New upper limit for collapse models reduction rate parameter

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

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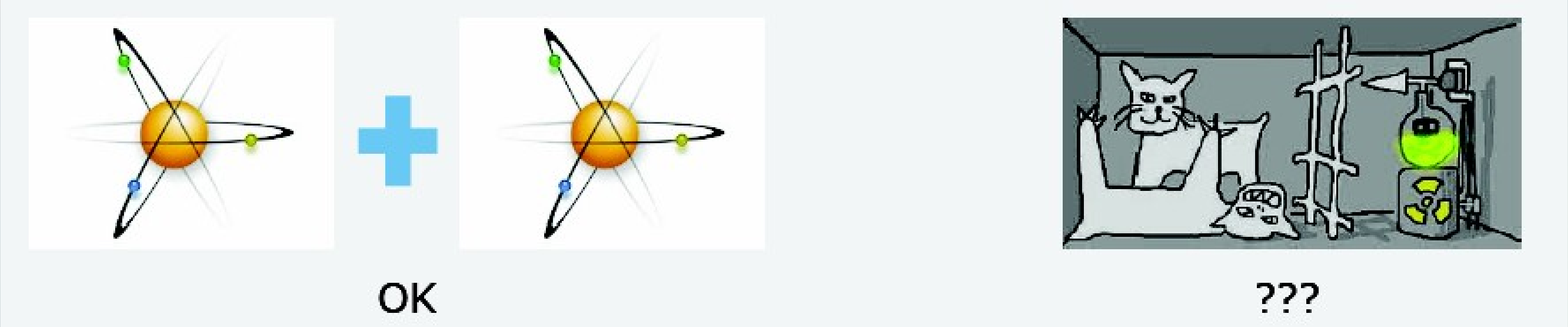
- COLLAPSE MODELS

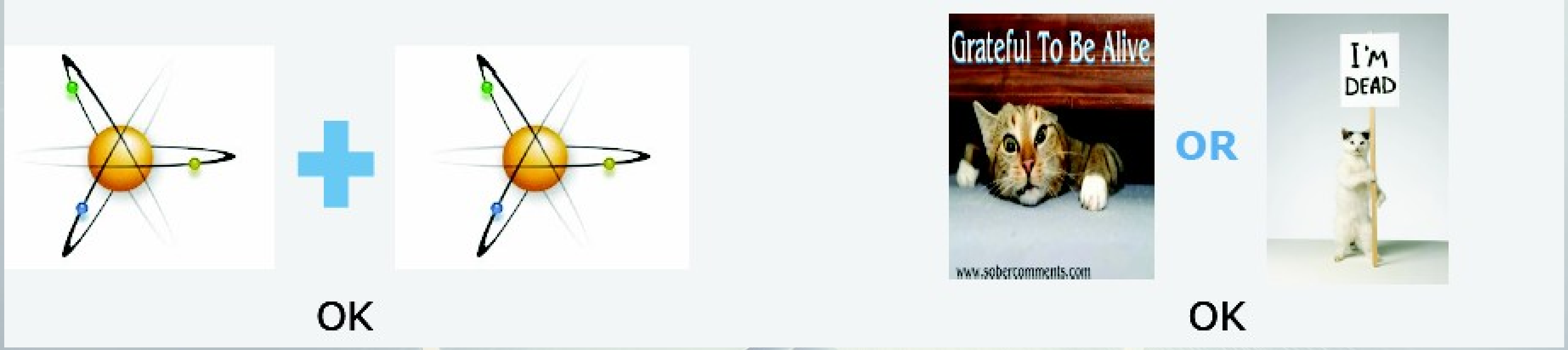
an answer to the measurement problem?

Collapse models

The shrödinger equation is linear → superposition principle



Collapse models' equation → 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)

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 $\lambda = 10^{-16}\ \mathrm{s}^{-1}$.

(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. $\lambda = 2.2 \times 10^{-17}\ \mathrm{s}^{-1}$

CSL model

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

NEW COLLAPSE TERMS ➡ **New Physics**

$N(\mathbf{x}) = a^\dagger(\mathbf{x})a(\mathbf{x})$ particle density operator — **choice of the preferred basis**

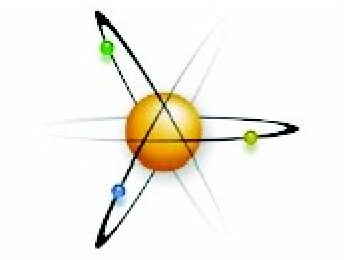
$\langle N(\mathbf{x})\rangle_t = \langle\psi_t|N(\mathbf{x})|\psi_t\rangle$ — **nonlinearity**

$W_t(\mathbf{x}) =$ 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**

$\lambda =$ collapse strength $\quad r_C = 1/\sqrt{\alpha} =$ correlation length — **two parameters**

Which values for λ and r_c ?

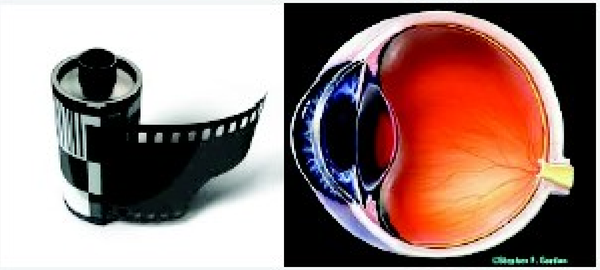
Microscopic world
(few particles)



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

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 bounds on λ

Laboratory experiments	Distance (orders of magnitude) from Adler's value for λ	Cosmological data	Distance (orders of magnitude) from Adler's value for λ
Fullerene diffraction experiments	**3**	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

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

Present day technology allows for meaningful tests

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

… spontaneous photon emission

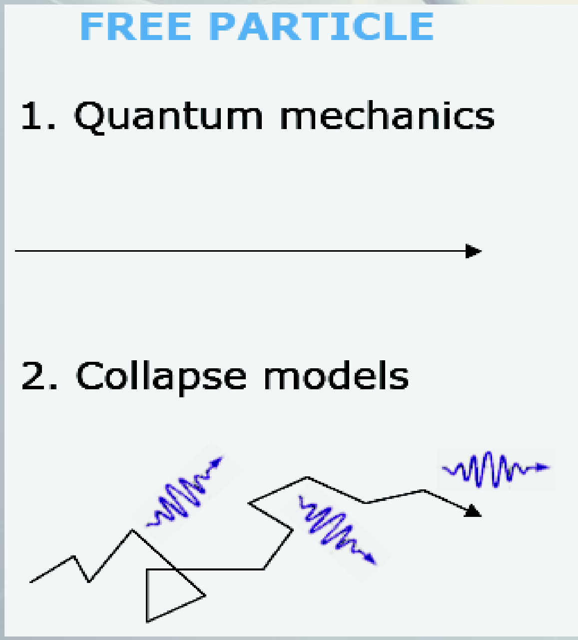
Besides collapsing the state vector to the position basis in non relativistic QM the interaction with the stochastic field increases the expectation value of particle's energy

↓

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

1) Plausibility test of collapse models.

2) The comparison between theoretical prediction and experimental results will provide constraints on the parameters of the CSL model



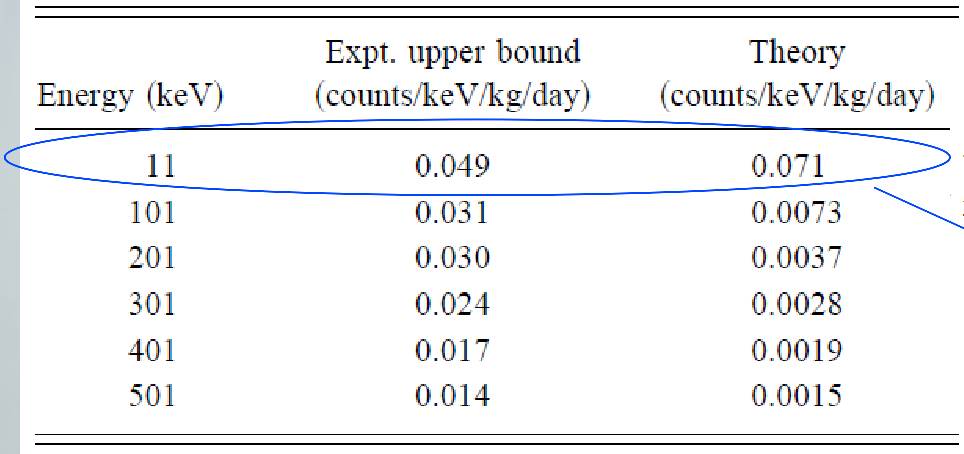
$$\frac{d\Gamma_k}{dk} = \frac{e^2 \lambda \hbar}{2\pi^2 \epsilon_0 m^2 c^3 k}$$

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

Expected X-ray rate from Ge low activity experiments

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

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

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

(Atoms / Kg) in Ge

1 day

4 valence electrons are considered
BE ~ 10 eV « energy of emitted γ ~ 11 keV
***quasi-free* electrons**

Result → λ < 0.55 x 10^{-16} s^{-1} the GRW theory predicts 45% more radiation than the observed upper bound.

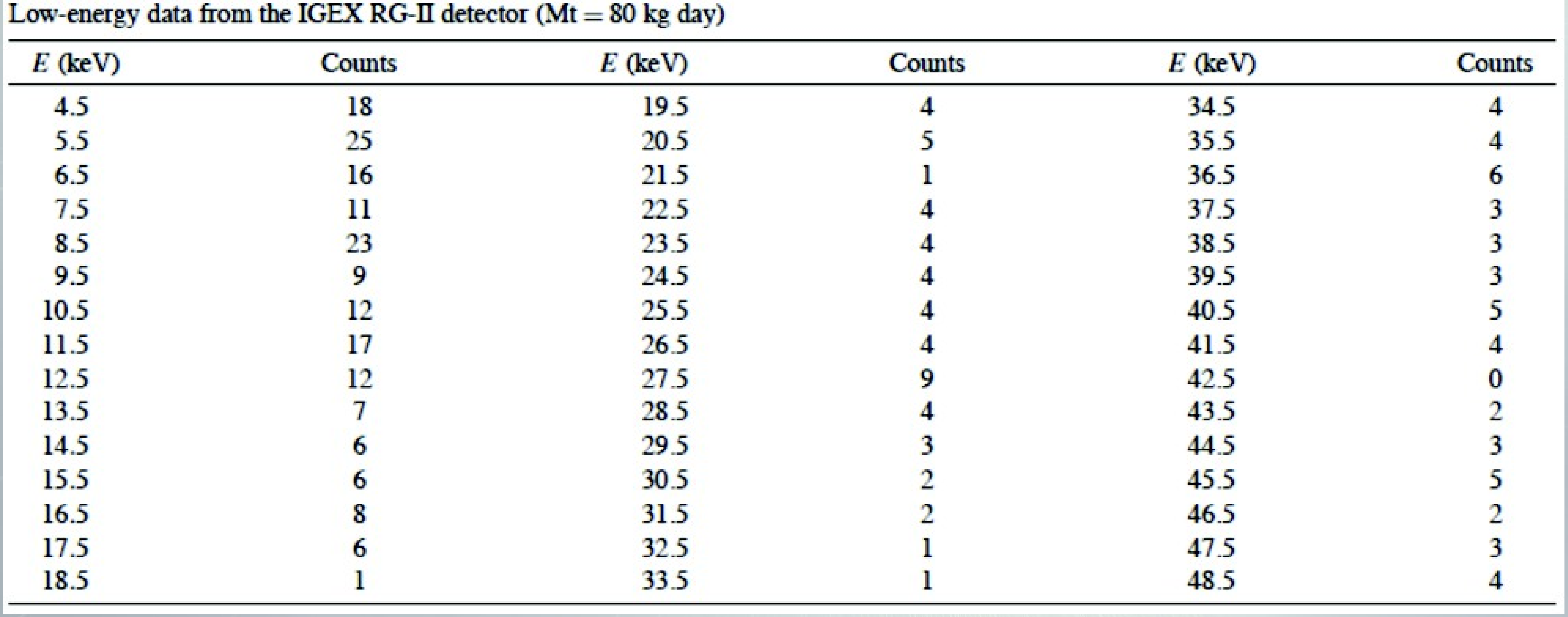
Result <u>possibly biased by the punctual evaluation of the rate</u> at one single energy bin.

New analysis: using published data of the IGEX experiment

The IGEX experiment is a low-activity Ge based experiment dedicated to the ββ0ν 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 range:

$\Delta E = (4 - 49)\ keV \ll m_e = 512\ keV$ → compatible with the non-relativistic assumption.



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

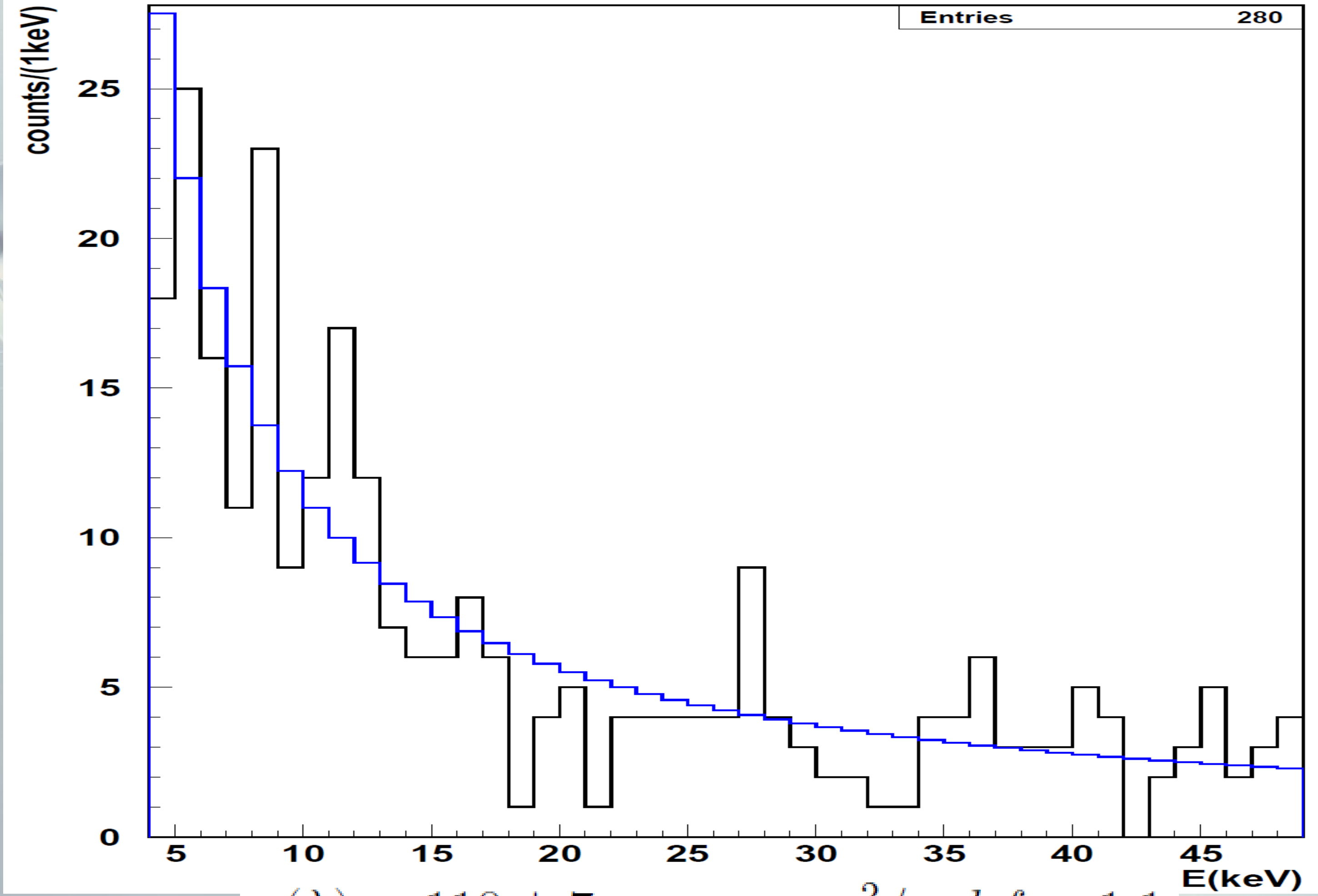
E (keV)	Counts	*E* (keV)	Counts	*E* (keV)	Counts
4.5	18	19.5	4	34.5	4
5.5	25	20.5	5	35.5	4
6.5	16	21.5	1	36.5	6
7.5	11	22.5	4	37.5	3
8.5	23	23.5	4	38.5	3
9.5	9	24.5	4	39.5	3
10.5	12	25.5	4	40.5	5
11.5	17	26.5	4	41.5	4
12.5	12	27.5	9	42.5	0
13.5	7	28.5	4	43.5	2
14.5	6	29.5	3	44.5	3
15.5	6	30.5	2	45.5	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 α(λ) free parameter, bin contents are treated with Poisson statistics.



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

New analysis: results and discussion

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

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

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)

$e^2 / 4\pi = 17137.04$ → $\lambda < 1.4 \times 10^{-17}\ s^{-1}$

3) if a mass-proportional model is assumed (the stochastic field is assumed to be coupled to the particle mass density) then:

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

New analysis: results and discussion

Further we took in the calculation the 22 outer electrons (down to the 3s orbit BE$_{3s}$ = 180.1 eV)

BE$_{3s}$ is 22 times smaller then the less energetic measured photon

compatible with the *quasi-free* approximation.

Corresponding limits:

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

No mass-proportional

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

mass-proportional

Spontaneous emission including nuclear protons

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

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

A. Bassi
S. Donadi

(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

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

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

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 « k_{min} → electrons can be considered as *quasi-free*

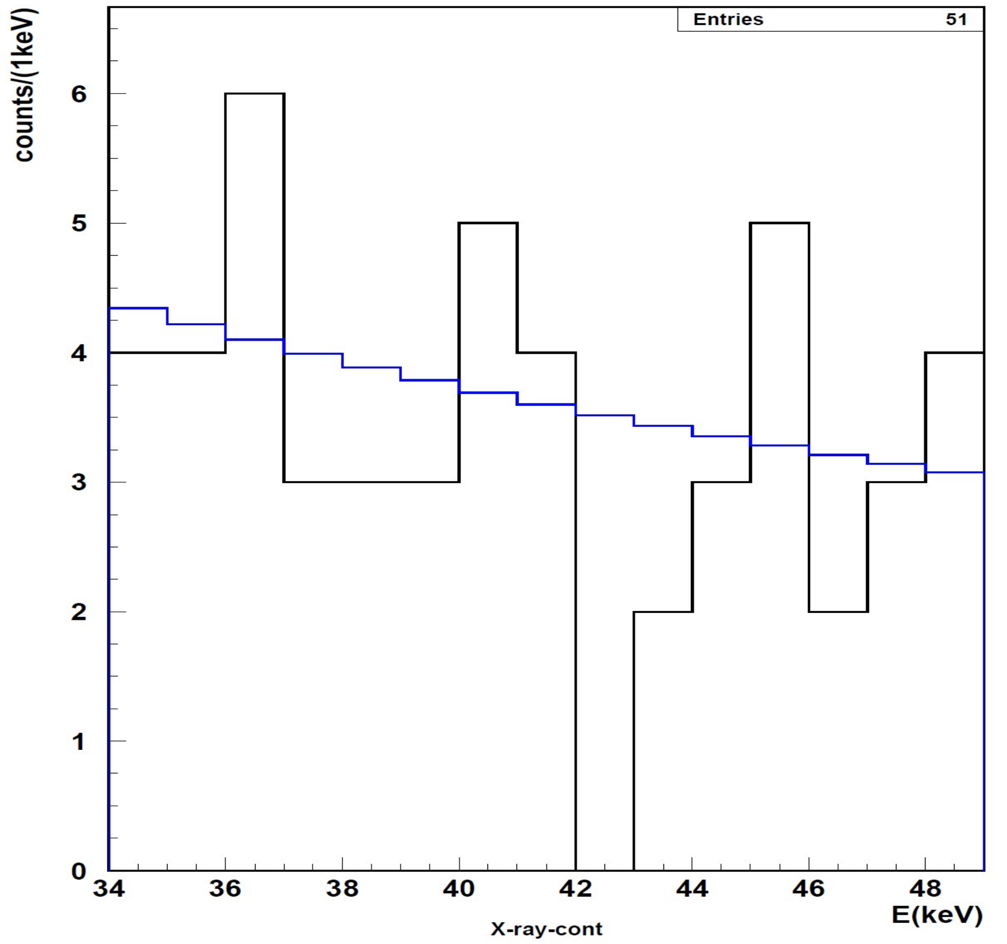
$\Delta E = (35 - 49)$ *keV* « $m_e = 512$ *keV* → compatible with the non-relativistic assumption.

Spontaneous emission including nuclear protons

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 α(λ) free parameter, bin contents are treated with Poisson statistics.



Fit result:

$\alpha(\lambda) = 148 \pm 21$
X^2 / n.d.f. = 0.8

corresponding to the limit on the collapse rate:

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

Mass-proportional

Summarizing ..

Best limits on the collapse rate:

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

No mass-proportional

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

Mass-proportional

Factor 20 better than Fu's result

The stability of the above limits were tested by varing the interval ΔE.
Fit results are consistent within 1σ.

The mass-proportional limit is also consistent with a punctual evaluation, performed using one bin from H. S. Miley, et al., Phys. Rev. Lett. 65, 3092 (1990) corresponding to $k = 101$ keV

The obtained limit for the Mass proportional assumption is:

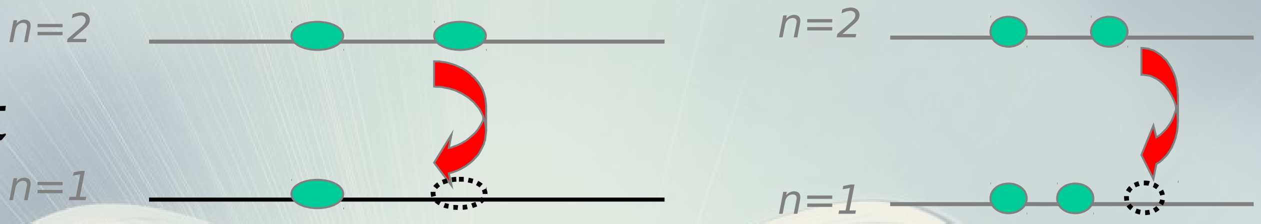
$\lambda < 3.1 \times 10^{-13}\ s^{-1}$

VIP experiment & VIP upgrade …

(see tomorrow's talk by Hexi Shi)

possible test of collapse models

VIP Experiment

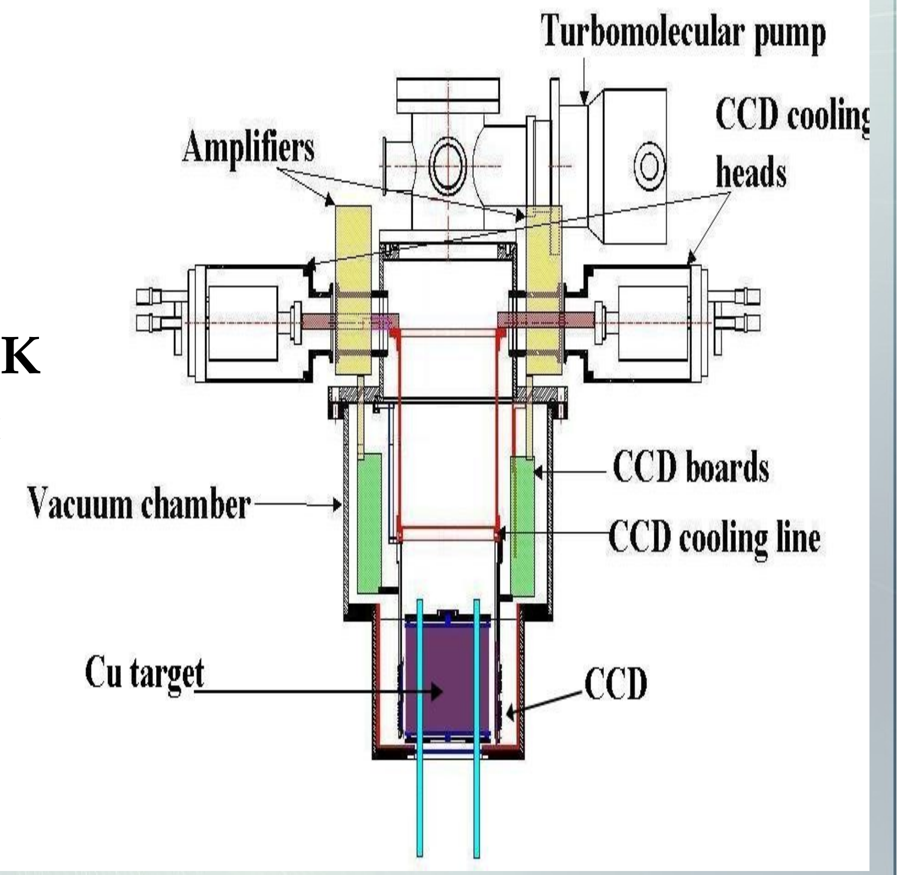


Aim: carry out precise tests of PEP validity for electrons.

Technique: introduce "fresh" electrons in a copper strip serching for non-Paulian 2P → 1S (K_α) transitions (7.729 KeV instead of 8.040 KeV) alternated to X-ray background measurements without current. (Ramberg & Snow 1990)

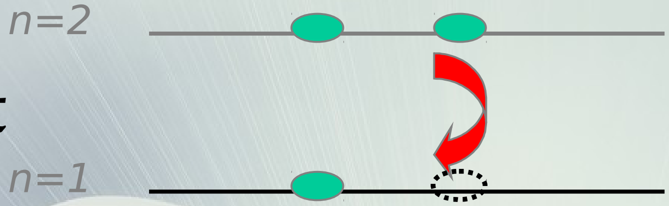
Goal: improve the R&S PEP violation limit ($\beta^2/2 < 1.7 \times 10^{-26}$) by 3-4 orders of magnitude!

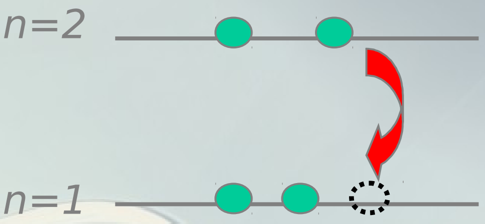
VIP setup: a) copper ultrapure cylindrical foil b) surrounded by 16 Charge Coupled Devices (CCD)
c) inside a vacuum chamber: CCDs cooled to 168K by a cryogenic system d) amplifiers + read out ADC boards.



Advantages
- High resolution CCDs
- Low background environment LNGS
- High statistics.

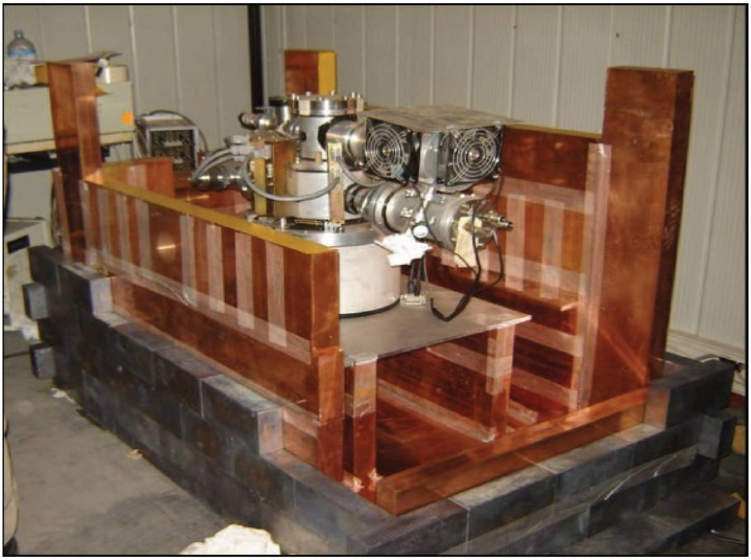
VIP Experiment





- **Result LNF collected data**: $\beta^2/2 < 4.5 \times 10^{-28}$ (99.7% c.l.) factor 40 w.r.t R&S
- **Result LNGS collected data**: $\beta^2/2 < 4.7 \times 10^{-29}$ (99.7% c.l.) (preliminary analysis)

Reduced cosmic ray background + massive shield



- **Bayesian analysis**:

calculation *probability distribution for expected value of X-rays signal counts :*

$$f(\lambda_{sg}|z_c,\lambda_{bk}) = \frac{(\lambda_{sg}+\lambda_{bk})^{z_c} e^{-\lambda_{sg}}}{z_c! \sum_{i=1}^{z_c} \frac{\lambda_{bk}^i}{i!}}$$

z_c = counts with current

$E[\lambda_{bk}] = z_{bk}+1$

$$F(\lambda_0|z_c,\lambda_{bk}) = 1 - \frac{e^{-\lambda_{bk}} \sum_{i=1}^{z_c} \frac{e^{-\lambda_0}(\lambda_0+\lambda_{bk})^i}{i!}}{e^{-\lambda_{bk}} \sum_{i=1}^{z_c} \frac{\lambda_{bk}^i}{i!}}$$

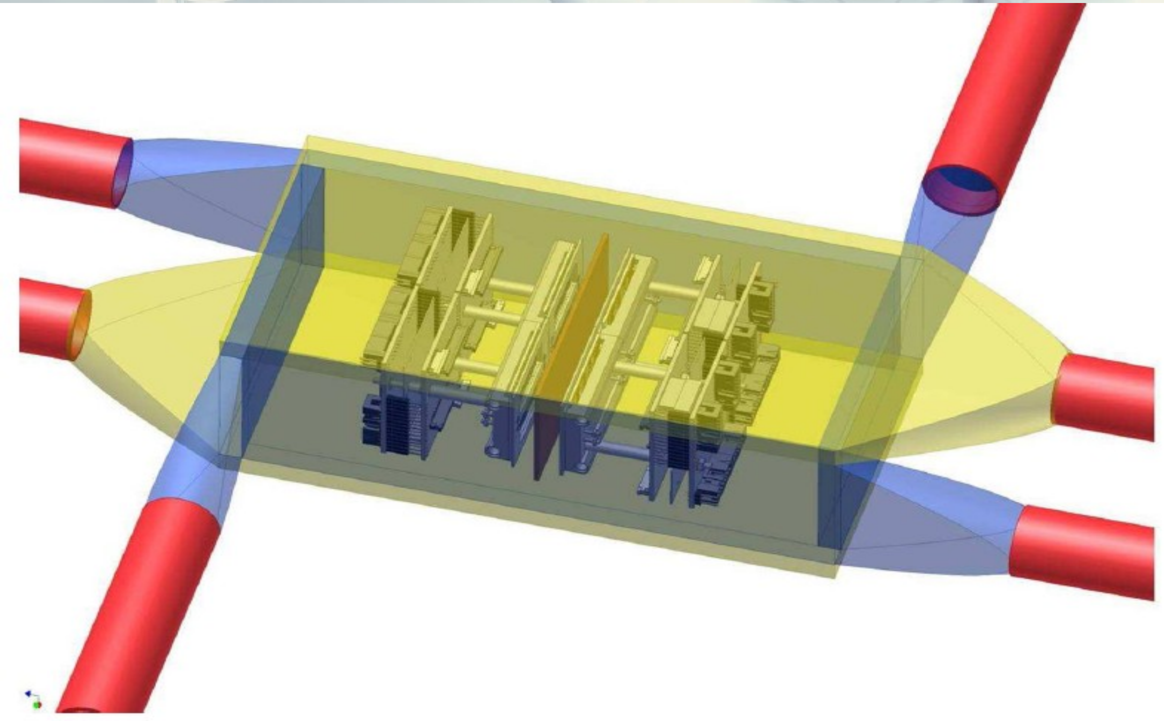
- **Cumulative distribution function → $\lambda_{sg} \leq \lambda_0$ with probability 99.7 %**

LNF data: $\beta^2/2 < 2.9 \times 10^{-28}$ gain factor 1.6 !

VIP upgrade and beyond..

Improvements :

- Faster triggerable X-ray detectors.. Silicon Drift Detectors (SDD) background rejection from outside particles with VETO SYSTEM (scintillators + SiPM)
- More compact target → higher acceptance
- Target cooled down to 90 K → higher current (100 A)
- Expected gain factor 100



- This kind of experimental apparatus dedicated to rare processes of X-ray emission

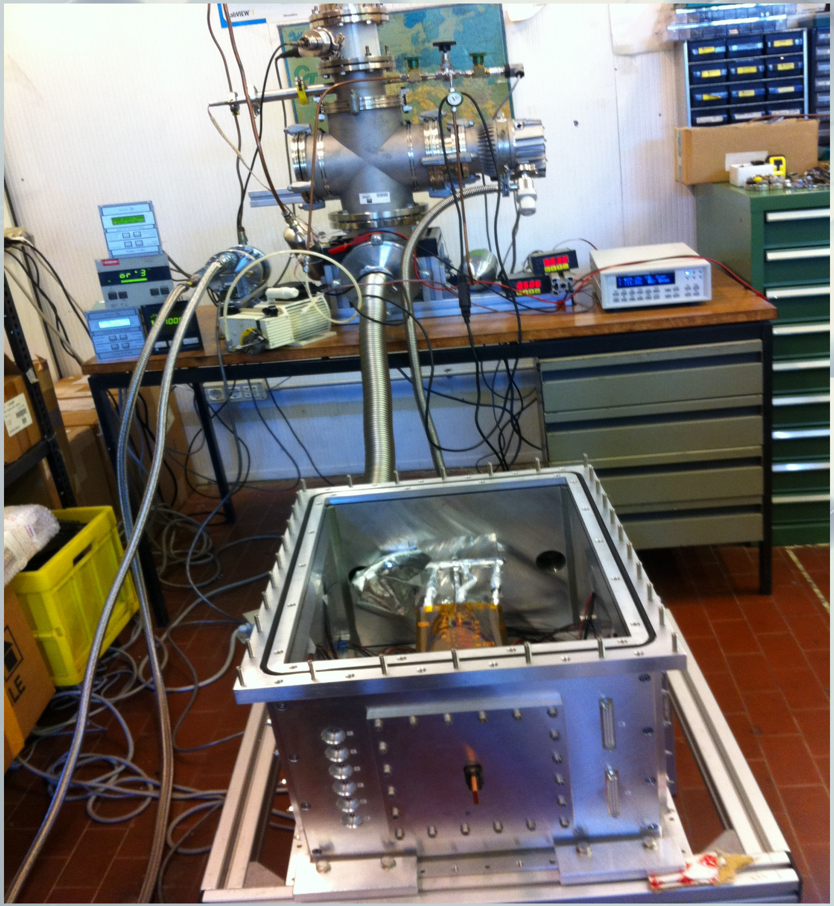
Is promising for collapse models testing ...

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 ...

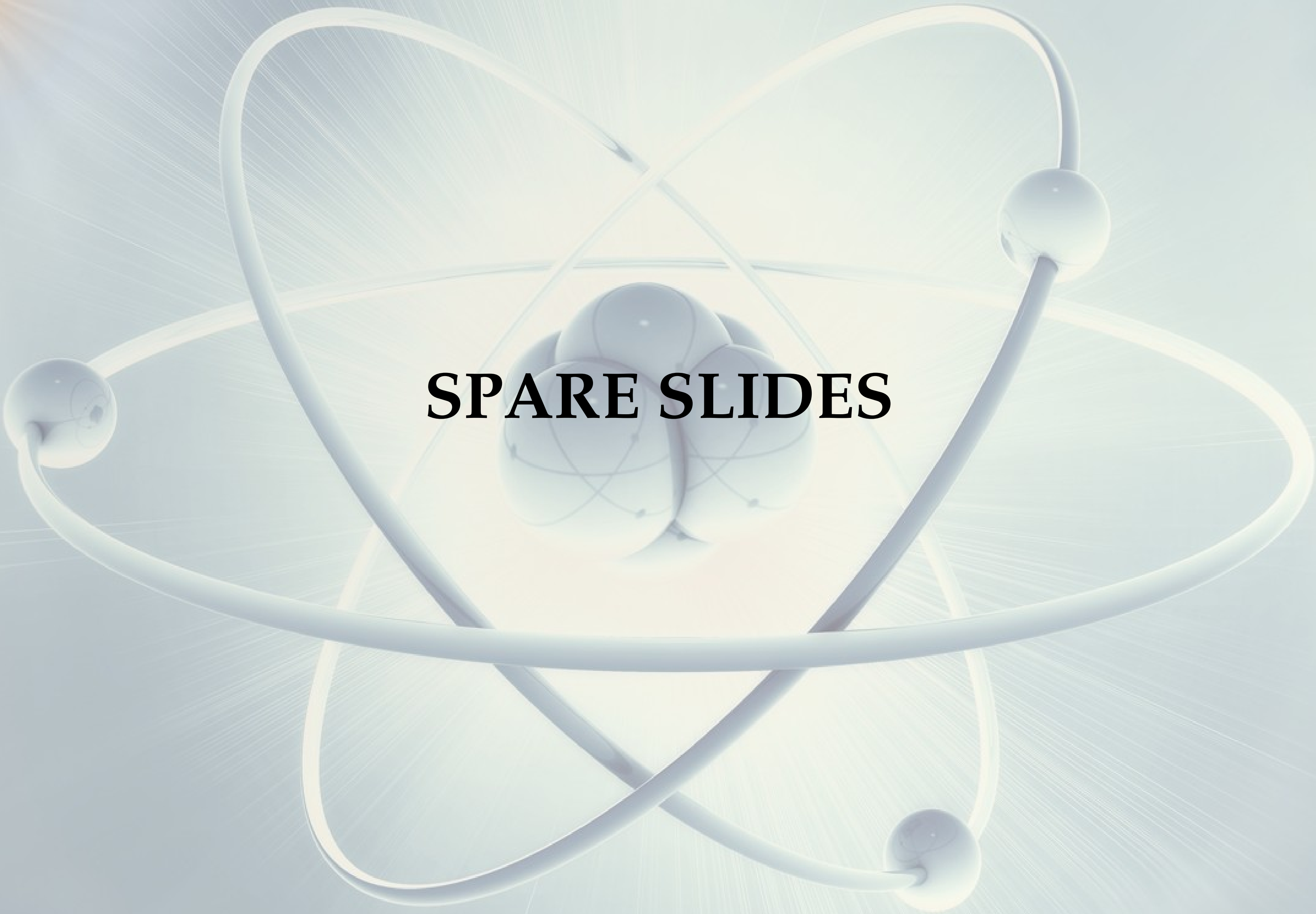
- Matherial characterization and selection (& BTF and LNGS testing facility)
- MC simulations (geometry, background, materials) realization of the DEDICATED SETUP
- run, data analysis.

Thank you

☺

&

Many thanks to Centro Fermi for giving me the opportunity of investigating this fascinating item.



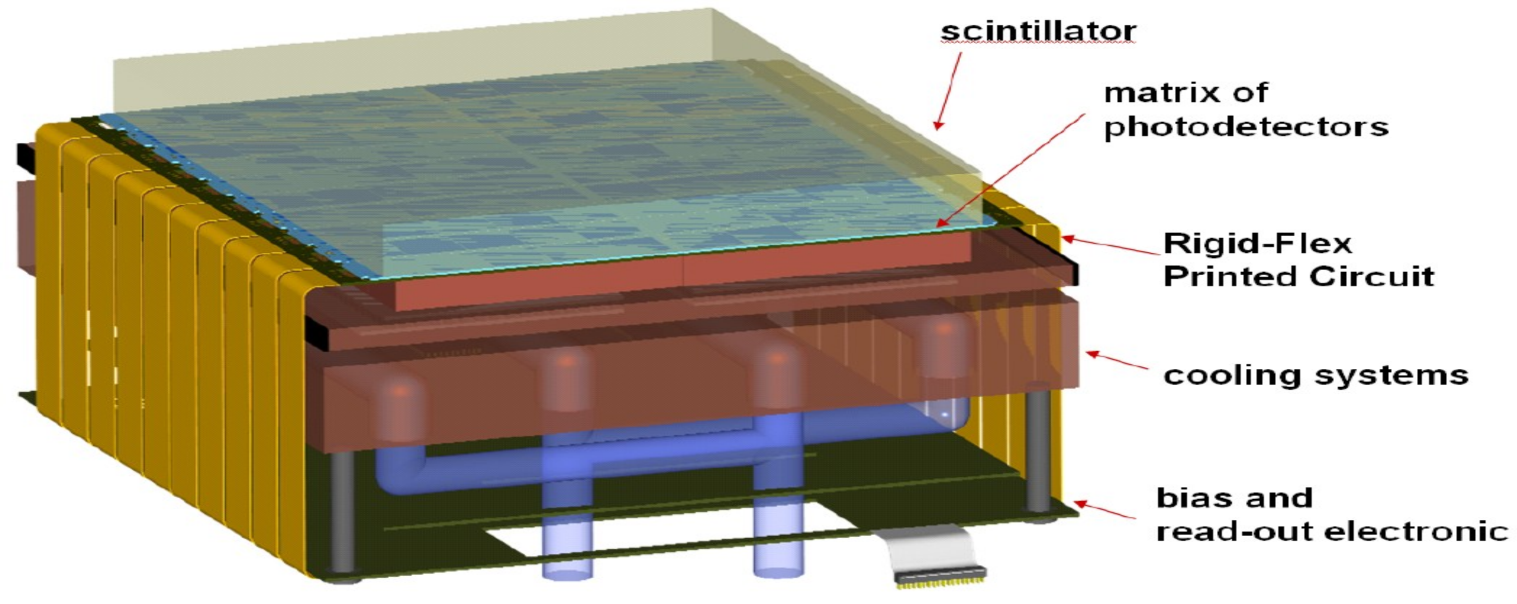
SPARE SLIDES

SDD .. a possible bio-medical application

Possible bio-medical application

Gamma imaging : SPECT - Single Photon Emission Computed Tomography

evolution of PET (PM → SDD) better energy and space resolution (some *mm* → 200 μm)



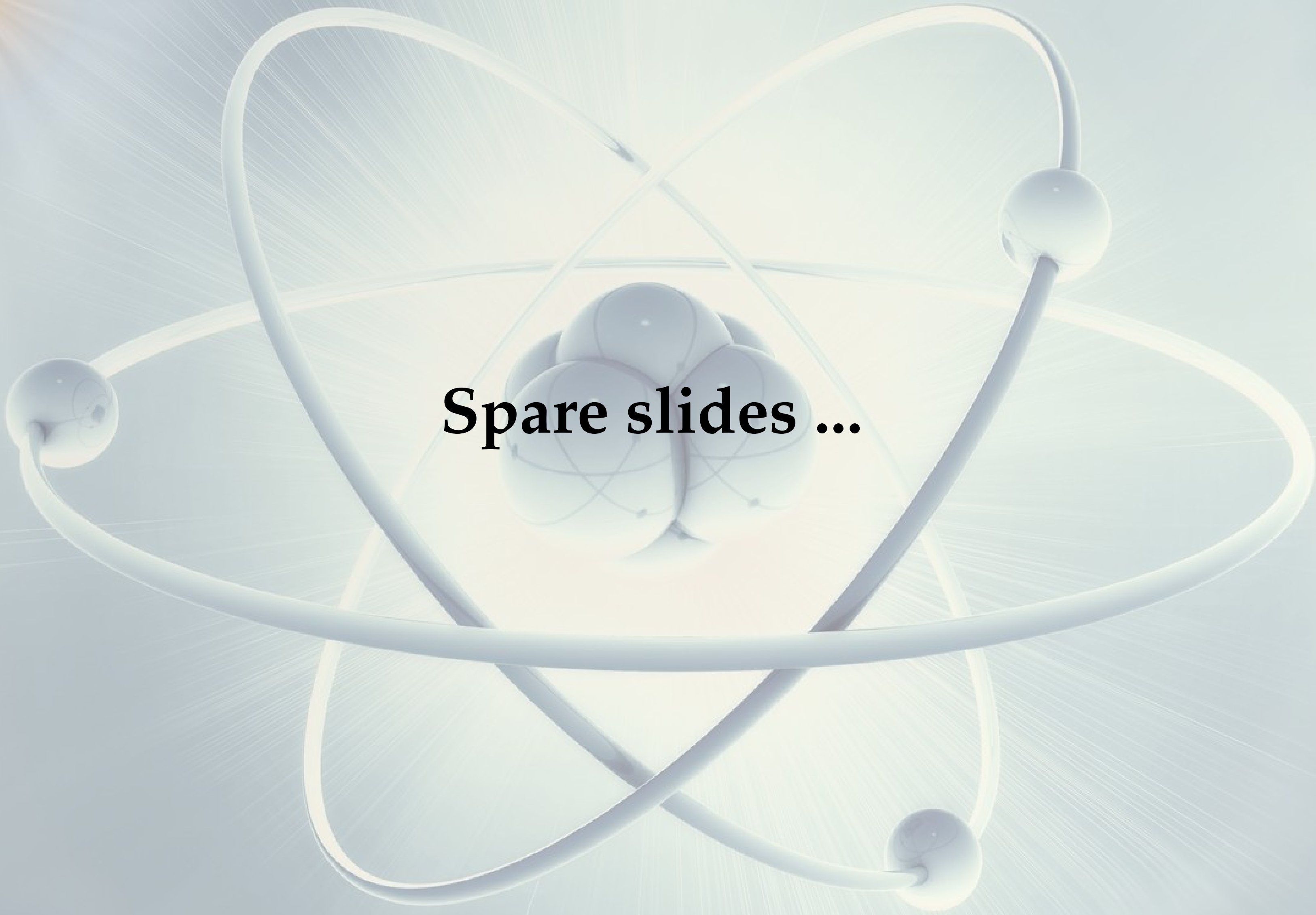
Detector :

Collimator - selects photons by incident direction

Scintillator - gamma photons are converted to visible

SDD - cooled to -10 °C to minimize thermal noise

Reconstruction method - an intensity map is created from the distribution of each SDD signal.



Spare slides ...

Collapse models

1) Deal with the mass density

2) The mass density is given by the wave function

3) The wave function evolves according to a modified Schrödinger equation, with the inclusion of nonlinear and stochastic terms (the collapse)

From which can be derived: microscopic (quantum) behavior,
macroscopic (classical) behavior,
quantum-to-classical transition …

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)