Wave function collapse and gravity

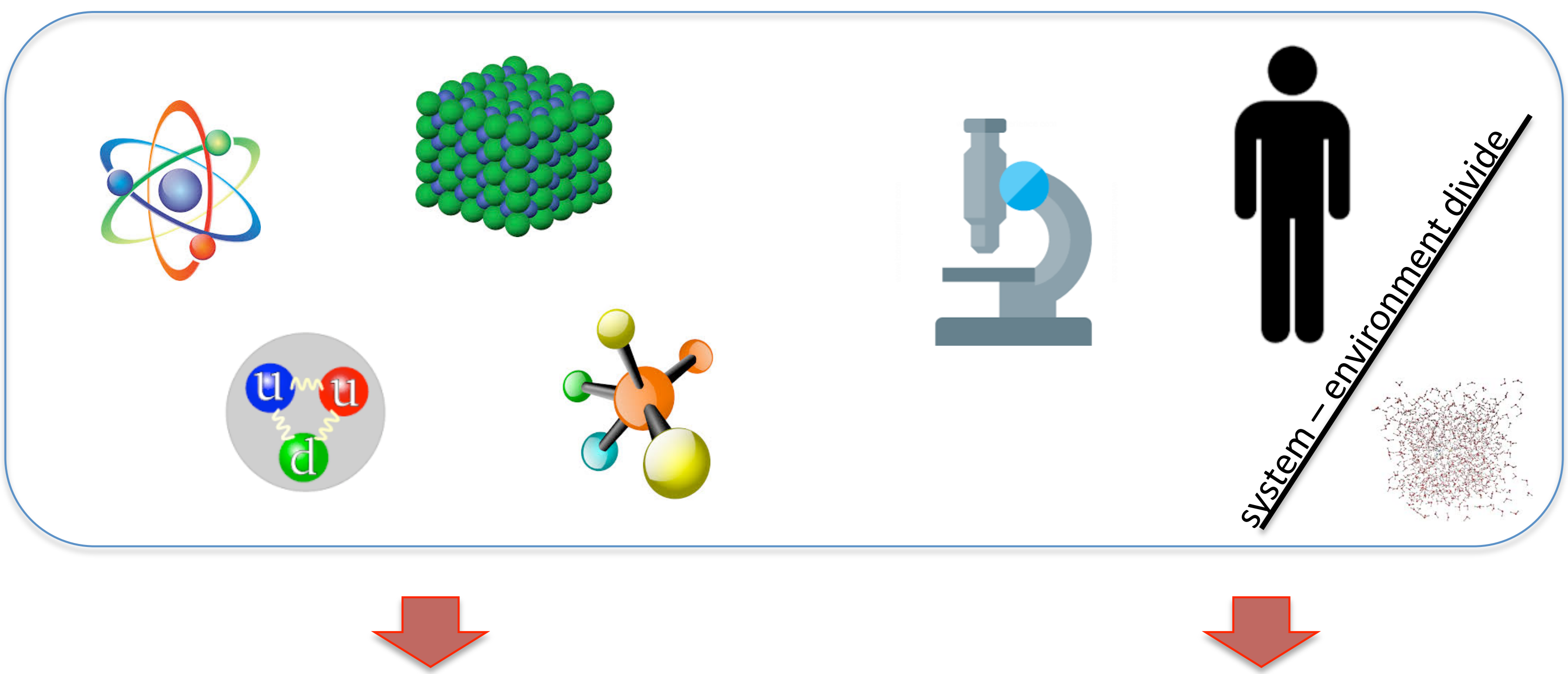
Is Quantum Theory Exact?
The quest for the spin-statistics connection violation and related items
Frascati – IT
2nd - 5th July 2018

(Angelo Bassi – University of Trieste & INFN)

In memory of GianCarlo Ghirardi
(1935 - 2018)

Decoherence

- The Schrödinger equation is correct
- Take system + environment
- Let them interact for a while, for correlations to be diluted in the environment
- Trace over the degrees of freedom of the environment
- Output: classicality (in some sense)



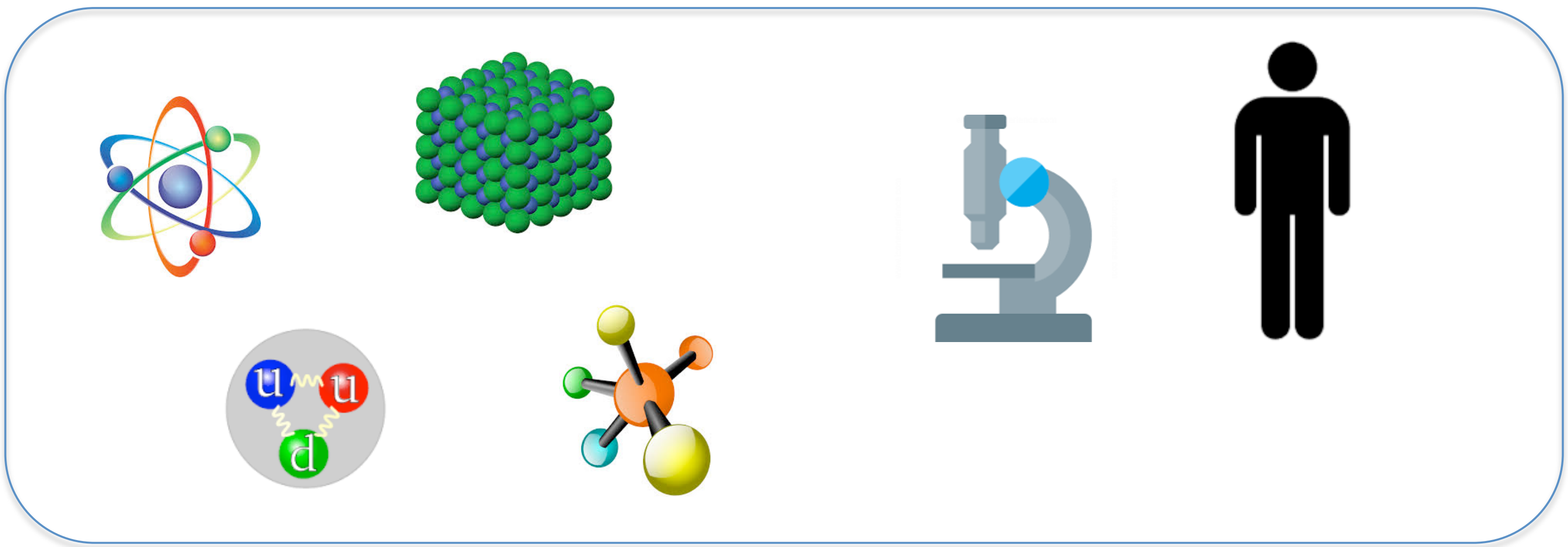
Quantum micro world

Quantum macro world
(but looks classical)

Wave function collapse (models)

- The Schrödinger equation is not 100% correct.
- Correction are negligible for micro systems and relevant for macro objects
- At the macroscopic level one recovers classicality

Progressive breakdown of quantum linearity with increasing mass



Quantum micro world

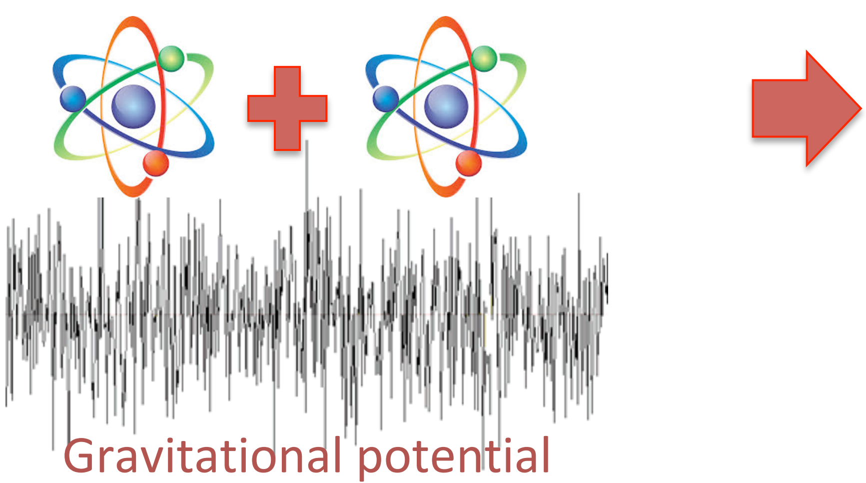
“Classical” macro world

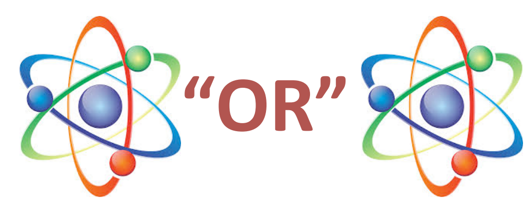
Gravitational decoherence

Schrödinger equation (at the Newtonian level)

$$\frac{d}{dt}|\psi_t\rangle = \left[-\frac{i}{\hbar}H_0 + V(x,t)\right]|\psi_t\rangle$$

Gravitational potential = the environment





Decoherence: impossibility to detect quantum coherence

Gravitational decoherence

Being a **standard quantum effect**, it does not affect the foundations of quantum mechanics (the measurement problem), in spite of its "unavoidability"

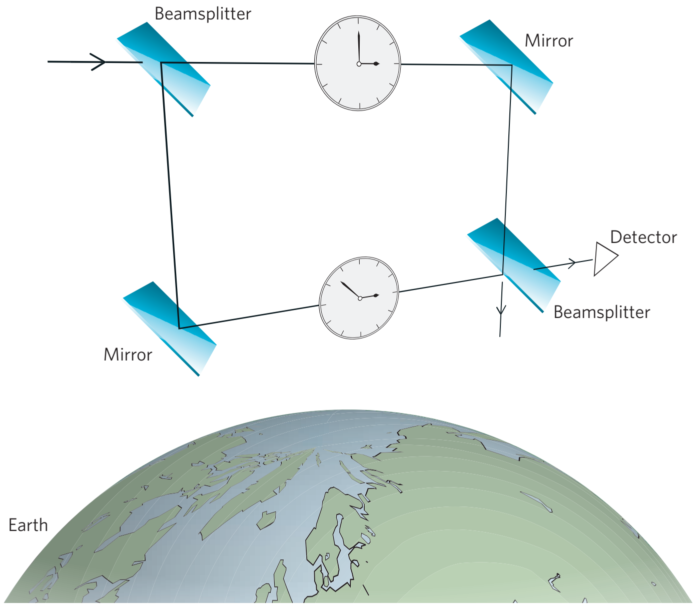
There are interesting theoretical aspect to clarify:

A. What is the **correct form** of the deocherence effect?

- Decoherence in position
  (B. Lamine *et al., PRL* 96, 050405 - 2006)
- Decoherence in energy
  (M.P. Blencowe, *PRL* 111, 021302 - 2013)

➔ Toll for gravitational wave detection (since quantum coherences are fragile)

B. Stochasticity is **not necessary** for decoherence
(I. Pikovski *et al. Nature Physics* - 2015)



C. What is the difference between decoherence from **gravitons** and decoherence from a **classical** stochastic gravitational background? ➔ Toll for graviton detection (speculation)

(Mass-proportional) CSL model

P. Pearle, *Phys. Rev. A* 39, 2277 (1989). G.C. Ghirardi, P. Pearle and A. Rimini, *Phys. Rev. A* 42, 78 (1990)

$$\frac{d}{dt}|\psi_t\rangle = \left[-\frac{i}{\hbar}H + \frac{\sqrt{\gamma}}{m_0}\int d^3x\,(M(\mathbf{x}) - \langle M(\mathbf{x})\rangle_t)\,dW_t(\mathbf{x}) - \frac{\gamma}{2m_0^2}\int\int d^3x d^3y\, G(\mathbf{x}-\mathbf{y})\,(M(\mathbf{x}) - \langle M(\mathbf{x})\rangle_t)\,(M(\mathbf{y}) - \langle M(\mathbf{y})\rangle_t)\right]|\psi_t\rangle$$

$$M(\mathbf{x}) = m a^\dagger(\mathbf{x})a(\mathbf{x}) \qquad G(\mathbf{x}) = \frac{1}{(4\pi r_C)^{3/2}}\,\exp[-(\mathbf{x})^2/4r_C^2]$$

The operators are function of the space coordinate. **The collapse occurs in space.**

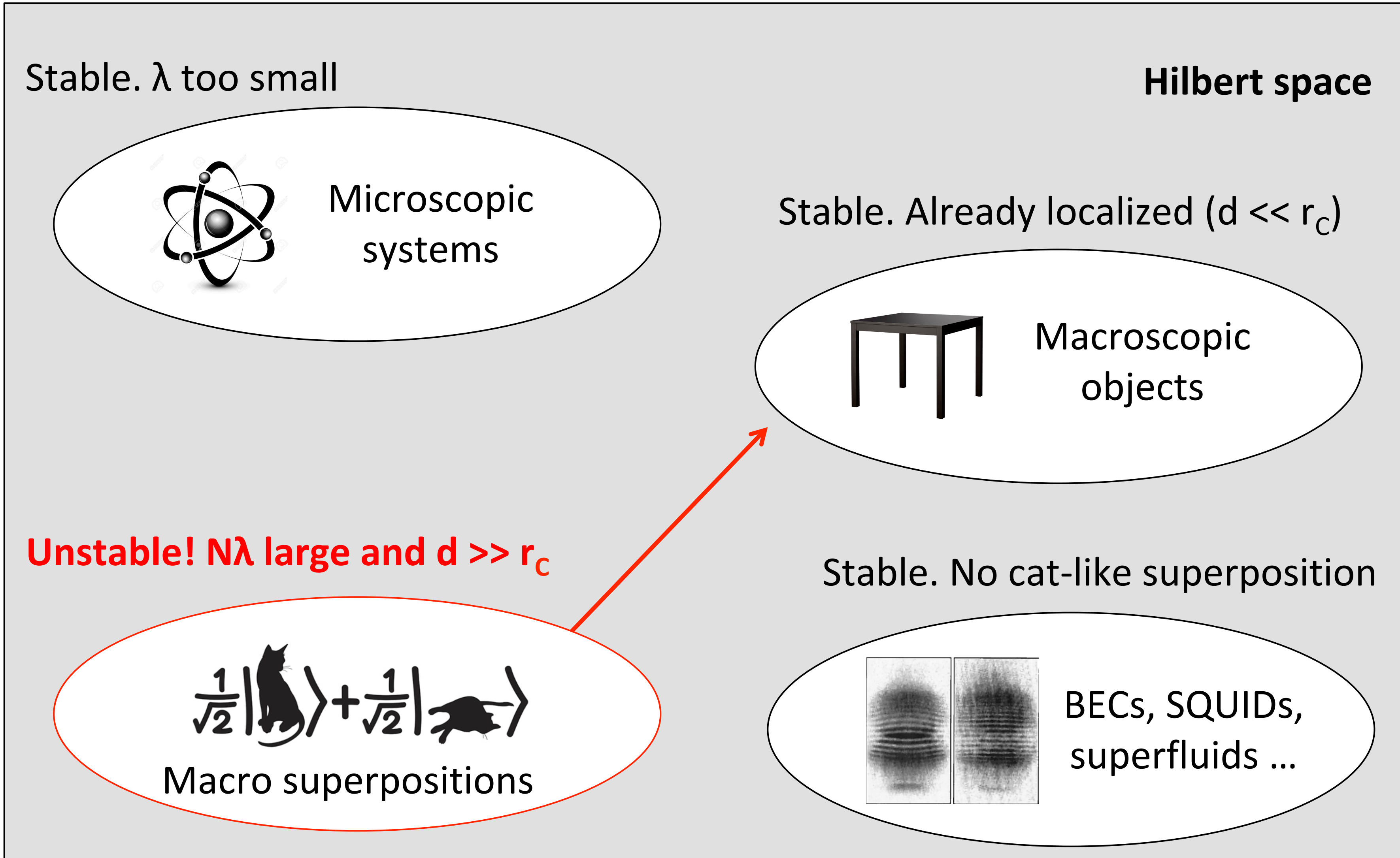
Two parameters $\gamma = \text{collapse strength}$ $\quad r_C = \text{localization resolution}$

$$\lambda = \gamma/(4\pi r_C^2)^{3/2} = \text{collapse rate}$$

REVIEW: A. Bassi and G.C. Ghirardi, *Phys. Rept.* 379, 257 (2003)

A. Bassi, K. Lochan, S. Satin, T.P. Singh and H. Ulbricht, *Rev. Mod. Phys.* 85, 471 (2013)

The overall picture

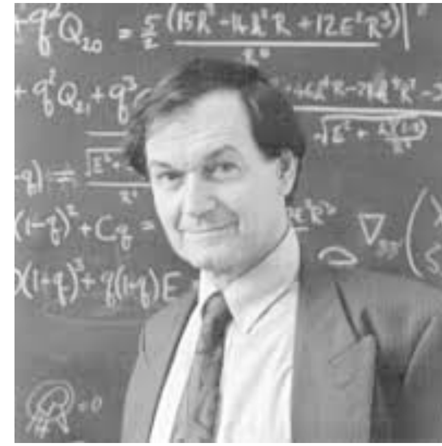


Collapse and gravity

It is an attempt to answer the question: why should the wave function collapse?

Fundamental properties of the collapse & the possible role of gravity

- It occurs in space
- It scales with the mass/size of the system



The obvious way to describe it mathematically, is to couple the noise field to the **mass density** (the stress-energy tensor, in a relativistic framework).

Gravity naturally provides such a coupling.

Moreover

The possibility is open for **gravity not to be quantum**, thus possibly providing the nonstandard (anti-hermitian, nonlinear) coupling necessary for the collapse.

REVIEW ARTICLE: A. Bassi, A. Grossardt and H. Ulbricht, "Gravitational Decoherence", Class. Quantum Grav. 34, 193002 (2017). ArXiv1706.05677

The Diosi – Penrose model

L. Diosi, Phys. Rev. A 40, 1165 (1989)

It is like the CSL model, the only difference being in the correlation function of the noise, which is

$$G(\mathbf{x}) = \frac{G}{\hbar} \frac{1}{|\mathbf{x}|}$$

→ **Gravity.** And no other free parameter (almost…)

Remarks:

- Model not derived from basic principles, but assumed phenomenologically
- There is no justification as to why gravity should be responsible for the collapse
- It is not clear with the correlation function should be Newtonian
- If there is truth in the model, then quantum gravity as we know it is wrong

Diosi – Penrose model

L. Diosi, Phys. Rev. A 40, 1165 (1989)

It leads to the collapse of the wave function. To measure how strong it is one can consider the (single-particle) master equation.

It is of the Lindblad type, and implies

$$\rho(\mathbf{x}, \mathbf{x}', t) = e^{-t/\tau(\mathbf{x},\mathbf{x}')}\rho(\mathbf{x}, \mathbf{x}', 0)$$

$$\tau(\mathbf{x}, \mathbf{x}') = \frac{\hbar}{U(\mathbf{x} - \mathbf{x}') - U(0)} \qquad U(\mathbf{x}) = -G\int d^3\mathbf{r}d^3\mathbf{r}'\,\frac{M(\mathbf{r})M(\mathbf{r}')}{|\mathbf{x} + \mathbf{r} - \mathbf{r}'|}$$

Penrose's idea

(Quantum) gravity does not tolerate quantum superpositions

It **diverges** for point-like particles

One needs a regularizing cut off

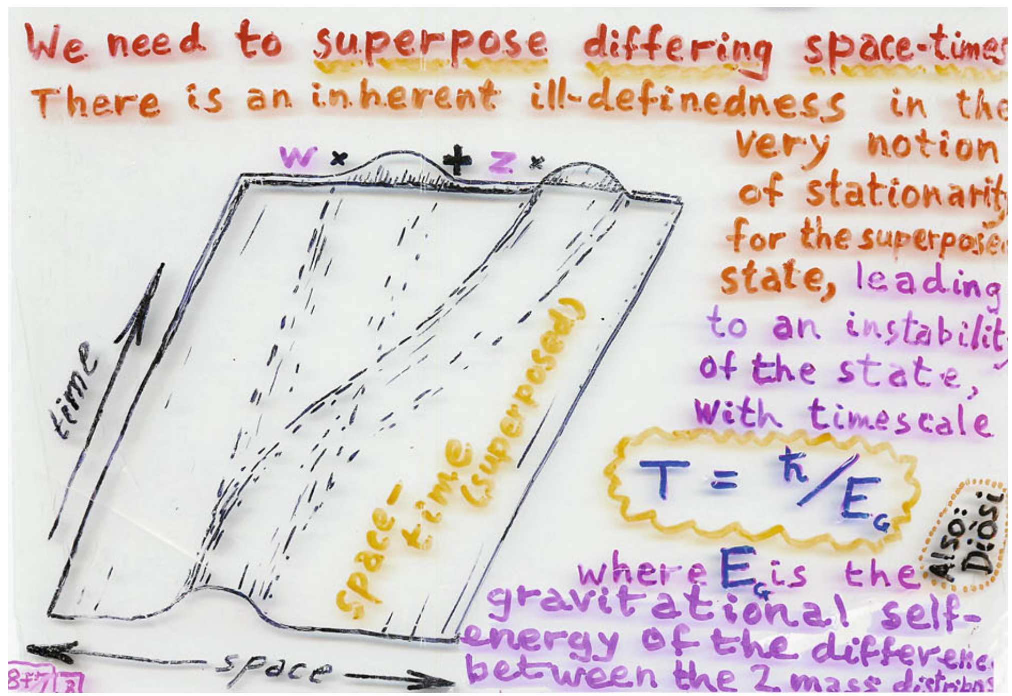
Diosi – Penrose model

R. Penrose, *Gen. Rel. Grav*. 28, 581 - 1996

We have to consider carefully what a 'stationary state' means in a context such as this. In a stationary spacetime, we have a well-defined concept of 'stationary' for a quantum state in that background, because there is a Killing vector T in the spacetime that generates the time-translations. Regarding T as a differential operator (the '∂/∂t' for the spacetime), we simply ask for the quantum states that are eigenstates of T, and these will be the stationary states, i.e. states with well-defined energy values. [...] **However, for the superposed state we are considering here we have a serious problem.** For we do not now have a specific spacetime, but a superposition of two slightly differing spacetimes. How are we to regard such a 'superposition of spacetimes'? Is there an operator that we can use to describe 'time-translation' in such a superposed spacetime? Such an operator would be needed so that we can identify the 'stationary states' as its eigenvectors, these being the states with definite energy. It will be shown that there is a fundamental difficulty with these concepts, and that the notion of time-translation operator is essentially ill defined […]

Penrose's idea: quantum superposition ➔ spacetime superposition ➔ energy uncertainty ➔ decay in time

Putting his reasoning into equations, Penrose come out with basically the same equations as Diosi's



Diosi – Penrose model

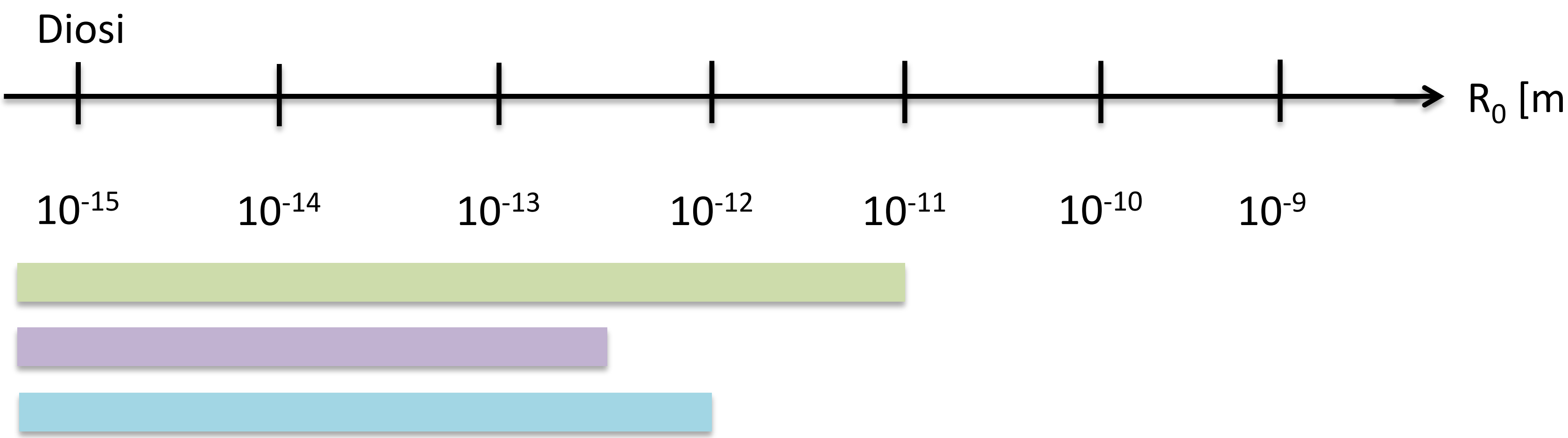
The model needs to be **regularized** (particles with finite size)

Penrose: Solution of the Schrödinger-Newton equation

Diosi: Compton wave length

In both cases: R_0 about 10^{-15} m, for a nucleon

Constraints on the cutoff



X-rays [Work in progress]

Cold atoms [T. Kovachy *et al.*, Phys. Rev. Lett. 114, 143004 (2015)]

Cantilever [A. Vinante *et al.,* Phys. Rev. Lett. 116, 090402 (2016)]

Adler's idea

S. Adler, in Quantum Nonlocality and Reality: 50 Years of Bell's Theorem. Cambridge University Press (2016)

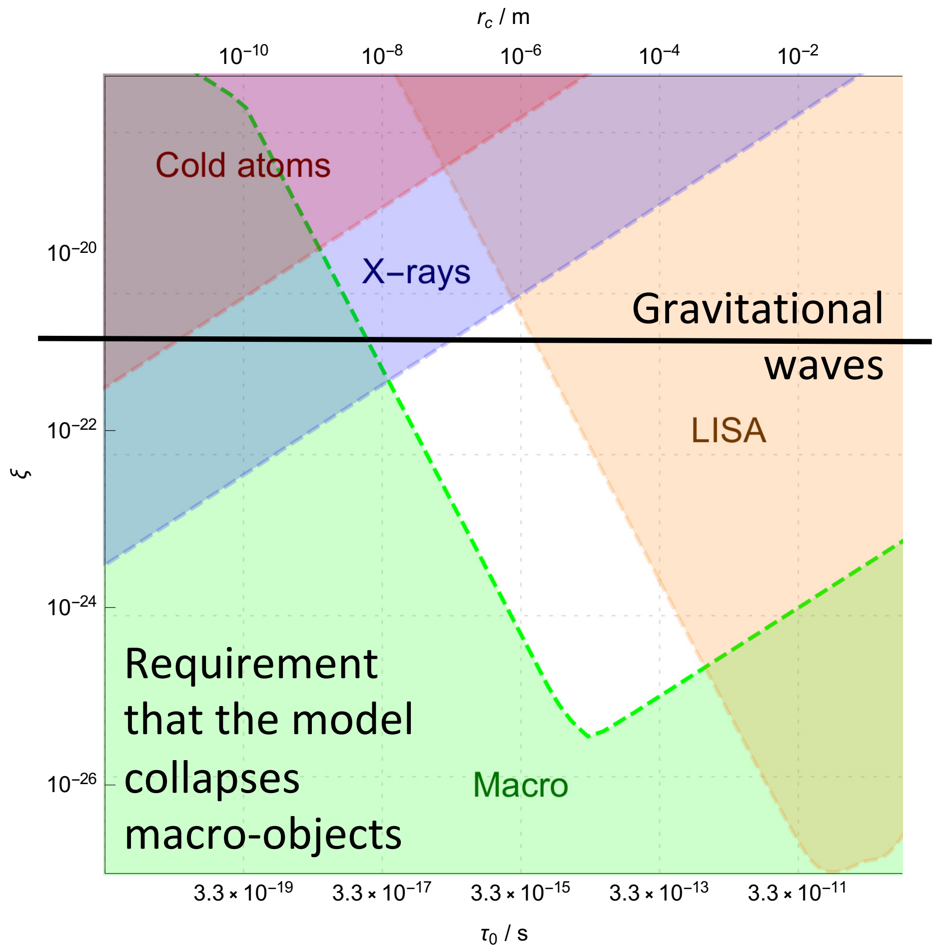
G. Gasbarri, M. Toros, S. Donadi & A. Bassi, Phys. Rev. D 96, 104013 (2017)

Motivation: the metric has **an irreducibly complex, rapidly fluctuating, component**, besides the usual real one. This component is responsible for the collapse. The correlation function of the noise is left unknown. This means that gravity is not quantum – Adler provides motivations for that.

The models has been **developed** (formal equation – rather messy – amplification mechanism, collapse properties) by Gasbarri et al. Everything works well.

Picture: bounds on the magnitude ξ of the complex fluctuations.

it is interesting to see that **weak complex fluctuations** – weaker than real waves recently measured by LIGO (10^{-21}) - are sufficient for an efficient collapse



The Schrödinger-Newton equation

$$i\hbar\frac{d}{dt}\psi(\mathbf{x},t) = \left(-\frac{\hbar^2}{2m}\nabla^2 - Gm^2\int d^3y\frac{|\psi(\mathbf{y},t)|^2}{|\mathbf{x}-\mathbf{y}|}\right)\psi(\mathbf{x},t)$$

L. Diósi. Phys. Lett. A 105, 199 (1984).
R. Penrose, Gen. Relat. Gravit. 28, 581 (1996).
D. Giulini and A. Grossardt, *Class. Quantum Grav.* 29, 215010 (2012)

quantum spread

gravitational collapse

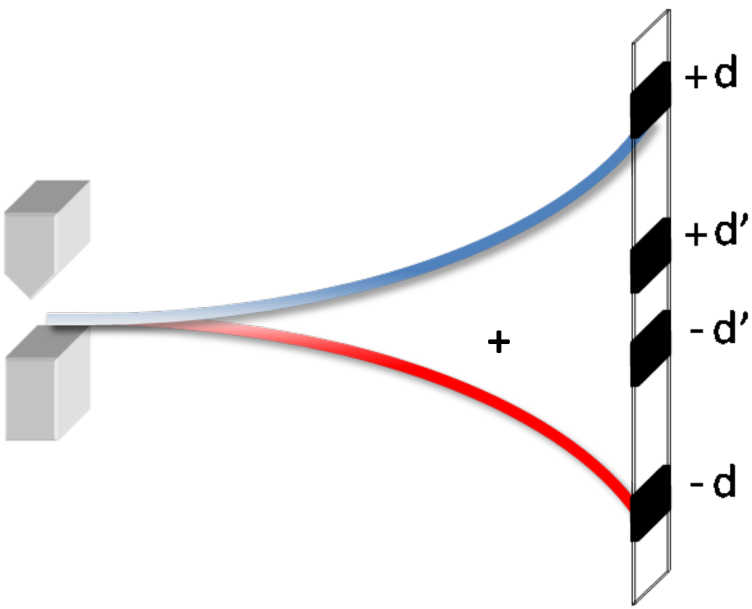
It comes from semi-classical gravity if taken **as a fundamental theory** = matter is fundamentally quantum and gravity is fundamentally classical, and they couple as follows

$$G_{\mu\nu} = \frac{8\pi G}{c^4}\langle\psi|\hat{T}_{\mu\nu}|\psi\rangle$$

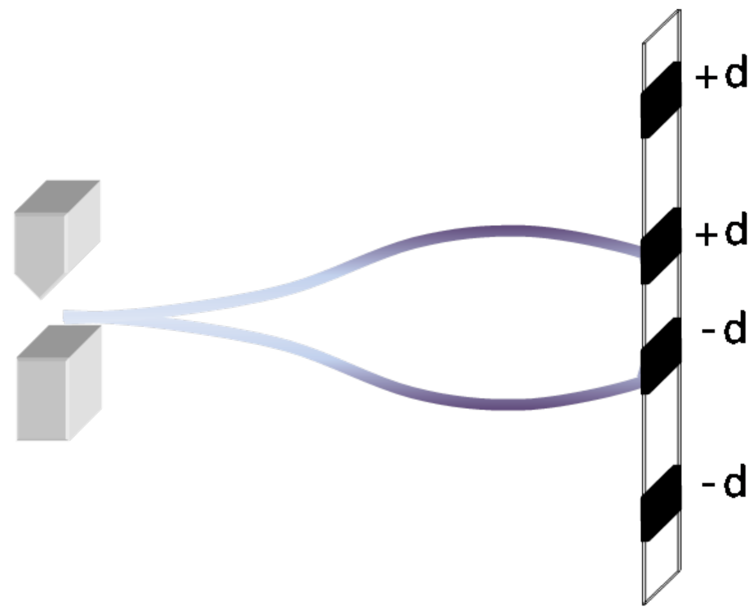
The term on the right is nonlinear in the wave function

Wrong collapse

It **collapses** the wave function, but **not** as prescribed by the Born rule



Double slit experiment according to standard QM



Double slit experiment according to the Schrödinger-Newton equation

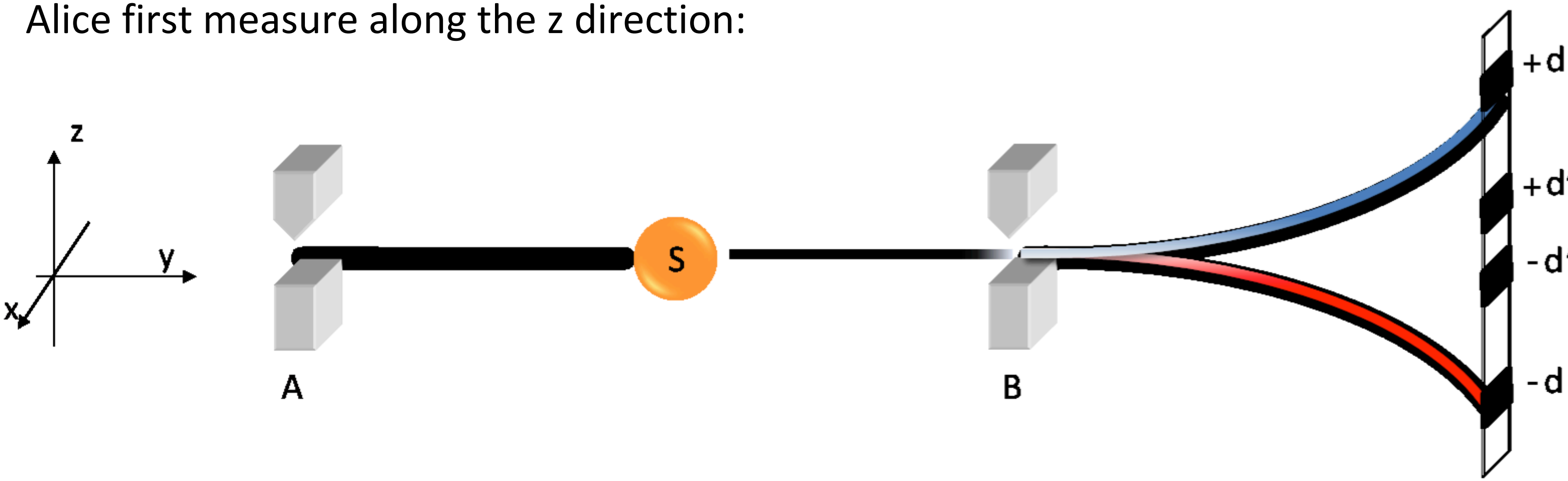
But there are smarter ways of testing the equation

H. Yang, H. Miao, D.-S. Lee, B. Helou, Y. Chen*, Phis. Rev. Lett.* 110, 170401 (2013)
A. Großardt, J. Bateman, H. Ulbricht, A. Bassi, *Phys. Rev. D* 93, 096003 (2016)

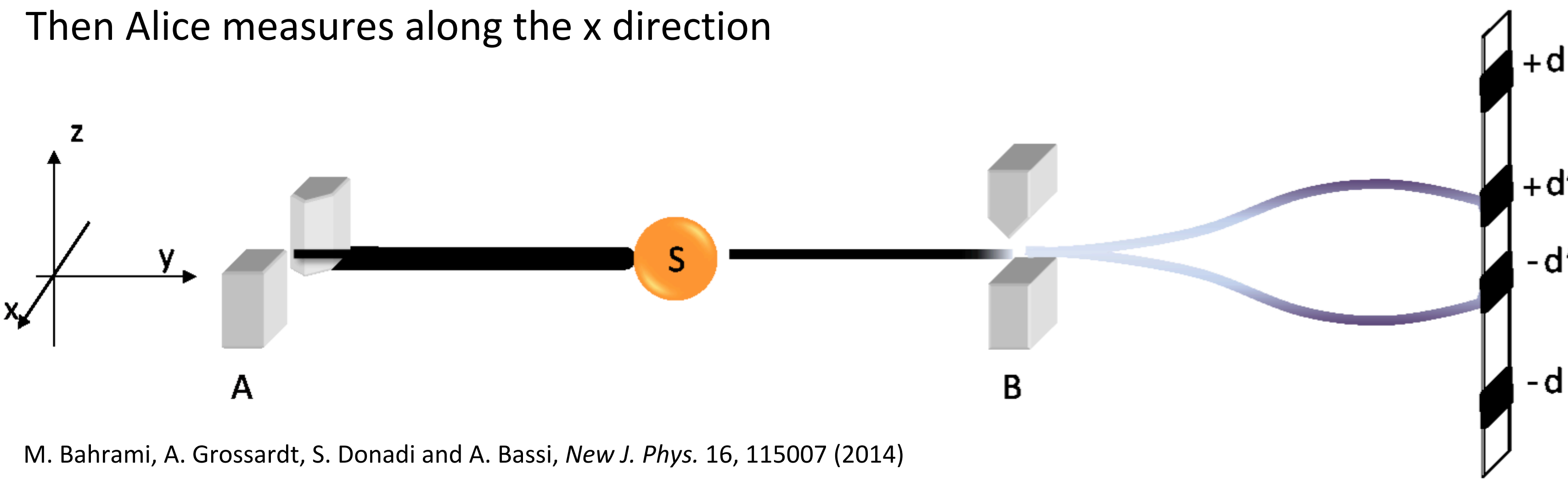
It does faster-than-light

Consider the usual "Alice & Bob sharing an entangled spin state" scenario.

Alice first measure along the z direction:



Then Alice measures along the x direction



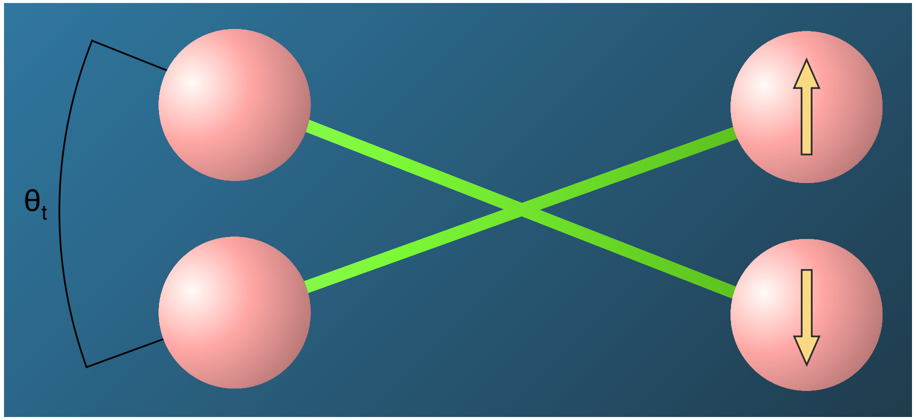
M. Bahrami, A. Grossardt, S. Donadi and A. Bassi, *New J. Phys.* 16, 115007 (2014)

Is gravity quantum?

M. Carlesso, M. Paternostro, H. Ulbricht and A. Bassi, "When Cavendish meets Feynman: A quantum torsion balance for testing the quantumness of gravity"
ArXiv:1710.08695 (2017)

BACKGROUND: Are quantum gravity effects testable in the lab?

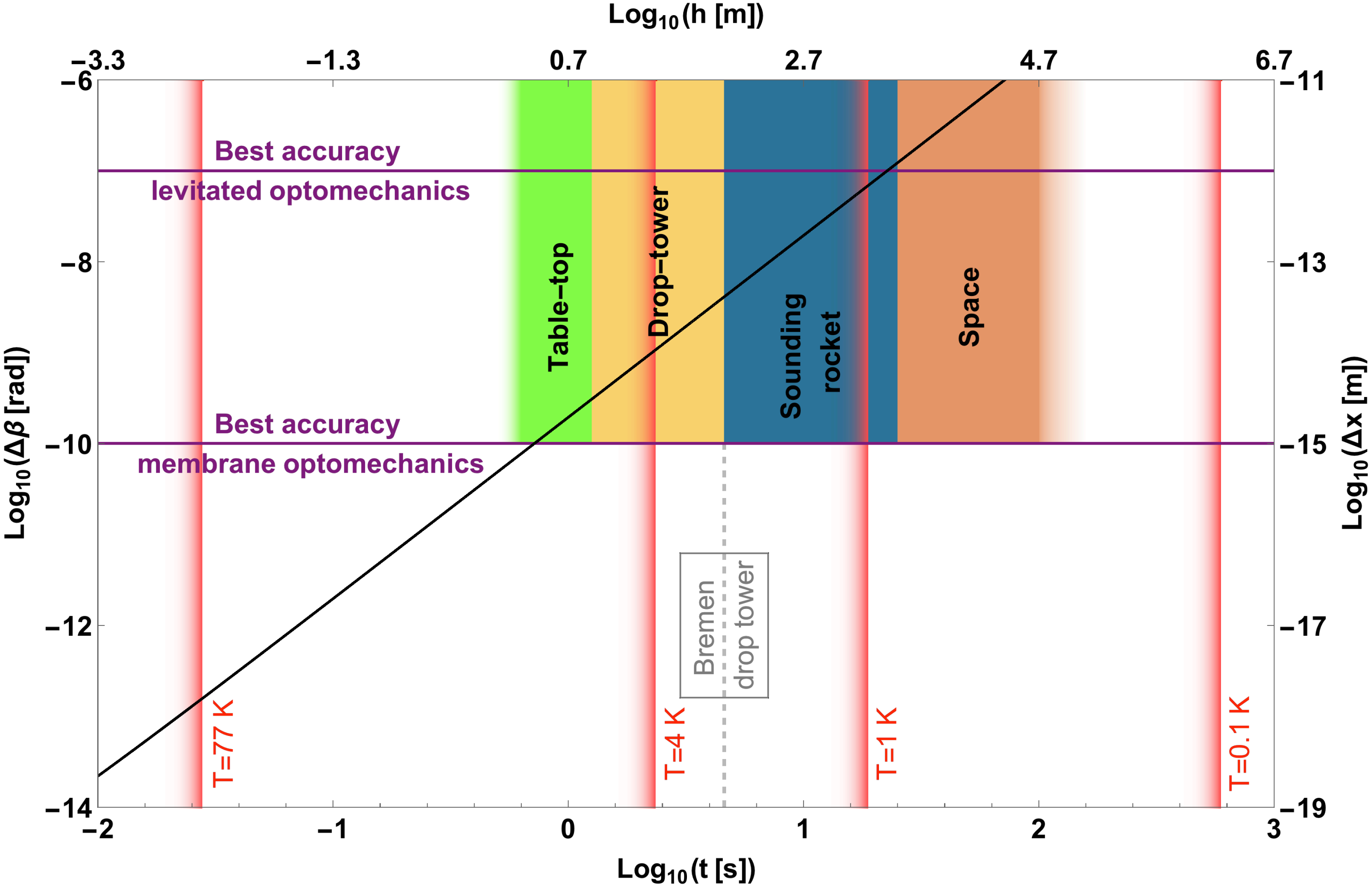
IDEA: Create a macroscopic (angular) superposition. If gravity is **quantum**, the superposition will persist. If gravity is **classical**, likely it will be reduced



Protocol

1. Take a nano-rod − with an angular degree of freedom − in lab vacuum
2. Cool its rotational motion close to the ground sate (few phonons)
3. Generate a spin superposition (via microwave π/2-pulse)
4. Transfer the spin superposition to a rotational superposition (via magnetic field)
5. Decouple the spin-angular superposition (spin measurement)
6. Allow for enough free evolution − long enough time (drop tower?)
7. Detect the angular state of the nano-rod

Is gravity quantum?



Feasible with current technology

Acknowledgments

The Group (www.qmts.it)

- Postdocs: M. Carlesso, G. Gasbarri
- Ph.D. students: L. Curcuraci, L. Asprea, C. Jones, J. Reyes

Collaborations with: S.L. Adler, M. Paternostro, H. Ulbricht, A. Vinante, C. Curceanu.

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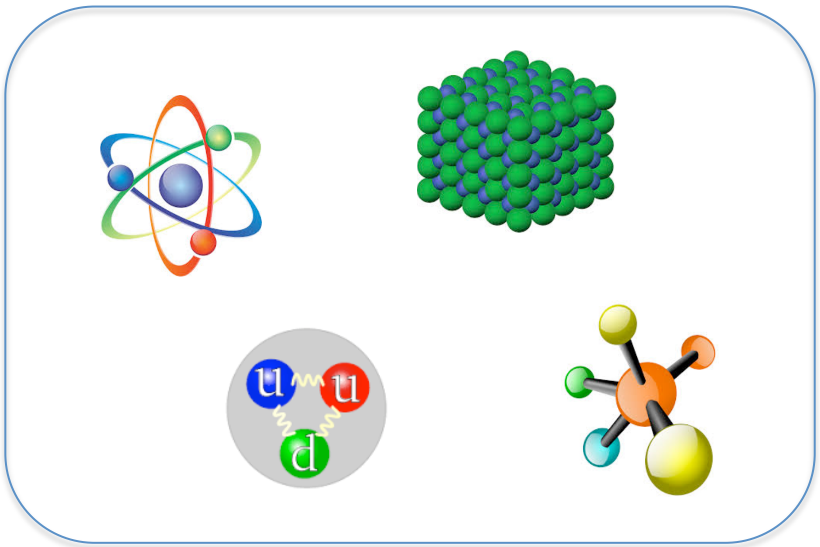
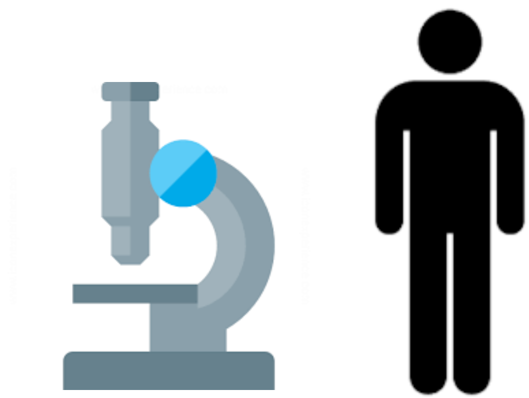
Standard Quantum Mechanics

Quantum world



Classical world



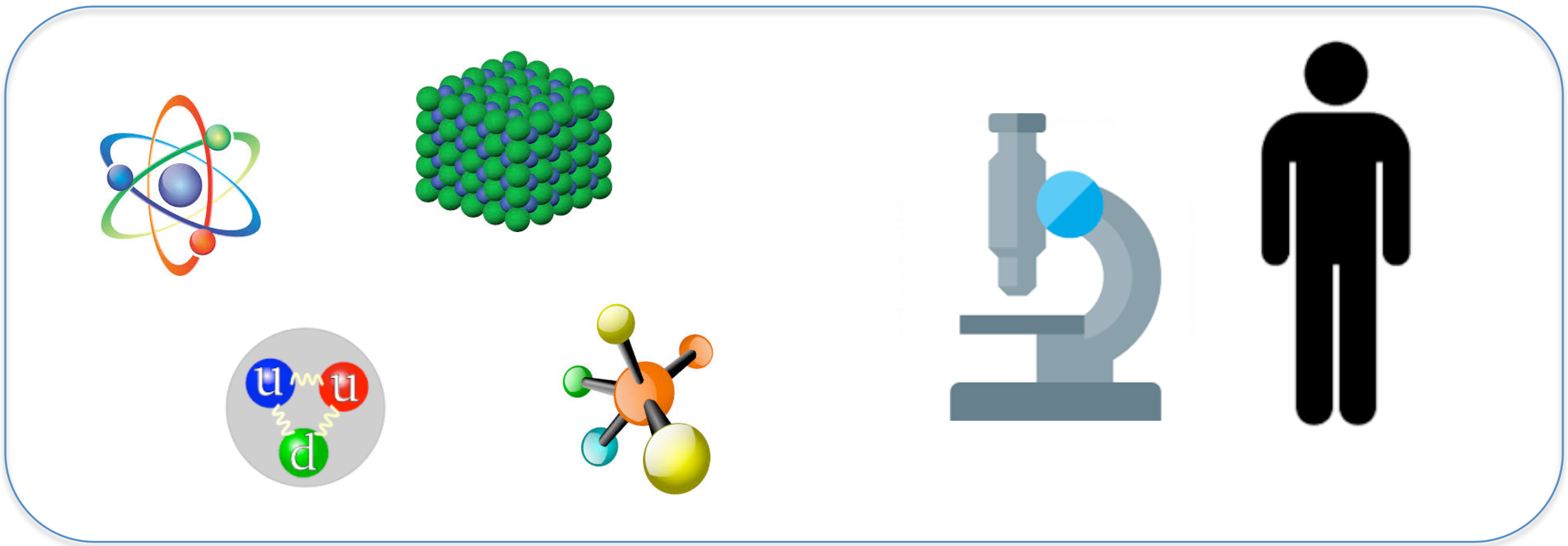
The wave function gives the probabilities of outcomes of measurements

The Copenhagen interpretation assumes a **mysterious division** between the microscopic world governed by quantum mechanics and a macroscopic world of apparatus and observers that obeys classical physics. […] S. Weinberg, Phys. Rev. A 85, 062116 (2012)

How we would like Quantum Mechanics to be

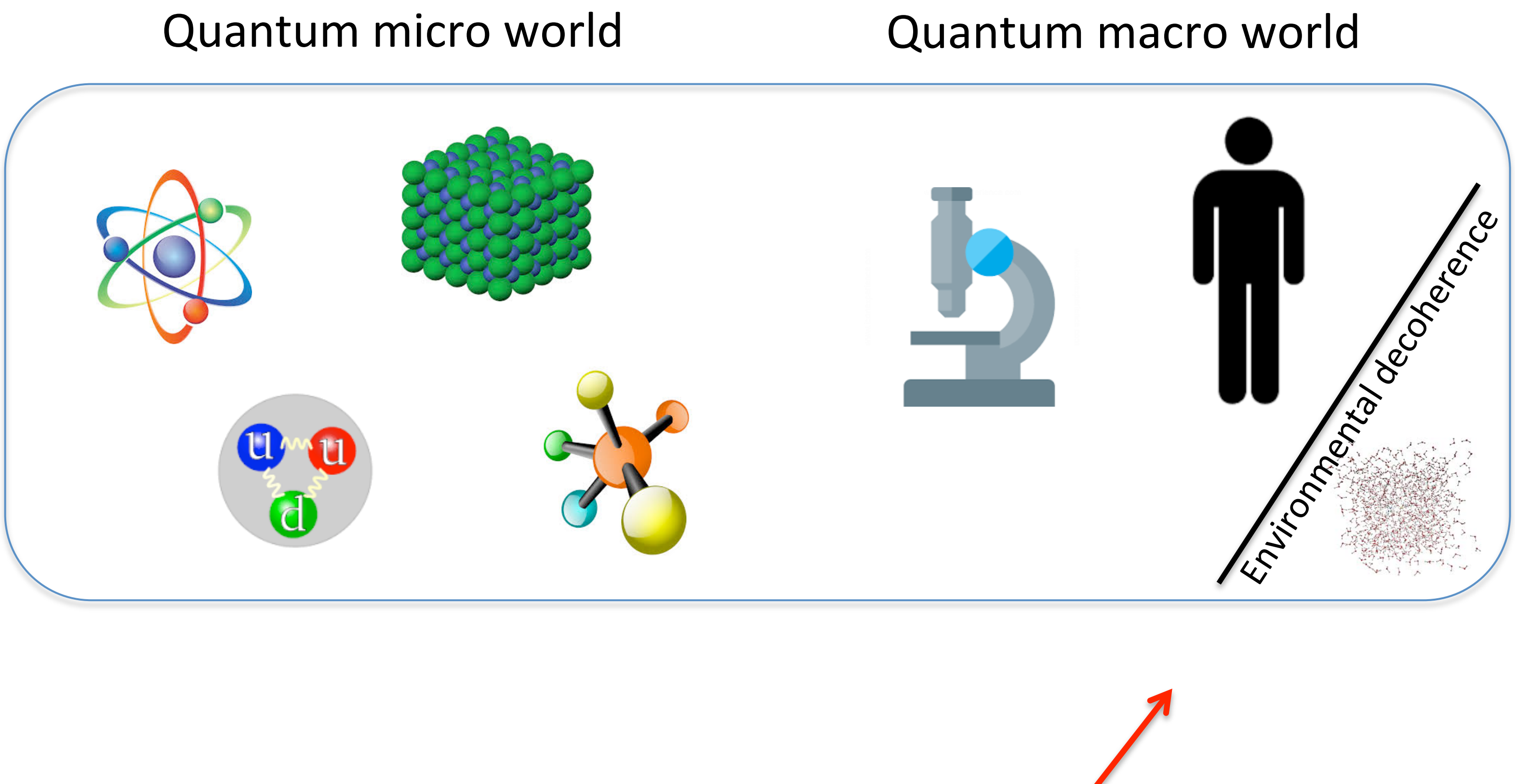
Quantum micro world

Quantum macro world



Problem: **What is the meaning of the wave function, now that there is no external observer giving a (probabilistic) meaning to it? Who collapses the wave function? Is there a collapse? If not, how do we explain the absence of macroscopic superpositions?** ➔ Schrödinger's cat paradox

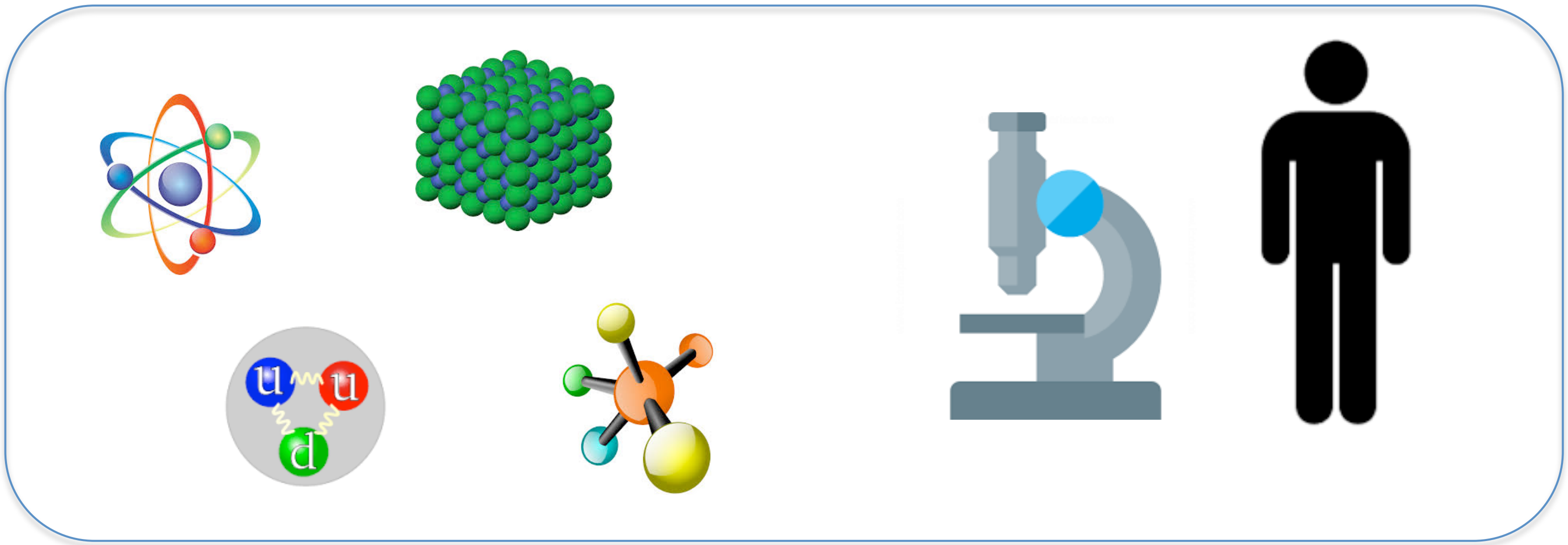
Decoherence does not fix the problem



Problem: The division system-environment is **arbitrary**, and very much similar to the division quantum-classical in the Copenhagen interpretation.

Ways to fix Quantum Mechanics

Quantum world



Bohmian Mechanics
Many Worlds
Collapse models