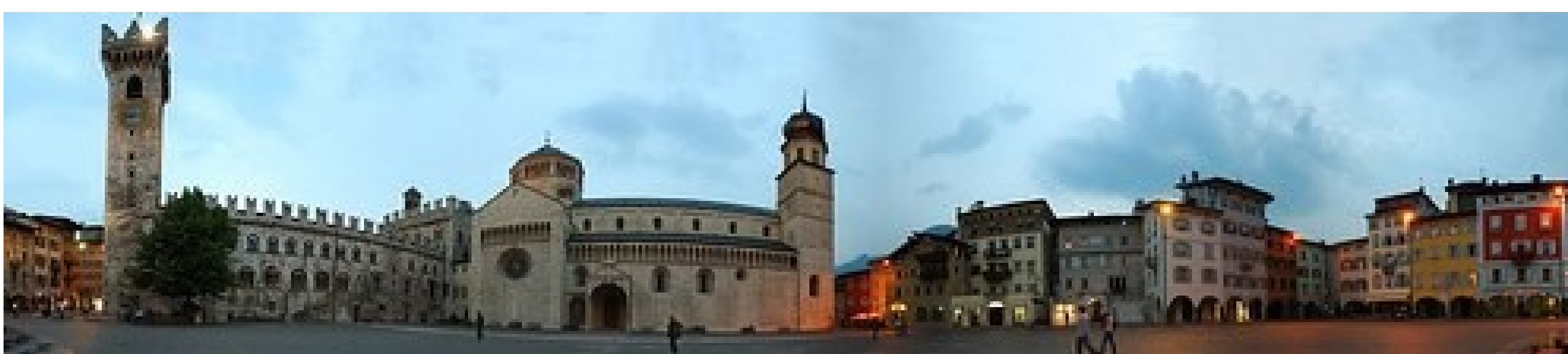
Spin oscillations of normal Fermi gases at Unitarity

Alessio Recati & Sandro Stringari

CNR-INO BEC Center/
Dip. Fisica, Univ. di Trento (I)



Normal Fermi gases at Unitarity

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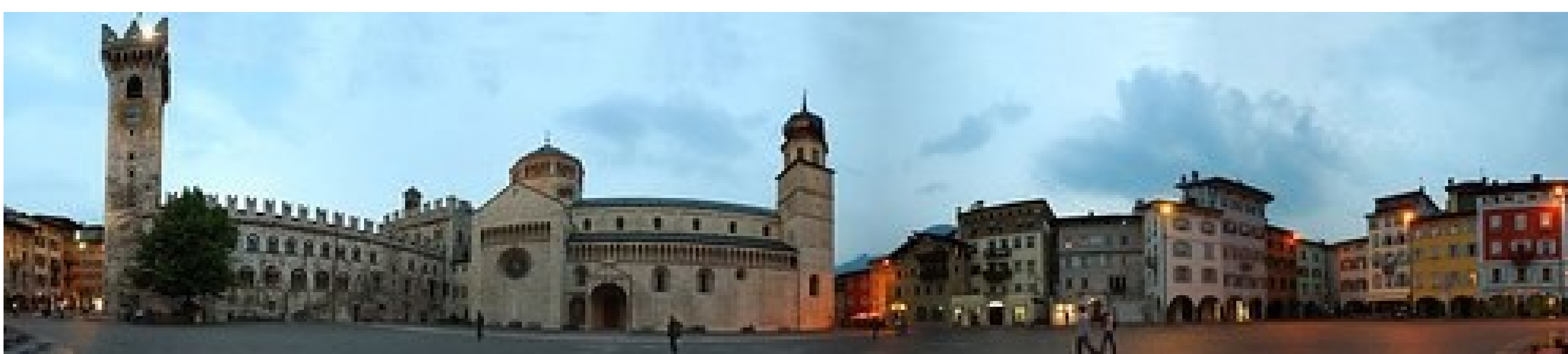
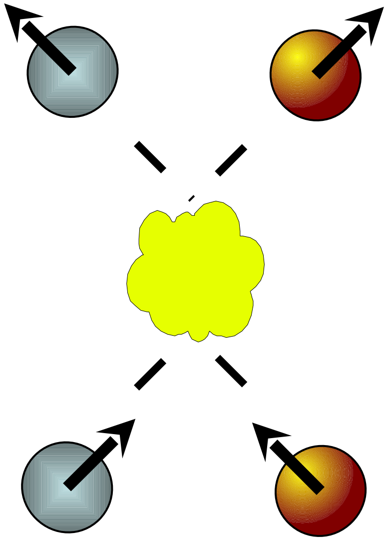
In coll. with
Stefano Giorgini (I), Carlos Lobo (UK)
Roland Combescot, Fred Chevy (F), Chris Pethick (DK)

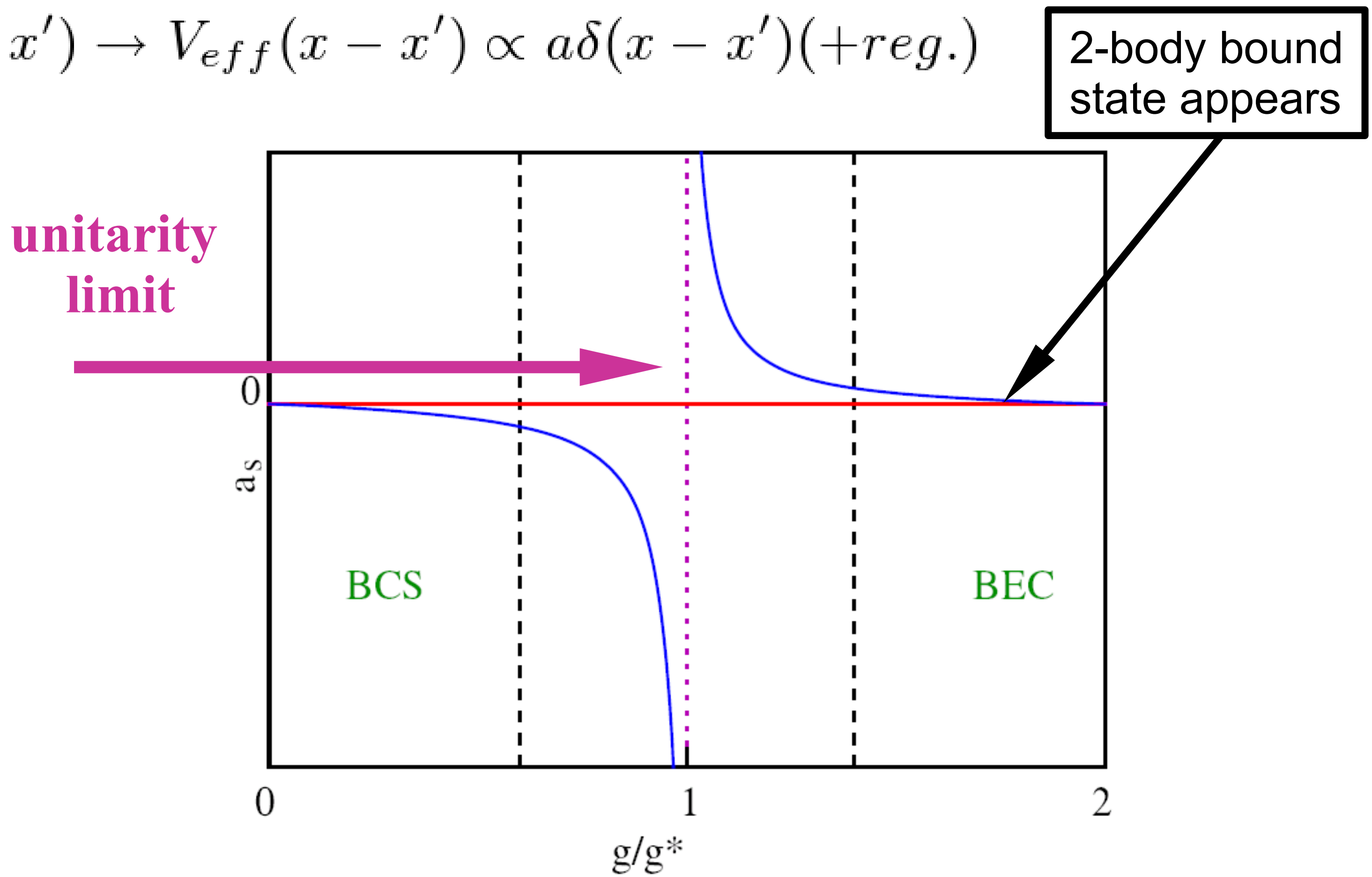


BCS vs Bose-Einstein Condensation

The behaviour of the s-wave scattering length is ***not continous***



$$V(x-x') \rightarrow V_{eff}(x-x') \propto a\delta(x-x')(+reg.)$$



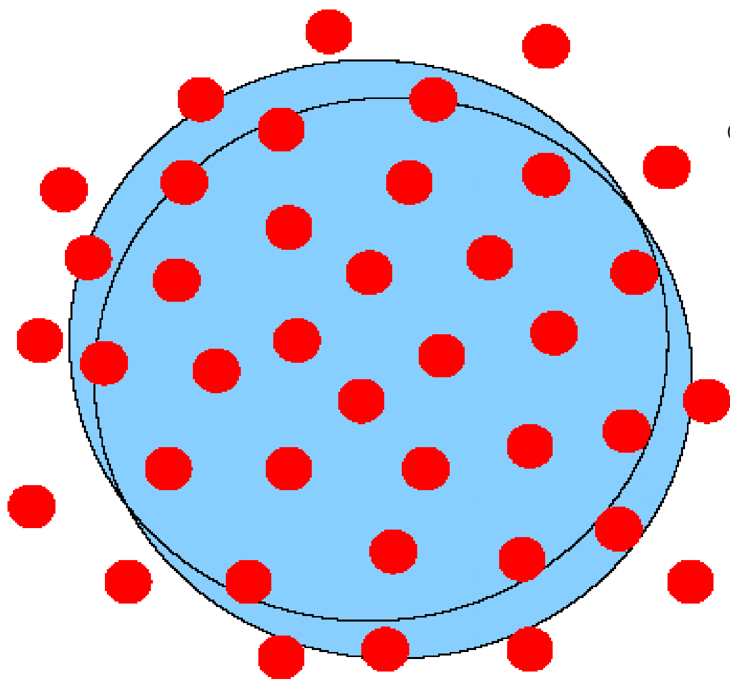
Crossover postulate: even though the scattering length changes abruptly in the many-body problem the ***crossover is smooth***

[Leggett; Nozieres/Schmitt-Rink]

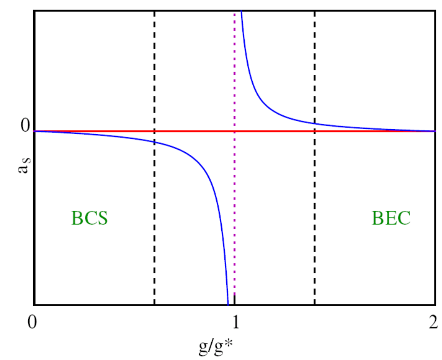
BCS vs Bose-Einstein Condensation

Weak Coupling: $k_F|a_s| \ll 1$
Ovelapping Cooper Pairs

$$\xi_b = \xi_0 = \frac{\hbar v_F}{\pi \Delta_0} \gg k_F^{-1}$$

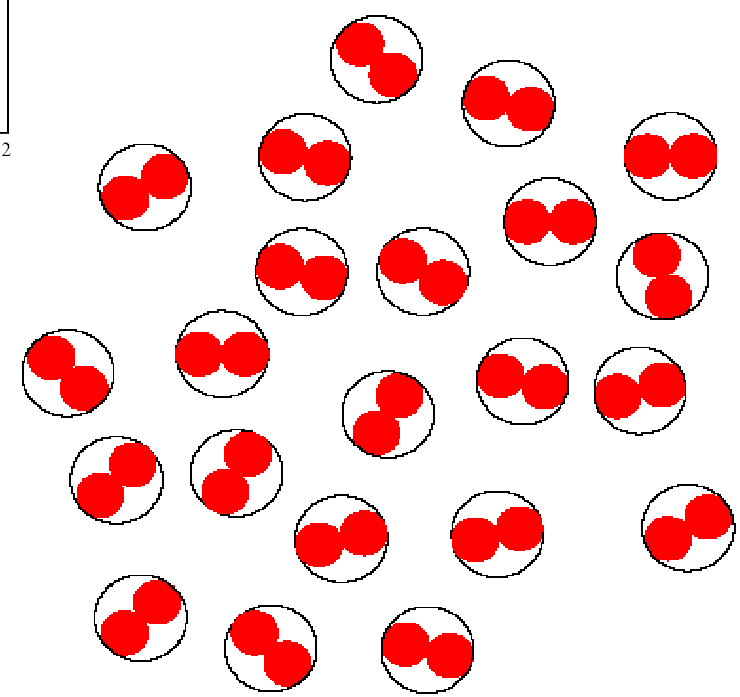


$T^* = T_c^{(BCS)}$



Strong Coupling: $k_F a_s \ll 1$
(Ideal) gas of molecules

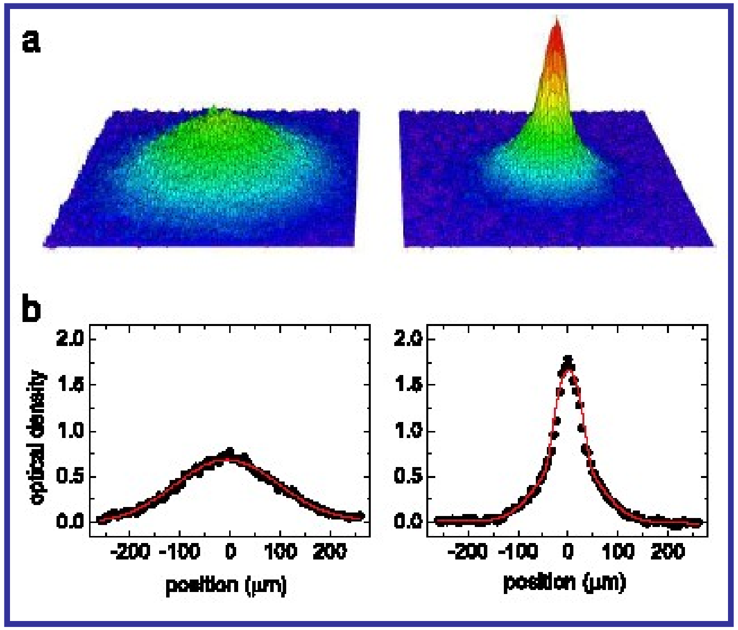
$$\xi_b \sim a_s \ll k_F^{-1} \quad E_b = \frac{\hbar^2}{m a_s^2}$$



$T^* \gg T_c^{(BEC)}$

Note on finite T: Except for very weak coupling (BCS) pairs form and condense at different temperature, ***T^**** and ***T_c***

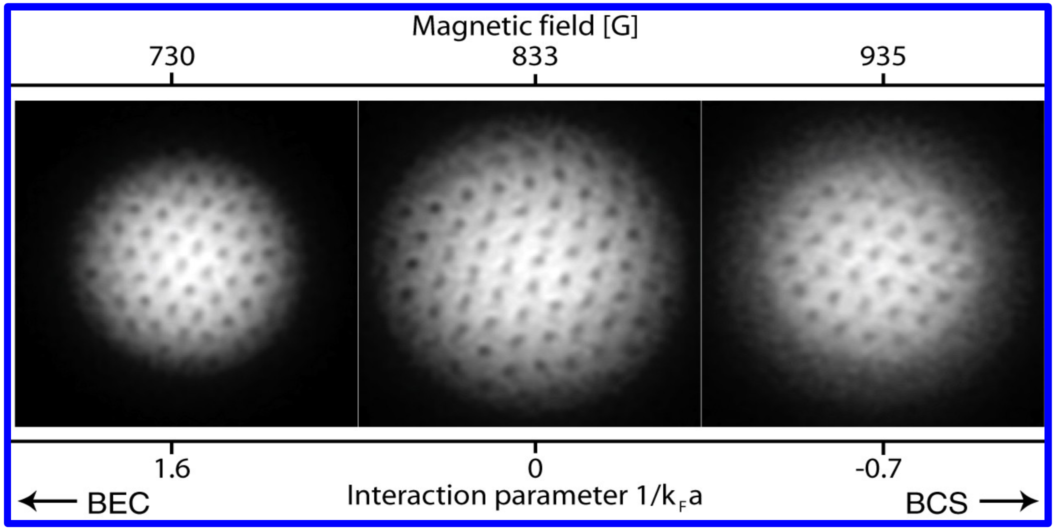
Superfluid fermions



Molecular Bose-Einstein condensation from a fermionic gas

[JILA, Innsbruck, MIT, ENS, RICE, 2003]

Vortex lattice on the BCS-BEC crossover [MIT, 2005]



Observation of High-Tc superfluidity

Indeed T_c/T_F

1) 10^{-5}-10^{-4} conventional SC and ^{3}He

2) 10^{-2} high-Tc SC

3) 0.15 unitary superfluid Fermi gas

Superfluid fermions at unitarity

- The only scales at unitarity are the Fermi energy and the temperature.
- The thermodynamic properties have an “universal” form.

In particular at *T=0*

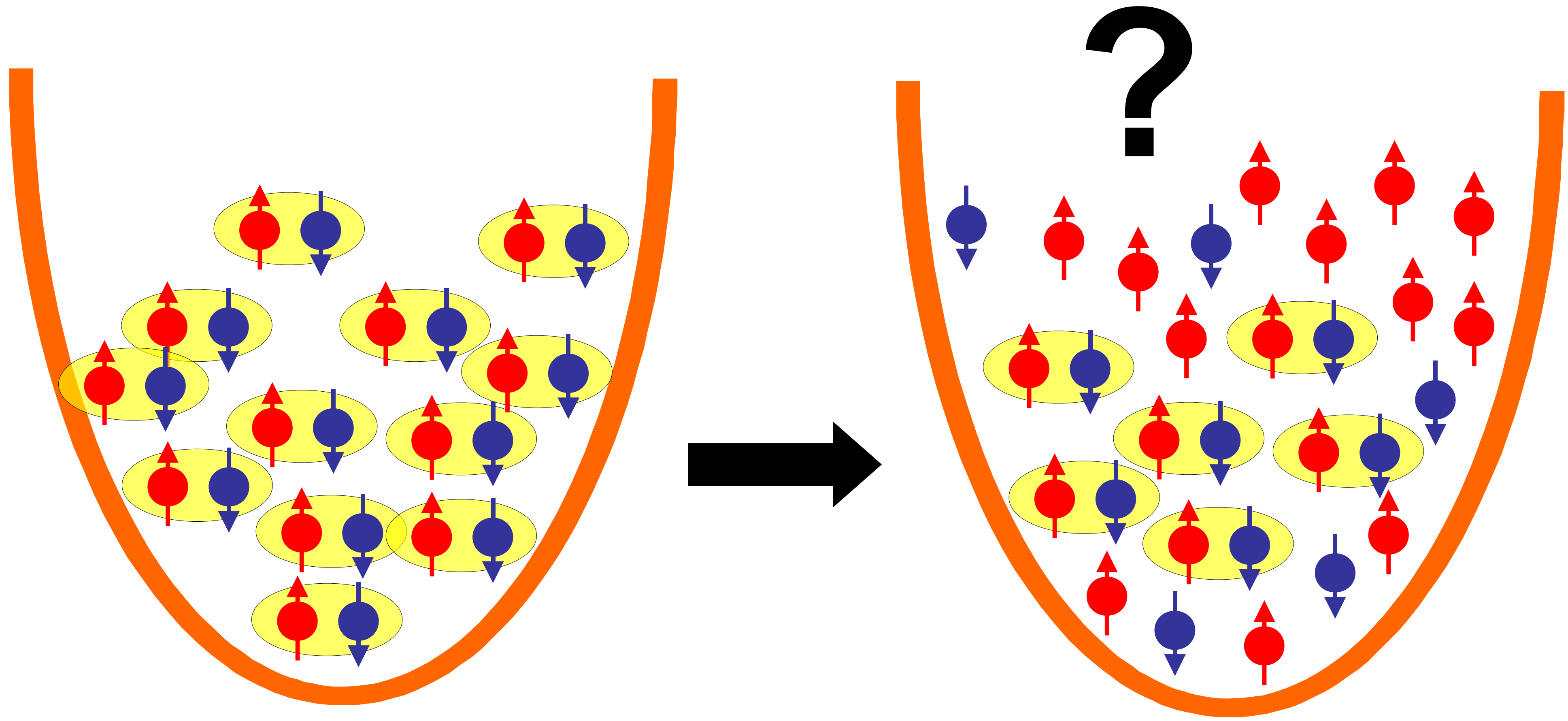
energy density, pressure, chemical potential are ***proportional***
to the ones of an ideal Fermi gas with a density equal
to the superfluid one.

The universal parameter (via Montecarlo & Experiments)

$$\xi_S \simeq 0.42$$

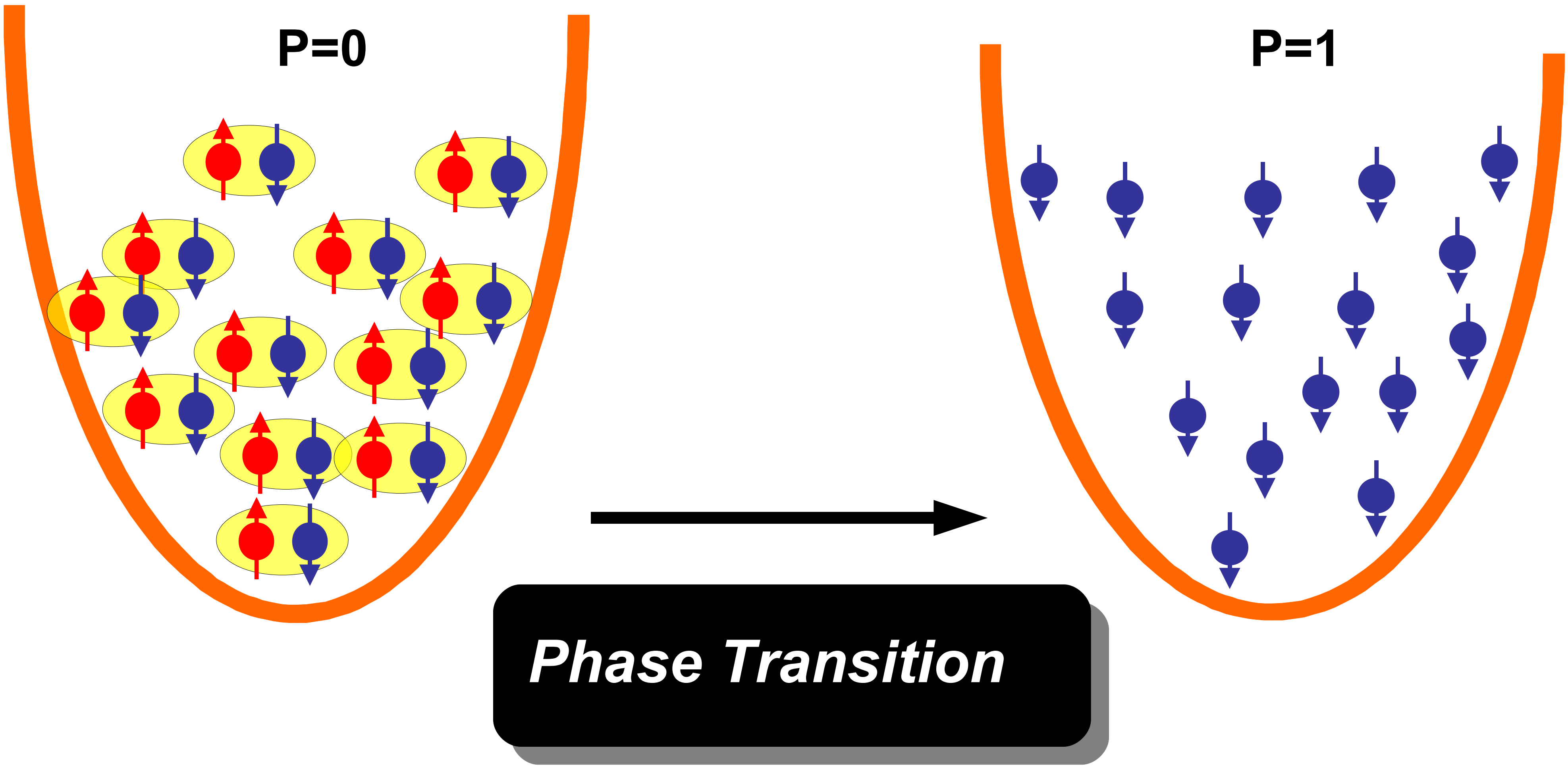
$$\frac{E_S}{N_S} = 2\xi_S \frac{3}{5}\frac{\hbar^2}{2m}(6\pi^2 n_S)^{2/3} \equiv 2\epsilon_S(n_S)$$

Imbalanced Fermi gases at unitarity



Polarization: $P = \dfrac{N_\uparrow - N_\downarrow}{N_\uparrow + N_\downarrow}$

Balanced Fermi gases at unitarity



[Phase Transition to a normal phase for large magnetic field
B. S. Chandrasekhar (1962), A. M. Clogston (1962)]

Experimental evidence of a critical value of P

Normal phase of polarized Fermi gas at unitarity

Assumption:
at high polarization homogeneous phase,
NORMAL FERMI LIQUID: consider a very dilute mixture of spin-↓ atoms immersed in non-interacting gas of spin-↑ atoms

Energy expansion for small concentration $x = \frac{n_\downarrow}{n_\uparrow}$

$$\frac{E(x)}{N_\uparrow} = \frac{3}{5}\epsilon_{F\uparrow}\left(1 - Ax + \frac{m}{m^*}x^{5/3} + \cdots\right) = \frac{3}{5}\epsilon_{F\uparrow}\epsilon(x)$$

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Non interacting gas

single-particle energy

quantum pressure
of a Fermi gas of quasi-particles
with an effective mass

> *A* and *m** determined by solving the N+1 problem:
good approximation is obtained
by single particle-hole excitations

Superfluid-Normal phase coexistence at unitarity

$$\frac{E(x)}{N_\uparrow} = \frac{3}{5}\epsilon_{F\uparrow}\left(1 - Ax + \frac{m}{m^*}x^{5/3} + Bx^2\right) = \frac{3}{5}\epsilon_{F\uparrow}\epsilon(x)$$

interaction between quasi-particles

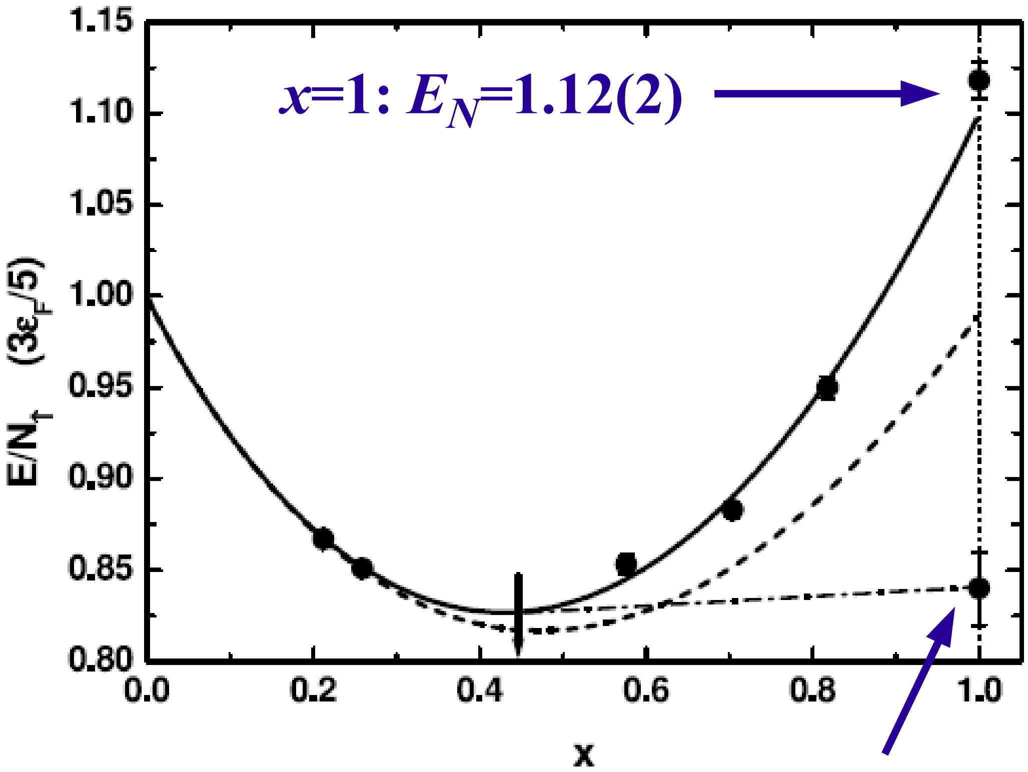
Most recent values using FN-QMC

***A* = 0.99(2)**

***m*/m* = 1.09(3)**

***B* = 0.14**

[S. Pilati and S. Giorgini, Phys. Rev. Lett. ***100****, 030401 (2008)]*



***x*=1: E_N=1.12(2)**

***x*=1: E_S=0.84(2)**

Superfluid-Normal phase coexistence at unitarity

$$\frac{E(x)}{N_\uparrow} = \frac{3}{5}\epsilon_{F\uparrow}\left(1 - Ax + \frac{m}{m^*}x^{5/3} + Bx^2\right) = \frac{3}{5}\epsilon_{F\uparrow}\epsilon(x)$$

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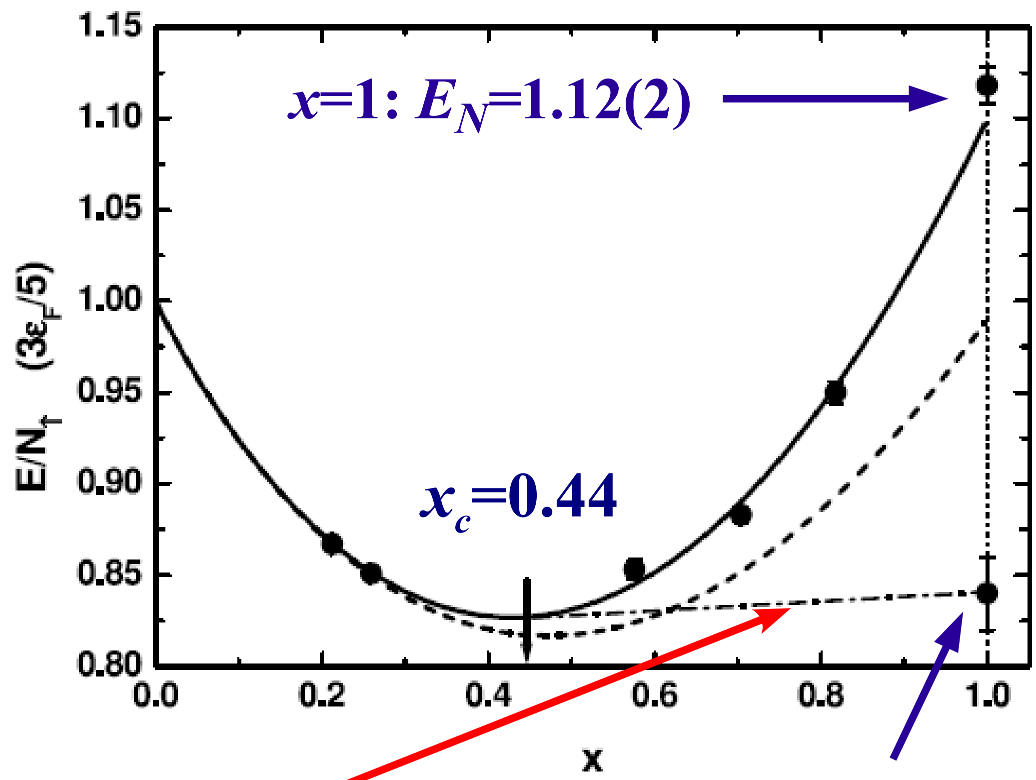

Coexistence line

x=1: E_S=0.84(2)

Critical concentration x_c:

$P_{SF} = P_N$

$$\boxed{\frac{\epsilon'(x_c)}{\epsilon(x_c)} = \frac{5}{3}\,\frac{\epsilon(x_c)^{3/5} - (2\xi_S)^{3/5}}{x_c - 1}}$$

SF	N with x_c=0.44

Phase Separation

Superfluid-Normal phase coexistence at unitarity

$$\frac{E(x)}{N_\uparrow} = \frac{3}{5}\epsilon_{F\uparrow}\left(1 - Ax + \frac{m}{m^*}x^{5/3} + Bx^2\right) = \frac{3}{5}\epsilon_{F\uparrow}\epsilon(x)$$

interaction between quasi-particles

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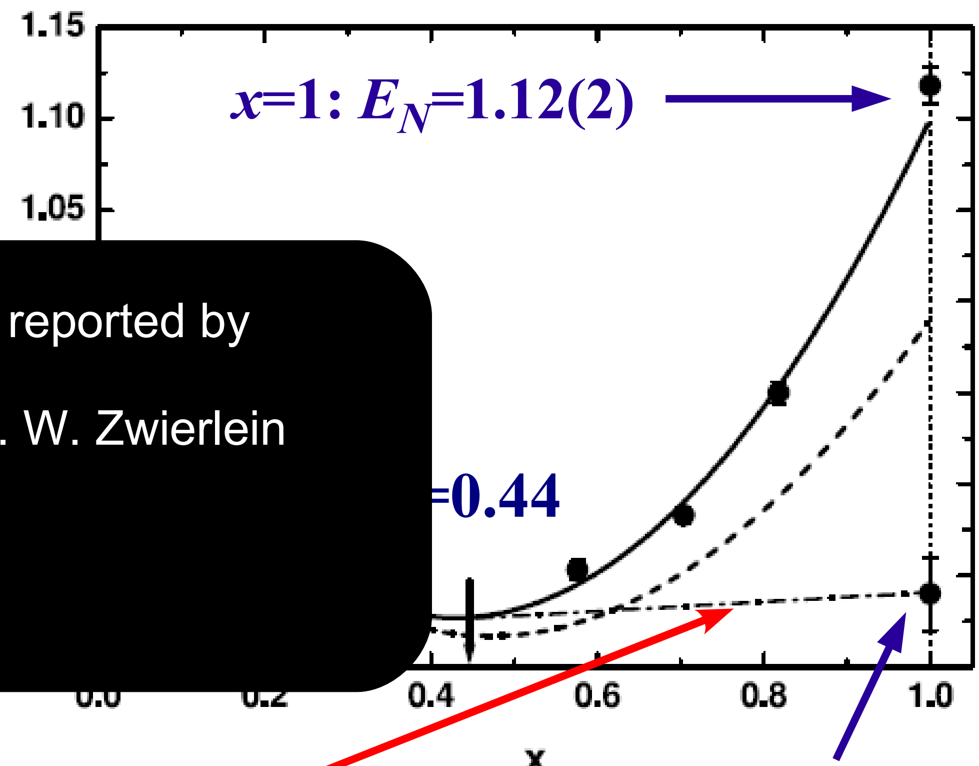


First measurements of the coefficient *A* reported by

A. Schirotzek, C. Wu, A. Sommer, and M. W. Zwierlein
PRL **102**, 230402 (2009)

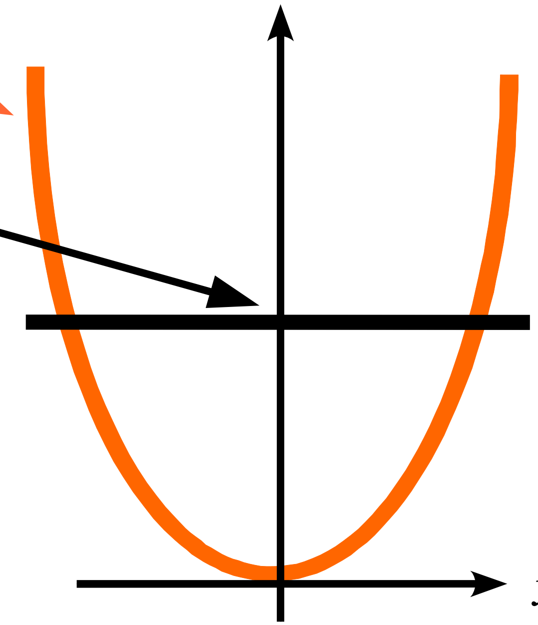
A=1.06(7)

SF	N with x_c=0.44

Phase Separation

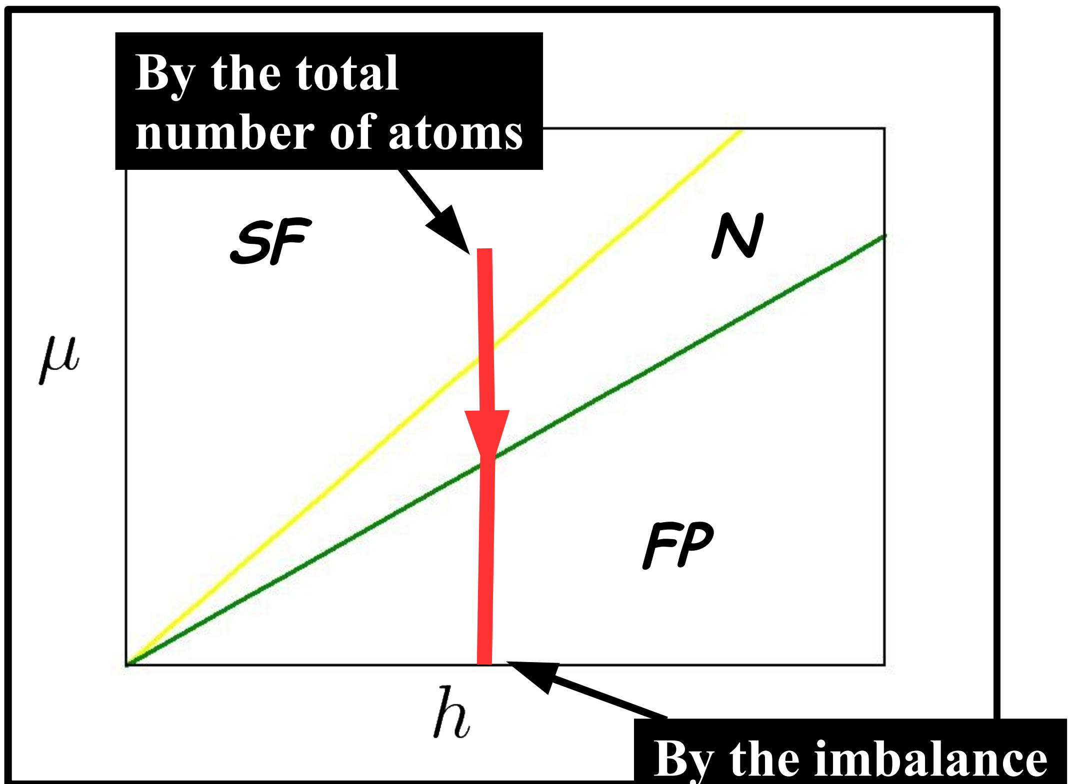
Exploring Phase diagram in the Trap: LDA

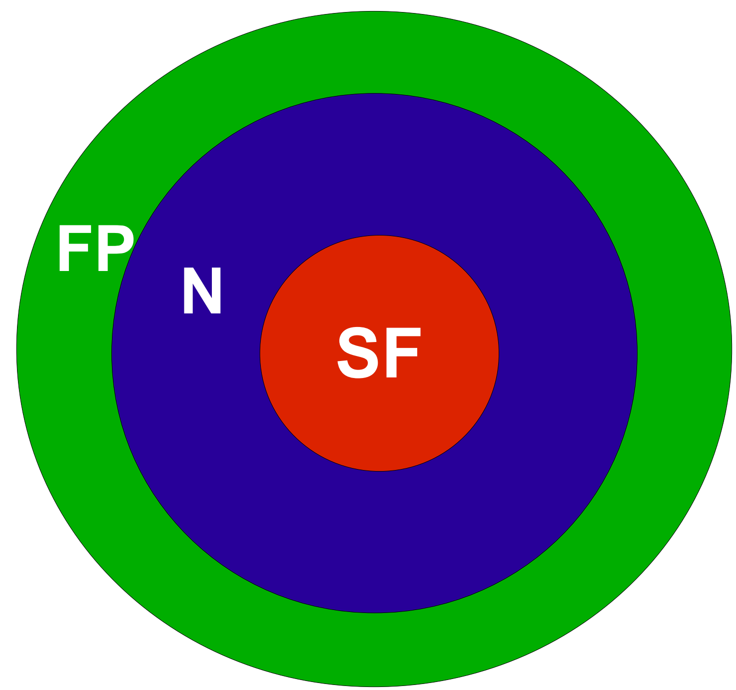
LDA : $$\boxed{\mu_\sigma(\mathbf{x}) = \mu_\sigma^0 - V(\mathbf{x}) = \mu_\sigma^0 - \frac{1}{2}m\omega x^2}$$



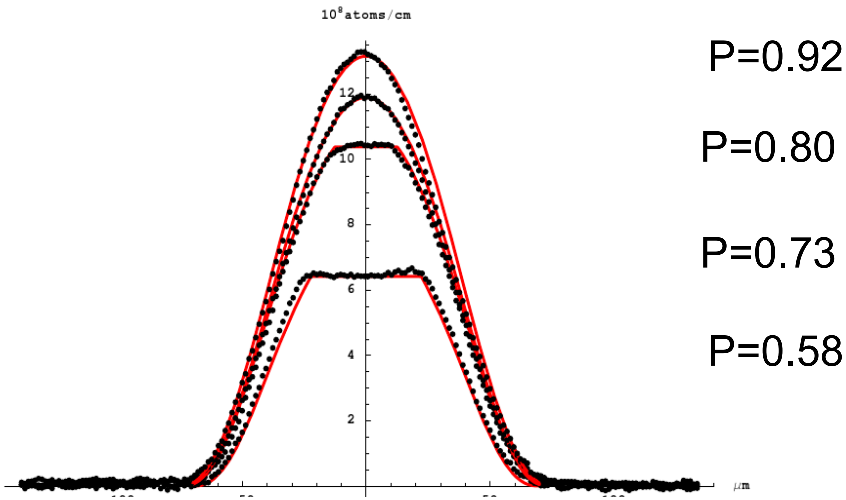
$$\mu(\mathbf{x}) = \mu^0 - \frac{1}{2}m\omega x^2$$ Decreasing outward

$$h(\mathbf{x}) = h^0$$ Constant also inside the trap



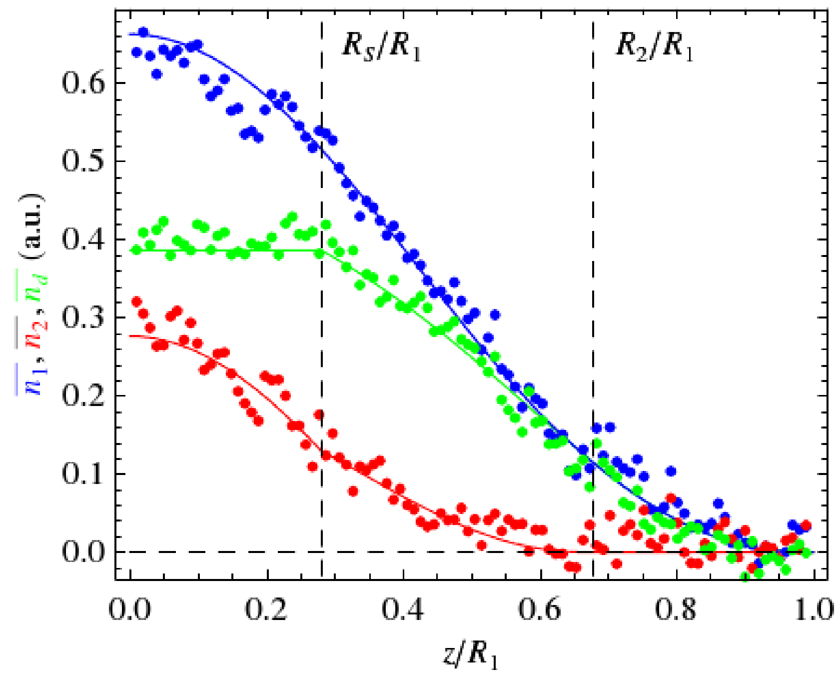


Some Experimental results for trapped gases

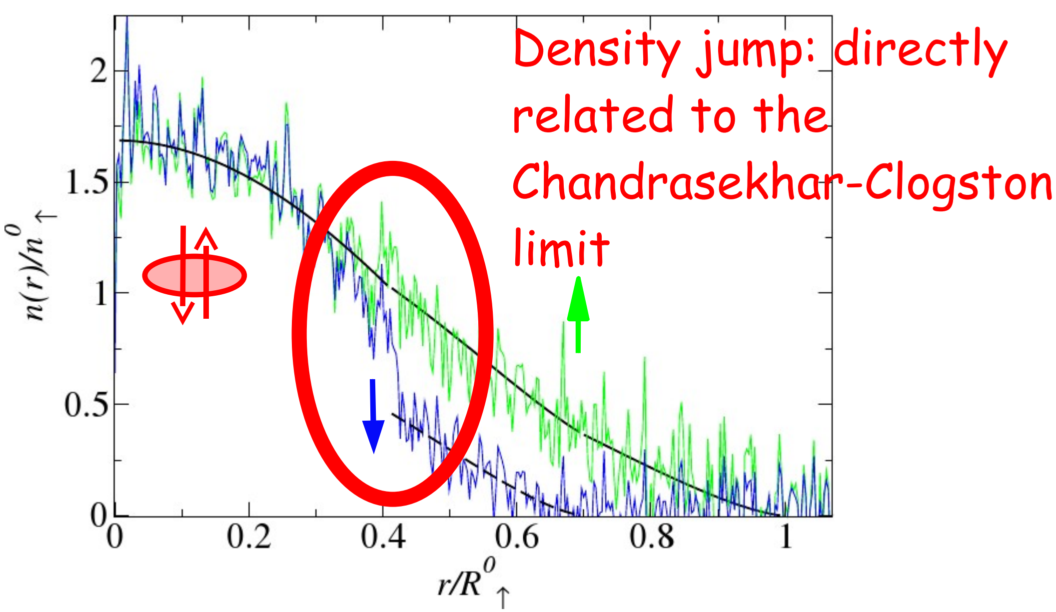


$$n_d(x) = 2\pi \int_{-\infty}^{\infty} d\rho\rho(n_\uparrow(x,\rho) - n_\downarrow(x,\rho))$$

[Exp. data from MIT]



[N. Navon *et al. PRL 103, 18 (2009)*]



Experiments agree (very) well with the description (smooth lines in the figures) of the polarized normalized phase in terms of polarons

[A. Recati, C. Lobo, S.Stringari, PRA **78**, 023633 (2008)]

Polaron modes frequencies

Polaron effective Hamiltonian:

renormalized mass **and** ***trapping potential***

$$H_{sp} = \frac{p^2}{2m^*} + V(\mathbf{r})\left(1 + \frac{3}{5}A\right)$$

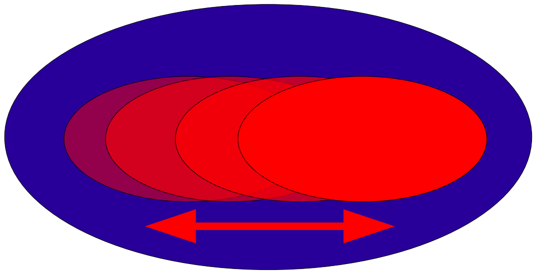
Polaron modes frequencies

Polaron effective Hamiltonian:
renormalized mass* and *trapping potential

$$H_{sp} = \frac{p^2}{2m^*} + V(\mathbf{r})\left(1 + \frac{3}{5}A\right)$$

Spin-dipole mode

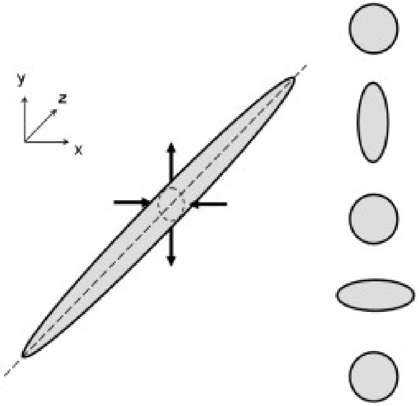
$$\boxed{\omega_D^{(s)} = \omega_i\sqrt{\frac{m}{m^*}(1+(3/5)A)}}$$



$$\simeq 1.26\omega_i$$

Spin-transverse-Quadrupole mode

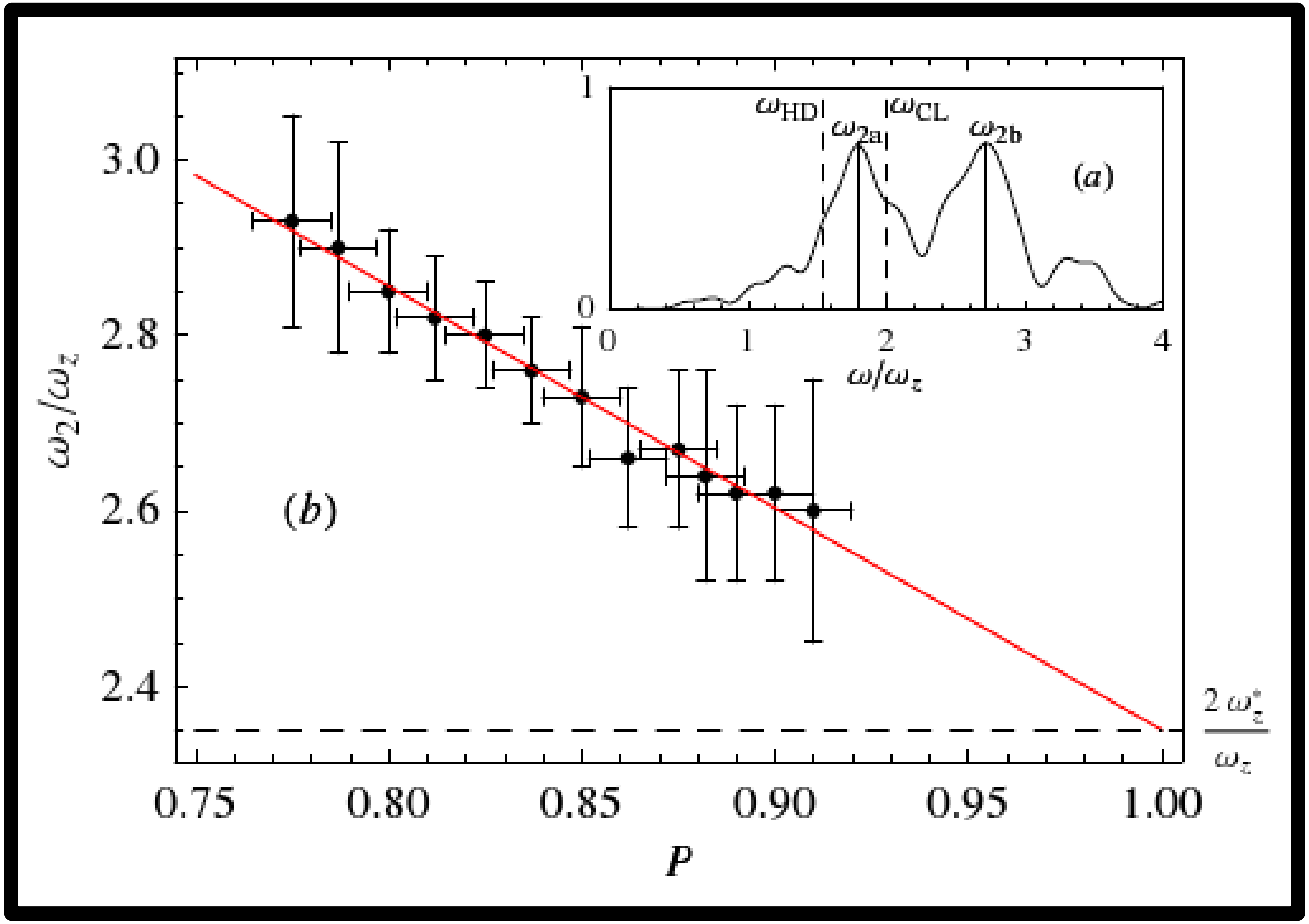
$$\boxed{\omega_Q^{(s)} = 2\omega_\perp\sqrt{\frac{m}{m^*}(1+(3/5)A)}}$$



Altmeyer *(IBK)*

Finite P (many-Polaron) modes frequencies

Quadrupole compressional mode



[S. Nascimbene, *et al.* PRL **103**, 107402 (2009)]

Finite P (many-Polaron) modes frequencies

Method:
Collective oscillation via variational principle $\delta S = 0$ applied to the action

$$S = \int dt \langle \Psi | H - i\hbar\partial_t | \Psi \rangle = \int dt (E - \langle \Psi | i\hbar\partial_t | \Psi \rangle)$$

We take the scaling ansatz (with 4+4 time dependent parameters):

$$\psi_\sigma(r,z,t) = \mathrm{e}^{-1/2(2\alpha_\sigma+\beta_\sigma)} \psi^0_\sigma(\mathrm{e}^{-\alpha_\sigma} r, \mathrm{e}^{-\beta_\sigma} z) \mathrm{e}^{i(\chi_\sigma r^2 + \xi_\sigma z^2)}$$

1) Axially symmetric
2) Compressional modes of axial/radial nature

Collective modes: equation of motion given by the second order expansion of *S* w.r.t. the scaling parameters (4-by-4 linear system).

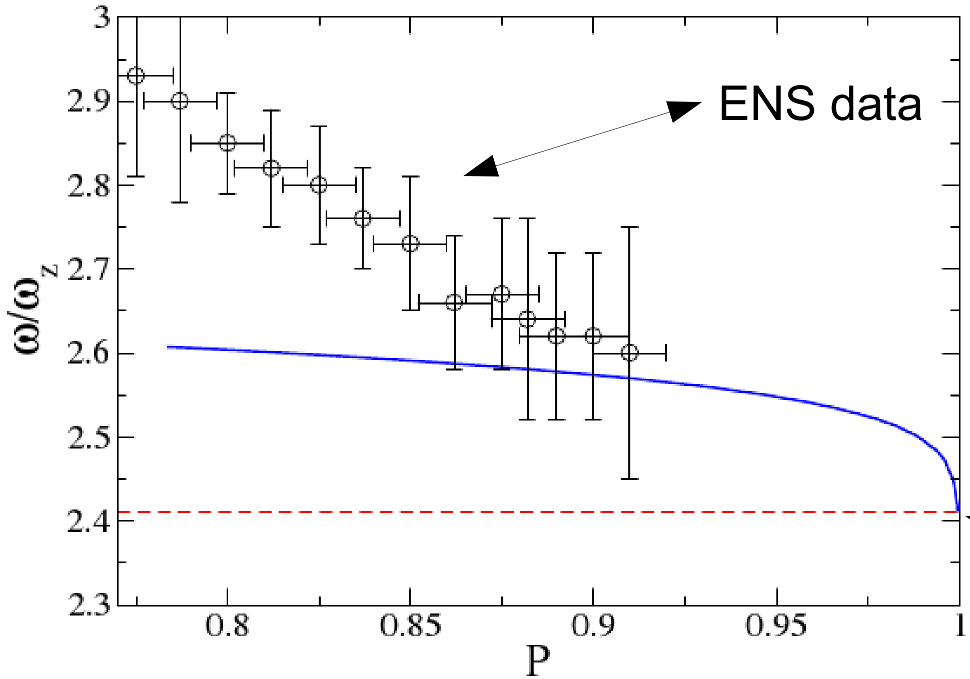
Finite P (many-Polaron) modes frequencies

First order expansion (virial- like expressions)

$$-\frac{4}{3}\int \frac{\tau_\uparrow}{2m} + N_\uparrow m\omega_\perp^2 \langle r^2\rangle_\uparrow - N_\downarrow \frac{\hbar^2(6\pi^2)^{2/3}}{2m} A\left(\langle r\partial_r n_\uparrow^{2/3}\rangle_\downarrow + \frac{4}{3}\langle n_\uparrow^{2/3}\rangle_\downarrow\right) = 0$$

$$-\frac{4}{3}\int \frac{\tau_\downarrow}{2m^*} + N_\downarrow m\omega_\perp \langle r^2\rangle_\downarrow + N_\downarrow \frac{\hbar^2(6\pi^2)^{2/3}}{2m} A\langle r\partial_r n_\uparrow^{2/3}\rangle_\downarrow = 0$$

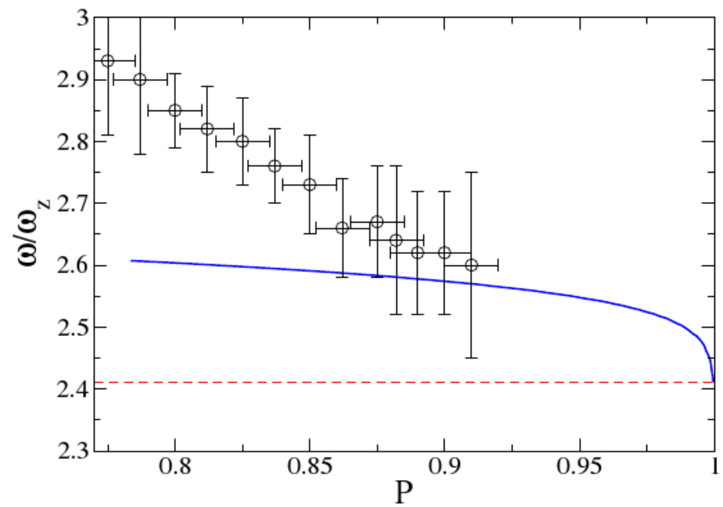
Results for the axial compressional mode



Single polaron

$$\sqrt{\left(1+\frac{3}{5}A\right)\frac{m}{m^*}}$$

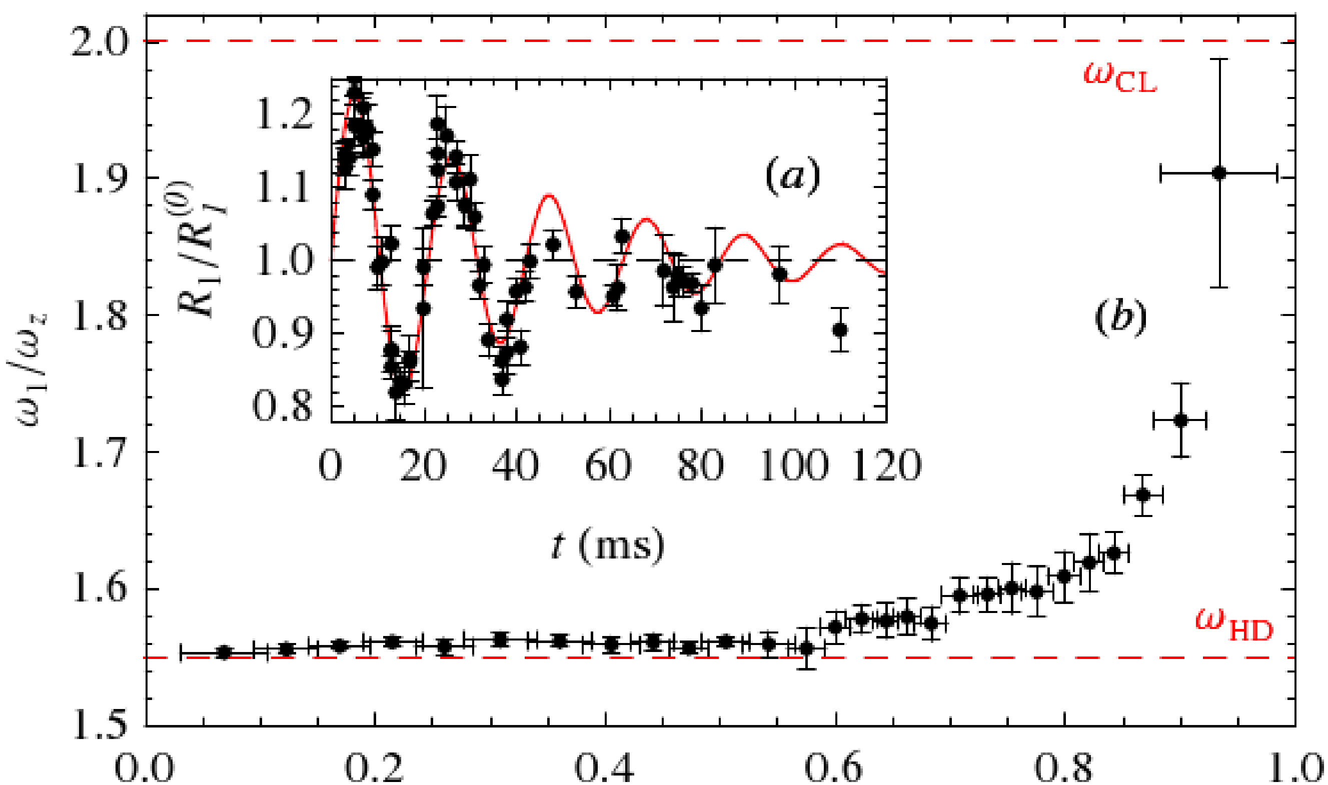
Finite P (many-Polaron) modes frequencies



Possible issue with the comparison:
- Theory result for the **collisionless** regime.

- In the experiment **collision very effective**:
  Difficult to see minority oscillation

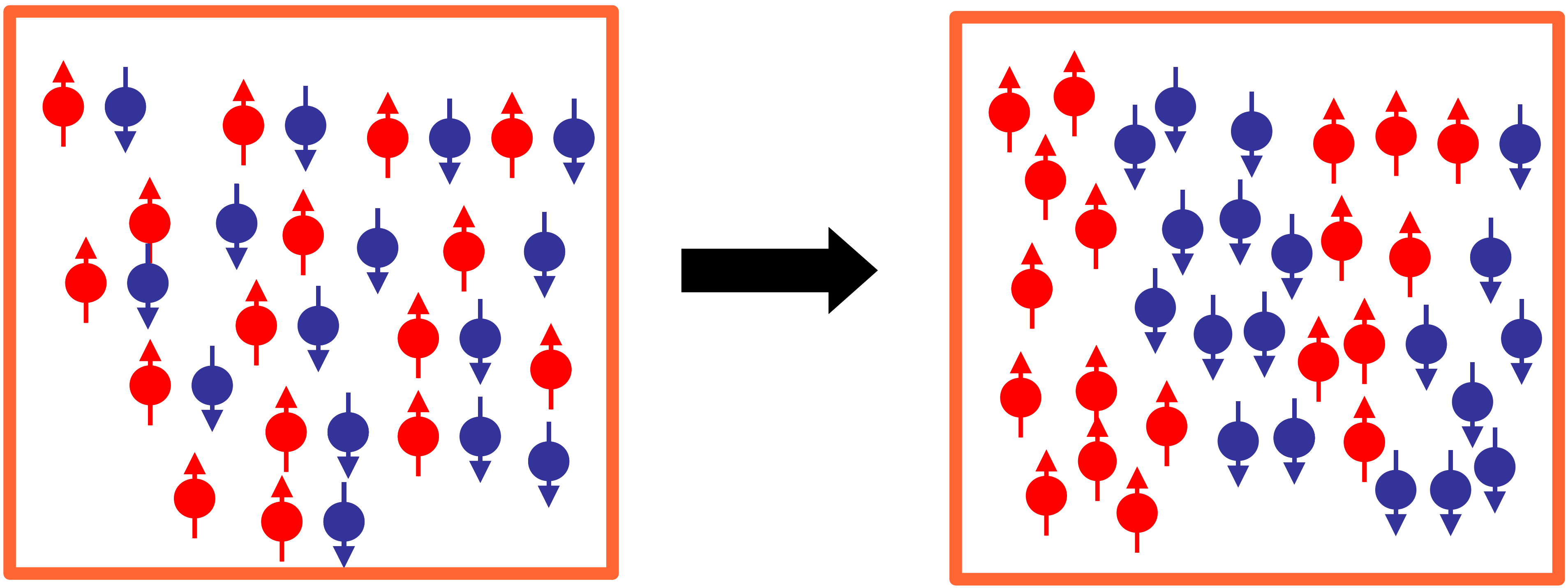
  Majority component oscillation
  not in the colisionless regime



Repulsive Fermi gas vs. Itinerant Ferromagnetism

For $a>0$ and $k_F\, a$ small: **Fermi liquid**

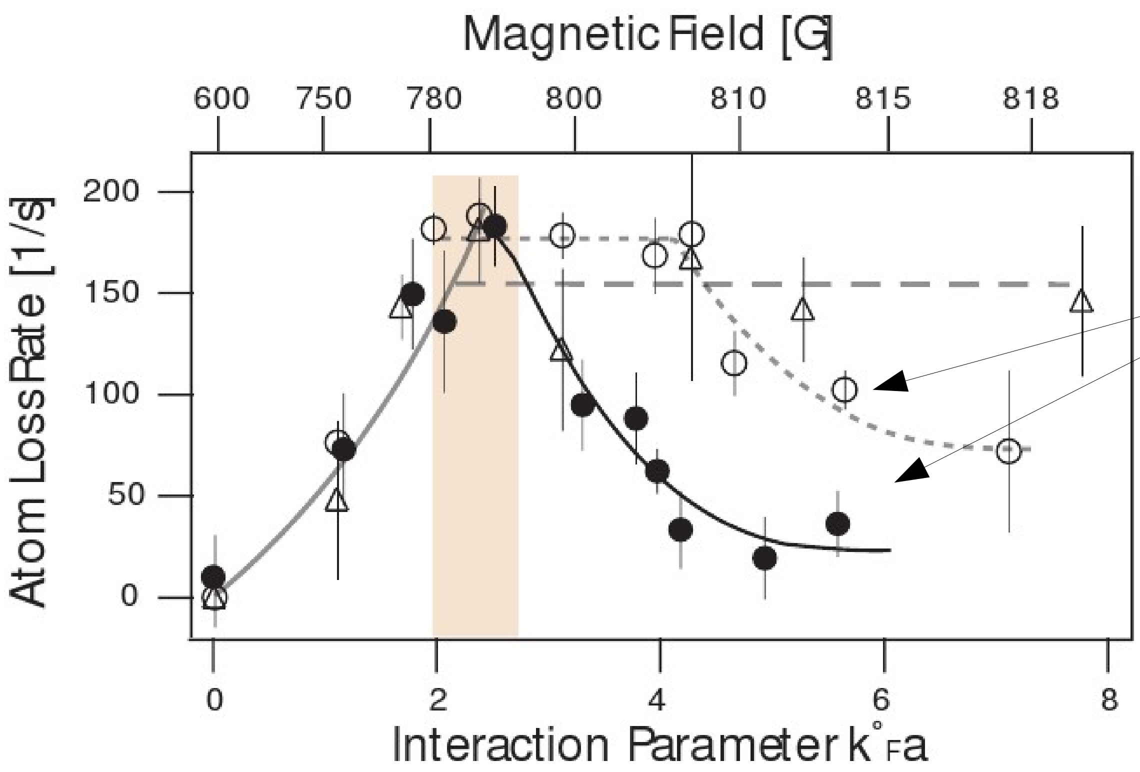
When the intercation increases one can hope to reach the so-called **Itinerant Ferromagnetic Phase**



“Fermi liquid” “Itinerant ferromagnetism”

Repulsive Fermi gas vs. Itinerant Ferromagnetism

Recent experiment at MIT [G.-B. Jo et al., Science **325**, 1521 (2009)]



Decrease due probably to (local) polarization of the gas - first in the center

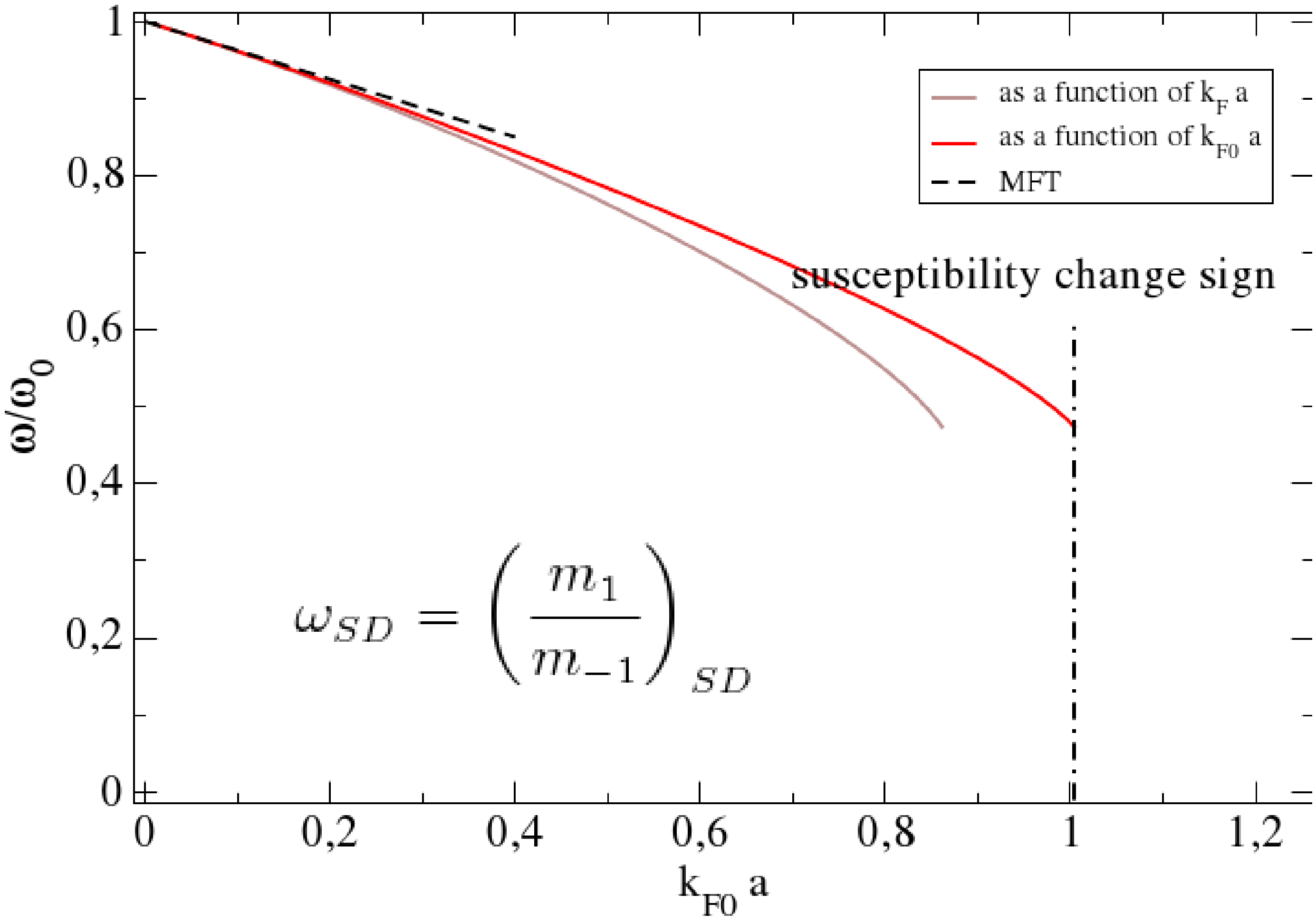
Note that is not a direct measurement of any magnetic property.
How can we get more insight?

Can we get, e.g., any infos on the magnetic susceptibility of the system?

$$\boxed{\chi = n^2 \left(\frac{\partial^2 A/V}{\partial P^2} \right)^{-1}}$$

Spin-dipole mode of a repulsive Fermi gas

Using the previous energy functional to calculate the spin-dipole frequncy in a trap:



$$\omega_{SD} = \left(\frac{m_1}{m_{-1}} \right)_{SD}$$

$$m_{-1} = \int z^2 n^2 \left(\frac{\partial^2 \epsilon}{\partial P^2} \right)^{-1}$$

Conclusions

Normal phase of polarized Fermi gas at Unitarity
[A.Recati, S.Stringari, PRA**82**, 013635 (2010)]

An elastic theory (collisionless) of the mode of a Fermi gas at Unitarity as a function of its polarization gives a behaviour understandable in terms of the size of the minority cloud, BUT in diseagreement with recent experimets.

Are collisions responsible for?

Measuring transverse modes could give a partial answer and is a very important test for the theory of the normal phase when applied to dynamics

Normal phase of repulsive Fermi gas and itinerant ferromagnetism
[A.Recati, S.Stringari, arXiv:1007.4504]

The spin dipole mode frequency – and the spin fluctuations - of a repulsive Fermi gas represent a direct measurement of magnetic properties of such a system.

We calculate it within MF to O(k_F a) and to all orders using a functional theory for *P~0* built using the available MC data.

Is the lifetime of the system long enough? Probably.

ost-Doc position vailable!

A <u>new experimental activity</u> on ultracold atoms is starting at the CNR- BEC Centre, University of Trento

Focus will be on:

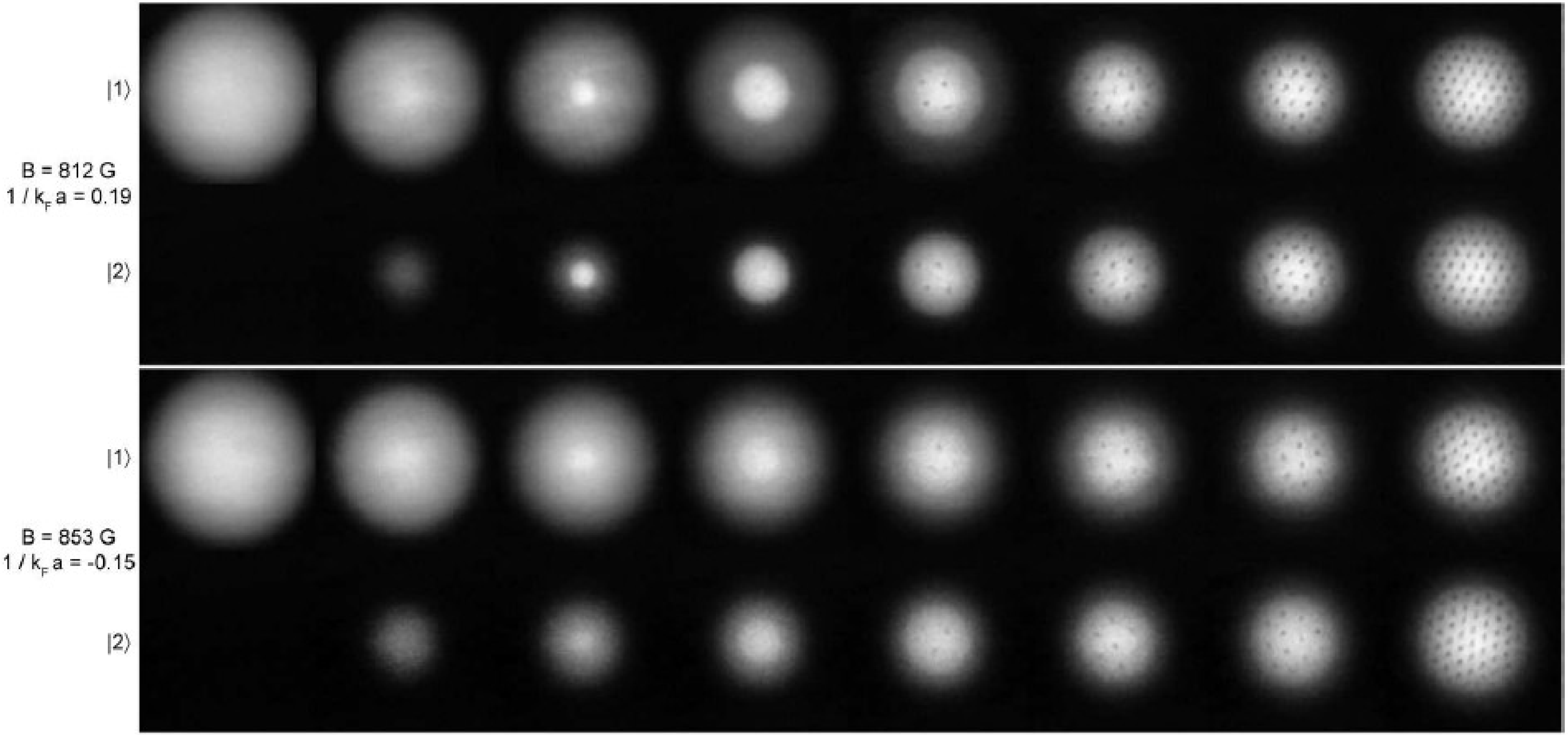
1) pure and mixed quantum gases (Fermi - Bose, Bose – Bose)

2) Fermionic superfluidity

3) transport phenomena

Contact: GABRIELE FERRARI ferrari@lens.unifi.it

Recent Experiments on imbalanced Fermi gases at unitarity



MIT, Science **311**, 492 (2006)

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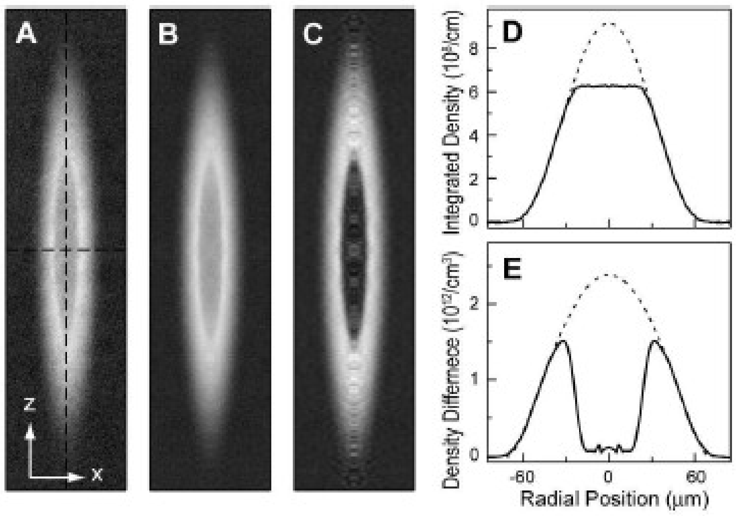
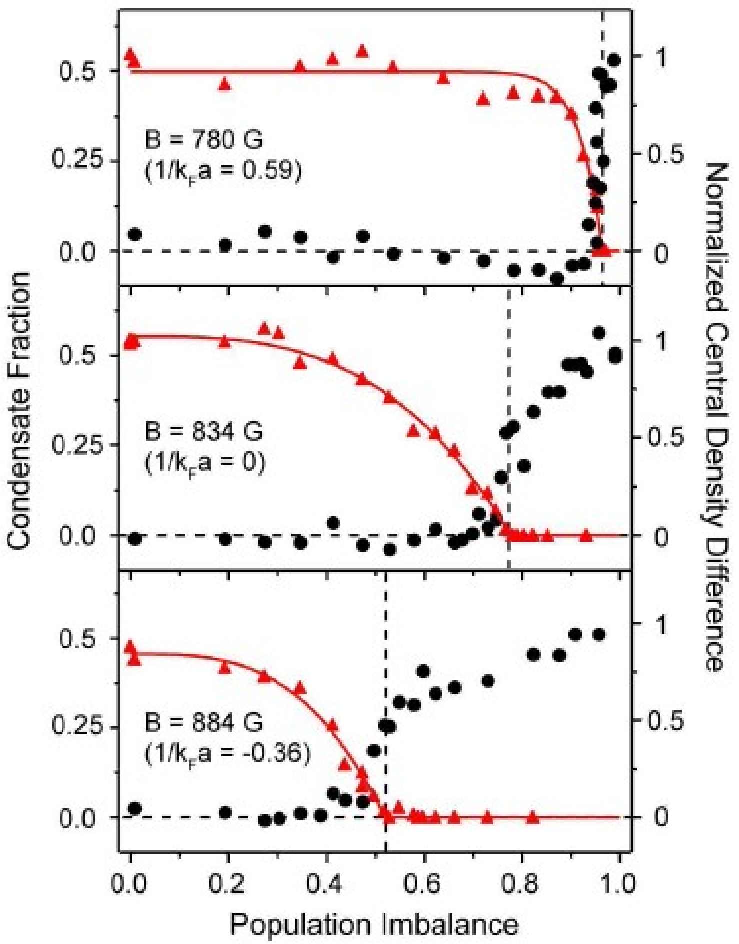




BEC

Unitarity

BCS

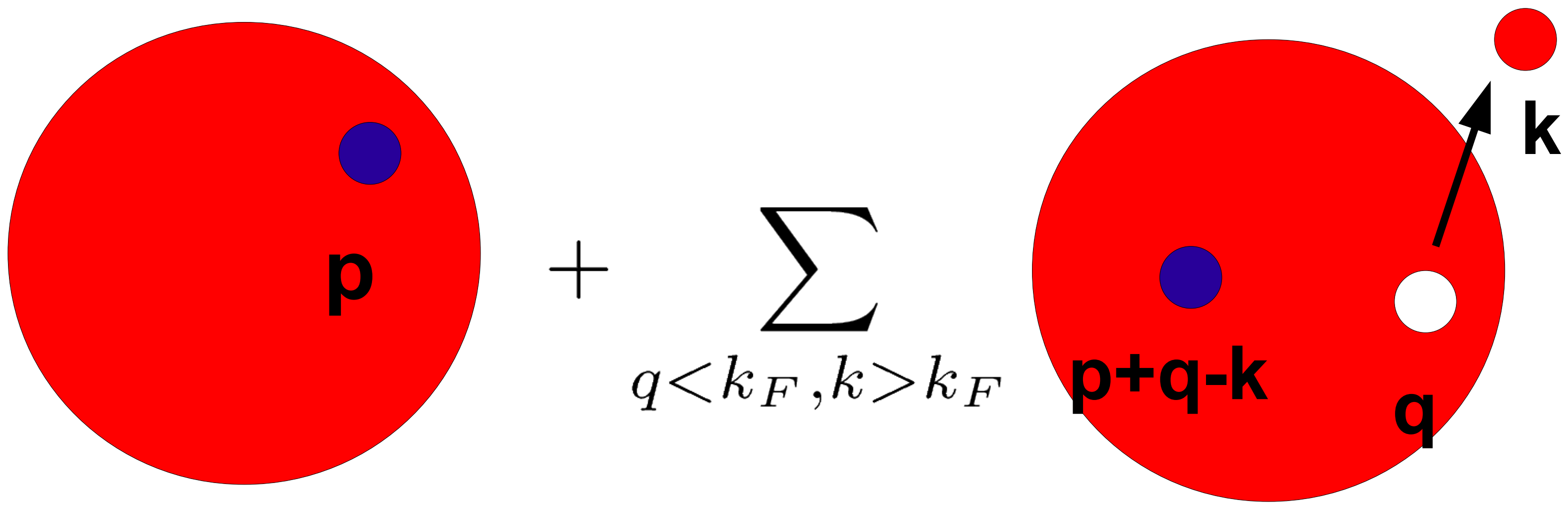
[MIT, Phys. Rev. Lett. **97**, 030401 (2006)]

Normal phase of polarized Fermi gas at unitarity

Consider a SINGLE down atom interacting with an ideal Fermi gas (up-atoms).

Variational Ansatz (single particle hole excitations):

$$\boxed{|\psi\rangle = \phi_0 |\mathbf{p}\rangle_\downarrow \, |0\rangle_\uparrow + \sum_{q<k_F}^{k>k_F} \phi_{\mathbf{qk}} |\mathbf{p}+\mathbf{q}-\mathbf{k}\rangle_\downarrow \, c^\dagger_{\mathbf{k}_\uparrow} \, c_{\mathbf{q}_\uparrow} \, |0\rangle_\uparrow}$$



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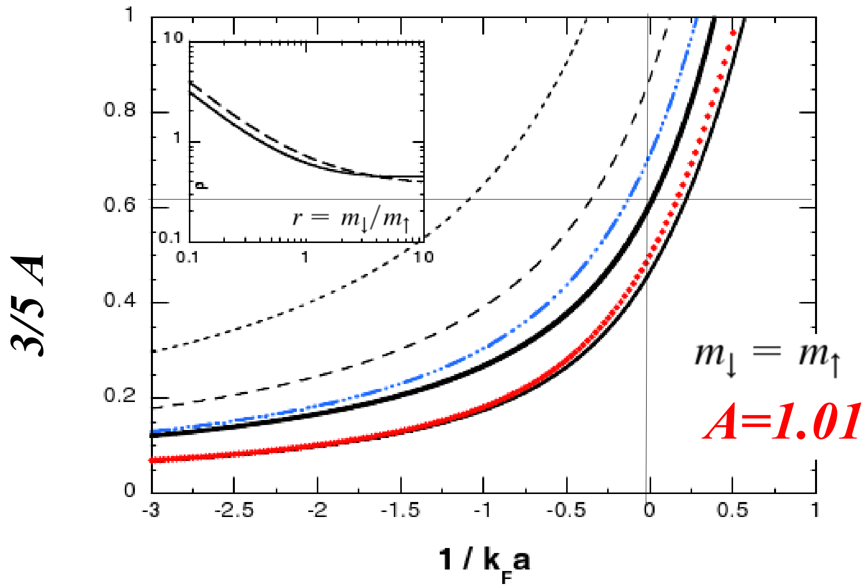

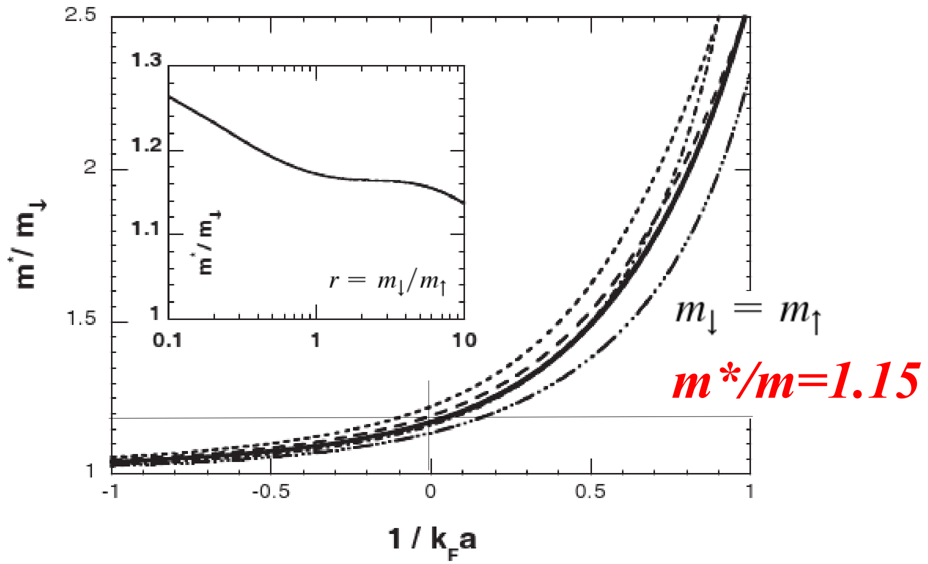

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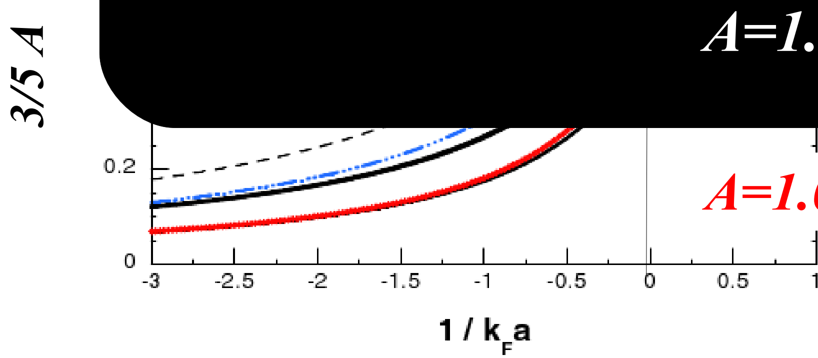
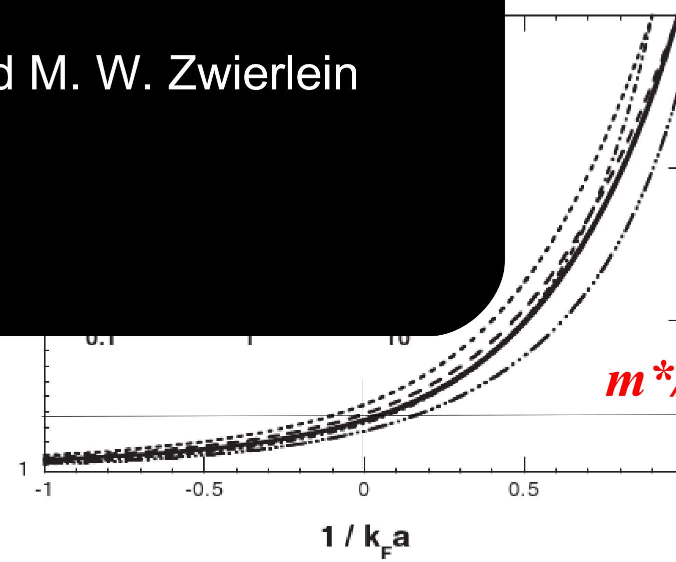
First measurements of the coefficient *A* reported by

A. Schirotzek, C. Wu, A. Sommer, and M. W. Zwierlein
arXiv:0902.3021

A=1.06(7)



A=1.01



m*/m=1.15

Note: it is equivalent to a T-matrix approach

$$\omega - \epsilon_{\downarrow,k} + \mu_\downarrow - \Sigma(k,\omega) = 0 \quad \Rightarrow \quad \boxed{\mu_\downarrow = \Sigma(0,0) \;\; \& \;\; \frac{m^*}{m_\downarrow} = \frac{1 - \frac{\partial \Sigma}{\partial \omega}}{1 - 2m_\downarrow \frac{\partial \Sigma}{\partial k^2}}}$$

Finite P (many-Polaron) modes frequencies

Method:
Collective oscillation via variational principle $\boxed{\delta S = 0}$ **applied to the action**

$$S = \int dt \langle \Psi | H - i\hbar\partial_t | \Psi \rangle = \int dt (E - \langle \Psi | i\hbar\partial_t | \Psi \rangle)$$

We write the energy functional as:

Equilibrium:
Normal Phase Energy Functional

$$\begin{aligned} E &= \sum_\sigma \int d\mathbf{x} \left(\frac{\tau_\sigma}{2m} + \frac{m}{2}(\omega_\perp^2 r^2 + \omega_z^2 z^2) n_\sigma \right) \\ &+ \frac{3}{5} A \frac{\hbar^2 (6\pi^2)^{2/3}}{2m} \int d\mathbf{x} n_\downarrow n_\uparrow^{2/3} + a \int d\mathbf{x} \left(\frac{\tau_\downarrow}{2m} - \cancel{\frac{n_\downarrow}{2m} \frac{j_\uparrow^2}{n_\uparrow^2}} \right) \end{aligned}$$

$$\boxed{\tau_\sigma = \hbar^2 (6\pi^2 n_\sigma)^{2/3} n_\sigma}$$

counter current term
(Galilean Invariance)

Decaying time of the collective modes

We consider the *momentum relaxation* of an homogeneous highly polarized Fermi gas.

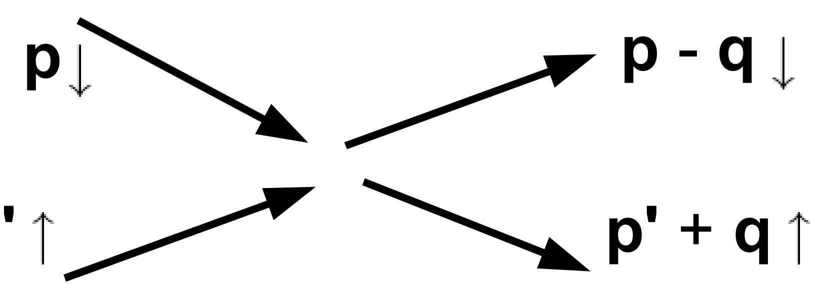
$$\frac{d\mathbf{P}_\downarrow}{dt} = -\frac{\mathbf{P}_\downarrow}{\tau_\mathbf{p}}$$

The minority component have a mean momentum **k** with respect to the majority one: total momentum per unit volume $\mathbf{P}_\downarrow = n_\downarrow \mathbf{k}$

$$\boxed{\begin{aligned}\frac{d\mathbf{P}_\downarrow}{dt} = -2\pi\frac{|U|^2}{V^3}\sum_{\mathbf{p},\mathbf{p}',\mathbf{q}} \mathbf{p}[n_p n_{p'}(1-n_{\mathbf{p}-\mathbf{q}})(1-n_{\mathbf{p}'+\mathbf{q}})- \\ n_{\mathbf{p}-\mathbf{q}} n_{\mathbf{p}'+\mathbf{q}}(1-n_p)(1-n_{p'})]\delta(\epsilon_p+\epsilon_{p'}-\epsilon_{\mathbf{p}-\mathbf{q}}-\epsilon_{\mathbf{p}'+\mathbf{q}})\end{aligned}}$$

$$n_{\mathbf{p}\downarrow} = f[\beta(\epsilon_{p\downarrow} - \mathbf{p}\cdot\mathbf{v} - \mu_\downarrow)]$$

$$\epsilon_{p\downarrow} = p^2/2m^*_\downarrow$$



$$\epsilon_{p'\uparrow} = p'^2/2m_\uparrow$$

$$n_{p'\uparrow} = f[\beta(\epsilon_{p'\uparrow} - \mu_\uparrow)]$$

Decaying time of the collective modes

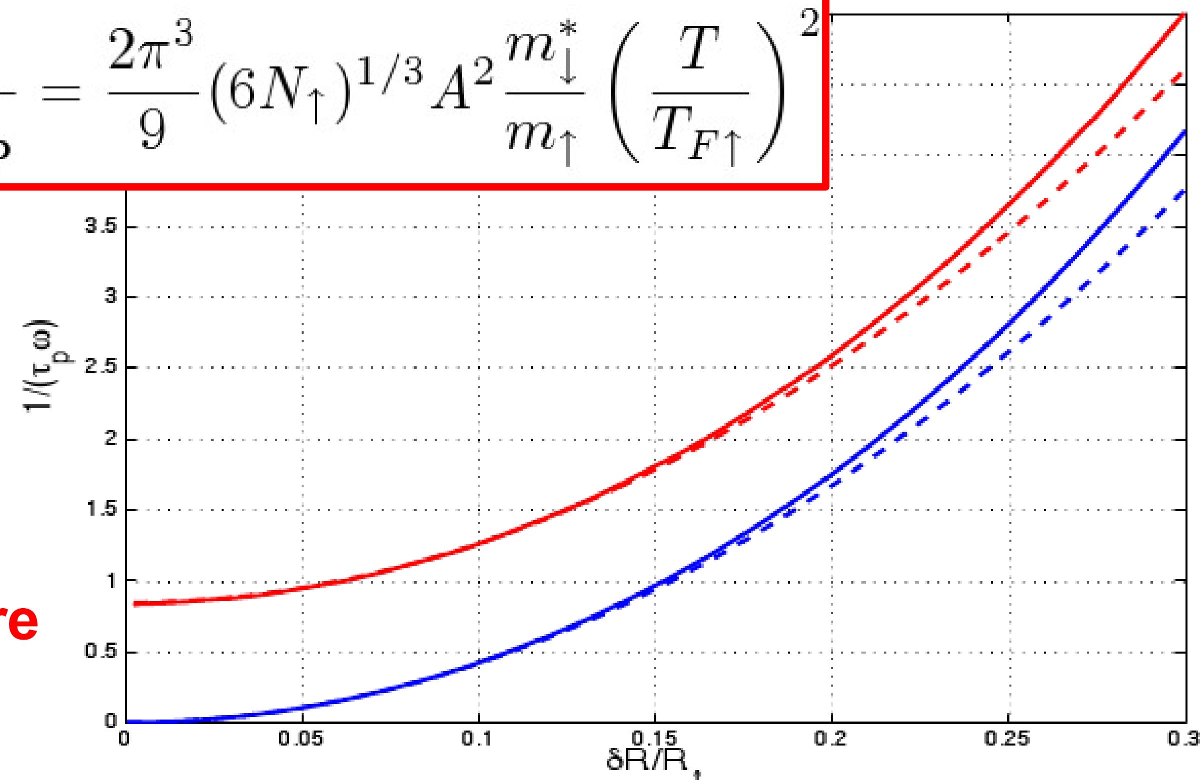
$$\begin{cases} \omega_D \tau_{\mathbf{p}} \gg 1 \\ \omega_D \tau_{\mathbf{p}} \ll 1 \end{cases}$$

Collisionless regime: possible to see the dipole mode

Hydrodynamic regime: the dipole mode overdamped

$$\boxed{\delta R/R_{\downarrow} \ll T/T_{F\downarrow} : \frac{1}{\omega \tau_{\mathbf{p}}} = \frac{2\pi^3}{9}(6N_{\uparrow})^{1/3} A^2 \frac{m^*_{\downarrow}}{m_{\uparrow}} \left(\frac{T}{T_{F\uparrow}}\right)^2}$$

MIT lowest temperature



$$\boxed{T = 0 : \frac{1}{\omega \tau_{\mathbf{p}}} = \frac{8\pi}{25}(6N_{\uparrow})^{1/3} A^2 \frac{m^*_{\downarrow}}{m_{\uparrow}} \left(\frac{T_{F\downarrow}}{T_{F\uparrow}}\right)^2 \left(\frac{\delta R}{R_{\uparrow}}\right)^2}$$

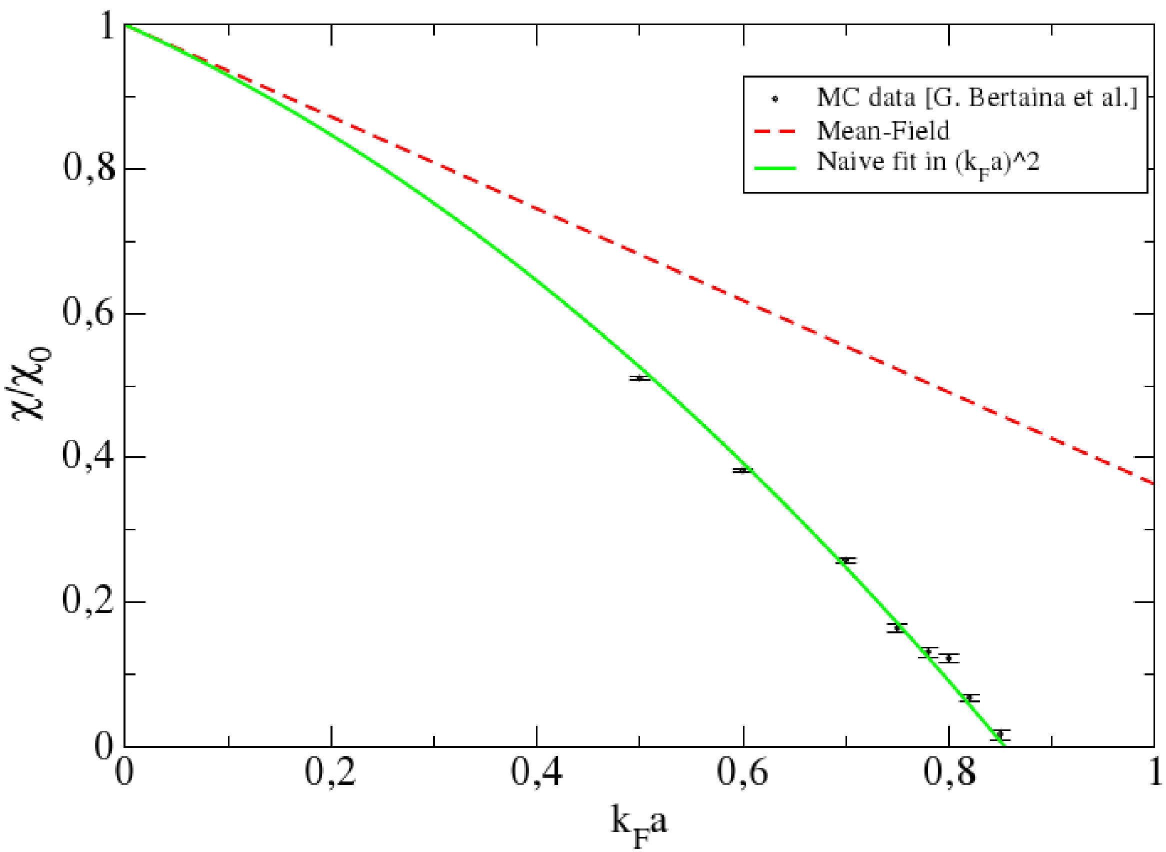
Spin-dipole mode of a balanced Fermi gas

Interestingly with the same parameter and a dimensional argument we can fit pretty well also the spin susceptibility!

$$\frac{E}{V} = \frac{E_{MFT}}{V} + \frac{3}{5} N \epsilon_F C_E (k_F a)^2 (1-P)^{7/6} (1+P)^{7/6}$$

$$\frac{\chi}{\chi_0} = 1 - \frac{2}{\pi} k_F a - C_\chi (k_F a)^2$$

where $\quad C_\chi = \frac{10}{21} C_E$



Spin-dipole mode of a balanced Fermi gas

Theoretically we expect that the spin susceptibilty goes to infinity ⇒ **the spin-dipole mode (could) become soft**

At the MF level:

$$\frac{E_{MFT}}{V} = \frac{3}{5} N \epsilon_F \left(\frac{1}{2}(1+P)^{5/3} + \frac{1}{2}(1-P)^{5/3} \right) + \frac{10}{9\pi} k_F a (1-P)(1+P) \Big)$$

Inverse Susceptibility: $\frac{\partial^2 E}{\partial P^2} \propto 1 - \frac{2}{\pi} k_F a$ ⇒ $(k_F a)_{MF} \sim \pi/2$

et us consider the axial (along *z*) spin-dipole mode $\omega_{SD} = \left(\frac{m_1}{m_{-1}} \right)_{SD}$

d *ε[n,P]* be the energy functional of the system, we have:

$$m_{-1} = \int z^2 n^2 \left(\frac{\partial^2 \epsilon}{\partial P^2} \right)^{-1}$$

i.e., it depends on an integrated spin-susceptibility

Spin-dipole mode of a balanced Fermi gas

Mean-field

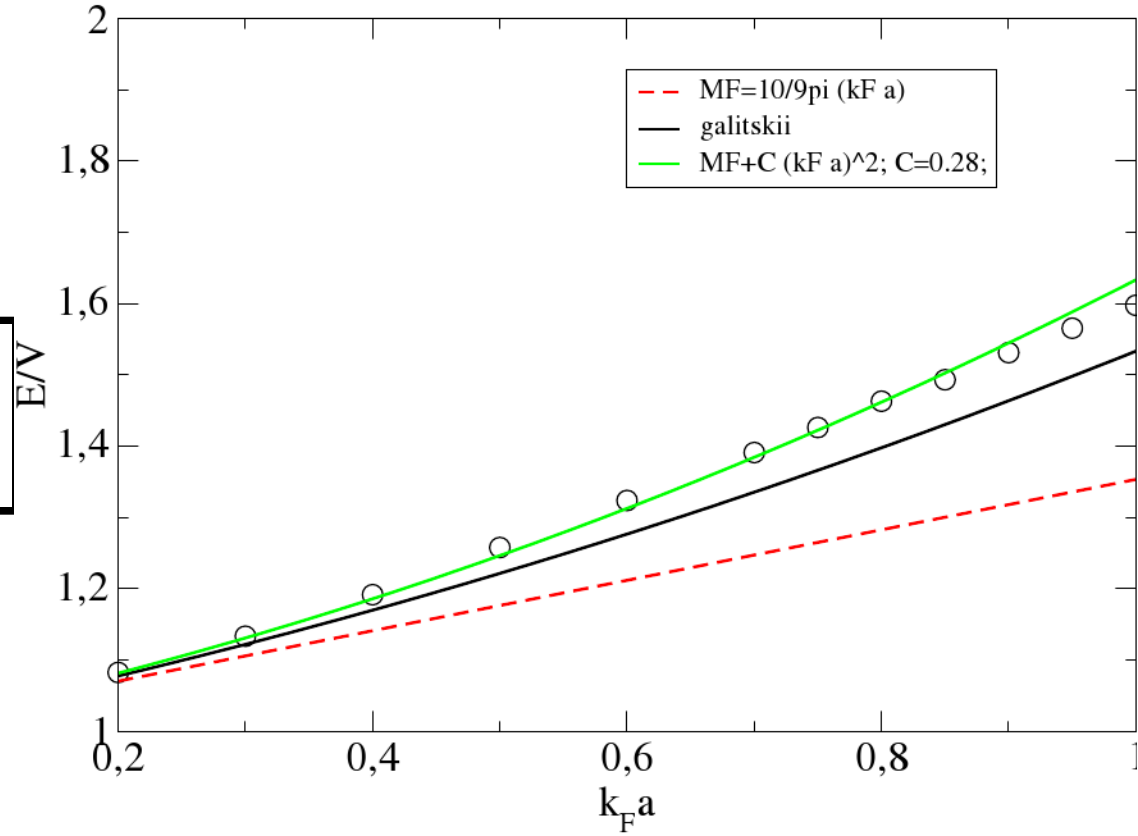
$$\frac{E_{MFT}}{V} = \frac{3}{5} N \epsilon_F \left(\frac{1}{2}(1+P)^{5/3} + \frac{1}{2}(1-P)^{5/3} \right) + \frac{10}{9\pi} k_F a (1-P)(1+P) \Big)$$

$$\boxed{\omega_{SD,MF} = \omega_{ho} \left(1 - \frac{2^7}{35\pi^2} k_{F,0} a \right) = \omega_z \left(1 - \frac{128\sqrt{2}(3N)^{1/6}}{35\pi^2} \frac{a}{a_{ho}} \right)}$$

Building a simple energy functional from MC recent data:
[G. Bertaina et al., arXiv:1004.1169]

$$\boxed{\frac{E}{V} = \frac{3}{5} N \epsilon_F \left(1 + \frac{10}{9\pi} k_F a + C_E (k_F a)^2 \right)}$$

& the same for the susceptibility..



Spin-fluctuations in a repulsive Fermi gas

Let us consider a part of the sample of which we measure the relative number fluctuations:

$$\frac{\Delta(N_\uparrow - N_\downarrow)^2}{N} = k_B T \frac{\chi(T)}{n}$$

At low-T and close to Stoner instability they diverge since χ has a pole.

But what about the quantum fluctuations, which could dominate at very low-T and small N?

Quantum fluctuations scales diffently with *N:*

$$\frac{\Delta(N_\uparrow - N_\downarrow)^2}{N} = 2\alpha \left(\frac{12}{\pi^4 N}\right)^{1/3} \ln(CN^{1/3})$$

Where α is the low-q behaviour of the static structure factor.
We find, within Landau theory that it also diverges at the Stoner instability but only logarithmically

bec.science.unitn.it

Post-Doc positions available!!

A new <u>experimental activity</u> on ultracold atoms is starting at *INO-BEC CNR Centre*, Trento Univ.

BOSE EINSTEIN CONDENSATION

Focus will be on:

i) pure and mixed quantum gases (Fermi - Bose, Bose -Bose)

ii) Fermionic superfluidity

iii) transport phenomena

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