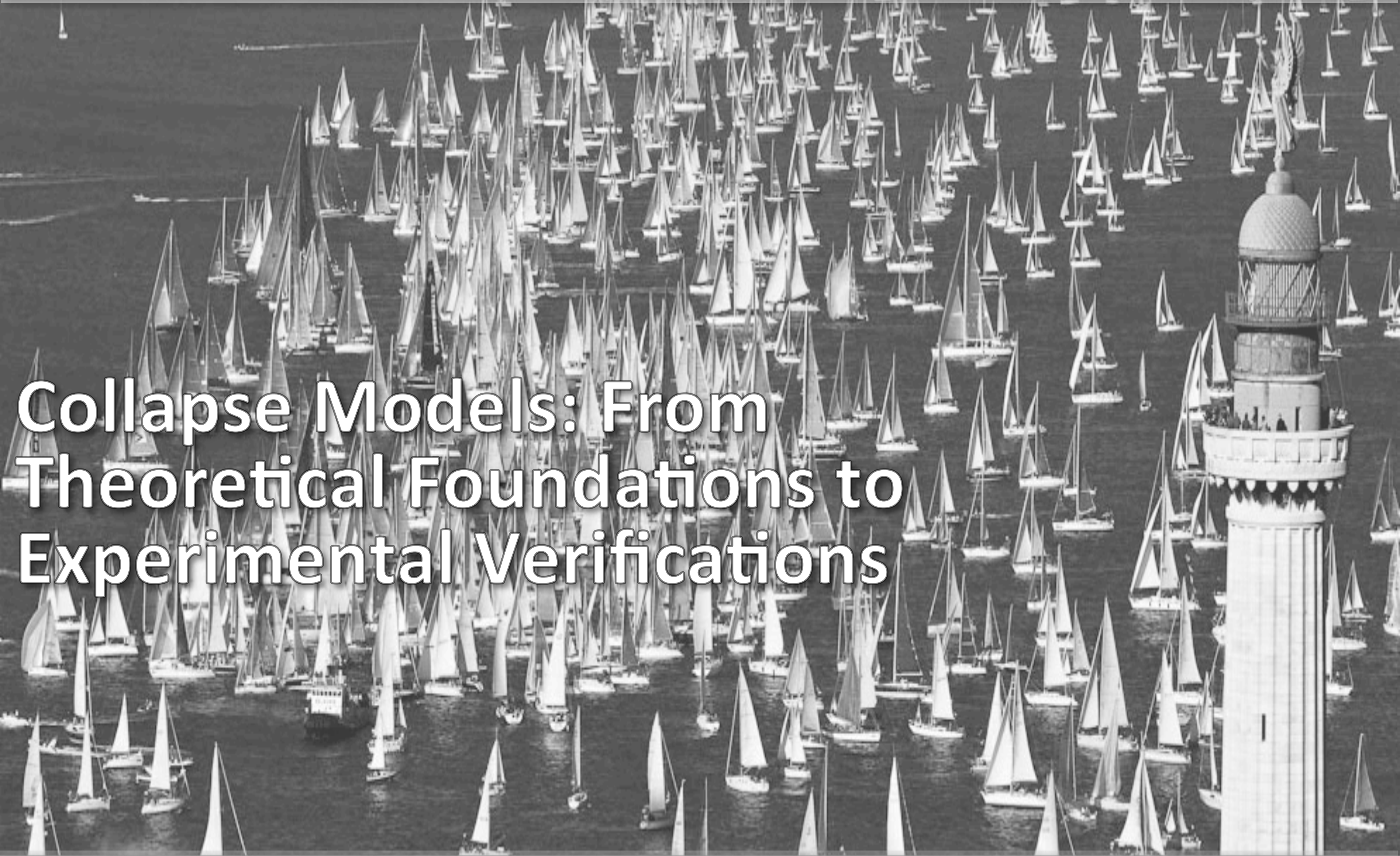
Emergent Quantum Mechanics
Austrian Academy of Sciences (October 3rd- 6th, 2013)

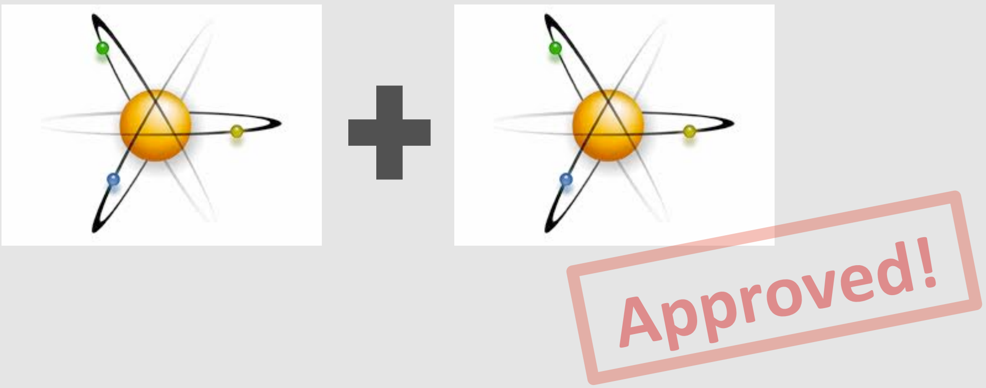


Collapse Models: From Theoretical Foundations to Experimental Verifications

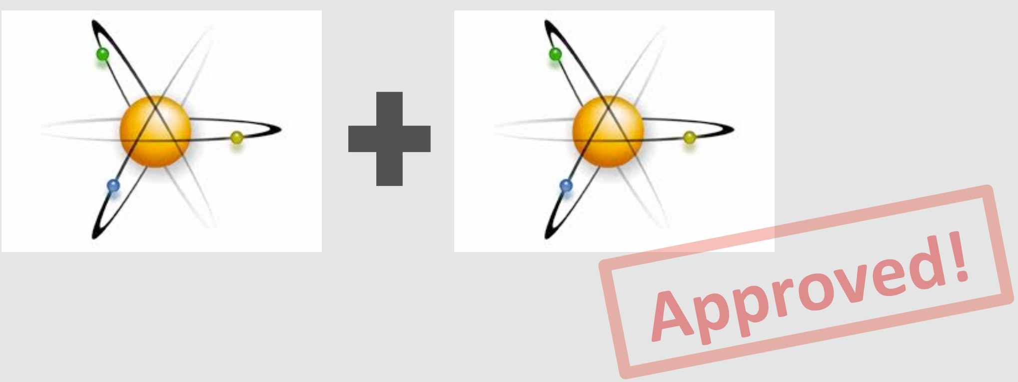
Angelo Bassi - University of Trieste & INFN - Italy

"Collapses occur more or less all the time, more or less everywhere" (J.S. Bell)

The Schrödinger equation is linear ➔ superposition principle



Collapse models ➔ no macroscopic superpositions



OR

Collapse models

GRW MODEL: G.C. Ghirardi, A. Rimini and T. Weber, *Phys. Rev. D* 340, 470 (1986)

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

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

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

Also: Diosi, Gisin, Adler, Wiseman, Tumulka, Dowker, Bedingham …

Question: Which form for the modified dynamics (E_t) for the state vector?

Answer: The form of E_t is "uniquely identified" by the no-faster-than-light condition (and norm conservation)

N. Gisin & I.C. Percival, *J. Phys. A* 25, *5677 (1992)*

H.M. Wiseman & L. Diosi, *Chem. Phys.* 268, *91 (2001)*

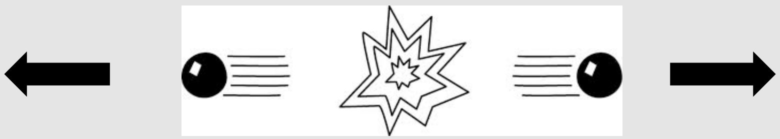
S.L. Adler & T.A. Brun, *J. Phys. A* 34, *1 (2001)*

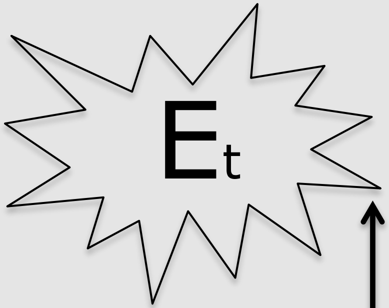
S. Weinberg, *Phys. Rev. A 85, 062116 (2012). See also: Ann. Phys.* 194, *336 (1989); Phys. Rev. Lett.* 62, *485 (1989)*

A. Bassi, D. Duerr & G. Hinrichs, ArXiv:1303:4284 (2013)

Gisin's argument

N. Gisin, *Helv. Phys. Acta* 62, 363 (1989)





1. INITIALLY ENGANGLED STATE

2. ALICE MAKES A MEASUREMENT

THE WAVE FUNCTION COLLAPSES ON BOTH SIDES

BOB RECEIVES EQUIVALENT ENSEMBLES

3. THE SYSTEM FURTHER EVOLES

IF THE EQUIVALENCE RELATION IS NOT PRESERVED, THEN FASTER-THAN-LIGHT SIGNALING

THE EVOLUTION FOR THE DENSITY MATRIX MUST BE LINEAR (that for the wave function can be nonlinear, stochastic ...)

Consequence 1: Lindblad equation

A. Bassi, D. Duerr & G. Hinrichs, ArXiv:1303:4284 (2013)

1. Linear evolution for the density matrix (no faster-than-light signaling)

2. Markovian assumption

Then the dynamics must be of the Lindblad type

$$\frac{\mathrm{d}\rho_t}{\mathrm{d}t} = -i[H, \rho_t] + \sum_{k=1}^{n} \left(L_k \rho_t L_k^\dagger - \frac{1}{2} L_k^\dagger L_k \rho_t - \frac{1}{2} \rho_t L_k^\dagger L_k \right)$$

Consequence 2: Collapse equations

H.M. Wiseman & L. Diosi, *Chem. Phys.* 268, *91 (2001)*, A. Bassi, D. Duerr & G. Hinrichs, ArXiv:1303:4284 (2013)

Given a generic diffusion for the wave function

$$\mathrm{d}\psi_t = A(\psi_t)\mathrm{d}t + \sum_{k=1}^{N} B_k(\psi_t)\mathrm{d}W_{k,t},$$

such that

$$\frac{\mathrm{d}\rho_t}{\mathrm{d}t} = -i[H, \rho_t] + \sum_{k=1}^{n} \left(L_k \rho_t L_k^\dagger - \frac{1}{2} L_k^\dagger L_k \rho_t - \frac{1}{2} \rho_t L_k^\dagger L_k \right)$$

Then

$$A(\psi) = -iH - \frac{1}{2} \sum_{k=1}^{N} \left(L_k^\dagger L_k - 2\ell_{k,t}^{(\psi)} L_k^{(\psi)} + |\ell_{k,t}^{(\psi)}|^2 \right)$$

$$B_k(\psi) = L_k^{(\psi)} - \ell_{k,t}^{(\psi)}, \qquad \ell_{k,t}^{(\psi)} = \frac{1}{2} \langle \psi_t, (L_k^{(\psi)\dagger} + L_k^{(\psi)})\psi_t \rangle$$

$$L_k^{(\psi)} := \sum_{j=1}^{N} u_{kj}(\psi)\, L_j, \qquad L_k^{(\psi)\dagger} := \sum_{j=1}^{N} u_{kj}^*(\psi)\, L_j^\dagger$$

The structure is completely defined, the only degrees of freedom being the complex coefficients of the N×N unitary matrix $u_{kj}(\psi)$.

Which models?

The general structure is

$$d|\psi\rangle_t \;=\; \left[-\frac{i}{\hbar}H\,dt \;+\; \sqrt{\lambda}(A - \langle A\rangle_t)dW_t - \frac{\lambda}{2}(A - \langle A\rangle_t)^2 dt\right]|\psi\rangle_t$$

$$\langle A\rangle_t \;=\; \langle\psi_t|A|\psi_t\rangle$$

Which kind of operators?

Reasonable assumption: the collapse operators – which identify the "preferred basis", should be **connected to position**

NOTE: The Born rule comes out automatically

Space-collapse models

	White noise models All frequencies appear with the same weight	Colored noise models The noise can have an arbitrary spectrum
Infinite temperature models No dissipative effects	**GRW / CSL** G.C. Ghirardi, A. Rimini, T. Weber , *Phys. Rev. D* 34, 470 (1986) G.C. Ghirardi, P. Pearle, A. Rimini, *Phis. Rev. A* 42, 78 (1990) **QMUPL** L. Diosi, *Phys. Rev. A* 40, 1165 (1989)	**Non-Markovian CSL** P. Pearle, in *Perspective in Quantum Reality* (1996) S.L. Adler & A. Bassi, *Journ. Phys. A* 41, 395308 (2008). arXiv: 0807.2846 **Non-Markovian QMUPL** A. Bassi & L. Ferialdi, *PRL* 103, 050403 (2009)
Finite temperature models Dissipation and thermalization	**Dissipative QMUPL model** A. Bassi, E. Ippoliti and B. Vacchini, *J. Phys. A* 38, 8017 (2005). ArXiv: quant-ph/0506083	**Non-Markovian & dissipative QMUPL** (L. Ferialdi, A. Bassi, PRL 108, 170404 (2012))

CSL model

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

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

System's Hamiltonian

NEW COLLAPSE TERMS ➡ **New Physics**

$$N(\mathbf{x}) = a^\dagger(\mathbf{x}) a(\mathbf{x}) \quad \text{particle density operator}$$

choice of the preferred basis

$$\langle N(\mathbf{x}) \rangle_t = \langle \psi_t | N(\mathbf{x}) | \psi_t \rangle$$

nonlinearity

$$W_t(\mathbf{x}) = \text{noise} \quad \mathbb{E}[W_t(\mathbf{x})] = 0, \quad \mathbb{E}[W_t(\mathbf{x}) W_s(\mathbf{y})] = \delta(t-s) e^{-(\alpha/4)(\mathbf{x}-\mathbf{y})^2}$$

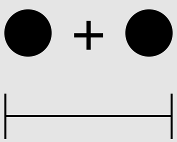
stochasticity

$$\lambda = \text{ collapse strength} \qquad r_C = 1/\sqrt{\alpha} = \text{ correlation length}$$

two parameters

Collapse rate

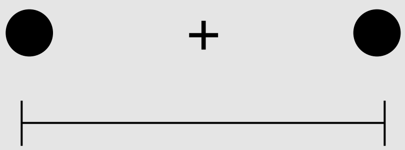
Small superpositions



$\ll r_C$

Collapse NOT effective

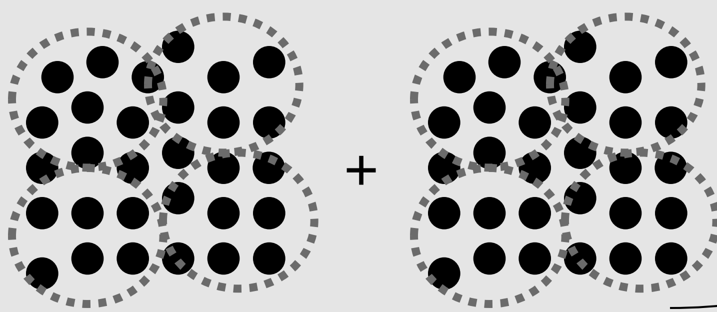
Large superpositions



$\geq r_C$

Collapse effective

$$\Gamma = \lambda n^2 N$$



n = number of particles within r_C

N = number of such clusters

Amplification mechanics

Few particles

no collapse

quantum behavior

Many particles

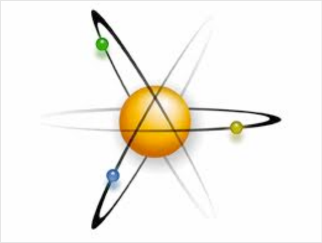
Fast collapse

classical behavior

Which values for λ and r_c?

Increasing size of the system

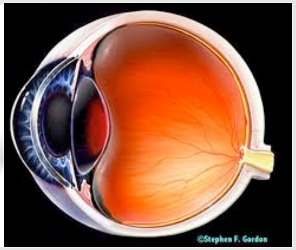
Microscopic world
(few particles)



$$\lambda \sim 10^{-8\pm 2}\mathrm{s}^{-1}$$

QUANTUM – CLASSICAL TRANSITION (Adler - 2007)

Mesoscopic world
Latent image formation
+
perception in the eye
($\sim 10^4$ - 10^5 particles)



S.L. Adler, JPA 40, 2935 (2007)

A. Bassi, D.A. Deckert & L. Ferialdi, EPL 92, 50006 (2010)

$$\lambda \sim 10^{-17}\mathrm{s}^{-1}$$

QUANTUM – CLASSICAL TRANSITION (GRW - 1986)

Macroscopic world
($> 10^{13}$ particles)

G.C. Ghirardi, A. Rimini and T. Weber, PRD 34, 470 (1986)

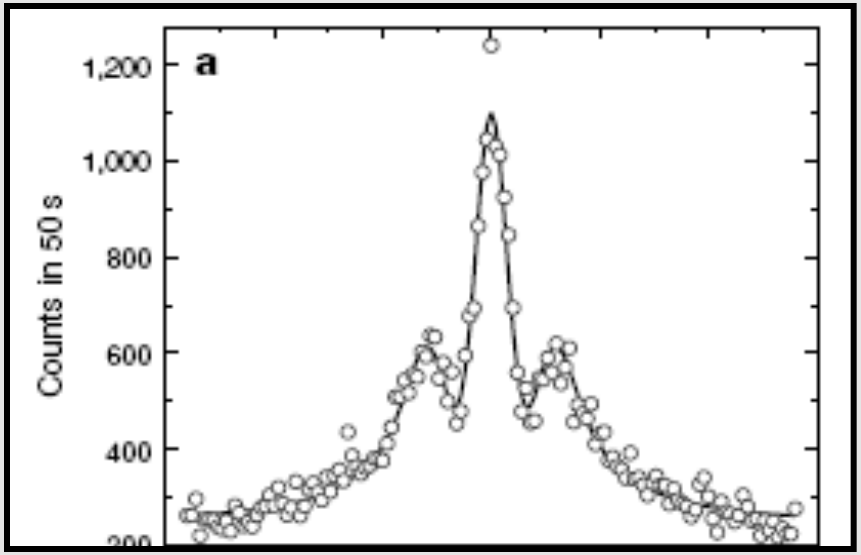
$$r_C = 1/\sqrt{\alpha} \;\sim\; 10^{-5}\mathrm{cm}$$

Constraints from Experiments

Matter-wave interferometry

Diffraction of macro-molecules:

- **C_{60} (720 AMU)**
  M. Arndt et al, *Nature* 401, 680 (1999)
- **C_{70} (840 AMU)**
  L. Hackermüller et al, *Nature* 427, 711 (2004)
- **$C_{30}H_{12}F_{30}N_2O_4$ (1,030 AMU)**
  S. Gerlich et al, *Nature Physics* 3, 711 (2007)
- **Larger Molecules (10,000 AMU)**
  S. Eibenberger *et al.* PCCP 15, 14696 (2013)



C_{60} diffraction experiment

The experimental bounds are some 2 orders of magnitude higher than Adler's proposed value (therefore some 10 orders of magnitude away from GRW's proposed value)

Future experiments: ~10^6 AMU
K. Hornberger *et al.*, Rev. Mod. Phys. 84, 157 (2012)
P. Haslinger *et al.*, Nature Phys. 9, 144 (2013)

Outer space for higher masses?

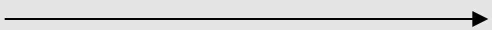
ALSO:
Micro-mirrors, nano-spheres
Marshall, W., et al., *Phys. Rev. Lett.* 91, 130401 (2003)
Romero-Isart, O., et al., *Phys. Rev. A* 83, 013803 (2011)

Spontaneous photon emission

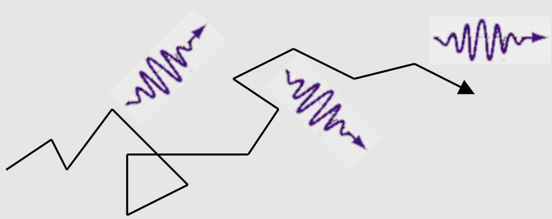
Q. Fu, *PRA* 56, 1806 (1997), S.L. Adler, F. Ramazanoglu, *JPA* 40, 13395 (2007), S.L. Adler, A. Bassi & S. Donadi, JPA 46, 245304 (2013) …

FREE PARTICLE

1. Quantum mechanics

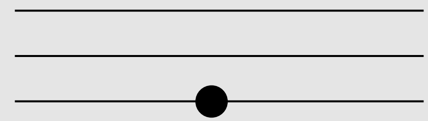


2. Collapse models

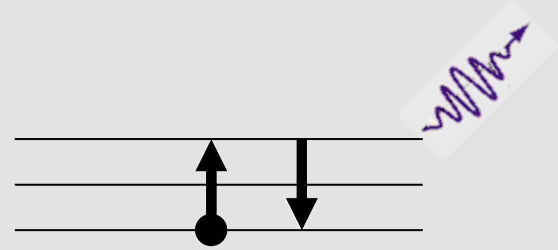


BOUND STATE

1. Quantum mechanics



2. Collapse models



1. One needs to introduce mass proportionality in the model
2. Adler’s value for λ is ruled out by 2 orders of magnitude
3. Adler’s value for λ comes back in the game if the noise spectrum has cut off

Energy non-conservation

Cosmological observations

The smart thing to do is to look at large structures in the universe.

The larger the system, the bigger the spontaneous-collapse effect.

So far, cosmological data are compatible with collapse models.

Cosmological data	Distance (orders of magnitude) from GRW value for λ	Distance (orders of magnitude) from Adler's value for λ
Dissociation of cosmic hydrogen	17	9
Heating of the Intergalactic medium (IGM)	8	0
Heating of protons in the universe	12	4
Heating of Interstellar dust grains	15	7

Energy non-conservation is very model dependent

S.L. Adler, *Jour. Phys. A* 40, 2935 (2007), arXiv:quant-ph/0605072

Upper bounds on λ. Summary

Laboratory experiments	Distance (orders of magnitude) from Adler's value for λ	Cosmological data	Distance (orders of magnitude) from Adler's value for λ
Matter-wave interference experiments	2	Dissociation of cosmic hydrogen	9
Decay of supercurrents (SQUIDs)	6	Heating of Intergalactic medium (IGM)	0
Spontaneous X-ray emission from Ge	-2	Heating of protons in the universe	4
Proton decay	10	Heating of Interstellar dust grains	7

S.L. Adler and A. Bassi, *Science* 325, 275 (2009)

Present day technology allows for meaningful tests

One has to be careful in reading the table

Laboratory experiments	Distance (orders of magnitude) from Adler's value for λ	Cosmological data	Distance (orders of magnitude) from Adler's value for λ
Matter-wave interference experiments	2	Dissociation of cosmic hydrogen	9
Decay of supercurrents (SQUIDs)	6	Heating of Intergalactic medium (IGM)	0
Spontaneous X-ray emission from Ge	-2	Heating of protons in the universe	4
Proton decay	10	Heating of Interstellar dust grains	7

?

It depends on the type of noise

PROBABLY THE MOST RELIABLE

They all assume that no dissipative effects take place.

Other possible tests

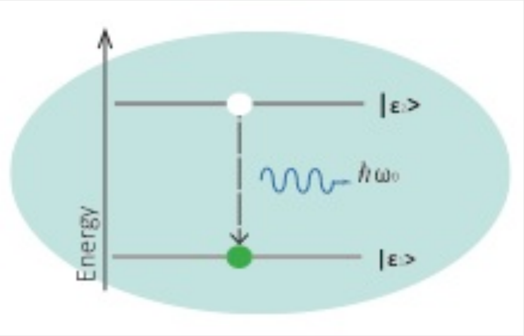
Some quantum systems naturally oscillate: neutrinos, kaons, chiral molecules

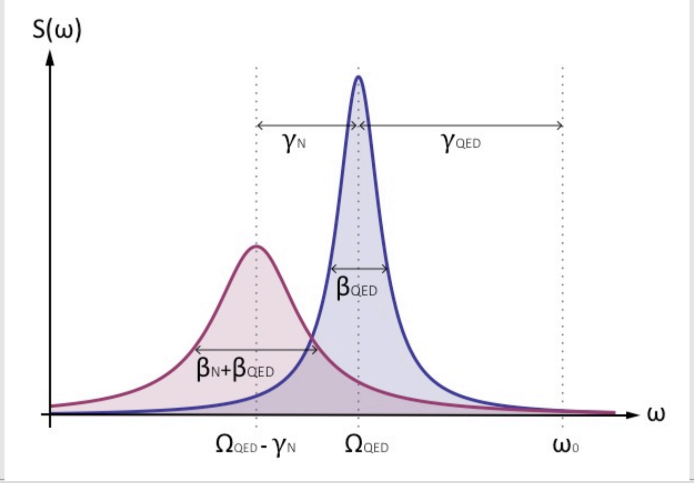
They offer natural tests for collapse models CSL predictions

M. Bahrami, S. Donadi, L. Ferialdi, A. Bassi, C. Curceanu, A. Di Domenico, B. Hiesmayr, *Nature Sci. Reports (2013)*

Why not performing experiments in the frequency domain?

M. Bahrami, A. Bassi and H. Ulbricht, *arXiv:1309.5889*





Inflation, cosmic seeds & collapses

Can collapse models explain the emergence of the seeds of cosmic structure?

How does the inflationary history of the universe change, if collapses occur?

- A. Perez, H. Sahlmann and D. Sudarsky, Class. Quant. Grav. 23, 2317 (2006)
- A. De Unanue and D. Sudarsky, Phys. Rev. D 78, 043510 (2008)
- A. Diez-Tejedor, G. Leon and D. Sudarsky, Gen. Rel. Grav. 44, 2965 (2012)
- S. J. Landau, C. G. Scoccola and D. Sudarsky, Phys. Rev. D 85, 123001 (2012)
- J. Martin, V. Vennin and P. Peter, arXiv:1207.2086.
- P. Canate, P. Pearle and D. Sudarsky, arXiv:1211.3463.
- S. Das, K. Lochan, S. Sahu and T. P. Singh, arXiv:1304.5094

Gravity induced collapse?

Quantum fields + gravity (semi-classical limit) + non-relativistic limit

Schrödinger-Newton equation:

$$i\hbar\frac{\partial}{\partial t}\psi(x,t) = \left(-\frac{\hbar^2}{2m}\frac{\partial^2}{\partial x^2} - Gm^2\int\frac{|\psi(y,t)|^2}{|x-y|}dy\right)\psi(x,t)$$

D. Giulini and A. Grossardt, *Class. Quantum Grav.* 29, 215010 (2012) and references therein

Nonlinear deterministic equation. It collapses the wave function in space (in which precise sense?), but allows for superluminal signaling

Diosi-Penrose model

$$\frac{d}{dt}\hat{\rho} = -\frac{i}{\hbar}[\hat{H},\hat{\rho}] - \frac{\mathrm{G}}{2\hbar}\int\int\frac{d\mathbf{r}\,d\mathbf{r}'}{|\mathbf{r}-\mathbf{r}'|}[\hat{f}(\mathbf{r}),[\hat{f}(\mathbf{r}'),\hat{\rho}]] \qquad \hat{f}(\mathbf{r}) = \frac{M}{V}\theta(R-|\hat{\mathbf{q}}-\mathbf{r}|)$$

L. Diosi, *J. Phys. A* 21, 2885 (1988); *Phys. Lett. A* 129, 419 (1988). R. Penrose, *Gen. Rel. Grav*. 28, 581 (1996)

Good collapse equation. However it diverges. A (large) cutoff is needed

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THE GROUP

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- Graduate students: M. Toros, A. Codutti, M Carlesso

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