TESTING THE PAULI EXCLUSION PRINCIPLE AND COLLAPSE MODEL IN UNDERGROUND EXPERIMENTS

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Outline: Line of Research at LNGS
From the shoulders of Giants

Wave-function Collapse Problem

Testing Pauli Exclusion Principle

Wave-function Collapse Problem

Schrödinger Equation

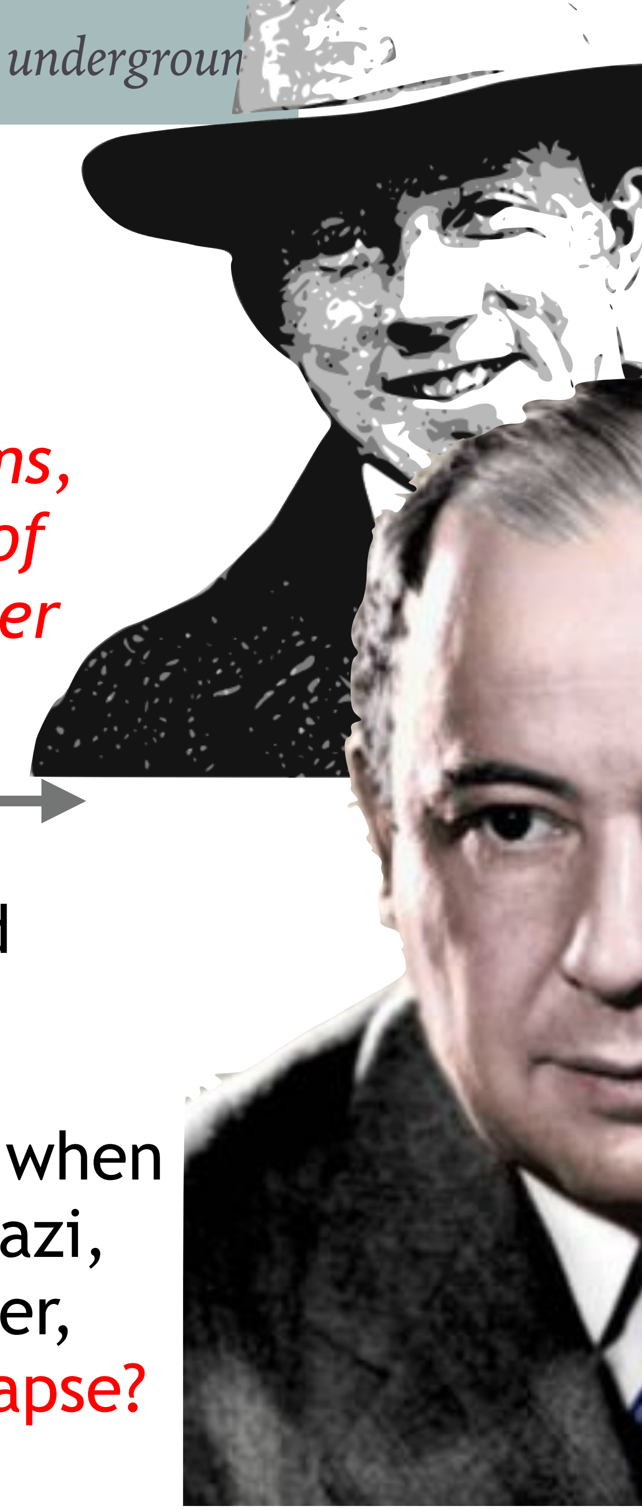
$$i\hbar \frac{d}{dt} |\Psi(t)\rangle = H |\Psi(t)\rangle$$

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

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

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

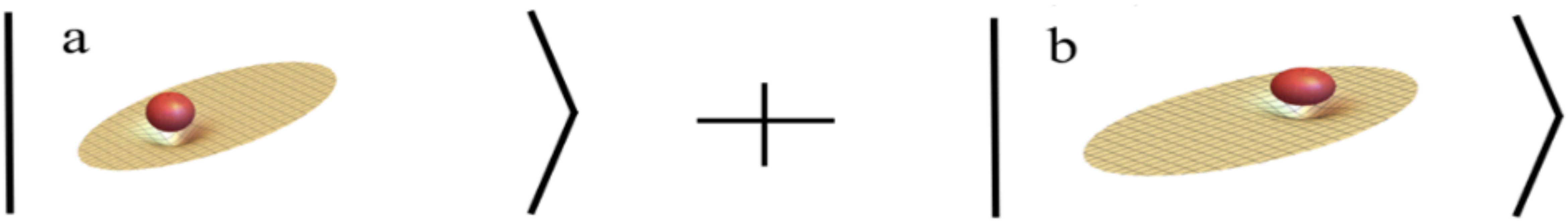
Collapse Models: is it possible to add additional terms to the Schrödinger equation such for more massive objects the wave function collapses faster?

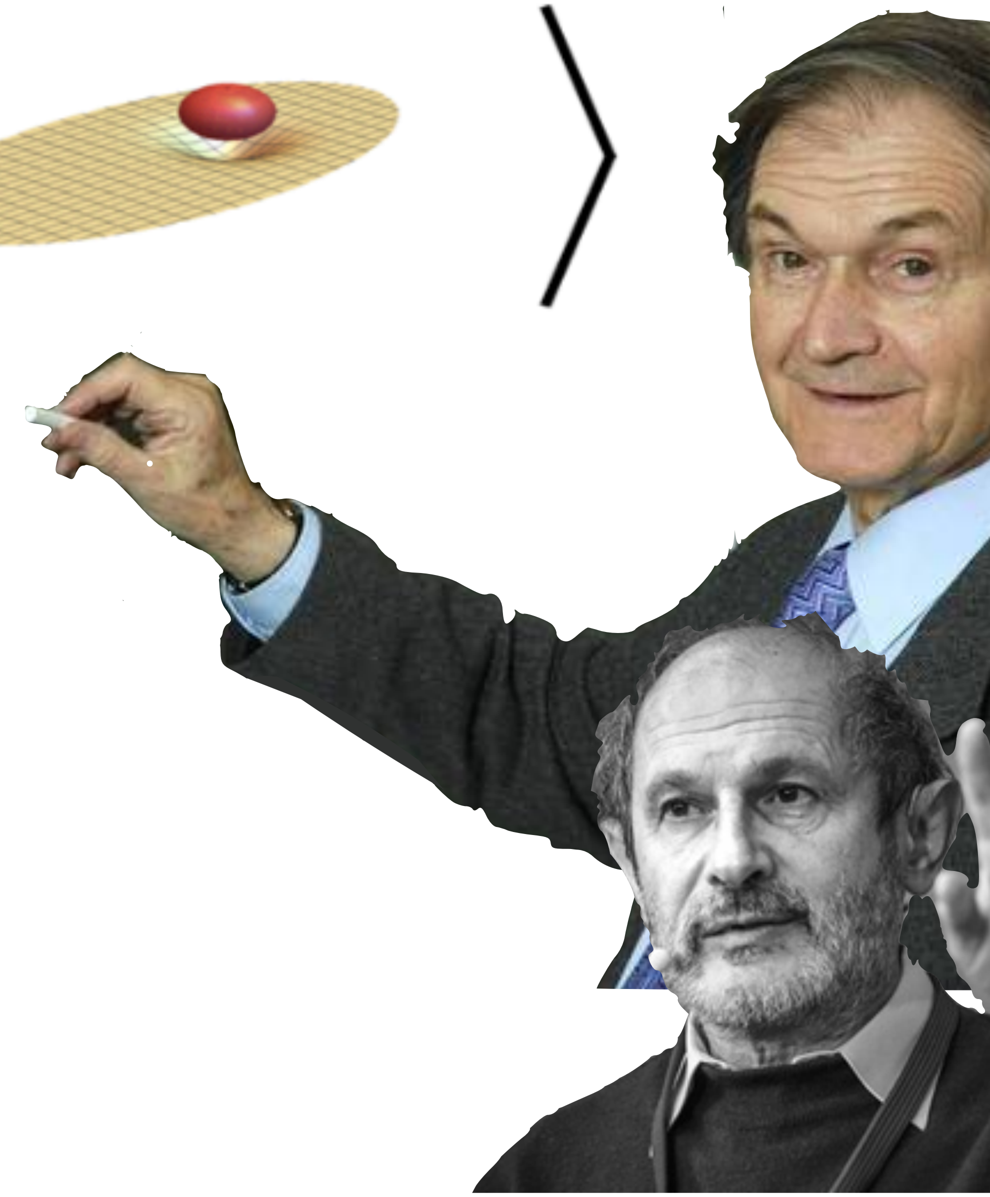
Schrödinger Equation

$$i\hbar \frac{d}{dt} |\Psi(t)\rangle = H |\Psi(t)\rangle \quad + \text{ additional terms}$$

linear and deterministic

Diósi-Penrose (DP) Collapse model





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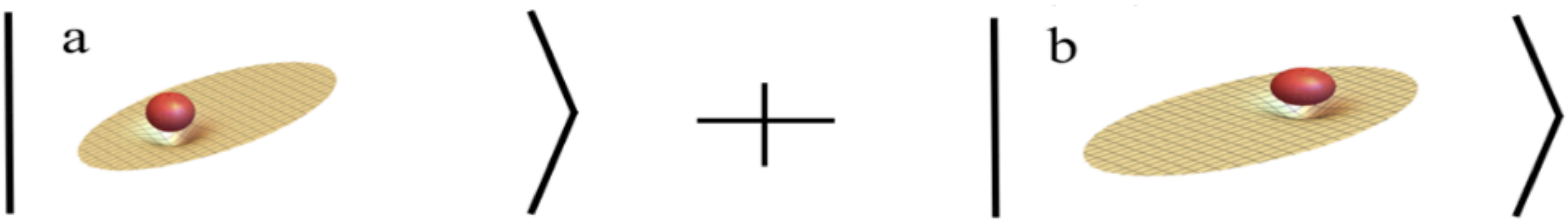
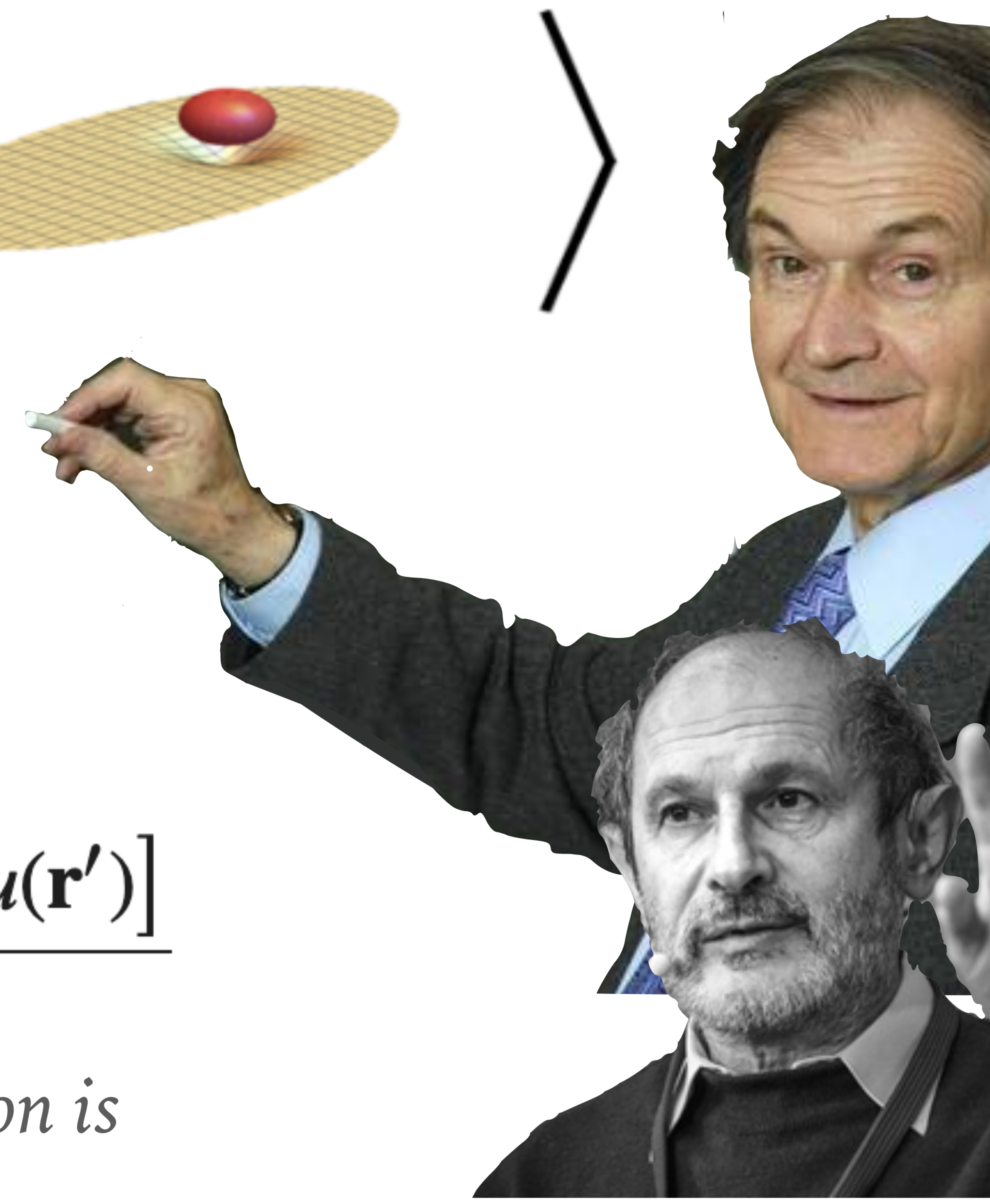




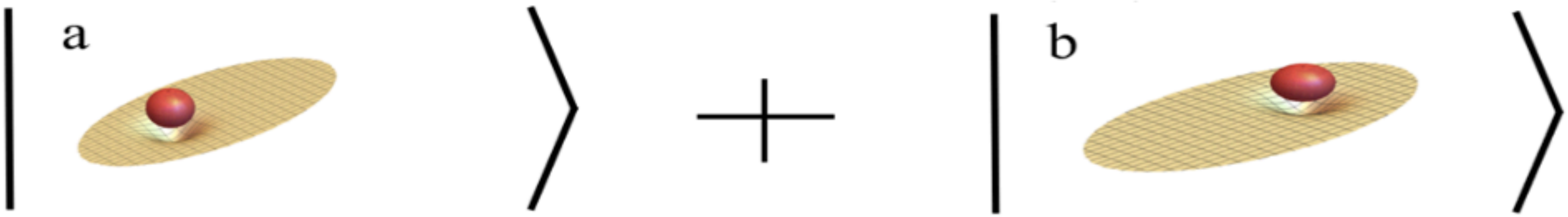
"*as soon as a 'significant' amount of space-time curvature is introduced, the rules of quantum linear superposition must fail*" (R. Penrose)

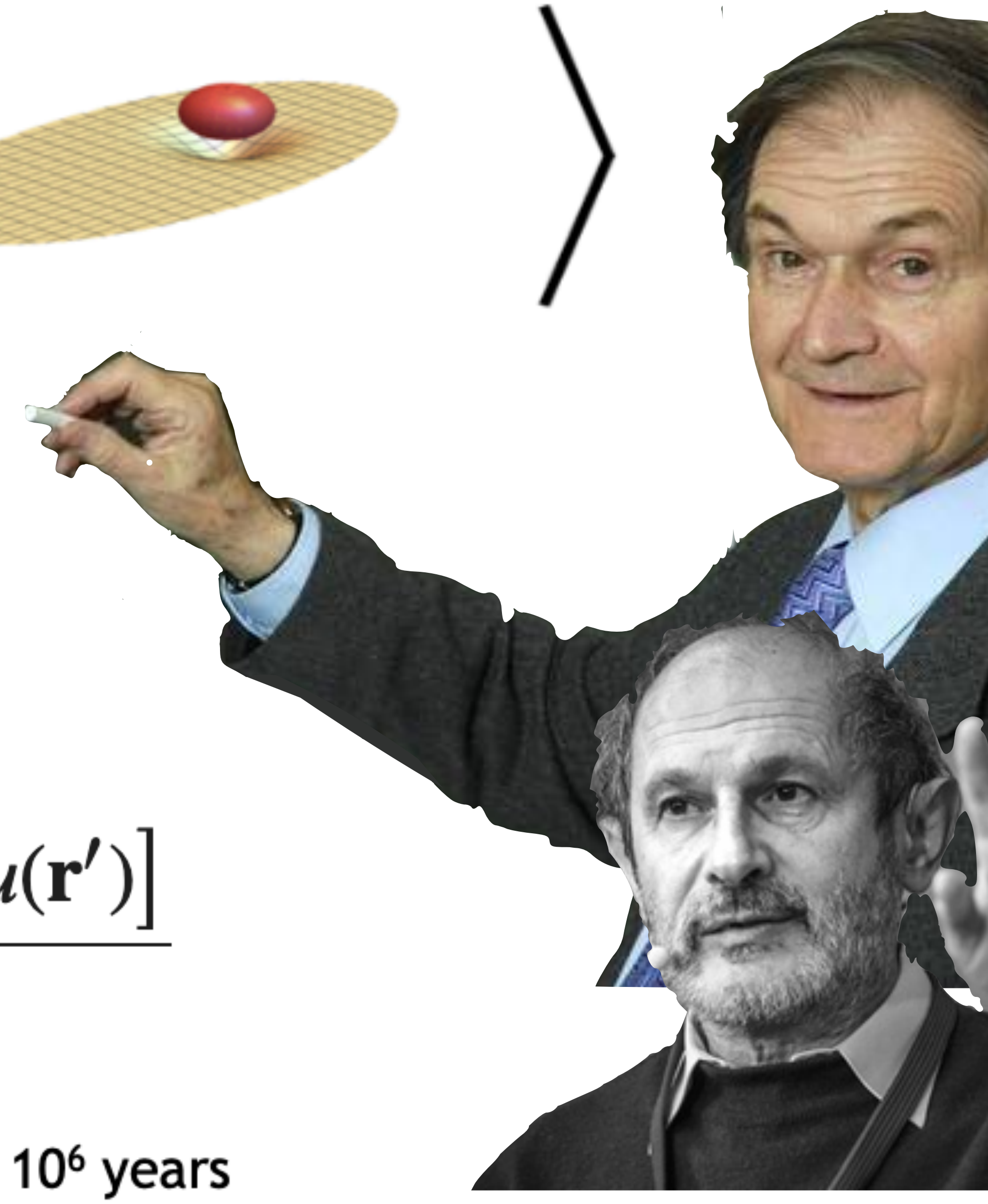
$$\Delta E_{\mathrm{DP}}(\mathbf{d}) = -8\pi G \int \mathrm{d}\mathbf{r} \int \mathrm{d}\mathbf{r}' \frac{\mu(\mathbf{r})\left[\mu(\mathbf{r}'+\mathbf{d}) - \mu(\mathbf{r}')\right]}{|\mathbf{r}-\mathbf{r}'|}$$

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





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

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).

Continuous Spontaneous Localization (CSL) model

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

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

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*

$\lambda \sim 10^{-8\pm 2}\ s^{-1}$ $\lambda \sim 10^{-17}\ s^{-1}$ $r_c \sim 10^{-5}$ 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.;

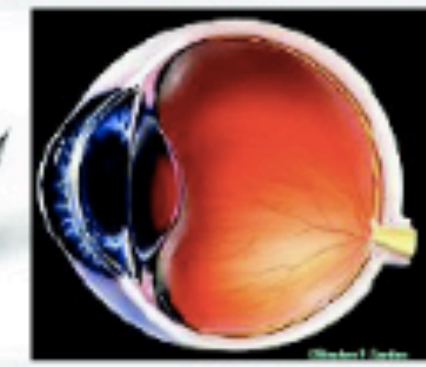
Donadi, S., JPA 46, (2013) 245304.

Microscopic world
(few particles)

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

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)

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

QUANTUM – CLASSICAL TRANSITION (GRW - 1986)

Macroscopic world
(> 10^{13} particles)

G.C. Ghirardi, A. Rimini and T. Weber, PRD 34, 470 (1986)

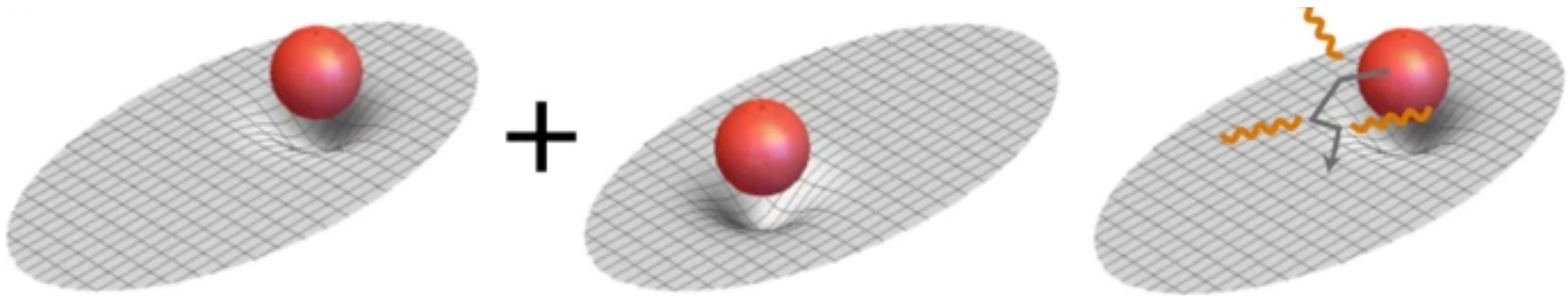
$r_C = 1/\sqrt{\alpha} \sim 10^{-5} \text{cm}$

Increasing size of the system

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

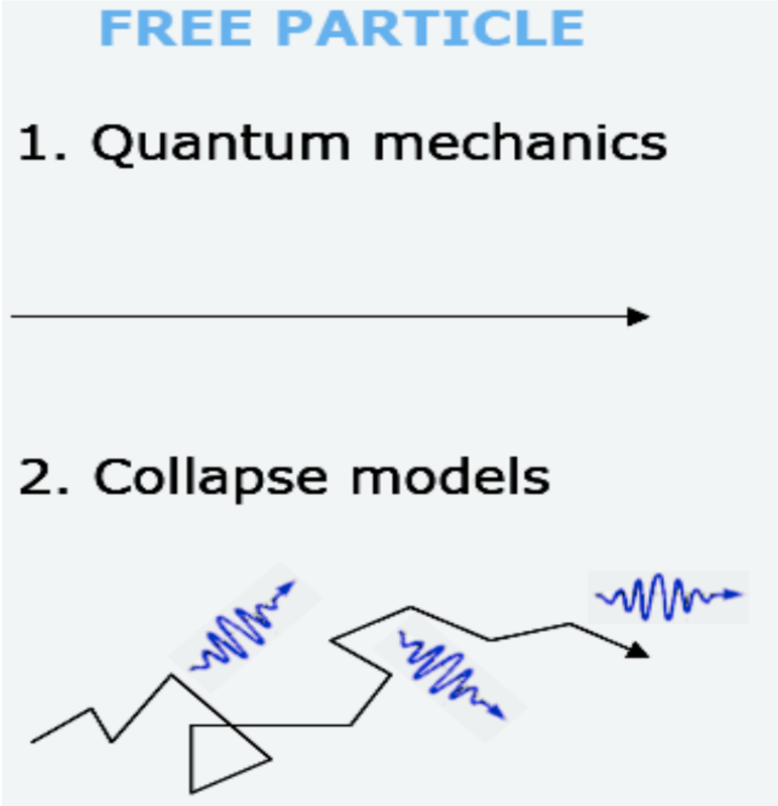
S. L. Adler, JPA 40, (2007) 2935, Adler, S.L.; Bassi, A.;
Donadi, S., JPA 46, (2013) 245304.

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)

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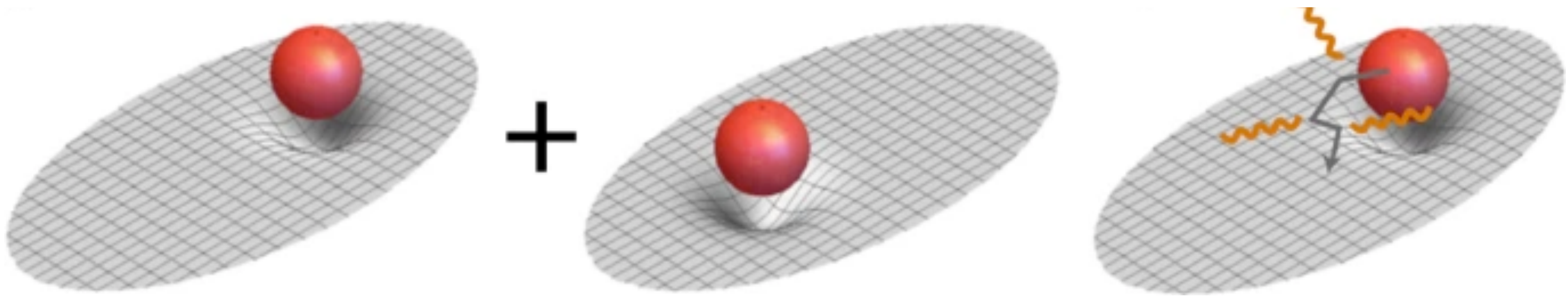
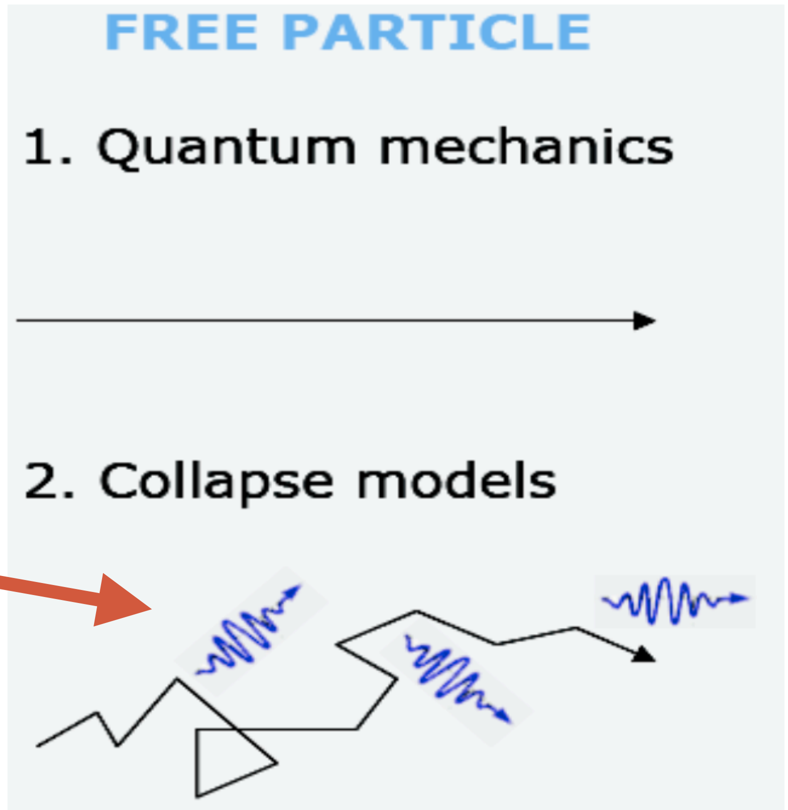


Collapse happens → the centre of mass is shifted towards the localized wave function position → since the process is random this results in a diffusion process

Deviation from standard QM: emission of radiation from charged particles

→ Anomalous amount of radiation can prove the collapse models



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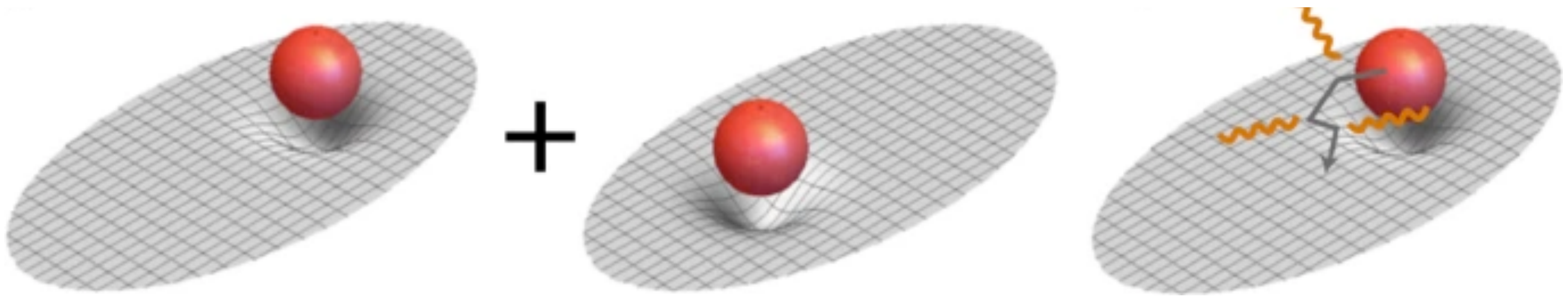


We search for spontaneous radiation emission from a germanium crystal and the surrounding materials in the experimental apparatus.

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:

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

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

where:

λ - collapse strength

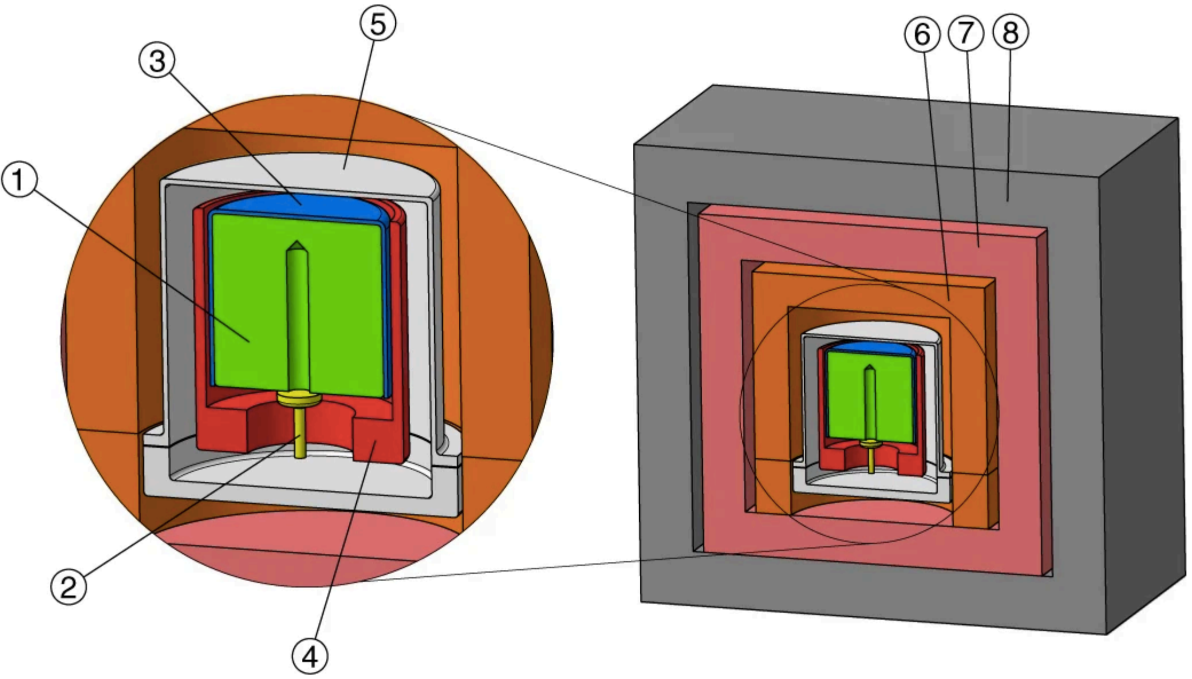
r_C - correlation length

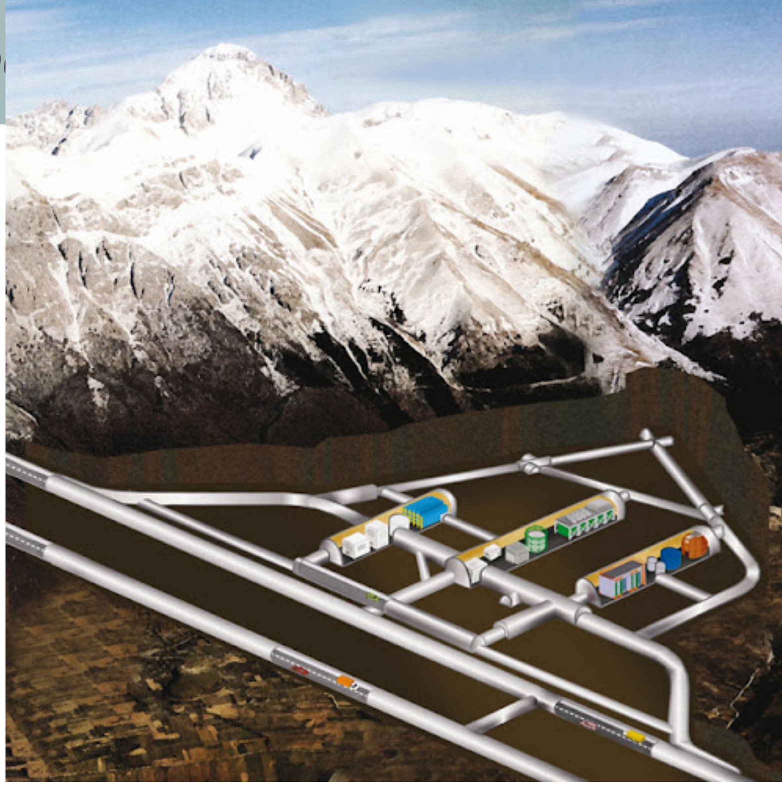
→ see e. g. *S. L. Adler, JPA 40, (2007) 2935, Adler, S.L.; Bassi, A.; Donadi, S., JPA 46, (2013) 245304.*

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).*

The experiment at LNGS

The experiment at LNGS





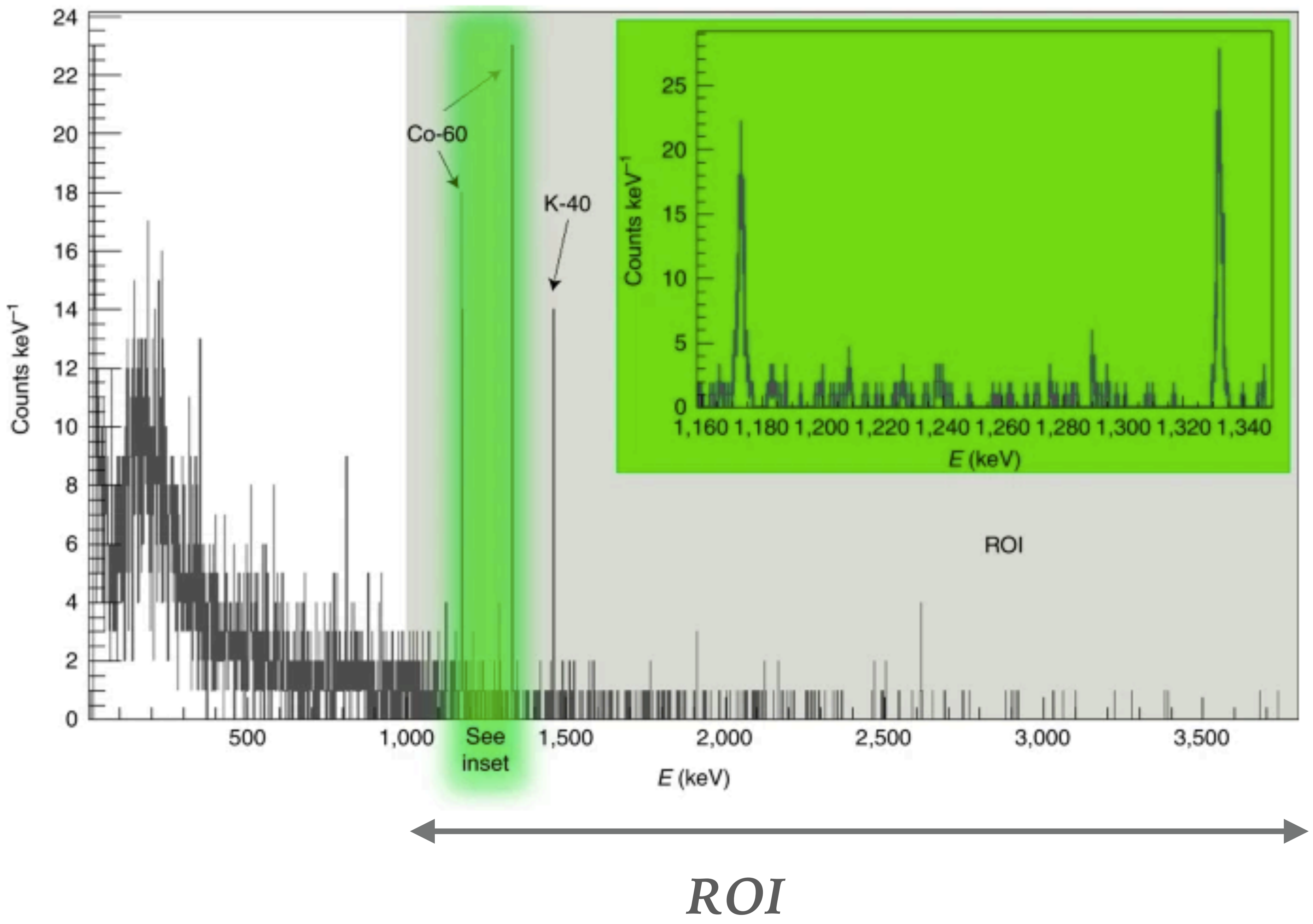
- minimum overburden 3100 m w.e.
- cosmic radiation flux reduction factor 10^6
- main background source: γ-radiation produced by long-lived γ-emitting primordial isotopes and their decay products.

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.

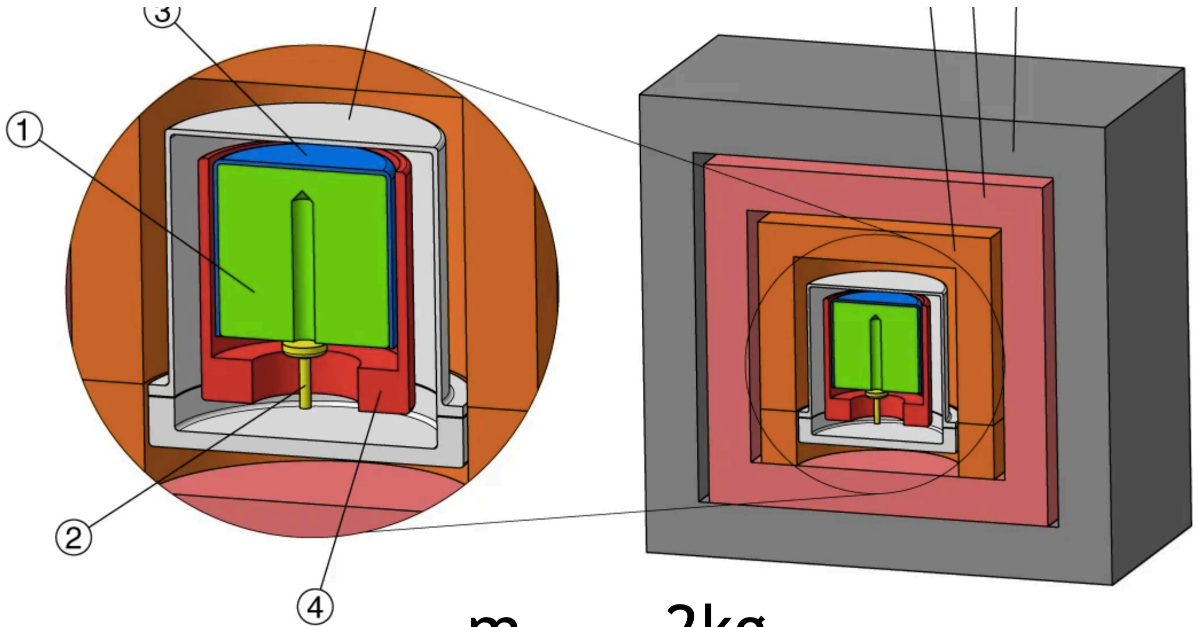
Measurement and MC validation

Nat. Phys. **17,** 74–78 (2021)

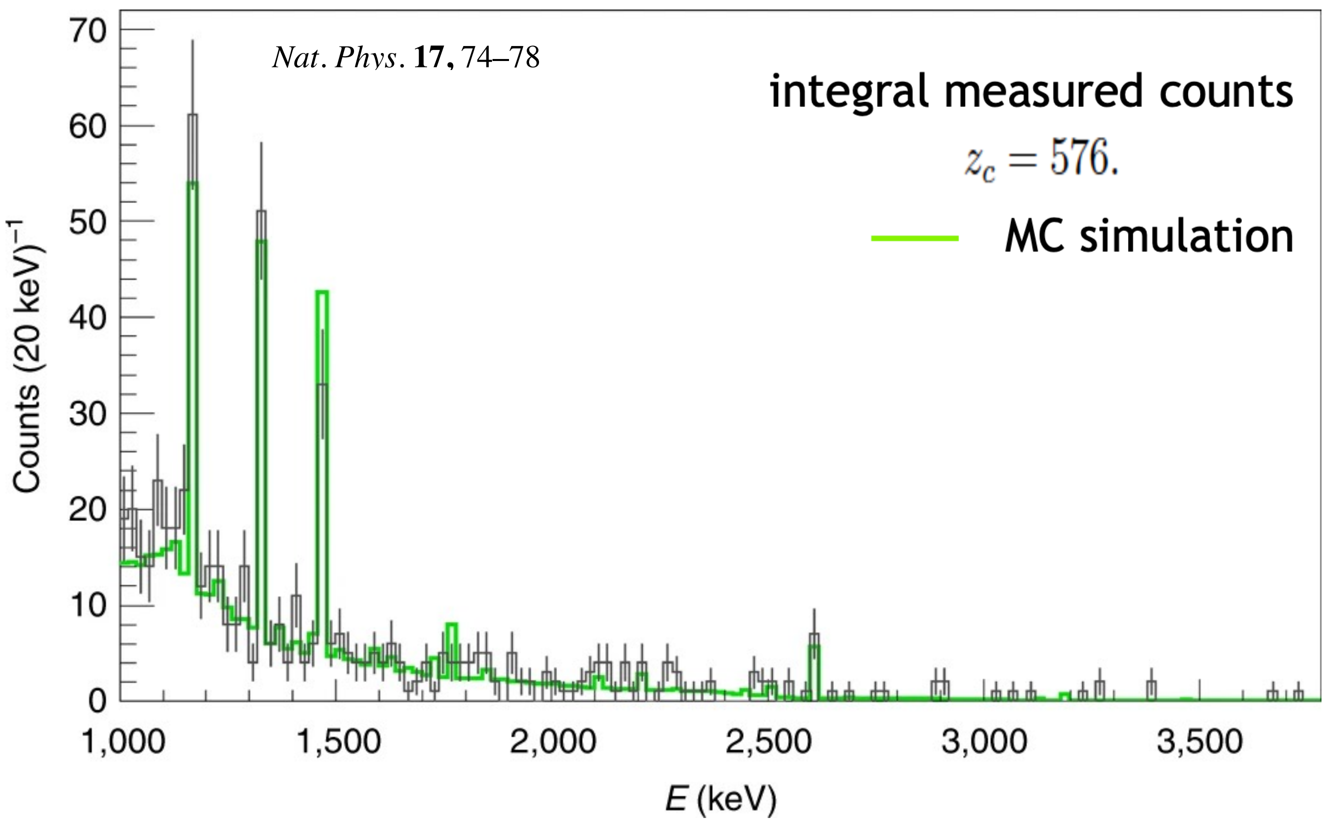


Measurement and MC validation

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



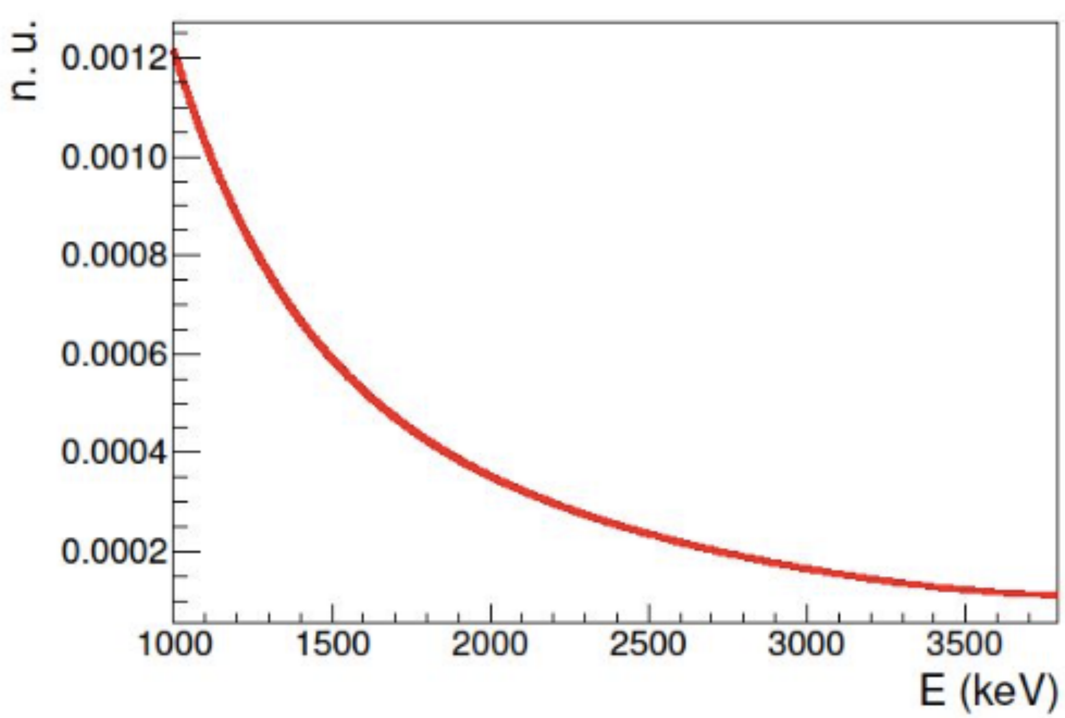
m_{Ge} ~ 2kg



- 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.

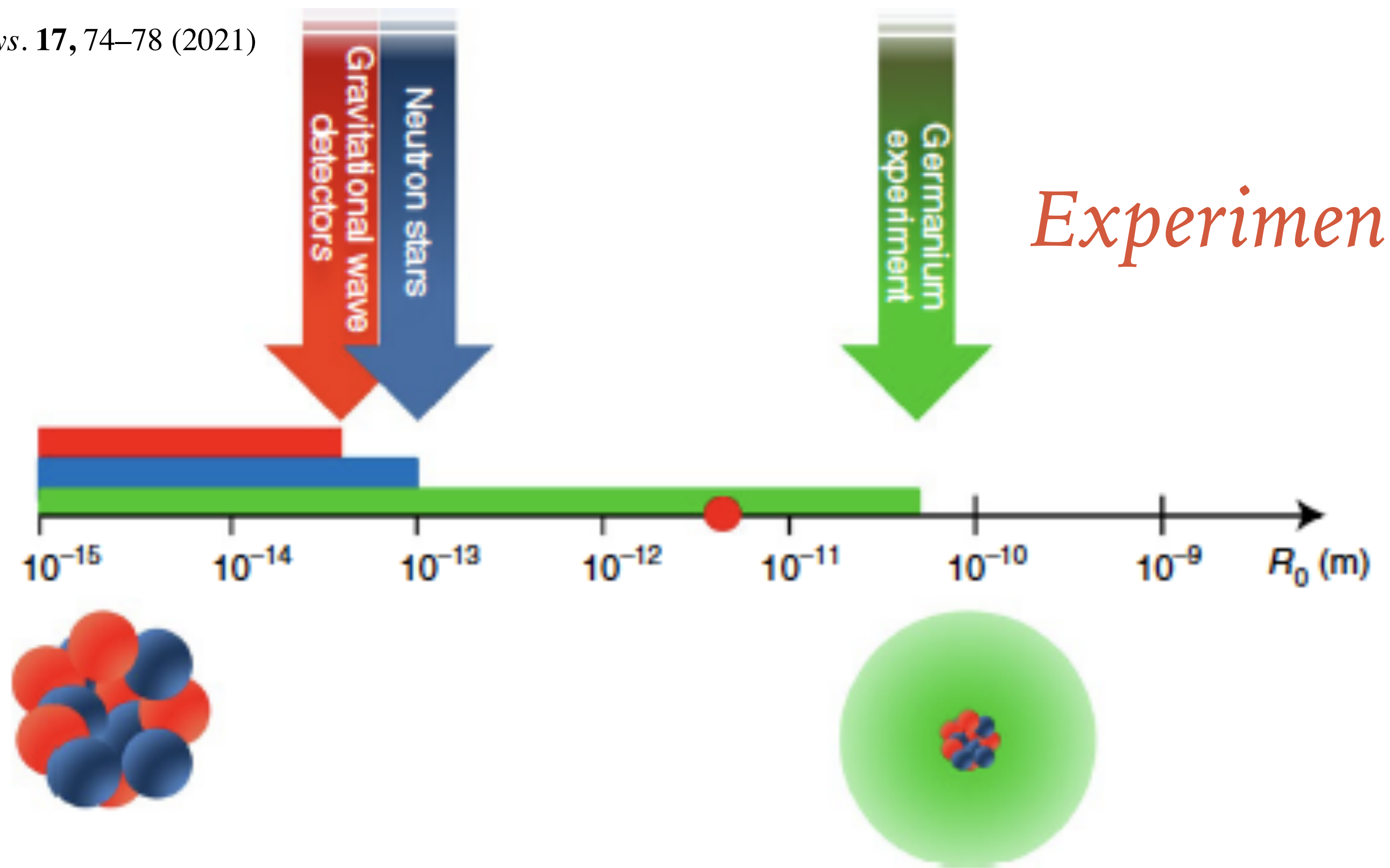
The simulation describes 88% of the integral counts:

expected signal contribution



Results

Nat. Phys. **17,** 74–78 (2021)

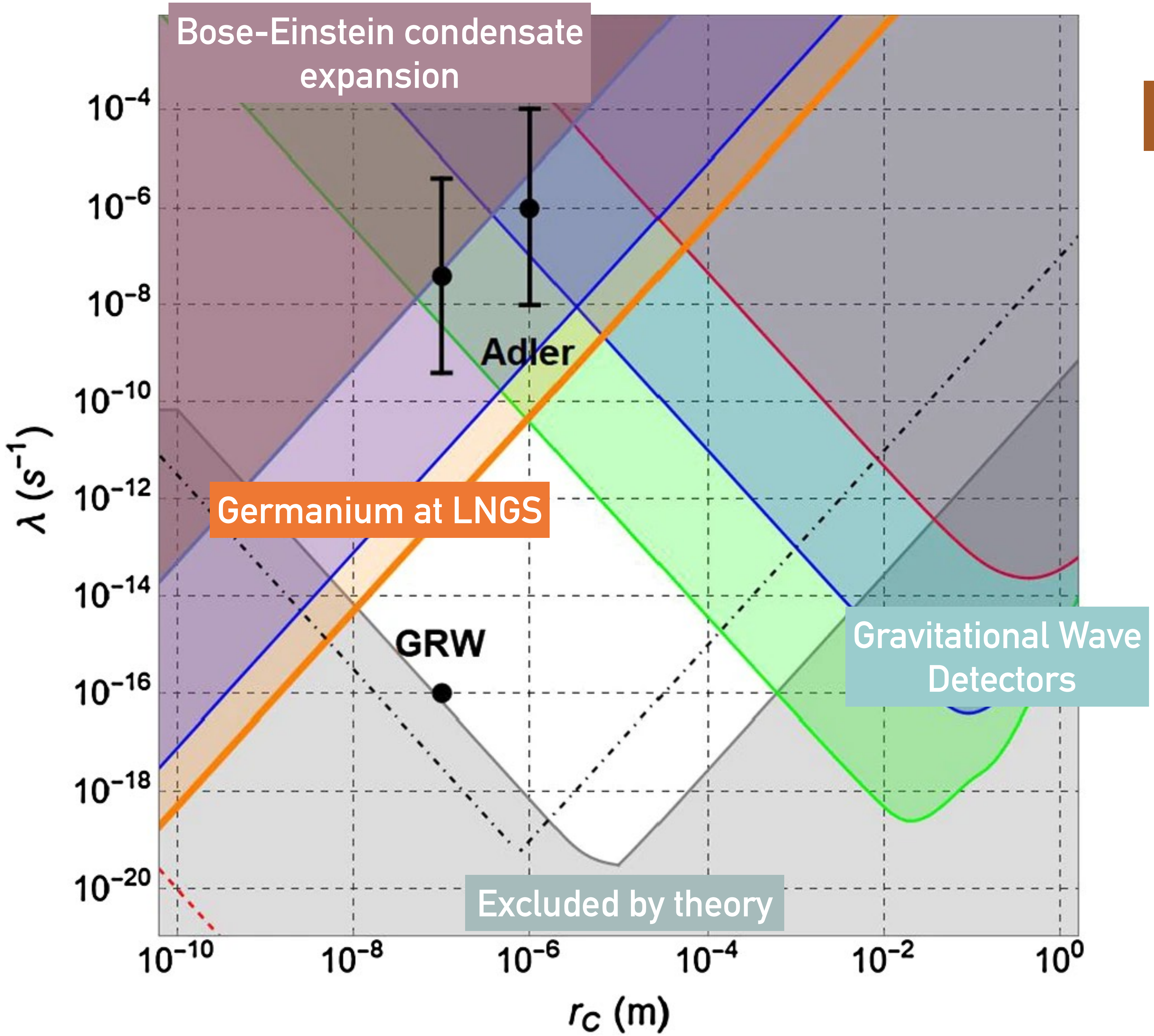


Experimental: $R_0 > 0.54 \times 10^{-10}$ m

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



CSL Model

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

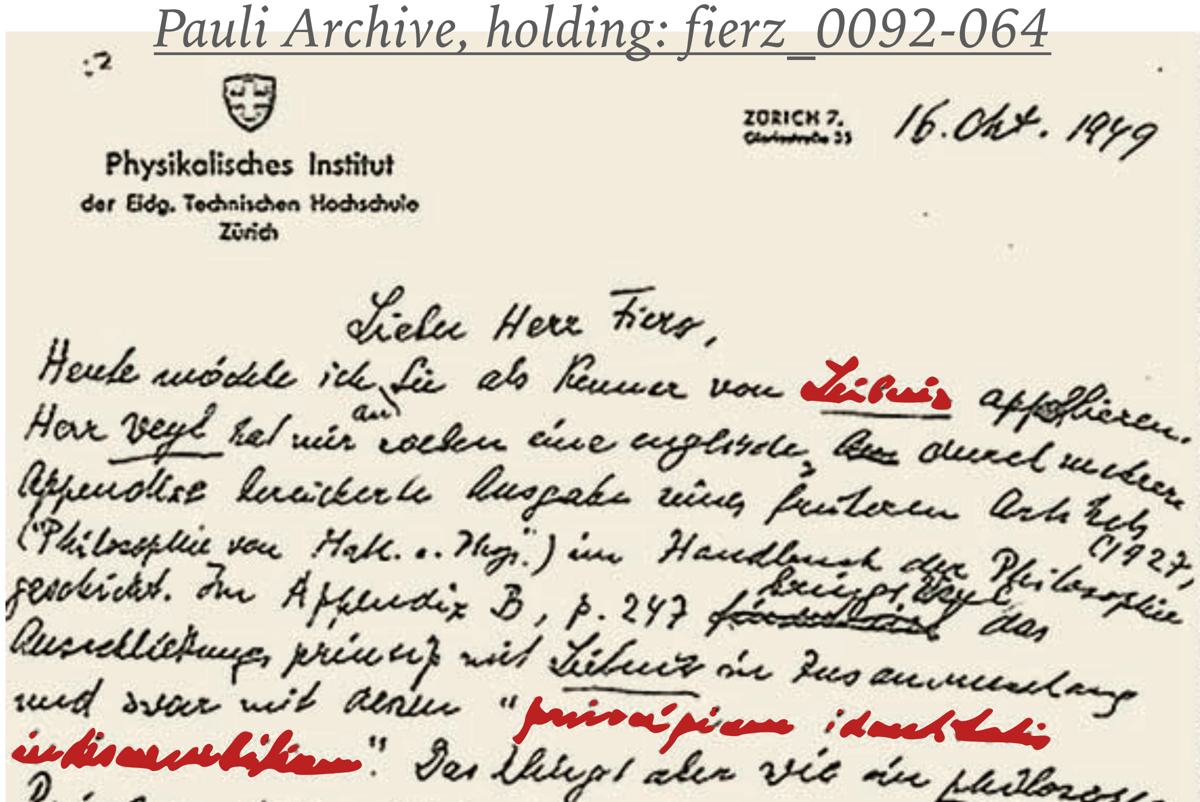
Testing Pauli Exclusion Principle

Outline: Line of Research at LNGS
From the shoulders of Giants

In an atom there cannot be two or more equivalent electrons for which the values of all four quantum numbers coincide. If an electron exists in an atom for which all of these numbers have definite values, then the state is occupied.

W.Pauli, Über den Zusammenhang des Abschlusses der Elektronengruppen im Atom mit der Komplexstruktur der Spektren, Zeitschrift für Physik 31 (1925) 765.

Pauli Archive, holding: fierz_0092-064


Physikalisches Institut
der Eidg. Technischen Hochschule
Zürich

ZÜRICH 7,
16. Okt. 1949

Lieber Herr Fierz,

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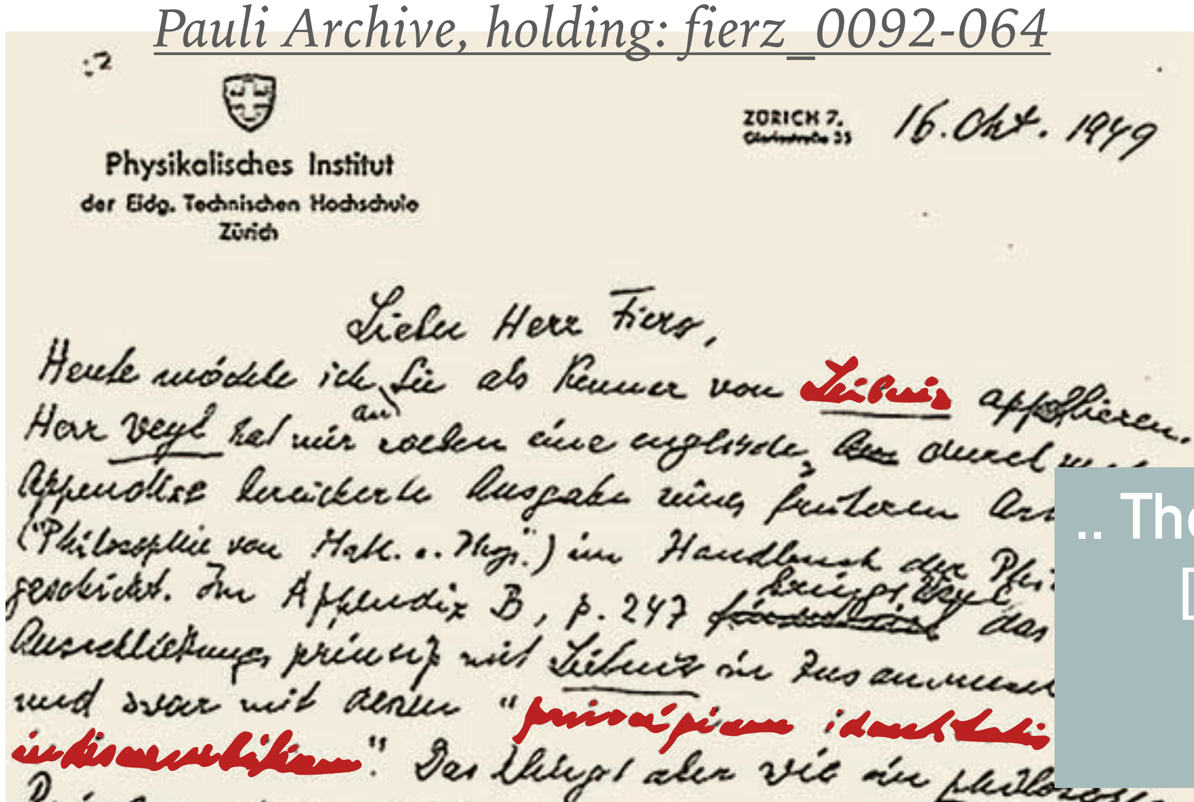
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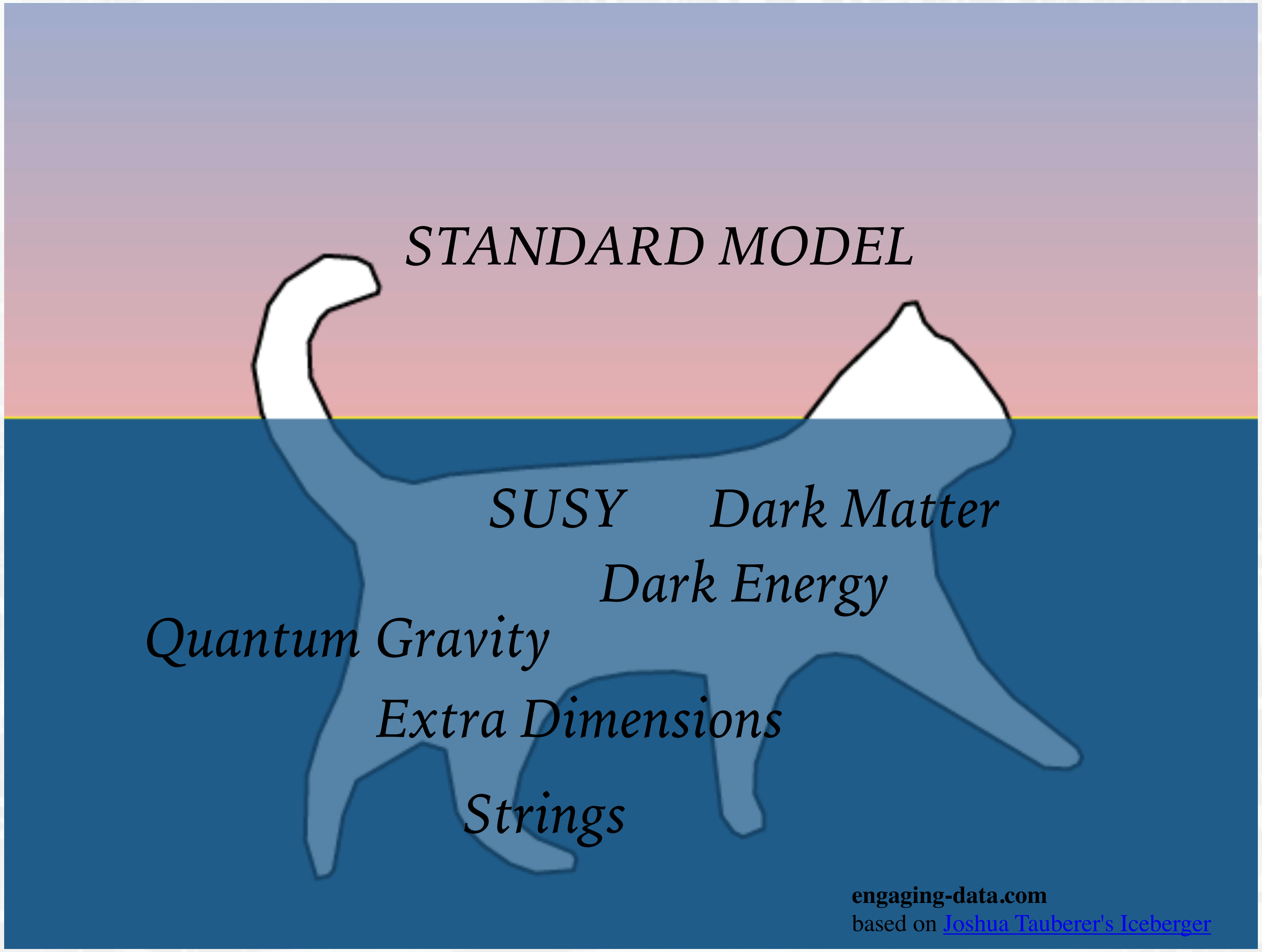
der Eidg. Technischen Hochschule
Zürich

ZÜRICH 7, 16. Okt. 1949

Lieber Herr Fierz,
Heute möchte ich Sie als Kenner von Leibniz apostrophieren.

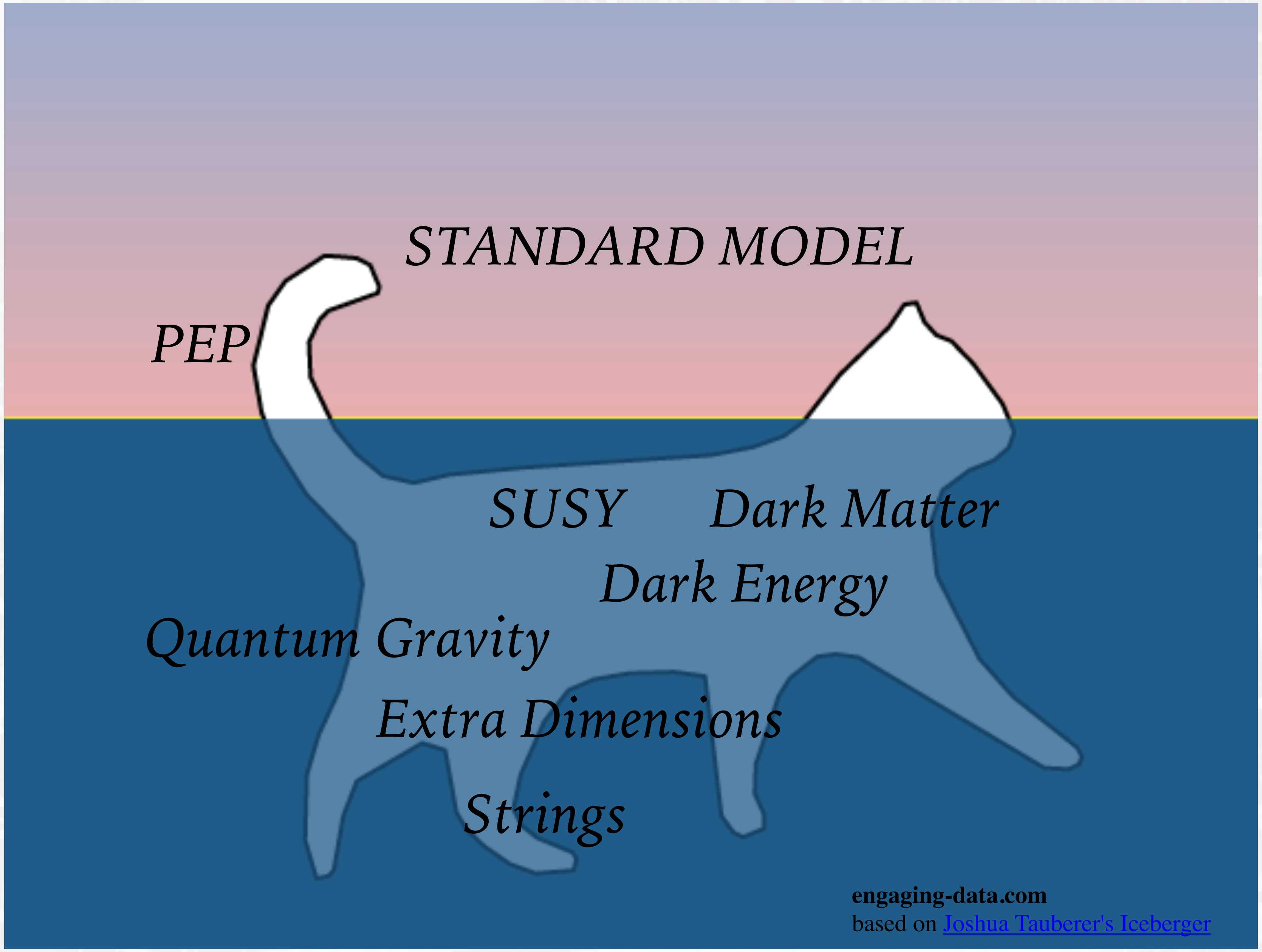
.. The impression that the shadow of some incompleteness [falls] here on the bright light of success of the new quantum mechanics seems to me unavoidable.
W. Pauli, Nobel lecture 1945

The Pauli Exclusion Principle (PEP)



BSM theories embedding extra dimensions, non commutative and/or discrete spacetime could have effect on PEP

The Pauli Exclusion Principle (PEP)



BSM theories embedding extra dimensions, non commutative and/or discrete spacetime could have effect on PEP

How to model PEP violations

- *Ignatiev & Kuzmin model: Fermi oscillator with a third state*

(Ignatiev, A.Y., Kuzmin, V. , Quarks '86: Proceedings of the 229 Seminar, Tbilisi, USSR, 1517 April 1986)

$$
\begin{aligned}
a^{+}|0\rangle &= |1\rangle & a|0\rangle &= 0 \\
a^{+}|1\rangle &= \beta|2\rangle & a|1\rangle &= |0\rangle \\
a^{+}|2\rangle &= 0 & a|2\rangle &= \beta|1\rangle
\end{aligned}
$$

β quantifies the degree of violation in the transition

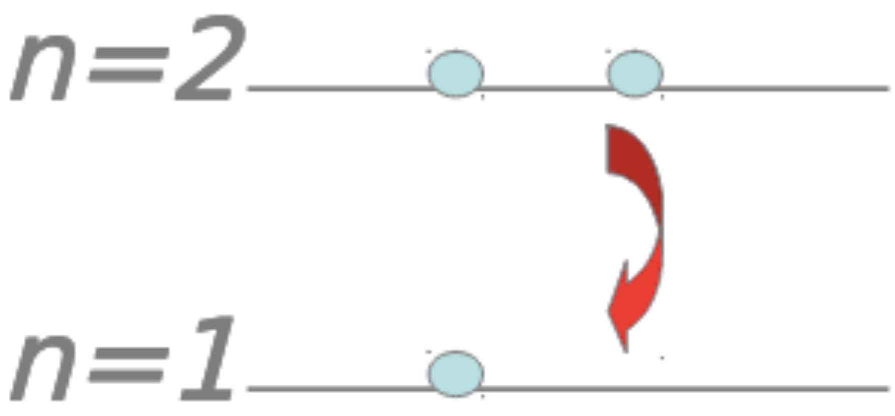
- *Greenberg & Mohapatra: Local Quantum Field Theory, q parameter deforms anticommutators [Phys. Rev. Lett. 1987,59,2507]:*

$$a_k a^{+}_l - q a^{+}_l a_k = \delta_{k,l}$$

- *Rahal & Campa: global wave function of the electrons not exactly antisymmetric, PEP holds as long as the number of wrongly entangled pairs is small*

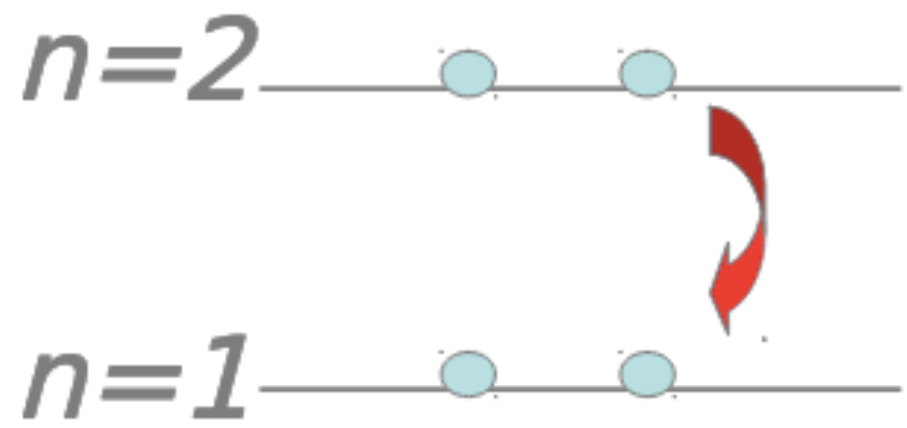
All respect the Messiah-Greenberg super-selection rule!

Search for anomalous X-ray transitions performed by electrons introduced in a target trough a DC current (open system)



Normal 2p → 1s transition

~ 8.05 keV in Cu



2p → 1s transition violating Pauli principle

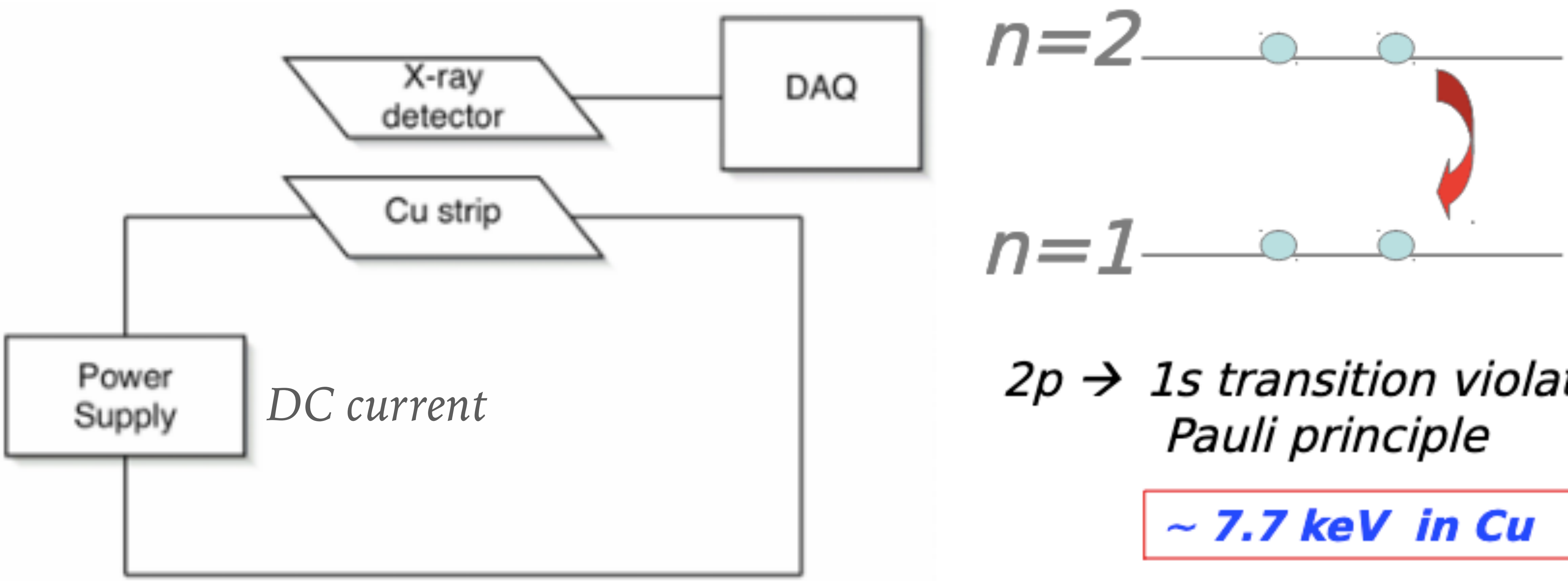
~ 7.7 keV in Cu

Paul Indelicato (Ecole Normale Supérieure et Université Pierre et Marie Curie)

Multiconfiguration Dirac-Fock approach

Accounts for the shielding of the two inner electrons

Search for anomalous X-ray transitions performed by electrons introduced in a target trough a DC current (open system)



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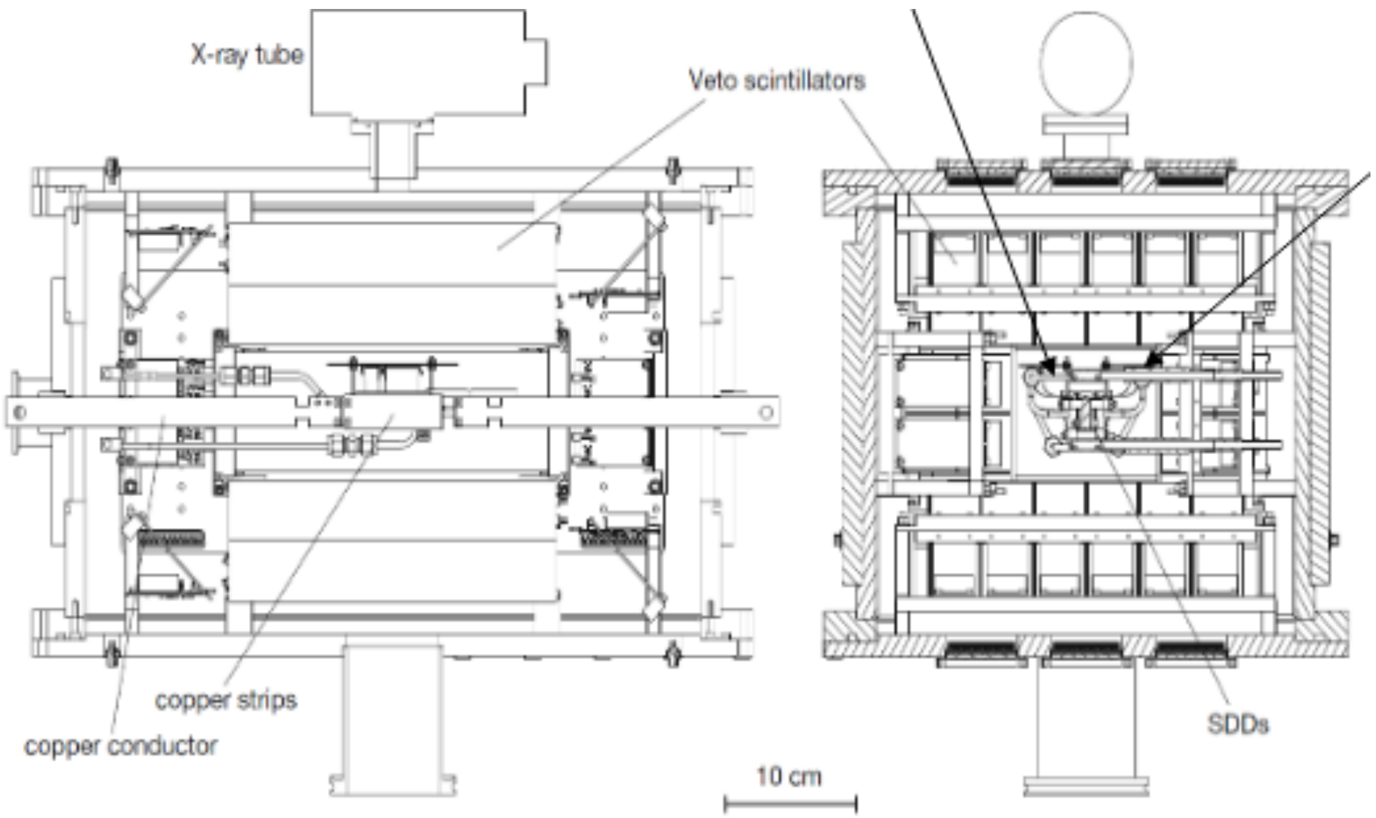
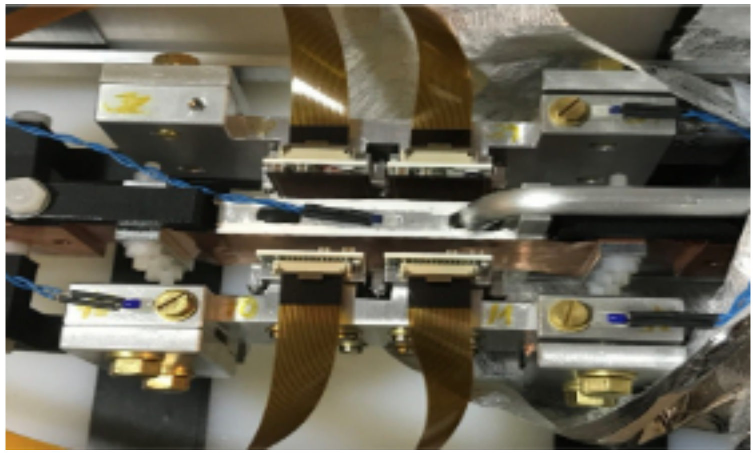
Multiconfiguration Dirac-Fock approach

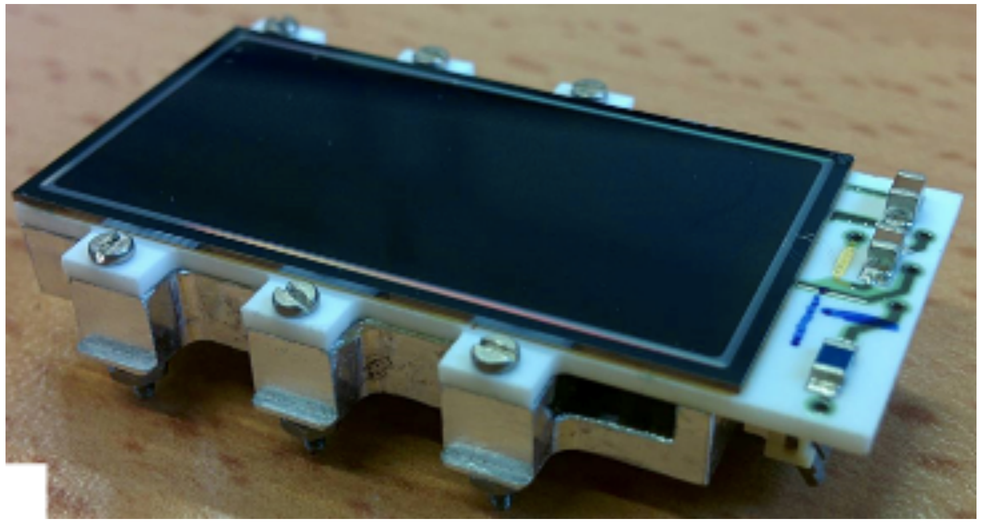
Accounts for the shielding of the two inner electrons

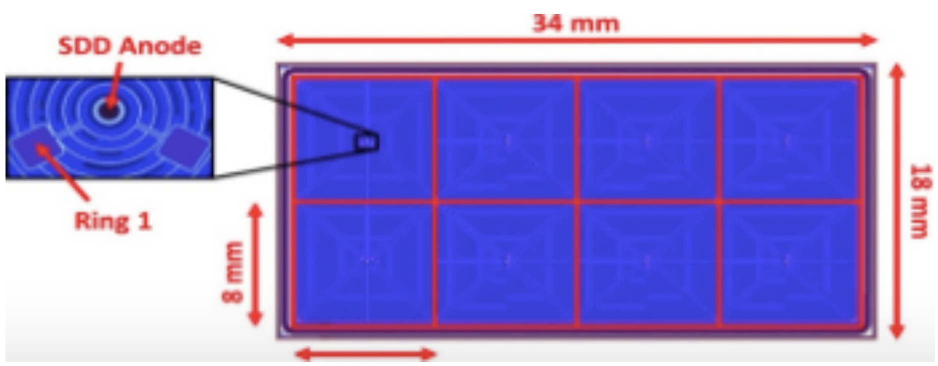
The VIP-2 Experiment

Silicon Drift Detectors (SDDs) higher resolution (190 eV FWHM at 8.0 →keV), faster (triggerable) detectors. 4 arrays of 2 x 4 SDDs 8mm x 8mm each, liquid argon closed circuit cooling 170 °C









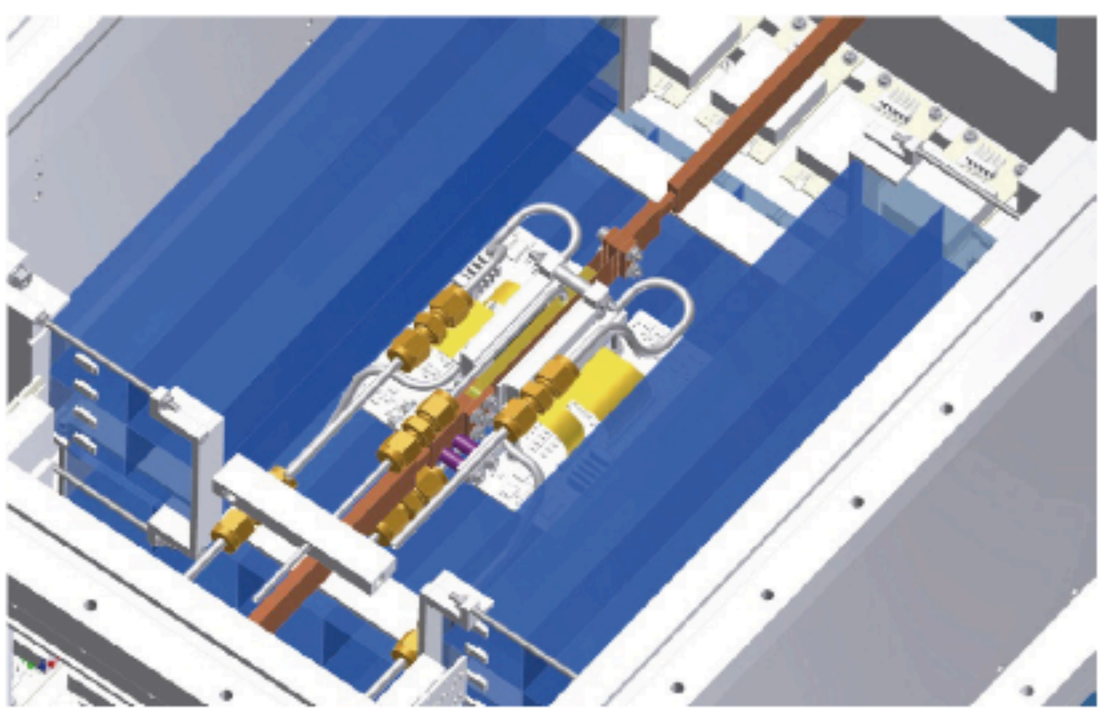
The VIP-2 Experiment

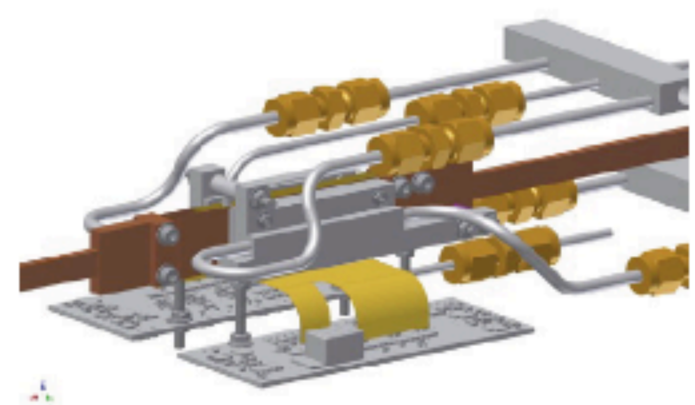
2 strip shaped Cu targets (25 um x 7 cm x 2 cm) more compact target → higher acceptance, thinner → higher efficiency
DC current supply to Cu bars

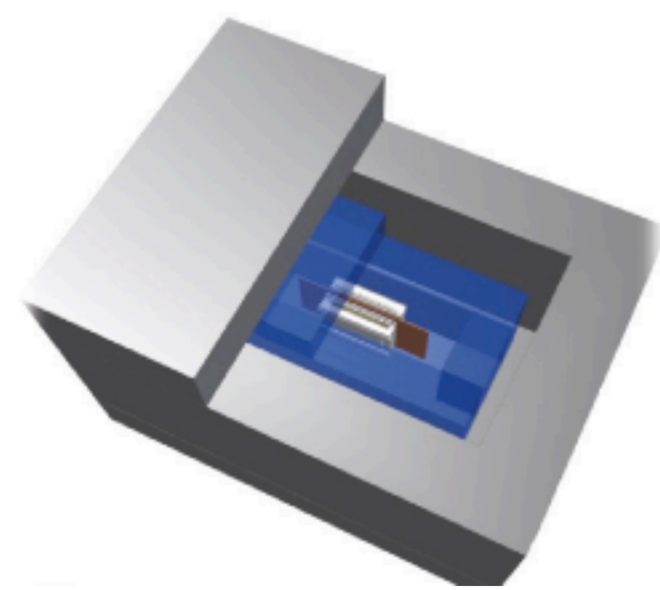
Cu strips cooled by a closed Fryka chiller circuit →higher current

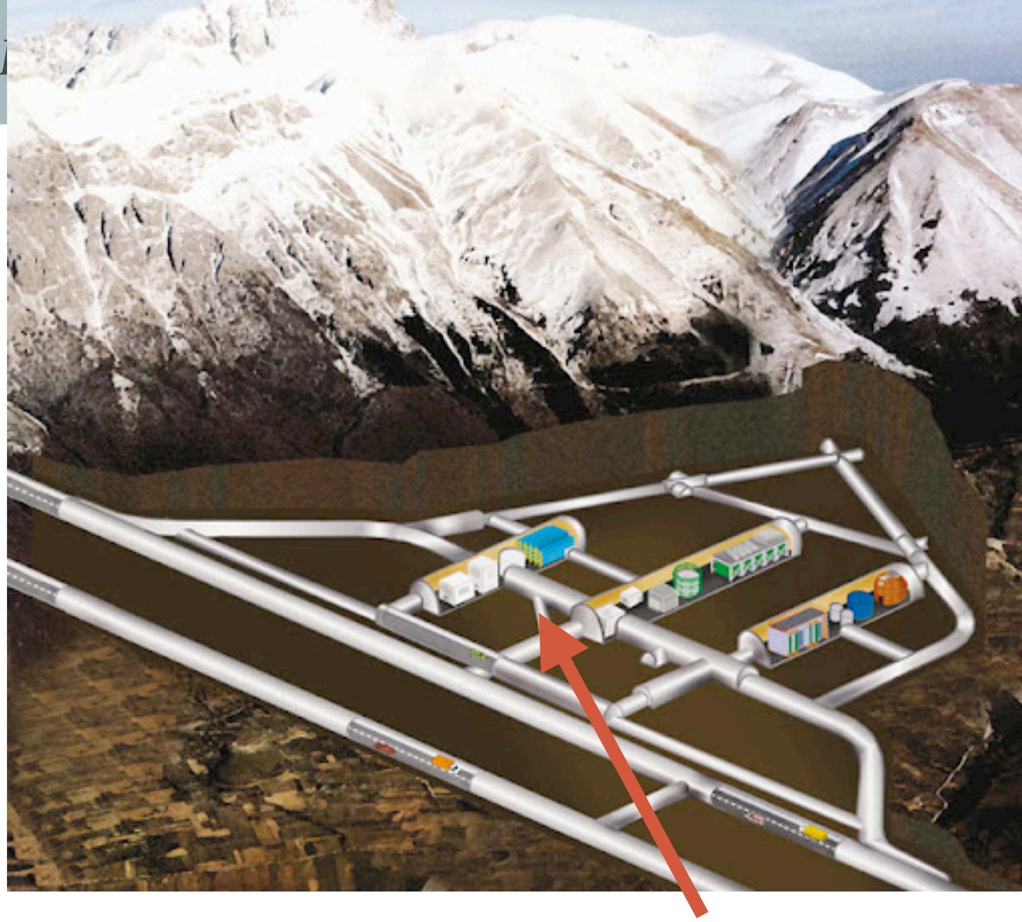
(100 A) @ 20 °C of Cu target implies 1 °K heating in SDDs

Sketch of the VIP2 Setup:



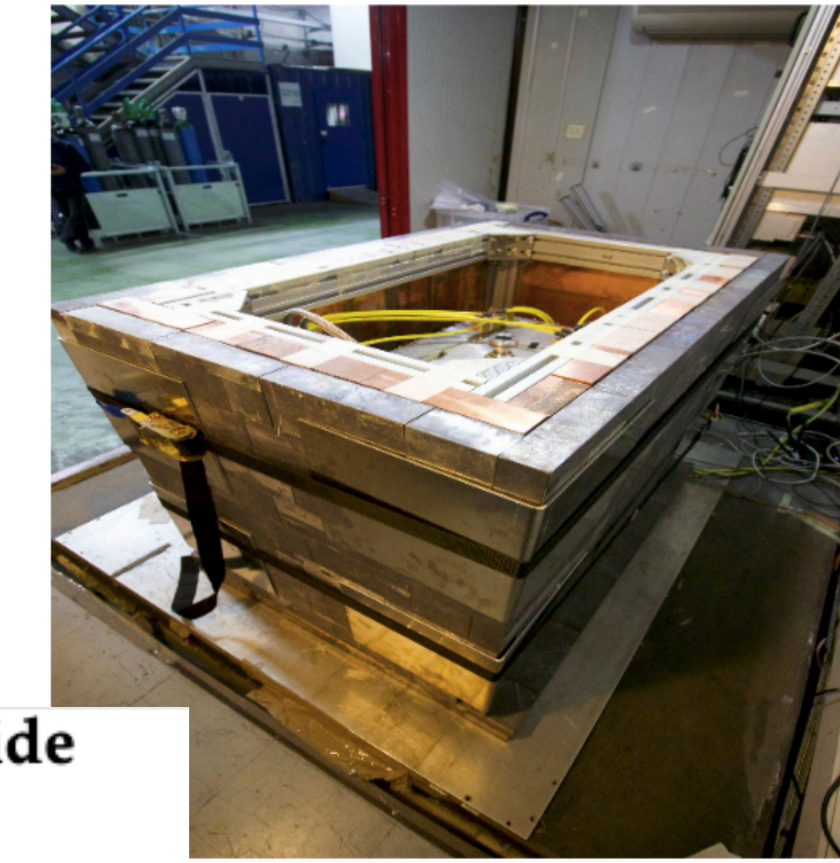




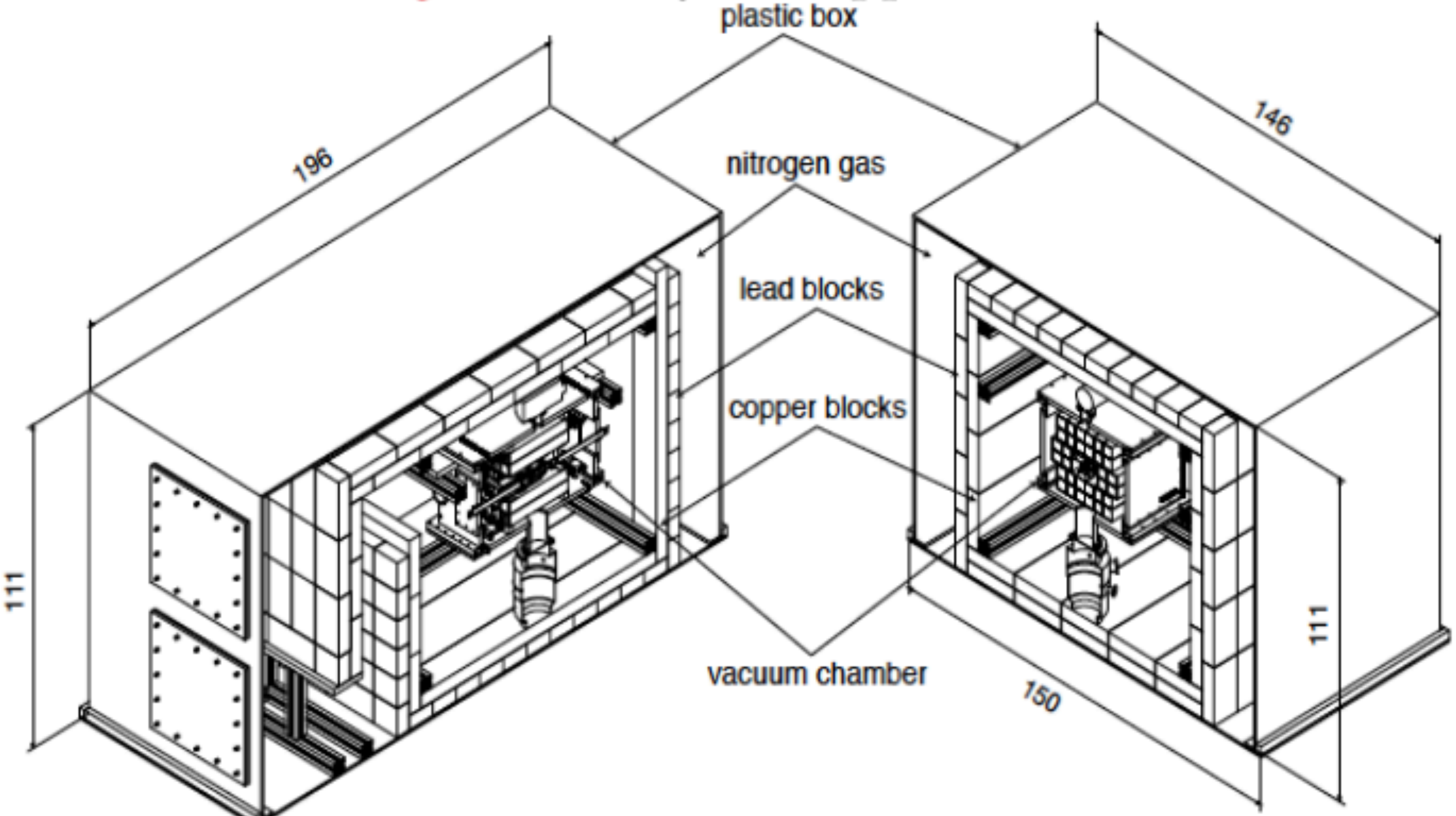


1400 m rock coverage

Upgrade concluded in April 2019:



Passive scielding → two layers, copper inside lead outside



symmetry
Symmetry **2022**, *14*(5), 893; https://doi.org/10.3390/sym14050893
MDPI

Article

Testing the Pauli Exclusion Principle with the VIP-2 Experiment

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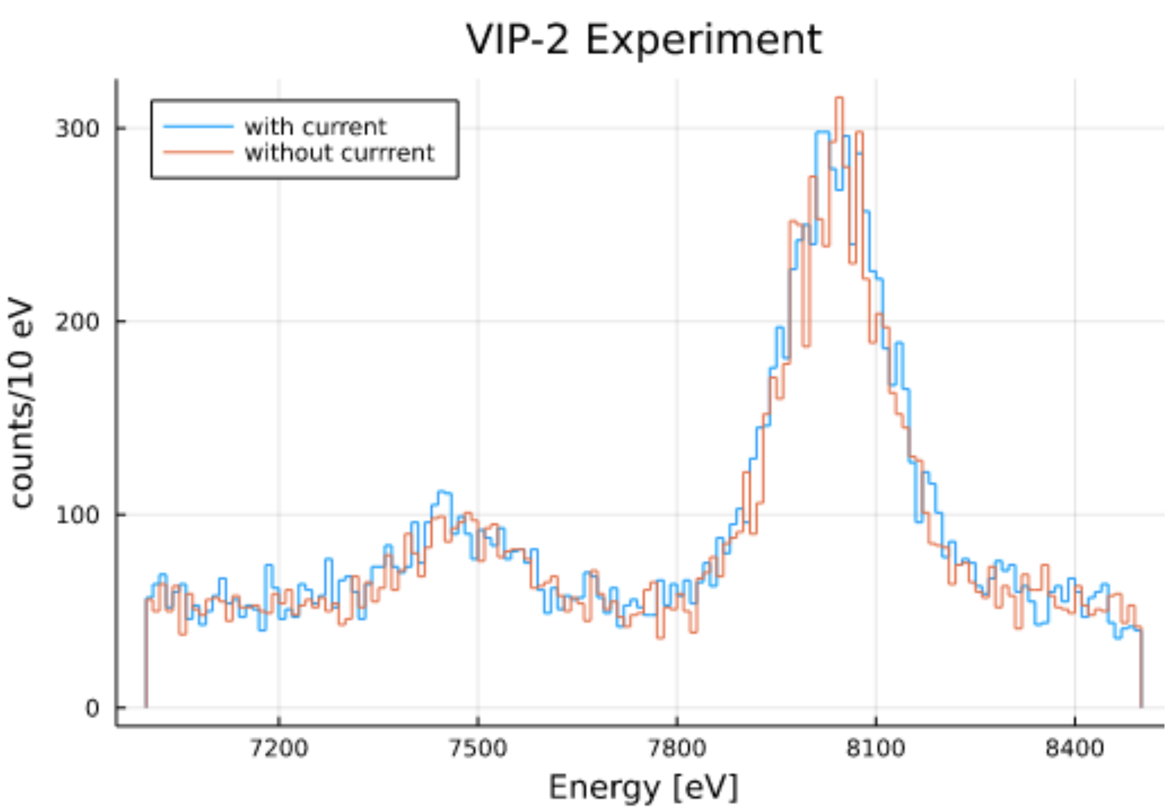

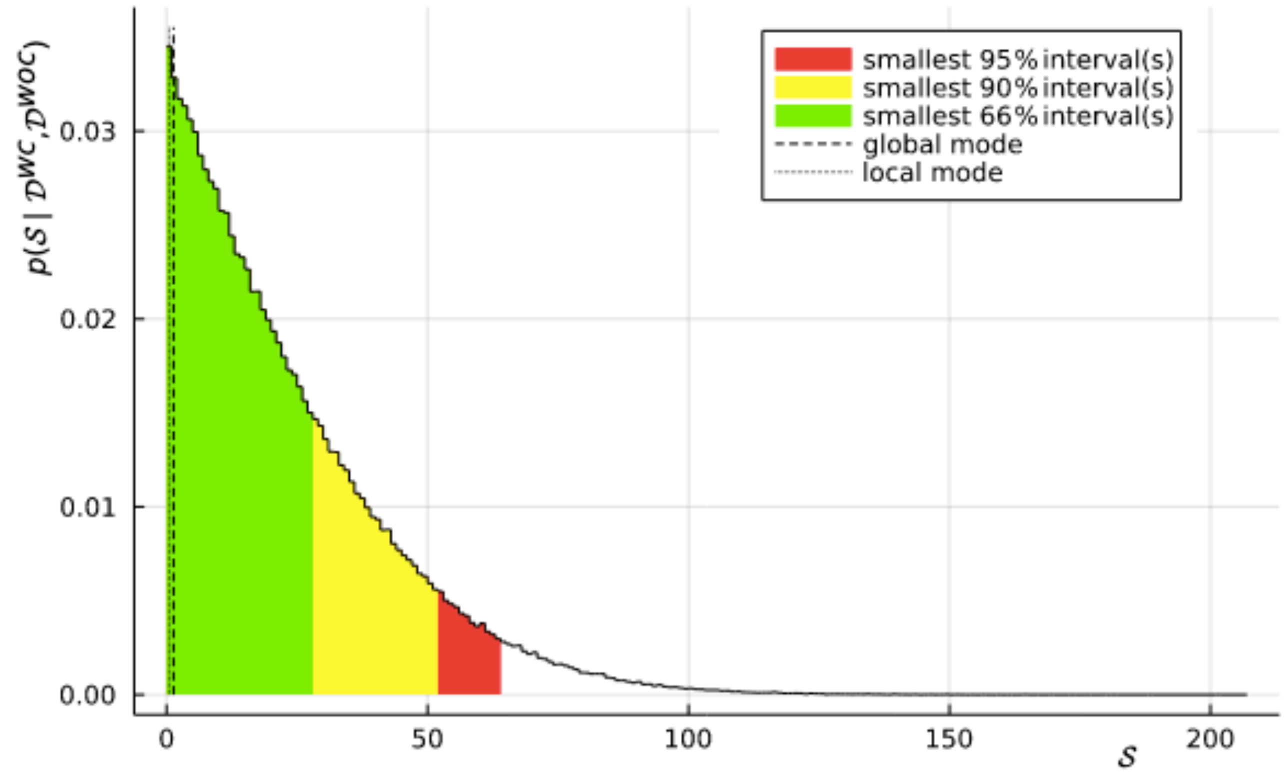

Figure 4. The posterior distribution for the signal yield S obtained by marginalization on all the parameters. Red, yellow, and green show the 95%, 90%, and 66% intervals, respectively.

$$\beta^2/2 \leq 6.8 \times 10^{-43} \text{ (Bayesian)}$$

New paradigm for VIP-2

Quantum gravity models can embed PEP violating transitions!

PEP is a consequence of the spin statistics theorem based on: Lorentz/Poincaré and CPT symmetries; locality; unitarity and causality. Deeply related to the very same nature of space and time

↓

most effective theories of QG foresee the non-commutativity of the space-time quantum operators (e.g. *k*-Poincarè, θ-Poincarè)

↓

non-commutativity induces a deformation of the Lorentz symmetry and of the locality → naturally encodes the violation of PEP

S. Majid, Hopf algebras for physics at the Planck scale, Class. Quantum Grav. 5 (1988) 1587.
S. Majid and H. Ruegg, Bicrossproduct structure of Kappa Poincare group and noncommutative geometry, Phys. Lett. B 334 (1994) 348, hep-th/9405107.
M. Arzano and A. Marciano, Phys. Rev. D 76, 125005 (2007) [arXiv:0707.1329].
G. Amelino-Camelia, G. Gubitosi, A. Marciano, P. Martinetti and F. Mercati, Phys. Lett. B 671, 298 (2009) [arXiv:0707.1863].
A. Addazi, A. Marcianò International Journal of Modern Physics A Vol. 35, No. 32, 2042003 (2020)

↓

PEP violation is suppressed with $(E/\Lambda)^n$, n depends on the specific model, E is the energy of the PEP violating transition, Λ is the scale of the space-time non-commutativity emergence.

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Strongest Atomic Physics Bounds on Noncommutative Quantum Gravity Models

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Investigations of possible violations of the Pauli exclusion principle represent critical tests of the microscopic space-time structure and properties. Space-time noncommutativity provides a class of universality for several quantum gravity models. In this context the VIP-2 lead experiment sets the strongest bounds, searching for the Pauli exclusion principle violating atomic transitions in lead, excluding the θ-Poincaré noncommutative quantum gravity models far above the Planck scale for nonvanishing $\theta_{\mu\nu}$ electriclike components, and up to 6.9×10^{-2} Planck scales if $\theta_{0i} = 0$.

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Conclusions

- *Wave function collapse still an open question*
- *Many collapse models: Diòsi-Penrose and CSL*
  - *Both predict emission of spontaneous radiation*

- *Experiment carried out at LNGS using high purity Germanium detectors*
- *Bounds are set on R_0 of DP model at 95% CL, excluding the model in the present formulation*
- *Strongest bound are set on the CSL model in the region $r_c < 10^{-6}$ m*

- *VIP-2 Experiment in data taking: pushing the limit on Pauli exclusion principle violations*

Thank you for your attention!

Questions?

Proof of spin-statistics theorem by Lüders and Zumino

Postulates:

- *The theory is invariant with respect to the proper inhomogeneous Lorentz group (includes translations, does not include reflections)*
- *Two operators of the same field at points separated by a spacelike interval either commute or anticommute (locality – microcausality)*
- *The vacuum is the state of lowest energy*
- *The metric of the Hilbert space is positive definite*
- *The vacuum is not identically annihilated by a field*

From these postulates it follows that (pseudo)scalar fields commute and spinor fields anticommute.

(G. Lüders and B. Zumino, Phys. Rev. 110 (1958) 1450)

Models of Pauli Exclusion Principle (PEP) Violations

Some more PEP Violating models:

Greenberg, O.W. Mohapatra, R.N. Physical Review Letters 1987, 59, 2507
Govorkov, A. Physica A: Statistical Mechanics and its Applications 1994, 203, 655
Rahal, V.; Campa, A. , Physical Review A (1988) 38, 3728

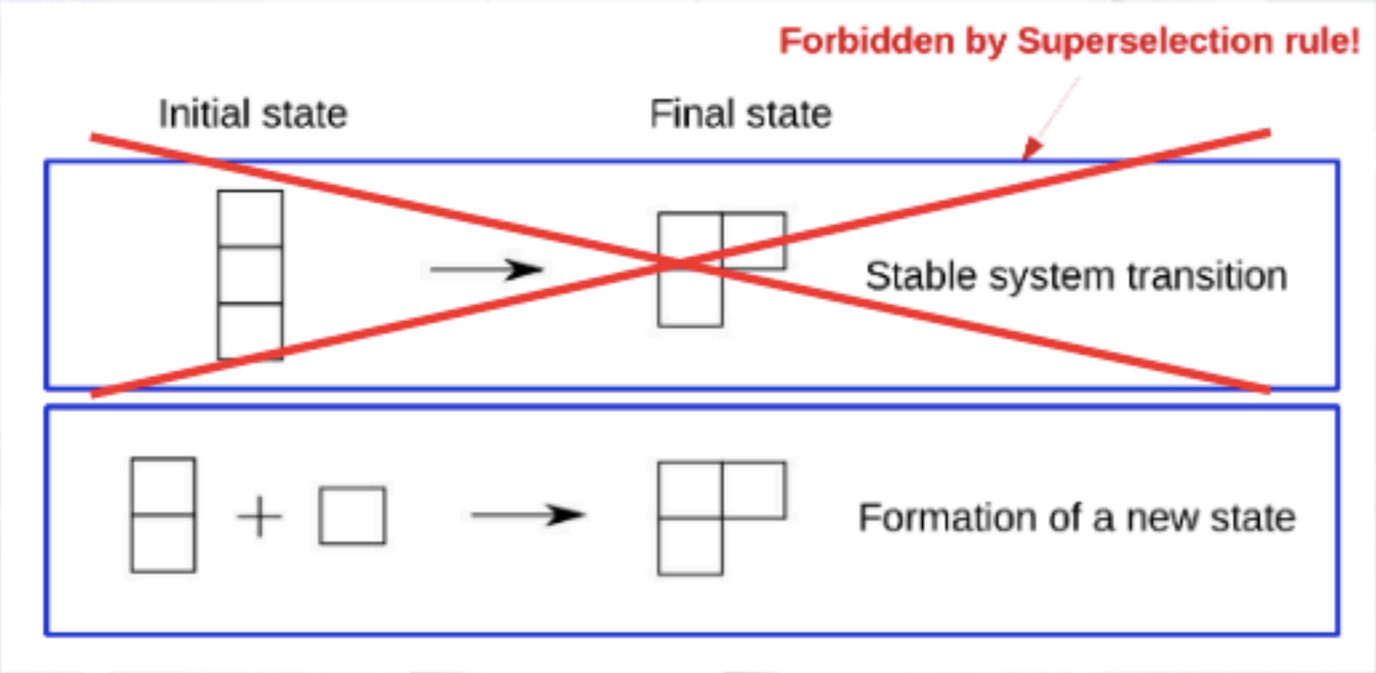
Messiah - Greenberg superselection rule

Superpositions of states with different symmetry are not allowed →
transition probability between two symmetry states is ZERO

Messiah-Greenberg superselection rule **:**

Closed system →

Open system →



VIP-open systems sets the best limit on PEP violation for an elementary particle respecting the M-G superselection rule

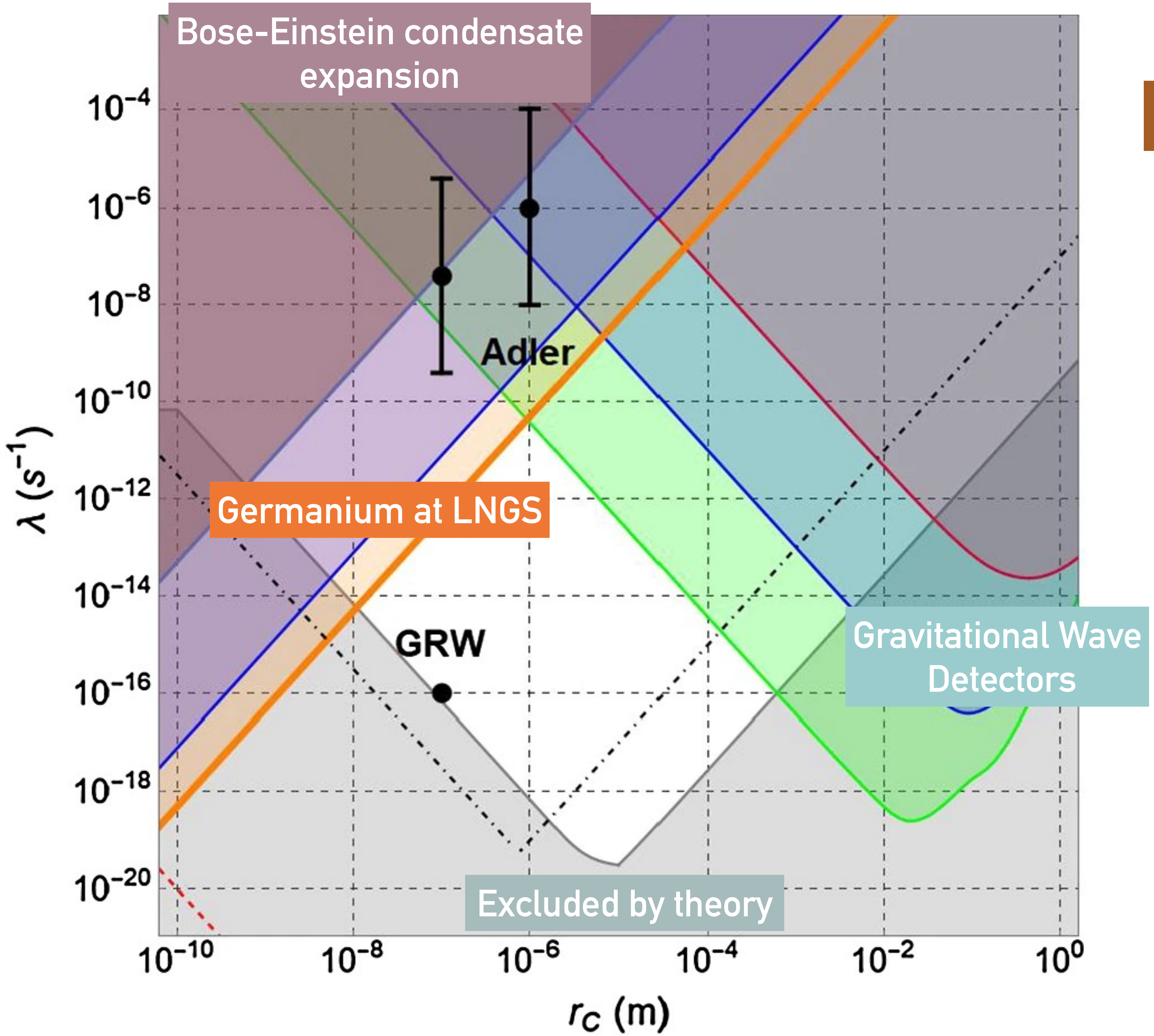
VIP-2 experiment goal

(Upper limit not using Close Encounters (CE) treatment)

As reference for past experiments

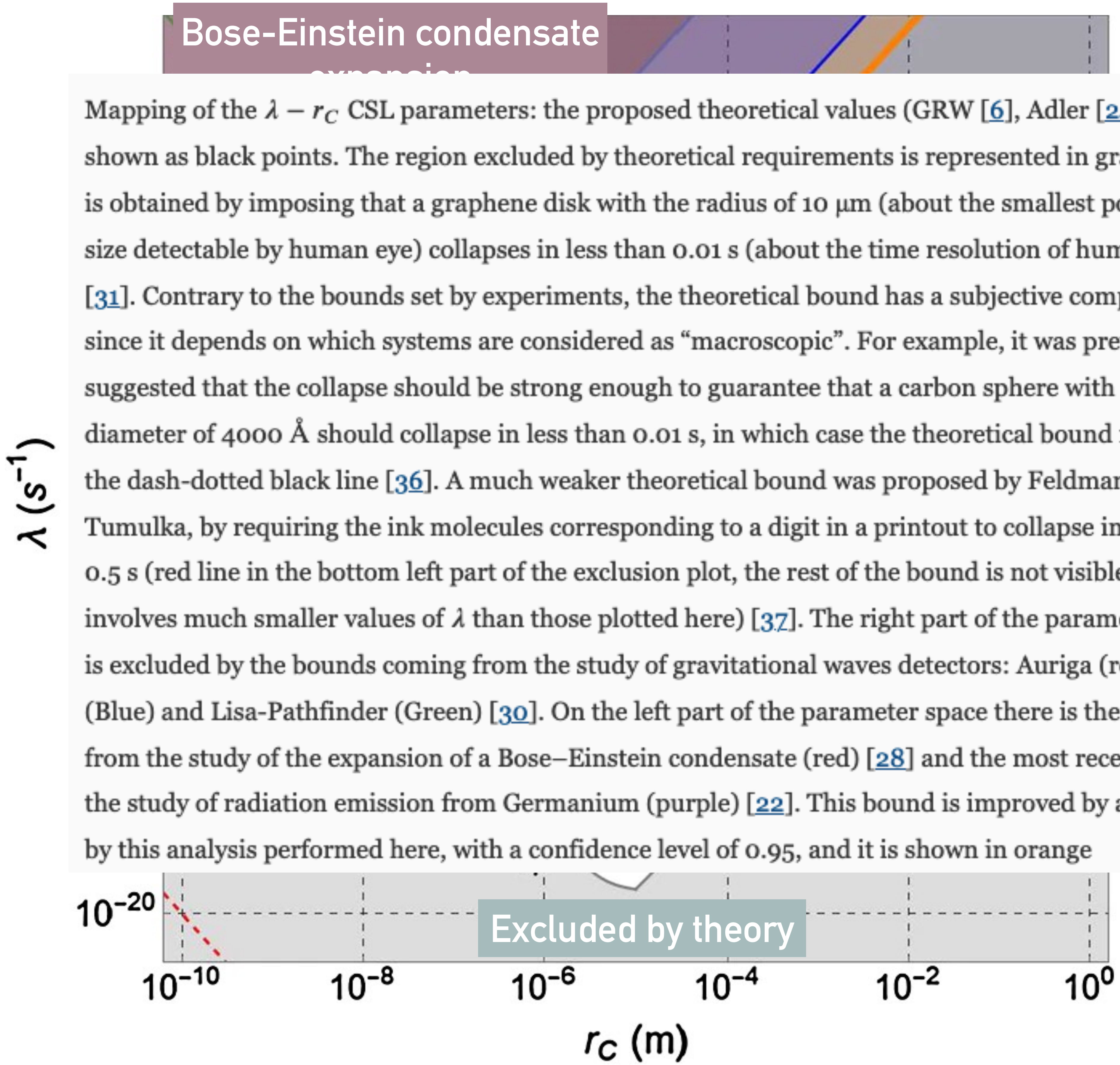
Experiment	Target	Upper limit of $\beta^2/2$	reference
Ramberg-Snow	Copper	1.7×10^{-26}	[5]
S.R. Elliott et al.	Lead	1.5×10^{-27}	[14]
VIP(2006)	Copper	4.5×10^{-28}	[12]
VIP(2012)	Copper	4.7×10^{-29}	[13]
VIP2(goal)	Copper	$\times 10^{-31}$	[15]

CSL Model



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

Model



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).**

Diósi-Penrose (DP) Collapse model

$$d|\psi_t\rangle = \Big[-\frac{i}{\hbar}\hat{H}dt + \sqrt{\frac{G}{\hbar}}\int d\mathbf{x}(\hat{\mu}(\mathbf{x}) - \langle\hat{\mu}(\mathbf{x})\rangle)dW_t(\mathbf{x}) - \frac{G}{2\hbar}\int d\mathbf{x}d\mathbf{y}\frac{(\hat{\mu}(\mathbf{x})-\langle\hat{\mu}(\mathbf{x})\rangle)(\hat{\mu}(\mathbf{y})-\langle\hat{\mu}(\mathbf{y})\rangle)}{|\mathbf{x}-\mathbf{y}|}\Big]|\psi_t\rangle$$

Schrödinger

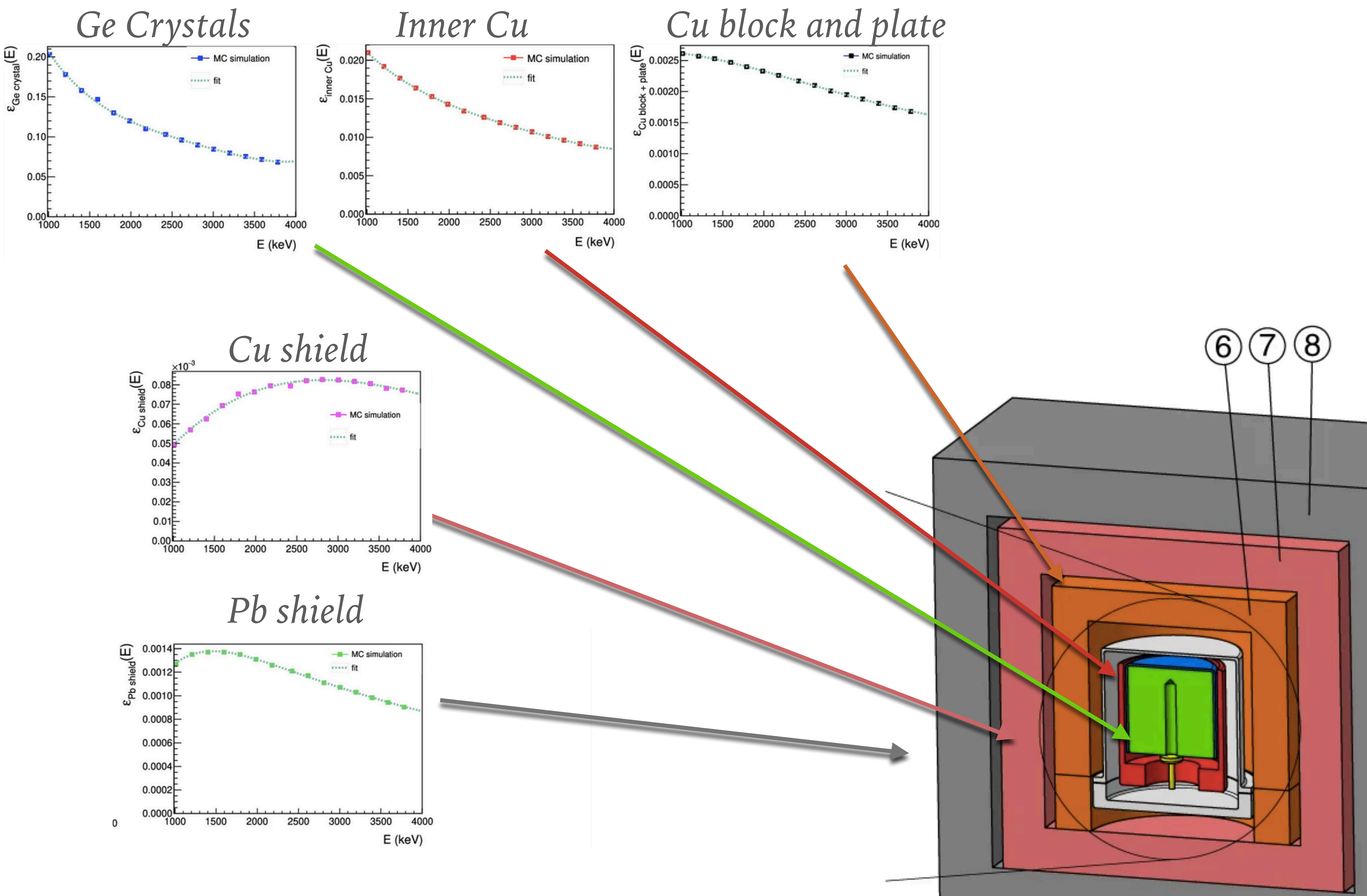
Specific dynamics for the collapse

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).

Measurement and MC validation



Models of Pauli Exclusion Principle (PEP) Violations

Theories of Statistics Violation

O.W. Greenberg: AIP Conf.Proc.545:113-127,2004

*"Possible external **motivations for violation of statistics** include: (a) violation of CPT, (b) violation of locality, (c) violation of Lorentz invariance, (d) extra space dimensions, (e) discrete space and/or time and (f) non-commutative spacetime……"*

Ignatiev & Kuzmin model: Fermi oscillator with a third state

(Ignatiev, A.Y., Kuzmin, V. , Quarks '86: Proceedings of the 229 Seminar, Tbilisi, USSR, 1517 April 1986)

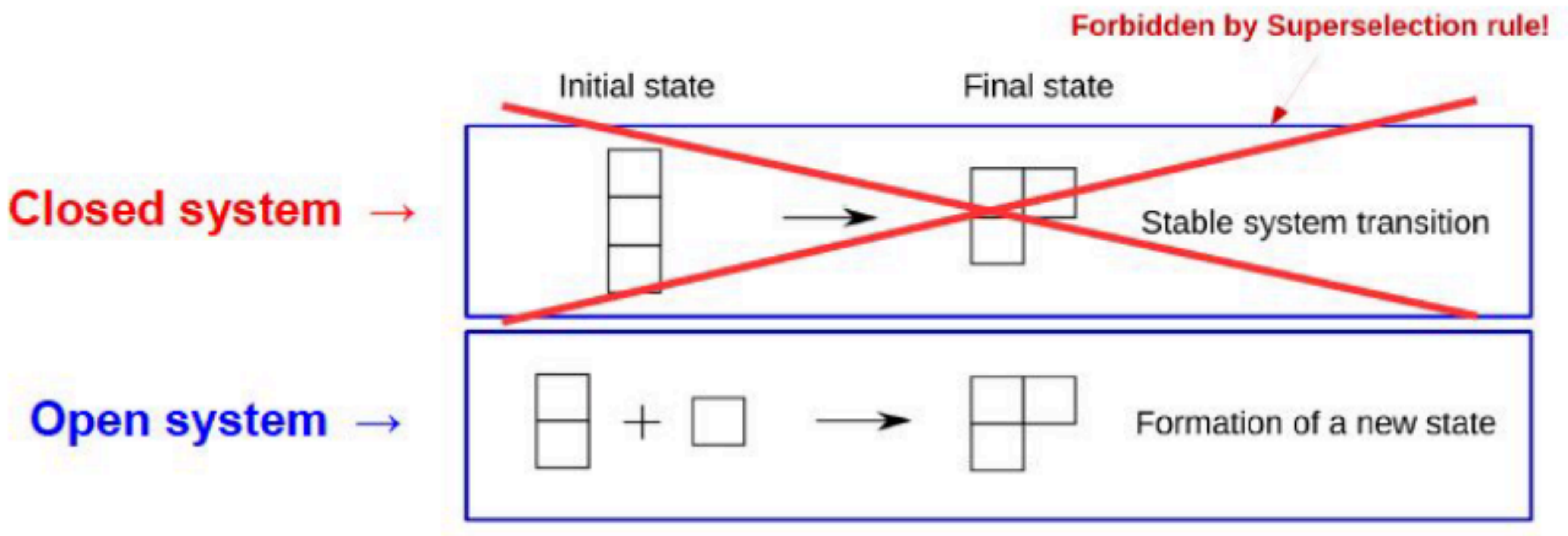
$$a^+|0\rangle = |1\rangle \qquad a|0\rangle = 0$$
$$a^+|1\rangle = \beta|2\rangle \qquad a|1\rangle = |0\rangle$$
$$a^+|2\rangle = 0 \qquad a|2\rangle = \beta|1\rangle$$

β quantifies the degree of violation in the transition

Messiah-Greenberg super-selection rule:

Superposition of states with different symmetry are not allowed →

<u>Transition probability between two symmetry states is ZERO</u>



VIP-2 Experiment: best limits on PEP violation of an elementary particle respecting the Messiah-Greenberg super-selection rule

New paradigm for VIP-2

Are Quantum Gravity models experimentally testable?

A. Addazi (Chengdu Univ.) A. Marcianò (Fudan University)

VIP-2 underground experiment as a *Crash-Test* of Non-Commutative Quantum Gravity

Pauli Exclusion Principle (PEP) violations induced from non-commutative space-time can be searched VIP-2 experiment set-up. We show that the limit from VIP-2 experiments on non-commutative space-time scale Λ, related to energy dependent PEP violations, are severe: κ-Poincaré non-commutativity is ruled-out up to the Planck scale. In the next future θ-Poincaré will be probed until the Grand-Unification scale! This highly motivates Pauli Exclusion Principle tests from underground experiments as a test of quantum gravity and space-time microscopic structure.

See also A. Addazi et al., 2018 Chinese Phys. C 42 094001, arXiv:1712.08082 [hep-th]