Exploring the Quantum-Gravity Connection with Underground Experiments

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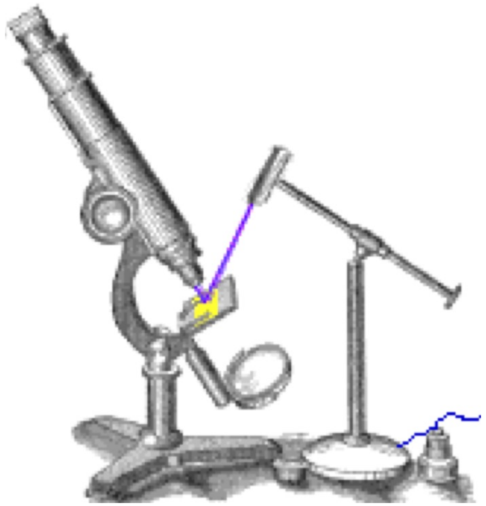
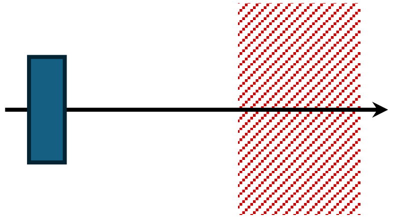
Quantum mechanics + general relativity **do not allow infinite localization!** **(Matvei Bronstein 1934)**



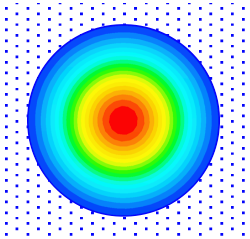


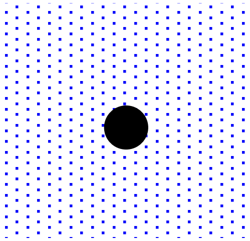
E

BH
creation

Heisenberg
uncertainty

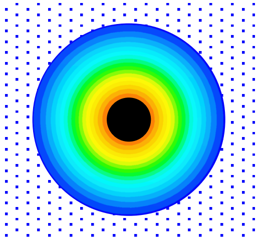
Schwarzschild
radius





$\Delta x \sim 1/E$

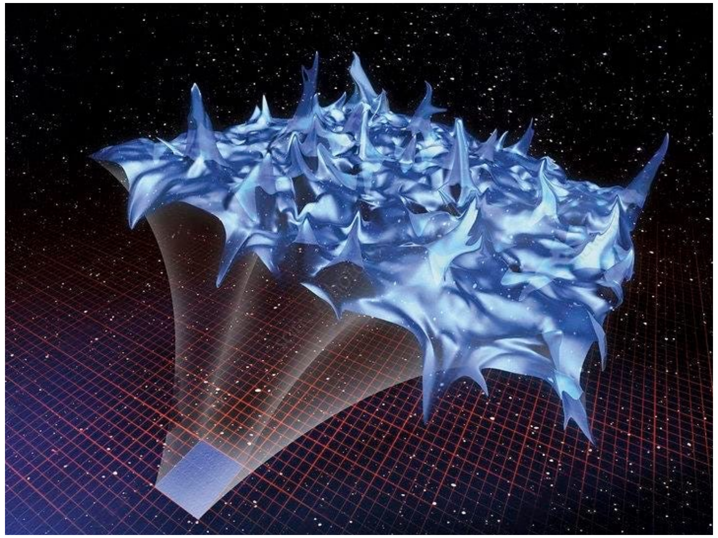
$r_s \sim E$

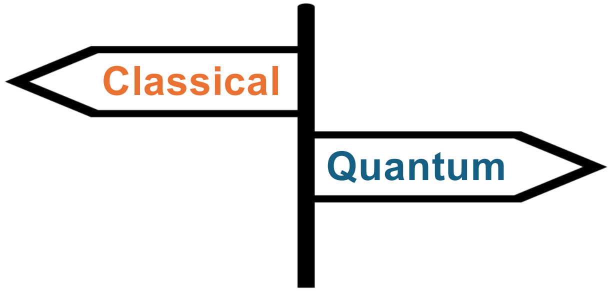


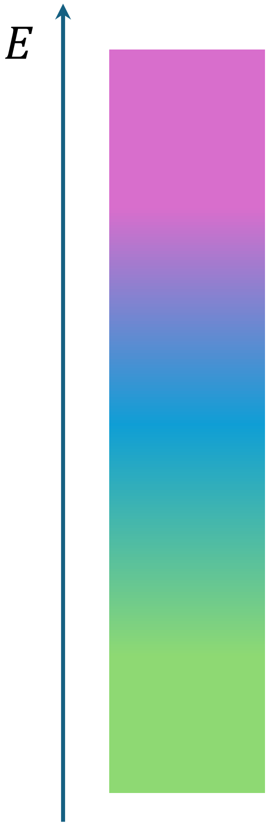
For $\Delta x < r_s$
BH creation:

$\boldsymbol{\Delta x_{\mathrm{min}} \sim \ell_p}$
$\mathbf{= 1.6 \times 10^{-34}\ m}$

Intrinsic spacetime uncertainty



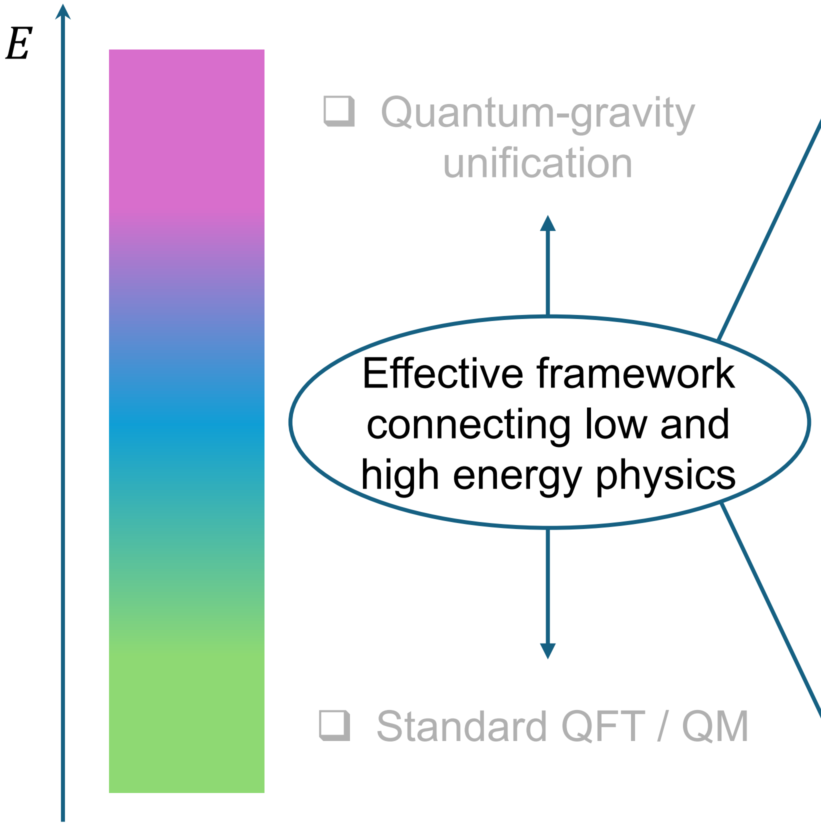




- ❑ Quantum-gravity unification

Effective framework connecting low and high energy physics

- ❑ Standard QFT / QM



Abandon local physics

- Generalized uncertainty principle (GUP)
- Noncommutative spacetime (NCST)
- …

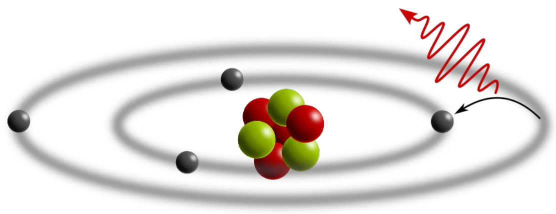
Introduce **irreversibility** through a stochastic component of the metric

- Gravity-related quantum collapse/decoherence
- Postquantum theory of classical gravity
- …

Goal of the talk

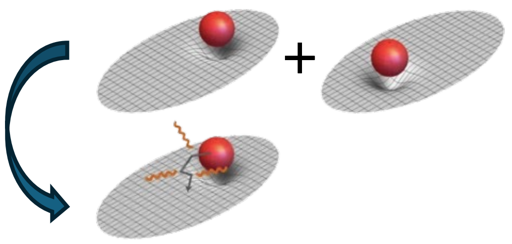
Nonlocality

Pauli violation



Irreversibility

Spontaneous radiation



- Characteristic X-ray emission
- Probability of emission is small (e.g. suppressed by the Planck scale)
- All atoms/charged particles can emit: **probability scales with the number of atoms!**

→ Experimental strategy: **extremely low background + high statistics**

Goal of the talk

Search for anomalous X-ray emission in the low-background environment of the underground Gran Sasso National Laboratory (INFN)

- Overburden corresponding to a minimum thickness of 3100 m w.e.
- **The muon flux is reduced by almost 10^{-6}**
- **The neutron flux by 10^{-3}**

Bayesian analysis to extract pdf $p(S)$ for the # of expected counts S

$$p(S) = \int d\boldsymbol{\theta}\, p(S,\boldsymbol{\theta}|data) \longleftarrow p(S,\boldsymbol{\theta}|data) = \frac{\mathcal{L}(data|S,\boldsymbol{\theta})P_0(S)P_0(\boldsymbol{\theta})}{\int dSd\boldsymbol{\theta}\mathcal{L}(data|S,\boldsymbol{\theta})P_0(S)\,P_0(\boldsymbol{\theta})}$$

- $\mathcal{L}(data|S,\boldsymbol{\theta}) = \prod_i \mathrm{Pois}\,(\lambda_i)$

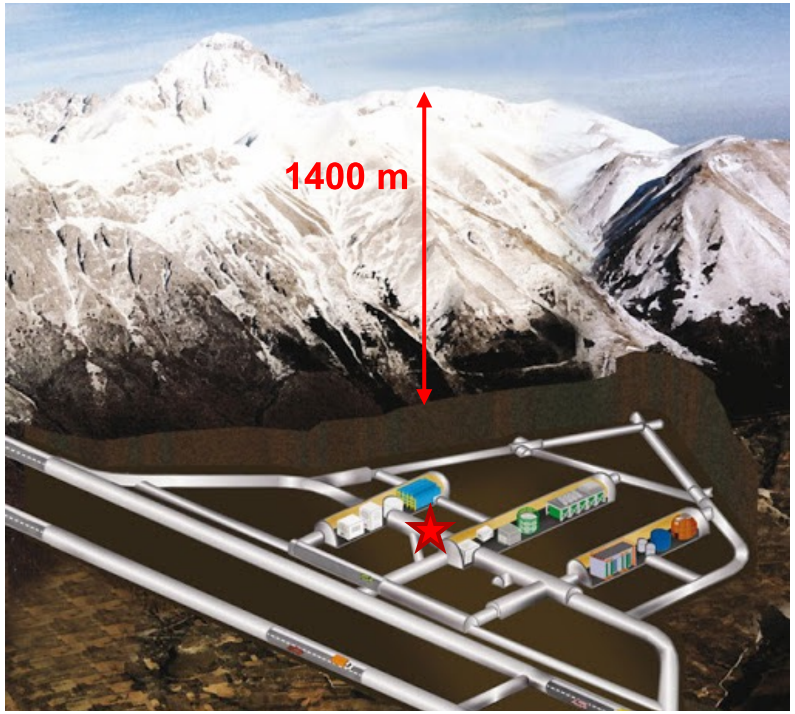
  $\lambda_i = \int_{\Delta E_i} dE\; f(E;S,\boldsymbol{\theta})$: exp counts at bin-i

  fit function

- P_0: prior

- Markov-Chain MC numerical integration: $\int_0^S dS\; p(S) = 0.9$

Connect S to model's parameters ➡ **constraint theory**



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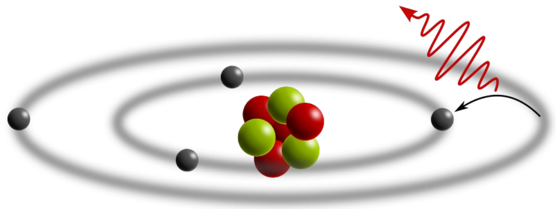

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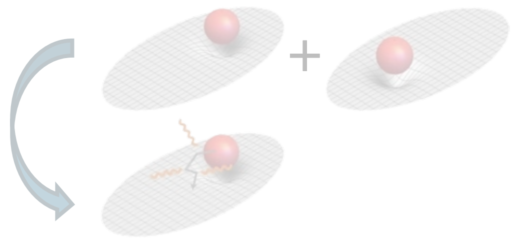

Leaving the spin-statistics connection toward QG

The spin-statistics theorem is a **necessary manifestation** of:

- **Locality** $\xrightarrow{\text{QG}}$ fails (LQG, strings, causal sets,…)
- **Poincaré covariance** $\xrightarrow{\text{QG}}$ expected either modifications or violations (Hořava gravity,…)

$\Downarrow$

PEP violations provide smoking gun for quantum gravity

Fate of relativistic invariance

- Breaks down: problems with renormalization ❌
- Holds: which symmetry group?

Fate of relativistic invariance

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- Holds: which symmetry group? In the presence of a **minimal length** ℓ Lorentz invariance fails (e.g. NCST)

  Similar to Galilean non-invariance of EM: **Deform Lorentz transformations** s.t. ℓ becomes invariant

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- Holds: which symmetry group? In the presence of a **minimal length** ℓ Lorentz invariance fails (e.g. NCST)

  Similar to Galilean non-invariance of EM: **Deform Lorentz transformations** s.t. ℓ becomes invariant

Spacetime uncertainty modeled as: $[x^\mu, x^\nu] = \Theta^{\mu\nu}(x) \sim i\theta^{\mu\nu} + iC^{\mu\nu}_\rho x^\rho + \cancel{\mathcal{O}(x^2)}$

$\theta^{\mu\nu} \sim (B_{\mu\nu})^{-1}$

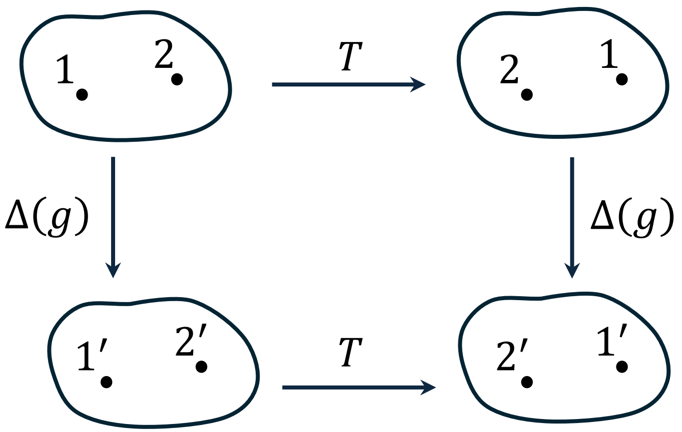
- ➢ $\boldsymbol{\theta^{\mu\nu}}$ leads to **"$\boldsymbol{\theta}$-Minkowski"** or **"Moyal plane"** noncommutativity:
  Open strings on Dp-branes with a background B-field

- ➢ $\boldsymbol{C^{\mu\nu}_\rho x^\rho}$ leads to Lie algebra type of noncommutativity. E.g. **"$\boldsymbol{\kappa}$-Minkowski":**
  From **LQG**-modification of the hypersurface-deformation algebra (rigorous proofs only in 3D)

- ➢ **Deformation** of ST transformations on **multiparticles** (non-trivial coproducts $\Delta(g) \neq g \otimes g$)

Covariant Fock space

$g = a, \Lambda$ are ST transformations

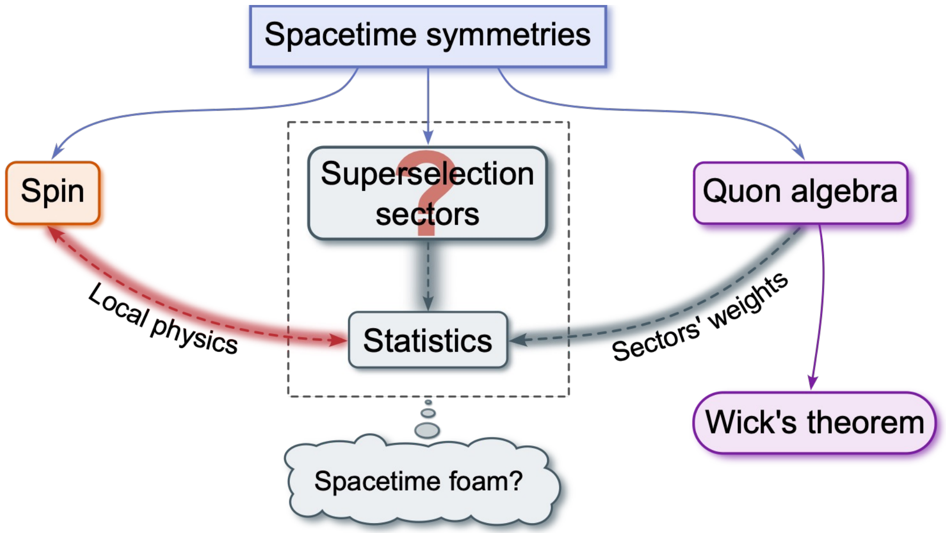


$$[\boldsymbol{\Delta(g), T}] = \mathbf{0}$$

$$T = \tau_R \eta \equiv \tau R \eta$$

fixed by symmetries

$$\tau_R^2 = 1 \;\; vs \;\; T^2 \neq 1$$



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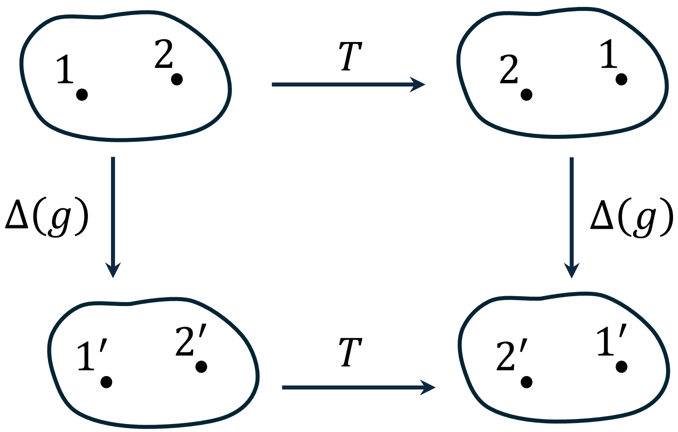

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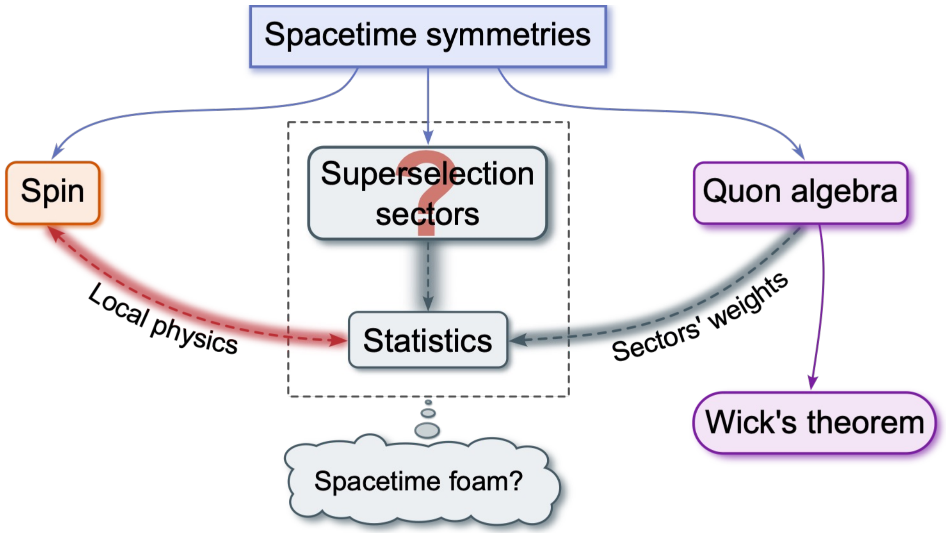

❖ The state space of a system of **distinguishable** identical particles is the **full Fock space** $\mathfrak{F}(\mathfrak{H}) = \bigoplus_{n=0}^{\infty} \mathfrak{H}^{\otimes n}$

The **inner product** of each $\mathfrak{H}^{\otimes n}$ is **fixed by the T:**

$$a(\tilde{p})a^\dagger(\tilde{q}) - \eta(p,q)R(p,q)a^\dagger(\tilde{q})a(\tilde{p}) = \delta(\tilde{p},\tilde{q})$$

The **flip operator τ_R** defines **sectors** $\mathfrak{H}^{\otimes n} = \oplus_\lambda \mathfrak{H}_\lambda^{\otimes n}$:

$$|\psi\rangle = \frac{1+\tau_R}{2}|\psi\rangle + \frac{1-\tau_R}{2}|\psi\rangle \equiv |\psi\rangle_{s_R} + |\psi\rangle_{a_R}$$

Indistinguishability is guaranteed by **superselection rules (SSRs)**:

$${}_{a_R}\langle\psi|O|\phi\rangle_{s_R} = 0 \;\; \forall \text{ observables } O$$

Quantum field theory

N.B., et al, arXiv:2603.25552 (2026)

$$\Psi^{(n)}(x) = \sum_{\sigma} \int \widetilde{dp} \left[a_{\sigma}^{(n)}(\boldsymbol{p}) u_{\sigma}^{(n)}(\boldsymbol{p}) e^{-ip\cdot x} + b_{\sigma}^{(n)\dagger}(\boldsymbol{p}) v_{\sigma}^{(n)}(\boldsymbol{p}) e^{ip\cdot x} \right]$$

$$i\partial_{\mu}\Psi(x) = \left[\Psi(x), P_{\mu}\right]$$

Q-deformed algebra, with $|Q_{nm}| < 1$:

$$a^{(n)}(\tilde{p})a^{(m)\dagger}(\tilde{q}) - Q^{*}_{nm}\,(p,q)a^{(m)\dagger}(\tilde{q})a^{(n)}(\tilde{p}) = \delta_{nm}\delta(\tilde{p},\tilde{q})$$
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- This scheme of quantization is consistent provided that **operators have infinite expansions in $\boldsymbol{a}^{\#}$**

$$P_{\mu} = \int_{\tilde{p}} p_{\mu} N(\tilde{p}),\ \ N(\tilde{p}) = \sum_{n} \sum_{x=a,b} x^{(n)\dagger}(\tilde{p}) x^{(n)}(\tilde{p}) + \sum_{nm}\sum_{xy} \int_{\tilde{q}} \frac{1}{1-|Q|_{nm}^{2}(p,q)} \left[y^{(m)\dagger}(\tilde{q}), x^{(n)\dagger}(\tilde{p})\right]_{Q_{mn}} \underbrace{\left[x^{(n)}(\tilde{p}), y^{(m)}(\tilde{q})\right]_{Q_{nm}}}_{x^{(n)}(\tilde{p}) y^{(m)}(\tilde{q}) - Q_{nm}(p,q) y^{(m)}(\tilde{q}), x^{(n)}(\tilde{p})} + \cdots$$

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- **But the S-matrix is invariant:** $\int dxdy\; x[\mathcal{H}_I(\boldsymbol{x},0), \mathcal{H}_I(\boldsymbol{y},0)] \neq 0,$ which ensures $U(\Lambda)^\dagger S U(\Lambda) = S$

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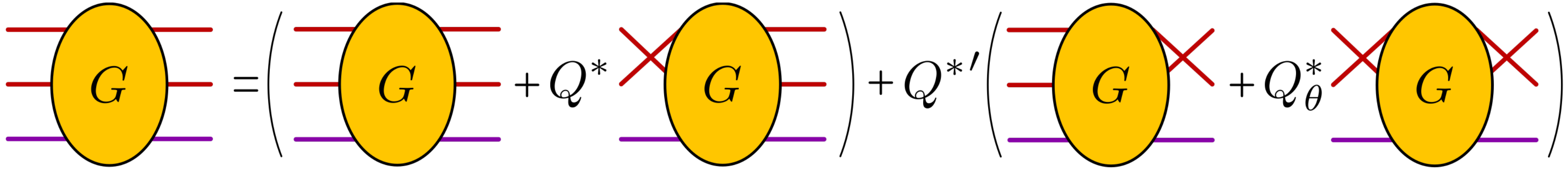
$|Q| < 1$ is crucial to obtain UV regularization

Atomic states

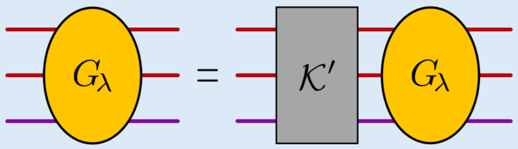
Rigorous relativistic treatment of atomic states is based on Green functions

- pole structure contains bound states
- treat interactions nonperturbatively
- provide dynamical evolution

Electron exchange is governed only by the Q-commutation relations regardless of interactions:



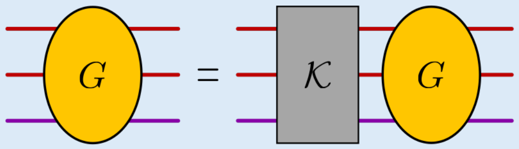
The kernel preserves superselection rules



The physical states are those with **twisted statistics**

VS

The kernel breaks superselection rules



Identical particles are slightly different

Examples

Undeformed Poincaré

$$Q(p,q) = \eta(p,q)$$

Greenberg quon model

$$a(\tilde{p})a^{\dagger}(\tilde{q}) - \eta(p,q)a^{\dagger}(\tilde{q})a(\tilde{p}) = \delta(\tilde{p},\tilde{q})$$

$$\psi_{s,a}(\tilde{p},\tilde{q}) = \pm\psi_{s,a}(\tilde{q},\tilde{p})$$

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$\boldsymbol{\theta}$-Poincaré

$$Q(p,q) = \eta(p,q)\exp\left(i\theta^{\mu\nu}p_{\mu}q_{\nu}\right)$$

$\theta^{\mu\nu}$ defines the *Moyal spacetime* $[x^{\mu}, x^{\nu}] = \theta^{\mu\nu}$

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$\eta(p,q)$ can be any function that:

i) is **Lorentz invariant**

ii) is **real**

iii) is bounded $\boldsymbol{-1 \leq \eta(p,q) \leq 1}$ (positivity of norms)

iv) **reduces to $\boldsymbol{\pm 1}$ at $\boldsymbol{E \ll E_{pl}}$**

$$\eta(p,q) \sim \pm\left(1 - \left(\frac{\sigma(p,q)}{\Lambda_{QG}}\right)^\kappa\right)$$

σ has dimensions of energy, κ a free parameter and Λ_{QG} is the QG scale

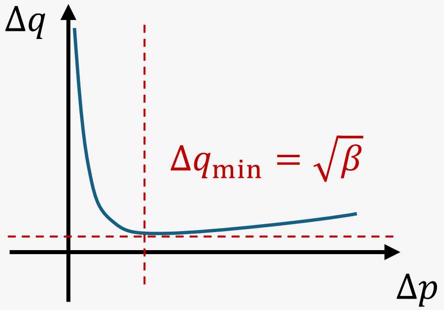
Quon realization from generalized uncertainty principle

By modifying the HUP a **minimal length** appears

$$[\hat{q}, \hat{p}] = i[1 + \beta \hat{p}^2]$$

$$\Delta q \Delta p = \frac{1}{2}[1 + \beta \Delta p^2]$$

from **string theory**



Deformed ladder operators for the h.o.

$$\hat{c}^\dagger |n\rangle = \sqrt{\frac{E_{n+1} - E_0}{\hbar\omega}} |n+1\rangle, c|n\rangle = \sqrt{\frac{E_n - E_0}{\hbar\omega}} |n-1\rangle$$

$$H = \hbar\omega c^\dagger c + E_0 \mathbb{I}, \qquad [c, c^\dagger] = \sqrt{1 + 2\beta m H} + \frac{\beta\hbar\omega m}{2}$$

(P. Bosso, G.G. Luciano *EPJC* **81**, 982 2021)

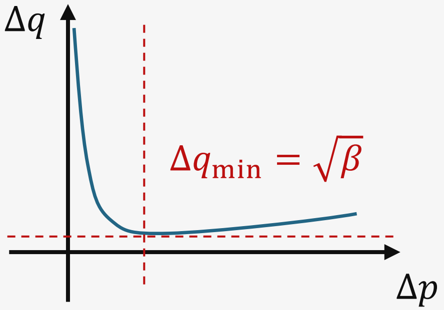
Quon realization from generalized uncertainty principle

By modifying the HUP a **minimal length** appears

$$[\hat{q},\hat{p}] = i[1+\beta\hat{p}^2]$$

$$\Delta q \Delta p = \frac{1}{2}[1+\beta \Delta p^2]$$

from **string theory**



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QFT can be constructed using such operators

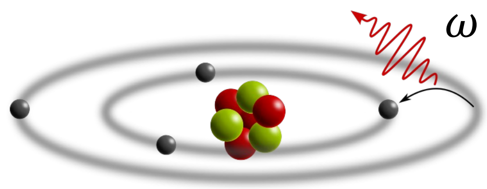
Spinor fields: $a(\tilde{p})a^\dagger(\tilde{q}) + \eta_\beta(p,p')a^\dagger(\tilde{q})a(\tilde{p}) = \delta^{(3)}(\tilde{p},\tilde{q})$

$\{a(\tilde{p}), a(\tilde{q})\} = 0, \quad \{a^\dagger(\tilde{p}), a^\dagger(\tilde{q})\} = 0,$ for $\tilde{p} \neq \tilde{q}$

Quon deformation of fermions: $\eta_\beta(\boldsymbol{p},\boldsymbol{p}') = 1 - \beta m E_p^4 \delta^{(3)}(\boldsymbol{p}-\boldsymbol{p}')$

PEP forbidden atomic transitions with SSRs

- One atom



Transition rate per atom

$$d\Gamma^{\lambda} = 2\pi\delta(E' - E + \omega)\left|H_{if}^{\lambda}\right|^{2}\frac{d^{3}k}{(2\pi)^{3}}$$

Lorentz-invariant: $\psi_{a}^{\mathrm{PEPV}}(\tilde{p},\tilde{q}) = \varphi(\tilde{p})\varphi(\tilde{q}) - \varphi(\tilde{q})\varphi(\tilde{p}) = 0$ $\Rightarrow$ PEP-violation **only in non-antisymmetric sectors**

Lorentz-deformed: $\psi_{a_\theta}^{\mathrm{PEPV}}(\tilde{p},\tilde{q}) = \varphi(\tilde{p})\varphi(\tilde{q})(1 - e^{i\theta^{\mu\nu}p_\mu q_\nu}) \neq 0$ $\Rightarrow$ PEP-violation **also in the antisymmetric sector**

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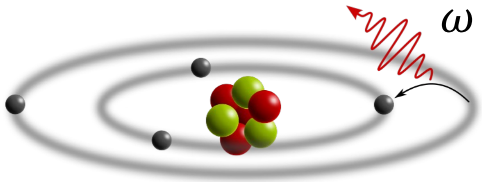

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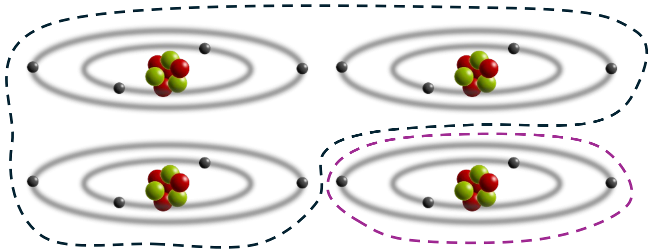
- N (identical) atoms

$\mathfrak{H}_{a_R}^{\otimes 4}$

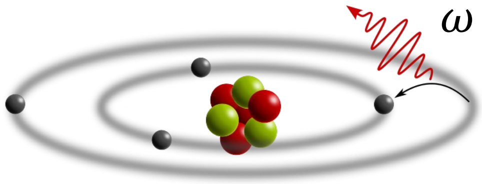


Fraction of atoms in antisymmetric states: $N_a/N = p_a = \dfrac{\left\|\psi_{a_R}\right\|^2}{\sum_{\gamma'}\left\|\psi_{\gamma'_R}\right\|^2} \sim 1$

Fraction of atoms with wrong symmetry: $\dfrac{N_w}{N} = p_w = \sum_{\lambda\neq a} p_\lambda \sim \left(\dfrac{\sigma}{\Lambda_{QG}}\right)^{\kappa} \ll 1$

PEP forbidden atomic transitions with SSRs

- One atom



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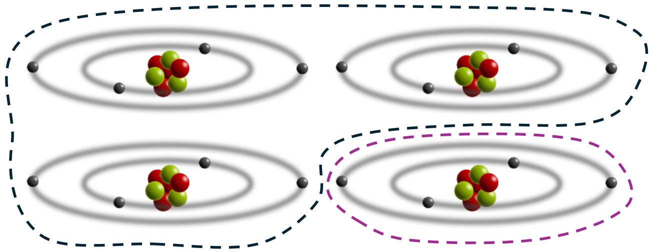

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The **Lorentz-invariant** scenario allows PEP-violations only in the non-antisymmetric sectors: **suppressed probability**

The **Lorentz-deformed** scenario allows PEP-violations in the antisymmetric sector: **large probability**

Pauli forbidden atomic transitions without SSRs

$\psi(p_1, p_2)$ and $\psi(p_2, p_1)$ describe different physical states:

Initial state
$\psi^{\pm}(\boldsymbol{p}, \boldsymbol{q}) = \psi_s(\boldsymbol{p}, \boldsymbol{q}) \pm \psi_a(\boldsymbol{p}, \boldsymbol{q})$

PEPV state
$\psi'(\boldsymbol{p}, \boldsymbol{q}) = \psi'_s(\boldsymbol{p}, \boldsymbol{q})$

$$\begin{cases} d\Gamma^{\pm}_{\mathrm{PEPV}} = 2\pi\delta(E' - E + \omega)\left|H^s_{if} \pm H^a_{if}\right|^2 \dfrac{d^3k}{(2\pi)^3} \\ H^{\gamma}_{if} = \dfrac{e}{\sqrt{2\omega}} \displaystyle\int d^3p d^3q \, D^{\gamma} \psi'_s(\boldsymbol{p} - \boldsymbol{k}, \boldsymbol{q}) \, \boldsymbol{\alpha}_{(1)} \cdot \boldsymbol{\varepsilon}^* \psi_{\lambda}(\boldsymbol{p}, \boldsymbol{q}) \end{cases}$$

Deformation factor due
to modified statistics

QED matrix elements are deformed by

$$D^{s,a} = \frac{[1 \pm Q(p,q)][1 + Q(p-k,q)] \pm [1 - \eta^2(p-k,q)]}{\|\psi'_s\| \|\psi\|}$$

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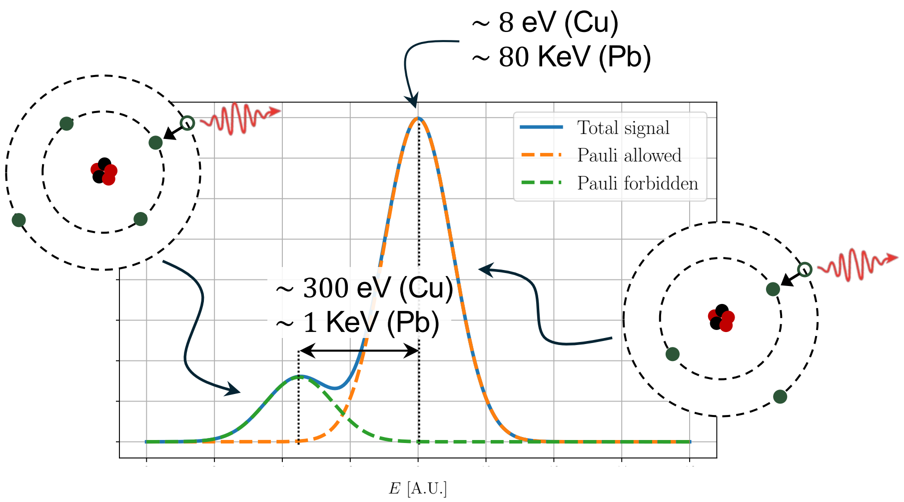
$$\Gamma^{\pm}_{\text{PEPV}} \sim \left(\frac{E_{\text{at}}}{\Lambda_{QG}}\right)^{f(\kappa)} \Gamma_0,$$ where E_{at} is an atomic energy scale

The exact expression of Γ_{PEPV} depends on the specific form of $\eta(p,q)$ and spacetime symmetries

VIP experiments

- Search for the X-rays signature of PEP violating K transitions in Cu and Pb

- **Transition energies are shifted downward** with respect to the standard ones due to additional shielding of the nuclear field



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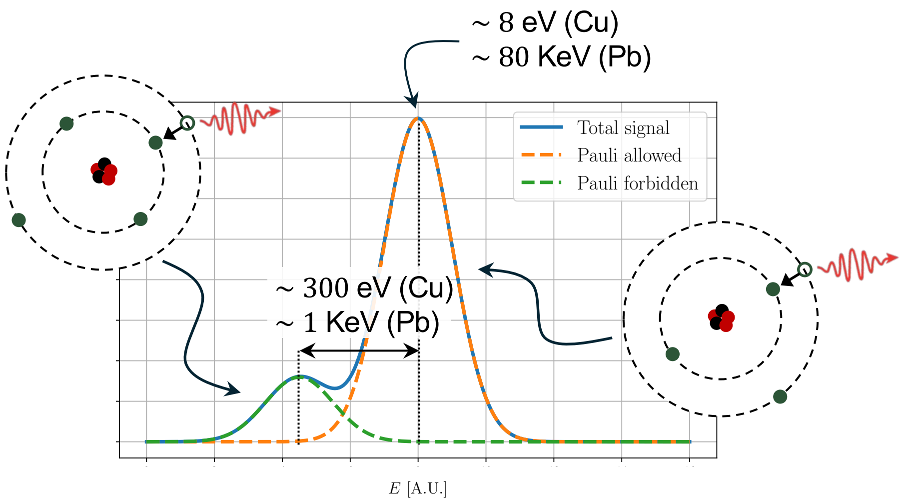
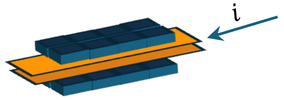


$$N_{\text{events}} = N_{at} \cdot P_{PEPV}^{atom}$$

VIP-Cu "open system": superselection rules

Fast PEPV transitions but only for a small fraction p_w of atoms: **use a current** to enhance the numbers of PEPV transitions

32 Silicon Drift Detectors (SDDs) facing two target copper strips (76x20x0.25 mm)



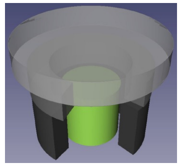
Background provided by data acquisition without current

$S = p_w N_{\text{new}}\, N_{\text{int}}\, \epsilon \sim \left(E_{\text{at}}/\Lambda_{QG}\right)^{\kappa}$ ⟹ **lower limit on** Λ_{QG}

VIP-Pb "closed system": no superselection rules (NCST)

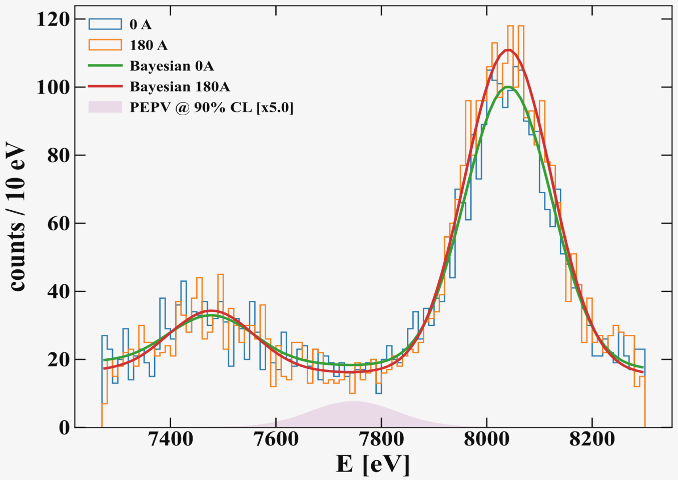
PEPV probability suppressed by $\sim \left(E_{\text{at}}/\Lambda_{\text{QG}}\right)^{a}$ but for all atoms

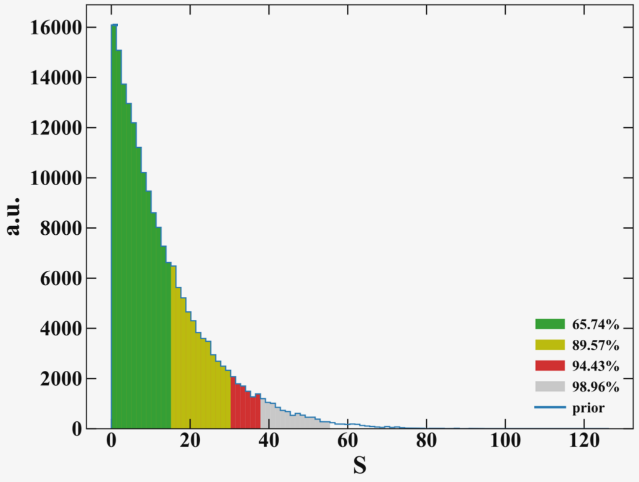
High-purity germaniumn (HPGe) detector (8x8 cm)
Target: 3 cylindrical sections of radio-pure Roman lead completely surrounding the detector



$S \sim \left(E_{\text{at}}/\Lambda_{QG}\right)^{a}$ ⟹ **lower limit on** Λ_{QG}

Test of GUP with VIP-Cu





$S = p_w N_{\mathrm{new}} N_{\mathrm{int}} \epsilon$

$\Rightarrow$ $p_w < \mathbf{6.74 \times 10^{-43}}$

Strongest limit on PEPV in open systems

A. Porcelli, **N.B**. et al. *EPJC* 84.3 2024

A. Porcelli, **N.B.** et al. *Scientific Reports* 15.1 2025

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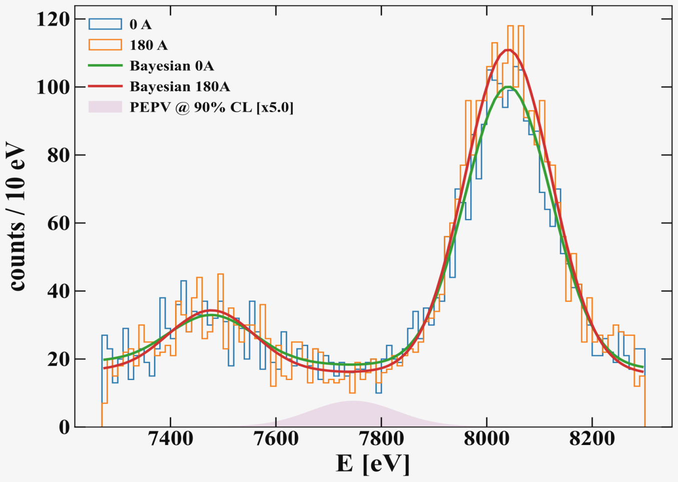

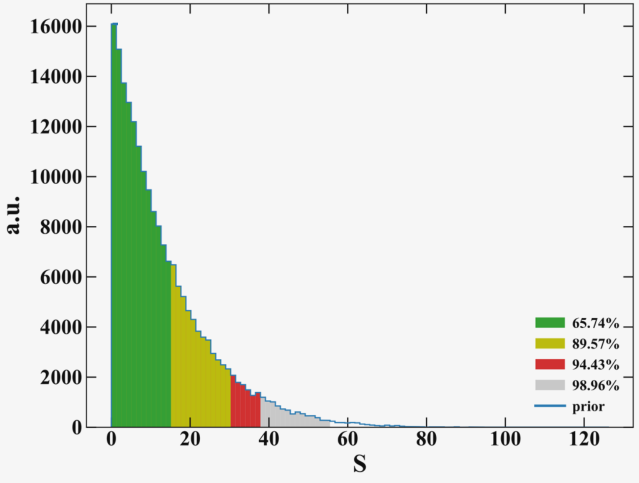

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GUP PEPV probability: $p_w = \beta \underbrace{\frac{m^5}{\Delta^3_{(\chi)}} \sum_{nl} BR_{nl} I_{nl}}_{\text{known parameters}}$

$$\beta/\ell_p^2 < 4.62\times10^{-2}$$

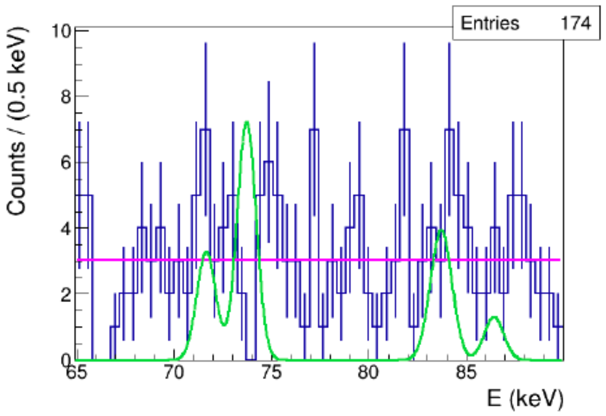
Previous strongest limit:
$\beta/\ell_p^2 < 10^{16}$**!**

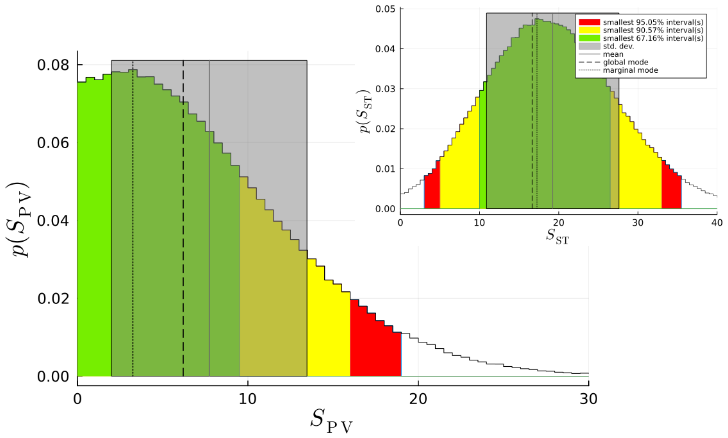
Paper under finalization in collaboration with A. Porcelli, P. Bosso, L. Petruziello, F. Illuminati

Test of different classes of NCSTs with VIP-Lead

$$\Gamma_{PEPV} = \left(\frac{E_{\rm at}}{\Lambda_{QG}}\right)^a \Gamma_0$$

$Z_{Pb} = 82 \rightarrow$ test Λ at the highest transition energy





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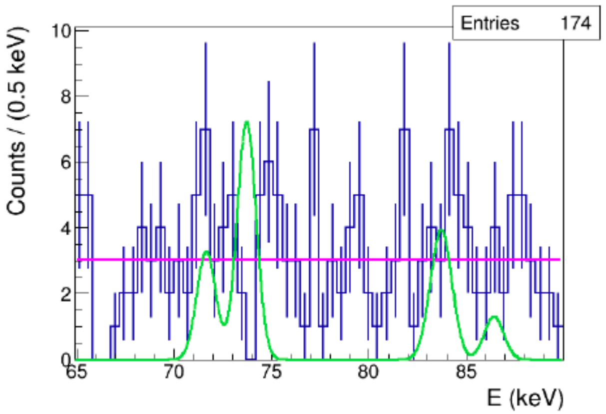

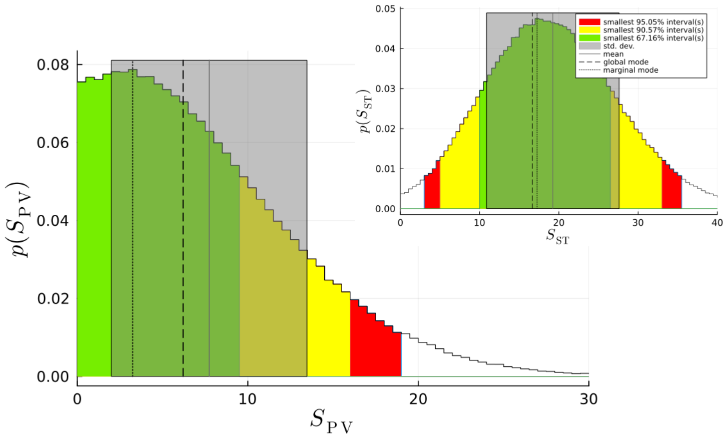

MODEL	Relevant for κ-Minkowski (LQG)	Moyal spacetime (strings with background B-field)	Triply special relativity
Scaling	Linear	Quadratic	Cubic **(first bound ever)**
$\Lambda_{QG}/\mathrm{E}_{pl} >$	$\mathbf{4.2\times10^{21}}$	$\mathbf{1.6\times10^{-1}}$	$\mathbf{5.6\times10^{-9}}$

K. Piscicchia, **N.B.**, et al *Universe*, 9.7, 2023

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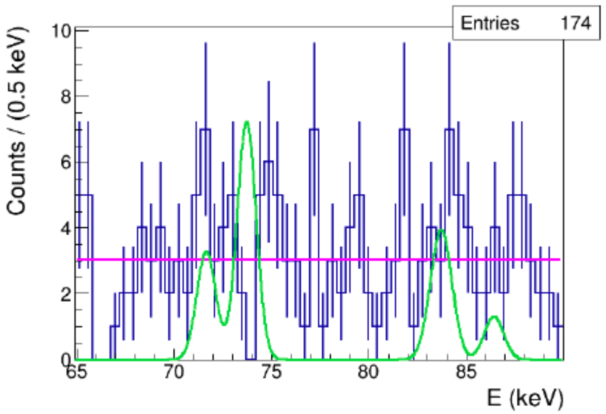

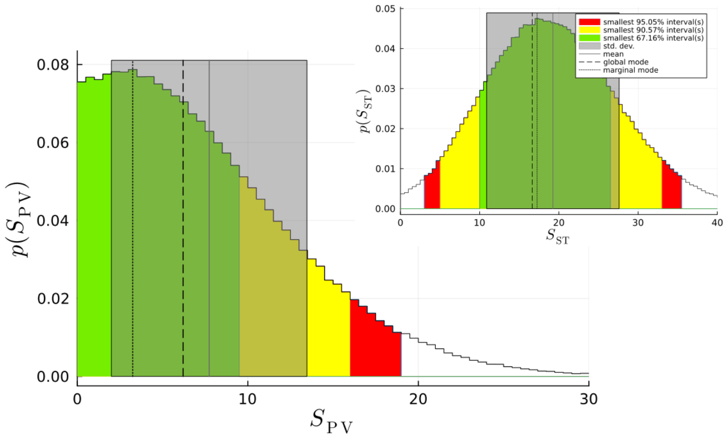

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K. Piscicchia, **N.B.**, et al Universe, 9.7, 2023

Stronger bounds arise in the hadronic sector from DAMA/LIBRA, Borexino and Kamiokande
(A. Addazi, et al, Chinese Physics C 42 094001 2018)

Test of both sectors are needed as in principle different particles may have different couplings to noncommutativity

Current experimental improvements

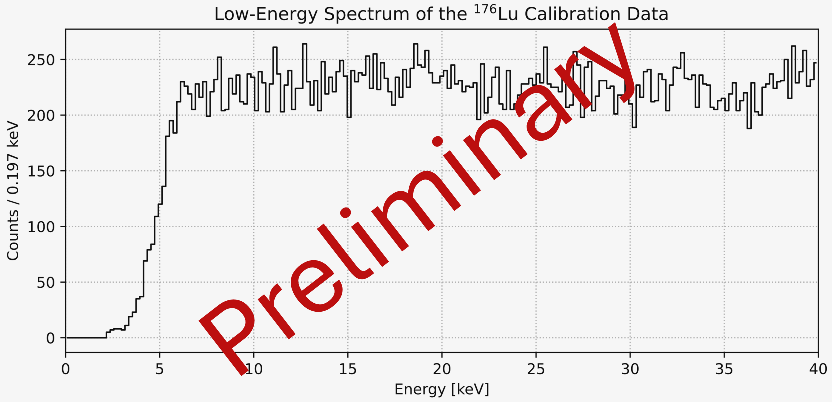
Improve on efficiency: **use Ge detector as active material** → gain of about four orders of magnitude

2 O.o.m. improvement on Λ_{QG} from PEPV

For Ge standard $K_\alpha = 9.9$ keV

Use a **Broad Energy Germanium (BEGe) detector** **to push down the energy range of the spectrum**

- Ranges from ~ 1 keV up to several MeV
- Excellent resolution and efficiency at low energies



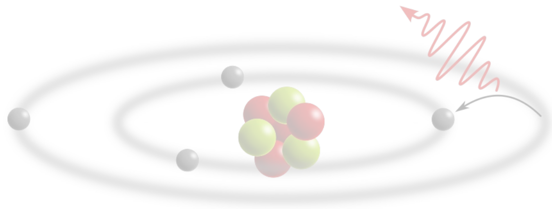
Ongoing work:

- MC characterization of the background
- ML-based event selection. Already **improved SNR** by 14% and **reduced the energy threshold** (S. Manti, **N.B.**, et al, JINST 21.01 01036 2026)
- Pulse-shape analysis for **directionality effects**

P. Kristian, **N.B.**, et al Condensed Matter 9.2 2024

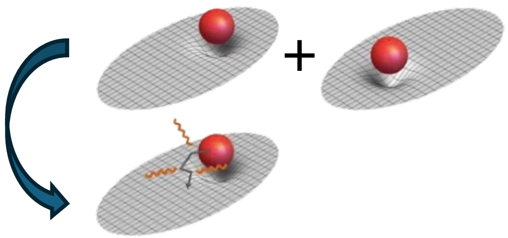
Nonlocality

Pauli violation



Irreversibility

Spontaneous radiation



Classical-quantum hybrid dynamics

- Standard approach: $G_{\mu\nu} = \frac{8\pi G}{c^4} \langle \psi | \hat{T}_{\mu\nu} | \psi \rangle$ ✚ QFT on curved spacetime

  Yields **faster-than-light communication** and **wrong predictions** for large quantum fluctuations of matter

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  Random field

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Newtonian theory constructed by L. Diosi and A. Tilloy (PRD 93.2 024026 2016)

$$\mathbb{E}[\delta\phi(\boldsymbol{x},t)] = 0,$$

$$\mathbb{E}[\delta\phi(\boldsymbol{x},t)\delta\phi(\boldsymbol{y},t')] = \mathcal{D}_\phi(\boldsymbol{x}-\boldsymbol{y})\delta(t-t')$$

also colored $\mathcal{G}(t-t')$

Relativistic extension by J. Oppenheim (PRX 13.4 041040 2023)

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Relativistic extension by J. Oppenheim (PRX 13.4 041040 2023)

- ✓ Consistent coupling between matter & gravity
- ✓ **Solution of the measurement problem**
- ✓ **Experimental signatures**

Irreversibility

In the presence of a stochastic component $\delta\phi$ of the Newtonian field

$$\frac{d}{dt}|\psi_t\rangle = -\frac{i}{\hbar}\Big[\underbrace{\hat{H}}_{\text{Standard Hamiltonian}} + \int d^3x\, \underbrace{\hat{\mu}}_{\text{Mass density operator}}(\boldsymbol{x})\delta\phi(\boldsymbol{x},t)\Big]|\psi_t\rangle, \qquad \frac{d\hat{\rho}}{dt} = -\frac{i}{\hbar}[\hat{H},\hat{\rho}] \underbrace{- \frac{1}{2\hbar^2}\int d^3x d^3y \mathcal{D}_\phi(\boldsymbol{x}-\boldsymbol{y})\,[\hat{\mu}(\boldsymbol{x}),[\hat{\mu}(\boldsymbol{y}),\hat{\rho}]]}_{\textbf{gravity-induced decoherence}}$$

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Standard Hamiltonian

Mass density operator

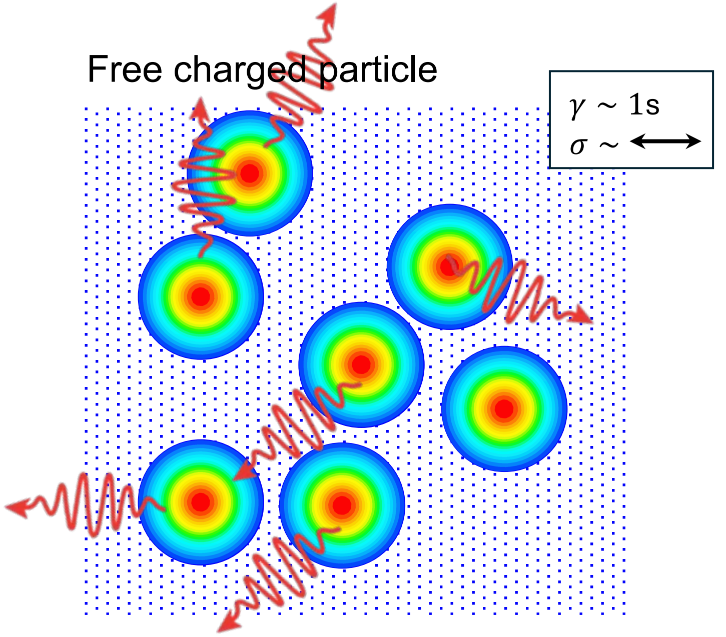
$$\frac{d\hat{\rho}}{dt} = -\frac{i}{\hbar}[\hat{H},\hat{\rho}] \underbrace{- \frac{1}{2\hbar^2}\int d^3x d^3y \mathcal{D}_\phi(\boldsymbol{x}-\boldsymbol{y})\,[\hat{\mu}(\boldsymbol{x}),[\hat{\mu}(\boldsymbol{y}),\hat{\rho}]]}_{\textbf{gravity-induced decoherence}}$$

Diffusive dynamics

The fluctuating field randomly kicks particles at different times and locations

$\mathcal{D}_\phi$ sets the **localization rate $\boldsymbol{\gamma}$** and **spatial resolution $\boldsymbol{\sigma}$**

Standard Schrödinger evolution for **microscopic systems**, instantaneous localization for **macroscopic masses**

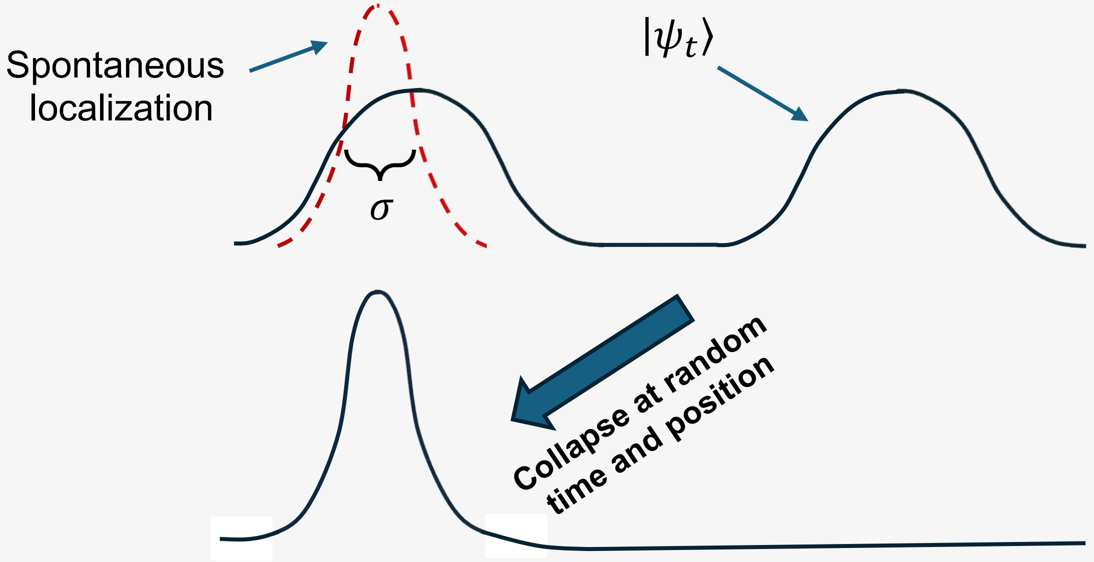


Spontaneous collapse models (SCMs)

$$\frac{d}{dt}|\psi_t\rangle = \overbrace{-\frac{i}{\hbar}\hat{H}|\psi_t\rangle}^{\textbf{linear determ.}} + \overbrace{\left[\int d^3x\, \hat{\mathrm{M}}_t(\boldsymbol{x})\, \delta\phi_t(\boldsymbol{x}) - \frac{1}{2}\int d^3x d^3y\, \mathcal{D}(\boldsymbol{x}-\boldsymbol{y})\hat{\mathrm{M}}_t(\boldsymbol{x})\hat{\mathrm{M}}_t(\boldsymbol{y})\right]|\psi_t\rangle}^{\textbf{nonlinear stochastic}}$$

$$\hat{\mathrm{M}}_t(\boldsymbol{x}) \equiv \hat{\mu}(\boldsymbol{x}) - \langle\psi_t|\hat{\mu}(\boldsymbol{x})|\psi_t\rangle$$

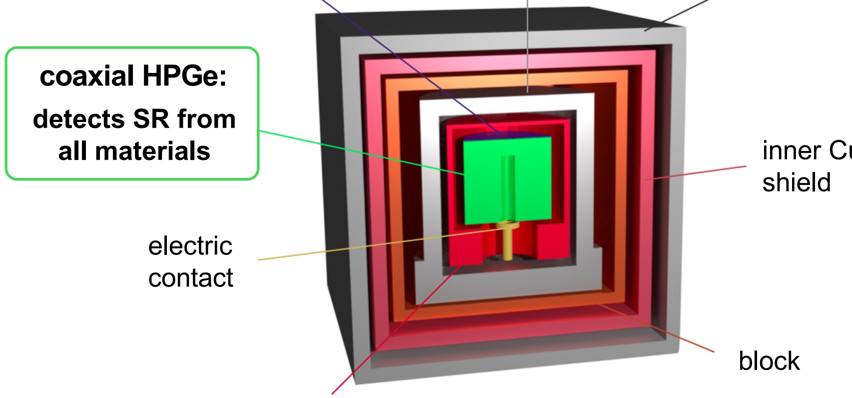
For leading models CSL and Diosi-Penrose:
$\hat{\mu}$ is the mass density and $\delta\phi$ the Newtonian field



Reproduces the Born rule!

Effective only for macroscopic objects!

VIP experiment



Each material emits with a rate $d\Gamma_{\mathrm{mat}}/dE$

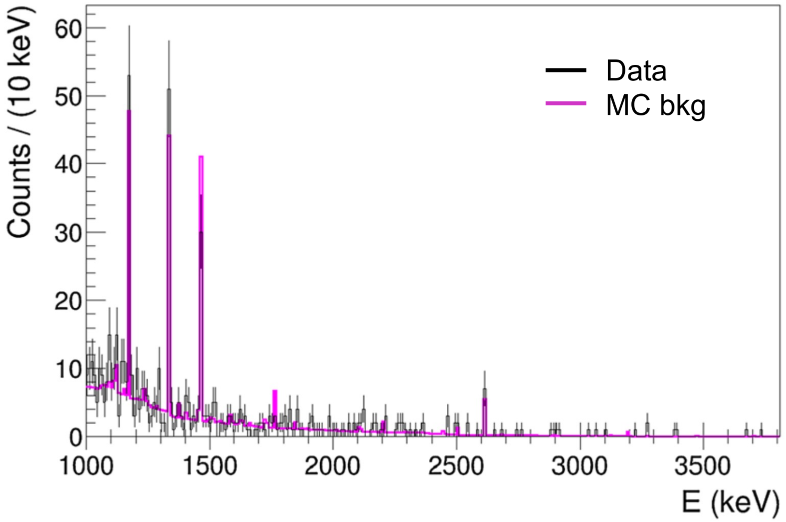
Detection efficiencies $\epsilon_{\mathrm{mat}}(E)$ and background obtained via MC simulation

Analysis

1 parameter: $p(S|data) = \dfrac{\mathcal{L}(data|S)P_0(S)}{\int dY \mathcal{L}(data|S)P_0(S)}$,

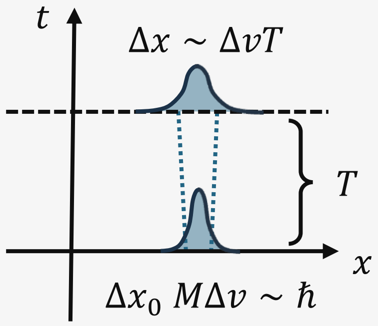
$\lambda_i = b_i^{\mathrm{MC}} + \int_{\Delta E_i} dE\, f(E;S)$: exp counts at bin- i

b_i^{MC}: MC simulated bkg, $f(E;S) = T \sum_{\mathrm{mat}} \dfrac{d\Gamma_{\mathrm{mat}}}{dE} \epsilon_{\mathrm{mat}}(E)$



Károlyházy – first gravity-related decoherence model

In 1966 K. derives a limit to the precision a quantum probe can measure a time-like length $s = cT$



- $\Delta s \sim \Delta x$ minimized when $\Delta x = \Delta x_0$ and $M \to M_{\max}$
- $M_{\max}$ follows requiring that no black hole appears: $\Delta x > r_s$

$$\Delta s^3 = \ell_p^2 \bar{s}$$

stochastic

$$\frac{s}{c} = \int_0^{\bar{s}/c} dt \sqrt{g_{\mu\nu} \dot{x}^\mu \dot{x}^\nu}\,, \qquad + \qquad g_{00}(\boldsymbol{x}, t) = 1 + \frac{2}{c^2} \phi(\boldsymbol{x}, t) \quad \Longrightarrow \quad \boxed{\int_0^{\bar{s}/c} dt \int_0^{\bar{s}/c} dt' \, \mathbb{E}[\phi(\boldsymbol{x}, t) \phi(\boldsymbol{x}, t')] = \left(\ell_p^2 \bar{s}\right)^{2/3}}$$

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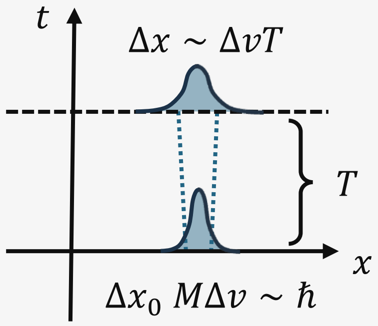

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❖ **The original version** assumes the wave equation for ϕ, but **predicts too much emission of spontaneous radiation!** (L. Diosi, B. Lukács PRA 181.5 366-368 1993)

❖ Assuming instead a generic $\mathbb{E}[\phi(\boldsymbol{x},t)\phi(\boldsymbol{x}',t')] = \mathcal{D}(|\boldsymbol{x}-\boldsymbol{x}'|)\mathcal{G}(|t-t'|)$, the K. uncertainty Δs fixes $\tilde{\mathcal{G}}(\omega) = \frac{4}{\sqrt{3}}\Gamma\left(\frac{2}{3}\right) t_p^{1/3}\omega^{1/3}$ and drastically reduces the radiation emitted (L. Figurato, et al, NJP 26.1 013001 2024)

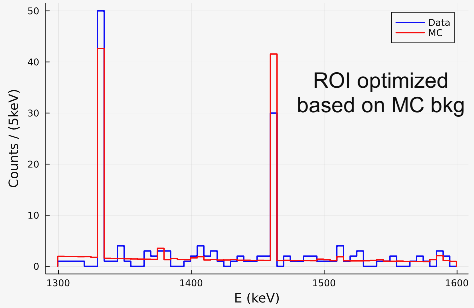
Károlyházy – experimental analysis

The Gaussian K. model is experimentally equivalent to a **non-Markovian version of the CSL!**

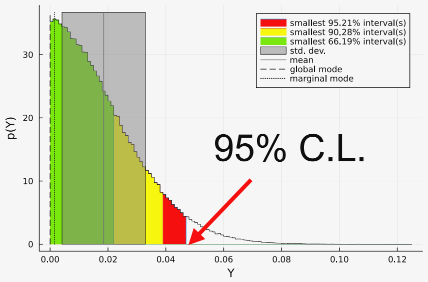
Collapse rate fixed by the Planck time $\lambda = \frac{t_p m_0^2 c^4}{4\hbar^2} = 27.5\ \mathrm{kHz}$ ⟺ **only 1 free parameter**: the correlation length $\boldsymbol{R_K}$

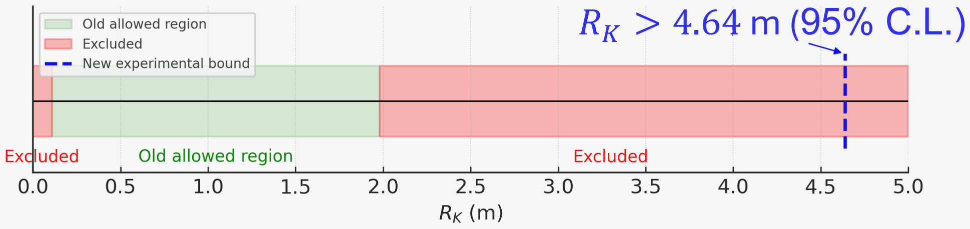
Exact emission rate at energy $E = \hbar\omega = c\hbar k$: $$\frac{d\Gamma}{dE} = \frac{\tilde{\mathcal{G}}(E)}{6\pi^2\epsilon_0 c^3 E}\sum_{ij} q_i q_j \frac{\sin kr_{ij}}{kr_{ij}}\left(-\nabla^2\mathcal{D}(\boldsymbol{r}_{ij})\right)$$

Optimal range $\mathbf{10 - 10^5}$ keV: protons emit coherently, electrons incoherently $$\frac{d\Gamma}{dE} = \frac{N_{at}\left(N_p^2 + N_e\right)\Gamma(2/3)\alpha_{\mathrm{QED}} c^2 t_p^{4/3}}{\sqrt{3}\pi\hbar^{1/3} R_K^2 E^{2/3}}$$



$Y = 1/R_K^2$





Generalized Károlyházy & colored CSL excluded

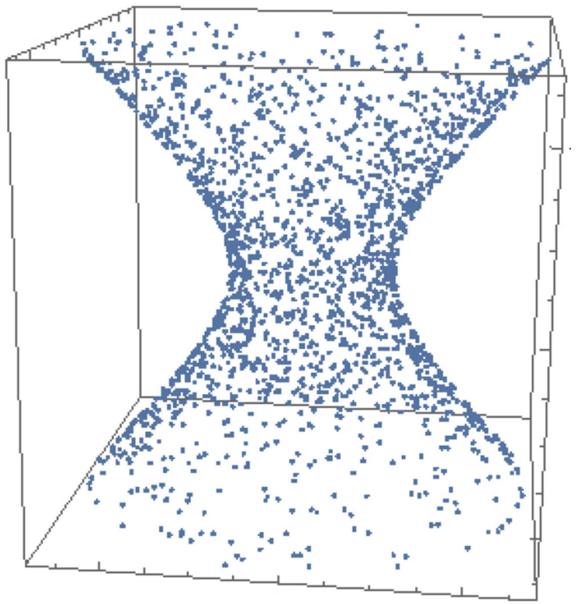
N.B., et al. *New J. Phys.* 28.6 (2026): 064511

Spacetime discreteness

A continuum manifold is an approximation of an underlying causal set, characterized by a fundamental **discrete volume** ℓ_c^3

Lorentz invariance can be preserved by randomly distributing, in the continuum manifold, the elements of the causal set according to a **Poisson process**

Geometric quantities such as the **length** of a geodesic become **stochastic variables**



(S. Surya *Living Rev Relativ* **22**, 5 2019)

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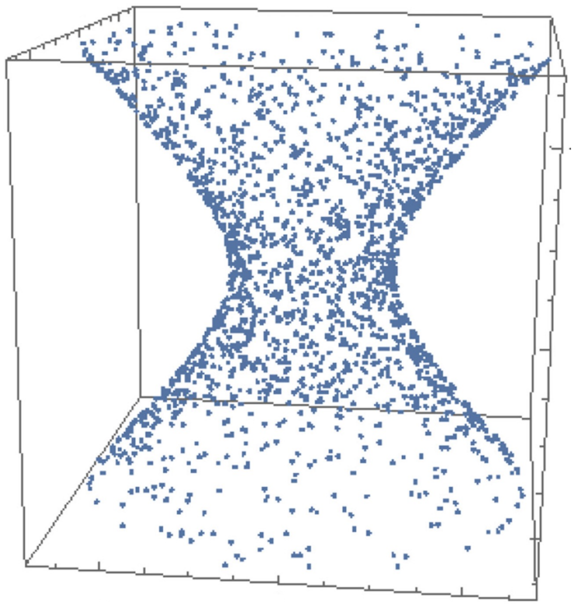
Same situation of **Károlyházy**; the only difference is the uncertainty



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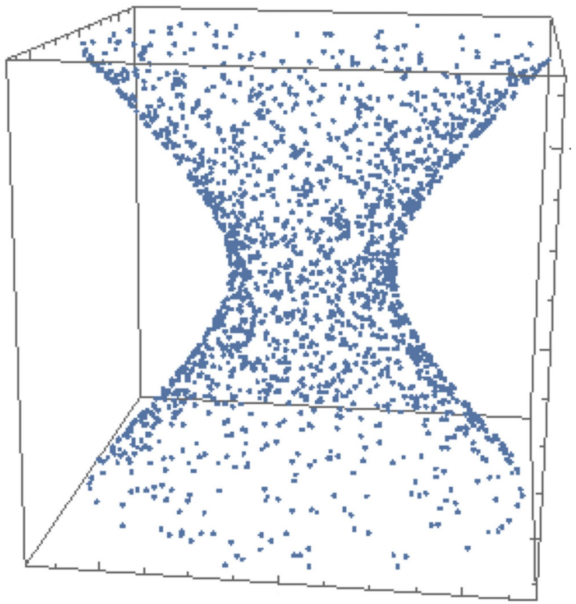

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Same situation of **Károlyházy**; the only difference is the uncertainty

For example, assumming **poissonian clock ticks** with average time interval t_c **predicts the rate**

(single particle) $$\frac{\mathrm{d}\Gamma}{dE} \sim t_d \frac{\alpha_{QED} c^2 E}{6\pi^3 \hbar^2}$$

Notably, $\boldsymbol{\kappa}$**-Minkowski spacetime** originates from such a time discretization (A. Arzano et al. PRD 111.2 025010 2025)

In general, we can assume the expression $\Delta l = \sqrt{\mathbb{E}[l]^\gamma \ell_c^{2-\gamma}}$, restricting $0 < \gamma < 2$ and yields $\frac{\mathrm{d}\Gamma}{dE} \sim (\ell_c E)^{2-\gamma}$

Conclusions

- The unification of quantum mechanics and gravity generally predicts **rare EM radiation** from **PEP violation** or fundamental **uncertainty of the gravitational field**. Each process is characterized by a peculiar spectrum
- Spontaneous radiation probes both **QG scenarios** (e.g. CST and NCST) and **fundamentally classical gravity scenarios** (e.g. SCMs, postquantum theory of classical gravity)
- **Underground X-ray experiments** provide a unique opportunity to explore the quantum-gravity connection at interesting scales

  - Quadratic GUP model $\boldsymbol{\beta/\ell_p^2 < 4.62\times10^{-2}}$
  - NCSTs must **break indistinguishability**

  (κ-Poincaré): $\boldsymbol{\Lambda_1 > 10^{21}}$ **Planck energy**
  (θ-Poincaré): $\boldsymbol{\Lambda_2 > 0.1}$ **Planck energy**
  (Triply SR): $\boldsymbol{\Lambda_3 > 5.6\times10^{-9}}$ **Planck energy**

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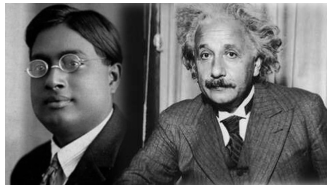
Thank you for your attention!

Backup slides

Quantum statistics:
A (partial) hystorical perspective

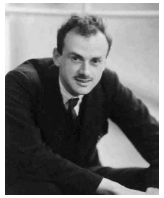
1911: W. Natanson discovers **indistinguishability** of Planck's quanta

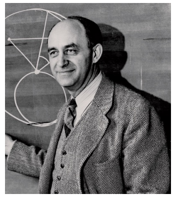


1924: Bose-Einstein statistics for photons and matter

1925: **Pauli's exclusion principle (PEP)**

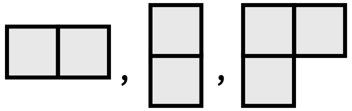
1926: Fermi-Dirac statistics for particles that obey the PEP





1934: Fermi investigates the case of **"slightly non identical"** particles

<u>Large</u> violations of statistics

$\left[a_i, [a_j, a_k]_\pm\right] = 0$: 

1953

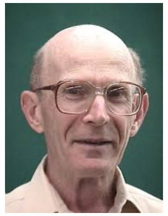
H.S. Green shows that **local QFT** is compatible with **parastatistics**

1940

Spin-statistics theorem

G. Gentile Jr looked at intermediate statistics

1964

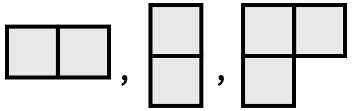


Messiah & Greenberg:
indistinguishability = parastatistics + selection rules

Color degree of freedom

Large violations of statistics

$$\left[a_i, [a_j, a_k]_{\pm}\right] = 0:$$



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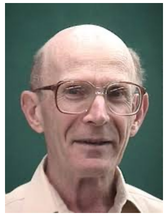
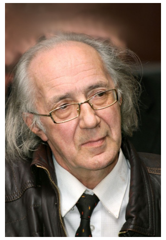


Messiah & Greenberg:
indistinguishability = parastatistics + selection rules

Color degree of freedom

All known particles are either bosons or fermions → Is this the end of the story?

Small violations of statistics



1974 — Reines & Sobel: first test of the PEP in “closed systems”

1985 — Vadim Kuzmin estimates the **QG-induced PEPV**

1987 — Ignatiev & Kuzmin toy model

Ramberg & Snow experiment in “open system”

1991 — Greenberg formulates the **quon model**

2001 — VIP-Cu “open system” experiment: best limit on quon

Ongoing… — **Connection with QG frameworks**

Hilbert space structure

- The state space of a system of **distinguishable** identical particles is the **full Fock space** $\mathfrak{F}(\mathfrak{H}) = \bigoplus_{n=0}^{\infty} \mathfrak{H}^{\otimes n}$

For all n, finite linear combinations of product states $|\xi_1, \dots, \xi_n\rangle \equiv |\xi_1\rangle \otimes \cdots \otimes |\xi_n\rangle$ span the n-particle Hilbert space $\mathfrak{H}^{\otimes n}$

- The inner product of $\mathfrak{H}^{\otimes n}$ can always be written as
  - $\langle \xi_n, \dots, \xi_1 | \chi_1, \dots, \chi_n \rangle = (\xi_n, \dots, \xi_1 | W_{(n)} | \chi_1, \dots, \chi_n)$
  - $(\xi_n, \dots, \xi_1 | \chi_1, \dots, \chi_n) = \langle \xi_1 | \chi_1 \rangle \cdots \langle \xi_n | \chi_n \rangle$
  - $W_{(n)}$ is positive: squared norms are non-negative

In second quantization, **$W_{(n)}$ is determined by the exchange relation**

$$a(\tilde{p})a^\dagger(\tilde{q}) - \int_{\tilde{p}\tilde{q}} T(\tilde{k}, \tilde{l} | \tilde{p}, \tilde{q}) a^\dagger(\tilde{k}) a(\tilde{l}) = \delta(\tilde{p}, \tilde{q})$$

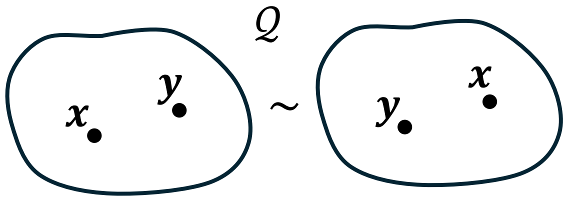
e.g. $W_{(2)} = \frac{1}{2}(1 + T)$

Hilbert space structure

Define the **flip operator** $\tau_R \equiv \tau R$ where $\tau|\tilde{p},\tilde{q}\rangle = |\tilde{q},\tilde{p}\rangle$ and $R|\tilde{p},\tilde{q}\rangle = \int_{\tilde{k}\tilde{l}} R(\tilde{k},\tilde{l}|\tilde{p},\tilde{q})|\tilde{k},\tilde{l}\rangle$

$|\psi\rangle = \int_{\tilde{p}\tilde{q}} \psi(\tilde{p},\tilde{q})|\tilde{p},\tilde{q}\rangle \in \mathfrak{H}^{\otimes 2}$ can always be decomposed as: $|\psi\rangle = \frac{1+\tau_R}{2}|\psi\rangle + \frac{1-\tau_R}{2}|\psi\rangle \equiv |\psi\rangle_{s_R} + |\psi\rangle_{a_R}$

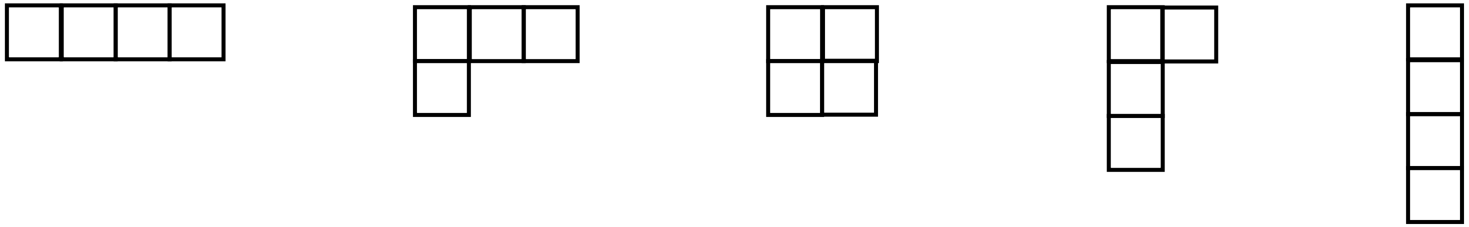
$\hat{\tau}_R$ must generate a unitary representations of the fundamental group $\pi_1(Q)$ of the configuration space



- In $d \geq 3$: Q is simply connected $\rightarrow \pi_1(Q)$ = symm. group S_n $\longrightarrow$ $\tau_R^2 = 1$
- In $d < 3$: Q is multiply connected $\rightarrow \pi_1(Q)$ = braid group B_n $\longrightarrow$ $\tau_R^2 = e^{i\phi}$ (anyons)

For arbitrary n, $|\psi\rangle = \sum_\lambda |\psi_\lambda\rangle$, where $|\psi_\lambda\rangle$ has exchange-symmetry given by the Young diagram λ

$n = 4$:



Indistinguishability of identical particles

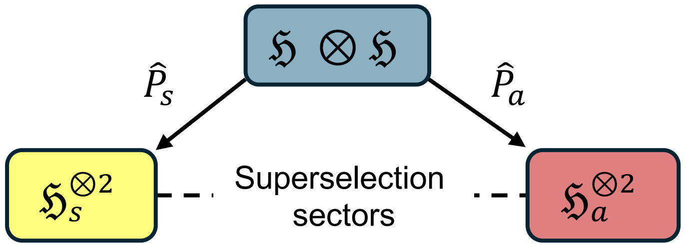
❖ At least at energies ≪ Planck scale, identical particles are indistinguishable

Indistinguishability DOES NOT require the symmetrization postulate: $|\xi,\chi\rangle \nrightarrow |\chi,\xi\rangle_{\lambda_R}$, $\cancel{a(\tilde{p})a(\tilde{q}) = \int_{\tilde{p}\tilde{q}} R(\tilde{k},\tilde{l}|\tilde{p},\tilde{q})a(\tilde{k})a(\tilde{l})}$

It is sufficient the existence of **superselection rules (SSRs):** ${}_{a_R}\langle\psi|O|\phi\rangle_{s_R} = 0\ \ \forall$ observables O

- $\hat{\rho}$ can be written in **block-diagonal** form! $\hat{\rho} = \sum_\gamma p_\gamma |\psi_{\gamma_R}\rangle\langle\psi_{\gamma_R}|$
- **States are incoherent mixtures of different permutation symmetries, with weights**

$$\boldsymbol{p_\gamma = \frac{\left\|\psi_{\gamma_R}\right\|^2}{\sum_{\gamma'}\left\|\psi_{\gamma'_R}\right\|^2}}$$

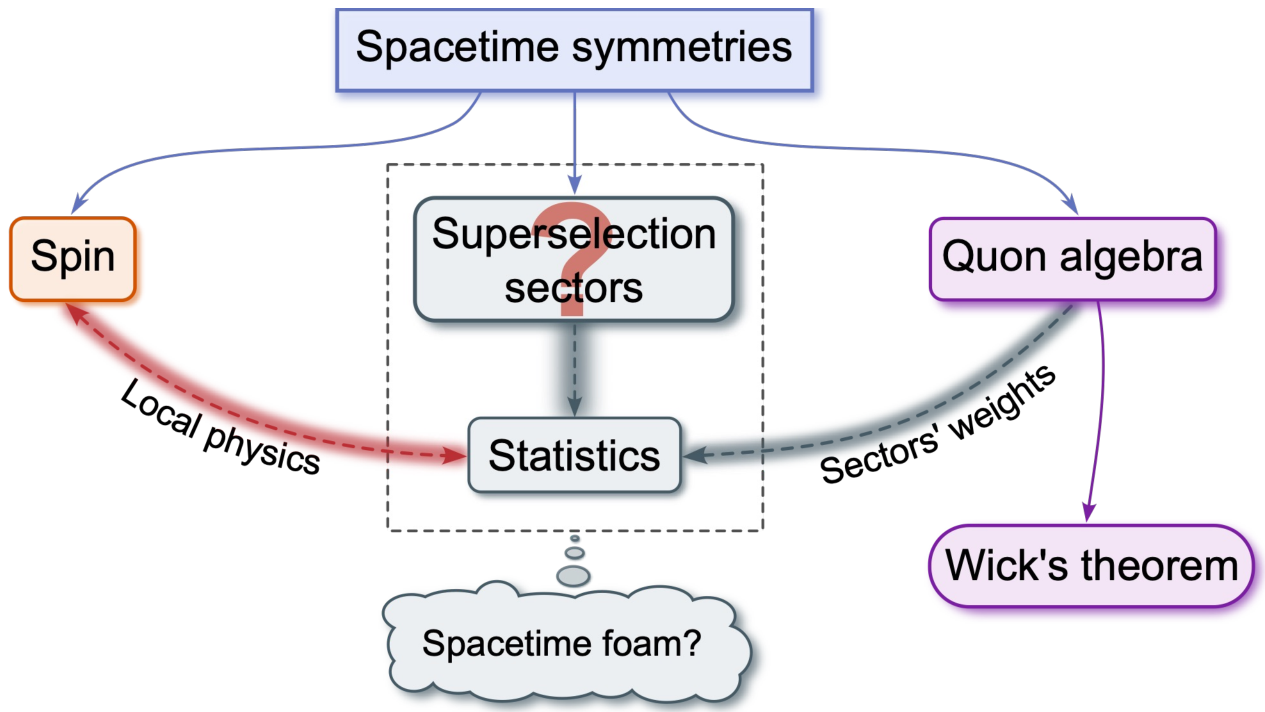


- $\left\|\psi_{\gamma_R}\right\|^2 = \langle\psi_{\gamma_R}|\psi_{\gamma_R}\rangle \Longrightarrow$ **p_γ depend on the T operator**
- Superselection sectors $\mathfrak{H}_\lambda^{\otimes n}$ + weights p_γ = **statistics**

Spacetime symmetries

Let $U(g)$ be a unitary representation of the Poincaré group on $\mathfrak{H}^{\otimes n}$, where $g = \{a, \Lambda\}$. Then:

- The inner product must be invariant $(U(g)\psi|W|U(g)\phi) = (\psi|U(g)^{\dagger}WU(g)|\phi)$ $\Rightarrow$ $U(g)T = TU(g)$
- Permutation of particles must be compatible with spacetime transformations $\Rightarrow$ $U(g)\tau_R = \tau_R U(g)$

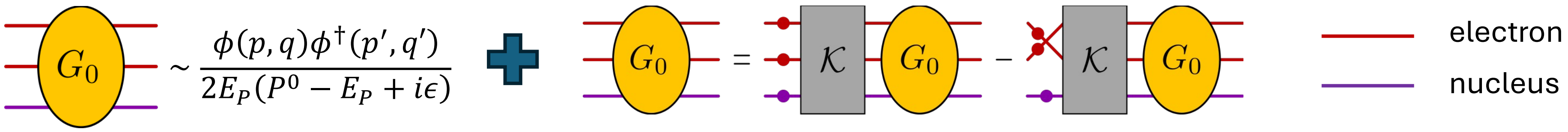


Atomic states

Rigorous relativistic treatment of atomic states is based on Green functions

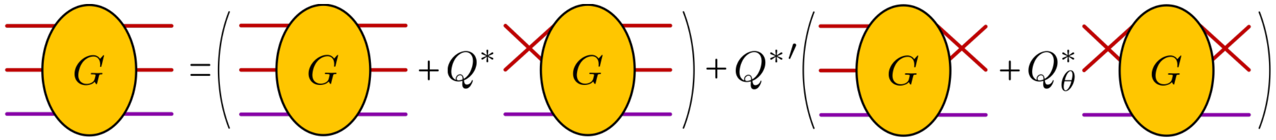
- pole structure contains bound states
- treat interactions nonperturbatively
- provide dynamical evolution

Bethe-Salpeter (BS) amplitudes: $\phi(x,y) = \langle\Omega|T\{\Psi(x)\Psi(y)\}|B\rangle$

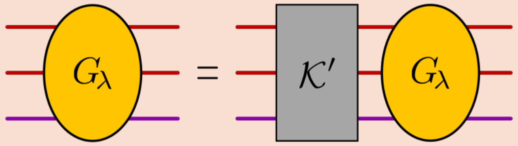


BS equation for the amplitude $\boldsymbol{\phi(p,q)}$

❖ The generalization to twisted-quons leads to **two distinct scenarios:**

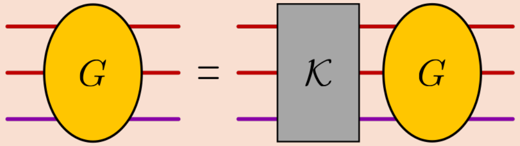


The kernel preserves superselection rules



The physical states are those with **twisted statistics**

The kernel breaks superselection rules



Identical particles are slightly different

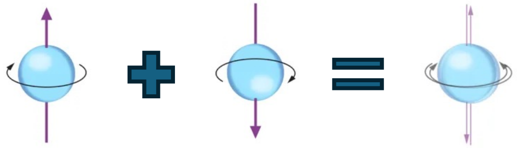
Poincaré Hopf-algebra

Poincaré **algebra**	
$[P_\mu, P_\nu] = 0$ $[M_{\mu\nu}, M_{\rho\sigma}] = i\,(\eta_{\nu\rho} M_{\mu\sigma} - \eta_{\mu\rho} M_{\nu\sigma} - \eta_{\nu\sigma} M_{\mu\rho} + \eta_{\mu\sigma} M_{\nu\rho})$ $[M_{\mu\nu}, P_\rho] = -i(\eta_{\mu\rho} P_\nu - \eta_{\nu\rho} P_\mu)$	Action of the generators on **single particle states**
Poincaré **co-algebra**	
$\Delta(Y) = Y \otimes \mathbb{1} + \mathbb{1} \otimes Y\,, \quad Y = \{P_\mu, M_{\mu\nu}\}$	Action of the generators on **multi particle states**

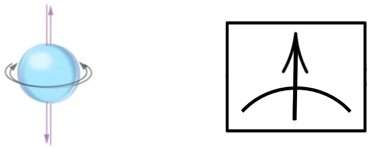
Quantum mechanics à la Copenhagen

Quantum systems:
linear and deterministic

$$\frac{d}{dt}|\psi_t\rangle = -\frac{i}{\hbar}\hat{H}|\psi_t\rangle$$

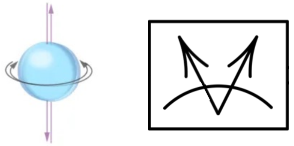


$(\alpha|\uparrow\rangle + \beta|\downarrow\rangle)$ $|m_0\rangle$



Quantum measurement →

$\alpha|\uparrow\rangle|m_\uparrow\rangle + \beta|\downarrow\rangle|m_\downarrow\rangle$

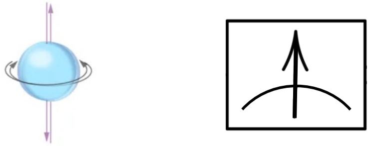


?

Interaction with measurement devices:
nonlinear and stochastic

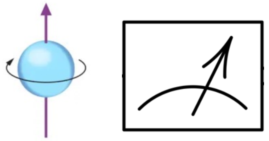
There are other interpretations but yields same predictions

$(\alpha|\uparrow\rangle + \beta|\downarrow\rangle)$ $|m_0\rangle$



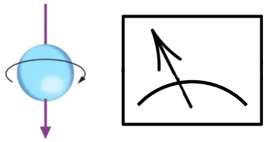
Collapse postulate →

$|\uparrow\rangle|m_\uparrow\rangle$ $p_\uparrow = |\alpha|^2$



OR

$|\downarrow\rangle|m_\downarrow\rangle$ $p_\downarrow = |\beta|^2$



Current goals

Test of PEP-violation at the Planck scale

Improve on efficiency: use Ge detector as active material → gain of about four orders of magnitude

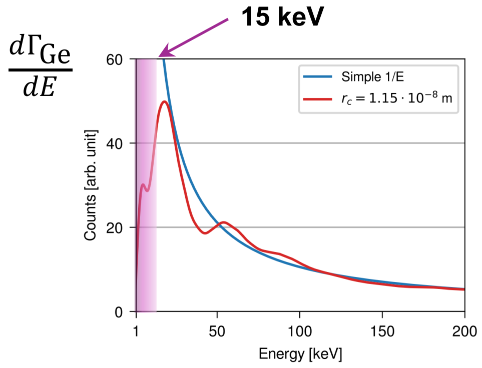
2 orders of magnitude improvement on Λ from PEPV

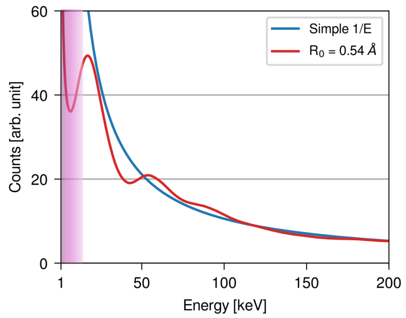
For Ge standard $K_\alpha = 9.9$ keV:

need a lower energy threshold around 6 keV

Low energy behavior of spontaneous radiation

- At low energy DP and CSL modulate the rate in different ways!





- Energy cutoff E_c is expected for colored models

Use a Broad Energy Germanium (BEGe) detector to push down the energy range of the spectrum

- Ranges from ~ 1 keV up to several MeV
- Excellent resolution and efficiency at low energies