X-ray spectroscopy at the Gran Sasso underground laboratory to test foundations of Quantum Mechanics

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Challenges in Photon Induced Interactions
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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: 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**

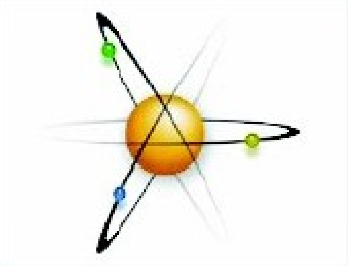
$\langle N(\mathbf{x})\rangle_t = \langle\psi_t|N(\mathbf{x})|\psi_t\rangle$ — **nonlinearity**

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

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

Which values for λ and r_c?

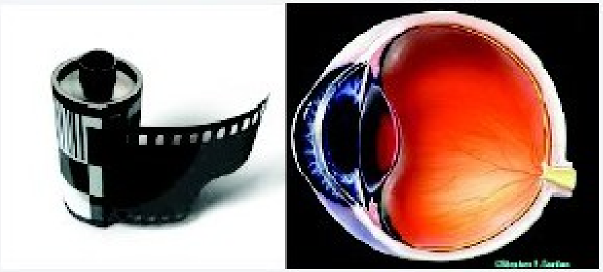
Microscopic world
(few particles)



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

QUANTUM – CLASSICAL TRANSITION (Adler - 2007)

Mesoscopic world
Latent image formation
+
perception in the eye
($\sim 10^4$ - 10^5 particles)



S.L. Adler, JPA 40, 2935 (2007)

A. Bassi, D.A. Deckert & L. Ferialdi, EPL 92, 50006 (2010)

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

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 in non relativistic QM the interaction with the stochastic field increases the expectation value of particle's energy

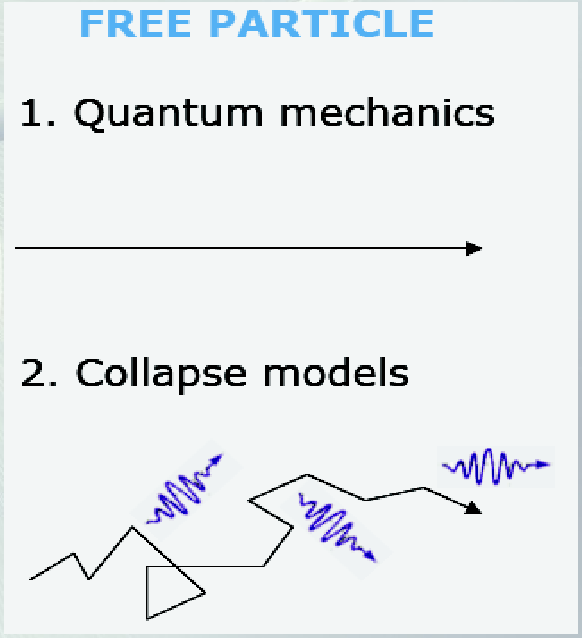
↓

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

1) 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)



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, 13395
J. Mullin, P. Pearle, Phys. Rev. A90, 052119

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

Improvement from IGEX data

ADVANTAGES:

- 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))

- exposure of 80 *kg day* in the energy range: ΔE = (4 – 49) *keV* « m_e = 512 keV (A. Morales et al., IGEX collaboration Phys. Lett. B 532, 8-14 (2002)) → possibility to perform a fit,

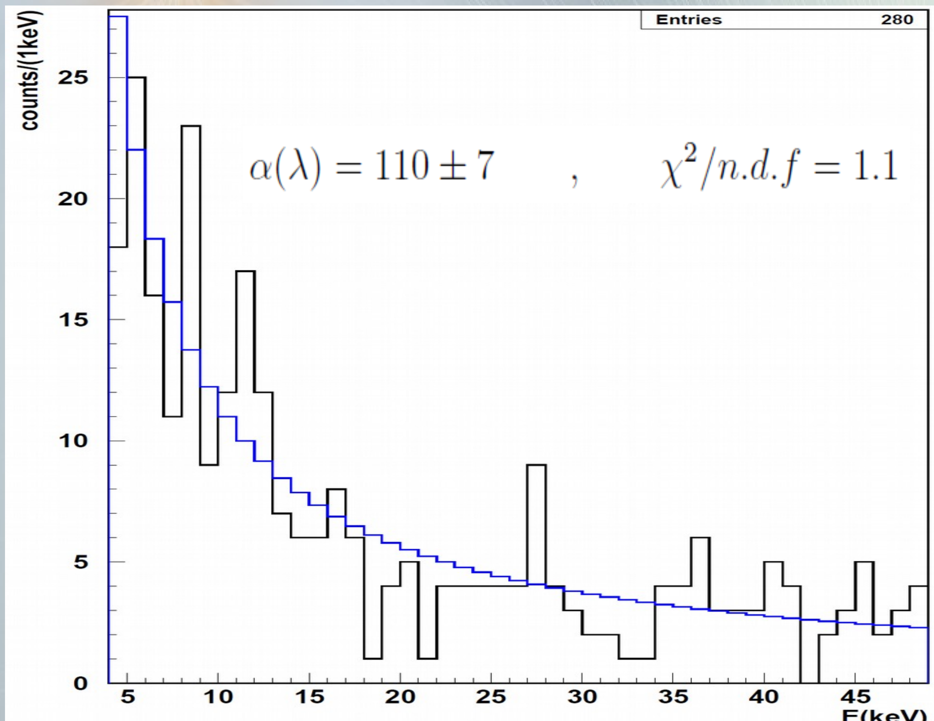
DISADVANTAGE:

- no simulation of the known background sources is available . . .

ASSUMPTION 1 - the upper limit on λ corresponds to the case in which all the measured X-ray emission would be produced by spontaneous emission processes

ASSUMPTION 2 - the detector efficiency in ΔE is one, muon veto and pulse shape analysis un-efficiencies are small above 4keV.

Improvement from IGEX data



Spectrum fitted with energy dependence:

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

bin contents are treated with Poisson statistics.

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

(assume $r_C = 10^{-7}$ m) ...

2 O.M. improovement

$\lambda < 2.5 \times 10^{-18}$ s^{-1}	**$\lambda < 8.5 \times 10^{-12}$ s^{-1}**
No mass-proportional	mass-proportional

J. Adv. Phys. 4, 263-266 (2015)

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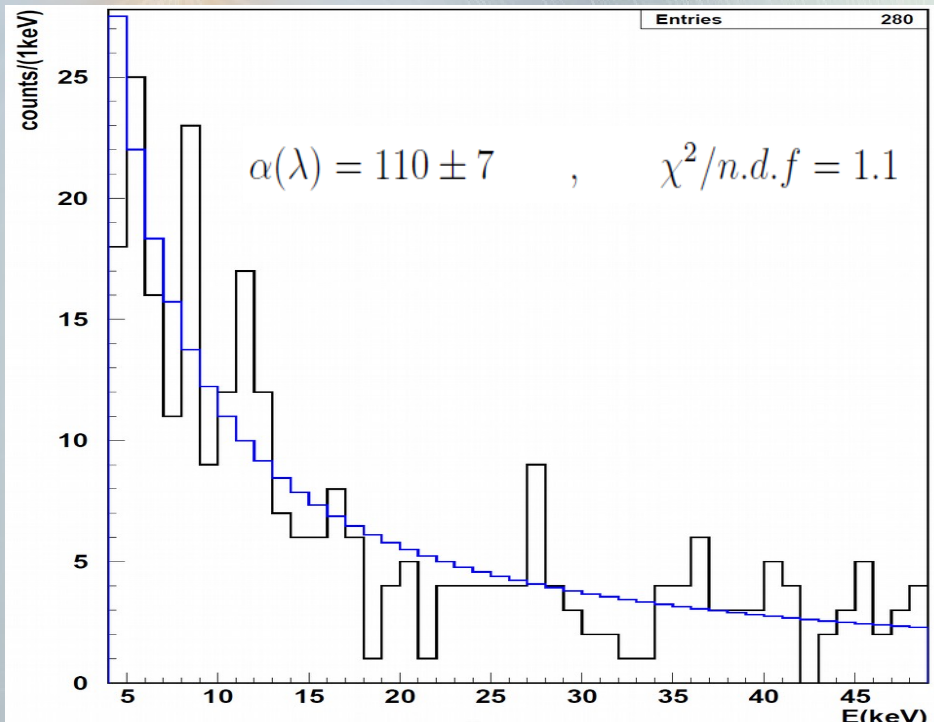

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J. Adv. Phys. 4, 263-266 (2015)

- **No mass-proportional model excluded (for white noise, $r_C = 10^{-7}$ m)**
- **Adler's value excluded even in the mass-proportional case (for white noise, $r_C = 10^{-7}$ m)**

Further increasing the number of emitting electrons

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

let's extract the p. d. f. of λ:

experimental ingredient

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

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

theoretical ingredient

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

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 :

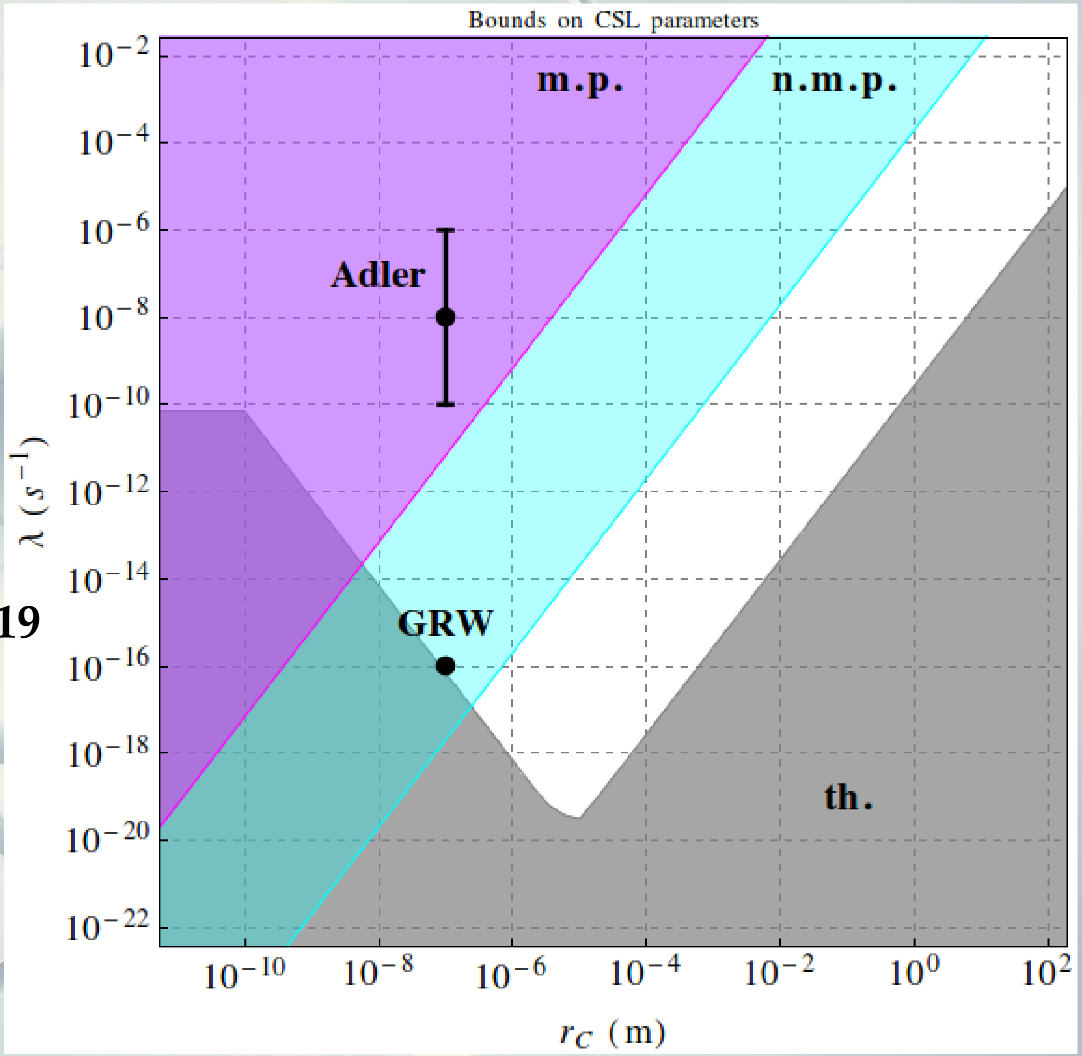
$$\int_0^{\lambda_0} G'(\lambda|G(y|P,\Lambda))\, d\lambda$$

Further increasing the number of emitting electrons

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

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

With probability 95%



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

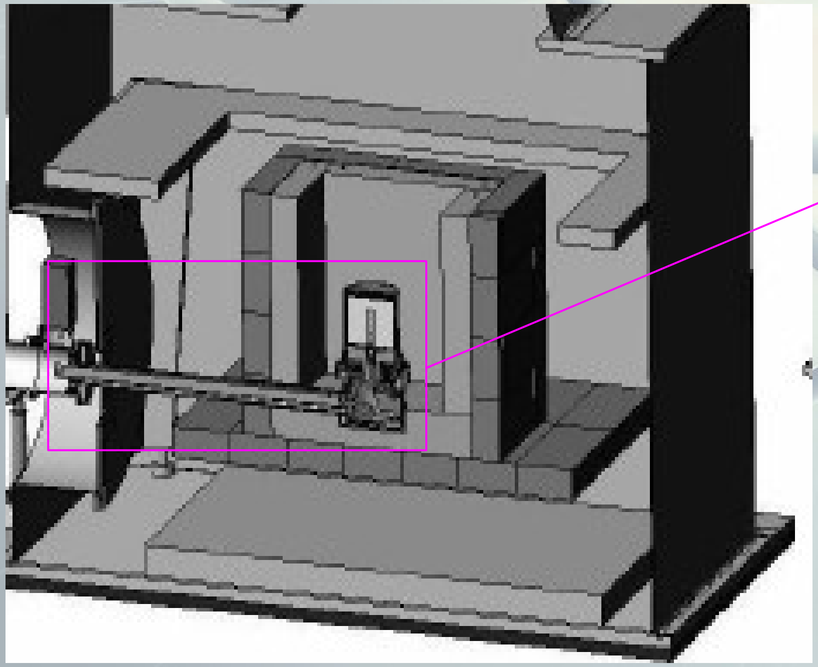
…

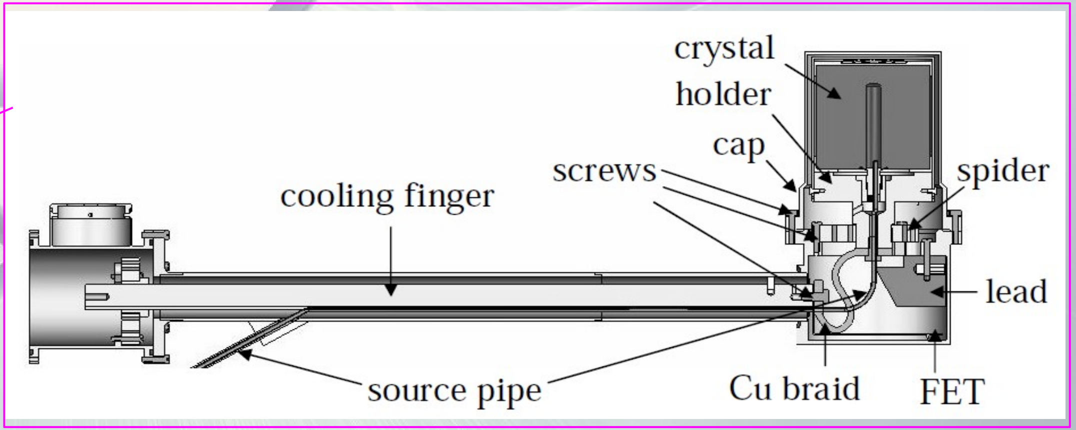
unfolding the BKG contribution from known emission processes.

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).**





p. d. f. of λ
theoretical information

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

- the theoretical information

A. Bassi & S. Donadi
University and INFN of Trieste

Rate of spontaneously emitted photons as a consequence of *p* and *e* interaction with the stochastic field,

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

(depending on λ)

as a function of *E*

(mass of the emitting material · number of atoms per unit mass · total acquisition time)

p. d. f. of λ
theoretical information

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

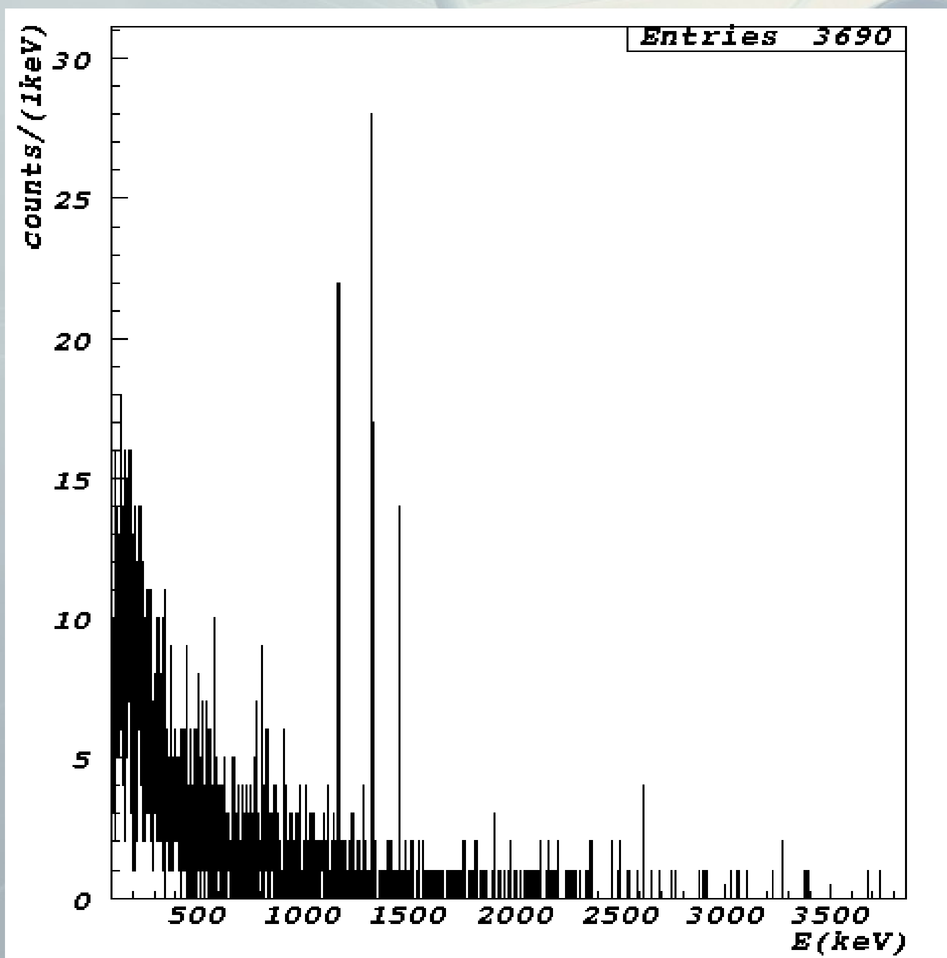
Provided that the wavelength of the emitted photon:

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

p. d. f. of λ
experimental information

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

- the experimental information



low background environment of the LNGS (INFN)

low activity Ge detectors.
(three months data taking with 2kg germanium active mass)

protons emission is considered in ΔE=(1000-3800)keV.

For lower energies residual cosmic rays and Compton in the outer lead shield complex MC staff.

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 →

from theory weighted by detector efficiency →

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

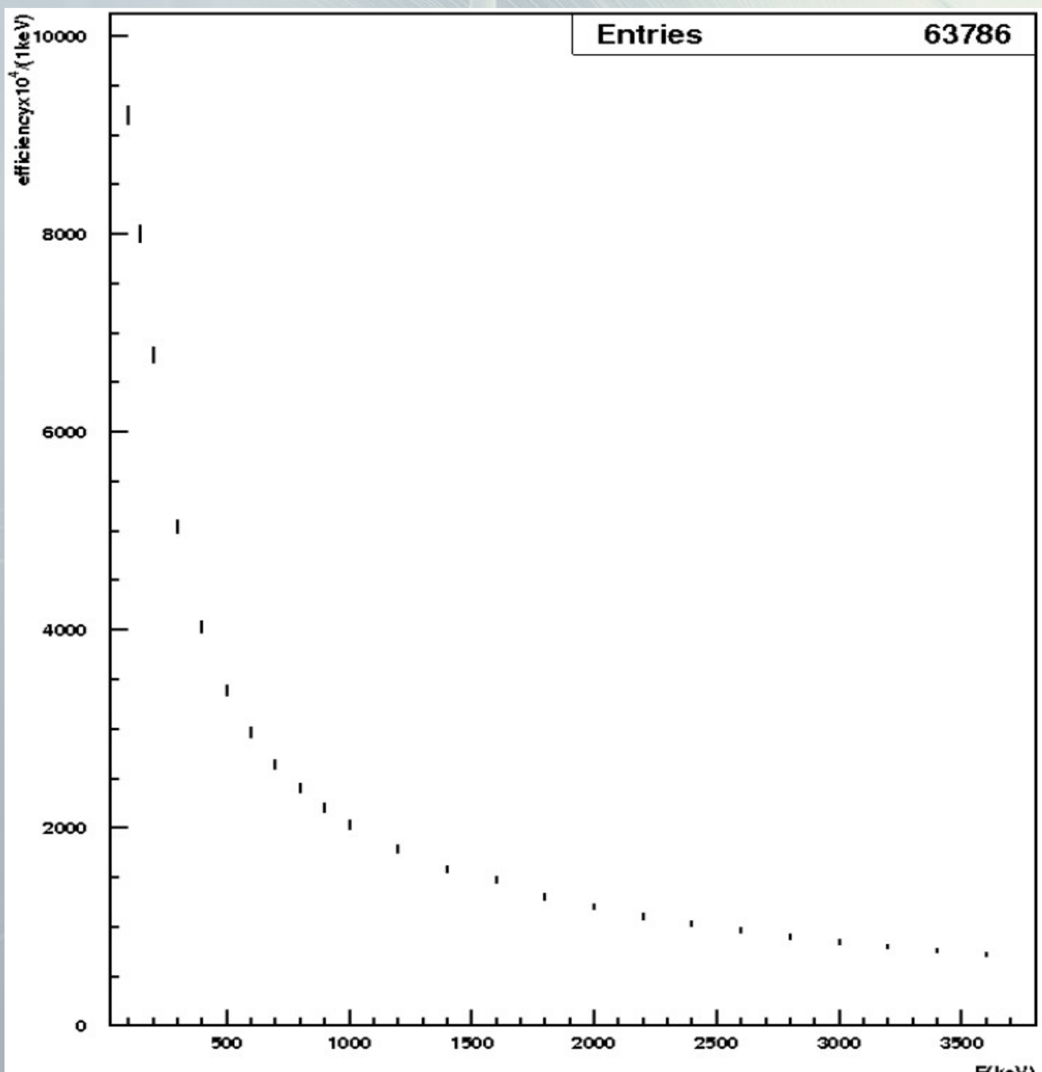
$$f(\lambda|\text{ex},\text{th}) = \frac{(\Lambda_s(\lambda) + \Lambda_b)^{z_c} \cdot e^{-(\Lambda_s(\lambda)+\Lambda_b)}}{z_c!} \qquad \lambda < 10^{-6}\text{s}^{-1}$$

Advantages .. - possibility to extract unambiguous limits corresponding to the probability level you prefer,
- $f(\lambda)$ 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:

$$\alpha_i = m_i n_i T,$$

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

Expected BKG

radionuclides decay simulation accounts for:

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

Considered 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**

Expected BKG

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- photons propagation and interactions inside the materials of the detector
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- 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 $\Lambda_b = z_b + 1$

Presently we can describe 88% of the measured spectrum

Upper limit for the collapse rate parameter λ

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

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

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

Preliminary

extract the limit at the desired probability level ...

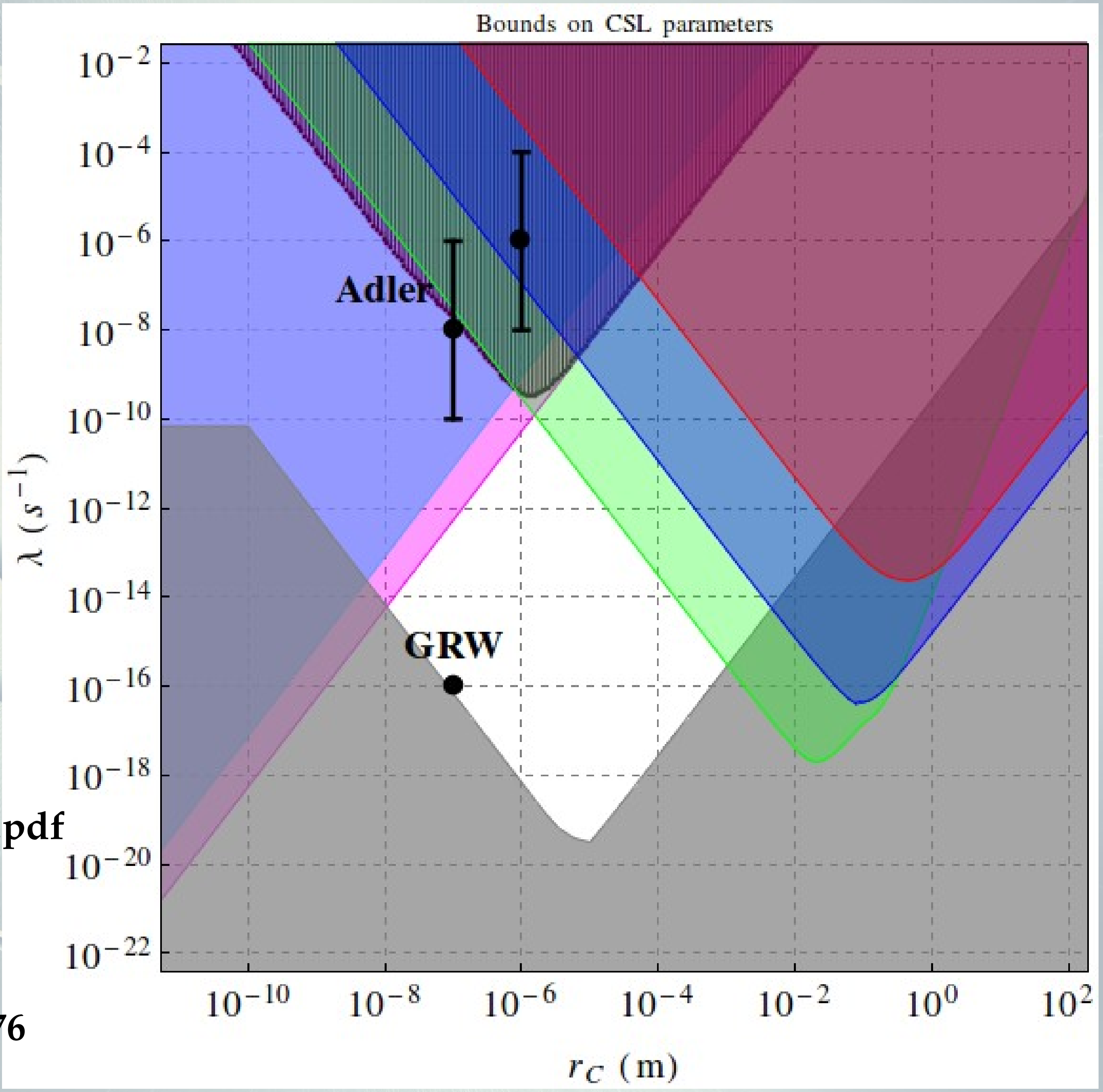
$\lambda < 5{,}2 \cdot 10^{-13}$ with a probability of 95%

Gain factor ~ 13

Upper limit for the collapse rate parameter λ

$\lambda < 5{,}3 \cdot 10^{-13}$ with a probability of 95%

Preliminary



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

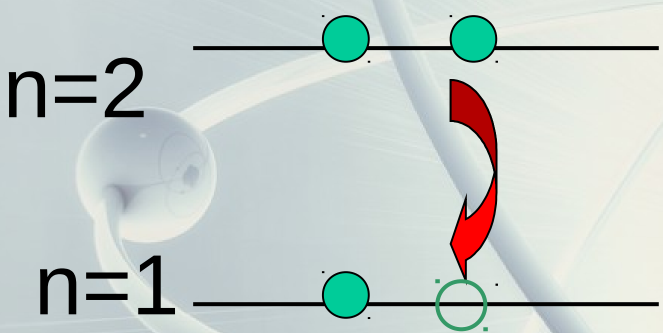
- Nanomechanical Cantilever Vinante, Mezzena, Falferi, Carlesso, Bassi, ArXiv 1611.09776

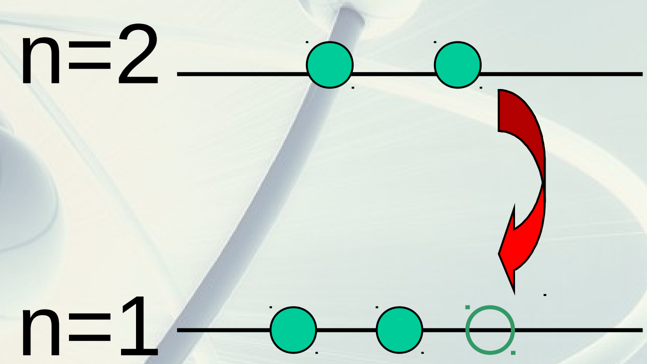
VIP experiment & VIP upgrade ...

An experiment to test the Pauli Exclusion Principle (PEP) for electrons in a clean environment (LNGS) using atomic physics methods.

Experimental method:

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





Normal 2p → 1s transition

2p → 1s transition violating Pauli principle

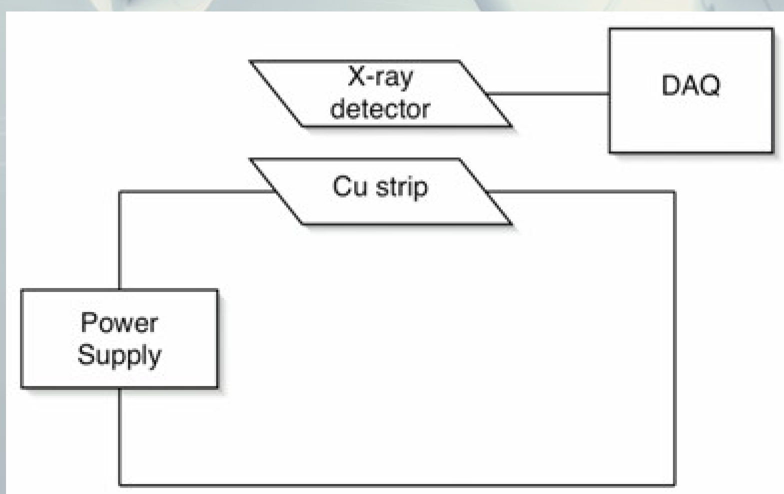
Energy 8.04 keV

Energy 7.7 keV

The pre-VIP experimental limit: Ramberg and Snow (RS)

Phys. Lett. ***B238*** *(1990) 438*

Search for anomalous electronic transitions in Cu induced by a circulating current ("new" external electrons, which interact with the valence electrons), namely transition from 2p to 1s already filled by 2 electrons, alternated to X-ray background measurements without current



$$N_X \geq \beta^2 \left(0.90 \cdot 10^{28}\right)$$

$$\beta^2/2 \leq 1.7 \cdot 10^{-26} \; (>95\; C.L.)$$

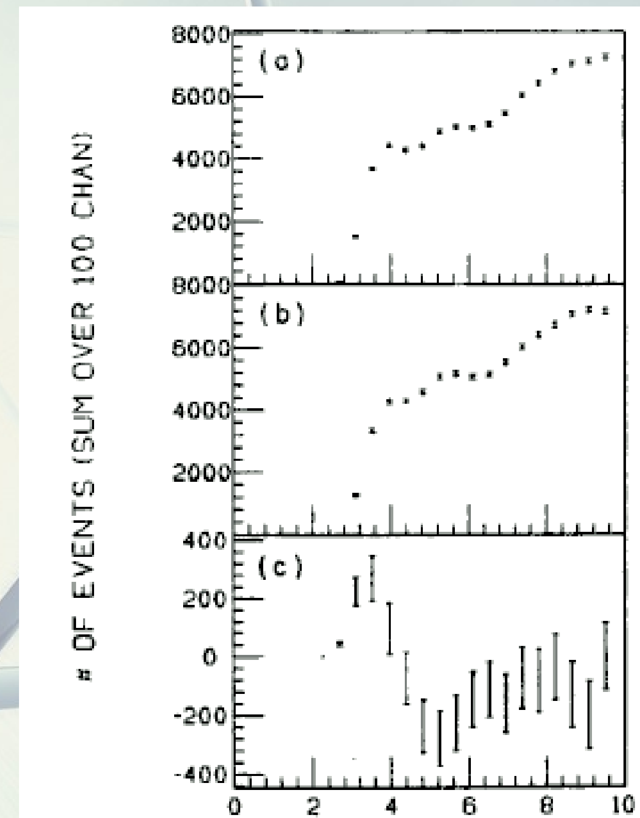


Fig. 2. (a) Number of triggers summed over 100 ADC channels, plotted versus equivalent X-ray energy with current-on in copper strip below X-ray counter. (Note the points are separated by 50 channels, so that only every other point is statistically independent). (b) Same as (a) but with no current passing through an identical strip of copper. (c) Difference between (a) and (b) after normalization at the 9.5 keV point.

VIP Experiment

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

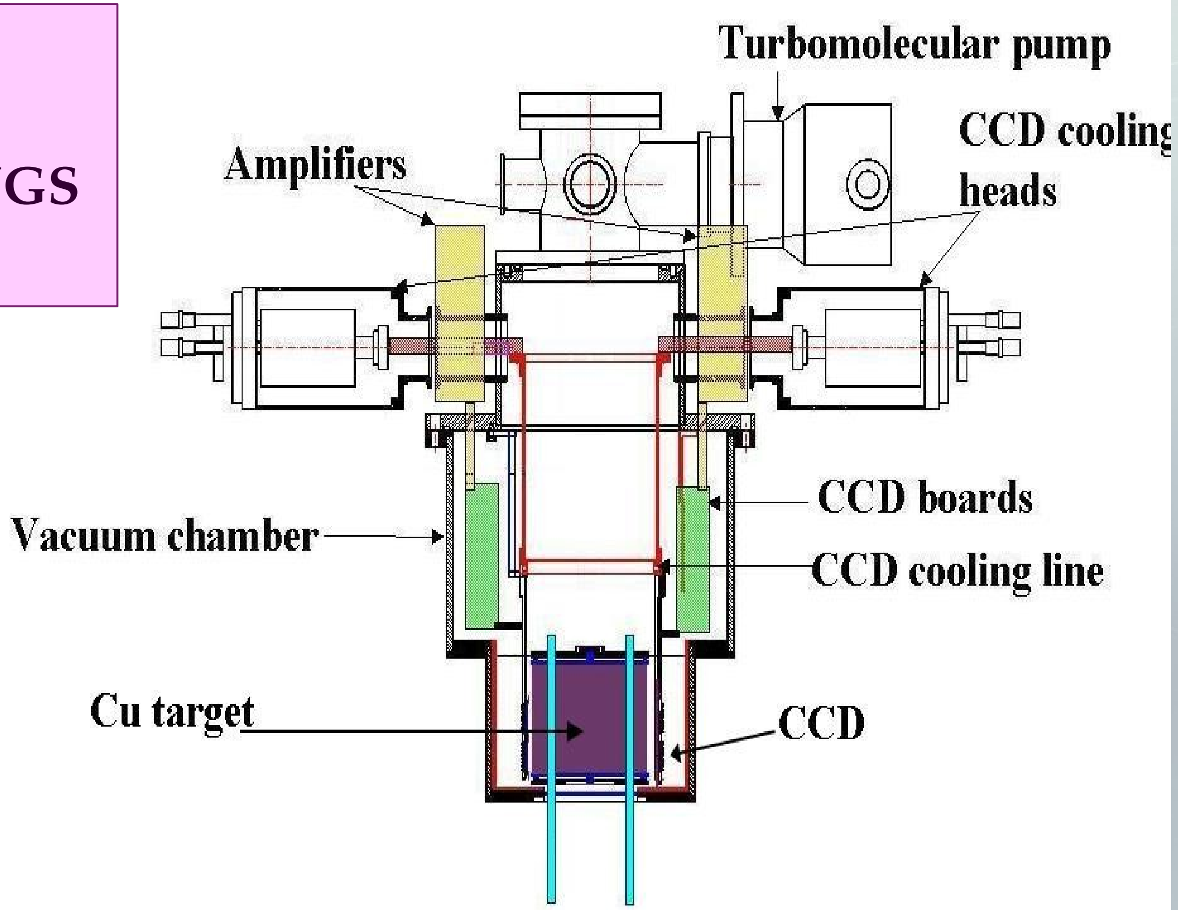
VIP setup: a) copper ultrapure cylindrical foil b) surrounded by 16 Charge Coupled Devices (CCD)

c) inside a vacuum chamber: CCDs cooled to 168K by a cryogenic system

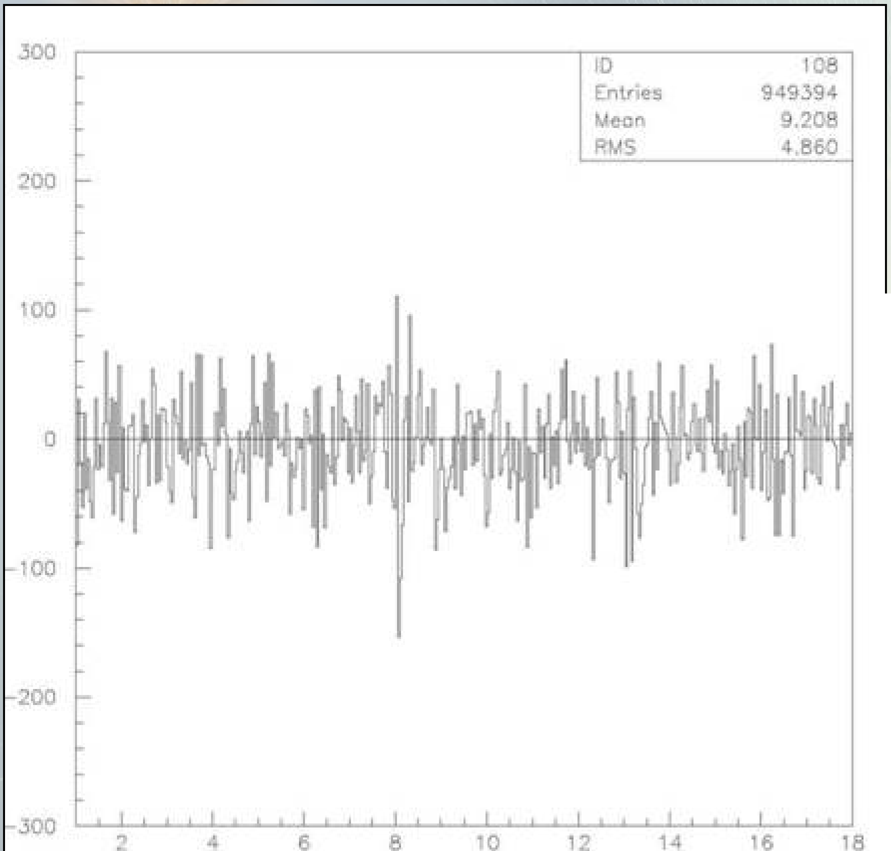
d) amplifiers + read out ADC boards.

Advantages

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



VIP Experiment



PEP violation Probability:

After about 2 years running

$$\beta^2/2 < 4.7 \times 10^{-29}$$

(Preliminary)

We have thus improved the limit obtained by Ramberg & Snow by a factor 400

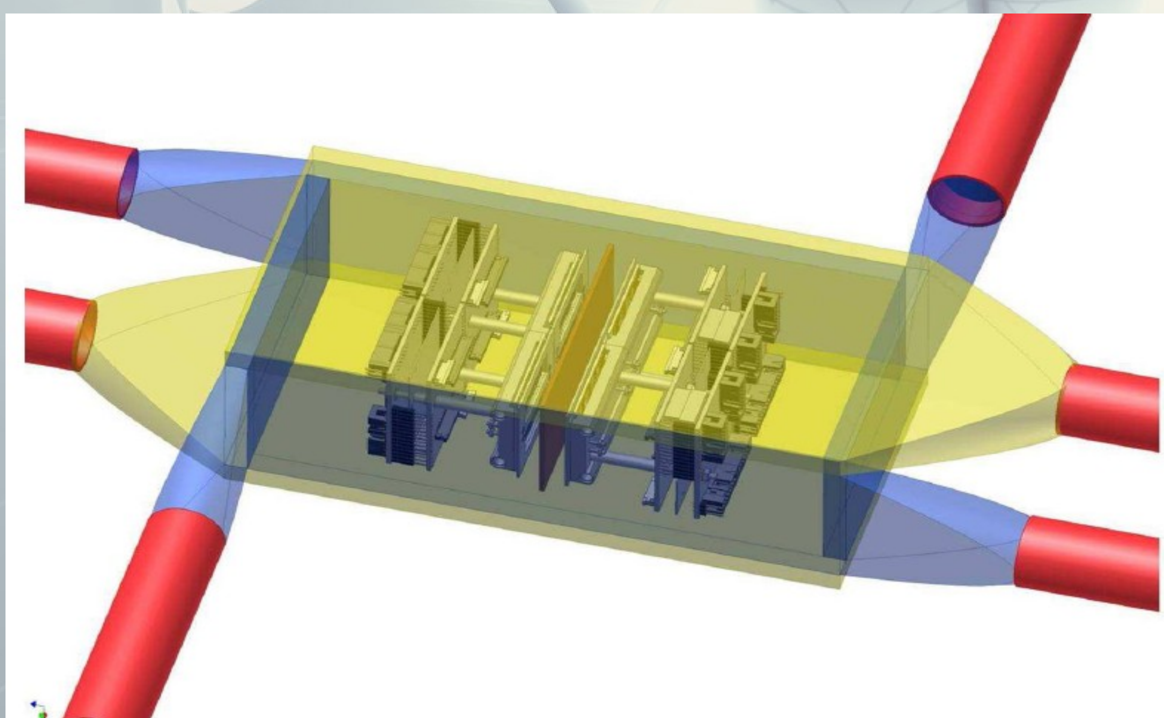
L. Sperandio Ph. D. Thesis, Univ. Roma2, 2008
C. Curceanu et al., Phys. Proc. 17 (2011) 40
C. Curceanu et al., Journal of Physics: Conference Series 361 (2012) 012006
J. Marton et al., J. Phys., Conf. Ser. 447 (2013) 012070

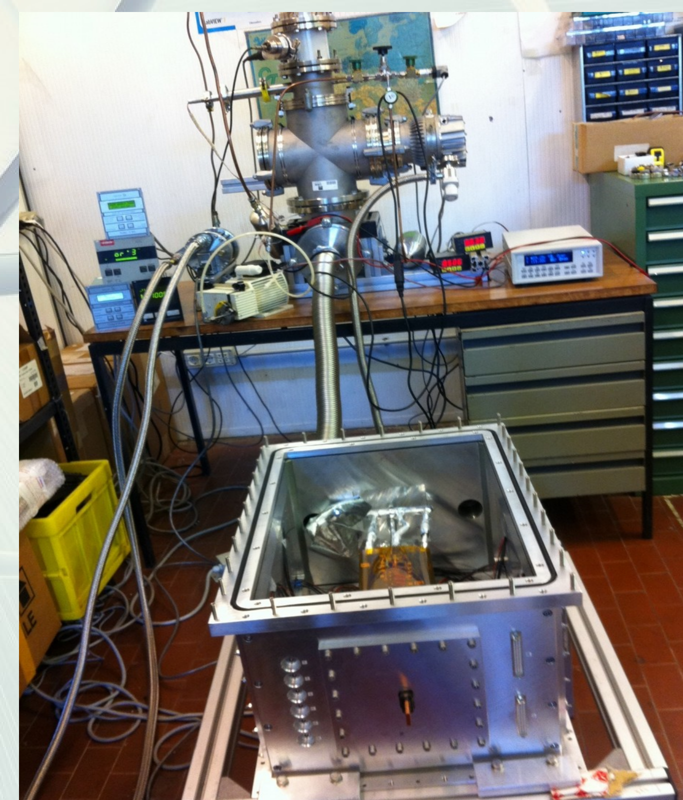
VIP upgrade

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 <u>gain factor 100</u> on $\beta^2/2$



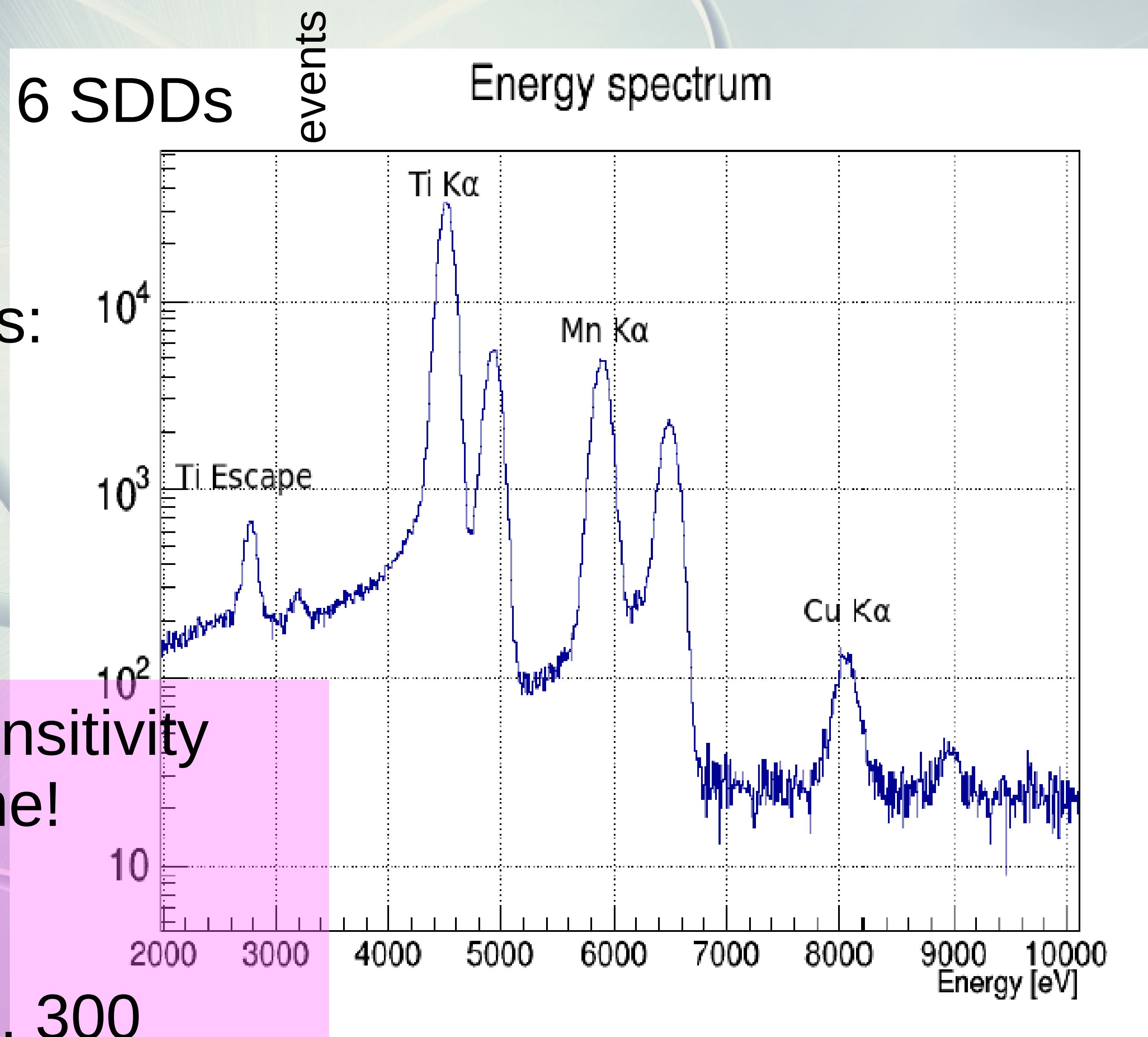


preliminary results

Energy spectrum of 6 SDDs
In about 70 days.

Preliminary analysis:

$\beta^2/2 < 4.2 \times 10^{-29}$



→ Already better sensitivity than VIP in short time!

C. Curceanu et al., Entropy 2017, 19(7), 300

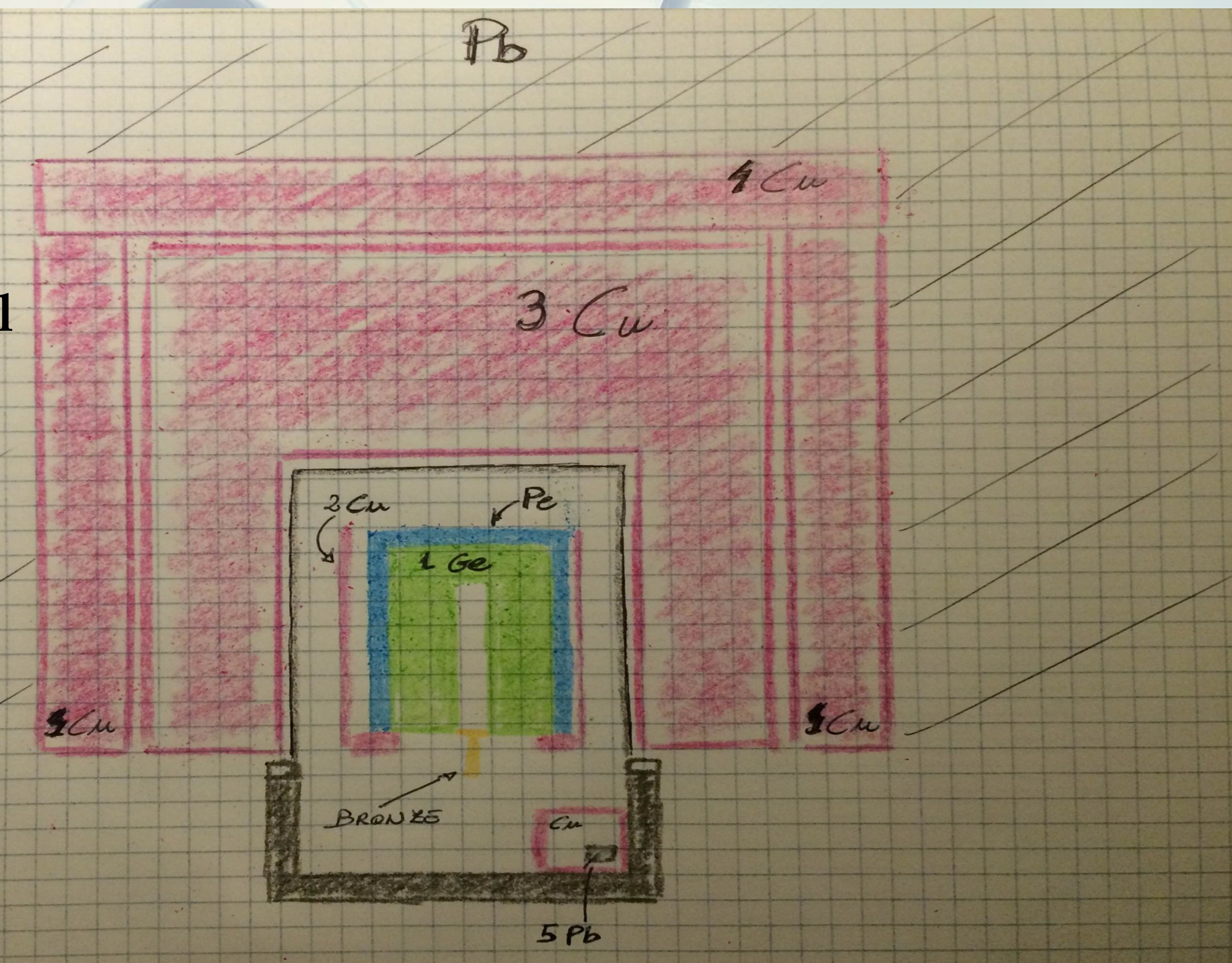

Thanks

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



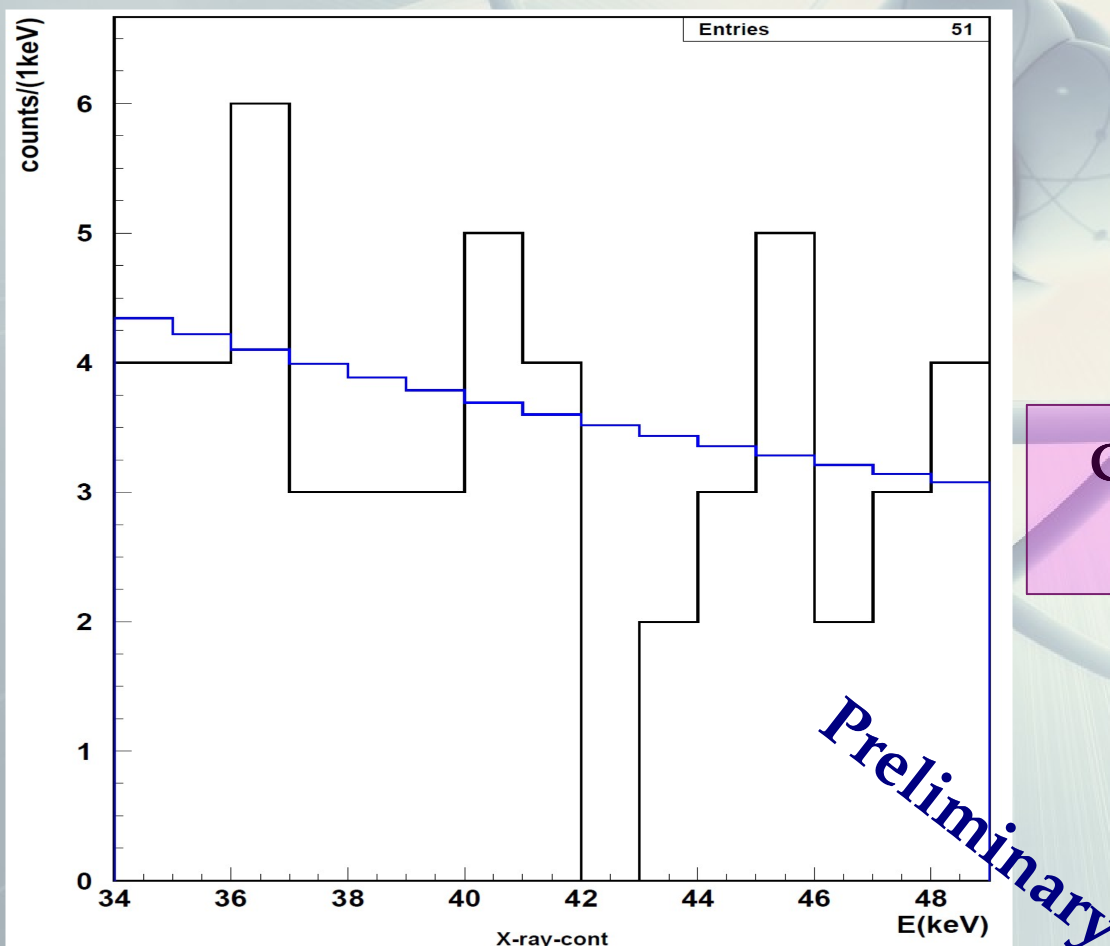
1 = Ge crystal
2 = inner Copper
3 = Copper block + plate
4 = Copper shield chamber
5 = Lead shield.

Spontaneous emission including nuclear protons

The interval ΔE = (35 – 49) *keV* of the IGEX measured X-ray spectrum was fitted assuming the predicted energy dependence:

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

Bayesian fit with α(λ) free parameter.



Fit result:

α(λ) = 148 ± 21

X^2/ n.d.f. = 0.8

Corresponding to the limit on the spontaneous emission rate:

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

Mass-proportional

3 O. M. improovement

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.

Probability distribution function 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:

from MC of the detector →

from theory weighted by detector efficiency →

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

$$f(z_c|P_{\lambda s}, P_{\lambda b}) = \sum_{z_s, z_b} \delta_{z_c, z_s + z_b} \, f(z_s|P_{\lambda s}) \, f(z_b|P_{\lambda b}) = \frac{(\Lambda_s + \Lambda_b)^{z_s + z_b} \, e^{(\Lambda_s + \Lambda_b)}}{z_c!}$$

The β parameter

$$N_X \geq \frac{1}{2}\beta^2 N_{new}\frac{N_{\text{int}}}{10} = \frac{\beta^2(\Sigma I \Delta t) D}{e \mu \rho z \sigma}$$

$$\int_T I(t)\,dt = 15.44 \cdot 10^6 C$$

$$D = 0.025\,m$$

$$m = 3.9 \cdot 10^{-8}\,m$$

$$\rho = 8.96 \cdot 10^3\,kg \cdot m^{-3}$$

$$s = 10\,m^2 \cdot kg^{-1}$$

$$z = 1.5 \cdot 10^{-3}\,m$$

$$N_X \geq \beta^2 (0.90 \cdot 10^{28})$$

$$\beta^2/2 \leq 1.7 \cdot 10^{-26}\ (>95\ C.L.)$$

The β parameter

Ignatiev & Kuzmin model ➡ **creation and destruction operators connect 3 states**

- the vacuum state |0>

- the single occupancy state |1>

- the <u>non-standard</u> double occupancy state |2>

through the following relations:

$a^{+}|0|1$ $a|0\ 0$

$a|1$

$a^{+}|1 = \beta\,|2 a^{+}|2 = 0$ $= |0 a|2 = \beta\,|1$

The parameter β quantifies the degree of violation in the transition.

|1> → |2>

It is very small and for <u>β → 0</u> we recover the <u>Fermi - Dirac statistic</u>.

The β parameter

this β can be simply related to the *q* parameter of the quon theory of Greenberg and Mohapatra

$$\frac{1}{2}\beta^2 = \frac{1+q}{2}$$

quon algebra is a sort of weighted average between fermion and boson algebra:

$$\frac{1+q}{2}\left[a_k, a_l^+\right]_- + \frac{1-q}{2}\left[a_k, a_l^+\right]_+ = \delta_{kl}$$

or also

$$a_k a_l^+ - q a_l^+ a_k = \delta_{kl}$$

Best Limits for PEP Violation

Nuclear transition	$^{12}C \rightarrow {}^{11}B + p$	BOREXINO	$\frac{\beta^2}{2} < 7.4 \cdot 10^{-60}$	G. Bellini et al., PRC 81 (2010) 034,317
Atomic transition	$I \rightarrow I + \gamma$ $Ge \rightarrow Ge + \gamma$ (K_α)	DAMA MALBEK	$\frac{\beta^2}{2} < 1{,}28 \cdot 10^{-47}$ $\frac{\beta^2}{2} < 2{,}92 \cdot 10^{-47}$	R. Bernabei et al., Eur. Phys. J. C62 (2009) 327 N.Abgrall et al., Eur. Phys. J. C (2016) 76.

PHYSICAL REVIEW C 81, 034317 (2010)

New experimental limits on the Pauli-forbidden transitions in ^{12}C nuclei obtained with 485 days Borexino data

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S. Zavatarelli,[5] H. de Ker
I. Machulin,[8] A. Sabelni
S. Gazzana,[10] C. Ghiano,[10] Aldo Ianni,[10] G. Korga,[10] D. Montanari,[10] A. Razeto,[10] R. Tartaglia,[10] M. Goeger-Neff,[11]
T. Lewke,[11] Q. Meindl,[11] L. Oberauer,[11] F. von Feilitzsch,[11] Y. Winter,[11] M. Wurm,[11] C. Grieb,[12] S. Hardy,[12] M. Joyce,[12]
S. Manecki,[12] L. Papp,[12] R. S. Raghavan,[12] D. Rountree,[12] R. B. Vogelaar,[12] W. Maneschg,[13] S. Schönert,[13] H. Simgen,[13]
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(Borexino Collaboration)

However: Stable system transitions !

Nuclear Physics in Astrophysics IV — IOP Publishing
Journal of Physics: Conference Series 202 (2010) 012039 — doi:10.1088/1742-6596/202/1/012039

…Exclusion

…J. Dai[6],
A.d'Angelo…, H.L. He[6], A. Incicchitti…, H.H. Kuang[6], X.H. Ma[6],
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Abstract. Searches for non-paulian nuclear processes, i.e. processes normally forbidden by the Pauli-Exclusion-Principle (PEP) with highly radiopure NaI(Tl) scintillators allow the test of this fundamental principle with high sensitivity. Status and perspectives are briefly addressed.

PEP Tests with atomic transitions

From S.R. Elliott et al., Found. Phys. 42 (2012) 1015

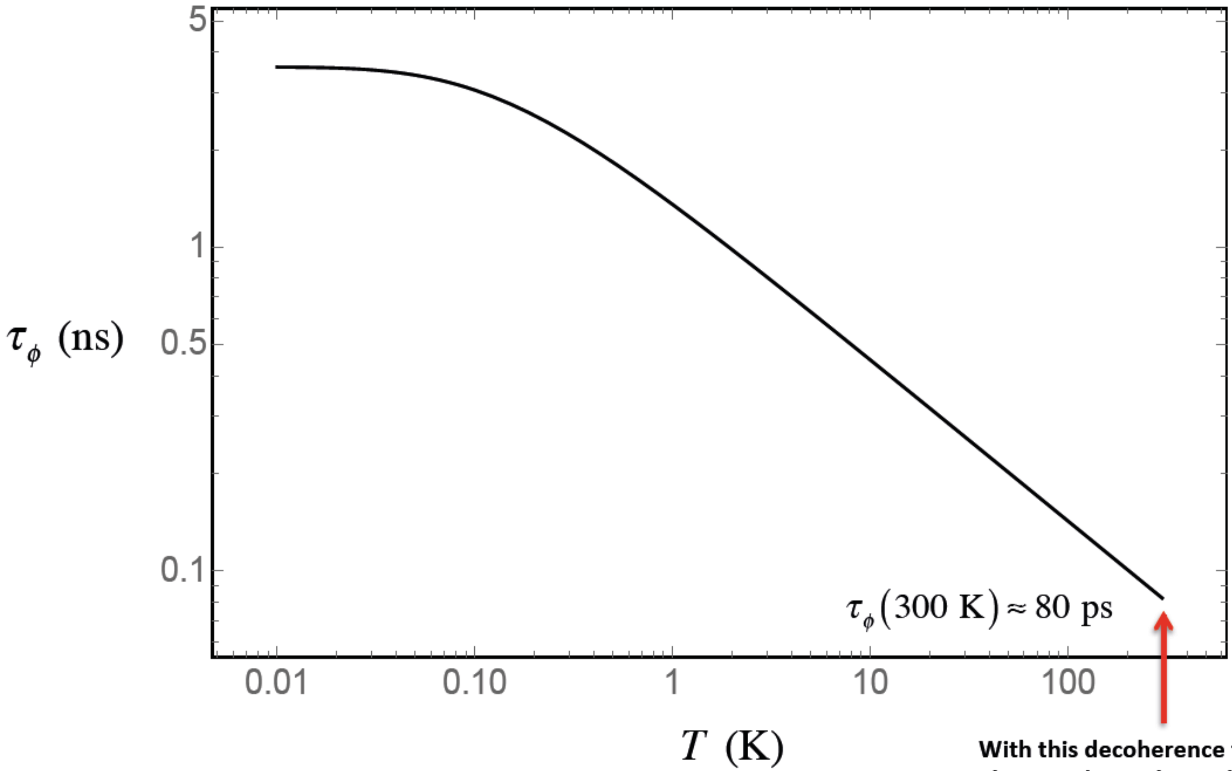
Process	Type	Experimental limit	$\frac{1}{2}\beta^2$ limit
Atomic transitions			
$\beta^- + \mathrm{Pb} \to \check{\mathrm{Pb}}$	Ia		3×10^{-2}
$e^-_{pp} + \mathrm{Ge} \to \check{\mathrm{Ge}}$	Ia		1.4×10^{-3}
$e^-_I + \mathrm{Cu} \to \check{\mathrm{Cu}}$	II		1.7×10^{-26}
$e^-_I + \mathrm{Cu} \to \check{\mathrm{Cu}}$	II		4.5×10^{-28}
$e^-_I + \mathrm{Cu} \to \check{\mathrm{Cu}}$	II		6.0×10^{-29}
$e^-_I + \mathrm{Pb} \to \check{\mathrm{Pb}}$	II		1.5×10^{-27}
$e^-_f + \mathrm{Pb} \to \check{\mathrm{Pb}}$	IIa		2.6×10^{-39}
$\mathrm{I} \to \check{\mathrm{I}} + \text{X-ray}$	III	$\tau > 2 \times 10^{27}$ sec	3×10^{-44}
$\mathrm{I} \to \check{\mathrm{I}} + \text{X-ray}$	III	$\tau > 4.7 \times 10^{30}$ sec	6.5×10^{-46}

Recently created fermions interacting with system

Distant fermions interacting with system

Stable system transition

Electron decoherence time at room temperature

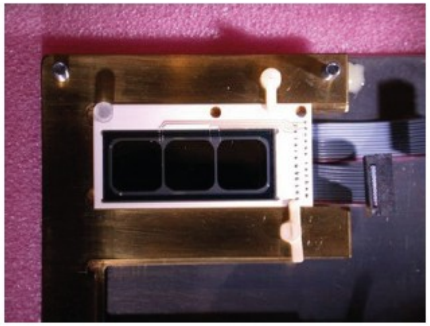


E. Milotti, Talk, May 29, 2015, Vienna

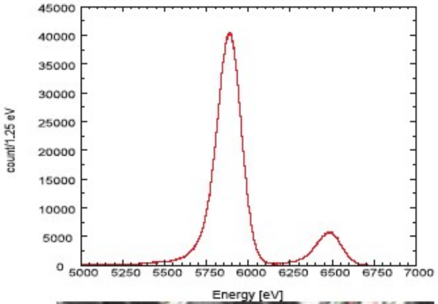
With this decoherence time and the electron thermal speed we find a decoherence length of about 10 μm

The conclusion is that after a time of the order of the *decoherence time* the electron wavefunctions are effectively decoupled and the environment acts on electrons by enforcing an effective locality.

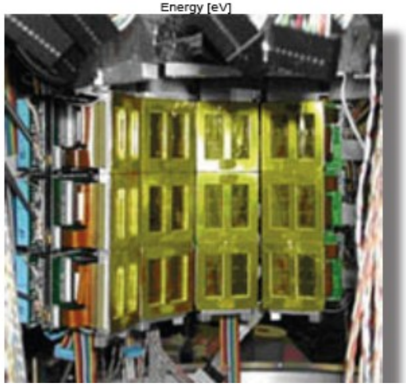
Improved experiment VIP2



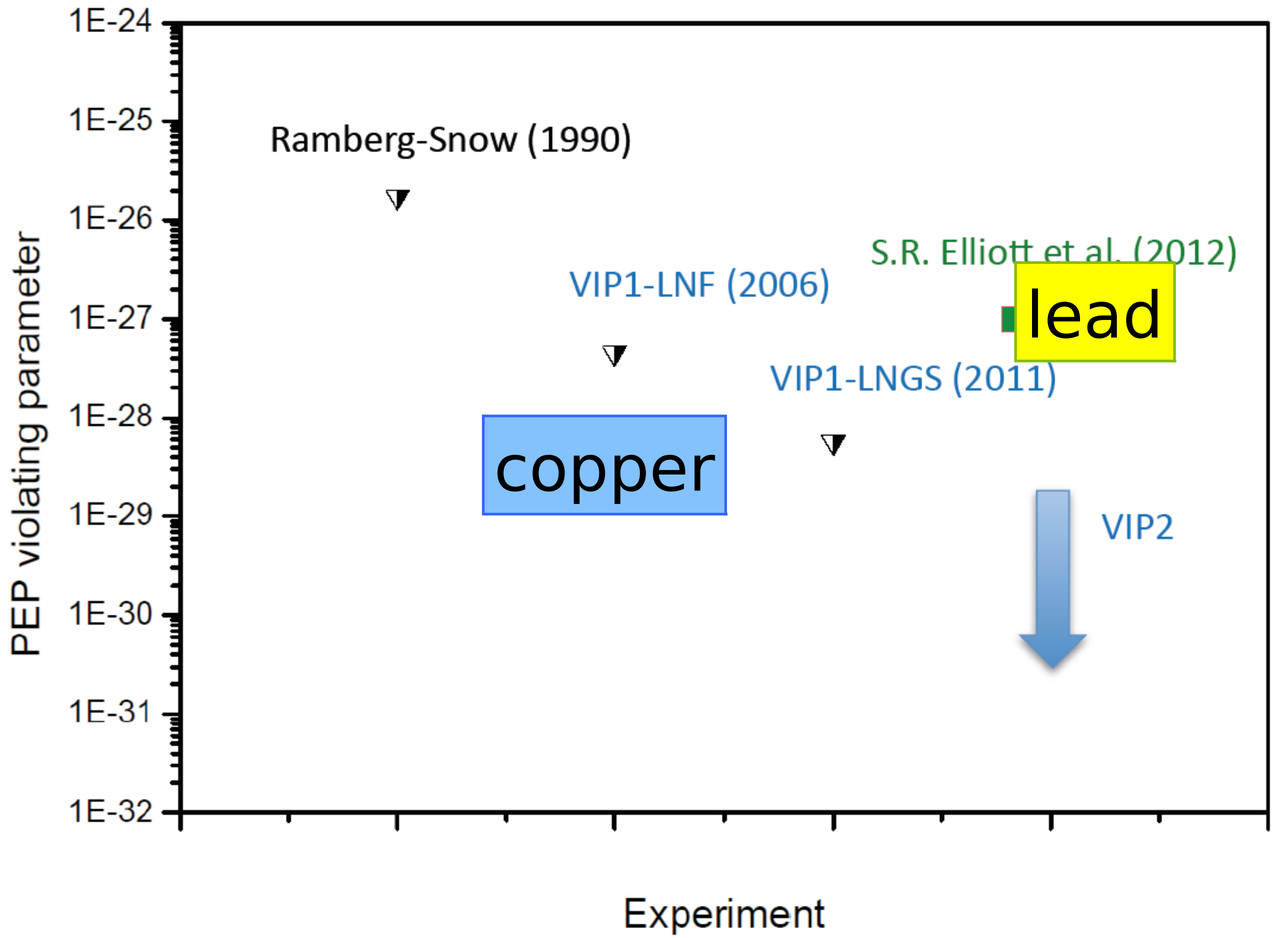
- Large (1 cm^2) SDDs provide excellent energy resolution (even superior than CCDs at 8keV)



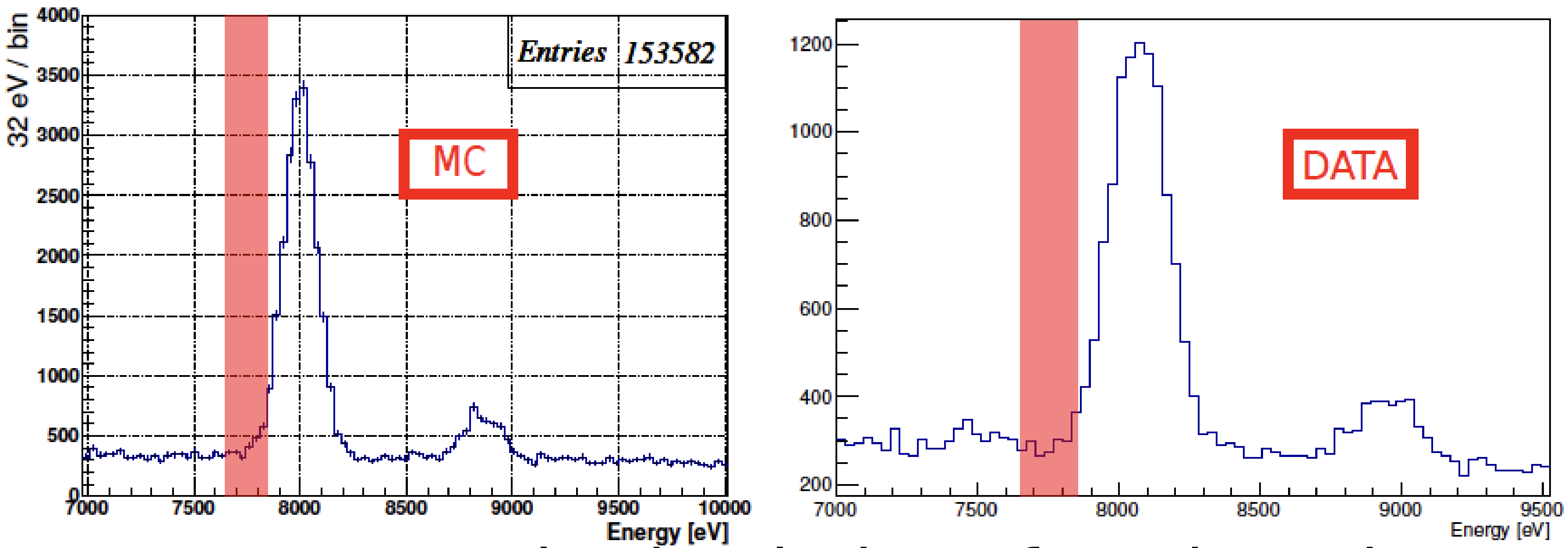
- Timing capability for triggering
- Compact design suitable for gaining larger solid angle



- Successfully used in the detection of kaonic atom x-ray spectroscopy at DAFNE (SIDDHARTA) with large background reduction


1E-24
1E-25
1E-26
1E-27
1E-28
1E-29
1E-30
1E-31
1E-32
PEP violating parameter
Ramberg-Snow (1990)
VIP1-LNF (2006)
S.R. Elliott et al. (2012)
lead
VIP1-LNGS (2011)
copper
VIP2
Experiment

Comparison MC and Data @ LNGS

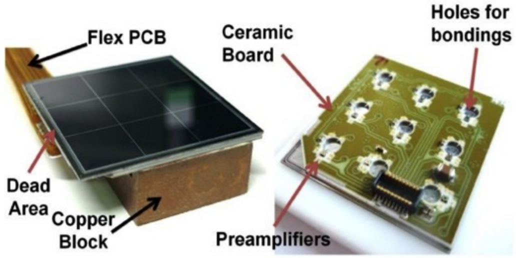


Monte Carlo simulation of 30 days data taking and actual data taken in 30 days

Future Research Plan

- Installation of part of the passive shielding

- New SDD detector system with new copper targe



- In 2017 new copper target with new SDDs will be installed

- Optimized shielding with data taking of about 3 years (i.e. approx. 2020)

- Goal after 3 years data taking with and without current
  → 10^2 improvement of VIP limit

Toward the final result