

# Azione a distanza: effetti quantistici in un mondo classico?

Mauro Paternostro  
Queen's University Belfast



Incontri di Fisica 2015  
9 Ottobre 2015



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*Belfast*







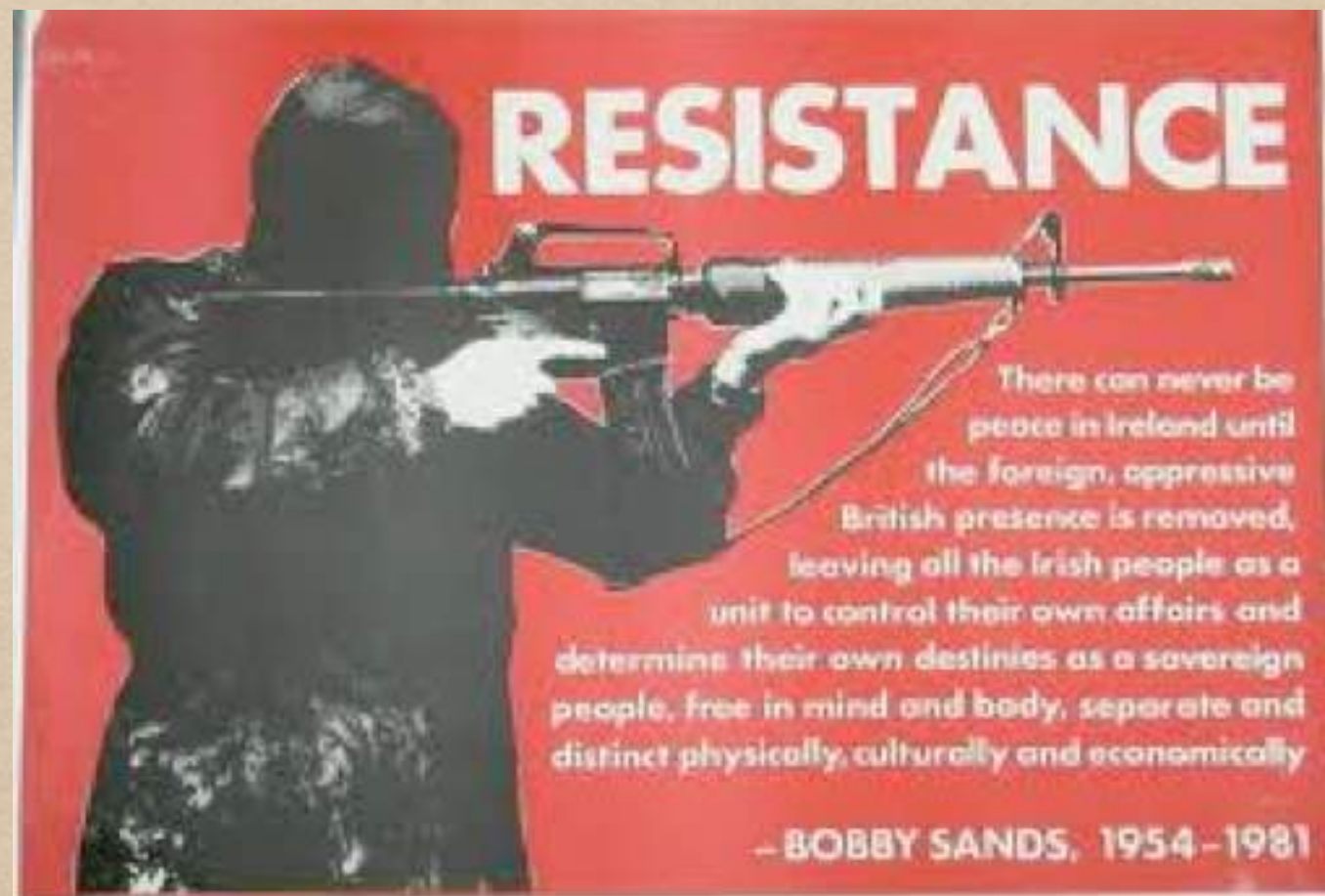
*Belfast*







*Belfast*







*Belfast*







*Titanic*





*Titanic*







*Titanic*







# *Titanic*



*“...il mondo ricorda la tragedia; solo noi celebriamo il trionfo...”*





# *Queen's University Belfast*



Joseph Larmor



John Stuart Bell



David Bates, FRS



Harrie Massey



Lord Kelvin





*Teoria quantica  
dell'informazione*





# *Teoria quantica dell'informazione*

Cosa succede se codifichiamo informazione in sistemi quantistici?







## *Teoria quantica dell'informazione*

Cosa succede se codifichiamo informazione in sistemi quantistici?



Tecnologie quantistiche

Sistemi quantistici a molti corpi

Fisica di atomi ultrafreddi

Optomeccanica quantistica

Fondamenti di meccanica quantistica

Termodinamica quantistica





# *Fisica & Servizi Sociali*



*Sara, 6 anni*





## *Fisica & Servizi Sociali*



*Mio padre studia cose  
che nessuno puo' vedere,  
scrive simboli strani, e parla  
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# La prima rivoluzione quantistica

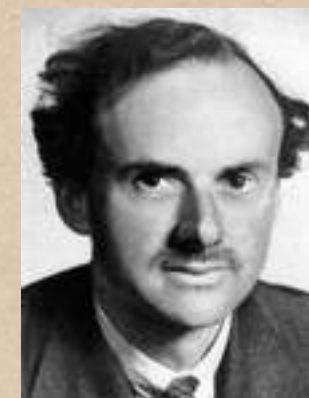


Planck

Schroedinger



Heisenberg



Dirac

Einstein



Bohr



Fermi

Pauli



Nuove “leggi” che governano la realta' fisica





# *La prima rivoluzione quantistica*

Nuove “leggi” che governano la realtà fisica





*La prima rivoluzione  
quantistica*

$|\psi\rangle$

vettore di stato (o ket)

Nuove “leggi” che governano la realtà fisica





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$$i\hbar\partial_t|\psi\rangle = \hat{E}|\psi\rangle \quad \text{Eq. di Schroedinger}$$

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$\rho$  matrice densità'

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Non evolve secondo l' Eq. di Schroedinger

Nuove "leggi" che governano la realta' fisica





*La divisione*





## *La divisione*

Che cosa divide il mondo classico da quello quantistico?





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Il principio di sovrapposizione

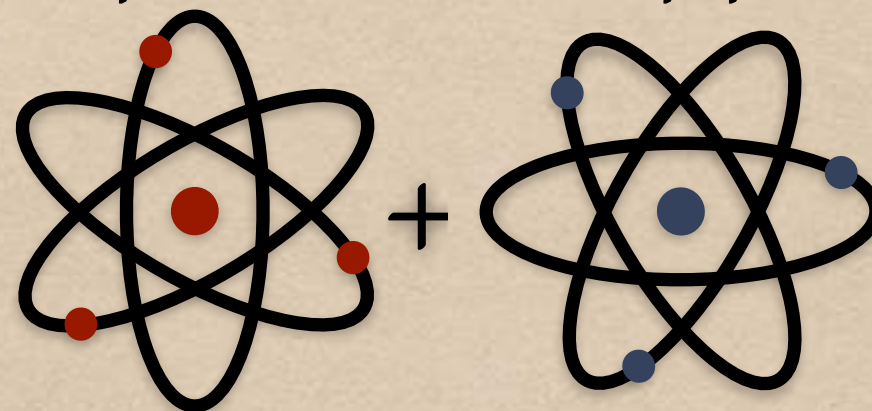




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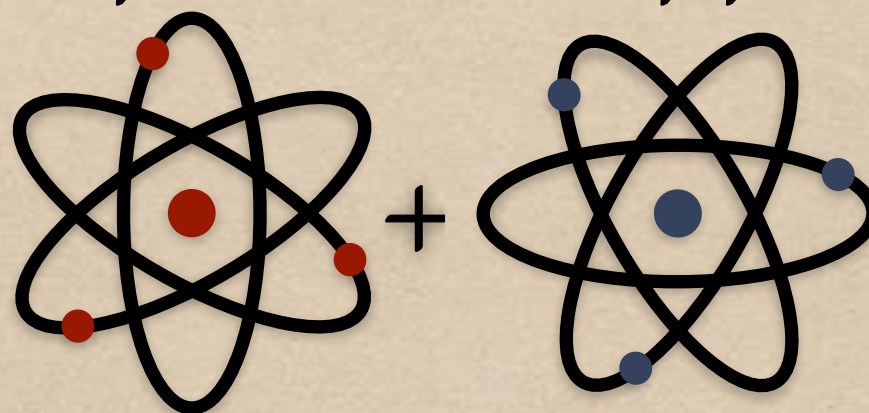




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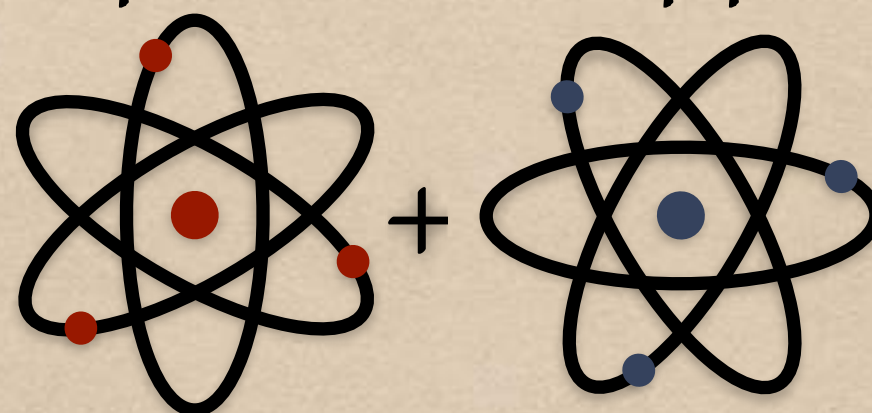


$$|\psi\rangle = \frac{|\text{Rosso}\rangle + |\text{Blue}\rangle}{\sqrt{2}}$$



Che cosa divide il mondo classico da quello quantistico?

Il principio di sovrapposizione



$$|\psi\rangle = \frac{|\text{Rosso}\rangle + |\text{Blue}\rangle}{\sqrt{2}}$$

Quando applicato a più' di una particella,  
implica entanglement





# Entanglement quantistico

Schroedinger



E. Schroedinger,  
*Naturwissenschaften* 23, 807 (1935)





# Entanglement quantistico

Schroedinger



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*“Thus one disposes provisionally (until the entanglement is resolved by actual observation) of only a **common** description of the two in that space of higher dimension. This is the reason that knowledge of the individual systems can decline to the scantiest, even to zero, while that of the combined system remains continually maximal. Best possible knowledge of a whole does **not** include best possible knowledge of its parts — and this is what keeps coming back to haunt us”*





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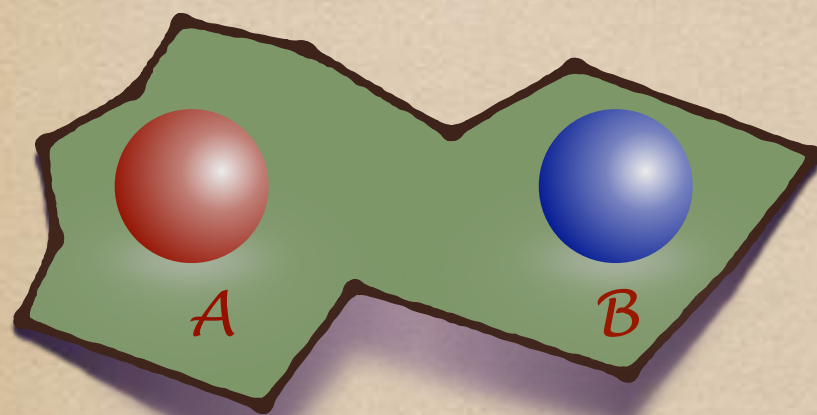
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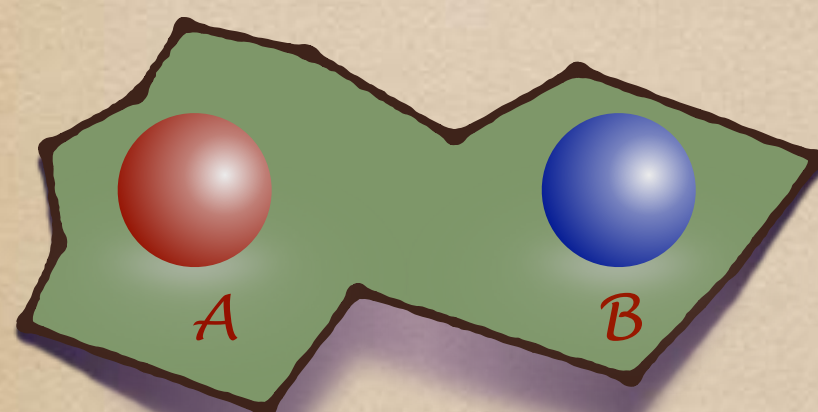


*Entanglement  
quantistico*

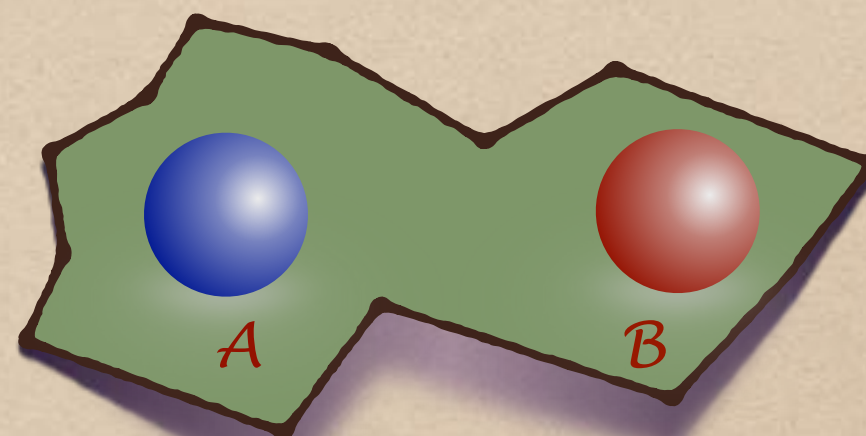




# Entanglement quantistico



+





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$$|\psi\rangle = \frac{|\text{Rosso}\rangle_A |\text{Blue}\rangle_B + |\text{Blue}\rangle_A |\text{Rosso}\rangle_B}{\sqrt{2}}$$



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L'entanglement e' una risorsa per le tecnologie quantistiche





*Entanglement  
quantistico*



*A*

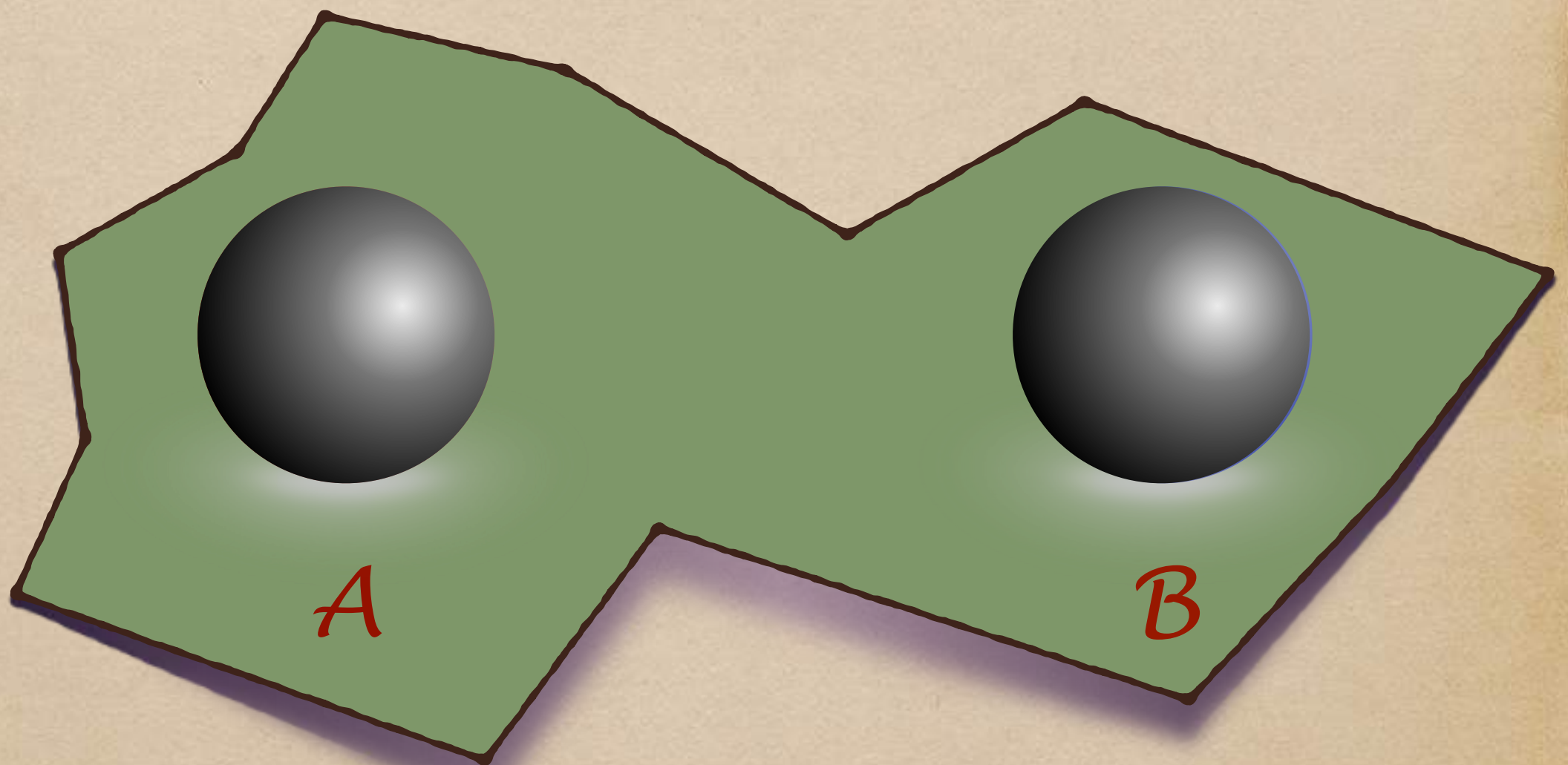


*B*





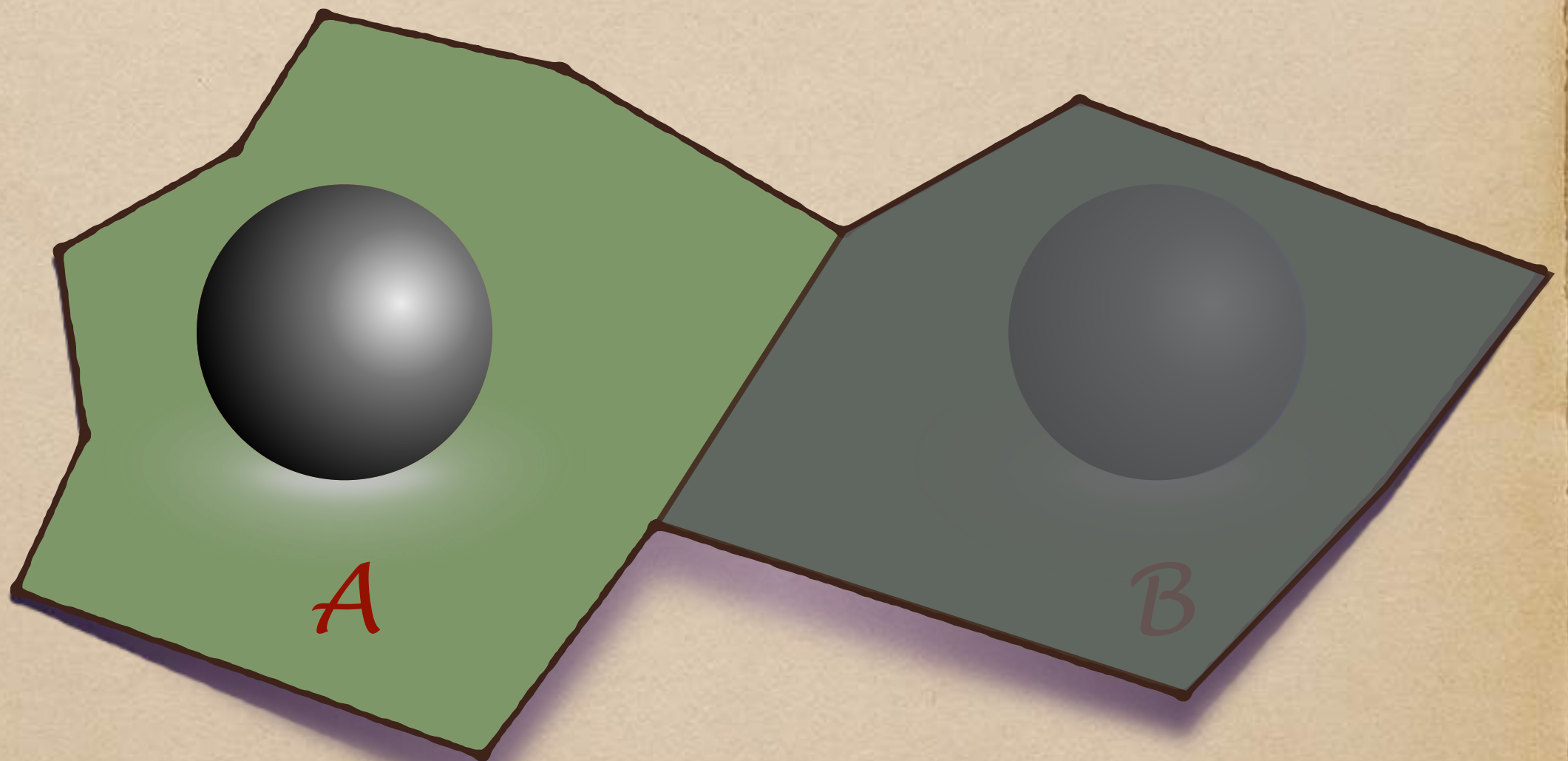
*Entanglement  
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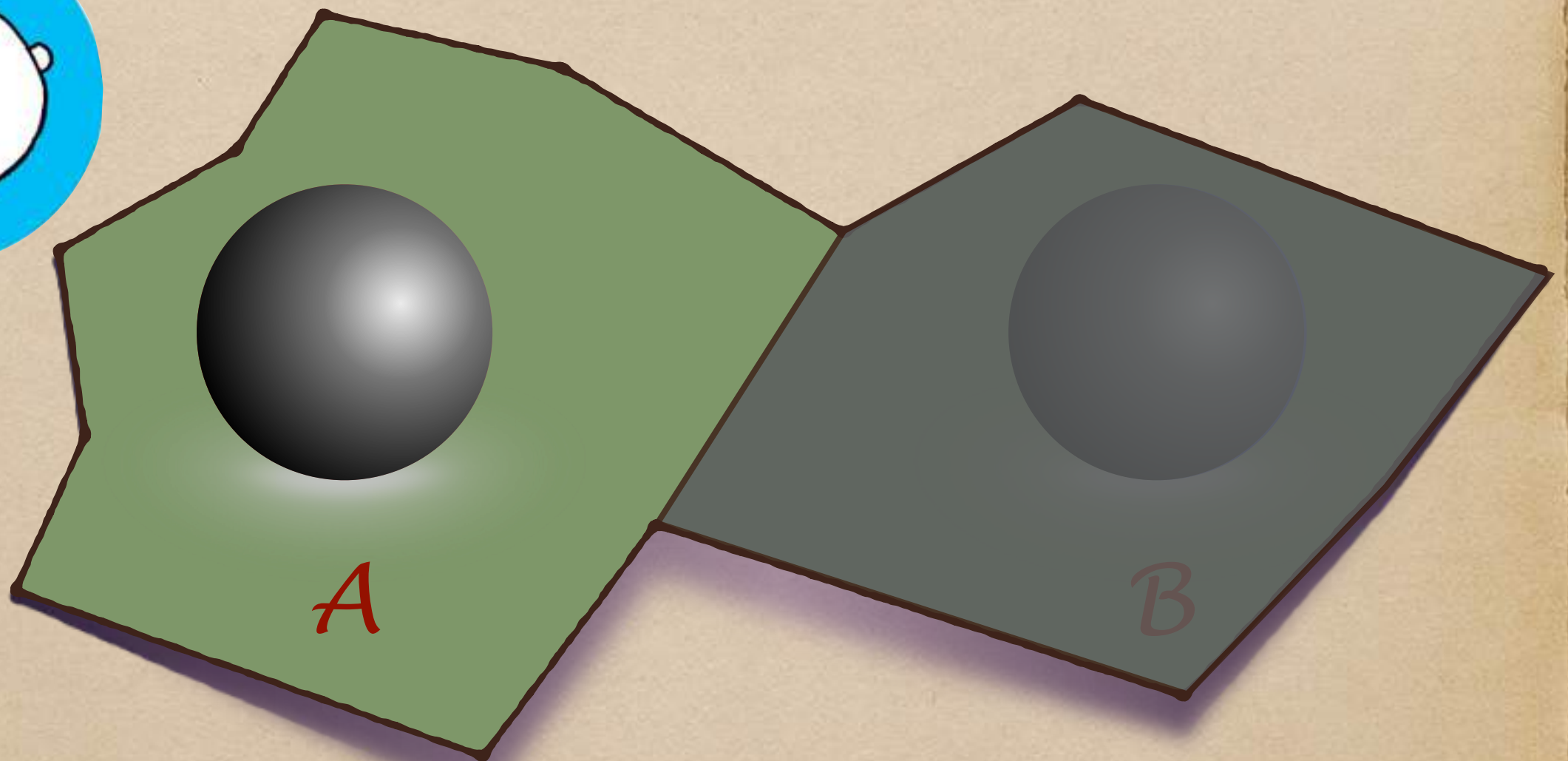
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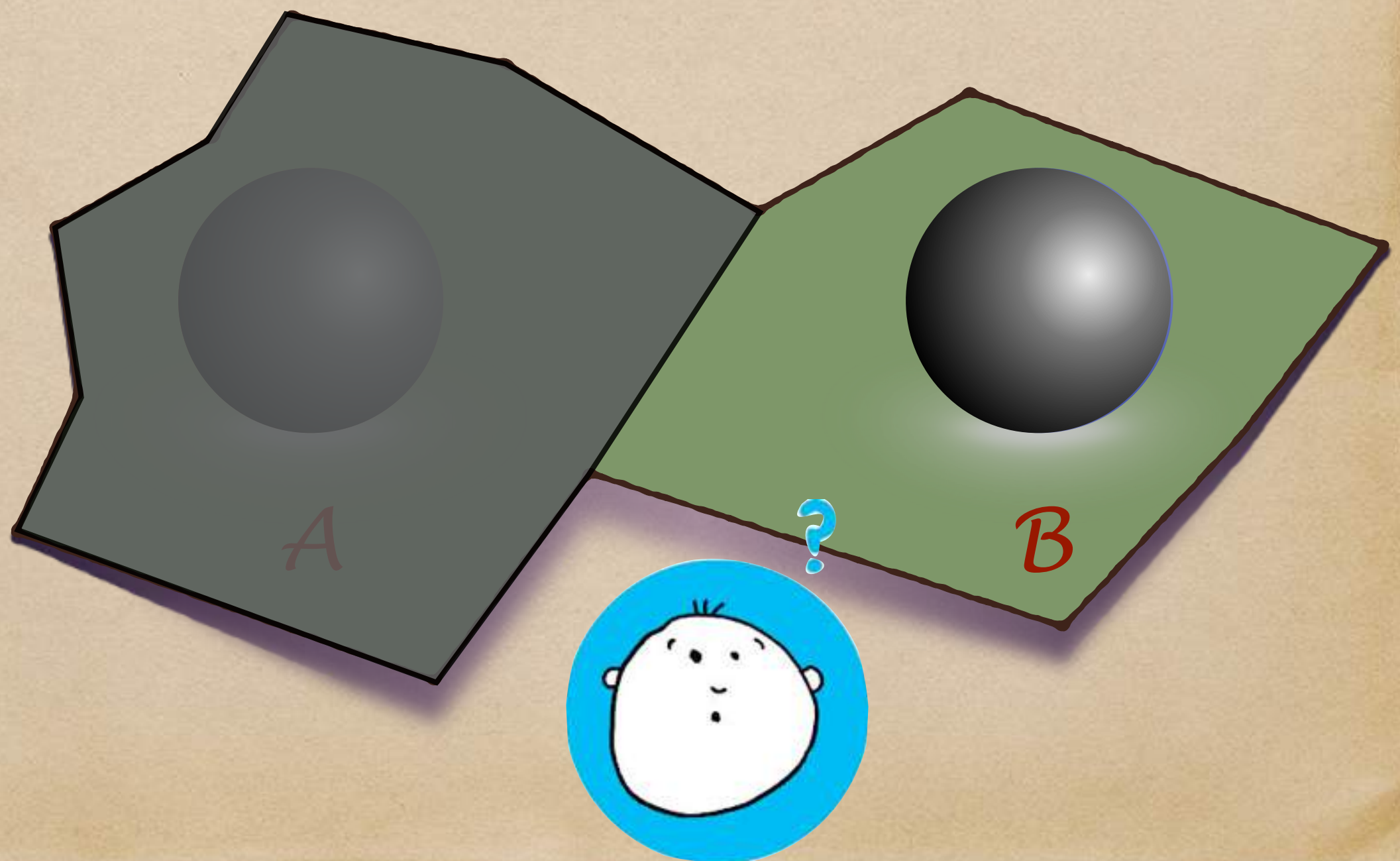
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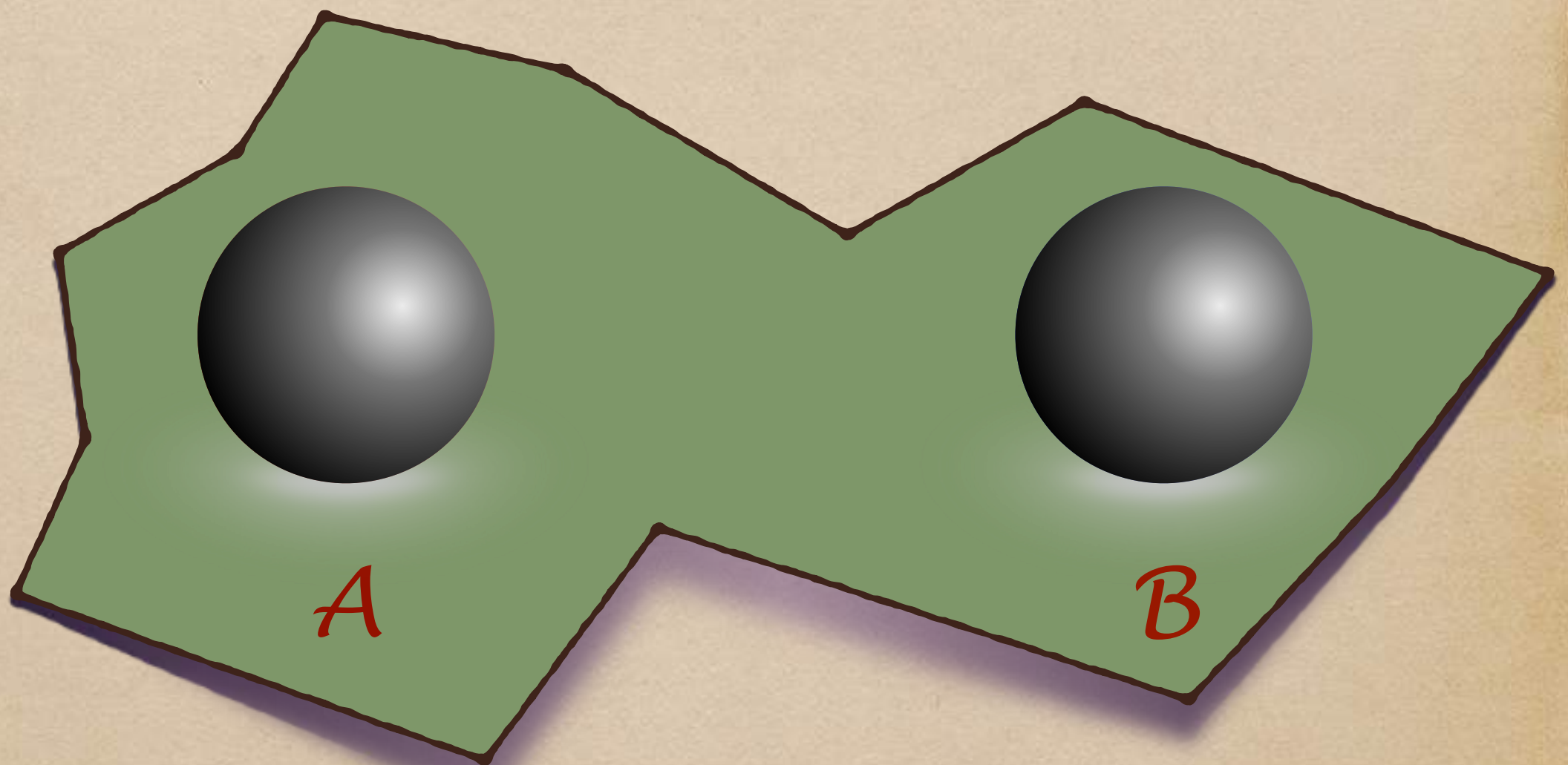
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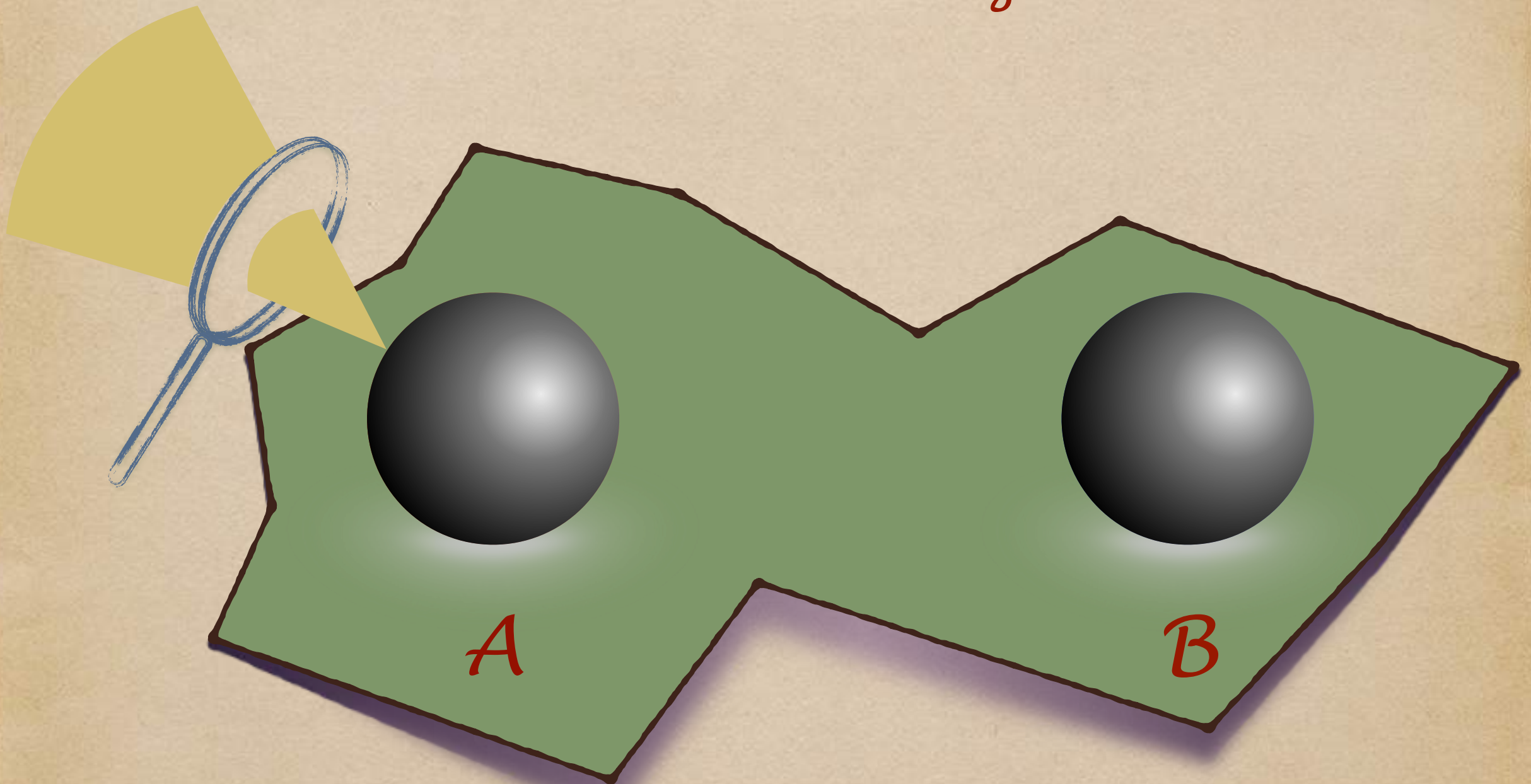
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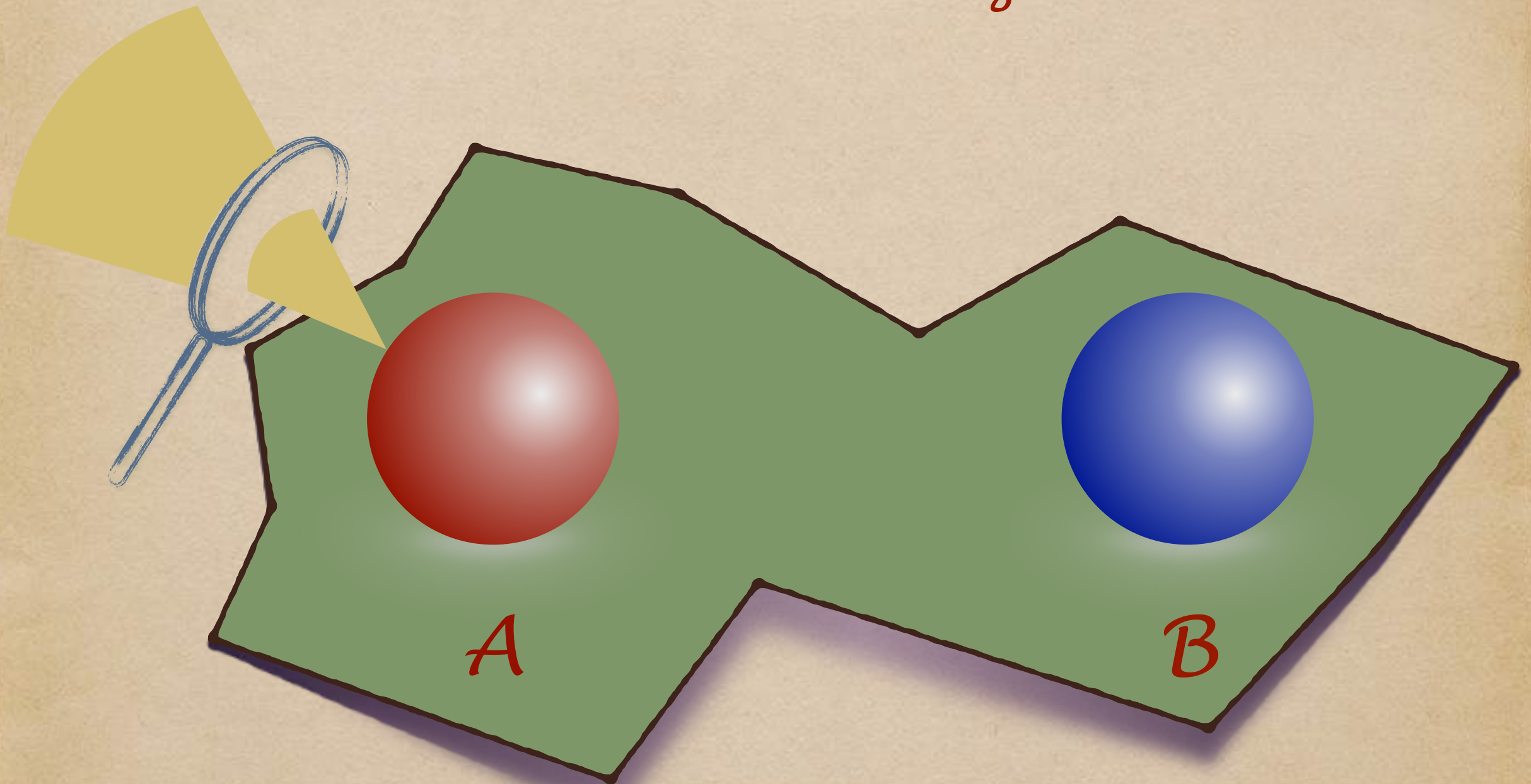
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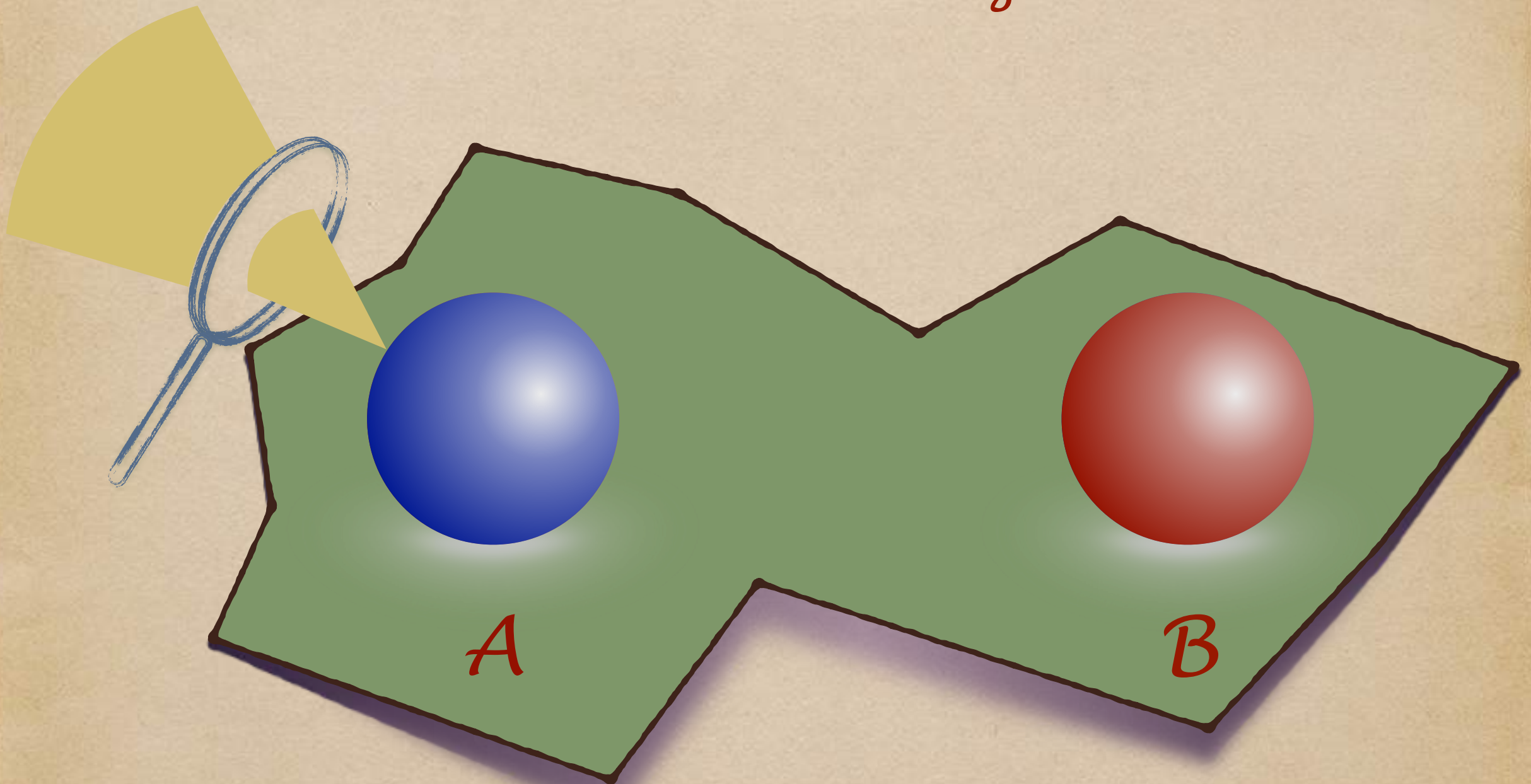
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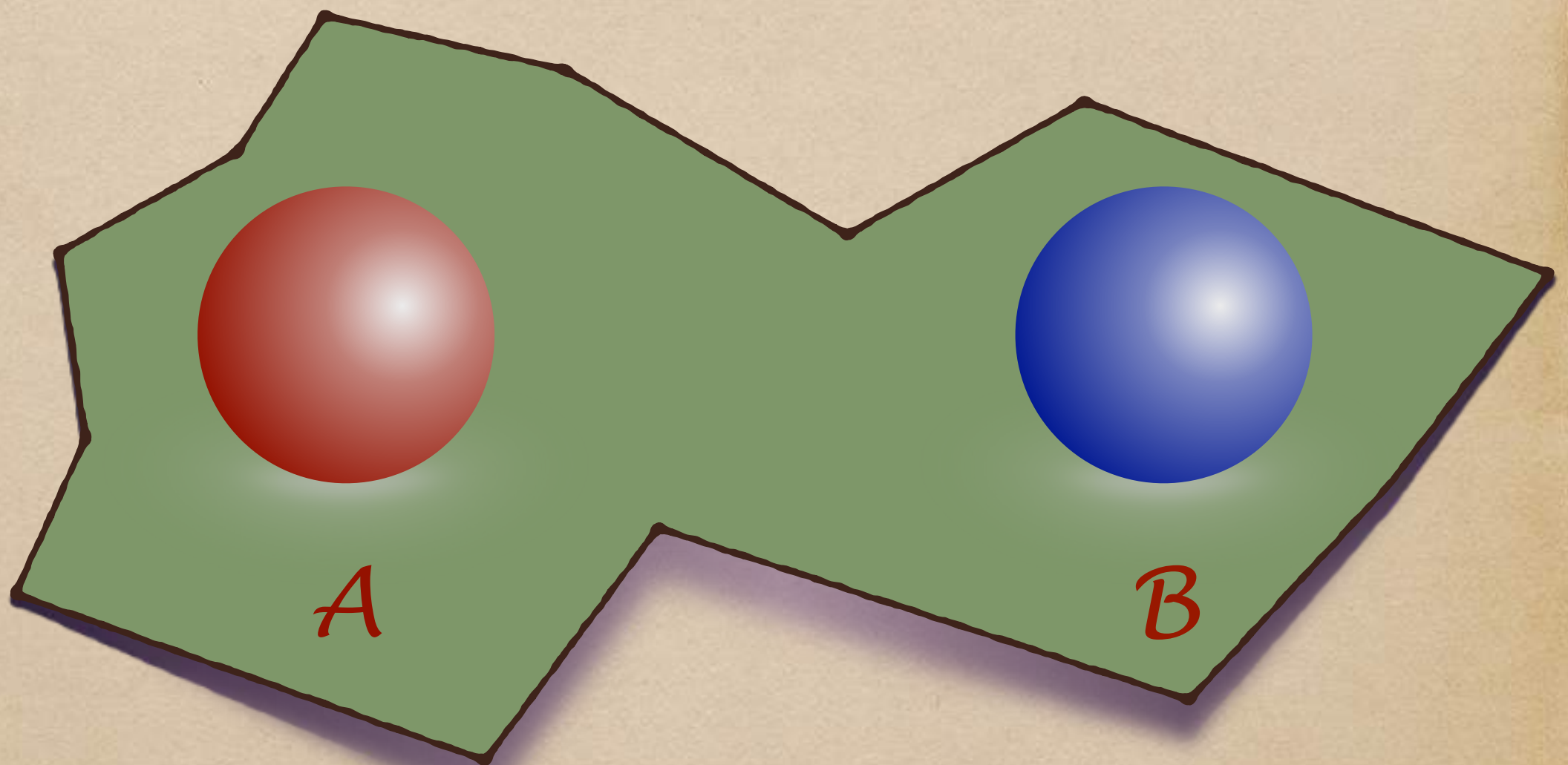
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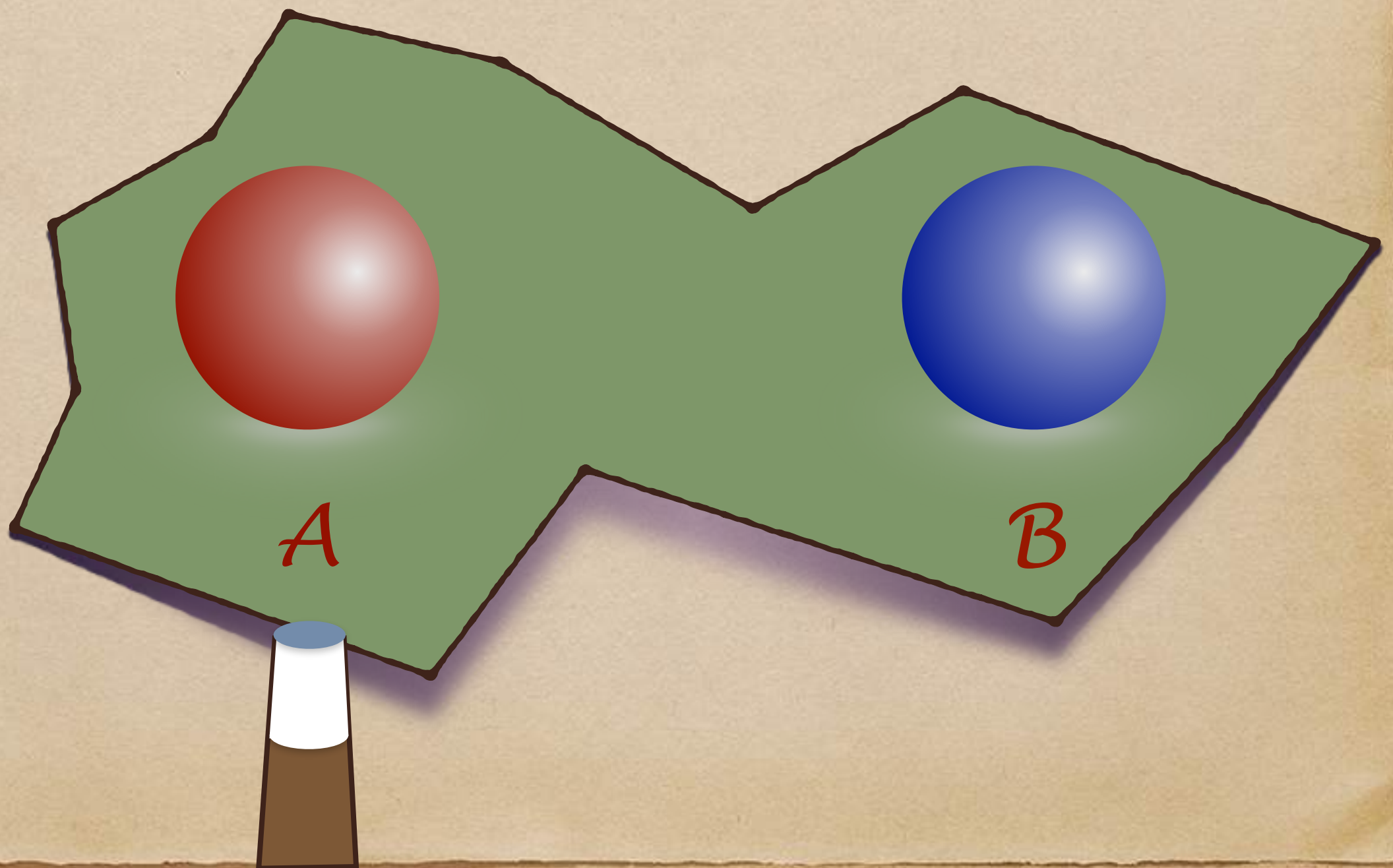
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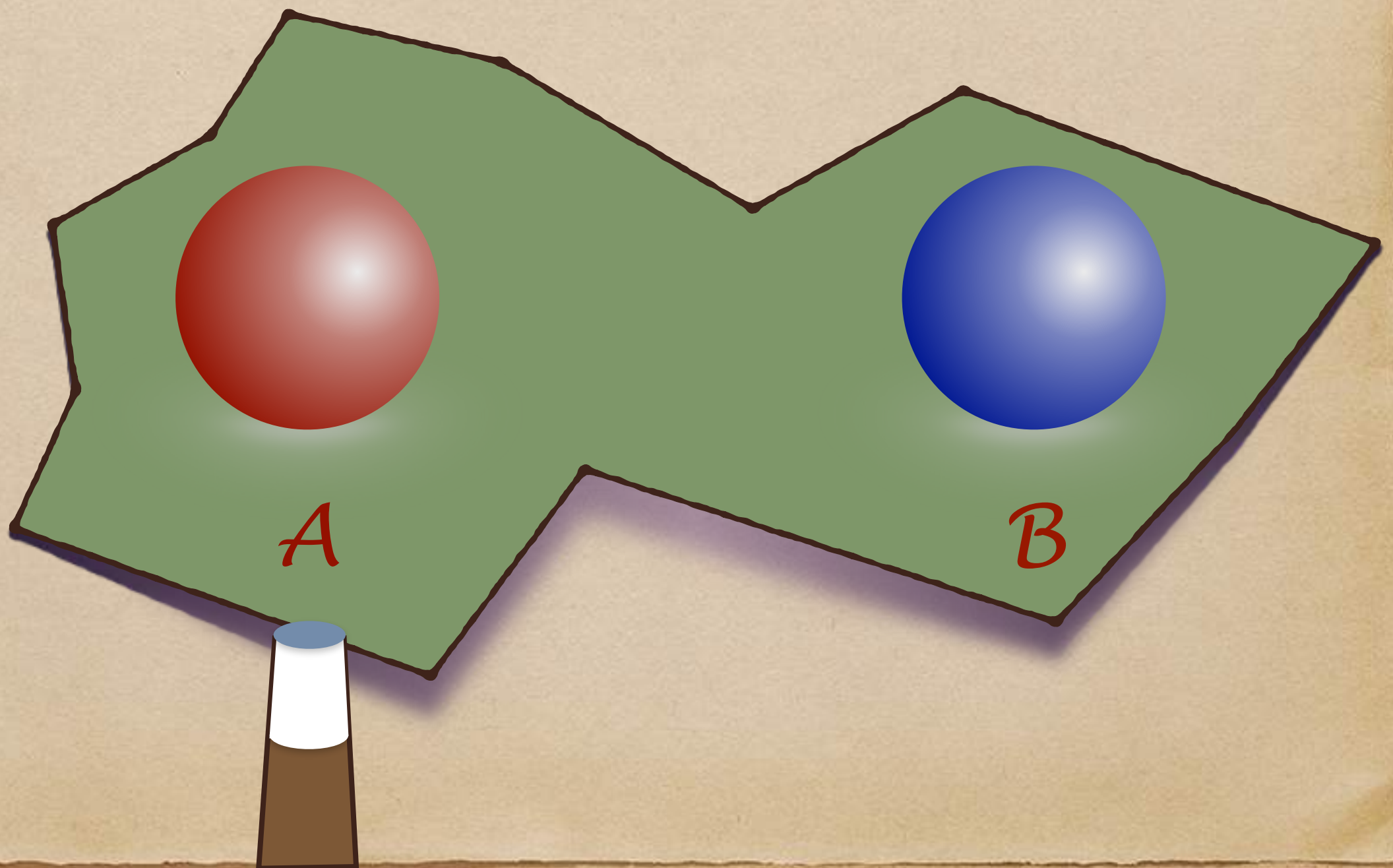
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*Moda quantistica...*

*Reinhold Bertlmann*







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## *Moda quantistica...*

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J. S. Bell, 'I calzini di Bertlman e la natura della realta',  
Journal de Physique 42, 41 (1981)

Fig 1

Les chaussettes  
de M. Bertlmann  
et la nature  
de la réalité

Fondation Hugot  
juin 17 1980





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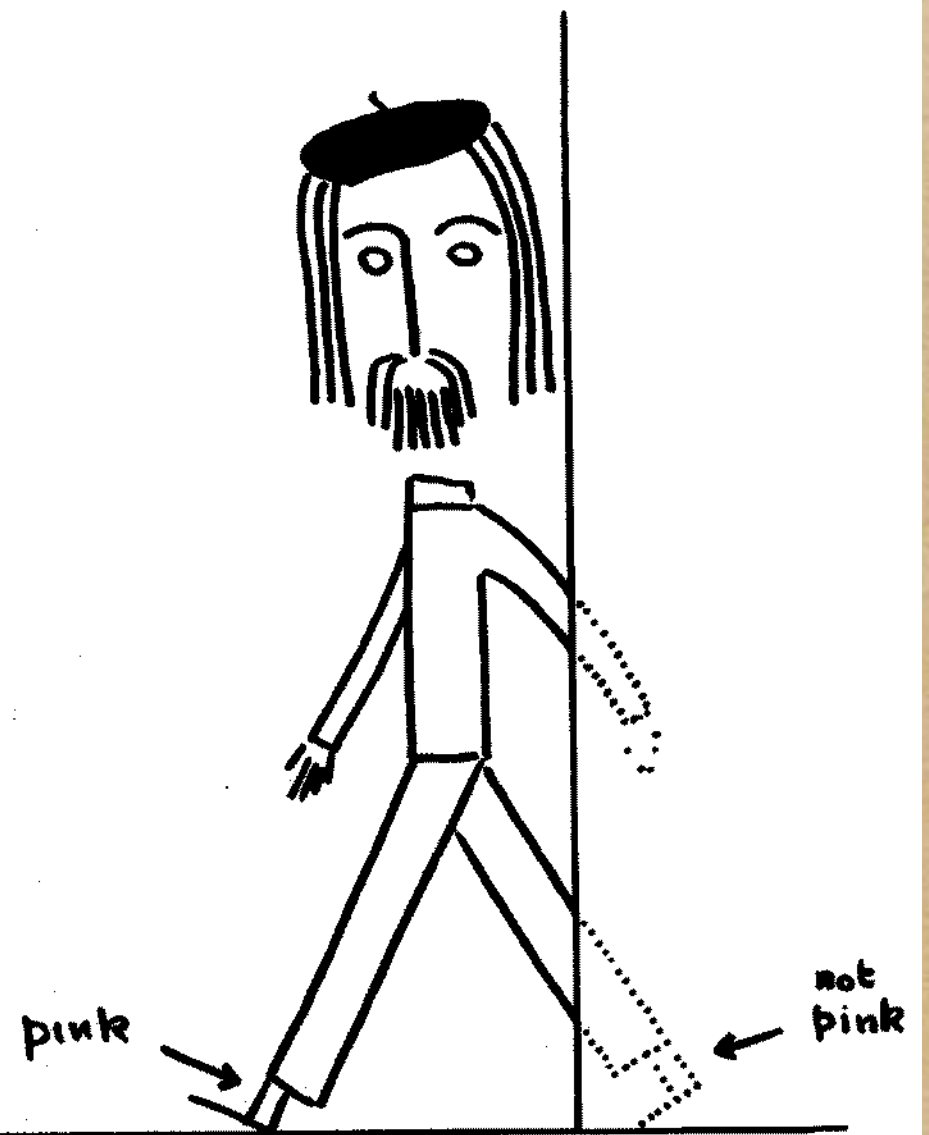


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*Battaglia tra giganti*

*Einstein*







# *Battaglia tra giganti*

Realismo

O contro l'aleatorietà  
quantistica

*Einstein*







## *Battaglia tra giganti*

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Località

O contro 'inquietanti'  
azioni a distanza





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Queste assunzioni definiscono la realtà classica  
e vincolano il grado di correlazione tra eventi  
separati spazialmente e disconnessi



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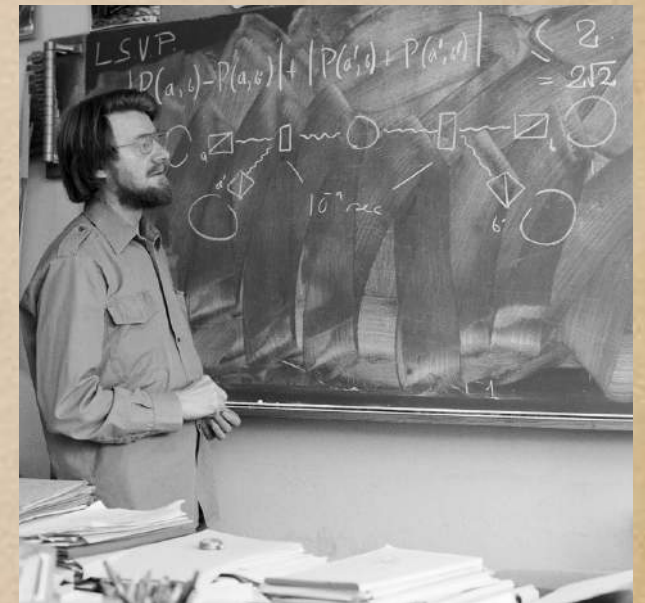
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(Teorema di Bell)

Sistemi entangled violano questo vincolo!!!



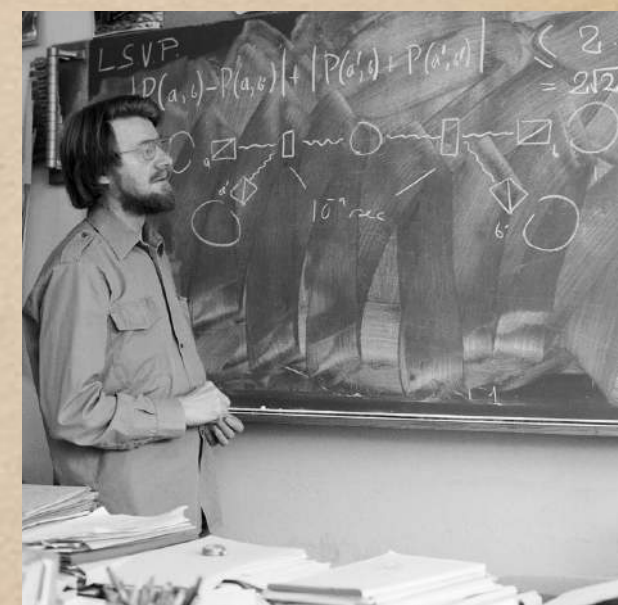
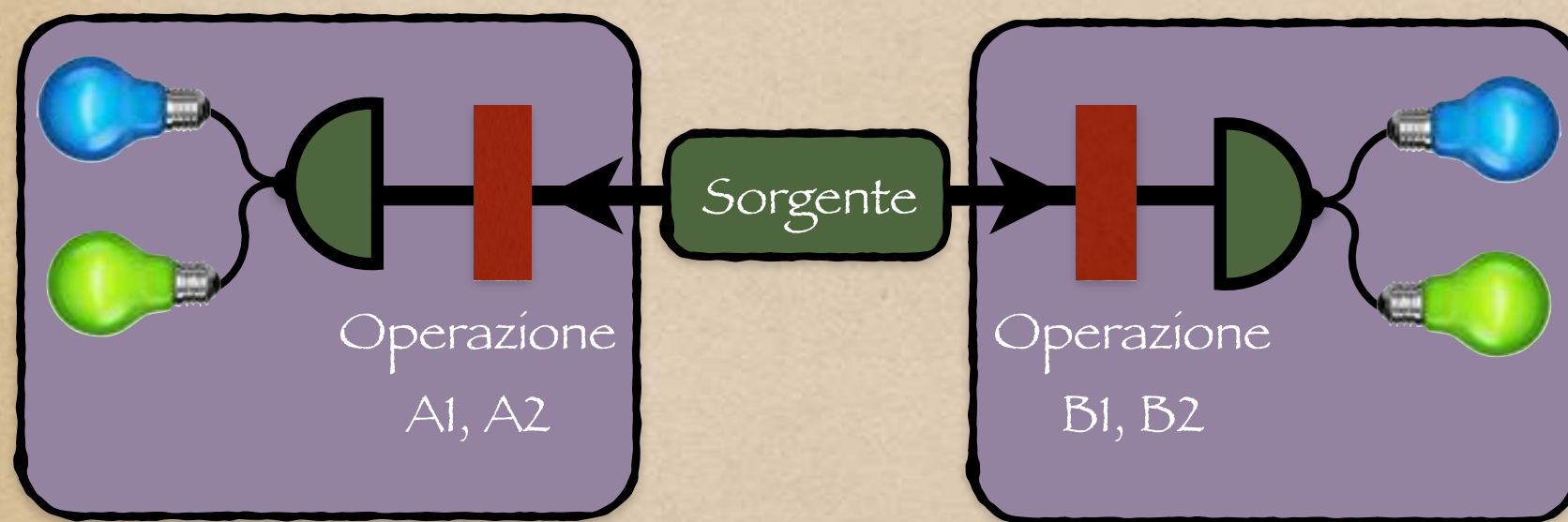


## *Il test di Bell*



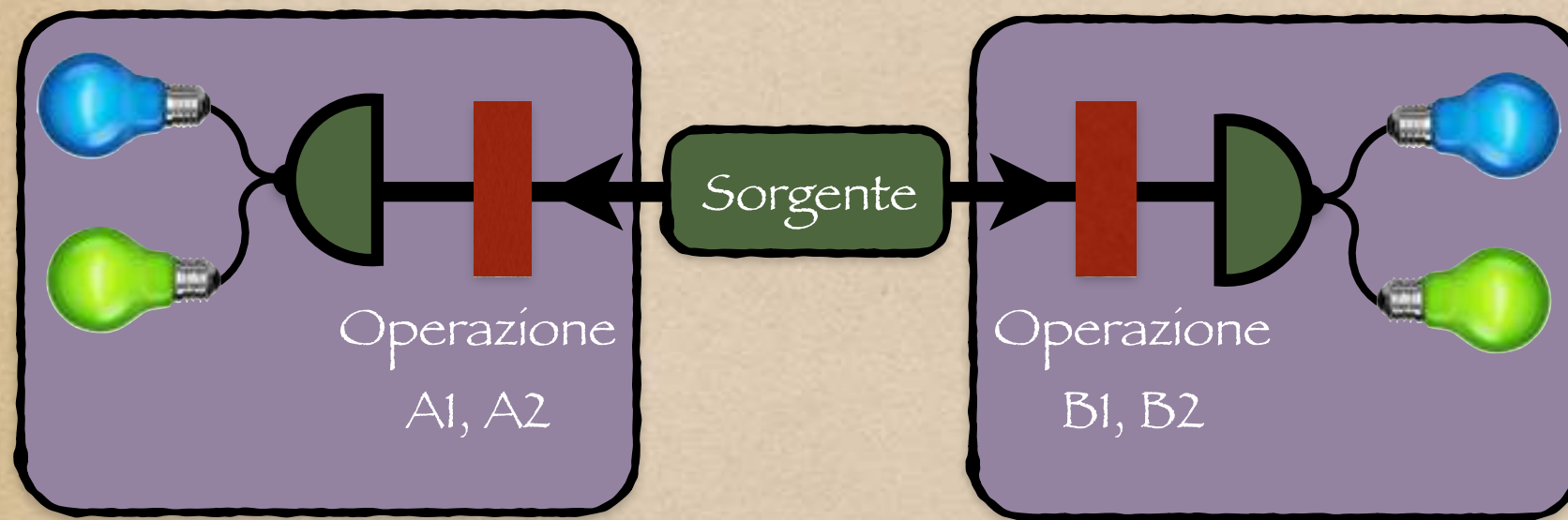
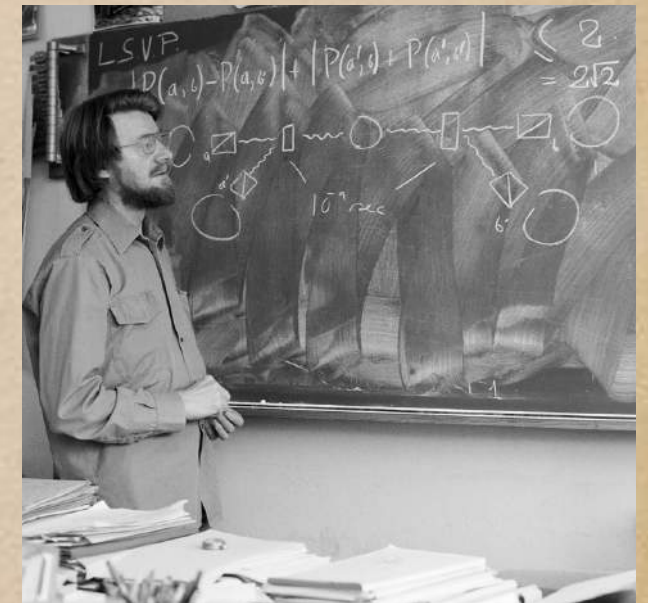


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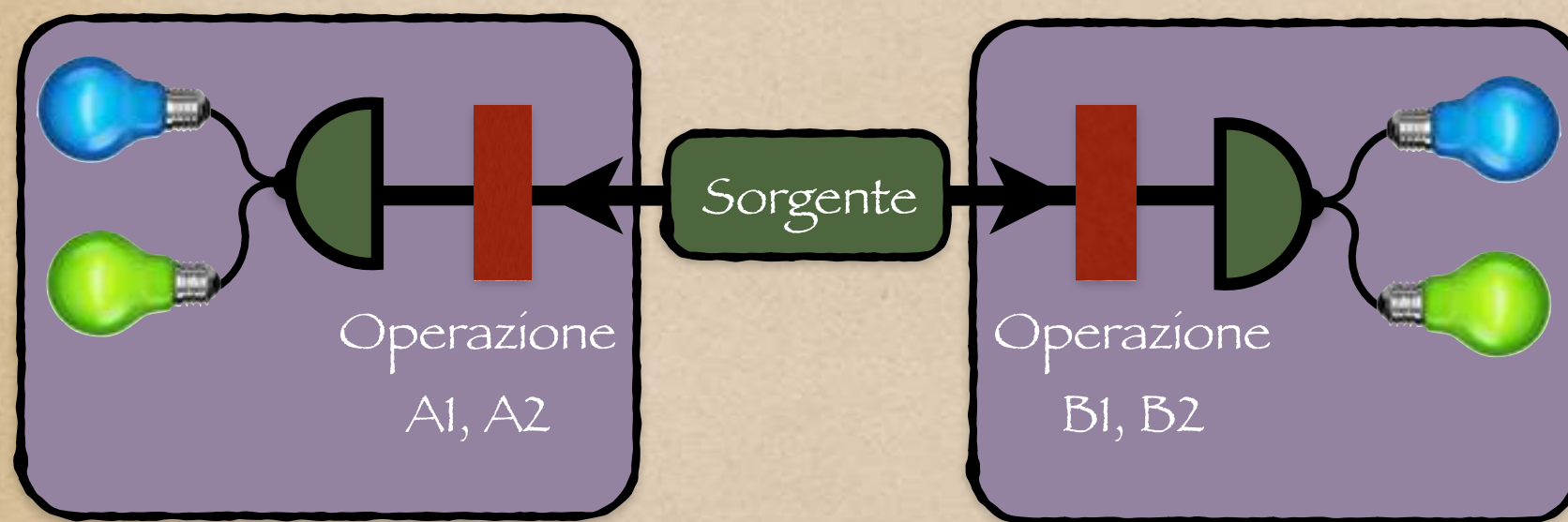
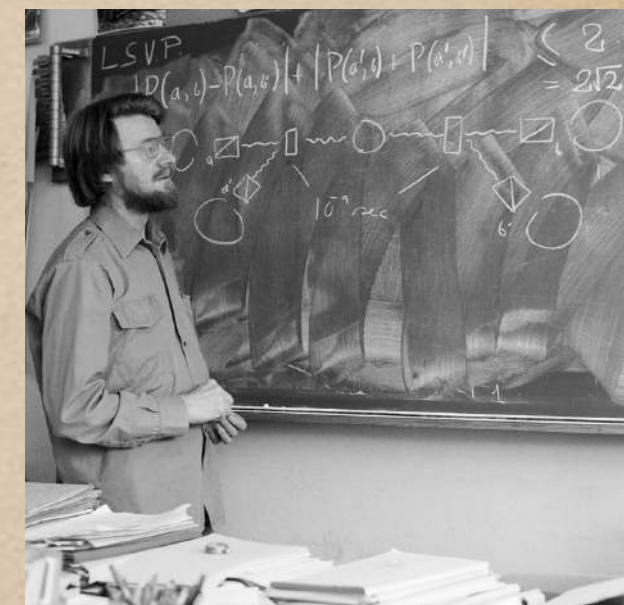


Classicamente

$$\mathcal{B} = |C(A1, B1) + C(A1, B2) + C(A2, B1) - C(A2, B2)| \leq 2$$



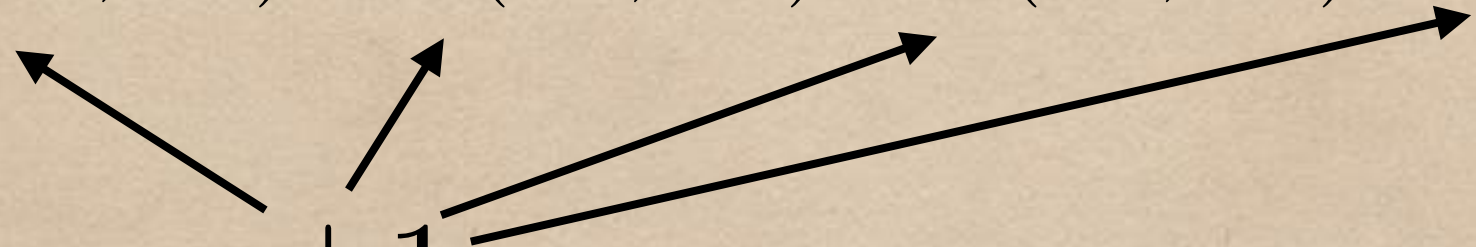
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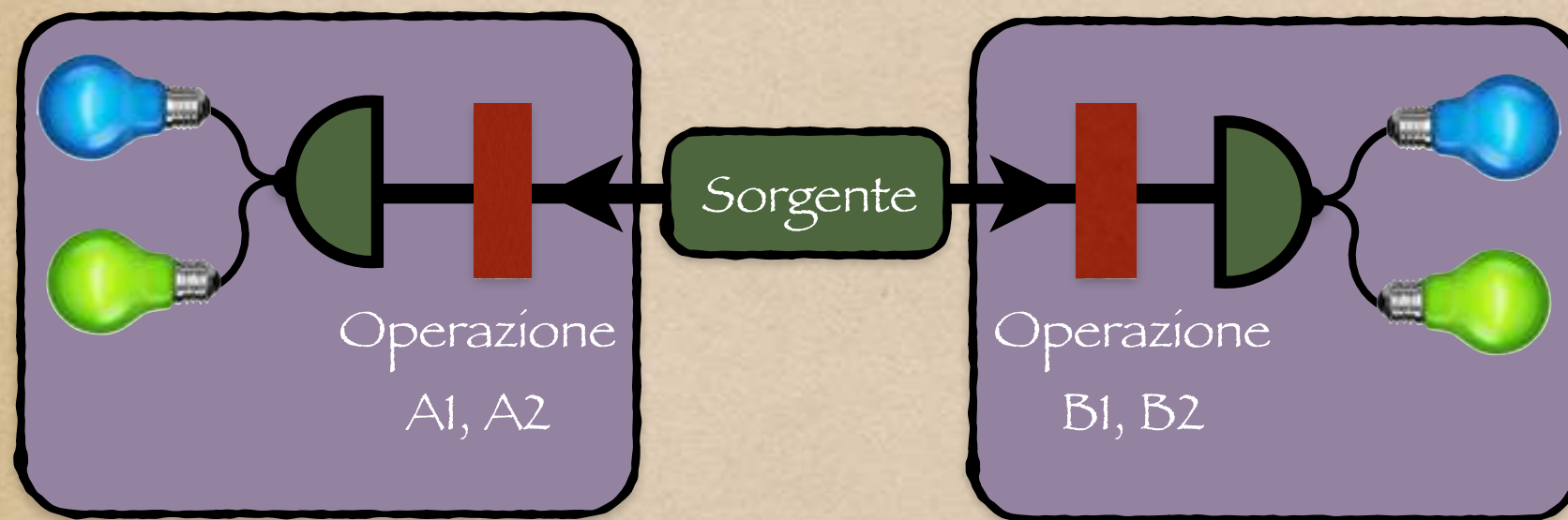
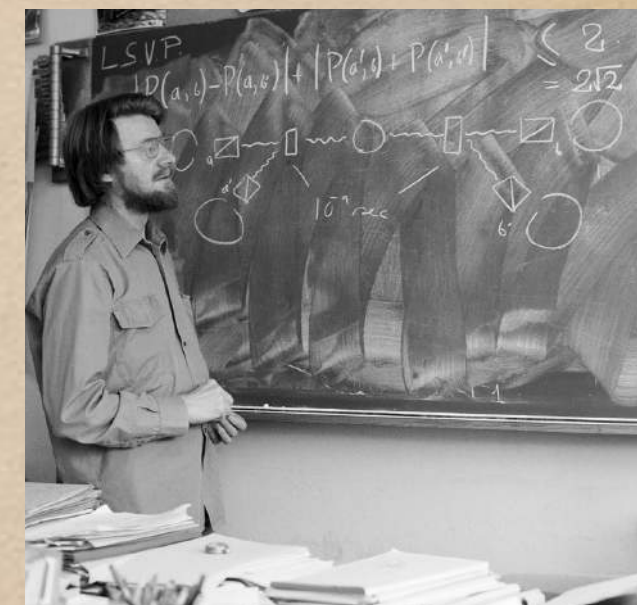
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$\pm 1$

Quantisticamente

$$2 < \mathcal{B} \leq 2\sqrt{2}$$





*Il secondo avvento*





## *Il secondo avvento*

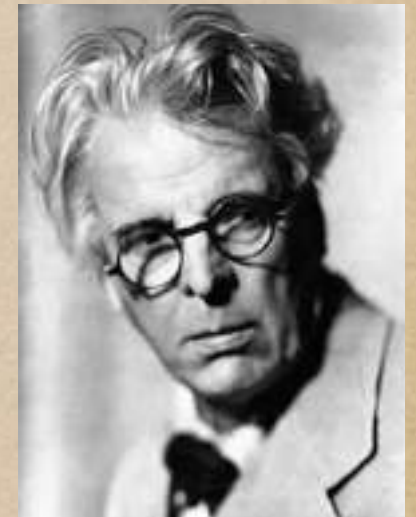






## *Il secondo avvento*

“Il secondo avvento”  
(W. B. Yeats, 1919)





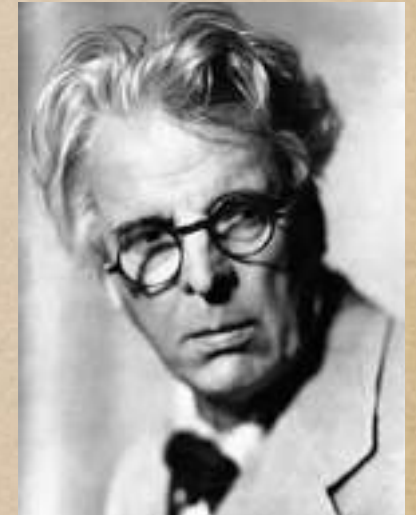


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“Il secondo avvento”

(W. B. Yeats, 1919)

“Certo è imminente una rivelazione.  
Certo è imminente il secondo avvento.  
Il secondo avvento! ”



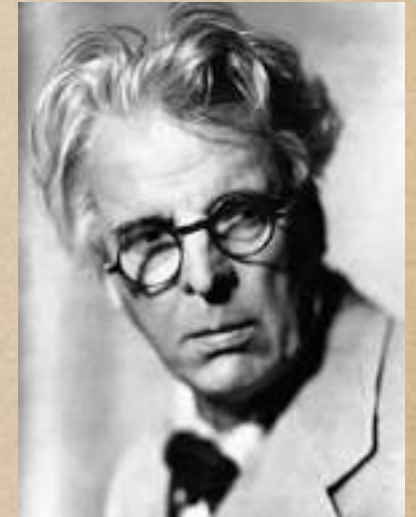


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“Il secondo avvento”

Icona Russa

c. 1700.

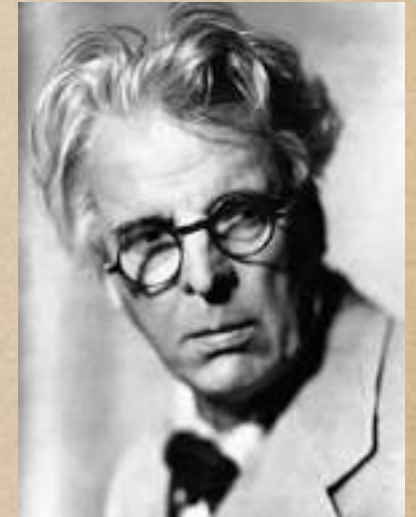


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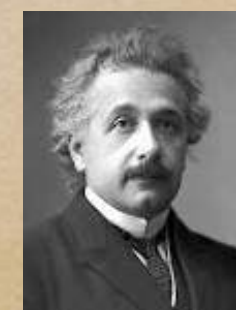
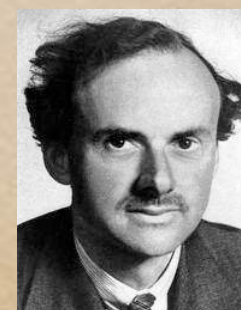
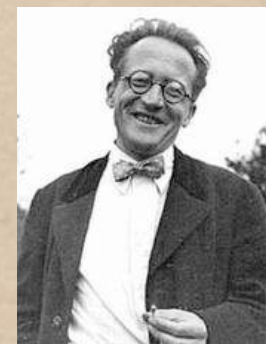
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“Il secondo avvento”

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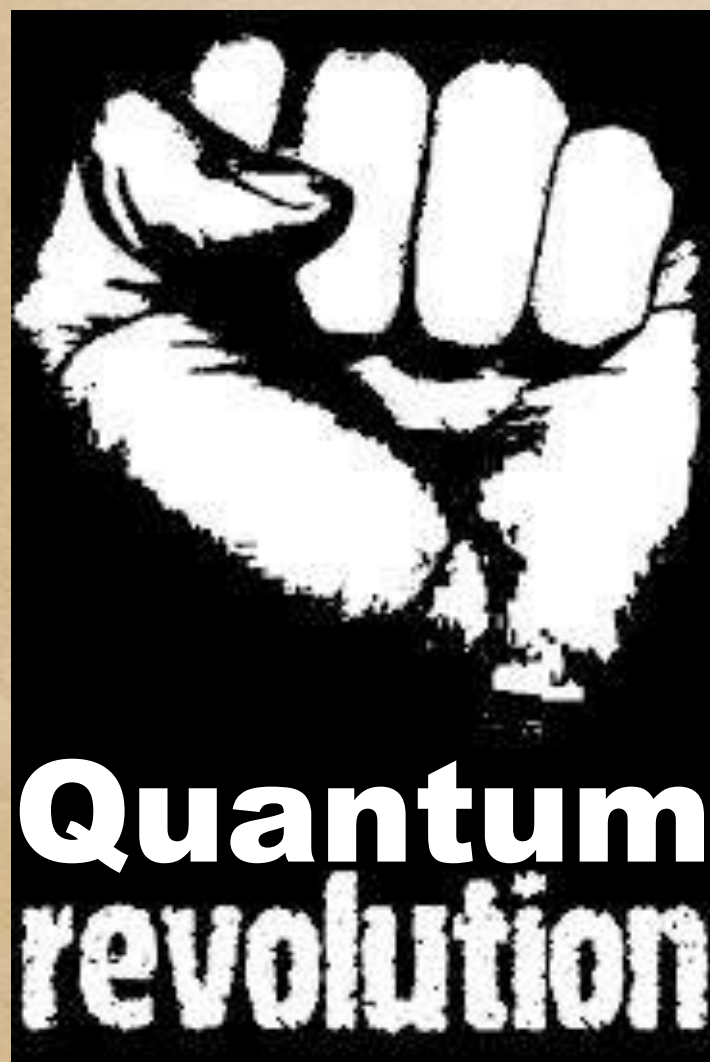
c. 1700.







*La seconda venuta*







*La seconda venuta*







*La seconda venuta*



*Feynman*



*Deutsch*



*Grover*



*Bell*



*Bennett*



*Shor*



*Ekert*



*Zeilinger*





## *La seconda venuta*



*Feynman*



*Deutsch*



*Grover*



*Bell*



*Bennett*



*Shor*



*Ekert*



*Zeilinger*

La seconda rivoluzione quantistica:  
possiamo controllare il mondo  
microscopico





*Realta' quantiche*





*Realta' quantiche*



**Quantum cryptography**

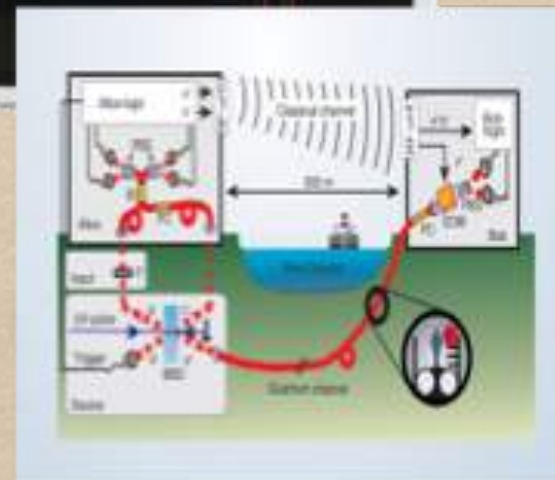




*Realta' quantiche*



**Quantum cryptography**



**Quantum teleportation**

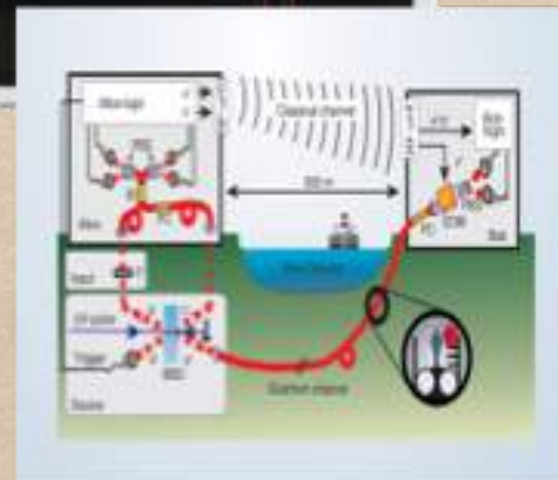




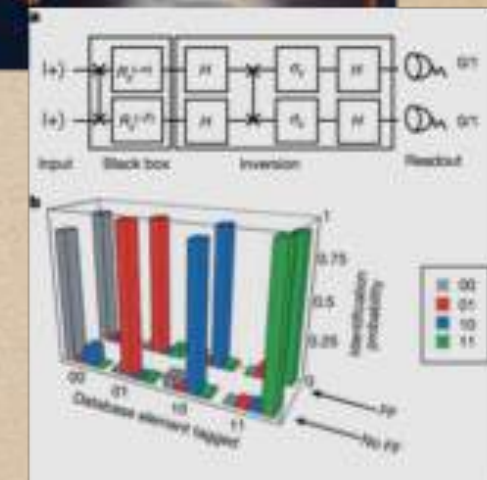
# *Realta' quantiche*



**Quantum cryptography**



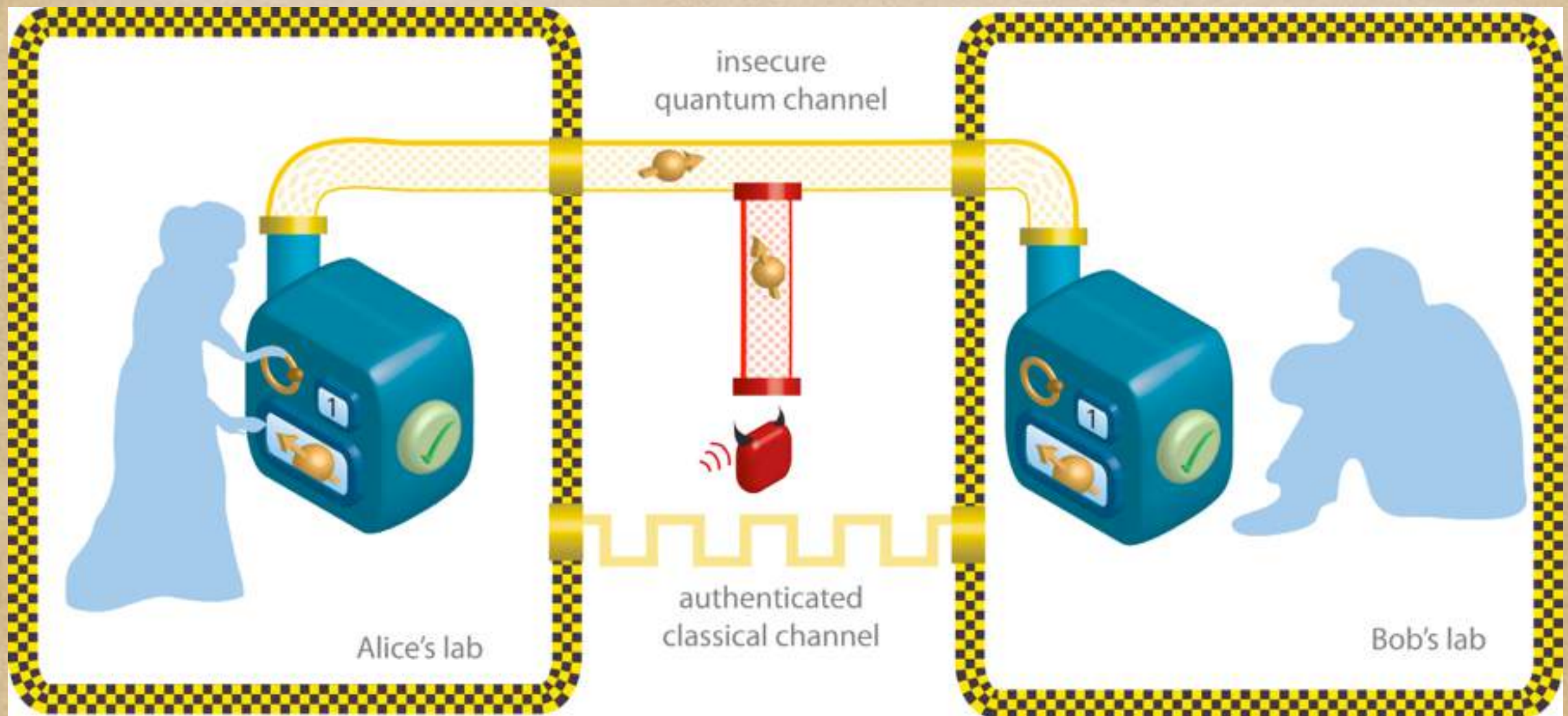
**Quantum teleportation**



**Quantum computation**



# *Criptografia*







*Teleportazione*



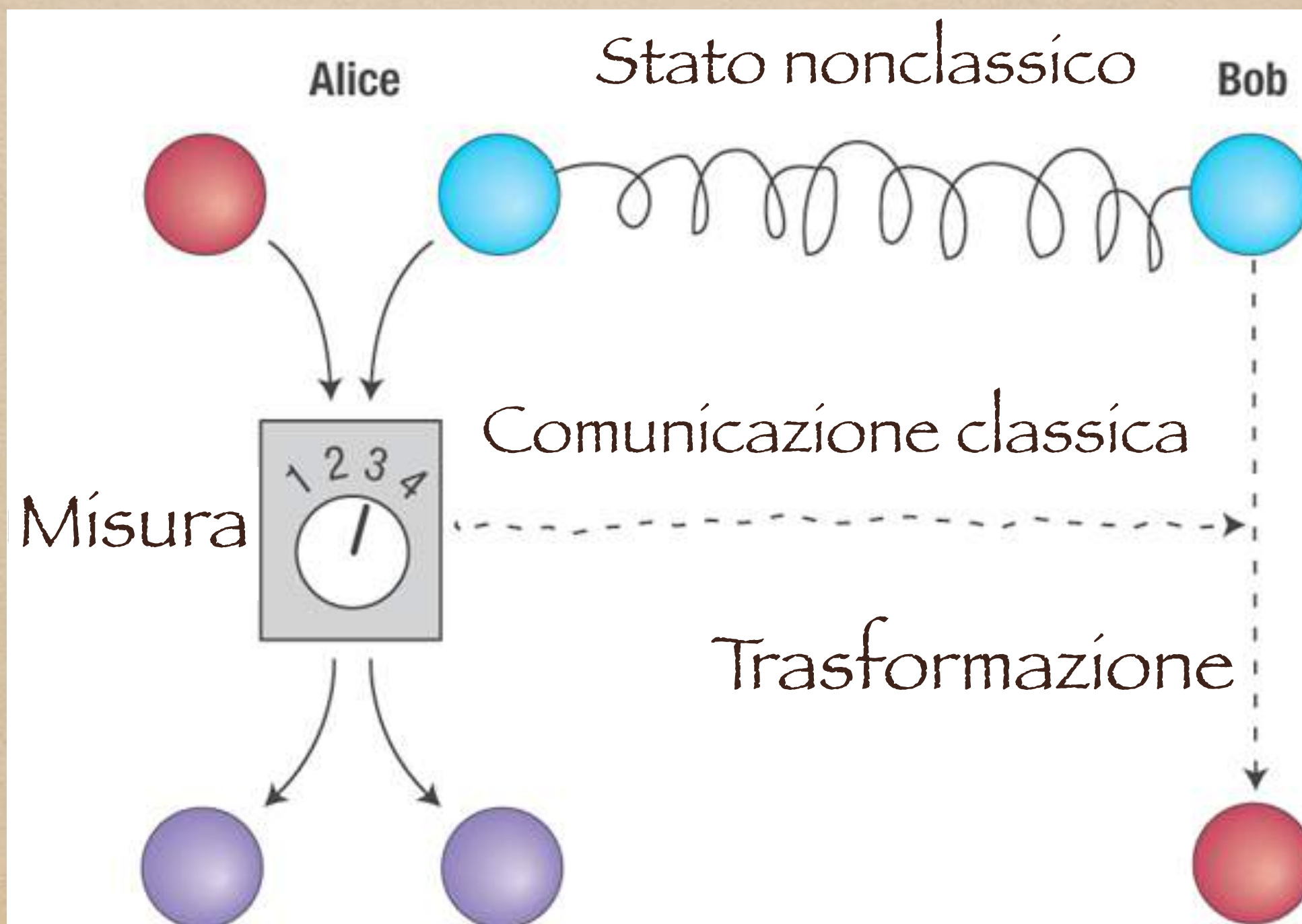


# *Teleportazione*





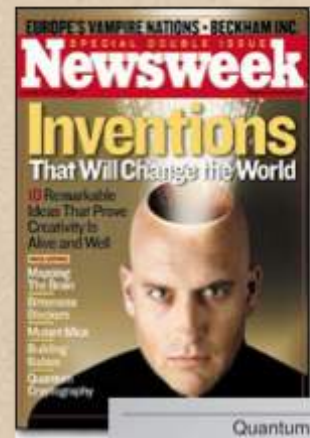
# Teleportazione



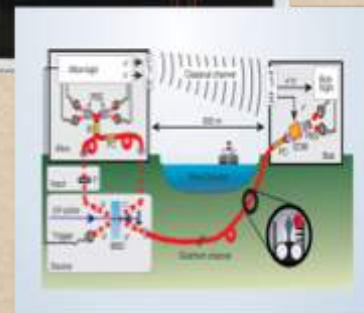




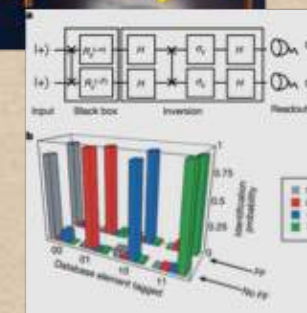
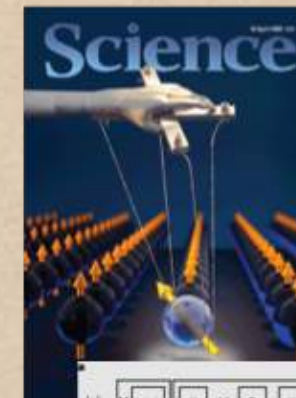
Uhhh....



Quantum cryptography



Quantum teleportation



Quantum computation

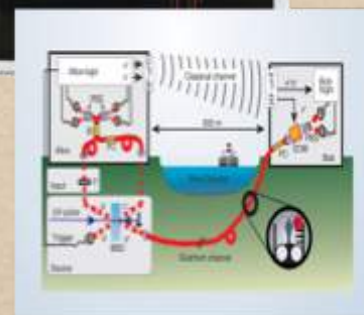




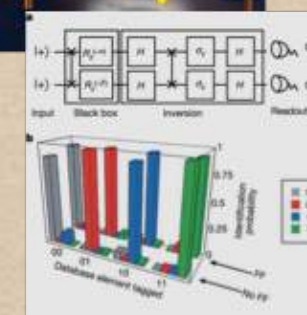
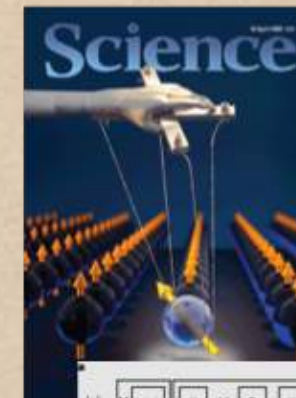
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Quantum cryptography



Quantum teleportation



Quantum computation

Abbiamo bisogno di sistemi microscopici

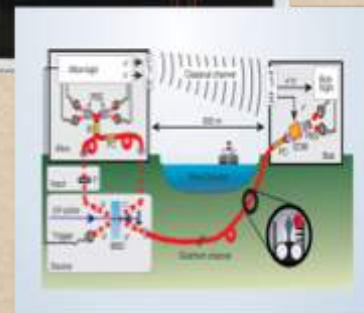




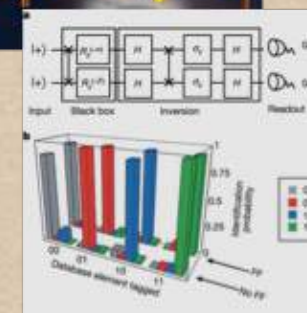
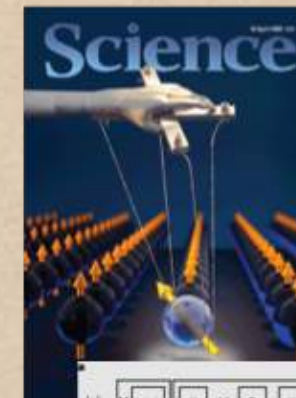
Ummm....



Quantum cryptography



Quantum teleportation



Quantum computation

Abbiamo bisogno di sistemi microscopici  
Tutto deve essere ben isolato

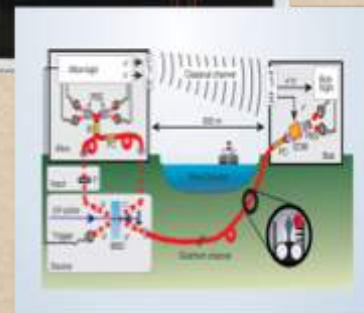




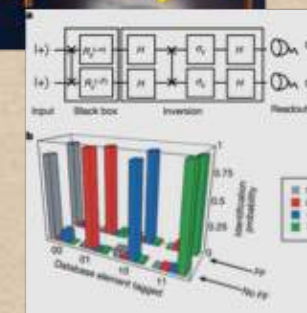
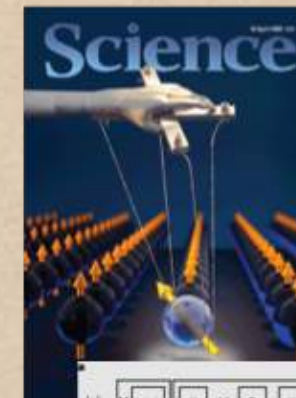
Ummm....



Quantum cryptography



Quantum teleportation



Quantum computation

Abbiamo bisogno di sistemi microscopici  
Tutto deve essere ben isolato  
Il controllo deve essere perfetto!

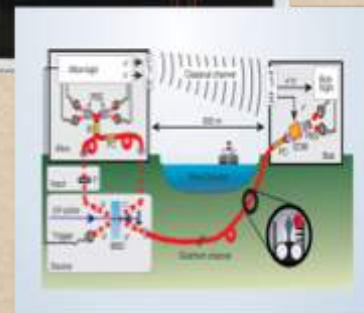




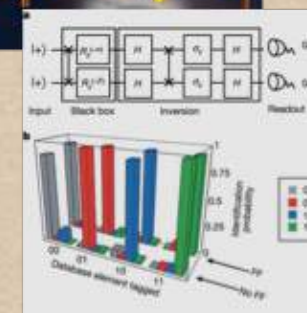
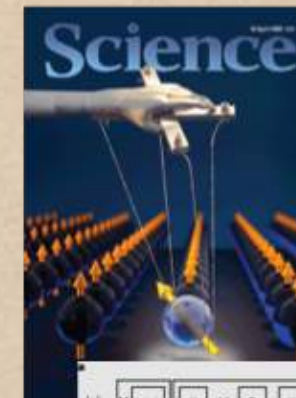
Ummm....



Quantum cryptography



Quantum teleportation



Quantum computation

Abbiamo bisogno di sistemi microscopici

Tutto deve essere ben isolato

Il controllo deve essere perfetto!

Sono solo sistemi microscopici  
e condizioni speciali ad essere importanti?





*Allargando il  
contesto*







*Allargando il  
contesto*



Effetti quantistici sono certificati





*Allargando il  
contesto*



Effetti quantistici sono certificati  
nei nostri migliori laboratori





*Allargando il  
contesto*



Effetti quantistici sono certificati  
nei nostri migliori laboratori

Effetti quantistici macroscopici non sembrano osservabili



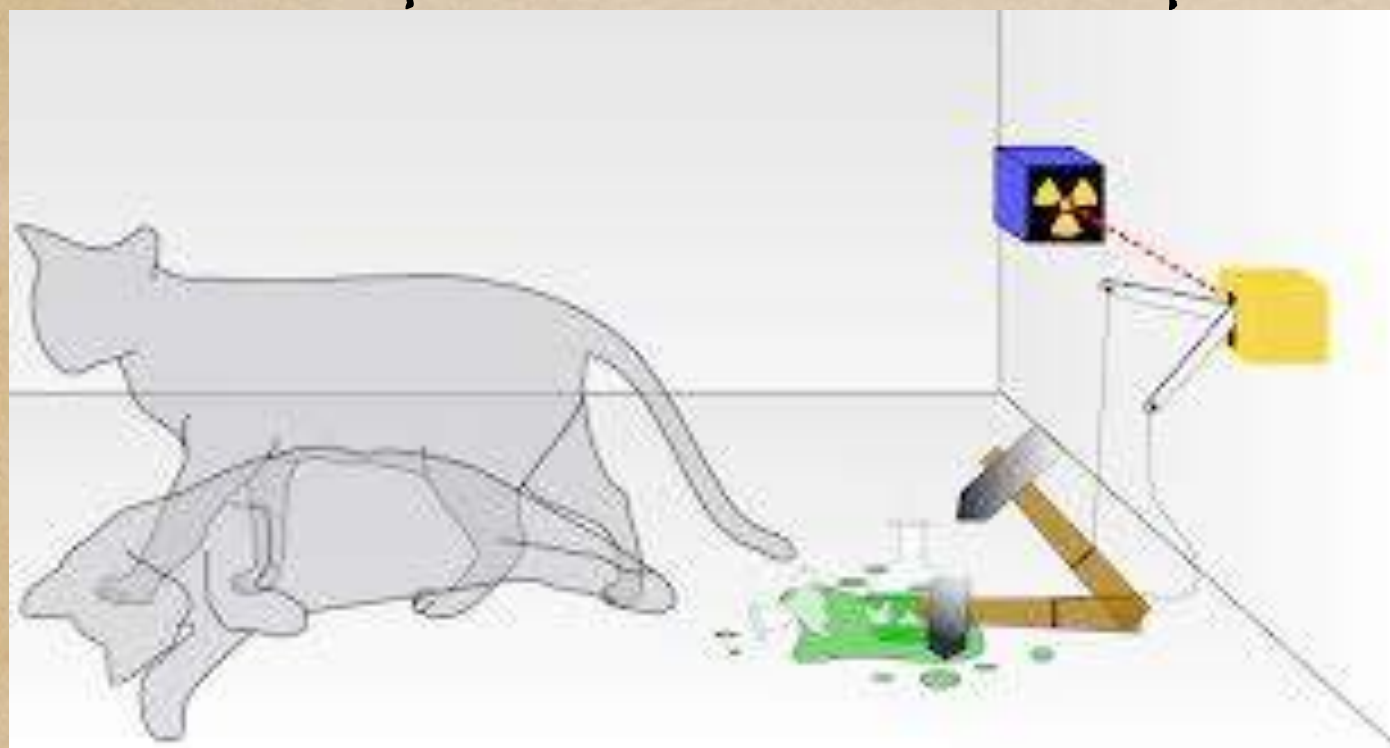


*Allargando il  
contesto*



Effetti quantistici sono certificati  
nei nostri migliori laboratori

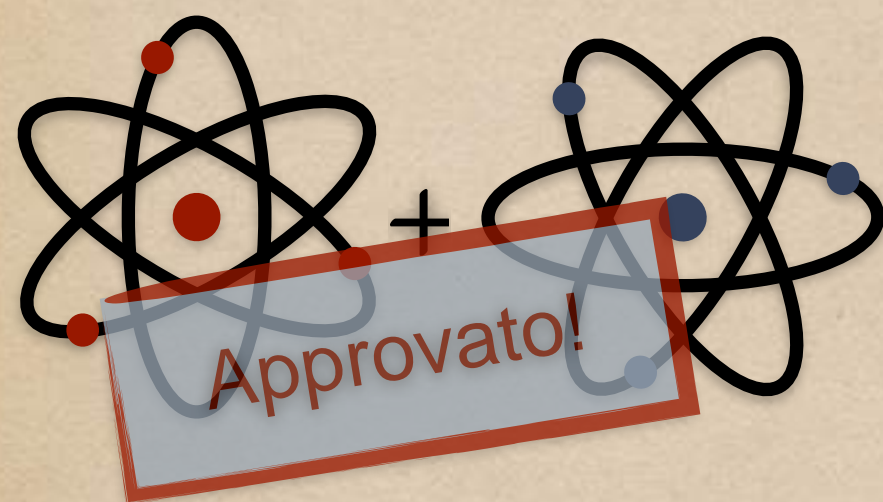
Effetti quantistici macroscopici non sembrano osservabili





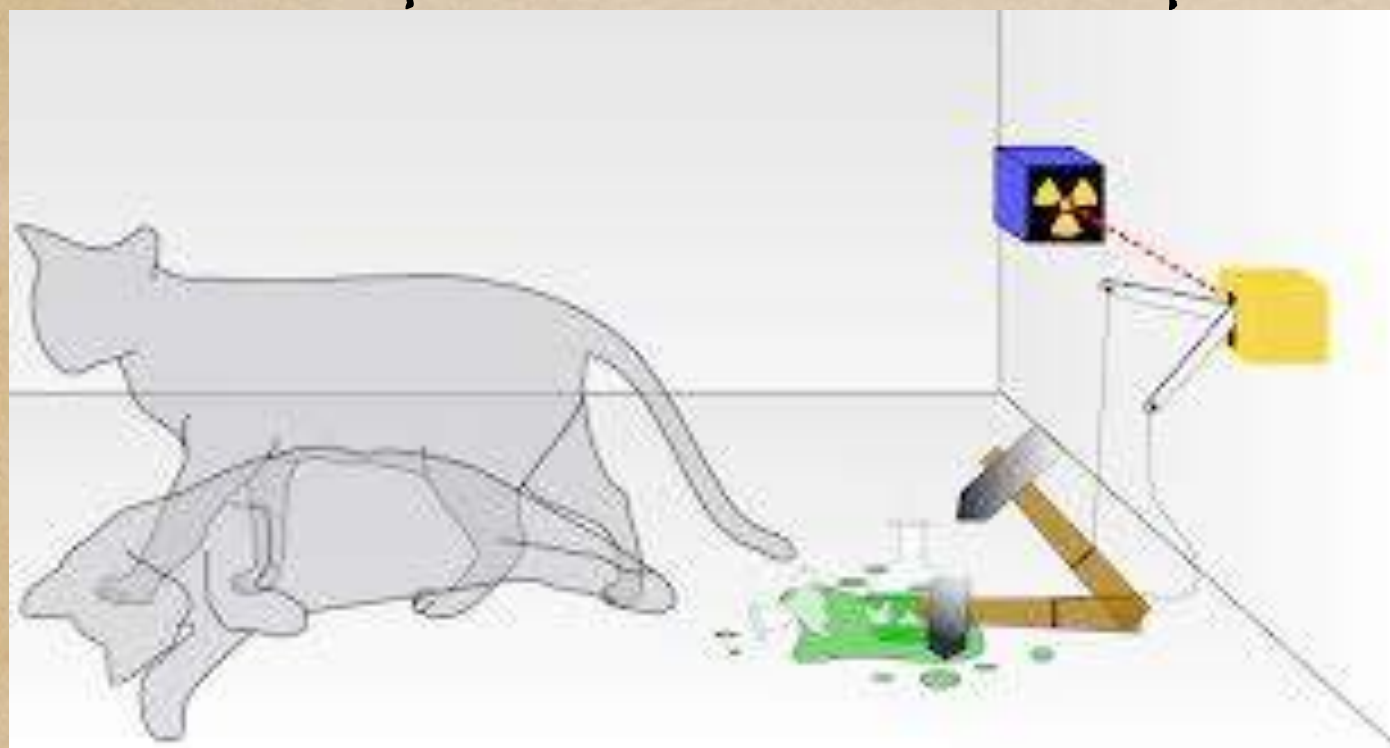


*Allargando il  
contesto*



Effetti quantistici sono certificati  
nei nostri migliori laboratori

Effetti quantistici macroscopici non sembrano osservabili



$$\frac{1}{\sqrt{2}}|\text{cat}\rangle + \frac{1}{\sqrt{2}}|\text{dead cat}\rangle$$





*Allargando il  
contesto*



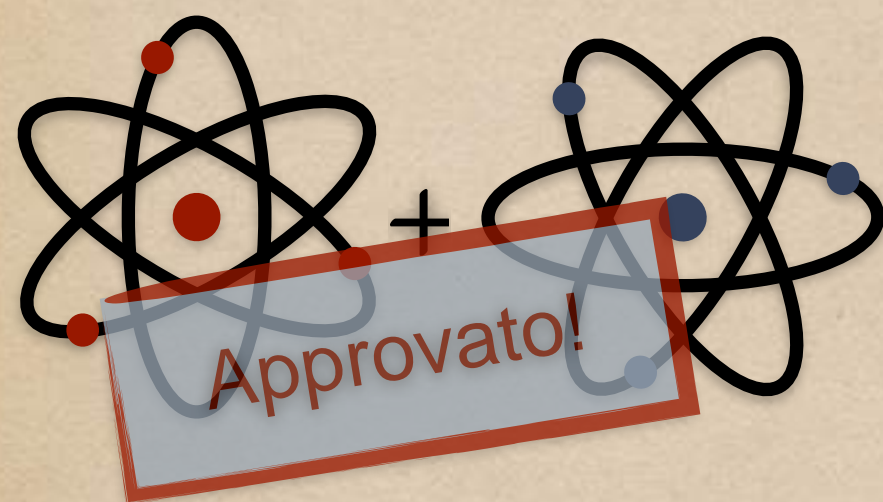
Effetti quantistici sono certificati  
nei nostri migliori laboratori

Effetti quantistici macroscopici non sembrano osservabili





*Allargando il  
contesto*



Effetti quantistici sono certificati  
nei nostri migliori laboratori

Effetti quantistici macroscopici non sembrano osservabili







*Decoerenza*





*Decoerenza*



Wojciech Zurek, LANL





*Decoerenza*



Wojciech Zurek, LANL

Ambiente

Sistema

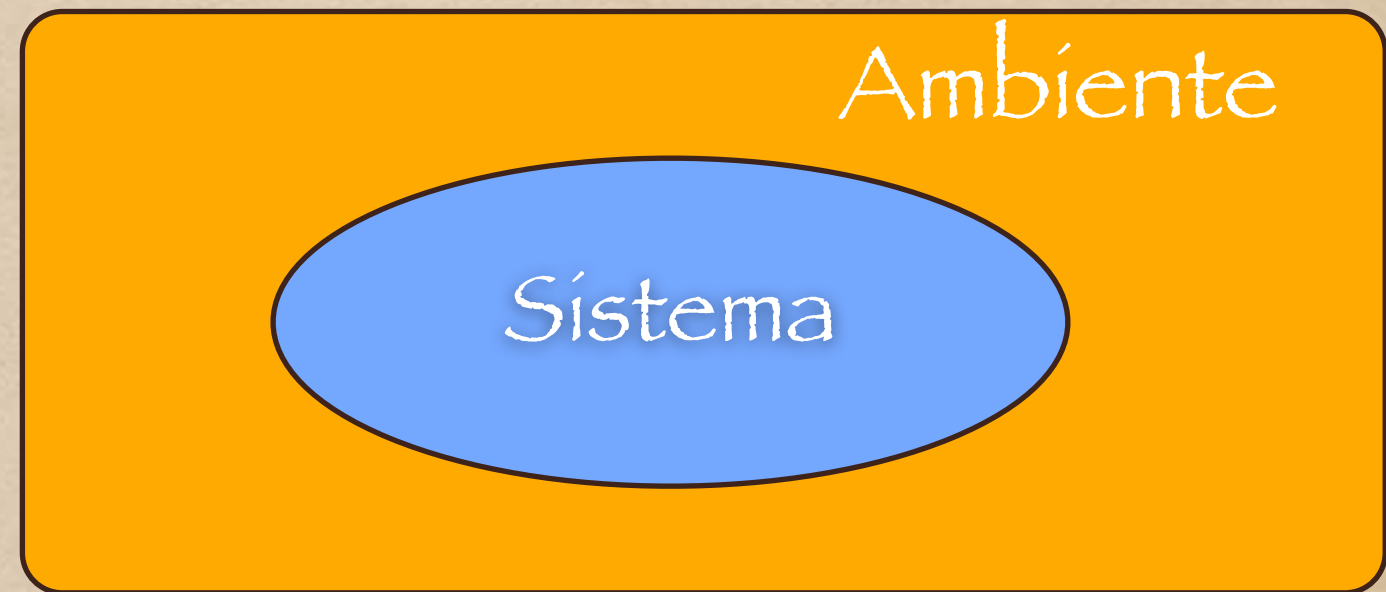




*Decoerenza*



Wojciech Zurek, LANL



Ambiente: = tutto ciò che non è il sistema

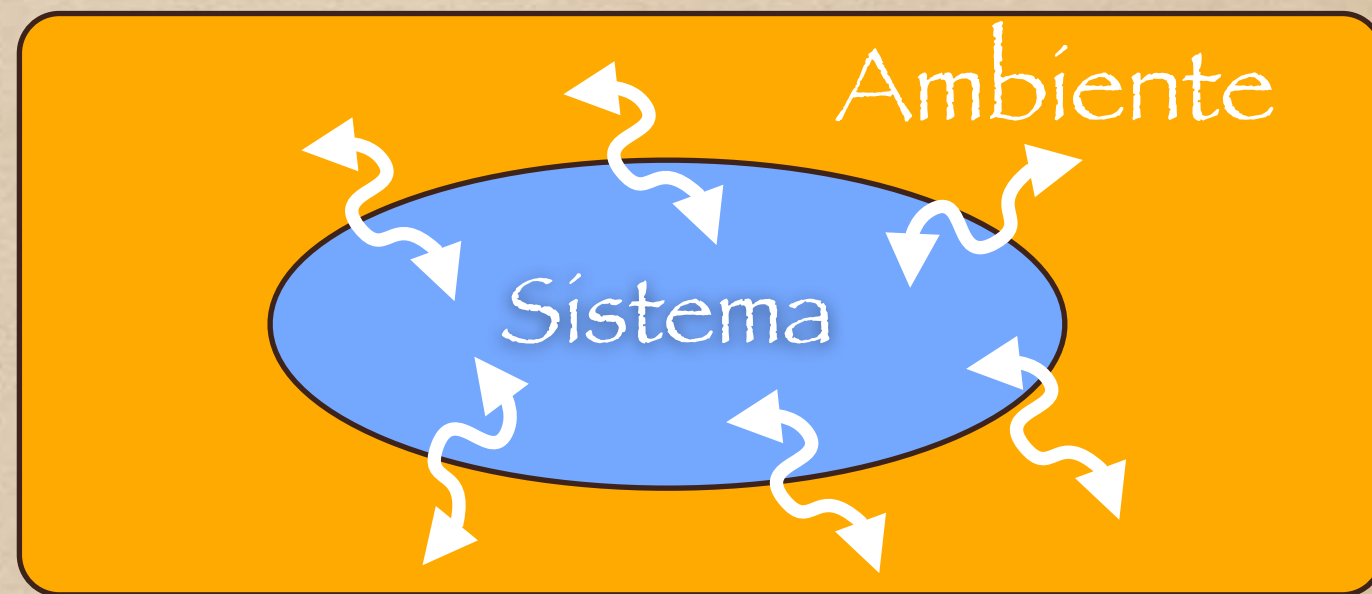




## *Decoerenza*



Wojciech Zurek, LANL



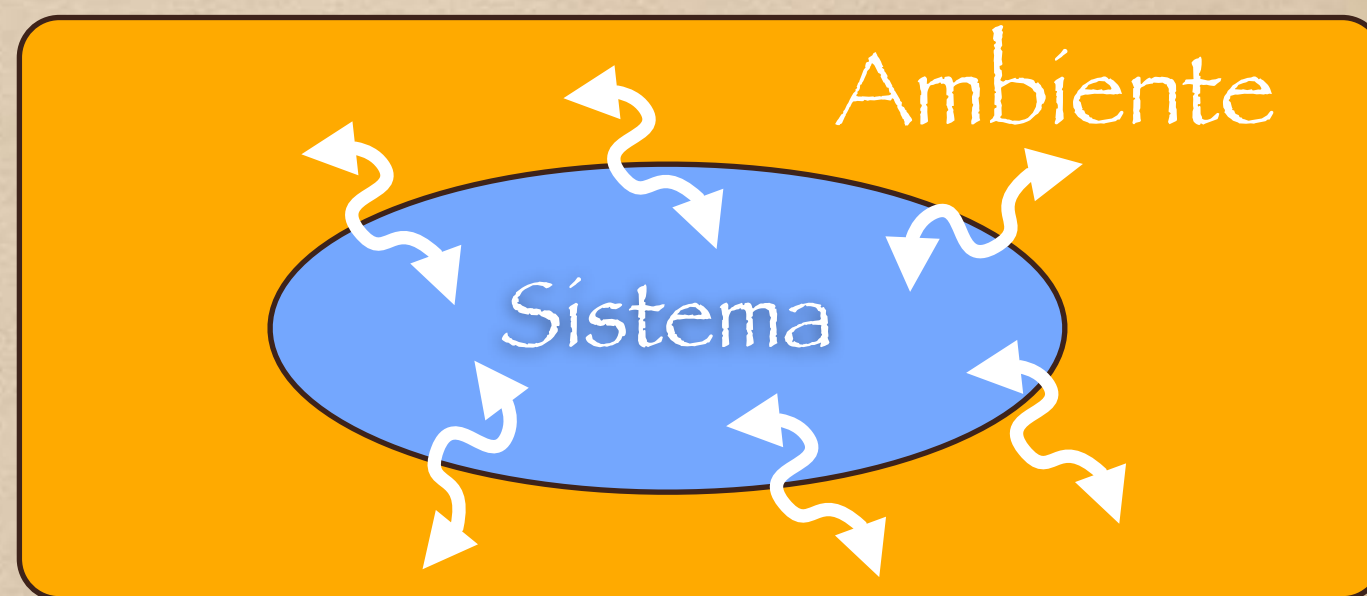
Ambiente:  $\equiv$  tutto ciò che non è il sistema



## Decoerenza



Wojciech Zurek, LANL



Ambiente: = tutto ciò che non è il sistema

$$i\hbar\partial_t|\psi\rangle = \hat{E}|\psi\rangle$$

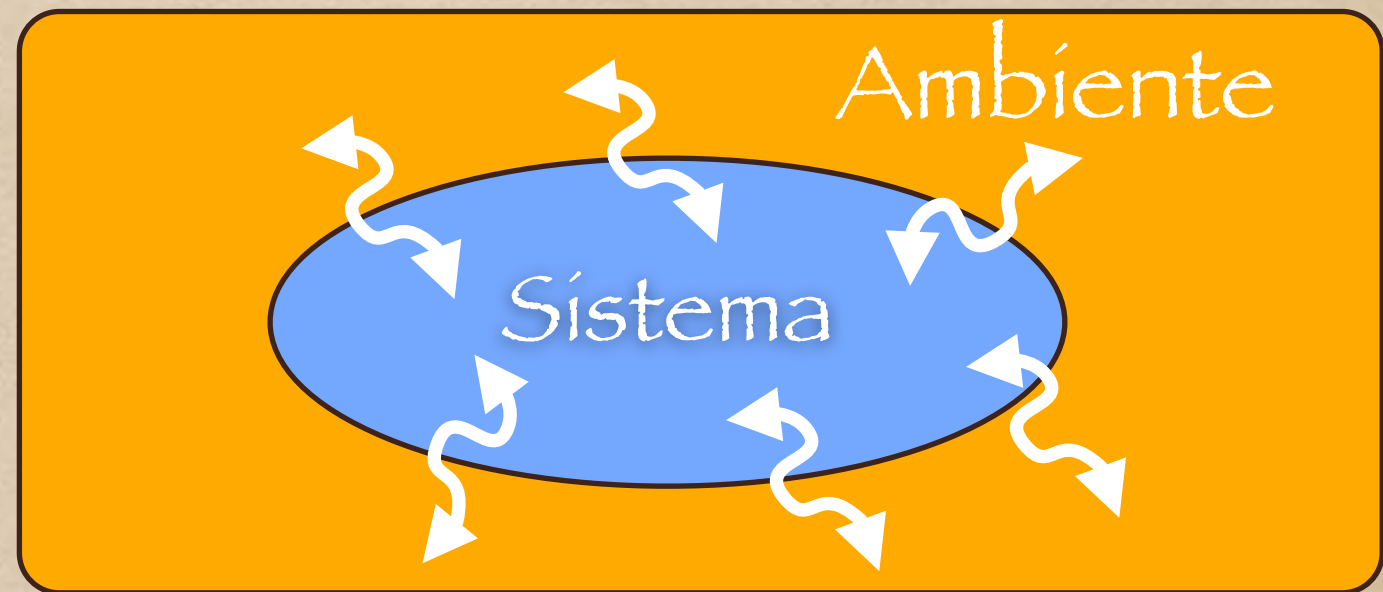
Eq. di Schroedinger:  
nessun ambiente



# Decoerenza



Wojciech Zurek, LANL



Ambiente: = tutto ciò che non è il sistema

$$i\hbar\partial_t|\psi\rangle = \hat{E}|\psi\rangle$$

Eq. di Schroedinger:  
nessun ambiente

$$\partial_t\rho = \mathcal{L}(\rho)$$

Master Equation:  
ho un ambiente

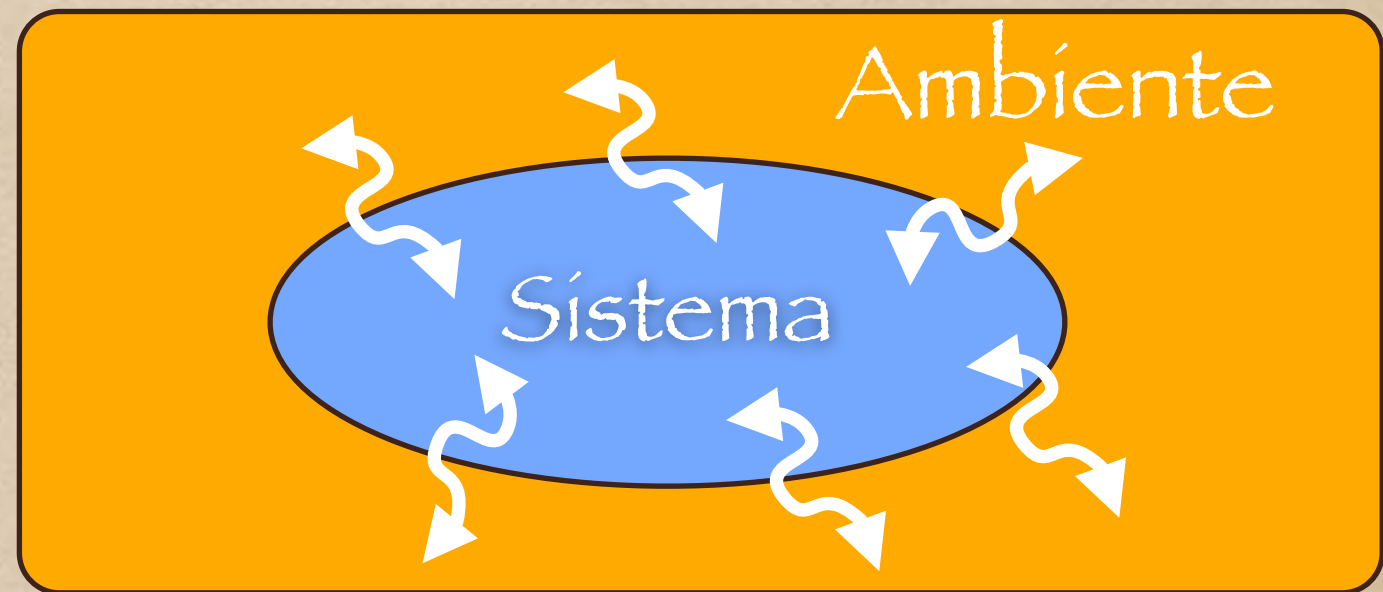




## Decoerenza



Wojciech Zurek, LANL



Ambiente: = tutto ciò che non è il sistema

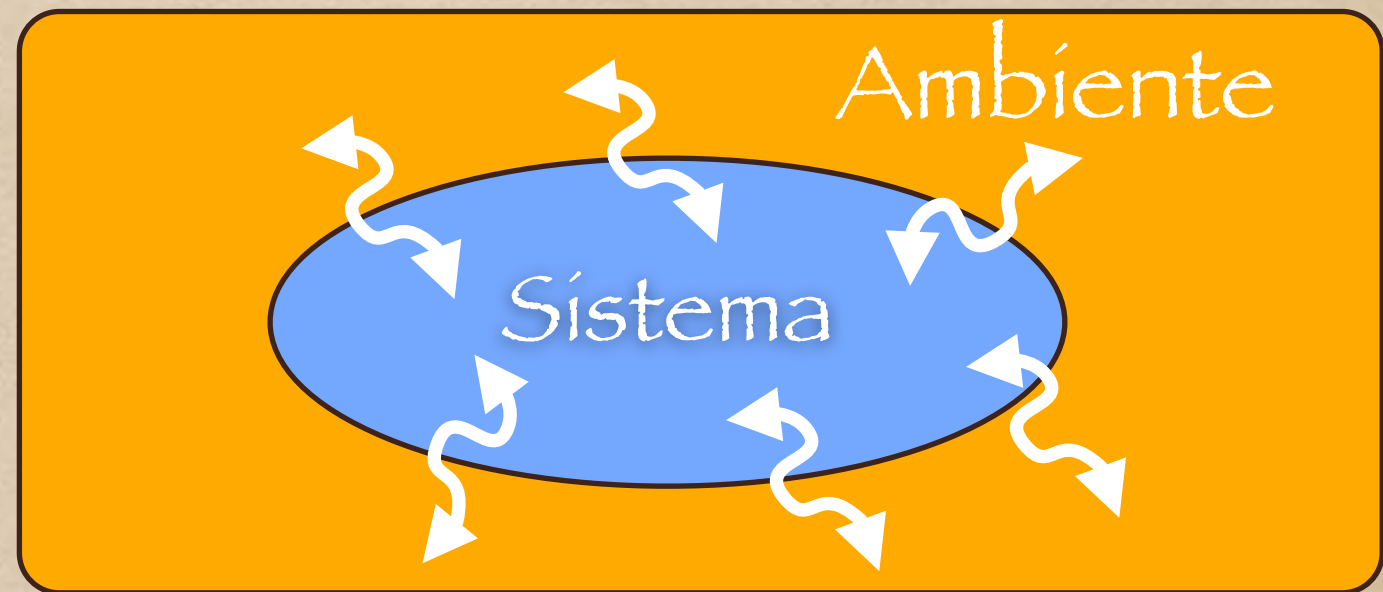




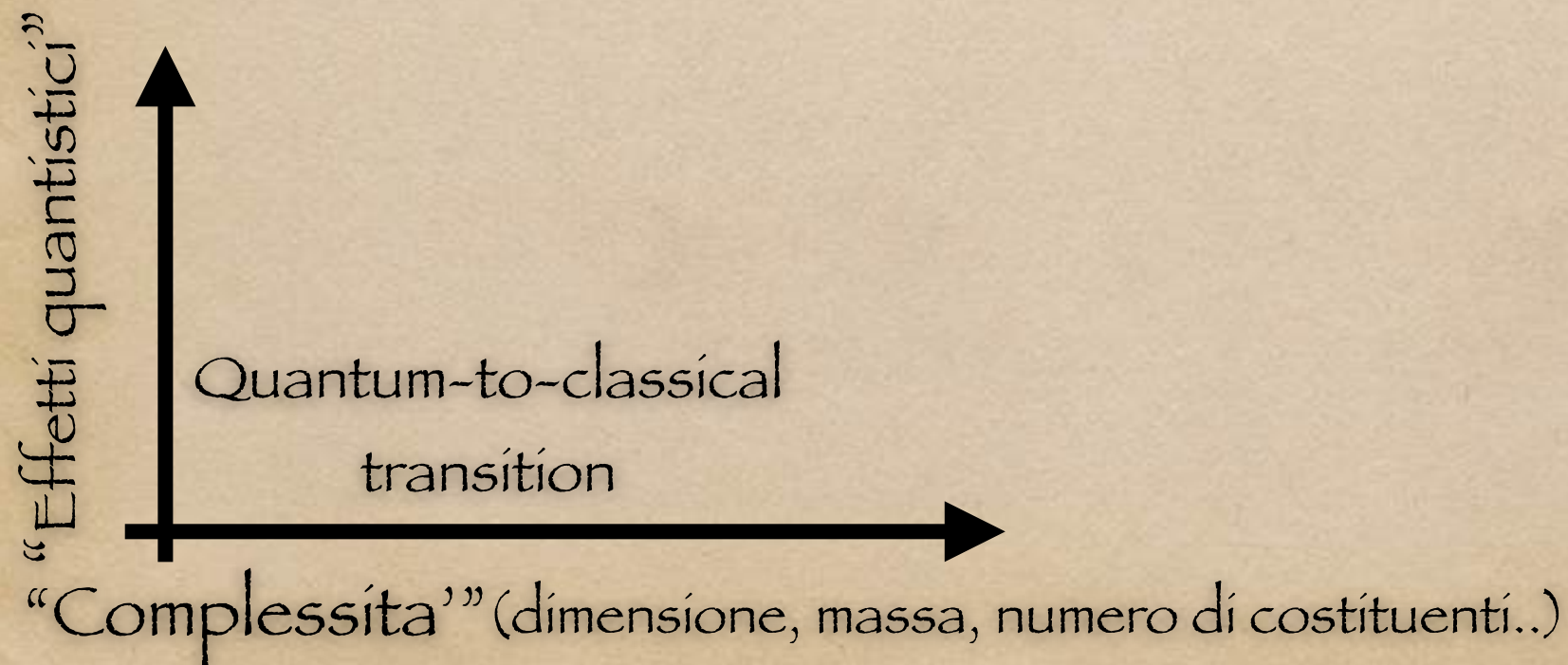
# Decoerenza



Wojciech Zurek, LANL



Ambiente: = tutto ciò che non è il sistema



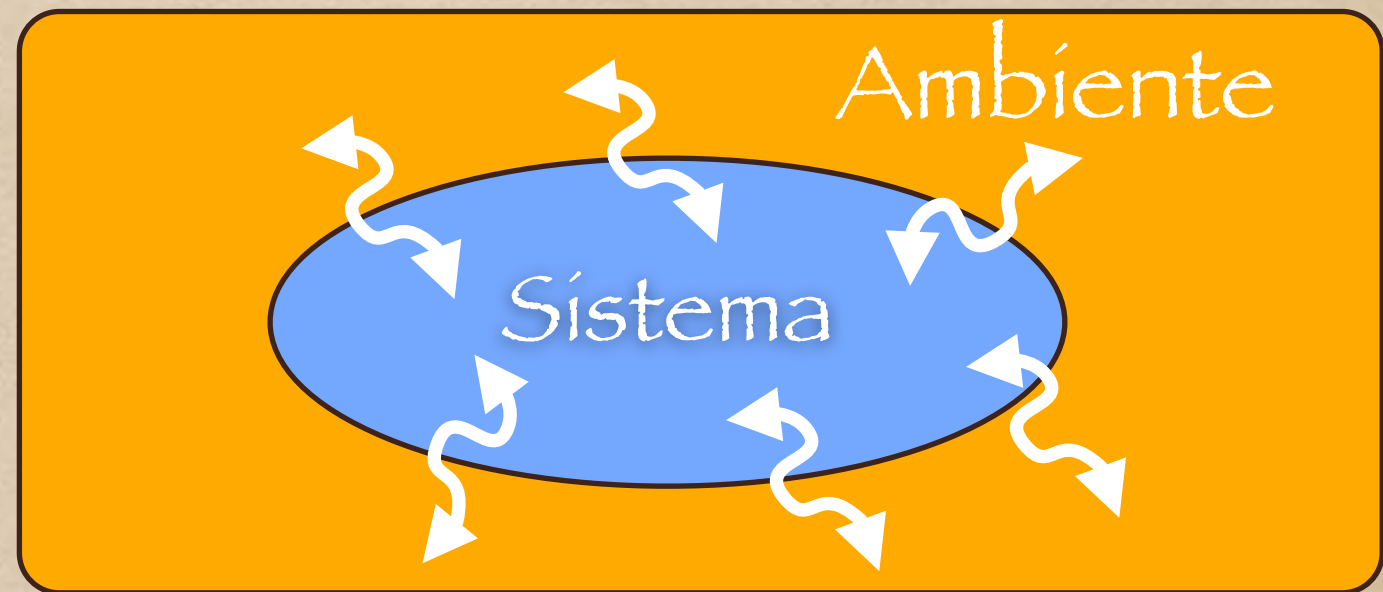




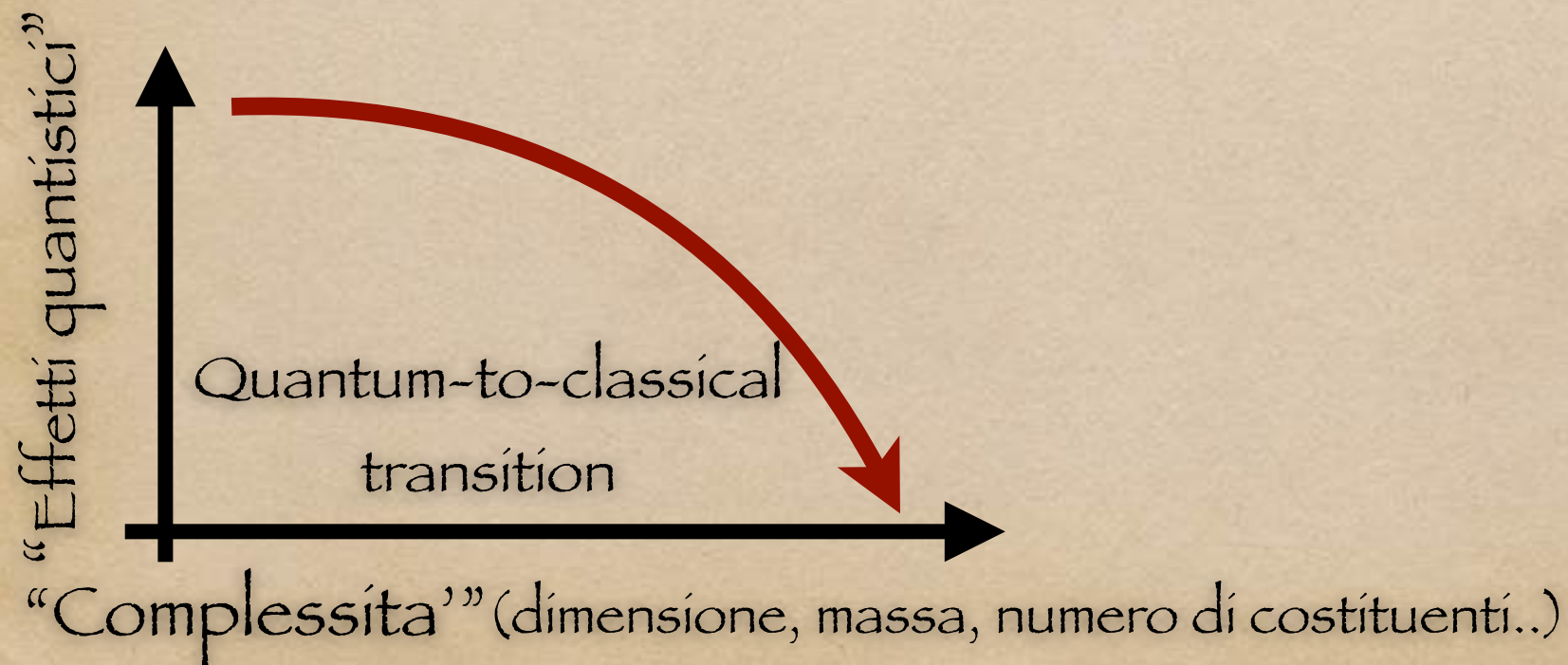
# Decoerenza



Wojciech Zurek, LANL



Ambiente := tutto ciò che non è il sistema

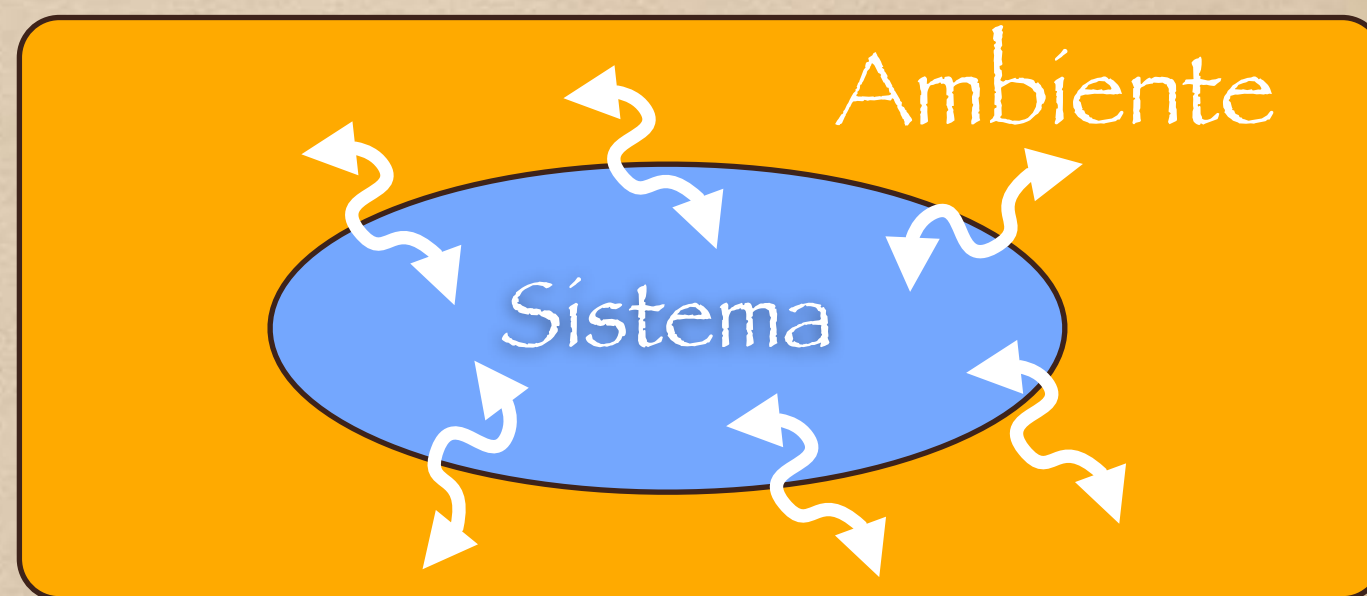




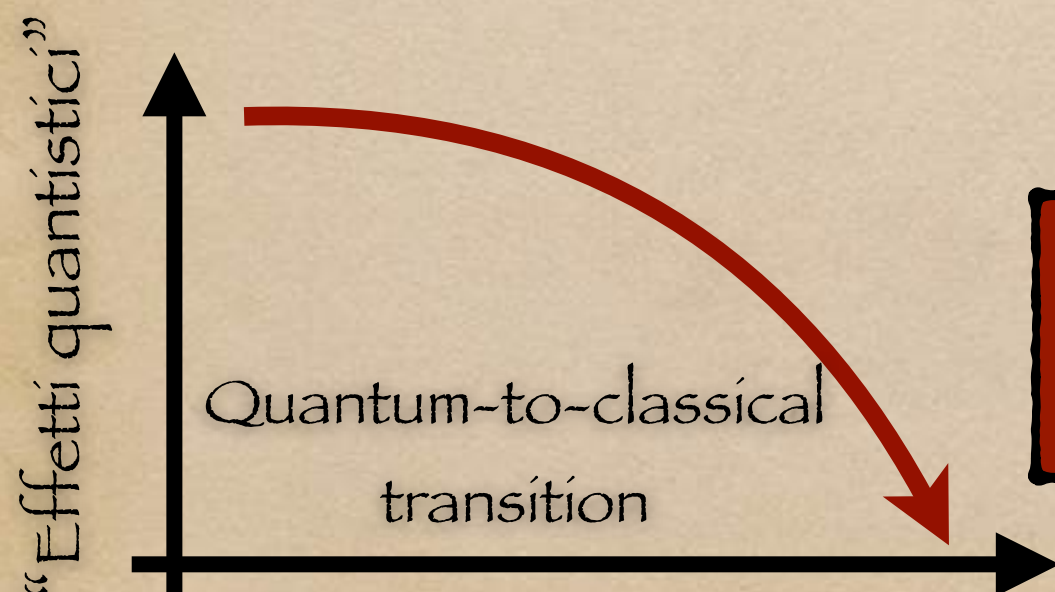
## Decoerenza



Wojciech Zurek, LANL



Ambiente: = tutto ciò che non è il sistema



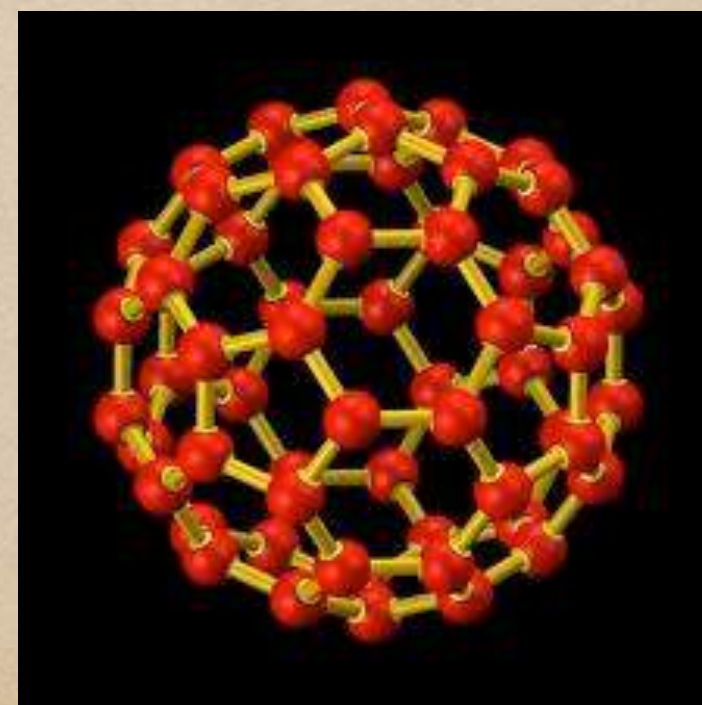
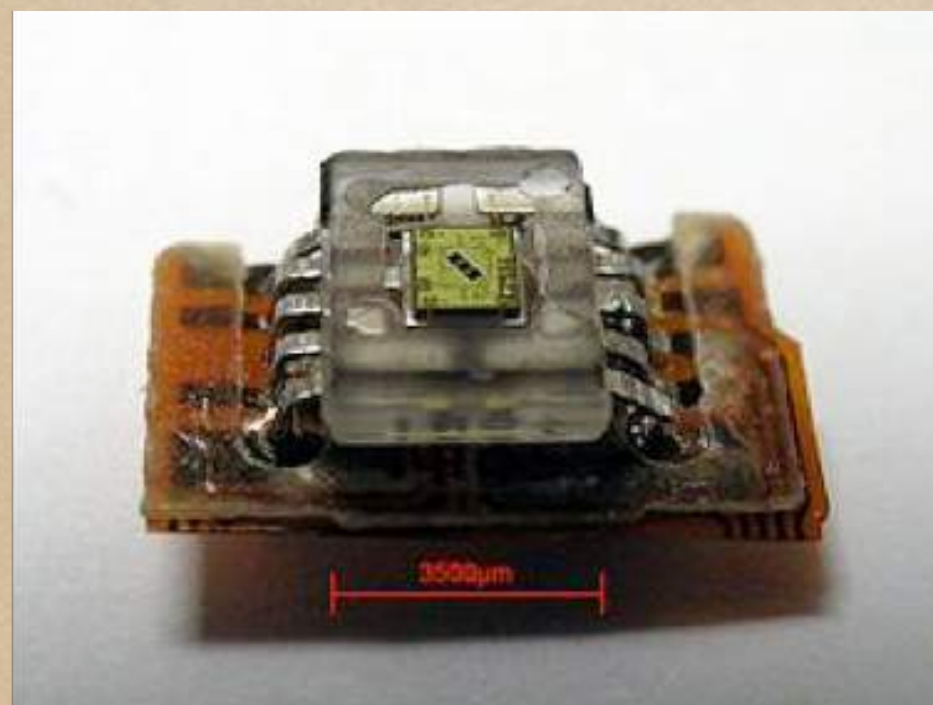
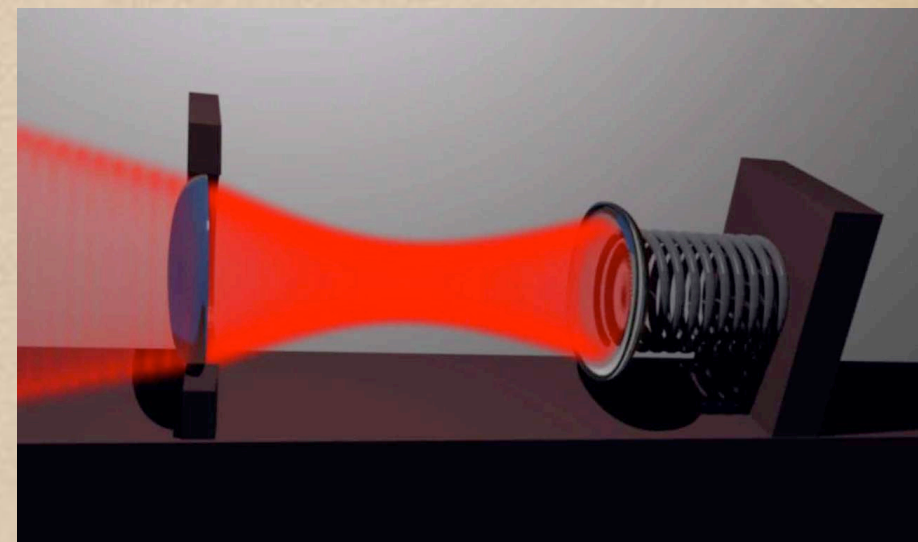
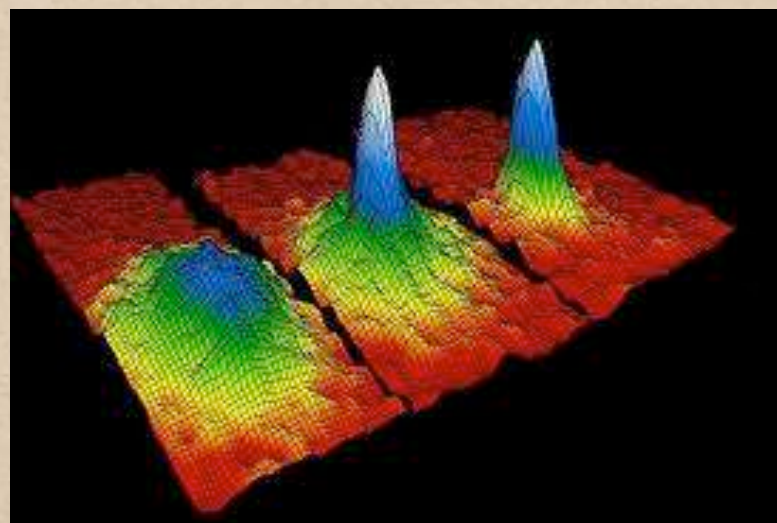
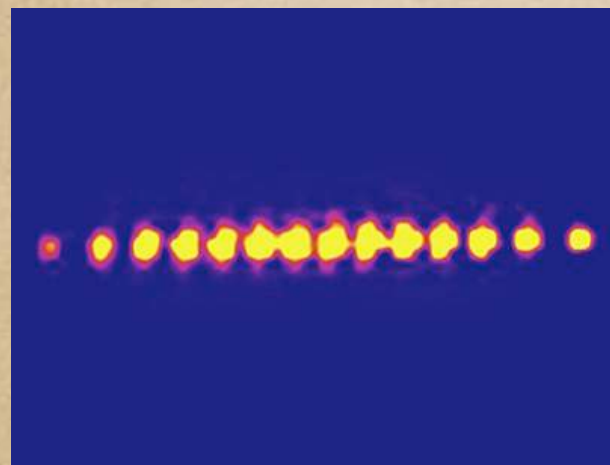
È impossibile osservare effetti quantistici su scala macroscopica?

"Complessità" (dimensione, massa, numero di costituenti..)





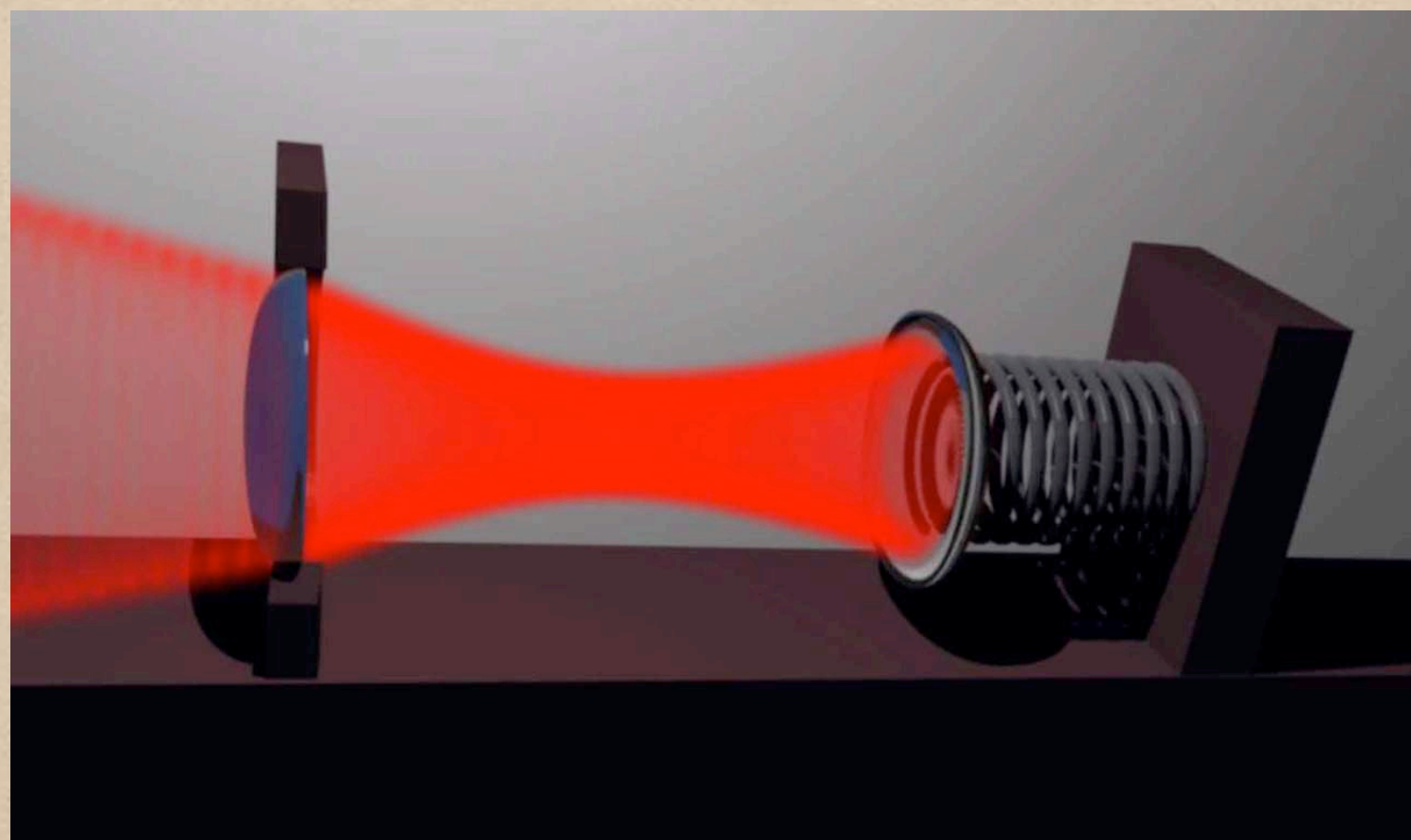
*No, no, e ancora no!*







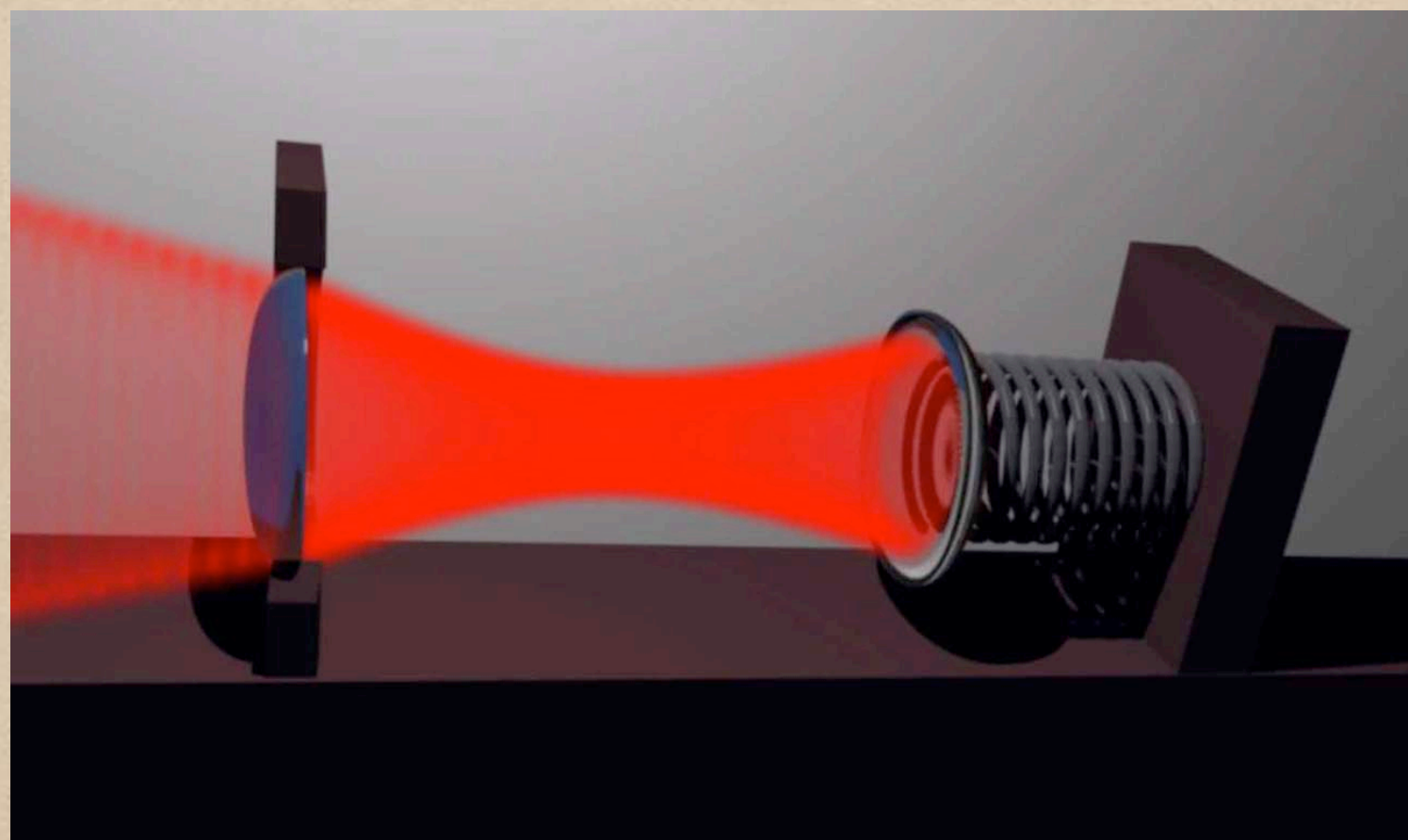
*Lux fiat!*  
*ed uno specchio, che vibra...*







*Lux fiat!*  
*ed uno specchio, che vibra...*

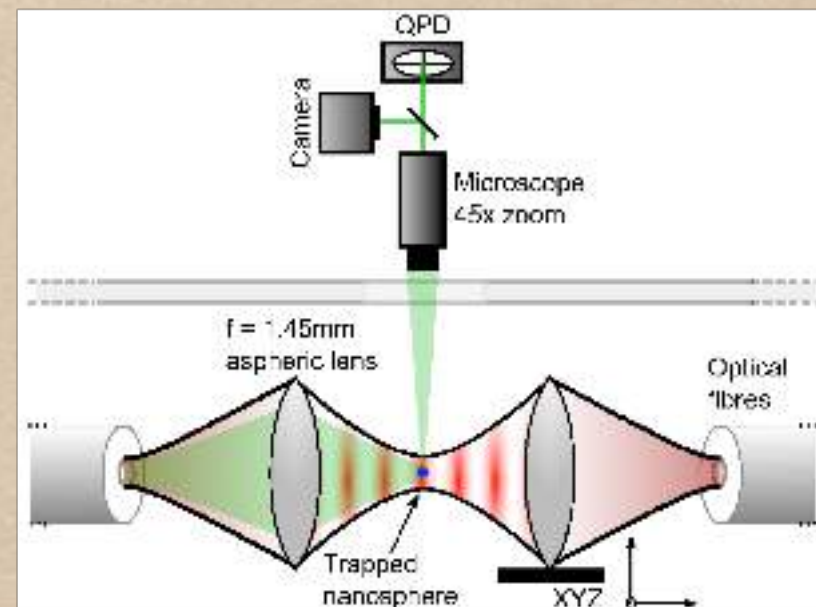
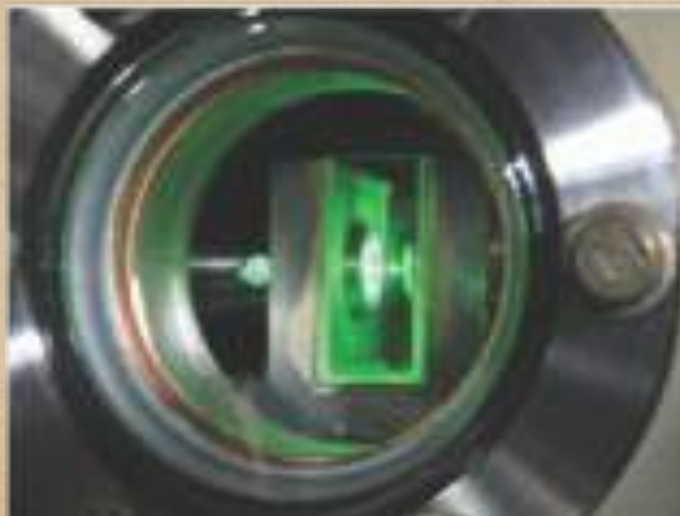
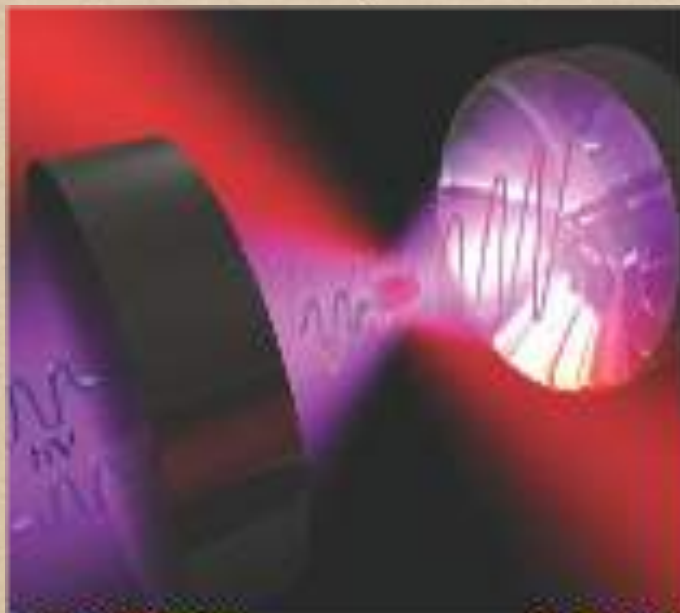






*Lux fiat!*  
*ed uno specchio, che vibra...*

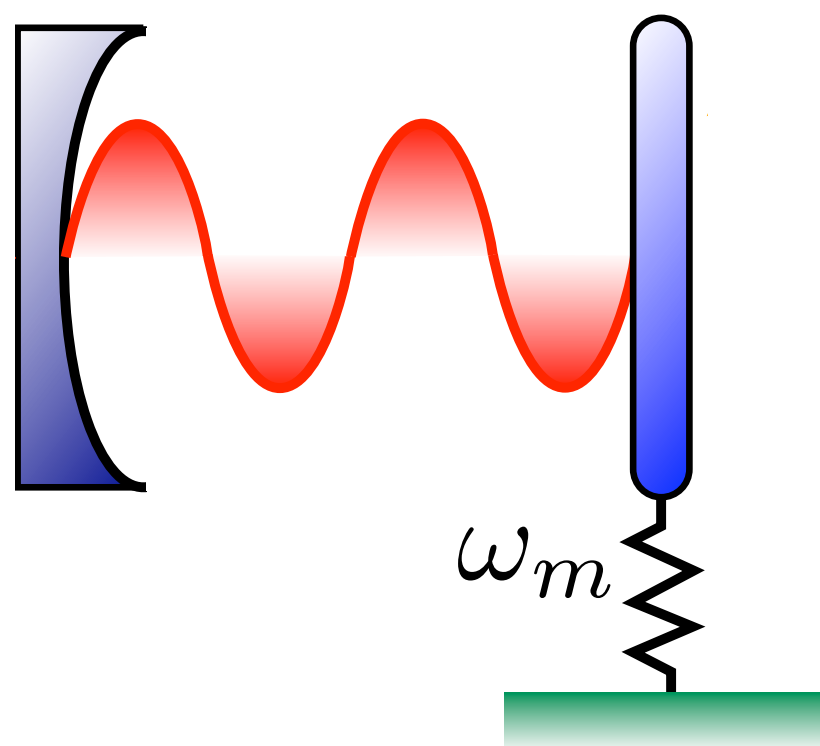
# Sfere dielettriche sospese







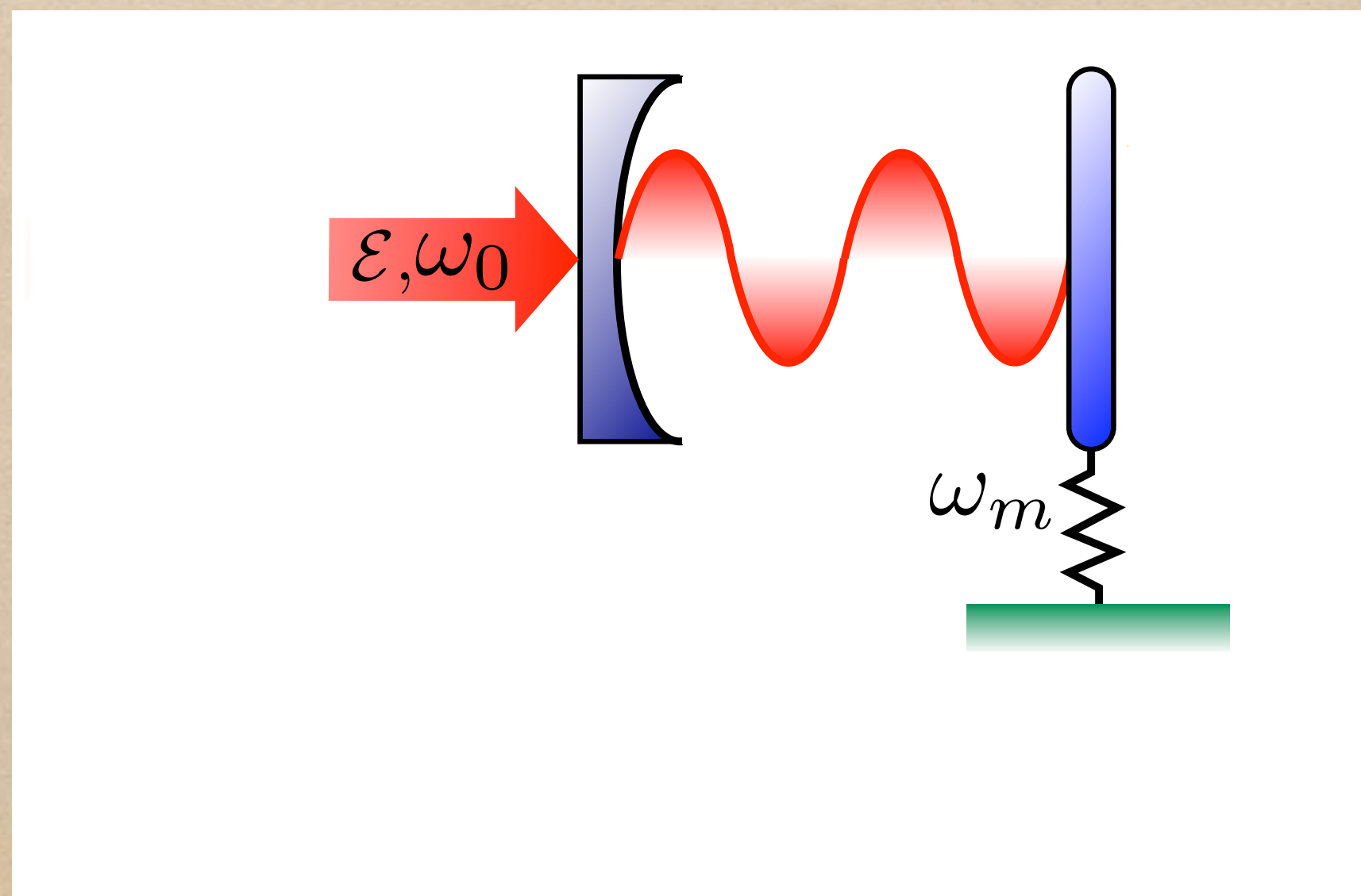
*Lux fiat!*  
*ed uno specchio, che vibra...*







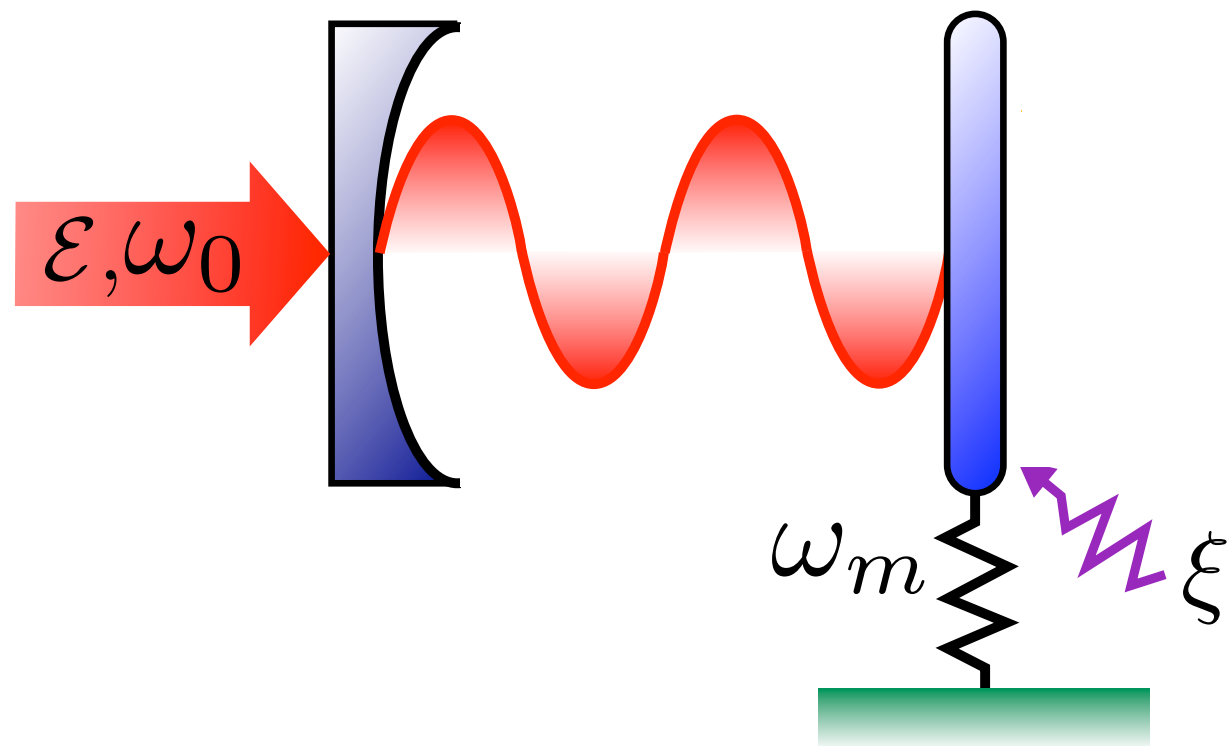
*Lux fiat!*  
*ed uno specchio, che vibra...*







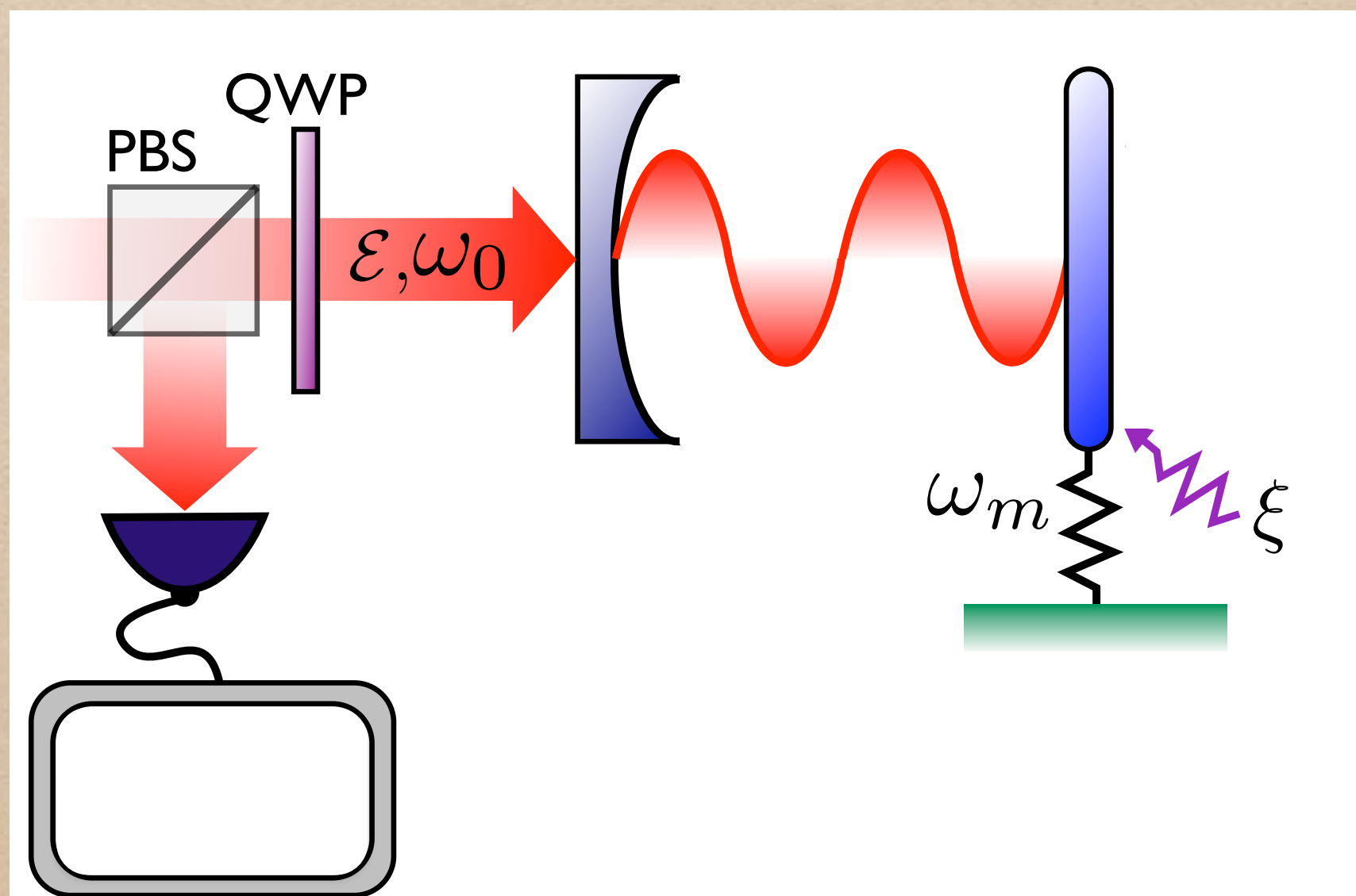
*Lux fiat!*  
*ed uno specchio, che vibra...*







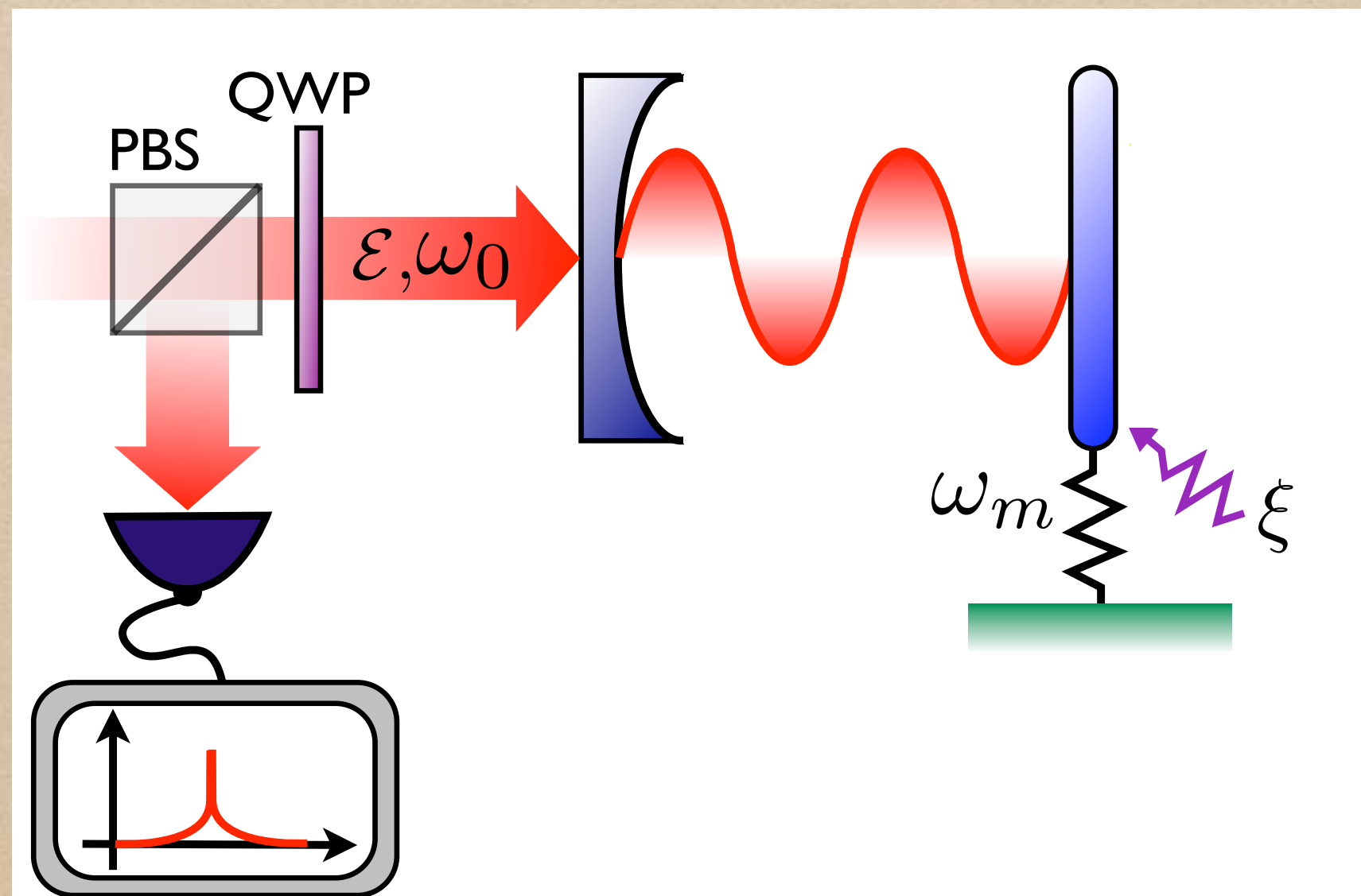
*Lux fiat!*  
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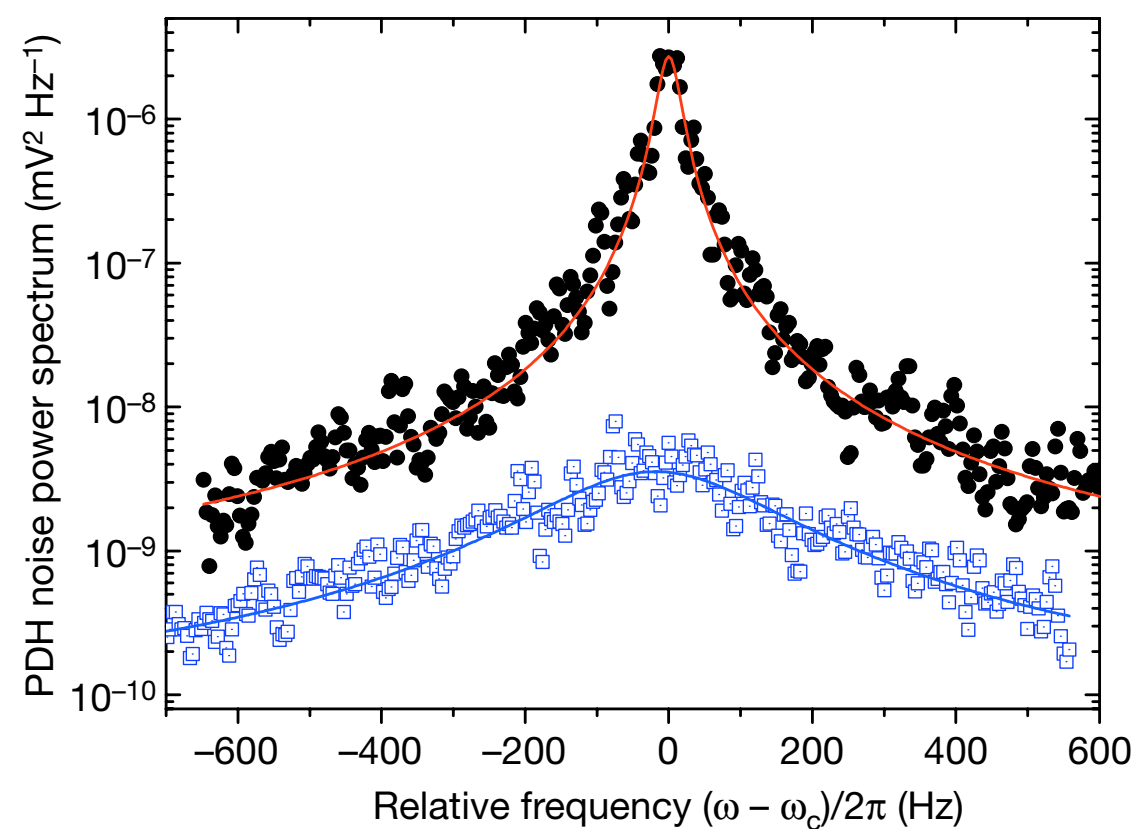


*Lux fiat!*  
*ed uno specchio, che vibra...*





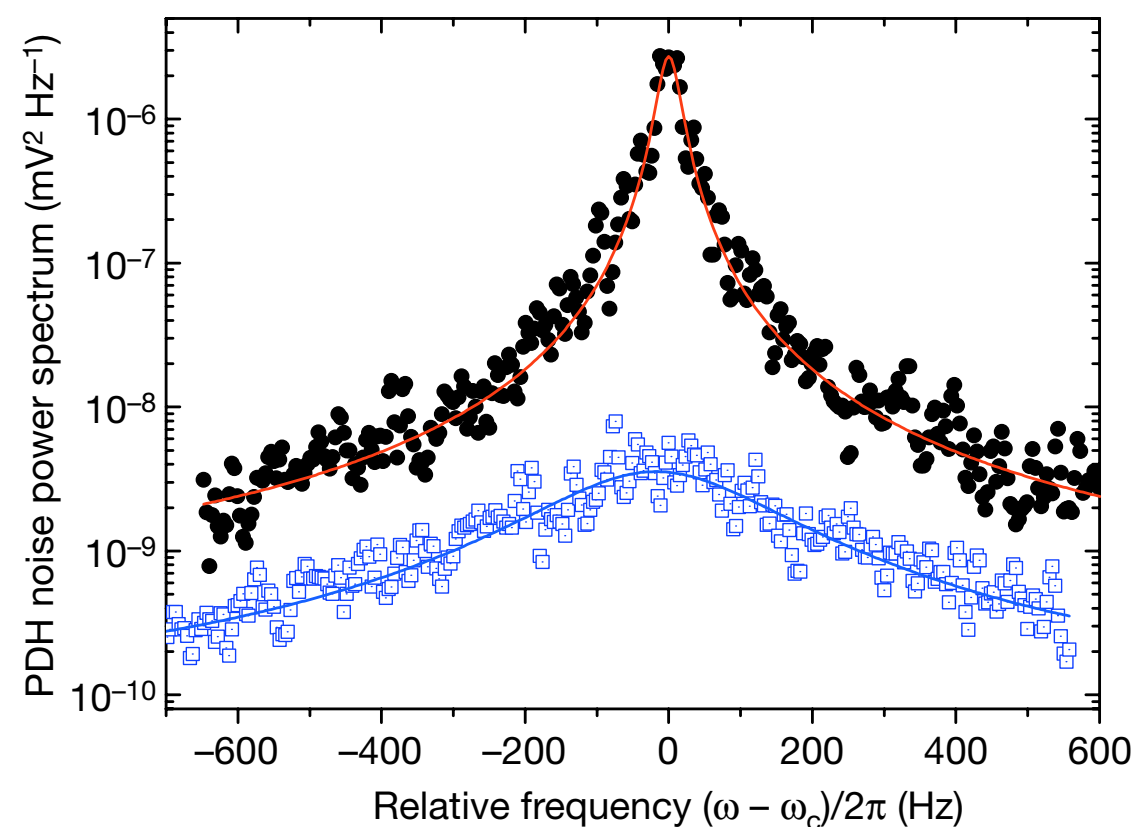
*Lux fiat!*  
*ed uno specchio, che vibra...*







*Lux fiat!*  
*ed uno specchio, che vibra...*



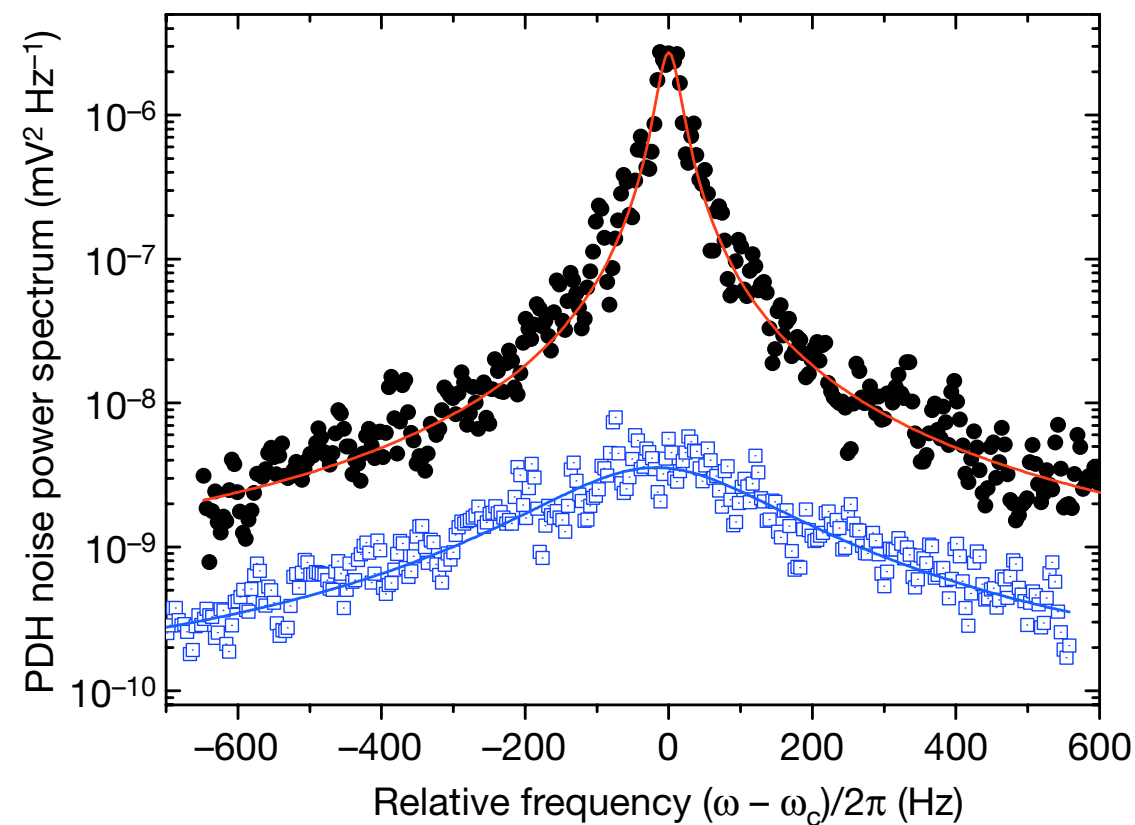
Classicamente

$$E = \frac{p^2}{2m} + \frac{1}{2}m\omega^2 x^2$$





*Lux fiat!*  
*ed uno specchio, che vibra...*

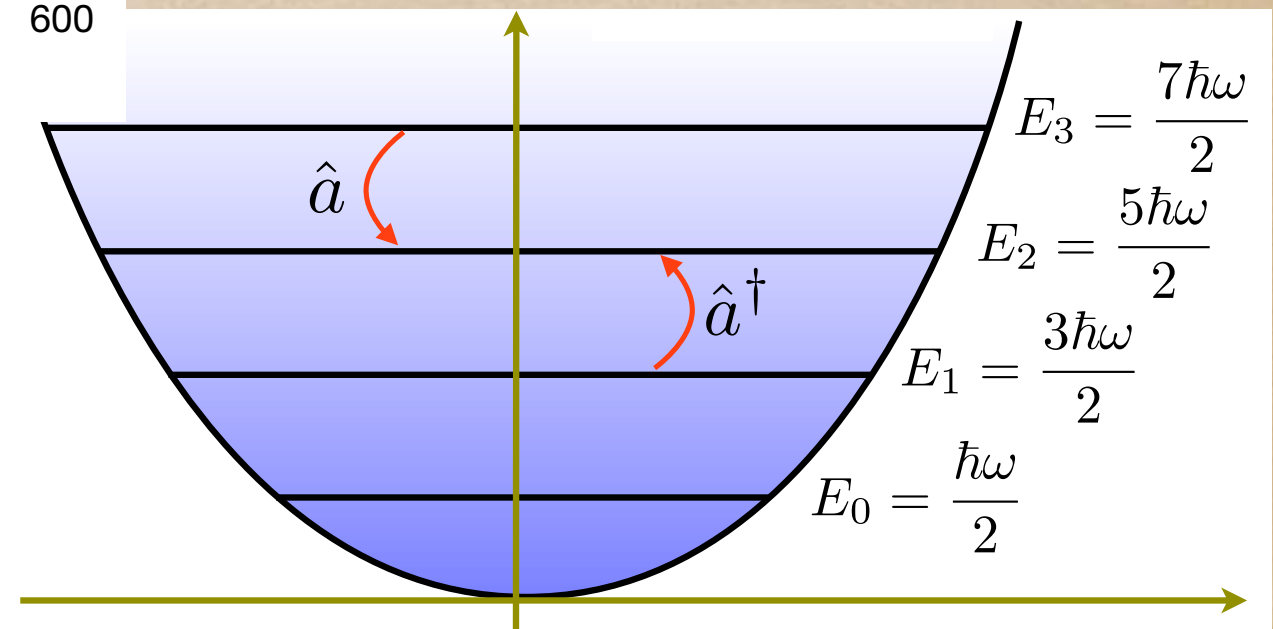


Classicamente

$$E = \frac{p^2}{2m} + \frac{1}{2}m\omega^2 x^2$$

Quantisticamente

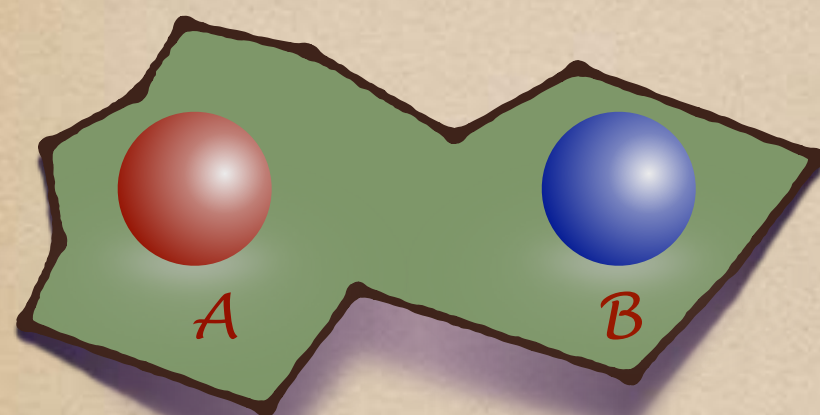
$$E = \hbar\omega(n + 1/2)$$



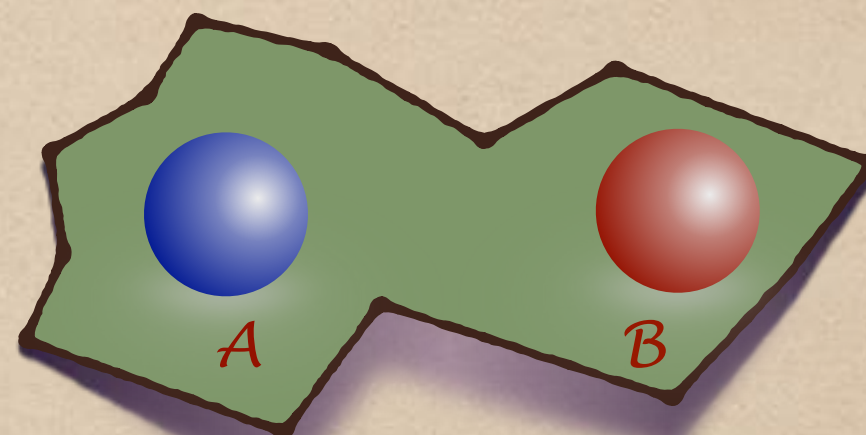




*Entanglement  
optomeccanico*



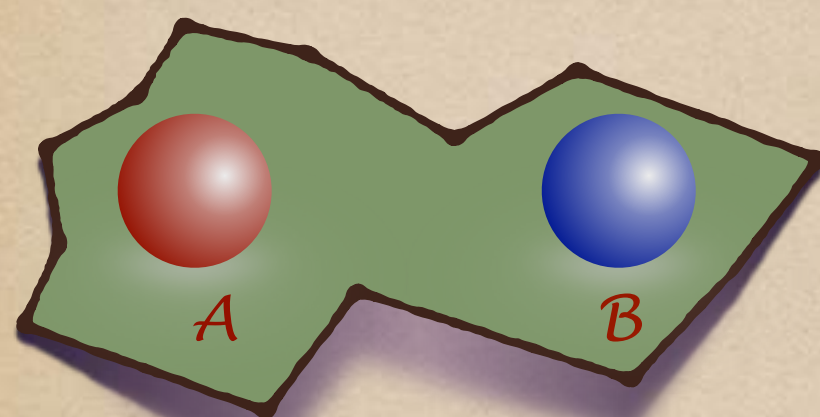
+



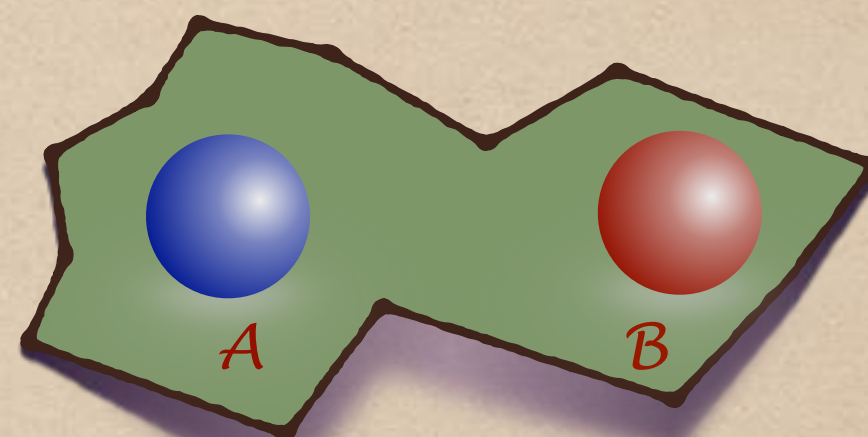




# *Entanglement optomeccanico*



+







*Gatti quantistici*

$$\frac{1}{\sqrt{2}}|\text{cat sitting}\rangle + \frac{1}{\sqrt{2}}|\text{cat jumping}\rangle$$



# *Gatti quantistici*

$$\frac{1}{\sqrt{2}}|\text{cat sitting}\rangle + \frac{1}{\sqrt{2}}|\text{cat lying}\rangle$$

$$| \text{cavita}' \rangle + | \text{cavita}' \rangle$$





# *Gatti quantistici*

*Schroedinger*





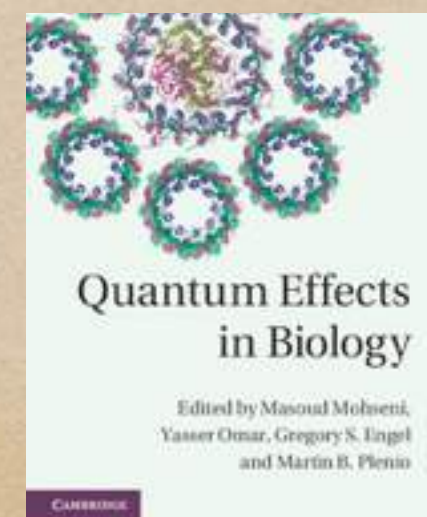
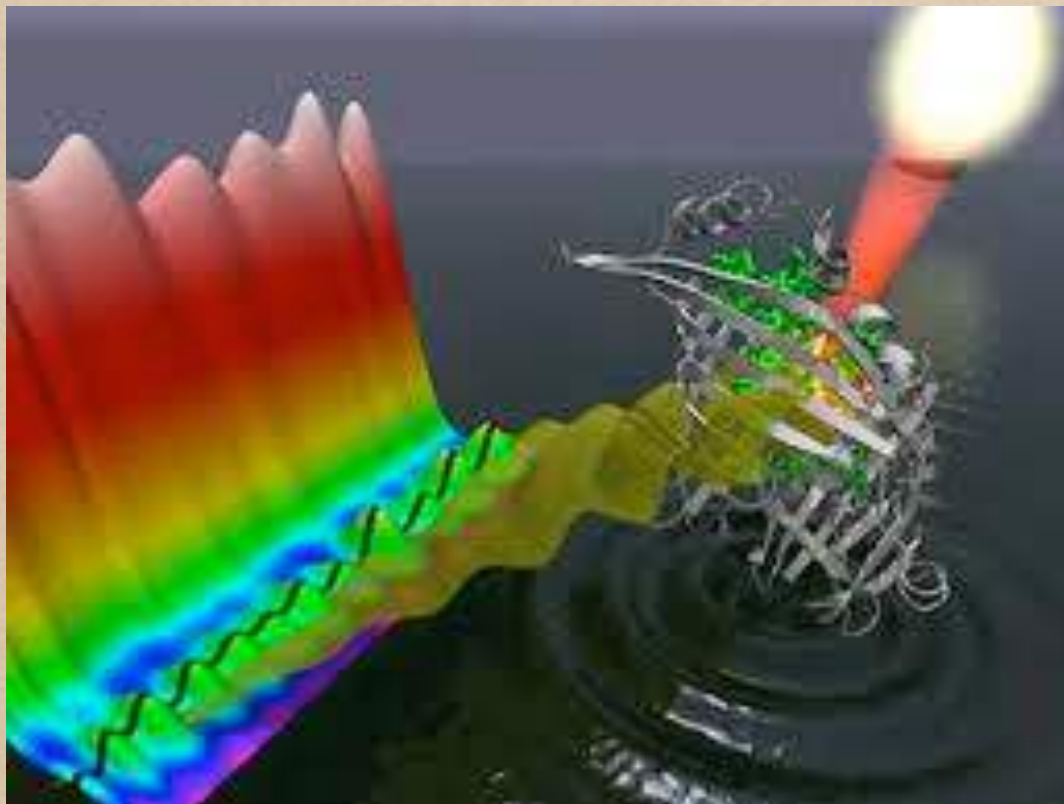


*No, no, e ancora no!*





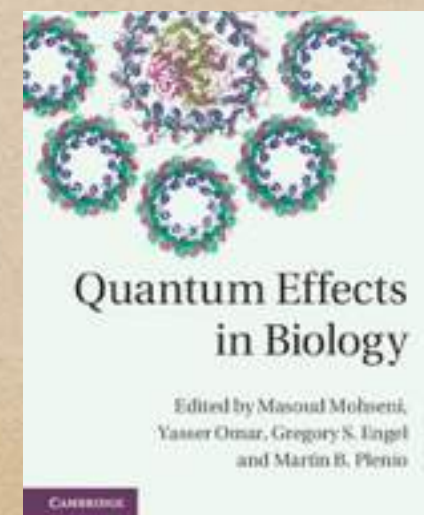
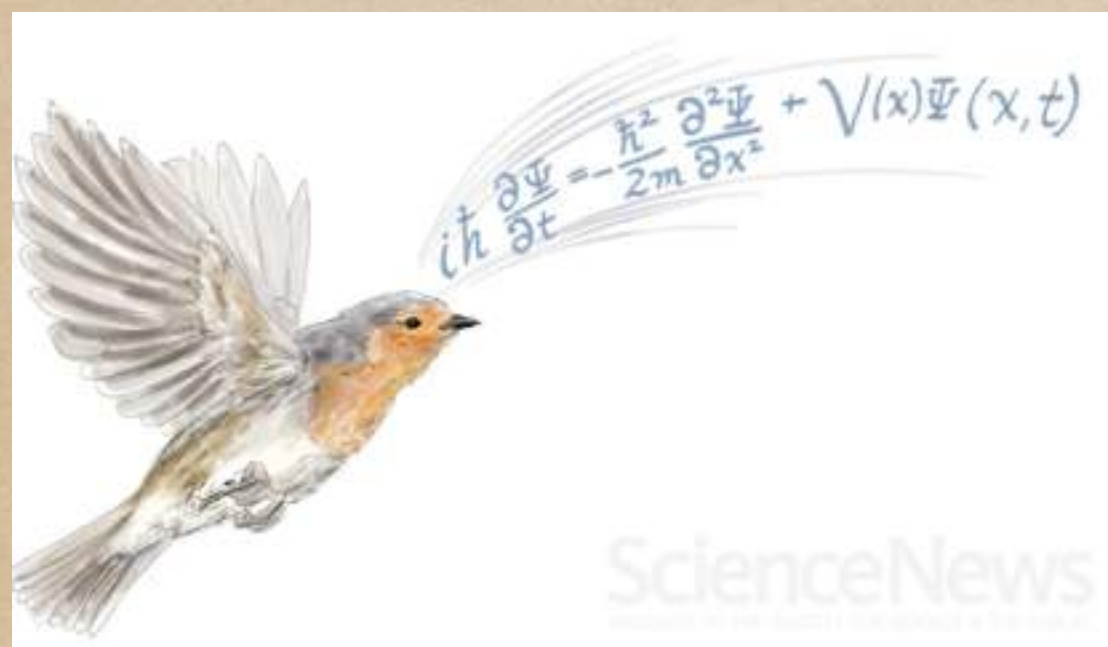
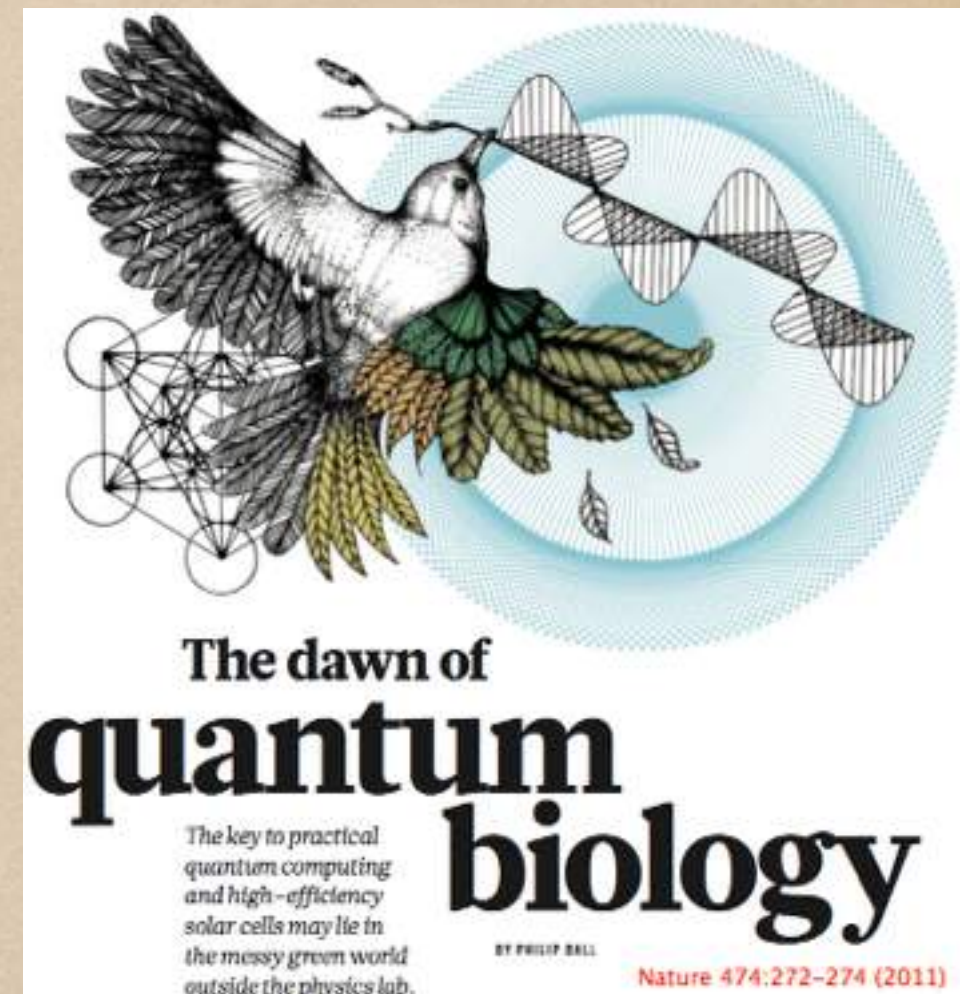
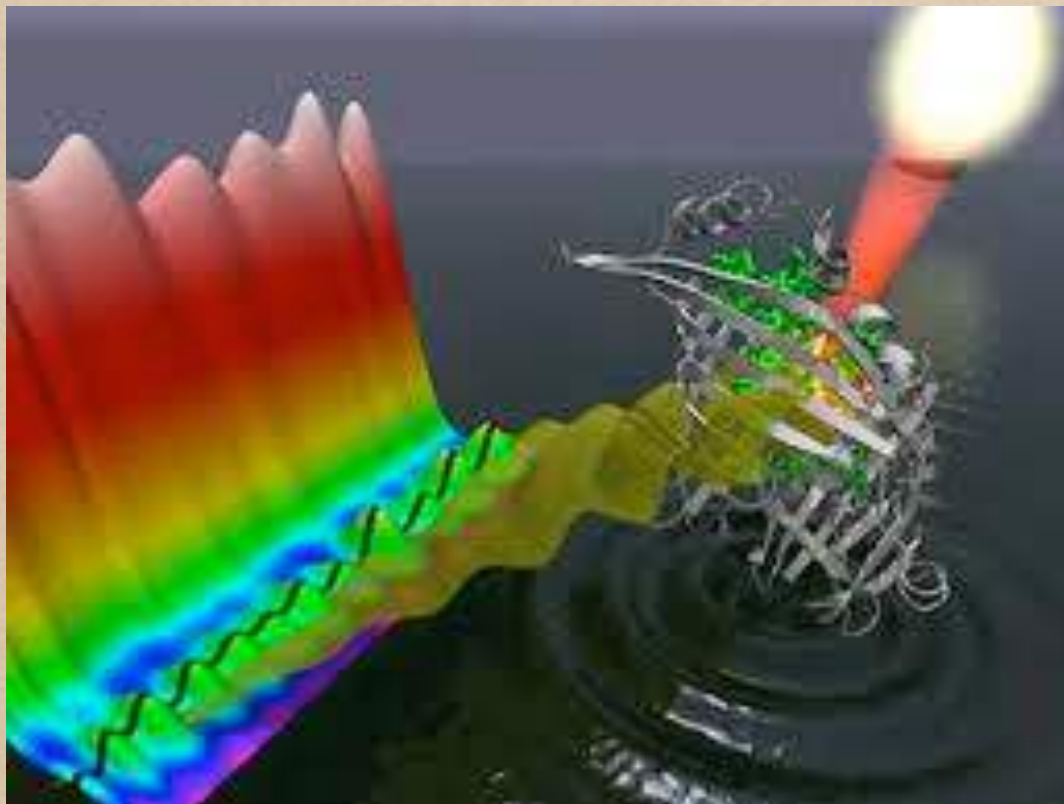
*No, no, e ancora no!*







*No, no, e ancora no!*







*No, no, e ancora no!*

# Termodinamica di sistemi quantistici



Lord Kelvin



*No, no, e ancora no!*

# Termodinamica di sistemi quantistici



Lord Kelvin

Tutte le nostre attività  
possono essere interpretate  
termodinamicamente



*No, no, e ancora no!*

# Termodinamica di sistemi quantistici



Lord Kelvin

Tutte le nostre attività  
possono essere interpretate  
termodinamicamente







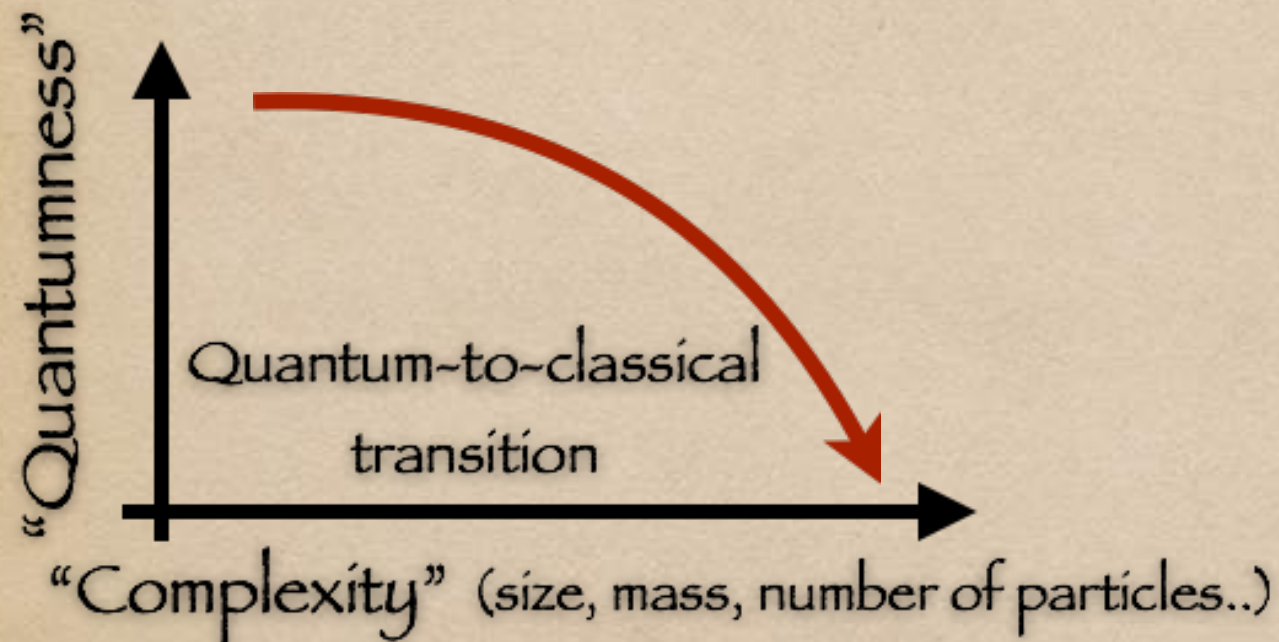
*Termodinamica  
quantistica*





# *Termodinamica quantistica*

Punto di vista fondamentale



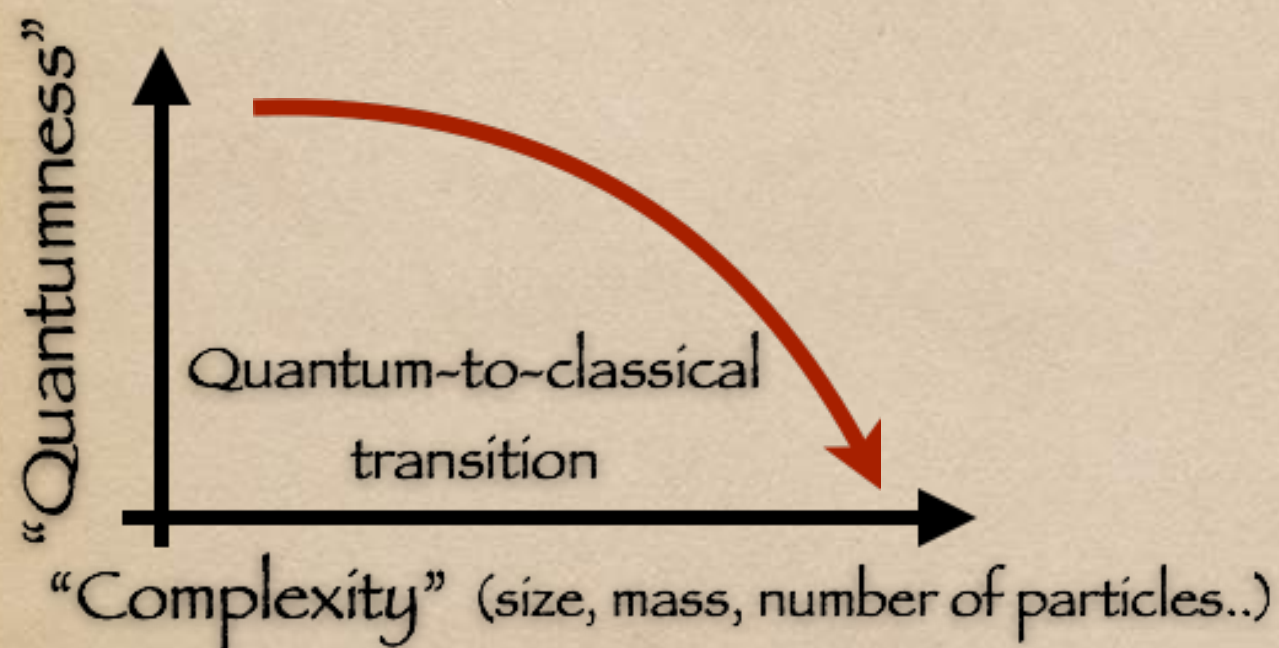
Termodinamica e' una teoria  
di sistemi inerentemente complessi





# *Termodinamica quantistica*

Punto di vista fondamentale



Termodinamica e' una teoria di sistemi inerentemente complessi

Prospettiva tecnologica



Uso di effetti quantistici per ottimizzare l'efficienza di una macchina





# *Termodinamica quantistica*

Punto di vista fondamentale

Prospettiva tecnologica

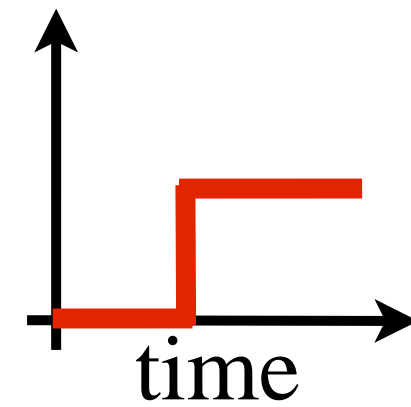
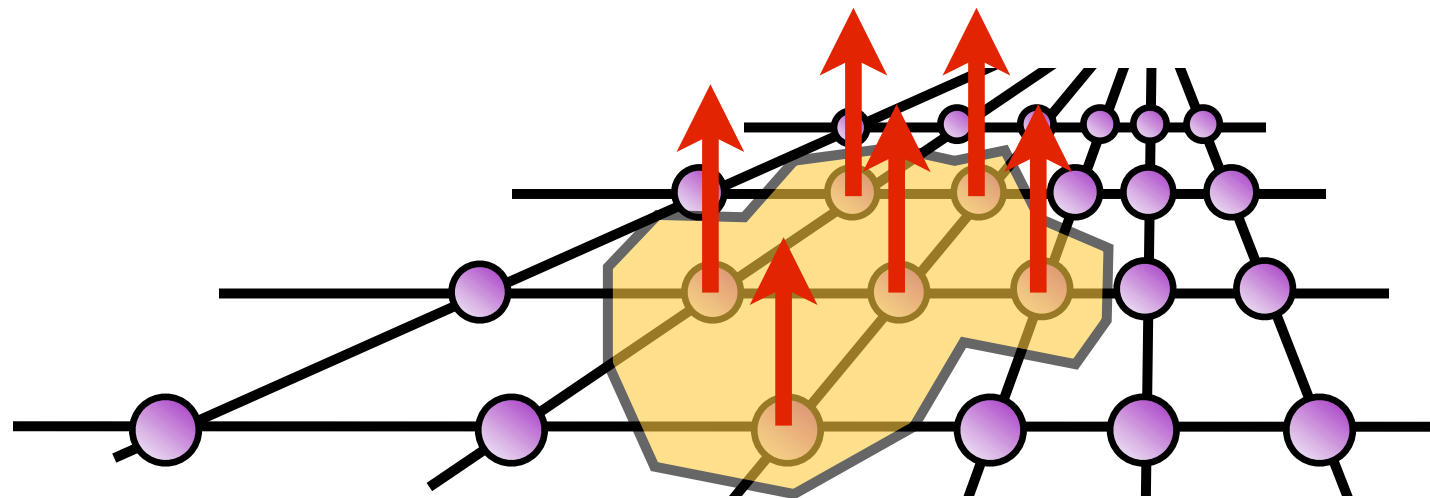
E' possibile esplorare la  
transizione quanto-classica usando un  
approccio termodinamico?

Termodinamica e' una teoria  
di sistemi inerentemente complessi

Uso di effetti quantistici per  
ottimizzare l'efficienza di  
una macchina

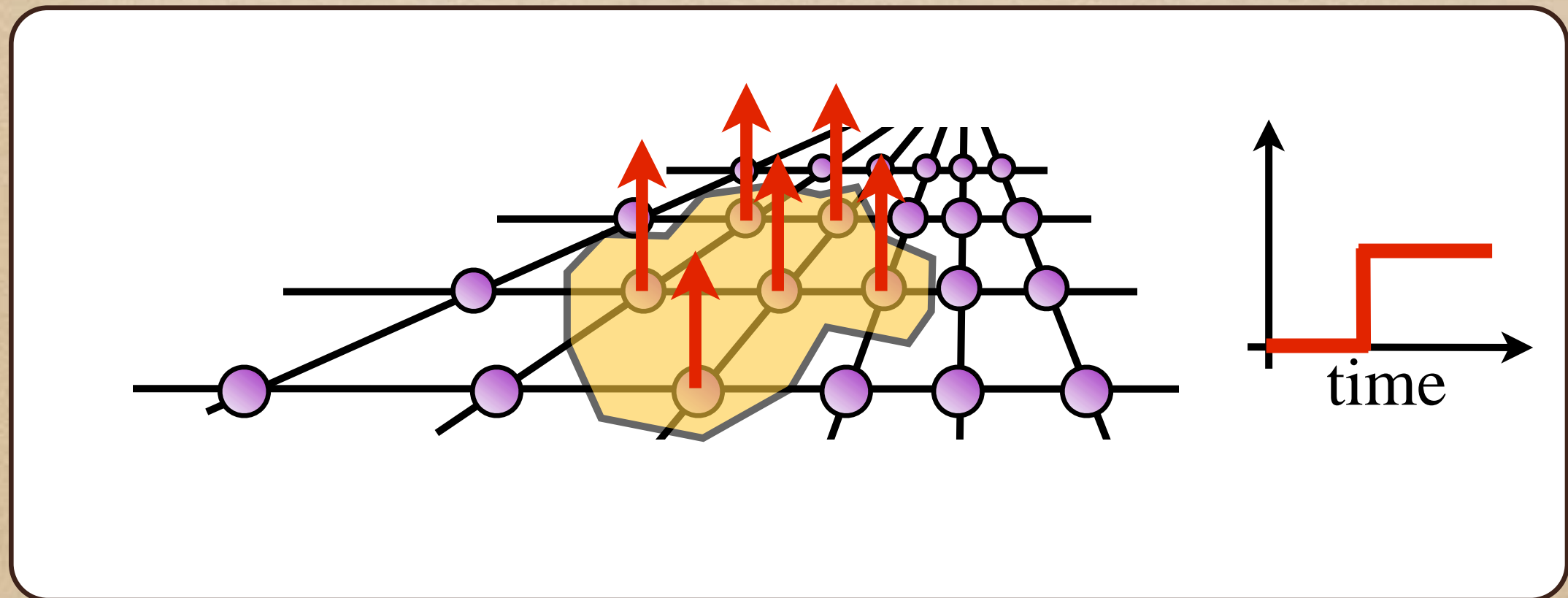


## *Scenario generale*





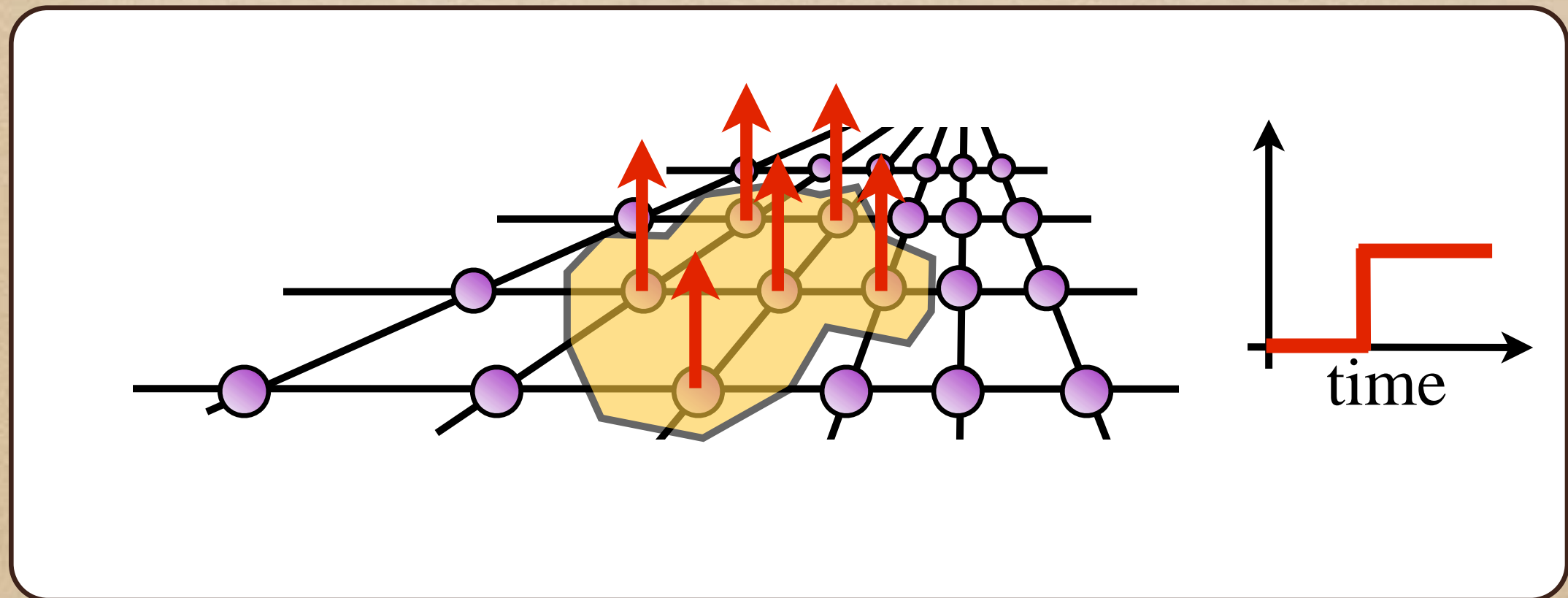
## *Scenario generale*



Legame tra effetti quantistici in sistemi a molti corpi  
e termodinamica



## *Scenario generale*



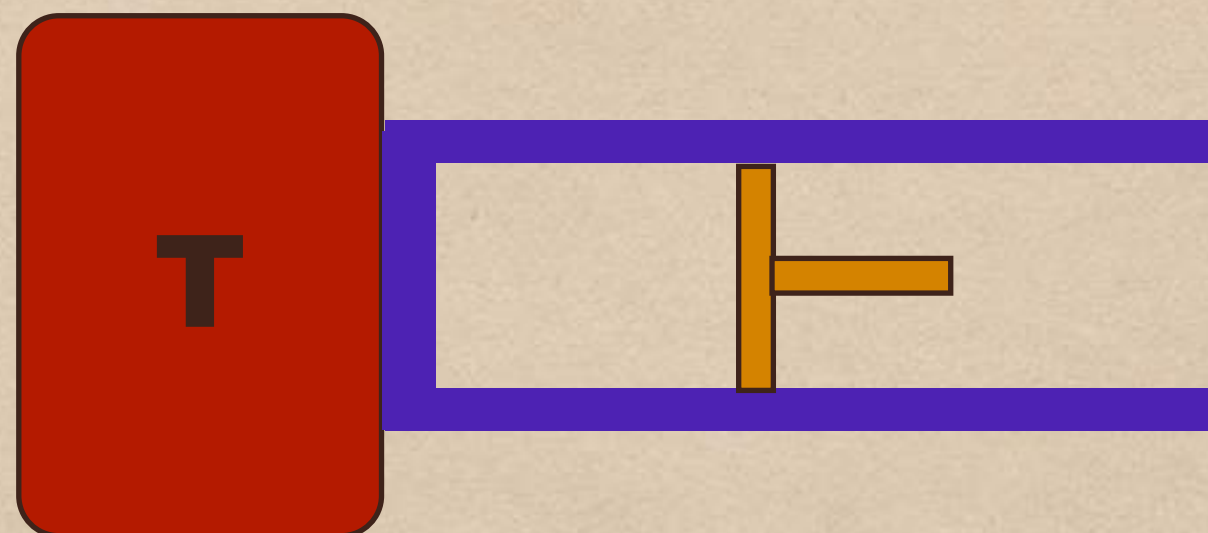
Legame tra effetti quantistici in sistemi a molti corpi  
e termodinamica

Emergenza della termodinamica da dinamiche quantistiche





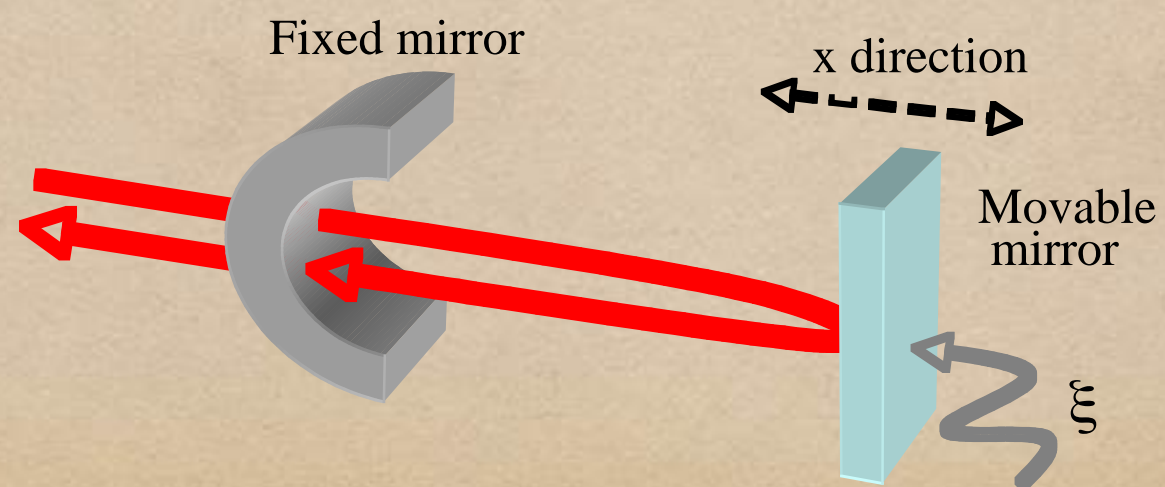
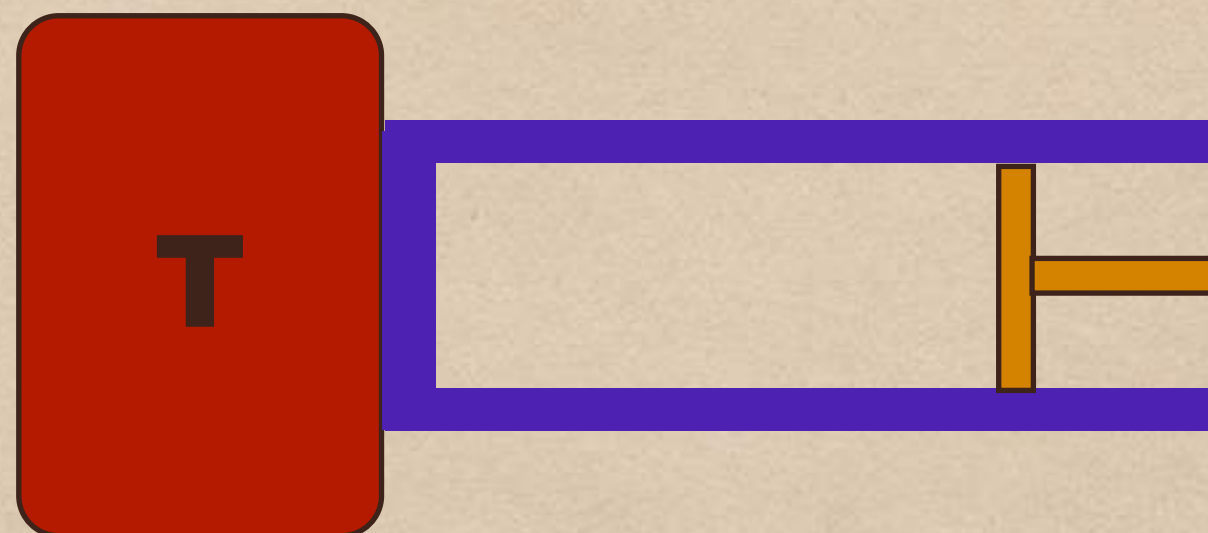
*Termodinamica  
quantistica*







# *Termodinamica quantistica*





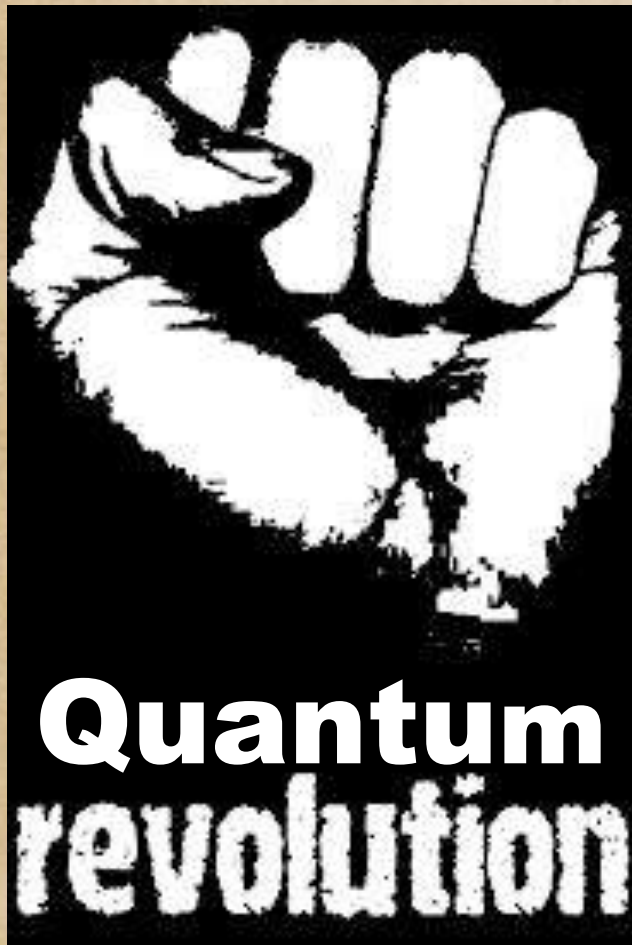


*Un'altra rivoluzione?*





*Un'altra rivoluzione?*







*Un'altra rivoluzione?*







*Un'altra rivoluzione?*



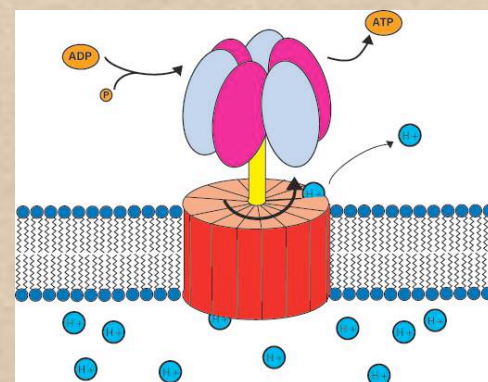
La terza rivoluzione quantistica:  
...tutto e' quantistico...



*Un'altra rivoluzione?*

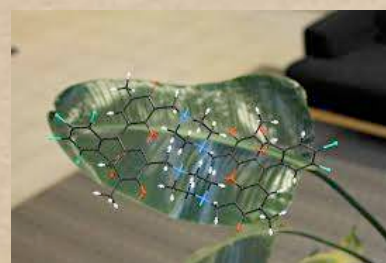
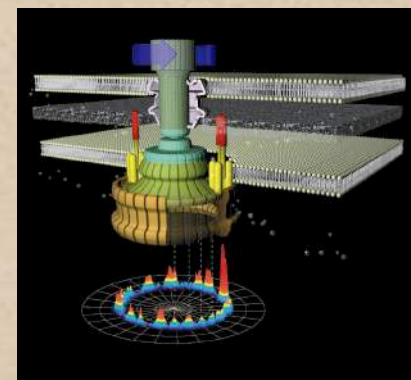
# 3 Quantum revolution

La terza rivoluzione quantistica:  
...tutto e' quantistico...



Molecular motors

Biomolecular/Biochemical networks

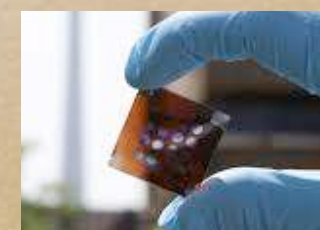
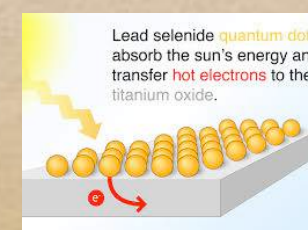


Quantum effects in  
biological systems

Spintronics/Magnetic memories



'Quantum-dot'  
solar cells







# The Belfast crew

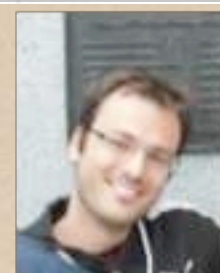
## PhDs



Matteo  
Brunelli



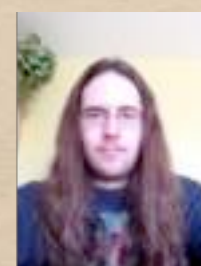
Andrew  
Carlisle



Lorenzo  
Fusco



Ruari  
McCloskey



Darren  
Moore



Matthew  
Power



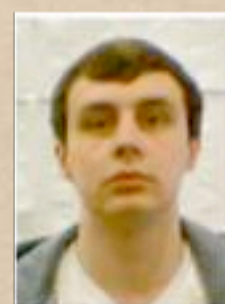
Ben  
Rogers



Jader Pereira  
dos Santos



Brendan  
Reid



Kenneth  
McAlpine



Sam  
McMillen



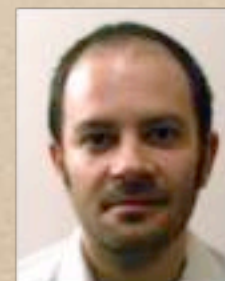
Conor  
Gallagher



Mariona Moreno



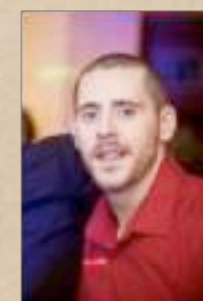
Francesco Francica



Simon Pigeon



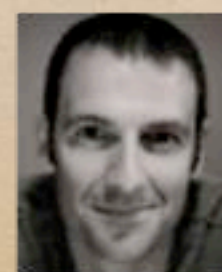
Fernando Nicacio



Steve Campbell

## PostDocs

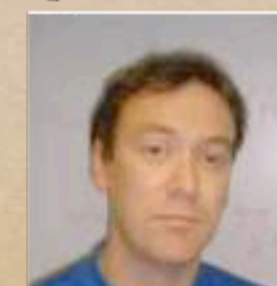
## Staff



Gabriele De Chiara



Alessandro Ferraro



Jim McCann



MP





*Go raibh  
maith agaibh*



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