Is quantum theory exact?

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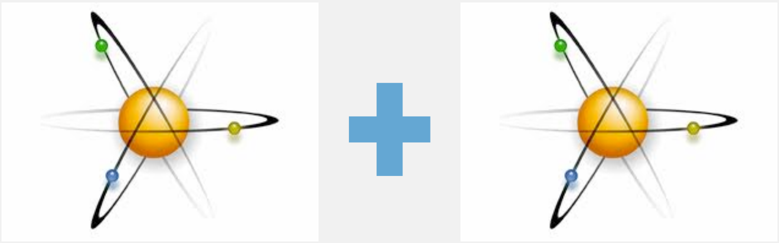
1. Measurement problem
2. Ways out
3. Collapse models
4. Lower bounds on the collapse parameters
5. Upper bounds on the collapse parameters
6. Conclusion

The measurement problem

Quantum mechanics is **linear** at all scales



Microscopic superpositions

Tested experimentally

Macroscopic superpositions

What do they mean?

Textbook solution: collapse of the wave function after a measurement

Ok at the phenomenological level, not acceptable at the fundamental level

Ways out

✓ **Bohmian mechanics**	→ Hidden variable theories
✓ **Decoherent histories approach**	→ Minimal change
✓ **Many worlds, many minds** ✓ **Modal interpretation** ✓ **Everything is information**	} New interpretation of the wave function
✓ **Decoherence**	→ No change
✓ **Collapse models**	→ Change the dynamics

About decoherence

1. Initial state	$\frac{1}{\sqrt{2}}[\lvert\text{here}\rangle + \lvert\text{there}\rangle]$
2. Density matrix	$\frac{1}{2}\begin{pmatrix} 1 & 1 \\ 1 & 1 \end{pmatrix}$
3. Turn decoherence on	$\frac{1}{2}\begin{pmatrix} 1 & 0 \\ 0 & 1 \end{pmatrix}$
4. Read it as	either $\lvert\text{here}\rangle$ or $\lvert\text{there}\rangle$

Problem with decoherence

either $\lvert\text{here}\rangle$ or $\lvert\text{there}\rangle$

YES → $\frac{1}{2}\begin{pmatrix} 1 & 0 \\ 0 & 1 \end{pmatrix}$

$\frac{1}{2}\begin{pmatrix} 1 & 0 \\ 0 & 1 \end{pmatrix}$ → NO!

either $\lvert\text{here}\rangle$ or $\lvert\text{there}\rangle$

There exist many linear dynamics giving the same decoherence effect

Collapse Models

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

IDEA: *"Spontaneous collapses occur more or less all the time, more or less everywhere"* (J. Bell).

The Schrödinger equation is modified, to include such effects.

They are **nonlinear** and **stochastic**.

CONSTRAINTS:

- ✓ **Norm preserving equation**
- ✓ **No faster than light**

The structure of the equation almost uniquely identified

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

$$\langle A\rangle_t = \langle\psi_t|A|\psi_t\rangle \longrightarrow$$ **nonlinear**

$dW_t \rightarrow$ **stochastic**

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 Only the noise acts on the wave function	**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 Noise & wave function act on each other	**Dissipative QMUPL model** A. Bassi, E. Ippoliti and B. Vacchini, *J. Phys. A* 38, 8017 (2005). ArXiv: quant-ph/0506083	**Work in progress** (L. Ferialdi, A. Bassi)

The CSL Model

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

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

Quantum Hamiltonian

NEW COLLAPSE TERMS ➡ **New Physics**

$N(\mathbf{x}) = a^\dagger(\mathbf{x}) a(\mathbf{x})$ particle density operator, $\langle N(\mathbf{x})\rangle_t = \langle \psi_t | N(\mathbf{x}) | \psi_t \rangle$ **nonlinearity**

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

$\lambda \sim 10^{-17}\mathrm{s}^{-1}$ collapse strength $r_C = 1/\sqrt{\alpha} \sim 10^{-5}\mathrm{cm}$ correlation length

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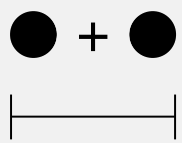
Mass proportional CSL model: $\lambda \longrightarrow \lambda \left(\frac{m}{m_N} \right)^2$, $m_N =$ nucleon mass

Collapse rate

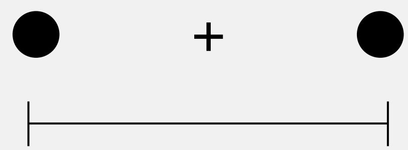
Small superpositions



$\ll r_C$

No collapse

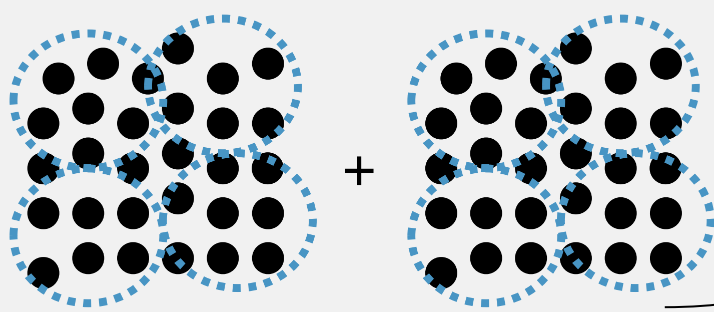
Large superpositions



$\geq r_C$

Collapse

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



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

Value of λ - lower bounds

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

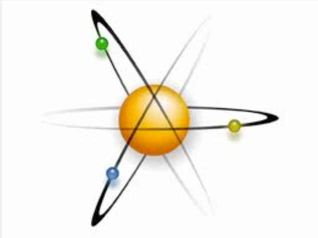
QUANTUM

CLASICAL

$\lambda \sim 10^{-8\pm2} s^{-1}$

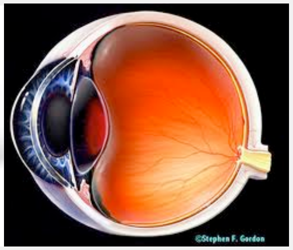
QUANTUM

Microscopic world
(few particles)



CLASSICAL

Latent image formation
+
perception in the eye
(~ 10^4 - 10^5 particles)



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

A. Bassi, D.A. Deckert & L. Ferialdi, EPL, to appear

COLLAPSE DUE TO GRAVITY: S. Carlip, Class. Quant. Grav. 25, 154010 (2008)

Macroscopic world
(> 10^{13} particles)

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

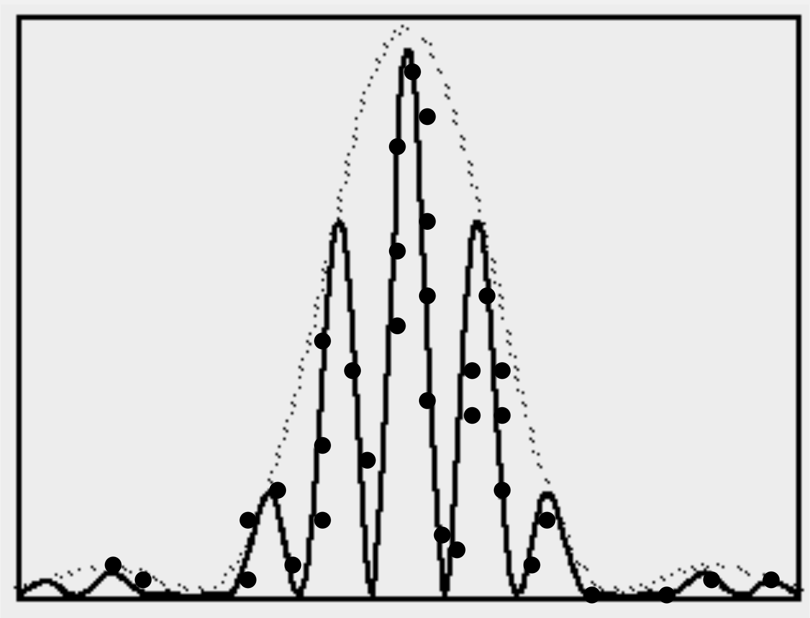
n increasingì'i

Upper bounds

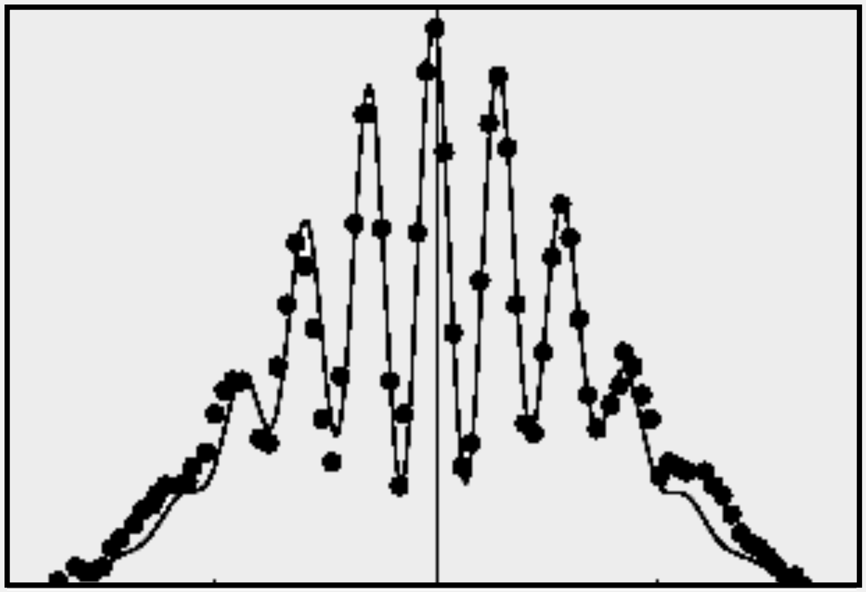
Destruction of quantum interference

The nonlinear terms work against the superposition principle.

In interference experiments, one should see a reduction of interference fringes



Prediction of quantum mechanics
(no environmental noise)

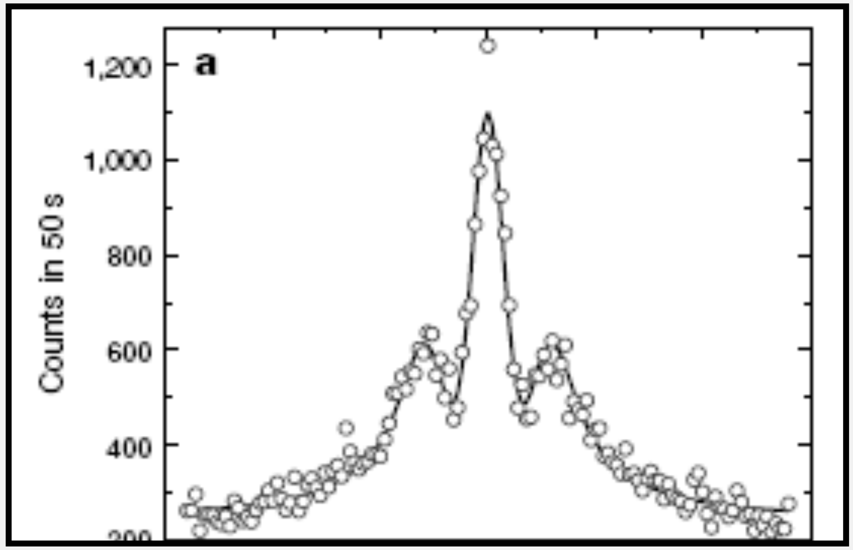


Prediction of collapse models
(no environmental noise)

Destruction of quantum interference

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)



C_{60} diffraction experiment

Future experiments
Much larger molecules

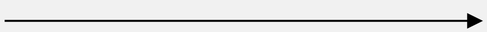
~11,000 AMU
(possibly up to **1,000,000 AMU**)

	Distance (decades) from the standard CSL value	Distance (decades) from the enhanced value
Diffraction of macro-molecules	**12-13**	**3-4**

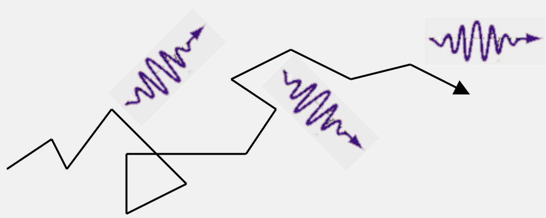
Spontaneous photon emission

FREE PARTICLE

1. Quantum mechanics



2. Collapse models



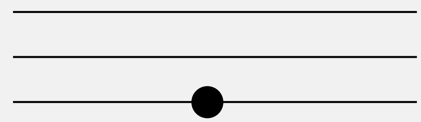
$$\frac{d\Gamma_k}{dk} = \frac{e^2 \lambda \hbar}{2\pi^2 \epsilon_0 m^2 c^3 k}$$

Q. Fu, *Phys. Rev. A* 56, 1806 (1997)

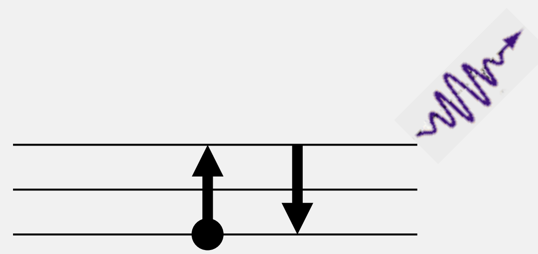
S.L. Adler, A. Bassi & S. Donadi, ArXiv 1011.3941

BOUND STATE

1. Quantum mechanics



2. Collapse models



$$\frac{d\Gamma_k}{dk} = 2\left[1 - \frac{1}{(1+(ka_0/2)^2)^2}\right]\frac{e^2 \lambda \hbar}{2\pi^2 \epsilon_0 m^2 c^3 k}$$

S.L. Adler, F. Ramazanoglu, *J. Phys. A* 40, 13395 (2007)

Spontaneous photon emission

Comparison with experimental data

↓

Original CSL models (with the weak value for λ) is ruled out!

Mass-proportional model (noise having a gravitational origin?)

$$\lambda \rightarrow \lambda \left(\frac{m}{m_N} \right)^2$$

then:

$$\frac{d\Gamma_k}{dk} = \frac{e^2 \lambda \hbar}{2\pi^2 \epsilon_0 m^2 c^3 k} \rightarrow \frac{e^2 \lambda \hbar}{2\pi^2 \epsilon_0 m_N^2 c^3 k}$$

→ **Compatibility is restored**

TABLE I. Experimental upper bounds and theoretical predictions of the spontaneous radiation by free electrons in Ge for a range of photon energy values.

Energy (keV)	Expt. upper bound (counts/keV/kg/day)	Theory (counts/keV/kg/day)
11	0.049	0.071
101	0.031	0.0073
201	0.030	0.0037
301	0.024	0.0028
401	0.017	0.0019
501	0.014	0.0015

Q. Fu, *Phys. Rev. A* 56, 1806 (1997)

Spontaneous photon emission

Current upper bound on the *mass proportional CSL model*, coming from spontaneous X-ray emission

Strongest known upper bound.

Colored-white noise model

	Distance (orders of magnitude) from the standard CSL value	Distance (orders of magnitude) from the enhanced value
Spontaneous X-ray emission from Ge	**6**	**-2**

$$\left.\frac{d\Gamma_k}{dk}\right|_{\text{colored}} = \gamma(\omega_k) \left.\frac{d\Gamma_k}{dk}\right|_{\text{white}}$$

γ = Fourier transform of the correlation function of the noise.

S.L. Adler, F. Ramazanoglu, *J. Phys. A* 40, 13395 (2007)

Cutoff at frequencies ~ 10^{18} s^{-1} sufficient for compatibility with known data

S.L. Adler, F. Ramazanoglu, ibid.

Cutoff at frequencies c/r_C ~ 10^{15} s^{-1}

A. Bassi and G.C. Ghirardi, *Phys. Rep.* 379, 257 (2003)

Energy non-conservation

The stochastic terms induce a random motion of particles.

The noise pumps energy into the system.

For one nucleon (GRW's value)

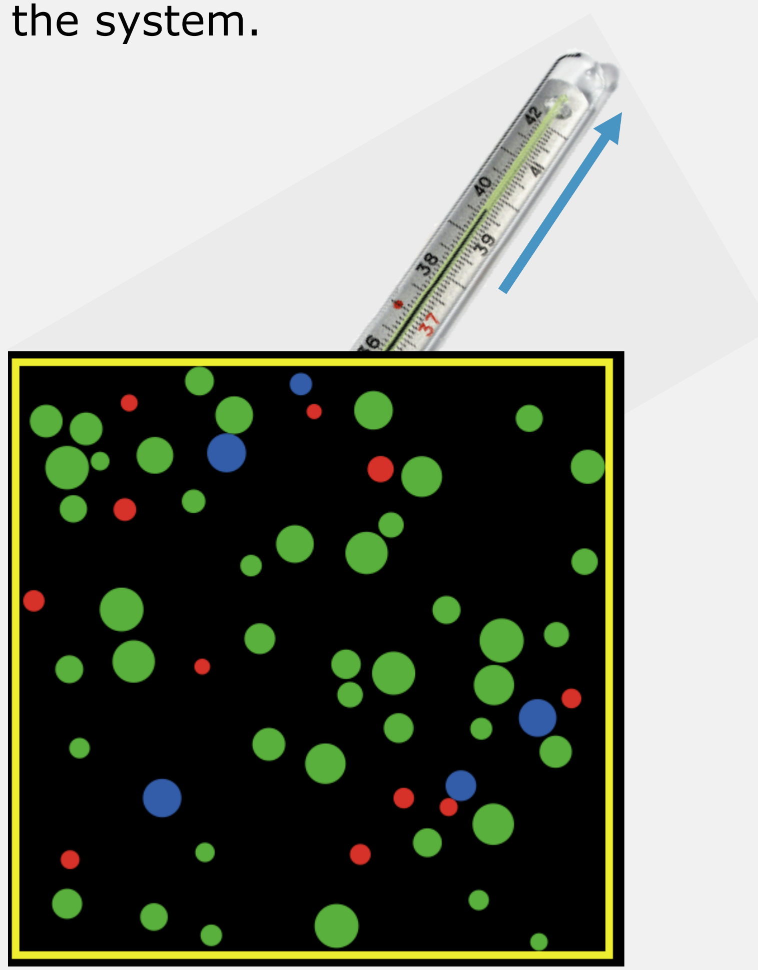
$$\frac{dE}{dt} = \frac{\lambda \alpha \hbar^2}{4m} \simeq 10^{-25} \text{eV s}^{-1}$$

→ 1 eV increase in 10^{18} yr

For a gas (GRW's value)

Temperature increase 10^{-15} K/yr

G.C. Ghirardi, A. Rimini, T. Weber, *Phys. Rev. D* 34, 470 (1986)



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.

Energy non-conservation is very model dependent

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

Cosmological data	Distance (orders of magnitude) from the standard CSL value	Distance (orders of magnitude) from the enhanced value
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

Upper bounds on λ

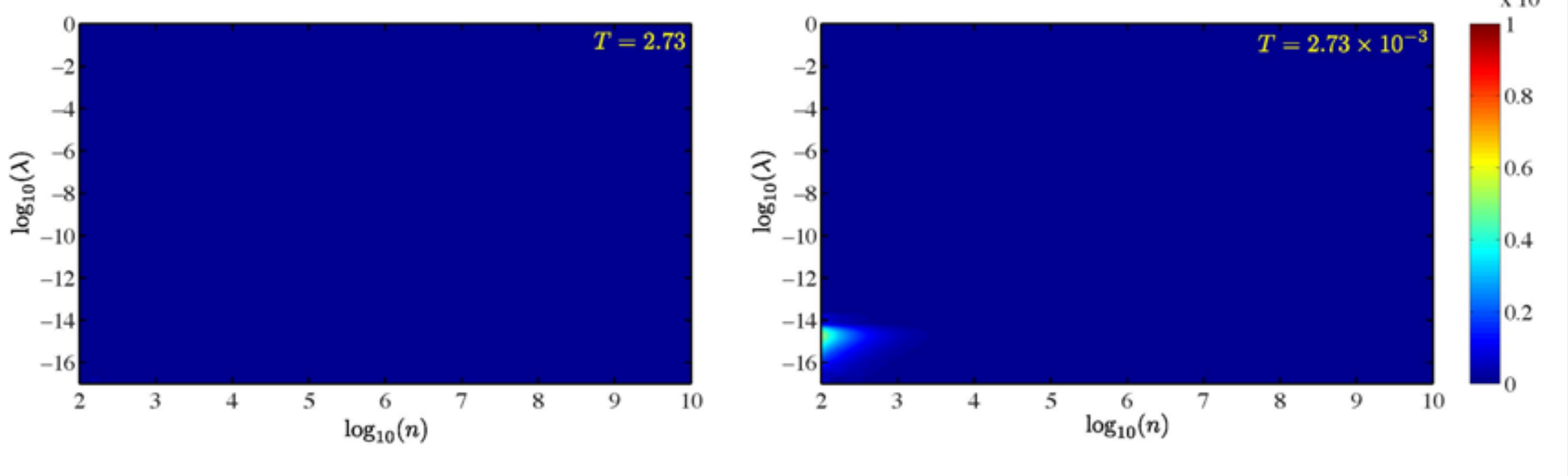
Laboratory experiments	Distance (decades) from the enhanced CSL value	Cosmological data	Distance (decades) from the enhanced CSL value
Fullerene diffraction experiments	**3-4**	Dissociation of cosmic hydrogen	**9**
Decay of supercurrents (SQUIDs)	**6**	Heating of Intergalactic medium (IGM)	**0**
Spontaneous 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 crucial tests

Finite-temperature field

A. Bassi, D.A. deckert, I. Ferialdi, EPL, to appear



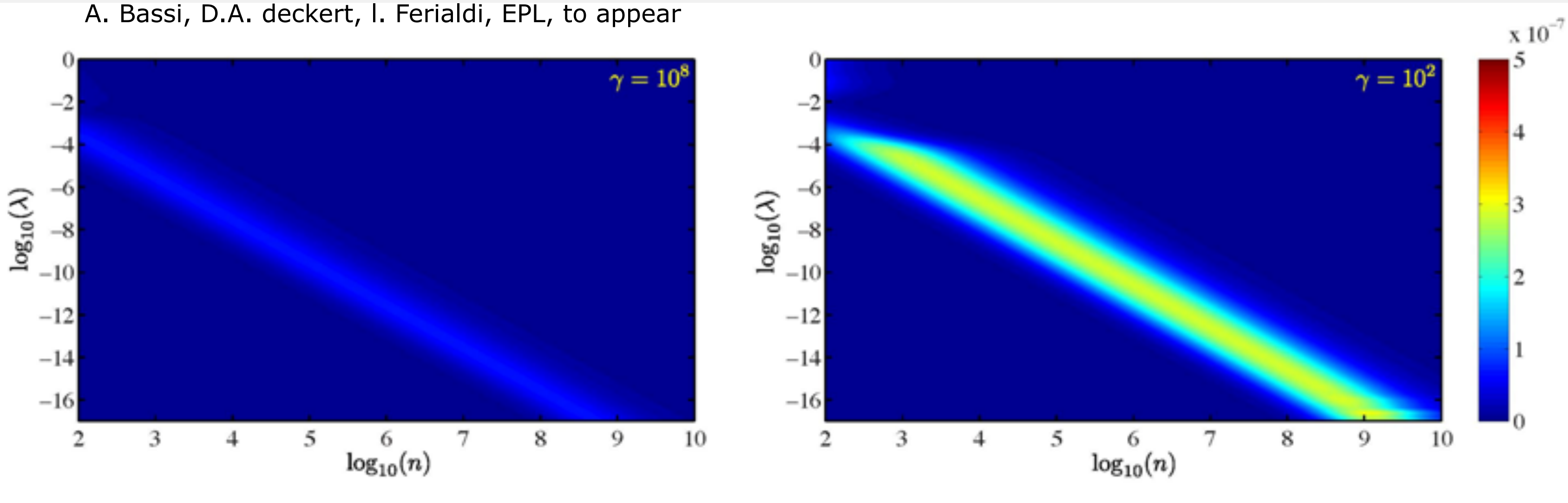
Difference of the spread in position of the wave function, as given by the **infinite temperature model** and by the **finite temperature model**

↓

A noise field with a typical cosmological temperature can induce an efficient collapse of the wave function

Noise with frequency cut off

A. Bassi, D.A. deckert, l. Ferialdi, EPL, to appear



Difference of the spread in position of the wave function, as given by the white-noise model and by the colored-noise model

↓

A noise field with a typical cosmological cut-off can induce an efficient collapse of the wave function

Open questions for research

1. Collapse models assume the existence of a **random field filling space.** What is the origin of such a field? Does it have a **gravitational** nature? Can it be a **cosmological field?**

   (S.L. Adler and A. Bassi: *J. Phys. A* 41, 395308, 2008)

2. The coupling between the random field and the wave function is **anti-Hermitian**: what is the origin of this non-standard coupling? Could it be cosmological?

3. Collapse models appear as **phenomenological models of an underlying pre-quantum theory**: what does this theory look like?

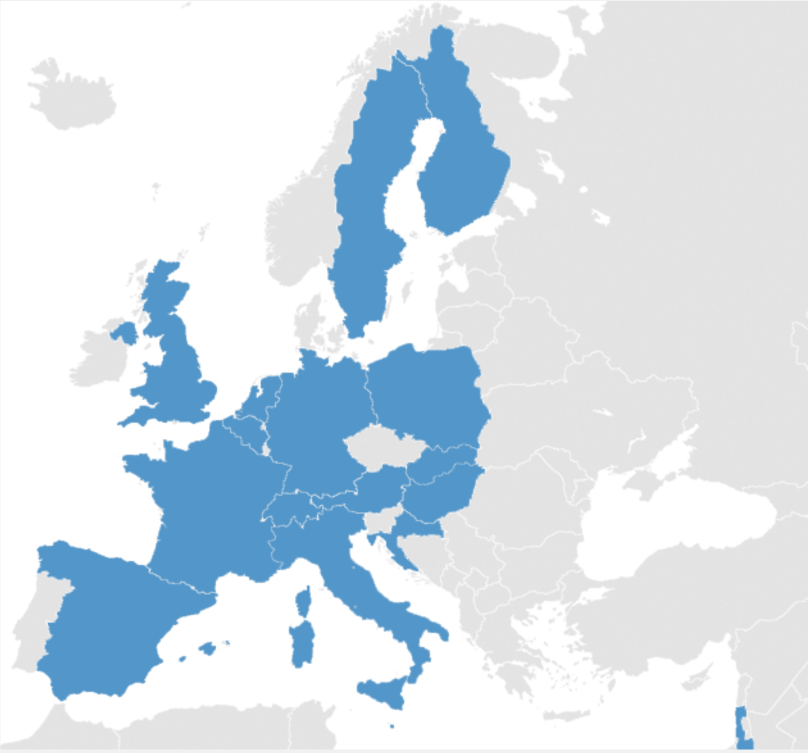
   (S.L. Adler, "Quantum Theory as an Emergent Phenomenon", C.U.P. 2004)

4. What are the most promising **experiments**, which can detect possible violations of quantum mechanics, as predicted by collapse models?

   A.J. leggett, New Scintist 23 June 2010

The COST Network (2011-15)

"Fundamental Problems in Quantum Physics"



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Conclusion

Two messages:

1. **Threshold micro-macro (quantum-classical) for 10^4-10^5 particles**

   Present-day technology allows for crucial tests of the superposition principle.

   Collapse models provide quantitative estimates.

2. **A random cosmological field with "typical" features for temperature and spectrum can induce an efficient collapse of the wave function**

   The collapse as a physical process, caused a background cosmological field

   Underlying deeper lever theory?