Title: Time and Einstein in the 21st Century: The coolest stuff in the universe

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Abstract: At the beginning of the 20th century Einstein published three revolutionary ideas that changed forever how we view Nature. At the beginning of the 21st century Einstein\'s thinking is shaping one of the key scientific and technological wonders of contemporary life: atomic clocks, the best timekeepers ever made. Such super-accurate clocks are essential to industry, commerce, and science; they are the heart of the Global Positioning System (GPS), which guides cars, airplanes, and hikers to their destinations. Today, atomic clocks are still being improved, using Einstein\'s ideas to cool the atoms to incredibly low temperatures. Atomic gases reach temperatures less than a billionth of a degree above Absolute Zero, without solidifying. Such atoms enable clocks accurate to better than a second in 60 million years as well as both using and testing some of Einstein\'s strangest predictions. This will be a lively, multimedia presentation, including experimental demonstrations and down-to-earth explanations about some of today\'s most exciting science. <kw> Low temperature physics, atomic clock, global positioning system, laser cooling, Bose Einstein condensate, photoelectric effect, Brownian motion, special relativity </kw>

Time and Einstein in the 20th Century:
the coolest stuff in the universe

Perimeter Institute
Waterloo, 4 June 2008

William D. Phillips
Joint Quantum Institute
National Institute of Standards and Technology, Gaithersburg, MD
University of Maryland, College Park, MD

NIST Laser Cooling and Trapping Group:
Kris Helmerson, Paul Lett, Trey Porto, Ian Spielman

$upport: NIST, Office of Naval Research

NIST Physics Laboratory

NIST laser cooling group

Celebrating 1905, Einstein's miraculous year of three revolutionary ideas.

World Year of PHYSICS 2005

- Photoelectric effect
- Brownian motion
- Special relativity

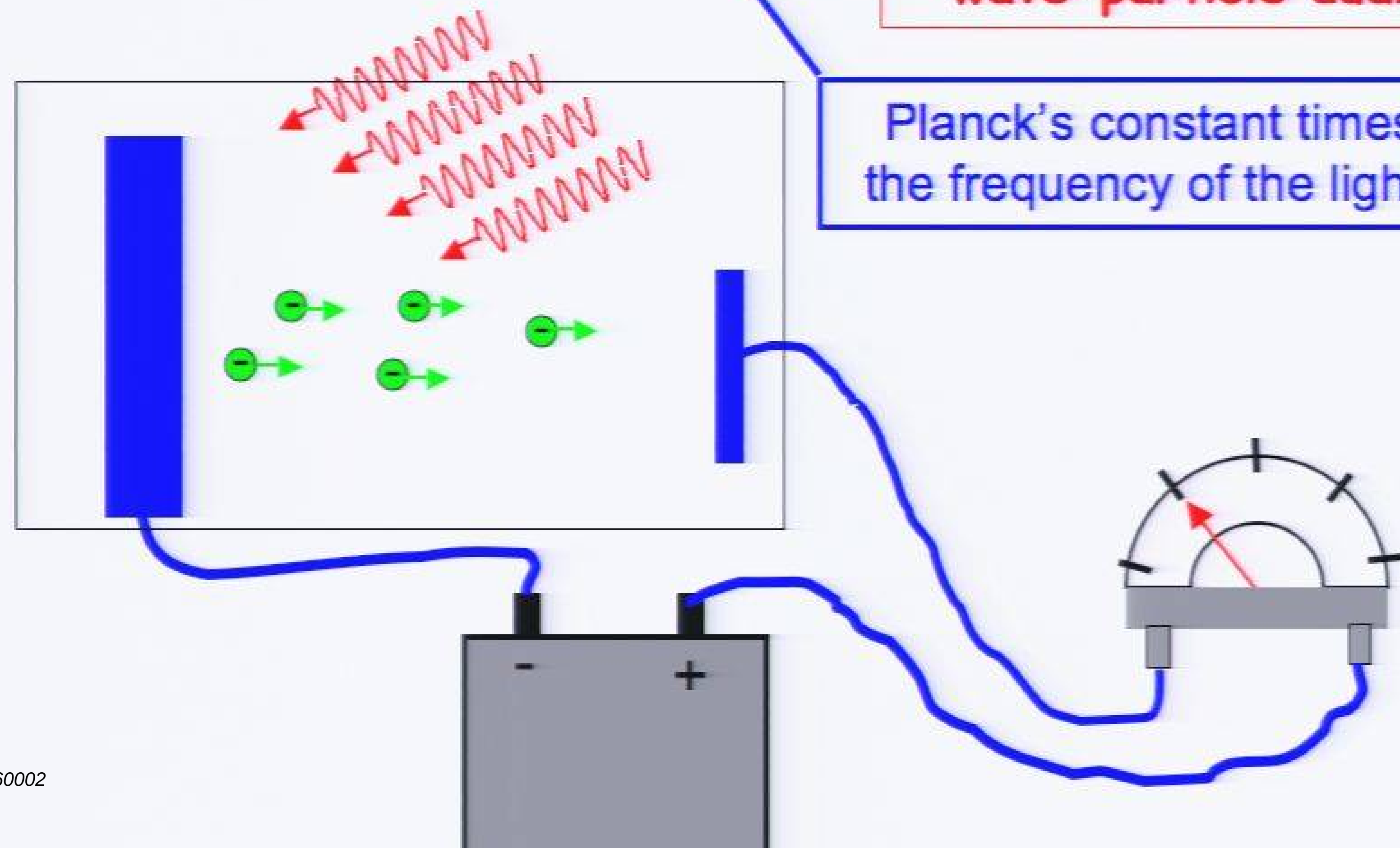
www.physics2005.org

Photoelectric Effect

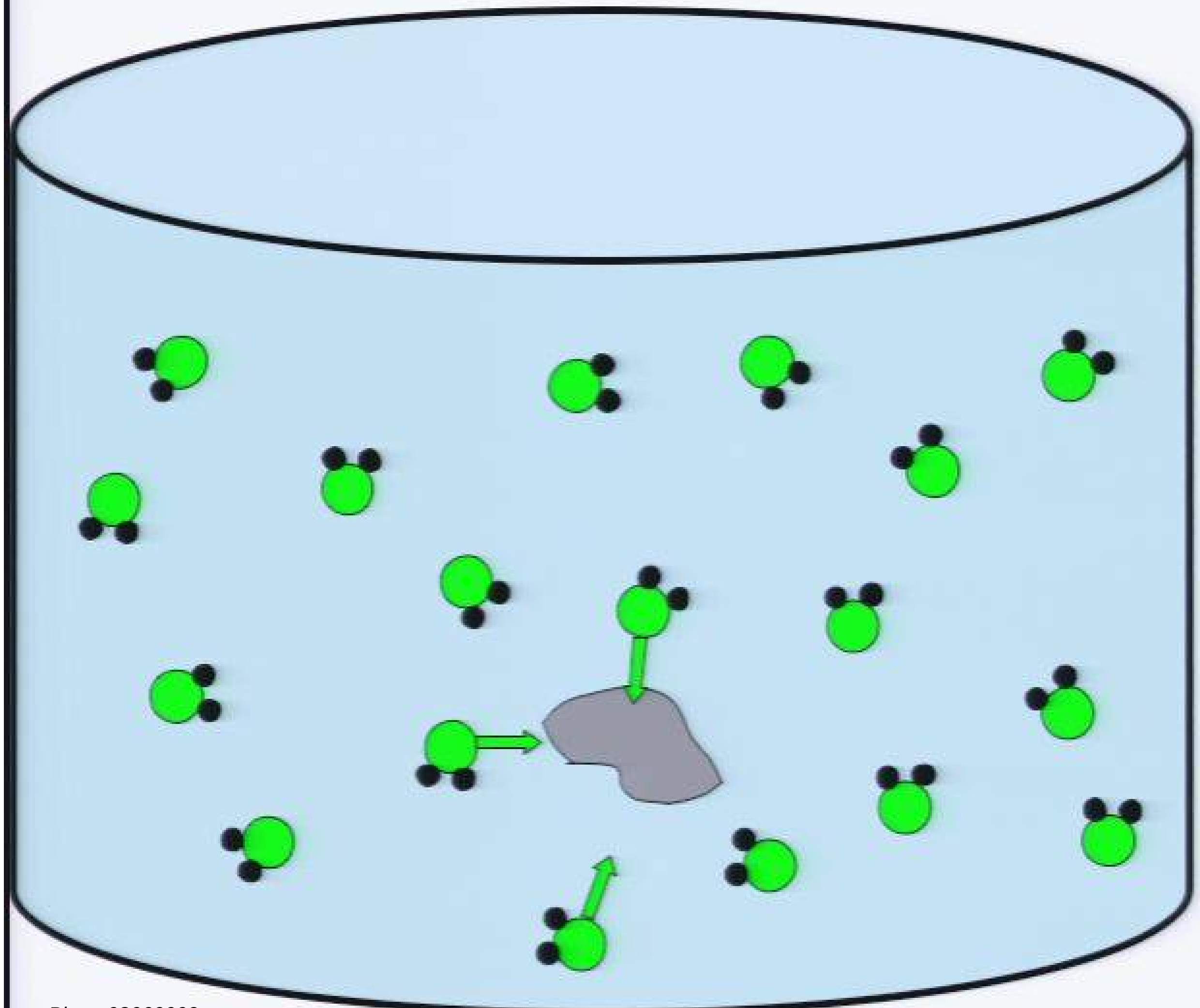
Einstein explained the light-induced emission of electrons from a metal as single particles of light (now called photons) delivering their energy, *hν*, to the electrons in the metal.

This was the beginning of wave-particle duality.

Planck's constant times the frequency of the light.



Brownian Movement

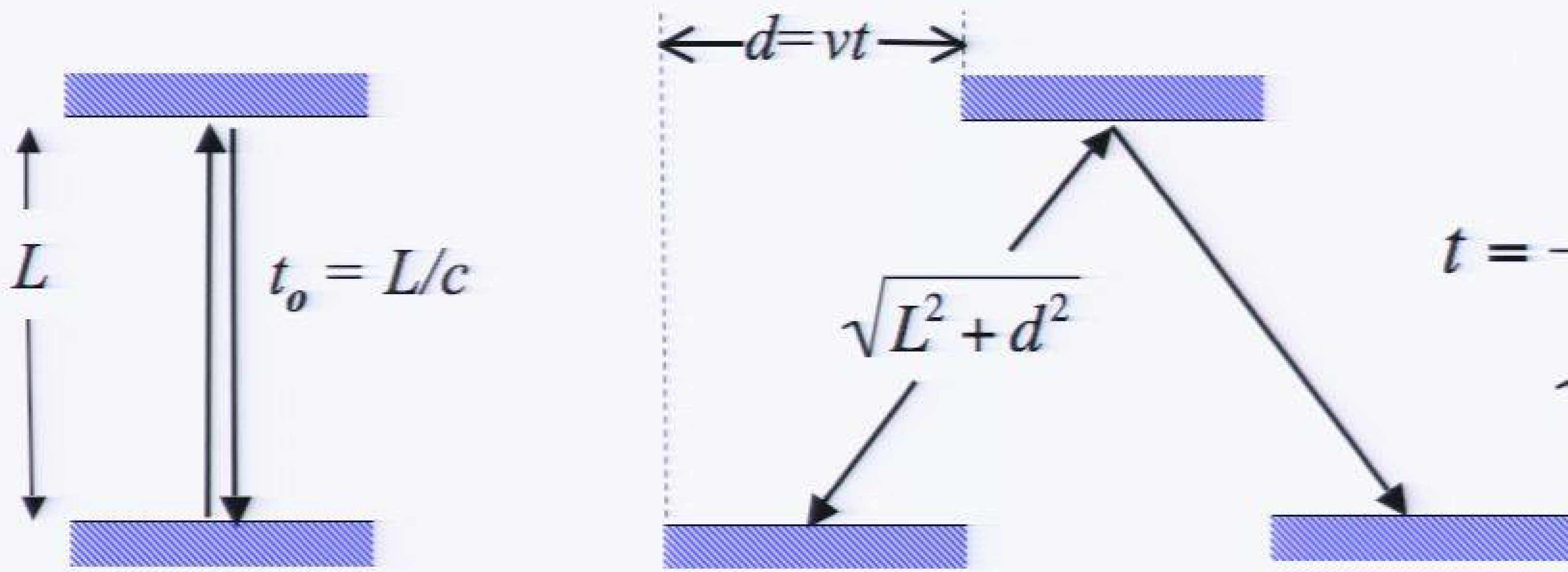


Einstein explained the jiggling of tiny particles suspended in water as coming from the random impacts of the water molecules. This was the most convincing evidence for the atomic/molecular theory of matter.

Special Relativity

Einstein assumed that the laws of physics are unchanged when you move with constant velocity and that the speed of light in vacuum is always the same. Asking “what is time?” and concluding that “time is what a clock measures” he changed our concepts of both space and time.

Consider a clock whose “tick” is the time for light to go between two mirrors.



$$t = \frac{t_o}{\sqrt{1 - \frac{v^2}{c^2}}}$$

Like Einstein, we are interested in time and clocks

At NIST, making clocks, standards of time, is our business. Throughout history, clocks have continually improved.

Harrison's H4 won the famous £20 000 Longitude Prize in the 18th century. The prize required 2 minutes accuracy on a voyage from Great Britain to the West Indies

Trials in 1762 and 1764 won the prize (39.2 s in 47 days in 1764)

Today, most quartz watches are better than H4!

All of these clocks are imperfect.

The length of a pendulum may stretch or shrink.

Each quartz crystal is a little different from all others, and may change with heat, humidity, ...

Even the rotation of the earth is slowed by tides and affected by storms and ocean currents.

Atoms also "tick."

Atoms "vibrate" at specific frequencies, and all atoms of the same kind vibrate at the same frequency.

Every quartz watch is a little different from every other one. Every ^{133}Cs atom (the atom used to define time) is absolutely identical to every other one in the universe. And atoms are little affected by the environment.

Atom tickers make the best clocks.

How good are these clocks?

For less than $100 you get a quartz watch good to better than 10^{-6}, or 30 seconds/year

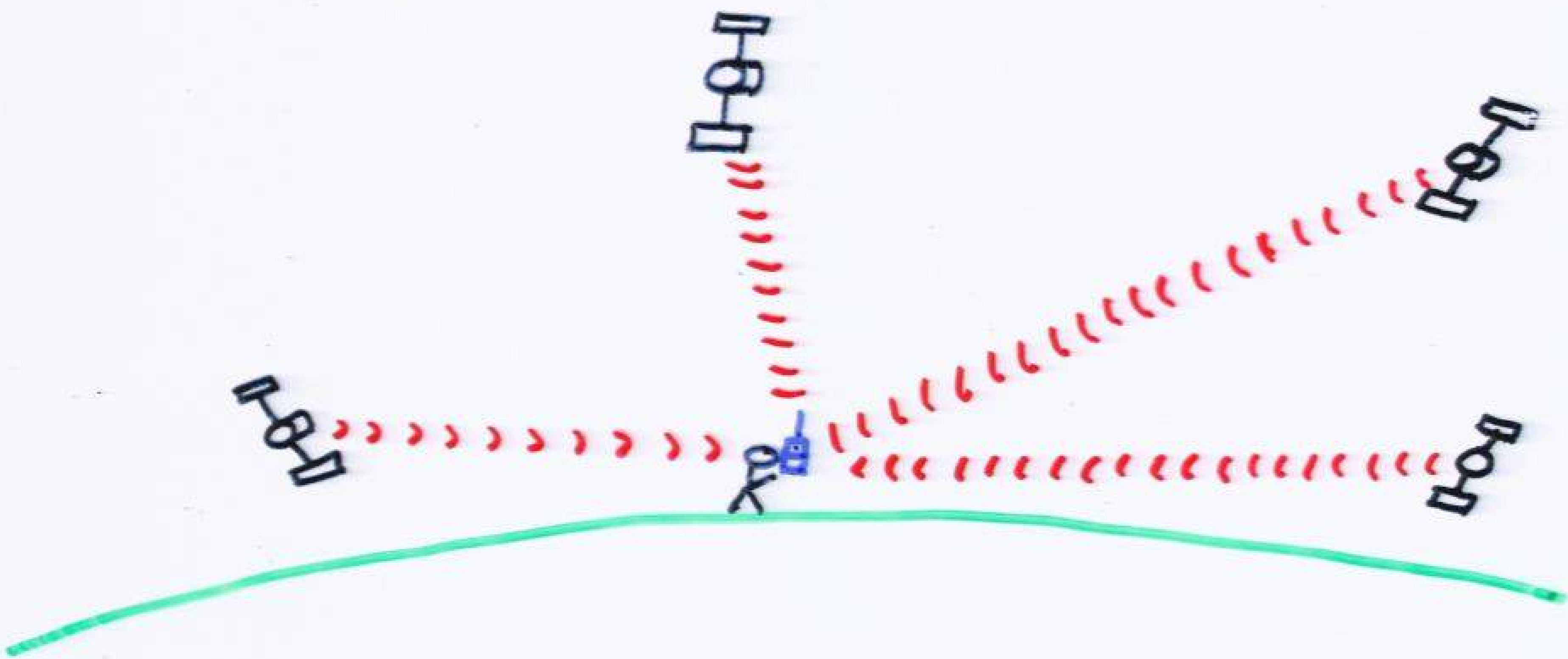
For around $100,000 you can buy an atomic clock good to 10^{-12} or 30 seconds/million years

Who needs a clock that good?

My goodness, it's 12:15:0936420175. Time for lunch

courtesy Ford Motor Company

Today, super-accurate atomic clocks aboard a constellation of 24 earth satellites ensure reliable navigation of ships at sea, plus military and civilian land and air transport.



Einstein and GPS

When Einstein first formulated the theory of General Relativity it was considered so complicated and esoteric that the press claimed only three people in the world understood it.

Today, without an understanding of the results of General Relativity, the Global Positioning System would be off by kilometers.

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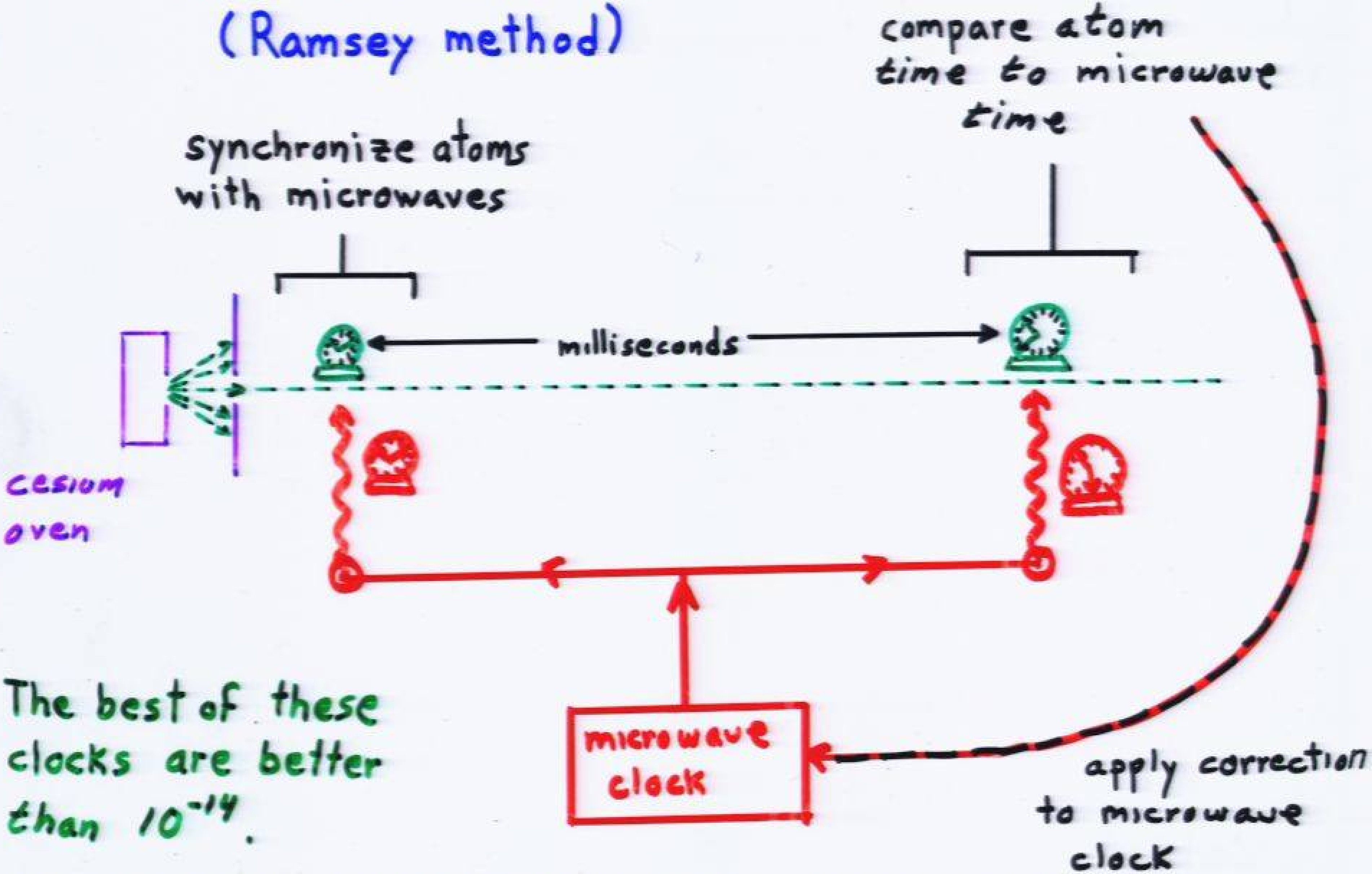
General Relativity allows you to find your car in a crowded parking lot.

What do these GPS clocks look like?

ATOMIC CLOCK

(Ramsey method)



The best of these clocks are better than 10^{-14}.

Atomic motion (~200 m/s) limits performance because of observation time, Doppler shifts, and time dilation.

Doppler Effect

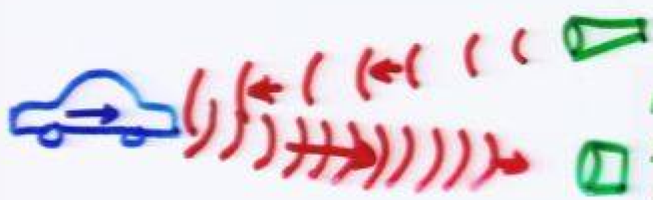
clock, broadcasting "ticks" at frequency f

moving receiver, sees ticks at $f(1+v/c)$

↑ speed of light

whether the receiver moves or the transmitter moves, there is a Doppler shift.

This effect allows police to measure the speed of your car.



radar transmitter

radar receiver-sees a higher frequency

Fractional Doppler Shift

$$\frac{\Delta f}{f} = \frac{v}{c}$$

Atom velocity (v)

Speed of light (c)

$V_{\text{thermal}} \cong 300$ m/s

$c = 3 \times 10^{8}$ m/s

So, $\frac{\Delta f}{f} = 1 \times 10^{-6}$ A disaster !

Various tricks reduce this a lot, but do not eliminate it.

Time dilation shift

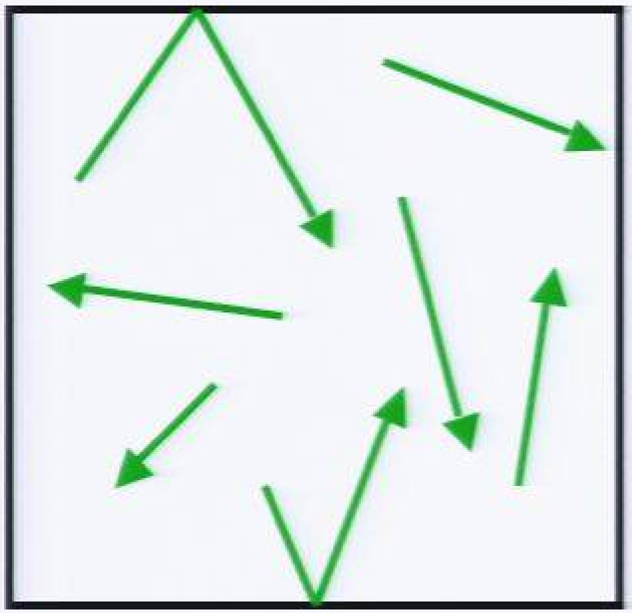
Einstein's theory of relativity tells us that moving clocks run slow

(recall the twin "paradox")

$$\frac{\Delta f}{f} = -\frac{1}{2}\frac{v^2}{c^2} \approx 10^{-12}$$

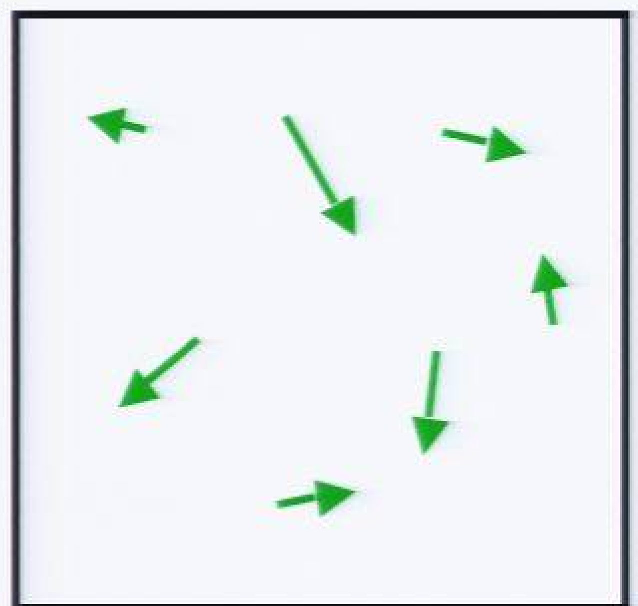
There are no tricks to get rid of this shift.
We must reduce the velocity!

Hot and Cold



HOT:

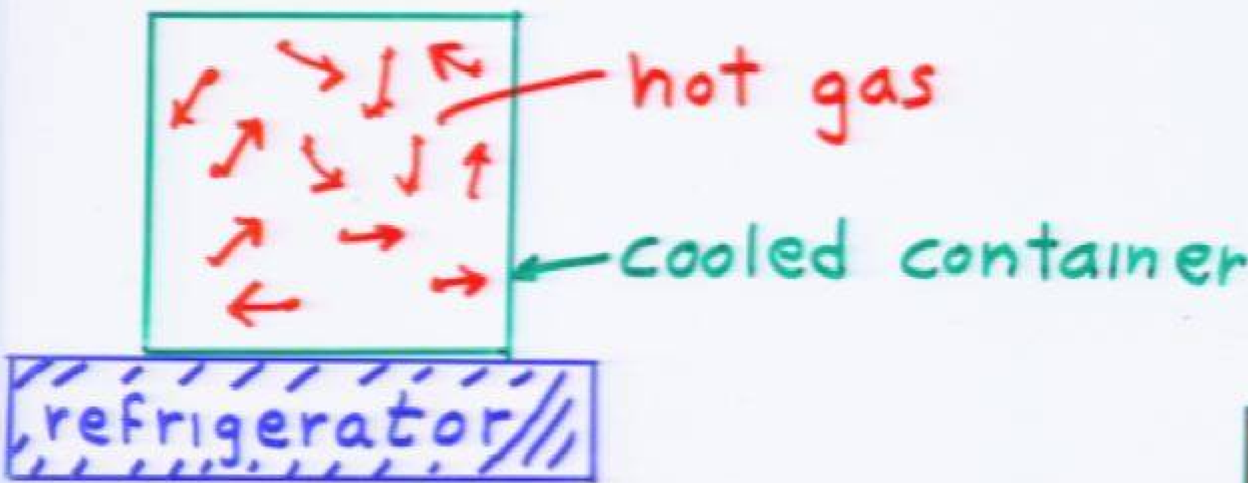
fast atoms

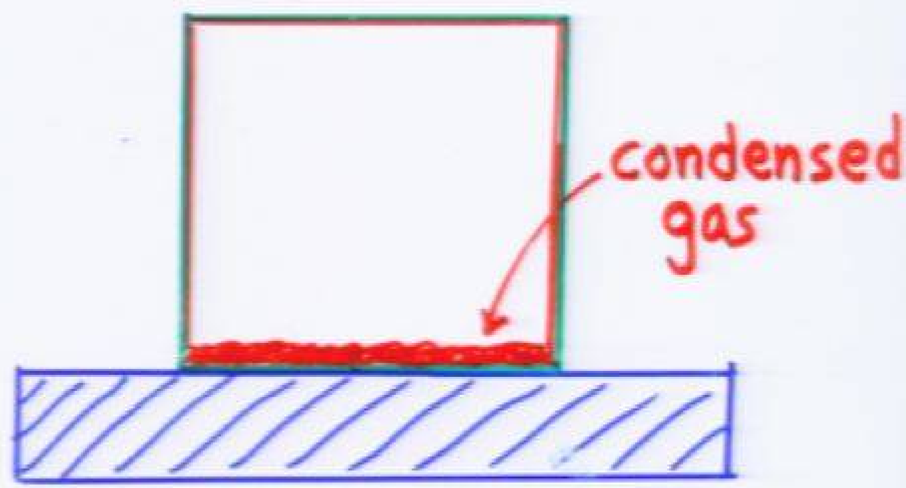


COLD:

slow atoms

We cannot use conventional refrigeration to cool a gas to millikelvin temperatures:





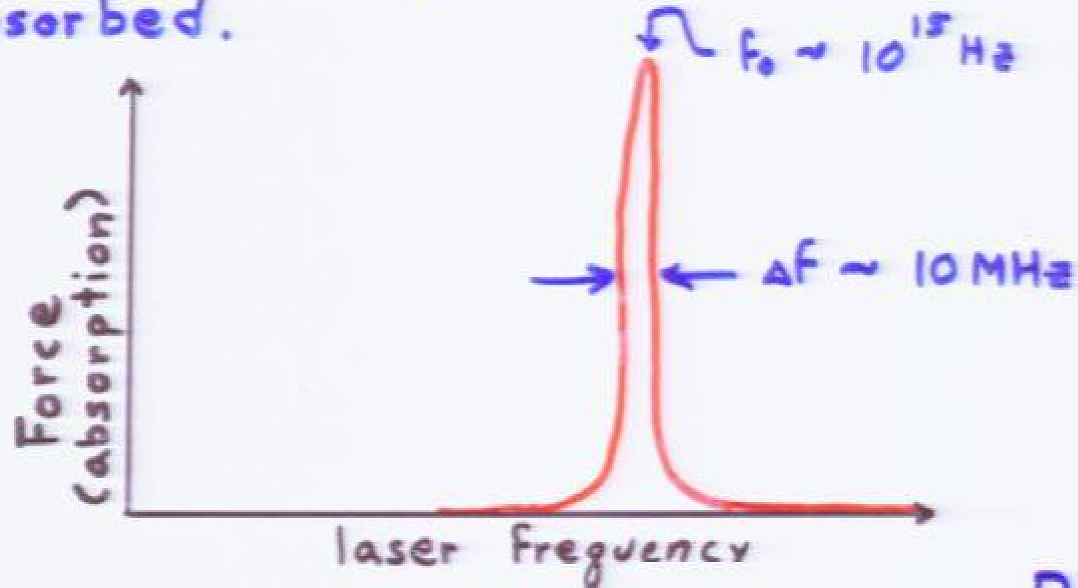
How do we cool something without touching it?


Comet photo courtesy NASA

We use the pressure of light to push on atoms and slow them down.

Resonance

Light exerts a force on atoms, but only when absorbed; only light of specific frequencies (color) is absorbed.

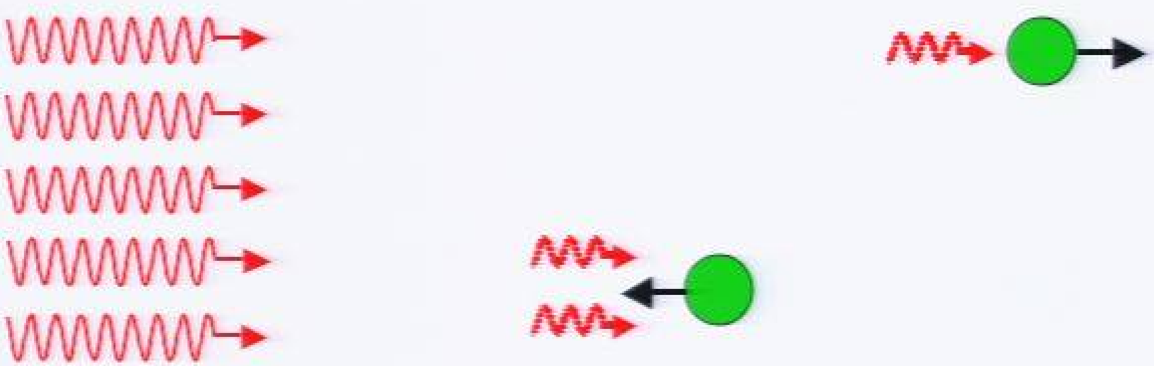


Doppler Shift

observer moving toward a light source sees it as having a higher frequency (bluer)

Laser Cooling (1975)

Wineland & Dehmelt and Hänsch & Schawlow



laser beam tuned
below resonance

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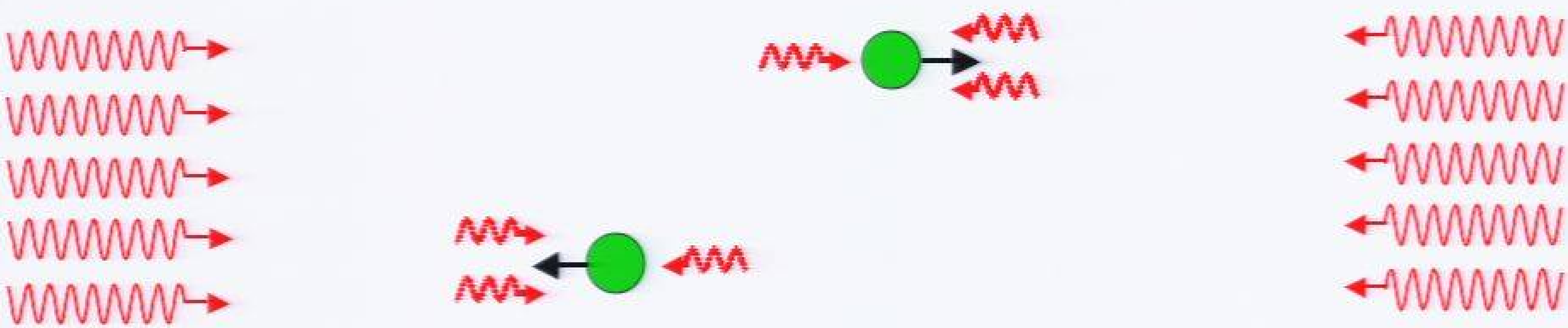

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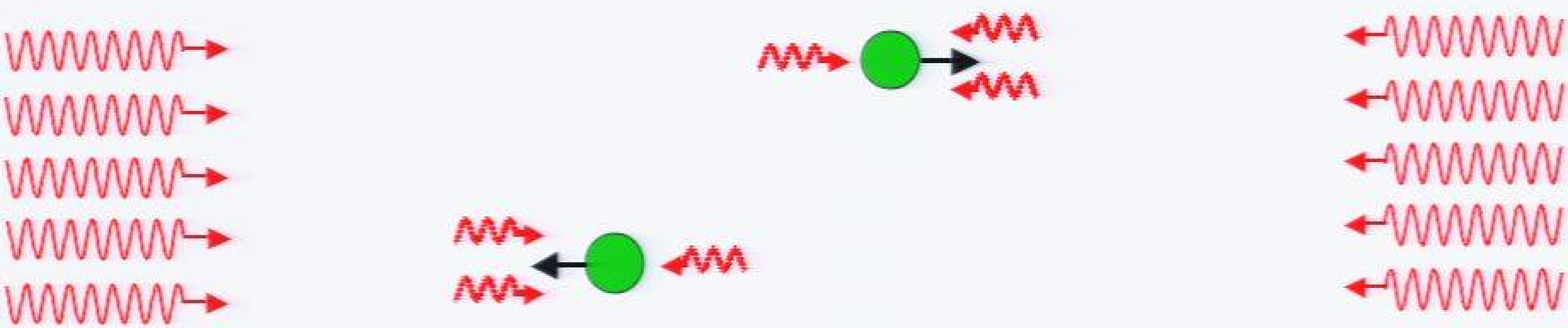
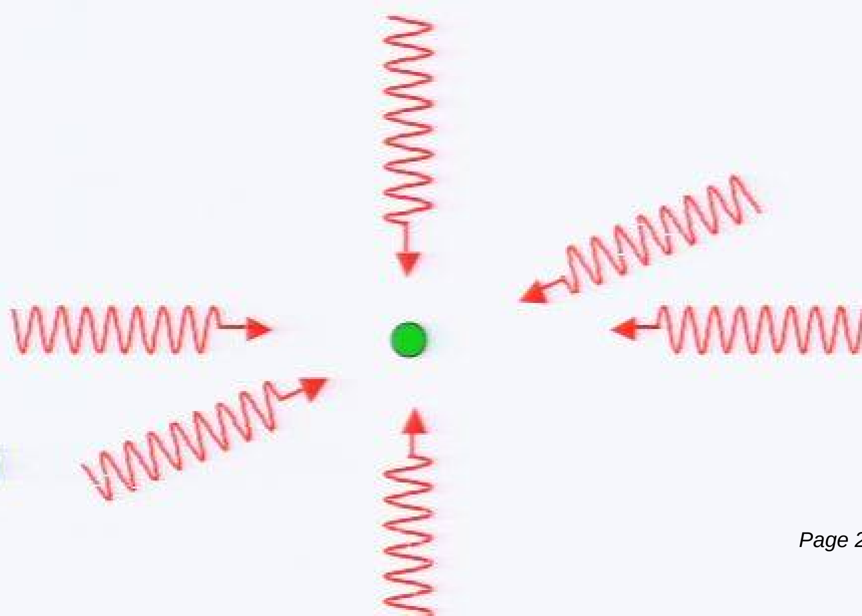


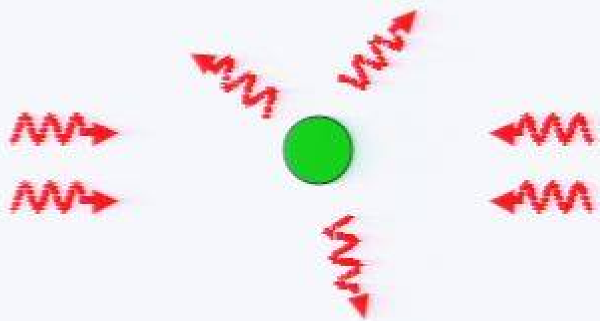
laser beam tuned
below resonance



Optical Molasses
Chu *et al*. 1985

Laser Heating

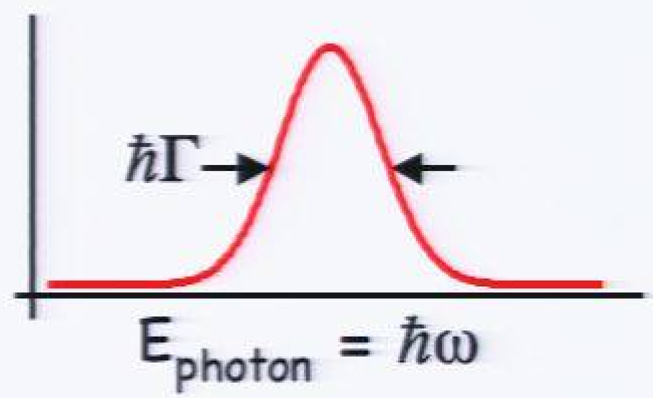
Letokhov, Minogin, and Pavlik (1977); Wineland and Itano (1979)



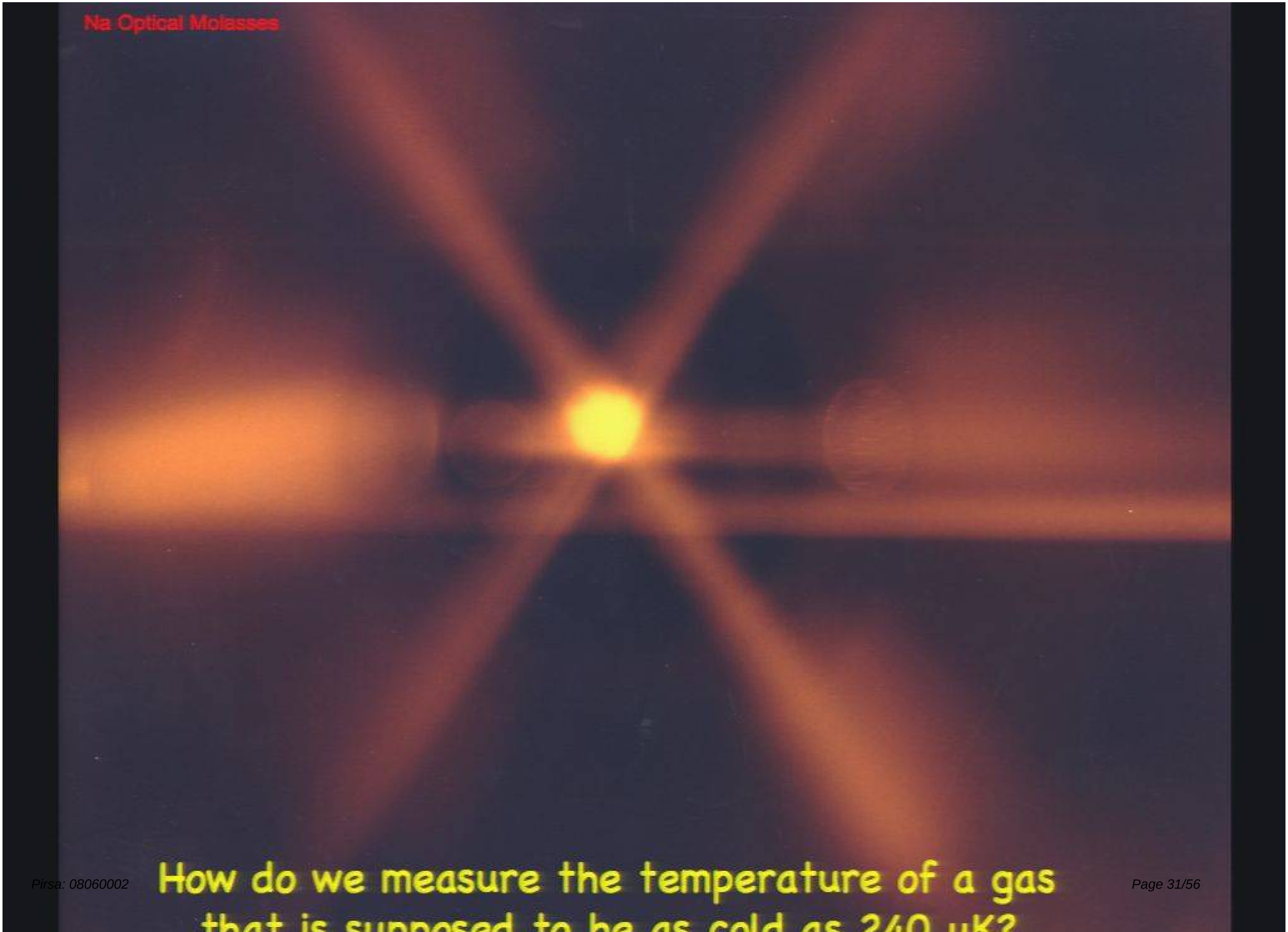
Randomness of absorption and emission HEATS the atoms.

Doppler COOLING balances the heating, producing equilibrium at a temperature, T_{Dopp}

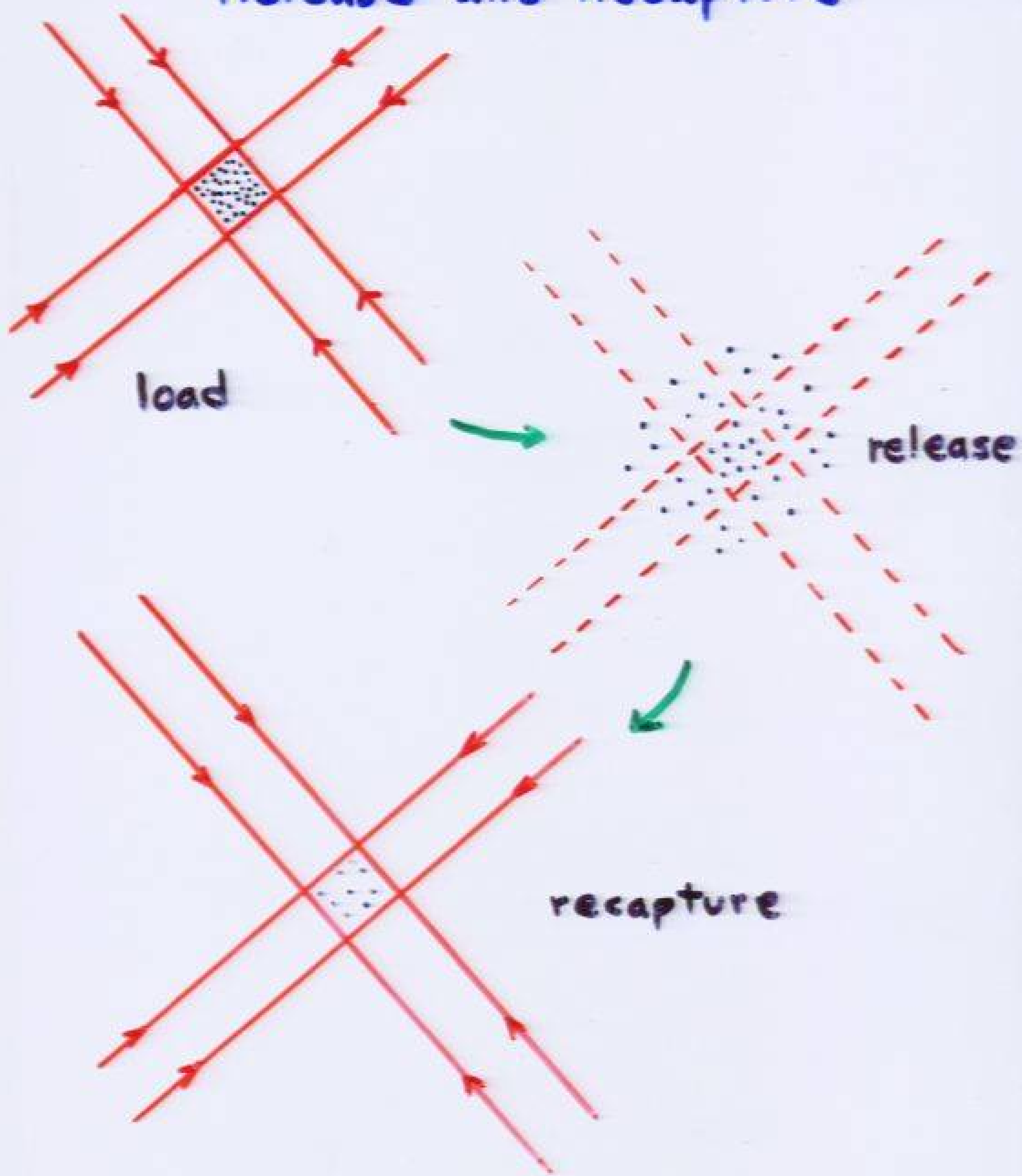
"Doppler Limit" $k_B\ T_{Dopp} \geq \hbar\Gamma$



For Na, $T_{Dopp} \geq 240\ \mu K$; $v_{thermal} = 30\ cm/s$


Na Optical Molasses
How do we measure the temperature of a gas
that is supposed to be as cold as 240 μK?

Temperature measurement by Release and Recapture



Laser-Cooling Temperatures by Release-and-Recapture

Bell Labs (1985):

S. Chu, L. Hollberg, J. Bjorkholm, A. Cable, Art Ashkin

$$T = 240^{+200}_{-60}\ \mu K$$

NBS-Gaithersburg (1987)

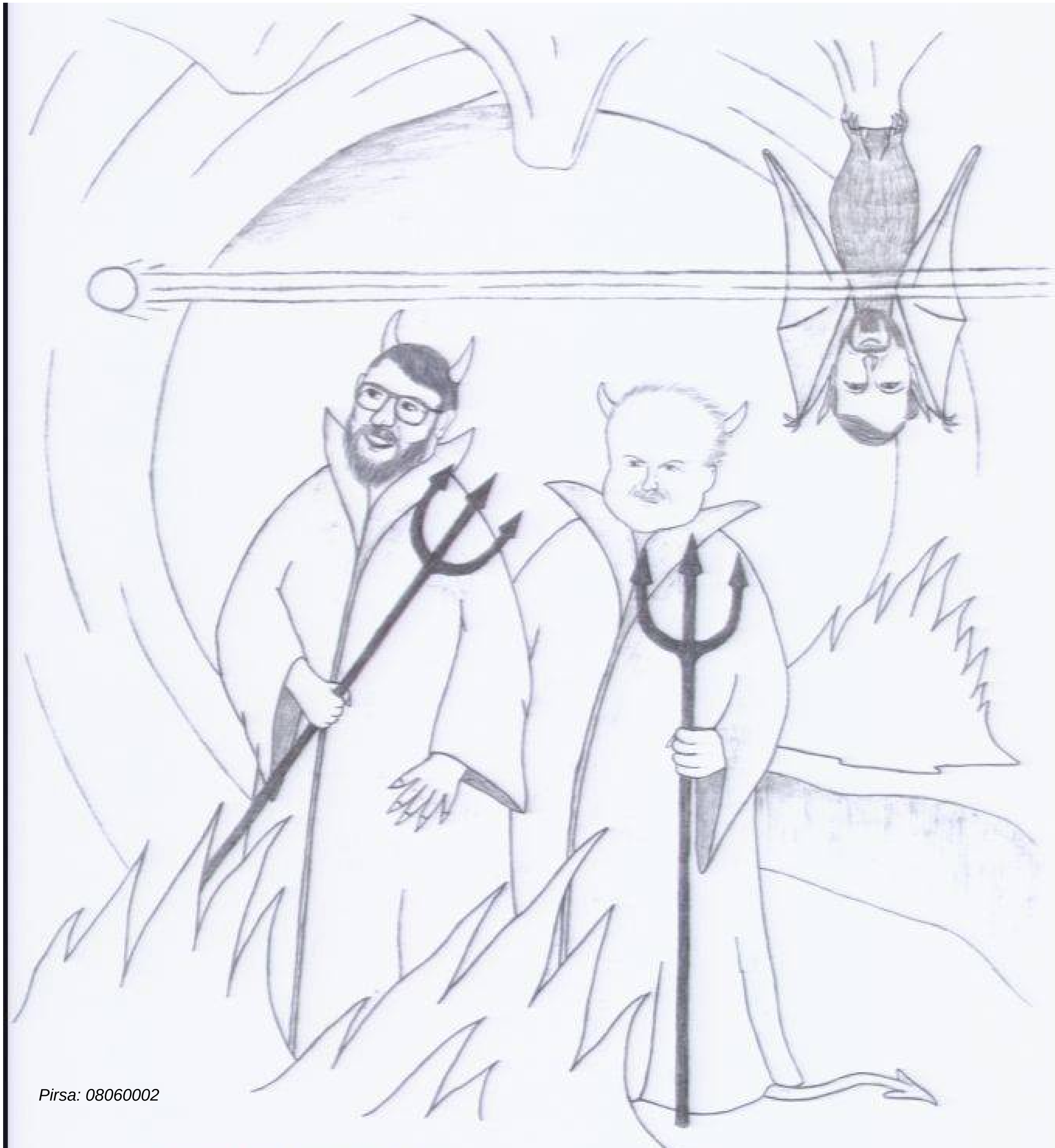
$$T \approx 240\ \mu K$$

other measurements were consistent with Doppler-cooling theory....

until ...

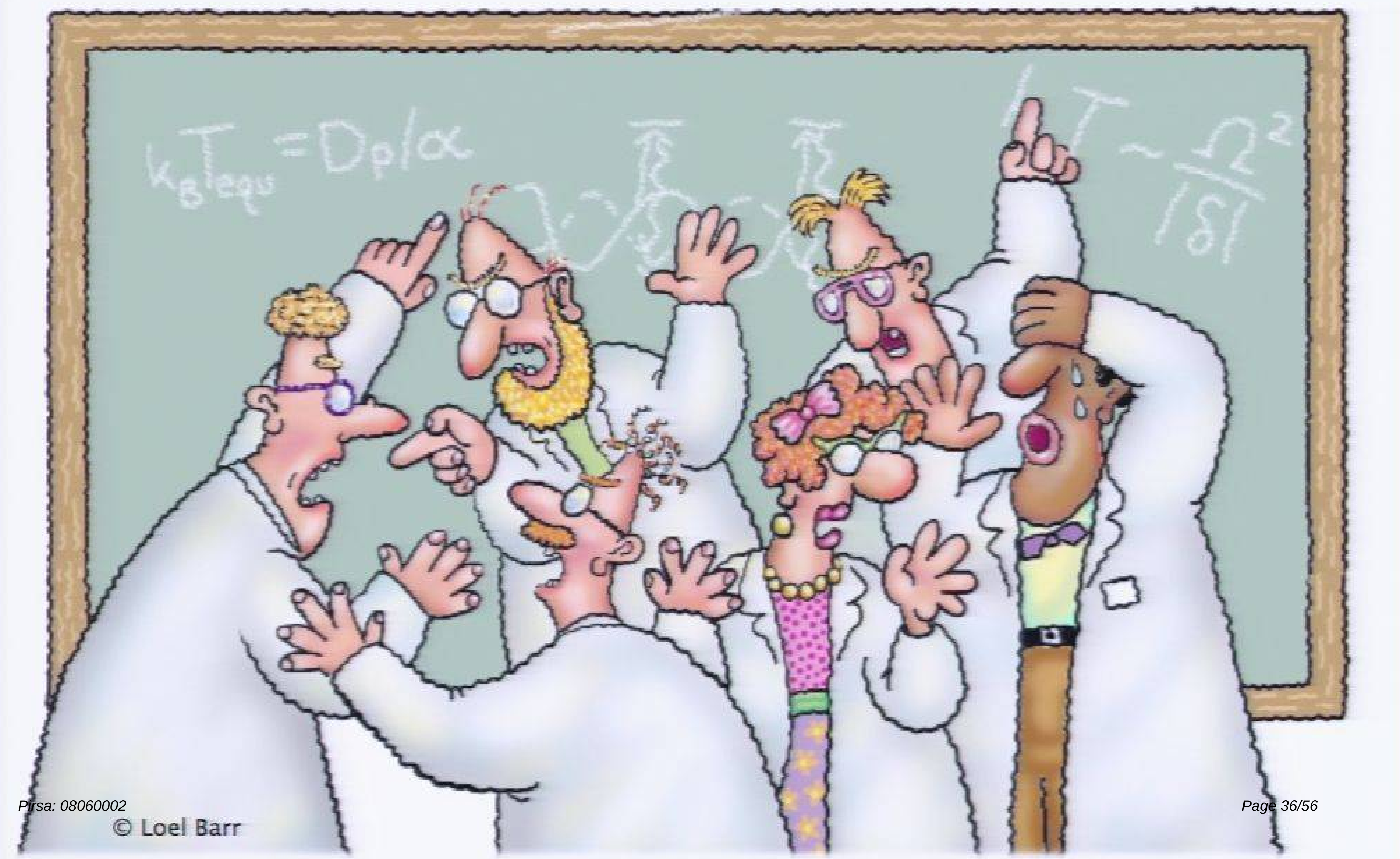
Unexpectedly, we discovered in 1988 that the temperatures could be much colder than had been predicted.

This was an astounding violation of Murphy's Law



"Look Hal, another snowball !!... I tell you, this place is slipping."

Heated discussions about the nature of laser cooling ensued. Eventually a new theory emerged.



How cold can we get?

By 1995 we had cooled Cs atoms to

T = 700 nK! (about 200 times colder than expected)

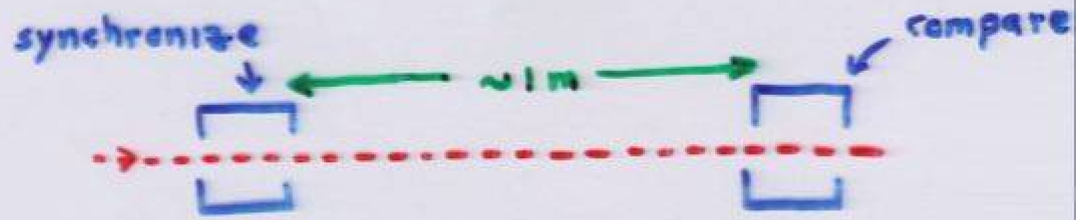
(The lowest temperature is related to the "recoil" energy)

- A hundred million times colder than liquid nitrogen
- 4 million times colder than outer space
  (3 K cosmic background)

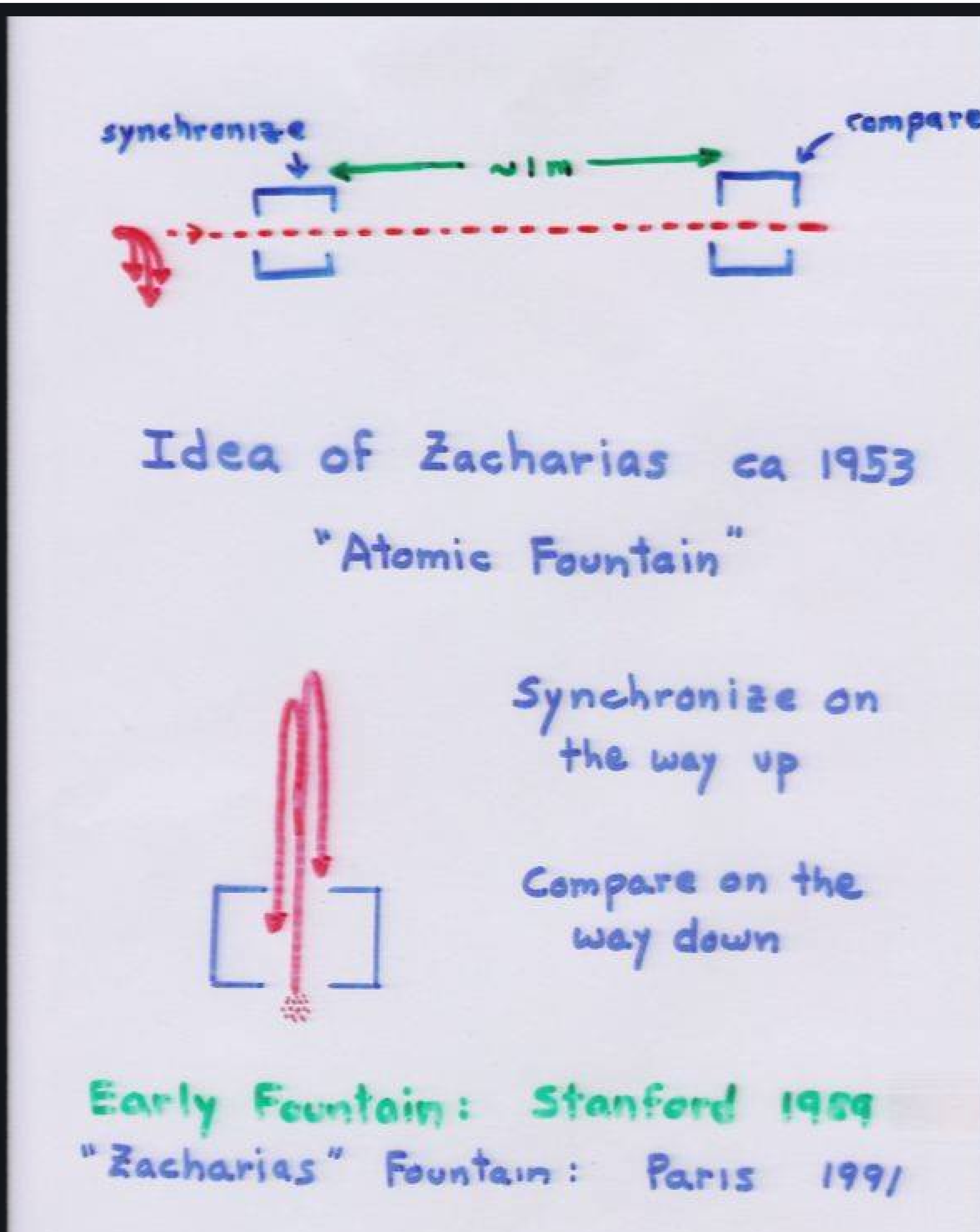
The thermal velocity of these atoms is

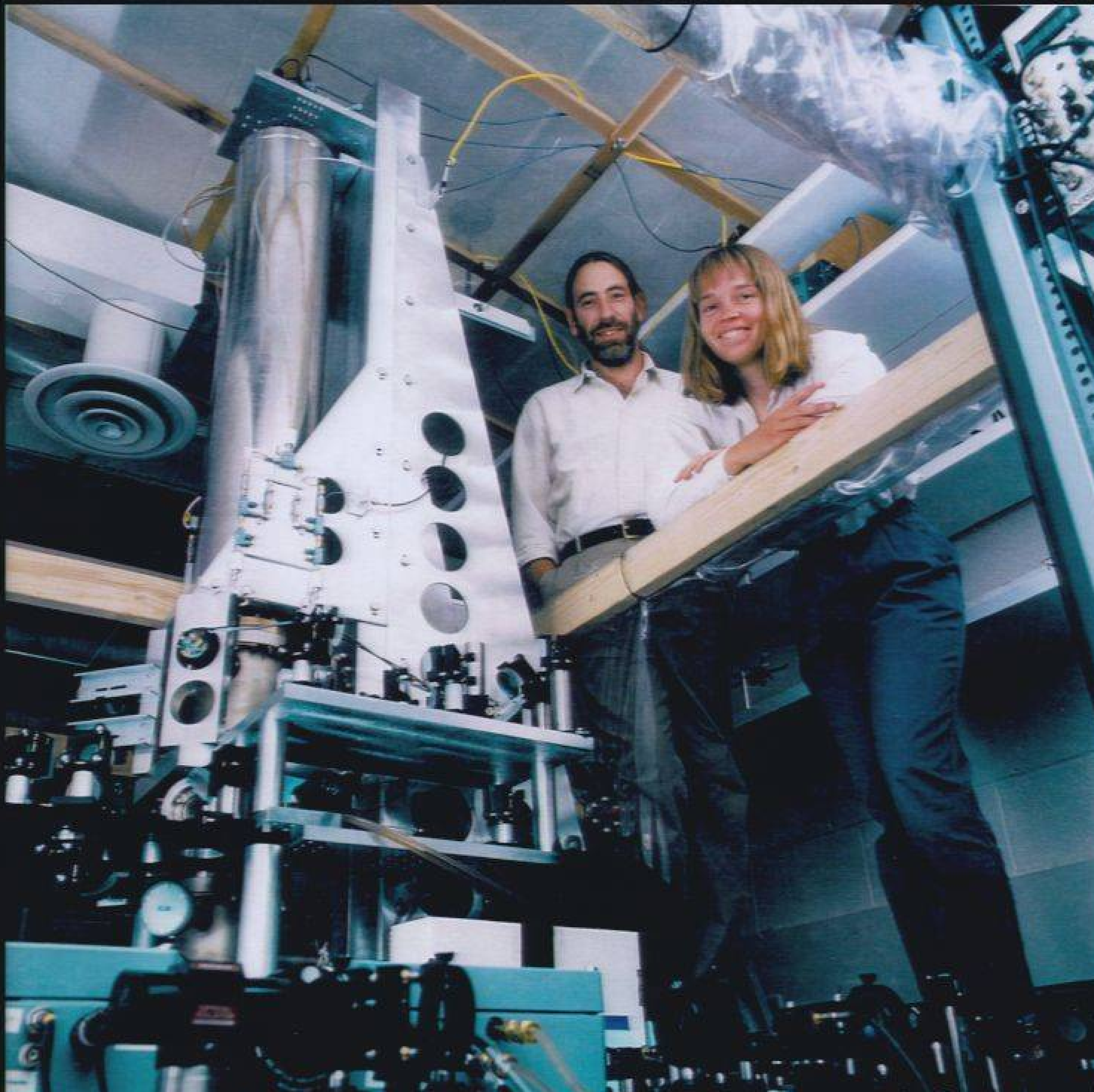
$$V_{thermal} < 1 \text{ cm/s}$$

What sort of clock can we make with atoms this cold?


synchronize
~1m
compare

Zacharias


synchronize
~1m
compare
Idea of Zacharias ca 1953
"Atomic Fountain"
Synchronize on the way up
Compare on the way down
Early Fountain: Stanford 1959
"Zacharias" Fountain: Paris 1991



Atomic fountain clocks are the most accurate primary frequency standards ever made.

At 4×10^{-16} fractional uncertainty, they are accurate to one second in 80 million years !

(and getting better)

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At 4×10^{-16} fractional uncertainty, they are accurate to one second in 80 million years !
(and getting better)
Close enough for government work!

The low temperature achieved with laser cooling has been great for clocks! It also brings us into contact with another amazing prediction of Einstein.

In 1924 Einstein predicted that if a gas of "bosons," for example:

- Na atoms
- Rb atoms

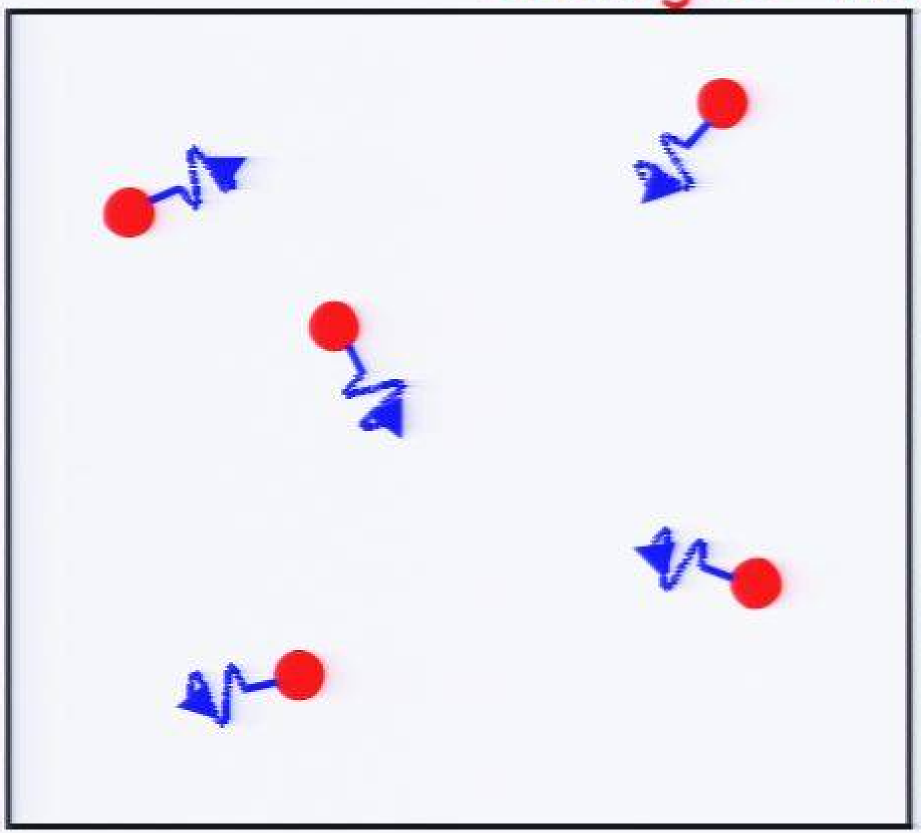
were cold enough and dense enough, something weird and wonderful would happen –

Bose-Einstein Condensation:
A phase transition where a large fraction of the atoms stop moving ! (or, at least as much as the Heisenberg uncertainty principle allows)

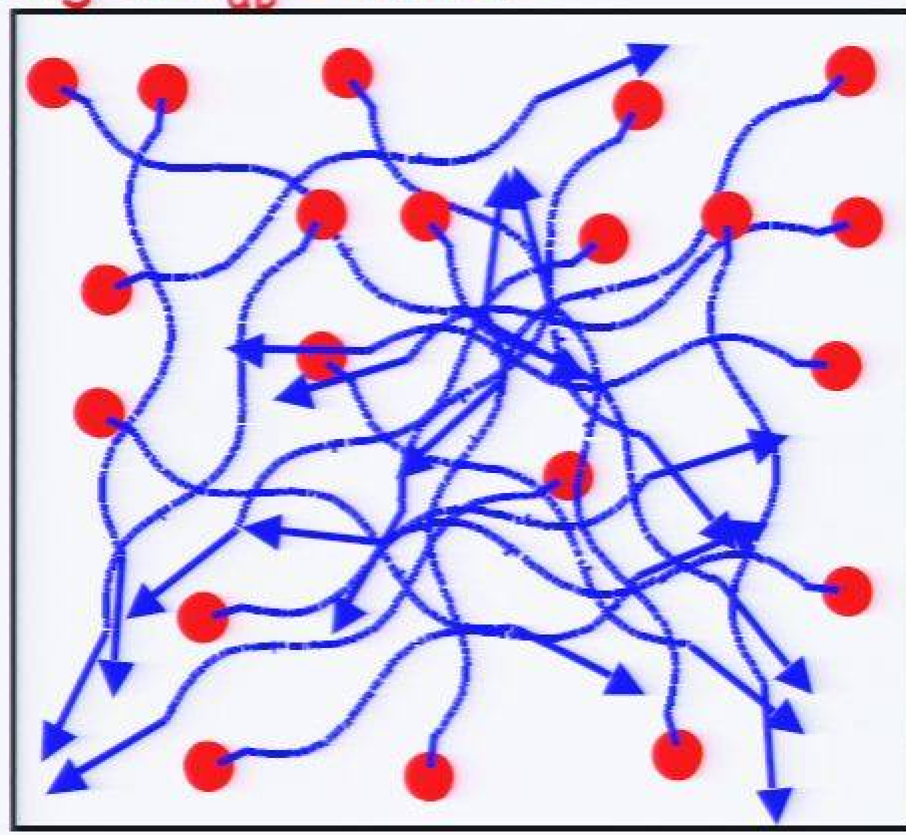
How cold and how dense?

(N.B.: This was not the way Einstein thought about it)

Recall that all material particles have a wavelike nature, with "deBroglie" wavelength $\lambda_{dB} = h/mv$



In a hot, dilute gas, λ_{dB} is so short that it makes no difference.



In a cold, dense gas, the wavelength can become comparable to the average interatomic spacing

How do we get that cold?

Laser cooling is a good start,but doesn't get cold or dense enough

To get colder and denser, we use evaporative cooling

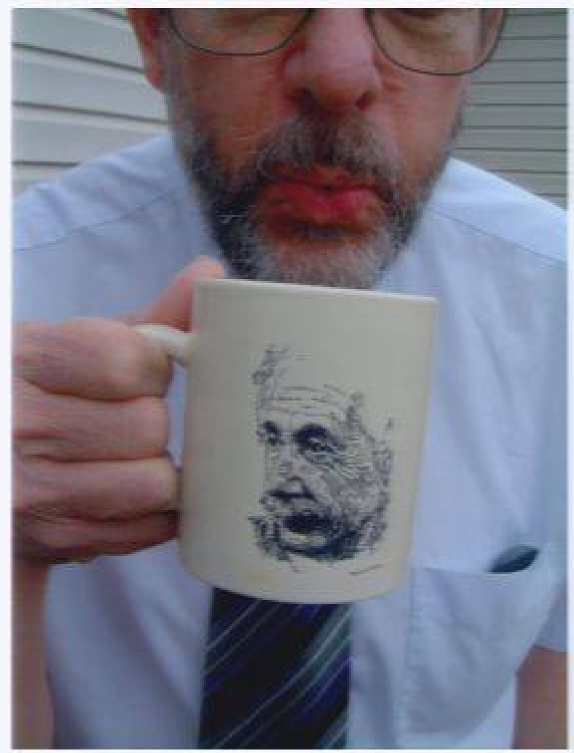


photo and Einstein drawing by Bülent Atalay

How do we get that cold?

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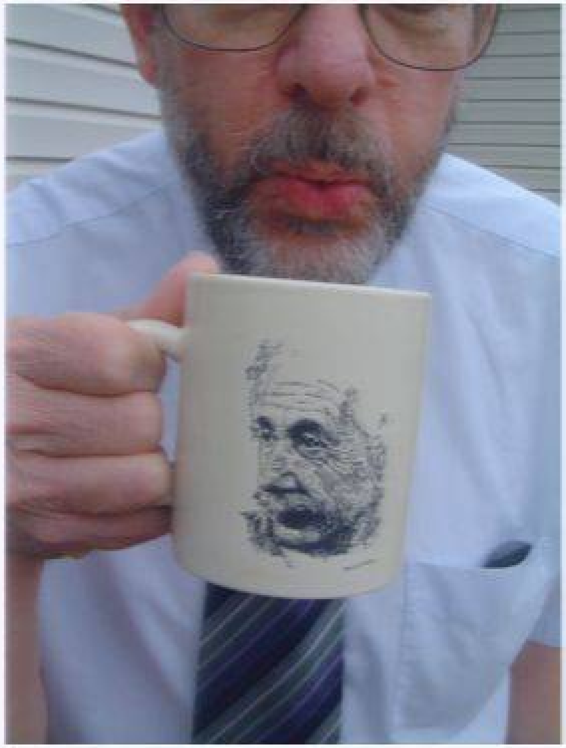
But what do we use for a container?



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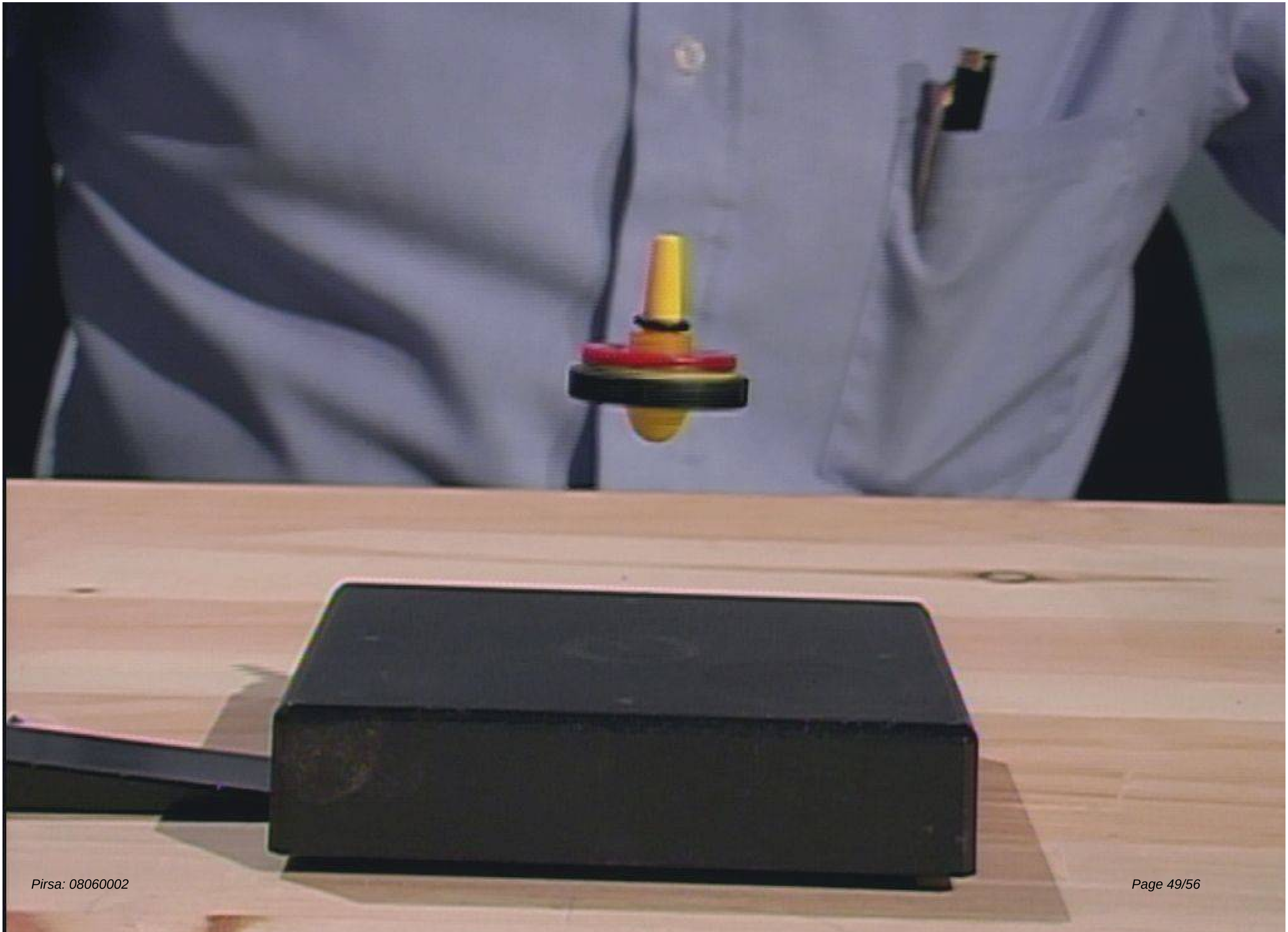

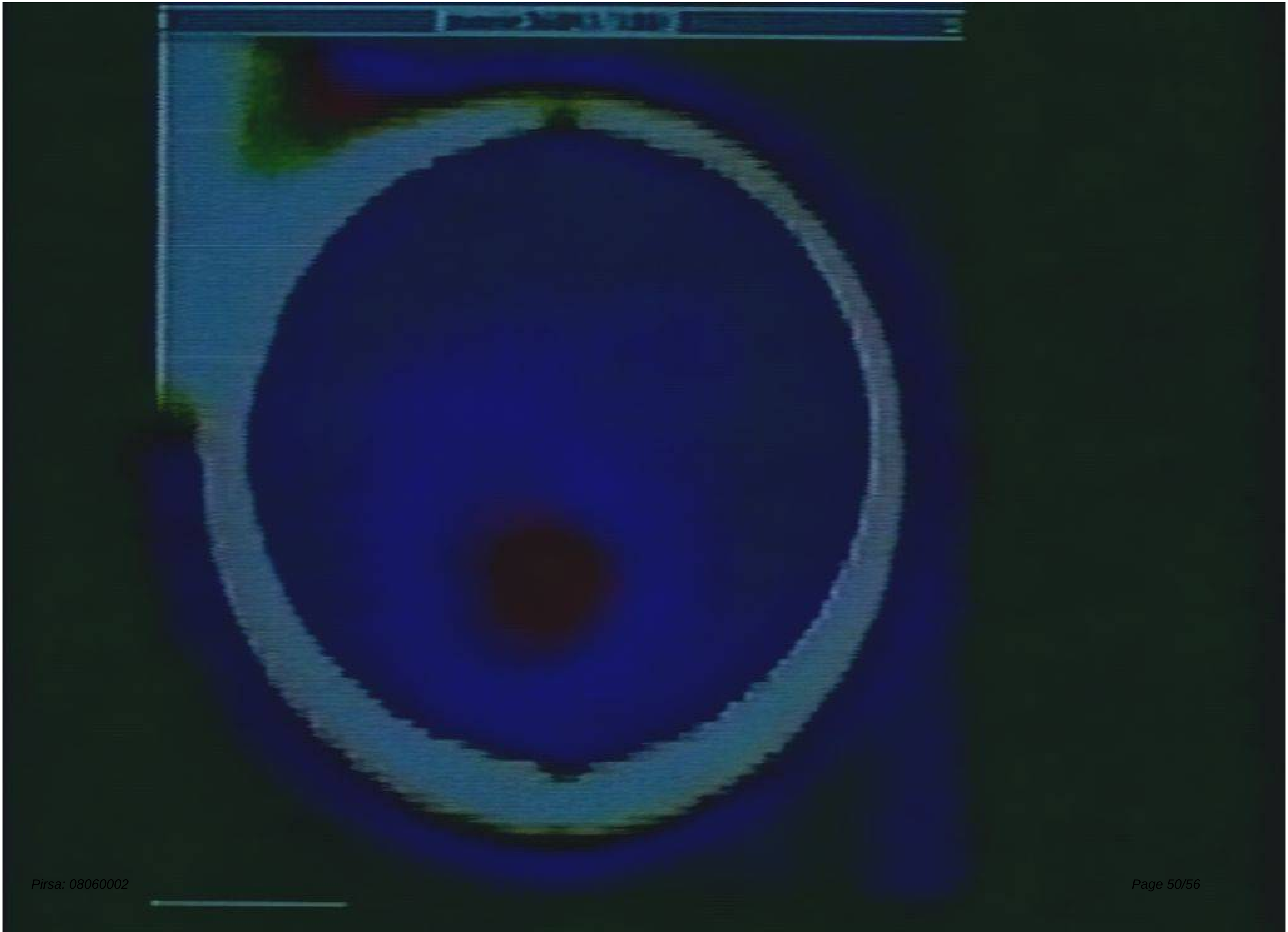

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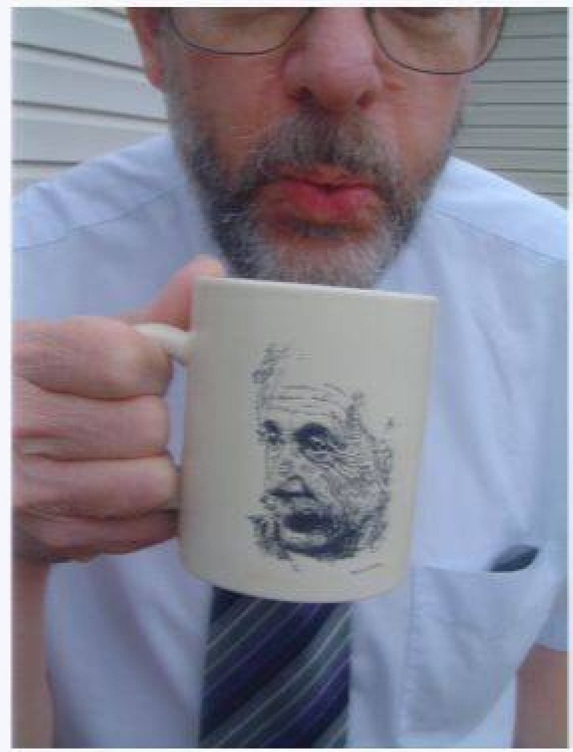
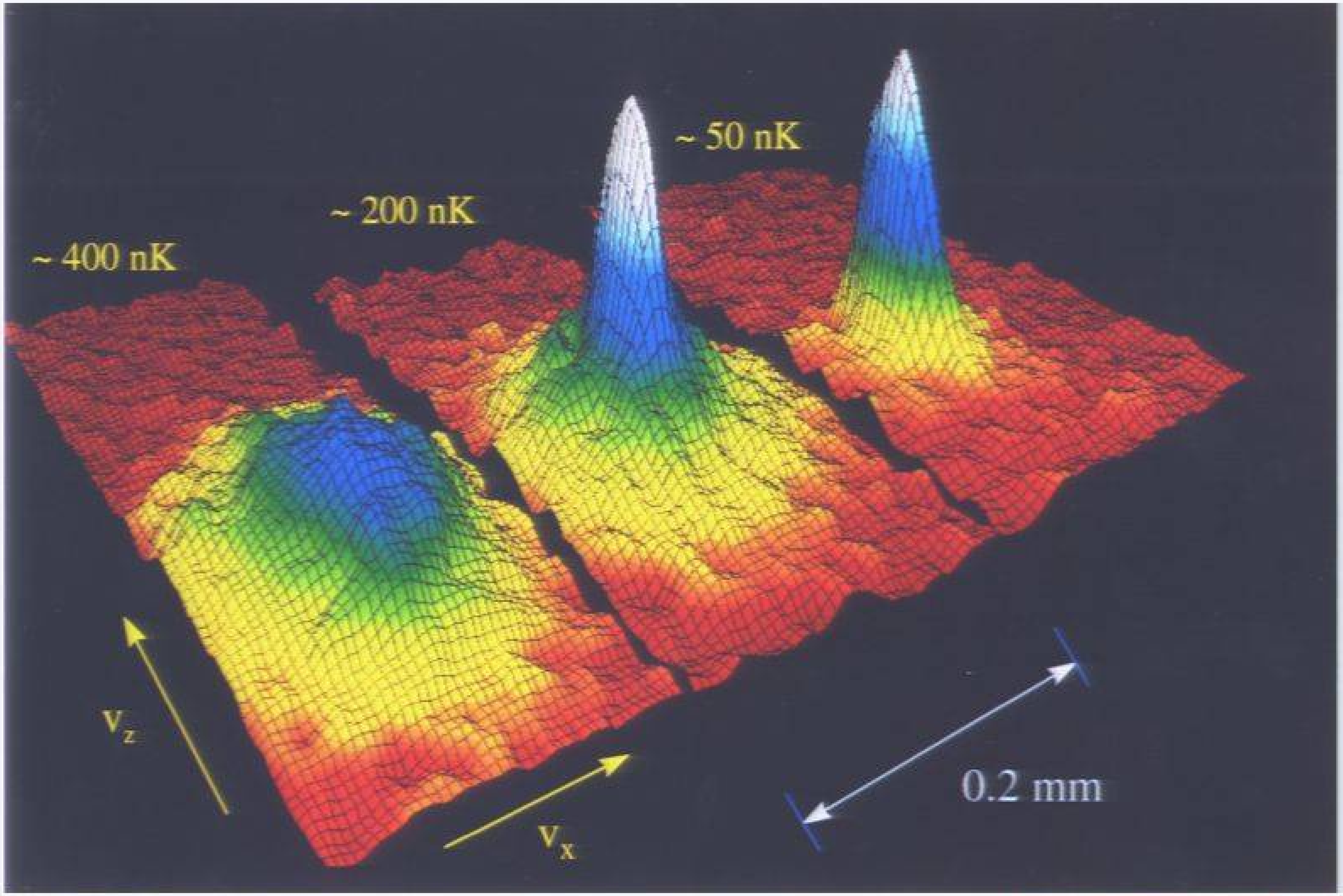


photo and Einstein drawing by Bülent Atalay

In 1995 (70 years after Einstein's prediction) teams in Boulder, Colorado and Cambridge, Massachusetts achieved Bose-Einstein Condensation in super-cold gas (and opened a new and rapidly advancing area of research).

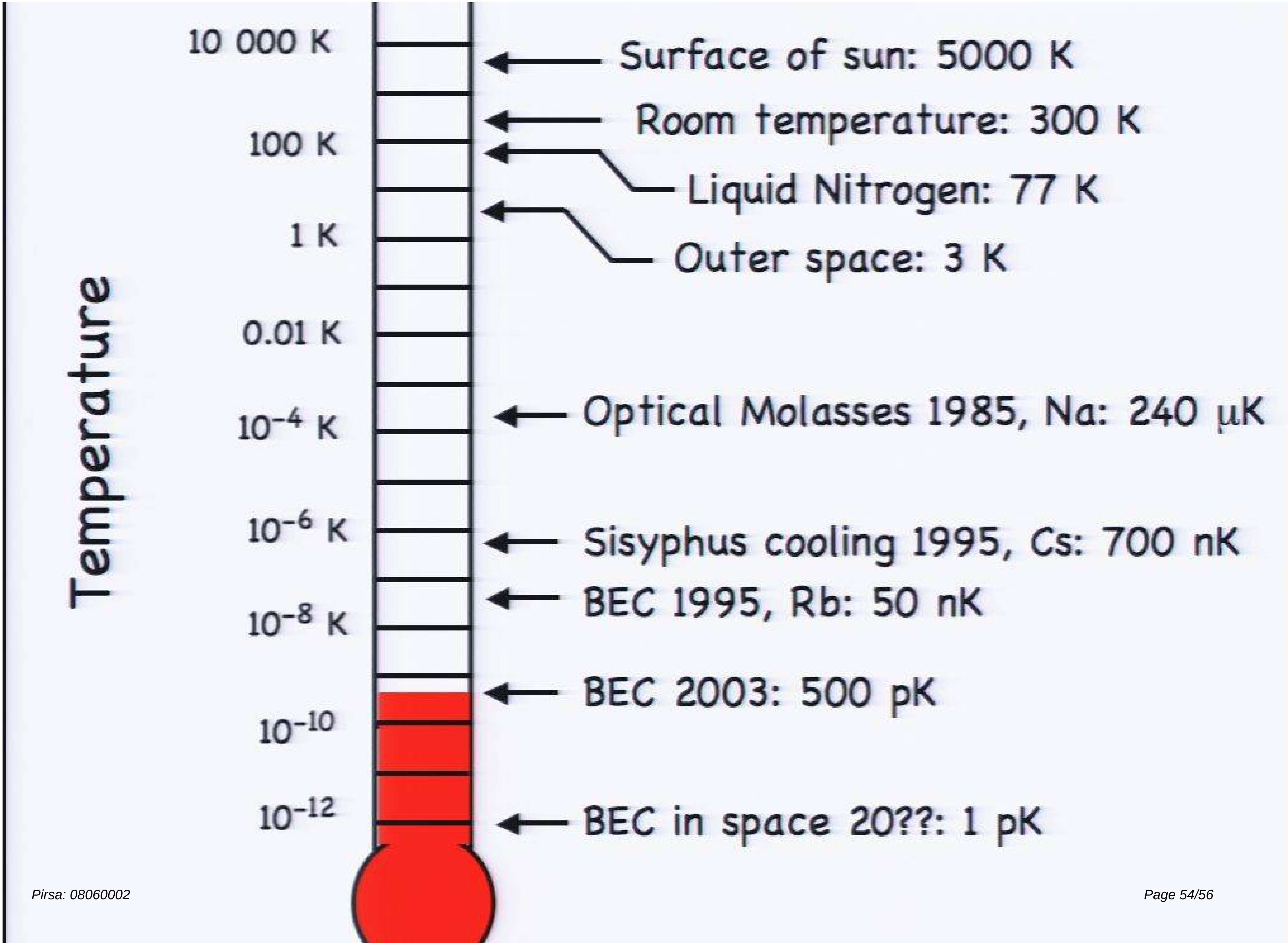
This feat earned those scientists the 2001 Nobel Prize for physics.

They and others have reached temperatures lower than one nanokelvin !


~ 400 nK
~ 200 nK
~ 50 nK
v_z
v_x
0.2 mm


University of


University of


Temperature
10 000 K
100 K
1 K
0.01 K
10⁻⁴ K
10⁻⁶ K
10⁻⁸ K
10⁻¹⁰
10⁻¹²
Surface of sun: 5000 K
Room temperature: 300 K
Liquid Nitrogen: 77 K
Outer space: 3 K
Optical Molasses 1985, Na: 240 μK
Sisyphus cooling 1995, Cs: 700 nK
BEC 1995, Rb: 50 nK
BEC 2003: 500 pK
BEC in space 20??: 1 pK

What's Next?

- Better clocks
- Tests of the fundamental understanding of Nature
- Quantum Computers
- More...

PERIMETER PI INSTITUTE FOR THEORETICAL PHYSICS