Ultra-cold gases

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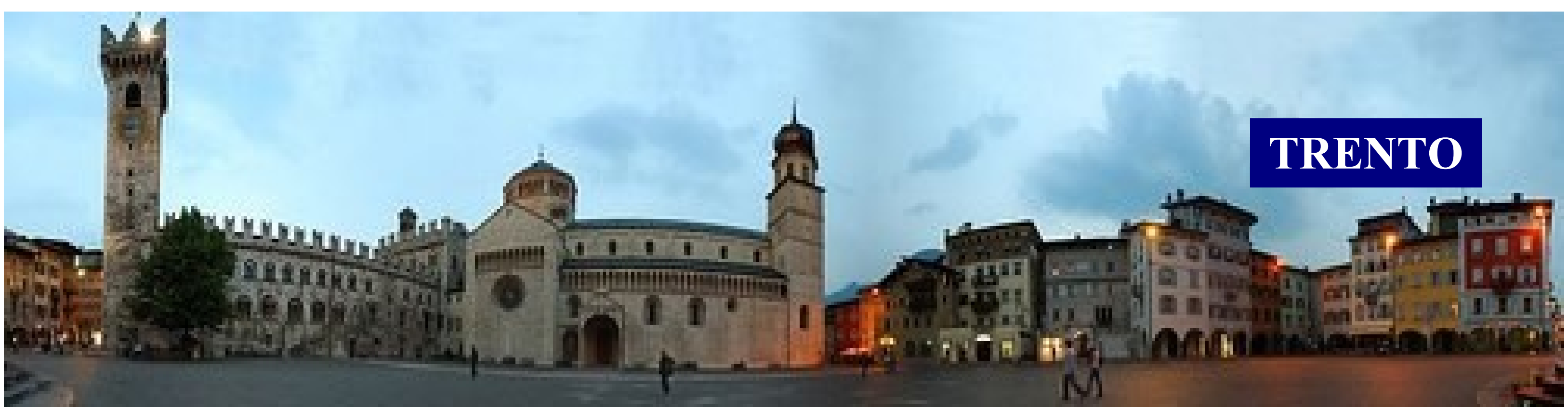


Lectures

L. 1)

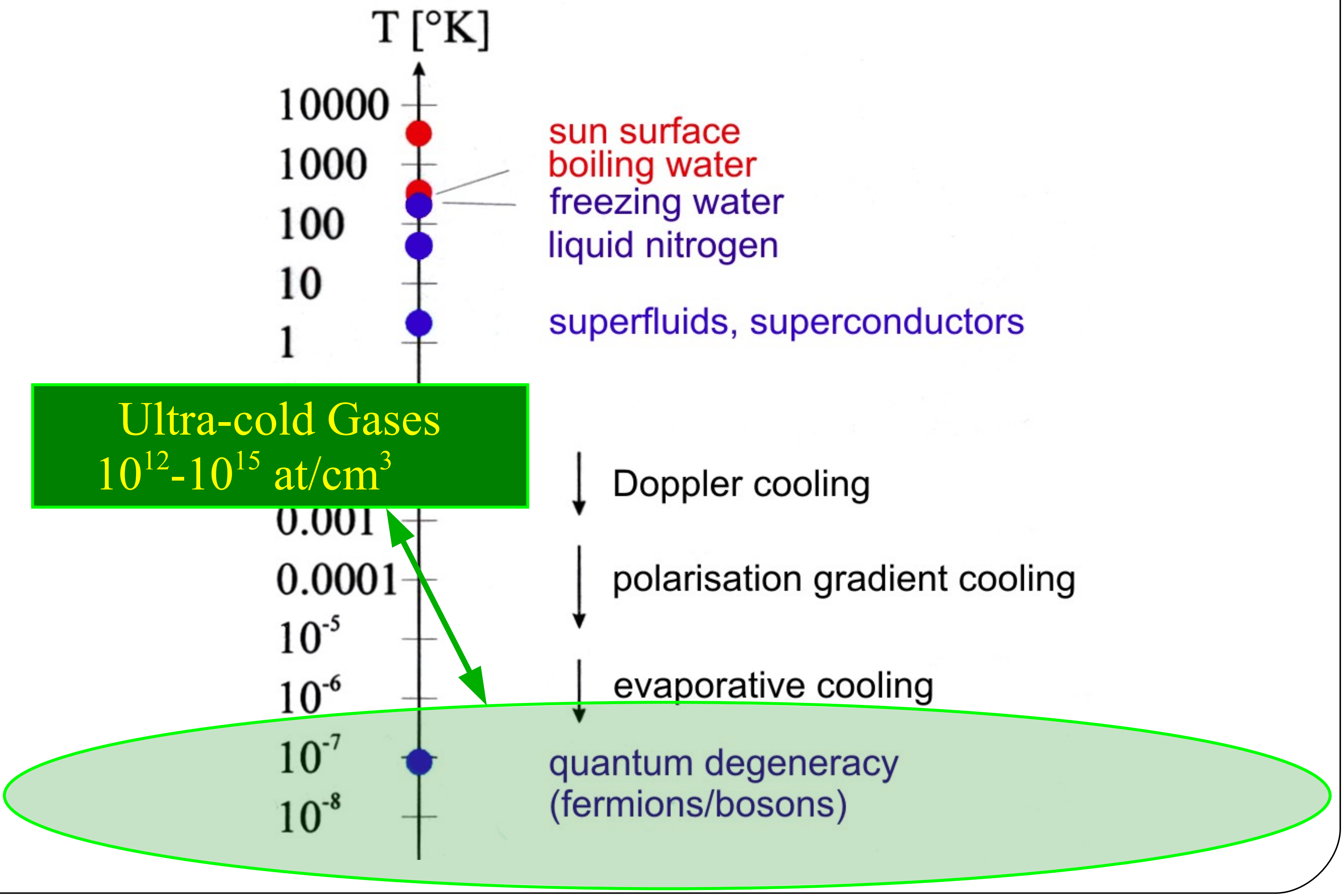
- Introduction to ultracold gases
- Bosonic atoms:
  - From weak to strong interacting gases
  - An application to precise measurement (Casimir forces)

L. 2)

- Feshbach resonance and strongly interacting Fermi gas/the Unitarity limit
- BCS-BEC crossover
- Polarized Fermi gases:
  - "a" polaron problem
  - new Fermi-Landau liquid

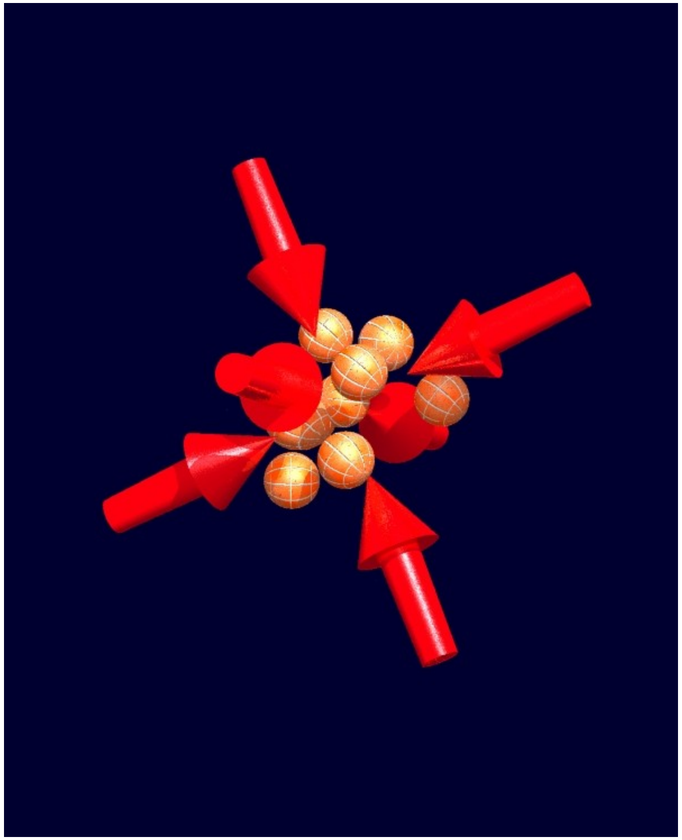
"Why should I care about a bunch of atoms which do what they are expected to do?"

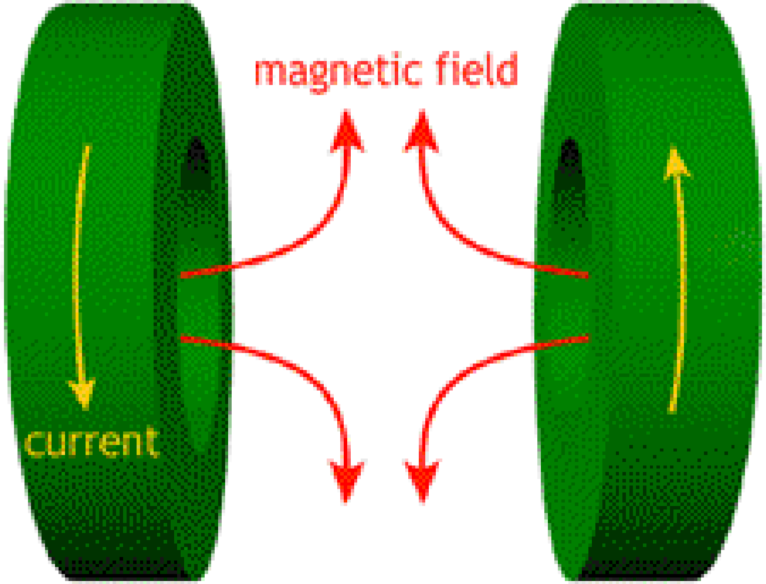
Temperature scale



Cooling & Trapping neutral cold gases

1. Laser light pressure (laser cooling)
2. Electric and/or magnetic confinement: harmonic traps
3. Evaporative cooling   (a.k.a. cup of coffee cooling)





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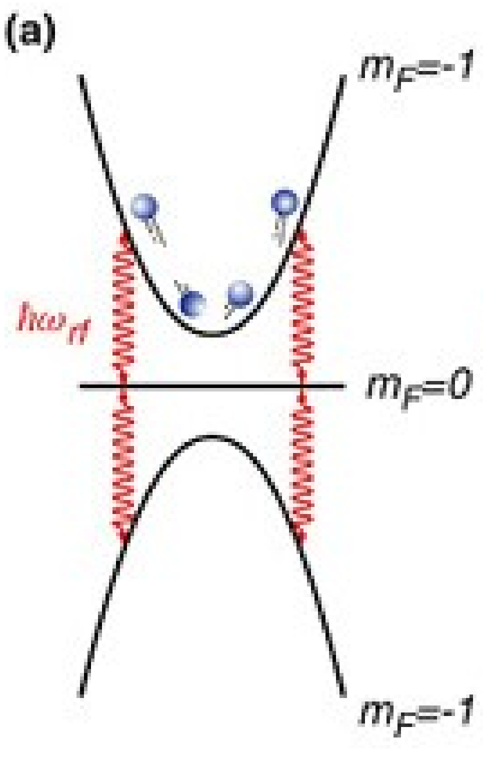

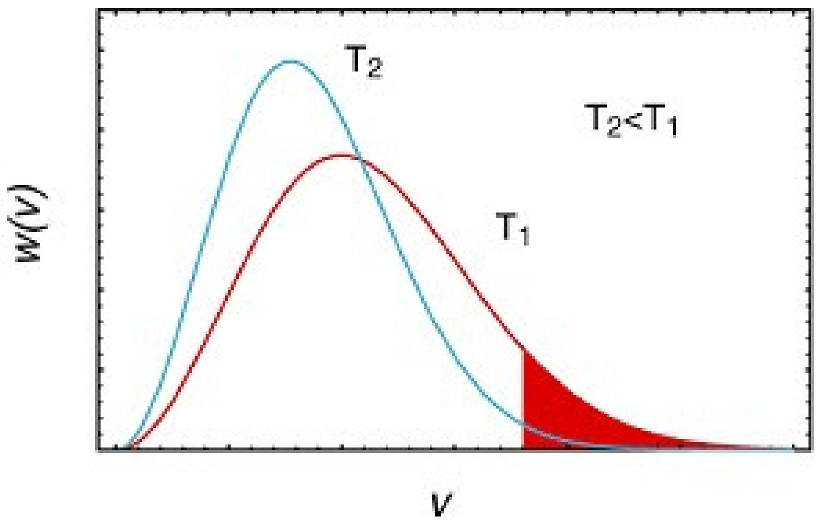

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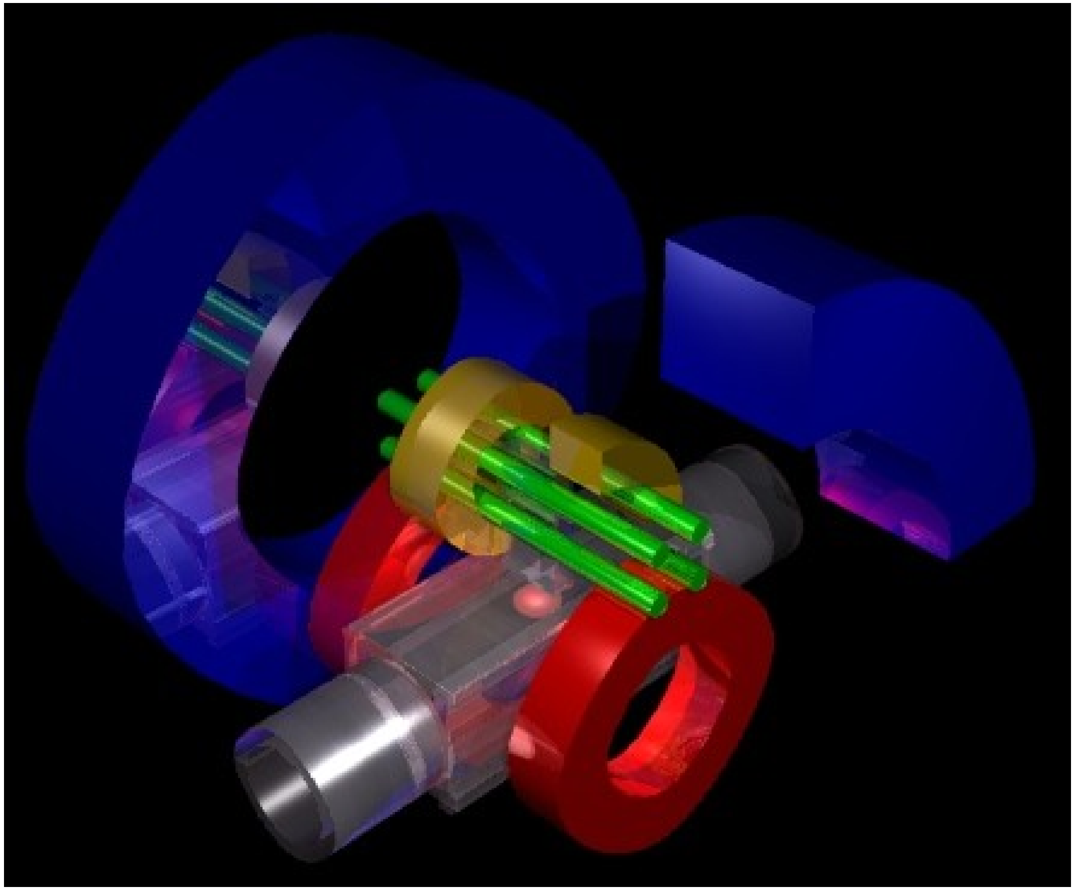

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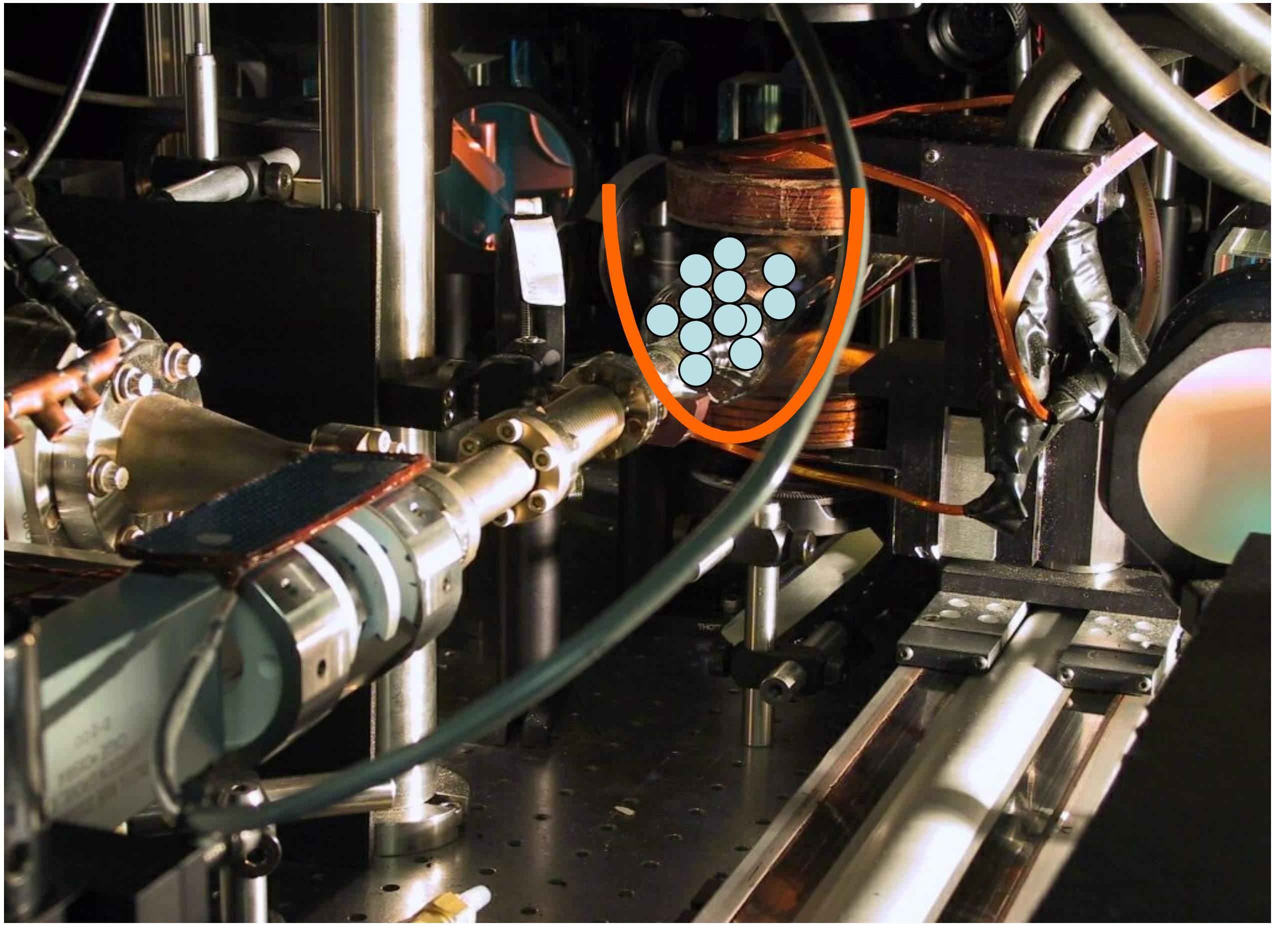
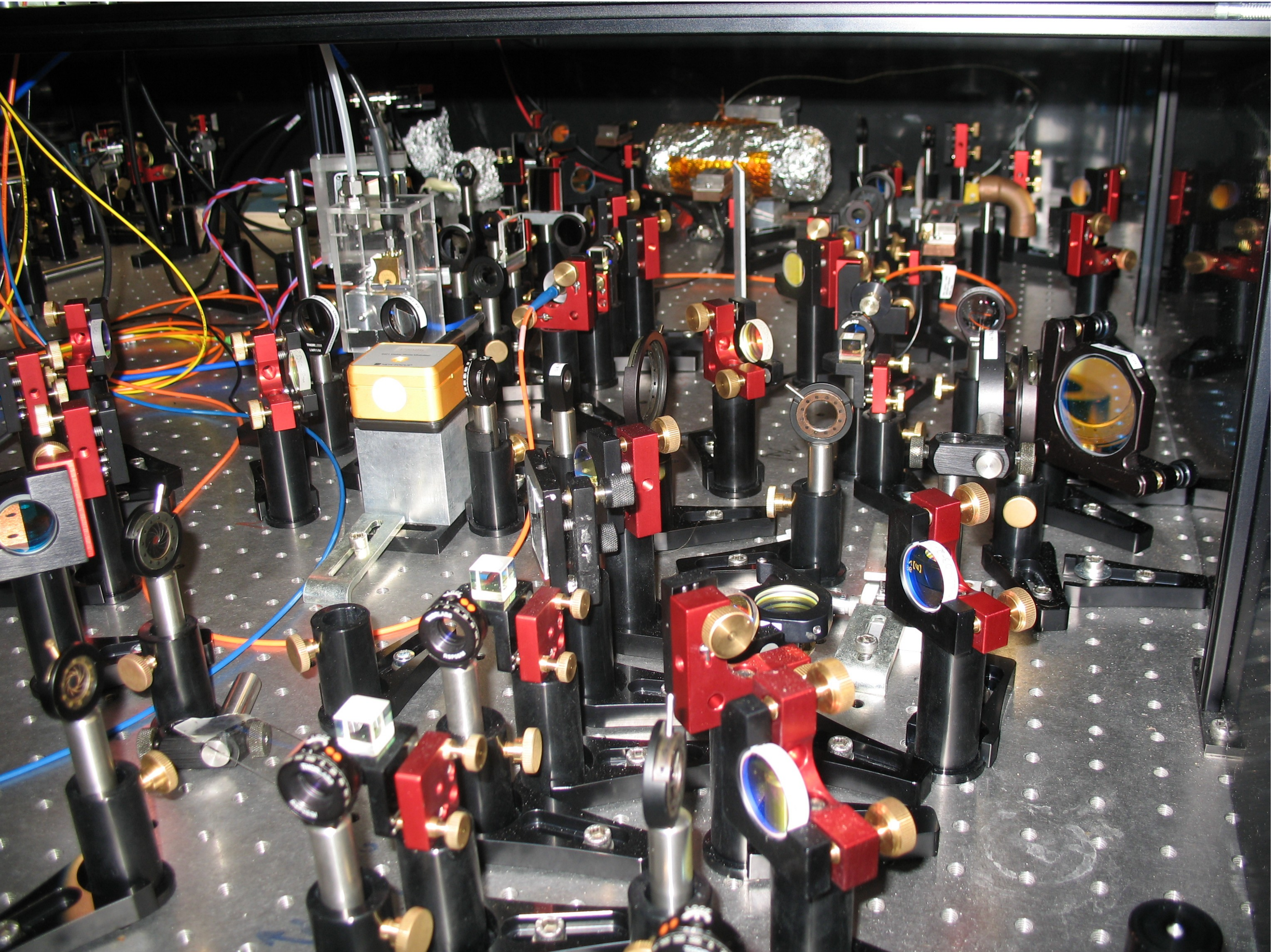
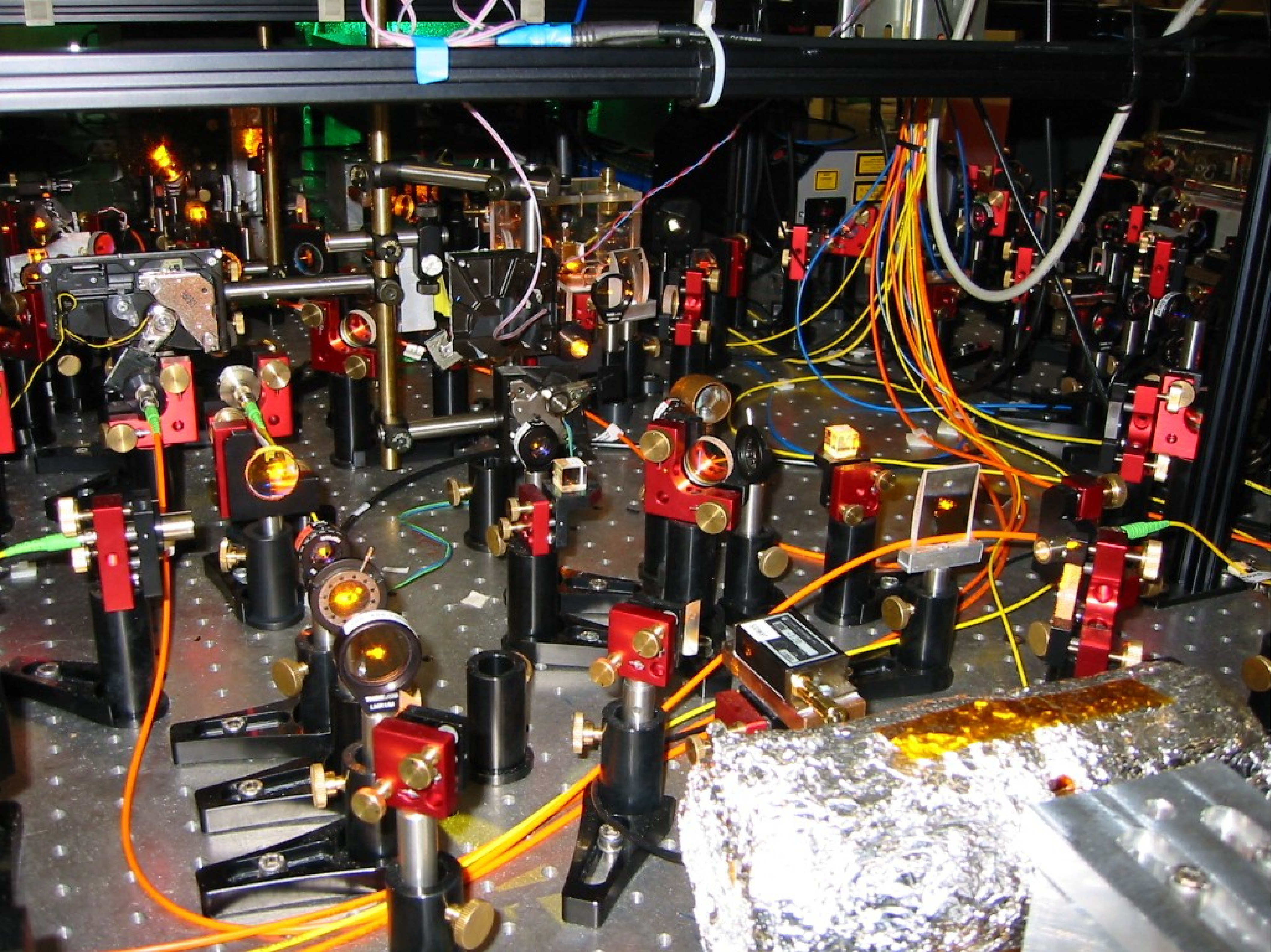
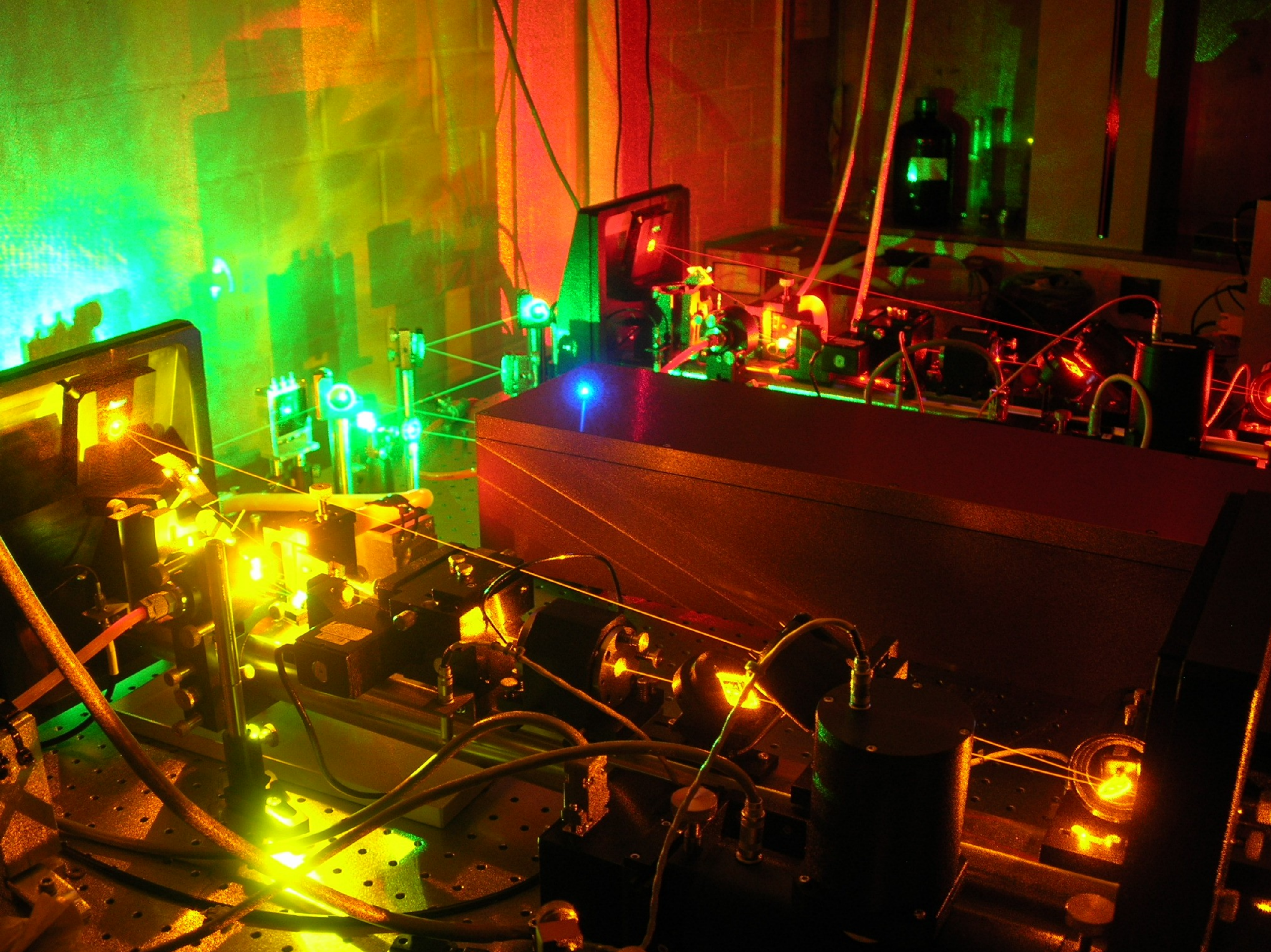
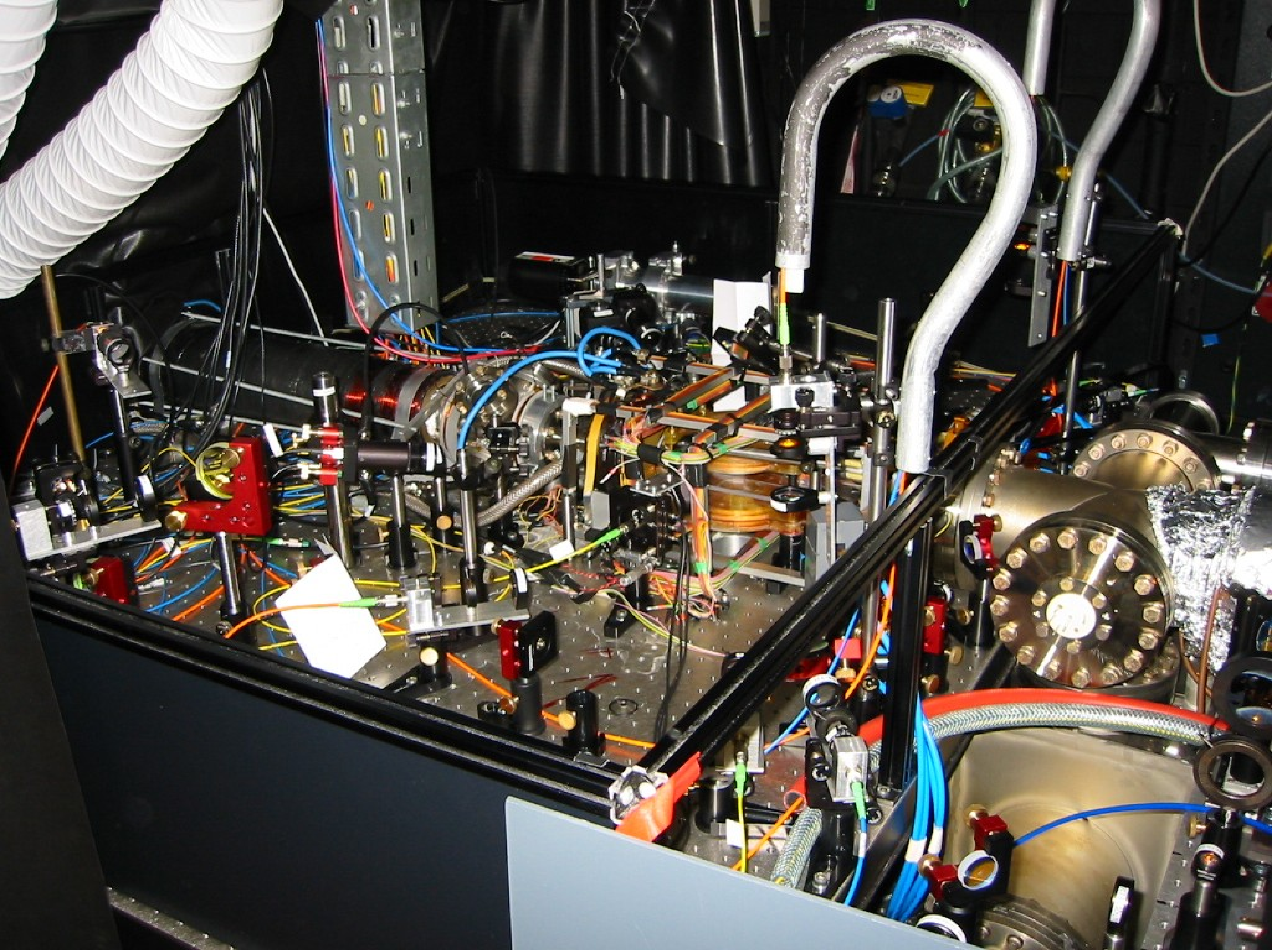


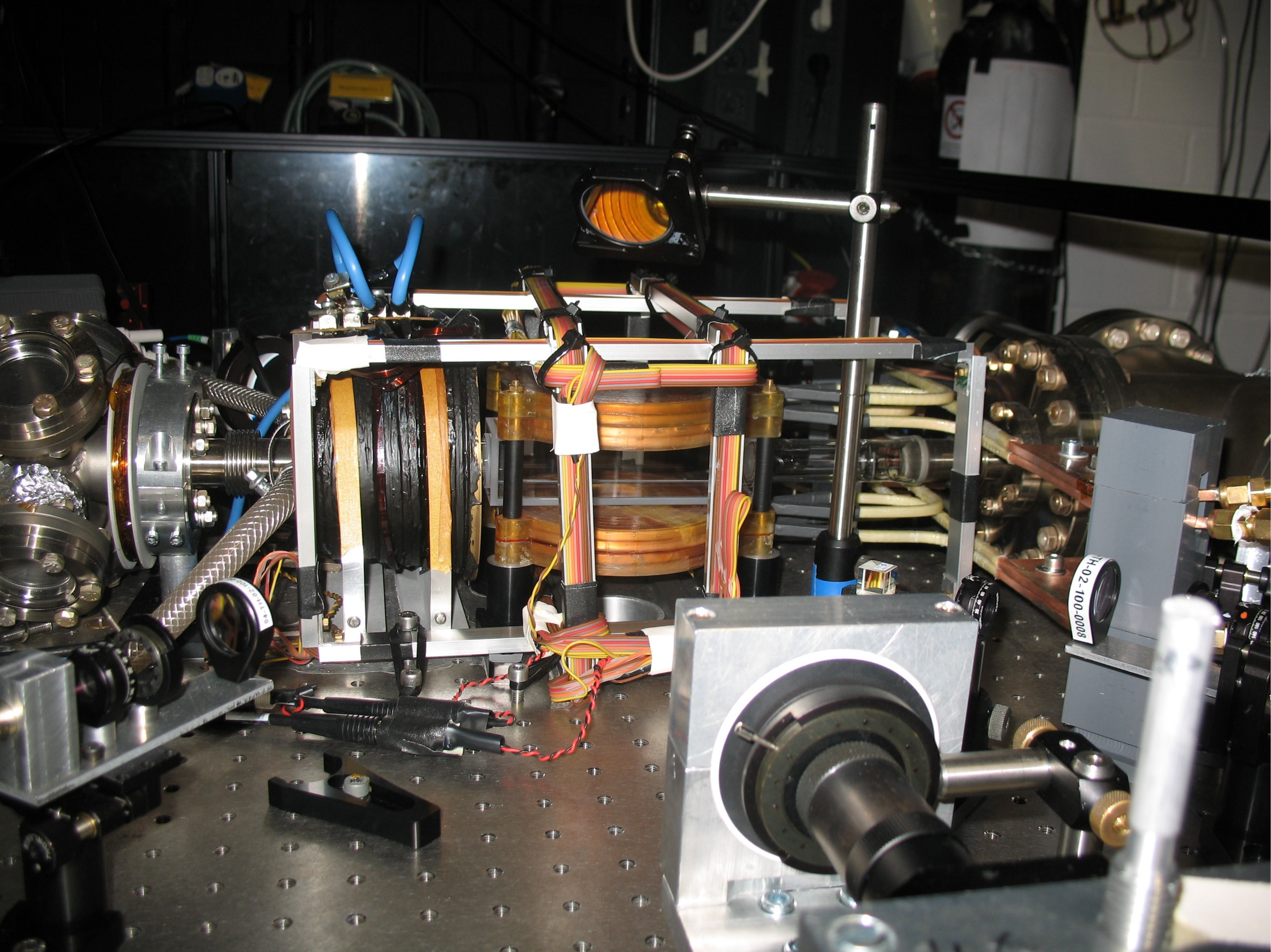
Experimental setup Bose-Einstein condensation at JILA







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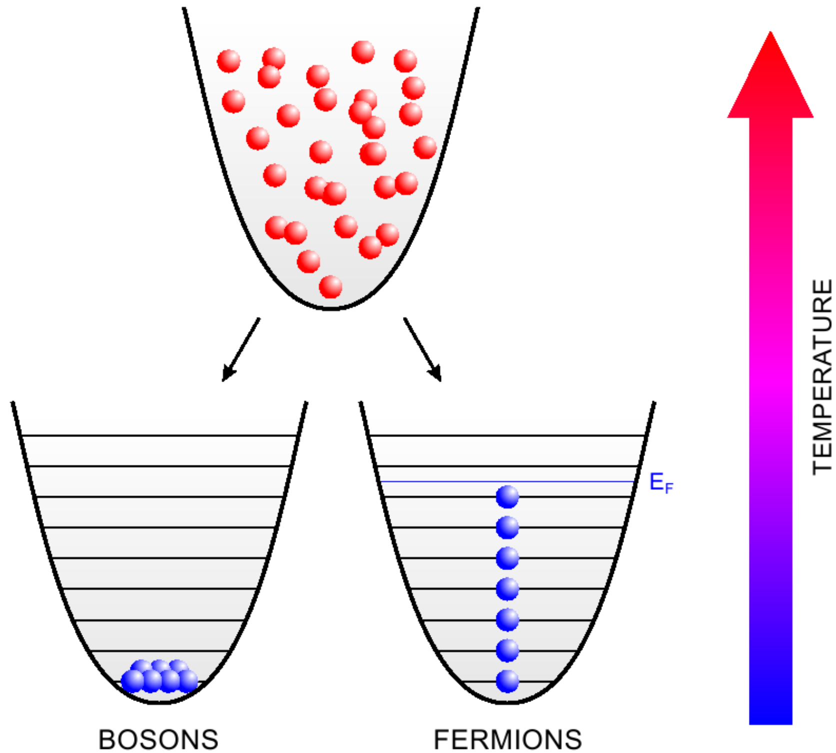
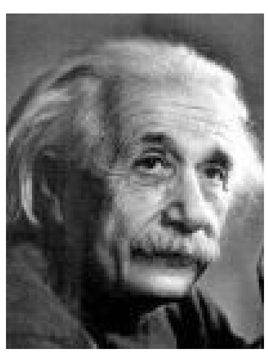
Statistica Quantistica: bosoni e fermioni

“Ai bosoni piace stare insieme, nello stesso stato”

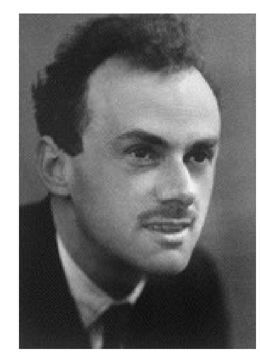


“Ai fermioni non piace stare insieme, nello stesso stato”

- Bose-Einstein statistics (1924)



- Fermi-Dirac statistics (1926)

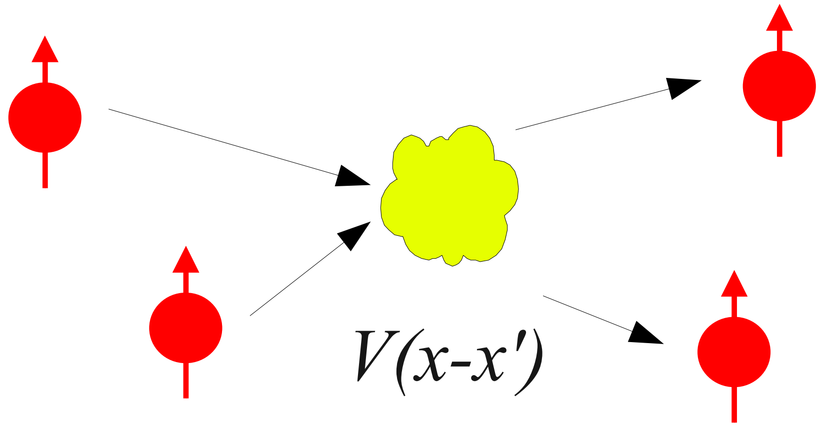


Dilute gases: 1995, JILA, MIT

Dilute gases: 1999, JILA

Interaction: s-wave scattering length

At low density and temperature the 2- body interaction is conveniently described by an
effective contact potential
which reproduces the low-energy behaviour of the microscopic potential



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

s-wave scattering length

i) *a>0* : positive scattering & a Bound State (D=2,3)

ii) *a<0* : negative scattering & NO Bound State (D=2,3)

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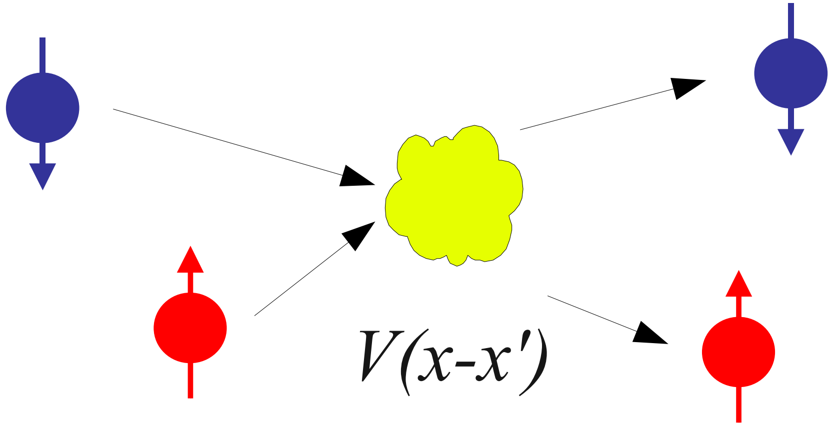

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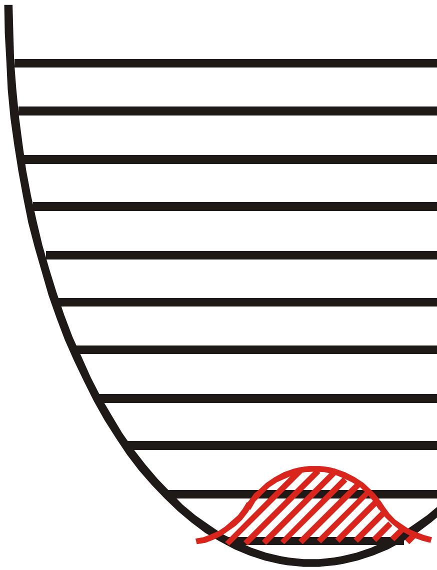
s-wave scattering length

i) *a>0* : positive scattering & a Bound State (D=2,3)

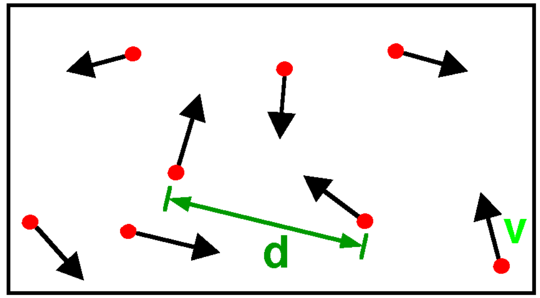
ii) *a<0* : negative scattering & NO Bound State (D=2,3)

Due to Pauli principle only fermions in different internal states can – at this level- interact

Ultra-Cold Bosons: from BEC to strongly interacting systems



What is Bose-Einstein condensation (BEC)?

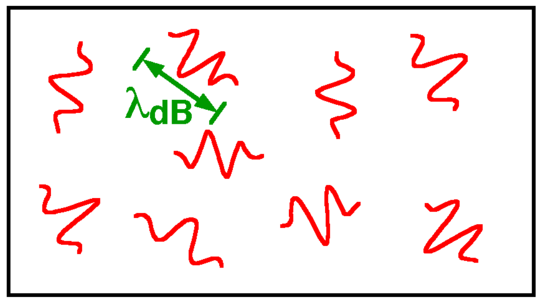


High Temperature T:

thermal velocity v

density d^{-3}

"Billiard balls"

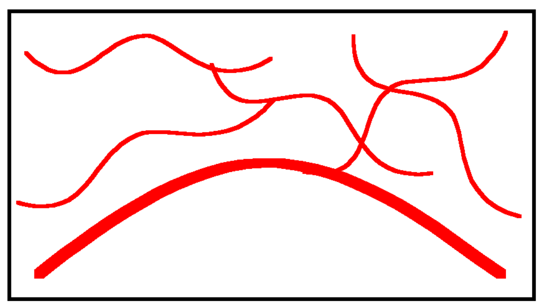


Low Temperature T:

De Broglie wavelength

$\lambda_{dB} = h/mv \propto T^{-1/2}$

"Wave packets"

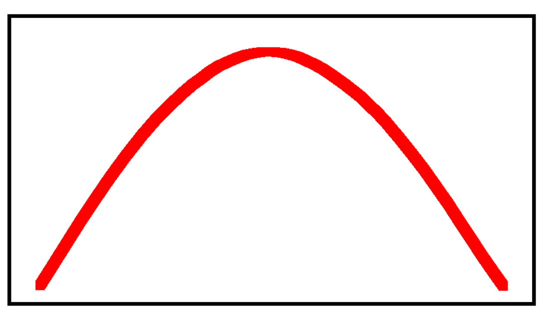


$T = T_{crit}$:

Bose-Einstein Condensation

$\lambda_{dB} \approx d$

"Matter wave overlap"



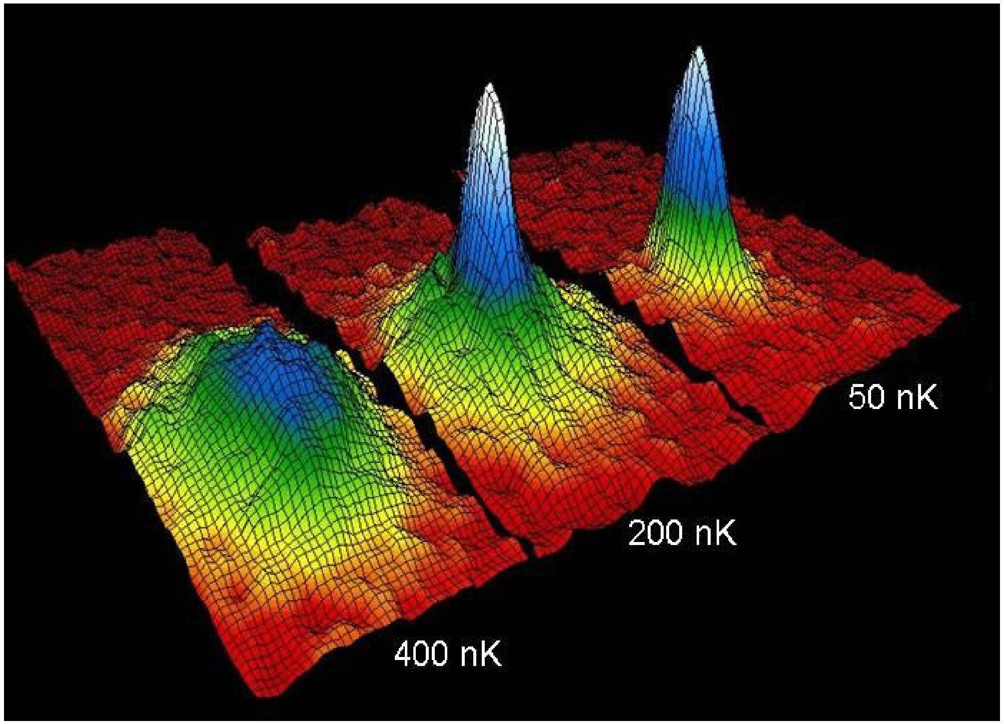
T=0:

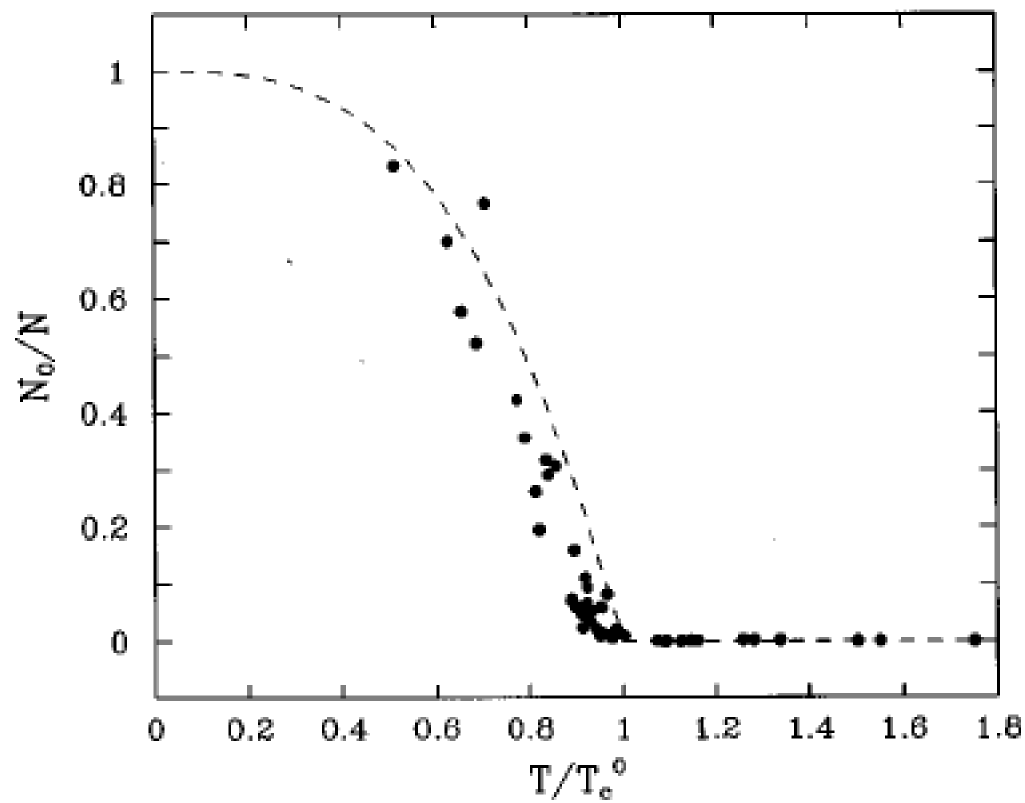
Pure Bose condensate

"Giant matter wave"

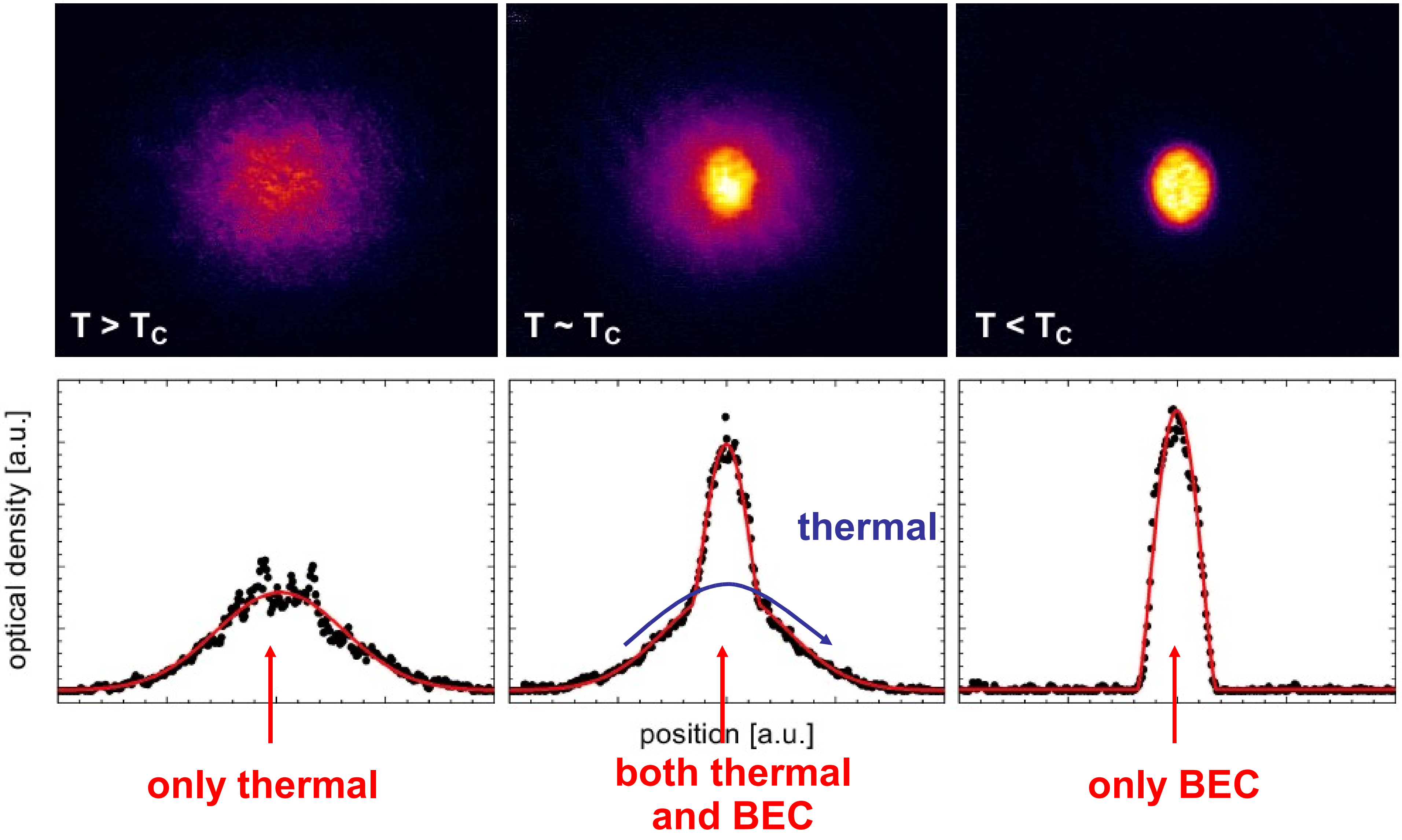
New state of matter…

One of the first BEC images (JILA 1995)





Below a certain temperature a macroscopic atomic fraction occupies the lowest energy state



Temperature measured thruogh thermal component tails

Physics Nobel Laureates

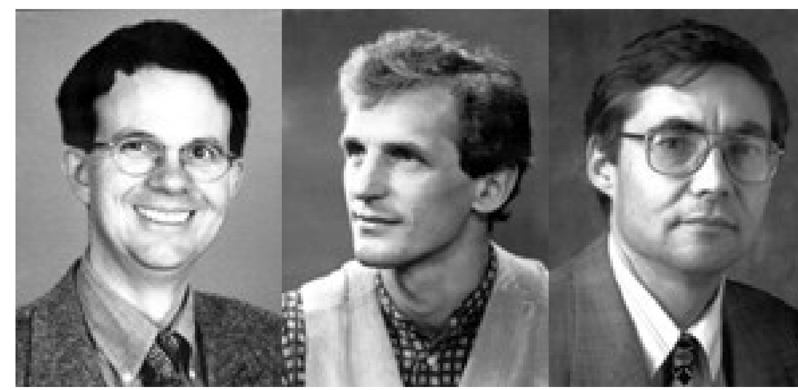
1997

"for development of methods to cool and trap atoms with laser light"

Steven Chu | **Claude Cohen-Tannoudji** | **William D. Phillips**

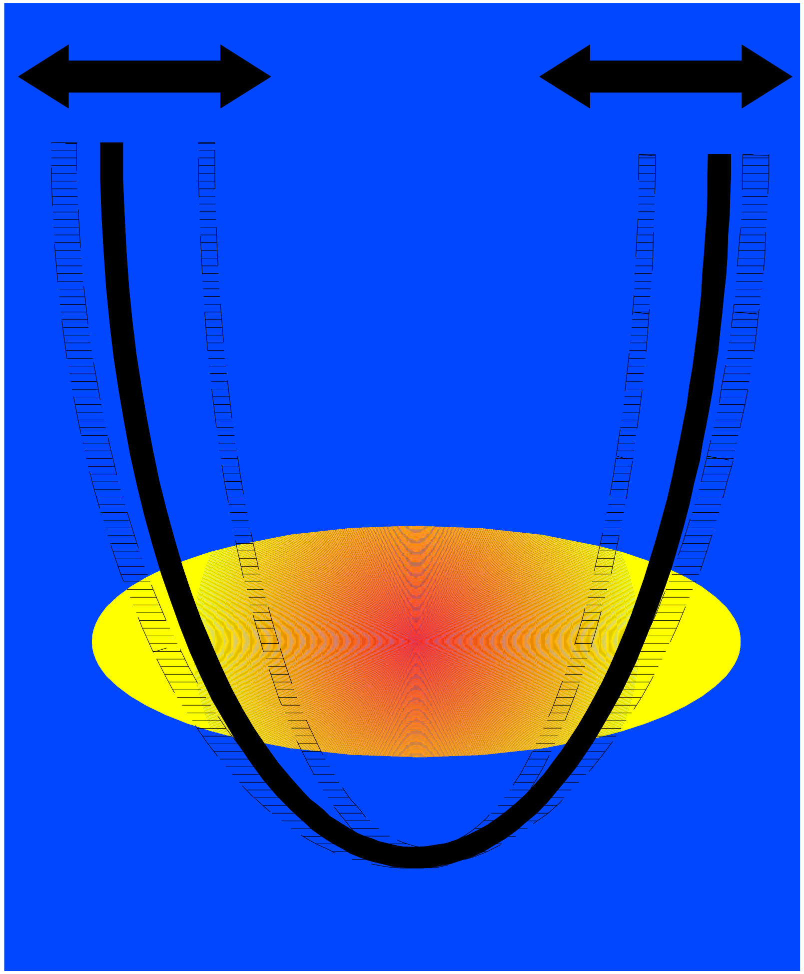
2001

"for the achievement of Bose-Einstein condensation in dilute gases of alkali atoms, and for early fundamental studies of the properties of the condensates"



Eric A. Cornell | **Wolfgang Ketterle** | **Carl E. Wieman**

Collective and Josephson like oscillations/Interference

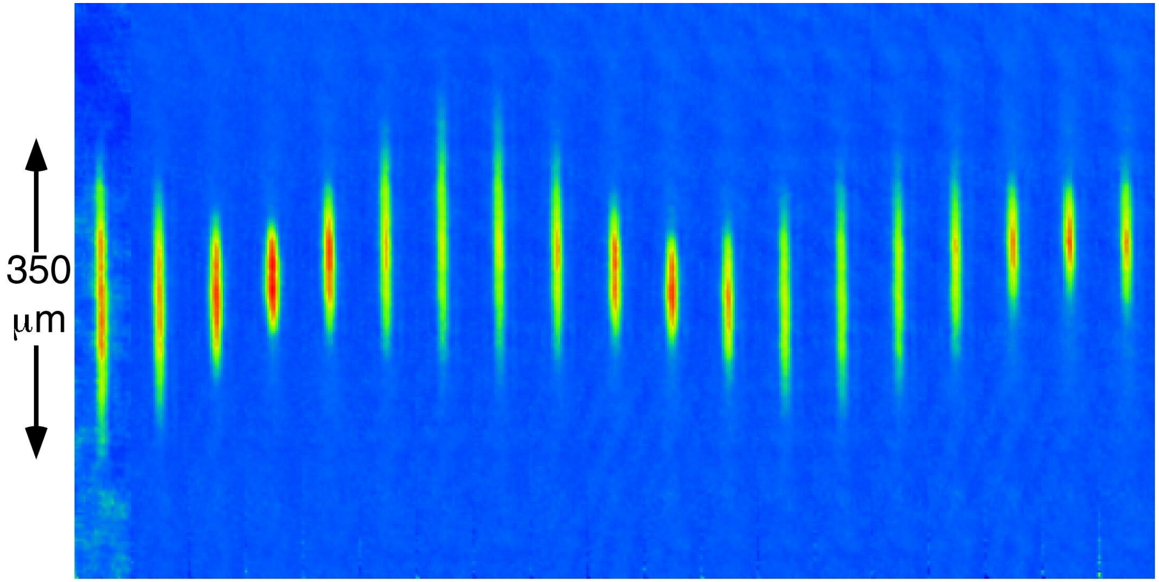


Collective Oscillations:

exp. (MIT '97): $\omega=1.57\omega_z$

teory (HD): $\omega=1.58\omega_z$

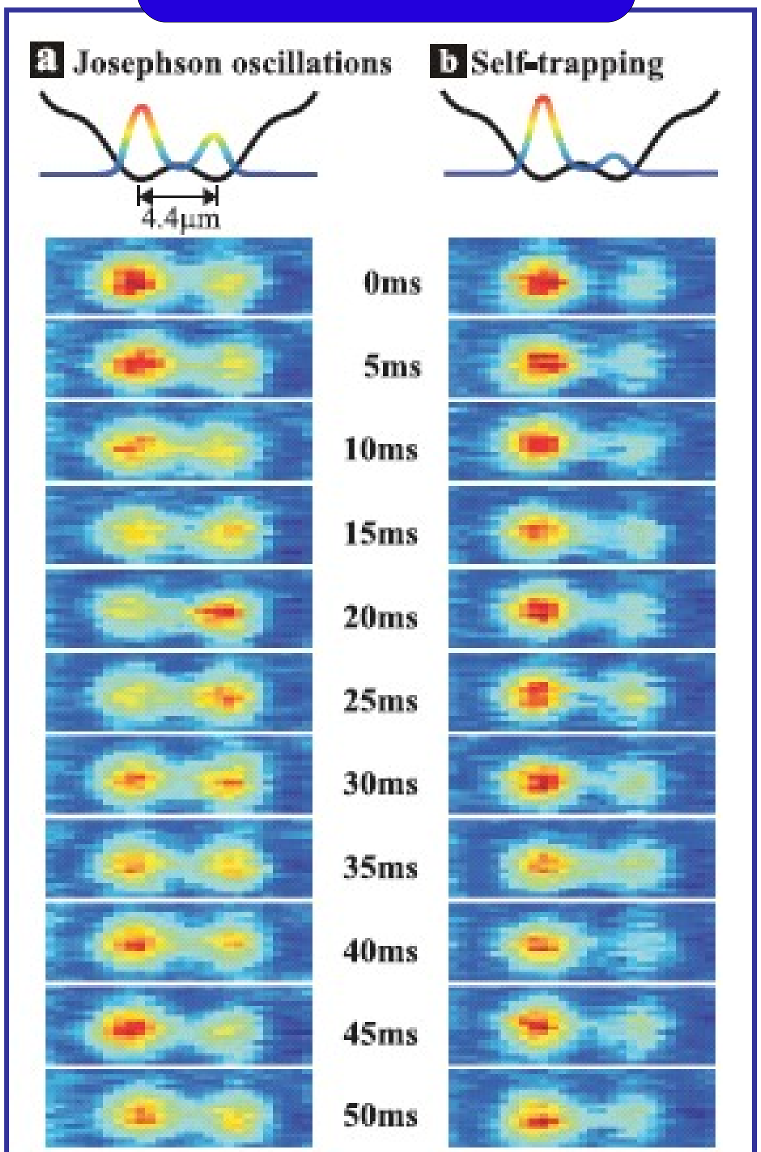
ideal gas: $\omega=2\ \omega_z$

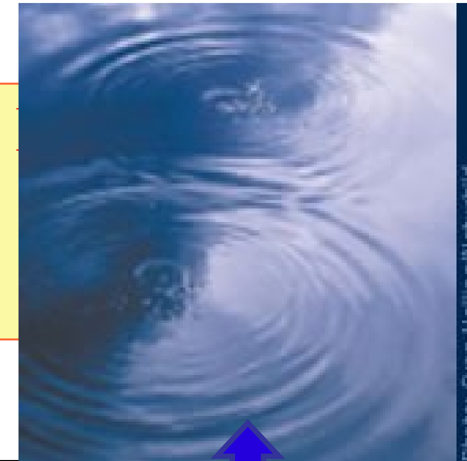


5 milliseconds per frame

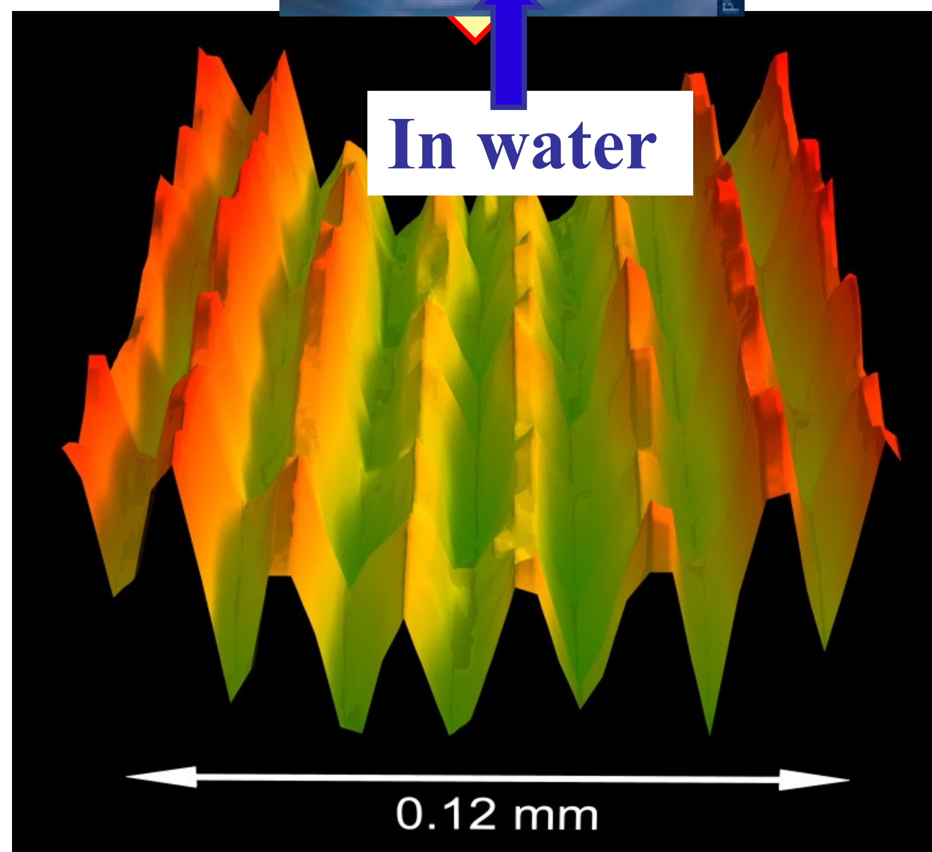
Collective and Josephson like oscillations/Interference

Double well (Heidelberg 2004)





In water



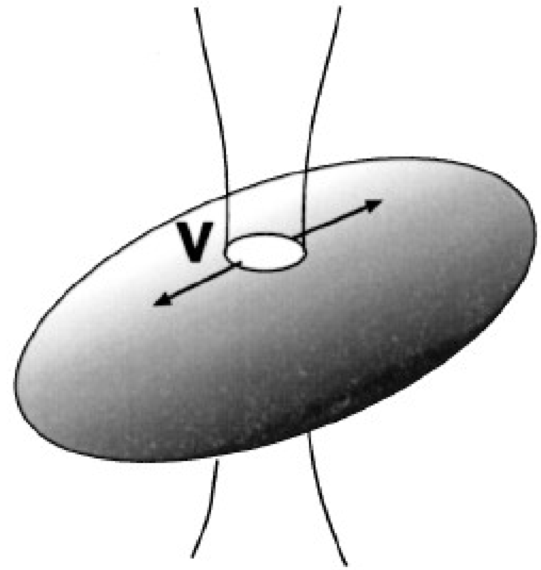
Gross-Pitaevskii equation

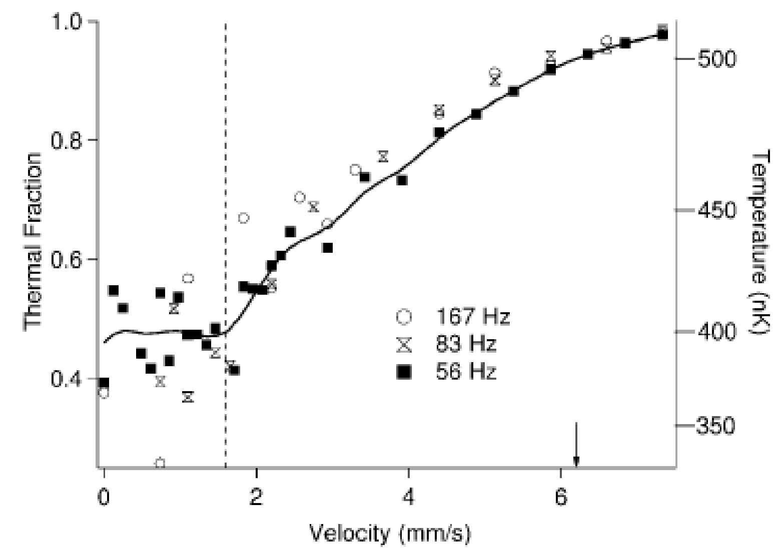
$$i\hbar\partial_t\Psi(\mathbf{x}) = \left(-\frac{\hbar^2}{2m}\Delta + V(\mathbf{x}) + \frac{4\pi\hbar a}{m}|\Psi(\mathbf{x})|^2\right)\Psi(\mathbf{x})$$

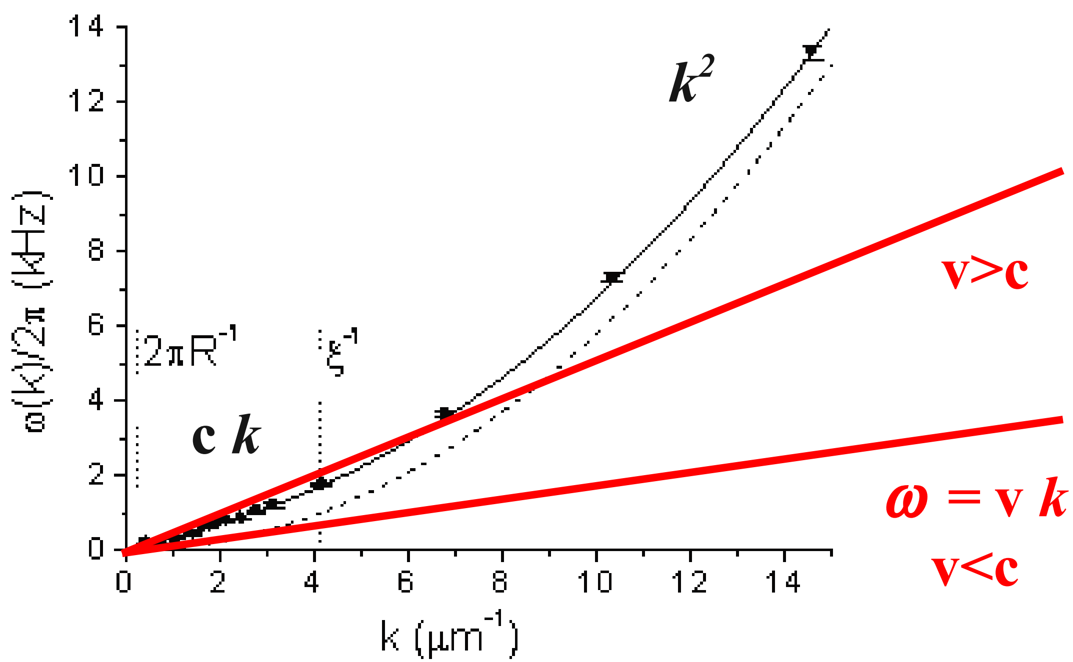
$$\mu\Psi(\mathbf{x}) = \left(-\frac{\hbar^2}{2m}\Delta + V(\mathbf{x}) + \frac{4\pi\hbar a}{m}|\Psi(\mathbf{x})|^2\right)\Psi(\mathbf{x})$$

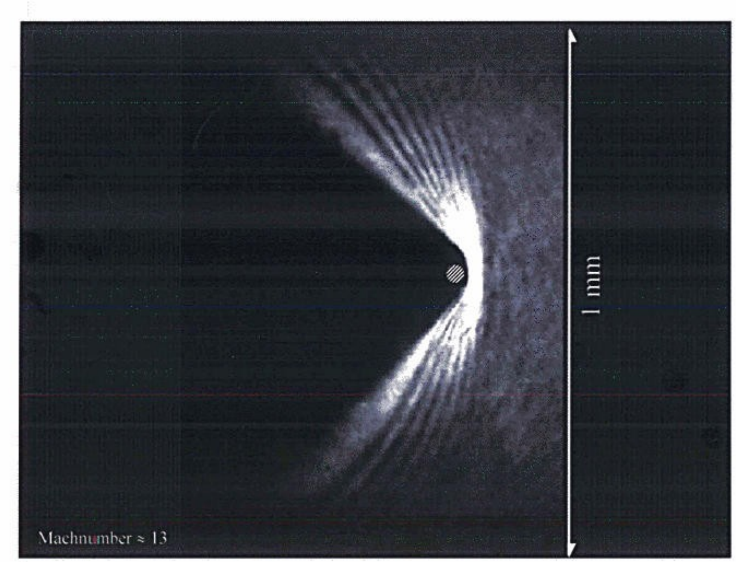
- μ: Chemical potential
- $-\frac{\hbar^2}{2m}\Delta$: Kin. Energy
- $V(\mathbf{x})$: Ext. Potential energy
- $\frac{4\pi\hbar a}{m}$: 2-body interaction
- $\Psi(\mathbf{x})$: Order Parameter $\Psi = \sqrt{n}e^{iS}$

Superfliudity of a BEC





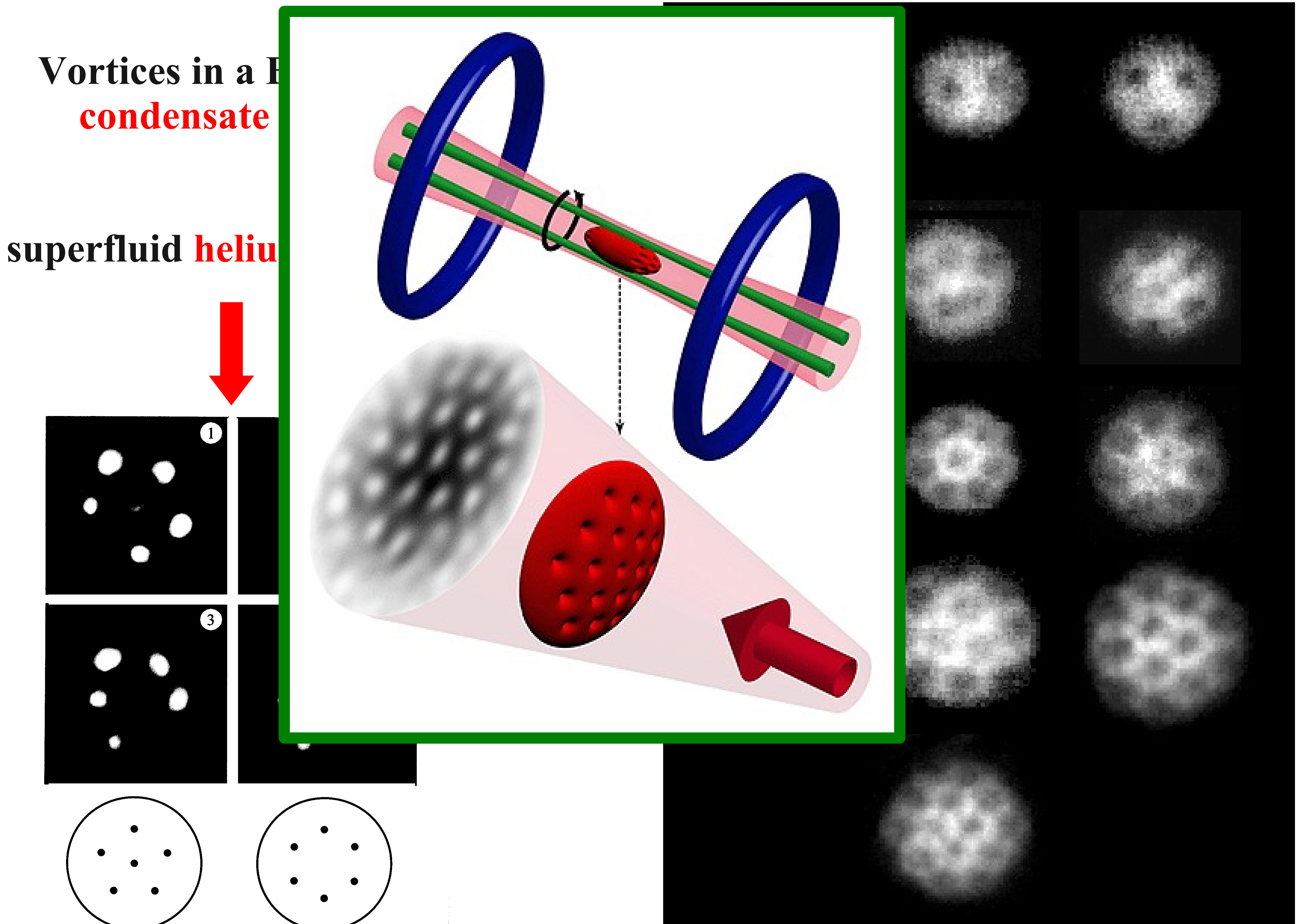




Cherenkov phonons

Vortices in a BEC

In rotating condansate vortices are produced



Vortices in a BEC

In rotating condansate vortices are produced "quantized"

In a superfluid the motion is irrotational (free vortex)

$$\Psi = \sqrt{n} e^{iS}$$

$$v_\theta = \frac{\hbar}{m} \nabla S = \frac{C}{r}$$

Where C is an integer multiple, n, of a minimum value:

$$C = \frac{\hbar}{m} n$$

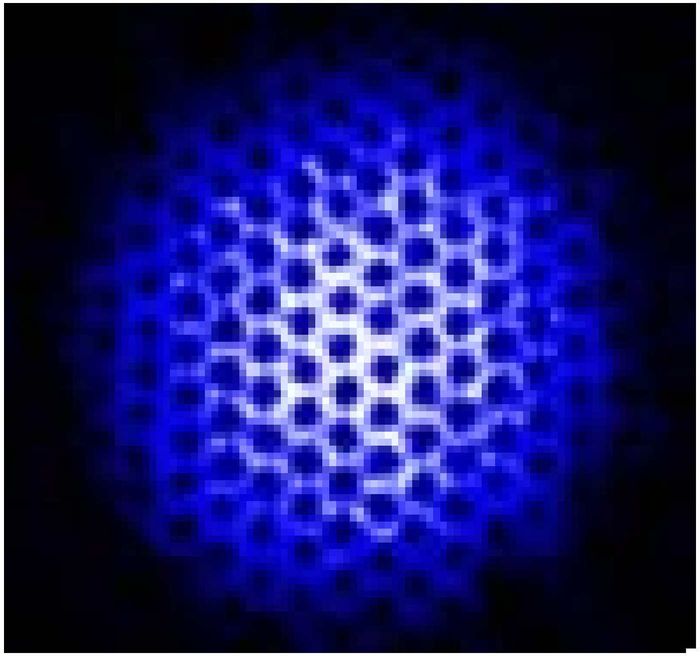
quantum of circulation

Indeed by definition one must have:

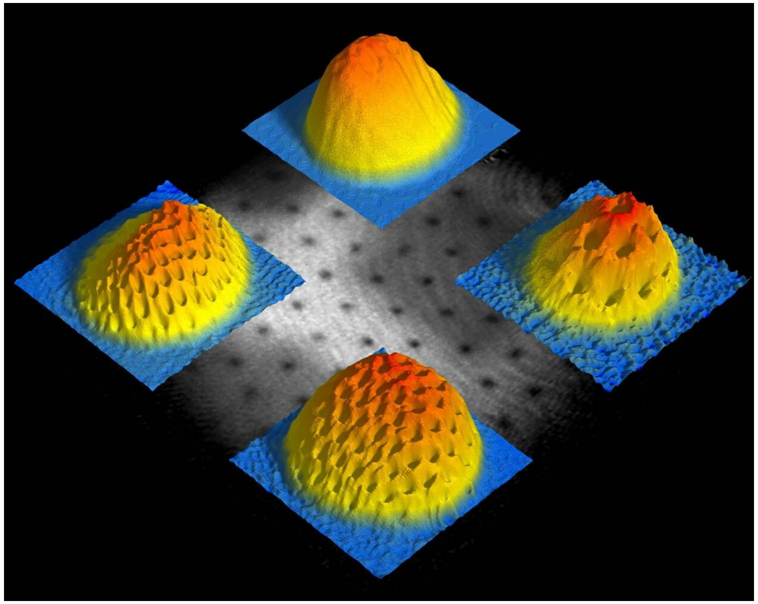
$$\oint \mathbf{v} \cdot d\mathbf{l} = \frac{\hbar}{m} 2\pi n$$

Vortices in a BEC

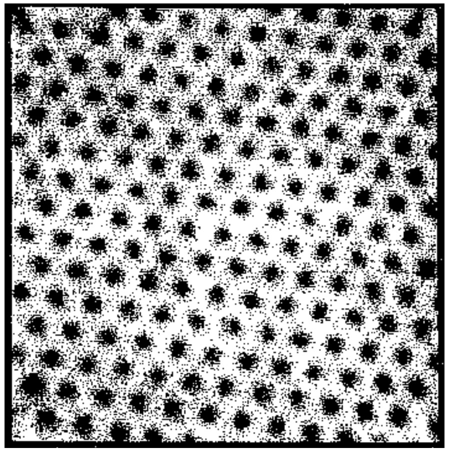
In rotating condansate vortices are produced "quantized" and cristallize (Vortex Lattice)



[JILA, 2002]



[MIT, 2002]



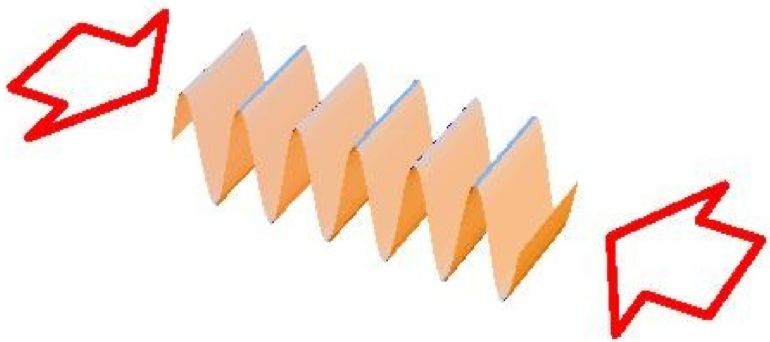
Vortices in $NbSe_2$ defined by scanning tunneling microscopy (STM).

Optical Lattices

Periodic potential via the dipole force

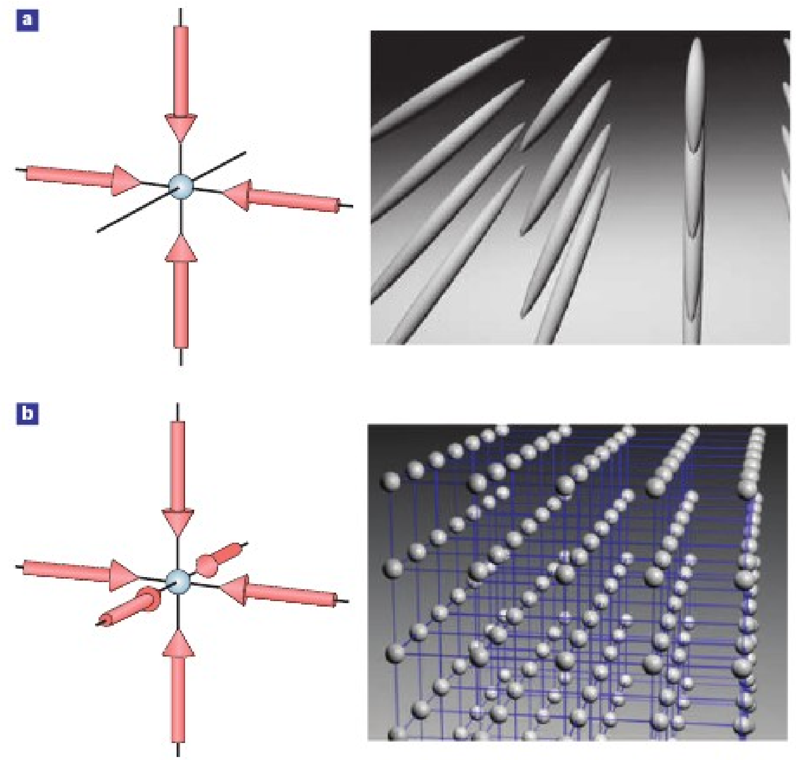
$$\mathbf{F}(\mathbf{x}) = -(\alpha(\omega)|\mathbf{E}(\mathbf{x})|^2/2)$$

Laser standing wave



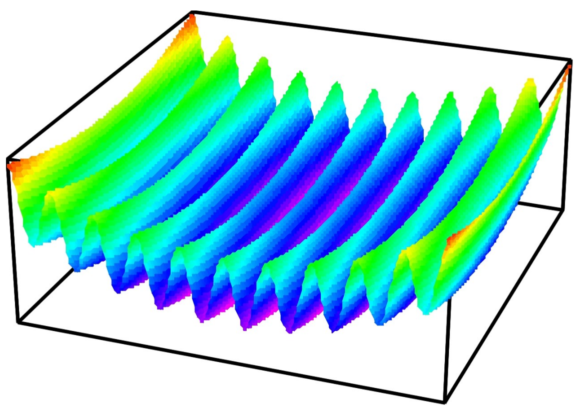
1D (optical) lattice

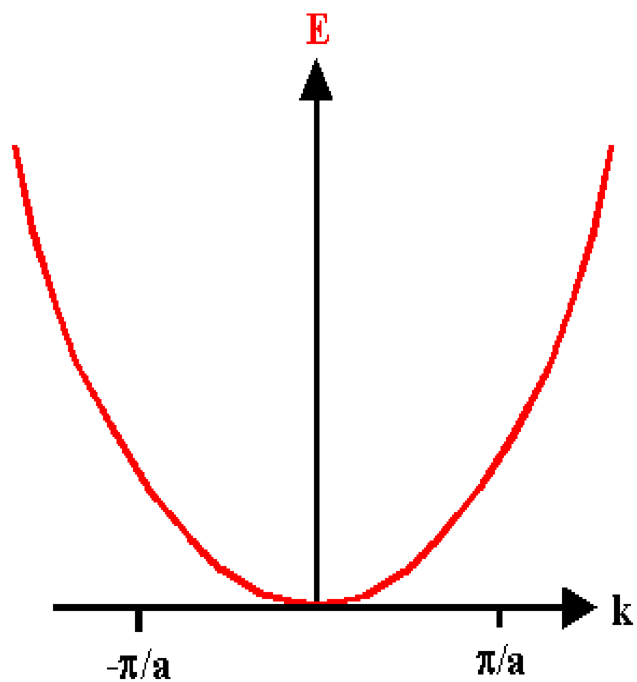
$$V(\mathbf{x}) = sE_r \sin^2(kx)$$

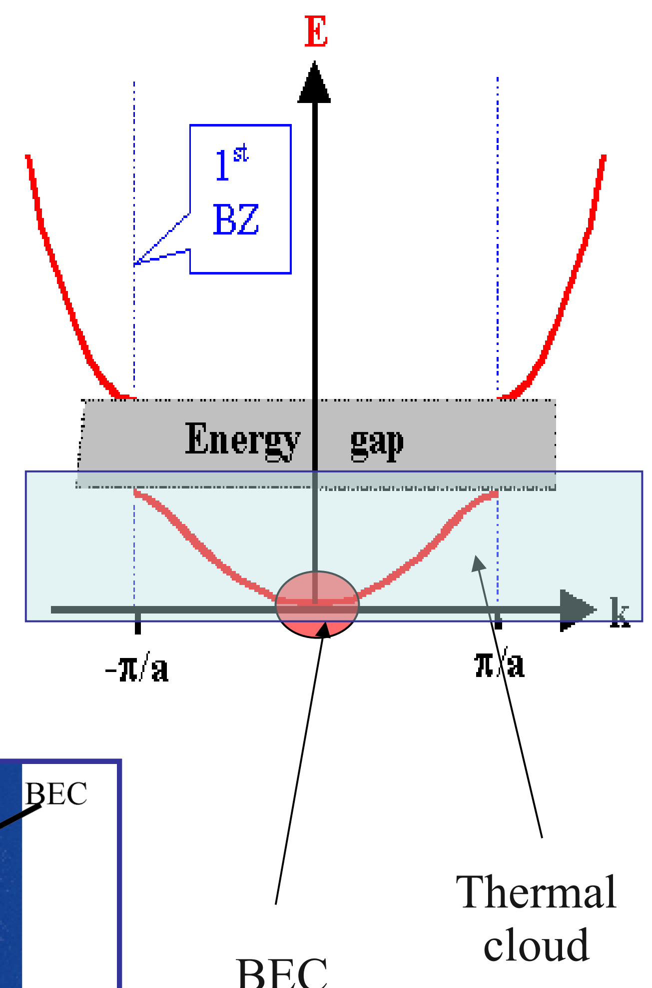


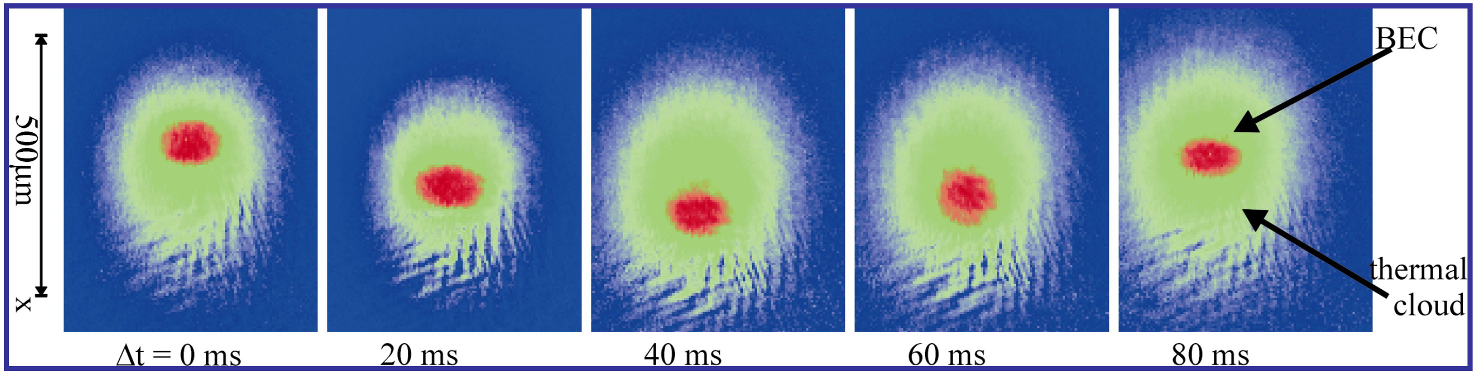
1D dynamics, (Fermi/Bose) Hubbard model description, Mott insulating phase…

Bose-Einstein (superfluid) vs. Normal component oscillations





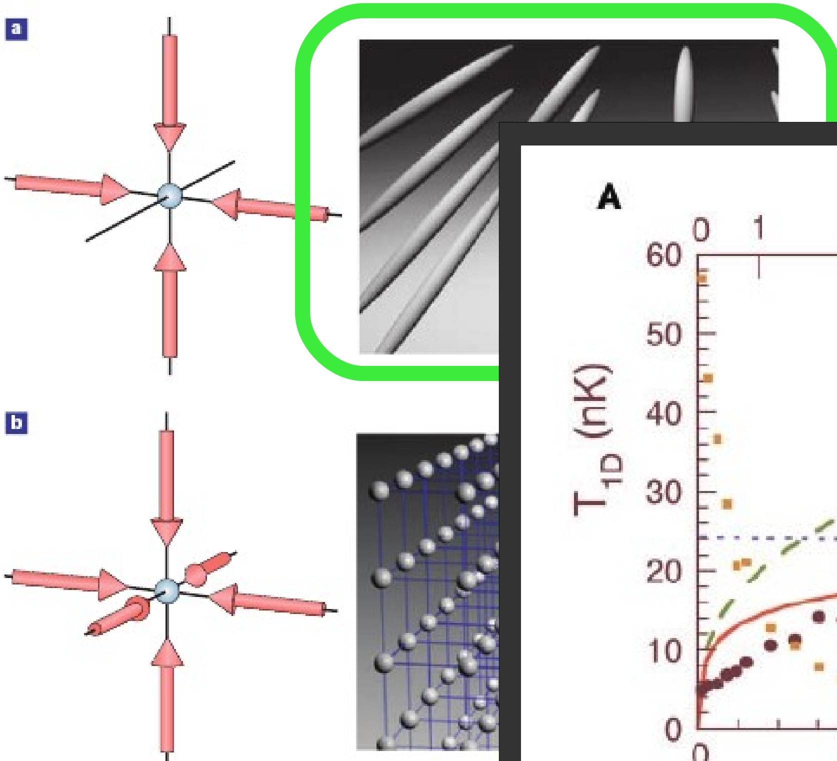


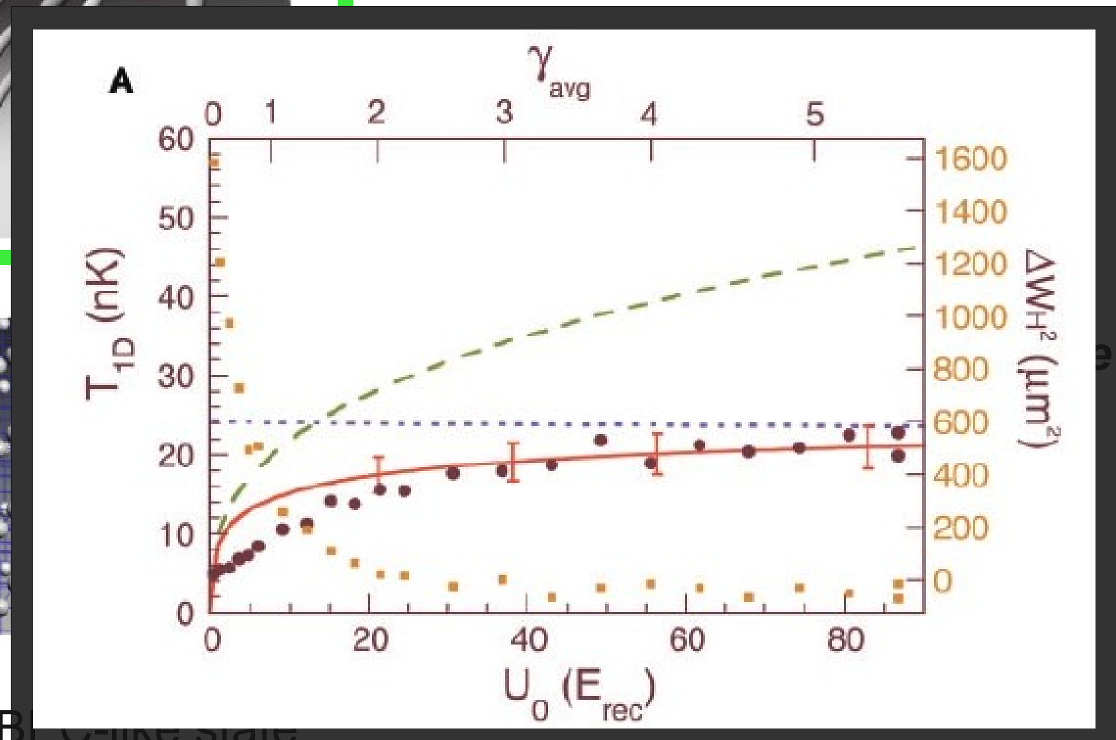


Periodic potential
(Florence 2001)

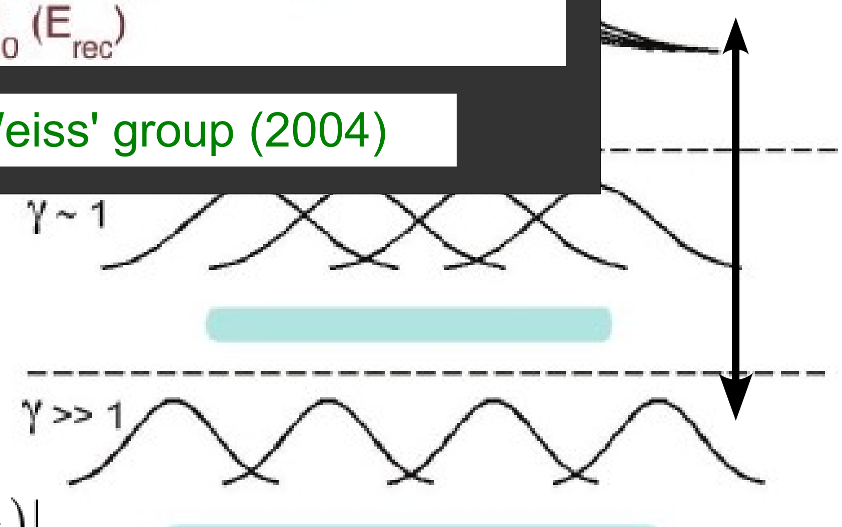
Only condensate coherently tunnels through the barriers

1D Tonks-Girardeau gas (or how to fermionize bosons)





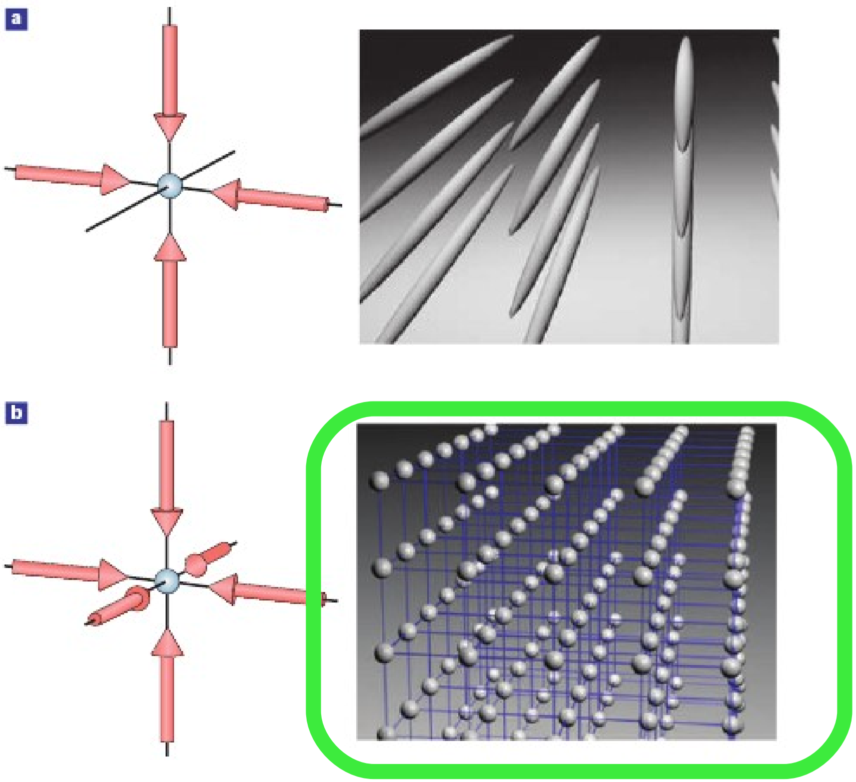
David Weiss' group (2004)

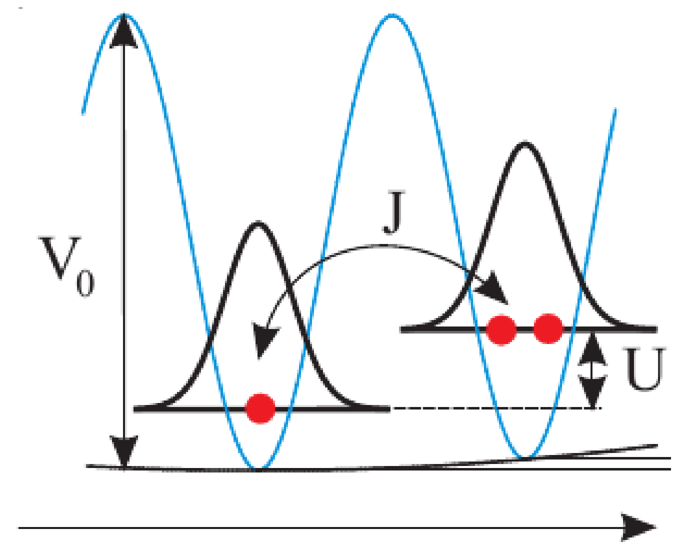


Tonks-Girardeau gas

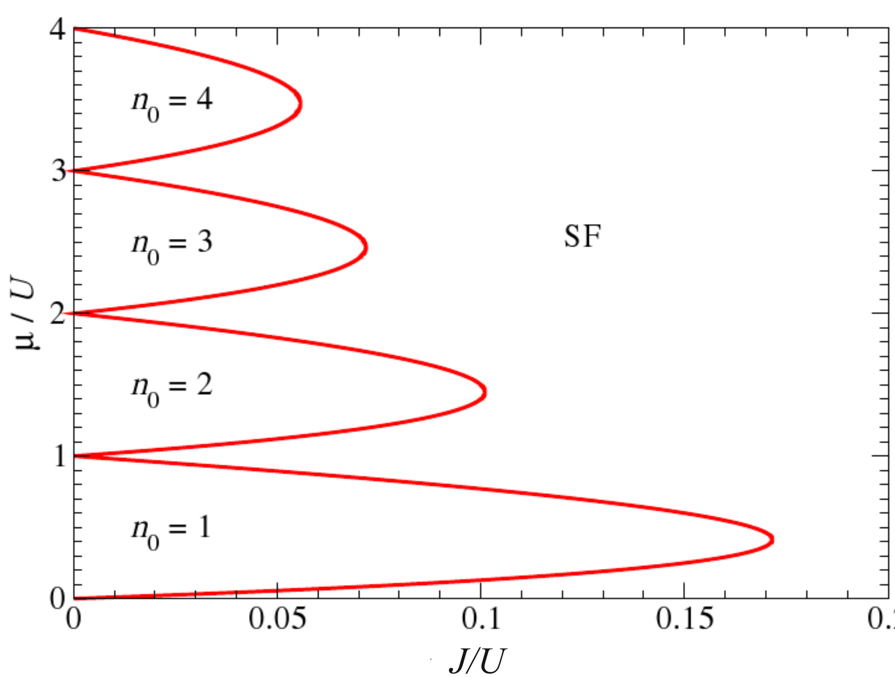
$$\Psi_B(x_1, x_2, ..., x_N) = |\Psi_F(x_1, x_2, ..., x_N)|$$

Bose- Hubbard Hamiltonian





$$H = \sum_{i,j} J_{ij} b_i^\dagger b_j - \mu \sum_i n_i + U \sum_i n_i(n_i - 1)$$

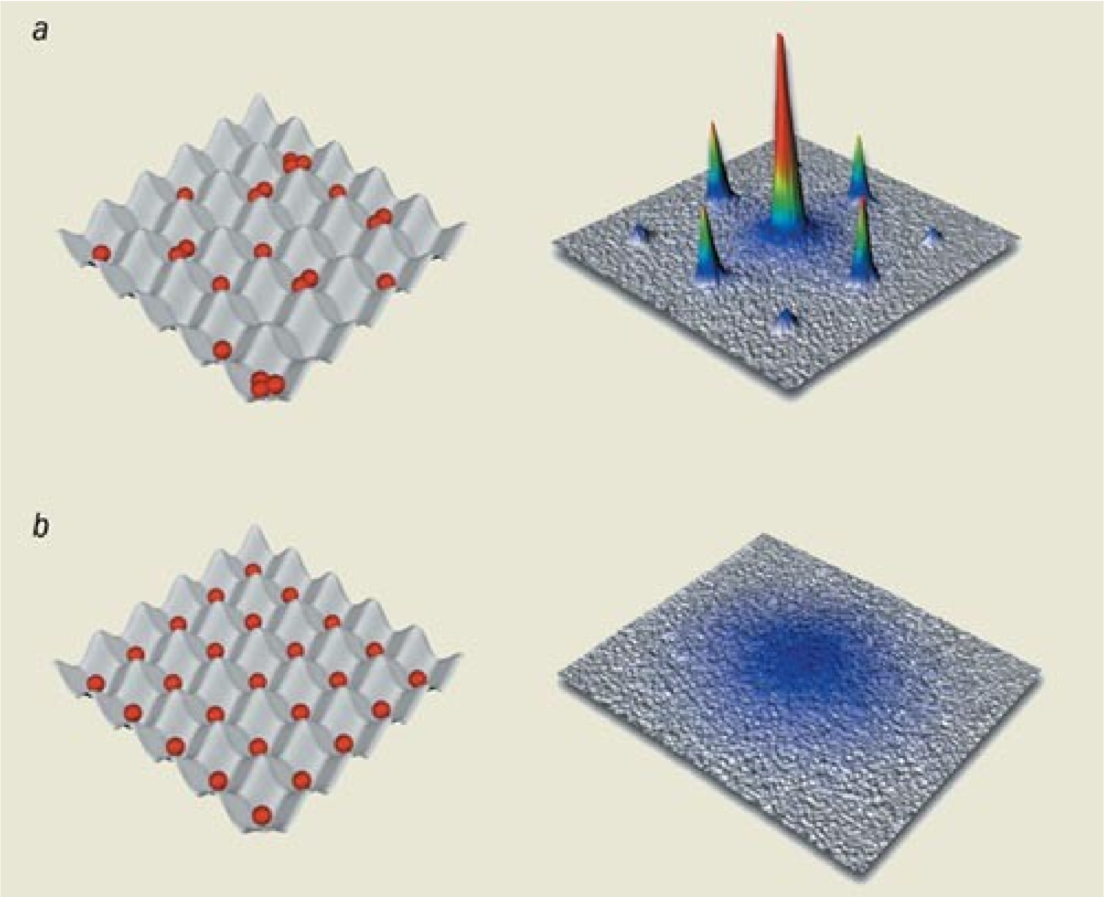


Quantum phase transition from superfluid to Mott insulator

Atoms move around,
delocalized on
many lattice site

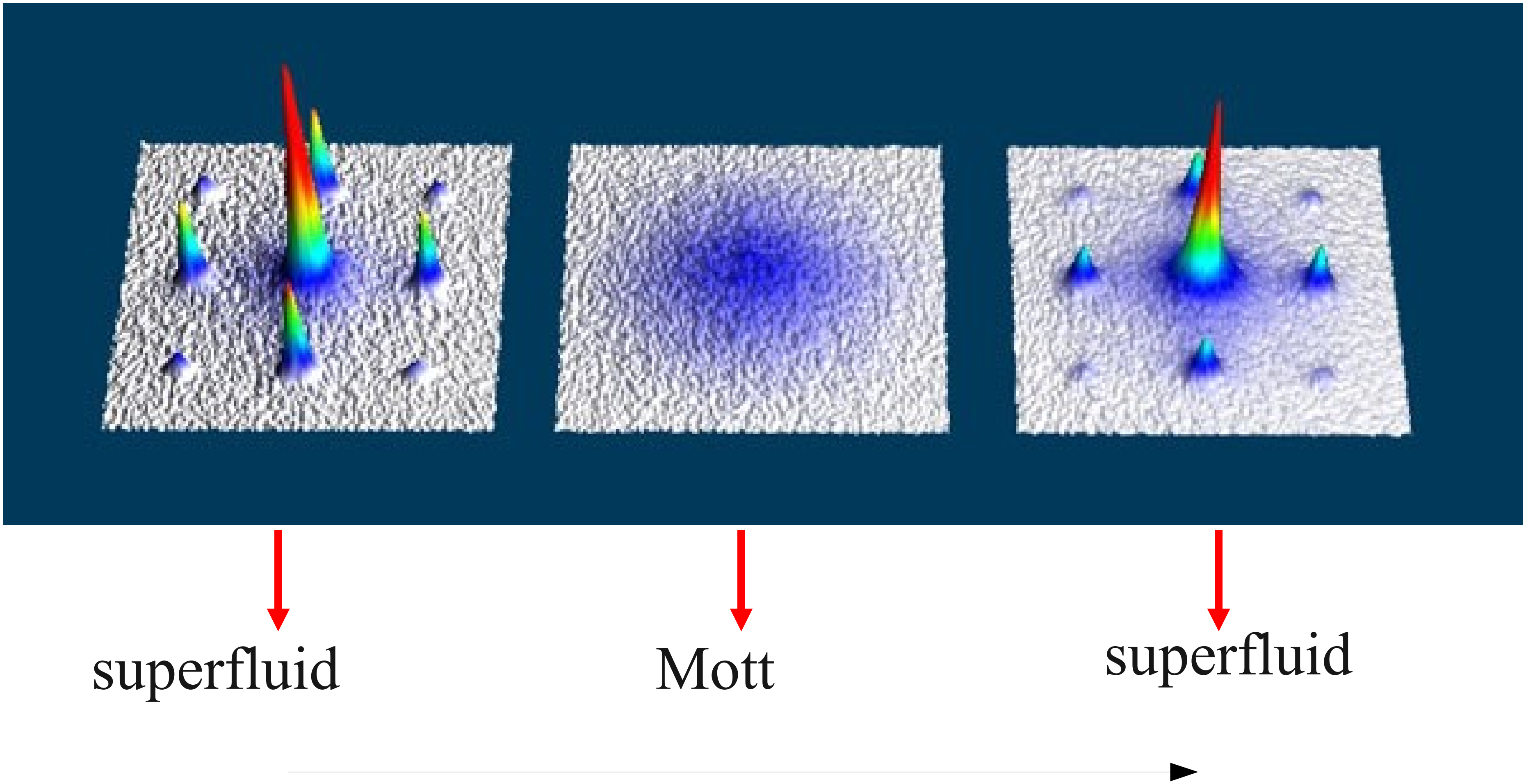
Incresing the lattice strength

Atoms are
localized on
a single lattice site



[I. Bloch et al. (2002)]

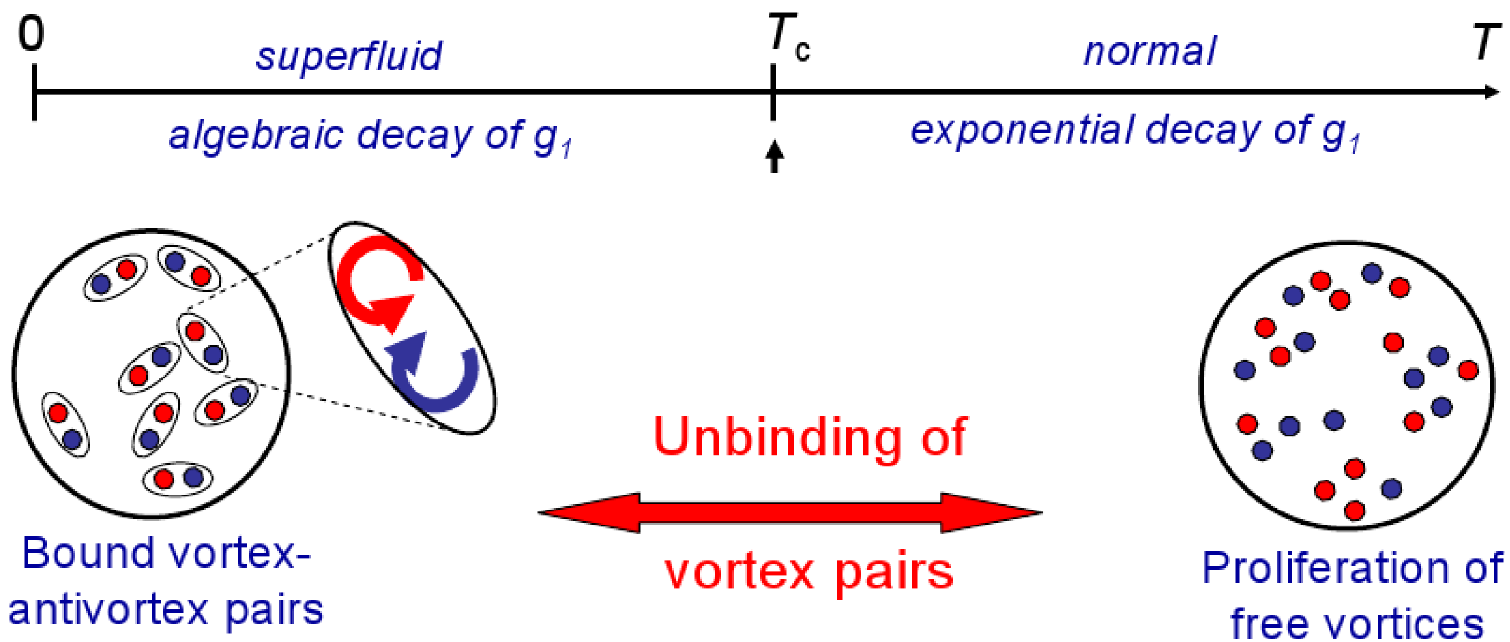
Quantum phase transition from superfluid to Mott insulator



SF – Mott and SF again: a coherent path through a quantum phase transition

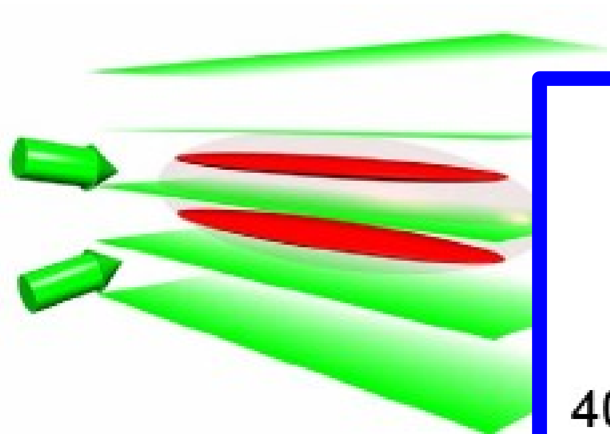
BKT phase transition in 2D BEC

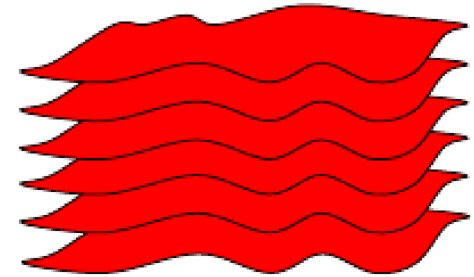
Mermin-Wagner-Hohenberg Theorem:
No true long range order at any finite temperature in 2D

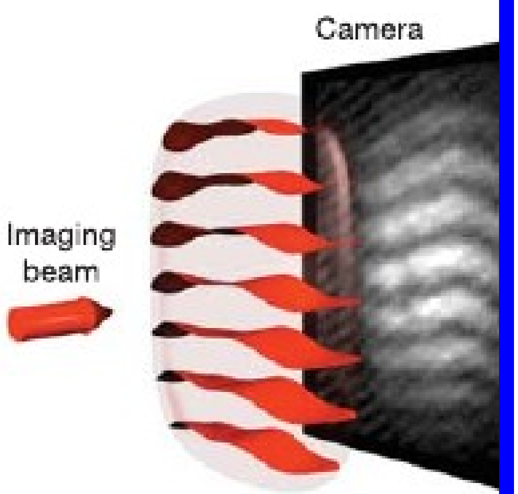


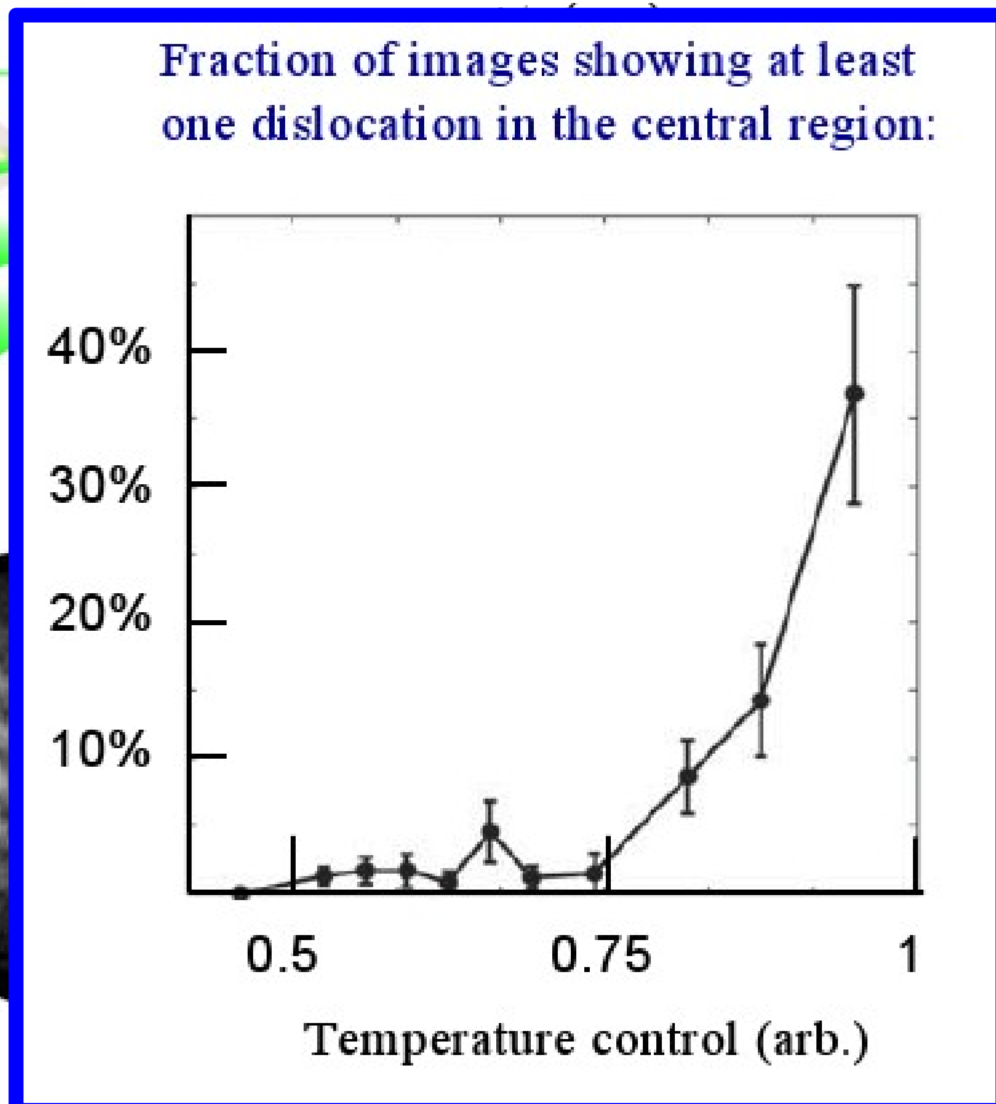
Berezinskii-Kostrelitz-Thouless Transition

BKT phase transition in 2D BEC

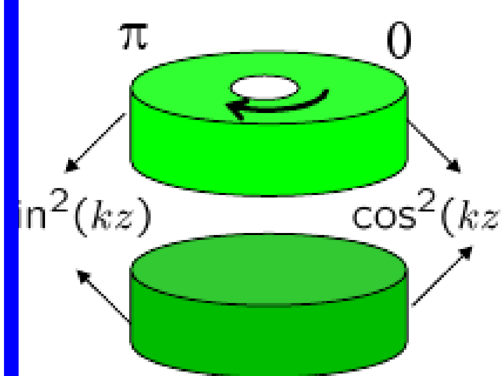








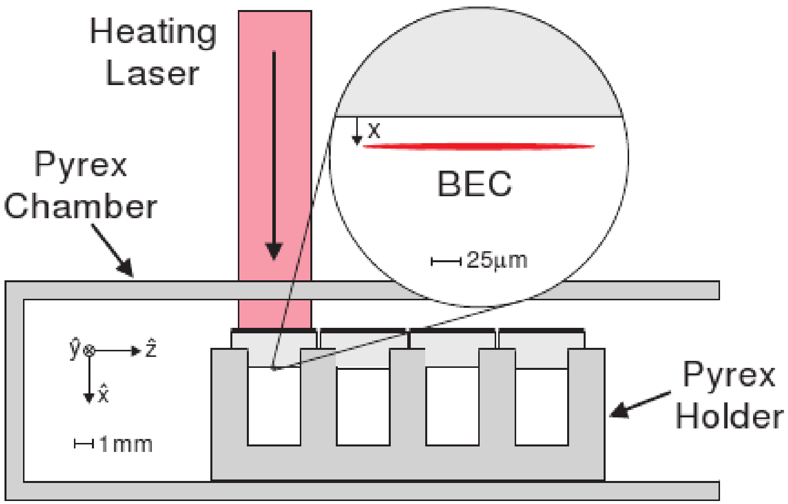
rtex

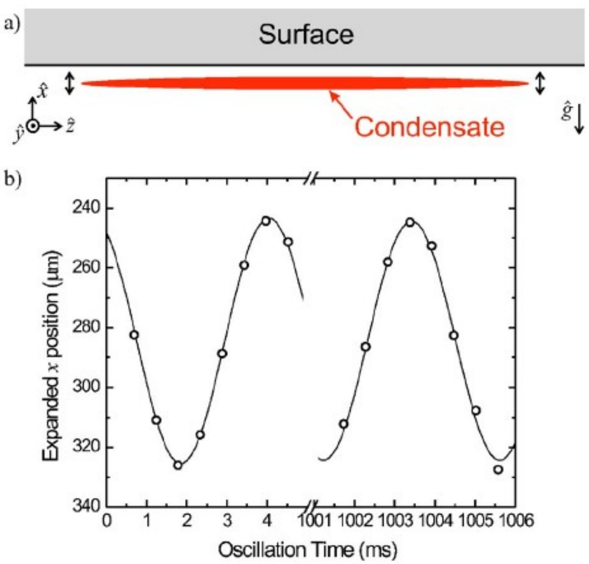


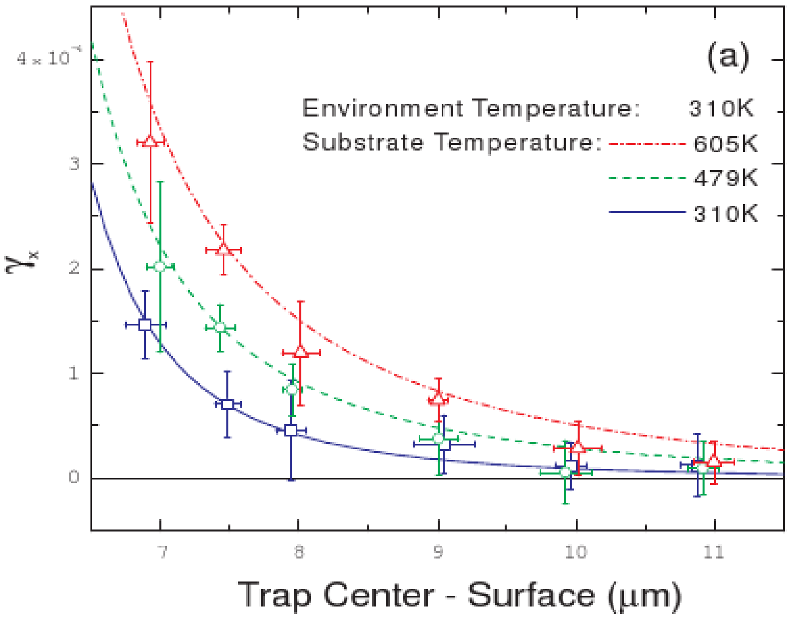
variation dislocation

[Dalibard's group (2006)]

BEC to measure the temperature dependence of Casimir-Polder forces







$$\gamma_x \equiv \frac{\omega_o - \omega_x}{\omega_o} \simeq \frac{1}{2m\omega_o^2} \langle \partial_x F_{CP} \rangle$$

[From Eric Cornell, 2006]