Realizing Richard Feynman's Dream of a Quantum Simulator

Exploring and Controlling Quantum Matter using Ultracold Atoms

IB, Paco-Yndurain Lecture

www.quantum-munich.de

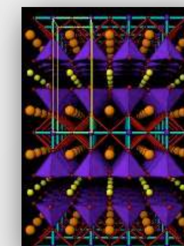
Overview

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

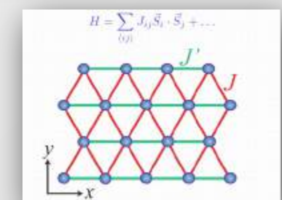
The Challenge of Many-Body Quantum Systems

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

- **Technological Relevance**

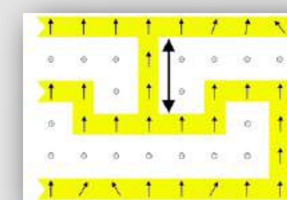


High-Tc Superconductivity (Power Delivery)



Magnetism (Storage, Spintronics...)

Novel Quantum Sensors (Precision Detectors)



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

Many cases: lack of basic understanding of underlying processes

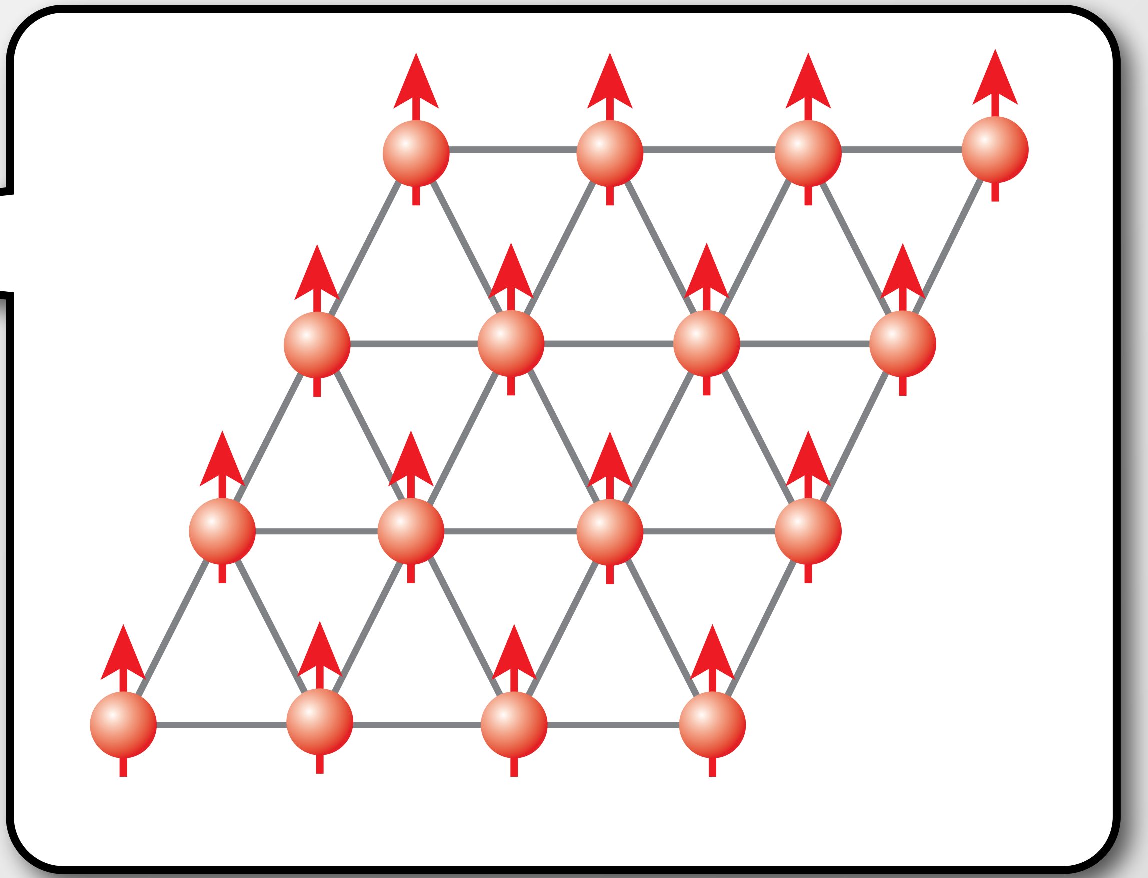
Difficulty to separate effects: probe impurities, complex interplay, masking of effects...

Many cases: even simple models "not solvable"

Need to synthesize new material **to analyze effect of parameter change**

Quantum Complexity

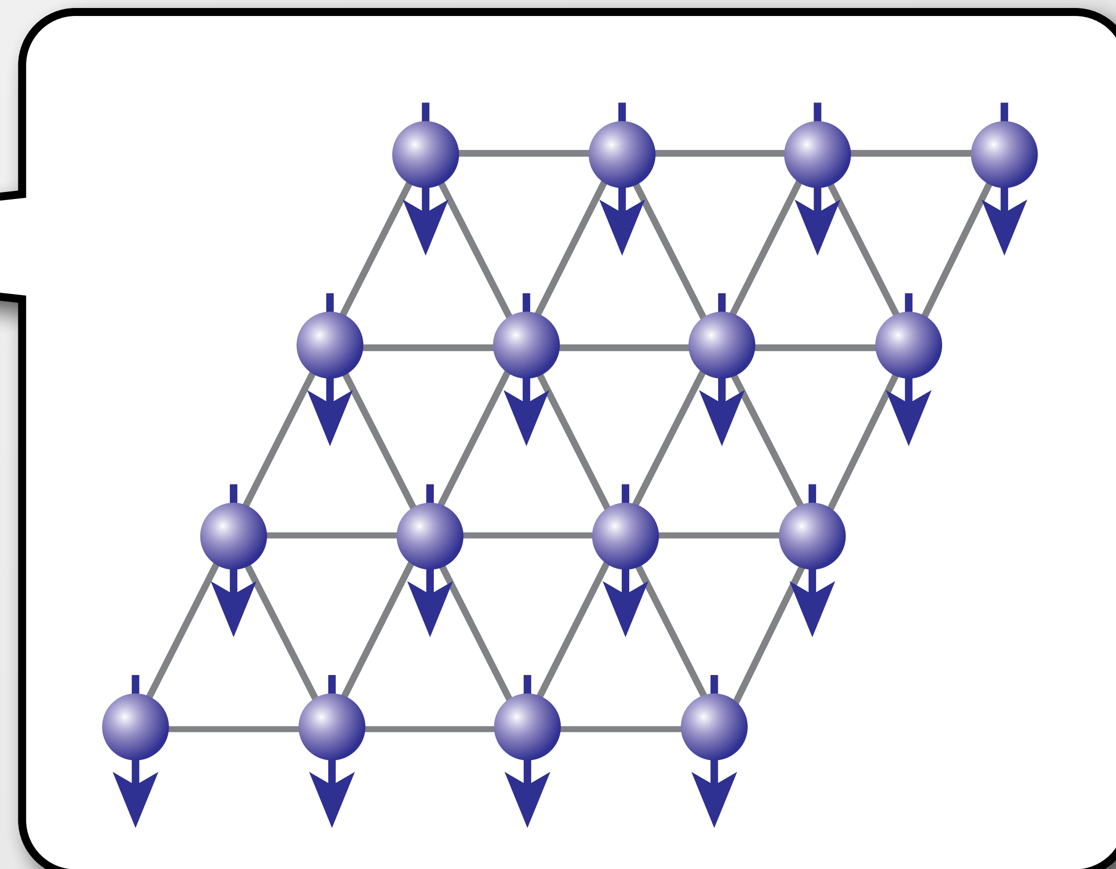
the 'ultimate' hard drive



Crystal of spins

Quantum Complexity

the 'ultimate' hard drive



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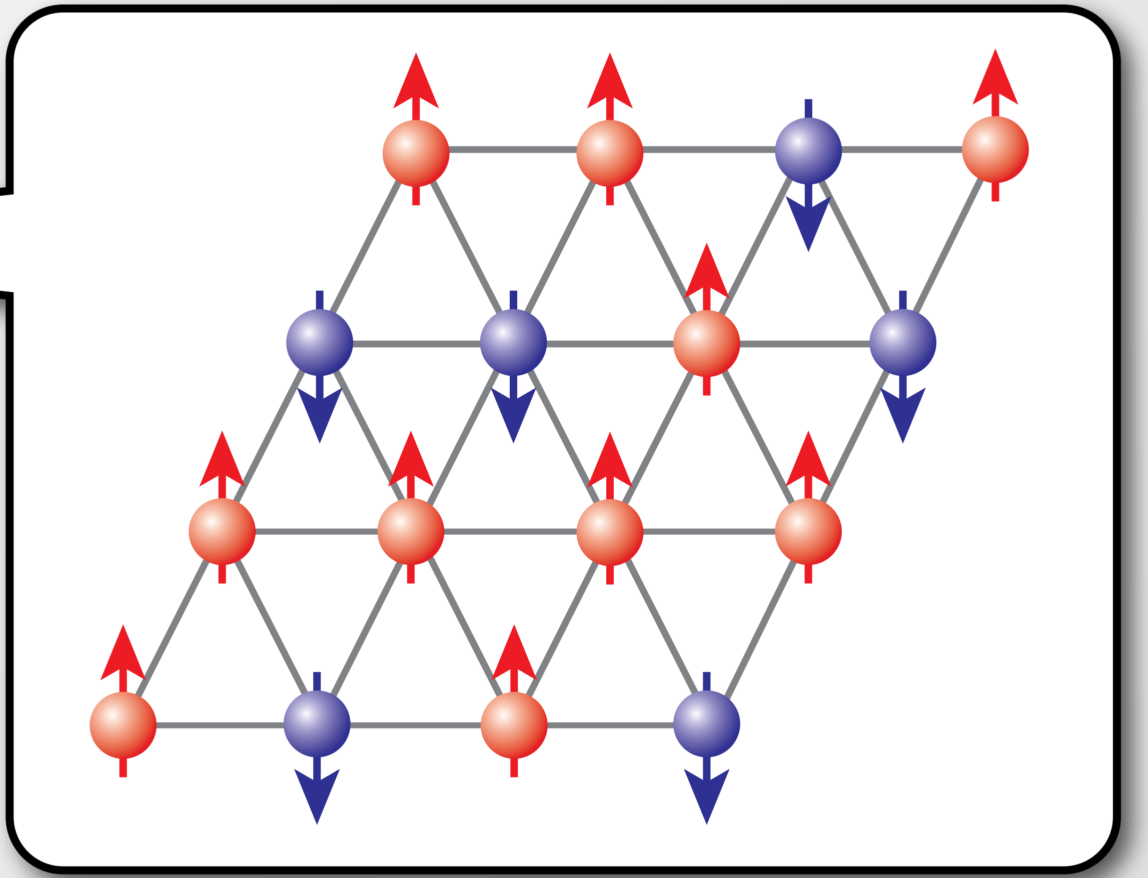
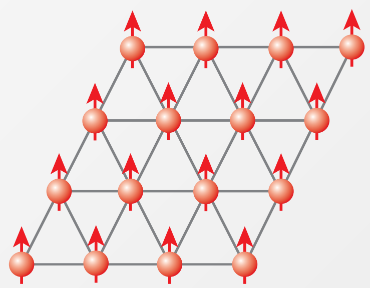
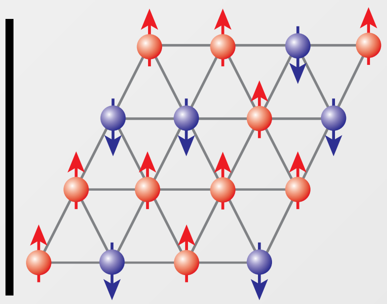
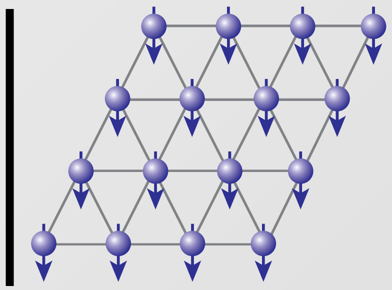


Crystal of spins

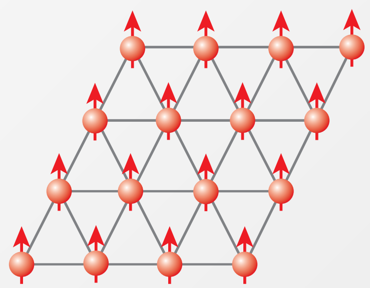
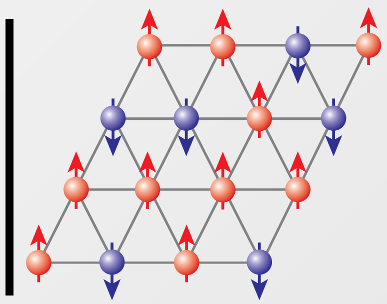
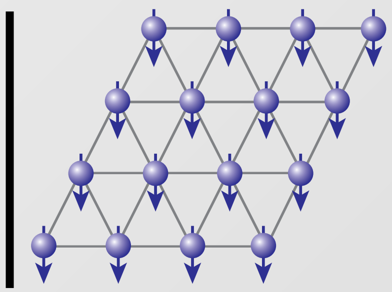
Quantum Complexity

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

AND AND AND

2^N Configurations simultaneously!

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!

Roadrunner – Los Alamos

1.1 Petaflops/s
2000 t
3.9 MW

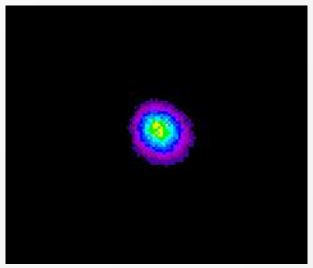
State of the art: < 40 spins (2^{40}x 2^{40}) (what does it take to simulate 300 spins ?)

each doubling allows for one more spin 1/2 only

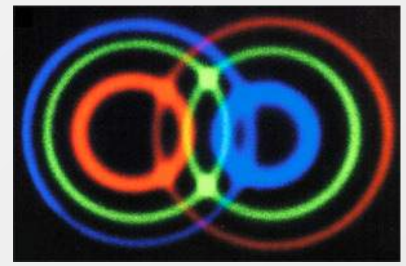
2^{300} estimated number of protons in the universe

The Challenge of Many-Body Quantum Systems

Control of single and few particles



Single Atoms and Ions



Photons

D. Wineland

S. Haroche

The Challenge of Many-Body Quantum Systems

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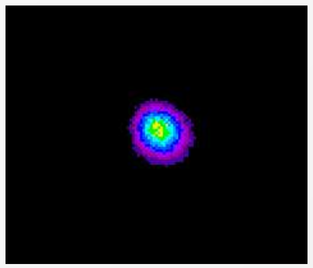

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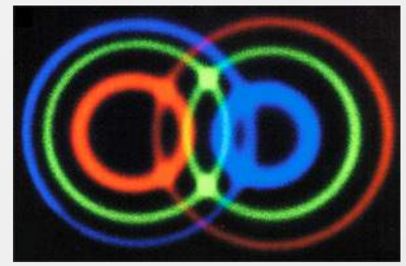

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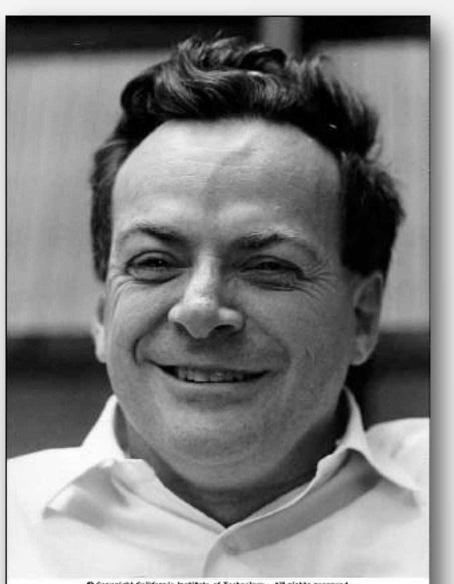
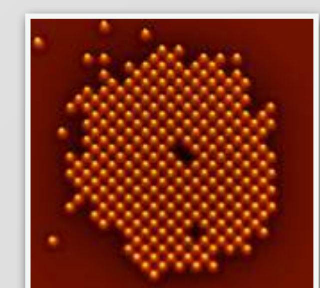
Challenge: ... towards ultimate control of many-body quantum systems



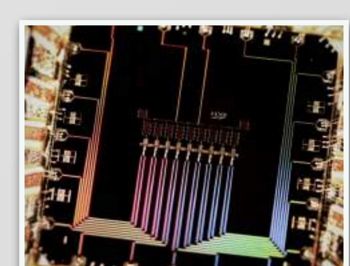
R. P. Feynman‘s Vision

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)

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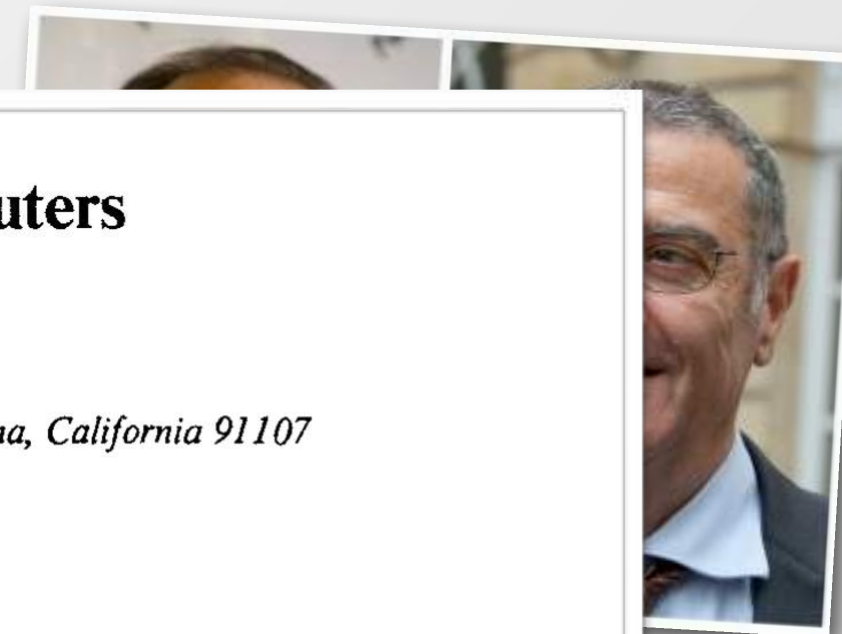
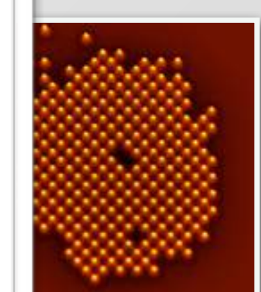
Control of single and few particles



Sing

Haroche

Challen ... ystems



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Devices
rtinis, UCSB,
Google)

Simulating Physics with Computers

Richard P. Feynman

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

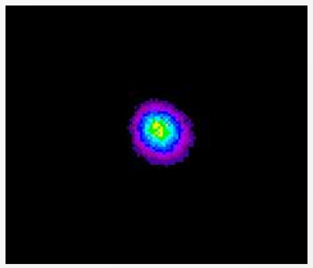
Received May 7, 1981

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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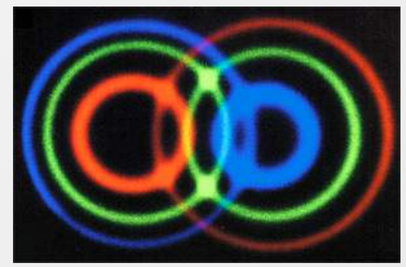

Photons

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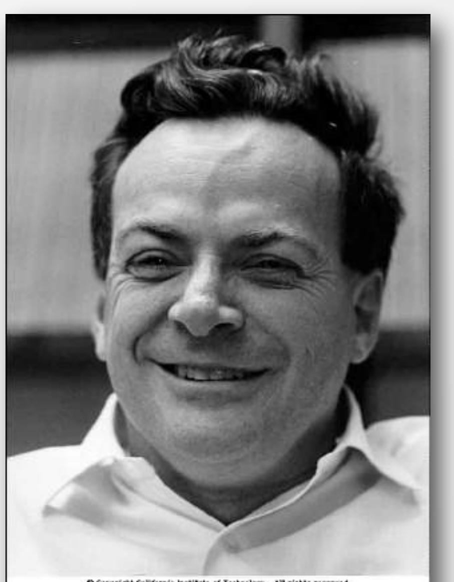
Challenge: ... towards ultimate control of many-body quantum systems



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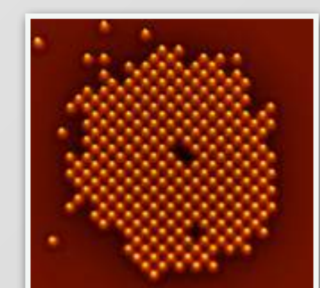
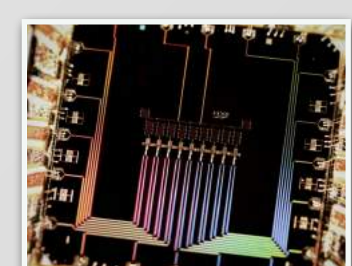


Crystal of Atoms
Bound by Light



Superconducting
Devices
(J. Martinis, UCSB,
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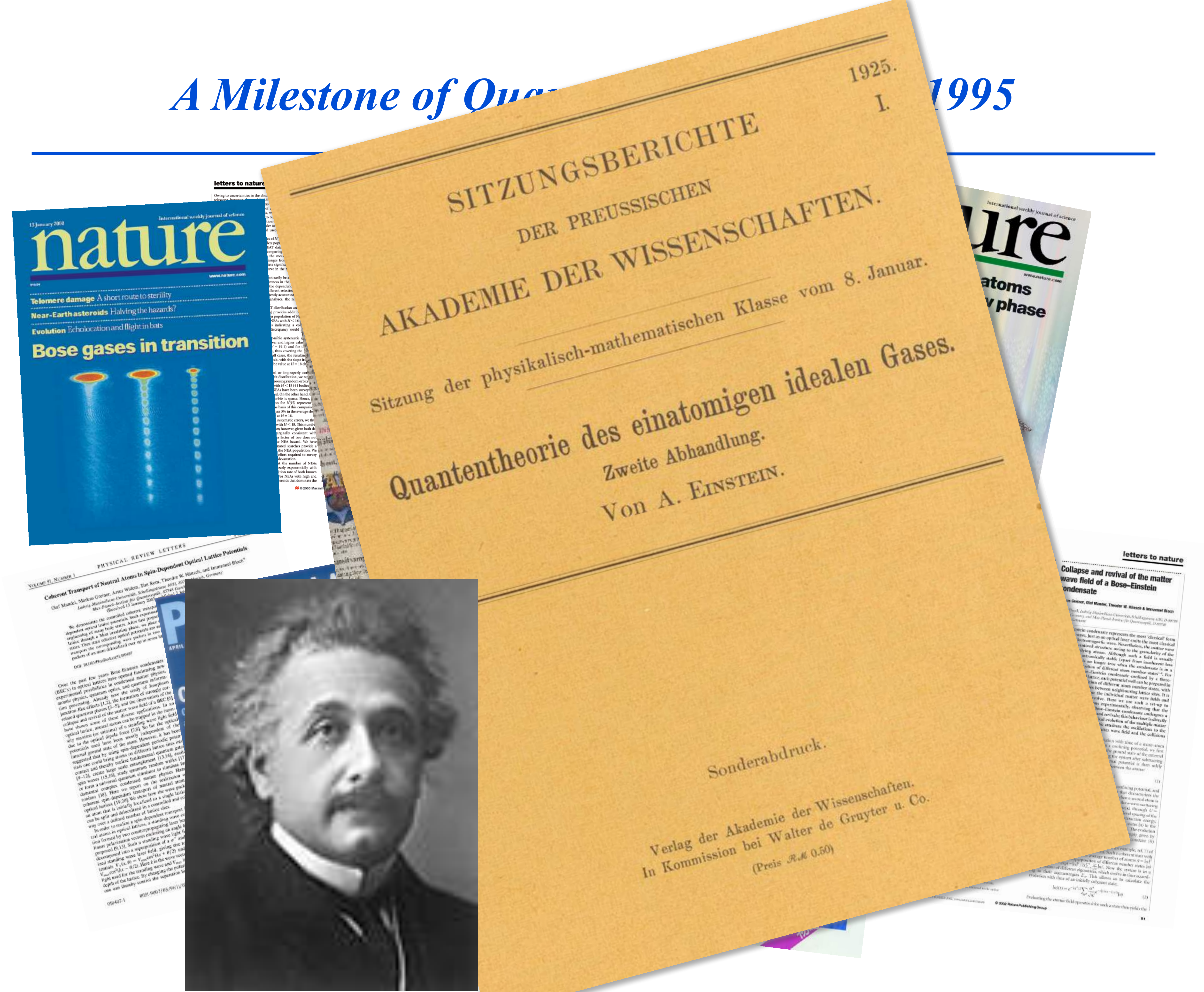
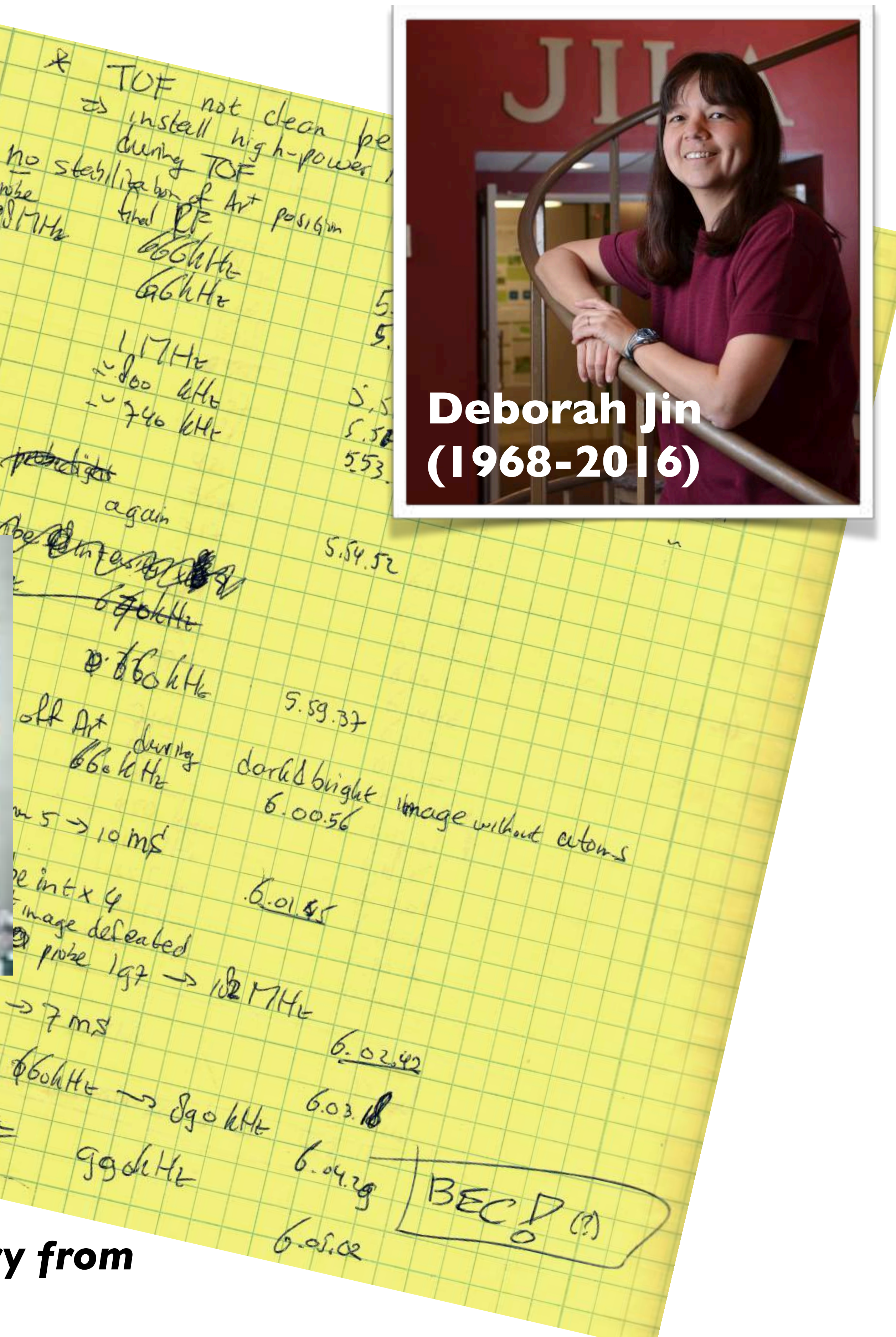
Ultracold Quantum Gases

A Milestone of Qu… 1995



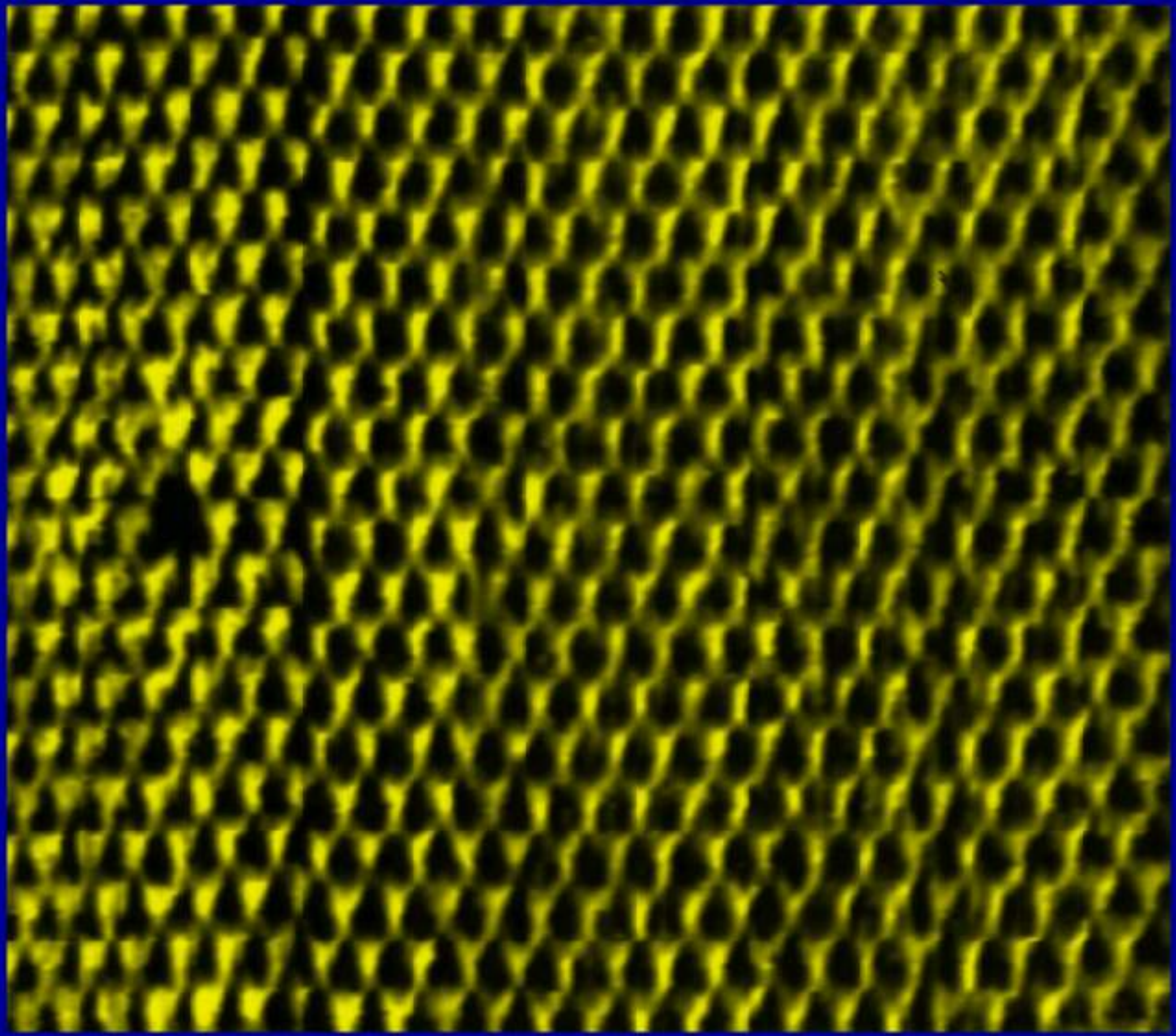


Centennial Nobel Prize in Physics! (2001)

Original lab book entry from W. Ketterle!

Molybdändisulfid

Schwefelatome unter dem Rastertunnelmikroskop



What is Matter ?

MoS2.ps

Matter is a Wave

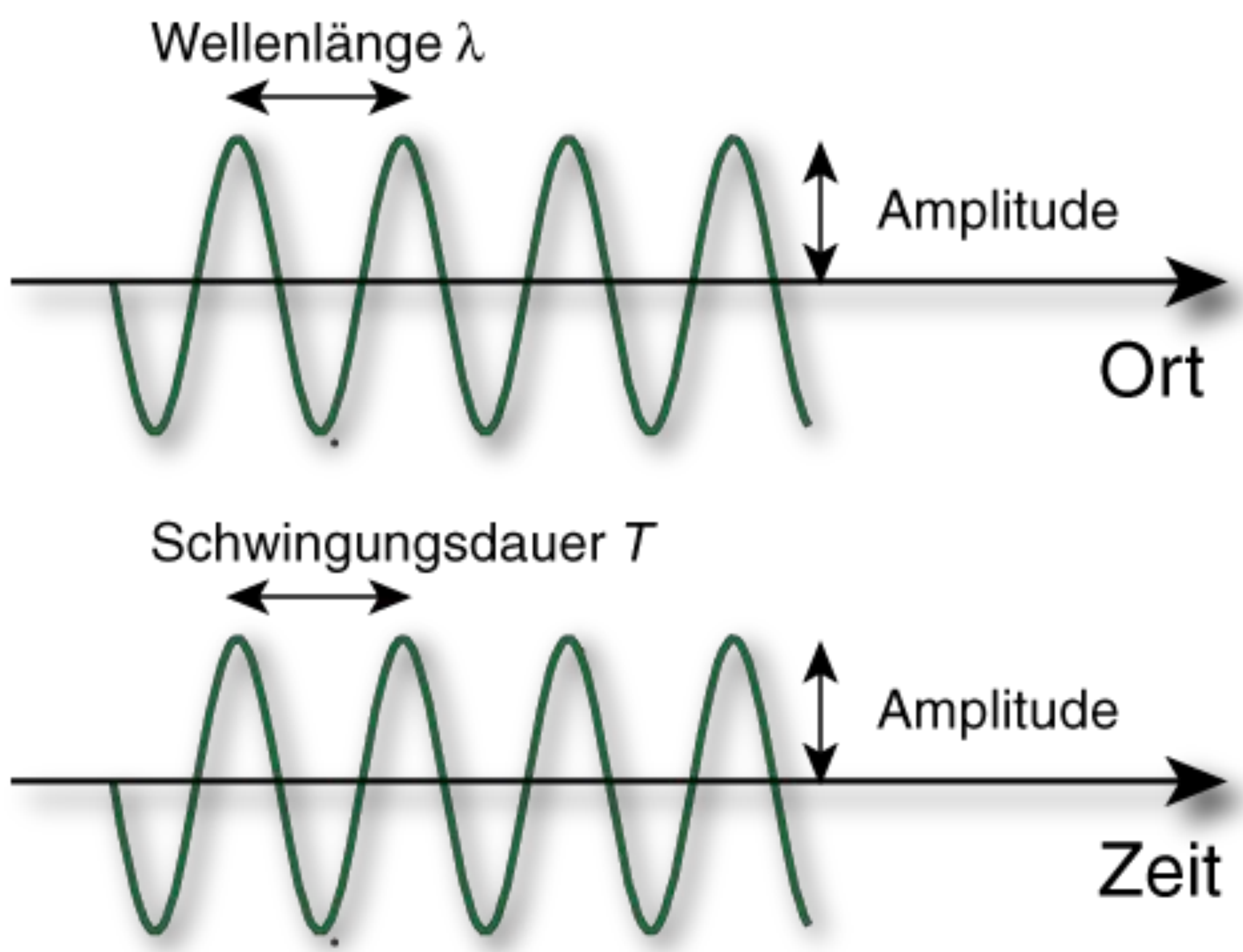
Louis-Victor de Broglie
(1892-1987)

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

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

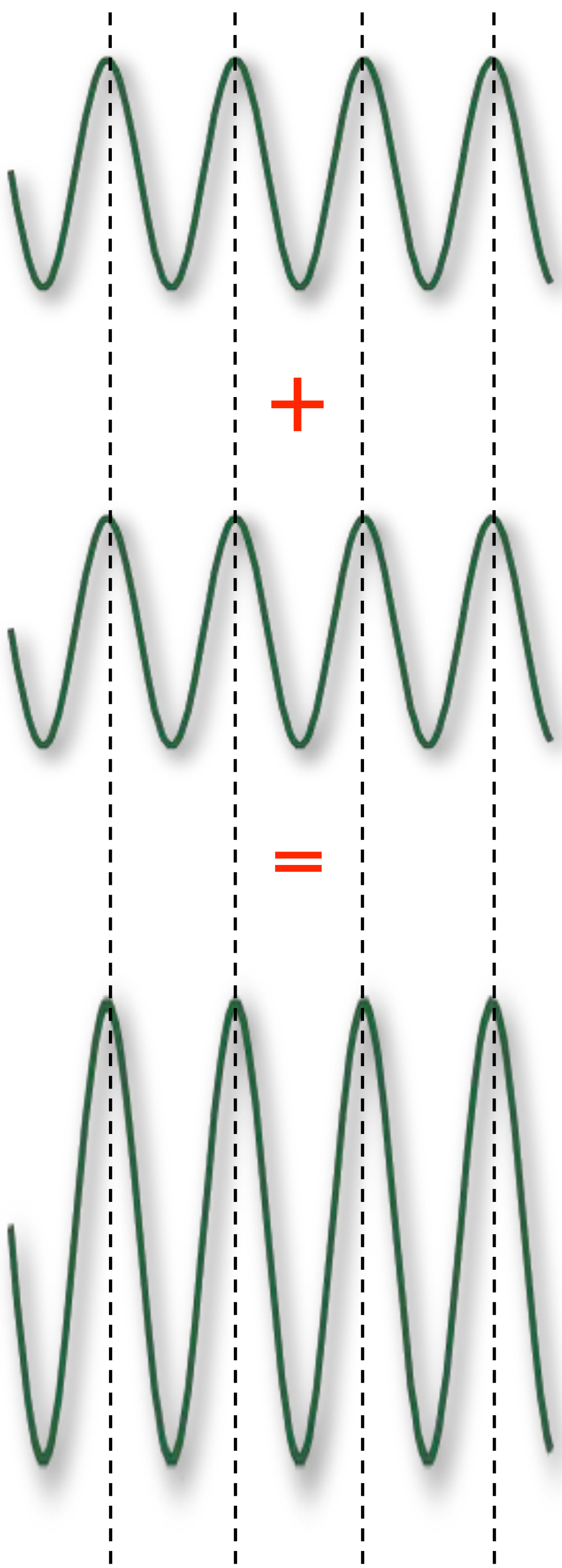
+

Matter

=

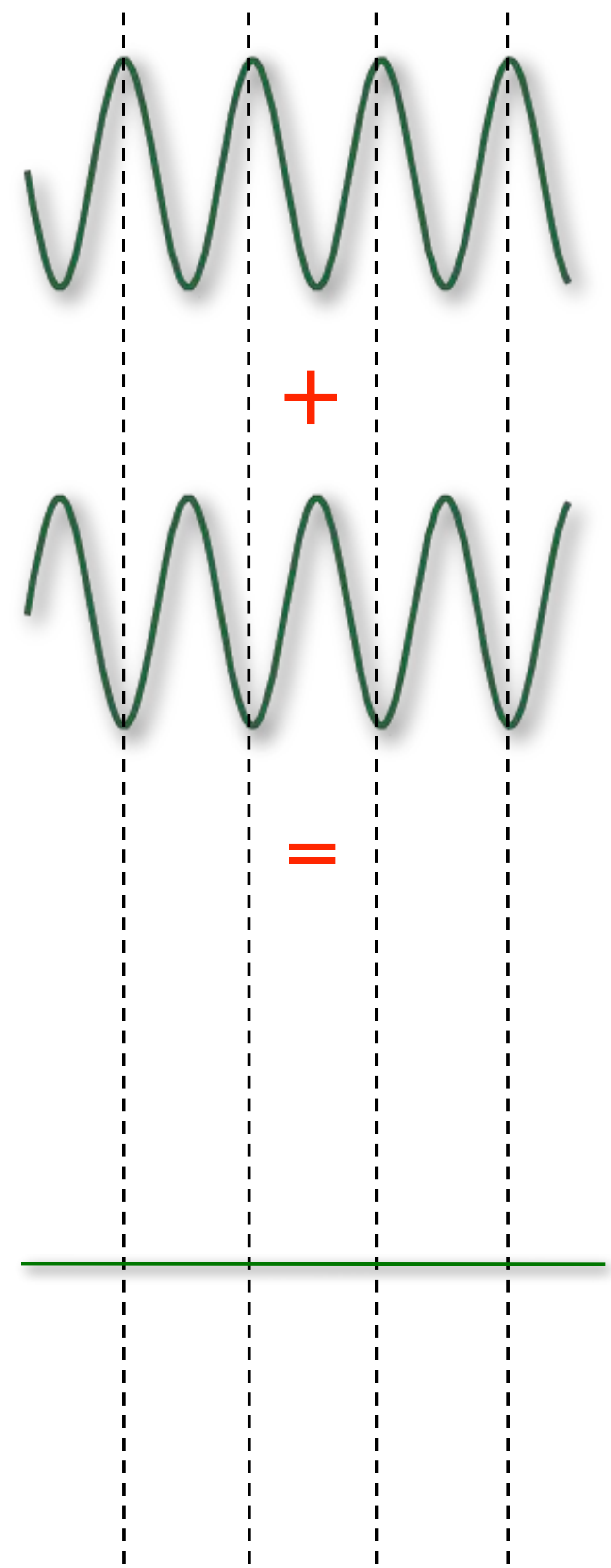
Twice as much matter

Superposition Principle for Waves



Waves can enhance each other!

constructive interference when two waves are added in phase

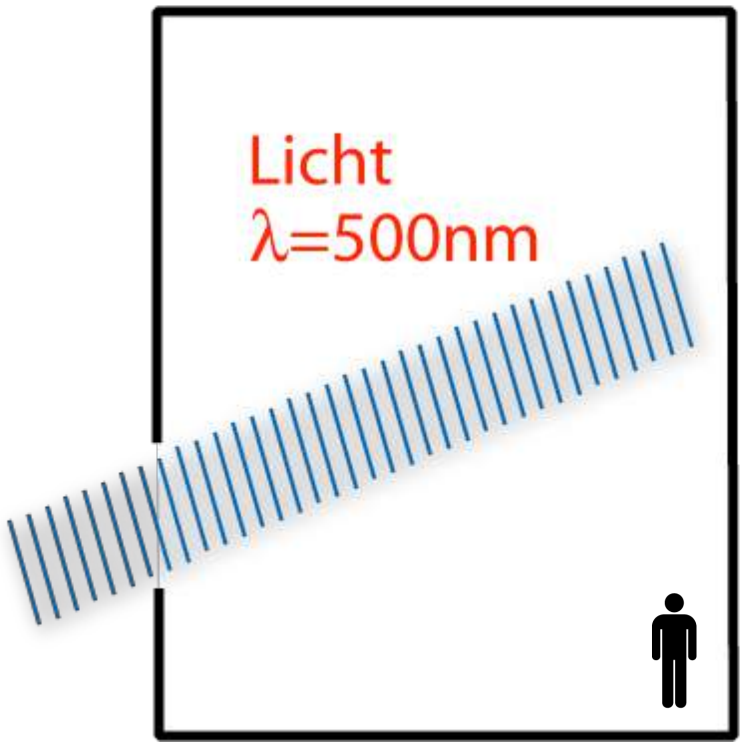


Waves can eliminate each other!

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

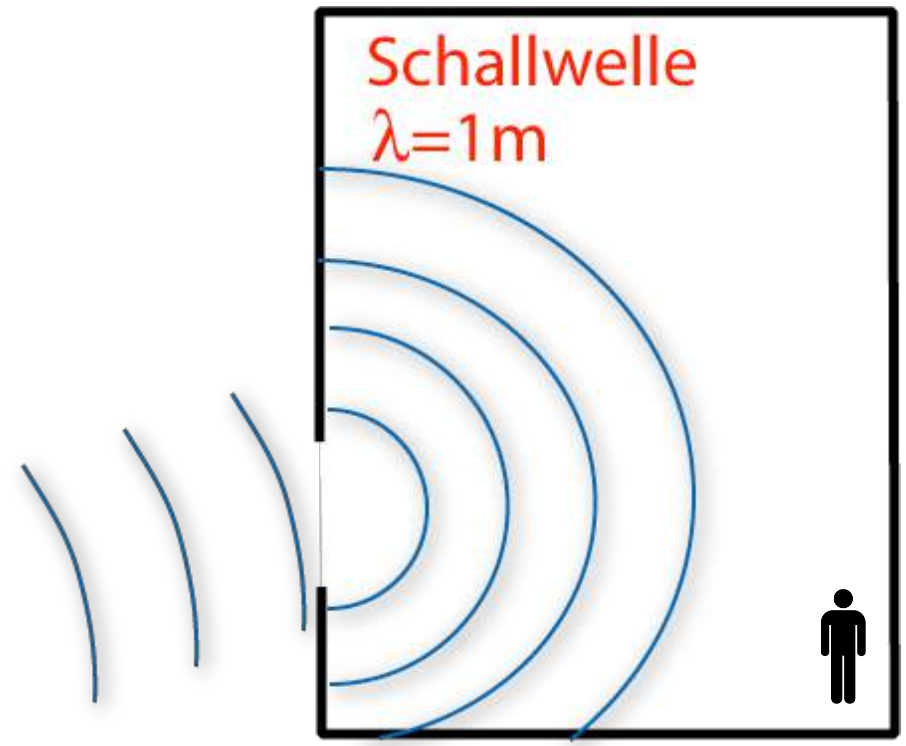
Go To Interference Program...

When can we perceive this wave character?



$\lambda \ll$ Size of Object

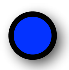
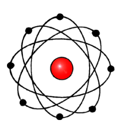
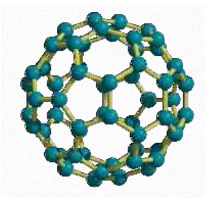
Propagation along straight lines



$\lambda \approx$ Size of Object

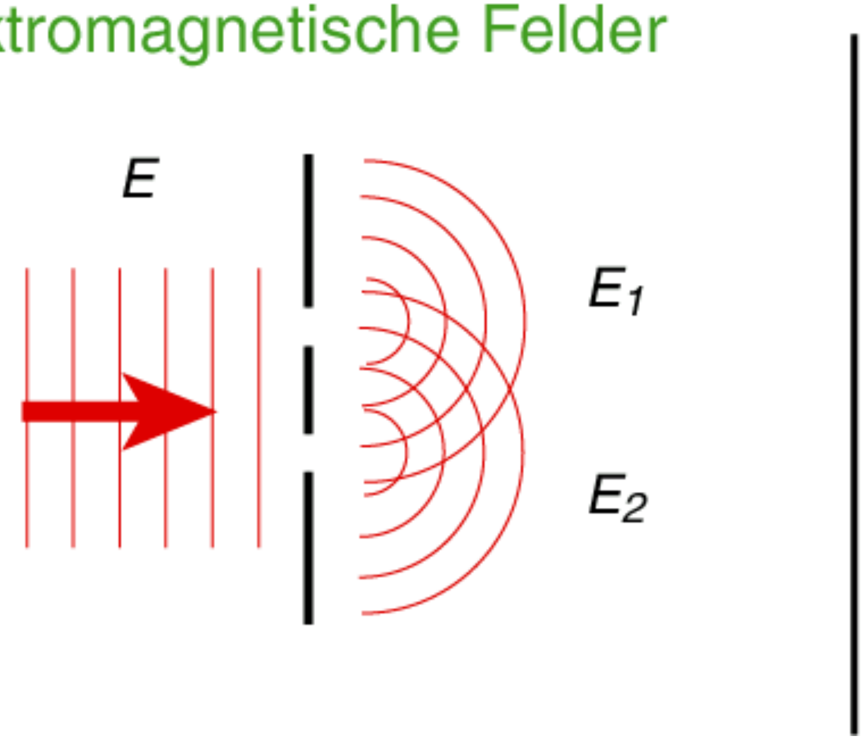
Waves are diffracted!

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?

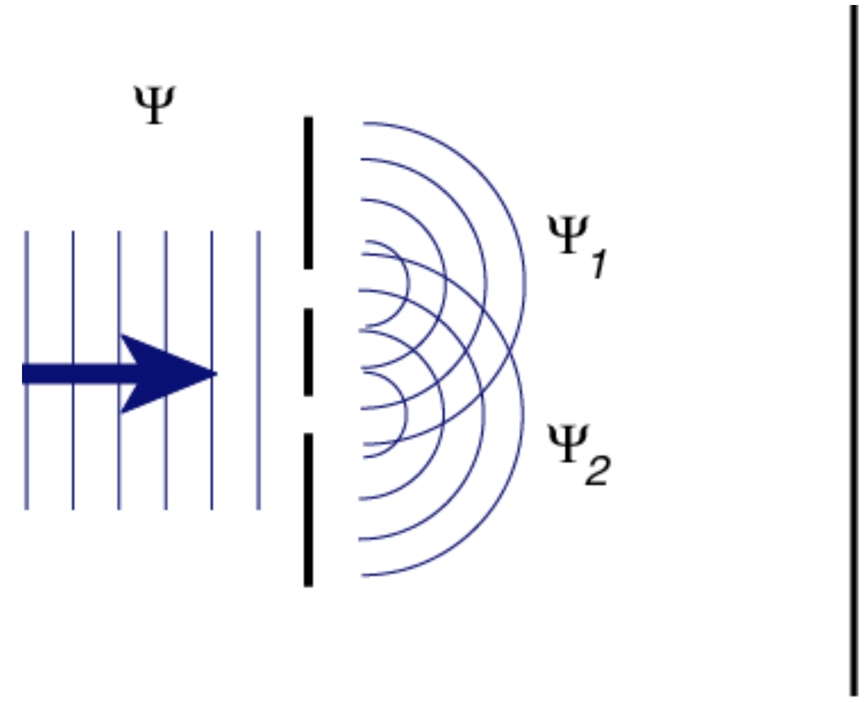
Elektromagnetische Felder



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

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

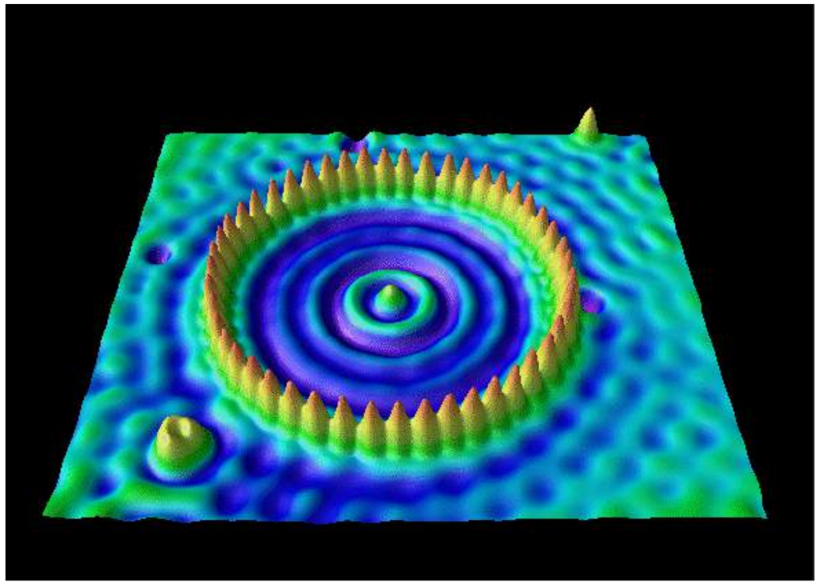
Quantenmechanische Wellenfunktionen



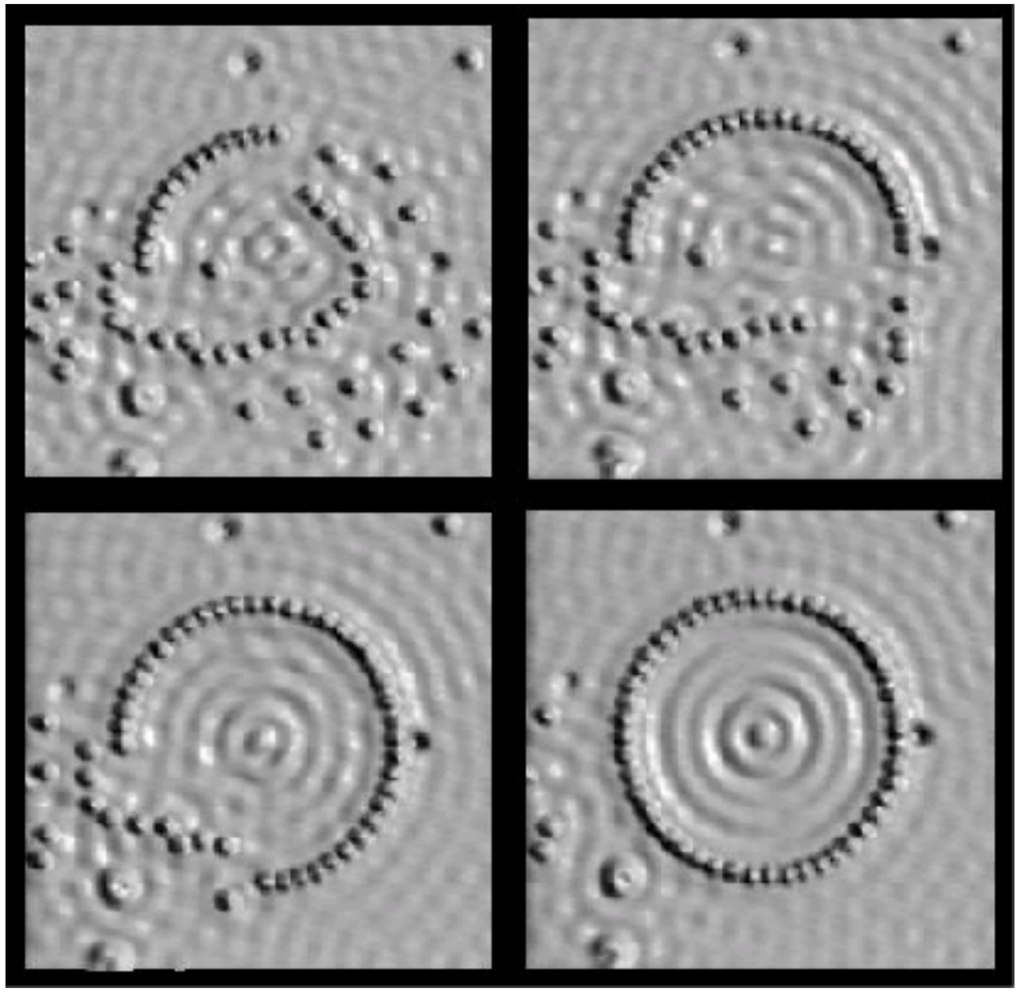
$$\Psi_{det} = \Psi_1 + \Psi_2$$

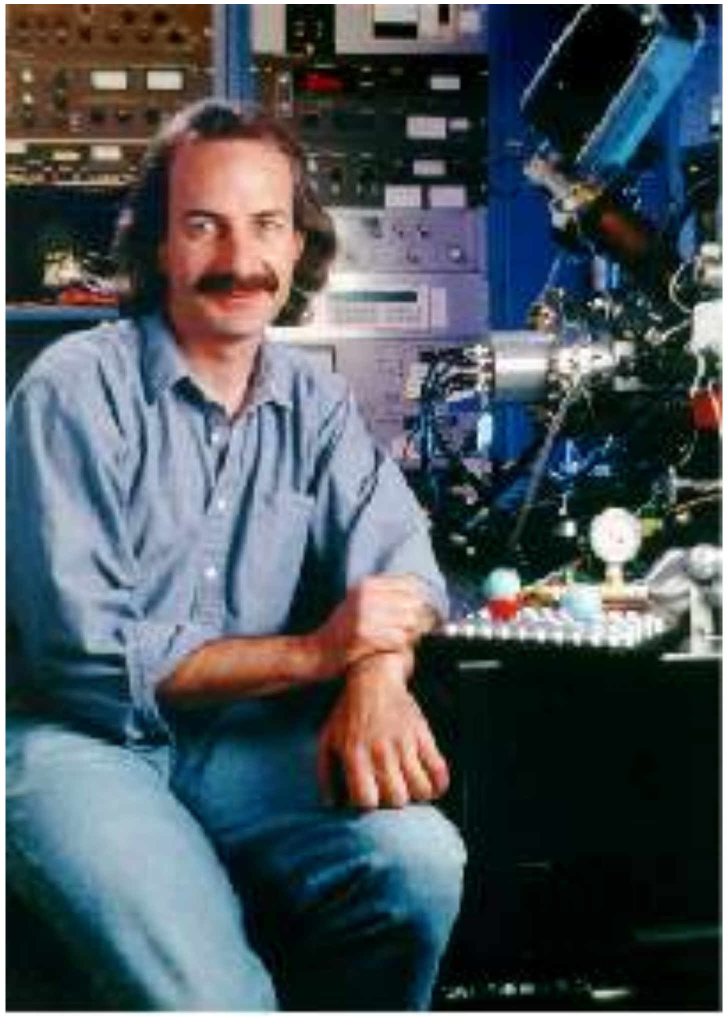
$$n \propto |\Psi_1 + \Psi_2|^2$$

STM Images of Electron Surface Waves



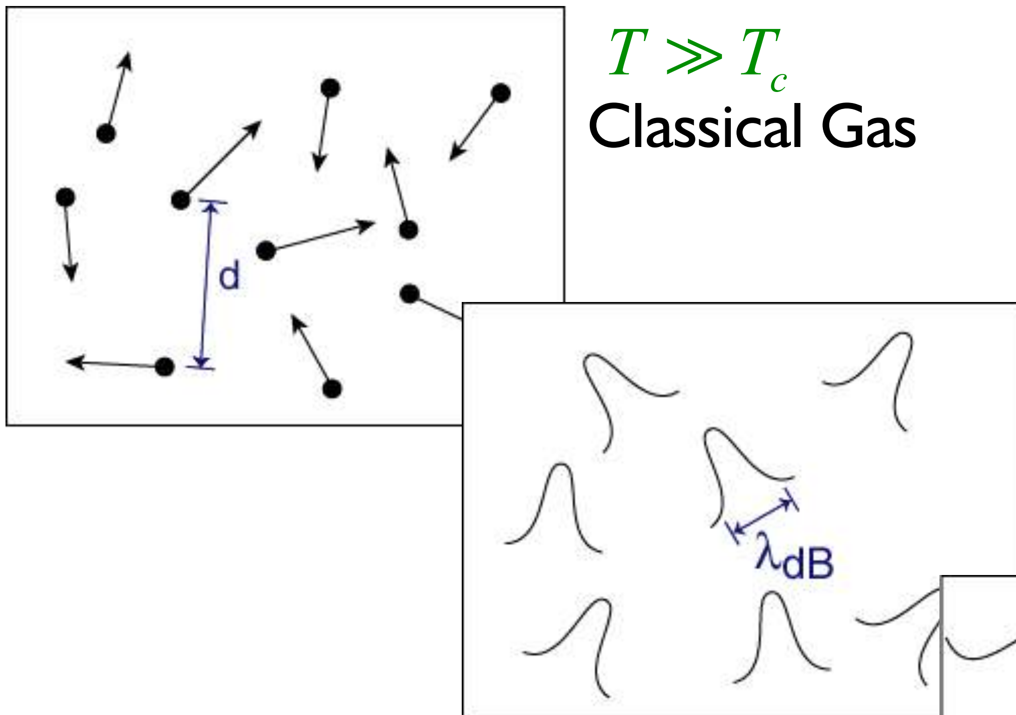
Fe auf Cu (111)

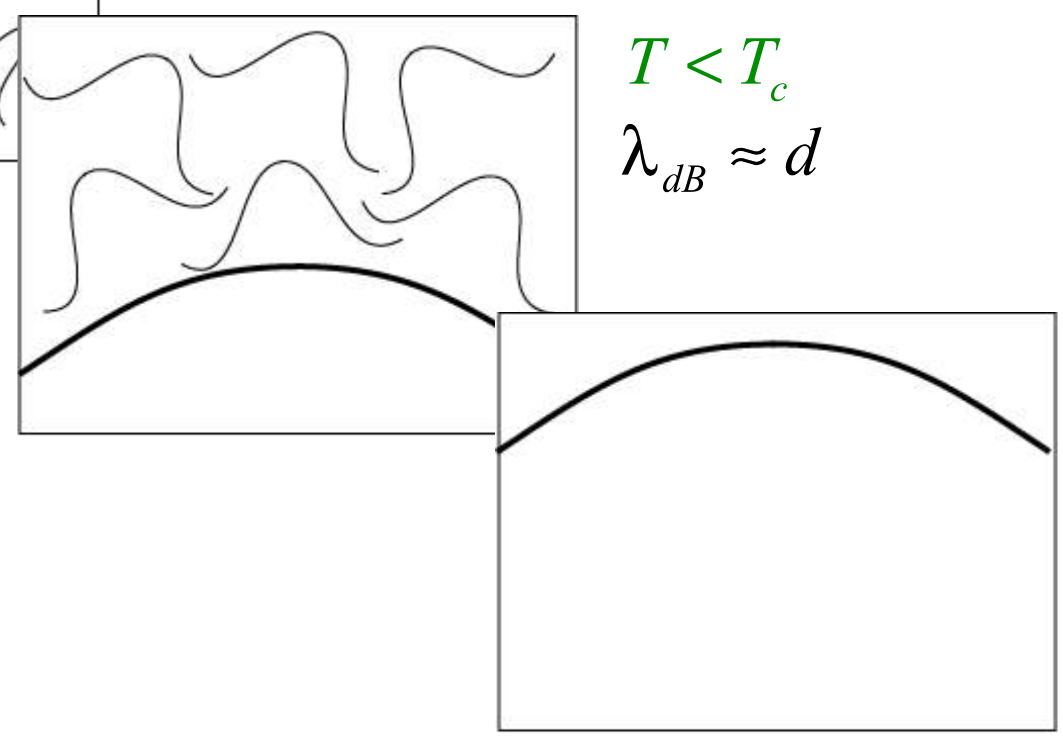




Don Eigler
IBM Almaden Research Labs
http://www.almaden.ibm.com/vis/stm/

From a Classical Gas to a Bose-Einstein Condensate



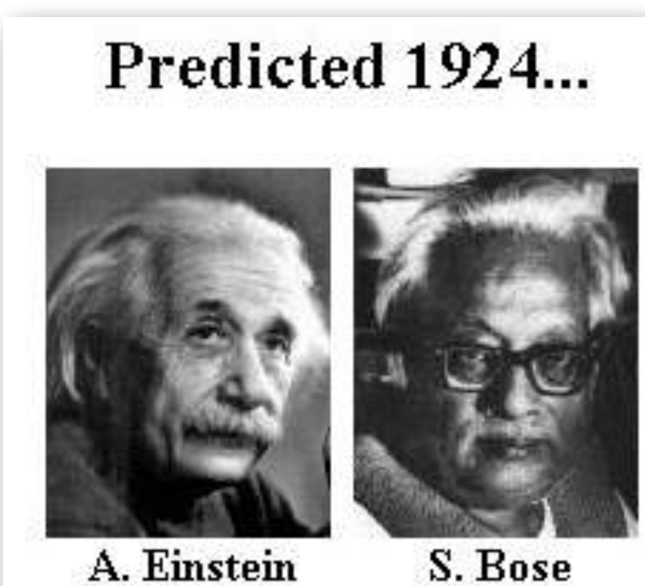


$T \gg T_c$
Classical Gas

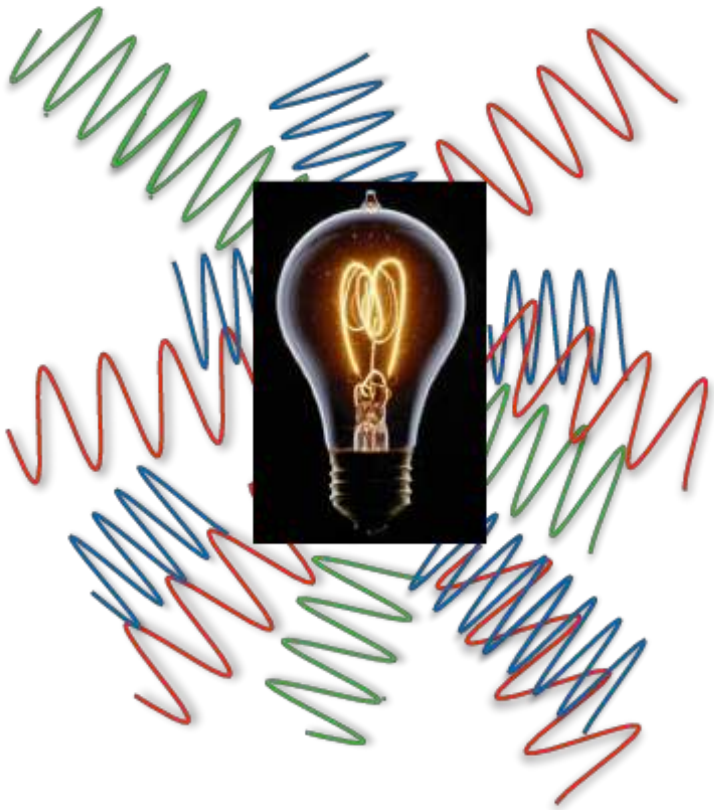
$T > T_c$
$\lambda_{dB} = h/mv \propto T^{-1/2}$

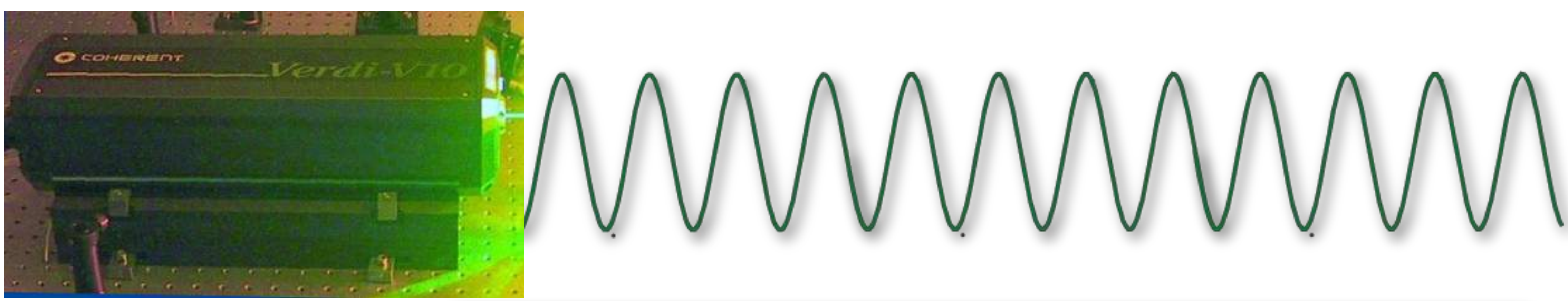
$T < T_c$
$\lambda_{dB} \approx d$

$T = 0$
Coherent Matter Wave



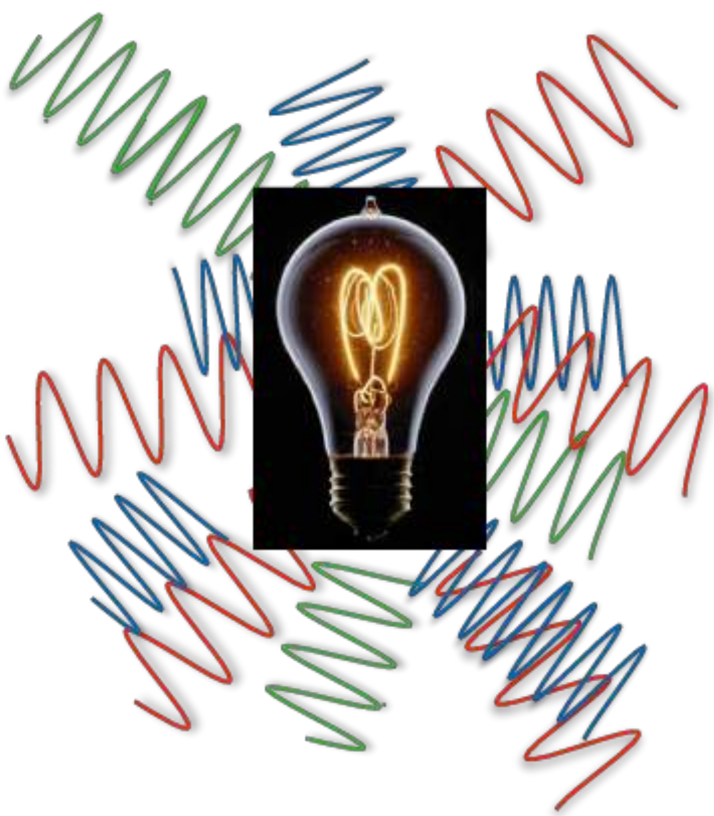
Thermal Light & Laser Light



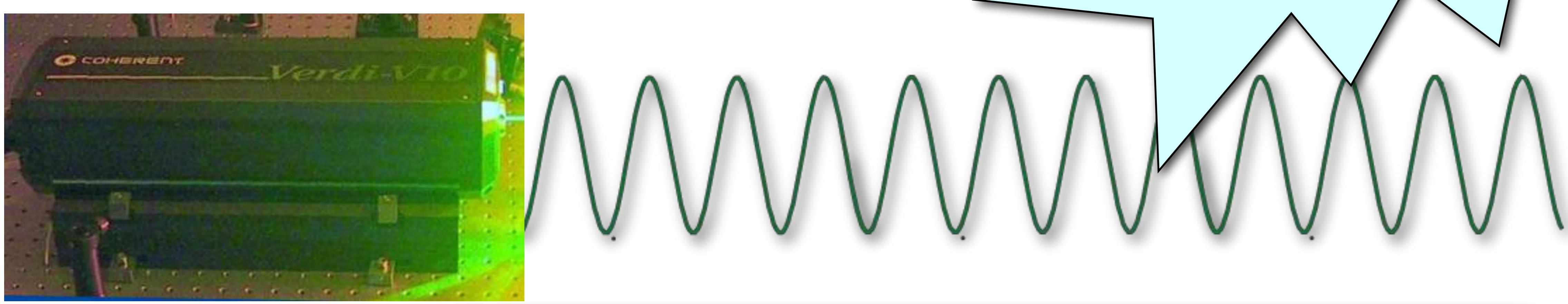


Laser emits one *one continuous wavetrain* ***with a perfectly*** *defined frequency!*

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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Conditions for BEC:

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

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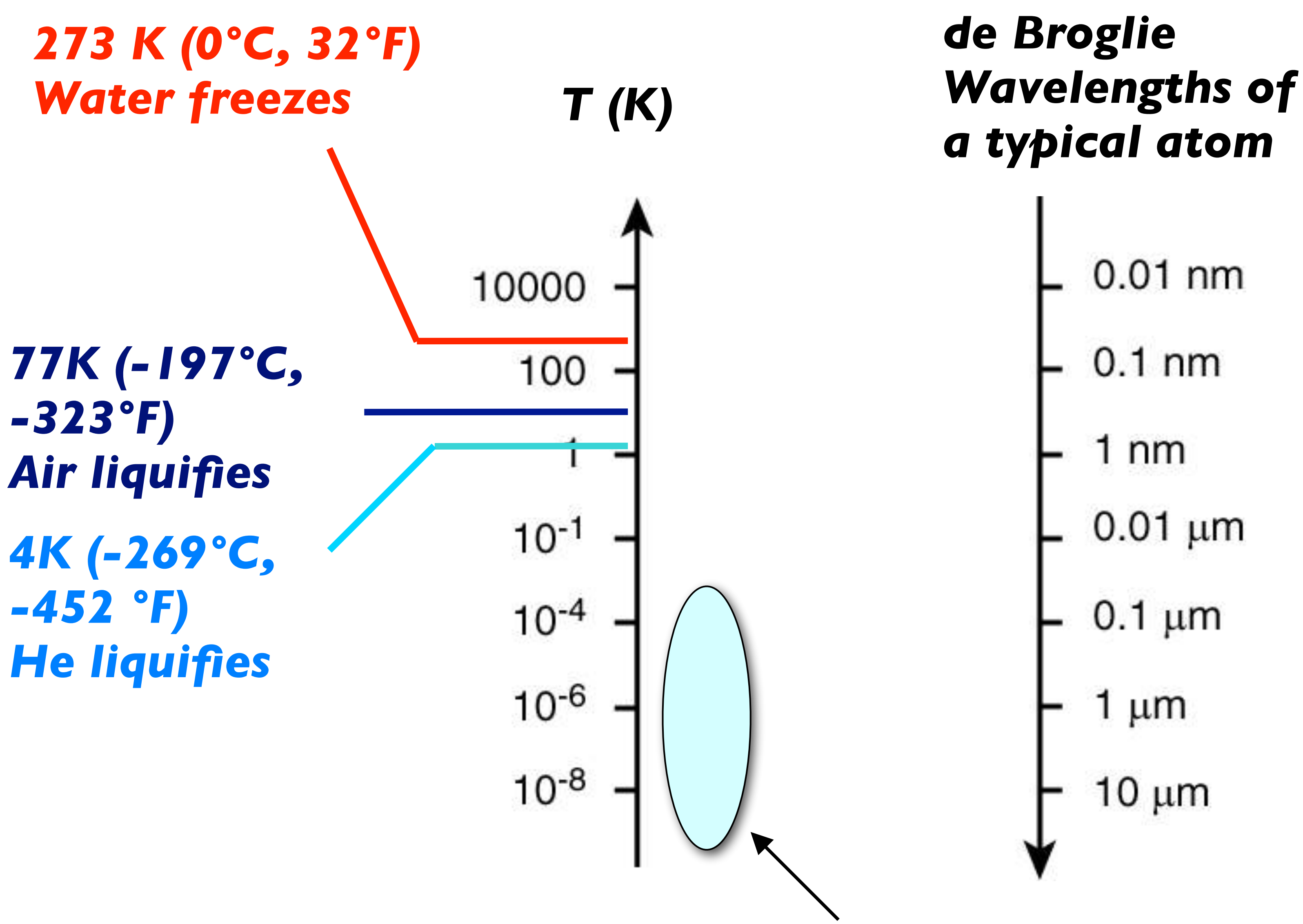
Solution: Density has to be lowered by several orders of magnitude to prolong timescale for solid formation!

Even lower temperatures are needed!

de Broglie Wavelengths

Thermal deBroglie wavelengths

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

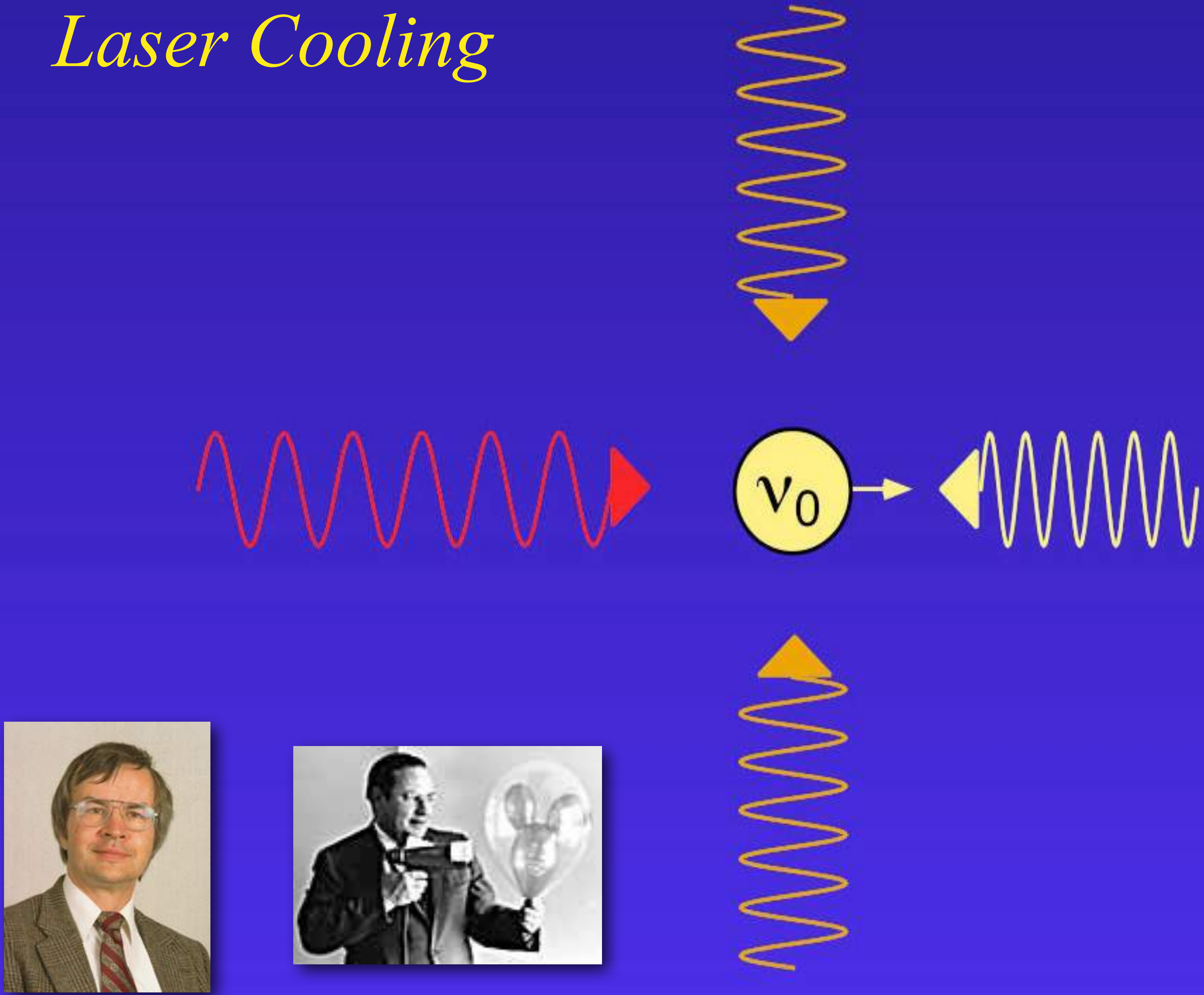


These are temperatures we need to reach to create macroscopic matter waves !

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

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

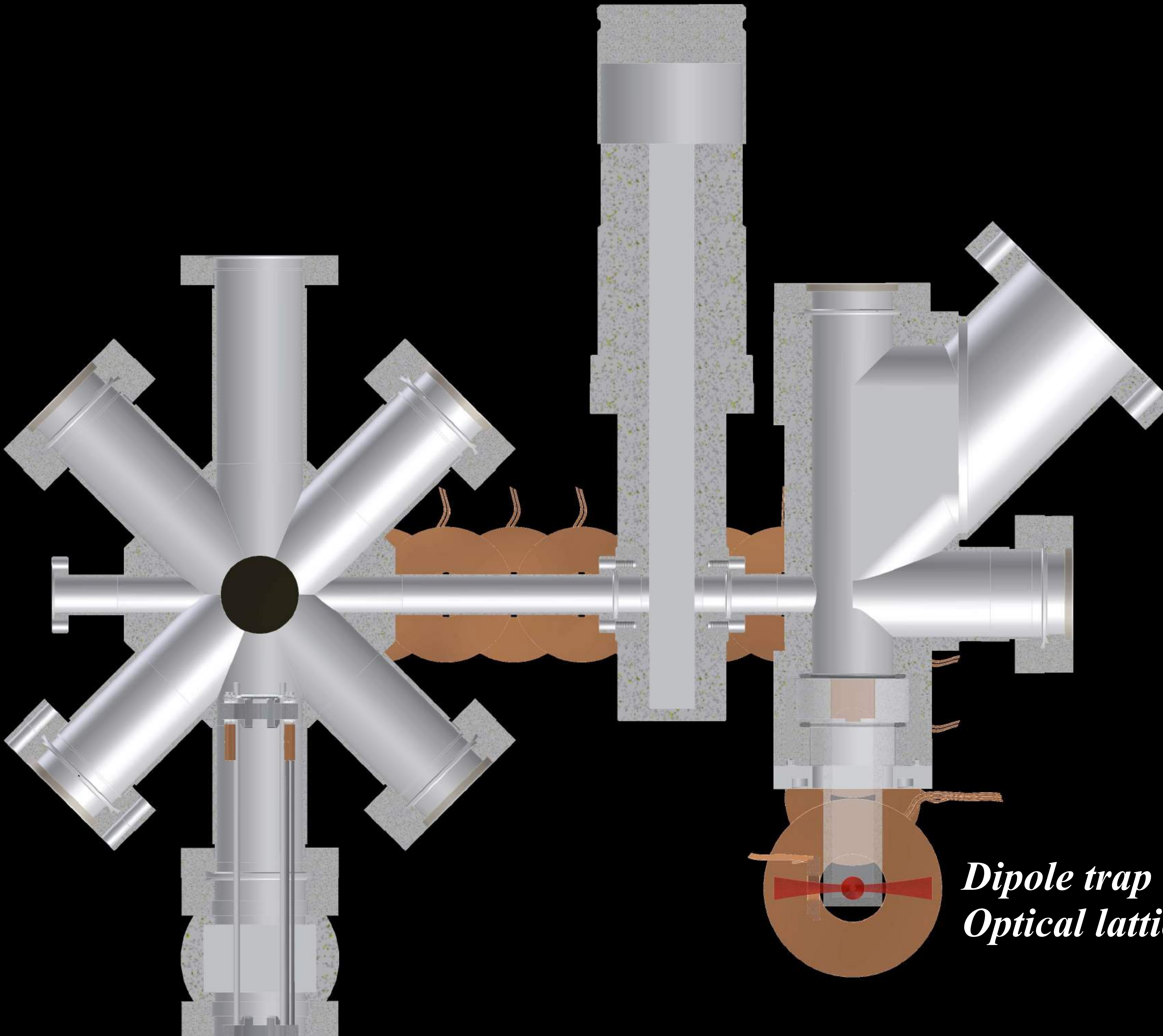
e.g. for ^{87}Rb

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

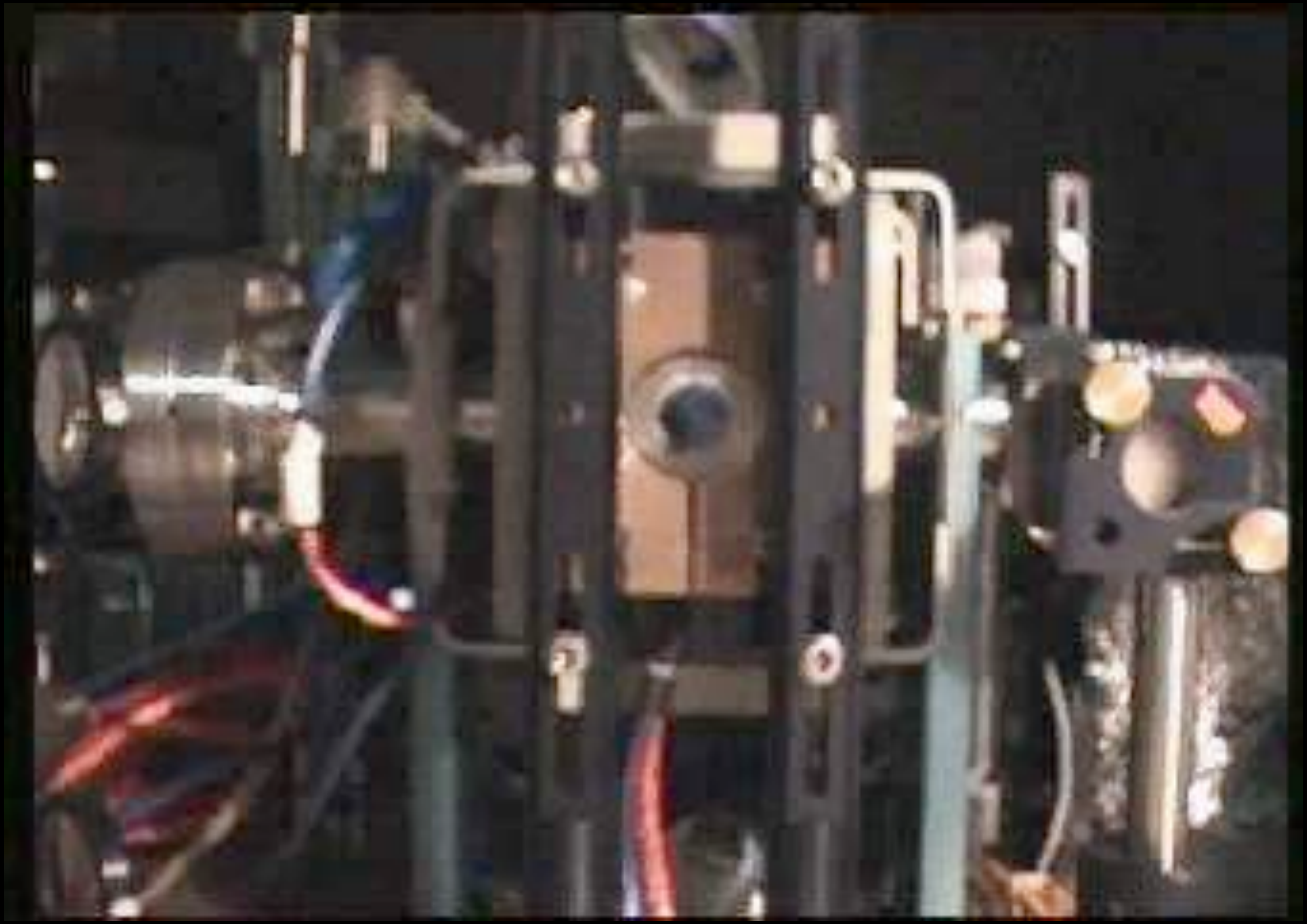
10000 g !

Minimum Temperature

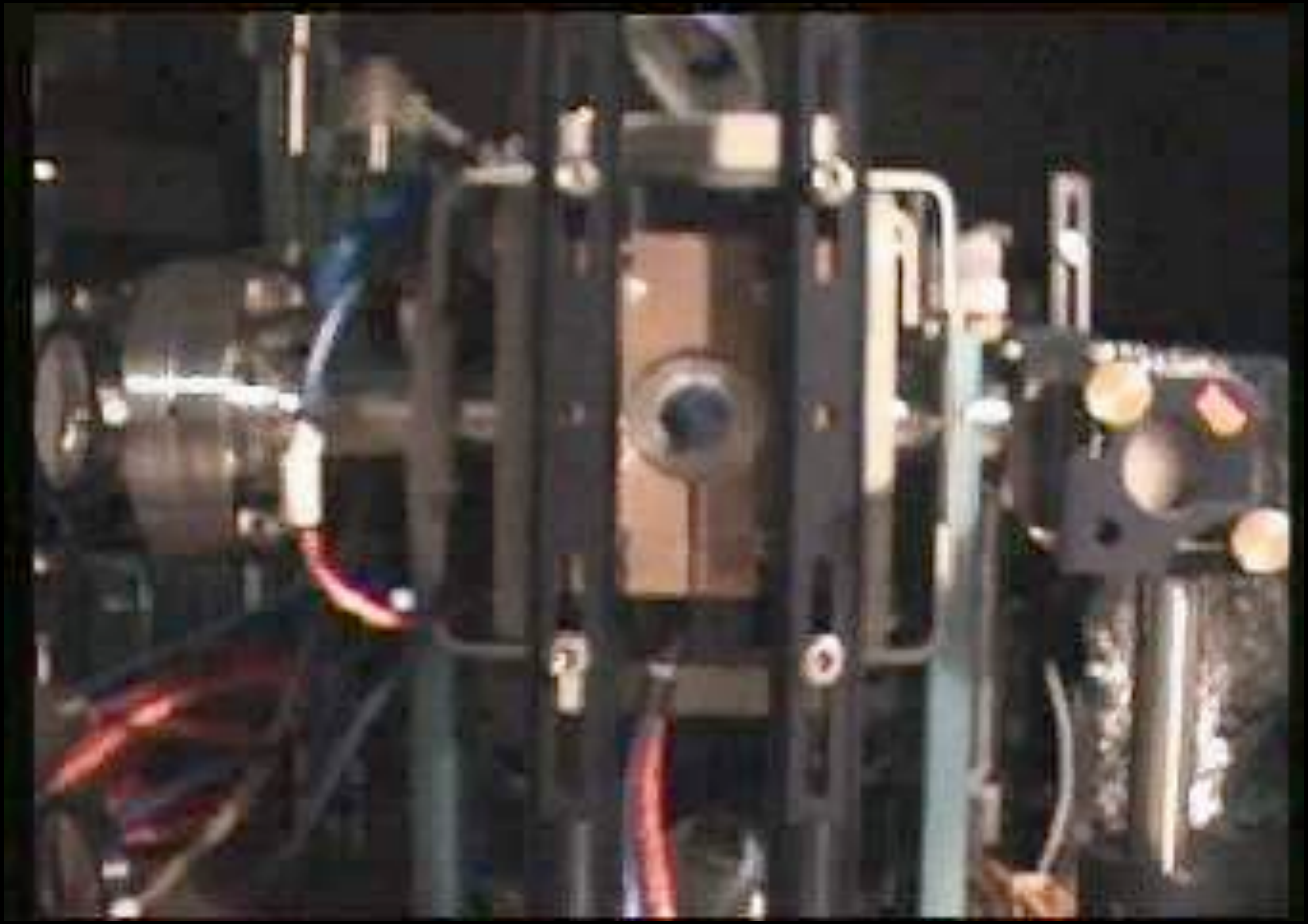
$$T_{\min} \approx 10 \mu K$$


Dipole trap +
Optical lattices

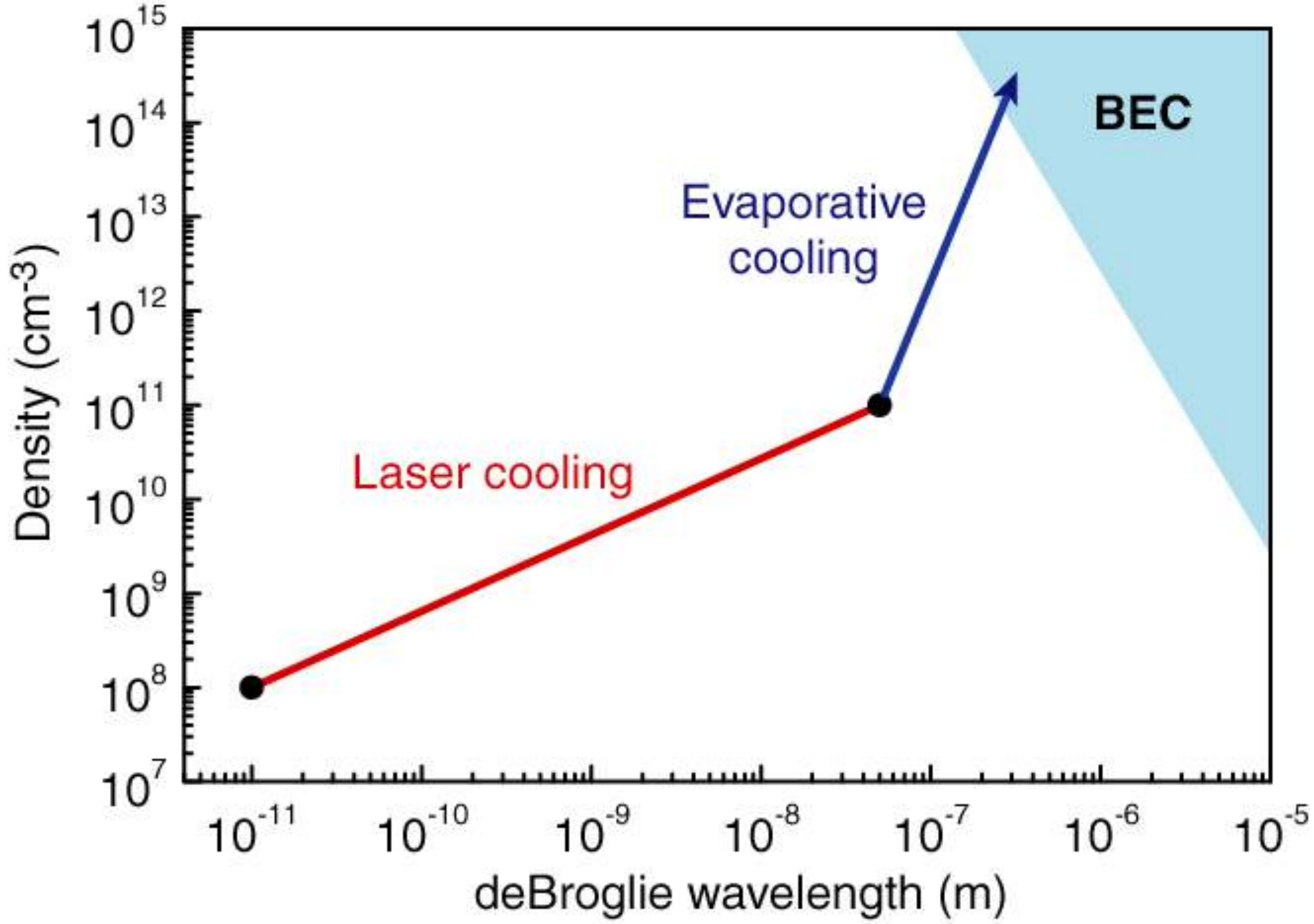
Laser Cooling at Work



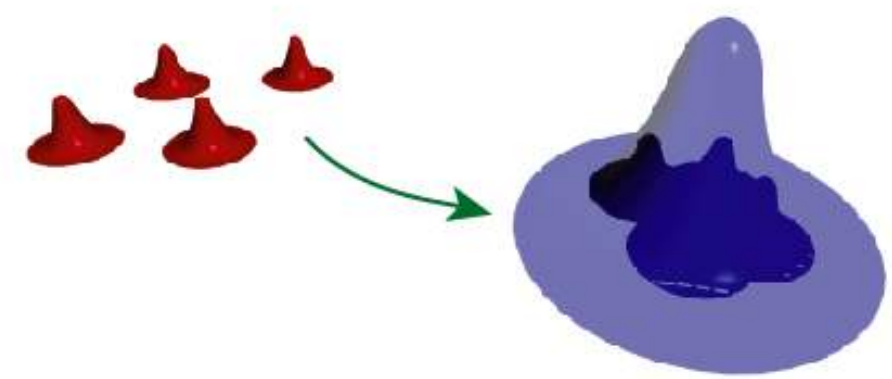
Laser Cooling at Work



The Path to Bose-Einstein Condensation



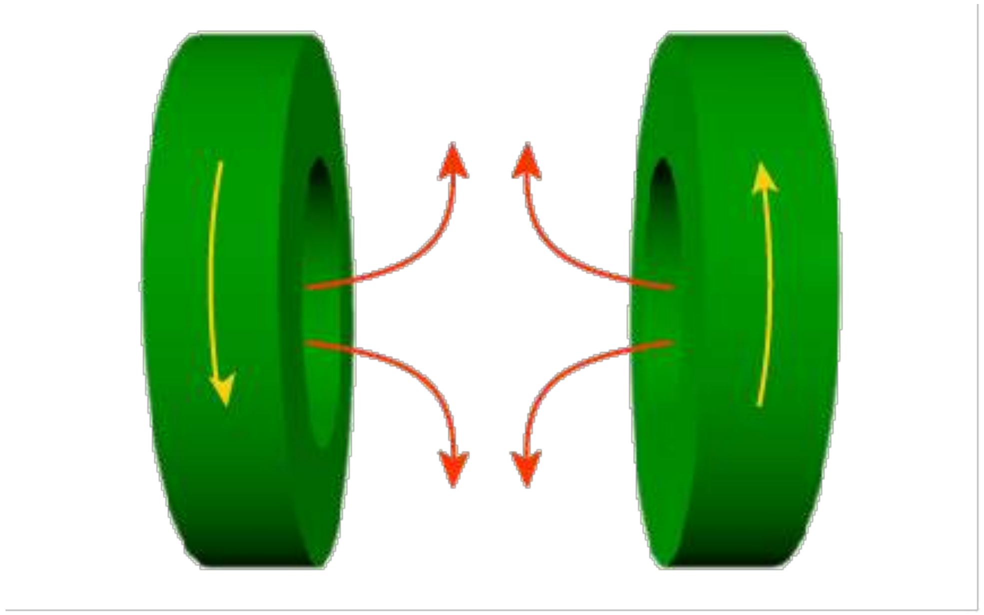
$$n \cdot \lambda^3 \approx 1$$

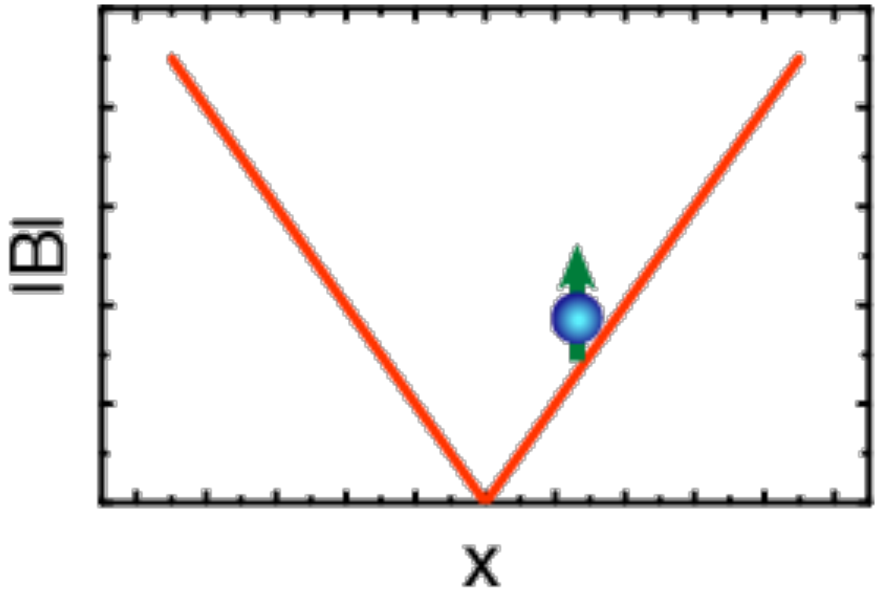


Magnetic Traps for Neutral Atoms

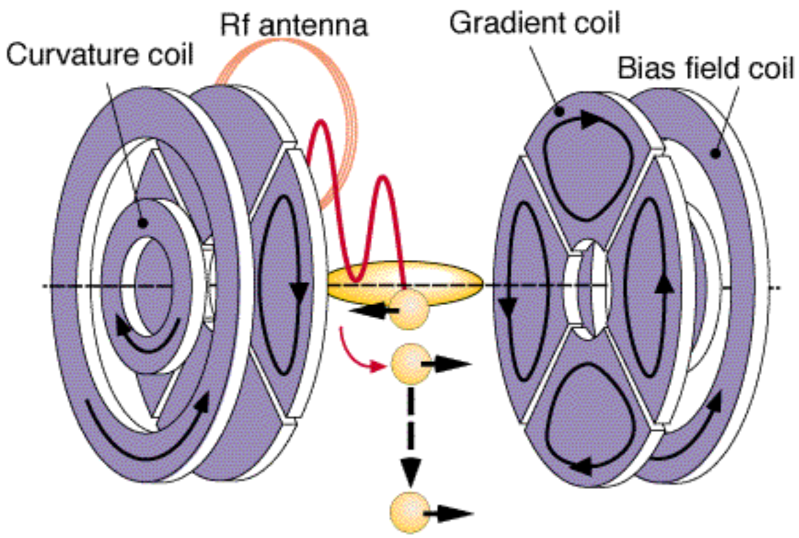
Energy of an atom
in an external magnetic field $E = -\vec{\mu} \cdot \vec{B}$

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



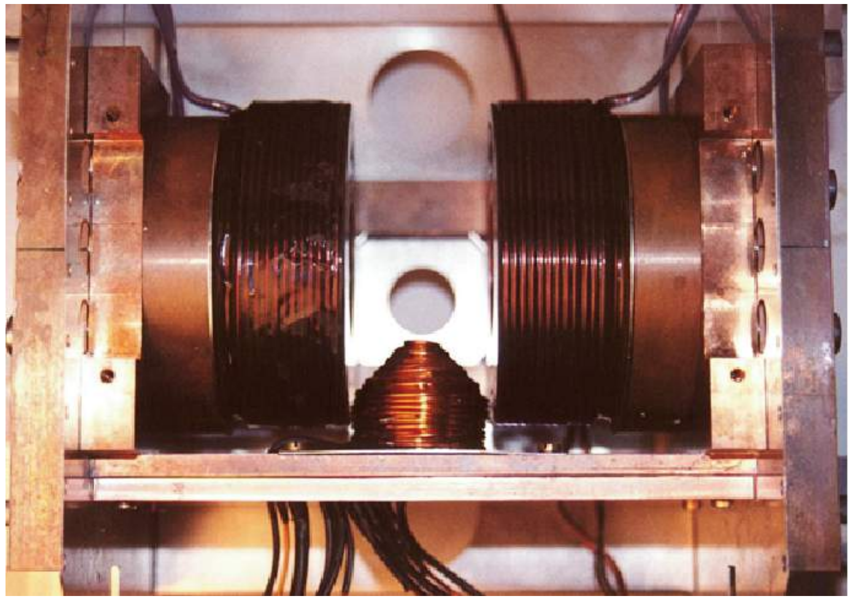


Magnetic Trap 'Zoology'

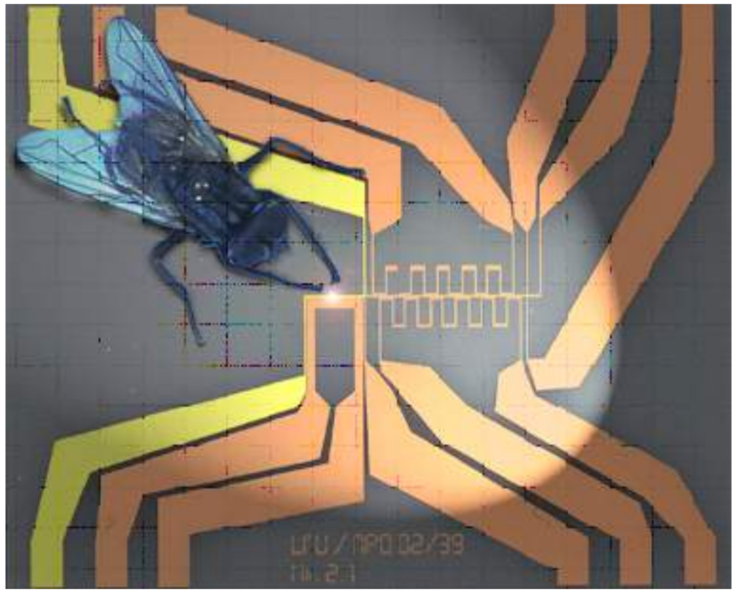


MIT, March '96 [M.-O. Mewes et al., PRL 77, 416 (1996)]

Cloverleaf Trap

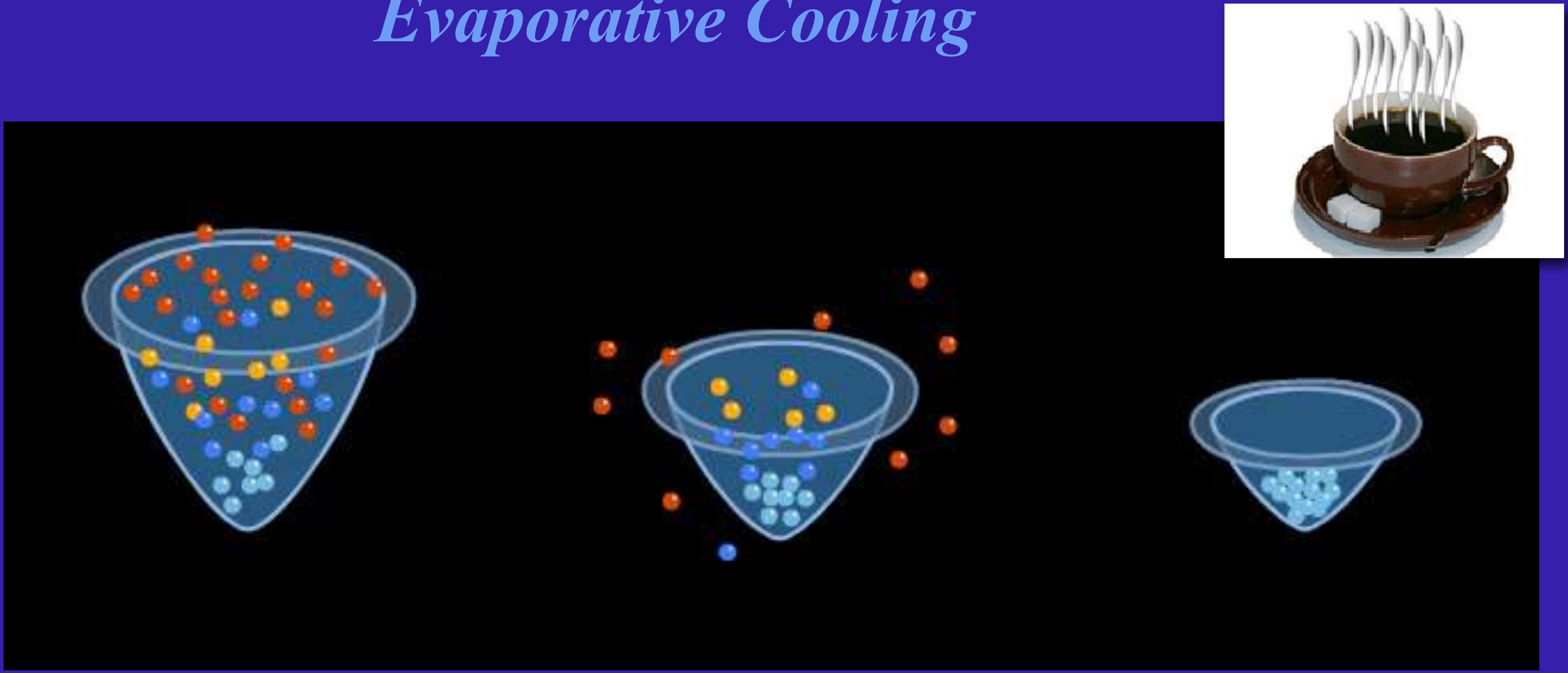


QUIC-Trap



Miniaturized Magnetic Traps

Evaporative Cooling

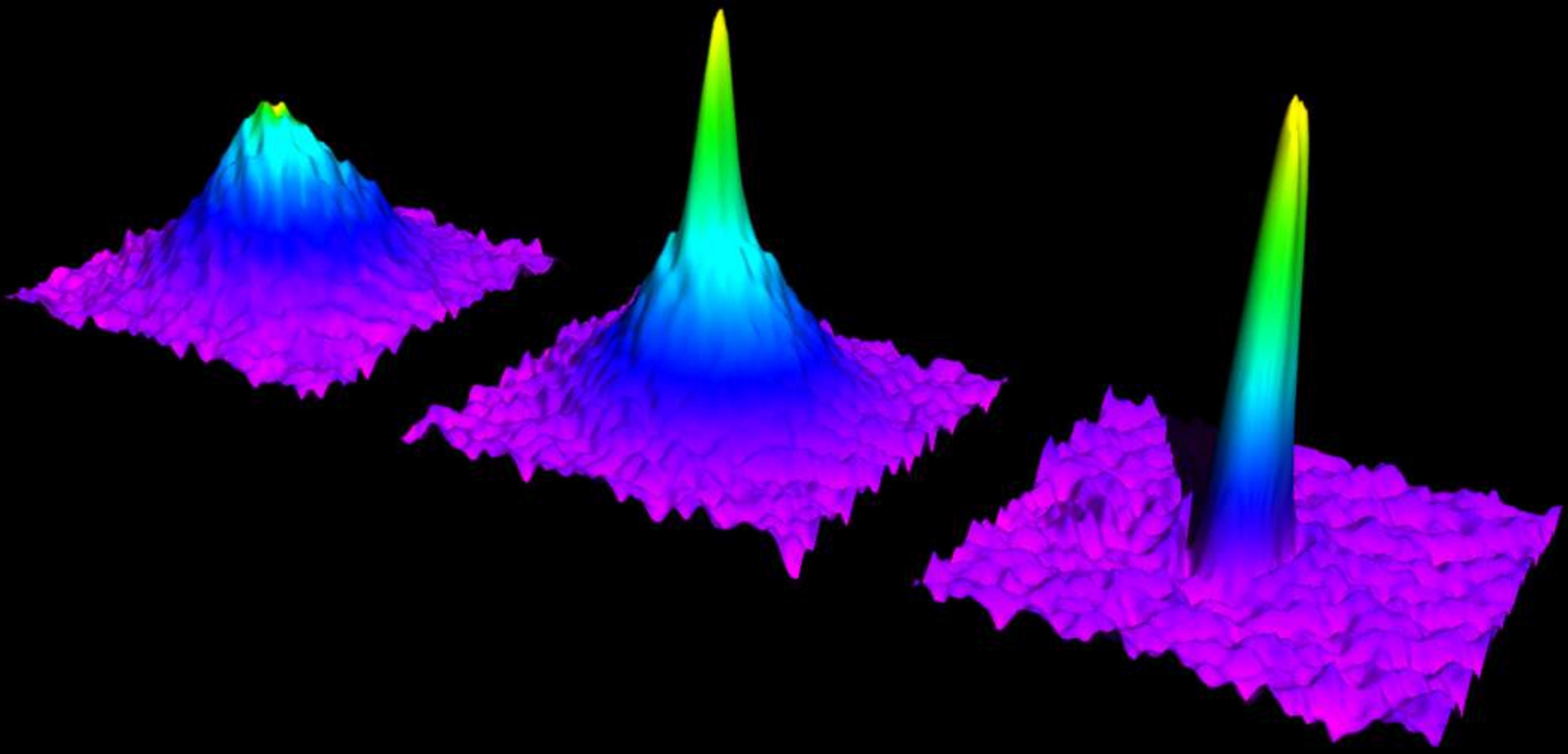


Tom Greytak

Daniel Kleppner

Time-of-Flight Imaging

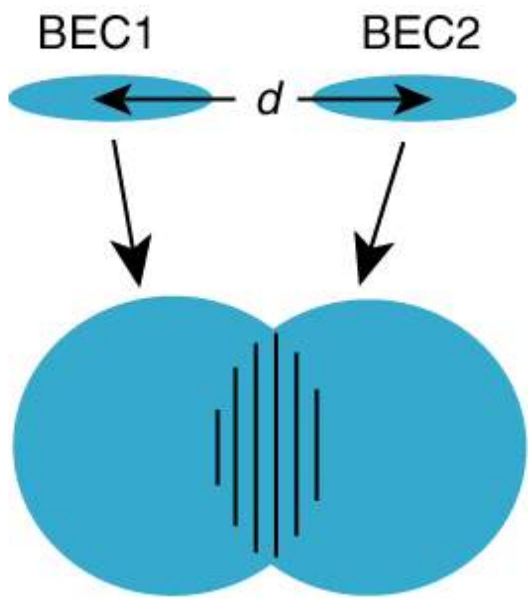
Time-of-Flight Imaging



Interference of Two Bose-Einstein Condensates

Trapped BEC's

BEC's after expansion time t

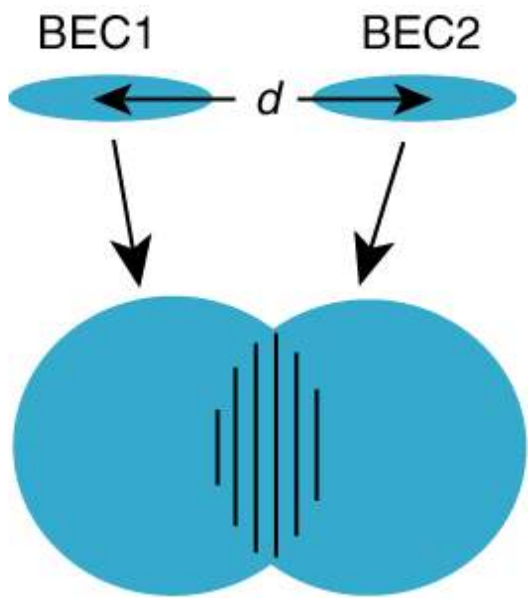


$$\lambda = \frac{h}{m\Delta v} = \frac{ht}{md}$$

Interference of Two Bose-Einstein Condensates

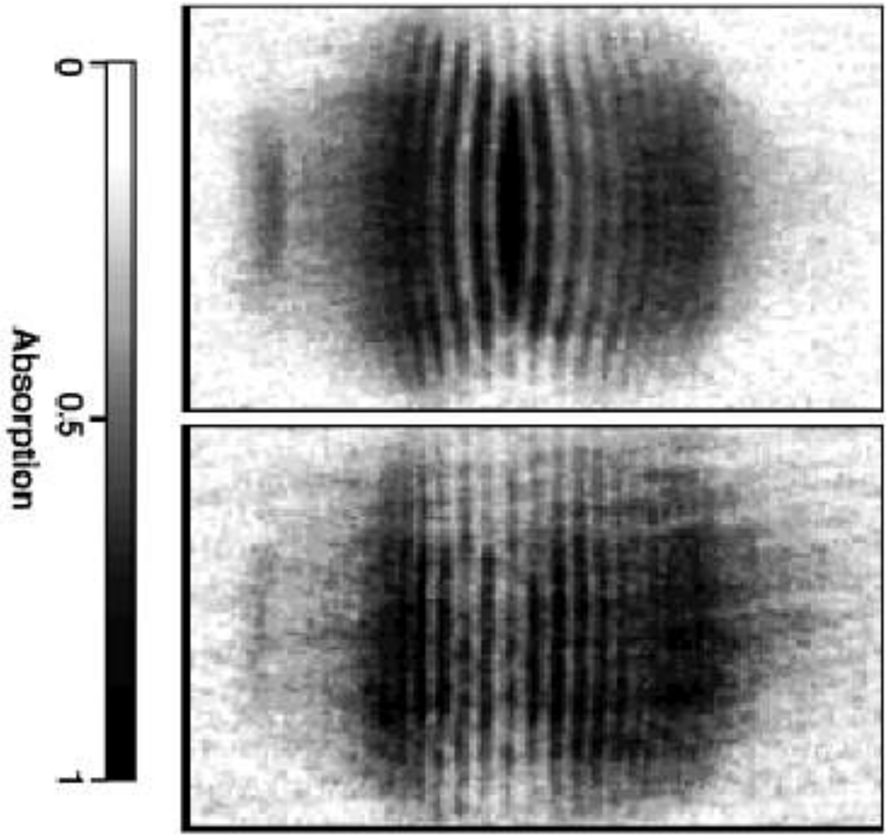
Trapped BEC's

BEC's after expansion time t

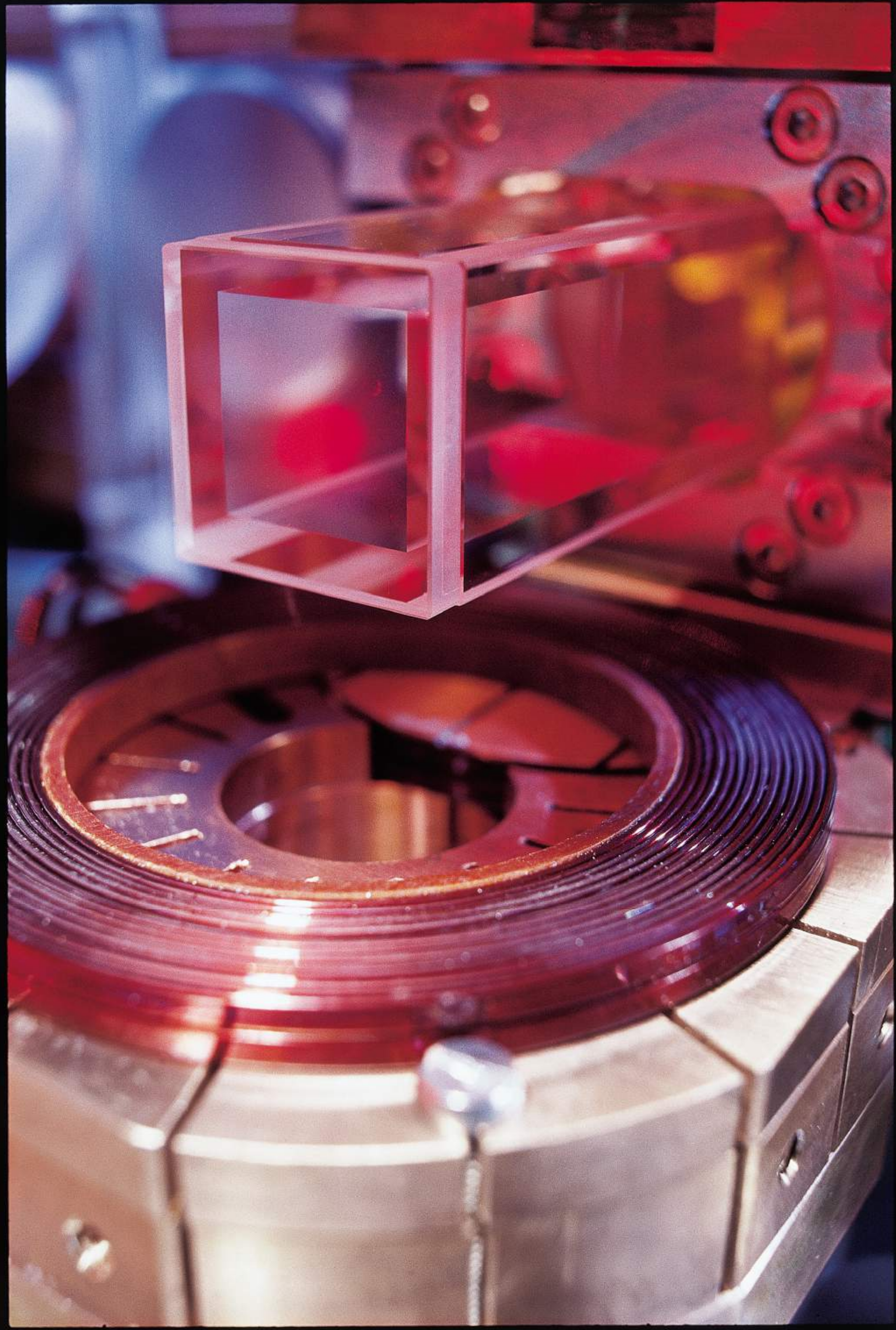


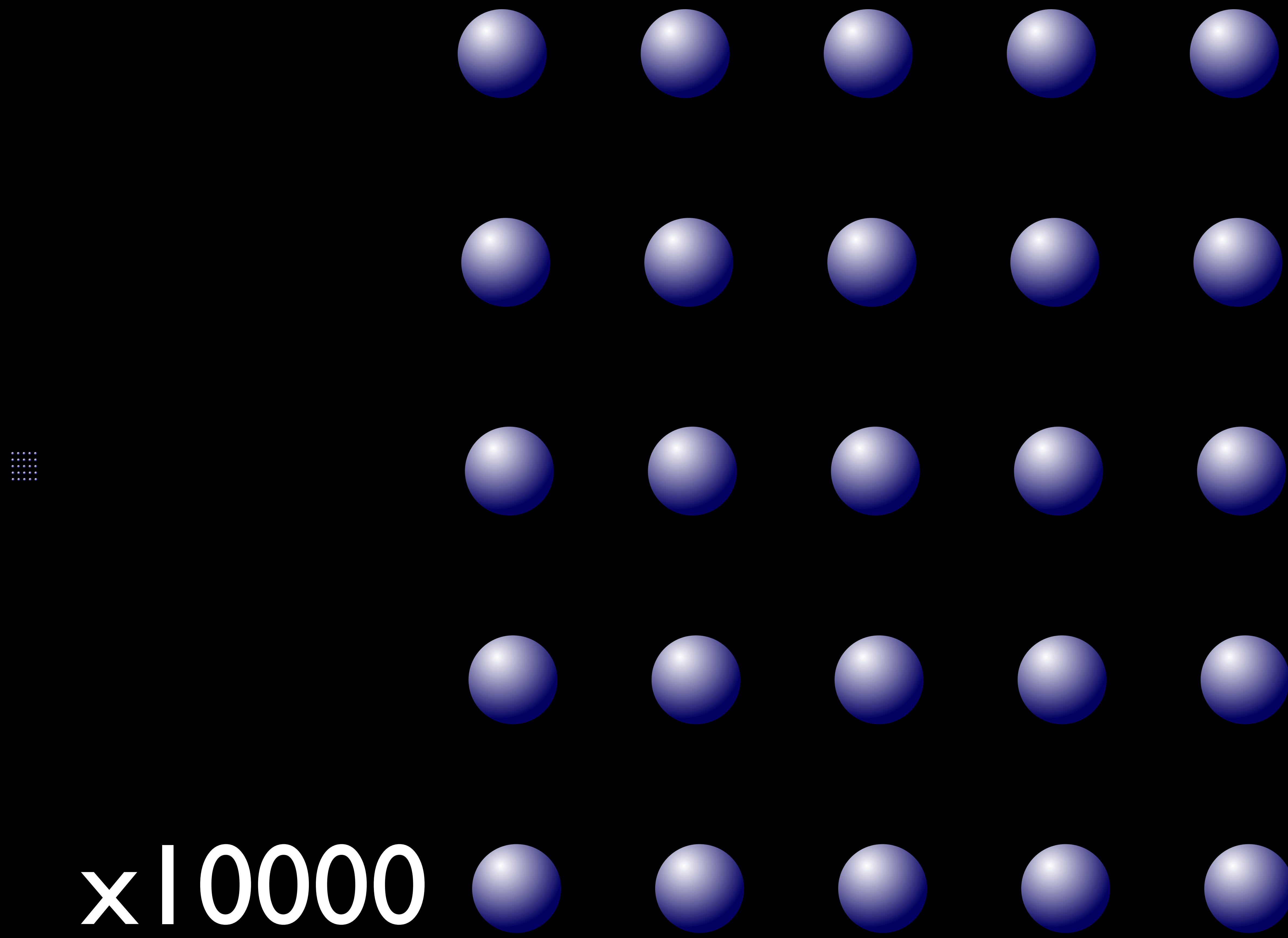
$$\lambda = \frac{h}{m\Delta v} = \frac{ht}{md}$$

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

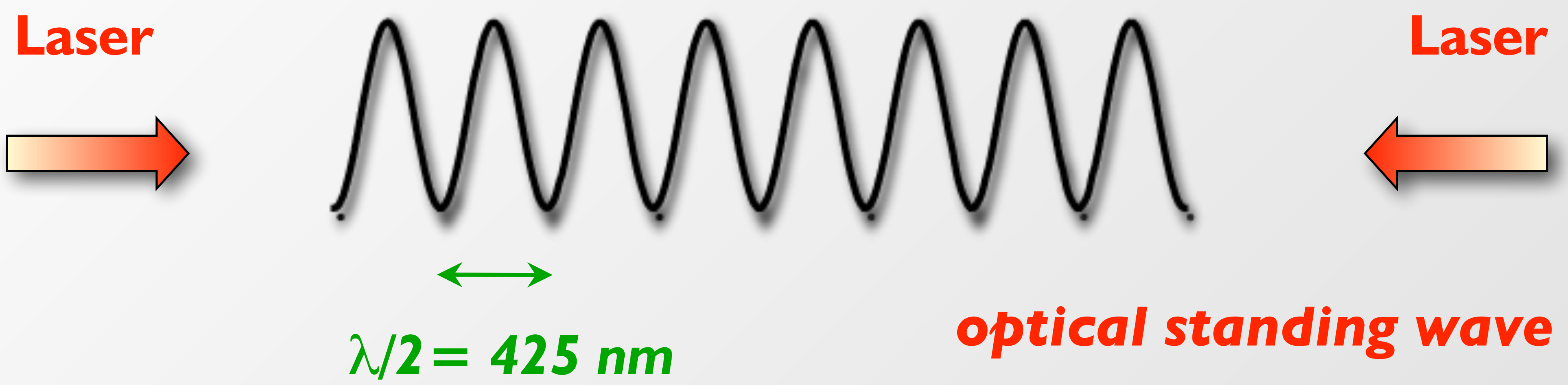



We need a lot of optics!

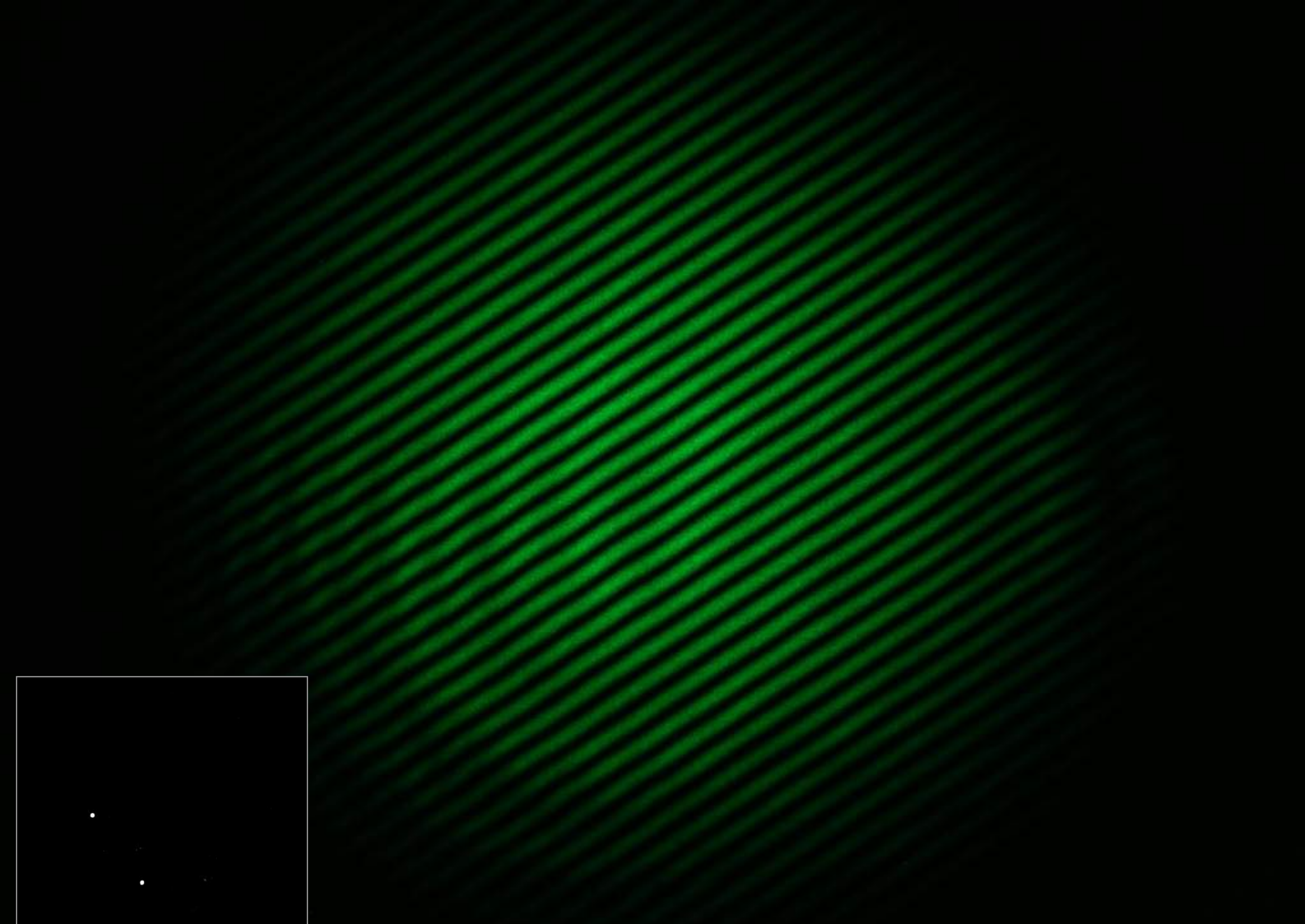



x10000

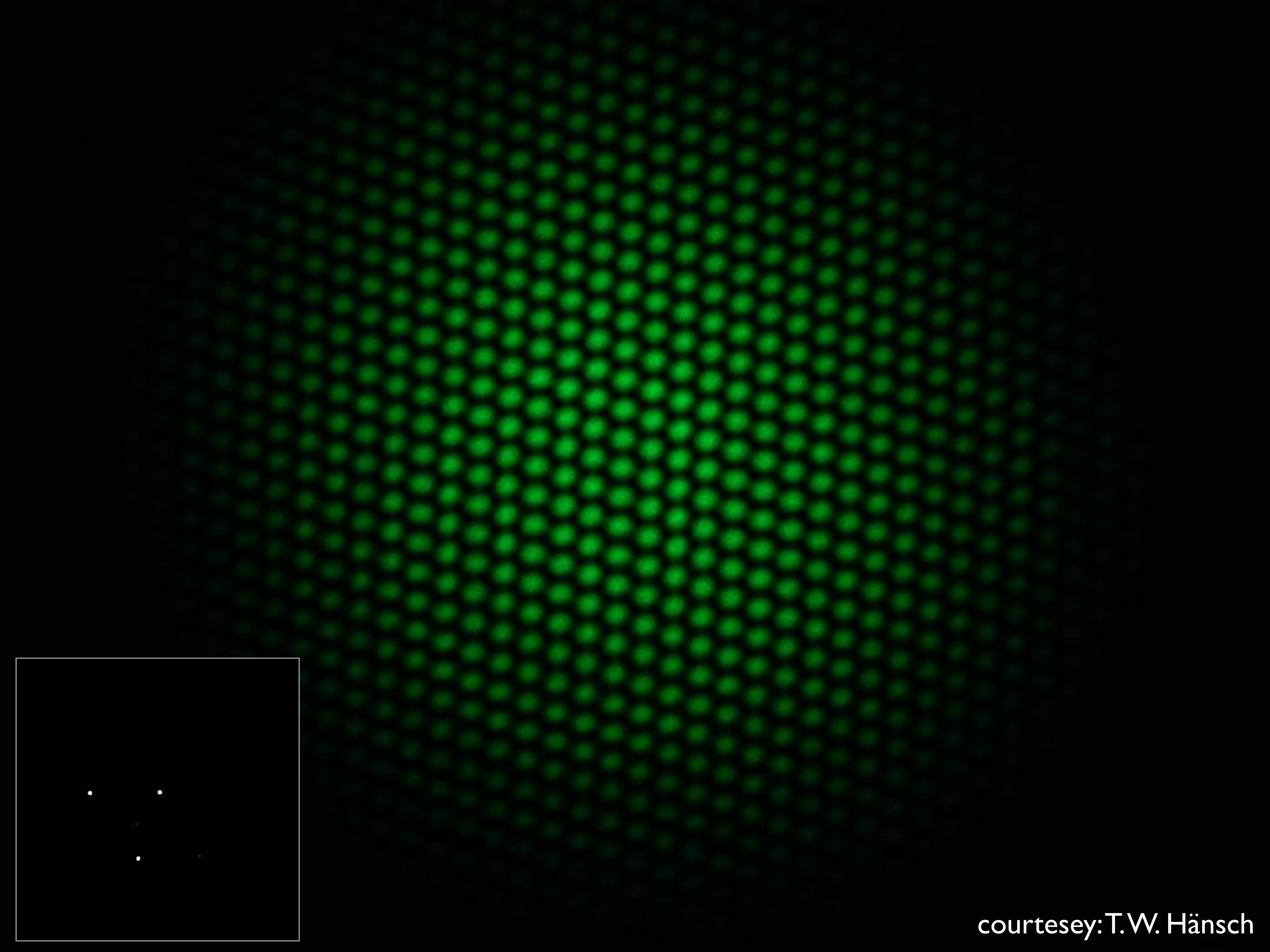
Optical Lattice Potential – Perfect Artificial Crystals



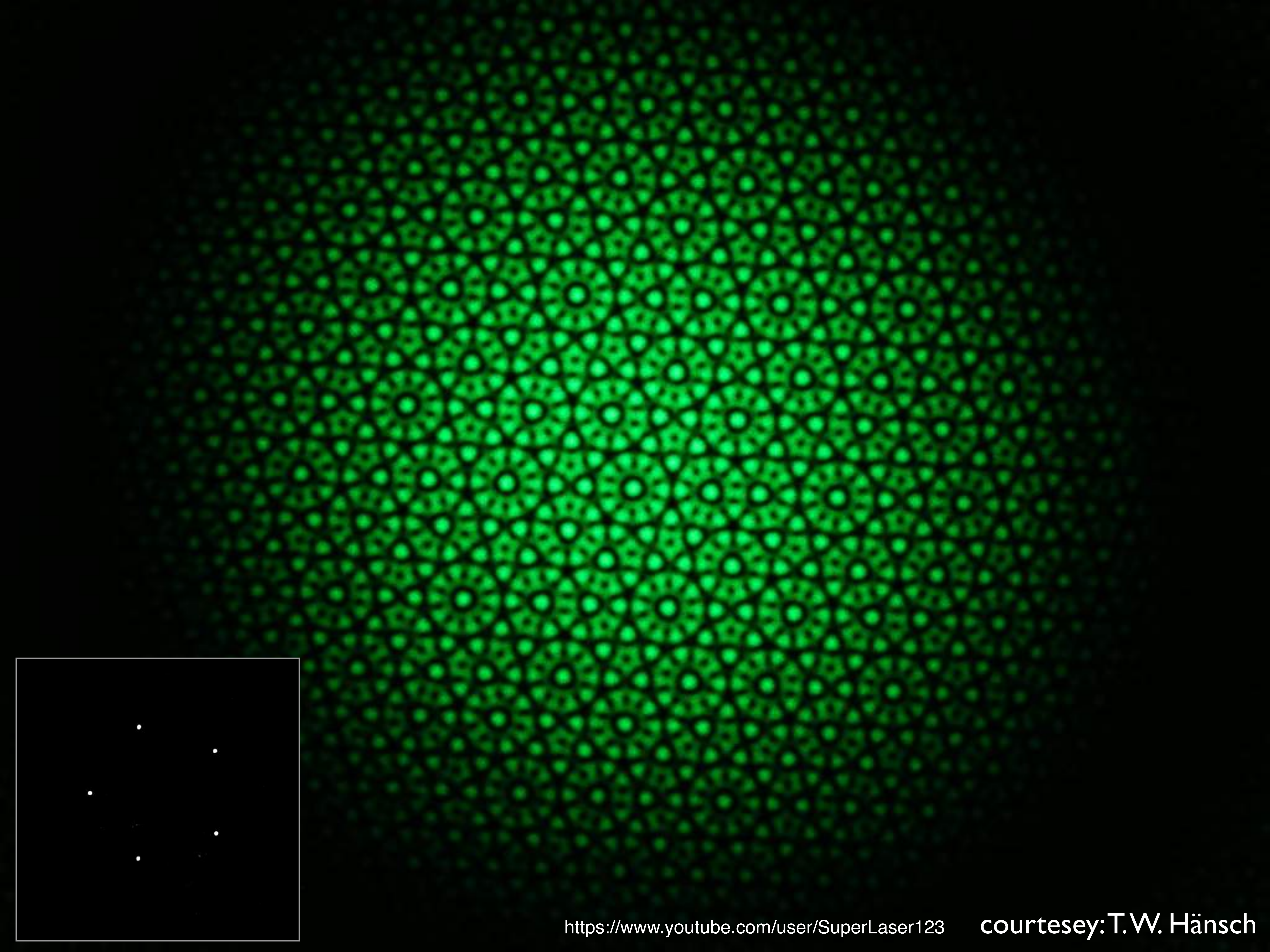
Perfect model systems for a fundamental understanding of quantum many-body systems



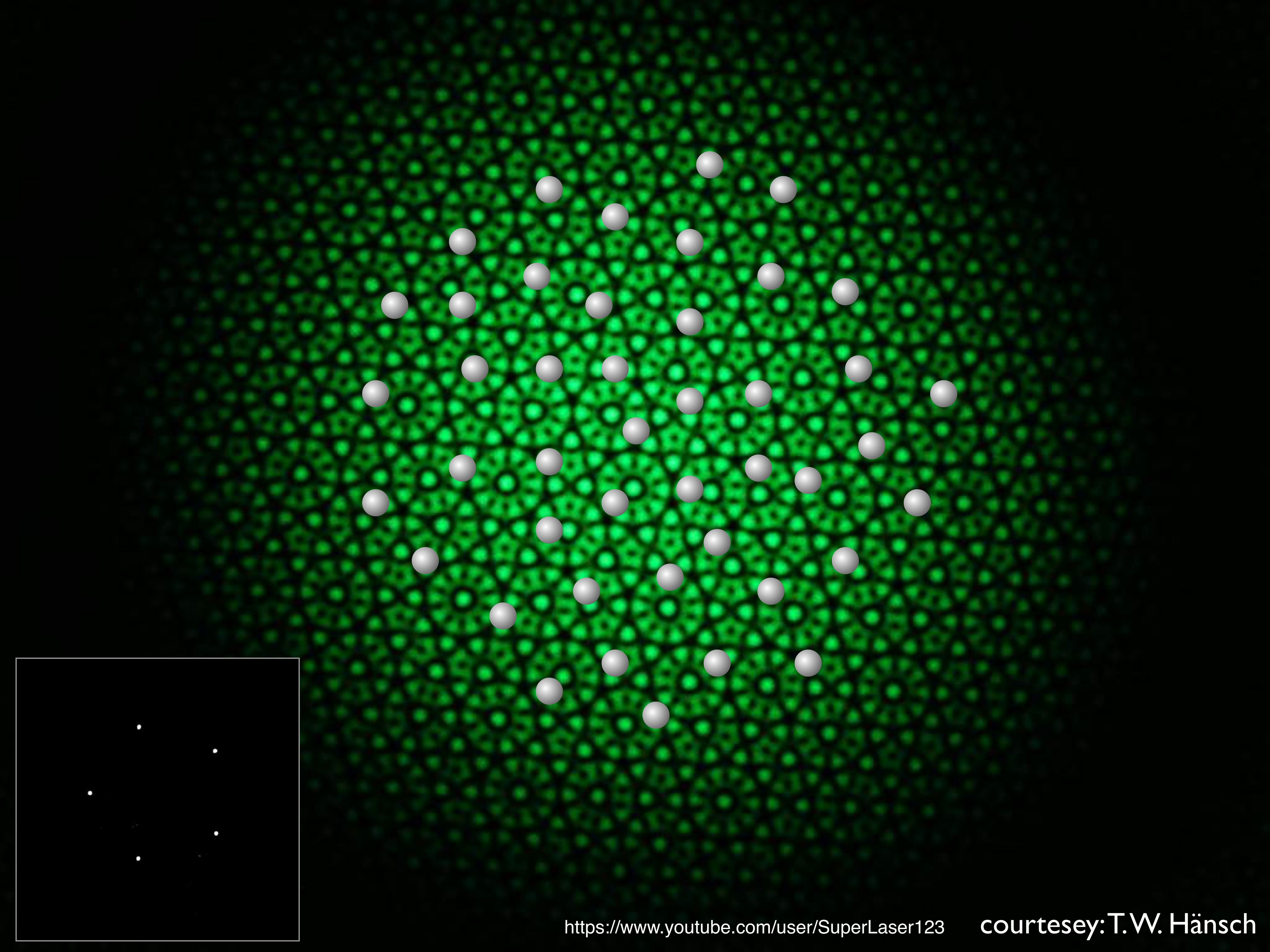
courtesey: T. W. Hänsch

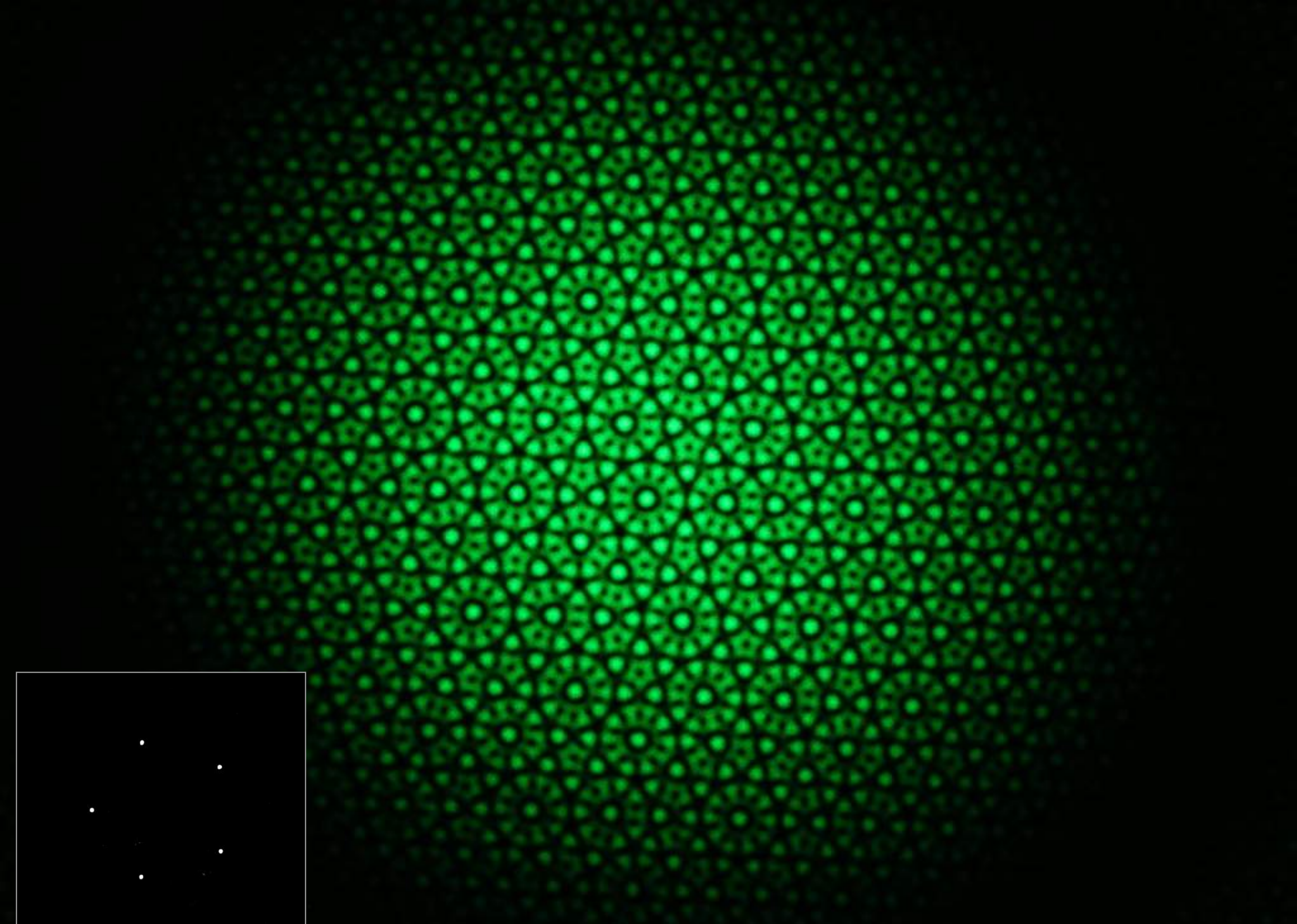


courtesey: T.W. Hänsch



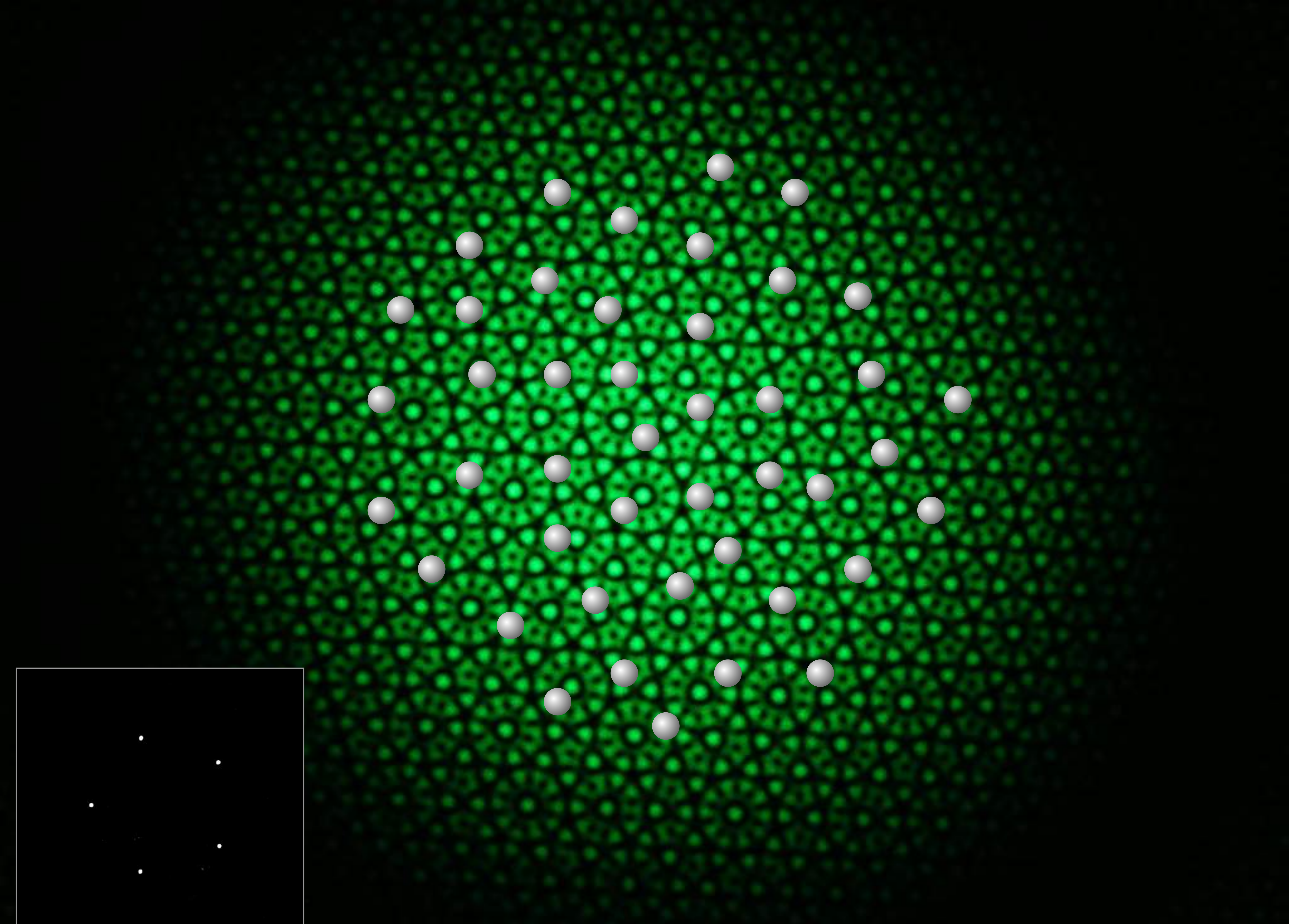
https://www.youtube.com/user/SuperLaser123 courtesey: T. W. Hänsch


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



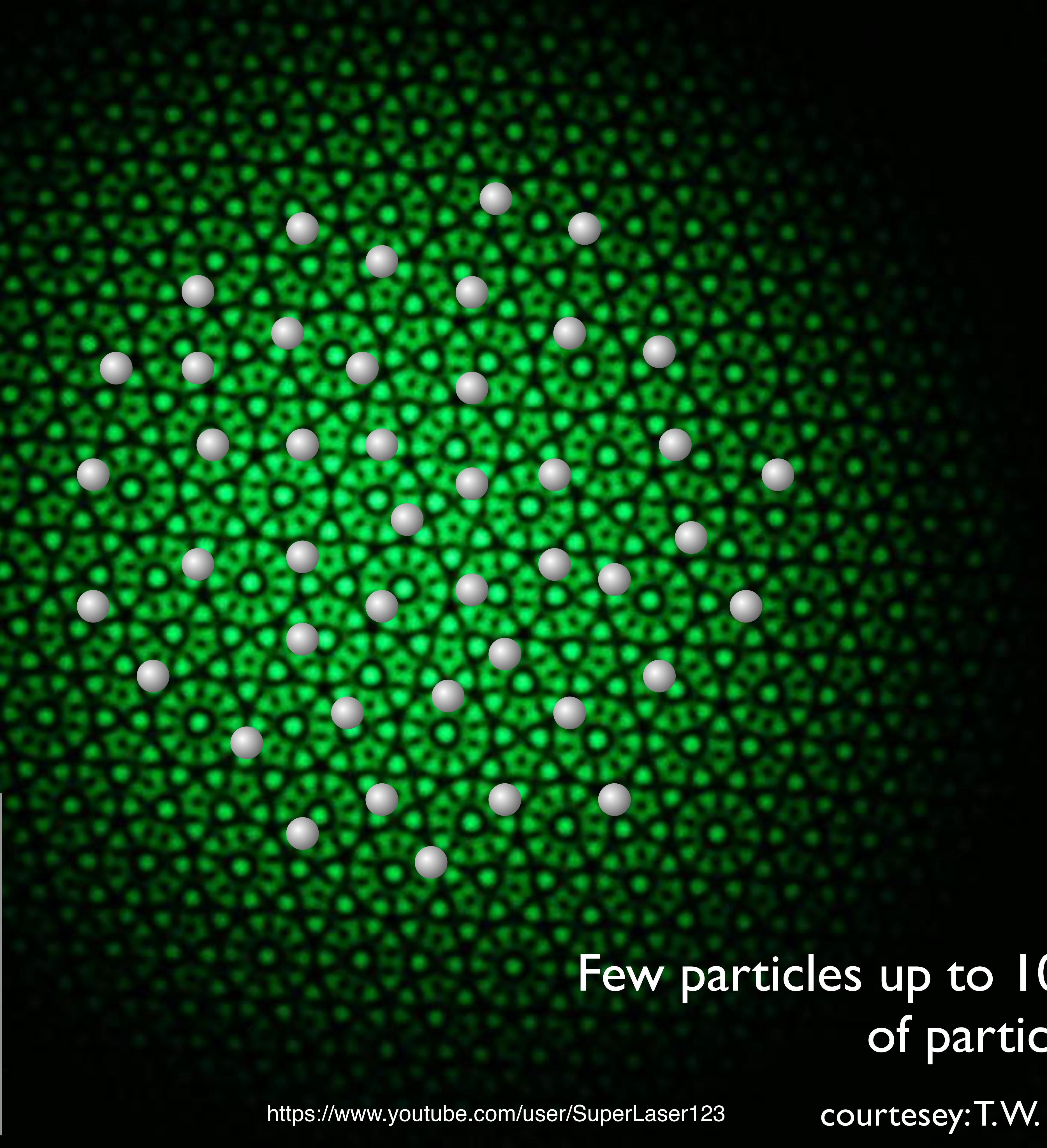
https://www.youtube.com/user/SuperLaser123

courtesey: T. W. Hänsch



https://www.youtube.com/user/SuperLaser123

courtesey: T.W. Hänsch



Few particles up to 1000s of particles !

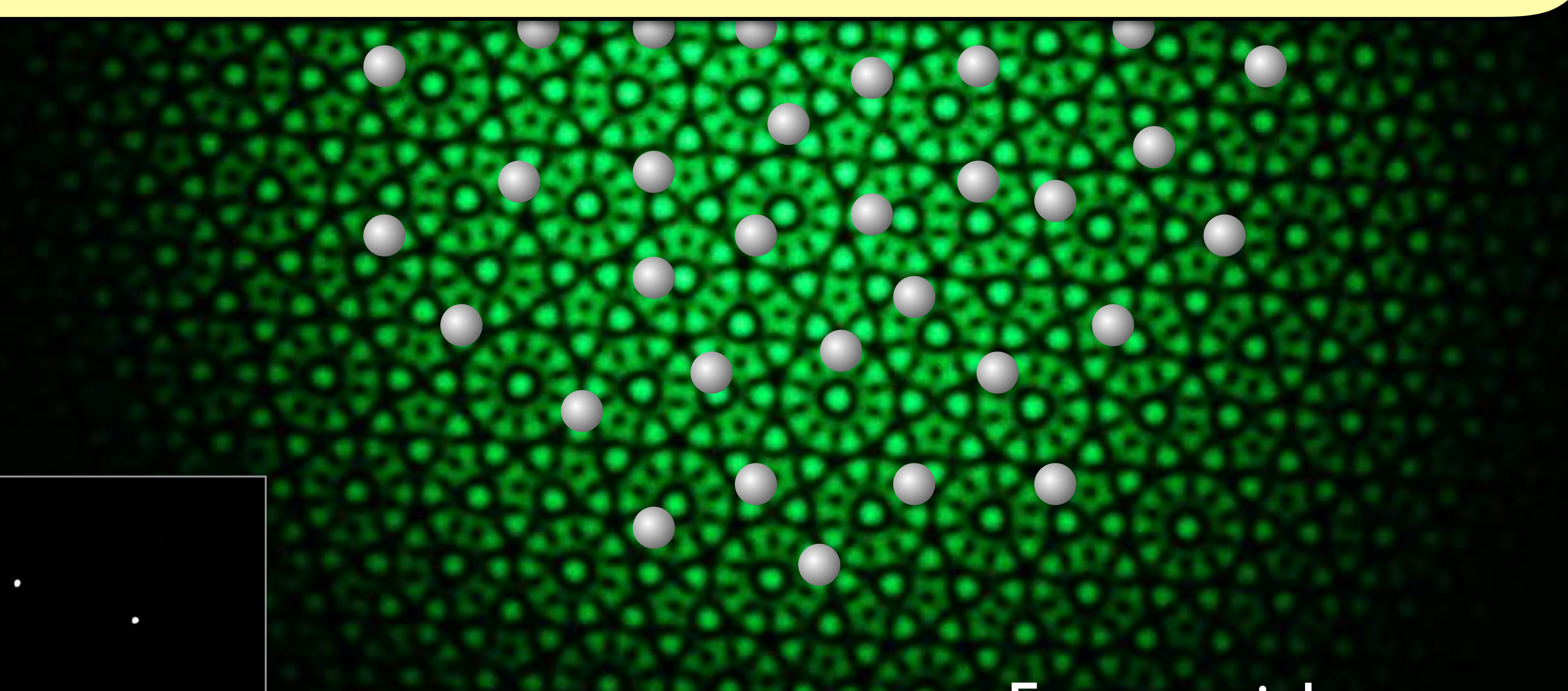
https://www.youtube.com/user/SuperLaser123

courtesey: T.W. Hänsch

Quantum Spin Systems

Particle Systems: Bosons, Fermions, Mixtures

Classically Intractable Computational Regimes



Few particles up to 1000s of particles !

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courtesey: T.W. Hänsch

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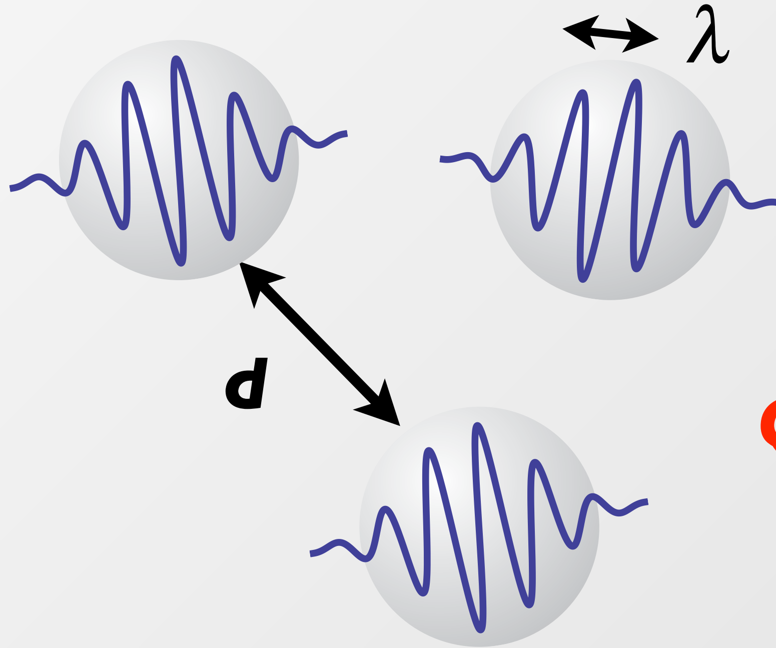
From Artificial Quantum Matter to Real Materials

Quantum Regime

$$\lambda/d \gtrsim 1$$



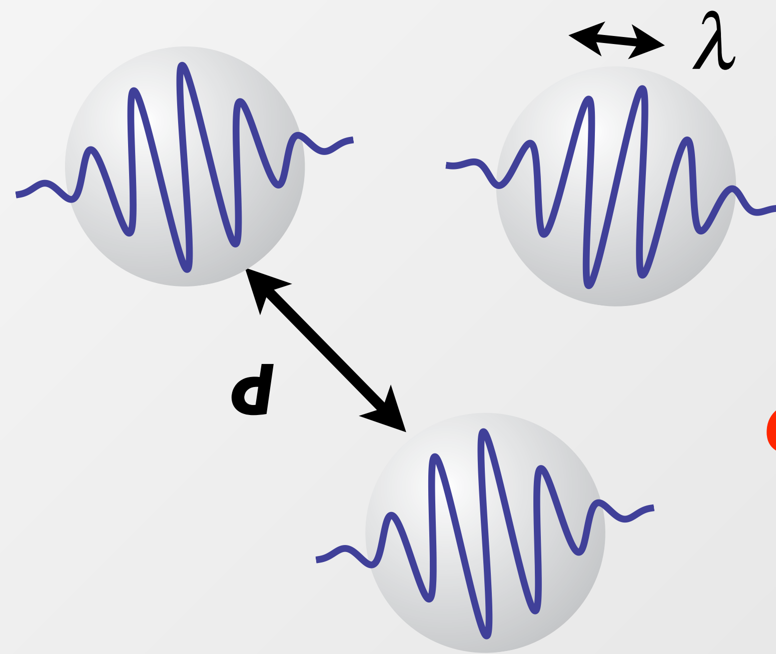
de Broglie Wavepackets

Universality of Quantum Mechanics!

From Artificial Quantum Matter to Real Materials

Quantum Regime

$$\lambda/d \gtrsim 1$$

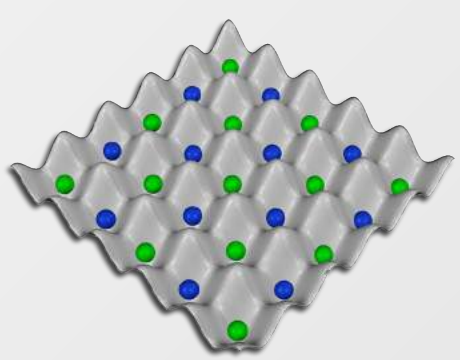


de Broglie Wavepackets

Universality of Quantum Mechanics!

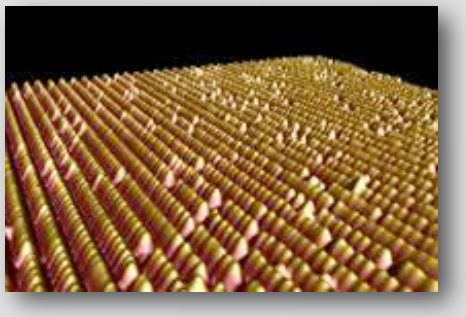
Ultracold Quantum Matter

- ***Densities:*** ***$10^{14}/cm^3$***
  (100000 times thinner than air)
- ***Temperatures:*** ***few nK***
  (100 million times lower than outer space)



Real Materials

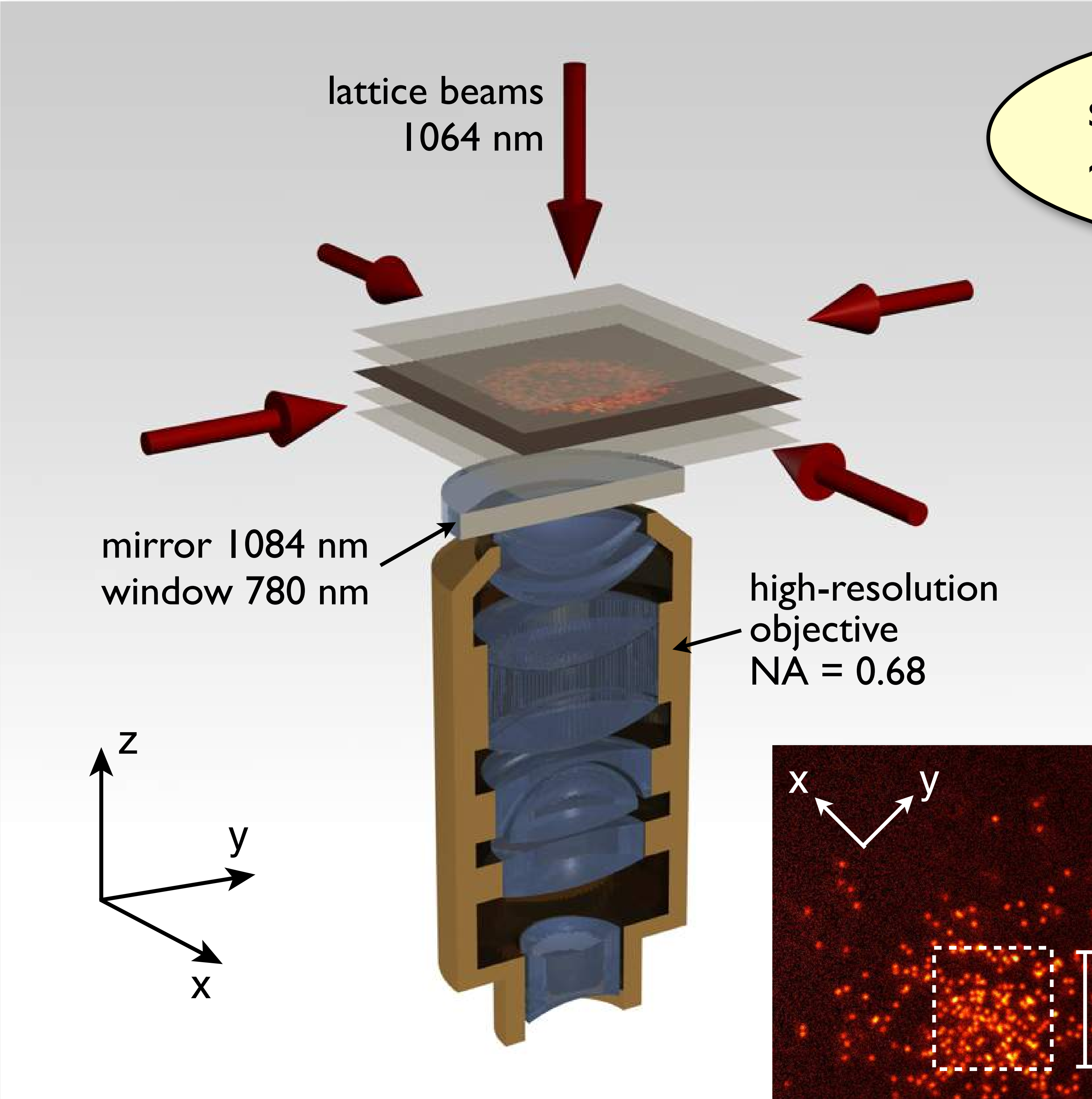
- ***Densities:*** ***10^{24}-$10^{25}/cm^3$***
- ***Temperatures:*** ***mK – several hundred K***



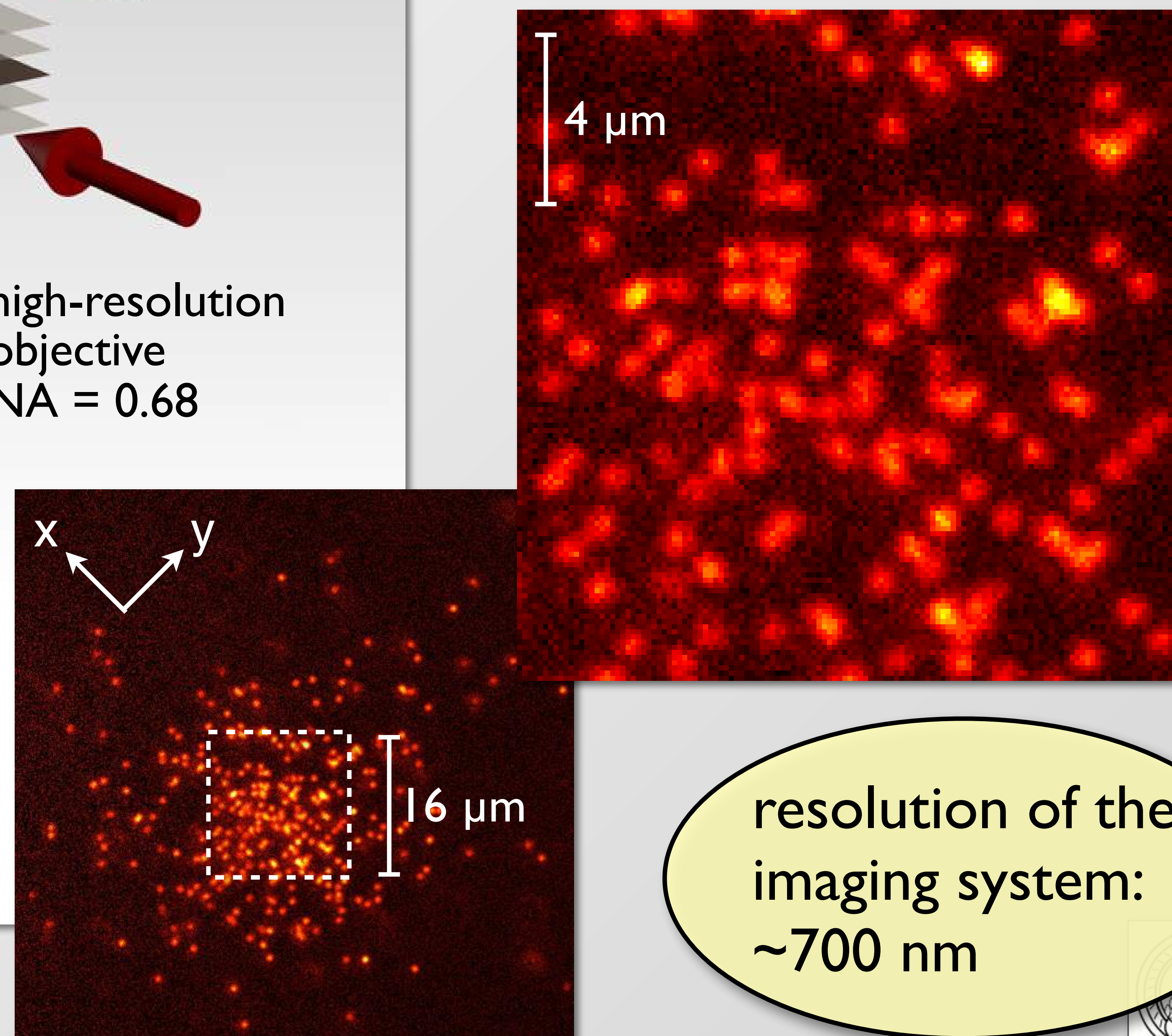
(Neuchatel)

Same λ/d !

Seeing Single Atoms

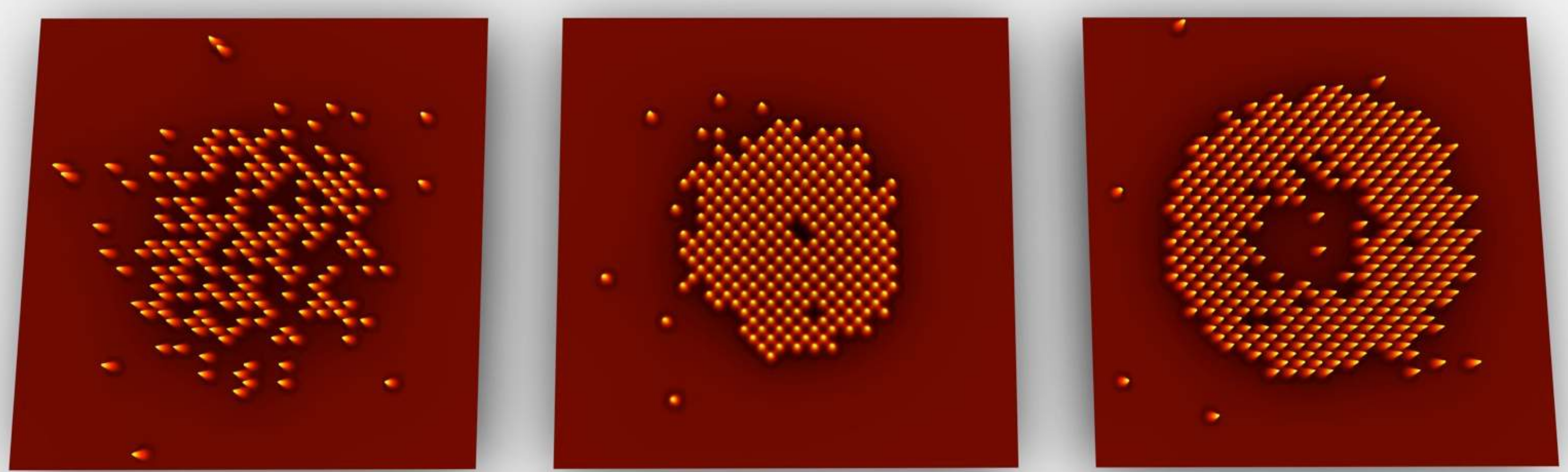


single 2D degenerate gas
~ 1000 ^{87}Rb atoms (bosons)



resolution of the imaging system: ~700 nm

Snapshot of an Atomic Density Distribution



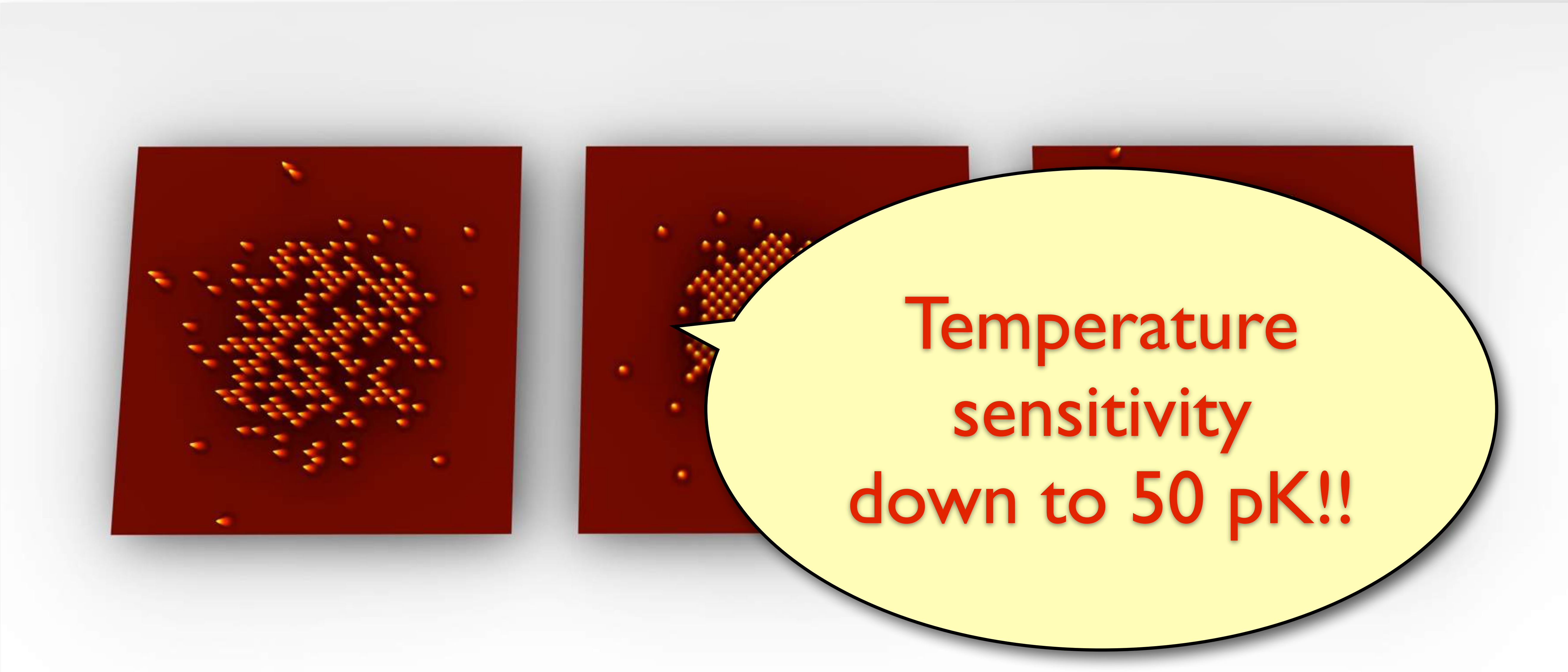
BEC

n=1
Mott Insulator

n=1 & n=2
Mott Insulator

M. Greiner *et al.* Nature 415, 39 (2002),
J. Sherson *et al.* Nature **467**, 68 (2010), W. Bakr *et al.* Science **329**, 547 (2010)
Cold atom prediction: D. Jaksch *et al.* **81**, 3108 (1998)

Snapshot of an Atomic Density Distribution



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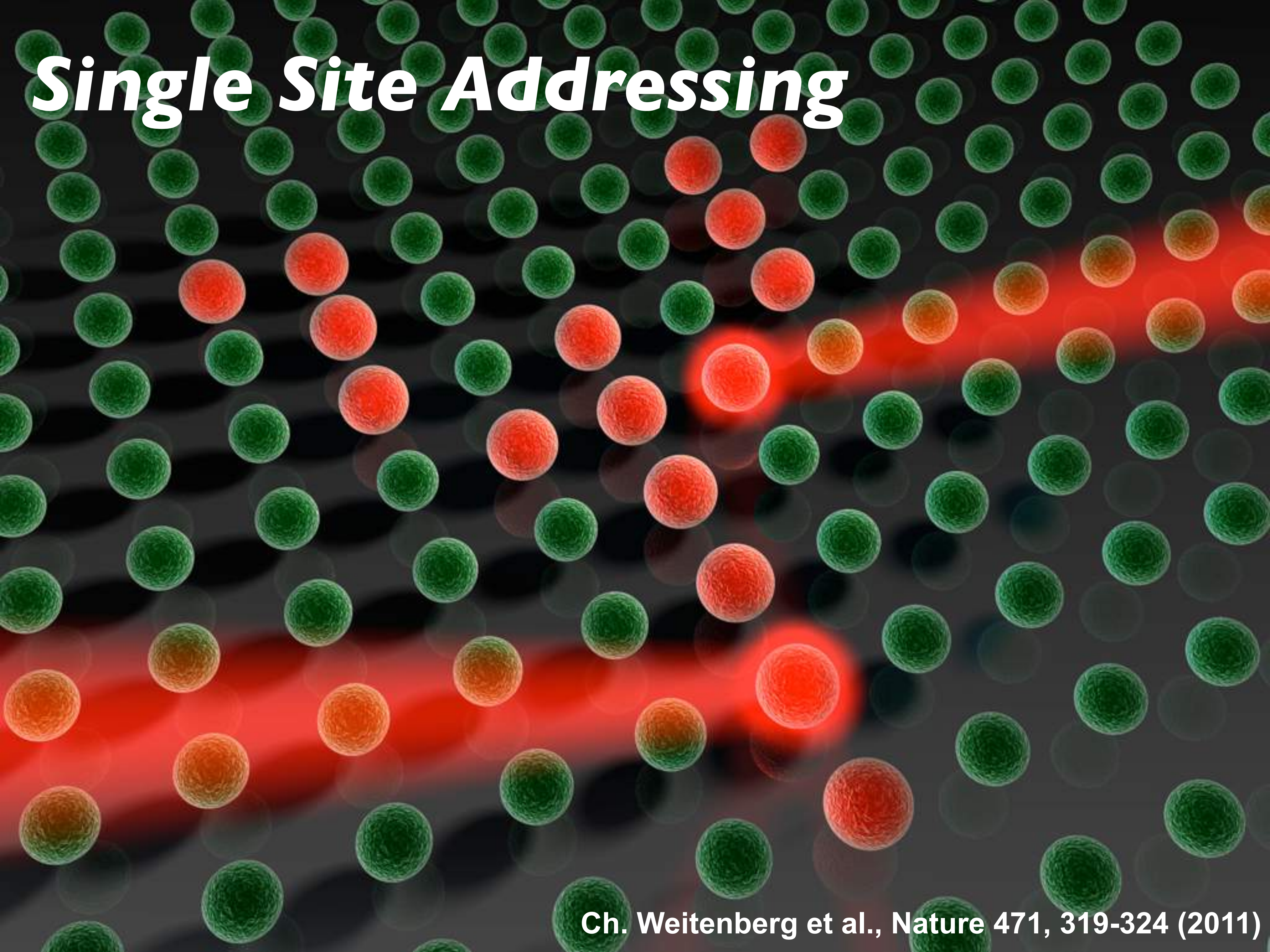
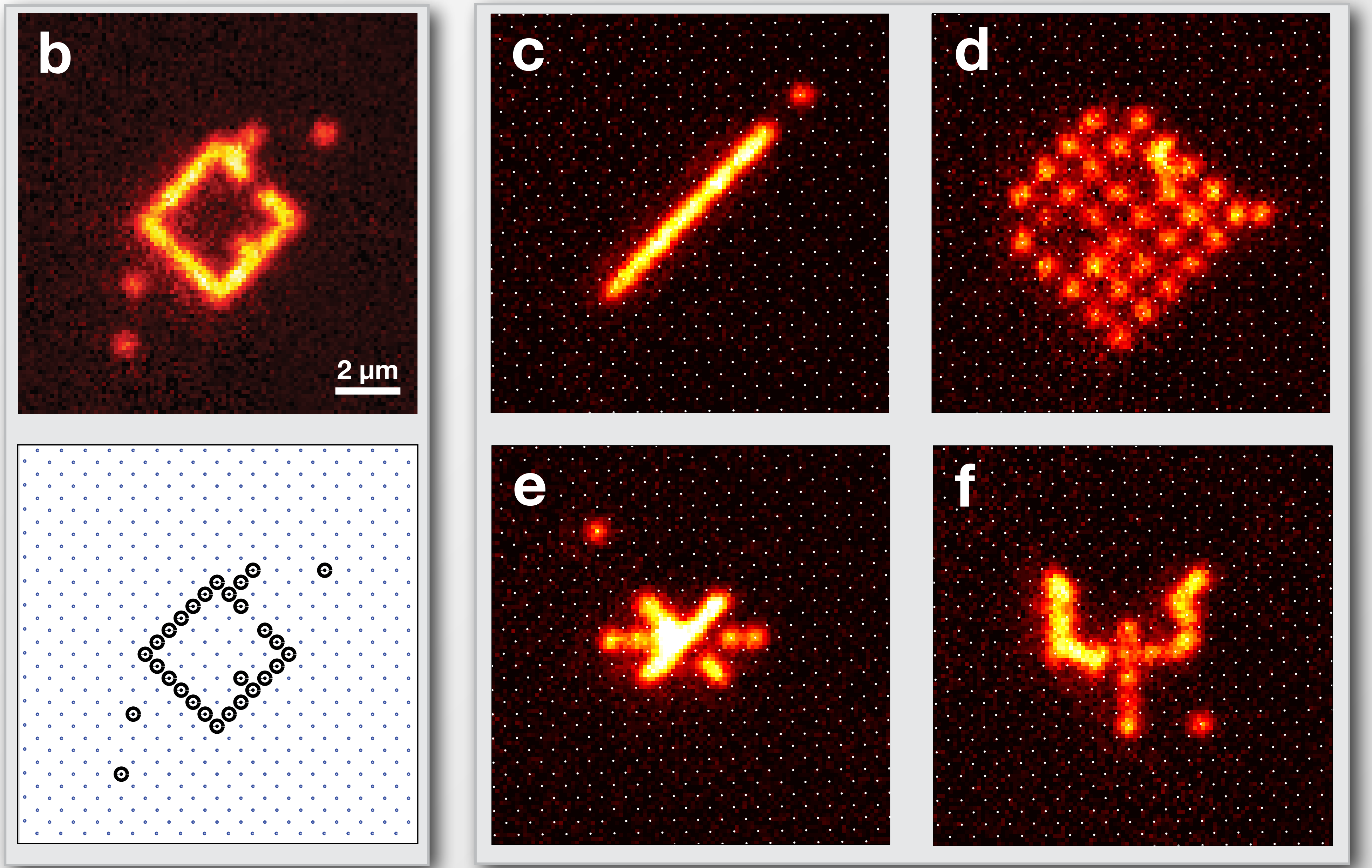
M. Greiner *et al.* Nature 415, 39 (2002),
J. Sherson *et al.* Nature **467**, 68 (2010), W. Bakr *et al.* Science **329**, 547 (2010)
Cold atom prediction: D. Jaksch *et al.* **81**, 3108 (1998)

Single Site Addressing



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

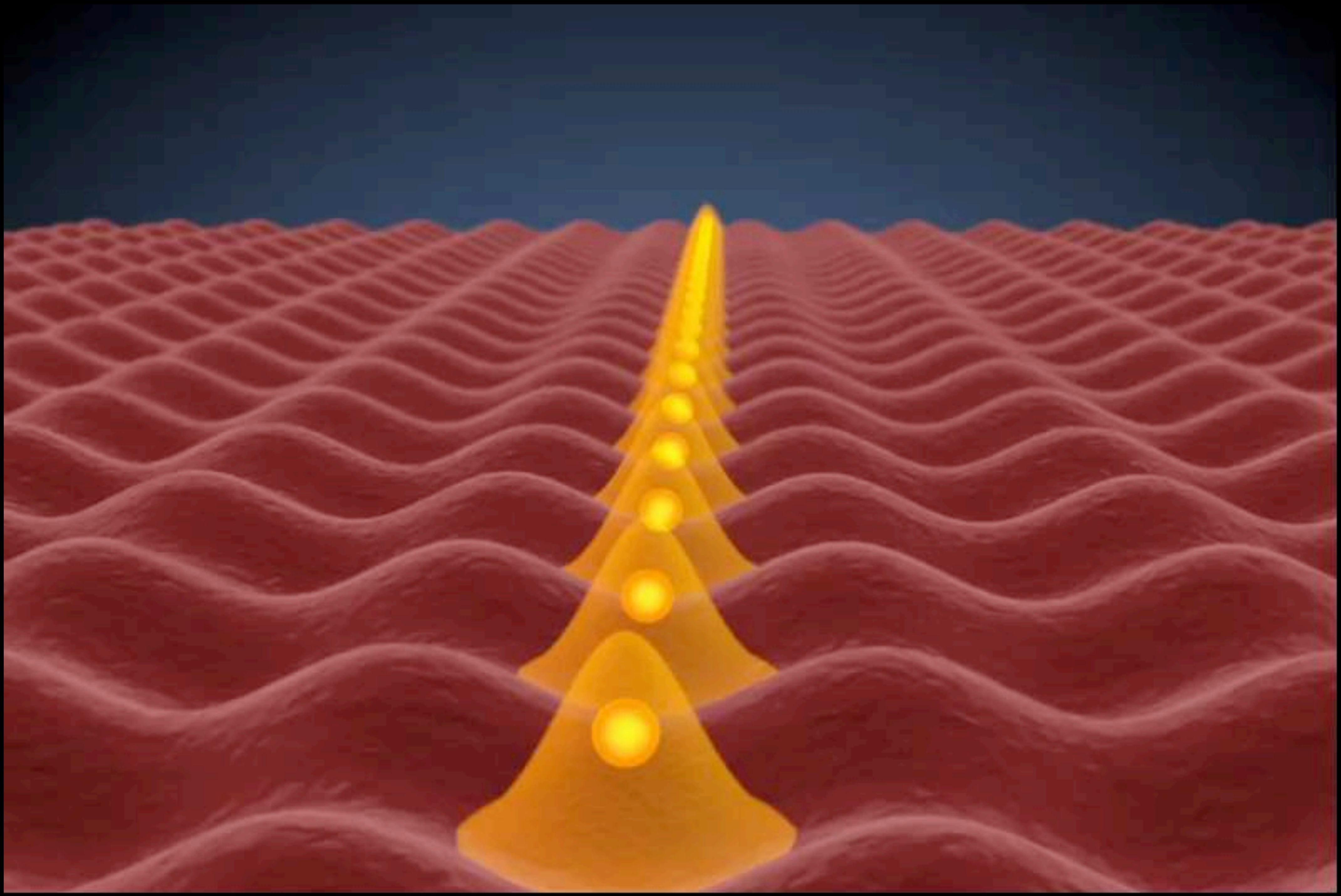
Coherent Spin Flips - Positive Imaging



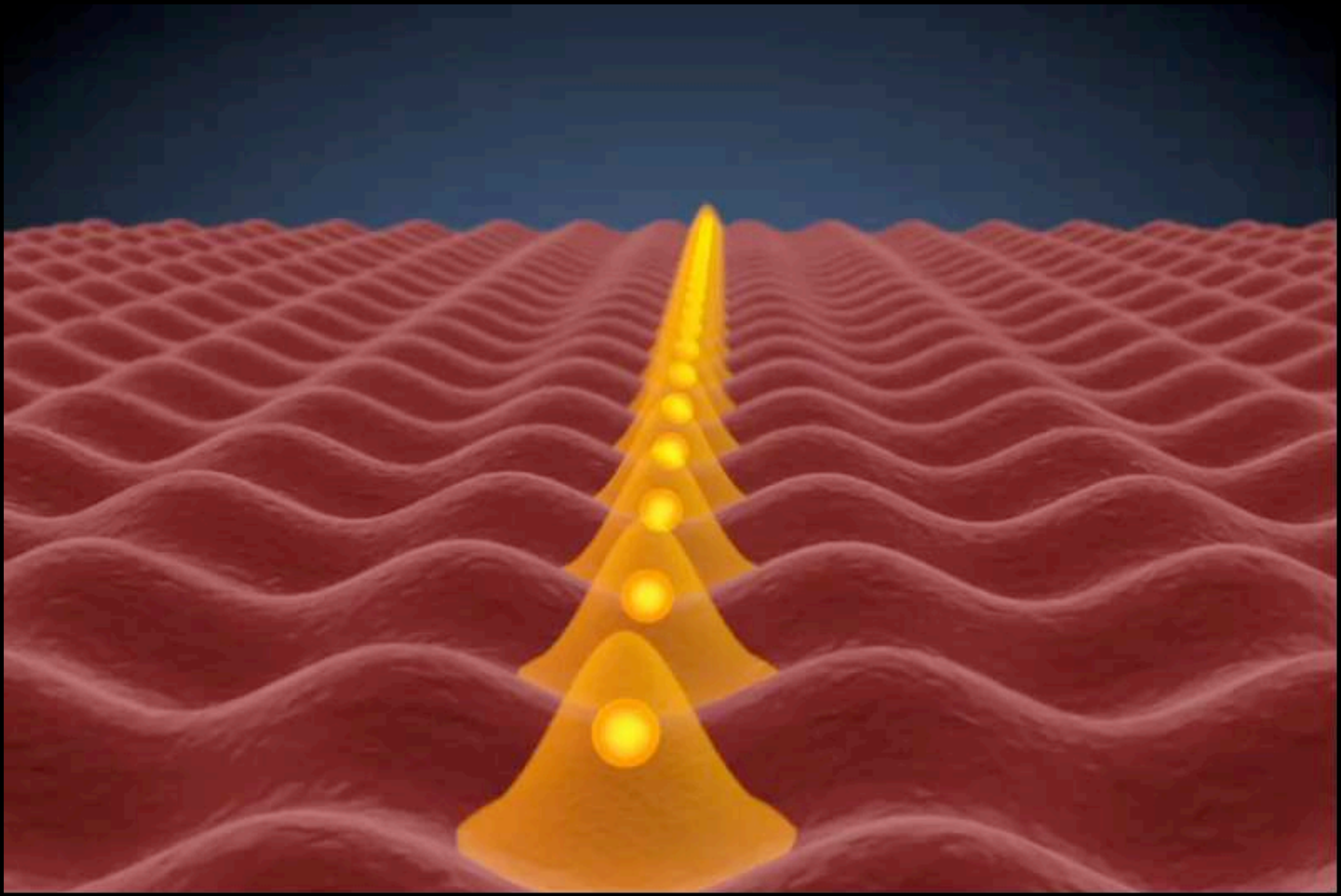
Subwavelength spatial resolution: 50 nm

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

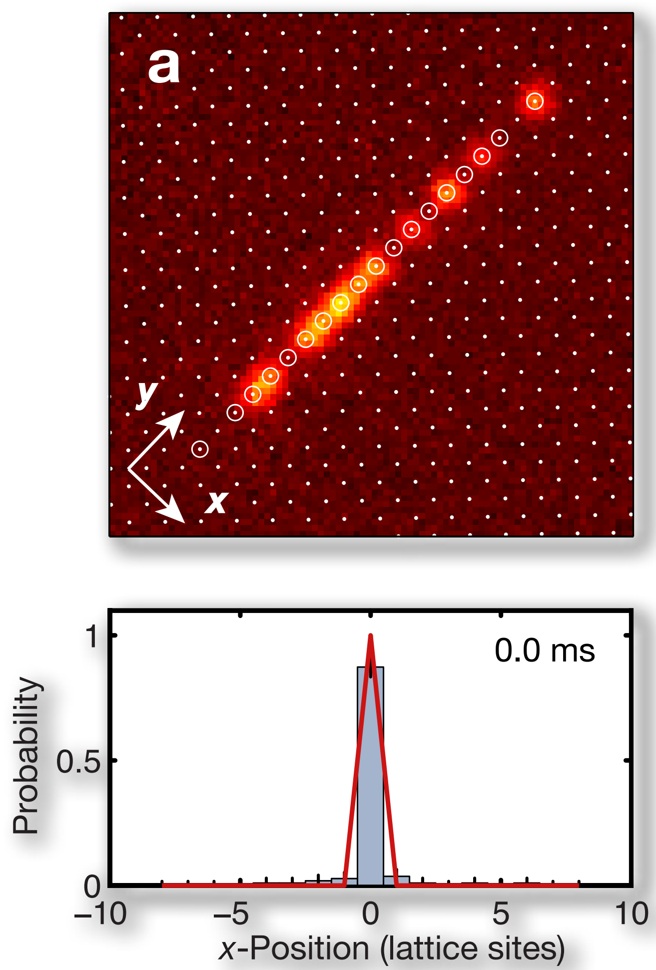
Single Atom Tunneling



Single Atom Tunneling

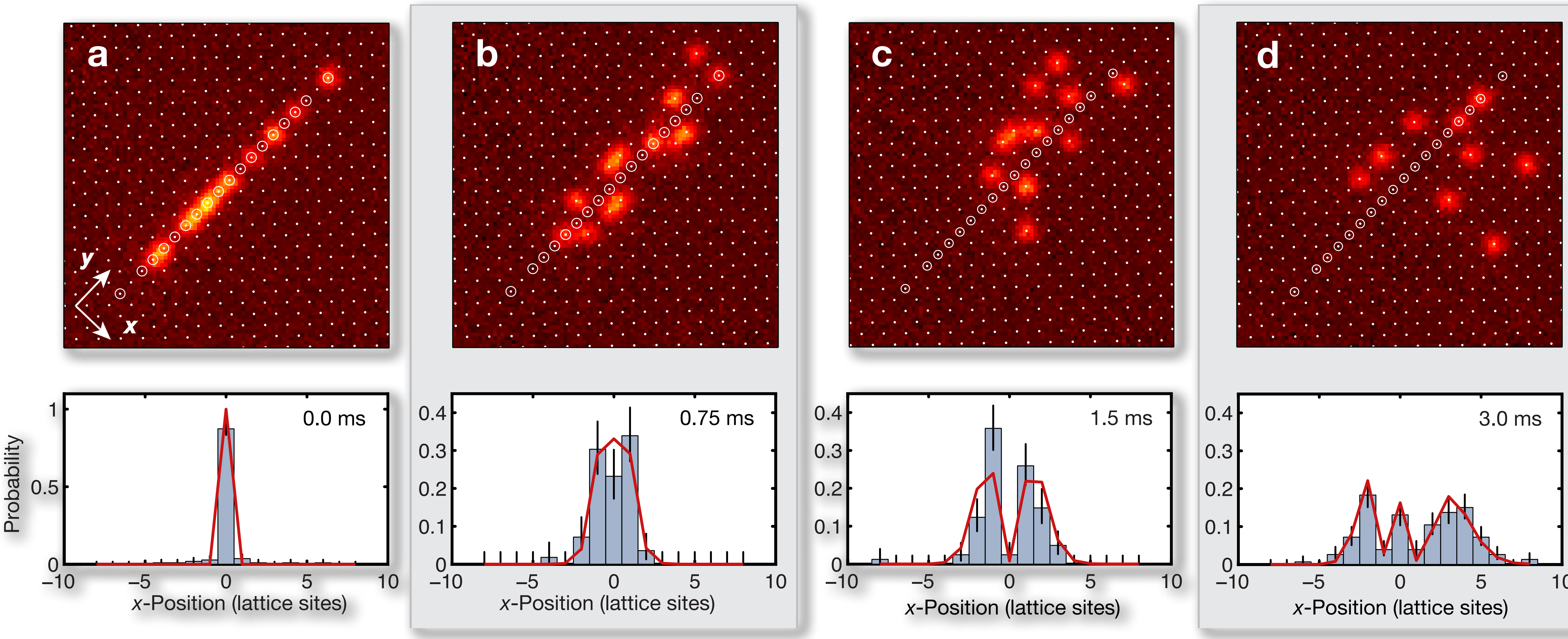


Motional State Affected?



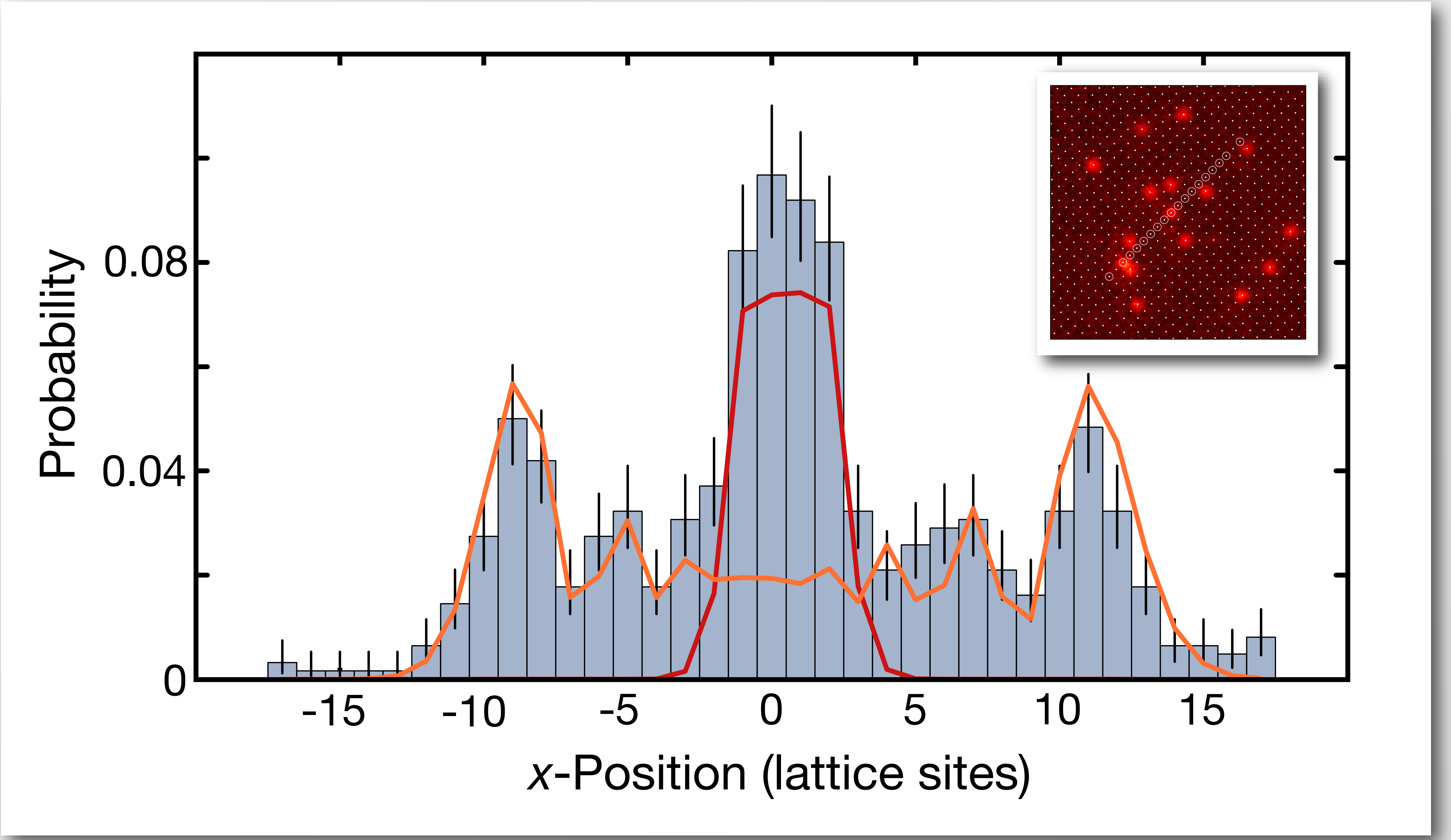
see exp: Y. Silberberg (photonic waveguides), D. Meschede & R. Blatt (quantum walks)...

Motional State Affected?



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

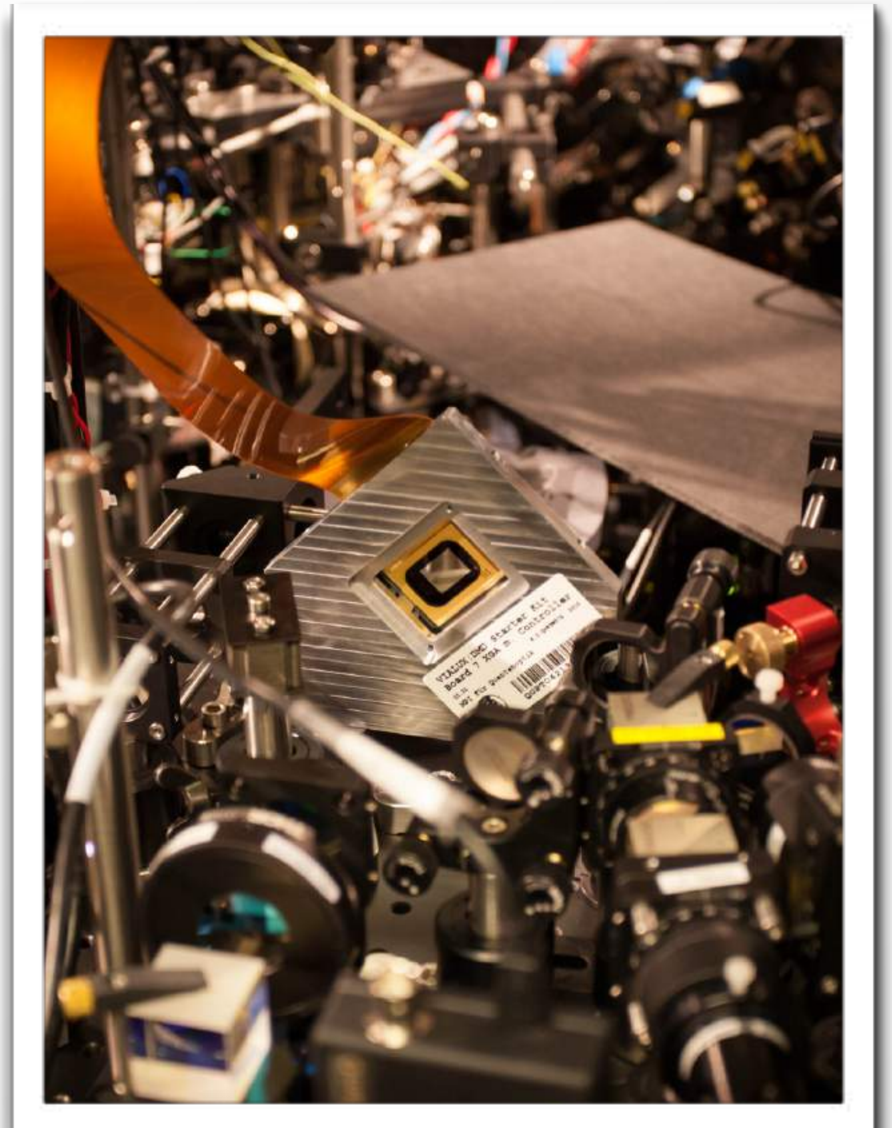
Higher Band Tunneling



Excellent agreement with simulation.

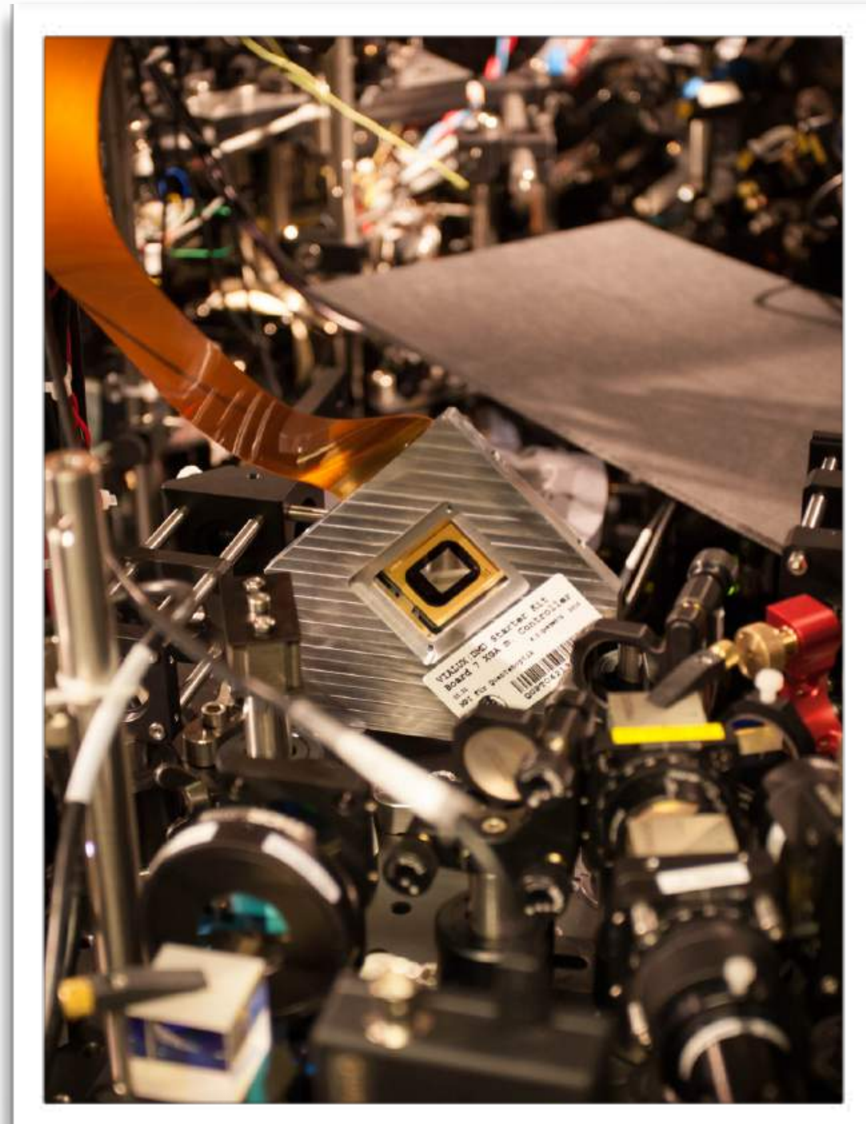
Interesting extension: Quantum walks of correlated atoms/spins...

Arbitrary Light Patterns

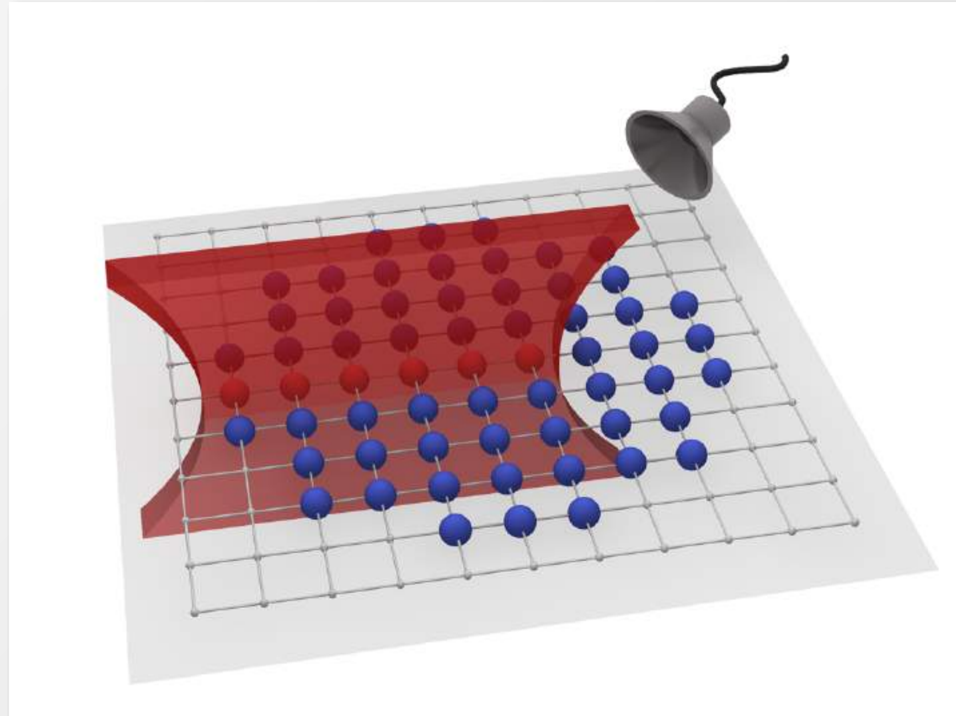


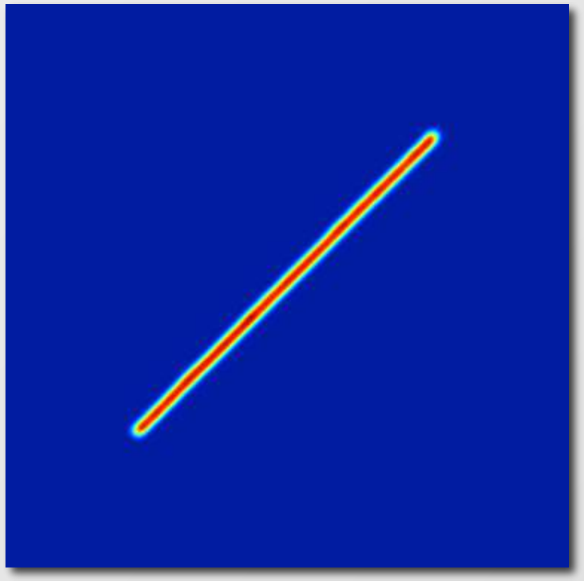
Digital Mirror Device
(DMD)

Arbitrary Light Patterns



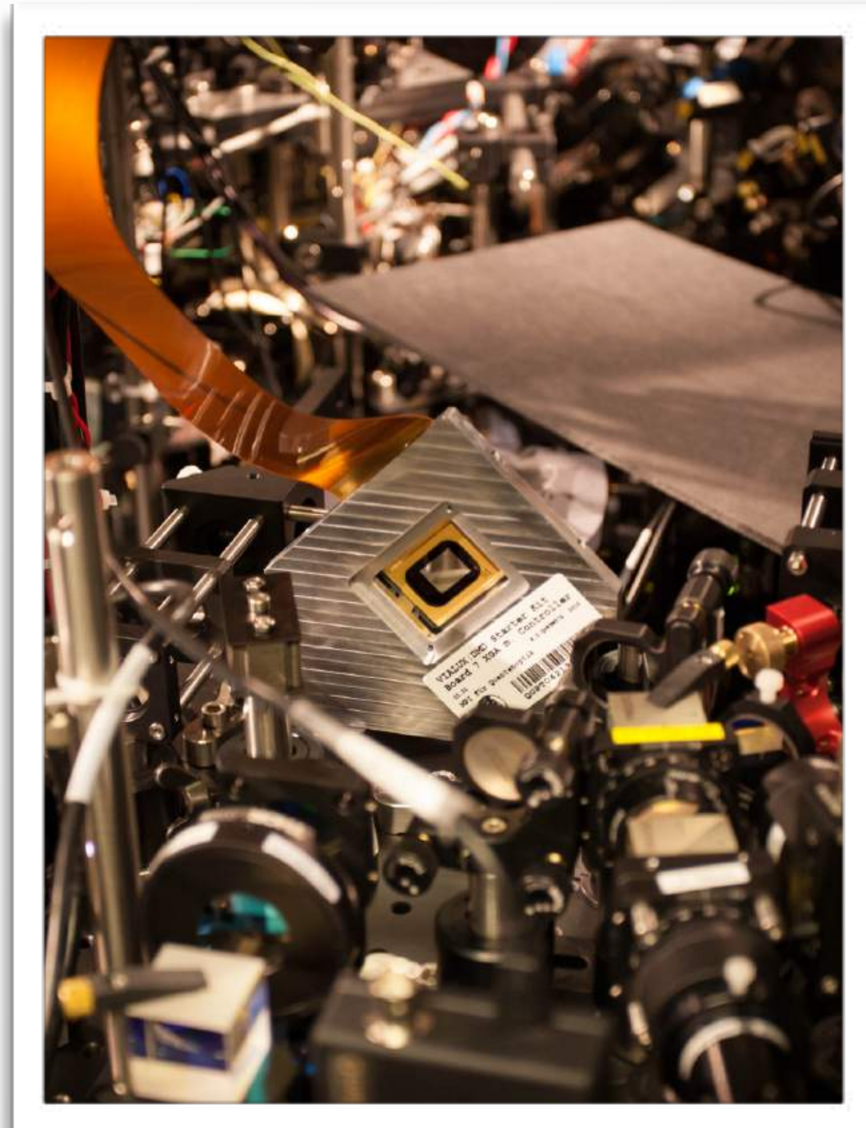
Digital Mirror Device
(DMD)



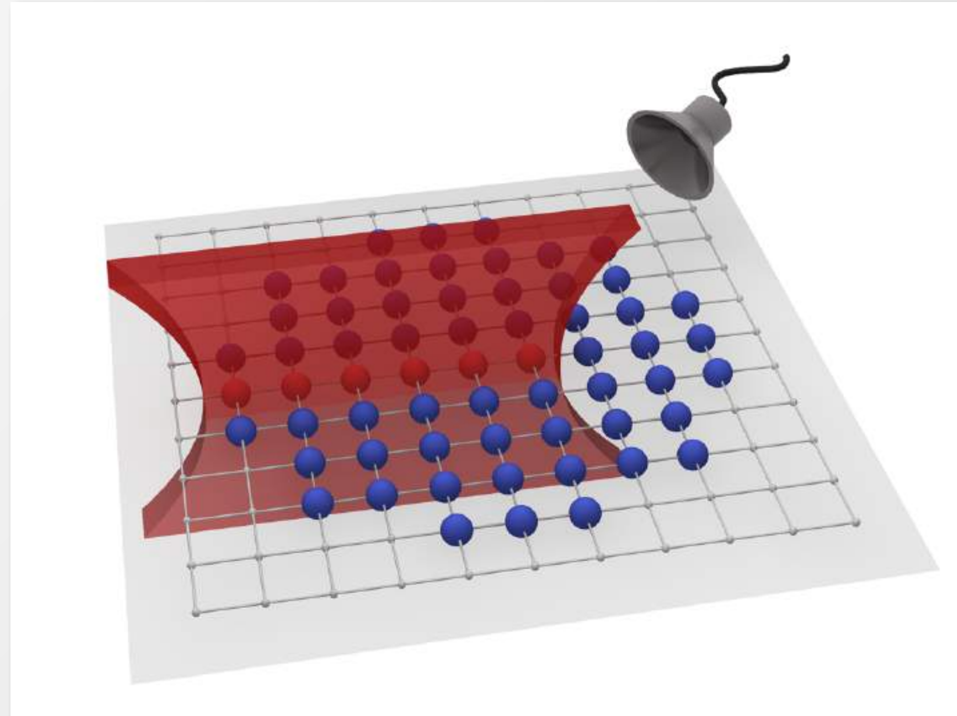


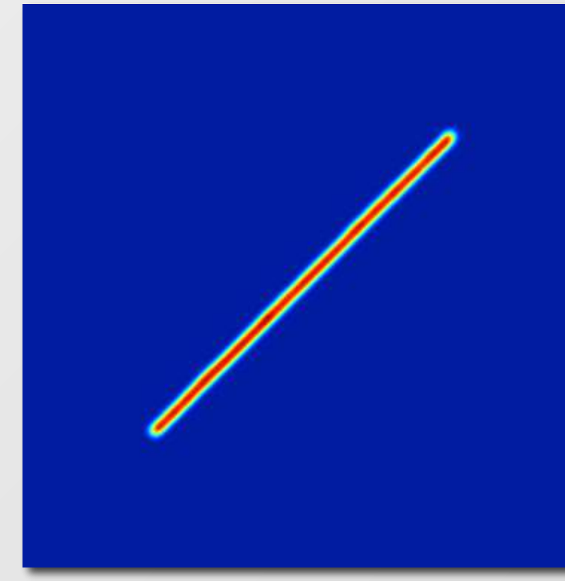
Measured Light Pattern

Arbitrary Light Patterns

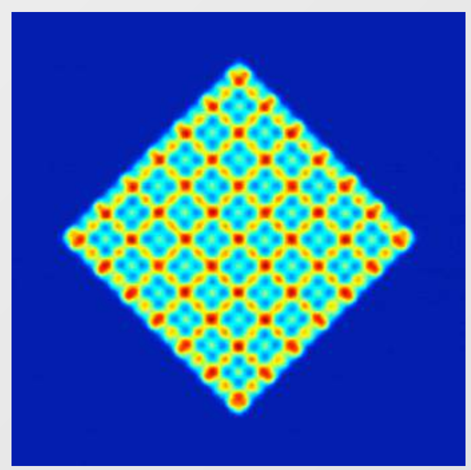


Digital Mirror Device (DMD)

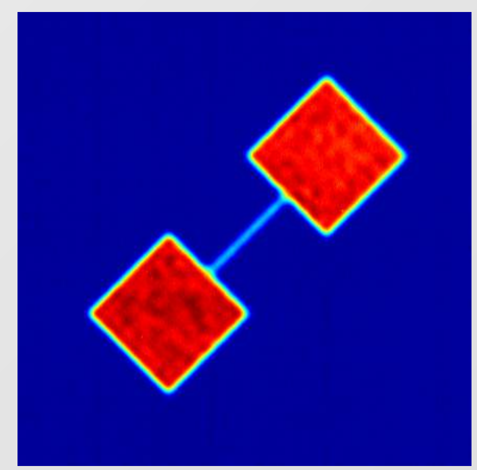




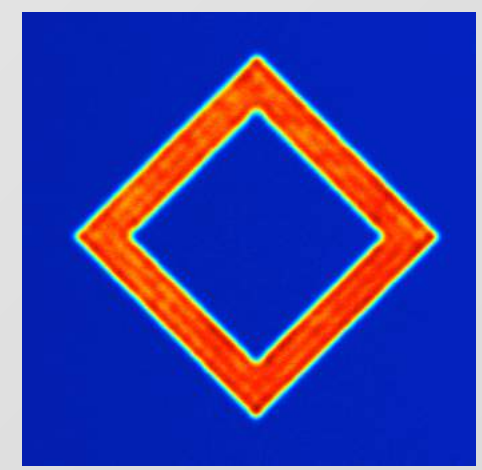
Measured Light Pattern



Exotic Lattices



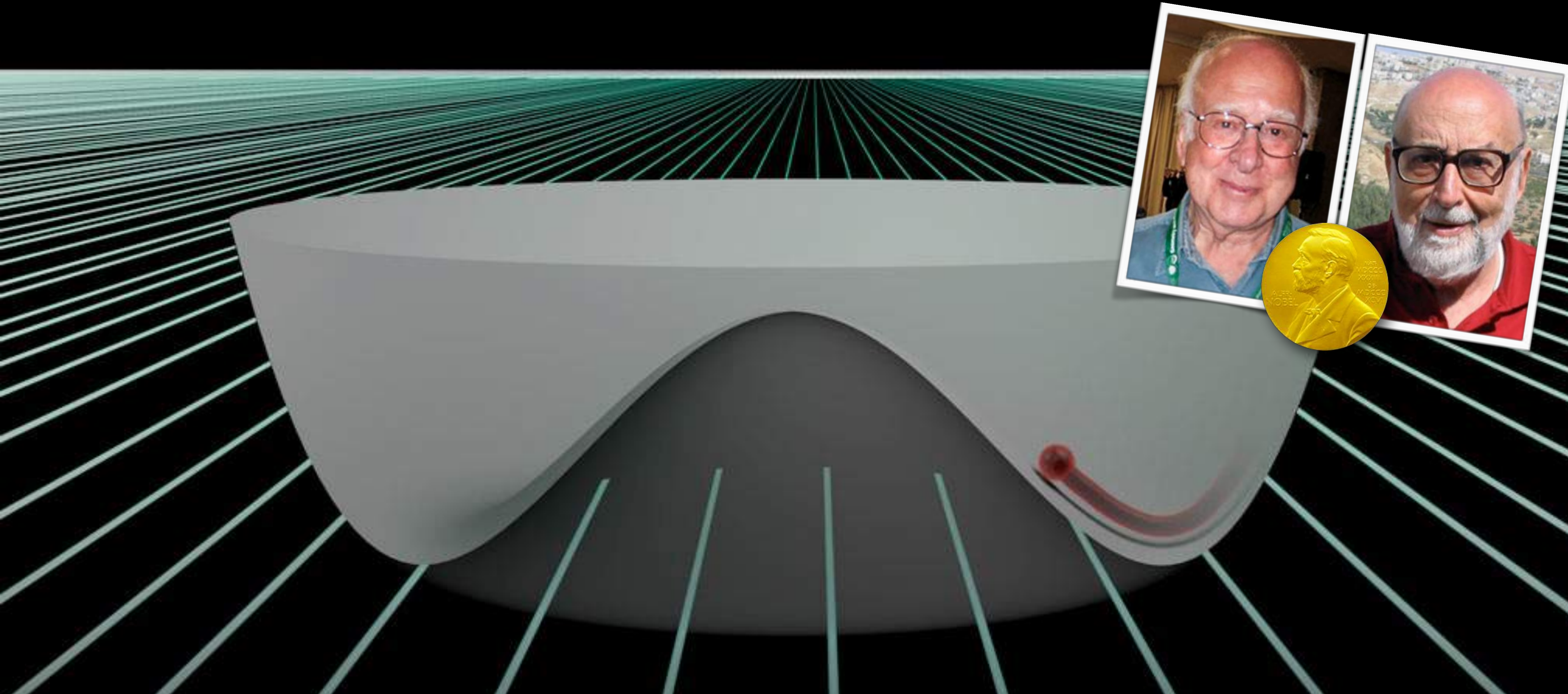
Quantum Wires



Box Potentials

Almost Arbitrary Light Patterns Possible!

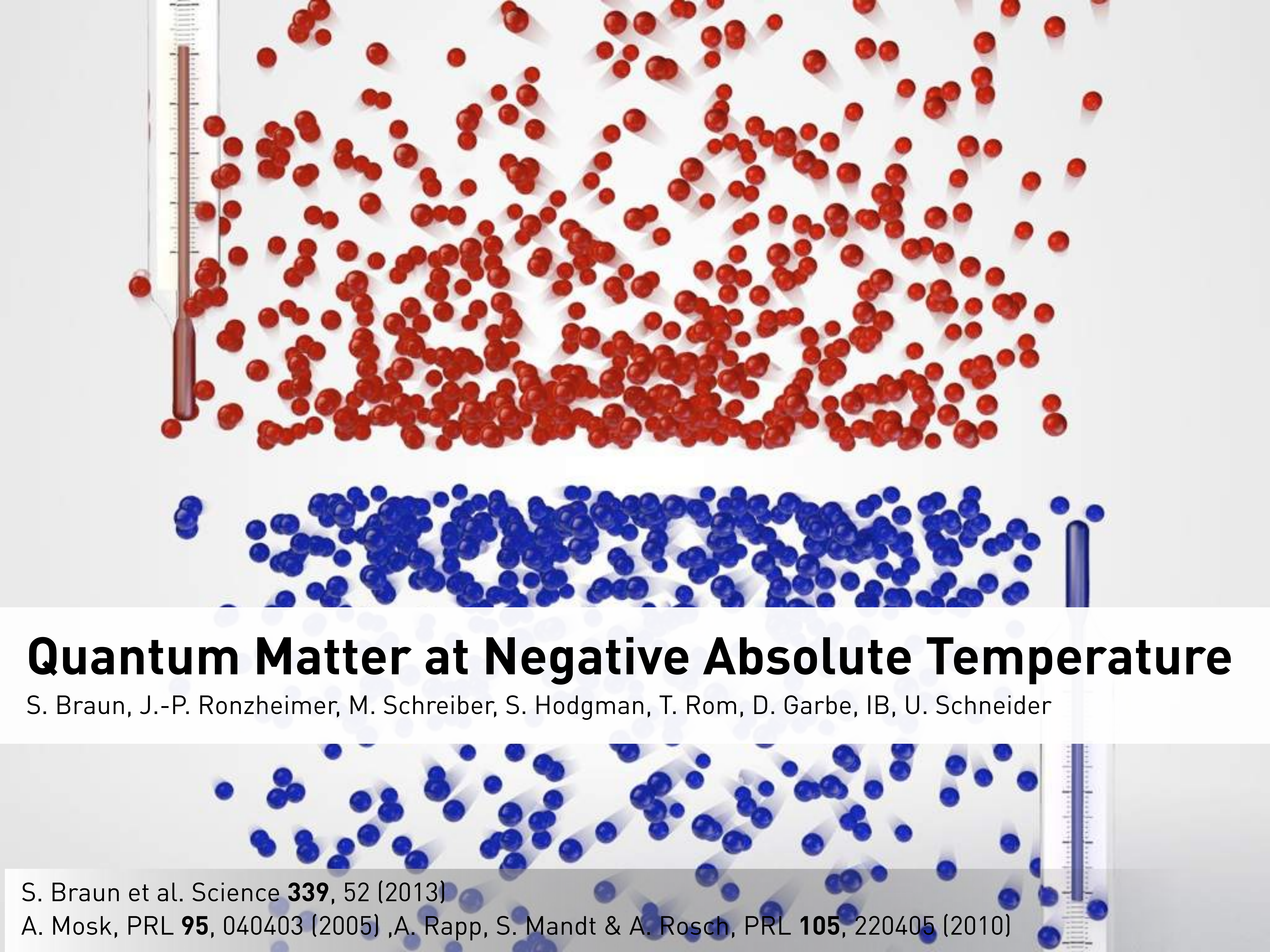
Single Spin Impurity Dynamics, Domain Walls, Quantum Wires, Novel Exotic Lattice Geometries, ...



‘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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What Does "Negative Temperature" Mean, Anyway?
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THE COLLAPSE WAVEFUN
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has an article entitled "N
potassium ions th
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erature of
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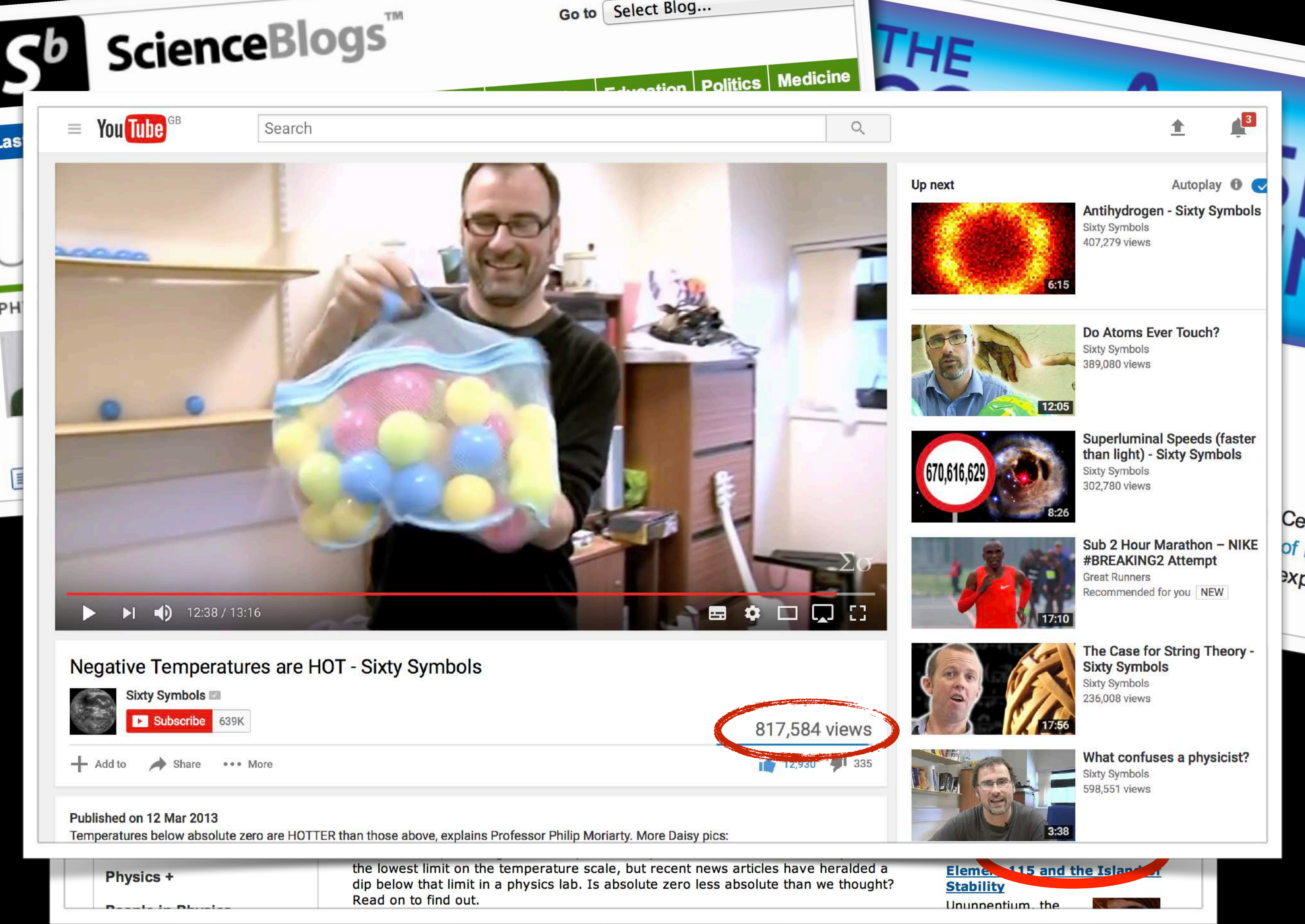
Below Absolute Zero: Negative Temperatures Explained
Absolute zero, or 0 degrees Kelvin, is the temperature where all motion stops. It's the lowest limit on the temperature scale, but recent news articles have heralded a dip below that limit in a physics lab. Is absolute zero less absolute than we thought? Read on to find out.
Latest from Physics in Action
115 and the Island
Stability



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Published on 12 Mar 2013
Temperatures below absolute zero are HOTTER than those above, explains Professor Philip Moriarty. More Daisy pics:
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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.
Stability

Beyond Statistical Mechanics

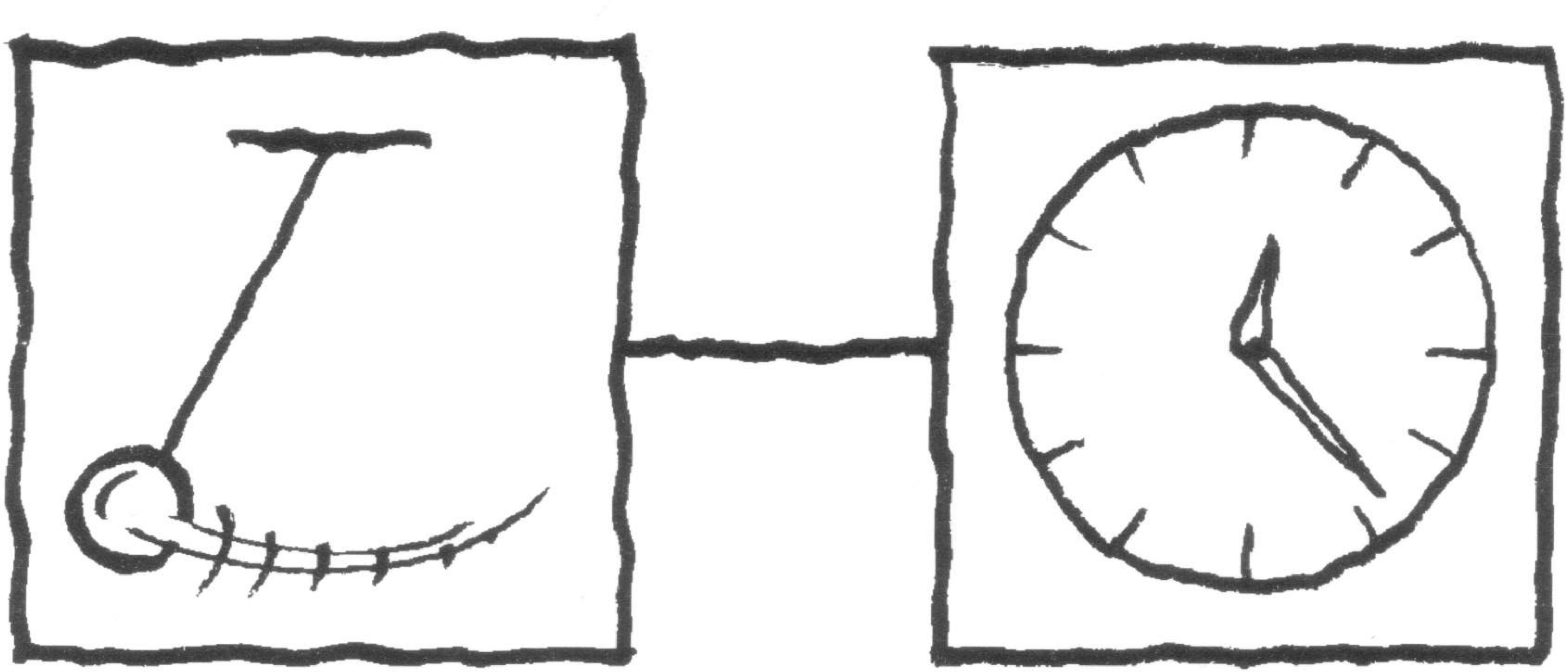
Many-Body Localization

The world best clocks:

Application of Atomic Clocks

- **Navigation, Positioning**
  GPS, GLONASS, deep space probes
- **Geodesy**
  Dating 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 :
  $\dot{\alpha}/\alpha$ at 10^{-16}/year

Measurement of Time



Clock = Oscillator + Counter

Measurement of Time

Measurement of Time

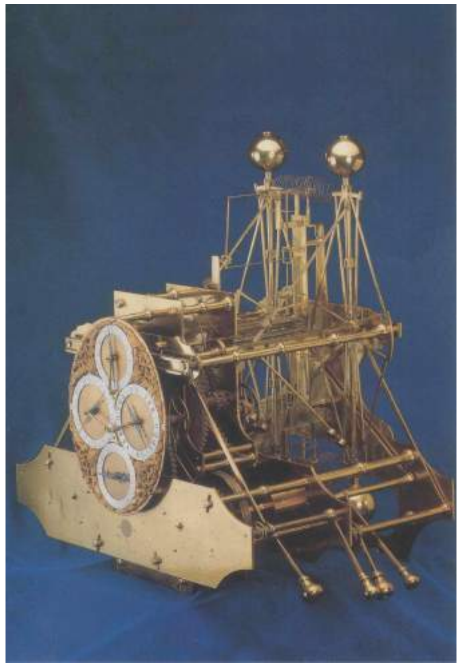
Sundial since 3500 v. Chr.

One period per day

Measurement of Time

Sundial since 3500 v. Chr.

One period per day



Pendulum clock since 1656

One period per second

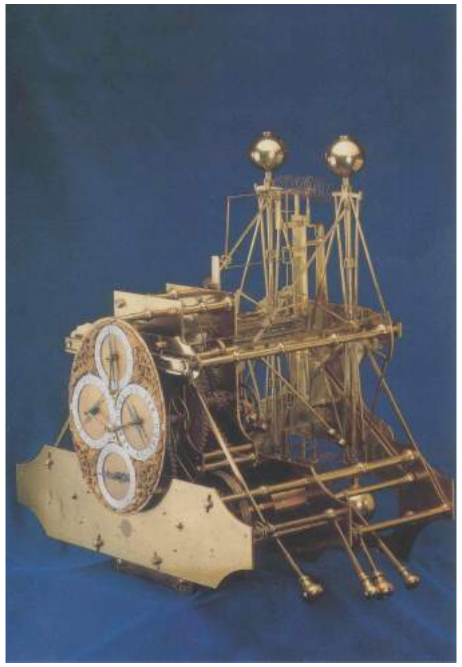
Measurement of Time

Sundial since 3500 v. Chr.

One period per day

Quartz oscillator since 1918

32.768 periods per second



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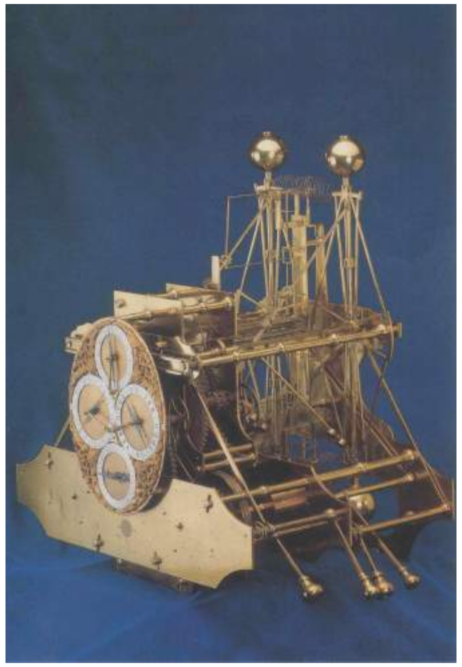


Pendulum clock since 1656

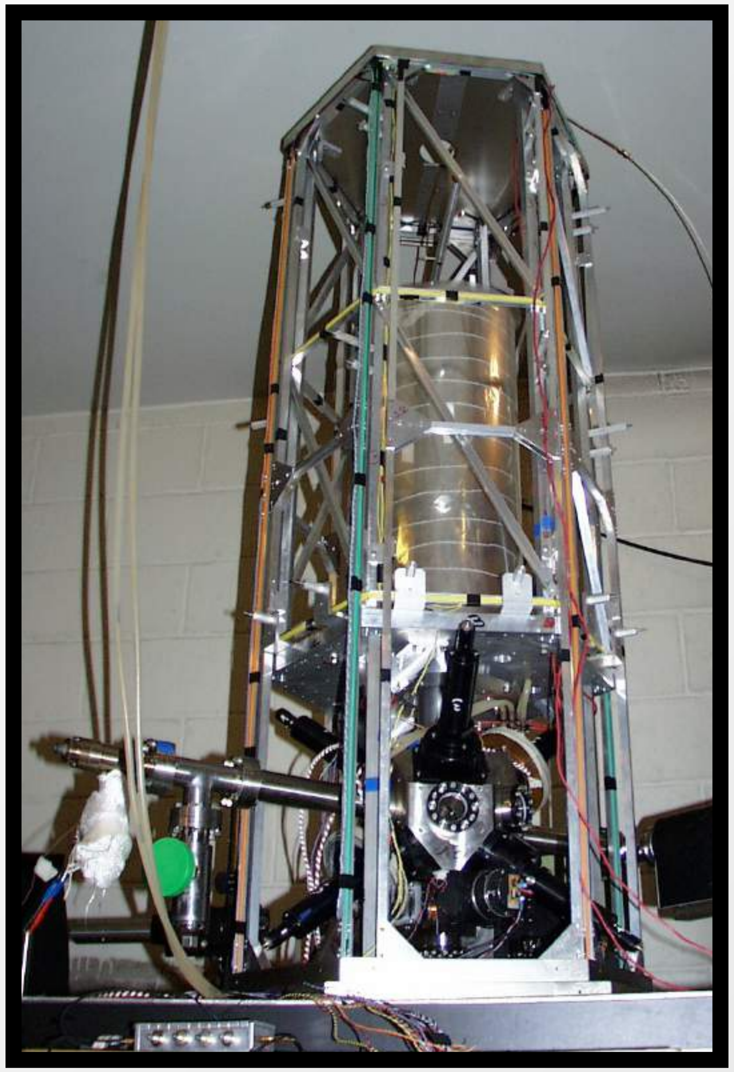
One period per second

Cesium atomic clock since 1955

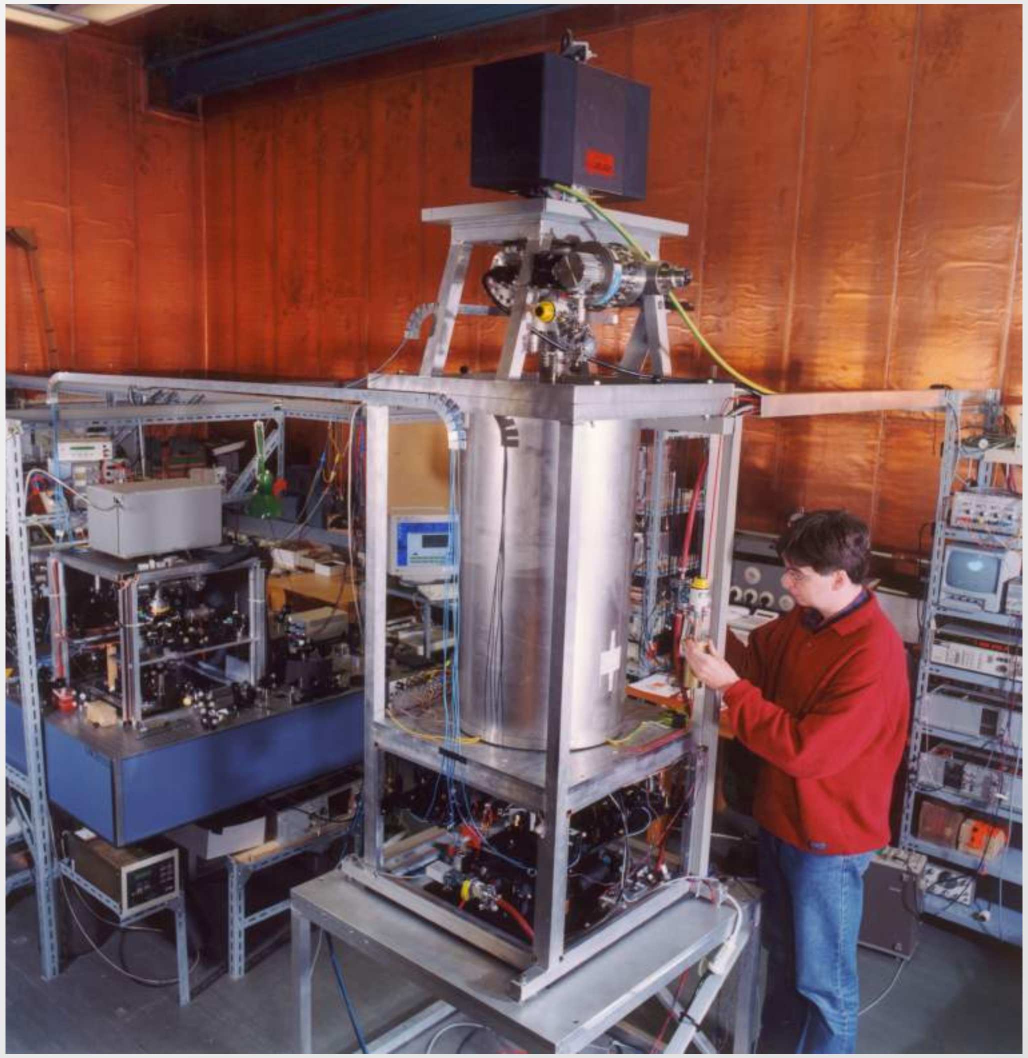
9.192.631.770 oscillations per second

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.



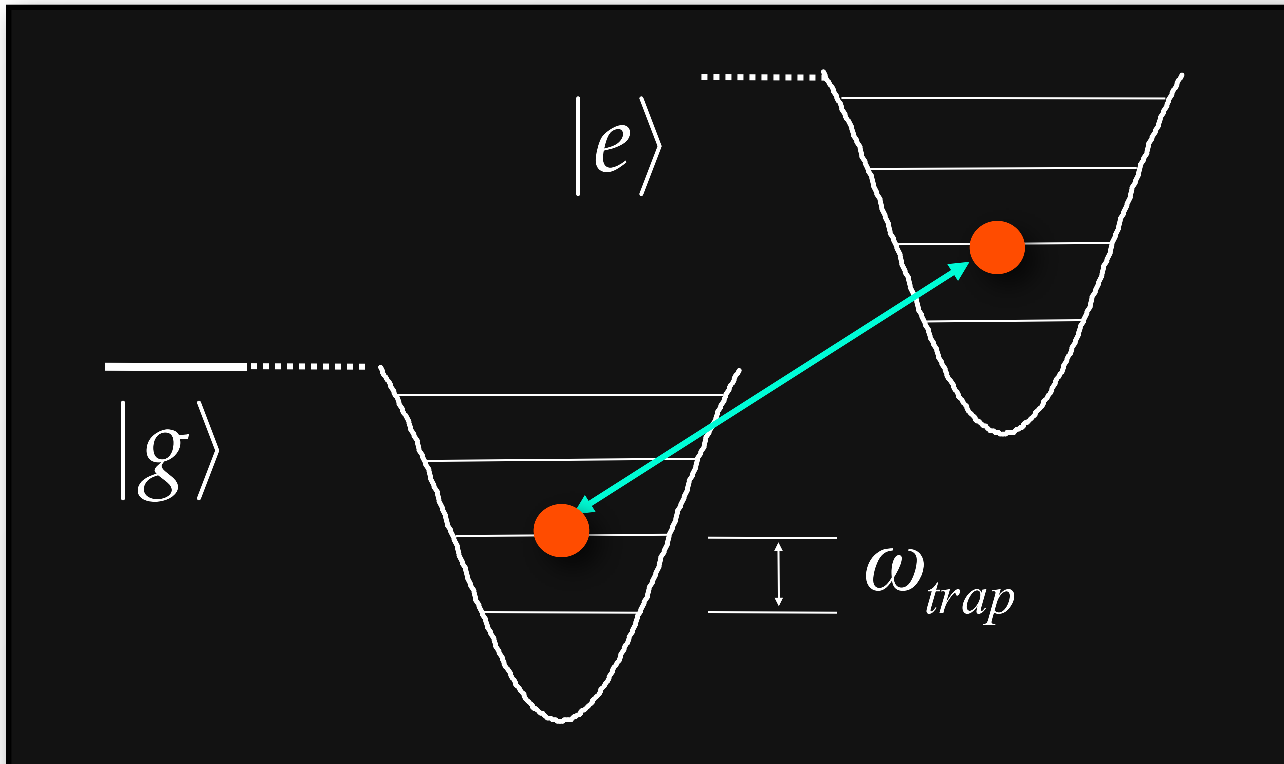
BNM-SYRTE, FR

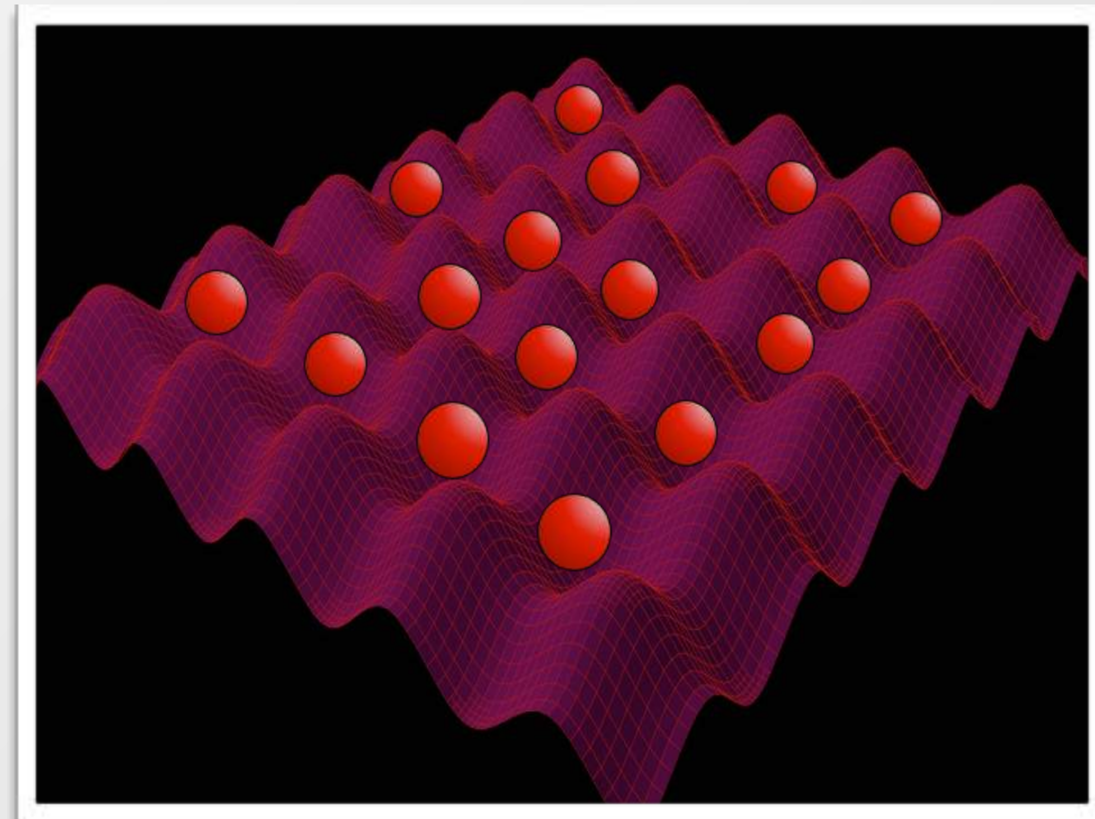


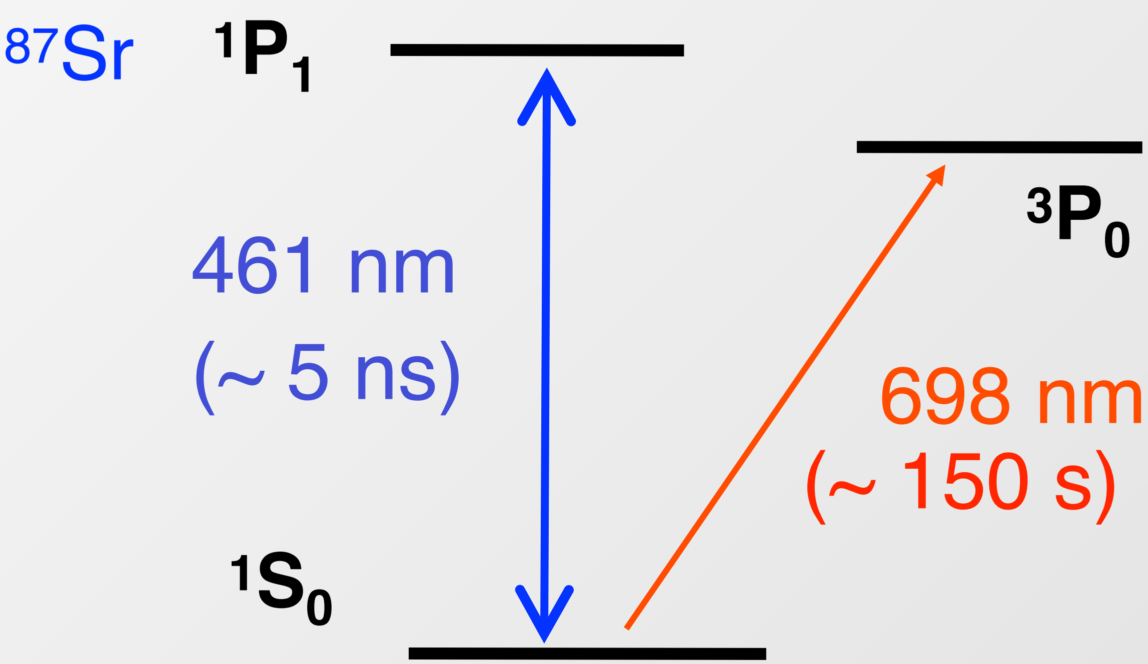
PTB, D

NIST, USA

Best Atomic Clocks: 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)

(In)Accuracy

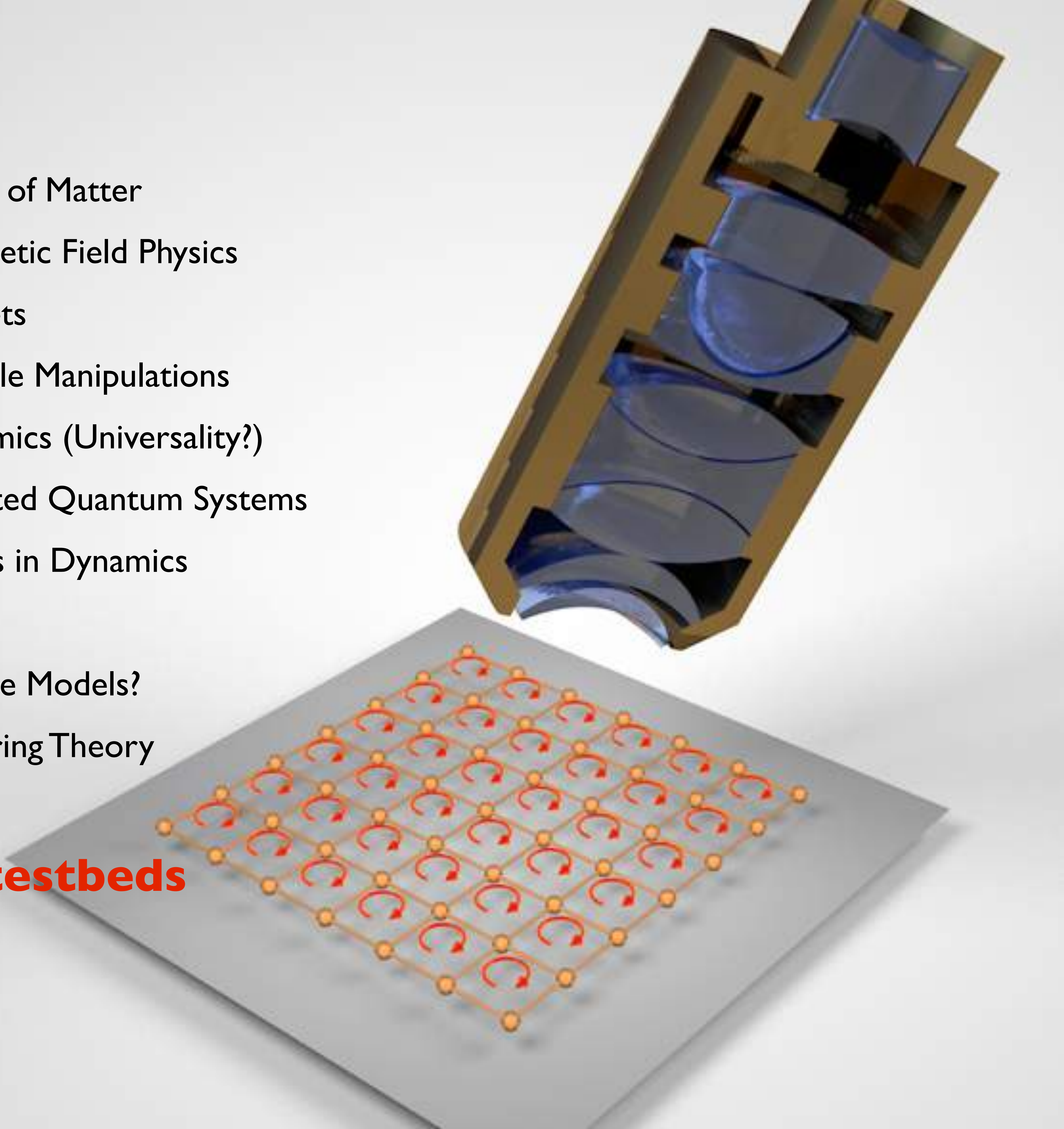
The inaccuracy of such a clock corresponds to 1s over the entire lifetime of the universe!

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!

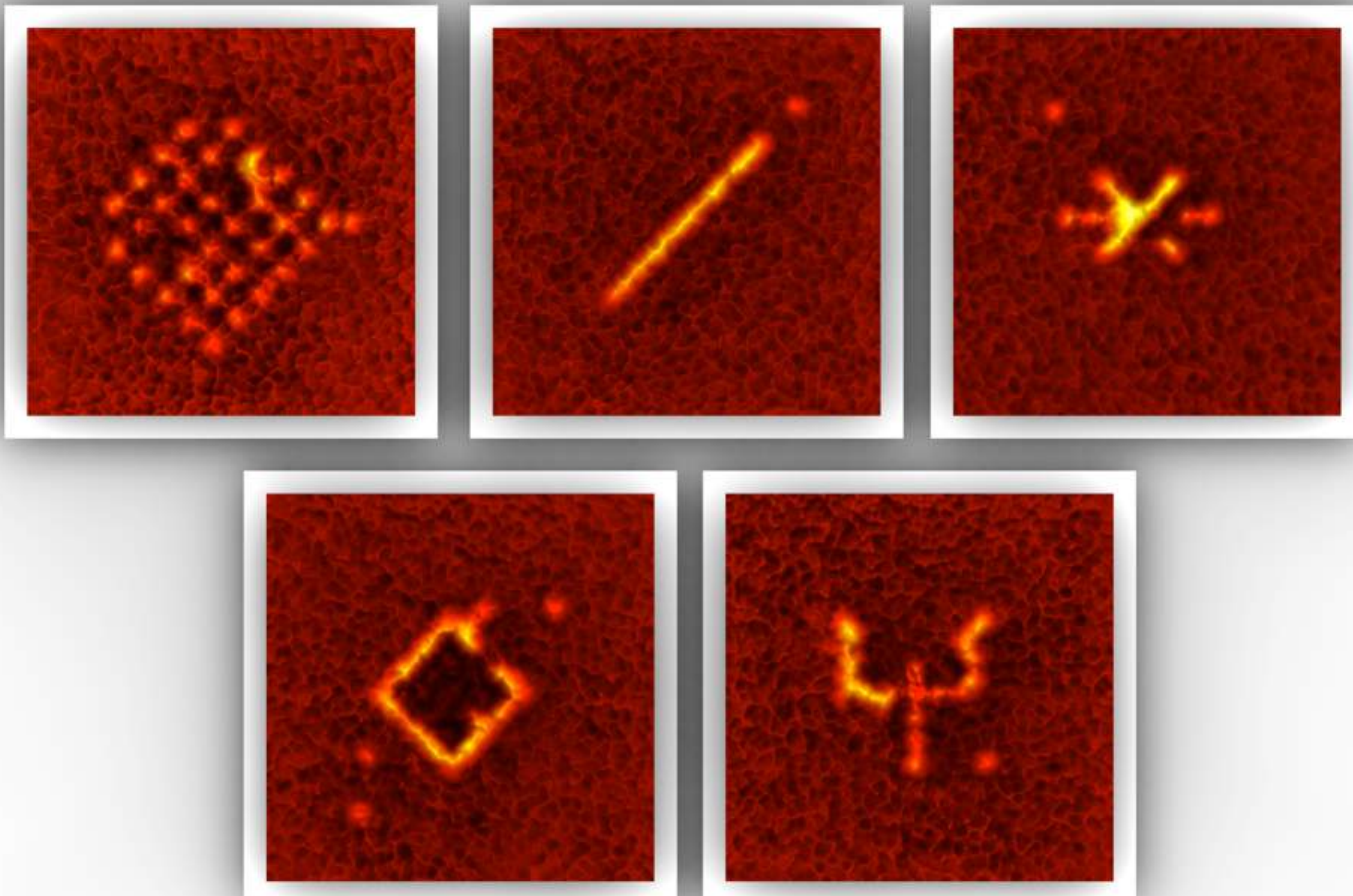
⋮

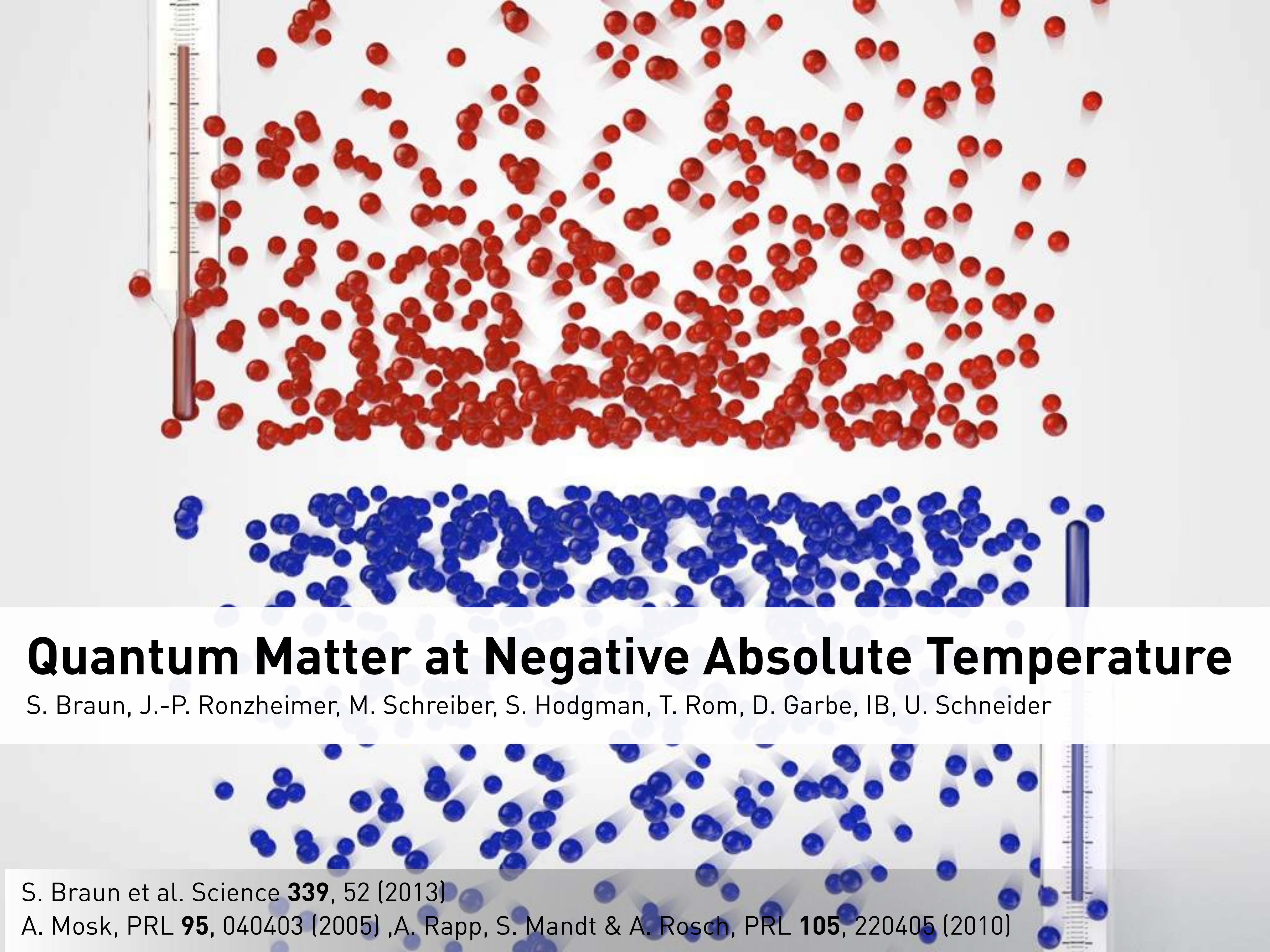


UQUAM
ultracold quantum matter

erc

www.quantum-munich.de





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)

Thermodynamic Definition of Temperature

$$\frac{1}{T} = \left(\frac{\partial S}{\partial E}\right)_V$$

Positive Temperature

Entropy increases with Energy

Negative Temperature

Entropy decreases with Energy

Thermodynamic Definition of Temperature

$$\frac{1}{T} = \left(\frac{\partial S}{\partial E}\right)_V$$

Positive Temperature

Entropy increases with Energy

Negative Temperature

Entropy decreases with Energy

Thermodynamic theorems apply in negative as well as positive temperature regime!

Thermodynamic Definition of Temperature

mperature

with Energy

$$\frac{1}{T} = \left(\frac{\partial S}{\partial E}\right.$$

Warning:

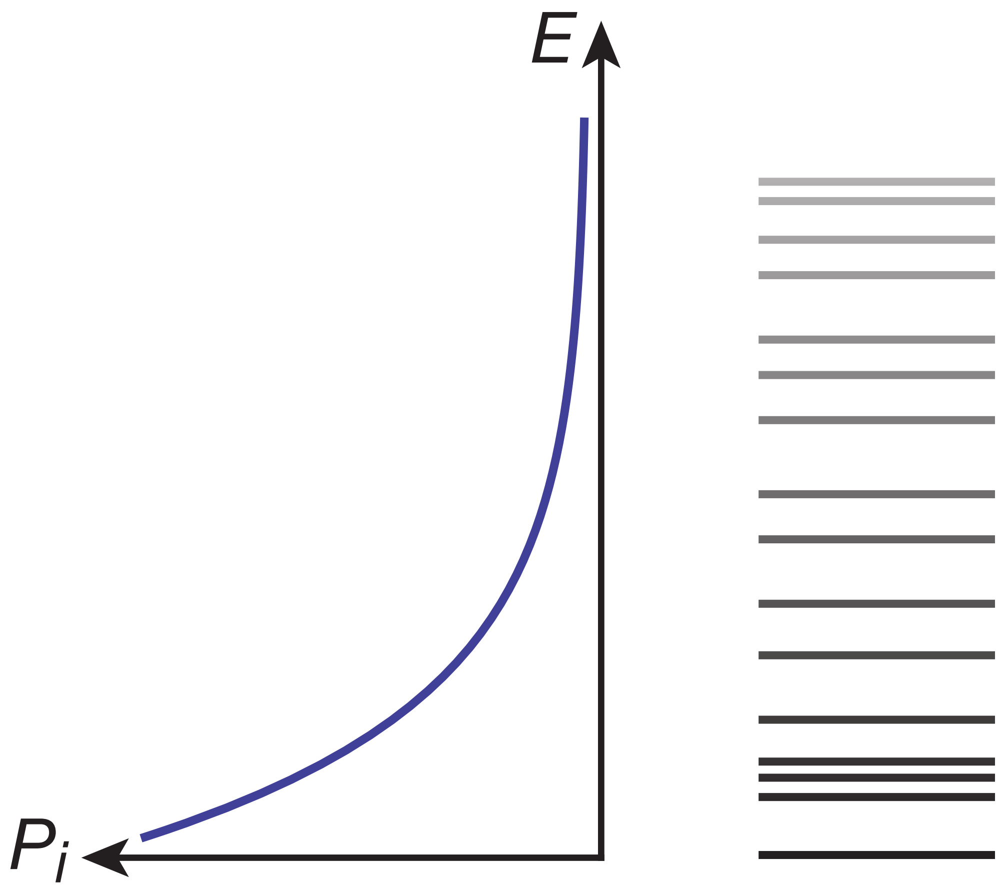
Temperature does not measure energy content!!!

erature

es with Energy

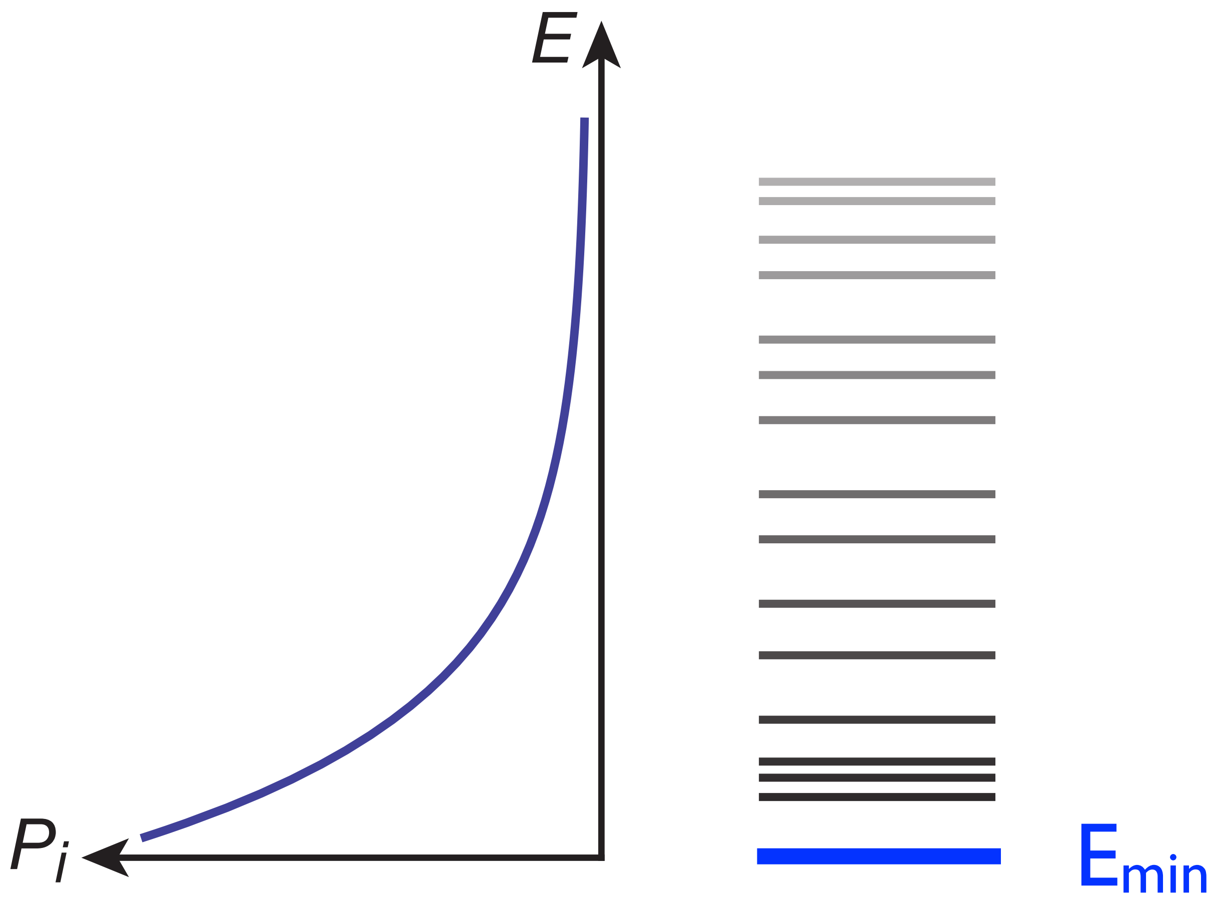
Thermodynamic theorems apply in negative as well as positive temperature regime!

Requirements



$$P_i \propto e^{-\frac{E_i}{k_B T}}$$

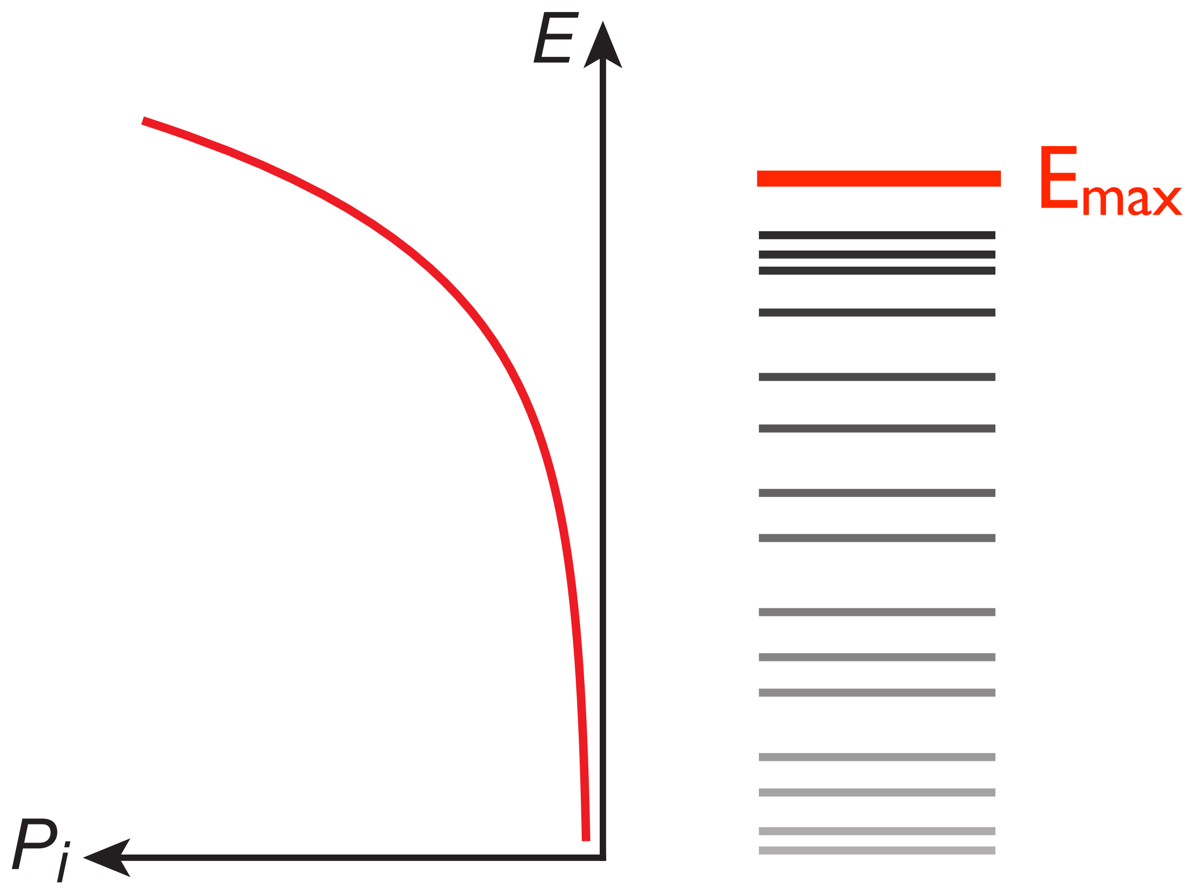
Requirements



$$P_i \propto e^{-\frac{E_i}{k_B T}}$$

For positive temperatures, we require lower energy bound E_{min}!

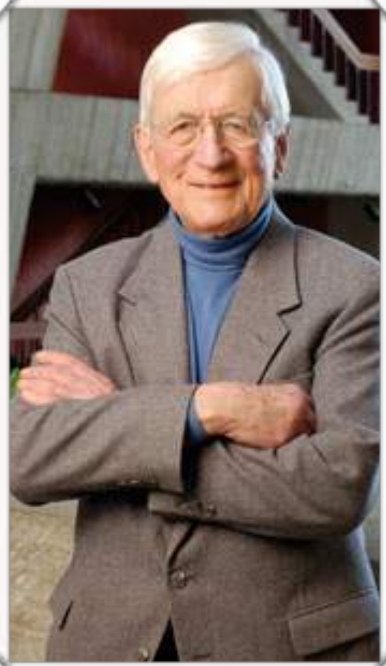
Requirements



$$P_i \propto e^{-\frac{E_i}{k_B(-T)}}$$

For negative temperatures, we require upper energy bound E_{max}!

Requirements



Norman Ramsey
(1915-2011)

PHYSICAL REVIEW — VOLUME 103, NUMBER 1 — JULY 1, 1956

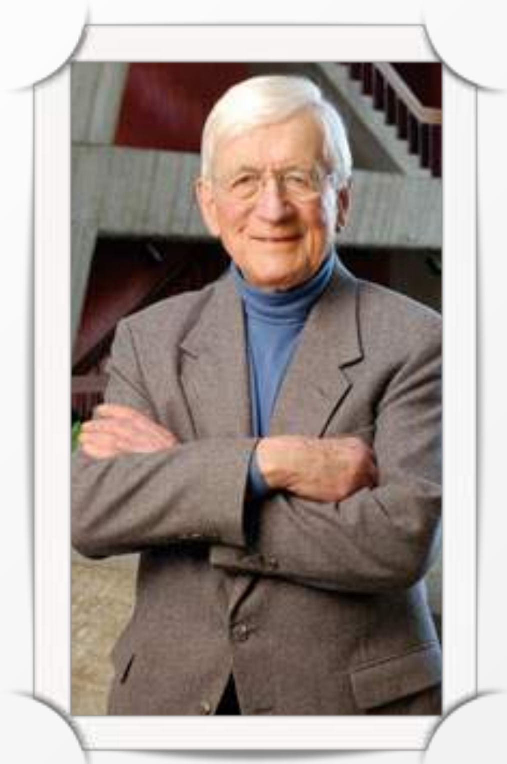
Thermodynamics and Statistical Mechanics at Negative Absolute Temperatures

NORMAN F. RAMSEY*
Harvard University, Cambridge, Massachusetts, and Clarendon Laboratory, Oxford, England
(Received March 26, 1956)

As discussed in Sec. III below, the conditions for the existence of a system at negative temperatures are so restrictive that they are rarely met in practice except with some mutually interacting nuclear spin systems.

L. Onsager, N. Cim. **6**, 279 (1949)
E.M. Purcell & R.V. Pound, Phys. Rev. **81**, 279 (1951)
N. Ramsey, Phys. Rev. **103**, 20 (1956)
M.J. Klein, Phys. Rev. **104**, 589 (1956)
P. Hakonen & O. Lounasmaa, Science **265**, 1821 (1994)
P. Medley et al, Phys. Rev. Lett **106**, 195301 (2011)

Requirements



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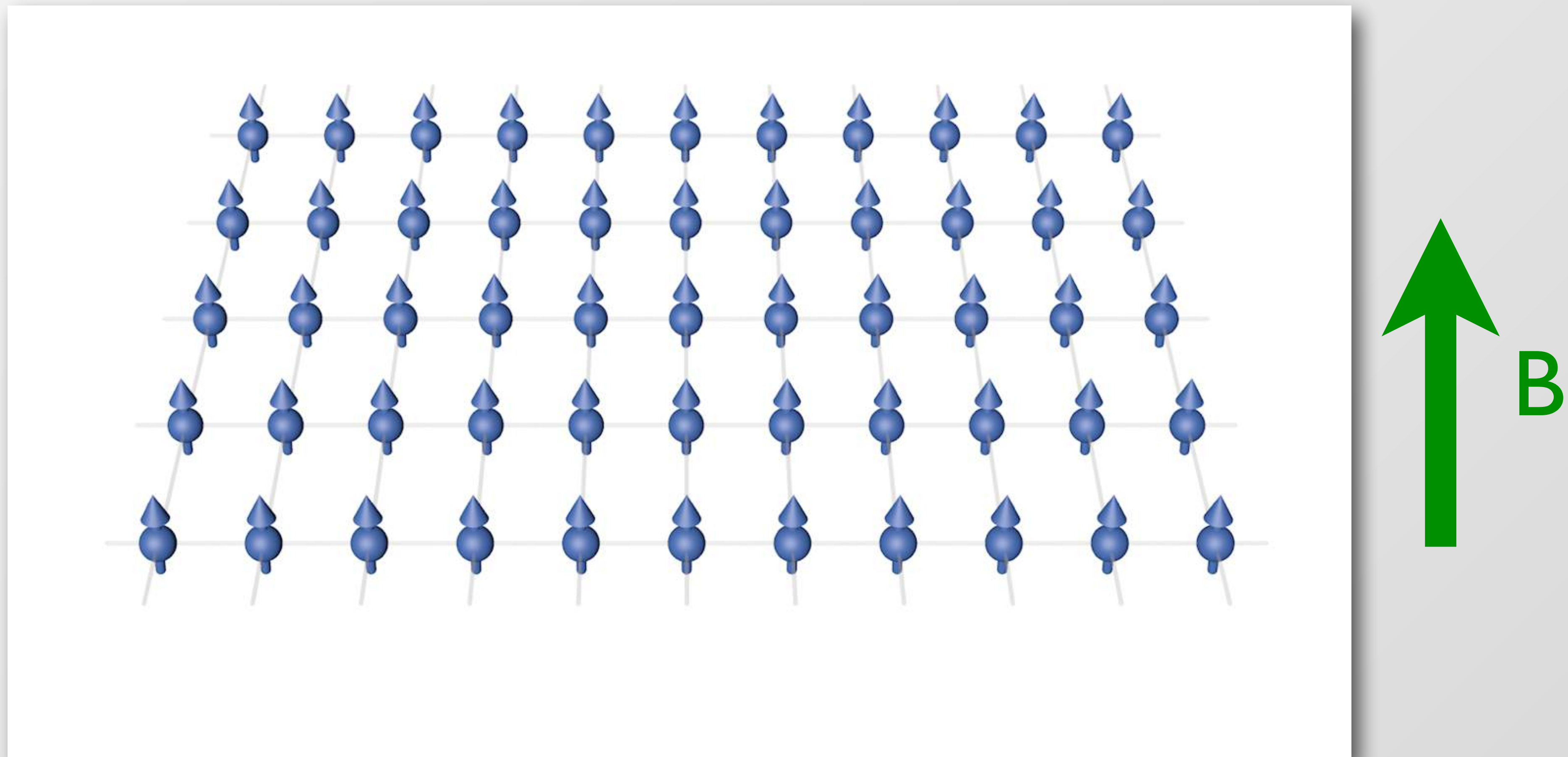

Lowest Energy State E_{min}

L. Onsager, N. Cim. **6**, 279 (1949)
E.M. Purcell & R.V. Pound, Phys. Rev. **81**, 279 (1951)
N. Ramsey, Phys. Rev. **103**, 20 (1956)
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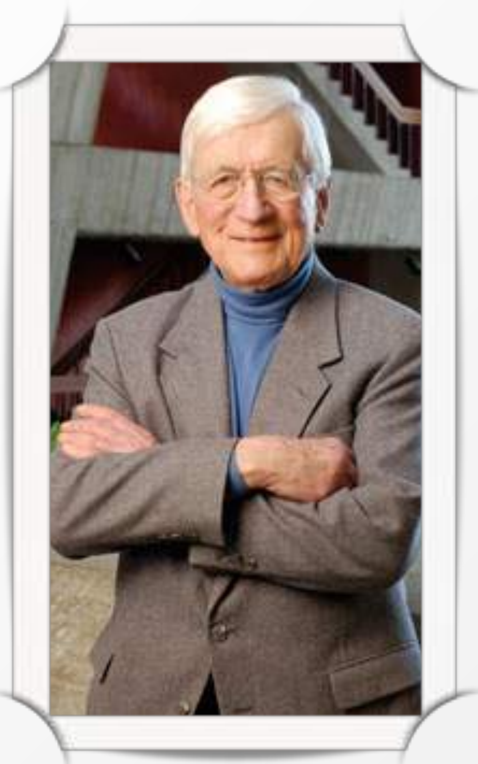

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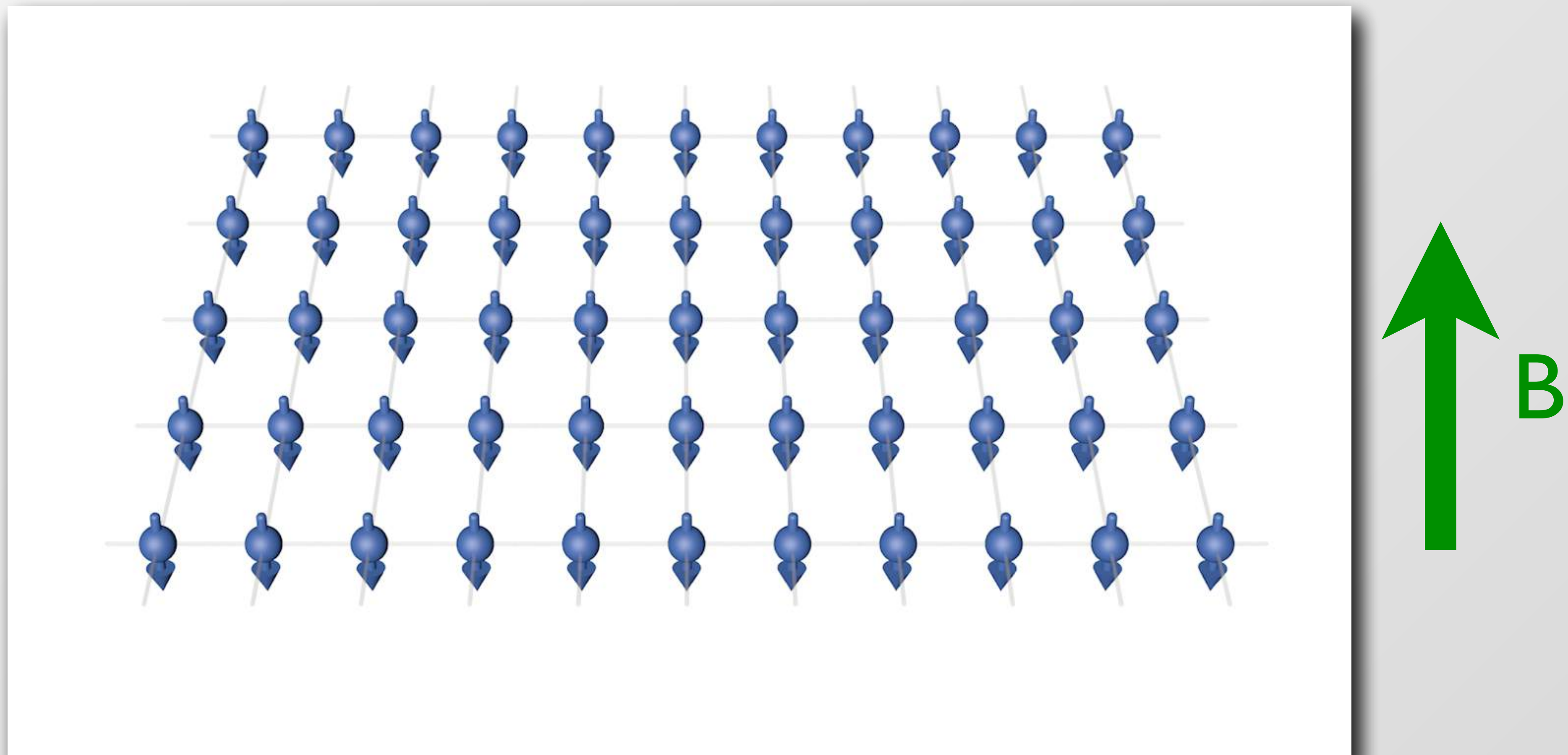

Highest Energy State E_{max}

L. Onsager, N. Cim. **6**, 279 (1949)
E.M. Purcell & R.V. Pound, Phys. Rev. **81**, 279 (1951)
N. Ramsey, Phys. Rev. **103**, 20 (1956)
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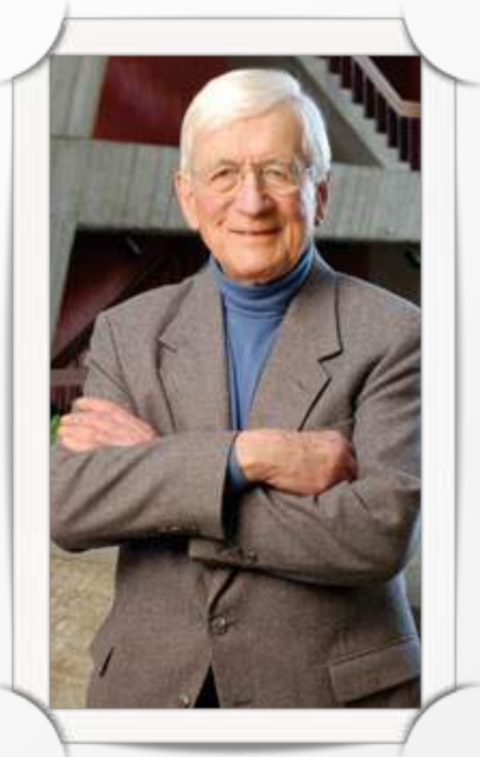


Norman Ramsey
(1915-2011)

PHYSIC... JULY 1, 1956

Th... ...olute Temperatures

...ford, England

A Nuclear Spin System at Negative Temperature

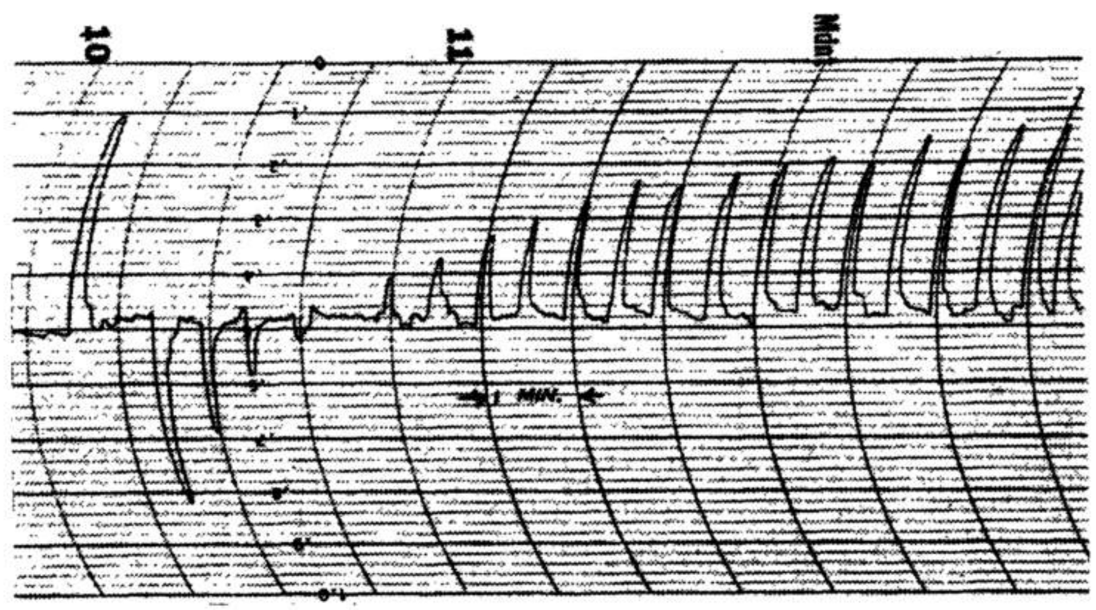
E. M. Purcell and R. V. Pound
Department of Physics, Harvard University, Cambridge, Massachusetts

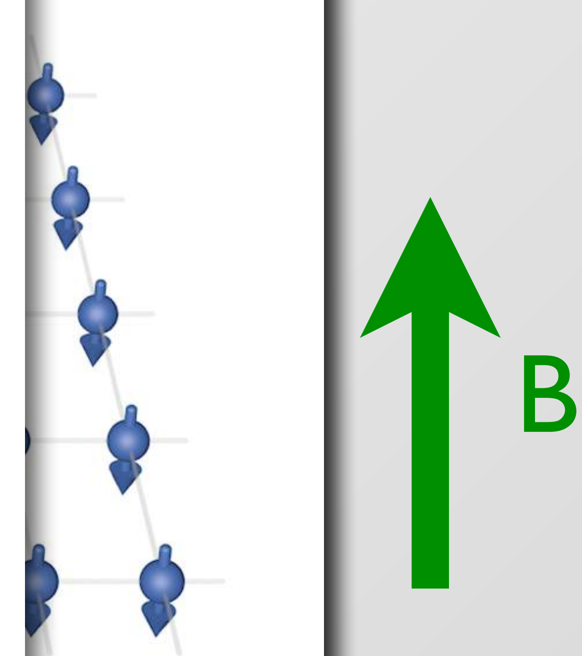
November 1, 1950

A NUMBER of special experiments have been performed with a crystal of LiF which, as reported previously,[1] had long relaxation times both in a strong field and in the earth's field. These experiments were designed to discover the conditions determining the sense of remagnetization by a strong field when the initially magnetized crystal was put for a brief interval in the earth's field.

At field strengths allowing the system to be described by its net magnetic moment and angular momentum, a sufficiently rapid reversal of the direction of the magnetic field should result in a magnetization opposed to the new sense of the field. The reversal must occur in such a way that the time spent below a minimum effective field is so small compared to the period of the Larmor precession that the system cannot follow the change adiabatically. The experiments in zero field reported above[2] showed a zero field resonance at about 50 kc and therefore the following experiment was tried.

The crystal, initially at equilibrium magnetization in the strong (6376 gauss) field, was quickly removed, through the earth's field, and placed inside a small solenoid, the axis of which was





L. Onsager, N. Cim. **6**, 279 (1949)
E.M. Purcell & R.V. Pound, Phys. Rev. **81**, 2...
N. Ramsey, Phys. Rev. **103**, 20 (1956)
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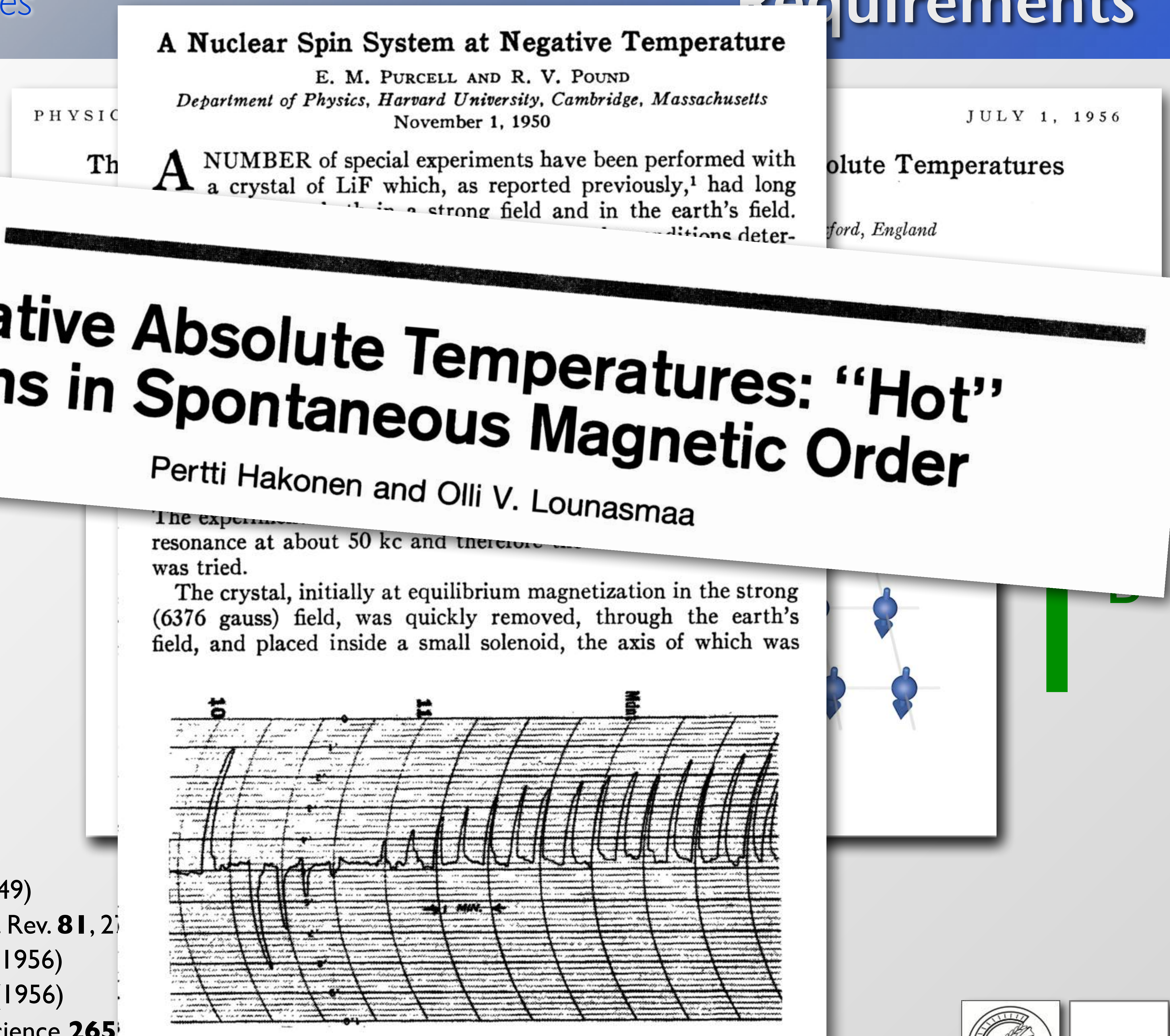
P. Hakonen & O. Lounasmaa, Science **265**...
P. Medley et al, Phys. Rev. Lett **106**, 195301 (2011)

Requirements

Norman Ramsey
(1915-2011)



PHYSIC

Th

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JULY 1, 1956

...olute Temperatures

...ford, England

ARTICLES

Negative Absolute Temperatures: "Hot" Spins in Spontaneous Magnetic Order

Pertti Hakonen and Olli V. Lounasmaa

L. Onsager, N. Cim. **6**, 279 (1949)
E.M. Purcell & R.V. Pound, Phys. Rev. **81**, 27
N. Ramsey, Phys. Rev. **103**, 20 (1956)
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JULY 1, 1956

olute Temperatures

ford, England

ARTICLES

Negative Absolute Temperatures: "..."
Spins in Spontan...

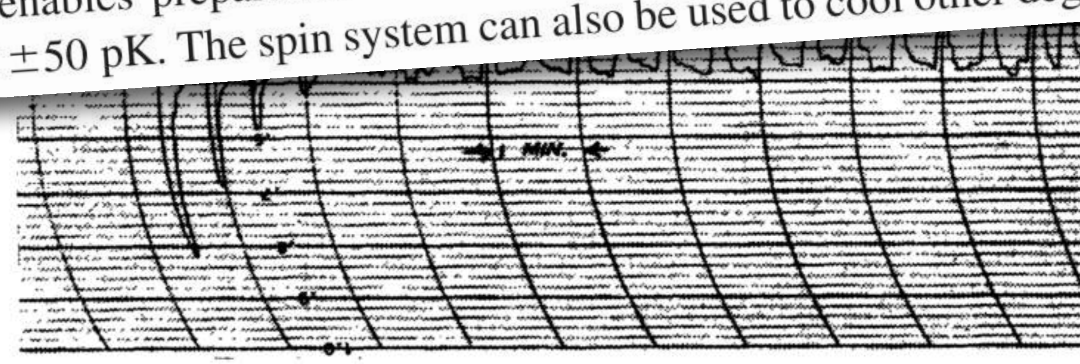
PRL **106,** 195301 (2011) PHYSICAL REVIEW LETTERS week ending 13 MAY 2011

Spin Gradient Demagnetization Cooling of Ultracold Atoms

Patrick Medley,* David M. Weld,† Hirokazu Miyake, David E. Pritchard, and Wolfgang Ketterle
MIT-Harvard Center for Ultracold Atoms, Research Laboratory of Electronics, and Department of Physics, Massachusetts Institute of Technology, Cambridge, Massachusetts 02139, USA

(Received 12 January 2011; revised manuscript received 16 March 2011; published 12 May 2011)

We demonstrate a new cooling method in which a time-varying magnetic field gradient is applied to an ultracold spin mixture. This enables preparation of isolated spin distributions at positive and negative effective spin temperatures of ±50 pK. The spin system can also be used to cool other degrees of freedom,



L. ..., 279 (1949)
E.M. Purcell & R.V. Pound, Phys. Rev. **81**, 27...
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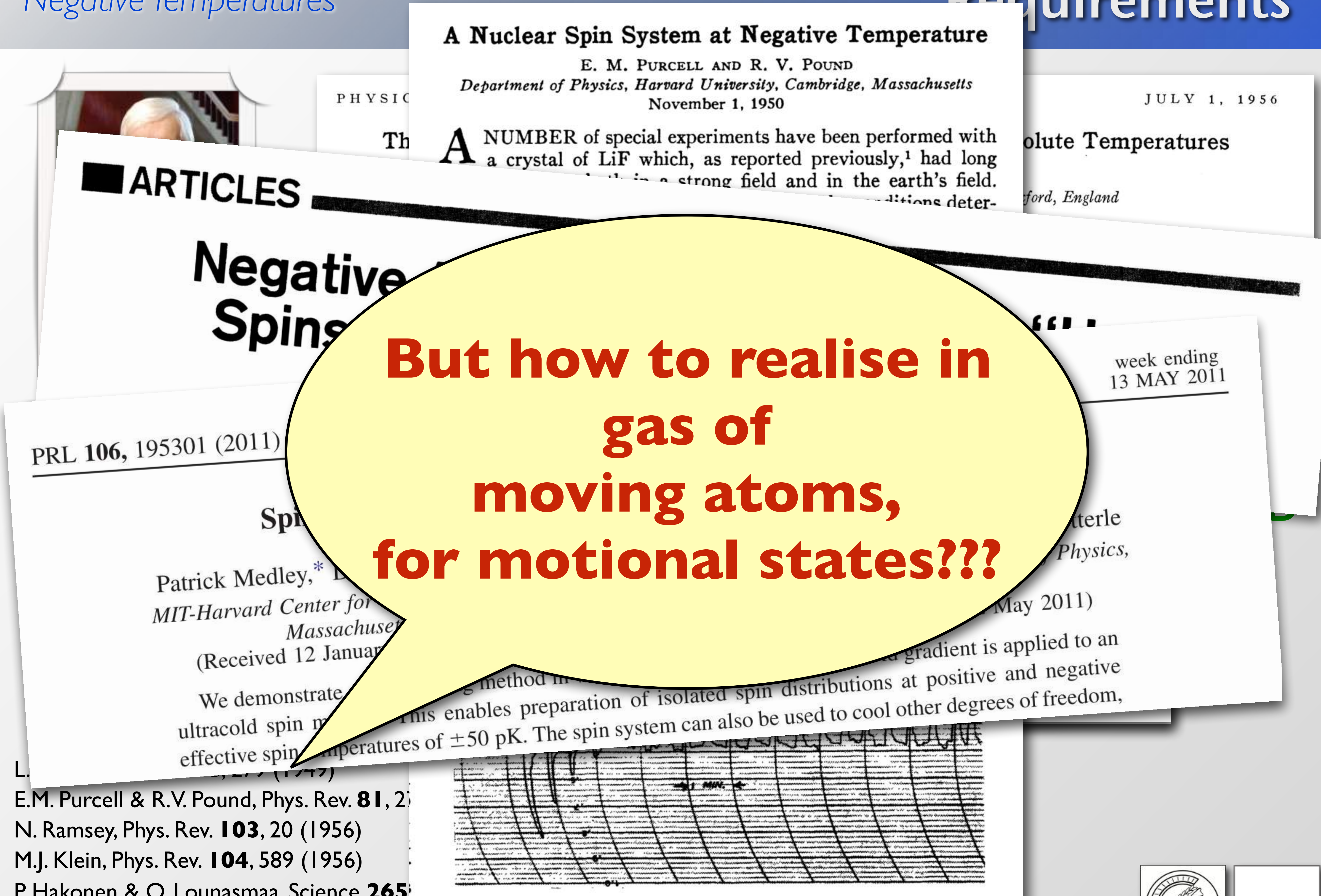
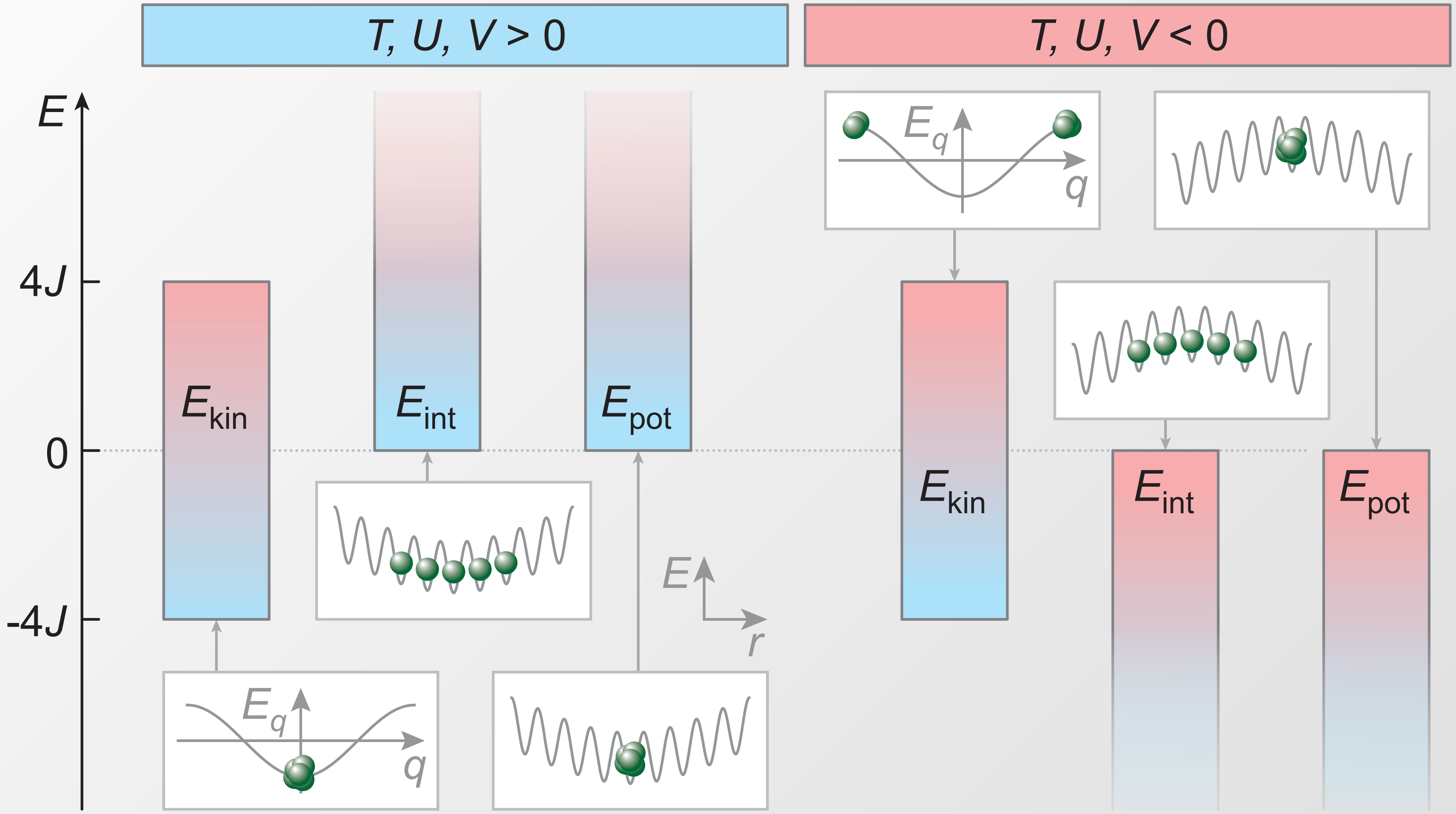


L. ... (1949)
E.M. Purcell & R.V. Pound, Phys. Rev. **81**, 2...
N. Ramsey, Phys. Rev. **103**, 20 (1956)
M.J. Klein, Phys. Rev. **104**, 589 (1956)
P. Hakonen & O. Lounasmaa, Science **265**...
P. Medley et al, Phys. Rev. Lett **106**, 195301 (2011)

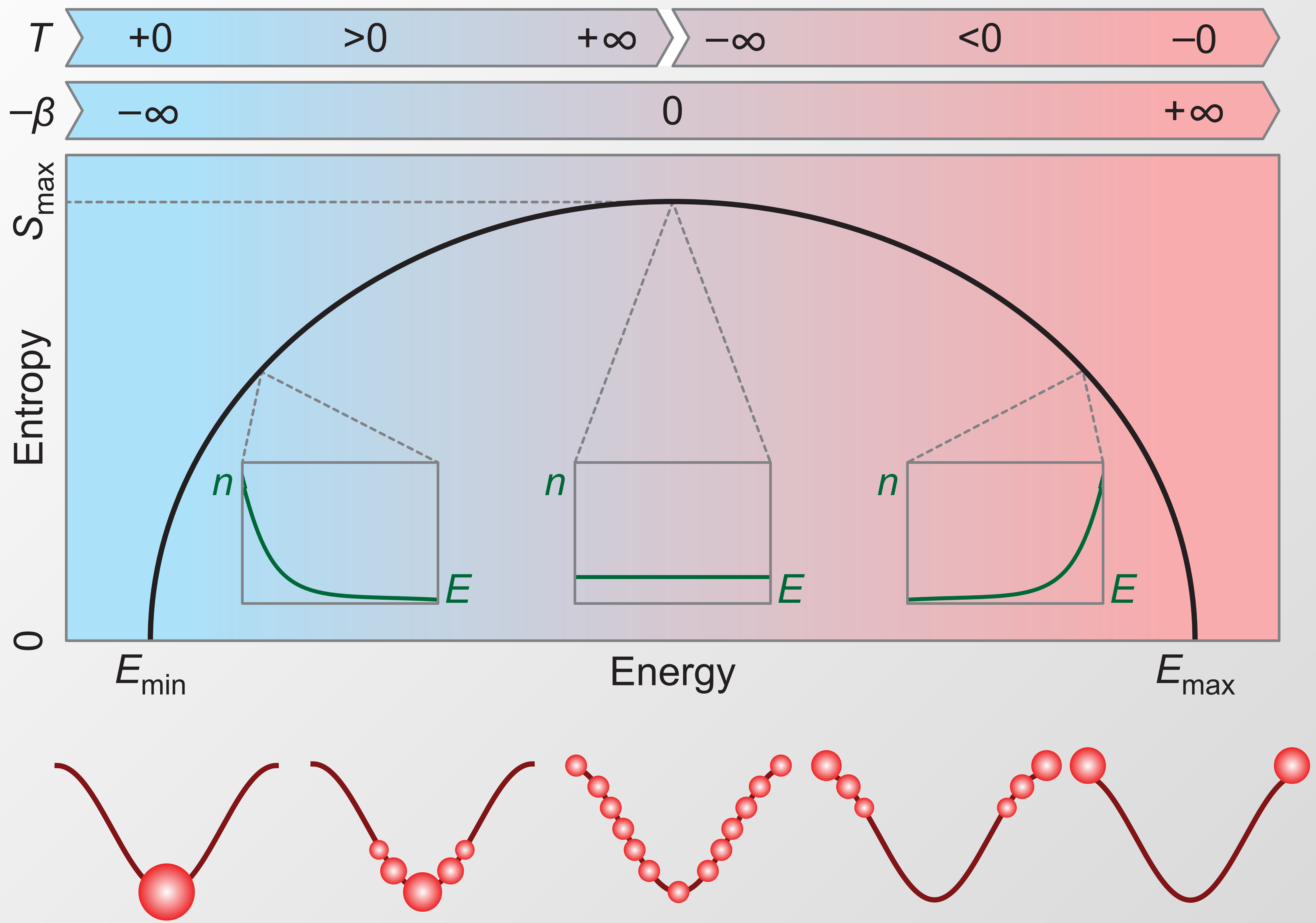
Energy Bounds of the BH Model



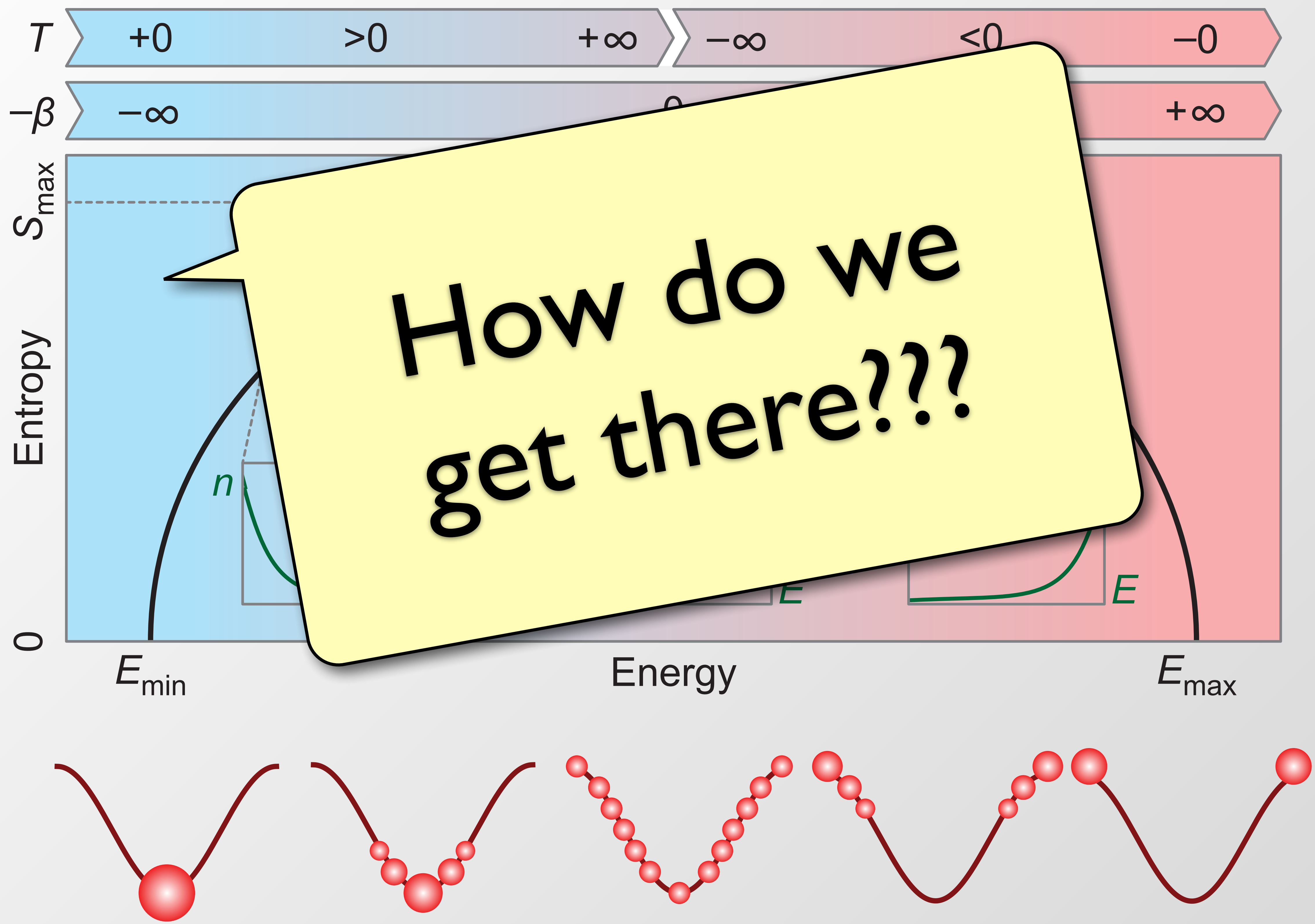
$$\hat{H} = -J \sum_{\langle i,j \rangle} \hat{a}_i^\dagger \hat{a}_j + \frac{U}{2} \sum_i \hat{n}_i \left(\hat{n}_i - 1 \right) + V \sum_i \mathbf{R}_i^2 \hat{n}_i$$

U,V < 0 required for upper energy bound!

Entropy vs Energy

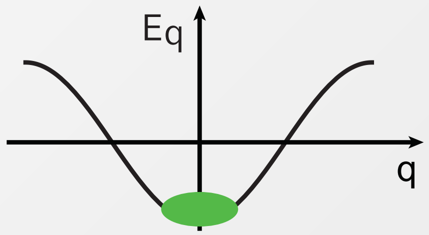


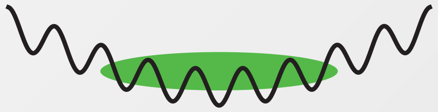
Entropy vs Energy



Experimental Sequence

Superfluid

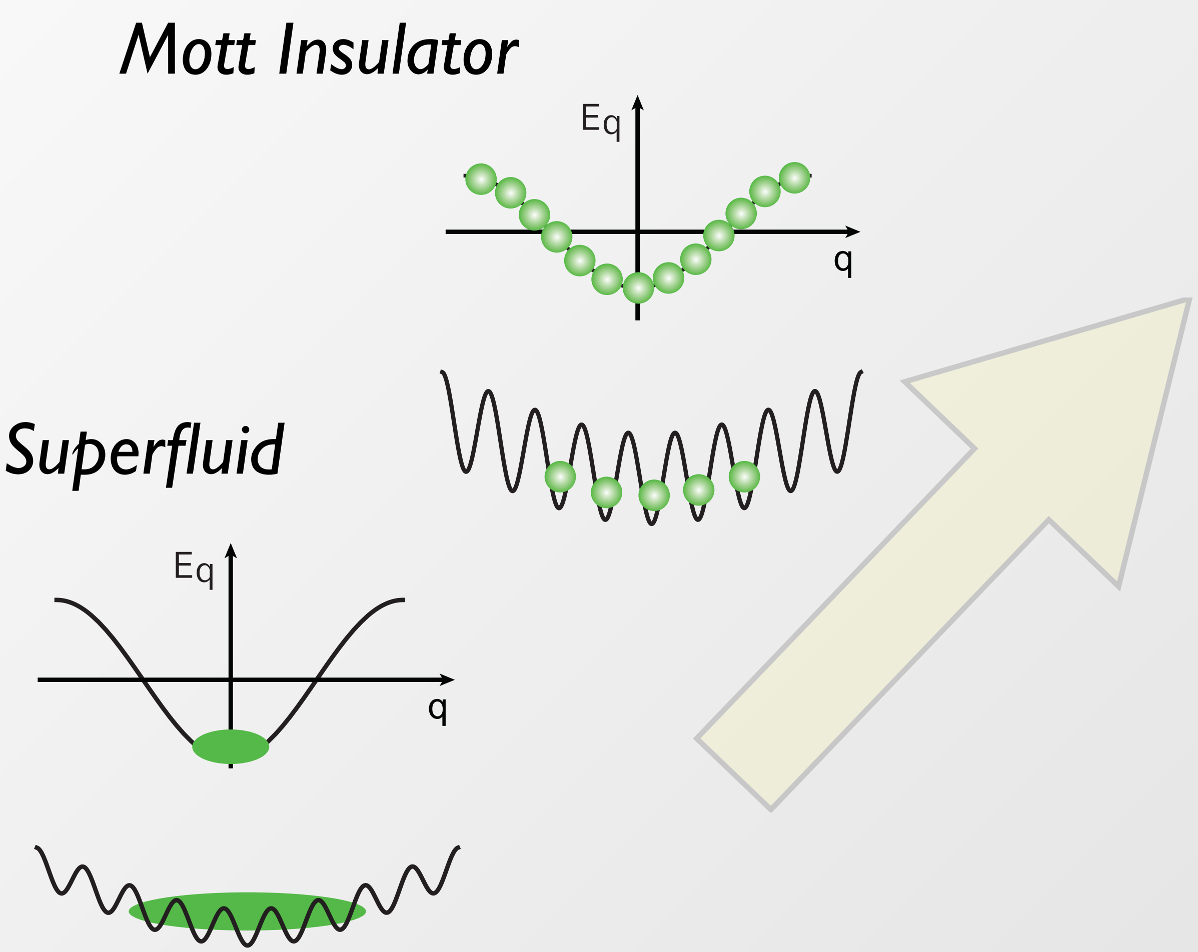




T,U,V >0

Sequence: A. Rapp, S. Mandt & A. Rosch, PRL (2010)

Experimental Sequence



T,U,V >0

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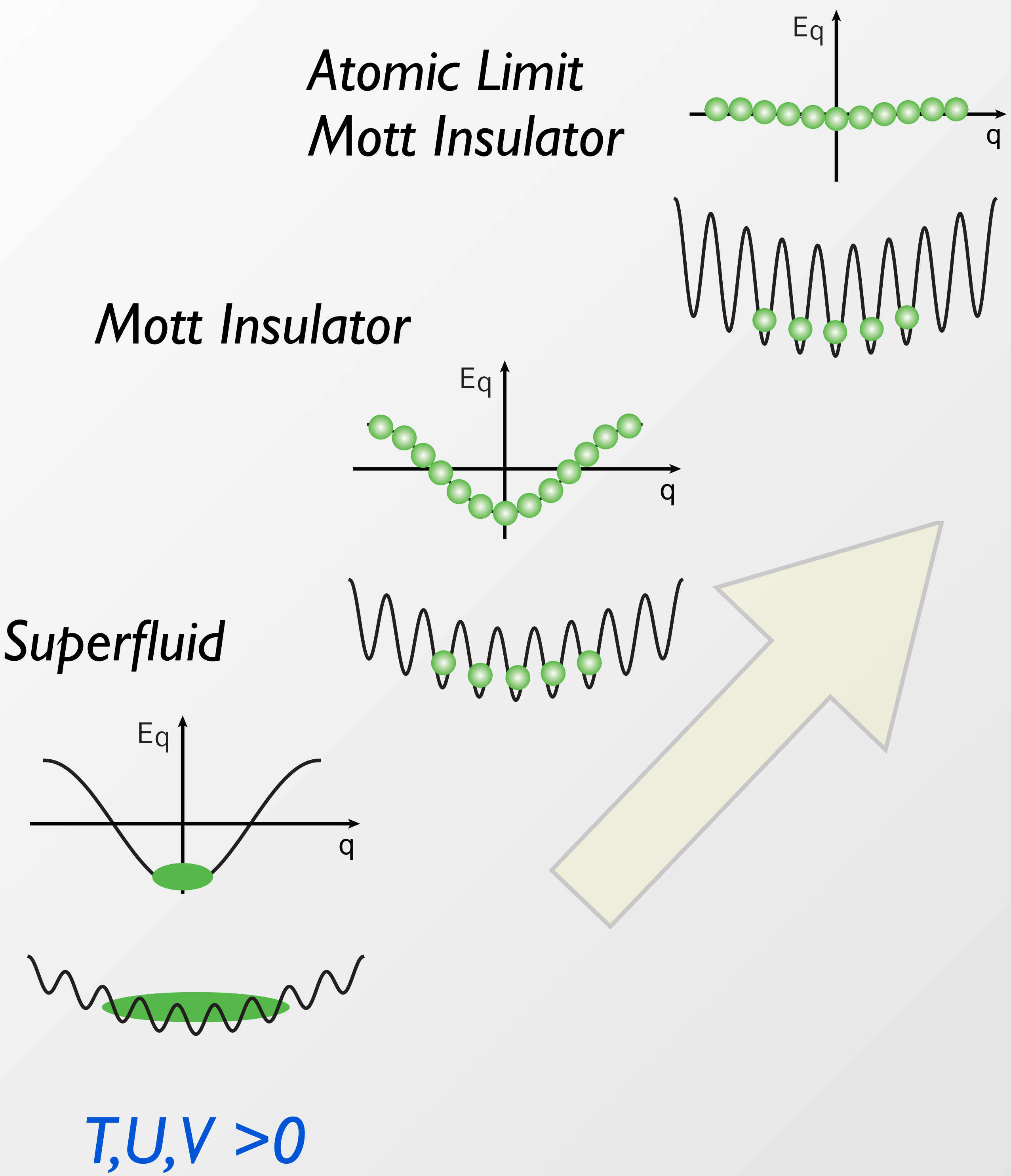
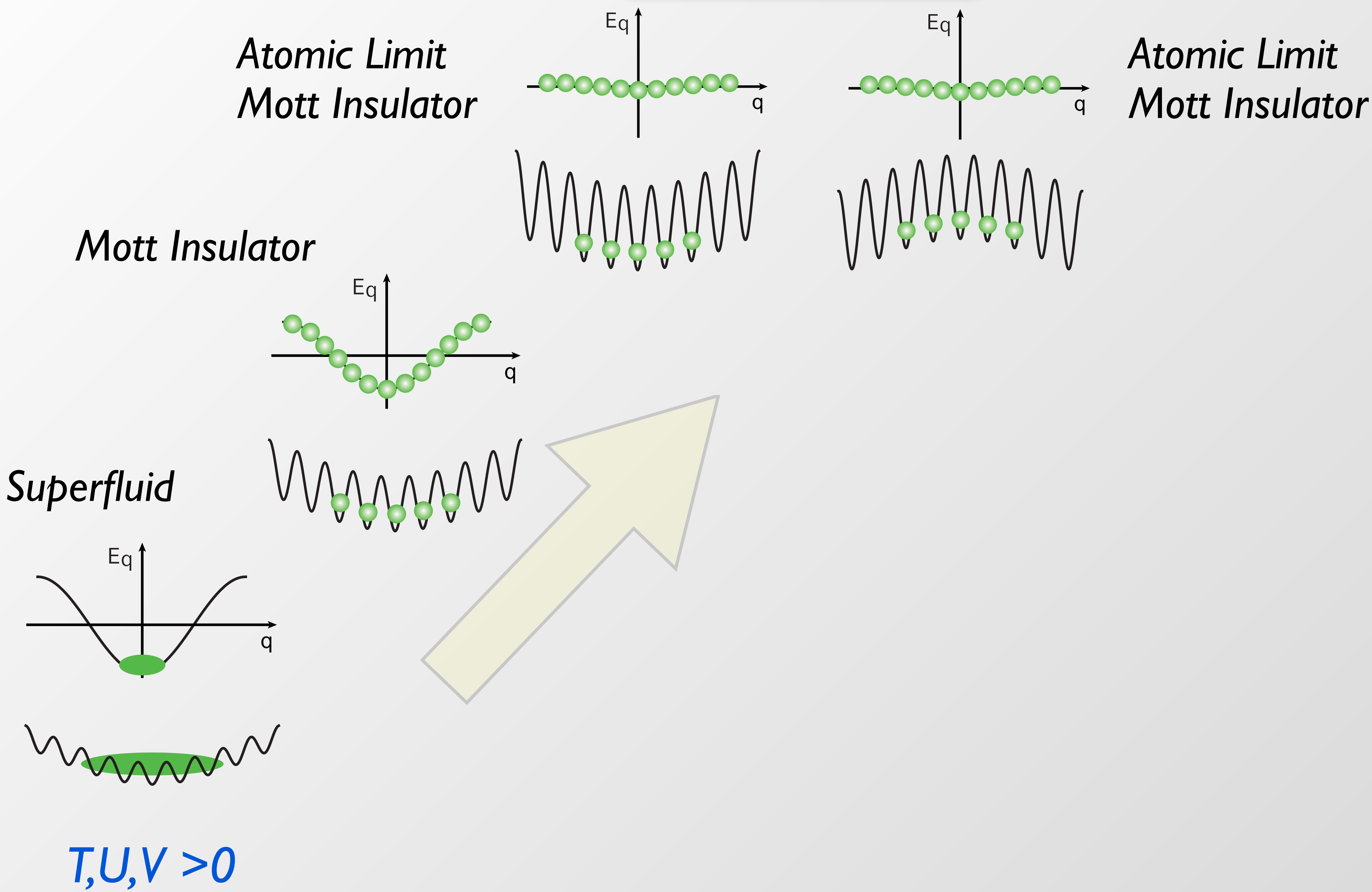
Experimental Sequence



Sequence: A. Rapp, S. Mandt & A. Rosch, PRL (2010)

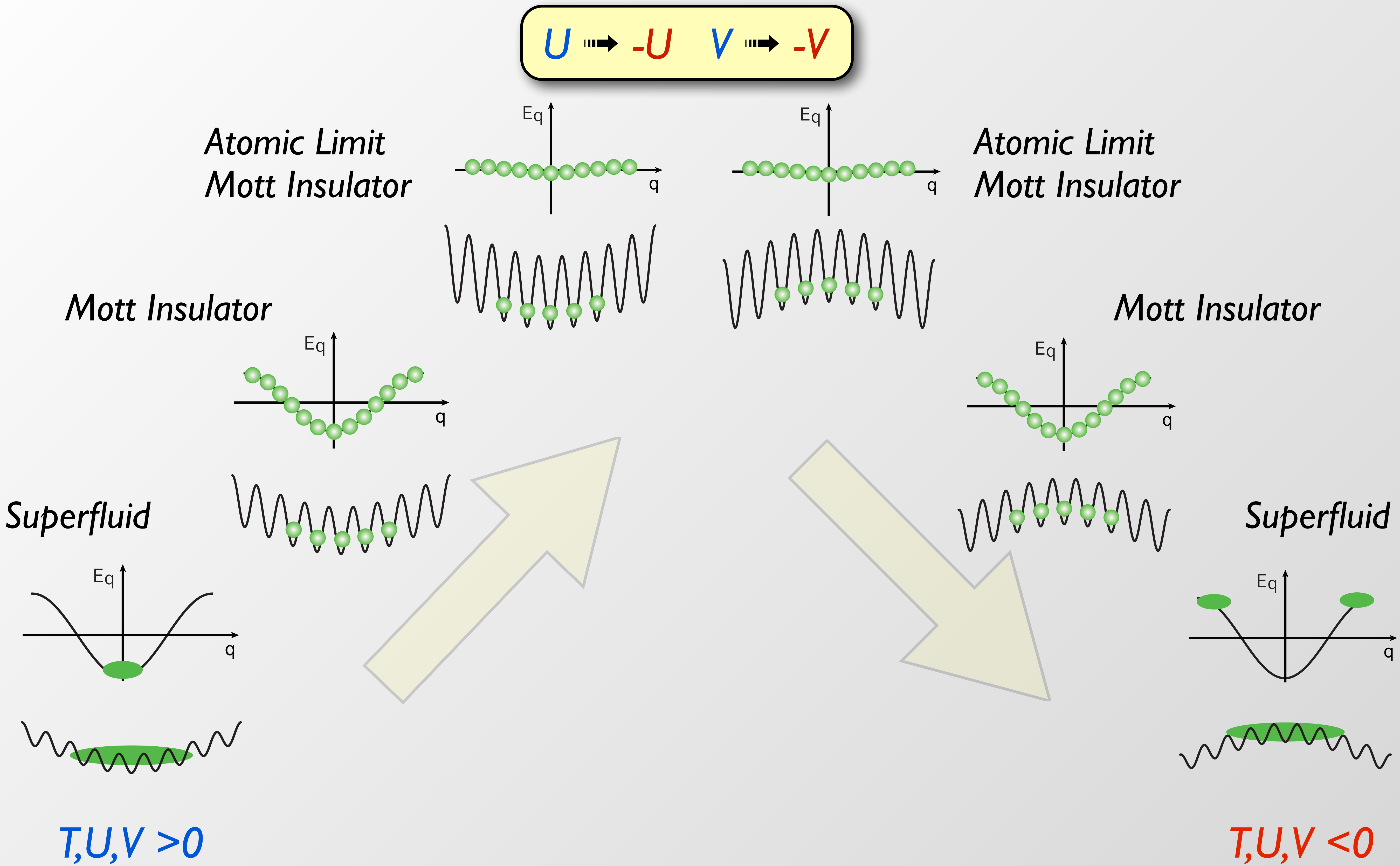
Experimental Sequence

U ➡ *-U* *V* ➡ *-V*



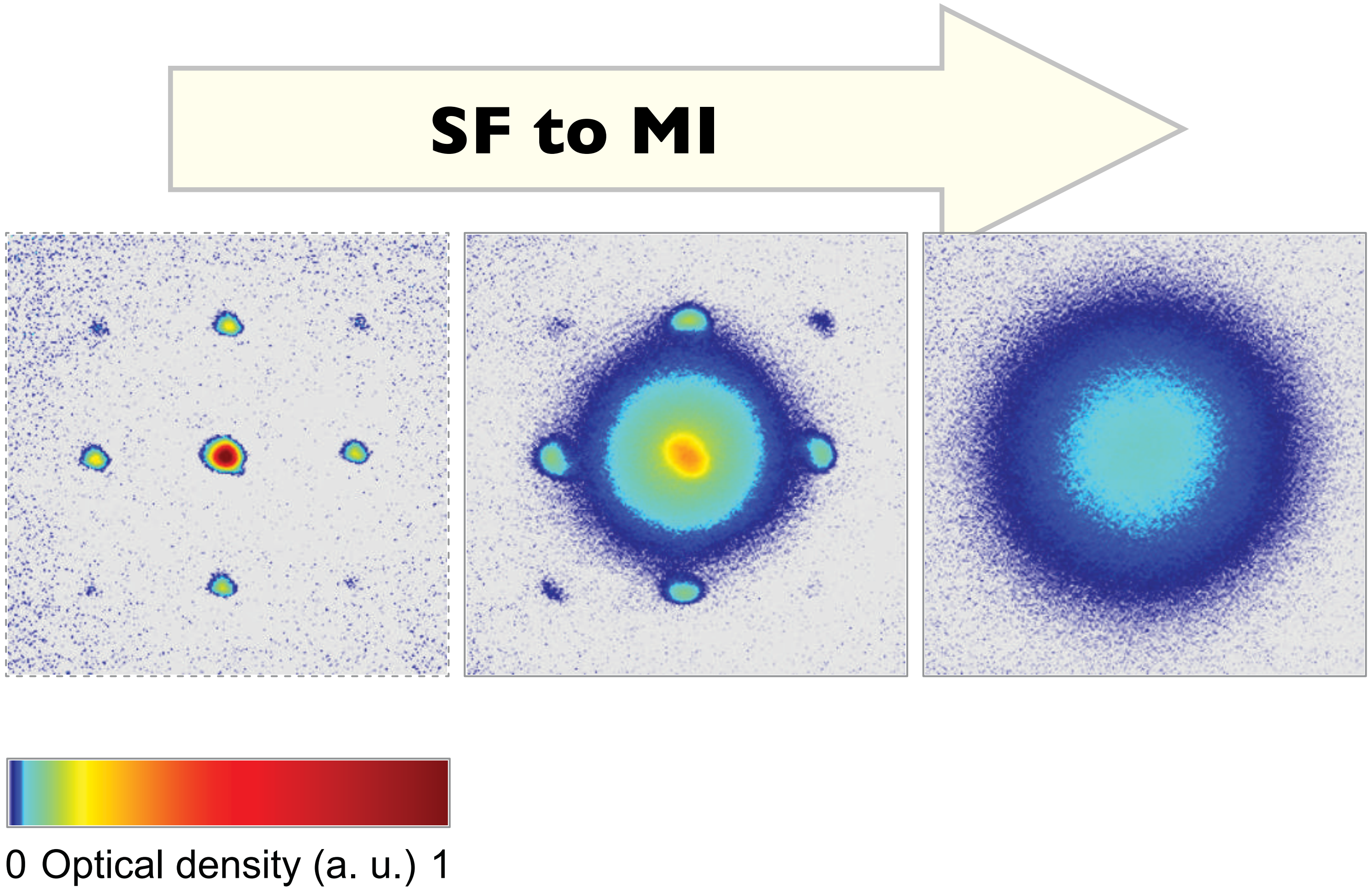
Sequence: A. Rapp, S. Mandt & A. Rosch, PRL (2010)

Experimental Sequence

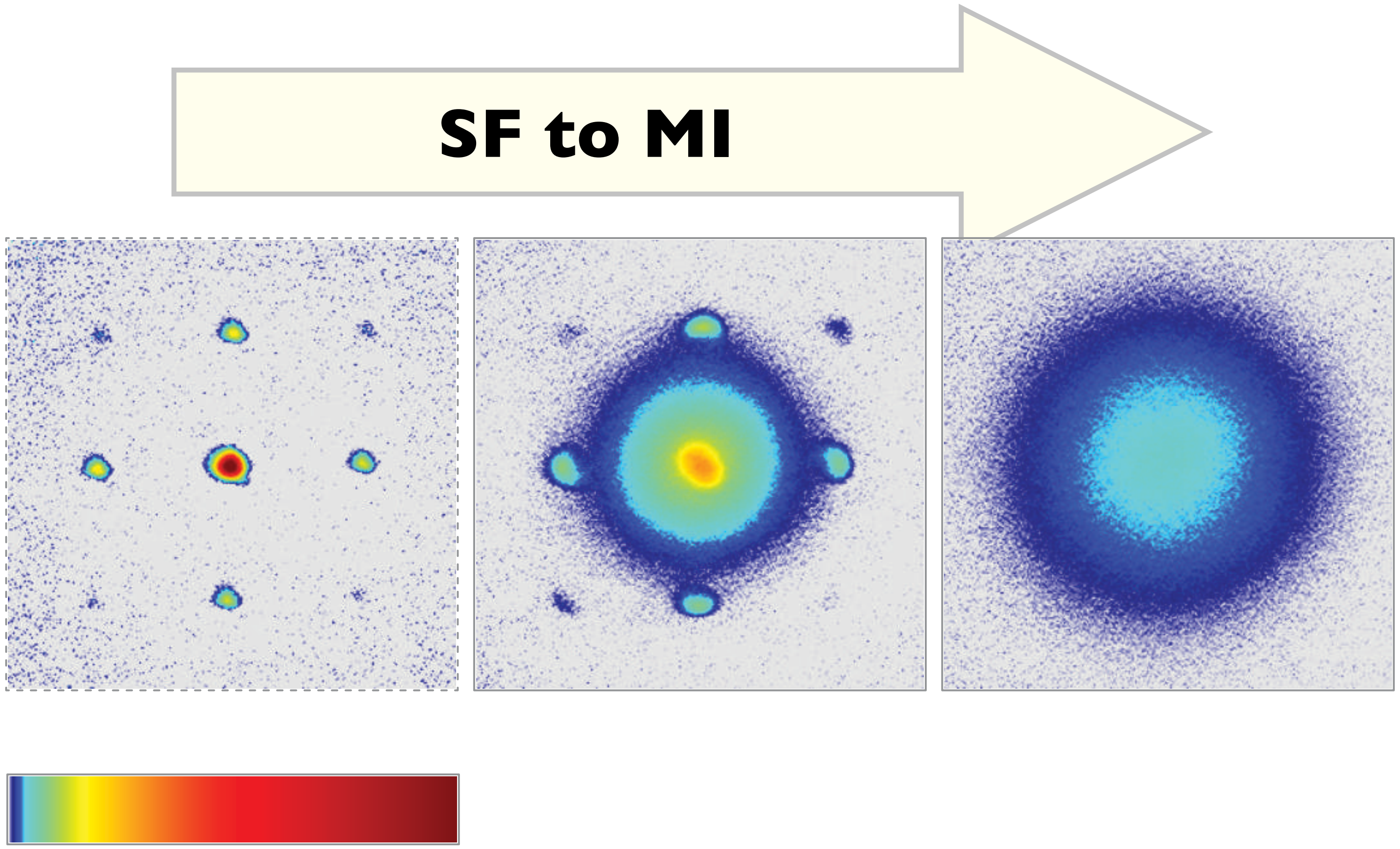


Sequence: A. Rapp, S. Mandt & A. Rosch, PRL (2010)

Experimental Results

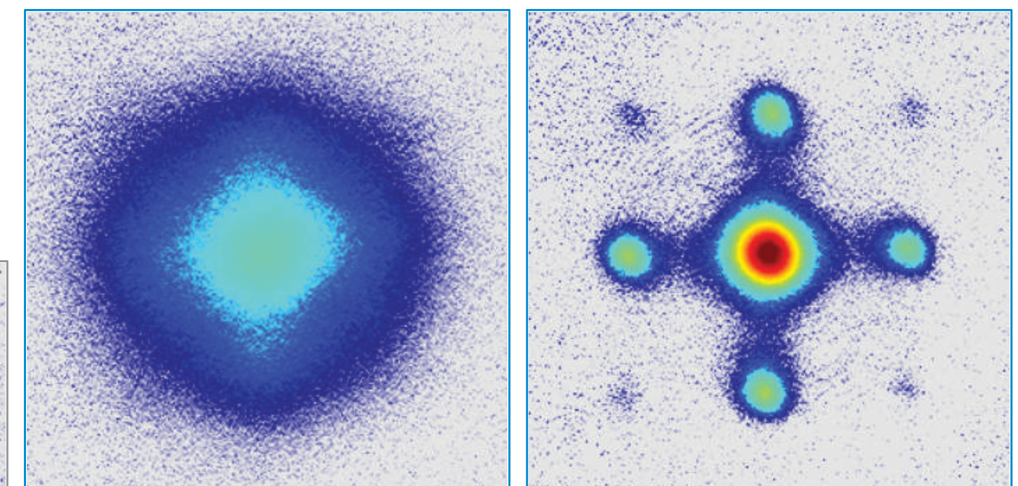


Experimental Results

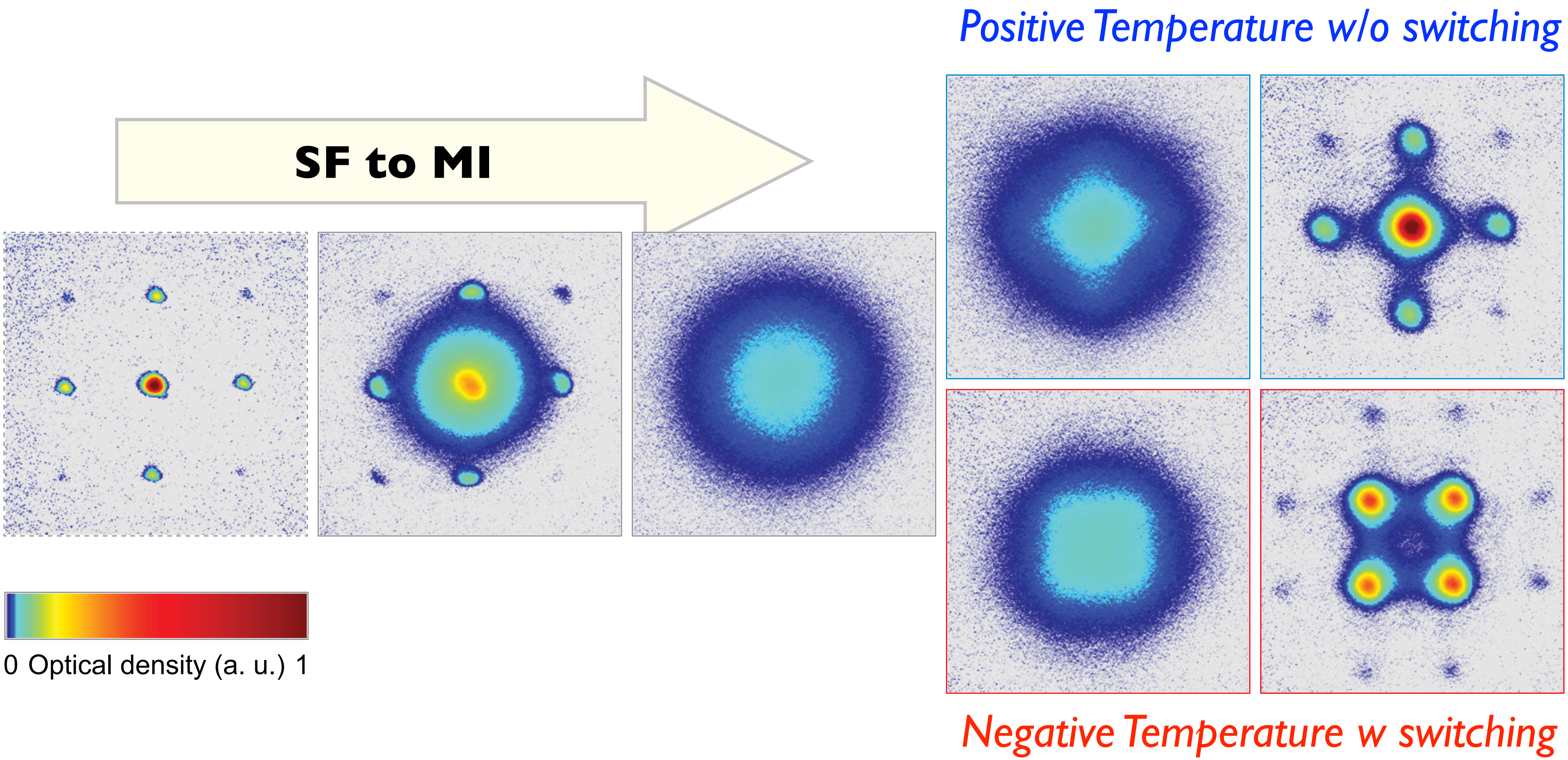


0 Optical density (a. u.) 1

Positive Temperature w/o switching

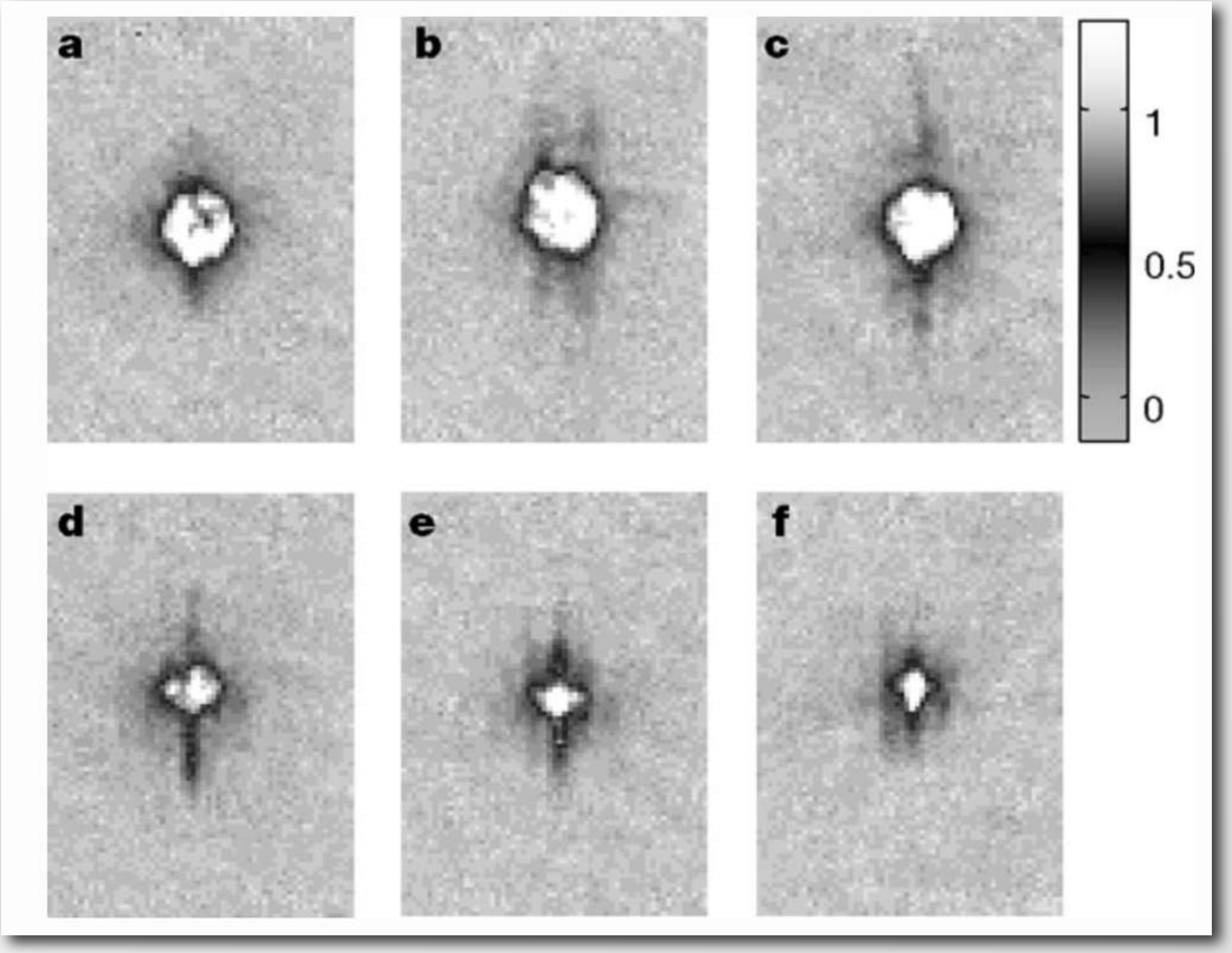


Experimental Results



Collapse of Condensate

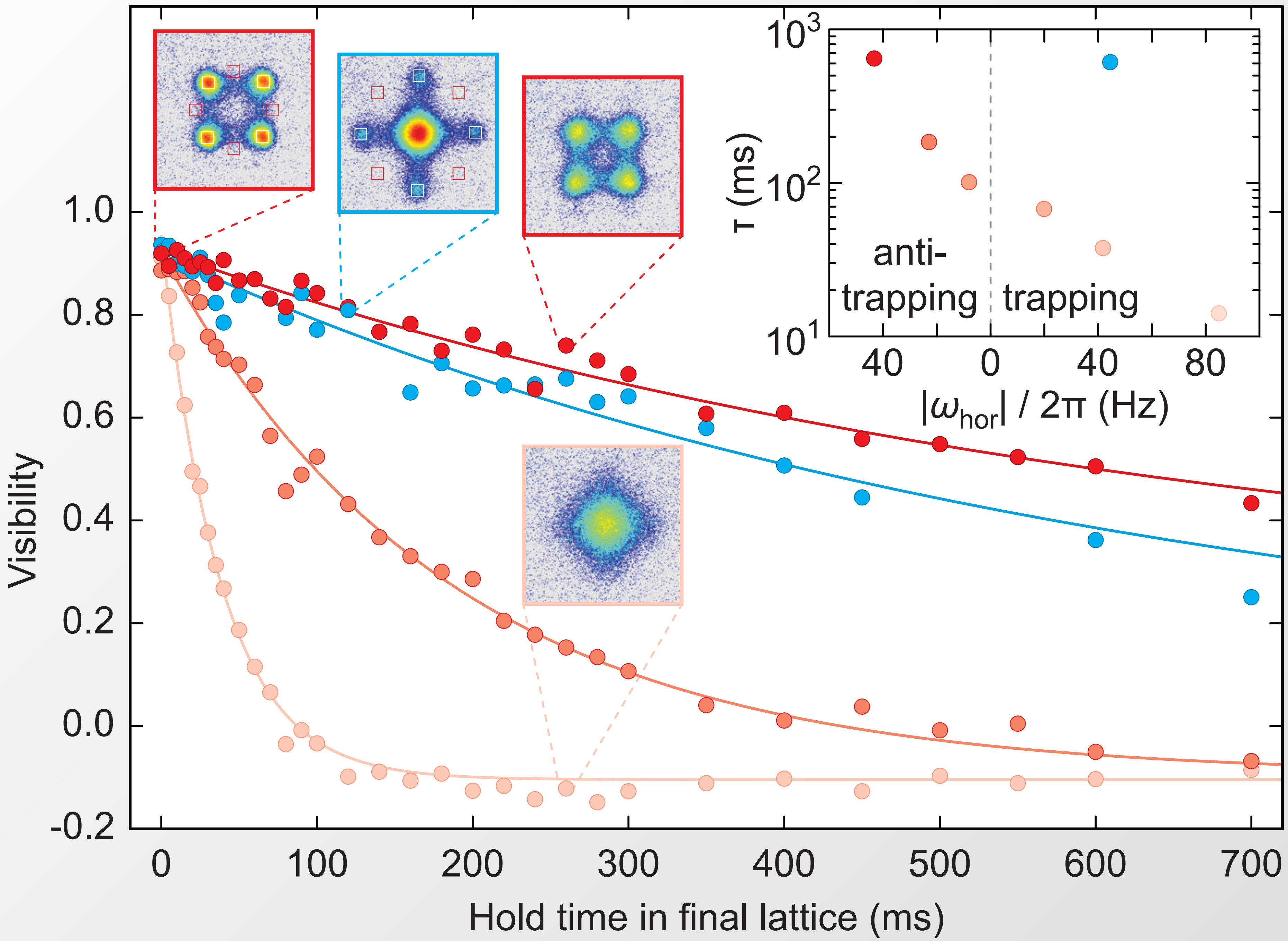
For attractive interactions (a<0), condensate collapses!



E.A. Donley et al. *Nature* **412,** 295-299 (2001)

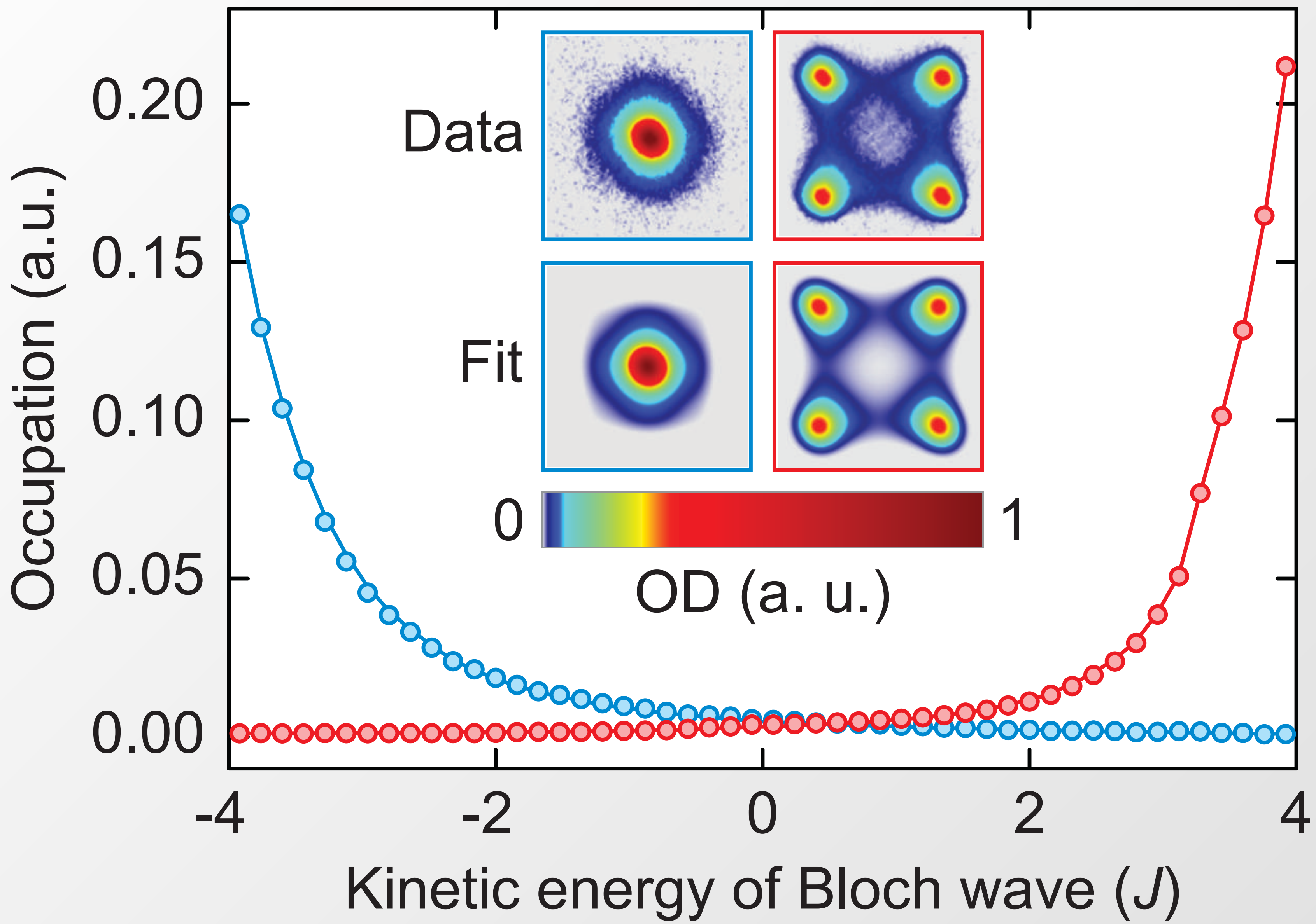
J. M. Gerton et al. *Nature* 408, 692 (2000)

Stability



Negative Temperature State as Stable as Positive Temperature State!

Occupation of Energy States

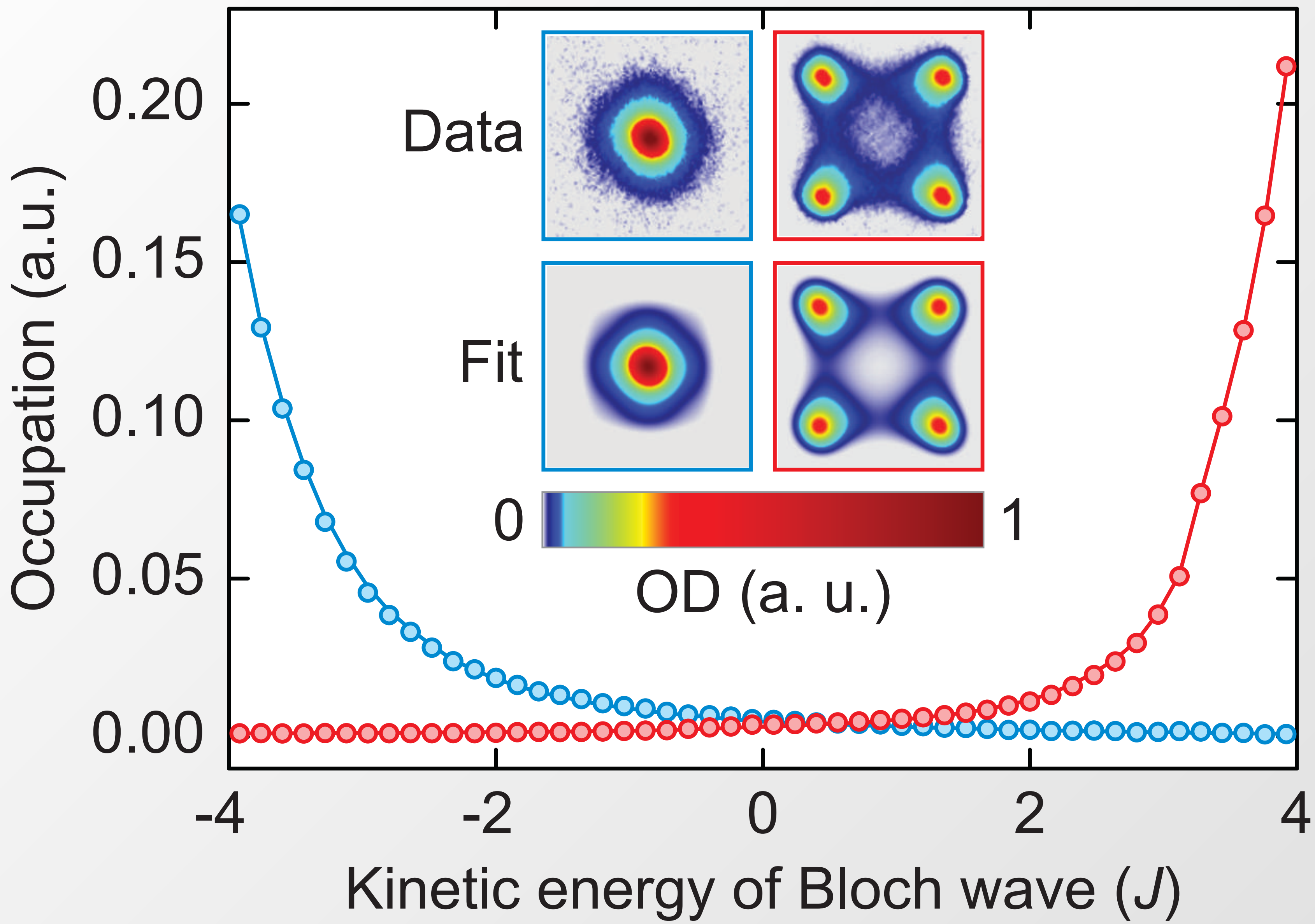


Kinetic energy well fitted by Bose-Einstein distribution

$$n(q_x, q_y) = \frac{1}{e^{(E_{kin}(q_x,q_y)-\mu)/k_B T} - 1}$$

$$E_{kin}(q_x, q_y) = -2J\,[\cos(q_x d) + \cos(q_y d)]$$

Occupation of Energy States



T=-2.2J/k_B

Kinetic energy well fitted by Bose-Einstein distribution

$$n(q_x, q_y) = \frac{1}{e^{(E_{kin}(q_x,q_y)-\mu)/k_B T} - 1}$$

$$E_{kin}(q_x, q_y) = -2J\left[\cos(q_x d) + \cos(q_y d)\right]$$

Implications

Gases with **negative temperature** possess **negative pressure**!

$$\left.\frac{\partial S}{\partial V}\right|_E \geq 0 \qquad \text{and} \qquad dE = TdS - PdV$$

$$\Rightarrow \left.\frac{\partial S}{\partial V}\right|_E = \frac{P}{T} \geq 0$$

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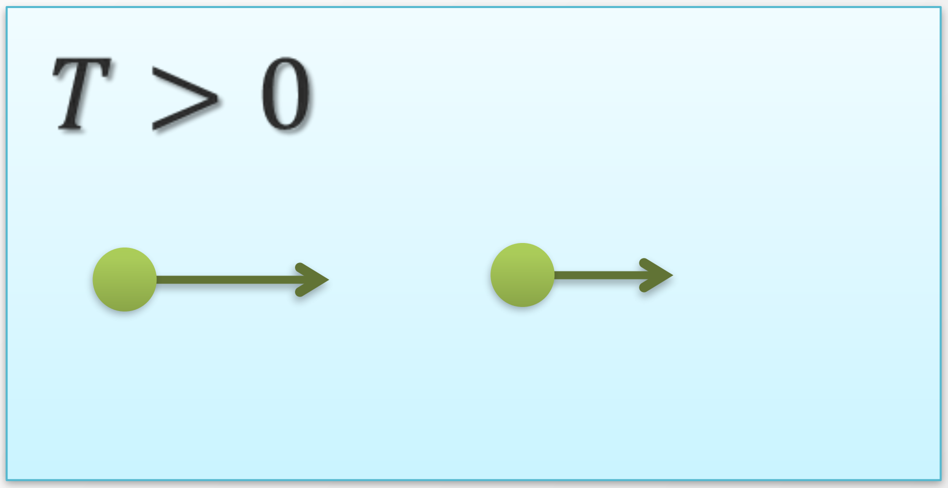
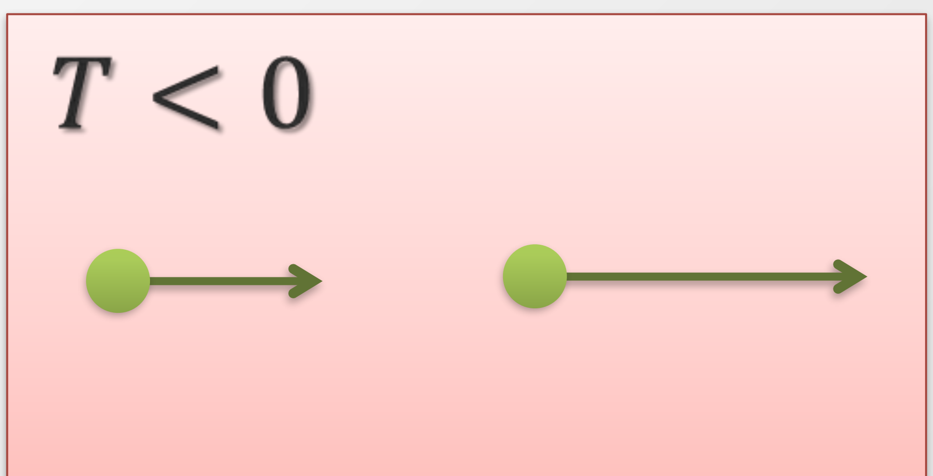
Some statements for the second law of thermodynamics become invalid!

Anti-Friction at Negative Temperature



Friction:

- entropy increases
  → Medium heats up
- Particle slows down



particle spectrum is
assumed to be unbounded

Anti-Friction:

- entropy increases
  → Medium cools down
- Particle accelerates

(but direction is randomized
in long-term limit)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