# Quantum Gravity in LAB

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Summer Conferences 2023

# Based on a series of recent works

A. Addazi, P. Belli, R. Bernabei, A. Marciano,
arXiv:1712.08082, CPC

A. Addazi, A. Marciano, arXiv:1811.06425, IJMPA 2019

A. Addazi, R. Bernabei, MPLA 2019

A. Addazi, H. Shababi, arXiv: 2005.14000v1, IJGMPA

A. Addazi, P. Belli, R. Bernabei, A. Marciano, H. Shababi,
*Eur.Phys.J.C* 80 (2020) 8, 795

K. Pisticchia et al, arXiv:2209.00074, Phys.Rev.Letters, PRD,
MDPI

# “Santo Graal” of Theoretical Physics

## Quantum Gravity!

UV completion of General Relativity

# Top-Down QG

String theory, M-theory

Super-renormalizable non-local theories

Loop Quantum Gravity

Asymptotic Safety

Causal Sets

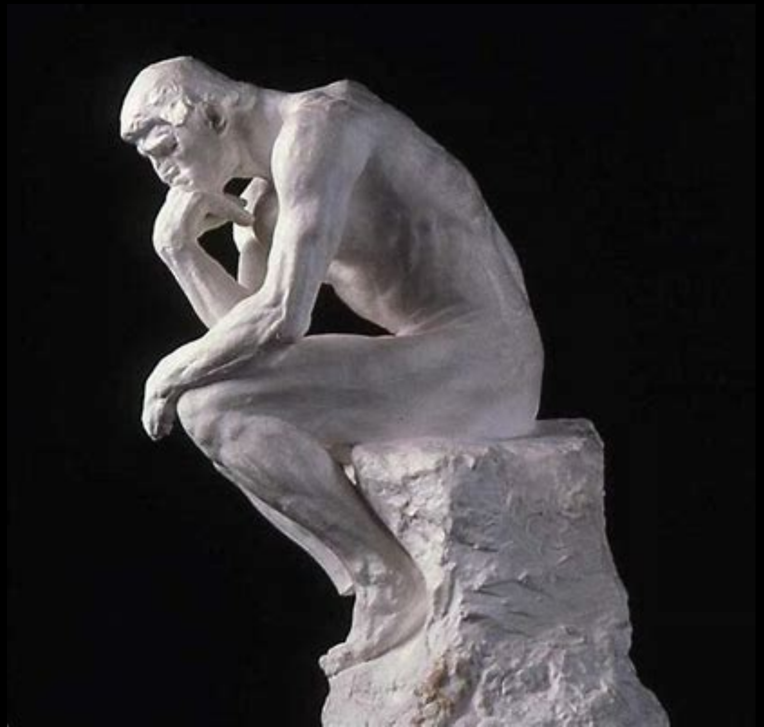
Asymptotic Darkness/Classicalization

Dynamical Triangulation

Gauge reformulations of gravity

Some of the previous theories may be “dual”
of having common hidden theoretical features

Quantum gravity phenomenology is commonly considered as a sort of metaphysics chimera or even an oxymoron… common pessimistic approach



# Bottom-up: QG phenomenology Effective theories and parametrization of our "ignorance" on UV completion

Quantum Field Theory in
Non-commutative space-time;
Theta- and kappa-Poincare

Higher derivatives actions

Modified Gravity

Quantum Groups

Generalized Uncertainty Principle (GUPs)

Modified Dispersion Relations (MDRs)

Large Extra Dimensions

Lorentz Violations, CPT violations

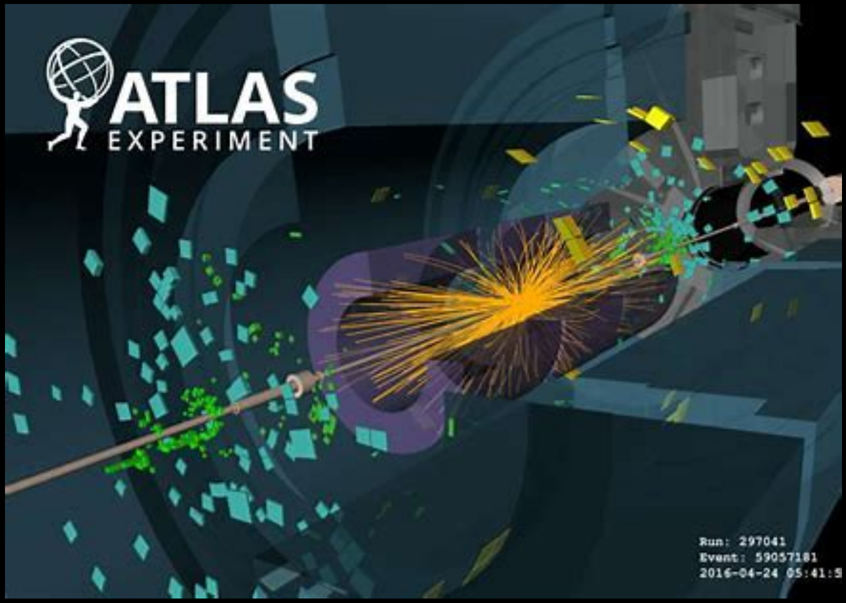
Decoherence, density matrix

Extended Standard Model

Effective Theory
*N free parameters*

Vs

Low (in Planck unit) energy physics
Observations



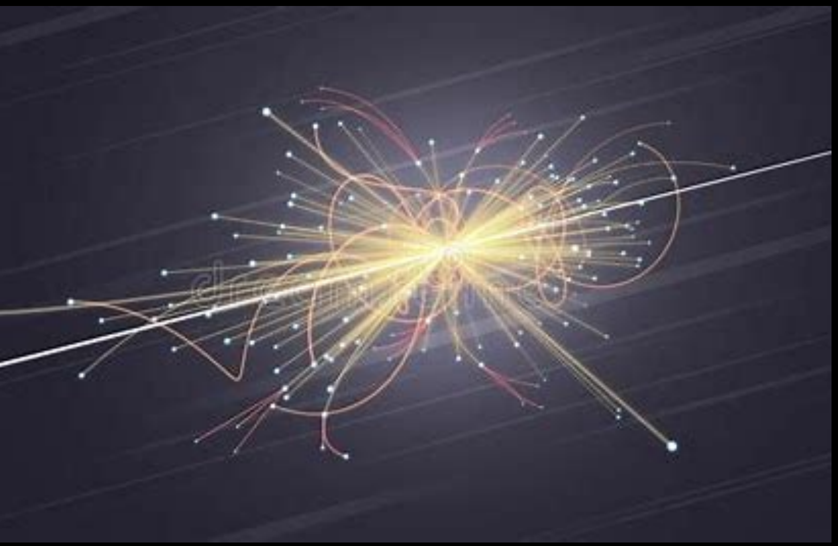

**Direct probe** of Planck scale **impossible** with our current and next future technology (at least if extra dimensions are not fine-tuned to be around 1-0.0001mm, ADD/RS).

Nevertheless tiny residual quantum gravity effects can **survive** at “mesoscopic”scales,

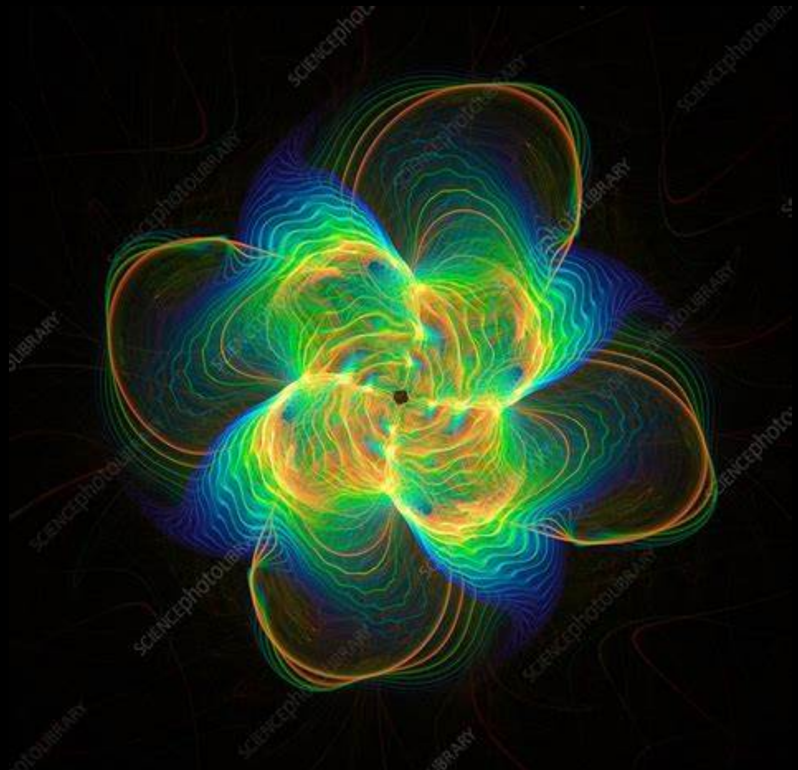
Lower energy physics.

This is possible if a **“scale amplifier”**

Cumulative overall “deviations”



# Quantum gravity memory lost …
# And regained..



# QG probes in Astrophysics and cosmology, multi-messenger physics GRBs, AGN, BH-BH mergings, NS-NS mergings. MDRs, Horizons, Love number etc

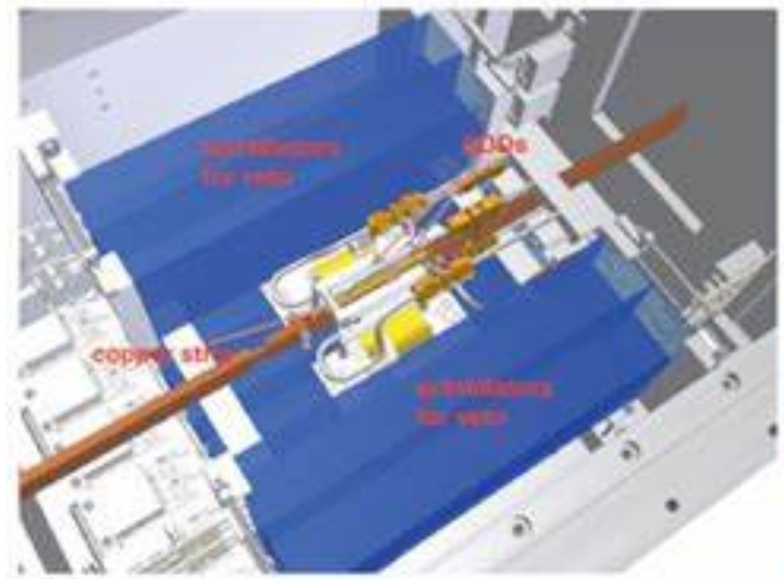
*Gamma ray windows, GRBs, AGNs,*
*G.Amelino-Camelia, J. Ellis, et al.*

*A. Addazi, N. Yunes,*
*A. Marciano PRL highlights 2019*

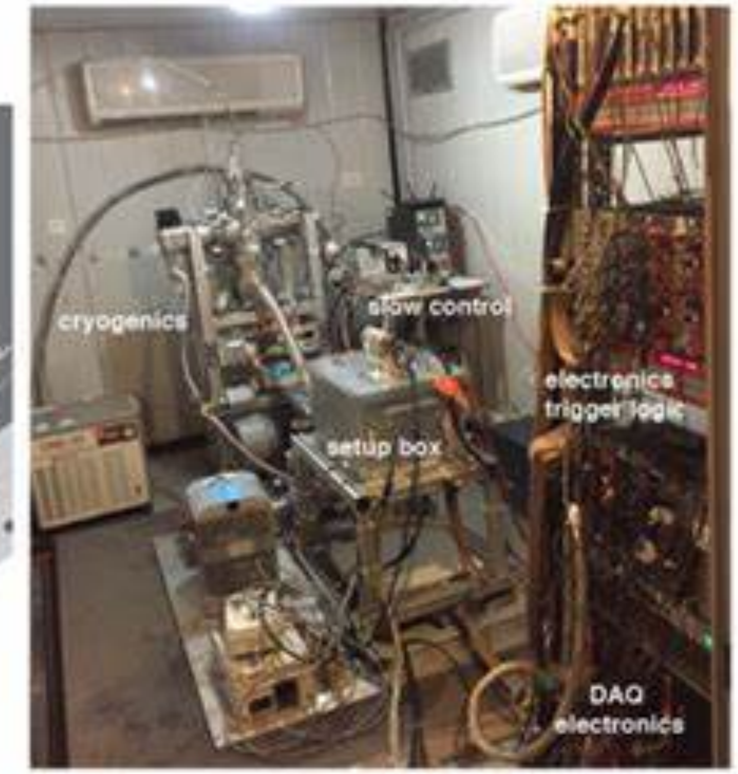
# Deep Underground Experiments!

# Gran Sasso National Laboratory INFN

## VIP-II

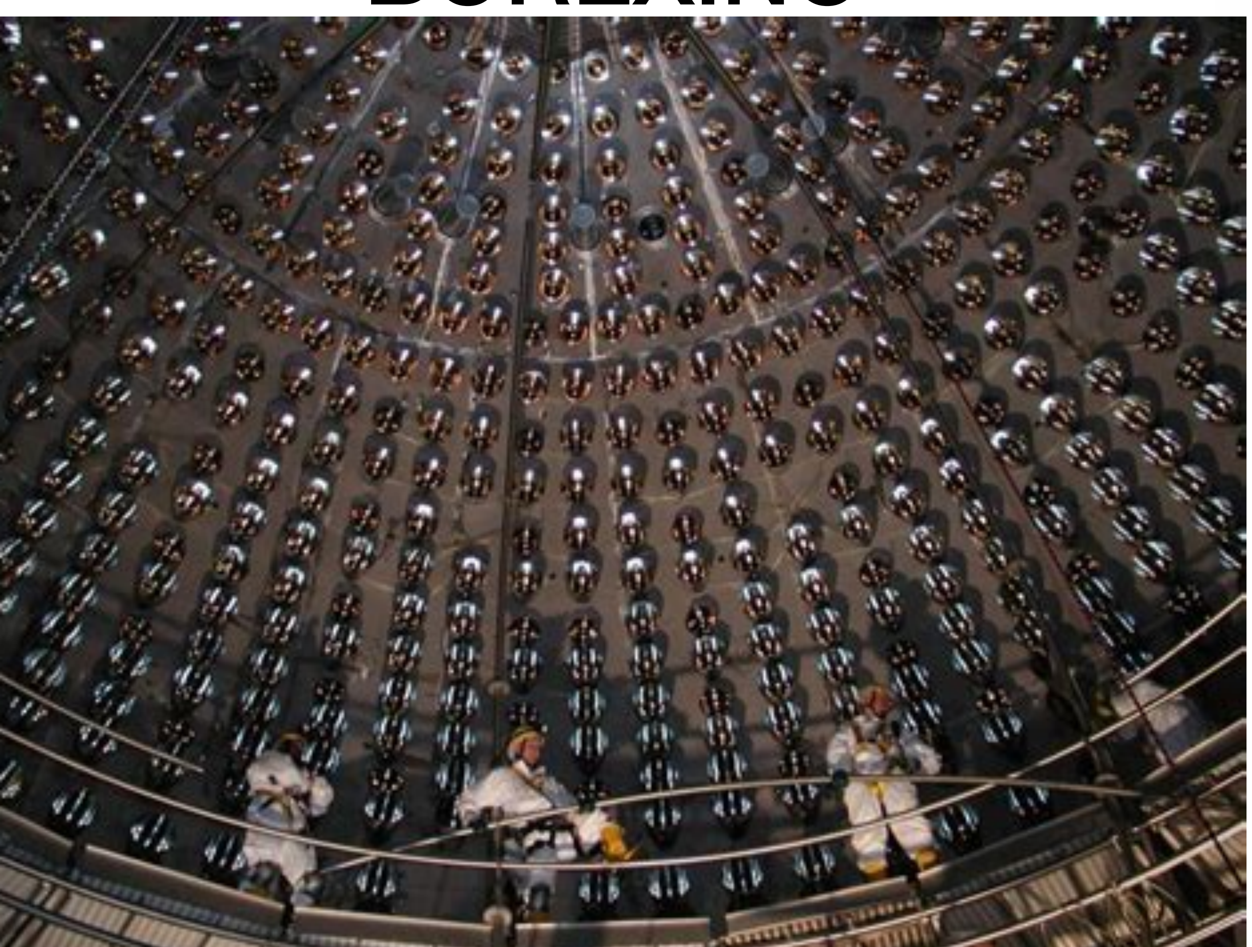


(a)



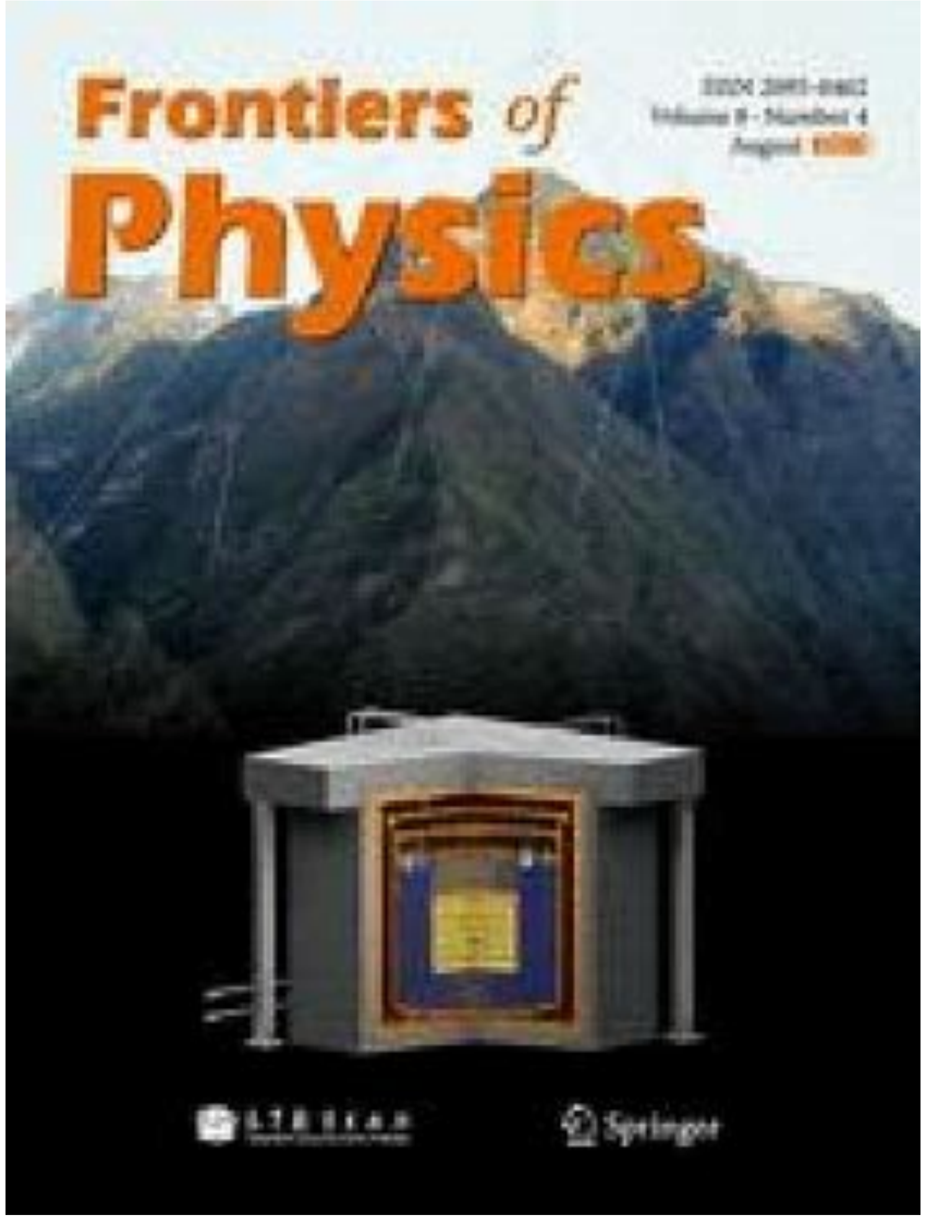

(b)

## BOREXINO



## DAMA-LIBRA

# CDEX, PANDA-X for Dark Matter searches


# The “power” of underground experiments

Large Statistics and Data taking

Low and Controllable Background

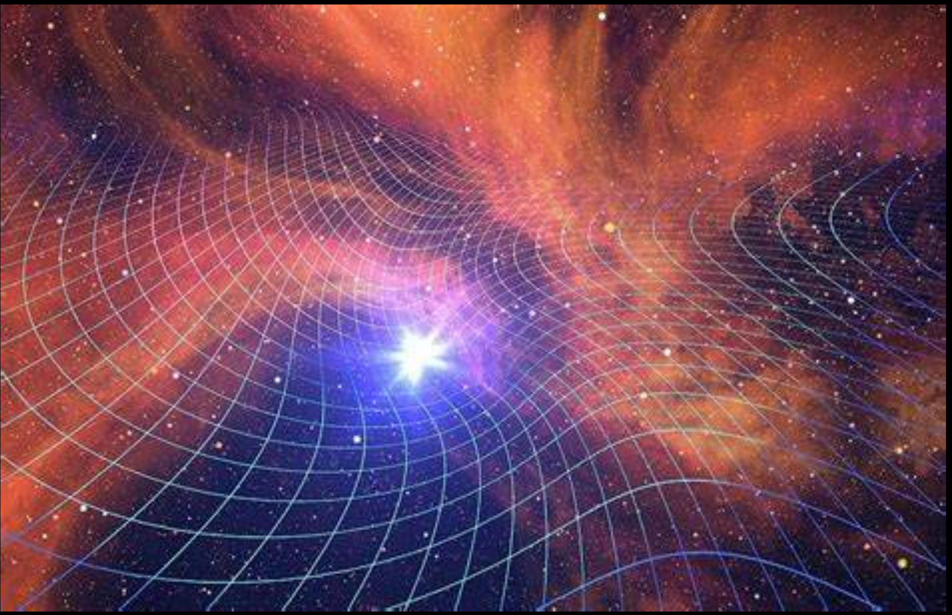
High precision atomic physics

A multitude of techniques:
Different nuclei and atoms,
Typical energy scales, temperature,
Crystals, liquid, double phases etc

# Pauli Spin Statistics Theorem

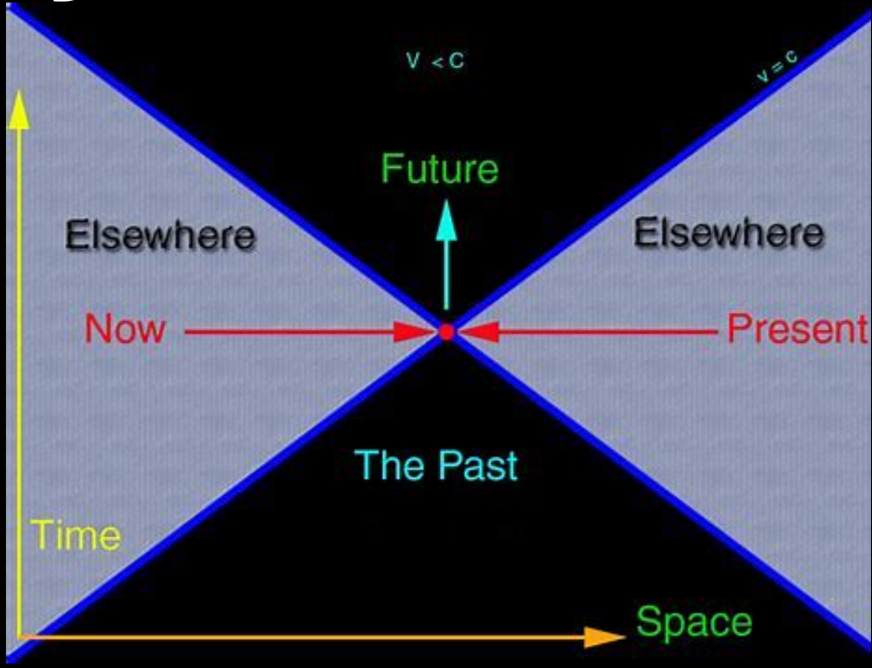
**Fermions:**
**spin 1/2**

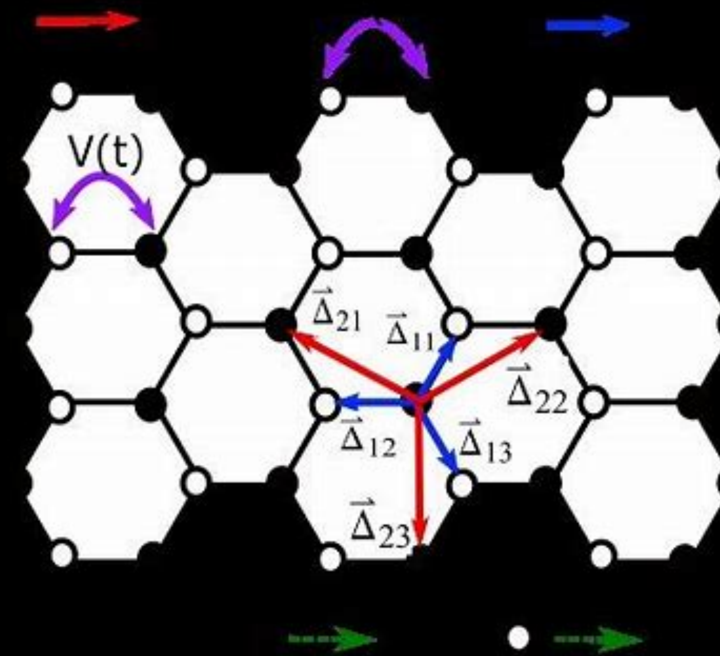
**Bosons:**
**integer spin 0,1**



The Theorem is connected to several deep issues:

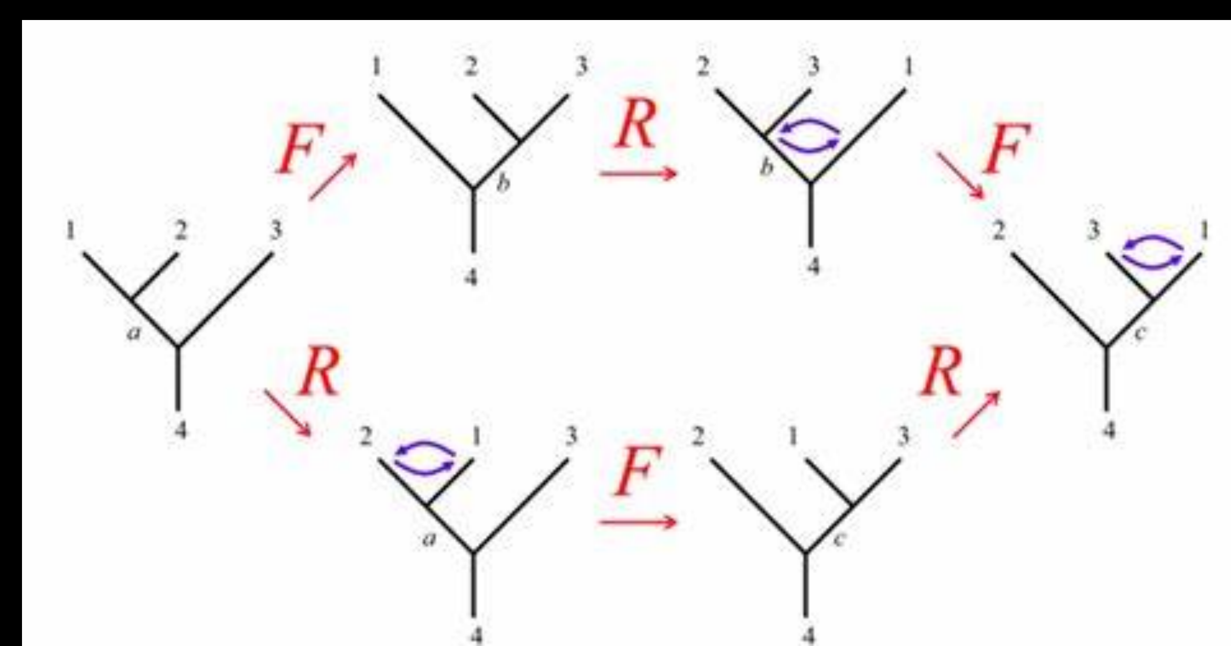
**space-time symmetries, locality, causality**






Examples of "Effective" Violations in Condensed Matter:

**Topological Materials and Superconductors,**
**Anyons (F. Wilczek),**
**Haldane-Wu statistics**



If I exchange double times two creation/annihilation operators the final quantum state must be unchanged. Three possibility:

$$|q| = 1$$

$$a_i a_j^\dagger - q a_i^\dagger a_j = \delta_{ij}$$

**Boson** → $q = 1$

**Fermions** → $q = -1$

Generalized: **Anyons** $q = e^{i\delta}$

**In principle delta can be a function of energy and momentum** *(AA et al 2017-2023)*

# Anyons (Haldane-Wu statistics)

*Haldane 91', Wu 94'*

*When we exchange two particles in presence of magnetic flux tubes, a relative phase related to the fluxes is obtained (from Aharanov-Bohm effect)*

Coordinates start to be effectively **non-commutative!**

$$\exp(i\theta_{12}) = \exp[-i(q_1\phi_2 + q_2\phi_1)] .$$

$$[R_i^\mu, R_j^\mu] = i l^2 \delta_{ij} q_i \epsilon^{\mu\nu} .$$

But it is not a violation
for fundamental particles.
**Can we introduce a PEP violating algebra in fundamental laws of Nature?**

# q-Algebra

Yu, Ignatiev, Kuzmin, 87’; Greenberg, Mohapatra, 87’

$$aa^\dagger - q_\pm a^\dagger a = 1$$

$$q_\pm = \pm 1 + \frac{1}{2}\delta^2$$

Observable:
transition rates

$$\Gamma_i = \delta_i^2 \tilde{\Gamma}_i .$$

Here: (i) $\delta_i^2$ is the mixing probability of non-fermion statistics allowing for the transition to the occupied state $i$; (ii) $\tilde{\Gamma}_i$ is the width of the corresponding PEP-allowed transition whenever the final state ($i$) would be empty.

Difficulties:
To build a self-consistent
quantum field theory with causality, locality,
unitarity, Lorentz/Poincaré symmetry
appears at the moment impossible.

# Where may Quantum Gravity and Spin Statistics meet?

Quantum Gravity

Space-Time structure

PEP

# A “class” of Quantum gravity models predicts tiny violations of PEP

## PEPV in Non-commutative space-time: Theta-Poincare, kappa-Poincare…

Addazi *et al* in a series of works 2017-2023,
CPC, PRL, PRD, MDPI, IJMPA, IJMPA
In collaboration with VIP and DAMA

## Non-linear Generalized Uncertainty Principle

Addazi, Bernabei, Belli, Marciano, Shababi
EPJC 2020

Energy dependence of PEP violations
Natural in the logic
of **effective theories**,
Beyond q-models

$$a_i a_j^\dagger - q(E) a_j^\dagger a_i = \delta_{ij}\,,$$

**Energy of the characteristic transition process**

$$q(E) = -1 + \beta^2(E),$$

$$\delta^2(E) = \beta^2(E)/2\,.$$

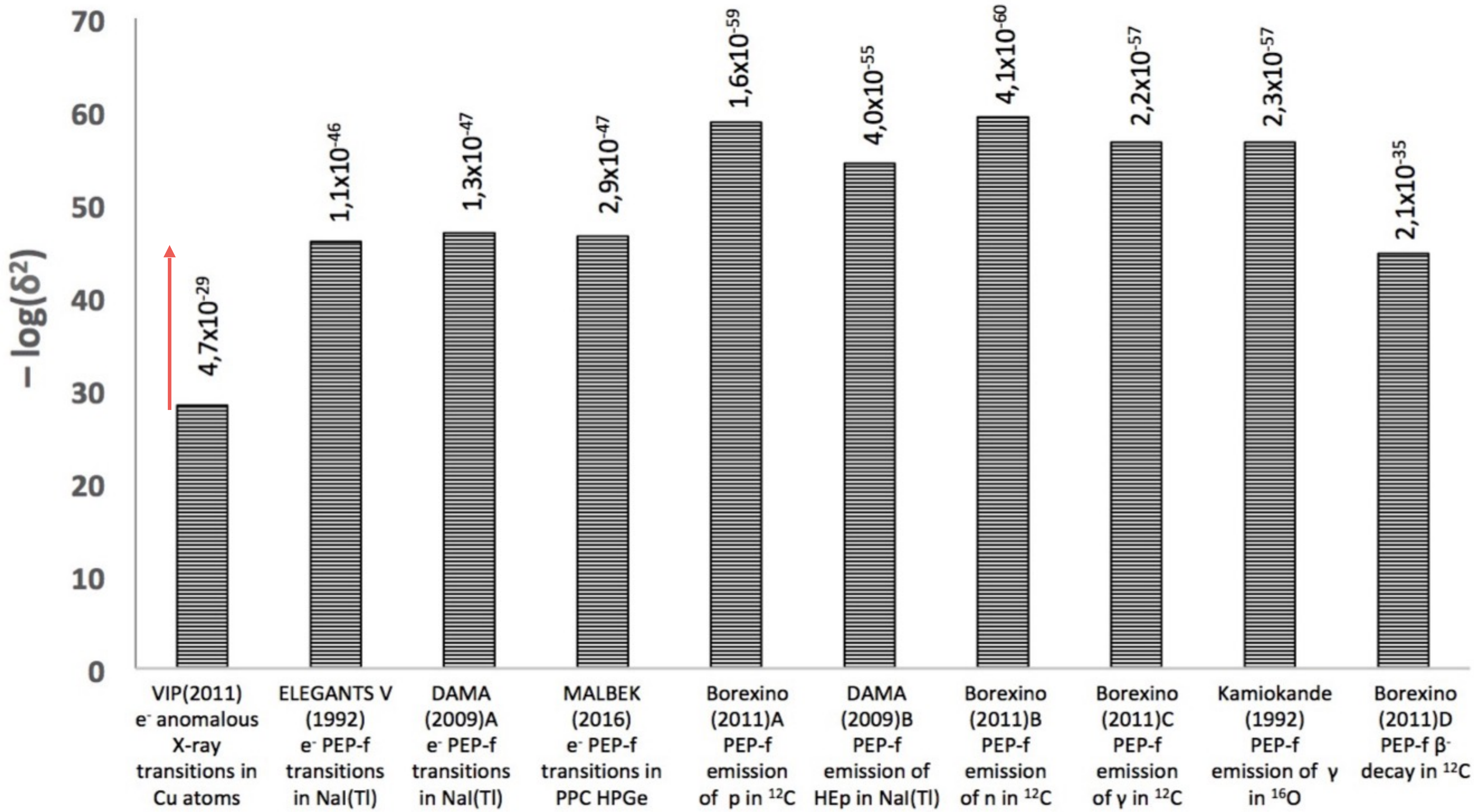
$$\delta^2(E) = c_k \frac{E^k}{\Lambda^k} + O(E^{k+1})$$

# All possible PEPV transition rates. Nuclear or atomic transitions.

$$\Gamma_i = \delta_i^2 \tilde{\Gamma}_i .$$

Here: (i) $\delta_i^2$ is the mixing probability of non-fermion statistics allowing for the transition to the occupied state $i$; (ii) $\tilde{\Gamma}_i$ is the width of the corresponding PEP-allowed transition whenever the final state ($i$) would be empty.

# COMPILATION



From these limits,
One can put constraints
on the new physics scale

# PEPV
# &
# Non-commutative space-time

# Non-commutative space-time is a “old” standing idea. Firstly quoted to *Heisenberg*

$$\theta^{\mu\nu} = -\theta^{\nu\mu} = \text{constant}.$$

$$\hat{x}^{\mu}(x) = x^{\mu}$$

$$(\hat{x}^{\mu} \star \hat{x}^{\nu} - \hat{x}^{\nu} \star \hat{x}^{\mu}) = [\hat{x}^{\mu}, \hat{x}^{\nu}]_{\star} = i\theta^{\mu\nu}.$$

Here we insert the effective non-commutative length

In other words we imagine that the non-commutativity of space-time coordinates emerges out at a critical length scale having in mind the quantum gravity Planck scale…In the macroscopic limit the NC vanishes as consequence of the *correspondence principle*

Such a new quantum uncertainty can delocalize the General Relativity singularities beyond the Classical Penrose theorem

The we can think to formulate a Quantum field theory in the NC background

But there is a problem:
NC is not compatible with local Lorentz invariance…
If we want a controllable new QFT we need new symmetries enlarging the Poincaré symmetry and compatible with NC

# Theta-Poincarè :in the Groenwald-Moyal arena

$$f \star g = f e^{\frac{i}{2}\overleftarrow{\partial}_\mu \theta^{\mu\nu} \overrightarrow{\partial}_\nu} g,$$

$$\theta^{\mu\nu} = -\theta^{\nu\mu} = \text{constant}.$$

$$\hat{x}^\mu(x) = x^\mu$$

$$(\hat{x}^\mu \star \hat{x}^\nu - \hat{x}^\nu \star \hat{x}^\mu) = [\hat{x}^\mu, \hat{x}^\nu]_\star = i\theta^{\mu\nu}.$$

$$\Delta_\theta(g) = e^{\frac{i}{2}P_\mu \otimes \theta^{\mu\nu} P_\nu}(g \otimes g) e^{-\frac{i}{2}P_\mu \otimes \theta^{\mu\nu} P_\nu} = \hat{F}_\theta^{-1}(g \otimes g)\hat{F}_\theta \ ,$$

# Groenwald-Mojal product deformation

$$\mathbf{GM}:\ \mathfrak{so}(3,1) \rightarrow \text{noncommutative dual } \text{``deformed''}\ \mathfrak{so}(3,1)$$

$$\mathbf{GM}:\ (\text{creation/annihilation ops.}) \rightarrow (\text{GM}-\text{phase})(\text{creation/annihilation ops.})\,,$$

$$\mathbf{GM}:\ (\text{fields}) \rightarrow (\text{GM}-\text{phase})(\text{fields})\,,$$

$$\mathbf{GM}:\ \text{N}-\text{field interactions} \rightarrow (\text{GM}-\text{phase})^{\text{N}}(\text{creation/annihilation ops.})^{\text{N}}\,.$$

# Quantum fields as Groenwald-Moyal representations

$$\varphi = \int d\mu(p)\, \tilde{\varphi}(p)\, \mathbf{e}_p \qquad \varphi = \int \frac{d^d p}{2p_0} \left( a(p)\, \mathbf{e}_p + a^\dagger(p) \mathbf{e}_{-p} \right) \ ,$$

$$\varphi \otimes \chi = \int d\mu(p)\, d\mu(q)\, \tilde{\varphi}(p) \tilde{\chi}(q)\, \mathbf{e}_p \otimes \mathbf{e}_q$$

$$\rho(\Lambda)\varphi \ = \ \int d\mu(p)\, \tilde{\varphi}(p)\, \mathbf{e}_{\Lambda p} = \int d\mu(p)\, \tilde{\varphi}(\Lambda^{-1} p)\, \mathbf{e}_p \ ,$$

$$\rho\left(e^{iP\cdot a}\right)\varphi \ = \ \int d\mu(p)\, e^{ip\cdot a} \tilde{\varphi}(p)\, \mathbf{e}_p \ .$$

$$\Delta_\theta(\Lambda)\left(\tilde{\varphi} \otimes \tilde{\chi}\right)(p,q) = \tilde{F}_\theta^{-1}\left(\Lambda^{-1} p, \Lambda^{-1} q\right) \tilde{F}_\theta\,(p,q)\, \tilde{\varphi}(\Lambda^{-1} p) \tilde{\chi}(\Lambda^{-1} q) \ .$$

$$F_\theta = e^{-\frac{i}{2}(-i\partial_\mu)\theta^{\mu\nu} \otimes (-i\partial_\nu)}$$

$$a(p) a^\dagger(q) = \tilde{\eta}'(p,q) \tilde{F}_\theta^{-2}\left(-q,p\right) a^\dagger(q) a(p) + 2p_0 \delta^d(p-q) \ .$$

# Overlap probability different from zero: PEPV

$$\begin{aligned} |\alpha, \alpha\rangle &= \langle a^\dagger, \alpha\rangle\langle a^\dagger, \alpha\rangle|0\rangle \\ &= \int \frac{d^d p_1}{2p_{10}}\frac{d^d p_2}{2p_{20}} e^{-\frac{i}{2}p_{1\mu}\theta^{\mu\nu}p_{2\nu}}\alpha(p_1)\alpha(p_2)c^\dagger(p_1)c^\dagger(p_2)|0\rangle \ . \end{aligned}$$

$$|\beta, \gamma\rangle = \langle a^\dagger, \beta\rangle\langle a^\dagger, \gamma\rangle|0\rangle, \quad \beta \neq \gamma.$$

We have

$$\langle \beta, \gamma|\alpha, \alpha\rangle = \int \frac{d^d p_1}{2p_{10}}\frac{d^d p_2}{2p_{20}}(\bar{\beta}(p_1)\alpha(p_1))(\bar{\gamma}(p_2)\alpha(p_2))[1 - e^{-ip_{1\mu}\theta^{\mu\nu}p_{2\nu}}]\frac{1}{N(\alpha, \alpha)} \ .$$

# CPT

$$\Delta_\theta(\mathcal{C}) = \Delta_0(\mathcal{C}) = \mathcal{C} \otimes \mathcal{C}\,,$$

$$\Delta_0(\mathcal{P}) = \mathcal{P} \otimes \mathcal{P}\,,$$

$$\Delta_0(\mathcal{T}) = \mathcal{T} \otimes \mathcal{T}\,.$$

$$\mathcal{CPT} : \phi_\theta = (\mathcal{CPT}\ \phi_0\ (\mathcal{CPT})^{-1})\, e^{\frac{1}{2}\overleftarrow{\partial}\wedge P}\,,$$

$$\Delta_\theta(\mathcal{CPT}) = \mathcal{F}_\theta^{-1}\Delta_0(\mathcal{CPT})\mathcal{F}_\theta\,.$$

# CPT and S-matrix

$$\mathcal{S}_\theta = T_\star \exp_\star\Big[ -\imath \int d^4x \mathcal{H}_{I,\theta}(x) \Big] \,,$$

$$\mathcal{H}^n \equiv \mathcal{H}_{1,\theta} \star \mathcal{H}_{2,\theta} \star \ldots \star \mathcal{H}_{n,\theta} = \mathcal{H}_{1,0} \mathcal{H}_{2,0} \ldots \mathcal{H}_{n,0} \, e^{\frac{\imath}{2} \overleftarrow{\partial} \wedge P} \equiv \mathcal{H}^{n\dagger} \,,$$

Hermitian at tree-level
(possible attacks from UV/IR mixings)

$$(\mathcal{CPT}) \mathcal{H}^n (\mathcal{CPT})^{-1} = \Big( \mathrm{MOYAL} \Big) \mathcal{H}^n \,.$$

Non-trivial transformation under CPT

# Microcausality: Bogoliubov-Shirkov condition

$$[\mathcal{H}_\star(x), \mathcal{H}_\star(y)] \neq 0, \quad (x-y)^2 < 0\,.$$

$$S[g] = 1 + \int dx_1 g(x_1) \star S_1(x_1) + \int dx_1 dx_2\, g(x_1) \star g(x_2) \star S_2(x_1, x_2) + \ldots.$$

$$= 1 + \sum_{n\geq 1} \frac{1}{n!} \int S_n(x_1, \ldots, x_n) \star g(x_1) \star \ldots \star g(x_n) dx_1 \ldots dx_n\,.$$

Then, the BS causality condition reads

$$\frac{\delta}{\delta g(x)} \Big( \frac{\delta S(g)}{\delta g(y)} \star S^\dagger(g) \Big) = 0, \qquad x < y,$$

**You can show that BS is violated!** proof in

*Addazi, Marciano IJMPA*

# UV/IR mixings

$$\Lambda_{\rm eff} = \Lambda_0 + C/(\theta^2 p^2)$$

**Appearing in one-loop radiative computation *Alvarez-Gaume et al***

Not fully understood and
In principle it may be cancelled by possible Cerenkov emission
Comment in Addazi-Marciano IJMPA review

# Mention: the case of kappa-Poincare

Ambiguity in quantization procedure,
M. Arzano, A. Marciano;
K, Glikman et al.
Ambiguity Vs PEPV

# Generalized Uncertainty Principle (GUP)

First appearance in the first works of *Amati, Ciafaloni and Veneziano 87'* on gravitational scatterings in the "Arena" of string theory. From Perturbative corrections the Heisenberg uncertainty principle gets an effective correction as follow:

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

Reconsider as basic new principle by

*Kempf-Mangano-Mann 95'*

Further non-perturbative quantum gravity effects motivate possible analysis of non-linear extensions!

# Example: Non-linear GUPs with a UV pole

$$[X_i, P_j] = \frac{i\hbar\delta_{ij}}{(1-(\beta P^2)^{m'})^k} \; , \quad [P_i, P_j] = 0 \; ,$$

$$[X_i, X_j] = \frac{2i\hbar\beta}{(1-(\beta P^2)^{m'})^{2k}}(P_i X_j - P_j X_i),$$

$$[L_i, L_j] = \frac{i\hbar}{(1-(\beta P^2)^{m'})^k}\left(X_i P_j - X_j P_i\right)$$
$$= \frac{i\hbar}{(1-(\beta P^2)^{m'})^k}\epsilon_{ijk}L_k \; ,$$

$$L_i = \frac{1}{(1-(\beta P^2)^{m'})^k}\epsilon_{ijk}r_j p_k \, .$$

$$[X_i, X_j] = \frac{-2i\hbar\beta}{(1-(\beta P^2)^{m'})^k}L_{ij} \, .$$

Addazi-Shababi AS model

# Around the UV pole super-uncertainty

$$\lim_{P \to \Lambda} \Delta X \Delta P \to \infty$$

$$\lim_{P \to \Lambda} \Delta X_i \Delta X_j \to \infty$$

$$\Delta L_i \Delta L_j \to \infty$$

# A 100% localization of an electron on a precise level is impossible. Example of a two level system

Quantum State of an almost first level electron:

$$|J', M'\rangle \simeq (1 - k(\beta P^2)^{m'})|j_1, m_1\rangle + k(\beta P^2)^{m'}|j_2, m_2\rangle,$$

Quantum State of an almost second level electron:

$$|J, M\rangle \simeq \left[k(\beta \tilde{P}^2)^{m'}|j_1, m_1\rangle + (1 - k(\beta \tilde{P}^2)^{m'})|j_2, m_2\rangle\right].$$

Non-zero overlap: PEP violating jumps

$$\begin{aligned}\langle J, M|J', M'\rangle|_{J,M \neq J',M'} \\ = [k(\beta \tilde{P}^2)^{m'}(1 - k(\beta P^2)^{m'}) \\ +k(\beta P^2)^{m'}(1 - n(\beta \tilde{P}^2)^{m'})].\end{aligned}$$

$$\langle J, M|J', M'\rangle \simeq 2k(\beta P)^m$$

# Results from DAMA/LIBRA

From exclusions of Na a I PEPV transitions

$$\Gamma_{PEPV} = n(\Lambda^{-1}P)^m \Gamma_{SM} ,$$

where $n = 4k^2, m = 4m'$.

$$n(\Lambda^{-1}P)^m < 4 \times 10^{-55} \text{ (90\% C.L.)}.$$

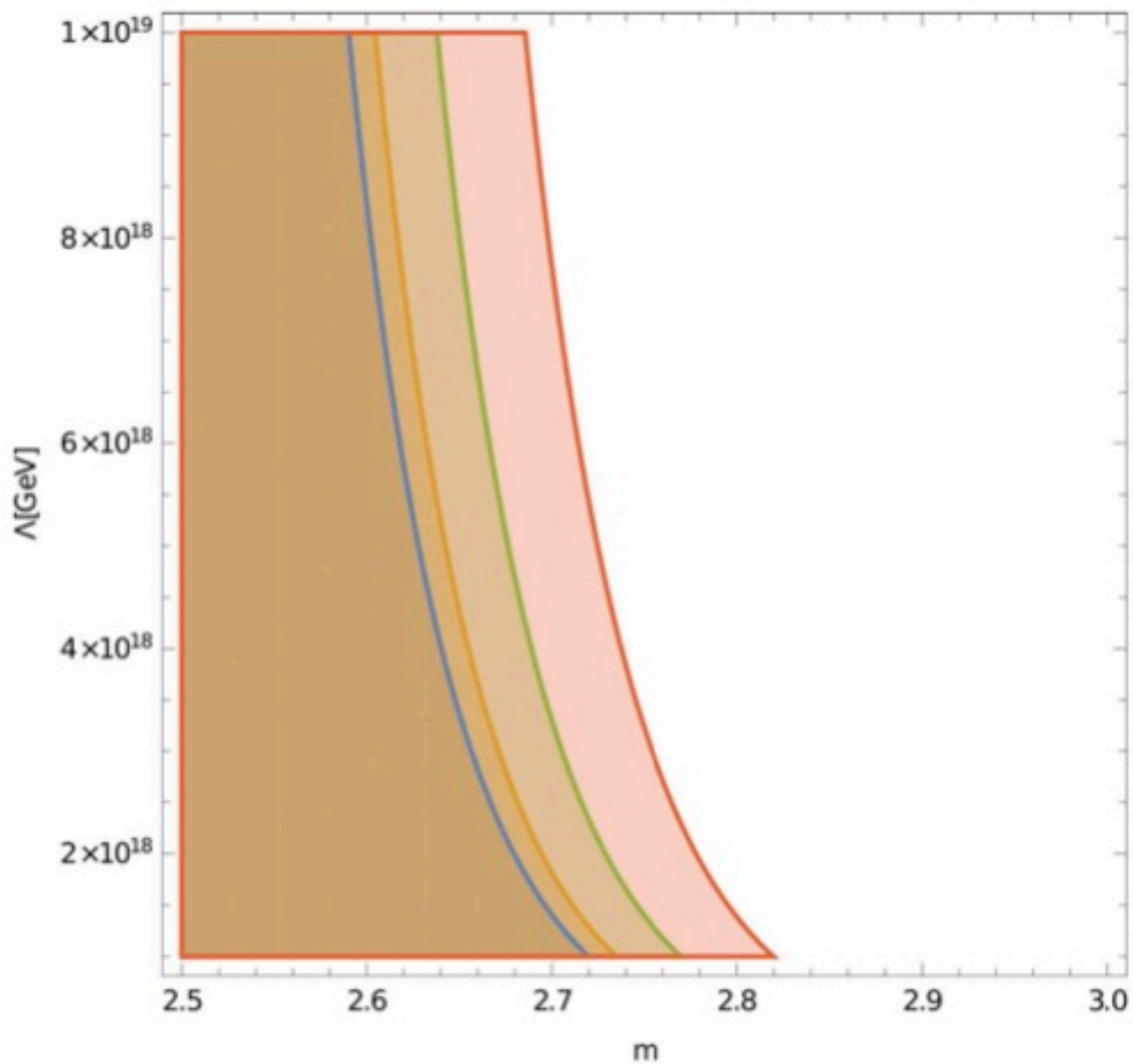



**Fig. 1** Excluded parameter space $(\Lambda, m)$ from DAMA experiment: the four contour limits correspond to fix $n = 1, 2, 10, 100$ respectively

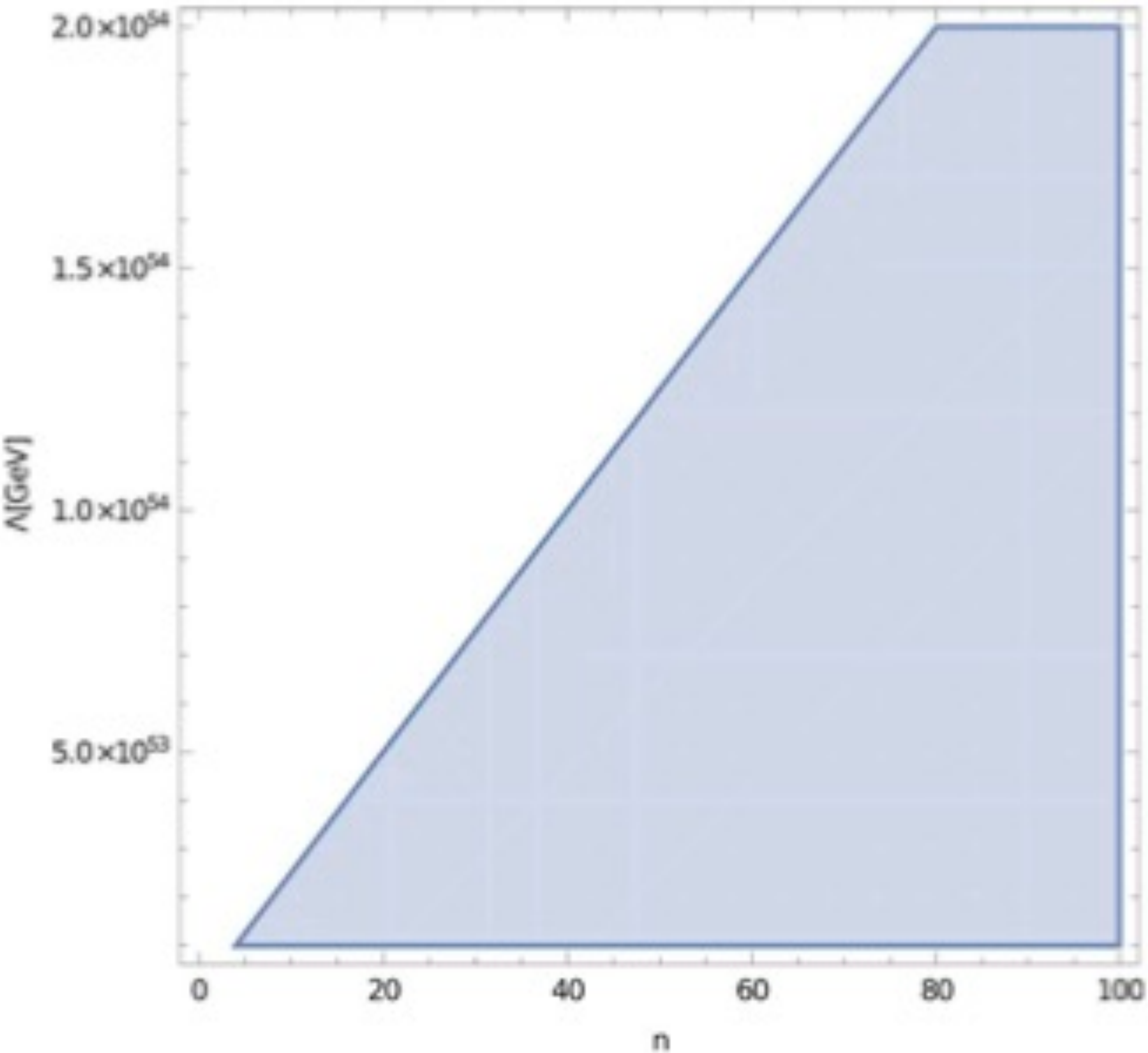
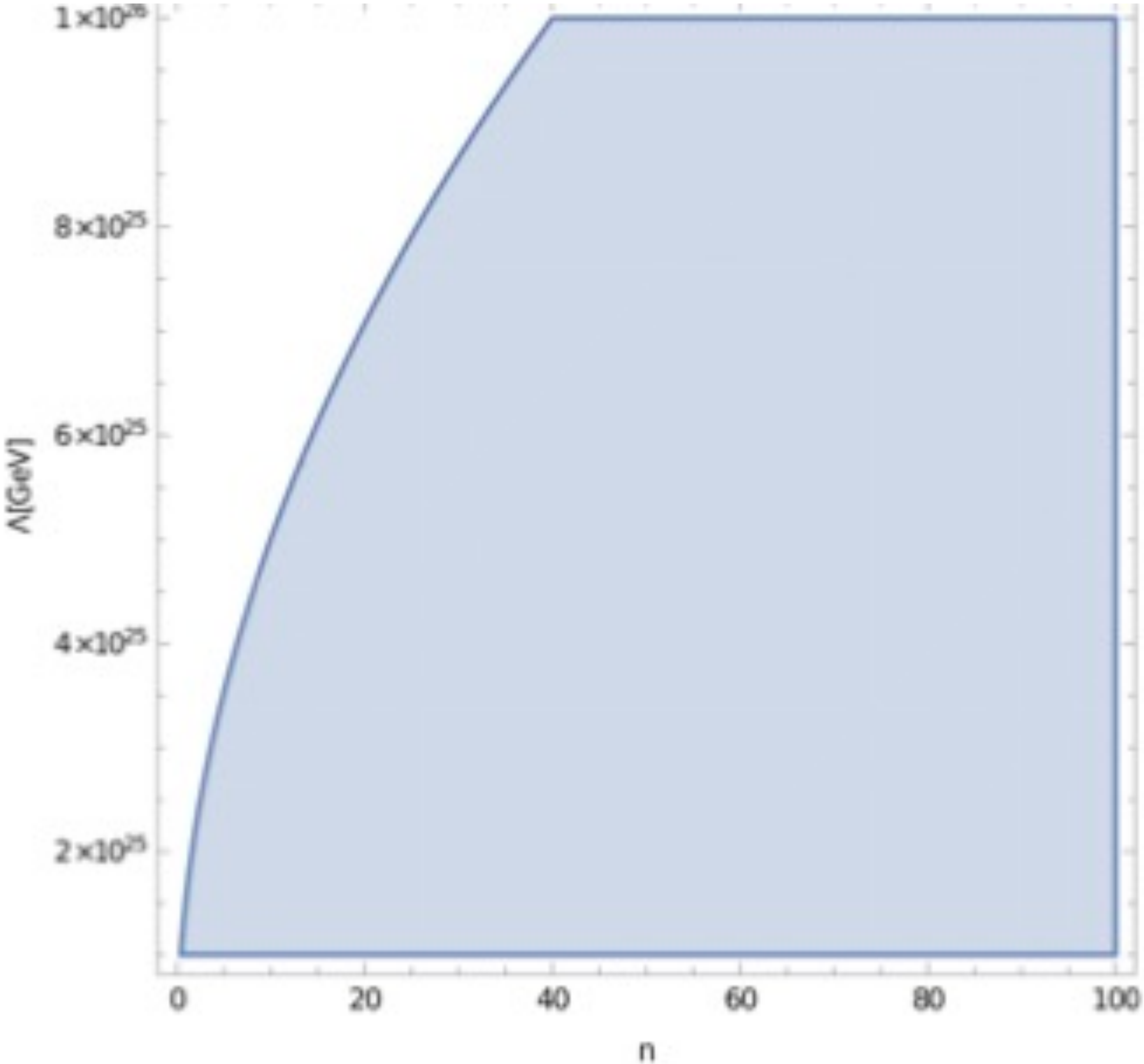



**Fig. 2** Excluded parameter space $(\Lambda, n)$ from DAMA experiment, fixing $m = 1$



1×10^26
8×10^25
6×10^25
4×10^25
2×10^25
Λ[GeV]
0
20
40
60
80
100
n

Let’s return to the model independent analysis well motivated by NC

$$a_i a_j^\dagger - q(E) a_j^\dagger a_i = \delta_{ij} \,,$$

**Energy of the characteristic transition process**

$$q(E) = -1 + \beta^2(E),$$

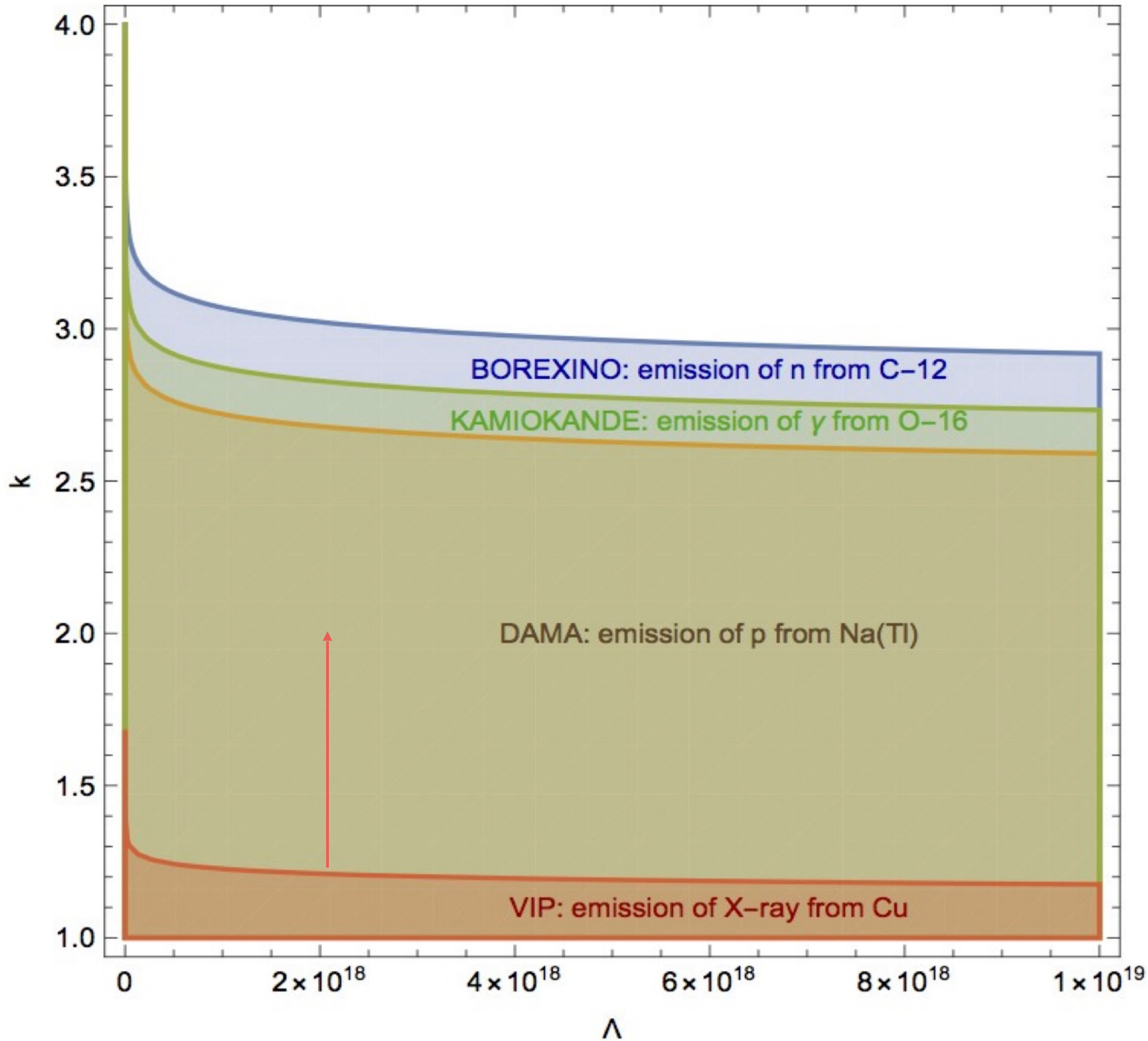
$$\delta^2(E) = \beta^2(E)/2 \,.$$

$$\delta^2(E) = c_k \frac{E^k}{\Lambda^k} + O(E^{k+1})$$

# Results

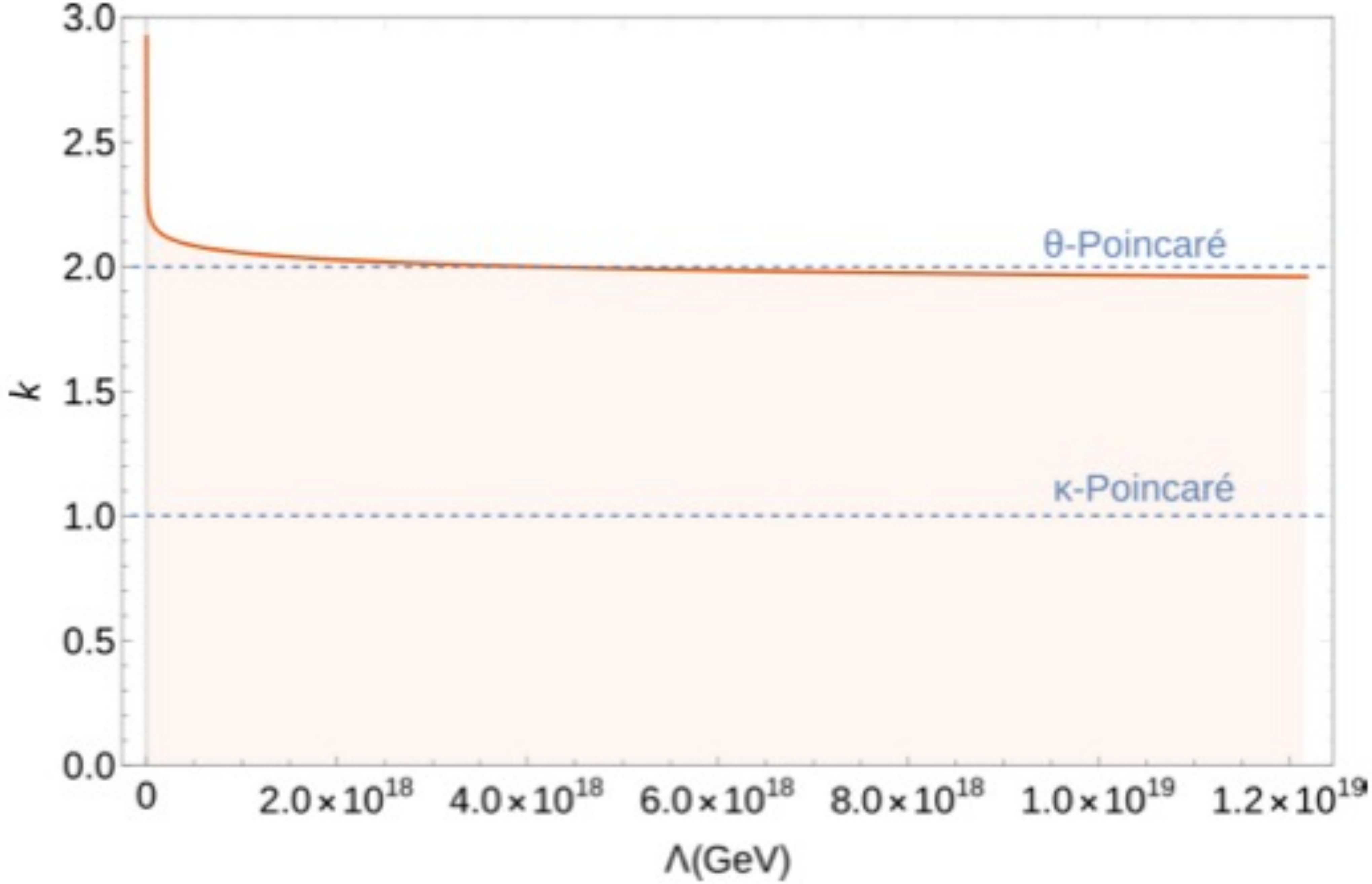
A. Addazi, P. Belli, R. Bernabei, A. Marciano

2017-2019



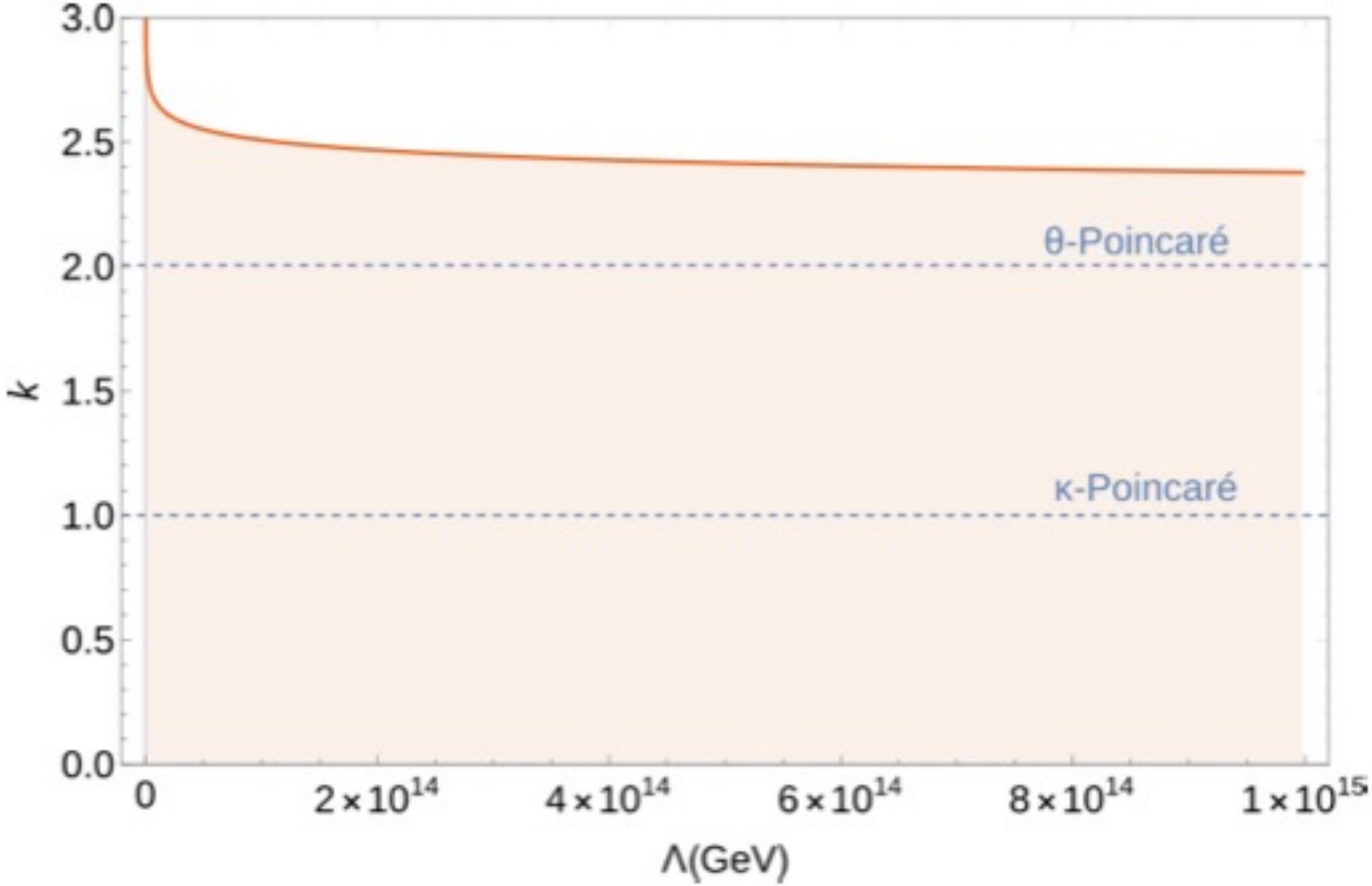
BOREXINO: emission of n from C−12
KAMIOKANDE: emission of γ from O−16
DAMA: emission of p from Na(Tl)
VIP: emission of X−ray from Cu
k
Λ
4.0
3.5
3.0
2.5
2.0
1.5
1.0
0
2×10^18
4×10^18
6×10^18
8×10^18
1×10^19

# VIP-II



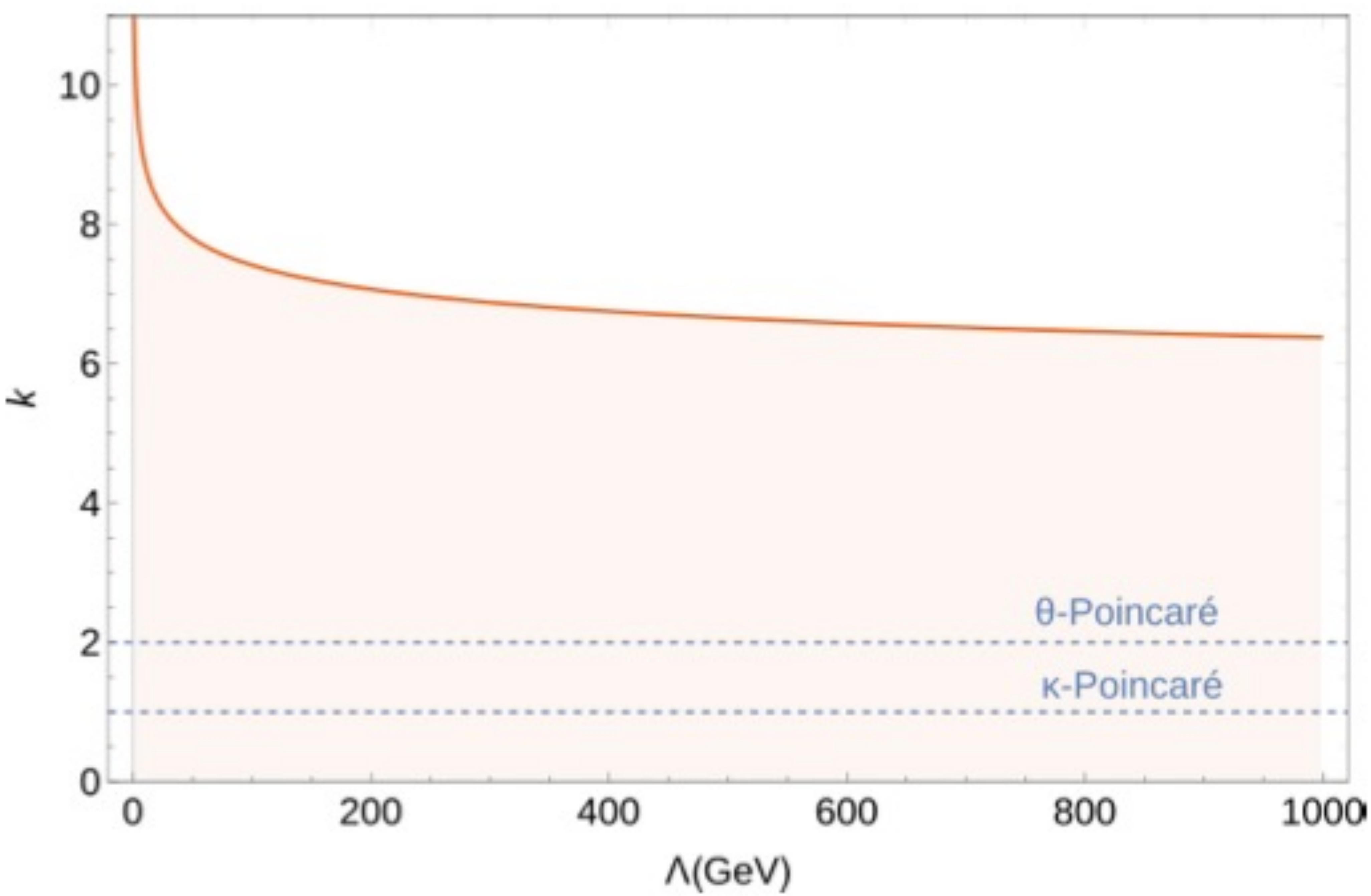
3.0
2.5
2.0
1.5
1.0
0.5
0.0
k
θ-Poincaré
κ-Poincaré
0
2.0×10^18
4.0×10^18
6.0×10^18
8.0×10^18
1.0×10^19
1.2×10^19
Λ(GeV)

# VIP-II



3.0
2.5
2.0
1.5
1.0
0.5
0.0
k
θ-Poincaré
κ-Poincaré
0
2×10^14
4×10^14
6×10^14
8×10^14
1×10^15
Λ(GeV)

# VIP-II



Thus, surprise, many quantum gravity models appear to be excluded yet!

# Importance of multi-channels: nuclear and atomic physics:

# Vexata quaestio:
# Democratic or non-democratic PEP violations???

- **Weak and Strong Equivalence Principle???**
- **B-form couplings with strings???**

**IT DESERVES A TEST IN ALL POSSIBLE CHANNELS!**

# < B > X X

Seidberg, Witten

“In principle its condensation may be highly non-trivial as a consequence of NS-NS or R-R string fluxes or exotic string instantons. B(x) with x space coordinate”

Addazi to Bernabei, private conversation 2017 Chengdu

**In this prospective we follow with great interests new experiments based on atomic transitions**

# VIP-2 improvements

$$\phi_{\rm PEPV} = \delta^2 \simeq \frac{D}{2}\frac{E_N}{\Lambda}\frac{\Delta E}{\Lambda}, \qquad D = p_1^0 \bar{\theta}_{0j} p_2^j + p_2^0 \bar{\theta}_{0j} p_1^j,$$

$$E_N \simeq m_N \simeq$$

$$\phi_{\rm PEPV} = \delta^2 \simeq \frac{C}{2}\frac{E_1}{\Lambda}\frac{E_2}{\Lambda},$$

$$\Delta E = E_2 - E_1$$

where $E_{1,2}$ are the energy levels occupied by the initial and the final electrons and $C = p_1^i \bar{\theta}_{ij} p_2^j$. The former

# Theta-Poincare from VIP

- $\Lambda > 6.9 \cdot 10^{-2}$ Planck scales for $\theta_{0i} = 0$
- $\Lambda > 2.6 \cdot 10^{2}$ Planck scales for $\theta_{0i} \neq 0$

Physical Review Letters result 2022

# New Plots and analysis VIP

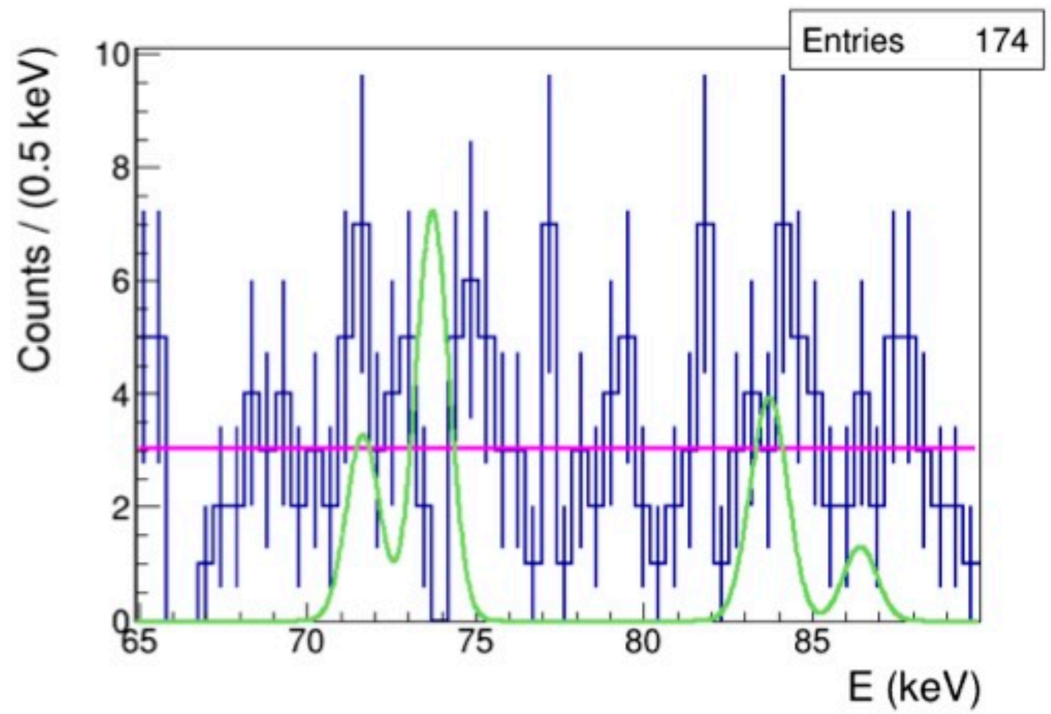



FIG. 1. The measured X-ray spectrum, in the region of the $K_\alpha$ and $K_\beta$ standard and PEP-violating transitions in Pb, is shown in blue; the magenta line represents the fit of the background distribution. The green line corresponds to the shape of the expected signal distribution (with arbitrary normalization) for $\theta_{0i} \neq 0$.

TABLE I. Calculated PEP-violating $K_\alpha$ and $K_\beta$ atomic transition energies in Pb (column labeled forb.). As a reference, the allowed transition energies are also quoted (allow.). Energies are in keV.

| Transitions in Pb | allow. (keV) | forb. (keV) |
|---|---|---|
| 1s - $2p_{3/2}$ $K_{\alpha 1}$ | 74.961 | 73.713 |
| 1s - $2p_{1/2}$ $K_{\alpha 2}$ | 72.798 | 71.652 |
| 1s - $3p_{3/2}$ $K_{\beta 1}$ | 84.939 | 83.856 |
| 1s - $4p_{1/2(3/2)}$ $K_{\beta 2}$ | 87.320 | 86.418 |
| 1s - $3p_{1/2}$ $K_{\beta 3}$ | 84.450 | 83.385 |

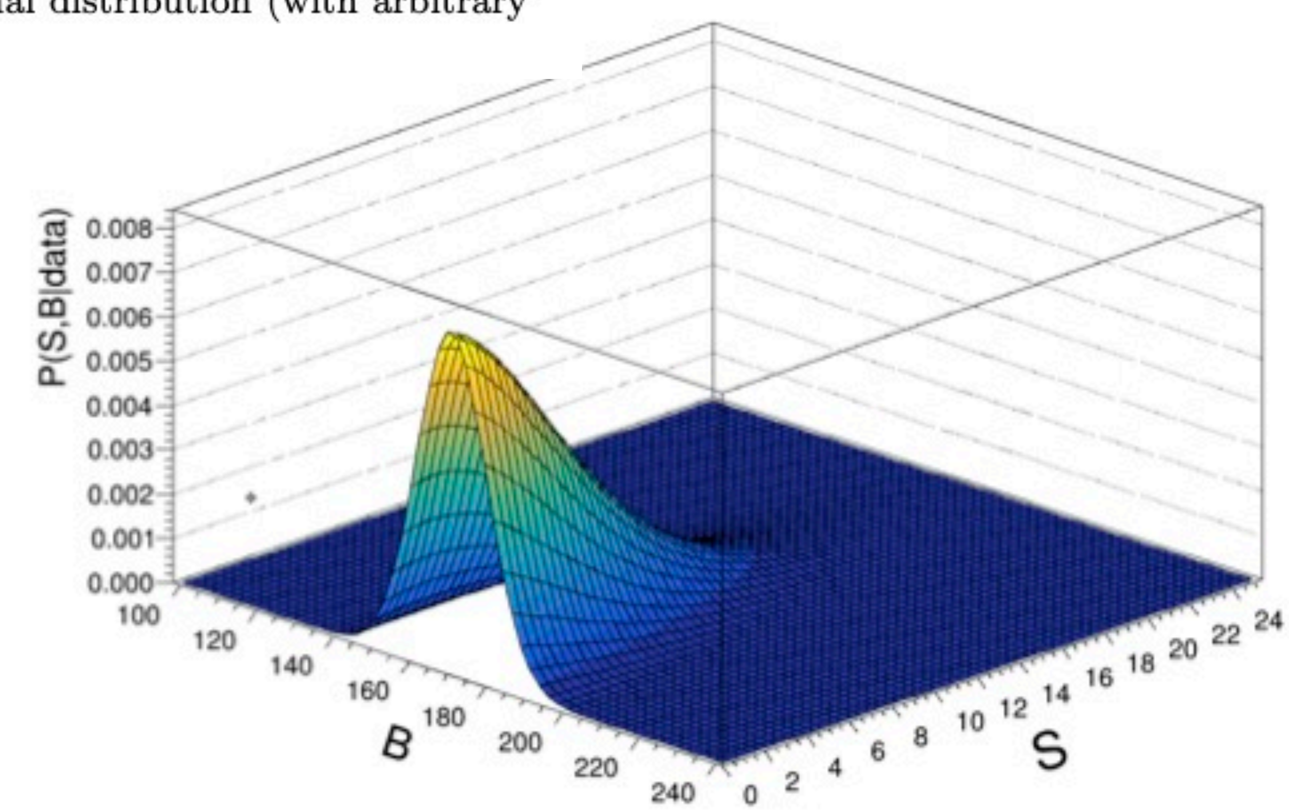



FIG. 2. Joint *pdf* $P(S, B|data)$ of the expected number of total signal and background counts corresponding to $\theta_{0i} \neq 0$.

Several open
Questions and Prospectives
Never explored before!

# Is it gravity emergent?

If the graviton is a spin 2 composite state or
a pseudo-particle emerging
From a fundamental renormalizable
quantum gauge field theory
like SU(N), SO(N)…

Obstacle: spin 2 massless particle
cannot be such a bound state if
Lorentz invariance is preserve.
Weinberg’s theorem

However, Lorentz invariance can be spontaneously or dynamically broken,

**Bjorken 63'**

No any no go theorem on the fact that tensor condensates
Cannot dynamically emerge from confinement in a generic gauge theory
We can test confinement in QCD which is theoretically still purely understood.

**Philips '66, Ohanian '69: Kostelecky, Berezhiani and Kanchelli: Carol, Tam, Wehus; Chkareuli, Jejelava, Tatishvili, Tomboulis**

In this case,
The confinement scale
Is assumed at or below the Planck scale, as UV completion

In general a tiny mass term for the graviton is generated out

The Equivalence Principle is violated from
Non-university of couplings

**Philips ’66, Ohanian ’69: Kostelecky, Berezhiani and Kanchelli: Carol, Tam, Wehus; Chkareuli, Jejelava, Tatishvili, Tomboulis**

Spin Statistics?
It is preserved in UV
But It can be touched after the
spontaneous Lorentz symmetry breaking

$$\langle \mathcal{T}_{\mu\nu}(x) \rangle = \int \mathcal{D}\Phi \; \mathcal{T}_{\mu\nu} \; e^{iS\{\Phi\}} \, .$$

$$\Phi = \phi, \psi, A_\mu$$

$$\mathcal{T}_{\mu\nu} = Tr[K_1 \mathcal{O}^{(1)}_{\mu\nu} + K_2 \mathcal{O}^{(2)}_{\mu\nu} + K_3 \mathcal{O}^{(3)}_{\mu\nu}] \, ,$$

$$\mathcal{O}^{(1)}_{\mu\nu} = \phi^\dagger \partial_\mu \partial_\nu \phi, \; \mathcal{O}^{(2)}_{\mu\nu} = \bar{\psi}(\partial_\mu \gamma_\nu + \partial_\nu \gamma_\mu \psi), \; \mathcal{O}^{(3)}_{\mu\nu} = B_{\mu\rho} B_{\nu\sigma} \eta^{\rho\sigma}$$

$$\langle \mathcal{T}_{\mu\nu} \rangle = G_{\mu\nu} \, .$$

$$\langle \mathcal{T}_{\mu\nu} \rangle = G_{\mu\nu} \, .$$

$$\phi \partial_\mu \partial_\nu G^{\mu\nu} \phi, \;\; \phi \partial_\mu \phi \partial_\nu \phi G^{\mu\nu}, \; \phi \partial_\mu \partial_\nu \phi G^{\mu\lambda} \eta^\nu_\lambda \, .$$

$$\Delta^{-1} = k^2 - m^2 + k_\mu k_\nu \Delta_{\mu\nu} + X_{\mu\nu\rho\sigma} k^\mu k^\nu k^\rho k^\sigma / \Lambda^2 + O(k^n) \, ,$$

$$\Delta_{\mu\nu} = a_1 G_{\mu\nu} + a_2 G^\lambda_\mu G_{\lambda\nu} + \ldots \, ,$$

$$a_{\mathbf{p}}a^\dagger_{\mathbf{q}} - f(p,q)a^\dagger_{\mathbf{q}}a_{\mathbf{p}} = (2\pi)^2\delta^{(3)}(\mathbf{p}-\mathbf{q})$$

$$f(p,q) = 1 + \frac{1}{Q^2}\left(\Delta_{\mu\nu}Q^\mu Q^\nu - \frac{1}{\Lambda^2}X_{\mu\nu\rho\sigma}Q^\mu Q^\nu Q^\rho Q^\sigma\right)\Big|_{q^0=p^0},$$

$$Q_\mu(p,q) = p_\mu + q_\mu$$

In non-relativistic limit and preserving Rotational invariance subrgoup SO(3):

$$\langle \mathcal{T}_{00}\rangle = \eta_{00}\,, \quad \langle \mathcal{T}_{ij}\rangle = \langle \mathcal{T}_{0i}\rangle = 0\,.$$

$$f(p,q) = 1 + \Delta_{00} - 4\frac{1}{\Lambda^2}X_{0000}E_p^2\,,$$

# QED, PEPV

$$\frac{1}{\Lambda} G_{\mu\nu} \gamma^{\mu} p^{\nu} ,$$

$$\langle \alpha\alpha | \beta\gamma \rangle \simeq N \int d\Sigma \bar{\alpha}\bar{\alpha}\beta\alpha \, G_{00}^{2} \, \Delta E_{\alpha\beta} \Delta E_{\alpha\gamma} / \Lambda^{2} ,$$

$$\Delta E_{\alpha\beta} = E_{\alpha} - E_{\beta}$$

# Conclusions:

Probes of Pauli Exclusion Principle Violations can provide a strong indirect test of quantum gravity models with physics observables much below the Planck physics domain

Both Non-commutative and Non-linear GUP models can be constrained up to the Planck Scale regime.
Not all of them but a large sub-group.

In particular the notorious Theta-Poincaré models seems already excluded in a "democratic scenario"

Consequences of energy dependent PEPV discovery for quantum gravity: a revolution of our picture of space-time, causality, locality, vacuum structure, …