Time, Einstein, and the coolest stuff in the universe

KITP Public Lecture in connection with Frontiers of Cold Atoms and Molecules

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:
Gretchen Campbell, Paul Lett, Trey Porto, Ian Spielman

$support: NIST, NSF, Office of Naval Research

Physics Frontier Center
Joint Quantum Institute


NIST/PFC@JQI Laser Cooling and Trapping Group
BUILDING 216

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Einstein in the 20th century

Brownian motion

photoelectric effect
(light as particles)

stimulated emission

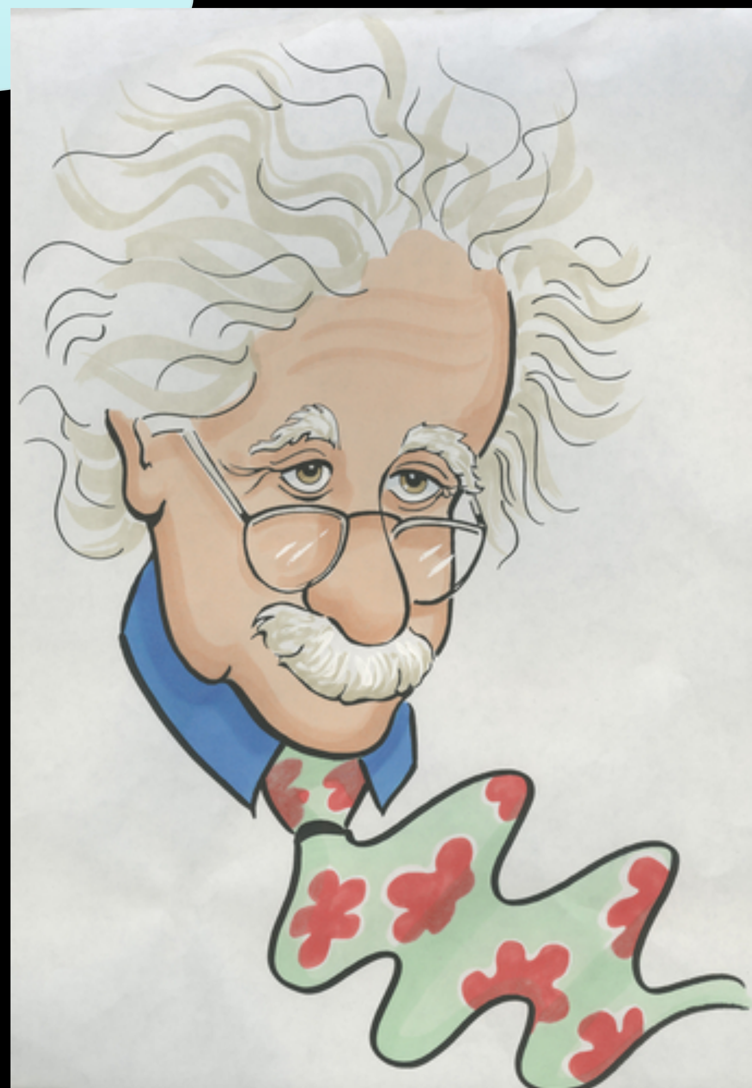
special relativity

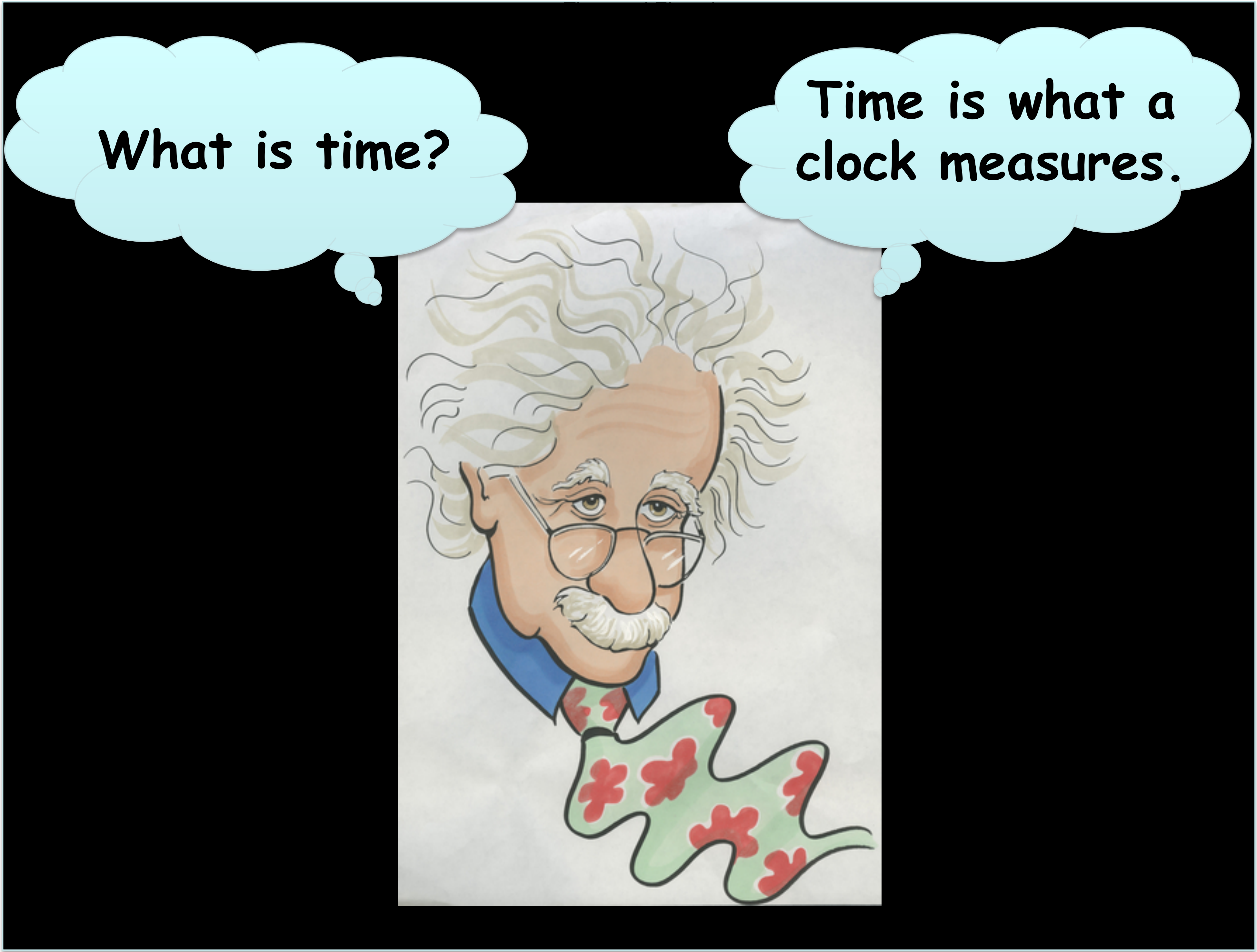
general relativity

Bose-Einstein condensation

Einstein-Podolsky-Rosen Paradox

What is time?




What is time?
Time is what a clock measures.

At NIST, making clocks, standards of time, is our business. Throughout history, clocks have continually improved. From the 20th century, NIST has played a major role.

Images Copyright Shutterstock

H4

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

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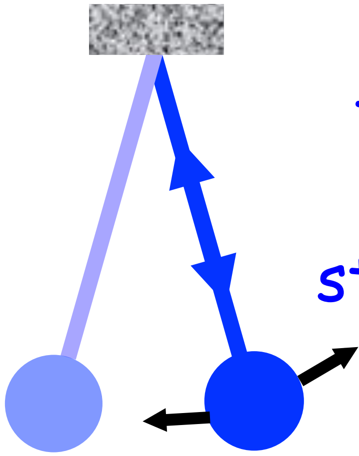
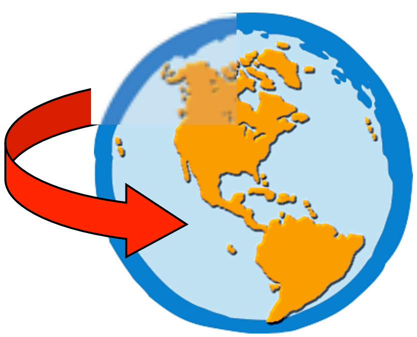
Today, most quartz watches are better than H4!

All of these clocks are imperfect.



The length of a pendulum may stretch or shrink.

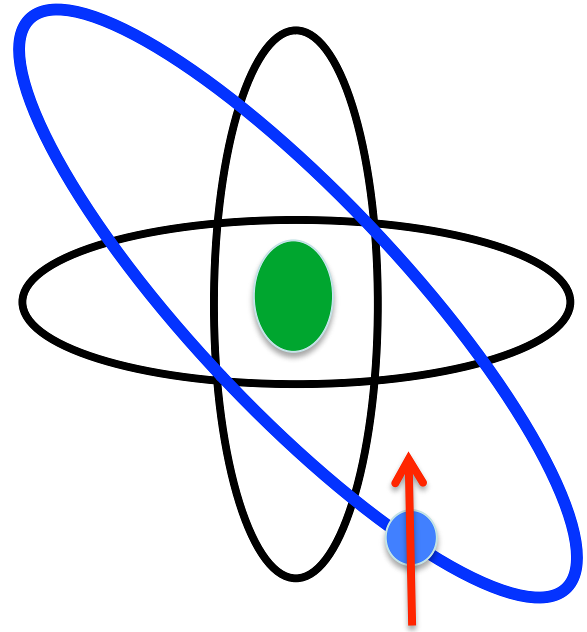
Each quartz crystal is a little different from all others, and may change with heat, humidity, ...



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

The best tickers are atoms.

Every ^{133}Cs atom is absolutely identical to every other one, and they all "vibrate" at the same frequency*.



*given by the energy difference between two atomic energy levels

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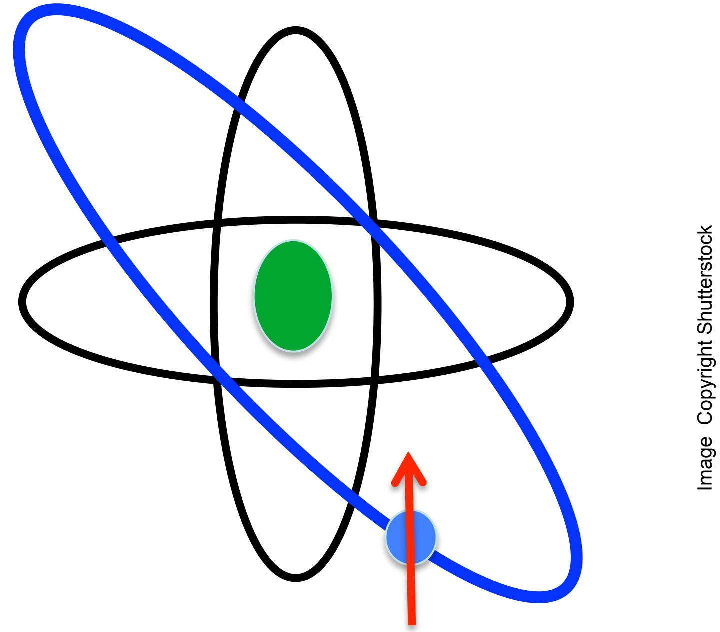

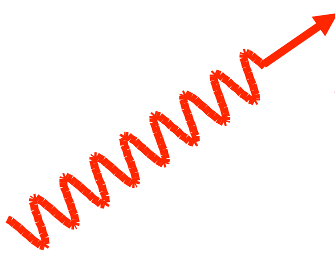

If you shine radiation of exactly the right frequency at the atom

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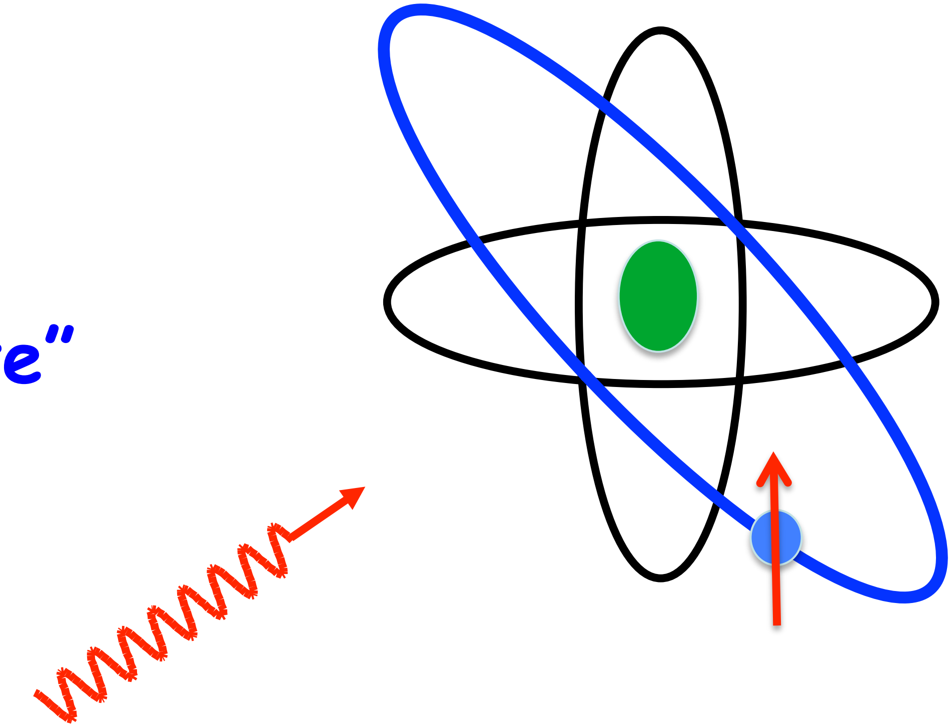

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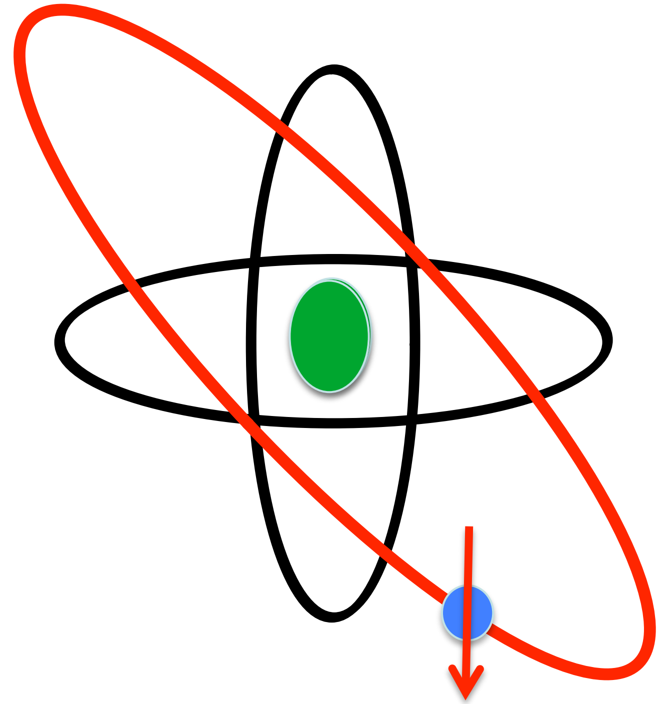


The atom absorbs the radiation (microwaves, or light, or whatever) and changes its state.

*given by the energy difference between two atomic energy levels

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 <u>that</u> good?

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

My goodness, it's 12:15:0936420175.

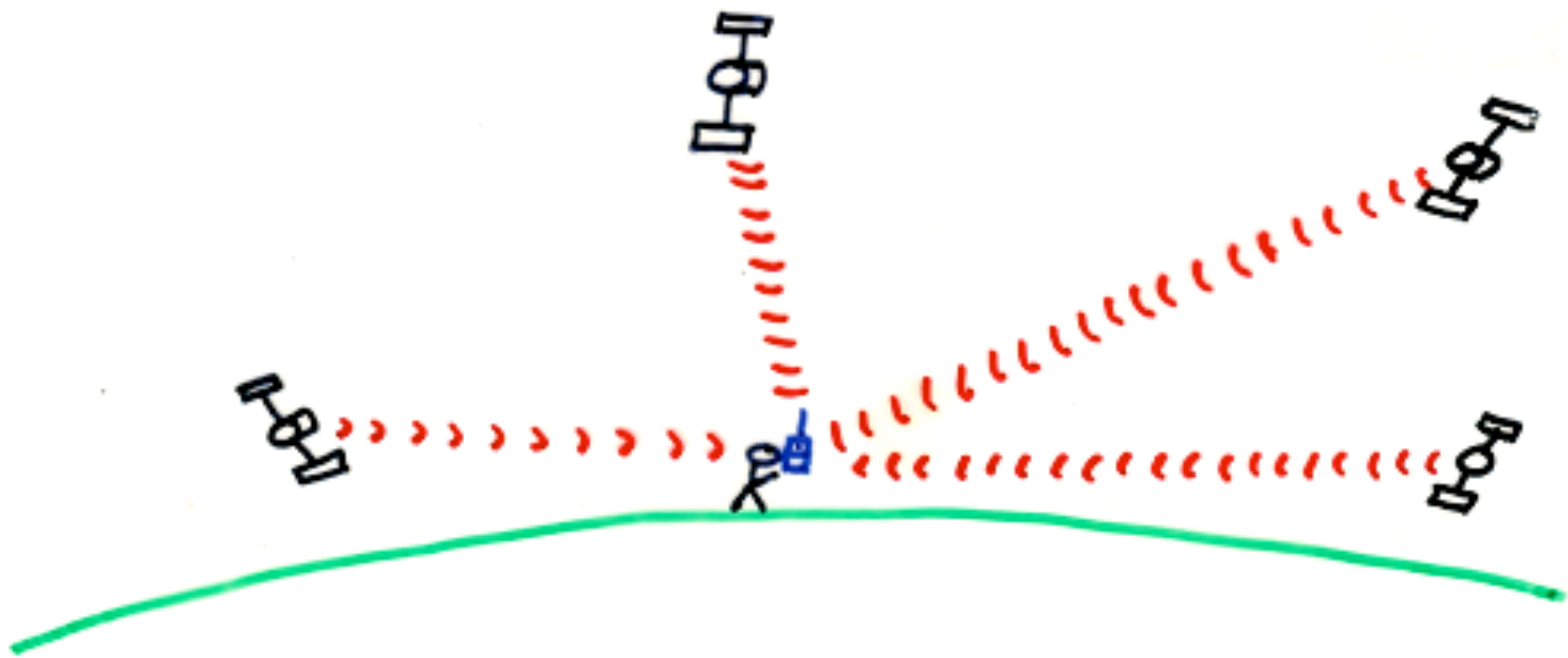
Time for lunch


Relax. Help Is Only 10,000 Miles Away.
Introducing Lincoln Continental's Exclusive
Personal Security Package With RESCU.
Ten-thousand miles above the earth, satellites orbit silently through space, waiting for the owner of a Lincoln Continental who might someday require emergency assistance. With the push of a button, the available RESCU System (Remote Emergency Satellite Cellular Unit) uses global positioning satellites to determine your location. Your position is then relayed via your cellular phone to the Lincoln Security Response Center which will dispatch assistance and keep you informed.* This innovative Personal Security Package also includes the SecuriTire System. A system that warns you of tire pressure loss and allows you to drive up to 50 miles even after a puncture.** Further proof that Lincoln will go to incredible lengths to bring you the ultimate luxury—peace of mind. For more information call 1 800 446-8888 or enter http://www.Lincolnvehicles.com for Internet access.
LINCOLN
What A Luxury Car Should Be
courtesy Ford Motor Company

GPS car ad

GPS system

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.



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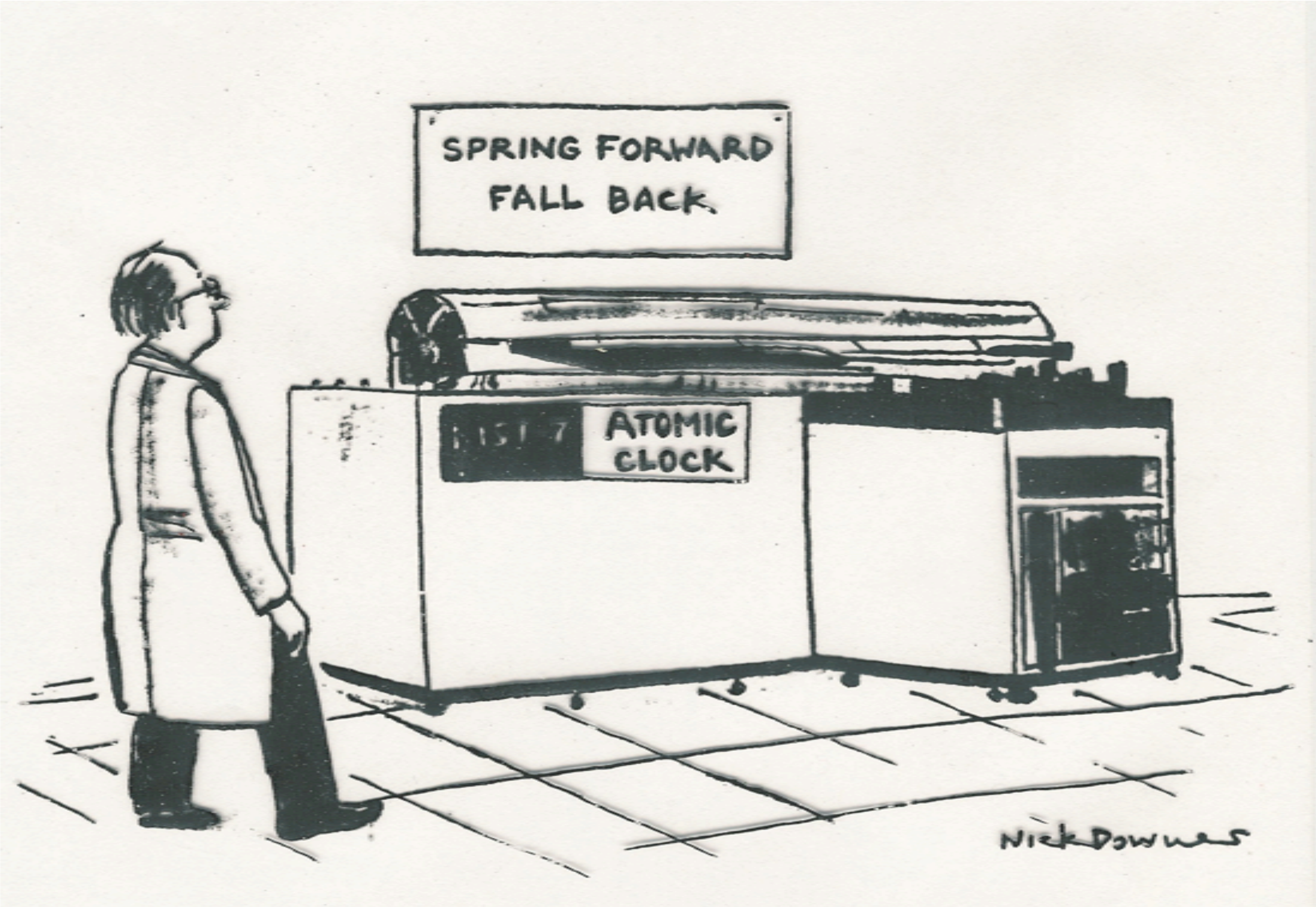
golfers, city taxis, surveyors, and

What do atomic clocks look like?

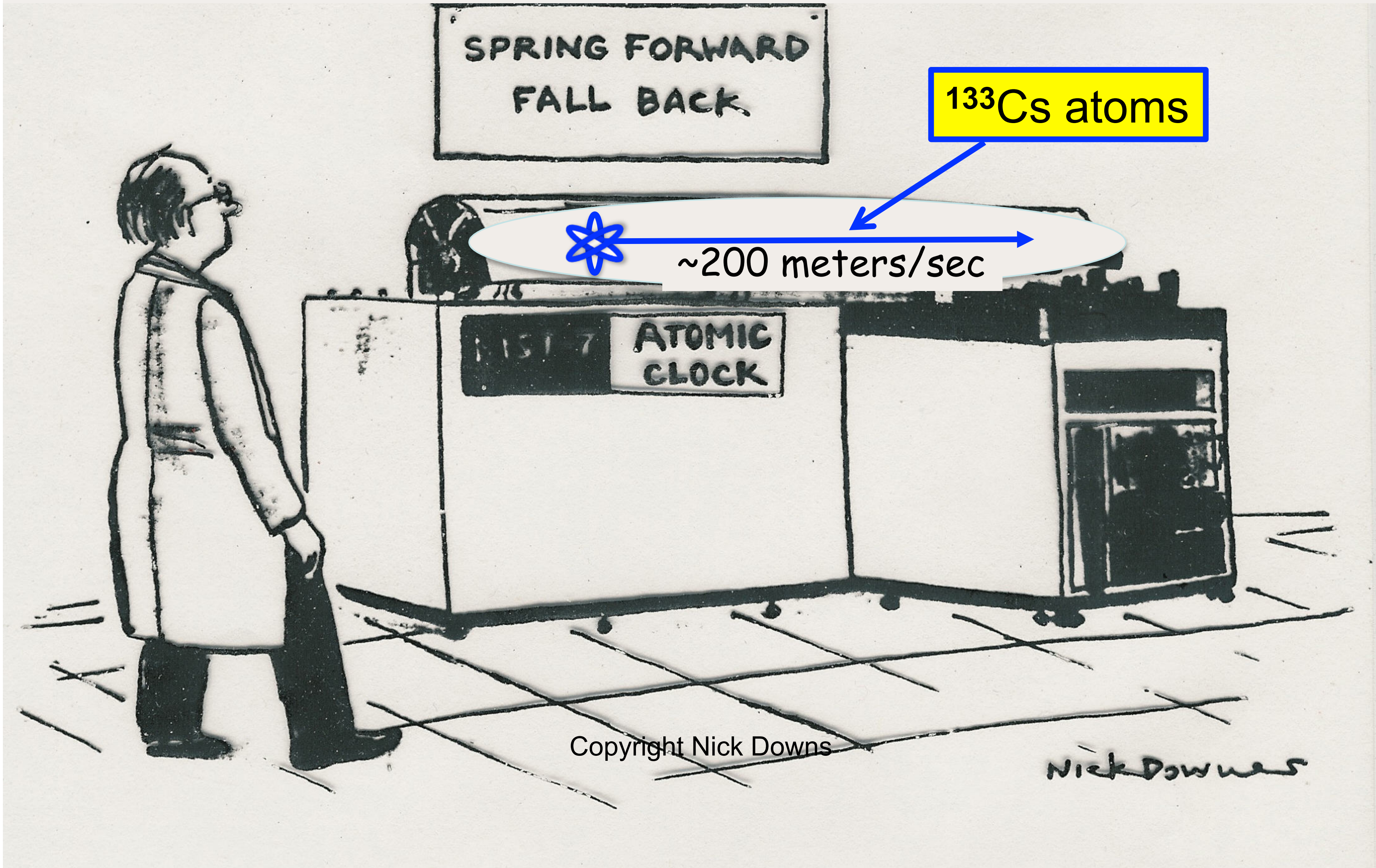
Spring forward



Time is

TEMPUS

Cesium metal in this clock is heated and vaporized, making a beam of atoms moving close to the velocity of sound.



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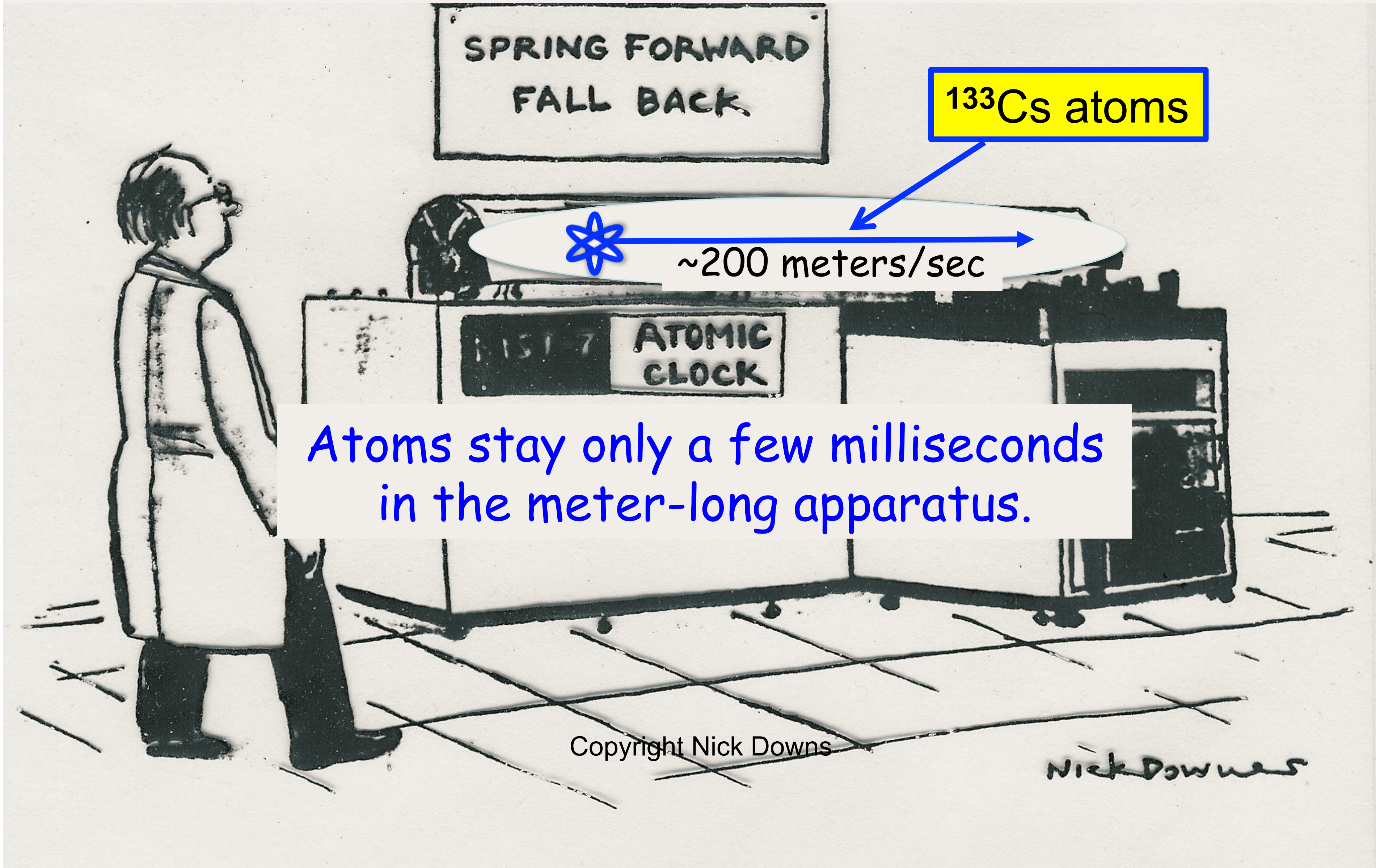
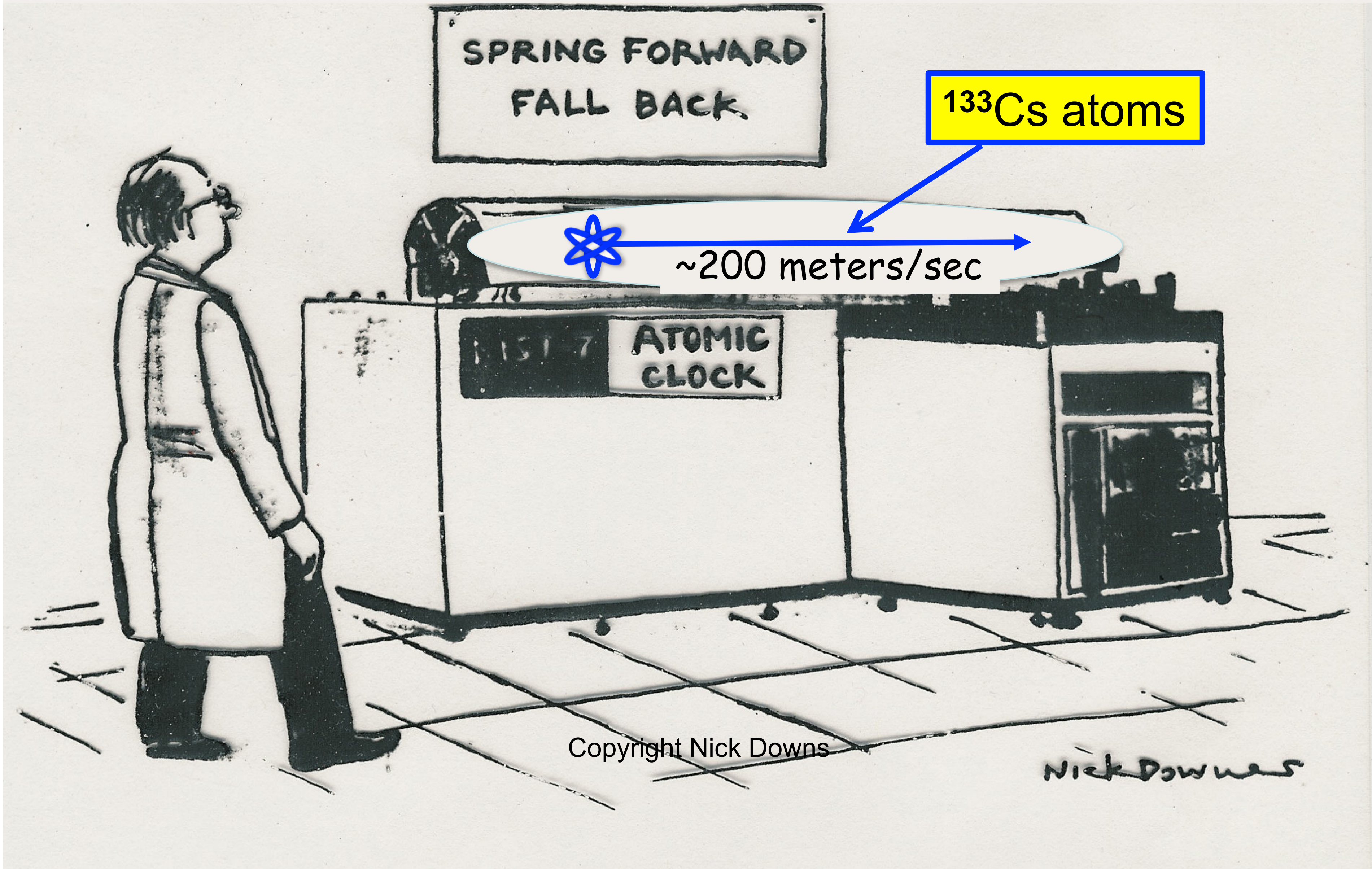
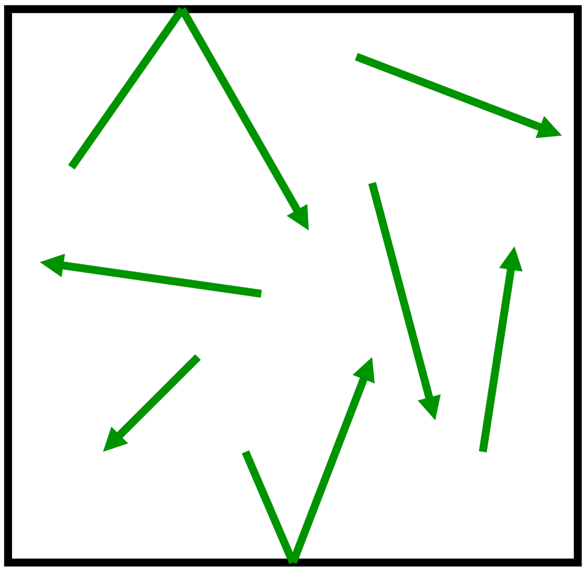


The high velocity the atoms limits how good these clocks can be—to do better, we need slower atoms.



Hot and Cold

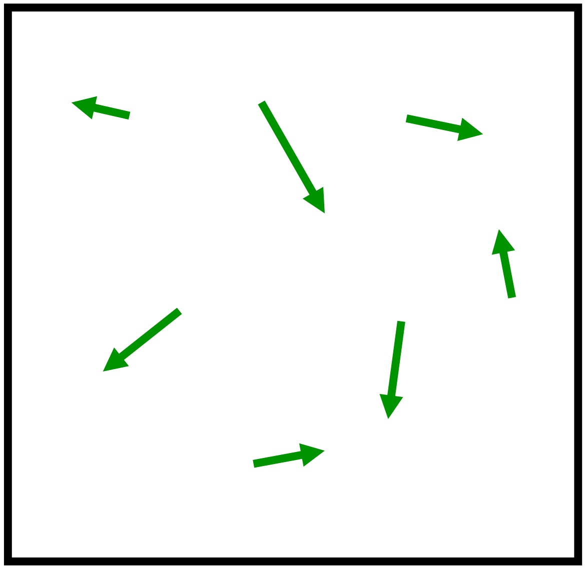


HOT:

fast atoms

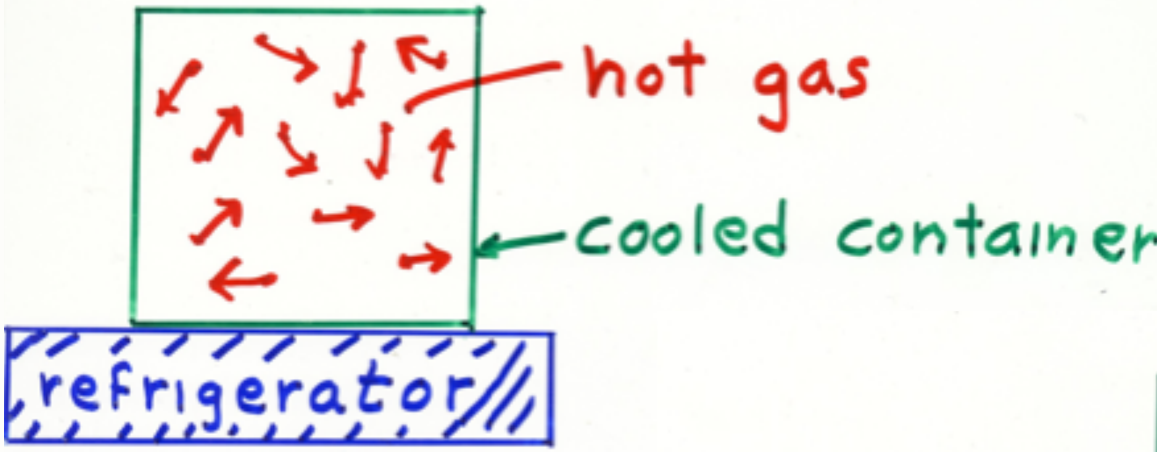
COLD:

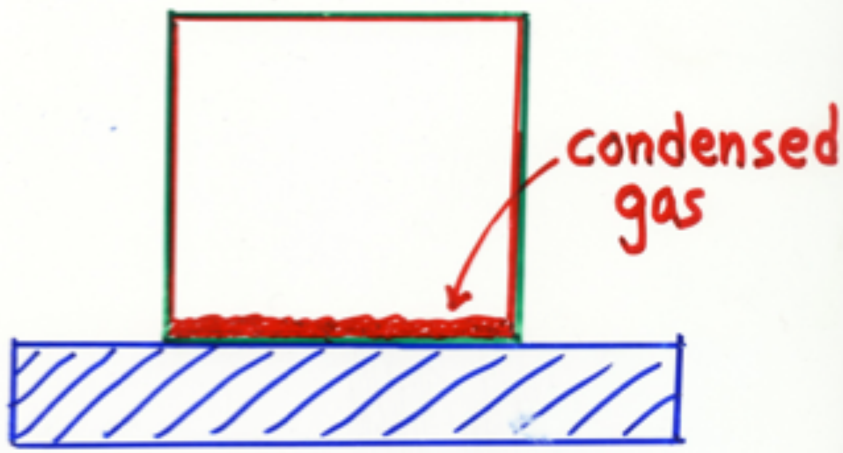
slow atoms



Demonstrations

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

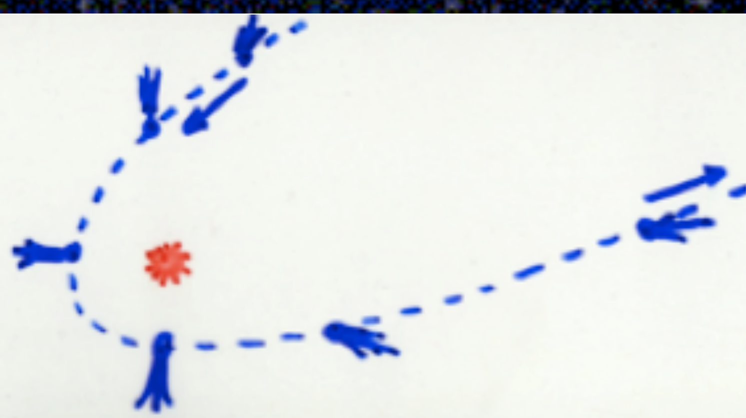




How do we cool something without touching it?

condensation


Comet photo courtesy NASA



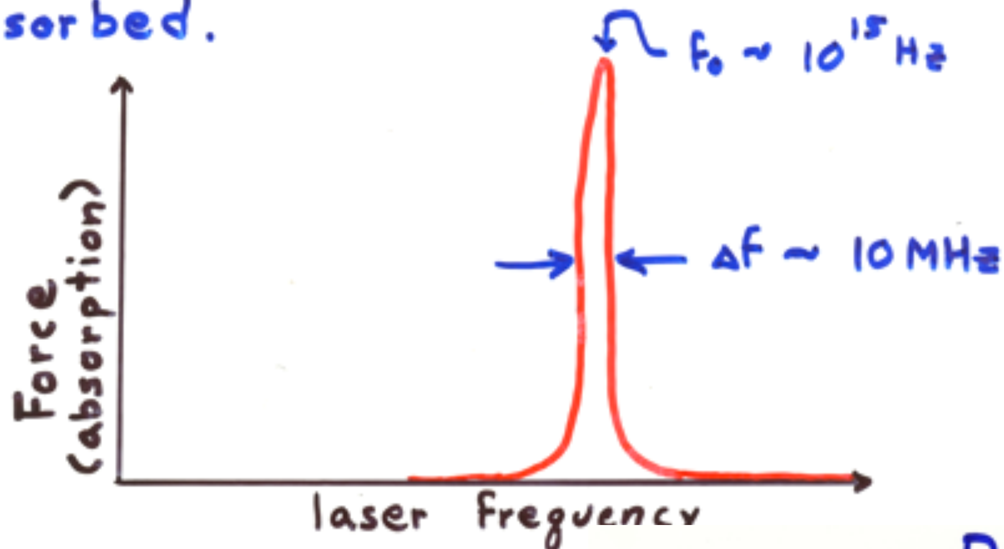
We use the pressure of laser light to push on atoms and slow them down.

Wait a minute…

…lasers heat, not cool, things!

Resonance

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



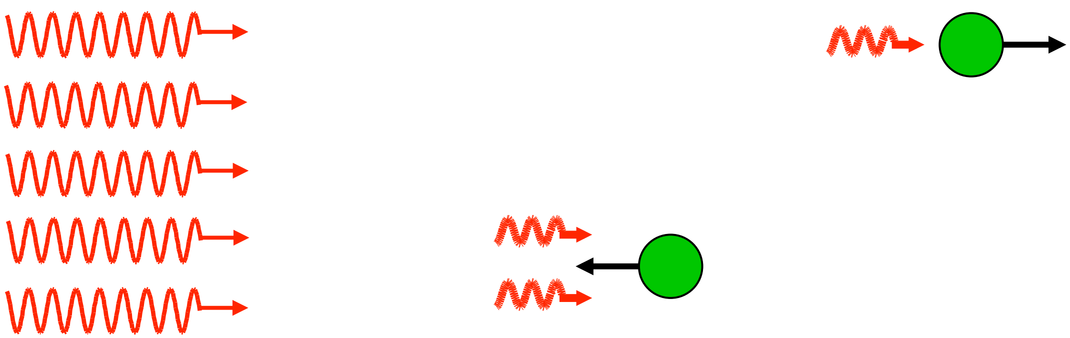
Doppler Shift

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

Resonance and Doppler shift

Laser Cooling (1975)

Wineland & Dehmelt and Hänsch & Schawlow



laser beam tuned
below resonance

Laser Cooling (1975)

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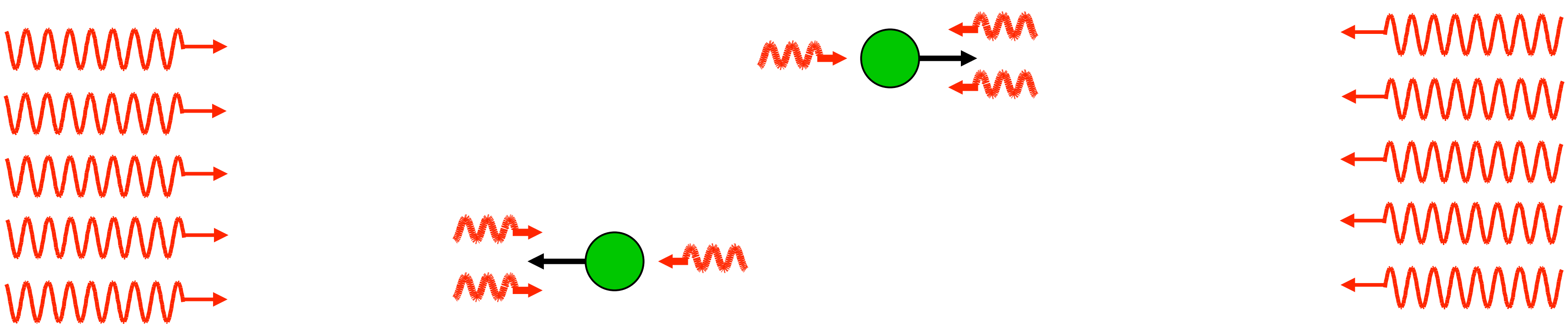

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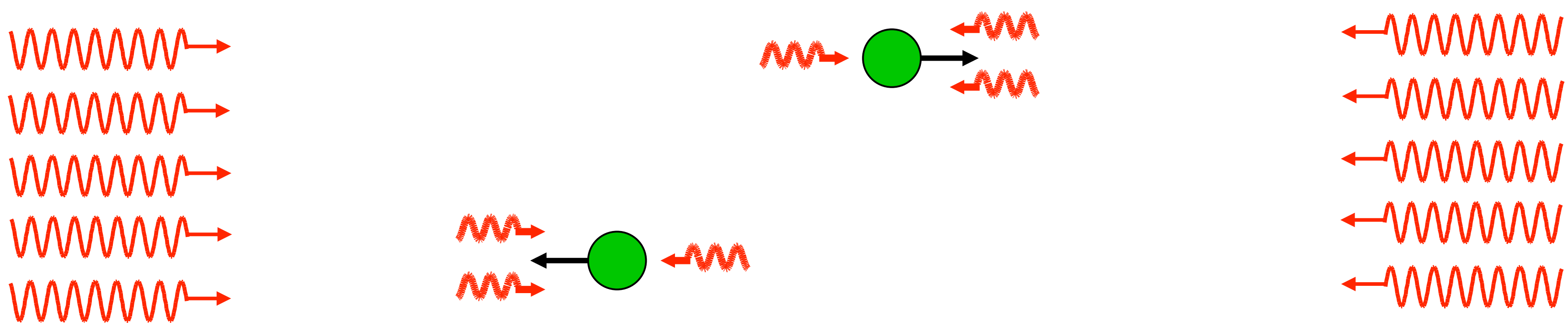

laser beam tuned
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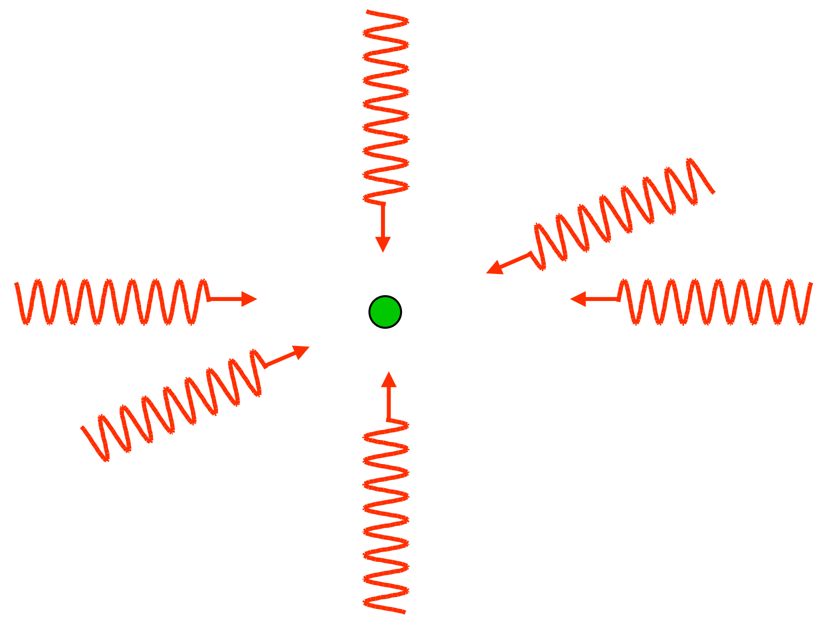
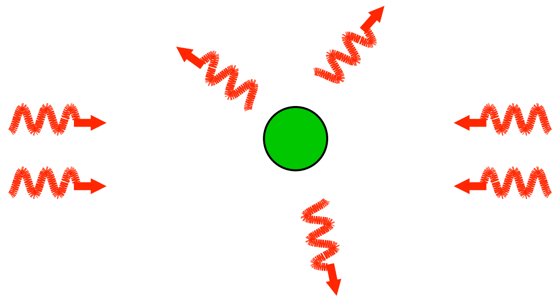


Optical Molasses
Chu *et al*. 1985

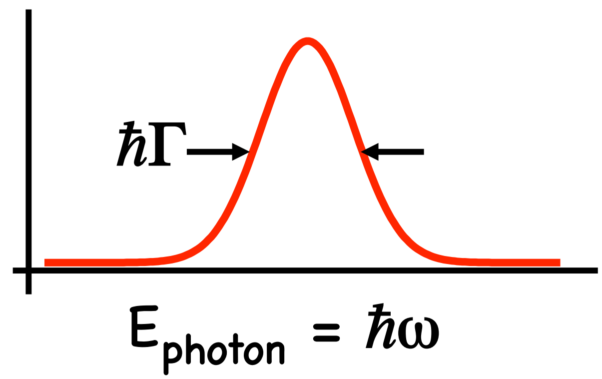
Laser Heating

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



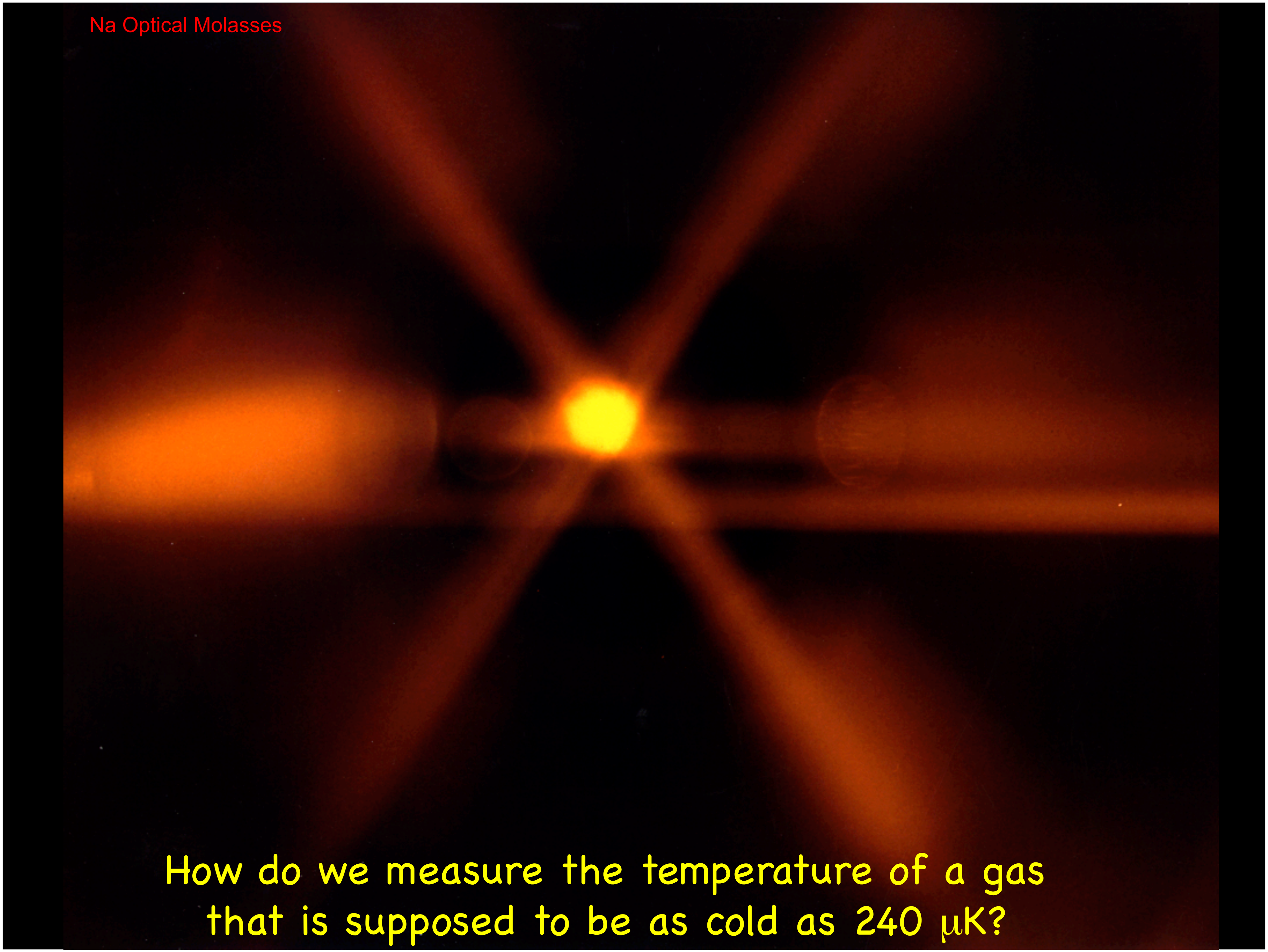
Randomness of absorption and emission **HEATS** the atoms.

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



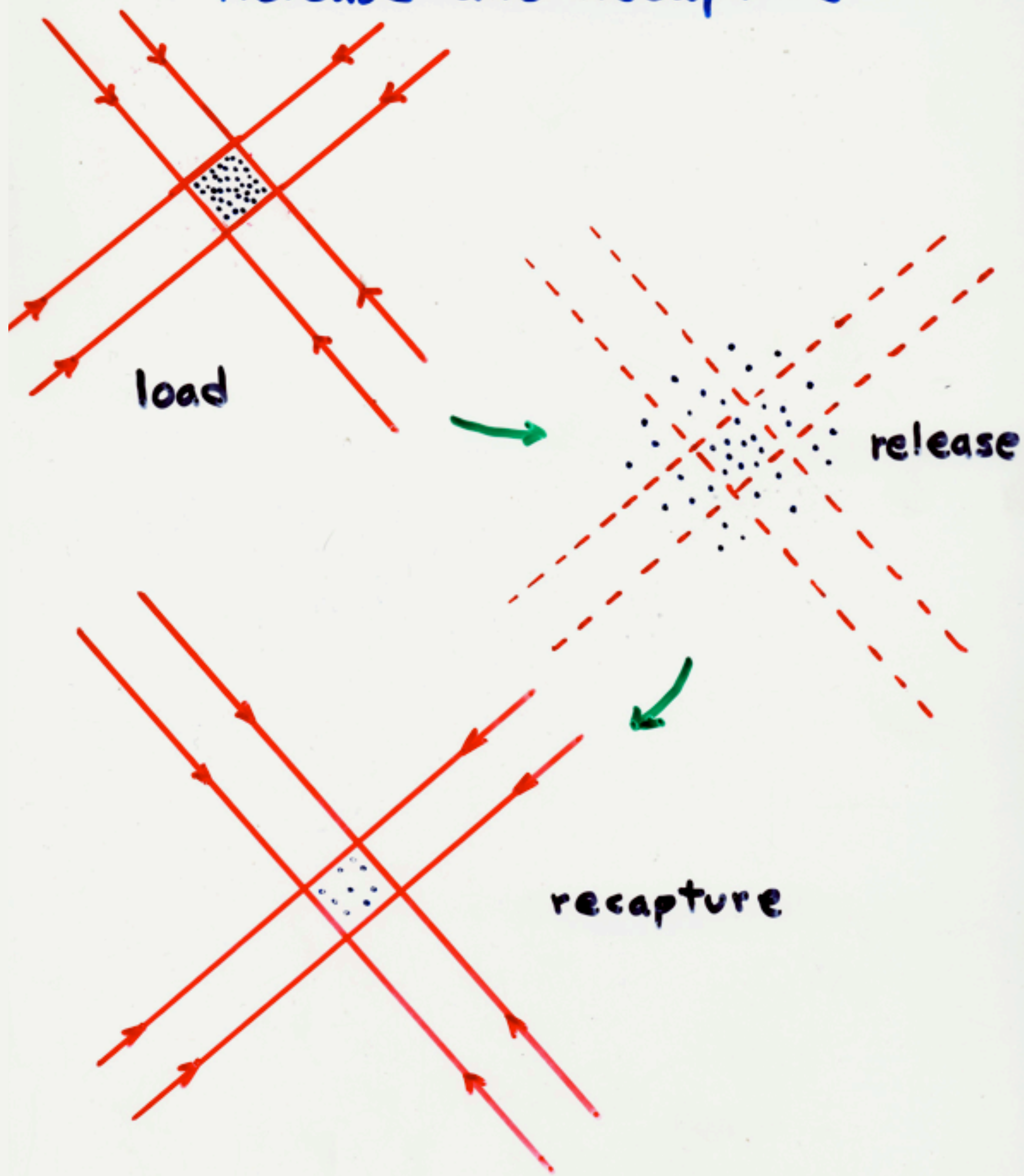
"Doppler Limit" $k_B T_{Dopp} \geq \hbar\Gamma$

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



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



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 ...

R&R temperatures

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

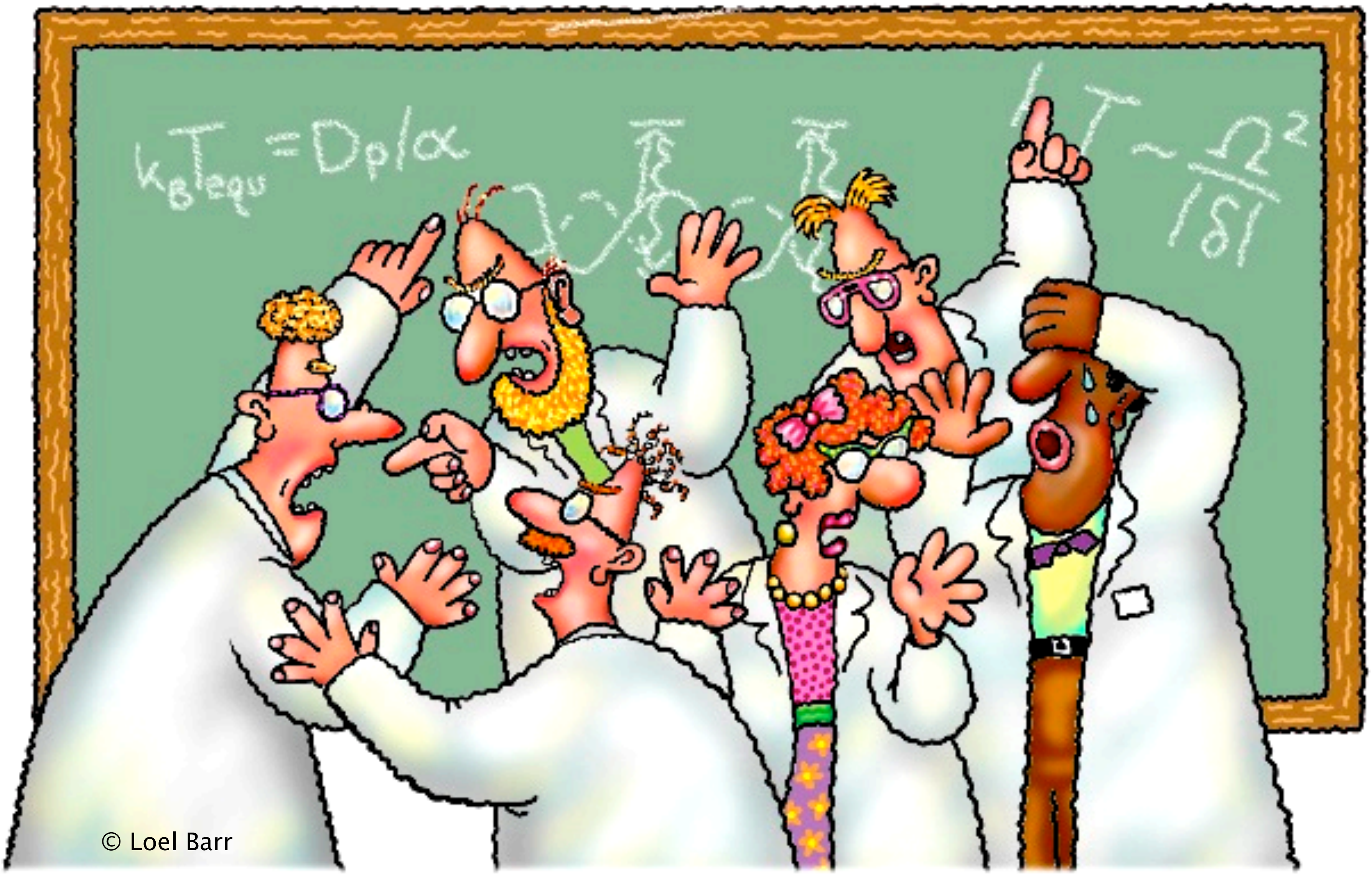
This was an astounding violation of Murphy's Law

Hal in Hell

drawing by Kris Helmerson

"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)

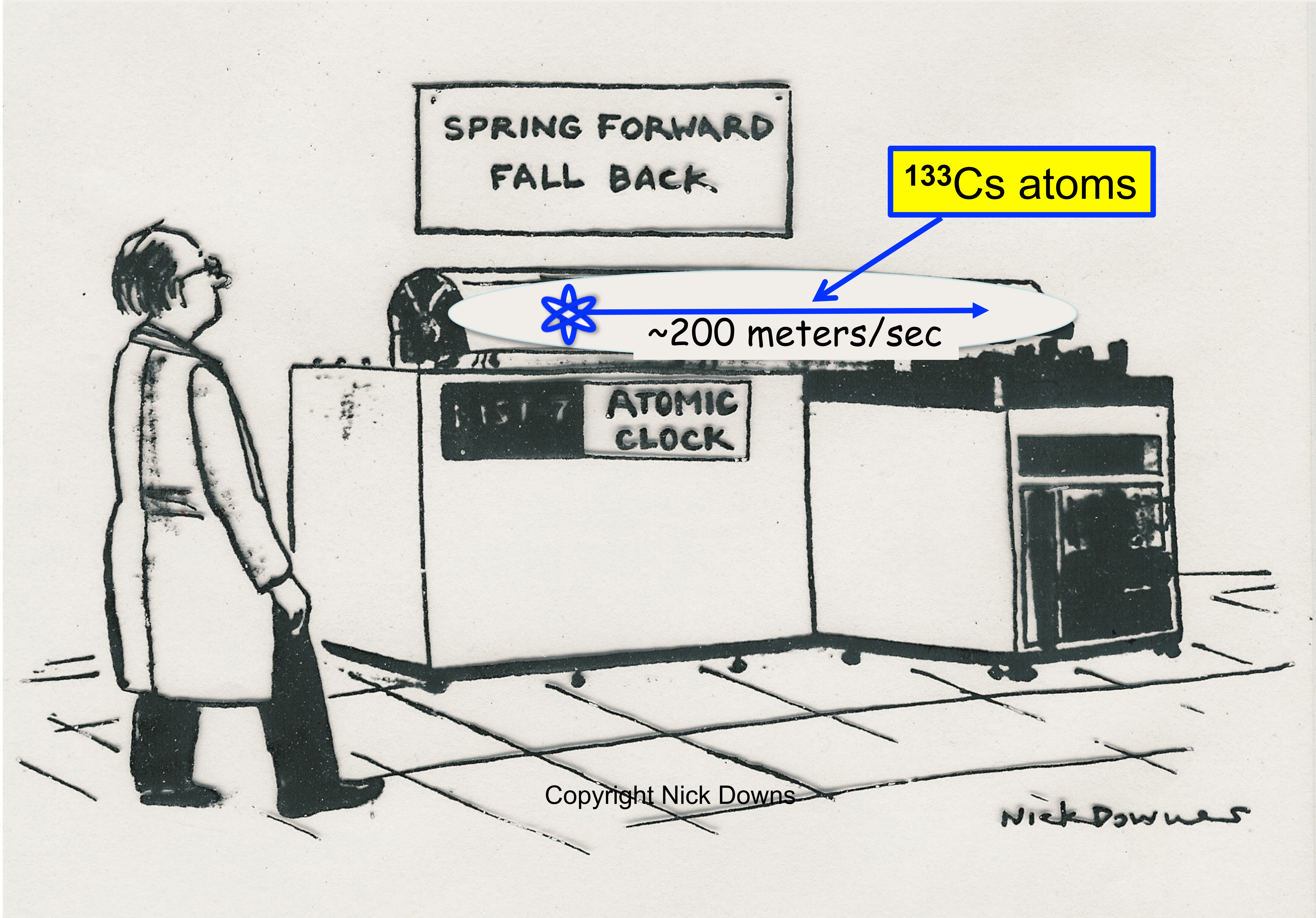
(The lowest temperature is related to the "recoil" energy)

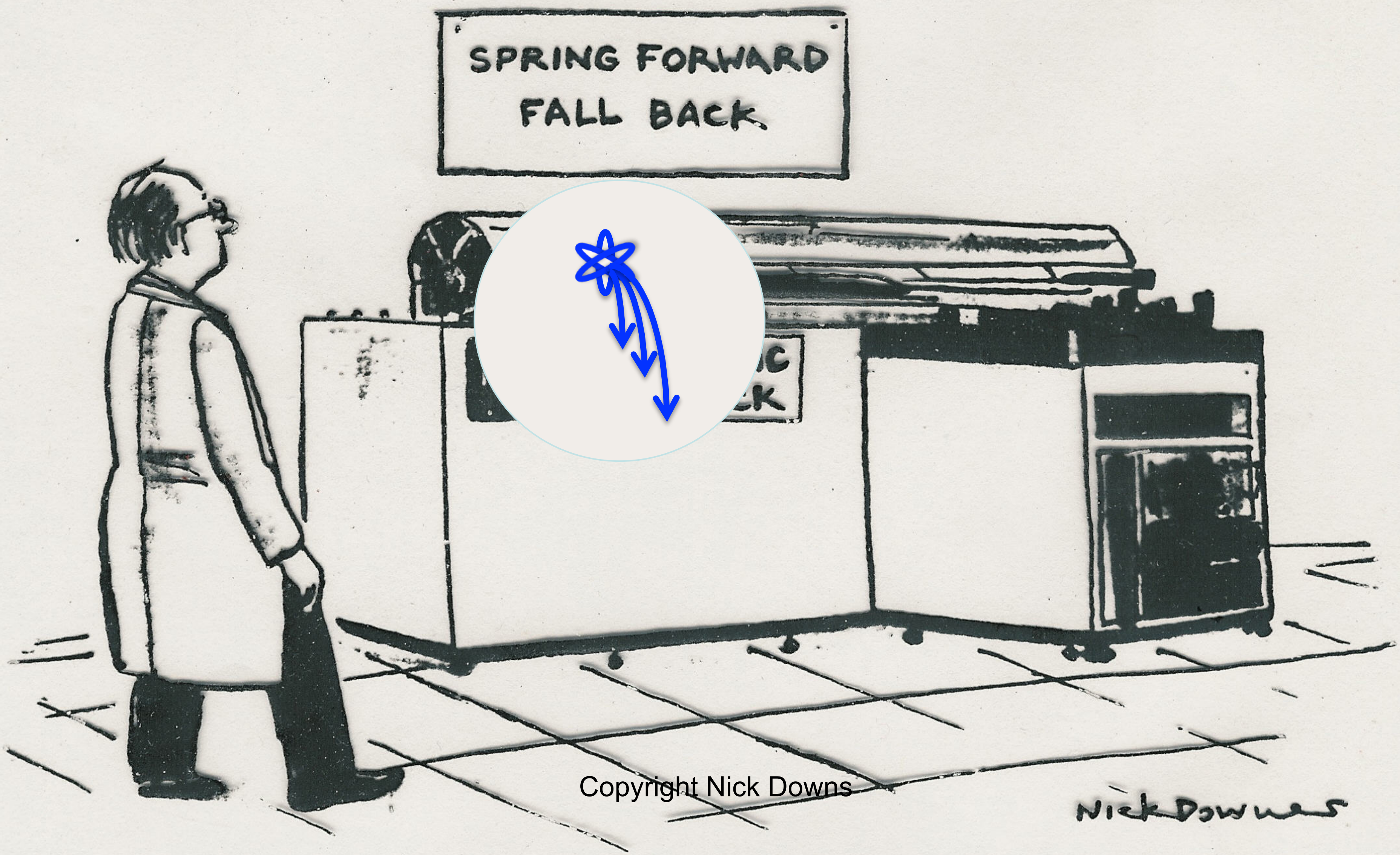
- A hundred million times colder than liquid nitrogen
- 4 million times colder than outer space
  (3 K cosmic background)

The thermal velocity of these atoms is

$V_{thermal} < 1$ cm/s

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

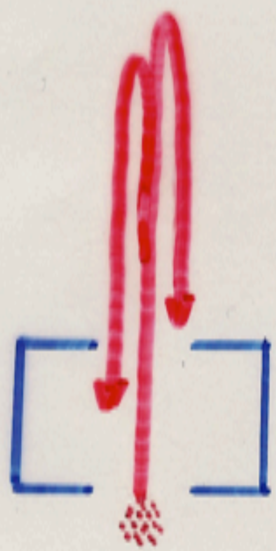

SPRING FORWARD
FALL BACK
^{133}Cs atoms
~200 meters/sec
ATOMIC
CLOCK
NICK DOWNES


SPRING FORWARD
FALL BACK
Nick Downes

Zacharias

Idea of Zacharias ca 1953

"Atomic Fountain"



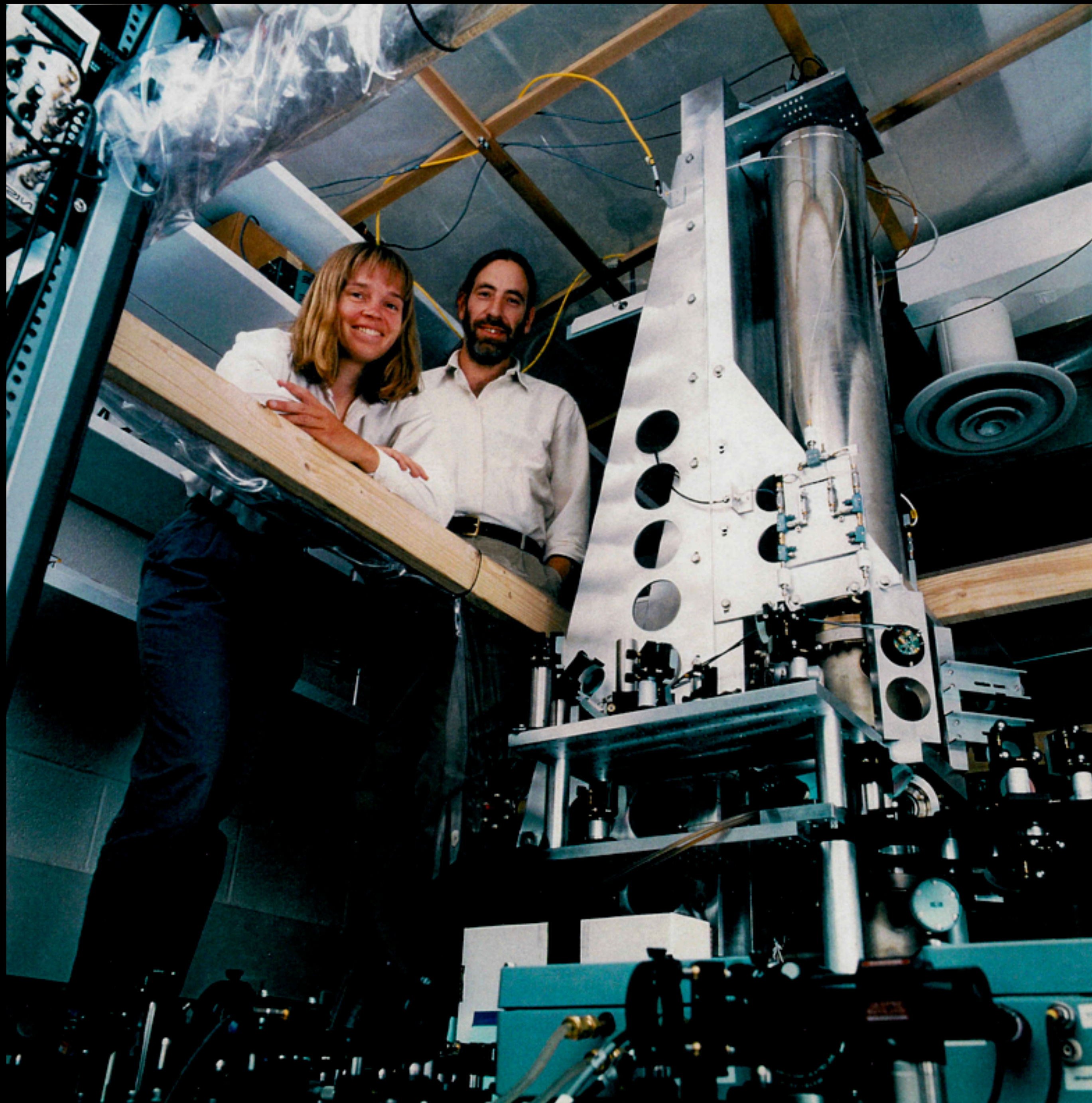
Synchronize on the way up

Compare on the way down

Early Fountain: Stanford 1989

"Zacharias" Fountain: Paris 1991

[redacted]



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

At 3×10^{-16} fractional uncertainty, they are accurate to one second in 100 million years !

(and getting better)

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Close enough for government work!

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At 3×10^{-16} fractional uncertainty, they are accurate to one second in 100 million years !

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Close enough for government work!

Clocks at NIST using laser-cooled ions (electrically charged atoms) are even better — 9×10^{-18} (a second in 3 billion years) — but these are not (yet) primary frequency standards.

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

At 3×10^{-16} fractional uncertainty, they are accurate to one second in 100 million years !

(and getting better)

Close enough for government work!

But where do you store the coldest stuff in the universe? What container can keep it that cold?

Demonstration of Magnetic Trapping

Using evaporative cooling in a magnetic trap, researchers reached temperatures colder than possible with laser cooling, and realized one of Einstein's strangest ideas.

photo and Einstein drawing by Bülent Atalay

Using evaporative cooling in a magnetic trap, researchers reached temperatures colder than possible with laser cooling, and realized one of Einstein's strangest ideas.

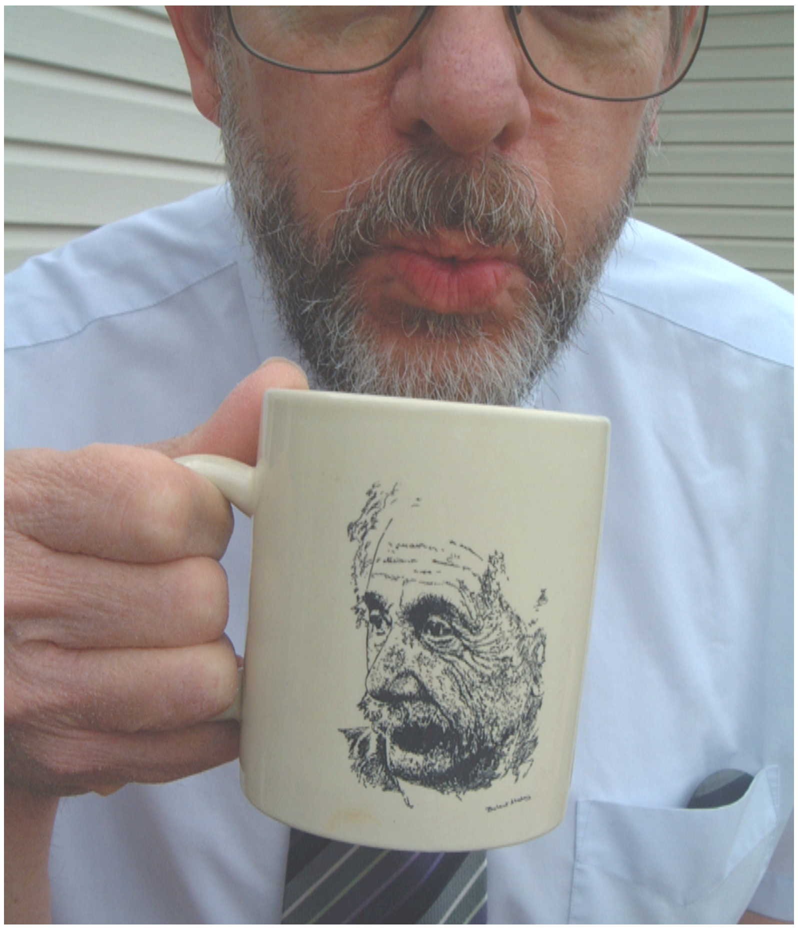
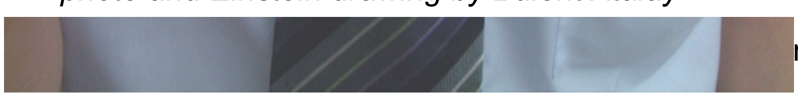


photo and Einstein drawing by Bülent Atalay

In evaporation, the most energetic water molecules escape, leaving the remaining water colder.

We do the same thing to our atoms, allowing the most energetic to escape from a magnetic trap.



nstein predicts BEC

Einstein predicts BEC

In 1924, building on the new work by Bose, Einstein predicted that if a gas of atoms like ours was cold enough and dense enough, something weird and wonderful would happen –

Bose-Einstein Condensation:

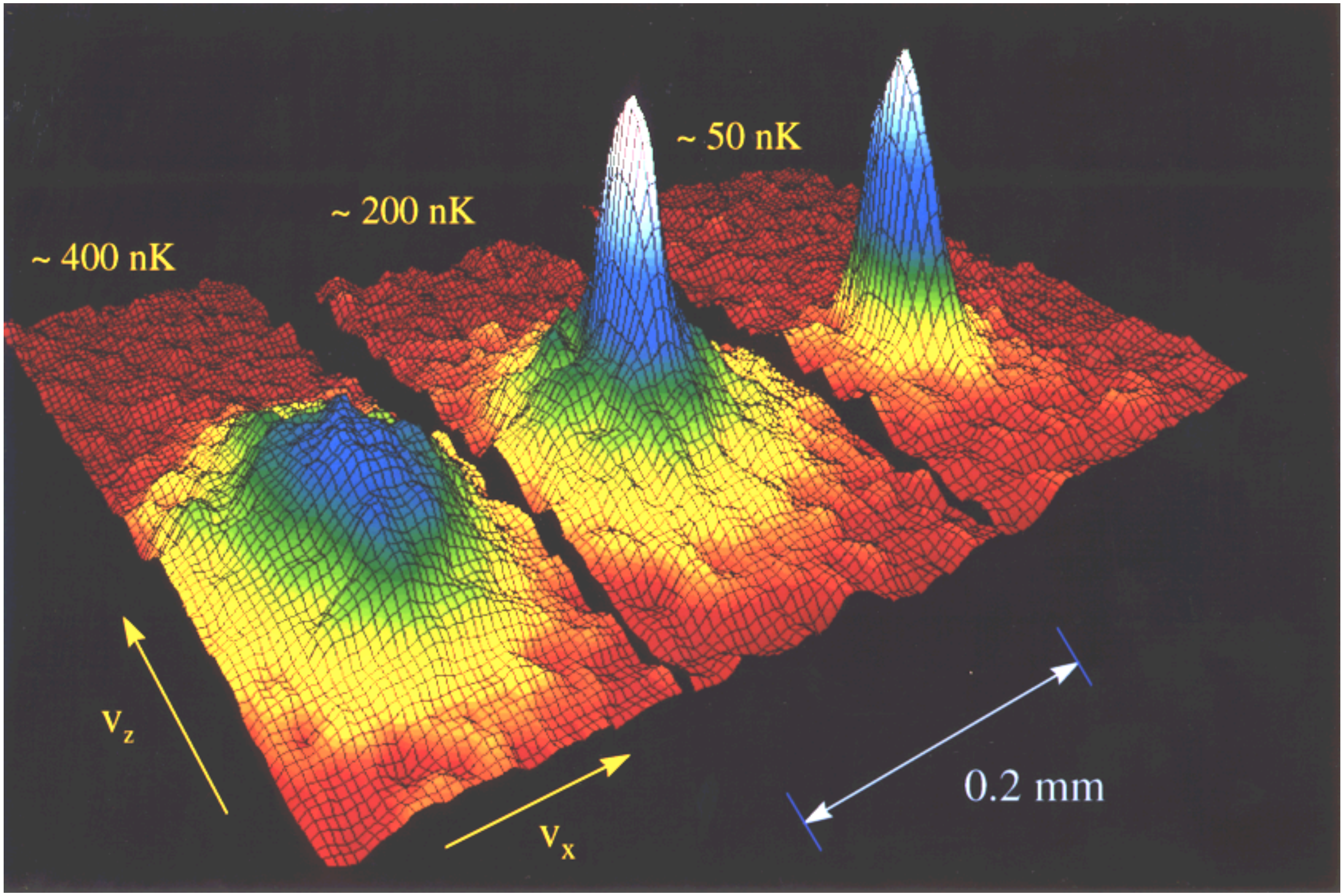
A phase transition where a large fraction of the atoms <u>stop moving</u> ! (or, at least as much as the Heisenberg uncertainty principle allows)

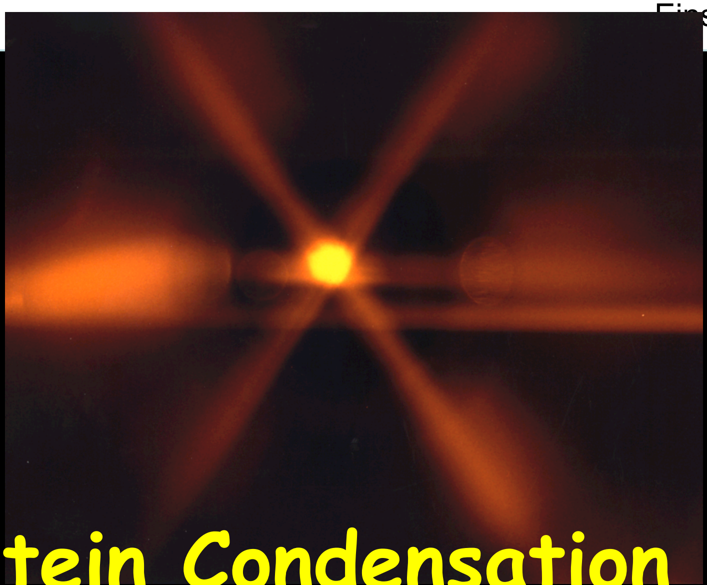
In 1995 (70 years after Einstein's prediction) teams in Boulder, Colorado and Cambridge, Massachusetts achieved Bose-Einstein Condensation in super-cold gas

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

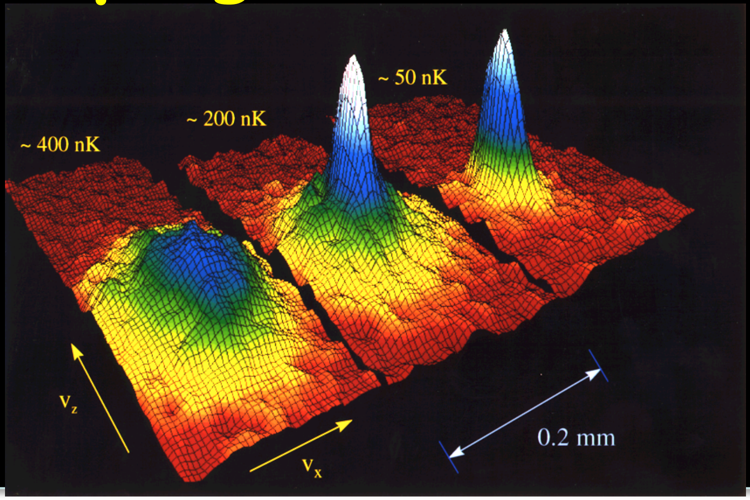
They and others have reached temperatures lower than one nanokelvin !

3 peaks& laureates

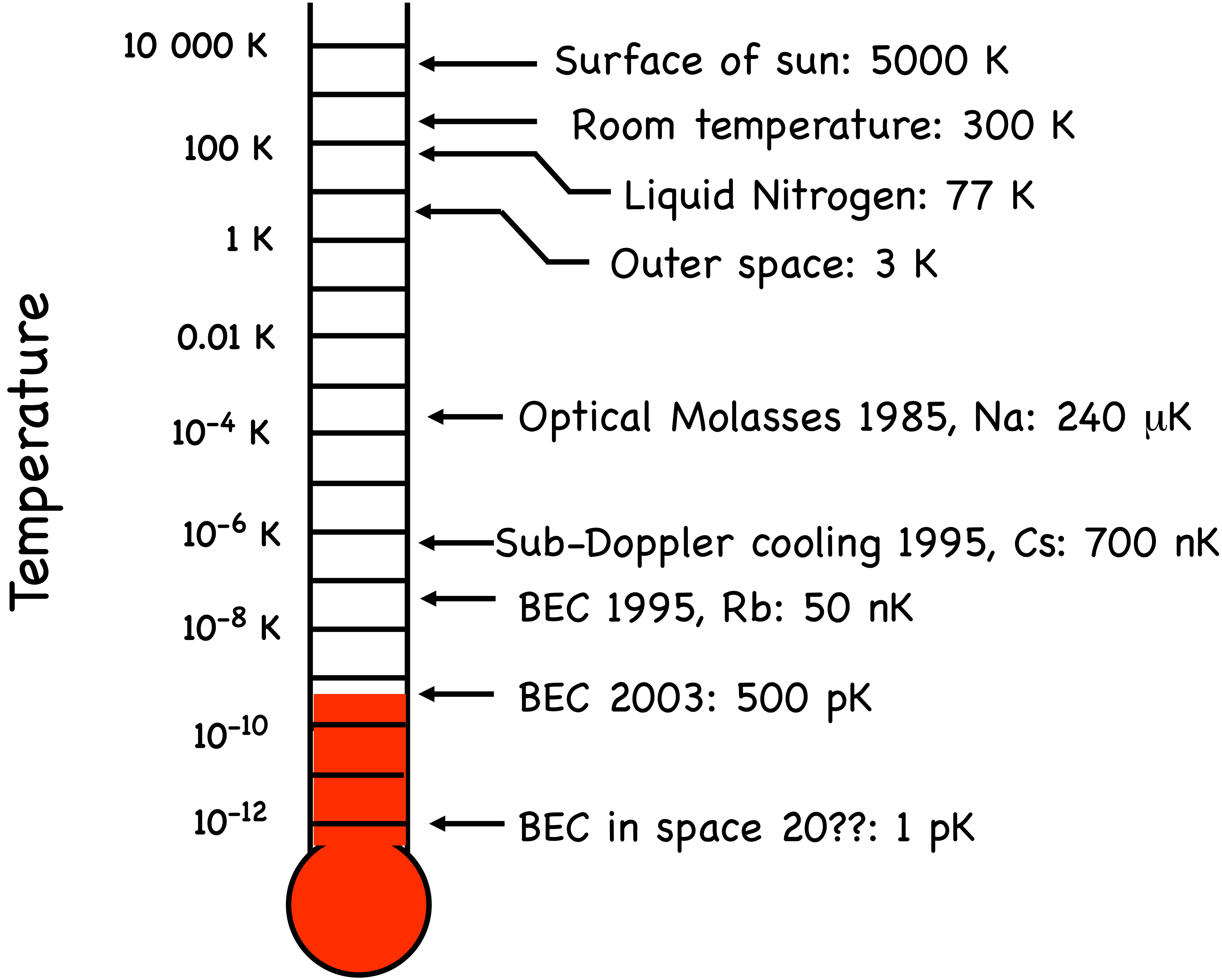




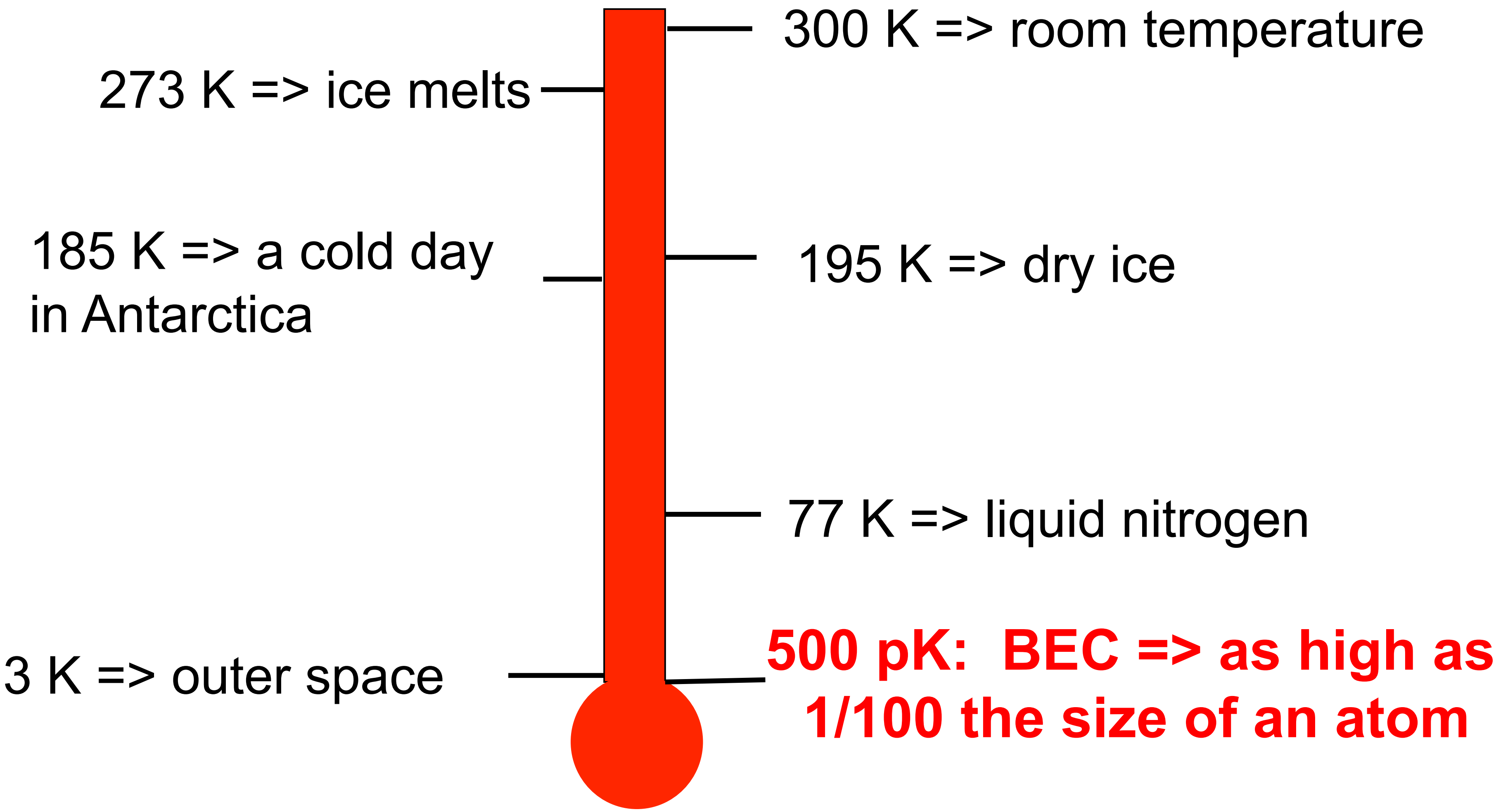
Laser cooling, Bose-Einstein Condensation (BEC) and techniques for making ultra-cold atomic gases have opened a new and rapidly advancing area of research, one which is being intensively studied in the current KITP program.



Log thermometer



The Absolute or "Kelvin" temperature scale



What's Next?

- **Better clocks—in Boulder neutral atoms in lattices are even better than in fountains and trapped ions are better still**
- **Measuring fundamental constants**
- **Tests of the fundamental understanding of Nature**
- **Quantum Simulation (solving intractable materials problem)**
- **Quantum Computers**
- **More...**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The End