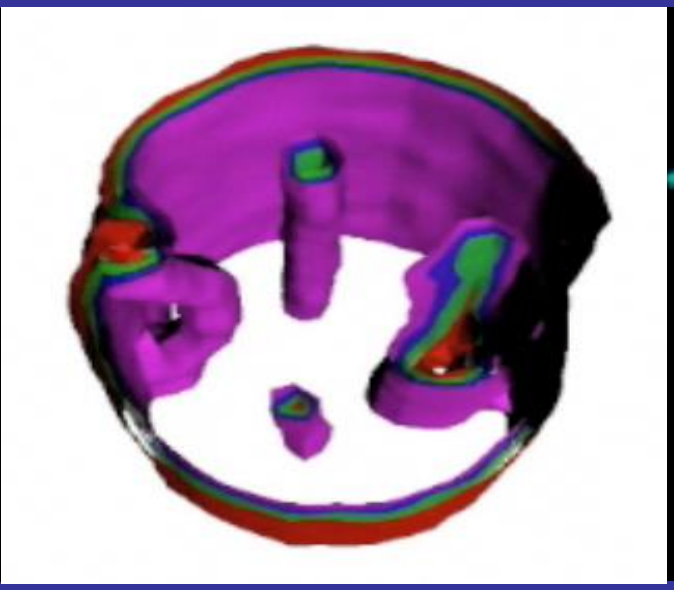
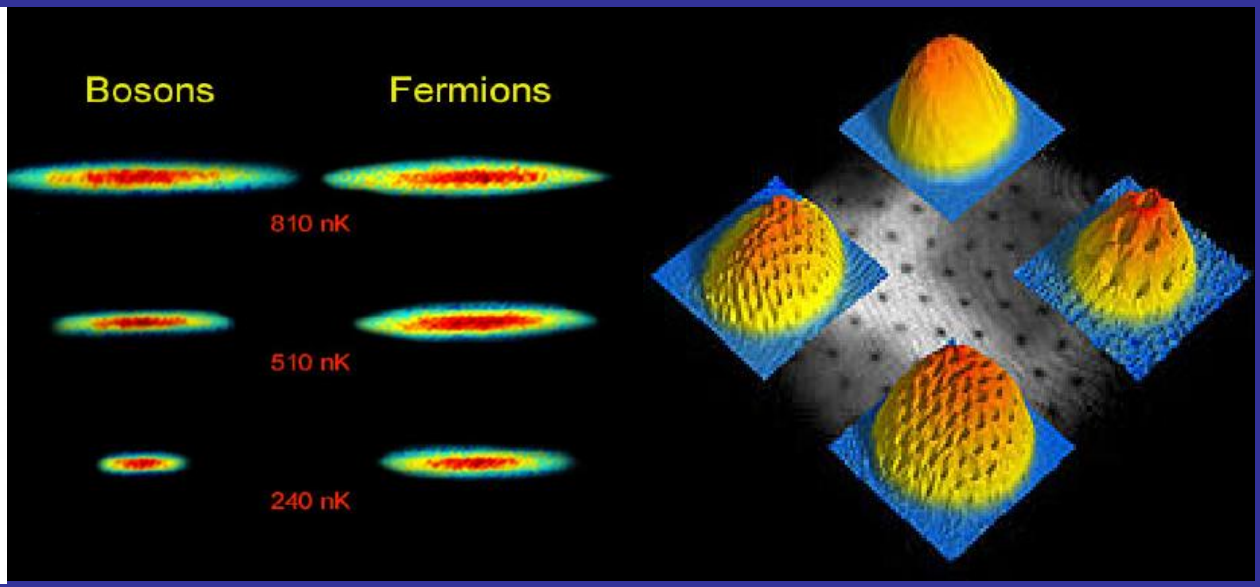
# Equilibrium and nonequilibrium properties of unitary Fermi gas



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## What is a unitary gas?

A gas of interacting fermions is in the unitary regime if the average separation between particles is large compared to their size (range of interaction), but small compared to their scattering length.

$n\, r_0^3 \ll 1$ | $n\, |a|^3 \gg 1$

n - particle density
a - scattering length
$r_0$ - effective range

i.e. $r_0 \to 0, a \to \pm\infty$ ← **NONPERTURBATIVE REGIME**

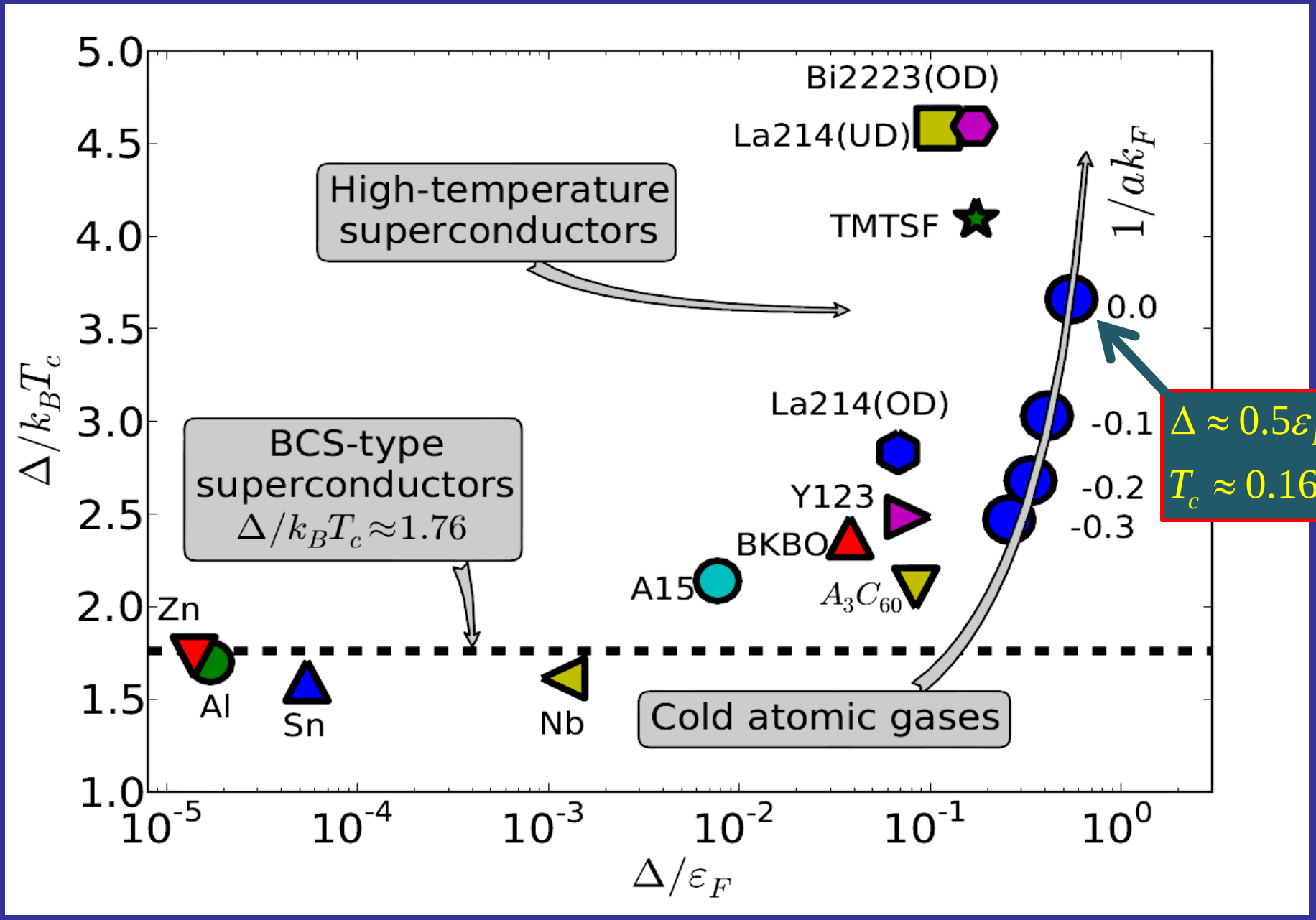
**System is dilute but strongly interacting!**

**Universality:** $E(x) = \xi(x) E_{FG}$ ; $x = T/\varepsilon_F$

$\xi(0) = 0.37(1)$ - **Exp. estimate**

$E_{FG}$ - **Energy of noninteracting Fermi gas**

# Cold atomic gases and high Tc superconductors




From Fischer et al., Rev. Mod. Phys. 79, 353 (2007) & P. Magierski, G. Wlazłowski, A. Bulgac, Phys. Rev. Lett. 107, 145304 (2011)

# Expected phases of a two species dilute Fermi system
# BCS-BEC crossover

T

Characteristic temperature:
$T_C$ superfluid-normal phase transition

Characteristic temperatures:
$T_C$ superfluid-normal phase transition
$T^*$ break up of Bose molecule
$T^* > T_C$

**Strong interaction**
**UNITARY REGIME**

**weak interaction**

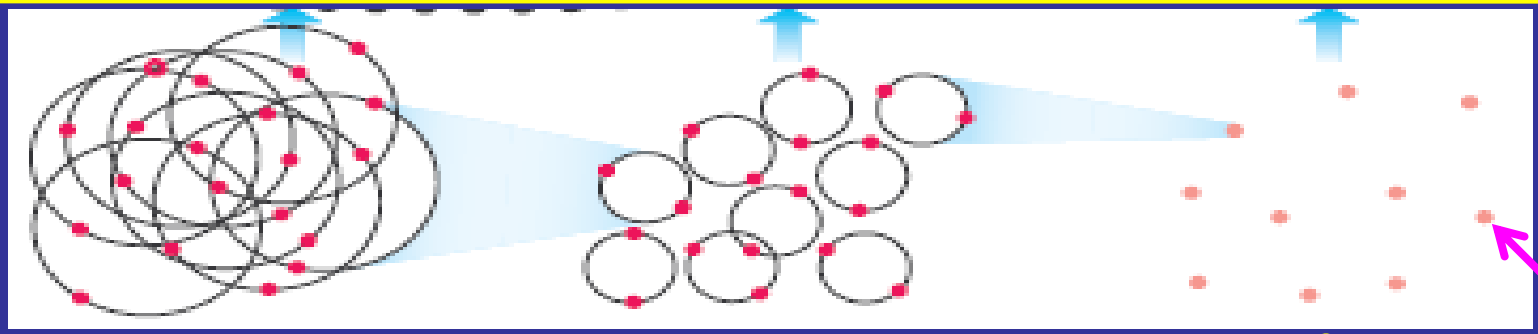
**?**

**weak interactions**

**Molecular BEC and Atomic+Molecular Superfluids**

**BCS Superfluid**

1/a




**a<0**
**no 2-body bound state**

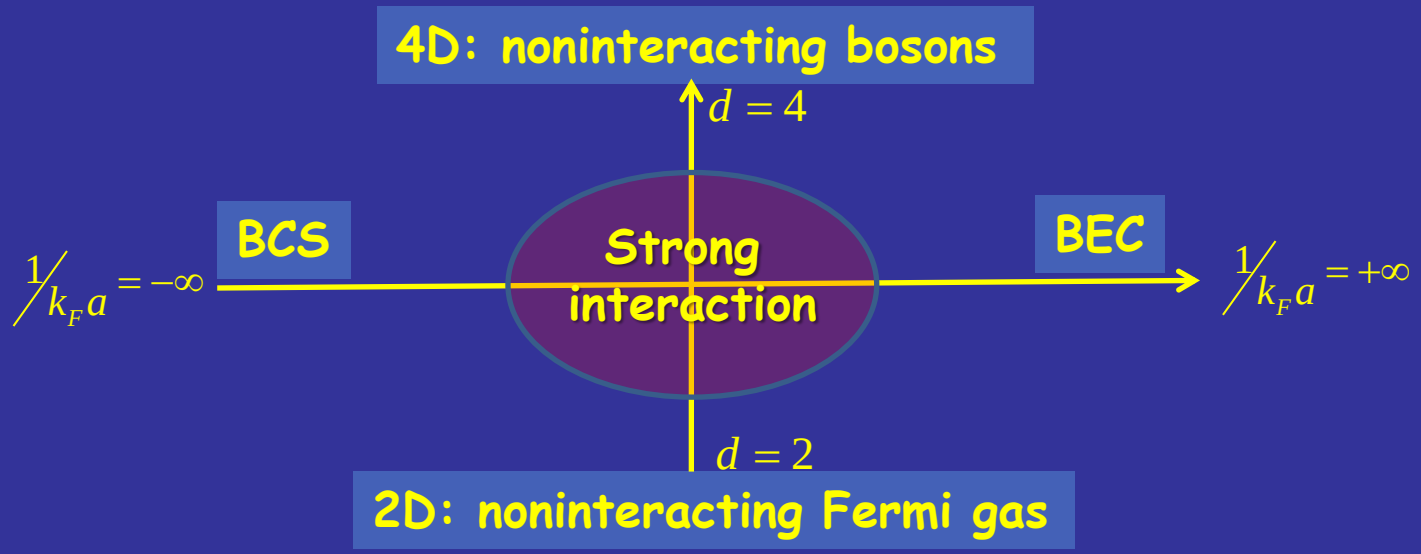
**a>0**
**shallow 2-body bound state**

# Unitary limit in 2 and 4 dimensions:

$$a \to \infty: \; R(r) \propto \frac{1}{r^{d-2}} + O(r^{4-d}), \quad \textit{Two body wave function for } r \to 0.$$

**Intuitive arguments:**

- For d=4 $\int R(r)^2 d^d r$ diverges at the origin
- For d=2 the singularity of the wave function disappears = interaction also disappears.




***The only nontrivial case of unitary regime is in 3D***

Nussinov,Nussinov, Phys.Rev. A74, 053622(2006)

# Effective Hamiltonian of an atom-atom system

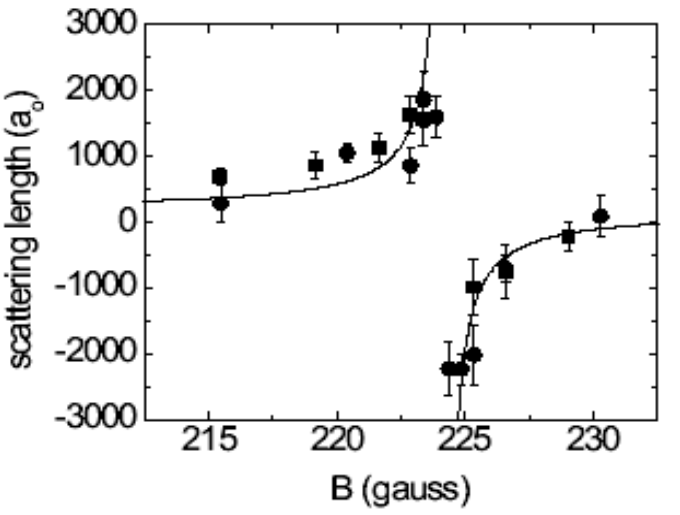
$$H = \frac{\vec{p}^2}{2\mu} + \sum_{i=1}^{2}(V_i^{hf} + V_i^{Z}) + V_0(\vec{r})P_0 + V_1(\vec{r})P_1 + \ldots$$

$$V^{hf} = \frac{a_{hf}}{\hbar^2}\vec{I}\cdot\vec{J},\ V_i - \text{Coulomb term}$$

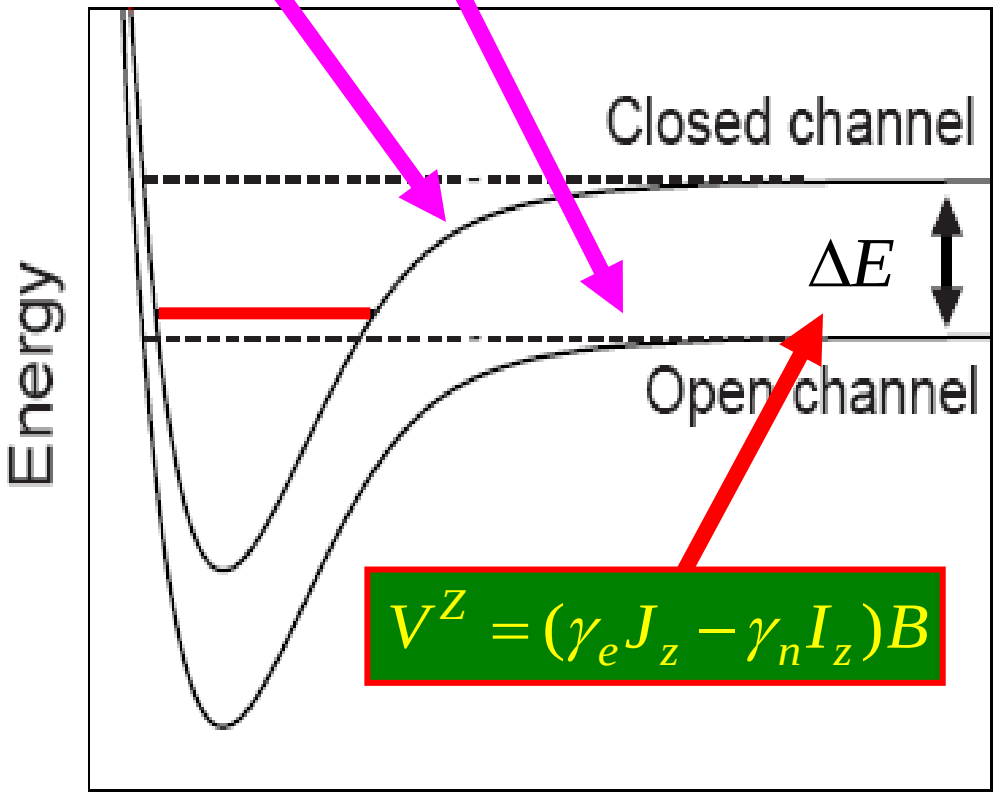
Tiesinga, Verhaar, Stoof, Phys. Rev. A**47**, 4114 (1993)

**Channel coupling**

**Feshbach resonance**

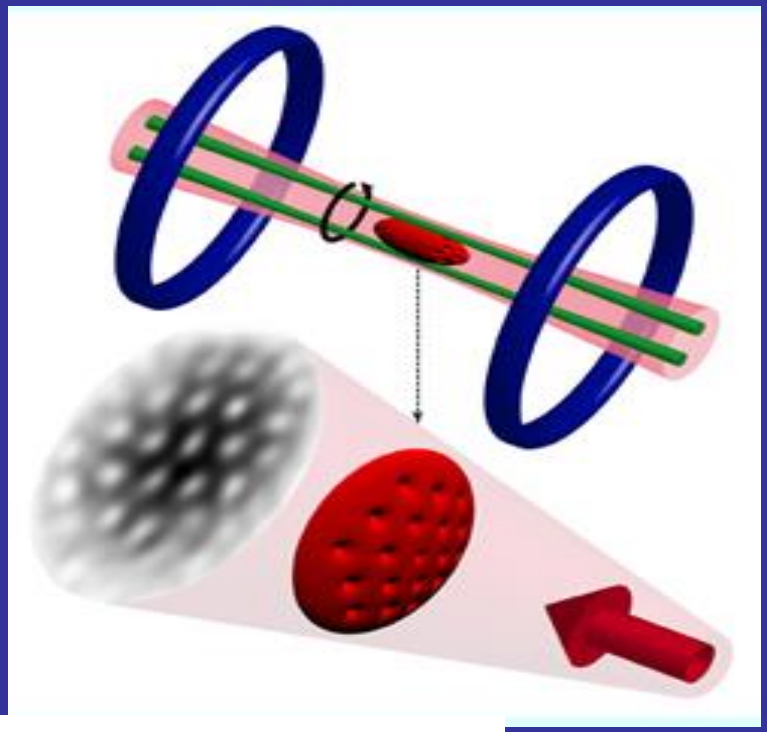



Regal and Jin, PRL **90**, 230404 (2003)



## Short (selective) history:

- ✓In 1999 DeMarco and Jin created a degenerate atomic Fermi gas.
- ✓In 2005 Zwierlein/Ketterle group observed quantum vortices which survived when passing from BEC to unitarity – evidence for superfluidity!

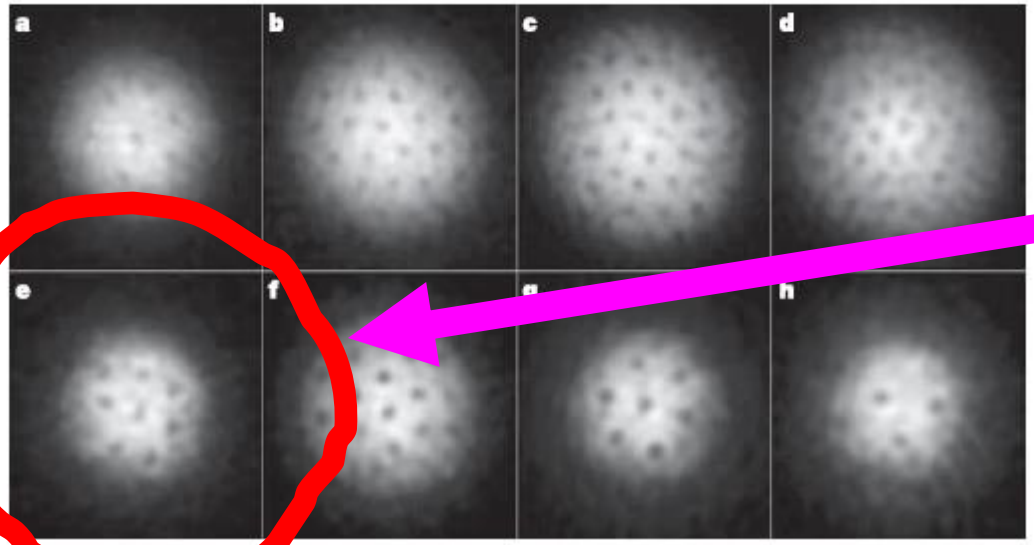


system of fermionic $^6Li$ atoms

**Feshbach resonance: B=834G**

BEC side: a>0

BCS side: a<0




UNITARY REGIME

**Figure 2 | Vortices in a strongly ... fermionic atoms on the BEC- and the BCS-side of the Feshbach resonance.** At the given field, the cloud of lithium atoms was stirred for 300 ms (**a**) or 500 ms (**b**–**h**) followed by an equilibration time of 500 ms. After 2 ms of ballistic expansion, the magnetic field was ramped to 735 G for imaging (s... magnetic fields were 740 G (**a**), 766 G (**b**), 792 G (**c**... 843 G (**f**), 853 G (**g**) and 863 G (**h**). The field of vie... 880 μm × 880 μm.

M.W. Zwierlein *et al.*, Nature, 435, 1047 (2005)

## Hamiltonian

$$\hat{H} = \hat{T} + \hat{V} = \int d^3r \sum_{s=\uparrow\downarrow} \hat{\psi}_s^{\dagger}(\vec{r}) \left( -\frac{\hbar^2 \Delta}{2m} \right) \hat{\psi}_s(\vec{r}) - g \int d^3r \, \hat{n}_{\uparrow}(\vec{r}) \hat{n}_{\downarrow}(\vec{r})$$

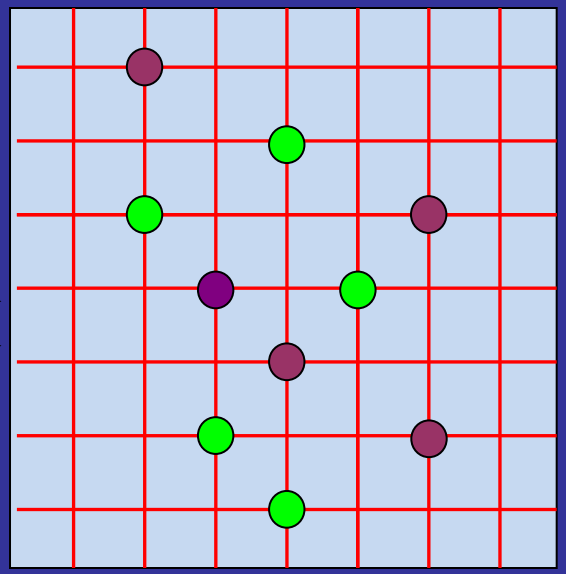
$$\hat{N} = \int d^3r \left( \hat{n}_{\uparrow}(\vec{r}) + \hat{n}_{\downarrow}(\vec{r}) \right); \quad \hat{n}_s(\vec{r}) = \hat{\psi}_s^{\dagger}(\vec{r}) \hat{\psi}_s(\vec{r})$$

## Path Integral Monte Carlo for fermions on 3D lattice

**Coordinate space**

L –limit for the spatial correlations in the system

$$k_{cut} = \frac{\pi}{\Delta x}; \quad \Delta x$$



$$Volume = L^3$$

$$lattice\ spacing = \Delta x$$

- Spin up fermion:
- Spin down fermion:

**External conditions:**

$T$ - temperature

$\mu$ - chemical potential

Periodic boundary conditions imposed

# Basics of Auxiliary Field Monte Carlo (Path Integral MC)

$$\hat{H} = \hat{T} + \hat{V} = \int d^3r \sum_{s=\uparrow\downarrow} \hat{\psi}_s^{\dagger}(\vec{r}) \left( -\frac{\hbar^2 \Delta}{2m} \right) \hat{\psi}_s(\vec{r}) - g \int d^3r \, \hat{n}_{\uparrow}(\vec{r}) \hat{n}_{\downarrow}(\vec{r})$$

$$\hat{N} = \int d^3r \left( \hat{n}_{\uparrow}(\vec{r}) + \hat{n}_{\downarrow}(\vec{r}) \right); \quad \hat{n}_s(\vec{r}) = \hat{\psi}_s^{\dagger}(\vec{r}) \hat{\psi}_s(\vec{r})$$

$$\frac{1}{g} = -\frac{m}{4\pi\hbar^2 a} + \frac{m k_{cut}}{2\pi^2 \hbar^2}$$

Running coupling constant g defined by lattice

$$\frac{1}{g} = \frac{m}{2\pi\hbar^2 \Delta x}$$ - UNITARY LIMIT

$$\hat{U}(\{\sigma\}) = T_{\tau} \exp\{-\int_0^{\beta} d\tau [\hat{h}(\{\sigma\}) - \mu]\}; \quad \hat{h}(\{\sigma\}) - \text{one-body operator}$$

$$U(\{\sigma\})_{kl} = \langle \psi_k | \hat{U}(\{\sigma\}) | \psi_l \rangle; \quad |\psi_l\rangle - \text{single-particle wave function}$$

$$E(T) = \langle \hat{H} \rangle = \int \frac{D[\sigma(\vec{r},\tau)] e^{-S[\sigma]}}{Z(T)} E[U(\{\sigma\})]$$

$E[U(\{\sigma\})]$- energy associated with a given sigma field

$$\mathrm{Tr}\, \hat{U}(\{\sigma\}) = \{\det[1 + \hat{U}_{\uparrow}(\sigma)]\}^2 = \exp[-S(\{\sigma\})] > 0$$

- No sign problem for spin symmetric system!

# Details of calculations, improvements and problems

- Currently we can reach $16^3$ lattice and perform calcs. down to x = 0.06 (x – temperature in Fermi energy units) at the densities of the order of 0.03.

- Effective use of FFT(W) makes all imaginary time propagators diagonal (either in real space or momentum space) and there is no need to store large matrices.

- Update field configurations using the Metropolis importance sampling algorithm. QMC calculations can be split into two independent processes:
  1) sample generation (generation of sigma fields),
  2) calculations of observables.

- Change randomly at a fraction of all space and time sites the signs the auxiliary fields $\sigma(r,\tau)$ so as to maintain a running average of the acceptance rate between 0.4 and 0.6 .

- At low temperatures use Singular Value Decomposition of the evolution operator $U(\{\sigma\})$ to stabilize the numerics.

- MC correlation "time" $\approx$ 200 time steps at $T \approx T_c$ for lattices $10^3$ . Unfortunately when increasing the lattice size the correlation time also increases. One needs few thousands uncorrelated samples (we usually take about 10 000) to decrease the statistical error to the level of 1%.

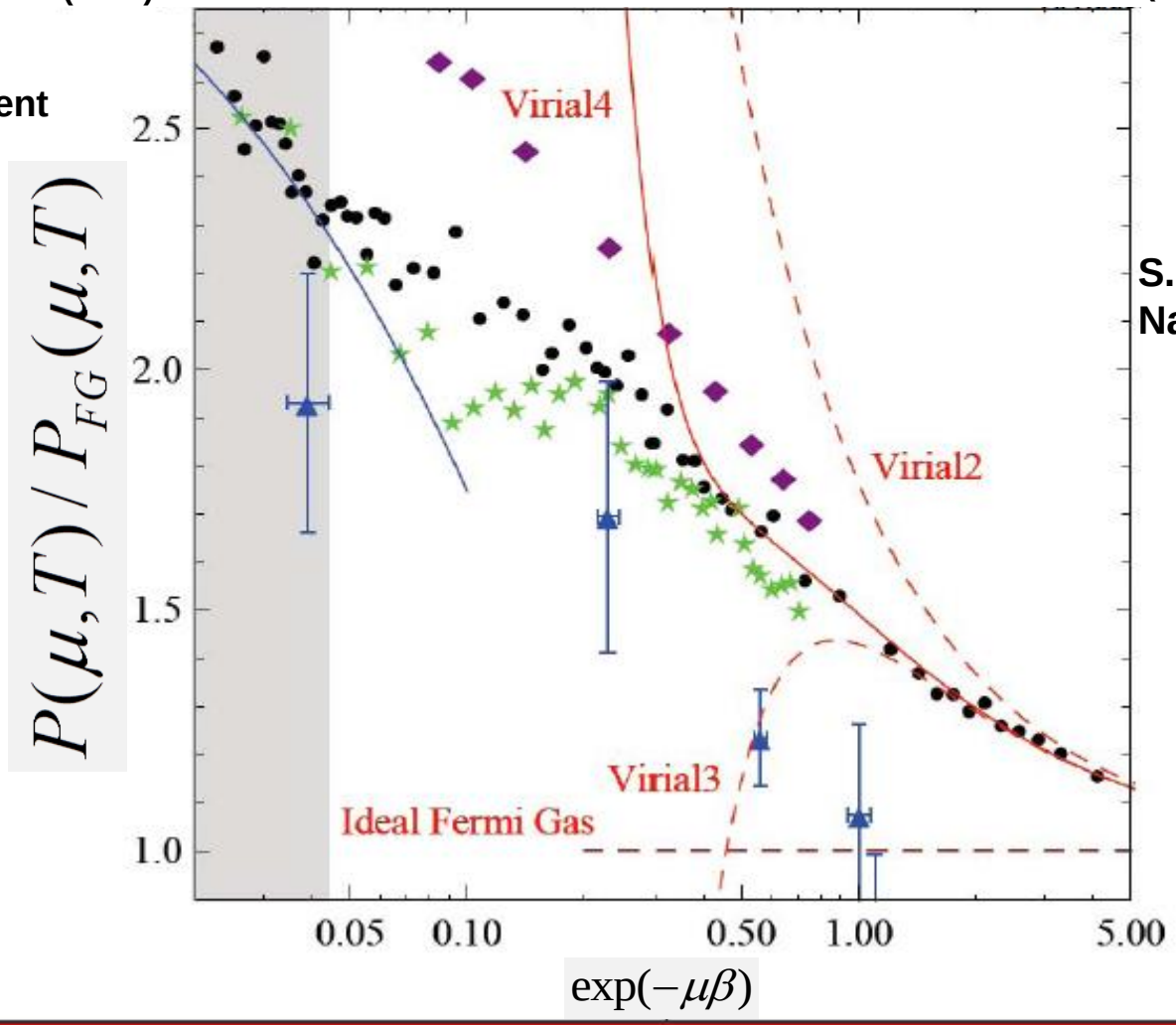
# Comparison with Many-Body Theories (1)

**Diagram. MC**
Burovski et al.
PRL96, 160402(2006)

**QMC**
Bulgac, Drut, Magierski,
PRL99, 120401(2006)

**Diagram. + analytic**
Haussmann et al.
PRA75, 023610(2007)

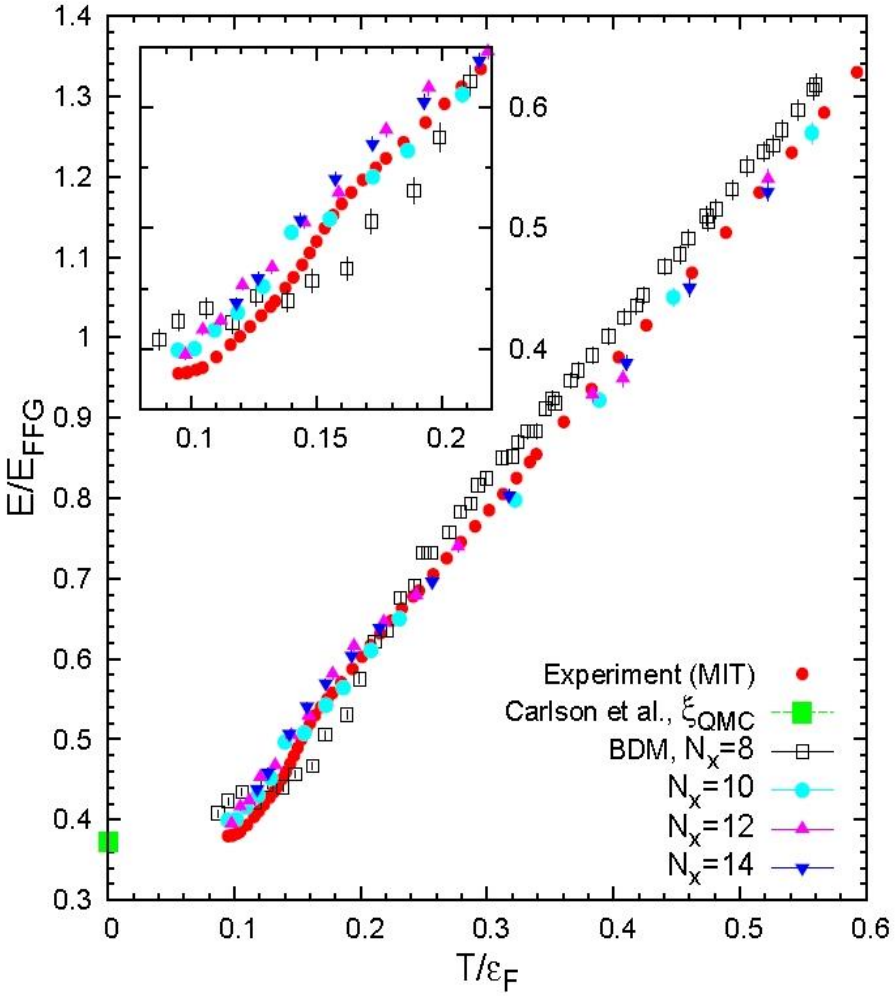
**Experiment**

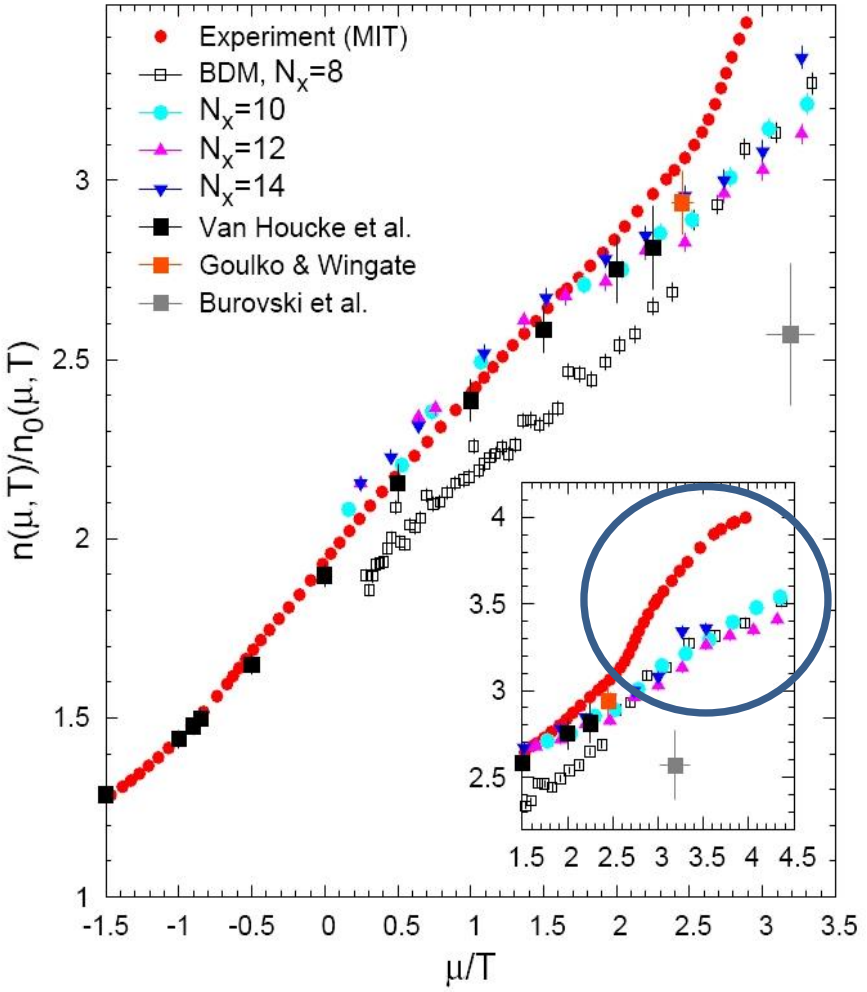



**S. Nascimbene et al.**
**Nature 463, 1057 (2010)**

**Courtesy of C. Salomon**

# Equation of state of the unitary Fermi gas - current status




Experiment: M.J.H. Ku, A.T. Sommer, L.W. Cheuk, M.W. Zwierlein , Science 335, 563 (2012)

QMC (PIMC + Hybrid Monte Carlo): J.E.Drut, T.Lähde, G.Wlazłowski, P.Magierski, Phys. Rev. A 85, 051601 (2012)

## Local density approximation (LDA) from QMC

Uniform system

$$\Omega = F - \lambda N = \frac{3}{5}\varphi(x)\varepsilon_F N - \lambda N$$

Nonuniform system

*(gradient corrections neglected)*

$$\Omega = \int d^3r \left[ \frac{3}{5}\varepsilon_F(\vec{r})\varphi(x(\vec{r})) + U(\vec{r}) - \lambda \right] n(\vec{r})$$

$$x(\vec{r}) = \frac{T}{\varepsilon_F(\vec{r})}; \quad \varepsilon_F(\vec{r}) = \frac{\hbar^2}{2m}\left[3\pi^2 n(\vec{r})\right]^{2/3}$$

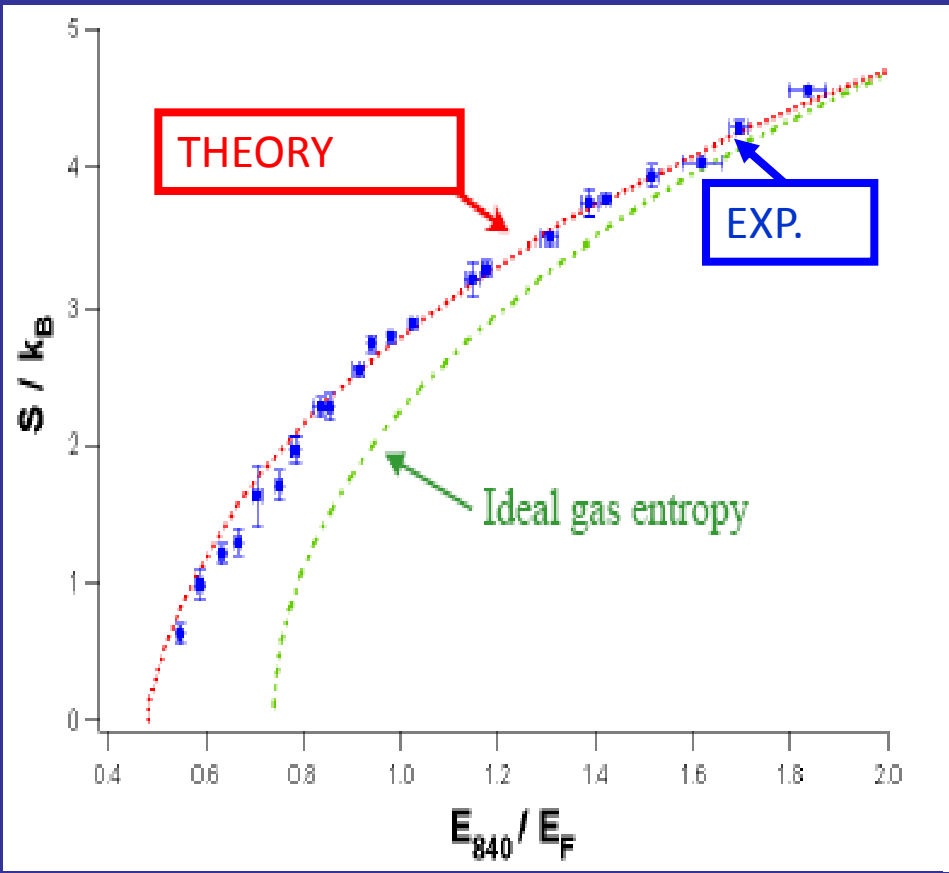
The overall chemical potential $\lambda$ and the temperature *T* are constant throughout the system. The density profile will depend on the shape of the trap as dictated by:

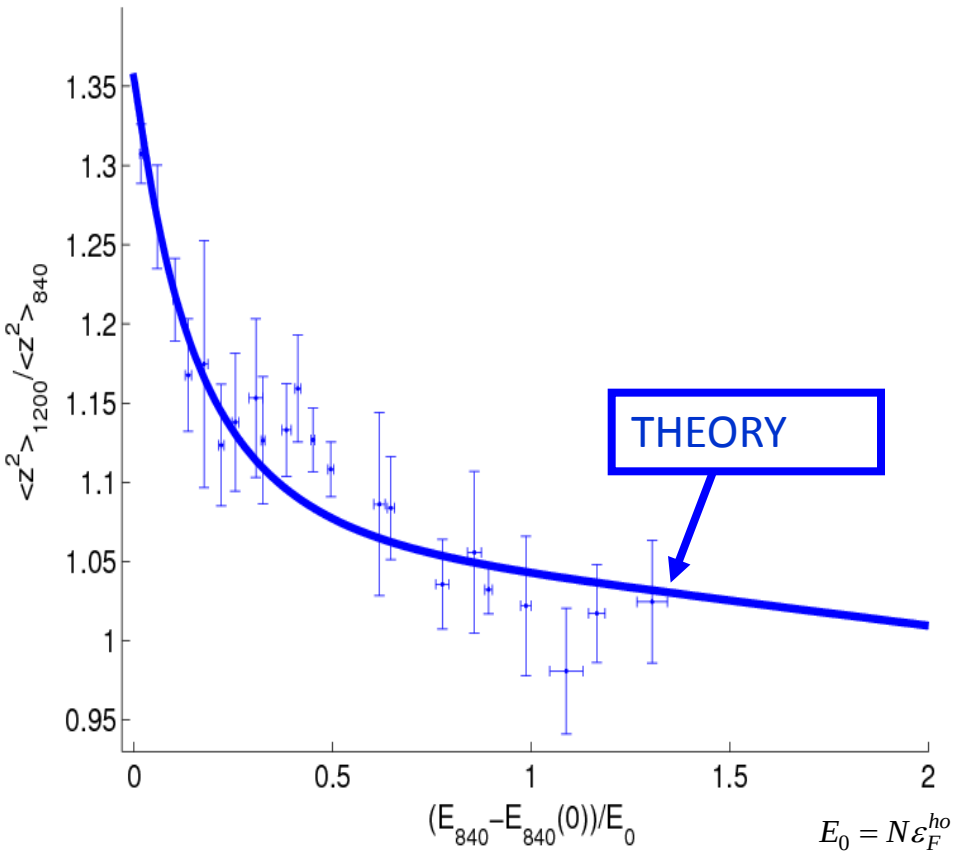
$$\frac{\delta\Omega}{\delta n(\vec{r})} = \frac{\delta(F - \lambda N)}{\delta n(\vec{r})} = \mu(x(\vec{r})) + U(r) - \lambda = 0$$

**Using as an input the Monte Carlo results for the uniform system and experimental data (trapping potential, number of particles), we determine the density profiles.**

## Comparison with experiment

John Thomas' group at Duke University,
**L.Luo, et al. Phys. Rev. Lett. 98, 080402, (2007)**



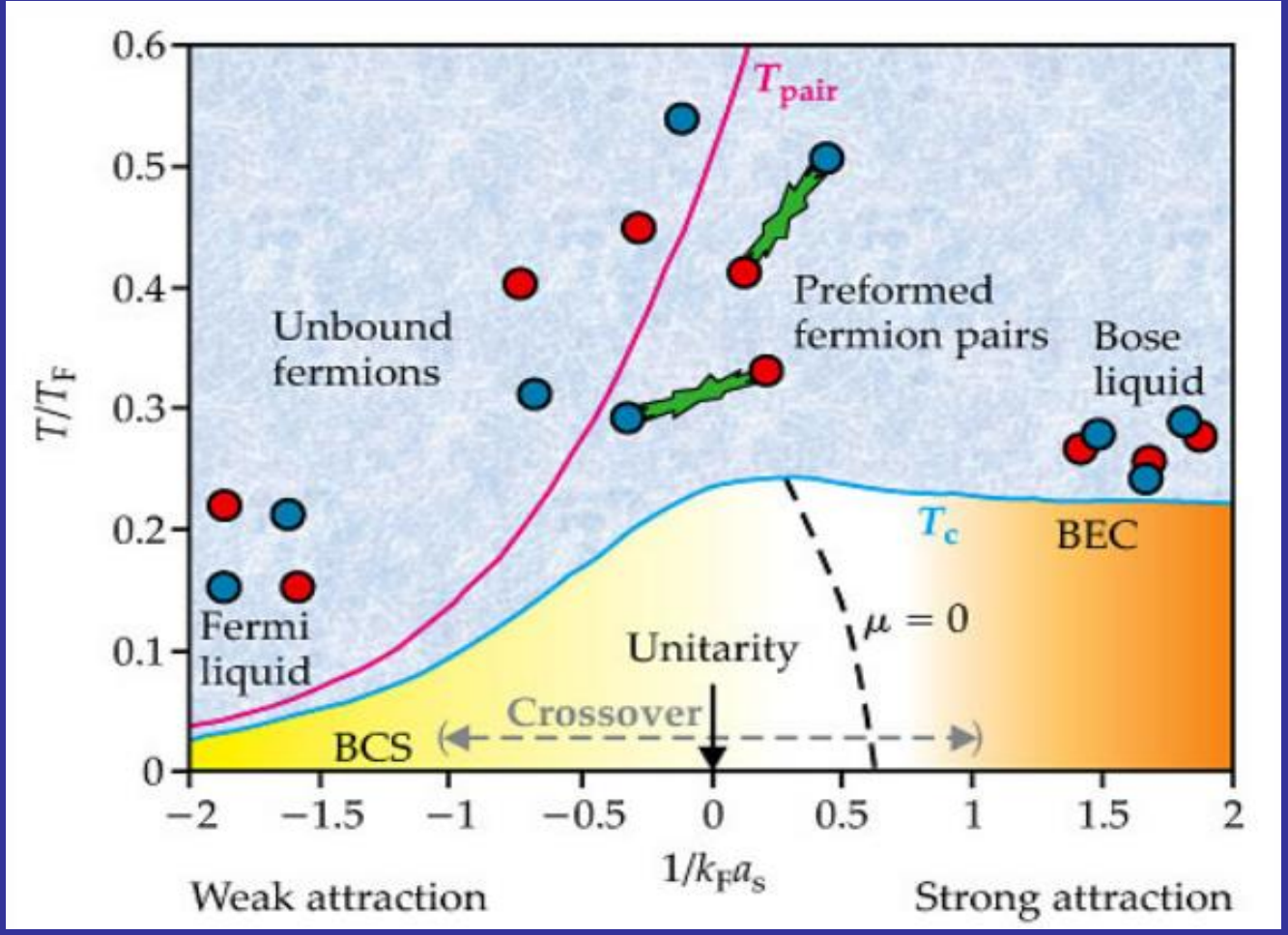




**Entropy as a function of energy (relative to the ground state) for the unitary Fermi gas in the harmonic trap.**

**Ratio of the mean square cloud size at B=1200G to its value at unitarity (B=840G) as a function of the energy. Experimental data are denoted by point with error bars.**

$B = 1200G \Rightarrow 1/k_F a \approx -0.75$

Theory: **Bulgac, Drut, and Magierski PRL 99, 120401 (2007)**



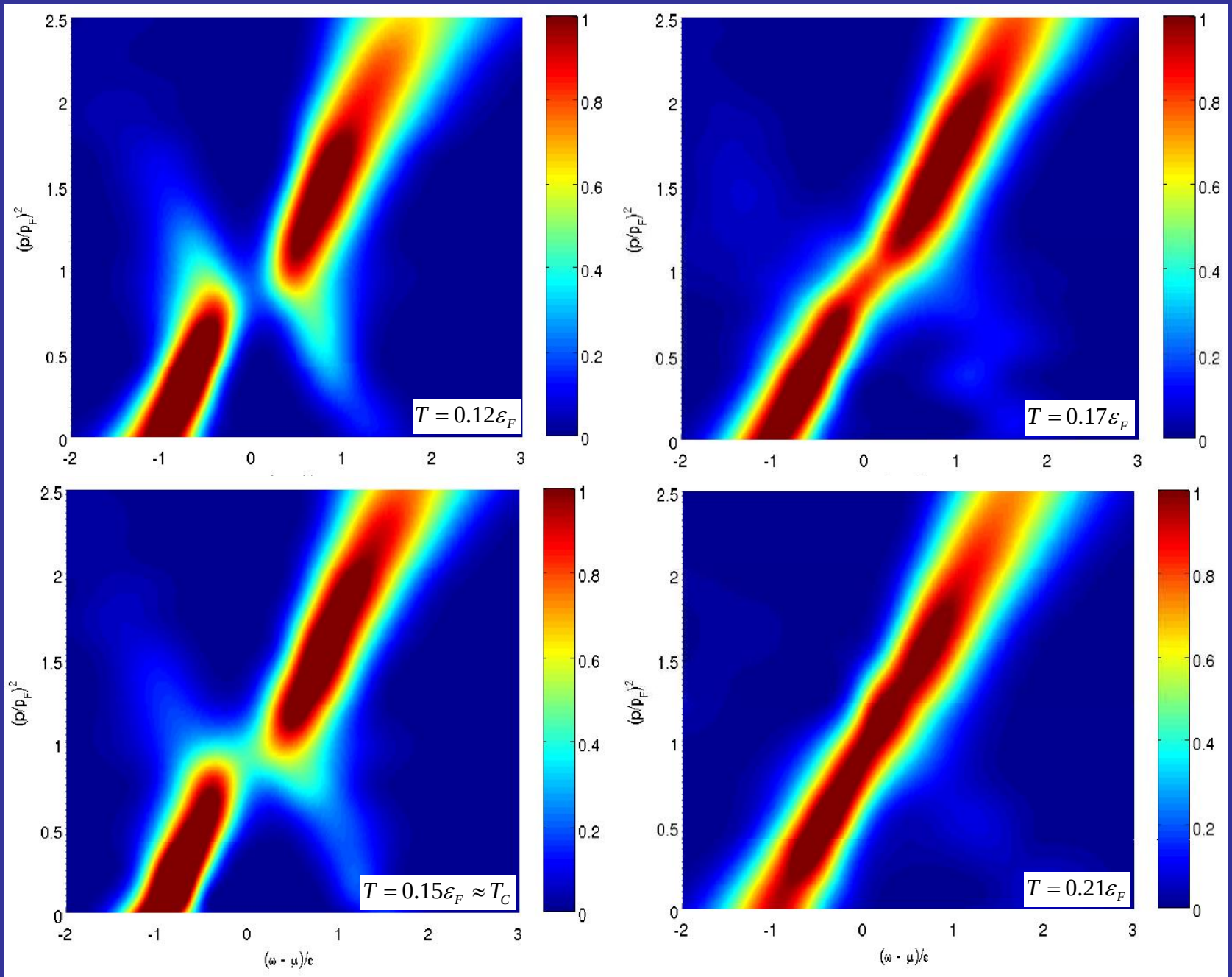

From Sa de Melo, Physics Today (2008)

**Pairing pseudogap:** suppression of low-energy spectral weight function due to incoherent pairing in the normal state ($T > T_c$)

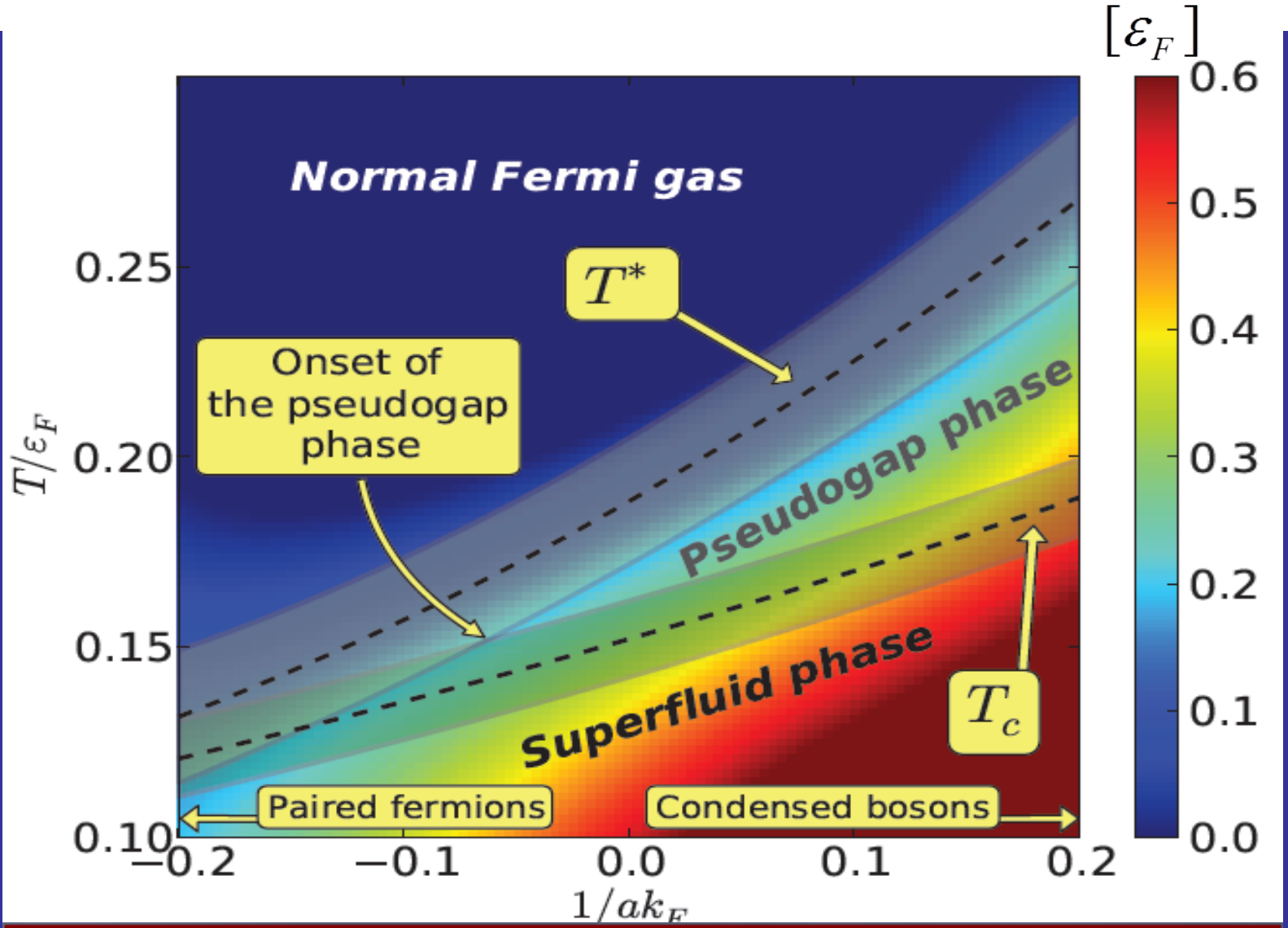
**Important issue related to pairing pseudogap:**

- Are there sharp gapless quasiparticles in a normal Fermi liquid
  YES: Landau's Fermi liquid theory;
  NO: breakdown of Fermi liquid paradigm

## Spectral weight function at unitarity: $(k_F a)^{-1} = 0$



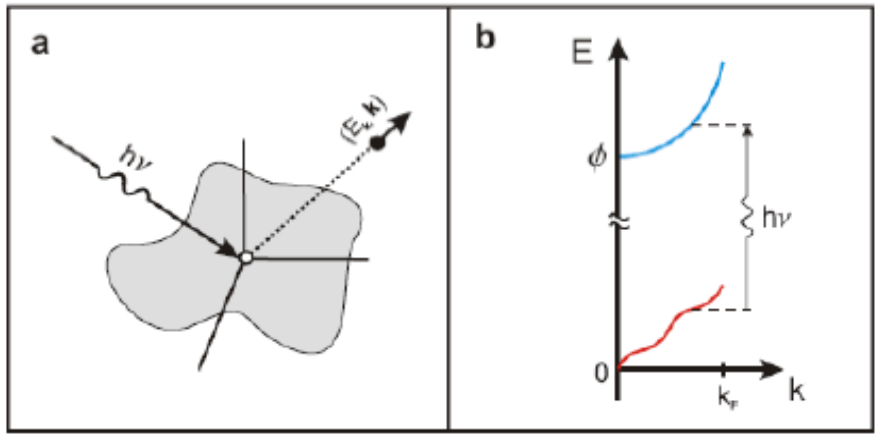
# Gap in the single particle fermionic spectrum - theory




***Ab initio*** **result: The onset of pseudogap phase at $1/ak_F \approx -0.05$.**


Magierski, Wlazłowski, Bulgac, *Phys. Rev. Lett.*107,145304(2011)
Magierski, Wlazłowski, Bulgac, Drut, *Phys. Rev. Lett.*103,210403(2009)

# RF spectroscopy in ultracold atomic gases

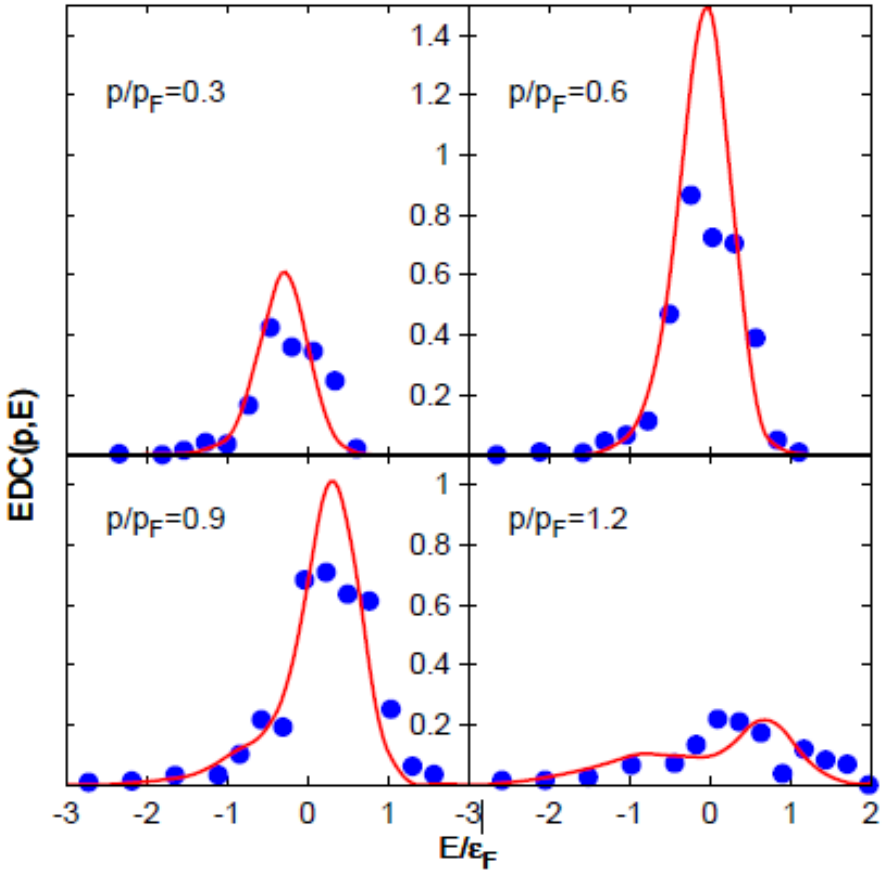



$$-E_s + h\nu = \frac{\hbar^2 k^2}{2m} + \phi$$

$$E(N) = E(N-1) + E_s$$

**Stewart, Gaebler, Jin, Using photoemission spectroscopy to probe a strongly interacting Fermi gas, Nature, 454, 744 (2008)**

$$\mathrm{EDC}(p,E,T) = \mathcal{C}p^2 \int_0^\infty dr\, r^2 \frac{1}{\varepsilon_F(r)} A\left[\frac{p}{p_F(r)}, \frac{E-\mu(r)}{\varepsilon_F(r)}, \frac{T}{\varepsilon_F(r)}\right] f(E-\mu(r)),$$



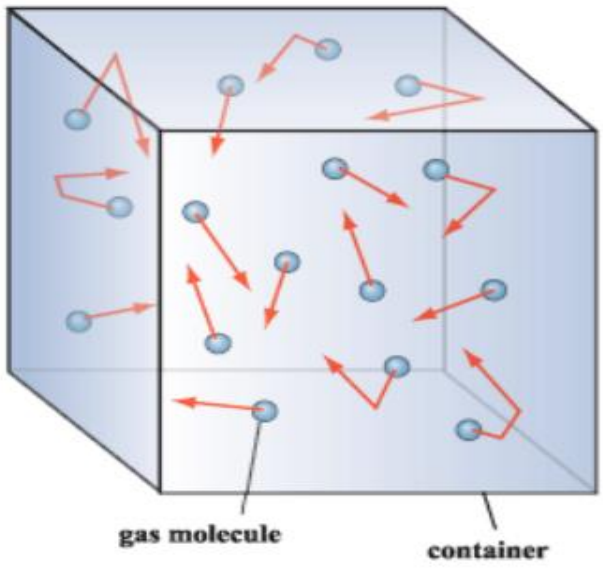

Experiment (blue dots): D. Jin's group
Gaebler et al. *Nature Physics 6, 569(2010)*

Theory (red line):
Magierski, Wlazłowski, Bulgac,
Phys.Rev.Lett.107,145304(2011)

# Viscosity in strongly correlated quantum systems:

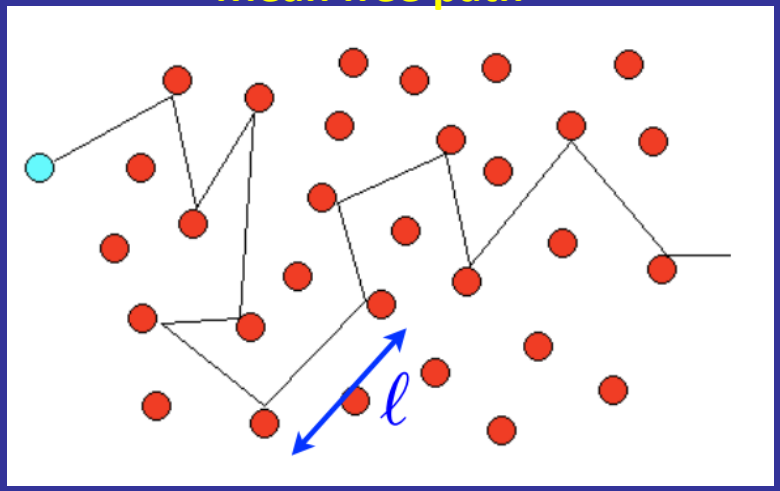
WWW.FOTOBANK.COM FCDO-6654 FoodCollection
Pouring water out of glass jug into glass

Water and honey flow with different rates: different viscosity




**In the light of the kinetic theory of gases molecules are moving mostly along straight lines and occasionally bump onto each other.**

**Mean free path**




This leads to the Maxwell's formula for viscosity (1860):

$$\eta \sim \rho v \ell = \text{mass density} \times \text{velocity} \times \text{mean free path}$$

**Consequences:**

- Non interacting gas is a pathological example of the system with an infinite viscosity
- Strongly interacting system can have low viscosity since the mean free path is short **but…**

…but when the system is strongly correlated then the kinetic theory fails!

However:
If we blindly use this formula we may notice that the Heisenberg uncertainty principle would give the following relation:

$$\frac{\eta}{\rho} \sim \bar{p} l \geq \hbar$$

$\bar{p}$ - average momentum

*For any physical fluid:*

$$\frac{\eta}{S} \geq \frac{\hbar}{4\pi k_B}$$

**KSS conjecture**
Kovtun, Son, Starinets, Phys.Rev.Lett. 94, 111601, (2005)
from AdS/CFT correspondence

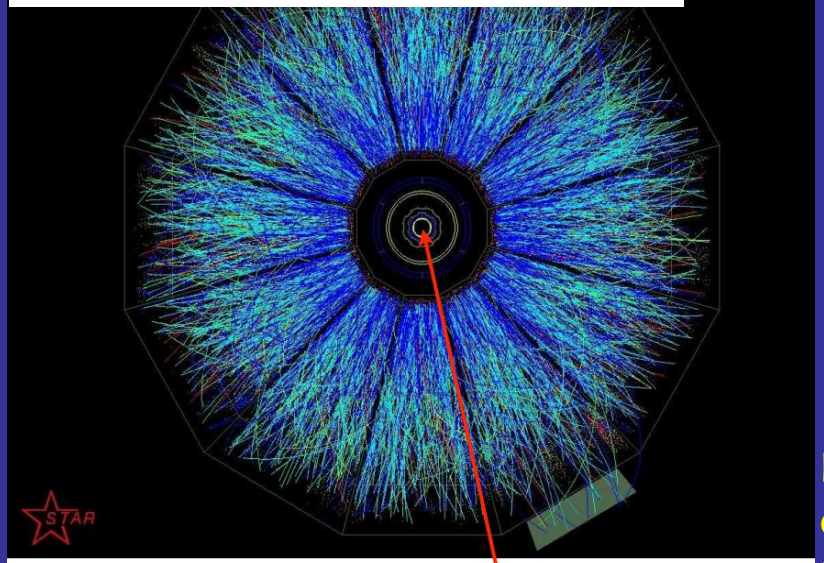
Perfect fluid $\frac{\eta}{S} = \frac{\hbar}{4\pi k_B}$ - strongly interacting quantum system = No well defined quasiparticles

**Candidates: quark gluon plasma, atomic gas**

Gold nucleus Gold nucleus

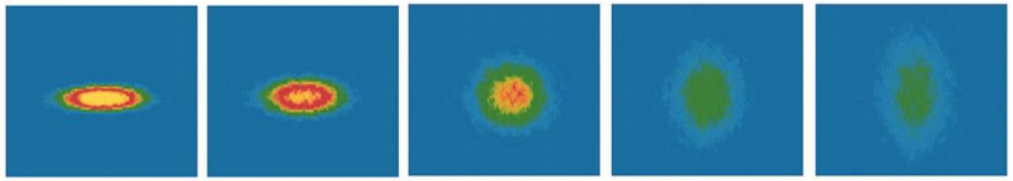
v=0.99995 c v=0.99995 c

**Extremely high temperatures: thousands billion degrees**



a very dense droplet of matter in the beginning

## Expansion of a atomic gas cloud



(Cao et al, Science 2010)

Extremely low temperatures: 1 billionth of a degree

**Despite of energy scales differing by many orders of magnitude, expansion of both system is pretty much similar and in particular exhibts the so-called elliptic flow.**

## Shear viscosity

$$\eta(\omega) = \pi \rho_{xyxy}(q=0,\omega)/\omega$$

$$G_{xyxy}(q,\tau) = \int d^3 r \left\langle \hat{\Pi}_{xy}(r,\tau)\hat{\Pi}_{xy}(0,0)\right\rangle e^{iqr}$$

$$G_{xyxy}(q,\tau) = \int_0^\infty \rho_{xyxy}(q,\omega)\frac{\cosh\left[\omega(\tau-\beta/2)\right]}{\sinh\left[\omega\beta/2\right]} d\omega$$

$$i\left[\hat{j}_k(r),\hat{H}\right] = \partial_l \hat{\Pi}_{kl}(r)$$

## Additional symmetries and sum rules:

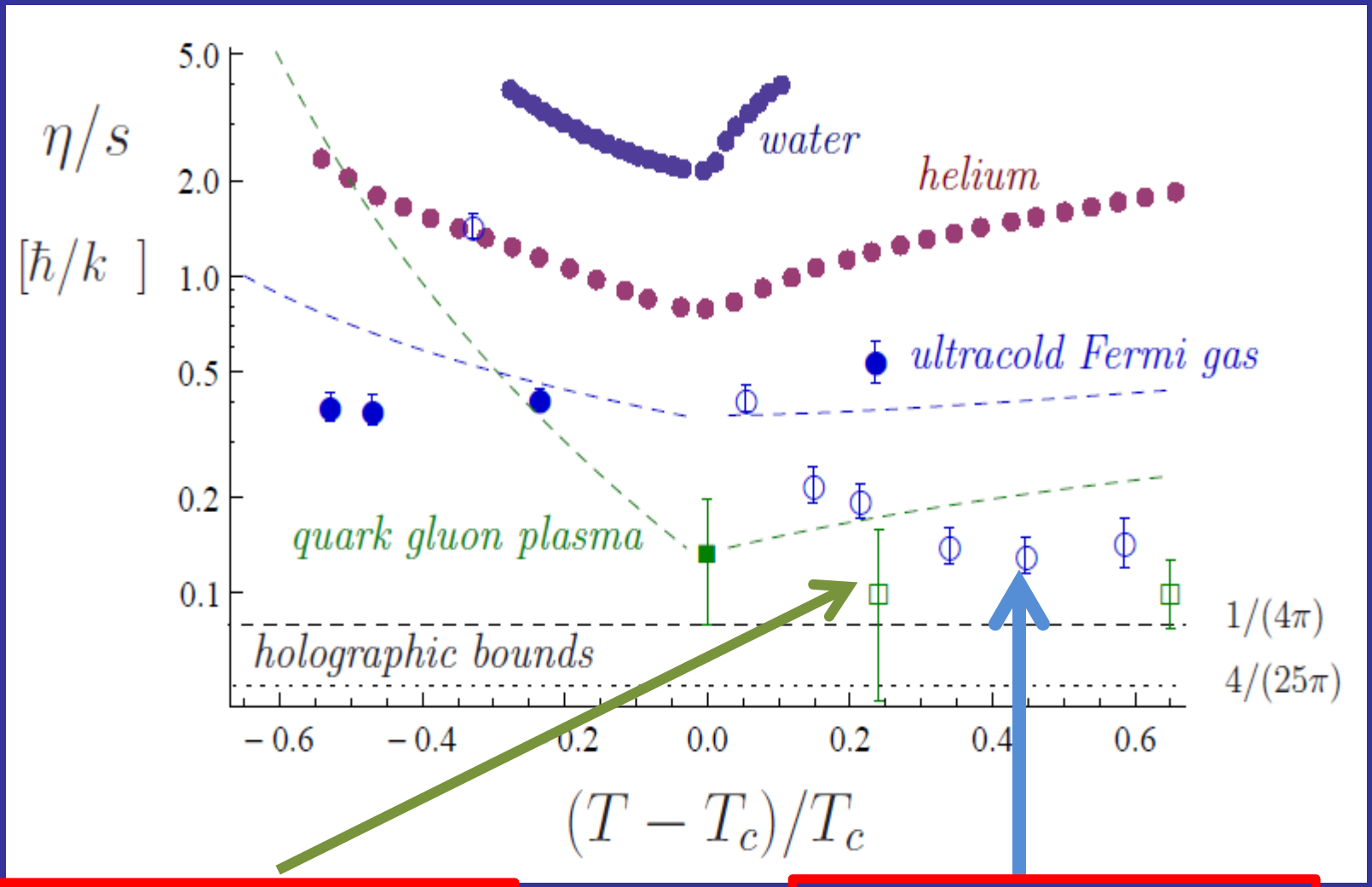
$$G(\tau) = G(\beta-\tau)$$

$$\frac{1}{\pi}\int_0^\infty d\omega \left[\eta(\omega) - \frac{C}{15\pi\sqrt{m\omega}}\right] = \frac{\varepsilon}{3}, \qquad \varepsilon - \textit{energy density}$$

$$\eta(\omega \to \infty) \backsimeq \frac{C}{15\pi\sqrt{m\omega}}.$$

# Shear viscosity to entropy ratio – experiment vs. theory

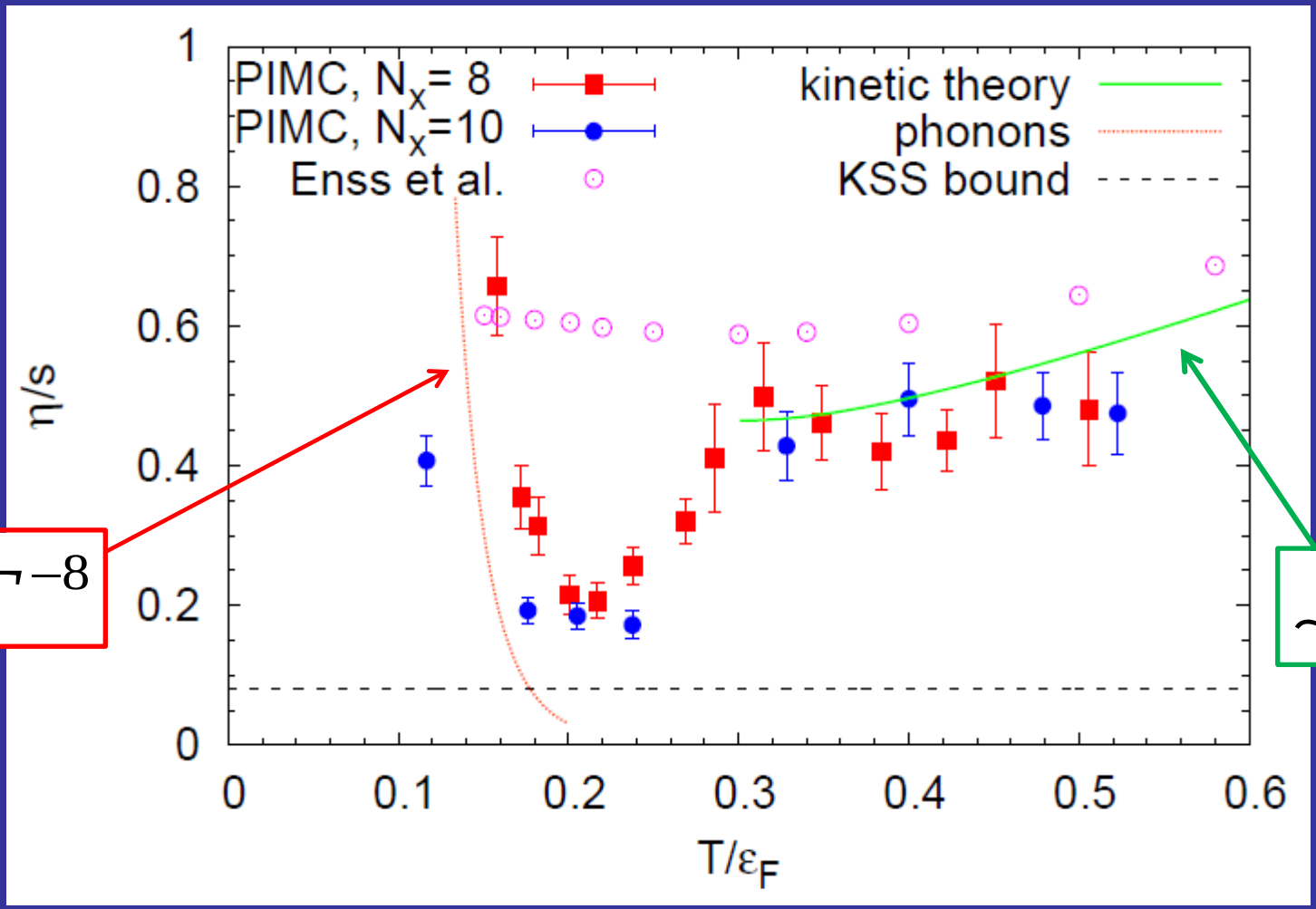
***(from A. Adams et al.*** New Journal of Physics, "Focus on Strongly Correlated Quantum Fluids: from Ultracold Quantum Gases to QCD Plasmas„ arXive:***1205.5180)***




Lattice QCD ( SU(3) gluodynamics ):
H.B. Meyer, Phys. Rev. D 76, 101701 (2007)

QMC calculations for UFG:
G. Wlazłowski, P. Magierski, J.E. Drut,
Phys. Rev. Lett. 109, 020406 (2012)

# Shear viscosity to entropy density ratio

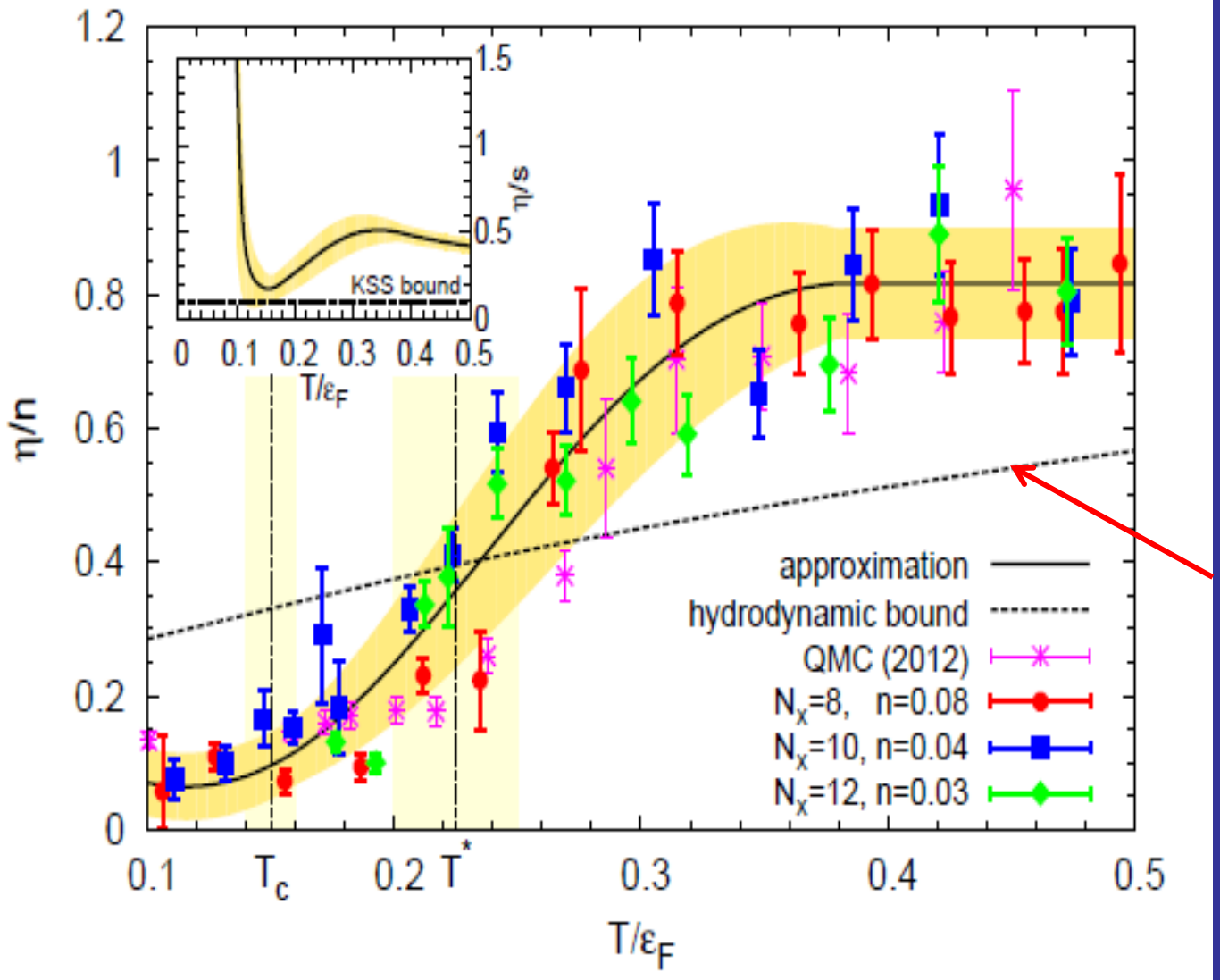



$\sim T^{-8}$

$\sim T^{3/2}$

G.Wlazłowski, P.Magierski,J.E.Drut,
Phys. Rev. Lett. 109, 020406 (2012)

# Shear viscosity per unit density as a function of temperature




C. Chafin, T. Schafer,
PRA87,023629(2013)
P.Romatschke, R.E. Young,
arXiv:1209.1604

Wlazłowski, Magierski, Bulgac, Roche, Phys. Rev. A88, 013639 (2012)

# Spin susceptibility and spin drag rate

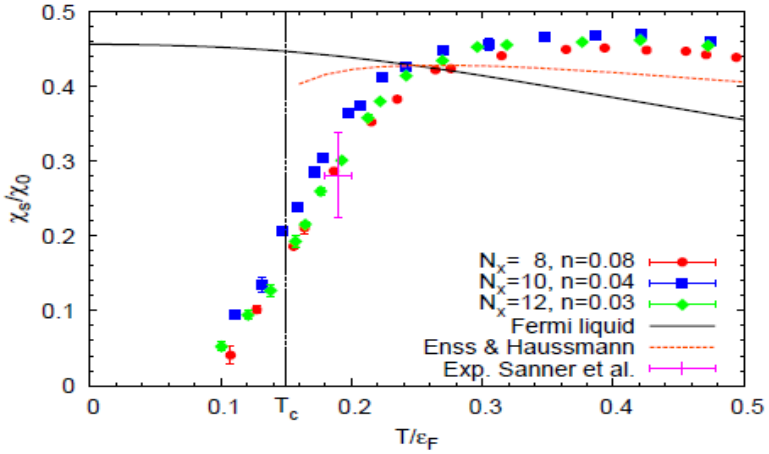



FIG. 2: (Color online) The static spin susceptibility as a function of temperature for an $8^3$ lattice solid (red) circles, $10^3$ lattice (blue) squares and $12^3$ lattice (green) diamonds. Vertical black dotted line indicates the critical temperature of superfluid to normal phase transition $T_c = 0.15\,\varepsilon_F$. For comparison Fermi liquid theory prediction and recent results of the $T$-matrix theory produced by Enss and Haussmann [25] are plotted with solid and dashed (brown) lines, respectively. The experimental data point from Ref. [15] is also shown.

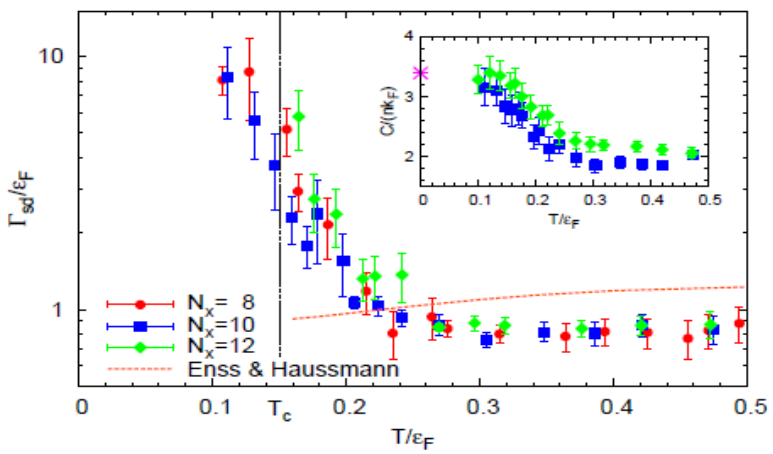



FIG. 3: (Color online) The spin drag rate $\Gamma_{sd} = n/\sigma_s$ in units of Fermi energy as a function of temperature for an $8^3$ lattice solid (red) circles, $10^3$ lattice (blue) squares and $12^3$ lattice (green) diamonds. Vertical black dotted line locates the critical temperature of superfluid to normal phase transition. Results of the $T$-matrix theory are plotted by dashed (brown) line [25]. The inset shows extracted value of the contact density as function of the temperature. The (purple) asterisk shows the contact density from the QMC calculations of Ref. [29] at $T = 0$.

$$\Gamma = \frac{n}{\sigma_s}$$ - spin drag rate

$$\sigma_s(\omega) = \pi\rho_s(q=0,\omega)/\omega$$ - spin conductivity

$$G_s(q,\tau) = \frac{1}{V}\left\langle \left(\hat{j}^z_{q\uparrow}(\tau) - \hat{j}^z_{q\downarrow}(\tau)\right)\left(\hat{j}^z_{-q\uparrow}(0) - \hat{j}^z_{-q\downarrow}(0)\right)\right\rangle$$

$$G_s(q,\tau) = \int_0^\infty \rho_s(q,\omega)\frac{\cosh\left[\omega(\tau-\beta/2)\right]}{\sinh\left[\omega\beta/2\right]}d\omega$$

Wlazłowski, Magierski, Bulgac, Drut, Roche,
Phys. Rev. Lett. 110, 090401,(2013)

# Formalism for Time Dependent Phenomena: TDSLDA

A.K. Rajagopal and J. Callaway, Phys. Rev. B 7, 1912 (1973)
V. Peuckert, J. Phys. C 11, 4945 (1978)
E. Runge and E.K.U. Gross, Phys. Rev. Lett. 52, 997 (1984)

$$i\hbar\frac{\partial}{\partial t}\begin{pmatrix} u_{k\uparrow}(\mathbf{r},t) \\ u_{k\downarrow}(\mathbf{r},t) \\ v_{k\uparrow}(\mathbf{r},t) \\ v_{k\downarrow}(\mathbf{r},t) \end{pmatrix} = \begin{pmatrix} h_{\uparrow,\uparrow}(\mathbf{r},t) & h_{\uparrow,\downarrow}(\mathbf{r},t) & 0 & \Delta(\mathbf{r},t) \\ h_{\downarrow,\uparrow}(\mathbf{r},t) & h_{\downarrow,\downarrow}(\mathbf{r},t) & -\Delta(\mathbf{r},t) & 0 \\ 0 & -\Delta^*(\mathbf{r},t) & -h^*_{\uparrow,\uparrow}(\mathbf{r},t) & -h^*_{\uparrow,\downarrow}(\mathbf{r},t) \\ \Delta^*(\mathbf{r},t) & 0 & -h^*_{\uparrow,\downarrow}(\mathbf{r},t) & -h^*_{\downarrow,\downarrow}(\mathbf{r},t) \end{pmatrix} \begin{pmatrix} u_{k\uparrow}(\mathbf{r},t) \\ u_{k\downarrow}(\mathbf{r},t) \\ v_{k\uparrow}(\mathbf{r},t) \\ v_{k\downarrow}(\mathbf{r},t) \end{pmatrix}$$

Density functional contains normal densities, anomalous density (pairing) and currents:

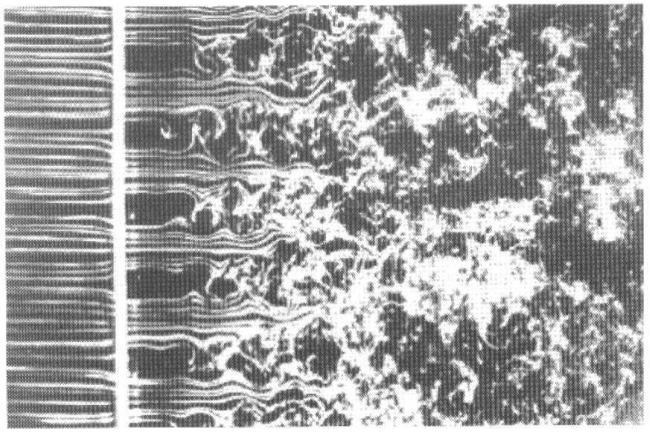
$$E(t) = \int d^3r \left[ \varepsilon(n(\vec{r},t),\tau(\vec{r},t),\nu(\vec{r},t),\vec{j}(\vec{r},t)) + V_{ext}(\vec{r},t)n(\vec{r},t) + \ldots \right]$$

Density functional for unitary Fermi gas

Nuclear energy functional: SLy4, SkP, SkM*,...

Both codes: SLDA and TDSLDA are formulated on the 3D lattice without any symmetry restrictions.
SLDA generates initial conditions for TDSLDA.

# Road to quantum turbulence



**Classical turbulence:** energy is transfered from large scales to small scales where it eventually dissipates.

**Kolmogorov spectrum:** $E(k)=C\,\varepsilon^{2/3}\,k^{-5/3}$

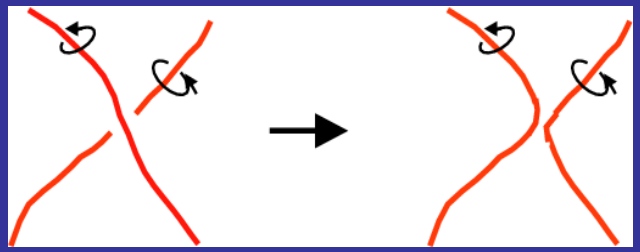
E – kinetic energy per unit mass associated with the scale 1/k
ε - energy rate (per unit mass) transfered to the system at large scales.
k - wave number (from Fourier transformation of the velocity field).
C – dimensionless constant.

**Superfluid turbulence (quantum turbulence):** disordered set of quantized vortices. The friction between the superfluid and normal part of the fluid serves as a source of energy dissipation.

**Problem:** how the energy is dissipated in the superfluid system at small scales at T=0? - „pure" quantum turbulence

**Possibility:** vortex reconnections → Kelvin waves → phonon radiation

# Vortex reconnections



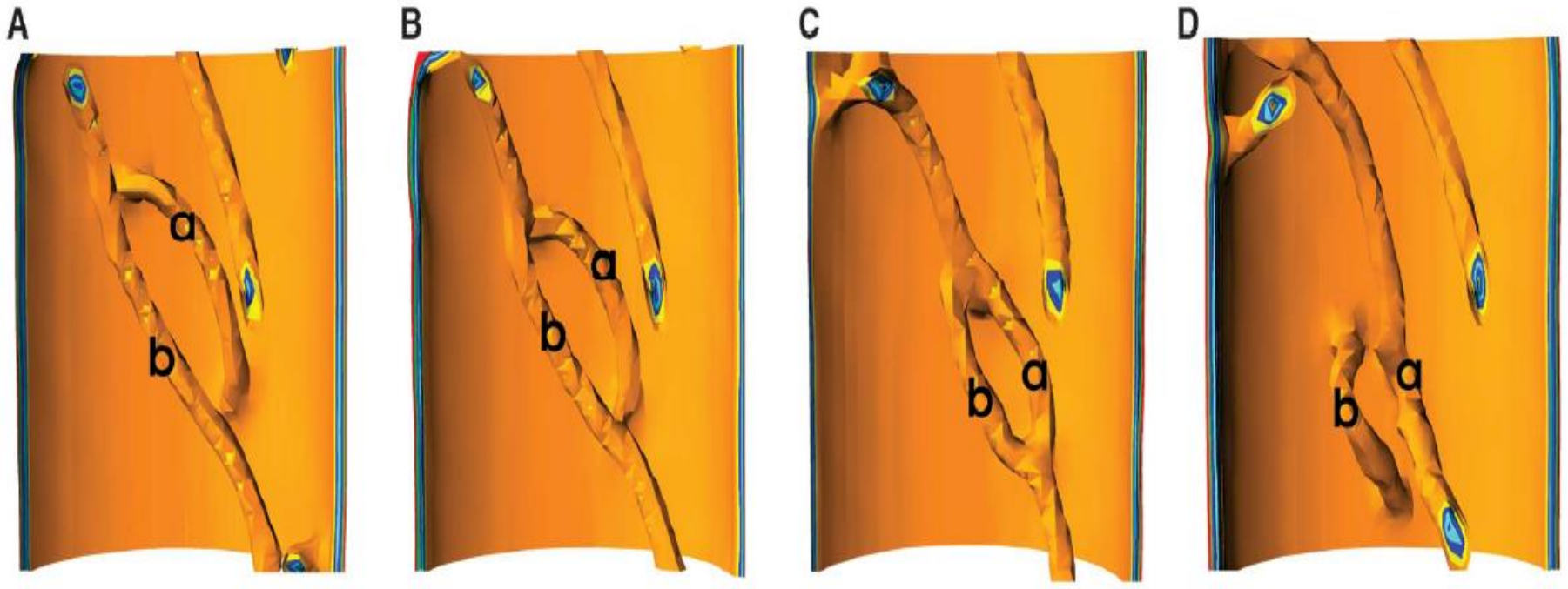
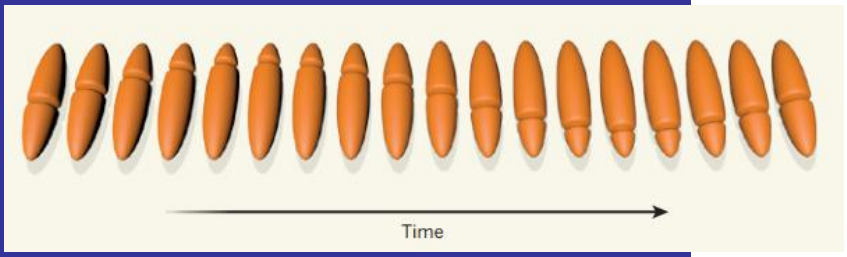



**Fig. 3.** (**A** to **D**) Two vortex lines approach each other, connect at two points, form a ring and exchange between them a portion of the vortex line, and subsequently separate. Segment (a), which initially belonged to the vortex line attached to the wall, is transferred to the long vortex line (b) after reconnection and vice versa.

Bulgac, Luo, Magierski, Roche, Yu, *Science* 332, 1288 (2011)

# Soliton dynamics vs ring vortex – a controversy




**MIT Experiment:**
**Nature 499 (2013) 426**

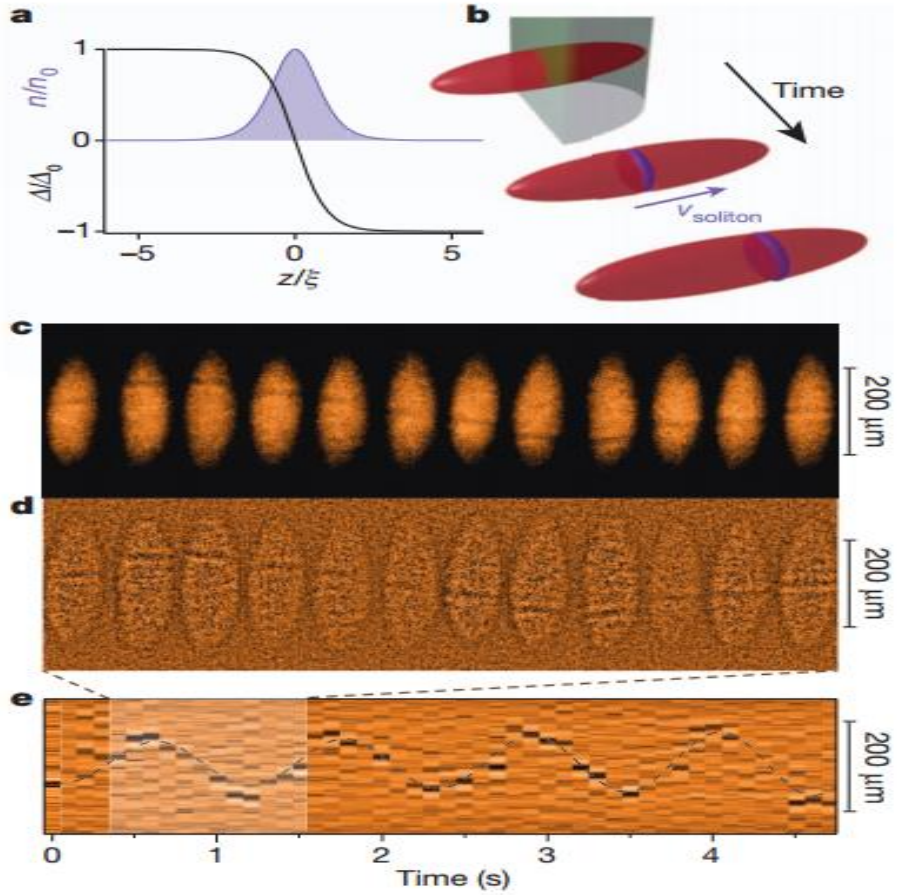



**Figure 1 | Creation and observation of solitons in a fermionic superfluid.** **a**, Superfluid pairing gap $\Delta(z)$ for a stationary soliton, normalized by the bulk pairing gap $\Delta_0$, and density $n(z)$ of the localized bosonic (fermionic) state versus position $z$, in the BEC (BCS) regime of the crossover, in units of the BEC healing length (BCS coherence length) $\xi$. **b**, Diagram of the experiment. A phase-imprinting laser beam twists the phase of one-half of the trapped superfluid by approximately $\pi$. The soliton generally moves at non-zero velocity $v_{soliton}$. **c**, Optical density and **d**, residuals (optical density minus a smoothed copy of the same image) of atom clouds at 815 G, imaged via the rapid ramp method[34], showing solitons at various hold times after creation. One period of soliton oscillation is shown. The in-trap aspect ratio was $\lambda = 6.5(1)$. **e**, Radially integrated residuals as a function of time revealing long-lived soliton oscillations. The soliton period is $T_s = 12(2)T_z$, much longer than the trapping period of $T_z = 93.76(5)$ ms, revealing an extreme enhancement of the soliton's relative effective mass, $M^*/M$.

**Theory prefers ring vortices:**
A. Bulgac, et al.,
Phys. Rev. Lett. 112, 025301 (2014)
G. Wlazłowski, et al.
Phys. Rev. Lett. (in press)