Breaking quantum linearity: constraints from human perceptions and implications at the cosmological scale

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1. Collapse models – general features – the CSL model
2. Lower bounds: the process of vision
3. Upper bounds: constraints from experiments
4. On the cosmological origin of the noise field

1. Collapse Models

Idea: Modify the Schrödinger equation, including the collapse of the wave function.

➡ **Wave function coupled nonlinearly to a random noise**

CONSTRAINTS:

- ✓ **Quantum coherence** for **microscopic** systems
- ✓ **Localized** wave function for **macroscopic** objects
- ✓ In **measurement** processes: **uniqueness** of outcomes
- ✓ **Born** probability **rule**
- ✓ **Nonlocality** (violation of Bell’s inequalities), but **no superluminal** signaling

➡ **Structure of the equation almost uniquely identified**

The CSL Model

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

$$\boxed{d|\psi_t\rangle = \Big[\underbrace{-\frac{i}{\hbar}H\,dt}_{\text{Quantum Hamiltonian}} + \underbrace{\sqrt{\lambda}\int d^3x(N(\mathbf{x})-\langle N(\mathbf{x})\rangle_t)dW_t(\mathbf{x}) - \frac{\lambda}{2}\int d^3x(N(\mathbf{x})-\langle N(\mathbf{x})\rangle_t)^2 dt}_{\text{NEW COLLAPSE TERMS} \;\Rightarrow\; \boxed{\textbf{New Physics}}}\Big]|\psi_t\rangle}$$

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

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

$\lambda \sim 10^{-17}\,\text{s}^{-1}$ collapse strength

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

Mass proportional CSL model:

$$\lambda \longrightarrow \lambda\left(\frac{m}{m_N}\right)^2, \qquad m_N = \text{nucleon mass}$$

Usefulness of collapse models

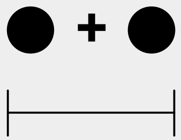
1. **Collapse models as a solution of the measurement problem of Quantum Mechanics.** These models offer a paradox-free description of quantum measurements (and of all physical processes).

2. **Collapse models as a rival theory of Quantum Mechanics.** Important, in order to give a quantitative meaning to experiments testing quantum linearity. They are an alternative theory, which makes different predictions, to which these experiments can be compared.

3. **Collapse models as phenomenological models of an underlying pre-quantum theory.** If quantum mechanics is not exact, and spontaneous collapse-type effects are seen in experiments, these model may offer a direction to look for a new theory.

Collapse rate

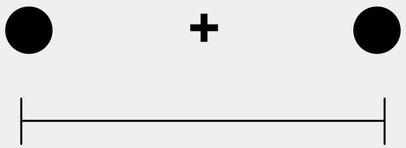
Small superpositions



$\ll r_C$

No collapse

Large superpositions



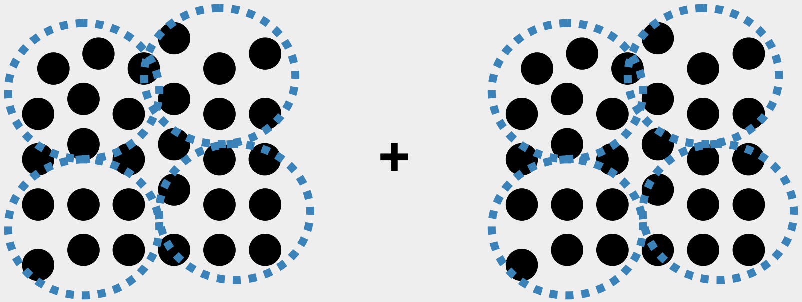
$\geq r_C$

Collapse

$$\boxed{\mathbf{\Gamma = \lambda n^2 N} \quad (\text{rate} = s^{-1})}$$

n = number of particles within r_C

N = number of such clusters



2. Lower bounds

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

QUANTUM

CLASSICAL

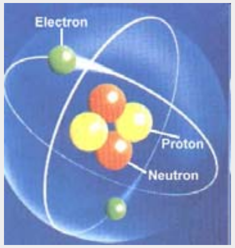
$\lambda \sim 10^{-8} s^{-1}$

QUANTUM

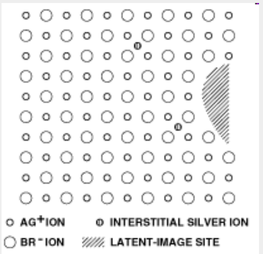
CLASSICAL

n increasing

**Microscopic world
(few particles)**

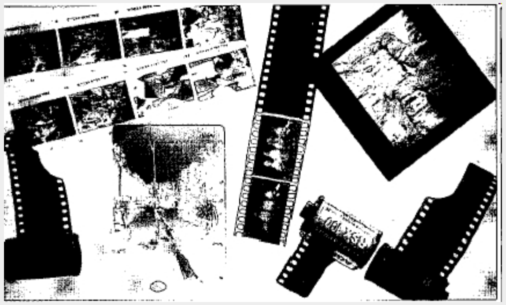


**Latent image formation
(~ 5-6000 particles)**

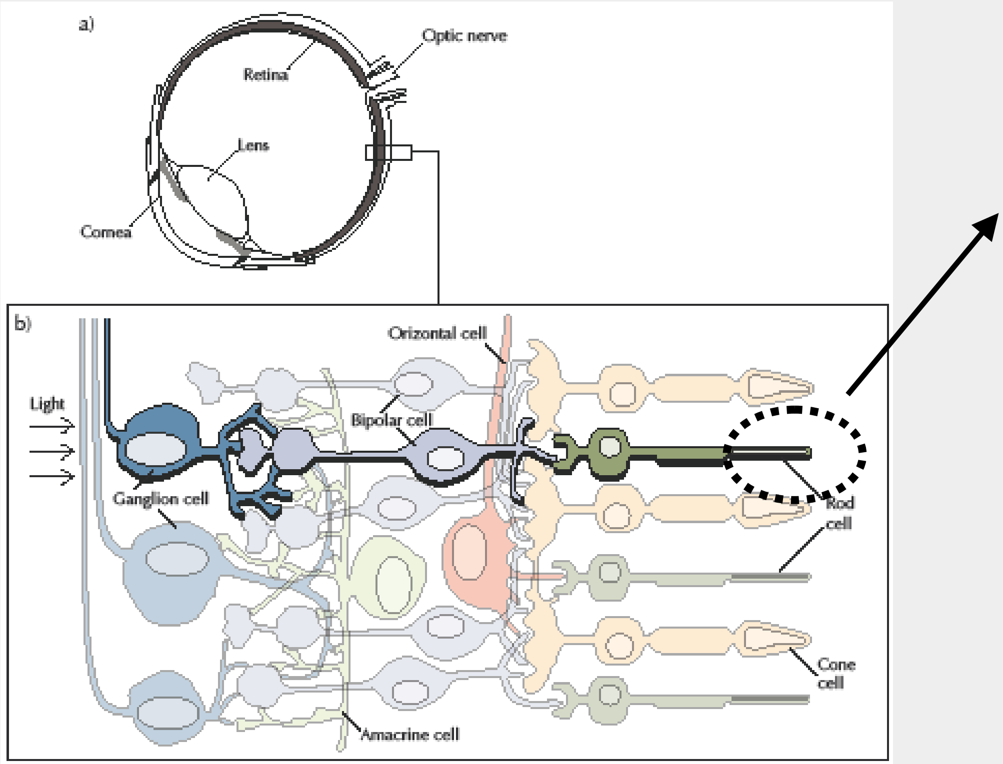


$$\begin{aligned}\gamma + AgBr &\rightarrow Ag^{+} + Br^{-}\\ &\rightarrow Ag^{+} + Br + e^{-} \quad (e^{-} \text{ trapped by a grain})\\ &\rightarrow Ag + Br \quad (Ag \text{ trapped by a grain})\end{aligned}$$

**Macroscopic world
(10^{13} particles)**



Collapse in the eye



Threshold of vision: ~6 photons

photon absorbed by the rhodopsin

cis-trans transf. of the rhodopsin

interaction with ~20 transducins

ɑ-subunit splits, binding to a PDE

PDE activated

PDE hydrolyzes ~100 cGMP to GMP

Closure of ~300 ionic channels

~10 Na^+/channel blocked

Time: ~100ms

ɑ-subunit of the transducin: $n \sim 3.9 \times 10^4, \quad N \sim 20$

Other terms give similar a contribution

$$\left.\right\} \quad \lambda \sim 1.4 \times 10^{-7}\,\mathrm{s}^{-1}$$

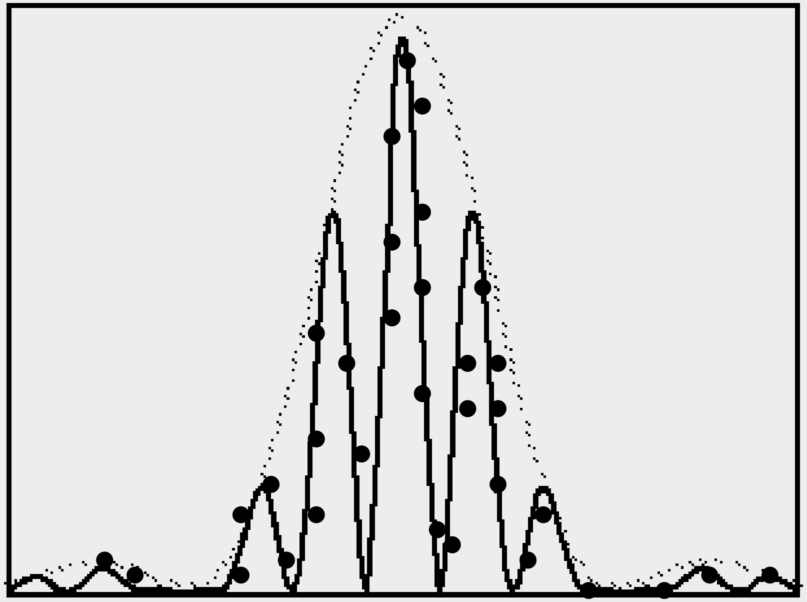
The collapse occurs when ~10^4-10^5 particles are involved

3. Upper bounds

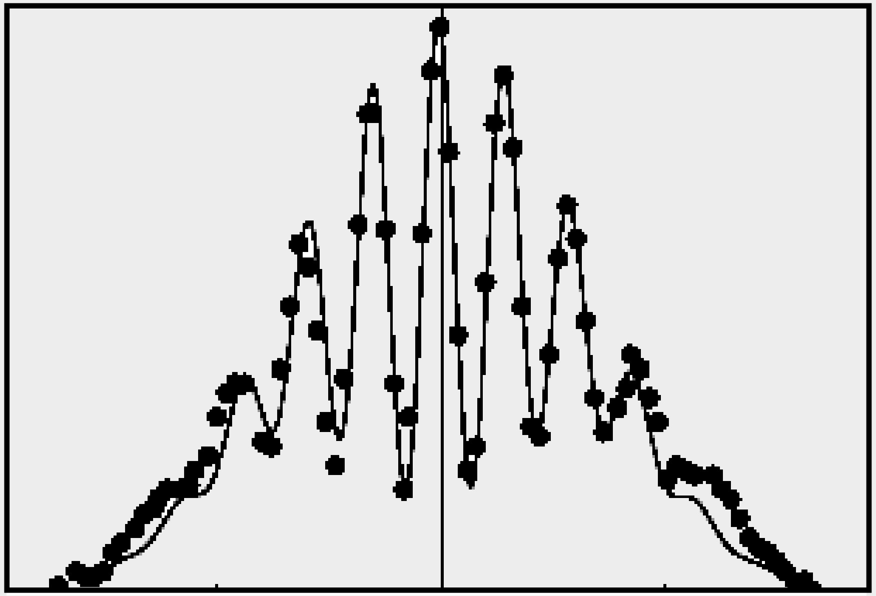
Destruction of quantum interference

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)

Upper bounds

Destruction of quantum interference

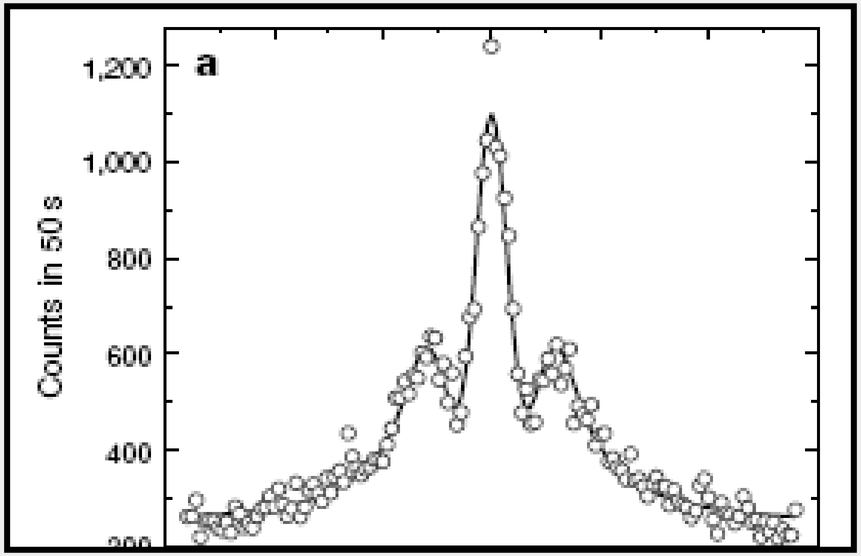
Diffraction of macro-molecules:

- **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)



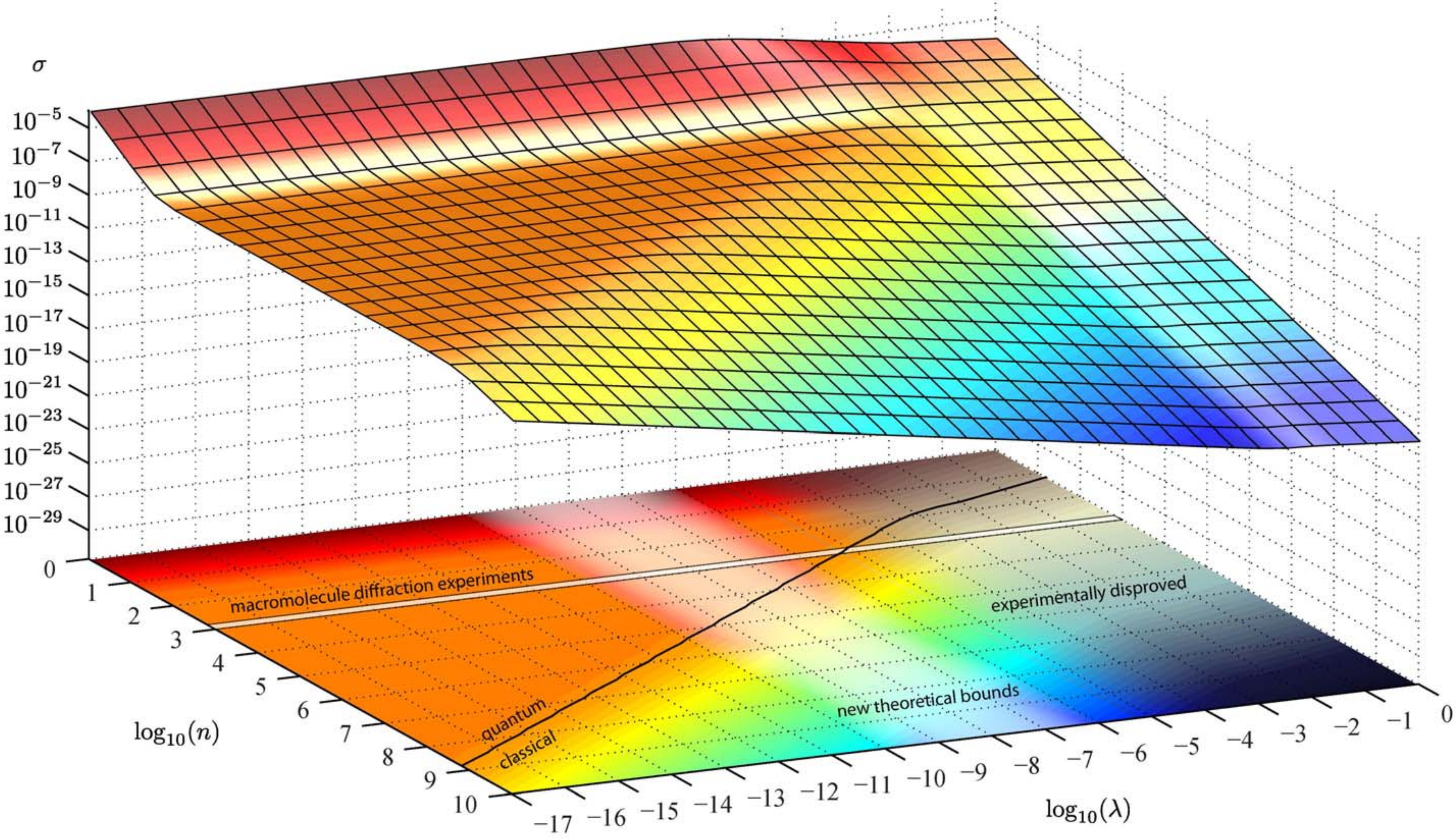
C_{60} diffraction experiment

Future experiments

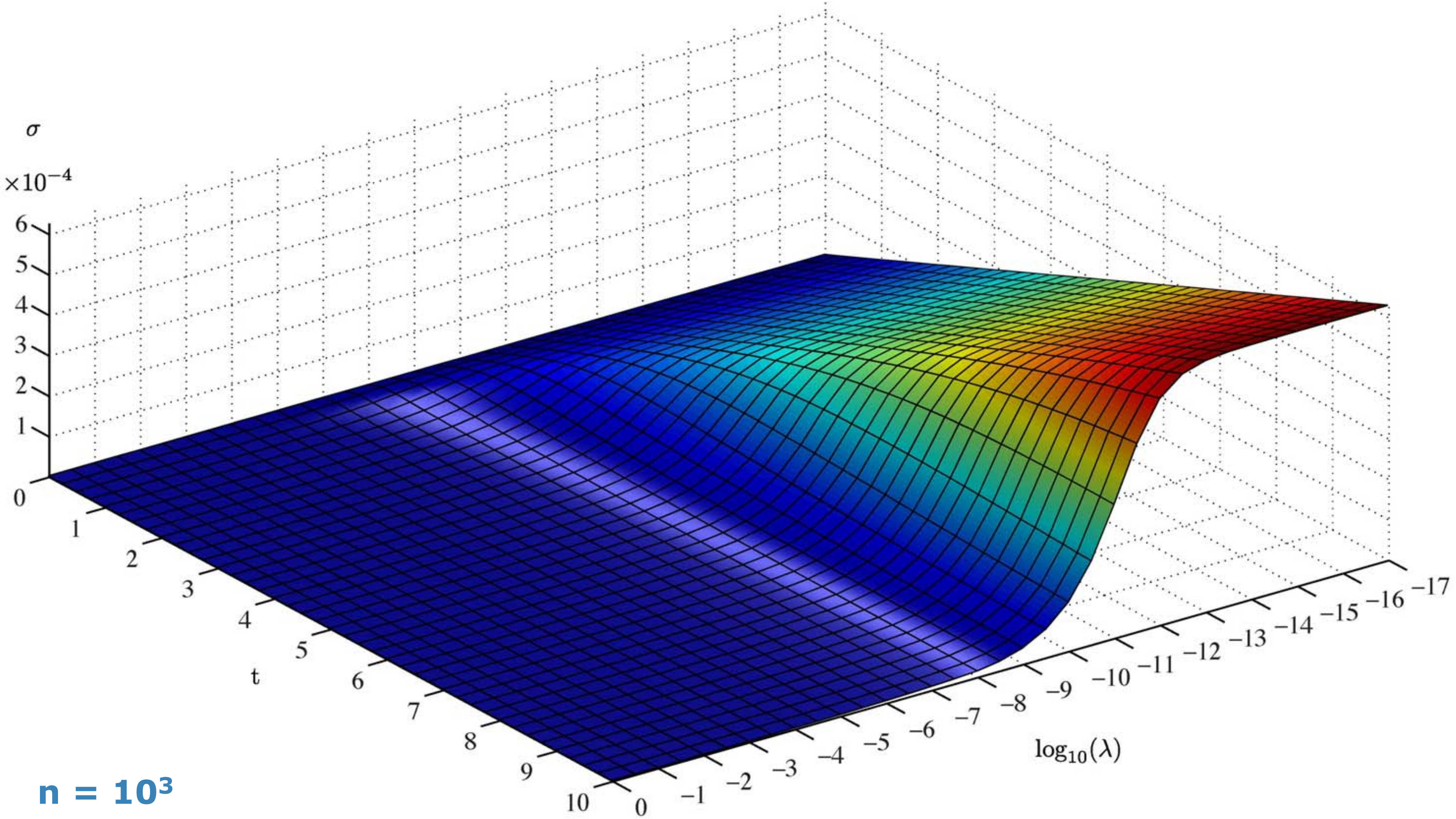
They include much larger molecules **(~11,000 a.m.u.,** possibly up to **1,000,000 a.m.u.**). A three orders of magnitude increase in the number of particles would become interesting

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

Destruction of quantum interference



Time evolution of the spread



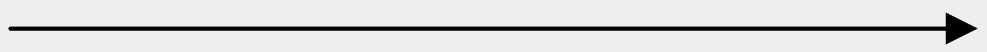
$n = 10^3$

Upper bounds

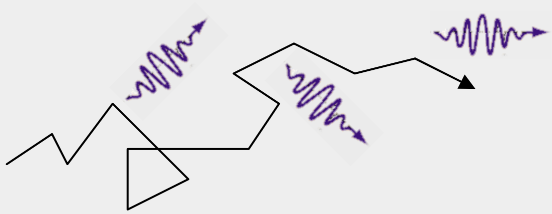
Spontaneous emission of radiation

FREE PARTICLE

1. Quantum mechanics



2. Collapse models

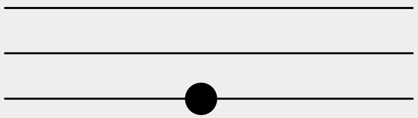


$$\frac{d\Gamma_k}{dk} = \frac{e^2\lambda\hbar}{2\pi^2\epsilon_0 m^2 c^3 k}$$

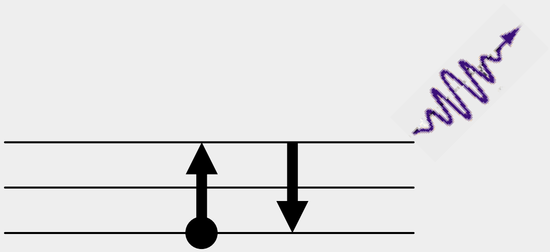
Q. Fu, *Phys. Rev. A* 56, 1806 (1997)

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)

Upper bounds

Spontaneous emission of radiation

Comparison with experimental data

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

In the **mass-proportional** model (noise having a gravitational origin?), one assumes

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

which implies, for example:

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

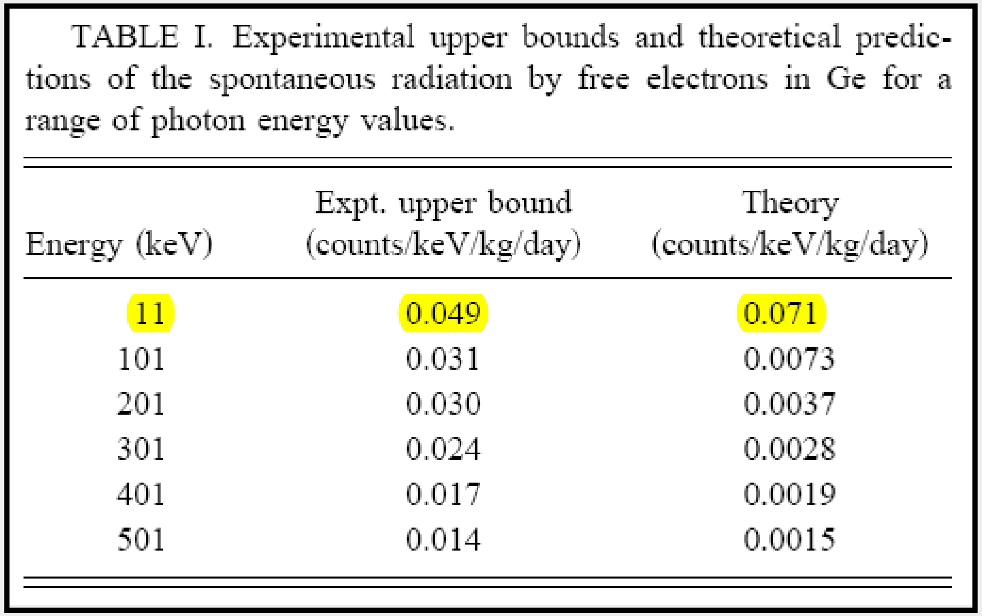


TABLE I. Experimental upper bounds and theoretical predictions of the spontaneous radiation by free electrons in Ge for a range of photon energy values.

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)

Compatibility is restored

Upper bounds

Spontaneous emission of radiation

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

So far, this is the strongest known upper bound.

If one takes non-white noises into account (non-Markovian dynamics)

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

	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**

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)

Upper bounds on the parameter λ

Laboratory experiments	Distance (in orders of magnitude) from standard CSL value	Cosmological data	Distance (in orders of magnitude) from standard 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**

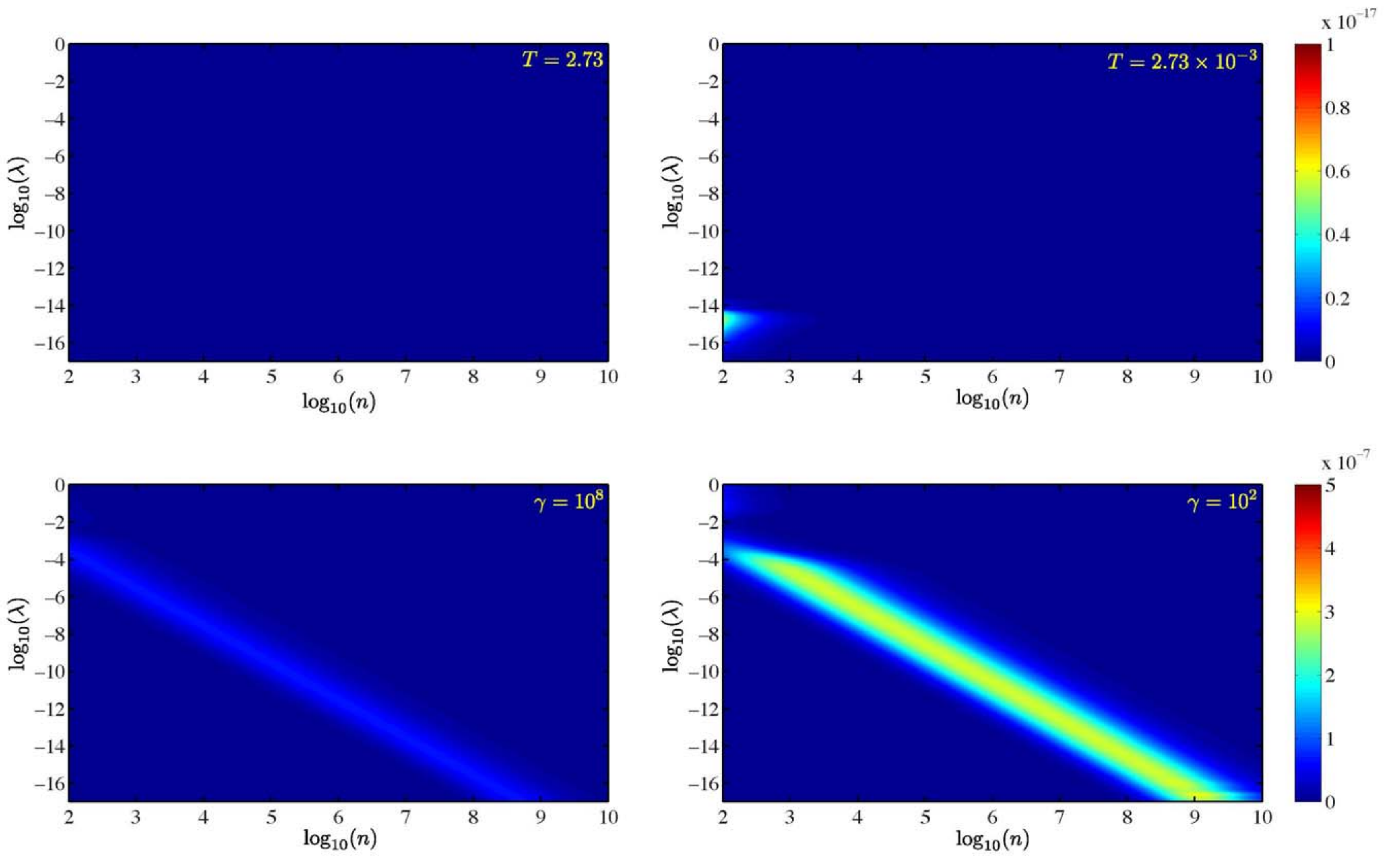
S.L. Adler and A. Bassi, *Science* 325, 275 (2009)

➡ **Present day technology allows for crucial tests.**

4. A cosmological noise field?

	Markovian models **(white noise)** **All frequencies appear with the same weight**	**non-Markovian models** **(colored noise)** **The noise can have an arbitrary spectrum**
Models without dissipation **(q-coupling)** **Only the noise acts on the wave function**	**GRW / CSL** **QMUPL** L. Diosi, *Phys. Rev. A* 40, 1165 (1989).	**non-Markovian CSL** P. Pearle, in *Perspective in Quantum Reality* (1996) S.L. Adler and A. Bassi, *Journ. Phys. A* 41, 395308 (2008). arXiv: 0807.2846 **non-Markovian QMUPL** A. Bassi and L. Ferialdi, *arXiv: 0901.1254*
Models with dissipation **([q+ip]-coupling)** **Noise and wave function act on each other**	**Thermal QMUPL model** A. Bassi, E. Ippoliti and B. Vacchini, *J. Phys. A* 38, 8017 (2005). ArXiv: quant-ph/0506083	? **The “true” model?**

Comparison between models



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?

Open questions

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 connected e.g. to **dark energy/matter?**

   (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?

   (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?

   (*Sience*, 1st July issue, 2005)

A dedicated experiment

Spontaneous emission of radiation

Spontaneous X-ray emission from Ge offers the strongest upper bound.

This suggests that a **dedicated experiment** which tests collapse models, thus the superposition principle of Quantum Mechanics, should look in this direction.

Main difficulty: one needs to isolate the experimental setup very well.

Solution: underground experiment.

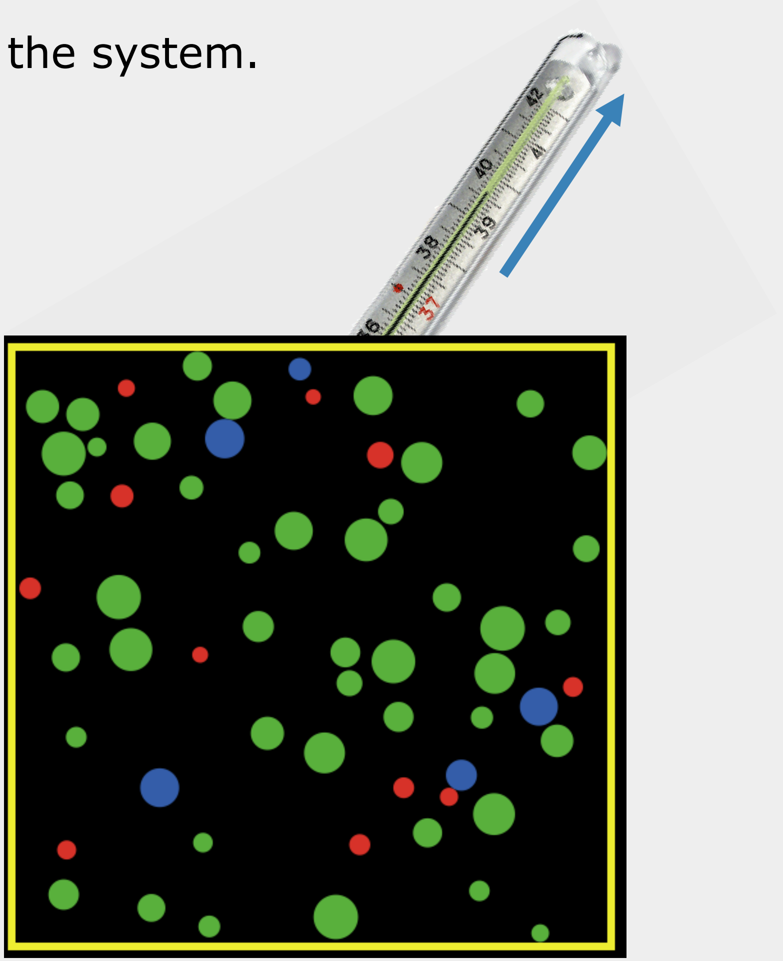
Collaboration with the INFN-LNF laboratories in Frascati, which have also underground facilities (Gran Sasso).

Upper bounds

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)

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

➡

$$1 \text{ eV increase in } 10^{18} \text{ yr}$$

For a gas (GRW’s value)

$$\text{Temperature increase: } 10^{-15} \text{ K/yr}$$

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

Upper bounds

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.

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