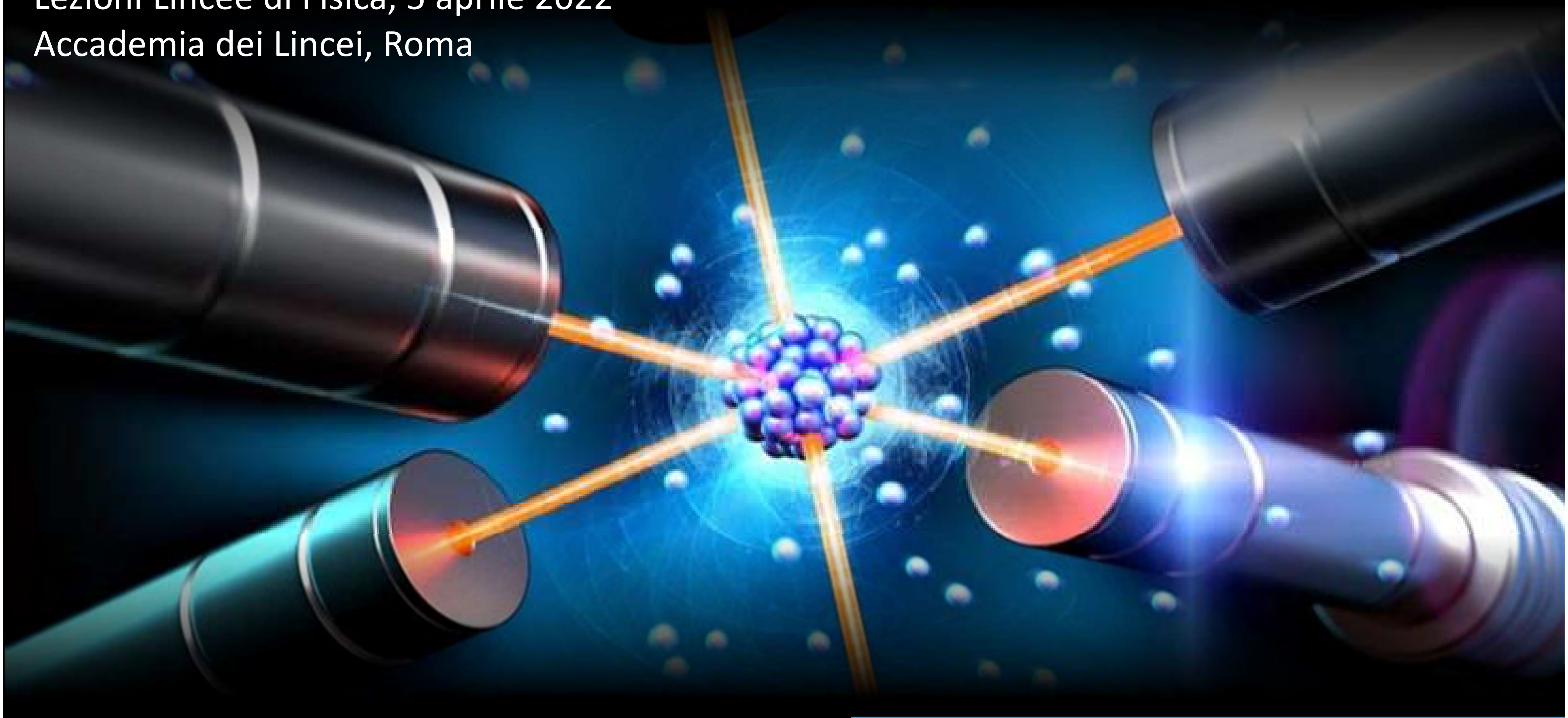
Il mondo quantistico a portata di mano: atomi freddi e condensazione di Bose-Einstein

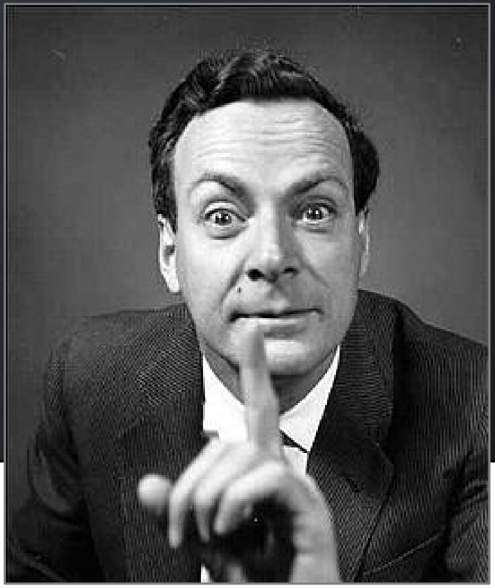
Lezioni Lincee di Fisica, 5 aprile 2022
Accademia dei Lincei, Roma



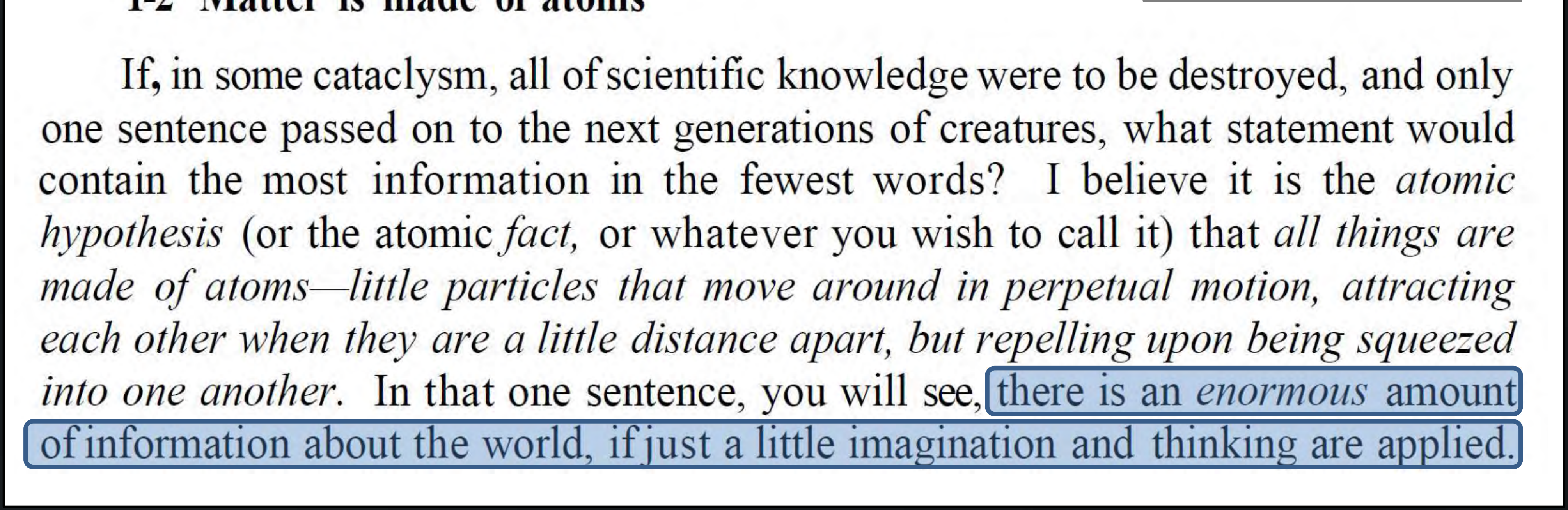
Massimo Inguscio

Accademia dei Lincei
Università Campus Bio-Medico di Roma
LENS & CNR-INO

Partiamo dagli atomi



R. P. Feynman, *Lectures on Physics*
Volume 1, Chapter 1



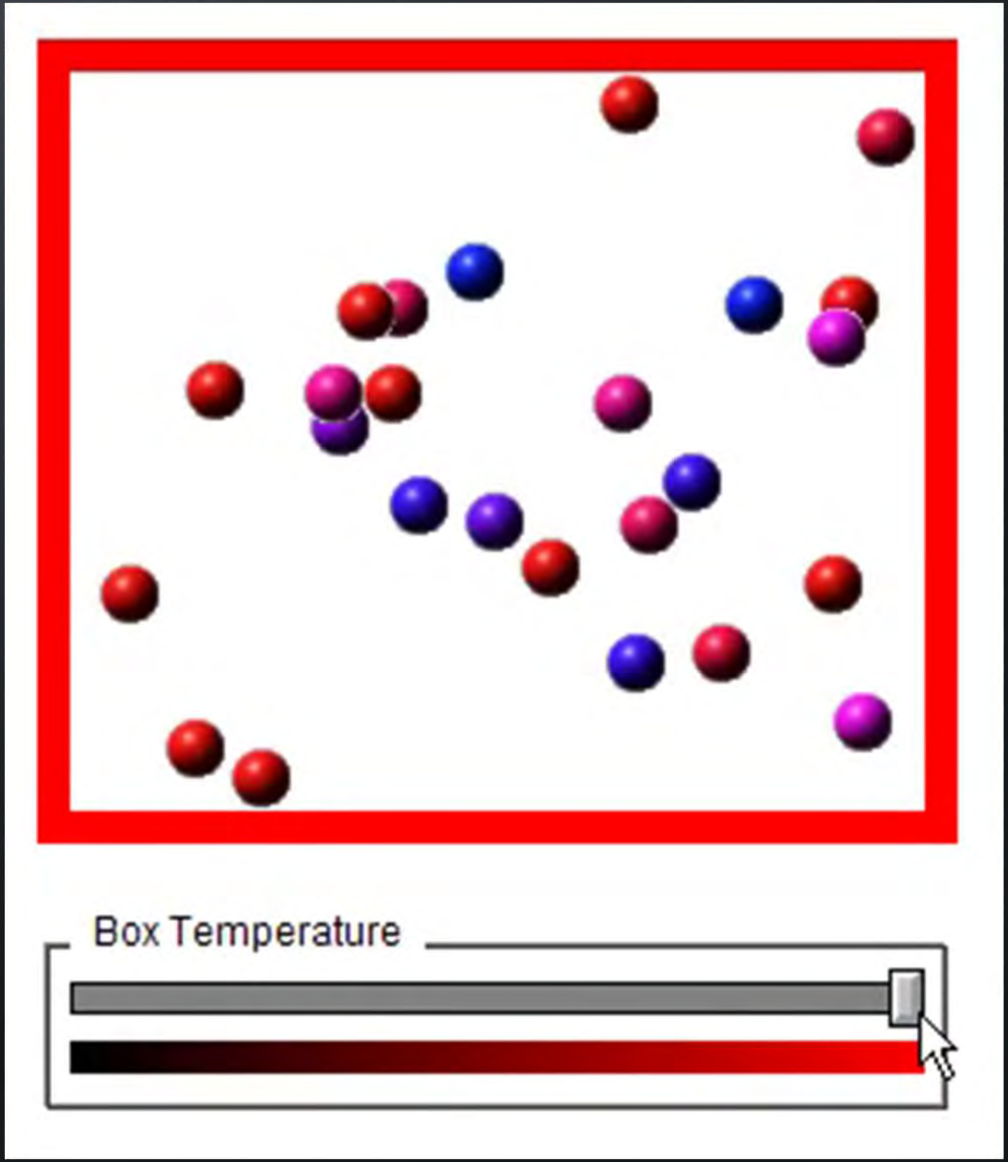
1-2 Matter is made of atoms

If, in some cataclysm, all of scientific knowledge were to be destroyed, and only one sentence passed on to the next generations of creatures, what statement would contain the most information in the fewest words? I believe it is the *atomic hypothesis* (or the atomic *fact,* or whatever you wish to call it) that *all things are made of atoms—little particles that move around in perpetual motion, attracting each other when they are a little distance apart, but repelling upon being squeezed into one another.* In that one sentence, you will see, there is an *enormous* amount of information about the world, if just a little imagination and thinking are applied.

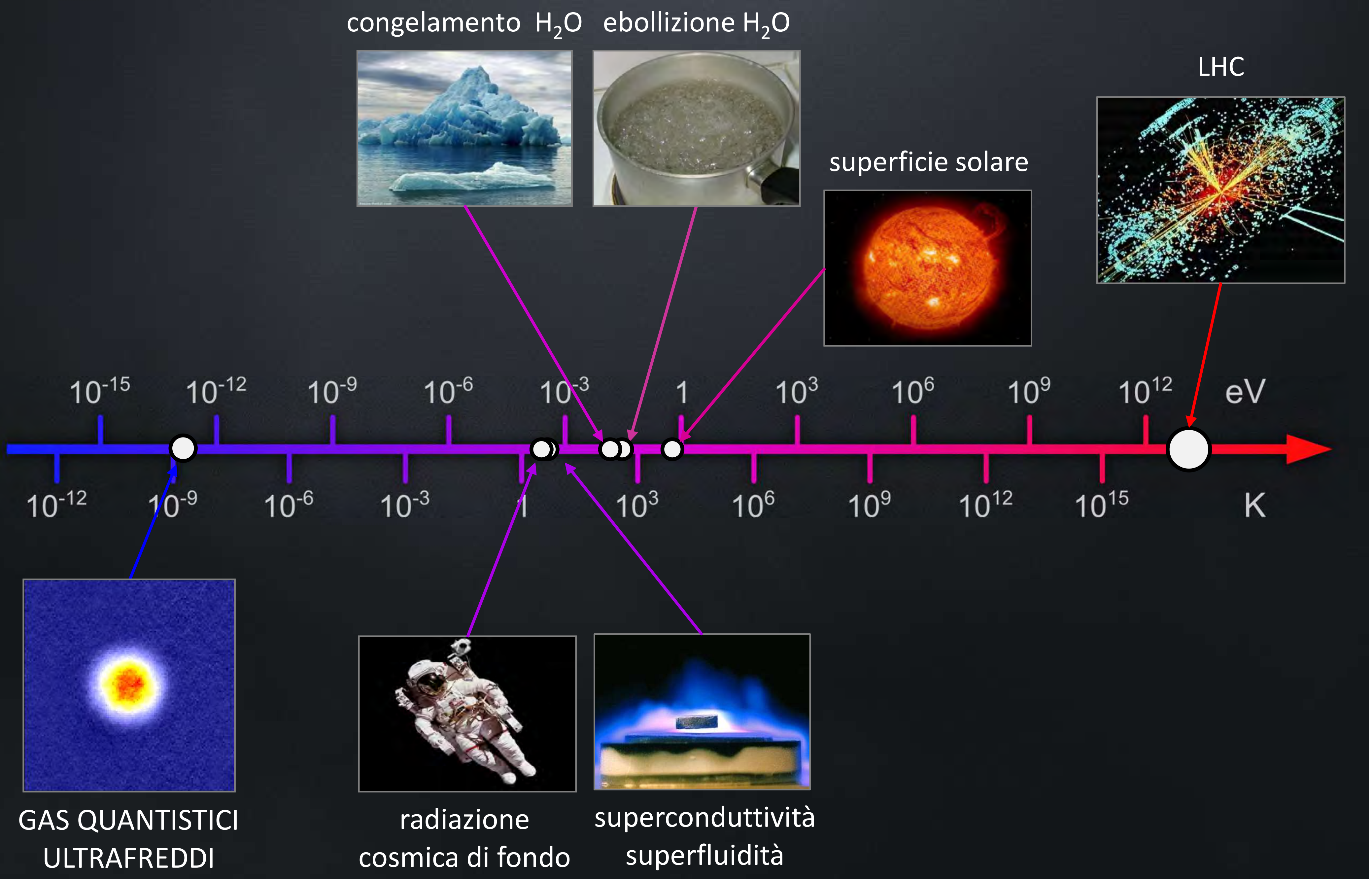
Cos'è la temperature?

La temperatura misura
l'agitazione termica

$$T = \frac{m\langle v^2\rangle}{3\ k_B}$$



Atomi ultrafreddi



congelamento H_2O

ebollizione H_2O

superficie solare

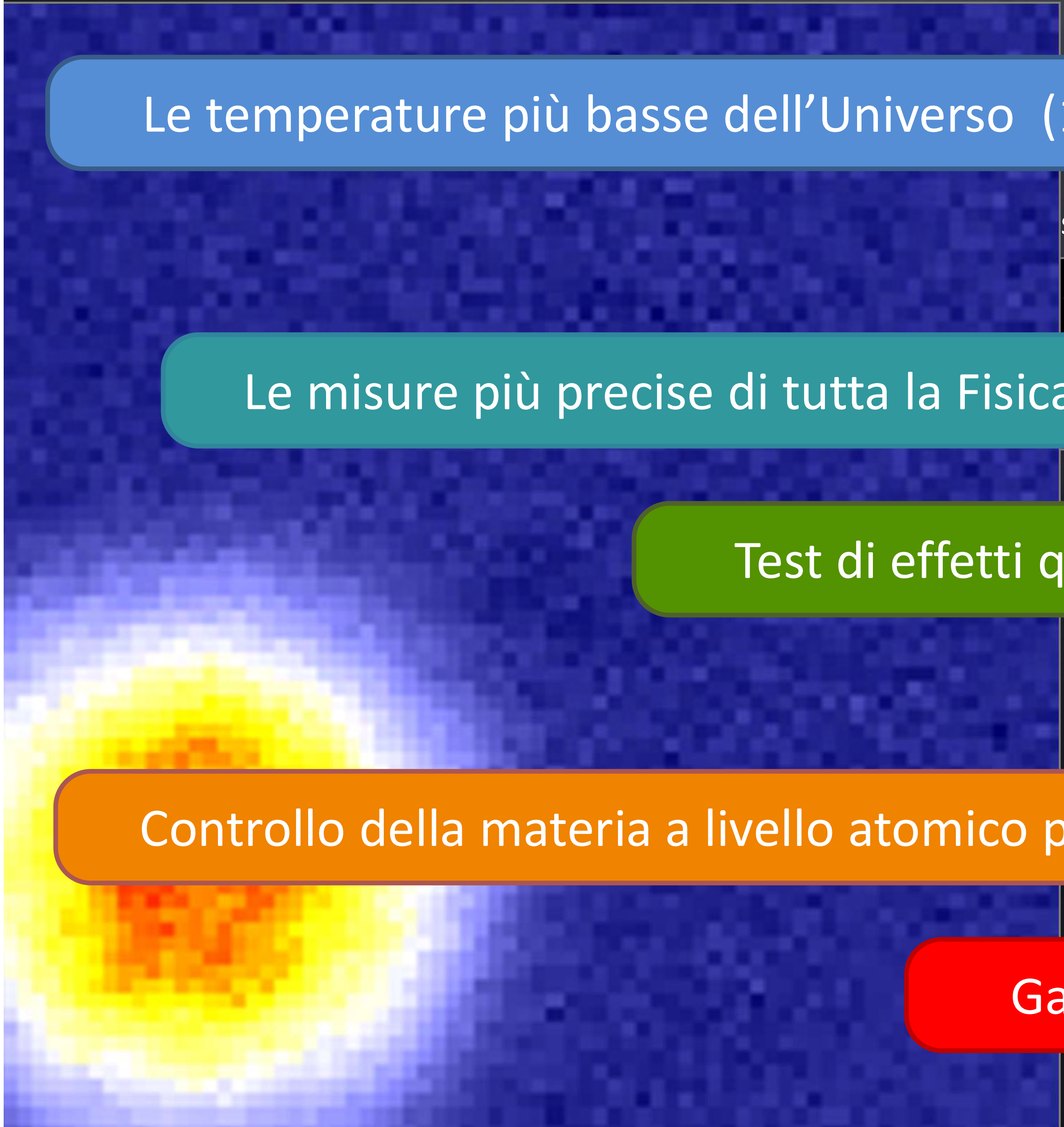
LHC

GAS QUANTISTICI
ULTRAFREDDI

radiazione
cosmica di fondo

superconduttività
superfluidità

Atomi ultrafreddi



Le temperature più basse dell'Universo (10^{-9} K)

Le misure più precise di tutta la Fisica (incertezza 10^{-18})

Test di effetti quantistici fondamentali

Controllo della materia a livello atomico per nuove tecnologie

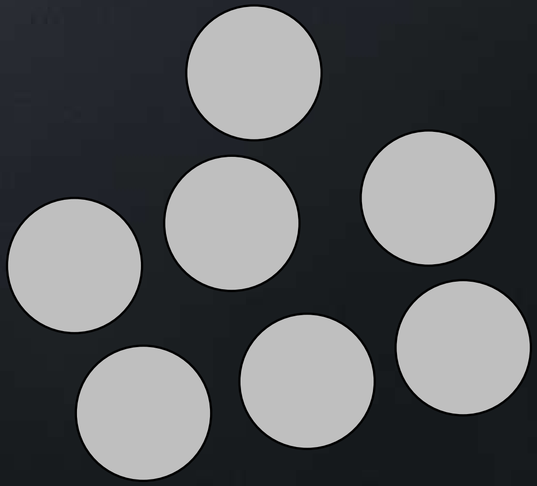
Gas quantistici ultrafreddi

Raffreddamento laser

Luce e atomi

La luce è fondamentale per lo studio e il controllo degli atomi

LUCE

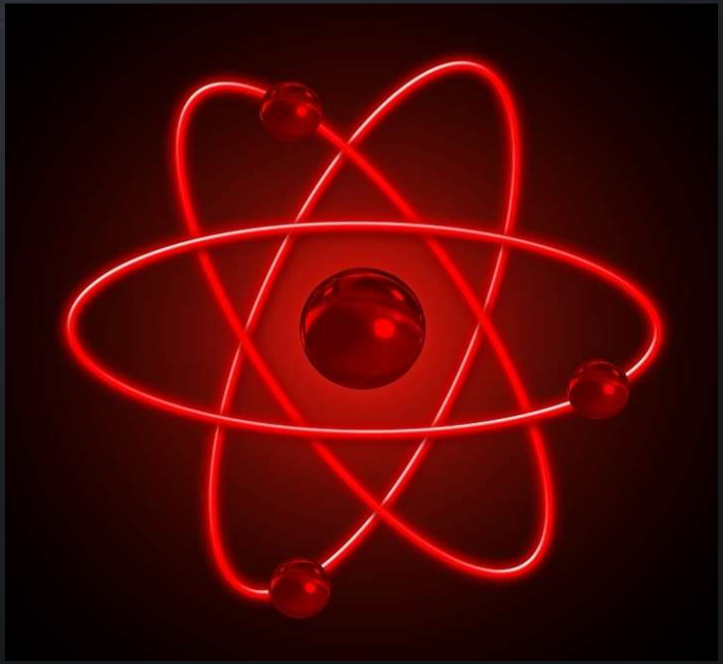


ATOMI

Luce e atomi

Spettroscopia: studio della struttura interna degli atomi

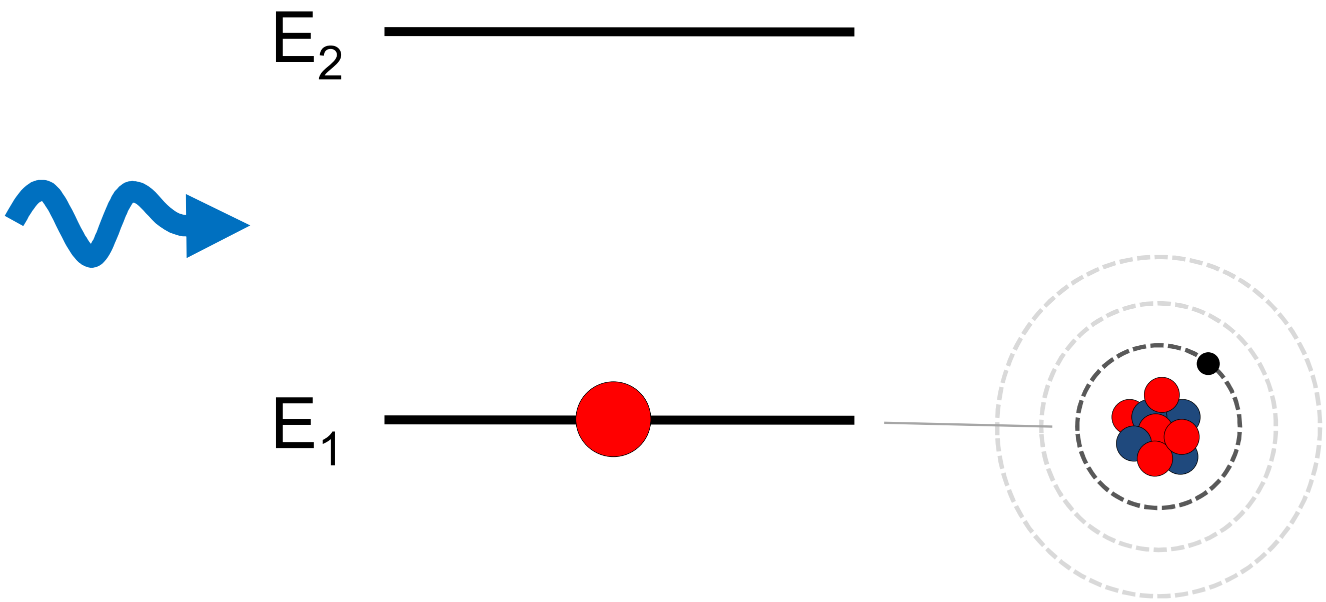
LUCE



ATOMI

Interazione atomo/luce

1a legge di conservazione: **energia**



soltanto luce del colore giusto
(frequenza giusta) viene assorbita

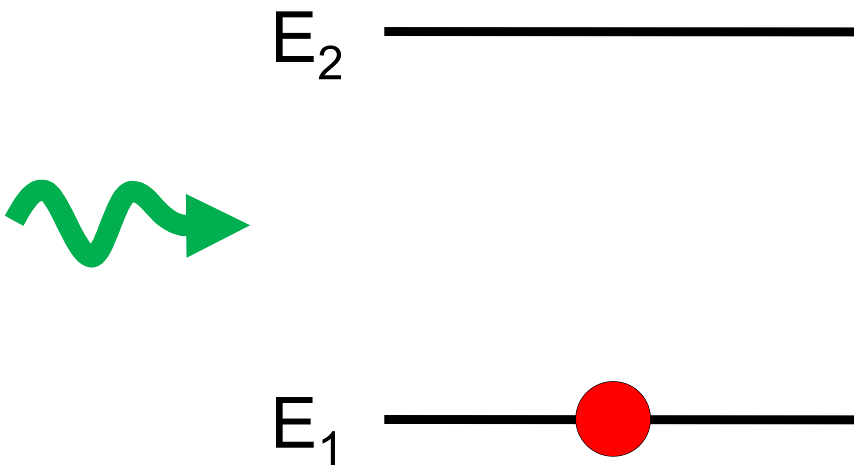
energia di un fotone

$$E = h\,f$$

constante di Planck
$h = 6.6\ 10^{-34}$ J s

Interazione atomo/luce

1a legge di conservazione: **energia**



soltanto luce del colore giusto
(frequenza giusta) viene assorbita

energia di un fotone

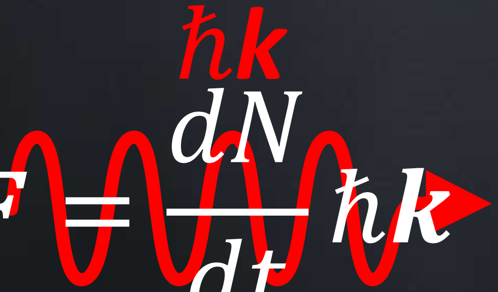
$$E = h\,f$$

constante di Planck
$h = 6.6\ 10^{-34}$ J s

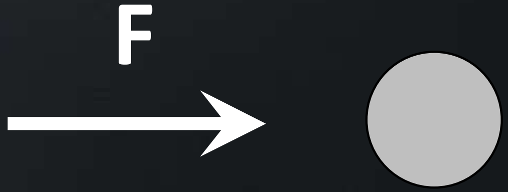
Forze radiative

Controllo del moto atomico

2a legge di conservazione: **impulso / quantità di moto**



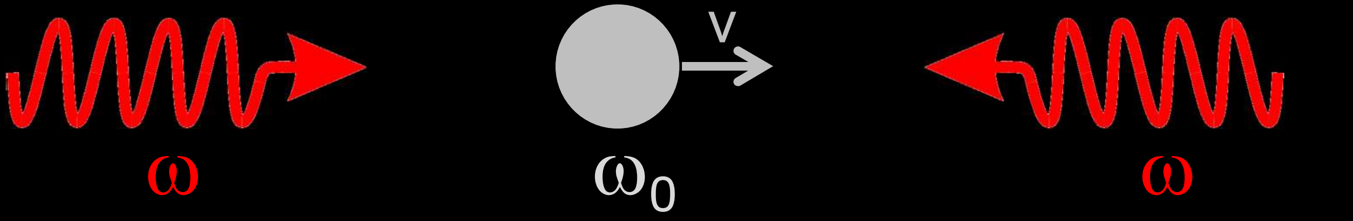
$$\boldsymbol{F} = \frac{dN}{dt}\hbar\boldsymbol{k}$$

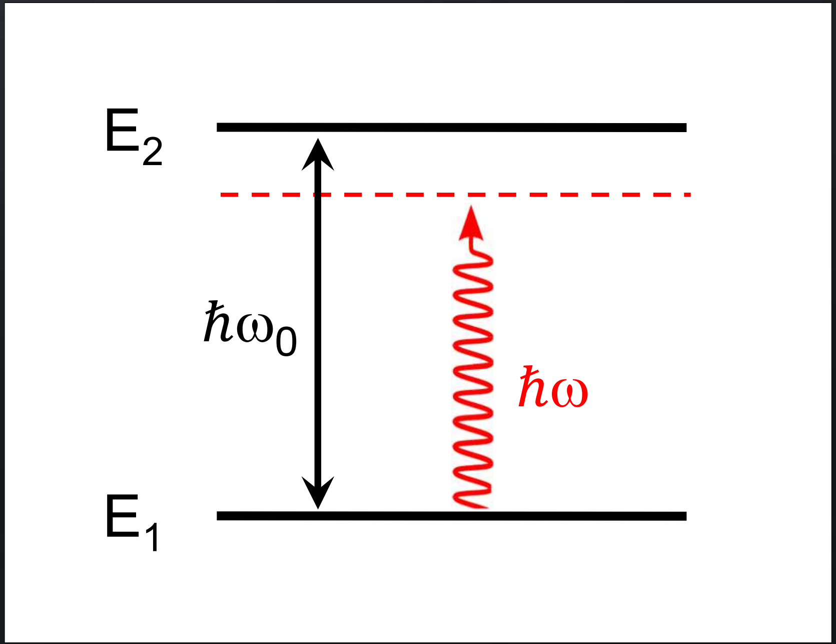


Trasferimento di impulso nell’assorbimento
Pressione di radiazione

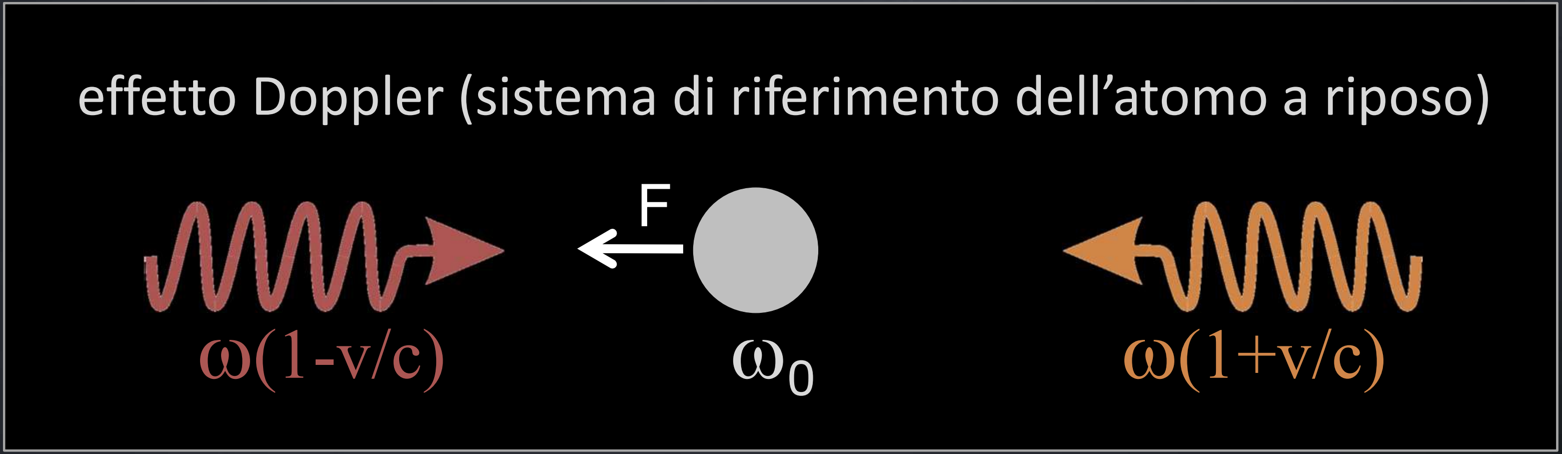
Raffreddamento Doppler

due fasci laser contropropaganti «red-detuned» ($\omega < \omega_0$)

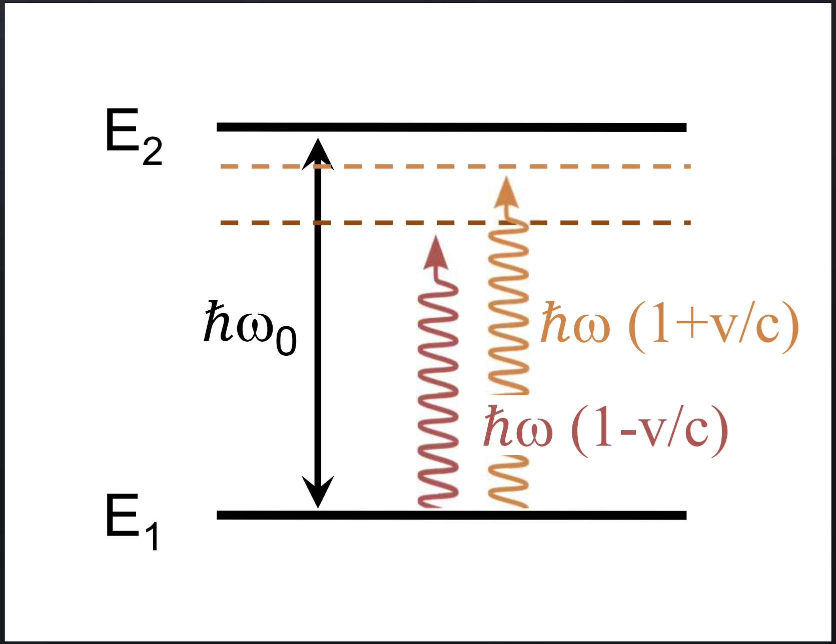




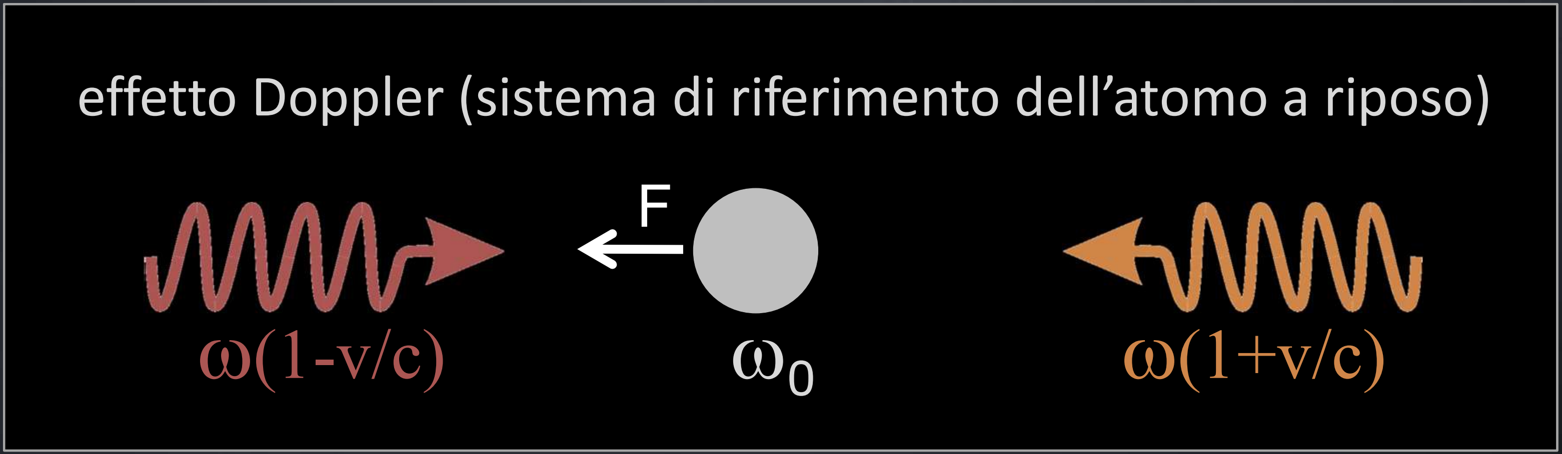
Raffreddamento Doppler



effetto Doppler (sistema di riferimento dell’atomo a riposo)



Raffreddamento Doppler


effetto Doppler (sistema di riferimento dell'atomo a riposo)

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

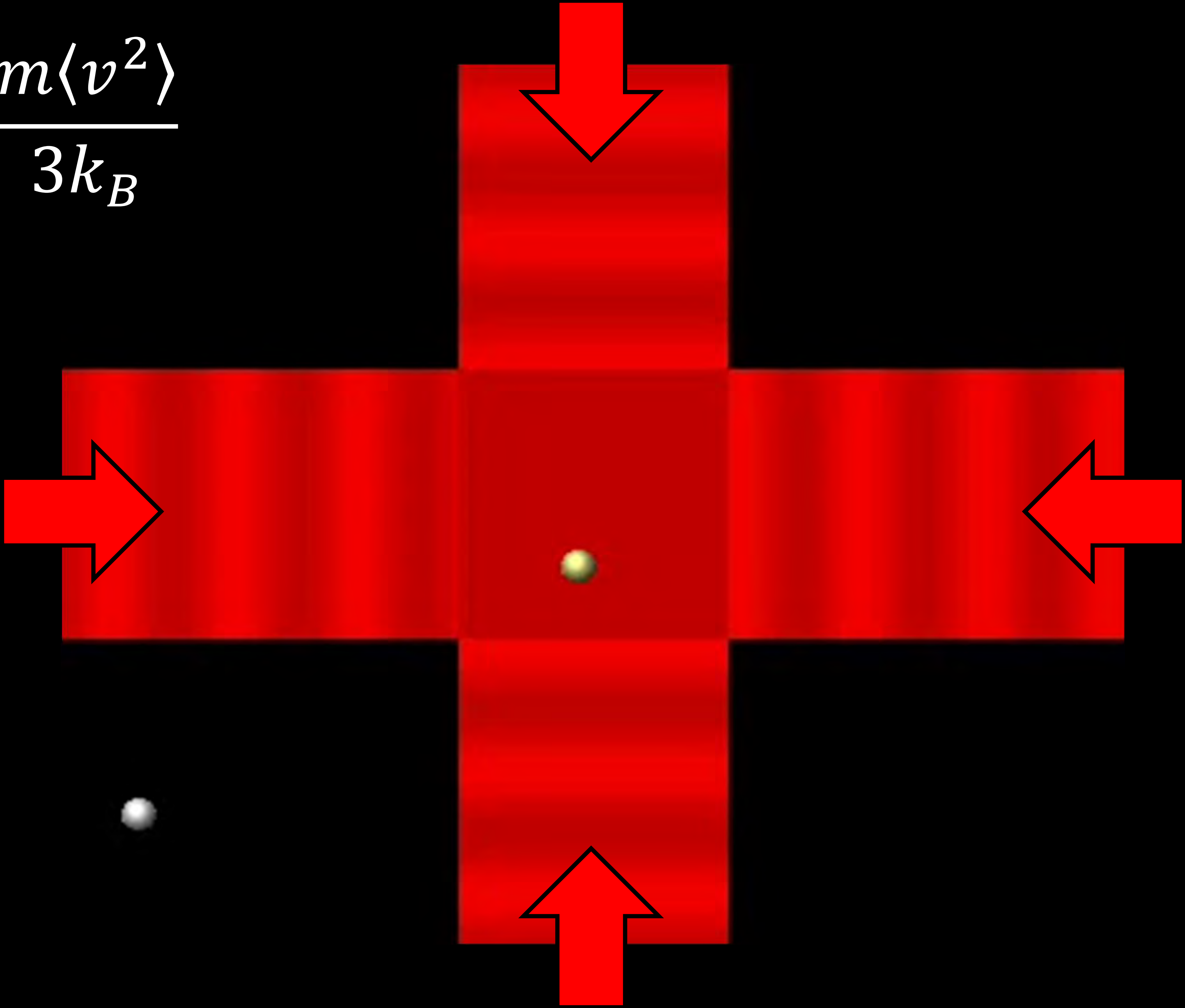
Forza di «attrito» (melassa ottica)

↓

RAFFREDDAMENTO

Raffreddamento laser

$$T = \frac{m\langle v^2\rangle}{3k_B}$$



Raffreddamento laser

Una nuvola di atomi ultrafreddi di ^{87}Rb

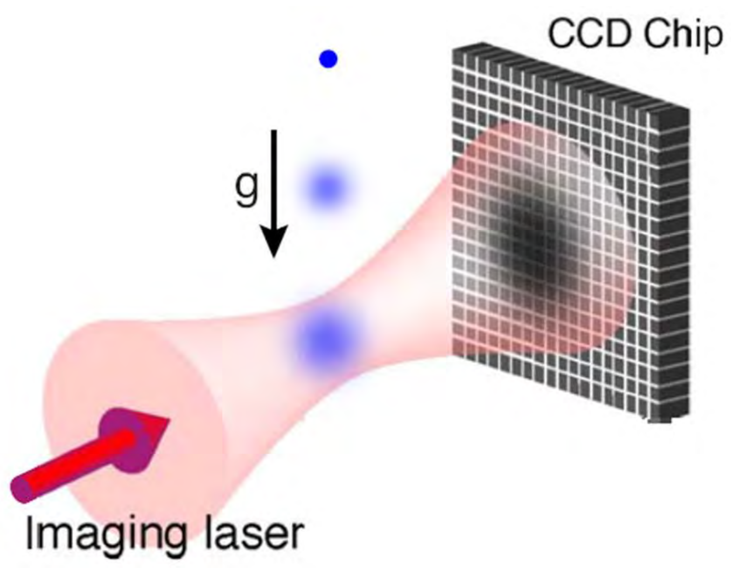
$N \approx 10^{10}$

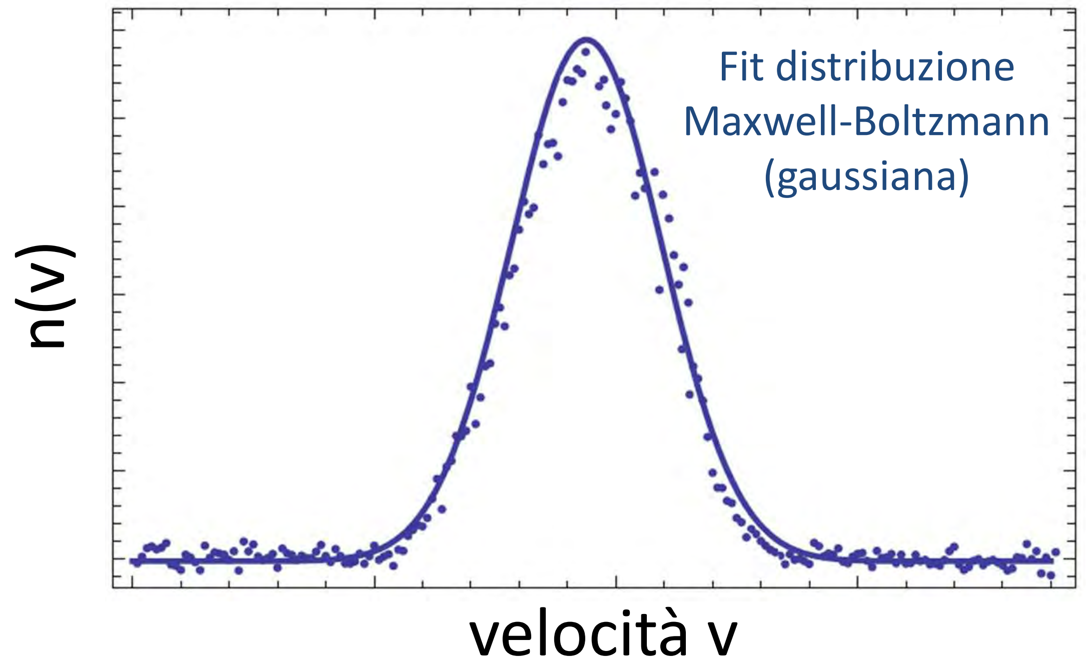
$T \approx 10\ \mu K$

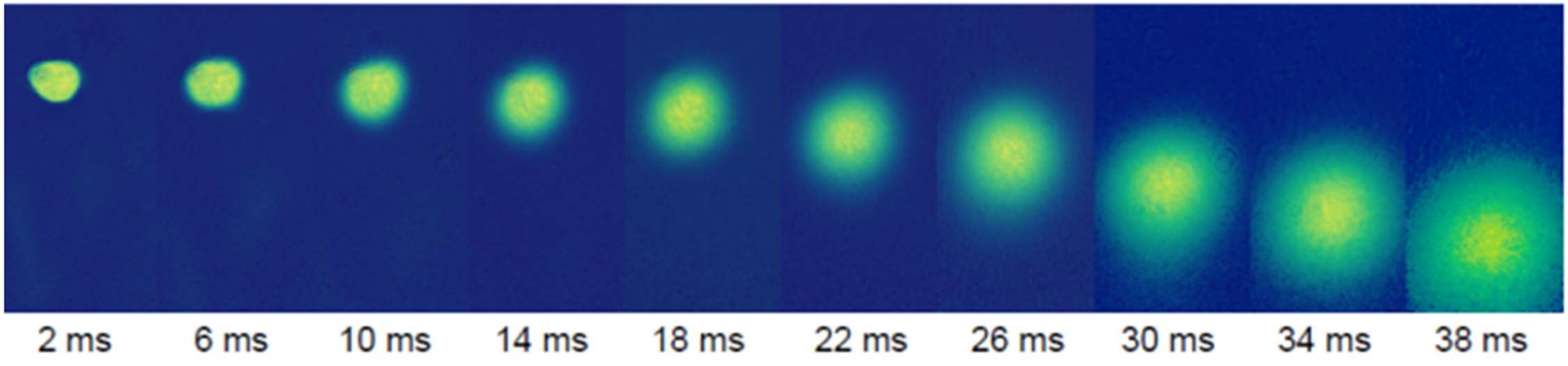
Credits: Chiara Fort

Quale termometro?

Imaging di assorbimento in tempo di volo (misura diretta di velocità)

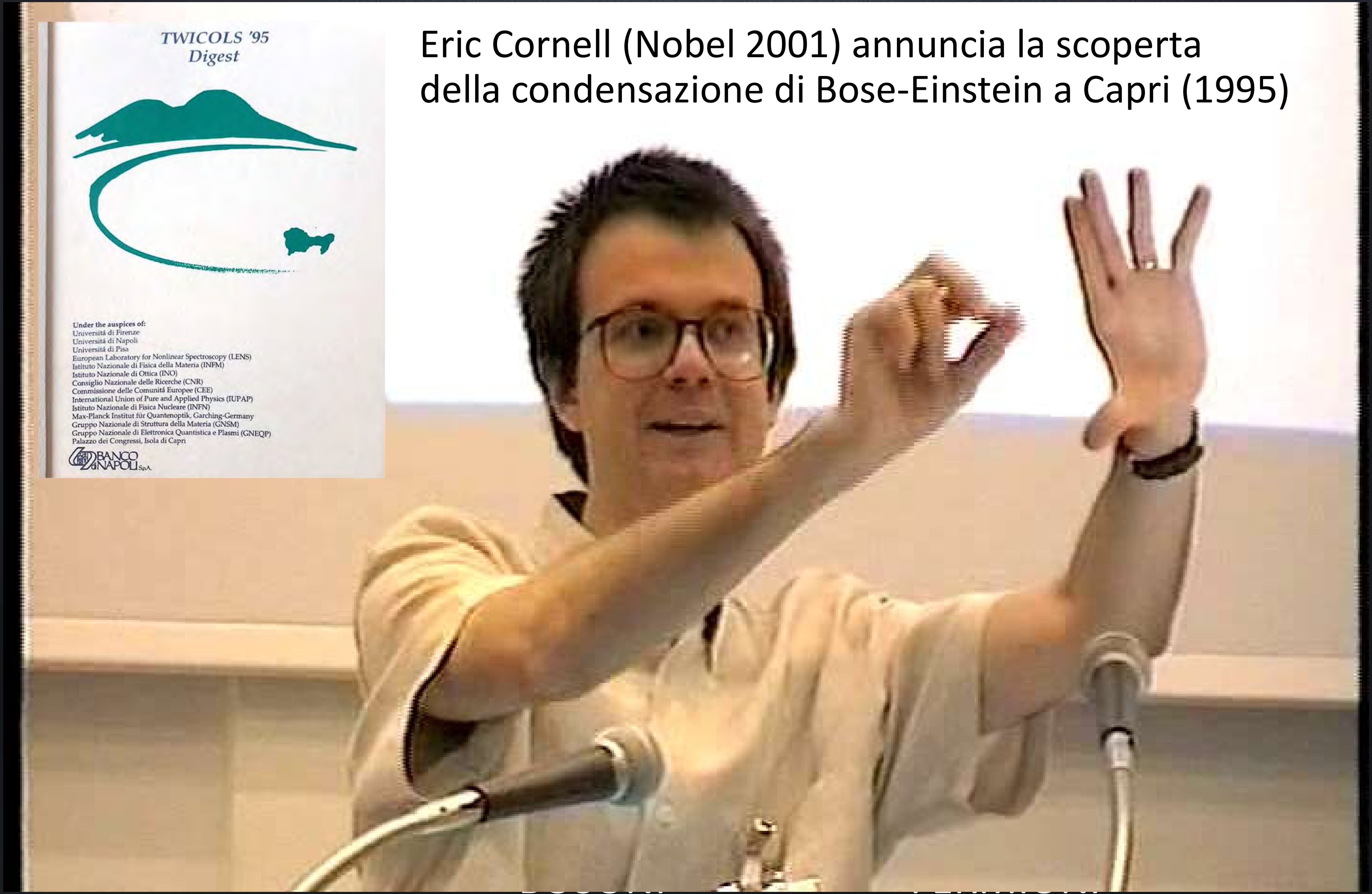






Condensati di Bose-Einstein

Gas quantistici



Eric Cornell (Nobel 2001) annuncia la scoperta della condensazione di Bose-Einstein a Capri (1995)

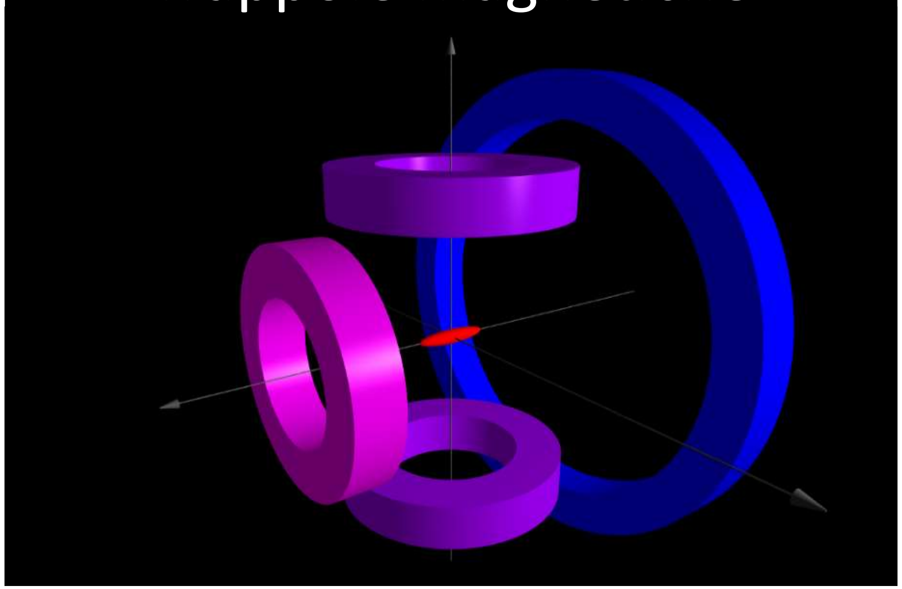
TWICOLS '95
Digest

Under the auspices of:
Universitá di Firenze
Universitá di Napoli
Universitá di Pisa
European Laboratory for Nonlinear Spectroscopy (LENS)
Istituto Nazionale di Fisica della Materia (INFM)
Istituto Nazionale di Ottica (INO)
Consiglio Nazionale delle Ricerche (CNR)
Commissione delle Comunitá Europee (CEE)
International Union of Pure and Applied Physics (IUPAP)
Istituto Nazionale di Fisica Nucleare (INFN)
Max-Planck Institut für Quantenoptik, Garching-Germany
Gruppo Nazionale di Struttura della Materia (GNSM)
Gruppo Nazionale di Elettronica Quantistica e Plasmi (GNEQP)
Palazzo dei Congressi, Isola di Capri

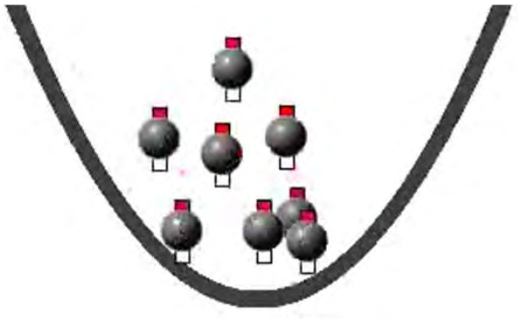
BANCO di NAPOLI SpA.

Trappole magnetiche e ottiche

Trappole magnetiche

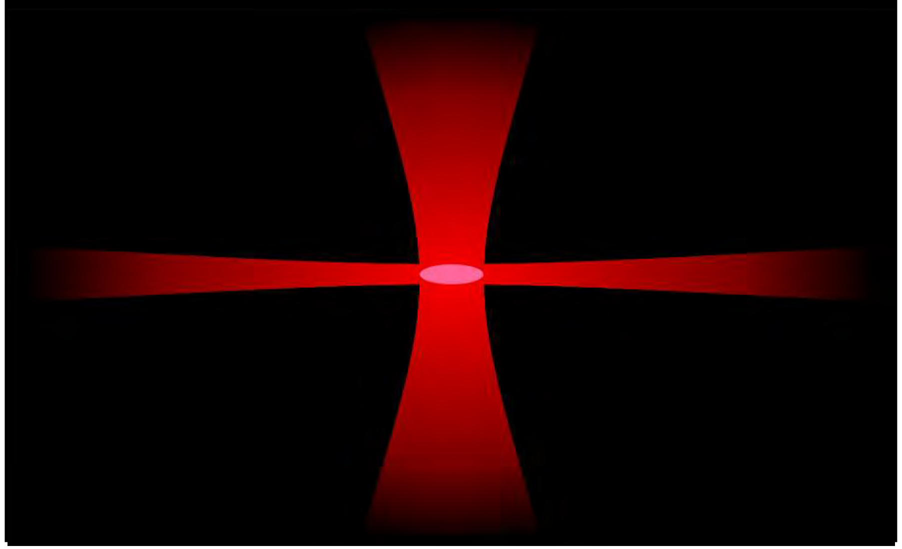


Interazione del dipolo magnetico con **B** generato da elettromagneti

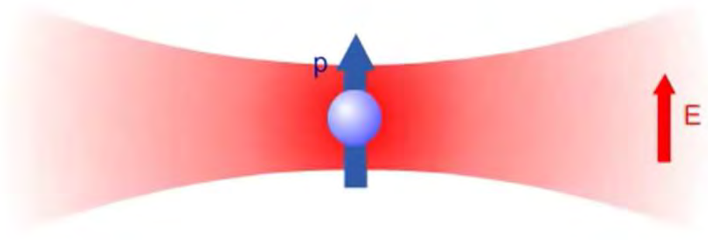


$$U(r) = -\vec{\mu} \cdot \vec{B}(r)$$

Trappole ottiche

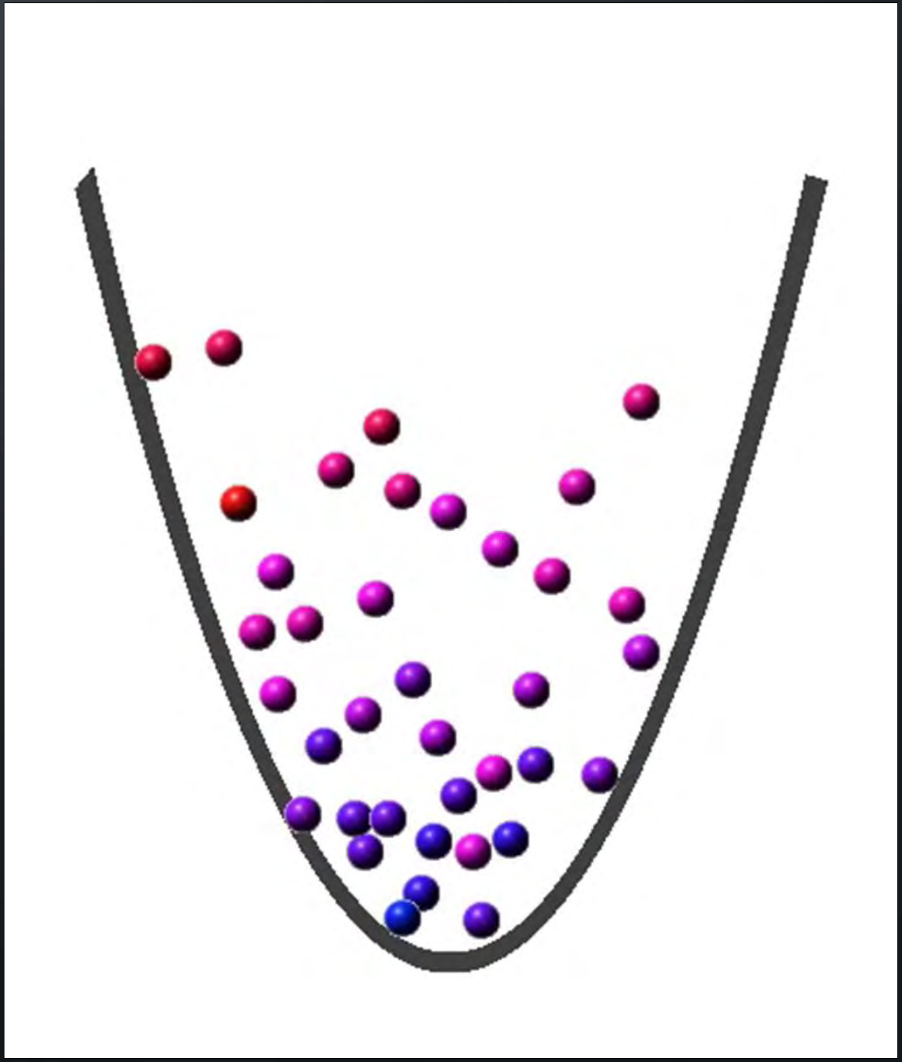


Interazione del dipolo elettrico indotto dal laser con il campo **E** del laser stesso



$$U(r) = -\vec{p} \cdot \vec{E}(r)$$

Raffreddamento evaporativo

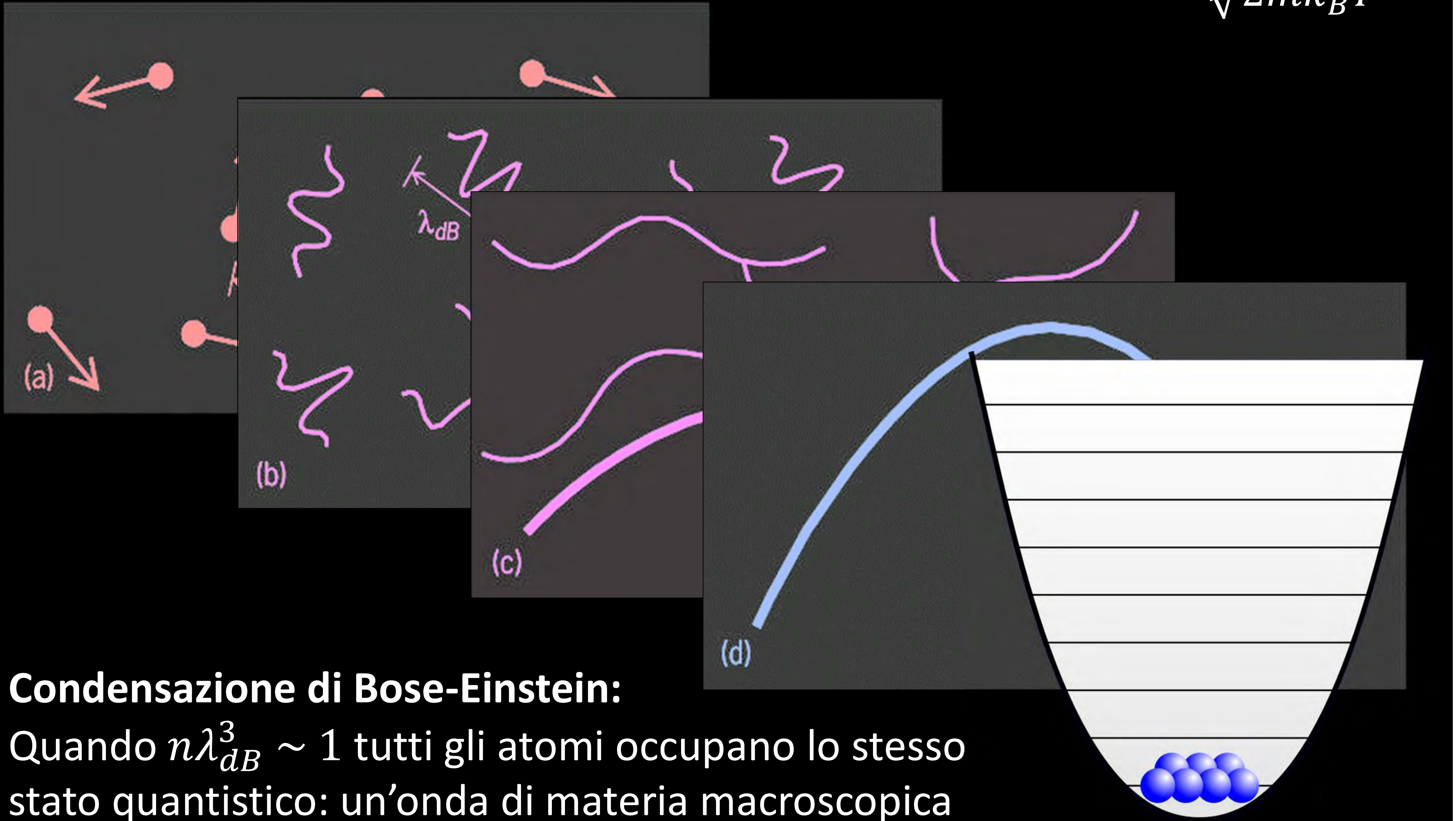


Rimozione degli atomi con energia più alta
+
Termalizzazione degli atomi rimanenti a T più bassa

Condensazione di Bose-Einstein (BEC)

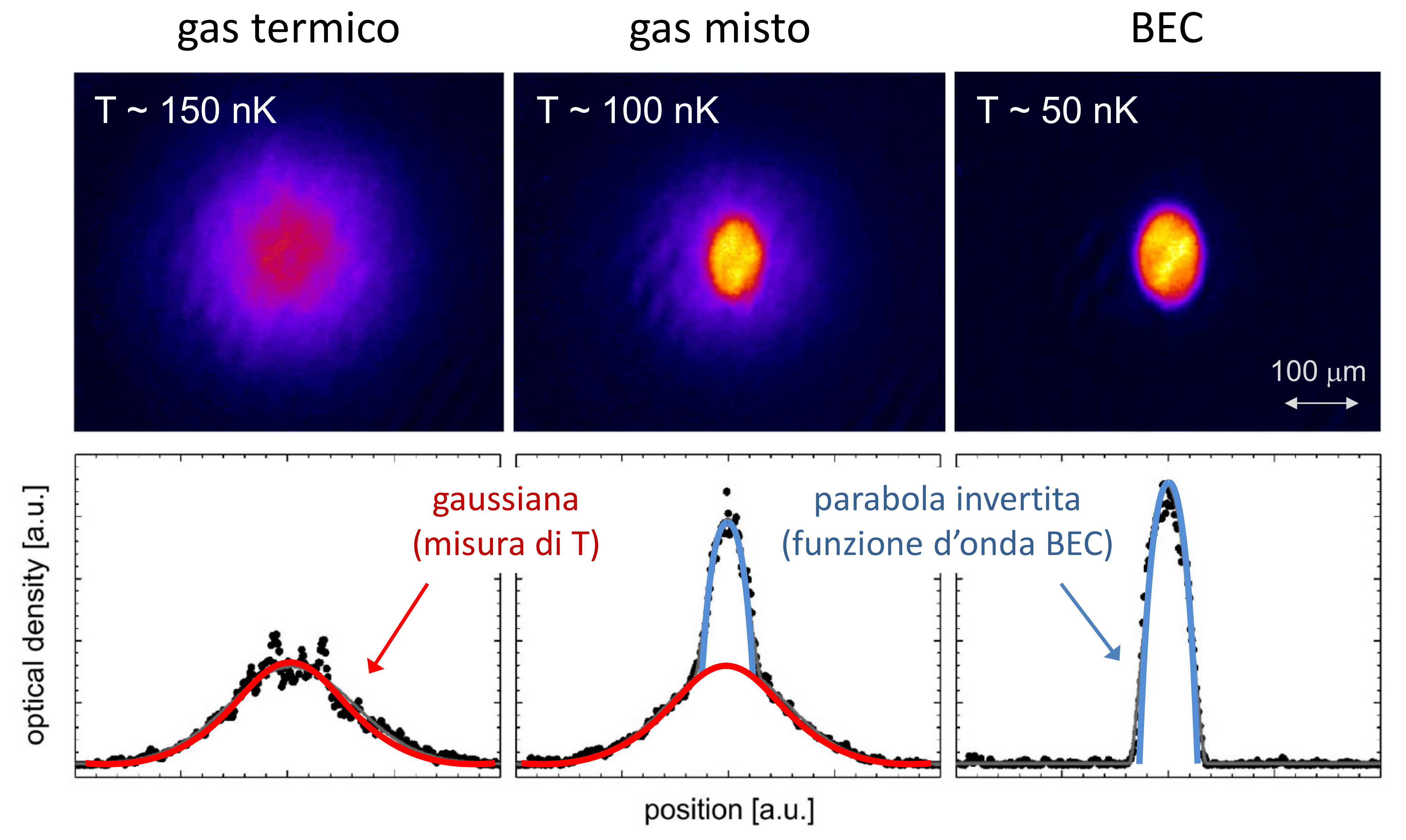
distanza media $d = n^{-1/3}$

l. d'onda de Broglie $\lambda_{dB} = \frac{h}{mv} \rightarrow \frac{h}{\sqrt{2mk_BT}}$



Condensazione di Bose-Einstein:
Quando $n\lambda_{dB}^3 \sim 1$ tutti gli atomi occupano lo stesso stato quantistico: un'onda di materia macroscopica

Condensazione di Bose-Einstein (BEC)



gas termico

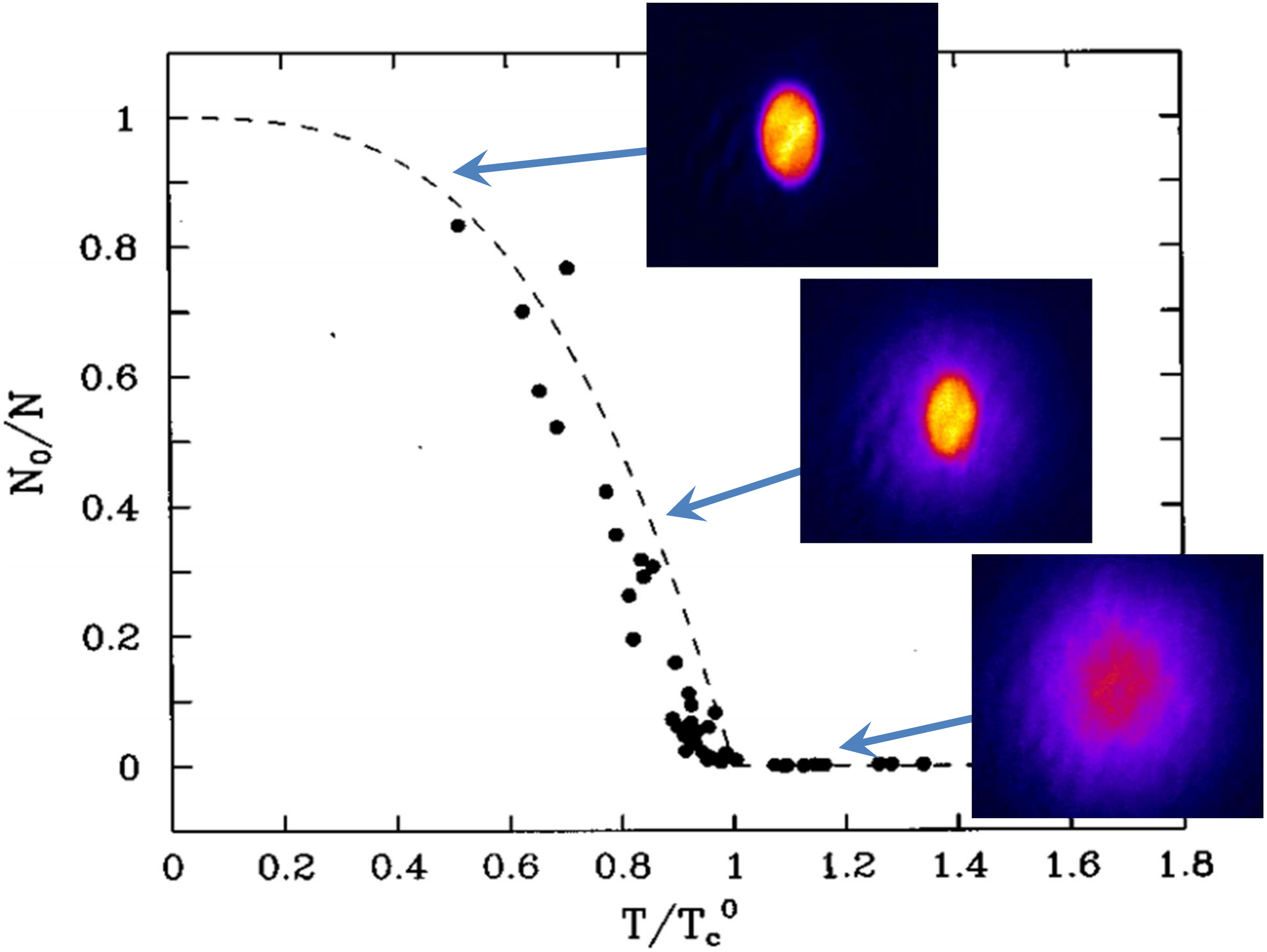
gas misto

BEC

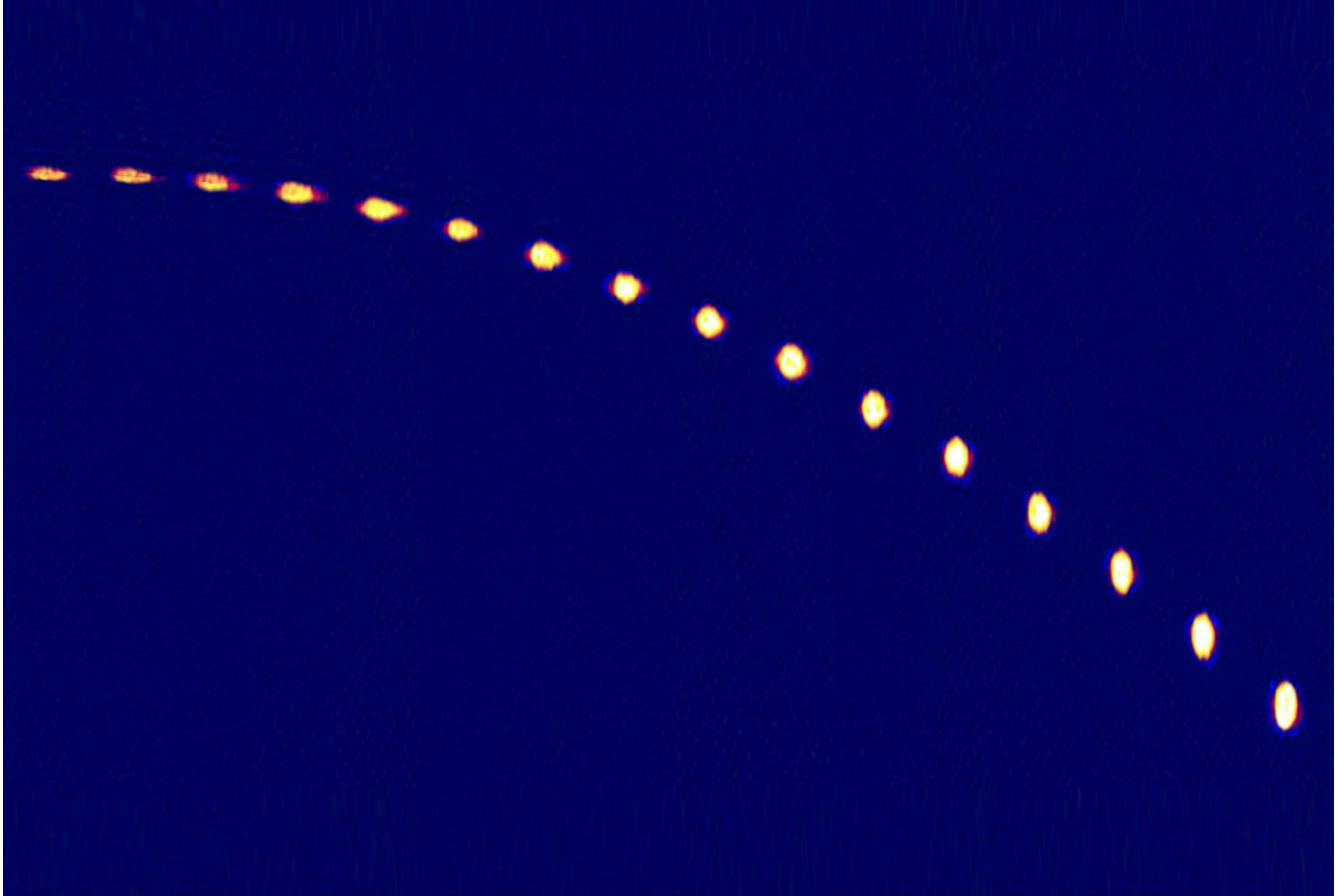
gaussiana
(misura di T)

parabola invertita
(funzione d’onda BEC)

Transizione di fase BEC

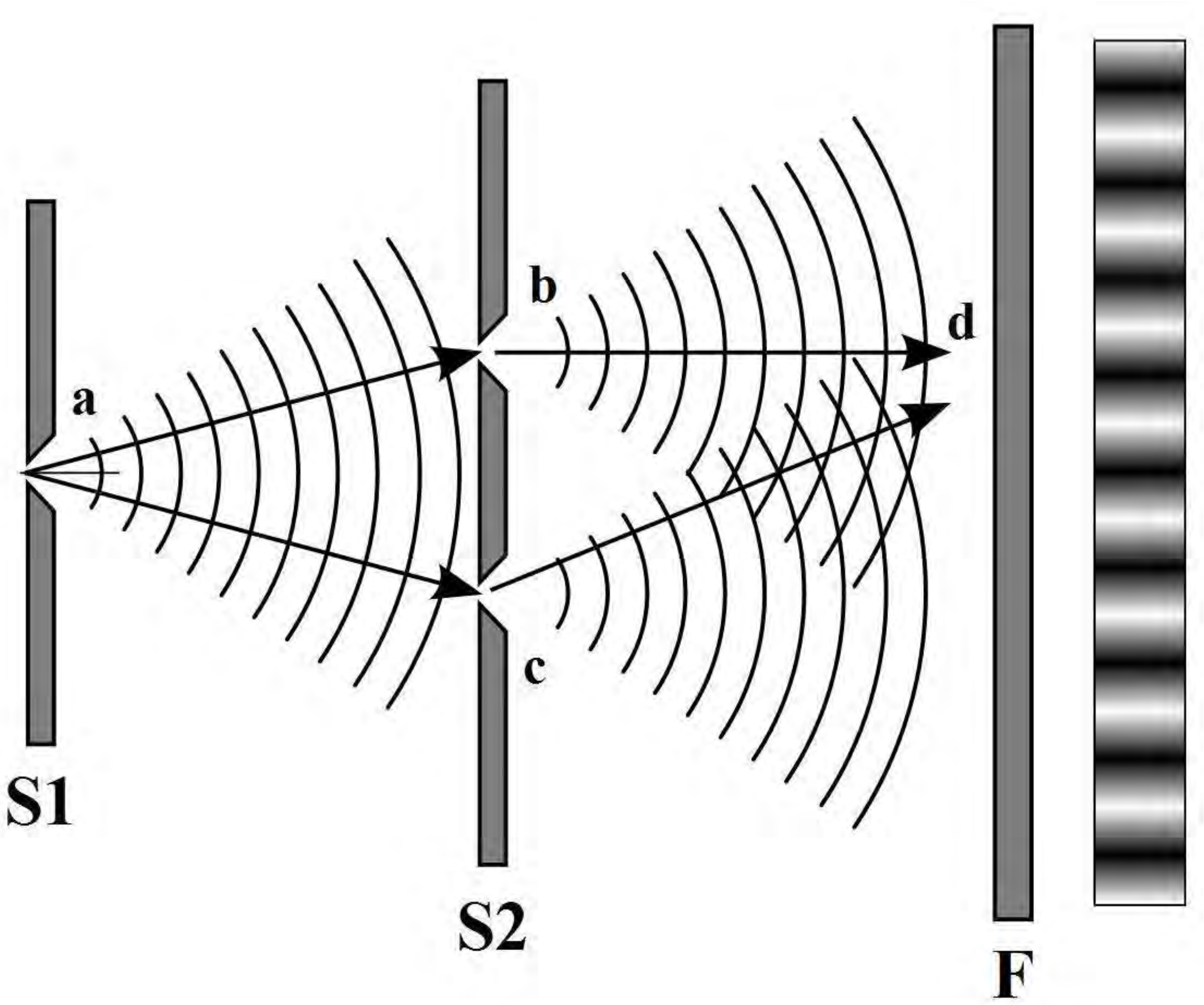


Espansione di un BEC



Coerenza di un’onda

Esperimento della doppia fenditura di Young con la luce:

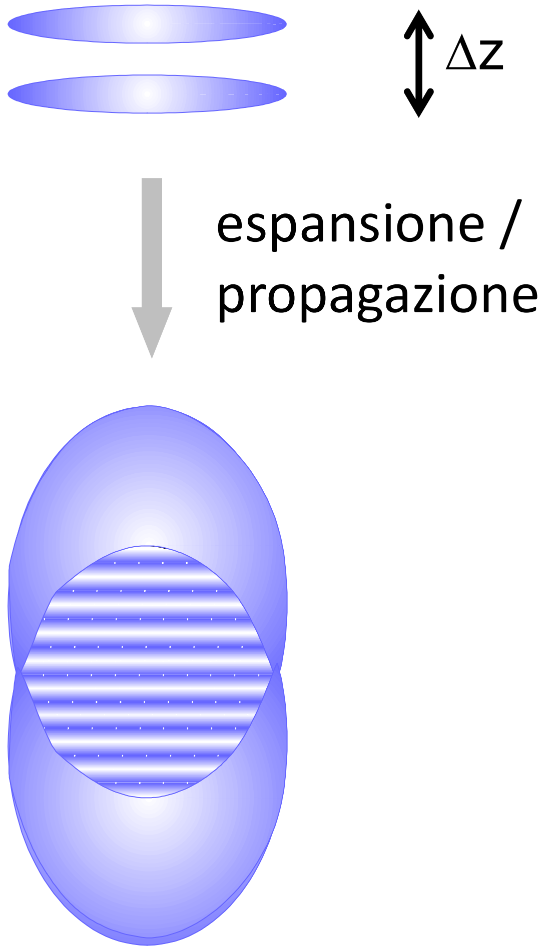


C. Fort et al., Opt. Lett. 26, 1039 (2001)

Coerenza di un BEC

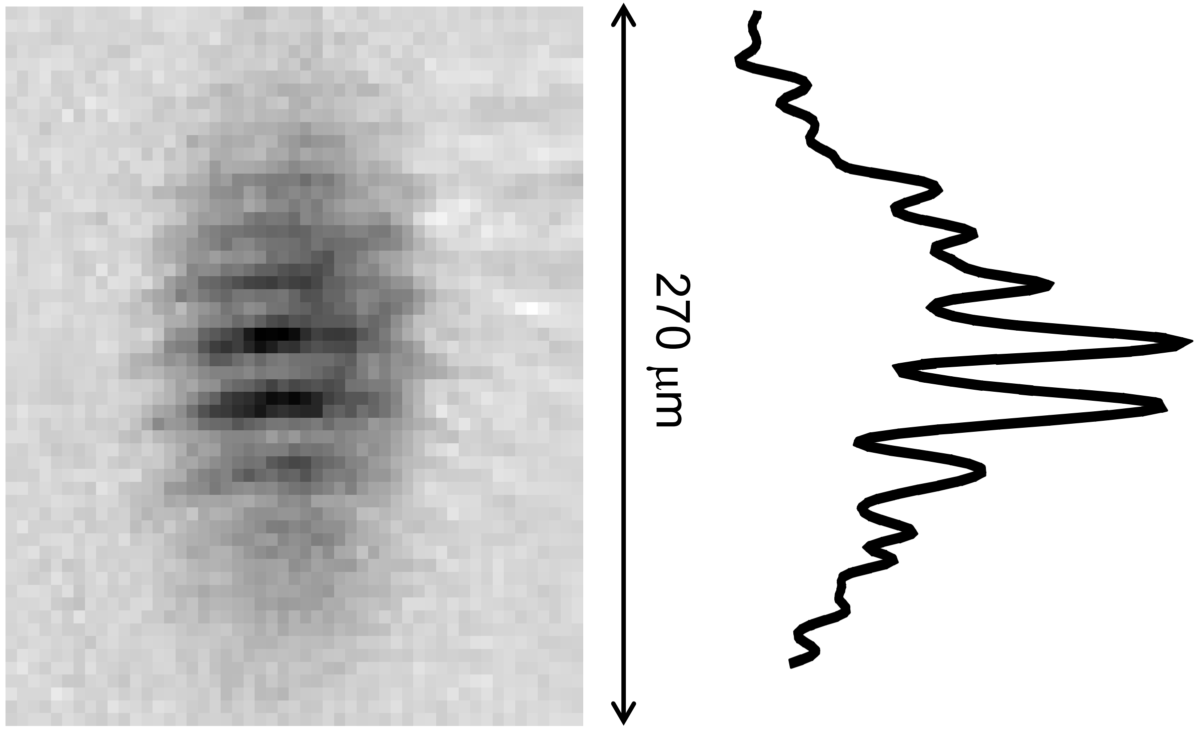
Esperimento della doppia fenditura di Young con 2 BEC:

2 BEC intrappolati



espansione /
propagazione

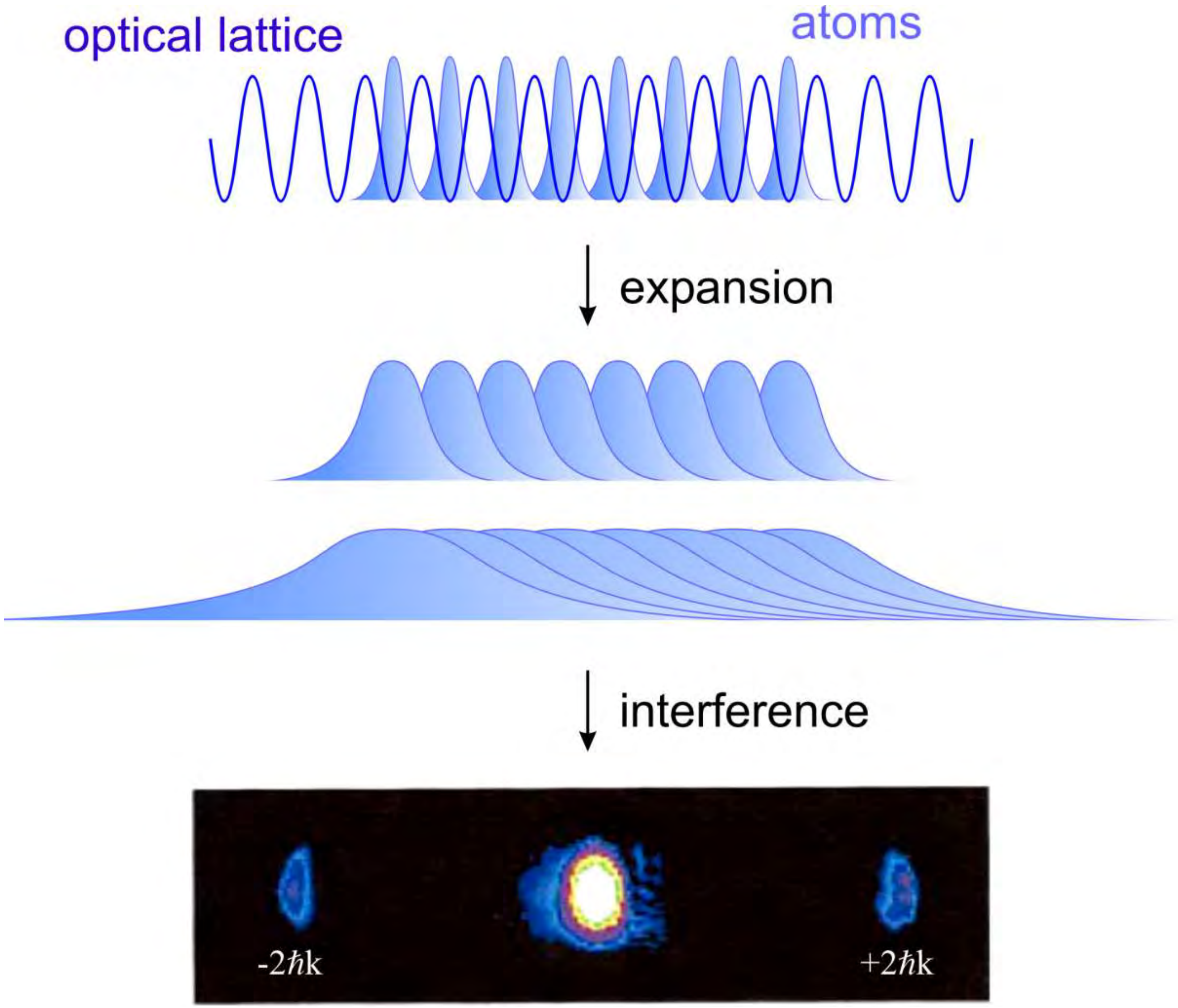
Interferenza ad alto contrasto:
coerenza quantistica di un BEC
(funzione d’onda macroscopia)



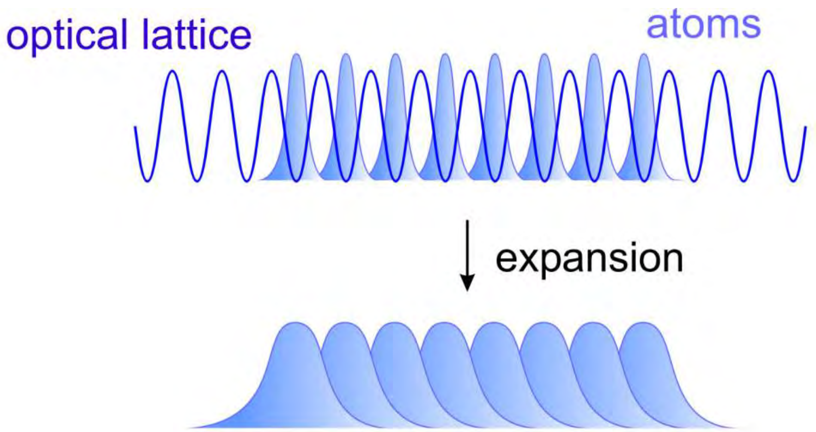
P. Pedri et al., PRL ***87****, 220401 (2001)*

Coerenza di un BEC

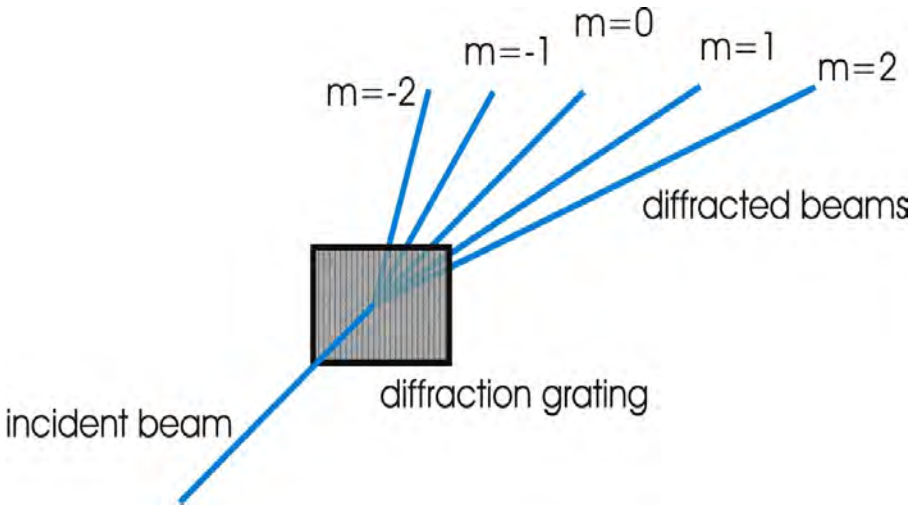
Interferenza da fenditure multiple

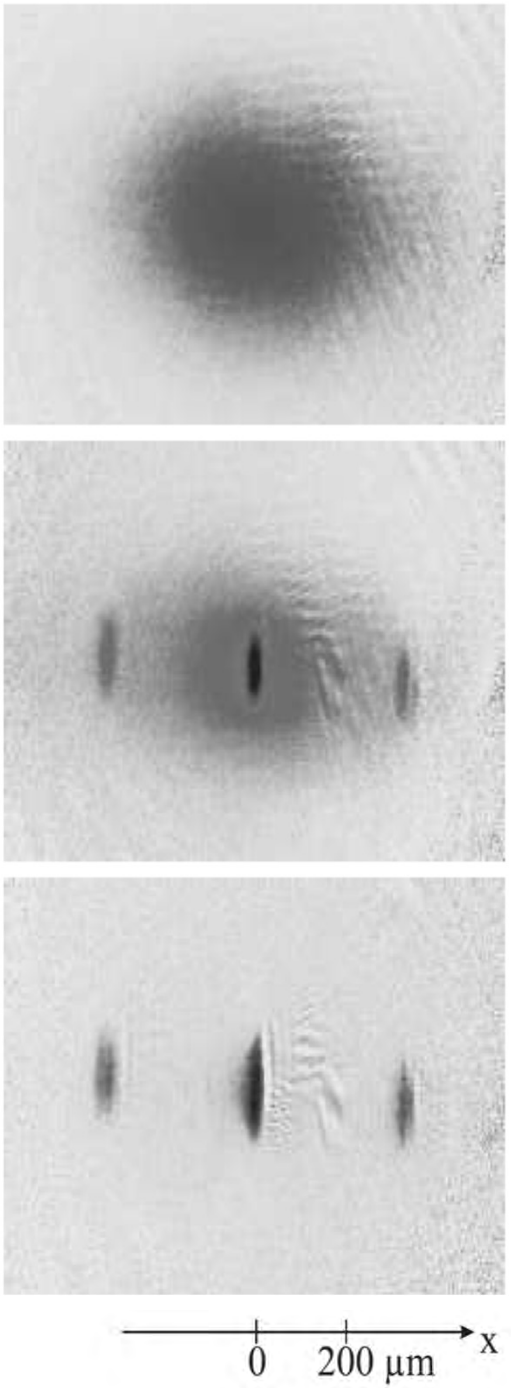


Coerenza di un BEC



analogia ottica: reticolo di diffrazione





gas termico
(T = 210 nK)
incoerente

gas misto
(T = 110 nK)

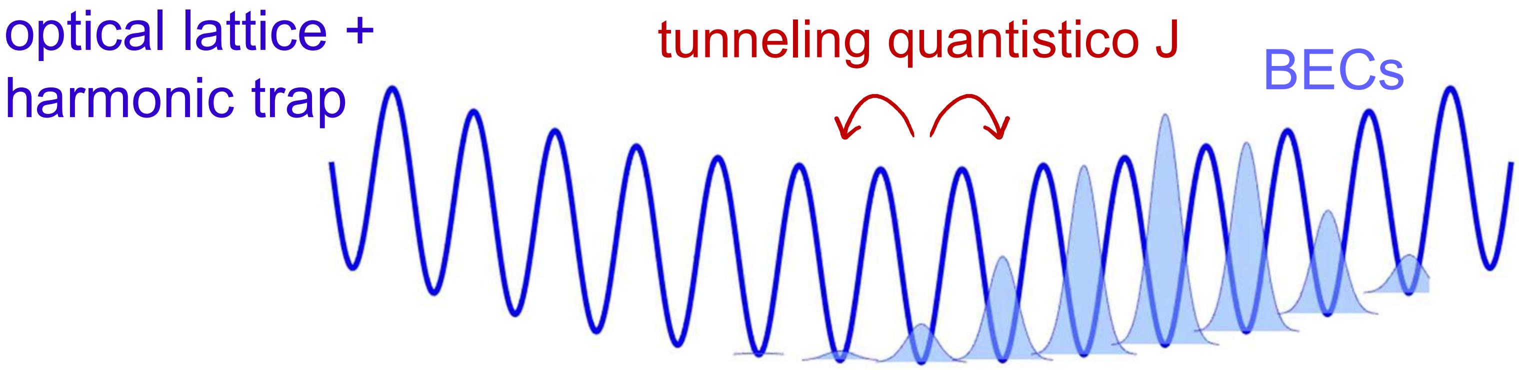
BEC
(T < 50 nK)
coerente

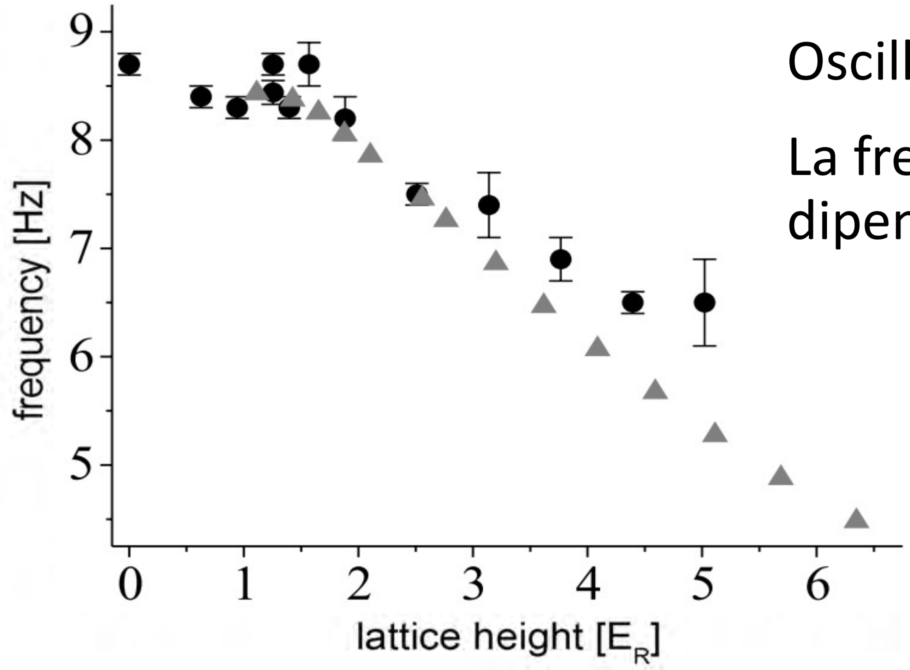
*F. S. Cataliotti et al., Science **293**, 843 (2001)*

Superfluidità di un BEC

Catene di giunzioni Josephson atomiche con BECs in reticoli ottici

Trasporto superfluido e coerenza quantistica

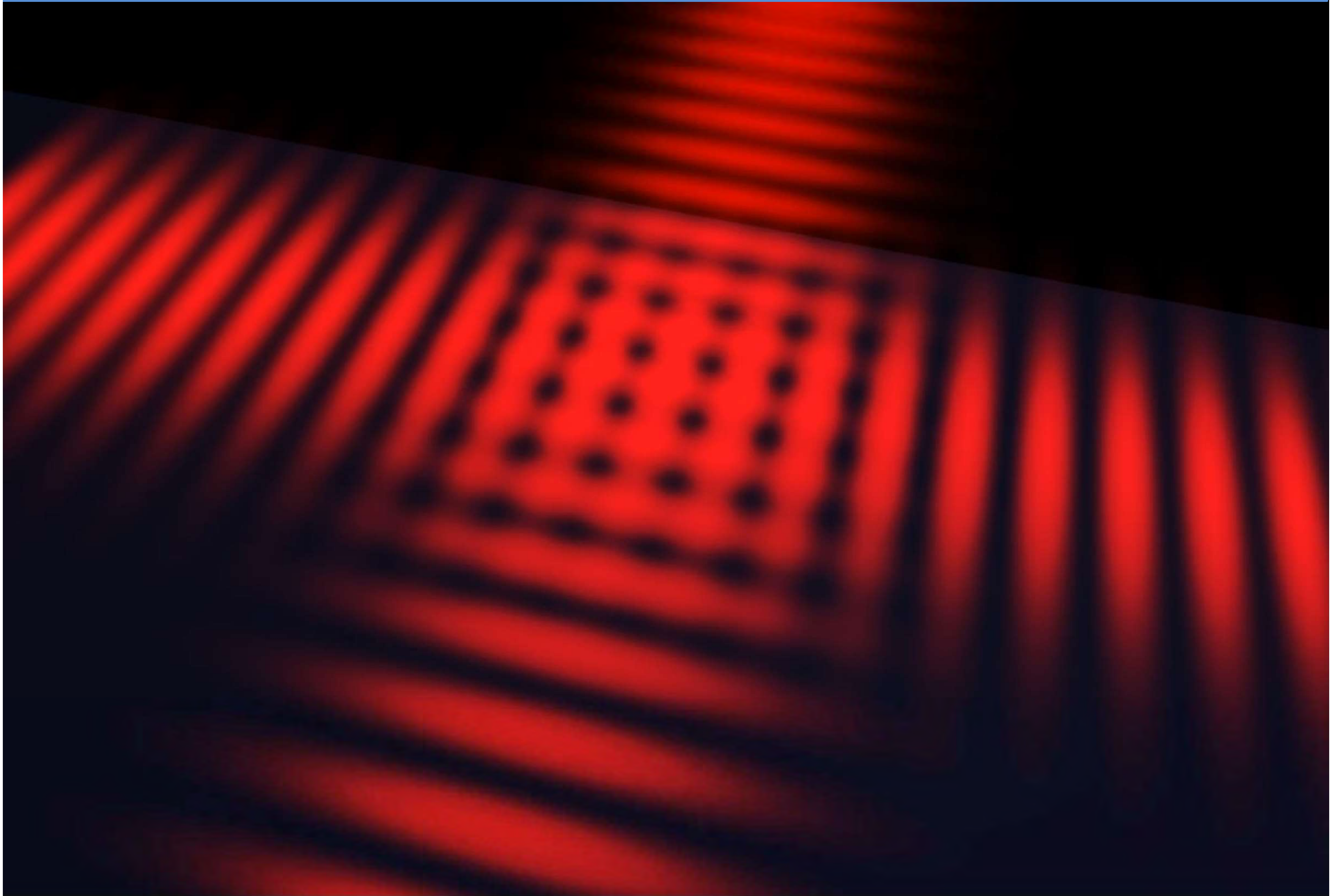




Oscillazioni coerenti

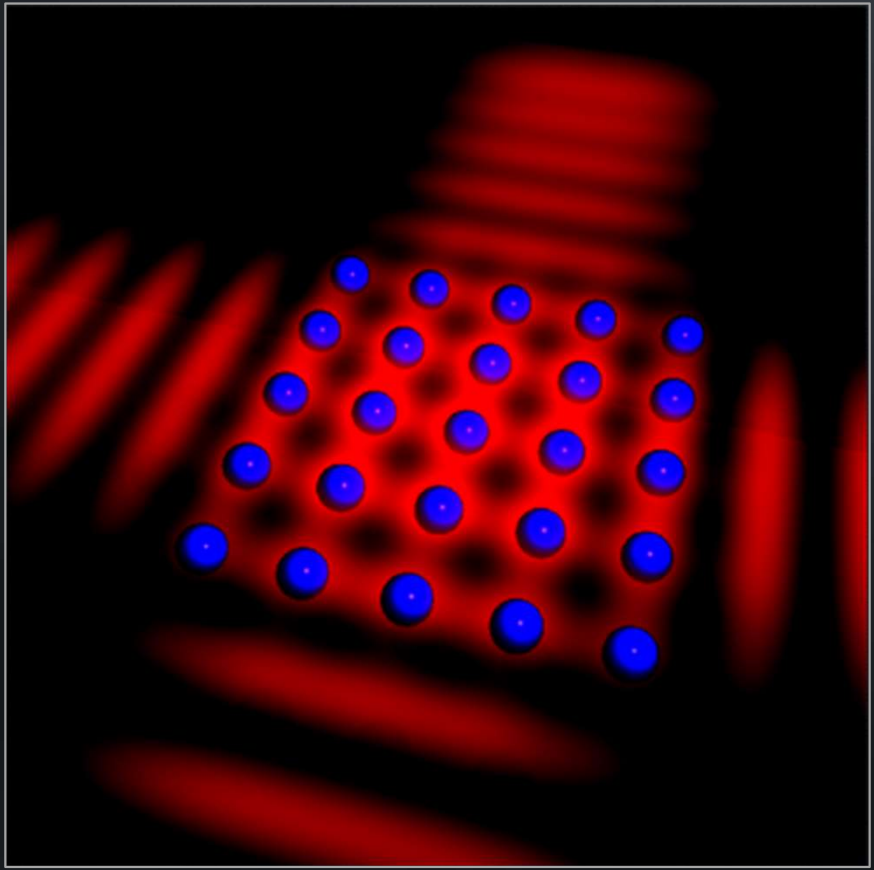
La frequenza di oscillazione dipende da J

Reticoli ottici

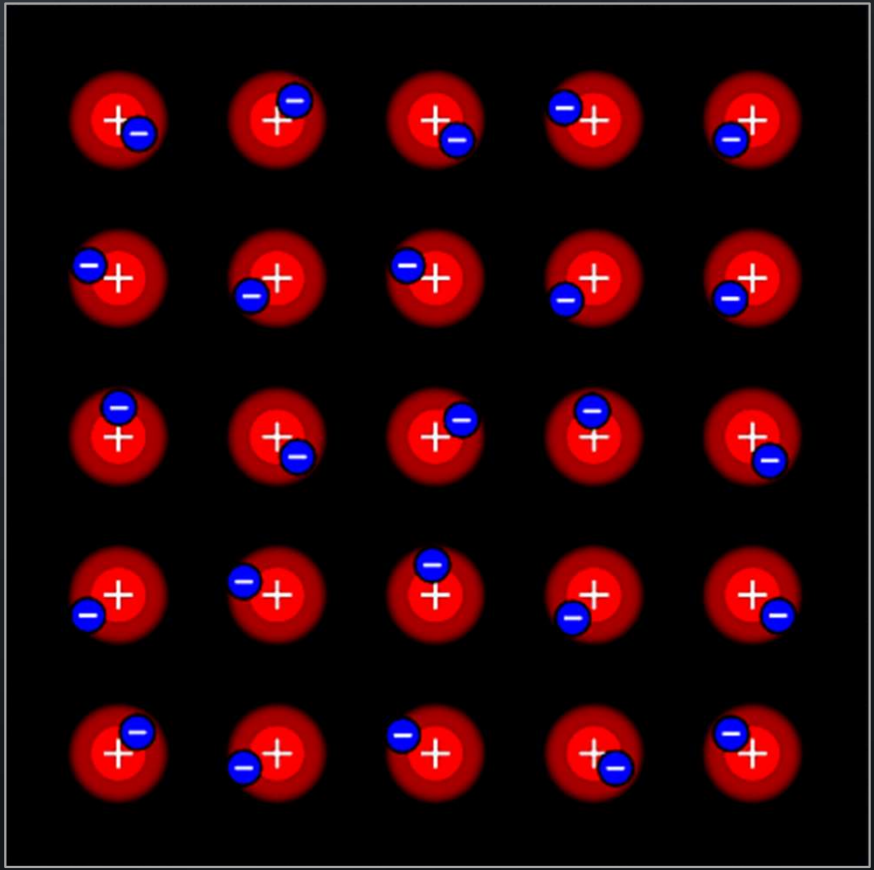


Reticoli ottici come cristalli ideali

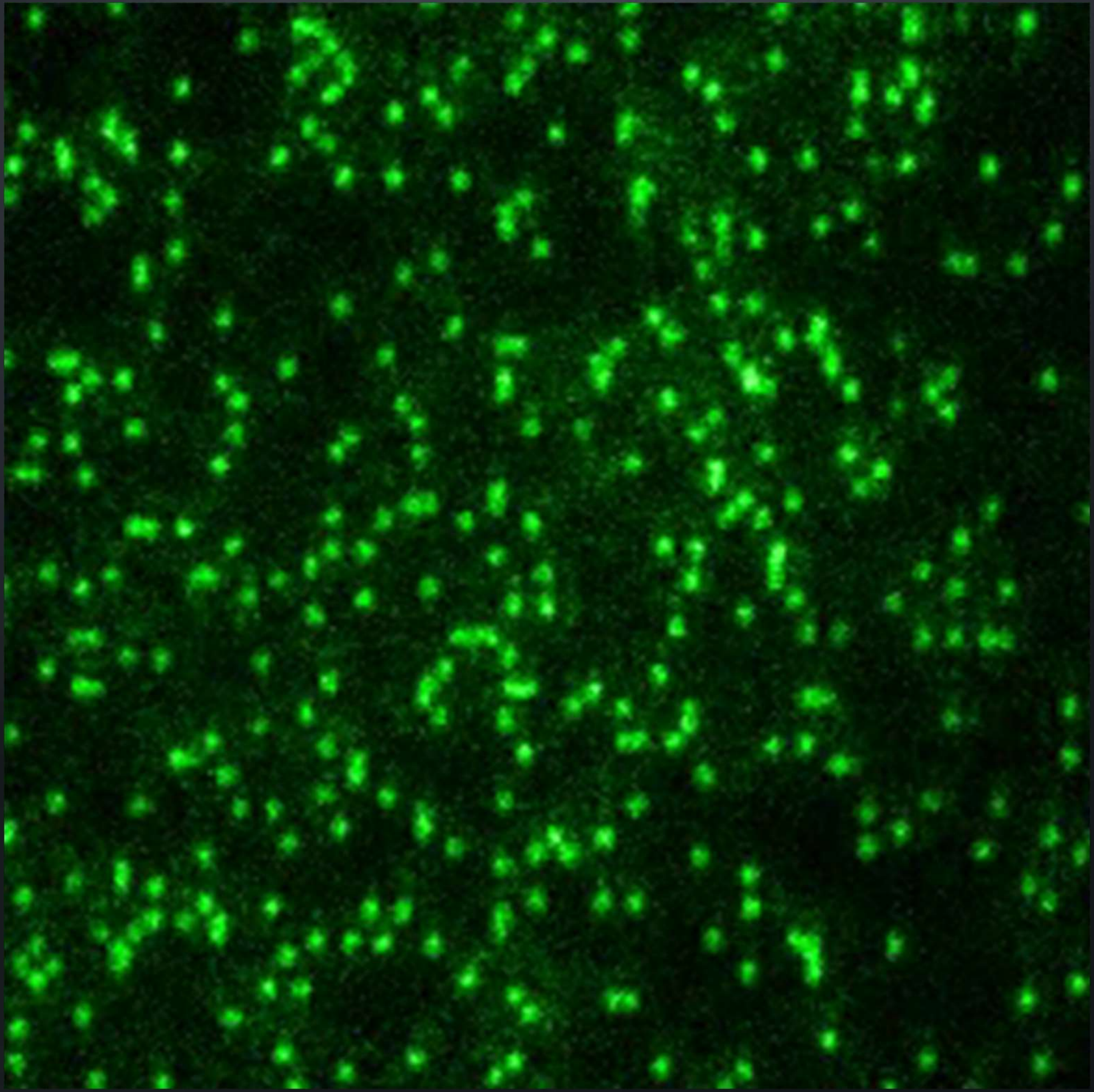
atomi in reticoli ottici



elettroni in un solido cristallino



Reticoli ottici come cristalli ideali



P. W. Anderson, Phys. Rev. ***109****, 1492 (1958)*

Localizzazione di Anderson

PHYSICAL REVIEW VOLUME 109, NUMBER 5 MARCH 1, 1958

Absence of Diffusion in Certain Random Lattices

P. W. ANDERSON
Bell Telephone Laboratories, Murray Hill, New Jersey

(Received October 10, 1957)

This paper presents a simple model for such processes as spin diffusion or conduction in the "impurity band." These processes involve transport in a lattice which is in some sense random, and in them diffusion is expected to take place via quantum jumps between localized sites. In this simple model the essential randomness is introduced by requiring the energy to vary randomly from site to site. It is shown that at low enough densities no diffusion at all can take place, and the criteria for transport to occur are given.

I. INTRODUCTION

A NUMBER of physical phenomena seem to involve quantum-mechanical motion, without any particular thermal activation, among sites at which the mobile entities (spins or electrons, for example) may be localized. The clearest case is that of spin diffusion[1,2]; another might be the so-called impurity band conduction at low concentrations of impurities. In such situations we suspect that transport occurs not by motion of free carriers (or spin waves), scattered as they move through a medium, but in some sense by quantum-mechanical jumps of the mobile entities from site to site. A second common feature of these phenomena is randomness: random spacings of impurities, random interactions with the "atmosphere" of other impurities, random arrangements of electronic or nuclear spins, etc.

Our eventual purpose in this work will be to lay the foundation for a quantum-mechanical theory of transport problems of this type. Therefore, we must start with simple theoretical models rather than with the complicated experimental situations on spin diffusion or impurity conduction. In this paper, in fact, we attempt only to construct, for such a system, the simplest model we can think of which still has some expectation of representing a real physical situation reasonably well, and to prove a theorem about the model. The theorem is that at sufficiently low densities, transport does not take place; the exact wave functions are localized in a small region of space. We also obtain a fairly good estimate of the critical density at which the theorem fails. An additional criterion is that the forces be of sufficiently short range—actually, falling off as $r \rightarrow \infty$ faster than $1/r^3$—and we derive a rough estimate of the rate of transport in the $V \propto 1/r^3$ case.

Such a theorem is of interest for a number of reasons: first, because it may apply directly to spin diffusion among donor electrons in Si, a situation in which Feher[3] has shown experimentally that spin diffusion is negligible; second, and probably more important, as an example of a real physical system with an infinite number of degrees of freedom, having no obvious oversimplification, in which the approach to equilibrium is simply impossible; and third, as the irreducible minimum from which a theory of this kind of transport, if it exists, must start. In particular, it re-emphasizes the caution with which we must treat ideas such as "the thermodynamic system of spin interactions" when there is no obvious contact with a real external heat bath.

The simplified theoretical model we use is meant to represent reasonably well one kind of experimental situation: namely, spin diffusion under conditions of

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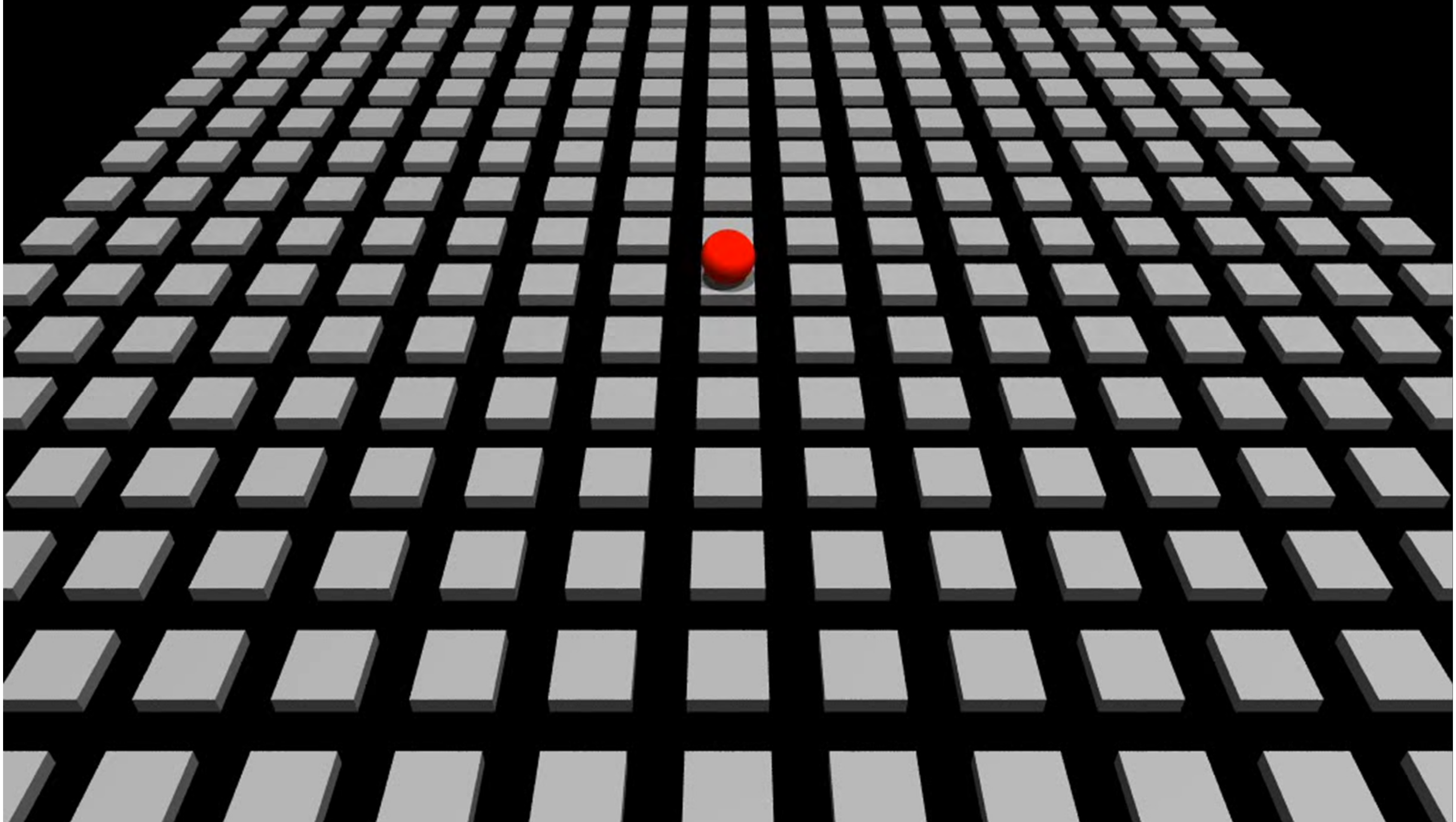
[1] N. Bloembergen, Physica **15**, 386 (1949).
[2] A. M. Portis, Phys. Rev. **104**, 584 (1956).
[3] G. Feher (private communication).

Localizzazione di Anderson

moto in un reticolo ideale senza disordine

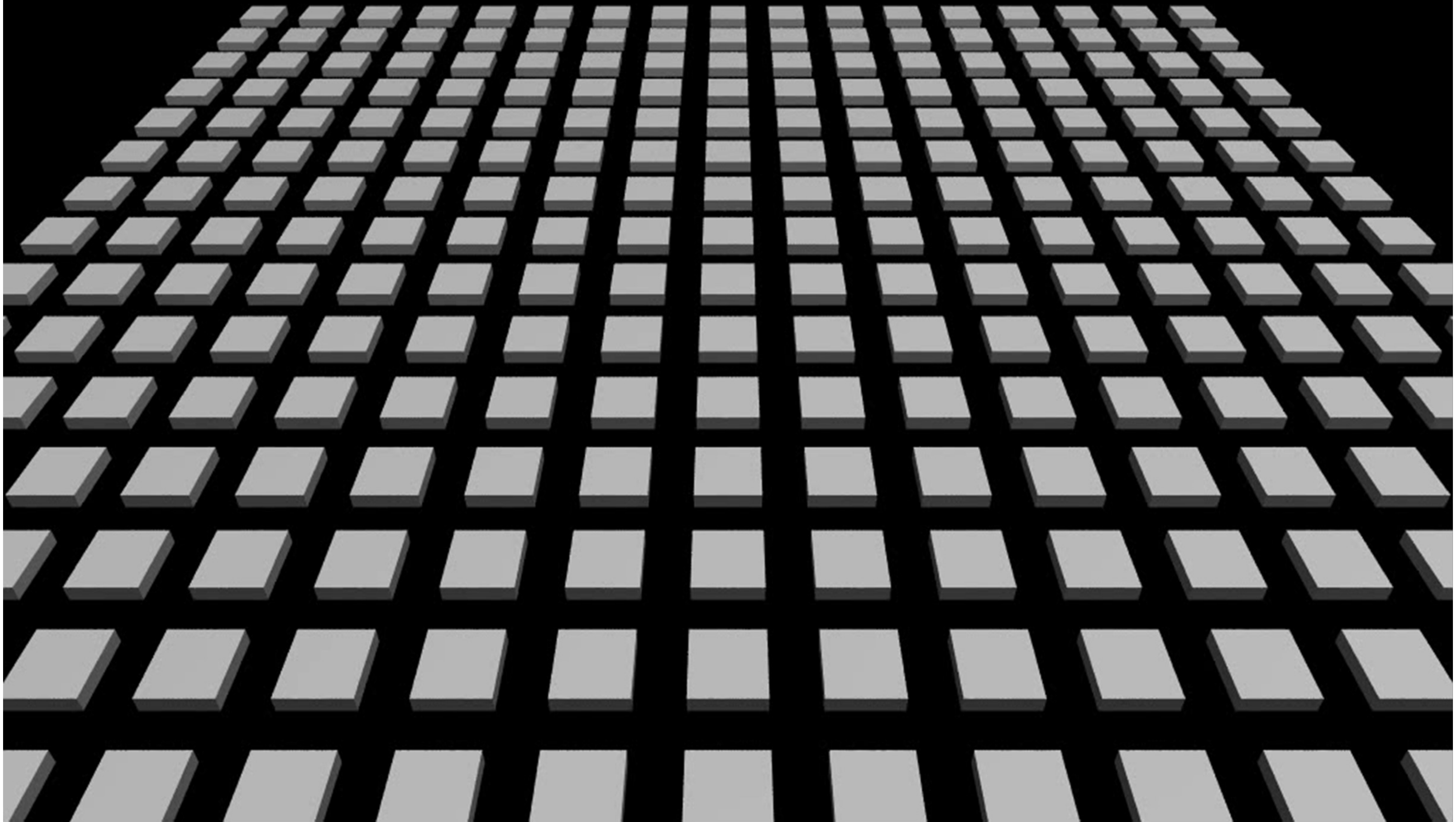
TRASPORTO (SUPERFLUIDO)



*L. Fallani et al., PRL **98**, 130404 (2007)*

Localizzazione di Anderson

reticolo disordinato

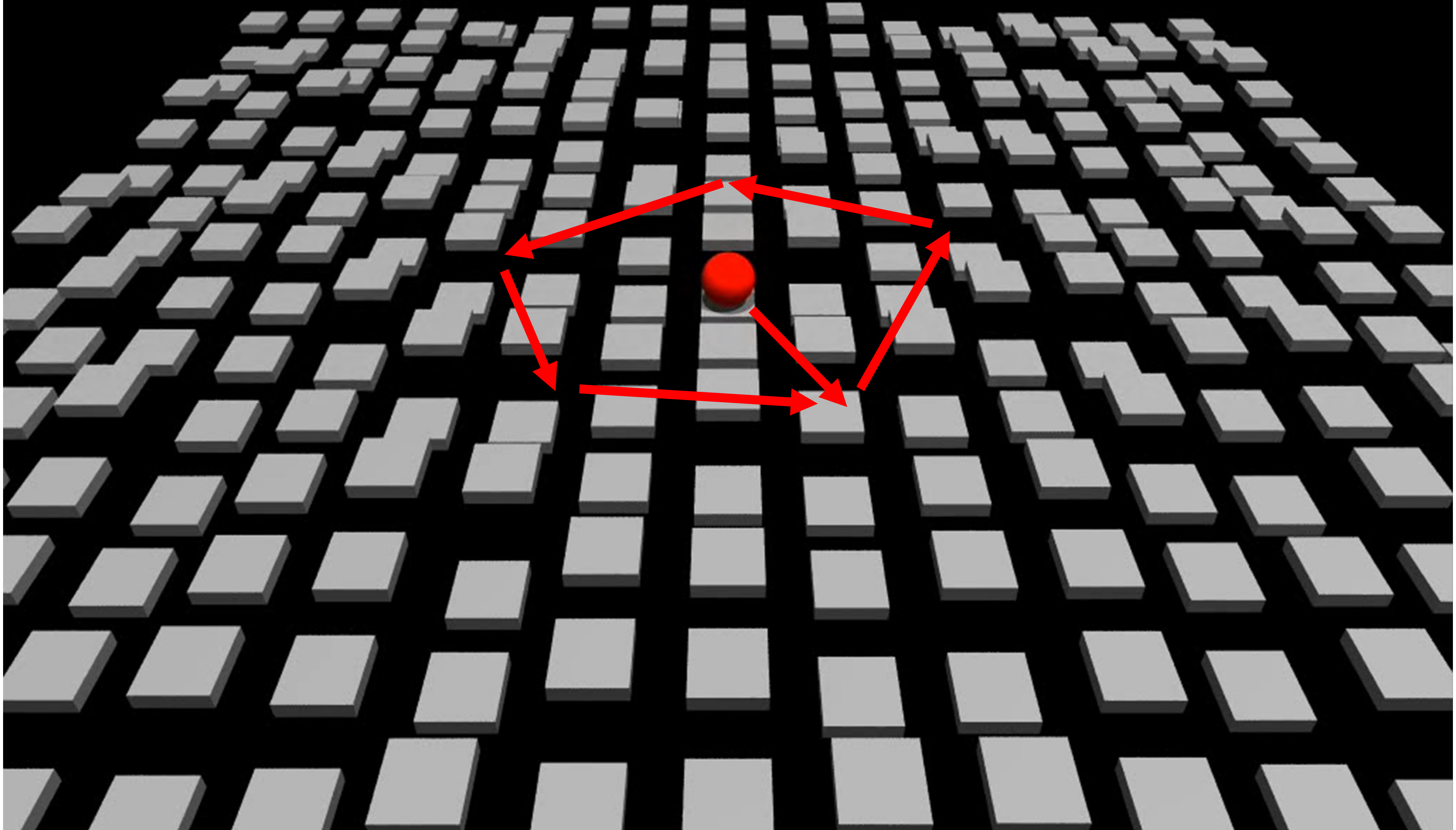


Localizzazione di Anderson

*L. Fallani et al., PRL **98**, 130404 (2007)*

moto in un reticolo disordinato

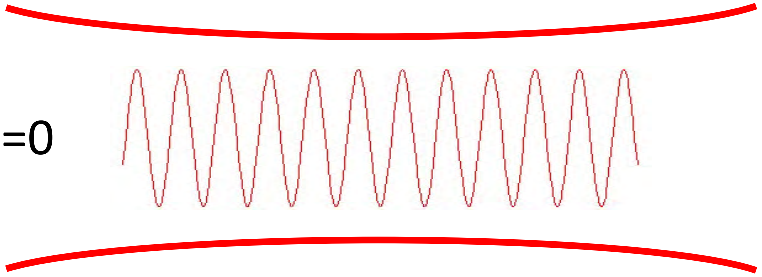
LOCALIZZAZIONE



G. Roati et al., Nature 453, 895 (2008)

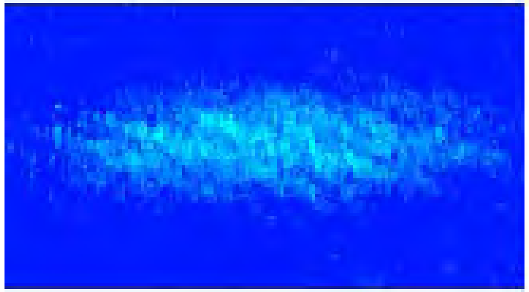
Localizzazione di Anderson

Δ=0

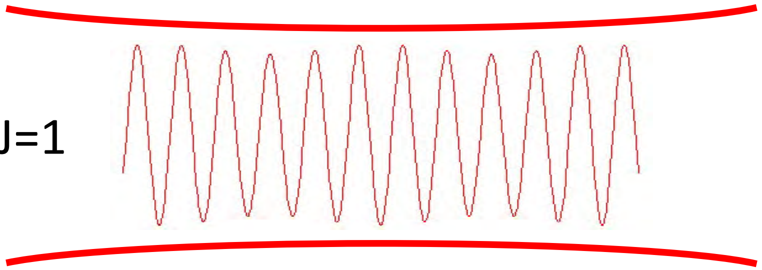


espansione di un BEC
inizialmente confinato

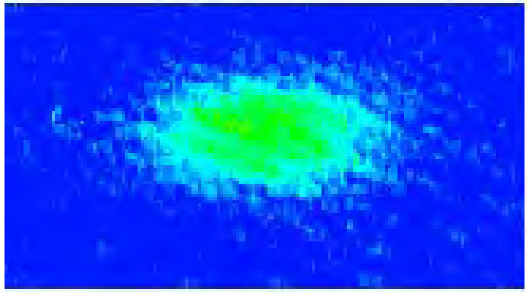
$$\langle r^2\rangle(t) \propto t^2$$



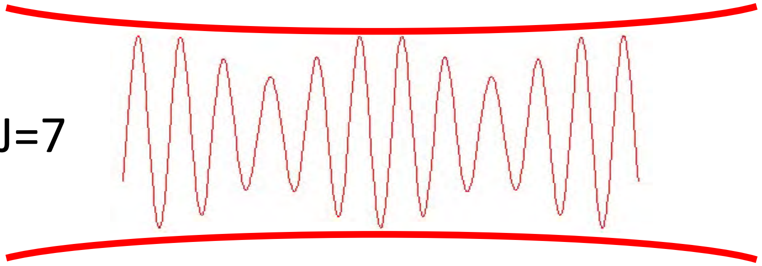
Δ/J=1



espansione
a velocità ridotta

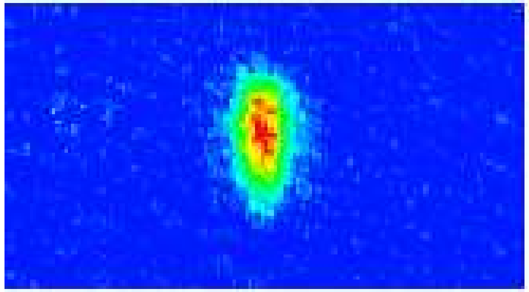


Δ/J=7



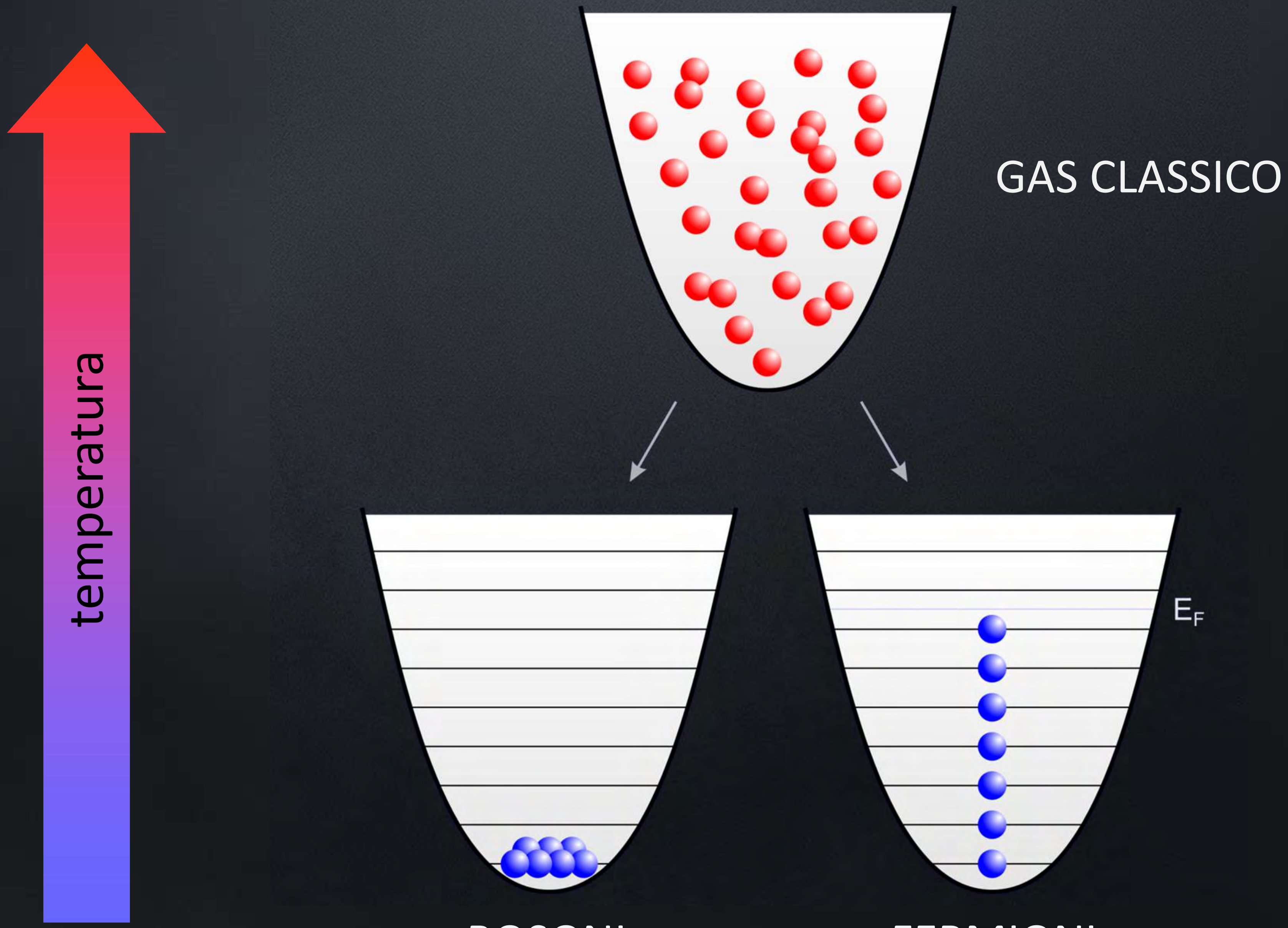
assenza di diffusione

$$\langle r^2\rangle(t) = \langle r^2\rangle(0)$$



Gas di Fermi ultrafreddi

Gas quantistici



temperatura

GAS CLASSICO

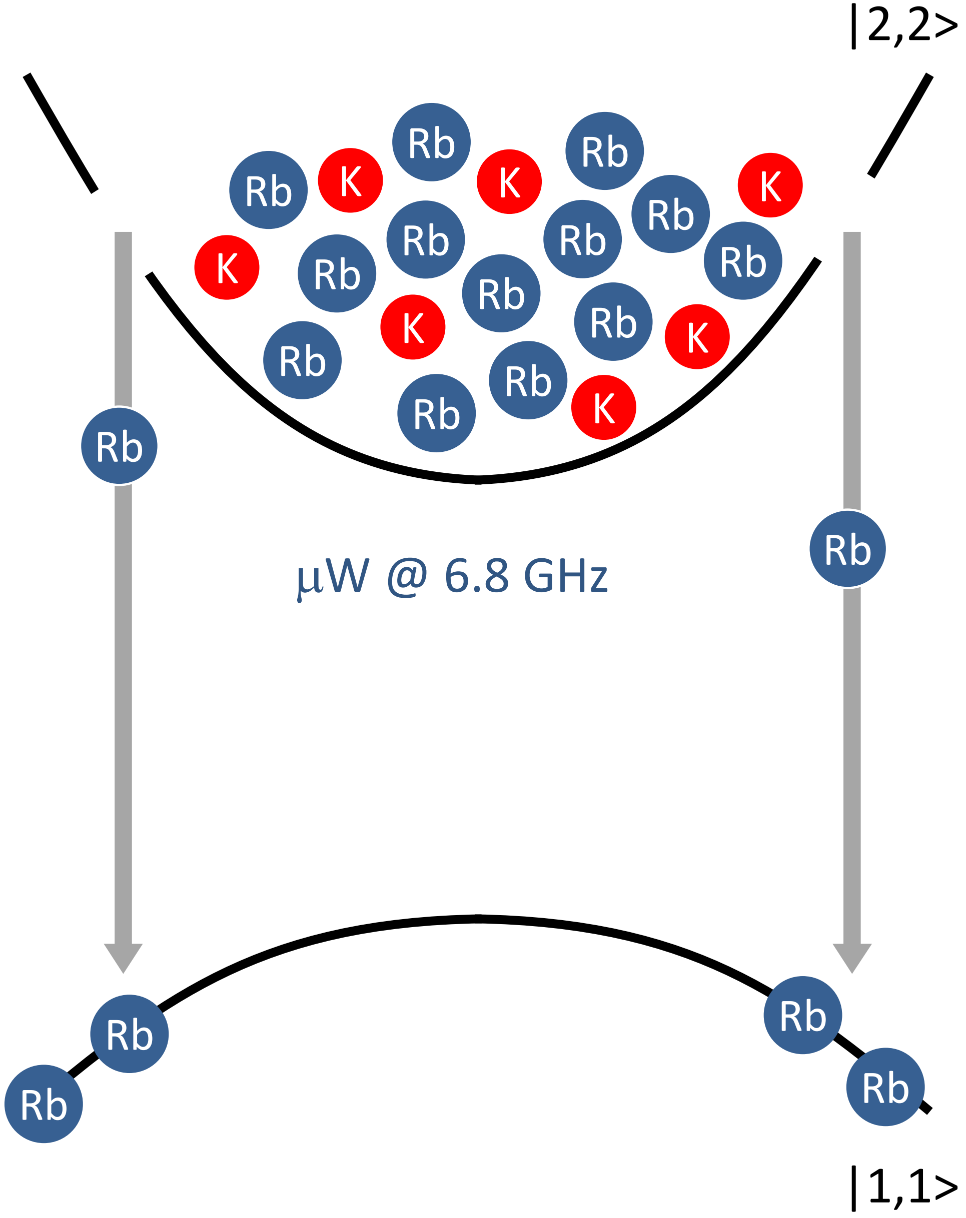
E_F

BOSONI

FERMIONI

Raffreddamento simpatetico

Intrappolamento simultaneo
di due specie, es. Rb e K



K: gas da raffreddare

Rb: gas “refrigerante”

1) Evaporazione degli atomi di **Rb**

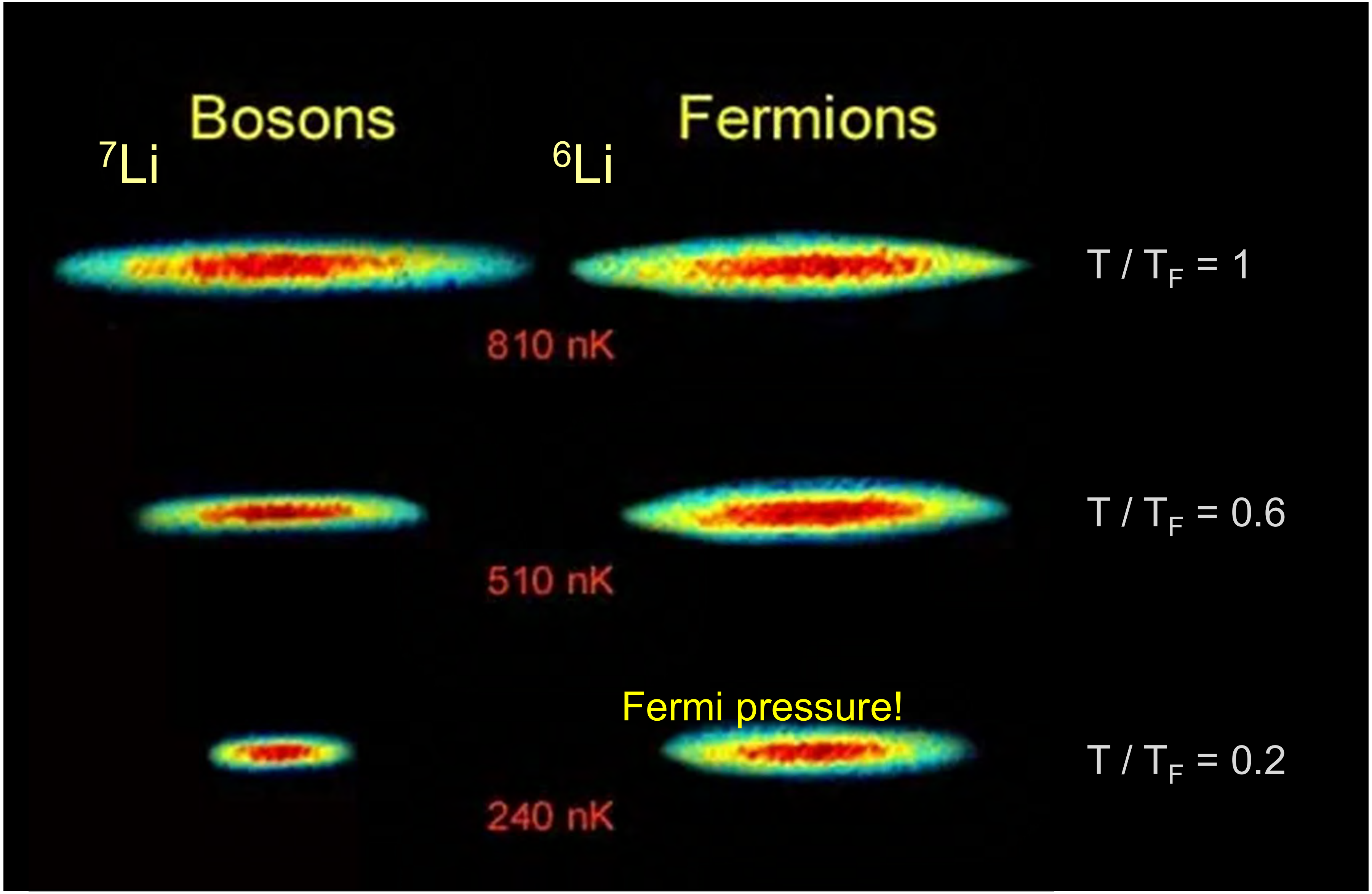
2) Collisioni **Rb-Rb** e **Rb-K**

3) Ritermalizzazione di **K** a T più bassa

A. G. Truscott et al., Science **291**, 5513 (2001)

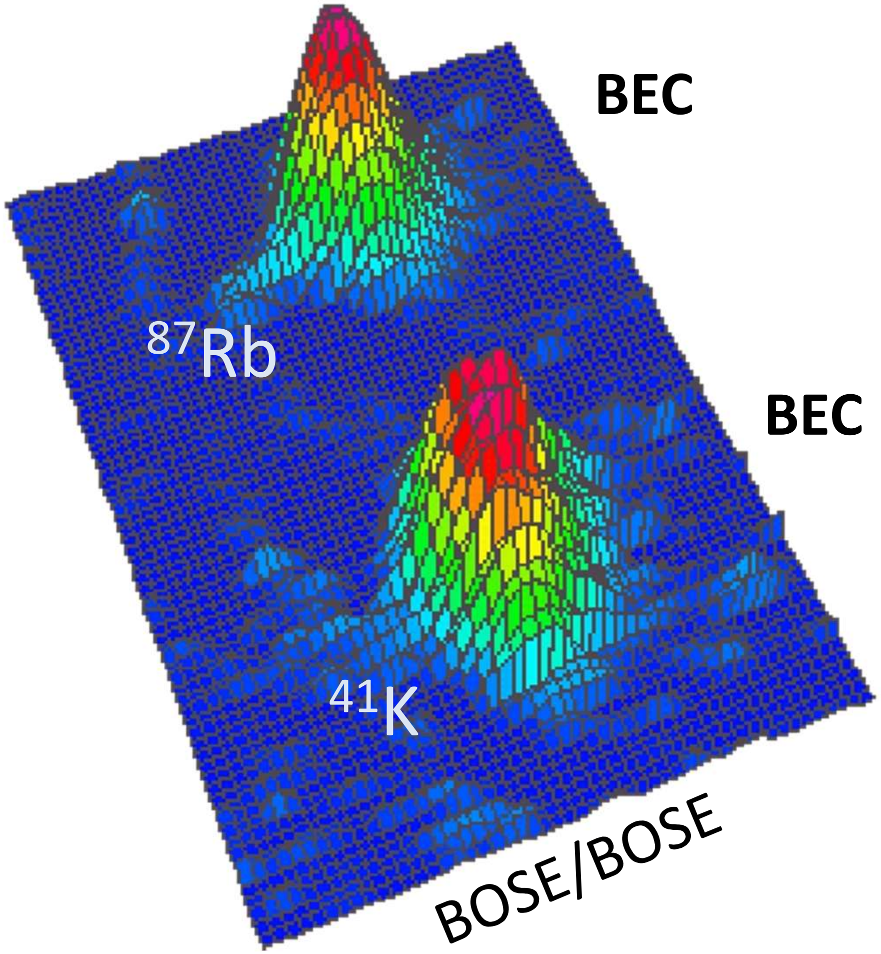
Raffreddamento simpatetico

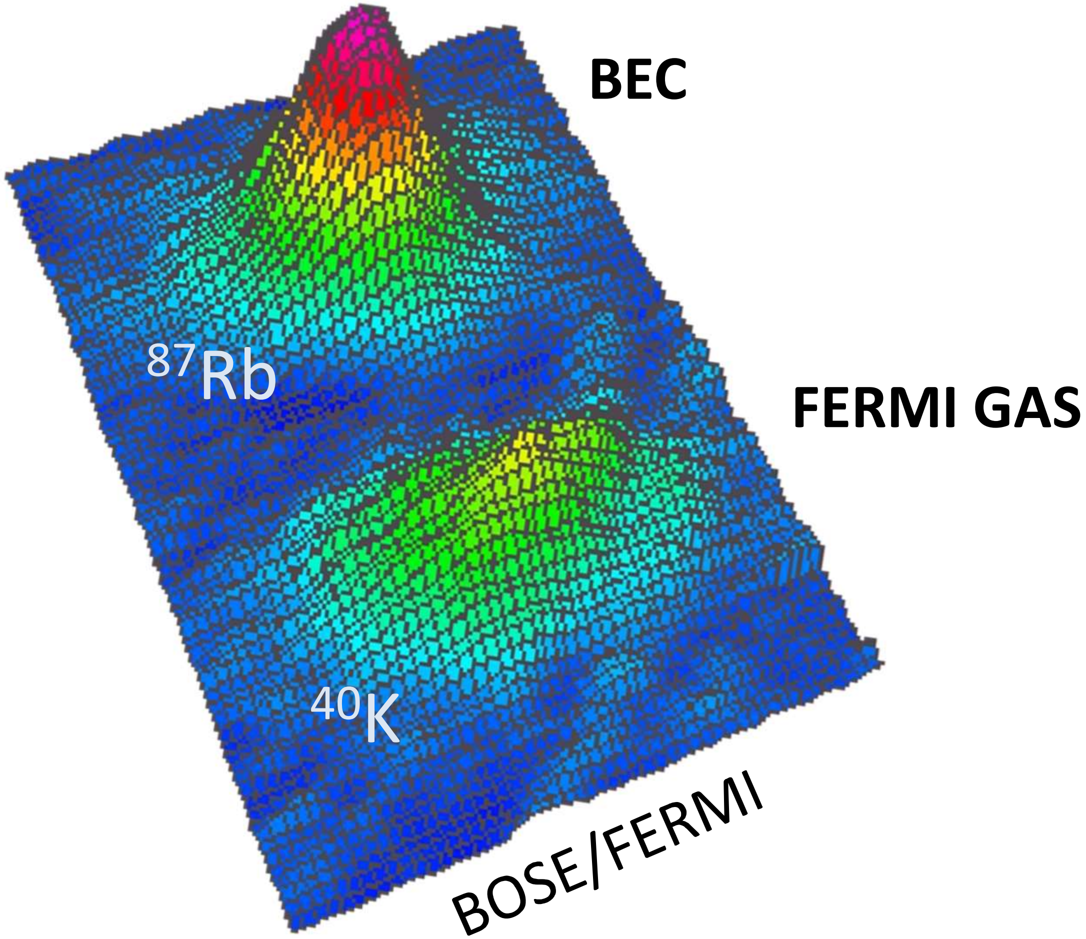
Raffreddamento simpatetico di una miscela Bose-Fermi di due isotopi di Litio



Raffreddamento simpatetico: miscele quantistiche

Raffreddamento simpatetico eteronucleare: miscele Bose-Bose e Bose-Fermi

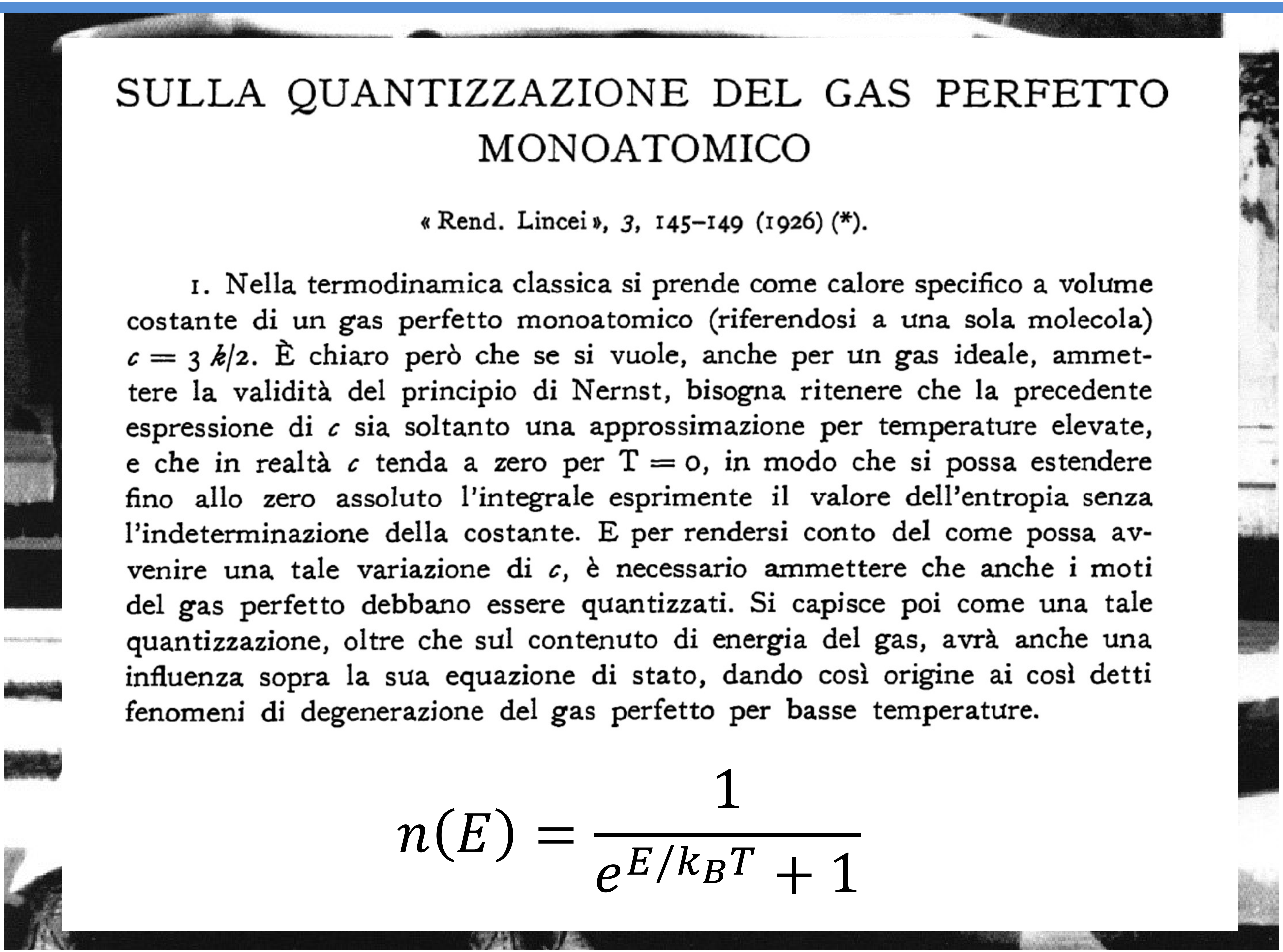




*G. Modugno et al., Science **294**, 1320 (2001)*
*G. Ferrari et al., PRL **89**, 053202 (2002)*

*G. Roati et al., PRL **89**, 150403 (2002)*

Fermi a Firenze



SULLA QUANTIZZAZIONE DEL GAS PERFETTO MONOATOMICO

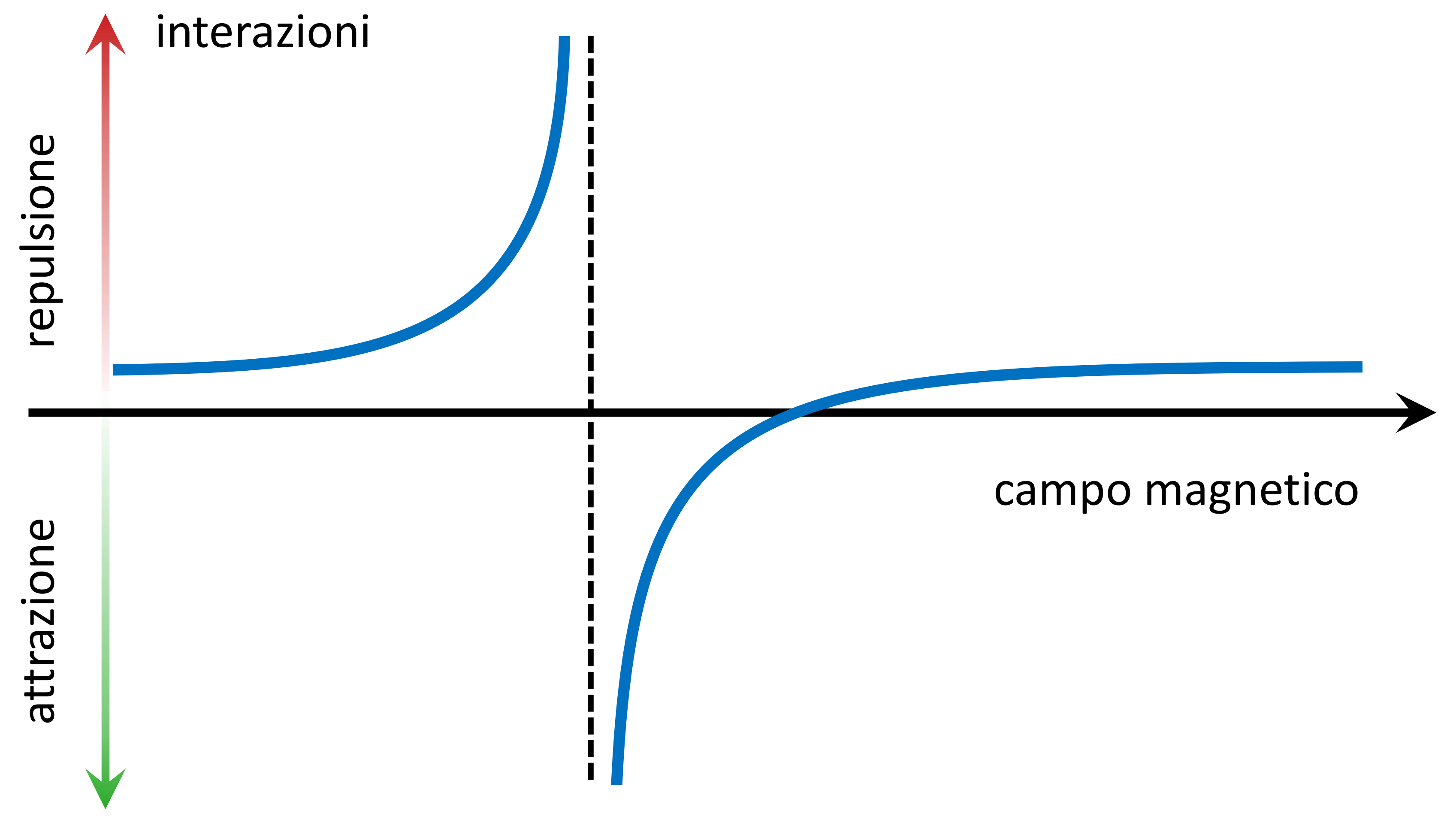
« Rend. Lincei », 3, 145–149 (1926) (*).

1. Nella termodinamica classica si prende come calore specifico a volume costante di un gas perfetto monoatomico (riferendosi a una sola molecola) $c = 3\,k/2$. È chiaro però che se si vuole, anche per un gas ideale, ammettere la validità del principio di Nernst, bisogna ritenere che la precedente espressione di c sia soltanto una approssimazione per temperature elevate, e che in realtà c tenda a zero per $T = 0$, in modo che si possa estendere fino allo zero assoluto l'integrale esprimente il valore dell'entropia senza l'indeterminazione della costante. E per rendersi conto del come possa avvenire una tale variazione di c, è necessario ammettere che anche i moti del gas perfetto debbano essere quantizzati. Si capisce poi come una tale quantizzazione, oltre che sul contenuto di energia del gas, avrà anche una influenza sopra la sua equazione di stato, dando così origine ai così detti fenomeni di degenerazione del gas perfetto per basse temperature.

$$n(E) = \frac{1}{e^{E/k_B T} + 1}$$

Come controllare le interazioni fra gli atomi?

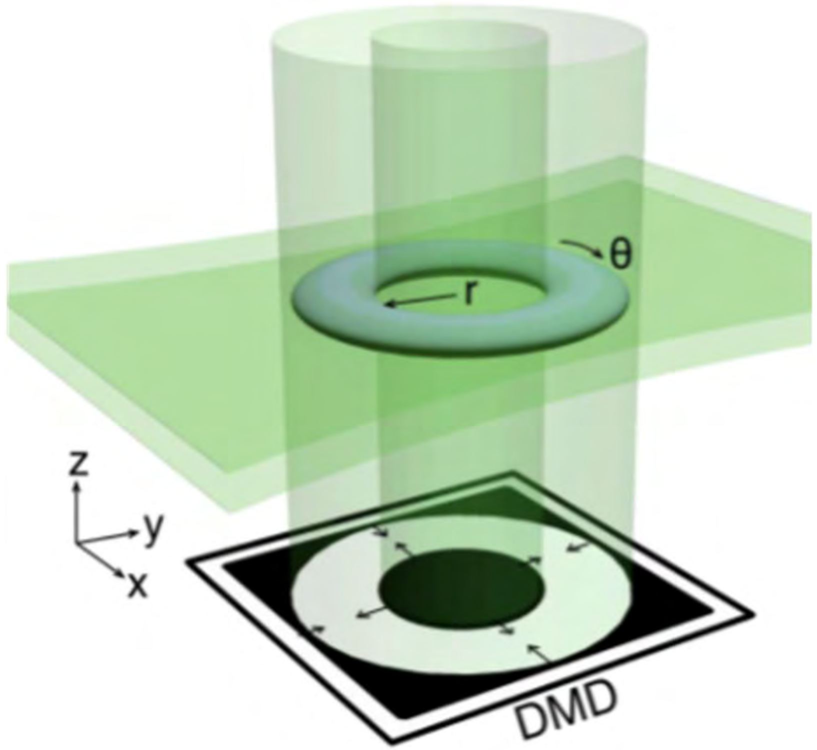
Risonanza di Fano-Feshbach: interferenza fra processi di scattering



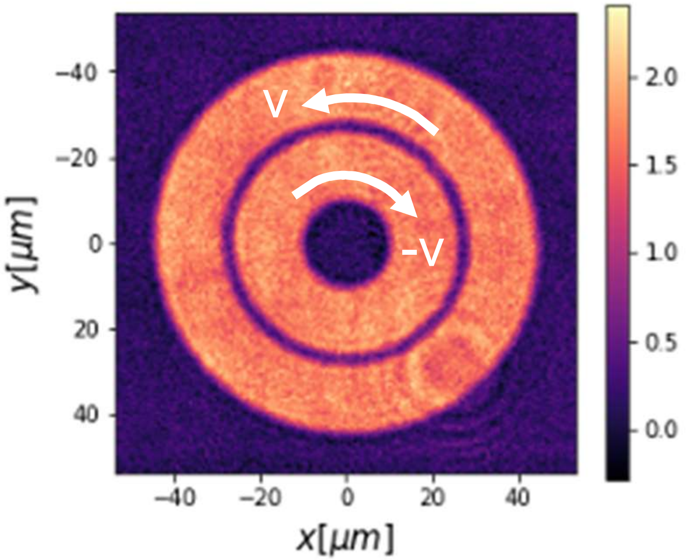
modificabile con un campo magnetico
(che sposta i livelli molecolari)

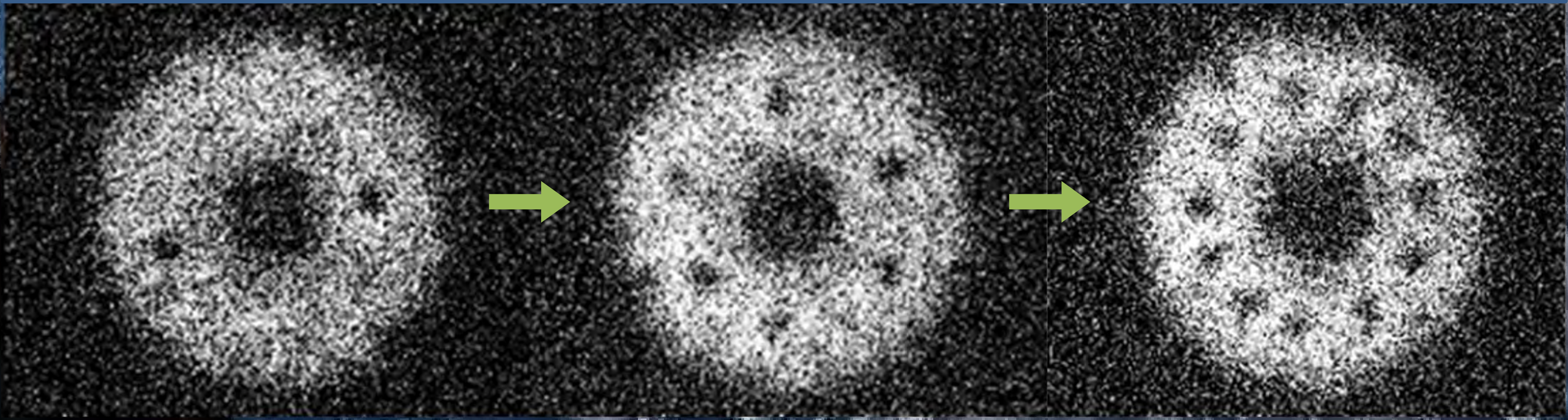
D. Hernandez et al., in preparation

Vortici in superfluidi fermionici



Trappole ottiche ad anello
Superfluido fermionico in rotazione

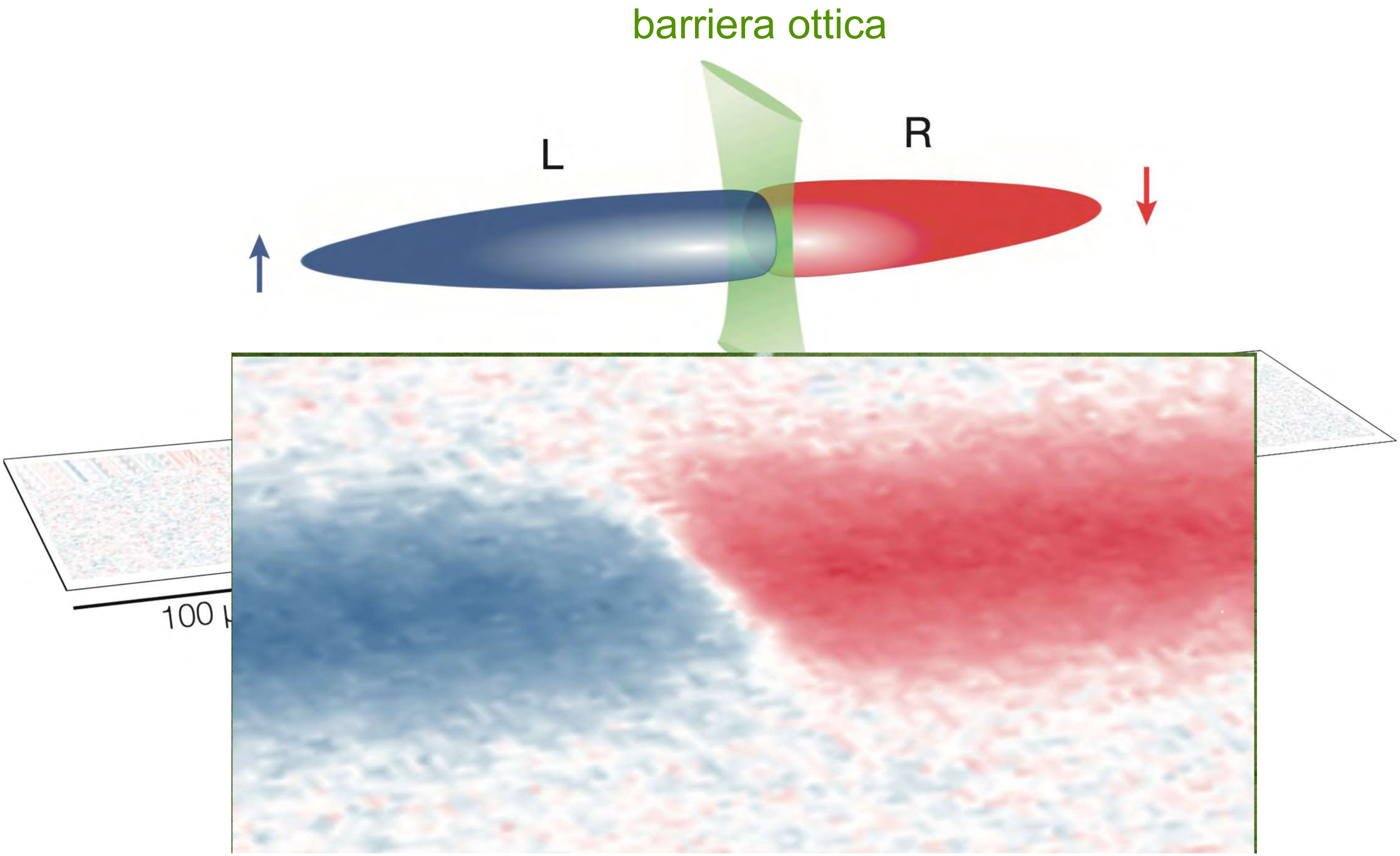




G. Valtolina et al., Nature Phys. 13 (2017)

Un ferromagnete “artificiale”

Fermioni con forti interazioni repulsive: uno stato ferromagnetico?



Gas quantistici ultrafreddi @ LENS