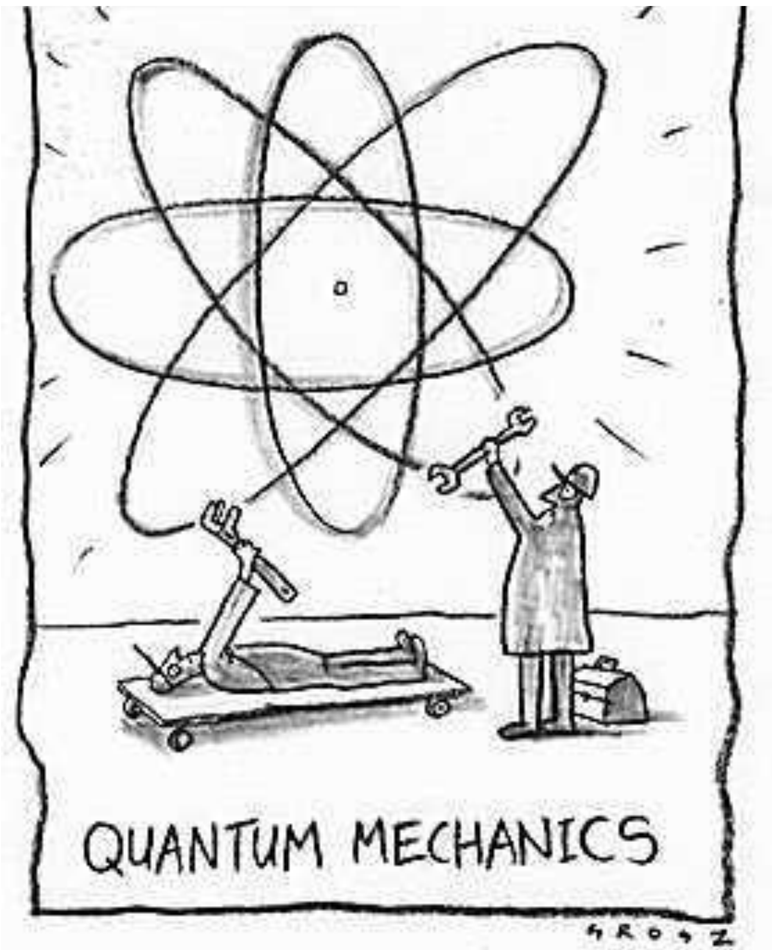
X-ray experiments to test collapse models



Catalina Curceanu,

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Collaboration with Group lead by A. Bassi

Questioning Fundamental Physics Principles
CERN 6-9 May 2014

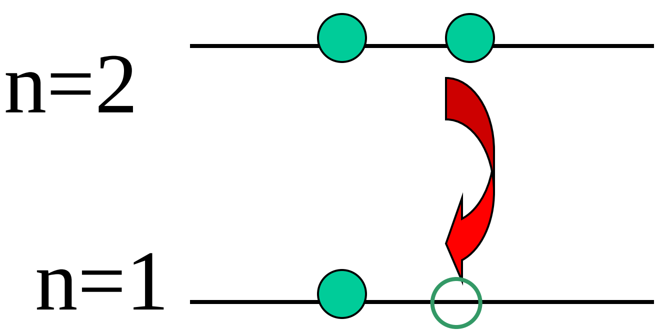
How we had this idea?

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

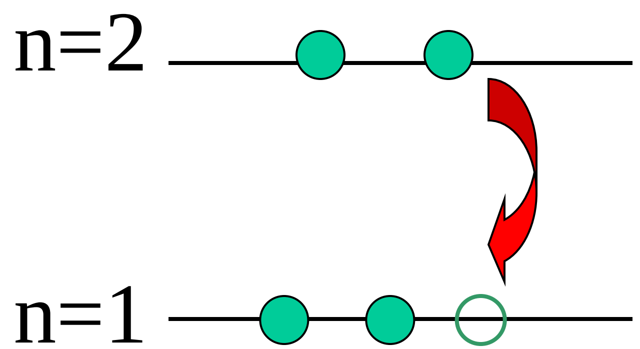
Experimental method:

Search for anomalous X-ray transitions when bringing "new" electrons



Normal 2p –>1s transition

Energy 8.04 keV



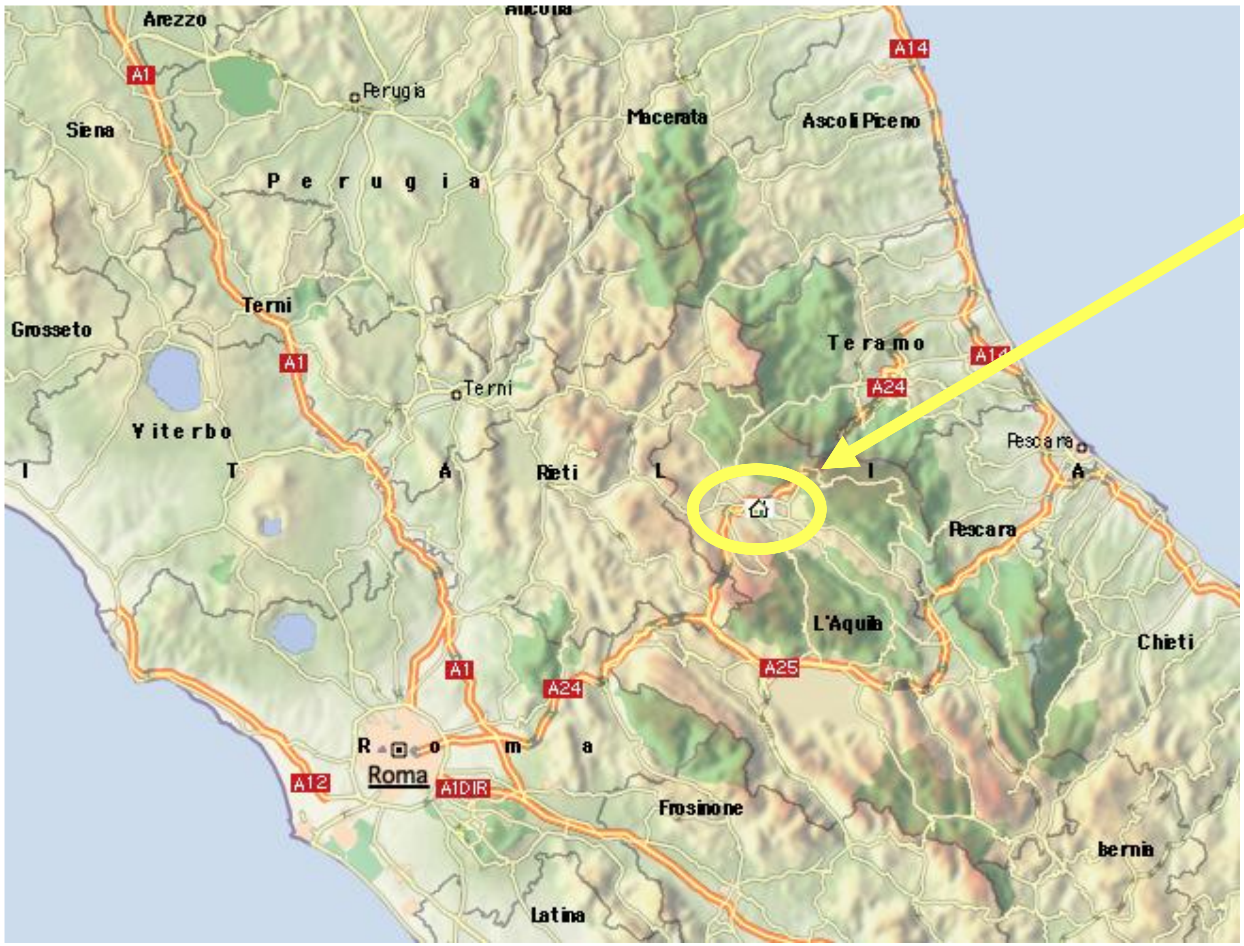
2p –>1s transition violating Pauli principle

Energy 7.7 keV

Messiah Greenberg superselection rule

Test site and final location:

Laboratori Nazionali del Gran Sasso, Istituto Nazionale di Fisica Nucleare



LNGS


Galilei
PARCHEGGIO
PARKING
DIREZIONE

VIP setup at LNGS

(we look for interpretations...)

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

AN OPEN PROBLEMS IN QUANTUM MECHANICS:

the “measurement problem”

collapse of the wave function


RESULTS
DEAD
ALIVE
BOTH
SCHRÖDINGER'S CAT
Experiment #001

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

The shrödinger equation is linear → superposition principle

OK

???

Collapse models' equation → no macroscopic superposition

OK

OK

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)

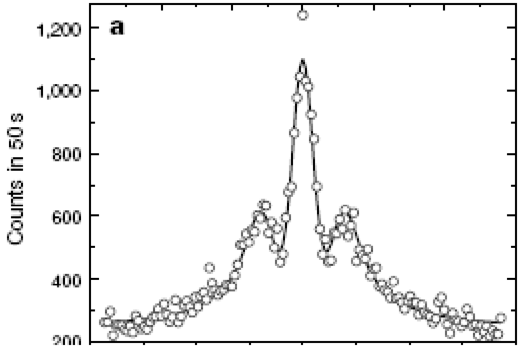
What are collapse models

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

   Paradox-free description of the quantum world

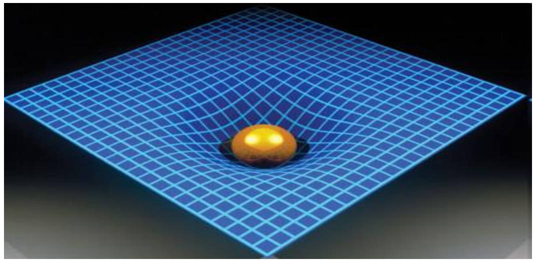
2. **Collapse models = rival theory of Quantum Mechanics**

   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?

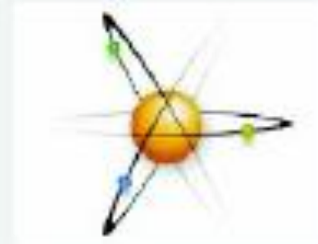
- Dynamical Reduction Models: nonlinear *and* stochastic modification of the Hamiltonian dynamics:

QMSL - particles experience spontaneous localizations around appropriate positions, at random times according to a Poisson distribution with $\lambda = 10^{-16}\ s^{-1}$.
(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. $\lambda = 2.2 \times 10^{-17}\ s^{-1}$

Which values for λ and r_c?

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
(~ 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)

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

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 λ

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. Basssi, *Science* 325, 275 (2009)

… spontaneous photon emission

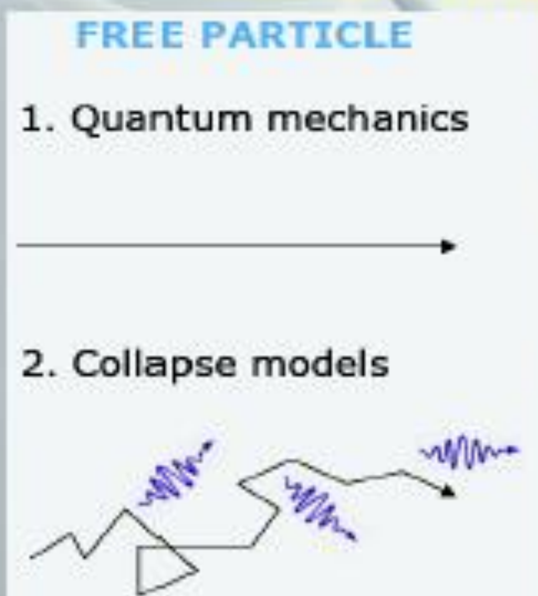
Besides collapsing the state vector to the position basis in non relativistic QM the interaction with the stochastic field increases the expectation value of particle's energy

↓

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 → 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**



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

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 λ 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 γ ~ 11 keV
***quasi-free* electrons**

(Atoms / Kg) in Ge

1 day

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

Result <u>possibly biased by the punctual evaluation of the rate</u> 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 $\beta\beta0\nu$ 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)

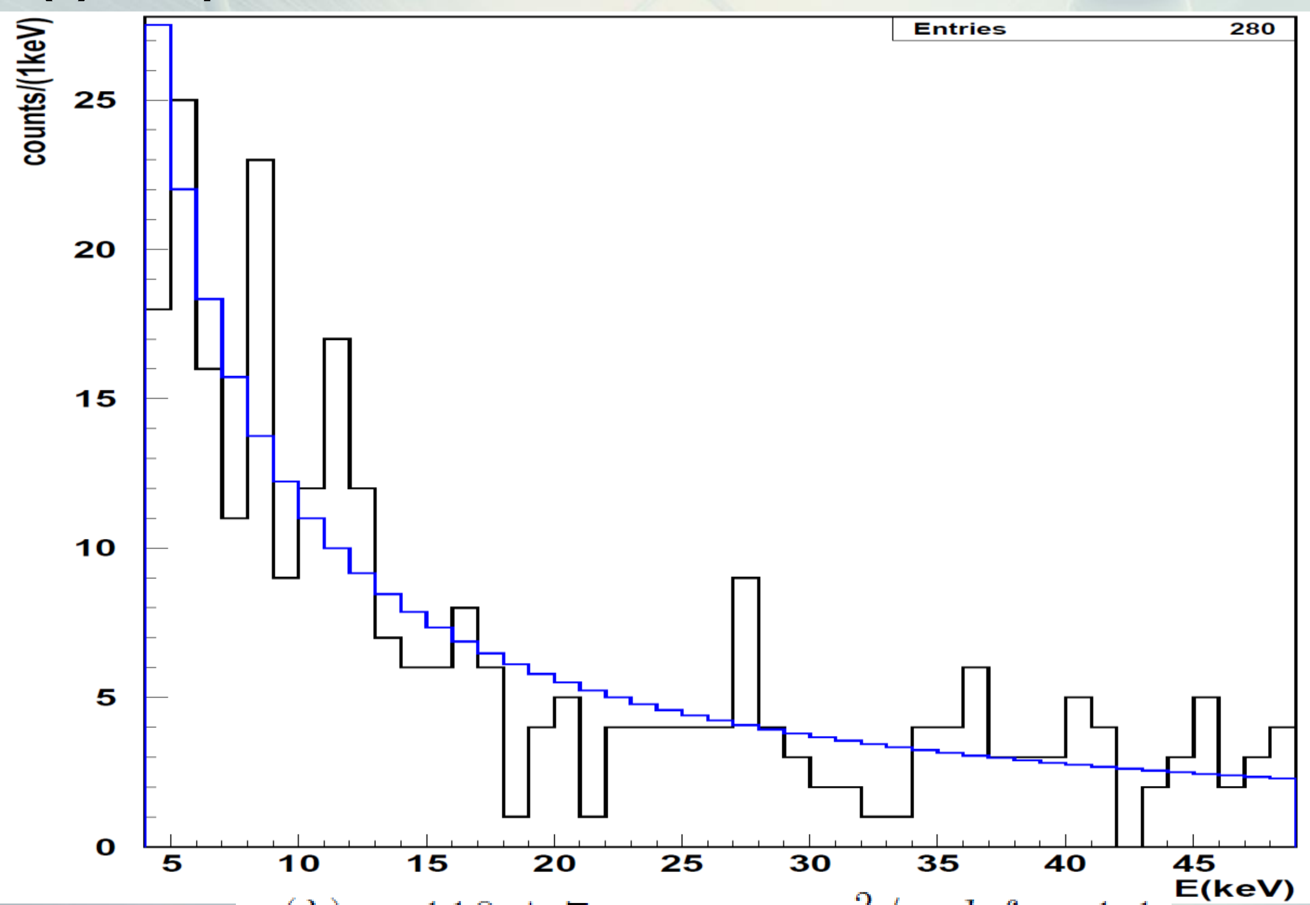
E (keV)	Counts	*E* (keV)	Counts	*E* (keV)	Counts
4.5	18	19.5	4	34.5	4
5.5	25	20.5	5	35.5	4
6.5	16	21.5	1	36.5	6
7.5	11	22.5	4	37.5	3
8.5	23	23.5	4	38.5	3
9.5	9	24.5	4	39.5	3
10.5	12	25.5	4	40.5	5
11.5	17	26.5	4	41.5	4
12.5	12	27.5	9	42.5	0
13.5	7	28.5	4	43.5	2
14.5	6	29.5	3	44.5	3
15.5	6	30.5	2	45.5	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 resul $\alpha(\lambda) = 110 \pm 7 \quad , \quad \chi^2/n.d.f = 1.1$

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 ($a_{GRW} = 10^{-7}$ *m*) →

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

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

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

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

New analysis: results and discussion

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

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

$\lambda < 4.7 \times 10^{-11}\ s^{-1}$

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

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

No mass-proportional

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

mass-proportional

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

Upper bounds on the parameter λ

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:

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

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

provided that the emitted photon wavelength λ_{ph} satisfies the following conditions:

1) $\lambda_{ph} > 10^{-15}$ **m (nuclear dimension) → protons contribute coherently**

2) $\lambda_{ph} <$ **(electronic orbit radius) → electrons and protons emit independently →**

→ NO cancellation

Spontaneous emission including nuclear protons

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

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

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

Moreover BE_{2s} = 1.4 keV « k_{min} → electrons can be considered as *quasi-free*

ΔE = (35 – 49) *keV* « $m_e = 512$ *keV* → compatible with the non-relativistic assumption.

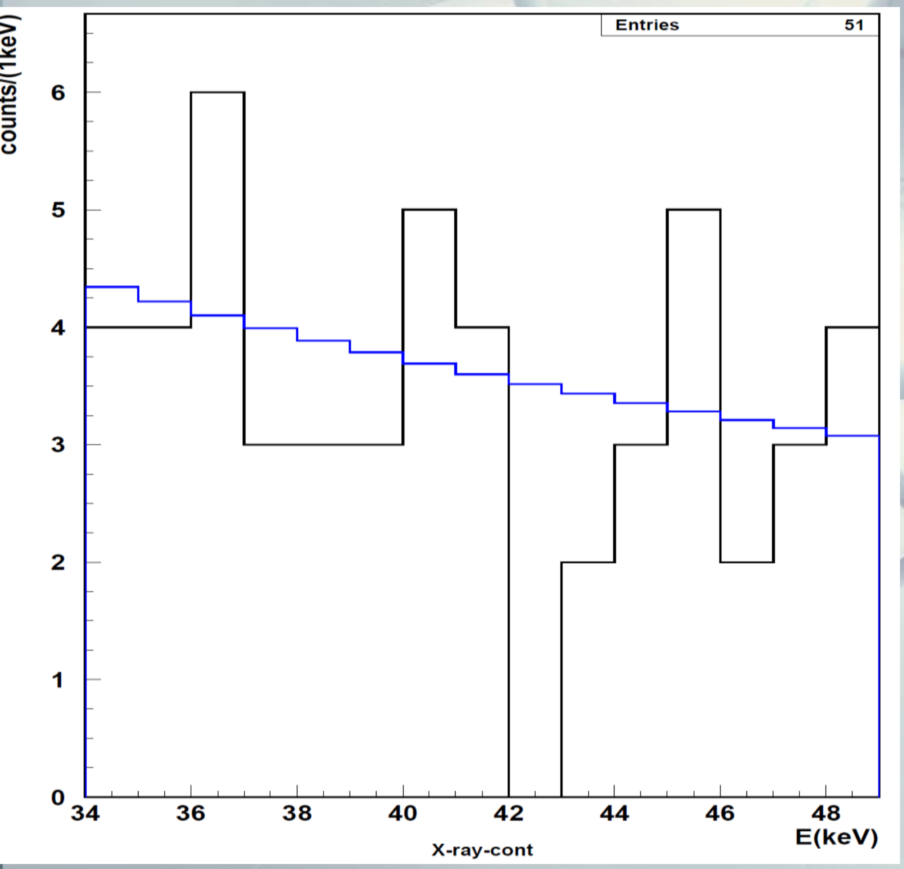
Spontaneous emission including nuclear protons – very preliminary!

The interval ΔE = (35 – 49) *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 ± 21

X/ n.d.f. = 0.8

Corresponding to the limits on the spontaneous emission rate:

$$\lambda < 2.7 \times 10^{-13}\ s^{-1}$$

Upper bounds on the parameter λ

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	**4 (-5)**	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

VIP experiment & VIP upgrade ...

possible test of collapse models

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 $3\text{-}4 \cdot 10^{-29}$ 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 constrains on λ

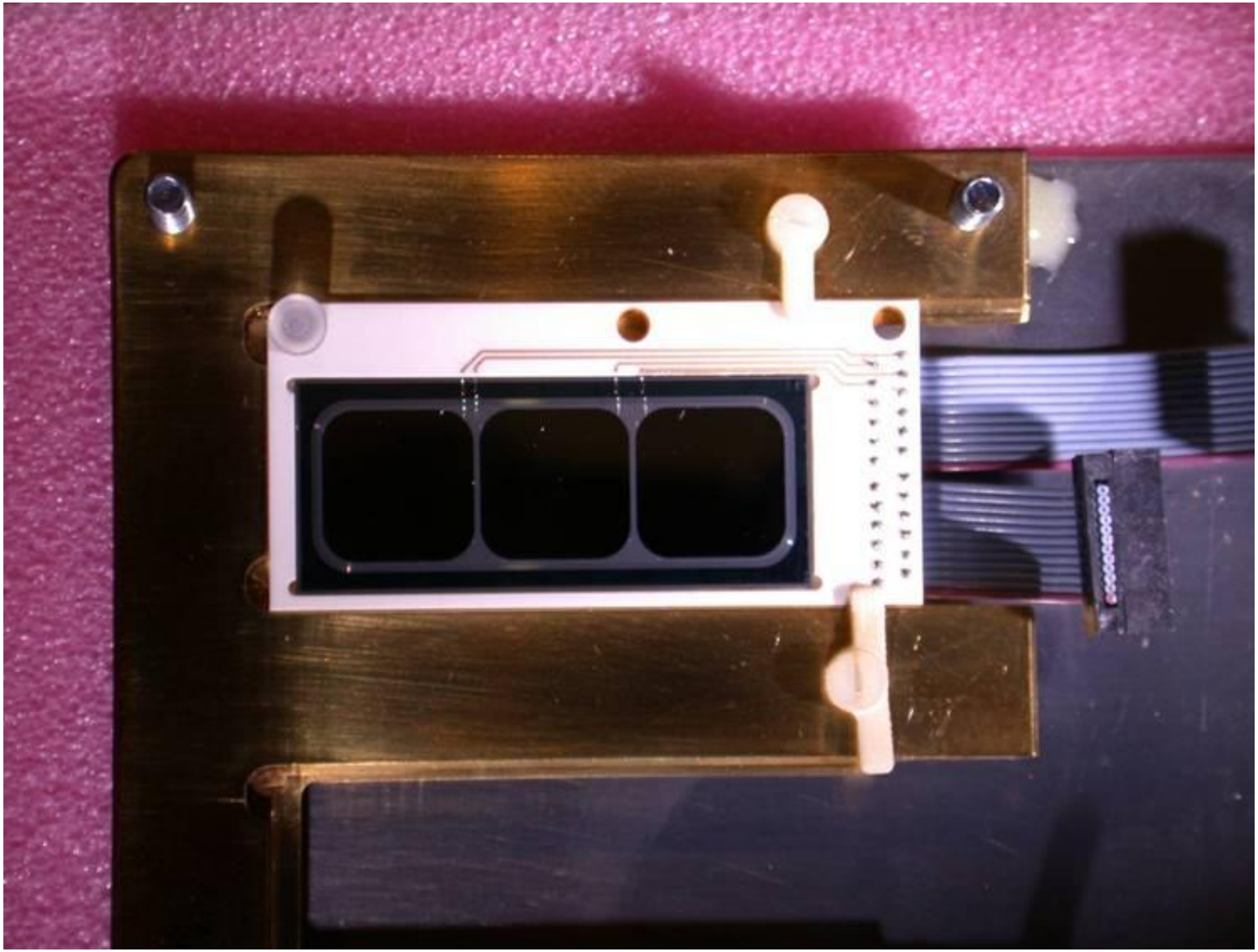
VIP setup: feasibility study of an experiment testing collapse models

- 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 upgarade setup presently under test & LNF ➔ summer 2013 installation & LNGS

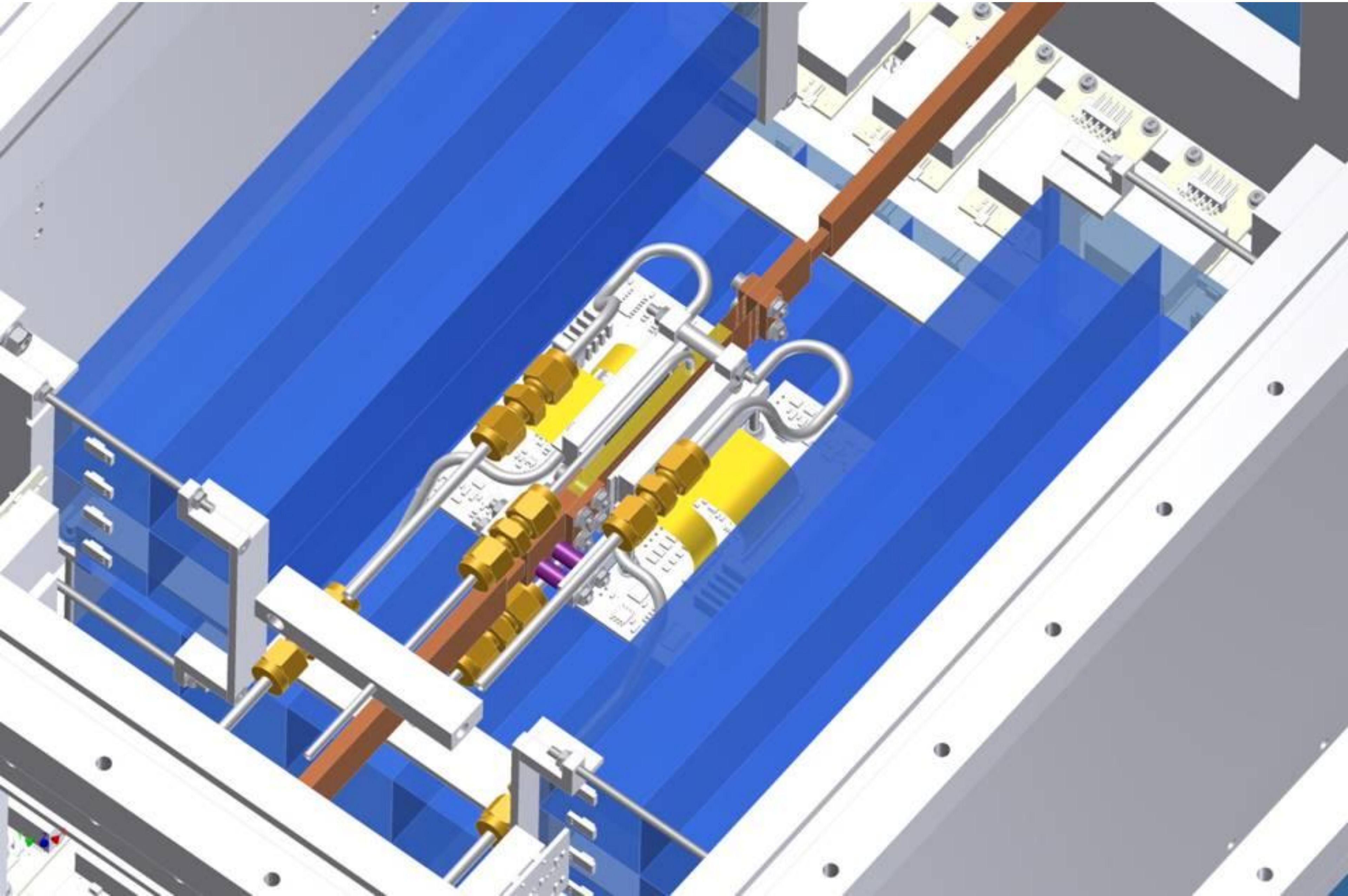
Next steps ...

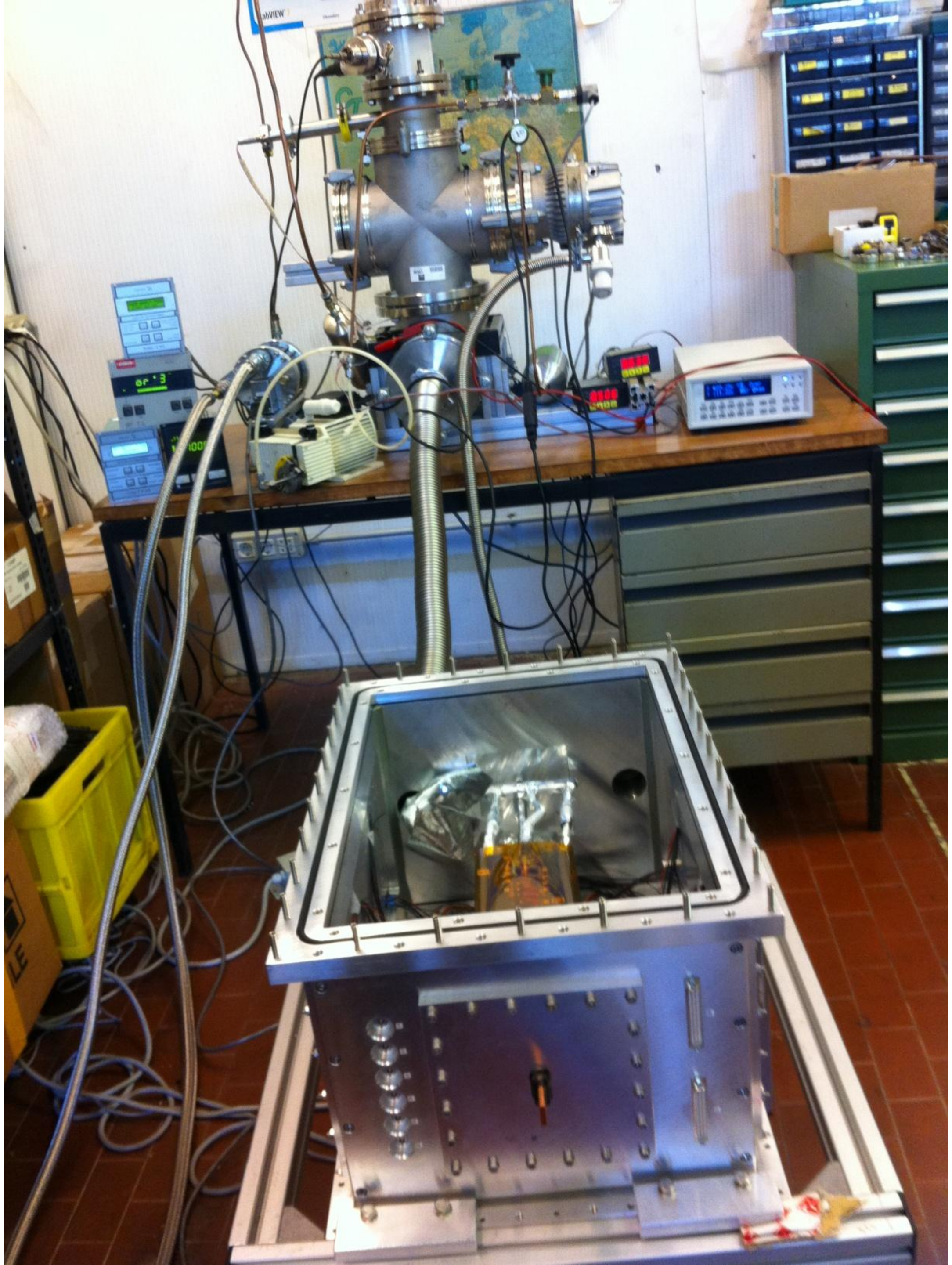
- Matherial characterization and selection (& BTF and LNGS testing facility)
- MC simulations (geometry, background, materials) realization of the DEDICATED SETUP
- run, data analysis.

SDD detectors (usati in SIDDHARTA)



The VIP-2 target – detector – veto counter setup





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?

“Only a few find the way, some don't recognize it when they do – some... don't ever want to.”

The Cheshire Cat