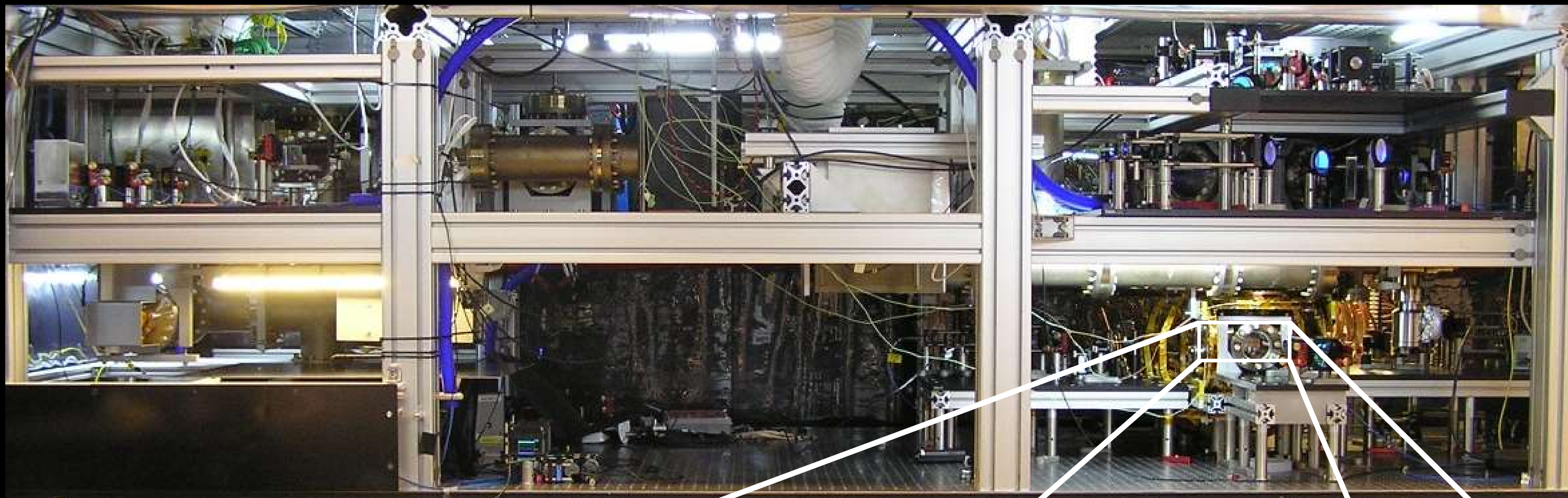
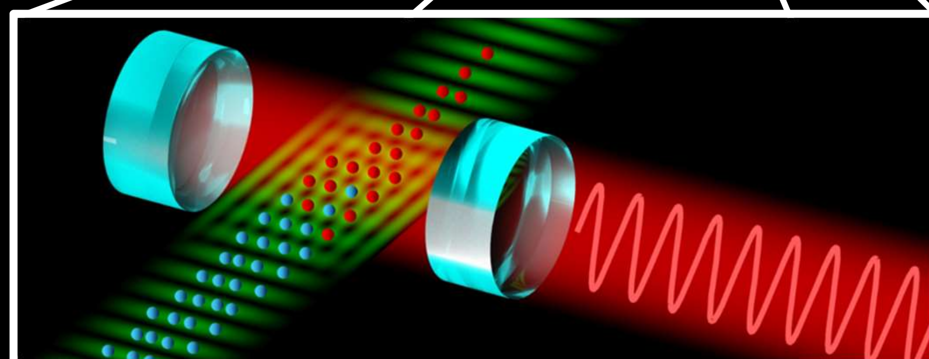
iqClock: Building the most accurate clock in the world



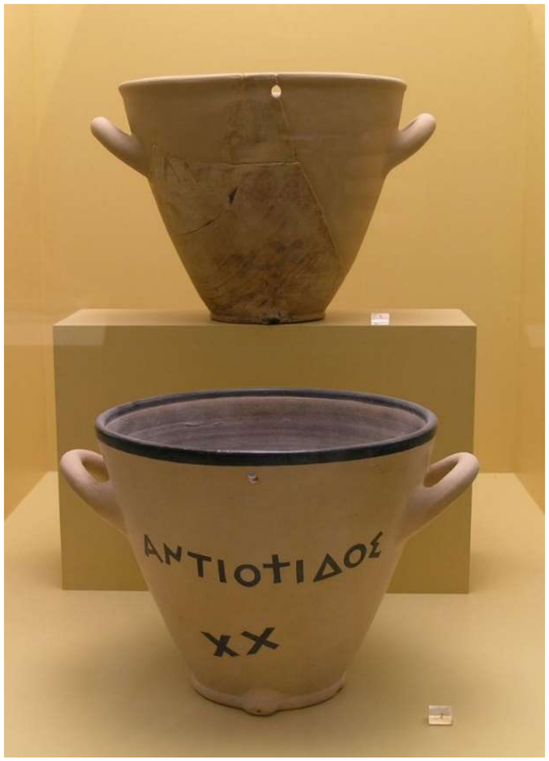


Shayne Bennetts

www.strontiumbec.com

Universiteit van Amsterdam

We have been making clocks for millenia



Accuracy: ~15 minutes in a day (10^{-2})

The Pendulum Clock (1657)

1000x more accurate!

Christiaan Huygens
(1629-1695)
a student from Leiden
Physicist/Mathematician

Salomon Coster
(1620-1659)
from Den Hague
an instrument maker

Period, $T = 2\pi\sqrt{\frac{l}{g}}$

Accuracy: 15 seconds in a day

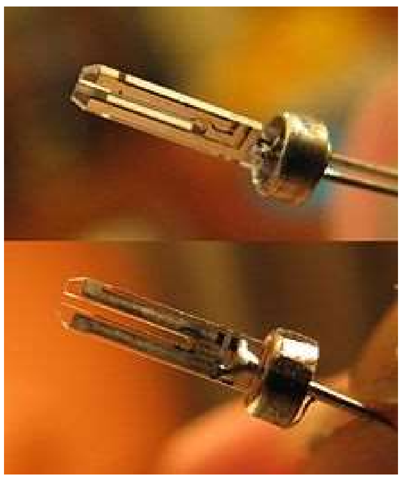
5500 seconds in a year (10^{-5})

Quartz Clock: simpler, cheaper, more accurate

1927 Bell Labs: A better oscillator:

Quartz crystal cut like a tuning fork.

Mechanical resonance generates a piezoelectric voltage.



Accuracy: ~100 seconds in a year (10^{-6})

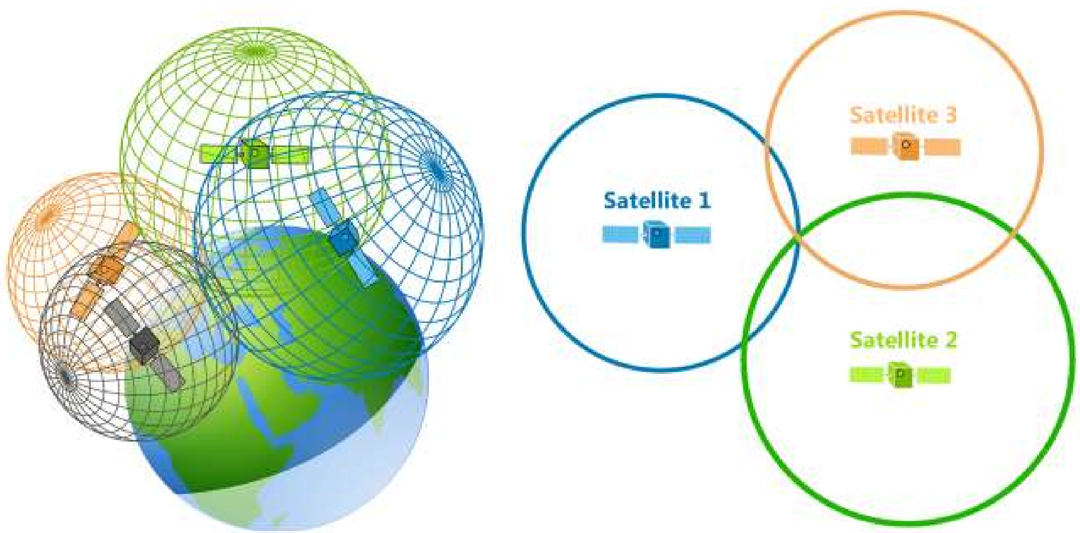
~1 second in a year (10^{-8}) temperature stabilized

Global Positioning System

If I **know** the position of each GPS satellite in space and time

If I **measure** the time difference between me and 4 of these satellites

I can **calculate** my position in space and time (x,y,z,t)



GPS is built on precision clocks

Global Positioning System

If we used the best quartz clock for a GPS system what is the location error?

1ns error gives ~30cm uncertainty
A clock of 10^{-8} will give an error of 0.8ms in 1 day
(Error: ± 260 km after just 1 day)

Quartz clocks (10^{-8}) are not good enough☹

Satellites **need <10^{-14}** for <1m drift per day
Satellites **need <10^{-17}** for <1m drift per year

(To check for signal hijacking I also need a precision clock at the receiver)

The Perfect Clock

Accurate: All clocks must read the same
(clocks must be identical)

Pendula and crystals are all
different☹

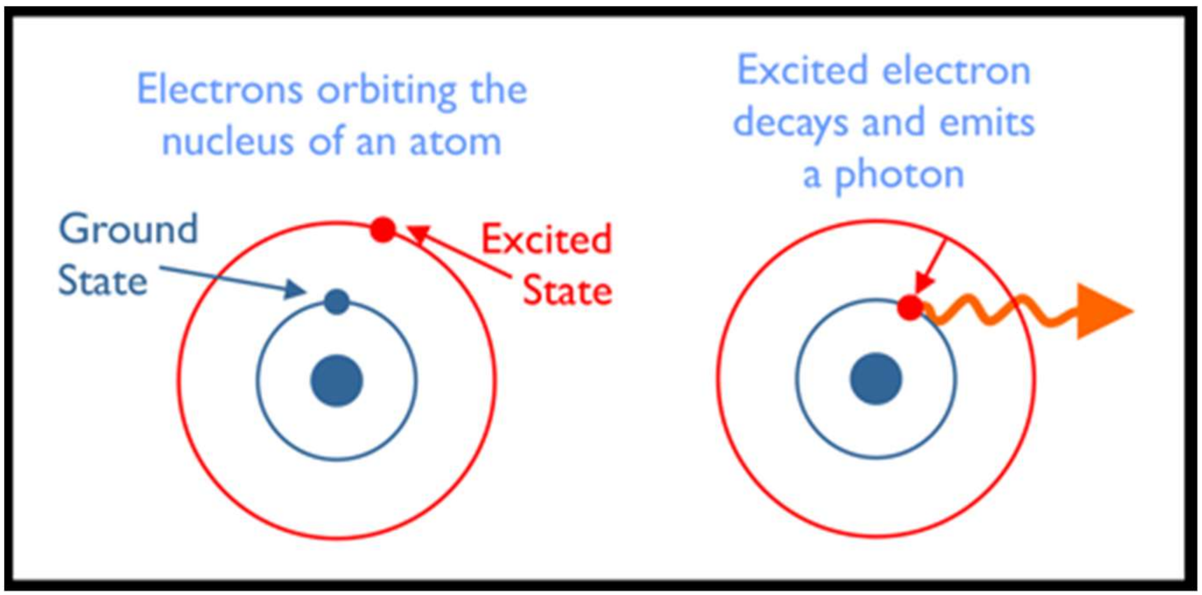
Atoms are identical ☺

The Perfect Clock: Atoms

Precise: Clocks must have a precise frequency

$$\frac{\Delta f}{f} \ll 10^{-8}$$

A precise transition frequency exists between energy levels:



The Perfect Clock: Atoms

- Electrons take >1000s to decay in forbidden transitions
- Transitions can have a very high frequency, eg 4x10^{14} Hz

This can give $\frac{\Delta f}{f} < 10^{-17}$

1,000,000,000 better than a quartz clock!

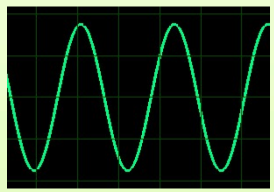
GPS should be possible ☺

Caesium microwave atomic clocks

Test

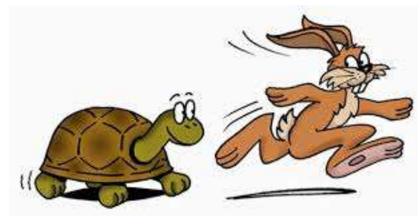
Use atoms to test if oscillator is too fast or too slow

Oscillator



9.2 GHz

Counter



Adjust

Definition

1 second = 9192631770 periods of a ^{133}Cs transition

Better Atomic Clocks?

Caesium clock has a frequency of 9.2GHz

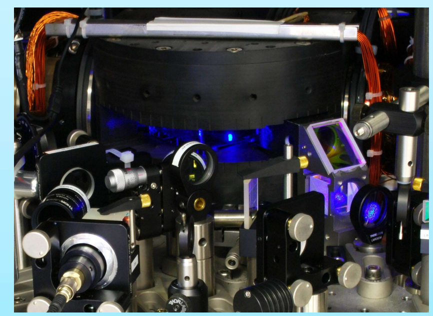
Strontium clock has a frequency of 429,228 GHz

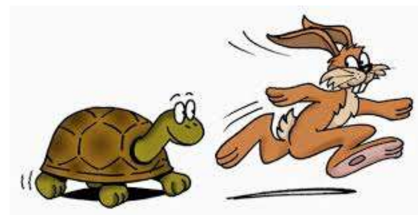
Use optical instead of microwave transitions (tick 100,000x faster)

Strontium optical atomic clocks

Test

Use atoms to test if oscillator is too fast or too slow



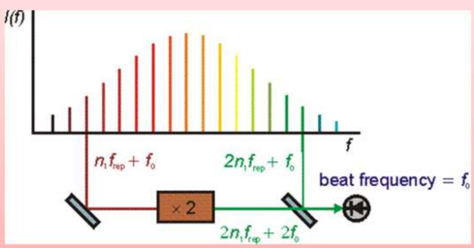


Adjust

Laser

429,228 GHz

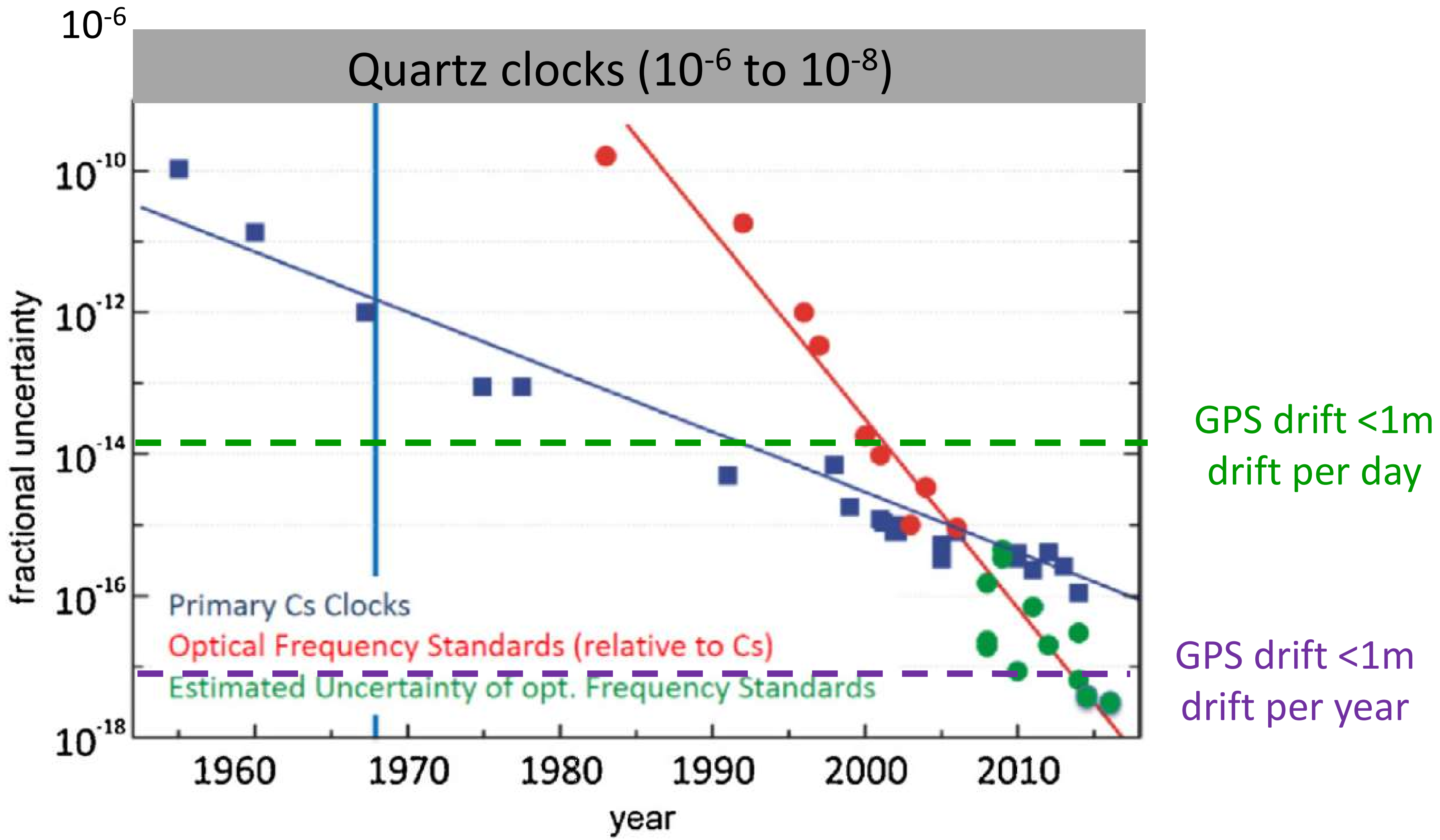
Divider



Frequency Comb

Counter

Optical atomic clocks



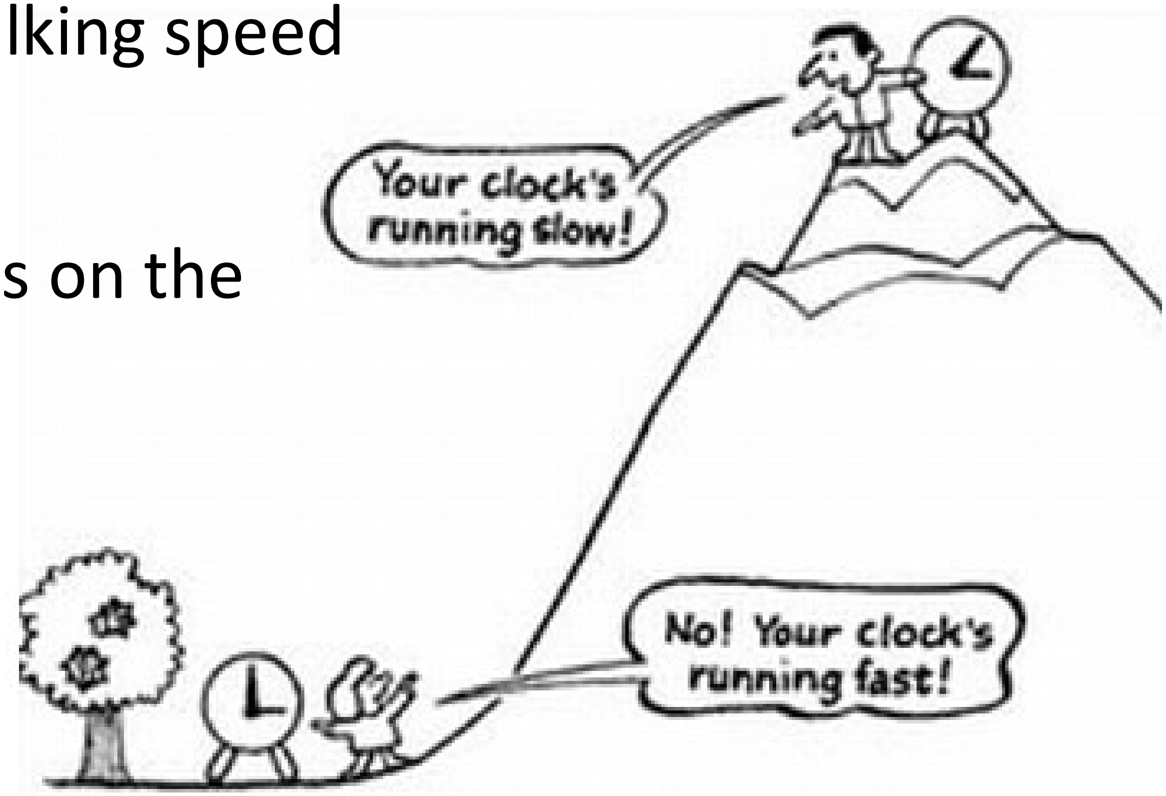
Optical atomic clocks

At the 10^{-17} and 10^{-18} accuracy level you start to see:

1. Differences in clock speed for <10cm change in height (General Relativity)

2. Time dilation at walking speed (Special Relativity)

3. Effects such as tides on the speed of clocks



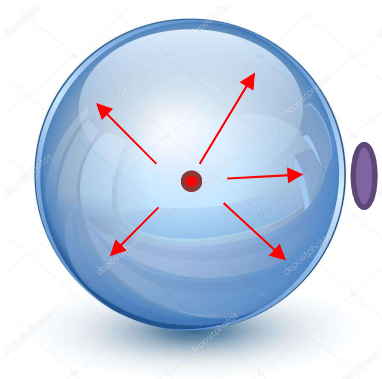
…so now things get interesting☺

Even Better Atomic Clocks?

- Smaller, simpler, more precise clocks?

Why not use light directly from atoms as our clock laser?

Can we use light directly from the atoms?



Low collection efficiency <5%

Forbidden Transitions: ~1 photon/1000s

Few atoms** (<10^7 atoms)

**Atoms must be cooled and trapped to avoid Doppler shifts

Effective output ~10^3 photons/s =10^{-16}W=0.1fW

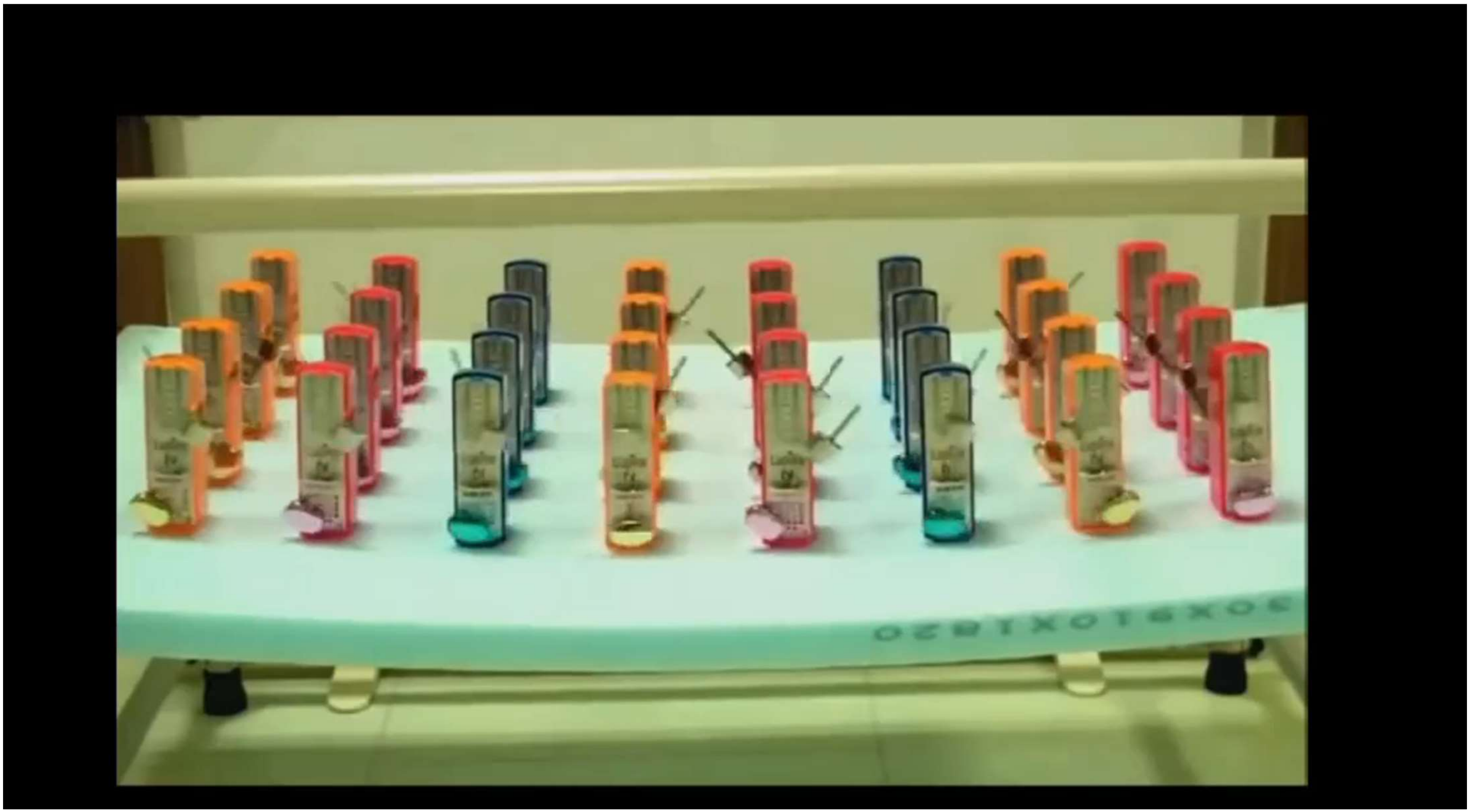
Not enough power ☹

Superradiance

Superradiance is a collective effect where ***identical*** atoms synchronize their outputs

Superradiance

Superradiance is a collective effect where ***identical*** atoms synchronize their outputs



Superradiance

Incoherent atoms add their output powers/intensity:

Power ∝ Number

Coherent, synchronized identical atoms add amplitude:

Amplitude ∝ Number

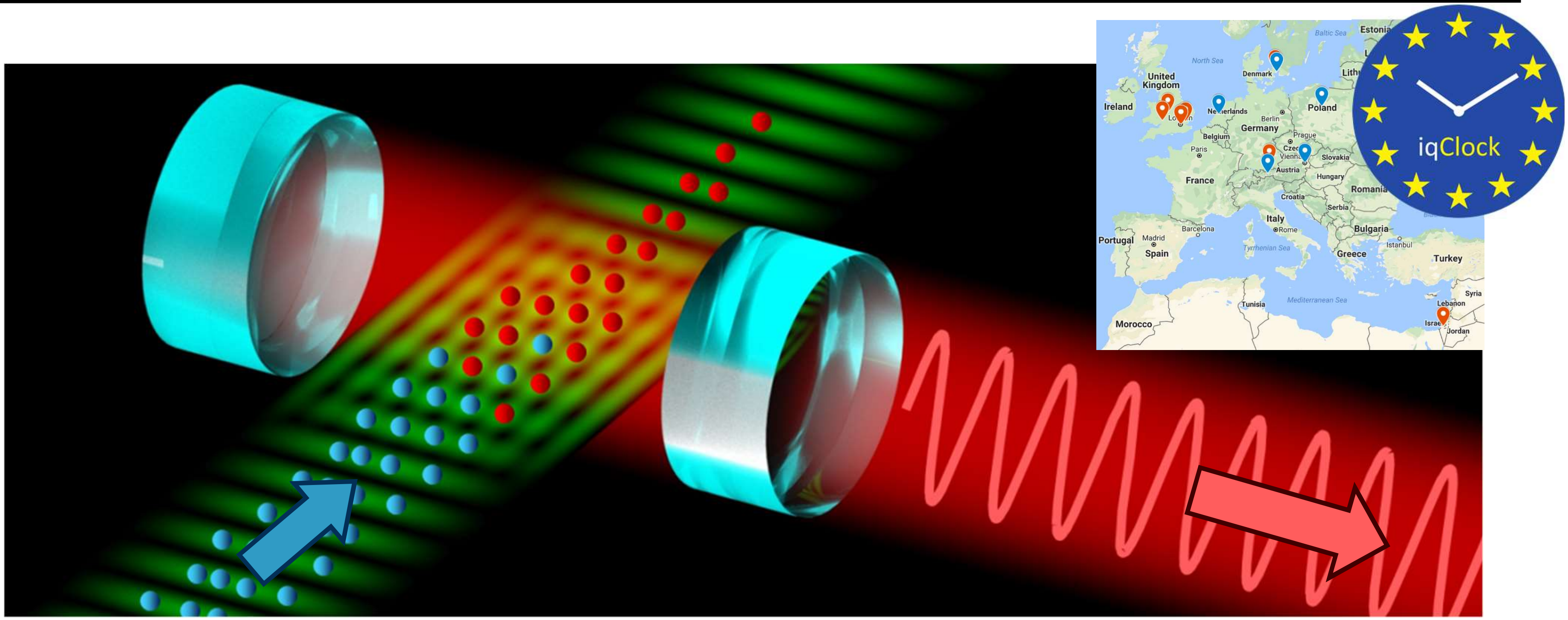
Power ∝ $(\text{Number})^2$

For 10^7 atoms this gives ~10^{11} photons/s =10 nW

**Limited by pumping rate to <10^7 photons/s =1pW

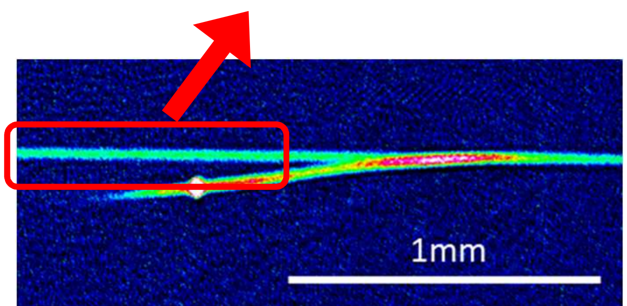
Enough power for a lock (>0.1pW) ✓

Superradiant clock laser



Continuous ultracold strontium beam in

Clock laser beam out

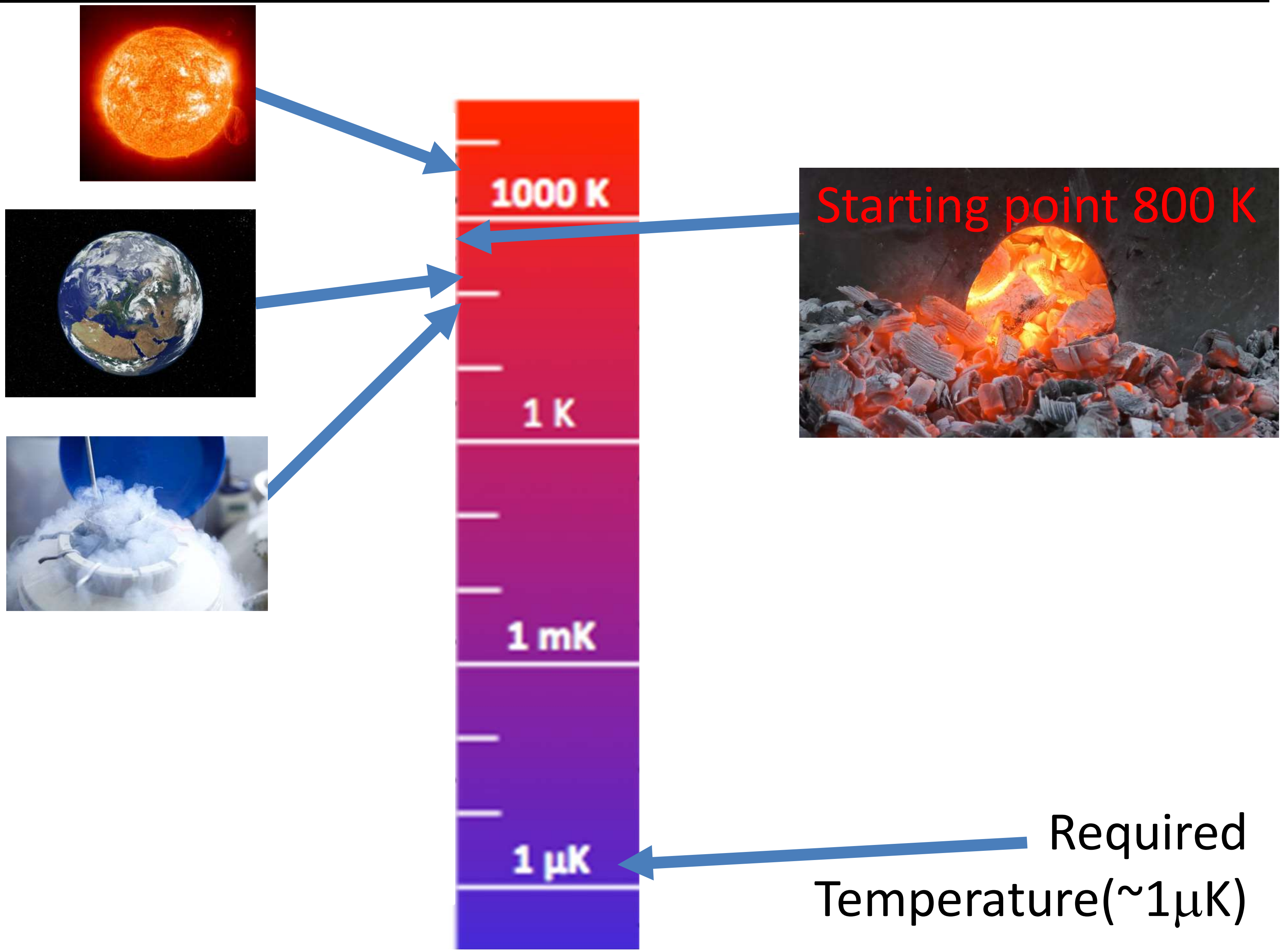


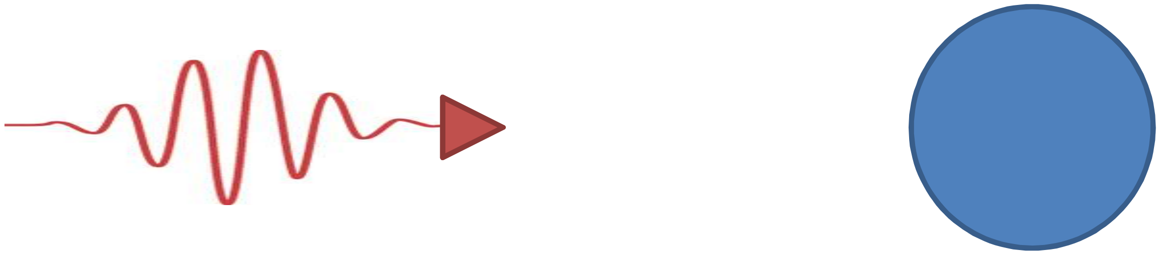
Some of the challenges:

- Lots (>10^7 atoms/s) of cold (1μK) atoms
- Steady state (continuous) operation

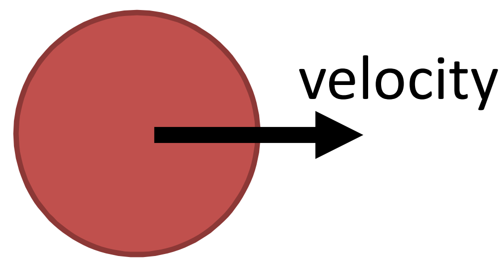
Amsterdam is the only group to have demonstrated such a beam (for a continuous atom laser)

Cooling atoms from 800K to 1μK?

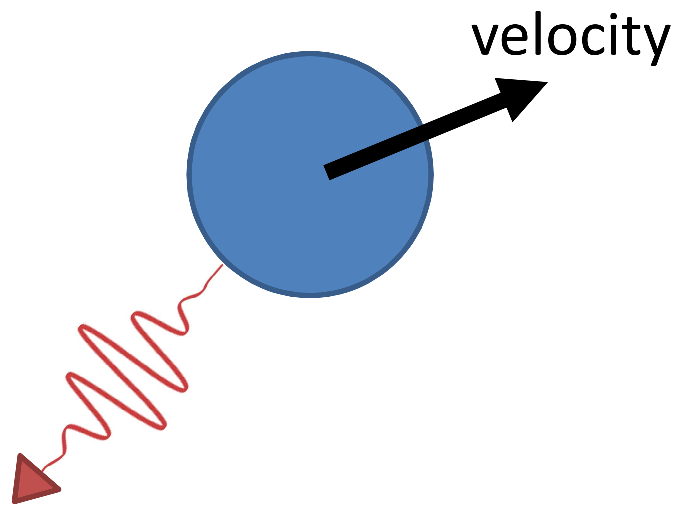




Absorption:

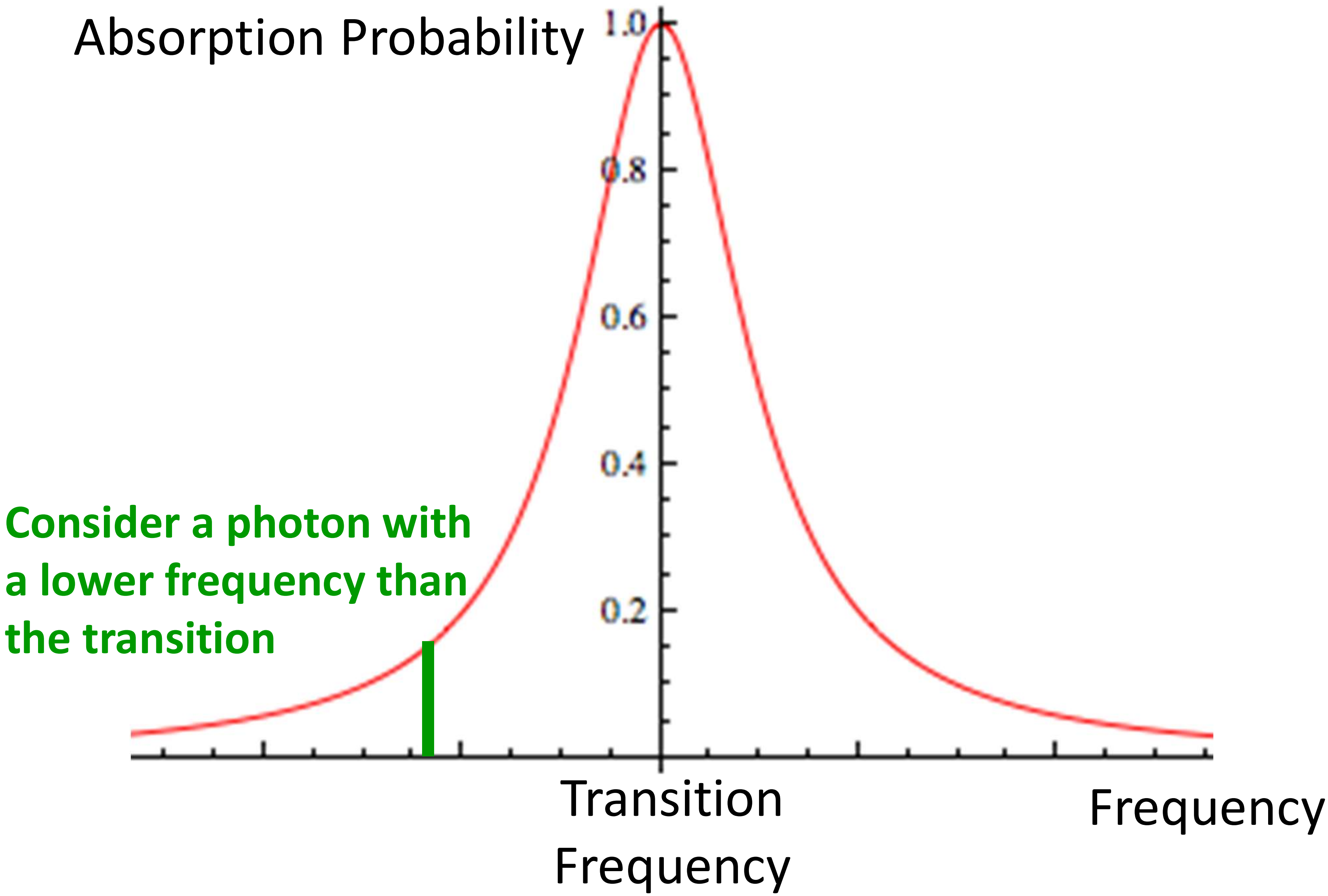


Spontaneous Emission:



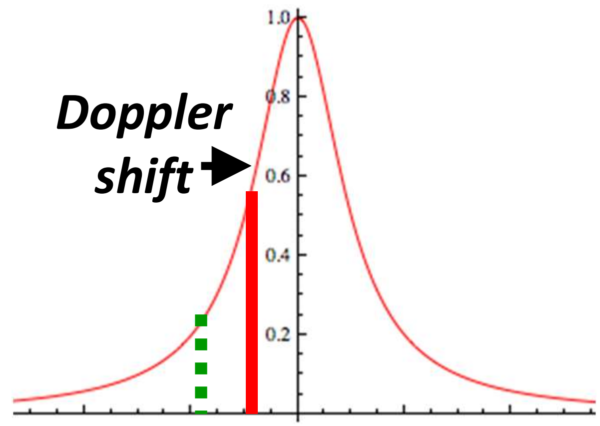
Photons can change an atom’s velocity

Laser Cooling



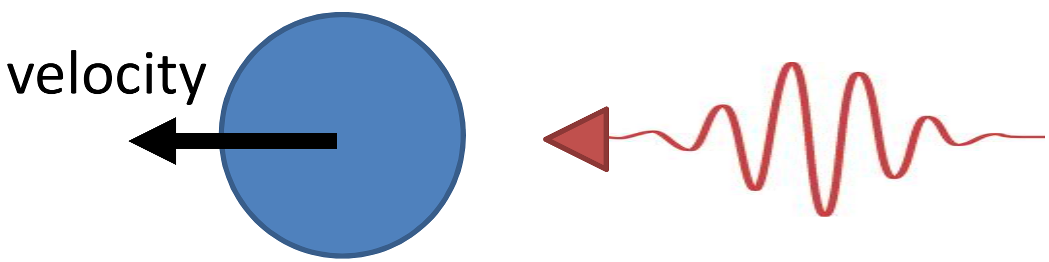
Laser Cooling

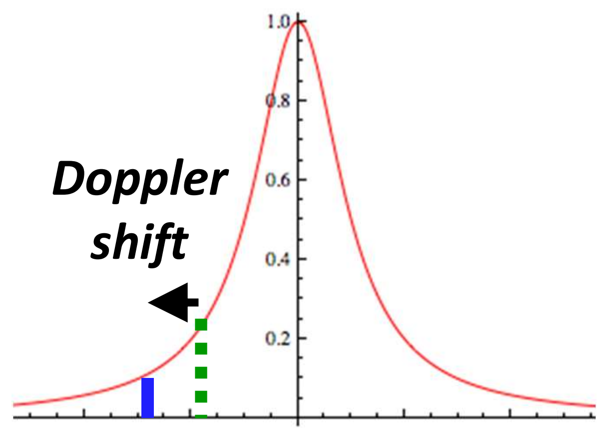
Moving towards: See photons at a higher frequency



Higher Probability of absorption

Moving away: See photon as a lower frequency

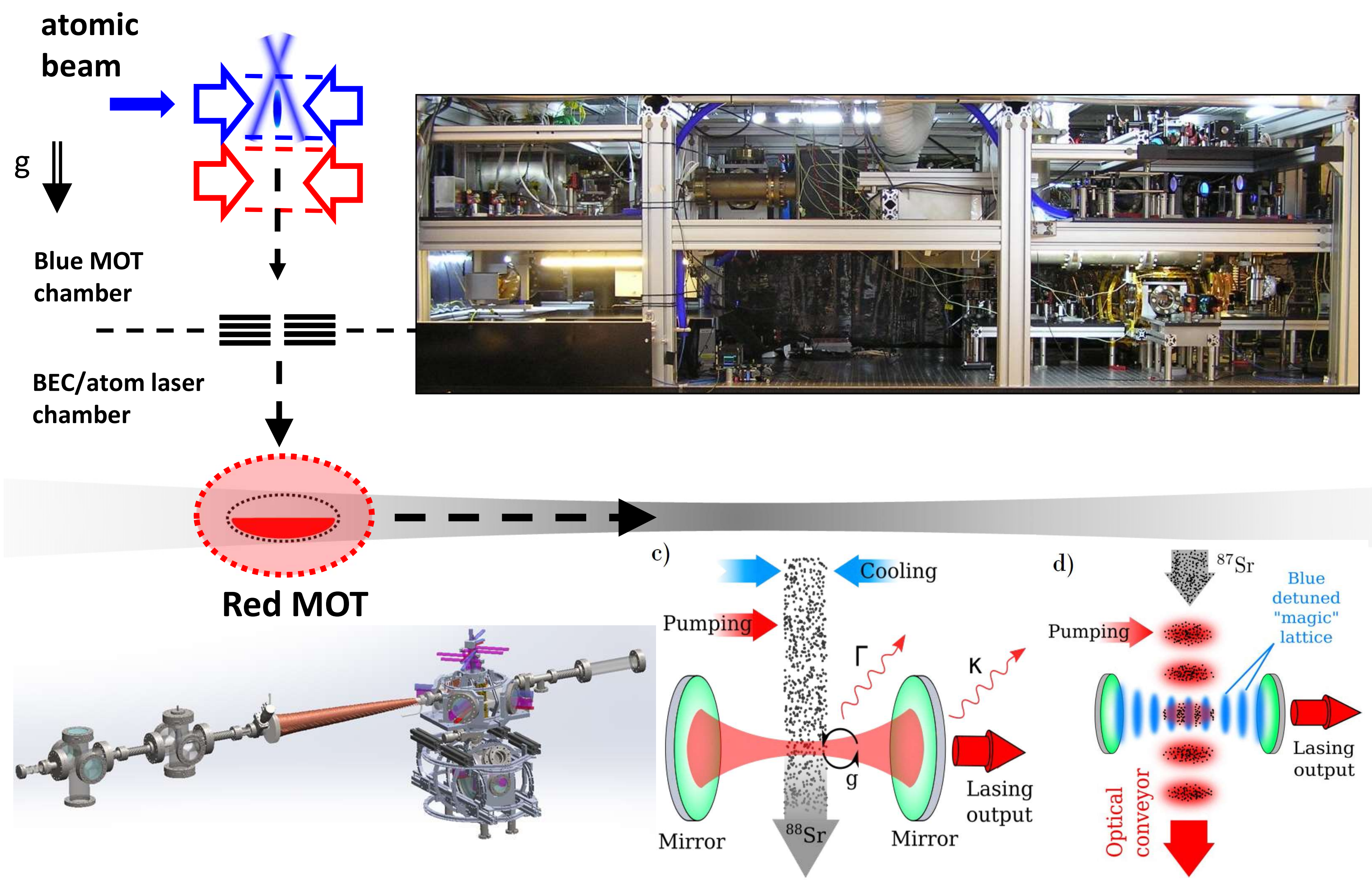




Lower Probability of absorption

Lasers can push atoms towards zero velocity: They can cool ☺

Superradiant optical clock in practice



Future applications: Time and Gravity

- Tests of special/general relativity and unified theories
- Variation in fundamental constants
- Phased sensor arrays eg for radio astronomy
- Precision and reliable navigation (GPS+++)
- Searches for dark matter
- Clock based geodesy

NWO VENI & VICI

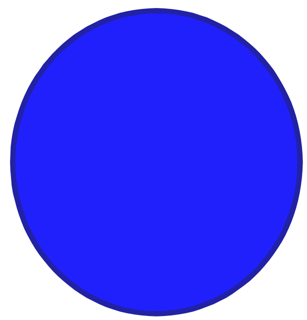
iqClock

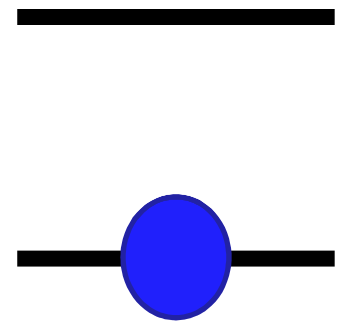
erc

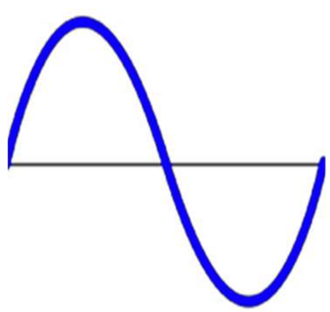
Reserve slides

How do we lock an Atomic Clock?

Begin with atoms in the ground state

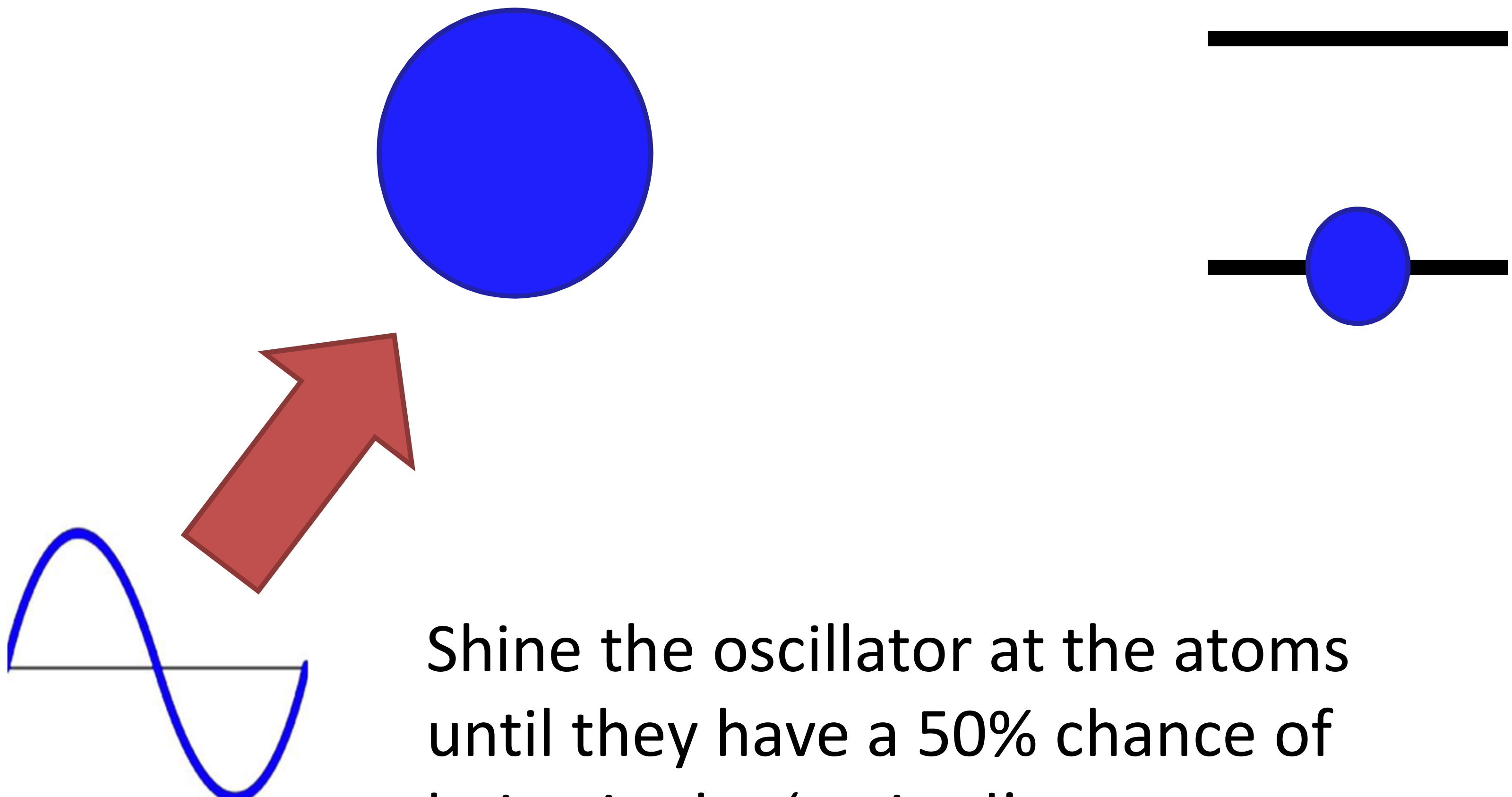






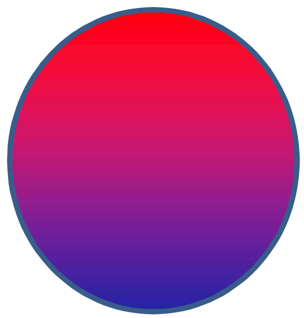
…and an oscillator at the frequency we think is the transition frequency

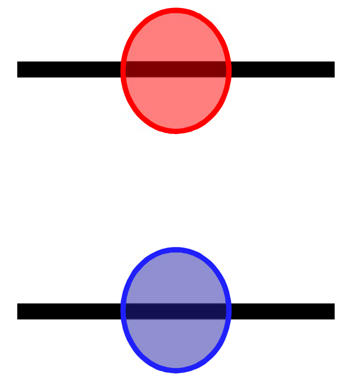
How do we lock an Atomic Clock?

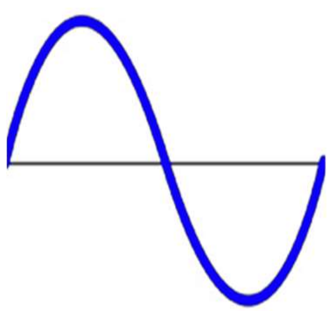


Shine the oscillator at the atoms until they have a 50% chance of being in the ‘excited’ state

How do we lock an Atomic Clock?



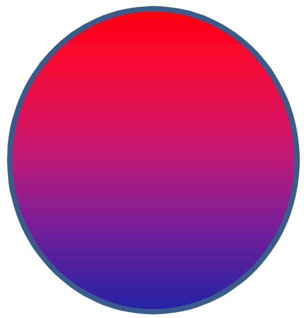


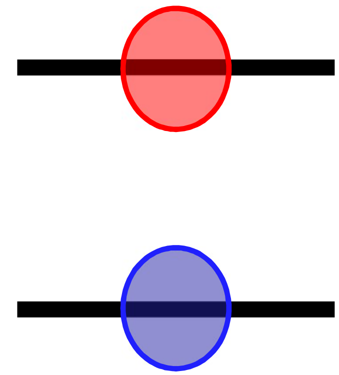


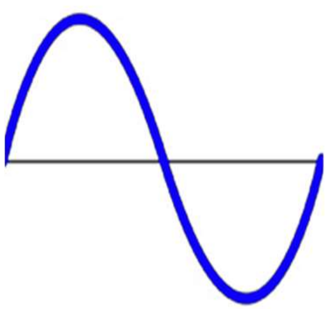
Now the atoms are in a superposition state, 50% chance of being excited.

How do we lock an Atomic Clock?

$\Delta f = 0$





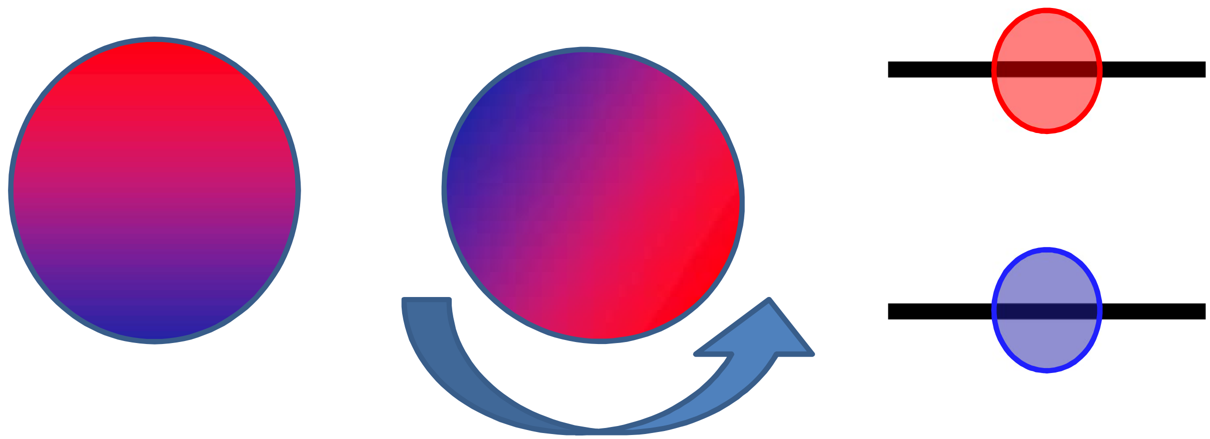


We wait for a while....

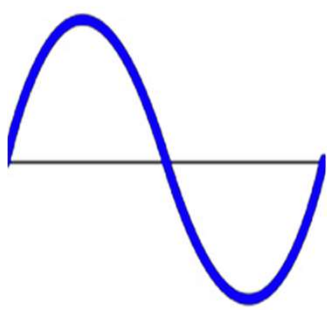
If the oscillator was at the ***same*** frequency as the transition...nothing happens

How do we lock an Atomic Clock?

$\Delta f = 0$ $\Delta f \neq 0$

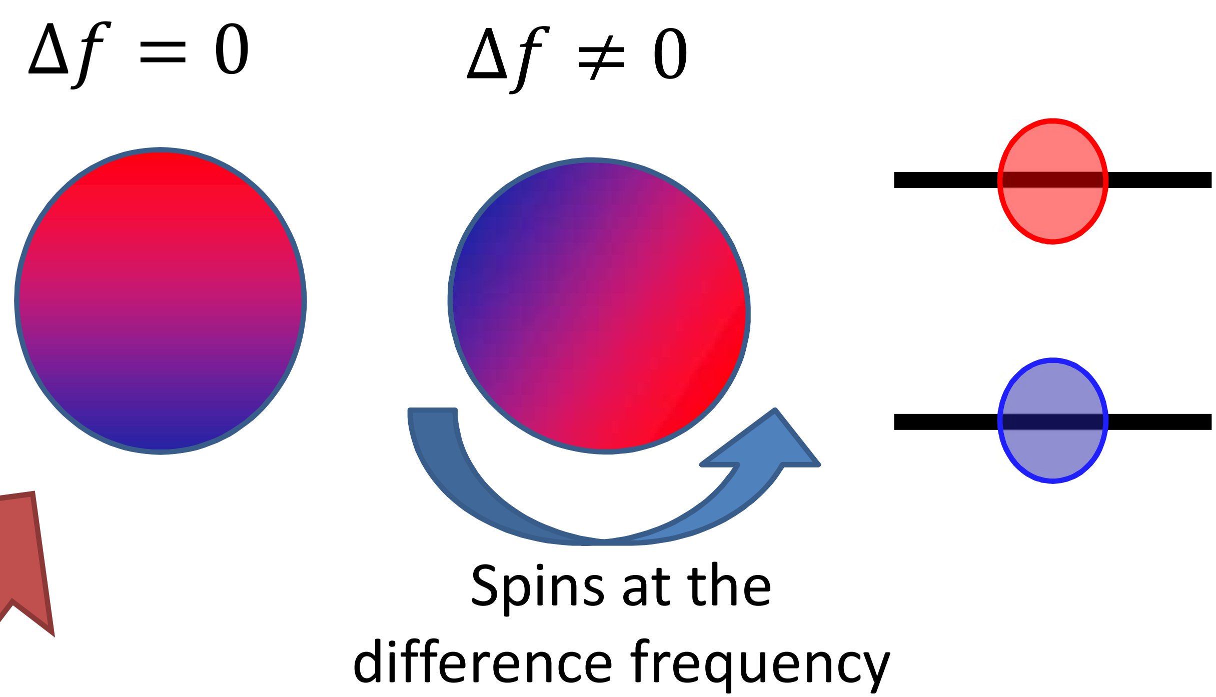


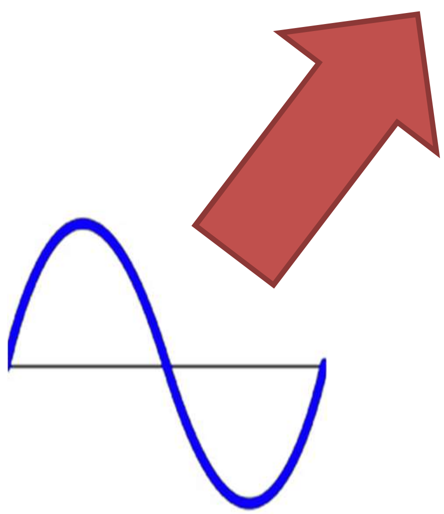
Spins at the difference frequency



If the oscillator was at a ***different*** frequency the relative phase between the states rotates

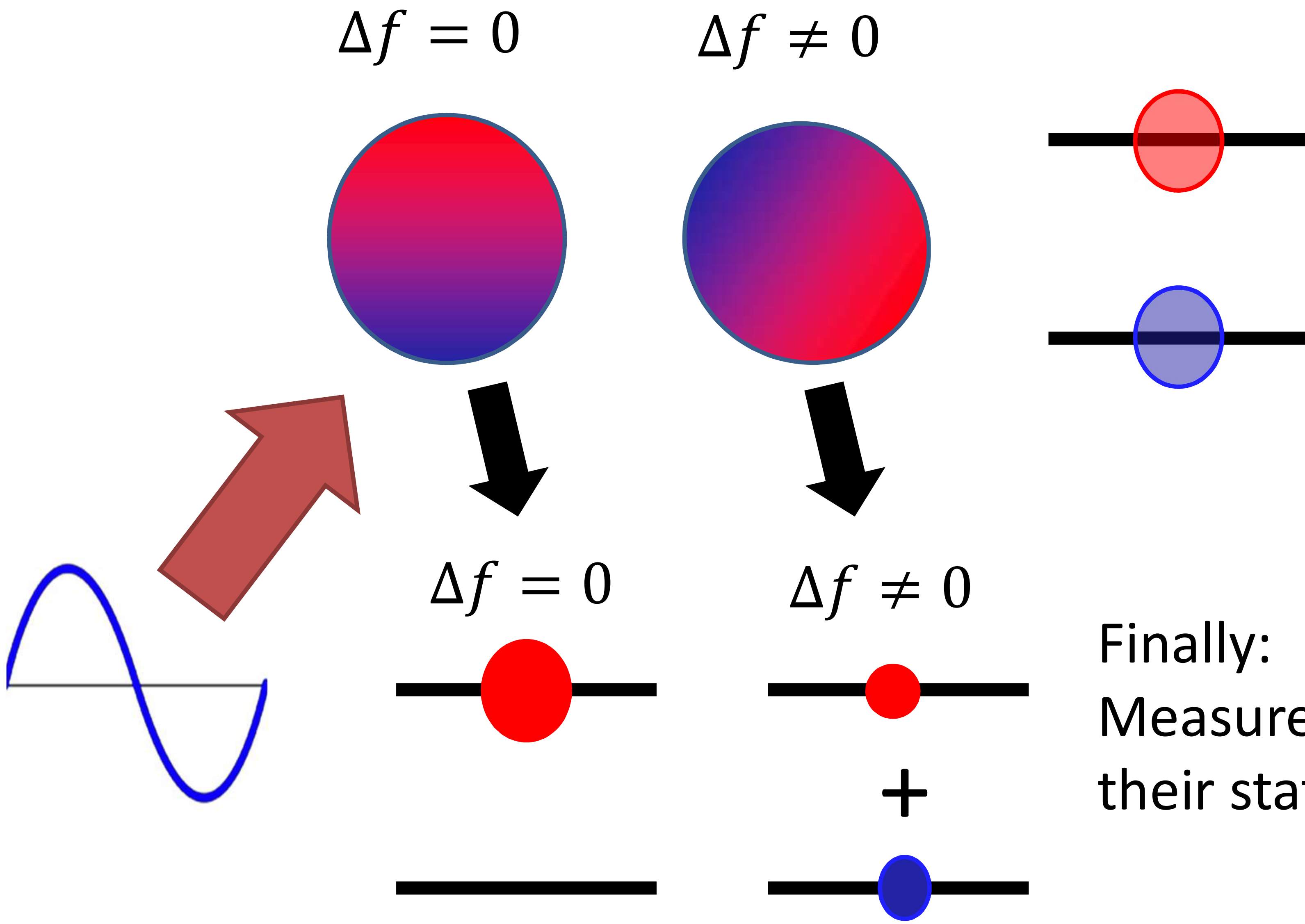
How do we lock an Atomic Clock?





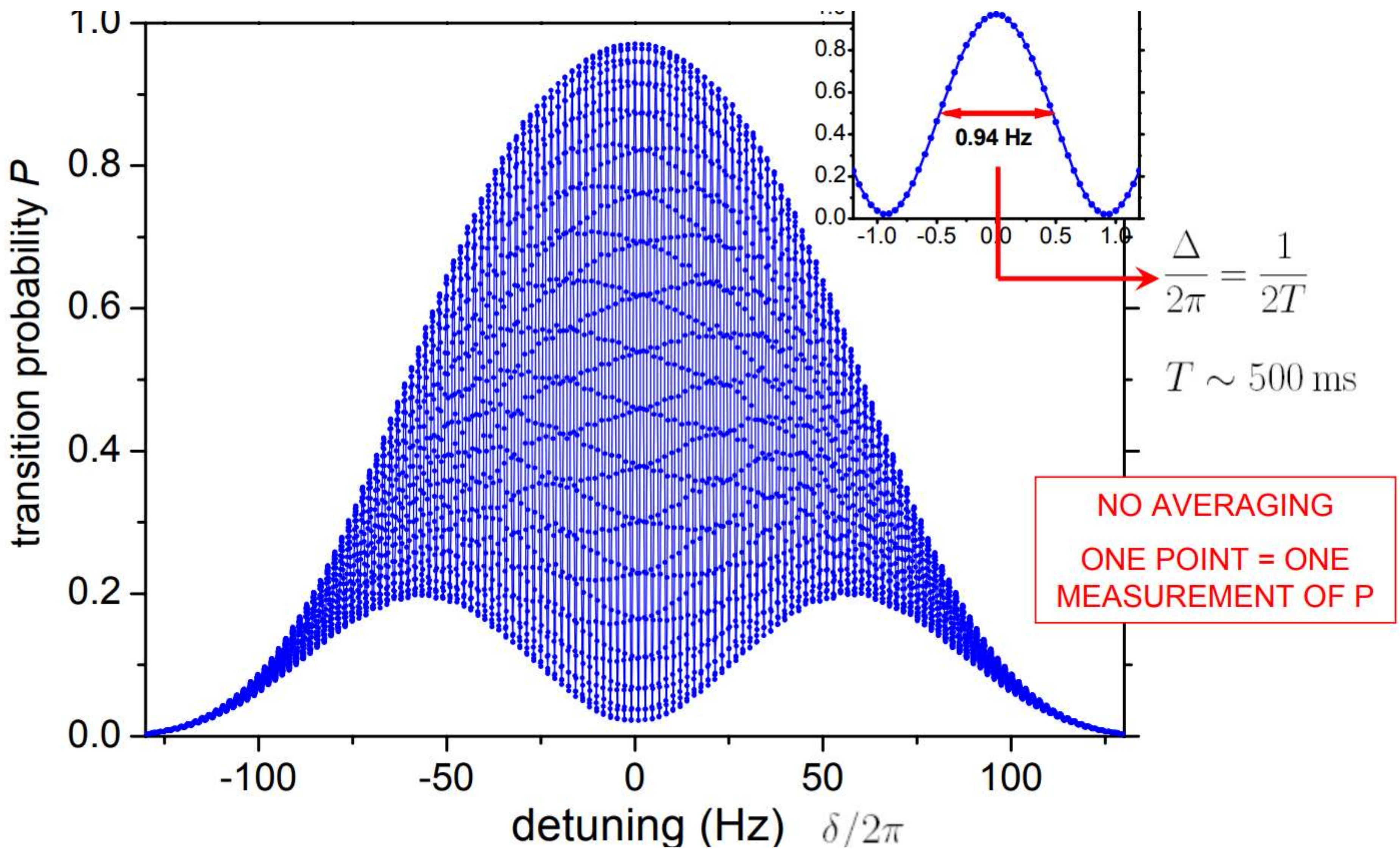
Again…Shine the oscillator at the atoms until they have a 50% chance of being in the ‘excited’ state

How do we lock an Atomic Clock?

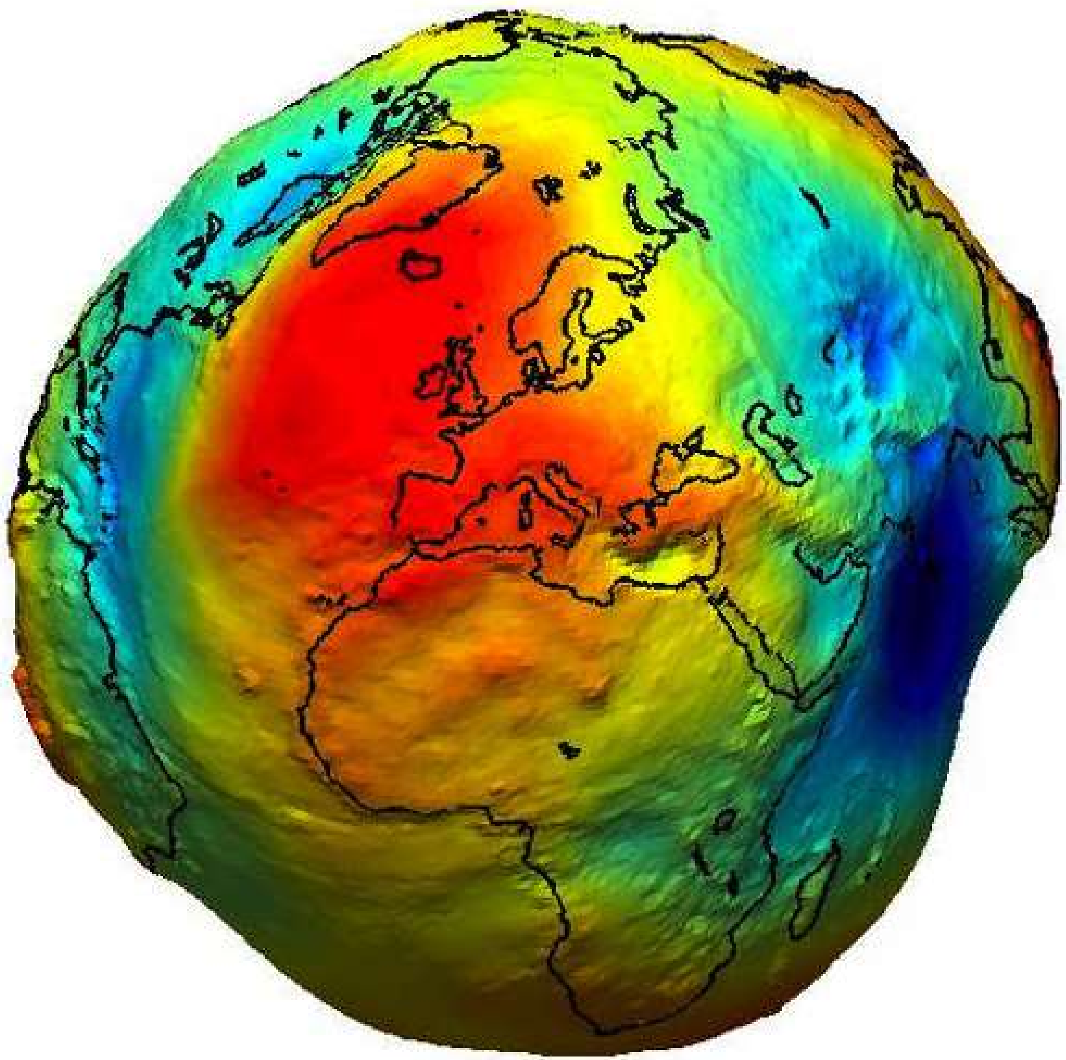


Finally: Measure their state

How do we lock an Atomic Clock?

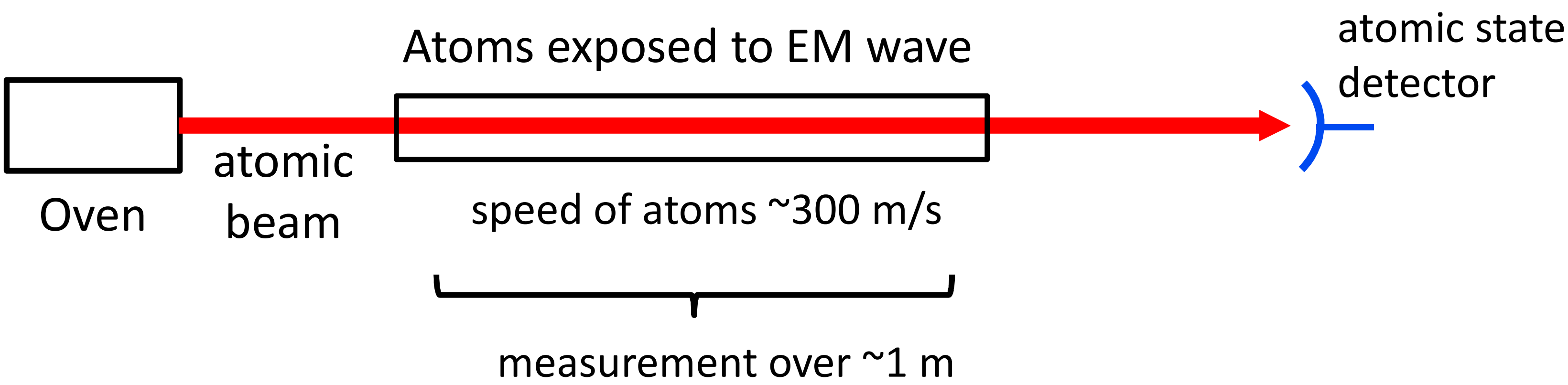


Geodesy



© QUEST, Hannover

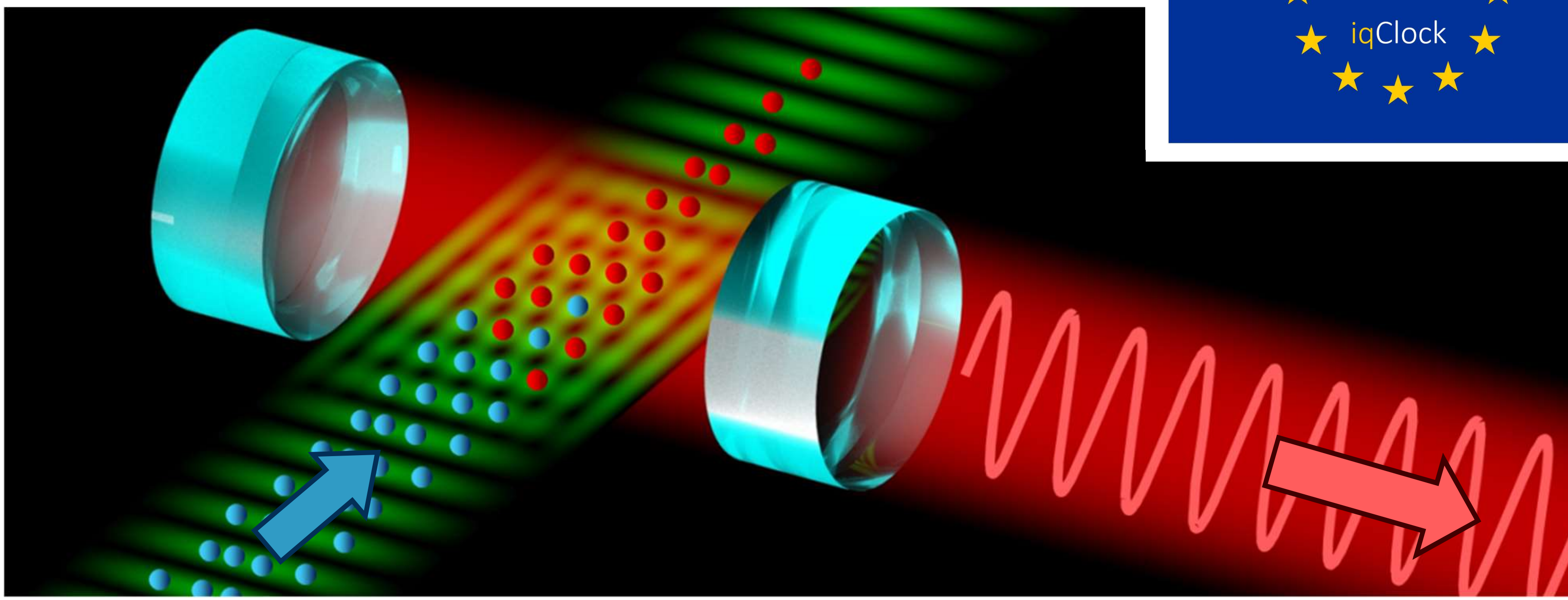
Limit of atomic beam clock



→ measurement time only ~ few ms

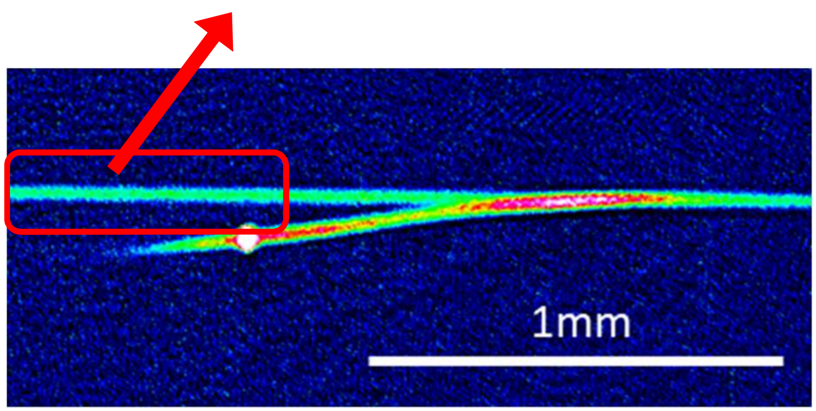
We need to slow atoms down…
→ We need to cool the atoms!

Superradiant clock laser



Continuous ultracold strontium beam in

Clock laser beam out



Pulsed version demonstrated by J. Thompson group, JILA, Boulder, USA
Science Advances, 2, e1601231 (2016)

iqClock Flagship – integrated quantum Clock

Goals

- Superradiant clock (5M€)
- Industrial optical clock (5M€)

Quantum Flagship Consortium

Officially begins October 2018

Steady-state Superradiant Clocks:

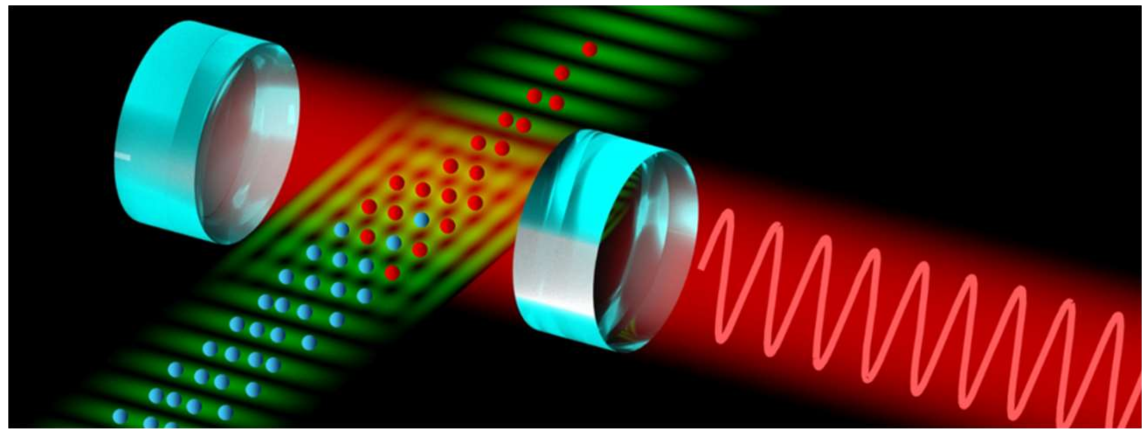
Combining key technologies/expertise from partners all across Europe:

- **Steady state Sr source technology** from Amsterdam (coordinator)
- Superradiant Laser technology from Copenhagen
- Clock technology/experience from Torun
- Theory from Innsbruck/Vienna

A superradiant optical clock

Guiding and Trapping lasers

Mirror cavity which entangles the atoms



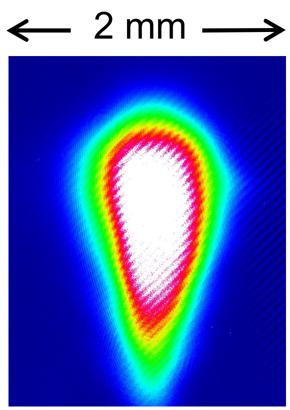
Atoms in

Clock light out

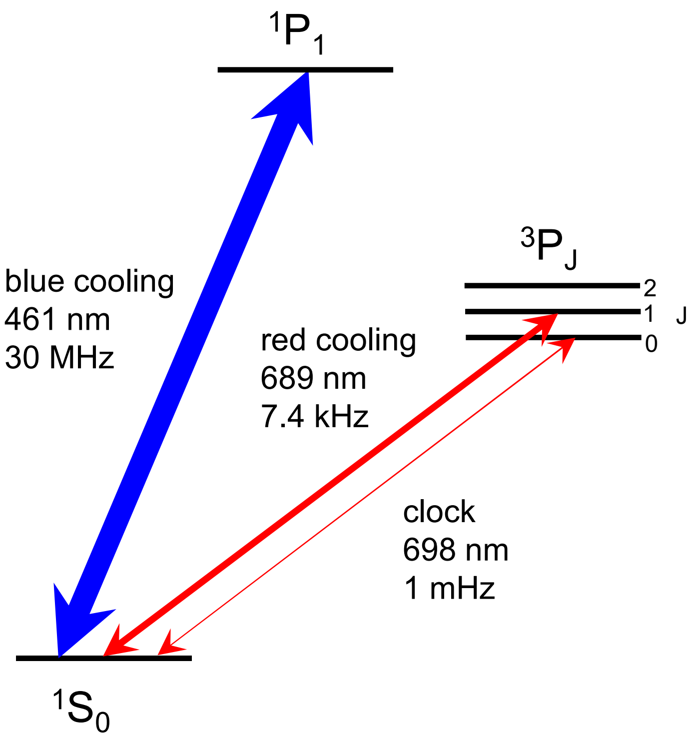
Some of the challenges:

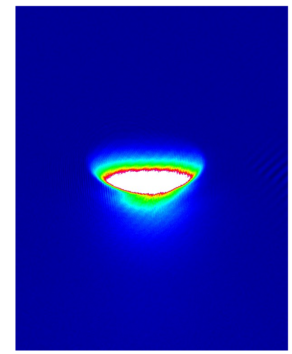
- Lots (>10^7 atoms/s) of very cold (1μK) atoms
- Steady state (continuous) operation

Sr transitions



blue laser cooling
hot gas T ~ 1 mK



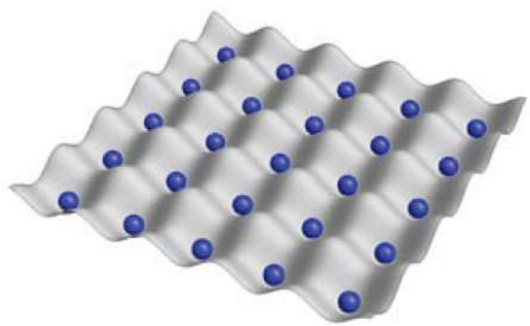


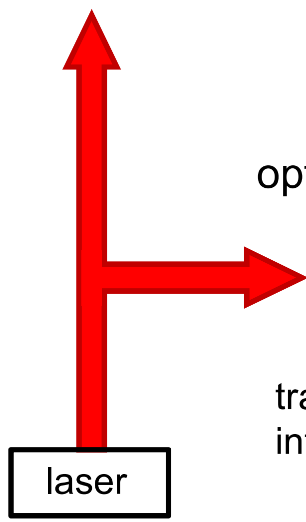
red laser cooling
cold gas T ~ 1 μK

Optical clock scheme

Frequency reference

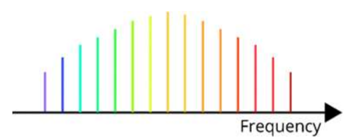
ultracold Sr atoms in lattice

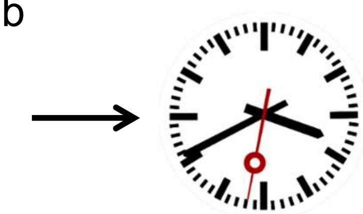




Clockwork

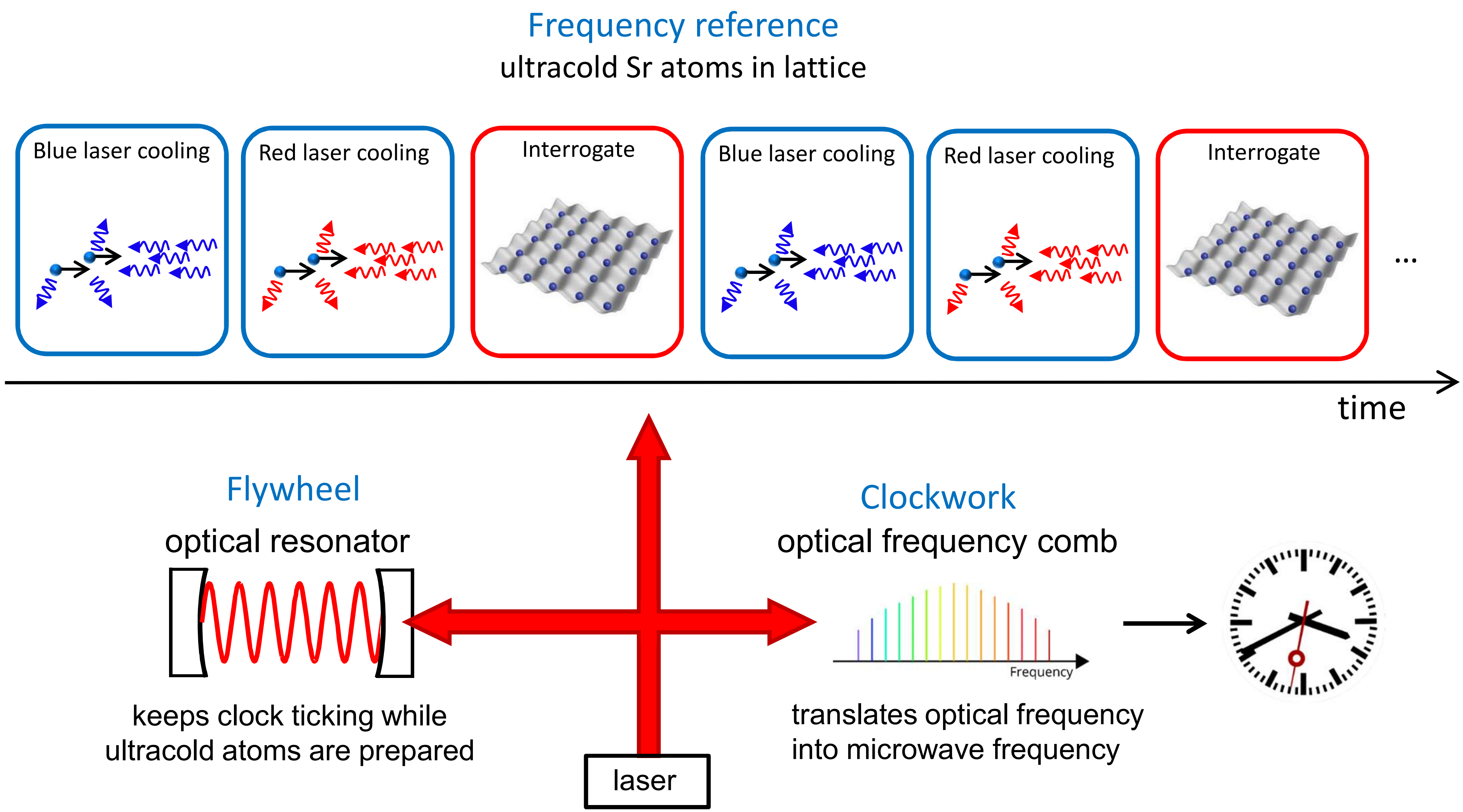
optical frequency comb



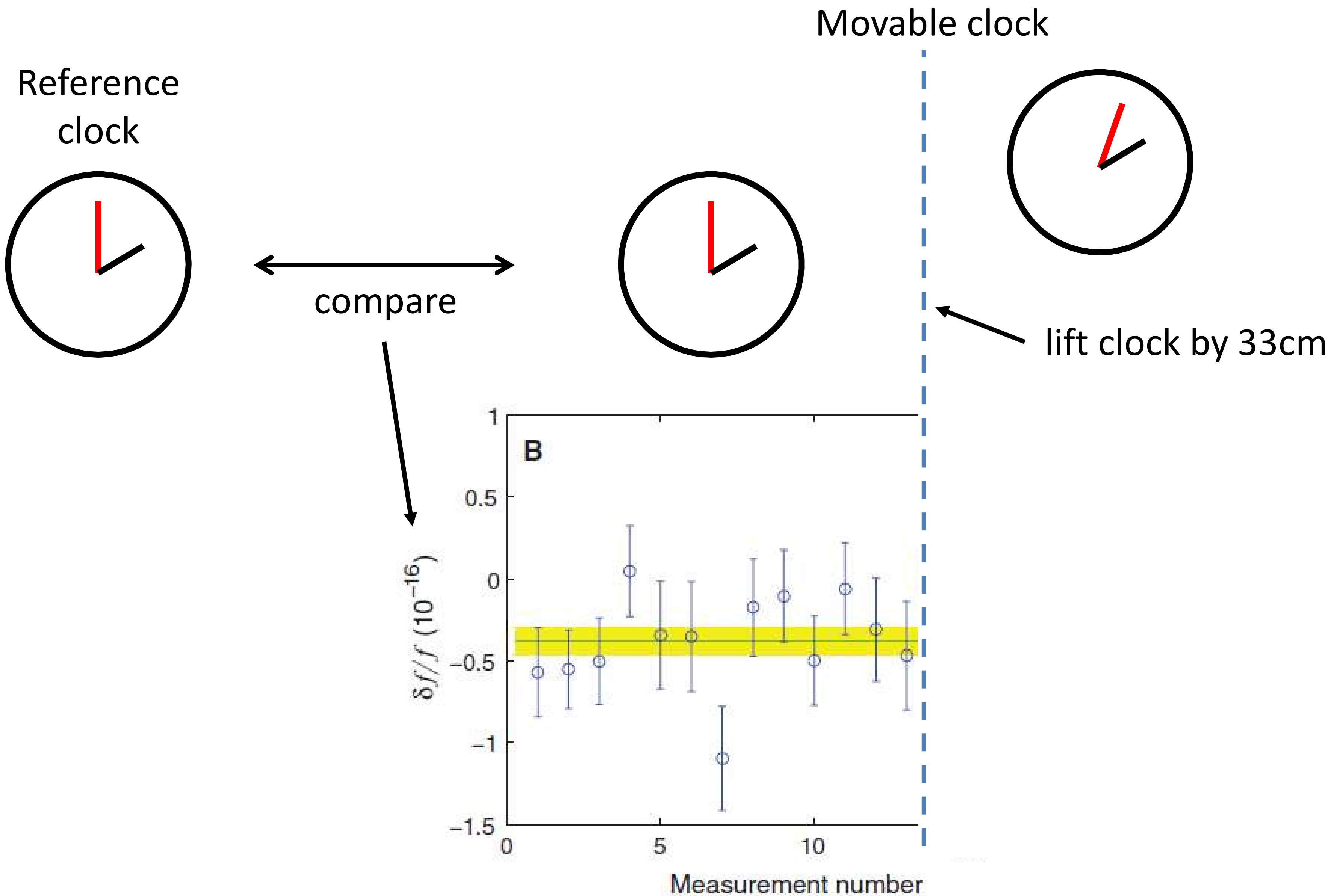


translates optical frequency
into microwave frequency

Optical clock scheme

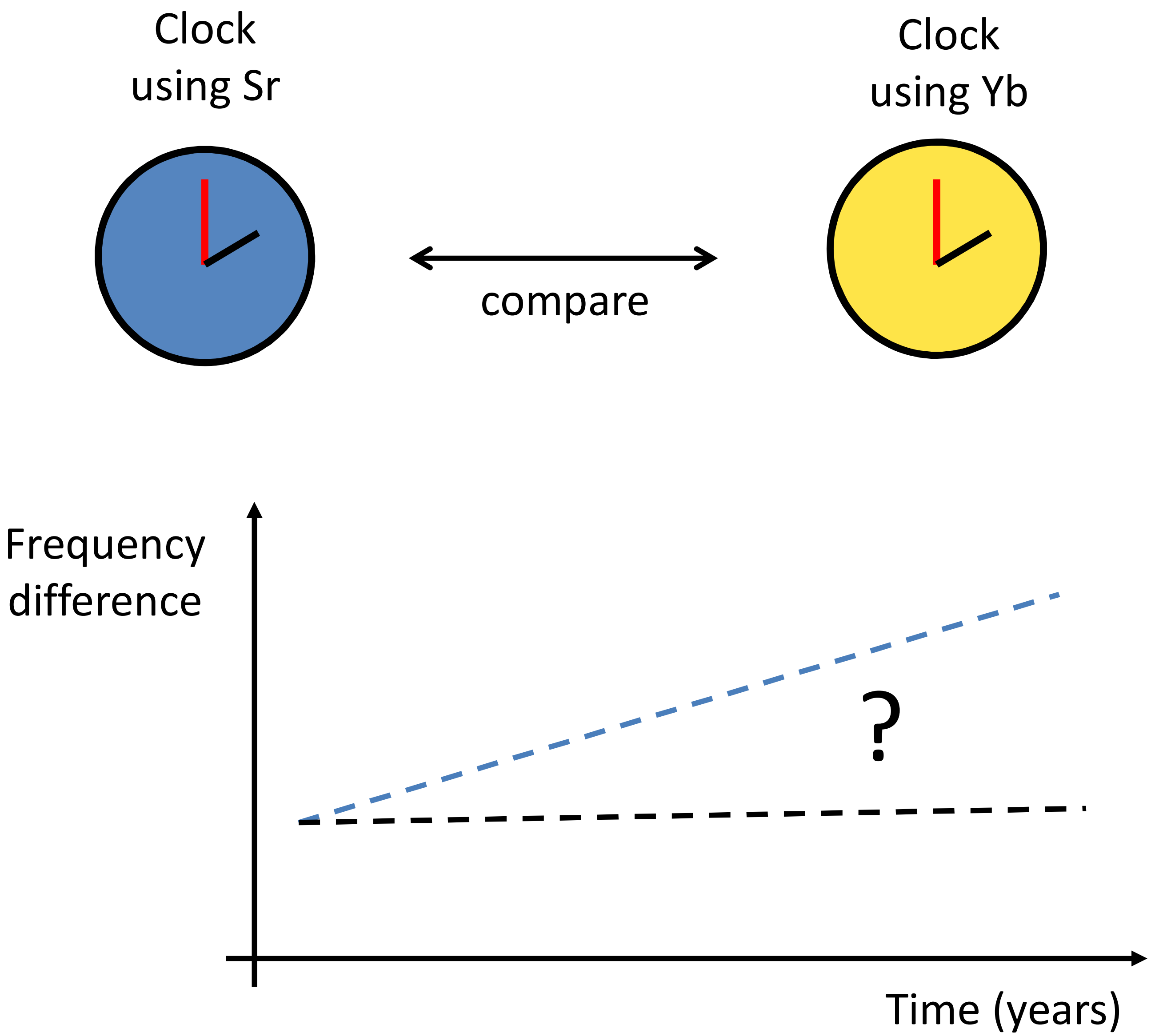


Time and gravity

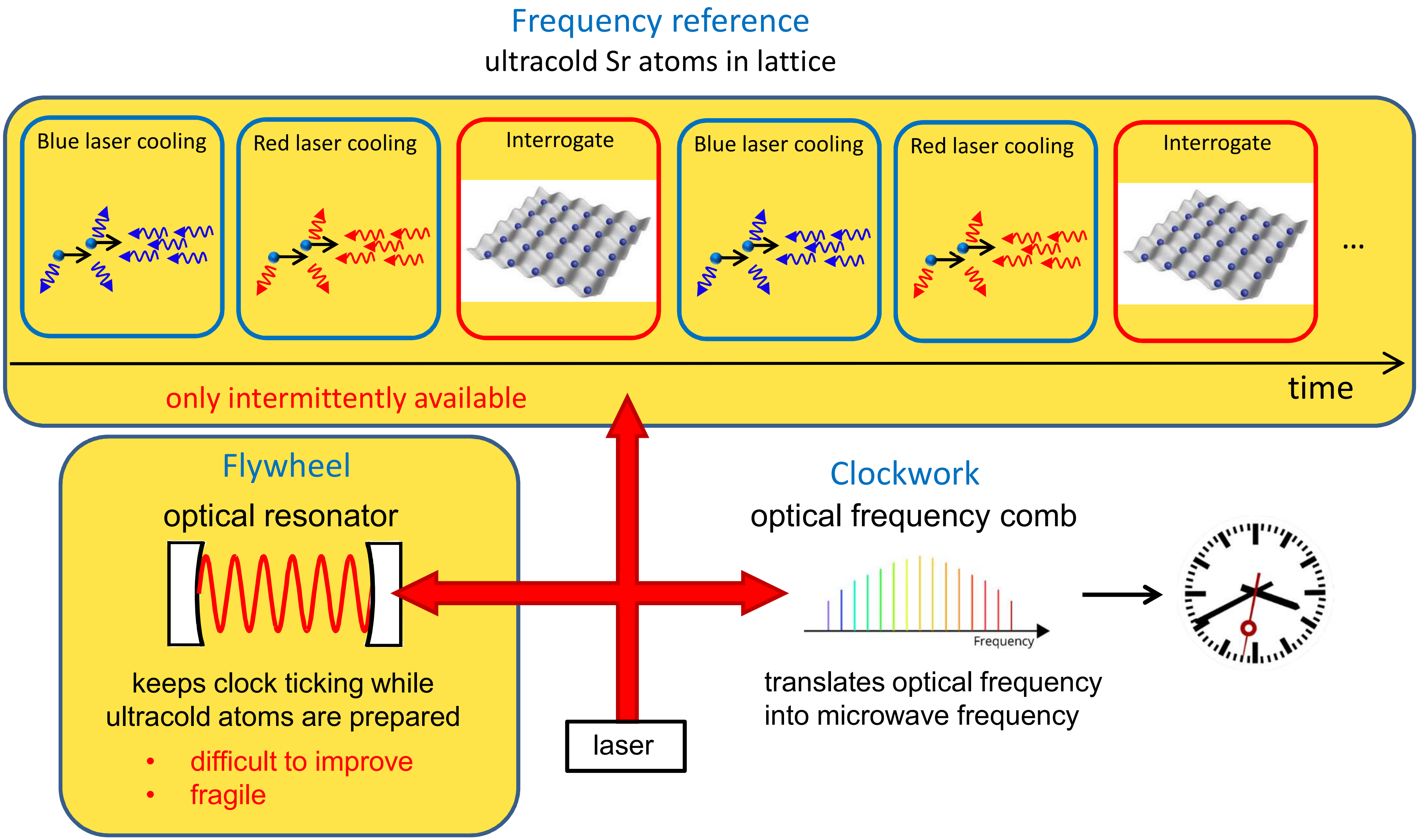


D. Wineland group, NIST, Boulder, USA, Science 329, 1630 (2010)

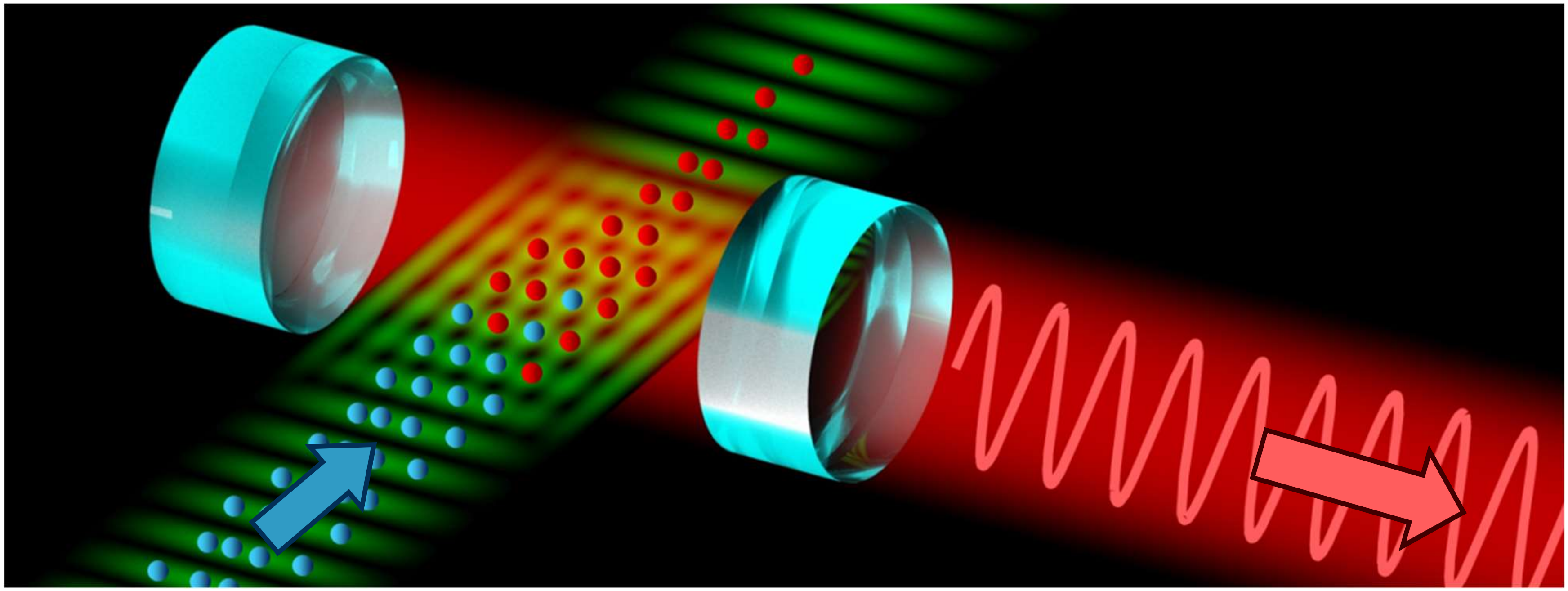
Are the „constants of nature“ constant?



Optical clock scheme



Superradiant clock



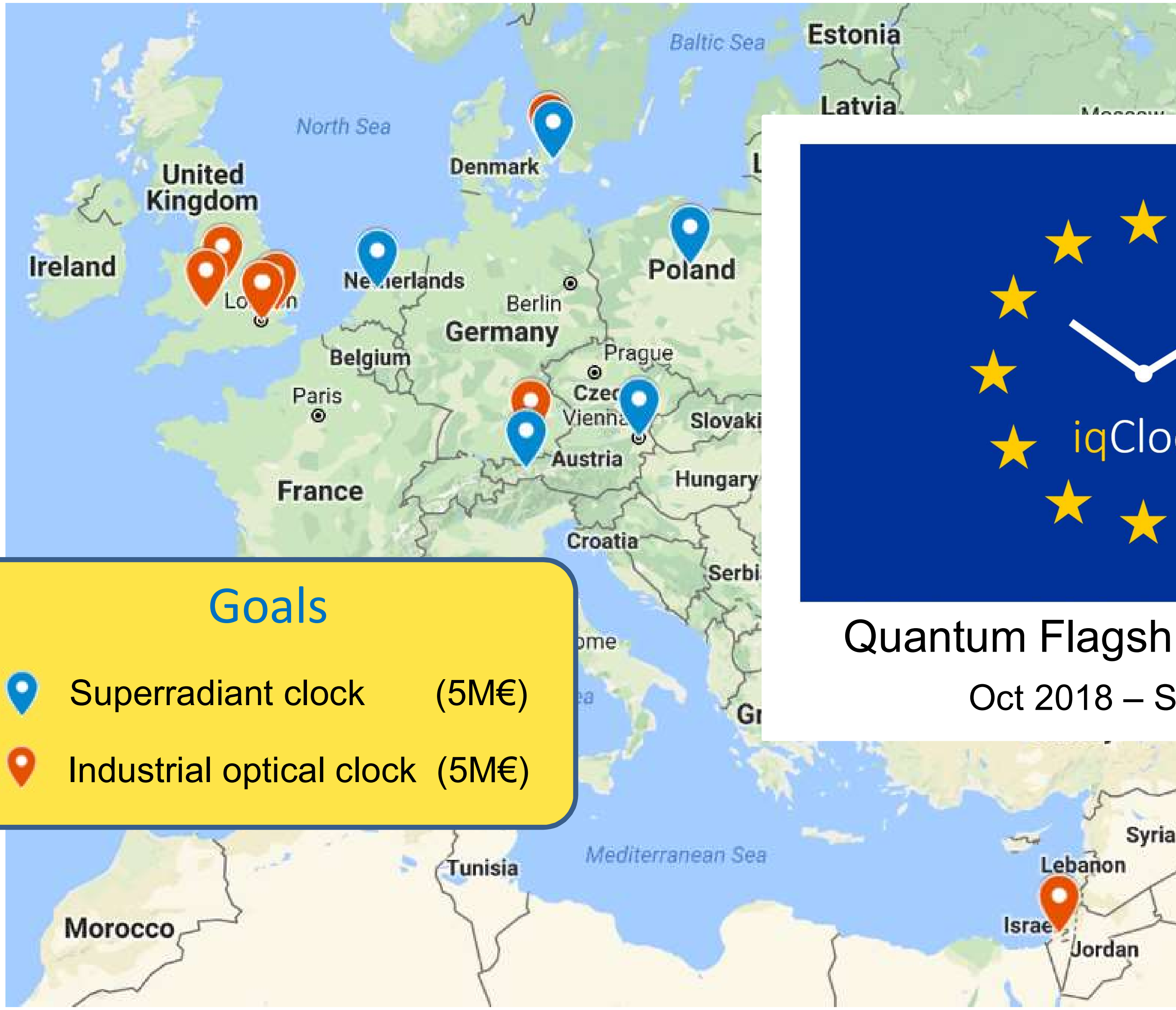
Continuous ultracold strontium beam in

Clock laser beam out

Pulsed version demonstrated by J. Thompson group, JILA, Boulder, USA

Science Advances, 2, e1601231 (2016)

iqClock – integrated quantum Clock



Goals

- Superradiant clock (5M€)
- Industrial optical clock (5M€)

iqClock

Quantum Flagship Consortium

Oct 2018 – Sep 2021