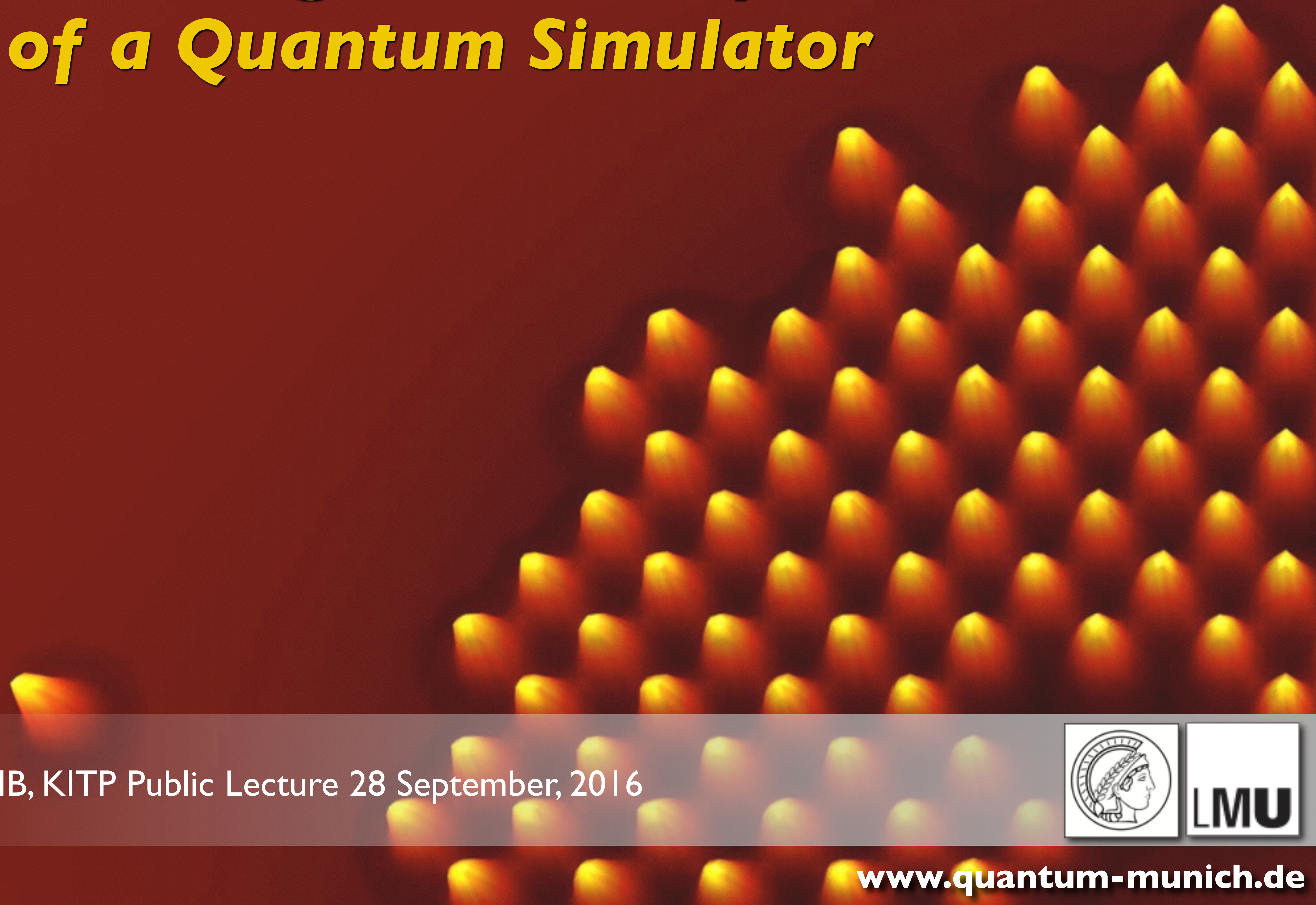
Realizing Richard Feynman's Dream of a Quantum Simulator



IB, KITP Public Lecture 28 September, 2016

www.quantum-munich.de

Overview

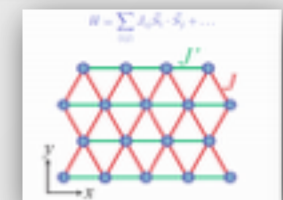
- Motivation
  - Matter as a Wave
  - The Path to Ultracold Quantum Matter
  - Optical Crystal Formed by Laser Light
  - Applications
- Outlook

The Challenge of Many-Body Quantum Systems

- **Understand and Design Quantum Materials -**
  one of the biggest challenge of Quantum Physics in the 21st Century

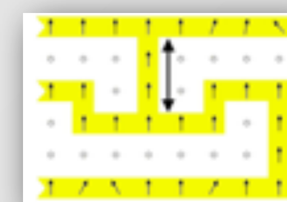
- **Technological Relevance**

  High-Tc Superconductivity (Power Delivery)



  Magnetism (Storage, Spintronics...)

  Novel Quantum Sensors (Precision Detectors)



  Quantum Technologies
  (Quantum Computing, Metrology, Quantum Sensors,...)

Many cases: lack of basic understanding of underlying processes

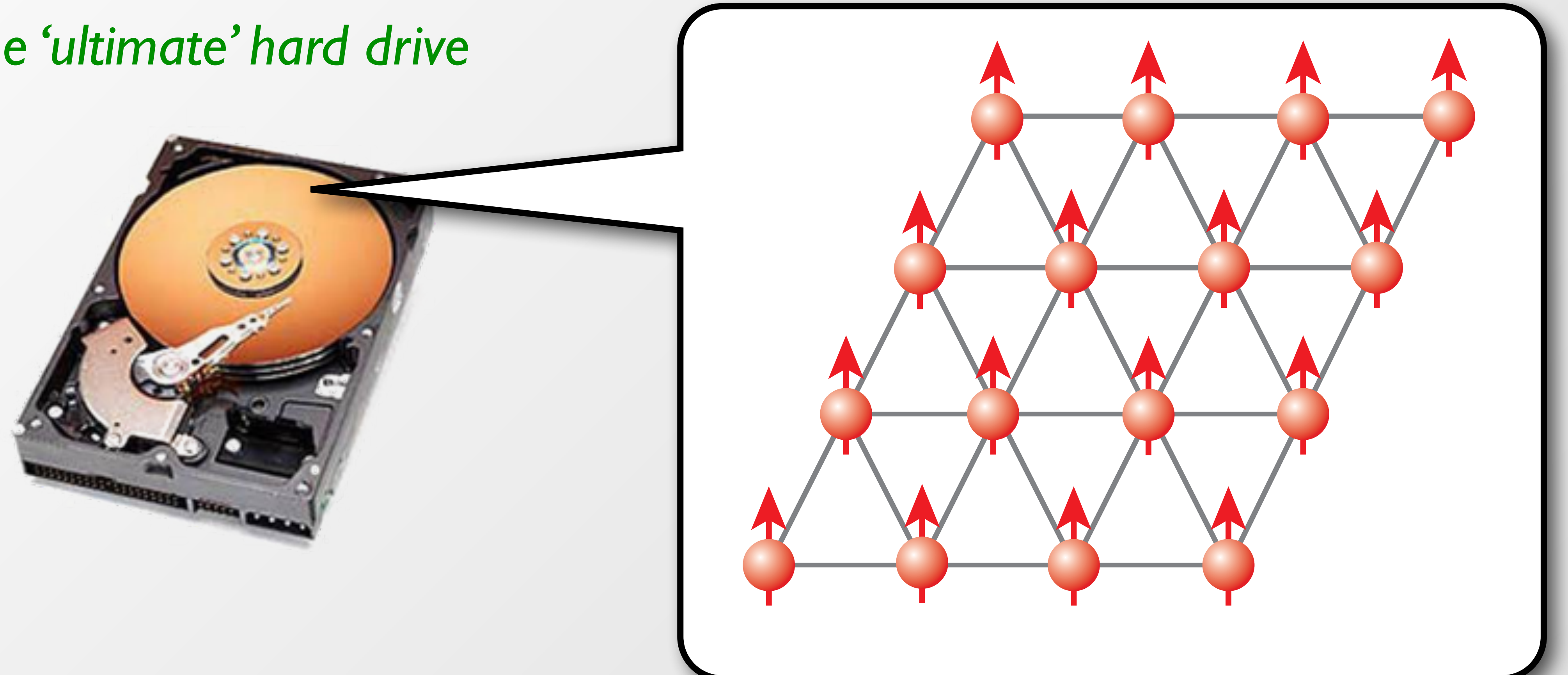
Difficulty to separate effects: probe impurities, complex interplay, masking of effects...

Many cases: even simple models "not solvable"

Need to synthesize new material to analyze effect of parameter change

Quantum Complexity

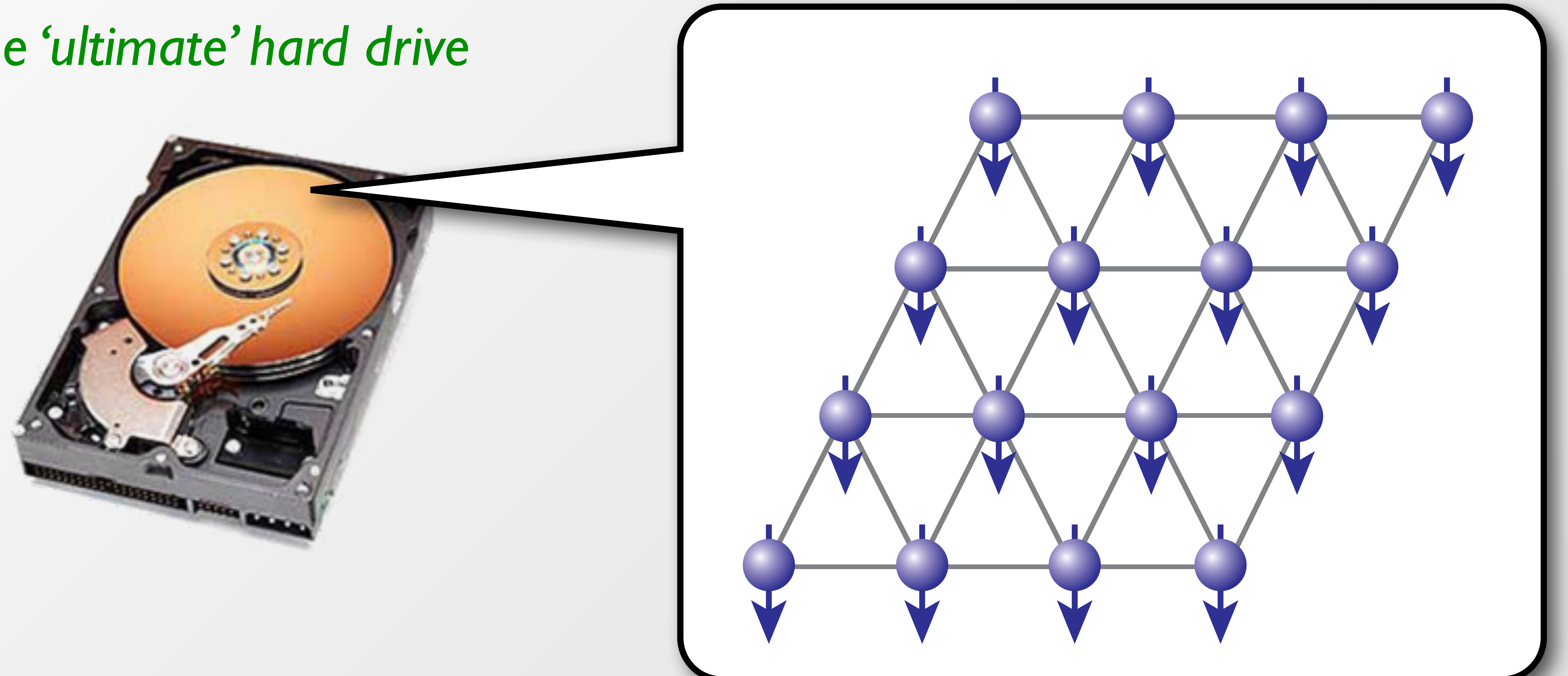
the 'ultimate' hard drive



Crystal of spins

Quantum Complexity

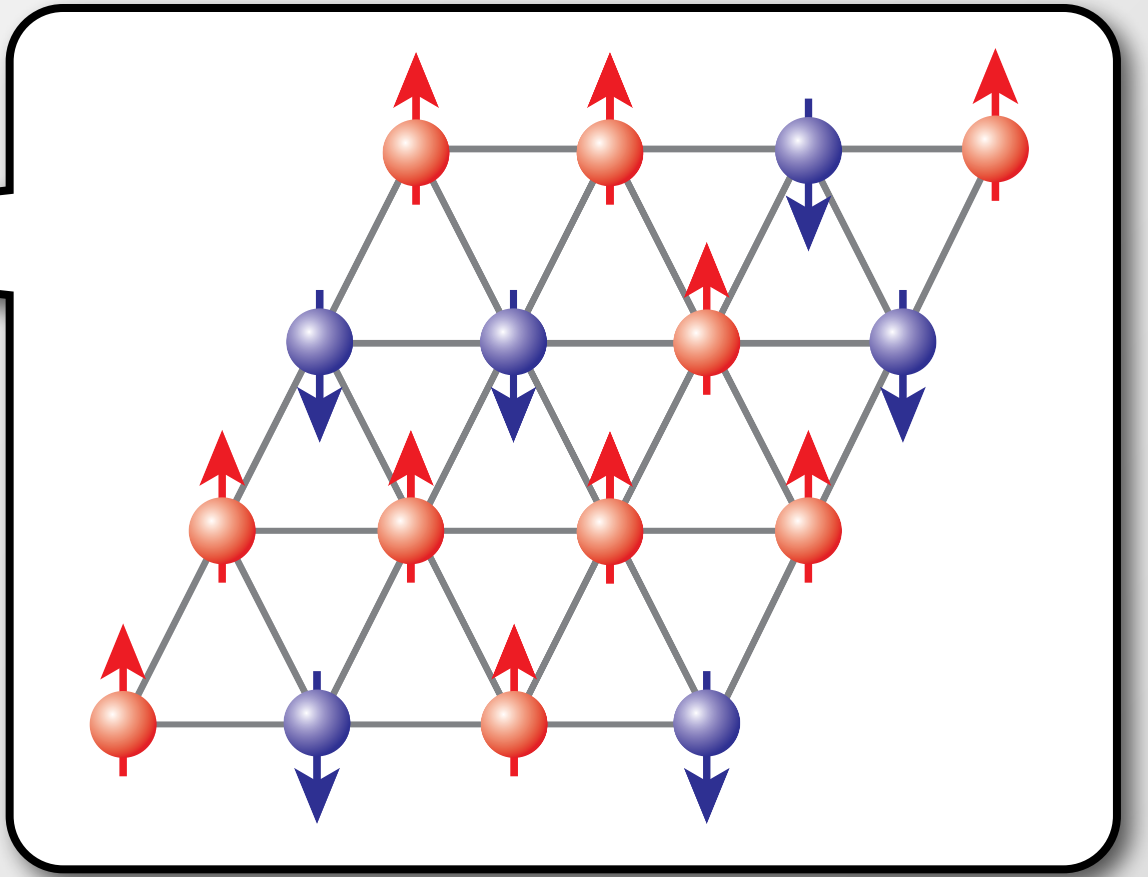
the 'ultimate' hard drive



Crystal of spins

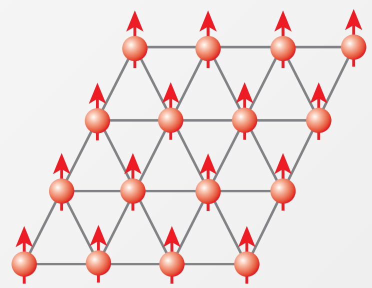
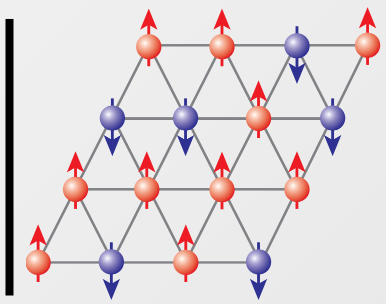
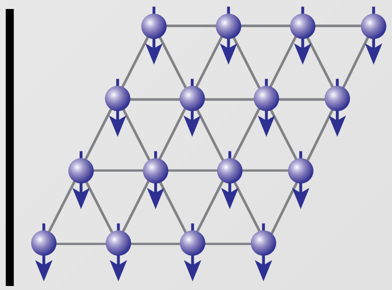
Quantum Complexity

the 'ultimate' hard drive



Crystal of spins

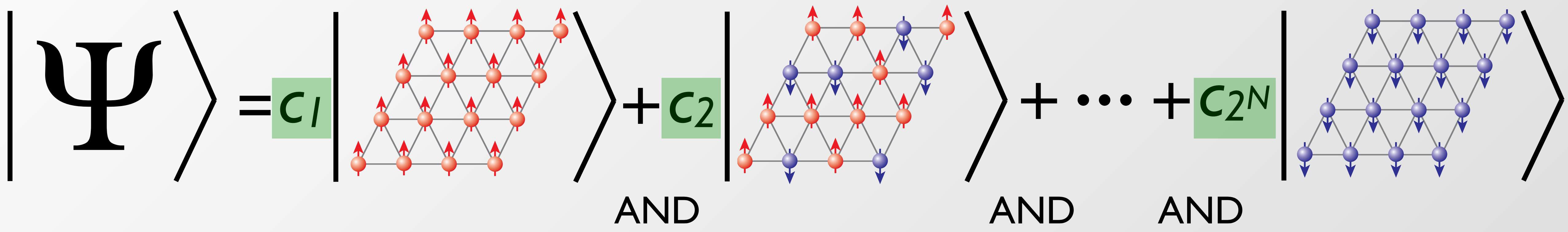
Quantum Complexity

$|\Psi\rangle = c_1 \big|$  $\big\rangle + c_2 \big|$  $\big\rangle + \cdots + c_{2^N} \big|$  $\big\rangle$

AND AND AND

2^N Configurations simultaneously!

Quantum Complexity



2^N Configurations simultaneously!

Roadrunner – Los Alamos

1.1 Petaflops/s
2000 t
3.9 MW

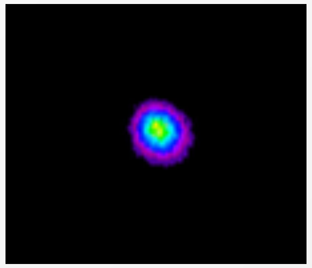
State of the art: < 40 spins (2^{40}x 2^{40}) (what does it take to simulate 300 spins ?)

each doubling allows for one more spin 1/2 only

2^{300} estimated number of protons in the universe

The Challenge of Many-Body Quantum Systems

Control of single and few particles

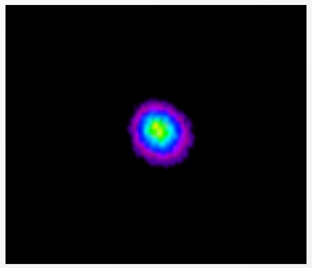


Single Atoms and Ions

Photons

The Challenge of Many-Body Quantum Systems

Control of single and few particles



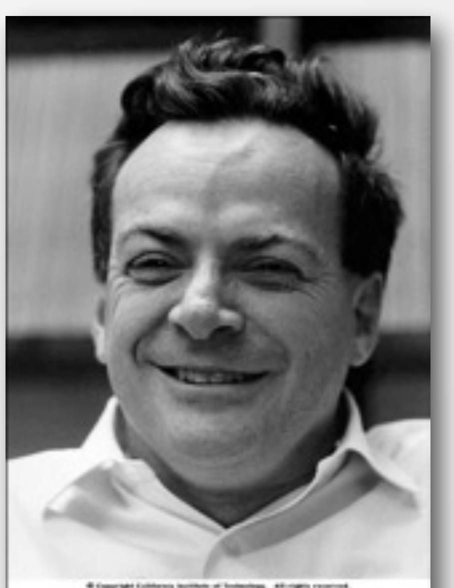
Single Atoms and Ions

Photons

D. Wineland

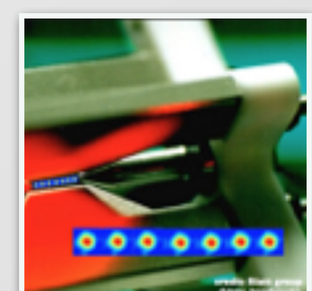
S. Haroche

Challenge: ... towards ultimate control of many-body quantum systems

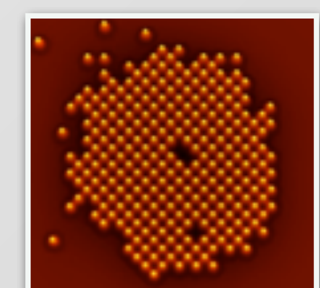


R. P. Feynman's Vision

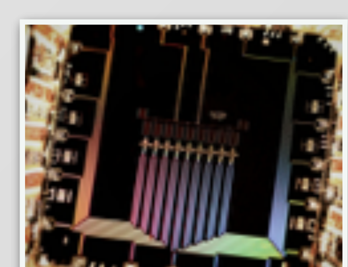
A Quantum Simulator to study the dynamics of another quantum system.



Ion Traps
(R. Blatt, Innsbruck)



Crystal of Atoms
Bound by Light



Superconducting
Devices
(J. Martinis, UCSB,
Google)

The Challenge of Many-Body Quantum Systems

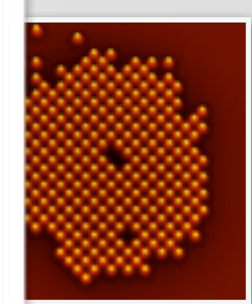
Control of single and few particles

Haroche

Sing

Challen

ystems



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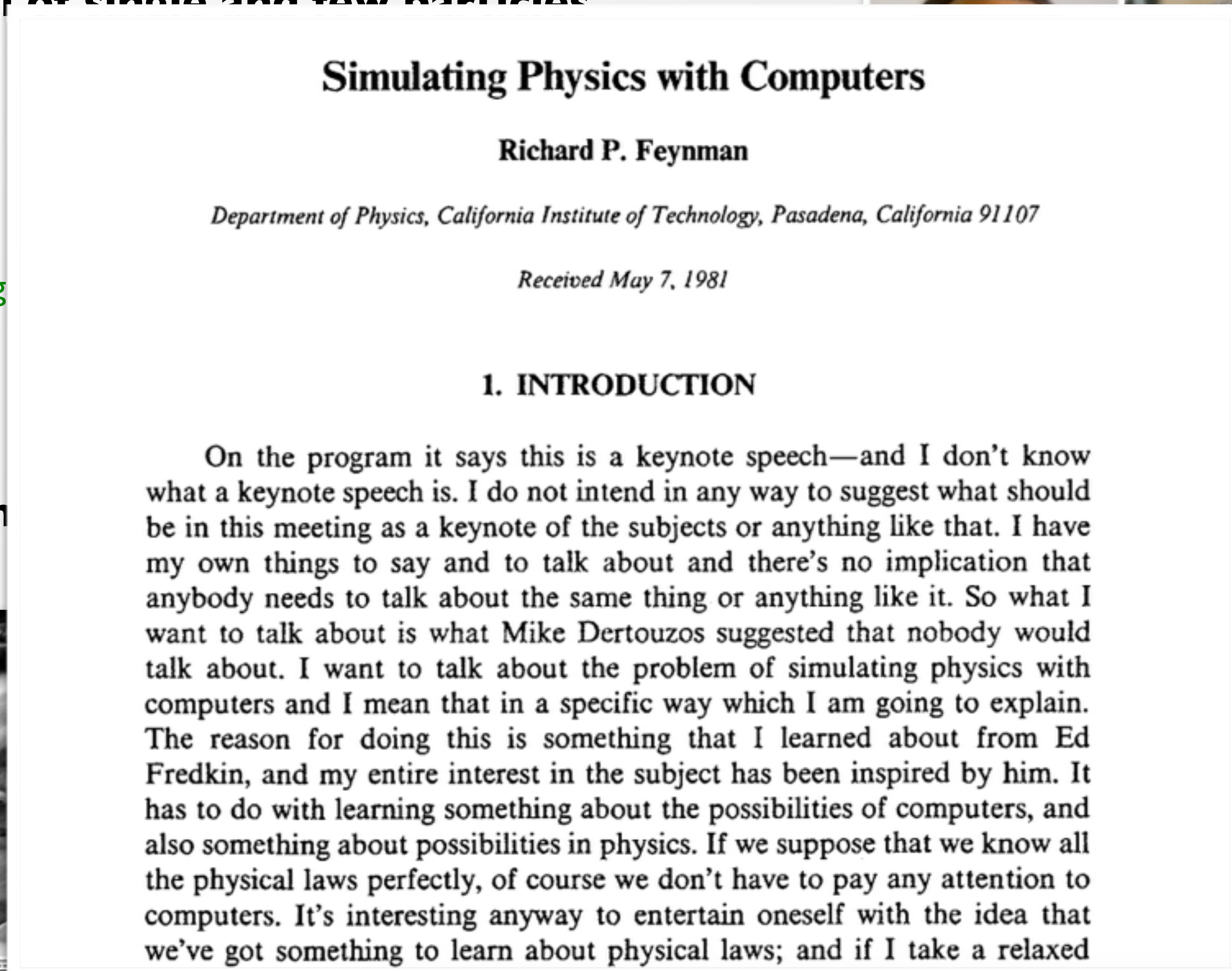


Simulating Physics with Computers

Richard P. Feynman

Department of Physics, California Institute of Technology, Pasadena, California 91107

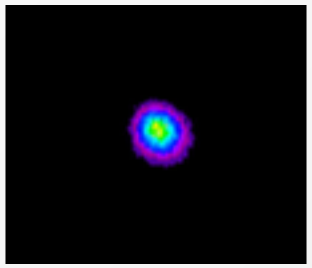
Received May 7, 1981

1. INTRODUCTION

On the program it says this is a keynote speech—and I don't know what a keynote speech is. I do not intend in any way to suggest what should be in this meeting as a keynote of the subjects or anything like that. I have my own things to say and to talk about and there's no implication that anybody needs to talk about the same thing or anything like it. So what I want to talk about is what Mike Dertouzos suggested that nobody would talk about. I want to talk about the problem of simulating physics with computers and I mean that in a specific way which I am going to explain. The reason for doing this is something that I learned about from Ed Fredkin, and my entire interest in the subject has been inspired by him. It has to do with learning something about the possibilities of computers, and also something about possibilities in physics. If we suppose that we know all the physical laws perfectly, of course we don't have to pay any attention to computers. It's interesting anyway to entertain oneself with the idea that we've got something to learn about physical laws; and if I take a relaxed

The Challenge of Many-Body Quantum Systems

Control of single and few particles



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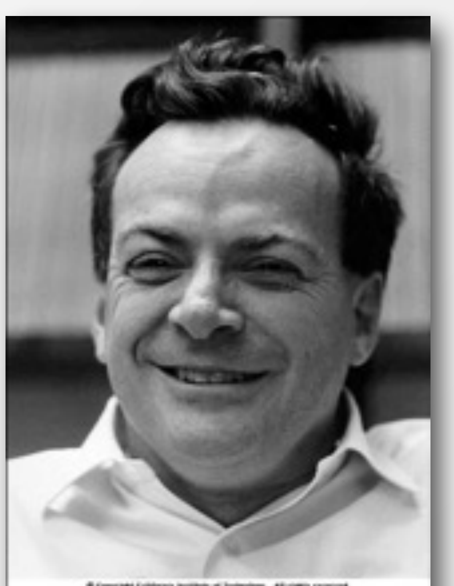

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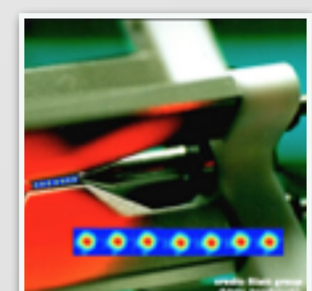

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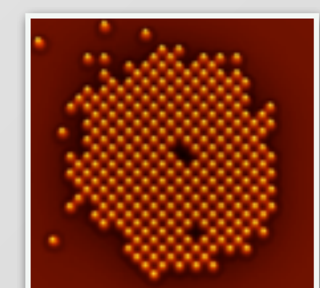

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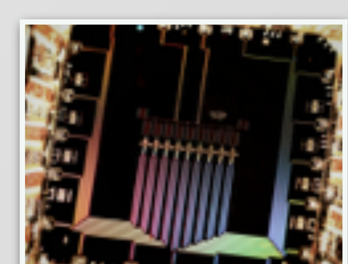
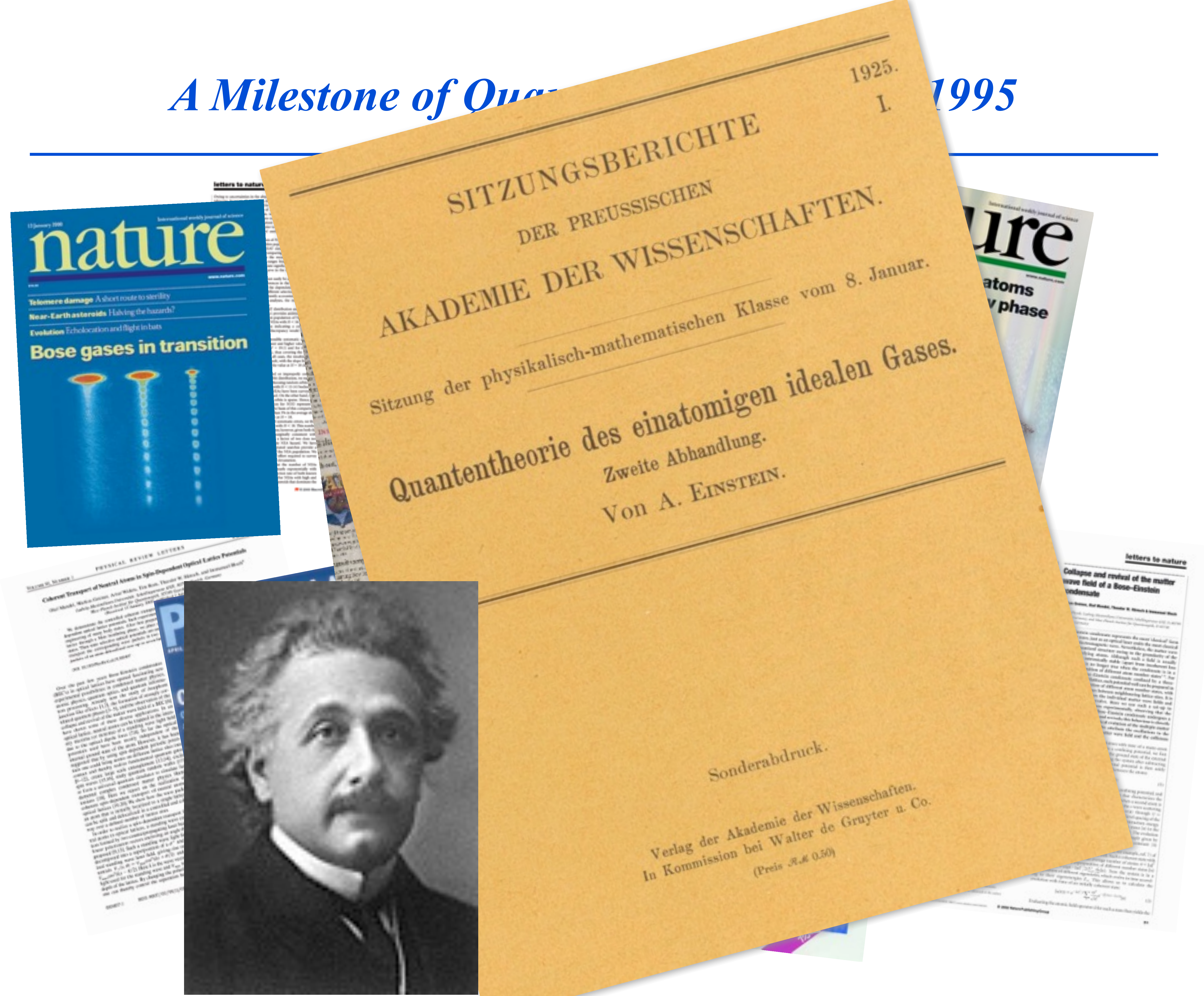
Bound by Light



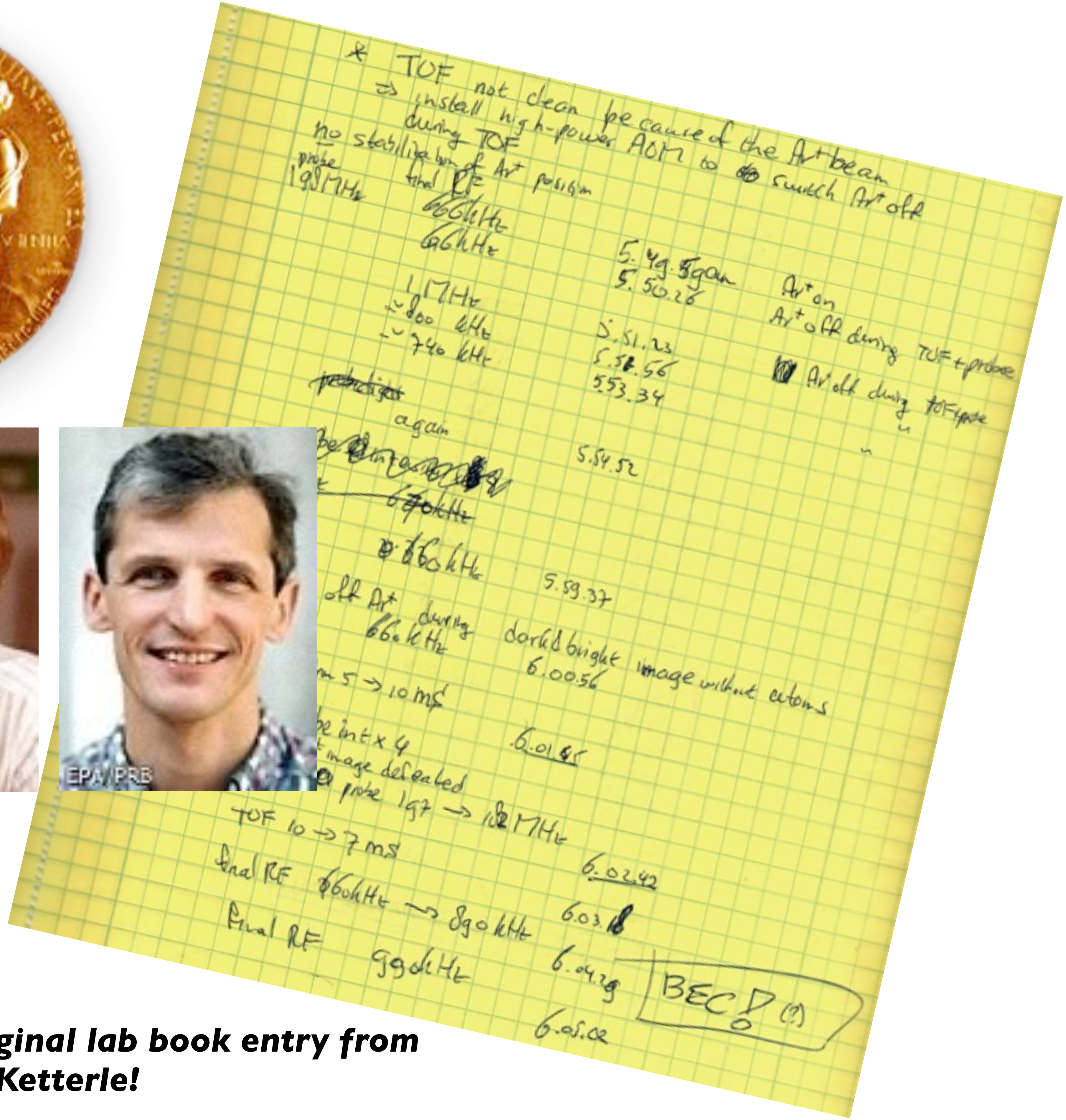
Superconducting
Devices
(J. Martinis, UCSB,
Google)

Ultracold Quantum Gases

A Milestone of Qu… 1995



Centennial Nobel Prize in Physics! (2001)



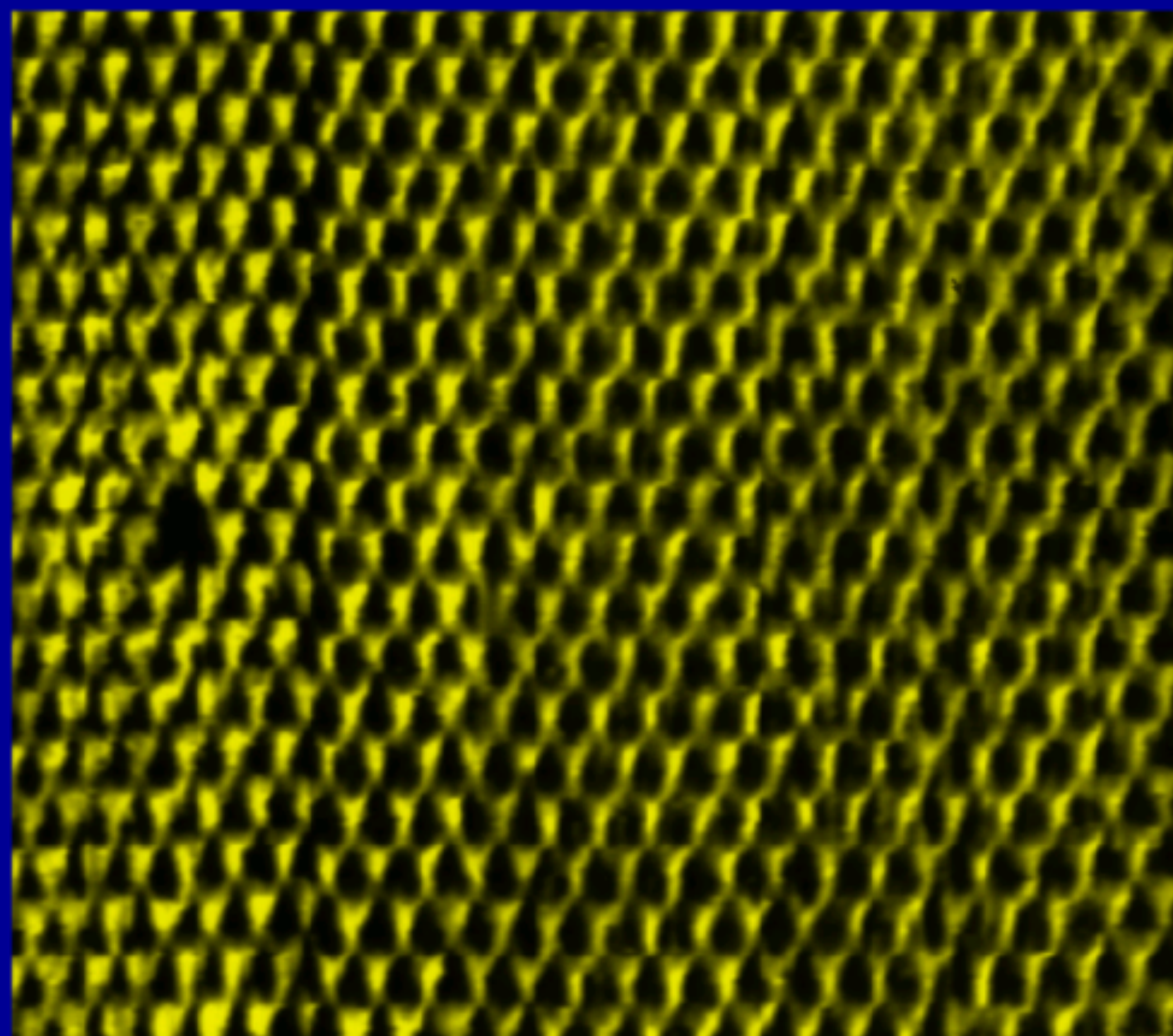
Original lab book entry from W. Ketterle!

Centennial Nobel Prize in Physics! (2001)

Original lab book entry from W. Ketterle!

Molybdändisulfid

Schwefelatome unter dem Rastertunnelmikroskop



What is Matter ?

MoS2.ps

Matter is a Wave

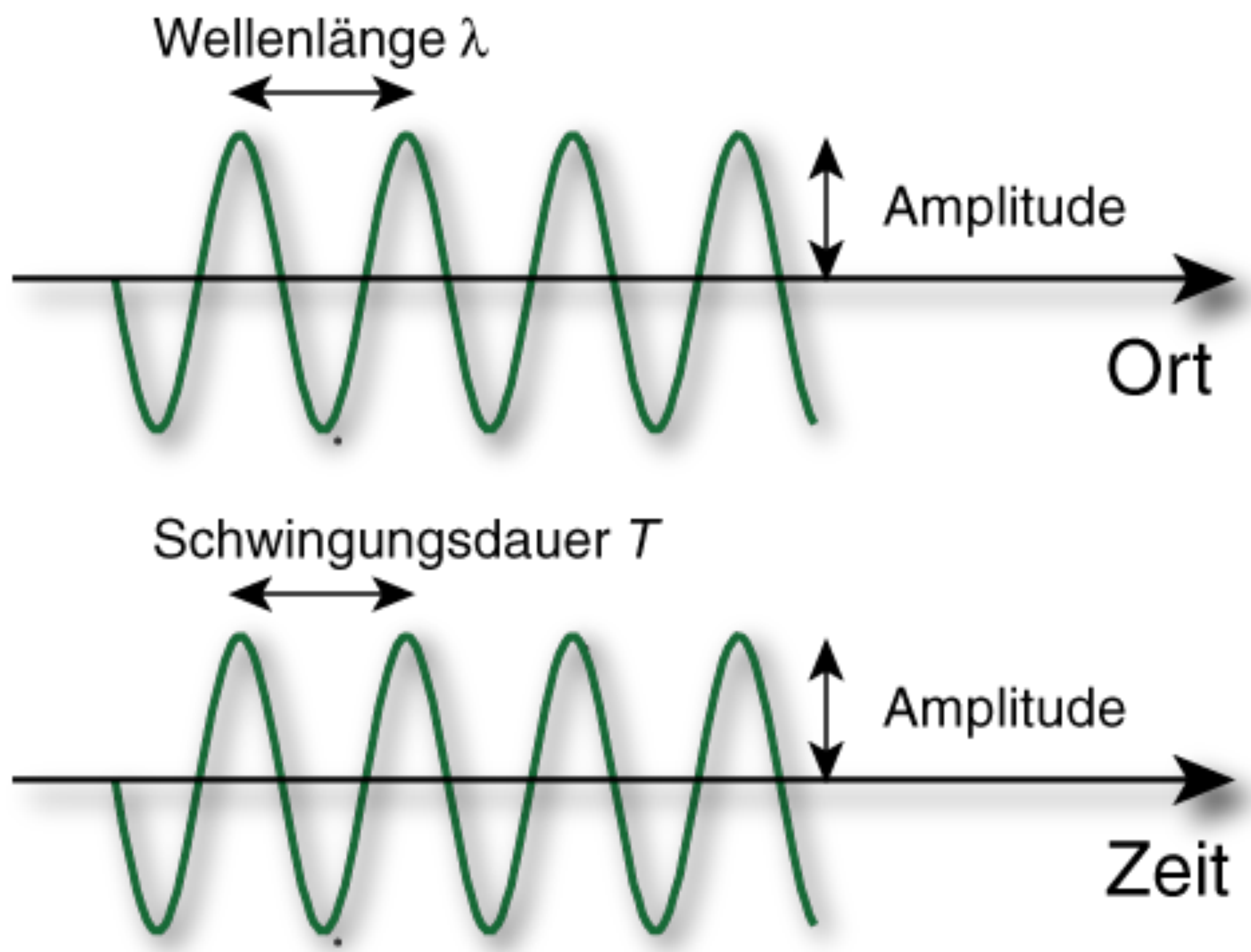
Louis-Victor de Broglie
(1892-1987)

$$\lambda = \frac{h}{p} = \frac{h}{mv}$$

Erwin Schrödinger
(1887-1961)

$$i\hbar \frac{\partial \Psi}{\partial t} = H\Psi$$

What characterizes a wave ?



Wave is a periodic oscillation in space and time !

Frequency (Oscillations per s) $\nu = 1/T$

Propagation velocity: $c = \lambda \cdot \nu$

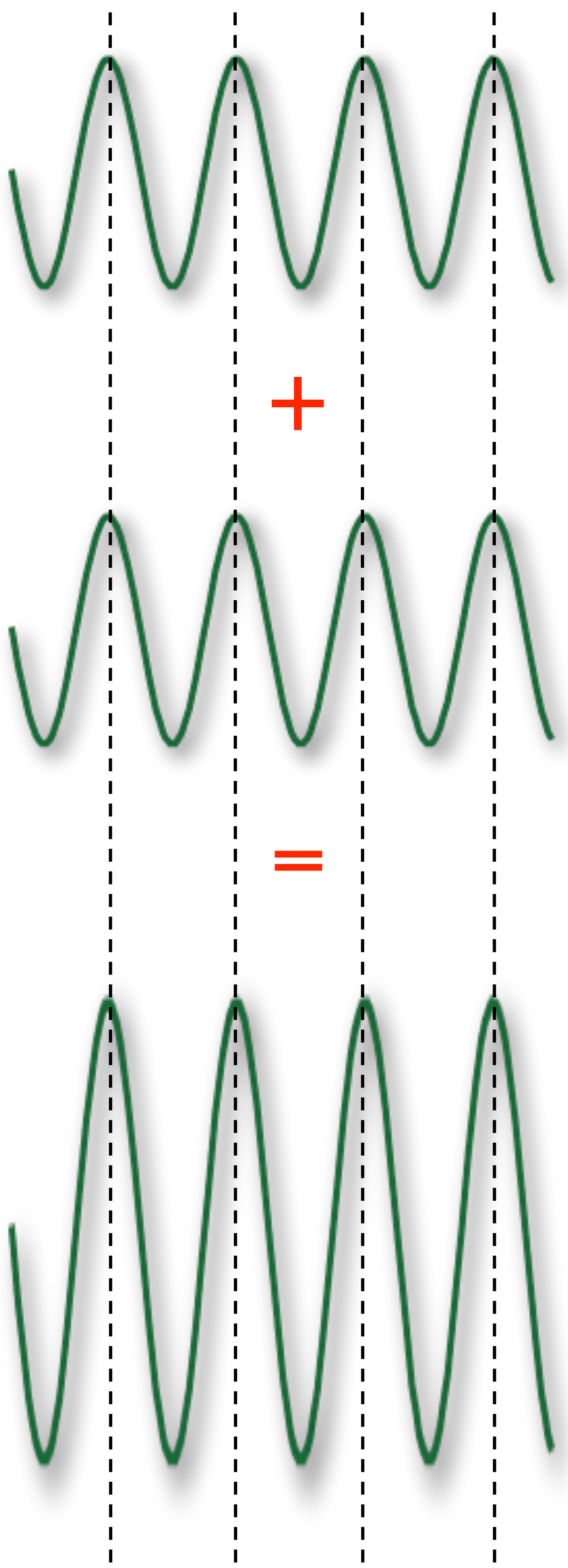
1+1=2? or not ?

Matter + ***Matter*** = ***Twice as much matter***

+

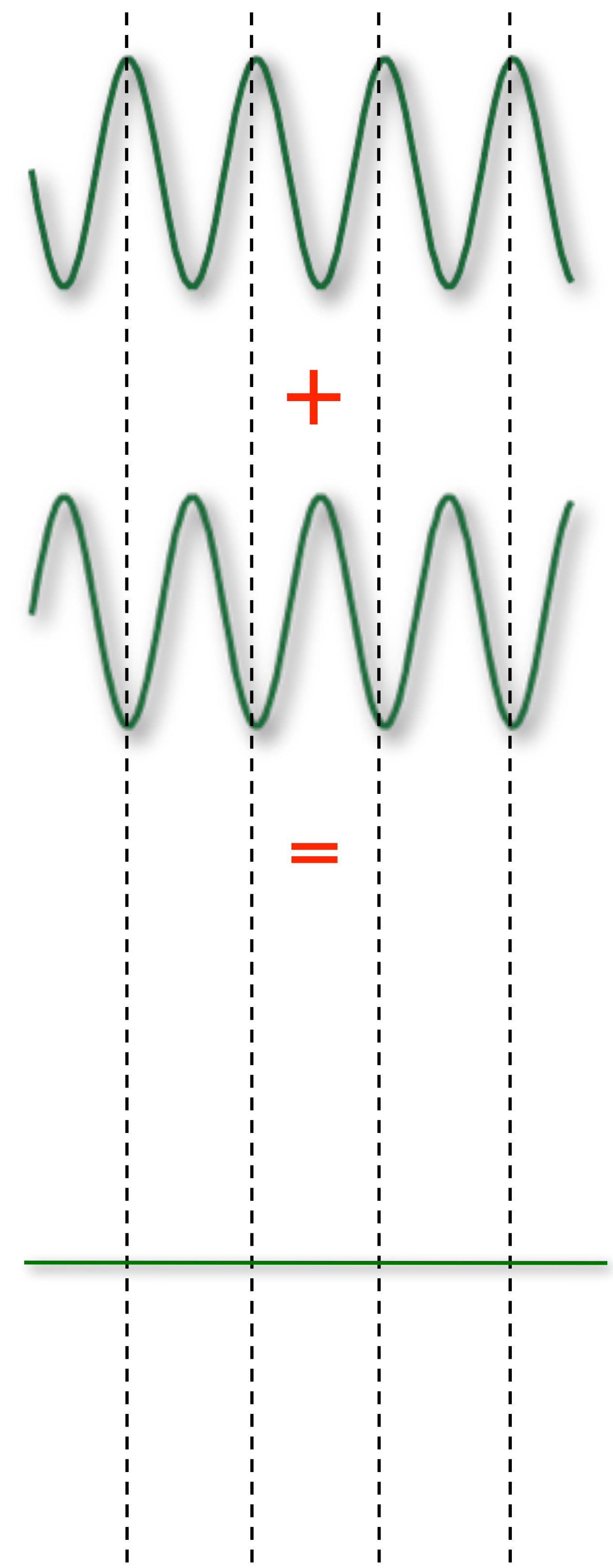
=

Superposition Principle for Waves



Waves can enhance each other!

contructive interference when two waves are added in phase

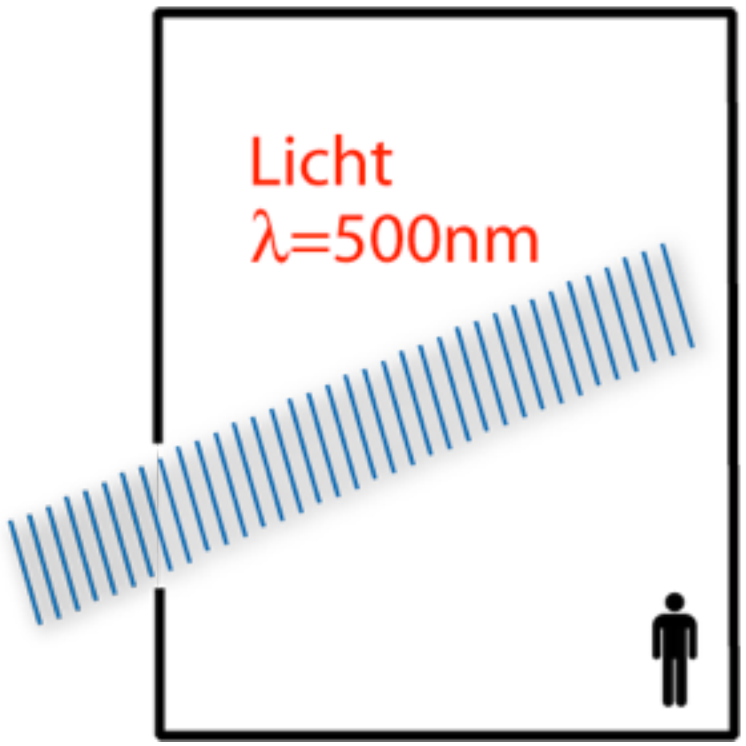


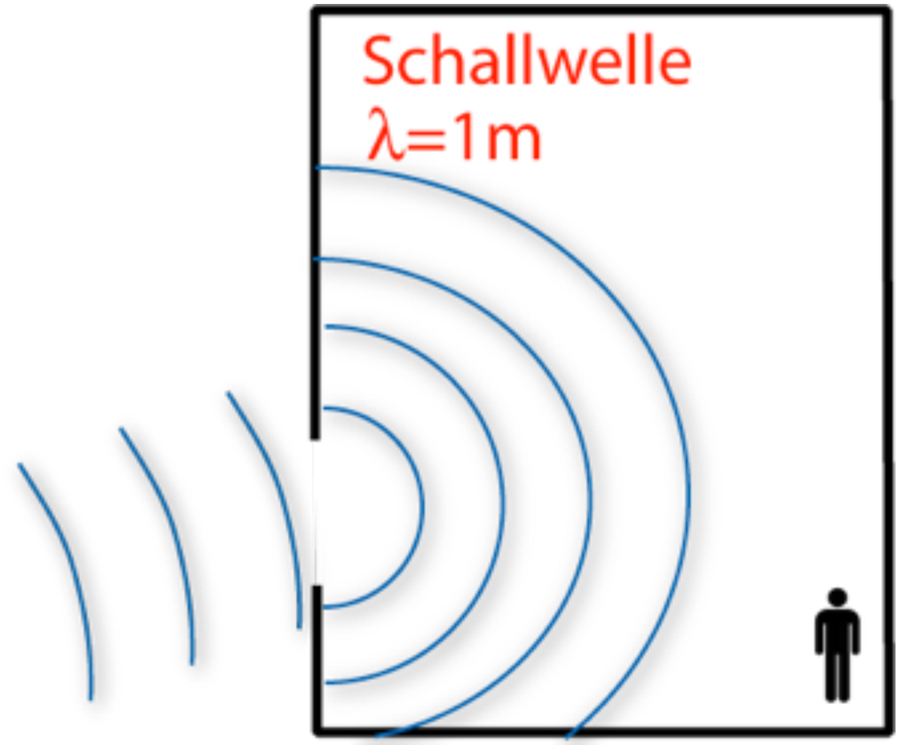
Waves can eliminate each other!

destructive interference whe
two waves are added $\lambda/2$ out of phase

Go To Interference Program...

When can we perceive this wave character?





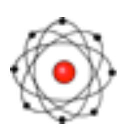
$\lambda \ll$ Size of Object

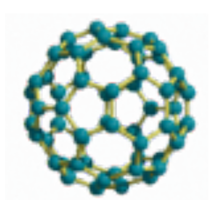
$\lambda \approx$ Size of Object

Propagation along straight lines

Waves are diffracted!

deBroglie Wavelength of Different Objects

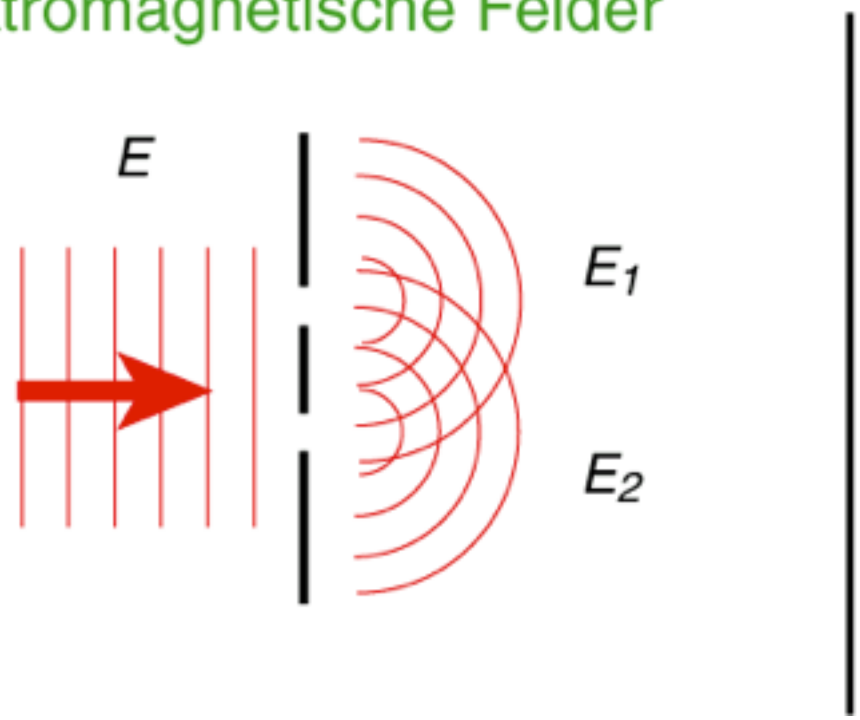




Objekt	m (kg)	v (m/s)	λ (mm)
Elektron	$9{,}1 \cdot 10^{-31}$	$2 \cdot 10^{6}$	$4 \cdot 10^{-7}$ (0,0000004)
Neutron	$1{,}7 \cdot 10^{-27}$	$4 \cdot 10^{3}$	$9 \cdot 10^{-8}$ (0,00000009)
^{87}Rb Atom	$1{,}5 \cdot 10^{-25}$	270	$2 \cdot 10^{-8}$ (0,00000002)
C_{60}	$1{,}2 \cdot 10^{-24}$	210	$3 \cdot 10^{-9}$ (0,000000003)
Fussball	0,5	20	$7 \cdot 10^{-32}$ (0,00000000000000000000000000000007)

What is interfering in the case of matter waves?

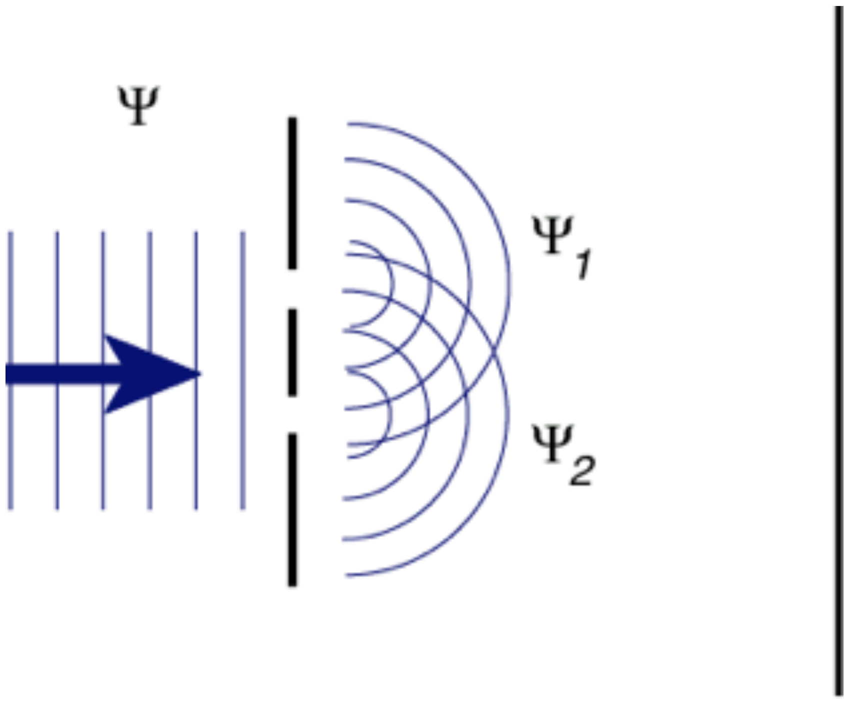
Elektromagnetische Felder



$$E_{det} = E_1 + E_2$$

$$I \propto |E_1 + E_2|^2$$

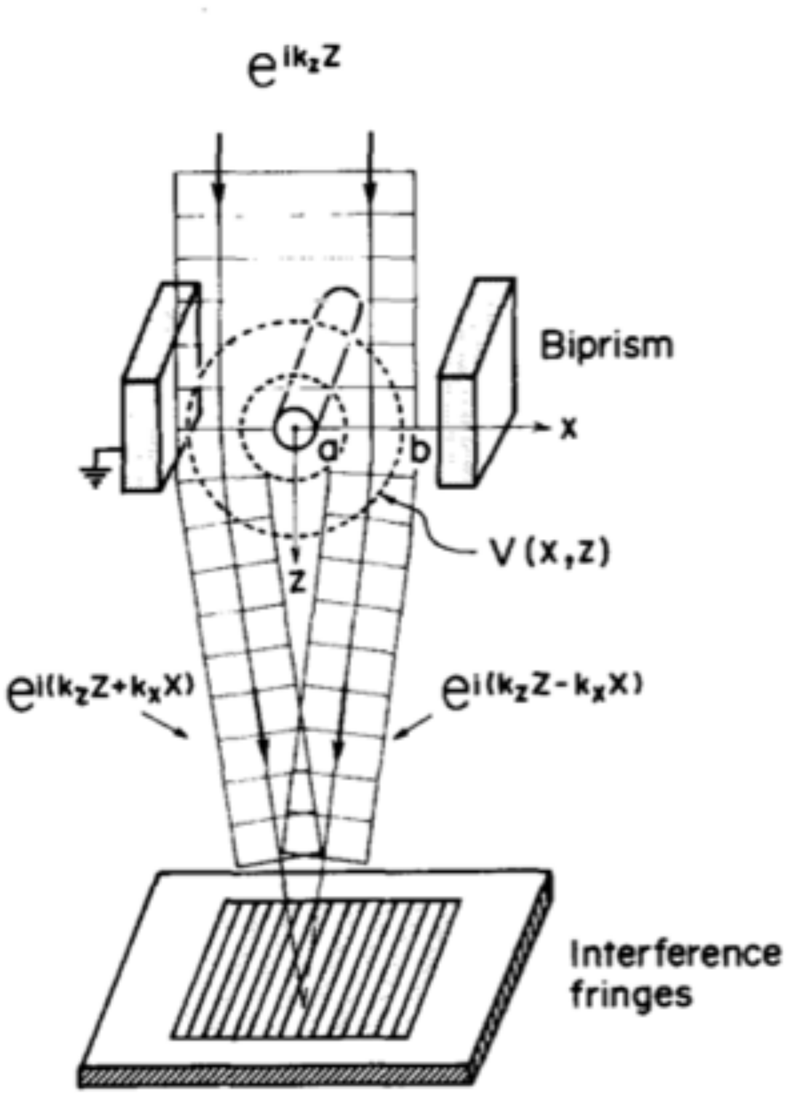
Quantenmechanische Wellenfunktionen

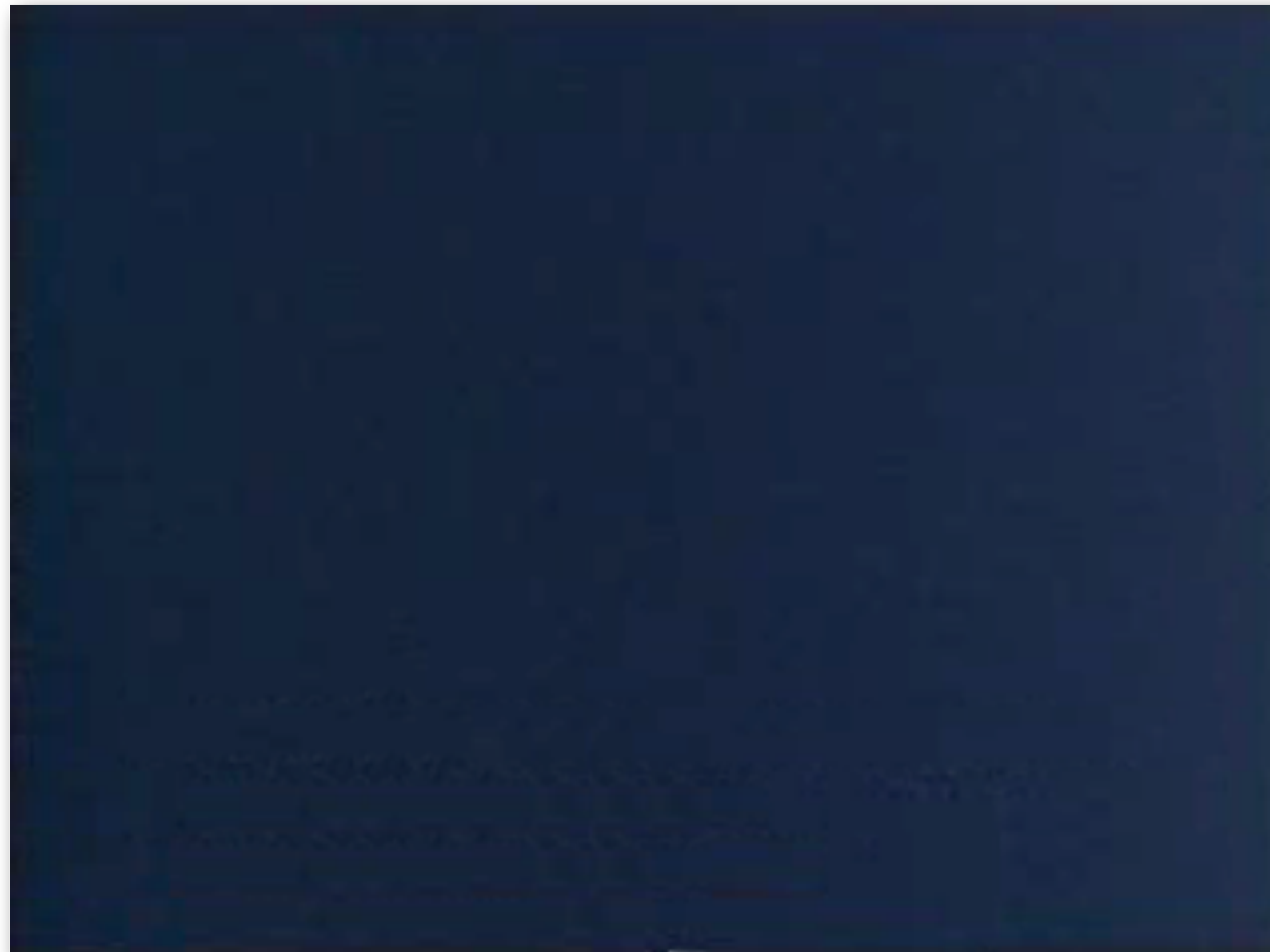


$$\Psi_{det} = \Psi_1 + \Psi_2$$

$$n \propto |\Psi_1 + \Psi_2|^2$$

Single Electron on Double Slit





A. Tonomura et al., Amer. J. Phys. **57** (1989) pp.117-120.

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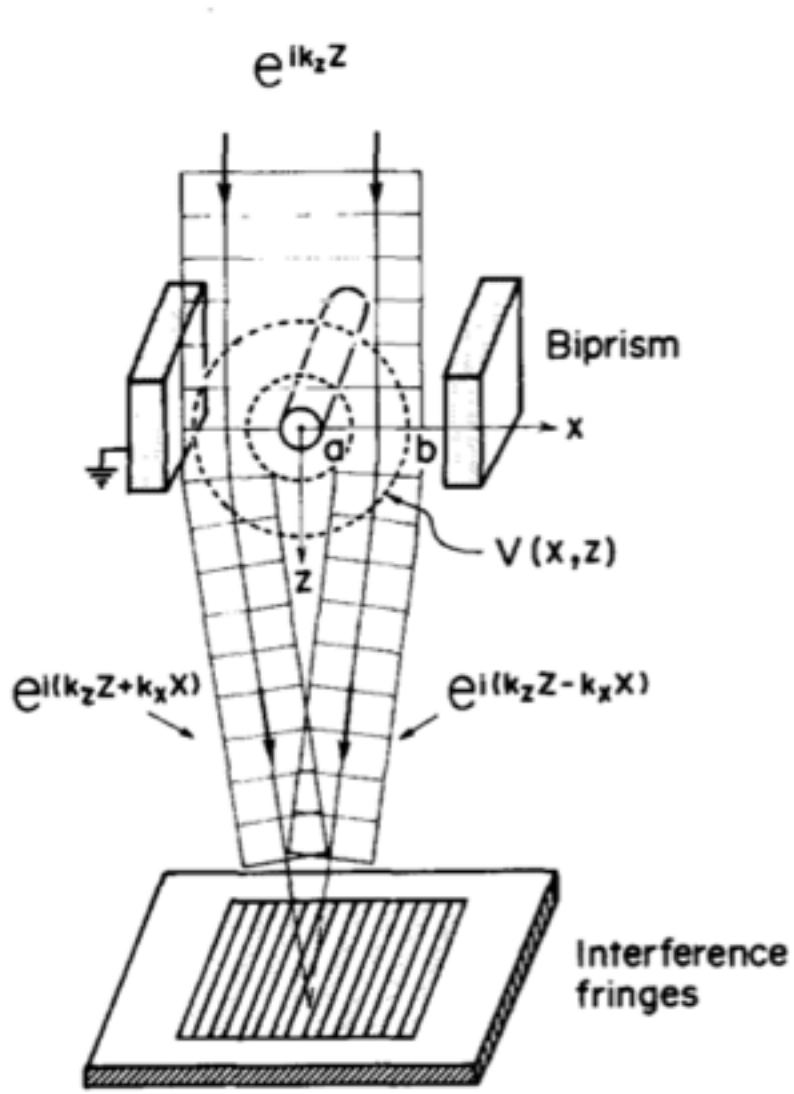

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Interference Phenomena with Matter Waves (2)

Beugung an einer Folie:

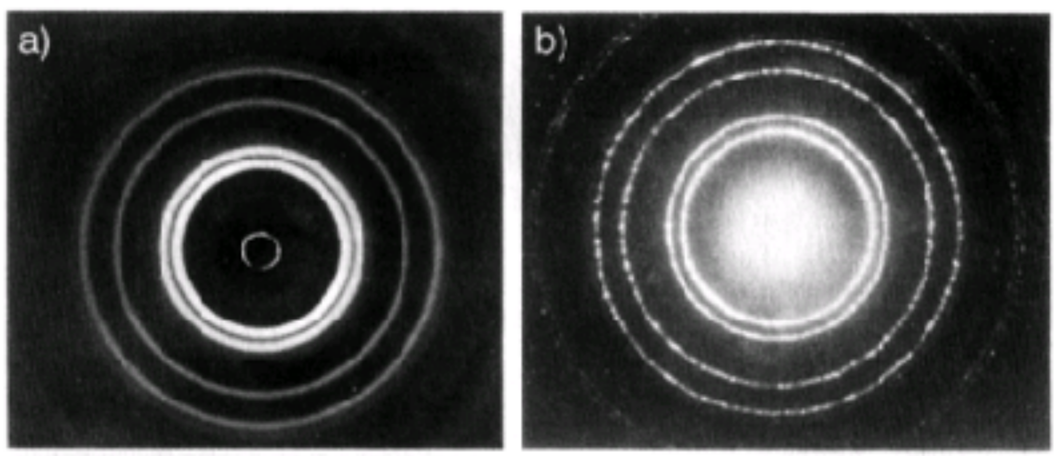
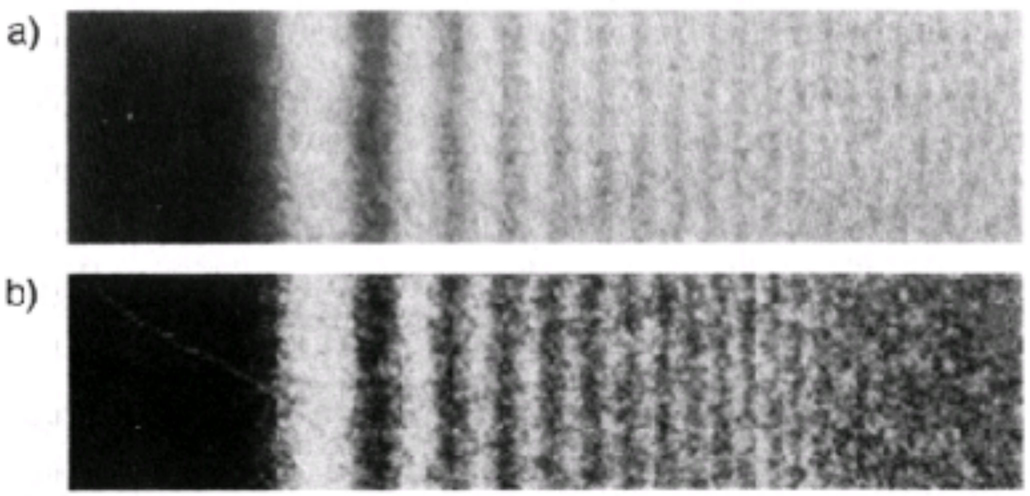
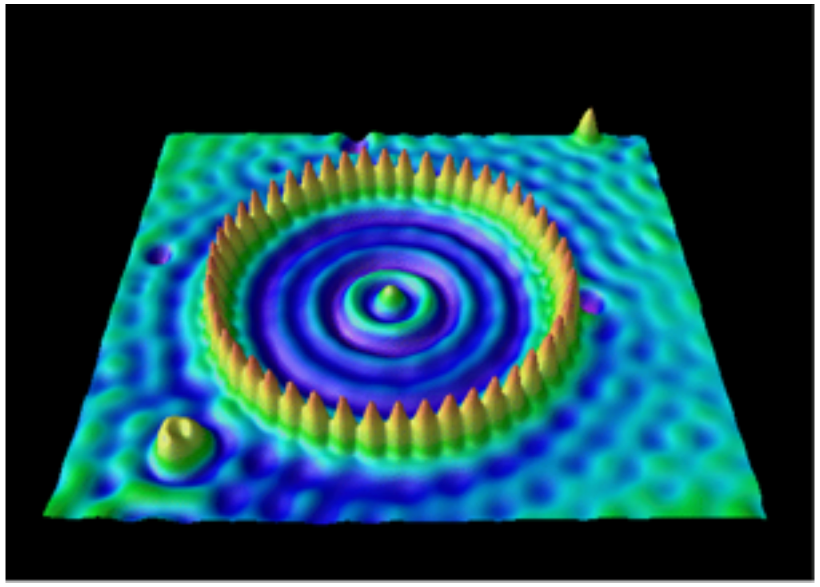


Abb. 3.18a,b. Vergleich (**a**) der Elektronenbeugung und (**b**) der Röntgenbeugung an einer dünnen Folie

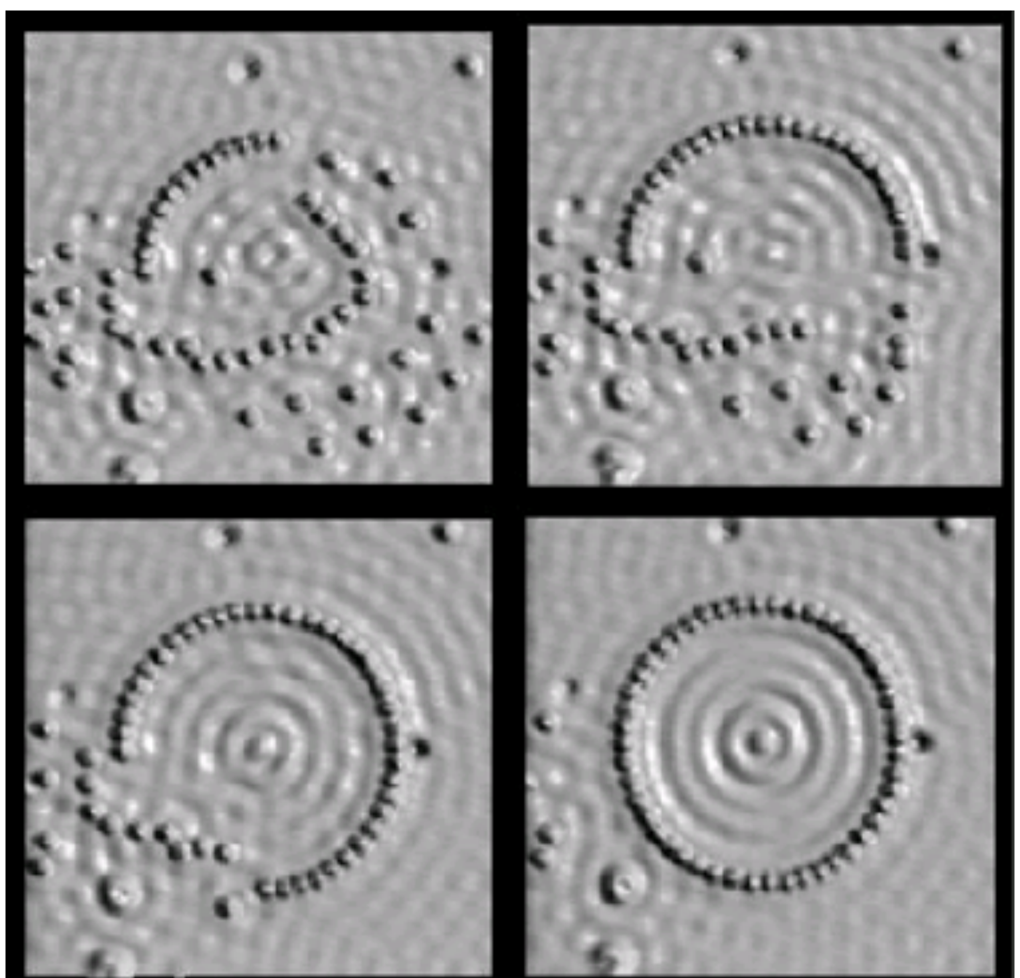
Beugung an einer Kante:

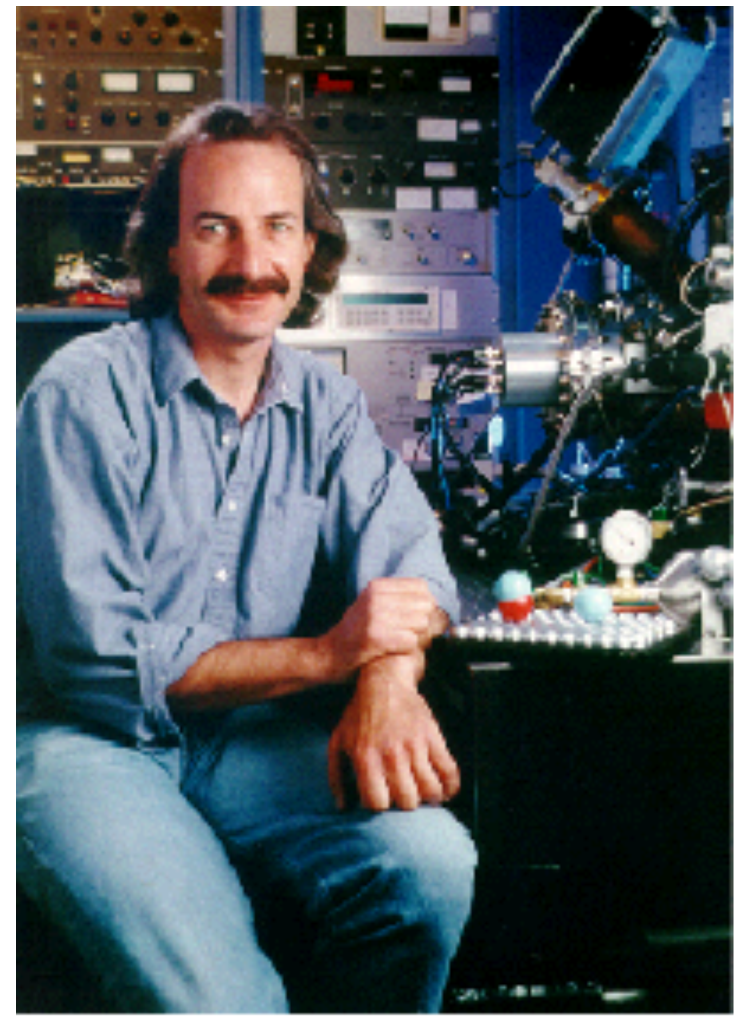


STM Images of Electron Surface Waves



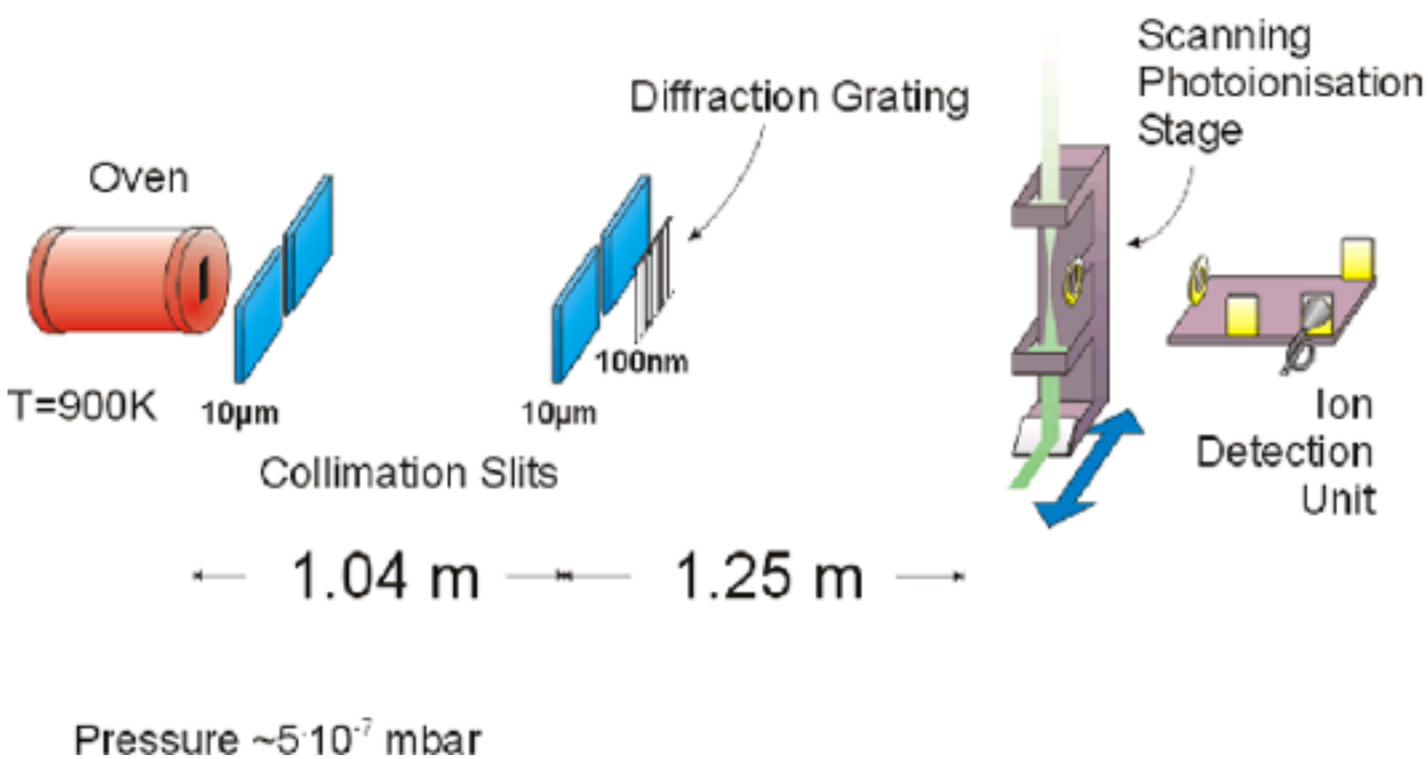
Fe auf Cu (111)

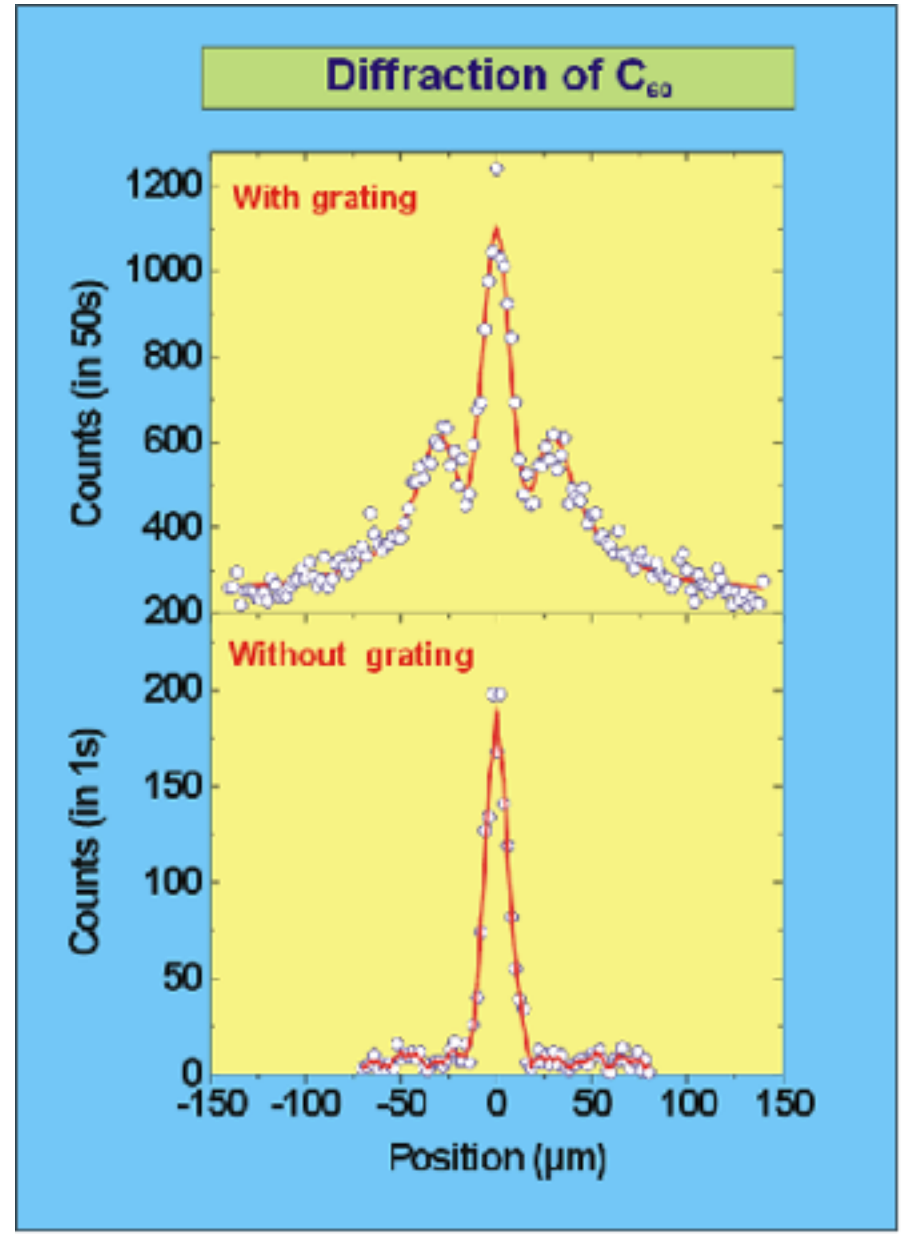




Don Eigler
IBM Almaden Research Labs
http://www.almaden.ibm.com/vis/stm/

Interference of C_{60} Matter Waves





C_{60} Parameter

$v = 220$ m/s

$\lambda = 2{,}5$ pm

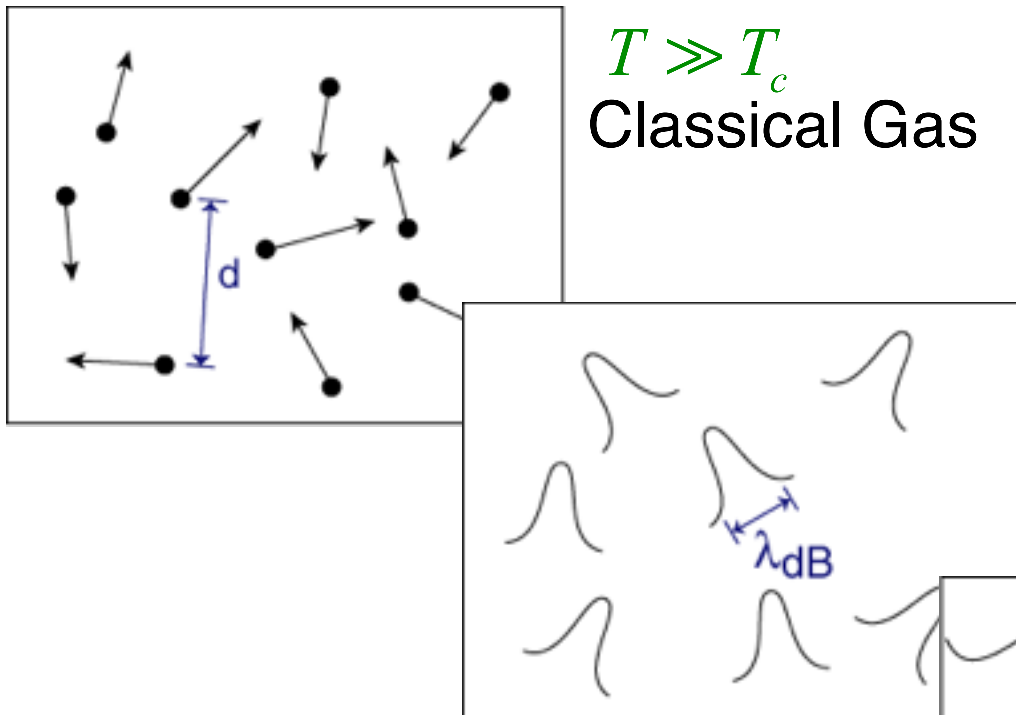
Gitter

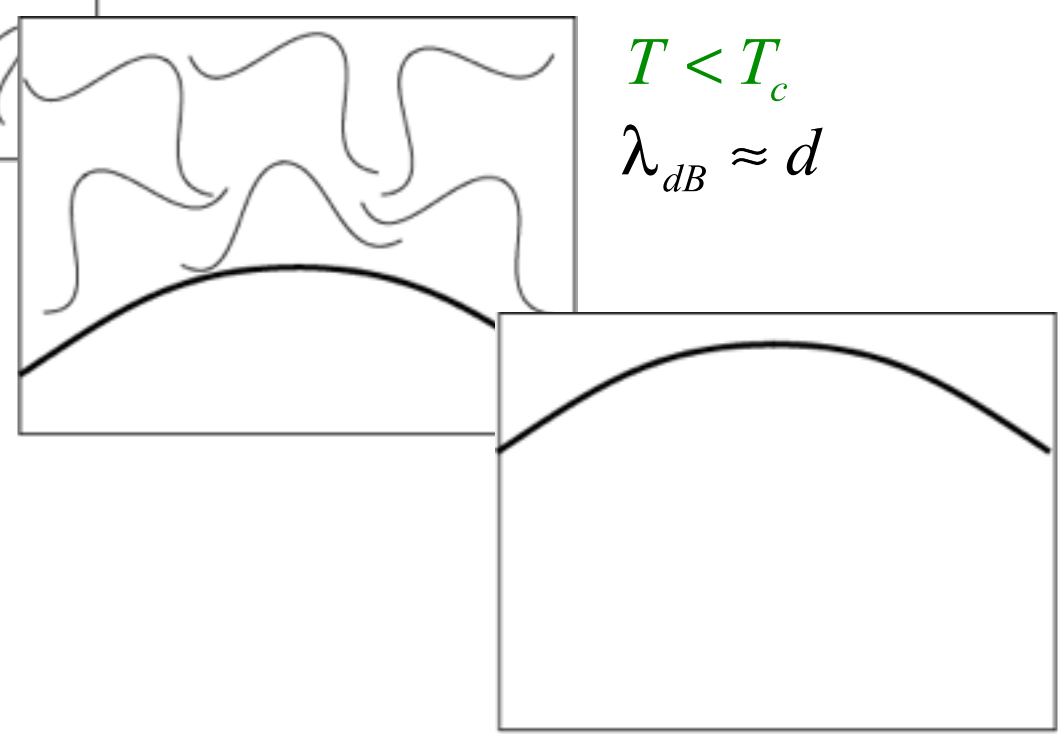
Spaltbreite: 50 nm

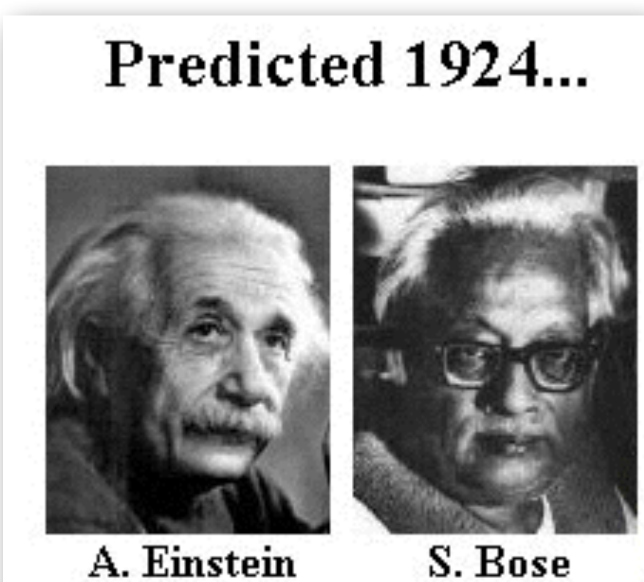
Spaltabstand: 100 nm

M. Arndt *et. al.*
Nature **401**, ff. 680, 1999
http://www.quantum.univie.ac.at/

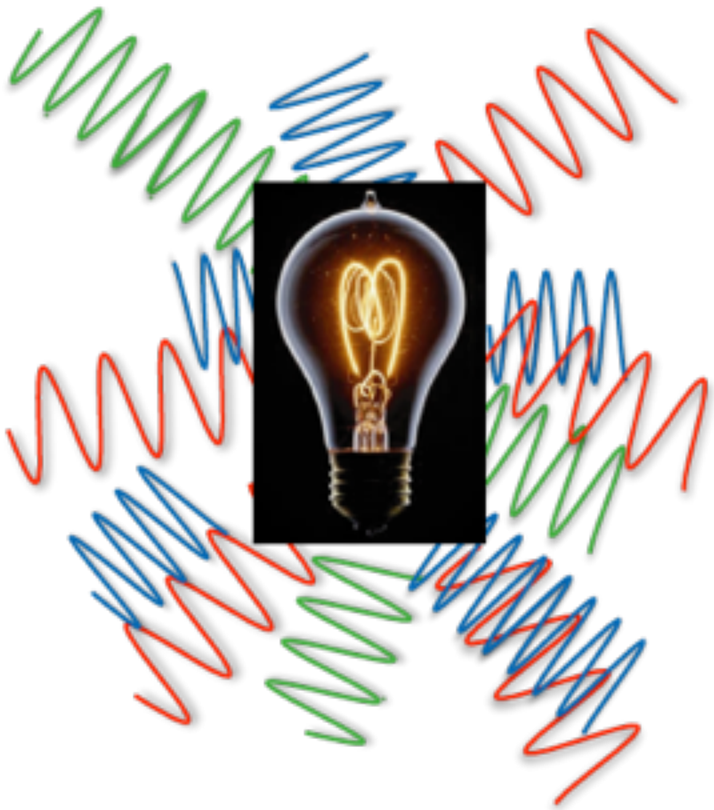
From a classical gas to a Bose-Einstein Condensate

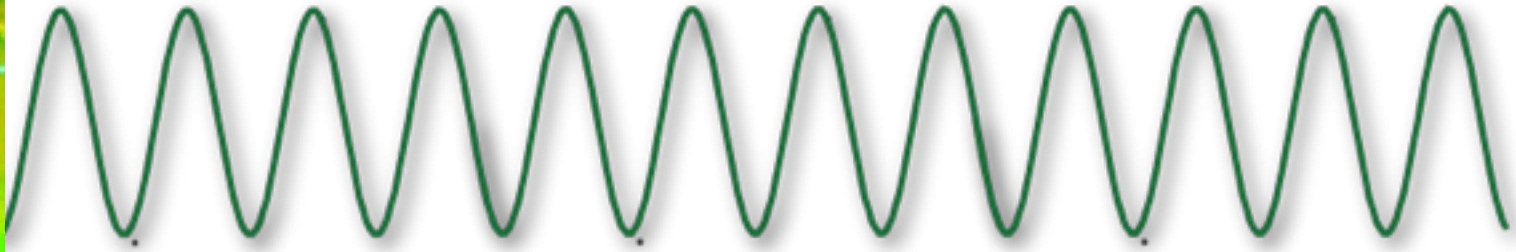






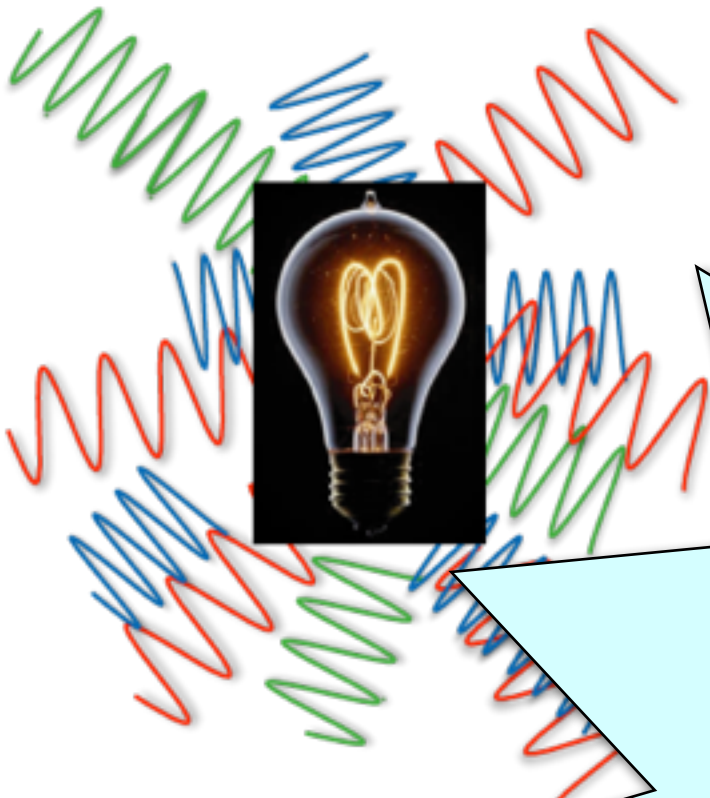
Thermal Light & Laser Light



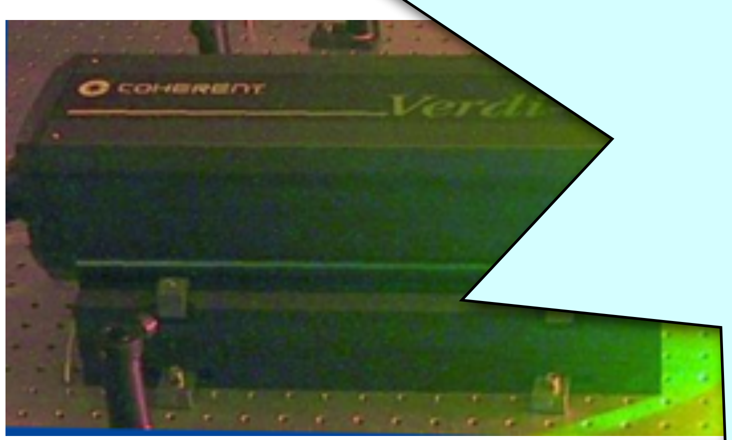


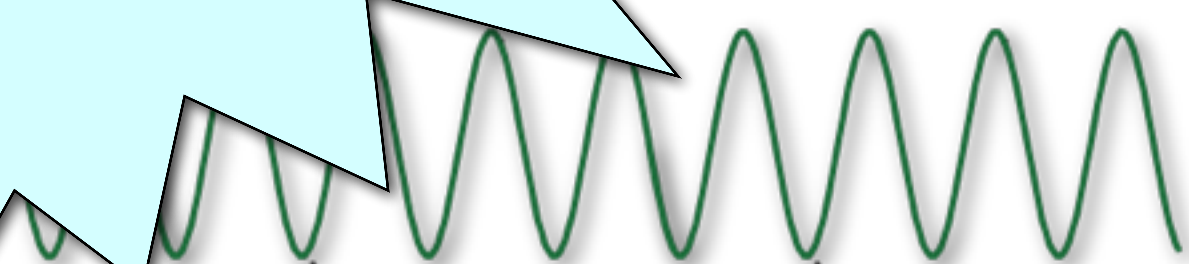
Laser emits one one continuous wavetrain with a perfectly defined frequency!

Thermal Light & Laser Light



BEC is for matter what the laser is for light!





Laser emits one one continuous wavetrain with a perfectly defined frequency!

Why is it hard to create a BEC?

Conditions for BEC:

$$n \cdot \lambda^3 \approx 1$$

z.B. Water

For a typical density of water n_{H20} we obtain T_c=1K

Problem: Water is a block of ICE @ 1K

***Solution:* Density has to be lowered by several orders of magnitude to prolong timescale for solid formation!**

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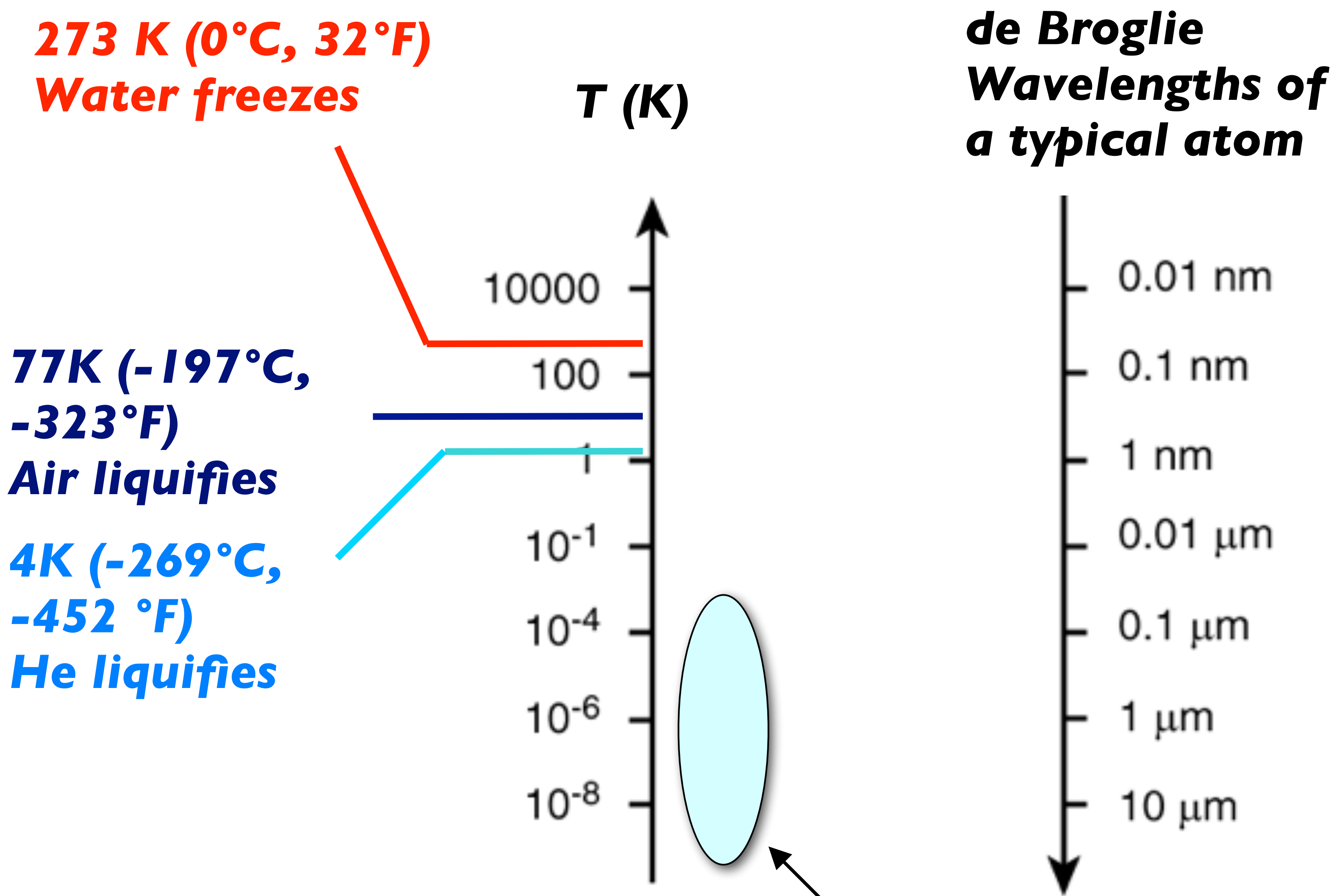
Even lower temperatures are needed!

de Broglie Wavelengths

Thermal deBroglie wavelengths

$$\lambda = \frac{h}{\sqrt{2\pi\, m\, k_B T}}$$

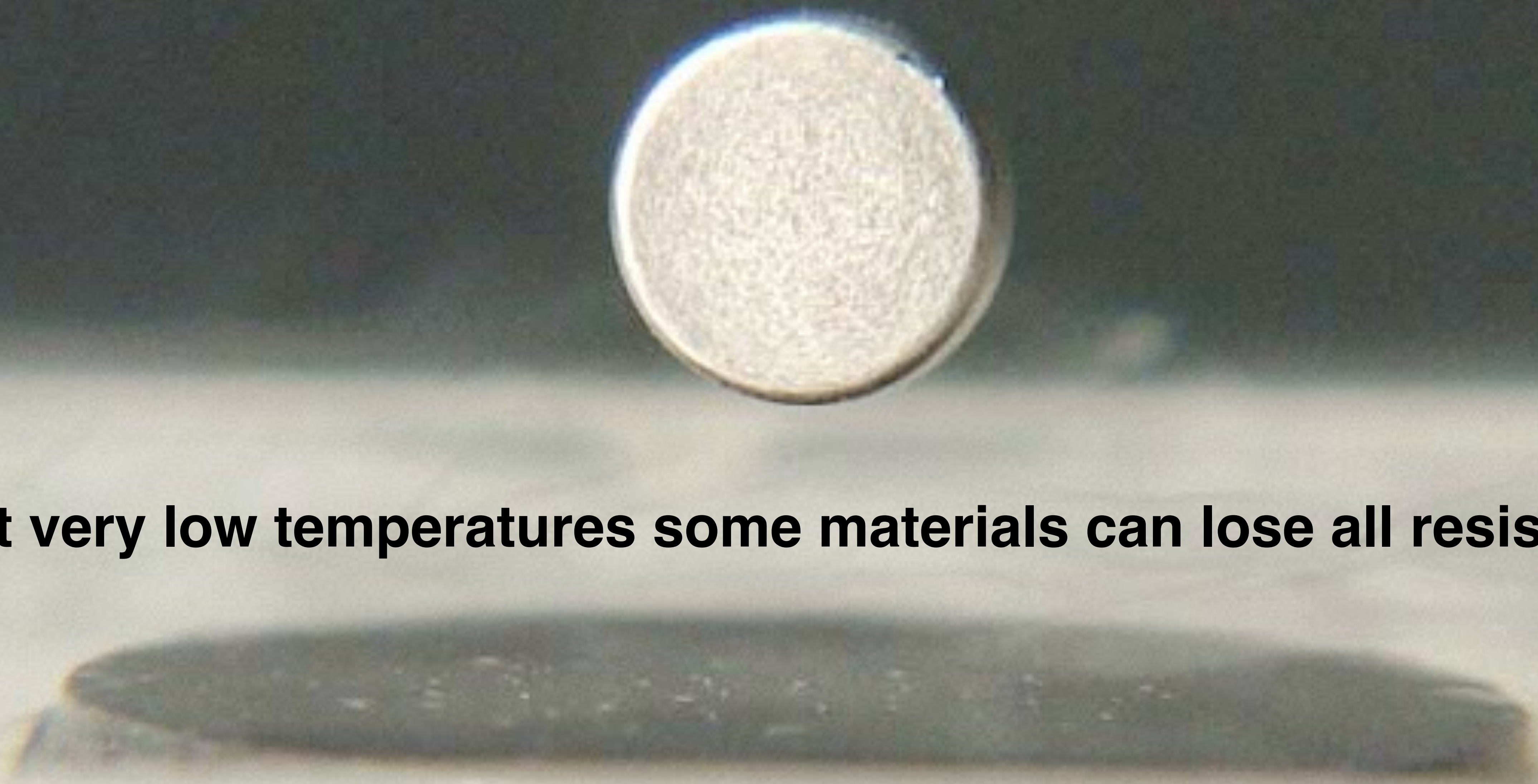


These are temperatures we need to reach to create macroscopic matter waves !

Matter changes at low temperatures!

- ***Matter can undergo a Phase Transition when lowering temperatures!***
  - ***Gas ⇨ Liquid***
  - ***Liquid ⇨ Solid***
  - ***Normal Conductor ⇨ Superconductor***
  - ***Normal Liquid ⇨ Superfluid***
  - ***Classical Gas ⇨ Quantum Gas (BEC)***

Superconductivity at Low Temperatures

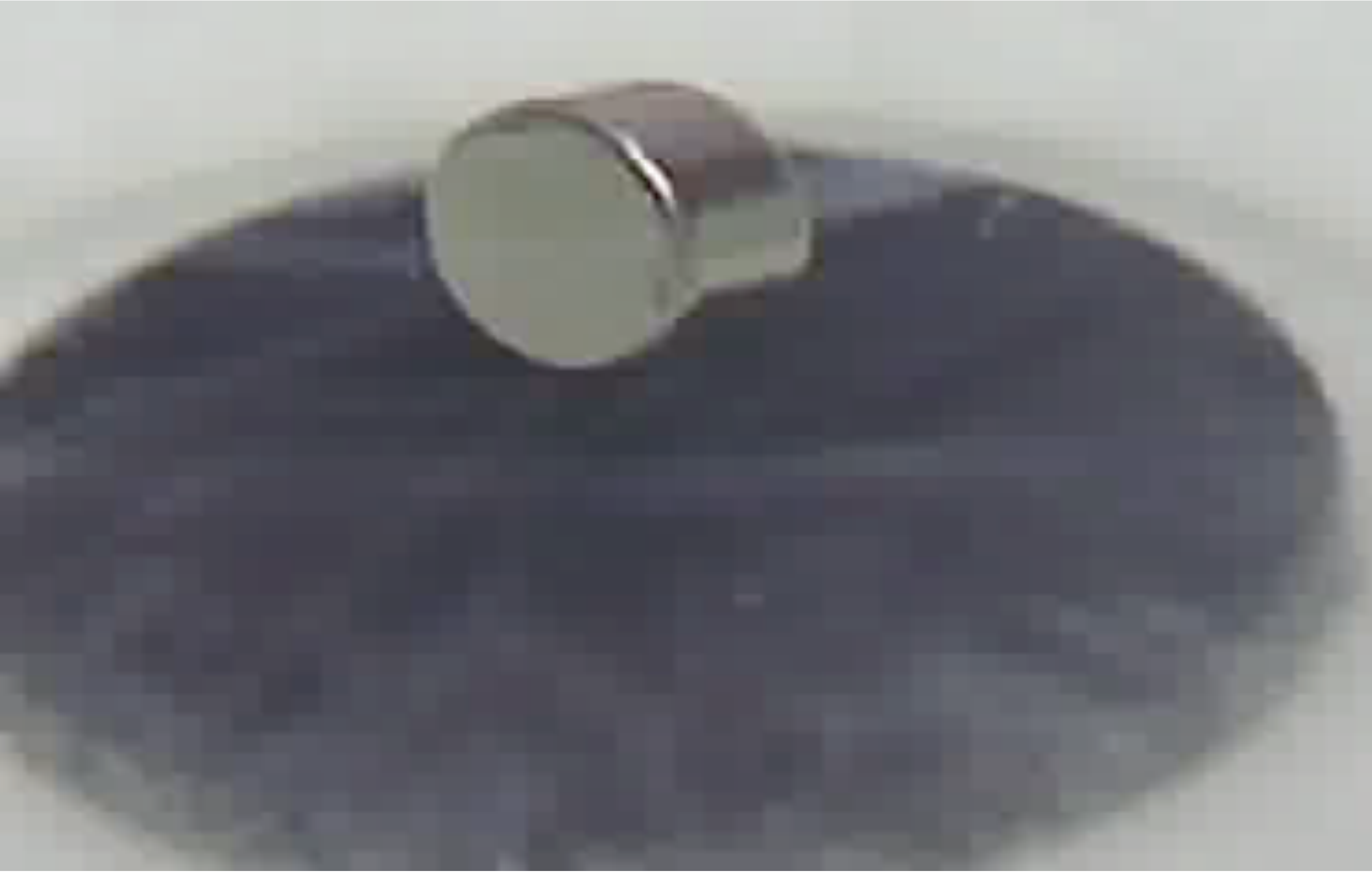


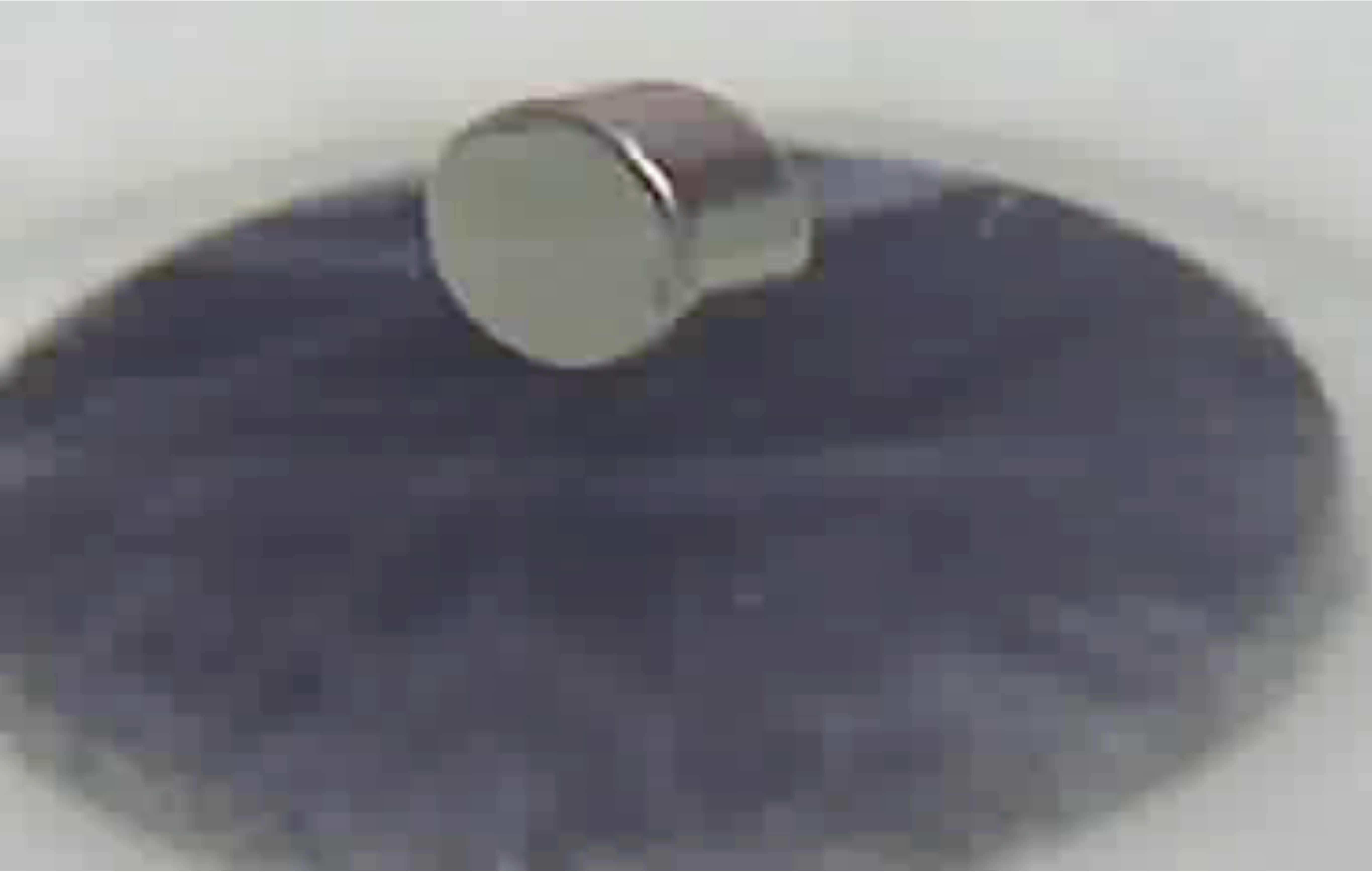
At very low temperatures some materials can lose all resistivity!

They become superconductors!

Meissner Effect

Meissner Effect

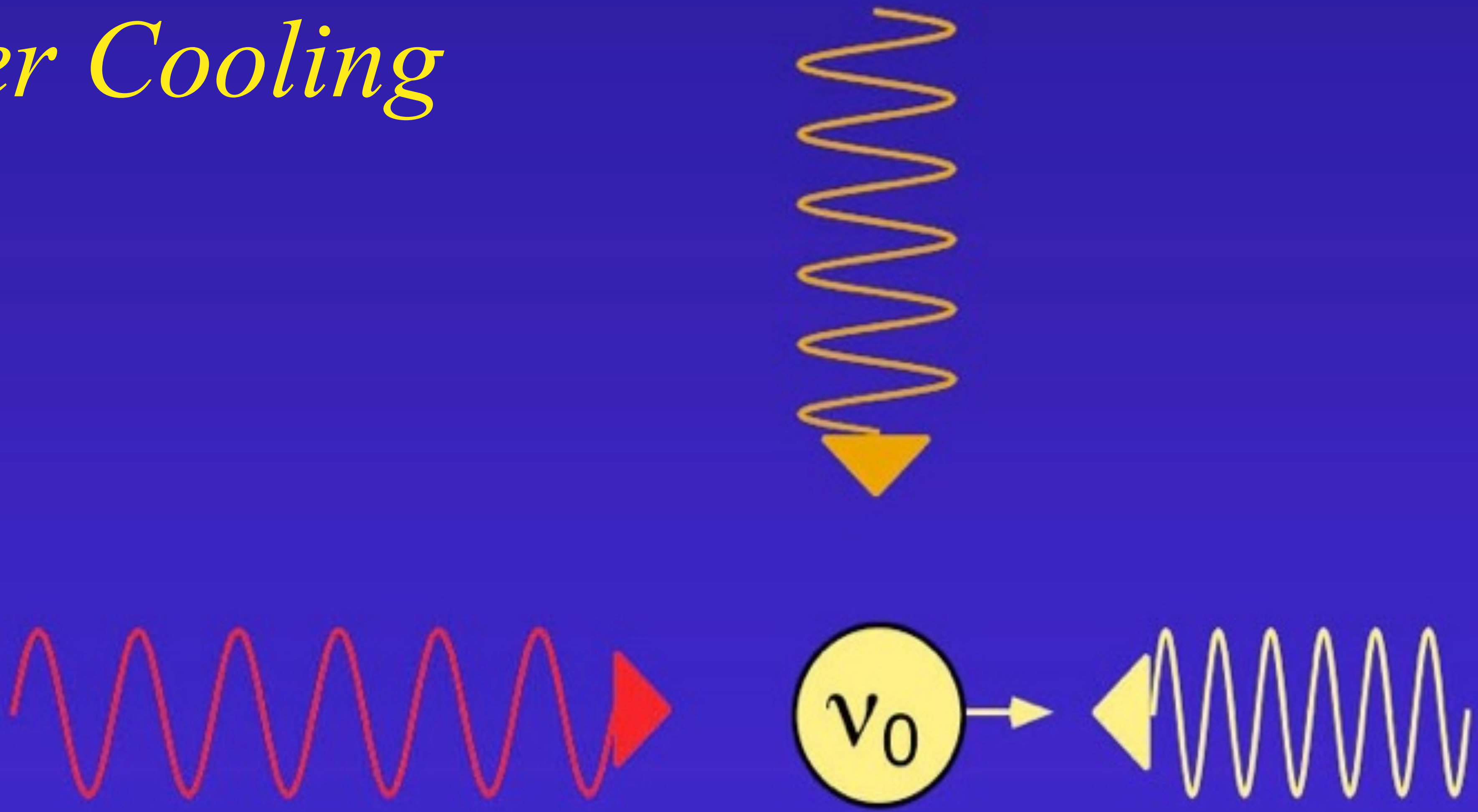




Radiation Pressure

A special way to cool!

Laser Cooling



T.W. Hänsch and A.L. Schawlow, Opt. Comm. 13, 68 (1975)

Laser Cooling

Nobel in Physics 1997

Steve Chu

Claude Cohen-Tannoudji

Bill Phillips

Laser Cooling some Facts

Maximum Acceleration

$$a_{\max} = \frac{\hbar k}{m} \times \frac{\Gamma}{2}$$

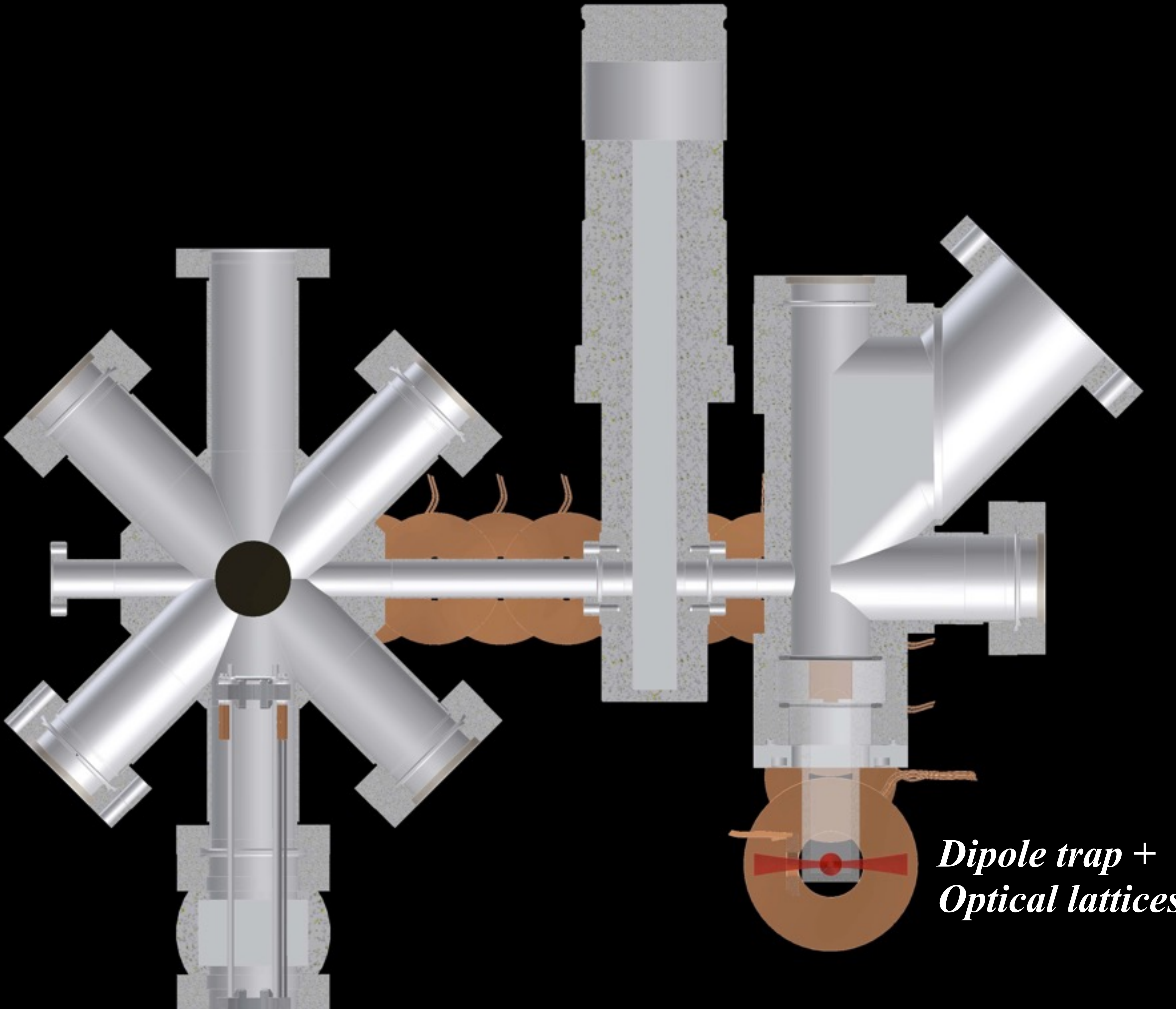
e.g. for ^{87}Rb

$$a_{\max} = 100000\, m/s^2$$

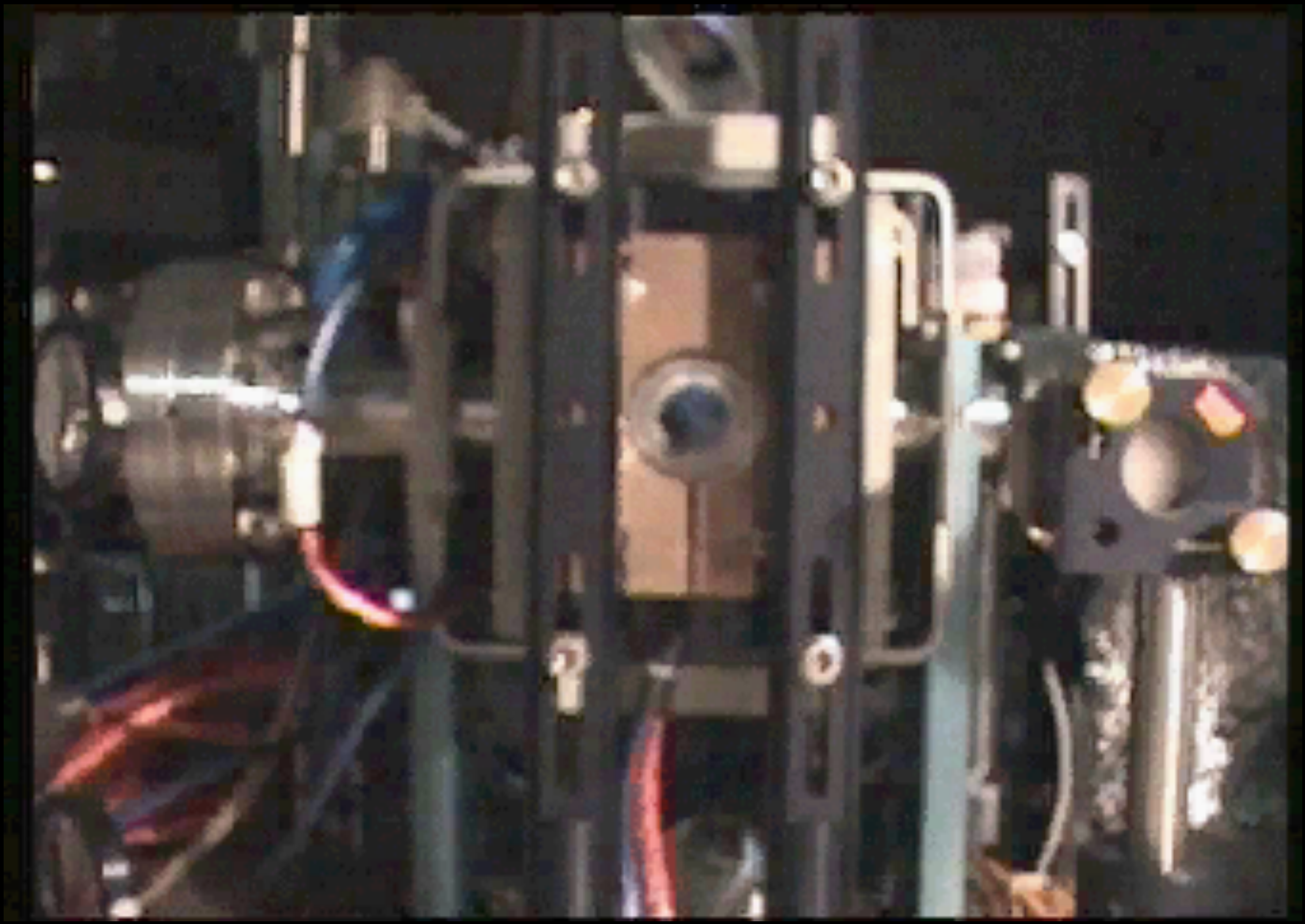
10000 g !

Minimum Temperature

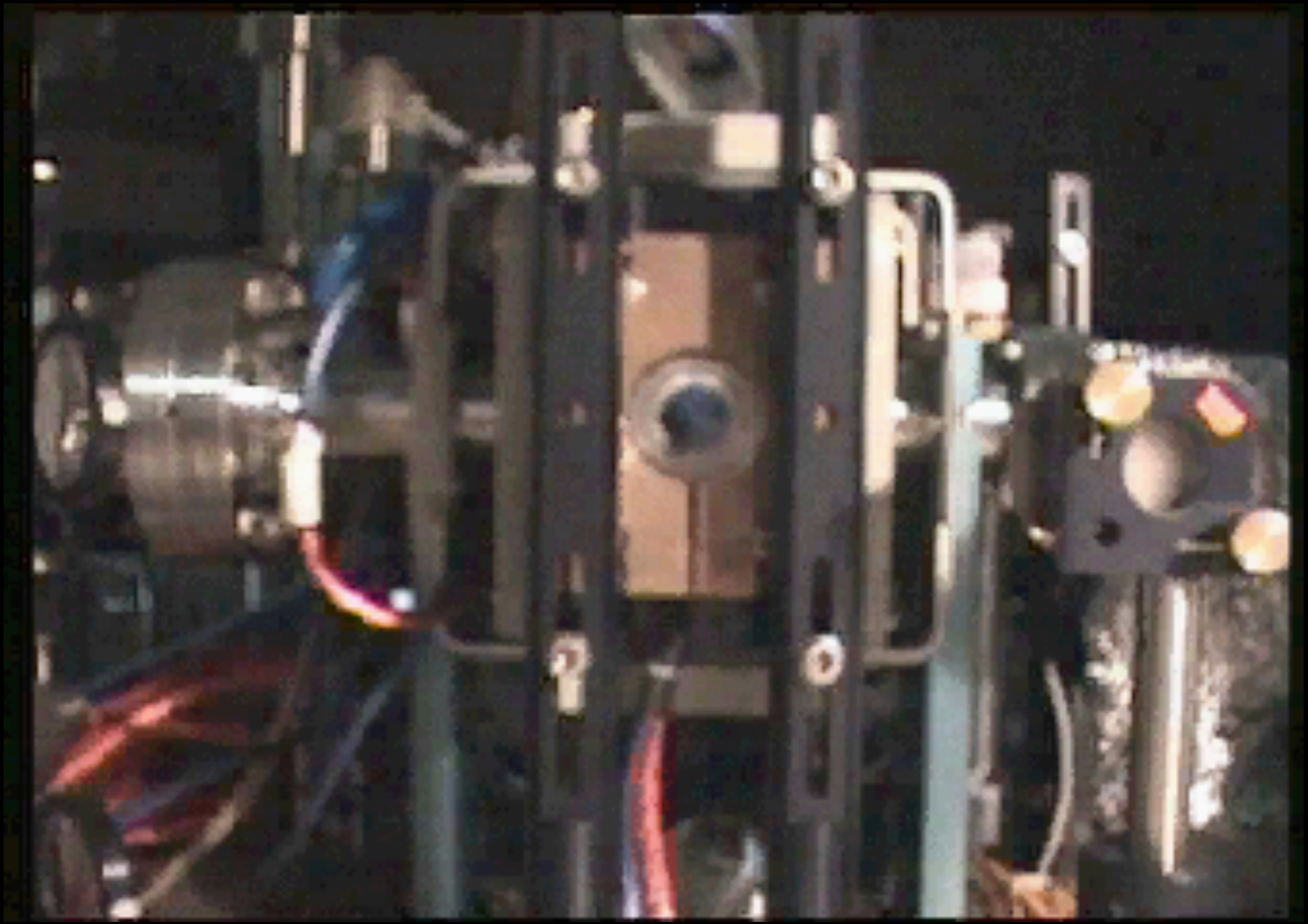
$$T_{\min} \approx 10 \mu K$$


Dipole trap +
Optical lattices

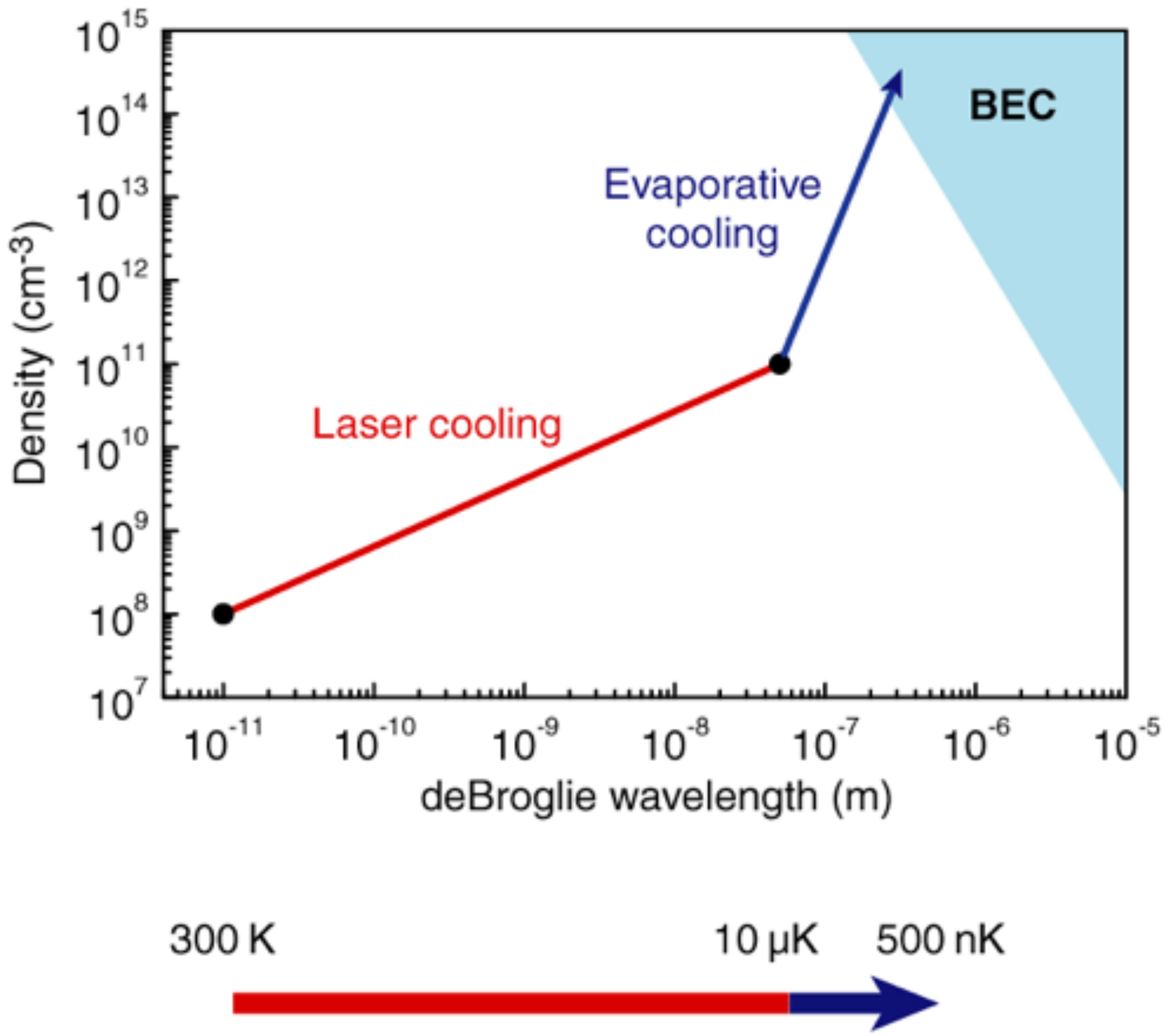
Laser Cooling at Work



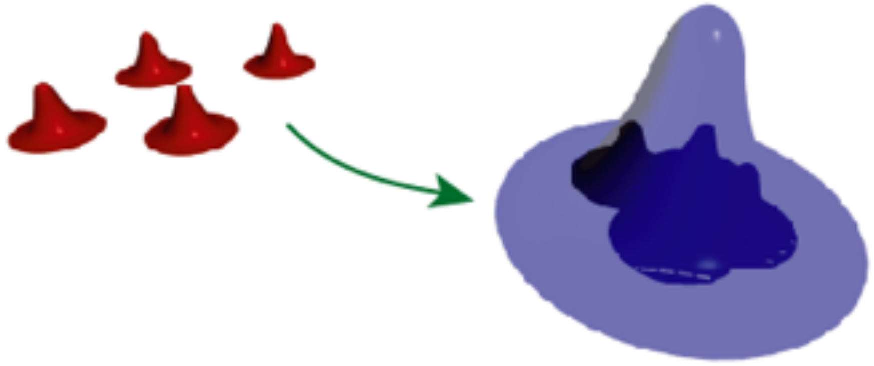
Laser Cooling at Work



The Path to Bose-Einstein Condensation



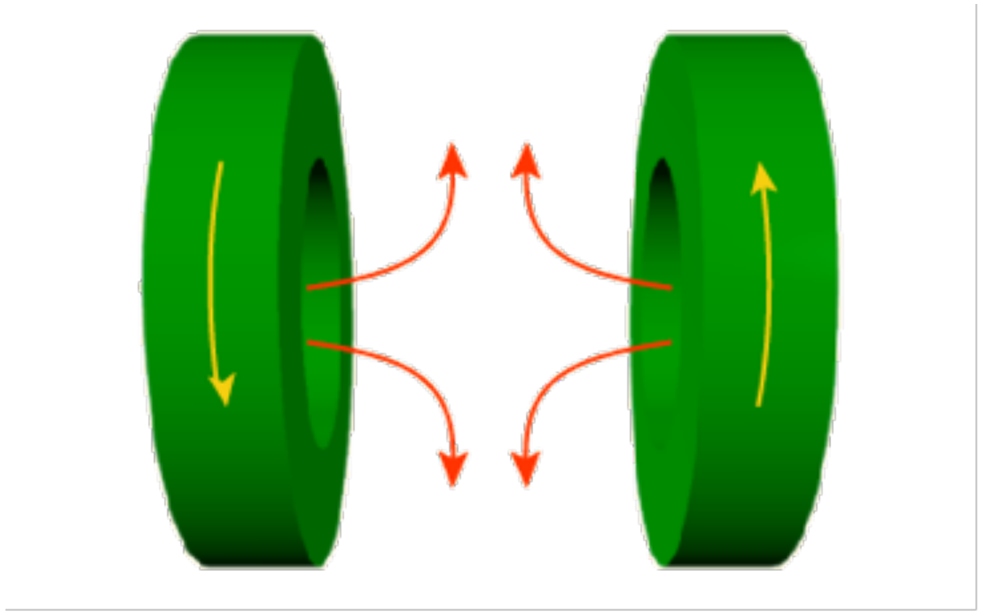
$$n \cdot \lambda^3 \approx 1$$

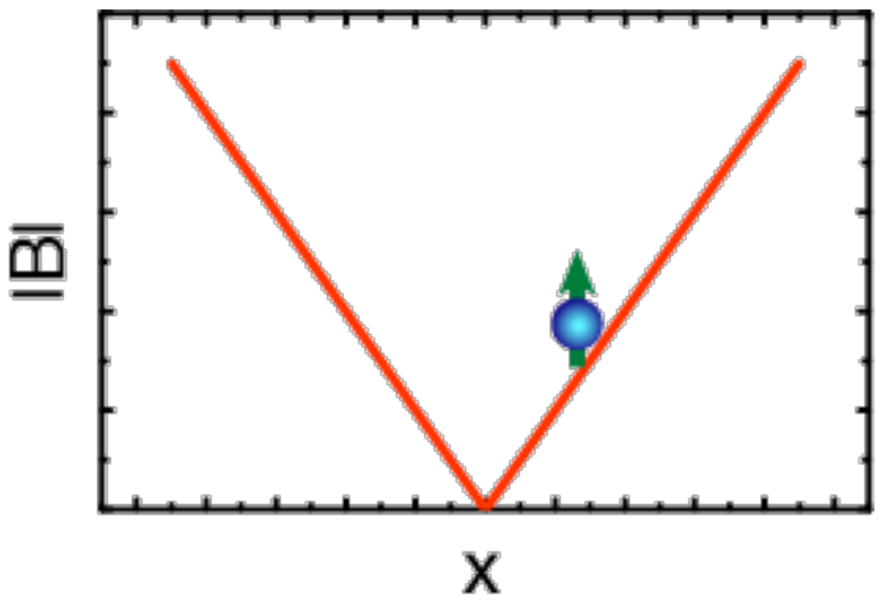


Magnetic Traps for Neutral Atoms

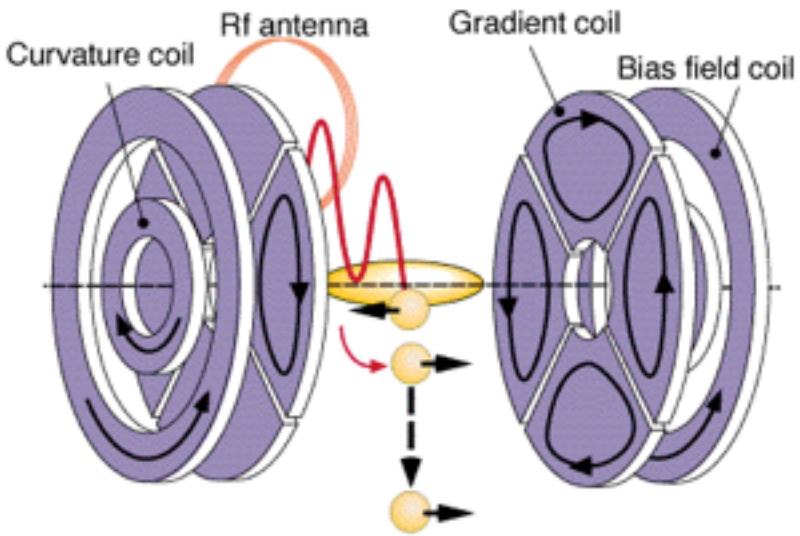
Energy of an atom
in an external magnetic field $E = -\vec{\mu} \cdot \vec{B}$

Force on an atom in an
inhomogeneous magnetic field $\vec{F} = -\mu \cdot \nabla B$



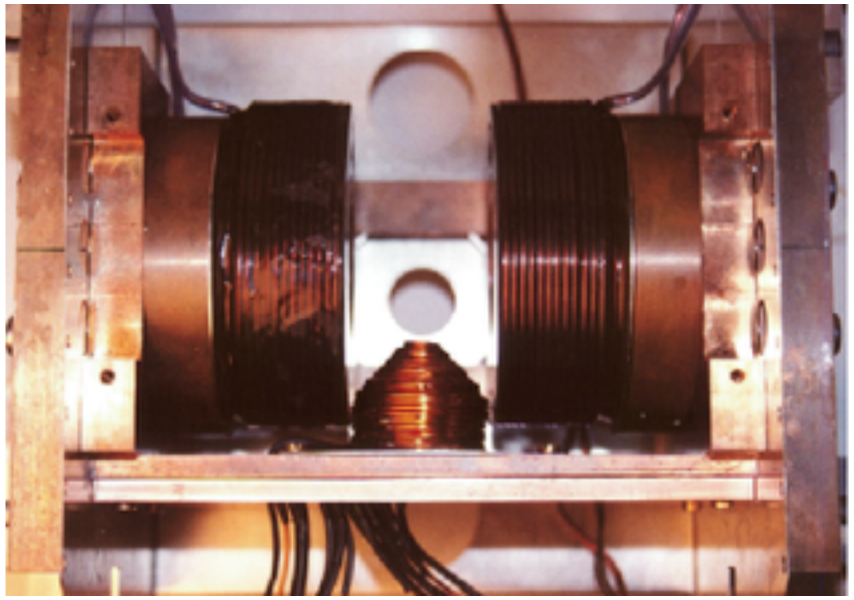


Magnetic Trap 'Zoology'



MIT, March '96 [M.-O. Mewes et al., PRL 77, 416 (1996)]

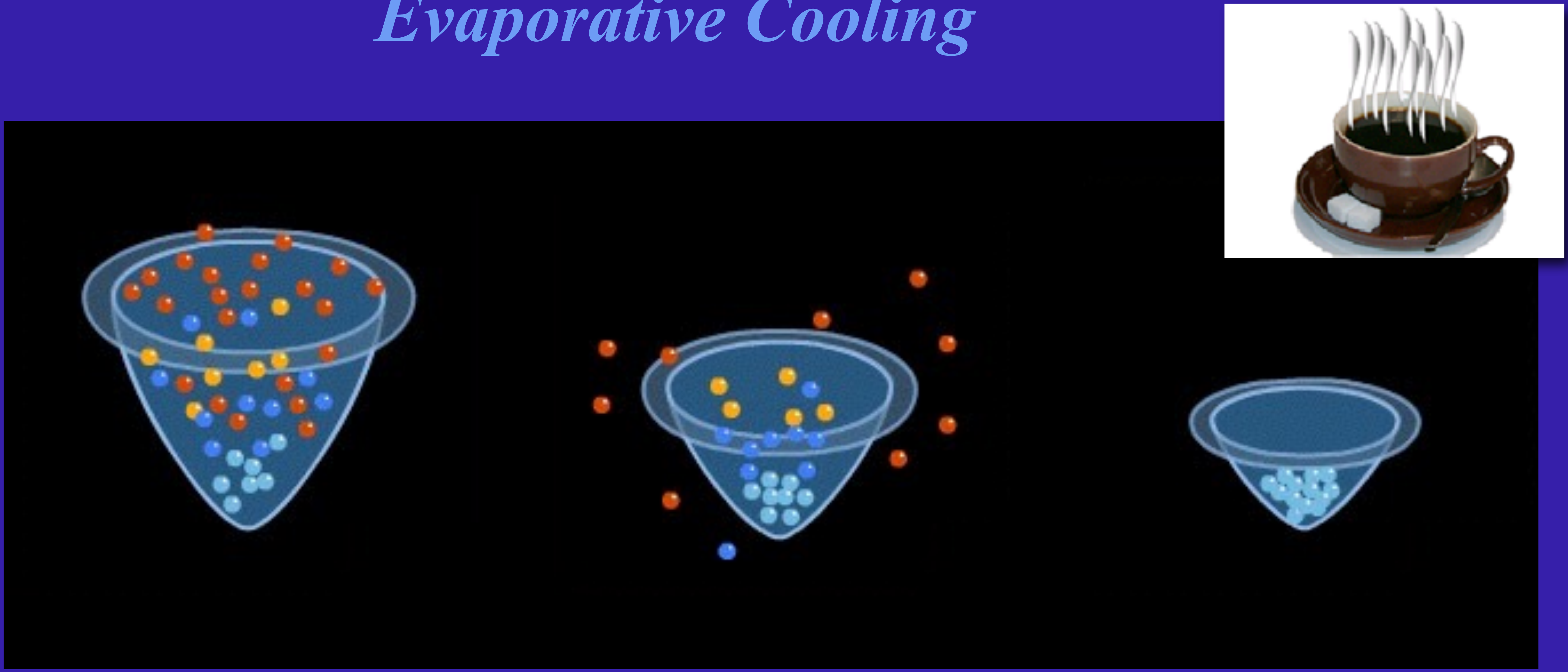
Cloverleaf Trap



QUIC-Trap

Miniaturized Magnetic Traps

Evaporative Cooling



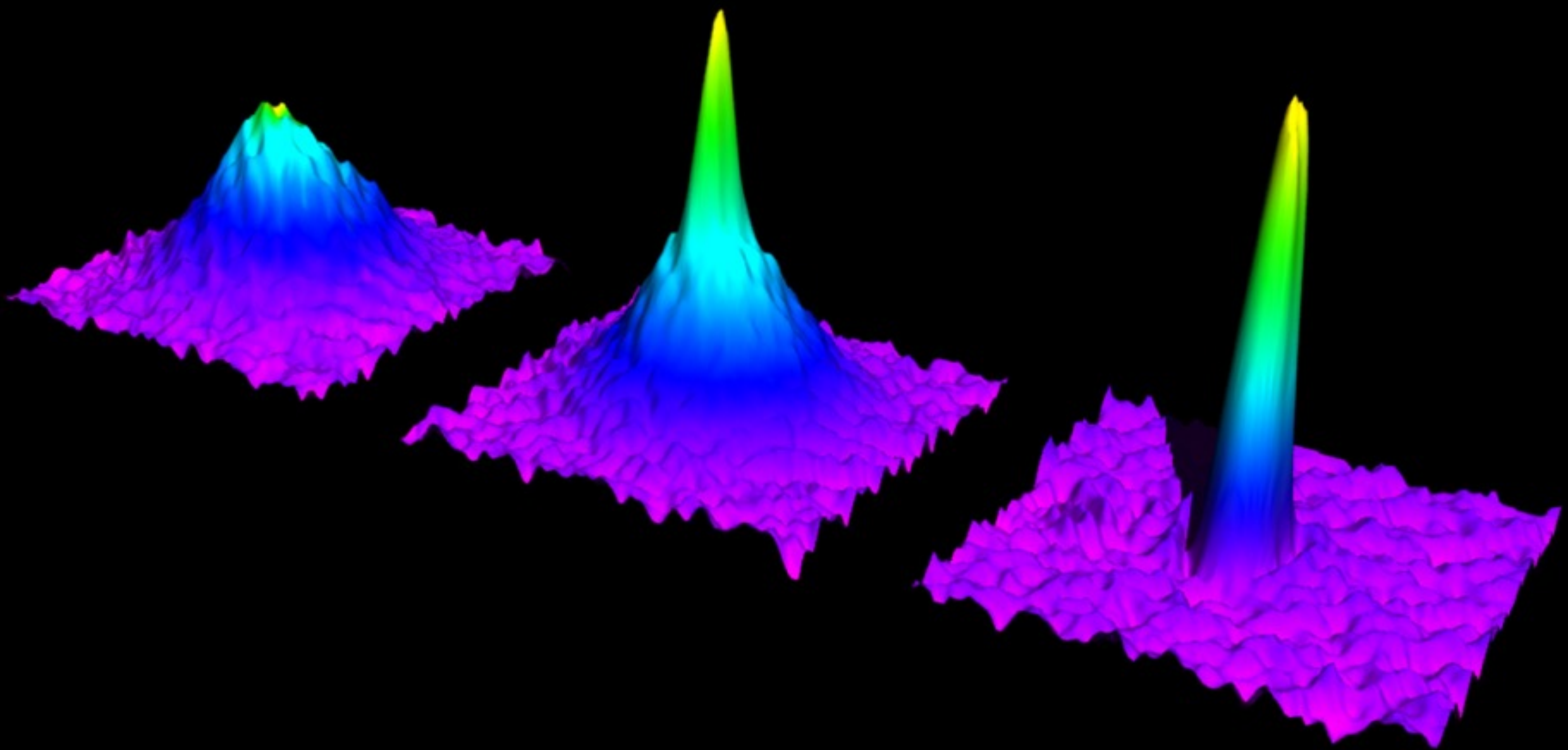
Tom Greytak

Daniel Kleppner

Go To Evap Applet...

Time-of-Flight Imaging

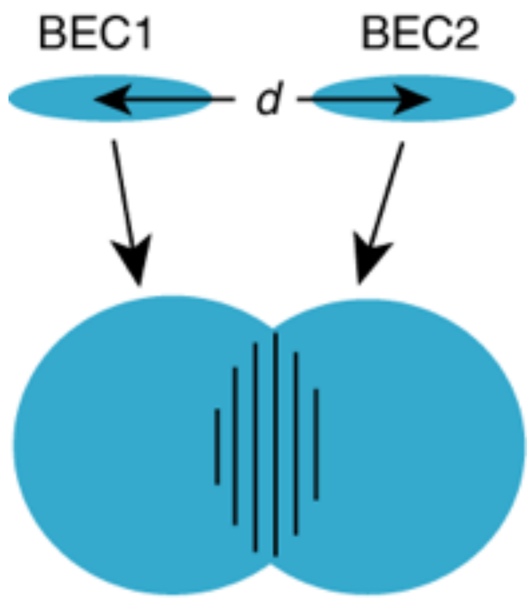
Time-of-Flight Imaging



Interference of Two Bose-Einstein Condensates

Trapped BEC's

BEC's after expansion time t

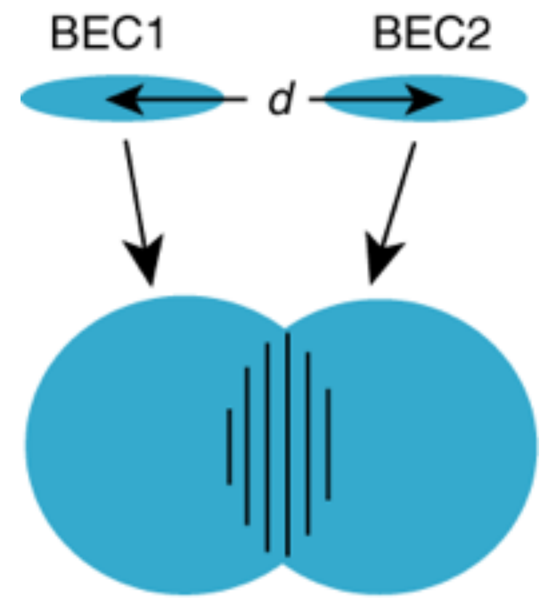


$$\lambda = \frac{h}{m\Delta v} = \frac{ht}{md}$$

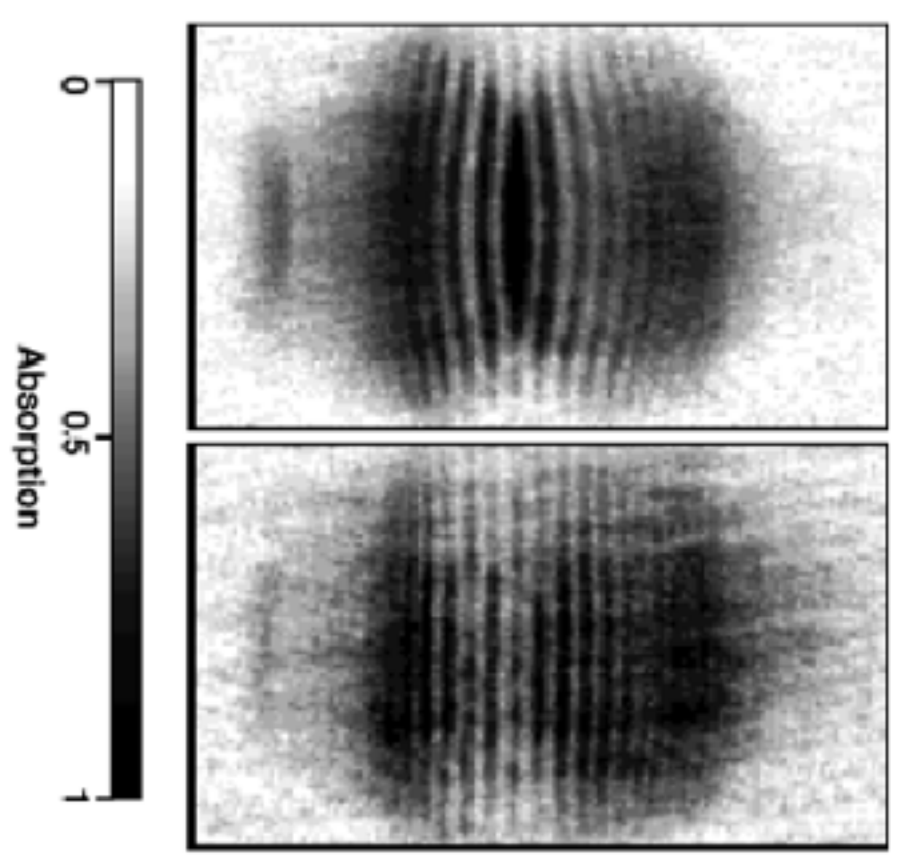
Interference of Two Bose-Einstein Condensates

Trapped BEC's

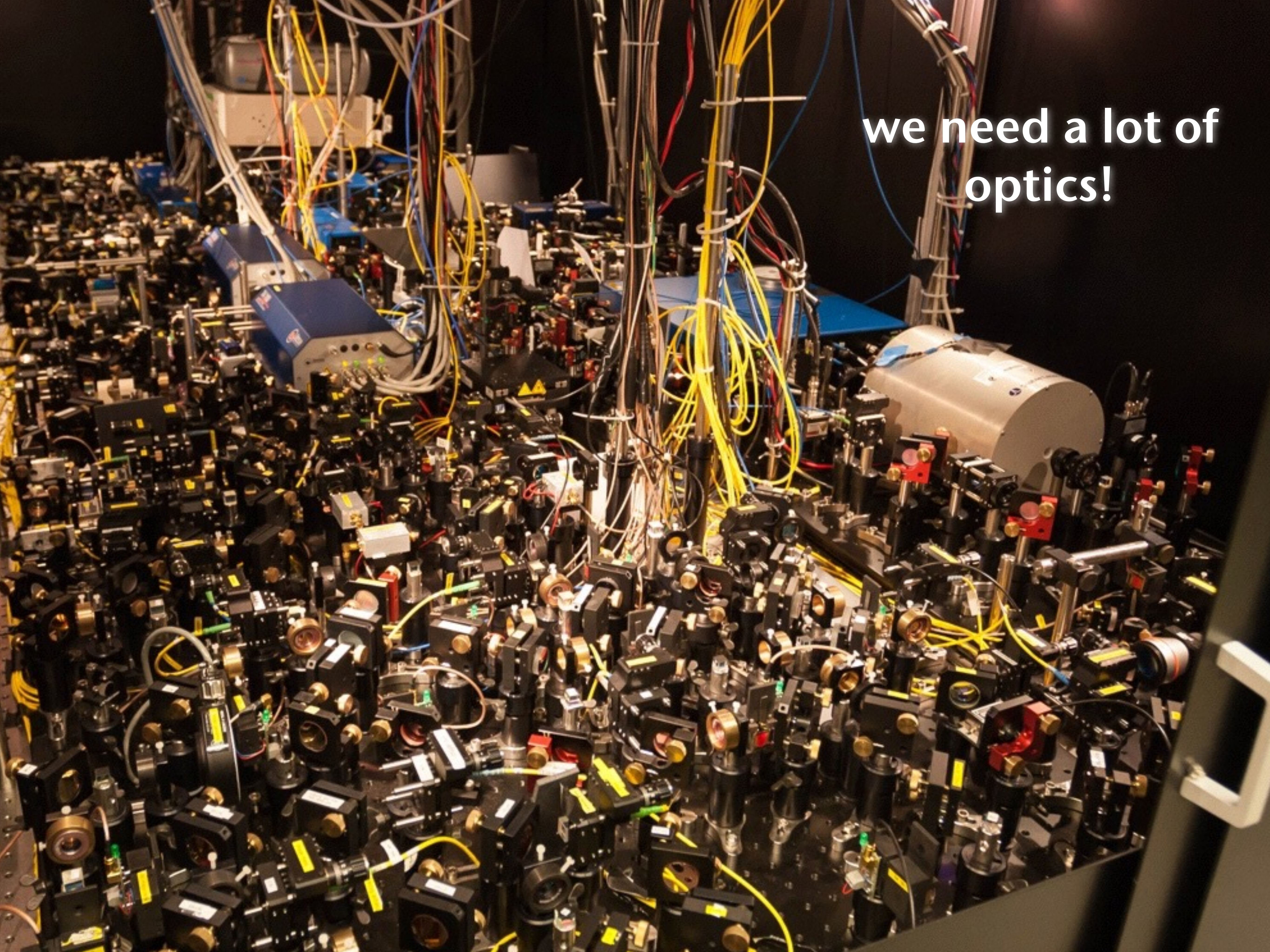
BEC's after expansion time t

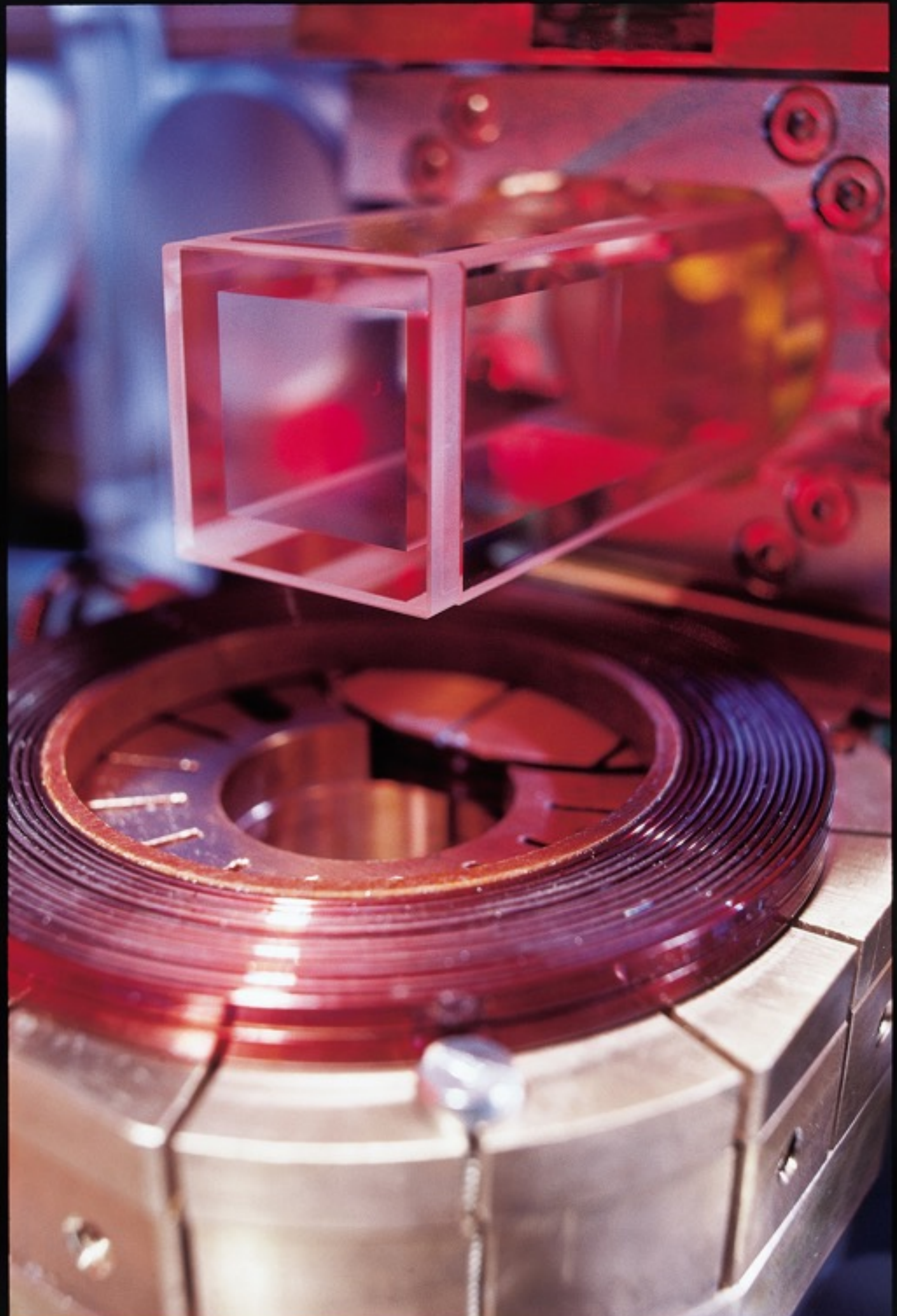


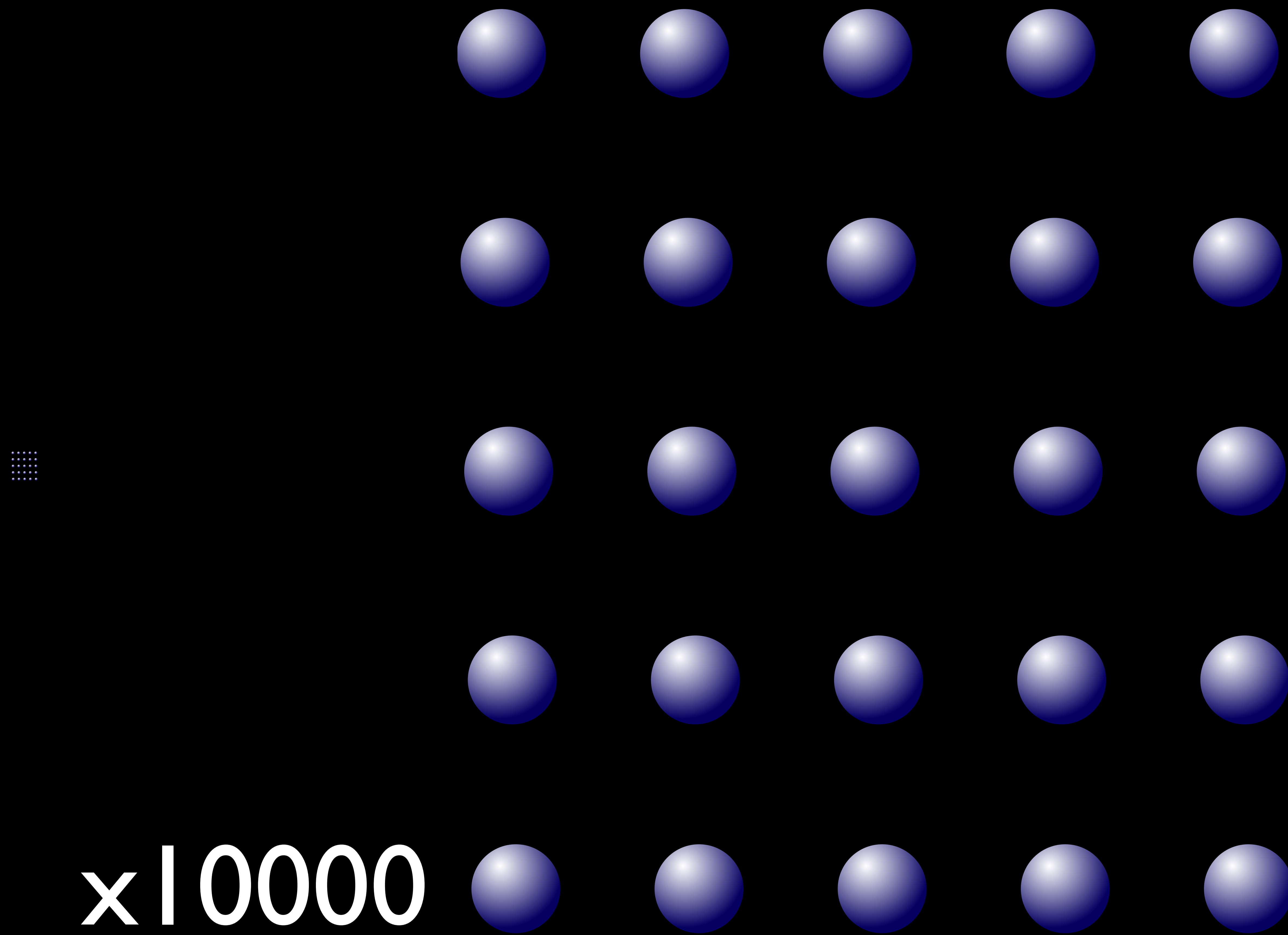
$$\lambda = \frac{h}{m\Delta v} = \frac{ht}{md}$$



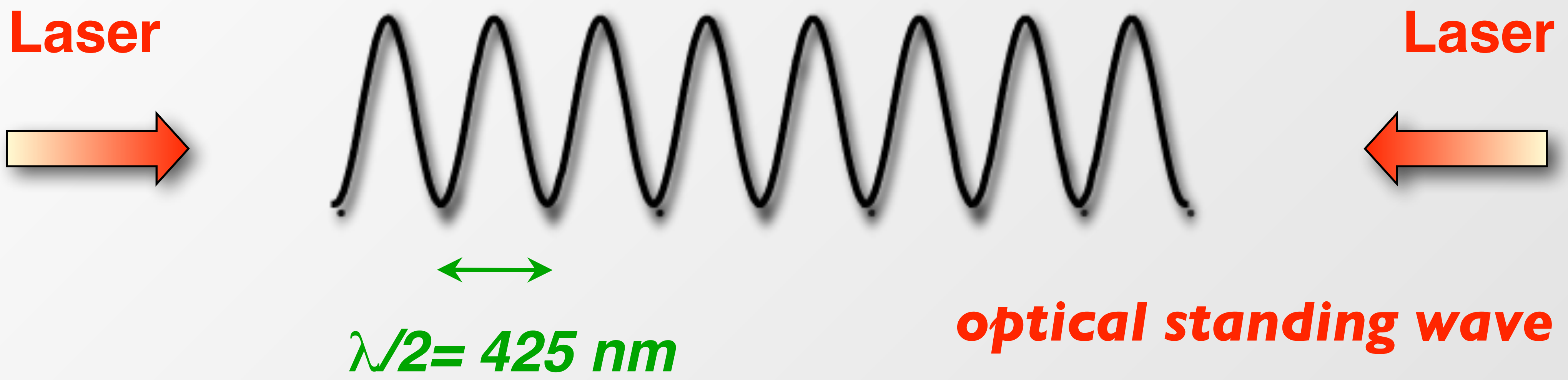
M. R. Andrews *et. al.*
Science 275, ff. 637, 1997


we need a lot of
optics!

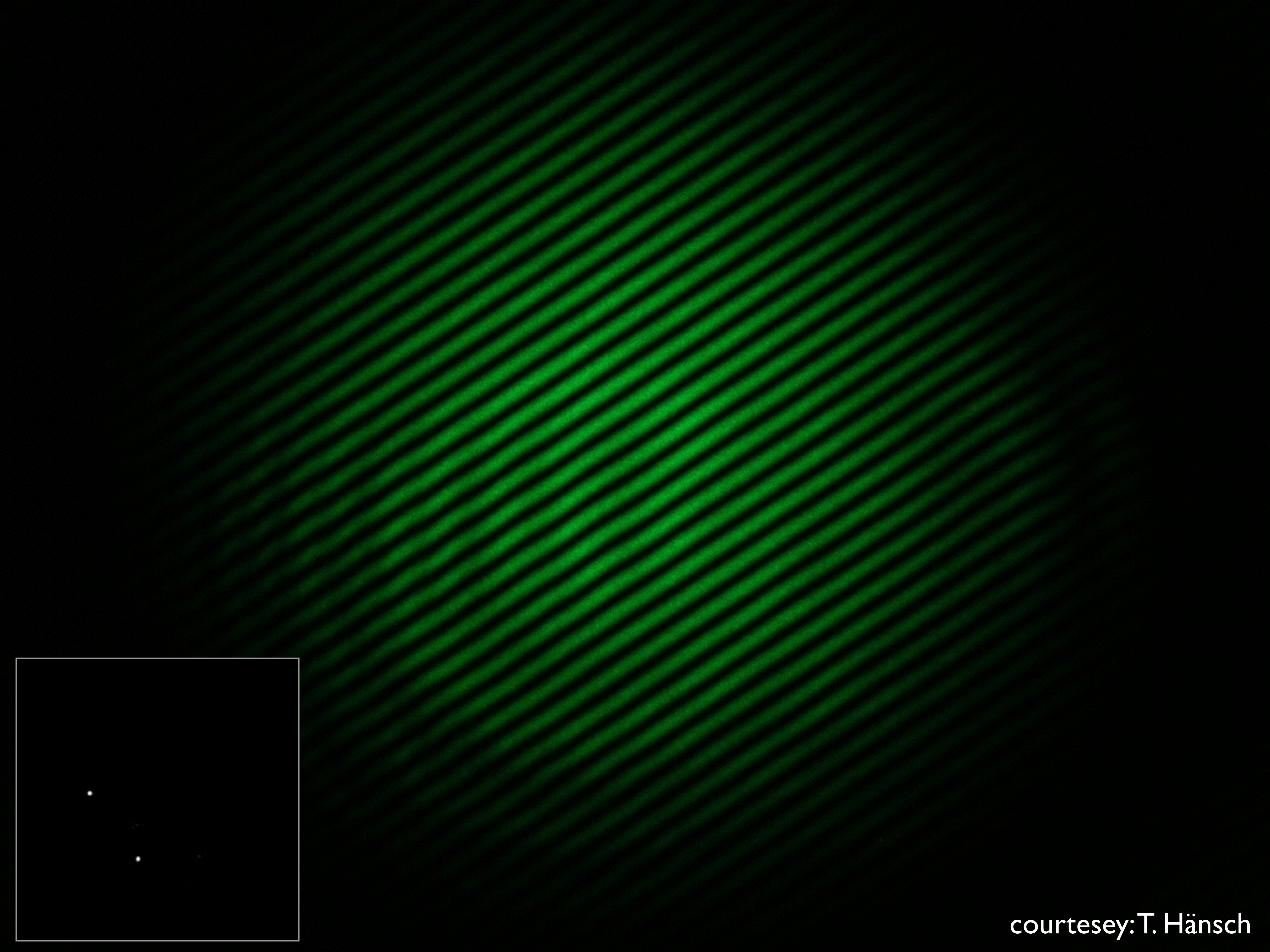



x10000

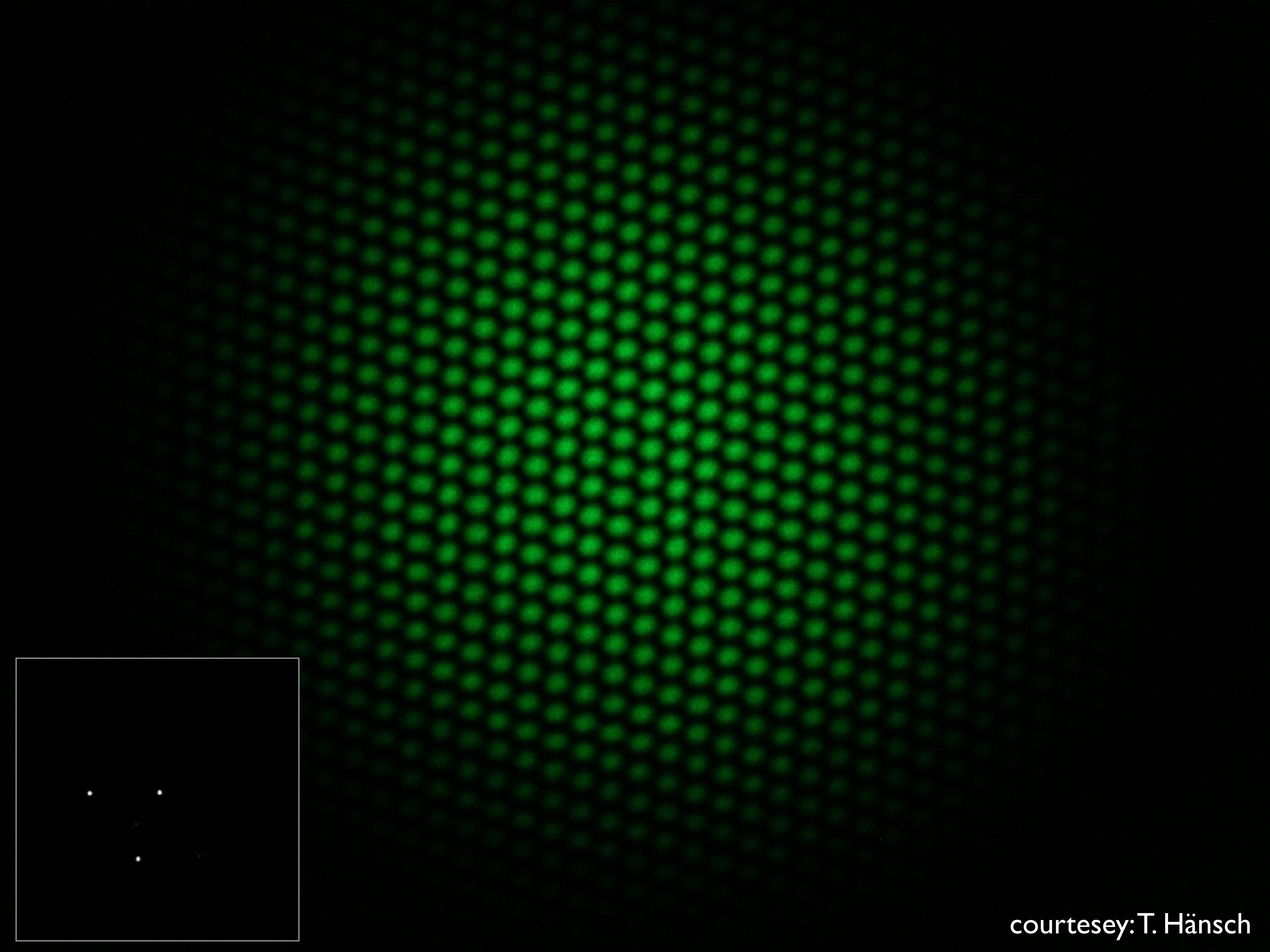
Optical Lattice Potential – Perfect Artificial Crystals



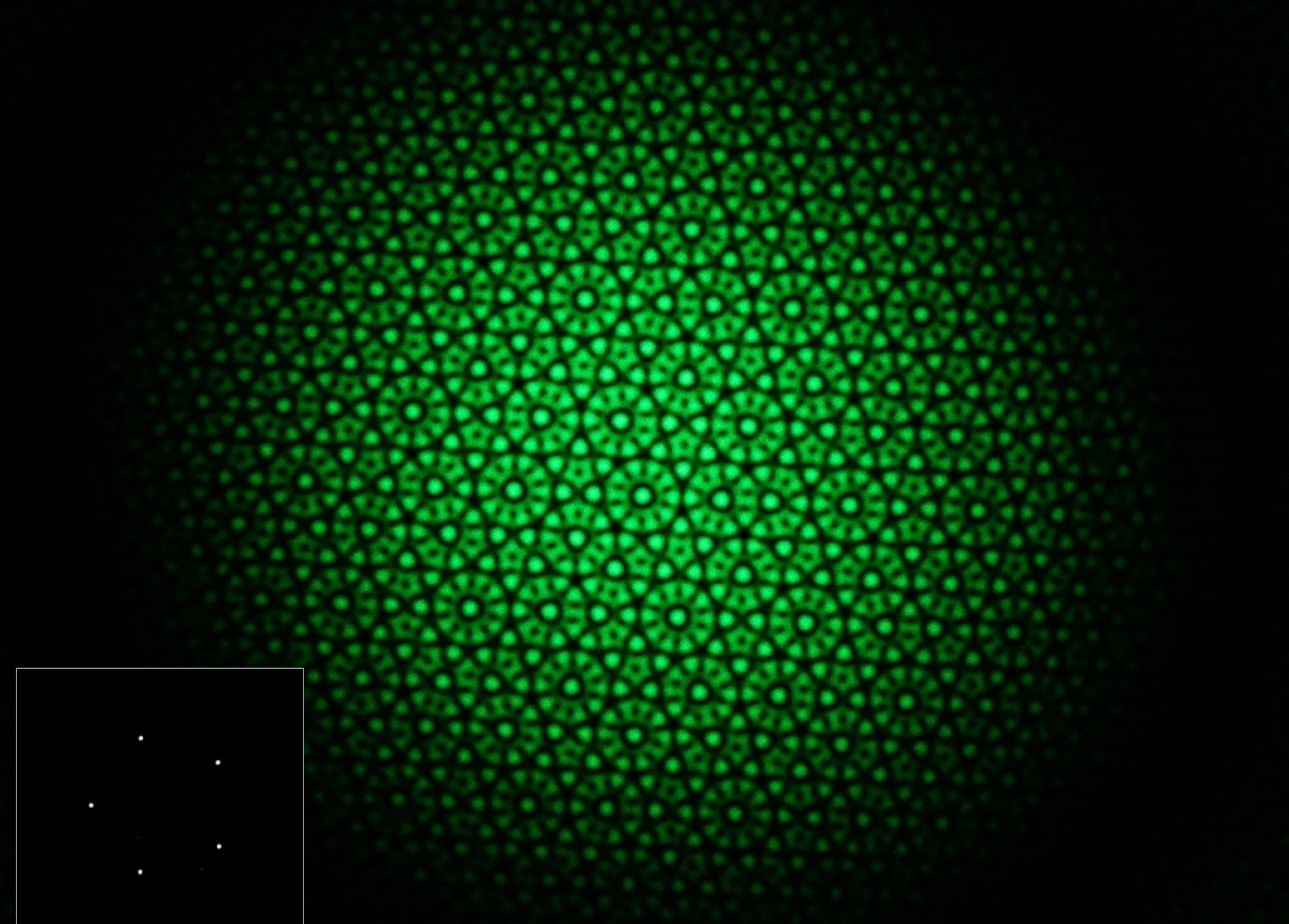
Perfect model systems for a fundamental understanding of quantum many-body systems



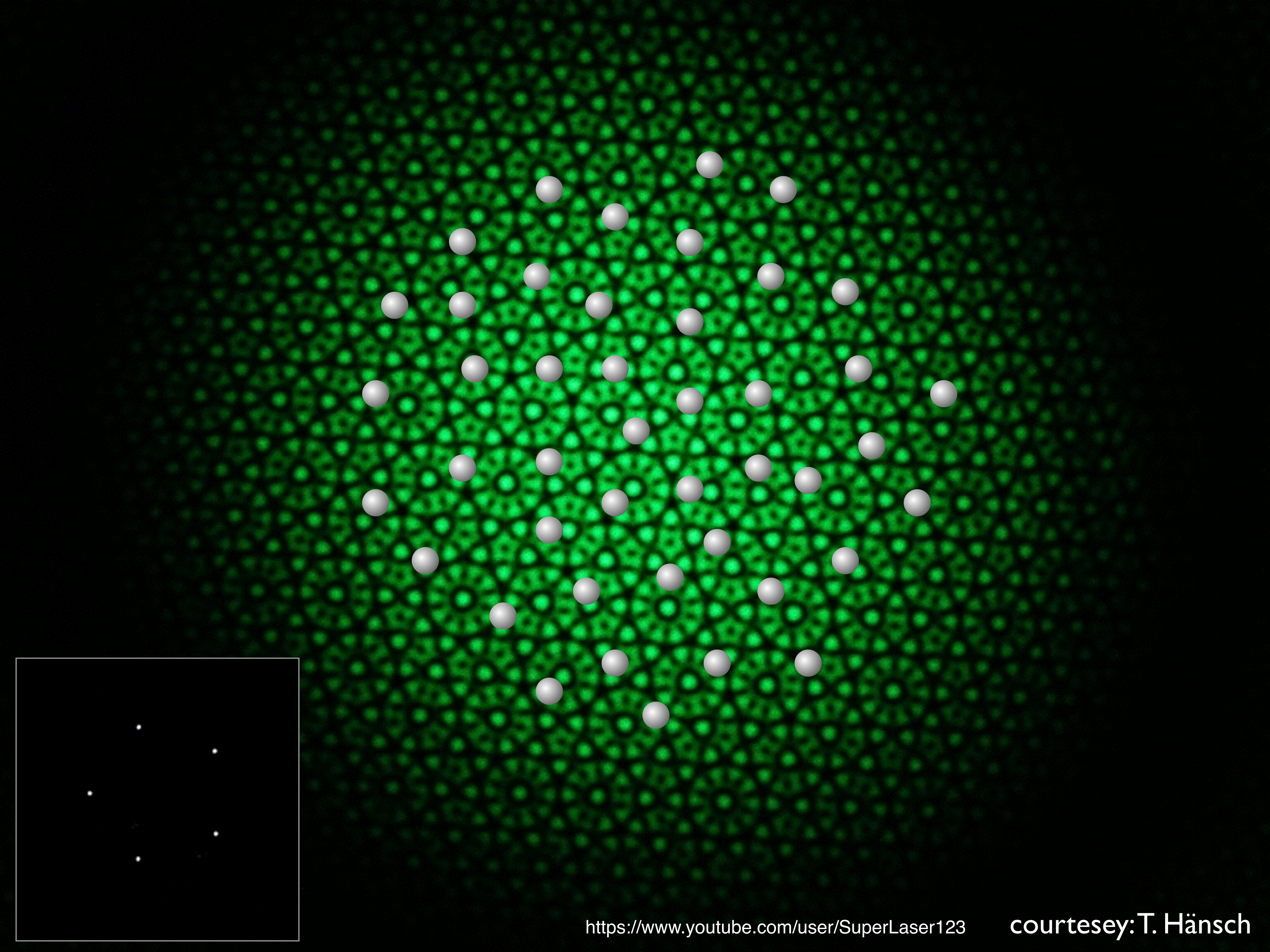
courtesey: T. Hänsch



courtesey: T. Hänsch



https://www.youtube.com/user/SuperLaser123 courtesey: T. Hänsch

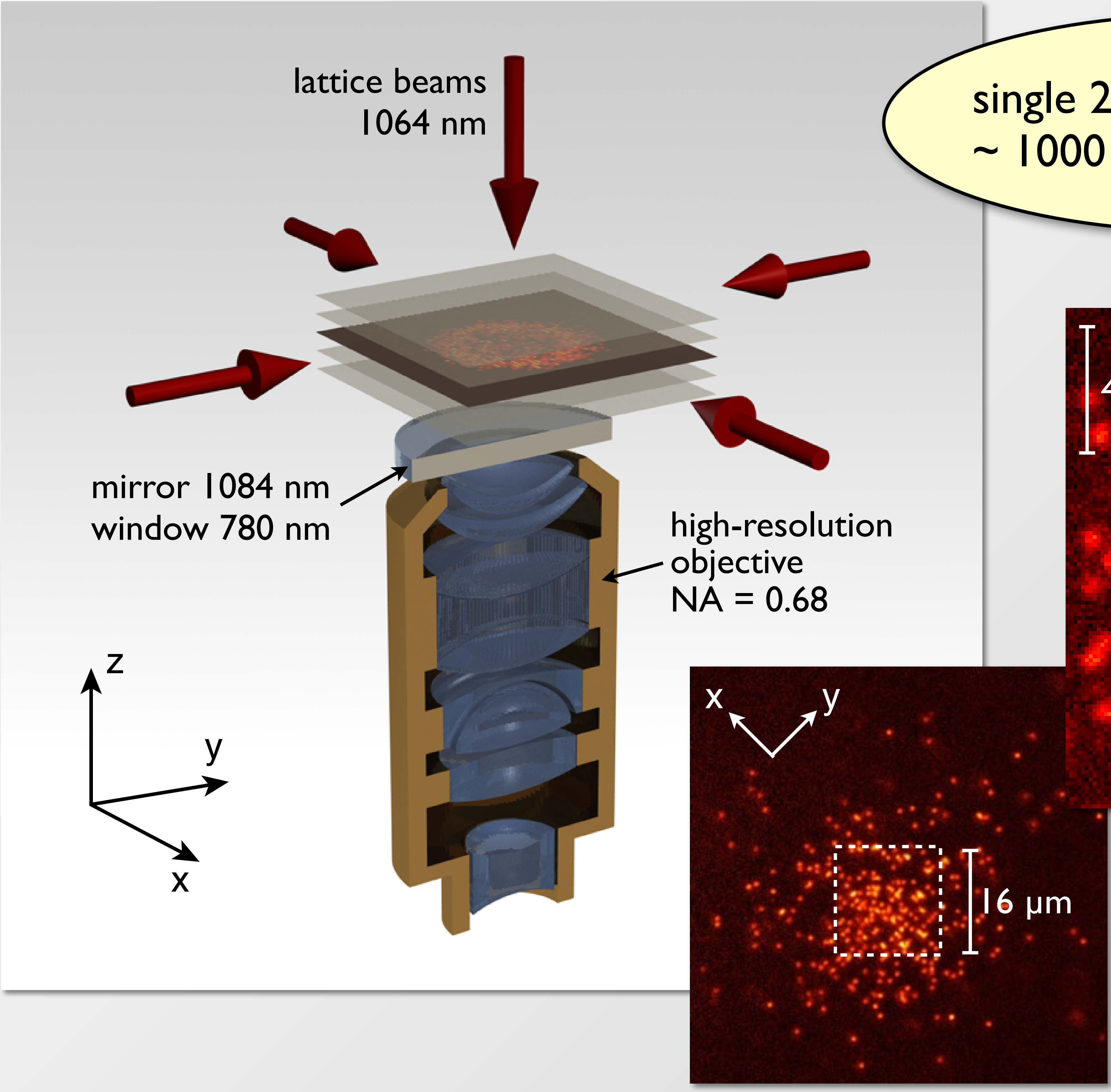


https://www.youtube.com/user/SuperLaser123 courtesey: T. Hänsch

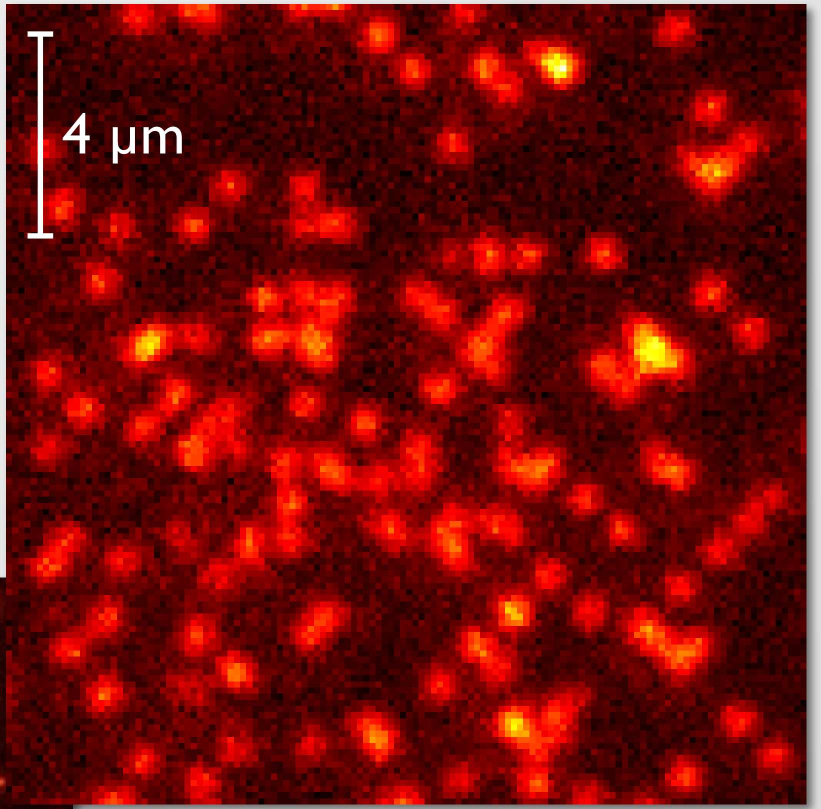
courtesey: T. Hänsch

courtesey: T. Hänsch

Seeing Single Atoms

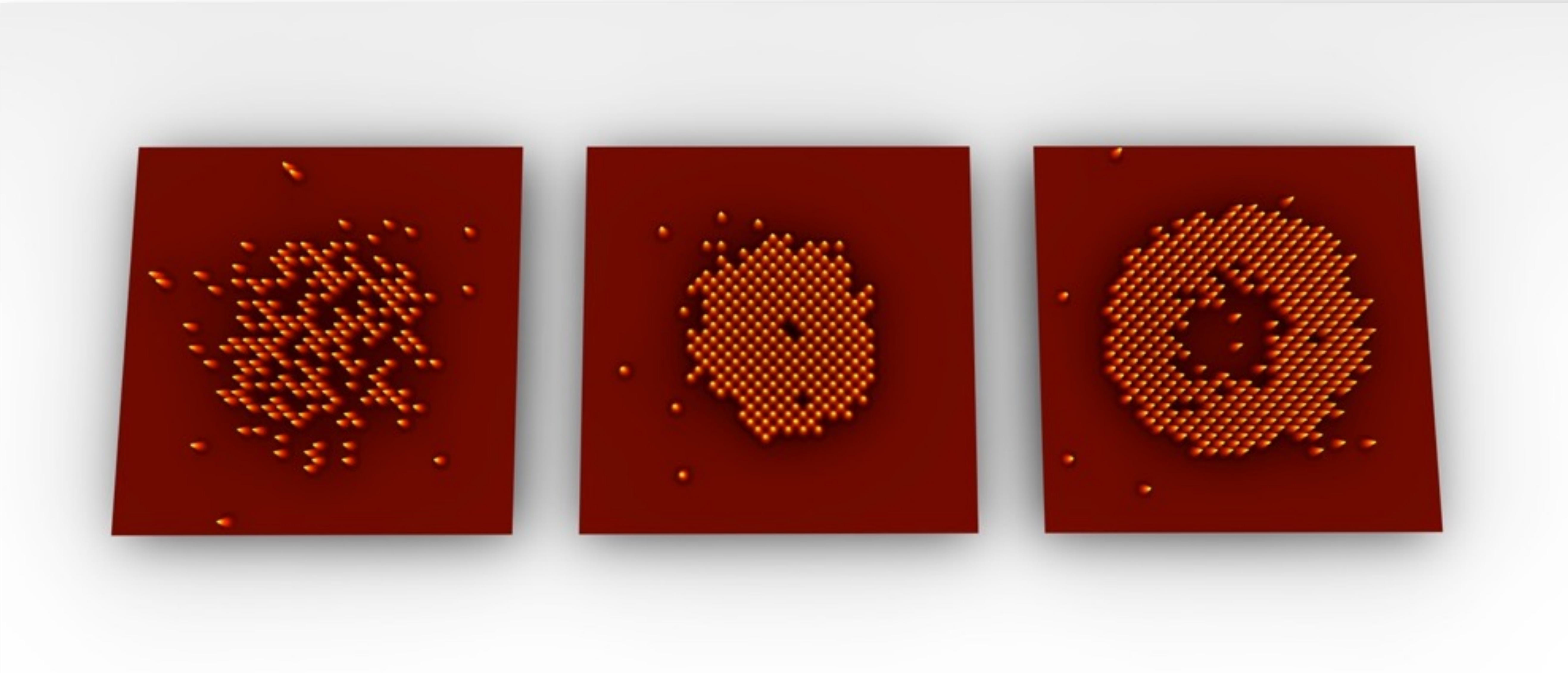


single 2D degenerate gas
~ 1000 ^{87}Rb atoms (bosons)



resolution of the imaging system: ~700 nm

Snapshot of an Atomic Density Distribution



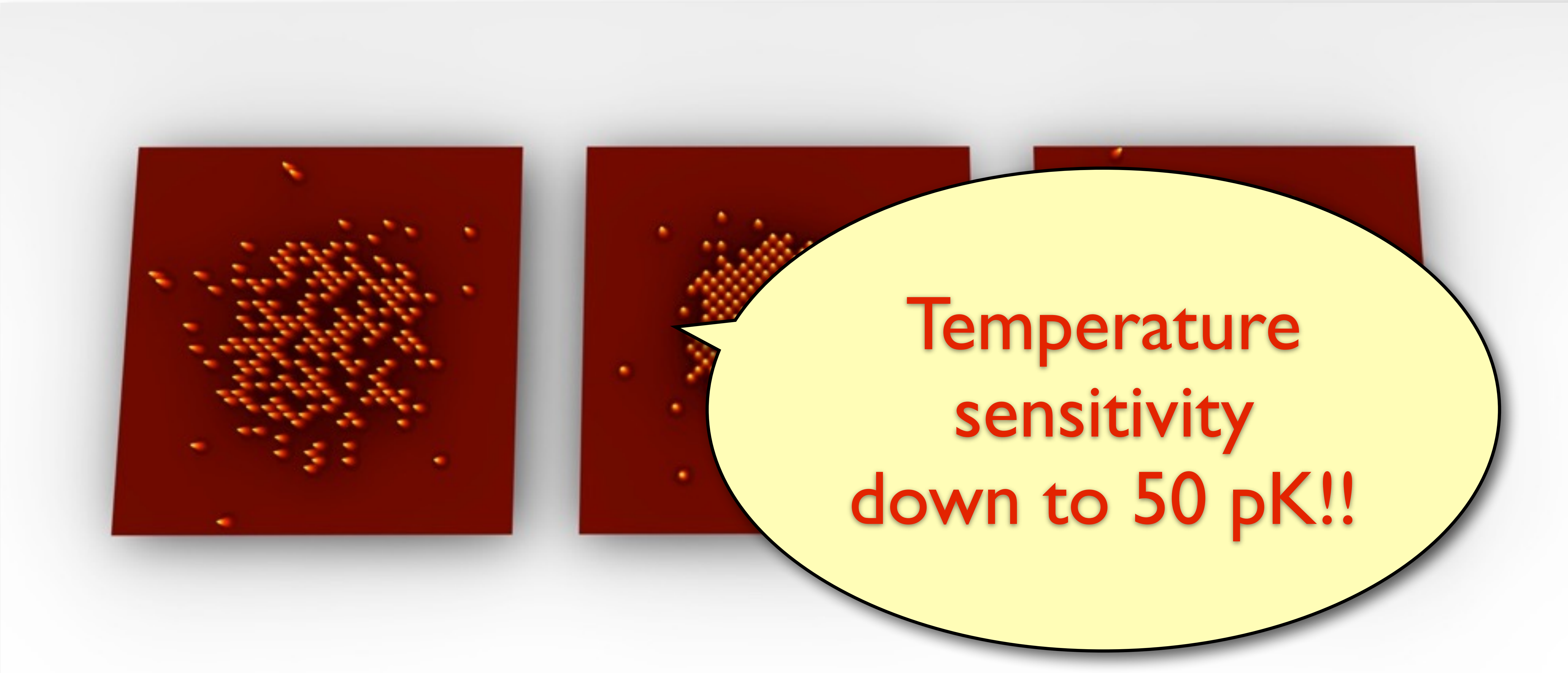
BEC

n=1
Mott Insulator

n=1 & n=2
Mott Insulator

J. Sherson *et al.* Nature **467**, 68 (2010)

Snapshot of an Atomic Density Distribution



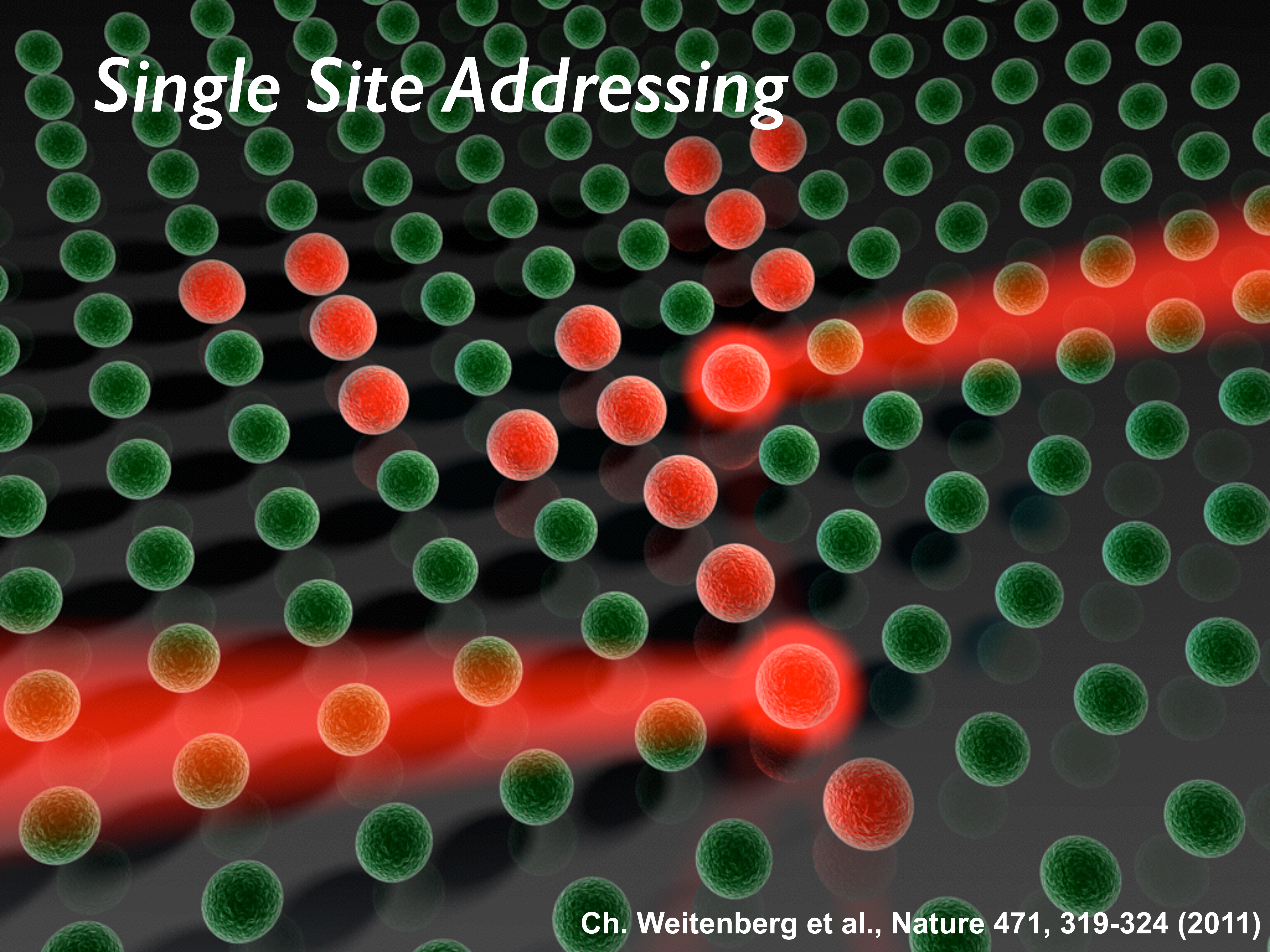
BEC

n=1
Mott Insulator

n=1 & n=2
Mott Insulator

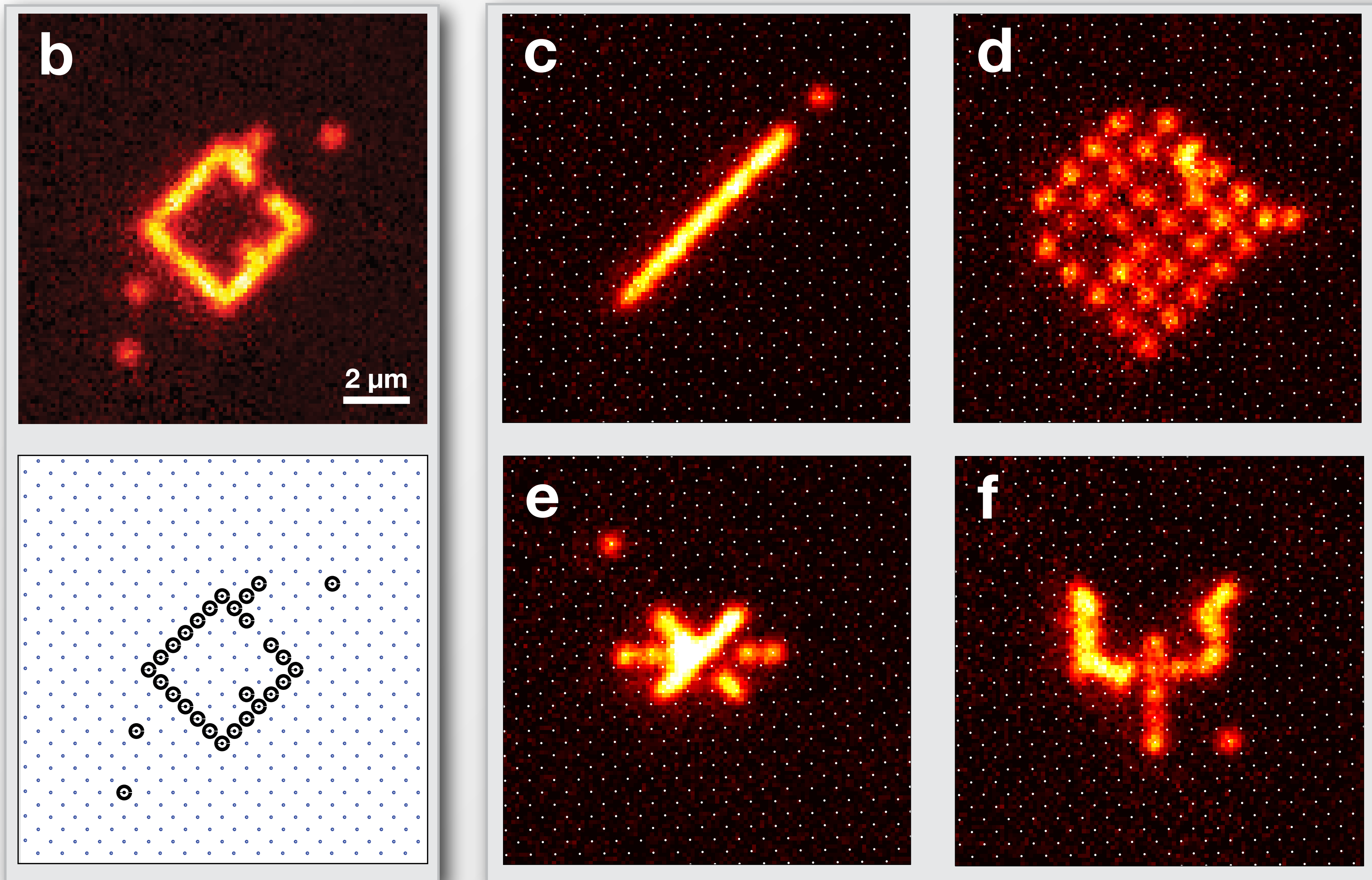
J. Sherson *et al.* Nature **467**, 68 (2010)

Single Site Addressing



Ch. Weitenberg et al., Nature 471, 319-324 (2011)

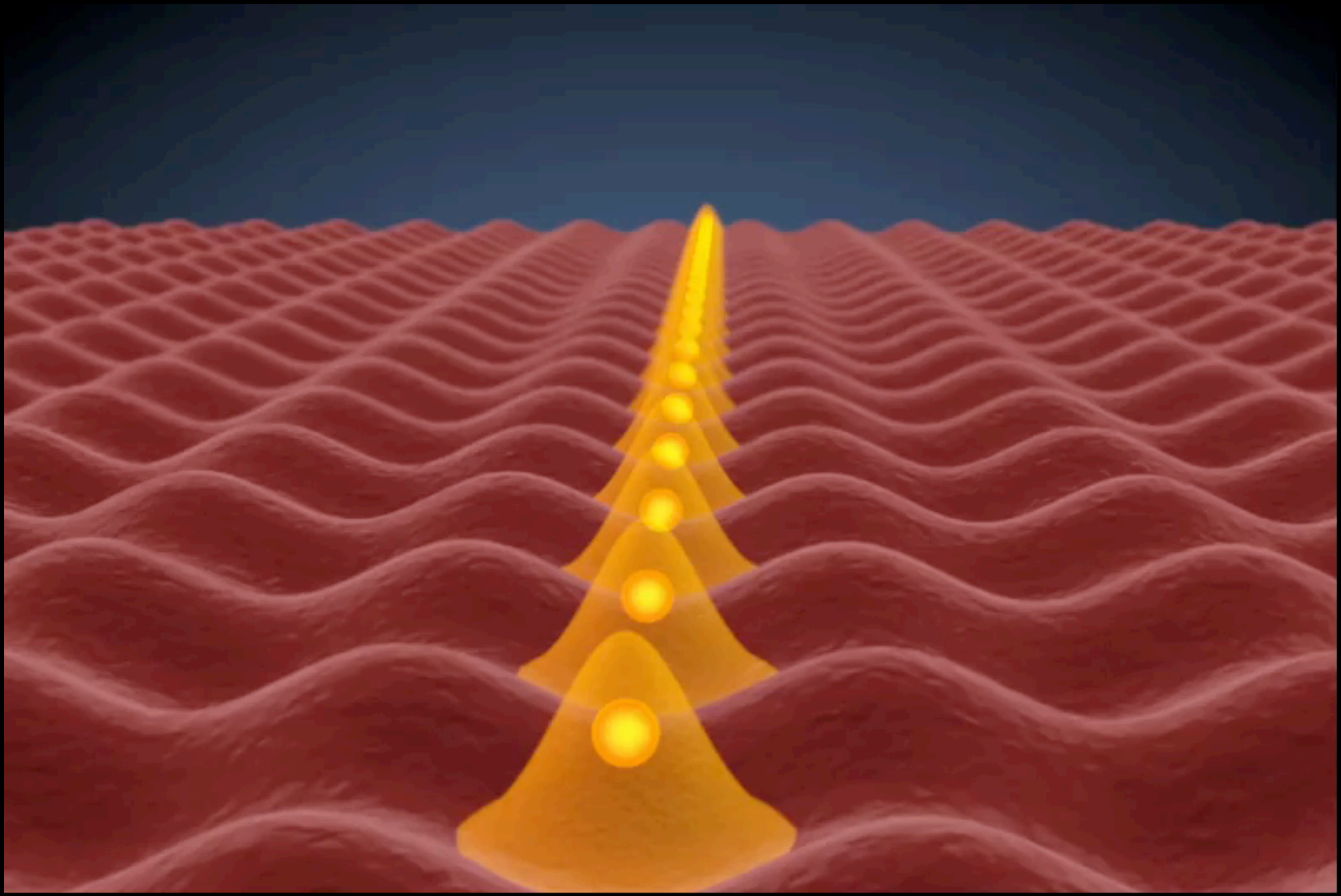
Coherent Spin Flips - Positive Imaging



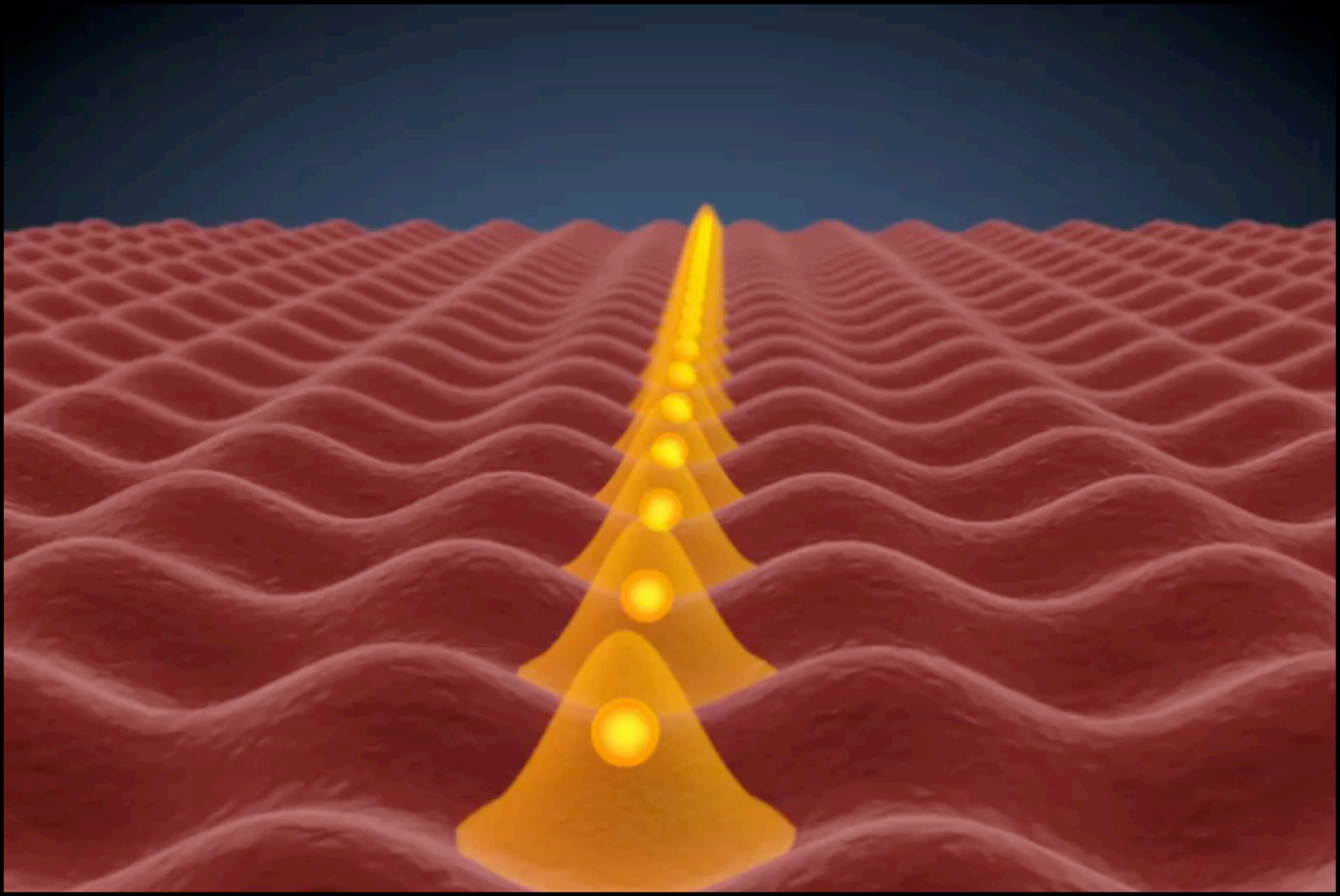
Subwavelength spatial resolution: 50 nm

Ch. Weitenberg et al., Nature **471**, 319-324 (2011)

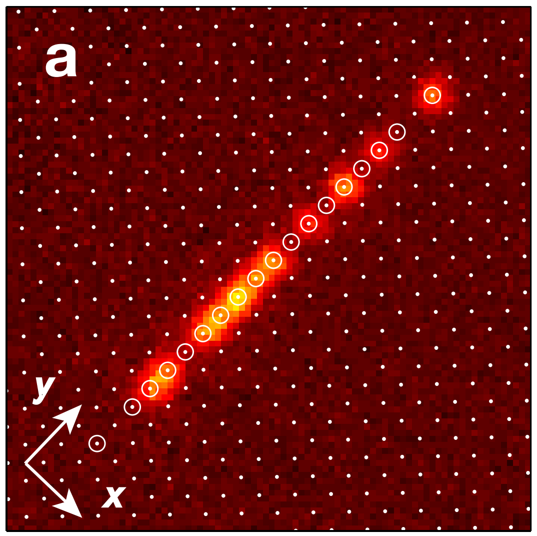
Single Atom Tunneling

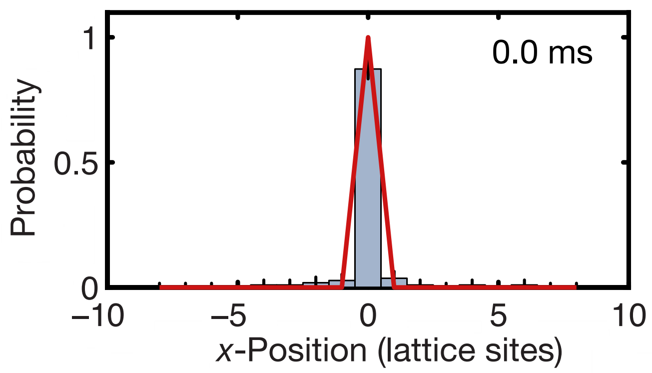


Single Atom Tunneling



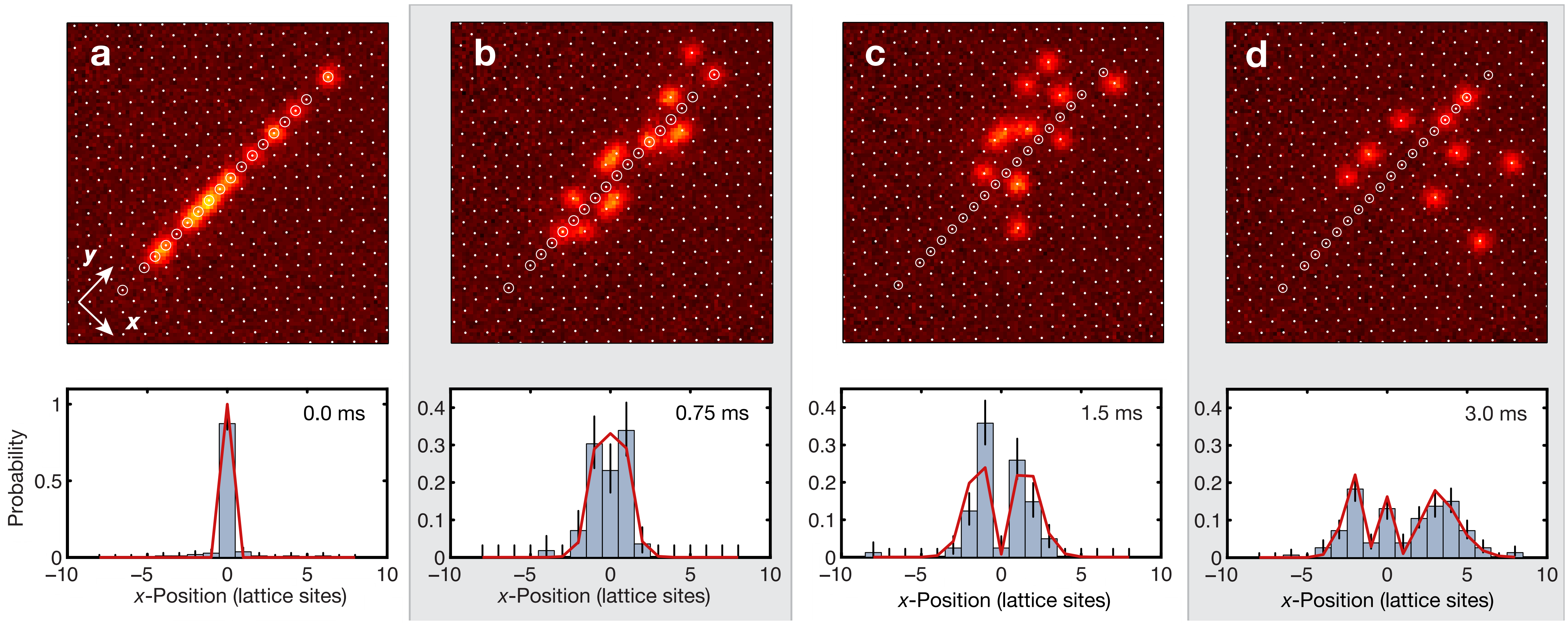
Motional State Affected?





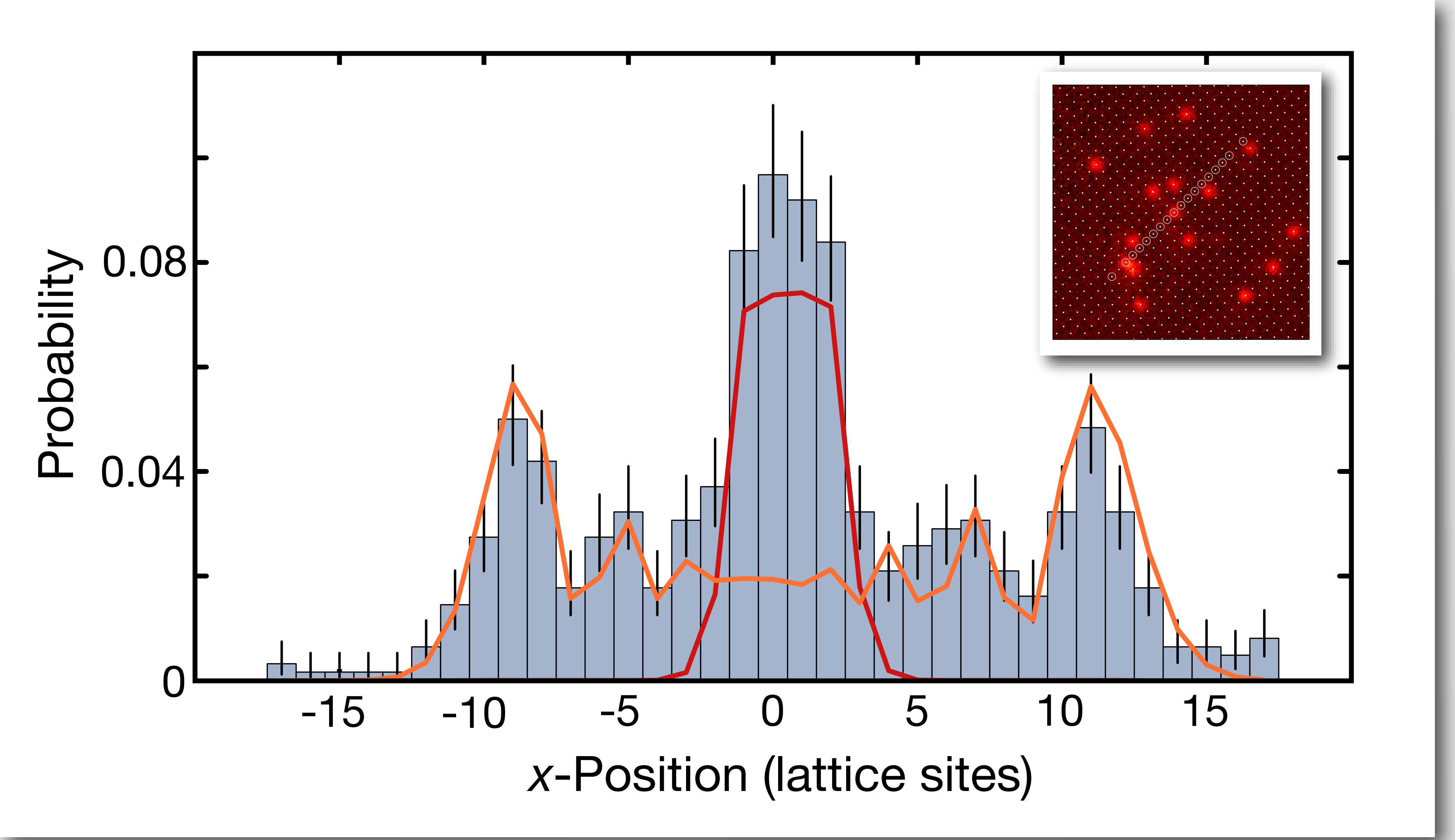
see exp: Y. Silberberg (photonic waveguides), D. Meschede & R. Blatt (quantum walks)...

Motional State Affected?



see exp: Y. Silberberg (photonic waveguides), D. Meschede & R. Blatt (quantum walks)...

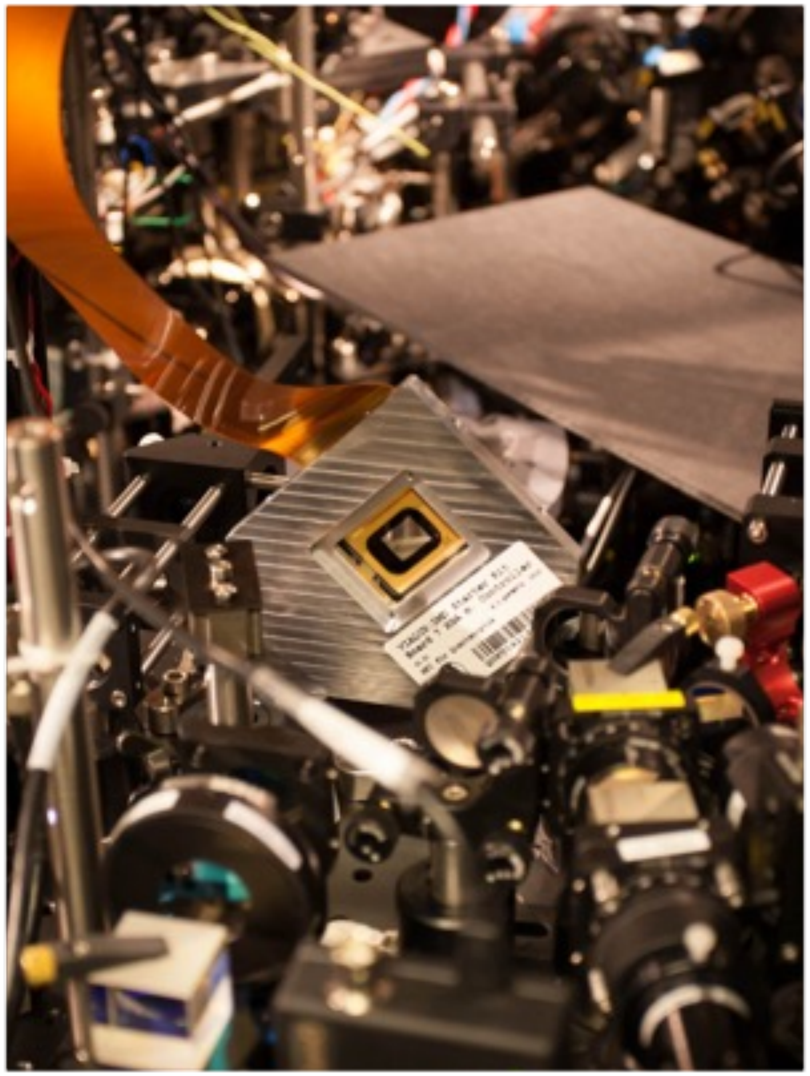
Higher Band Tunneling



Excellent agreement with simulation.

Interesting extension: Quantum walks of correlated atoms/spins...

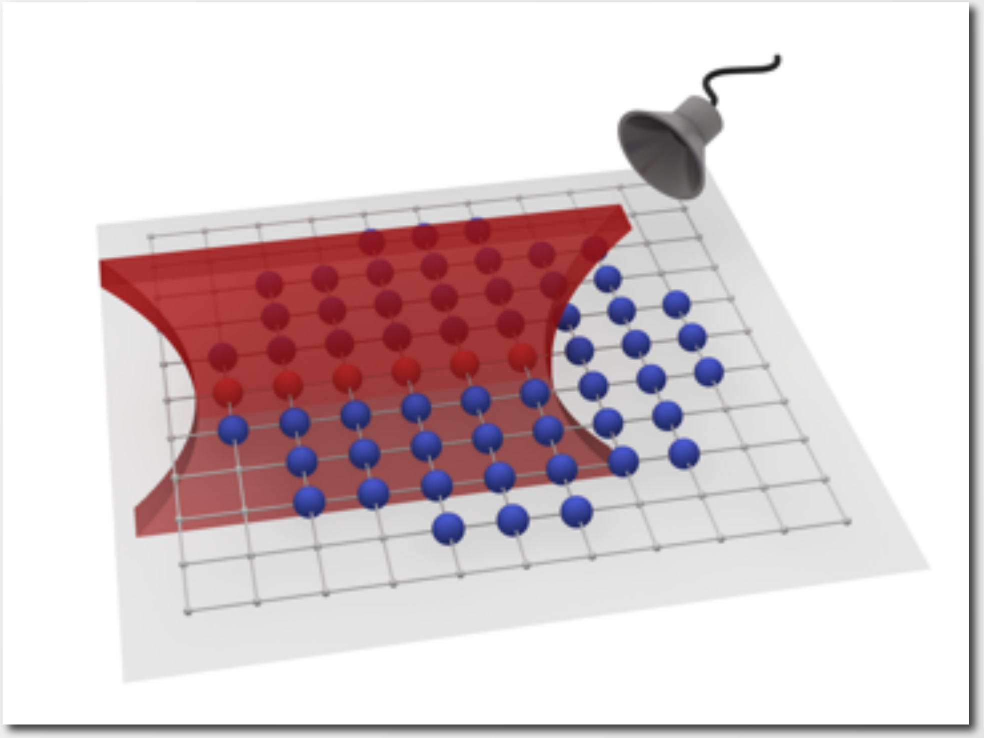
Arbitrary Light Patterns

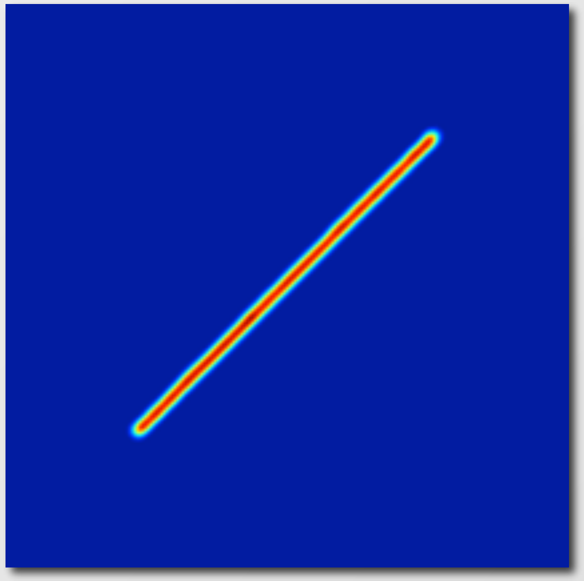


Digital Mirror Device
(DMD)

Arbitrary Light Patterns

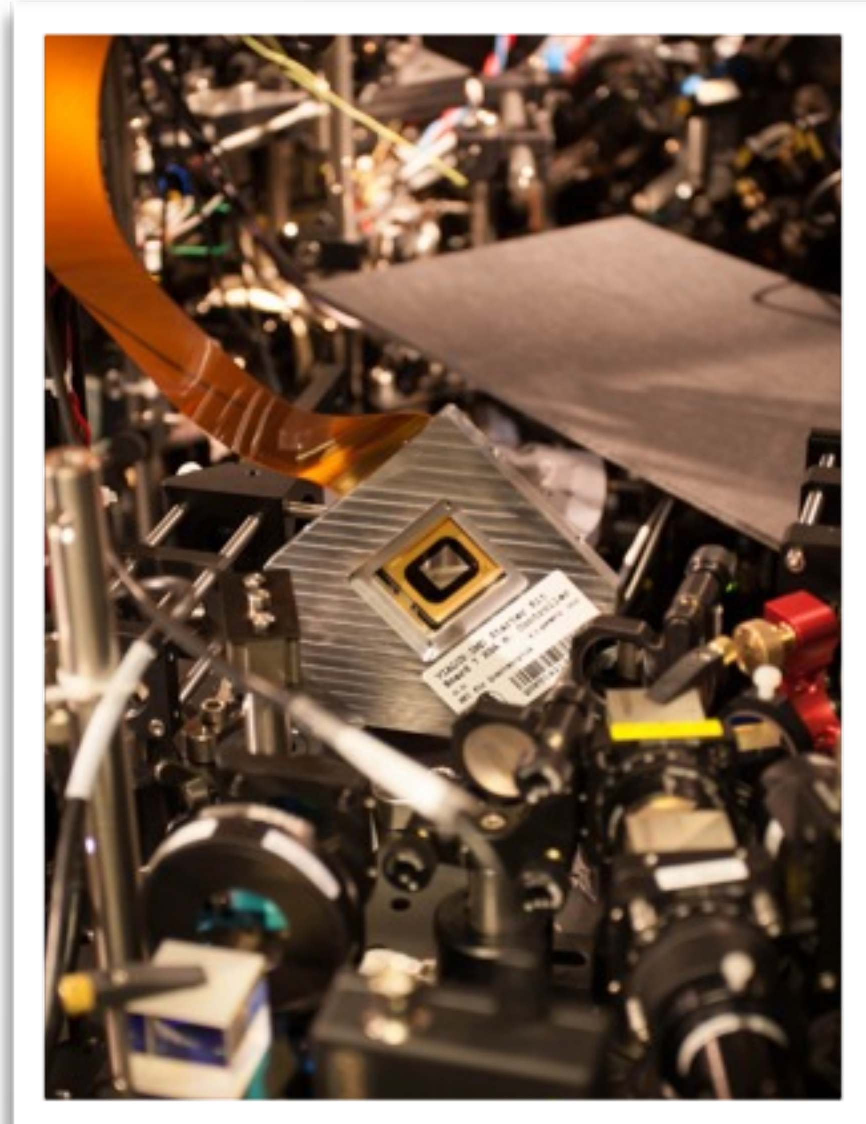
Digital Mirror Device
(DMD)



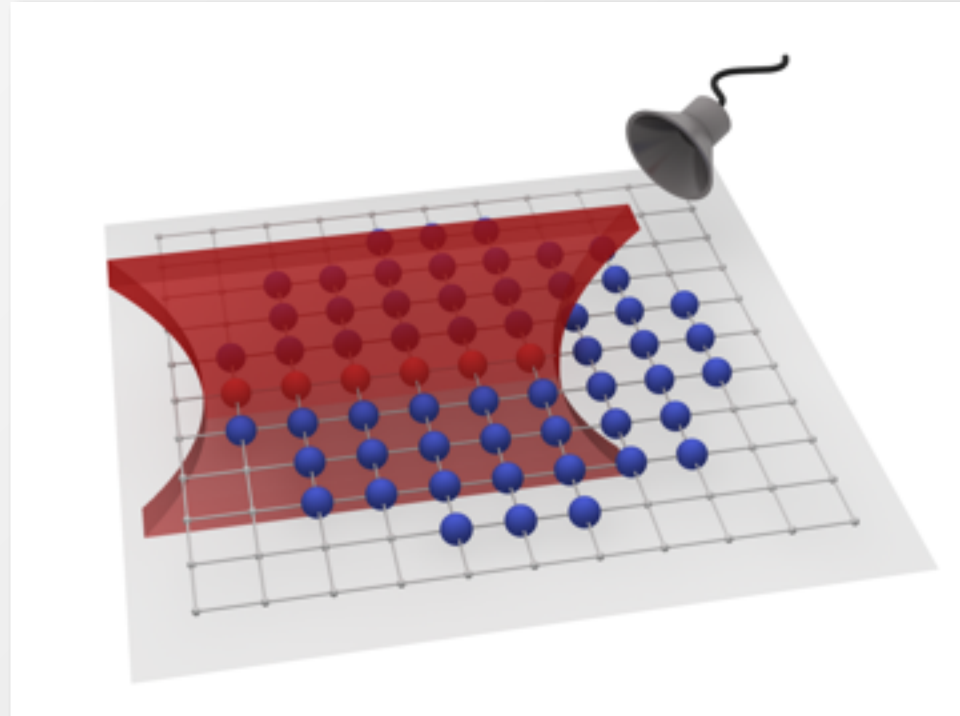


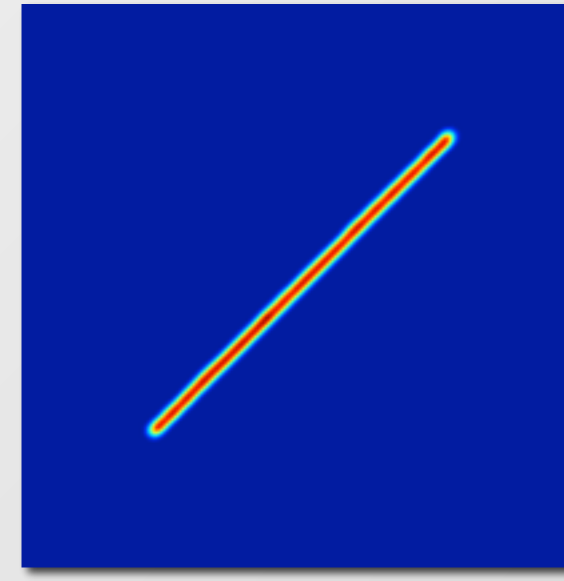
Measured Light Pattern

Arbitrary Light Patterns

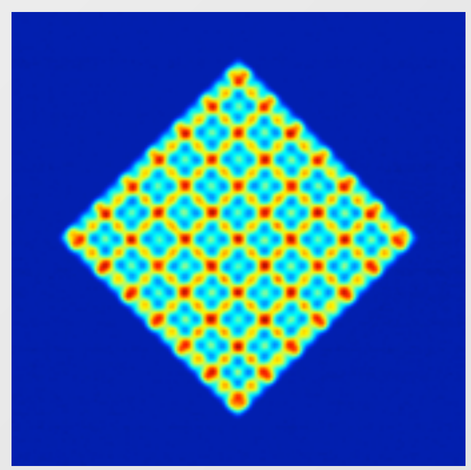


Digital Mirror Device (DMD)

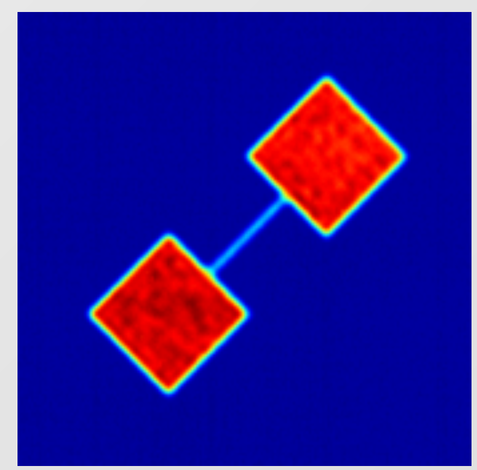




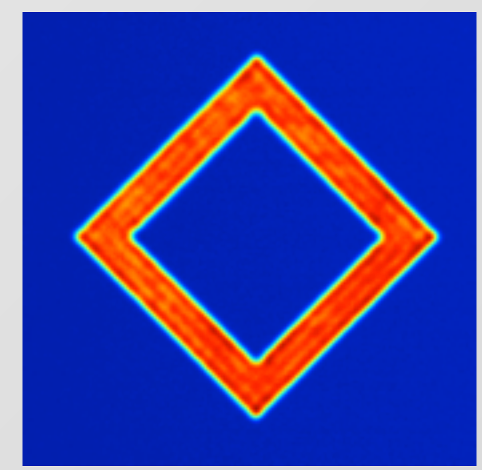
Measured Light Pattern



Exotic Lattices



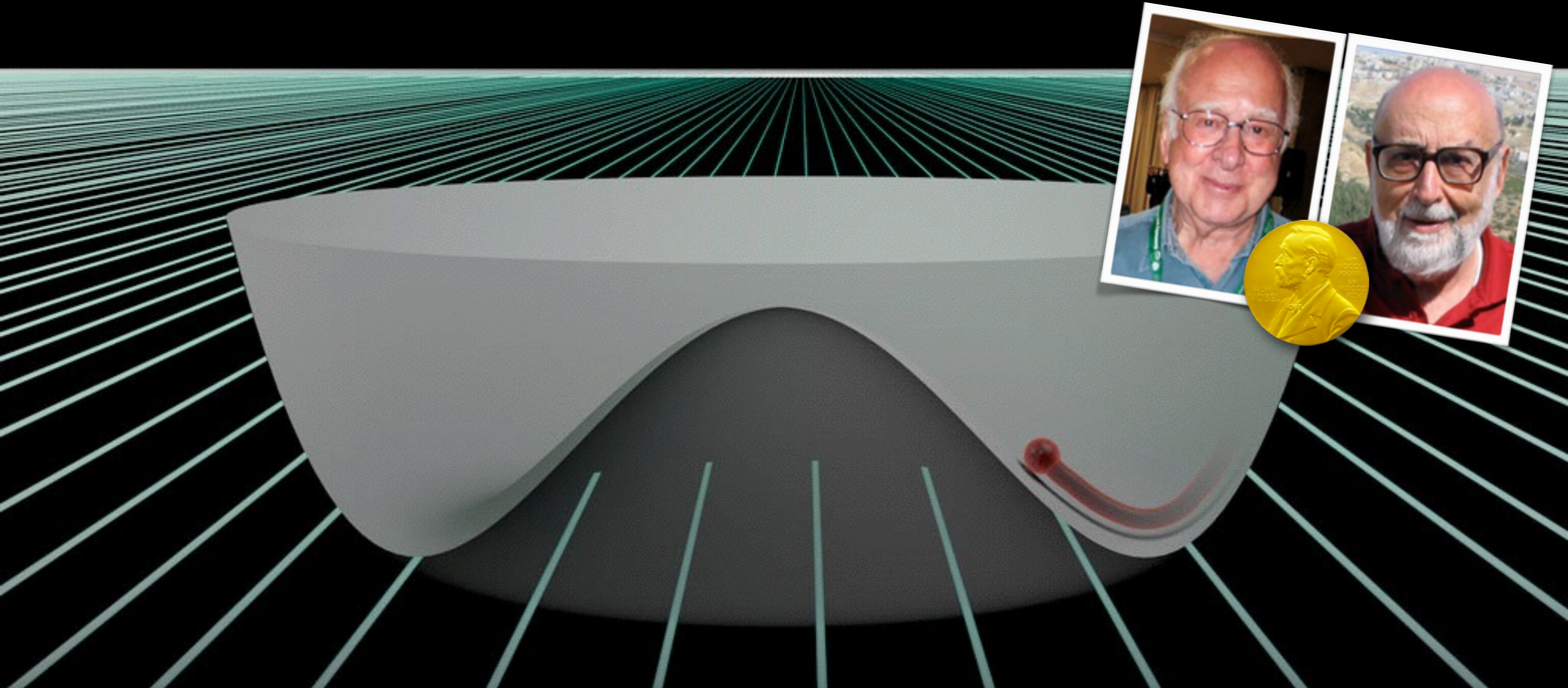
Quantum Wires



Box Potentials

Almost Arbitrary Light Patterns Possible!

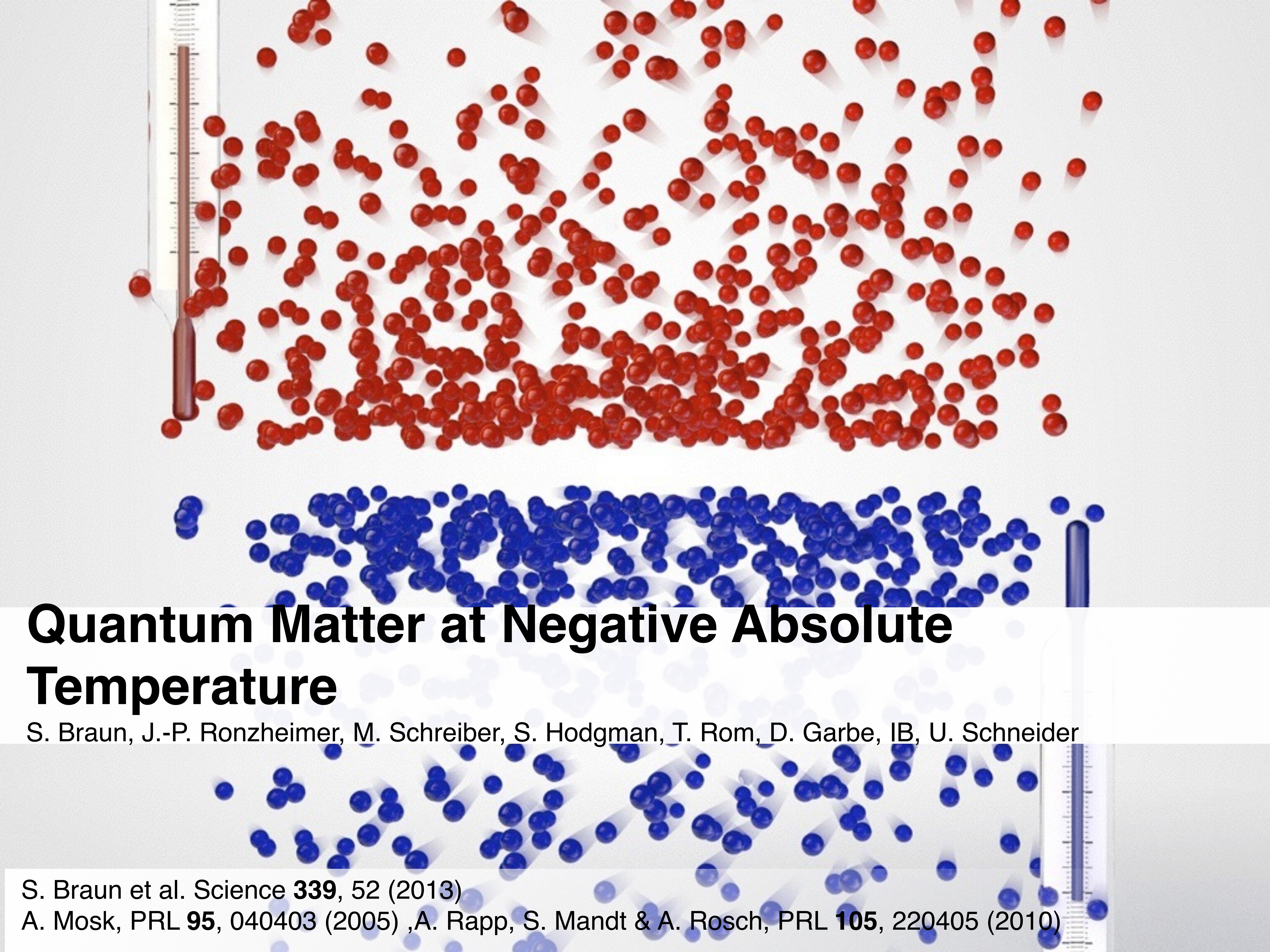
Single Spin Impurity Dynamics, Domain Walls, Quantum Wires, Novel Exotic Lattice Geometries, ...



‘Higgs’ Amplitude Mode in Flatland

M. Endres, T. Fukuhara, M. Cheneau, P. Schauss, D. Pekker, E. Demler, S. Kuhr & I.B.

M. Endres et al. Nature (2012)
Chubukov & Sachdev, PRB 1993; Sachdev, PRB 1999; Zwerger, PRL 2004; Altman, Blatter, Huber, PRB 2007, PRL 2008; U. Bissbort et al. Phys. Rev. Lett. (2011); D. Podolsky, A. Auerbach, D. Arovas, PRB 2011



Quantum Matter at Negative Absolute Temperature

S. Braun, J.-P. Ronzheimer, M. Schreiber, S. Hodgman, T. Rom, D. Garbe, IB, U. Schneider

S. Braun et al. Science **339**, 52 (2013)
A. Mosk, PRL **95**, 040403 (2005) ,A. Rapp, S. Mandt & A. Rosch, PRL **105**, 220405 (2010)

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Ultracold gas sets
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Uncertain PRINCIPLES
with CHAD ORZEL
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Posted by Chad Orzel on January 8, 2013
(10)
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3, 2013
emperature?
ence is measured in Kelvins (K), 0 degrees Ce
has an article entitled "Nega
potassium ions that
rature of
would exp
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physics central
learn how your world works
Explore the Science • Ask & Experiment • Physics Buzz
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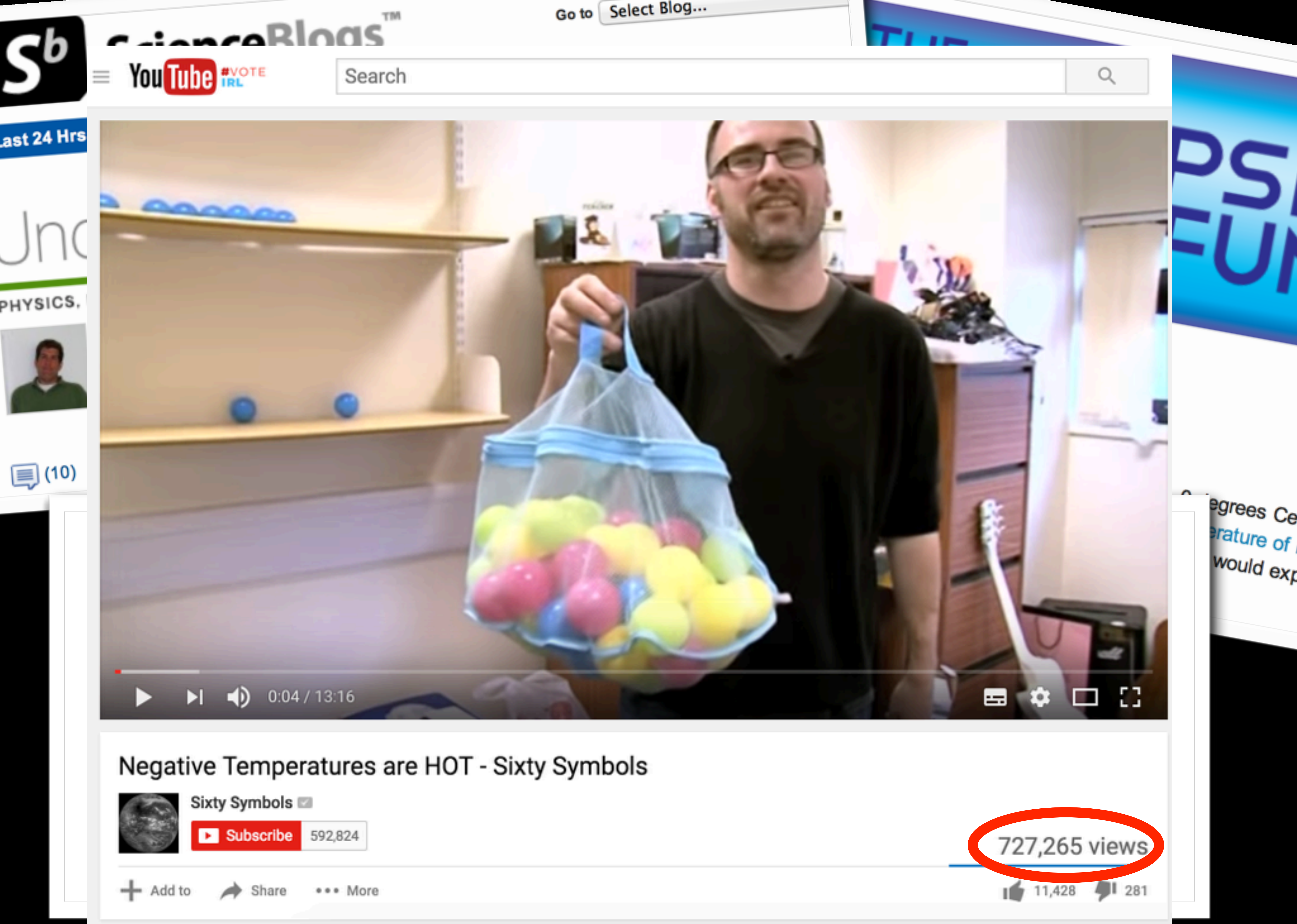
Physics in Action
Physics +
Below Absolute Zero: Negative Temperatures Explained
Absolute zero, or 0 degrees Kelvin, is the temperature where all motion stops. It's the lowest limit on the temperature scale, but recent news articles have heralded a dip below that limit in a physics lab. Is absolute zero less absolute than we thought? Read on to find out.
Latest from Physics in Action
Stability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would exp

The world best clocks:

Application of Atomic Clocks

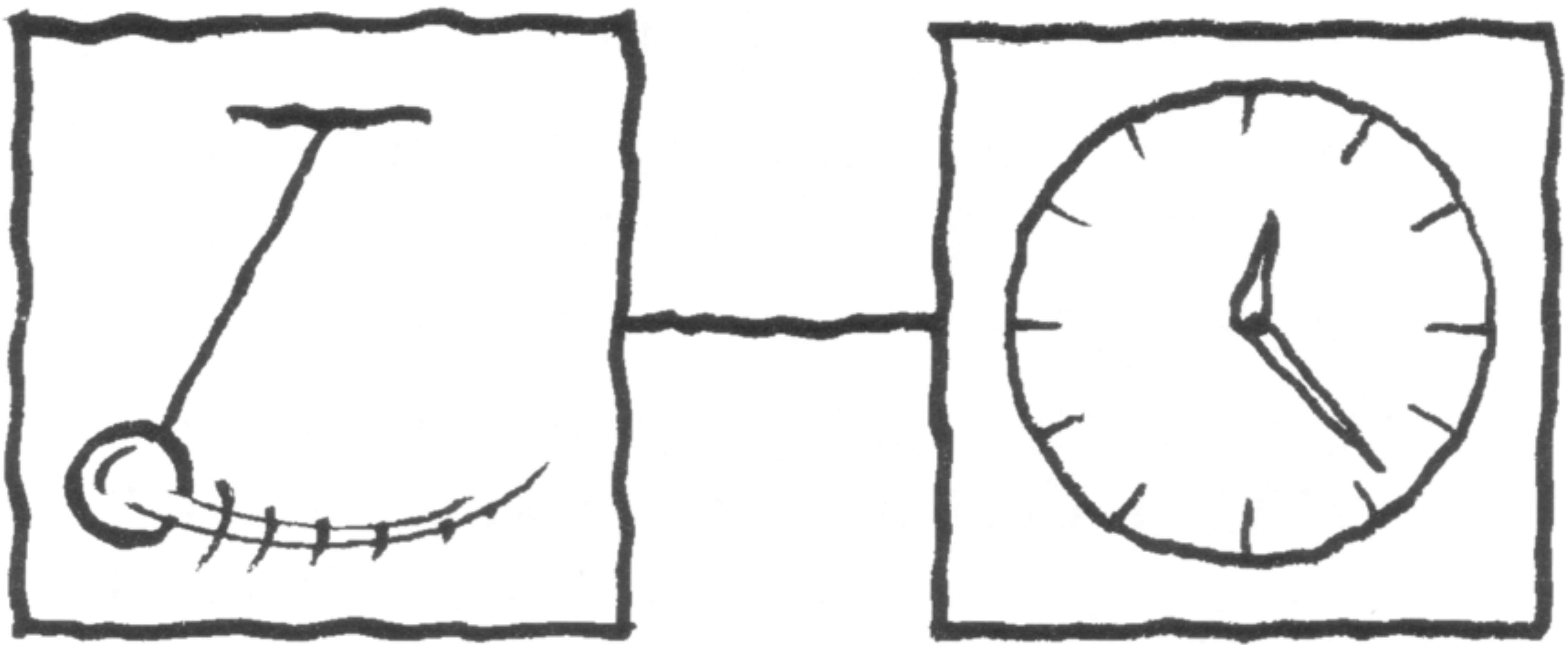
- **Navigation, Positioning**
  - GPS, GLONASS, deep space probes
- **Geodesy**
- **Datation of millisecond pulsars**
- **VLBI**
- **Synchronisation of distant clocks**
  - IAT
- **Fundamental physics tests**

Ex : general relativity

Search for a drift of the fine structure constant α :

$$\alpha^{-1} d\alpha / dt \text{ at } 10^{-16} / \text{year}$$

Measurement of Time



Clock = Oscillator + Counter

Measurement of Time

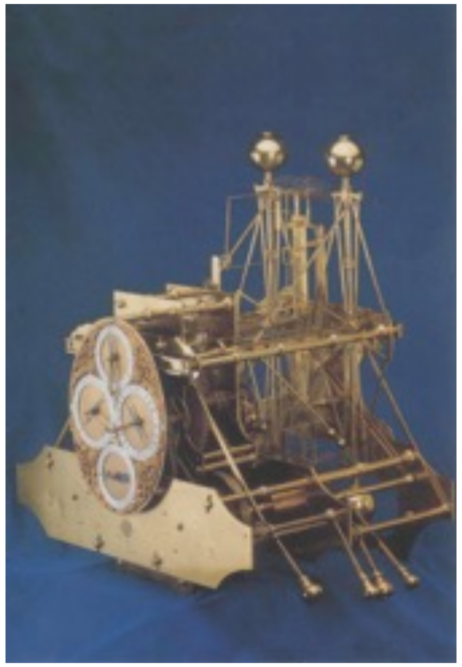
Measurement of Time

Sundial since 3500 v. Chr.

One period per dat

Measurement of Time

Sundial since 3500 v. Chr.
One period per dat



Pendulum clock since 1656
One period per second

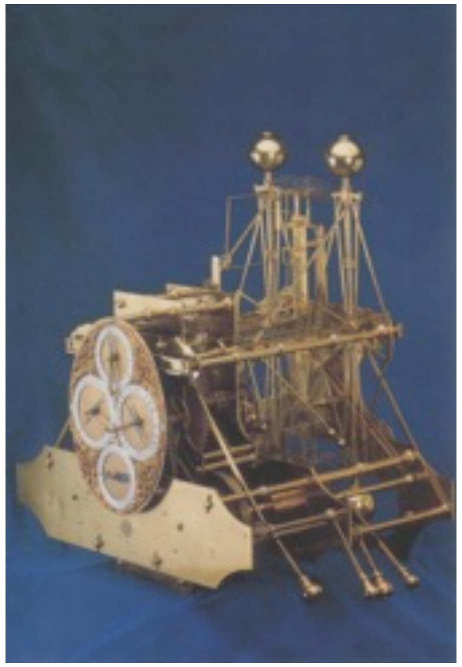
Measurement of Time

Sundial since 3500 v. Chr.

One period per dat

Quartz oscillator since 1918

32.768 periods per second



Pendulum clock since 1656

One period per second

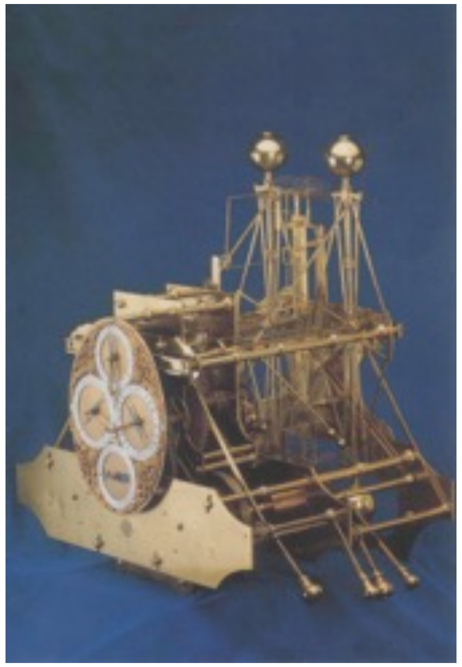
Measurement of Time

Sundial since 3500 v. Chr.

One period per dat

Quartz oscillator since 1918

32.768 periods per second



Pendulum clock since 1656

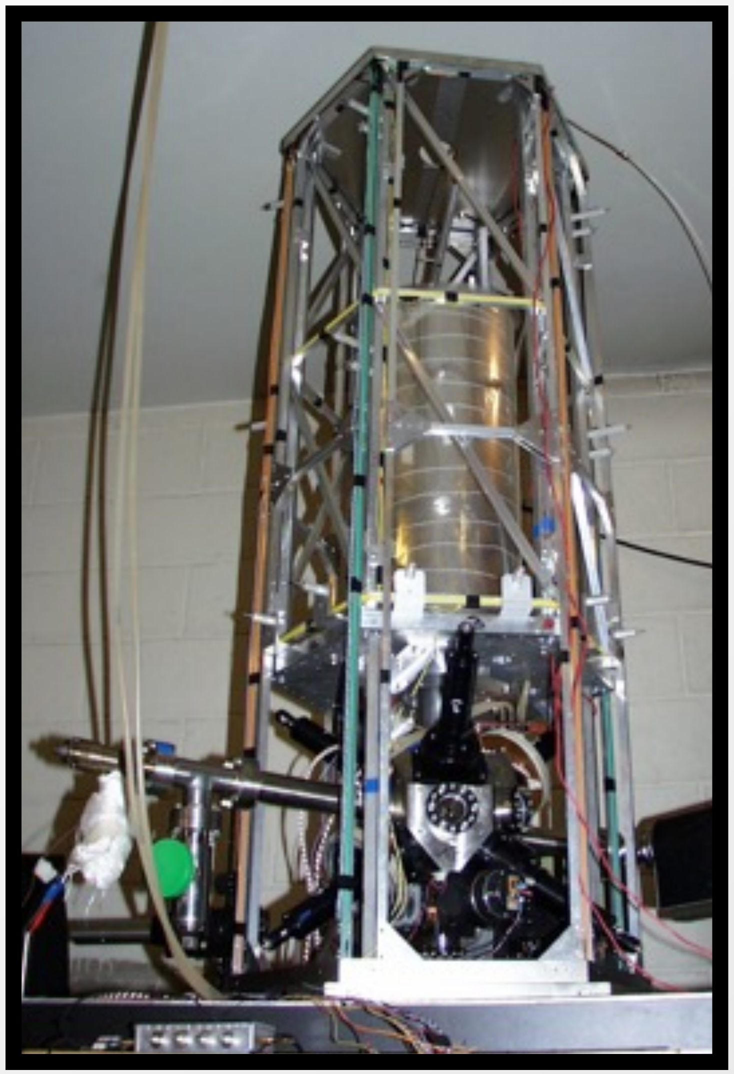
One period per second

Cesium atomic clock since 1955

9.192.631.770 oscillations per second

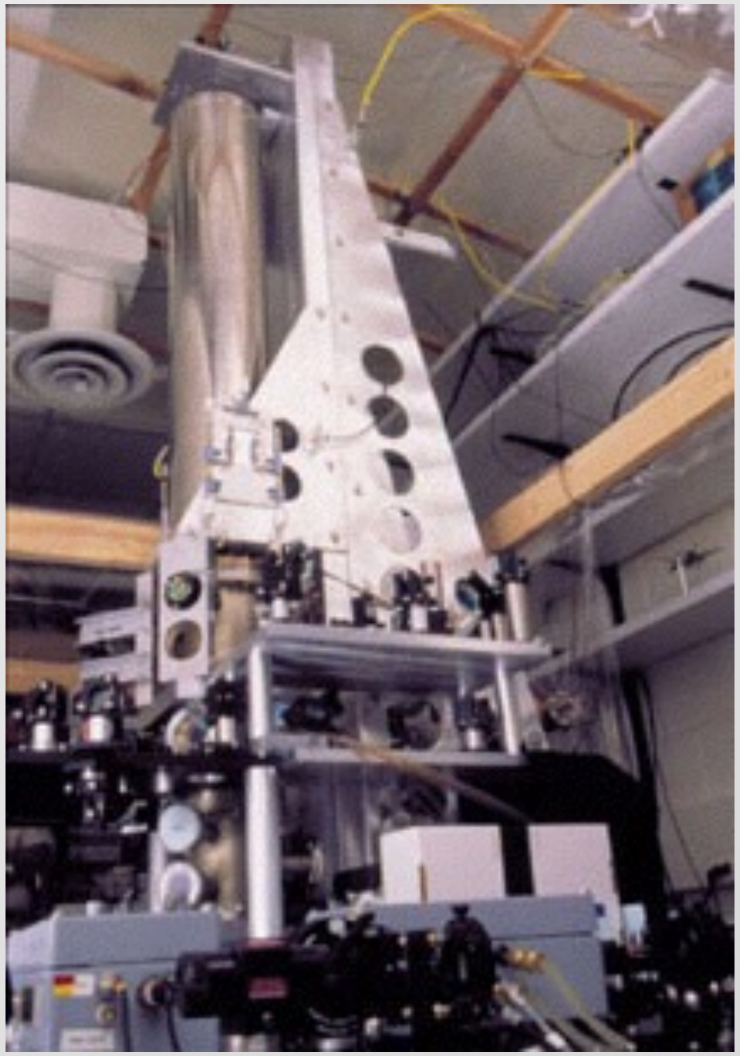
Atomic Fountain Clocks

8 fountains in operation at SYRTE, PTB, NIST, USNO, Penn St, IEN, ON. 5 with accuracy at 1 10^{-15} . More than 10 under construction.



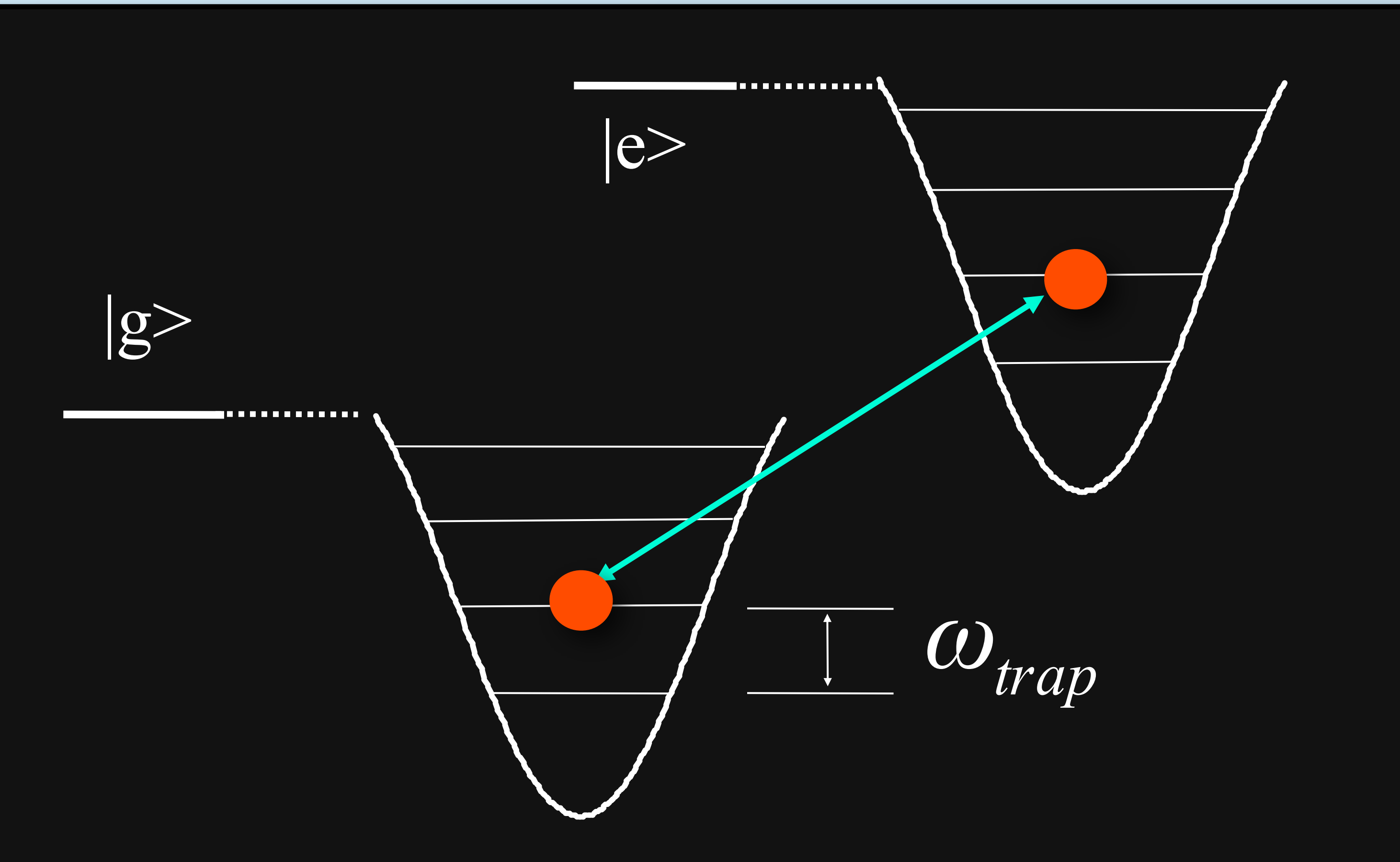
BNM-SYRTE, FR

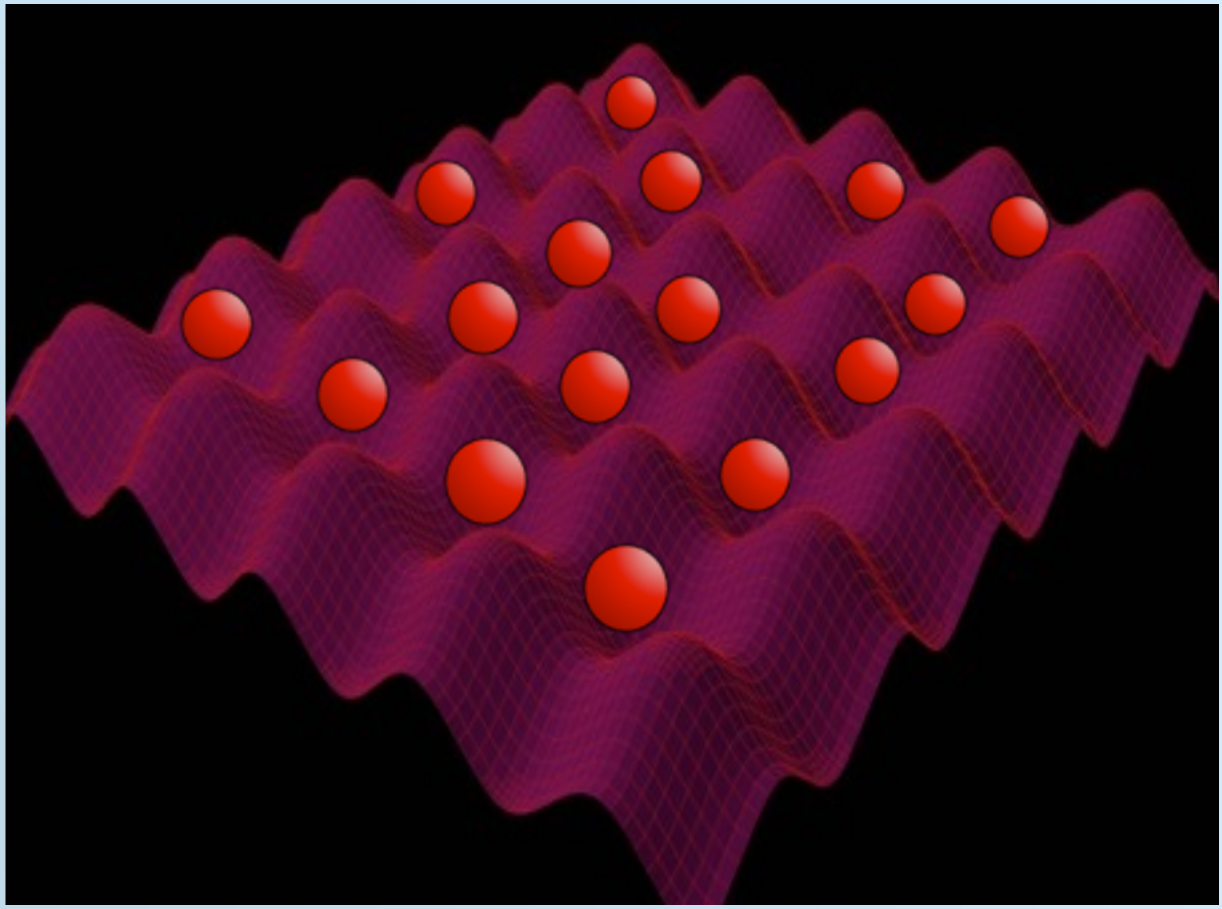
PTB, D

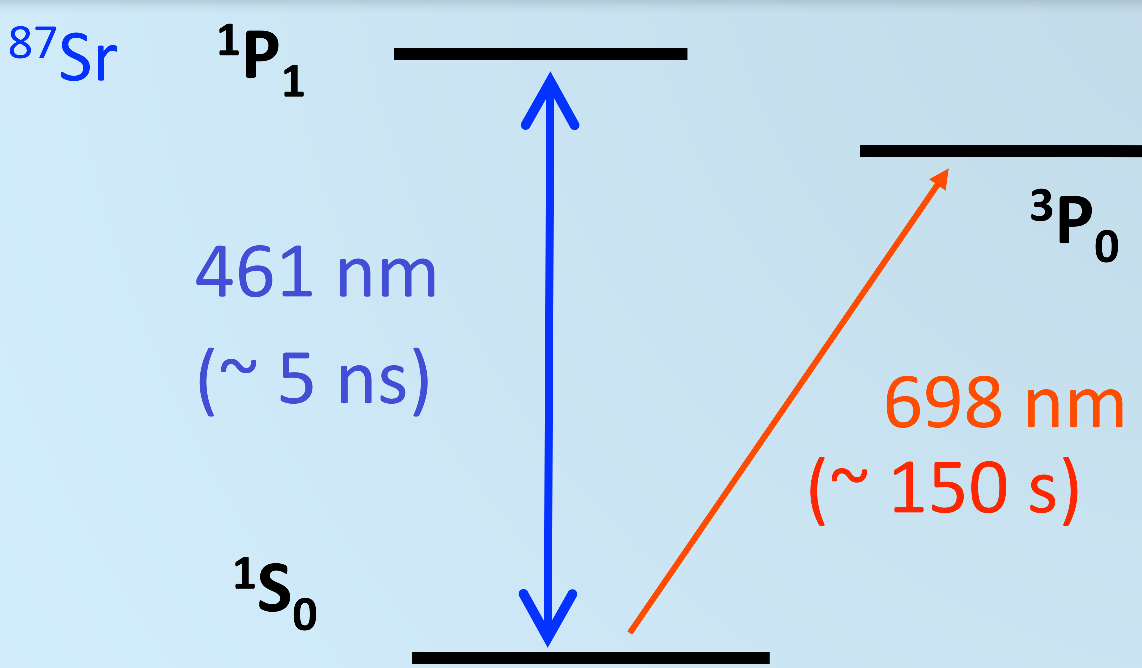


NIST, USA

The best clock: atoms in optical lattices







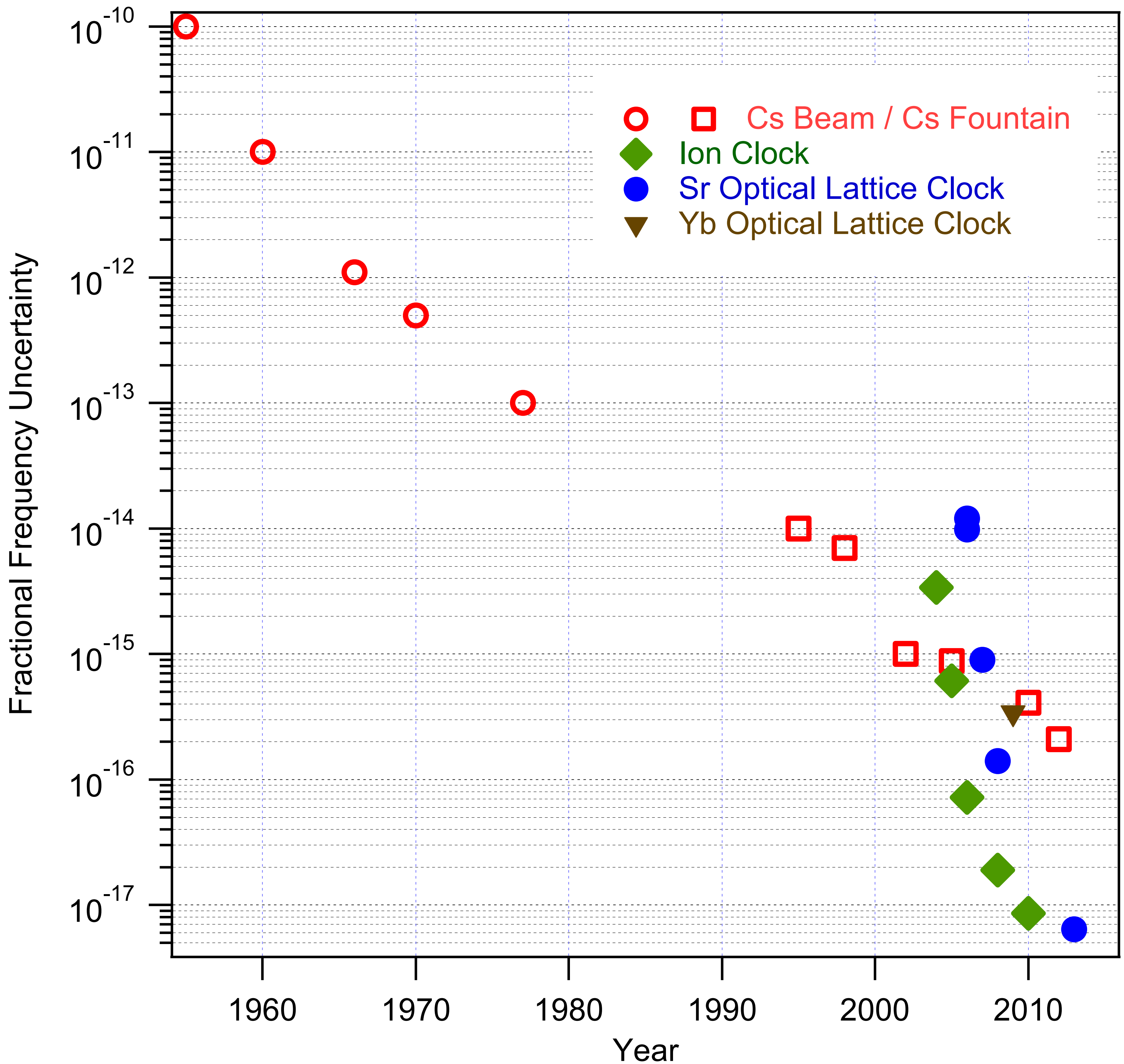
Quality factor > 10^{17}

Optical dipole moment
~ 10^{-4} – 10^{-5} Debye

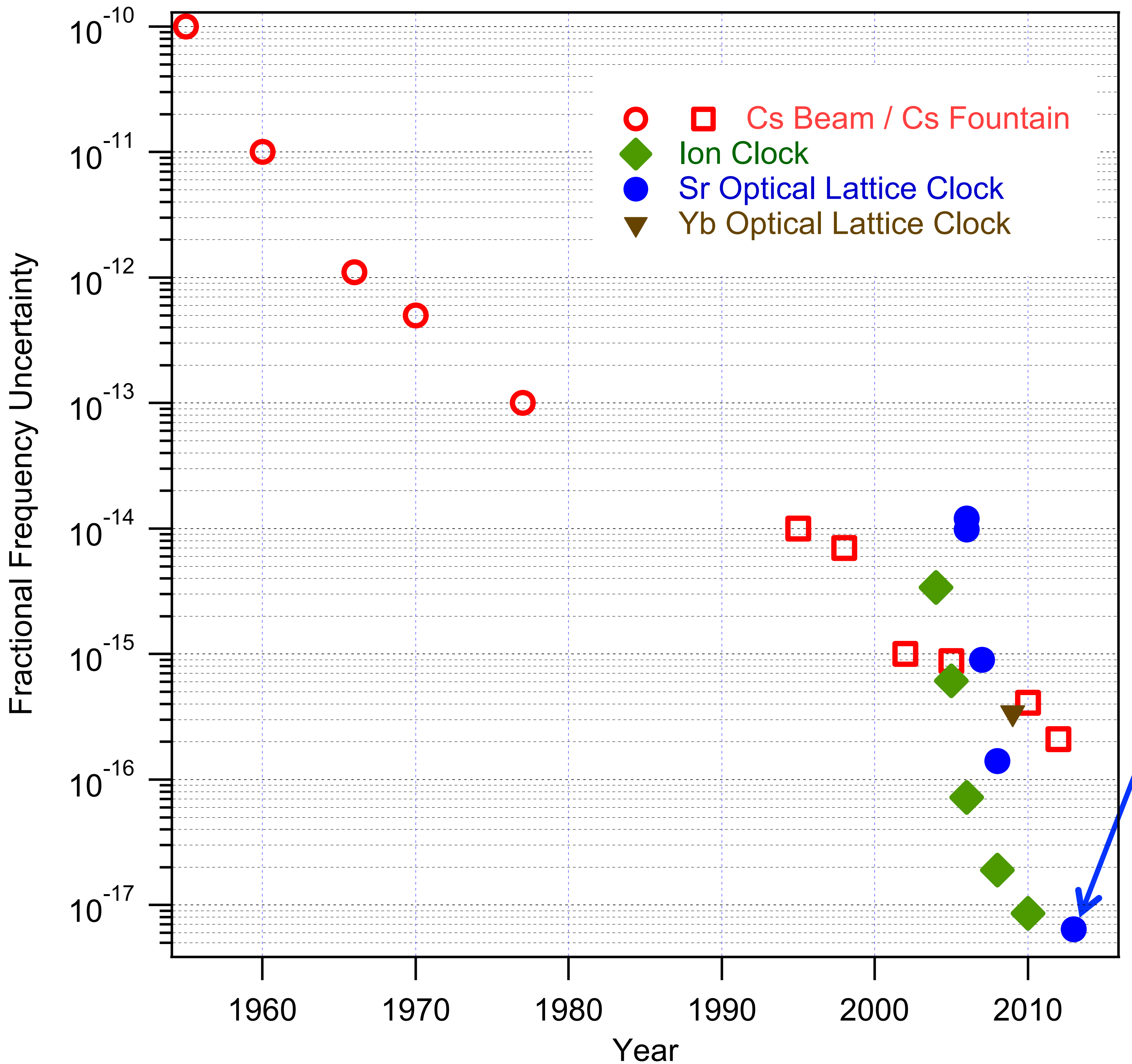
Boyd et al., Science **314**, 1430 (2006).

from: Jun Ye (JILA, Boulder)

Sr clock - a new frontier for stability & accuracy



Sr clock – a new frontier for stability & accuracy



Bloom *et al.*, arXiv:1309.1137

Sr: lowest uncertainty in all atomic clocks: 6.4×10^{-18}

Achieving this x 100 faster than ion clocks

Accuracy

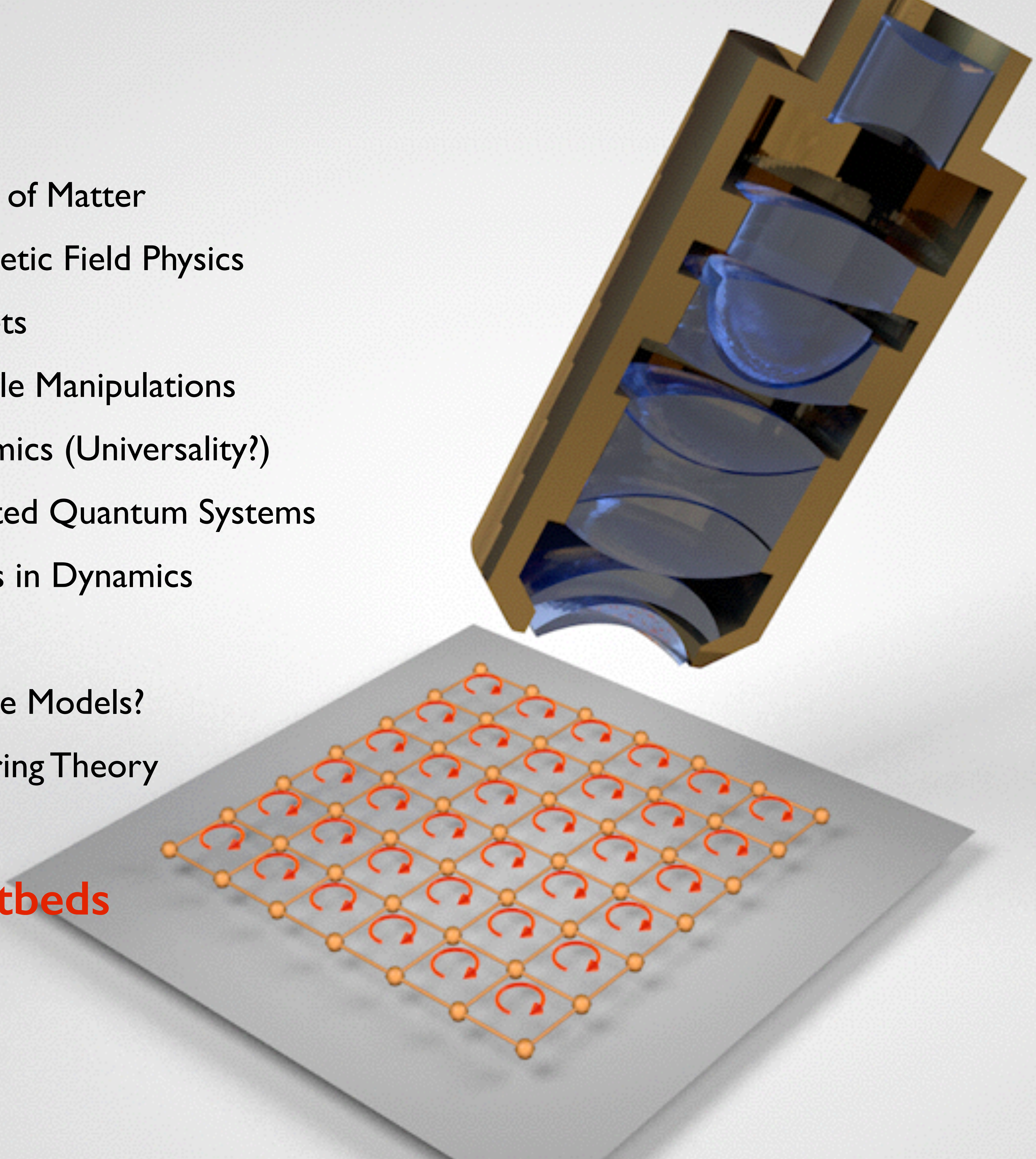
The inaccuracy of such a clock corresponds to 1s over the entire lifetime of the universe!

Outlook

- Search for New Phases of Matter
- Extremely Strong Magnetic Field Physics
- Novel Quantum Magnets
- Controlled Quasiparticle Manipulations
- Non-Equilibrium Dynamics (Universality?)
- Thermalization in Isolated Quantum Systems
- Entanglement Measures in Dynamics
- Supersolids
- Cosmology - Black Hole Models?
- High Energy Physics/String Theory
- New clocks/Navigation

Quantitative testbeds for theory!

⋮



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