A short history of cold atoms

Jean Dalibard
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Solvay Chair for Physics, 2021

Inaugural lecture

When light pushes on matter: the radiation pressure (Kepler)

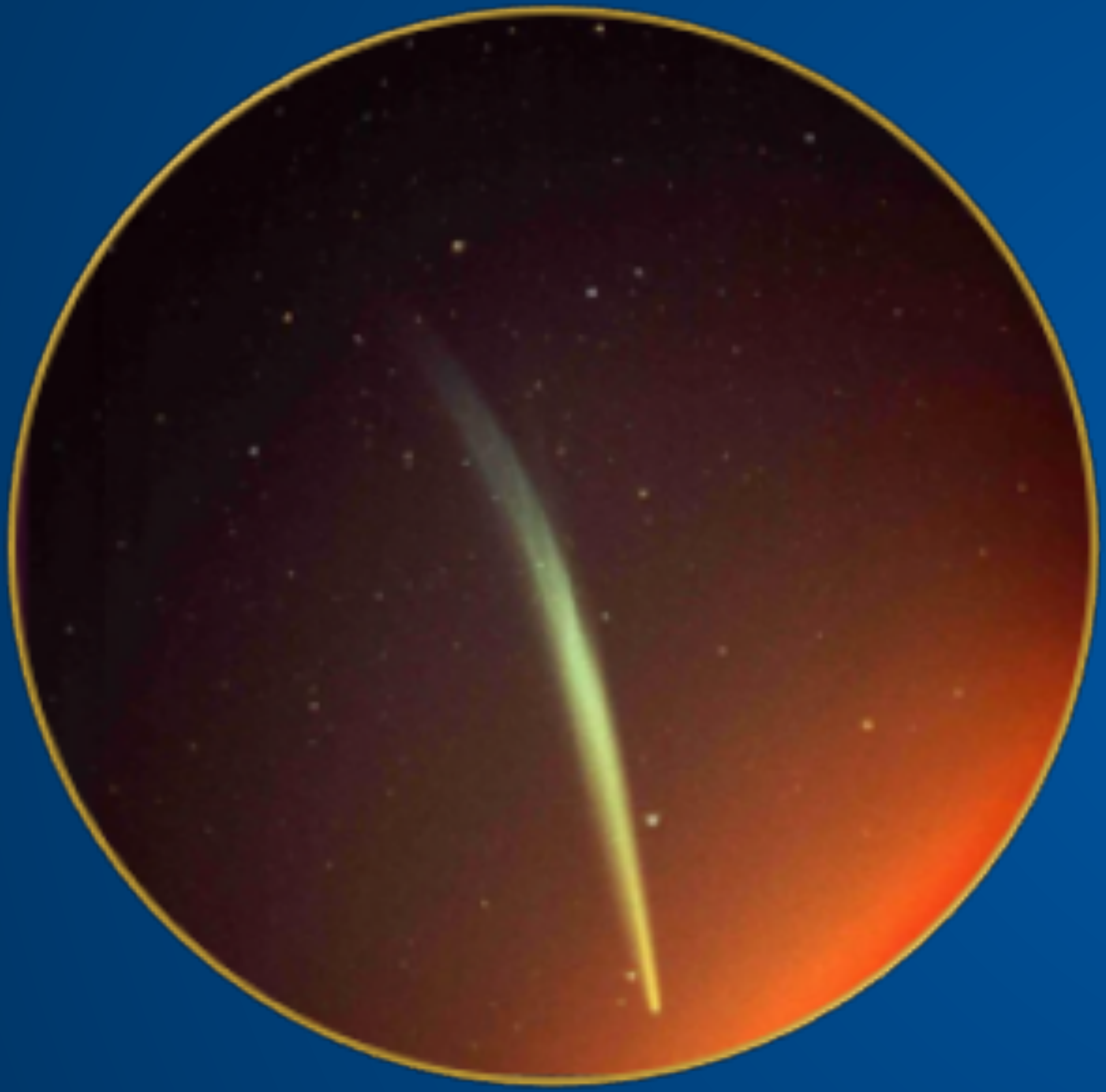
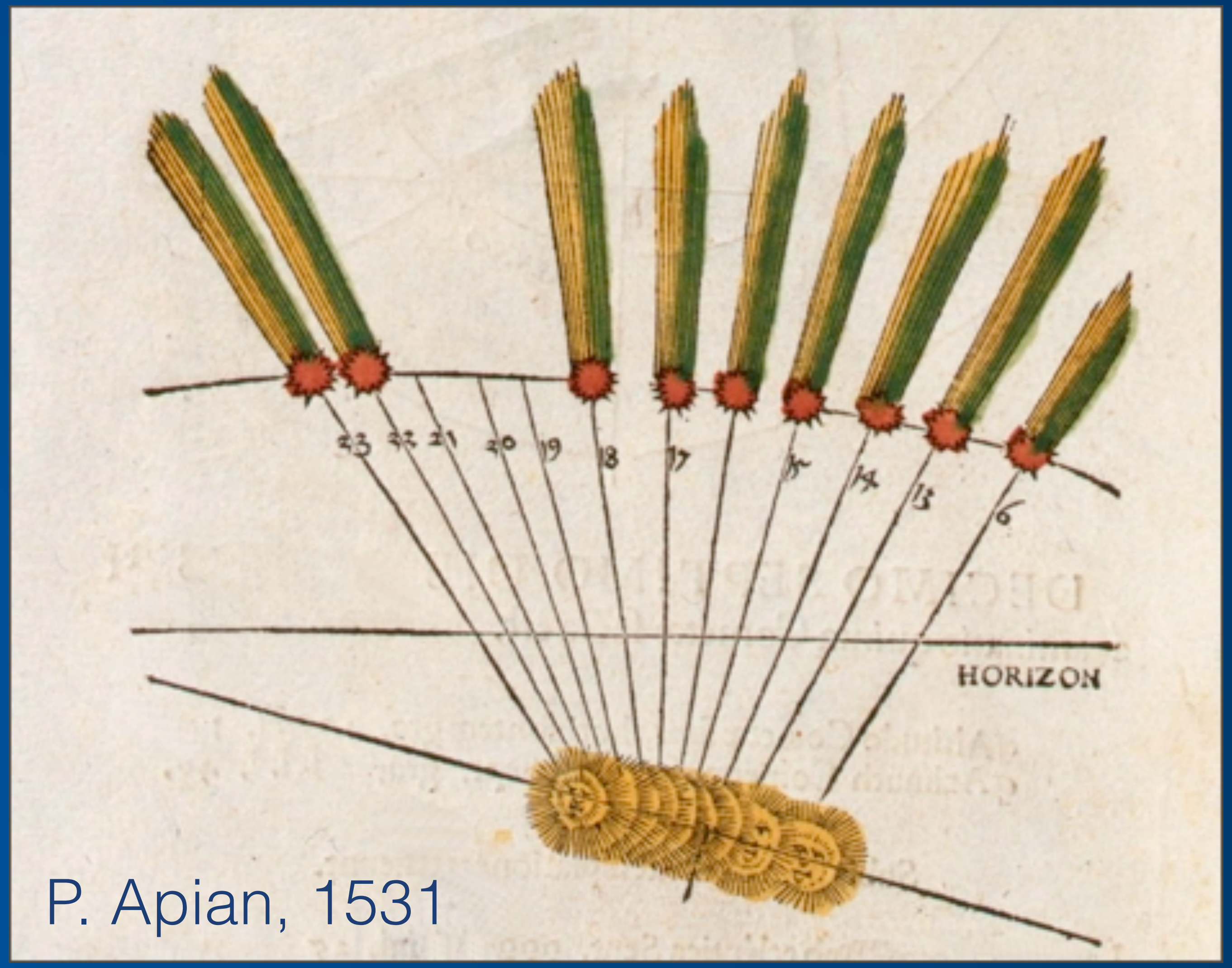


Photo : Observatoire de Paris



P. Apian, 1531

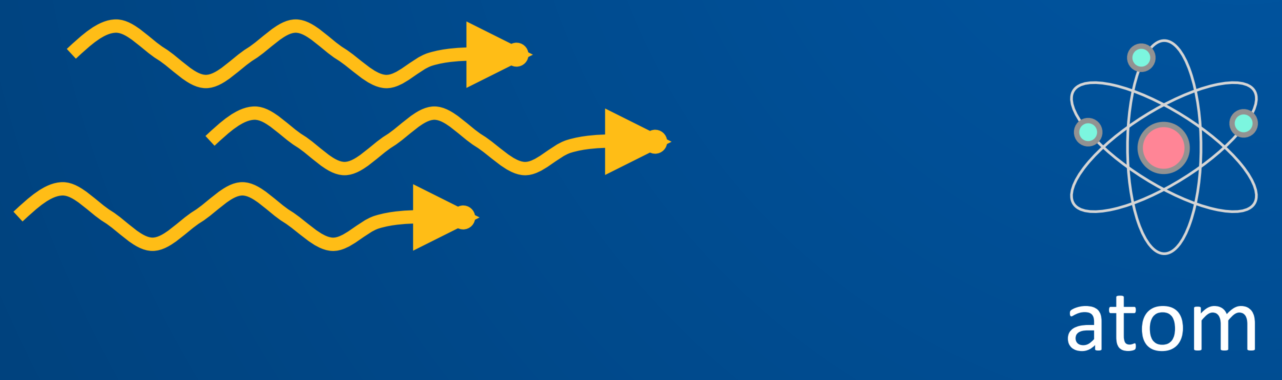
Kepler, 1619:
A comet tail is formed by dust particles that are pushed away by the light from the sun

From sun light to tunable lasers

The force created by the sun light on a atom in a lab is much too small to be of any use

1970's: development of continuous and tunable lasers

Photons resonant with the atomic transition



acceleration from 10^4 to 10^6 *g*

The velocity of the atoms can decrease from a few 100 m/s (typical of thermal velocities) down to 0 on a few tens of centimeters

1982-84: complete deceleration of an atom beam in Phillips and Hall groups

Trapping with an optical tweezer (Ashkin et al.)

A non-resonant laser beam induces a dipole in an material particle

$$\boldsymbol{d}(t) = \alpha \mathscr{E}(\boldsymbol{r}, t)$$

α : polarisability, $\mathscr{E}$: laser electric field

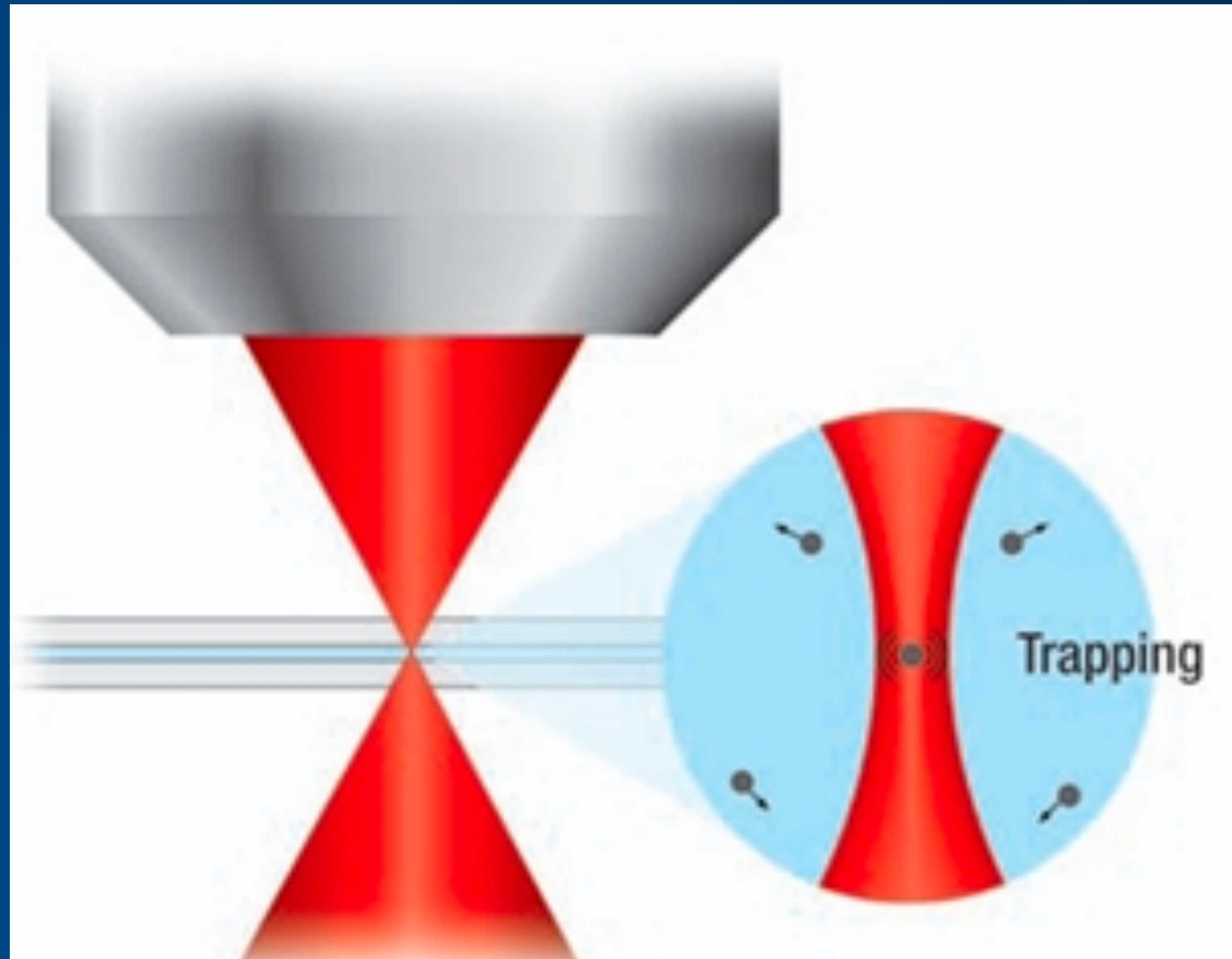


image: Thorlabs

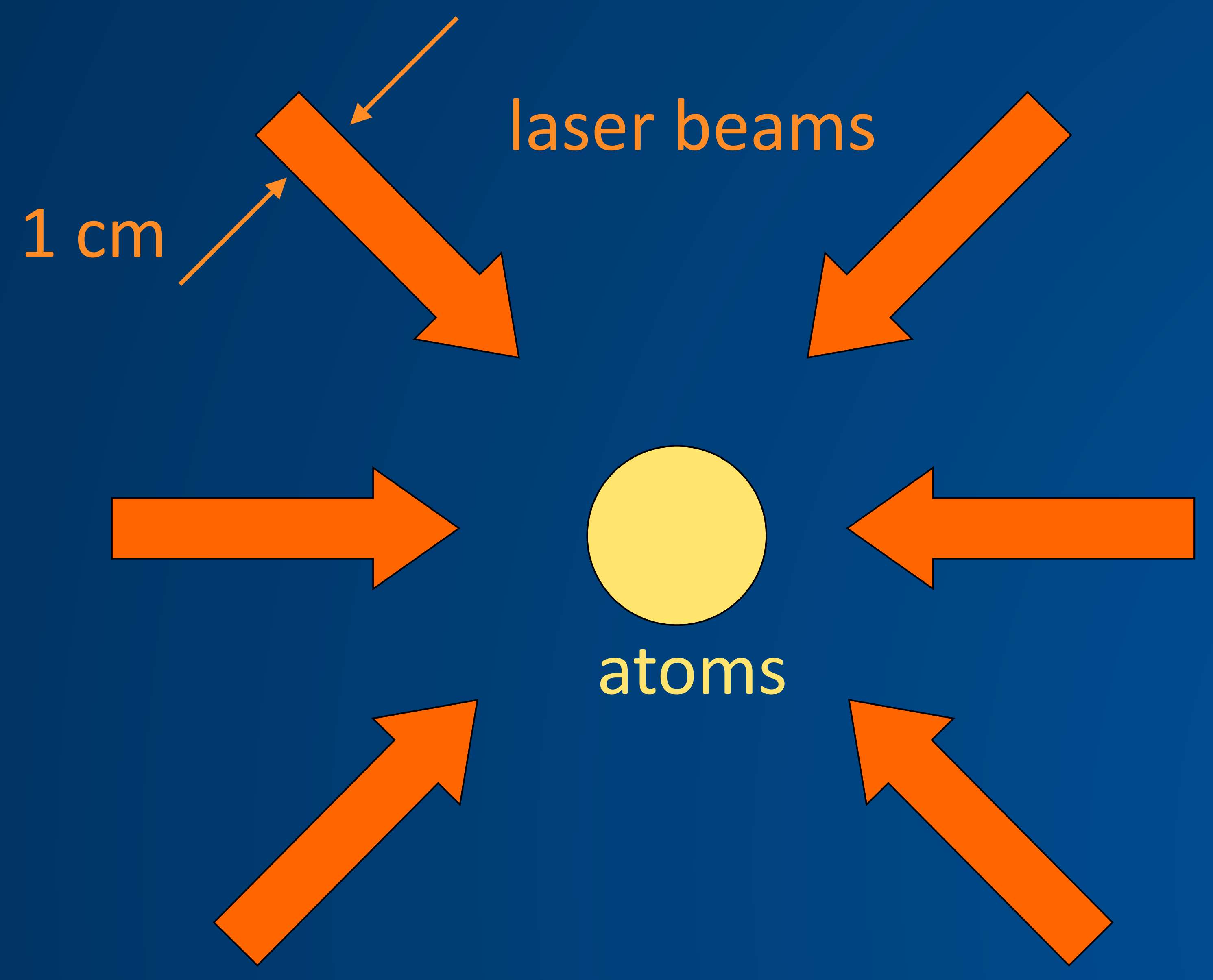
Average energy associated with this induced dipole:

$$E(\boldsymbol{r}) = -\frac{1}{2}\,\alpha\,\overline{\mathscr{E}^2((\boldsymbol{r}, t)}$$

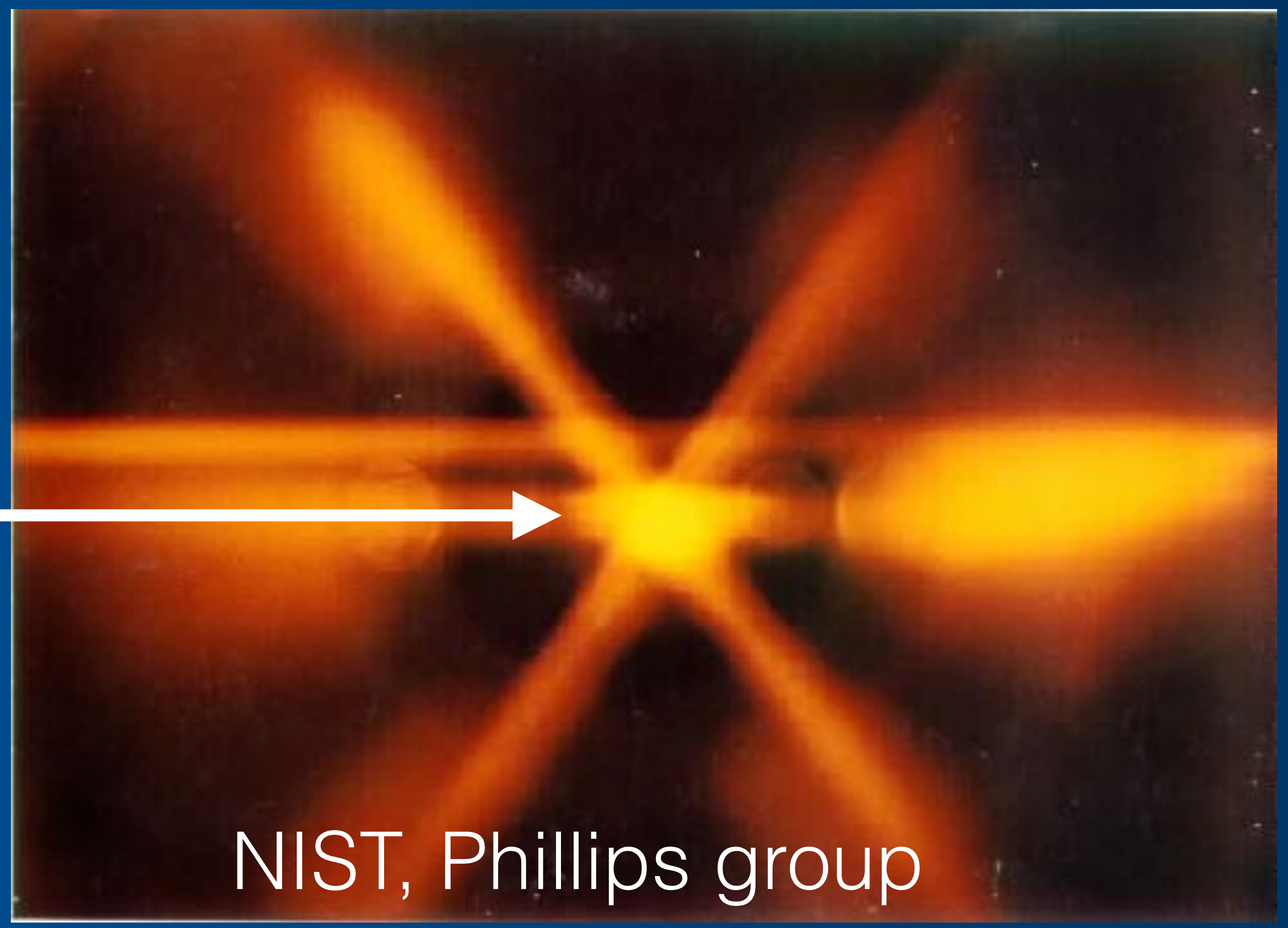
proportional to the light intensity

"Dipole potential" that can trap particles at the focus of a laser beam

The optical molasses (Chu et al., 1985)



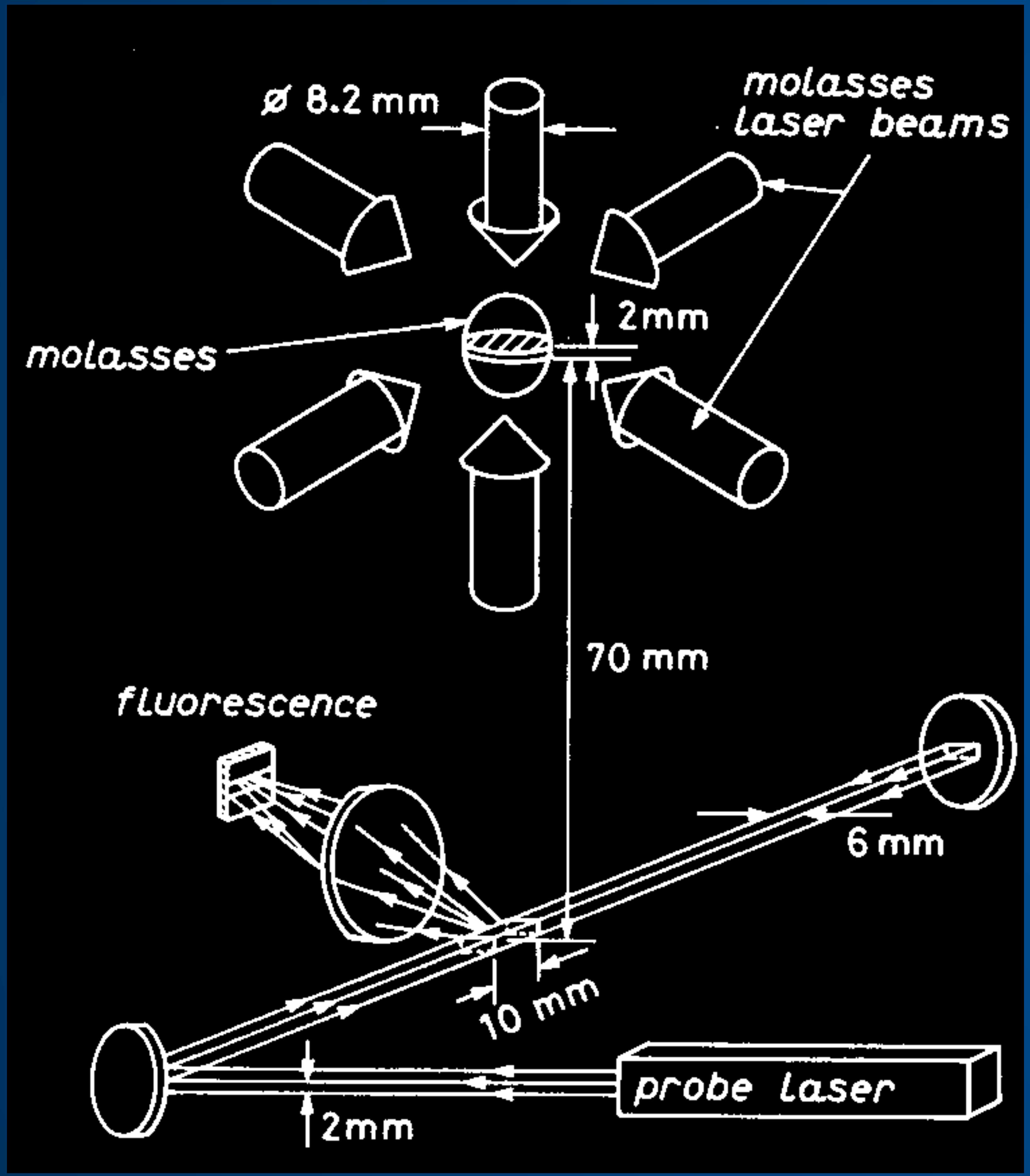
10^9 sodium atoms at the center of a vacuum chamber

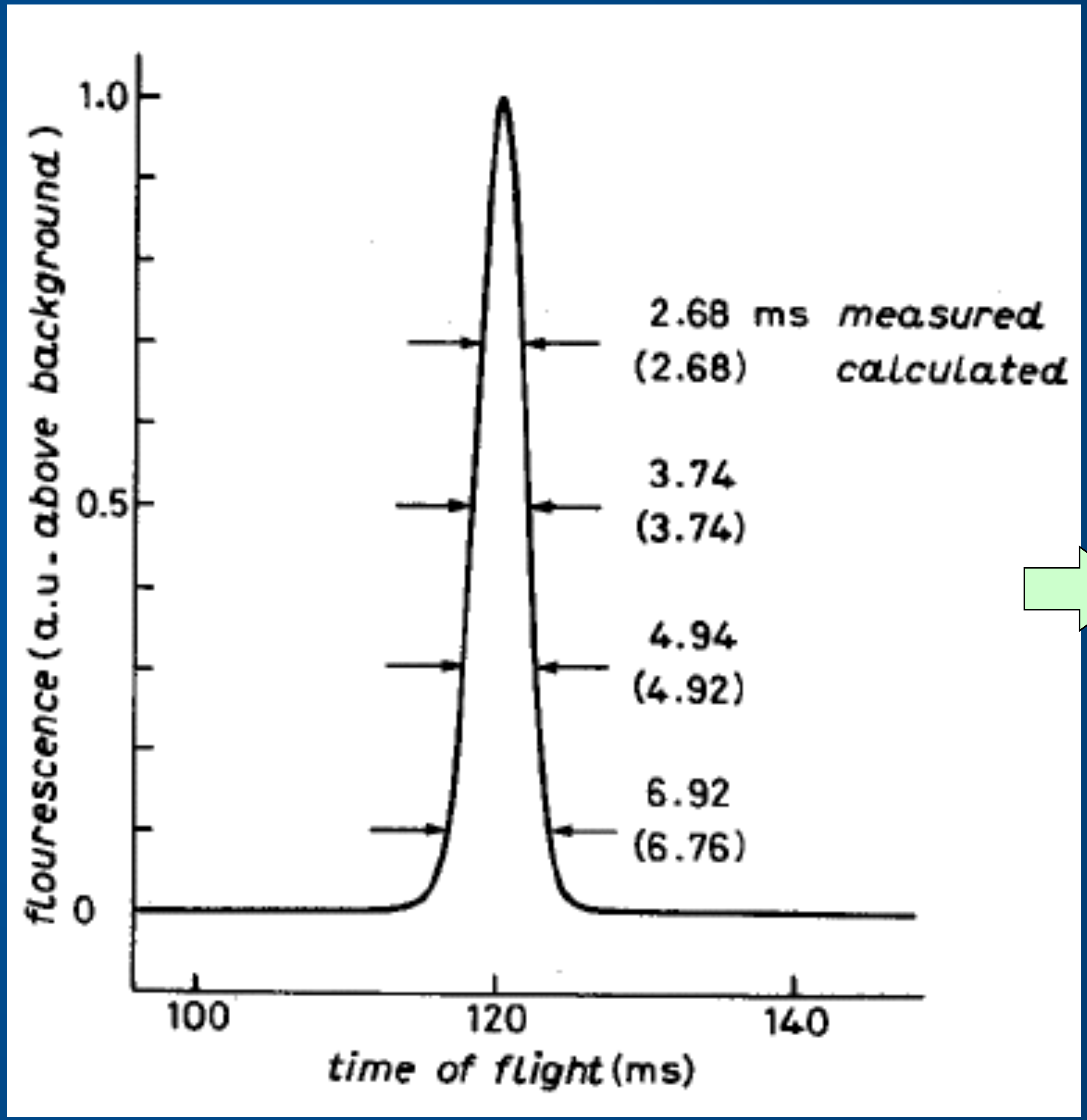


Atoms are cooled to extremely low temperature, i.e., microkelvin

- How can one measure such temperature ? — Ballistic expansion
- What is the mechanism for cooling? — Sisyphus effect
- What is it good for? — Quantum matter, metrology

How to measure such low temperatures?





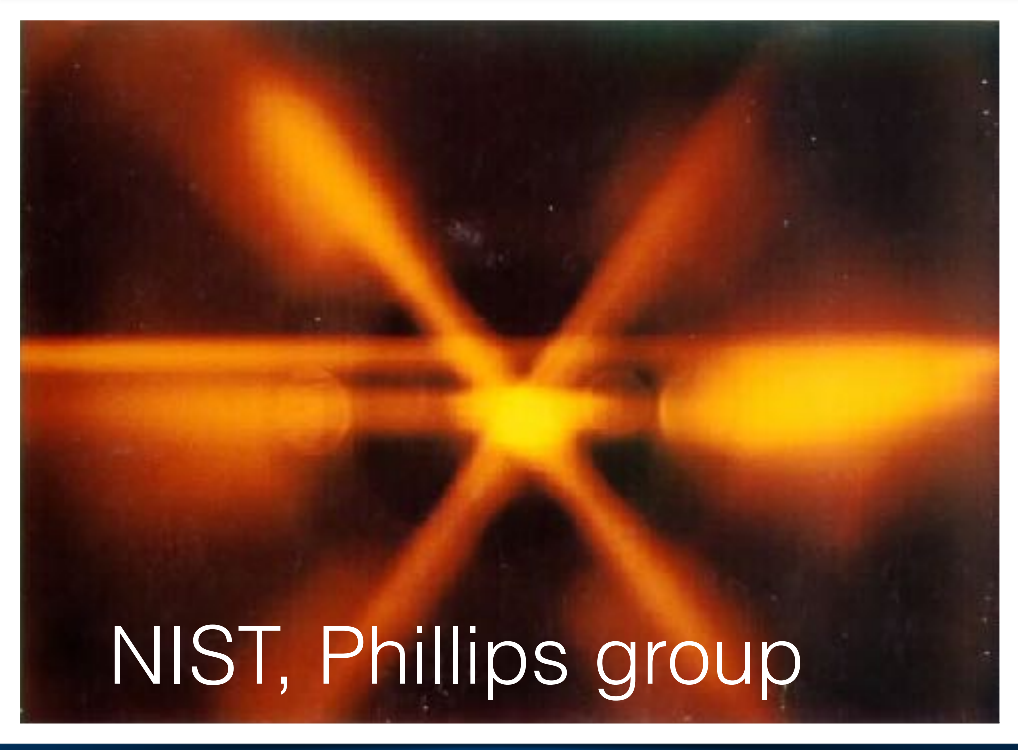
velocity width
$\Delta v = 1$ cm/s

$$\frac{1}{2}k_B T = \frac{1}{2}m\Delta v^2$$

T = 2 microKelvin

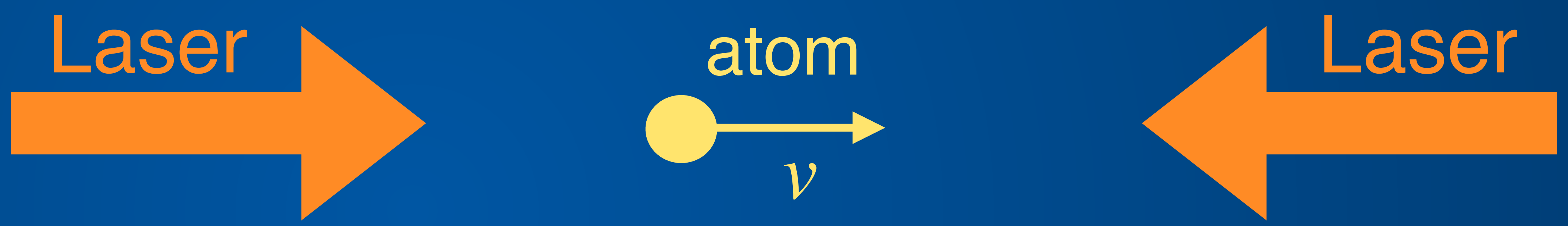
Salomon, Dalibard et al., 1990

What is the mechanism for cooling?


NIST, Phillips group

Initial guess: Doppler cooling (Hänsch & Schawlow 1975)

Laser frequency ω_L chosen slightly lower than the atomic resonance frequency ω_A



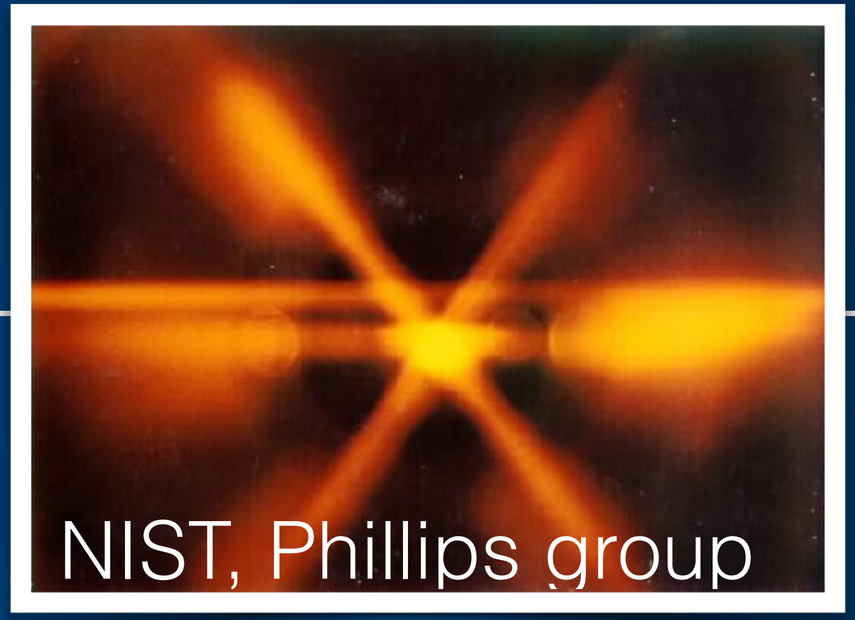
Frequency in lab frame: ω_L ω_L

Frequency in atom frame: $\omega_L - kv$ $\omega_L + kv$

Resulting force opposed to the atomic velocity: $\boldsymbol{F} = -\alpha \boldsymbol{v}$

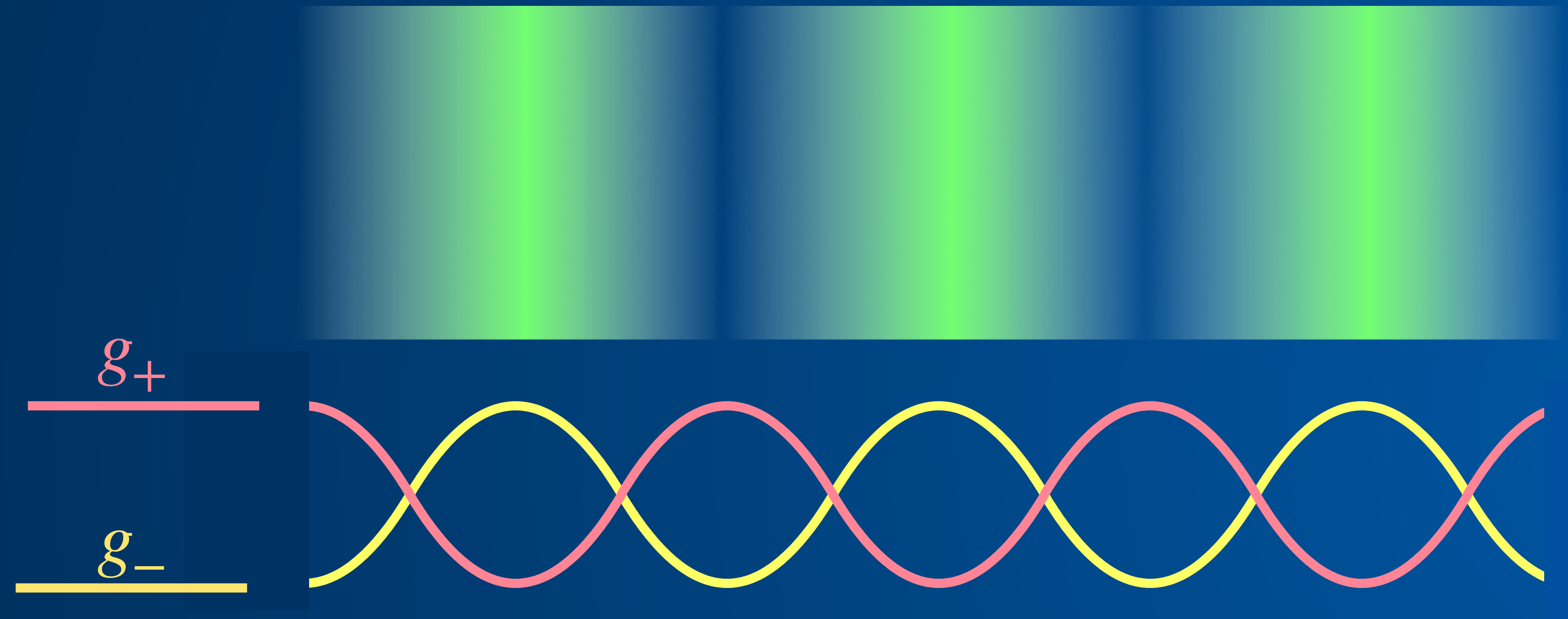
But the predicted temperature should be in the range 100 - 1000 microkelvins, not 1 microkelvin…

What is the mechanism for cooling (2)?


NIST, Phillips group

Sisyphus cooling (1988: Cohen-Tannoudji & Dalibard, Chu et al.)

Optical molasses = Laser standing wave



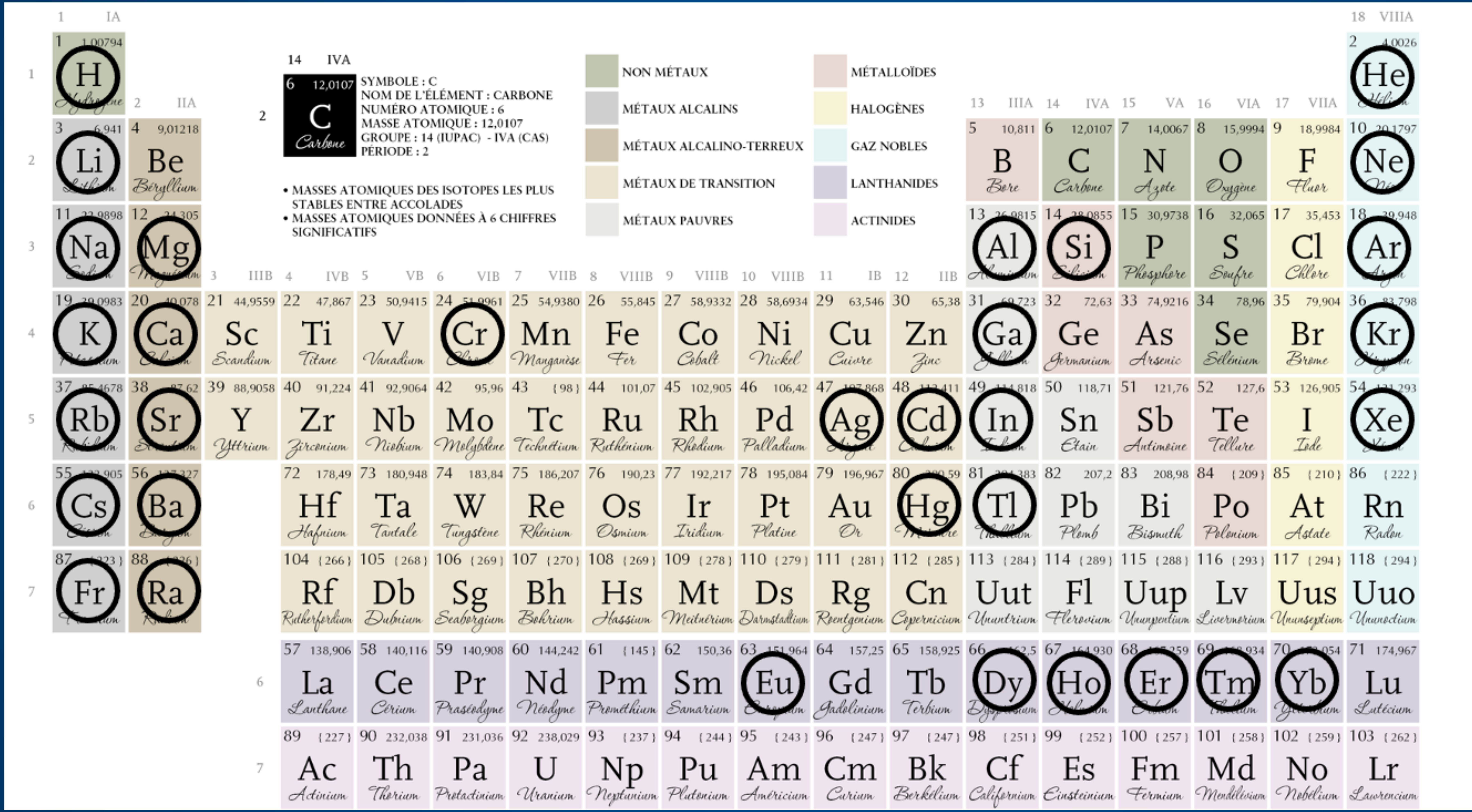
Two different atomic states, here g_+ and g_-, feel opposite dipole potentials


Nobel Foundation

Limit of Sisyphus cooling: $m\Delta v_{\text{atom}} \sim \hbar k$ ⟶ $k_B T = m(\Delta v_{\text{atom}})^2 \sim \dfrac{\hbar^2 k^2}{m}$: microkelvin

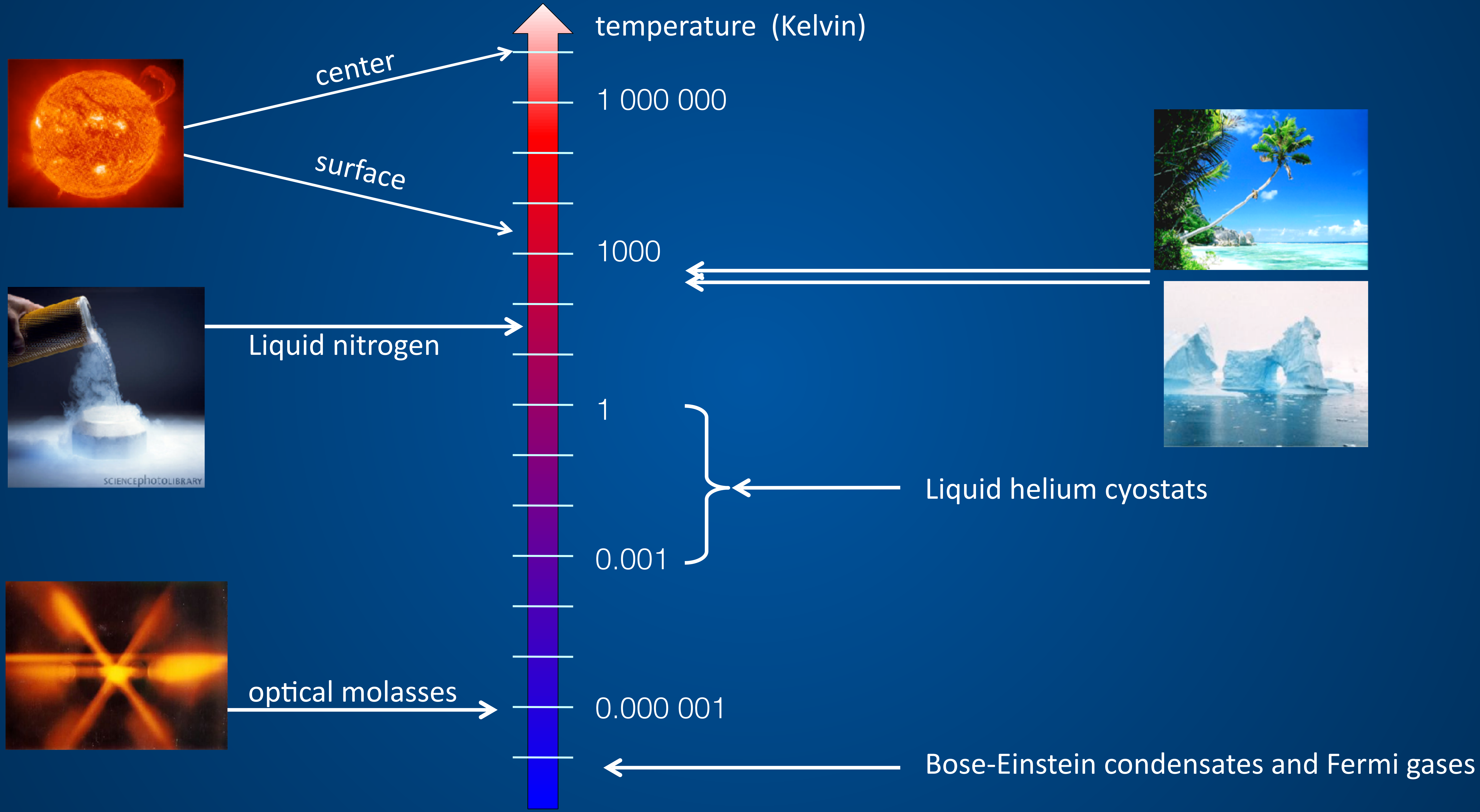
↑ momentum of a single photon

The atomic species that have been laser cooled

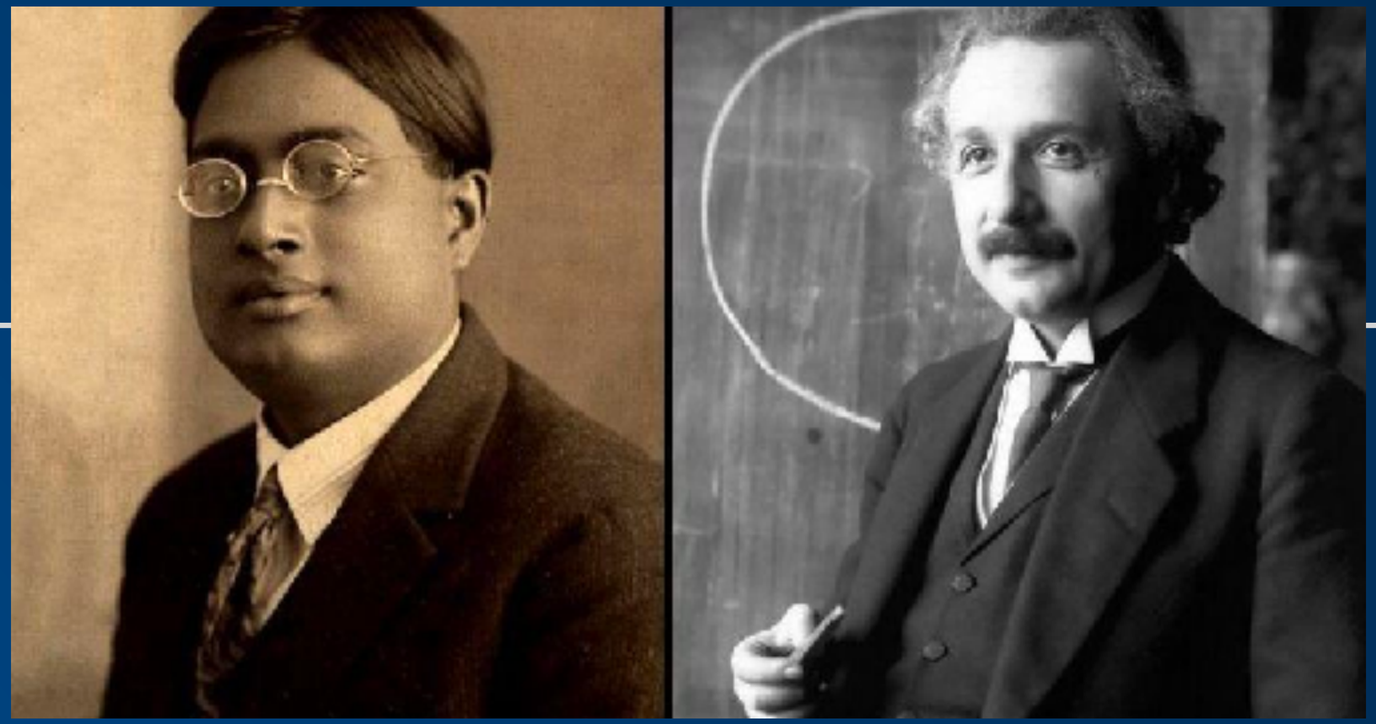


+ molecules : SrF, CaF, YO, CaOH

The temperature scale

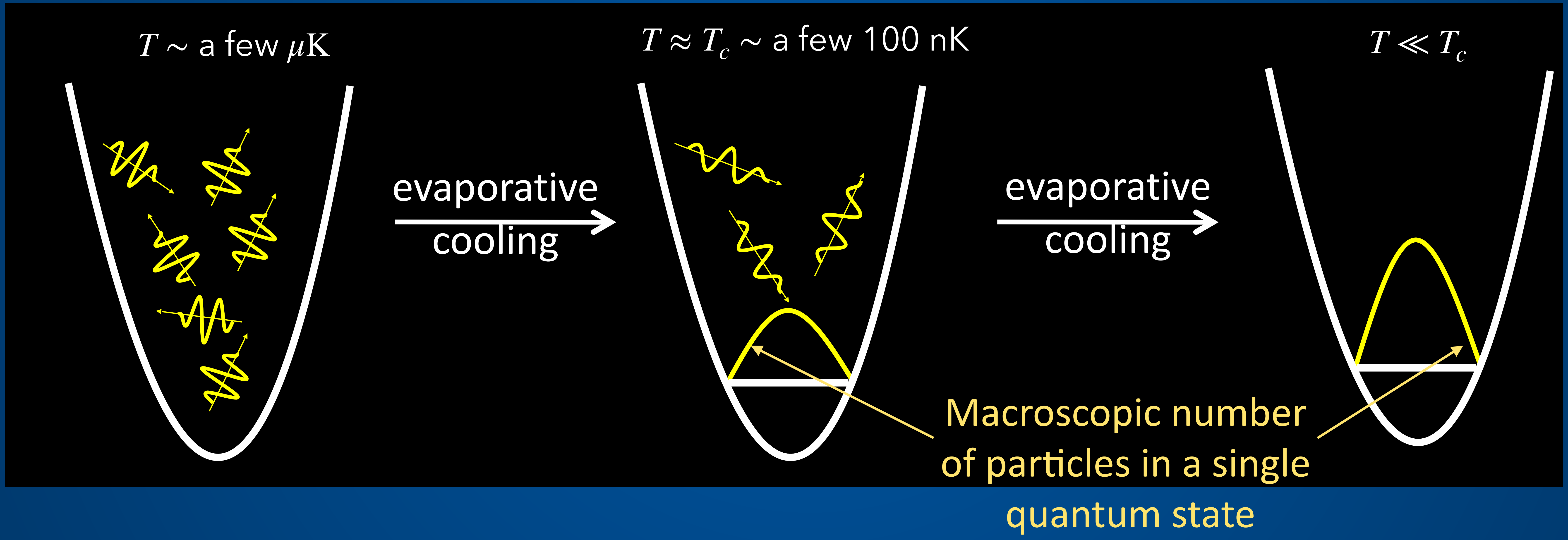


Bose-Einstein condensation



Predicted in 1924 for an ideal gas
Related phenomena for superfluid liquid helium (London, Tisza)

1990-95, Kleppner, Cornell & Wieman, Ketterle: optical molasses + additional evaporative cooling



Critical point: de Broglie wavelength ≈ interatomic distance

Na atoms @ 100 nK : $\lambda = 1$ µm

Other examples of dilute quantum matter (2000-05): atomic Fermi gases, Bose-Einstein condensates of cavity polaritons

A brief history of cold atoms:

What are they good for?

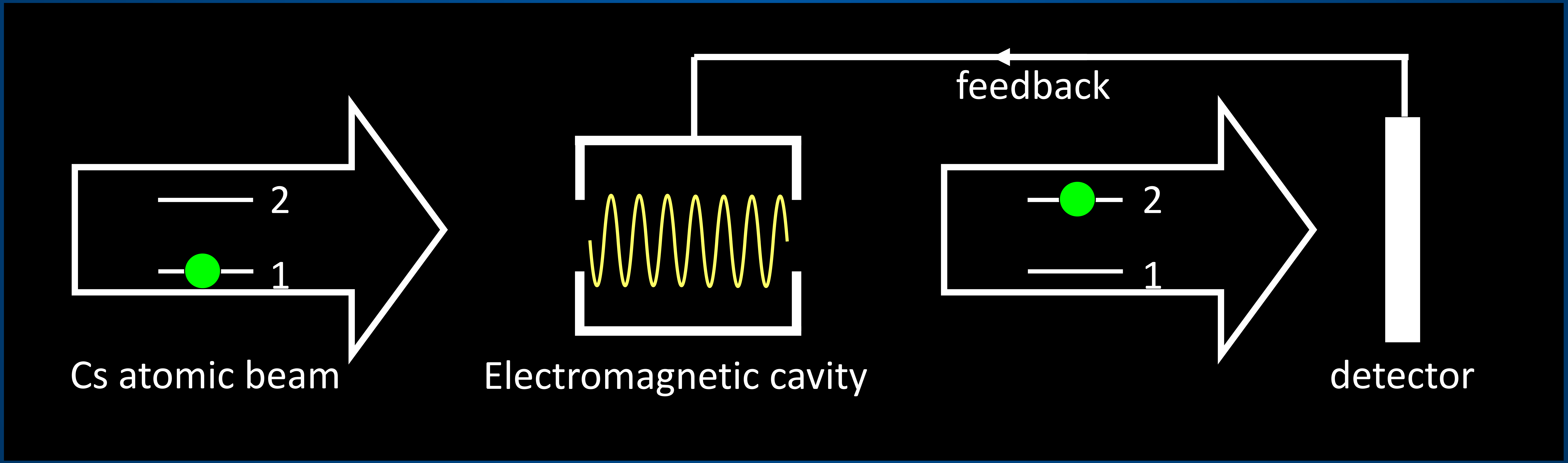
Answer 1: More precise measurements

The principle of an atomic clock

1967 : definition of the second (unit of time) from an atomic reference

1 and 2 : lowest energy levels of ^{133}Cs

The electromagnetic wave resonant with the 1 -2 transition makes 9 192 631 770 oscillations in one second



pendulum + counting system

Cold atom clocks

Major improvement: Essentially no Doppler effect + very long interrogation time

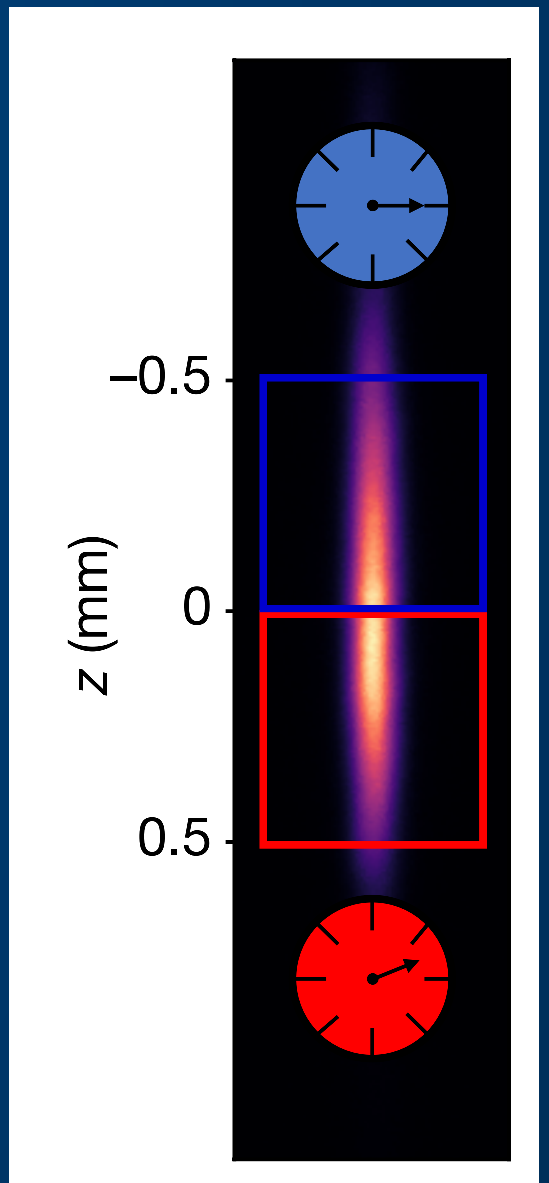
Cold atom clocks have led to a spectacular gain in precision: $10^{-14} \longrightarrow 10^{-16}$

Navigation, telecommunications, very long base interferometry (astronomy)

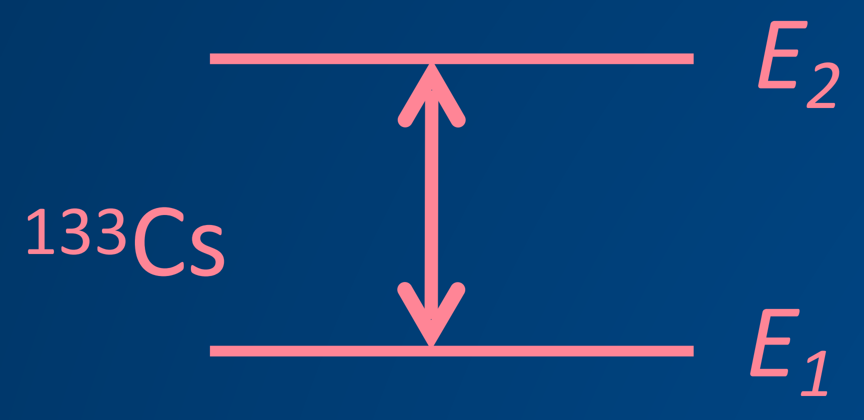
Technical progress in the fabrication of ultra-stable lasers:
Shift towards a reference in the visible range (10^{15} osc. / second) instead of microwave (10^{10} osc./second)

The accuracy of a clock is better the faster its 'pendulum' swings

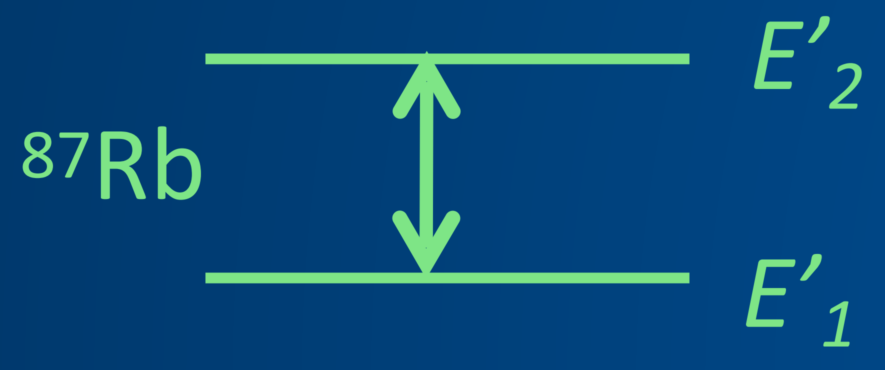
Jun Ye's lab (2022): precise measurement of the gravitational red shift over 1 mm: $\frac{\Delta\nu}{\nu} = \frac{gH}{c^2} \approx 10^{-19}$



Do all atomic clocks provide the same time?



Cesium clock : 9 192 631 770 osc. / second



Rubidium : 6 834 682 610, 904 ... osc. / second

Comparison of two pendulums: rule of three, based on the ratio between $E_2 - E_1$ and $E'_2 - E'_1$

This ratio is a function of fundamental constants, such as

$$\frac{m_{\text{proton}}}{m_{\text{electron}}} \approx 1840 \qquad \frac{e^2}{\hbar c} \approx \frac{1}{137}$$

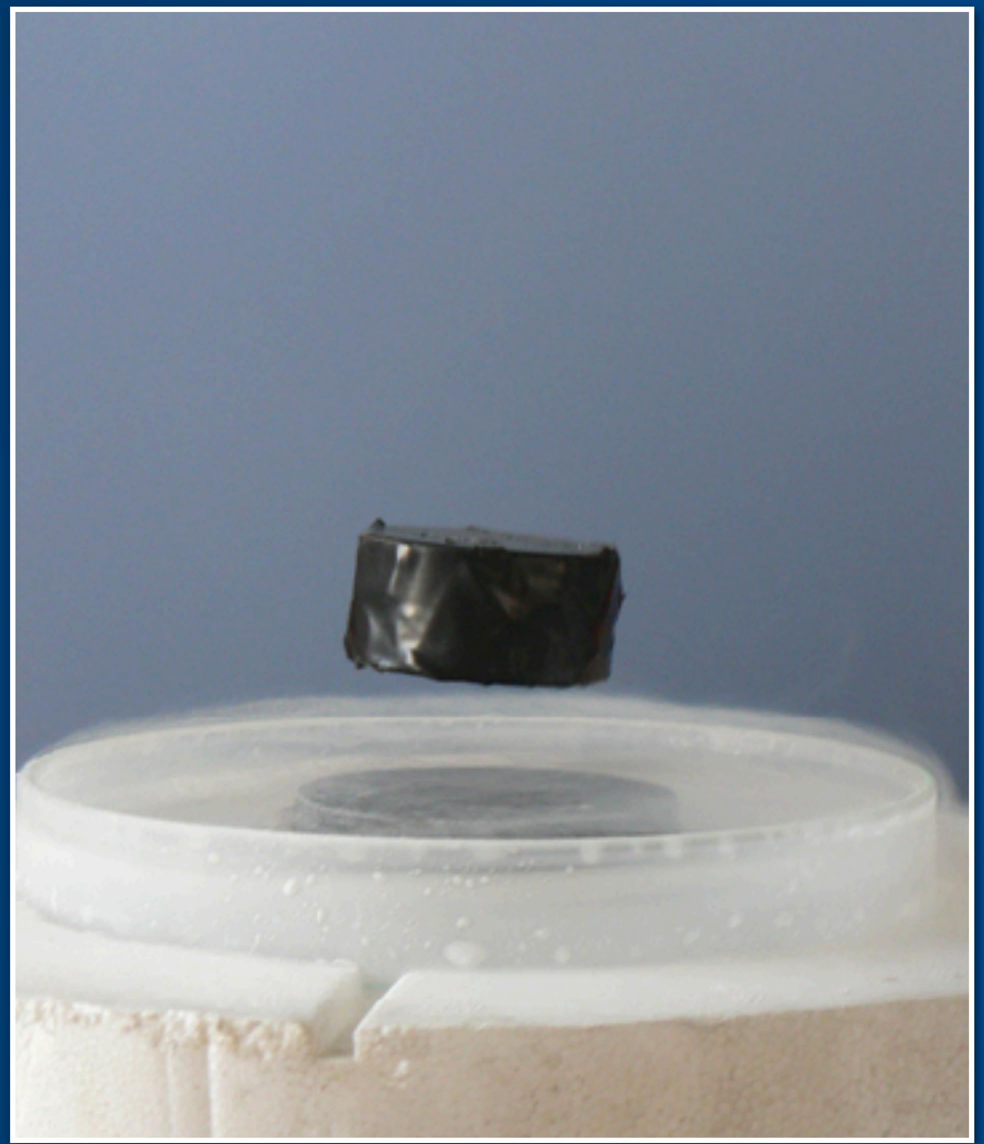
But are the fundamental constants really constant?

A brief history of cold atoms:

What are they good for?

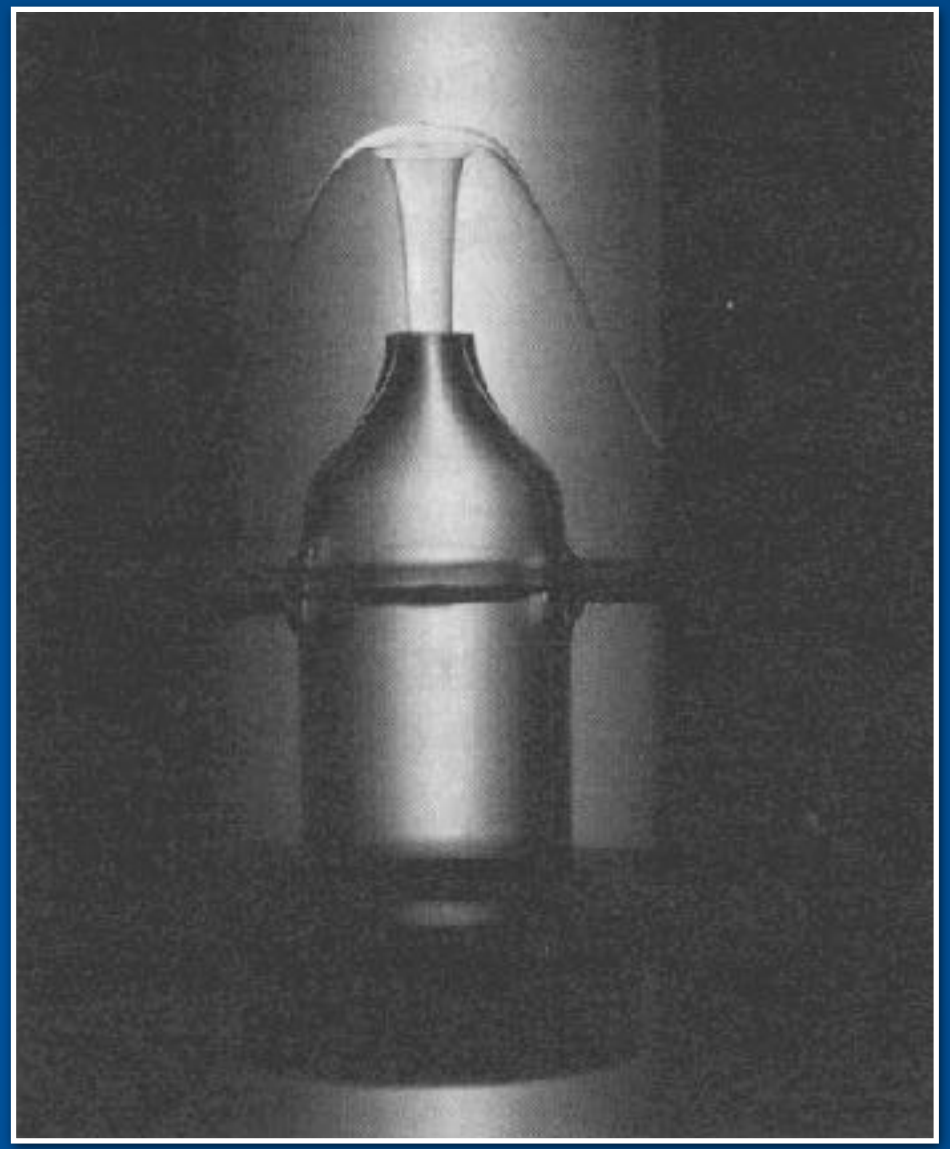
Answer 2: Exploring quantum matter

The first examples of quantum matter



Superconductivity

1911



Superfluidity

1937

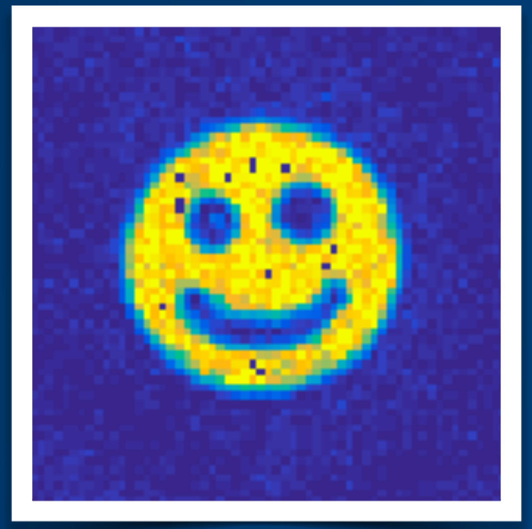
Laser

1960

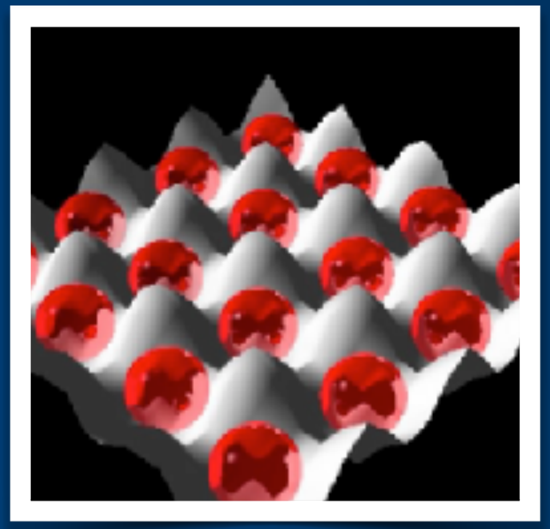
Macroscopic systems with a long-range phase coherence

The assets of atomic gases

Control of the environment: geometry and topology

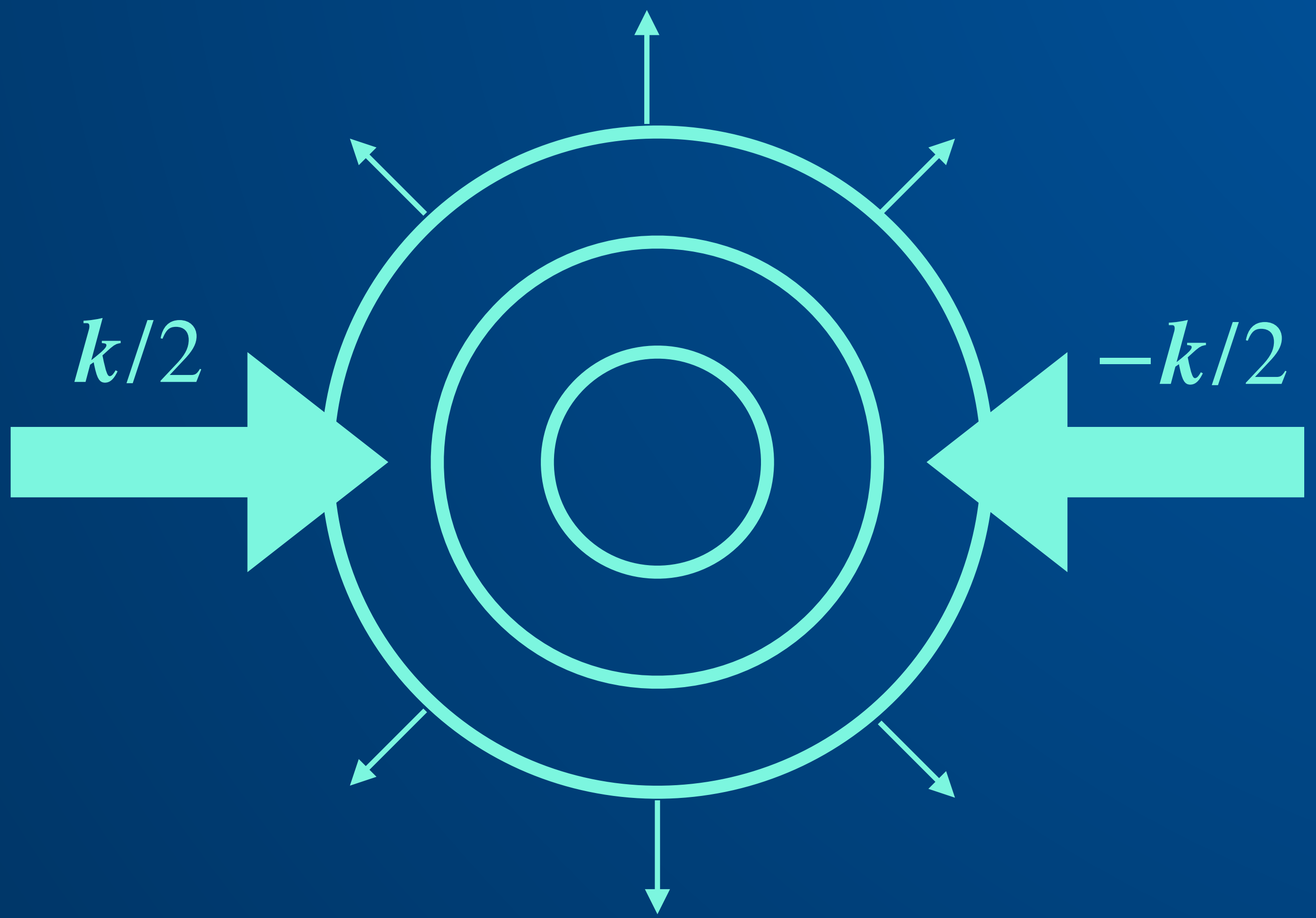


Tailored laser beams can produced confinement potentials of arbitrary shapes:
Harmonic, box-like, periodic (optical lattices), random



Control of the interactions

Low-temperature regime: atom-atom interactions essentially occur in the s-wave regime (+ magnetic dipolar forces)



$$\psi(\boldsymbol{r}) \sim \mathrm{e}^{\mathrm{i}\boldsymbol{k}\cdot\boldsymbol{r}} - a\frac{\mathrm{e}^{\mathrm{i}kr}}{r}$$

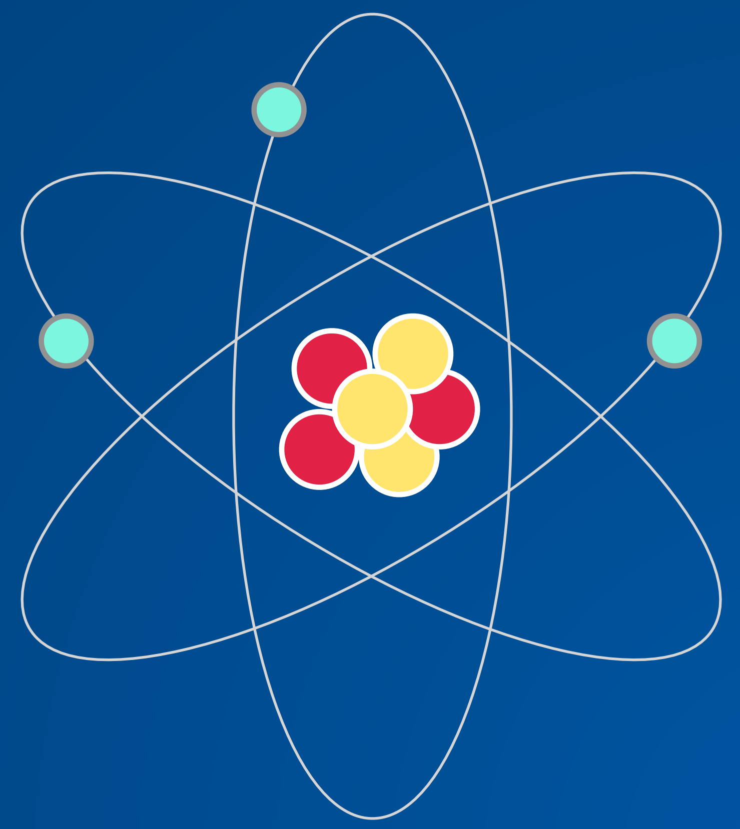
The scattering length a characterizes the physics of the collision.
It can be controlled in sign and magnitude (for some species)

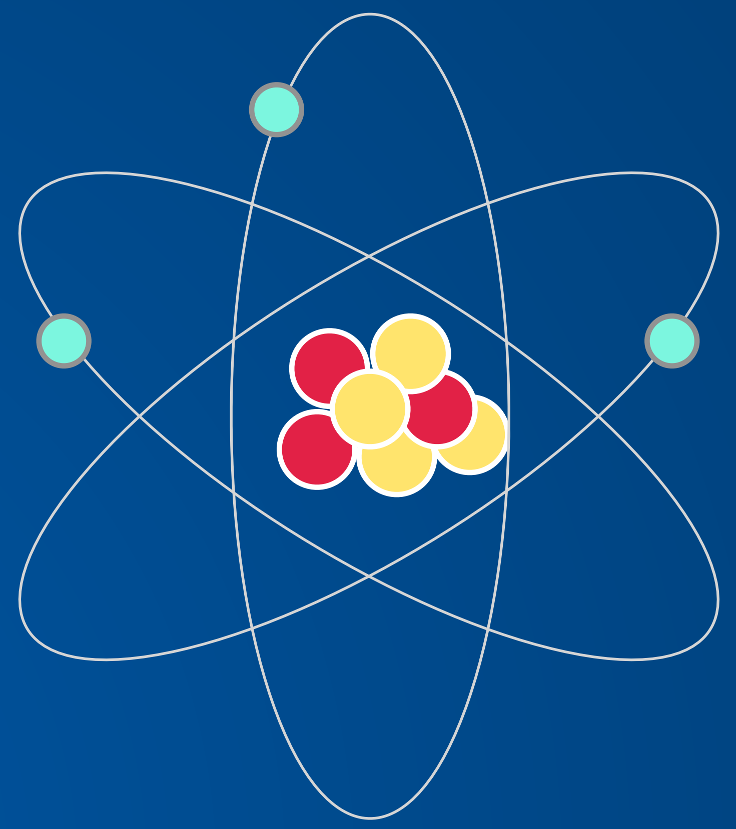
The assets of atomic gases (2)

Control of the statistics

^{6}Li: 3 protons
+ 3 electrons
+ 3 neutrons

Fermion



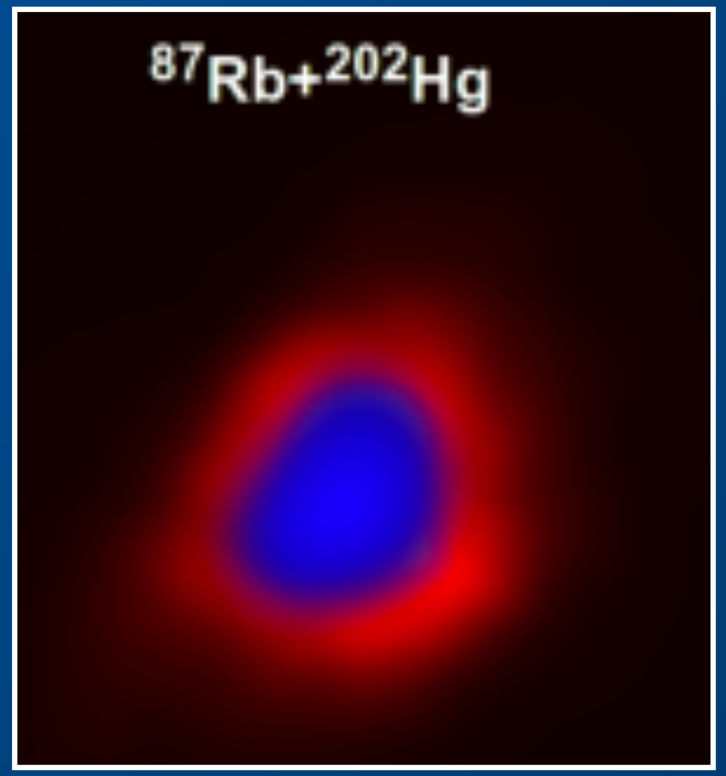


^{7}Li: 3 protons
+ 3 electrons
+ 4 neutrons

Boson

Control of the masses

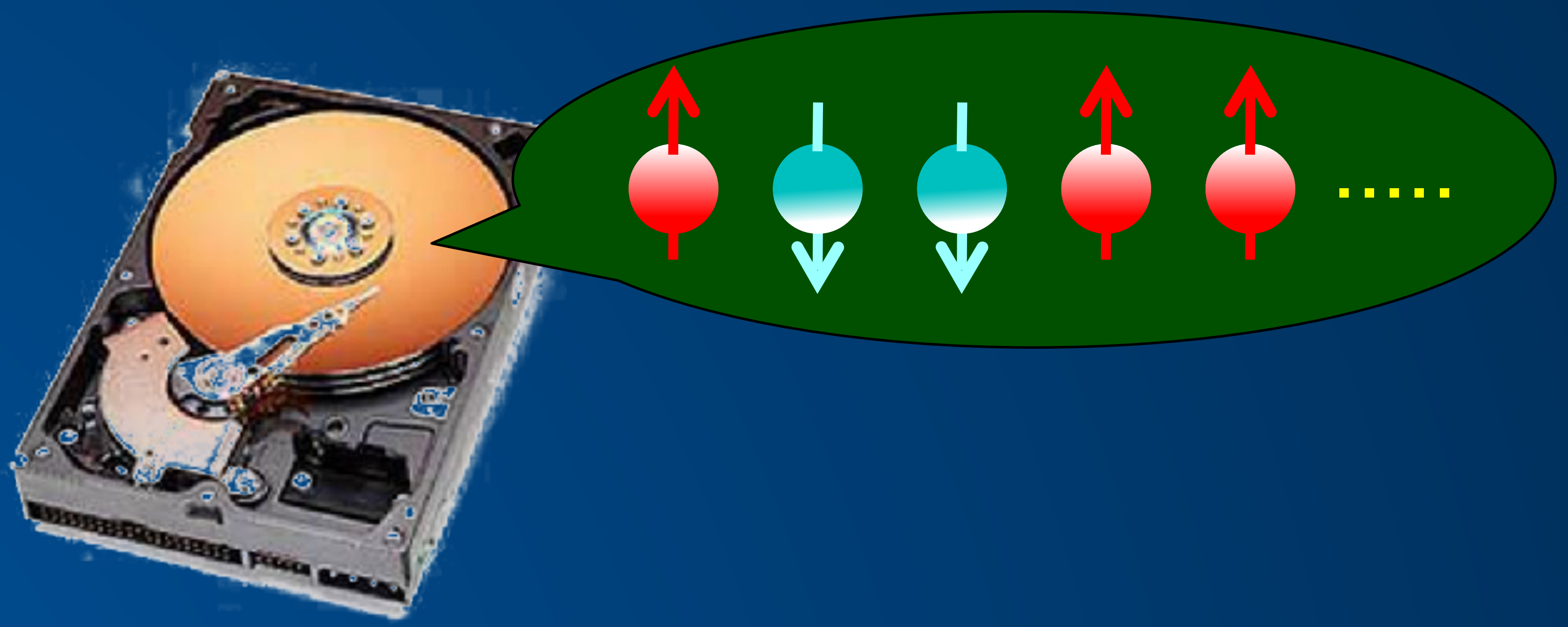
Realization of mixtures of various atomic species and various statistics (B+B, B+F, F+F)



Witkowski et al.,
Optics express 2017

Quantum Calculation & Quantum Simulation

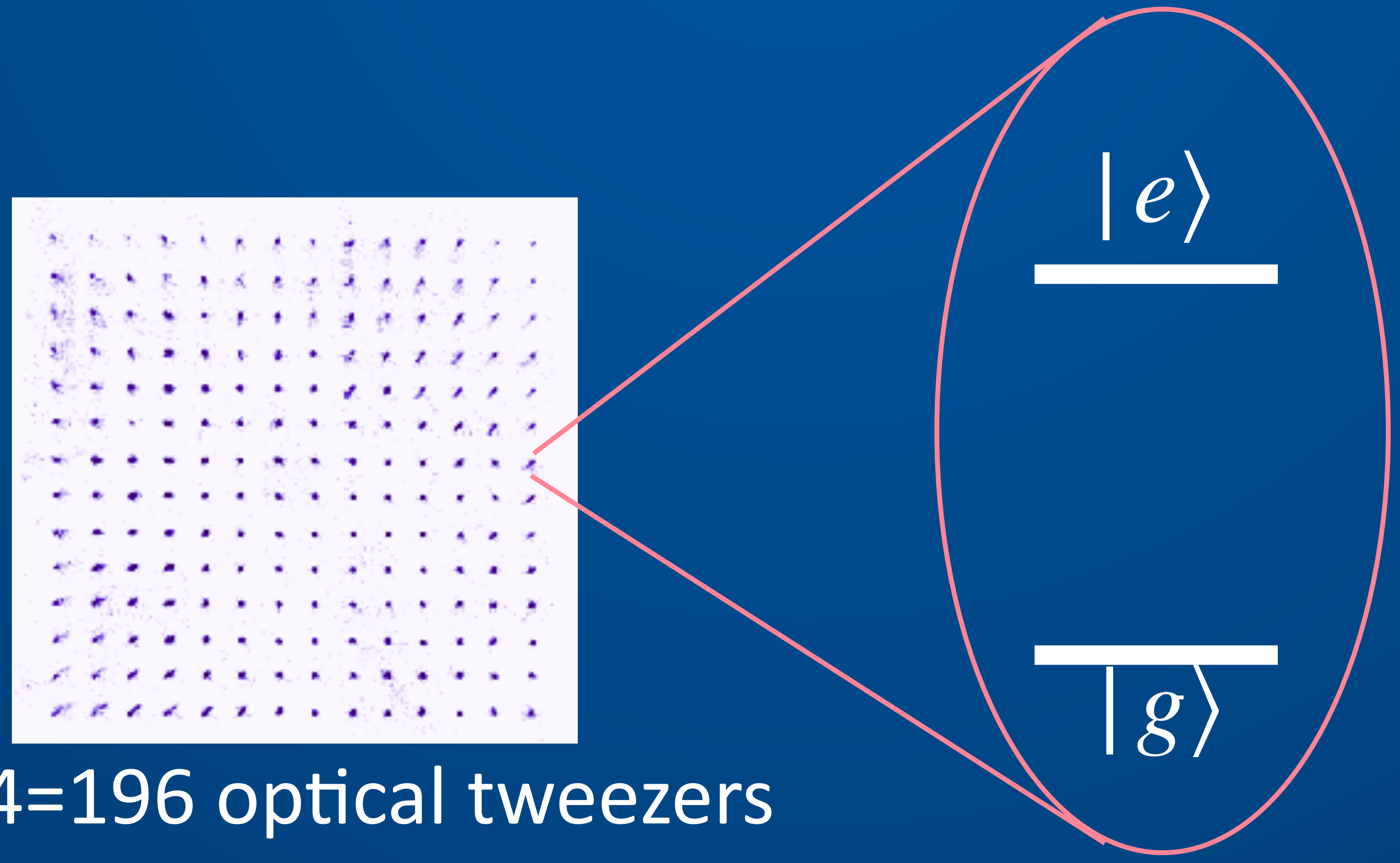
A universal quantum computer, with the proper error corrections, is still a far-future goal for cold atoms



But… cold atom systems are already well suited for fulfilling all criteria for a quantum simulator addressing problems from physics and chemistry

Emulation of model few-body and many-body Hamiltonians with an excellent control of relevant parameters

Browaeys-Lahaye & Lukin groups 2016-22



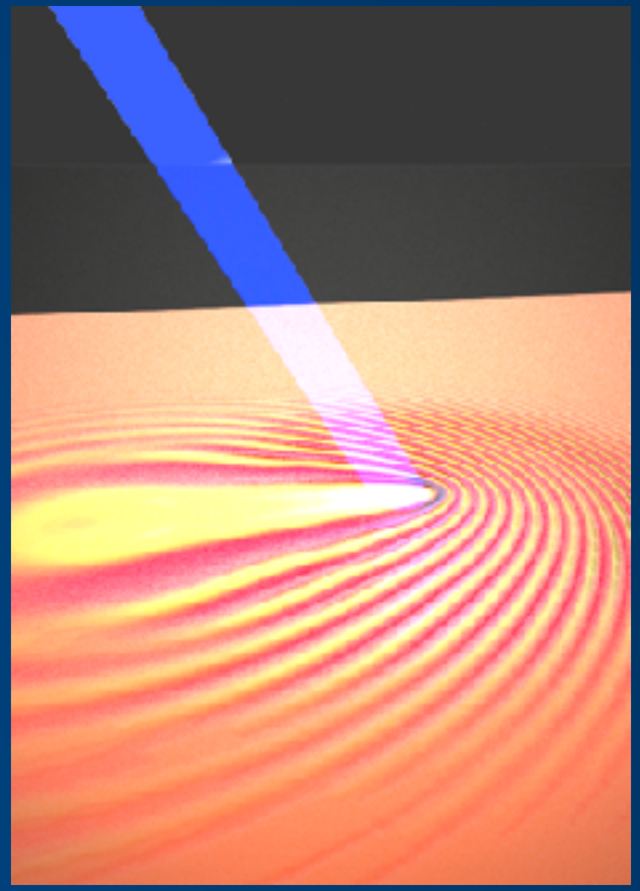
14x14=196 optical tweezers each containing a fixed atom

Spin Hamiltonians with arrays of Rydberg atoms

What I plan to cover in the Solvay lectures

Lecture 1: Quantum fluids in low dimension

Possibility to freeze one or two degrees of freedom: 1D or 2D gases



For low dimensional gases, the role of fluctuations (thermal or quantum) is strongly enhanced with respect to the textbook 3D case

In 2D, there is still possible to observe a superfluid transition even in the absence of a Bose condensate (Kosterlitz-Thouless)

By taking advantage of the spin degree of freedom, it is also possible to increase the dimensionality

PRL **112,** 043001 (2014) PHYSICAL REVIEW LETTERS week ending 31 JANUARY 2014

Synthetic Gauge Fields in Synthetic Dimensions

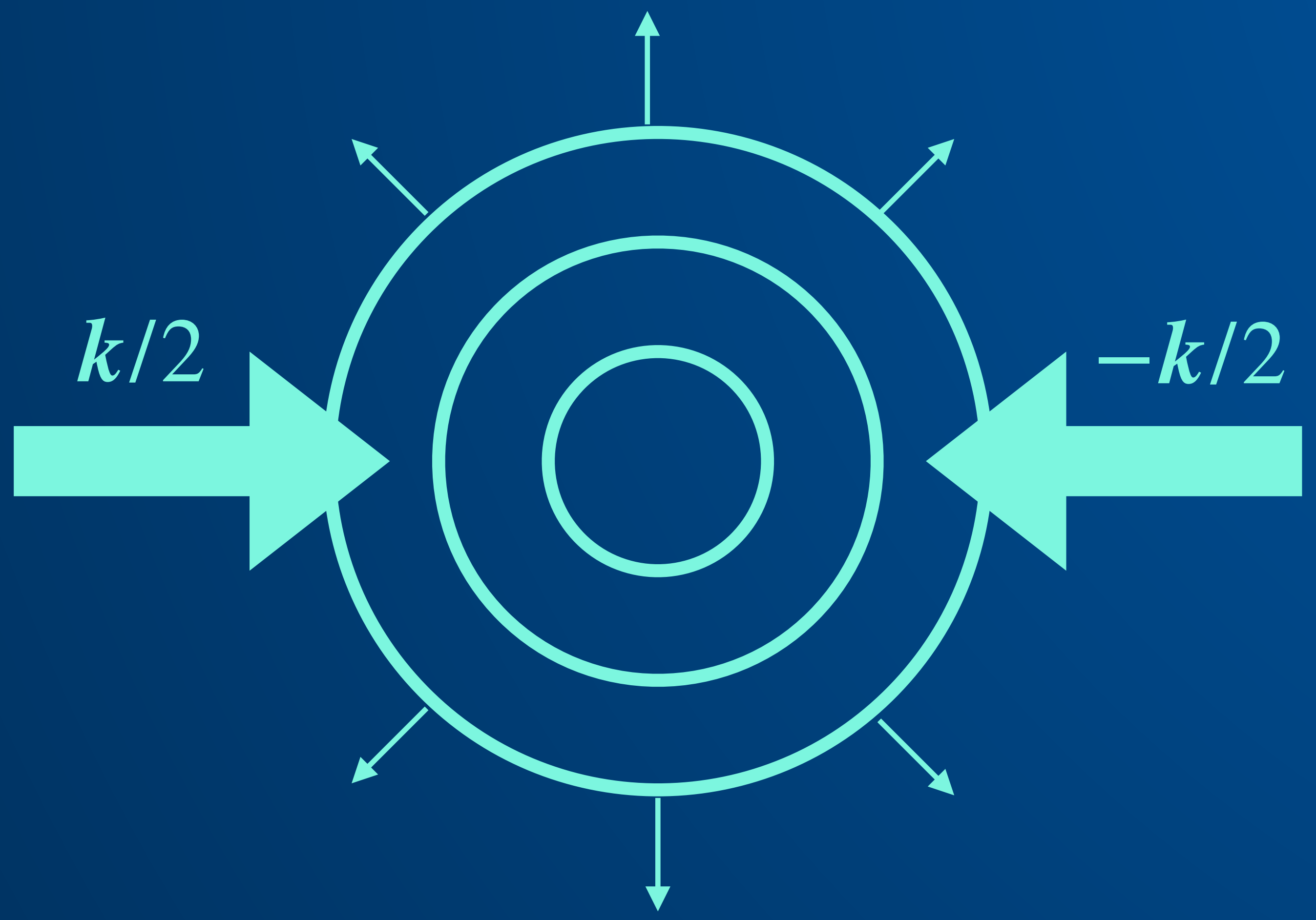
A. Celi,[1] P. Massignan,[1] J. Ruseckas,[2] N. Goldman,[3] I. B. Spielman,[4,5] G. Juzeliūnas,[2] and M. Lewenstein[1,6]

Lecture 2: Scale invariance explored with cold gases

Scale invariance: a concept that was introduced in the 70's in high-energy physics

Can there be physical systems with no intrinsic energy scale?

With cold fermionic atoms, unitary regime where $a \to \pm\infty$



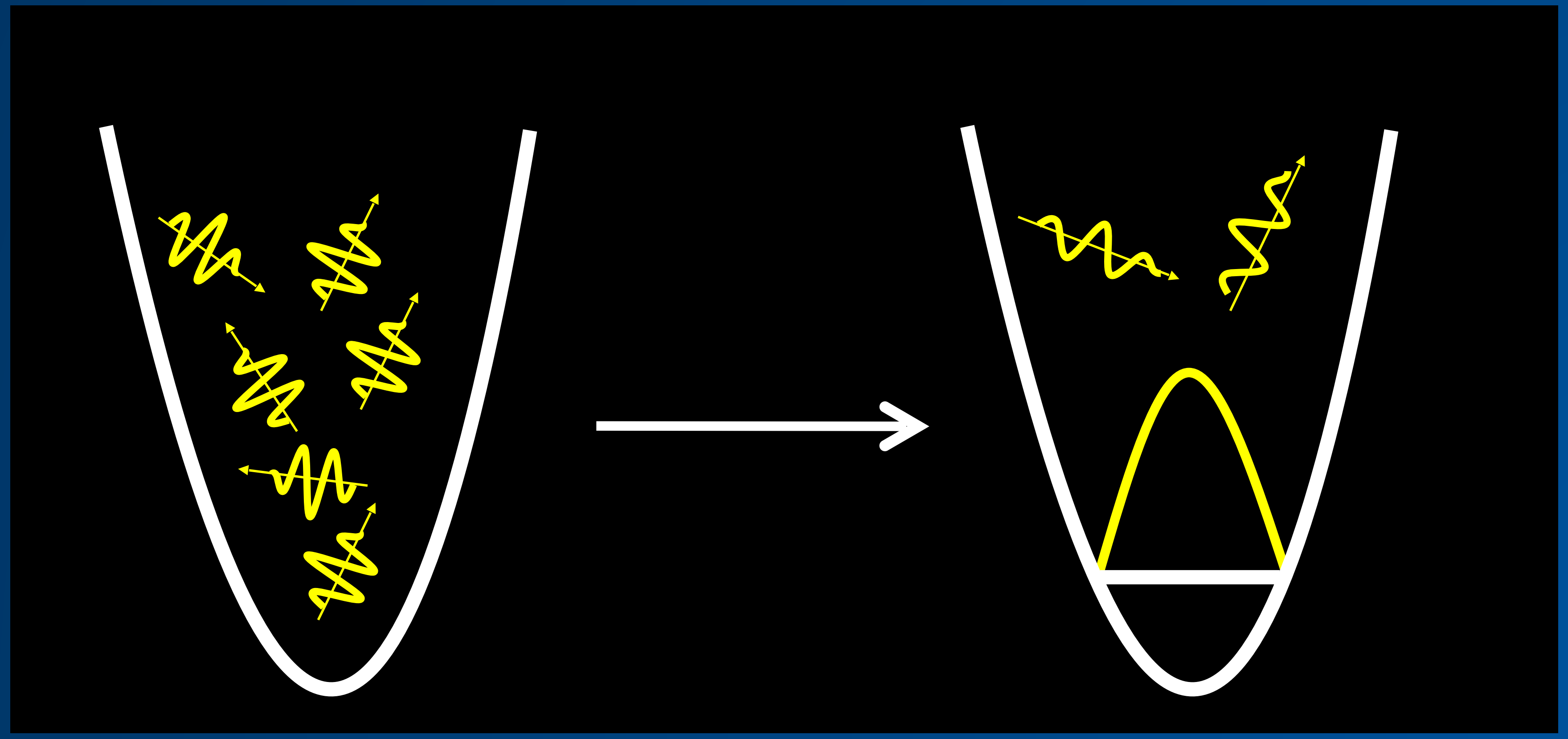
$$\psi(\boldsymbol{r}) \sim \mathrm{e}^{\mathrm{i}\boldsymbol{k}\cdot\boldsymbol{r}} - a\frac{\mathrm{e}^{\mathrm{i}kr}}{r} \longrightarrow \psi(\boldsymbol{r}) \sim \mathrm{e}^{\mathrm{i}\boldsymbol{k}\cdot\boldsymbol{r}} + \mathrm{i}\frac{\mathrm{e}^{\mathrm{i}kr}}{kr}$$

The disparition of a length scale associated to interactions has important consequences on the equilibrium state and the dynamics of the fluid

Scale invariance also occurs for a 2D Bose gas

Lecture 3: Spinor gases and mesoscopic physics

Bose-Einstein condensation is a genuine phase transition, with a spontaneous symmetry breaking



At each realization of the experiment, the system randomly chooses a phase for the macroscopic wave function

Penrose-Onsager: only one single-particle state acquires a macroscopic population

Nozières, Leggett, Baym, Ho,… :
Can there be "fragmented condensates", where a few single-particle states share the condensed population?

Yes, for systems small enough to avoid the usual symmetry breaking!

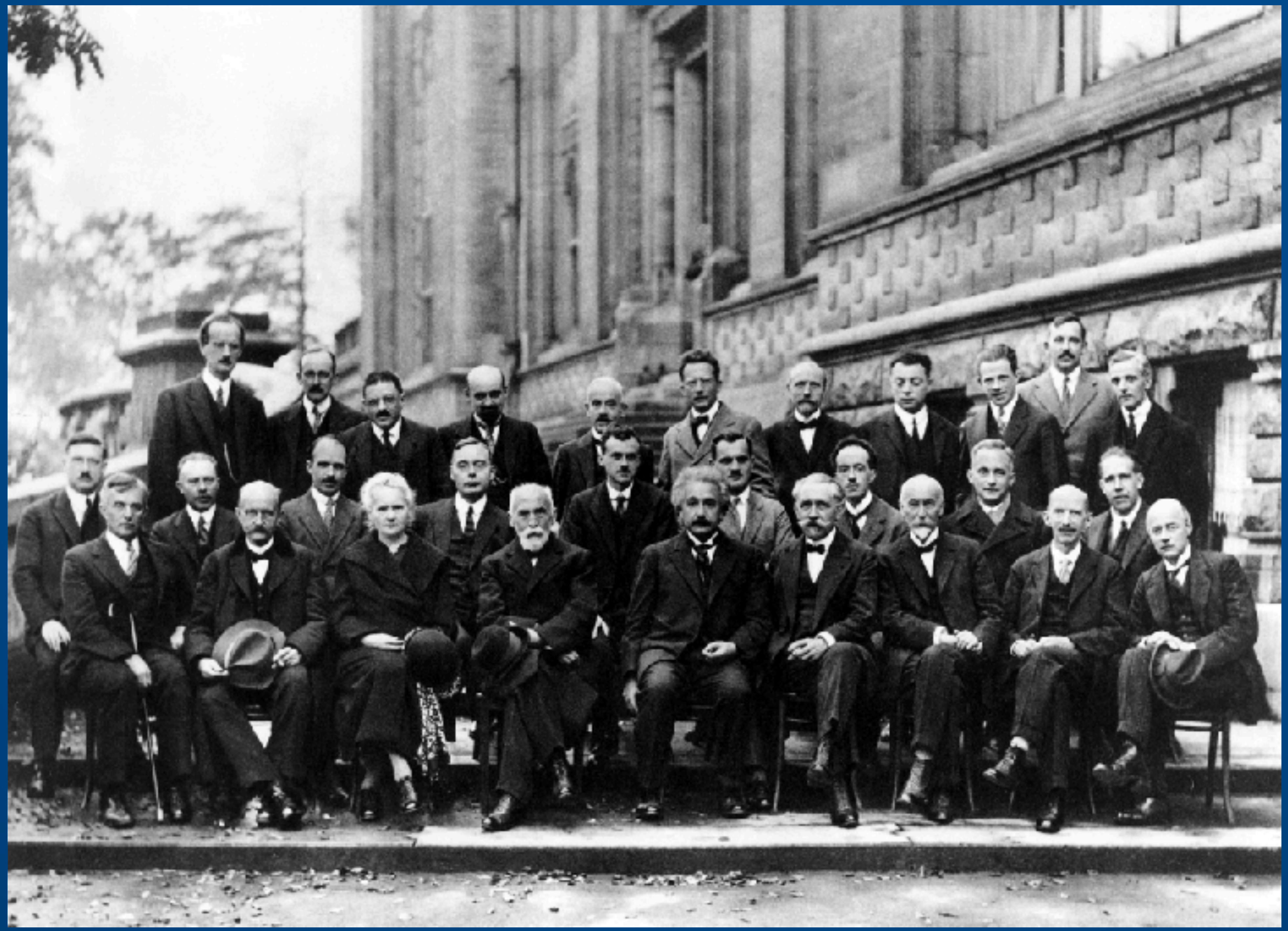
Connection between fragmentation and entanglement

On the shoulders of giants

Collective intellectual adventure, at the crossroad of atomic and optical physics, statistical physics, condensed matter physics, …

Perspectives in fields as diversed as few-body chemistry and high energy physics

common denominator: Quantum Physics



5th Solvay Conference in Physics, 1927

Thank you!