Resonant atomic gases

Leo Radzihovsky

for details see: *Gurarie, L.R., Annals of Physics, 322, 2-119 (2007)*
Sheehy, L.R., Annals of Physics, 322, 1790 (2007)

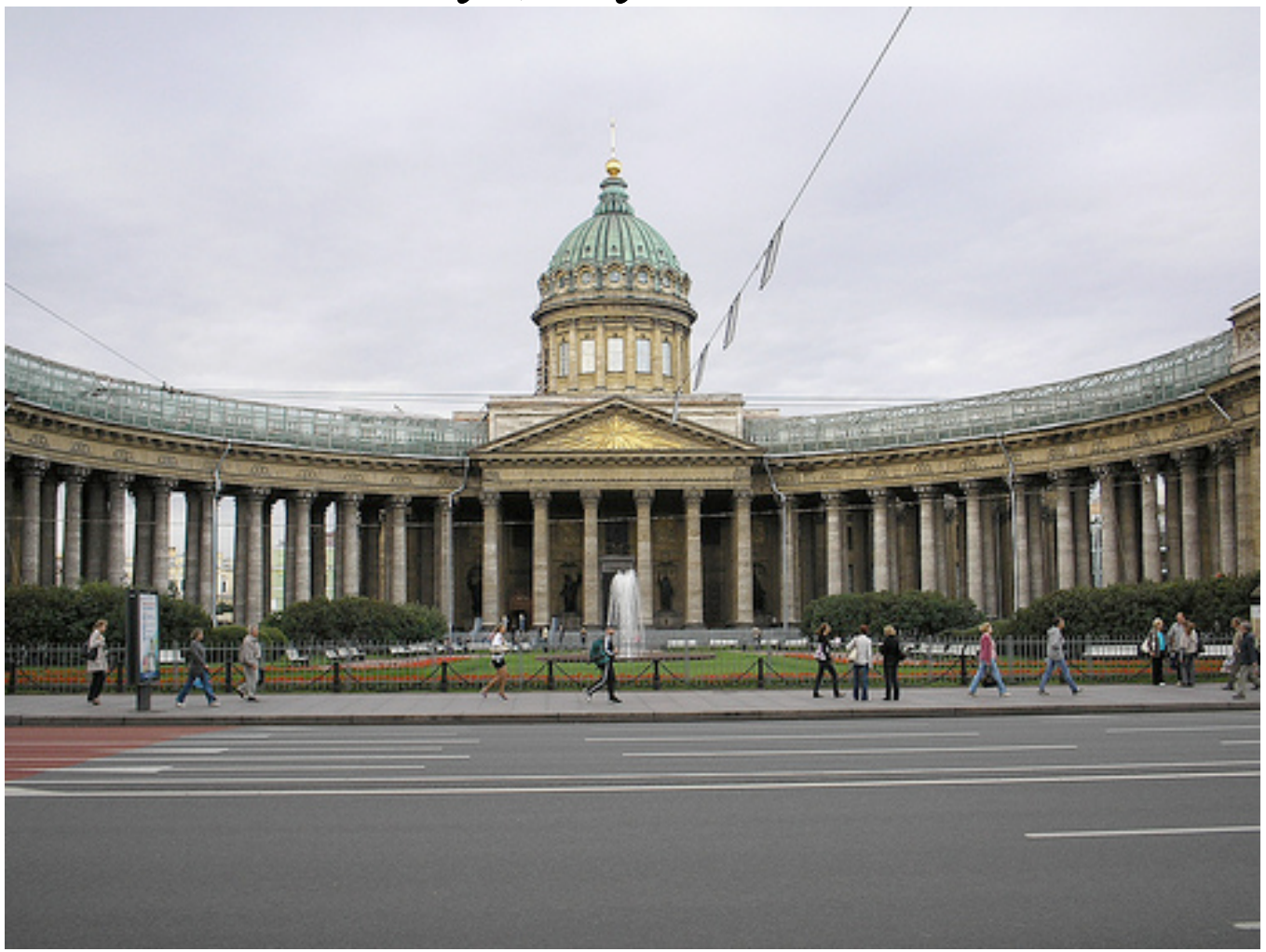
Giorgini, et al., RMP, 80, 885 (2008)
Ketterle and Zwierlein, Varenna lectures (2006)

$: NSF

Mysore, India, Dec 2010

Recognize this cathedral?

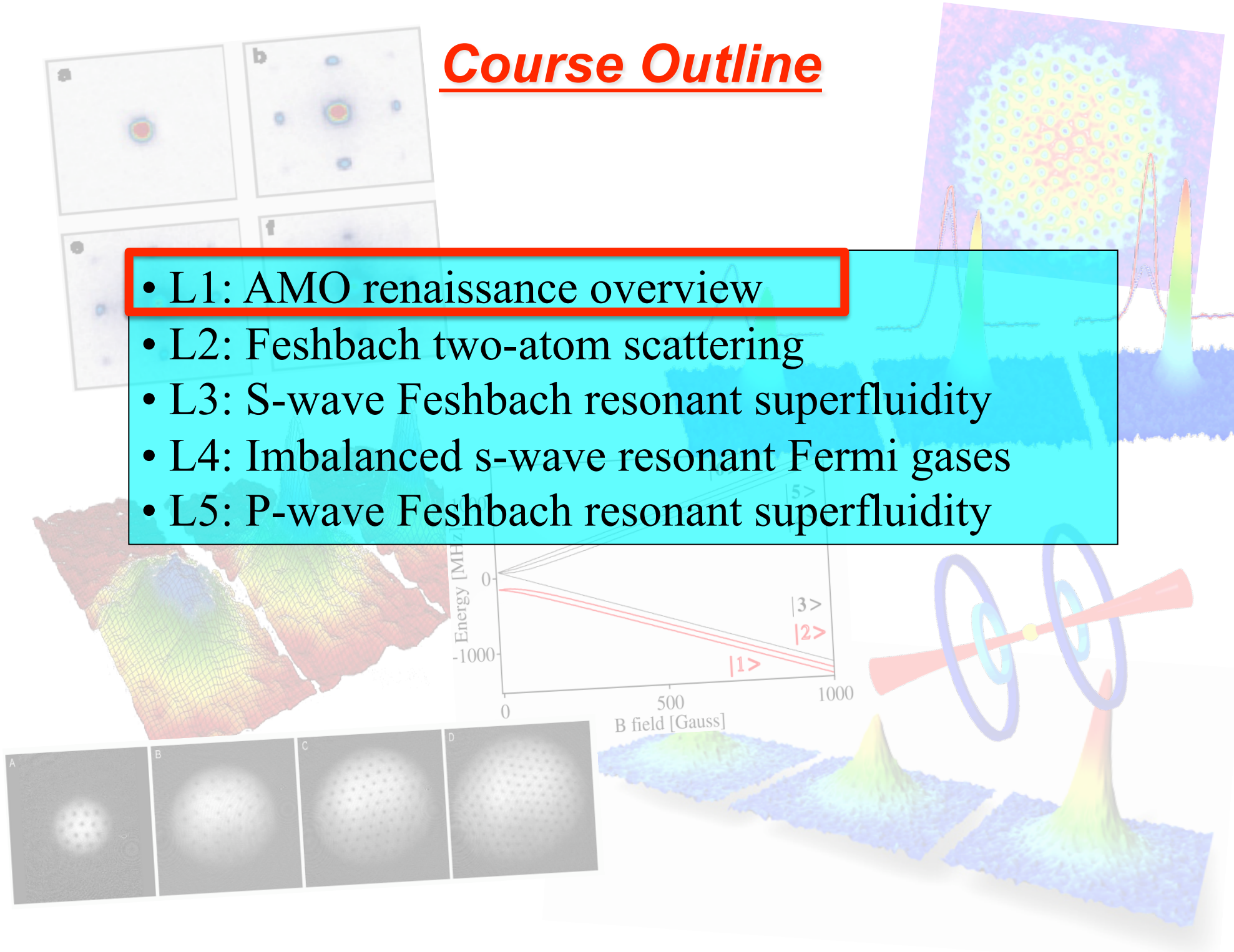
InfoSys, Mysore India?



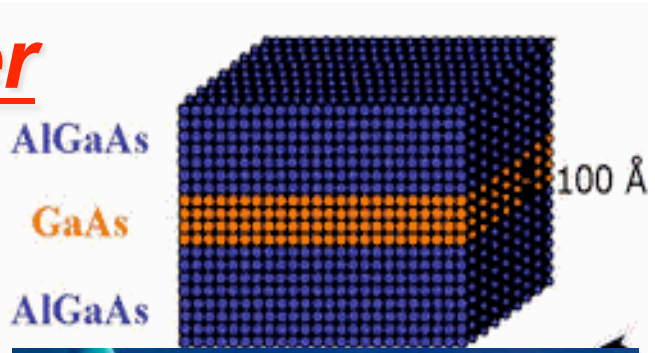
Kazansky Sabore, St. Petersburg

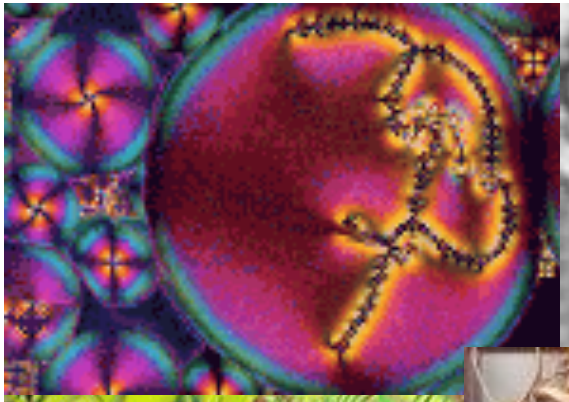
Course Outline

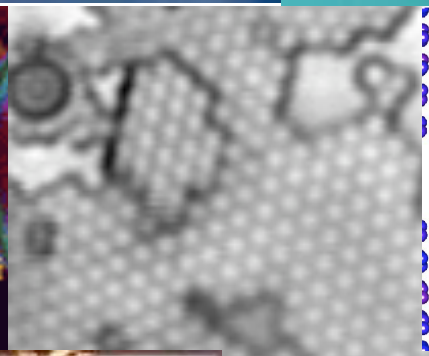
- L1: AMO renaissance overview
- L2: Feshbach two-atom scattering
- L3: S-wave Feshbach resonant superfluidity
- L4: Imbalanced s-wave resonant Fermi gases
- L5: P-wave Feshbach resonant superfluidity

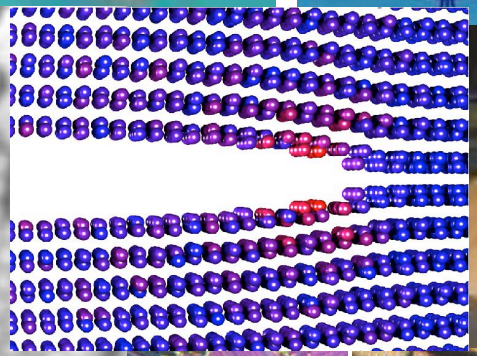


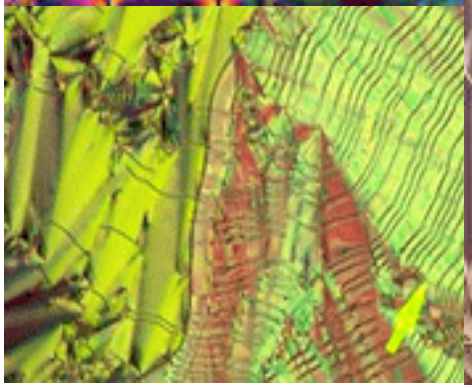
Condensed matter

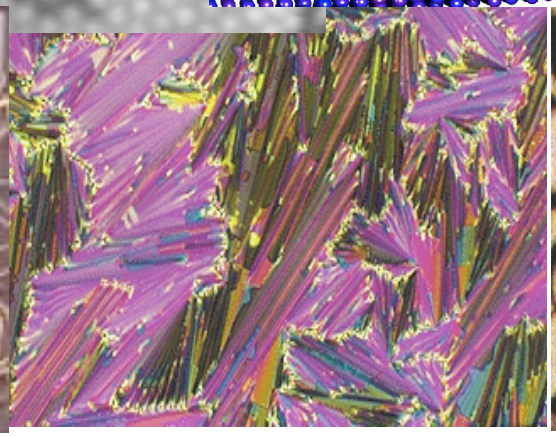


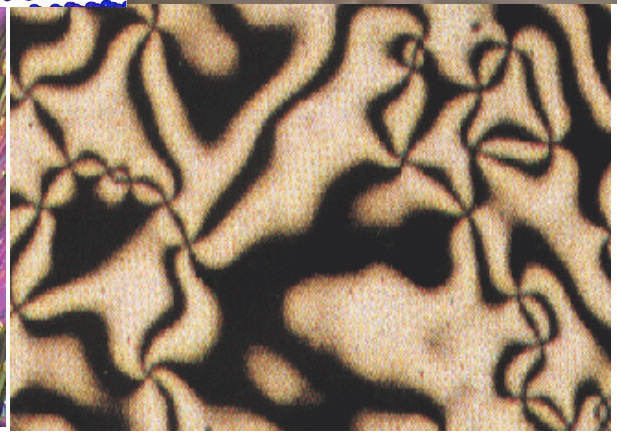






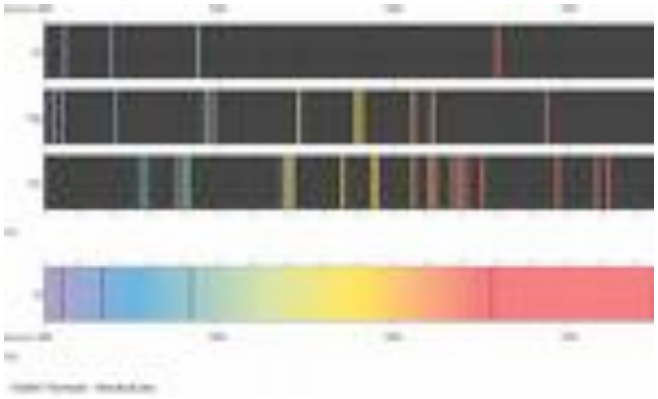


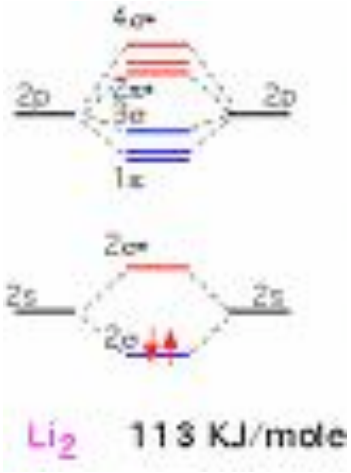


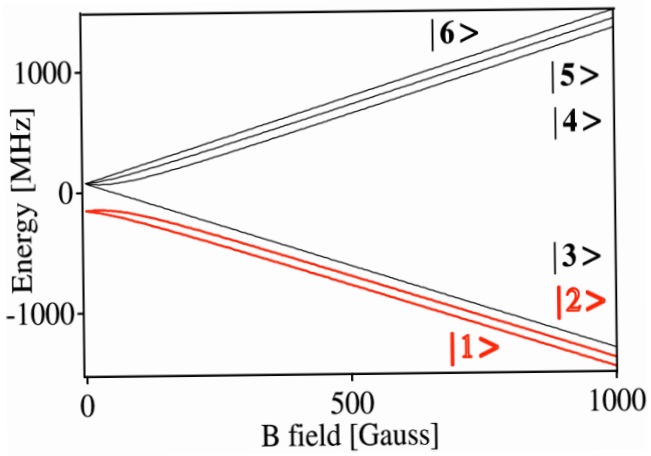


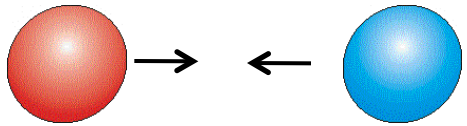
Atomic physics *(naïve view)*

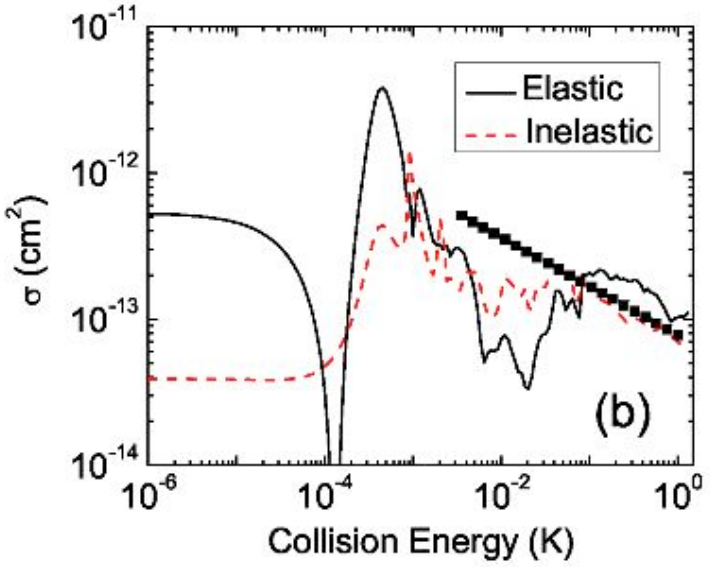
- atomic spectra
- collisions
- molecules
- laser-atom interaction







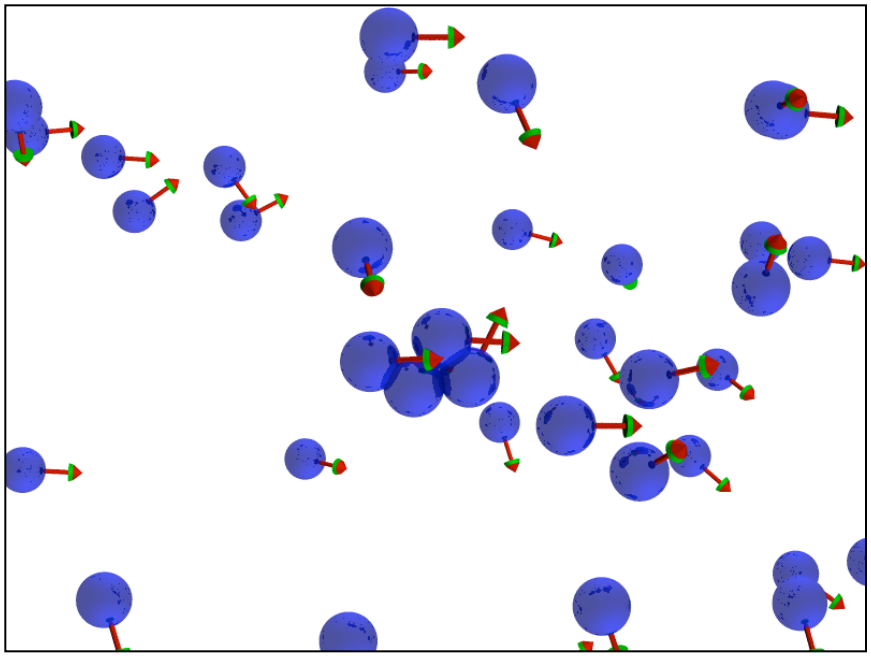




Dilute atomic gases

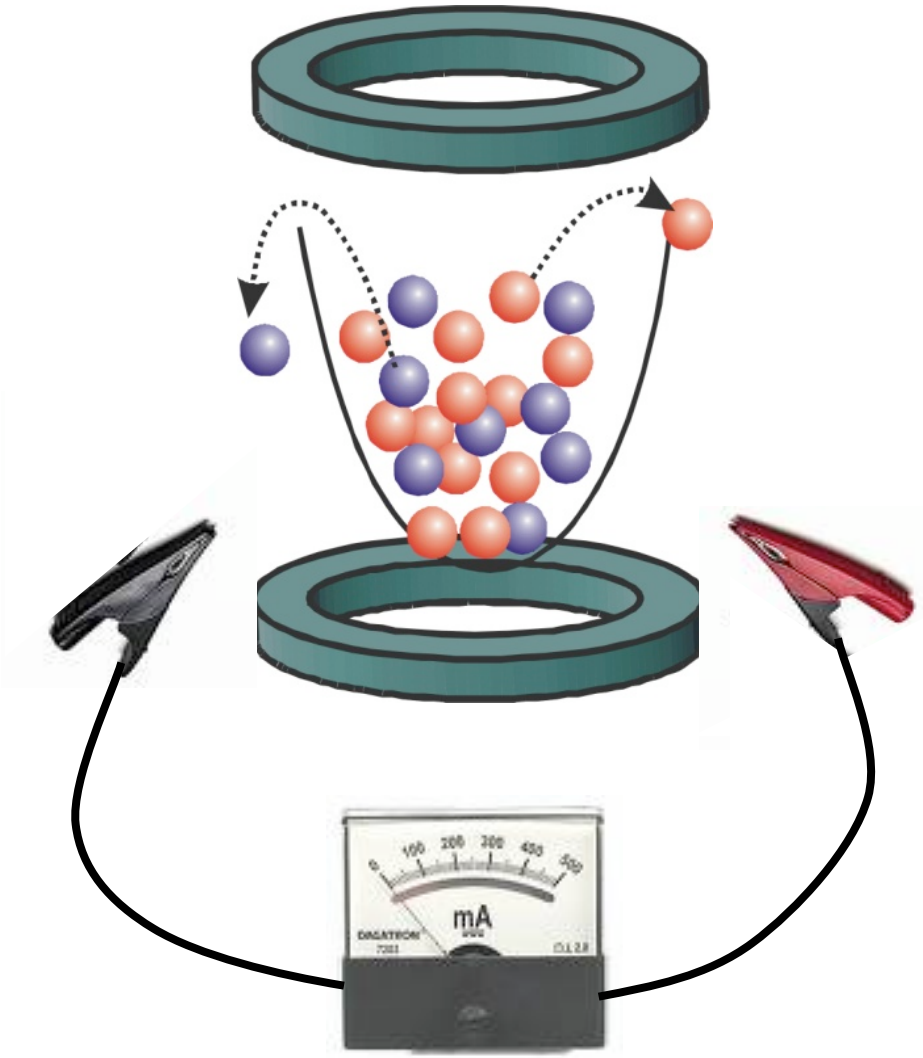
- density ~ 10^{12} cm^{-3} ⇔ d ~ 10^4 Å, mfp ~ 10 cm

  (cf. density$_{air}$ = 10^{19} cm^{-3} ⇔ d_{air} ~ 10^2 Å)



- classically: ⇒ (boring) IDEAL GAS

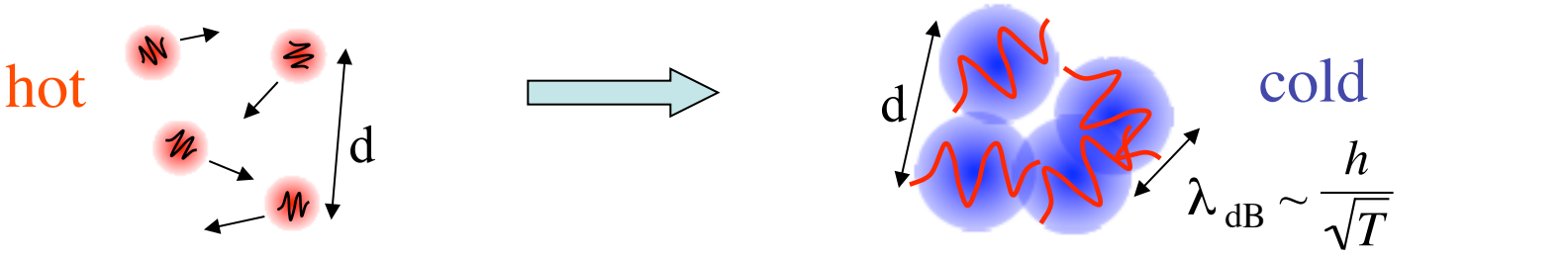
Condensed matter with cold atomic gases?



Quantum mechanics to the rescue

Heisenberg uncertainty principle: $\delta x\, \delta p \geq h$

$\delta p \sim \sqrt{T}$ small, $\delta x \sim \frac{h}{\sqrt{T}}$ big. Particles are fuzzy



classical ideal Boltzmann gas

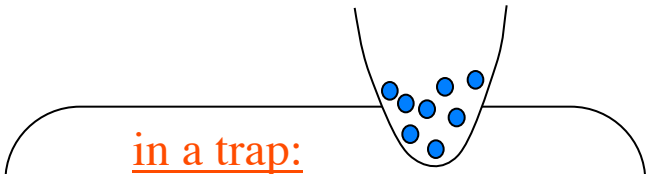
degenerate quantum gas: $\lambda_{dB}(T_d) \sim d$ *statistics matters*

$$T_d \approx \frac{\hbar^2}{2md^2}$$

$T_d^{metal} \sim 1eV \sim 10^4 Kelvin$

$T_d^{He4} \sim 10^4 K \times \frac{m_e}{m_{He4}} \sim 1Kelvin$

$T_d^{Rb87} \sim 1K \times \frac{1}{20} \times \frac{1}{10^7} \sim 5nK$



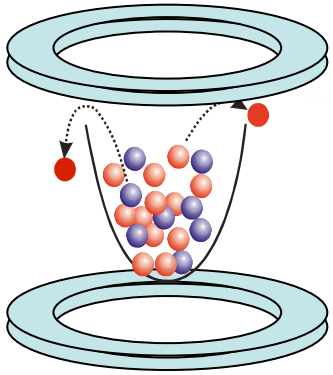
in a trap:

$d \to R(T)/N^{1/3}$

$\frac{1}{2} m\omega^2 R^2 \approx k_B T$

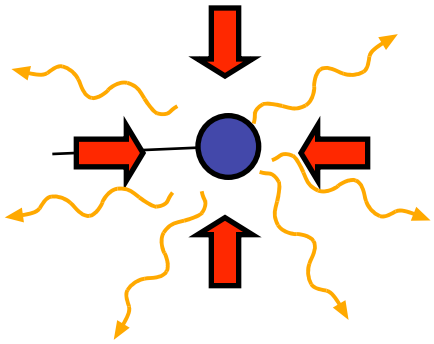
$T_d \approx \hbar\omega N^{1/3}$

Laser cooling, trapping and imaging



Evaporative cooling

1 mK to 1 μK
~$10^8 \rightarrow 10^6$ atoms



1997
Chu,
Cohen-Tannoudji,
Phillips

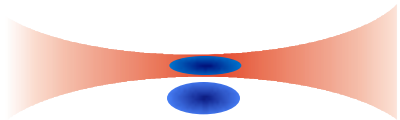
Laser (Doppler) cooling

300 K to 1 mK
~10^9 atoms

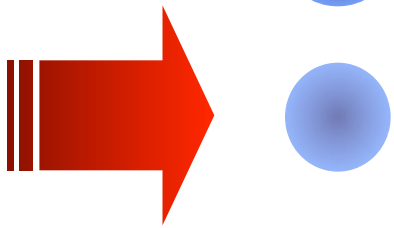
Ener

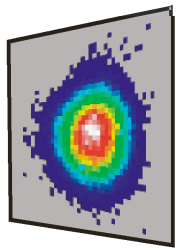
δ

T



probing w/ resonant laser





shadow image

$$n(r,t) \approx \tilde{n}(\hbar k = mr/t)$$

Degenerate quantum gas

$T < T_d$

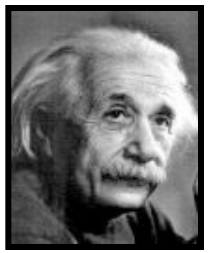
Bosons:

- *integer spin*
- *symmetric Ψ*
- *photons, W, Z, ^{1}H, ^{4}He, ^{87}Rb,…*

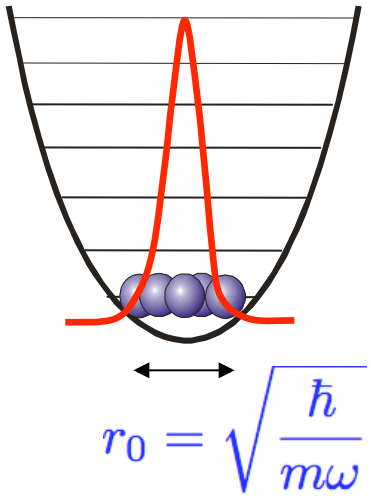
⇒ *Bose-condensate (BEC)*

Predicted 1924 by:

S. Bose



A. Einstein



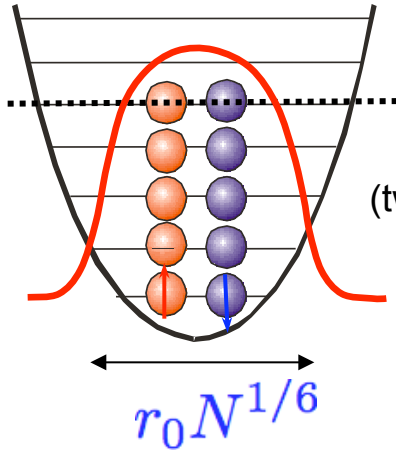
$r_0 = \sqrt{\frac{\hbar}{m\omega}}$

$(\frac{1}{2}m\omega^2 R^2 = \hbar\omega)$

Fermions:

- *half-integer spin*
- *anti-symmetric Ψ (Pauli-principle)*
- *quarks, electrons, protons, ^{3}He, ^{6}Li, ^{40}K,…*

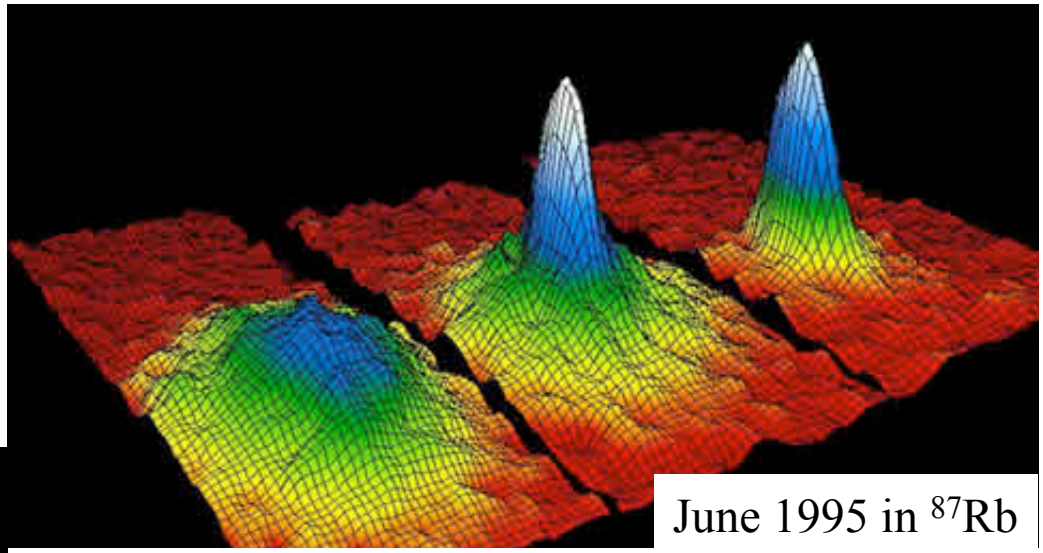
⇒ *Fermi-sea*



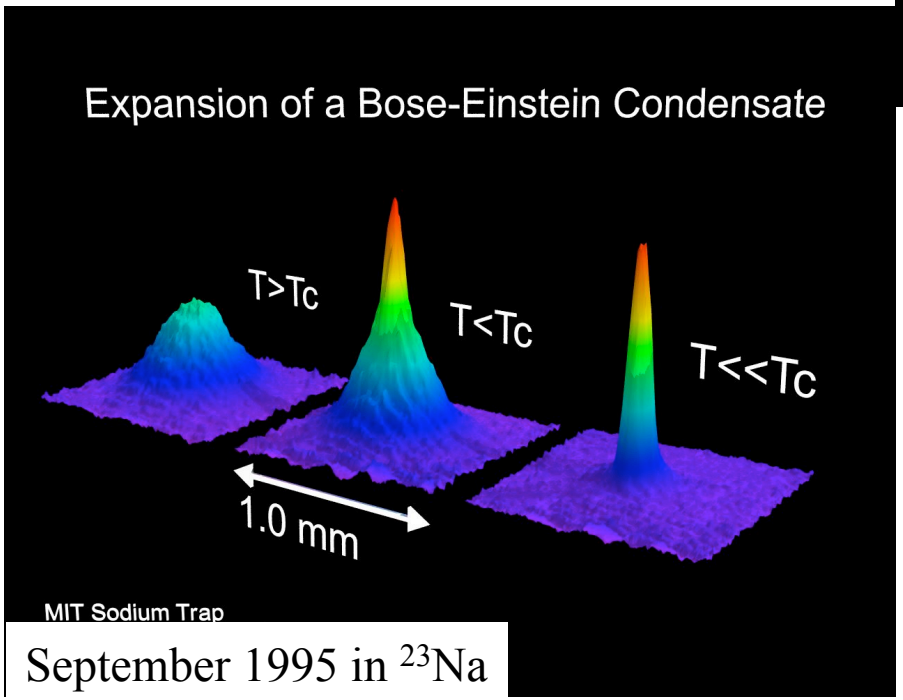
$(\frac{1}{2}m\omega^2 R^2 = E_F)$

Revolution in AMO physics

- degenerate Bose and Fermi atomic gases



June 1995 in ^{87}Rb



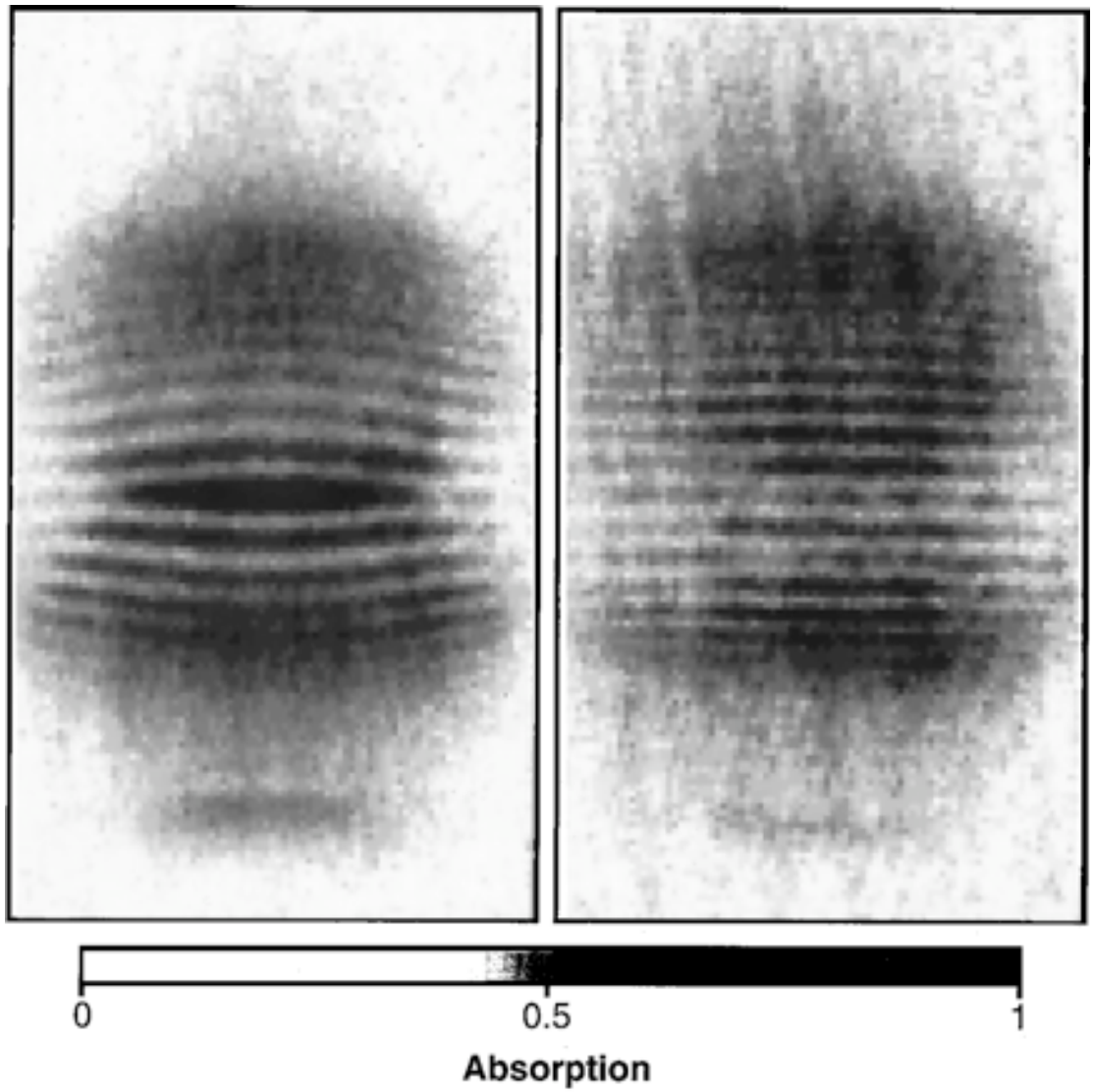
September 1995 in ^{23}Na

Matter-wave interference *(Ketterle '97)*

two ballistically expanding BEC clouds d apart, imaged after time t:

period: deBroglie wavelength

$$\lambda = \frac{ht}{md}$$



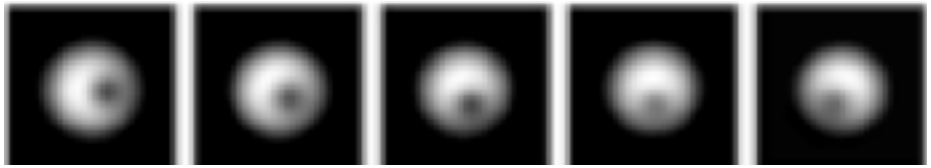
(Andrews, et al., Science '97)

Onsager, Feynman, Vinen

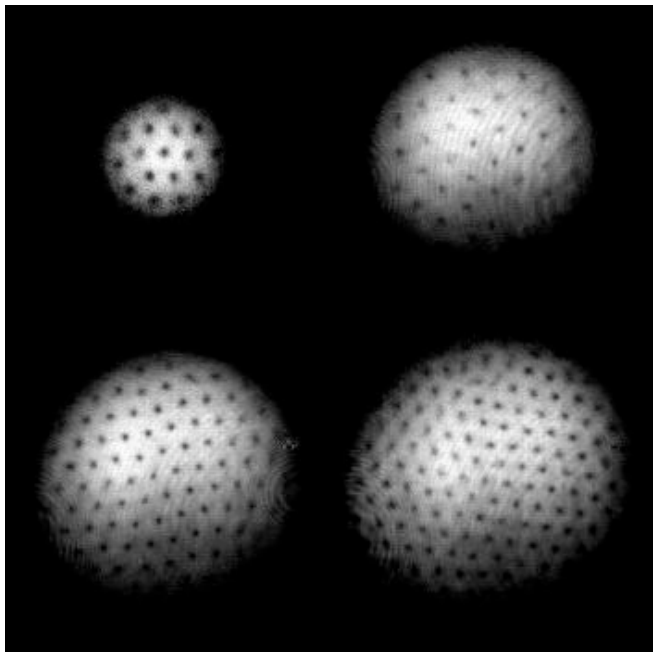
Vortices

Cornell '97

- hall-mark of superfluidity: $v_s = \hbar/m \nabla\varphi$, $\oint v_s \cdot dl = n\, h/m$
- precession in trap field $v_v \sim h/m\; z \times \nabla n_s$



- vortex lattice *(almost) uniform via correspondence principle,* $n_v = 2\Omega\, m/h$)



- bosonic QHE?

Coriolis $\Leftrightarrow$ *Lorentz force*

$2m\Omega \Leftrightarrow eB/c$

Coddington, et al. '04

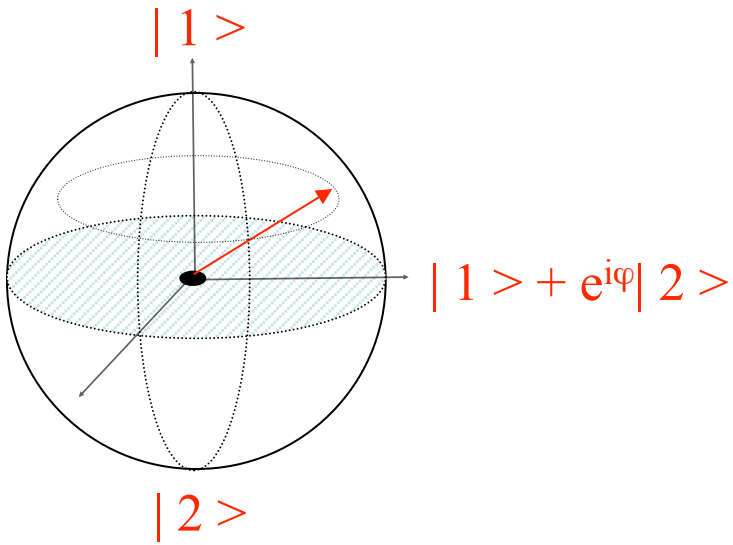
Spinor BEC

Cornell '97
Stamper-Kurn

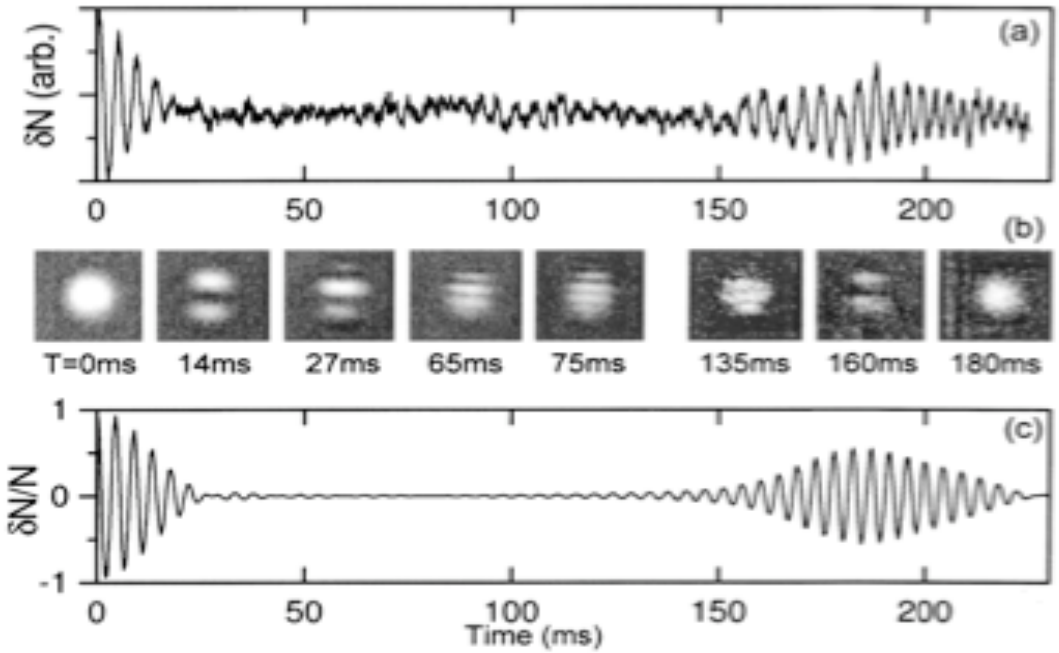
- Multicomponent BEC's:

  hyperfine states, isotopes, atomic species

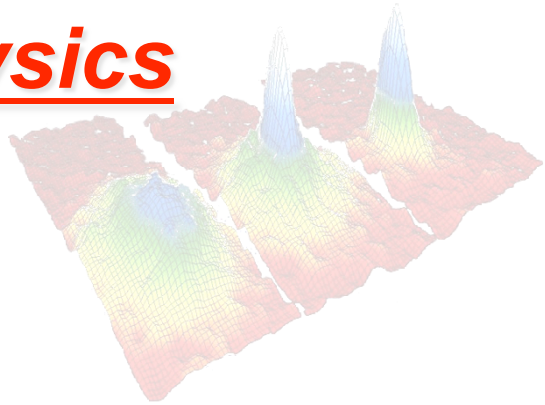
- *e.g.* "spin"-1/2 boson: $a \rightarrow a_\sigma = (a_1 , a_2)$



Phase contrast microscopy:

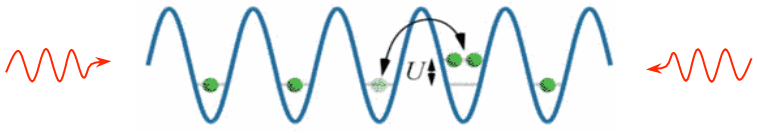


Revolution in AMO physics

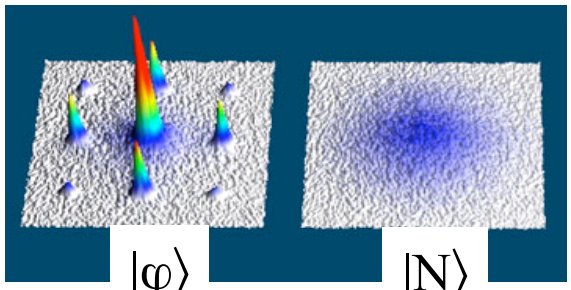


- degenerate Bose and Fermi atomic gases

- optical lattices

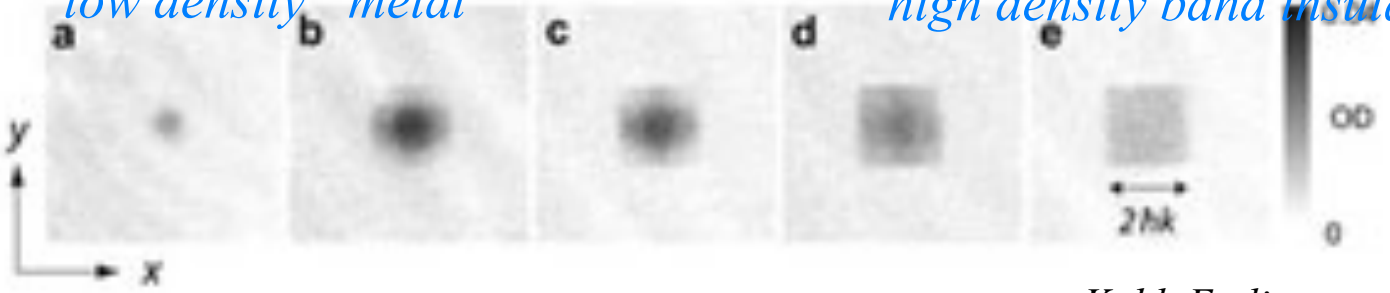


ac-Stark effect
(red-detuned, attractive)



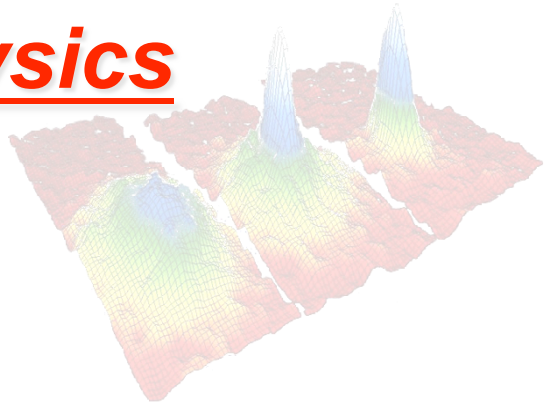
Greiner, et al.

low density "metal" *high density band insulator*



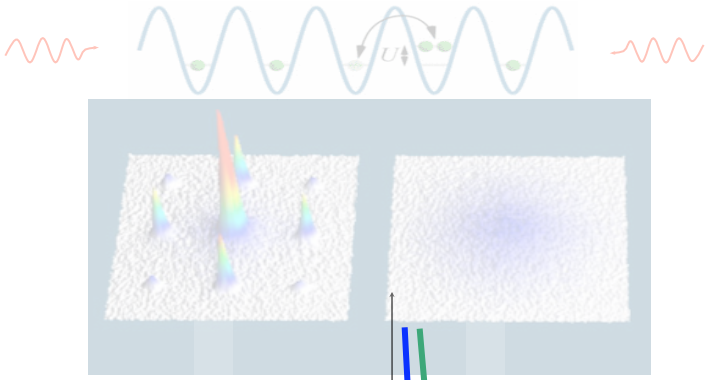
Kohl, Esslinger, et al. '05

Revolution in AMO physics

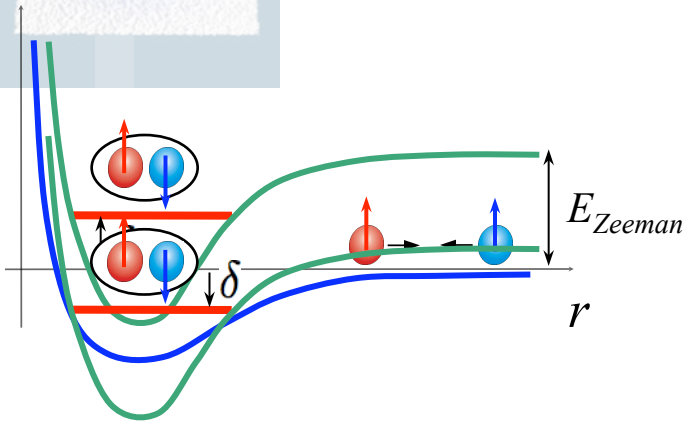


- degenerate Bose and Fermi atomic gases

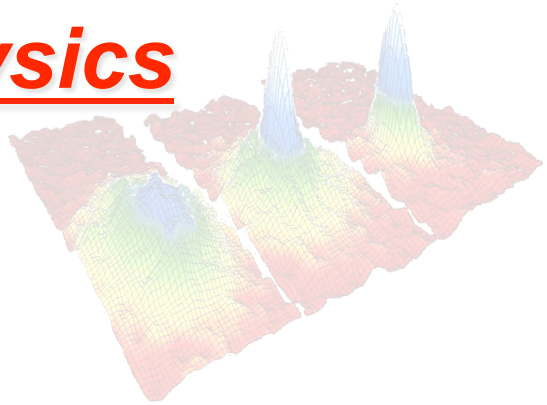
- optical lattices



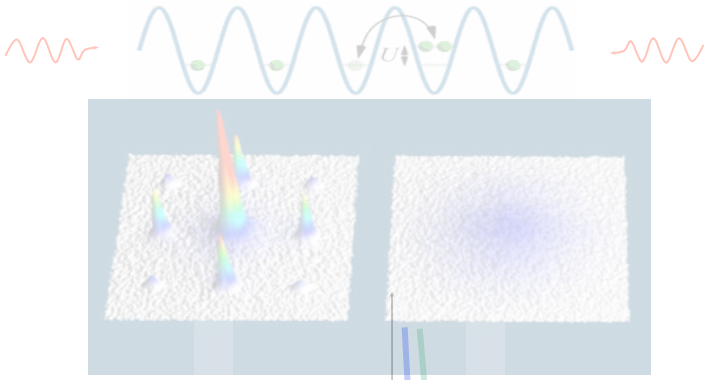
- Feshbach resonance



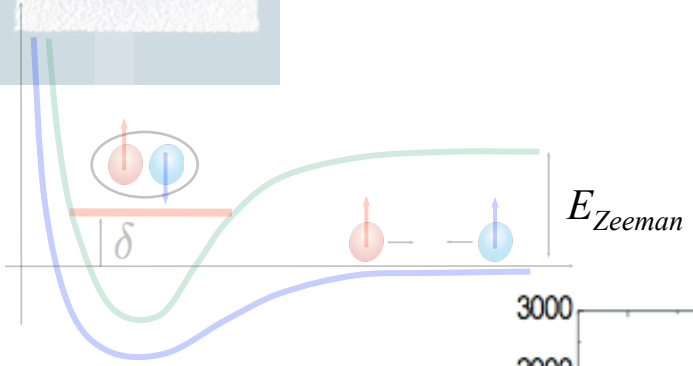
Revolution in AMO physics

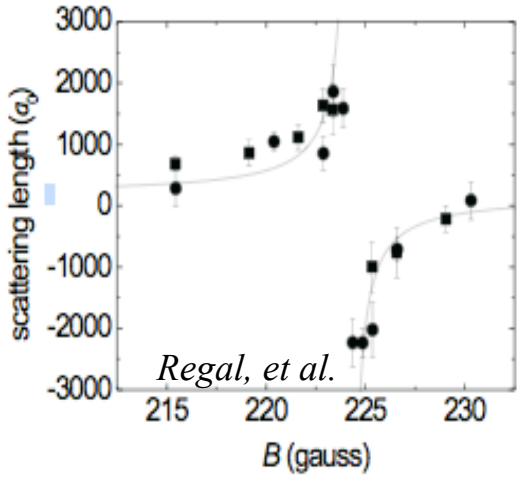


- degenerate Bose and Fermi atomic gases
- optical lattices

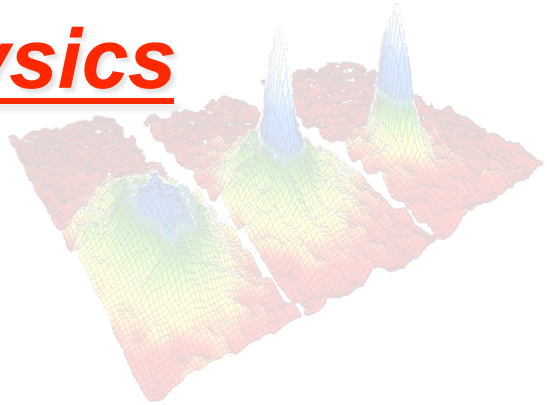


- Feshbach resonance
  - *weak to strong interactions*

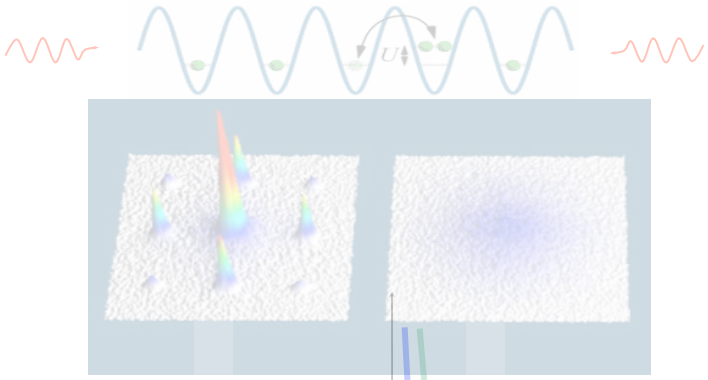




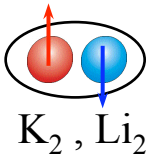
Revolution in AMO physics



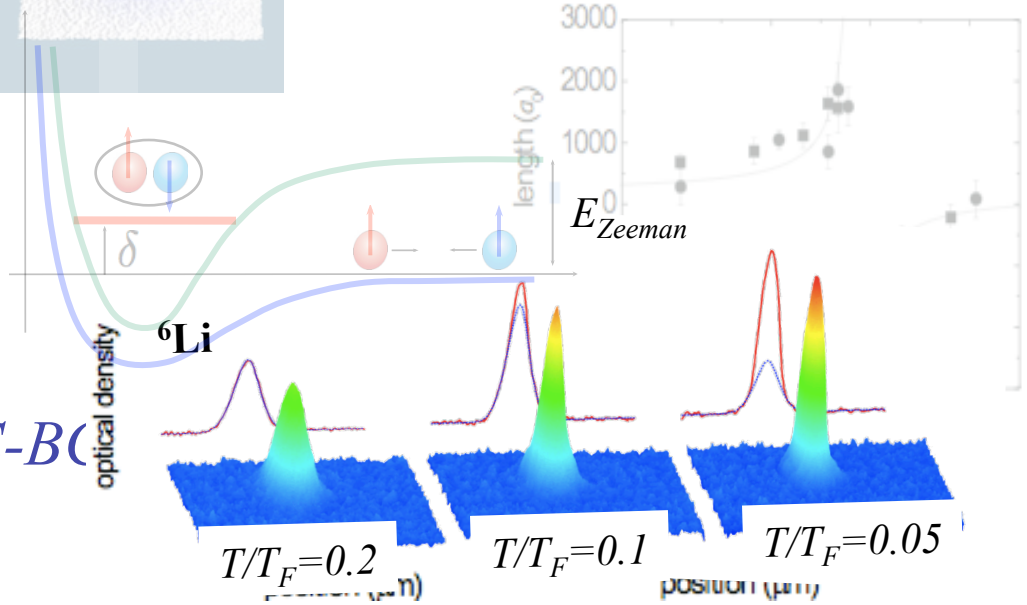
- degenerate Bose and Fermi atomic gases
- optical lattices



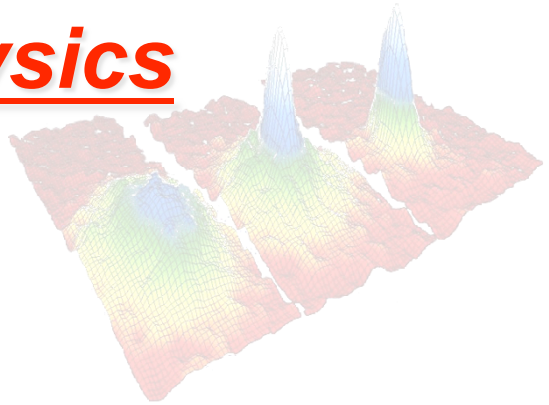
- Feshbach resonance
  - *weak to strong interactions*
  - *paired superfluidity and BEC-BC*



K_2 , Li_2

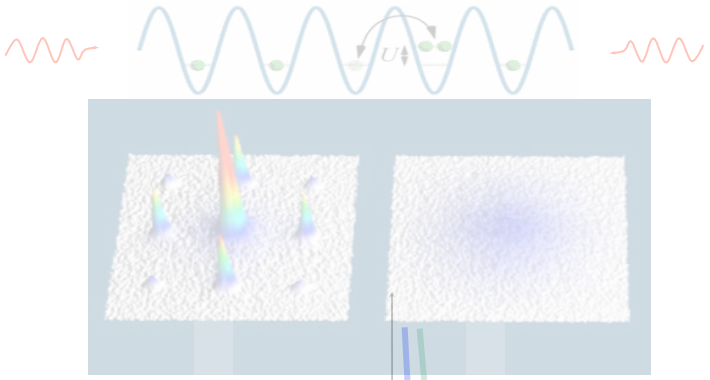


Revolution in AMO physics

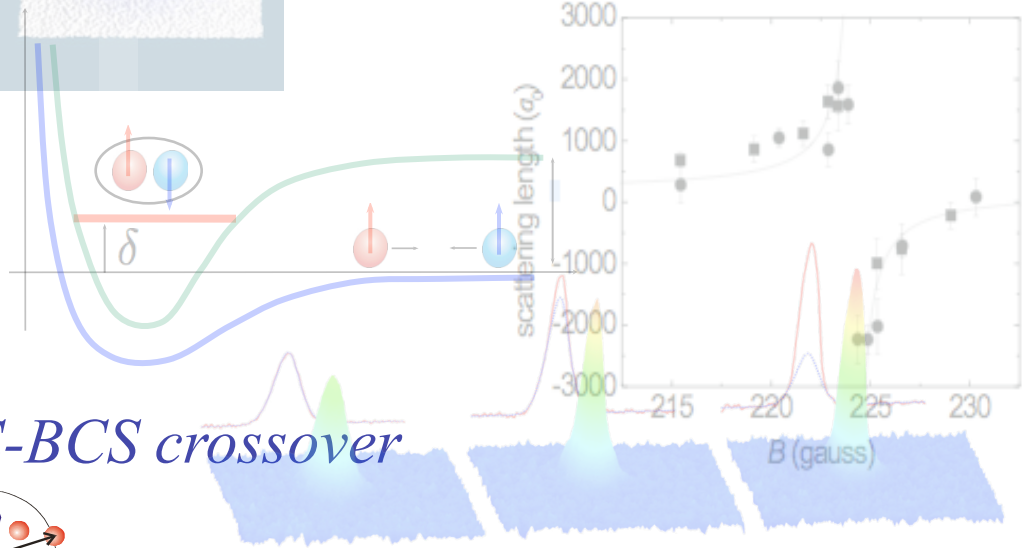


- degenerate Bose and Fermi atomic gases

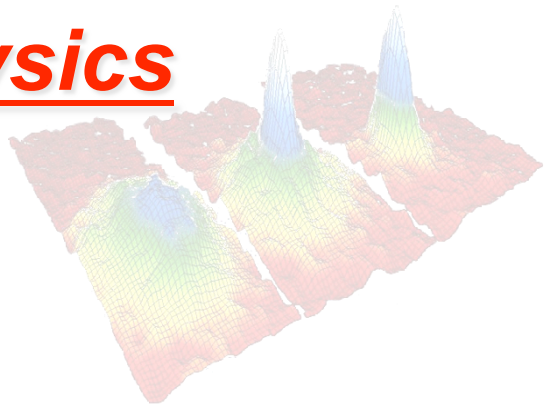
- optical lattices



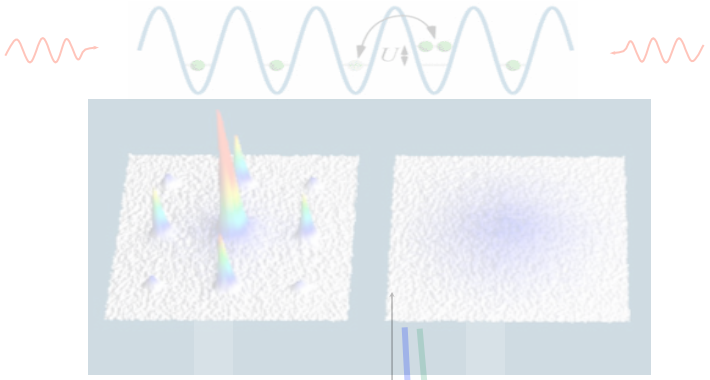
- Feshbach resonance
  - *weak to strong interactions*
  - *paired superfluidity and BEC-BCS crossover*



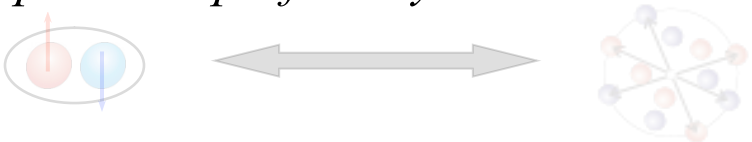
Revolution in AMO physics



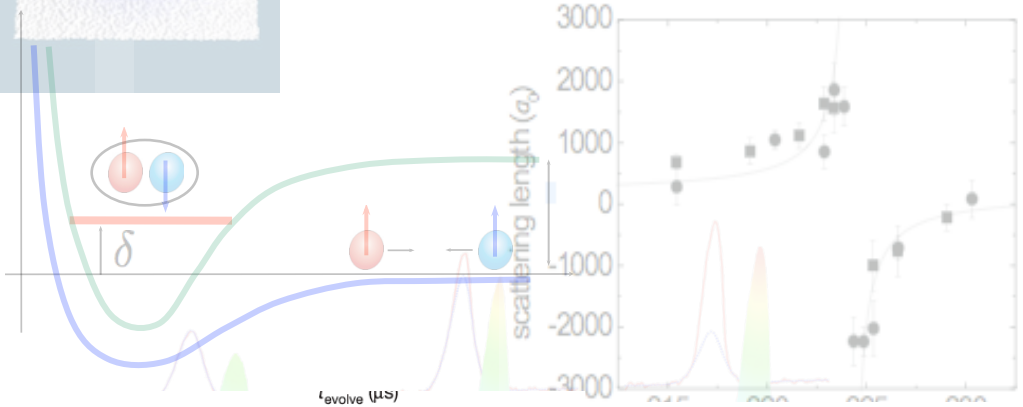
- degenerate Bose and Fermi atomic gases
- optical lattices

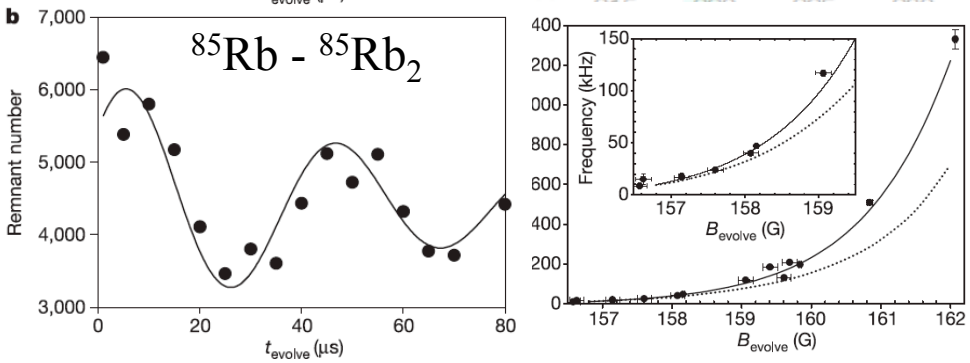


- Feshbach resonance
  - *weak to strong interactions*
  - *paired superfluidity and BEC-BCS cr*

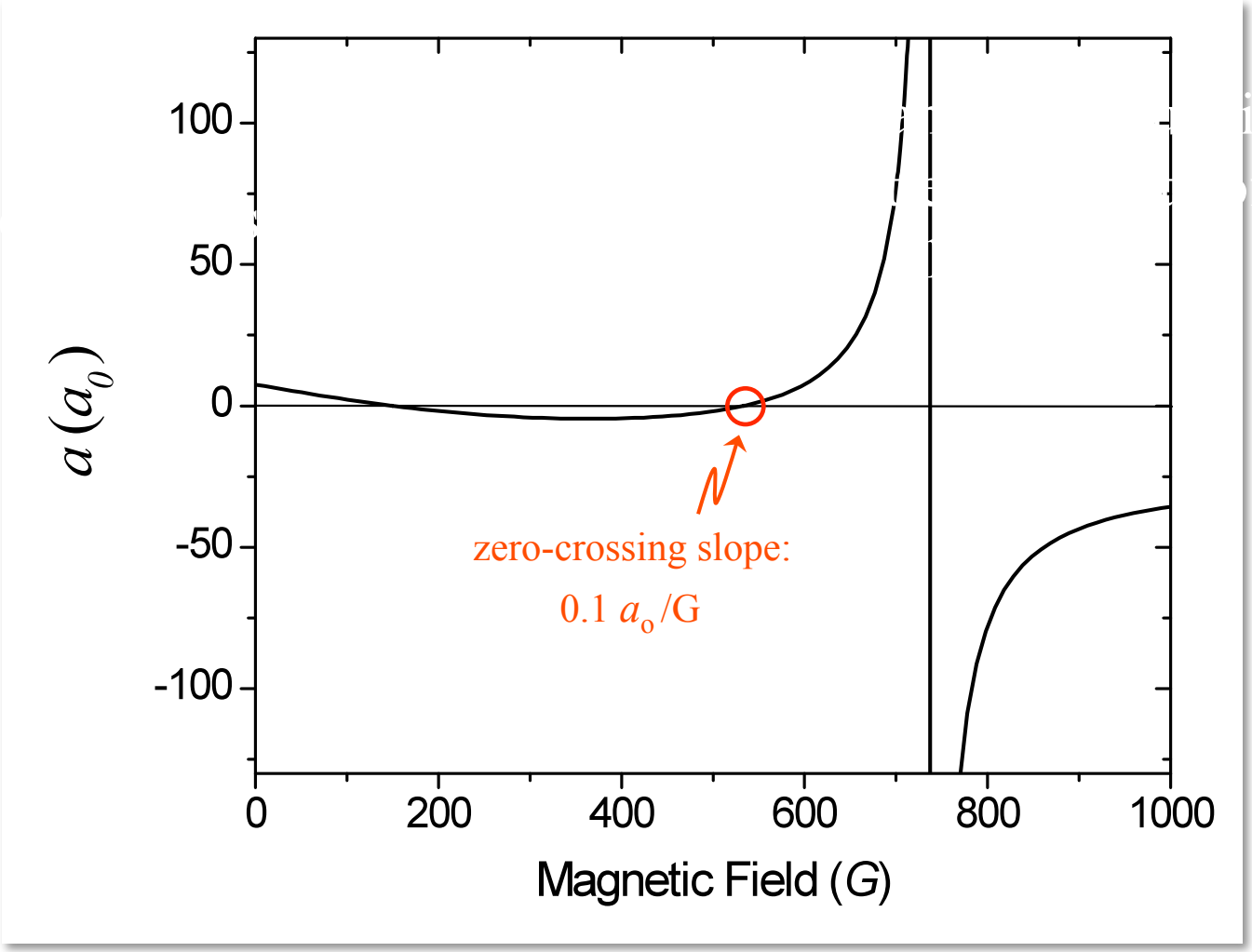


  - *quantum nonequilibrium CMP*

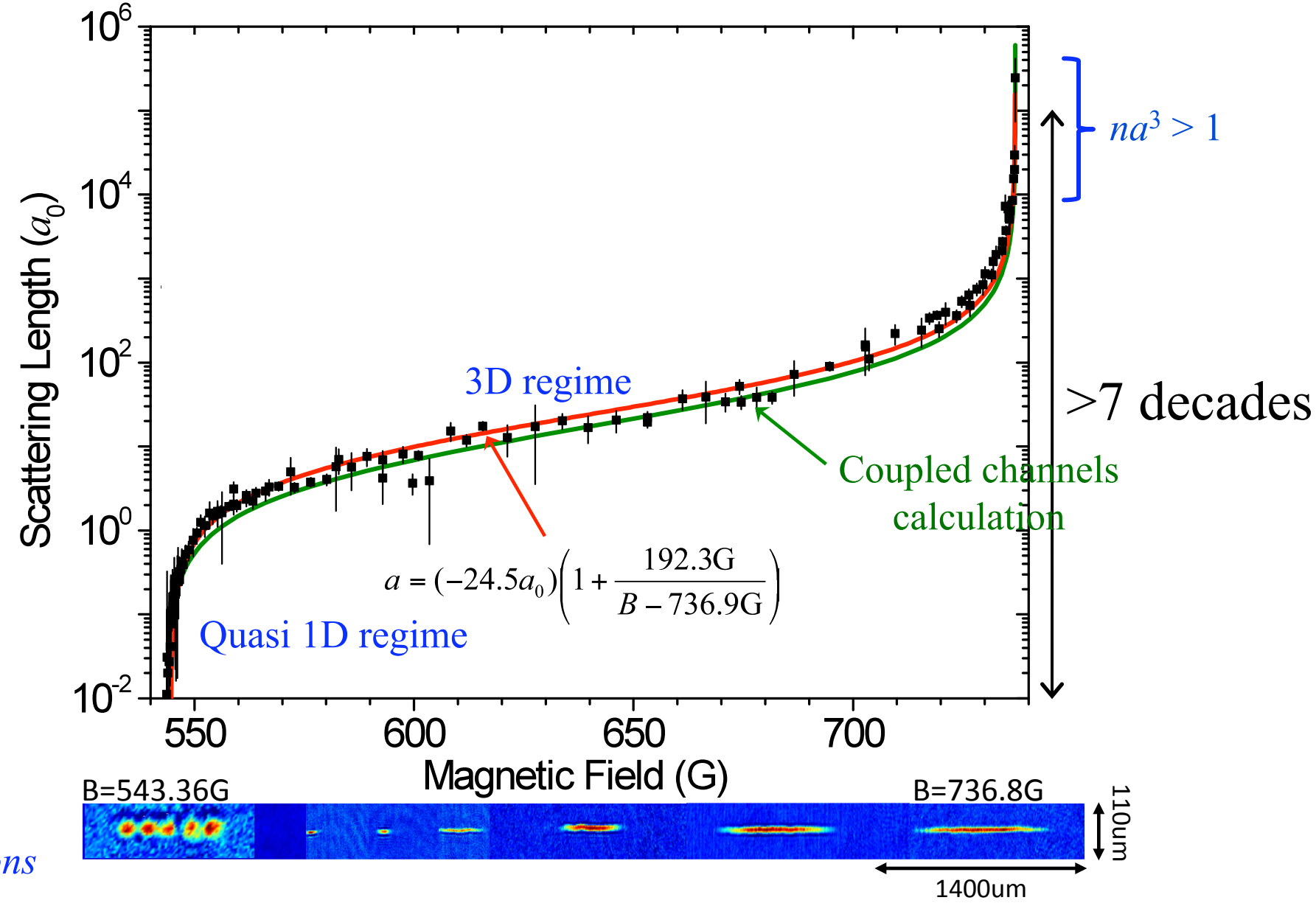




Feshbach Resonance in ^{7}Li (Boson)



Scattering Length vs. Field



Solitons

Pollack, Dries, Junker, Chen, Corcovilos, Hulet, PRL **102**, 090402 (2009)

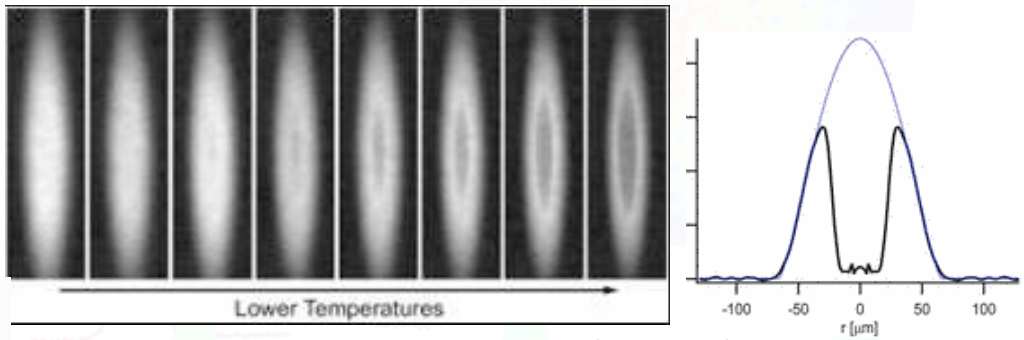
Feshbach resonances on youtube

"*Quantum decoupling transition in a one-dimensional* superfluid", Sheehy and Radzihovsky, PRL (2005)

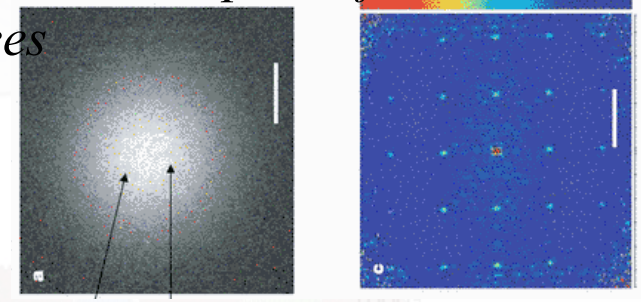
(song by Jonathan Mann, 2009)

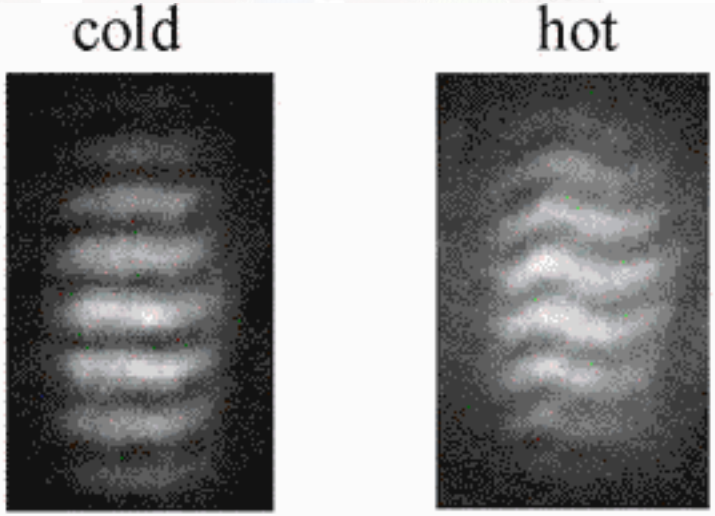
Variety of experimental probes

- Time-of-flight density imaging
  - *momentum distribution function*
  - *scattering length*
  - *temperature*
  - *noise → pairing correlations*
  - *interference → phase fluctuations*
  - *vortices*



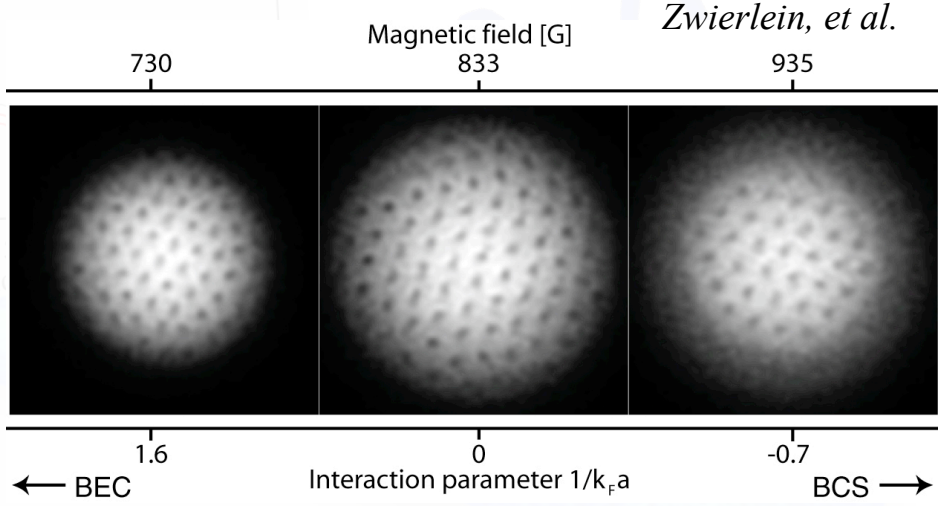
Zwierlein, et al.





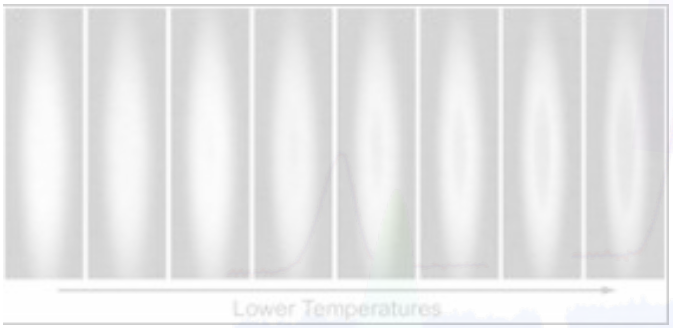
Hadzibabic, et al.

Zwierlein, et al.



Variety of experimental probes

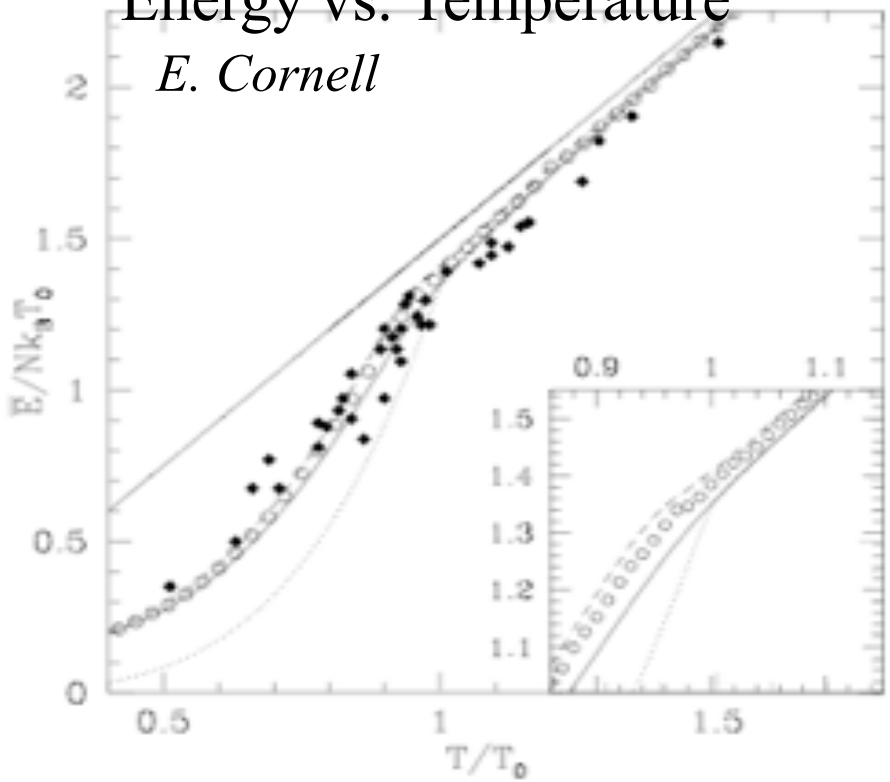
- Time-of-flight density imaging
  - *scattering length*
  - *temperature*
  - *noise → pairing correlations*
  - *quantum phase fluctuations*
  - *vortices*



- Thermodynamics

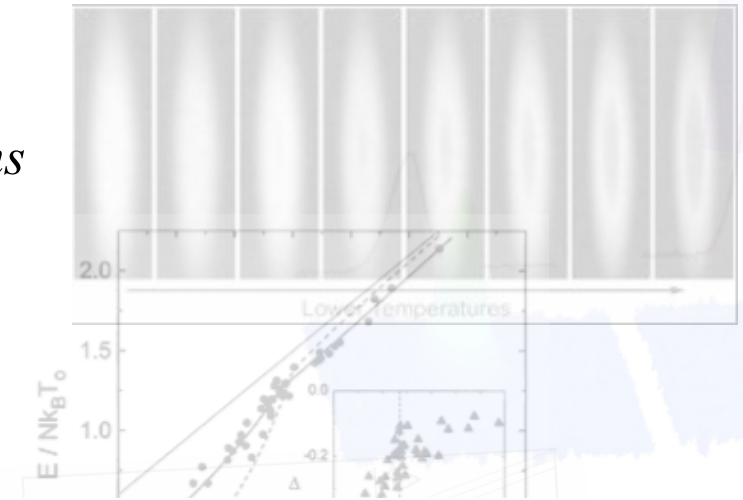
Energy vs. Temperature

E. Cornell



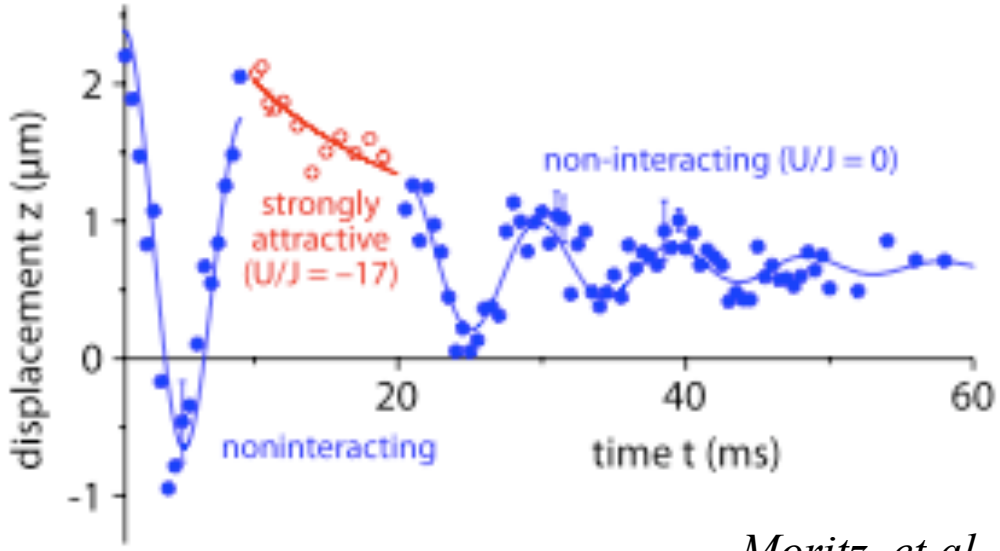
Variety of experimental probes

- Time-of-flight density imaging
  - *scattering length*
  - *temperature*
  - *noise → pairing correlations*
  - *quantum phase fluctuations*



- Thermodynamics

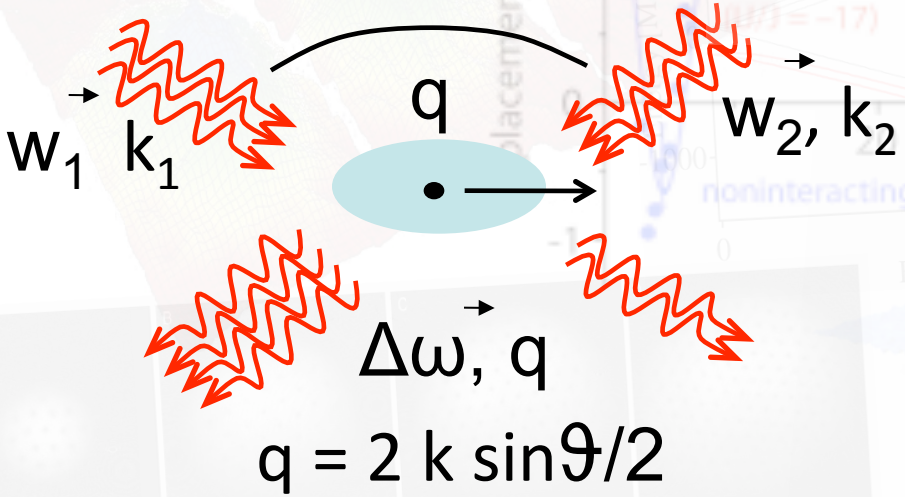
- Transport

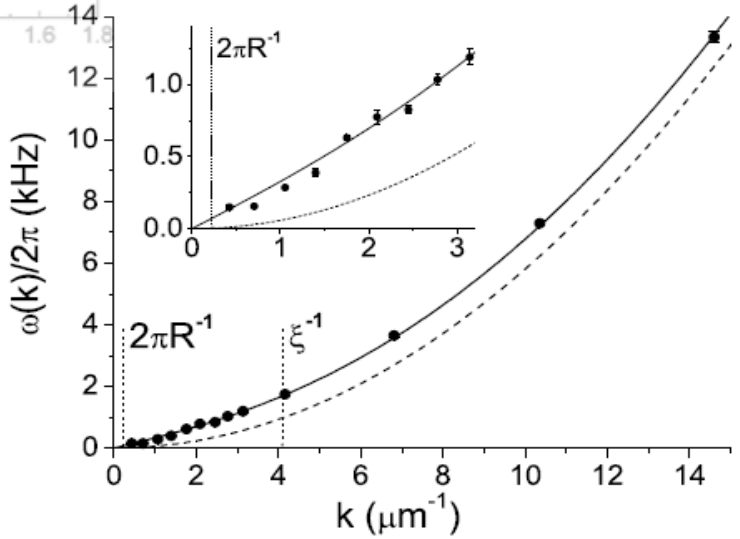


Moritz, et al.

Variety of experimental probes

- Time-of-flight density imaging
  - *scattering length*
  - *temperature*
  - *noise → pairing correlations*
  - *quantum phase fluctuations*
- Thermodynamics
- Transport
- Bragg spectroscopy: *collective excitations*





Steinhauer et al., *PRL* **88**, 2002

Variety of experimental probes

- Time-of-flight density imaging
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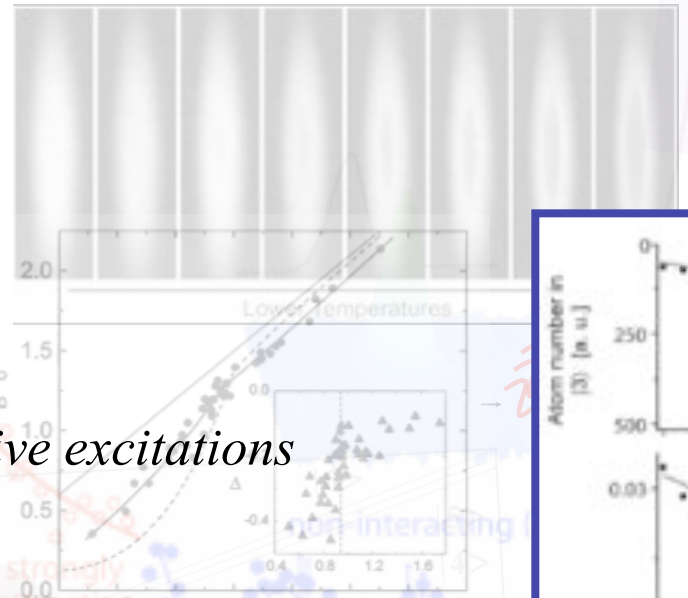
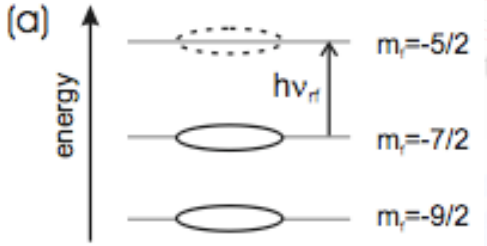
  - *temperature*
  - *noise → pairing correlations*
  - *quantum phase fluctuations*
- Thermodynamics
- Transport
- Bragg spectroscopy: *collective excitations*

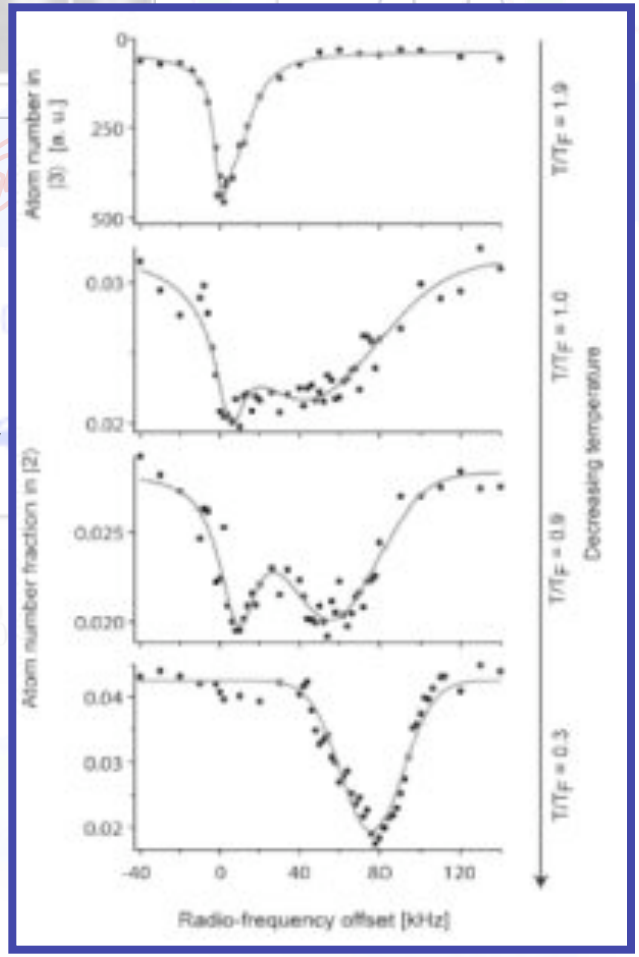


- RF spectroscopy: *single atom excitations*



Regal, Jin'03

Schunck, et al.



Variety of experimental probes

- Time-of-flight density imaging
  - *scattering length*
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  - *noise → pairing correlations*
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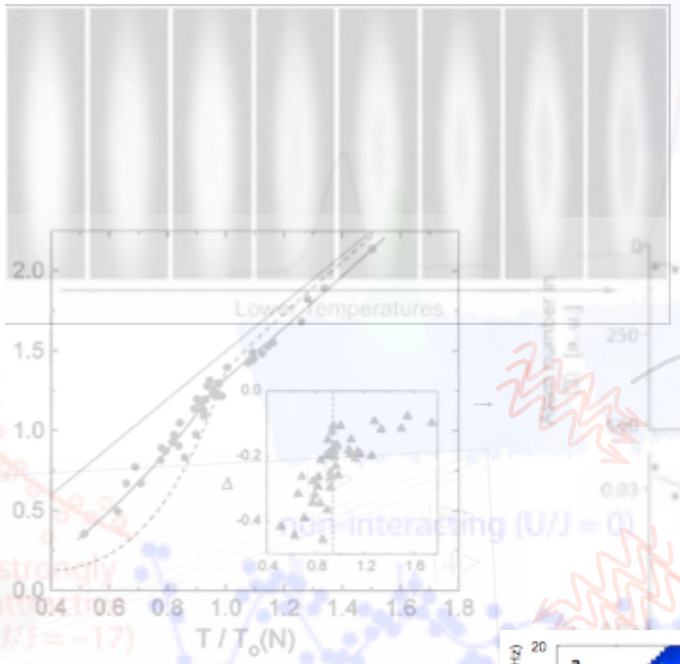


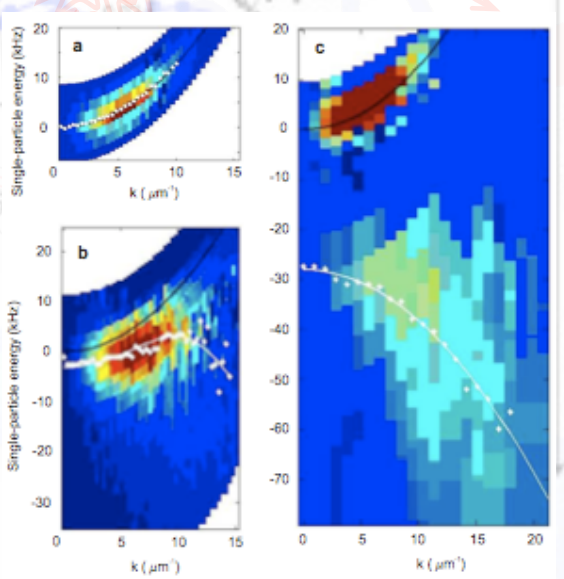
- Thermodynamics

- Transport

- Bragg spectroscopy: *collective excitations*

- RF spectroscopy: *single atom excitations*

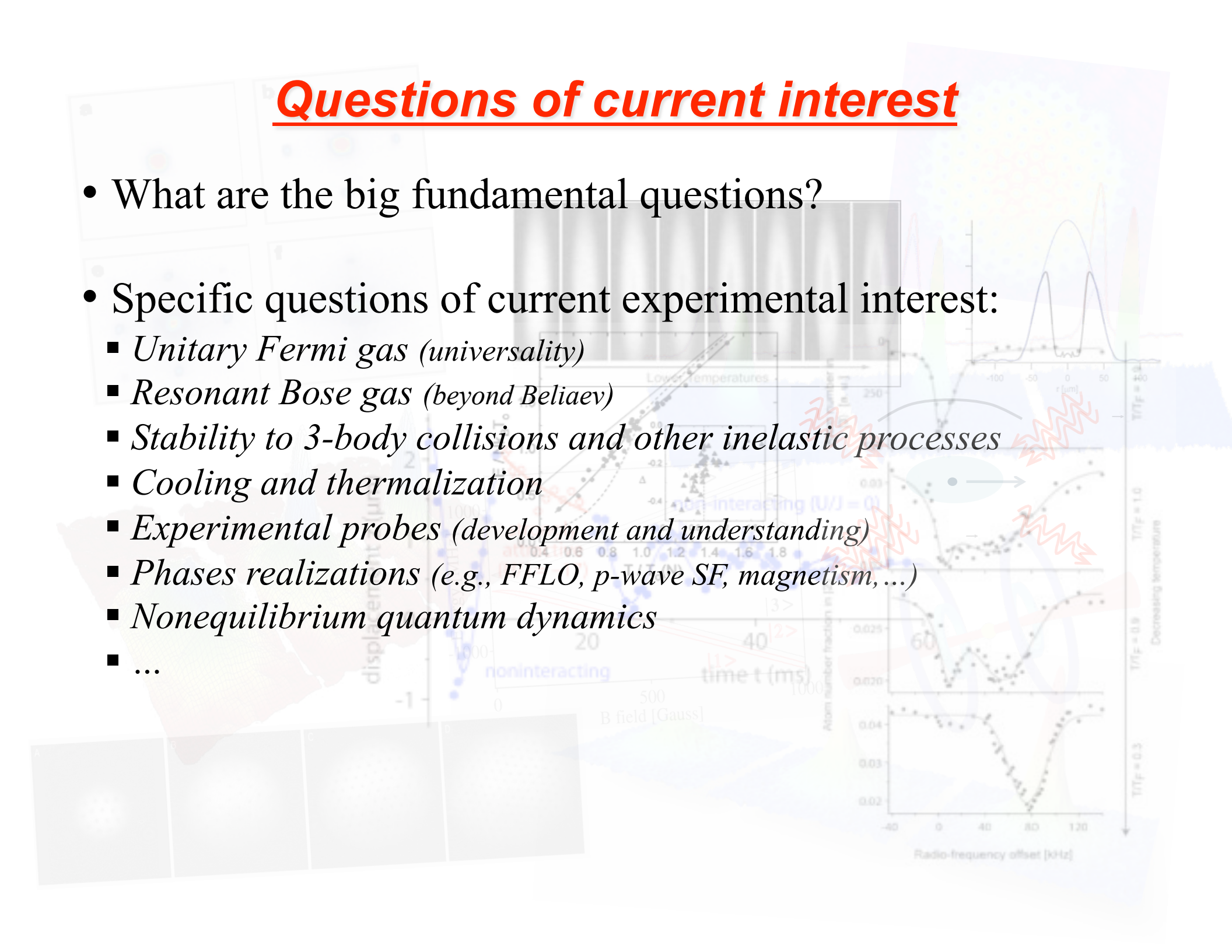
- k-resolved photoemission *Stewart, et al*



Questions of current interest

- What are the big fundamental questions?

- Specific questions of current experimental interest:
  - *Unitary Fermi gas (universality)*
  - *Resonant Bose gas (beyond Beliaev)*
  - *Stability to 3-body collisions and other inelastic processes*
  - *Cooling and thermalization*
  - *Experimental probes (development and understanding)*
  - *Phases realizations (e.g., FFLO, p-wave SF, magnetism, …)*
  - *Nonequilibrium quantum dynamics*
  - …



On the horizon

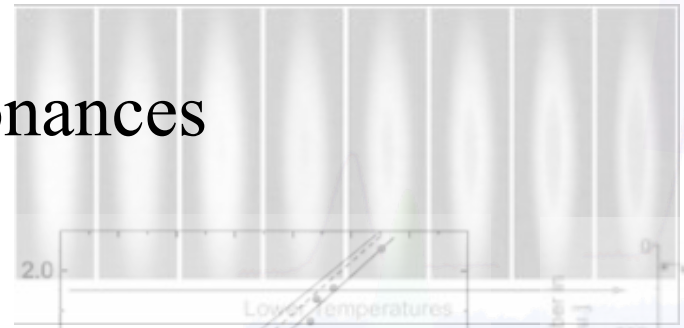
- p-wave superfluidity?
- degenerate molecular gases?
- local many-body lattice models
- multi-site many-body lattice models ⇒ exotic models?
- quantum Hall regime?
- …

…but not before technical hurdles are overcome:

- cooling
- off-site interactions
- stability to inelastic processes near Feshbach resonances
- much larger clouds
- flat traps
- better and wider range of experimental probes
- …

Lectures overview

- Lecture 2:
  2-body Feshbach resonances



- Lecture 3:
  s-wave paired superfluidity via FR: BCS-BEC crossover

- Lecture 4:
  imbalanced s-wave paired superfluidity via FR

- Lecture 5:
  p-wave paired superfluidity