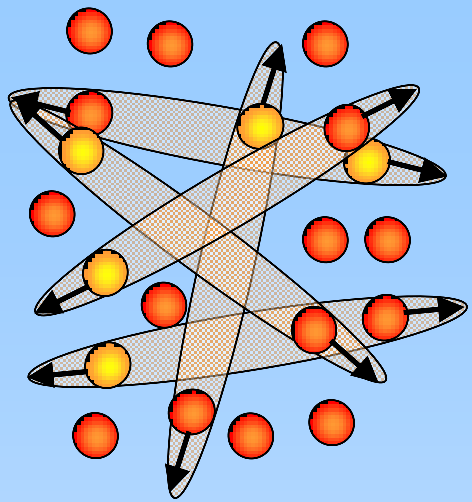

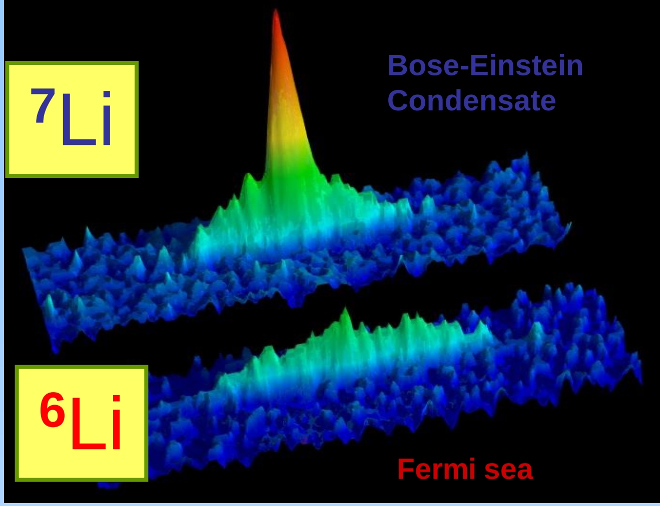

Ultracold Fermi Gases with unbalanced spin populations

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Physique quantique et applications

Fermix 2009 Meeting

Trento, Italy
3 June 2009

Outline

Introduction

- ♣ Concepts in imbalanced Fermi gas physics
- ♣ State of the art : MIT-Rice experiments

Experimental setup

- ♣ A new setup with improved performances
- ♣ Imbalanced gas preparation and detection

Results

- ♣ Study of the density profiles
- ♣ Axial compression mode

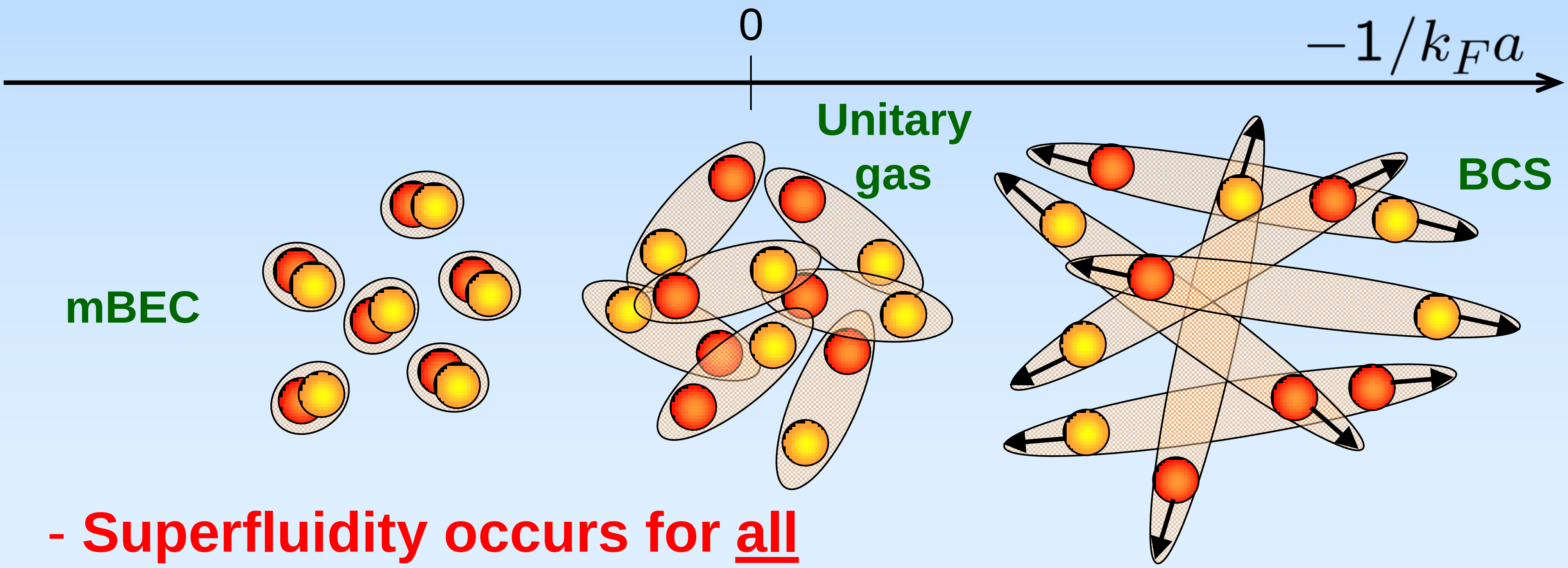
Superfluidity in a Fermi Gas

- **Recipe for fermionic superfluidity :**

  2 spin components Fermi gas $\{|\uparrow\rangle, |\downarrow\rangle\}$ $T \ll T_F$

  Interactions described by dimensionless parameter $k_F a$

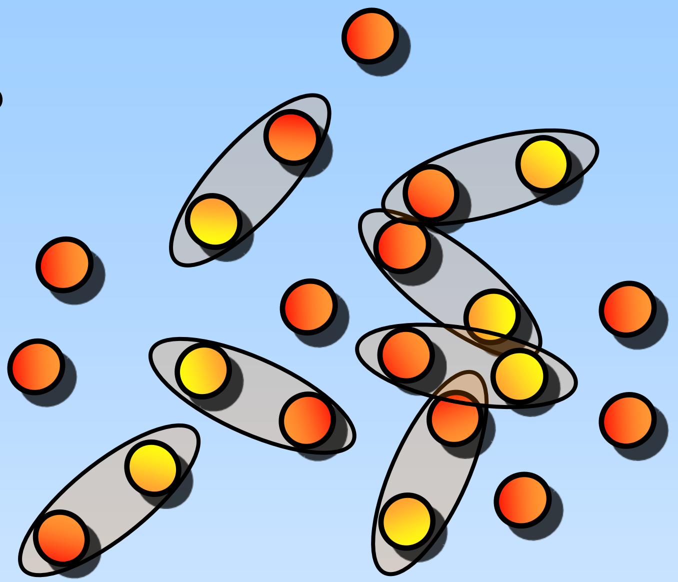
- **Key ingredient : pairing → BEC-BCS crossover**



- **Superfluidity occurs for <u>all</u> interactions value, if T is small enough**

Imbalanced Fermi Gas

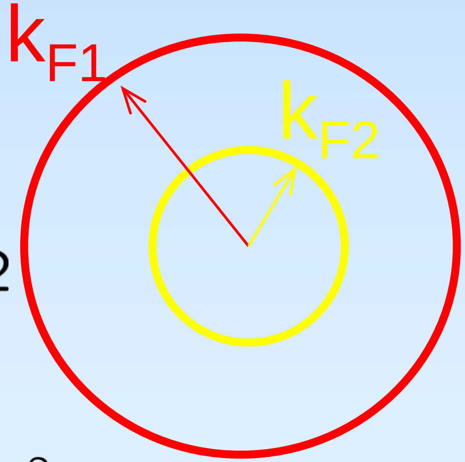
- **What happens if** $N_1 \neq N_2$ **?**



- **No possible symetric pairing superfluidity survives ? Mechanism ? Excess atoms ?**

- **Grand-canonical ensemble**

  mismatch of chemical potentials $\mu_1 > \mu_2$



- **Possible with mass imbalance (Fermix...)**

$$E_{F,\sigma} = \frac{\hbar^2 k_{F,\sigma}^2}{2m_\sigma} = \frac{\hbar^2}{2m_\sigma}(6\pi^2 n_\sigma)^{2/3}$$

Clogston-Chandrasekhar limit

- **Naive argument using BCS picture :**

the energy of excess particles must be compared with « robustness » of the fermion pairs :

$\delta\mu \lesssim \Delta$ **: SF is stable with equal densities**

$\delta\mu \gtrsim \Delta$ **: ? with unequal densities**

- **on BEC side, no CC-limit is expected :**

mBEC immersed in an ideal Fermi gas of excess atoms

- **Relation predicted by BCS theory :** $\delta\mu_c = \dfrac{\Delta}{\sqrt{2}}$

- **Definition :** $P = \dfrac{N_1 - N_2}{N_1 + N_2}$

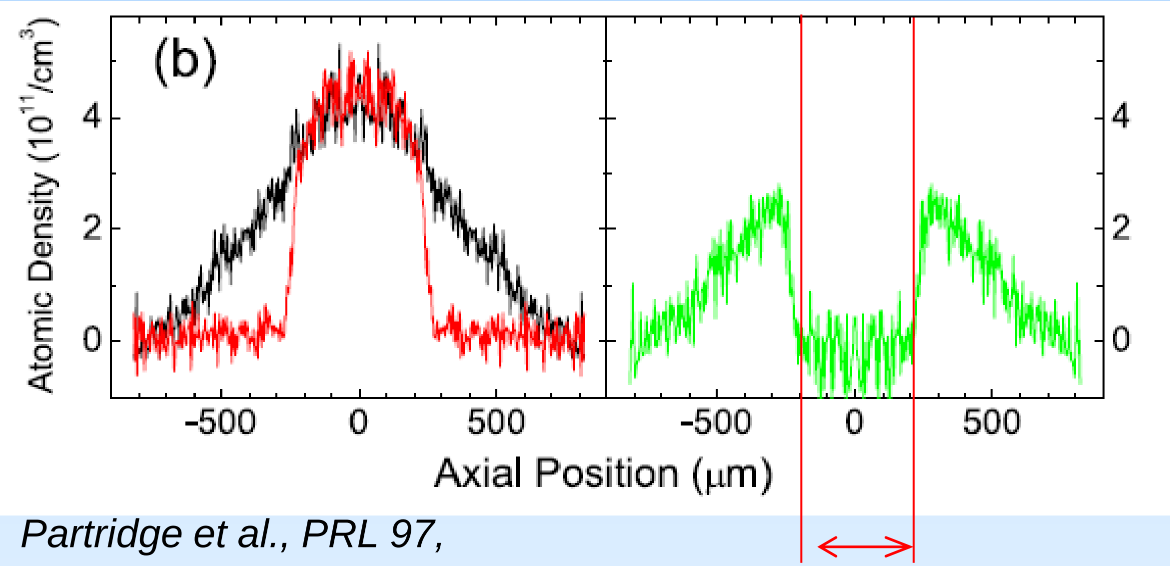
State of the art : Rice experiment

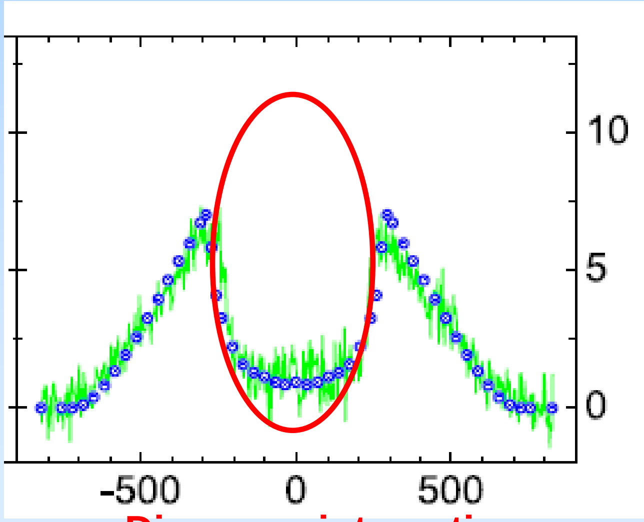
- **Pioneering experiments realized at Rice and MIT**

- **On resonance: both groups observed <u>phase separation</u> but...**

Center-line (r = 0) axial cut of reconstructed 3D profiles

Axial column density





Partridge et al., PRL 97, 190407 (2006)

Zero density difference in the SF core

Dip : very interesting <u>LDA violating</u> feature

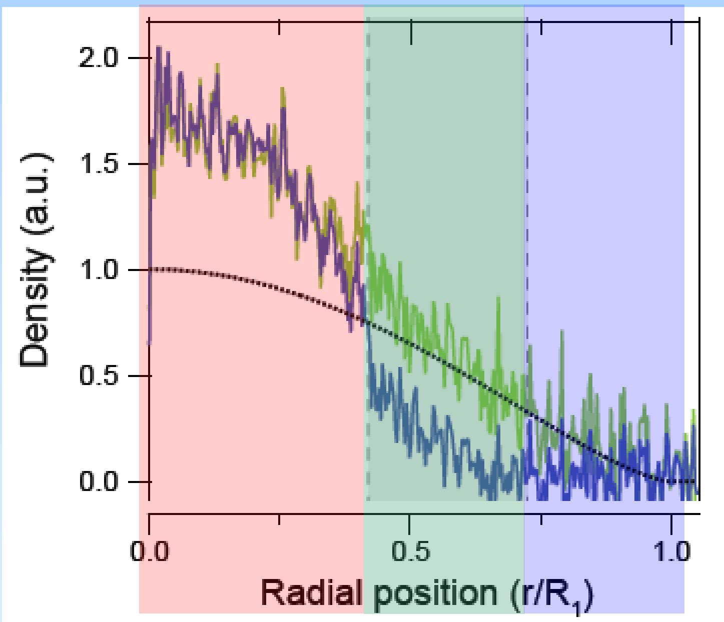
2 phases : <u>SF core</u> surrounded by <u>fully polarized shell</u>

Consequence : CC-limit P = 1

State of the art : MIT experiment

Y.Shin et al., Nature 451, 689 (2008)

Reconstruced 3D profile

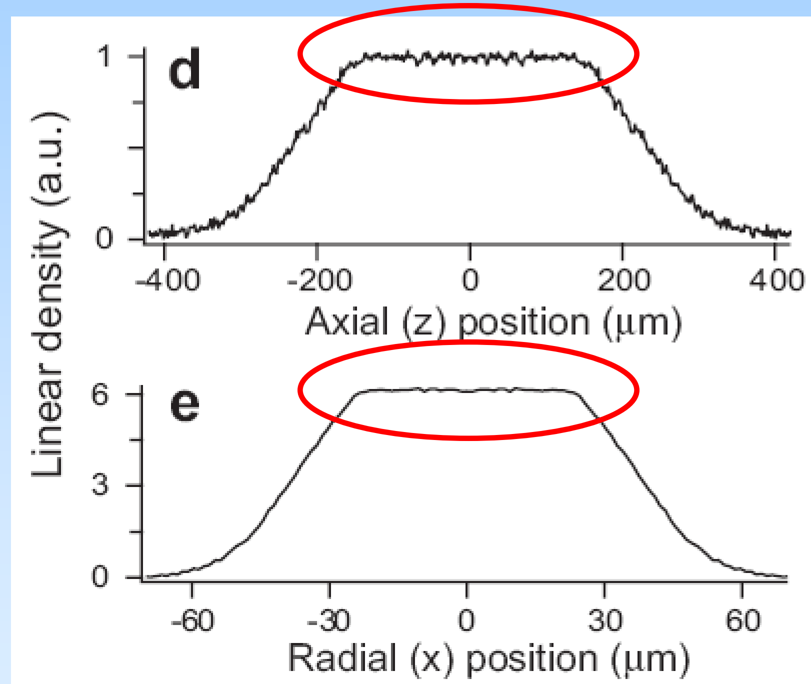


SF core : equal densities

Fully polarized outer shell

Partially polarized normal phase

Double-integrated profiles of density difference



Flat-topped distribution

3 phases ! No apparent LDA violation

CC-limit P ~ 0.75

So what do we do now ?

3rd experiment !

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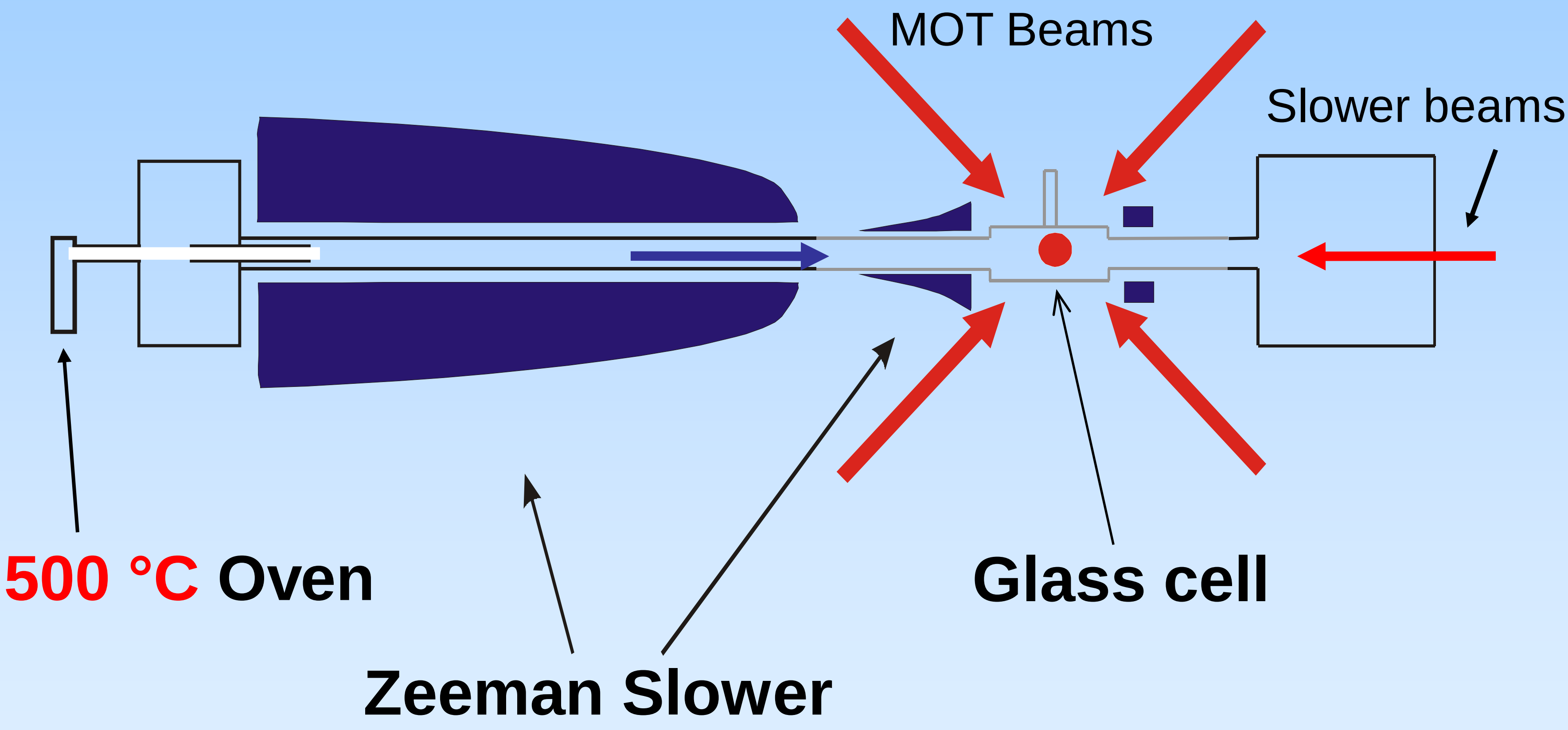
A new setup ...



Experimental sequence

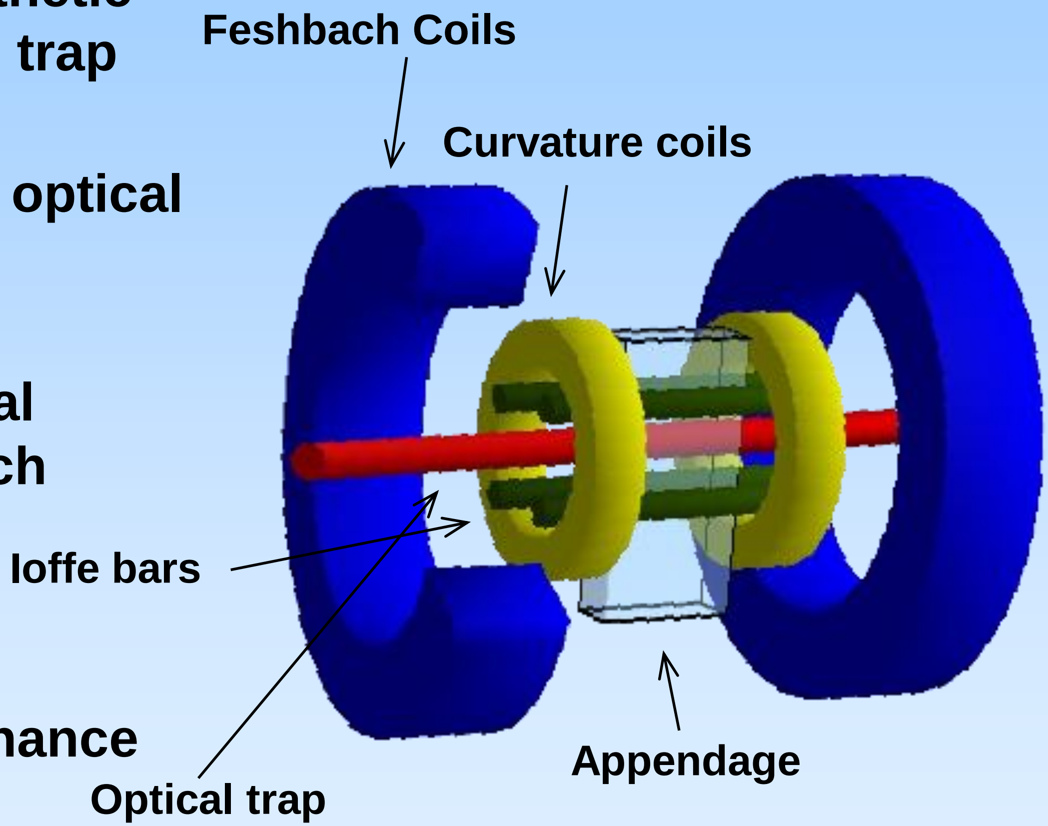
- RF evaporation of ^{7}Li, sympathetic cooling of ^{6}Li in Ioffe-Pritchard trap

- Loading of ^{6}Li in single beam optical dipole trap

- Magnetic fields ramps for axial curvature and bias for Feshbach resonance

- Spin mixture preparation and cooling in optical trap on resonance

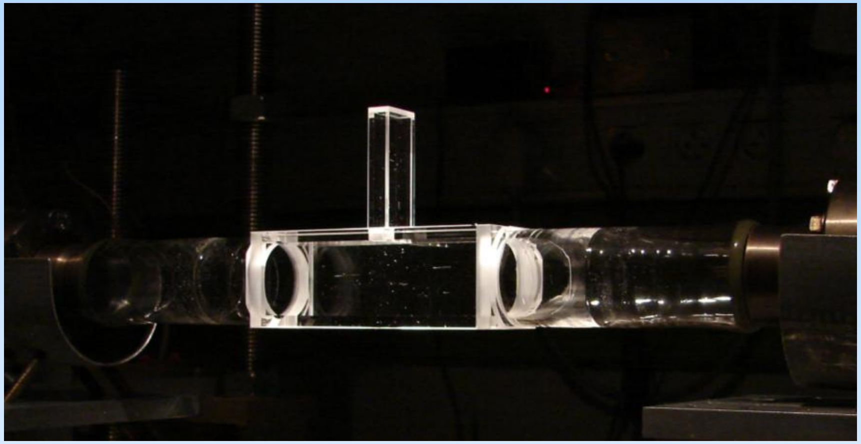
- Detection using high-field imaging



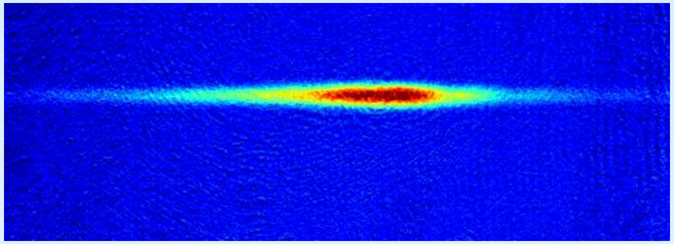
... with improved performances

Same design as previous experiment but many improvements

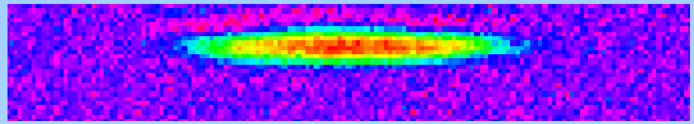
- **Enlarged appendage, allowing for higher atom numbers**
- **High power 130 mW laser diodes**
- **New Zeeman Slower**
- **120 W Fiber Laser (IPG)**

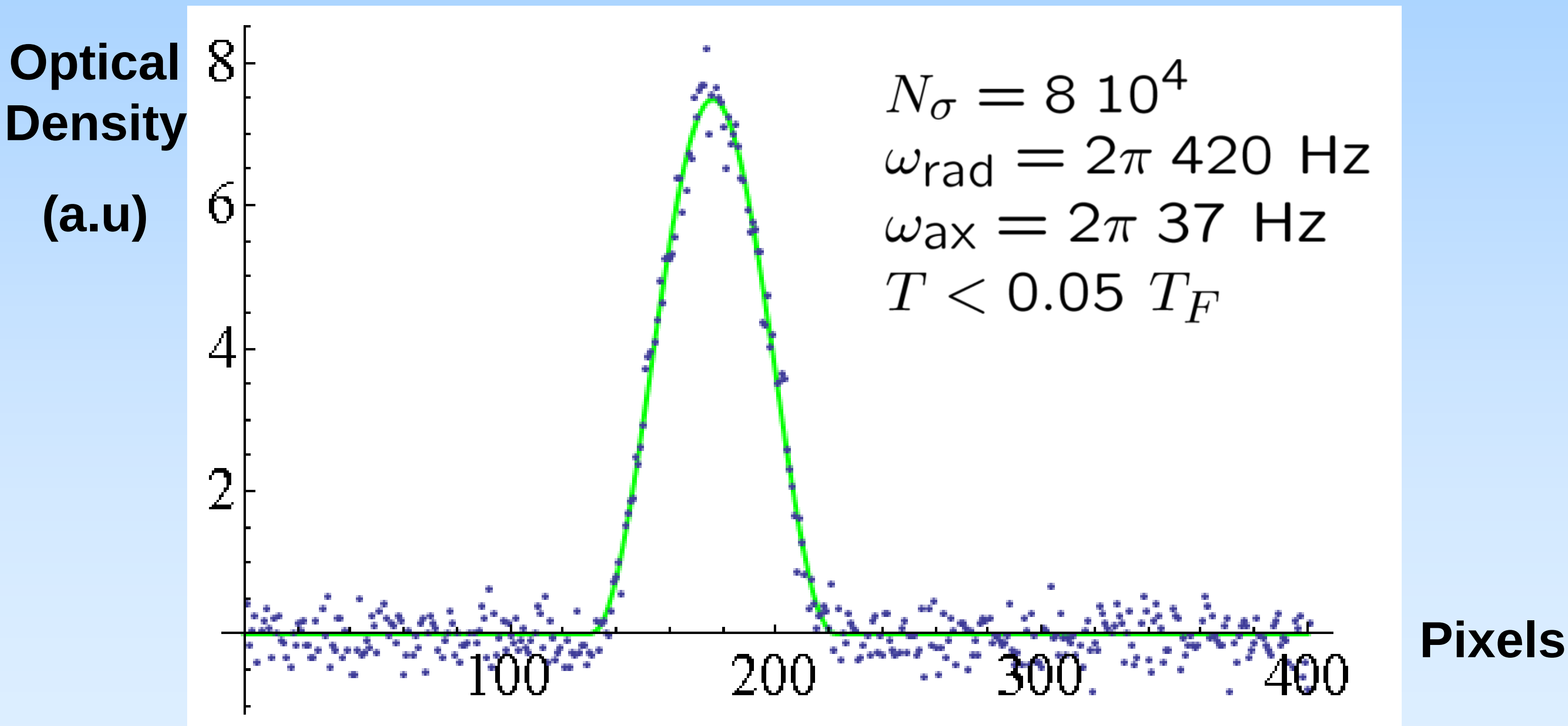


- **Loading ~10^{10} of ^{7}Li and 5 10^{8} of ^{6}Li in the MOT**
- **5 10^{6} atoms of ^{6}Li transfered in the optical trap at ~ 100 µK**
- **~3 10^{5} atoms in each spin state in a degenerate gas at T~0.1 T_F**



Unitary Fermi Gas (P=0)

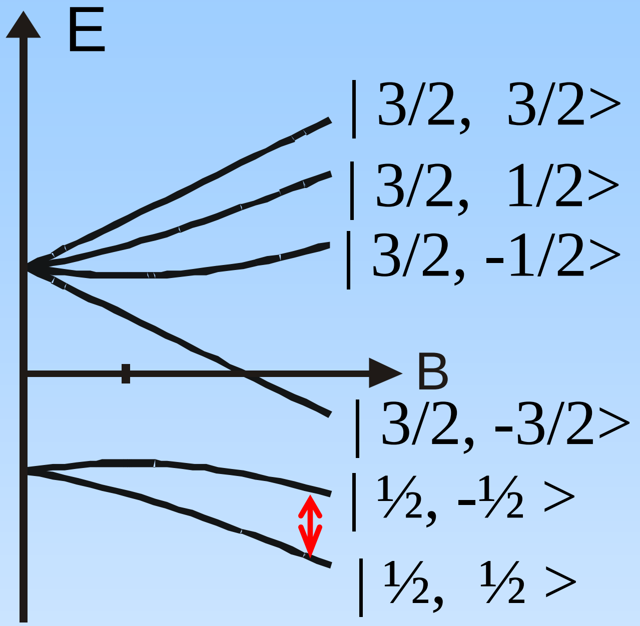




Imbalanced gas preparation

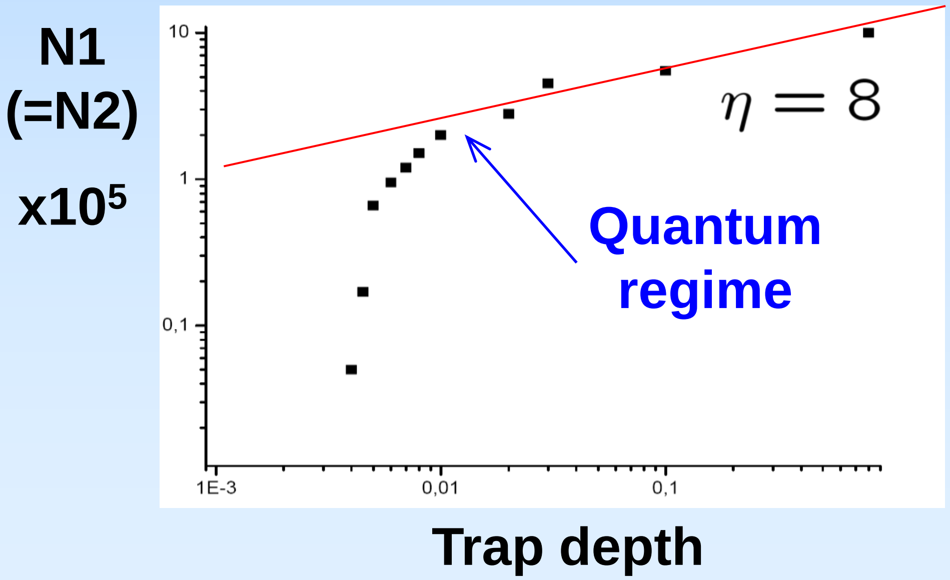
- **Landau-Zener sweep across |1>-|2> resonance to prepare an imbalanced mixture**

- **Evaporation of mixture by lowering trap depth**



~ 76.4 MHz @ 834 G

Evaporating a balanced mixture



Decrease of temperature by a factor > 100 with a loss of a factor ~ 10 on atom number

Evaporation lasts for 3 s (compare to 20 s in mag trap)

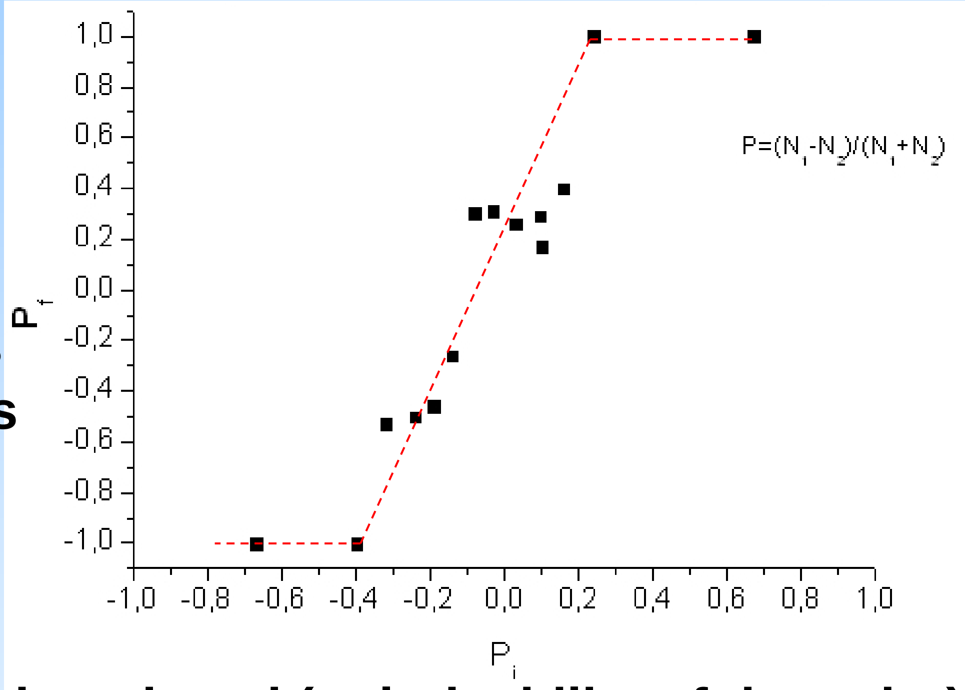
Polarized gas : evaporation issues

- **Not so simple because polarization is <u>not constant</u> during evaporation and it is forbidden to be fully polarized at any time !**

- **Actually, it is strongly varying !**

- **2 opposite trends**

Classical regime : evaporation is purifying the gas (minority atoms suffers most in relative value of losses in collisions)



Quantum regime : the imbalance is reduced (polarisability of the pairs)

→ Difficult to prepare highly polarized gases
Great sensitivity to initial conditions

Polarized gas : imaging

- **Necessary to image both spin states in a single experimental shot**

Solutions : phase contrast imaging of density difference (MIT), sequential imaging of 2 spin states (Rice)

- **Sequential imaging : the importance of being fast**

heating issues

strong interactions between |1> and |2>

Absorption pictures ***Reference pictures***

$$OD(x,y) = -\ln\left(\frac{I(x,y)}{I_0(x,y)}\right)$$

$$\delta OD(x,y) = -\ln\left(\frac{I_{|1\rangle}(x,y)}{I_{|2\rangle}(x,y)}\right)$$

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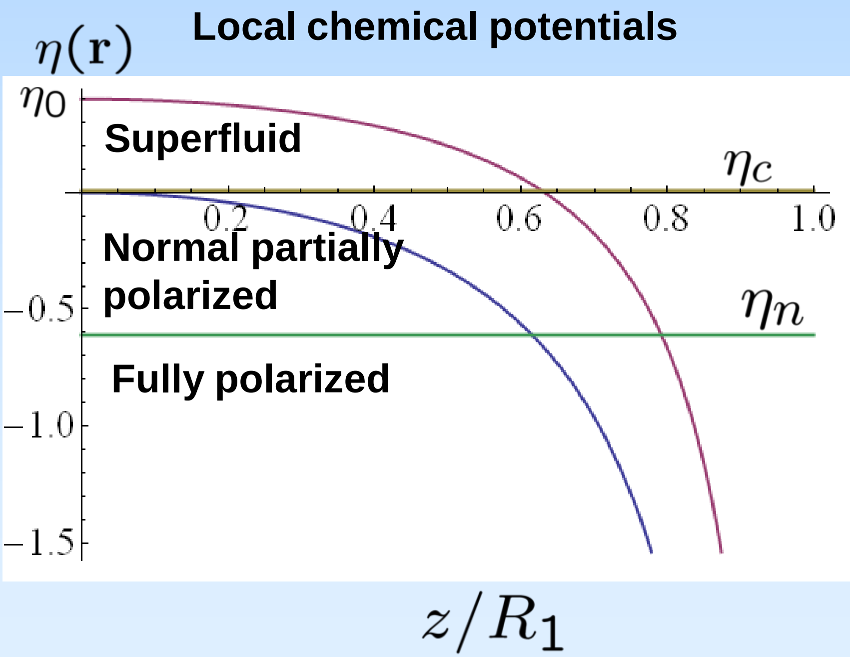
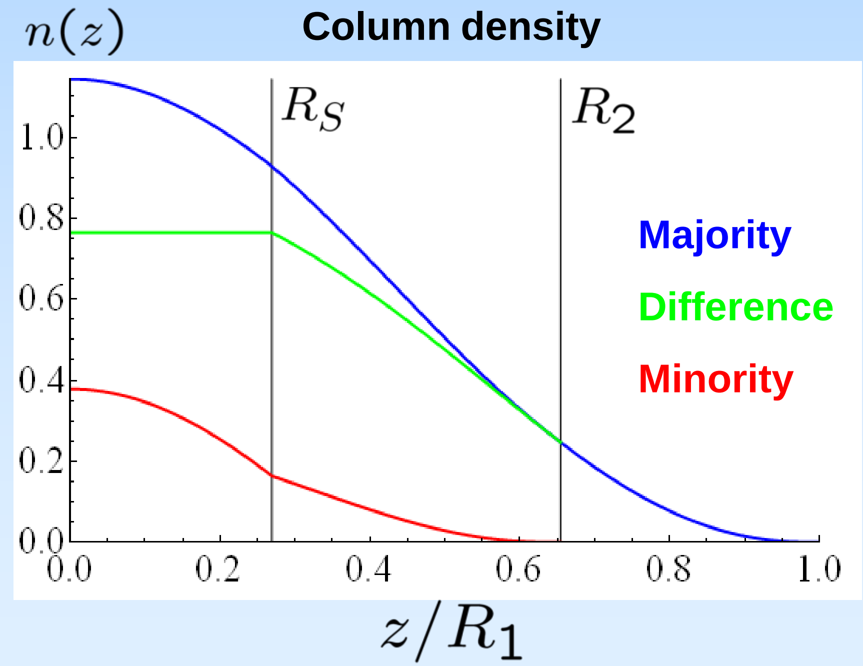
In-situ density profiles

- **Much easier to interpret**
- **Trapping potential is very useful (this time !)**

- under LDA, the trapping provides us with locally homogeneous gases with different values of $\eta = \mu_1/\mu_2$ **: in one shot, we have the full T=0 phase diagram of the system !**





- **Problems : optical depth, resolution limit**

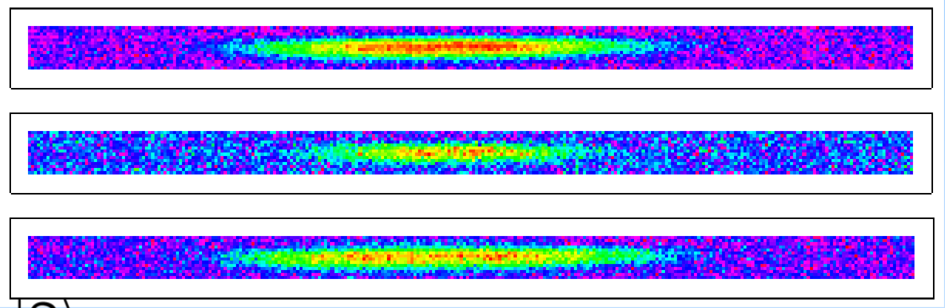
Density profiles : typical image

- **In-situ imaging at high field of 2 spin states**

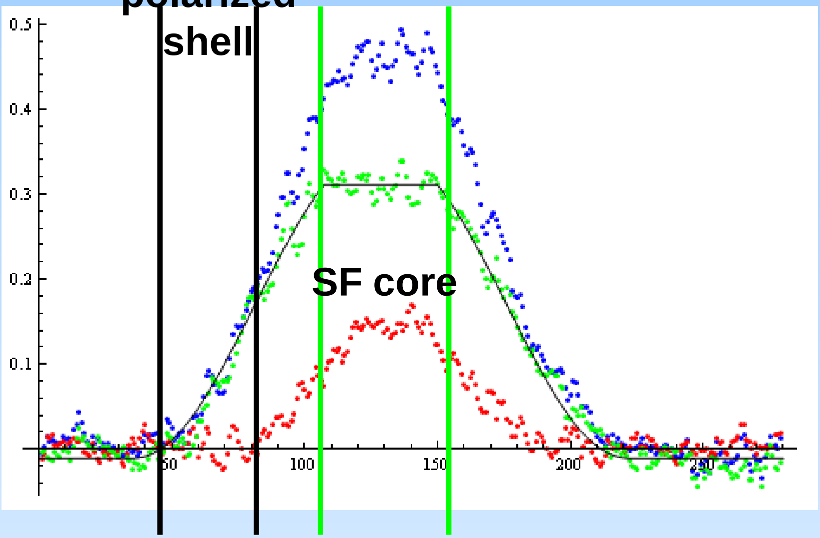
$|1\rangle$

$|2\rangle$

$|1\rangle - |2\rangle$



Vertical width = 40 µm



$N_1 = 6.0\ 10^4$

$N_2 = 1.3\ 10^4$

$P = 0.65$

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

$\omega_{\text{ax}} = 2\pi\ 19\ \text{Hz}$

- **Data consistent with 3 phases + LDA**

- **Which model to use to fit these data ? What physical quantites can we extract ?**

Theoretical *detour* I : superfluid phase

Simple geometric reason to the plateau

$f(x,y,z)$ is the atomic density

$F(z) = \int \mathrm{dx} \int \mathrm{dy}\ f(x,y,z)$ is the column density

Let's assume the LDA, in which case, we rescale the variables to obtain an isotropic problem $x_i \longrightarrow x_i / R_{\mathsf{TF}i}$

SF core : $f(r<a) = 0$

Calculate : $$\frac{\mathrm{d}F}{\mathrm{dz}}(z<a) \propto \frac{\mathrm{d}}{\mathrm{dz}} \int_{\sqrt{a^2-z^2}}^{\infty} \rho \mathrm{d}\rho f(\rho, z) = 0$$

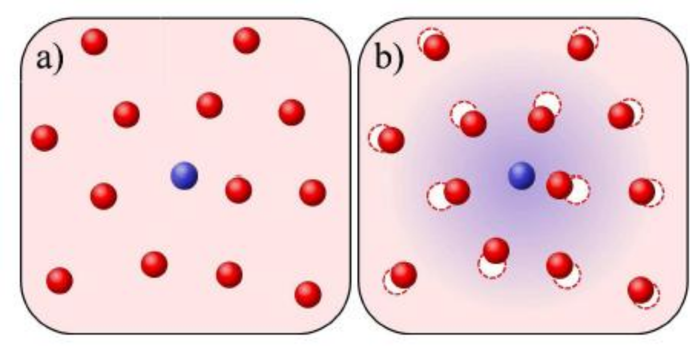
« Flat-topness » is just a consequence of equal central densities and LDA

Universal equation of state : $\mu(T=0) = \xi\ E_F$

$R_{\mathsf{TF}} = 195\ \mu\mathrm{m} \Rightarrow\ \xi = 0.45 \qquad (1/k_F a = 0)$

Theoretical *detour* II : partially polarized normal phase

Complex normal phase



Schirotzek et. al, arXiv:0902.3021

- Easier to understand in the limiting case of a single minority atom immersed in a majority Fermi sea : the Fermi polaron

- Description as a Fermi liquid of polarons :

  binding energy of a polaron in the Fermi sea A

  effective mass m^*

  interactions between polarons B

- Equation of state (approximate) $\frac{E(x)}{N_1} = \frac{3}{5}\epsilon_{F1}\left(1 + \frac{5}{3}Ax + \frac{m}{m^*}x^{5/3} + Bx^2\right)$

$x = n_1/n_2$

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

See P. Massignan talk tomorrow

Theoretical *detour* III : fully polarized outer shell

- Ideal Fermi gas : properties are perfectly understood however... $\mu = E_F$

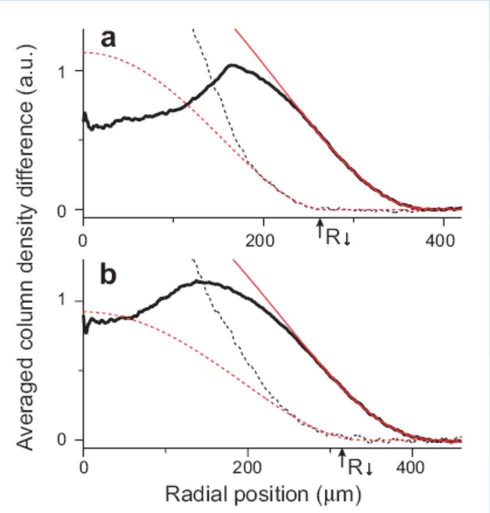
- This phase is in thermal equilibrium with the inner part of the cloud and its thermodynamics properties are exactly known

→ Ideal thermometer of the strongly interacting gas ! (cf. F Schreck talk)

- Not so easy : fitting the wings requires very high signal to noise ratio : not successful in our case so far for low temperatures (<0.1 T_F)

-Done at MIT

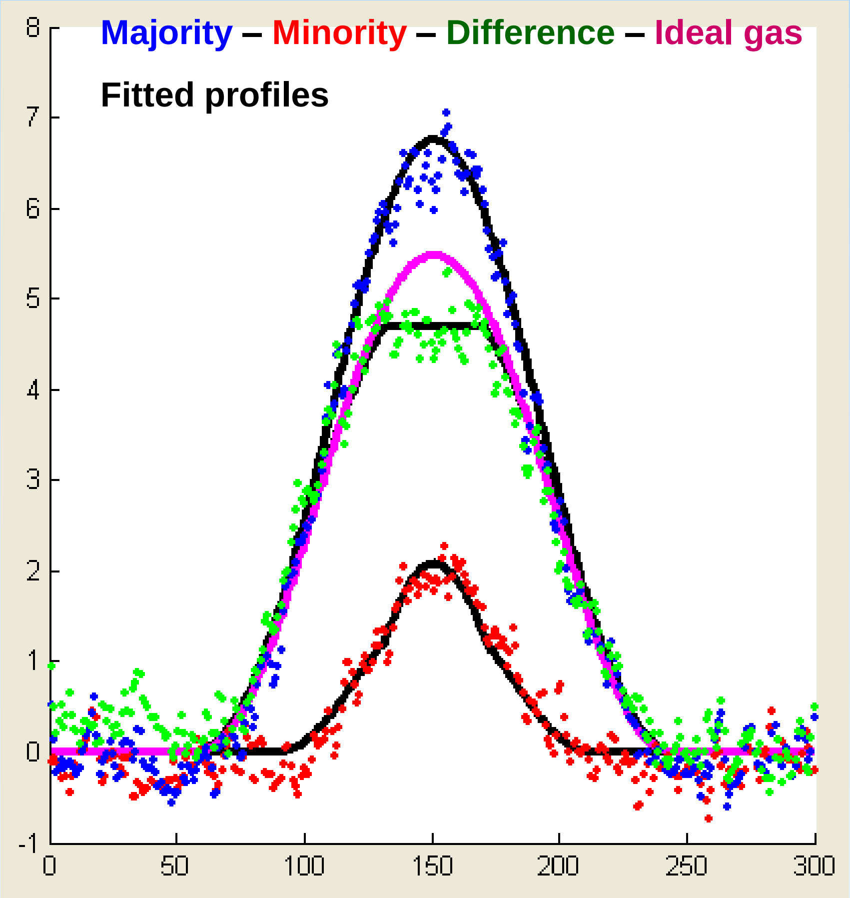
lowest measured T : T=0.03 T_F



Quantitative study of the density profiles

- 3 phases model (T=0) : SF core - non-interacting polarons – ideal gas
- Relevant parameters : $\xi, R_S, R_2, \eta_0, \eta_c, A, m^*$

Integrated OD (a.u)



Pixels

- Bimodal distribution on the minority profile (superfluid / polarons)
- Increase of majority distribution inside R_2 (compared to ideal profile) → attractive interactions
- Only one parameter fixed $\xi = 0.45$
- Fitting 2 profiles (minority + difference) with the same parameters

$$R_1, \eta_0, \eta_c, A, m^*$$

- We find : $\eta_c = 0.07 \Rightarrow P_c = 74\%$

(preliminary)

$$m^* = 1.06$$

$$A = -0.61$$

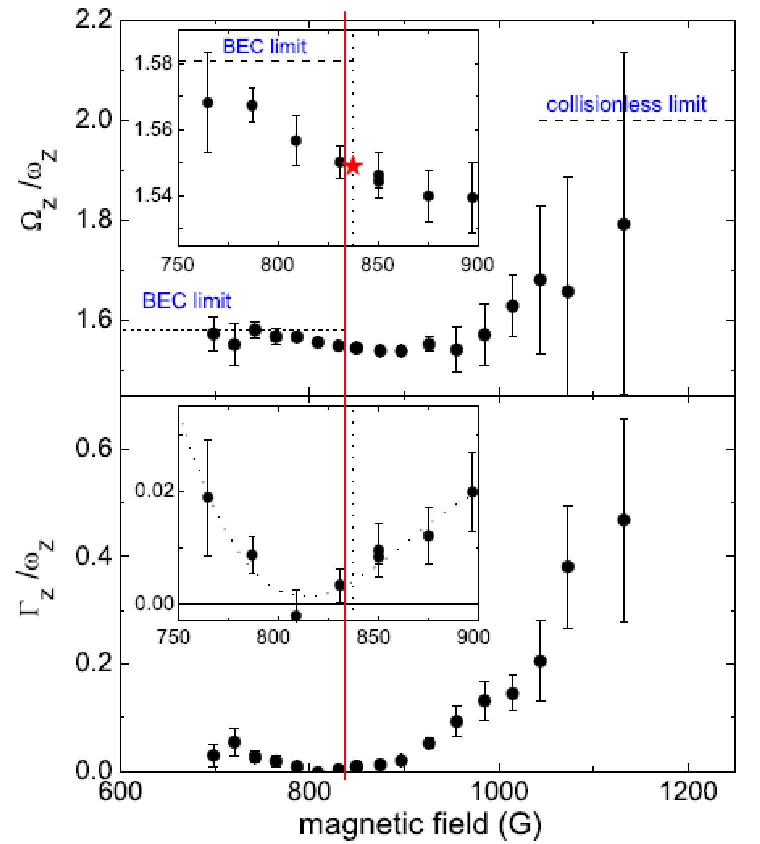
Good agreement with MIT and *C. Lobo, A. Recati, S. Giorgini, S. Stringari, PRL 97, 200403 (2006)*

Collective modes of a unitary Fermi Gas : axial compression mode

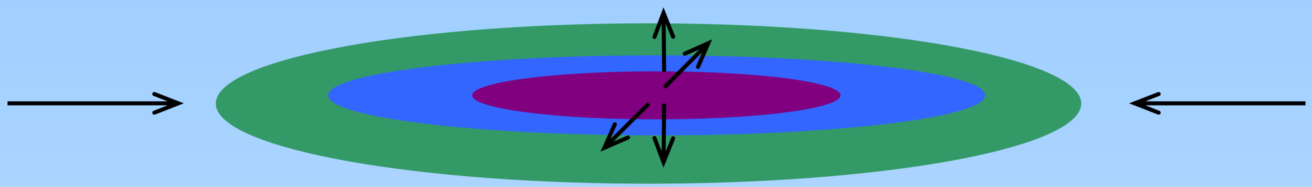
- Information about dynamic behavior of the gas
- Probe of the equation of state
- Experimental work showed (Duke, Innsbruck)
  - Hydrodynamic behavior on resonance
  - Strong dependance of damping on T

- What would happen to an imbalanced gas ?

Very complex problem : interacting phases with boundaries



Axial compression mode of an imbalanced gas



- Simple mode to excite

- We measure the *in-situ* outer shell radius

- Frequency measurement as a function of P : $\nu(P)$

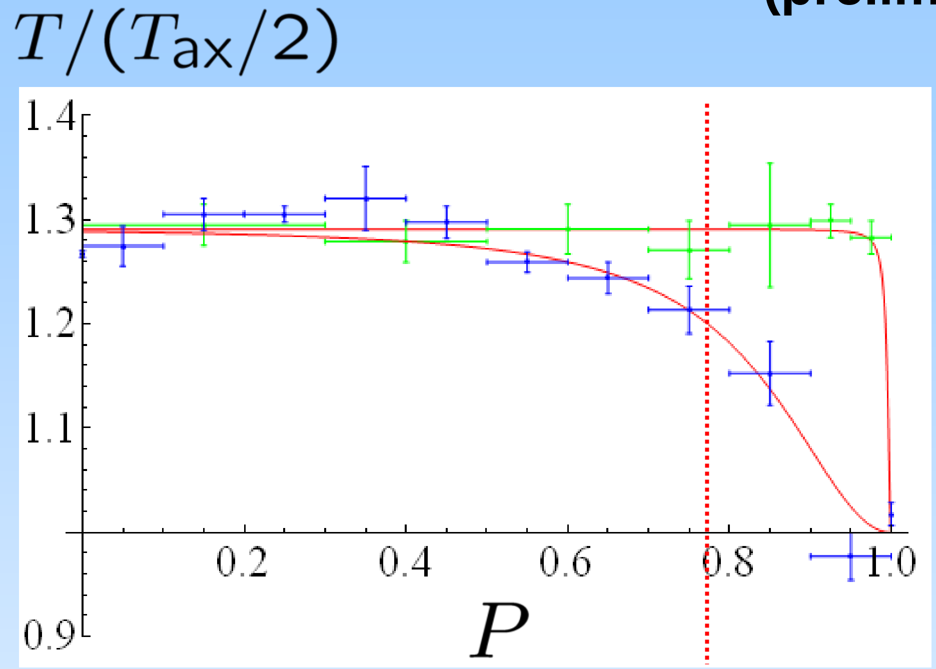
- Asymptotic values well known

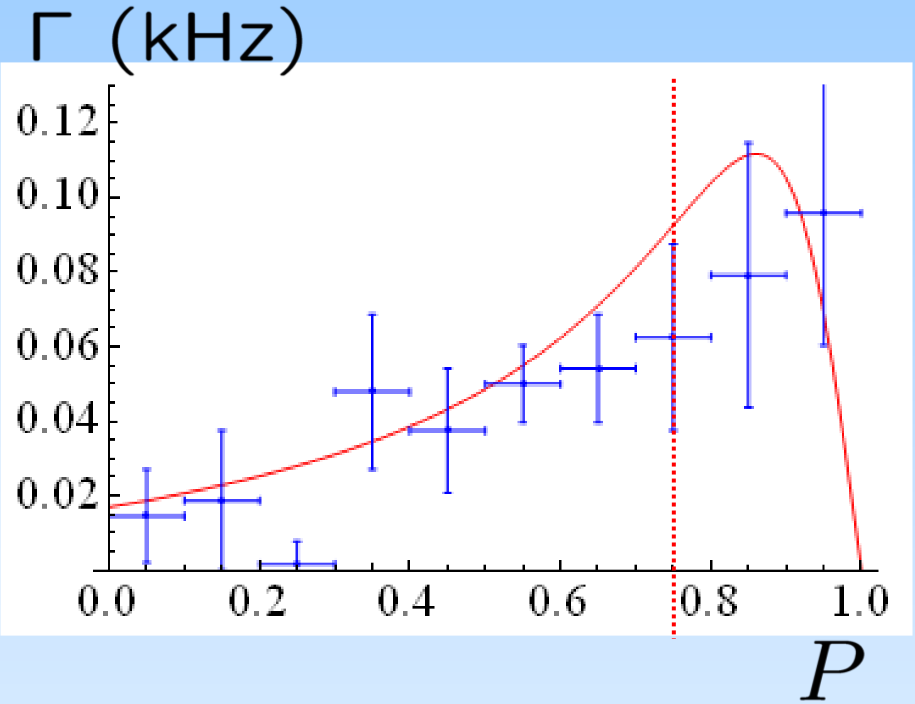
Superfluid hydrodynamic $\nu(P=0) = \sqrt{\frac{12}{5}}\nu_{\mathrm{ax}}$

Collisionless $\nu(P=1) = 2\nu_{\mathrm{ax}}$

Axial compression mode :
Period versus polarization

(preliminary)





- No dramatic change around Clogston limit
- Smooth crossover between hydrodynamic and collisionless regime (depending on aspect ratio)
- What happens to the other radii ?

Conclusion - Perspectives

- Imbalanced gas : 3 phases scenario confirmed

Rice puzzle remains…

- Quantitative results on Clogston-Chandrasekhar limit and Fermi polaron properties – analysis ongoing

Good agreement with existing results so far

- First investigation of collective modes for the imbalanced Fermi gas

No dramatic change around the CC-limit

→ More damping measurements

→ Other phases oscillations (normal phase and SF core) ?

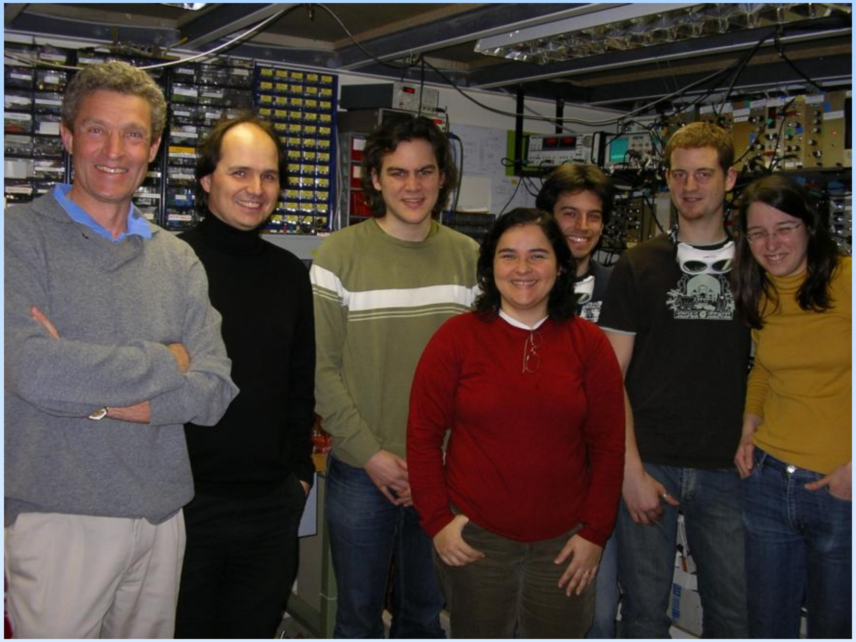
- Perspective : **Dynamic behavior of the imbalanced gas**

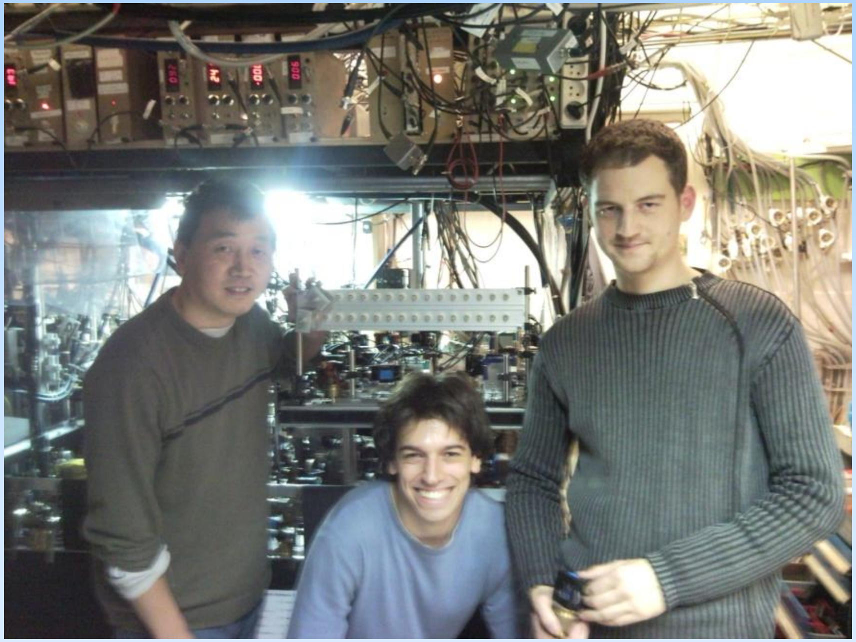
Fermi gases in low dimensions

Thank you for your attention !

F. Chevy
C. Salomon

K. Jiang
S. Nascimbène
N.N





Previous team members : L. Tarruell, G. Duffy, M. Teichmann, K. Magalhães, J. McKeever