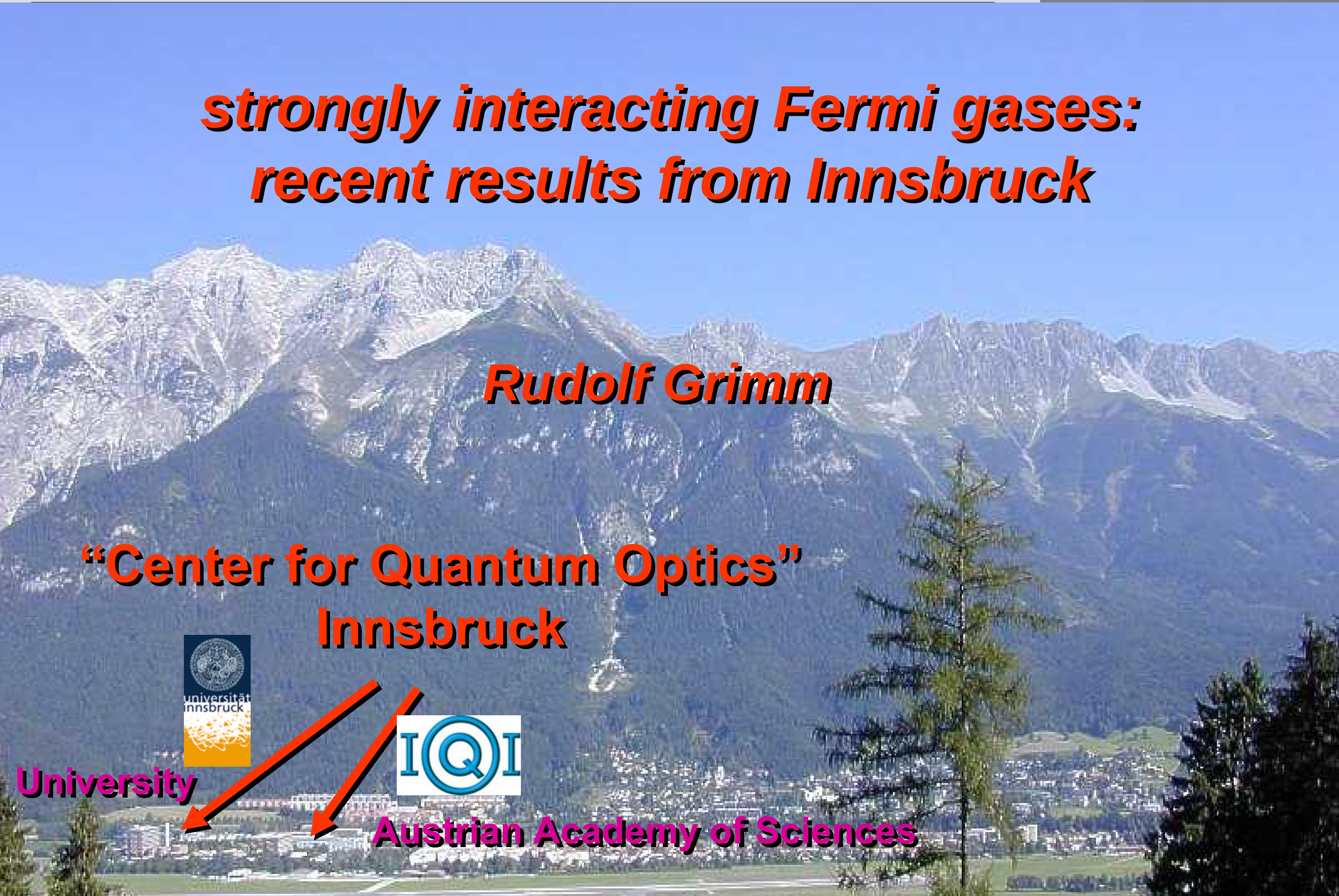
Ultracold atoms
quantum gases



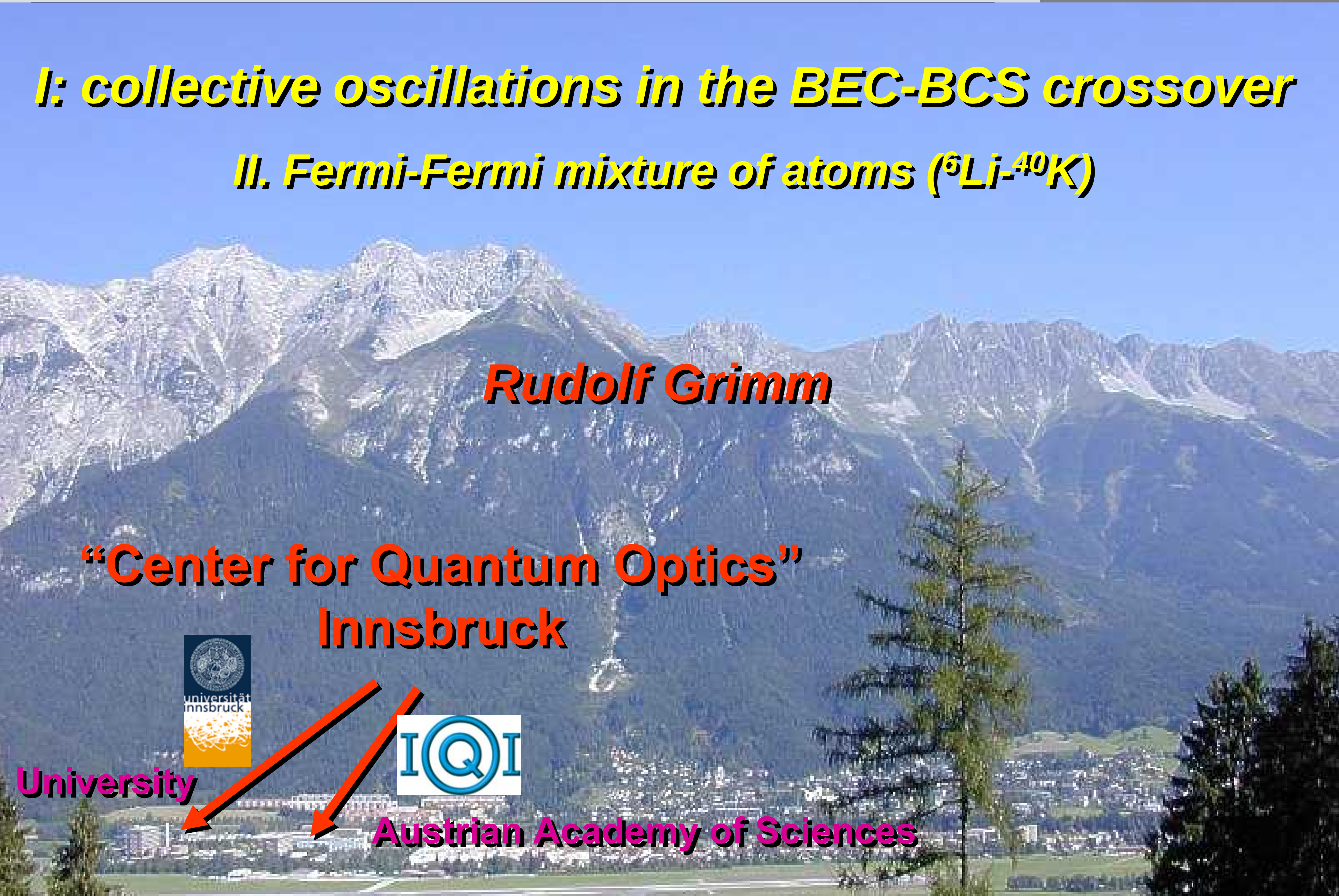
strongly interacting Fermi gases: recent results from Innsbruck

Rudolf Grimm

"Center for Quantum Optics"
Innsbruck

universität innsbruck
University

IQI
Austrian Academy of Sciences



I: collective oscillations in the BEC-BCS crossover

II. Fermi-Fermi mixture of atoms (^{6}Li-^{40}K)

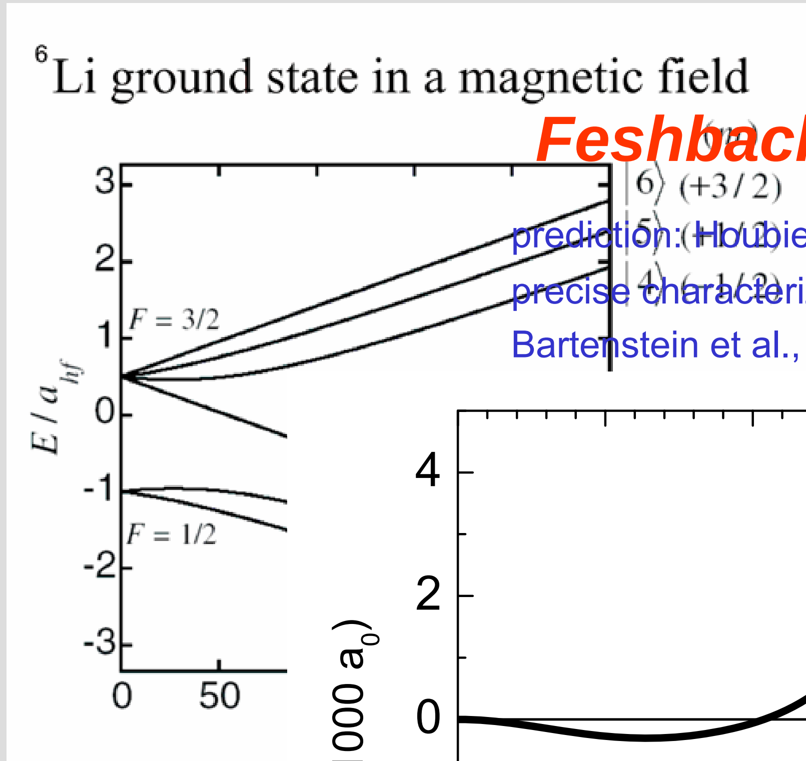
Rudolf Grimm

"Center for Quantum Optics"
Innsbruck

University

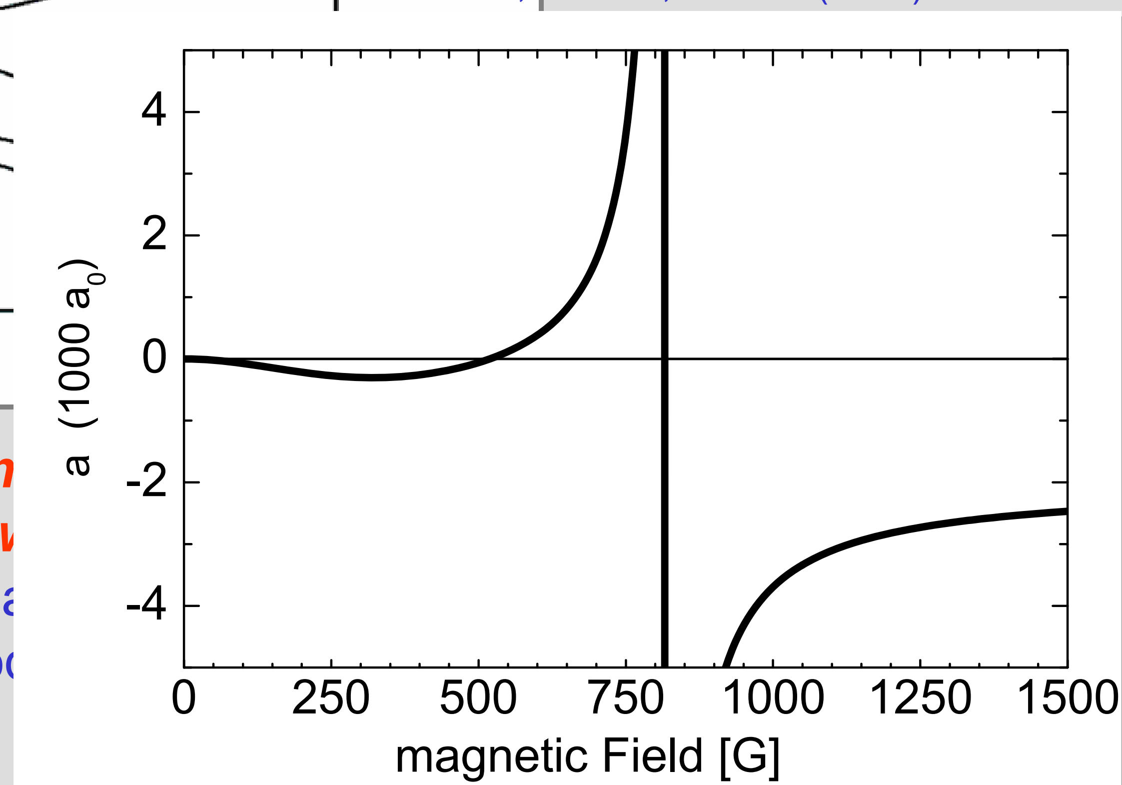
Austrian Academy of Sciences

^{6}Li spin mixture



Feshbach resonance

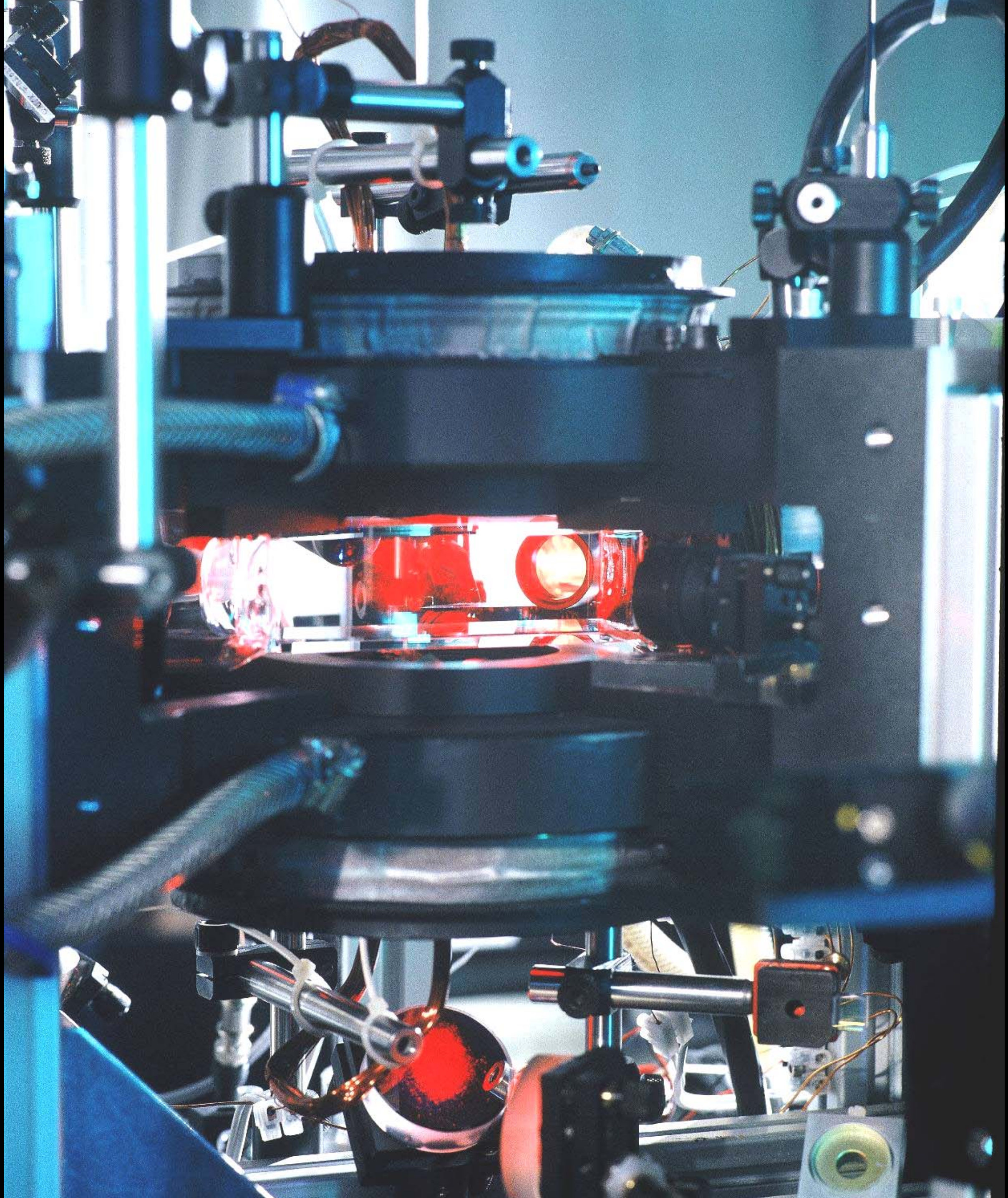
prediction: Houbiers et al., PRA **57**,R1497 (1998)
precise characterization:
Bartenstein et al., PRL **94**, 103201 (2005)



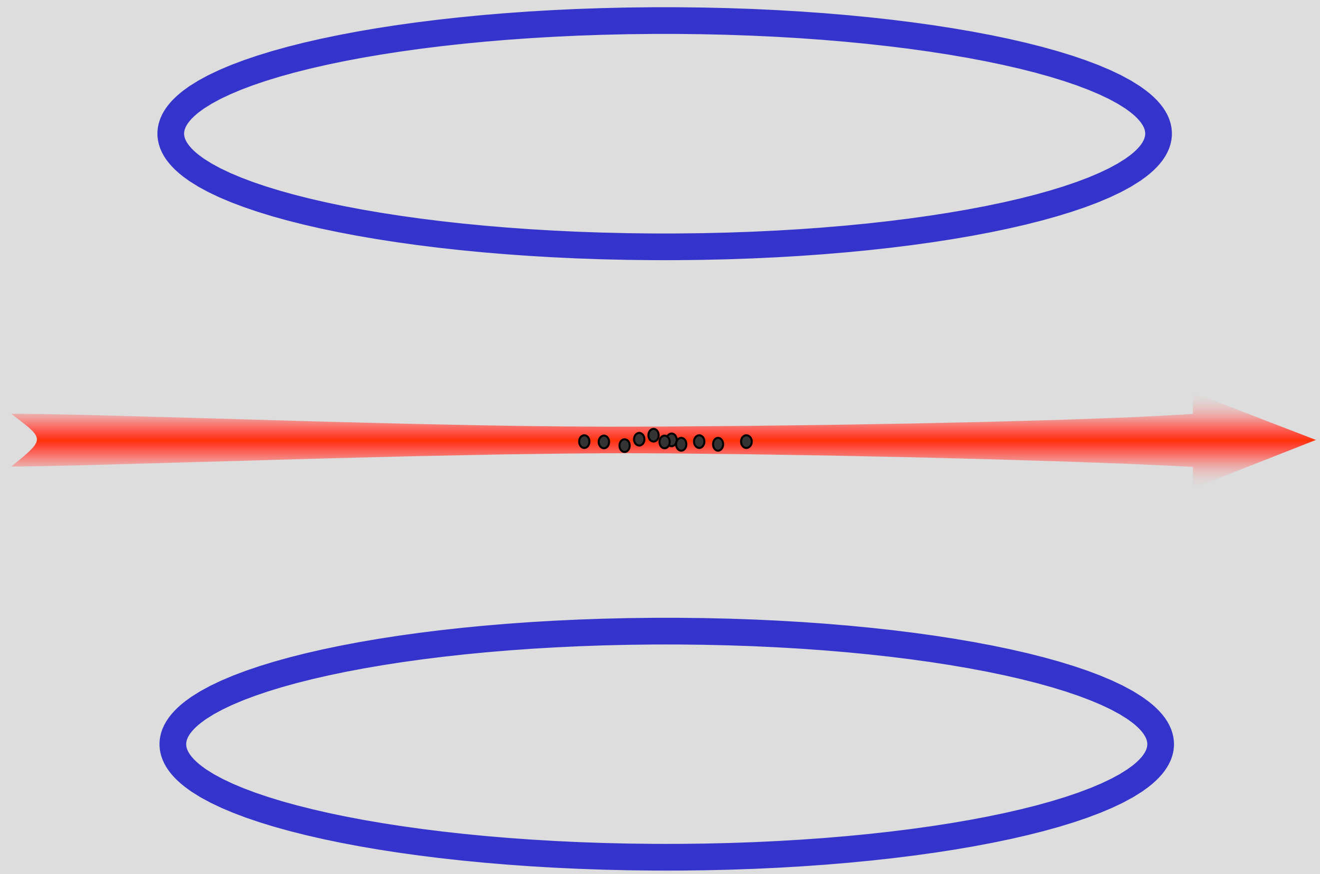
spin m
two low
stable a
two-bod

the ^{6}Li team


RG
Alexander Altmeyer
Matthew Wright
Stefan Riedl
Johannes Hecker Denschlag
Edmundo Sanchez



optical trap for evaporative cooling



collective modes

- Stringari, Europhys. Lett. **65**, 749 (2004)
- Hu, Minguzzi, Liu, Tosi, PRL **93**, 190403 (2004)
- Heiselberg, PRL **93**, 040402 (2004)
- Combescot, Leyronas, Europhys. Lett. **68**, 762 (2005)
- Manini, Salasnich, PRA **71**, 033625 (2005)
- Bulgac, Bertsch, PRL **94**, 070401 (2005)
- Kim, Zubarev, PRA **72**, 011603(R) (2005)
- Astrakharchik, Combescot, Leyronas, Stringari, PRL **95**, 030404 (2005)
- … *and many more recent papers…*

theory

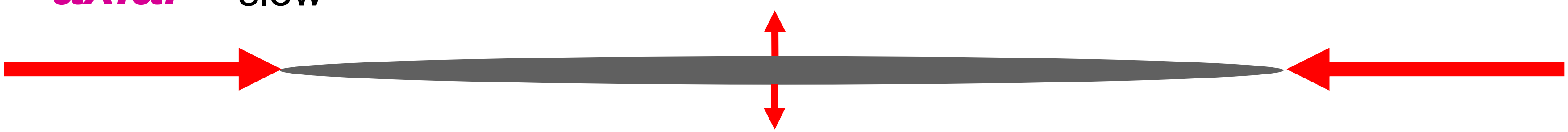
Duke Univ., J. Thomas group / Innsbruck

expt.

collective modes: elementary situation

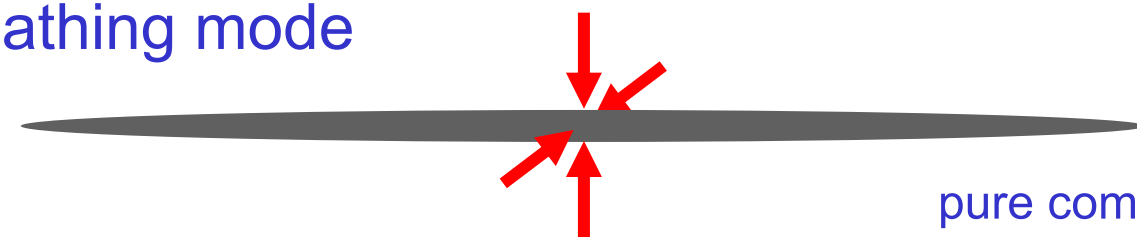
elongated trap limit ($\omega_r \gg \omega_z$ well fulfilled for all our expts.)
cylindrical symmetry (radial trap freq. ω_r), **3D harmonic potential**

axial slow



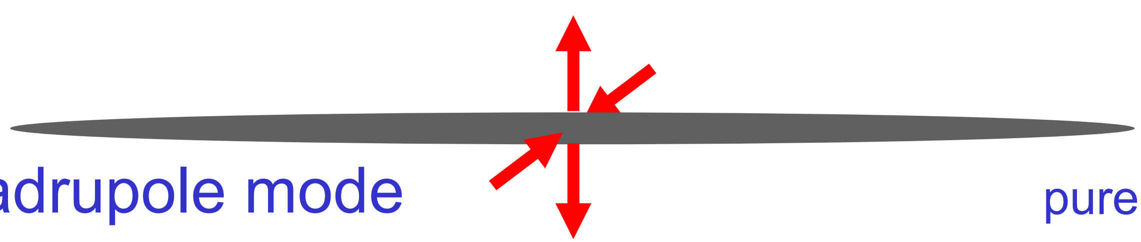
compression and surface character

radial breathing mode



pure compression mode

radial fast



radial quadrupole mode

pure surface mode

collective mode freq. in BEC-BCS crossover

polytropic index !!

$$\mu \propto n^{\gamma}$$ equation of state

frequencies of low-lying collective modes

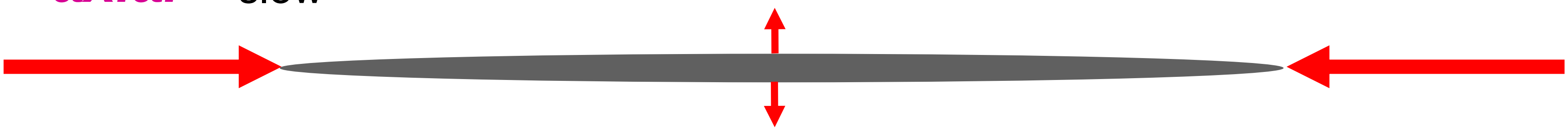
	general γ	BEC $\gamma = 1$	unitarity (and BCS limit) $\gamma = 2/3$	collisionless oscillation
axial ω_z	$\sqrt{3 - 1/(\gamma+1)}$	$\sqrt{5/2}$ $= 1.581$	$\sqrt{12/5}$ $= 1.549$	2
radial $\omega_\perp$ breathing	$\sqrt{2(\gamma+1)}$	2	$\sqrt{10/3}$ $= 1.826$	2
radial $\omega_\perp$ quadrupole	$\sqrt{2}$	$\sqrt{2}$	$\sqrt{2}$	2

hydrodynamic behavior

collisionless oscillation

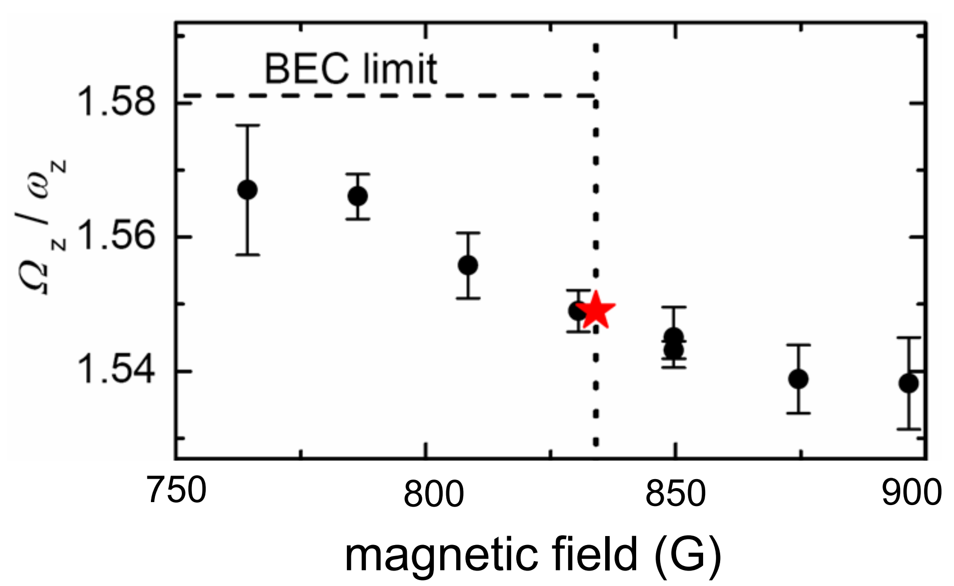
axial mode

axial slow



compression and surface character

Bartenstein et al., PRL **92**, 203201 (2004)



unitarity

$$\Omega_z / \omega_z = \sqrt{12/5}$$

confirms equation of state

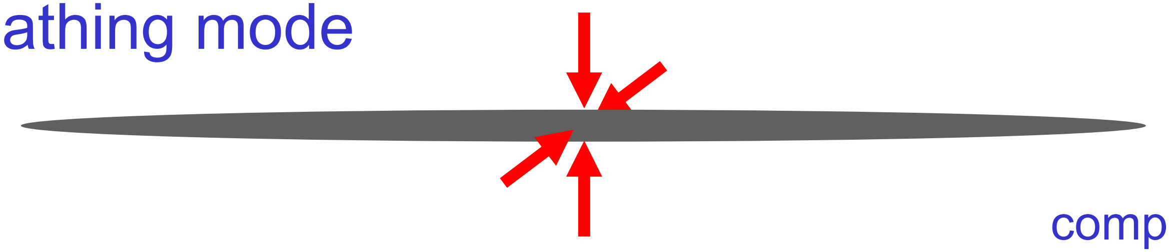
$$\mu \propto n^{2/3}$$

extremely weak damping in resonance region !!

hint on superfluidity

radial compression mode

radial breathing mode



fast

compression mode

Innsbruck

Bartenstein et al., PRL **92**, 203201 (2004)
see also Altmeyer et al., cond-mat/0611285

Altmeyer et al., PRL **98**, 0404401 (2007)

Duke

Kinast et al., PRL **92**, 150402 (2004)

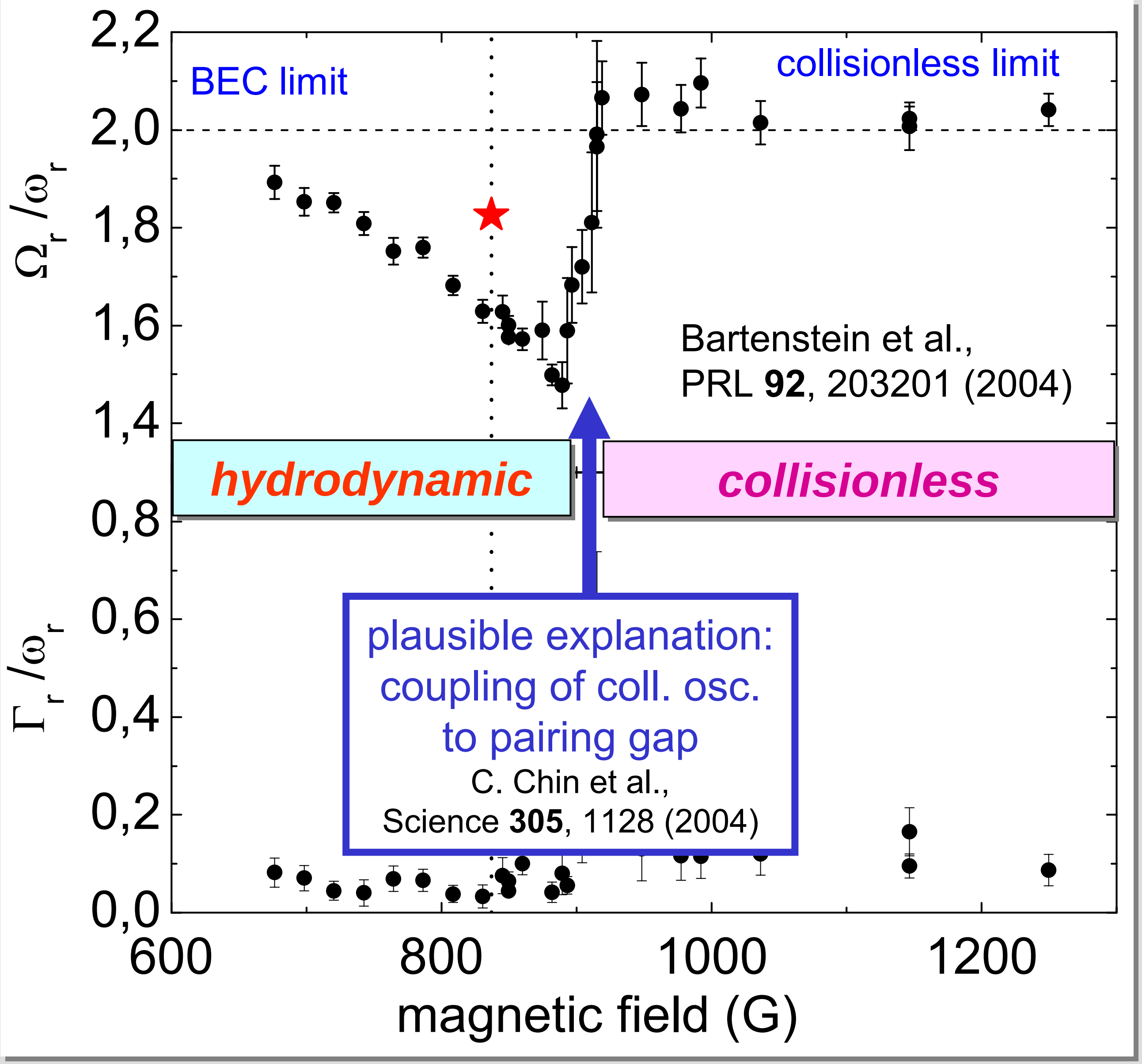
Kinast et al. PRA **70**, 051401(R) (2004)

Kinast et al., PRL **94**, 170404 (2005)

radial compression mode

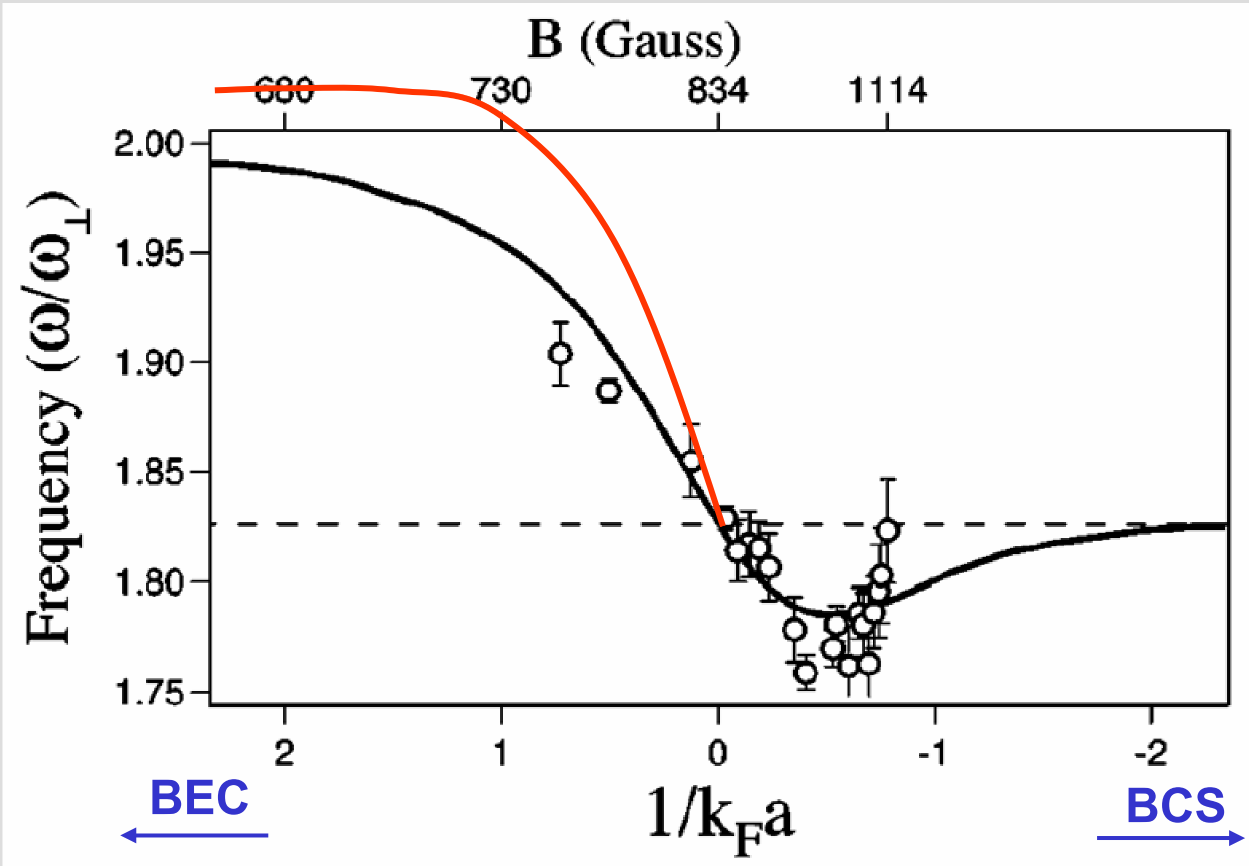
frequency
(normalized to sloshing mode)

damping



radial mode

exp. data from John Thomas group at Duke Kinast et al, PRA **70**, 051401 (2004)



theory: **mean field BCS** à la Leggett, Nozières & Schmitt-Rink

Hu et al., PRL 93, 190403 (2004)

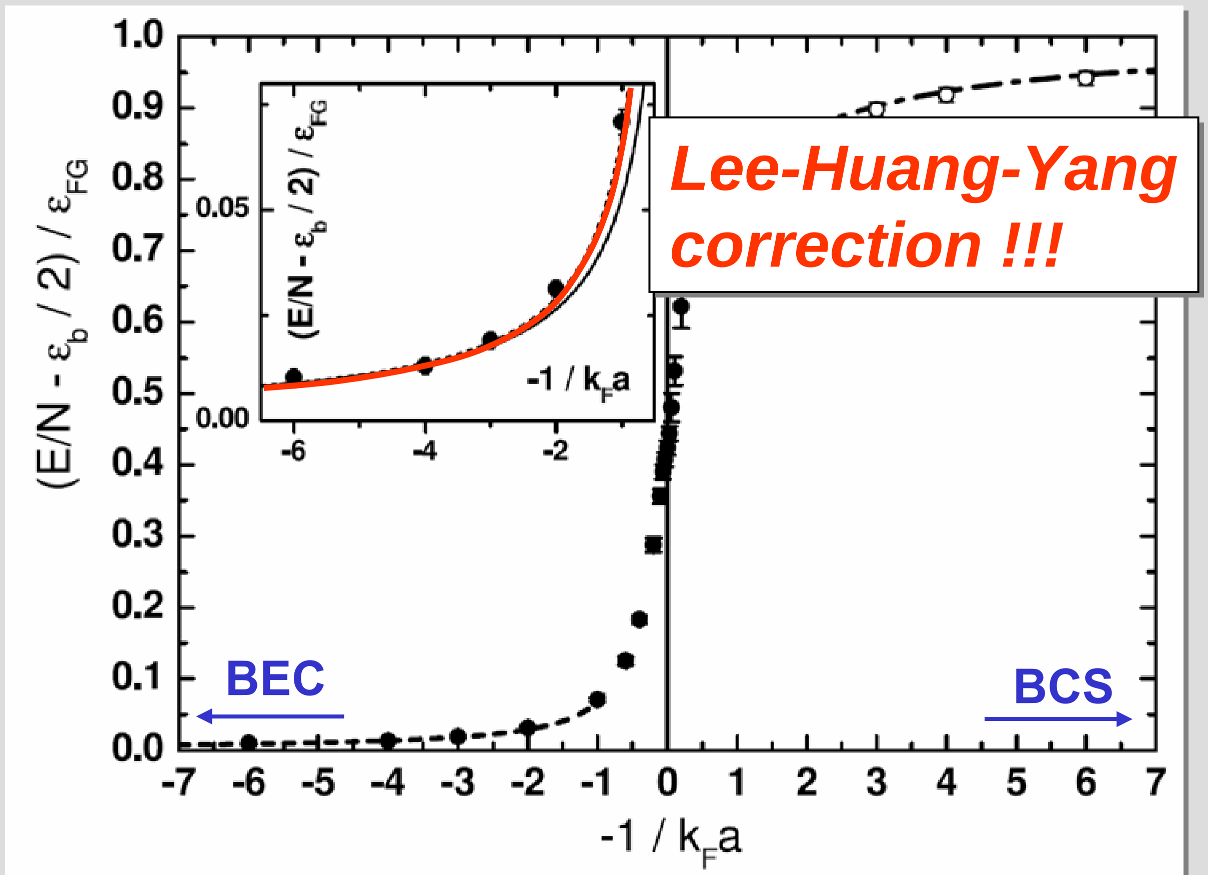
quantum Monte Carlo, Astrakharchik et al., PRL 95, 030404 (2005)

see also Manini and Salasnich, PRA 71, 033625 (2005)

quantum Monte Carlo

Equation of State of a Fermi Gas in the BEC-BCS Crossover: A Quantum Monte Carlo Study

G. E. Astrakharchik,[1,2] J. Boronat,[3] J. Casulleras,[3] and and S. Giorgini[1]
[1]*Dipartimento di Fisica, Università di Trento and BEC-INFM, I-38050 Povo, Italy*
[2]*Institute of Spectroscopy, 142190 Troitsk, Moscow region, Russia*
[3]*Departament de Física i Enginyeria Nuclear, Campus Nord B4-B5, Universitat Politècnica de Catalunya, E-08034 Barcelona, Spain*
(Received 4 June 2004; published 10 November 2004)



beyond mean field

Lee-Huang-Yang correction

Phys. Rev. **105**, 1119 (1957)

Many-Body Problem in Quantum Mechanics and Quantum Statistical Mechanics

T. D. LEE, *Columbia University, New York, New York*

AND

C. N. YANG, *Institute for Advanced Study, Princeton, New Jersey*

(Received December 10, 1956)

PHYSICAL REVIEW VOLUME 106, NUMBER 6 JUNE 15, 1957

Eigenvalues and Eigenfunctions of a Bose System of Hard Spheres and Its Low-Temperature Properties

T. D. LEE, *Columbia University, New York, New York*

AND

KERSON HUANG AND C. N. YANG, *Institute for Advanced Study, Princeton, New Jersey*

(Received March 19, 1957)

It is shown that the pseudopotential method can be used for an explicit calculation of the first few terms in an expansion in power of $(\rho a^3)^{\frac{1}{2}}$ of the eigenvalues and the corresponding eigenfunctions of a system of Bose particles with hard-sphere interaction. The low-temperature properties of the system are discussed.

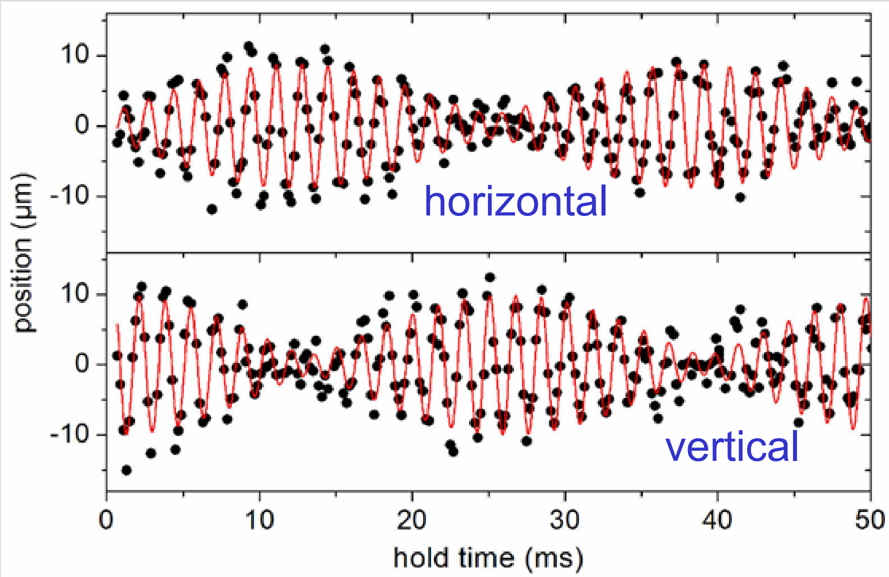
(E) The ground-state energy per particle for a Boltzmann gas and for a Bose gas at a finite density and infinite volume is

$$E/N = 4\pi a\rho[1 + 128(\rho a^3)^{\frac{1}{2}}/15\pi^{\frac{1}{2}} + O(\rho a^3)]. \qquad (7)$$

leading correction is <u>positive</u>

→ upshift of collective-mode frequency in mBEC regime !

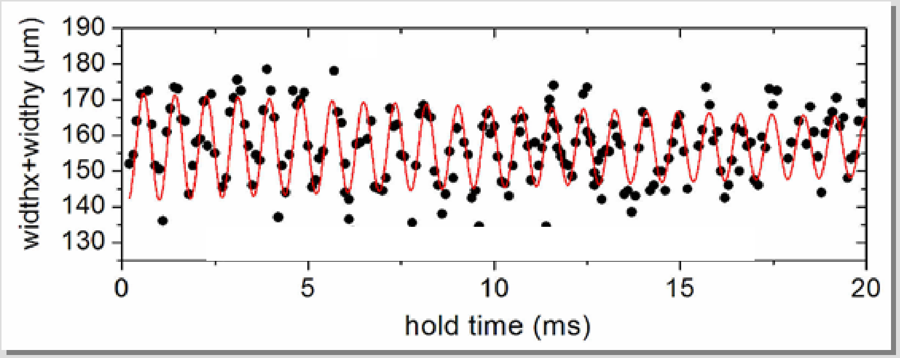
precision measurements



sloshing modes

beat reveals
trap ellipticity of ~6%

can be measured with
~10^{-3} uncertainty



compression mode

accurate determination
of frequency needs
very low damping
→ **optimized cooling !**

anharmonicity effects
in Gaussian trap potential ~2%

suppressed to **few 10^{-3}**
by normalization to sloshing mode

precision measurements

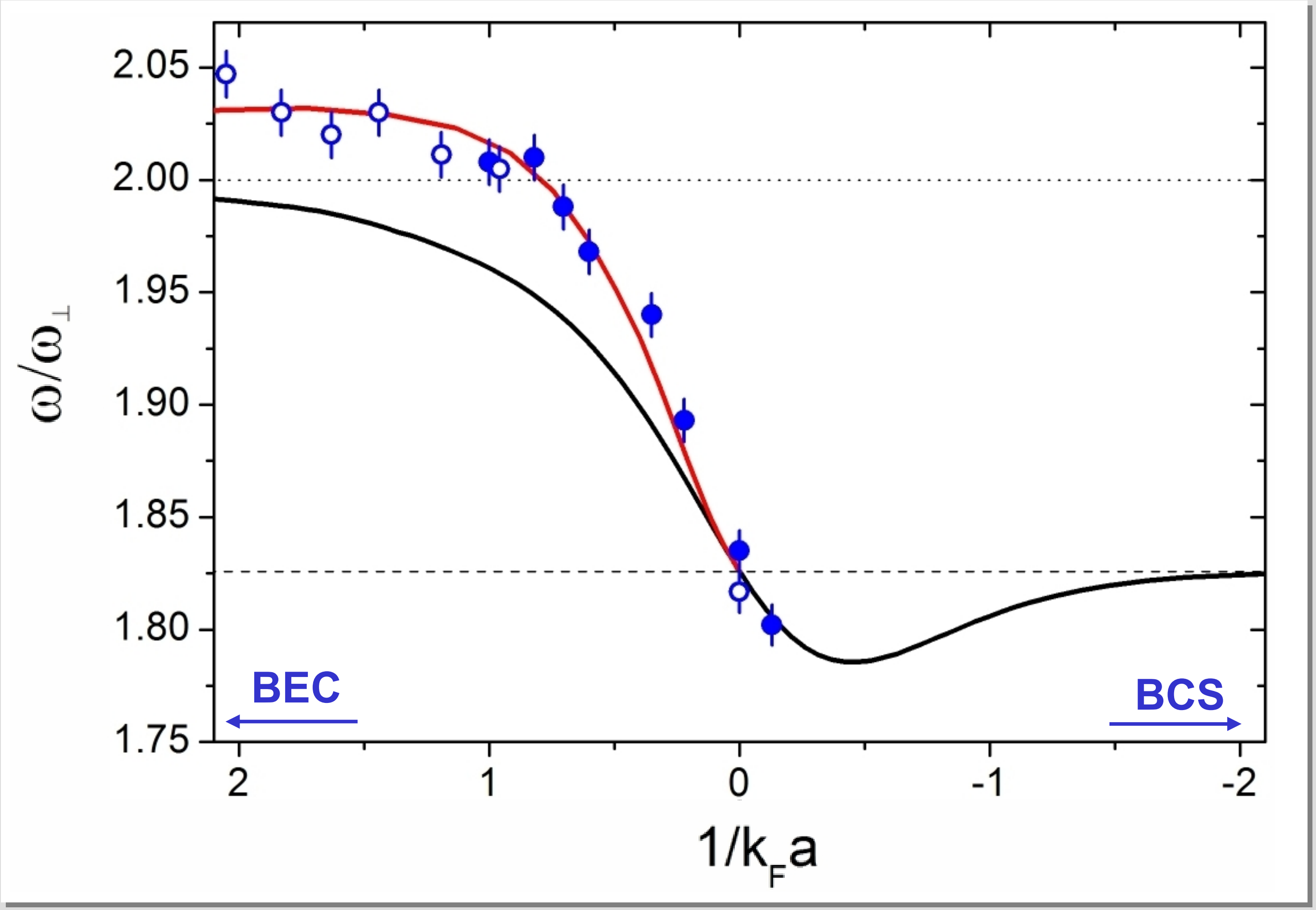
Ultracold atoms quantum gases

B (G)	$1/k_F a$	Sloshing $\omega_\perp/2\pi$ (Hz)	ϵ	Compression $\omega_c/2\pi$ (Hz)	$\gamma/\omega_\perp$	Correction $\kappa\epsilon^2$ (10^{-4})	$b\alpha$
727.8	2.21	292.7(5)	0.083(3)	596.3(6)	0.007(2)	48	20
735.1	1.96	298.6(5)	0.091(3)	602.8(8)	0.008(3)	60	26
742.5	1.75	294.5(5)	0.067(3)	593.2(7)	0.005(2)	53	28
749.8	1.55	296.3(4)	0.073(3)	599.0(7)	0.006(2)	38	28
760.9	1.27	296.0(4)	0.088(2)	592.3(7)	0.009(2)	58	24
771.9	1.03	293.6(7)	0.074(5)	586.2(8)	0.007(3)	41	27
834.1	0	287.5(7)	0.073(5)	579.4(9)	0.014(3)	55	94
757.2	1.07	605.0(9)	0.065(3)	1210.9(12)	0.010(2)	32	13
768.2	0.87	592.5(7)	0.069(2)	1186.6(12)	0.012(2)	36	16
775.6	0.75	590.2(4)	0.060(1)	1170.2(21)	0.007(4)	28	14
782.2	0.64	604.8(9)	0.061(3)	1187.1(16)	0.006(3)	29	16
801.3	0.38	586.8(7)	0.063(2)	1135.2(12)	0.010(2)	33	24
812.3	0.24	586.5(7)	0.058(2)	1106.9(16)	0.014(3)	30	33
834.1	0	596.3(9)	0.070(3)	1089.0(12)	0.010(2)	48	40
849.1	−0.14	583.2(7)	0.052(2)	1046.7(37)	0.007(2)	29	47

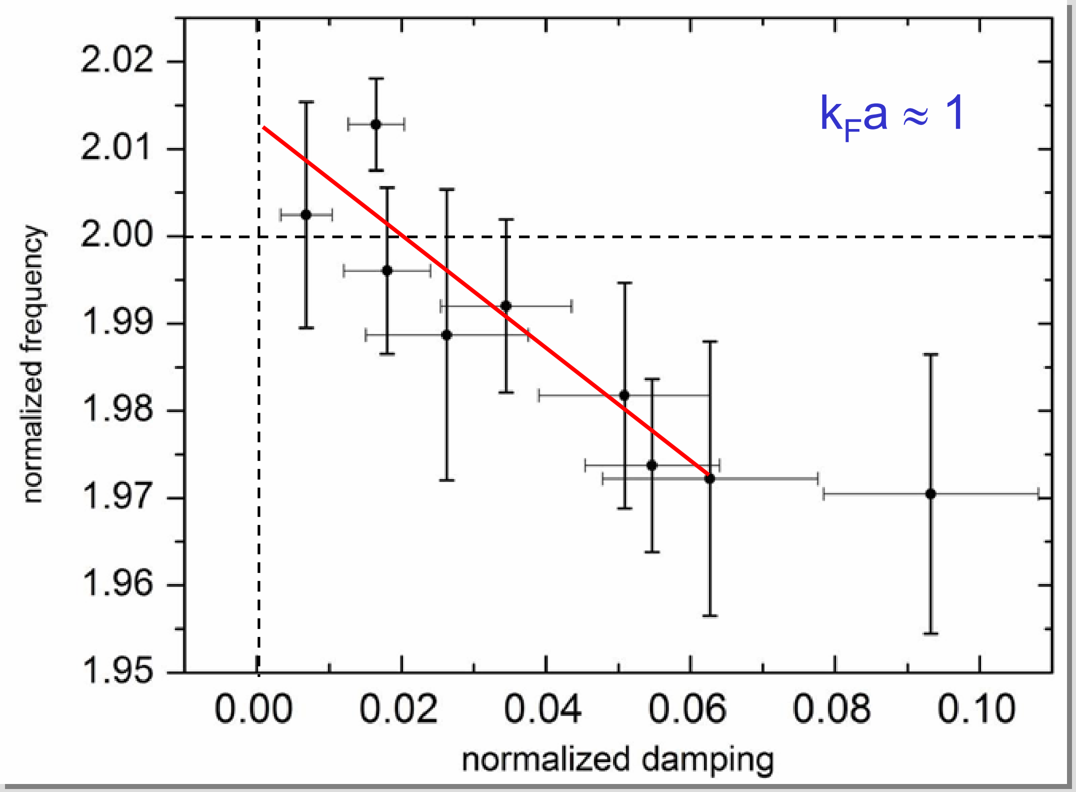
this took us a year !

precisions measurements

Altmeyer et al., PRL **98**, 0404401 (2007)



temperature shift



2006
Innsbruck expts.

2004
Duke expts.

temperature shifts explain previous "agreement" of expt. data with (too simple) BCS mean field theory

measurements on radial breathing mode

confirm

equation of state from quantum Monte-Carlo calculations
(including LHY correction)

rule out

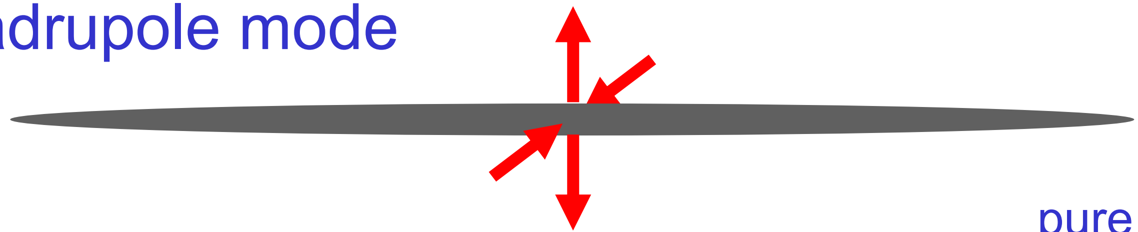
simple mean-field BCS theory for crossover

precision test of many-body theories !

radial quadrupole mode

Altmeyer et al., manuscript in preparation
(should appear on the arXiv this week)

radial quadrupole mode



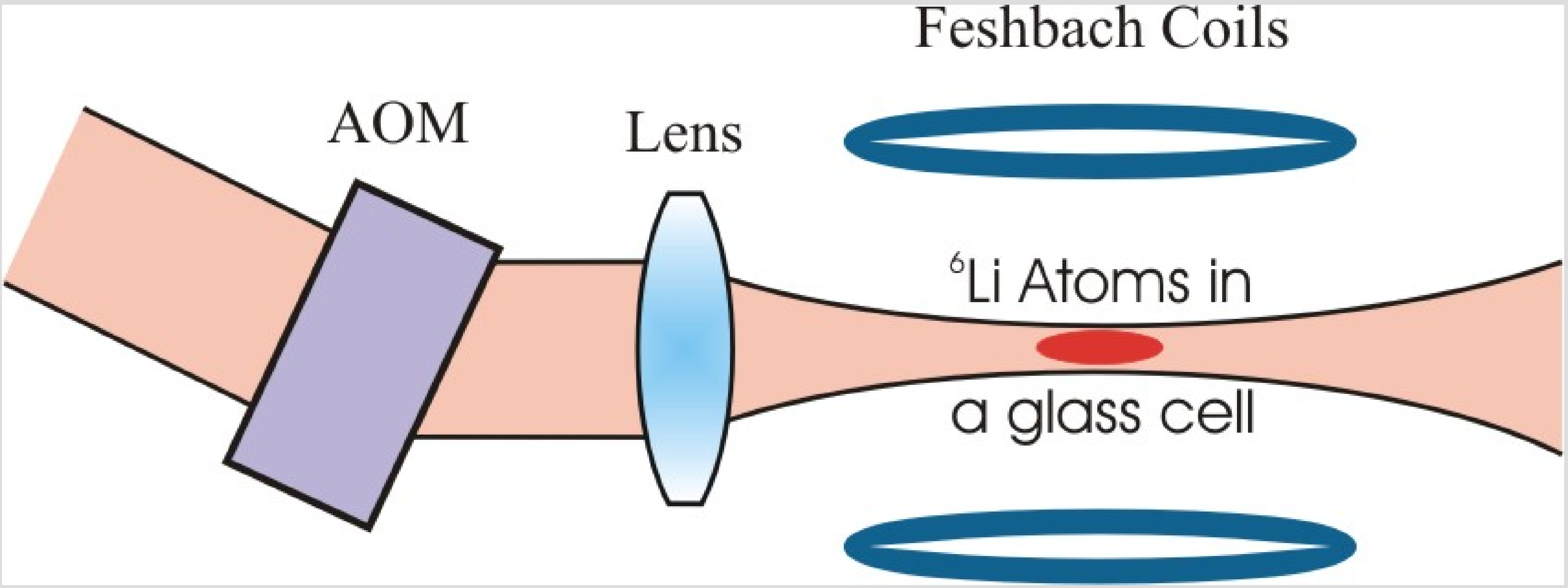
pure surface mode

pure test of hydrodynamics !

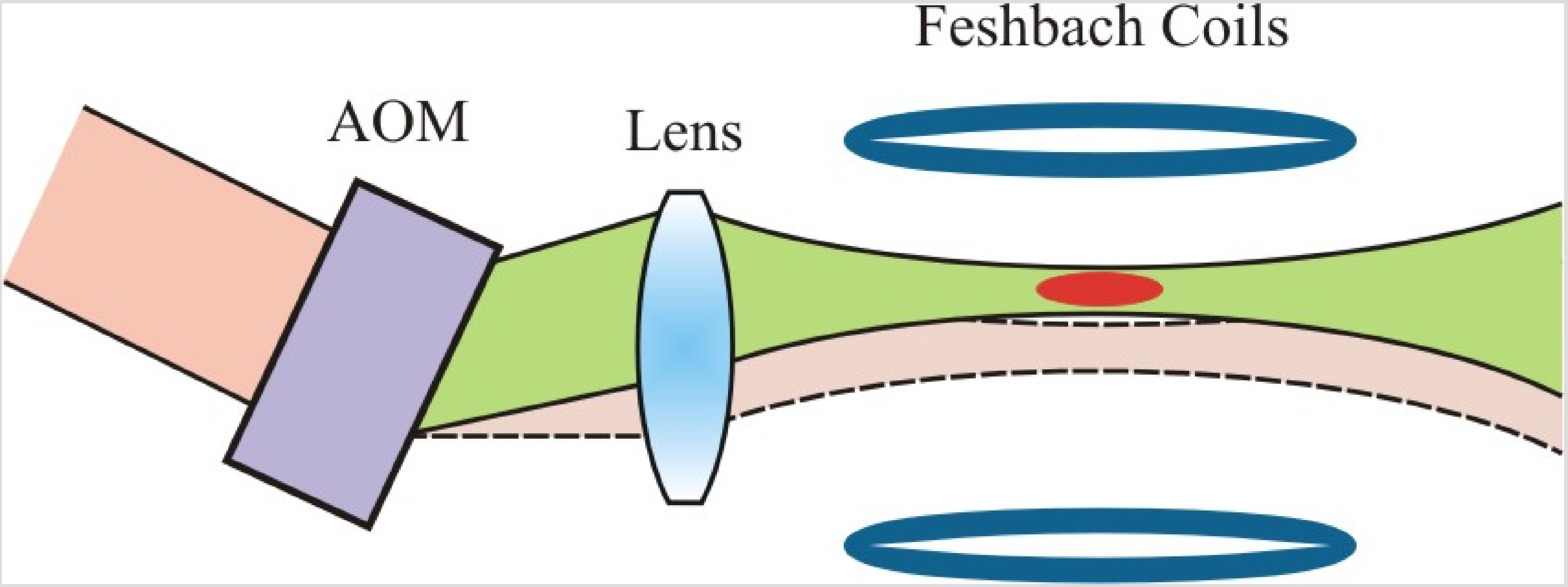
(mode freq. independent of eq. of state)

hydrodynamic freq. $\sqrt{2}\omega_r$ collisionless freq. $2\omega_r$

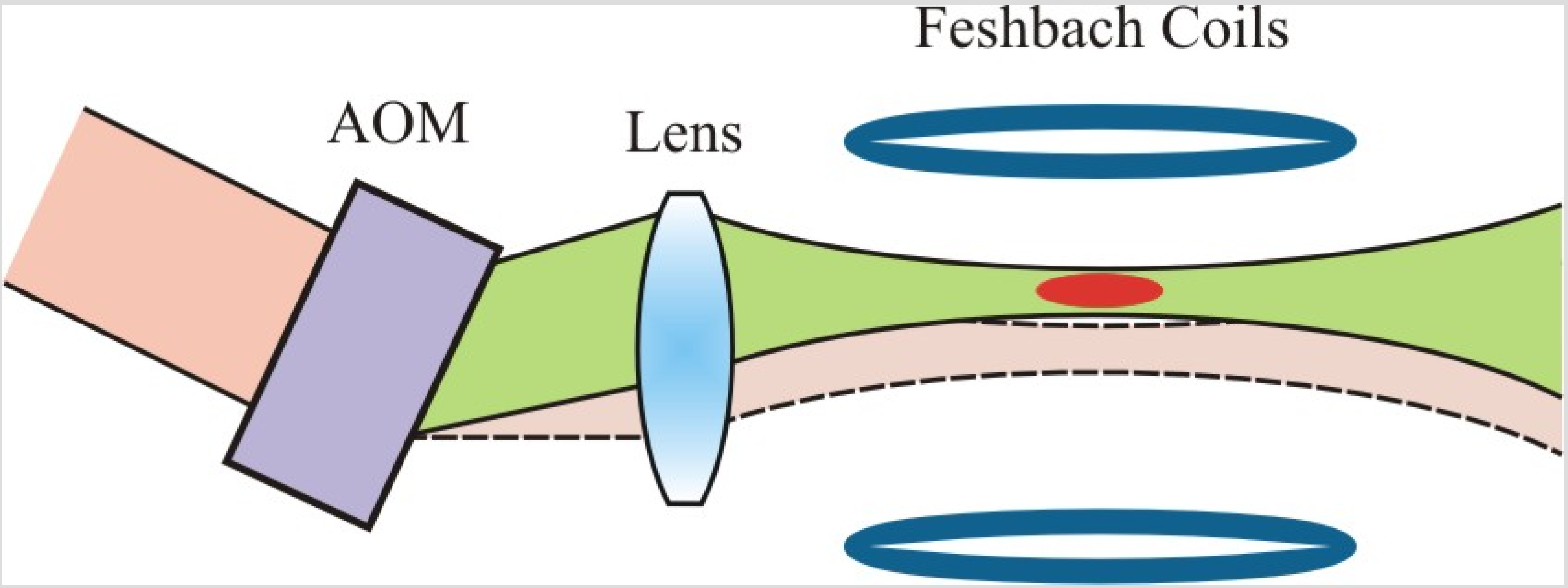
scanning the trap beam



scanning the trap beam

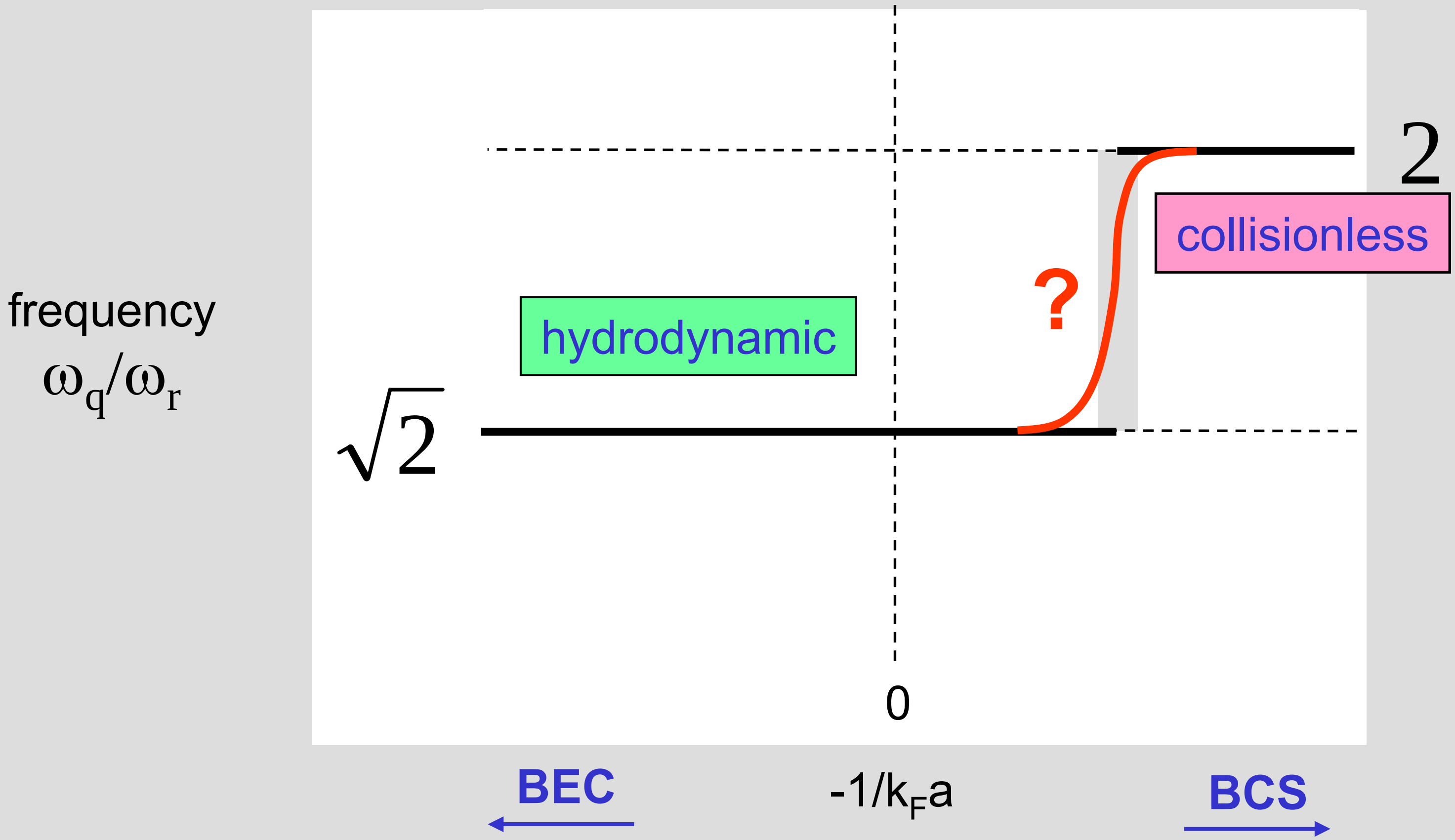


scanning the trap beam



time-averaged potentials:
a powerful tool for controlled trap deformations

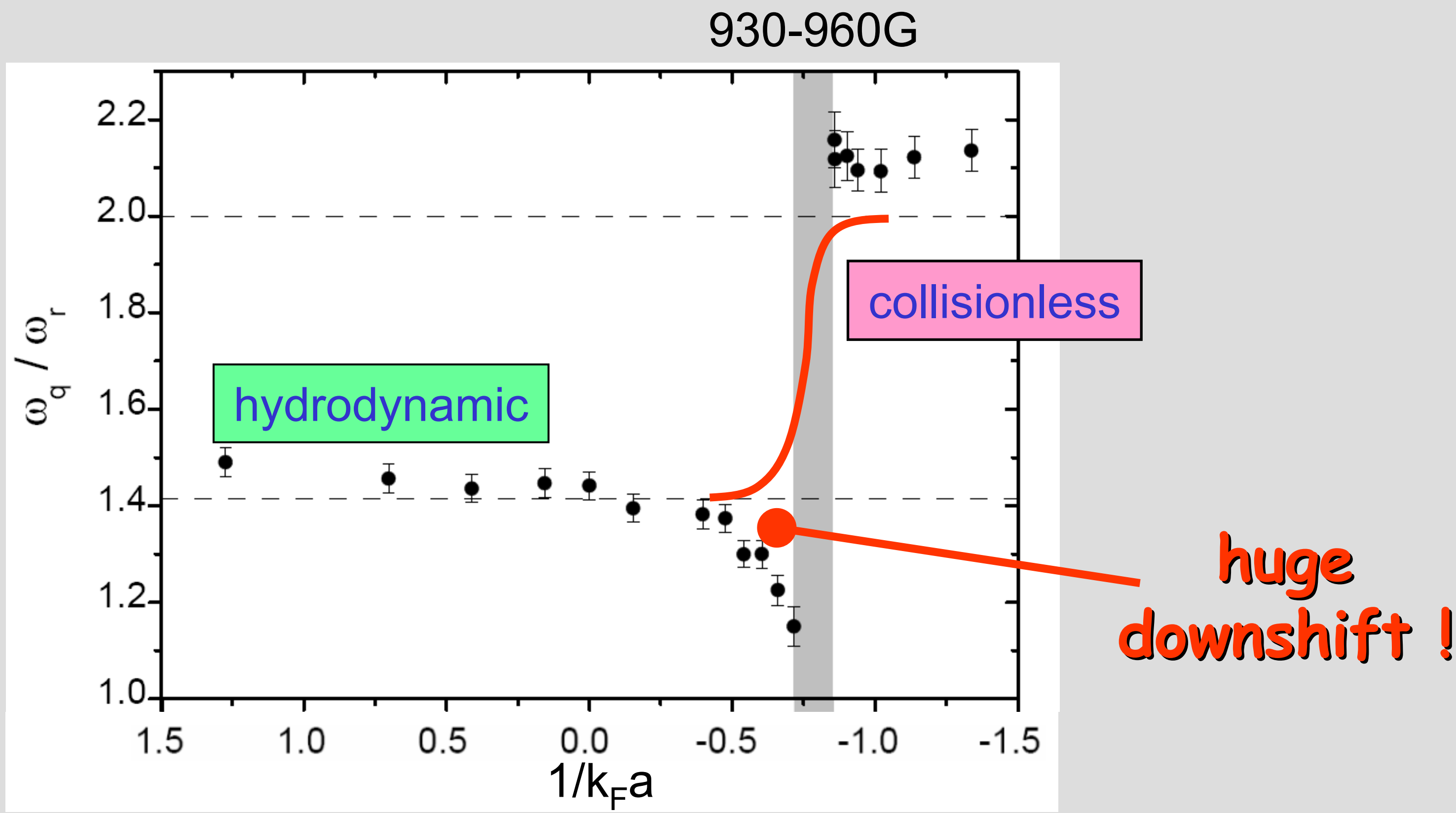
radial quadrupole mode: expectations



- how sharp is the transition ?
- does it show any structure ?
- smooth change between the two frequencies ?

results on radial quadrupole mode

frequency



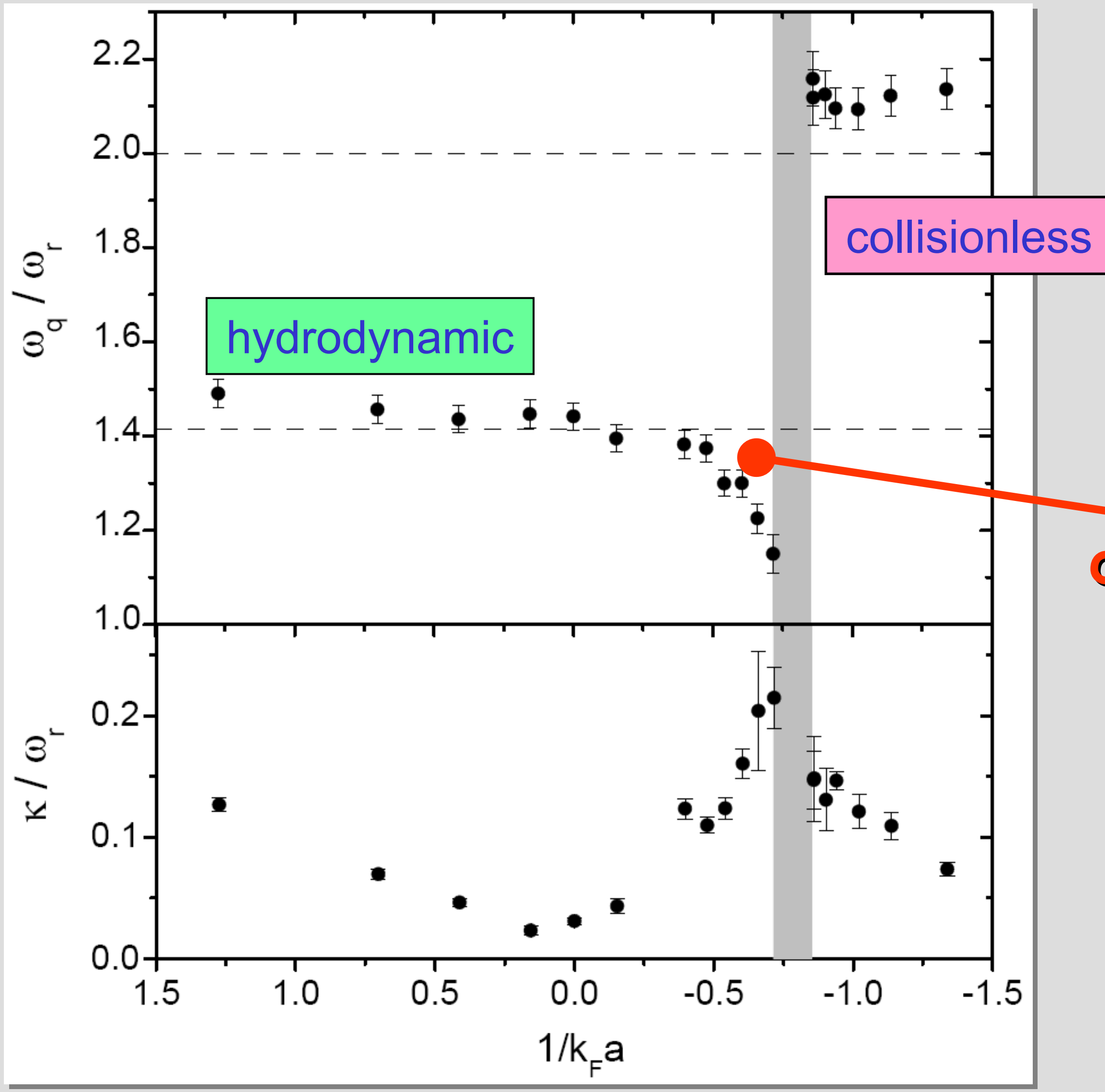
results on radial quadrupole mode

Ultracold atoms quantum gases

930-960G

frequency

damping rate

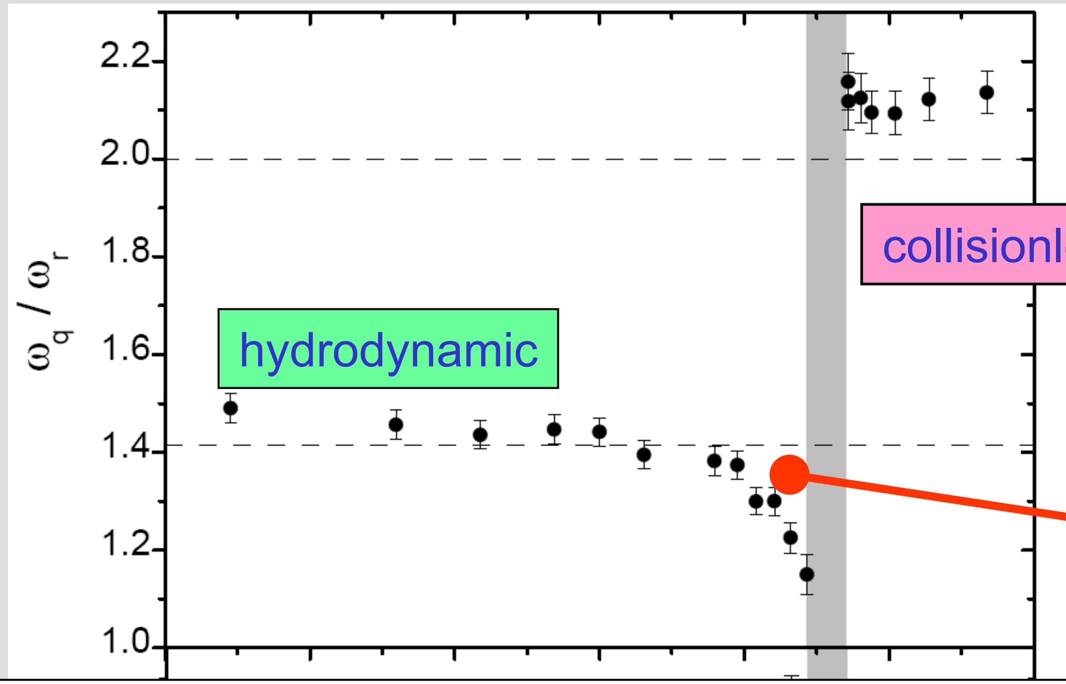


huge downshift !

results on radial quadrupole mode

930-960G

frequency



huge downshift !

standard hydrodynamic theory breaks down !

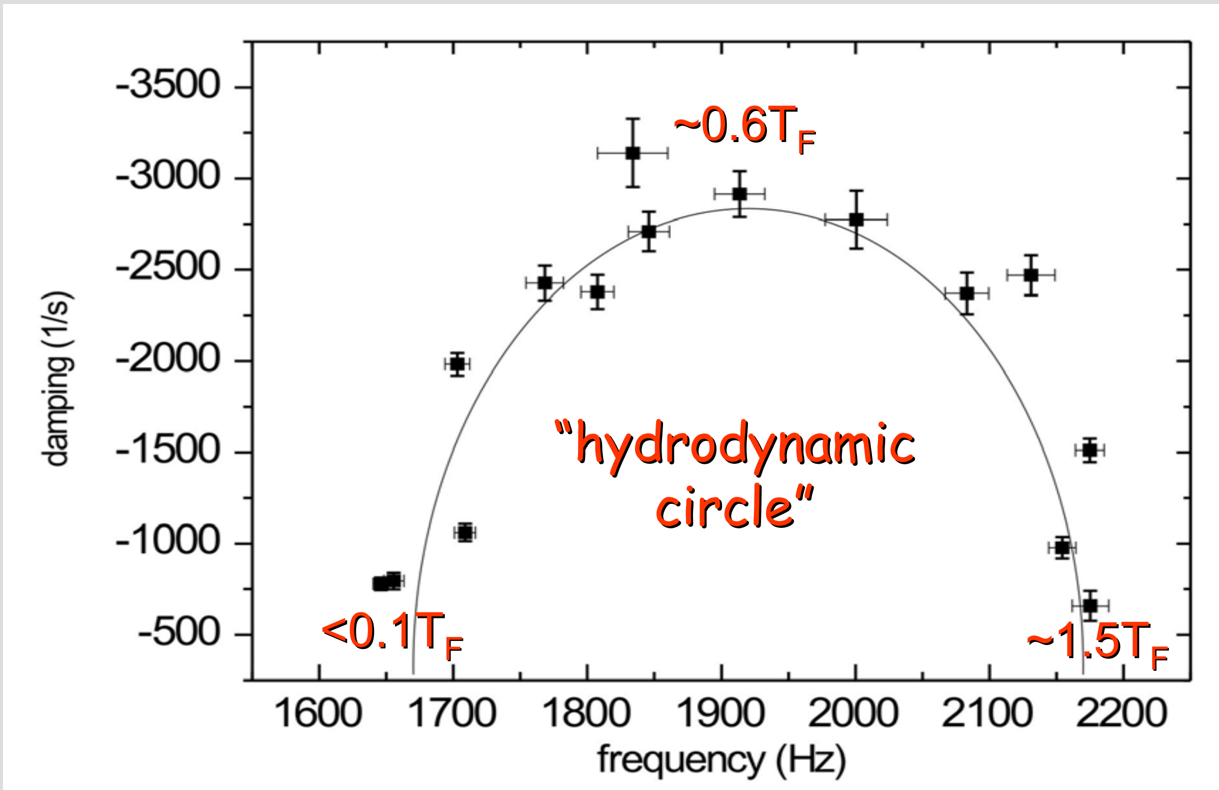
coupling of oscillations to pairing gap ?

R. Combescot and X. Leyronas, PRL **93**, 138901 (2005)

theory needed !!!

temperature-driven transition

at unitarity ($1/k_F a=0$)



temperature-driven transition from hydodyn. to coll´less shows "normal" behavior

(for atomic BEC see Buggle et al., PRA 72, 043610 (2005))

exploring BEC-BCS crossover physics
in ultracold Fermi gases

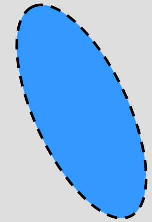
zero-temperature behavior quite well investigated

**but, temperature-dependent phenomena
widely unexplored !**

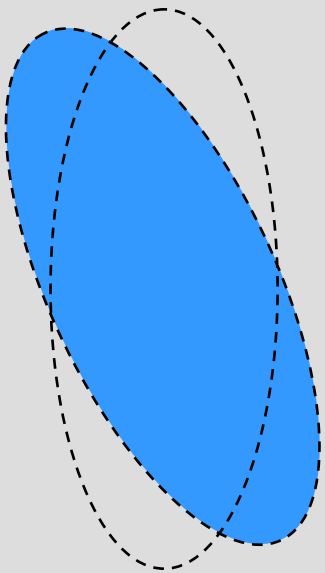
what is our best experimental tool to do this ?

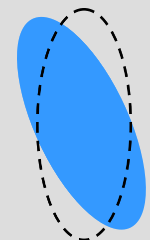
scissors modes

break cylindrical
symmetry of trap !

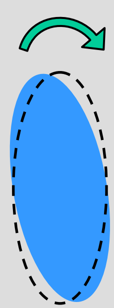


atoms in elliptic potential
aspect ratio ~ 2





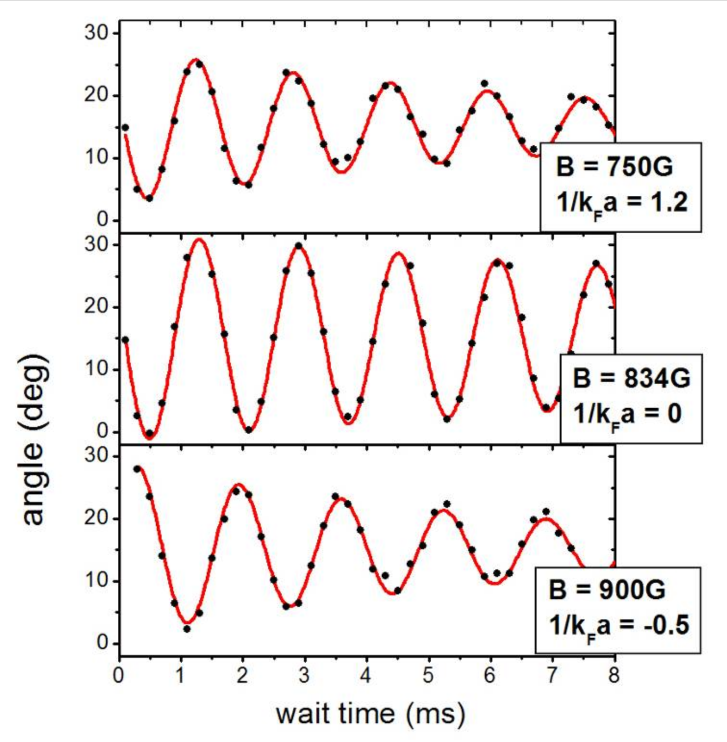
sudden change of angle
of the elliptic potential



angle of elliptic cloud
oscillates

- cloud shape doesn‘t change
- qualitative difference in the oscillation
  for hydrodynamic and collisionless regime

scissors oscillation at low T

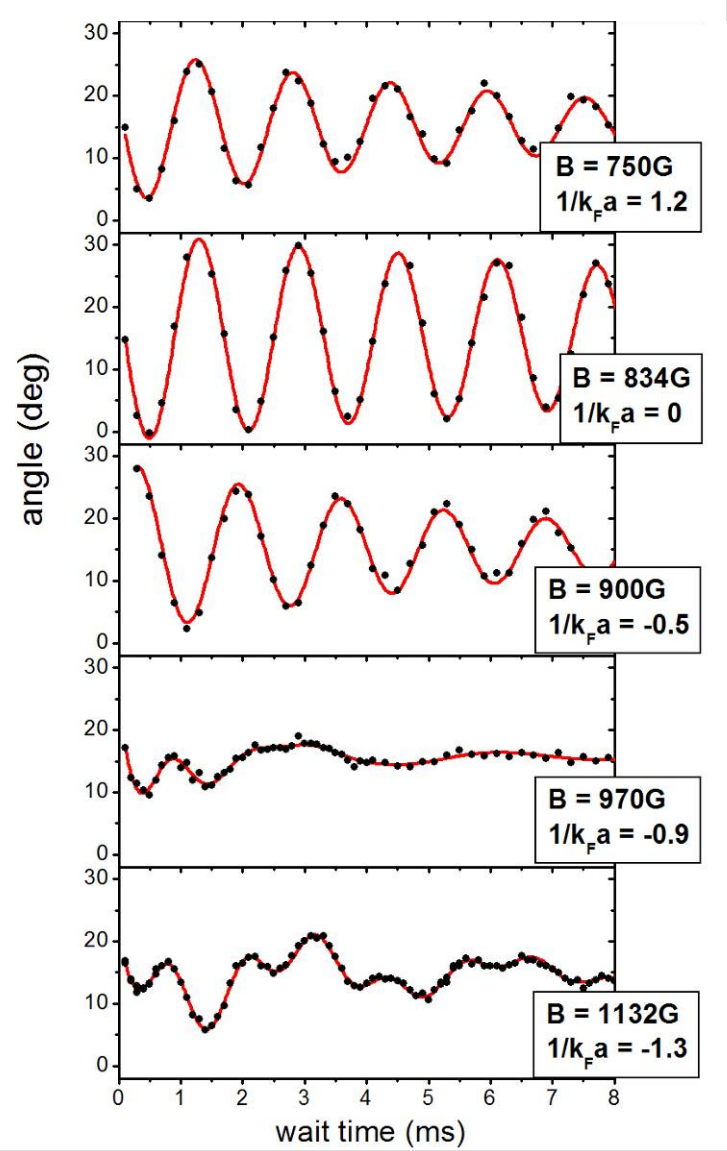


hydrodynamic gas

single frequency oscillation

$$\sqrt{\omega_x^2 + \omega_y^2}$$

scissors oscillation at low T



hydrodynamic gas

single frequency oscillation

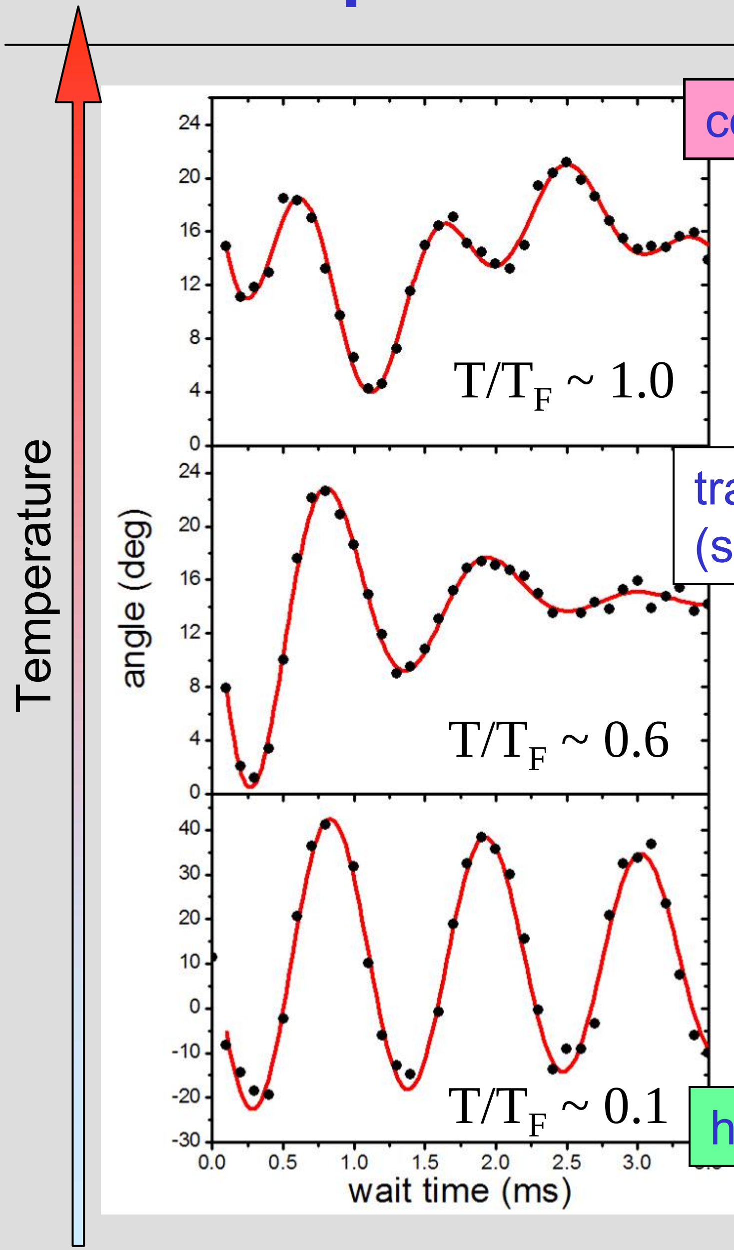
$$\sqrt{\omega_x^2 + \omega_y^2}$$

collisionless gas

oscillation with *two* frequencies

$$\omega_x + \omega_y \qquad \omega_x - \omega_y$$

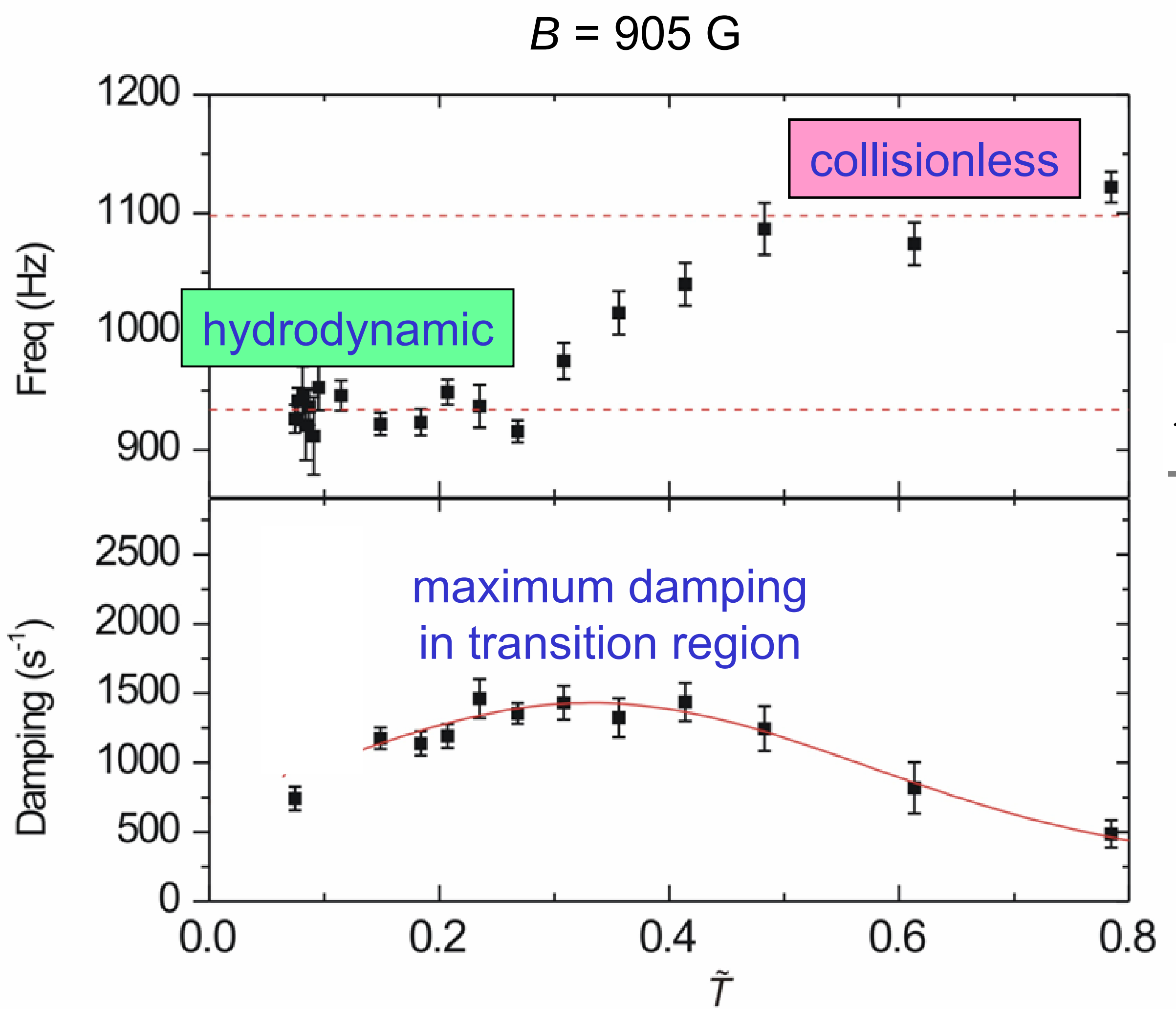
finite temperature



how does the transition temperature depend on the interaction strength ?

scissors mode excellent tool to probe this!

damping vs temperature



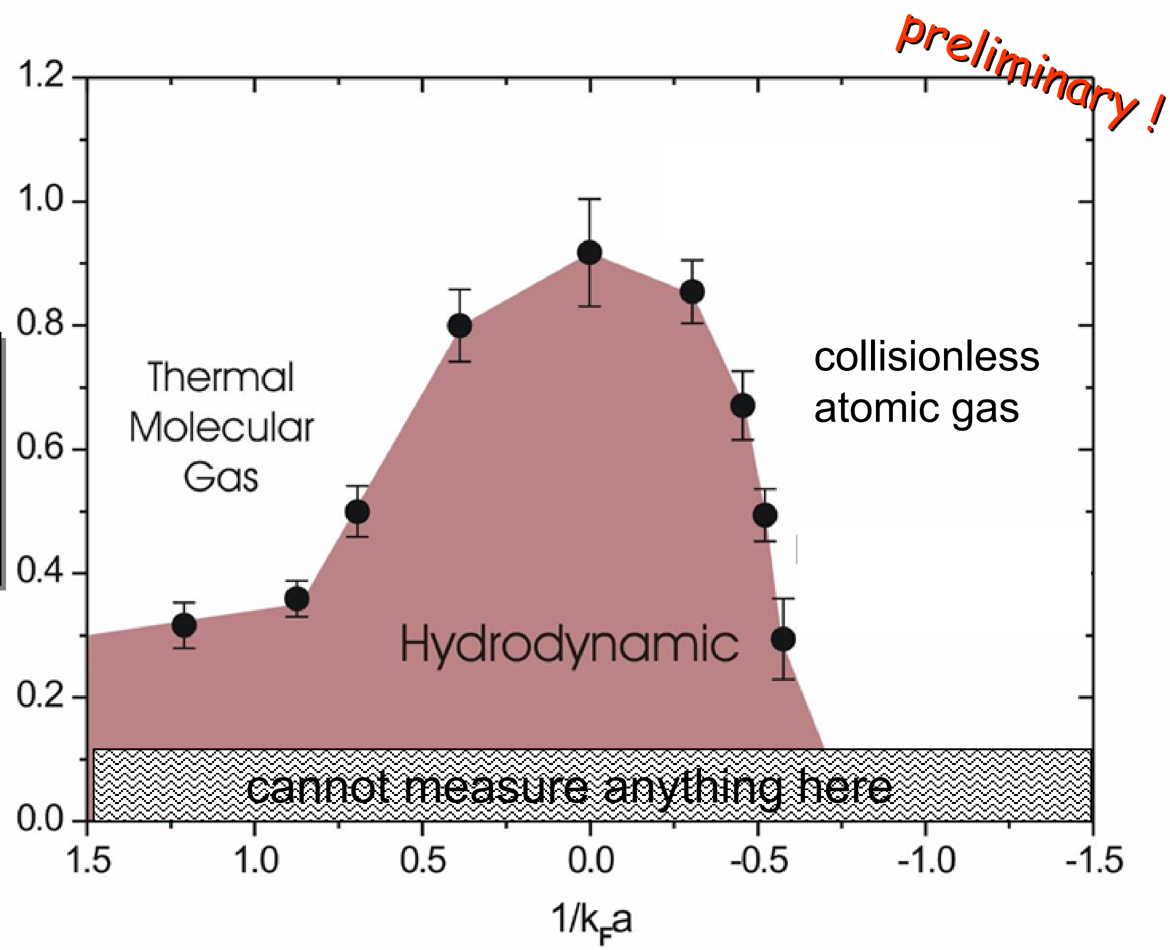
temperature parameter à la J. Thomas measured on resonance

$$\omega_x + \omega_y$$

$$\sqrt{\omega_x^2 + \omega_y^2}$$

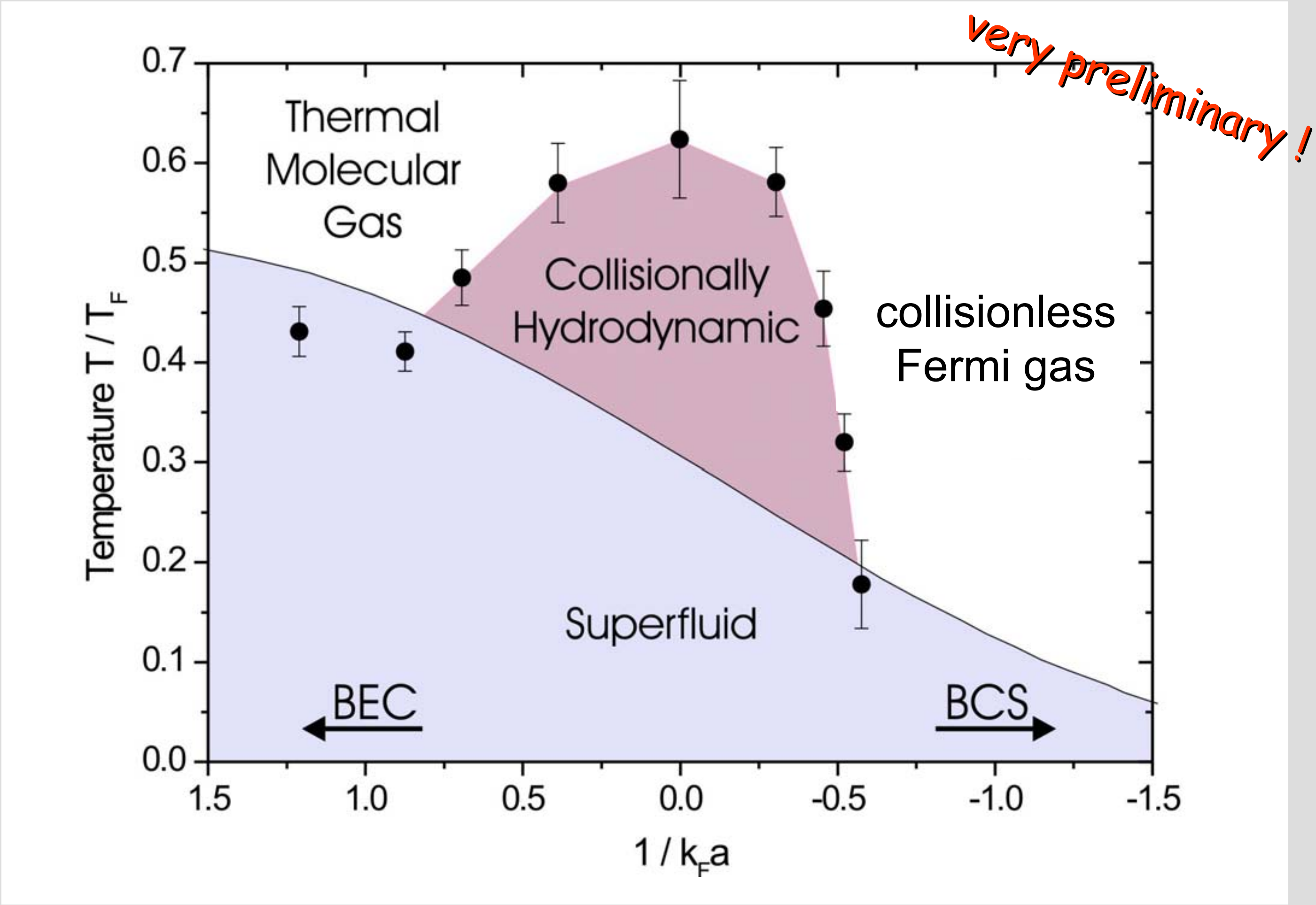
transition temperature

temperature parameter $\tilde{T}$ measures entropy

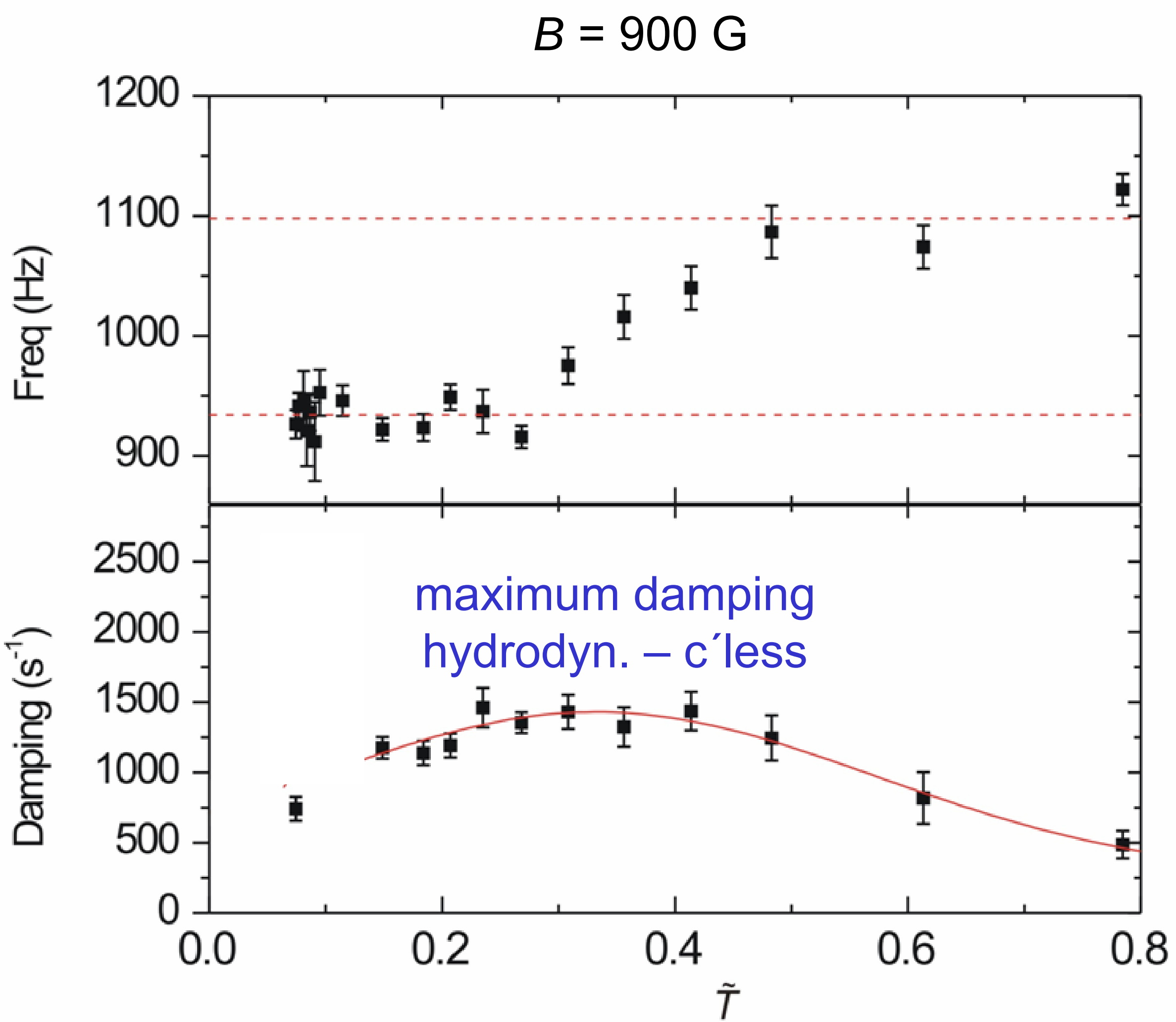


phase diagram

convert the data into a phase diagram
using entropy calculations from K. Levin group (PRL 95, 260405 (1995))



surprise

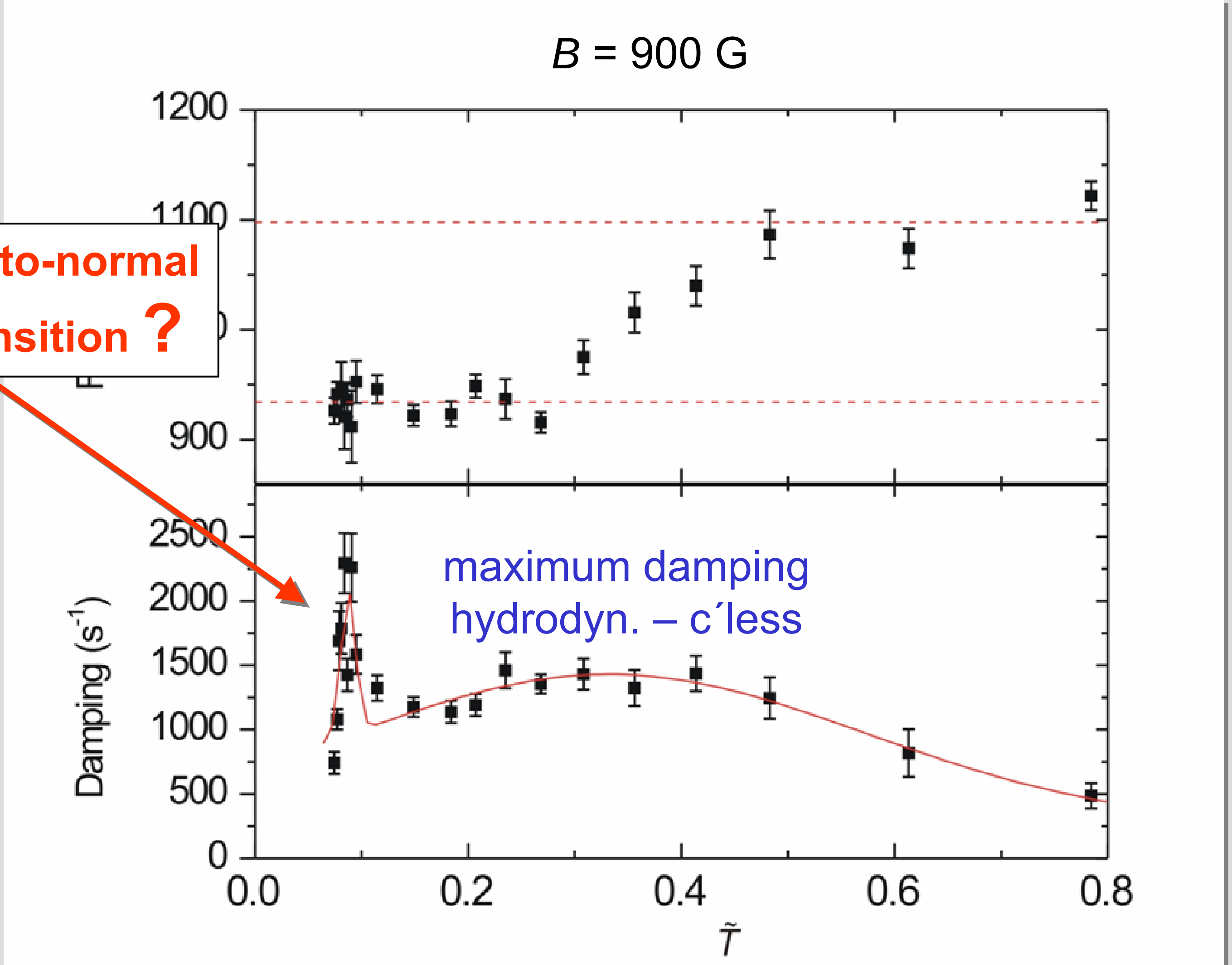


temperature parameter à la J. Thomas measured on resonance

surprise

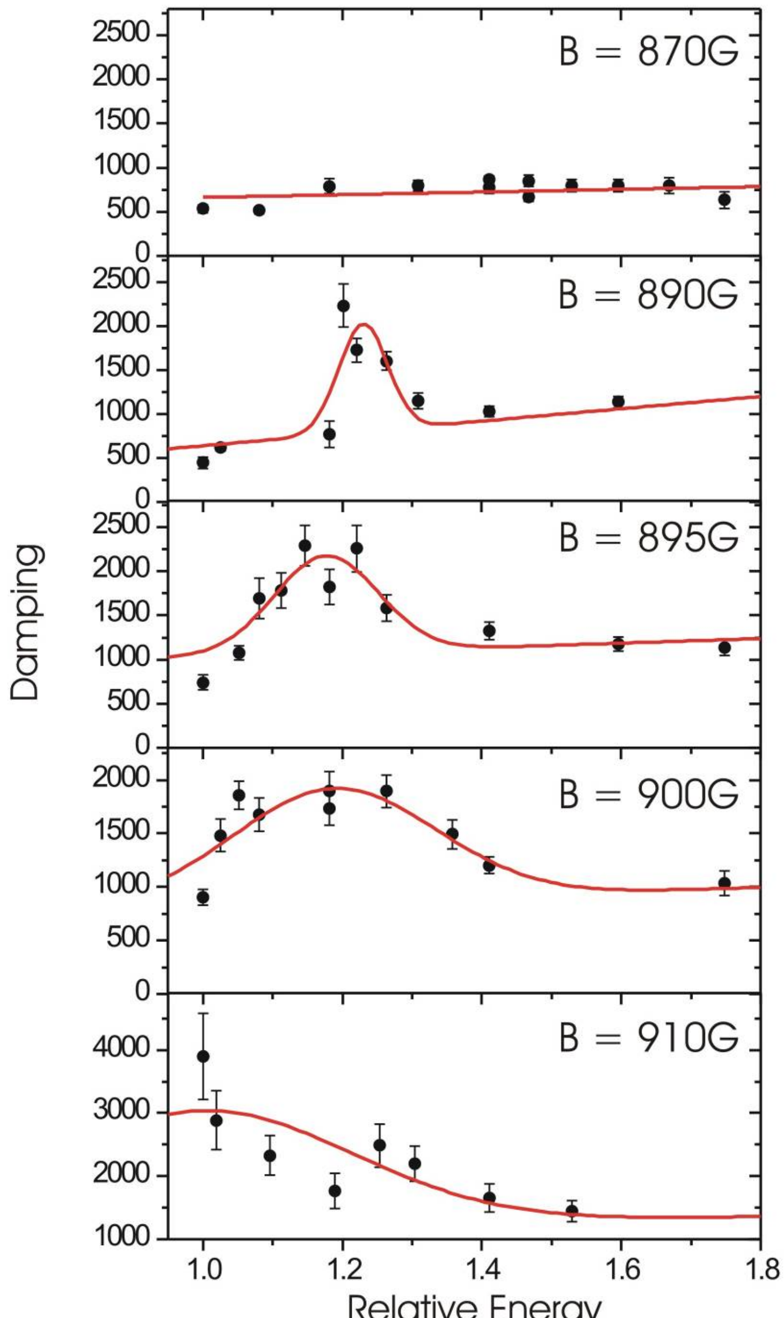
Ultracold atoms quantum gases

superfluid-to-normal phase-transition ?



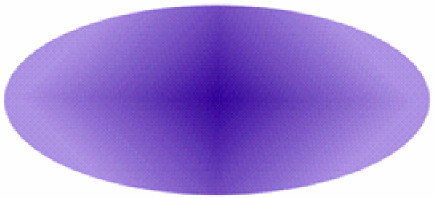
temperature parameter à la J. Thomas measured on resonance

various *B*



damping feature
only observable
in a narrow B-field
range
on BCS side of
resonance

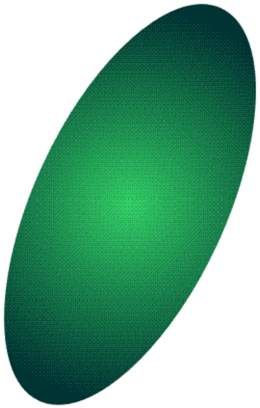
conclusion on surface modes



hydrodynamic-to-collisionless transition
with large change of frequency

strong damping

transition is not smooth!
puzzle of down-shift occuring as a precursor



hydrodynamic-collisionless transition
single frequency – two frequencies

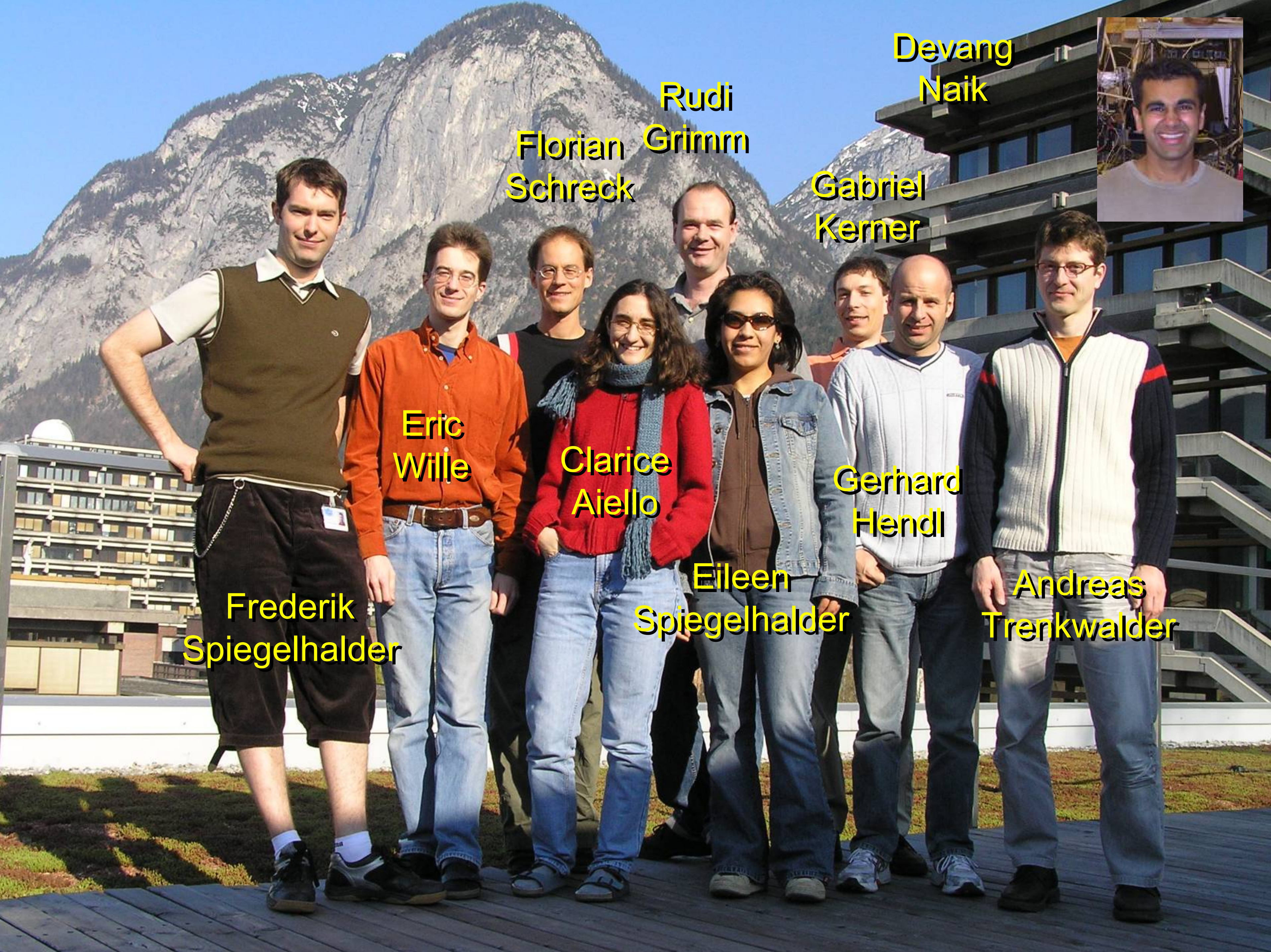
weak damping

temperature-induced transition:
phase diagramm for hydrodynamic behavior in crossover

striking damping peak at low temperature:
superfluid phase transition?

very preliminary !

^{6}Li-^{40}K: first results with a Fermi-Fermi mixture of atoms


Devang Naik
Rudi Grimm
Florian Schreck
Gabriel Kerner
Eric Wille
Clarice Aiello
Gerhard Hendl
Eileen Spiegelhalder
Andreas Trenkwalder
Frederik Spiegelhalder

plan to build a three-species fermion machine

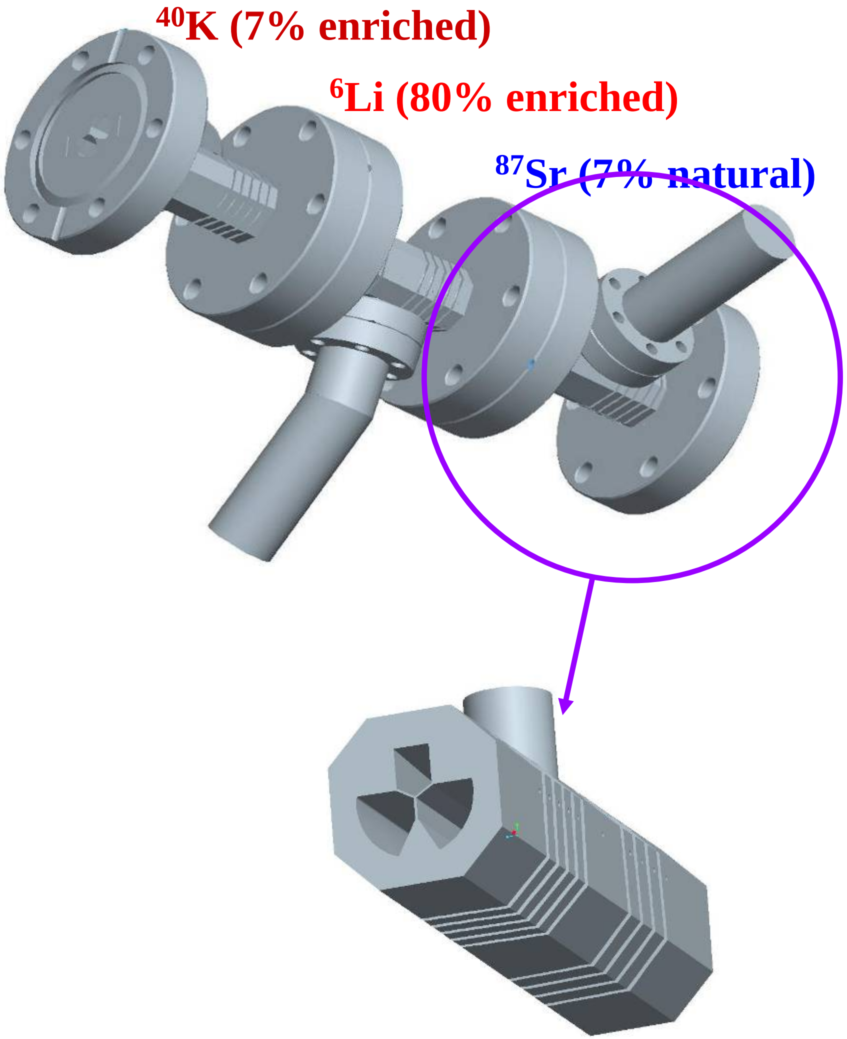
^{6}Li - ^{40}K - ^{87}Sr

IQI

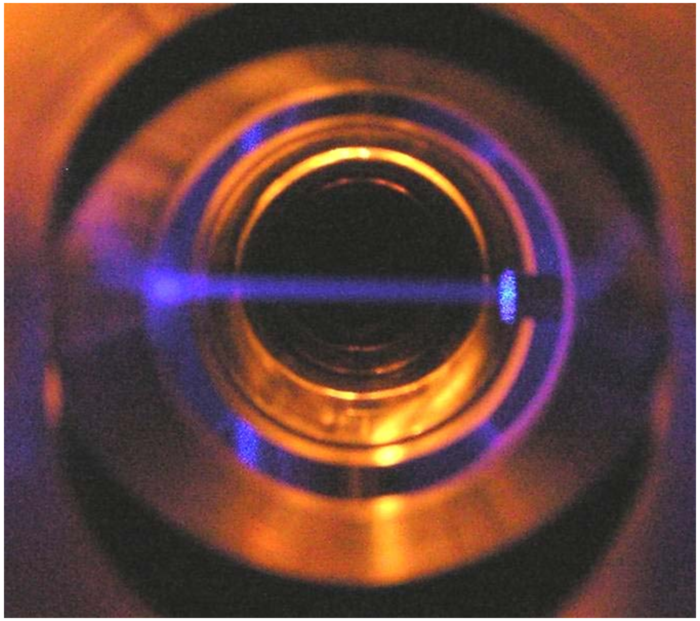
August 2005


IQI
Februar 2007
MELLES GRIOT
MELLES GRI

three-species oven



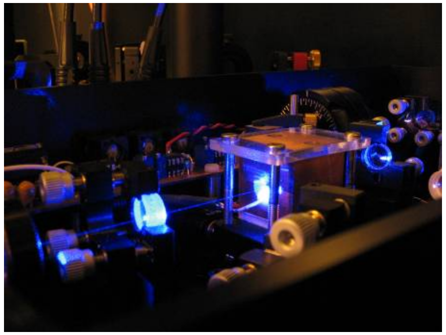
Microtubes inside



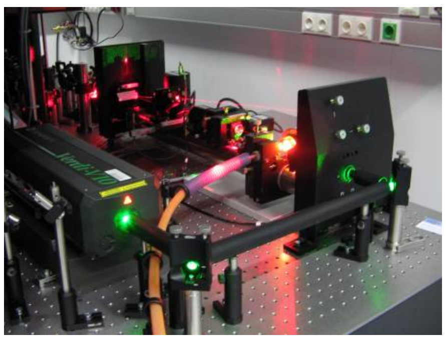
Strontium atomic beam

cooling laser system

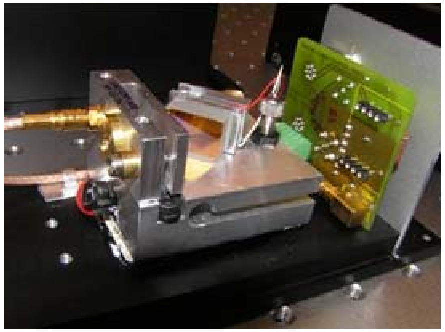
Sr, 461nm: doubled diode laser



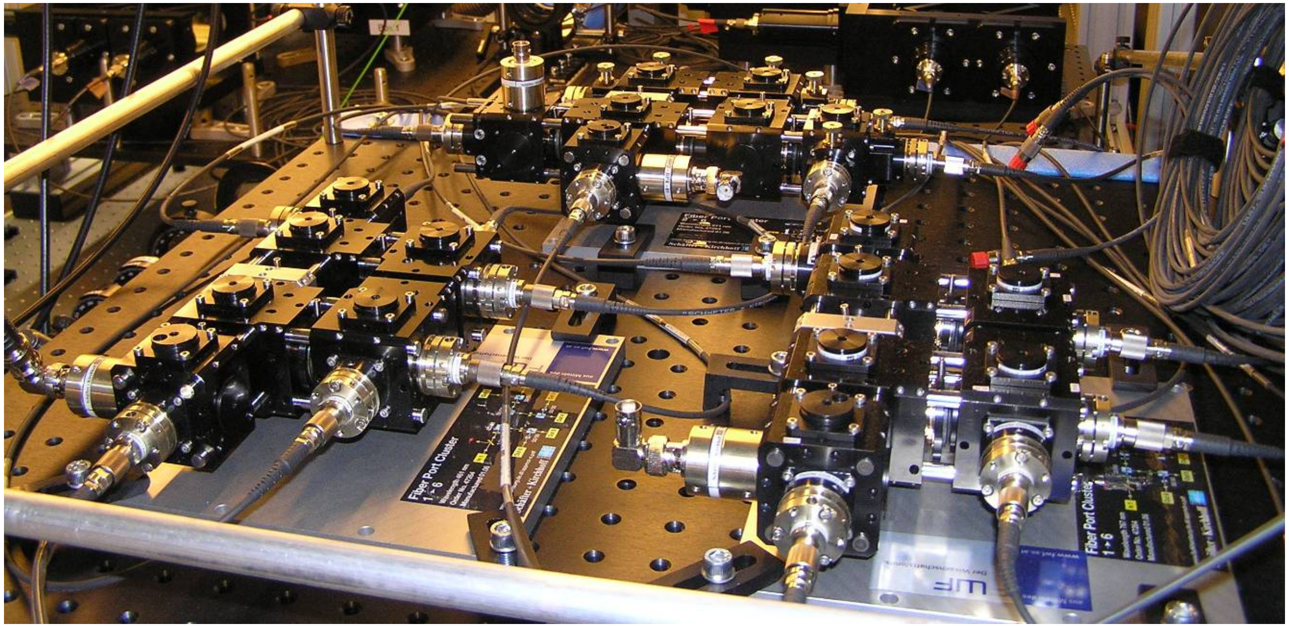
Li, 671nm: dye laser

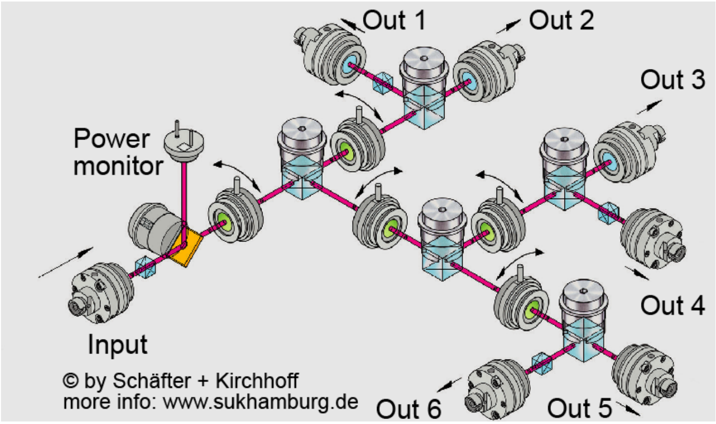


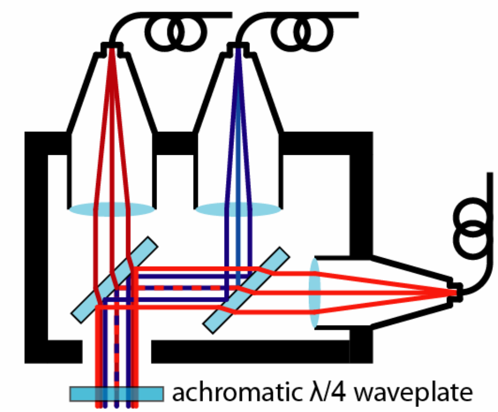
K, 767nm: diode lasers



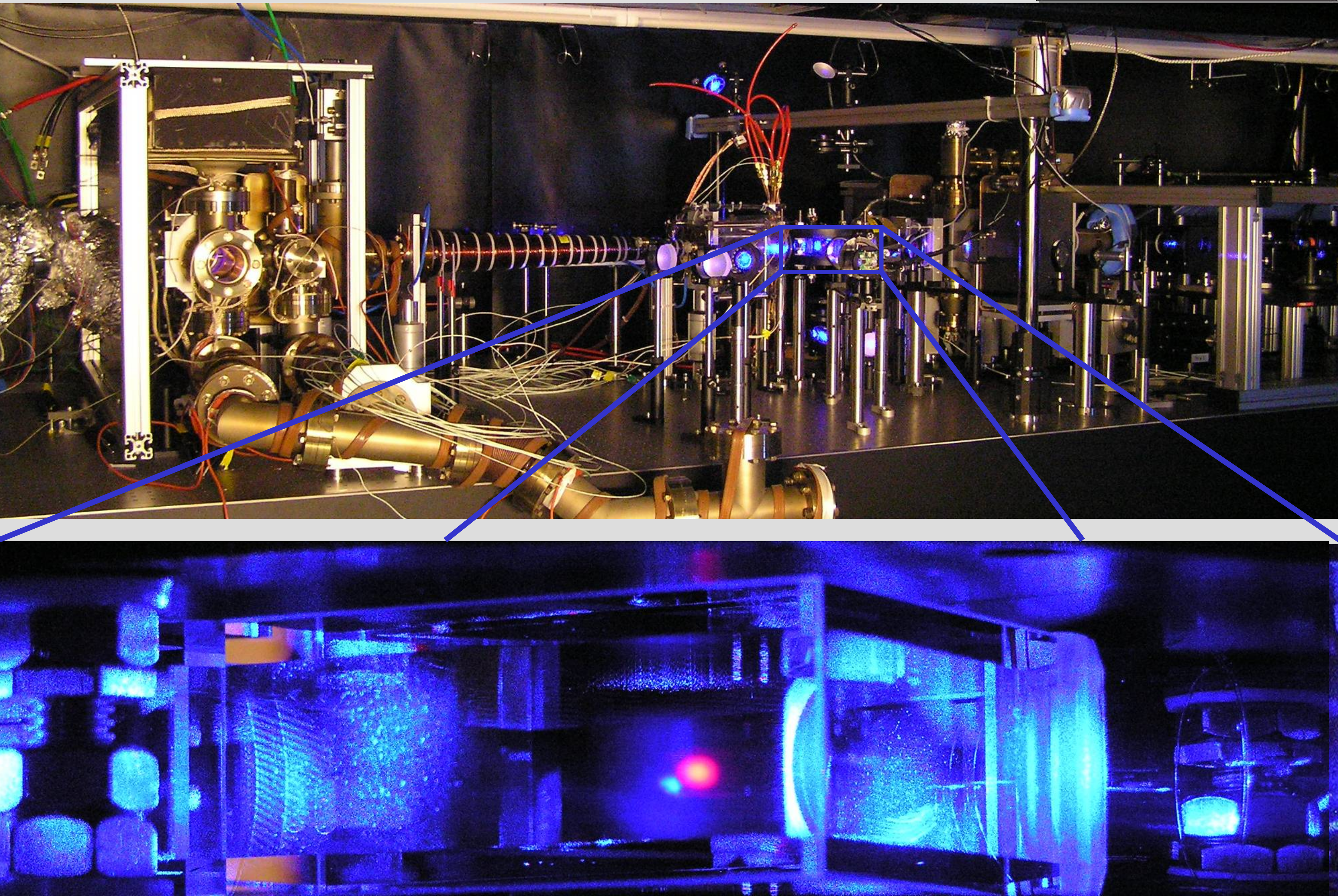
MOT beam delivery:



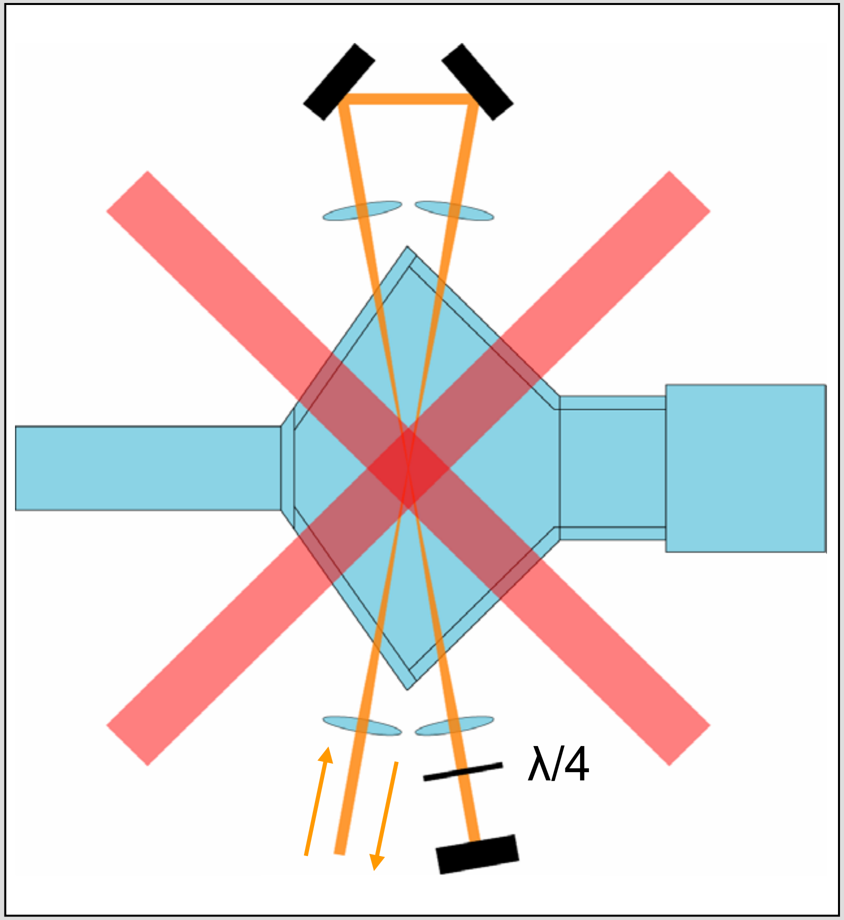




Lithium-Potassium-Strontium machine

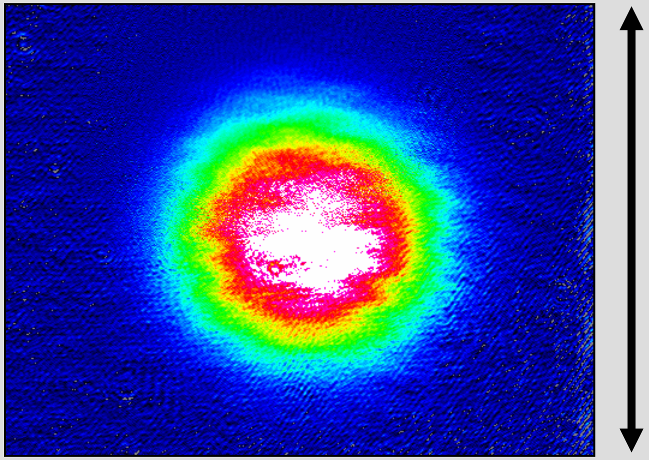


from MOT to dipole trap

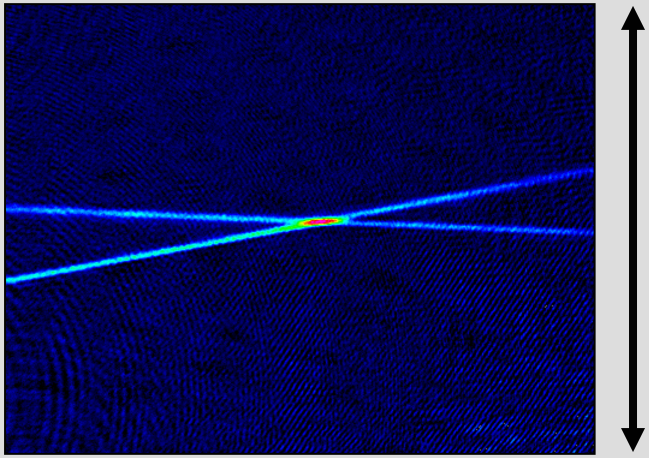


Dipole trap (100W 1075nm laser):
$U \sim k_B$ 1 mK
w ~ 60 μm

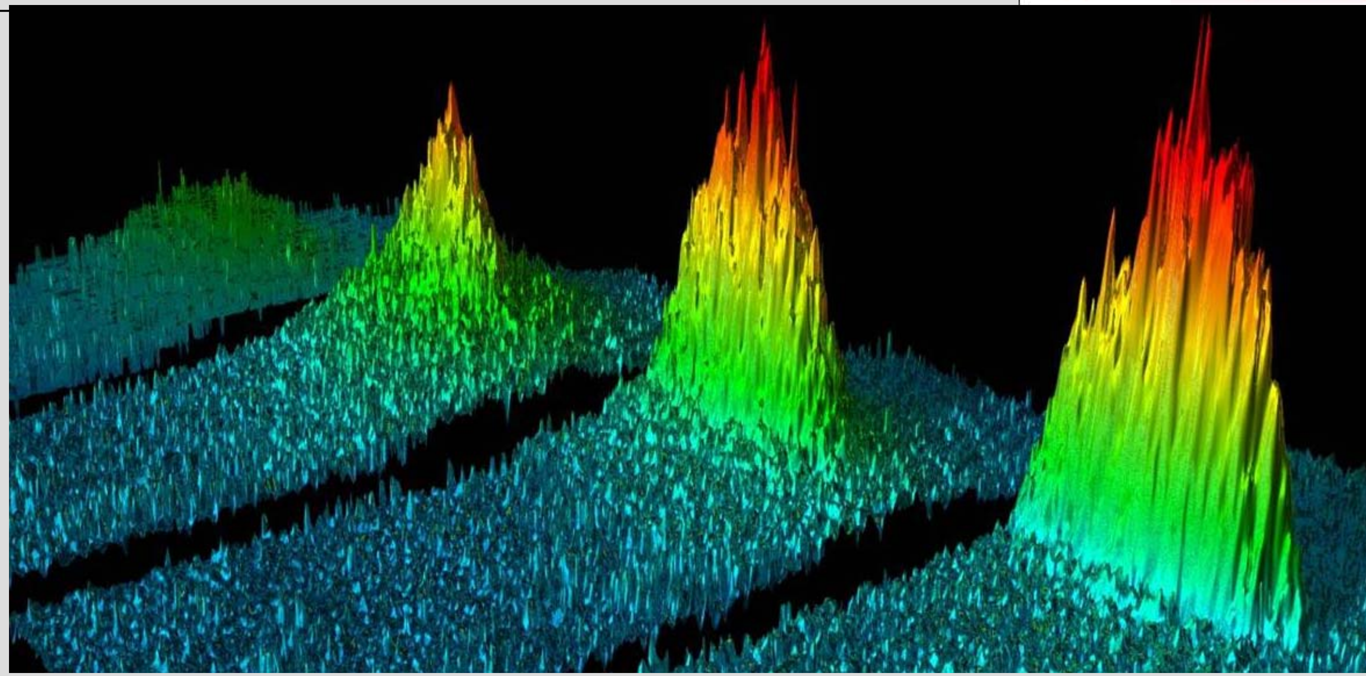
^{6}Li MOT: N ~ 10^9 T ~ 300μK



Dipole trap: N > 10^6



$^{6}Li_2$ molecular Bose condensation

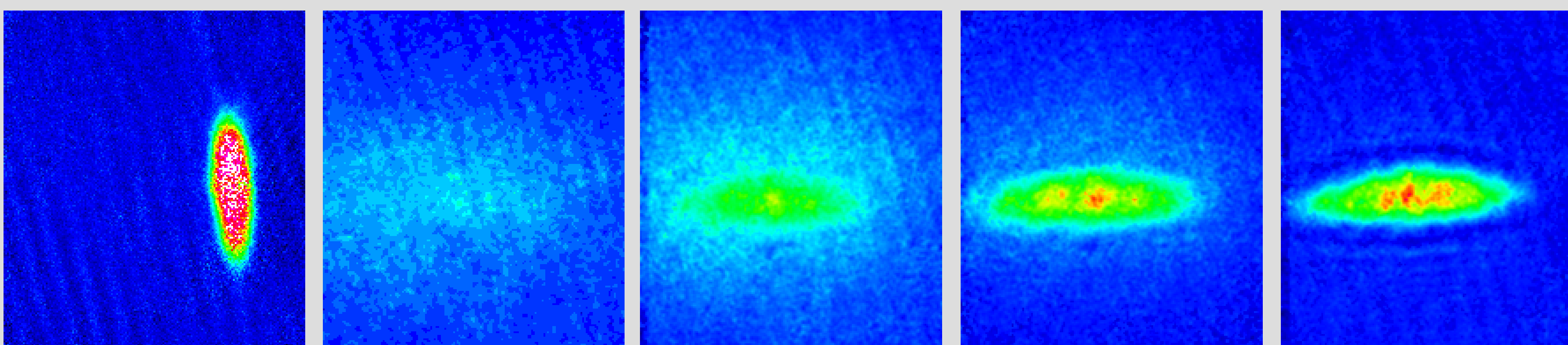


in dipole trap

After 10ms time of flight:

PURE BEC!

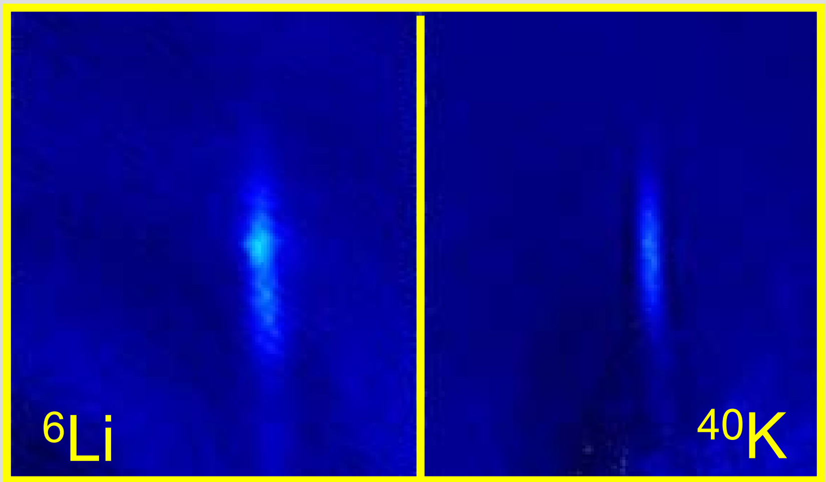
4.3 sec evap **4.7 sec evap** **4.8 sec evap** **5.1 sec evap**



heteronuclear FF mixture !

absorption images of ^{6}Li and ^{40}K atoms

after 3.9 s of forced evaporative cooling at 750G



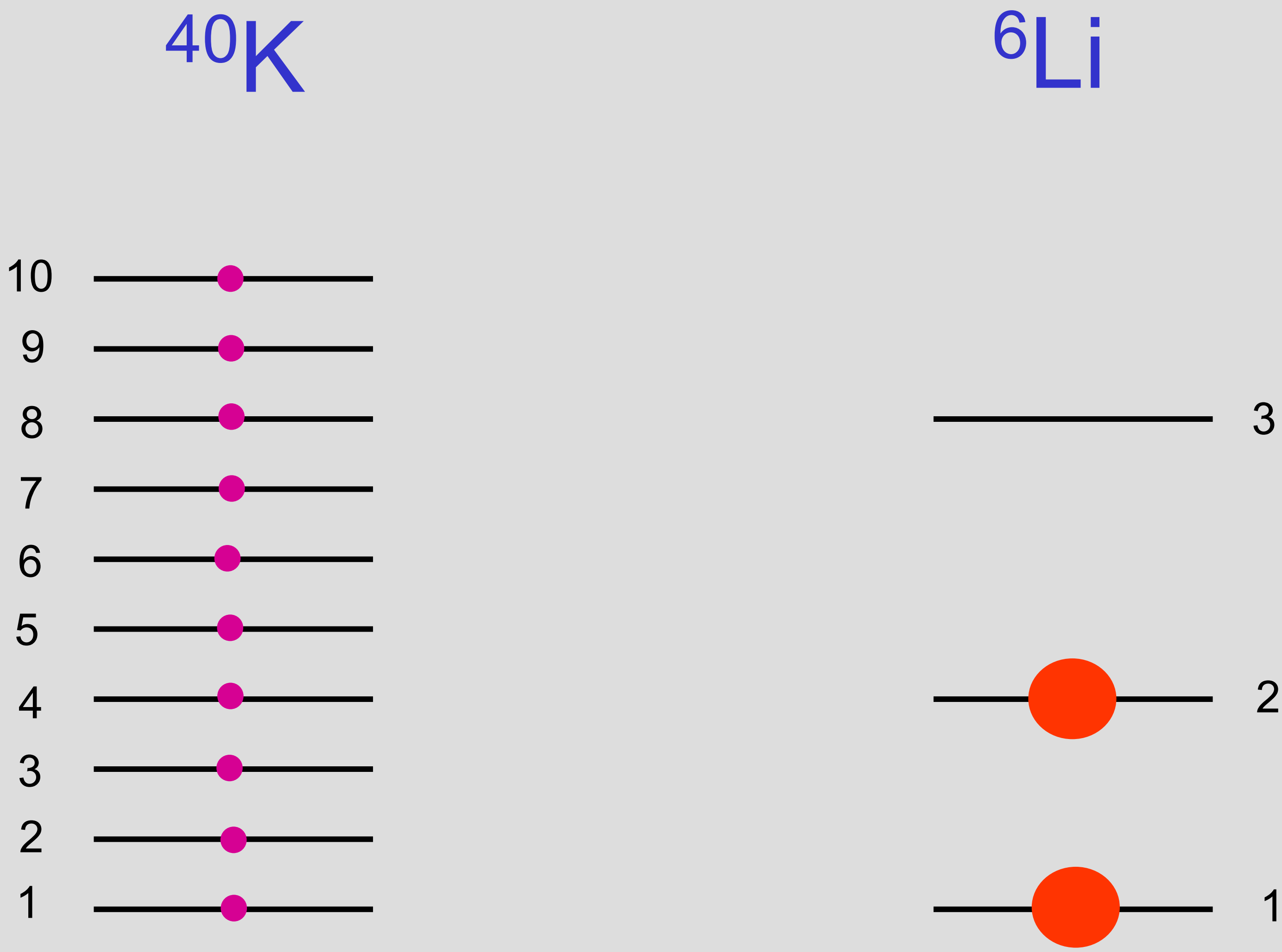
26 μK **trap depths** **55 μK**

estimated temperature ~2μK

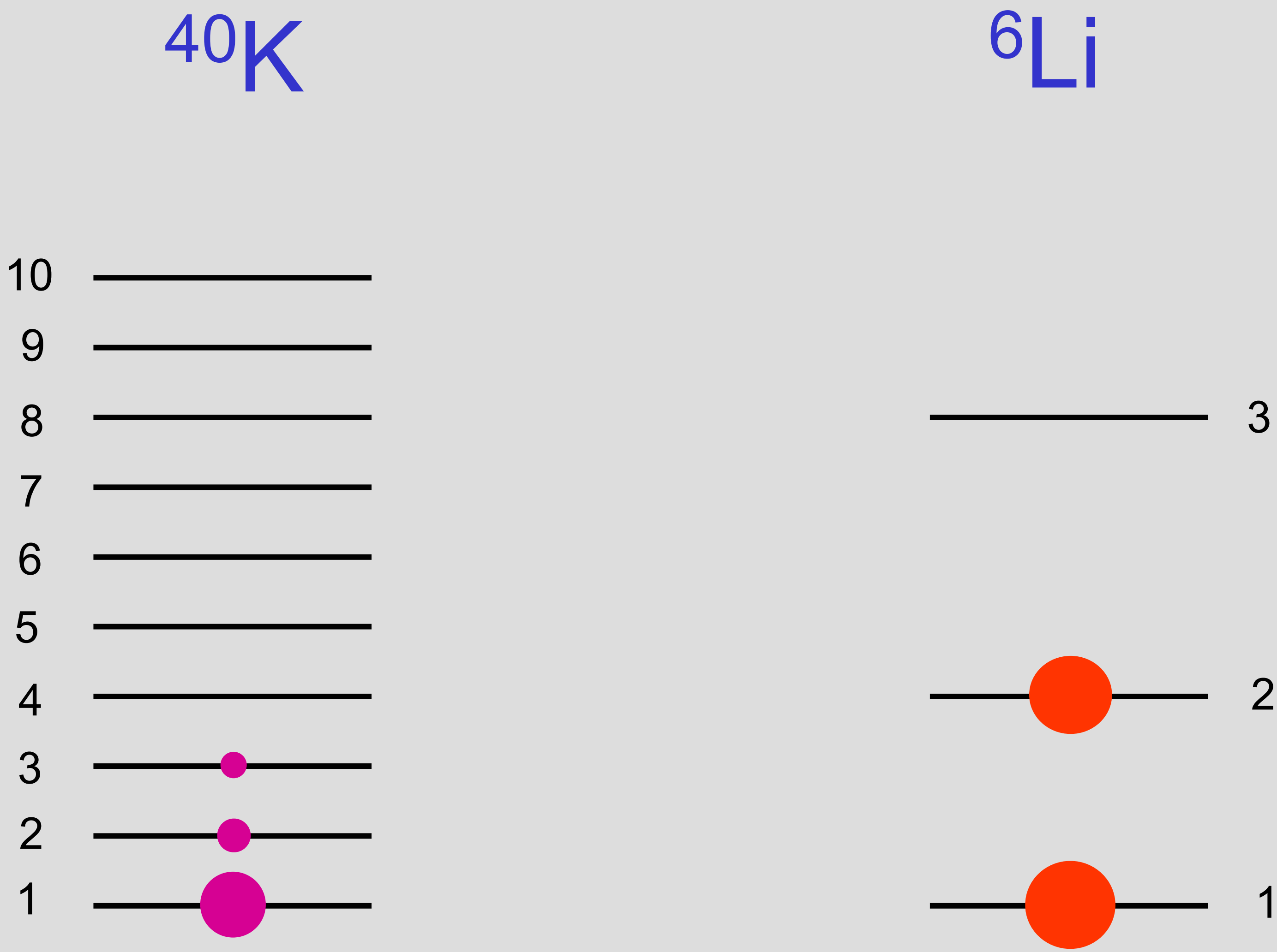
heteronuclear Fermi-Fermi mixture

(stable up to the point where $^{6}Li_2$ dimers are formed)

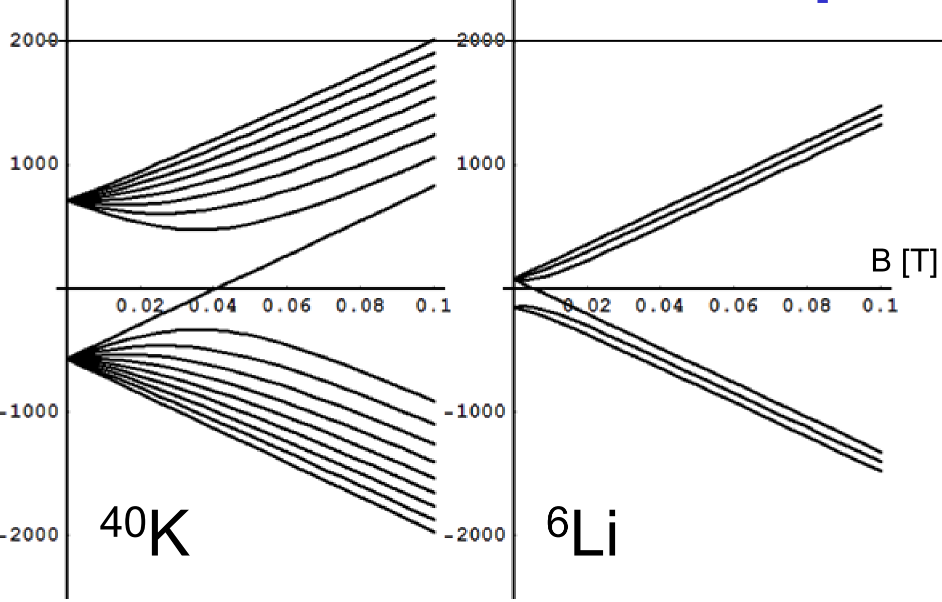
spin relaxation



spin relaxation

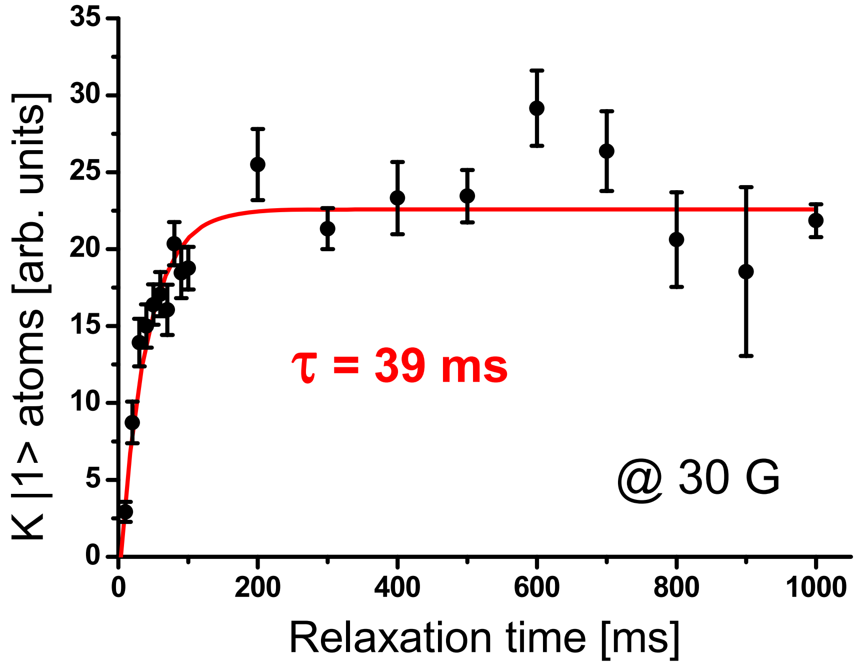


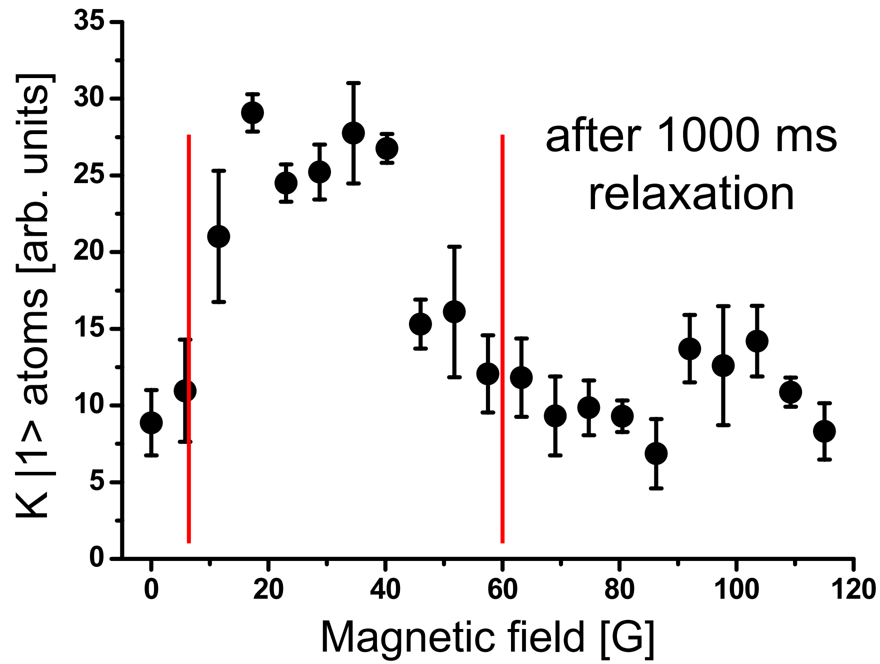
observation of spin relaxation



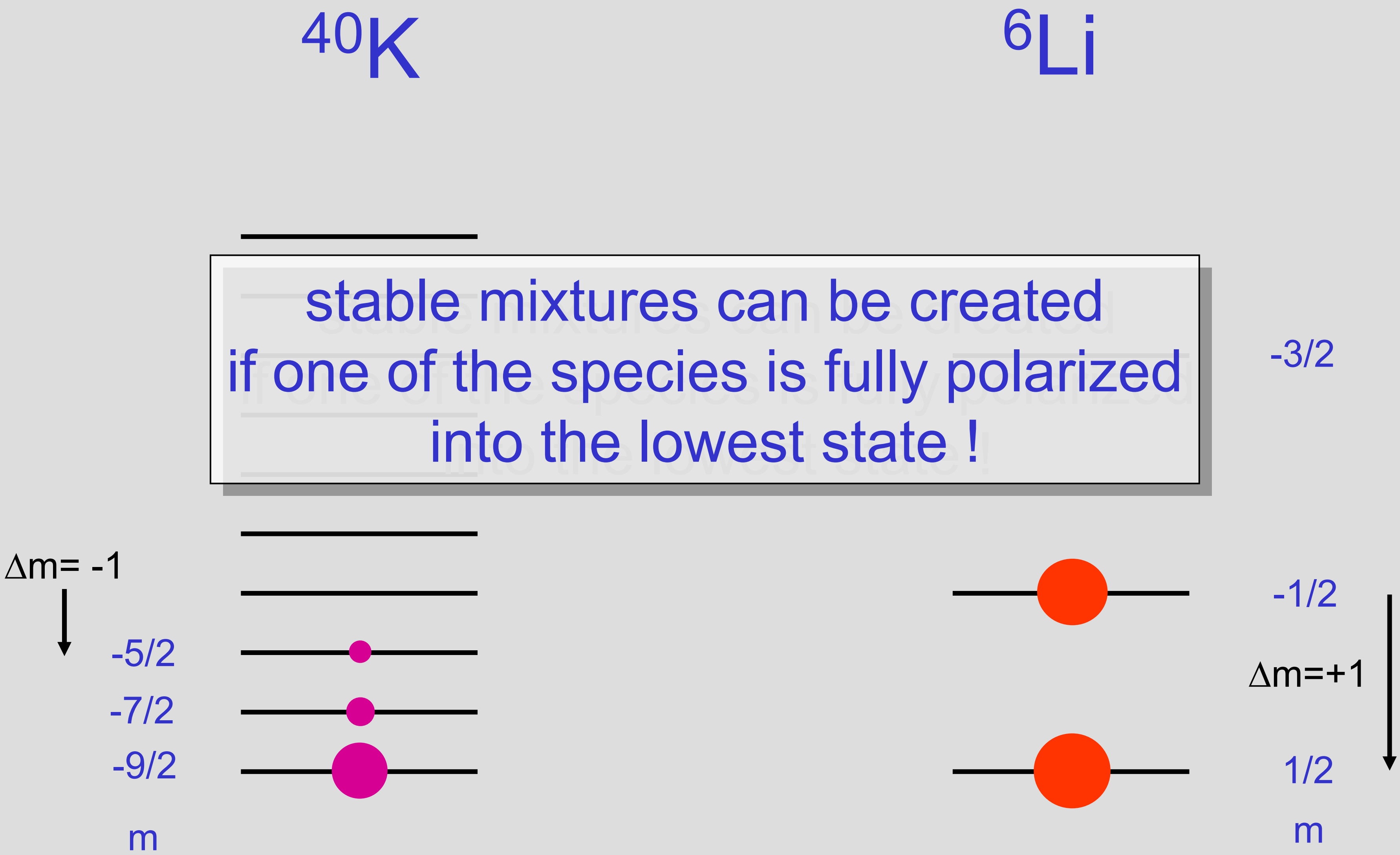
preliminary

- Energy splitting @ 6 G: ~ k_B 100 μK
- Energy transfer @ 60 G: ~ k_B 400 μK to the ^{40}K atom for a m_f changing collision
- Temperature: ~ 300 μK
- Trap depth: ~ 3000 μK for ^{40}K





spin relaxation

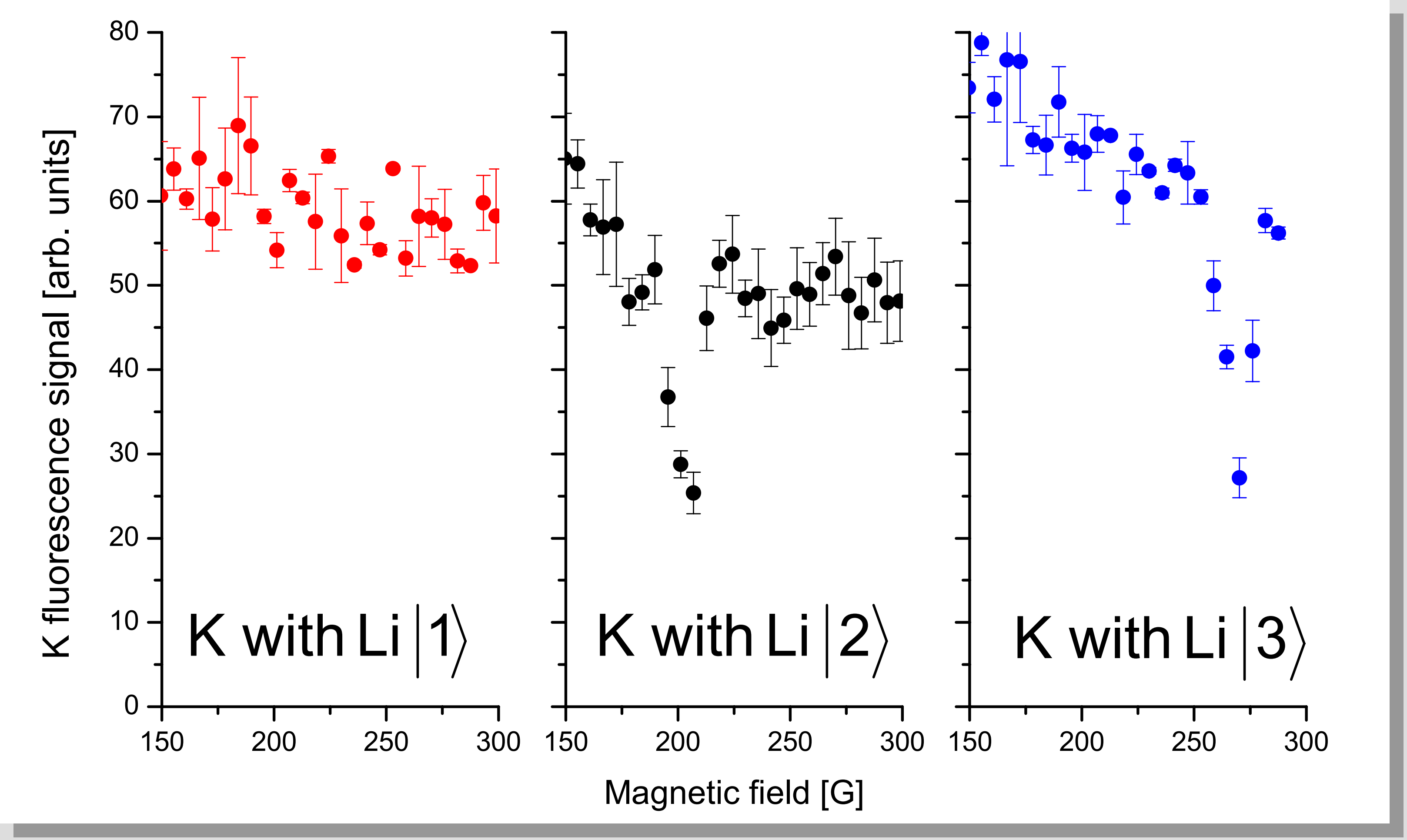


stable mixtures can be created
if one of the species is fully polarized
into the lowest state !

loss resonances

pure spin states of ^{6}Li prepared (optical cleaning, rf transfer)

^{40}K in a mixture of different states

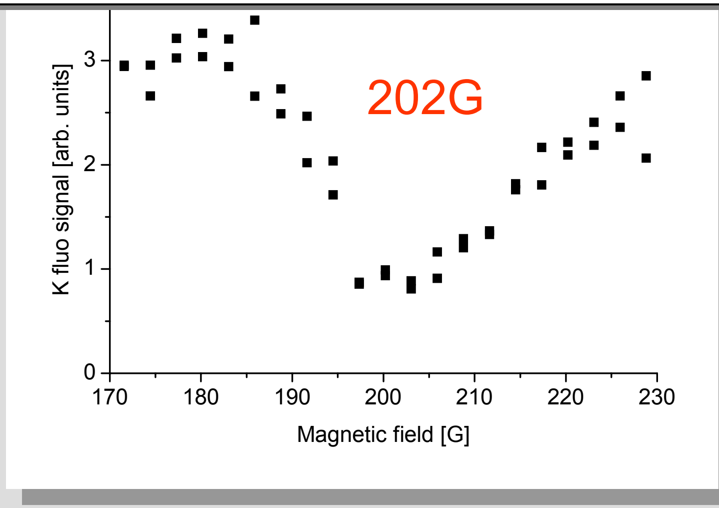


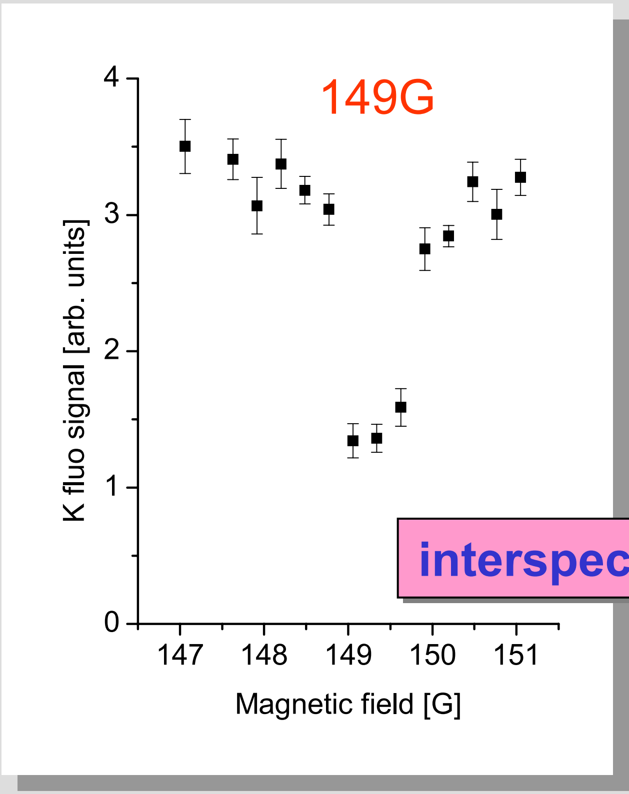
further resonances

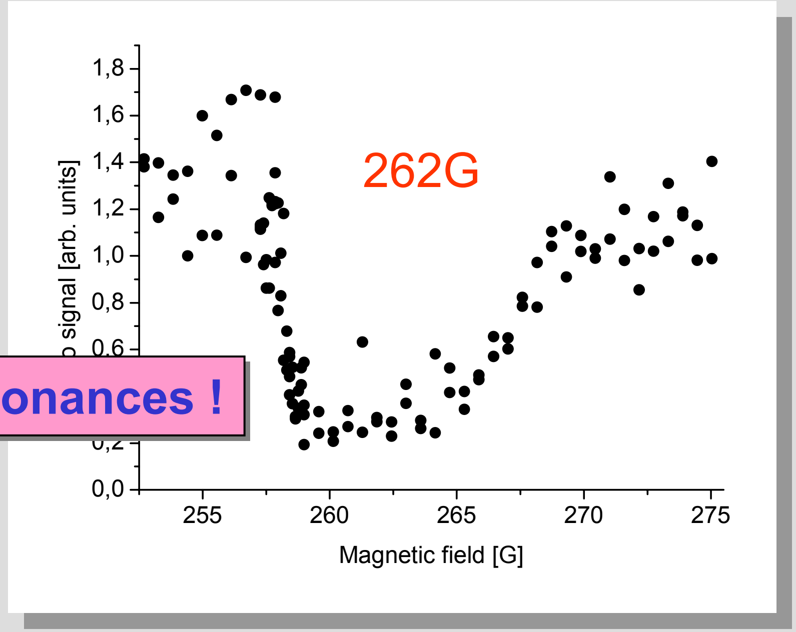
three-component mixture
of ^{6}Li (lowest state)
with ^{40}K (lowest two states)

monitor ^{40}K atom number

the “famous” ^{40}K resonance (homonuclear)



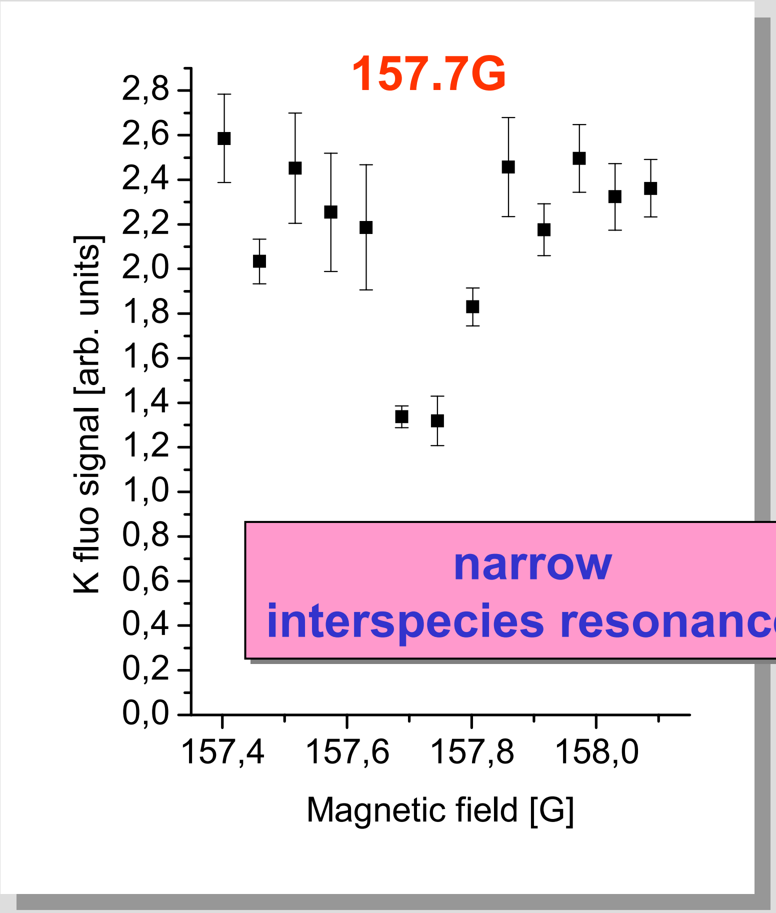




interspecies resonances !

further resonances

two-component mixture
of ^{6}Li (lowest state) with ^{40}K (lowest state)



narrow interspecies resonance

there is more to come (soon)...

preliminary conclusions on ^{6}Li-^{40}K

Fermi-Fermi mixtures available in the lab!

stable mixture if one species is in lowest state state
(otherwise spin relaxation)

sympathetic cooling of ^{40}K by ^{6}Li works well
at the large-a side of the Li-resonance
(at least until molecules are formed)

several interspecies resonances are observed
(^{40}K spin states tbd)

experiments in progress, right now in the lab in Innsbruck…

Ultracold atoms
quantum gases

universität
innsbruck

the end

IQI

funding

FWF Der Wissenschaftsfonds.

tirol

TIROLER
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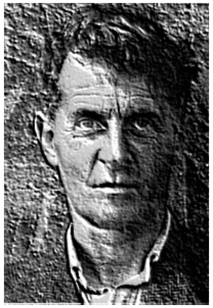
Land Tirol und Stadt Innsbruck

bm:bwk



Ludwig Wittgenstein
(1889-1951)
Austrian Philosopher