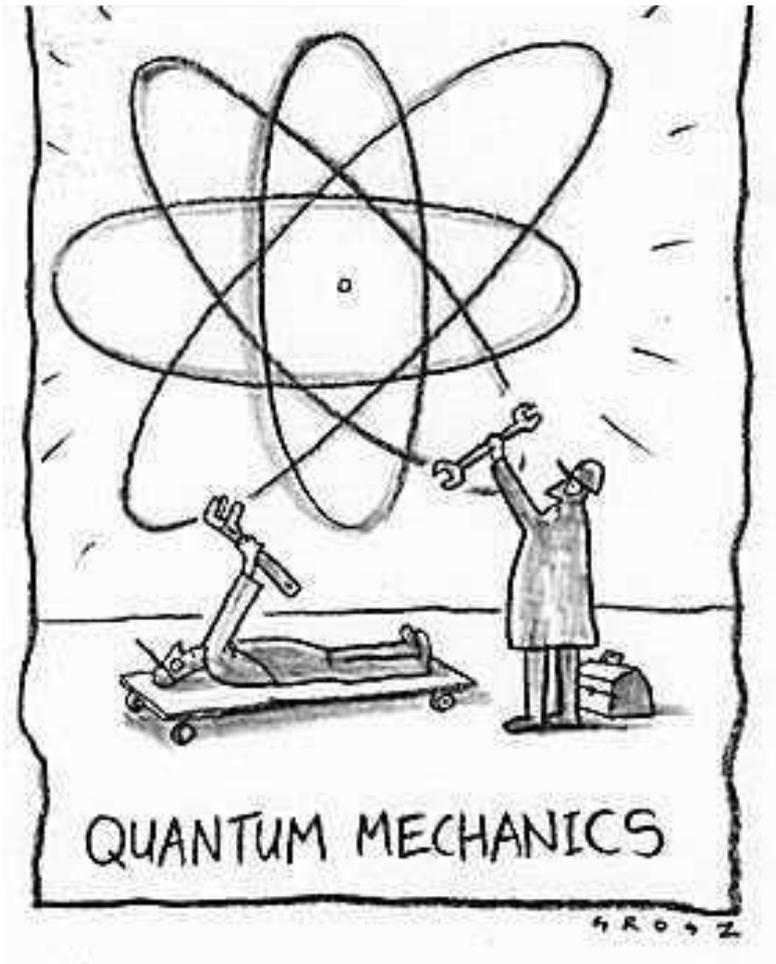


# *Whispers from the collapse of the w.f. spontaneously emitted radiation*



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**Collaboration with  
Group lead by A. Bassi**

***DISCRETE 2014***  
***London***  
***2-6 December 2014***

**AN OPEN PROBLEMS IN QUANTUM MECHANICS:**

**the “measurement problem”**

**collapse of the wave function**

I  Schrödinger



SCHRÖDINGERS CAT  
Experiment #001

**RESULTS**

DEAD

ALIVE

BOTH

**The concept of 'measurement' becomes so fuzzy on reflection that it is quite surprising to have it appearing in physical theory *at the most fundamental level...* does not any analysis of measurement require concepts more fundamental than measurement? And should not the fundamental theory be about these more fundamental concepts?**

**John Stewart Bell in  
"Quantum Mechanics  
for Cosmologists" (1981)**



## Possible "solutions":

- De Broglie - Bohm
- Many-World Interpretations
- Collapse of the w.f.
- .....

# Collapse models a short introduction

3

The Schrödinger equation is linear  $\rightarrow$  superposition principle



Collapse models' equation  $\rightarrow$  no macroscopic superposition



Great effort in this field:

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

(Works of Pearle, Diosi, Gisin, Percival, Tumulka, Dowker, Henson, Bedingham ...)

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)

# What are collapse models

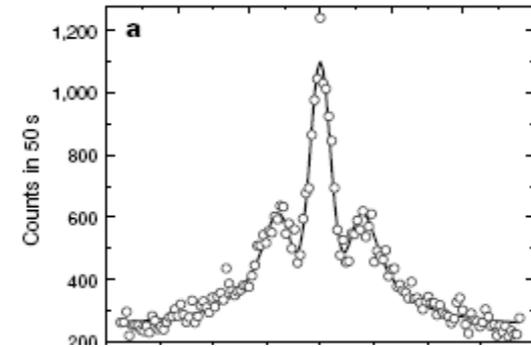
## 1. Collapse models = solution of the measurement problem

Paradox-free description of the quantum world



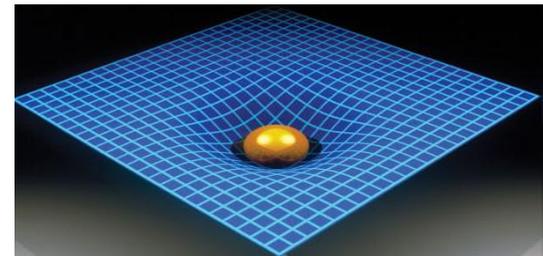
## 2. Collapse models = rival theory of Quantum Mechanics

They give quantitative meaning to experiments testing quantum linearity



## 3. Collapse models as phenomenological models of an underlying pre-quantum theory

Can gravity causes the collapse?



# Measurement problem

The linear nature of QM allows **superposition of macro-object states** → *Von Neumann measurement scheme* (A. Bassi, G. C. Ghirardi Phys. Rep 379 257 (2003))

If we assume the theory is complete .. two possible way out

**Two dynamical principles:** a) **evolution** governed by Schrödinger equation (**unitary, linear**)  
 b) measurement process governed by **WPR (stochastic, nonlinear)**. But .. where does quantum and classical behaviours split?

• **Dynamical Reduction Models:** **nonlinear and stochastic** modification of the Hamiltonian dynamics:

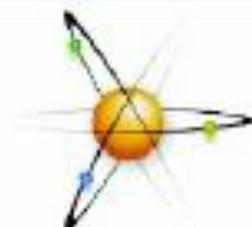
**QMSL** - particles experience spontaneous localizations around appropriate positions, at random times according to a Poisson distribution with  $\lambda = 10^{-16} \text{ s}^{-1}$ .

(Ghirardi, Rimini, and Weber, Phys. Rev. D 34, 470 (1986); *ibid.* 36, 3287 (1987); Found. Phys. 18, 1 (1988))

**CSL** - stochastic and nonlinear terms in the Schrödinger equation induce diffusion process for the state vector → reduction.  $\lambda = 2.2 \times 10^{-17} \text{ s}^{-1}$

# Which values for $\lambda$ and $r_c$ ?

## Microscopic world (few particles)



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

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)

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

QUANTUM - CLASSICAL  
TRANSITION  
(GRW - 1986)

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

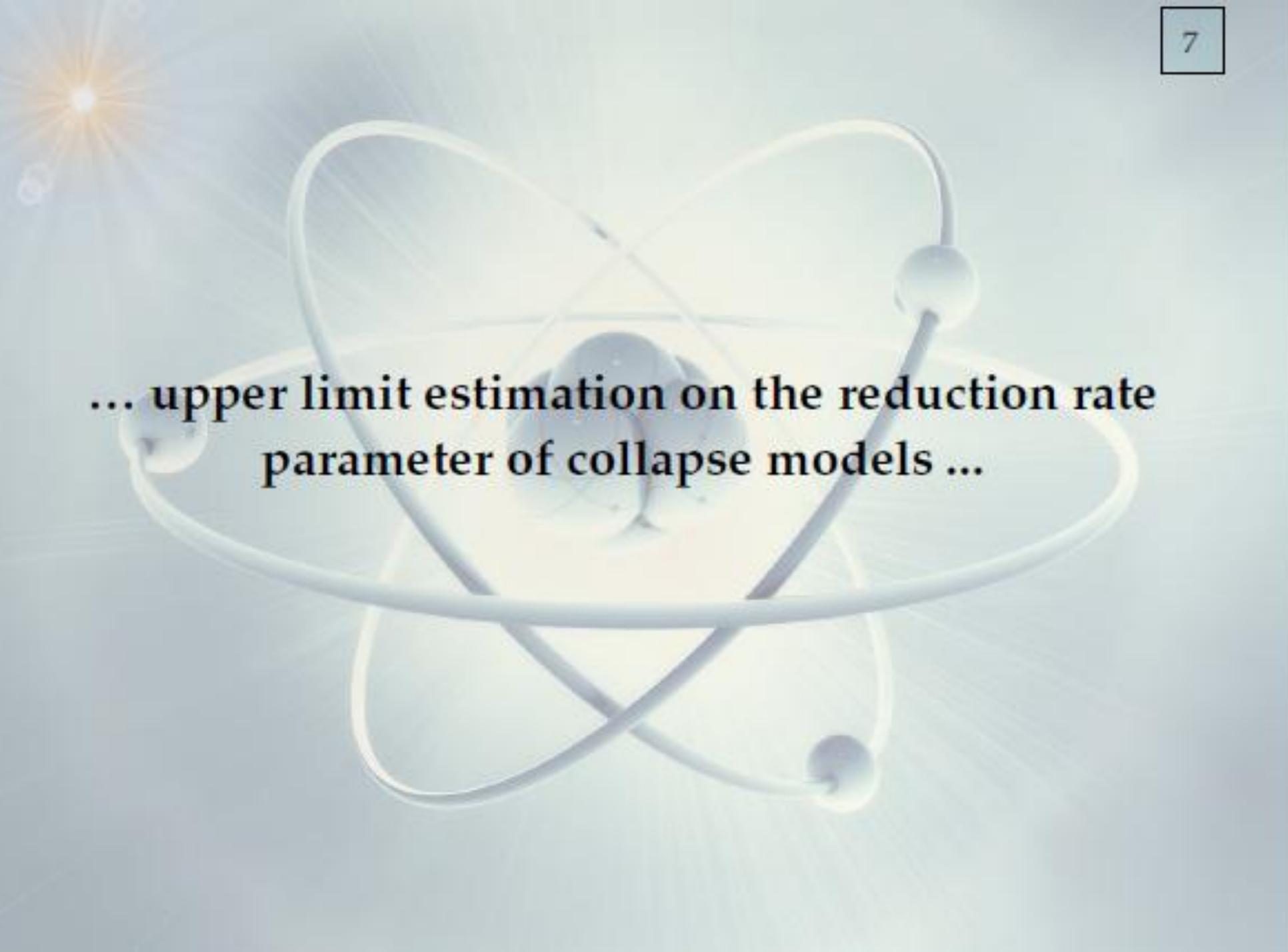


G.C. Ghirardi, A. Rimini and T. Weber, PRD 34, 470 (1986)

$$r_c = 1/\sqrt{\alpha} \sim 10^{-5} \text{cm}$$

Increasing size of the system

**PREDICTIONS** of collapse models are **different from standard quantum mechanical predictions** ... they can be tested experimentally! ...



**... upper limit estimation on the reduction rate  
parameter of collapse models ...**

# Upper bounds on the parameter $\lambda$

Laboratory experiments	Distance (decades) from the enhanced CSL value	Cosmological data	Distance (decades) from the enhanced CSL value
Fullerene diffraction experiments	12-13 (3-4)	Dissociation of cosmic hydrogen	18 (9)
Decay of supercurrents (SQUIDS)	15 (6)	Heating of Intergalactic medium (IGM)	9 (0)
Spontaneous X-ray emission from Ge	7 (-2)	Heating of protons in the universe	13 (4)
Proton decay	19 (10)	Heating of Interstellar dust grains	116 (7)

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

# ... spontaneous photon emission

Besides collapsing the state vector to the position basis in non relativistic QM the **interaction with the stochastic field increases the expectation value of particle's energy**



**implies for a charged particle energy radiation (not present in standard QM) !!!**

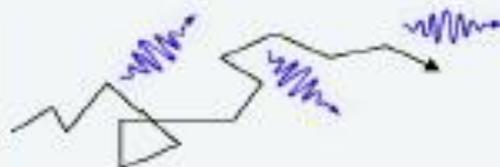
- 1) Plausibility test of collapse models (ex. Karolyhazy model, collapse is induced by fluctuations in space-time  $\rightarrow$  unreasonable amount of radiation in the X-ray range).
- 2) The comparison between theoretical prediction and experimental results will provide **constraints on the parameters of the CSL model**

## 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

# Expected X-ray rate from Ge low activity experiments

Q. Fu, Phys. Rev. A 56, 1806 (1997) → **only upper limit on  $\lambda$**  based on comparison with the radiation appearing in an isolated slab of Ge (raw data not background subtracted)

H. S. Miley, et al., Phys. Rev. Lett. 65, 3092 (1990)

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

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

Comparison with the lower energy bin, due to the non-relativistic constraint of the CSL model

$$\left. \frac{d\Gamma_k}{dk} \right|_{th} = (2.74 \cdot 10^{-31}) \cdot 4 \cdot (8.29 \cdot 10^{24}) \cdot (8.6 \cdot 10^4) \cdot \frac{1}{k} < \left. \frac{d\Gamma_k}{dk} \right|_{ex}$$

$$\frac{e^2 \lambda}{4\pi^2 a^2 m^2}$$

4 valence electrons are considered  
 BE ~ 10 eV « energy of emitted  $\gamma$  ~ 11 keV  
 quasi-free electrons

(Atoms/Kg) in Ge

1 day

Result →  $\lambda < 0.55 \times 10^{-16} \text{ s}^{-1}$  the GRW theory predicts 45% more radiation than the observed upper bound.

Result possibly biased by the punctual evaluation of the rate at one single energy bin.

# New analysis: using published data of the IGEX experiment (K. Piscicchia)

The IGEX experiment is a low-activity Ge based experiment dedicated to the  $\beta\beta 0\nu$  decay research. (C. E. Aalseth et al., IGEX collaboration Phys. Rev. C 59, 2108 (1999))

In (A. Morales et al., IGEX collaboration Phys. Lett. B 532, 8-14 (2002)) the published data acquired for an exposure of 80 *kg day* in the energy

Low-energy data from the IGEX RG-II detector ( $Mt = 80$  kg day)

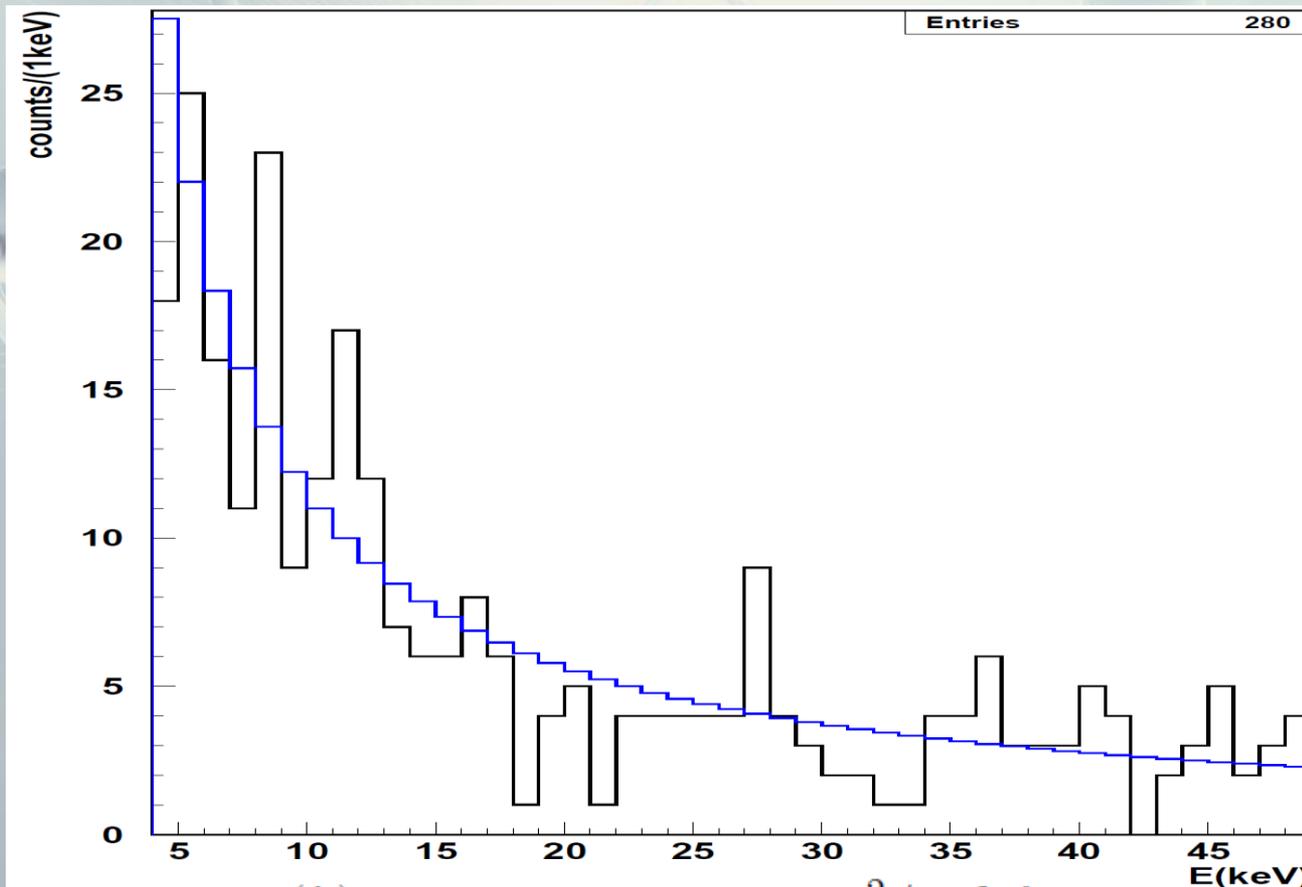
<i>E</i> (keV)	Counts	<i>E</i> (keV)	Counts	<i>E</i> (keV)	Counts
4.5	18	19.5	4	34.5	4
5.5	25	20.5	5	35.5	4
6.5	16	21.5	1	36.5	6
7.5	11	22.5	4	37.5	3
8.5	23	23.5	4	38.5	3
9.5	9	24.5	4	39.5	3
10.5	12	25.5	4	40.5	5
11.5	17	26.5	4	41.5	4
12.5	12	27.5	9	42.5	0
13.5	7	28.5	4	43.5	2
14.5	6	29.5	3	44.5	3
15.5	6	30.5	2	45.5	5
16.5	8	31.5	2	46.5	2
17.5	6	32.5	1	47.5	3
18.5	1	33.5	1	48.5	4

# New analysis: results and discussion

The X-ray spectrum was fitted assuming the predicted energy dependence:

$$\frac{d\Gamma_k}{dk} = \frac{\alpha(\lambda)}{k}$$

With  $\alpha(\lambda)$  free parameter, bin contents are treated with Poisson statistics.



**Fit result**  $\alpha(\lambda) = 110 \pm 7$  ,  $\chi^2/n.d.f = 1.1$

## New analysis: results and discussion

The performed fit enables to set an upper limit on the reduction rate parameter:

$$\left. \frac{d\Gamma_k}{dk} \right|_{th} = \frac{e^2 \lambda}{4\pi^2 a^2 m^2 k} = \frac{c\lambda}{k} < \frac{110}{k}$$

1) assuming the parameters used in Fu's work ( $a_{GRW} = 10^{-7} \text{ m}$ )  $\rightarrow$

$$\lambda < 1.8 \times 10^{-16} \text{ s}^{-1}$$

(Fu's result  $\lambda < 0.55 \times 10^{-16} \text{ s}^{-1}$ ) compatible with  $\lambda_{GRW}$  but...

2) ... correcting Fu's calculation according with (S. L. Adler, J. Phys. A40 (2007) 2935)

$$\rightarrow \lambda < 1.4 \times 10^{-17} \text{ s}^{-1}$$

## New analysis: results and discussion

- 3) if a mass-proportional model is assumed (noise having a gravitational origin?)  
then:

$$\left. \frac{d\Gamma_k}{dk} \right|_{th} = \frac{e^2 \lambda}{4\pi^2 a^2 m^2 k} = \frac{c\lambda}{k} < \frac{110}{k} \quad \lambda < 4.7 \times 10^{-11} \text{ s}^{-1}$$

- 4) taking the 22 outer electrons (down to the 3s orbit  $BE_{3s} = 180.1 \text{ eV}$ ) in the calculation:

$$\lambda < 2.5 \times 10^{-18} \text{ s}^{-1}$$

No mass-proportional

$$\lambda < 8.5 \times 10^{-12} \text{ s}^{-1}$$

mass-proportional

$$\lambda \rightarrow \lambda \left( \frac{m}{m_N} \right)^2, \quad \left. \frac{d\Gamma_k}{dk} \right|_{th} = \frac{e^2 \lambda}{4\pi^2 a^2 m_N^2 k}$$

# Upper bounds on the parameter $\lambda$

Laboratory experiments	Distance (decades) from the enhanced CSL value	Cosmological data	Distance (decades) from the enhanced CSL value
Fullerene diffraction experiments	12-13 (3-4)	Dissociation of cosmic hydrogen	18 (9)
Decay of supercurrents (SQUIDs)	15 (6)	Heating of Intergalactic medium (IGM)	9 (0)
Spontaneous X-ray emission (from Ge)	5 (-4)	Heating of protons in the universe	13 (4)
Proton decay	19 (10)	Heating of Interstellar dust grains	116 (7)

# Spontaneous emission including nuclear protons

When the emission of nuclear protons is also considered, the spontaneous emission rate is:

$$\frac{d\Gamma_k}{dk} = (N_P^2 + N_e) \frac{e^2 \lambda}{4\pi^2 a^2 m_N^2 k}$$

(the stochastic field is assumed to be coupled to the particle mass density)

provided that the emitted photon wavelength  $\lambda_{ph}$  satisfies the following conditions:

- 1)  $\lambda_{ph} > 10^{-15}$  m (nuclear dimension)  $\rightarrow$  protons contribute coherently
- 2)  $\lambda_{ph} <$  (electronic orbit radius)  $\rightarrow$  electrons and protons emit independently  $\rightarrow$   
 $\rightarrow$  NO cancellation

# Spontaneous emission including nuclear protons

When the emission of nuclear protons is also considered, the spontaneous emission rate is:

$$\frac{d\Gamma_k}{dk} = (N_P^2 + N_e) \frac{e^2 \lambda}{4\pi^2 a^2 m_N^2 k}$$

We consider in the calculation the 30 outermost electrons (down to 2s orbit)  $r_e = 4 \times 10^{-10}$  m and take only the measured rate for  $k > 35$  keV

Moreover  $BE_{2s} = 1.4$  keV  $\ll k_{min} \rightarrow$  electrons can be considered as *quasi-free*

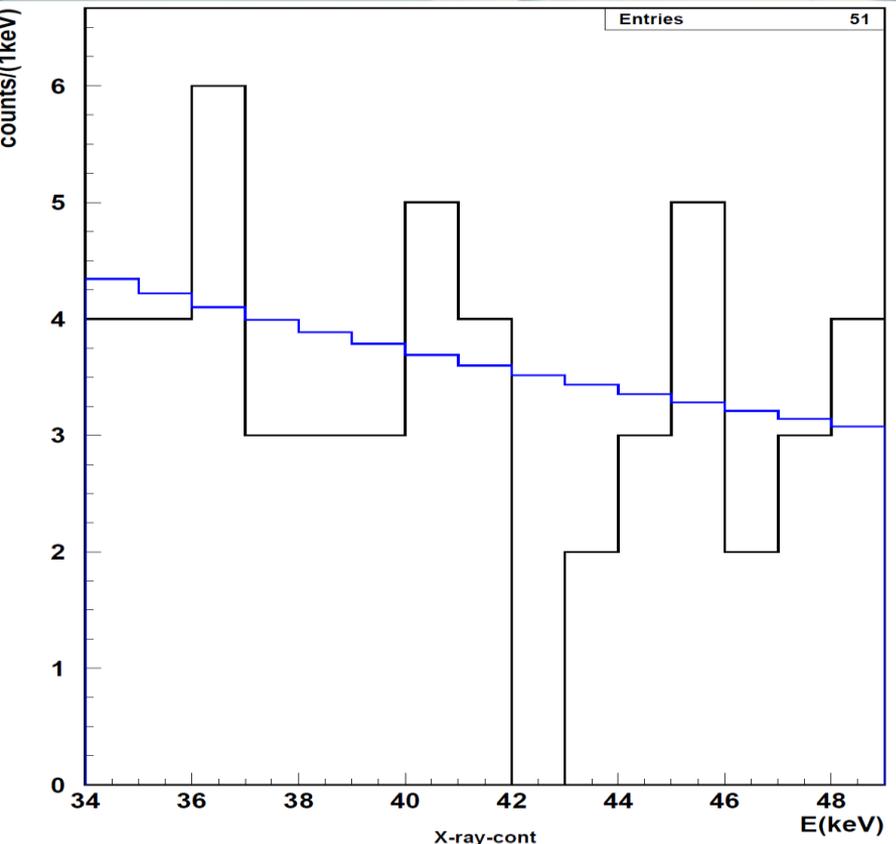
$\Delta E = (35 - 49)$  keV  $\ll m_e = 512$  keV  $\rightarrow$  compatible with the non-relativistic assumption.

# Spontaneous emission including nuclear protons – very preliminary!

The interval  $\Delta E = (35 - 49) \text{ keV}$  of the IGEX measured X-ray spectrum was fitted assuming the predicted energy dependence:

$$\frac{d\Gamma_k}{dk} = \frac{\alpha(\lambda)}{k}$$

With  $\alpha(\lambda)$  free parameter, bin contents are treated with Poisson statistics.



## Fit result:

$$\alpha(\lambda) = 148 \pm 21$$
$$\chi^2 / \text{n.d.f.} = 0.8$$

Corresponding to the limits on the spontaneous emission rate:

$$\lambda < 27 \times 10^{-13} \text{ s}^{-1}$$

# Upper bounds on the parameter $\lambda$

Laboratory experiments	Distance (decades) from the enhanced CSL value	Cosmological data	Distance (decades) from the enhanced CSL value
Fullerene diffraction experiments	12-13 (3-4)	Dissociation of cosmic hydrogen	18 (9)
Decay of supercurrents (SQUIDS)	15 (6)	Heating of Intergalactic medium (IGM)	9 (0)
<b>Spontaneous X-ray emission</b>	<b>4 (-5)</b>	Heating of protons in the universe	13 (4)
Proton decay	19 (10)	Heating of Interstellar dust grains	116 (7)

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

**Present day technology allows for crucial tests**

## ***How we had this idea?***

***It started with the experiment to test the Pauli***

***Exclusion Principle (PEP) for electrons in a***

***clean environment (LNGS) using atomic***

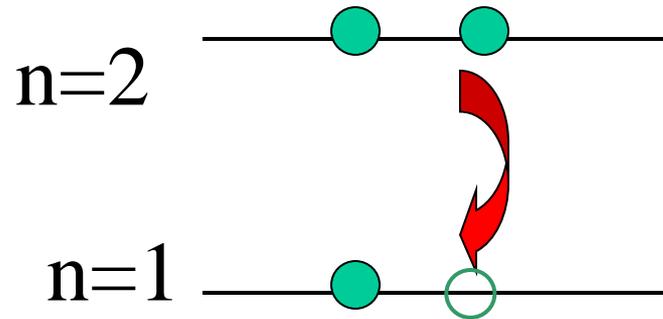
***physics methods – the VIP experiment ->***

***measuring rare X rays processes in a very***

***clean environment***

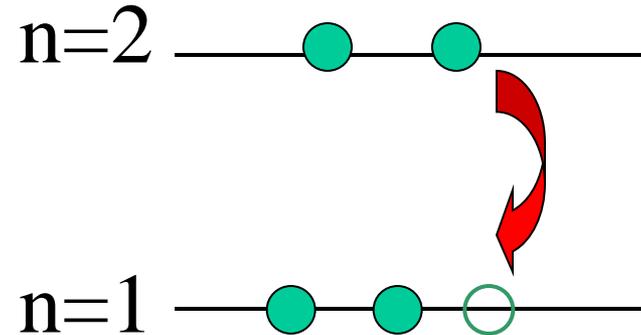
## Talk of Johann Marton

Experimental method:  
Search for anomalous X-ray transitions  
when bringing “new” electrons



Normal  $2p \rightarrow 1s$   
transition

Energy 8.04 keV



$2p \rightarrow 1s$  transition  
violating

Pauli principle

Energy 7.7 keV

# Test site and final location:

## Laboratori Nazionali del Gran Sasso, Istituto Nazionale di Fisica Nucleare



LNGS





# VIP setup at LNGS



(we look for interpretations...)

*Explore other type of physics –  
quantum mechanics (collapse  
models predictions)*

**VIP-upgrade: in the coming years  
we expect either to find a small  
violation or to be able to bound the  
probability that PEP is violated by  
electrons pushing it from  
 $3-4 \cdot 10^{-29}$  to  $10^{-31}$**

(we look for interpretations...)

*Explore other type of physics –  
quantum mechanics (collapse  
models predictions)*

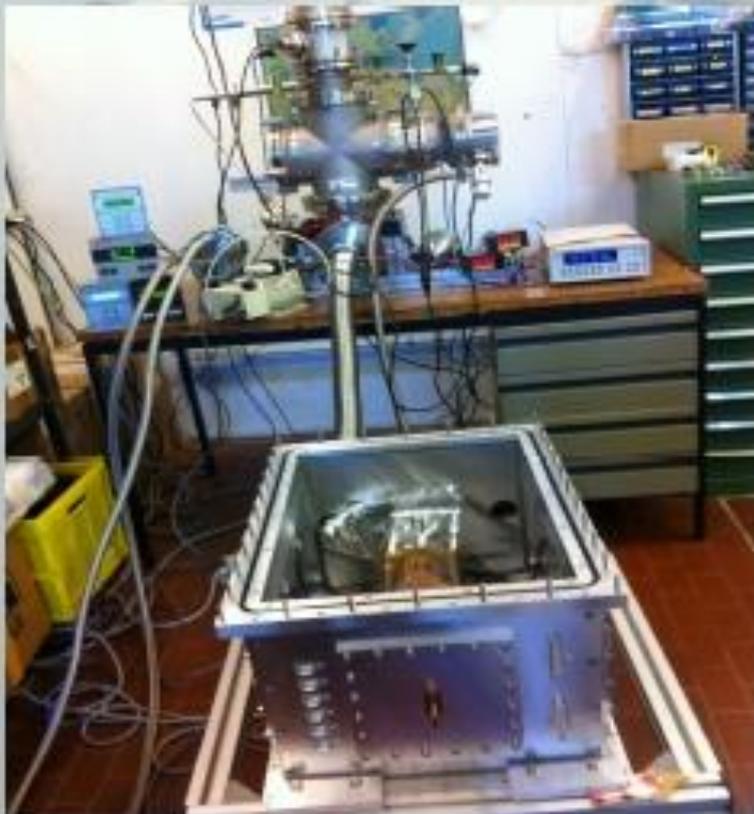
# Testing collapse models

Measurement of few KeV X-ray emission rate to set constraints on  $\lambda$

17

VIP setup: feasibility study of an experiment testing collapse models

- **SDD excellent energy resolution at few KeV** (160 eV FWHM at 7 KeV)
- SDD triggerable detectors: possibility to use a VETO SYSTEM (scintillators + SiPM) to reject background from outside.
- VIP upgrade setup presently under test & LNF → summer 2013 installation & LNGS



Next steps ...

- **Material characterization and selection** (& BTF and LNGS testing facility)
- **MC simulations** (geometry, background, materials) realization of the **DEDICATED SETUP**
- run, data analysis.

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Decay of supercurrents (SQUIDS)	15 (6)	Heating of Intergalactic medium (IGM)	9 (0)
<b>Spontaneous X-ray emission</b>	<b>0 (-9) ?</b>	Heating of protons in the universe	13 (4)
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S.L. Adler and A. Bassi, *Science* 325, 275 (2009)

**Present day technology allows for crucial tests**

*Test with same method different physics:  
Violation of the Pauli Exclusion Principle*

*&*

*Collapse of the wave function ->  
the best limit on lambda-parameter!*

## *Questions:*

- What induces the collapse:  
Could be related with gravity?*
- Has it anything to do with dark  
Sector (matter, energy)?*
- Is there any theory beyond QM?*

# Is quantum theory exact? The endeavor for the theory beyond standard quantum mechanics.

Laboratori Nazionali di Frascati, April 28-30 2014



**Organized by LNF-INFN and Centro Fermi**  
**Very successful activity!**

**<http://www.lnf.infn.it/conference/2014/FQT2014/>**

*A secret is not something  
unrevealed, but something told  
privately, in a whisper.*

*Marcel Pagnol*