UNDERGROUND TESTS OF QUANTUM COLLAPSE AT GRAN SASSO

Fabrizio Napolitano on behalf of the VIP Collaboration

fabrizio.napolitano@lnf.infn.it

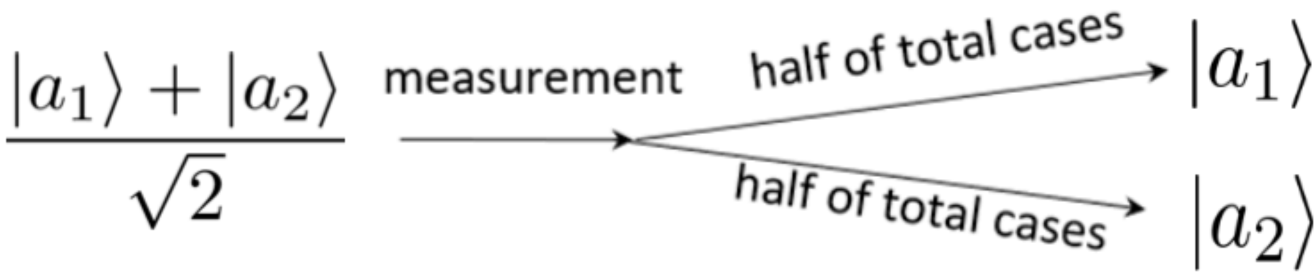
Wave-function Collapse Problem

Schrödinger Equation

$$i\hbar\frac{d}{dt}\left|\Psi\left(t\right)\right\rangle = H\left|\Psi\left(t\right)\right\rangle$$

linear and deterministic

Wave function reduction postulate:



$$\frac{|a_1\rangle + |a_2\rangle}{\sqrt{2}} \xrightarrow{\text{measurement}} \begin{cases} \xrightarrow{\text{half of total cases}} |a_1\rangle \\ \xrightarrow{\text{half of total cases}} |a_2\rangle \end{cases}$$

non-linear and stochastic

Wave-function Collapse Problem

Why the quantum properties of microscopic systems, e.g. the possibility of being in the superposition of different states at once, do not carry over to larger objects?

How and why do we have a boundary between the two dynamics?

Will isolated quantum system manifest linear and deterministic Schrödinger evolution forever?
→ direct impact on quantum technologies

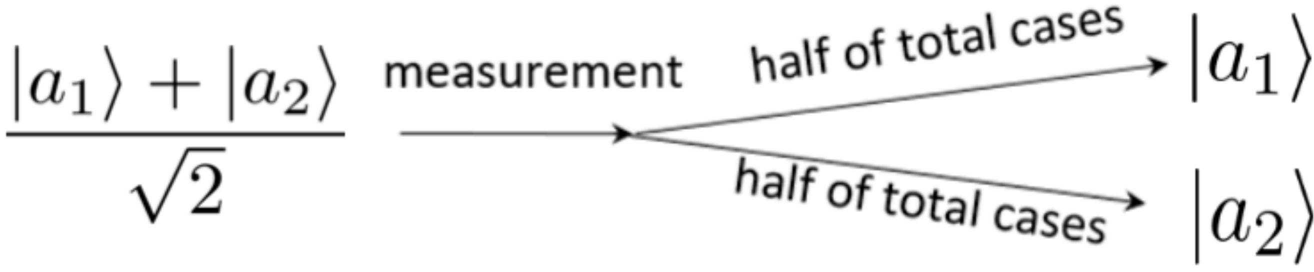
Superposition principle may progressively break down when atoms glue together to form larger systems (Karolyhazi, Ghirardi, Rimini, Weber, Pearle, Diosi, Penrose, Adler, Bassi, etc.). But what triggers the wave function Collapse?

Schrödinger Equation

$$i\hbar \frac{d}{dt} \left| \Psi(t) \right\rangle = H \left| \Psi(t) \right\rangle$$

linear and deterministic

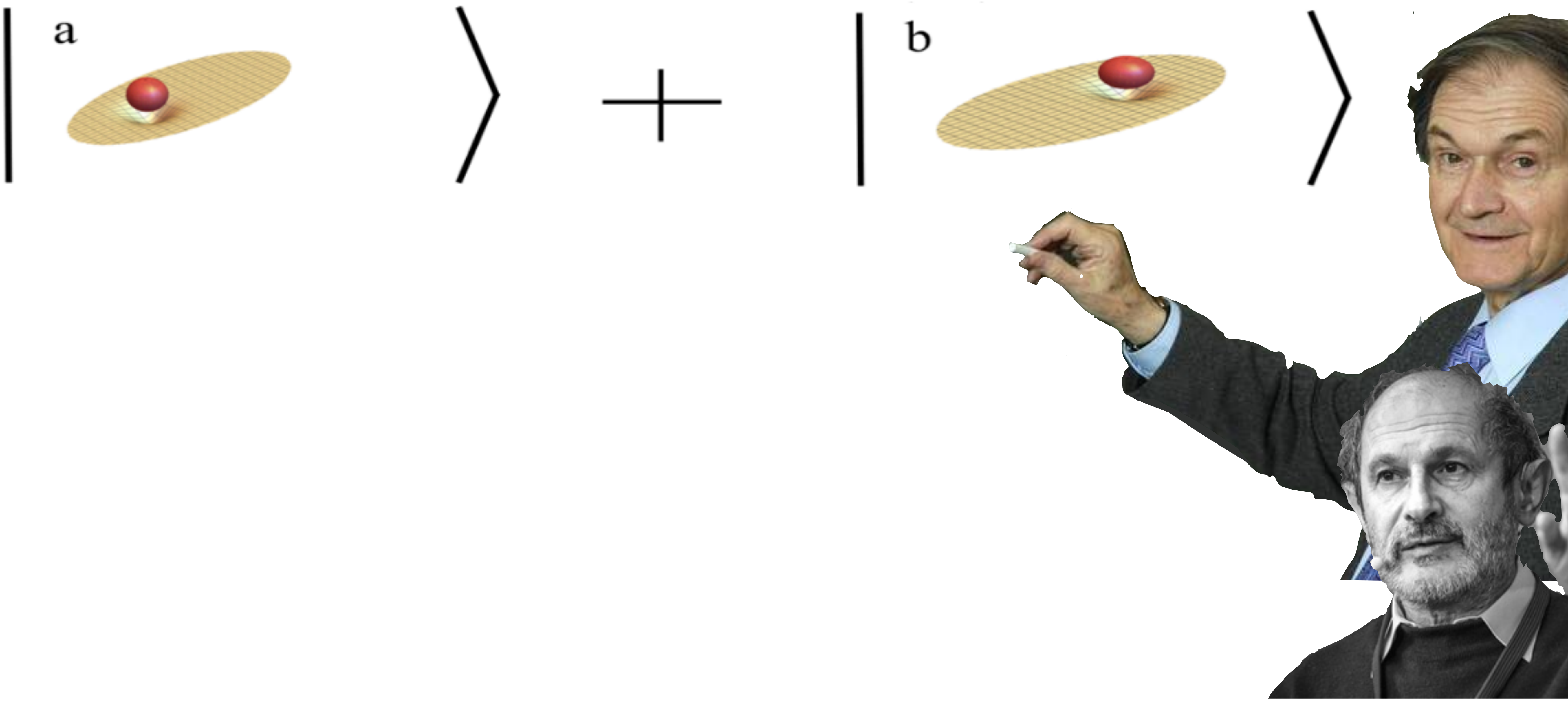
Wave function reduction postulate:



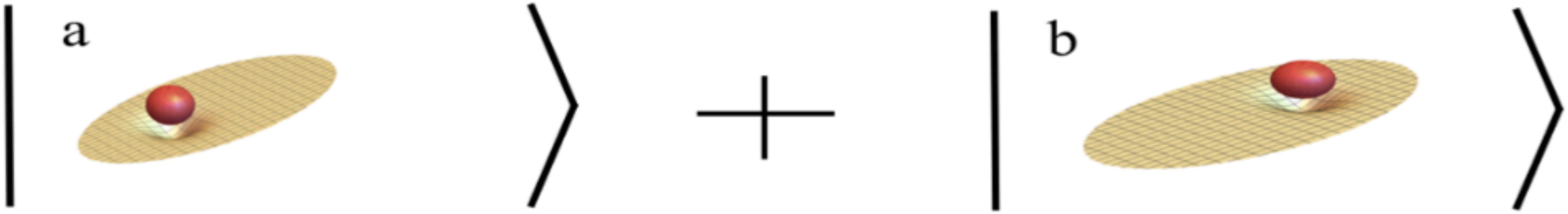
$$\frac{|a_1\rangle + |a_2\rangle}{\sqrt{2}}$$

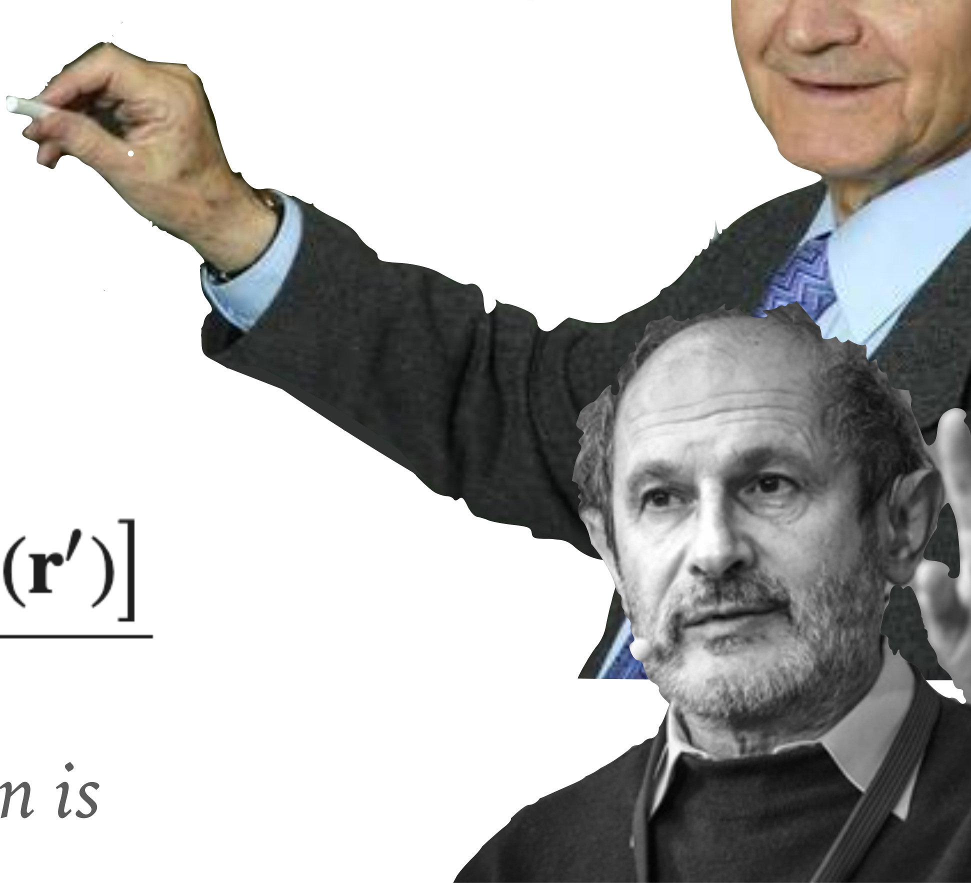
non-linear and stochastic

Diósi-Penrose (DP) Collapse model



Diósi-Penrose (DP) Collapse model





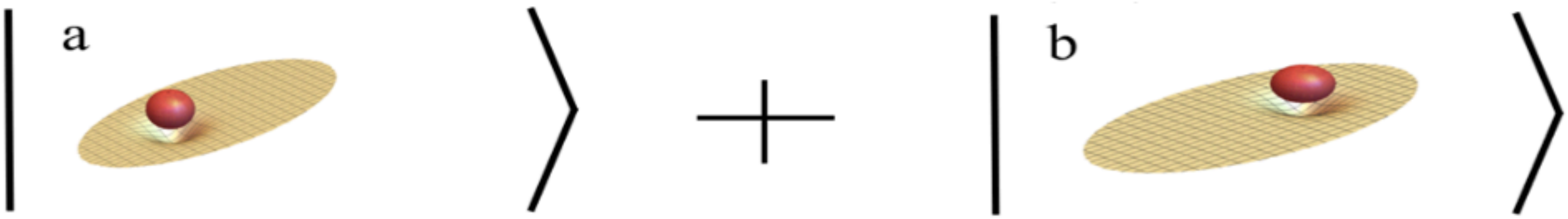
"*as soon as a 'significant' amount of space-time curvature is introduced, the rules of quantum linear superposition must fail*" (R. Penrose)

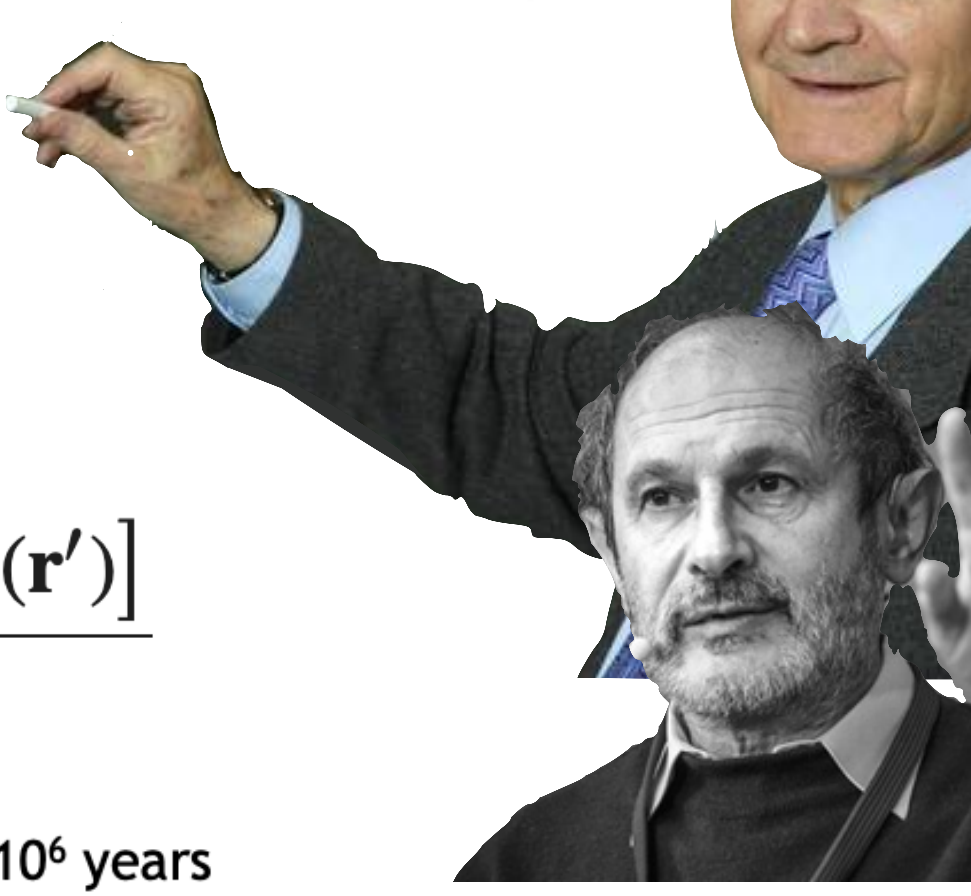
$$\Delta E_{\mathrm{DP}}(\mathbf{d}) = -8\pi G \int \mathrm{d}\mathbf{r} \int \mathrm{d}\mathbf{r}' \, \frac{\mu(\mathbf{r}) \left[\mu(\mathbf{r}' + \mathbf{d}) - \mu(\mathbf{r}')\right]}{|\mathbf{r} - \mathbf{r}'|}$$

Measures how rare the superposition is in gravitational terms

R. Penrose, Found. Phys. 44, 557–575 (2014), R. Penrose, Gen. Relativ. Gravit. 28, 581-600 (1996), L. Diósi, Phys. Rev. A **40**, 1165–1174 (1989).

Diósi-Penrose (DP) Collapse model





"*as soon as a 'significant' amount of space-time curvature is introduced, the rules of quantum linear superposition must fail*" (R. Penrose)

$$\Delta E_{\mathrm{DP}}(\mathbf{d}) = -8\pi G \int \mathrm{d}\mathbf{r} \int \mathrm{d}\mathbf{r}' \frac{\mu(\mathbf{r})\left[\mu(\mathbf{r}'+\mathbf{d}) - \mu(\mathbf{r}')\right]}{|\mathbf{r}-\mathbf{r}'|}$$

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

● Proton: $m \simeq 10^{-27}$ Kg, $R \simeq 10^{-15}$ m, $\tau_{DP} \simeq 10^{6}$ years

● Dust grain: $m \simeq 10^{-12}$ Kg, $R \simeq 10^{-5}$ m, $\tau_{DP} \simeq 10^{-8}$ s

R. Penrose, Found. Phys. 44, 557-575 (2014), R. Penrose, Gen. Relativ. Gravit. 28, 581-600 (1996), L. Diósi, Phys. Rev. A **40**, 1165–1174 (1989).

Diósi-Penrose (DP) Collapse model

$$d|\psi_t\rangle = \left[\underline{-\frac{i}{\hbar}\hat{H}dt} + \underline{\sqrt{\frac{G}{\hbar}}\int d\mathbf{x}(\hat{\mu}(\mathbf{x}) - \langle\hat{\mu}(\mathbf{x})\rangle)dW_t(\mathbf{x})} - \right.$$

$$\left. \underline{-\frac{G}{2\hbar}\int d\mathbf{x}d\mathbf{y}\frac{(\hat{\mu}(\mathbf{x})-\langle\hat{\mu}(\mathbf{x})\rangle)(\hat{\mu}(\mathbf{y})-\langle\hat{\mu}(\mathbf{y})\rangle)}{|\mathbf{x}-\mathbf{y}|}}\right]|\psi_t\rangle$$

Schrödinger

Specific dynamics for the collapse

Collapse in position, no superluminal signals and amplification mechanism

$$\tau^{-1} = \frac{G}{2\hbar}\int d\mathbf{x}d\mathbf{y}\frac{(\hat{\mu}_a(\mathbf{x})-\hat{\mu}_b(\mathbf{x}))(\hat{\mu}_a(\mathbf{y})-\hat{\mu}_b(\mathbf{y}))}{|\mathbf{x}-\mathbf{y}|}$$

R. Penrose, Found. Phys. 44, 557-575 (2014), R. Penrose, Gen. Relativ. Gravit. 28, 581-600 (1996), L. Diósi, Phys. Rev. A **40**, 1165–1174 (1989).

Continuous Spontaneous Localization (CSL) model

The CSL model is a stochastic and non-linear modification of the Schrödinger equation

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

Schrödinger

$N(x)$ $\langle N(x)\rangle_t$ *Particle density operator & non linearity*

$W_t(x)$ *Stocasticity*

λ
Collapse strength

$r_c = 1/\sqrt{\alpha},$
Correlation length

$W_t(x) = W_t(x)(\alpha)$

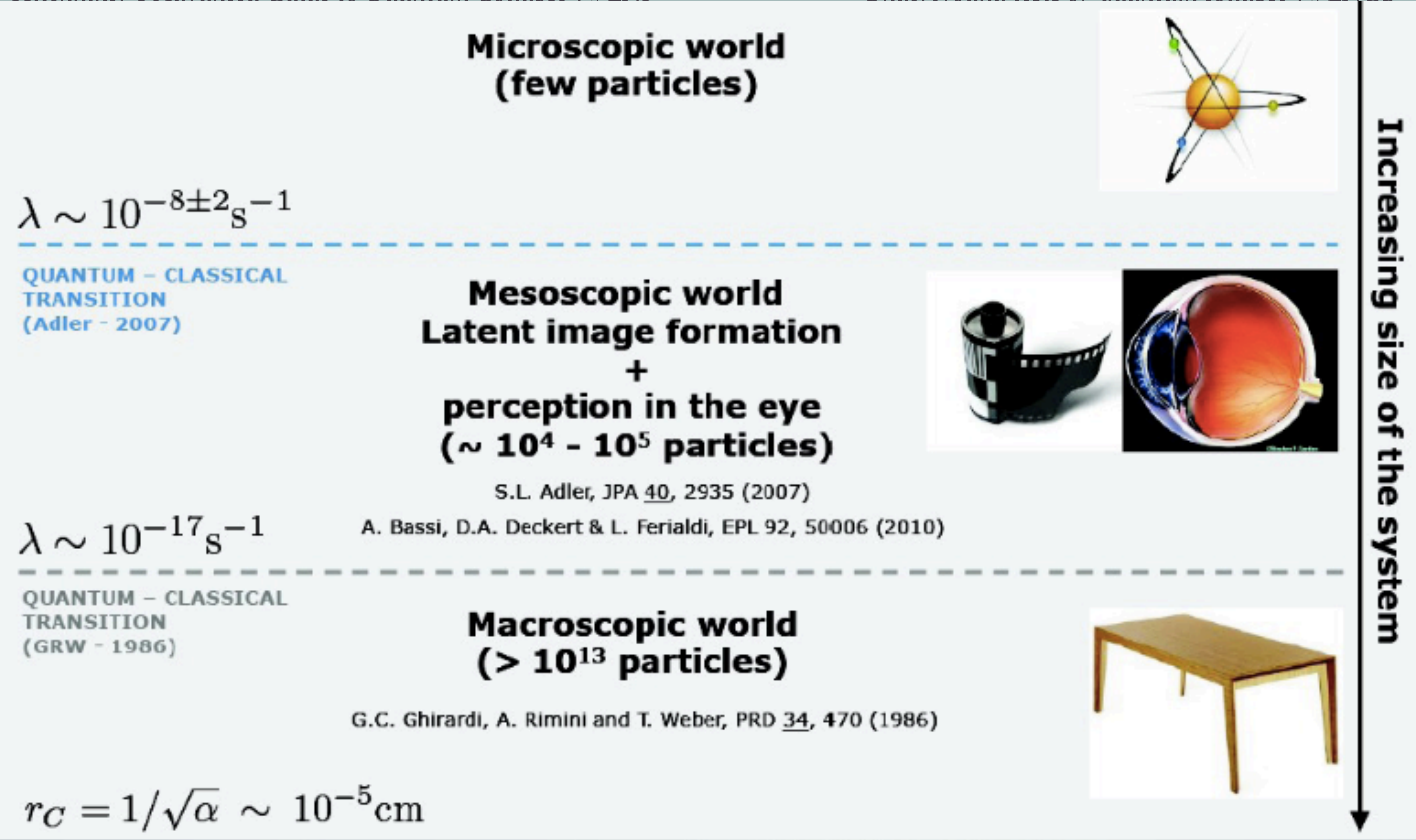
Microscopic *Mesoscopic* *Macroscopic*

$\lambda \sim 10^{-8\pm2}$ s^{-1} $\lambda \sim 10^{-17}$ s^{-1} $r_c \sim 10^{-5}$ cm

G. C. Ghirardi, P. Pearle, and A. Rimini, Phys. Rev. A 42, 78 (1990)

S. L. Adler, JPA 40, (2007) 2935, Adler, S.L.; Bassi, A.;

Donadi, S., JPA 46, (2013) 245304.



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)

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

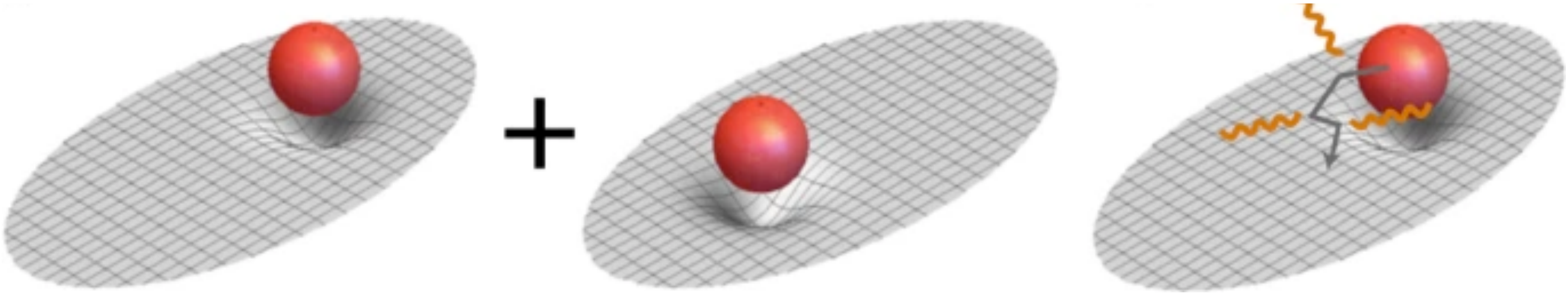
Increasing size of the system

G. C. Ghirardi, P. Pearle, and A. Rimini, Phys. Rev. A 42, 78 (1990)

S. L. Adler, JPA 40, (2007) 2935, Adler, S.L.; Bassi, A.;

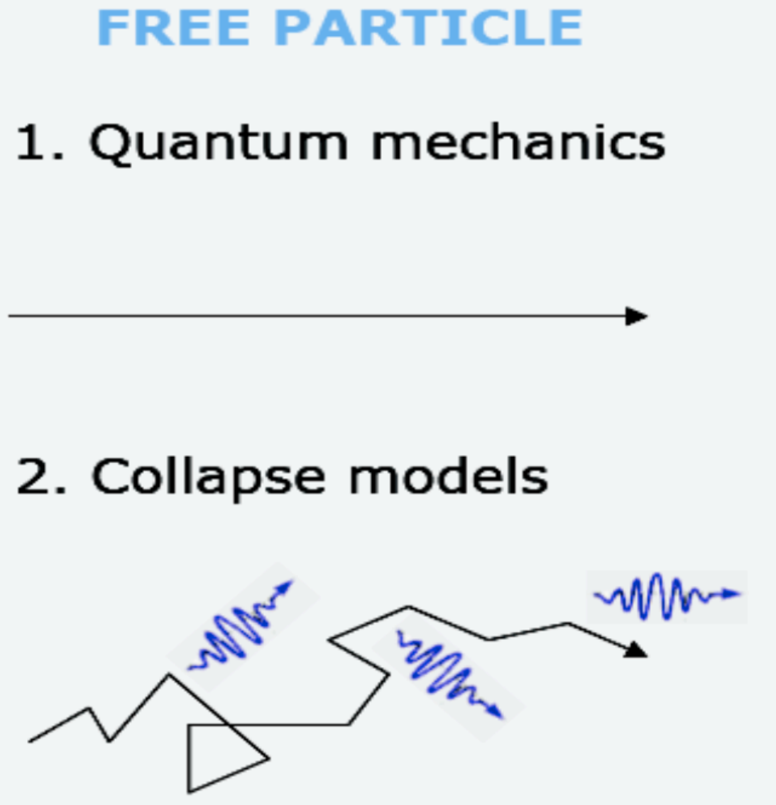
Donadi, S., JPA 46, (2013) 245304.

Testing Collapse Models with Gamma Ray spectroscopy



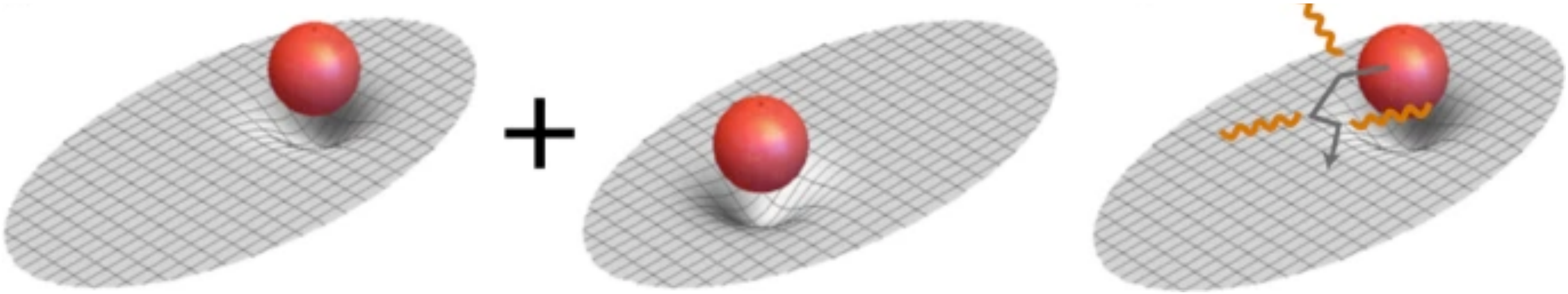
Collapse happens → the centre of mass is shifted towards the localized wave function position → since the process is random this results in a ***diffusion process***

Deviation from standard QM: emission of radiation from charged particles

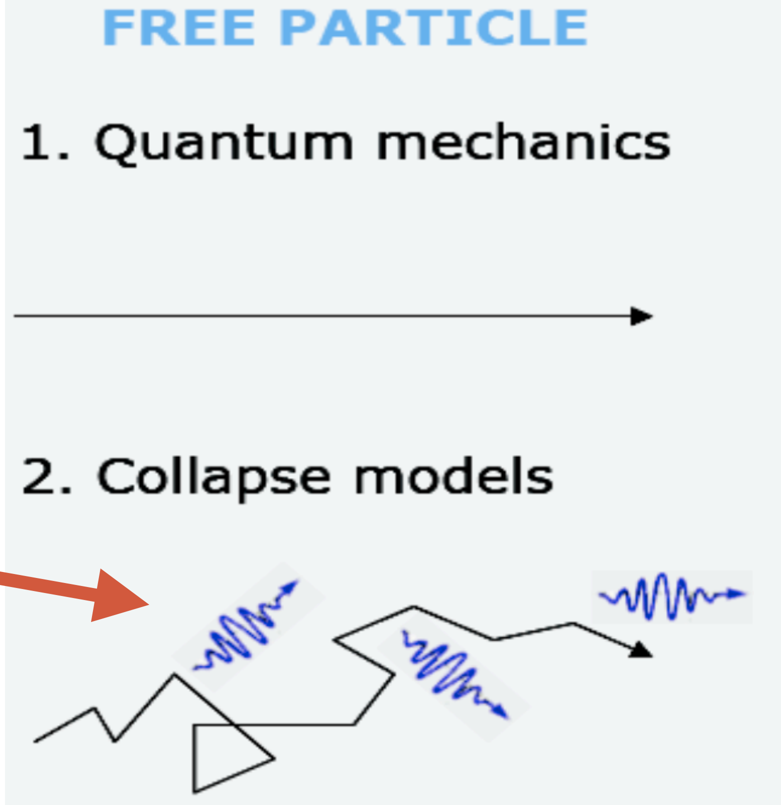


Q. Fu, Phys. Rev. A 56, 1806 (1997)
S. L. Adler and F. M. Ramazanoglu, J. Phys. A40, 13395 (2007);
J. Phys. A42, 109801 (2009)
S. L. Adler, A. Bassi and S. Donadi,
J. Phys. A46, 245304 (2013)
S. Donadi, D. A. Deckert and A. Bassi, Annals of Physics 340, 7086 (2014)

Testing Collapse Models with Gamma Ray spectroscopy



Collapse happens → the centre of mass is shifted towards the localized wave function position → since the process is random this results in a diffusion process

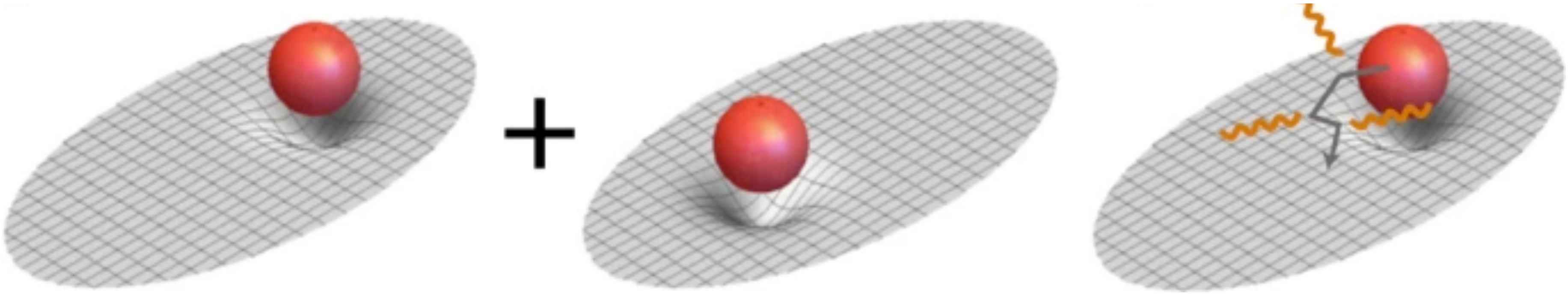


Deviation from standard QM: emission of radiation from charged particles

→ Anomalous amount of radiation can prove the collapse models

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, 7086 (2014)

Testing Collapse Models with Gamma Ray spectroscopy



We search for spontaneous radiation emission from a germanium crystal and the surrounding materials in the experimental apparatus.

Theoretical prediction for the expected spontaneous emission rate

DP - s. e. photons rate: *

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

CSL - s. e. photons rate: *

$$\frac{d\Gamma_t}{d\omega} = \frac{\lambda\hbar e^2 N^2 N_a}{4\pi^2\epsilon_0 c^3 m_0^2 r_C^2 E}$$

→ Calculated in collaboration with L. Diosi, A. Bassi & S. Donadi

where:

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).*

**: photon rates for energies > 100 keV*

The experiment at LNGS

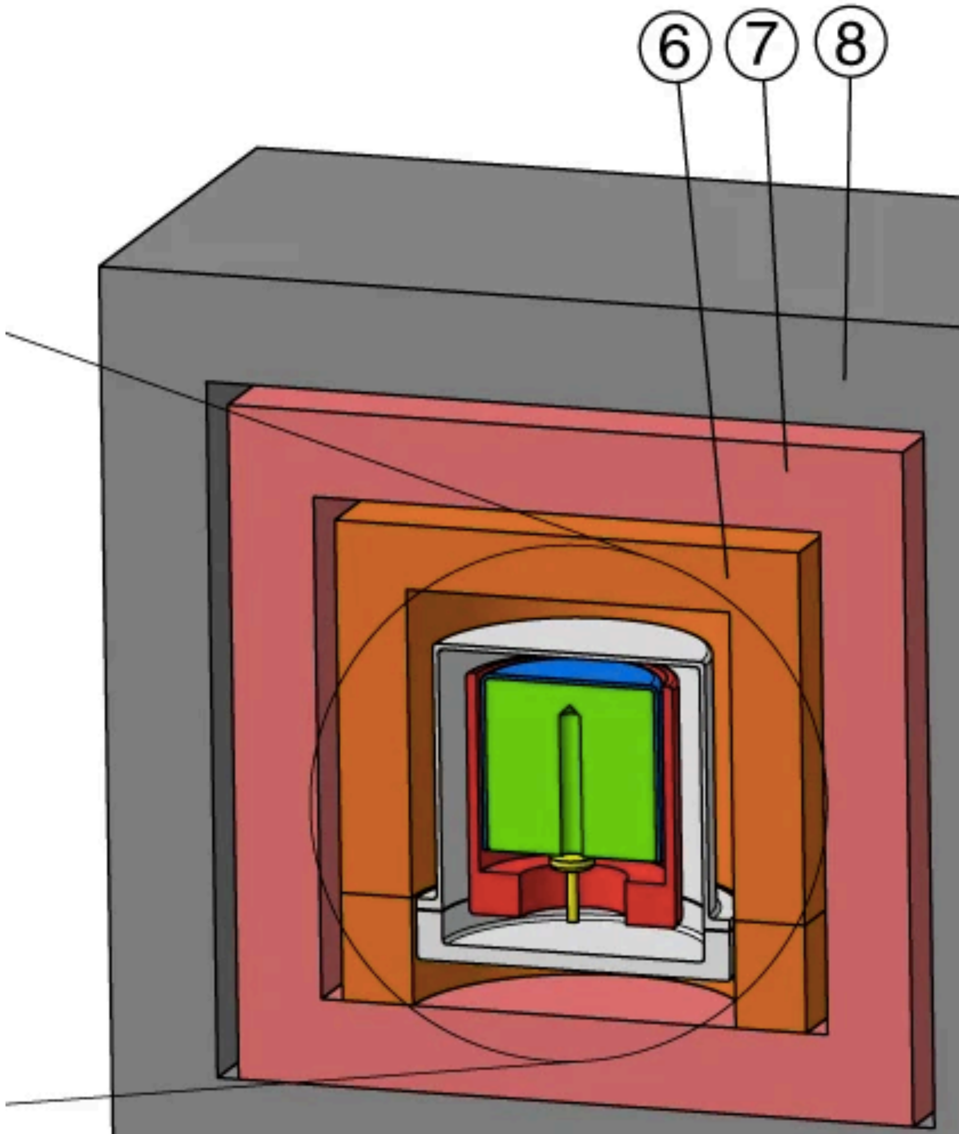
The experiment at LNGS

Measurement and MC validation

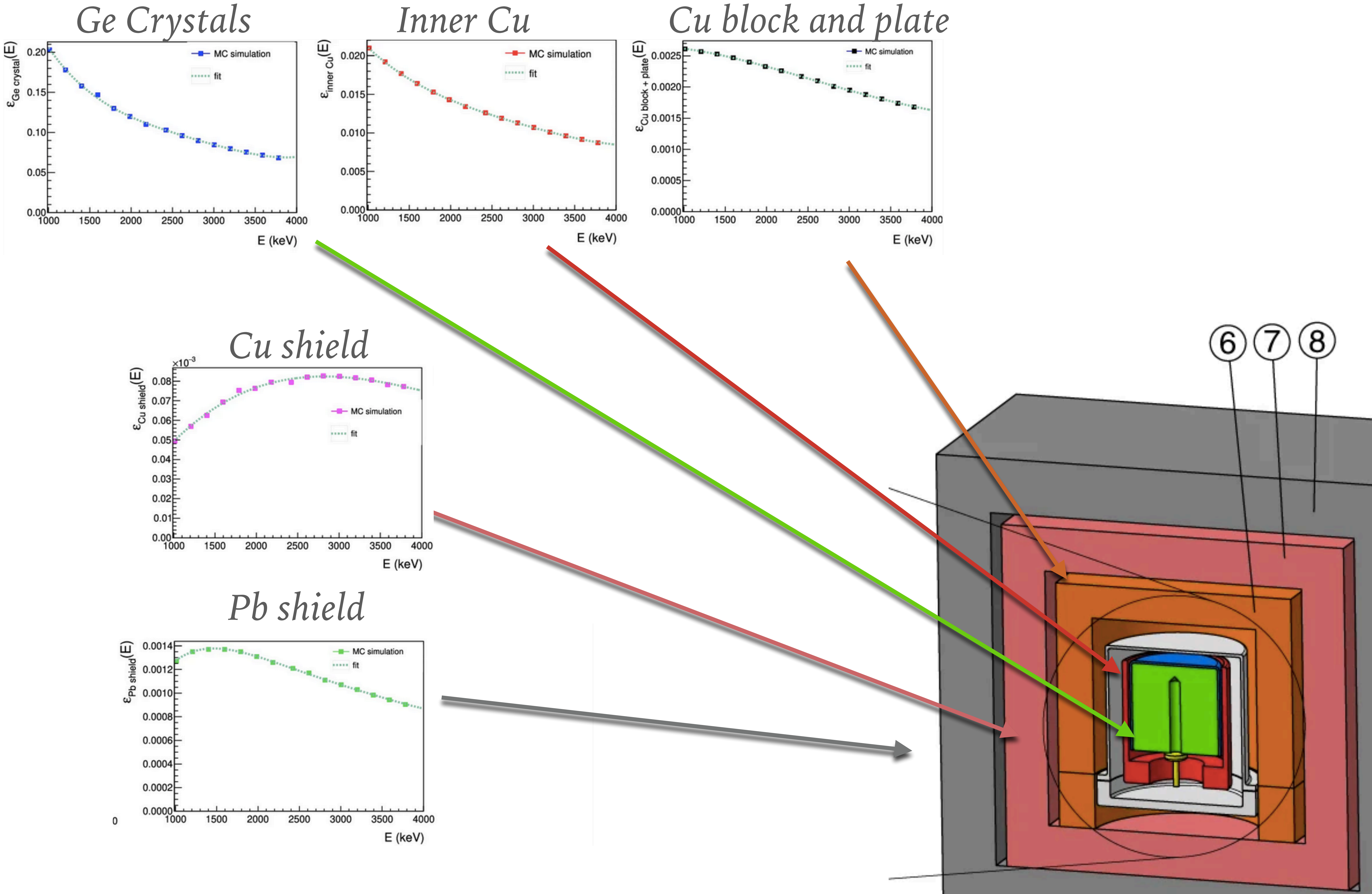
Coaxial p-type high purity germanium detector (HPGe):

- Exposure 124 kg · day, m_{Ge} ~ 2kg
- 5 cm thick borated polyethylene plates -> reduction of the neutron flux
- airtight steel housing encloses the shield and the cryostat, flushed with boil-off nitrogen to minimize the presence of radon.

- minimum overburden 3100 m w.e.
- cosmic radiation flux reduction factor 10^6
- main background source: γ-radiation produced by long-lived γ-emitting primordial isotopes and their decay products.



Measurement and MC validation



Ge Crystals

Inner Cu

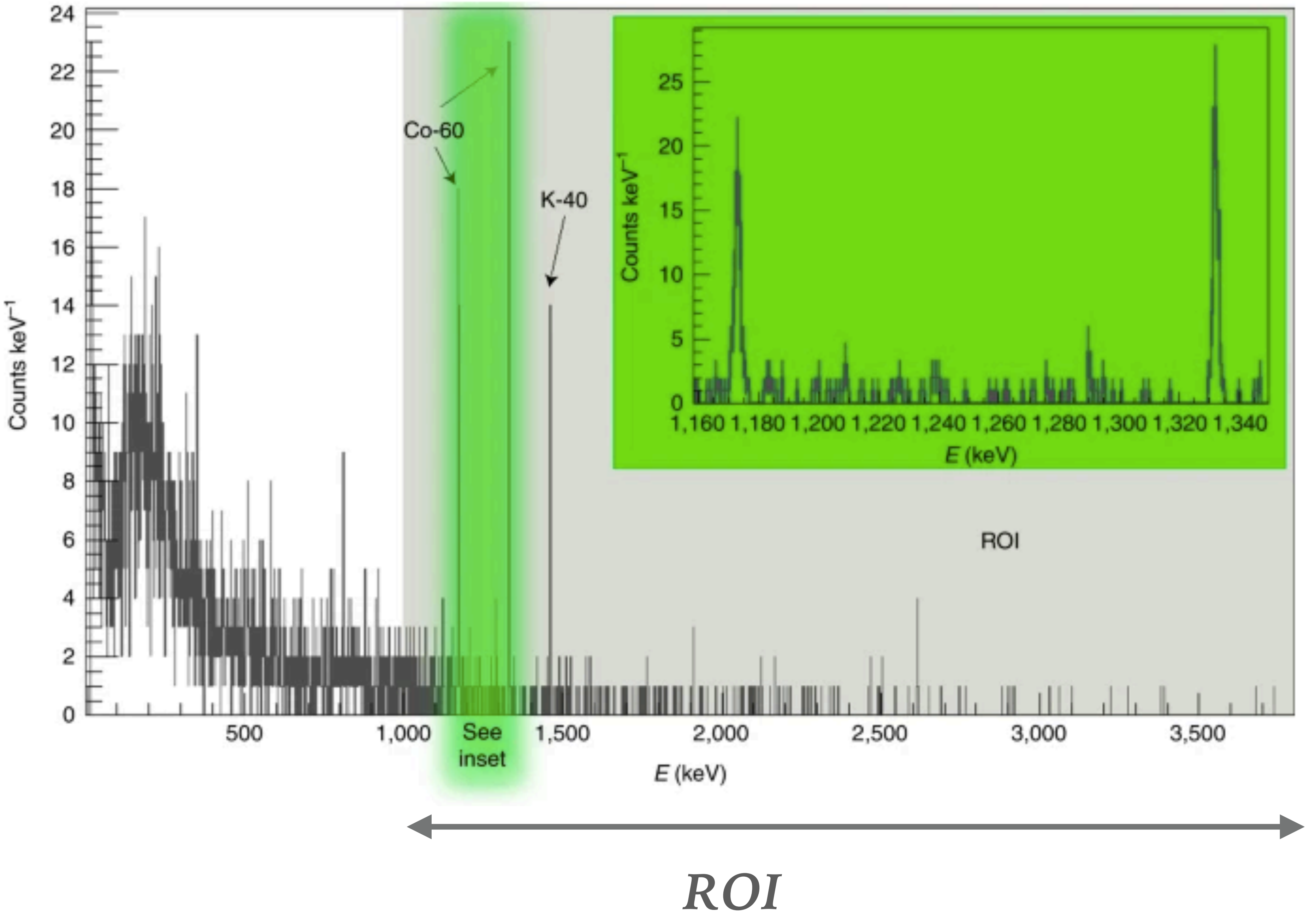
Cu block and plate

Cu shield

Pb shield

Measurement and MC validation

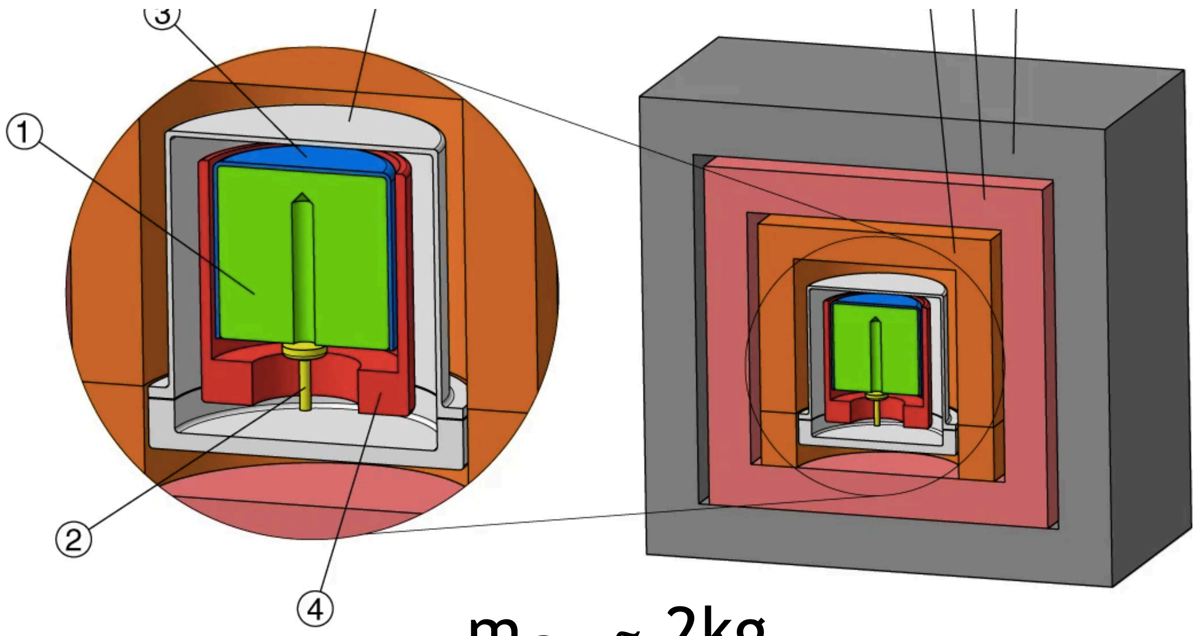
Nat. Phys. **17,** 74–78 (2021)



ROI

Measurement and MC validation

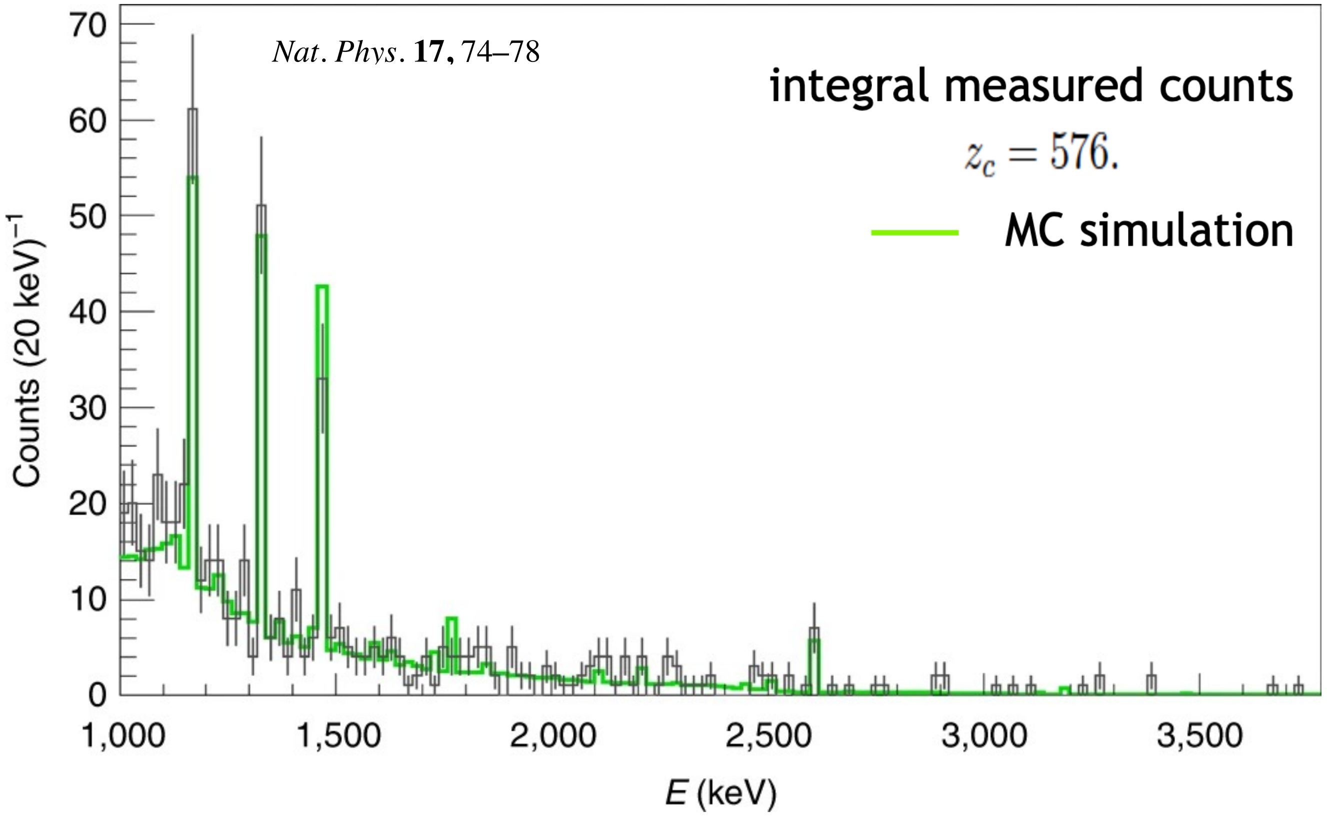
Coaxial p-type high purity germanium (**HPGe**)



m_{Ge} ~ 2kg

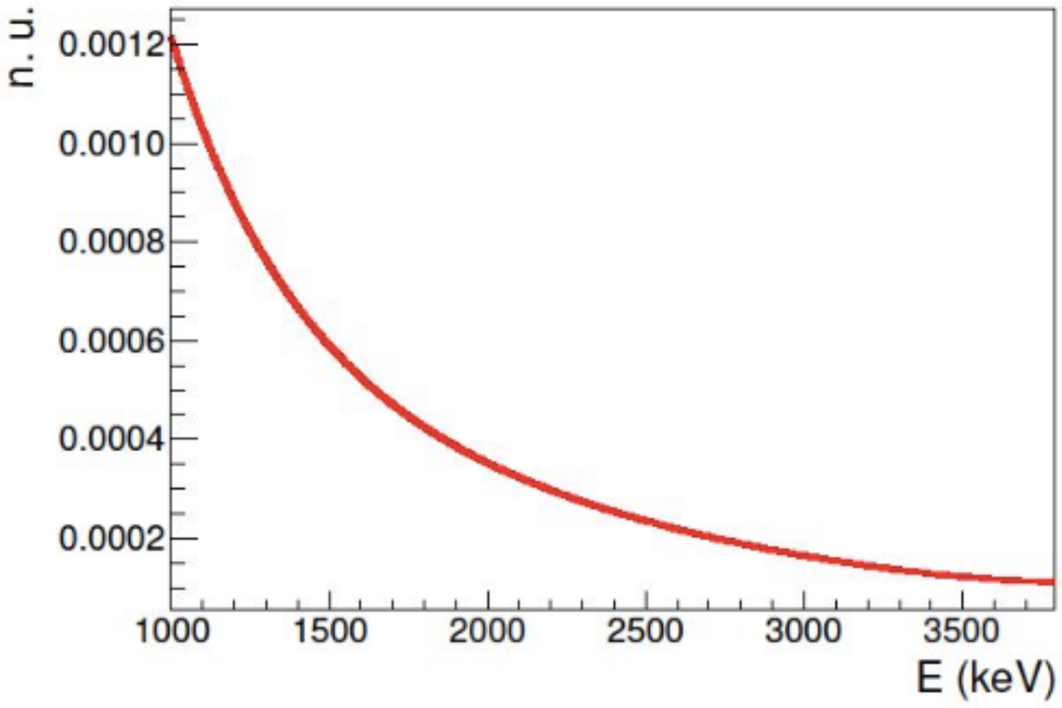
- the activities are measured for each component
- the MC simulation accounts for:
  1. emission probabilities and decay schemes for each radio-nuclide in each material
  2. photons propagation and interactions
  3. detection efficiencies.

The simulation describes 88% of the integral counts:



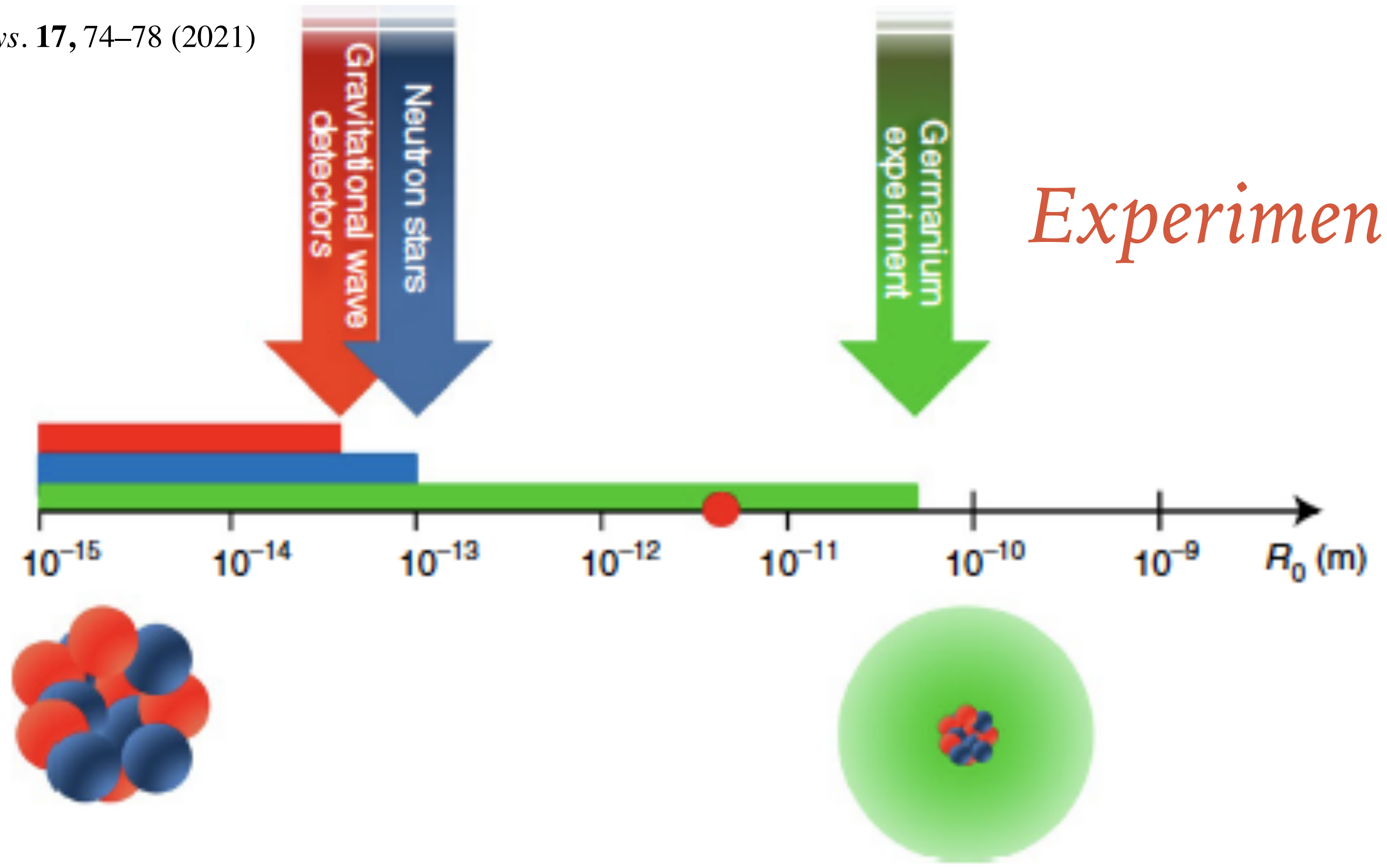
Nat. Phys. **17**, 74–78

expected signal contribution



Results

Nat. Phys. **17,** 74–78 (2021)



Experimental: $R_0 > 0.54 \times 10^{-10}$ *m*

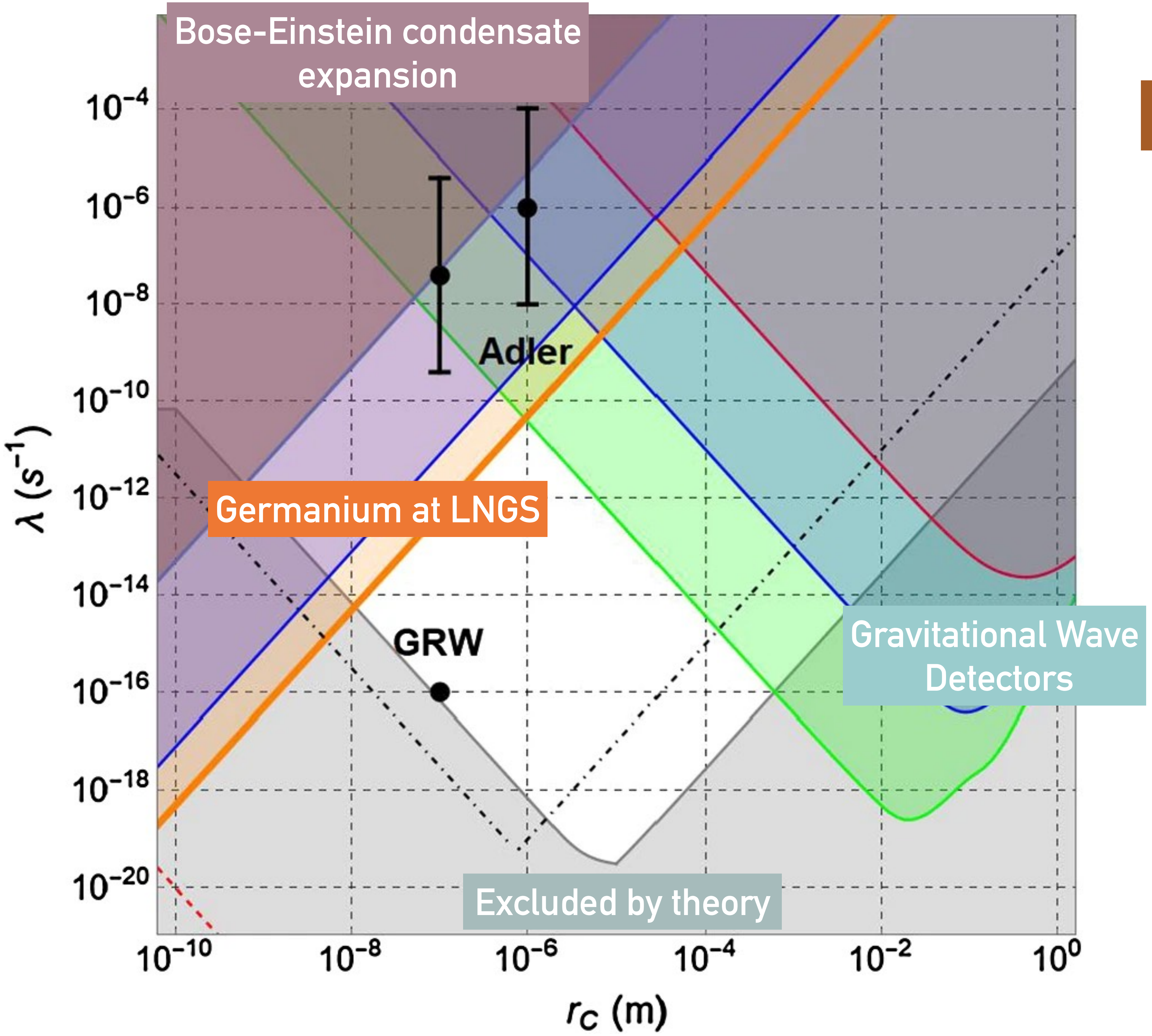
If R_0 *is the size of the nucleus' wave function as suggested by Penrose, in a germanium crystal* R_0^2 *is the mean square displacement of a nucleus in the lattice which, for Ge at liquid nitrogen temperature amounts to:*

Theoretical: $R_0 = 0.05 \times 10^{-10}$ *m*

DP model ruled out in the present formulation

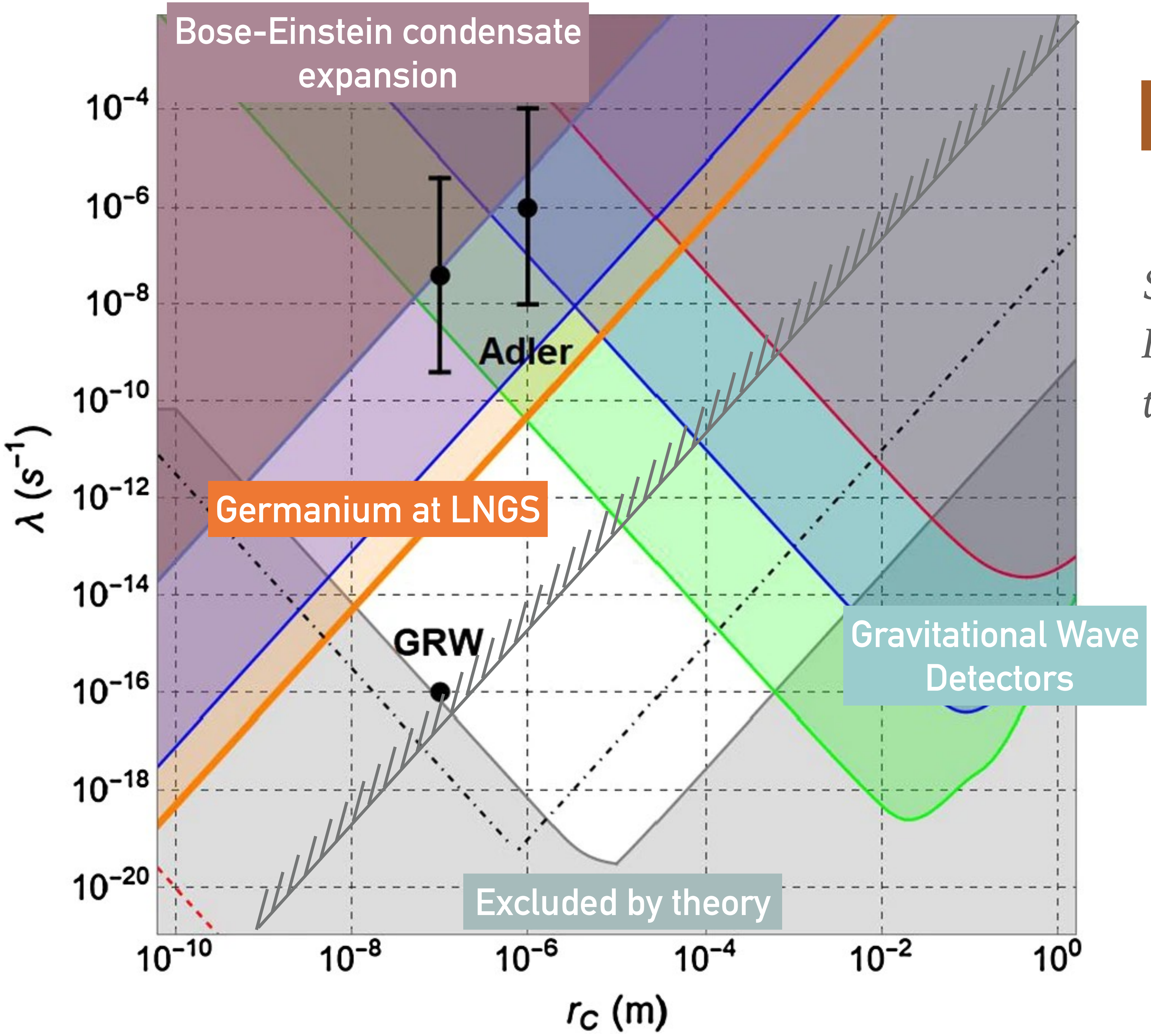
Underground test of gravity-related wave function collapse". Nature Physics 17, pages 74–78 (2021)

CSL Model



Donadi, S., Piscicchia, K., Del Grande, R. *et al.*. *Eur. Phys. J. C* **81, 773 (2021).**

CSL Model



See Inwook Kim's talk this afternoon

Donadi, S., Piscicchia, K., Del Grande, R. *et al.*. *Eur. Phys. J. C* **81, 773 (2021).**

Theory development - X-rays spontaneous radiation

Parameterless DP formulation is ruled out!

What can be done:

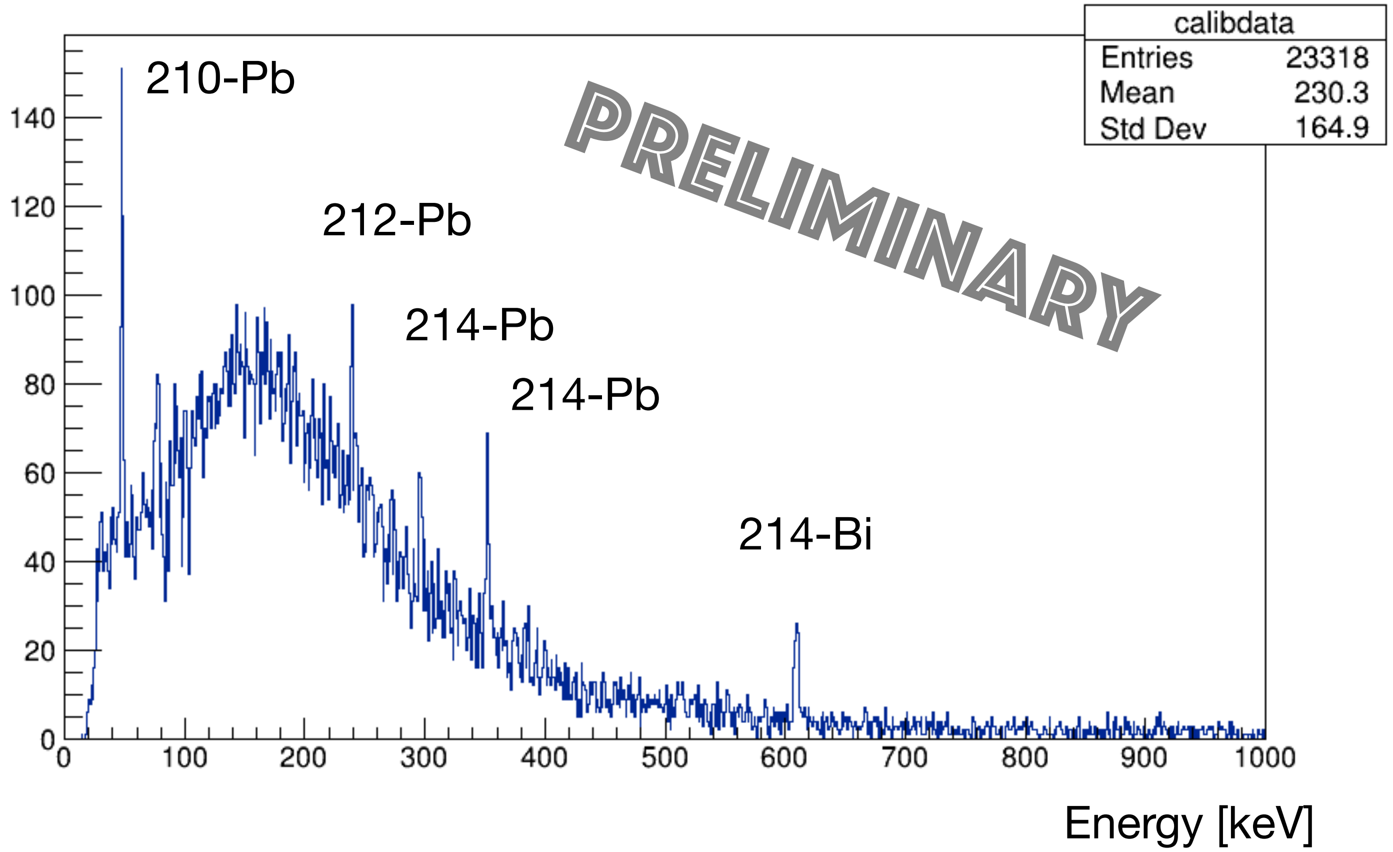
- Add dissipation terms to the master equation and stochastic nonlinear Schrödinger equation of the DP theory, to counteract the runaway energy increase
- Non-Markovian correlation function

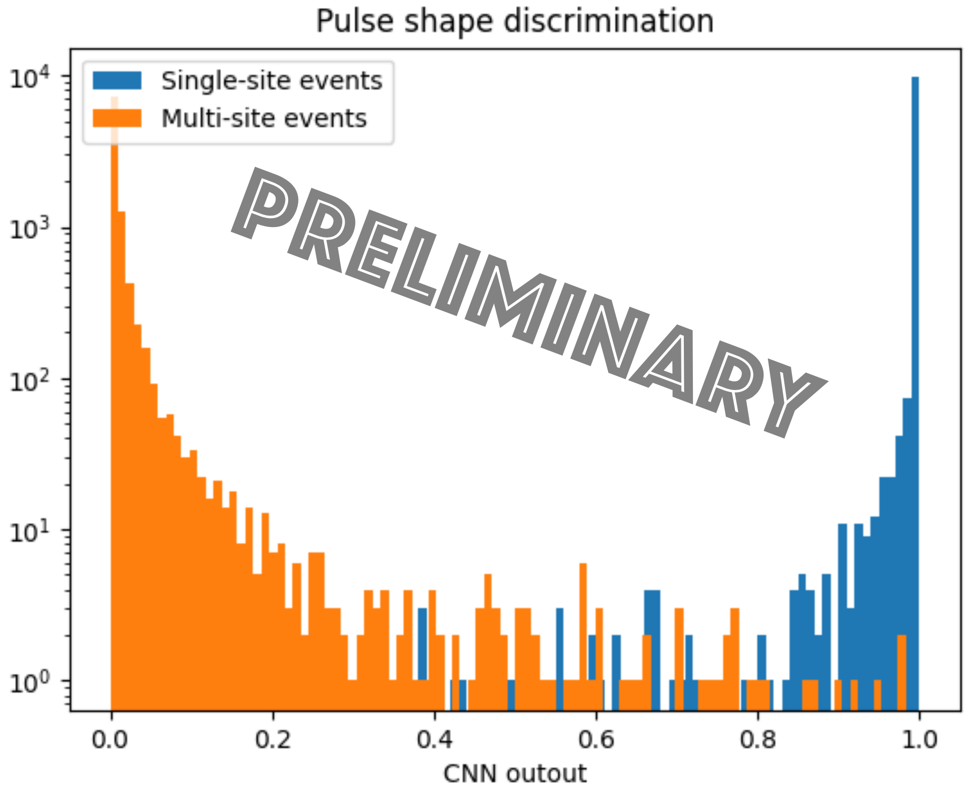
Generalized models lead to **strong dependence on the emission energy in relation to the atomic structure**

Spontaneous Radiation - Dedicated BEGe-like detector

Stronger limits possible at low energy with a Broad Energy (BE) Germanium

- Exploit shape dependence to enhance limit setting on different models
- Using a ~1 kg BEGe for preliminary studies, dedicated to spontaneous radiation
- Using ML techniques for pulse shape discrimination
    - Further enhance physics capabilities





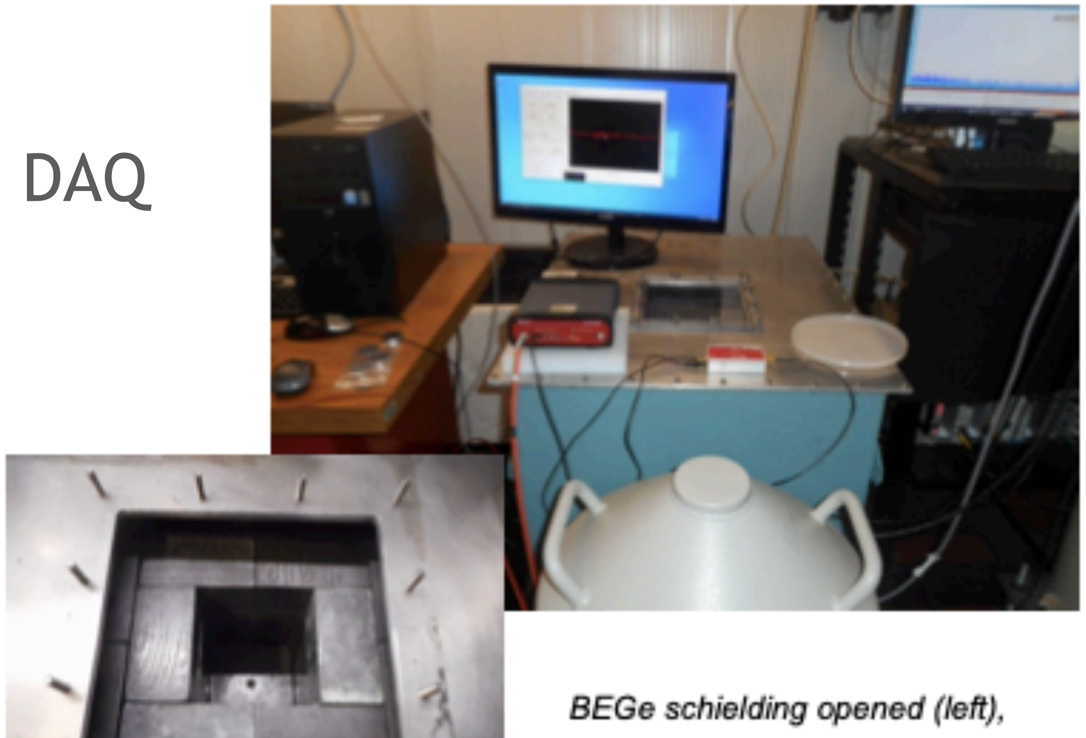
Spontaneous Radiation - Dedicated BEGe-like detector

Stronger limits possible at low energy with a Broad Energy (BE) Germanium

- Exploit shape dependence to enhance limit setting on different models
- Using a ~1 kg BEGe for preliminary studies, dedicated to spontaneous radiation
- Using ML techniques for pulse shape discrimination
  - Further enhance physics capabilities

- Plan to use different ultra-pure materials with different Z
- Plan to reach lower energies using different front-end electronics

- Test setup equipped with low noise DAQ
- High insulation low noise amplifier
  - Gain towards lower energies



BEGe schielding opened (left),

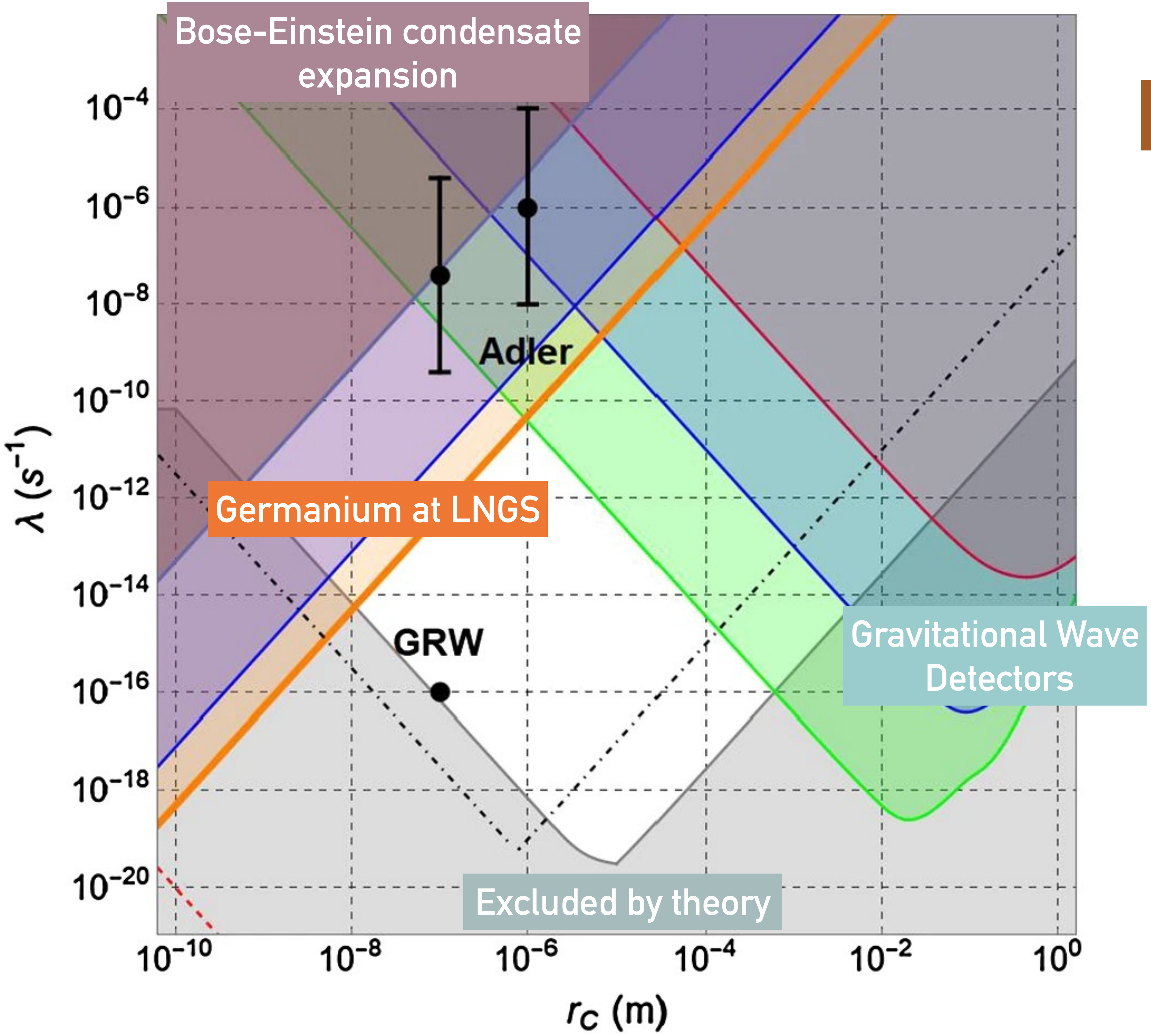
Conclusions

- Wave function collapse still an open question
- Many collapse models e.g. Diòsi-Penrose and CSL
  - Each predict emission of spontaneous radiation
- High purity germanium detector allow to set stringent limits on the models
  - Strong limits on CSL, DP ruled out in the simplest formulation
- Work in progress with a broad energy germanium detector

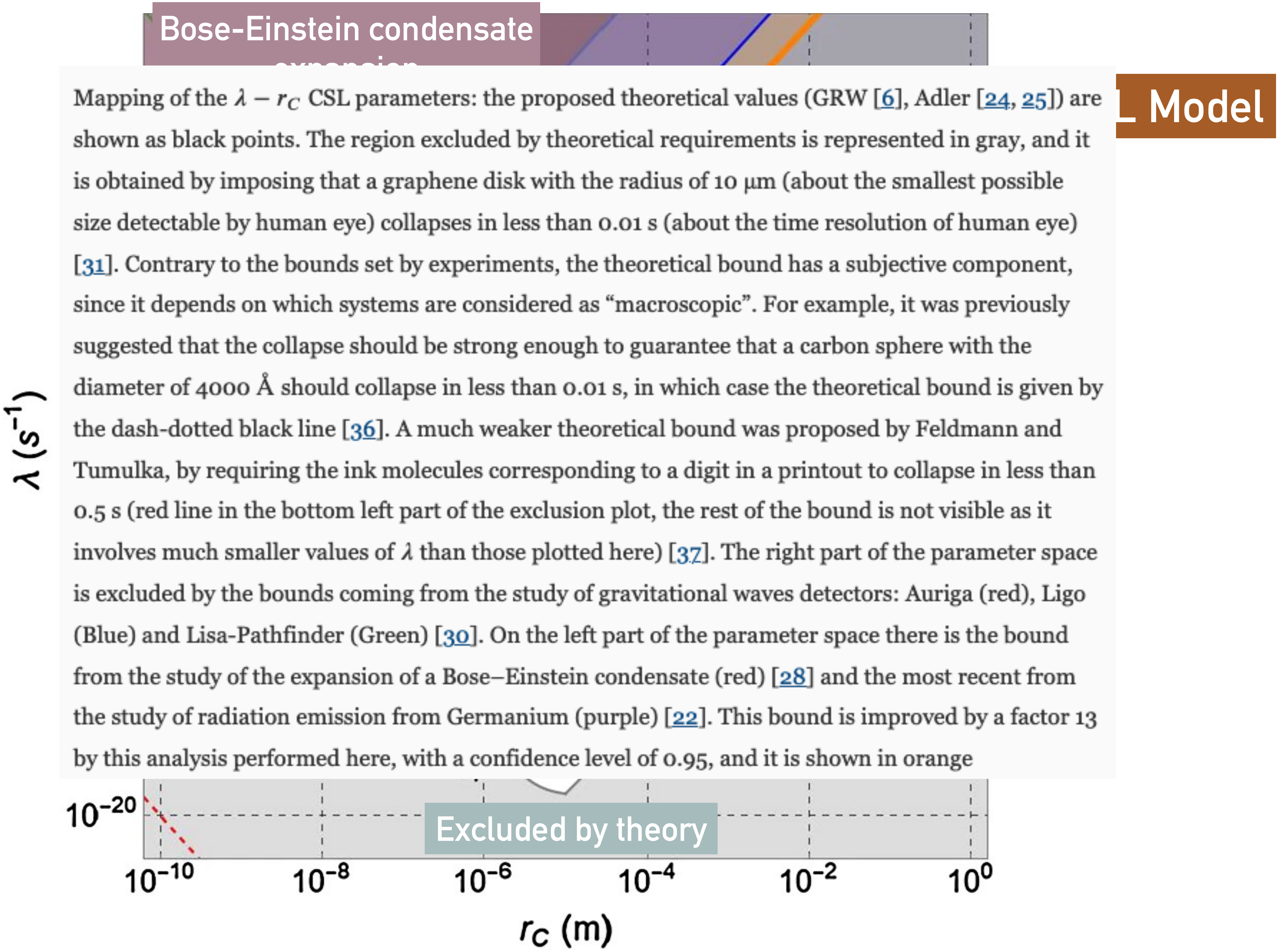
Thank you for your attention!

Questions?

CSL Model



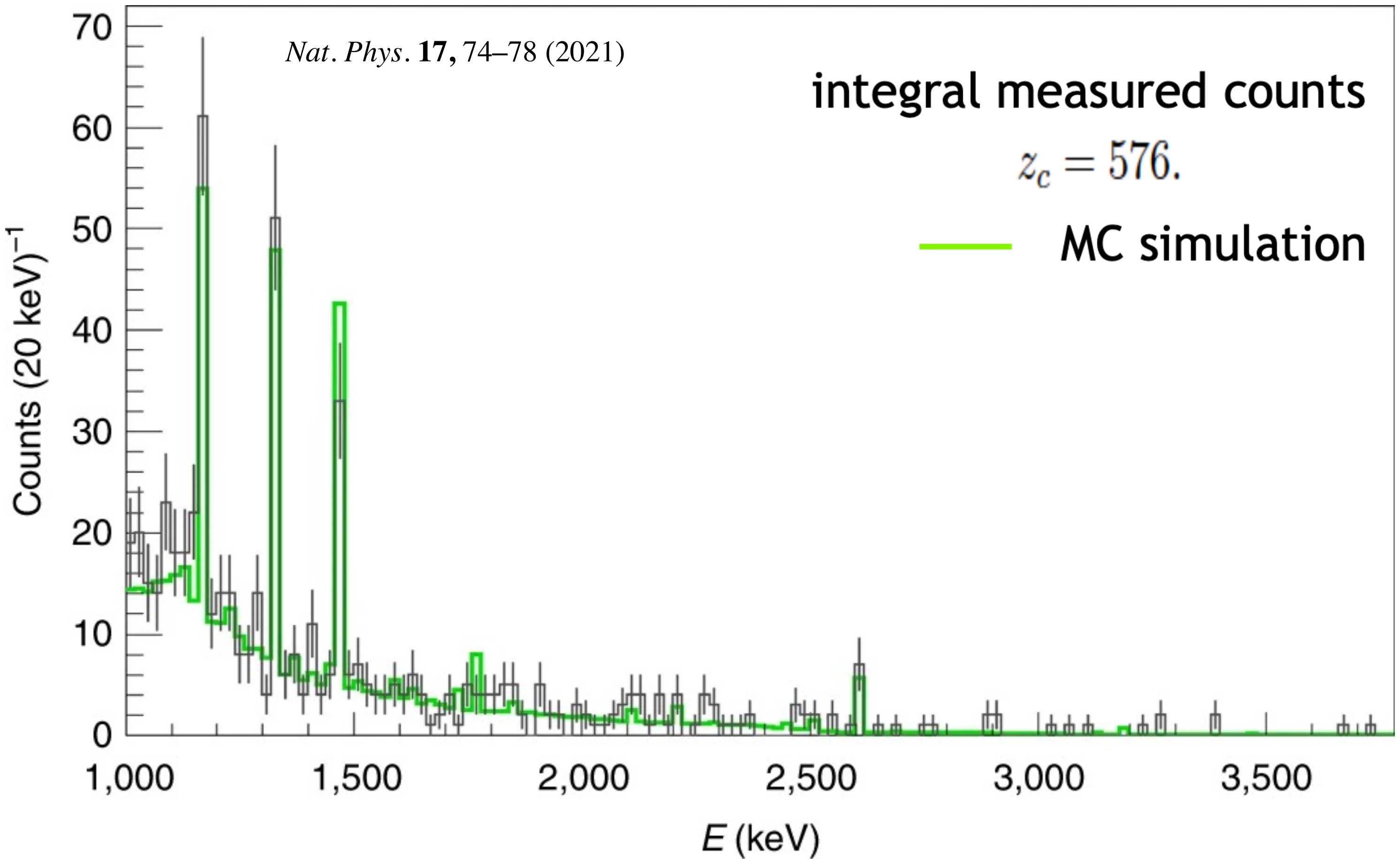
Donadi, S., Piscicchia, K., Del Grande, R. ***et al.*****.** ***Eur. Phys. J. C*** **81, 773 (2021).**



Mapping of the $\lambda - r_C$ CSL parameters: the proposed theoretical values (GRW [6], Adler [24, 25]) are shown as black points. The region excluded by theoretical requirements is represented in gray, and it is obtained by imposing that a graphene disk with the radius of 10 μm (about the smallest possible size detectable by human eye) collapses in less than 0.01 s (about the time resolution of human eye) [31]. Contrary to the bounds set by experiments, the theoretical bound has a subjective component, since it depends on which systems are considered as "macroscopic". For example, it was previously suggested that the collapse should be strong enough to guarantee that a carbon sphere with the diameter of 4000 Å should collapse in less than 0.01 s, in which case the theoretical bound is given by the dash-dotted black line [36]. A much weaker theoretical bound was proposed by Feldmann and Tumulka, by requiring the ink molecules corresponding to a digit in a printout to collapse in less than 0.5 s (red line in the bottom left part of the exclusion plot, the rest of the bound is not visible as it involves much smaller values of λ than those plotted here) [37]. The right part of the parameter space is excluded by the bounds coming from the study of gravitational waves detectors: Auriga (red), Ligo (Blue) and Lisa-Pathfinder (Green) [30]. On the left part of the parameter space there is the bound from the study of the expansion of a Bose–Einstein condensate (red) [28] and the most recent from the study of radiation emission from Germanium (purple) [22]. This bound is improved by a factor 13 by this analysis performed here, with a confidence level of 0.95, and it is shown in orange

Donadi, S., Piscicchia, K., Del Grande, R. *et al.*. *Eur. Phys. J. C* **81, 773 (2021).**

Measurement and MC validation



Nat. Phys. **17,** 74–78 (2021)

integral measured counts

$$z_c = 576.$$

- 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
  2. photons propagation and interactions
  3. detection efficiencies.

The simulation describes 88% of the integral counts:

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

expected signal contribution

The expected signal of spontaneous radiation is obtained weighting the theoretical rate for the detection efficiencies:

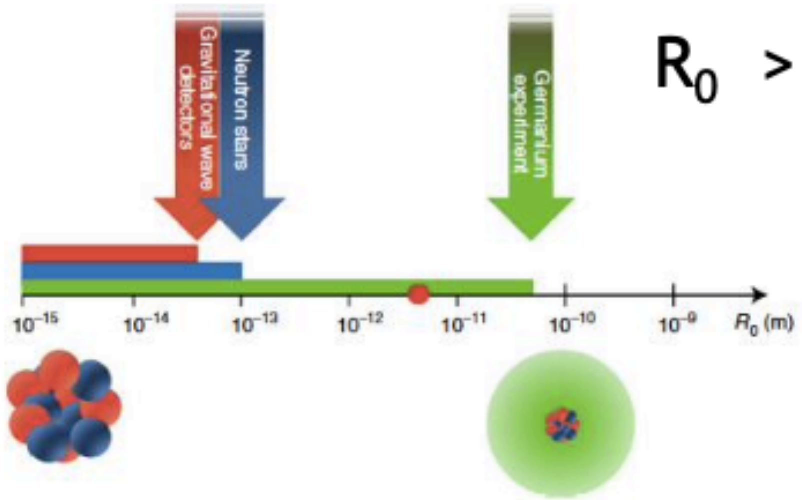
- 10^8 photons generated for each energy for each material
- efficiency functions are obtained by polinomial fits ➡ $\boxed{\epsilon_i(E) = \sum_{j=0}^{c_i} \xi_{ij} E^j}$
- the expected signal contribution is:

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

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

Results

Lower bound on R_0



Nat. Phys. **17,** 74–78 (2021)

$R_0 > 0.54 \cdot 10^{-10}$ m

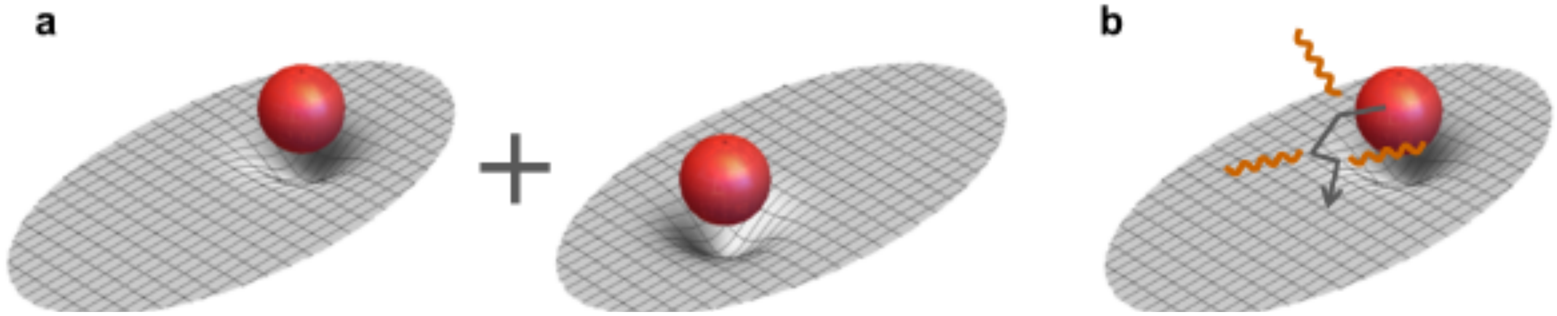
If R_0 is the size of the nucleus's wave function as suggested by Penrose, we have to compare the limit with the properties of nuclei in matter.

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

"Underground test of gravity-related wave function collapse". Nature Physics 1-5, (2020).

Diósi-Penrose (DP) Collapse model

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.



$$\Delta E_{\mathrm{DP}}(\mathbf{d}) = -8\pi G \int d\mathbf{r} \int d\mathbf{r}' \frac{\mu(\mathbf{r})\left[\mu(\mathbf{r}' + \mathbf{d}) - \mu(\mathbf{r}')\right]}{|\mathbf{r} - \mathbf{r}'|}$$

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

● Proton: m $\simeq 10^{-27}$ Kg, R $\simeq 10^{-15}$ m, $\tau_{DP} \simeq 10^{6}$ years

● Dust grain: m $\simeq 10^{-12}$ Kg, R $\simeq 10^{-5}$ m, $\tau_{DP} \simeq 10^{-8}$ s

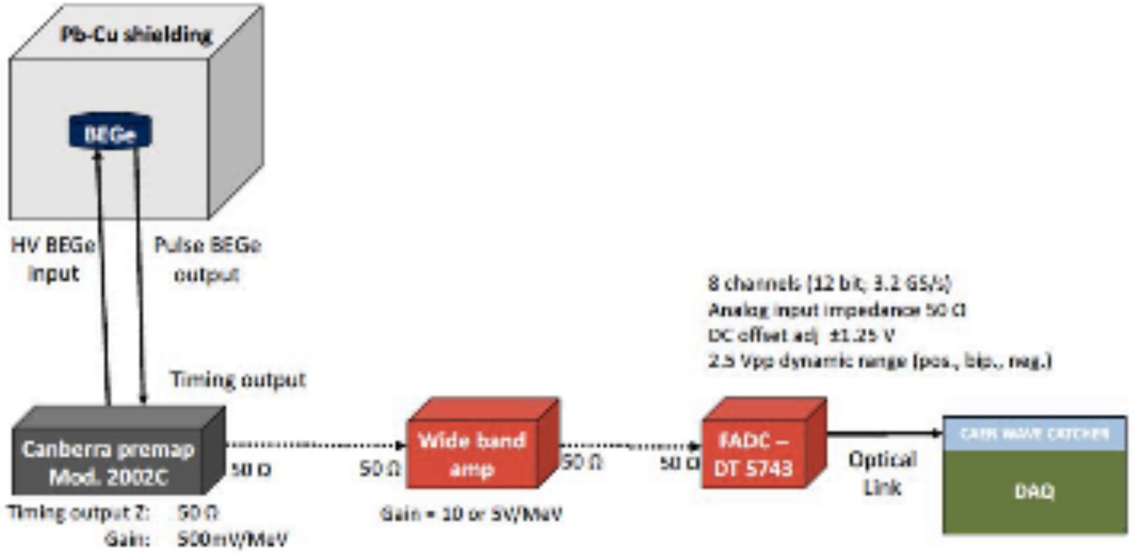
R_0 short-length cutoff: size of particle mass density

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).

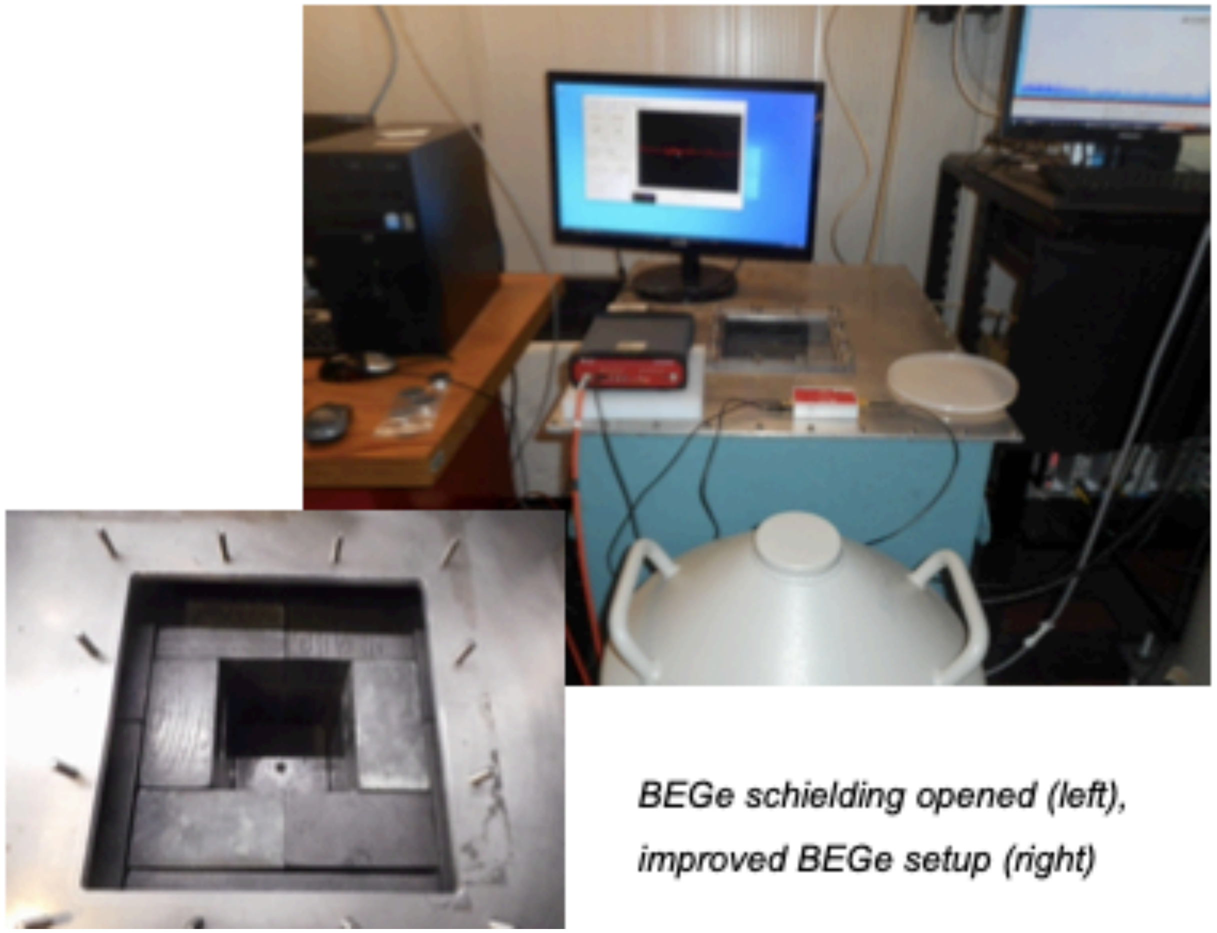
*R. Penrose, Found. Phys. **44**, 557-575 (2014), R. Penrose, Gen. Relativ. Gravit. **28**, 581-600 (1996),* L. Diósi, Phys. Rev. A **40**, 1165–1174 (1989).

Spontaneous Radiation - BEGe detector

<u>Stronger limits possible at low energy with a Broad Energy (BE) Germanium</u>



Block diagram of improved BEGe experimental apparatus



BEGe schielding opened (left), improved BEGe setup (right)

- Test setup equipped with low noise DAQ
- High insulation low noise amplifier
    - Gain towards lower energies