

# A short history of cold atoms

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Solvay Chair for Physics, 2021  
Inaugural lecture

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

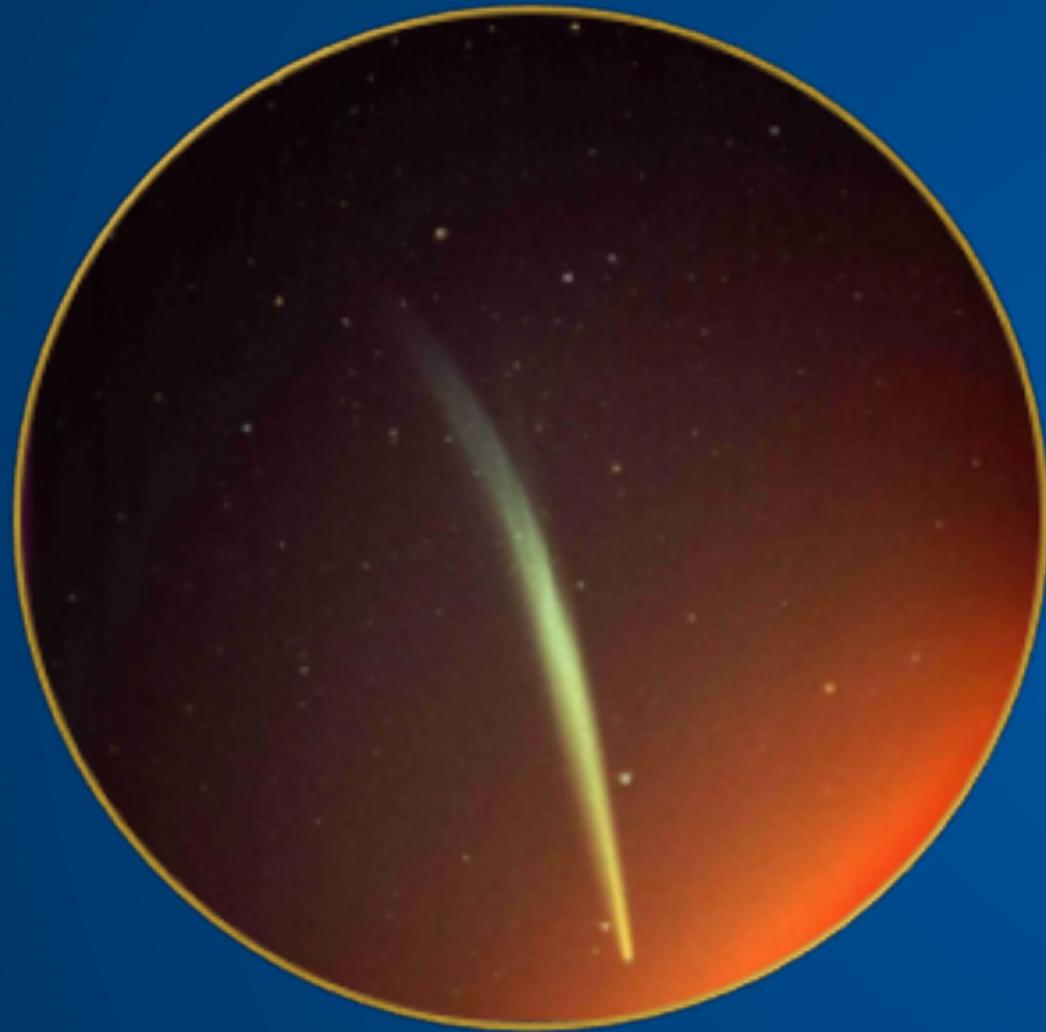
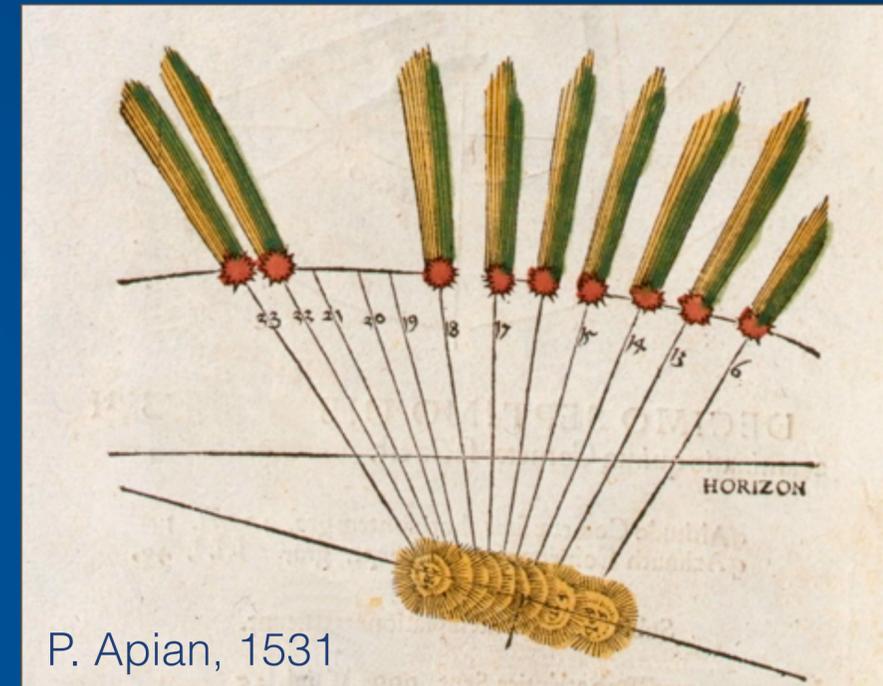


Photo : Observatoire de Paris



P. Apian, 1531

Kepler, 1619:

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

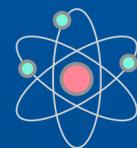
# From sun light to tunable lasers



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



atom

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.)

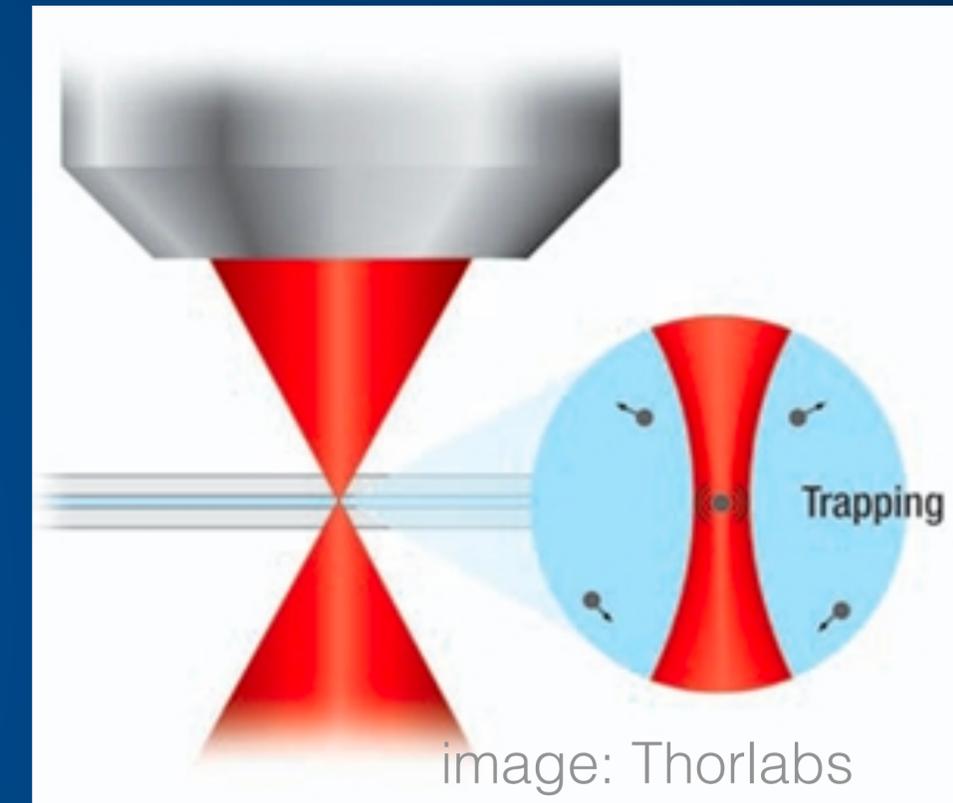
A non-resonant laser beam induces a dipole in an material particle

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

$\alpha$  : polarisability,  $\mathcal{E}$  : laser electric field

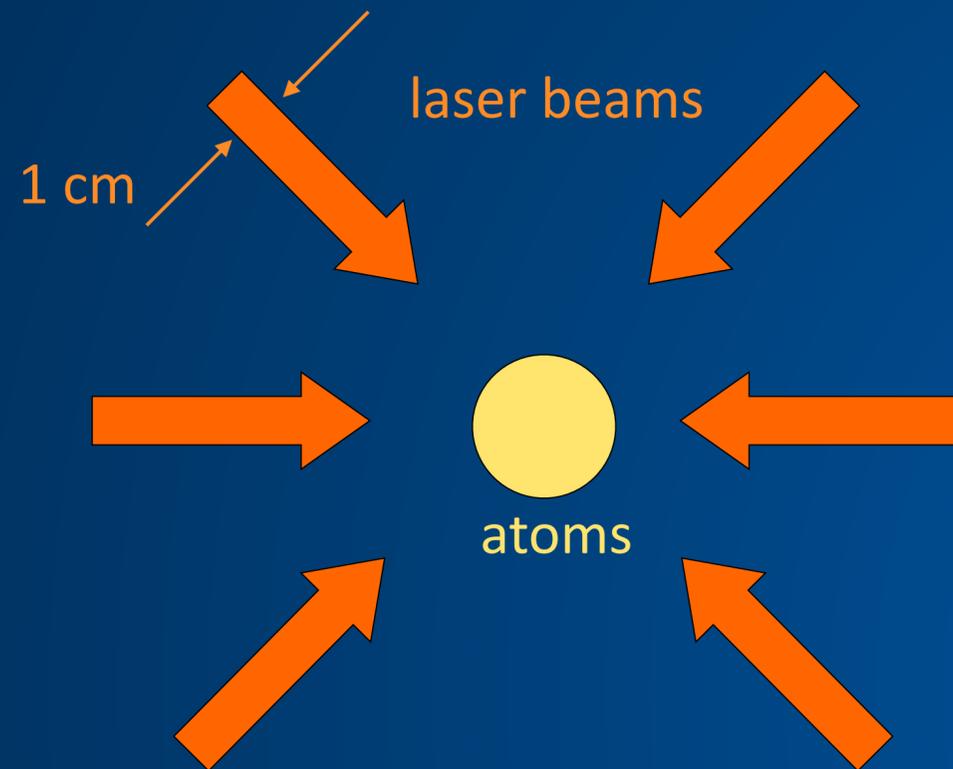
Average energy associated with this induced dipole:

$$E(\mathbf{r}) = -\frac{1}{2} \alpha \overline{\mathcal{E}^2(\mathbf{r}, t)} \quad \text{proportional to the light intensity}$$

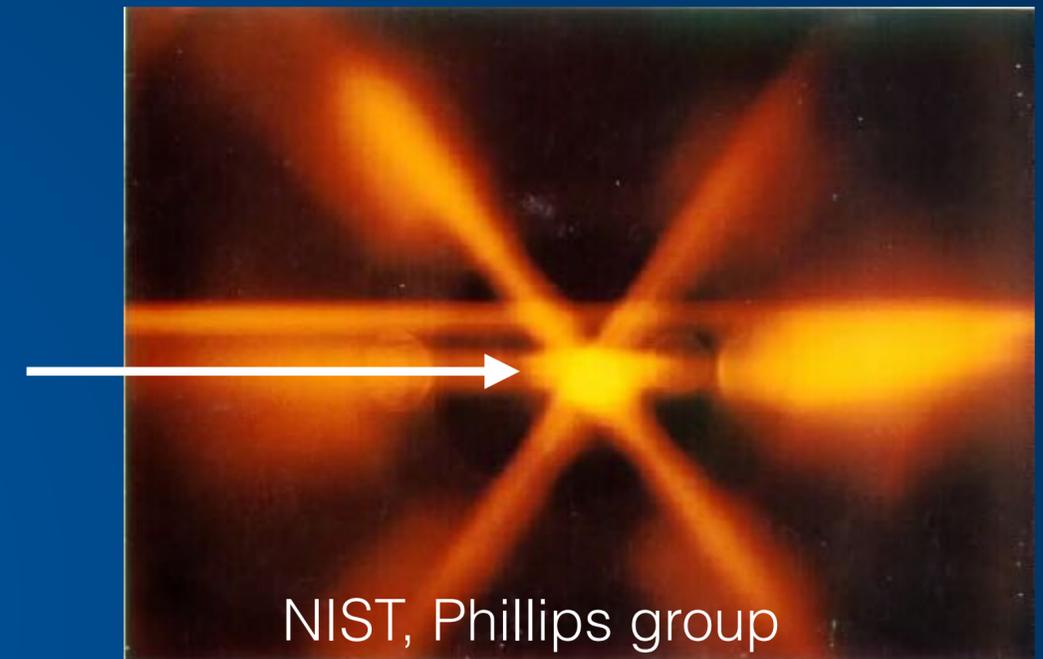


*“Dipole potential” that can trap particles at the focus of a laser beam*

# 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

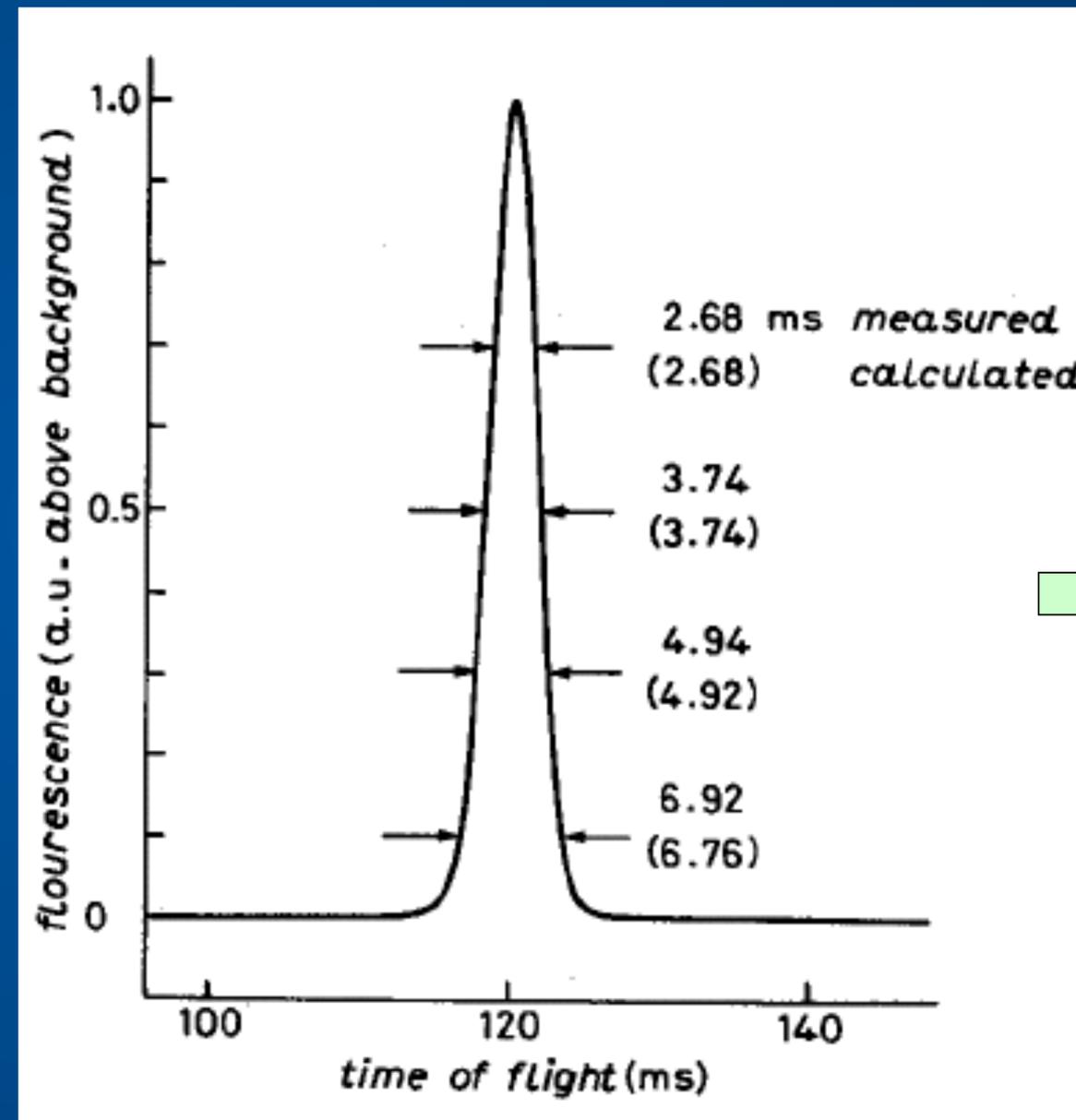
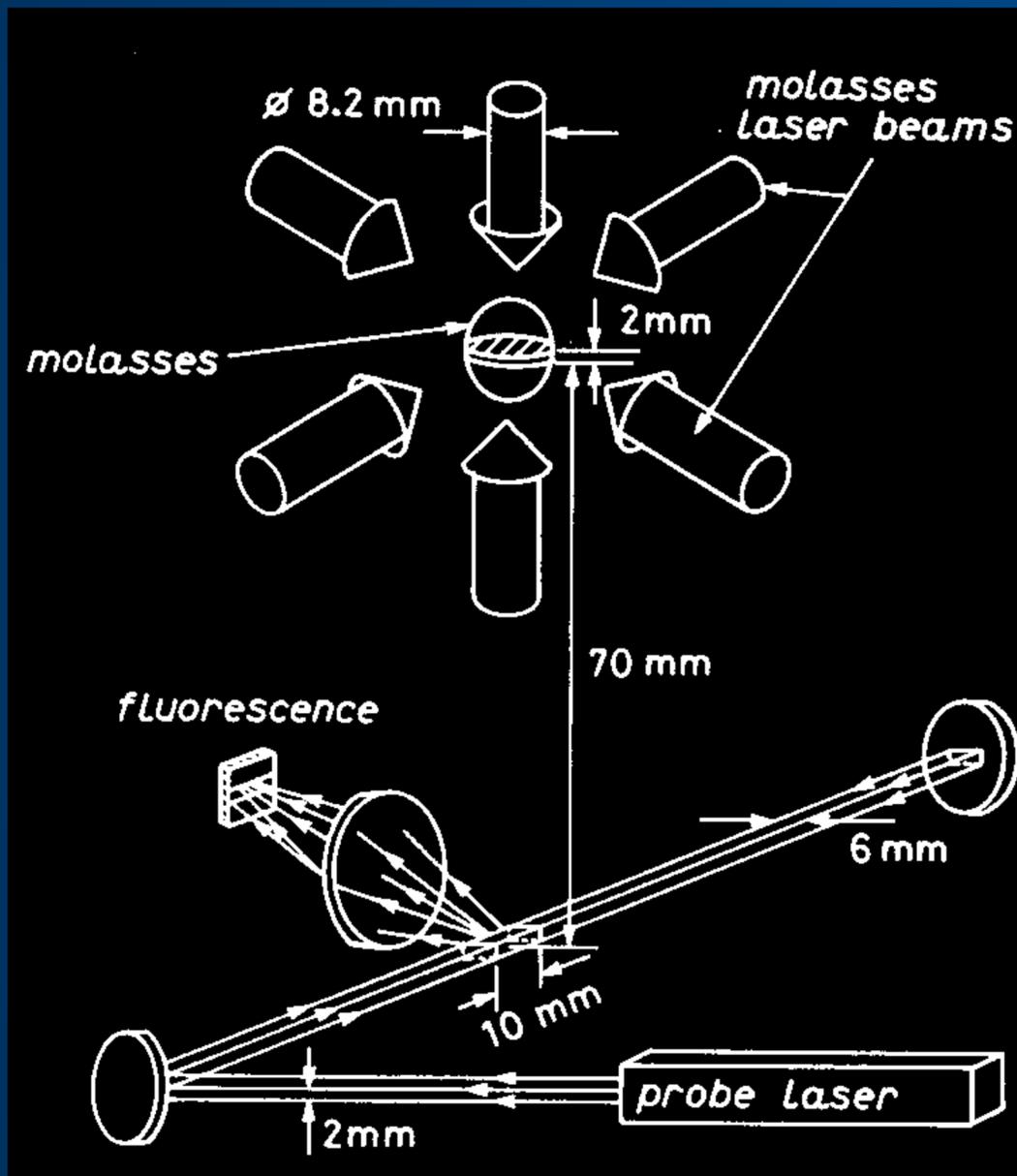
- How can one measure such temperature ?
- What is the mechanism for cooling?
- What is it good for?

Ballistic expansion

Sisyphus effect

Quantum matter, metrology

# How to measure such low temperatures?

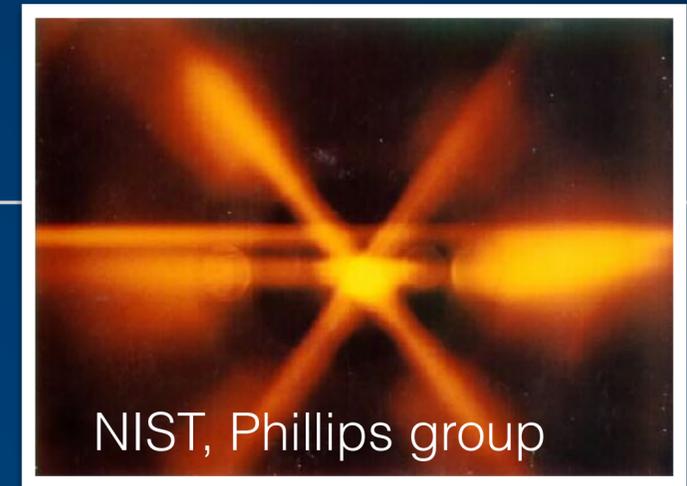


velocity width  
 $\Delta v = 1$  cm/s

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

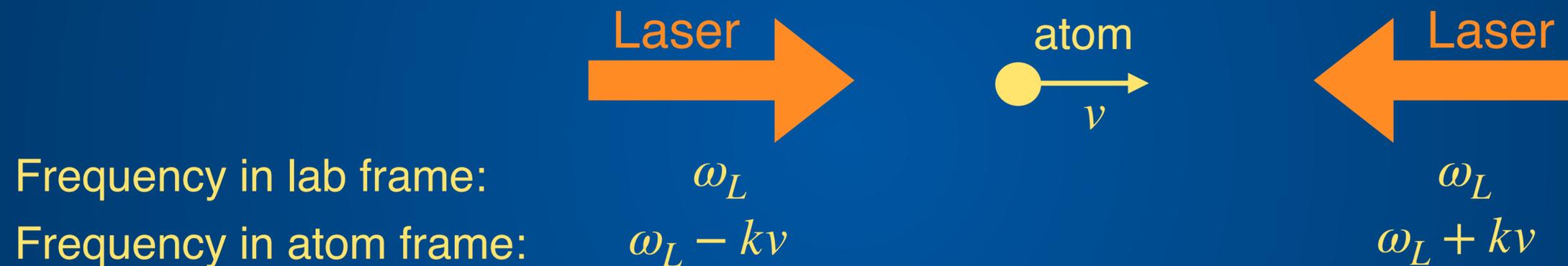
$T = 2$  microKelvin

# What is the mechanism for cooling?



Initial guess: Doppler cooling (Hänsch & Schawlow 1975)

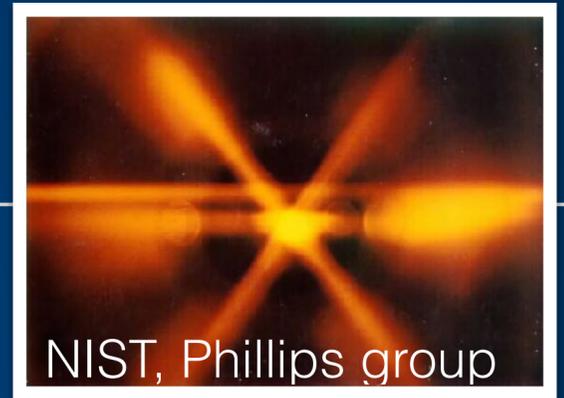
Laser frequency  $\omega_L$  chosen slightly lower than the atomic resonance frequency  $\omega_A$



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

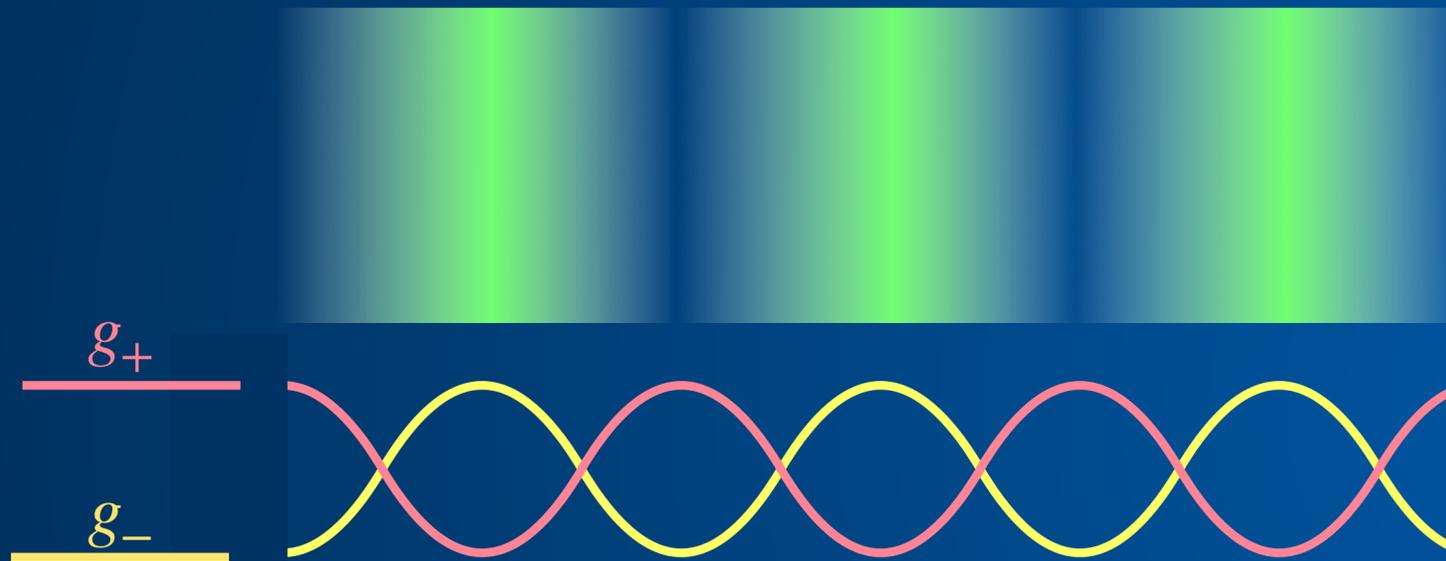
But the predicted temperature should be in the range 100 - 1000 microkelvins, not 1 microkelvin...

# What is the mechanism for cooling (2)?

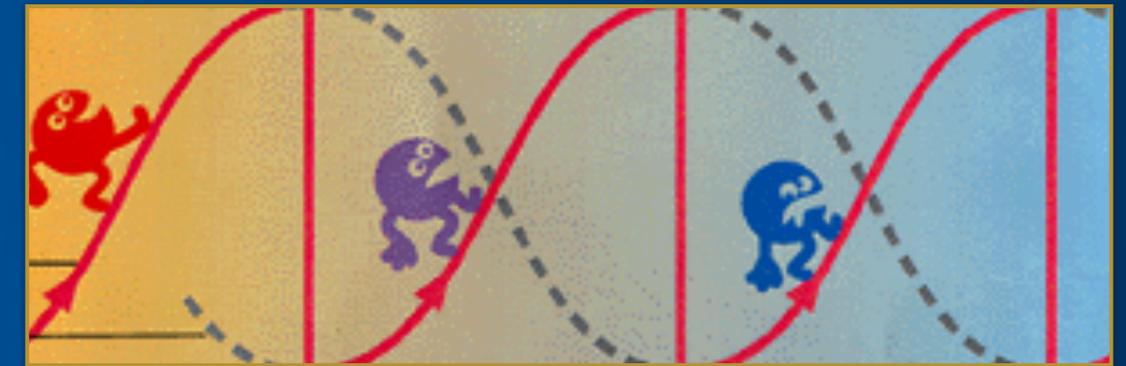


Sisyphus cooling (1988: Cohen-Tannoudji & Dalibard, Chu et al.)

Optical molasses = Laser standing wave



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



Nobel Foundation

Limit of Sisyphus cooling:  $m\Delta v_{\text{atom}} \sim \hbar k$   $\longrightarrow$   $k_{\text{B}}T = m(\Delta v_{\text{atom}})^2 \sim \frac{\hbar^2 k^2}{m}$  : microkelvin

↑  
momentum of a single photon

# The atomic species that have been laser cooled

1 IA												18 VIIIA						
1	1,00794 <b>H</b> <i>Hydrogène</i>											2	4,0026 <b>He</b> <i>Hélium</i>					
2	3 6,941 <b>Li</b> <i>Lithium</i>	4 9,01218 <b>Be</b> <i>Béryllium</i>											5 10,811 <b>B</b> <i>Bore</i>	6 12,0107 <b>C</b> <i>Carbone</i>	7 14,0067 <b>N</b> <i>Azote</i>	8 15,9994 <b>O</b> <i>Oxygène</i>	9 18,9984 <b>F</b> <i>Fluor</i>	10 20,1797 <b>Ne</b> <i>Neon</i>
3	11 22,9898 <b>Na</b> <i>Sodium</i>	12 24,305 <b>Mg</b> <i>Magnésium</i>	3 IIIB	4 IVB	5 VB	6 VIB	7 VIIB	8 VIIIB	9 VIIIB	10 VIIIB	11 IB	12 IIB	13 26,9815 <b>Al</b> <i>Aluminium</i>	14 28,0855 <b>Si</b> <i>Silicium</i>	15 30,9738 <b>P</b> <i>Phosphore</i>	16 32,065 <b>S</b> <i>Soufre</i>	17 35,453 <b>Cl</b> <i>Chlore</i>	18 39,948 <b>Ar</b> <i>Argon</i>
4	19 39,0983 <b>K</b> <i>Potassium</i>	20 40,078 <b>Ca</b> <i>Calcium</i>	21 44,9559 <b>Sc</b> <i>Scandium</i>	22 47,867 <b>Ti</b> <i>Titane</i>	23 50,9415 <b>V</b> <i>Vanadium</i>	24 51,9961 <b>Cr</b> <i>Chrome</i>	25 54,9380 <b>Mn</b> <i>Manganèse</i>	26 55,845 <b>Fe</b> <i>Fer</i>	27 58,9332 <b>Co</b> <i>Cobalt</i>	28 58,6934 <b>Ni</b> <i>Nickel</i>	29 63,546 <b>Cu</b> <i>Cuivre</i>	30 65,38 <b>Zn</b> <i>Zinc</i>	31 69,723 <b>Ga</b> <i>Gallium</i>	32 72,63 <b>Ge</b> <i>Germanium</i>	33 74,9216 <b>As</b> <i>Arsenic</i>	34 78,96 <b>Se</b> <i>Sélénium</i>	35 79,904 <b>Br</b> <i>Brome</i>	36 83,798 <b>Kr</b> <i>Krypton</i>
5	37 85,4678 <b>Rb</b> <i>Rubidium</i>	38 87,62 <b>Sr</b> <i>Strontium</i>	39 88,9058 <b>Y</b> <i>Yttrium</i>	40 91,224 <b>Zr</b> <i>Zirconium</i>	41 92,9064 <b>Nb</b> <i>Niobium</i>	42 95,96 <b>Mo</b> <i>Molybdène</i>	43 {98} <b>Tc</b> <i>Technétium</i>	44 101,07 <b>Ru</b> <i>Ruthénium</i>	45 102,905 <b>Rh</b> <i>Rhodium</i>	46 106,42 <b>Pd</b> <i>Palladium</i>	47 107,868 <b>Ag</b> <i>Argent</i>	48 112,411 <b>Cd</b> <i>Cadmium</i>	49 114,818 <b>In</b> <i>Indium</i>	50 118,71 <b>Sn</b> <i>Étain</i>	51 121,76 <b>Sb</b> <i>Antimoine</i>	52 127,6 <b>Te</b> <i>Tellure</i>	53 126,905 <b>I</b> <i>Iode</i>	54 131,293 <b>Xe</b> <i>Xénon</i>
6	55 132,905 <b>Cs</b> <i>Césium</i>	56 137,327 <b>Ba</b> <i>Baryum</i>	72 178,49 <b>Hf</b> <i>Hafnium</i>	73 180,948 <b>Ta</b> <i>Tantale</i>	74 183,84 <b>W</b> <i>Tungstène</i>	75 186,207 <b>Re</b> <i>Rhénium</i>	76 190,23 <b>Os</b> <i>Osmium</i>	77 192,217 <b>Ir</b> <i>Iridium</i>	78 195,084 <b>Pt</b> <i>Platine</i>	79 196,967 <b>Au</b> <i>Or</i>	80 200,59 <b>Hg</b> <i>Mercure</i>	81 204,383 <b>Tl</b> <i>Thallium</i>	82 207,2 <b>Pb</b> <i>Plomb</i>	83 208,98 <b>Bi</b> <i>Bismuth</i>	84 {209} <b>Po</b> <i>Polonium</i>	85 {210} <b>At</b> <i>Astate</i>	86 {222} <b>Rn</b> <i>Radon</i>	
7	87 {223} <b>Fr</b> <i>Francium</i>	88 {226} <b>Ra</b> <i>Radium</i>	104 {266} <b>Rf</b> <i>Rutherfordium</i>	105 {268} <b>Db</b> <i>Dubnium</i>	106 {269} <b>Sg</b> <i>Seaborgium</i>	107 {270} <b>Bh</b> <i>Bohrium</i>	108 {269} <b>Hs</b> <i>Hassium</i>	109 {278} <b>Mt</b> <i>Meitnerium</i>	110 {279} <b>Ds</b> <i>Darmstadtium</i>	111 {281} <b>Rg</b> <i>Röntgenium</i>	112 {285} <b>Cn</b> <i>Copernicium</i>	113 {284} <b>Uut</b> <i>Ununtrium</i>	114 {289} <b>Fl</b> <i>Flerovium</i>	115 {288} <b>Uup</b> <i>Ununpentium</i>	116 {293} <b>Lv</b> <i>Livermorium</i>	117 {294} <b>Uus</b> <i>Ununseptium</i>	118 {294} <b>Uuo</b> <i>Ununoctium</i>	
6	57 138,906 <b>La</b> <i>Lanthane</i>	58 140,116 <b>Ce</b> <i>Cérium</i>	59 140,908 <b>Pr</b> <i>Praséodyme</i>	60 144,242 <b>Nd</b> <i>Néodyme</i>	61 {145} <b>Pm</b> <i>Prométhium</i>	62 150,36 <b>Sm</b> <i>Samarium</i>	63 151,964 <b>Eu</b> <i>Europium</i>	64 157,25 <b>Gd</b> <i>Gadolinium</i>	65 158,925 <b>Tb</b> <i>Terbium</i>	66 162,5 <b>Dy</b> <i>Dysprosium</i>	67 164,930 <b>Ho</b> <i>Holmium</i>	68 167,259 <b>Er</b> <i>Érène</i>	69 173,054 <b>Tm</b> <i>Thulium</i>	70 174,967 <b>Yb</b> <i>Ytterbium</i>	71 174,967 <b>Lu</b> <i>Lutécium</i>			
7	89 {227} <b>Ac</b> <i>Actinium</i>	90 232,038 <b>Th</b> <i>Thorium</i>	91 231,036 <b>Pa</b> <i>Protactinium</i>	92 238,029 <b>U</b> <i>Uranium</i>	93 {237} <b>Np</b> <i>Neptunium</i>	94 {244} <b>Pu</b> <i>Plutonium</i>	95 {243} <b>Am</b> <i>Americium</i>	96 {247} <b>Cm</b> <i>Curium</i>	97 {247} <b>Bk</b> <i>Berkélium</i>	98 {251} <b>Cf</b> <i>Californium</i>	99 {252} <b>Es</b> <i>Einsteinium</i>	100 {257} <b>Fm</b> <i>Fermium</i>	101 {258} <b>Md</b> <i>Mendélium</i>	102 {259} <b>No</b> <i>Nobelium</i>	103 {262} <b>Lr</b> <i>Lawrencium</i>			

14 IVA  
6 12,0107  
**C**  
*Carbone*

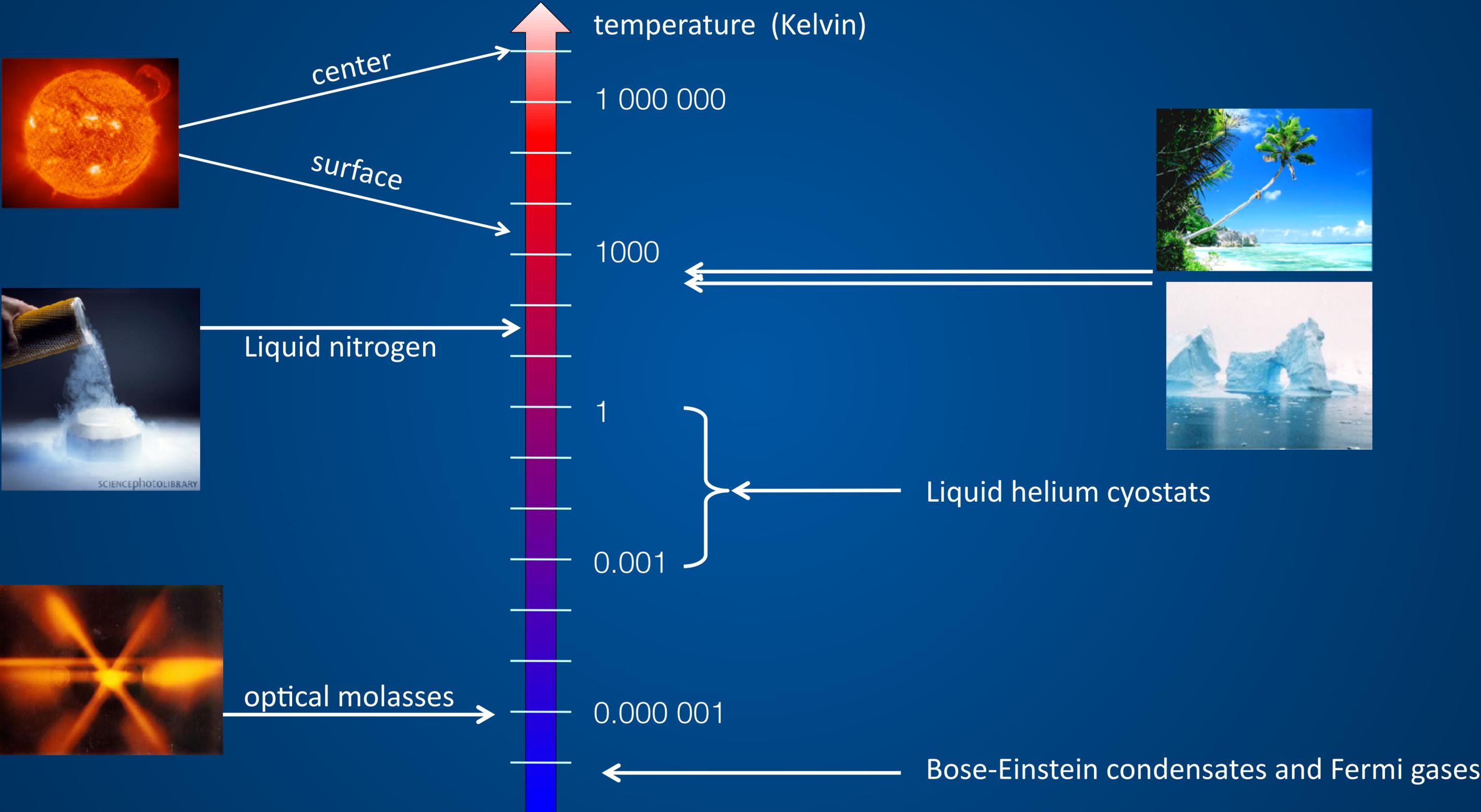
SYMBOLE : C  
NOM DE L'ÉLÉMENT : CARBONE  
NUMÉRO ATOMIQUE : 6  
MASSE ATOMIQUE : 12,0107  
GROUPE : 14 (IUPAC) - IVA (CAS)  
PÉRIODE : 2

- MASSES ATOMIQUES DES ISOTOPES LES PLUS STABLES ENTRE ACCOLADES
- MASSES ATOMIQUES DONNÉES À 6 CHIFFRES SIGNIFICATIFS

- NON MÉTAUX
- MÉTALLOÏDES
- MÉTAUX ALCALINS
- HALOGÈNES
- MÉTAUX ALCALINO-TERREUX
- GAZ NOBLES
- MÉTAUX DE TRANSITION
- LANTHANIDES
- MÉTAUX PAUVRES
- ACTINIDES

+ molecules : SrF, CaF, YO, CaOH

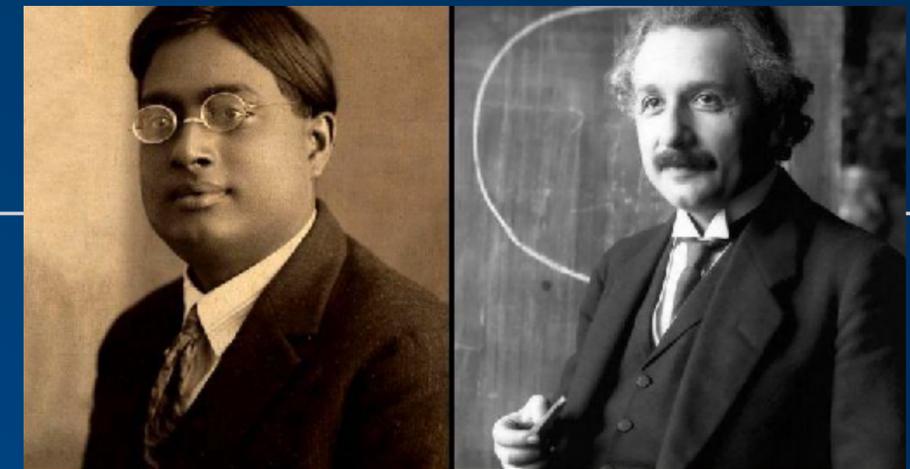
# The temperature scale



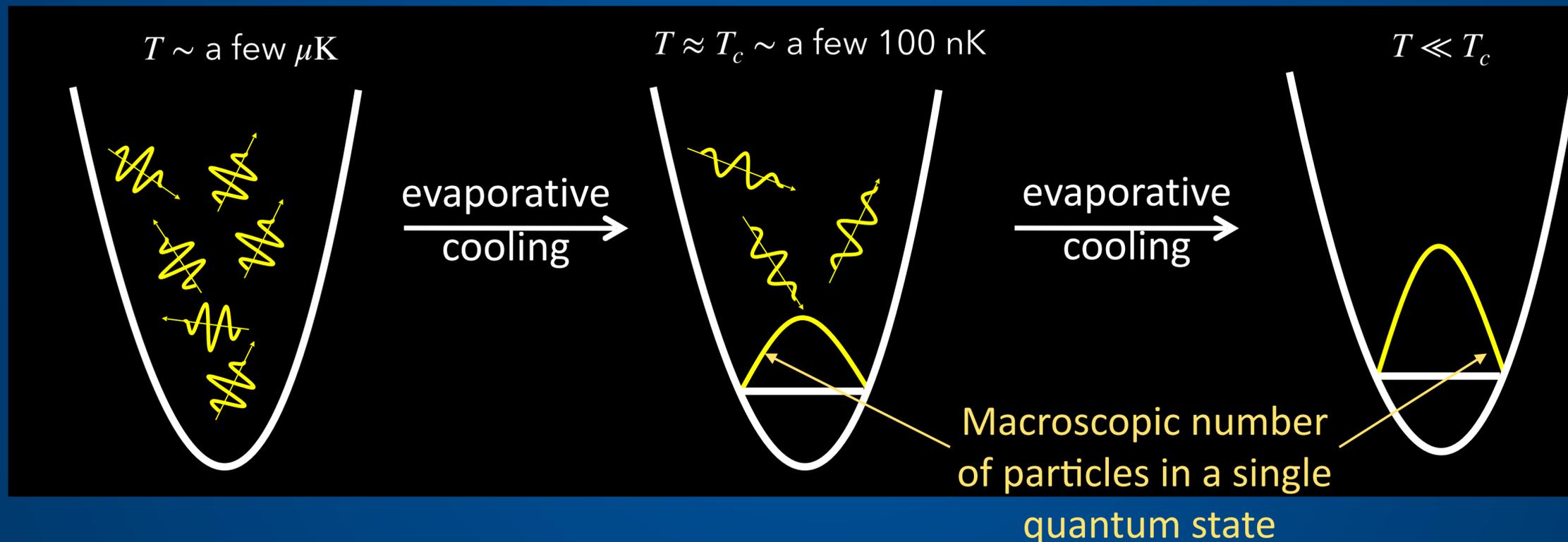
# Bose-Einstein condensation

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  $\approx$  interatomic distance

Na atoms @ 100 nK :  $\lambda = 1 \mu\text{m}$

*Other examples of dilute quantum matter (2000-05): atomic Fermi gases, Bose-Einstein condensates of cavity polaritons<sup>1</sup>*

A brief history of cold atoms:

What are they good for?

Answer 1: More precise measurements

# The principle of an atomic clock

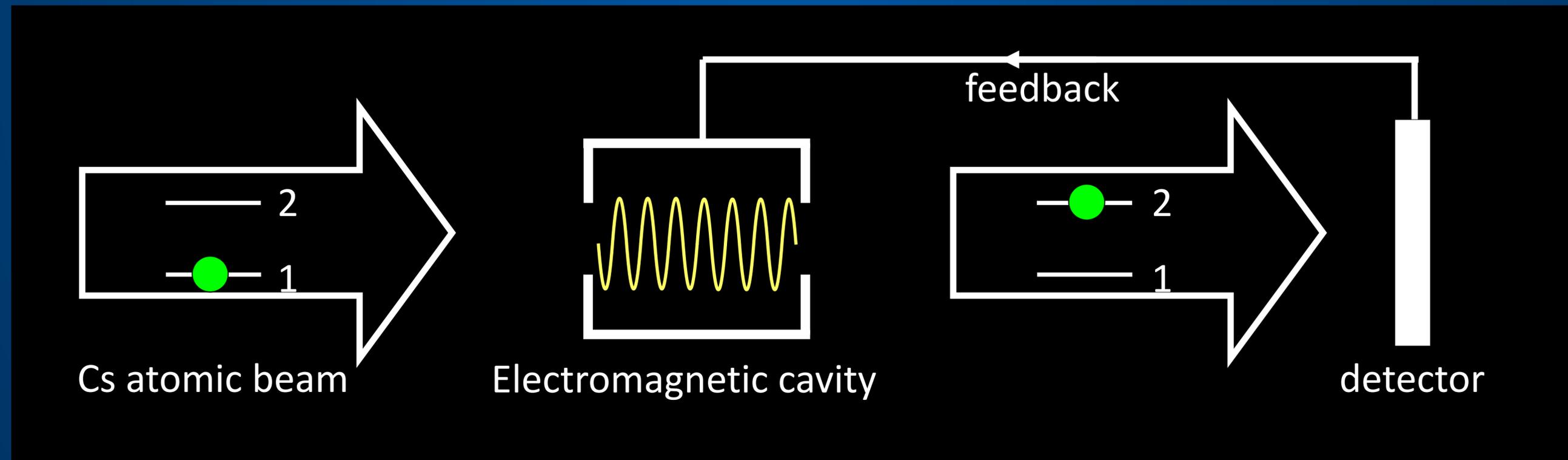
1967 : definition of the second (unit of time) from an atomic reference

—————  $E_2$

—————  $E_1$

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

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



pendulum + counting system

# Cold atom clocks



Syrte (Paris)  
atomic fountain

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

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

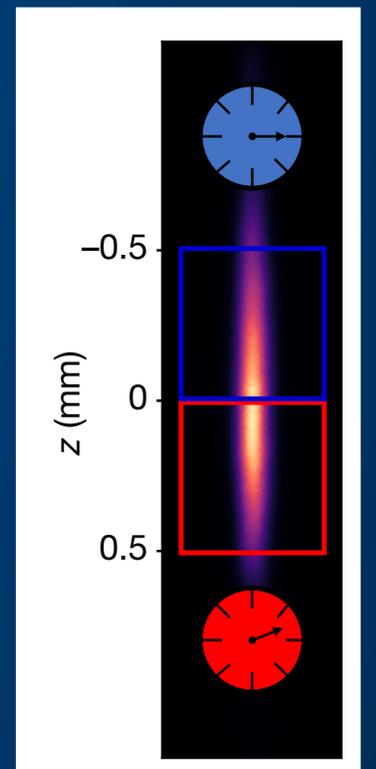
*Navigation, telecommunications, very long base interferometry (astronomy)*

Technical progress in the fabrication of ultra-stable lasers:

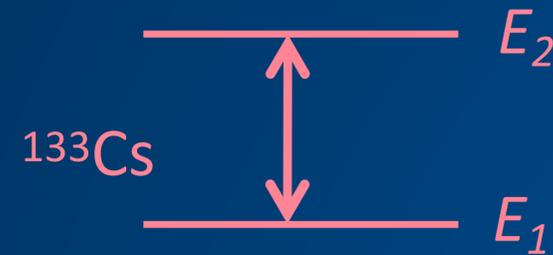
Shift towards a reference in the visible range ( $10^{15}$  osc. / second) instead of microwave ( $10^{10}$  osc./second)

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

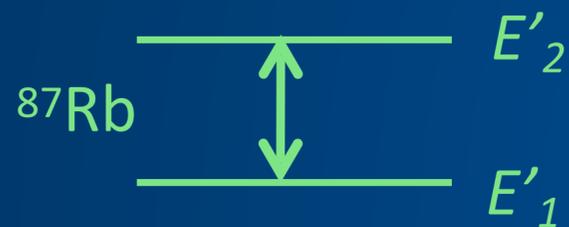
Jun Ye's lab (2022): precise measurement of the gravitational red shift over 1 mm:  $\frac{\Delta\nu}{\nu} = \frac{gH}{c^2} \approx 10^{-19}$



# 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

$$\frac{m_{\text{proton}}}{m_{\text{electron}}} \approx 1840$$

$$\frac{e^2}{\hbar c} \approx \frac{1}{137}$$

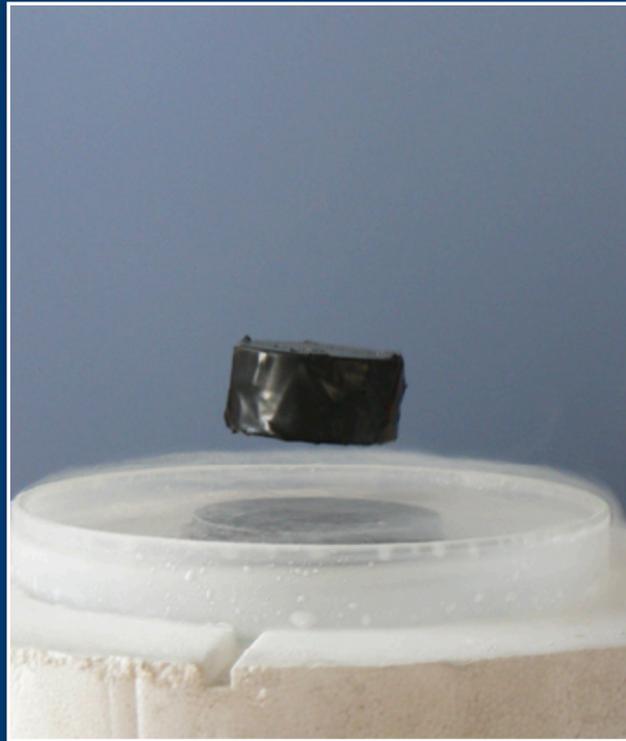
***But are the fundamental constants really constant?***

A brief history of cold atoms:

What are they good for?

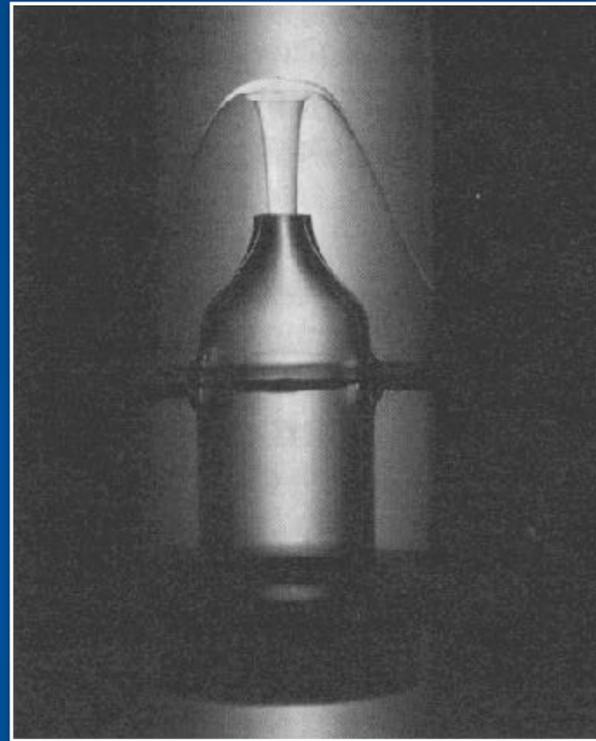
Answer 2: Exploring quantum matter

# The first examples of quantum matter



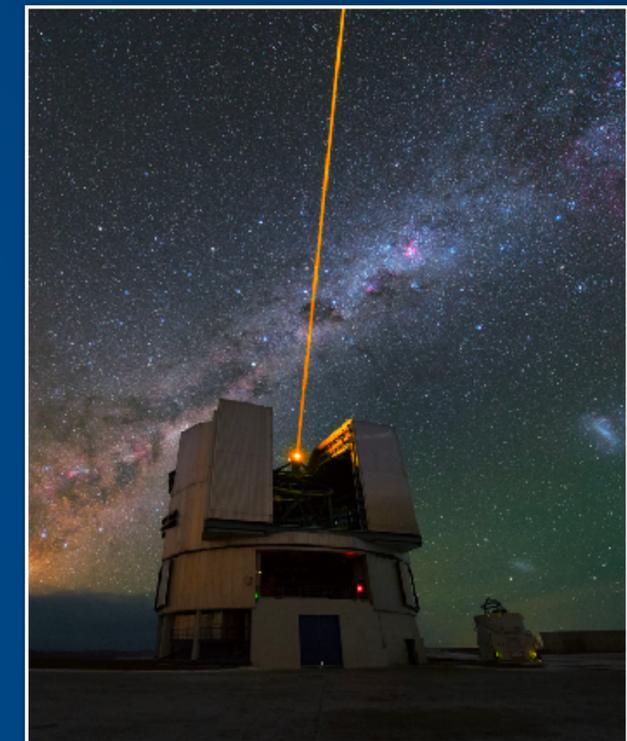
Superconductivity

1911



Superfluidity

1937



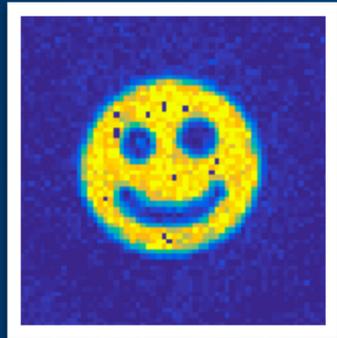
Laser

1960

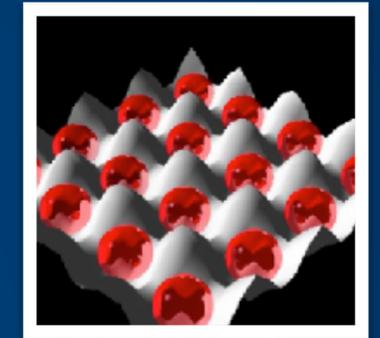
Macroscopic systems with a long-range phase coherence

# The assets of atomic gases

## Control of the environment: geometry and topology

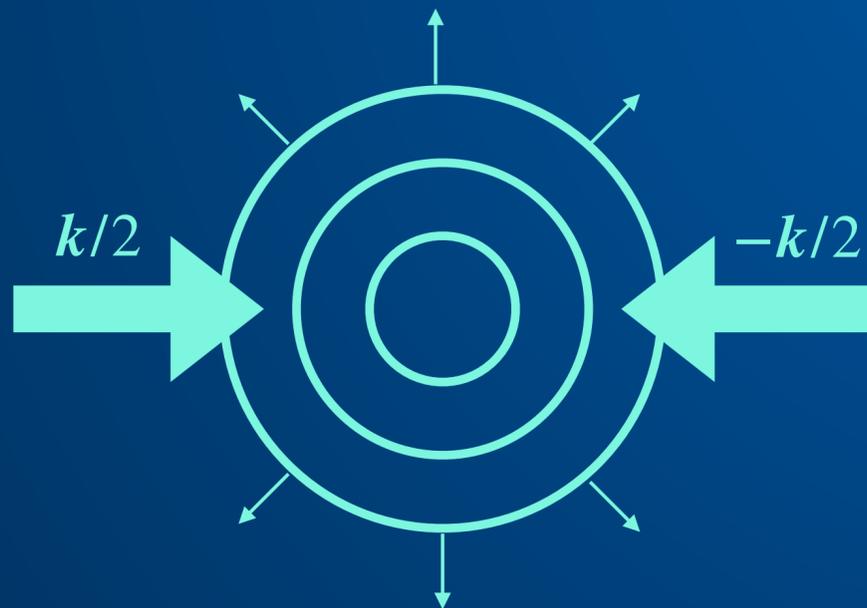


*Tailored laser beams can produce confinement potentials of arbitrary shapes:  
Harmonic, box-like, periodic (optical lattices), random*



## Control of the interactions

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



$$\psi(\mathbf{r}) \sim e^{i\mathbf{k}\cdot\mathbf{r}} - a \frac{e^{ikr}}{r}$$

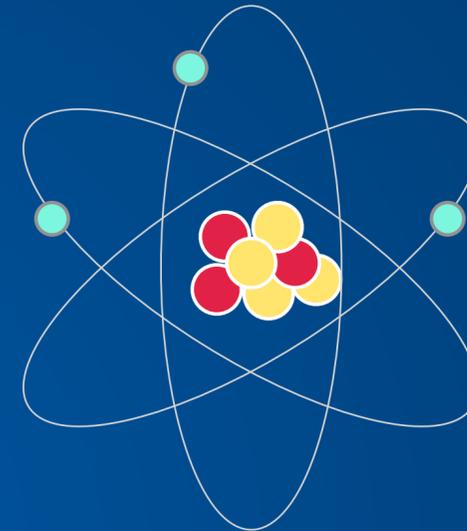
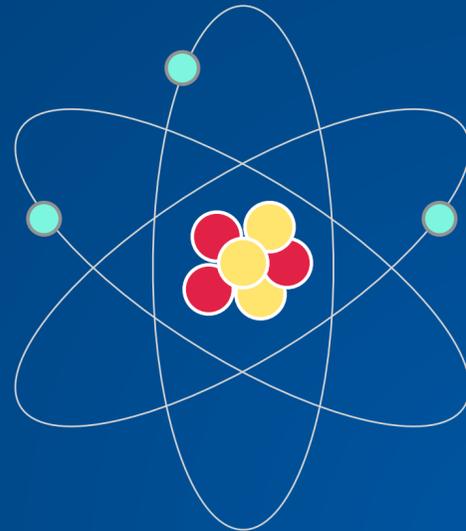
The scattering length  $a$  characterizes the physics of the collision.  
It can be controlled in sign and magnitude (for some species)

# The assets of atomic gases (2)

## Control of the statistics

${}^6\text{Li}$ : 3 protons  
+ 3 electrons  
+ 3 neutrons

**Fermion**

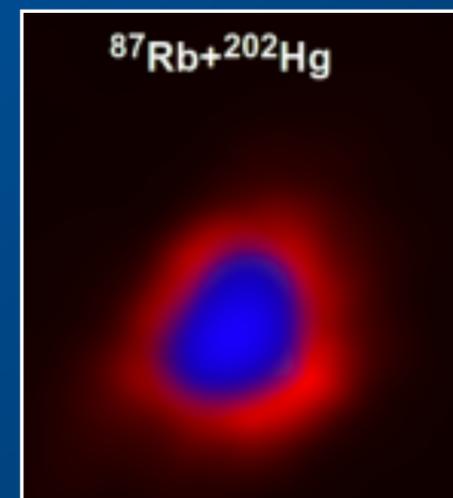


${}^7\text{Li}$ : 3 protons  
+ 3 electrons  
+ 4 neutrons

**Boson**

## Control of the masses

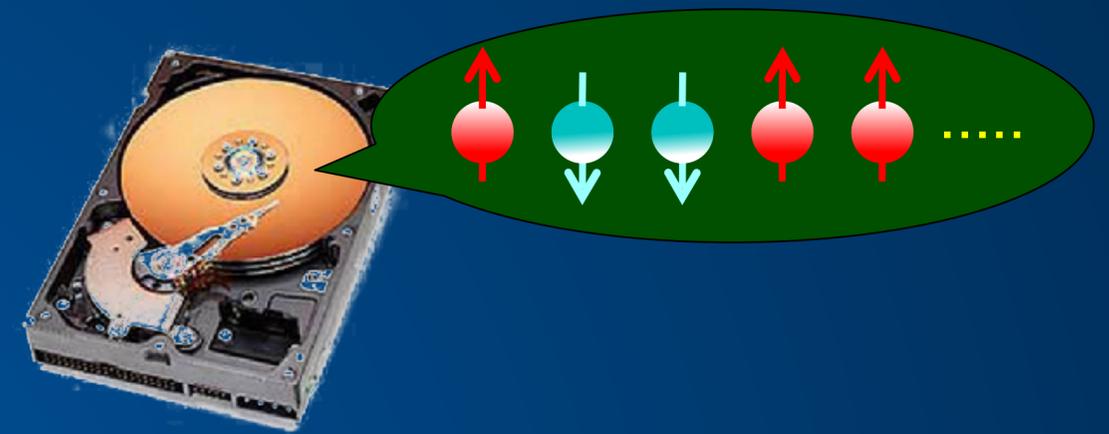
Realization of mixtures of various atomic species  
and various statistics (B+B, B+F, F+F)



Witkowski et al.,  
Optics express 2017

# Quantum Calculation & Quantum Simulation

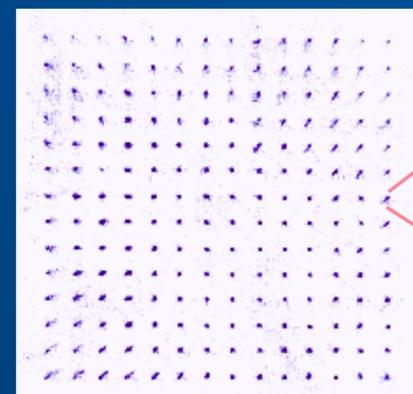
A universal quantum computer, with the proper error corrections, is still a far-future goal for cold atoms



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

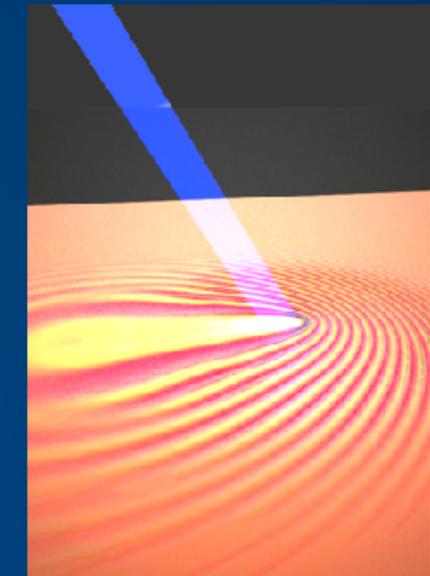
What I plan to cover in the Solvay lectures

# 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

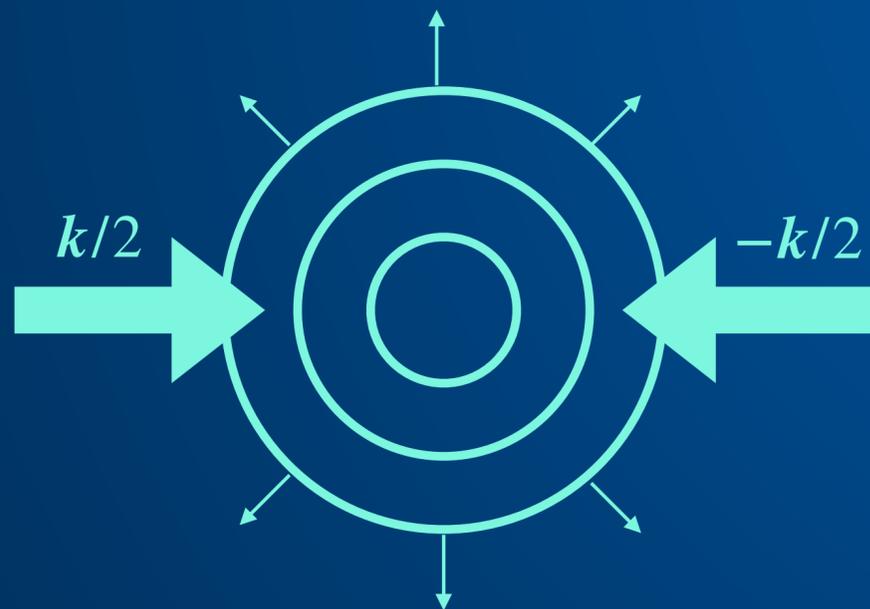
A. Celi,<sup>1</sup> P. Massignan,<sup>1</sup> J. Ruseckas,<sup>2</sup> N. Goldman,<sup>3</sup> I. B. Spielman,<sup>4,5</sup> G. Juzeliūnas,<sup>2</sup> and M. Lewenstein<sup>1,6</sup>

# 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  $a \rightarrow \pm \infty$



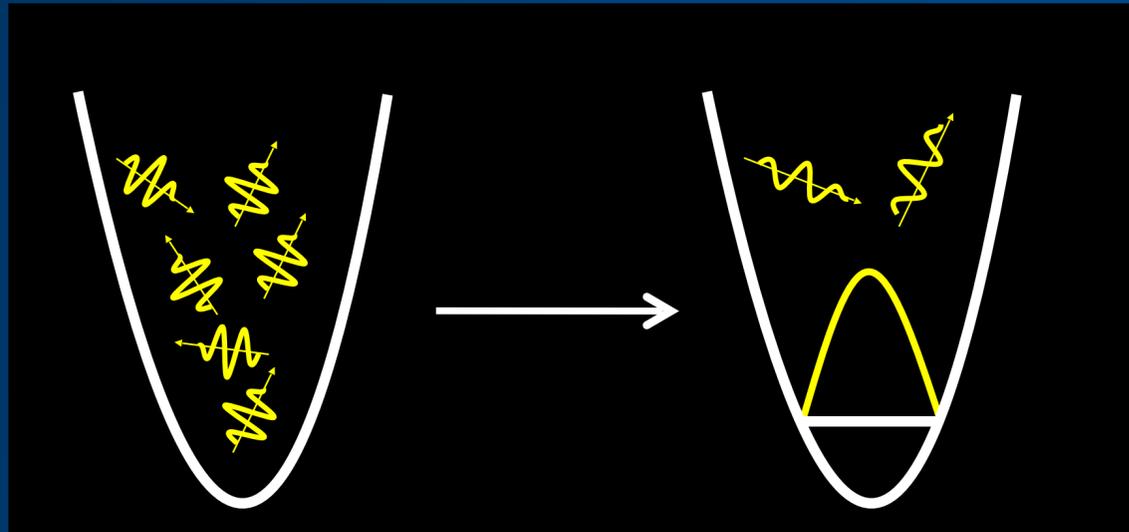
$$\psi(\mathbf{r}) \sim e^{i\mathbf{k}\cdot\mathbf{r}} - a \frac{e^{i\mathbf{k}\cdot\mathbf{r}}}{r} \longrightarrow \psi(\mathbf{r}) \sim e^{i\mathbf{k}\cdot\mathbf{r}} + i \frac{e^{i\mathbf{k}\cdot\mathbf{r}}}{kr}$$

*The disappearance 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!*

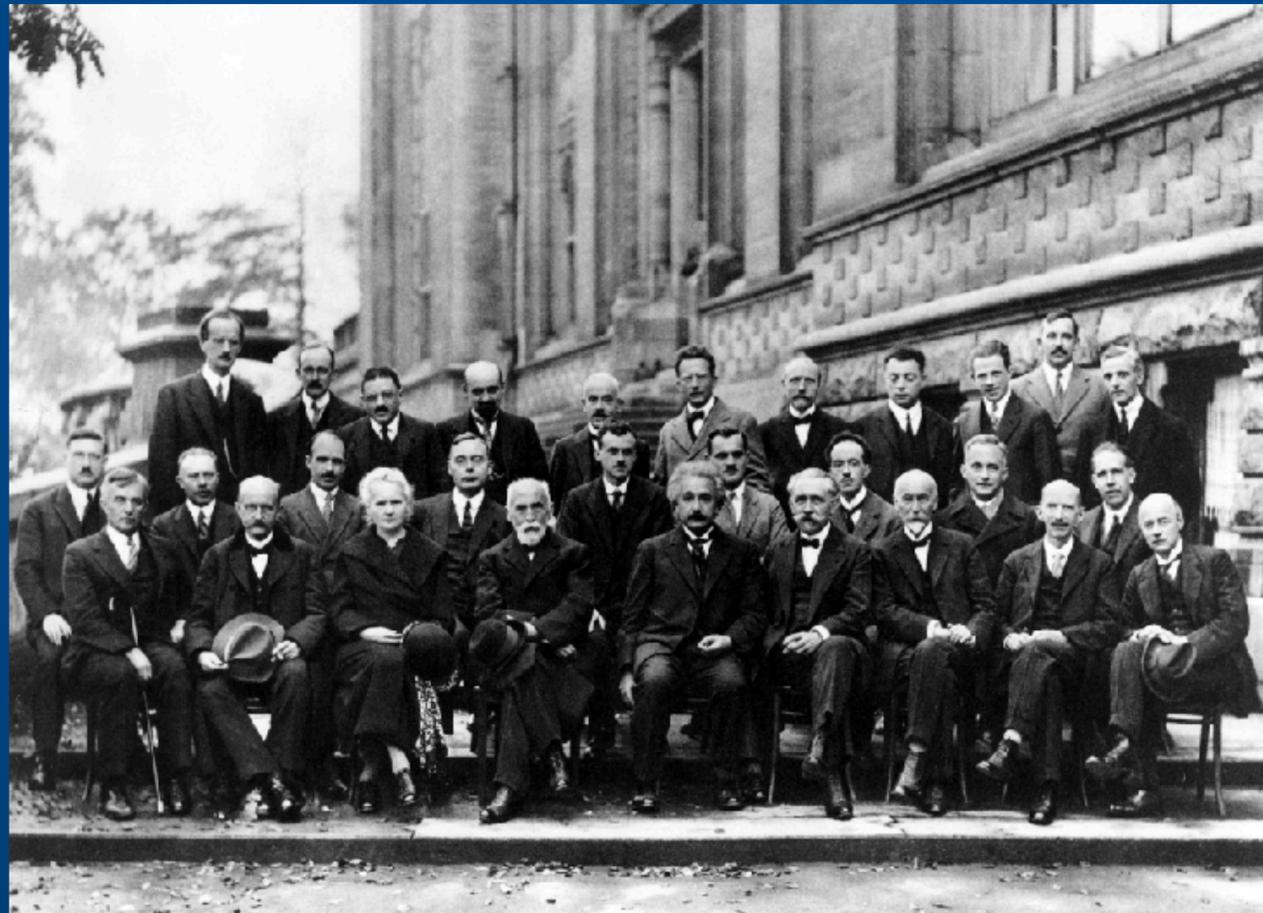
*Connection between fragmentation and entanglement*

# 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 diversified as few-body chemistry and high energy physics

**common denominator: Quantum Physics**



5th Solvay Conference  
in Physics, 1927

Thank you!