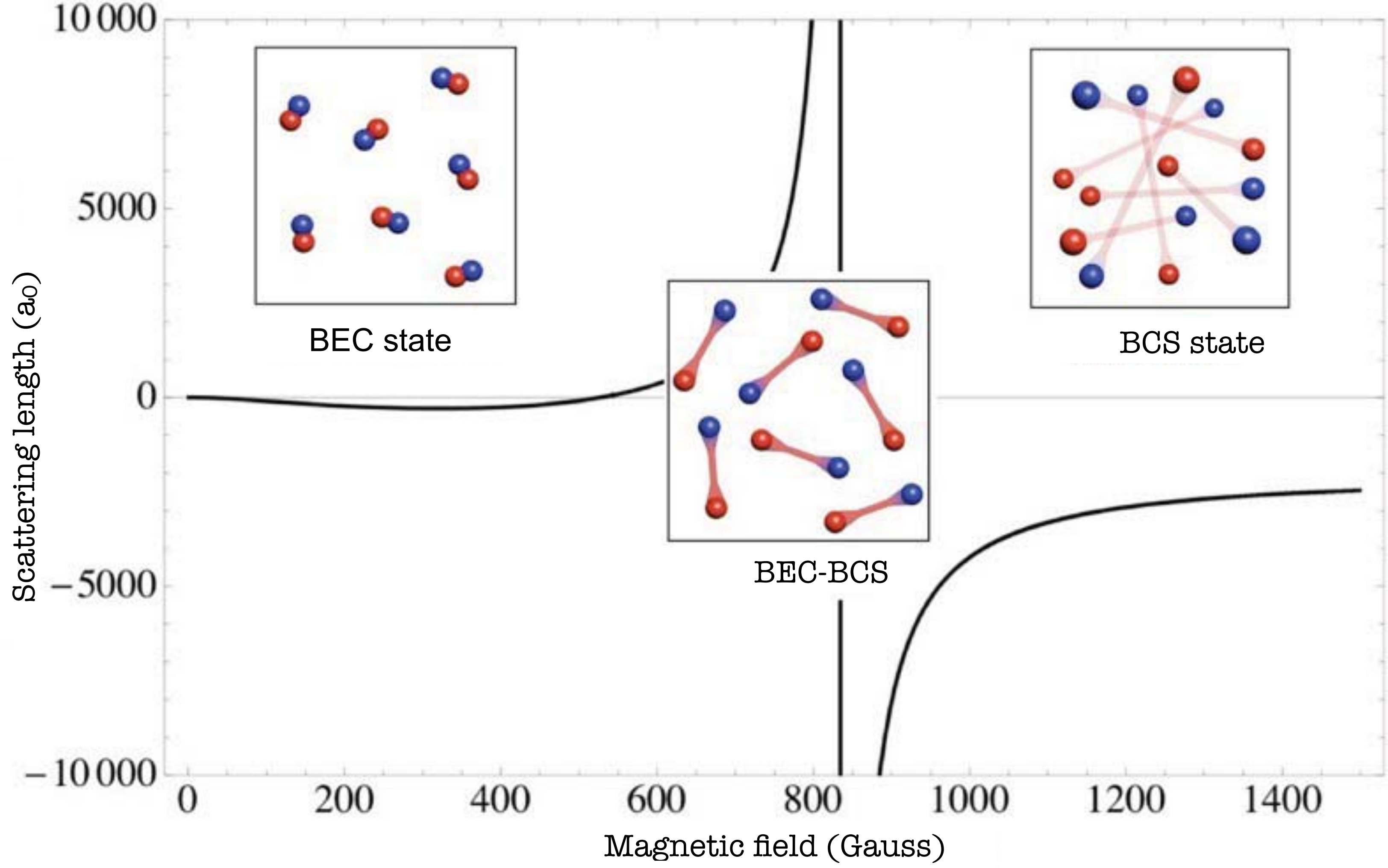
M. Zwierlein in Novel superfluids Vol. 2, K.H. Bennemann, J. B. Ketterson, Oxford Science Publication (2015)

How ?



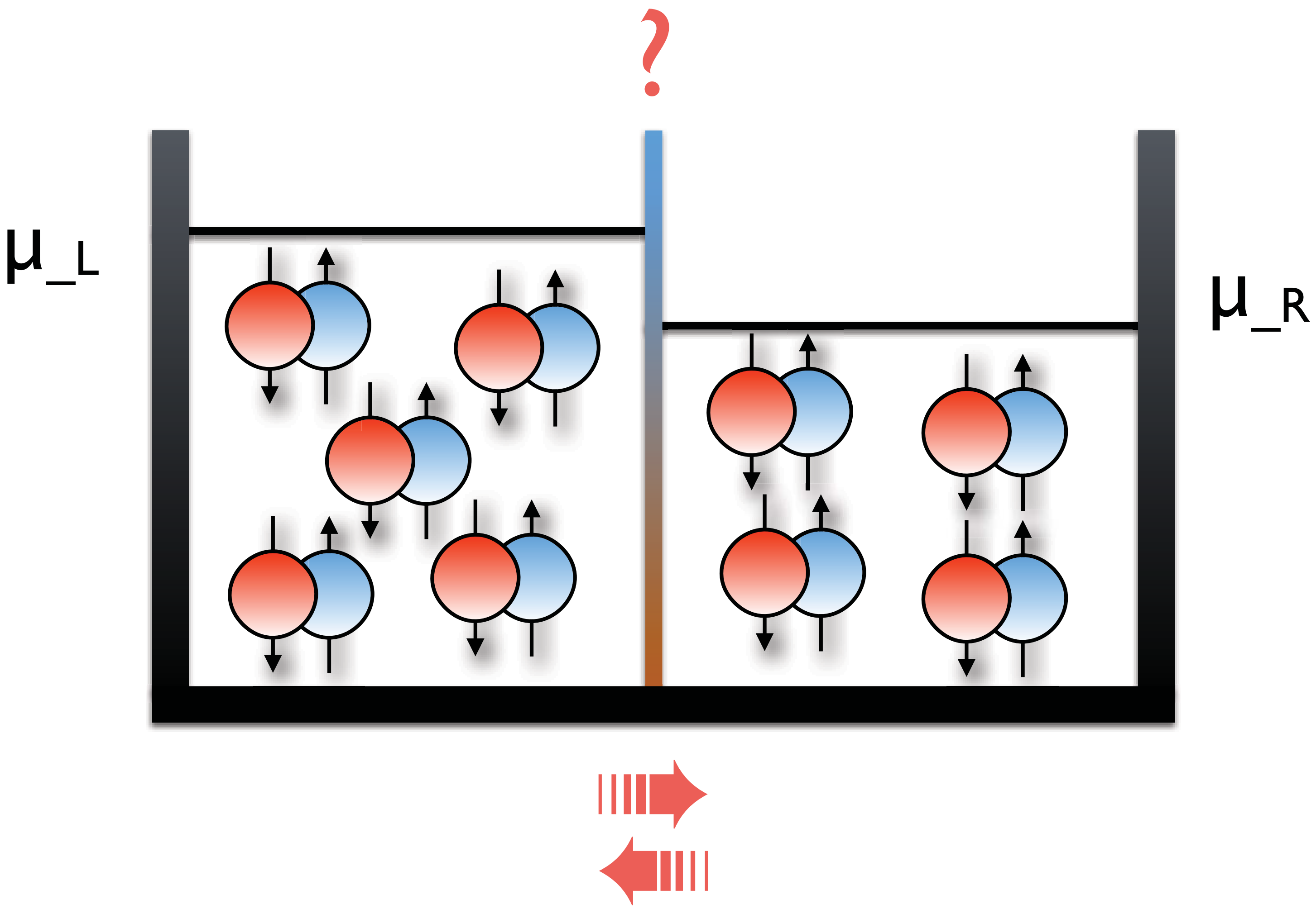
Energy Shift (MHz)
300
250
200
150
100
50
0
-50
-100
-150
-200
-250
-300
0
20
40
60
80
100
120
140
160
Magnetic Field (G)

How ?



Proceedings of the International School of Physics "Enrico Fermi", Course CLXIV, Varenna, edited by M. Inguscio, W. Ketterle, and C. Salomon (IOS Press, Amsterdam)

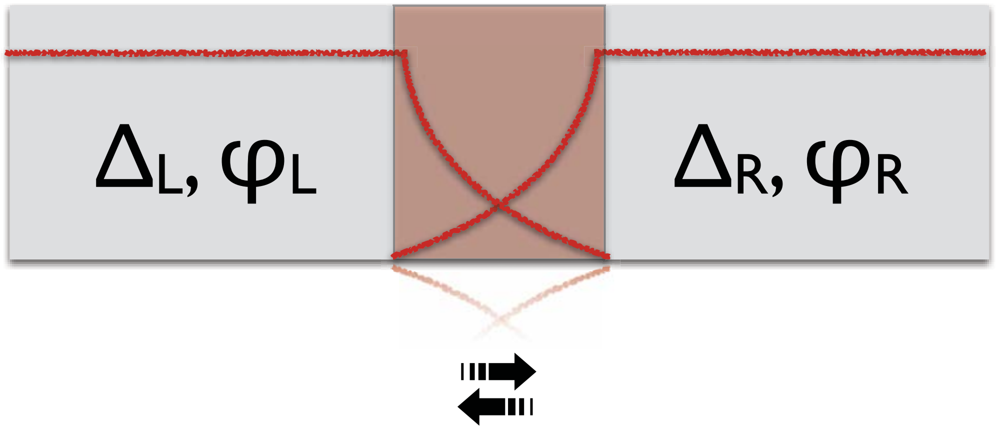
SCENARIO #1: fermionic pairs *(coherent)* tunneling



i.e. …

The Josephson effect (I)

B. D. Josephson, Phys. Lett.**1**, 251 (1962)



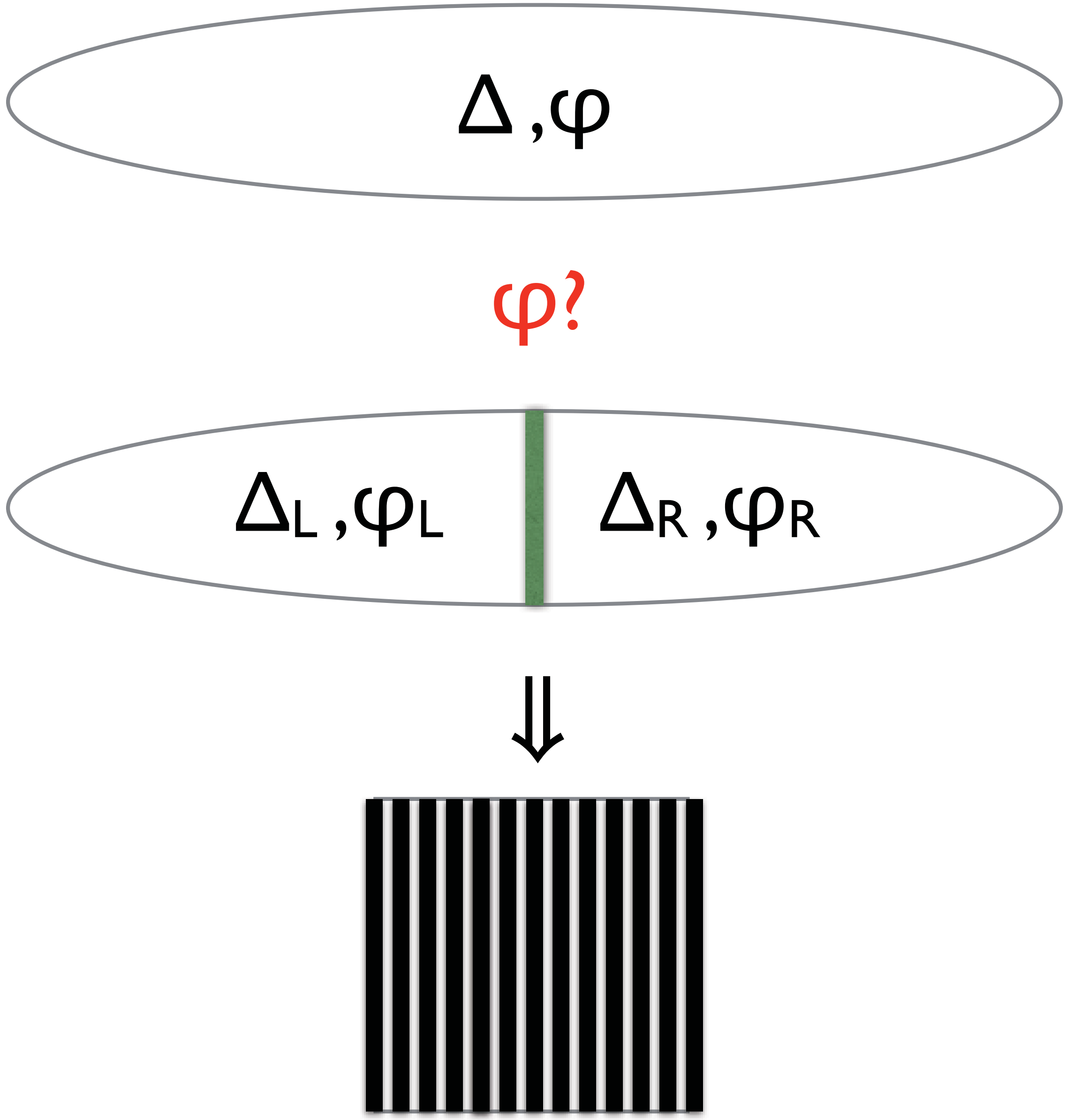
$$I_J = I_c \times \sin(\varphi_L - \varphi_R)$$

$$I_J = I_c \times \sin(\Delta\mu/\hbar \times t)$$

Pristine quantum phenomenon:

Pinning down superfluidity and phase-coherence in one measurement

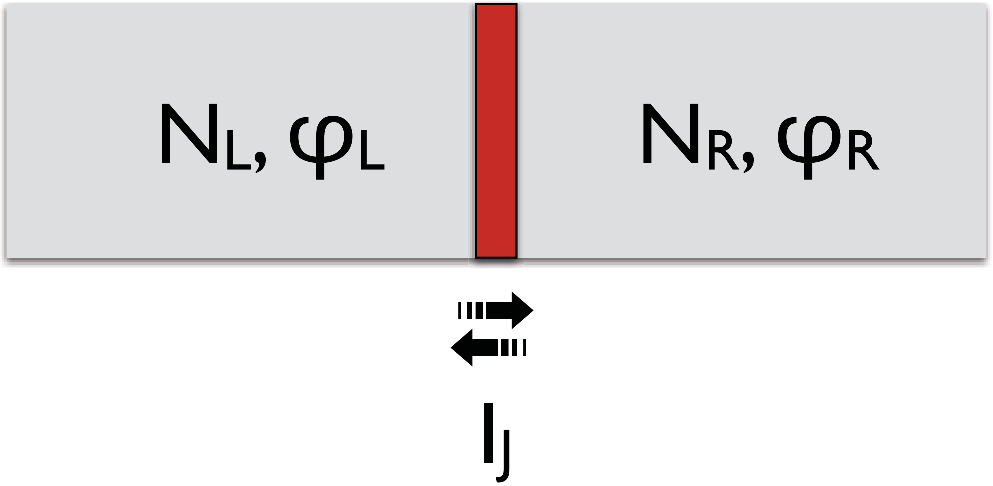
He (Packard), BCS and High-Tc SC, Polariton (J.Bloch), atomic BECs (Inguscio, Oberthaler, Steinhauer,)..



$$\sim \Delta_L^* \Delta_R \times \cos(\varphi_L - \varphi_R)$$

The Josephson effect (II)

B. D. Josephson, Phys. Lett.**1**, 251 (1962)



$\varphi = \varphi_L - \varphi_R$ $N = N_L - N_R$

$$\Delta N \Delta \varphi \sim 1$$

φ, N: conjugate quantum variables:

Essential parameters

P. W. Anderson in *Lectures on the Many-body Problems*, E.R. Caianiello (Eds.)-Elsevier Science (1964)

WHY Josephson dynamics in crossover SF?

Never studied…

Josephson effect: tunneling across the insulating barrier:

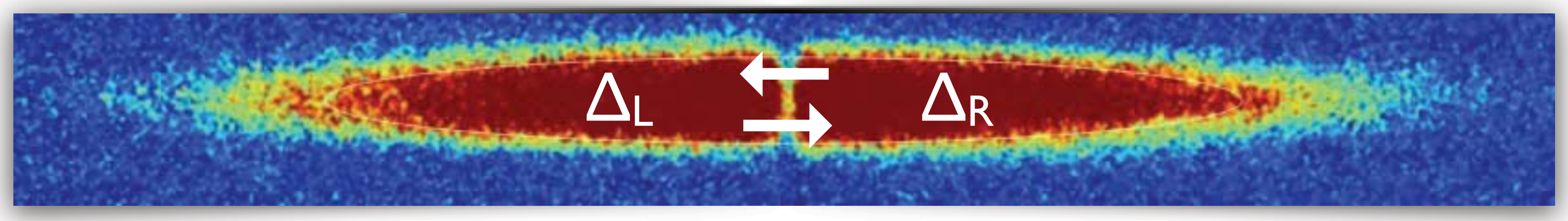
$$E_J \sim \Delta_L \Delta_R / (\Delta_L + \Delta_R) \times \cos(\varphi_L - \varphi_R)$$

- Distinguishing the composite fermionic nature of the **condensed** tunnelling particles
- Probing the excitation spectra of the superfluid/superconductor

Ideal probe of the peculiar-nature of crossover superfluid

An optical thin barrier (light) & superfluid atomic Fermi gases:

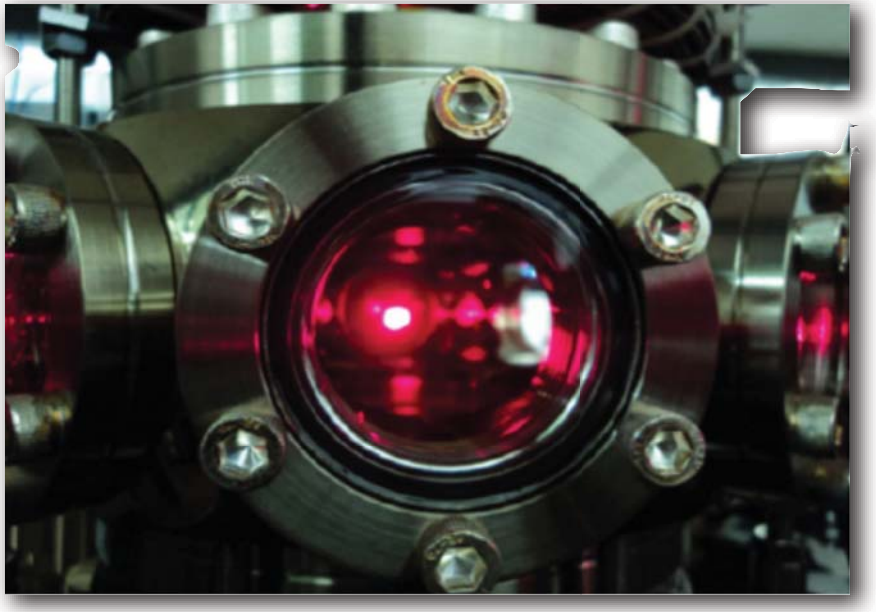
„Synthetic" Josephson junctions

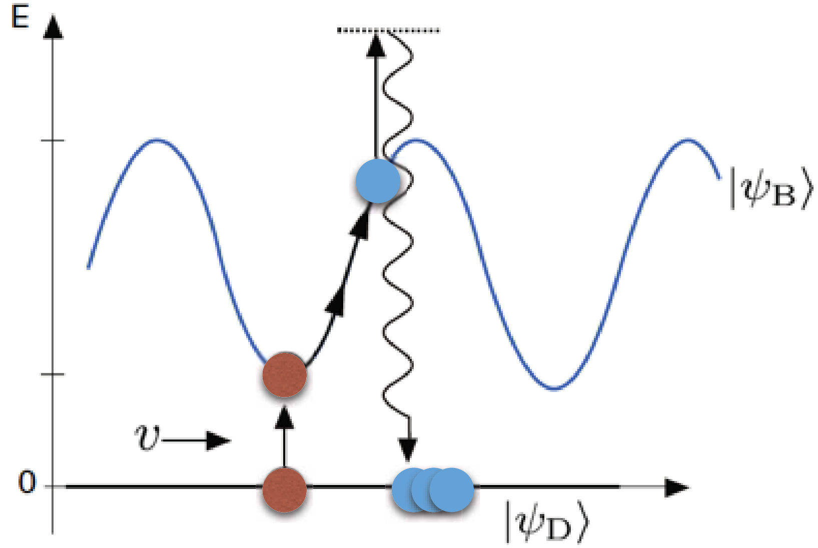


$$\Delta = |\Delta| e^{i\varphi}$$

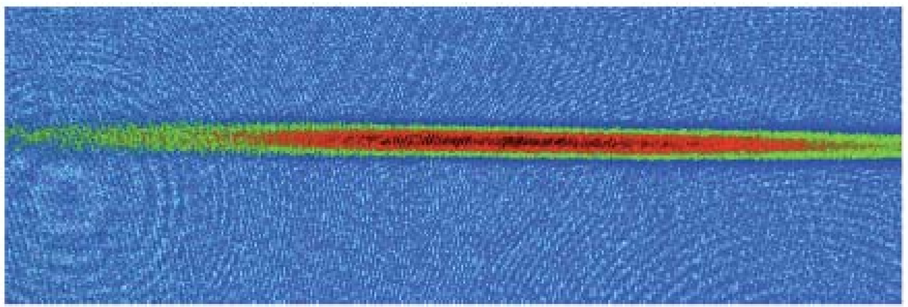
phase coherence (φ) ⇔ order parameter (Δ)

Our all-optical scheme



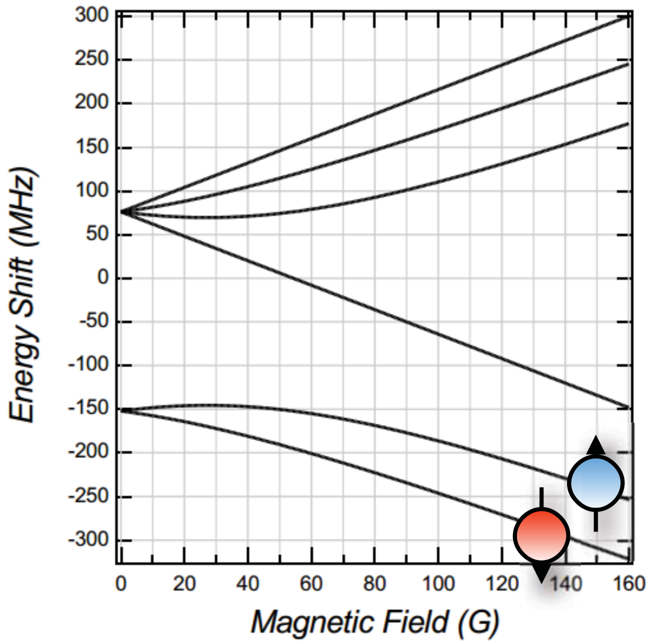


D1 molasses: 10^8 @40μK

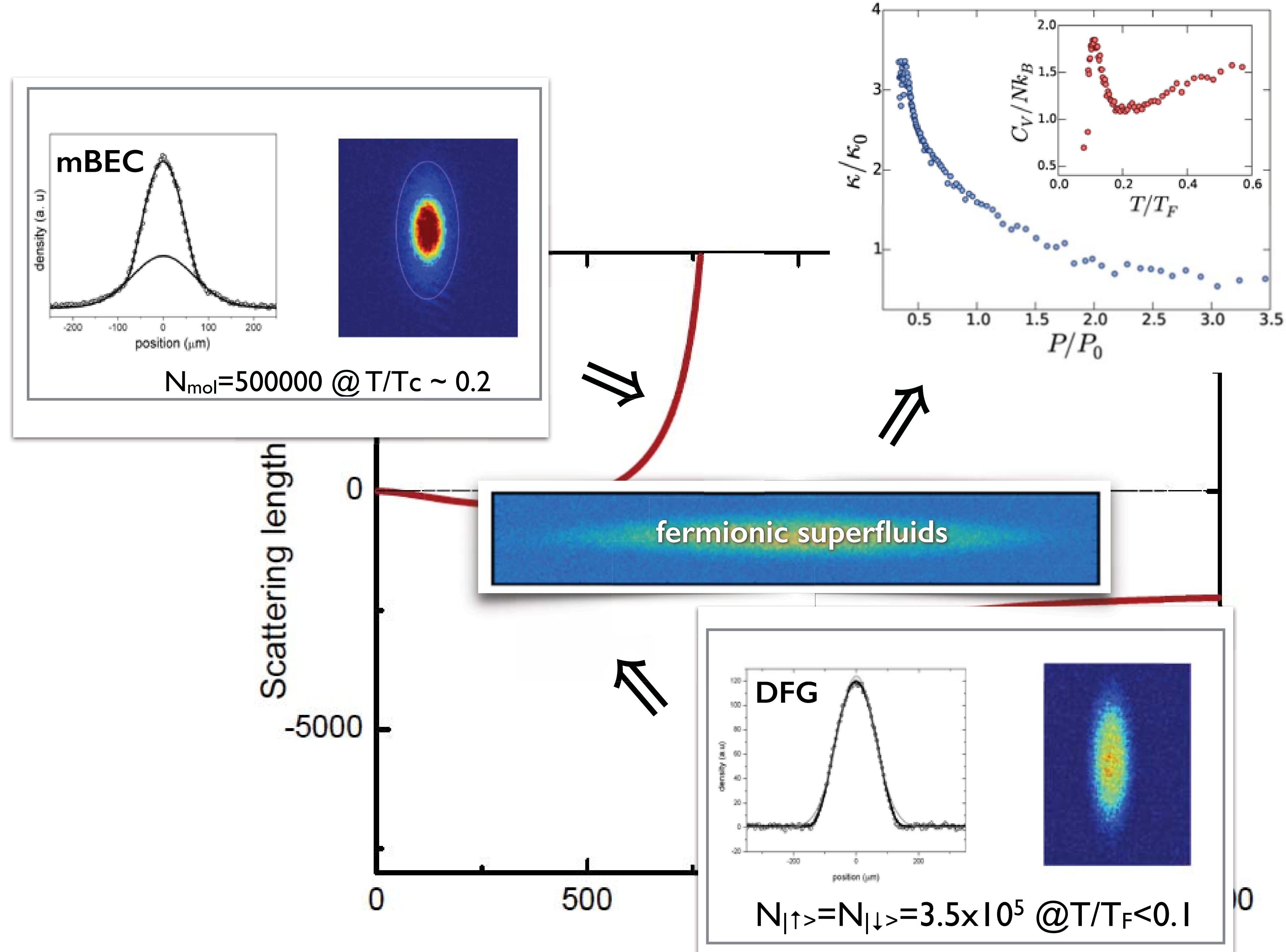


Single beam optical dipole trap

N ~ 10^7 atoms in F = 1/2 manyfold

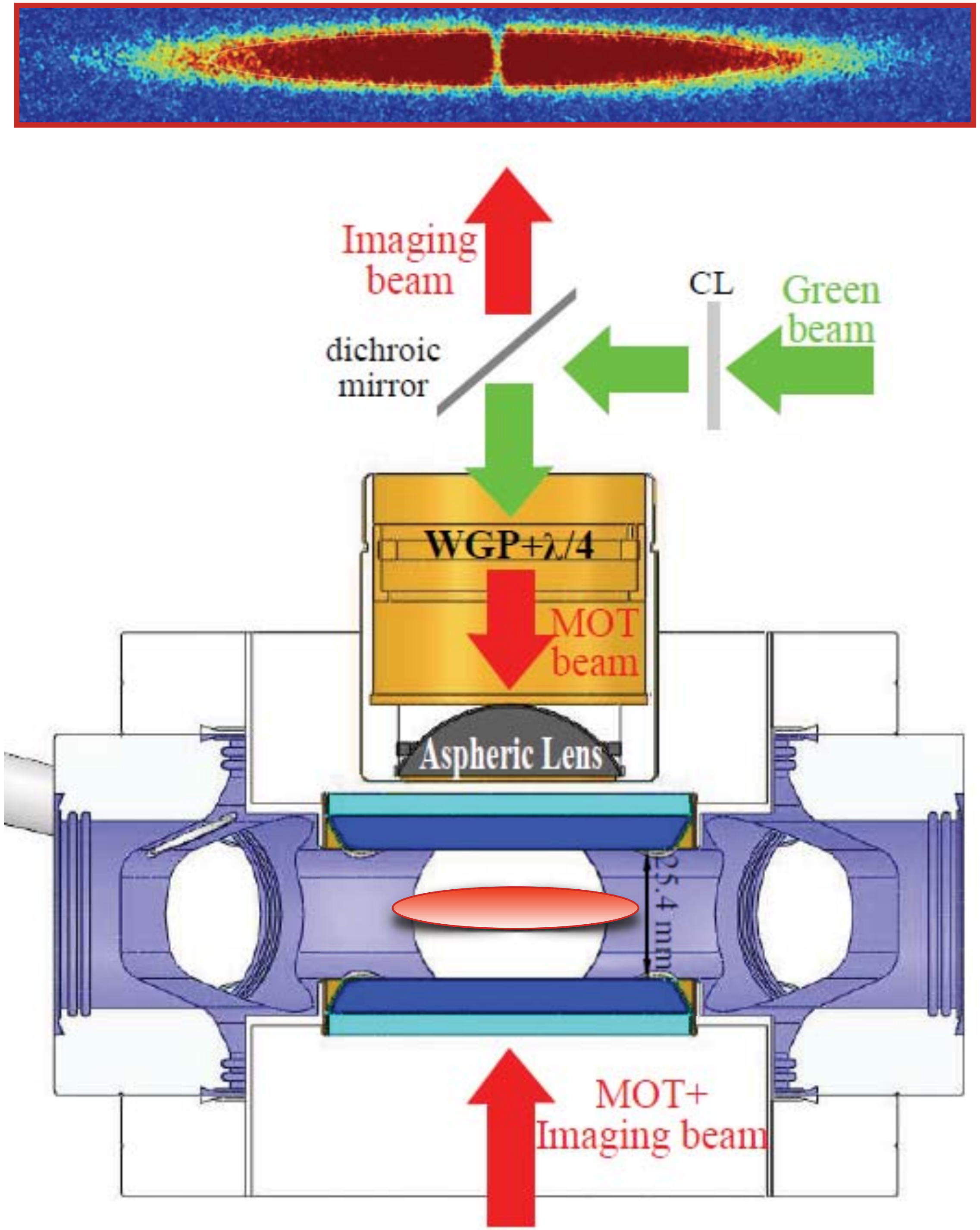


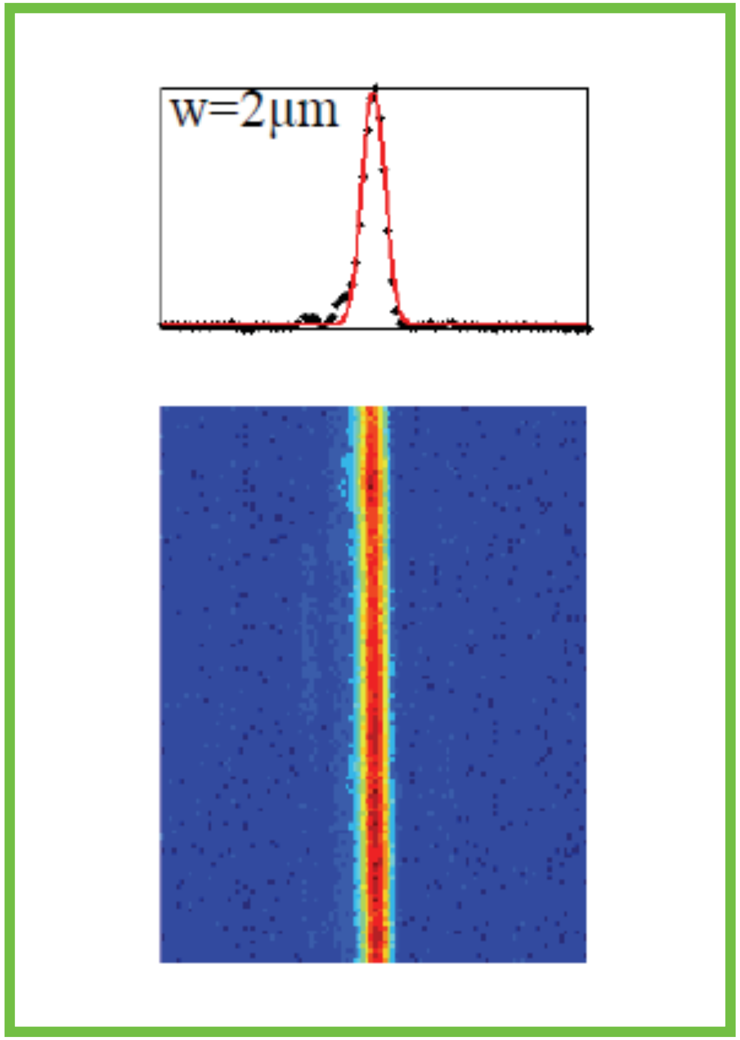
A. Burchianti et al. PRA 90, 043408 (2014)



A. Burchianti et al. PRA 90, 043408 (2014)

M. Ku et al. Science 335, 563 (2012).

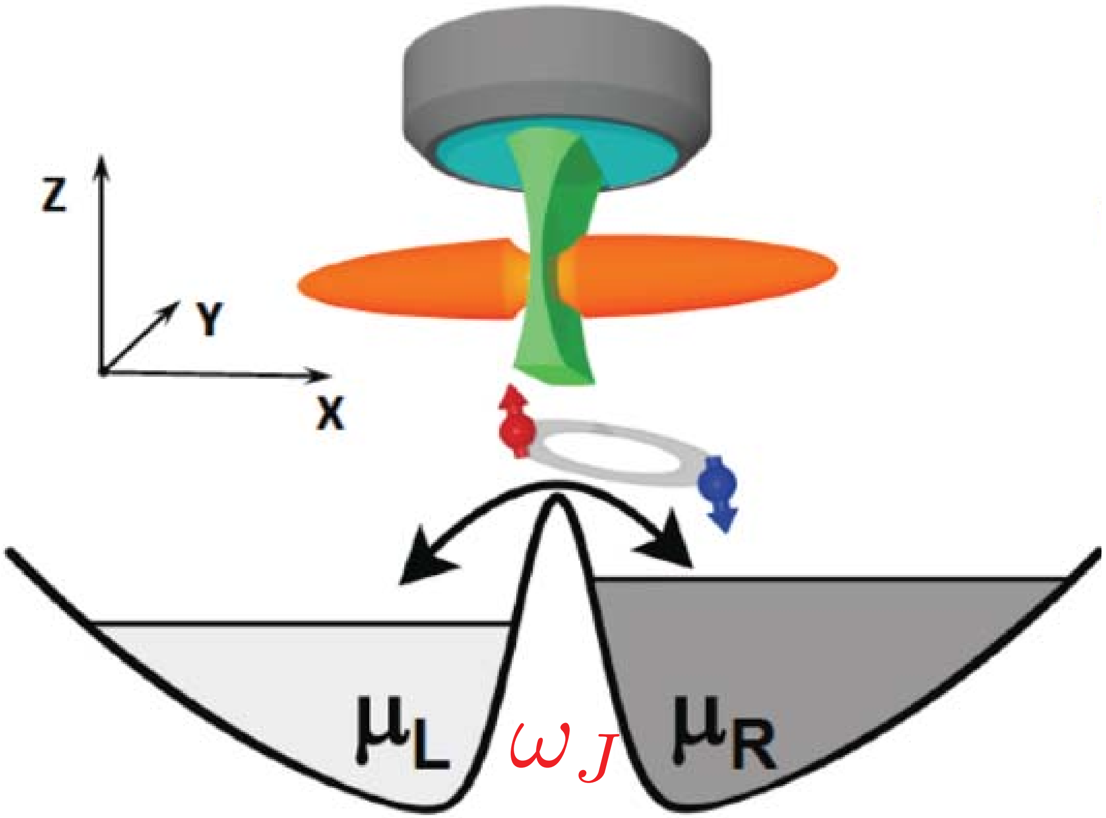




Imaging resolution at 670 nm: 1.4 μm

A. Morales, Master Thesis. Lithium group 2013

The observables



The relevant energy scales

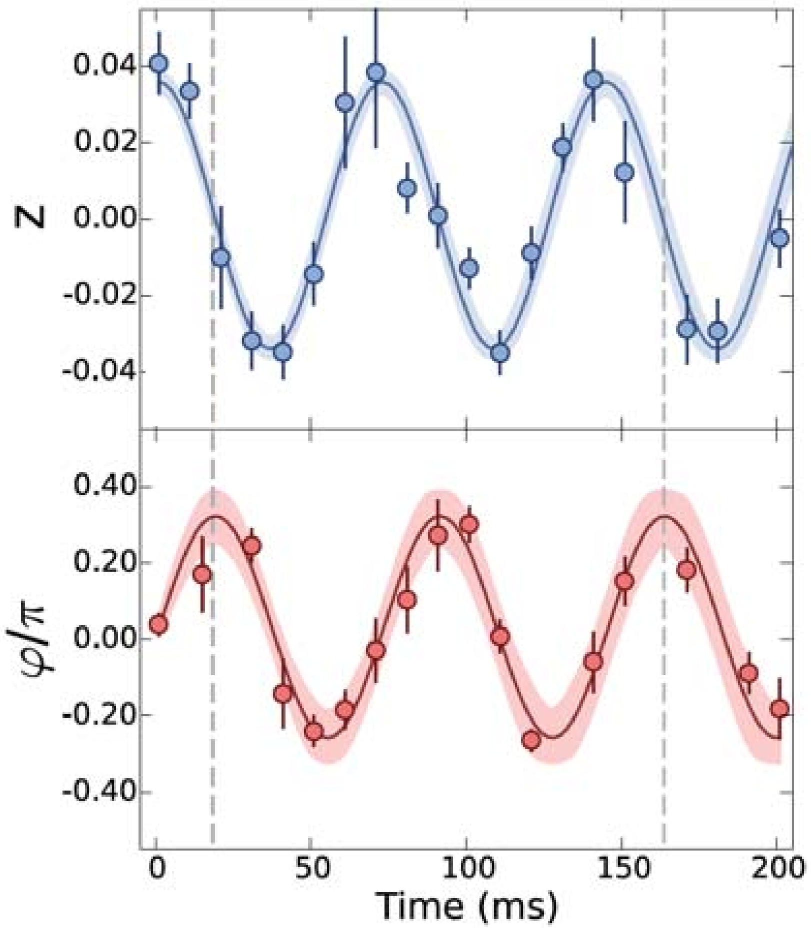
$$\omega_J = \frac{1}{\hbar}\sqrt{E_C E_J}$$

$E_C =$ Charging energy: localization energy "against" tunneling

$E_J =$ Josephson coupling energy: connection superfluids phases

$E_J > k_B T$ Phase coherence wins against thermal fluctuations

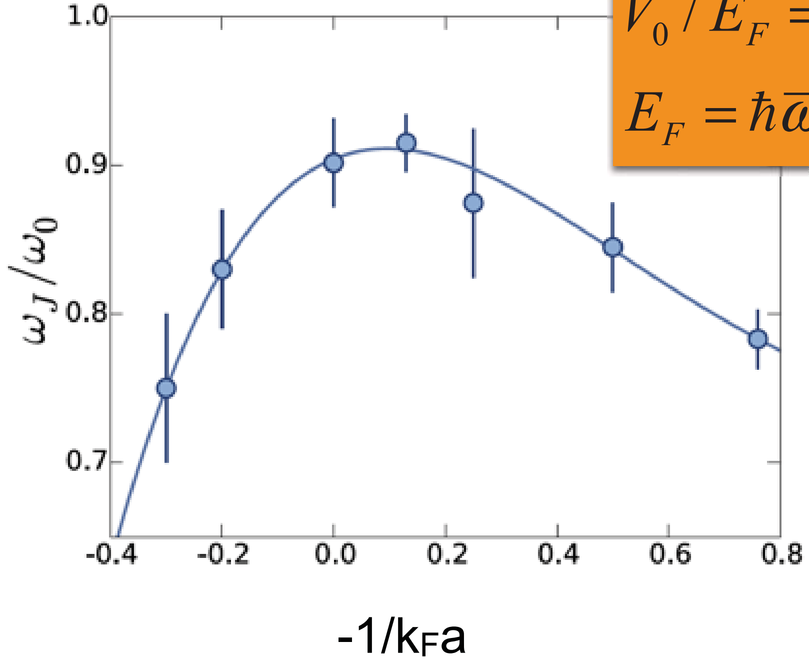
$E_J > E_C$ Phase coherence exists between the 2 superfluids mBEC: bosonic superfluid



z_0=3% & V_0/E_F =1.2

Conjugate dynamics (shift π/2) of $z \sim N_L - N_R$ and $\varphi = \varphi_L - \varphi_R$

G. Valtolina et al., Science in press



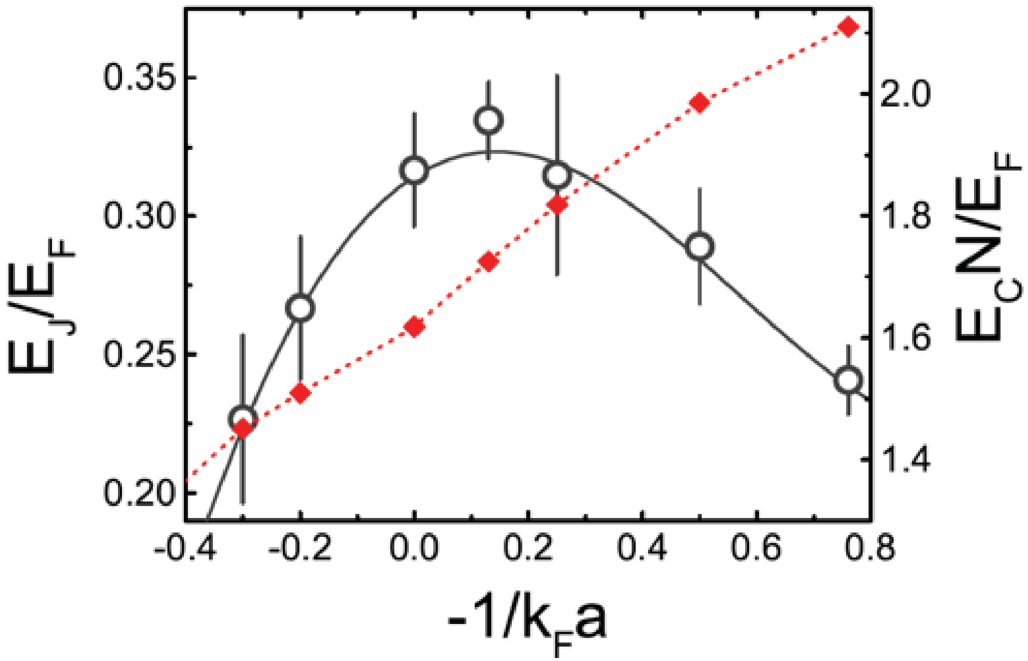
$V_0 / E_F = 1.2$

$E_F = \hbar\overline{\omega} \cdot (6N)^{1/3}$

$$\omega_J = \sqrt{E_C E_J}$$

$$E_c \approx \frac{\partial \mu}{\partial n}$$

$$\Rightarrow E_J = \frac{\omega_J^2}{E_C}$$



$$K = K(\mu, V_0, w)$$

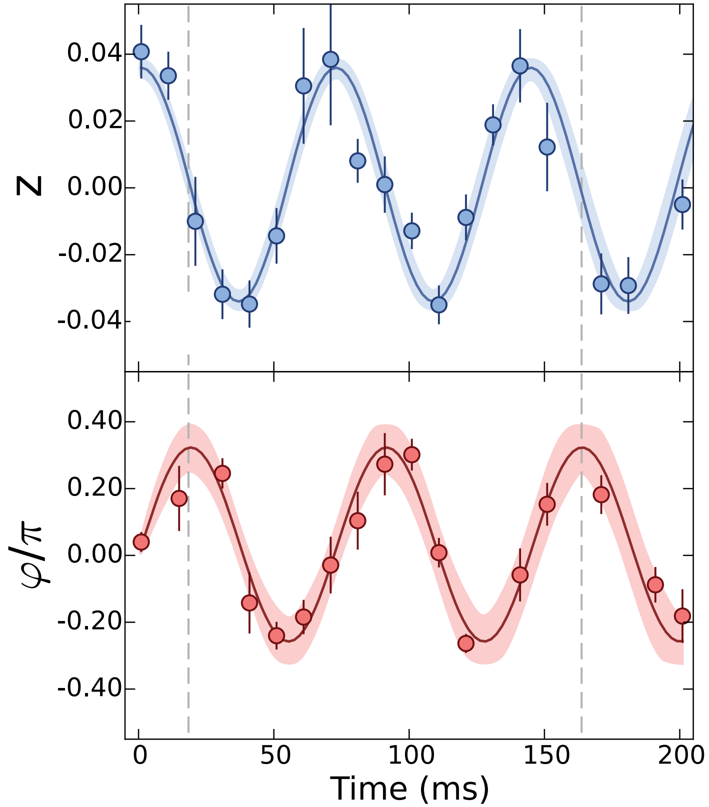
$$E_J \approx K \cdot N_0$$

$$BEC : N_0 = N$$

$$BCS : N_0 / N \propto \frac{\Delta}{E_F}$$

Ambegaokar-Baratoff @ T=0

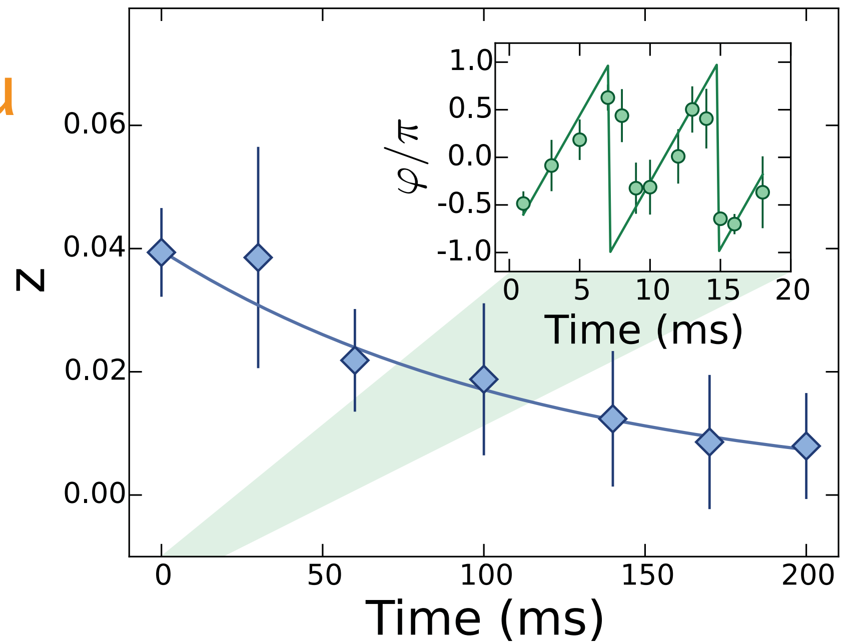
G.Valtolina et al., Science in press



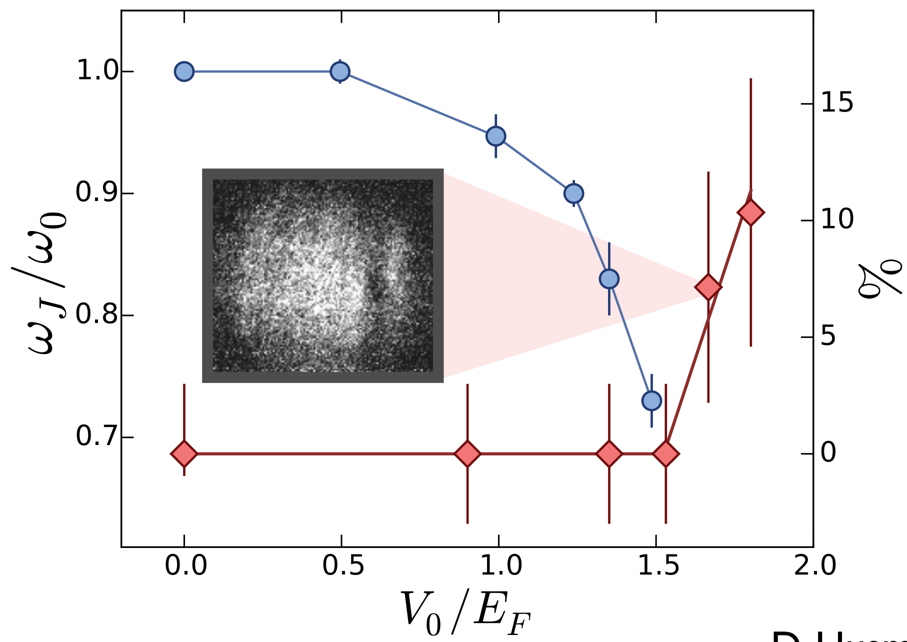
Increasing Δμ or V_0/μ

$$\omega_{ps} \sim \Delta\mu/\hbar \qquad \varphi(t) \sim E_C z_0 N t$$

⇒

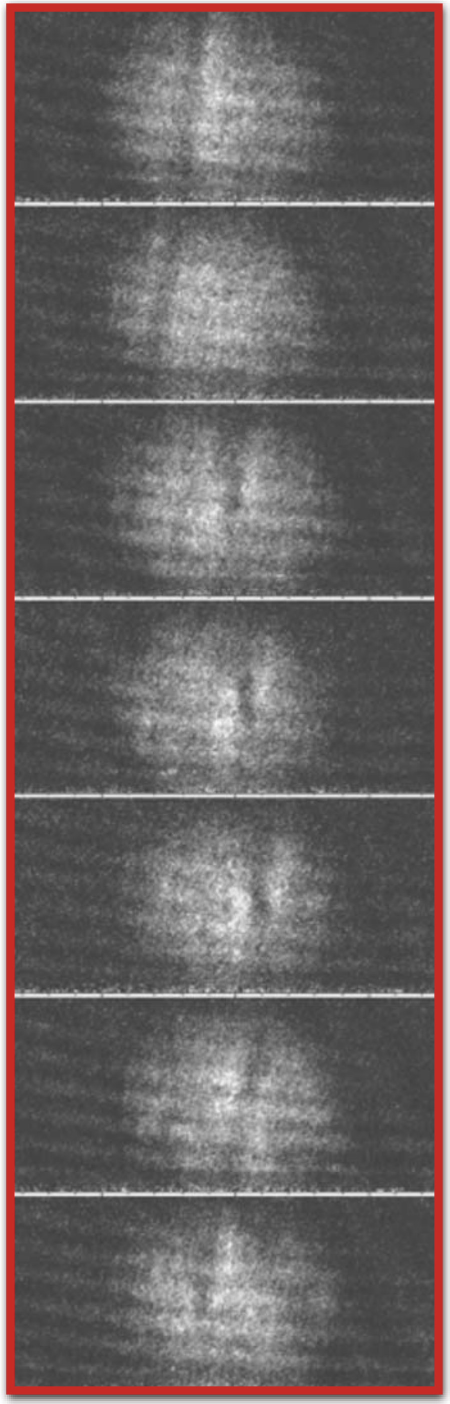


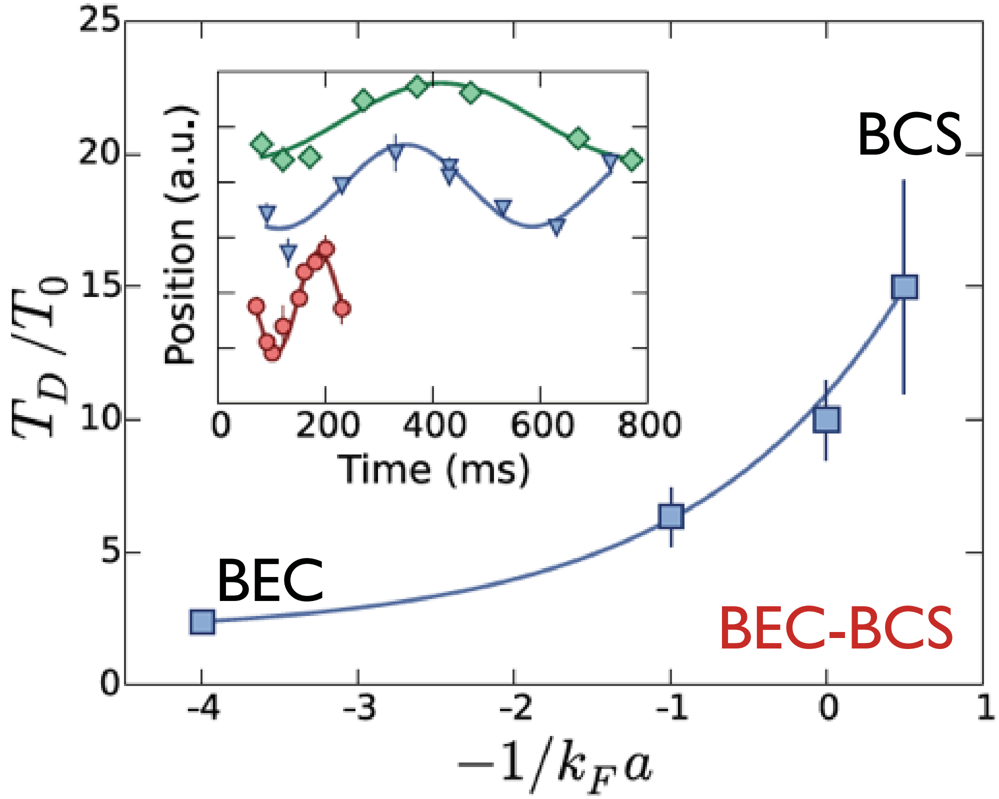
⇓



G. Valtolina et al., Science in press

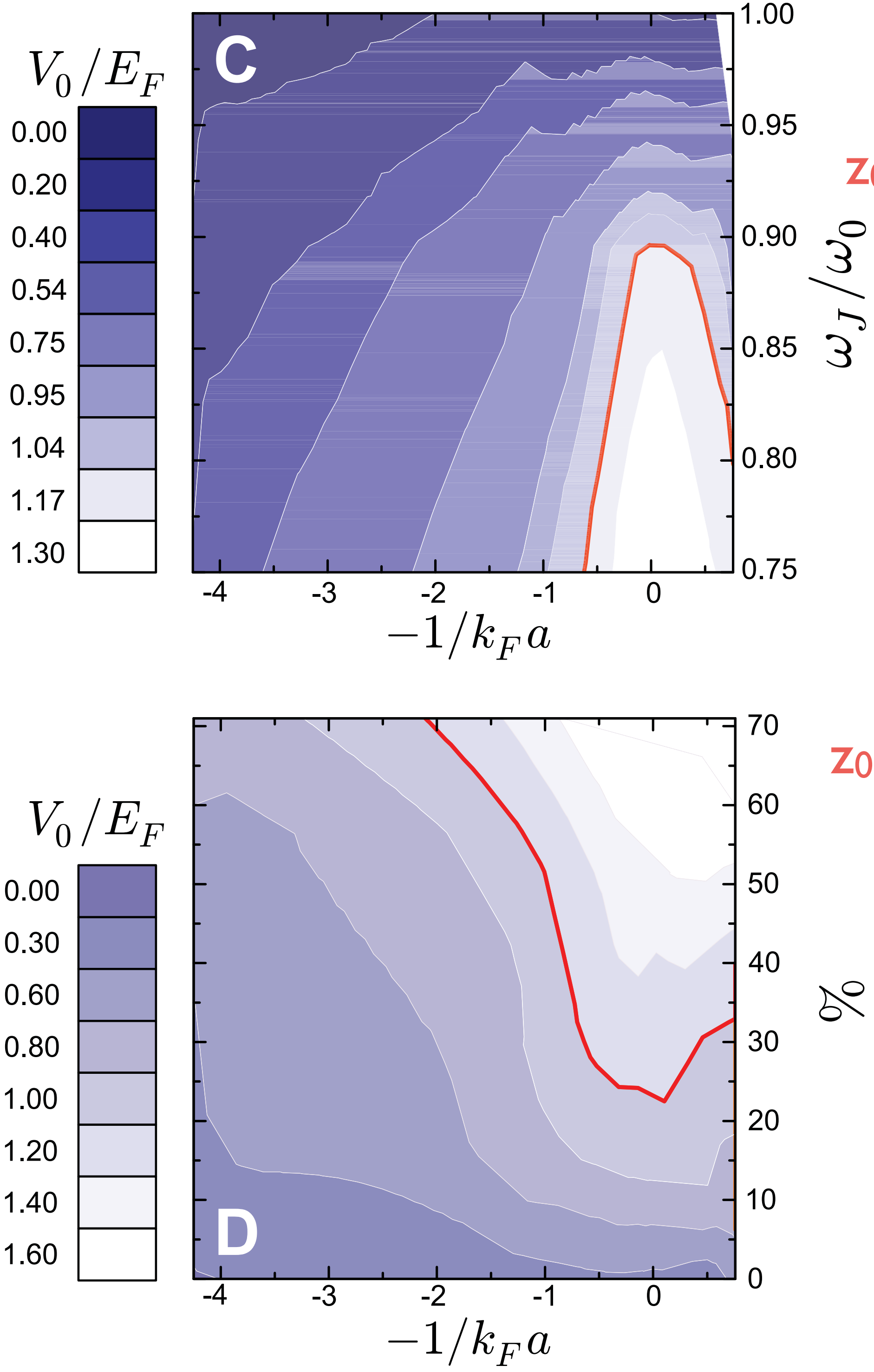
D. Husmann et al. arXiv:1508.00578 (2015).





Similar to soliton vortices observed in fermionic superfluids via phase-imprinting and in BEC via KZ mechanism.

T. Yefsah, et al. Nature **499,** 426, (2013).
G. Lamporesi et al. Nature Physics 9, 656, (2013) .



z_0=3%

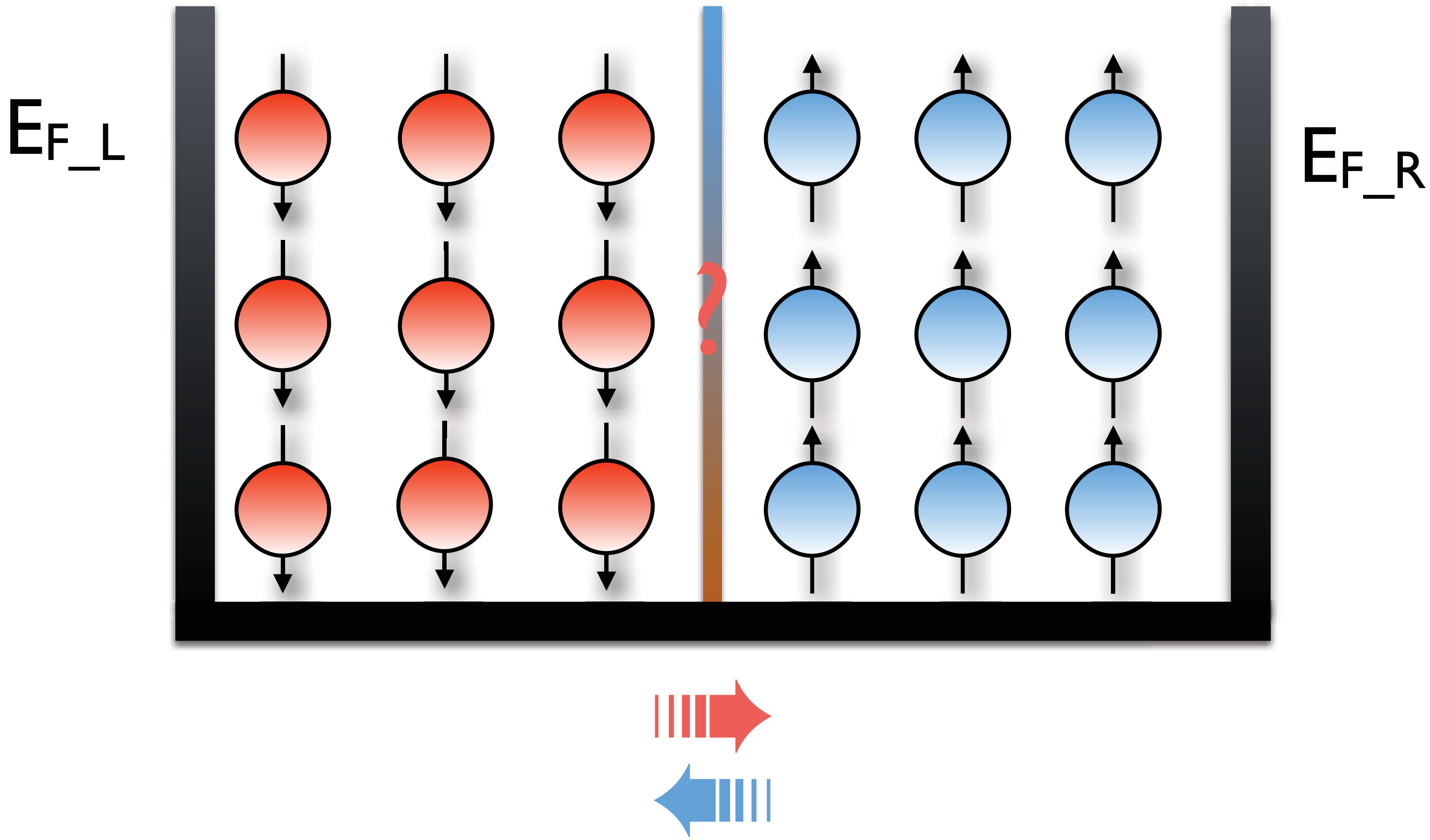
z_0=12%

V_0/E_F=1.2

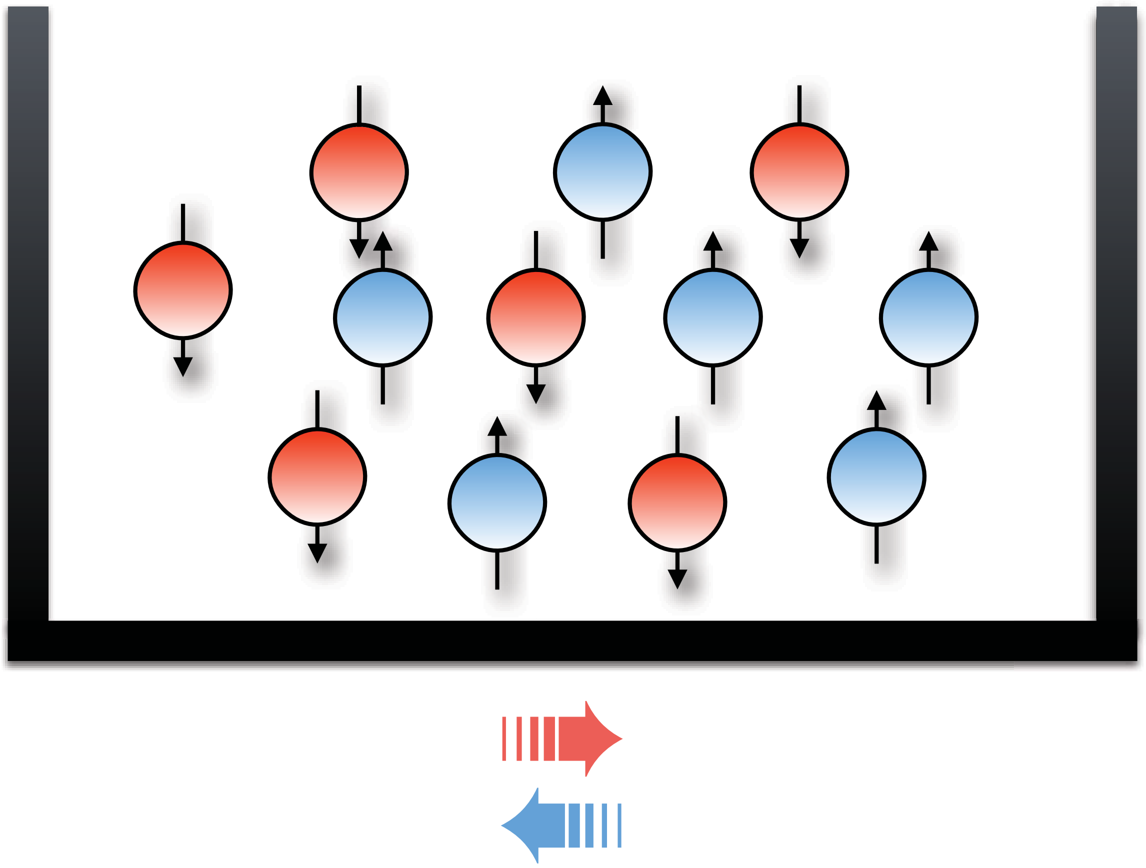
Reluctance of the crossover SF to vortices formation

G.Valtolina et al., Science in press

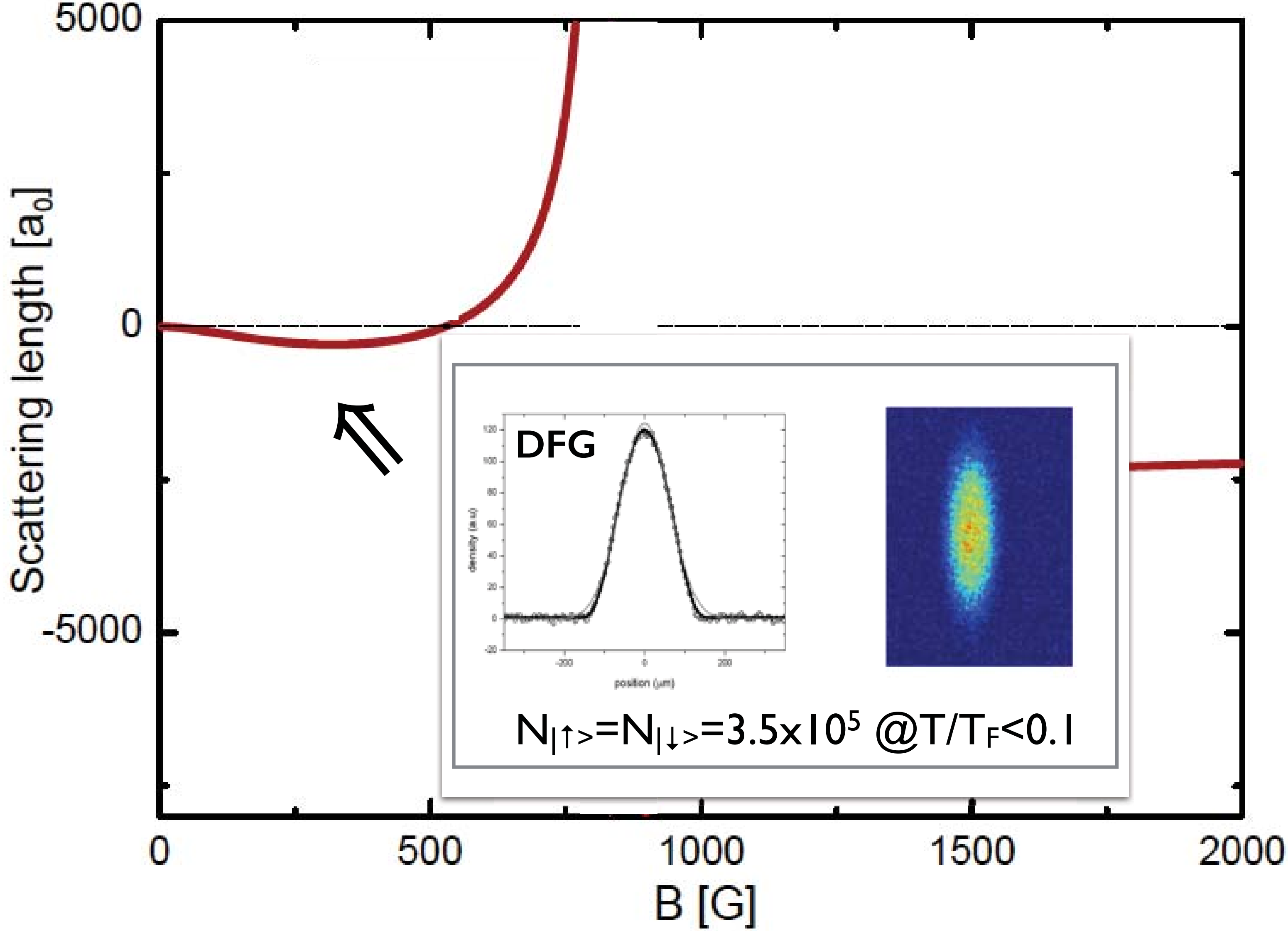
SCENARIO #2: spin diffusion with resonant interactions



SCENARIO #2: spin diffusion with resonant interactions



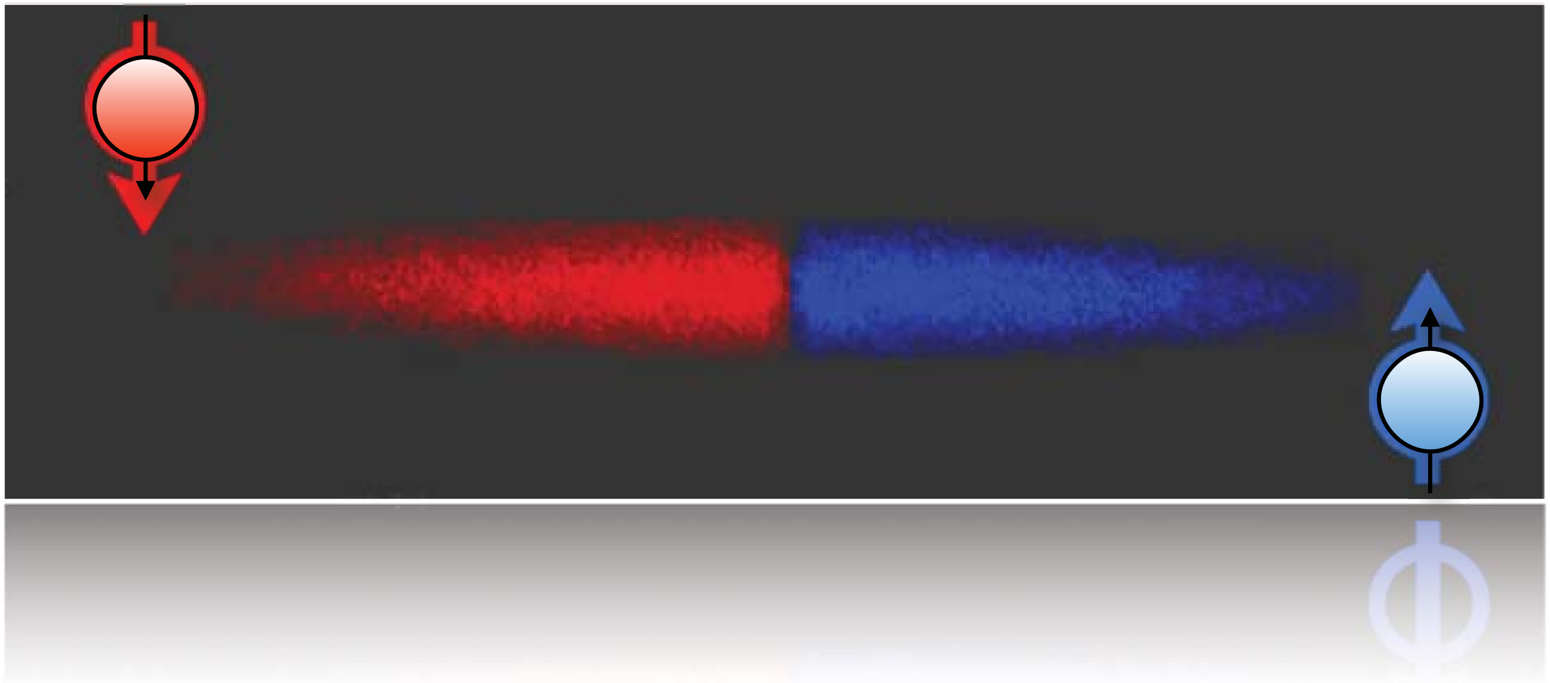
to a paramagnetic state?

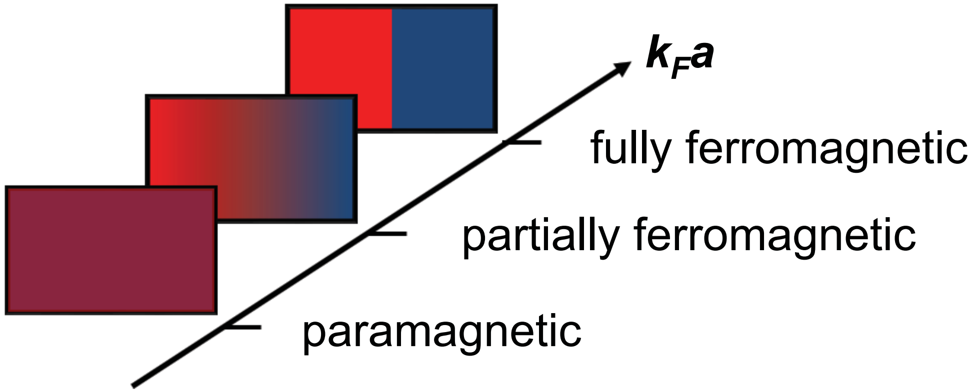


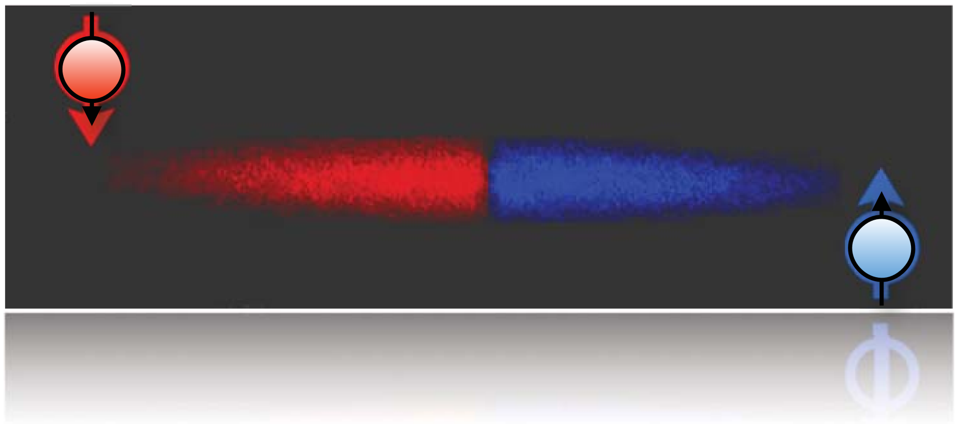
A. Burchianti et al. PRA 90, 043408 (2014)

WORK IN PROGRESS

Our initial state:
an "artificial" ferromagnet

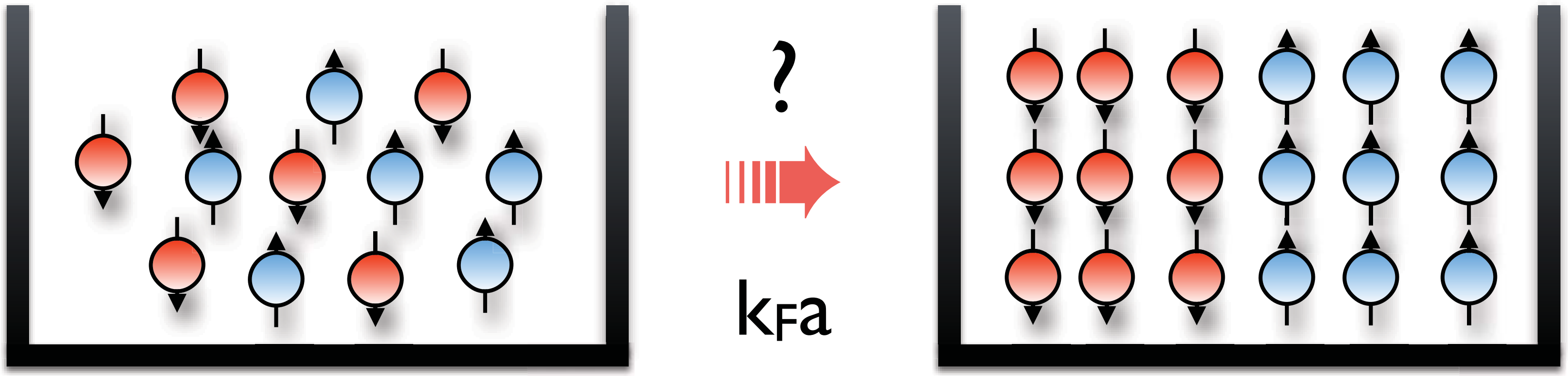






Short-range ***repulsion***: kinetic vs interaction energies:

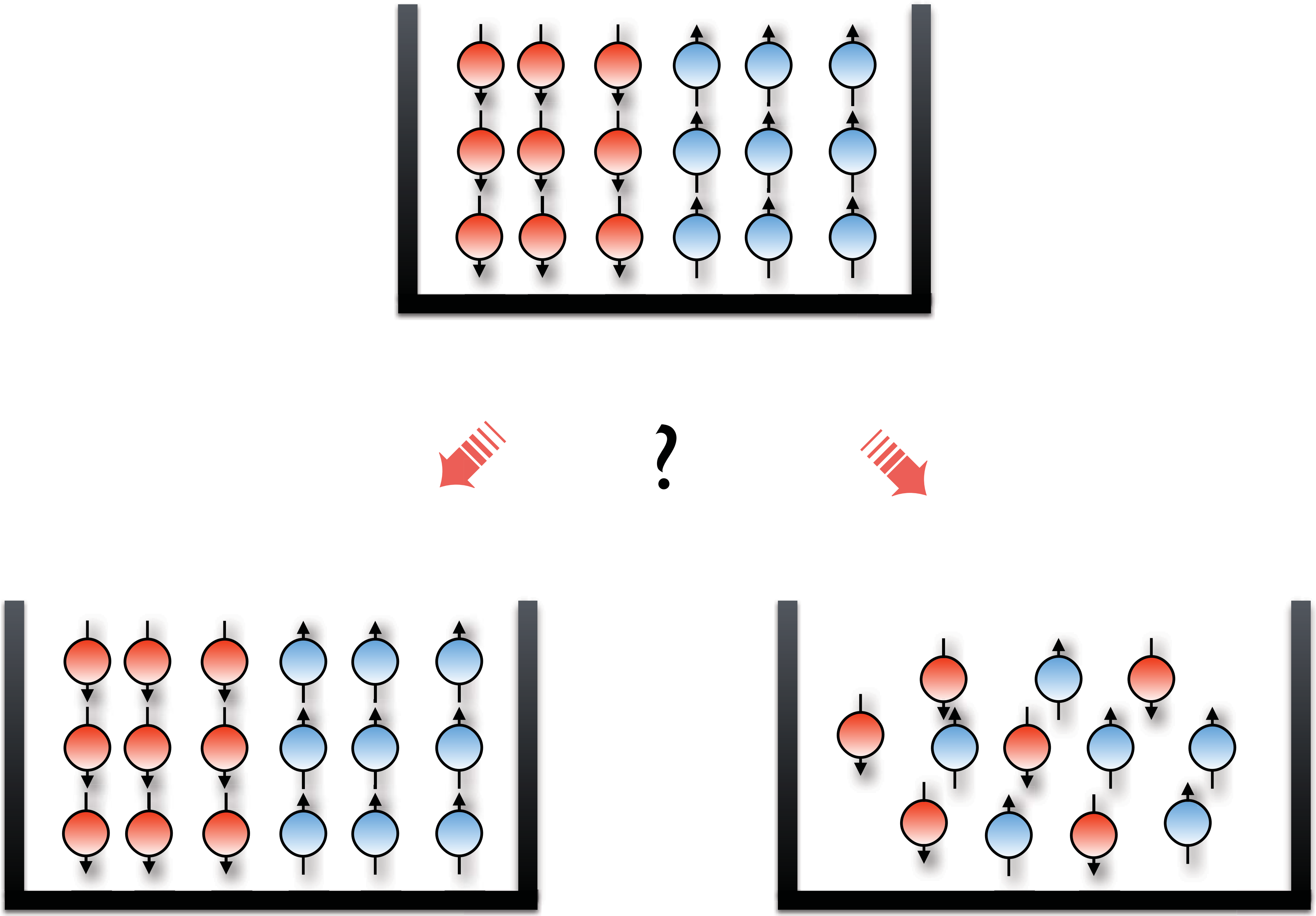
1. **minimal model for magnetism of delocalised fermions (Stoner '33)**



G.-B. Jo *et al*, Science, **325**, 1521 (2009)

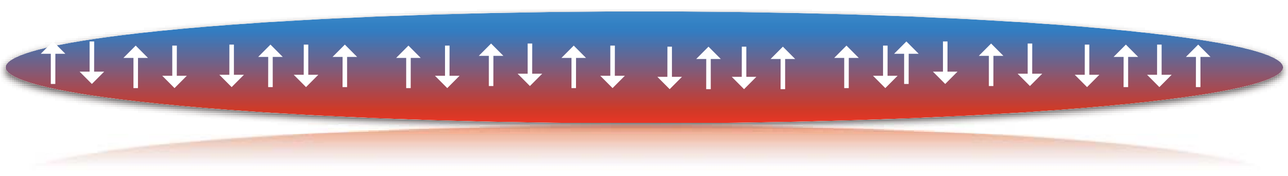
Short-range ***interactions***: kinetic vs interaction energies:

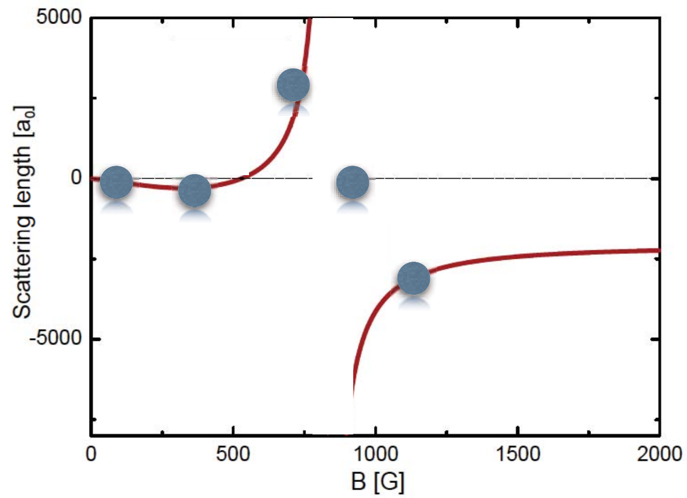
2. textbook spintronic experiments with controllable spins



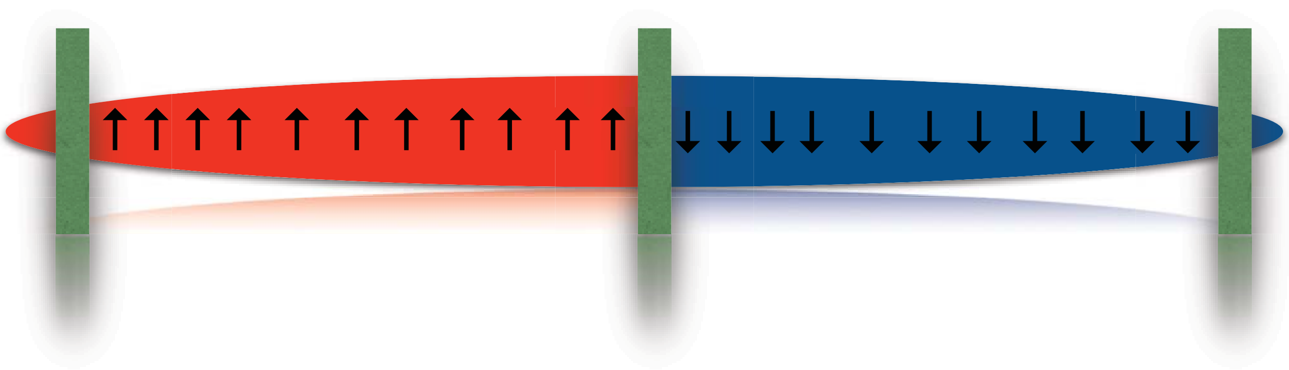
Sample preparation

Starting point. Paramagnetic state: degenerate Fermi gases

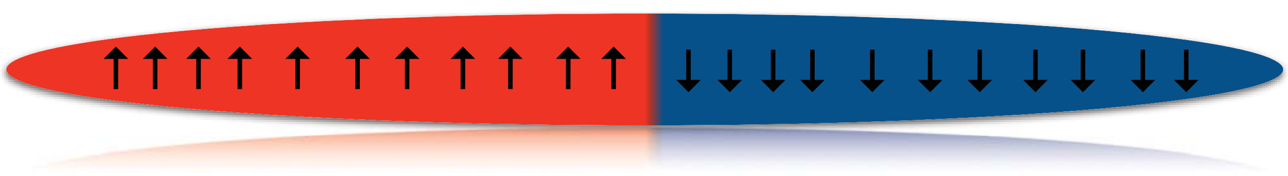


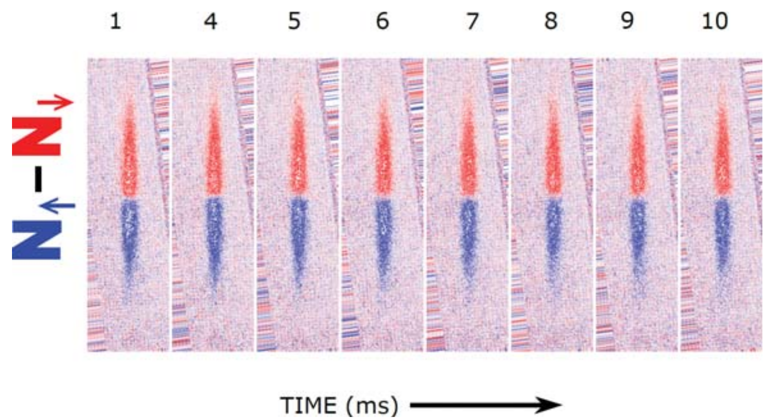


Magnetic field gradient at 2 G

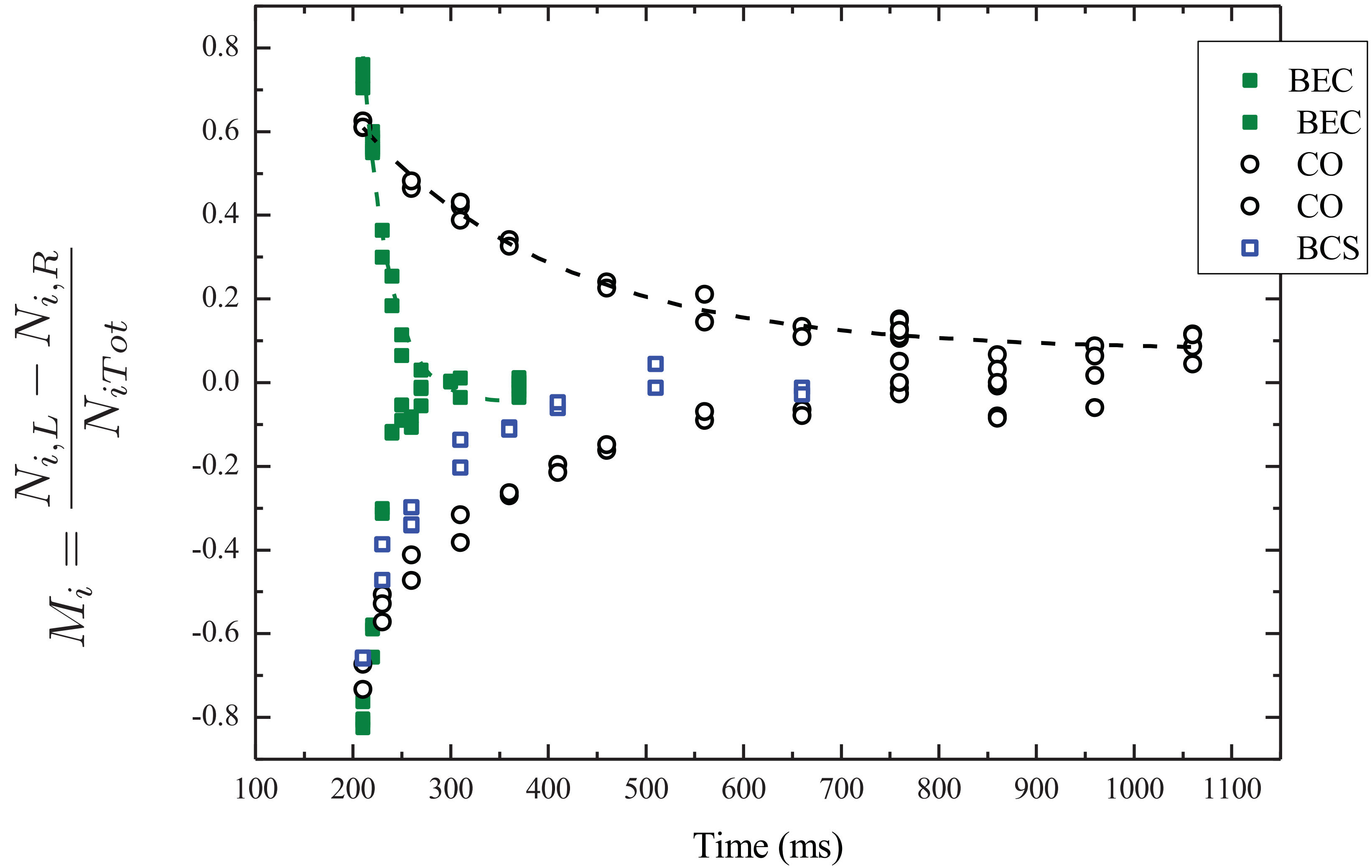


Dynamics across the BEC-BCS crossover





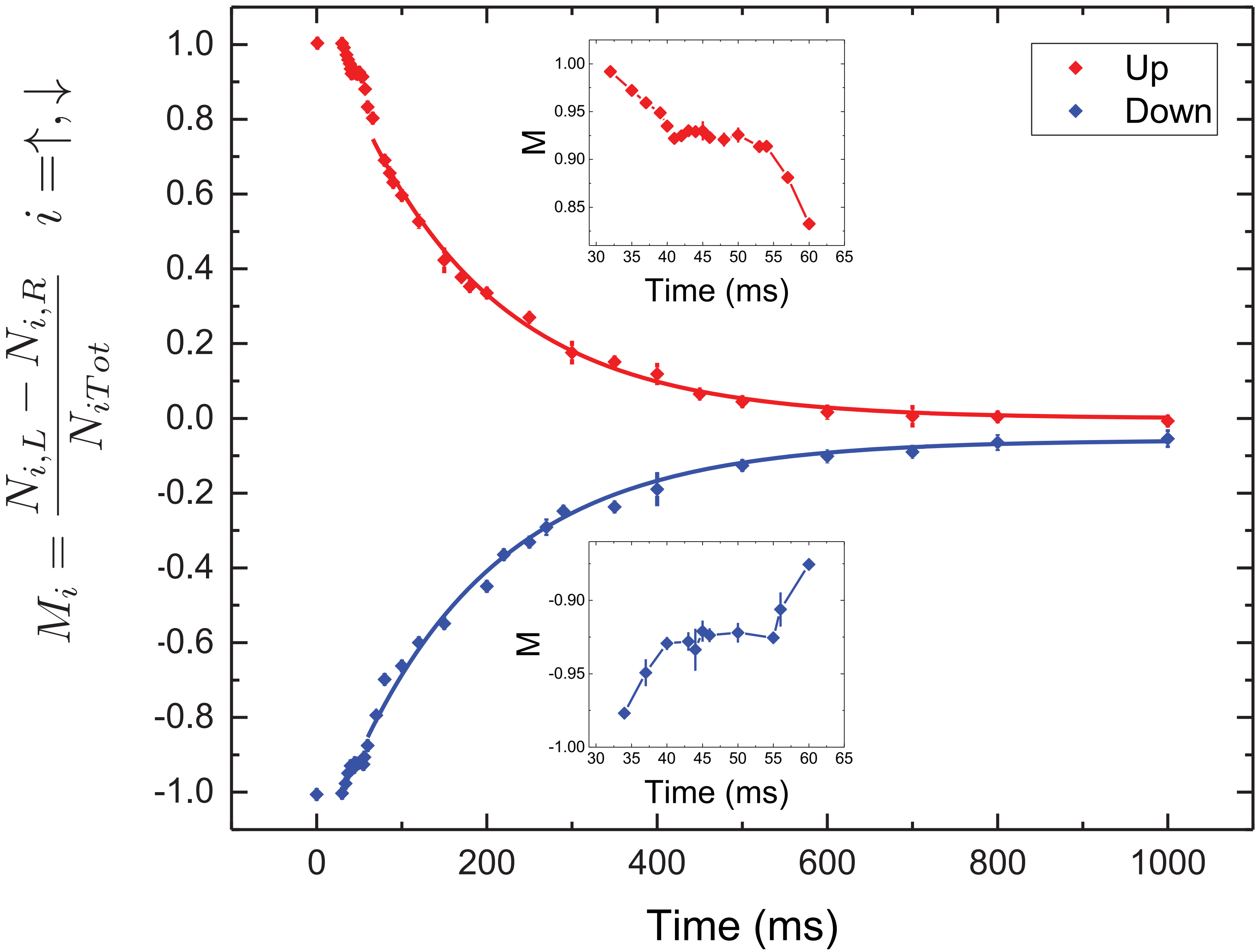
$T/T_F < 0.1$

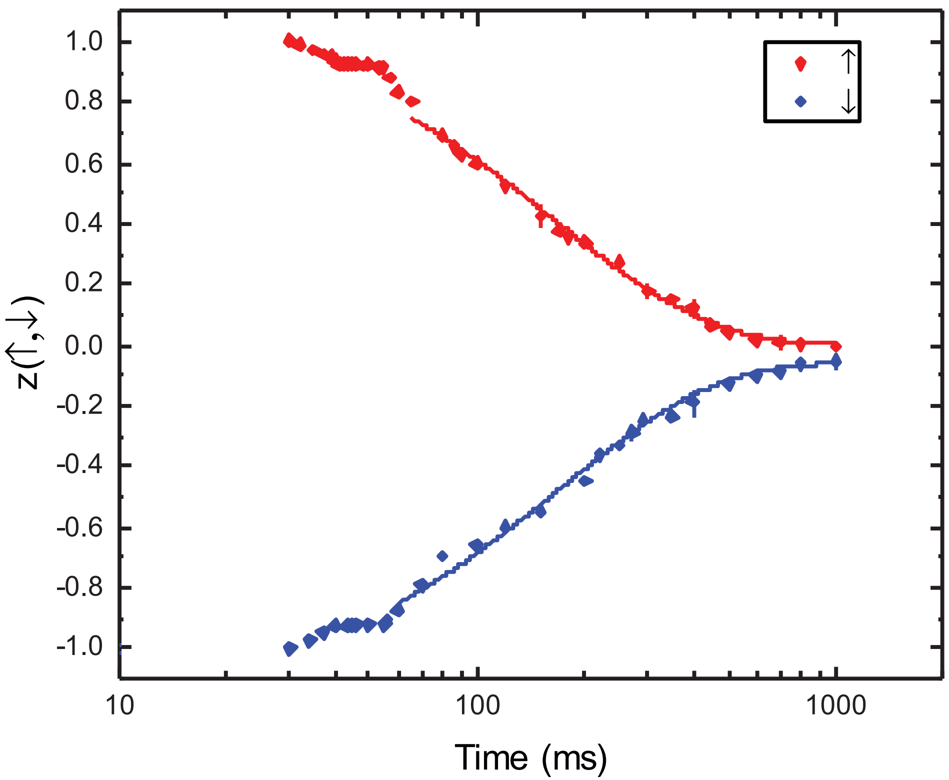


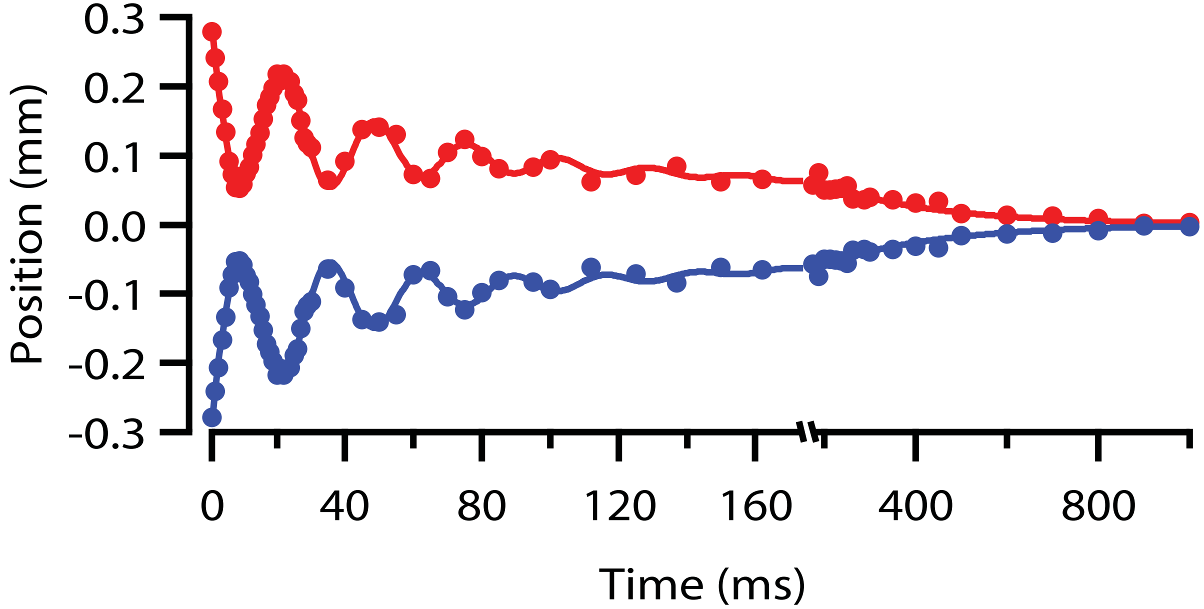
$M_i = \frac{N_{i,L} - N_{i,R}}{N_{iTot}}$
0.8
0.6
0.4
0.2
0.0
-0.2
-0.4
-0.6
-0.8
100
200
300
400
500
600
700
800
900
1000
1100
Time (ms)
BEC
BEC
CO
CO
BCS

$T/T_F < 0.1$

$1/k_F a \sim 0$







A. Sommer, M. Ku, G. Roati and M. Zwierlein, Nature, 427, 201 (2011).

Conclusions and Perspectives (I)

1. Thin optical barrier on superfluids (& degenerate Fermi gases) across the BEC-BCS crossover: interesting platform to study superfluidity and spin diffusion…

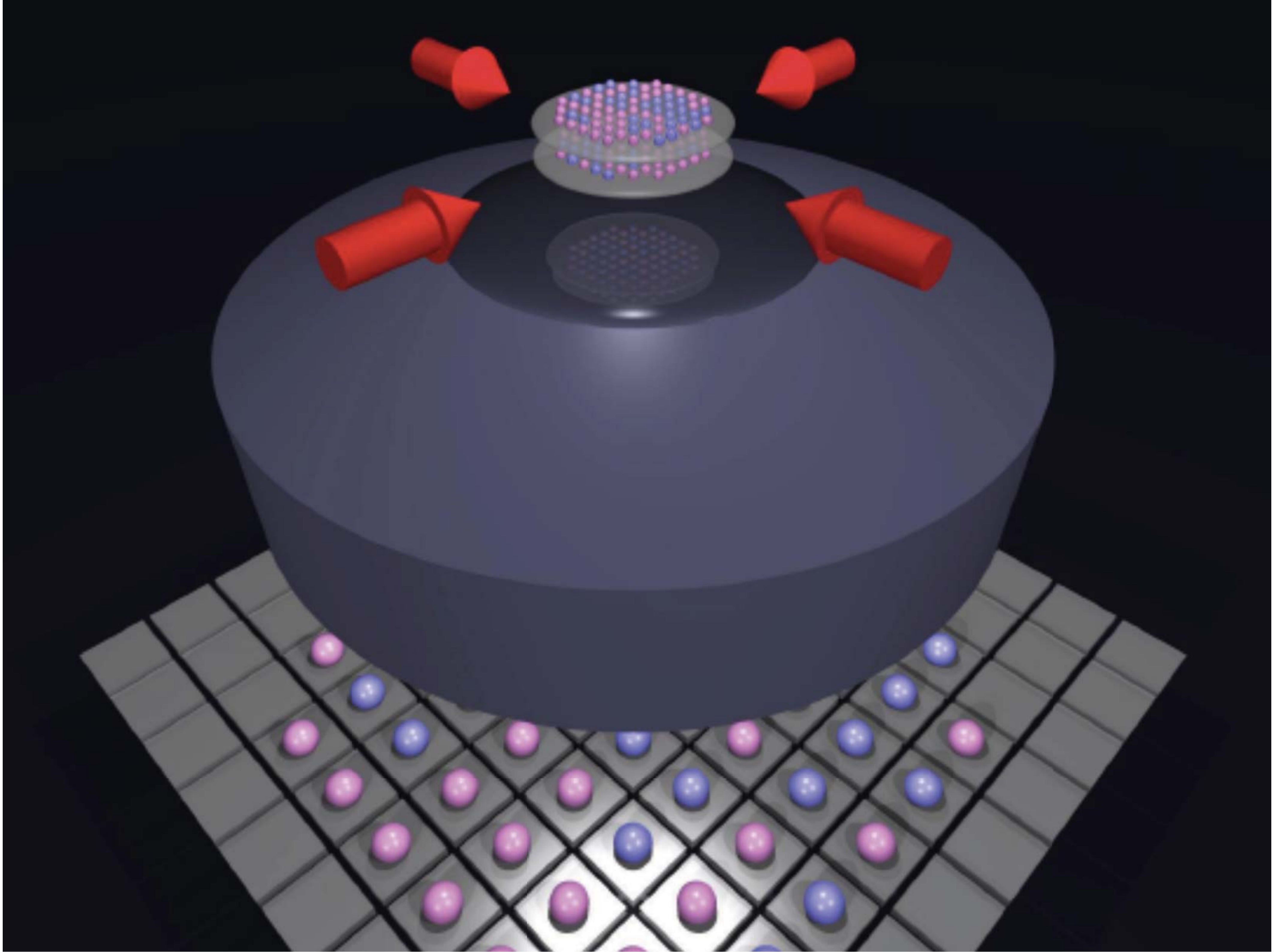
2. Coherent and dissipative dynamics: bosonic SF and fermionic SF

3. Spin-diffusion: anomalous (relevant) behavior?

4. Role of vortices in quenching coherent dynamics.

5. Tunneling of… vortices through the barrier: interesting or simply foolish ?

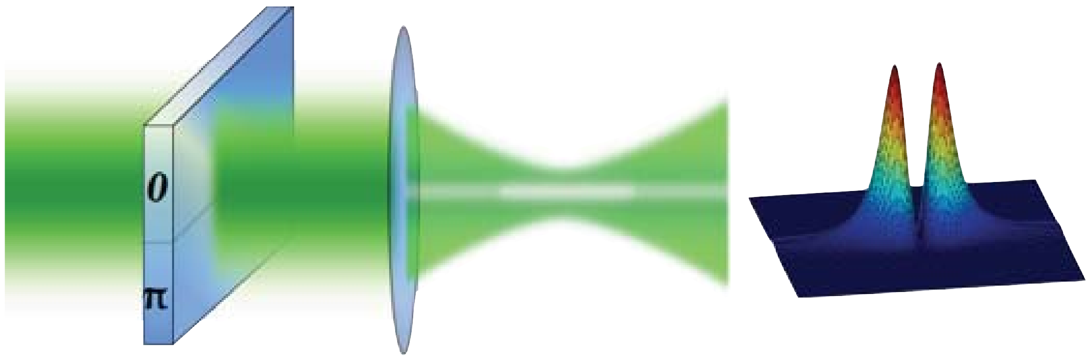
6. Ferromagnetic state (Stoner model): metastability (polaron physics) ??

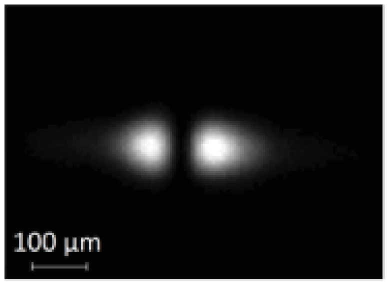


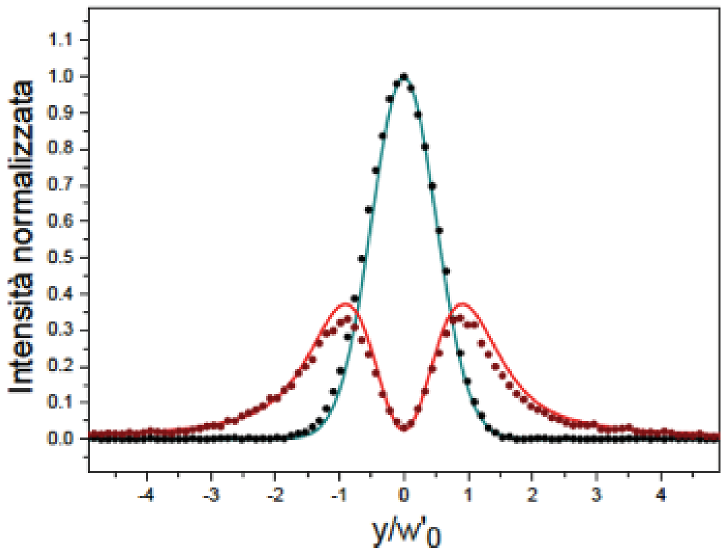
How to reach the 2D regime (Florence approach)?

$\hbar\omega_z \quad >> k_B T \, , E_F$

Holographic phase-plate: TEM_{01} laser mode: single layer.







A. Amico, Master Thesis (2012)

QuFerm2D (2012/2017)

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