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Wave function collapse searches in the cosmic silence

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Is Quantum Theory exact?
from quantum foundations to quantum applications

LNF-INFN, Frascati, Sept 23 - Sept 27, 2019, Aula Touschek

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 .. possible ways 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: non linear *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.

CSL model

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

System's Hamiltonian

NEW COLLAPSE TERMS → **New Physics**

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

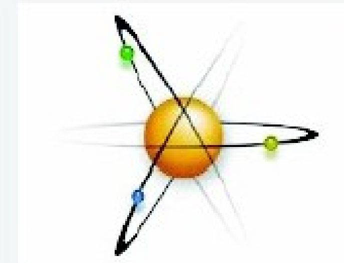
$\langle N(\mathbf{x})\rangle_t = \langle \psi_t | N(\mathbf{x}) | \psi_t \rangle$ — **nonlinearity**

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

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

Which values for λ and r_c?

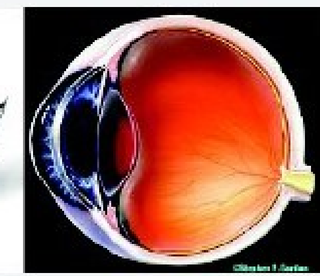
Microscopic world
(few particles)



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

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

… spontaneous photon emission

Besides collapsing the state vector to the position basis
the interaction with the stochastic field increases the expectation value of particle's energy,
collapse → the center of mass is shifted towards the localized wave function position
→ since the process is random this results in a diffusion process

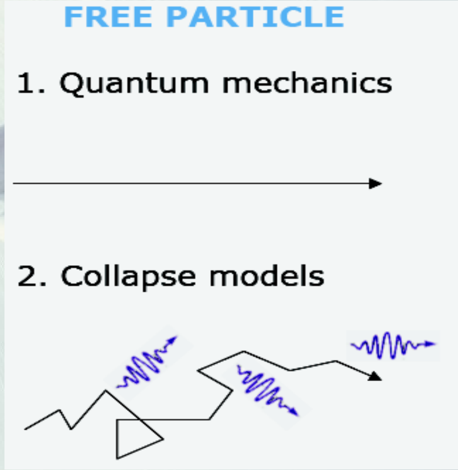
↓

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

1) 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) provides constraints on the parameters of the CSL model

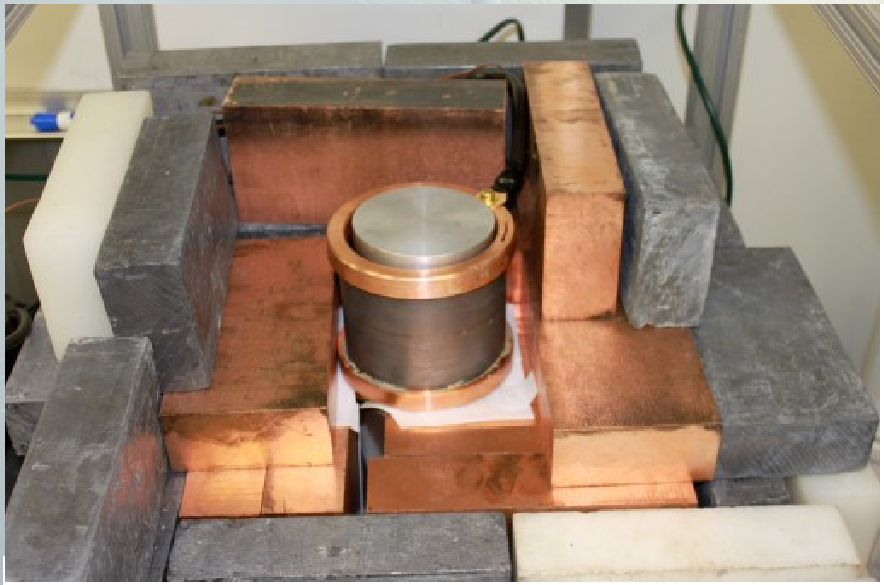
Q. Fu, Phys. Rev. A 56, 1806 (1997)
S. L. Adler and F. M. Ramazanoglu, J. Phys. A40, 13395 (2007);
J. Phys. A42, 109801 (2009)
S. L. Adler, A. Bassi and S. Donadi,
J. Phys. A46, 245304 (2013)
S. Donadi, D. A. Deckert and A. Bassi, Annals of Physics 340, 70-86 (2014)



Constraining collapse models in underground labs

IGEX low-activity Ge based experiment dedicated to the ββ0ν decay research. (C. E. Aalseth et al., IGEX collaboration Phys. Rev. C 59, 2108 (1999))

Consider the 30 outermost electrons emitting *quasi free* (B_{2s} = 1.4 keV) → we are confined to the experimental range: ΔE = (14 – 49) keV **<u>fit is not reliable</u> …**



<u>Spontaneous emission rate from theory:</u>
(non relativistic, for free electrons)

$$\frac{d\Gamma(E)}{dE} = \frac{\alpha(\lambda)}{E}.$$

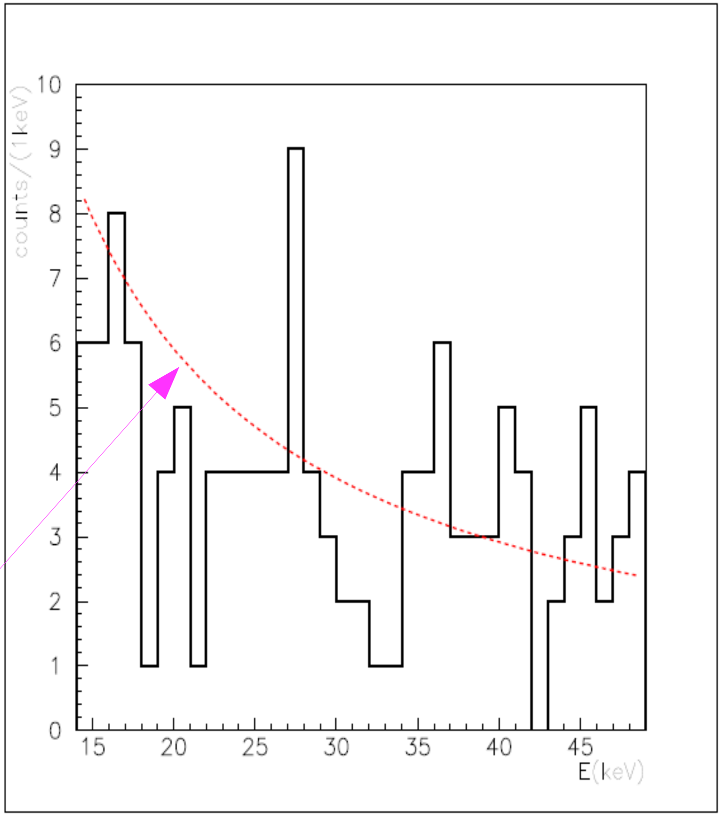


Figure 1. Fit of the X-ray emission spectrum measured by the IGEX experiment [14,15], using the theoretical fit function Equation (7). The black line corresponds to the experimental distribution; the red dashed line represents the fit. See the text for more details.

Constraining collapse models in underground labs

We extract the *p. d. f.* of λ:

measurement:

$$G(y_i|P,\Lambda_i) = \frac{\Lambda_i^{y_i} e^{-\Lambda_i}}{y_i!}$$

$$y = \sum_{i=1}^{n} y_i \quad , \quad \Lambda = \sum_{i=1}^{n} \Lambda_i$$

theoretical expectation:

$$\Lambda(\lambda) = y_s + 1 = \sum_{i=1}^{n} c\,\frac{e^2\lambda}{4\pi^2 r_C^2 m^2 E_i} + 1 = \sum_{i=1}^{n} \frac{\alpha(\lambda)}{E_i} + 1$$

$$c = \left(8.29 \times 10^{24}\,\frac{\text{atoms}}{\text{kg}}\right) \cdot (80\,\text{kg day}) \cdot \left(8.64 \times 10^4\,\frac{\text{n. of seconds}}{\text{day}}\right) \cdot (30)$$

Bayesian probability inversion

$$G'(\lambda|G(y|P,\Lambda)) \propto \left(\sum_{i=1}^{n} \frac{\alpha(\lambda)}{E_i} + 1\right)^{y} e^{-\left(\sum_{i=1}^{n} \frac{\alpha(\lambda)}{E_i} + 1\right)}$$

Upper limit on λ : $\int_0^{\lambda_0} G'(\lambda|G(y|P,\Lambda))\,d\lambda$

What we miss :
1) control of background (radionuclides)
2) knowledge of detection efficiency

Constraining collapse models in underground labs

$$\lambda \leq 6.8 \cdot 10^{-12} s^{-1} \quad \text{mass prop.,}$$

$$\lambda \leq 2.0 \cdot 10^{-18} s^{-1} \quad \text{non-mass prop..}$$

With probability 95%

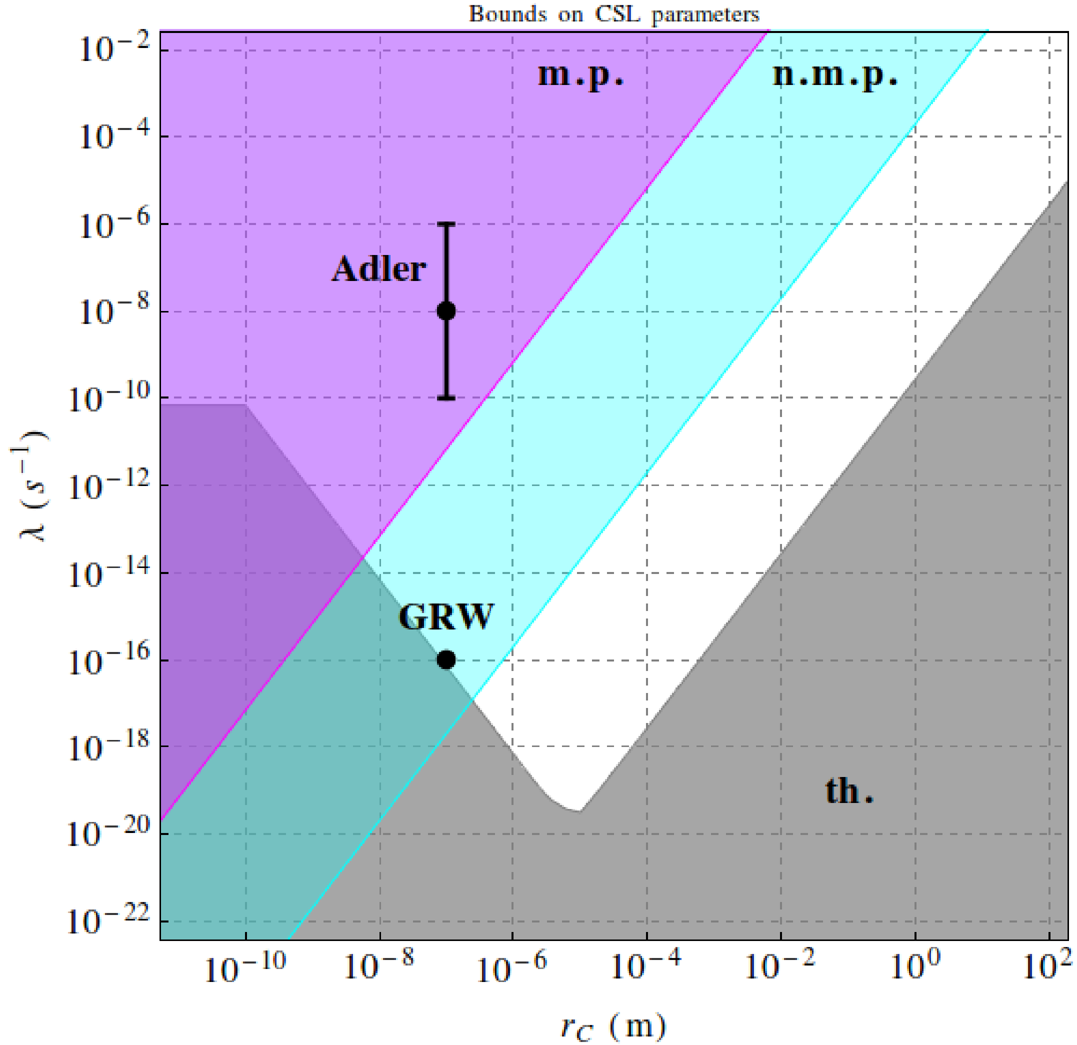
K. Piscicchia et al., Entropy 2017, 19(7) 319

(319http://www.mdpi.com/1099-4300/19/7/319)

th. gray bound:

- M. Carlesso, A. Bassi, P. Falferi and A. Vinante, Phys. Rev. D 94, (2016) 124036

- M. Toroš and A. Bassi, https://arxiv.org/pdf/1601.03672.pdf

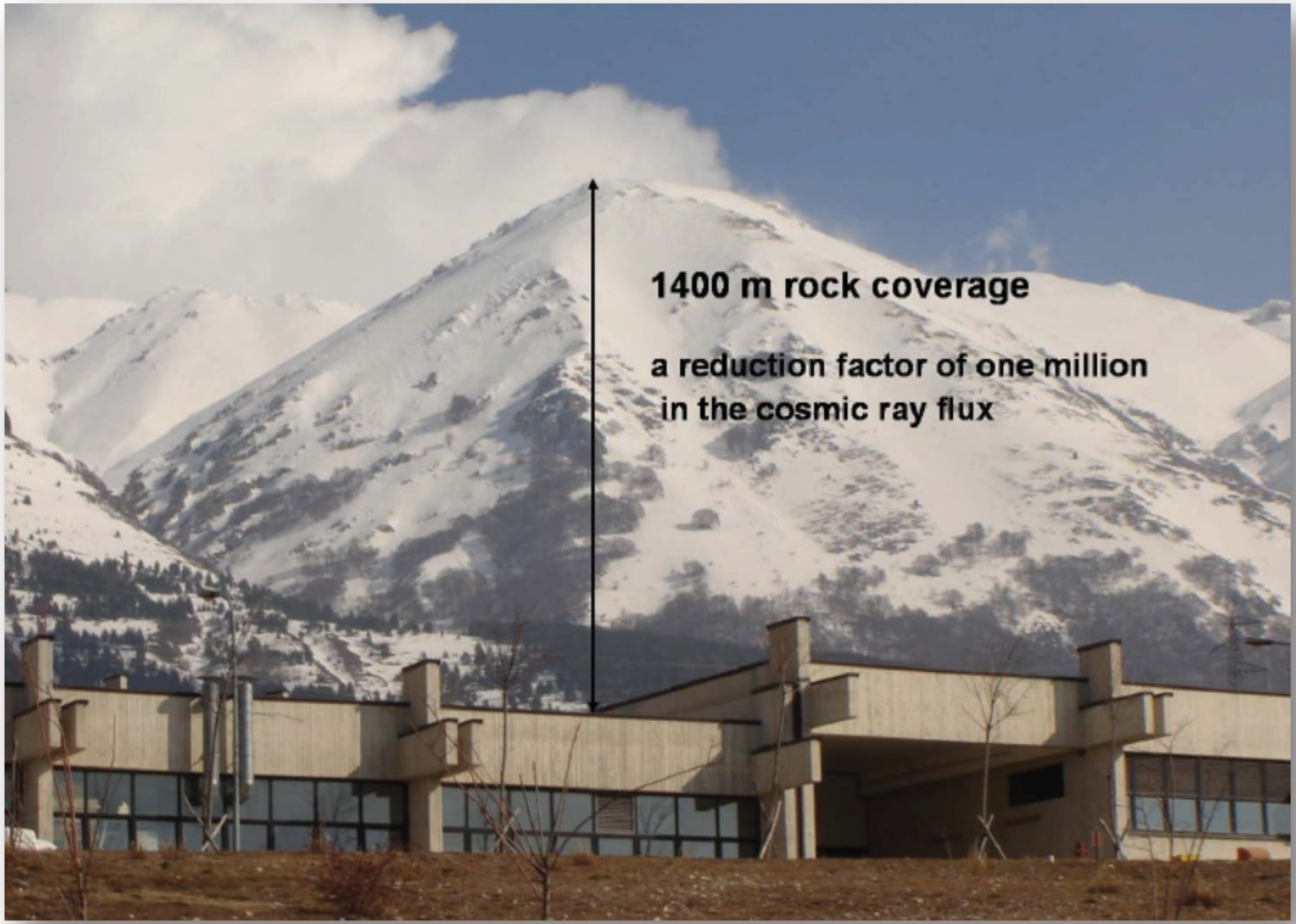


Applying the method to a dedicated experiment

…

unfolding the BKG contribution from known emission processes.

VIP Experiment & LNGS



The setup

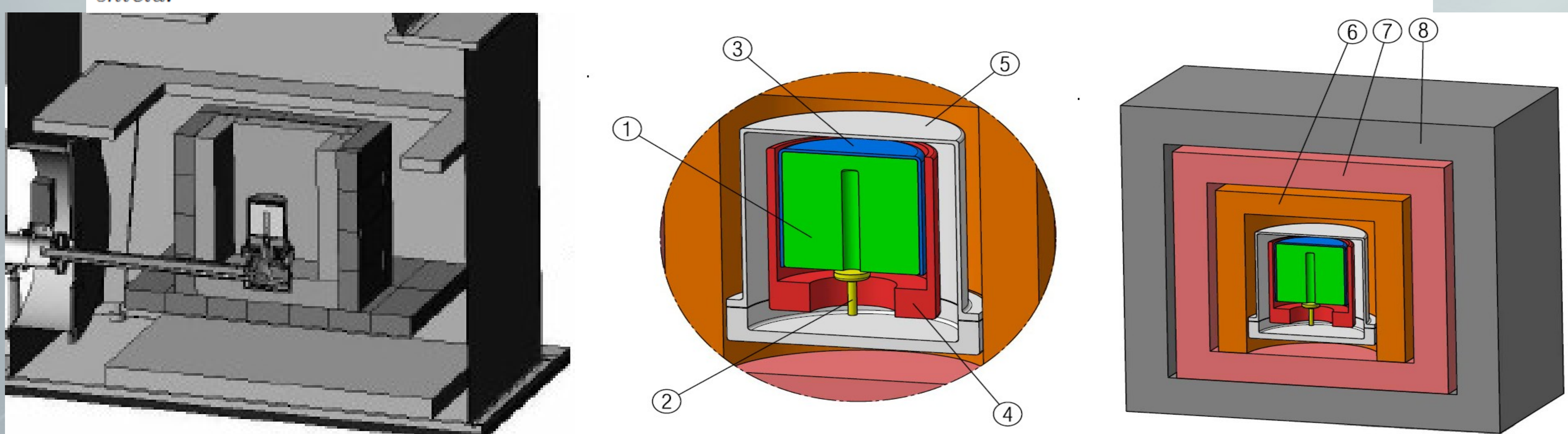
High purity Ge detector measurement:

- active Ge detector surrounded by complex electrolytic Cu + Pb shielding

- 10B-polyethylene plates reduce the neutron flux towards the detector

- shield + cryostat enclosed in air tight steel housing flushed with nitrogen to avoid contact with external air (and thus radon).

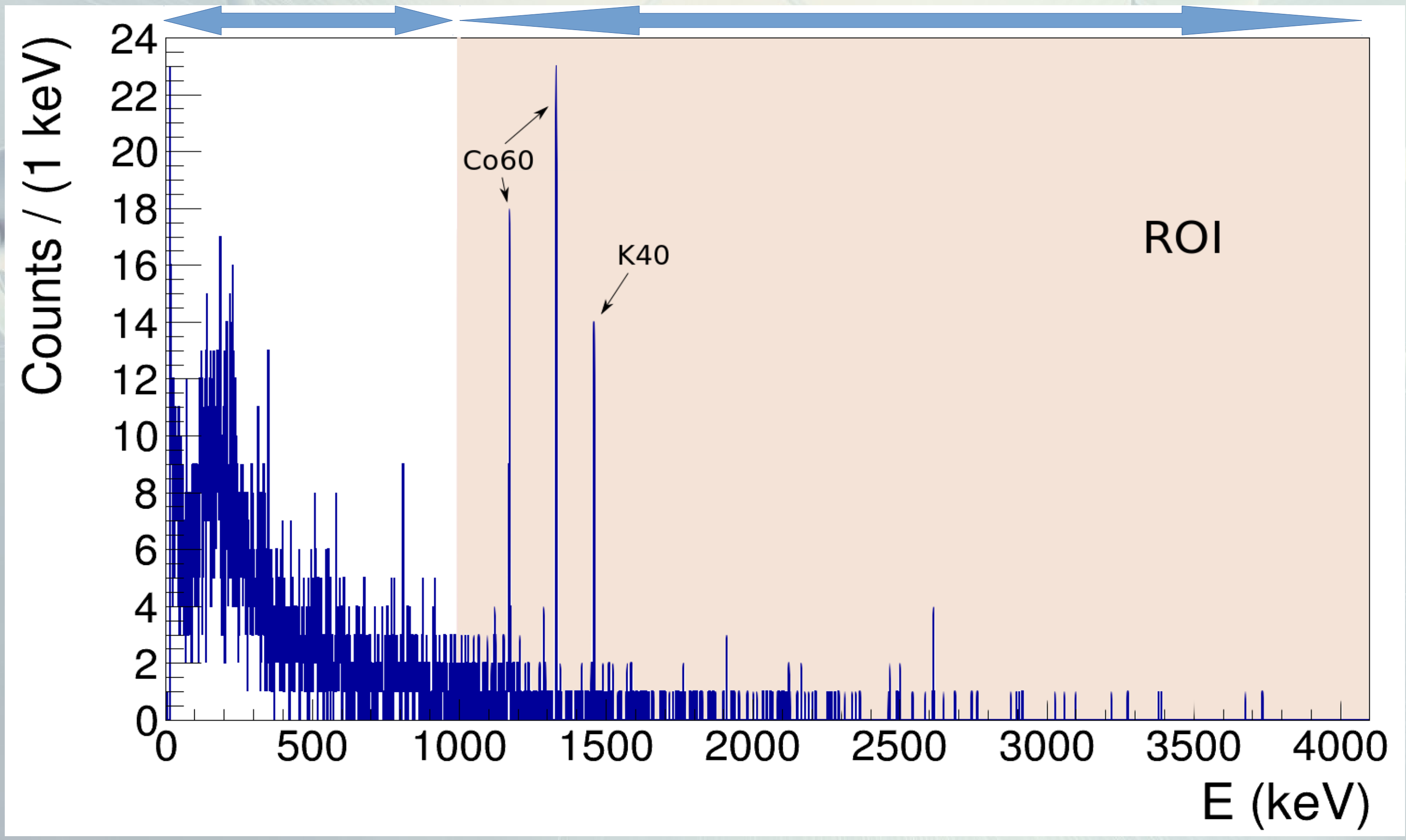
FIG. 1: *Schematic representation of the experimental setup: 1 - Ge crystal, 2 - Electric contact, 3 - Plastic isolator, 4 - Copper cup, 5 - Copper end-cup, 6 - Copper block + plate, 7 Inner Copper shield, 8 - Lead shield.*



p. d. f. of λ
experimental information:

cosmic rays, bremsstrahlung
from
^{210}Pb & daughters

Region Of Interest ΔE=(1000 – 3800)keV
compatible with theretical constrains



Three months data taking with 2kg Germanium active mass

p. d. f. of λ
theoretical information

Expected rate of spontaneous emitted photons due to interactions of atomic *p* and *e* with the stochastic field (S. Donadi, A. Bassi):

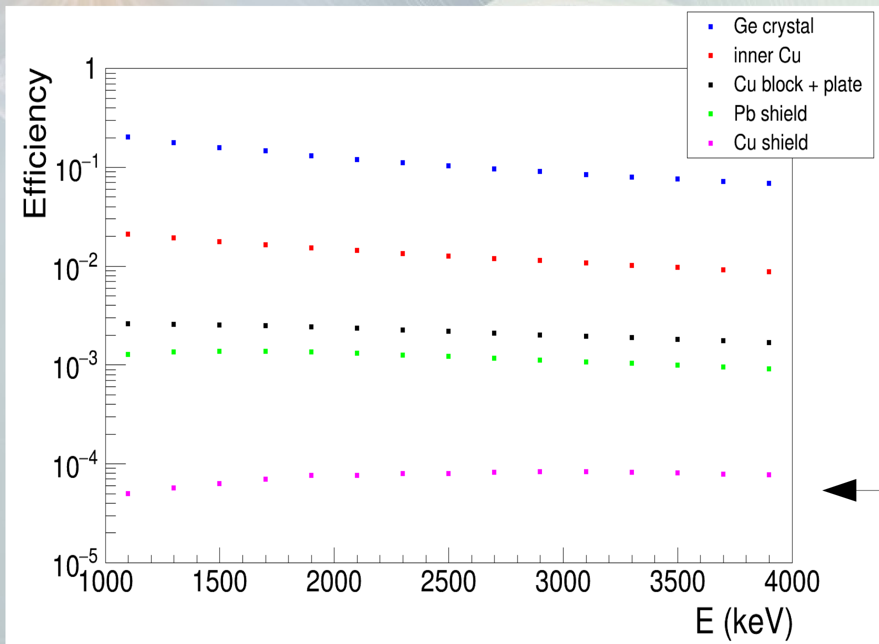
$$\frac{d\Gamma}{dE} = \left\{ \left(N_p^2 + N_e\right) \cdot (m\, n\, T) \right\} \frac{\lambda \hbar e^2}{4\pi^2 \epsilon_0 c^3 m_N^2 r_c^2 E}$$

Provided that the wavelength of the emitted photon:

- is greater then the nuclear dimensions → protons contribute coherently
- is smaller then the lower electronic orbit → protons and electrons emit independently
- electrons and protons can be considered as non-relativistic.

Efficiency distributions

Each material spontaneously emits: different *masses* , *densities*, *efficiencies* ε(*E*)



MC characterisation of the detector (MaGe, Boswell et al., 2011) based on the GEANT4 software library (Agostinelli et al., 2003).

Efficiency distribution in ΔE for each massive component of the setup.

Theoretical rate corrected for efficiecy → expected contribution of spontaneous photon emission:

$$z_s(\lambda) = \sum_i \int_{E_1}^{E_2} \frac{d\Gamma}{dE}\bigg|_i \epsilon_i(E)\, dE$$

***i*- th component of the setup**

predicted emission rate

detection efficiencies

Background simulation

radionuclides decay simulation accounts for :

- **emission probabilities & decay scheme of each radionuclide**
- **photons propagation and interactions inside the materials of the detector**
- **detection efficiency**

contributions:

- Co60 from the inner Copper
- Co60 from the Copper block + plate
- Co58 from the Copper block + plate
- K40 from Bronze
- Ra226 from Bronze
- Bi214 from Bronze
- Pb214 from Bronze
- Bi212 from Bronze
- Pb212 from Bronze
- Tl208 from Bronze
- Ra226 from Poliethylene
- Bi214 from Poliethylene
- Pb214 from Poliethylene

measured activities

$$z_{b,ij} = \frac{m_i \, A_{ij} \, T \, N_{rec,ij}}{N_{ik}}$$

detected MC γs

 # simulated events

expected number of background counts $\Lambda_b = z_b + 1$

88% agreement with the measured spectrum acieved

Upper limit for the collapse rate parameter λ

- From the *p.d.f* we obtain the cumulative distribution function:

$$F(\lambda) = \frac{\int_0^\lambda f(\lambda|\mathrm{ex,th})\mathrm{d}\lambda}{\int_0^\infty f(\lambda|\mathrm{ex,th})\mathrm{d}\lambda} = \frac{\int_0^\lambda \frac{1}{z_c!}(a\lambda+\Lambda_b+1)^{z_c} e^{-(a\lambda+\Lambda_b+1)}\mathrm{d}\lambda}{\int_0^\infty \frac{1}{z_c!}(a\lambda+\Lambda_b+1)^{z_c} e^{-(a\lambda+\Lambda_b+1)}\mathrm{d}\lambda}$$

which we express in terms of upper incomplete gamma functions

$$F(\lambda) = 1 - \frac{\Gamma(z_c+1, a\lambda+1+\Lambda_b)}{\Gamma(z_c+1, 1+\Lambda_b)}$$

- put the measured z_c and the calculated $\Lambda_s(\lambda) = a\lambda + 1$, Λ_b in the cumulative distribution function

extract the limit at the desired probability level ...

$\lambda < 5,2 \cdot 10^{-13}$ s^{-1} with a probability of 95%

Gain factor ~ 13

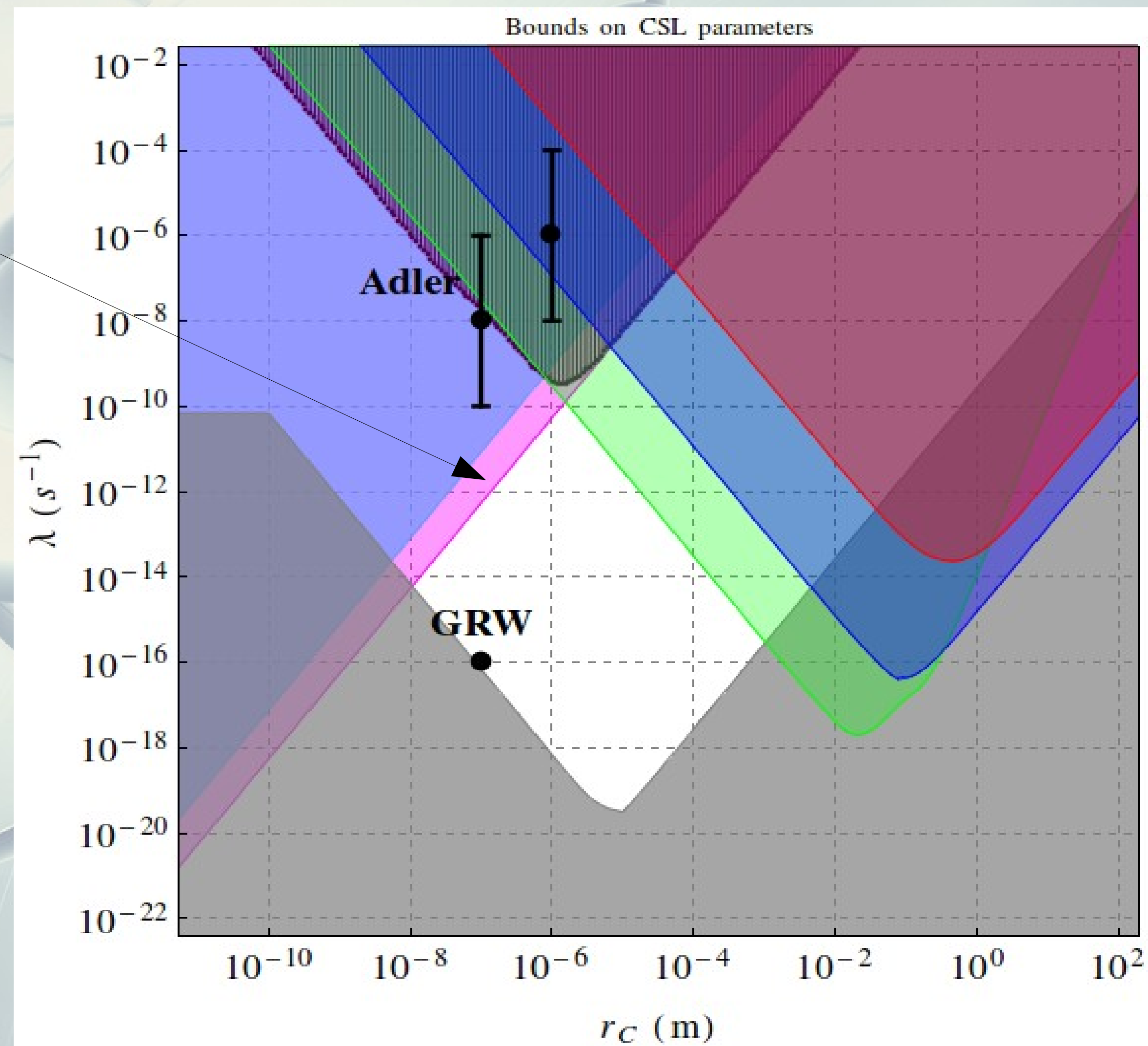
Upper limit on the collapse rate parameter λ

Substituting the estimated values in the cumulative p.d.f :

$$F(\lambda) = \frac{\int_0^{\lambda} f(\lambda|\mathrm{ex},\mathrm{th})d\lambda}{\int_0^{\infty} f(\lambda|\mathrm{ex},\mathrm{th})d\lambda} = \frac{\int_0^{\lambda} \frac{1}{z_c!}(a\lambda + \Lambda_b + 1)^{z_c} e^{-(a\lambda+\Lambda_b+1)}d\lambda}{\int_0^{\infty} \frac{1}{z_c!}(a\lambda + \Lambda_b + 1)^{z_c} e^{-(a\lambda+\Lambda_b+1)}d\lambda}$$

we get :

$\lambda < 5.2 \cdot 10^{-13}$ with a probability of 95%



See also

- M. Carlesso, A. Bassi, P. Falferi and A. Vinante, Phys. Rev. D 94, (2016) 124036

- M. Toroš and A. Bassi, https://arxiv.org/pdf/1601.03672.pdf

- Nanomechanical Cantilever Vinante, Mezzena, Falferi, Carlesso, Bassi, ArXiv 1611.09776

Accounting for the information in each bin

Upper limit on the PEP violation probability is obtained extracting the p.d.f. of the expected violation signal contribution S :

$$p(S, B|\text{data}) = \frac{p(\text{data}|S, B) \cdot p_0(S) \cdot p_0(B)}{\int p(\text{data}|S, B) \cdot p_0(S) \cdot p_0(B) dS dB}.$$

Joint *p.d.f.*
Bin contents fluctuate around the mean according to a Pois. Dist.

Likelihood →

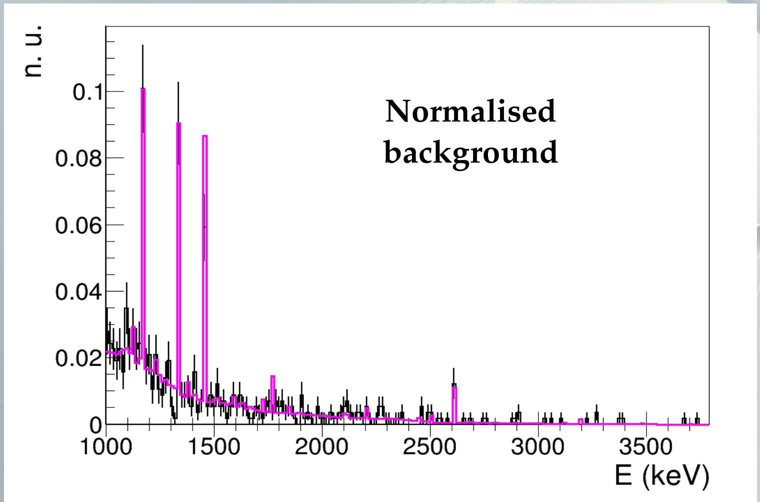
$$P(data|S,B) = \prod_{i=1}^{N} \frac{\lambda_i(S,B)^{n_i} \cdot e^{-\lambda_i(S,B)}}{n_i!}$$

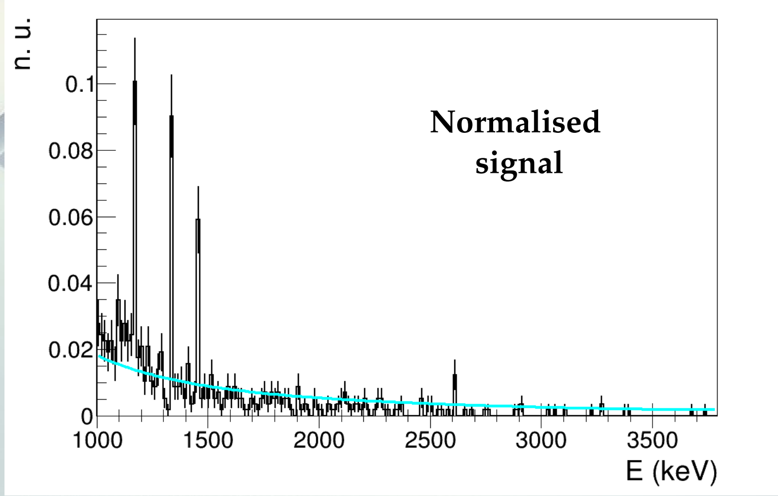
Posterior *p.d.f.* (model needs in input the bkg. and sig. normalised shapes):

$$P(S|data) = \int P(S,B|data)\ dB$$

$$\lambda_i = \lambda_i(S, B) = S \cdot \int_{\Delta E_i} f_S(E) dE + B \cdot \int_{\Delta E_i} f_B(E) dE,$$

Background → **from the MC simulation** **Signal** → **theory convoluted with exp. resolution**





Accounting for the information in each bin

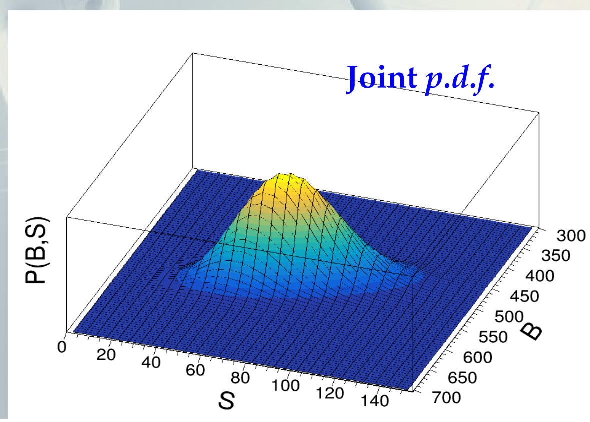
The prior probability for S is flat up to a maximum S_{max} consistent with existing limits [Entropy 2017, 19(7) 319].

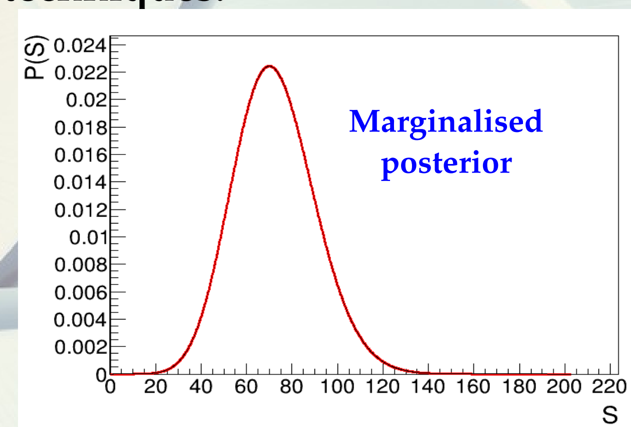
$$p_0(S) = \begin{cases} \frac{1}{S_{\max}} & 0 \le S \le S_{\max} \\ 0 & \text{otherwise} \end{cases}$$

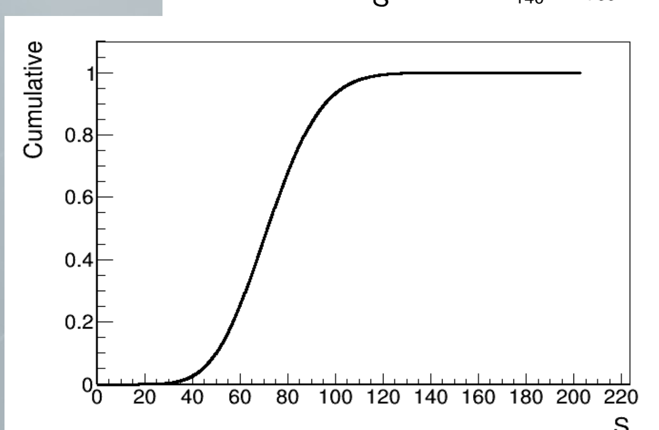
The mean value for the expected number of bkg. Events μ_b obtained from bkg. Spectrum. Prior is Gaussian with a width $\sigma_b = \mathrm{sqrt}(\mu_b)$.

$$p_0(B) = \begin{cases} \dfrac{e^{-((B-\mu_B)^2/2\sigma_B^2)}}{\int_0^\infty e^{-((B-\mu_B)^2/2\sigma_B^2)}dB} & B \ge 0 \\ 0 & B < 0 \end{cases}$$

Posterior calculated with Markow chain Monte Carlo techniques:





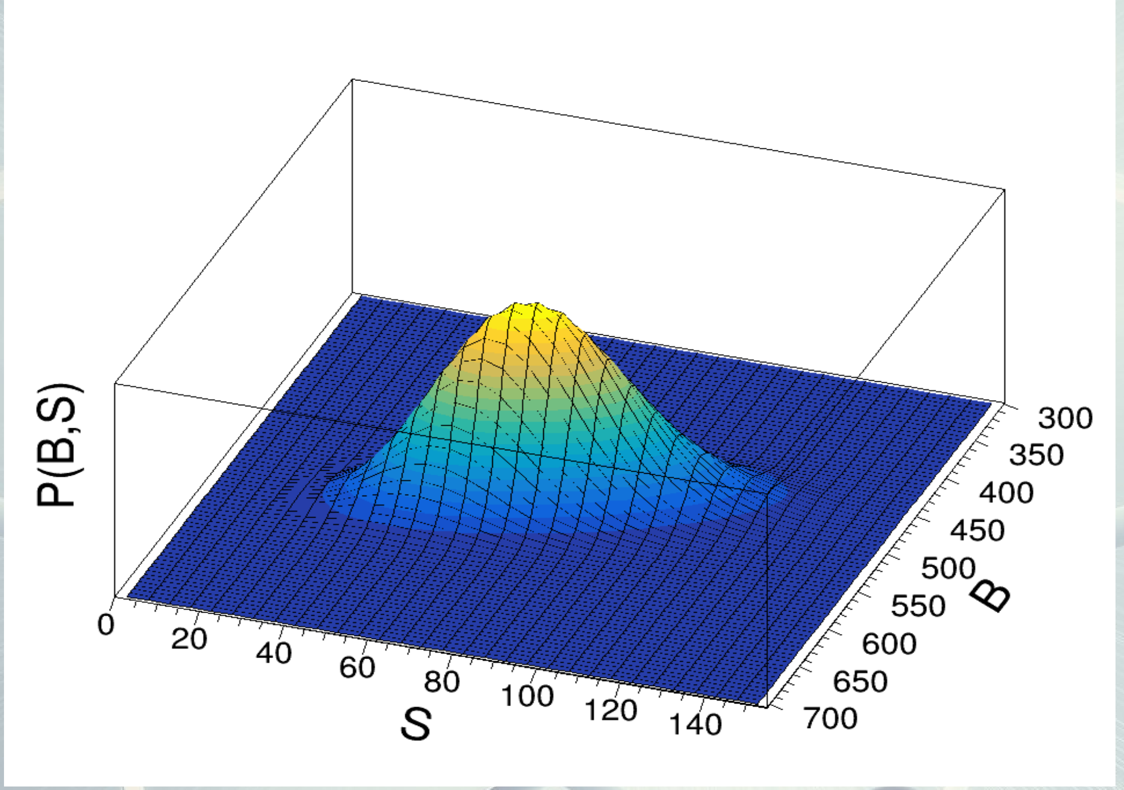


From which an upper limit on the PEP violation probability is obtained (90% Probability):

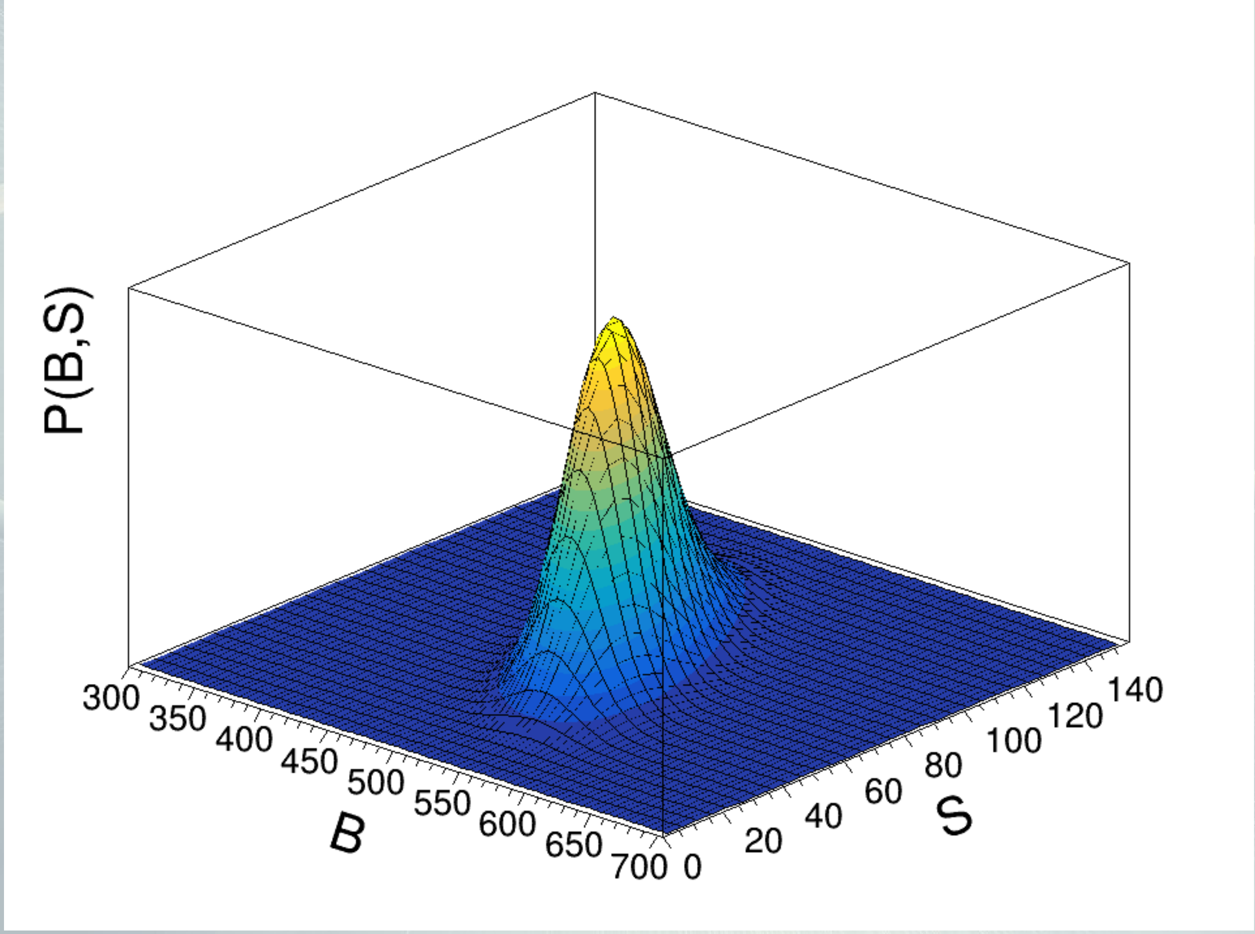
$$\lambda < 4 \cdot 10^{-13}$$

VERY VERY Preliminary

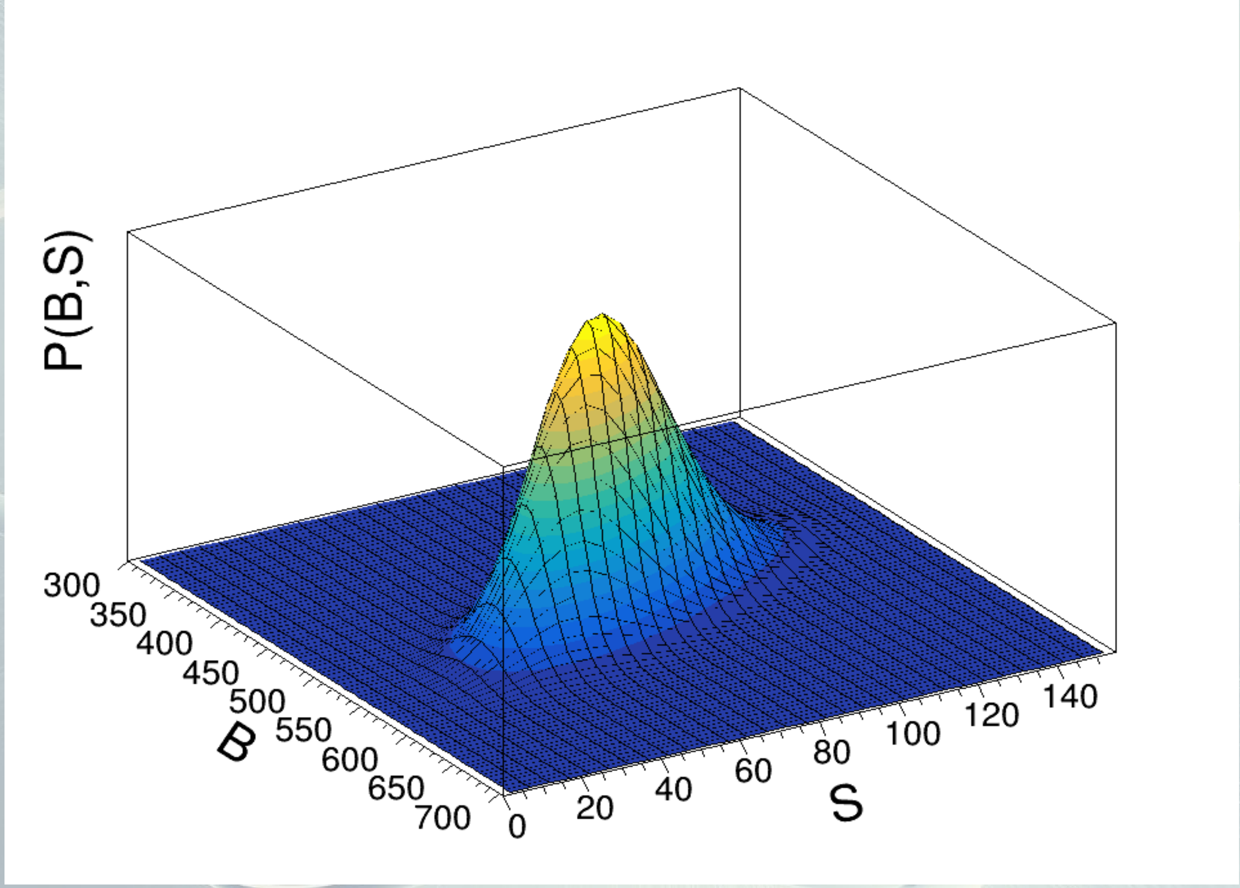
Accounting for the information in each bin



Accounting for the information in each bin

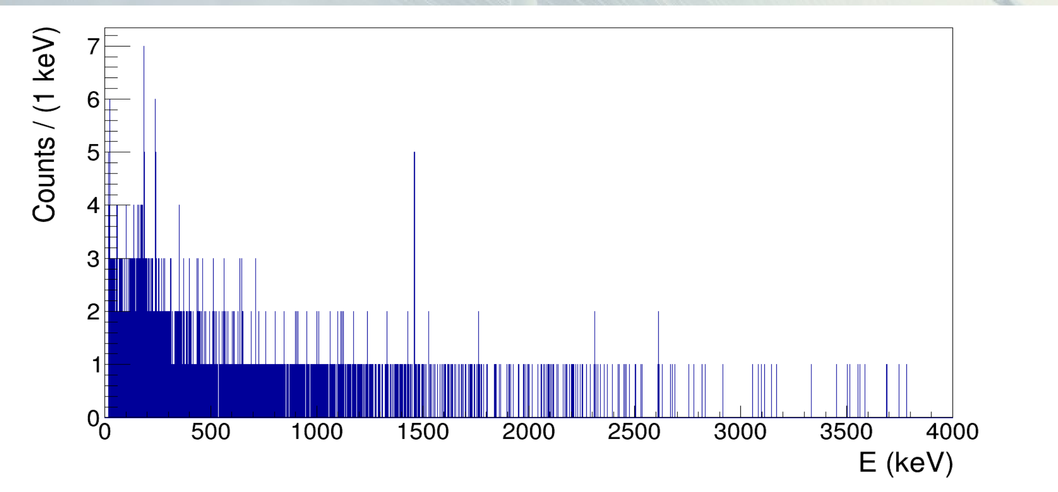


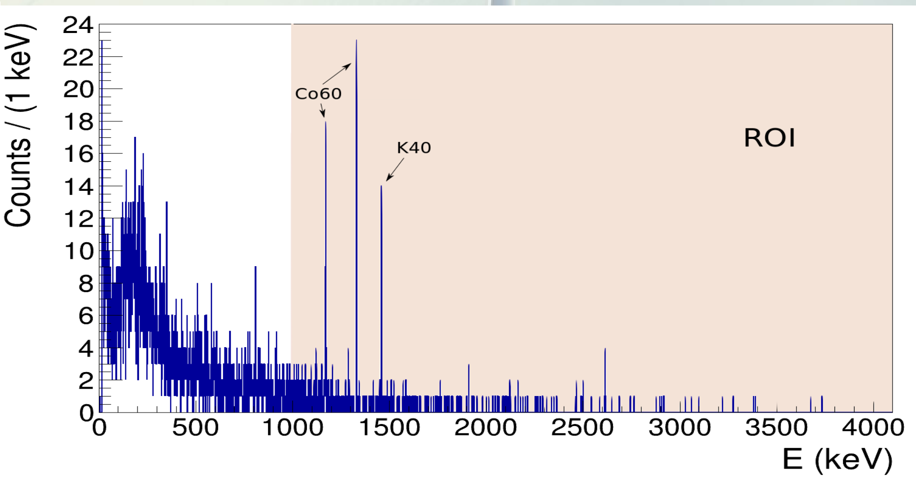
Accounting for the information in each bin

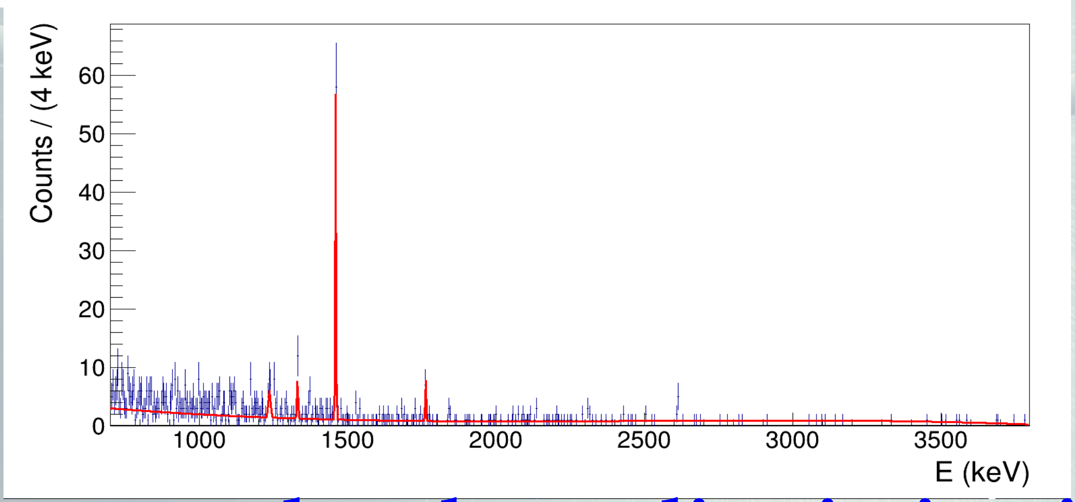


Future perspectives

HPGe detector + ultrapure Pb active shielding:







BEGe detector + pulse shape discrimination

pushing the lower E threshold to few keV


Thanks

p. d. f. of λ
experimental information

Goal: obtain the probability distribution function PDF(λ) of the collapse rate parameter given:

- the experimental information

total number of counts in the selected energy range:

$$f(z_c) = \frac{\Lambda_c^{z_c} e^{-\Lambda_c}}{z_c!}$$

from MC of the detector →

- z_b = number of counts due to background,

from theory weighted by detector efficiency →

- z_s = number of counts due to signal,
- $z_c = z_b + z_s \; ; \; z_s \sim P_{\Lambda_s} \; ; \; z_b \sim P_{\Lambda_b}$,

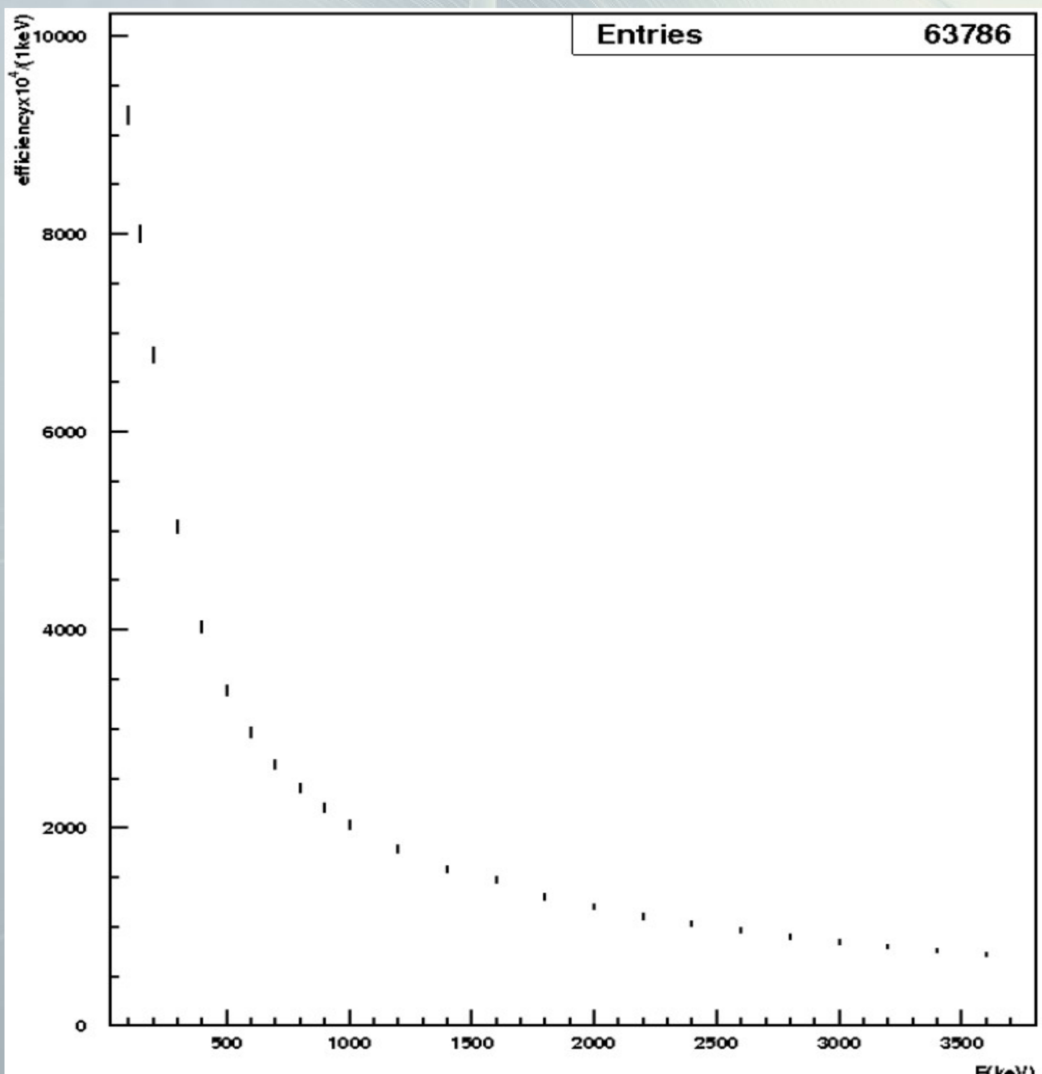
$$f(\lambda|\mathrm{ex},\mathrm{th}) = \frac{(\Lambda_s(\lambda)+\Lambda_b)^{z_c} \cdot e^{-(\Lambda_s(\lambda)+\Lambda_b)}}{z_c!} \qquad \lambda < 10^{-6}\mathrm{s}^{-1}$$

Advantages .. - possibility to extract unambiguous limits corresponding to the probability level you prefer,
- *f*(λ) can be updated with all the experimental information at your disposal by updating the likelihood,
- competing or future models can be simply implemented

Expected spontaneous emission signal

Each material spontaneously emits with different ***masses*** **,** ***densities*** **and ε(*E*)**

(depending on the material and the geometry of the detector)



Simulated detection eciency for γs produced inside the Germanium detector, multiplied by 10^4

Photon detection efficiencies obtained by means of MC simulations, ganerating γs in the range (E1 – E2) (25 points for each material).

The detector components have been put into a validated MC code
(MaGe, Boswell et al., 2011)
Based on the GEANT4 software library
(Agostinelli et al., 2003)

Expected spontaneous emission signal

Expected signal is obtained by weighting for the detection efficiencies

efficiency distributions fitted to obtain the efficiency functions:

$$\epsilon_i(E) = \sum_{j=0}^{ci} \xi_{ij} E^j$$

to obtain the signal predicted by theory & processed by the detector

$$z_s(\lambda) = \sum_i \int_{E_1}^{E_2} \frac{d\Gamma}{dE}\bigg|_i \epsilon_i(E)\, dE =$$

$$= \sum_i \int_{E_1}^{E_2} N_{pi}^2\, \alpha_i\, \beta\, \frac{\lambda}{E} \sum_{j=0}^{ci} \xi_{ij} E^j\, dE$$

with:

$$\alpha_i = m_i n_i T,$$

$$\beta = \frac{\hbar e^2}{4\pi^2 \epsilon_0 c^3 m_N^2 r_c^2}$$

Diosi – Penrose collapse model

- Wave function collapse induced by gravity:

When a system is in a quantum superposition of two different positions then a corresponding superposition of two
different space-times is generated, the superposition of the two bumps in space-time associated to
the two mass distributions.

Superpositions of different geometries would be suppressed.

- The more massive the superposition, the faster it is suppressed.

The model characteristic parameter:

R_0 - **size of the** wave function defining the mass distribution

First limit from Ge detector measurement

Q. Fu, Phys. Rev. A 56, 1806 (1997) → upper limit on λ comparing with the radiation measured with 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

$$\frac{d\Gamma(E)}{dE} = c\,\frac{e^2\lambda}{4\pi^2 r_C^2 m^2 E} = (4)\cdot(8.29\ 10^{24})\cdot(8.64\ 10^4)\frac{e^2\lambda}{4\pi^2 r_C^2 m^2 E} \leq \left.\frac{d\Gamma(E)}{dE}\right|_{ex}$$

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

(Atoms / Kg) in Ge

1 day

S. L. Adler, F. M. Ramazanoglu, J. Phys. A40 (2007), 13395
J. Mullin, P. Pearle, Phys. Rev. A90 (2014), 052119

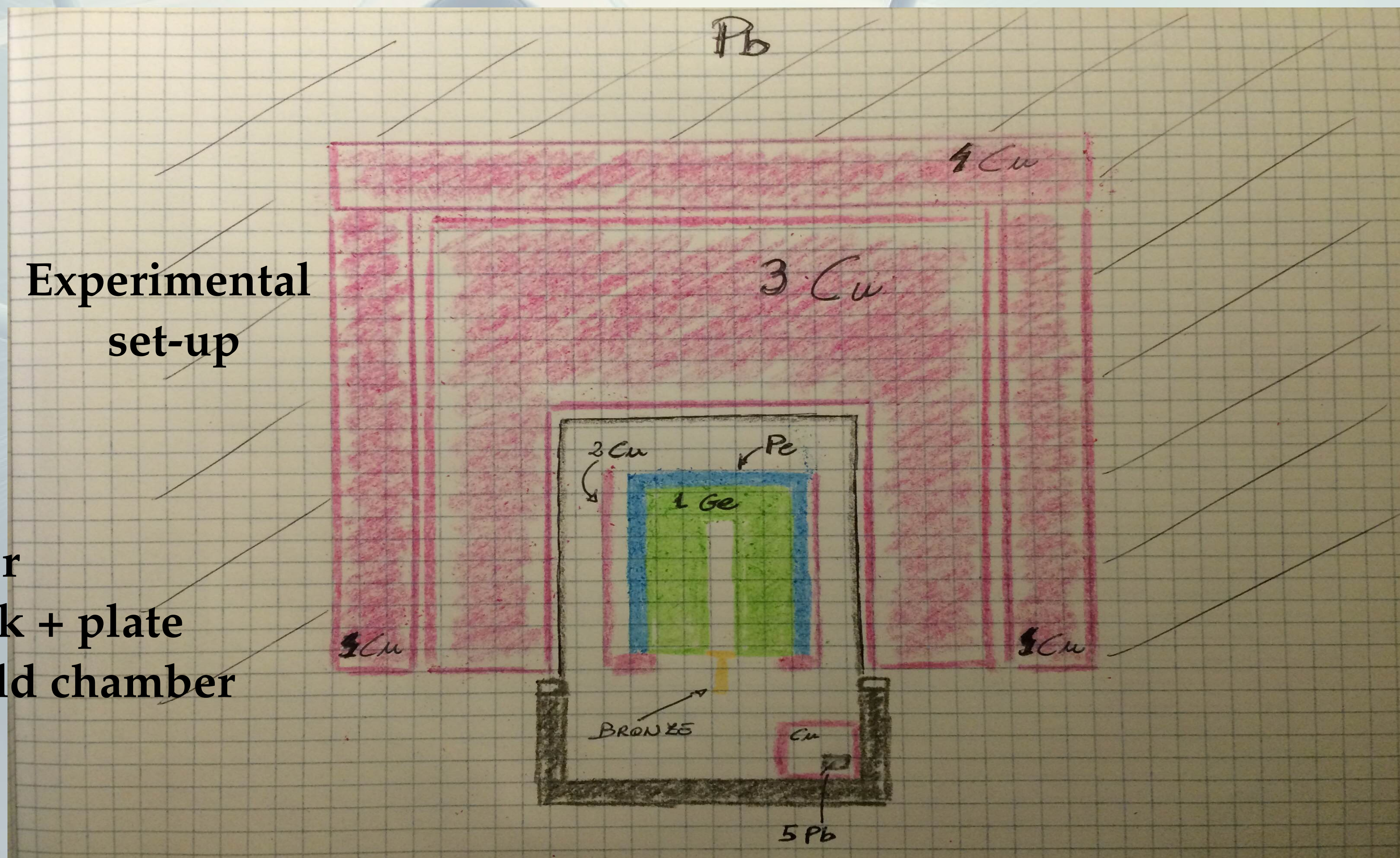
$\lambda < 2 \times 10^{-16}\ s^{-1}$ non-mass proportional
$\lambda < 8 \times 10^{-10}\ s^{-1}$ mass proportional

The setup

High purity Ge detector measurement collaboration with M. Laubenstein @ LNGS (INFN):

- **active Ge detector surrounded by complex electrolytic Cu + Pb shielding**
- **polyethylene plates reduce the neutron flux towards the detector**
- **shield + cryostat enclosed in air tight steel housing flushed with nitrogen to avoid contact with external air (and thus radon).**

Experimental set-up



1 = Ge crystal
2 = inner Copper
3 = Copper block + plate
4 = Copper shield chamber
5 = Lead shield.

Spontaneous emission including nuclear protons

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

A. Bassi & S. Donadi

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

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

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*

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

QMSL quantum mechanics with spontaneous localizations

- **The basis on which reduction takes place** must guarantee a definite position in space to macroscopic objects

Assumptions of the model:

a) each particle of a system of n distinguishable particles experiences sudden spontaneous localizations with mean rate λ_i

$$|\psi\rangle \quad \xrightarrow{\text{localization}} \quad \frac{|\psi^i_{\mathrm{x}}\rangle}{\||\psi^i_{\mathrm{x}}\rangle\|}$$

$$|\psi^i_{\mathrm{x}}\rangle = L^i_{\mathrm{x}}\,|\psi\rangle$$

linear operator in *n*-particle Hilbert space localizes particle *i* around x

$$L^i_{\mathrm{x}} \quad = \quad \left(\frac{\alpha}{\pi}\right)^{3/4} e^{-\frac{\alpha}{2}(\mathrm{q}_i - \mathrm{x})^2}$$

localization amplitude

q_i is the position operator for particle i

b) the probability for the occurrence of a localization around x is:

$$P_i(\mathrm{x}) \quad = \quad \||\psi^i_{\mathrm{x}}\rangle\|^2$$

c) between two localizations the system evolves according to the Schördinger equation.

QMSL quantum mechanics with spontaneous localizations

- Ex. Initial state is a superposition of two Gaussian functions

$$\psi(z) = \frac{1}{\mathcal{N}}\left[e^{-\frac{\gamma}{2}(z+a)^2} + e^{-\frac{\gamma}{2}(z-a)^2}\right]$$

with $a \gg 1/\sqrt{\alpha}$ and $1/\sqrt{\gamma} \ll 1/\sqrt{\alpha}$

a) localization around *a:*

$$\psi(z) \longrightarrow \psi_a(z) = \frac{1}{\mathcal{N}_a}\left[e^{-2\alpha a^2}\, e^{-\frac{\gamma}{2}(z+a)^2} + e^{-\frac{\gamma+\alpha}{2}(z-a)^2}\right]$$

Gaussian around -*a* exponentially suppressed

The state localizes around *a* with probability ~ ½

b) localization around x = 0:

- the w. f. does not change in an appreciable way
- the probability is extremely small ~ $e^{-\alpha a^2}$

QMSL choice of the parameters

We want the modification of the dynamics for microscopic systems with respect to the standard one to be totally irrelevant

$$\lambda_{\text{micro}} \simeq 10^{-16}\,\text{sec}^{-1}$$

Microscopic systems are localized once every $10^8 - 10^9$ years. For macroscopic objects made of N_{avogadro} constituents

$$\lambda_{\text{macro}} \simeq 10^{7}\,\text{sec}^{-1}$$

We want the localization amplitude large with respect to atomic dimensions → when a "rare" localization takes place for a constituent of an atomic system, the internal structure is not modified, but the decupling of internal and CM motion holds. At the same time should avoid superpositions of appreciably different locations of macroscopic objects:

$$1/\sqrt{\alpha} \simeq 10^{-5}\,\text{cm.}$$

The non-Hamiltonian term implies a non-conservation of energy, for a free particle:

Conserved energy for a Schördinger evolution

$$\langle\langle E \rangle\rangle = \langle\langle E \rangle\rangle_{\text{Sch}} + \frac{\lambda\alpha\hbar^2}{4m} t$$

$$\frac{\delta E}{t} \simeq 10^{-25}\ \text{eV sec}^{-1}$$

Lower limit on the R_0 parameter of the DP

- taking for the spontaneous emission rate:

$$\frac{d\Gamma_t}{d\omega} = \frac{2}{3}\frac{Ge^2N^2N_a}{\pi^{3/2}\varepsilon_0 c^3 R_0^3\omega}$$

- similarly the *pdf* (R_0):

$$\tilde{p}\left(\Lambda_c(R_0)|p(z_c|\Lambda_c)\right) = \frac{[\Lambda_c(R_0)]^{z_c}\, e^{-\Lambda_c}\, \theta(\Lambda_c^{max} - \Lambda_c)}{\int_0^{\Lambda_c^{max}} [\Lambda_c(R_0)]^{z_c}\, e^{-\Lambda_c}\, d\Lambda_c},$$

$$\Lambda_c(R_0) = \Lambda_s + \Lambda_b = \frac{a}{R_0^3} + 508.$$

from the cumulative :

$$\tilde{P}\left(\bar{\Lambda}_c\right) = \frac{\gamma(z_c+1, \bar{\Lambda}_c)}{\gamma(z_c+1, \Lambda_c^{max})} = 0.95$$

$$R_0 > 0.54 \times 10^{-10}\ \mathrm{m}$$

Diosi – Penrose collapse model

- Wave function collapse induced by gravity:

When a system is in a quantum superposition of two different positions then a corresponding superposition of two different space-times is generated, the superposition of the two bumps in space-time associated to the two mass distributions.

Superpositions of different geometries would be suppressed.

- The more massive the superposition, the faster it is suppressed.

The model characteristic parameter:

R_0 - size of the wave function defining the mass distribution