Searching for signal of quantum collapse through X-ray emission patterns

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on behalf of the VIP-2 collaboration

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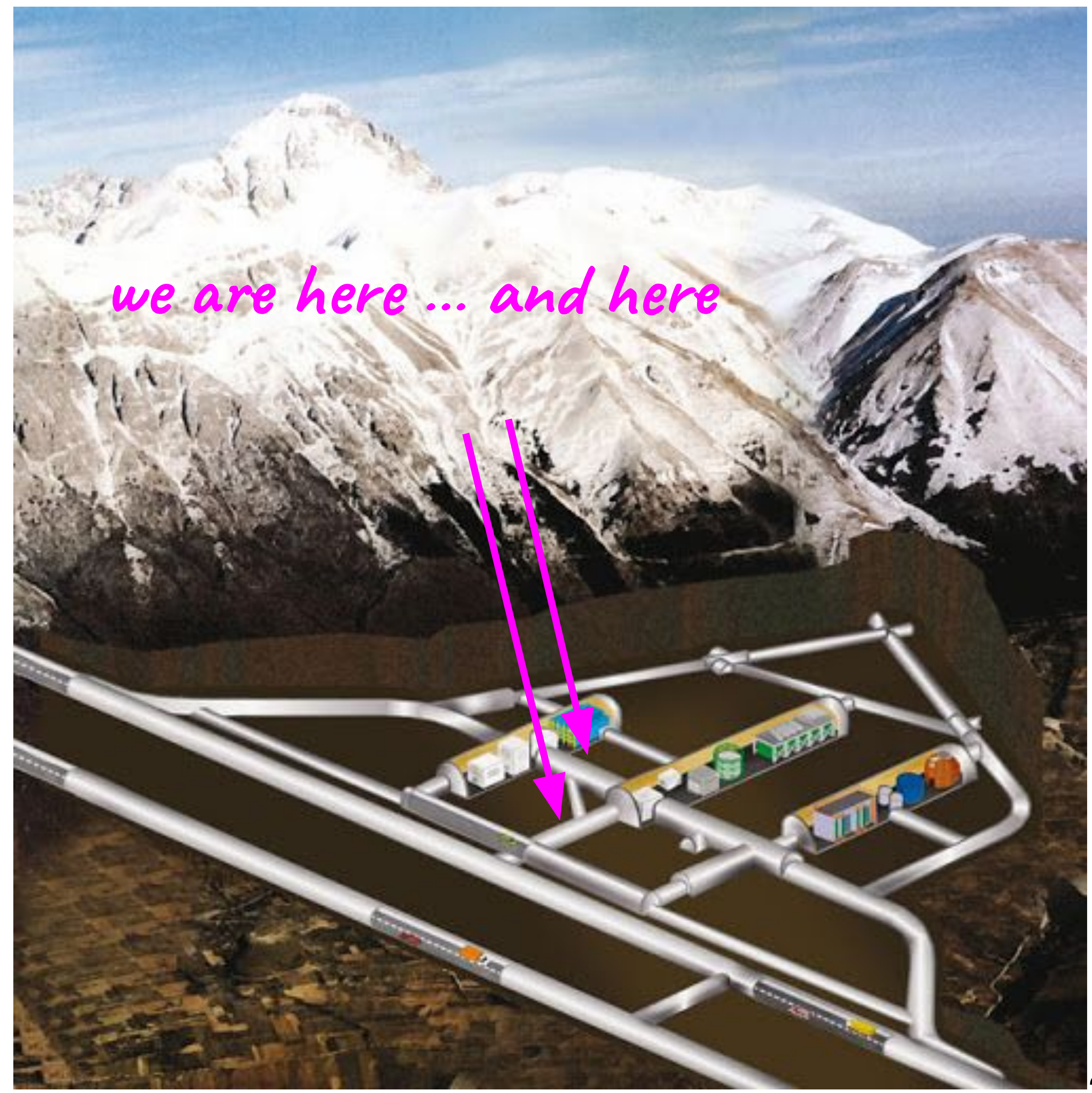
LNGS laboratories environment: the cosmic silence

The experiments are performed in the low-background environment of the underground Gran Sasso National Laboratory of INFN:



- overburden corresponding to a minimum thickness of 3100 m w.e.
- the muon flux is reduced by almost six orders of magnitude, n flux of three oom.
- the main background source consists of γ-radiation produced by long-lived γ-emitting primordial isotopes and their decay products.

Collapse Models

DYNAMICAL COLLAPSE MODELS:

- **Why the quantum properties (superposition) do not carry over to the macro-world?**

- **Stochastic and non-linear modifications of the Schroedinger dynamics -> spontaneous collapse, progressive reduction of the superposition, proportional to the increase of the mass of the system**

"spontaneous universal collapse in massive degrees of freedom, assuming a fundamental gravity-related irreversibility, may have perspectives for quantum cosmology as well"
L. Diósi (2023) J. Phys.: Conf. Ser. 2533 012005)

Spontaneous decoherence induced by space-time indeterminacy
&
Irreversibility in Quantum Gravity/Cosmology at the Planck scale

lead to the same structure of master equations

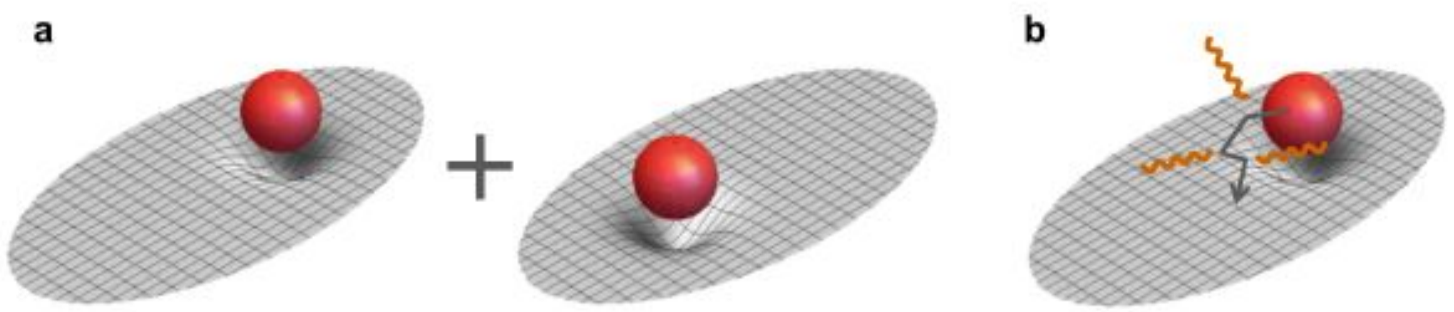
One way to perform sensitive tests - experimental search for
spontaneous radiation

Radiation measurements to test the collapse

- Side effect of the stochastic collapse dynamics:

a Brownian-like diffusion of the system in space Phys. Rev. Lett. 130, 230202 (2023).

Collapse probability is Poissonian in t -> Lindblad dynamics for the statistical operator -> free particle average square momentum increases in time.



- Then charged particles emit spontaneous radiation. We search for spontaneous radiation emission from a germanium crystal and the surrounding materials in the experimental apparatus.

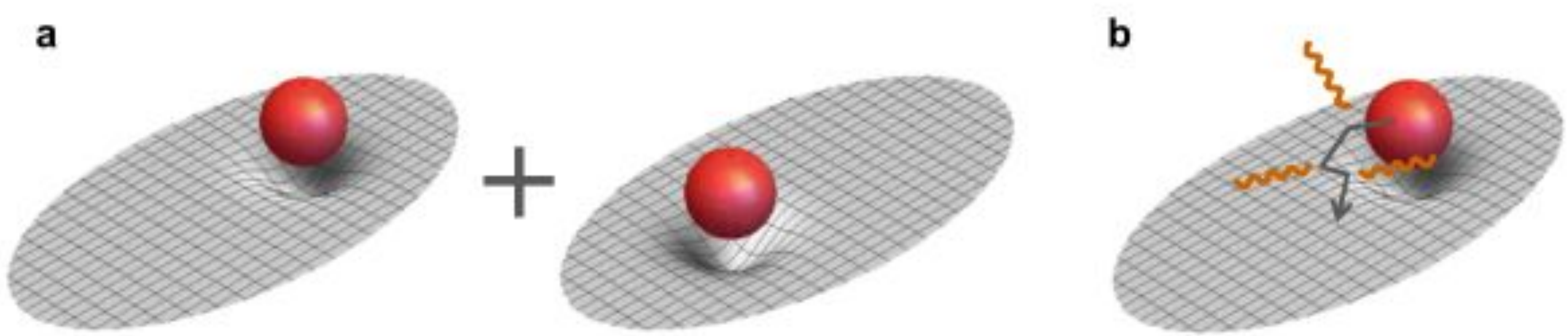
Strategy: simulate the background from all the known emission processes -> perform a Bayesian comparison of the residual spectrum with the theoretical prediction -> extract the pdf of the model parameters -> bound the parameters.

Gravity related collapse: the Diosi-Penrose model

Diósi: QT requires an absolute indeterminacy of the gravitational field, -> the local gravitational potential should be regarded as a stochastic variable, whose mean value coincides with the Newton potential, and the correlation function is:

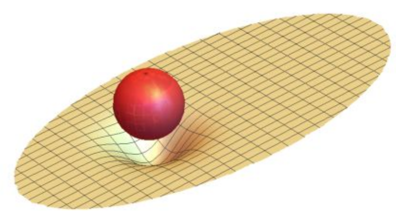
$$< \phi(\mathbf{r},t)\,\phi(\mathbf{r}',t') > - < \phi(\mathbf{r},t) >< \phi(\mathbf{r}',t') > \sim \frac{\hbar G}{|\mathbf{r}-\mathbf{r}'|}\,\delta(t-t')$$

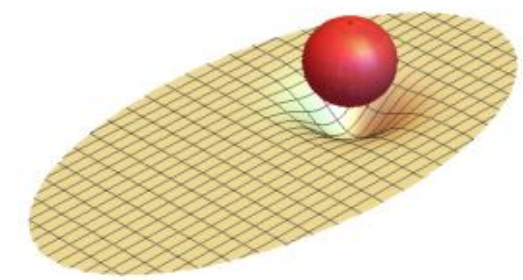
Penrose: When a system is in a spatial quantum superposition, a corresponding superposition of two different space-times is generated. The superposition is unstable and decays in time. The more massive the system in the superposition, the larger the difference in the two space-times and the faster the wave-function collapse.



L. Diósi and B. Lukács, Ann. Phys. 44, 488 (1987), L. Diósi, Physics letters A 120 (1987) 377, L. Diósi, Phys. Rev. A 40, 1165–1174 (1989), R. Penrose, Gen. Relativ. Gravit. 28, 581–600 (1996), R. Penrose, Found. Phys. 44, 557–575 (2014).

Gravity related collapse

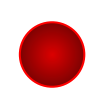
$\Big|$ 

$\Big\rangle + \Big|$ 

$\Big\rangle$

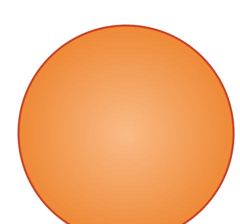
$$\Delta E_{\text{DP}} = 4\pi G \int d\boldsymbol{r} \int d\boldsymbol{r}' \frac{[\mu_a(\boldsymbol{r}) - \mu_b(\boldsymbol{r})]\,[\mu_a(\boldsymbol{r}') - \mu_b(\boldsymbol{r}')]}{|\boldsymbol{r} - \boldsymbol{r}'|}.$$

$$\tau_{\text{DP}} = \frac{\hbar}{\Delta E_{\text{DP}}}$$



Proton: m ≃ 10^{-27} Kg, R ≃ 10^{-15} m

$\tau_{\text{DP}} \simeq 10^{6}$ years



Dust grain: m ≃ 10^{-12} Kg, R ≃ 10^{-5} m

$\tau_{\text{DP}} \simeq 10^{-8}$ s

Gravity related collapse

The DP theory is parameter-free, but the gravitational self energy difference diverges for point-like particles -> a short-length cutoff R_0 is introduced to regularize the theory.

Diósi: minimum length R_0 limits the spatial resolution of the mass density, a short-length cutoff to regularize the mass density. EG becomes a function of R_0 the larger R_0 the longer the collapse time.

Penrose: solution of the stationary Shroedinger-Newton equation, with R_0 the size of the particle mass density.

Spontaneous emission in the γ-rays regime

- *CSL - s. e. photons rate:*

$$\left.\frac{d\Gamma}{dE}\right|_t^{CSL} = \frac{\hbar\,\lambda}{4\,\pi^2\,\epsilon_0\,c^3\,r_C^2\,m_0^2\,E}\,(N_p^2 + Ne)$$

- *DP - s. e. photons rate:*

$$\left.\frac{d\Gamma}{dE}\right|_t^{DP} = \frac{G}{12\pi^{3/2}\epsilon_0 c^3 R_0^3 E}\,\{N_p^2 + N_e\}$$

the photon w.l. λ_γ is intermediate between the nuclear dimension and the lower atomic orbit radius -> protons emit coherently, electrons emit independently

λ - *collapse strength*

r_C - *correlation length*

see e. g. S. L. Adler, JPA 40, (2007) 2935, Adler, S.L.; Bassi, A.; Donadi, S., JPA 46, (2013) 245304.

R_0 - *size of the particle mass density. See e.g. Diósi, L. J. Phys. Conf. Ser. 442, 012001 (2013)., Penrose, R. Found. Phys. 44, 557–575 (2014).*

Experimental bounds on DP and CSL

The experimental setup

The experimental apparatus is based on a coaxial p-type high purity germanium detector (HPGe):

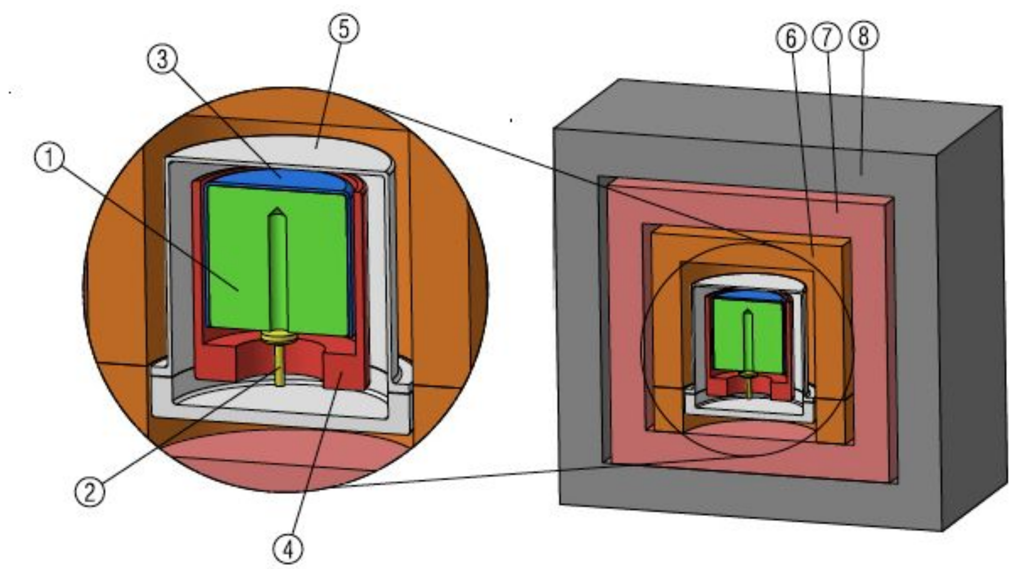
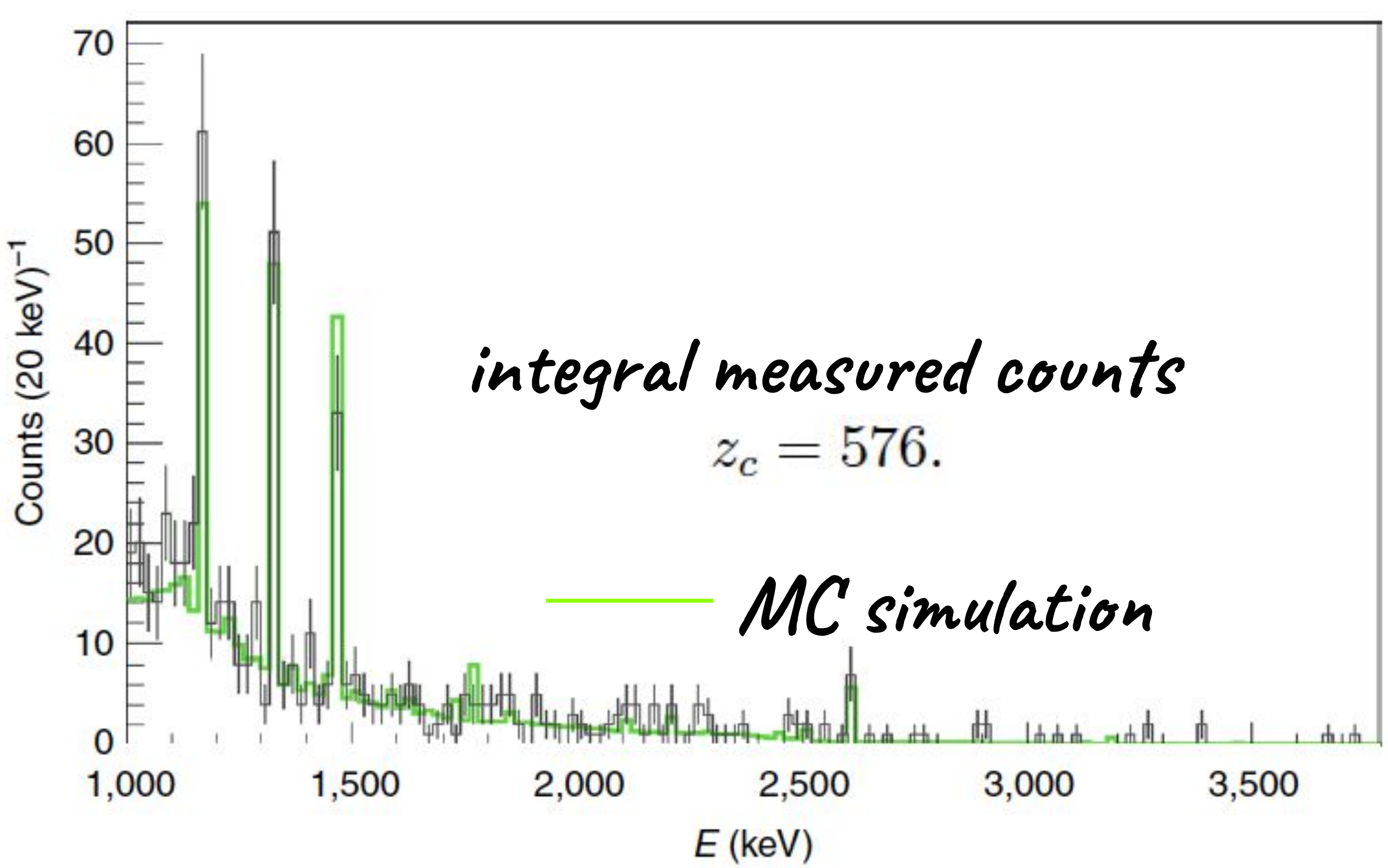


Figure 1: *Schematic representation of the experimental setup: 1 - Ge crystal, 2 - Electric contact, 3 - Plastic insulator, 4 - Copper cup, 5 - Copper end-cup, 6 - Copper block and plate, 7 - Inner Copper shield, 8 - Lead shield.*

- Exposure 124 kg · day, m_{Ge} ~ 2kg
- passive shielding: inner - electrolytic copper, outer - lead
- on the bottom and on the sides 5 cm thick borated polyethylene plates give a partial reduction of the neutron flux
- an airtight steel housing encloses the shield and the cryostat, flushed with boil-off nitrogen to minimize the presence of radon.

Measured spectrum and background simulation

The experimental apparatus is characterised, through a validated MC code, based on the GEANT-4 software library. The background is due to emission of residual radio-nuclides:



- the activities are measured for each component
- the MC simulation accounts for:

1. emission probabilities and decay schemes

   for each radio-nuclide in each material

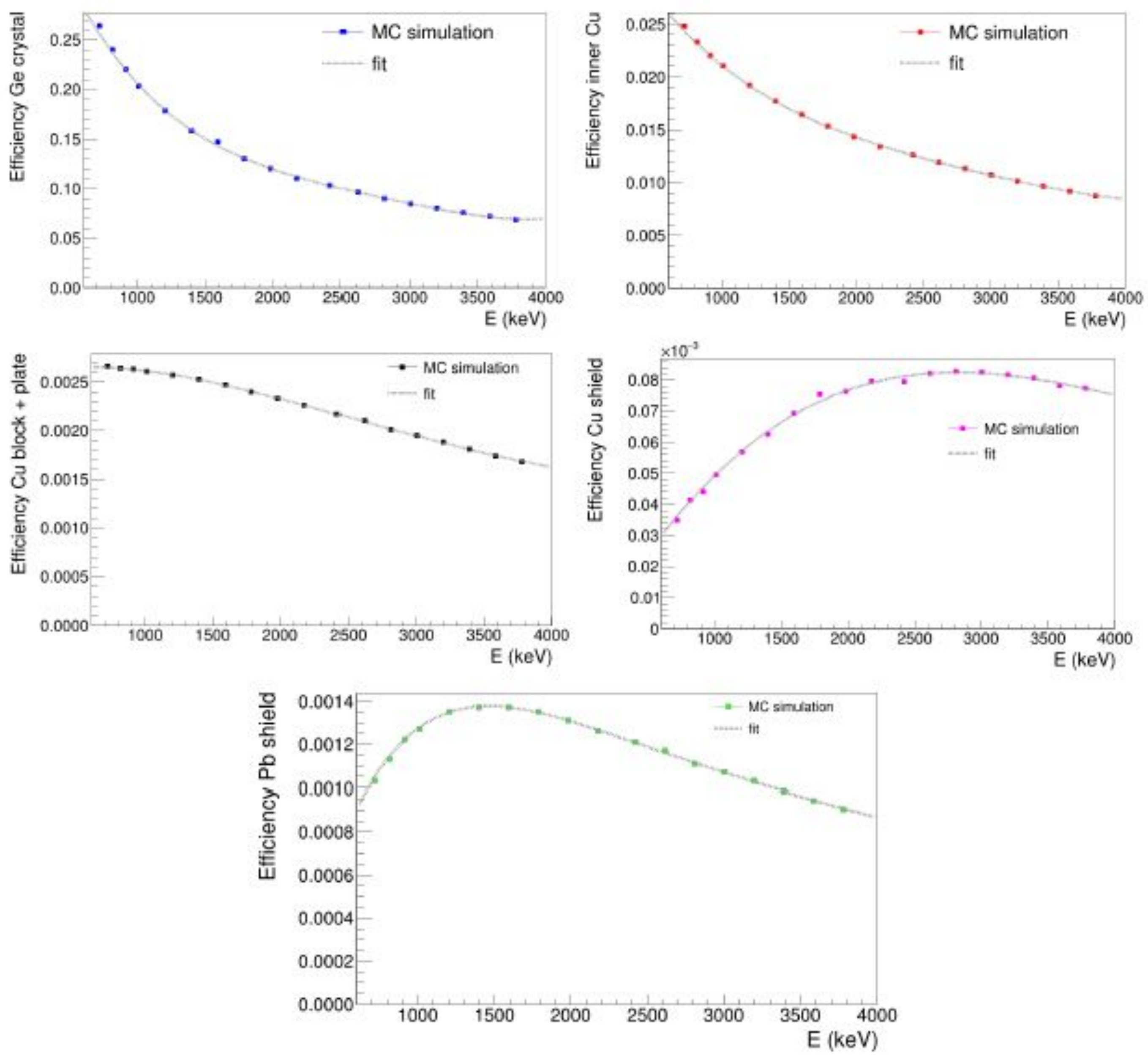
1. photons propagation and interactions
2. detection efficiencies.

The simulation describes 88% of the spectrum:

$$z_{b,ij} = \frac{m_i\, A_{ij}\, T\, N_{rec,ij}}{N_{ij}}, \quad z_b = \sum_{i,j} z_{b,ij} = 506.$$

Expected signal contribution

The expected number of photons spontaneously emitted by the nuclei of all the materials of the detector are obtained weighting the theoretical rate for the detection efficiencies:



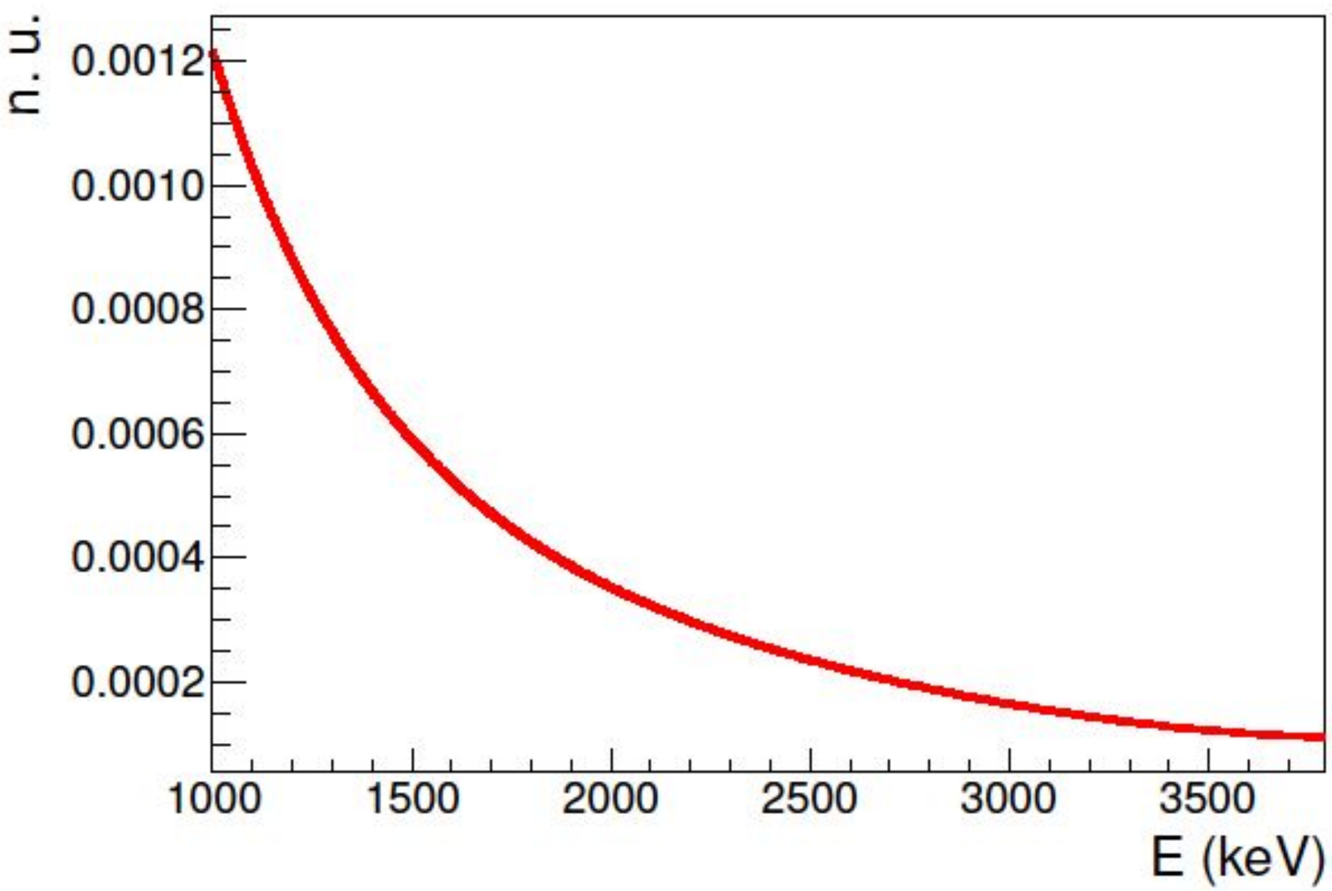
- 10^8 photons generated for each energy for each material
- efficiency functions are obtained by polinomial fits $\epsilon_i(E) = \sum_{j=0}^{c_i} \xi_{ij} E^j$
- the expected signal contribution is:

$$z_s(R_0) = \sum_i \int_{\Delta E} \left.\frac{\mathrm{d}\Gamma_t}{\mathrm{d}E}\right|_i T \epsilon_i(E)\,\mathrm{d}E = \frac{a}{R_0^3}$$

with $a = 1.8 \; 10^{-29}\ m^3$

Expected signal contribution

The expected signal of spontaneously emitted photons by the nuclei of all the materials of the detector is obtained weighting the theoretical rate for the detection efficiencies:



Energy distribution of the expected signal, resulting from the sum of the emission rates of all the materials, weighted for the eciency functions.

The area of the distribution is normalised to the unity (n. u.)

The statistical model

- bin-by-bin Bayesian comparison of data - MC -Th. expectation

- aim of the analysis: extract the posterior pdf for the parameters of the model (p)

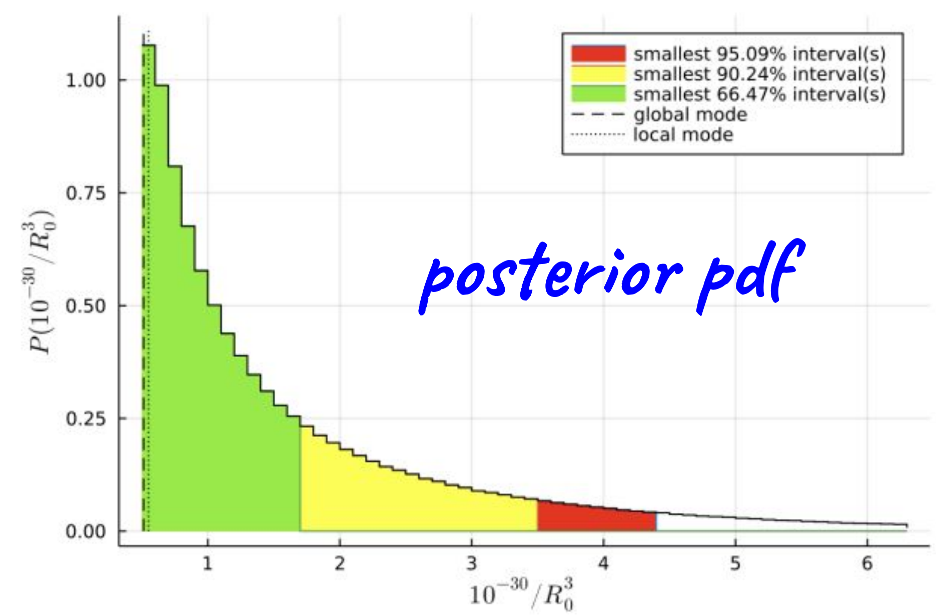
$$P(p|data) = \int_{\mathcal{D}_\mathbf{b}} P(p,\mathbf{b}|data)\; d\mathbf{b}$$

$$P(p,\mathbf{b}|data) = \\ = \frac{P(data|p,\mathbf{b}) \cdot P_0(p) \cdot P_0(\mathbf{b})}{\int P(data|p,\mathbf{b}) \cdot P_0(p) \cdot P_0(\mathbf{b})\; d\,(p)\; d\mathbf{b}}$$

Likelihood: $$P(data|p,\mathbf{b}) = \prod_{i=1}^{N} \frac{\lambda_i(p,\mathbf{b})^{n_i} \cdot e^{-\lambda_i(p,\mathbf{b})}}{\underbrace{n_i!}_{\text{data}}}$$

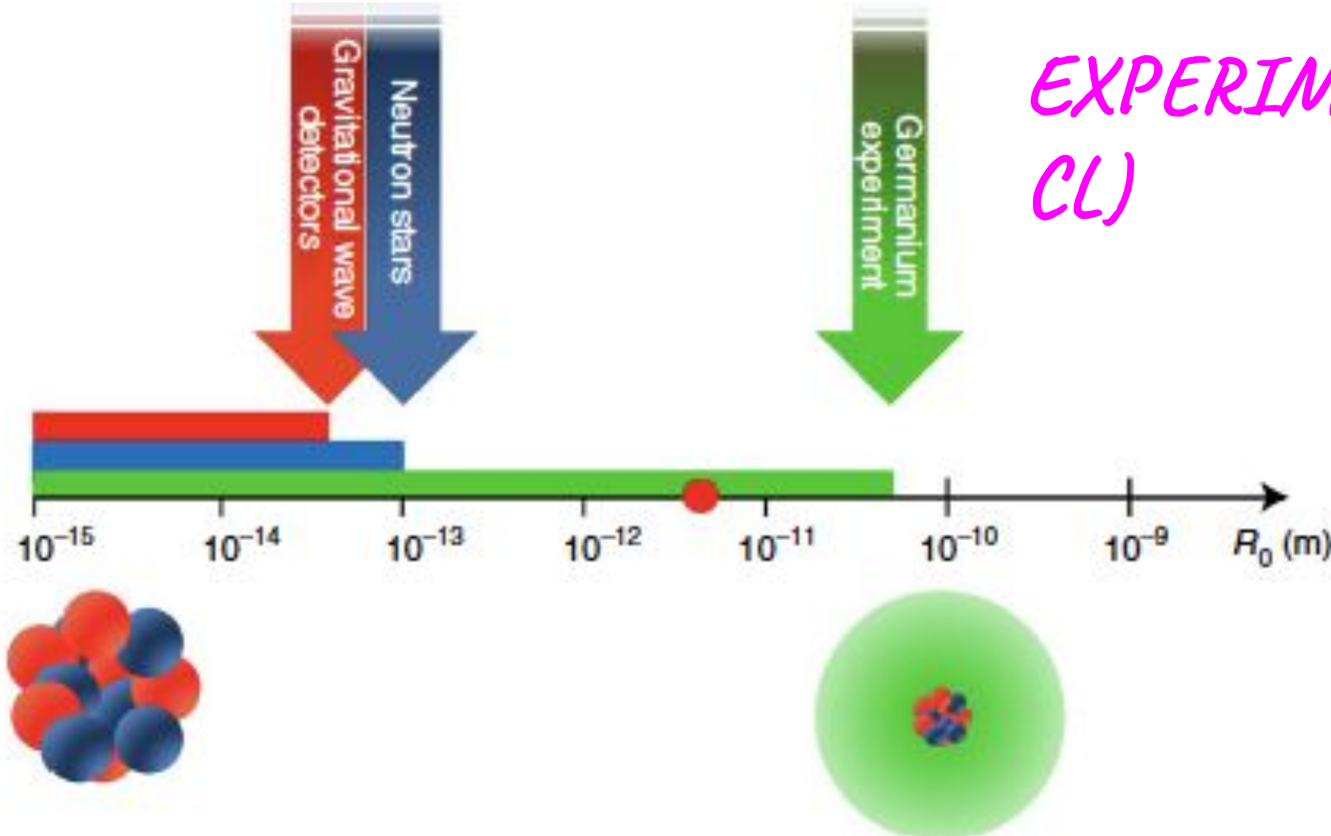
data

expected bin counts: $$\lambda_i(p,\mathbf{b}) = \int_{\Delta E_i} \overbrace{f_B(E,\mathbf{b})}^{\text{MC}}\; dE + \\ + \int_{\Delta E_i} \overbrace{f_S(E,p)}^{\text{Th. expectation}}\; dE.$$



posterior pdf

Lower bound on R_0



EXPERIMENTAL : $R_0 > 0.54 \cdot 10^{-10}$ m (90% CL)

If R_0 is the size of the nucleus's wave function as suggested by Penrose, we have to compare the limit with the properties of nuclei in matter.

In a crystal $R^2_0 = \langle u^2 \rangle$ is the mean square displacement of a nucleus in the lattice, which, for the germanium crystal, cooled to liquid nitrogen temperature amounts to:

THEORETICAL EXPECTATION $R_0 = 0.05 \cdot 10^{-10}$ m

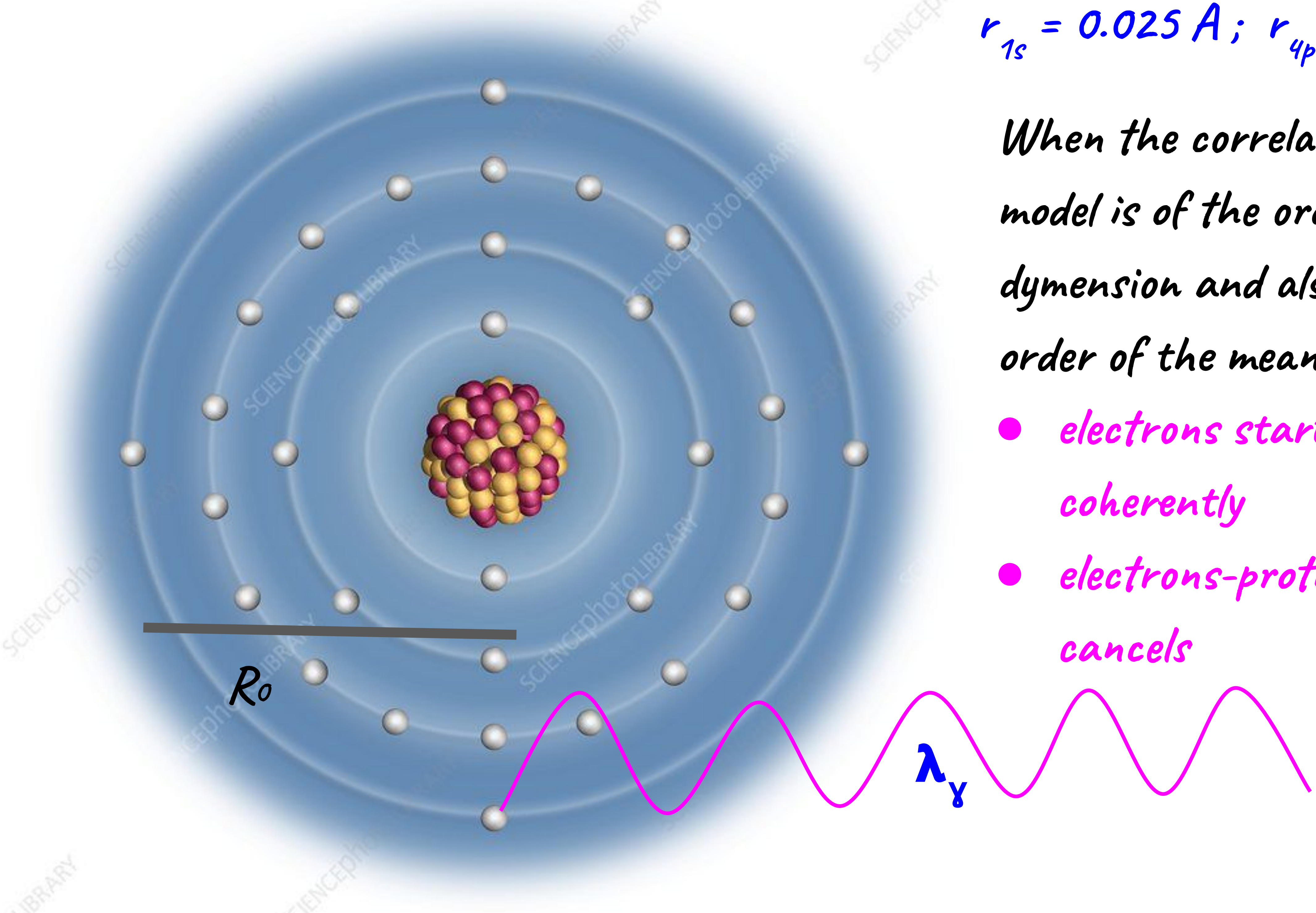
"Underground test of gravity-related wave function collapse". Nature Physics 17, pages 74–78 (2021)

Spontaneous emission in the X-rays regime

In the low-energy regime, the photon w.l. is comparable to the atomic orbits dimensions

e.g. $\lambda_{dB}(E=15\ keV) = 0.8\ A$

$r_{1s} = 0.025\ A\ ;\ r_{4p} = 1.5\ A$



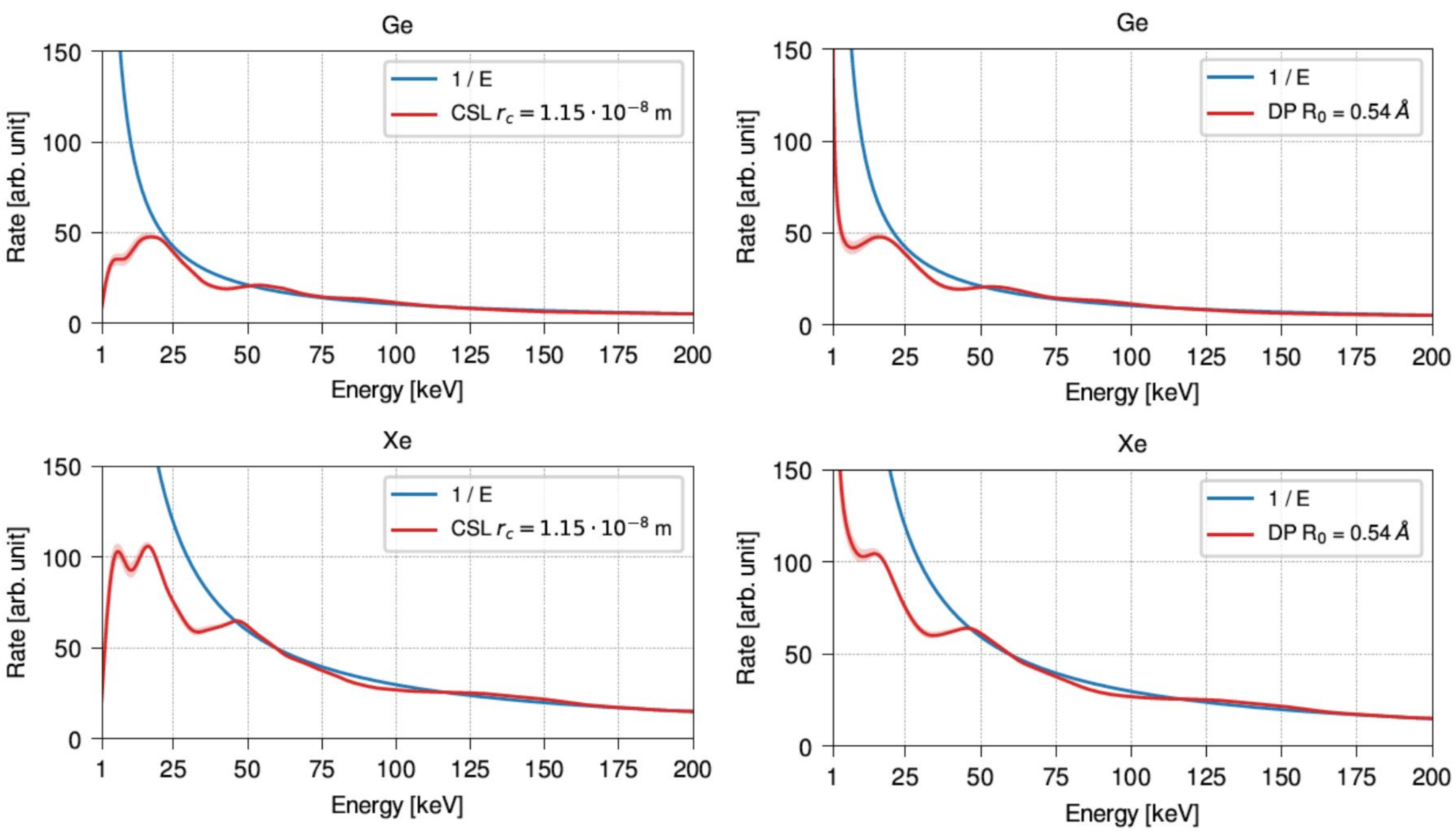
When the correlation length of the model is of the order of the atomic dymension and also λ_γ is of the order of the mean atomic radii:

- electrons start to emit coherently
- electrons-protons contribution cancels

Spontaneous emission in the X-rays regime

First model which predicts a characteristic spontaneous E. M. radiation distinctive of the decoherence mechanism:

Phys. Rev. Lett. 132, 250203 (2024)



Spontaneous radiation rate for the CSL model (left) and DP (right) calculated for a Ge atom (top panels) and a Xe atom (bottom panels. In blue the approximated theory.

- **The energy spectrum of this radiation is influenced by the atomic structure of the emitter.**
- **The spontaneous radiation rate, within the range of (1-15) keV, is unique to the specific decoherence mechanism.**

Strongest available bounds (preliminary)

Analysis performed in collaboration with XENONnT
arXiv:2506.05507v1 [hep-ex]

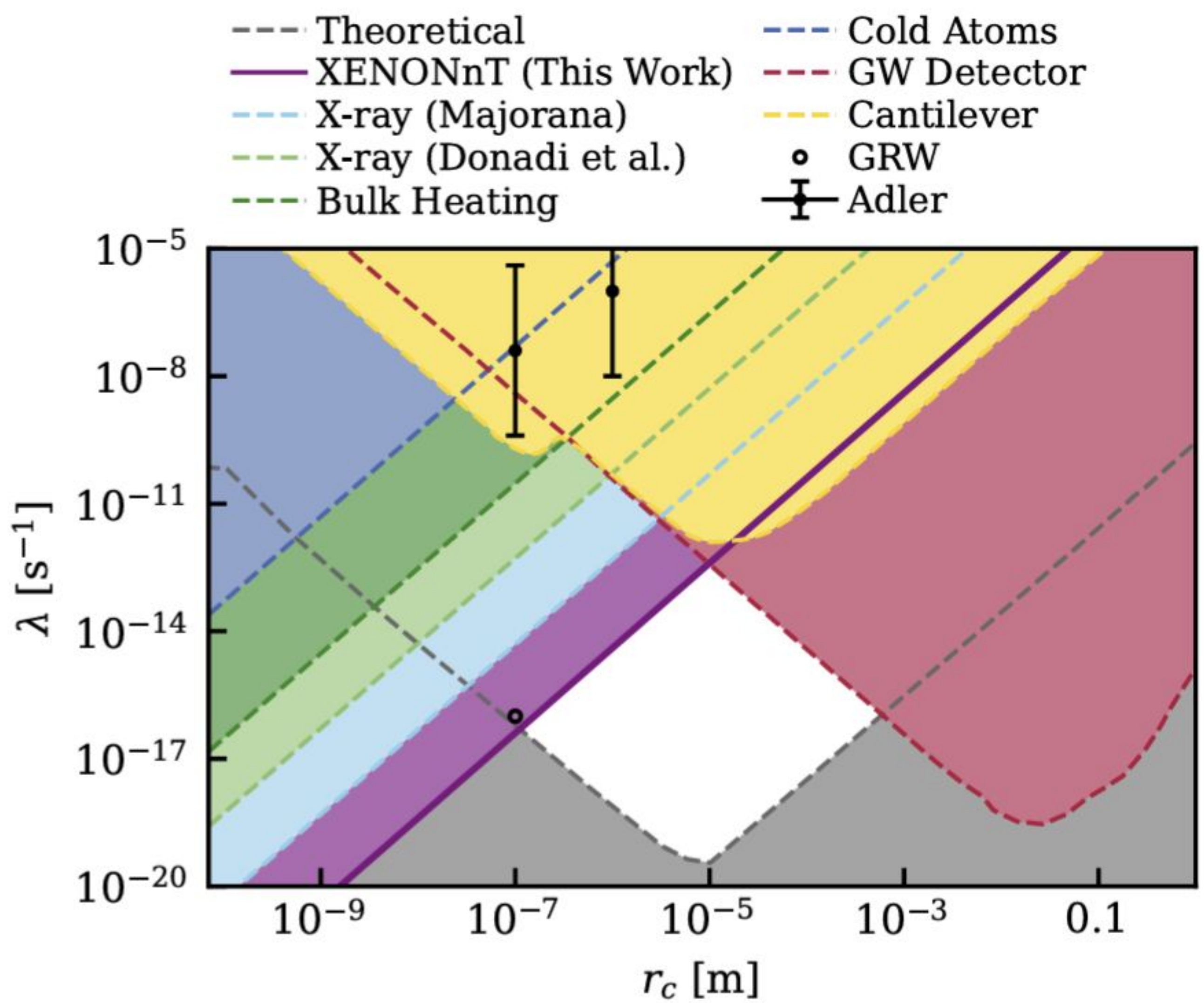


FIG. 2. XENONnT 95% C.L. upper bound on the CSL model parameters, compared to exclusion limits from other non-interferometric experiments and theoretical propositions

BOUND on the DP model

$R_0 > 0.54 \cdot 10^{-10}$ m (90% CL)

Experimental bounds on K-model and ML

Károlyházi model

With what precision can a time-like length s = cT in flat spacetime be measured using a quantum probe which obeys the HUP?

$$\Delta s^3 = l_p^2 s$$

stochastic fluctuation of the metric around the flat Minkowski metric -> minimal uncertainty in the length measurement.

In the non-relativistic, weak gravitational field limit $(g_{00})_\beta(\boldsymbol{x}, t) = 1 + \gamma_\beta(\boldsymbol{x}, t)$

From the mean proper length $s = \mathbb{E}[s_\beta] = cT$ -> $\mathbb{E}[\gamma_\beta(\boldsymbol{x}, t)] = 0$

Assumptions: $\Box\gamma_\beta(\boldsymbol{x}, t) = 0$ $\mathbb{E}[c_\beta(\boldsymbol{k})c^*_\beta(\boldsymbol{k'})] = \delta_{\boldsymbol{k},\boldsymbol{k'}} F(k)$

From the mean square spread: $F(k) = \frac{8\pi^2}{3\Gamma(\frac{1}{3})}\, l_p^{4/3} k^{-5/3}$

with a high energy cutoff

$\lambda_c \geq 10^{-15} m$

Károlyházi model

The stochastic fluctuation of the metric corresponds to the interaction with a random potential:

$$V^{\beta}(\mathbf{x},t) = m\,\Phi_N(\mathbf{x},t) = \frac{mc^2}{2}\,\gamma^{\beta}(x,t)$$

particle satisfies the SSE $\quad i\hbar\frac{\partial}{\partial t}\psi^{\beta}(\mathbf{x},t) = \left(\hat{H}_0 + \hat{V}^{\beta}(t)\right)\psi^{\beta}(\mathbf{x},t)$

In a pioneering work Diósi and Lukács [Physics Letters A 181, 366 (1993)] first calculated the spontaneous emission radiation rate

$$\frac{d\Gamma(t)}{d\omega_{\boldsymbol{k}}} = \frac{e^2\ell_P^{4/3}}{9\pi\epsilon_0\Gamma\left(\frac{1}{3}\right)c^{7/3}\hbar}\omega_{\boldsymbol{k}}^{4/3}$$

The Károlyházi model predicts an unphysically high amount of emitted radiation, more than 10 oom higher than the most sensitive measurement!

An attempt to revive the Károlyházi model

New J. Phys. 26 (2024) 013001

They relax the hypothesis that the fluctuations should satisfy the wave equation

$$\mathbb{E}[\gamma_\beta(\boldsymbol{x},t)\gamma_\beta(\boldsymbol{x}',t')] = g(\boldsymbol{x}-\boldsymbol{x}',|t-t'|)$$

Further they assume it is factorized:

$$g(\boldsymbol{y},|\tau|) = u(\boldsymbol{y})v(|\tau|)$$

The time corr. func. must satisfy:

$$v(|\tau|) = -\frac{4}{9}\left(\frac{l_p}{c}\right)^{\frac{4}{3}}\frac{1}{u(0)}|\tau|^{-\frac{4}{3}}$$

to cope with the K. uncertainty

The spacial correlation function is assumed Gaussian:

$$u(\boldsymbol{y}) = e^{-\frac{\boldsymbol{y}^2}{R_K^2}}$$

the correlator R_K is a free parameter.

An attempt to revive the Károlyházi model

New J. Phys. 26 (2024) 013001

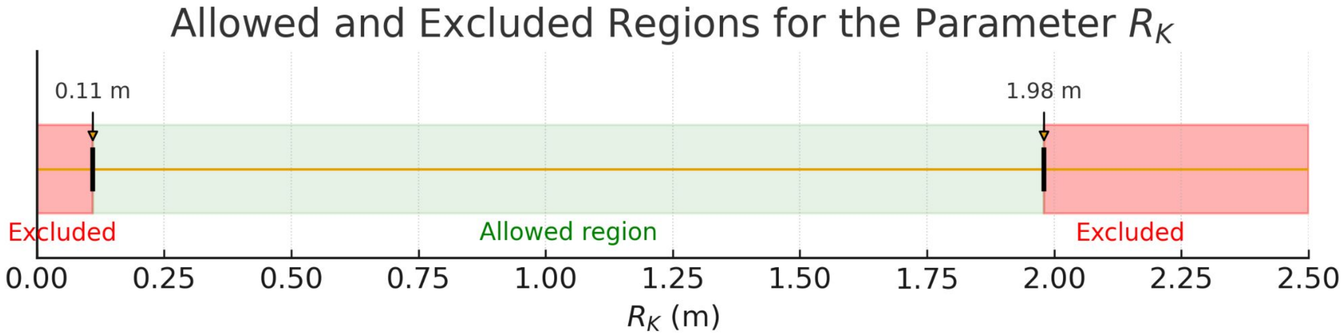
This generalization seems to restore compatibility with the experiment [Phys. Rev. Lett. 129(8), 080401 (2022)]

comparison with the data provides the constraint:

$$R_K \geq 0.11 \text{ m}$$

Un upper bound is also provided by requiring the collapse to be strong enough to guarantee that a single-layered graphene disk of the size of 10 μm (roughly the smallest visible size by human eye) is spatially localized in the time t = 0.01 s (about the smallest time resolution of the human eye)

$$R_K \leq 1.98 \text{ m}$$



1 oom room for the parameter R_K

But eventually the K-Model is killed again

paper in preparation

- We repeated the analysis of the data collected with our Ge based apparatus

- The spontaneous emission rate is updated for the generalized K-model

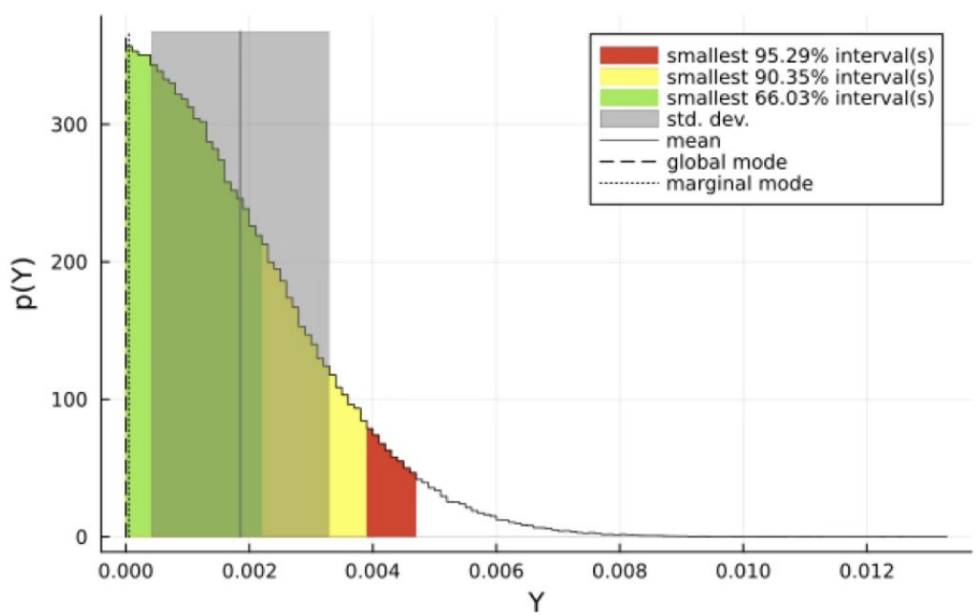
$$f(E) = T\beta_K E^{-2/3}\epsilon_{tot}(E)$$

$$S(E;Y) = \frac{Y}{a} f(E)$$

$$Y \equiv \frac{a}{r_K^2}$$

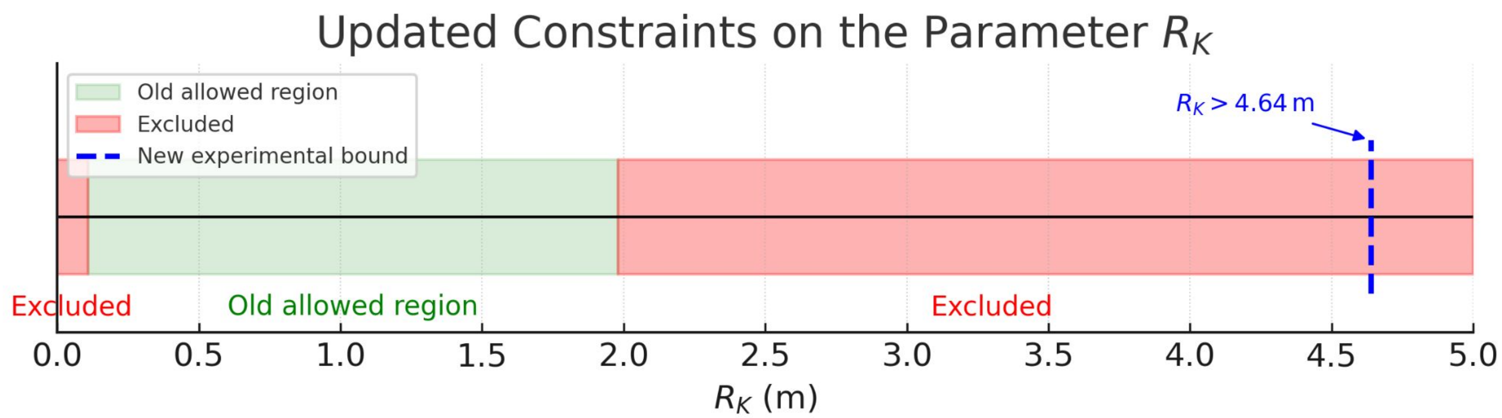
$$\mu_i(Y) = b_i^{MC} + \simeq \int_{E_i - \frac{\Delta E}{2}}^{E_i + \frac{\Delta E}{2}} S(E;Y)\, dE$$

$$\simeq b_i^{MC} + \Delta E\, S(E_i;Y)$$



New lower limit (90% CL)

$$R_K \geq 4.64 \text{ m}$$



Spontaneous radiation in a ML setting

preliminary

- Can our radiation data accomodate an eccess due to a decoherence mechanism triggered by stochastic metric fluctuations with the ML constraint?

GUP

$$\Delta x \, \Delta p \geq \frac{\hbar}{2}\left(1 + \beta(\Delta p)^2\right) \longrightarrow$$

$$\beta = (m_p c)^{-2}$$

ML

$$\Delta x_{\mathrm{min}} = \hbar\sqrt{\beta} = \ell_{\mathrm{P}}$$

If the particle obeys GUP the narrowest possible tube formed by a standing wave packet, which saturates GUP is the KMM state: $\Delta p = \dfrac{\Delta x \pm \sqrt{\Delta x^2 - \beta\hbar^2}}{\beta\hbar}$

Under the simplest assumption: the stochastic metric pert. satisfies the wave equation in empty space

correlation - $F(k) = 2\pi \, \beta \, \hbar^2 \; k^{-1}$

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Spontaneous radiation rate for a free particle of charge e:

$$\frac{d\Gamma(t)}{dE} = \frac{e^2\beta}{12\pi^2\epsilon_0 c^3\hbar}E^2$$

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comparison with the data is ongoing

Thank you