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**2030-24**

**Conference on Research Frontiers in Ultra-Cold Atoms**

***4 - 8 May 2009***

# Recent advances on ultracold fermions

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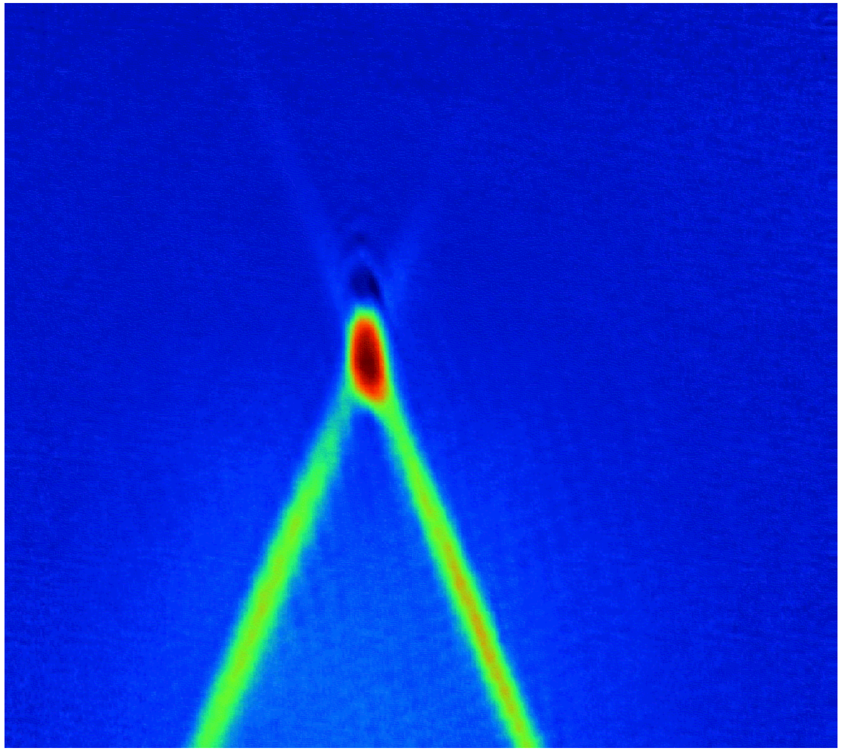
*FRANCE*

# Recent Advances on Ultracold Fermi Gases at ENS



C. Salomon

Laboratoire Kastler Brossel
Physique quantique et applications

ICTP, Trieste, May 4-8, 2009

# The ENS Fermi gas Team

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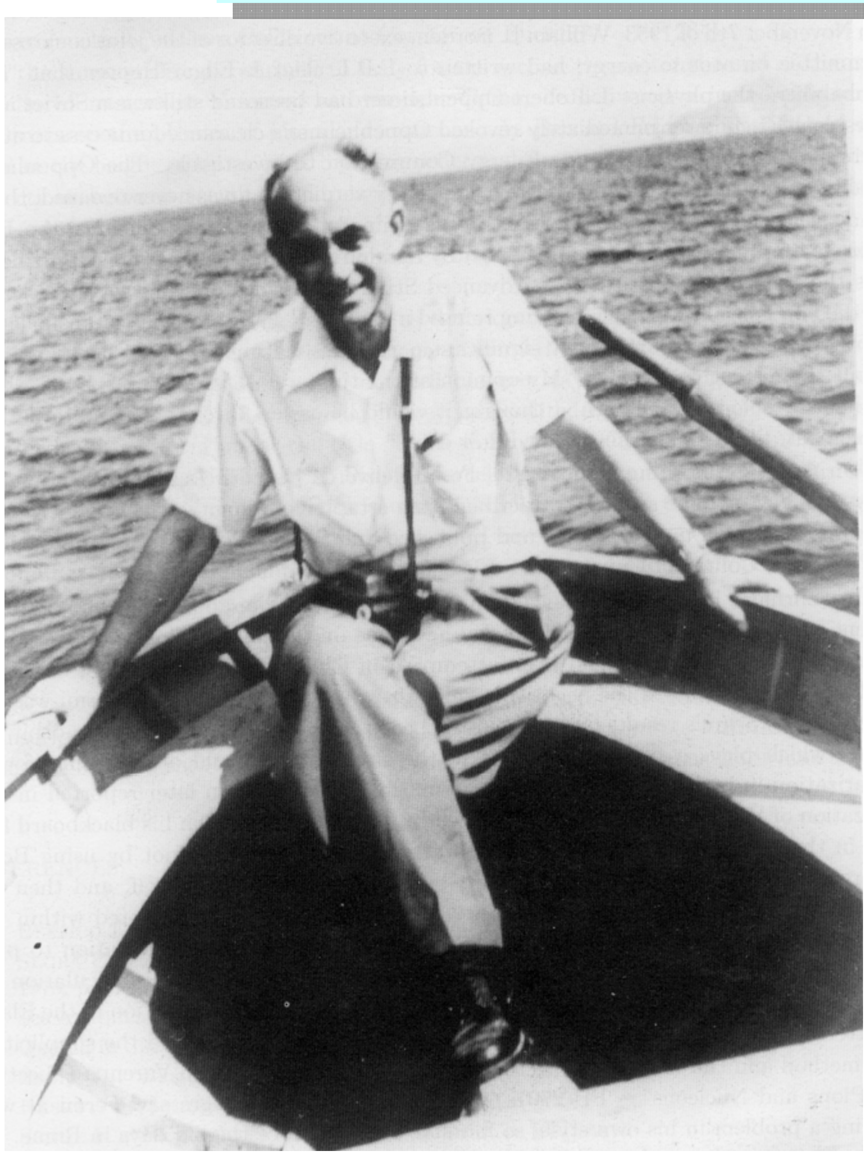
J. McKeever, K. Magalhães, V. Bagnato

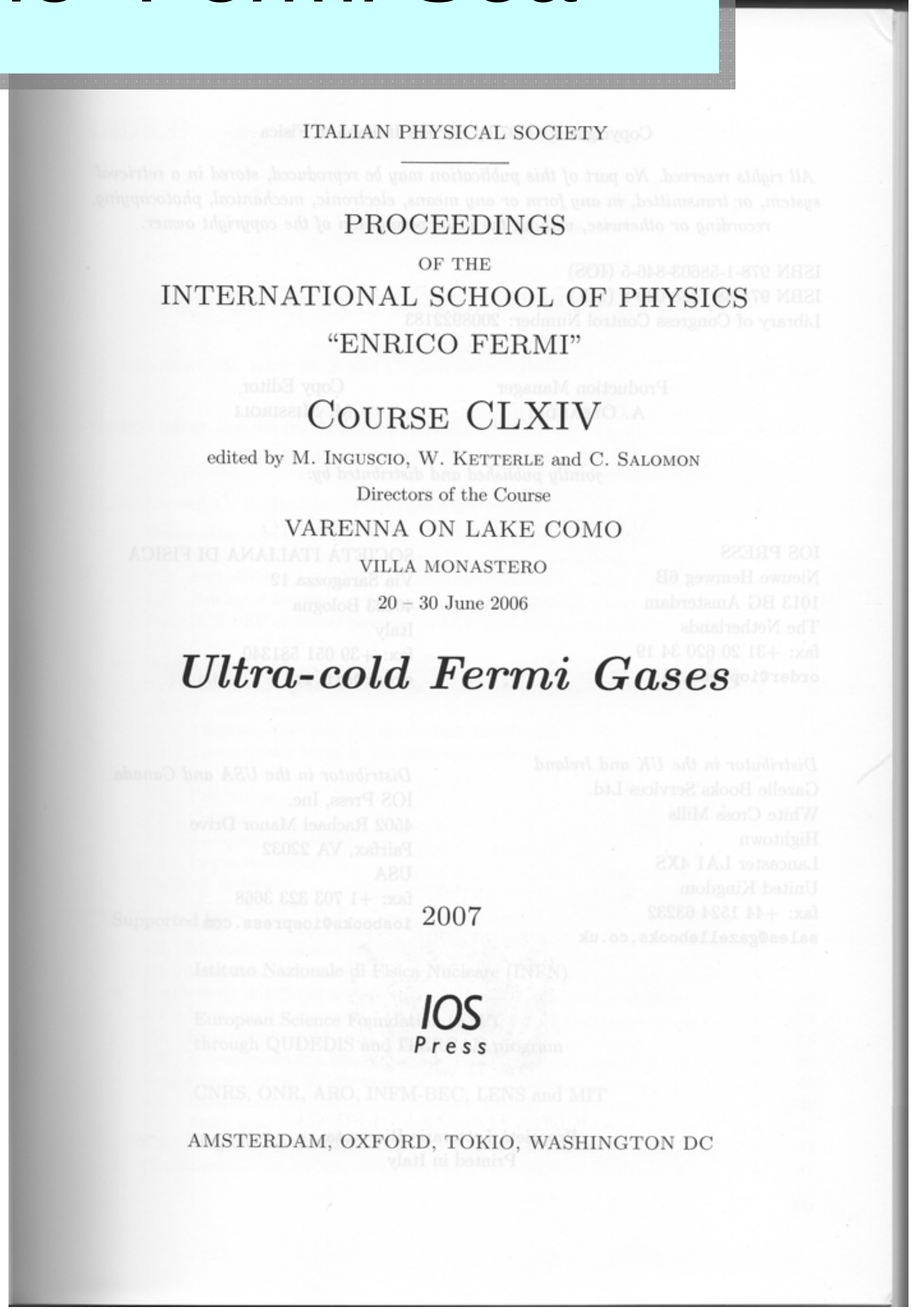
A. Ridinger, T. Salez, S. Chaudhuri,
U. Eismann, D. Wilkowski,
F. Chevy, Y. Castin, C. Salomon


Theory support: D. Petrov, G. Shlyapnikov , R. Combescot, I. Carusotto, C. Lobo, S. Stringari, L. Dao, A. Georges, O. Parcollet, C. Kollath, J.S. Bernier, L. De Leo, M. Köhl

# A Cruise on the Fermi Sea



Enrico Fermi on lake Como



ITALIAN PHYSICAL SOCIETY

PROCEEDINGS

OF THE

INTERNATIONAL SCHOOL OF PHYSICS
"ENRICO FERMI"

COURSE CLXIV

edited by M. INGUSCIO, W. KETTERLE and C. SALOMON
Directors of the Course

VARENNA ON LAKE COMO
VILLA MONASTERO
20 – 30 June 2006

*Ultra-cold Fermi Gases*

2007

IOS Press

AMSTERDAM, OXFORD, TOKIO, WASHINGTON DC

# Analog simulators
# classical vs quantum

Classical analog simulator:
Strasbourg astronomical clock

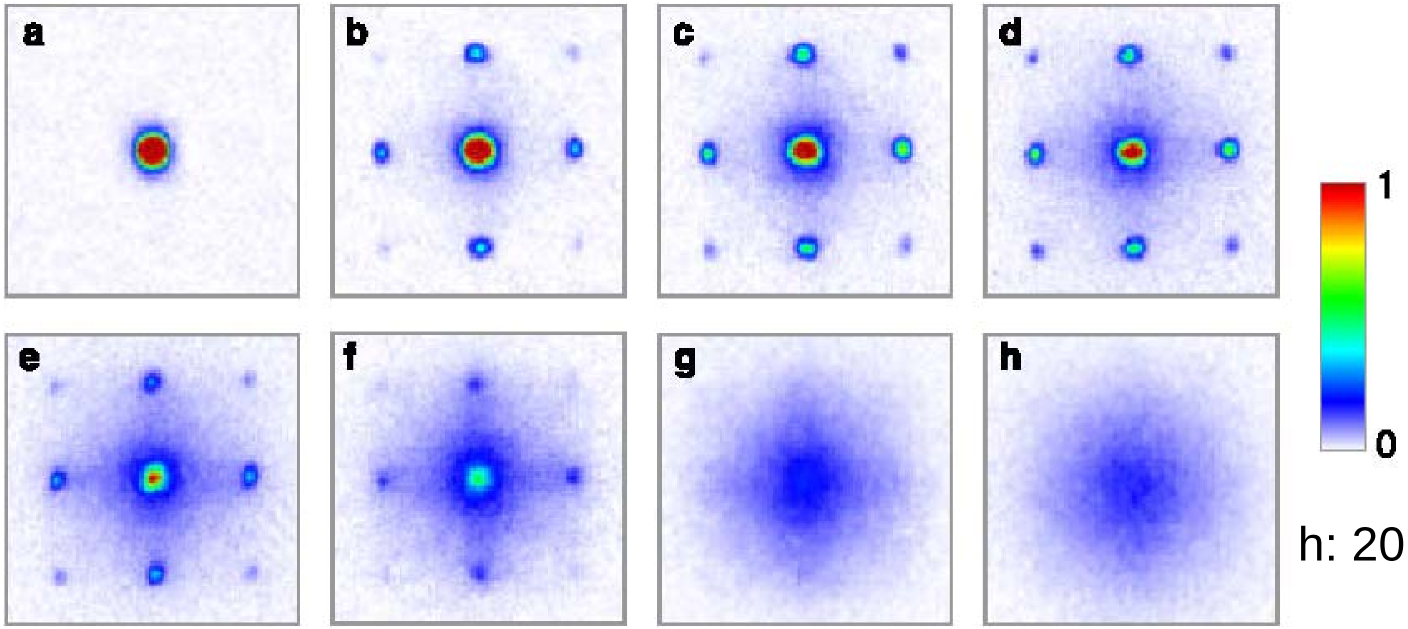
R.P. Feynman

Analog simulation of
many-body quantum effects

# Examples of quantum simulators

## 1) Mott-insulator transition in 3D Optical lattice: bosons

Markus Greiner*, Olaf Mandel*, Tilman Esslinger†, Theodor W. Hänsch* & Immanuel Bloch* Nature, 415, 39,2002




h: 20 $E_R$

Fermions: 3D Mott-insulator transition seen in Zurich and Mainz (2008)

# Second example of quantum simulator
# Universal equation of state of unitary Fermi gas

$$\mu = (1+\beta)\frac{\hbar^2}{2m}\left(6\pi^2 n\right)^{2/3} = \xi E_F$$

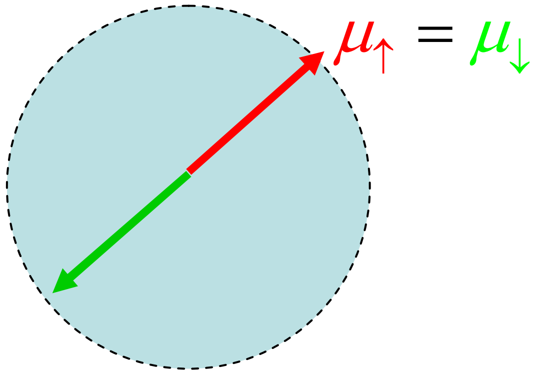
Determination of $\xi$

| Experiment | *ENS ($^6$Li)* | 0.42(15) |
|---|---|---|
| | *Rice ($^6$Li)* | 0.46(5) |
| | *JILA($^{40}$K)* | 0.46(10) |
| | *Innsbruck ($^6$Li)* | 0.27(10) |
| | *Duke ($^6$Li)* | 0.51(4) |

| Theory | *BCS* | 0.59 |
|---|---|---|
| | *Astrakharchik* | 0.42(1) |
| | *Perali* | 0.455 |
| | *Carlson* | 0.42(1) |
| | *Haussmann* | 0.36 |

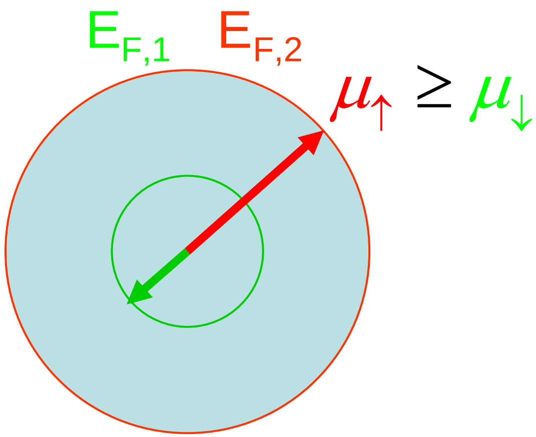
# Pairing with imbalanced Fermi surfaces motivation

Attractive Fermi gas with equal spin population
$\Rightarrow$ BCS theory, pairing at edge of Fermi surface




More than 20 theory papers in last 2 years !

What is the nature and existence of superfluidity
when spin population or mass is imbalanced ?
Mismatched density and/or pairing with different masses



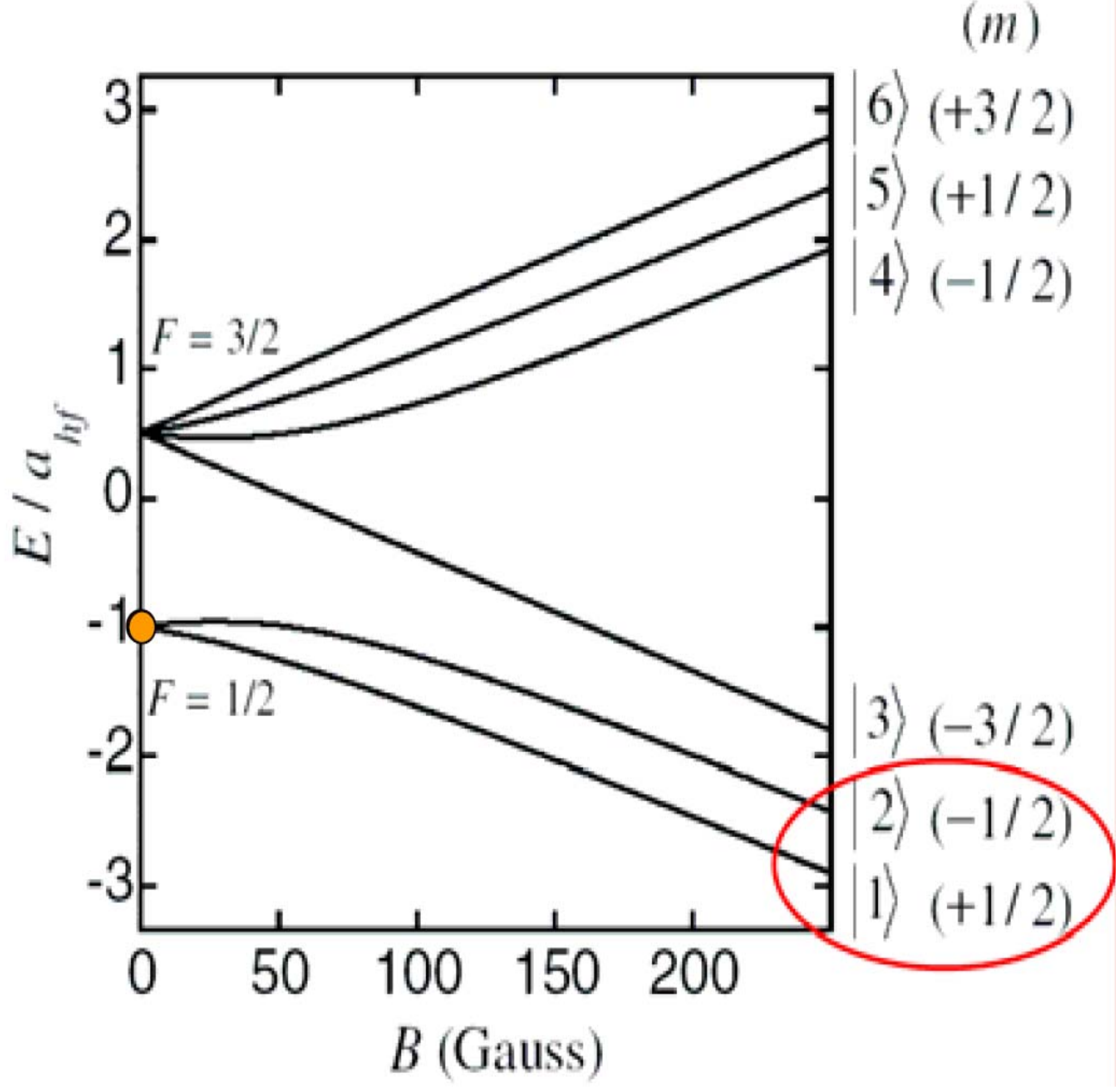

Ex:
Superconductors in magnetic field or quark matter

**Cold gases: spin imbalance**
MIT and Rice expt: phase separation

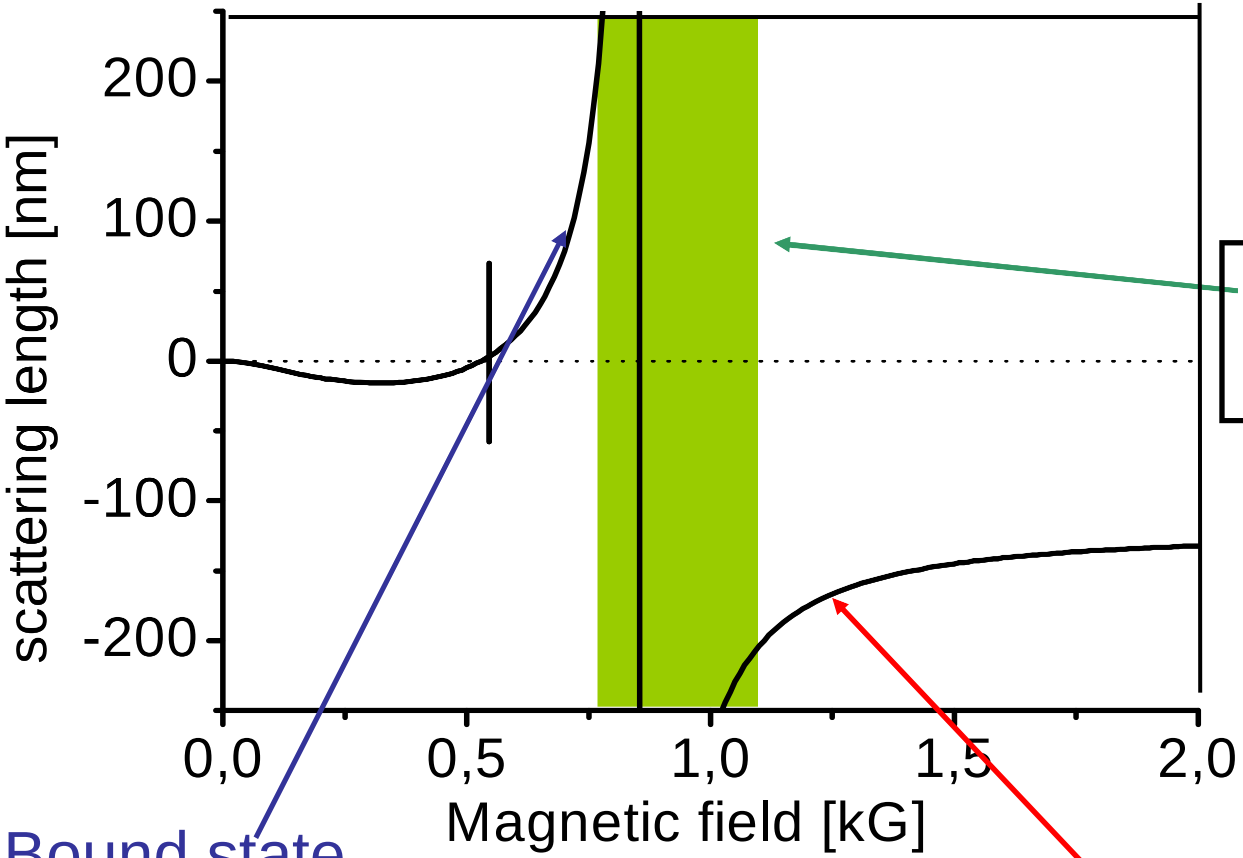
$$E_{F,i} = \frac{\hbar^2 k_{F,i}^2}{2m_i} = \frac{\hbar^2}{2m_i}\left(6\pi^2 n_i\right)^{2/3}$$

**Mixtures with different masses:**
**Innsbruck, Munich, Amsterdam, MIT, ENS**

# $^6$Li Ground state in magnetic field



# interacting fermions




BEC-BCS Crossover

Bound state

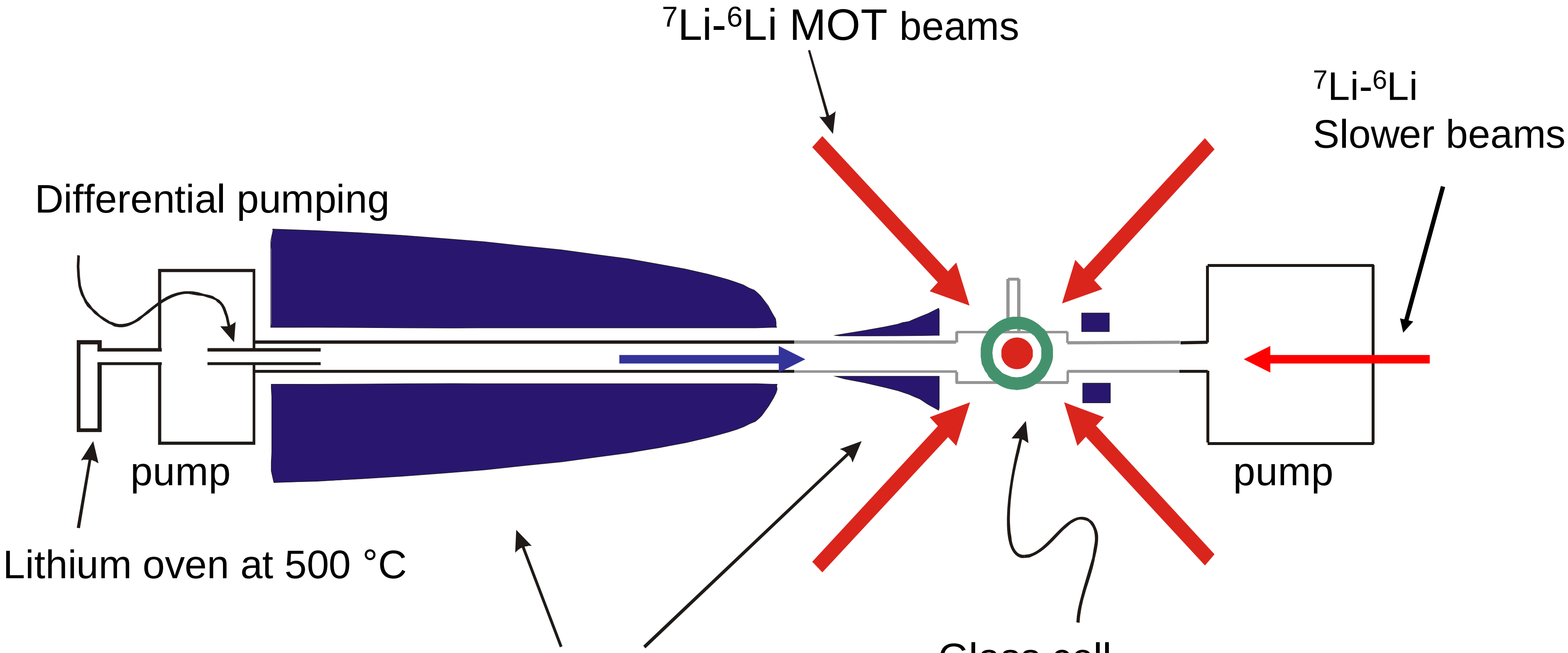
$$Eb = -\frac{\hbar^2}{ma^2}$$

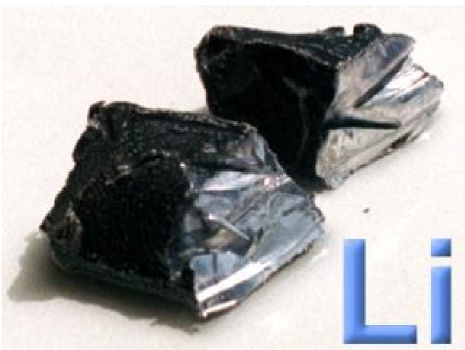
condensate of molecules

No bound state

BCS phase

# Second generation Set-up

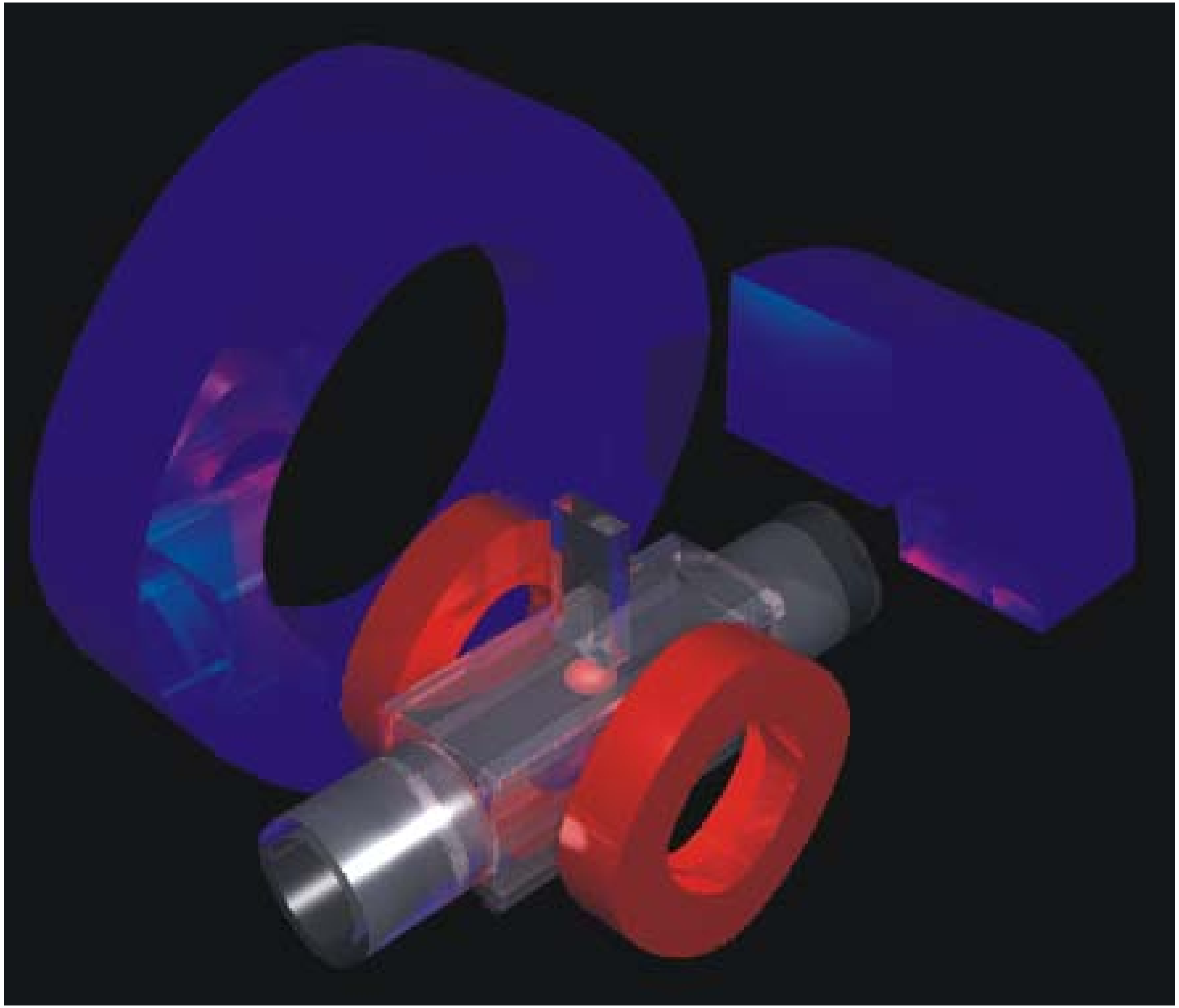


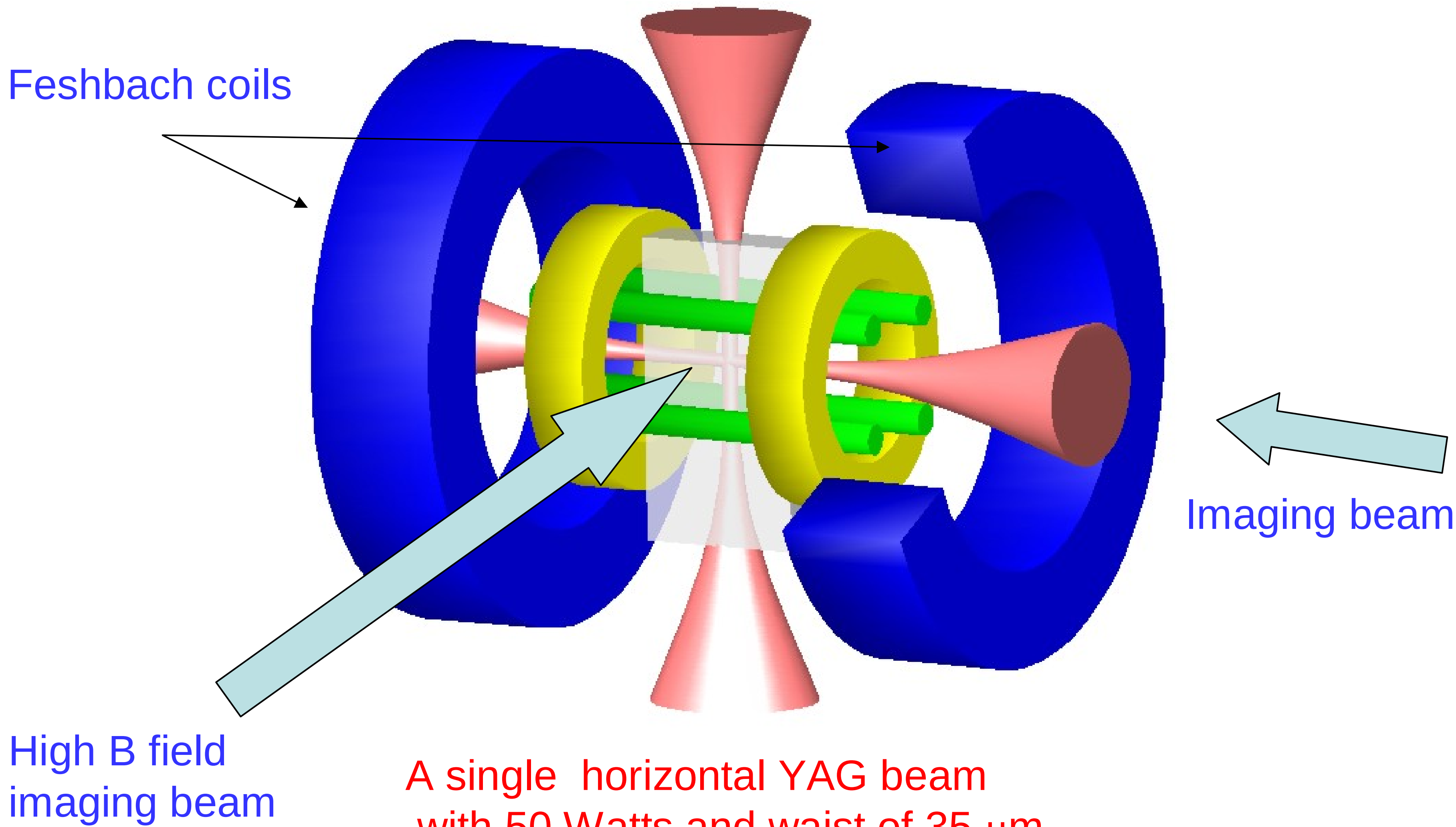

$10^{10}$ atoms in $^7$Li MOT

5 $10^8$ atoms in $^6$Li MOT

# Magnetic elevator



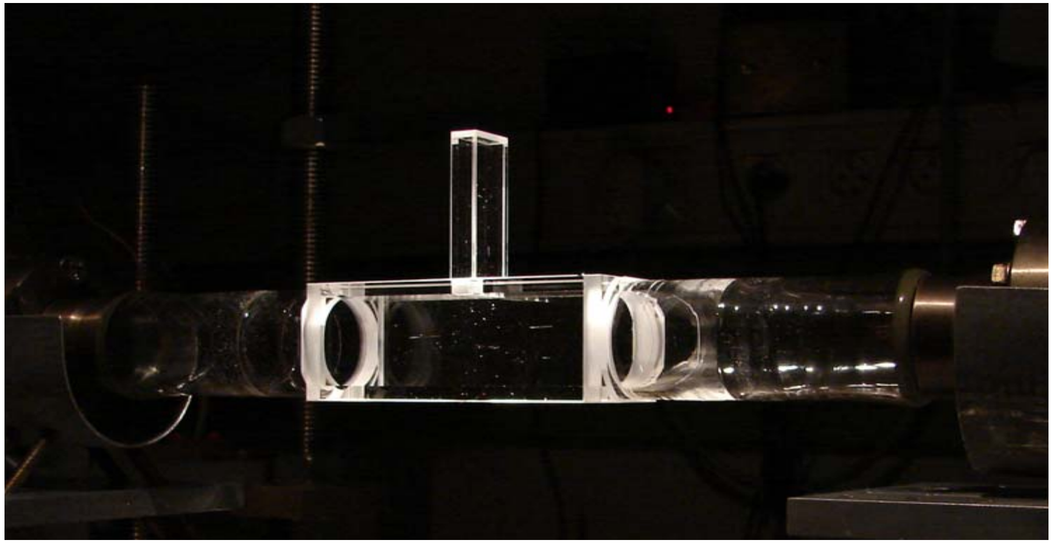
# $^6$Li gas in an optical trap




A single horizontal YAG beam
with 50 Watts and waist of 35 μm

Note: Vertical beam not used for the present data

# Improvements on Lithium experimental setup

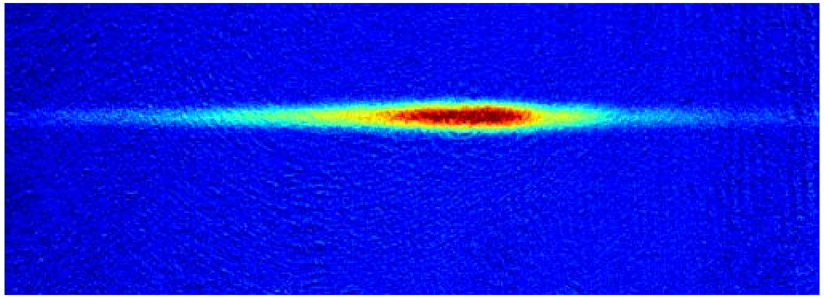


Enlarged glass cell
New laser sources: 120 mW diodes
New Zeeman slower
More stable Ioffe-Pritchard trap

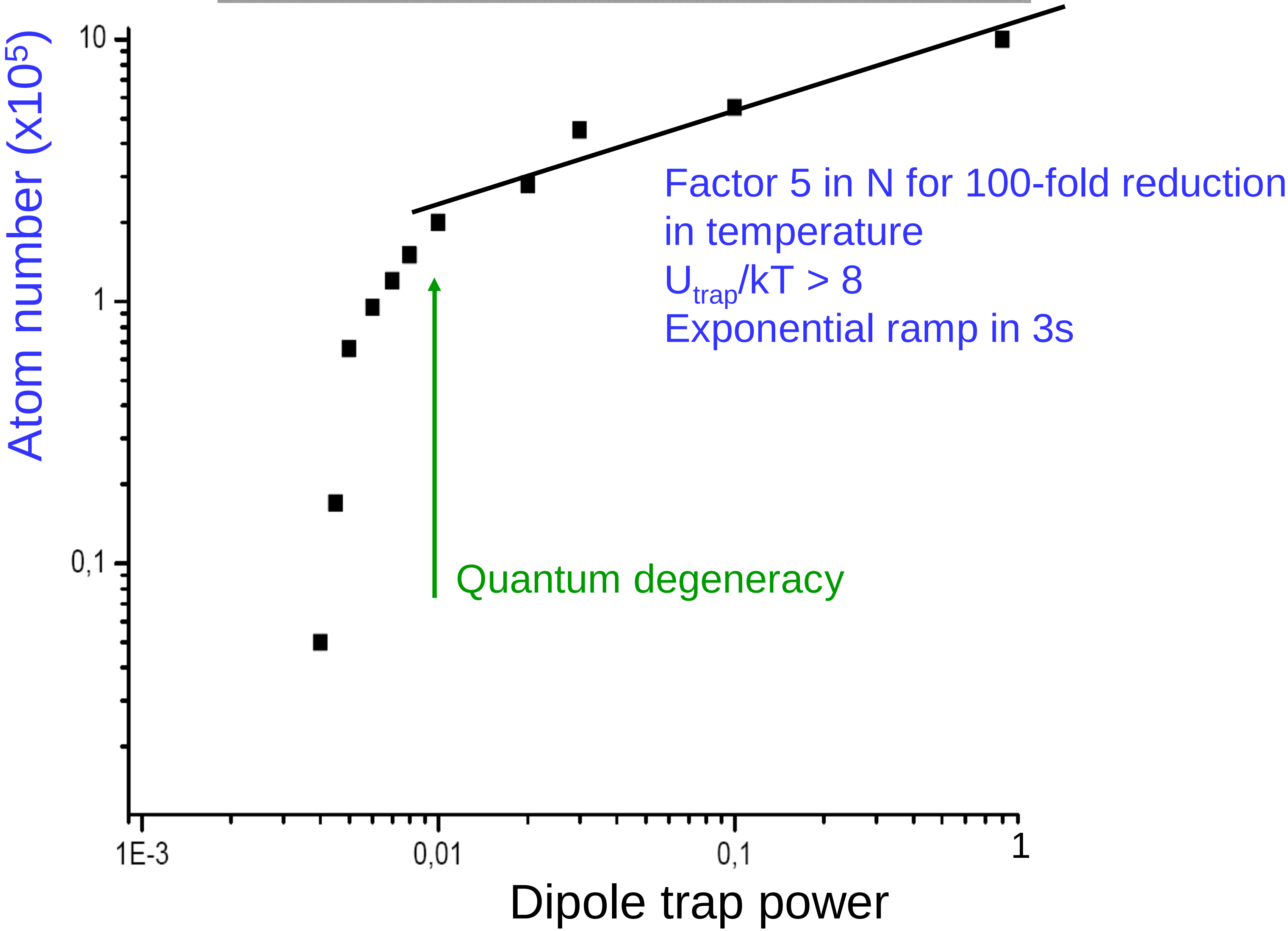
120 Watt far detuned optical trap
(IPG Fiber laser)
Access for 3D optical lattice
3D high field imaging

⇨ Sympathetic cooling of 6Li by 7Li in 20 seconds in magnetic trap followed by evaporation near Feshbach resonance in optical dipole trap (3 seconds).

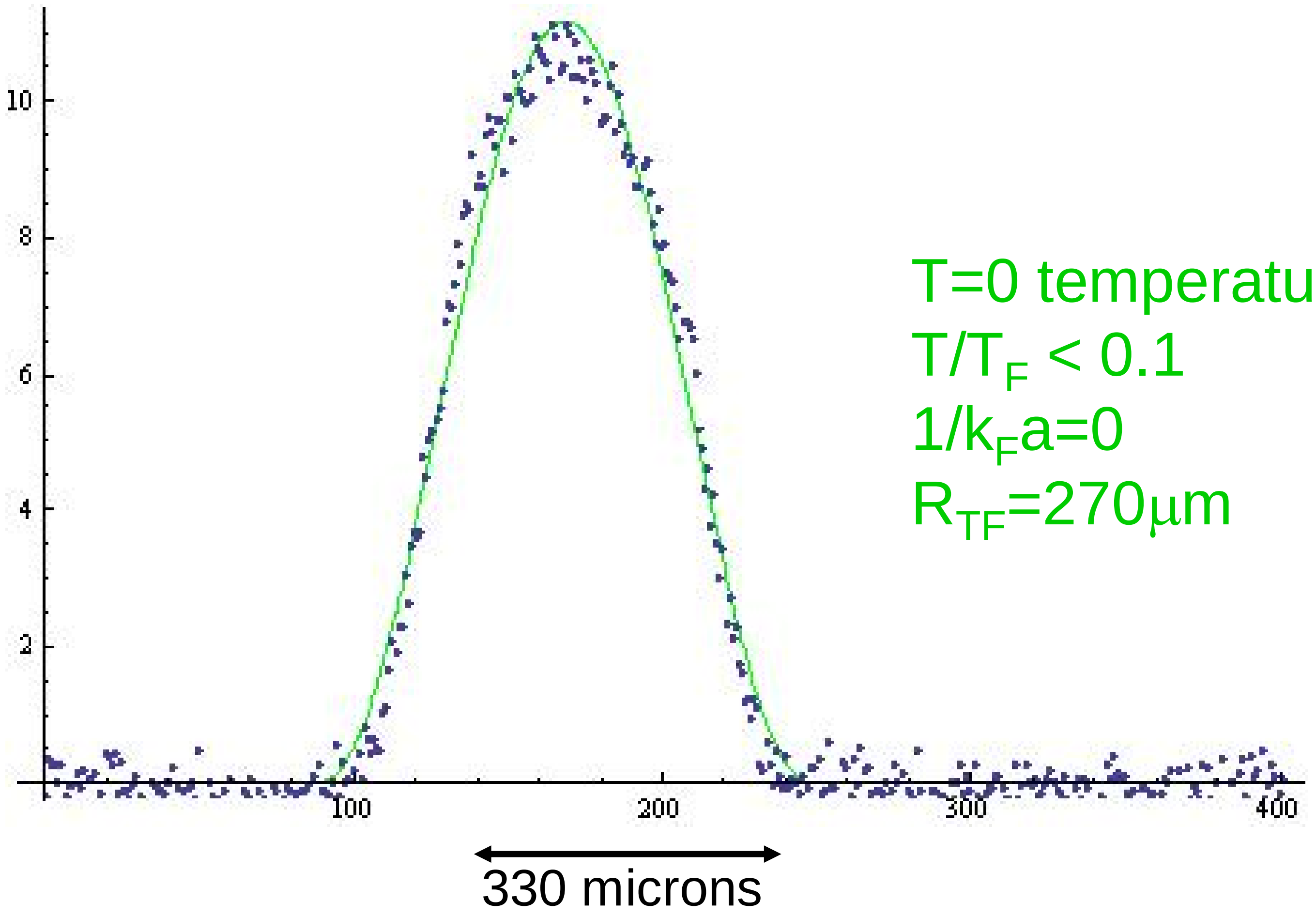
X10 increase in $^{6}$Li number in optical dipole trap:
5 $10^6$ atoms at 80μK
3 $10^5$ atoms per spin state
at $T/T_F \sim 0.1$
Cycle duration: 40 seconds



# Efficient $^6$Li evaporation



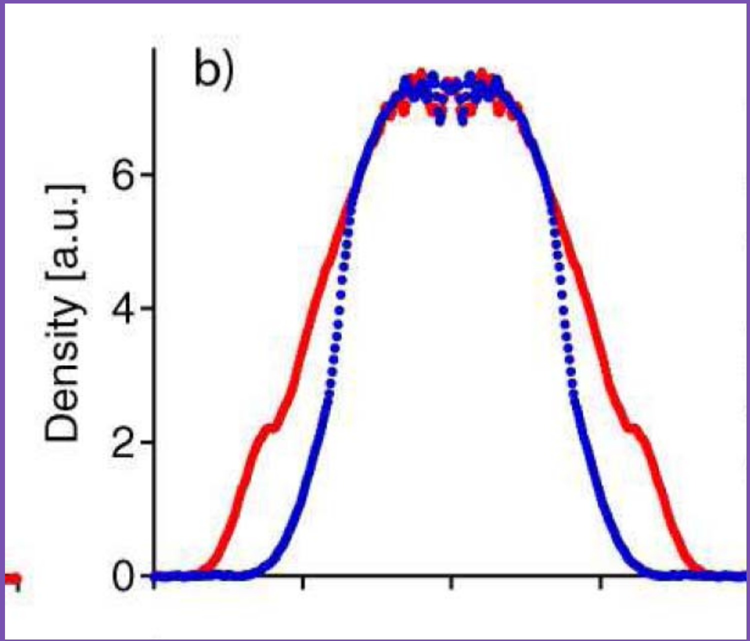
# Axial Thomas-Fermi profiles in the balanced case




T=0 temperature fit
$T/T_F < 0.1$
$1/k_F a=0$
$R_{TF}=270\mu m$

$10^5$ atoms per spin state in dipole trap
with 40 Hz axial, and 2 kHz radial frequencies

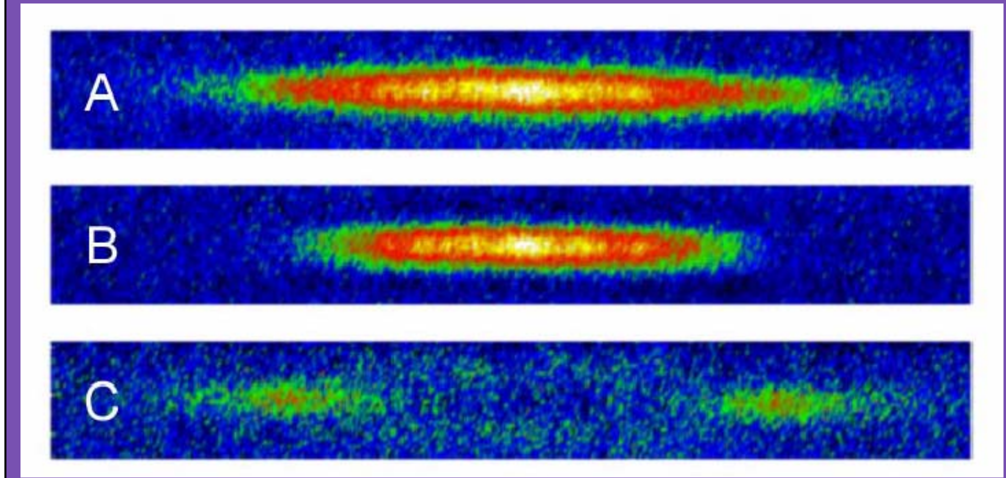
# Imbalanced case: previous work




MIT: 3 phases
- Fully paired superfluid core
-Intermediate mixture
-Fully polarized rim

M.W. Zwierlein, *et al.*, Science, **311** (2006) 492.

Rice: 2 phases
Fully paired superfluid core
Fully polarized rim

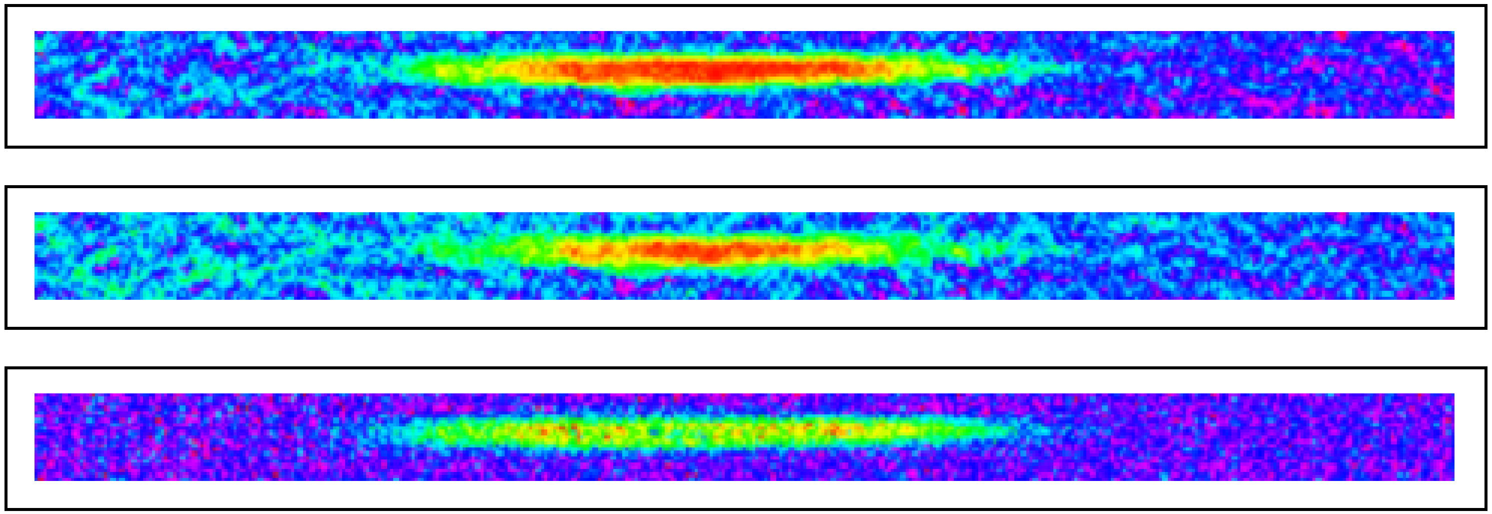



G.B. Partridge, W. Li , R.I. Kamar, Y.-A. Liao, R.G. Hulet, Science, **311** (2006) 503.

See Frédéric Chevy talk

# Imbalanced case: ENS

$$P = \frac{N_1 - N_2}{N_1 + N_2} = 0.39$$

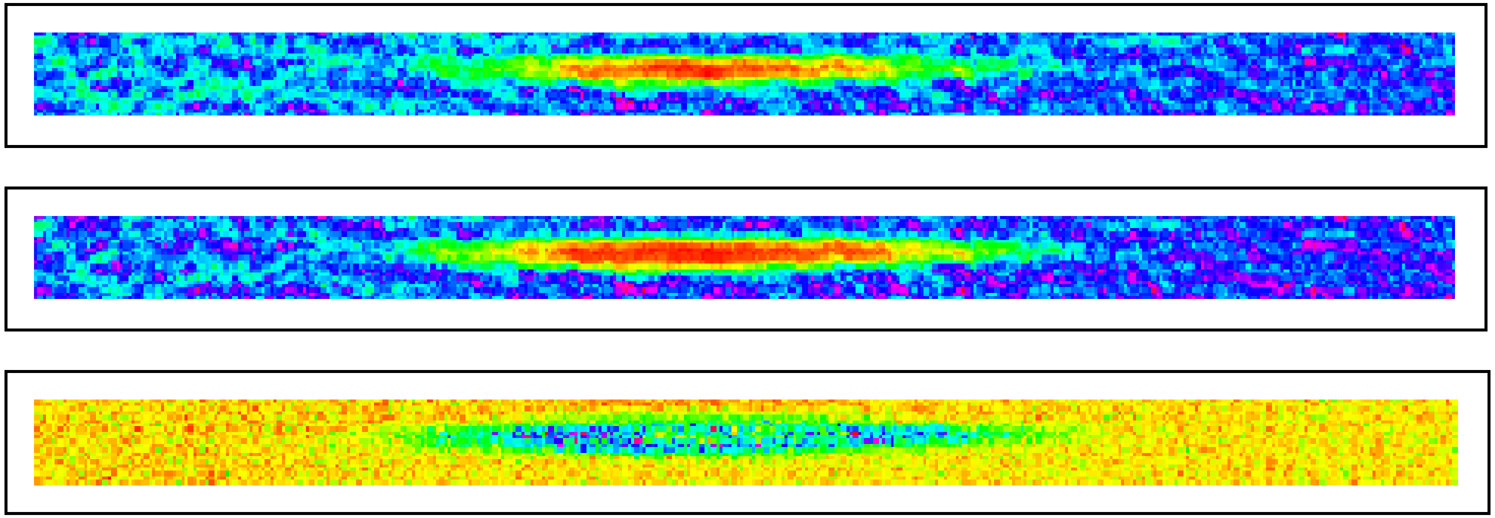



# Check: invert absorption image order

|2>

|1>

|1> - |2>

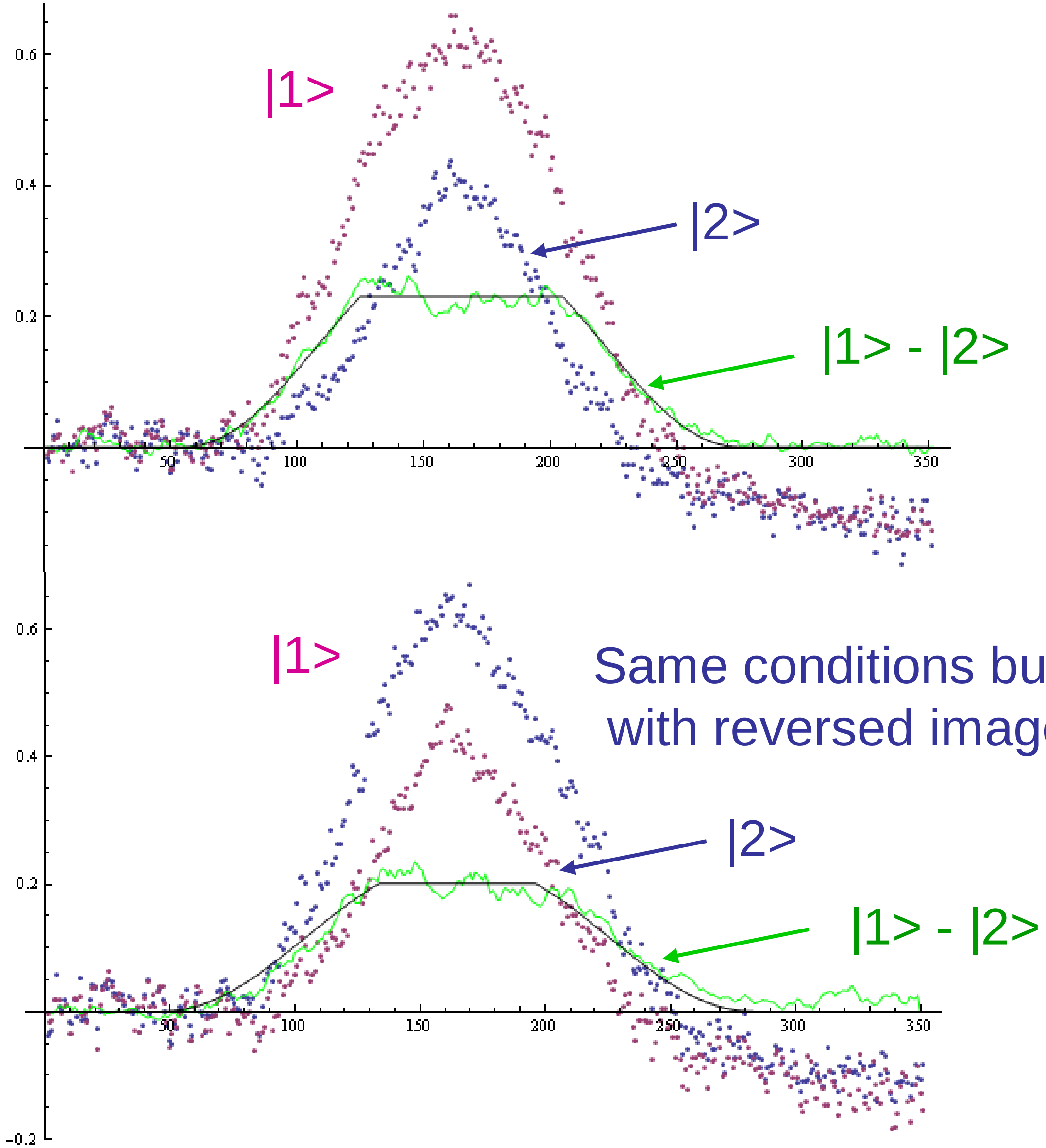


# Profiles integrated along vertical direction

P=0.39
N1= 1.1 E5
N2= 5.0 E4

Flat top: characteristic
of equal densities
in SF core.

No violation of LDA
Consistent with 3 phases
scenario.

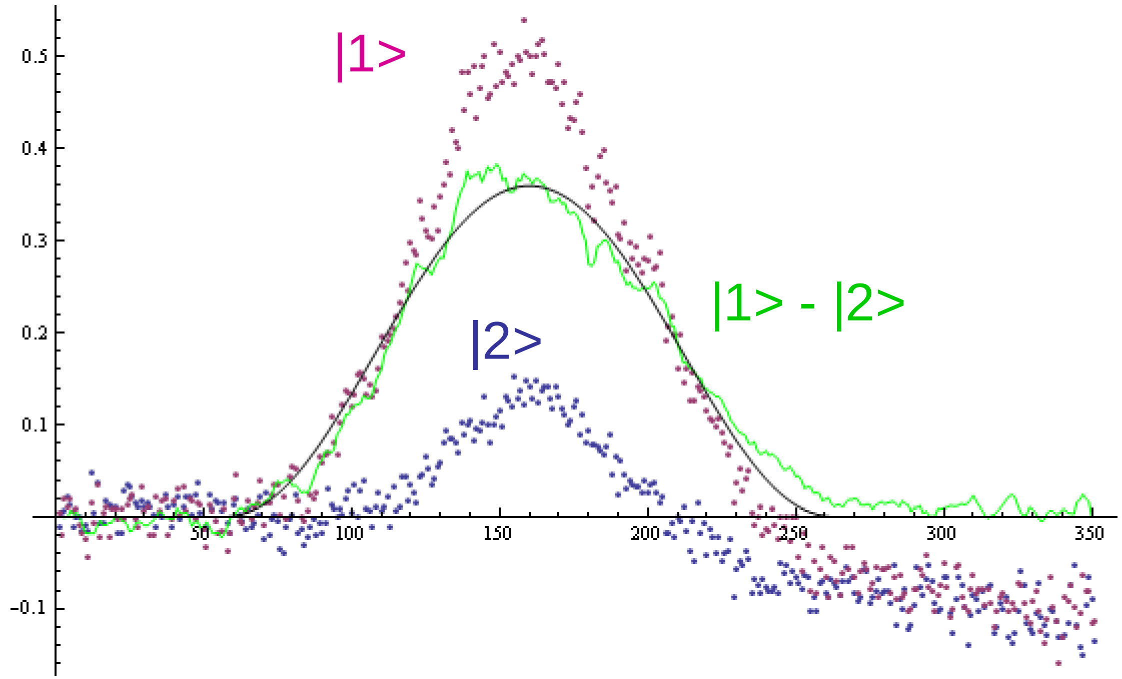



Same conditions but
with reversed image order

P= 0.34
N1= 1.1 E5
N2= 6.0 E4

# Clogston-Chandrasekhar limit

P=0.75 with N1=8.7e4 et N2=1.2e4




Plateau non longer present on difference of integrated densities. Breakdown of SF phase

# Outlook (1)

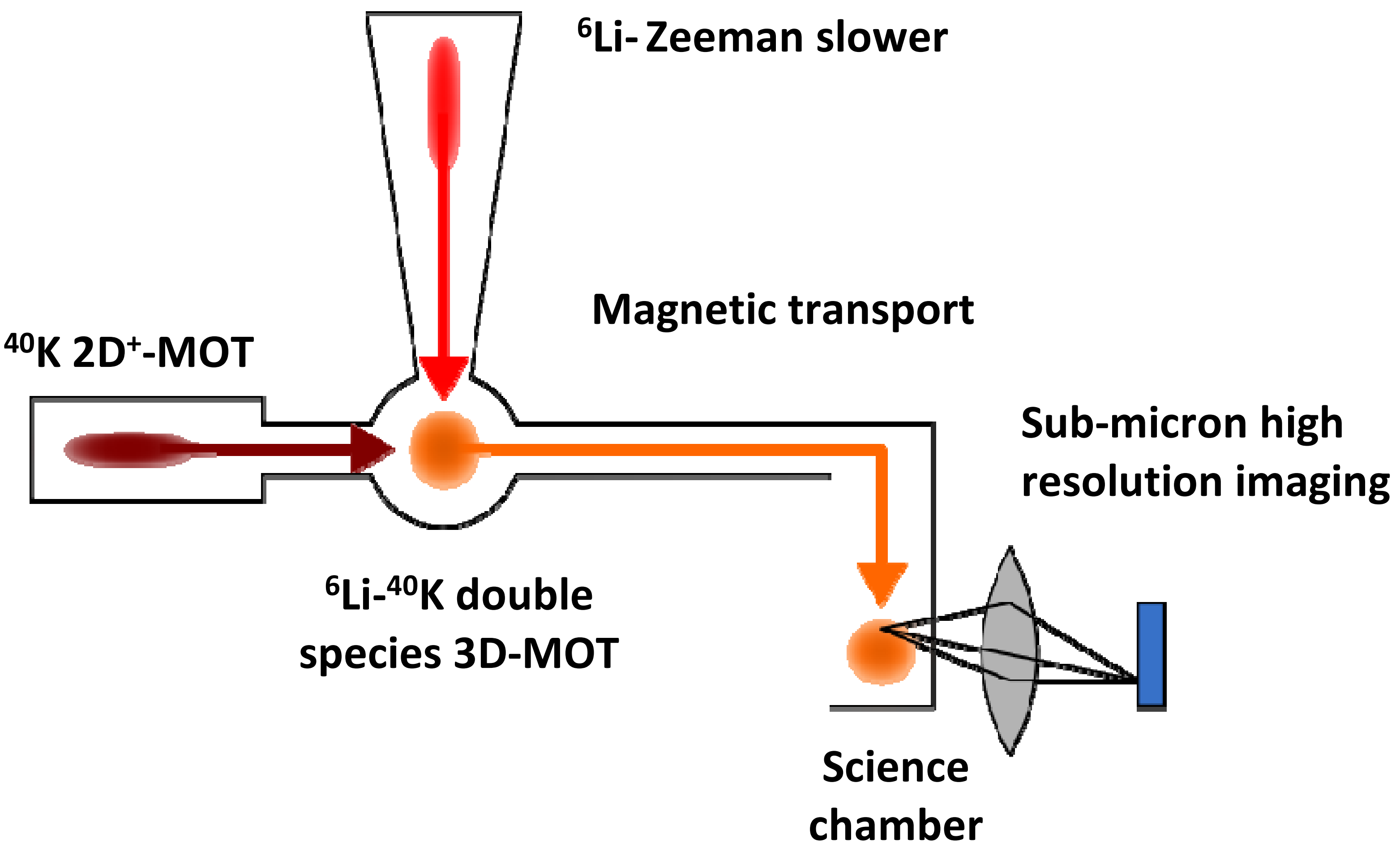
Preliminary results !
Data analysis and exp. checks ongoing !
Preliminary conclusion: 3 phases scenario as MIT despite of high aspect ratio (50).
Role of trap anisotropy to explore in more detail.

Dynamics:
Collective modes
second sound (recent paper by Trento group)
Temperature effects

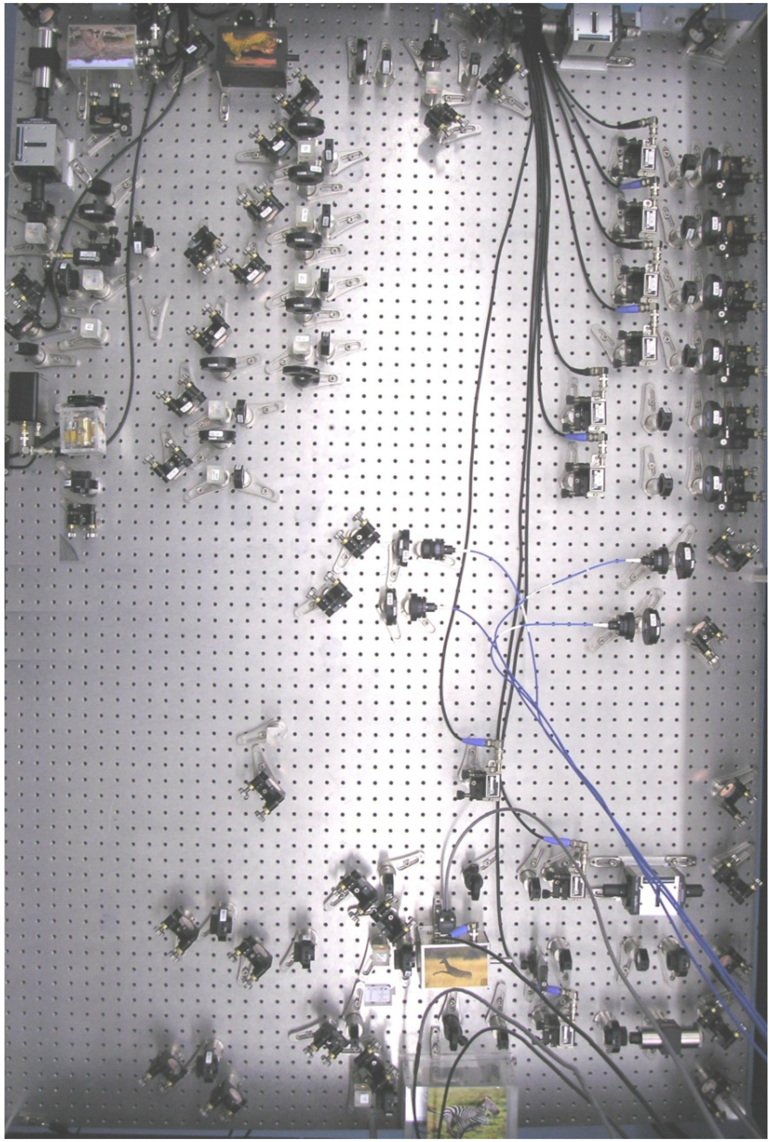
# Another way to imbalance Fermi spheres
# Fermi mixtures
# Ex: $^{6}$Li-$^{40}$K, $^{6}$Li-$^{173}$Yb, $^{6}$Li-$^{87}$Sr

Different masses
Different tunnel rates in optical lattices
Stability of Fermi-Fermi mixture (F. Schreck talk)
Heteronuclear bosonic molecules (K. Dieckmann talk)
Polar molecules
Few-body physics (D. Petrov talk)
Ground state in harmonic trap in the limit of large
mass imbalance: Wigner crystal
Quantum simulation of mixtures in optical lattices
Disorder induced by local interactions with impurities (Castin)

# The ENS Fermi mixture experiment $^6$Li-$^{40}$K

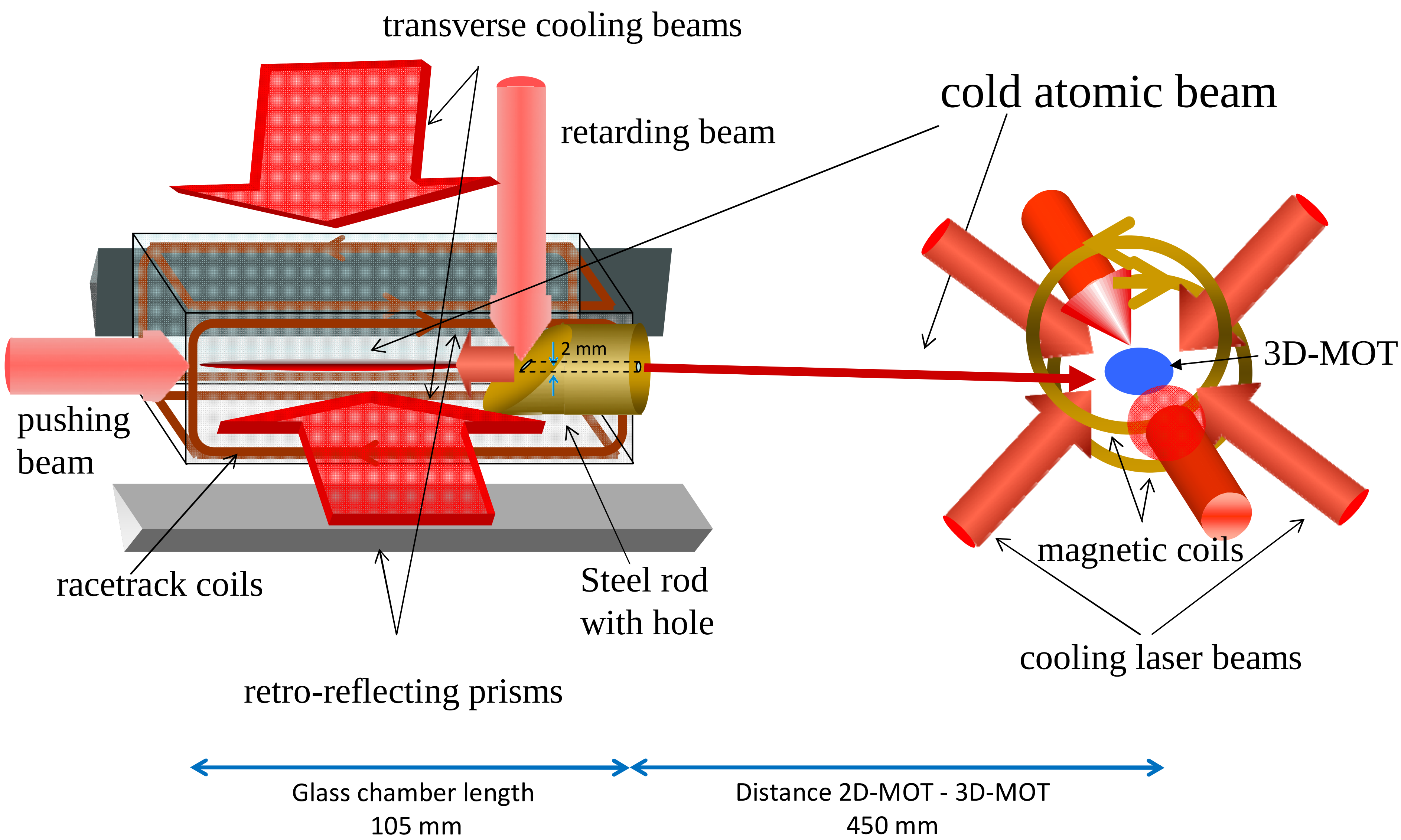


# Potassium 767 nm Laser Setup



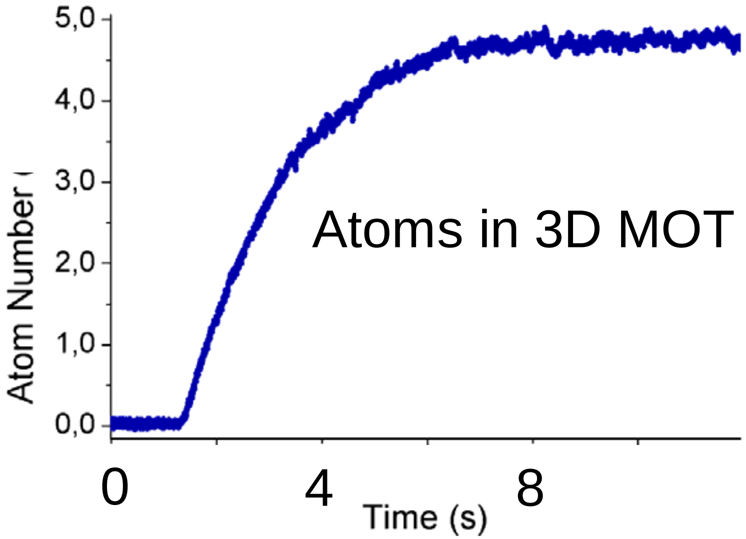
- Master laser diode
  - $P = 53$ mW @ $I = 105$ mA (200 mA max.)
- Toptica Pound-Drever-Hall locking system 20 MHz
- 3x Tapered amplifier (Eagleyard):
  - $P_{TA, max}$ = 1.5 W @ 3 A & 20 mW injection
  - $P_{TA, typ}$ = 700 mW @ 1.8 A & 15 mW injection (almost saturated)
  - $P_{2D/3D}$ = 190 mW after AOMs + fibers

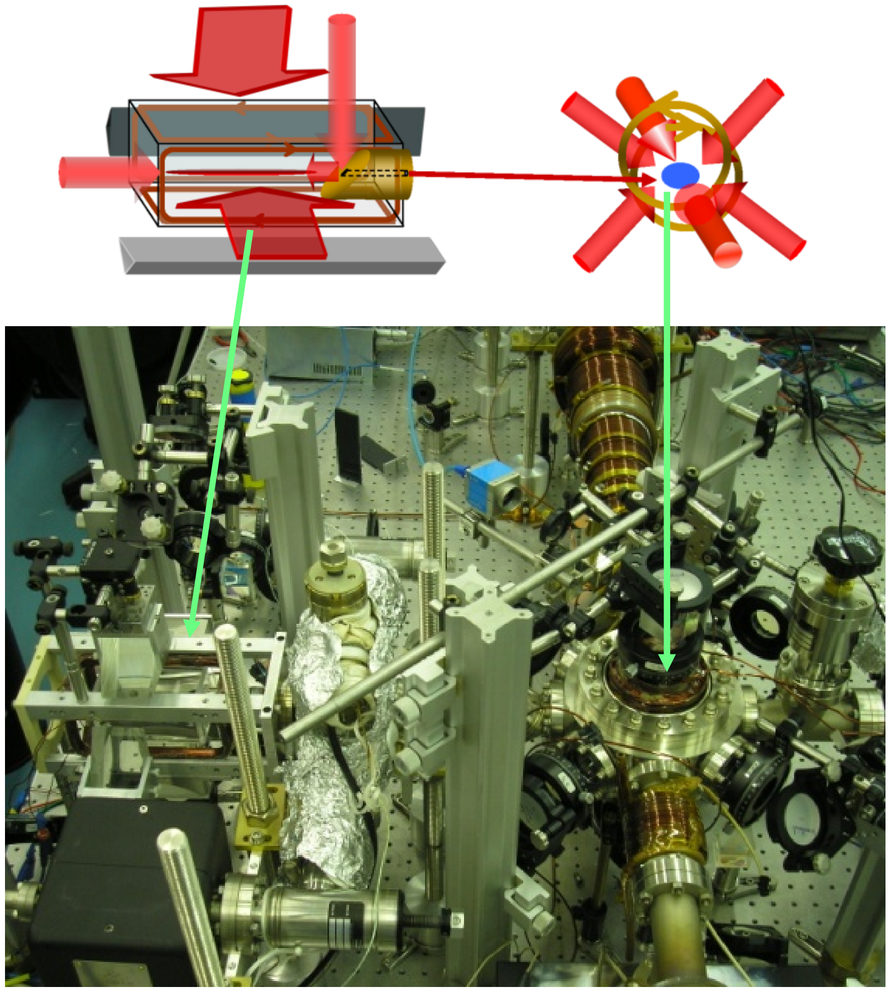
# Potassium 2D+ MOT



# $^{40}K$ 3D MOT loading

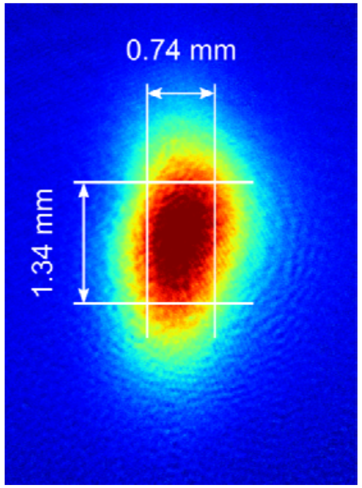
- $2D^+$ MOT
  - Flux : $2 \cdot 10^9$ at./s
  - Mean velocity 20 m/s



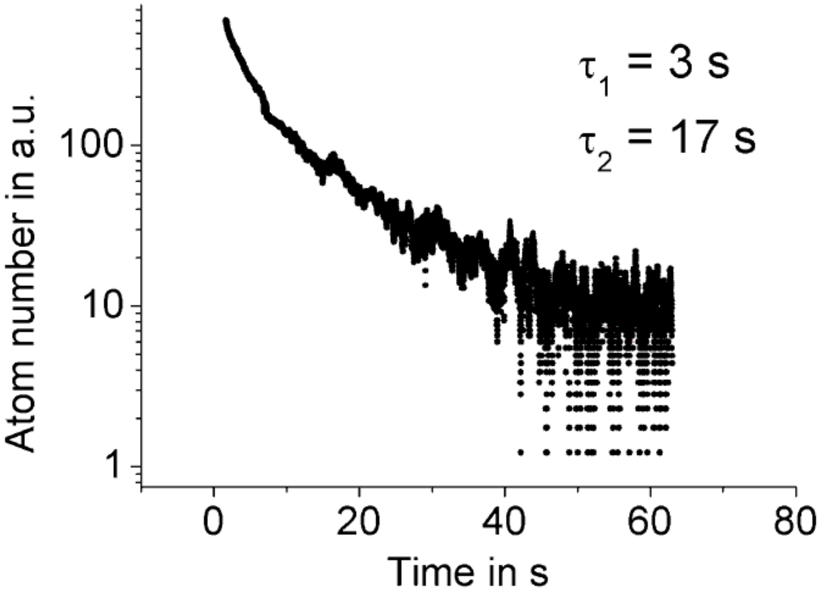



# $^{40}K$ 3D MOT parameters

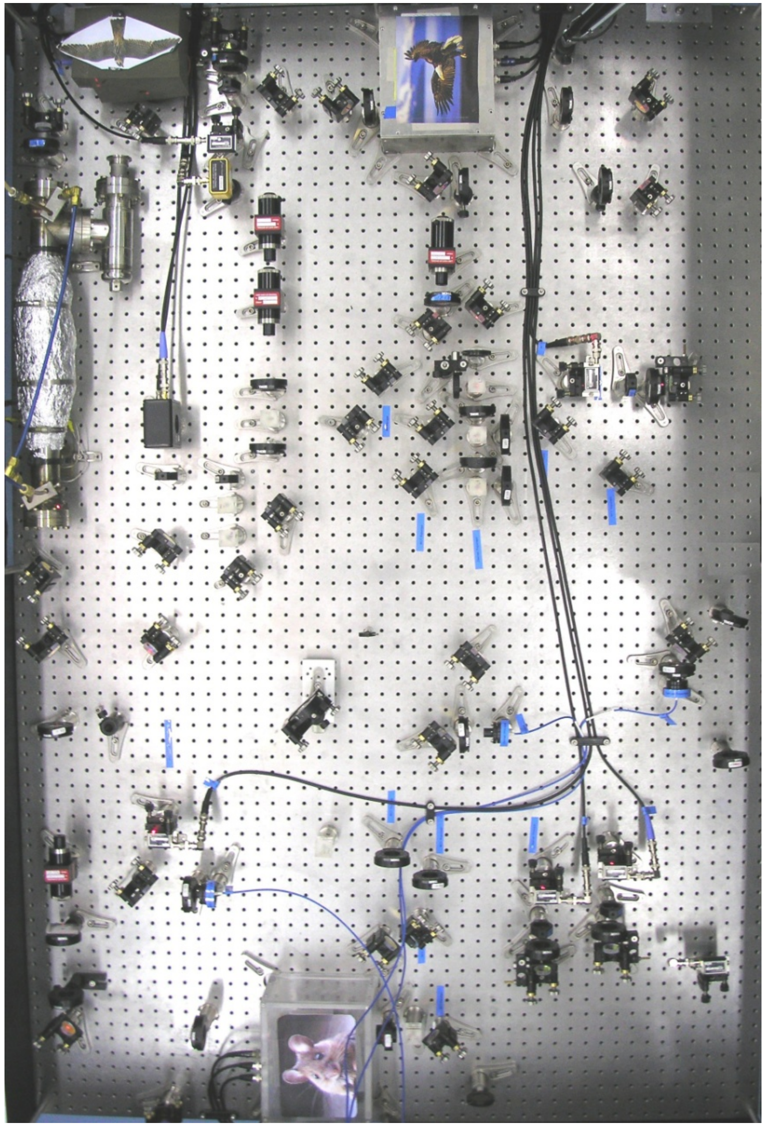
- 3D-MOT
  - Number of atoms $5 \cdot 10^9$ at.
  - Lifetime 3 s / 17 s
  - 3D-MOT temperature 230 µK
  - Compressed MOT temperature > 500 µK




  - $^{39}K$ MOT : Nat > 8 $10^9$



# Lithium 6 laser system at 671 nm



- Master laser diode
  - P = 40 mW @ I = 120 mA
- Toptica Pound-Drever-Hall locking system 20 MHz
- 2x Tapered amplifier (Toptica):
  - $P_{TA, max}$ = 500 mW @ 960 mA & 15 mW injection
  - $P_{Zeeman}$ = 120 mW after AOM + fibers
  - $P_{MOT}$ = 140 mW after AOMs + fibers

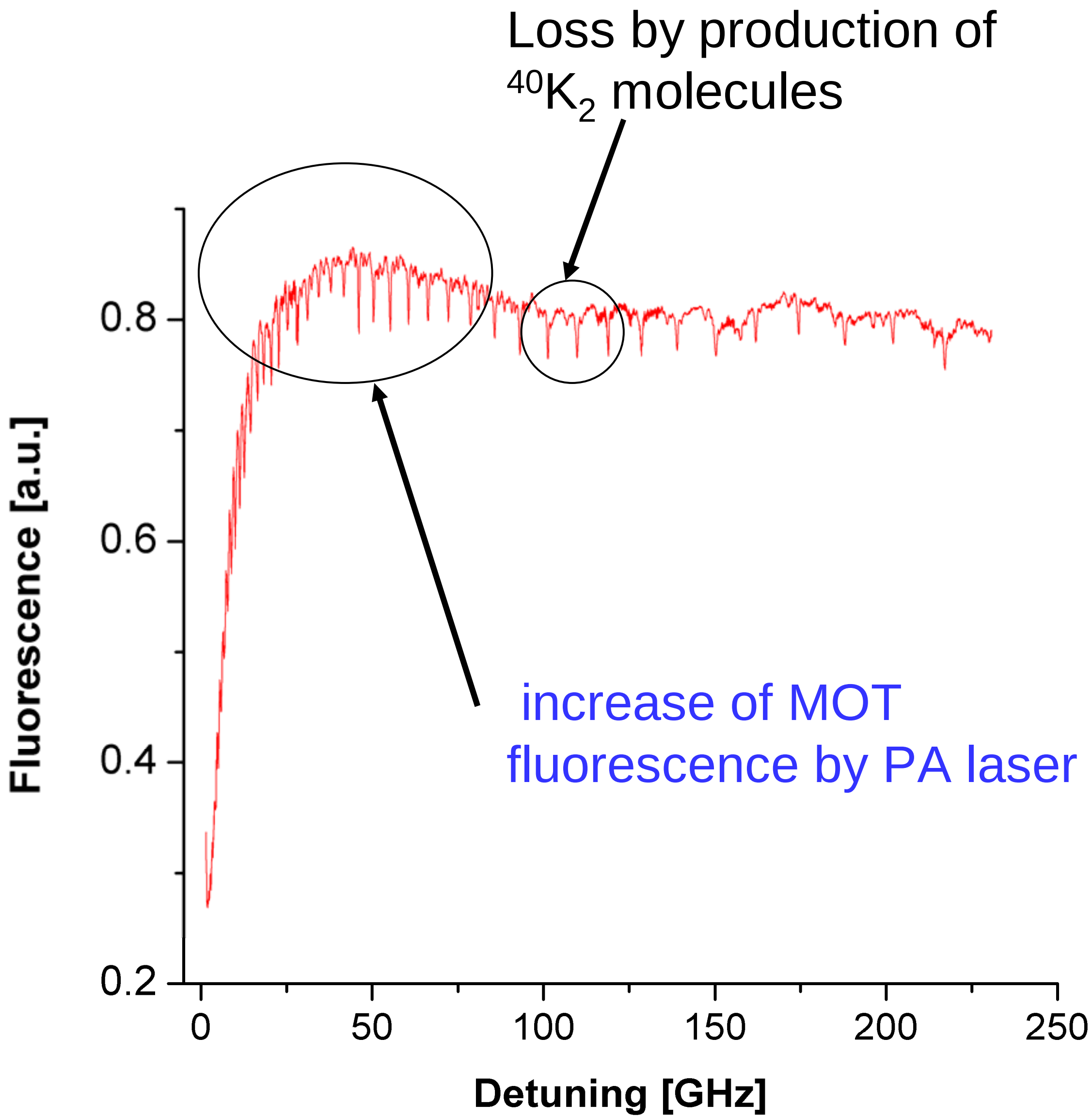
Double MOT

6Li: 5 $10^8$ atoms loaded in 5 s.

40K: 5 $10^9$ atoms loaded in 5 s.

# Photoassociation of Potassium 40

Scan an intense laser below S-P resonance
Look at MOT steady state fluorescence.
1.4 W/ 4.4 $mm^2$
retroreflected PA beam



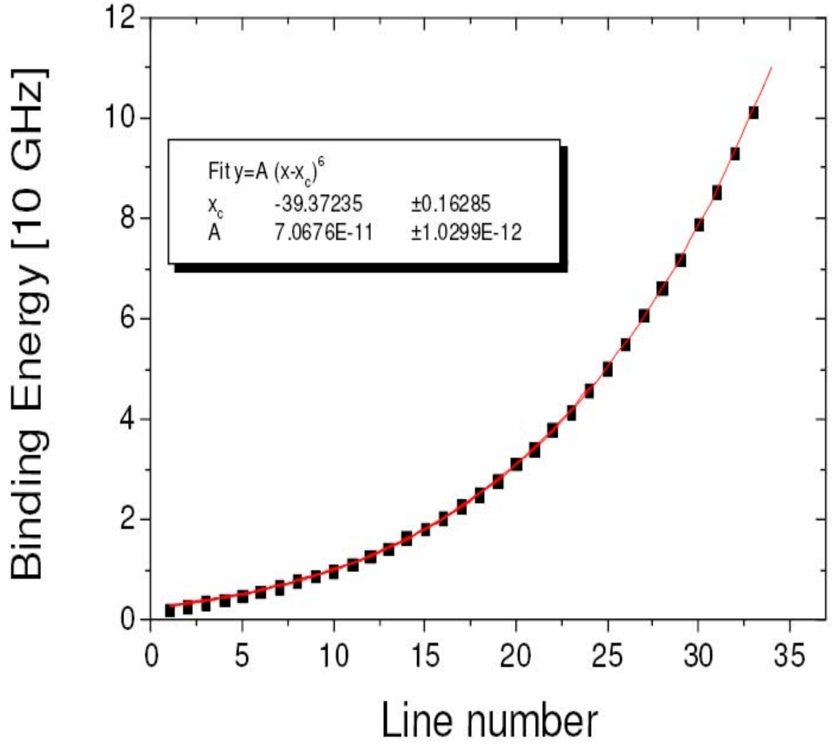
# Energy of photoassociation lines

For $V(R)= -C_3/R^3$ long range potential (dipole-dipole), the energy of high lying bound states scales as:

$$E_n = -A(n-n_0)^6$$

This is simply deduced from a WKB approx. with hard core at short range.

R. Le Roy and R. Bernstein, J. Chem. Phys. 52, 1970




A is related to $C_3$ and to the exponent of long range potential

We find A/h= 0. 7067
Giving $C_3$= 14.13 (20) a.u.

Very good agreement with Wang et al. value: 14.14 (5)

# Summary

- Next step: photoassociation of 40K-6Li mixture
  Towards polar molecules in GS with dipole moment of 3.6 D

- Magnetic transport and evaporation to quantum degeneracy

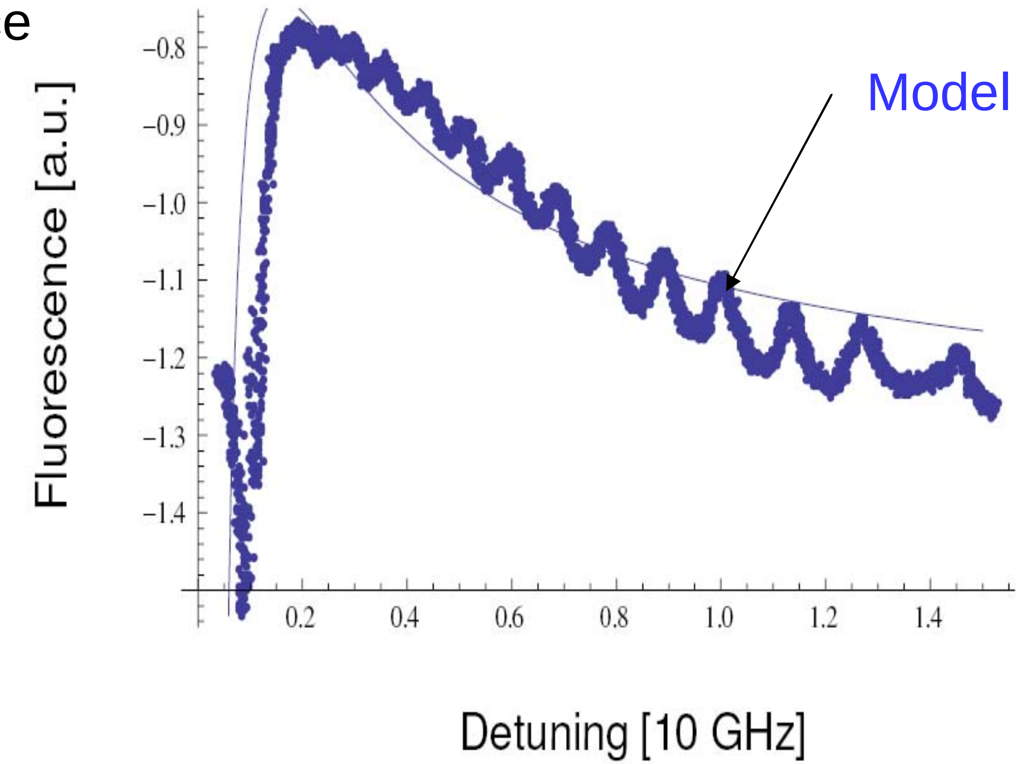
- Simulation in 2D and 1D of various Hamiltonians
  Lattices with frustration
  Challenge: cool in the lattice to get $k_B T < J_{ex} = t^2 / U$

See proposals to cool in lattice by removal of high entropy atoms

- T. L. Ho, Q. Zhou, arXiv:0808.2652
- J. S. Bernier, C. Kollath, A.Georges, L. De Leo, F. Gerbier, C. Salomon, M. Köhl , Arxiv 0902.0005

# Effect of photoassociation laser light shift

Overall shape of Fluorescence signal determined by :
MOT beam fluo.
PA laser fluo.
PA light shift,
which depends on detuning




Simple model:

$$\Phi_{\mathrm{MOT}} = \frac{\Gamma}{2}\left(\frac{s}{1+s}\right),$$

$$s = \frac{I_{\mathrm{MOT}}/I_{\mathrm{sat}}}{1+4\Delta_0^2/\Gamma^2}.$$

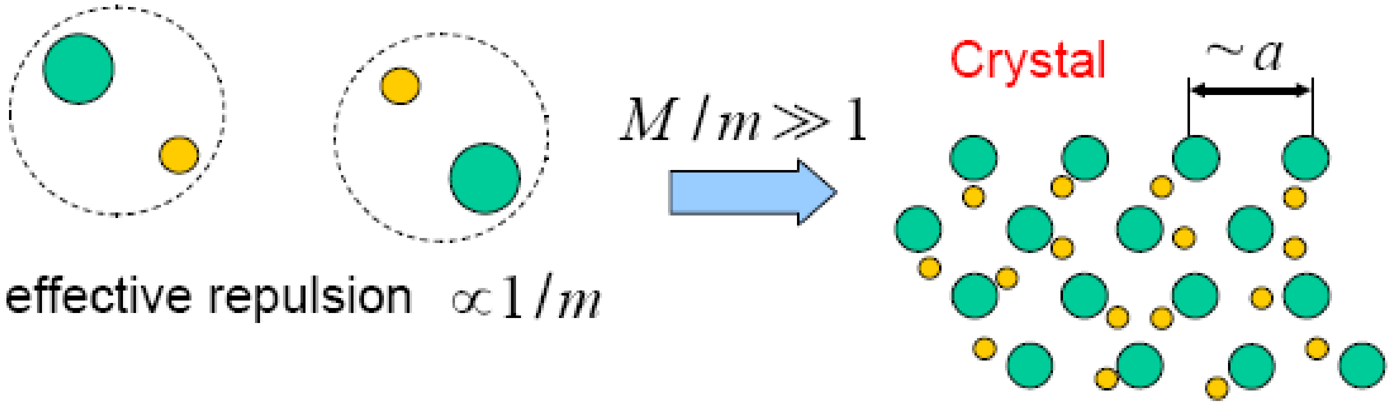
$$\Delta' = \frac{\Delta_{\mathrm{PA}}}{2}\ln(1+s_{\mathrm{PA}}),$$

Thus: $\Phi_{\mathrm{tot}} = A\left(\frac{s}{1+s}+\frac{s_{\mathrm{PA}}}{1+s_{\mathrm{PA}}}\right)$ with $s = \frac{I_{\mathrm{MOT}}/I_{\mathrm{sat}}}{1+4(\Delta_0-\Delta')^2/\Gamma^2}.$

# What is the ground state of a mixture of strongly interacting Fermi gases with large mass difference ?

## A Wigner Crystal !

D. Petrov, G Astrakharchik, D. Papoular, C. Salomon, G. Shlyapnikov, PRL 99 (2007)




$$[-\nabla^2/M + U_{eff}(R)]\psi(R) = E\psi(R)$$

$$R \gg a \Rightarrow U_{eff}(R) \approx \frac{2\hbar^2}{m\,a\,R}\exp[-2R/a]$$