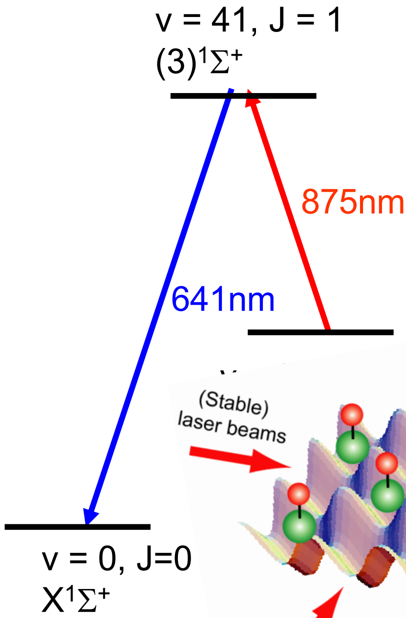
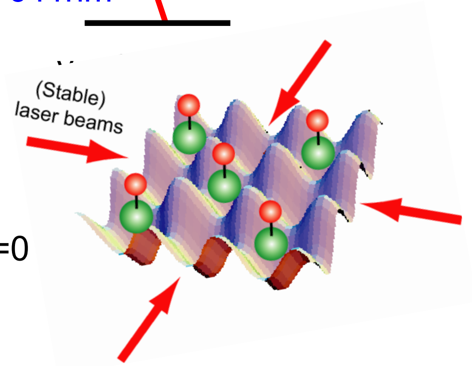
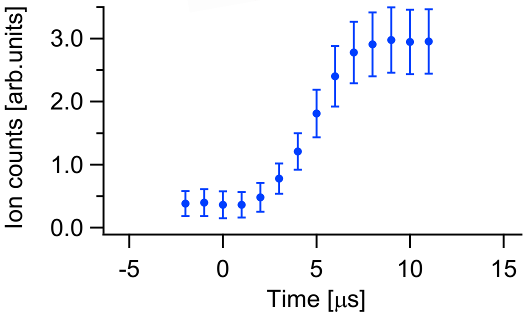
Nambu Symposium @OCU, Dec. 13, 2018

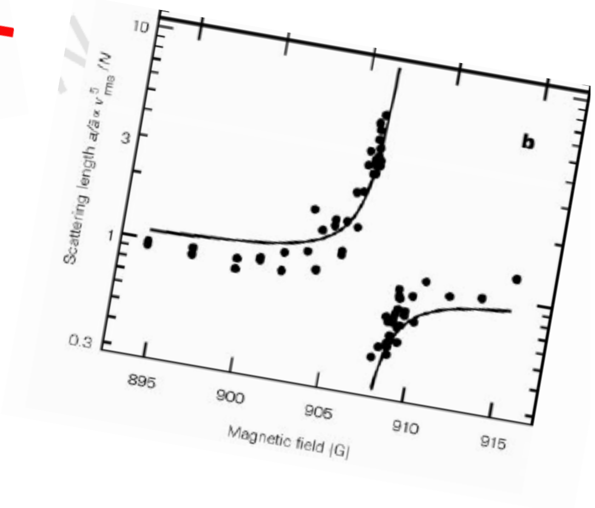
What can we do with a quantum degenerate mixture ?

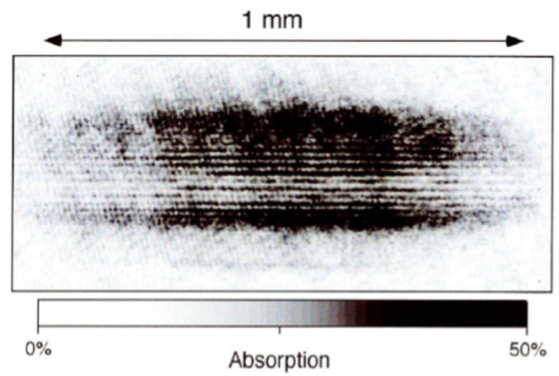
Shin Inouye
Osaka City University

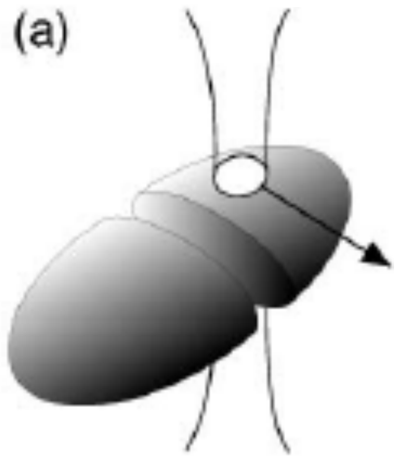












SINCE 1880 OSAKA CITY UNIVERSITY OCU

Outline

How to cool atoms

Properties of BEC

Tuning interactions (Feshbach resonance)

Cold molecules

Conclusion and Outlook

Everybody loves to cool liquids ...

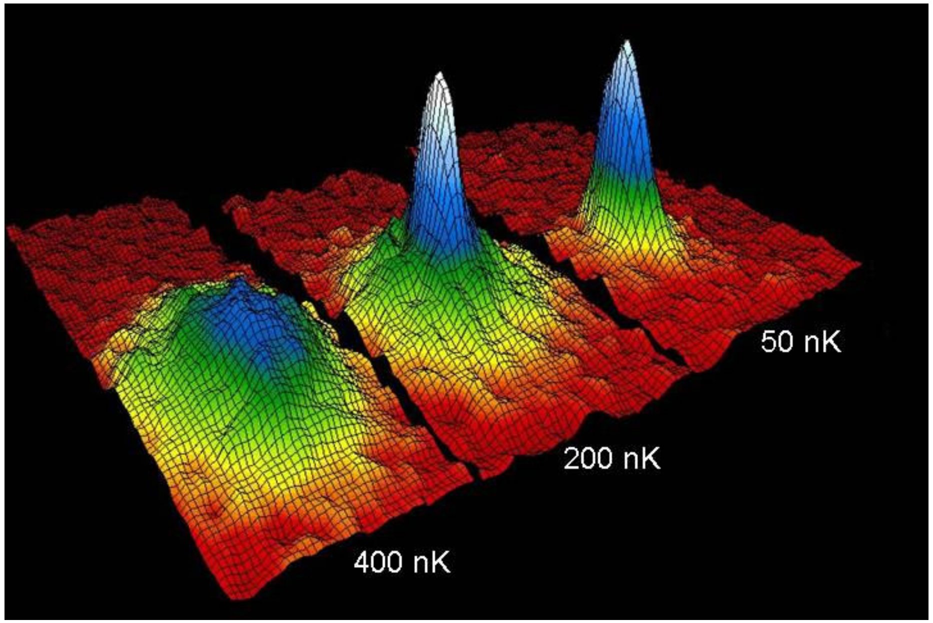
but, we are interested in cooling gases!

Significance of cold atom research

"Ideal system" to study Condensed Matter Physics!

Produced in 1995

Awarded in 2001
（Cornell, Ketterle, Wieman）



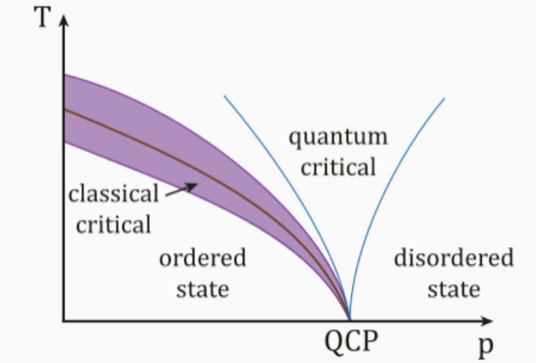
Anderson et al., Science, 269 198 (1995)

WIKIPEDIA
The Free Encyclopedia

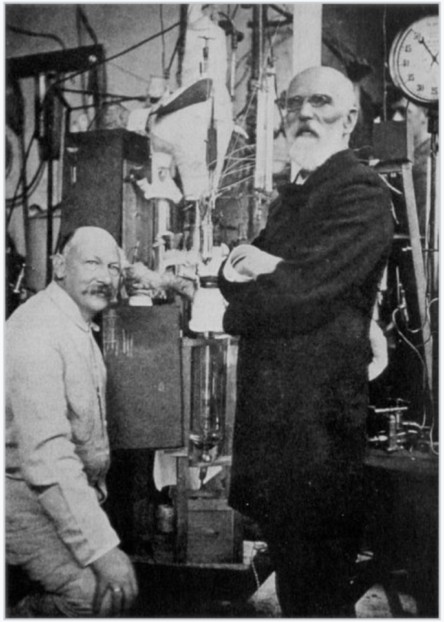
Article Talk

Condensed matter physics

From Wikipedia, the free encyclopedia

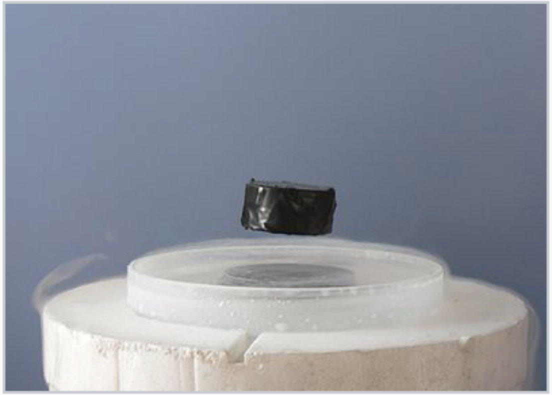


Phases · Phase transition · QCP



Heike Kamerlingh Onnes and Johannes van der Waals with the helium *liquefactor* at Leiden in 1908

A replica of the first point-contact transistor in Bell labs



A magnet levitating above a high-temperature superconductor. Today

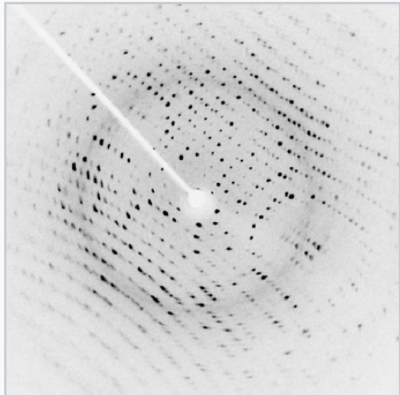
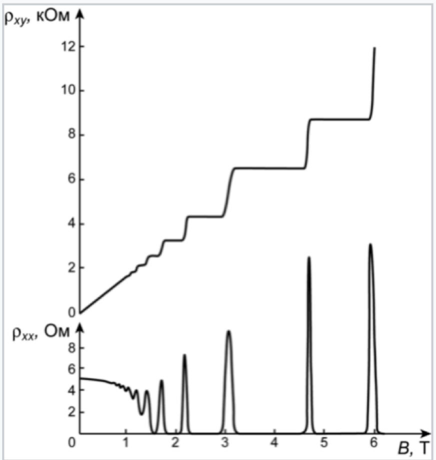
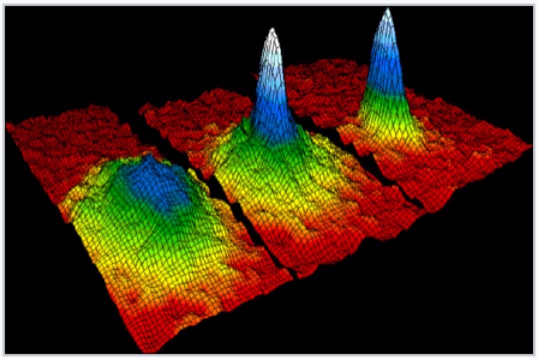


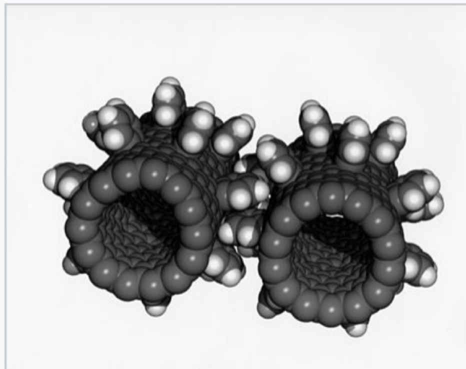
Image of X-ray diffraction pattern from a protein crystal.



The quantum Hall effect:

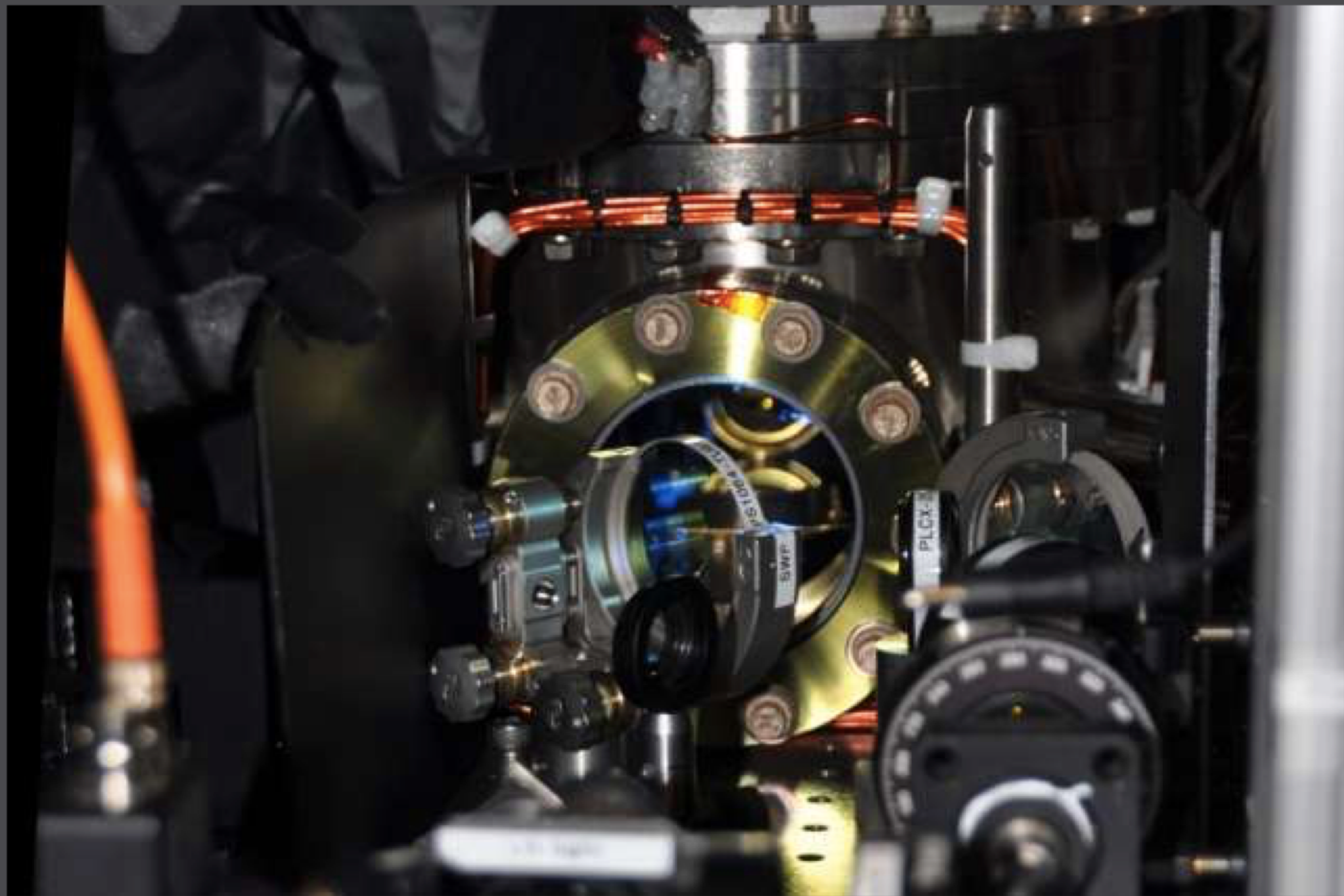


The first Bose–Einstein condensate



Computer simulation of *nanogears*

Researchers create new form of matter—supersolid is crystalline and superfluid at the same time

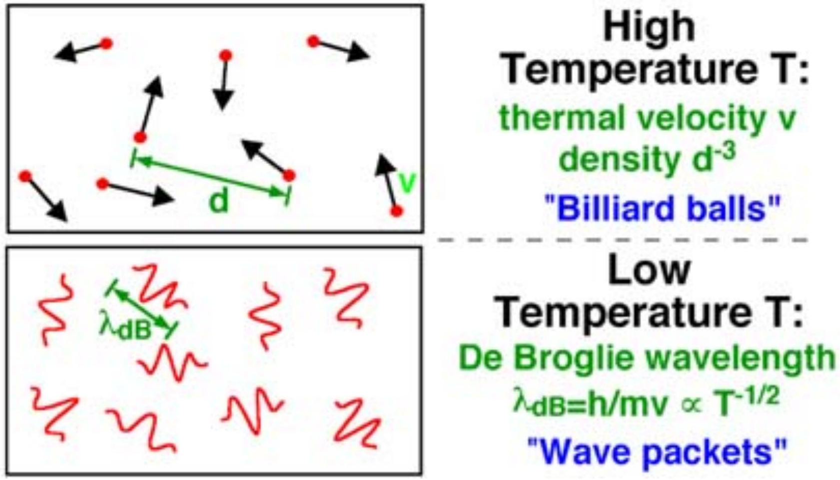


This image shows the equipment used by the Ketterle group to create a supersolid. Credit: Massachusetts Institute of Technology

MIT physicists have created a new form of matter, a supersolid, which combines the properties of solids with those of superfluids.

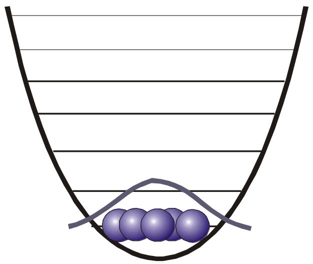
phys.org
March 3, 2017

What is ultracold quantum gas?

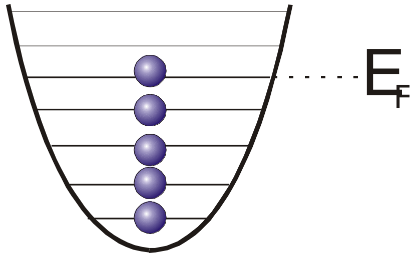


Further lower temperature

Bosons



Fermions



BEC

phase transition at T_C

Fermi sea of atoms

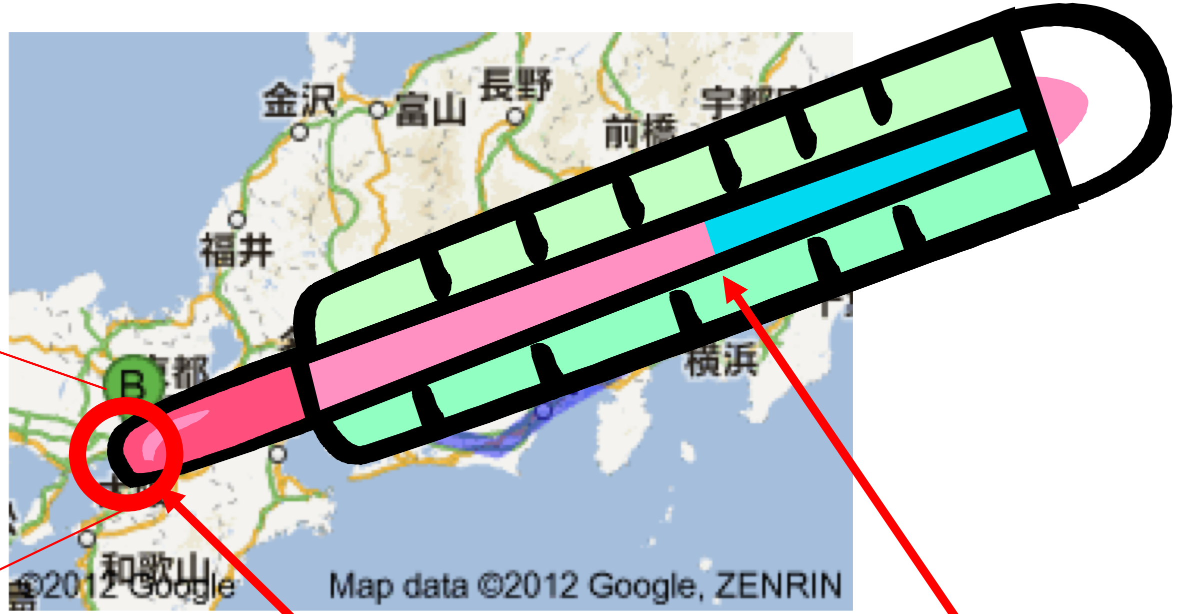
gradually emerges for $T<T_F$

Problem with gases: Typical Tc is quite low

$$T_c = \frac{h^2}{2\pi m k_B}\left(\frac{n}{2.612}\right)^{2/3}$$

0.000 000 1K = 100nK

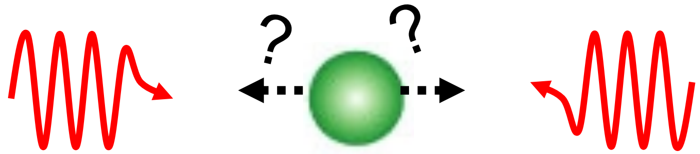
Tc < 1mm

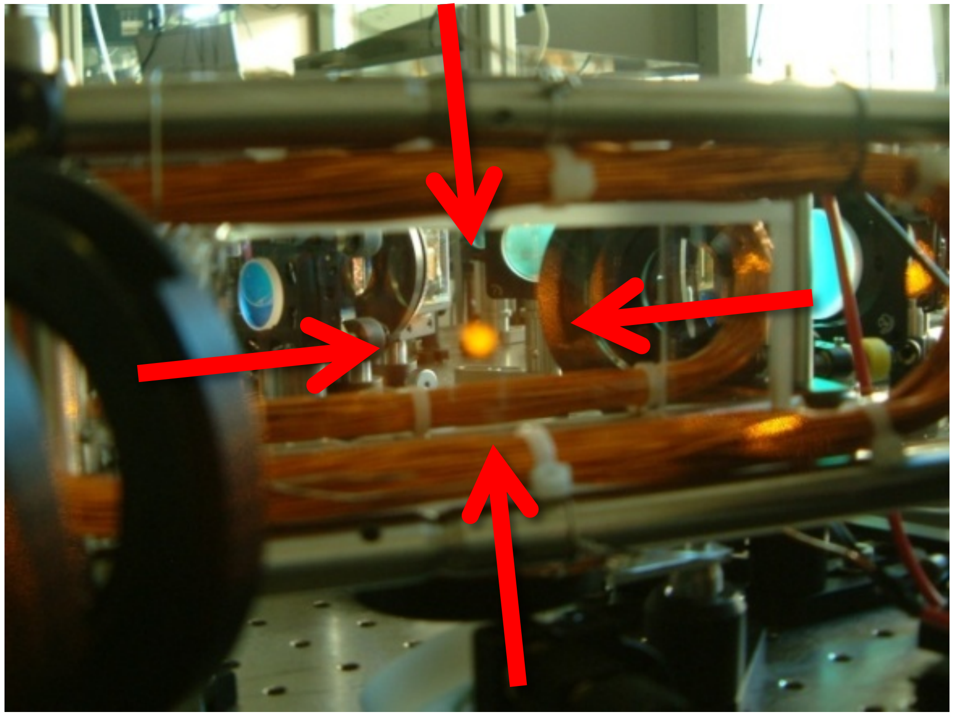


absolute zero ＝"Osaka"

300K ＝"Tokyo"

Laser cooling !



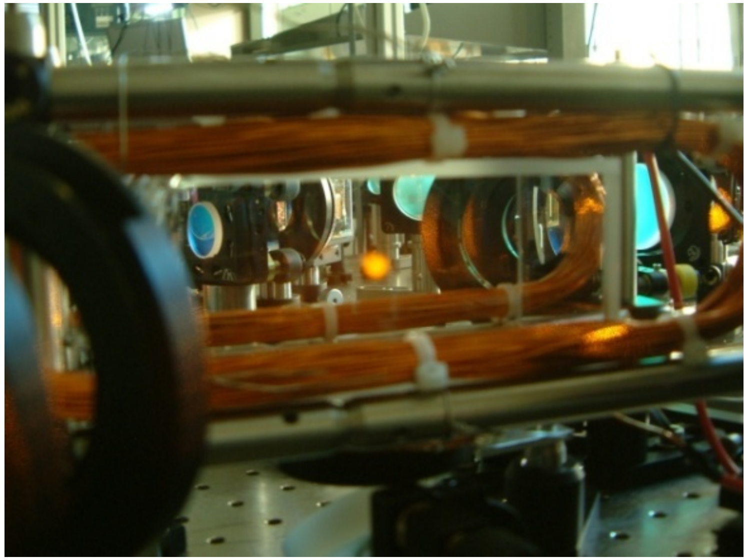


Technological breakthroughs

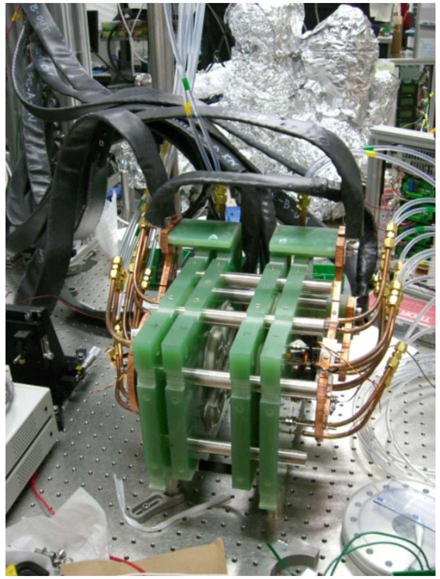
laser cooling + evaporative cooling

300 K to 1 mK

1 mK to 100 nK



(MOT)

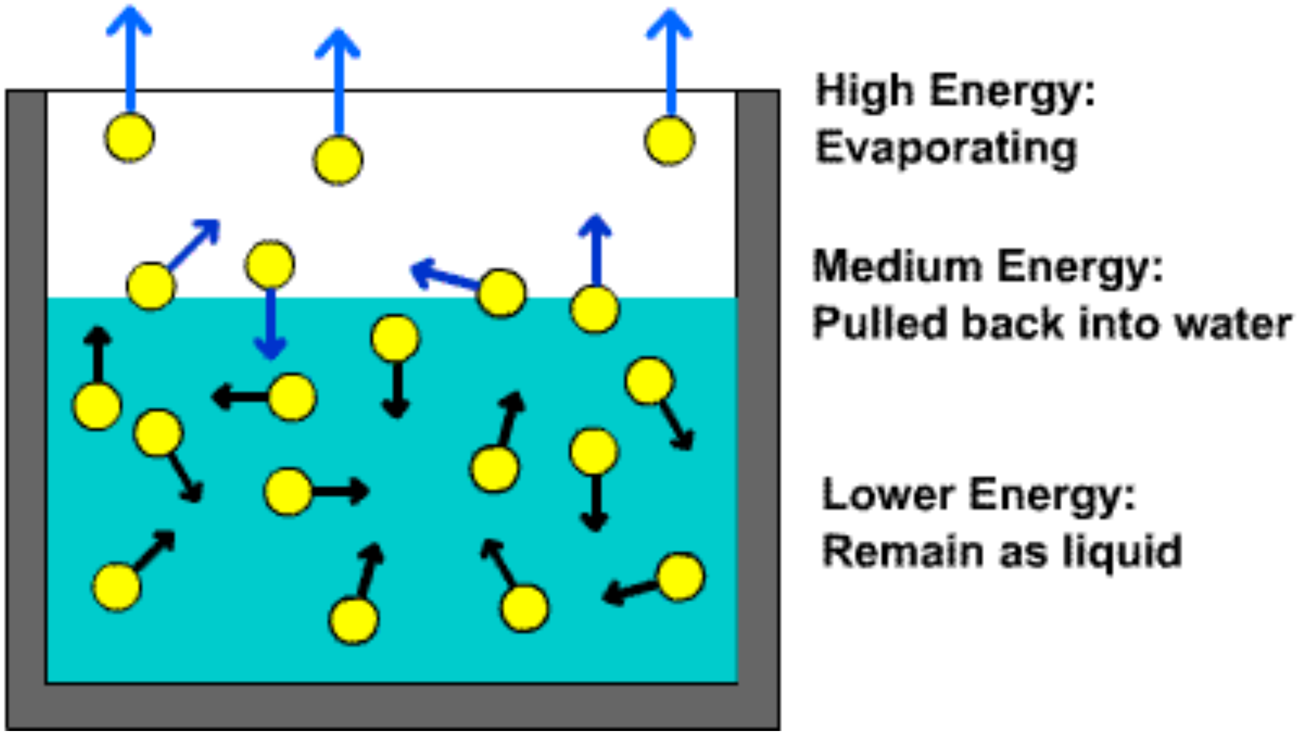


(Magnetic trap)

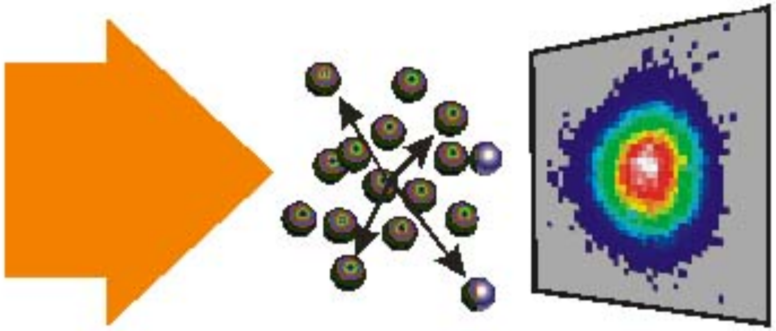
-> lowest man-made temperature !

A. E. Leanhardt, T. A. Pasquini, M. Saba, A. Schirotzek, Y. Shin, D. Kielpinski, D. E. Pritchard, and W. Ketterle:
Adiabatic and Evaporative Cooling of Bose-Einstein condensates below 500 Picokelvin.
Science 301, 1513-1515 (2003).

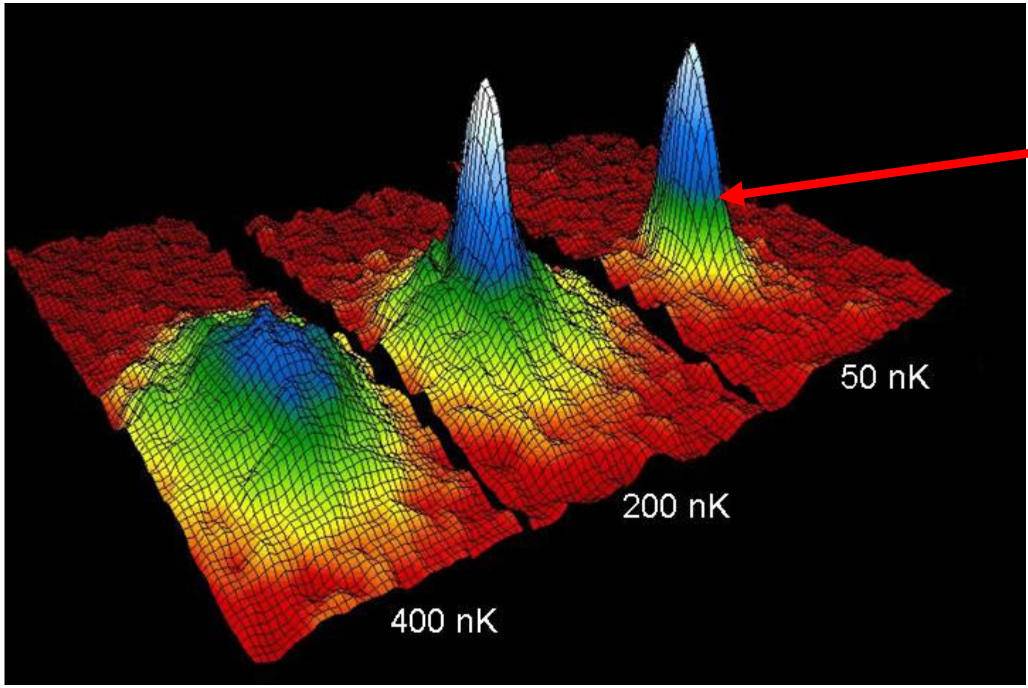
Evaporative cooling



Bose-Eintein condensation



Time-of-flight：
Release atoms from the trap, wait for tens of milli-seconds, and take shadow picture.



Suddenly momentum distribution becomes narrower.
↓
Bose-Einstein Condensation!

Anderson et al., Science, 269 198 (1995)

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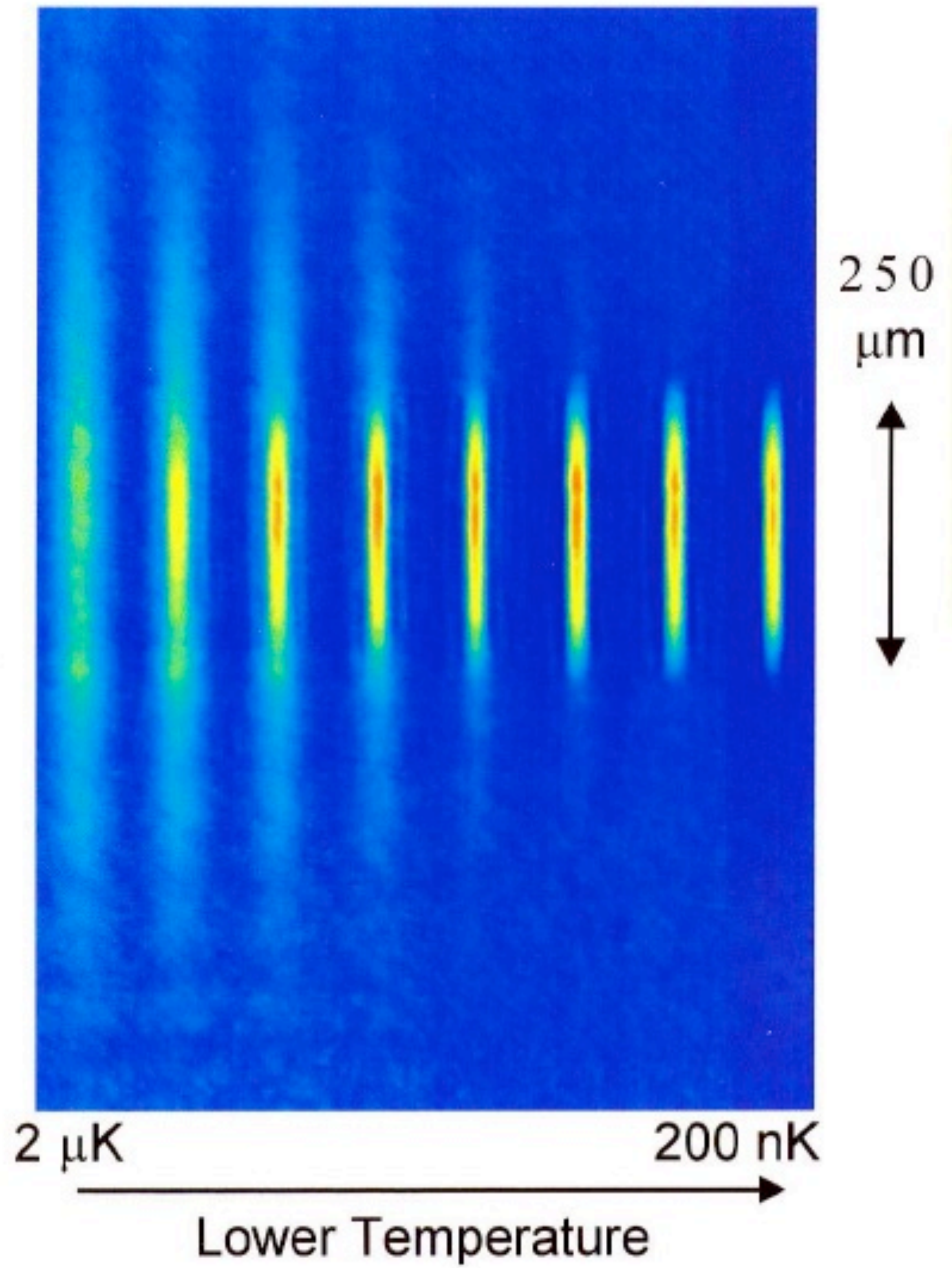
Conclusion and Outlook



Typical parameters

•Density: ~ 10^{14} cm^{-3}
•Temperature: < 100 nK
•Number of atoms: < 10^7
•Size: 20X20X200 μm
•Life time：> 10 s
•Atomic species：Rb, Na, Li, …

Properties of a BEC
•gaseous superfluid
•macroscopic wavefunction
(Quantum depletion:
alkali BEC < 1%, liq. He >90%)

What we are looking at?

$$\rho(\vec{r}) = \left\langle \hat{\psi}^{+}(\vec{r})\hat{\psi}(\vec{r}) \right\rangle$$

$$H = \int d\mathbf{r} \left[\underbrace{-\hat{\psi}^{\dagger}(\mathbf{r})\frac{\hbar^2}{2m}\nabla^2\hat{\psi}(\mathbf{r})}_{\text{Kinetic energy}} + \underbrace{V(\mathbf{r})\hat{\psi}^{\dagger}(\mathbf{r})\hat{\psi}(\mathbf{r})}_{\text{Confining potential}} + \underbrace{\frac{U_0}{2}\hat{\psi}^{\dagger}(\mathbf{r})\hat{\psi}^{\dagger}(\mathbf{r})\hat{\psi}(\mathbf{r})\hat{\psi}(\mathbf{r})}_{\text{Interaction between atoms}} \right]$$

$$U_0 = 4\pi\hbar^2 a/m$$

It is useful to introduce $\psi(r)$

$$\hat{\psi}(\mathbf{r}) = \underbrace{\psi(\mathbf{r})}_{\text{c-number}} + \underbrace{\delta\hat{\psi}(\mathbf{r})}_{\text{quantum fluctuation}}.$$

Order parameter and Spontaneous Symmetry Breaking

ψ(r) satisfies Penrose-Onsager relation:

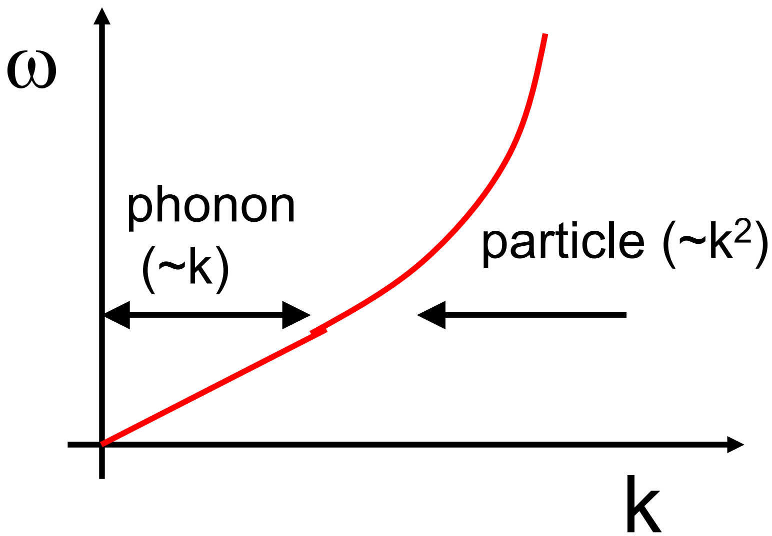
$$\left\langle \hat{\psi}^{+}(\vec{r})\hat{\psi}(\vec{r}\,')\right\rangle = \psi^{*}(\vec{r})\psi(\vec{r}\,') + \underline{\left\langle \delta\hat{\psi}^{+}(\vec{r})\delta\hat{\psi}(\vec{r}\,')\right\rangle}$$

vanishes as |r-r'|→∞

Hamiltonian is unchanged under global gauge transformation:

$$\psi(\vec{r}) \rightarrow e^{i\alpha}\psi(\vec{r})$$

Nambu-Goldstone mode: phonon



Propagation of Sound in a Bose-Einstein Condensate

M. R. Andrews, D. M. Kurn, H.-J. Miesner, D. S. Durfee, C. G. Townsend, S. Inouye, and W. Ketterle

Department of Physics and Research Laboratory of Electronics, Massachusetts Institute of Technology, Cambridge, Massachusetts 02139

(Received 20 March 1997; revised manuscript received 27 May 1997)

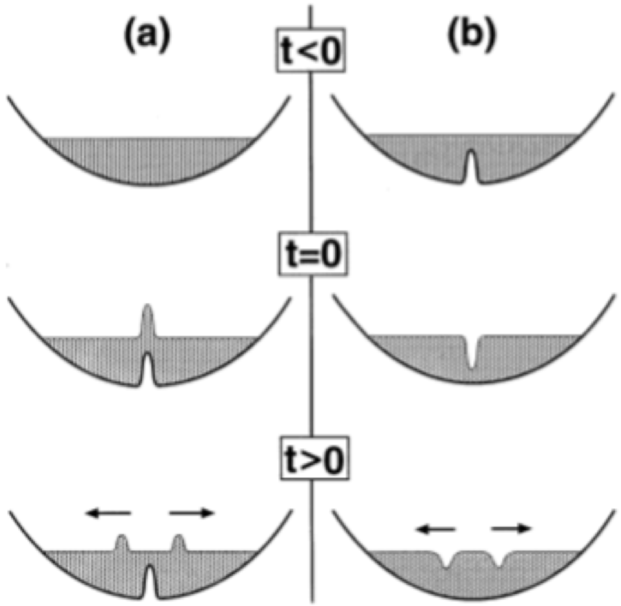
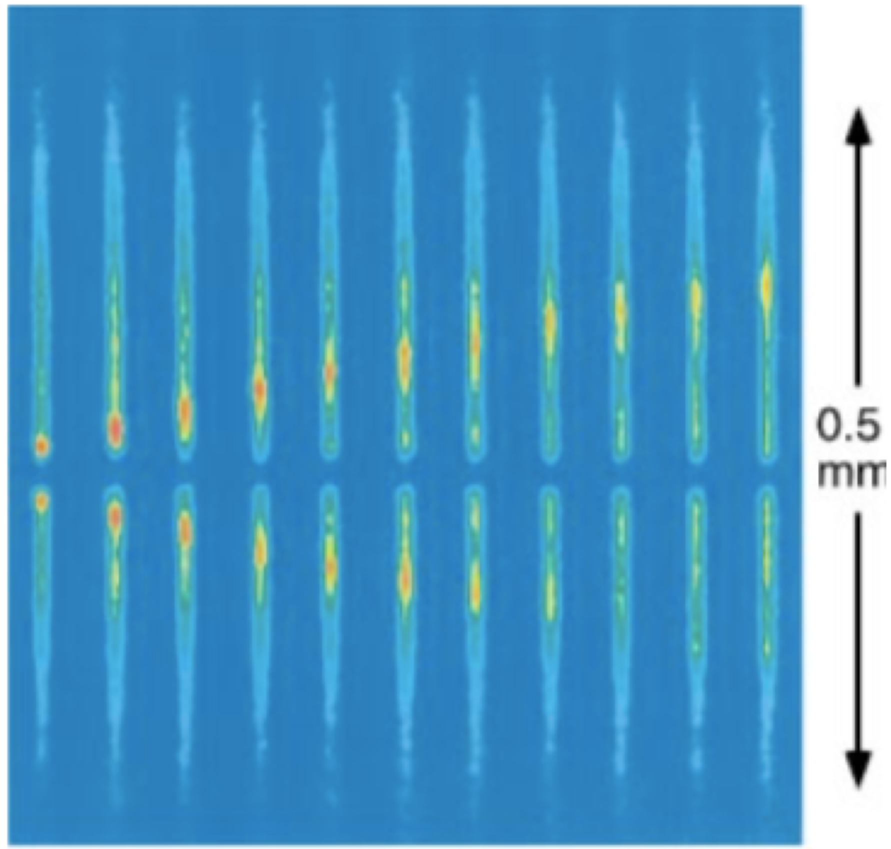


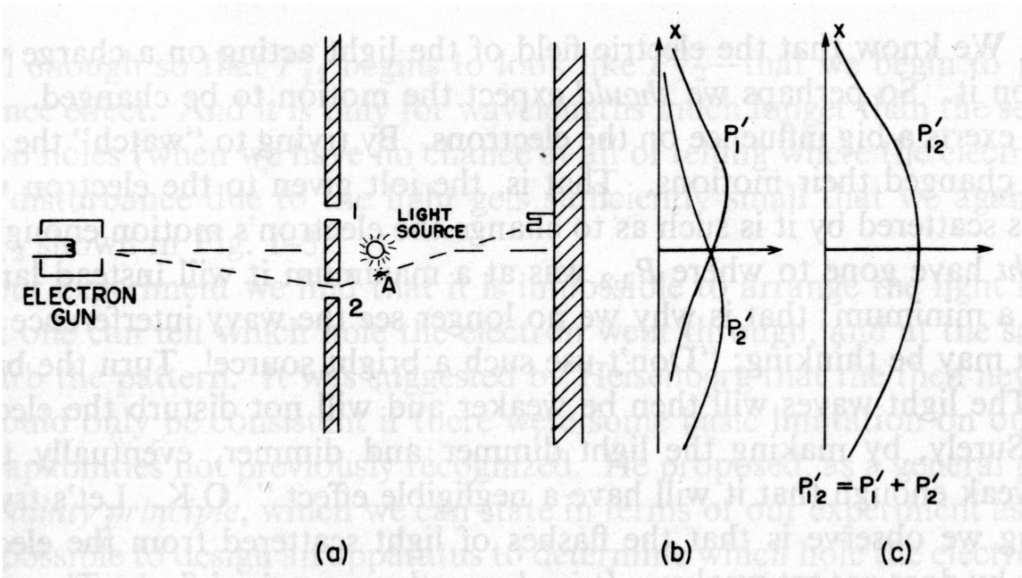
FIG. 1. Excitations of wave packets in a Bose-Einstein condensate. A condensate is confined in the potential of a magnetic trap. At time $t = 0$, a focused, blue-detuned laser beam is suddenly switched on (a) or off (b) and, by the optical dipole force, creates, respectively, two positive or negative pertubations in density which propagate at the speed of sound.



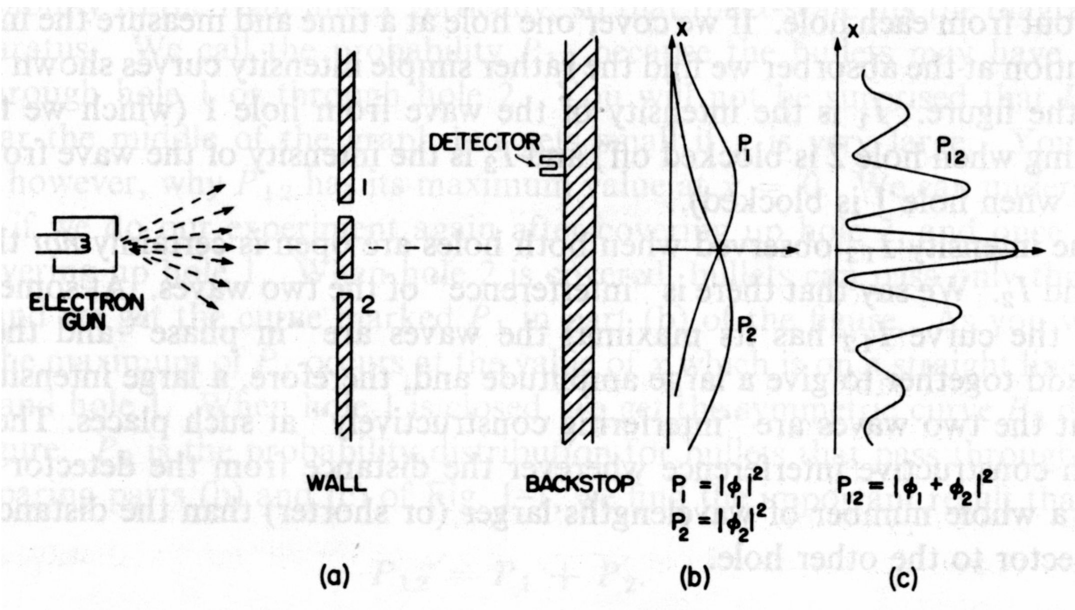
Direct confirmation of macroscopic wavefunction?

Interference!

Classical mechanics



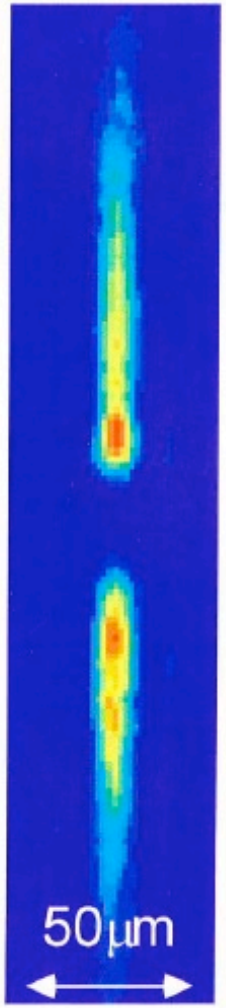
Quantum mechanics

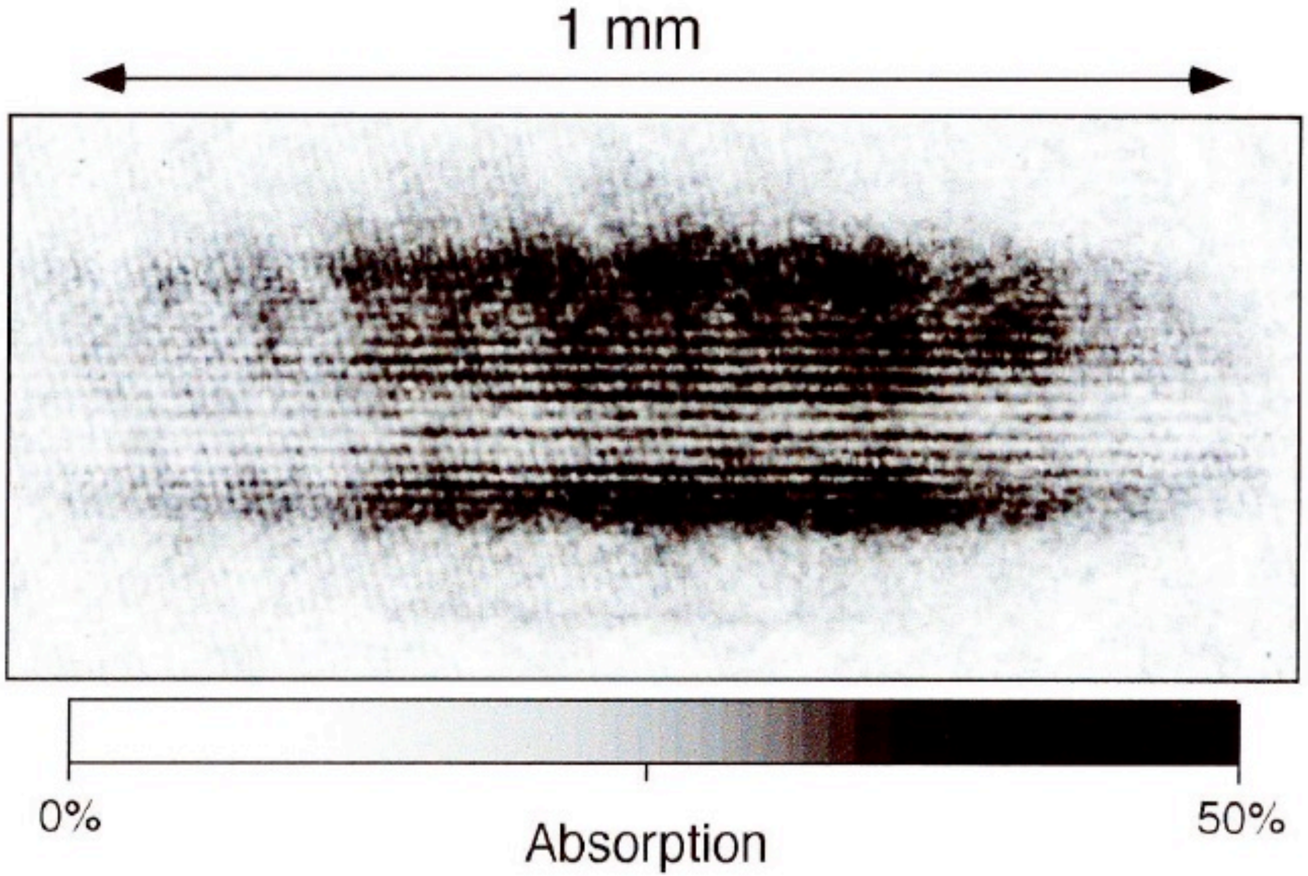


Two condensates ... interfere!

$|\psi_1(r,t=0)|^2$

$|\psi_2(r,t=0)|^2$





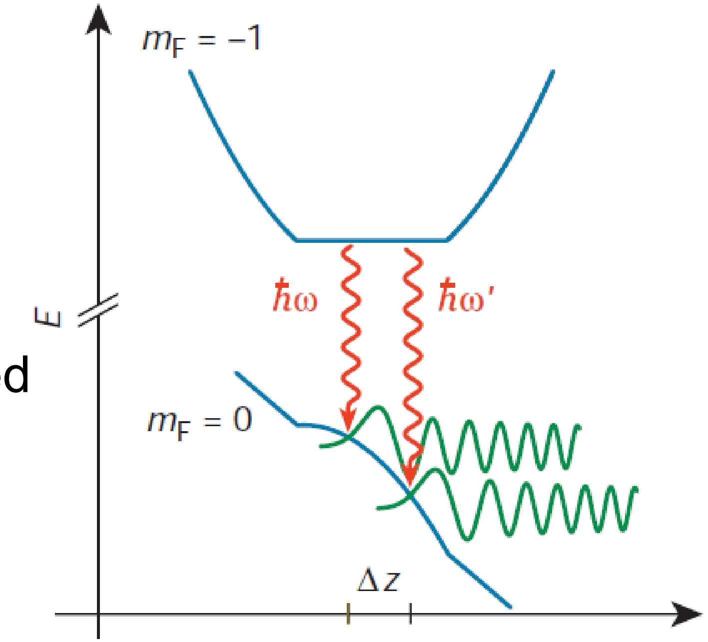
$|\psi_1(\,r,\ t = \mathrm{T}\,) + \psi_2(\,r,\ t = \mathrm{T}\,)\,|^2$

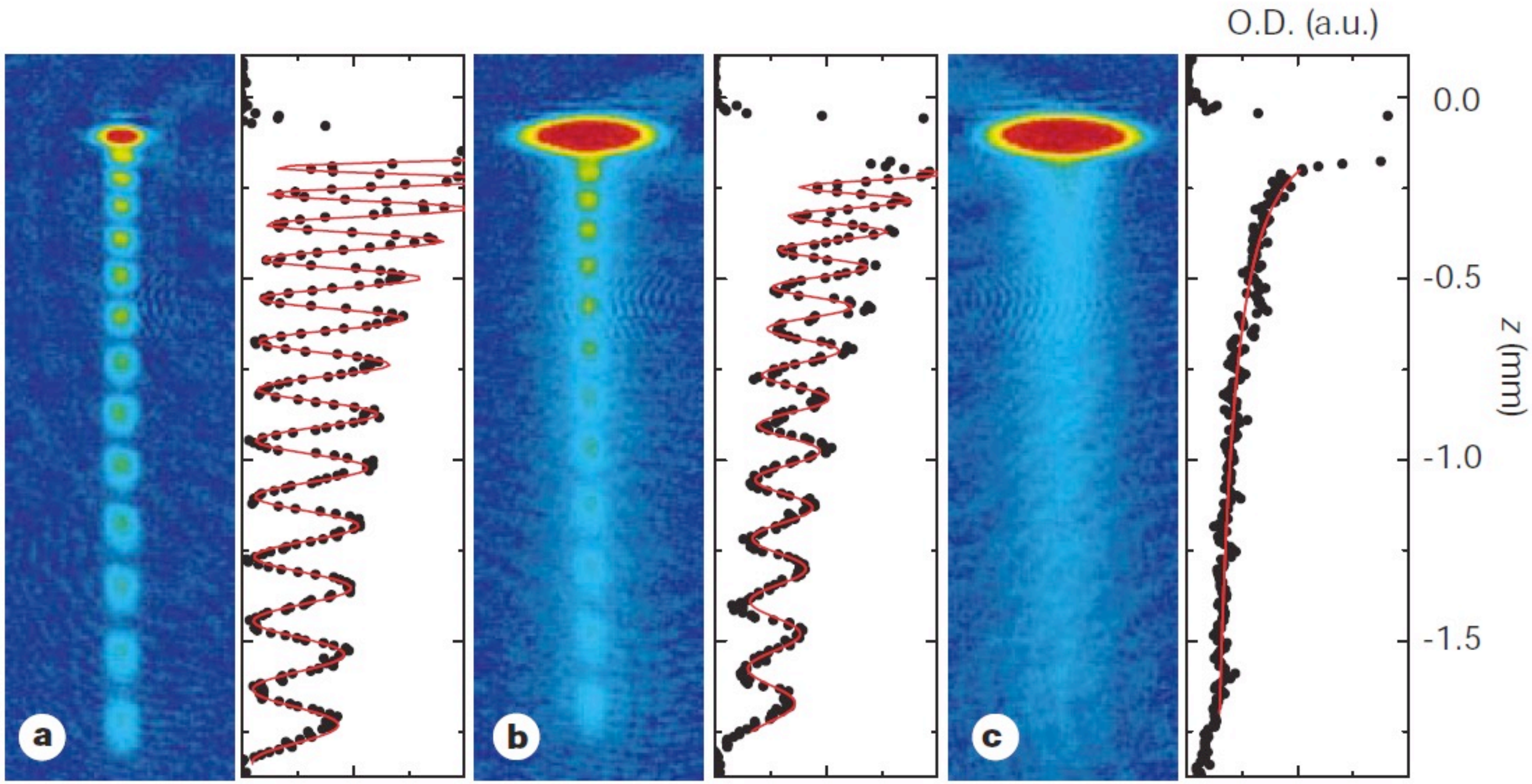
M. R. Andrews *et al*., Science **275**, 637 (1997)

Measurement of 1st-order **spatial** coherence

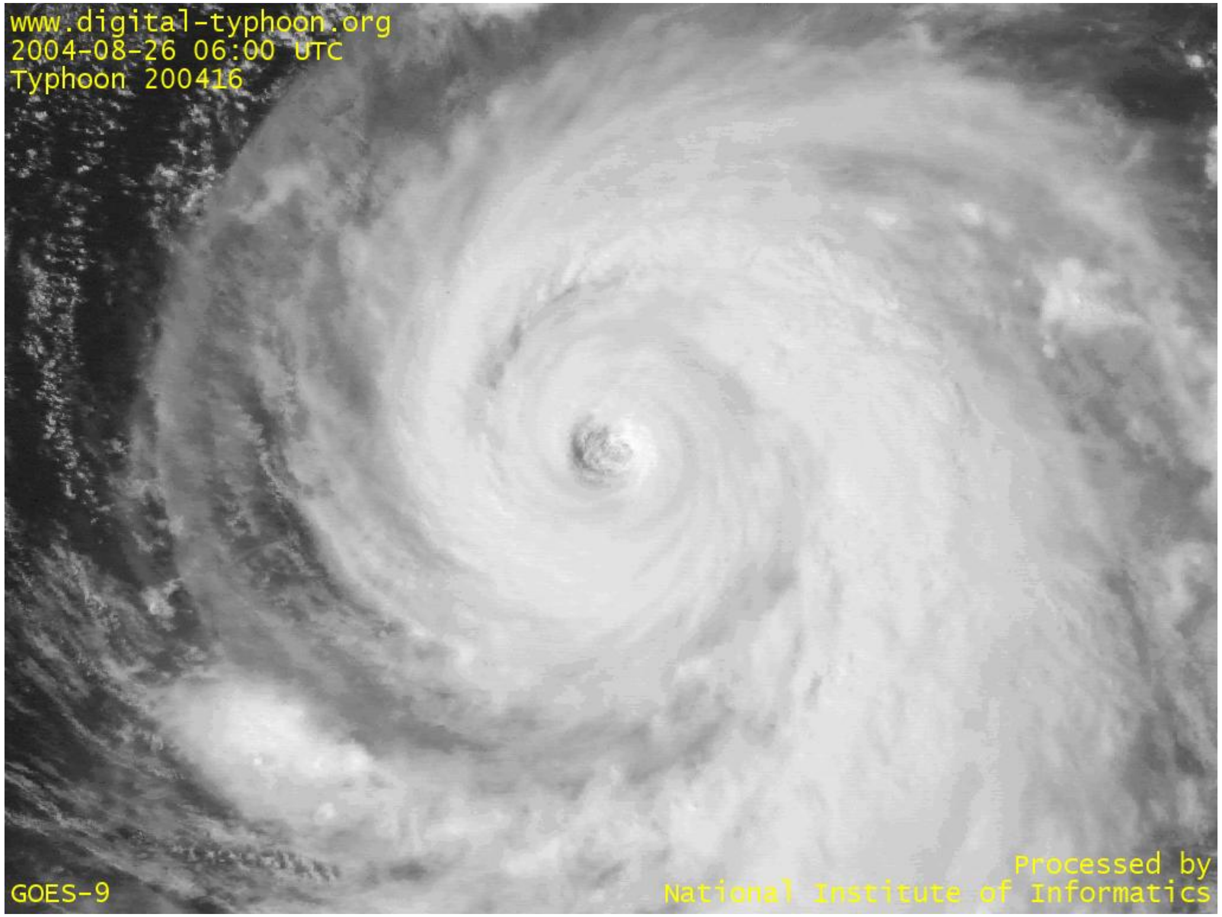
Extract matterwave from two separated points and make them interfere.

I. Bloch, T. W. Hänsch & T. Esslinger
Nature 403, 166–170 (2000)





Vortex !


www.digital-typhoon.org
2004-08-26 06:00 UTC
Typhoon 200416
GOES-9
Processed by
National Institute of Informatics

Rotate a BEC with a laser beam

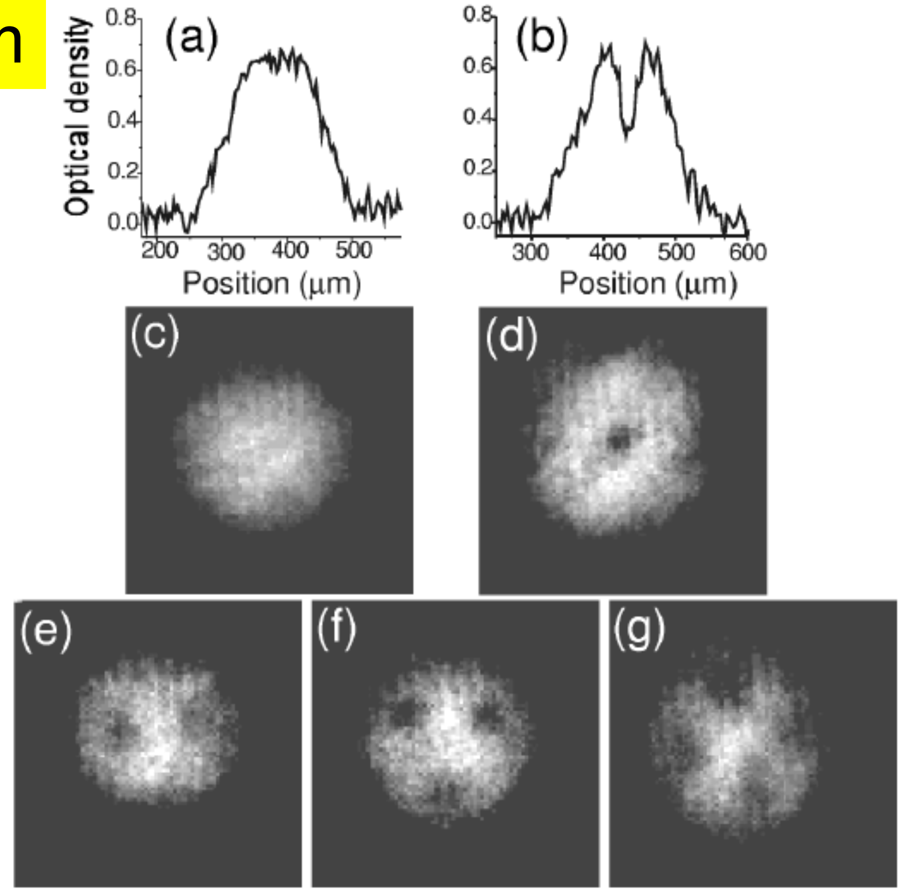


FIG. 1. Transverse absorption images of a Bose-Einstein condensate stirred with a laser beam (after a 27 ms time of flight). For all five images, the condensate number is $N_0 = (1.4 \pm 0.5)\ 10^5$ and the temperature is below 80 nK. The rotation frequency $\Omega/(2\pi)$ is, respectively, (c) 145 Hz, (d) 152 Hz, (e) 169 Hz, (f) 163 Hz, (g) 168 Hz. In (a) and (b) we plot the variation of the optical thickness of the cloud along the horizontal transverse axis for the images (c) (0 vortex) and (d) (1 vortex).

K. W. Madison, F. Chevy, W. Wohlleben*, and J. Dalibard
Phys. Rev. Lett. 84, 806–809 (2000)
Vortex Formation in a Stirred Bose-Einstein Condensate

Vortex lattice !

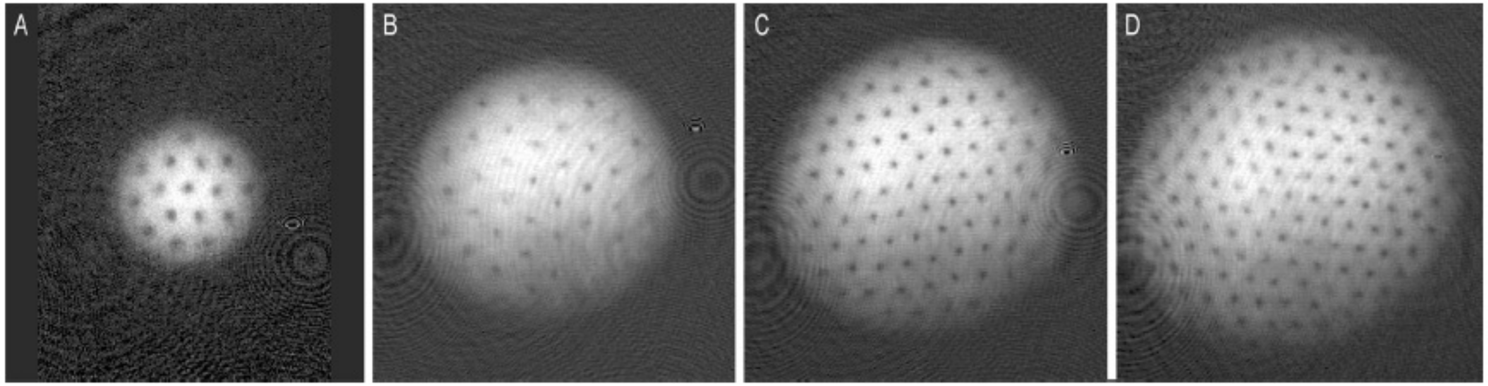
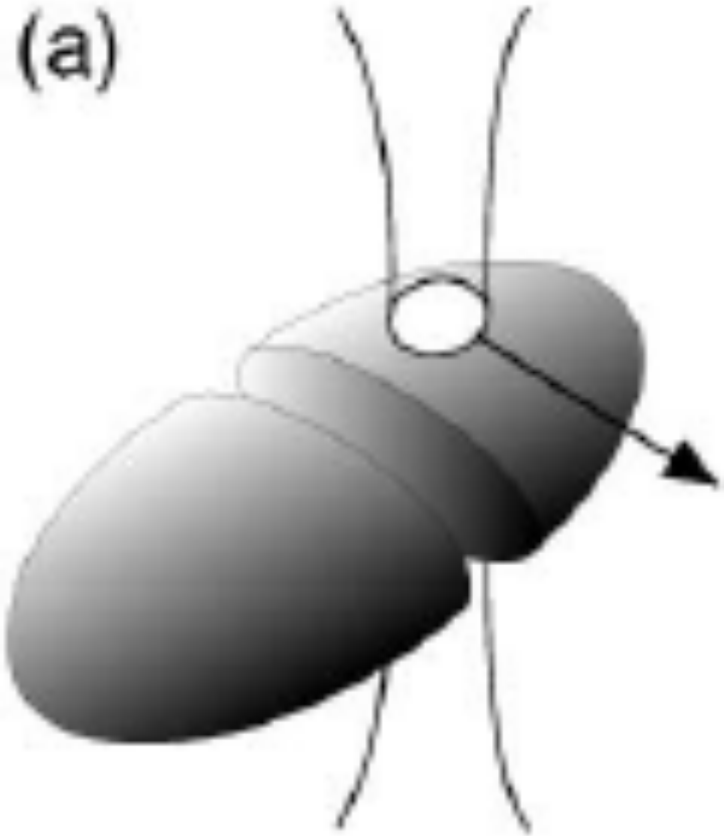


Fig. 1. Observation of vortex lattices. The examples shown contain approximately (**A**) 16, (**B**) 32, (**C**) 80, and (**D**) 130 vortices. The vortices have "crystallized" in a triangular pattern. The diameter of the cloud in (D) was 1 mm after ballistic expansion, which represents a magnification of 20. Slight asymmetries in the density distribution were due to absorption of the optical pumping light.

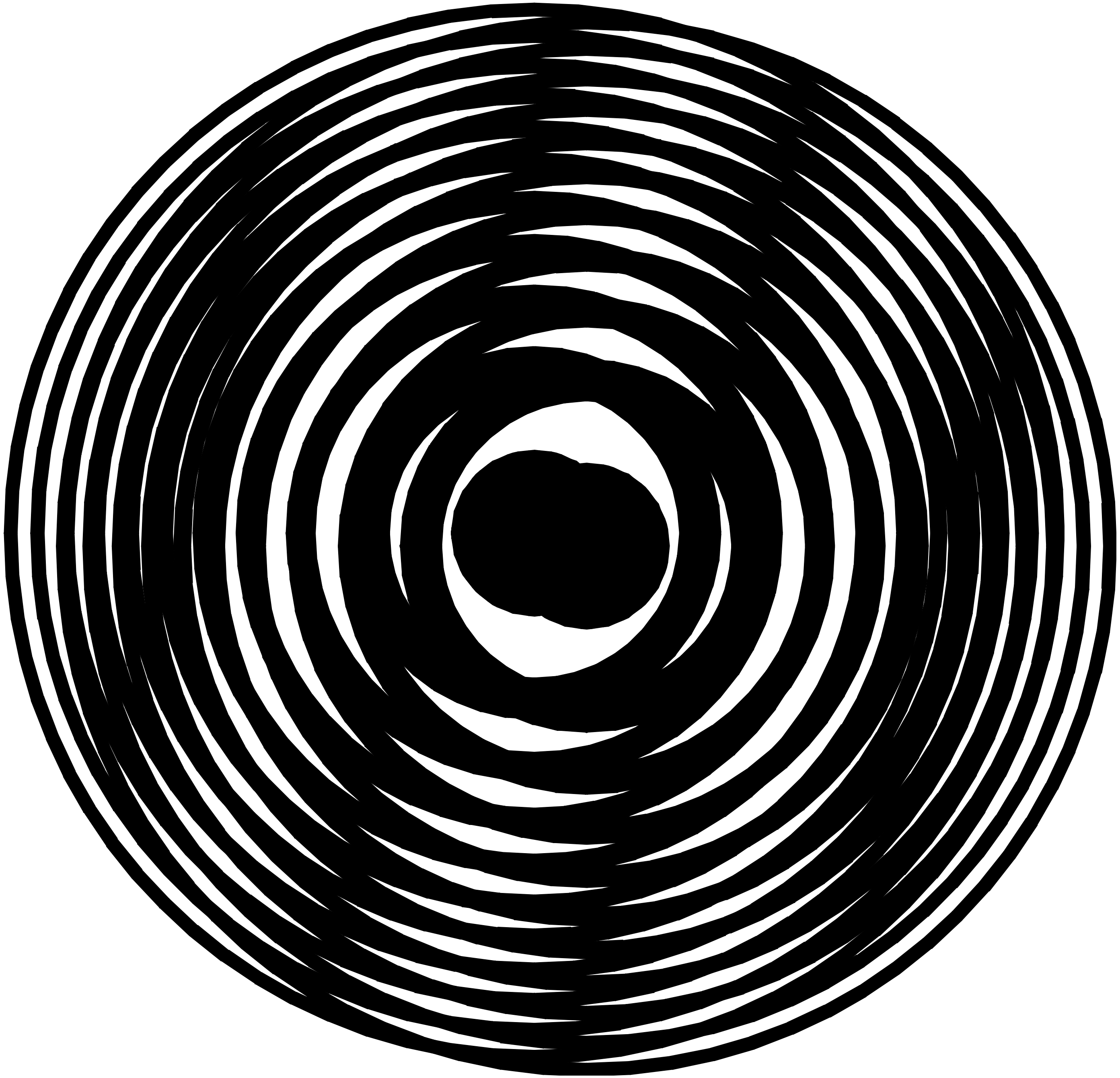
Abrikosov lattice

J.R. Abo-Shaeer, C. Raman, J.M. Vogels, and W. Ketterle:
Observation of Vortex Lattices in Bose-Einstein Condensates.
Science 292, 476-479 (2001).

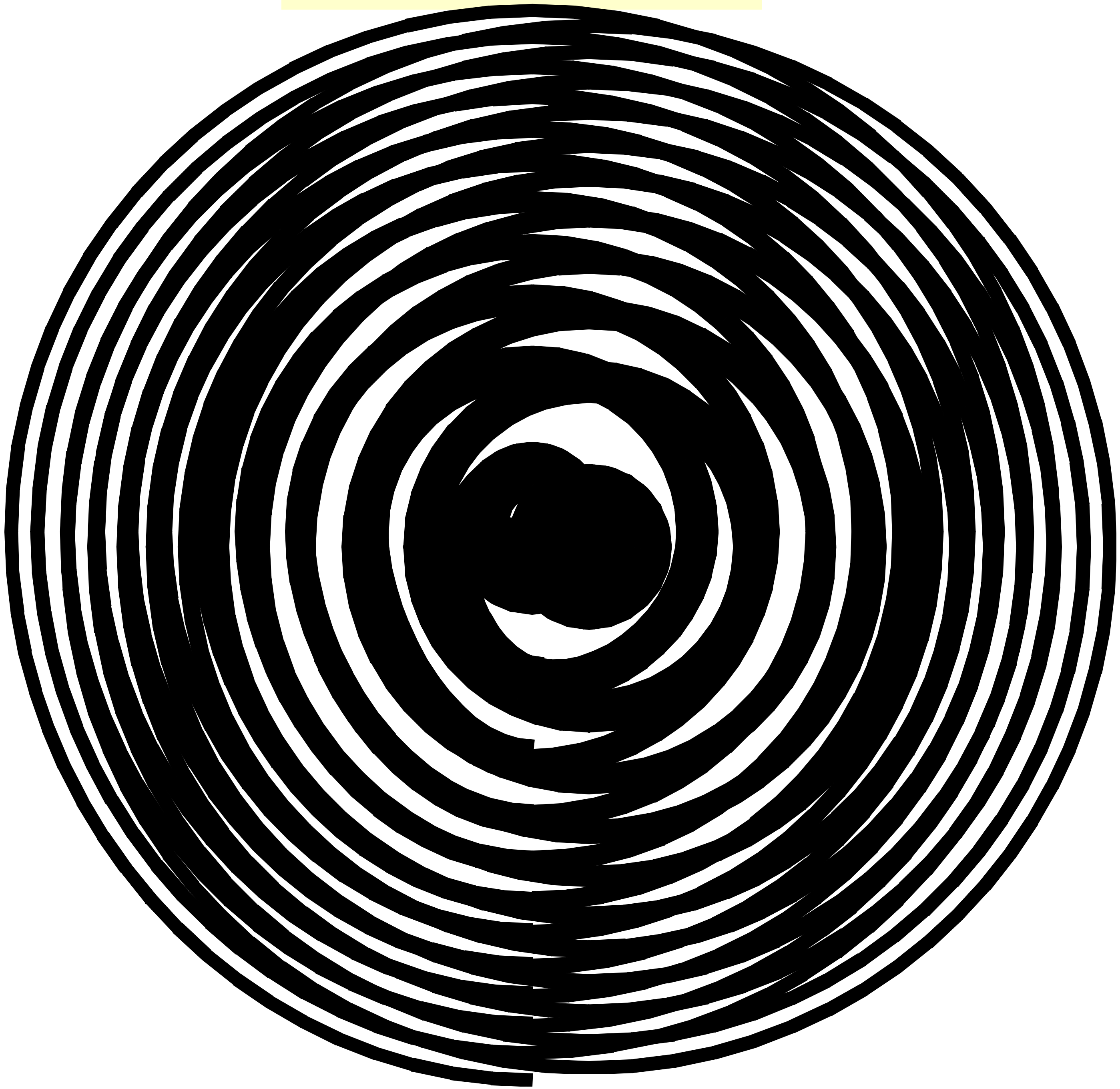
sweeping a laser beam to generate vortex!



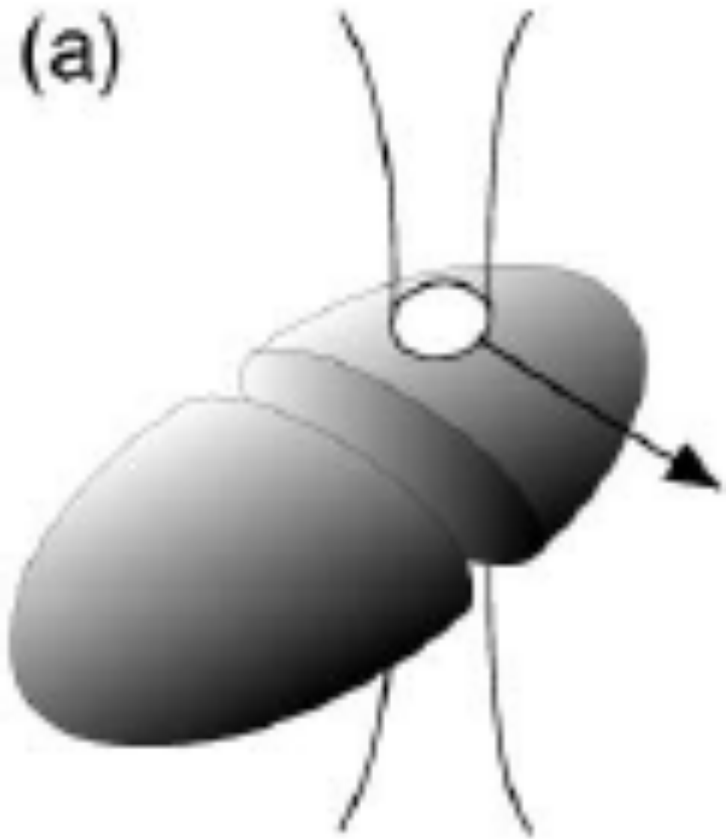
(wavefronts of matterwaves realeased from two BECs)

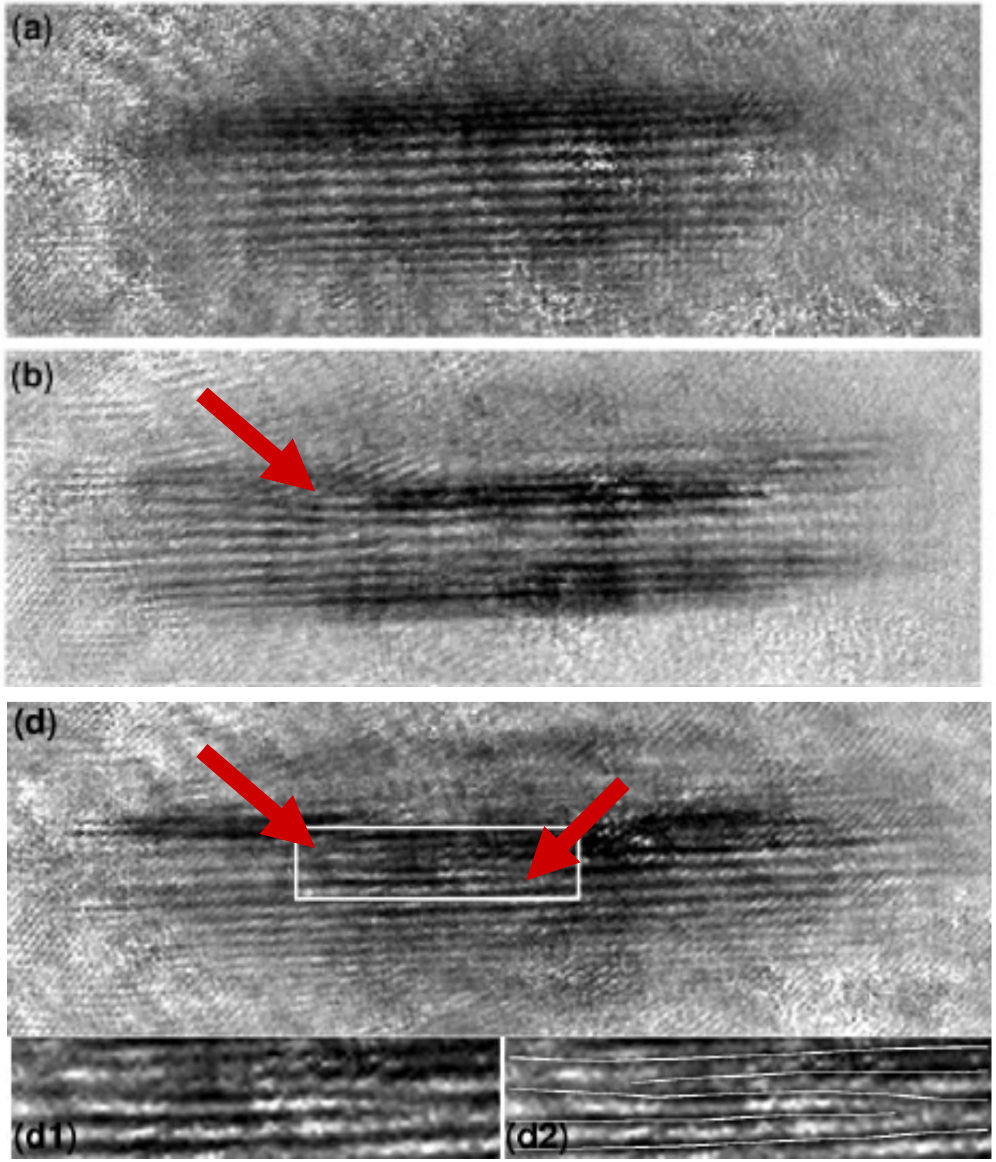


BEC with a vortex



Interferometric detection of vortex pair





"Observation of vortex phase singularities in Bose-Einstein condensates."
S. Inouye *et al.,* PRL, **87**, 080402 (2001).

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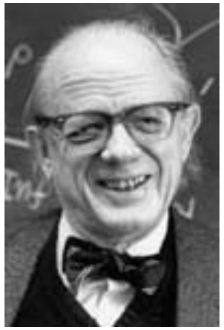
$$H = \int d\mathbf{r} \left[\underbrace{-\hat{\psi}^\dagger(\mathbf{r}) \frac{\hbar^2}{2m} \nabla^2 \hat{\psi}(\mathbf{r})}_{\text{Kinetic energy}} + \underbrace{V(\mathbf{r}) \hat{\psi}^\dagger(\mathbf{r}) \hat{\psi}(\mathbf{r})}_{\text{Confining potential}} + \underbrace{\frac{U_0}{2} \hat{\psi}^\dagger(\mathbf{r}) \hat{\psi}^\dagger(\mathbf{r}) \hat{\psi}(\mathbf{r}) \hat{\psi}(\mathbf{r})}_{\text{Interaction between atoms}} \right]$$

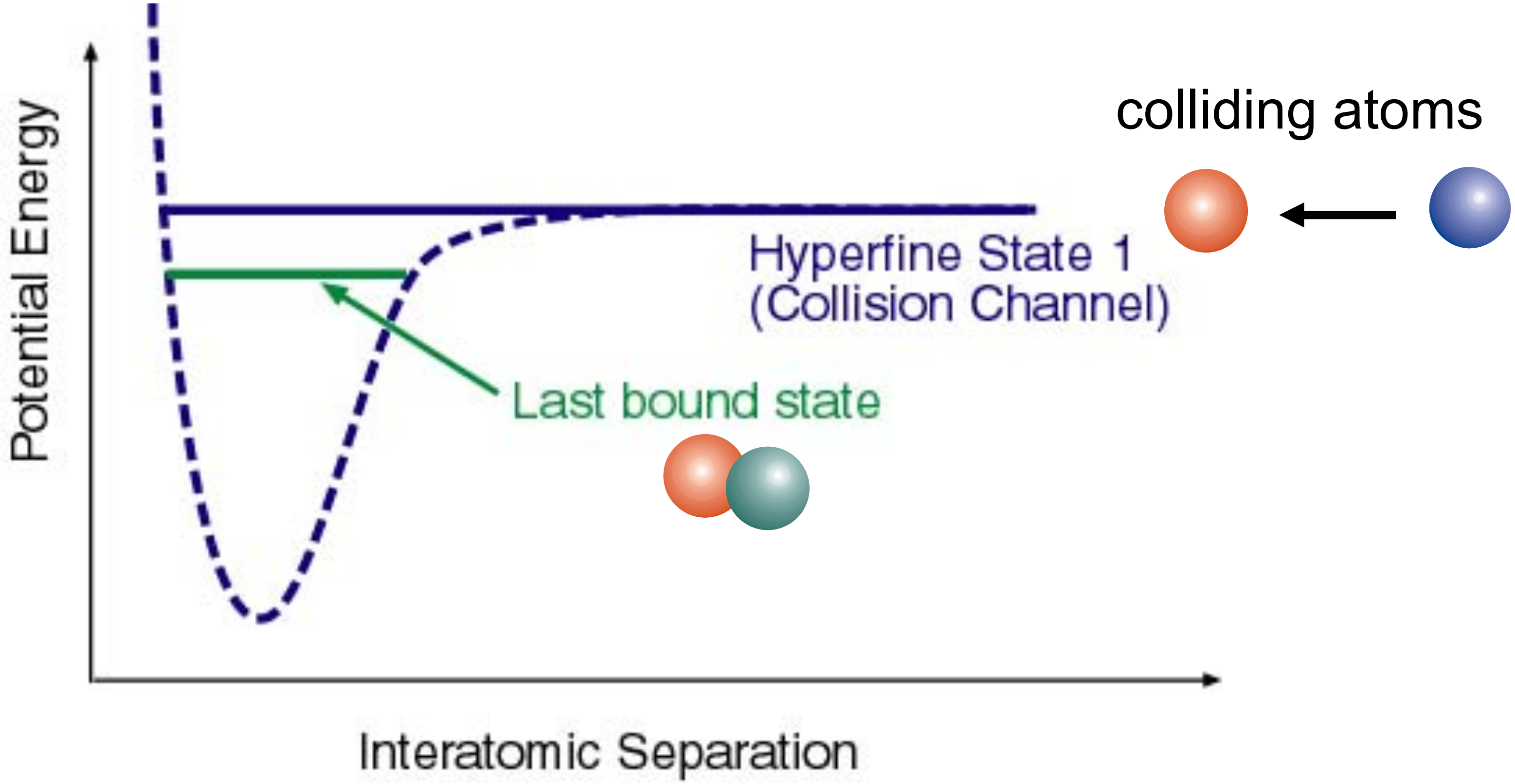
$$U_0 = 4\pi\hbar^2 a/m$$

Can we tune the scattering length?

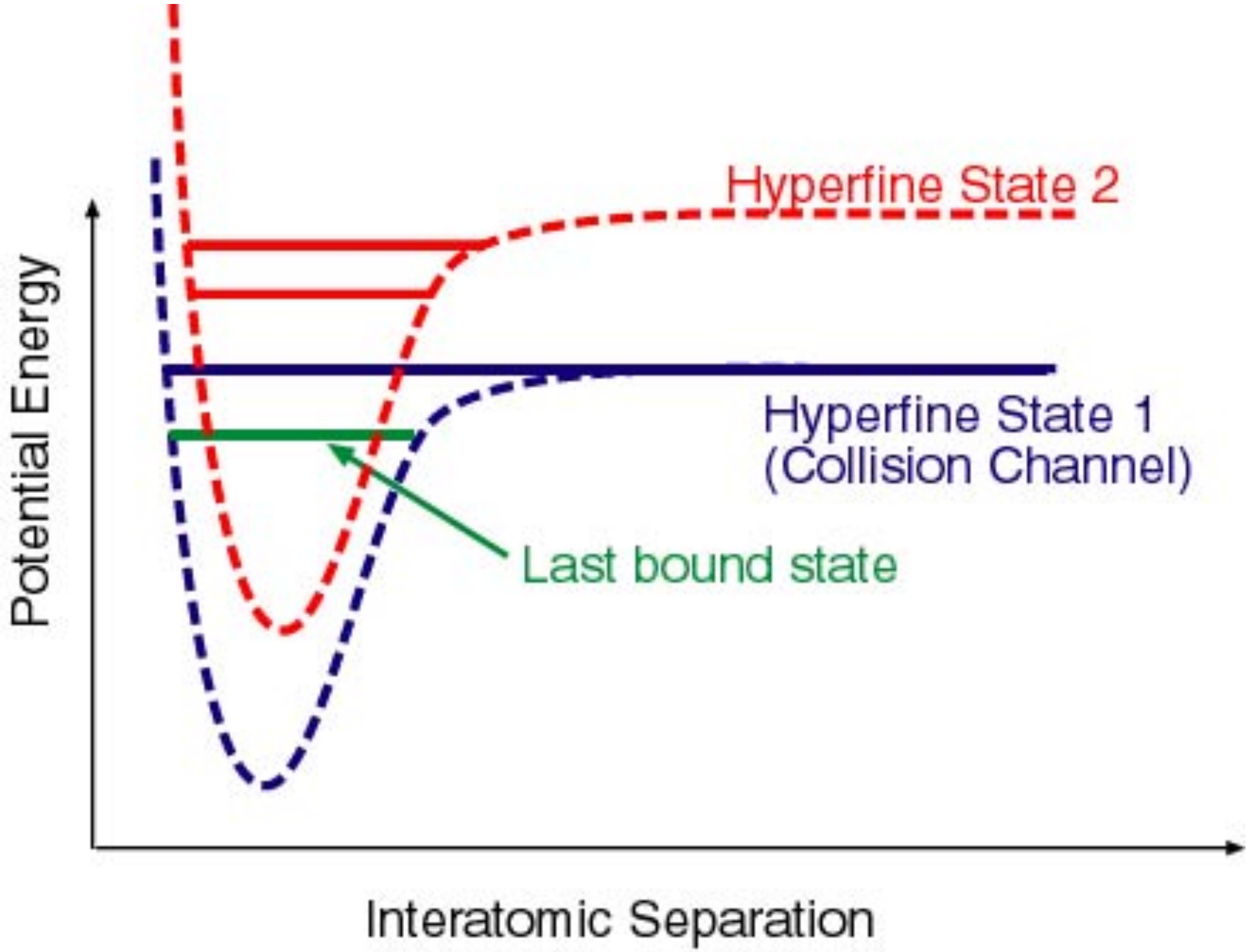
Tuning the interaction
(Feshbach resonance)



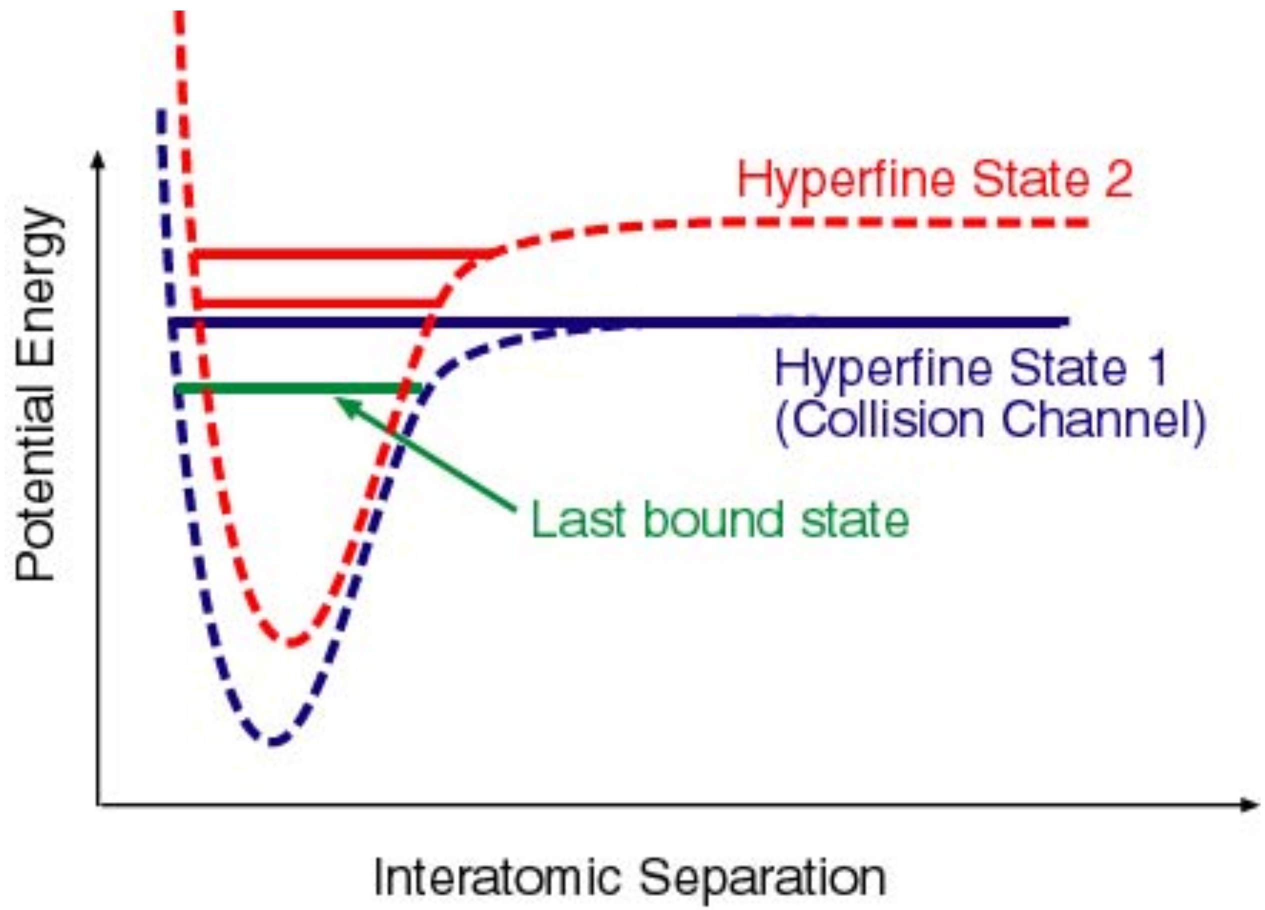
Herman Feshbach



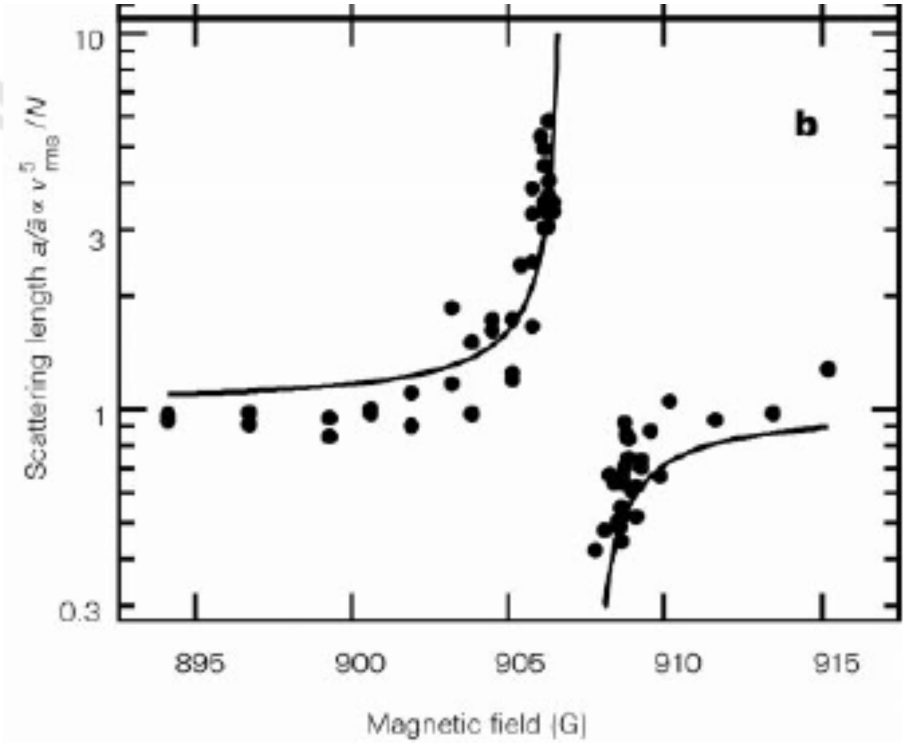
Use nuclear spin



Interference!

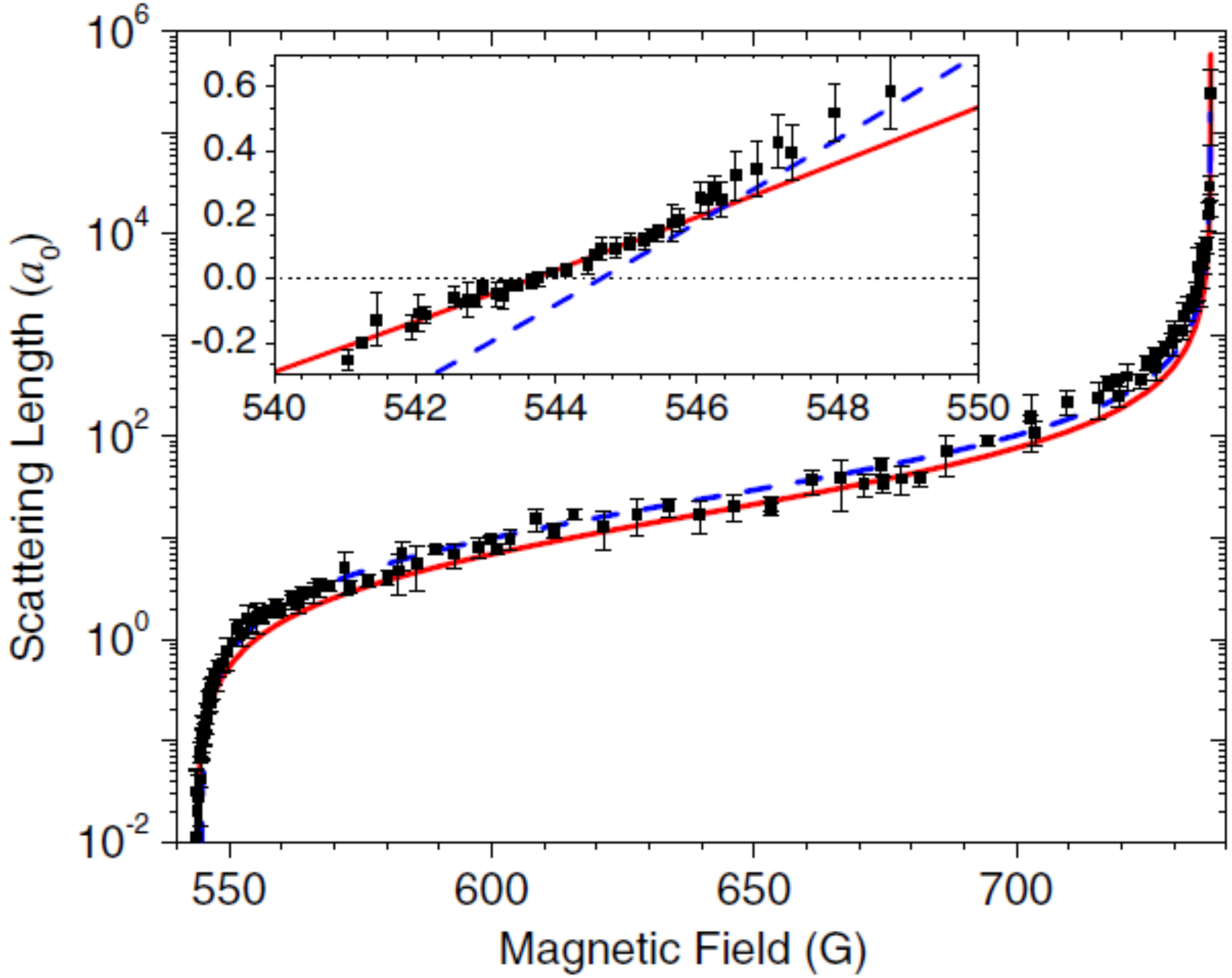


“U” is modified by factor of 20

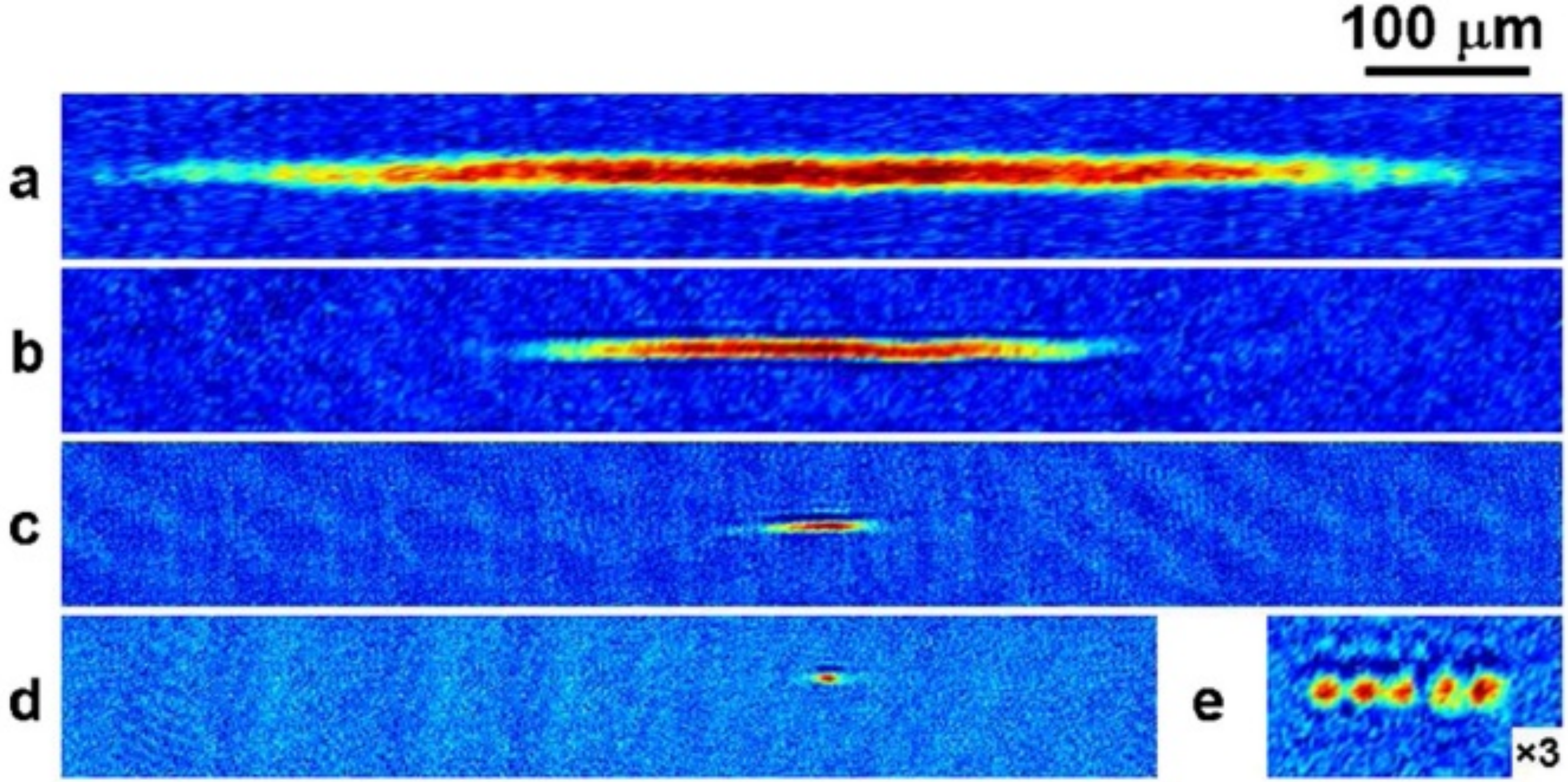


"Observation of Feshbach resonances in a Bose-Einstein condensate."
S. Inouye *et al.*, Nature **392**, 151 (1998).

"U" is modified by seven orders of magnitude



"Extreme Tunability of Interactions in a 7Li Bose-Einstein Condensate"
S. E. Pollack, D. Dries, M. Junker, Y. P. Chen, T. A. Corcovilos, and R. G. Hulet,
Physical Review Letters 102, 090402 (2009).



$$i\hbar\frac{\partial\psi(r)}{\partial t}=\left(-\frac{\hbar^2}{2m}\nabla^2+V_{trap}(r)+\frac{4\pi\hbar^2 a}{m}\left|\psi(r)\right|^2\right)\psi(r)$$

"Extreme Tunability of Interactions in a 7Li Bose-Einstein Condensate“
S. E. Pollack, D. Dries, M. Junker, Y. P. Chen, T. A. Corcovilos, and R. G. Hulet,
Physical Review Letters 102, 090402 (2009).

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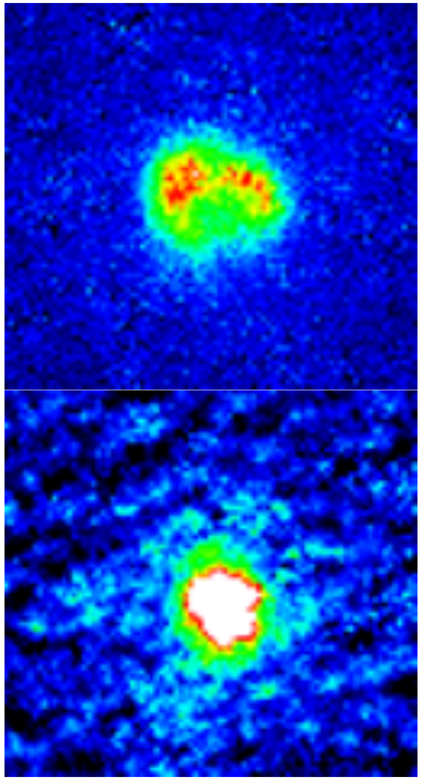
What can we do with two BECs?

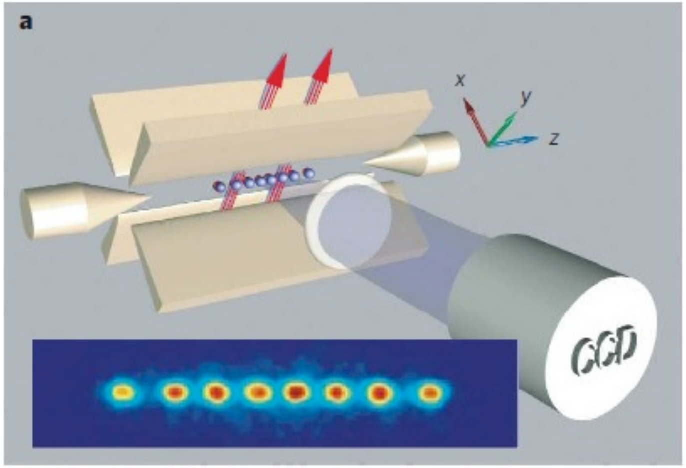
^{41}K

^{87}Rb



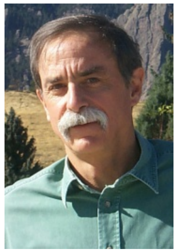
Make molecules!?

Cold ions
(trapped ions)

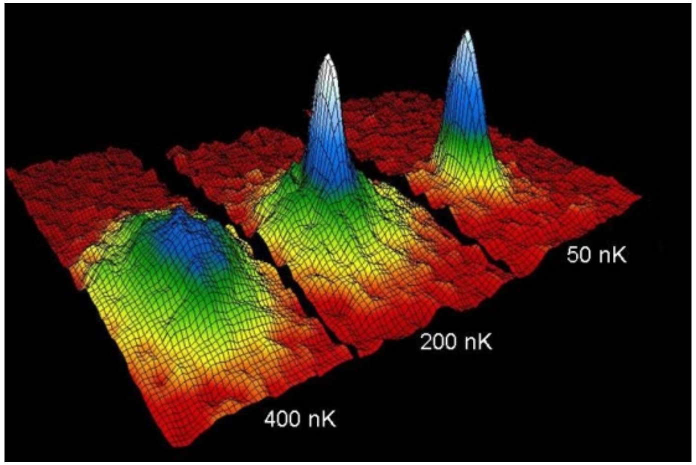


Blatt & Wineland, Nature
453 1008 (2008)

- Frequency standards
- Quantum Information

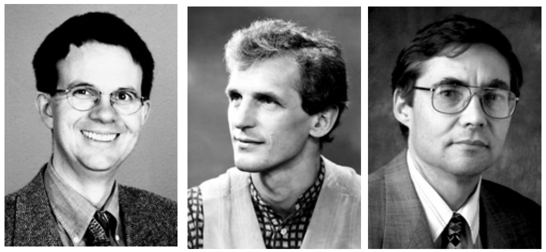


Cold atoms



Anderson et al., Science,
269 198 (1995)

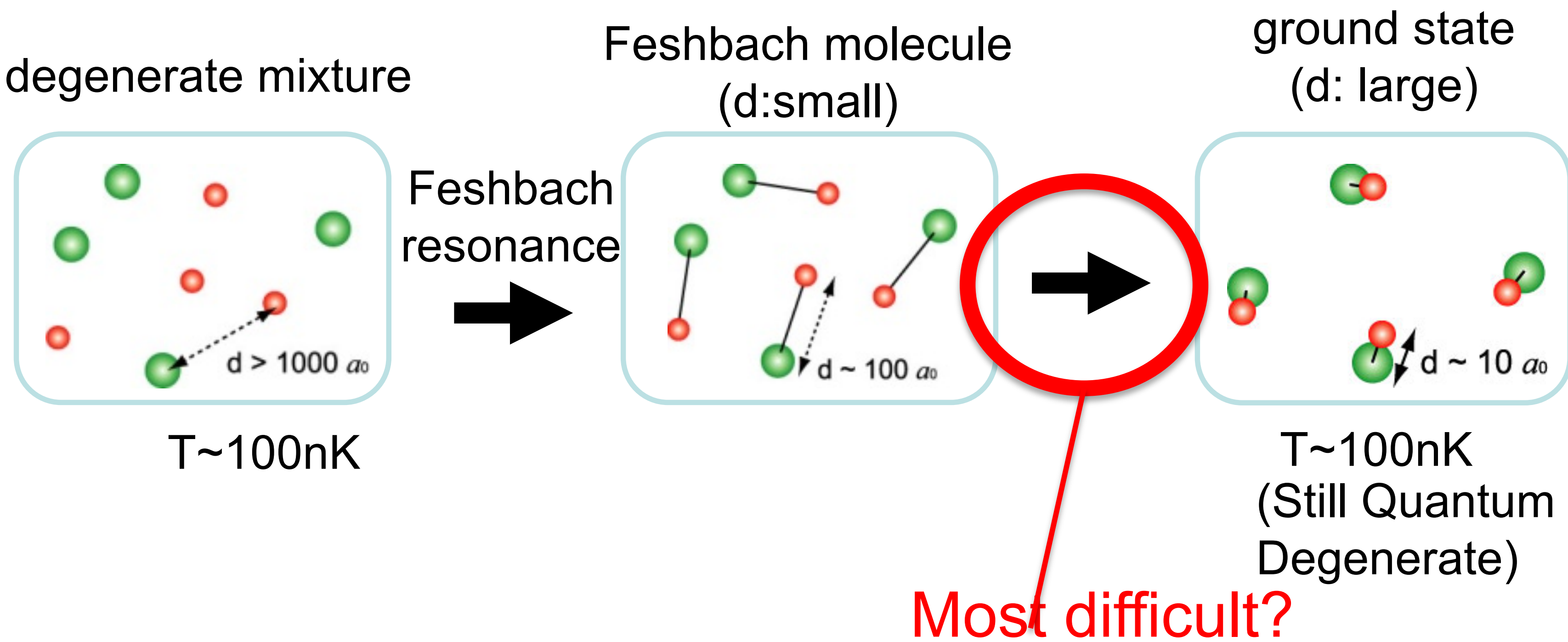
- Bose Condensation
- Strongly correlated gas
- Frequency standards



Cold molecules?

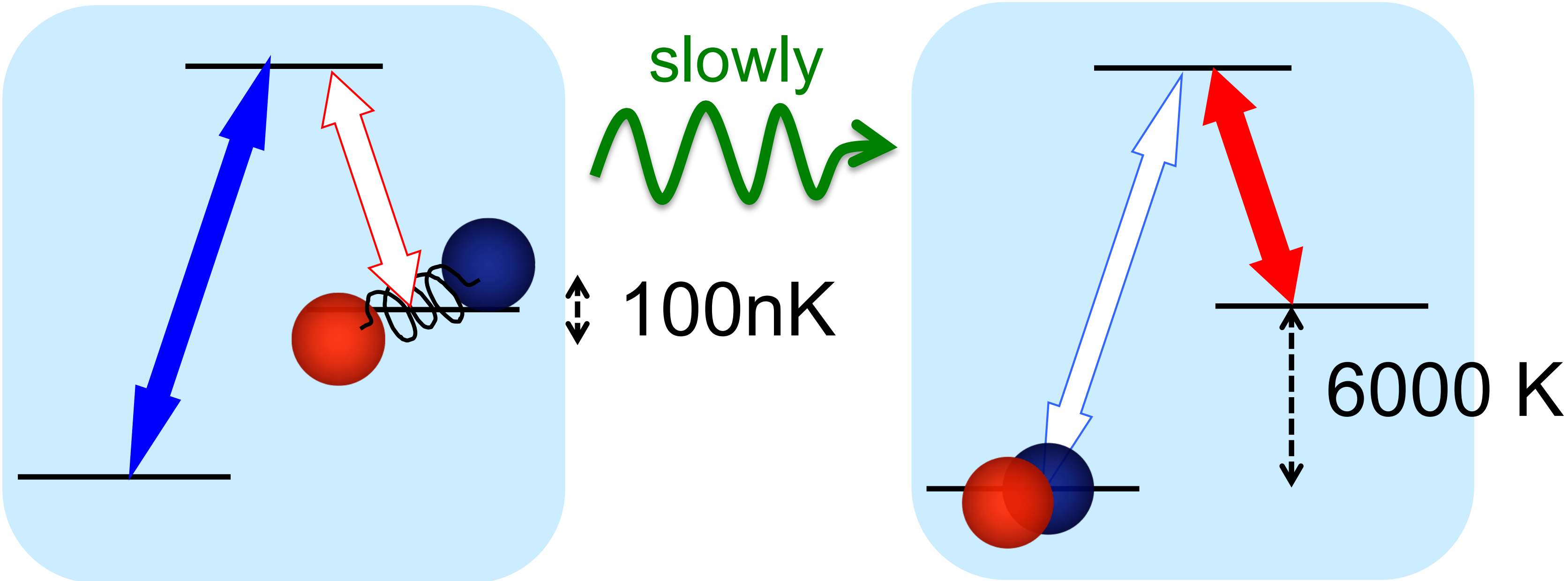
"New Frontier"

“Indirect” method (2005~)



No heating: 100nK out of 6000K will kill the sample!

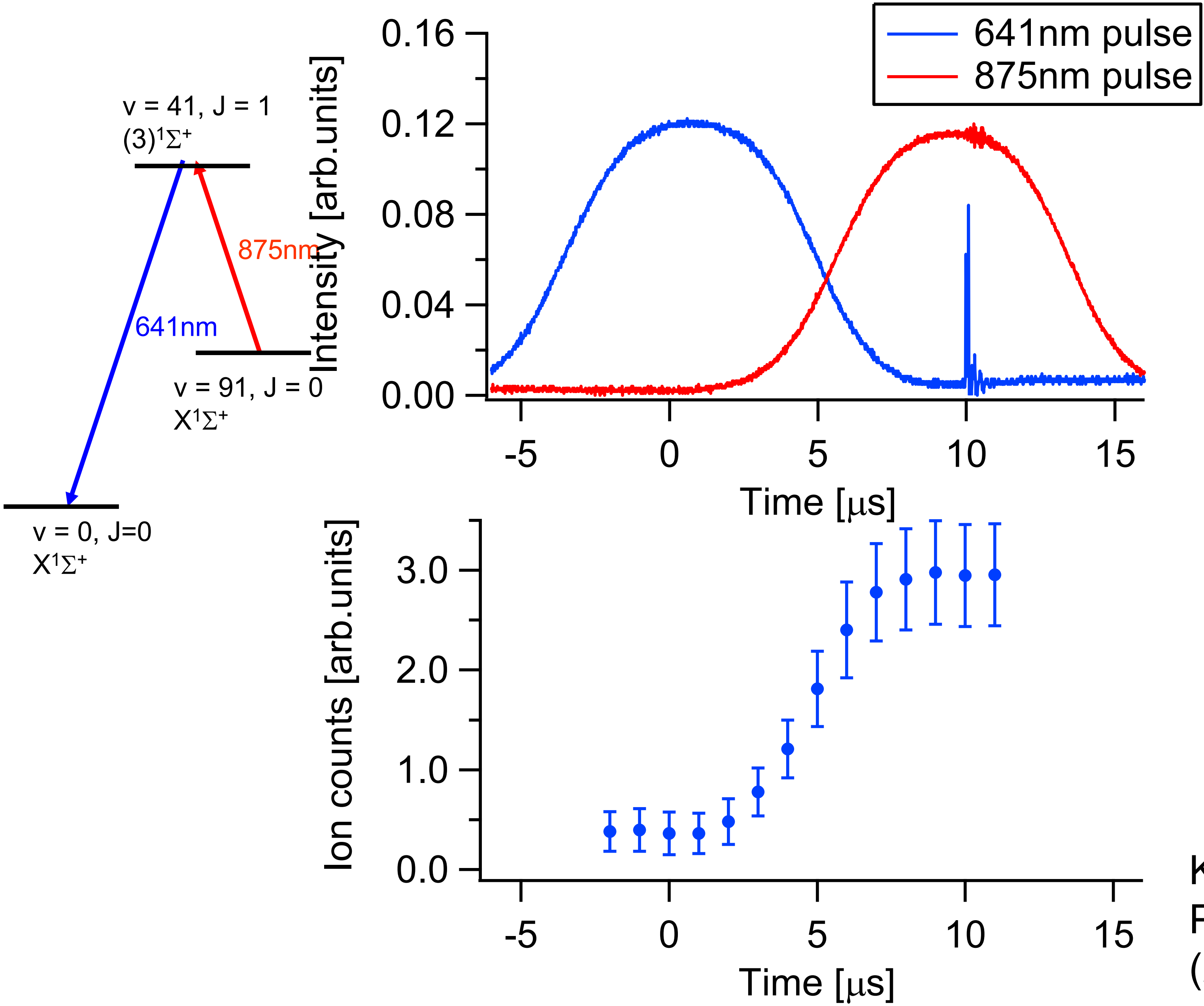
STIRAP



*Stimulated Raman Adiabatic Passag

- Find the right excited state
- Stabilize two laser frequencies in ~10^{-10} level (i.e. ~kHz leve

Achieving rovibrational ground state



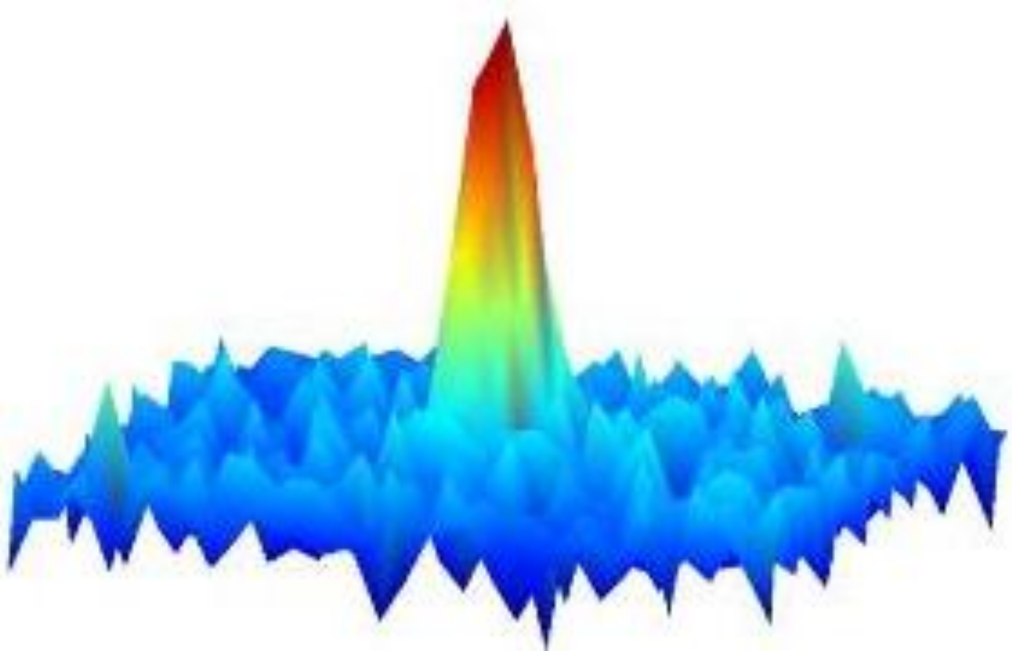
K. Aikawa et al., PRL **105**, 203001 (2010)

There is a good news and bad news...

--- Good news is we produced ultracold groundstate polar molecules!

--- Bad news is the density is really really low!

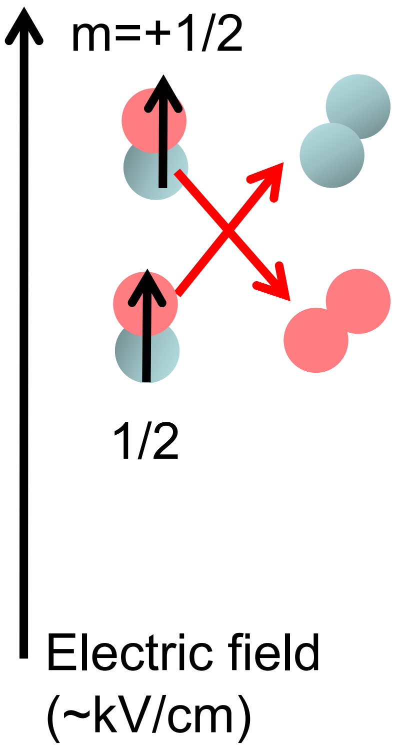
Ultracold polar molecules near degeneracy (by JILA)

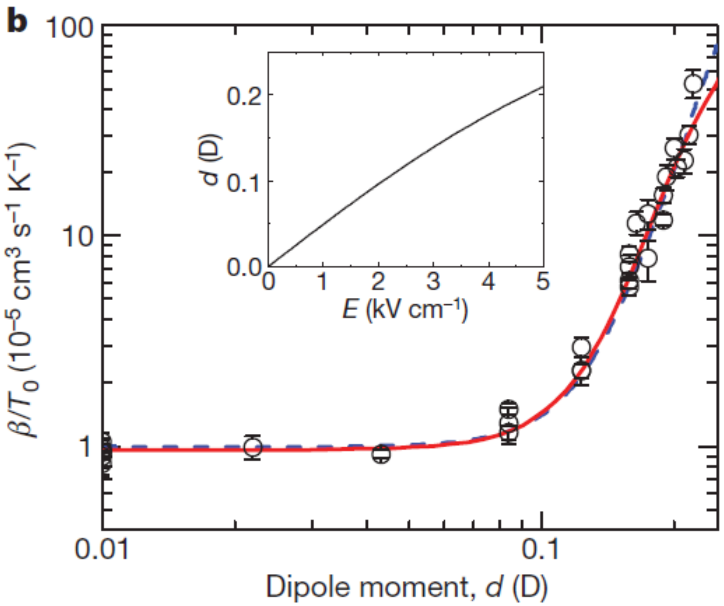


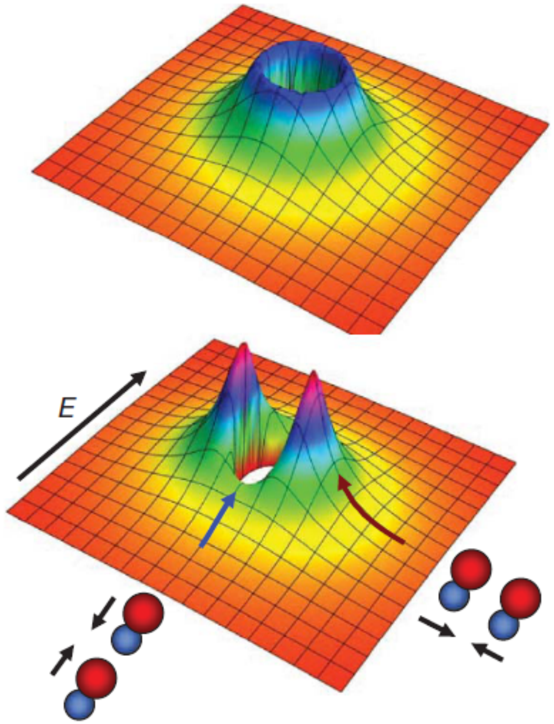
Ultracold KRb molecules imaged by direct absorption
D.S. Jin and J. Ye, Physics Today, May 2011

Directional chemistry (JILA)

same internal states AND
dipoles aligned by an external field

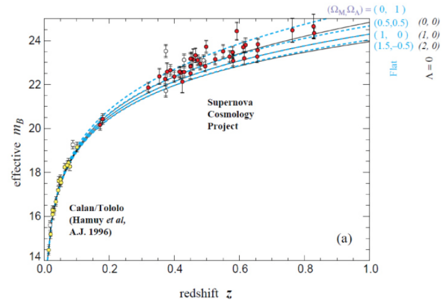






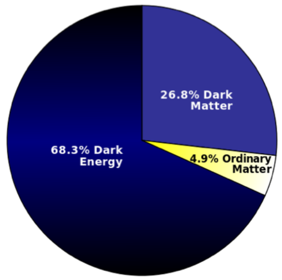
K.-K. Ni et al., Nature 464, 1324 (2010)

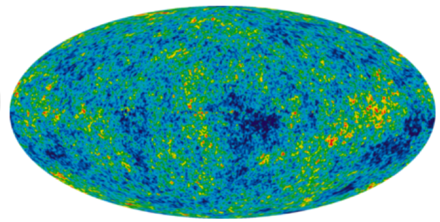
Measure time variation of fundamental constants!



General relativity + Λ-CDM model is successful in explaining following phenomena:

- accelerating expansion of universe
- Cosmic Microwave Background
- Large scale structure





However, origin of dark energy (and dark matter) is not understood.

Possible extensions to the Λ-CDM

Quintessence

$\rightarrow$Fluctuation of fundamental constants??

$$\alpha = \frac{1}{4\pi\varepsilon_0}\frac{e^2}{\hbar c} \qquad \mu = \frac{m_e}{m_p} \approx \frac{1}{1836} \qquad g_{\mathrm{P}} \quad \text{, etc.}$$

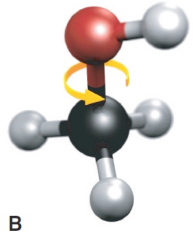
We focused on electron-to-proton mass ratio μ

The limit of time variation of $m_e/M_p(\equiv\mu)$

Radio-astronomical observations

Alcohol in the early universe
(J. Bagdonaite *et al*, Science 339, 46 (2013))

$$\Delta\mu/\mu = (0.0 \pm 1.0) \times 10^{-7} \quad \text{(in } 7 \times 10^9 \text{ years)}$$

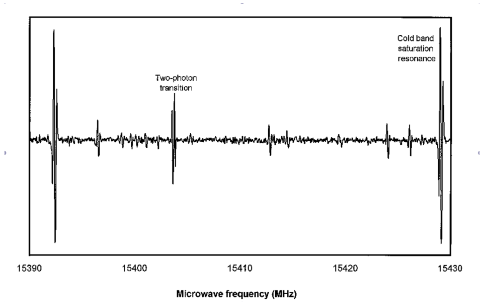


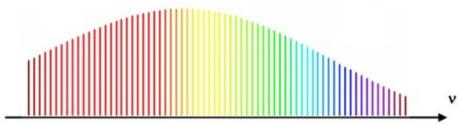
The limit of time variation of $m_e/M_p (\equiv\mu)$

Laboratory observations

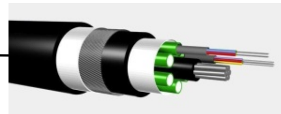
molecular spectroscopy of SF_6
A. Shelkovnikov et al, PRL 100, 150801 (2008)

$$\dot{\mu}/\mu = (3.8 \pm 5.6)\times 10^{-14} / year$$

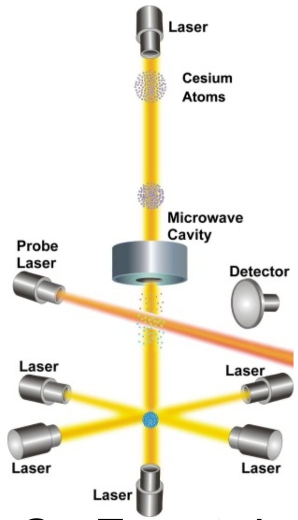




rovibrational transition in SF_6 + frequency comb

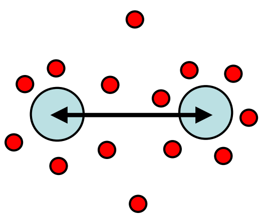


Optical Fiber link (~43km)

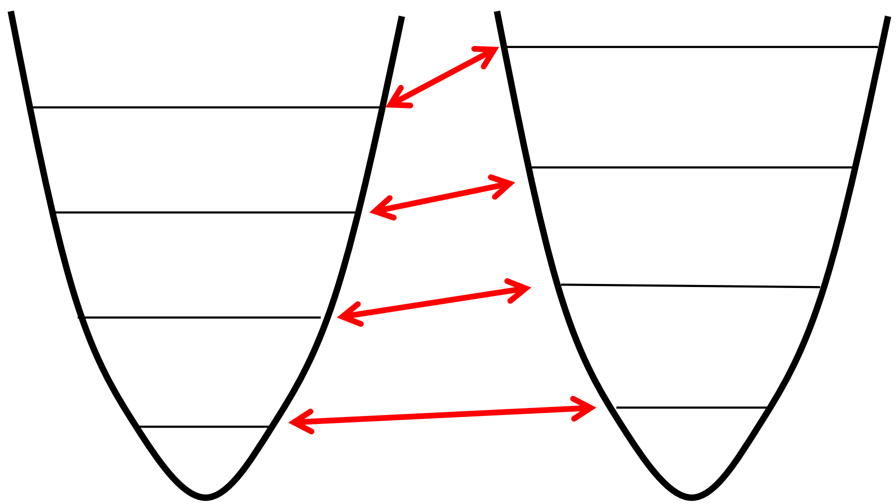


Cs Fountain

Why molecule?



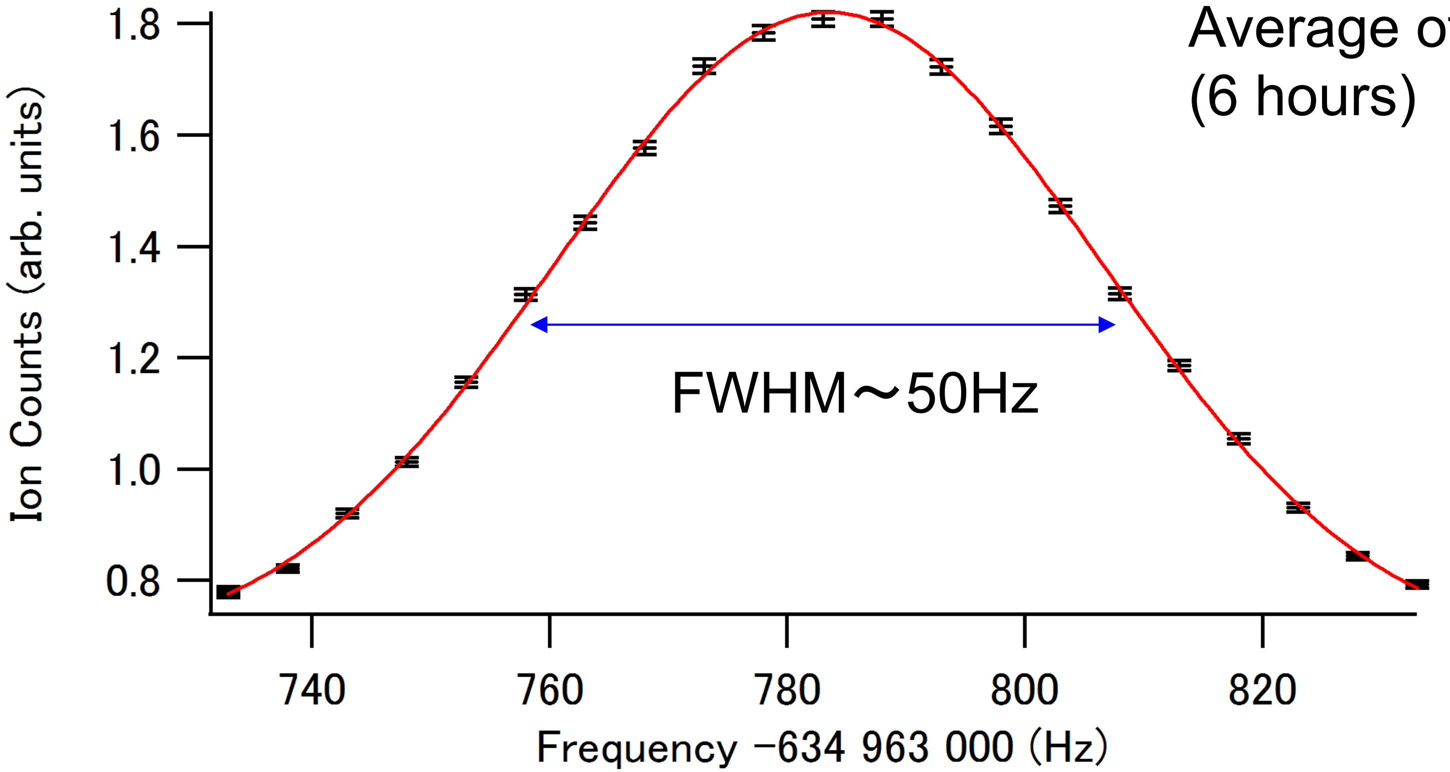
Frequencies are directly related to the inertial mass of nucleus.



Large m Small m

$$\frac{\delta E}{E} = \frac{1}{2}\frac{\delta m}{m}$$

Ultracold molecule is ideal for precision spectroscopy!



Average of 5000 sweeps
(6 hours)

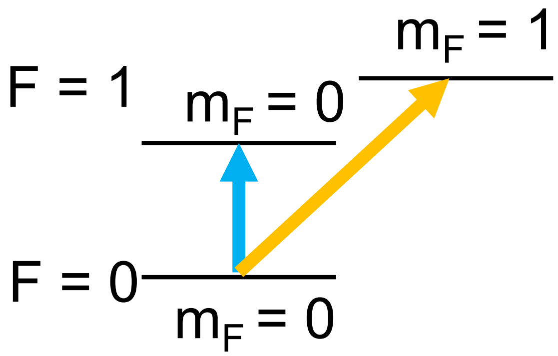
634 963 783.458±0.093 Hz

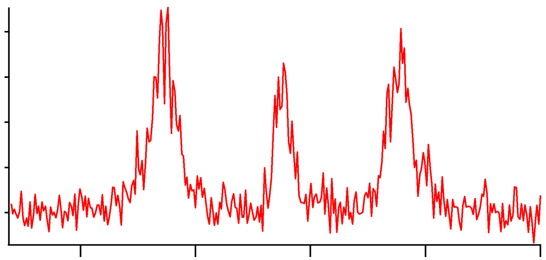
Zeeman shift compensation

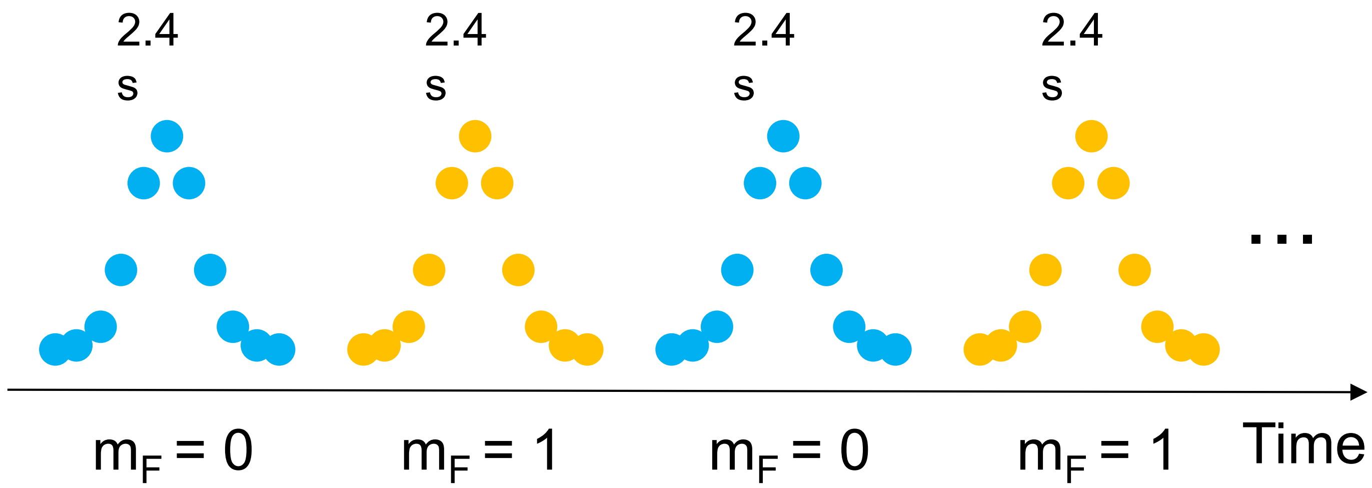
634 963 781.564±0.094 Hz

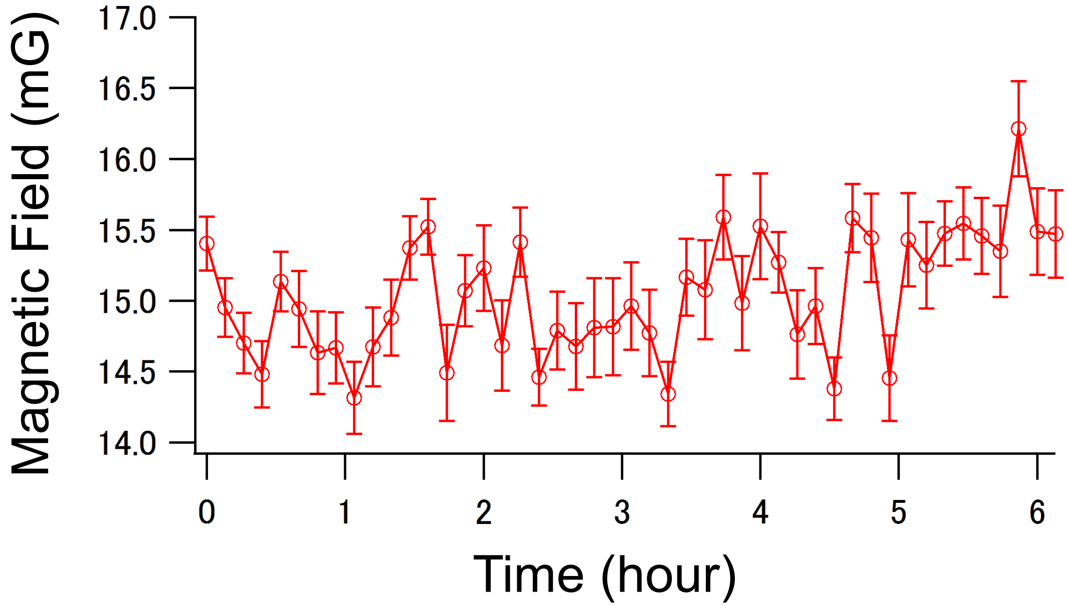
S/N ~ 500 (c.f. Number of molecules used ~ 10^6)

Calibration of the magnetic field

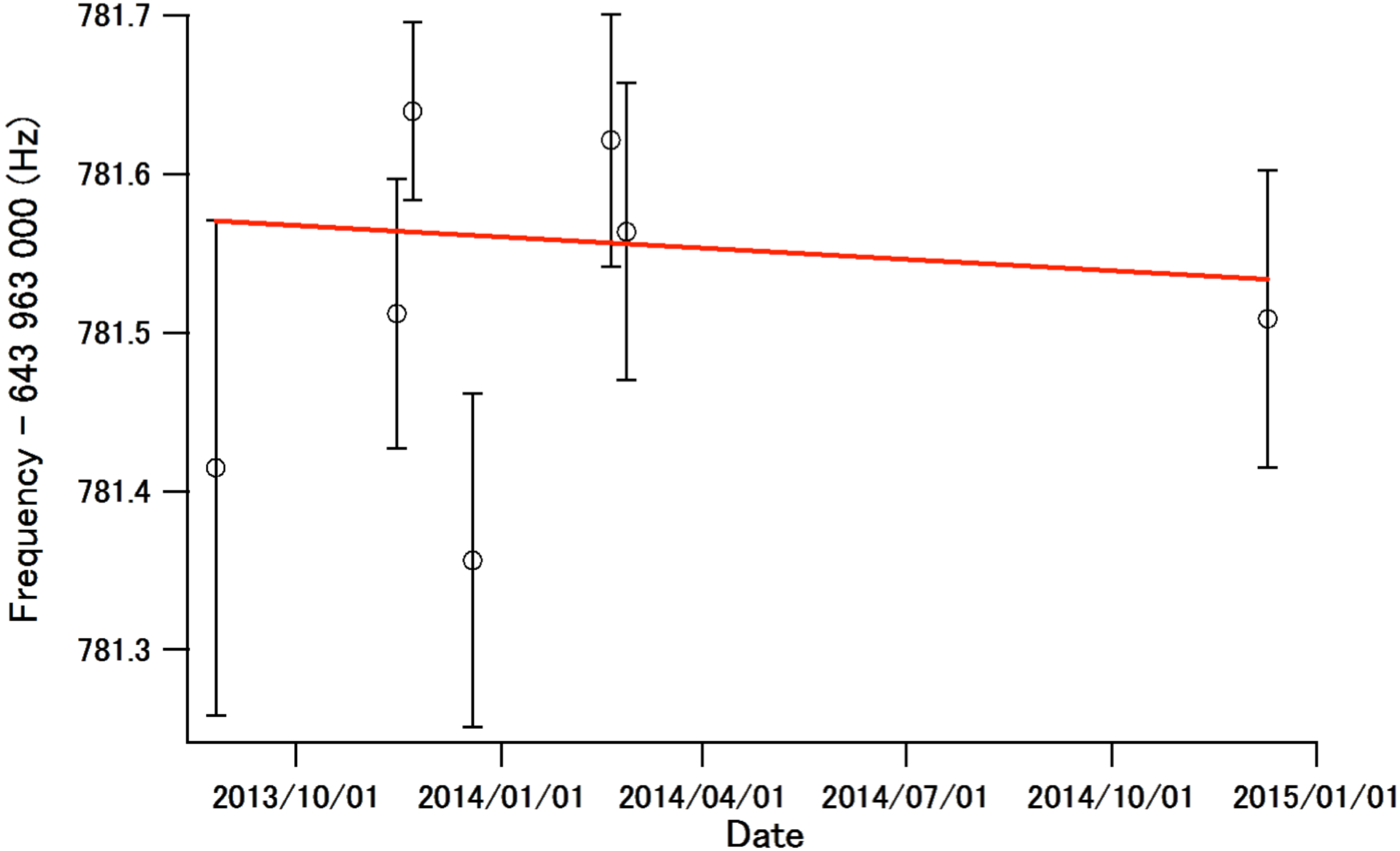








Good News: we broke the world record set by SF_6!

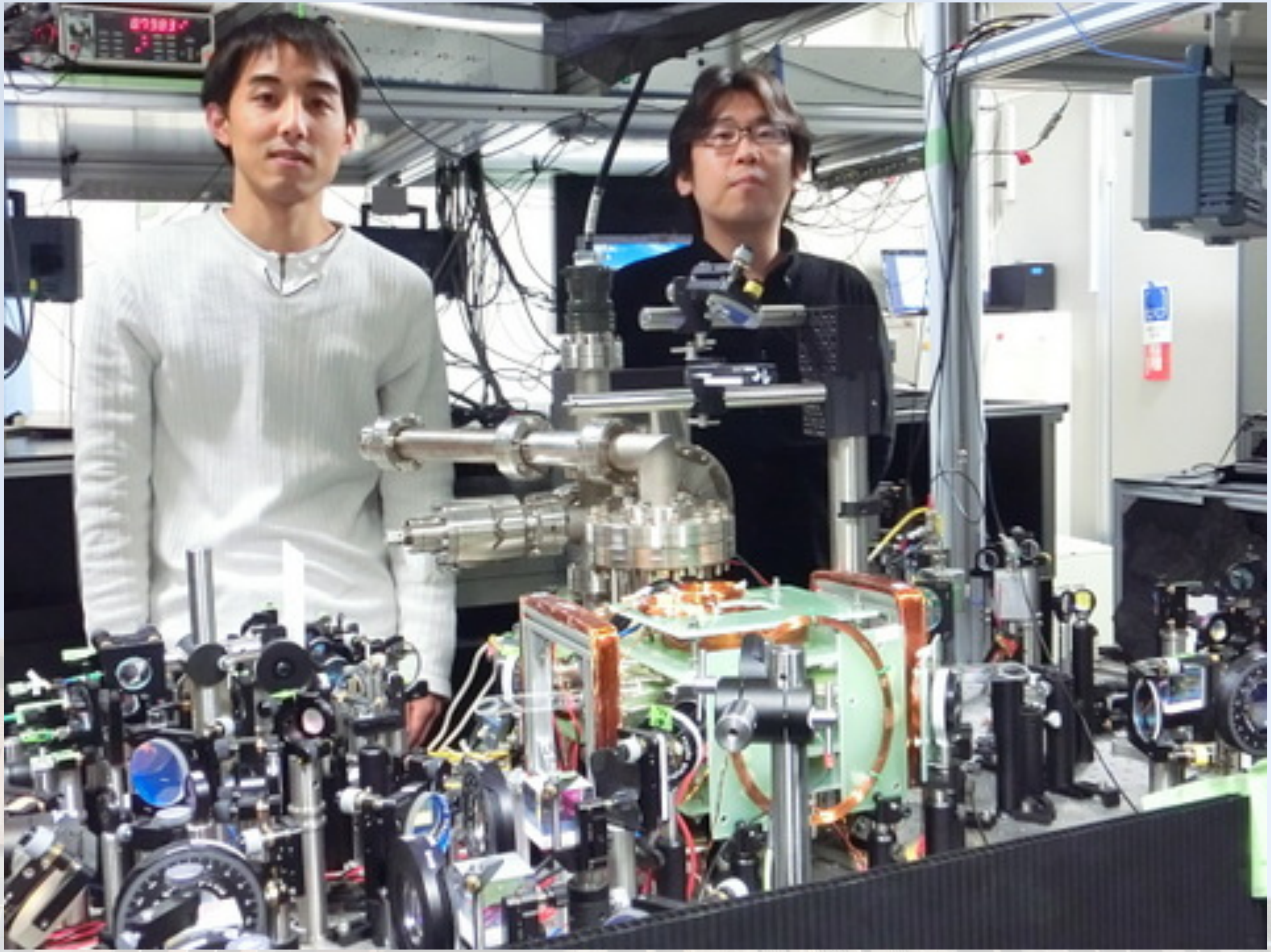


$$\frac{1}{\mu}\frac{\partial\mu}{\partial t} = \boxed{(0.30 \pm 1.00_{Stat} \pm 0.16_{Sys}) \times 10^{-14}} \text{ / year}$$

Factor of
five improvement

$$\frac{1}{\mu}\frac{\partial\mu}{\partial t} = (3.8 \boxed{\pm 5.6) \times 10^{-14}} \text{ / year}$$

A. Shelkovnikov et al.,
PRL 100, 150801(2008)



J. Kobayashi, A. Ogino, and SI

PRL 118, 163401 (2017) PHYSICAL REVIEW LETTERS week ending 21 APRIL 2017

Isotopic Shift of Atom-Dimer Efimov Resonances in K-Rb Mixtures: Critical Effect of Multichannel Feshbach Physics

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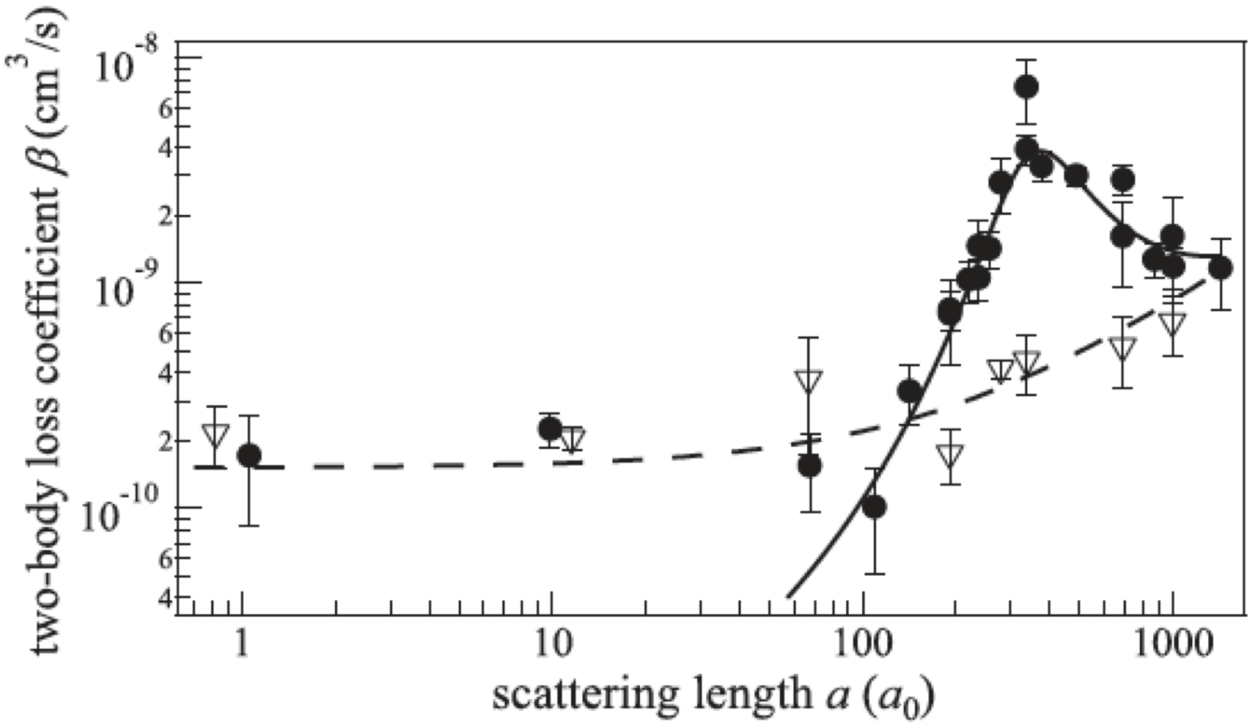
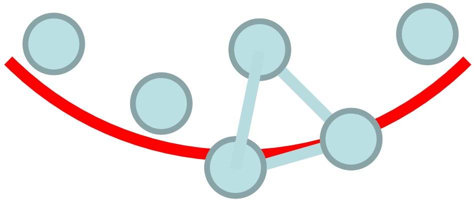
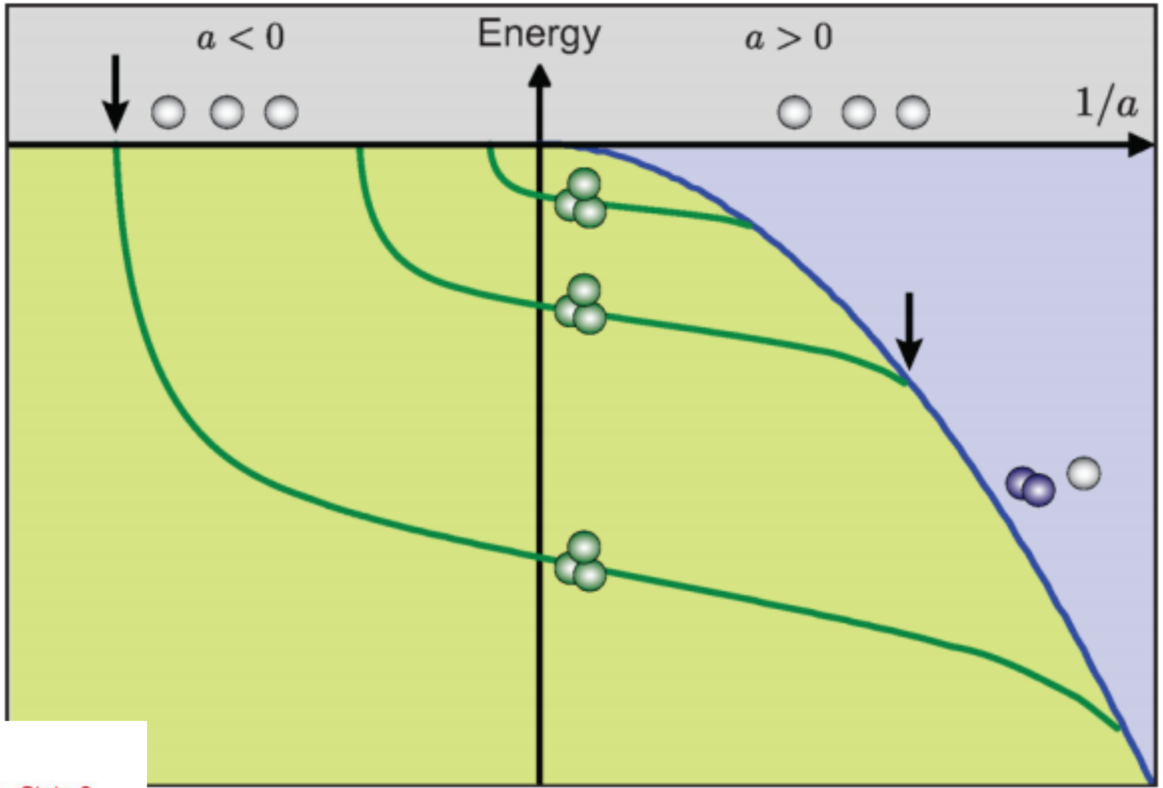
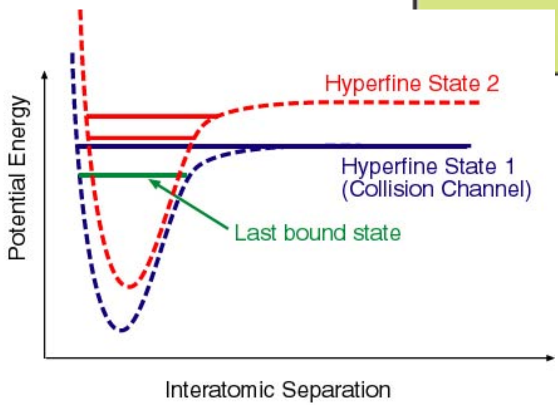
[4]*Joint Quantum Institute, University of Maryland and NIST, College Park, Maryland 20742, USA*

(Received 25 October 2016; published 17 April 2017)







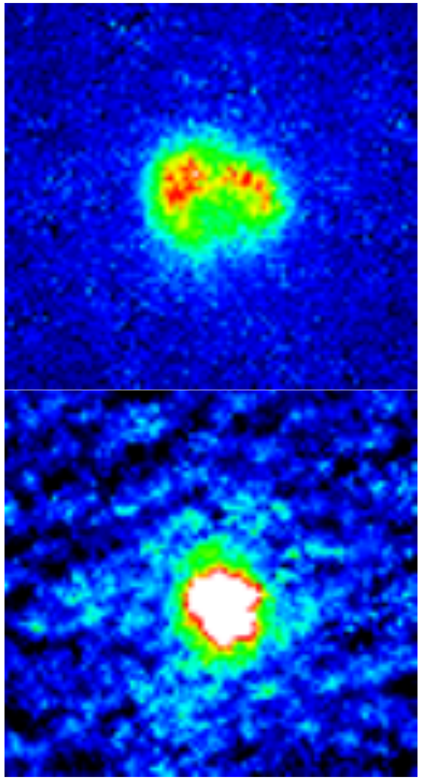


Francesca Ferlaino and Rudolf Grimm, *Physics* **3**, 9 (2010).

What can we do with two BECs?

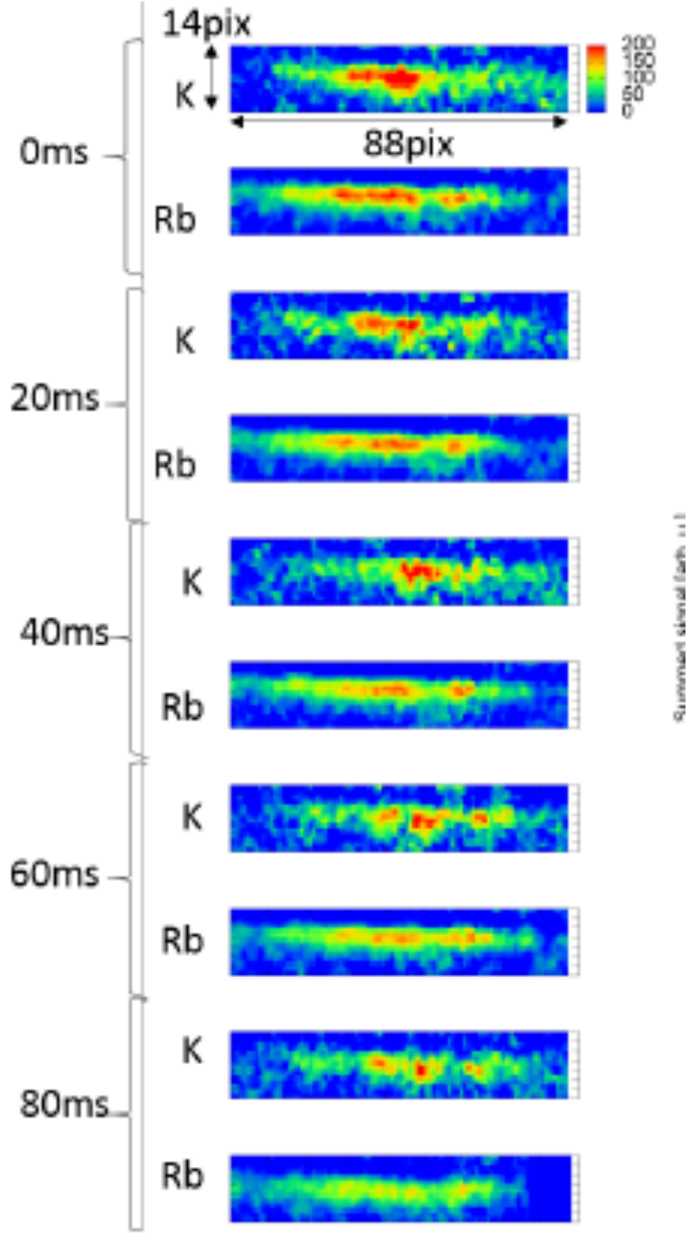
^{41}K

^{87}Rb

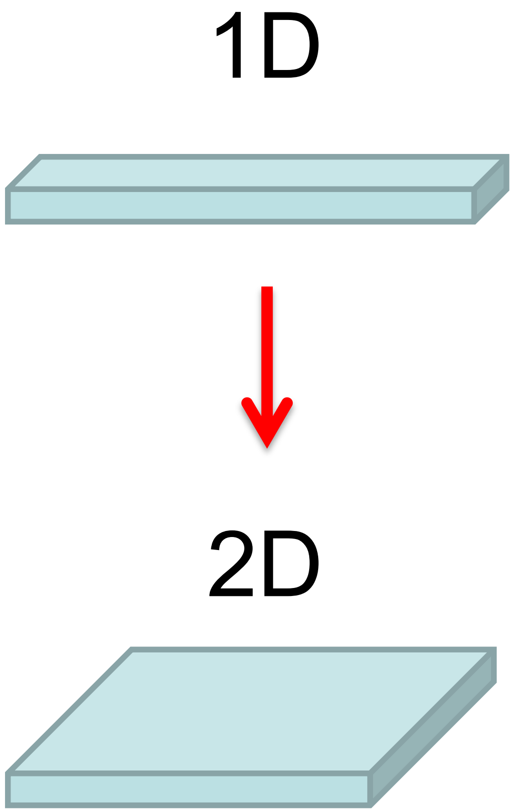


Phase separation!?

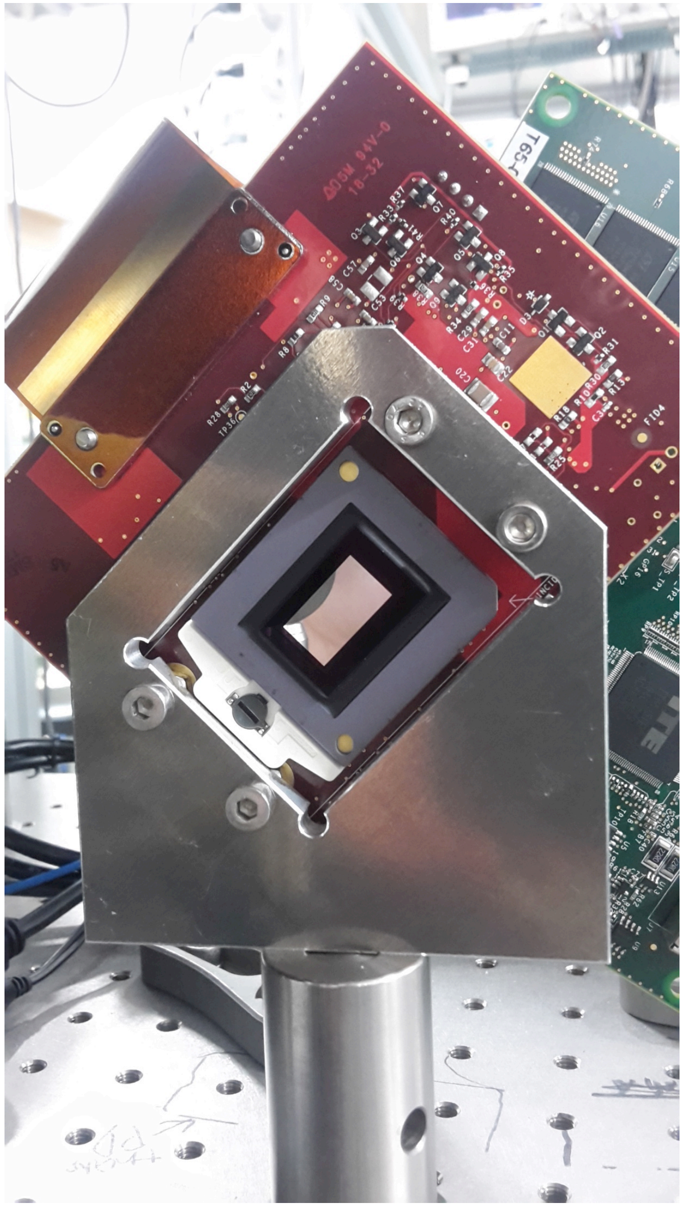
Phase separation after quenching the interaction



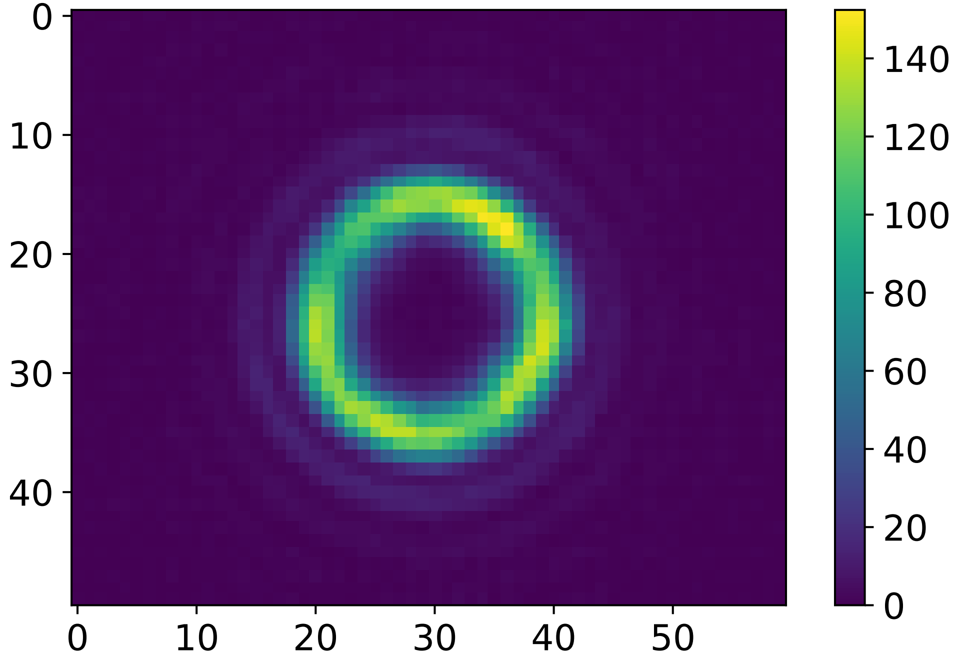
36μm x 208μm(1pix.=2.6μm)



Digital Mirror Device



Holographically generated ring beam



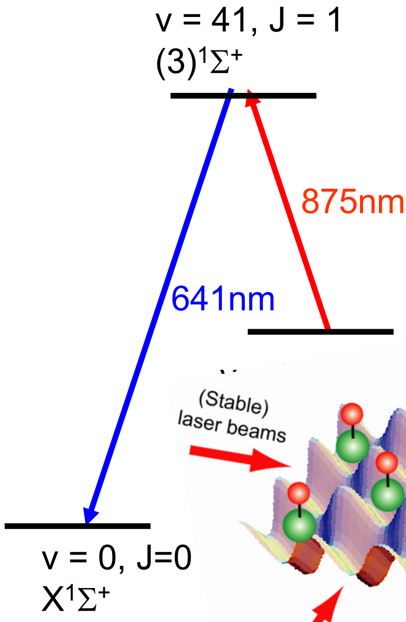
Conclusion

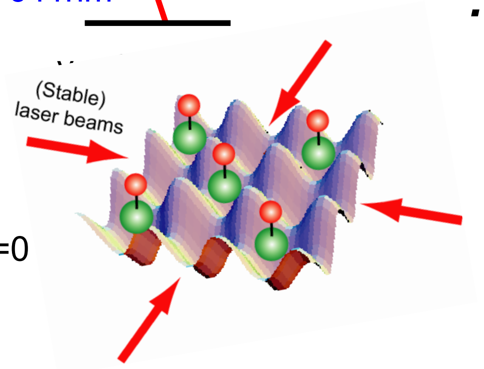
Cold atom is a versatile ground both for

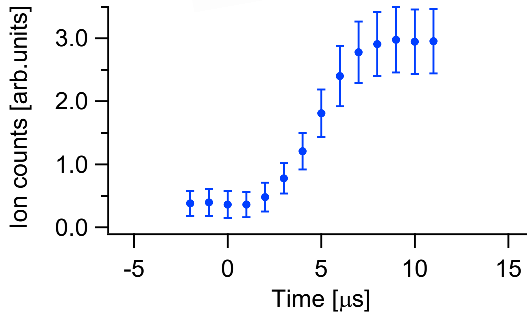
condensed matter physics

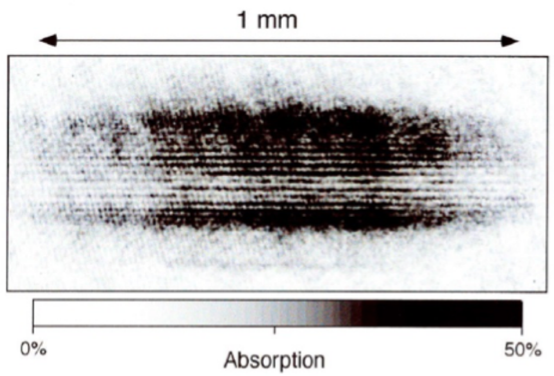
precision measurement

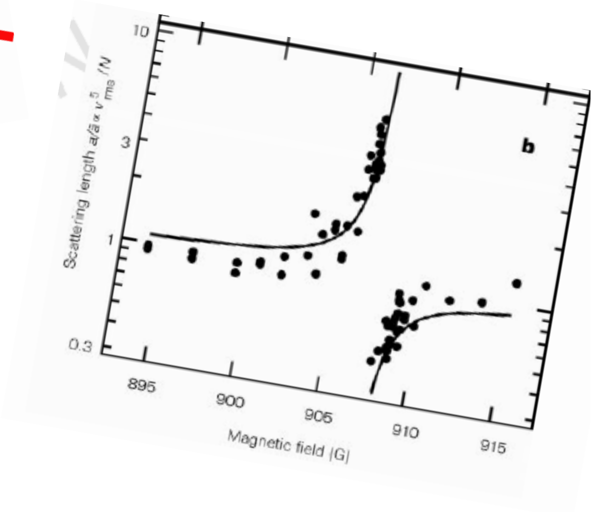
... please stay tuned

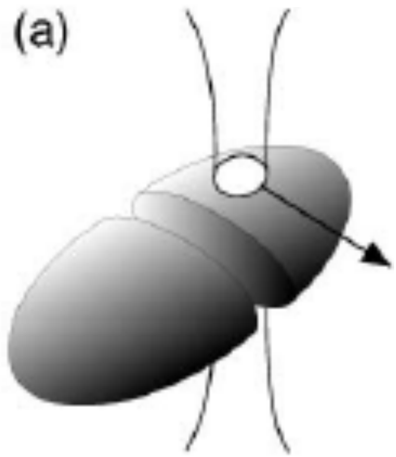












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