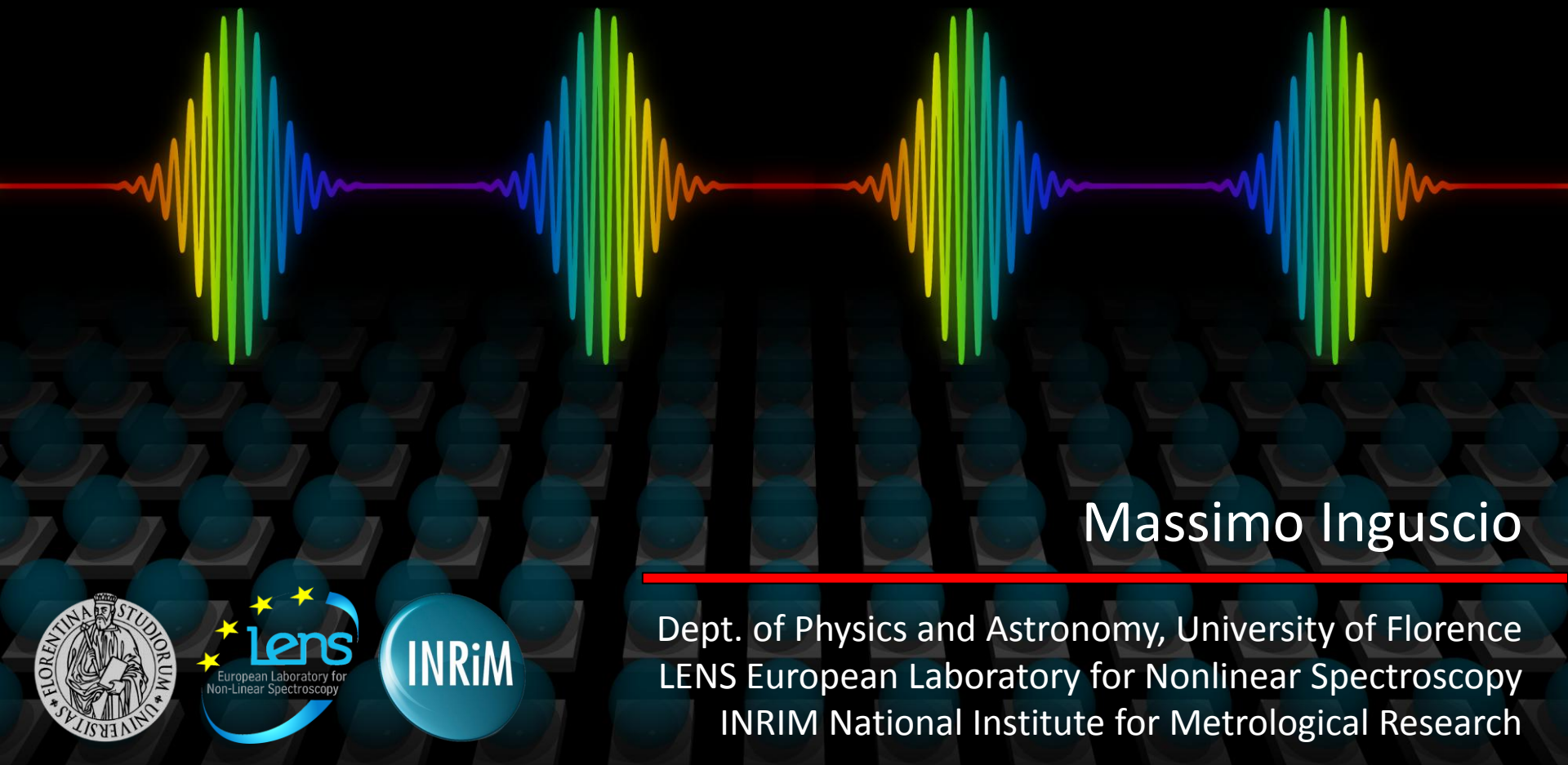


Il mondo quantistico degli atomi a 273 gradi sotto zero

Torino, 10 Aprile 2014



Massimo Inguscio

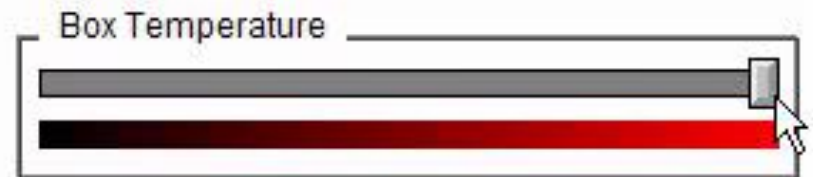
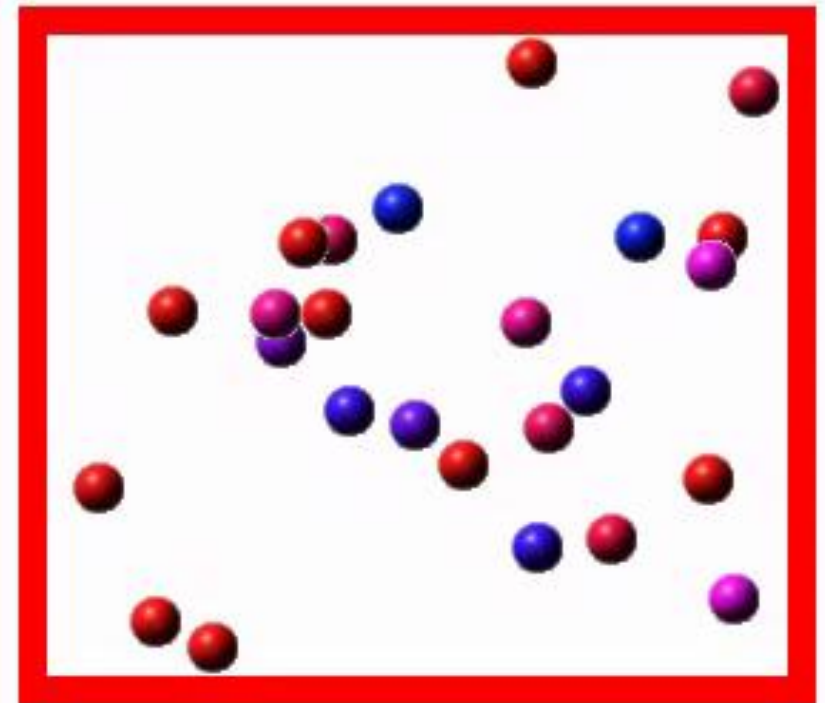


Dept. of Physics and Astronomy, University of Florence
LENS European Laboratory for Nonlinear Spectroscopy
INRIM National Institute for Metrological Research

Cos'è la temperatura?

Definizione cinetica di temperatura

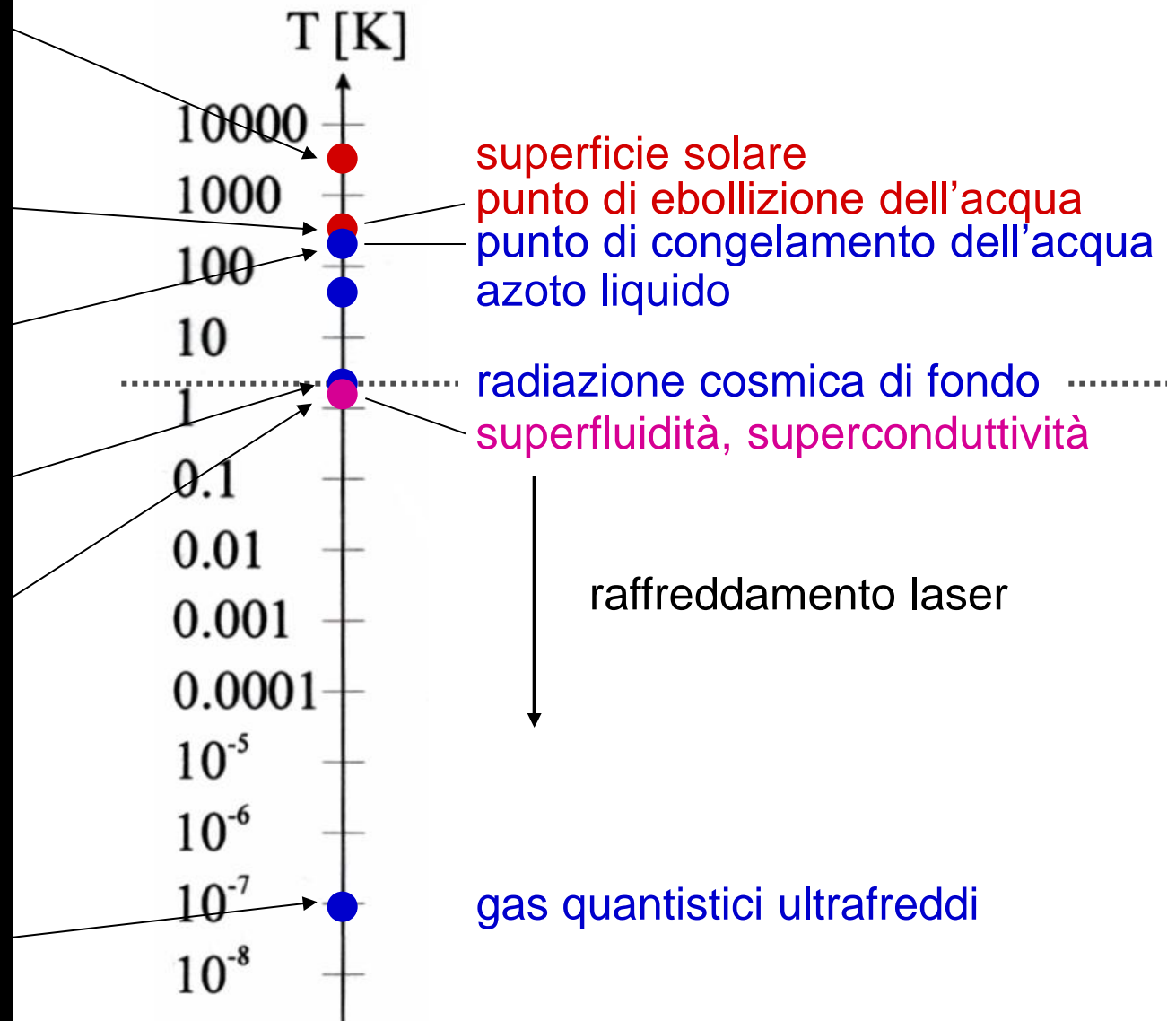
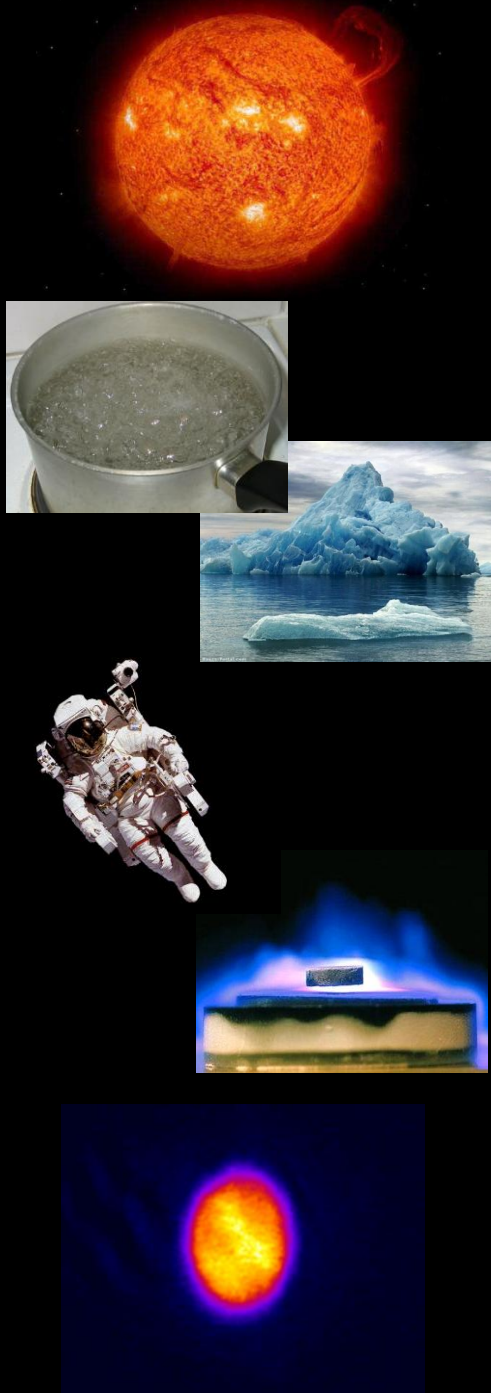
$$T = \frac{mv^2}{3k_B}$$



Come fermare gli atomi con la luce

Pressione di radiazione

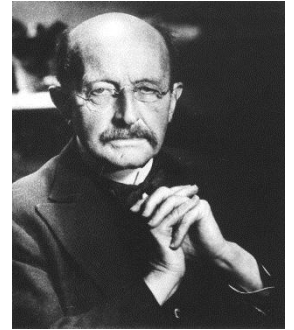
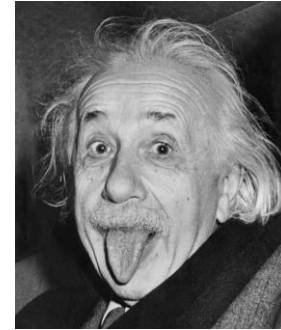




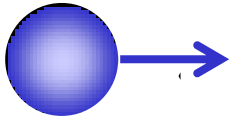
La luce è fatta di particelle!

1900: Max Planck – Spettro di corpo nero (Nobel 1918)

1905: Albert Einstein – Effetto fotoelettrico (Nobel 1921)



atomo



$$\vec{p} = m\vec{v}$$

$$E = \frac{1}{2}mv^2$$

fotone



$$\vec{p} = \hbar\vec{k}$$

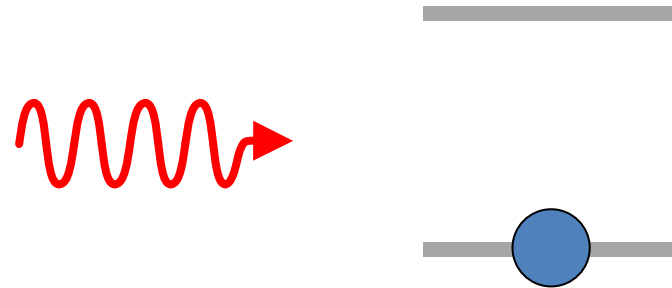
$$E = \hbar\omega$$

Costante di Planck: $h = 2\pi \times \hbar = 6.626\,069\,57(29) \times 10^{-34} \text{ J/s}$

Interazione atomo-fotone

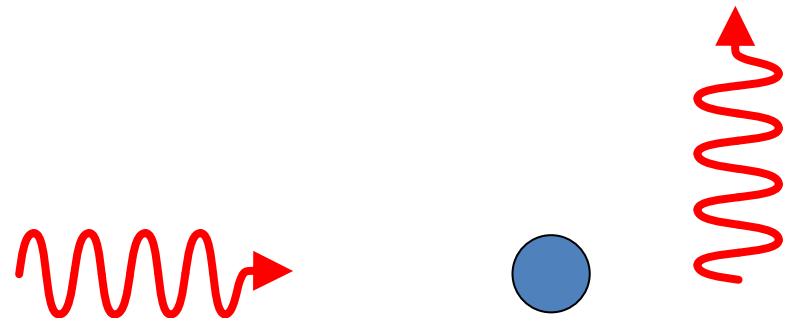
- **Principio di conservazione dell'energia**

Salti tra livelli energetici diversi → **spettroscopia**



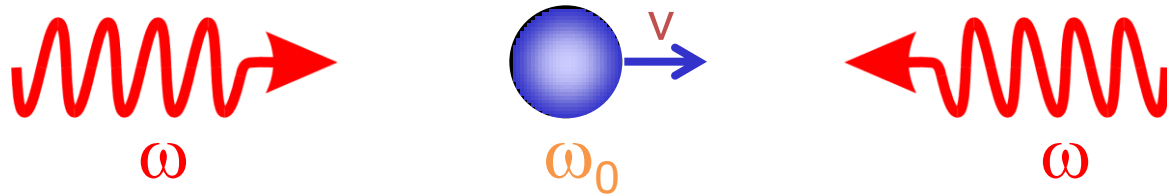
- **Principio di conservazione dell'impulso**

Rinculo dell'atomo → **forze radiative**

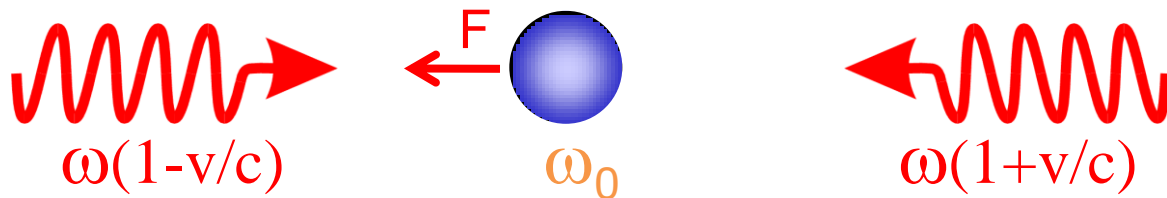


Raffreddamento Doppler

due fasci laser contropropaganti ($\omega < \omega_0$)



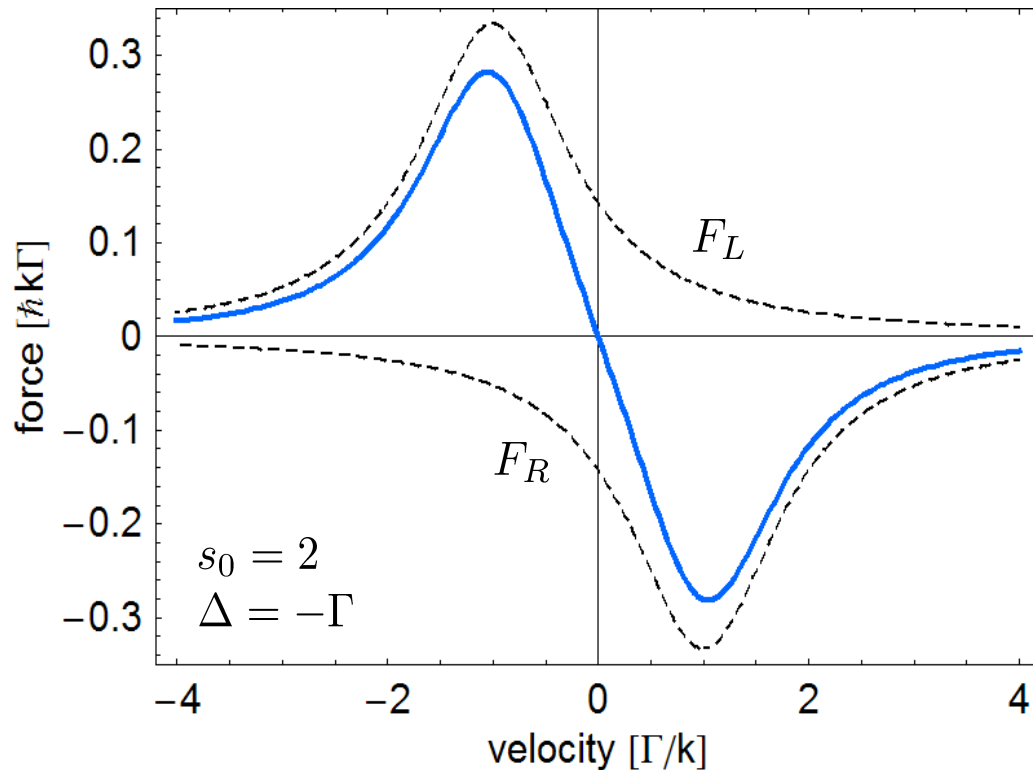
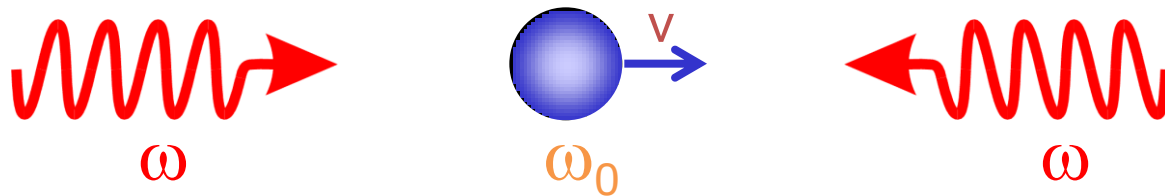
effetto Doppler (sistema di riferimento a riposo con l'atomo)



assorbimento del fascio contropropagante + rinculo

Raffreddamento Doppler

due fasci laser contropropaganti ($\omega < \omega_0$)



$$\vec{F} = -\gamma \vec{v}$$

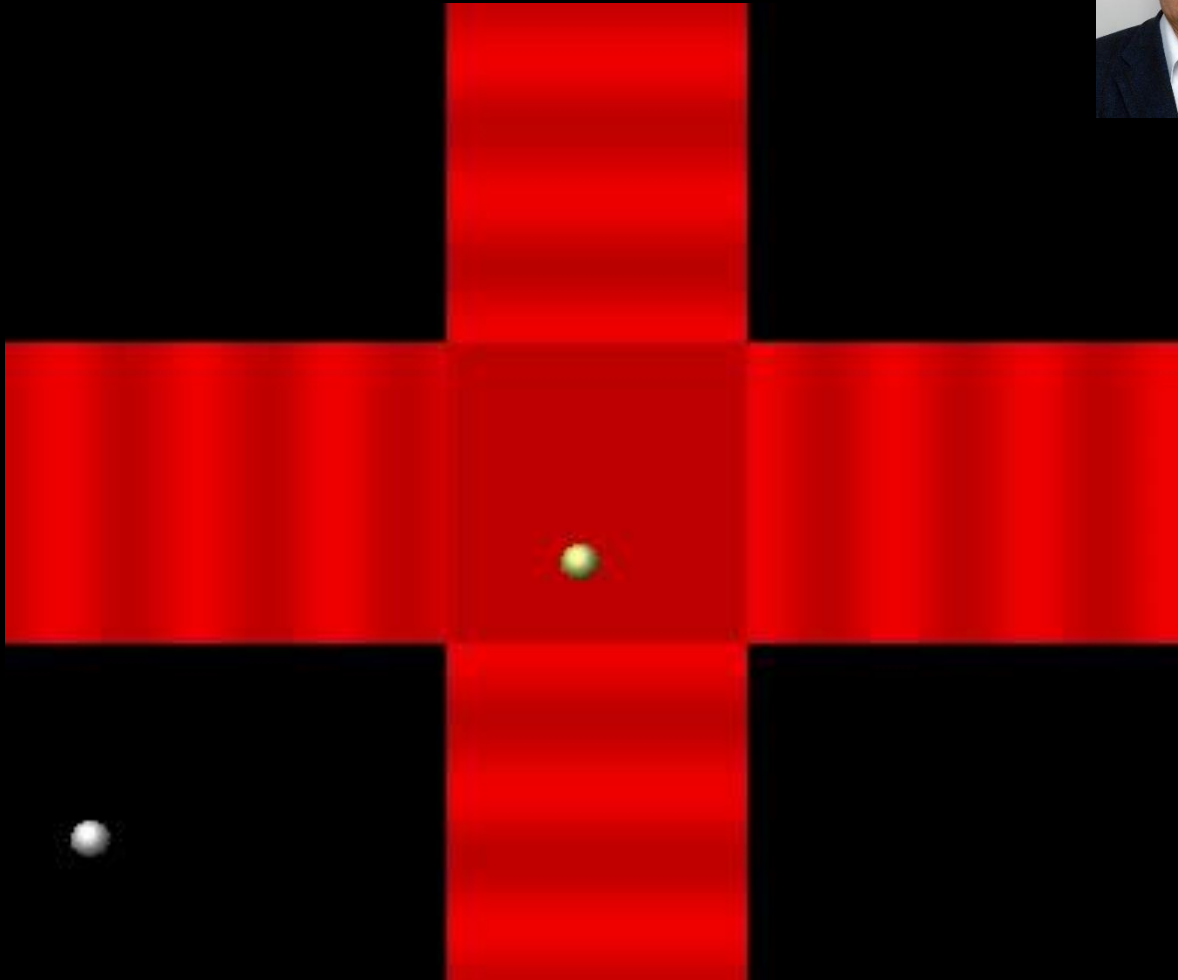
forza di attrito viscoso
(melassa ottica)



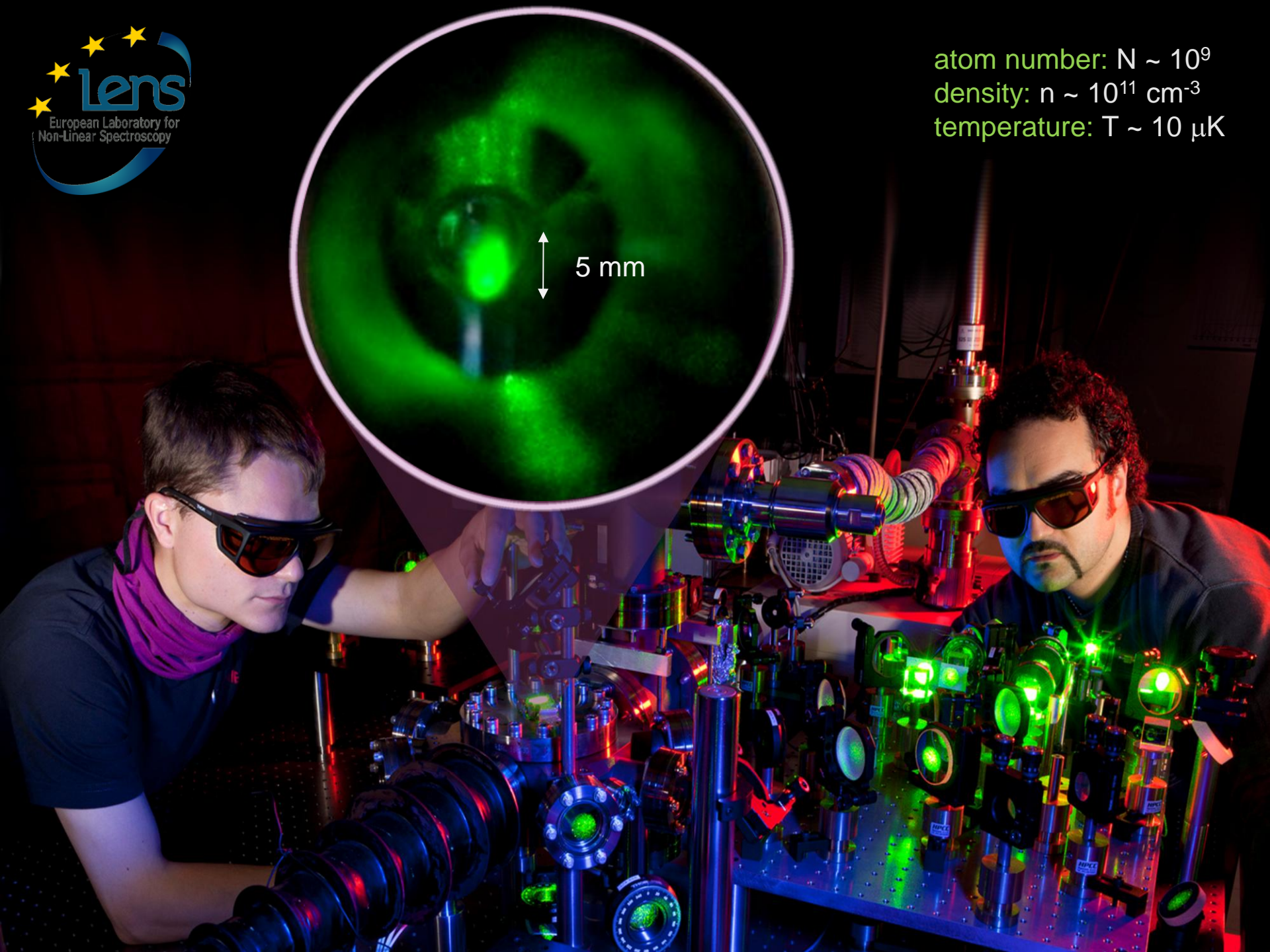
raffreddamento

Raffreddamento Doppler

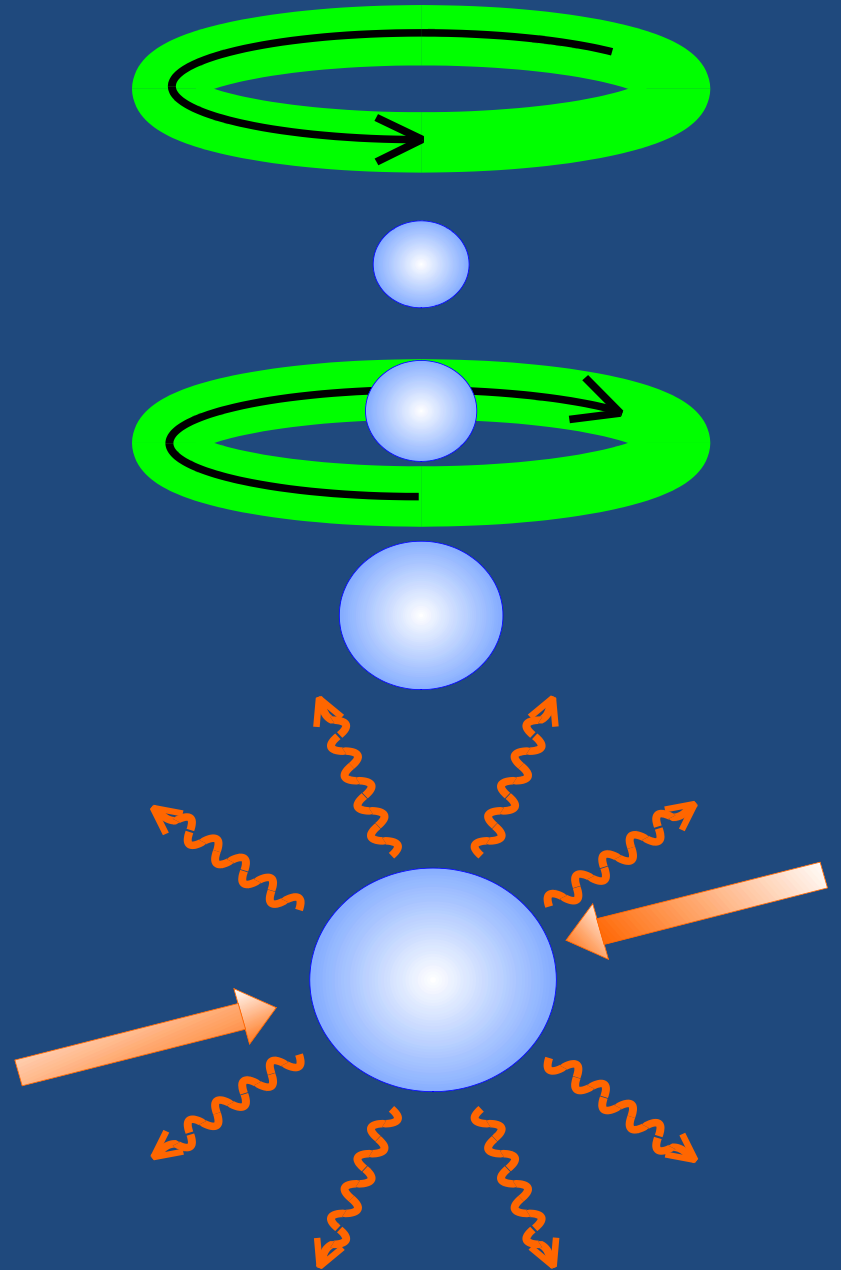
1974: T. W. Hansch & A. Shawlow (Nobel 2005 e 1981)



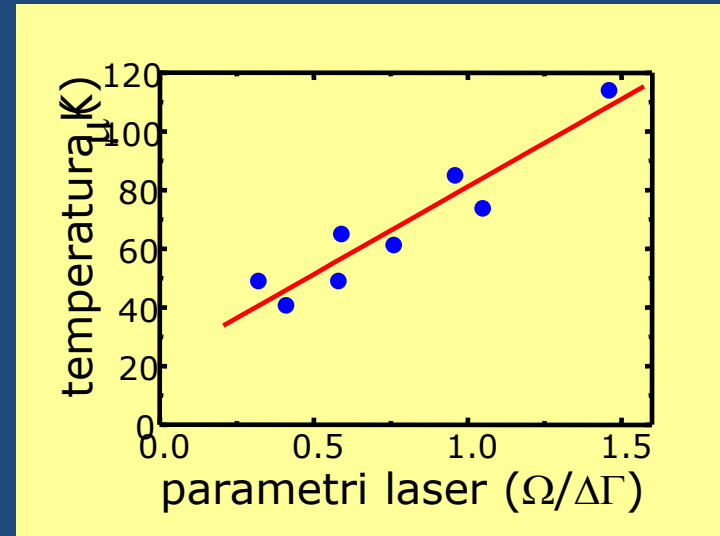
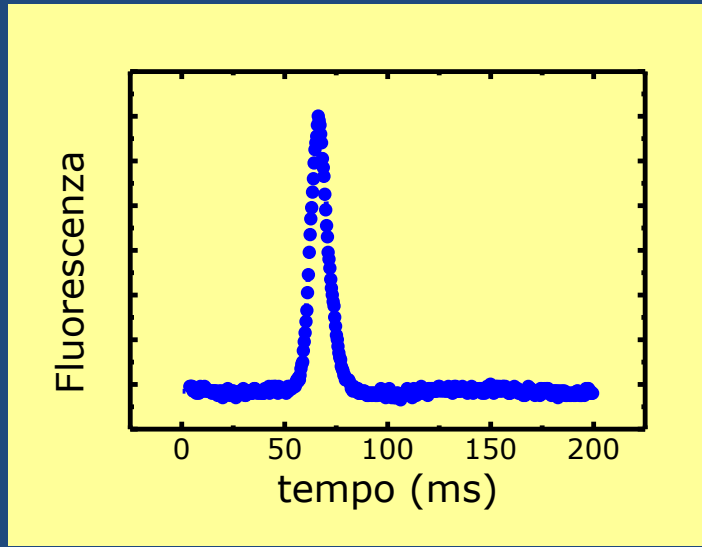
atom number: $N \sim 10^9$
density: $n \sim 10^{11} \text{ cm}^{-3}$
temperature: $T \sim 10 \text{ } \mu\text{K}$



$$s = s_0 + v_0 t + \frac{1}{2} g t^2$$



temperatura



$T=300\text{ K}$



$v \approx 100\text{ m/s}$

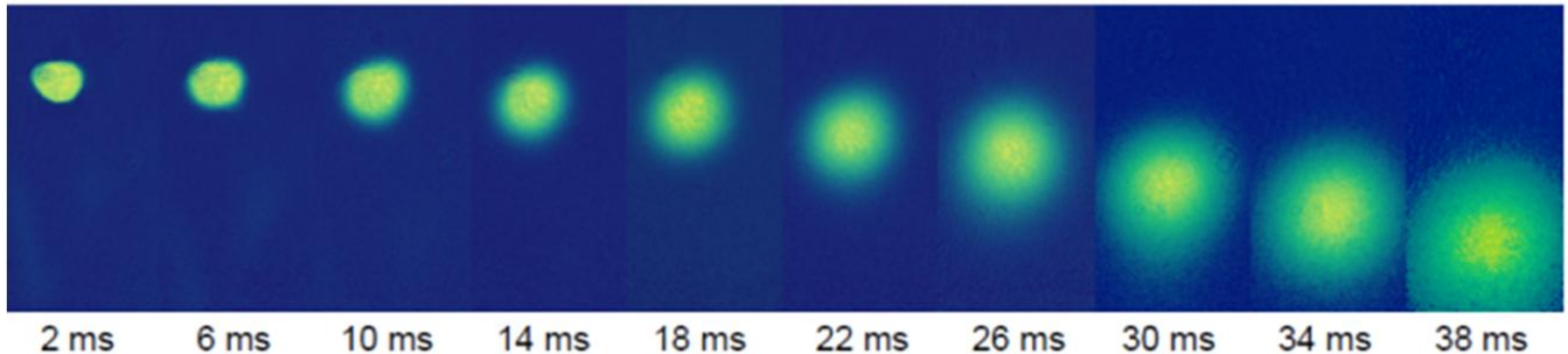
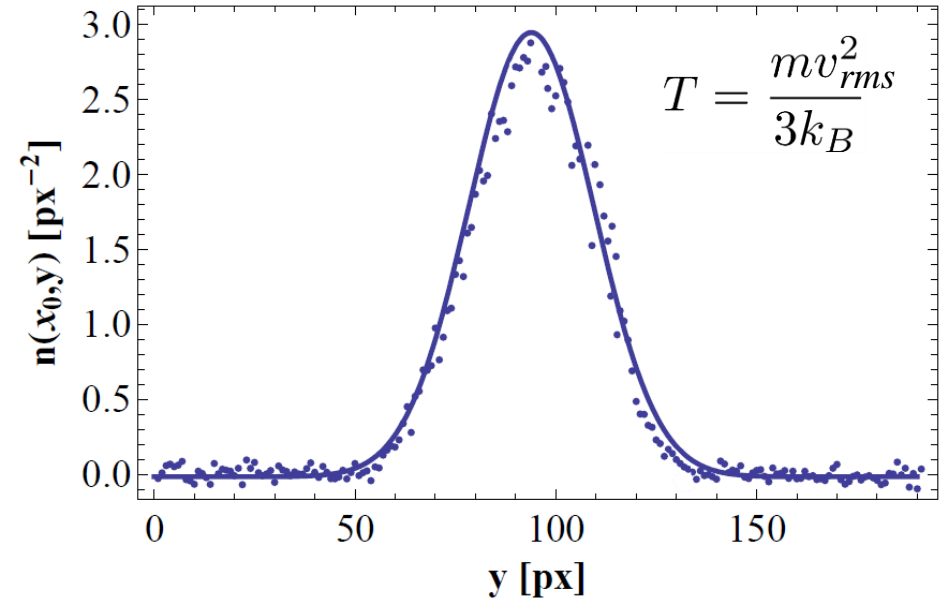
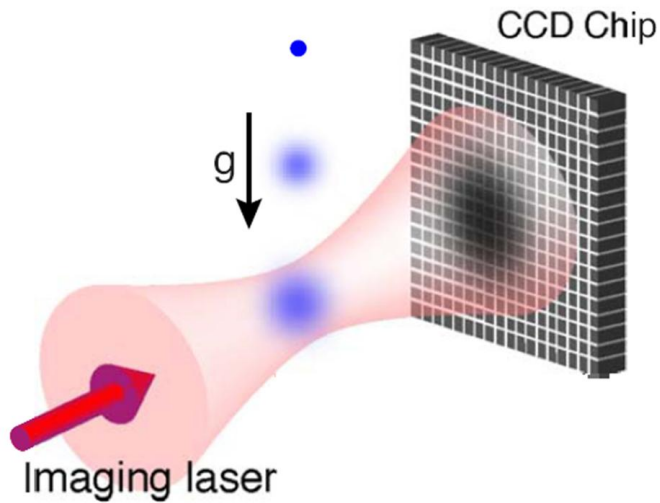
$T=1\text{ }\mu\text{K}$



$v \approx 1\text{ cm/s}$

Quale termometro per gli atomi?

Misura di temperatura in tempo di volo (time of flight, TOF)



Dalla teoria dei quanti alla condensazione di Bose–Einstein in un gas atomico diluito

Chiara Fort, Maurizio Artoni e Massimo Inguscio

Dipartimento di Fisica, INFN e Laboratorio Europeo di Spettroscopia Non Lineari (LENS), Università di Firenze, Italy

La teoria dei quanti, nata con Planck nel 1900, è stata di fondamentale importanza per la nascita della condensazione di Bose-Einstein. A distanza di un secolo la comunità scientifica guarda con grande interesse alla recente realizzazione di condensati di Bose-Einstein in gas atomici in quanto essa sta portando ad una importante verifica di diversi aspetti fondamentali della meccanica quantistica alcuni dei quali verranno qui analizzati e discussi.

1. Introduzione

Nel 1874, all'età di 16 anni, Planck cominciò i suoi studi all'Università di Monaco dove il suo relatore, durante una discussione sulle prospettive della ricerca, gli disse che la fisica era una scienza completa e con poco spazio per nuovi sviluppi. Nonostante questa desolante prospettiva, Planck decise ugualmente di studiare fisica...e per fortuna! Circa venti anni più tardi Planck pubblicò il suo famoso lavoro sull'interpretazione dello spettro del corpo nero introducendo per la prima volta il concetto “quanti di luce” [1], un lavoro che segnò la nascita della meccanica quantistica. Ed è proprio a tale interpretazione che dobbiamo

la prima proposta sulla possibile esistenza della condensazione di Bose-Einstein (BEC). Benchè la proposta di Einstein risalga ai primi anni del '900, è solo negli ultimi decenni che i fisici atomici, grazie ai continui progressi della fisica sperimentale, sono riusciti ad ottenere temperature via via più prossime allo zero assoluto necessarie per ottenere un condensato di Bose-Einstein in un gas diluito di atomi alcalini.

Alle temperature di qualche nanokelvin a cui si forma un condensato di Bose Einstein tutti gli atomi che lo compongono si trovano nello *stesso* stato quantico. Questo rende il condensato particolarmente adatto allo studio di aspetti fondamentali [2,3] della meccanica e della dinamica di un fluido quantistico. Nel seguito discuteremo in particolare aspetti legati alla coerenza ed alla superfluidità di un condensato, sottolineando peraltro il ruolo cruciale giocato dalla meccanica quantistica nel lungo cammino verso la realizzazione del primo condensato di Bose-Einstein in un gas atomico.

2. La nascita della BEC e la teoria dei quanti

La costante di Planck

h

$$6.626\,069\,57(29) \times 10^{-34} \text{ J/s}$$



C. Fort, M. Artoni, M. Inguscio

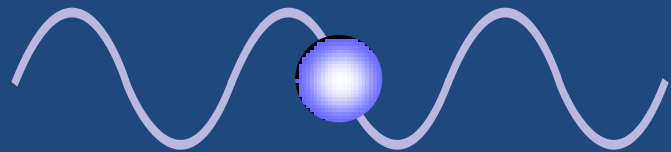
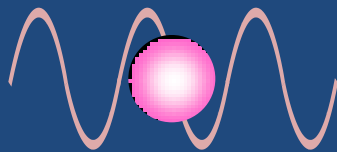
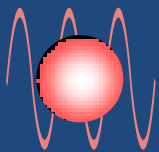
Dalla teoria dei quanti alla condensazione di Bose-Einstein in un gas atomico diluito

Quaderni di Storia della Fisica **9**, 57 (2001)

Gli atomi si comportano come onde

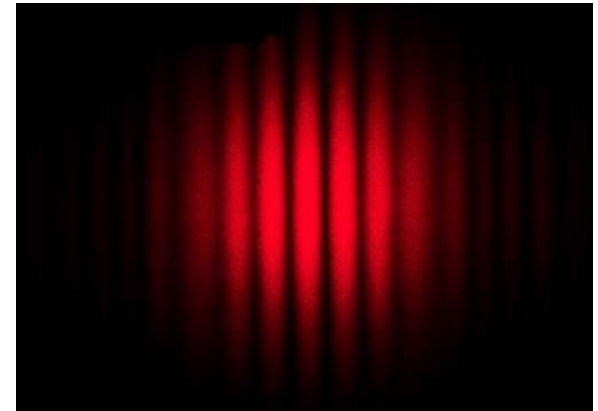
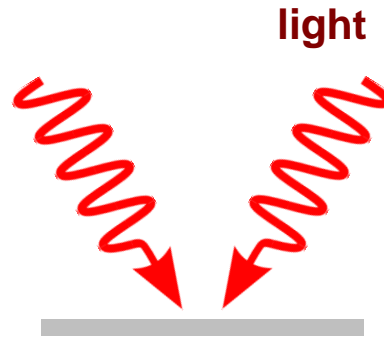
lunghezza d'onda di *de Broglie*

$$\lambda_{dB} = \frac{h}{mv}$$



Interferometri atomici

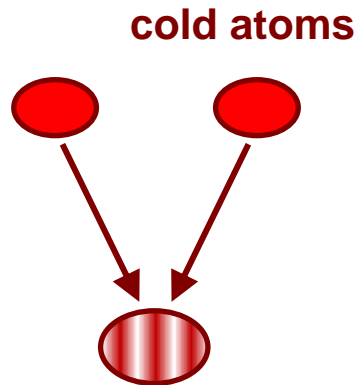
Interference of light:



two laser beams
(coherent waves of light)

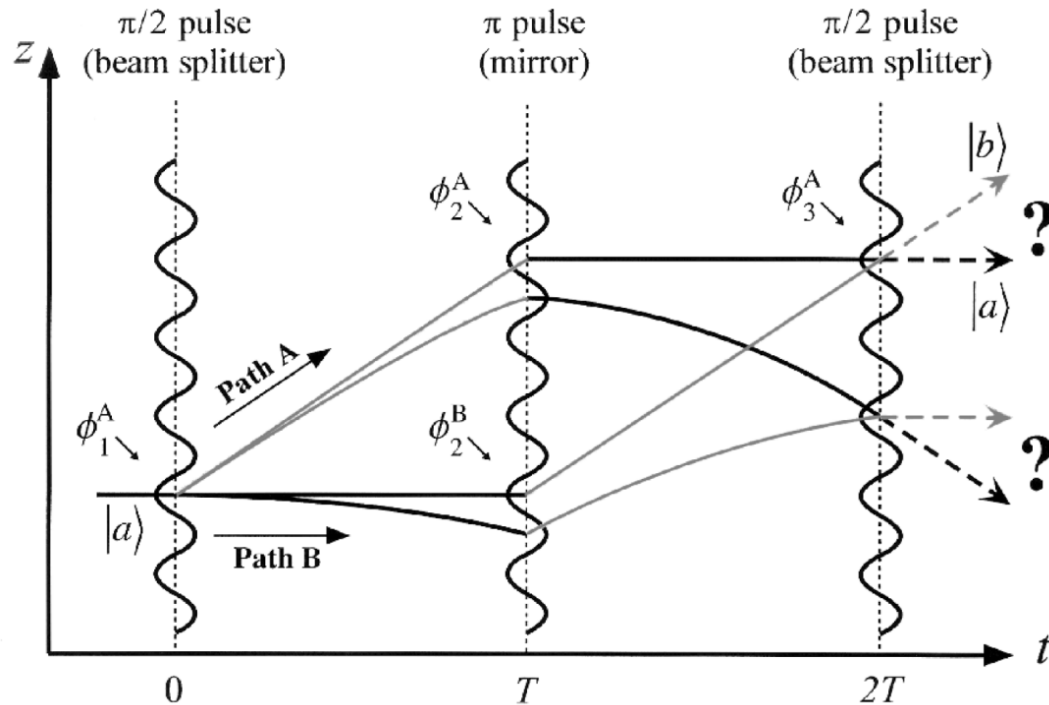
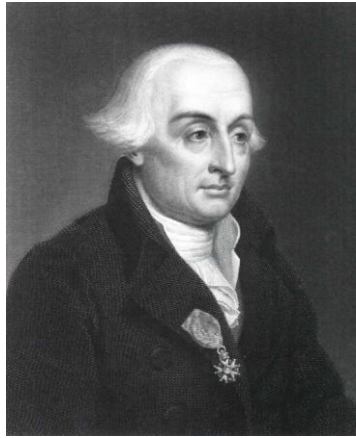
Interference of matter waves:

$$\lambda_{dB} = \frac{2\pi}{k_{dB}} = \frac{h}{p}$$



two Bose-Einstein condensates
(coherent atom waves)

The Lagrange operator in atom interferometry



Phase shift between two different atom trajectories:

$$\Delta\phi_{path} = (S_B - S_A)/\hbar$$

$$S_{A,B} = \int_0^{2T} L[\dot{z}_{A,B}(t), z_{A,B}(t)] dt$$

MISURA DELLA

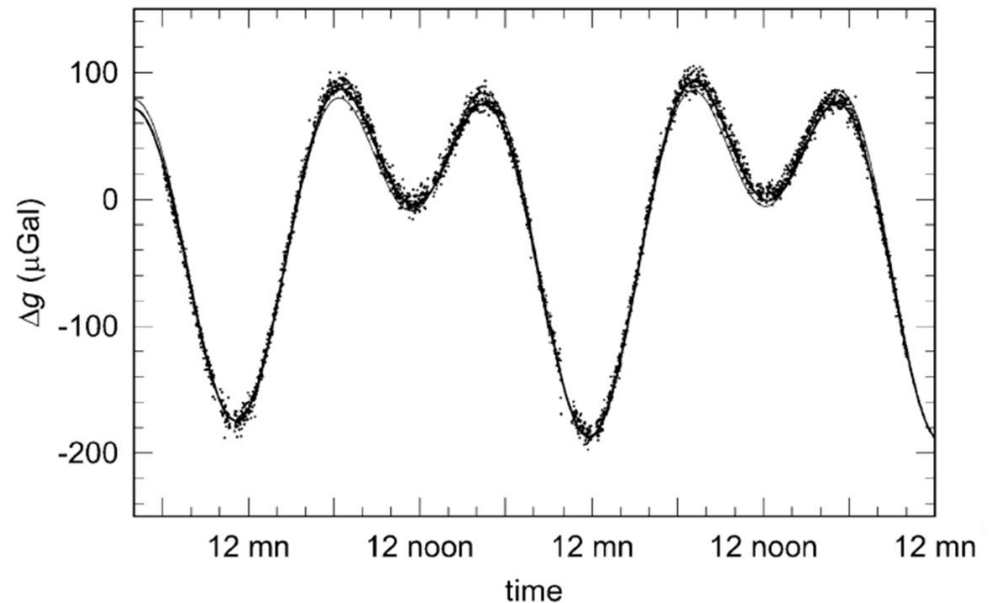
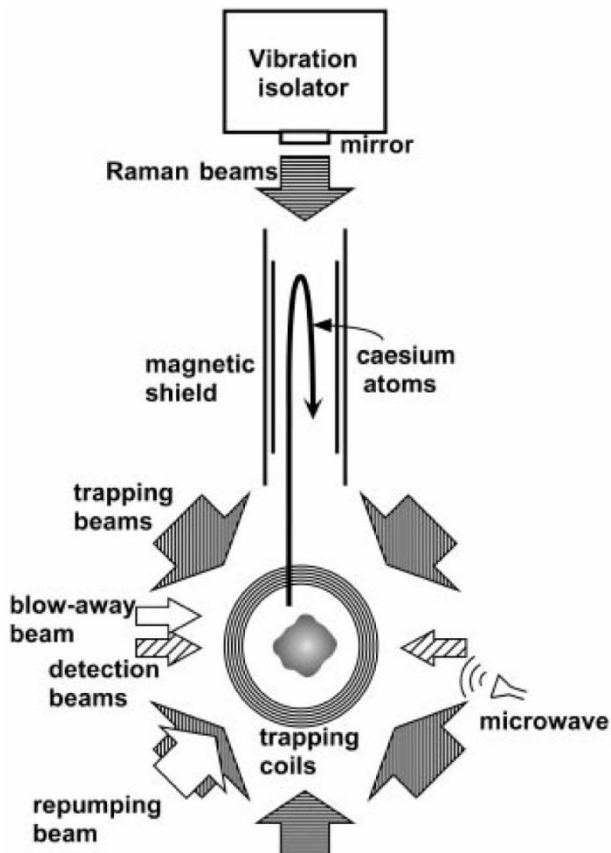
GRAVITA'

Atom interferometry

e.g. measurement of gravity (but also rotations, fundamental constants, ...)

atomic fountains:

$$\phi \dot{A} = 2k_L g T^2$$

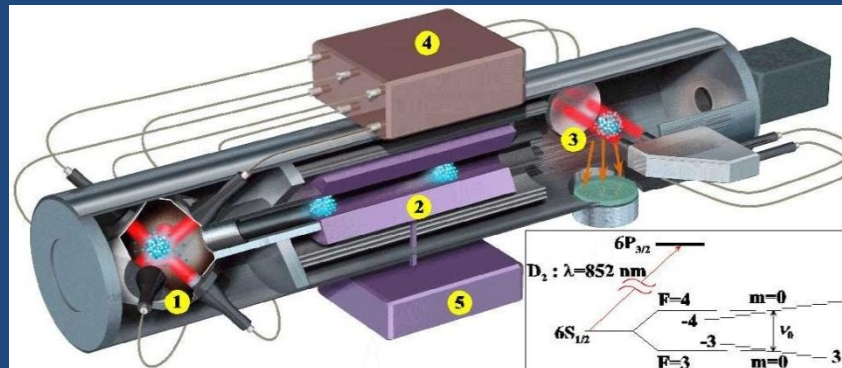
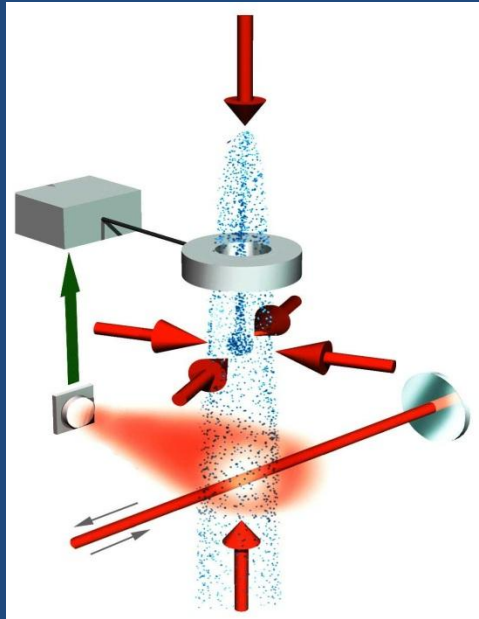


10^{-9} precision on g

A. Peters et al., Nature 400, 849 (1999).

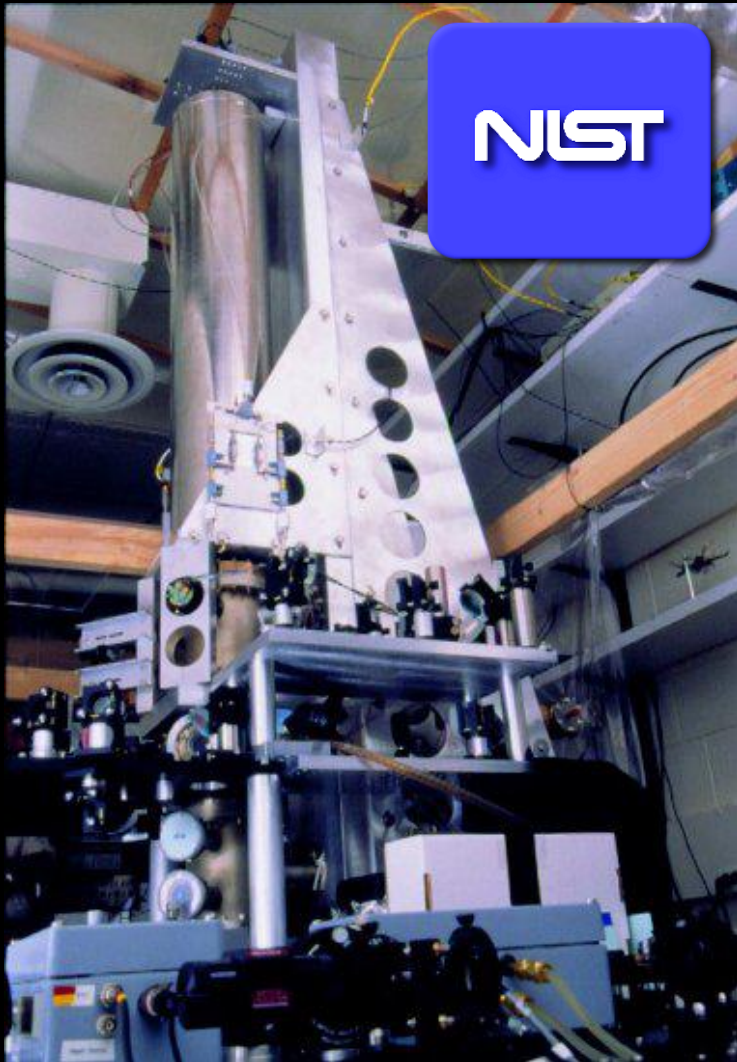
Atomi per misurare il tempo

Fontane atomiche



Orologi atomici criogenici

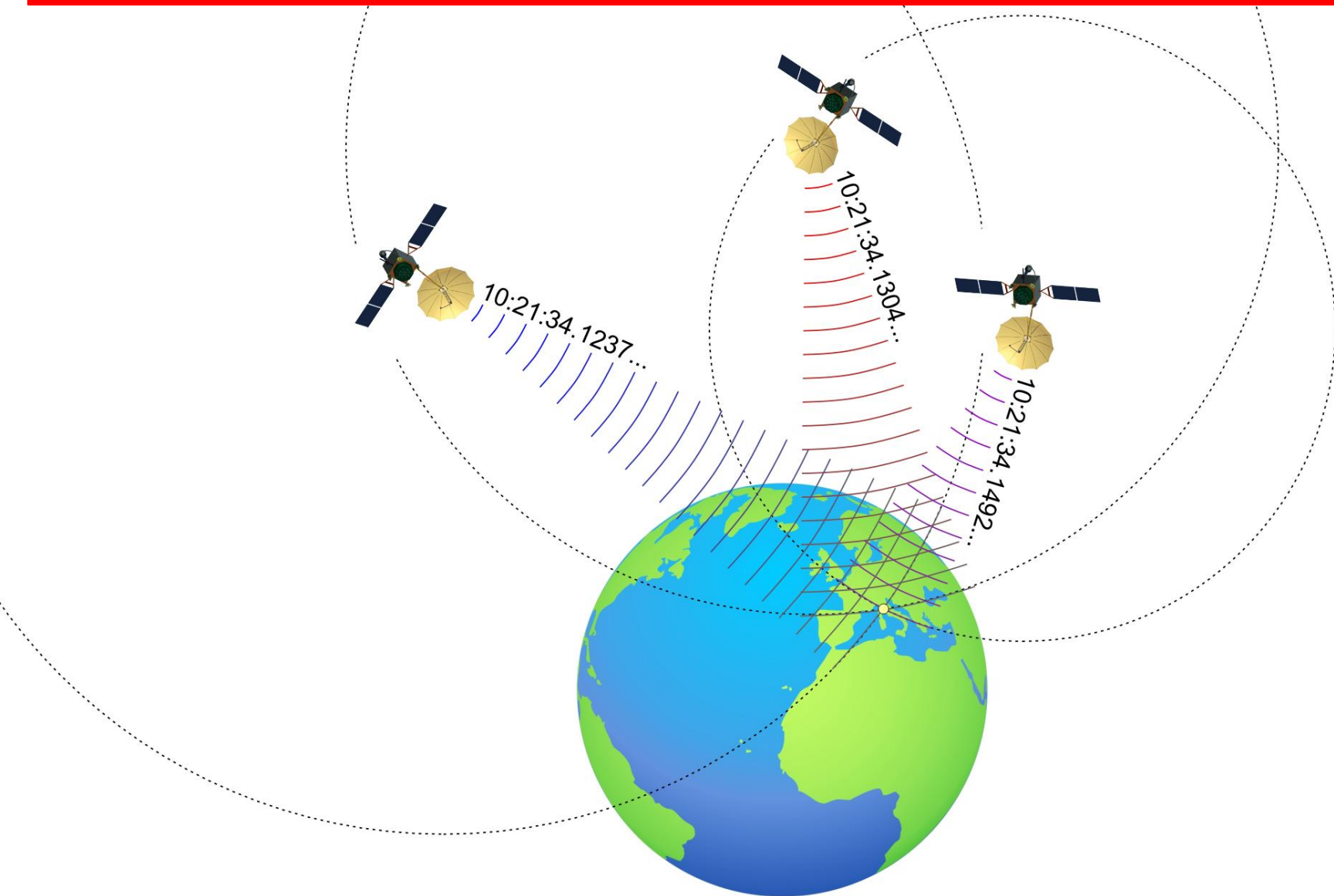
NIST-F2



ITCsF2

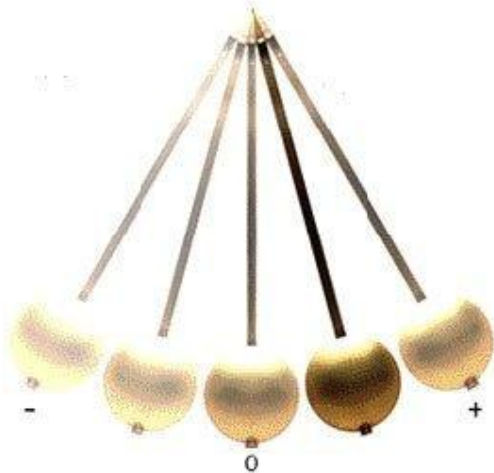


GPS Global Positioning System



Orologi più precisi → Posizionamento più accurato

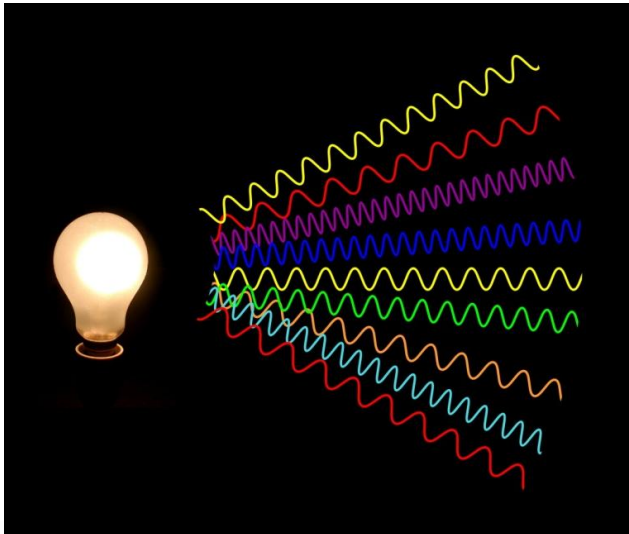
Misure di frequenza



Pendolo meccanico

$$\nu \approx 1 \text{ Hz}$$

(1 oscillazione al secondo)

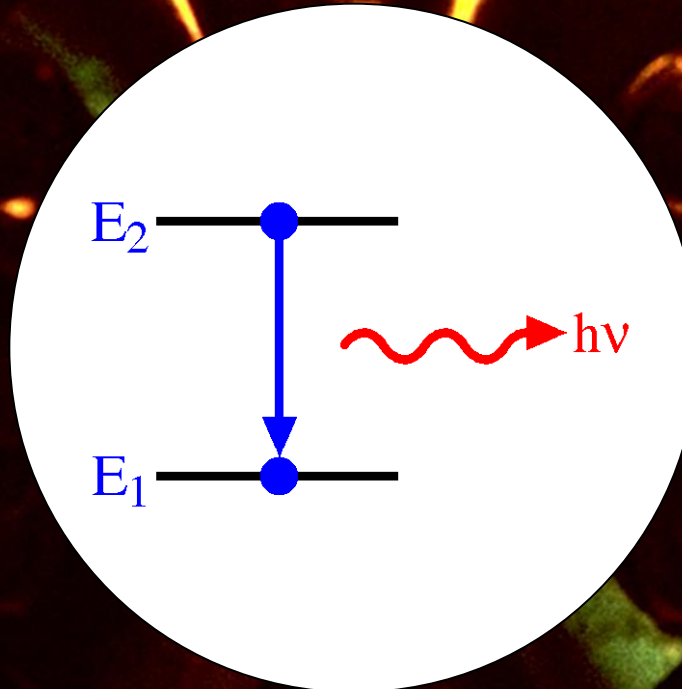


Onda elettromagnetica

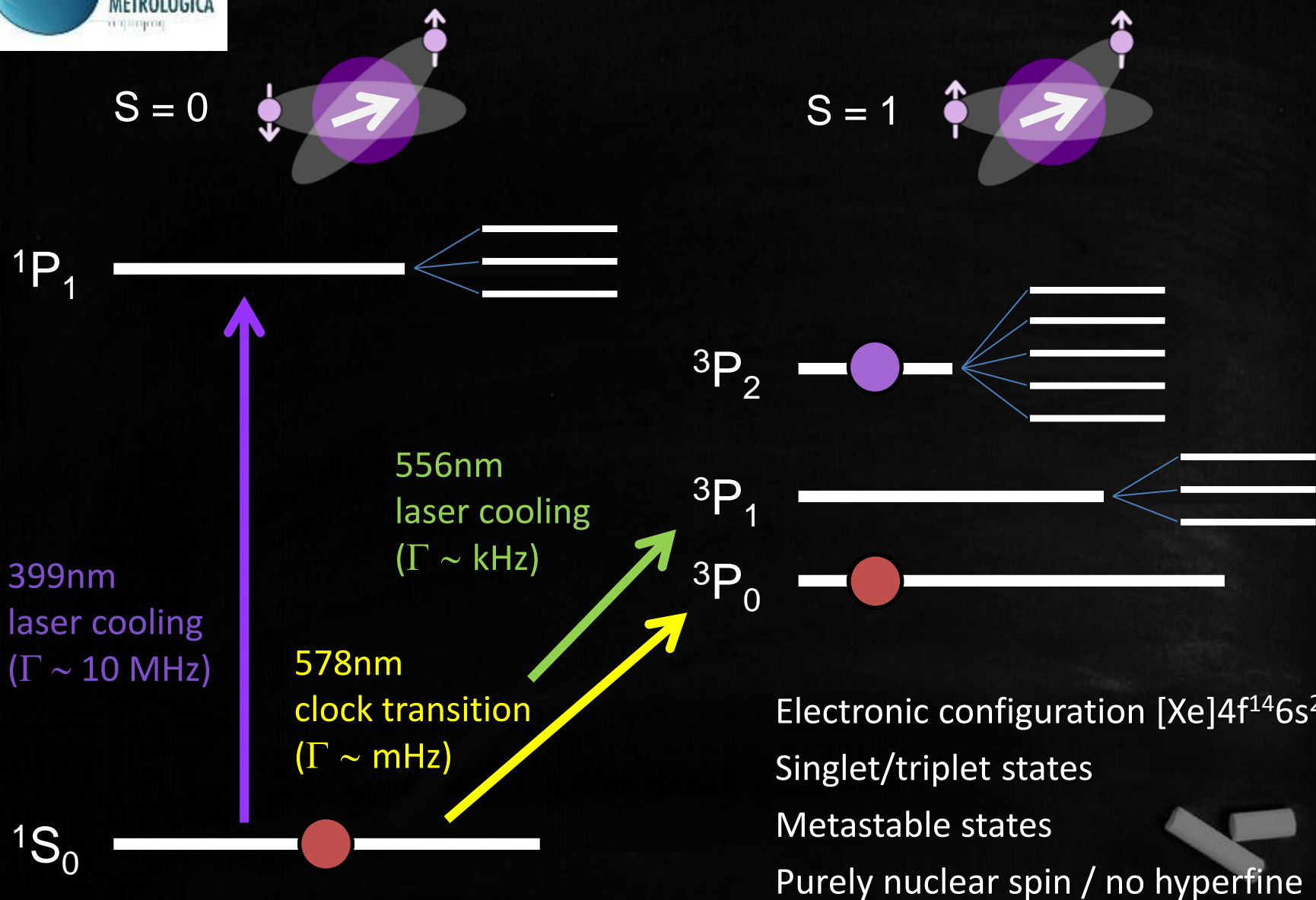
$$\nu \approx 10^{15} \text{ Hz}$$

(1.000.000.000.000.000 oscillazioni al secondo)

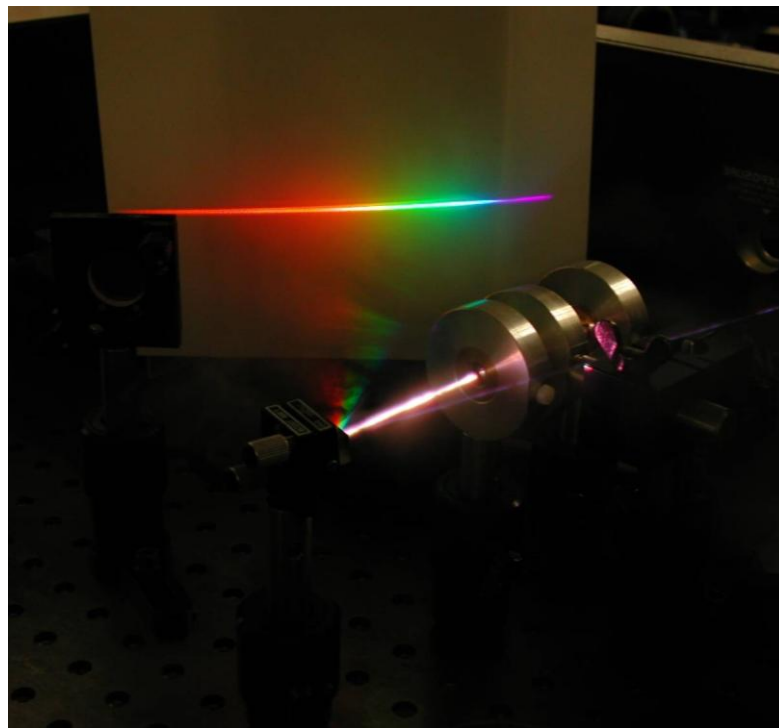
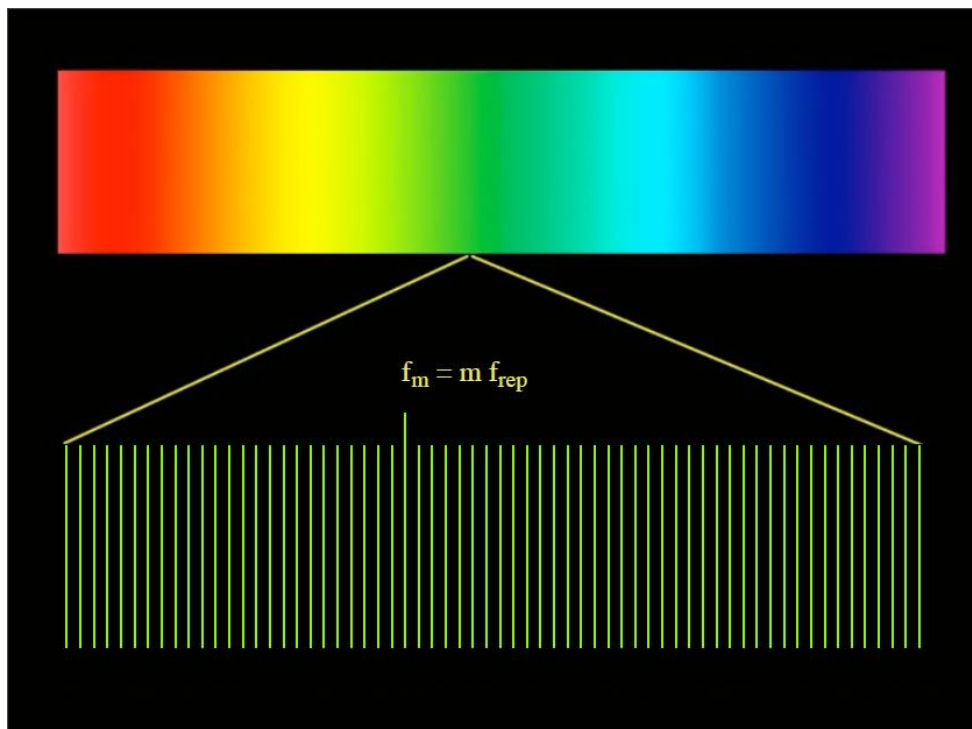
Battere il tempo con gli atomi



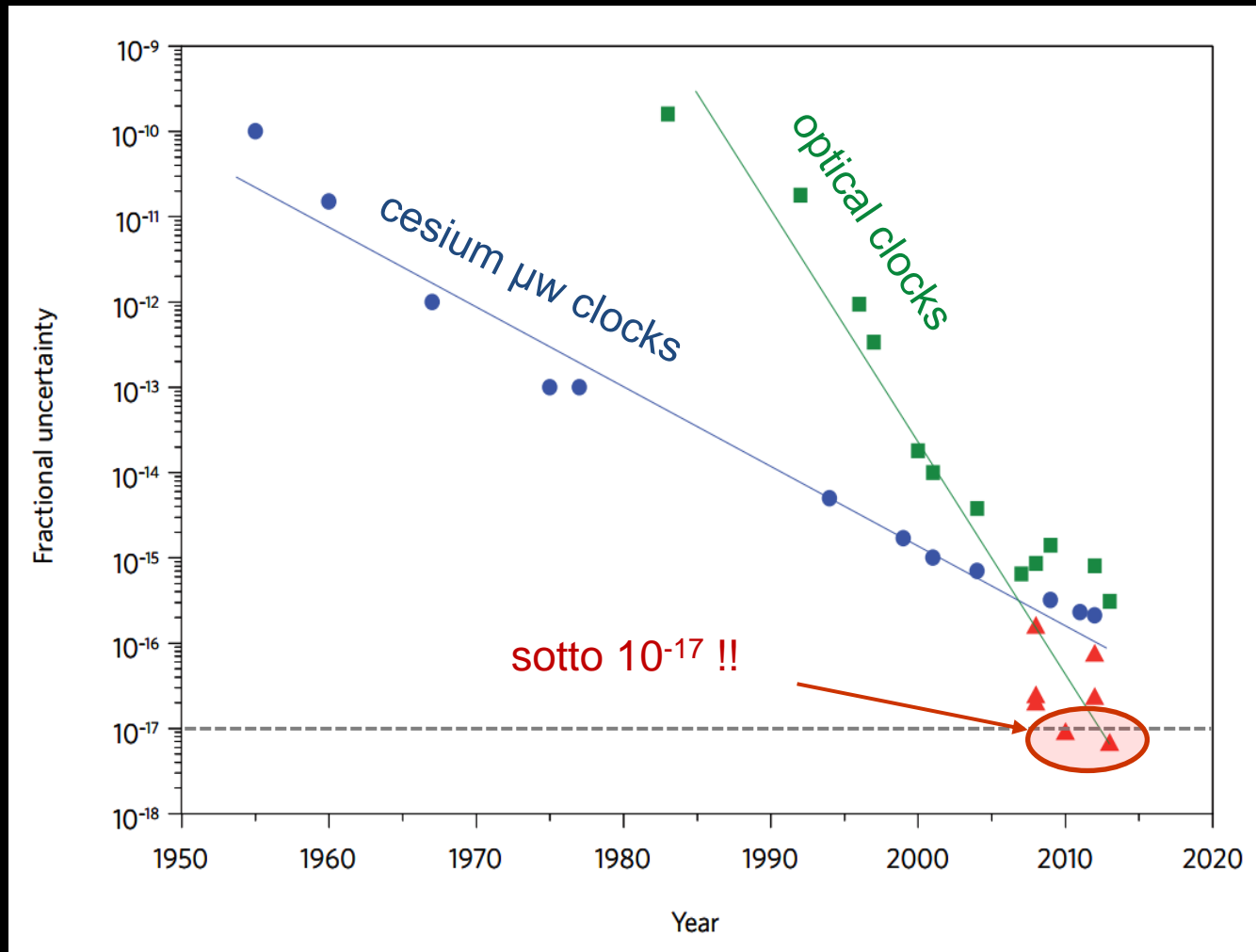
518 295 836 590 863 osc. / secondo



Un pettine di luce



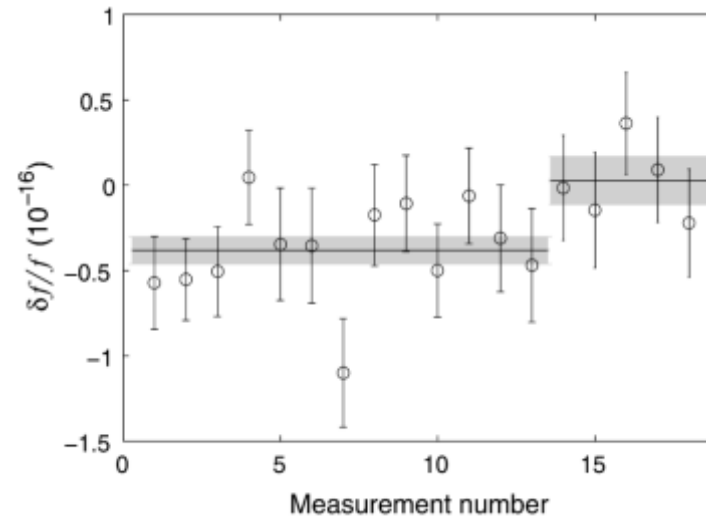
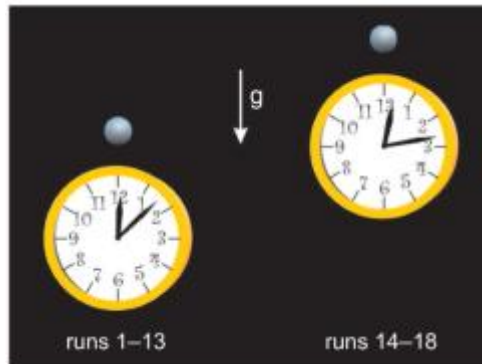
Incertezza relativa degli orologi atomici:



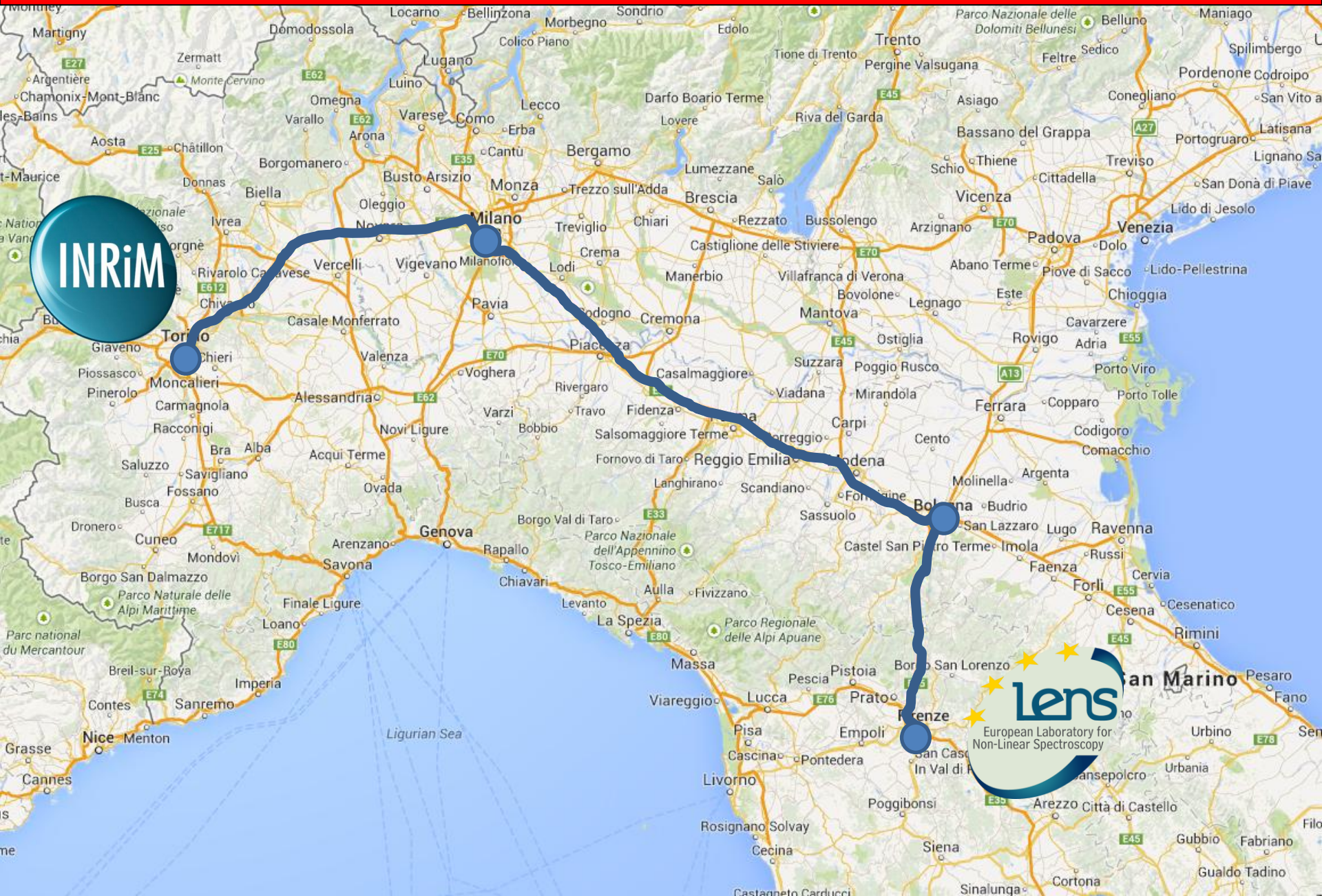
GPS Global Positioning System

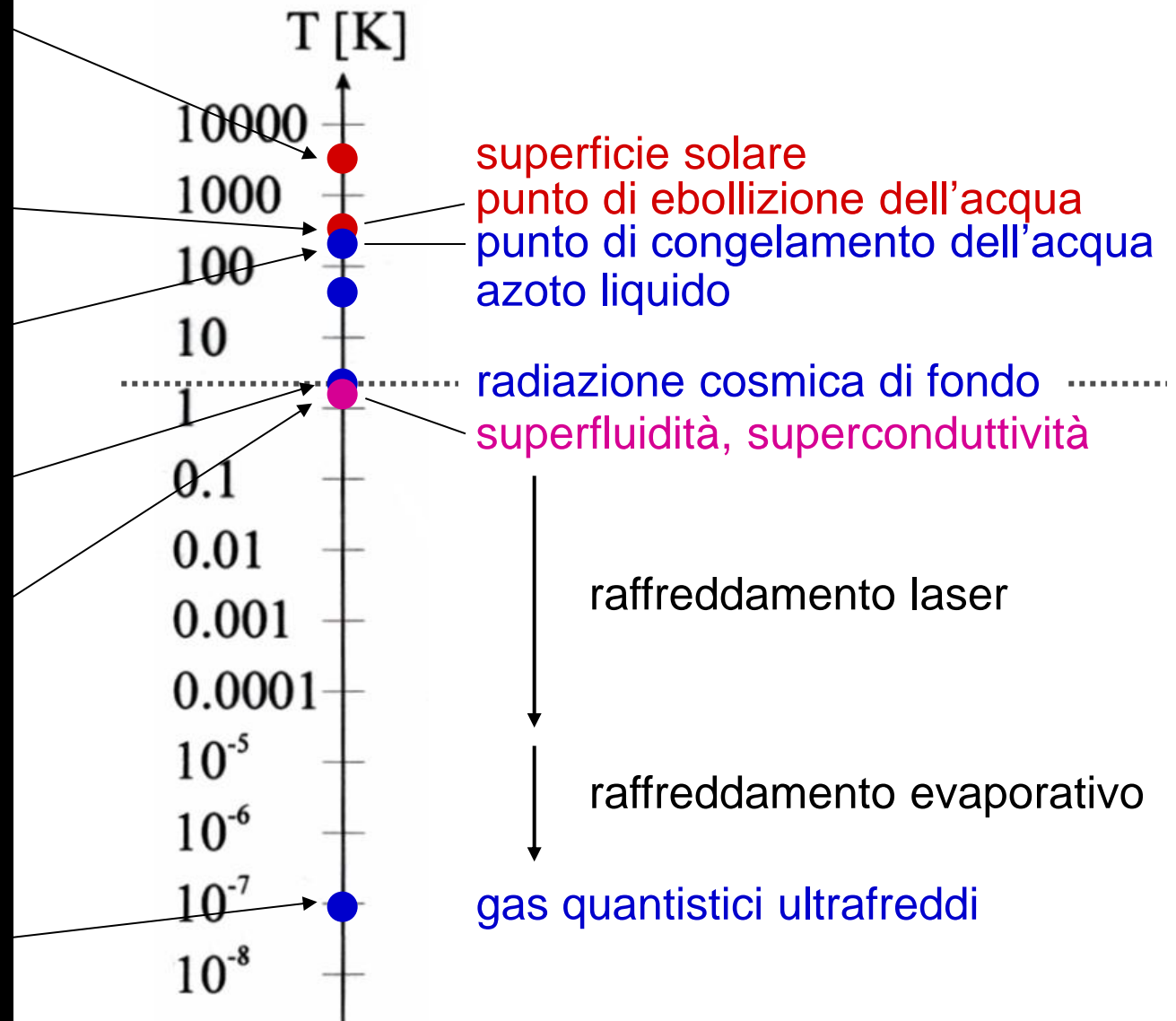
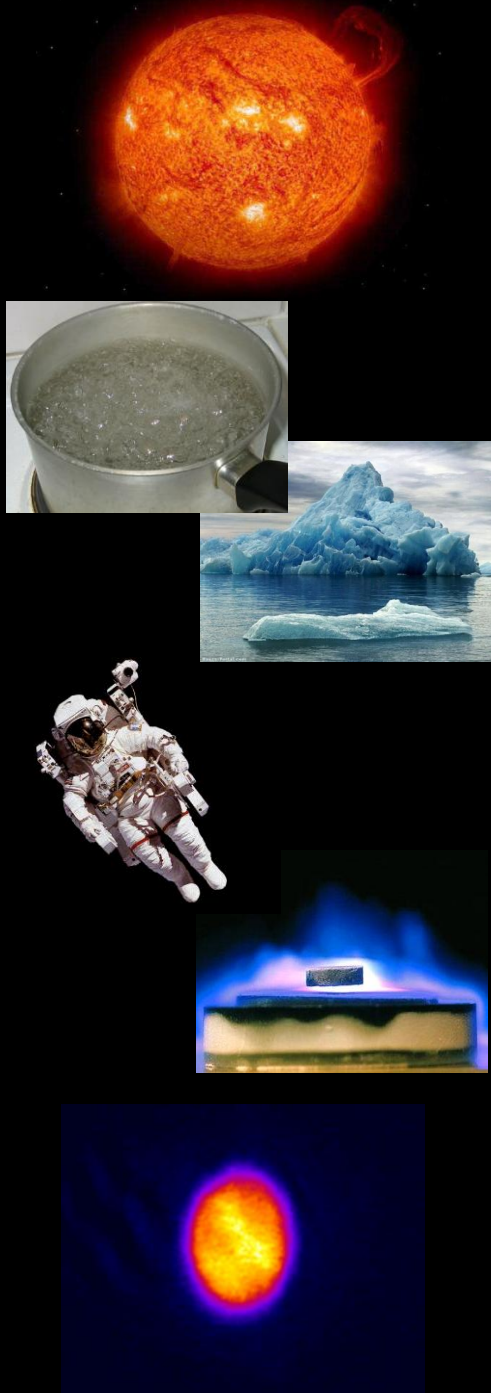


Observation of gravitational redshift atomic clocks displaced by 17cm



Optical fiber link





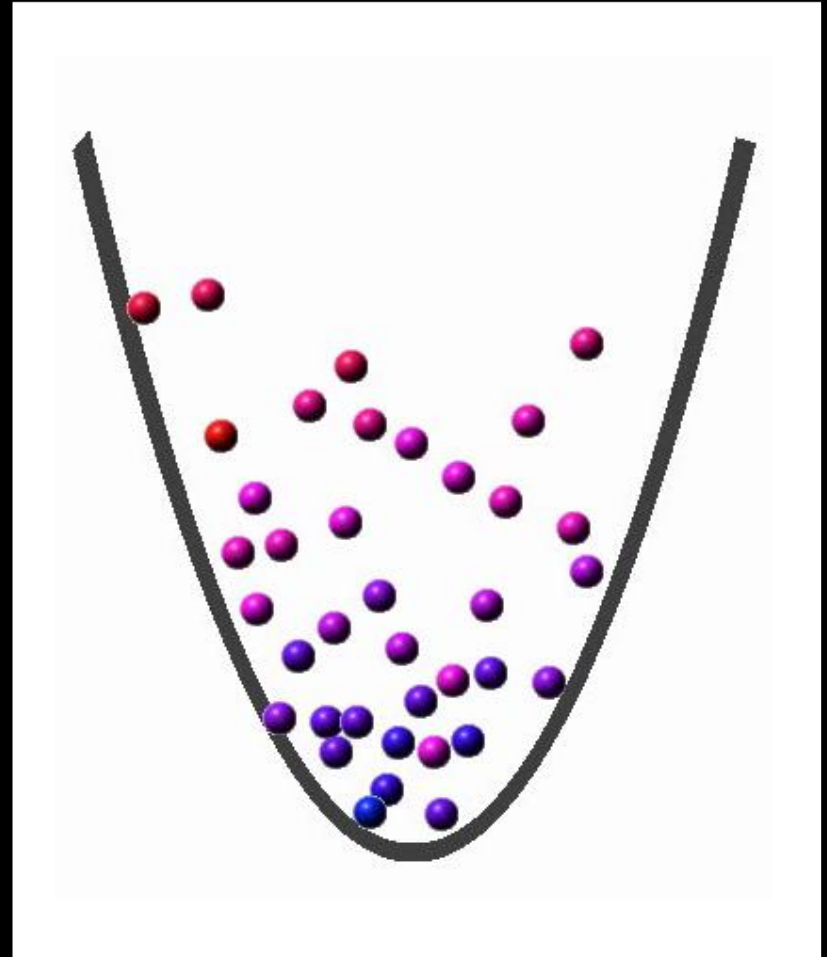
Raffreddamento evaporativo



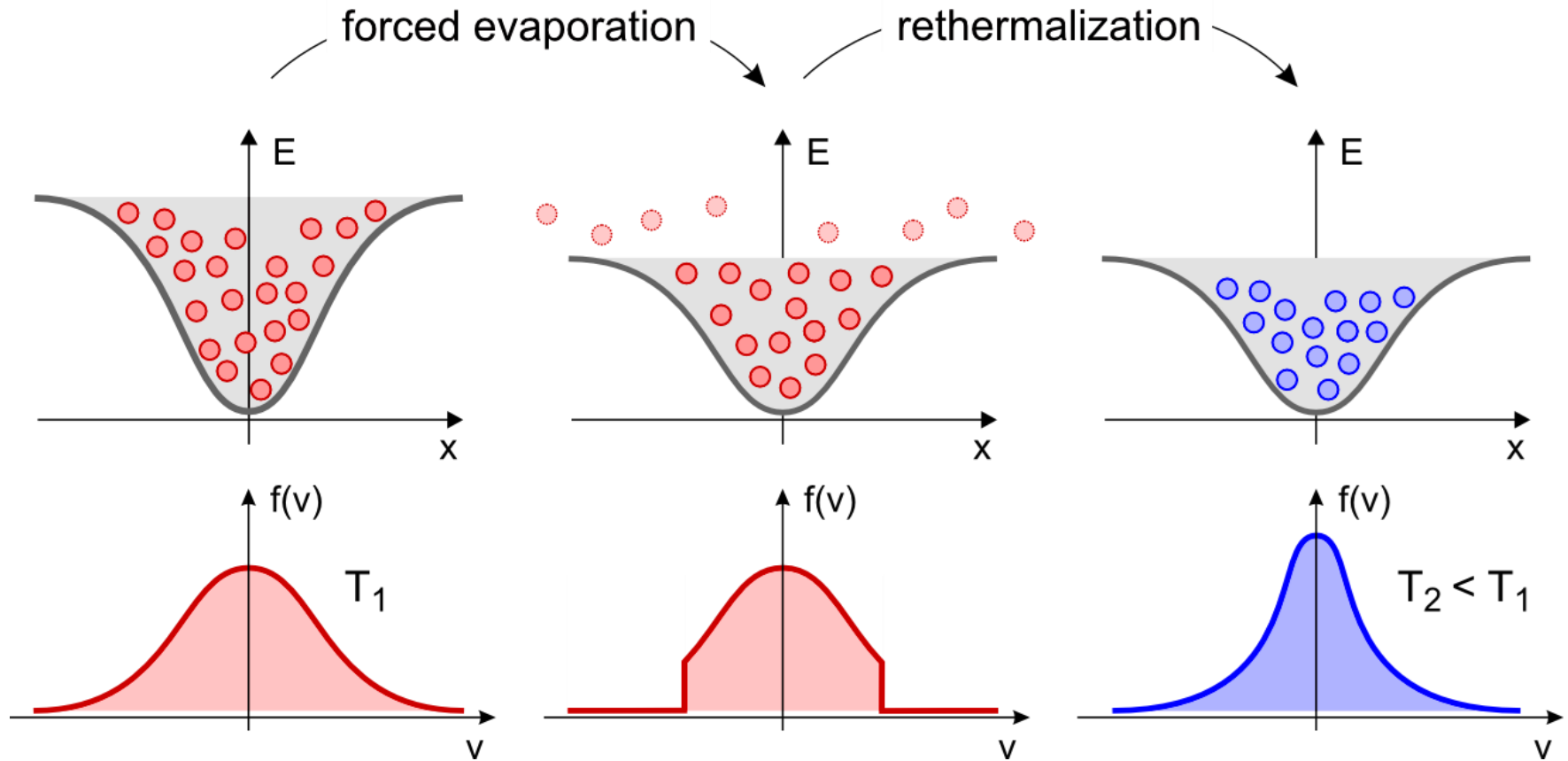
"evaporazione" degli atomi più caldi
+
collisioni fra gli atomi rimanenti



raffreddamento



Raffreddamento evaporativo



Atomi come onde

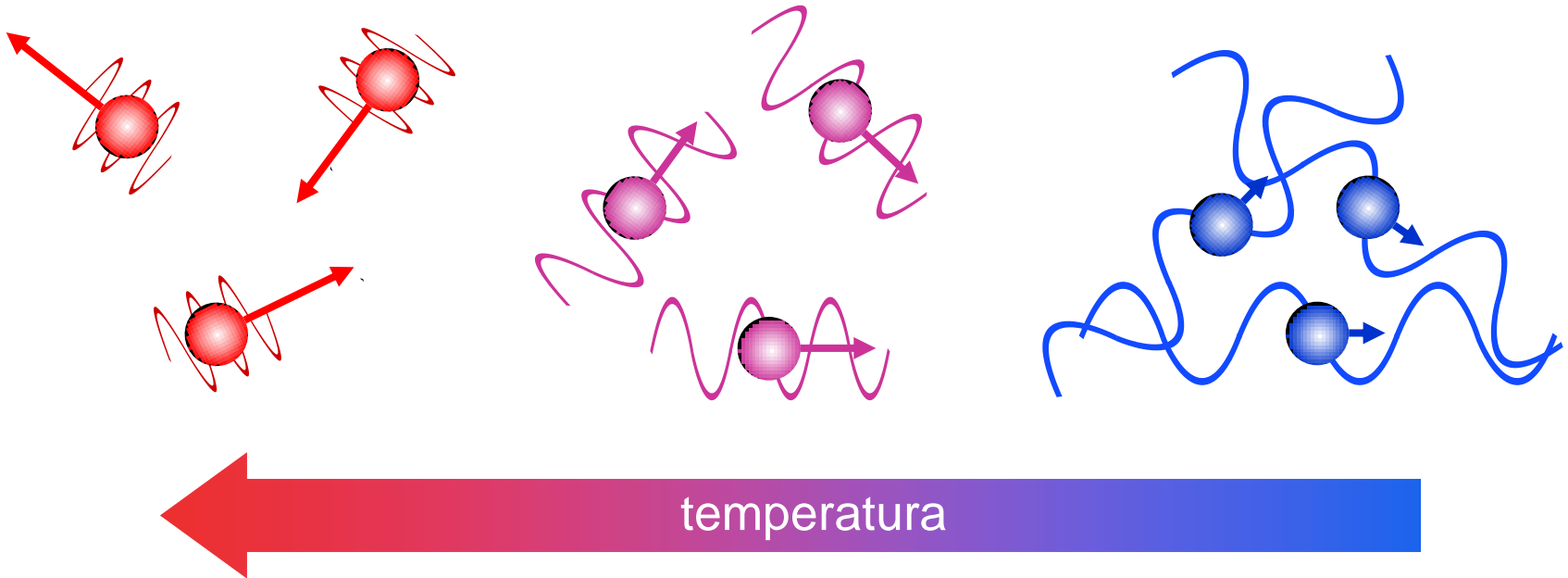
...anche gli atomi si comportano come onde!



1924: Luis De Broglie – dualismo onda-particella (Nobel 1929)

lunghezza d'onda di *de Broglie*

$$\lambda_{\text{dB}} = \frac{h}{mv}$$



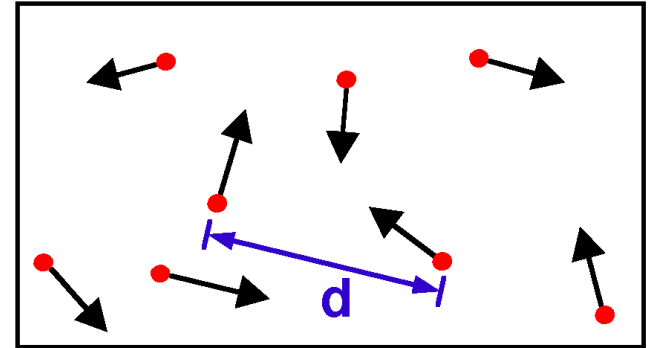
Costante di Planck: $h = 2\pi \times \hbar = 6.626\,069\,57(29) \times 10^{-34} \text{ J/s}$

Condensazione di Bose-Einstein



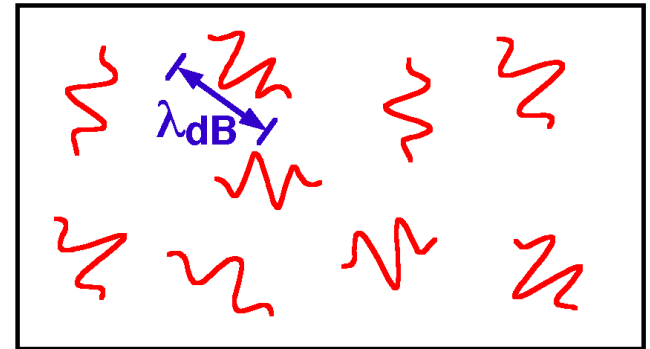
Alta Temperatura

“palle da biliardo”
meccanica statistica classica

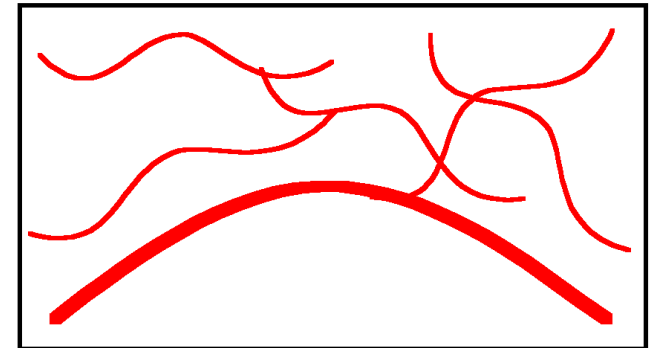


Bassa Temperatura

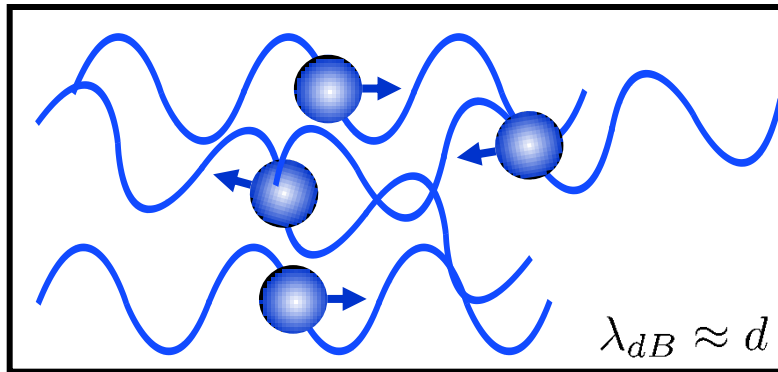
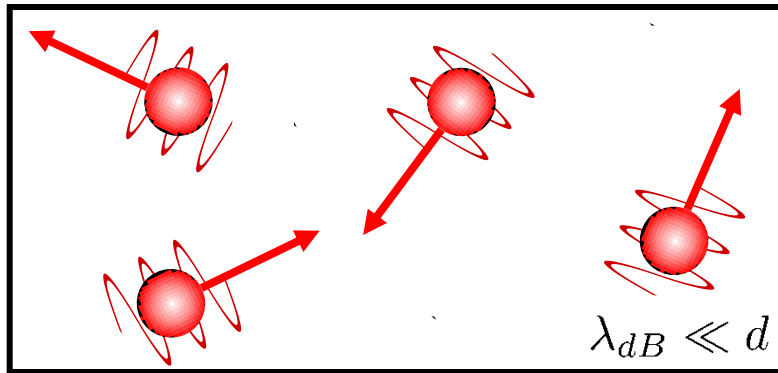
“pacchetti d'onda”
meccanica statistica quantistica



Condensazione di Bose-Einstein

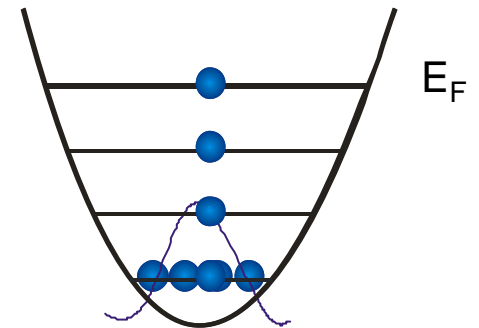


Gas quantistici



Bosoni

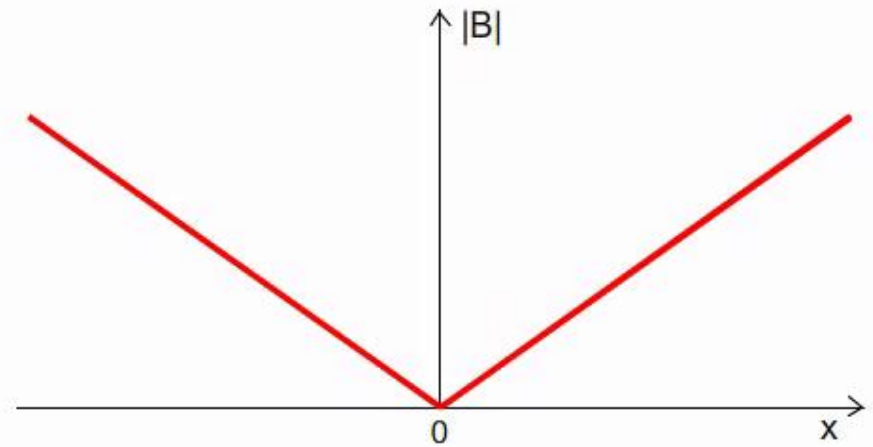
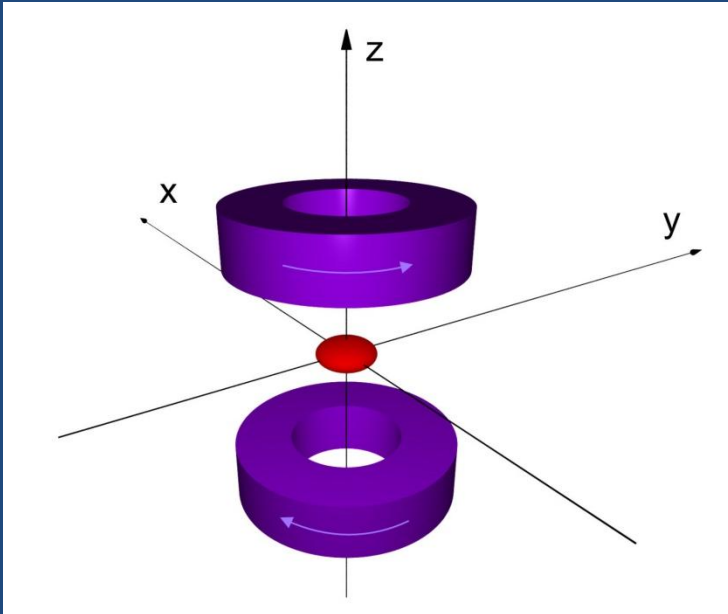
$$T < T_{CF}$$



Majorana spin-flip

Trappola di quadrupolo

- ✗ magnetic field = 0
- ✗ spin flips





Ettore Majorana
(1906-1938?)

ATOMI ORIENTATI IN CAMPO MAGNETICO VARIABILE

Nota di ETTORE MAJORANA

Sunto. - *L'autore calcola la probabilità che abbiano luogo processi non adiabatici quando un raggio di vapore orientato passa in prossimità di un punto in cui il campo magnetico si annulla.*

Un atomo orientato in un campo magnetico lentamente variabile segue, come è noto, adiabaticamente la direzione, supposta variabile, del campo. A ciò si deve il fatto recentemente posto in evidenza che sottoponendo un raggio molecolare proveniente da una esperienza di STERN e GERLACH a una seconda esperienza di STERN e GERLACH non si ottiene una nuova divisione del raggio, perchè tutti gli atomi hanno la stessa orientazione, avendo seguito esattamente il campo vagante, difficilmente eliminabile, nel tratto compreso fra le espansioni polari destinate a produrre il raggio orientato e quelle che devono saggiarne l'orientazione dopo un certo percorso. Tuttavia PHIPPS ha intrapreso delle esperienze per rivelare una variazione non adiabatica del campo in detta regione; la condizione a ciò necessaria è che il campo sia sufficientemente debole e la variazione della sua direzione sufficientemente rapida perchè la sua frequenza di rotazione divenga comparabile con la frequenza di Larmor. Poichè è difficile abbassare l'intensità del campo al disotto di alcuni gauss ⁽¹⁾, è necessario, per una velocità del raggio di 10^5 cm./sec. che la direzione del campo, vari di molto entro una frazione di millimetro; si tratta quindi di esperienze delicate che non hanno dato finora esito conclusivo.

Il problema è stato trattato teoricamente da GÜTTINGER ⁽²⁾ per il caso di un campo rotante uniformemente e di intensità costante. In questa nota supporremo invece che il raggio molecolare passi in prossimità di un punto in cui il campo magnetico si annulli; questo caso è particolarmente importante perchè se il raggio passasse esattamente

⁽¹⁾ T. E. PHIPPS e O. STERN, « ZS. f. Ph. », **73**, 185, 1932.

⁽²⁾ P. GÜTTINGER, « ZS. f. Ph. », **73**, 169, 1932.

- Estimates of lifetime for falling through the hole at $B' = 250 \text{ G/cm}$, $T = 250 \text{ mK}$, range for 20 to 2000 seconds.

All we really know is that it scales $\left(\frac{B'}{T}\right)^2$. Anyway, we can get a handle on this?

Maybe it currently is $\tau = 400 \text{ sec}$, so we don't notice, but if we cool a factor of 3 it will be $\tau = 44 \text{ sec}$, a big problem.

Merc

~~The~~ seeing a short term loss of atoms equal to about 30% of number loaded. Takes about 45-90 seconds to lose them. ~~the~~ After that, lifetime is 300 seconds or so.

When we load atoms very ~~hot~~ (by not doing molasses) we do not see the short term loss!

This suggests they are falling ~~through~~ through

the hole!! (Or could be relative collisions between trapped atoms)

We also see at least some evidence for probe light shortening lifetime - maybe contributes at $\frac{1}{400 \text{ sec}}$ rate.

$$\langle U \rangle_+ = \mu_0 m_F g_F \langle |B| \rangle_+$$

$$= \frac{\mu_0 m_F g_F}{2\pi/\omega_{\text{at}}} \int_0^{2\pi/\omega_{\text{at}}} dt \left| B_{\text{quad}}(z\hat{z} - x\hat{x} - y\hat{y}) - B_{\text{at}}(\hat{x}\cos\omega_{\text{at}}t + \hat{y}\sin\omega_{\text{at}}t) \right|$$

$$\langle \nabla \rangle = \nabla \quad \rightarrow \quad r_{\text{hole}} = \frac{B_{\text{at}}}{B'_{\text{quad}}}$$

$$\langle U \rangle_+ \approx \mu_0 m_F g_F \left[B_{\text{at}} + \frac{B'^2_{\text{quad}}}{4B_{\text{at}}} (x^2 + y^2 + 8z^2) \right]$$

$$\text{for } x, y, z \leq r_{\text{hole}}$$

In our trap,

$$\frac{\omega_{\text{at}}}{2\pi} = 7.5 \text{ kHz}$$

$$B_{\text{at}} = 10 \text{ G}$$

$$B'_{\text{quad}} = 120 \text{ G/cm}$$

$$r_{\text{hole}} \approx 0.08 \text{ cm}$$

$$\nu_z = 67 \text{ Hz}$$

$$\nu_x \approx \nu_y = 24 \text{ Hz}$$

$$^{87}\text{Rb}$$

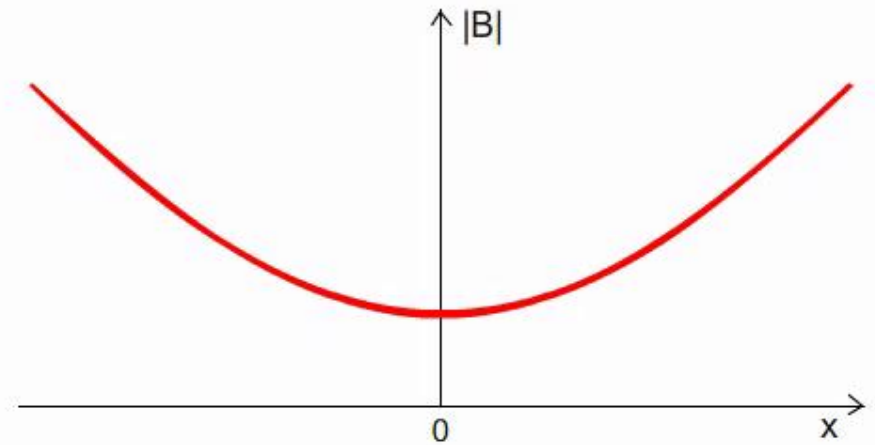
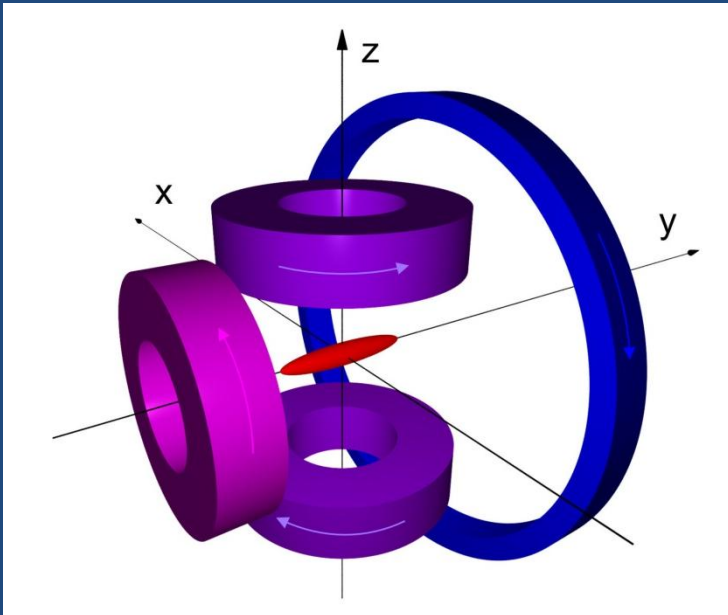
$$m = -1$$

$$g = \frac{1}{2}$$

Majorana spin-flip

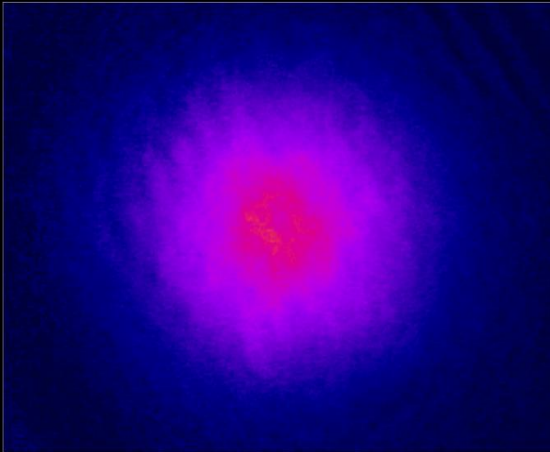
Ioffe-Pritchard trap

- ✓ magnetic field > 0
- ✓ no spin flips

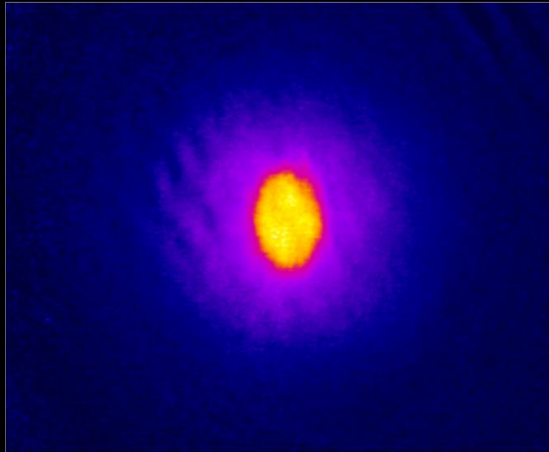


Condensazione di Bose-Einstein

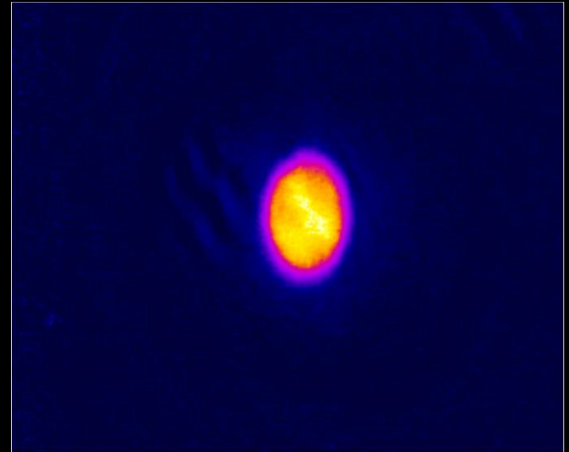
$T > T_c$



$T \sim T_c$



$T < T_c$

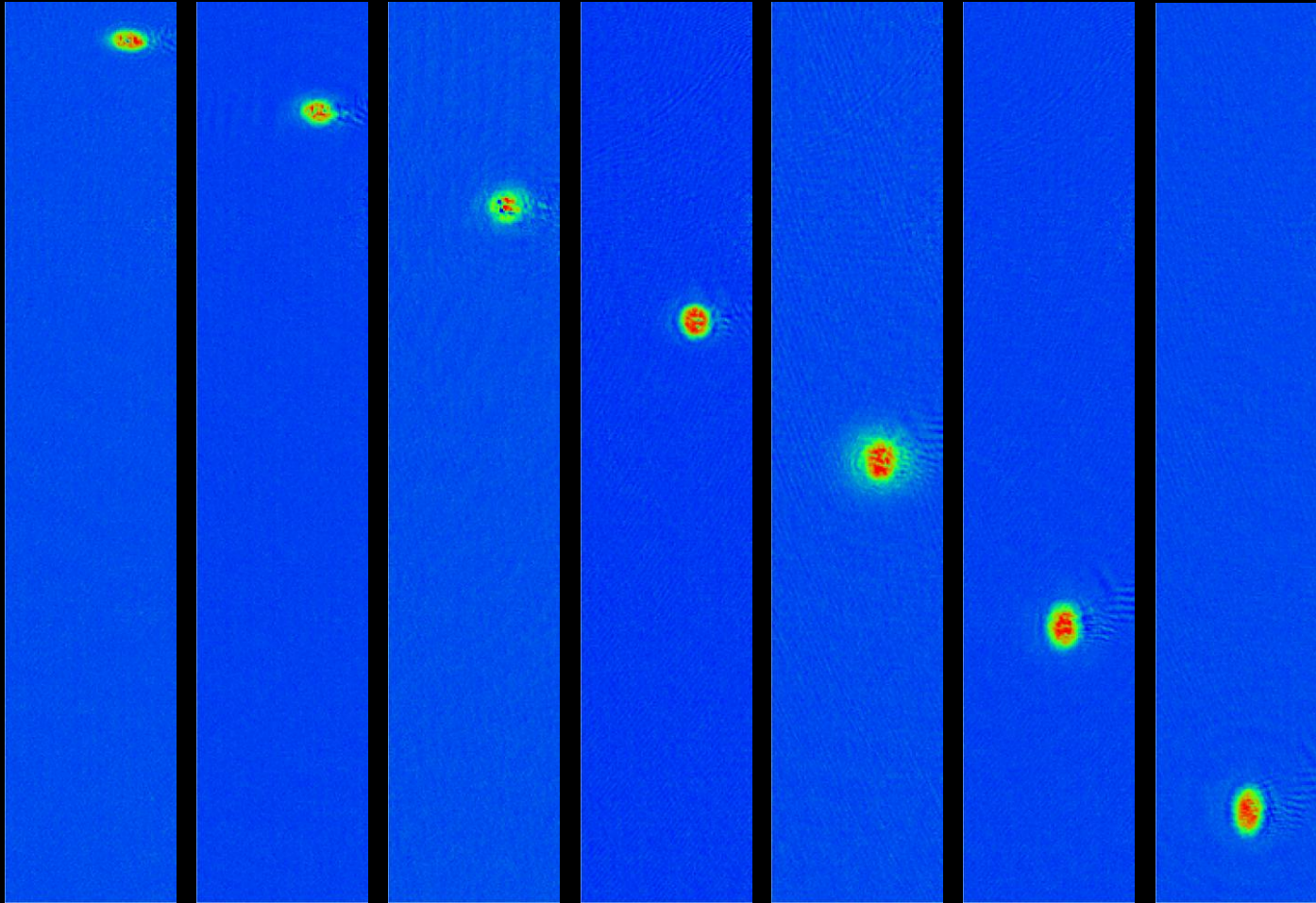


temperatura



Condensazione di Bose-Einstein

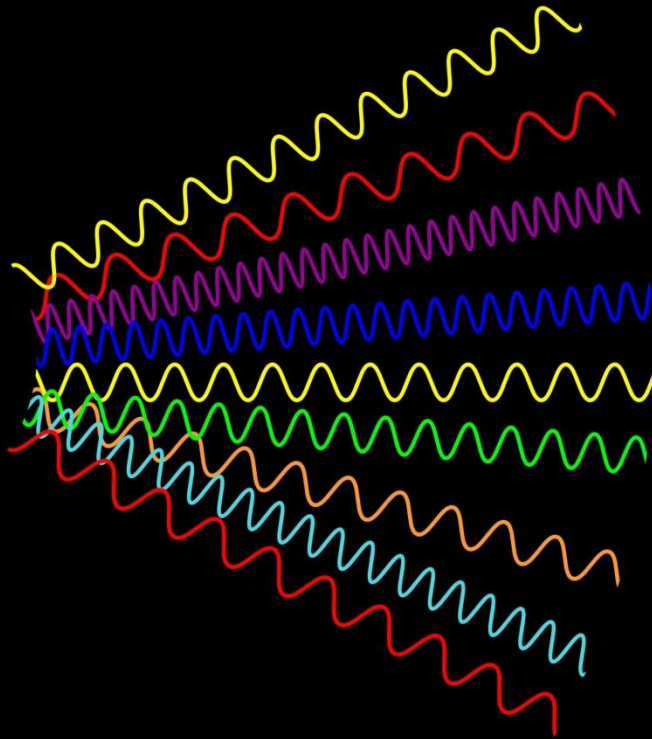
caduta libera di un condensato di Bose-Einstein



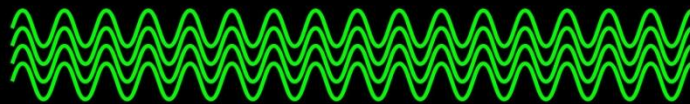
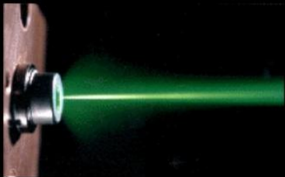
Principio di indeterminazione $\Delta x \Delta p > \hbar$

1927: W. Heisenberg

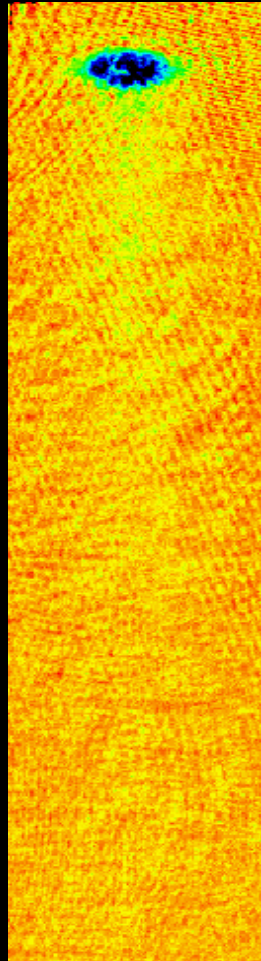




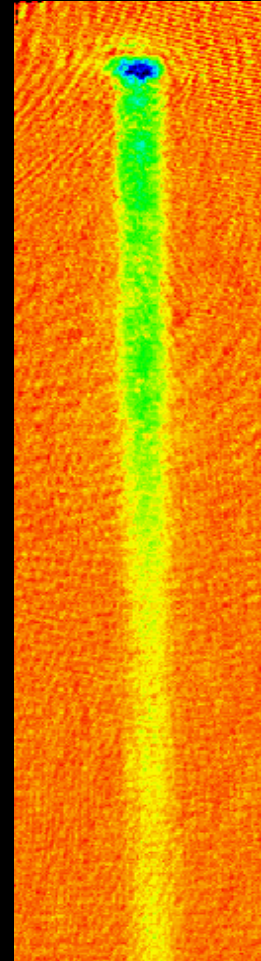
luce ordinaria



luce laser



$T > T_c$
atomi incoerenti



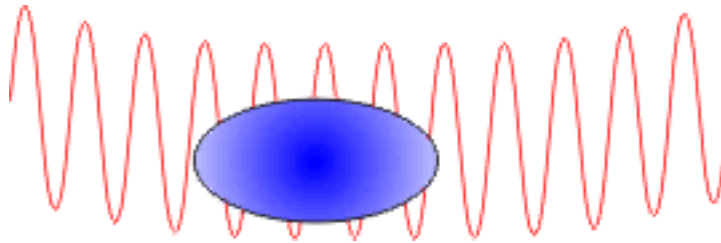
$T < T_c$
atomi coerenti



2 mm

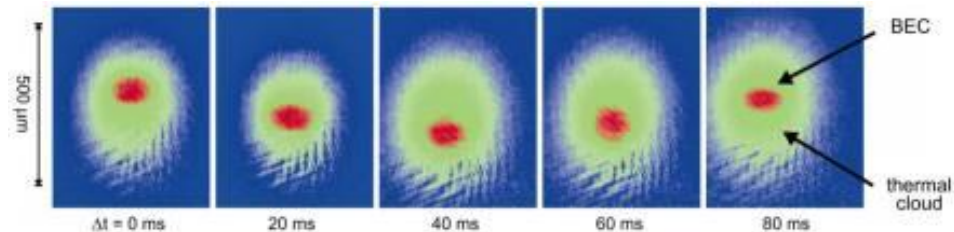
Campione quantistico di tensione elettrica

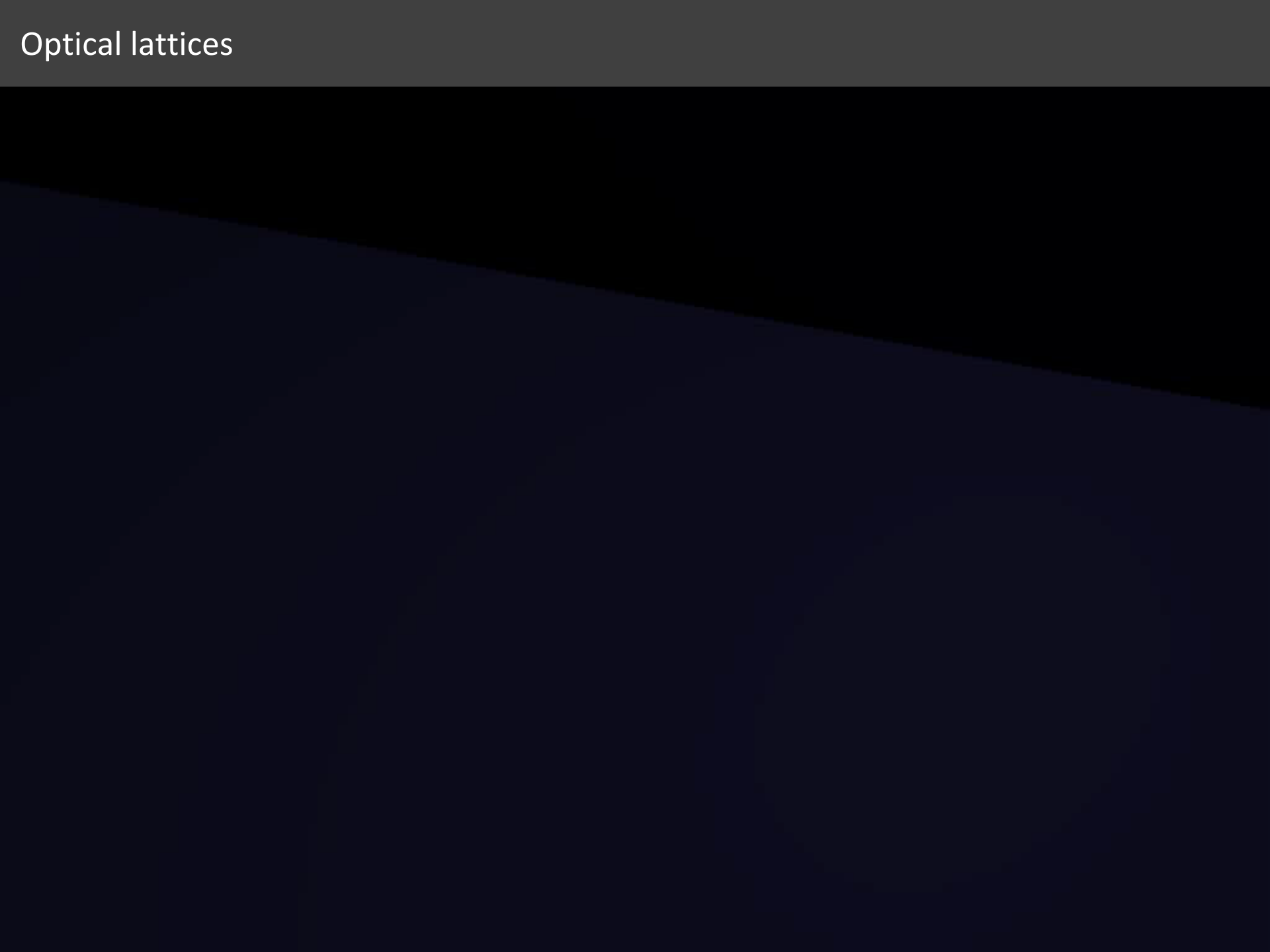
Effetto Josephson



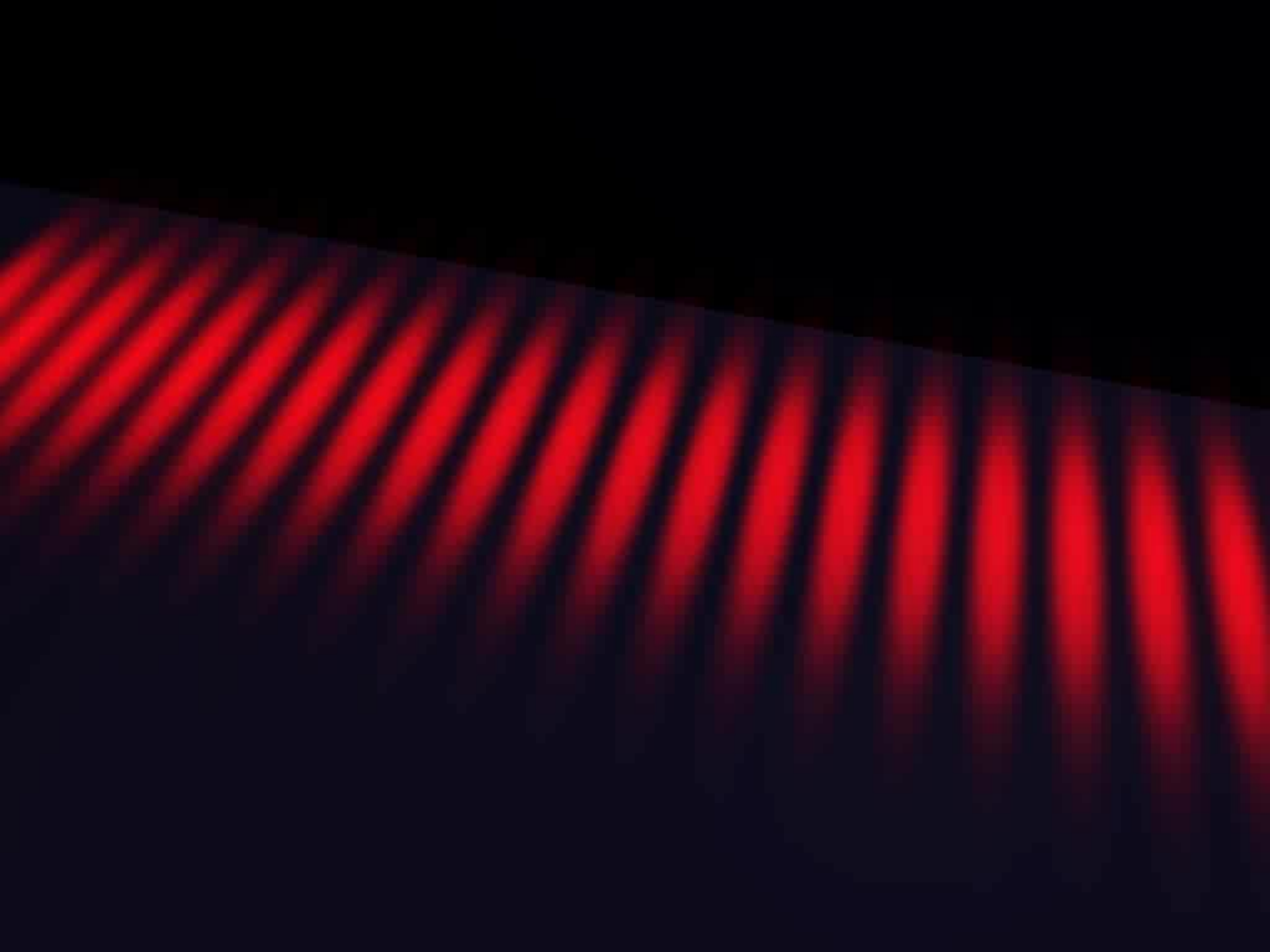
$$U(t) = \frac{\hbar}{2e} \frac{\partial \phi}{\partial t}$$

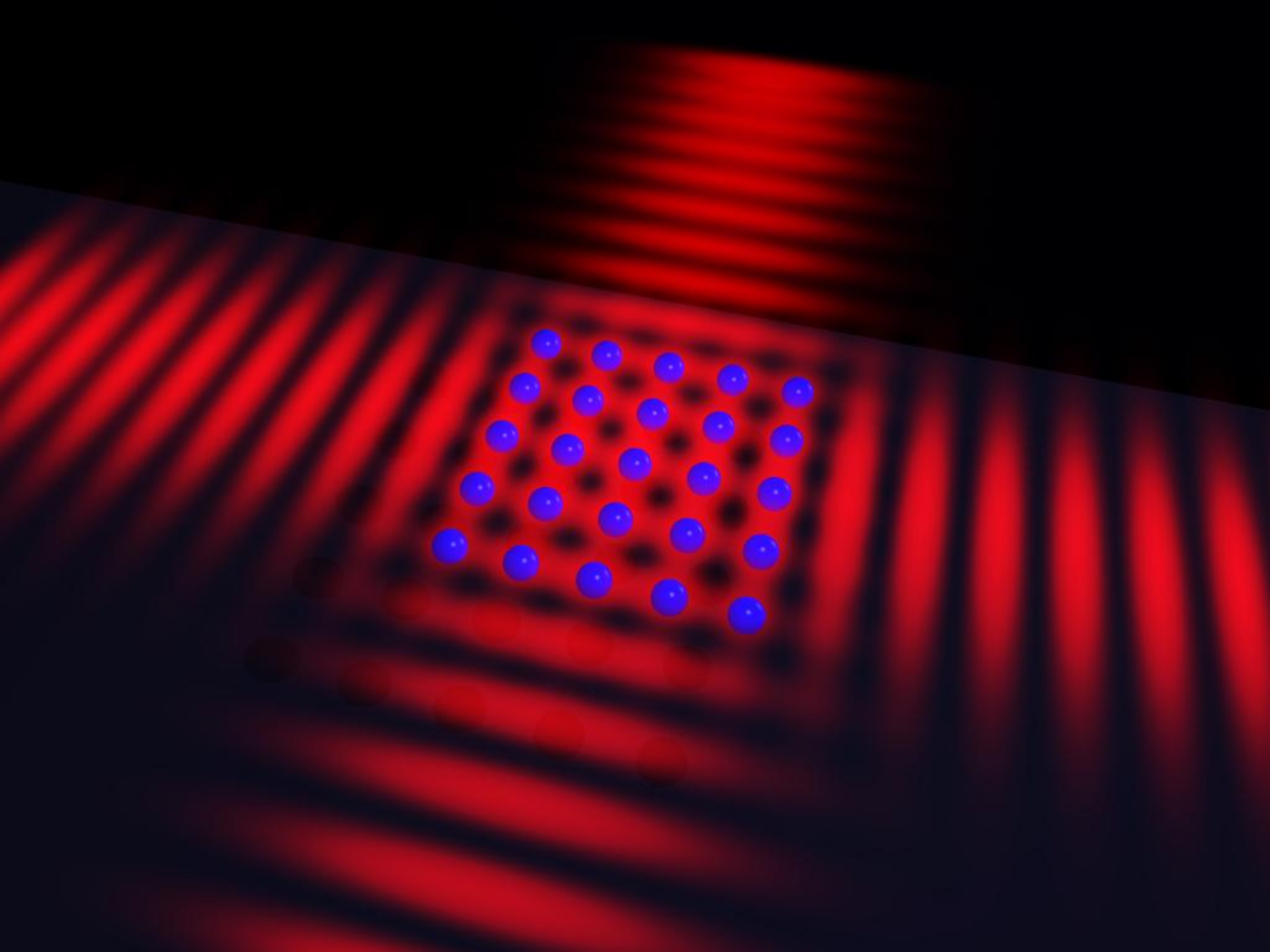
$$I(t) = I_c \sin(\phi(t))$$



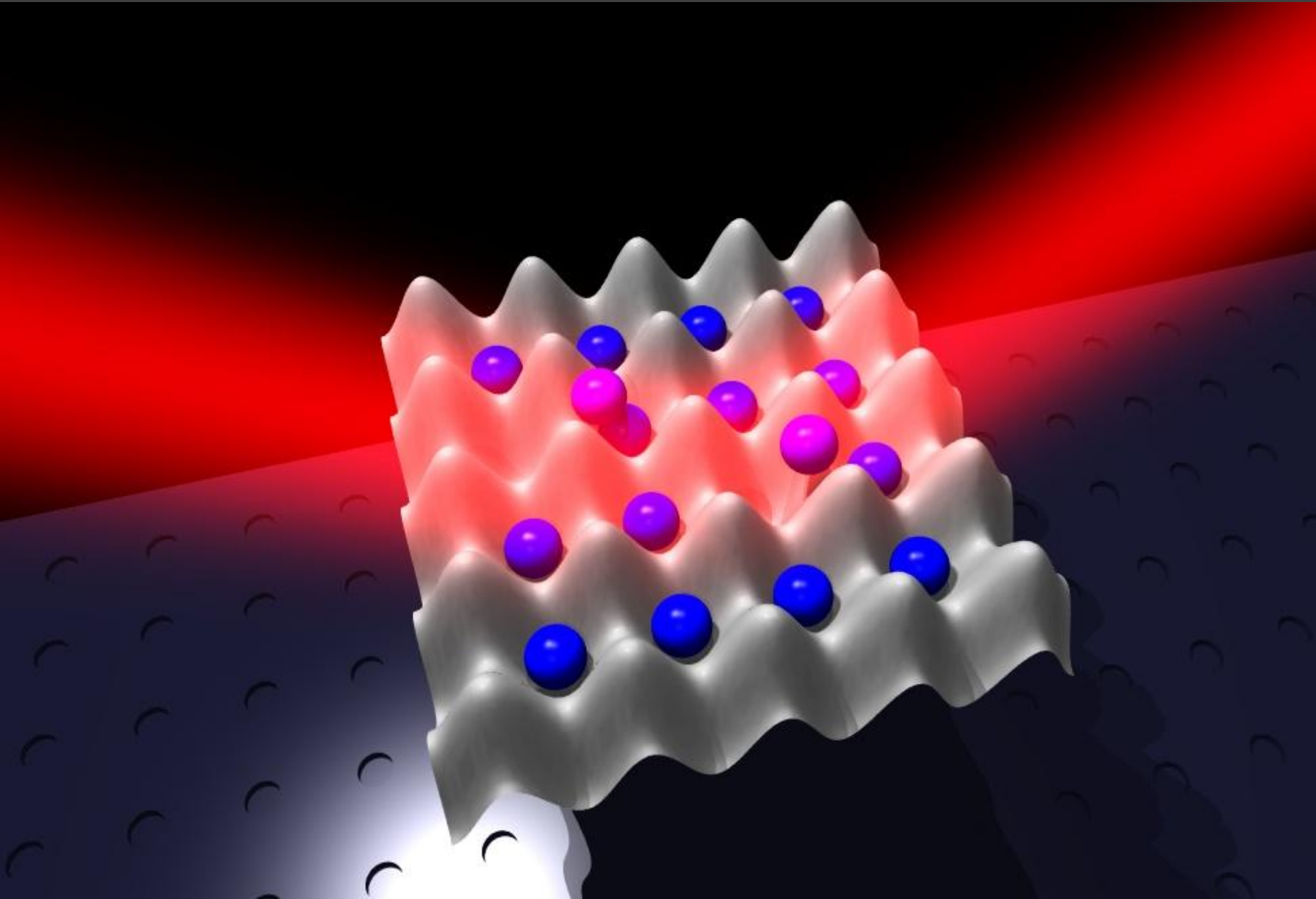


Optical lattices





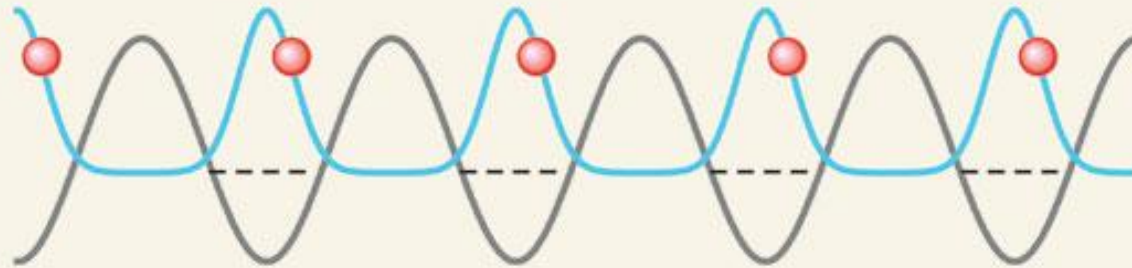
Ultracold atoms in optical lattices



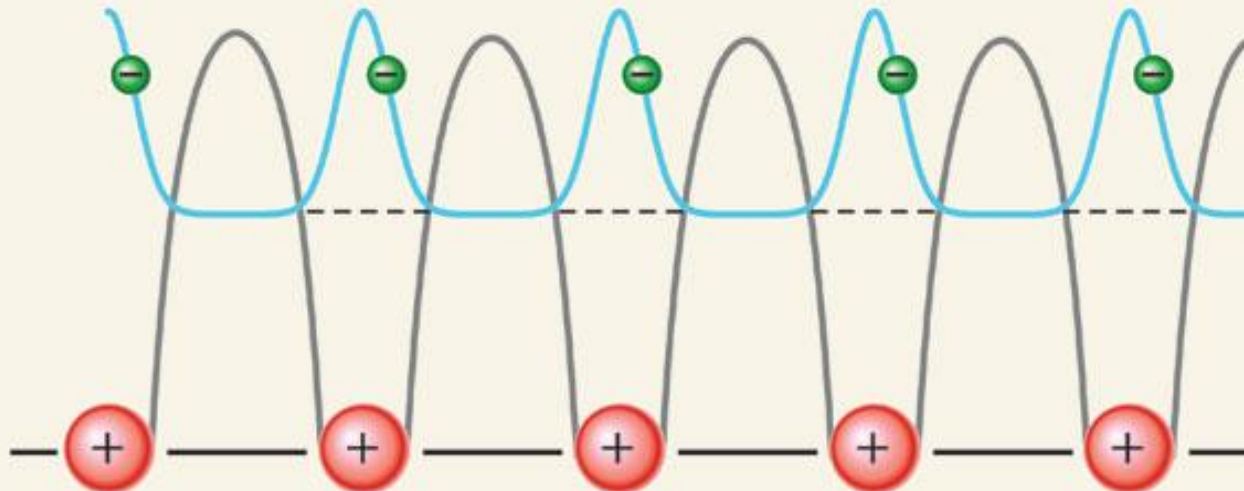
Electrons vs atoms

atom

a Optical lattice

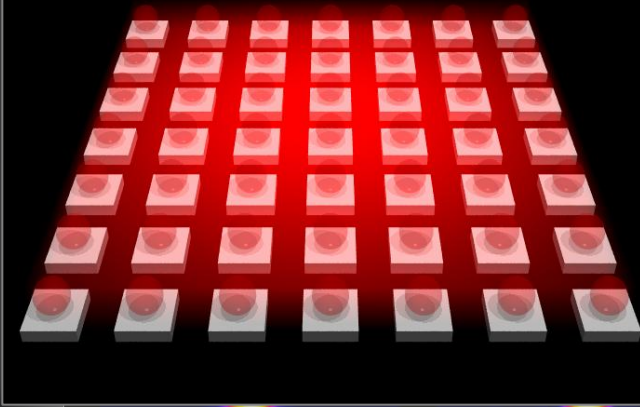


b Real crystal

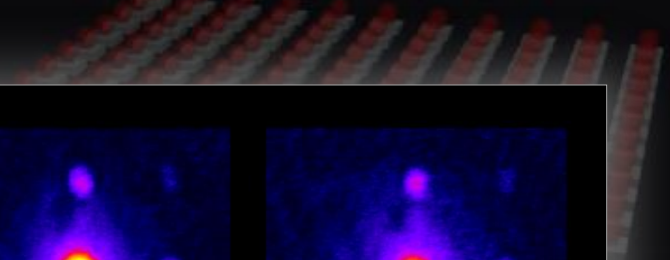


NS, 2005 Superfluid-Mott transition

superfluid



transition induced by repulsive interactions



$s=0$

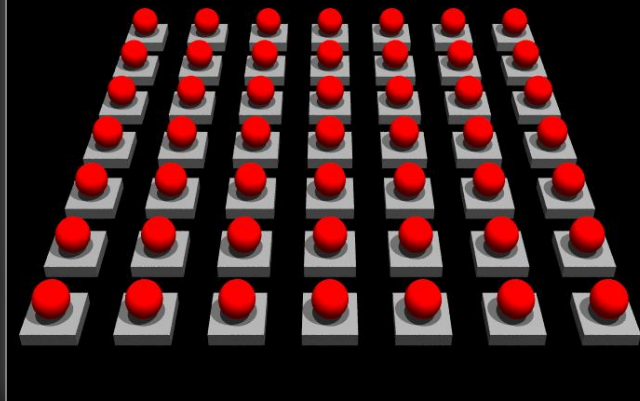
$s=2.5$

$s=5$

$s=7.5$

$s=10$

Mott insulator



$s=17.5$

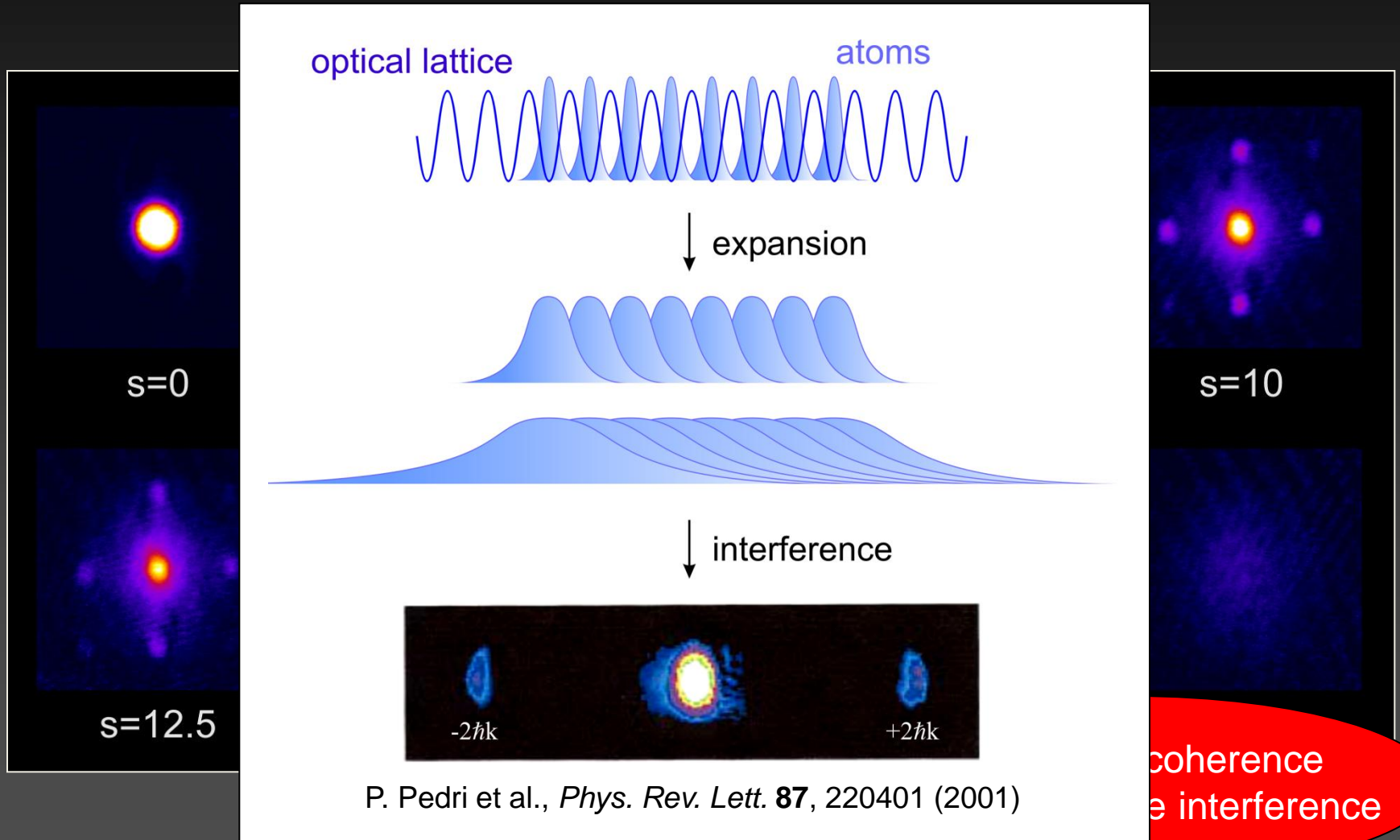
$s=20$

$s=22.5$

onstration in *M. Greiner et al., Nature* **415**, 39 (2002)

Superfluid to Mott Insulator transition

momentum distribution of the ^{87}Rb atomic sample after expansion



P. Pedri et al., *Phys. Rev. Lett.* **87**, 220401 (2001)

first experimental demonstration in *M. Greiner et al., Nature*

...Can physics be simulated by a universal computer?

Richard P. Feynman, Int. J. Theor. Phys 21, 467 (1982)

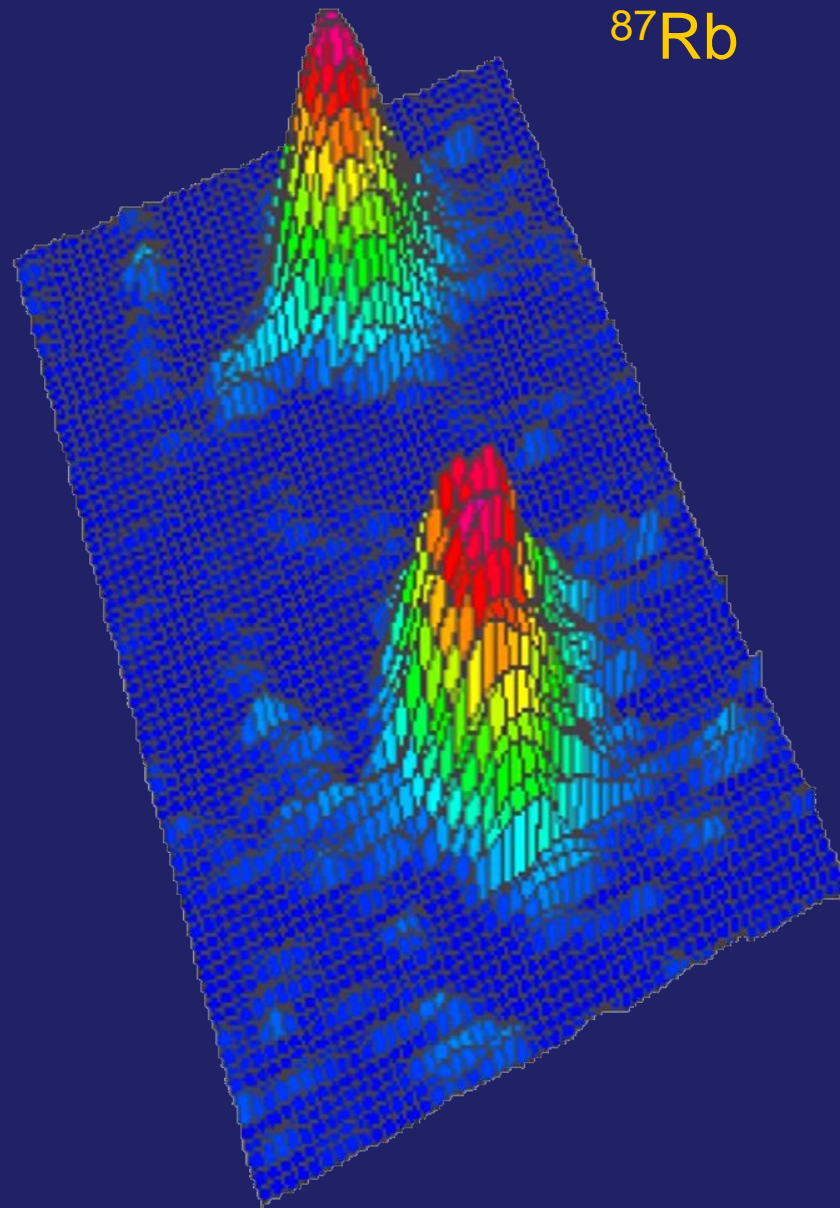
Richard P. Feynman realized that certain phenomena in Quantum Field Theory are well imitated by certain Condensed Matter systems...

He thought that there should be a certain class of quantum mechanical systems which would simulate any other system, a

UNIVERSAL QUANTUM SIMULATOR

that could serve as a quantum laboratory where the validity of several theoretical models may be tested.

2001
SCIENCE

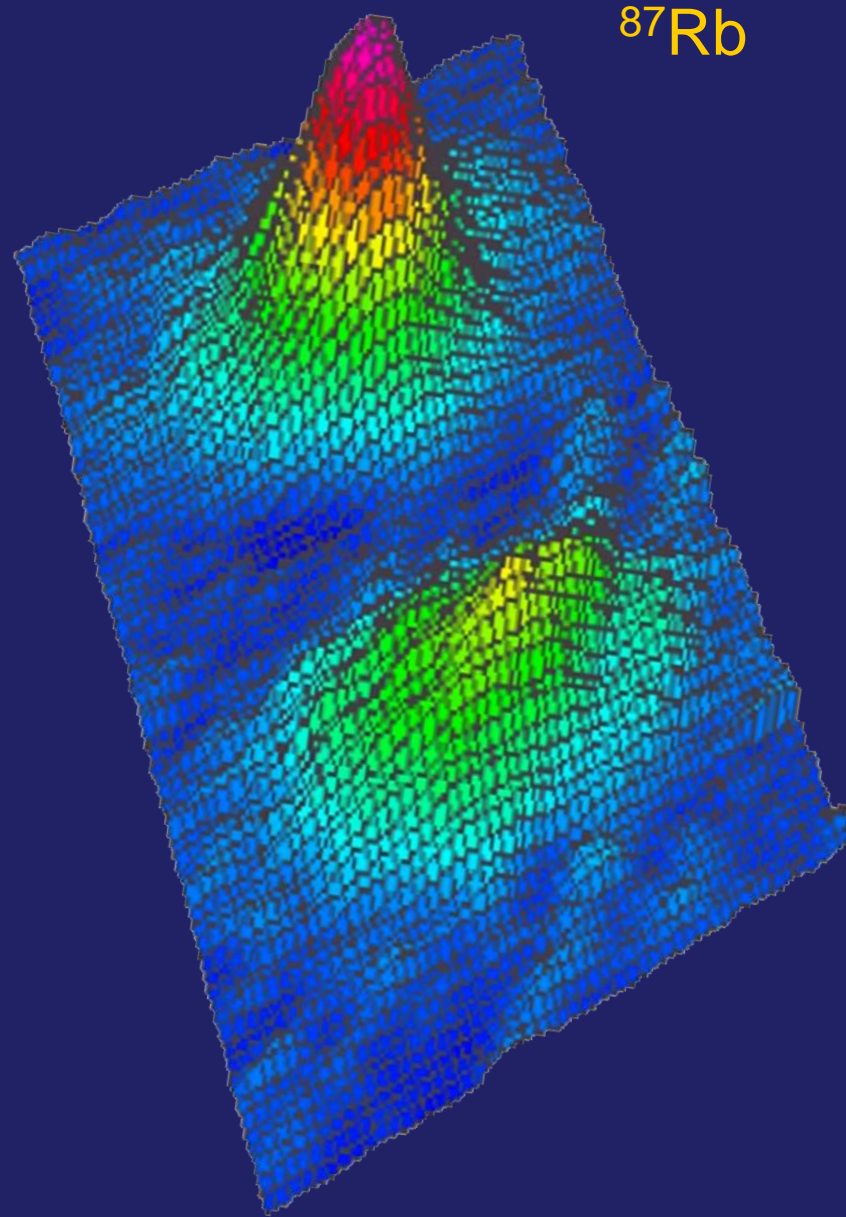


^{87}Rb

^{41}K *boson*

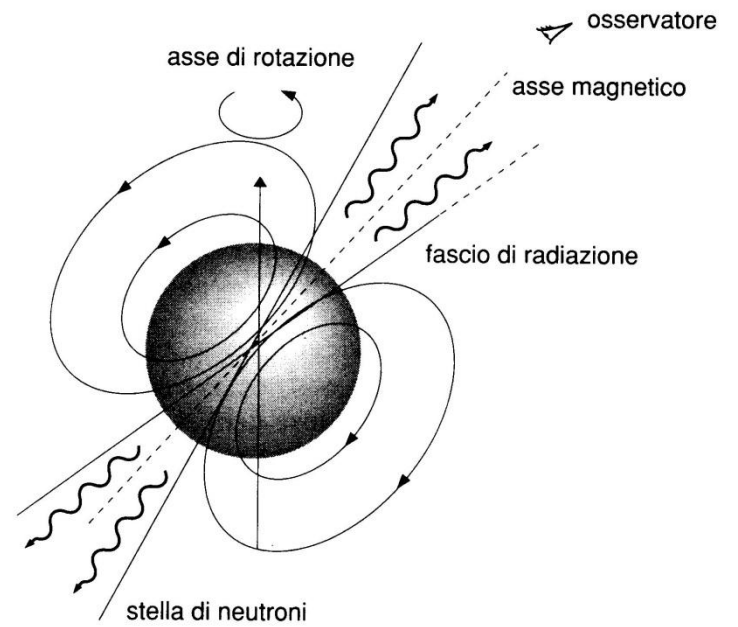
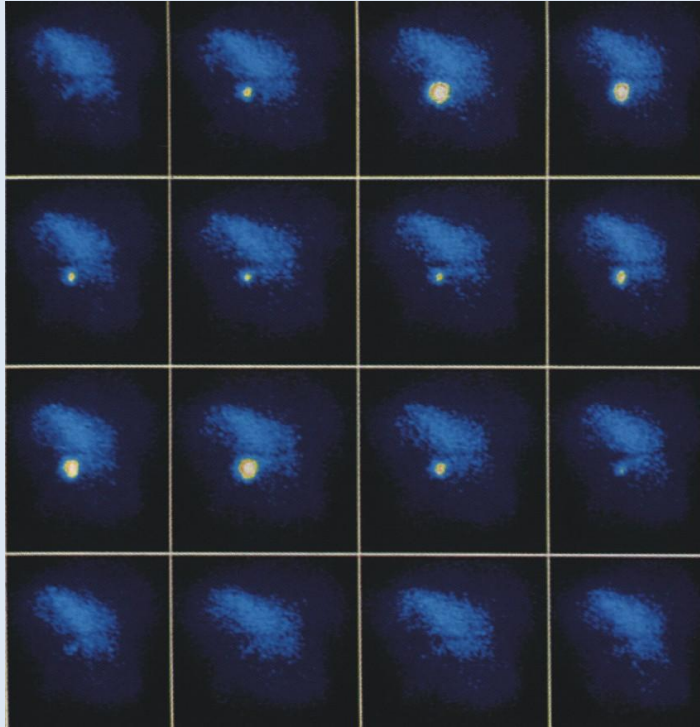
2002

PRL



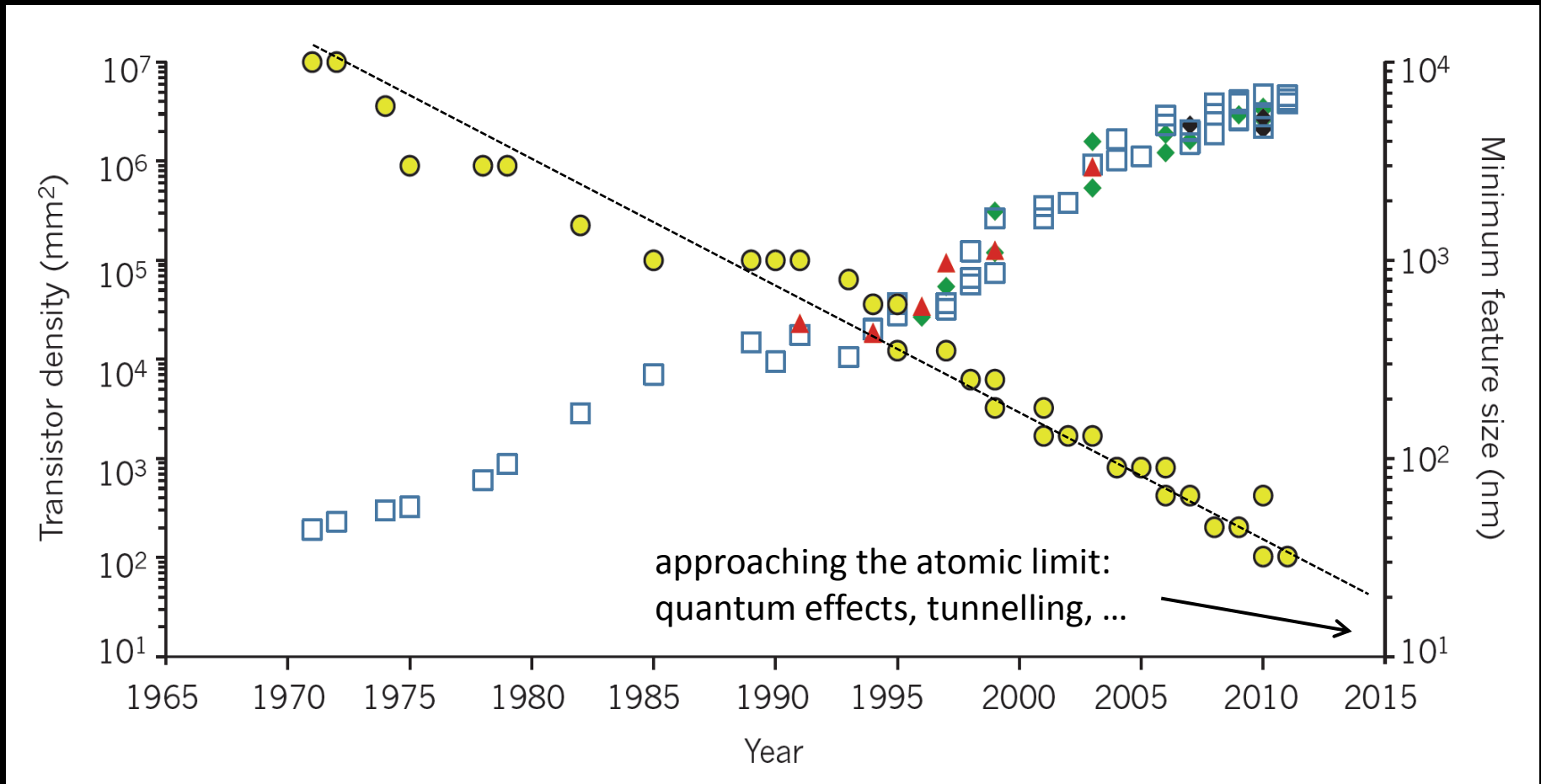
^{87}Rb

^{40}K fermion



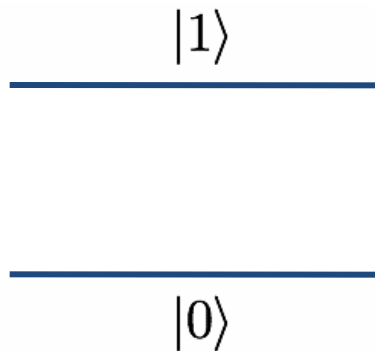
Classical Information Technology

Moore's law and decrease in transistor size



Computer classico

bit

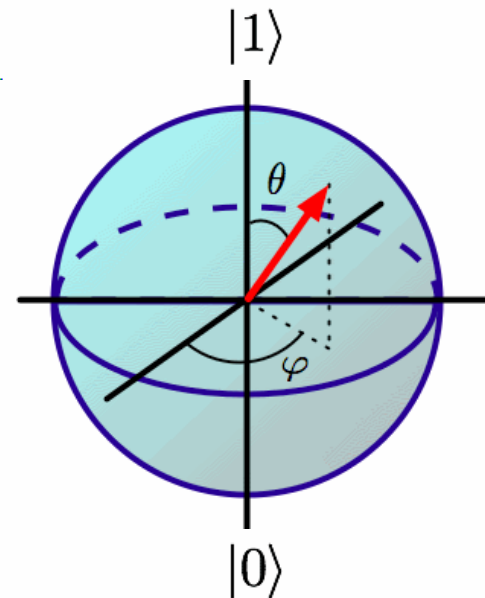


interruttore acceso/spento
corrente sì/no

$|0\rangle$ o $|1\rangle$

Computer quantistico

qubit



sovrapposizione coerente
di due stati interni

$\alpha|0\rangle + \beta|1\rangle$

Il gatto di Schrödinger



Erwin Schrödinger

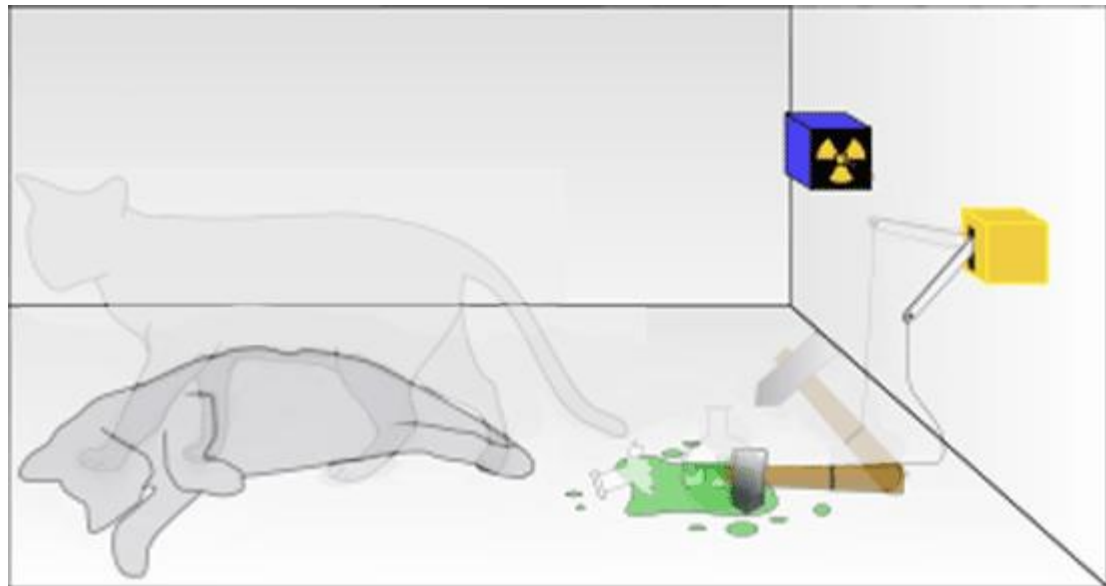
paradosso del gatto chiuso in una scatola

il gatto è in una sovrapposizione coerente di due stati

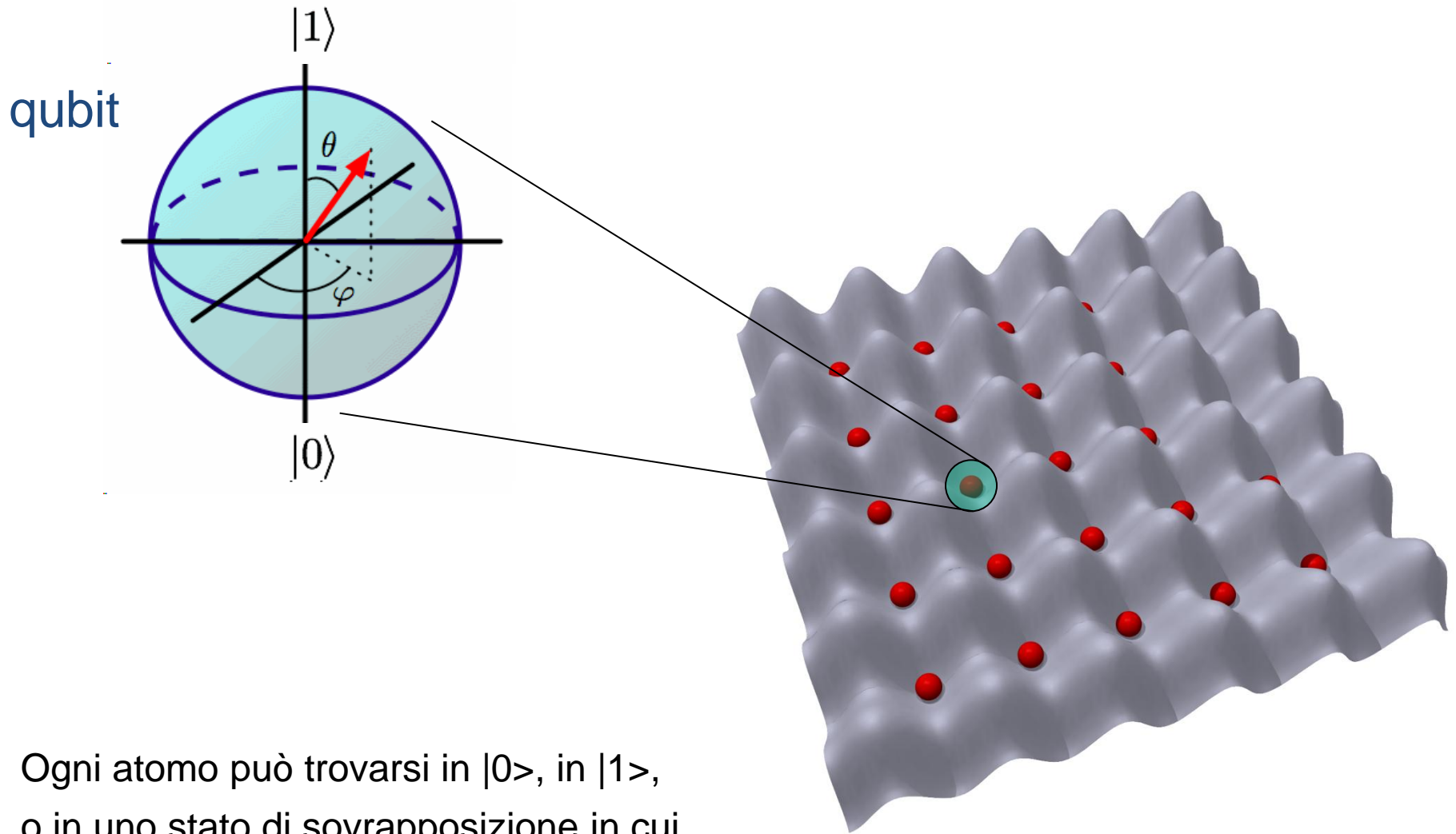
$$\alpha|0\rangle + \beta|1\rangle$$

$|0\rangle$ = gatto morto

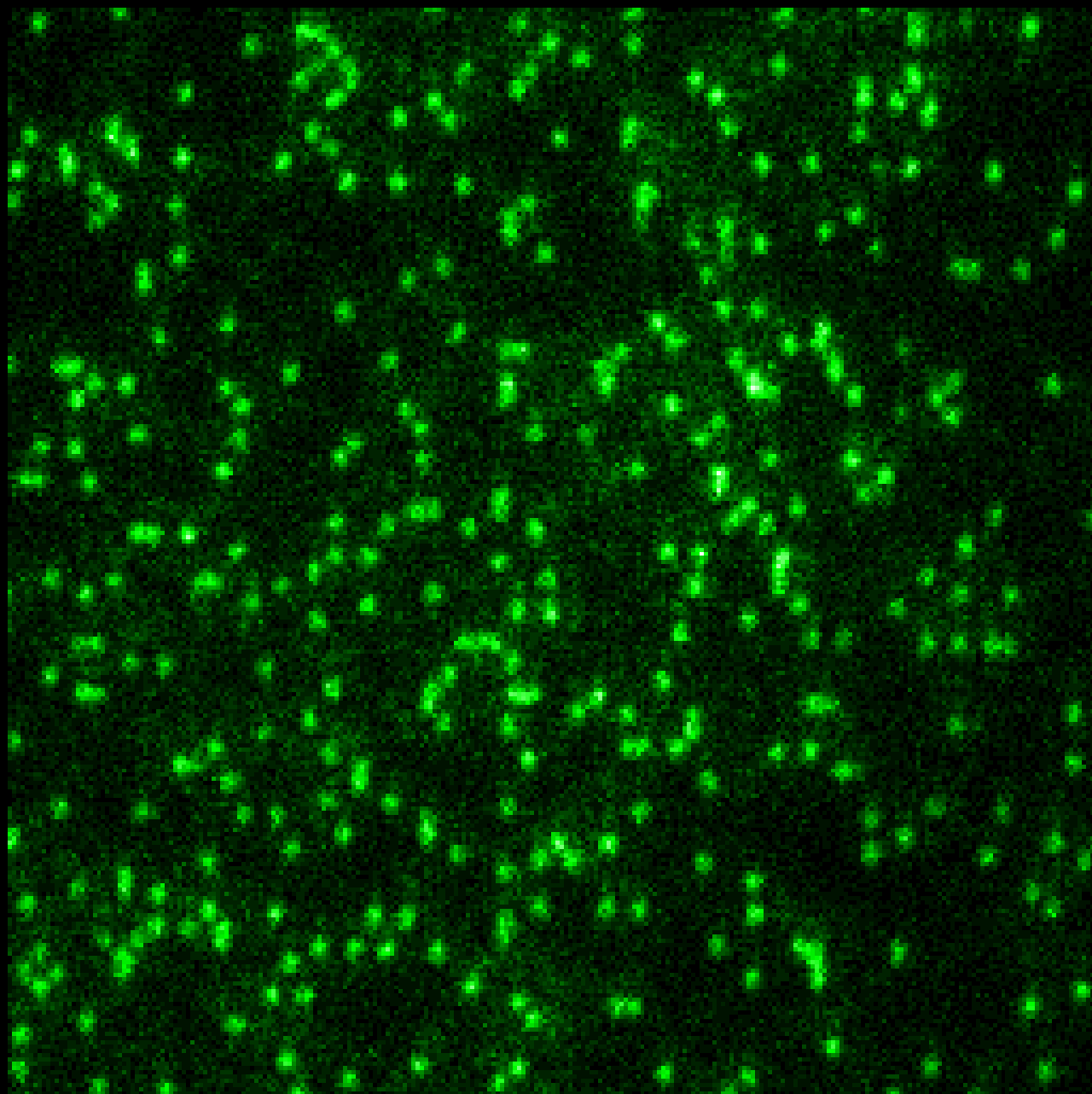
$|1\rangle$ = gatto vivo



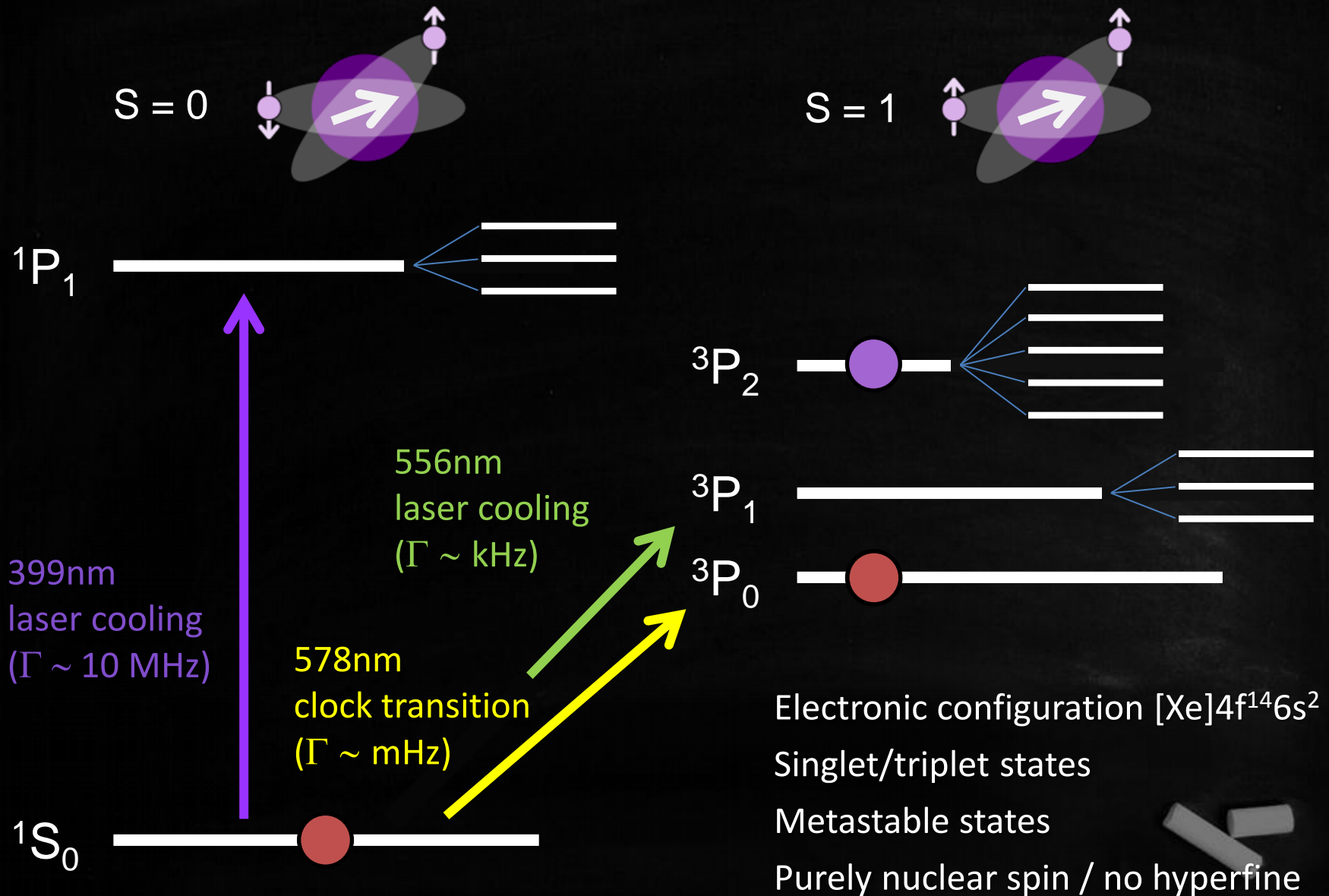
Registri di memoria quantistici



Ogni atomo può trovarsi in $|0\rangle$, in $|1\rangle$,
o in uno stato di sovrapposizione in cui
allo stesso tempo si trova sia in $|0\rangle$ che in $|1\rangle$



Ytterbium

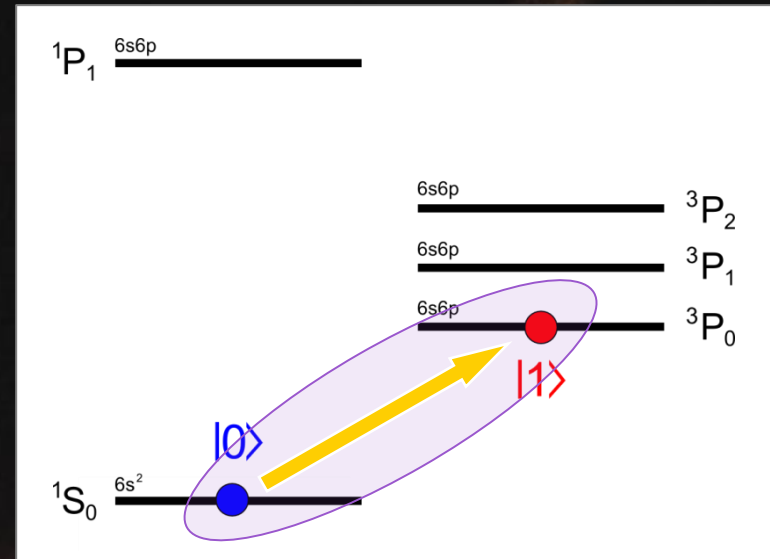


Excitation of the 3P_0 state

Q-bit



su transizione di orologio





MINISTERO DELLE FINANZE

NOTA N. 2

ESONERO TASSA RADIO



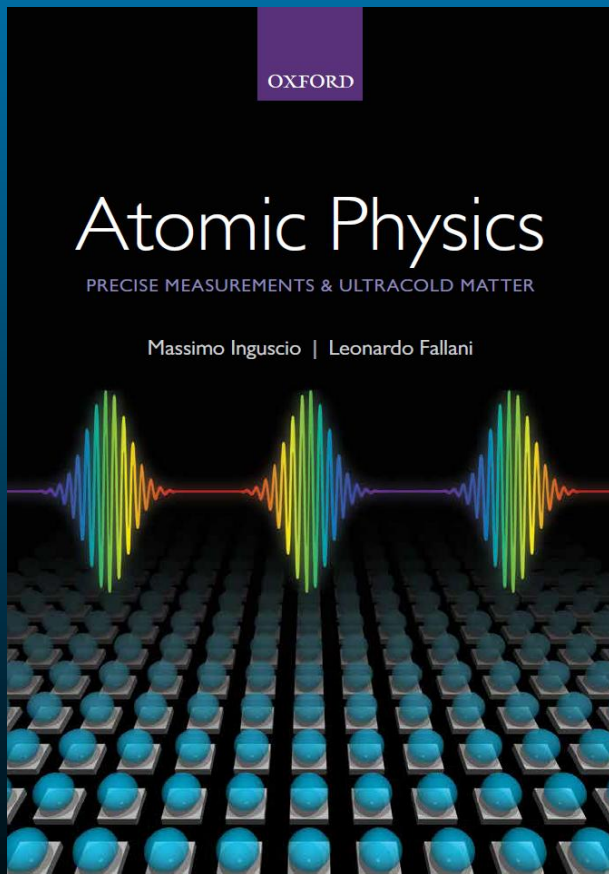
OPERE
DI
GALILEO GALILEI

VOLUME I

MILANO
VIA MARIO BETTONI 5 CORA.



Massimo Inguscio
Fisica atomica allo zero assoluto (Di Renzo, 2012)



Massimo Inguscio & Leonardo Fallani
Atomic Physics: Precise Measurements & Ultracold Matter
(Oxford University Press, 2013)

