The “Power” of underground experiments: Quantum Gravity Phenomenology “under the rocks”

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ECT* 2022 Trento

Based on a series of recent works

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

A. Addazi, A. Marciano, arXiv:1811.06425

A. Addazi, R. Bernabei, MPLA 2019

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

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

Few considerations as a “Warm up”

“Santo Graal” of Theoretical Physics

Quantum Gravity!

UV completion of General Relativity

Top-Down

String theory, M-theory

Loop Quantum Gravity

Asymptotic Darkness/Classicalization

Asymptotic Safety

Causal Sets

Superrenormalizable non-local theories

Dynamical Triangulation

Gauge reformulations of gravity

...

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

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

Bottom-up: quantum gravity 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)

Large Extra Dimensions

Modified Dispersion Relations (MDRs)

Lorentz Violations, CPT violations

Large Extra Dimensions

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.

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

G. Amelino-Camelia and J. Ellis talks
about gamma ray windows

A. Addazi, N. Yunes, A. Marciano PRL

Quantum gravity phenomenology at the dawn of the multi-messenger era — A review

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V. Pasic[cv], C. Pérez de los Heros[cw], C. Pfeifer[cx], M. Pieroni[cy], T. Piran[dz], A. Platania[cm], S. Rastgoo[cz],
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COST action

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 many deep issues:

space-time symmetries, locality, causality

Examples of “Effective” Violations in Condensed Matter:

Topological Materials and Superconductors, Anyons

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

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) δ_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.

On the other hand,
From **Quantum Gravity**
prospective

Searches of a self-consistent theory describing extreme gravity at microscopic scales. In particular in the Planckian energy and length scales

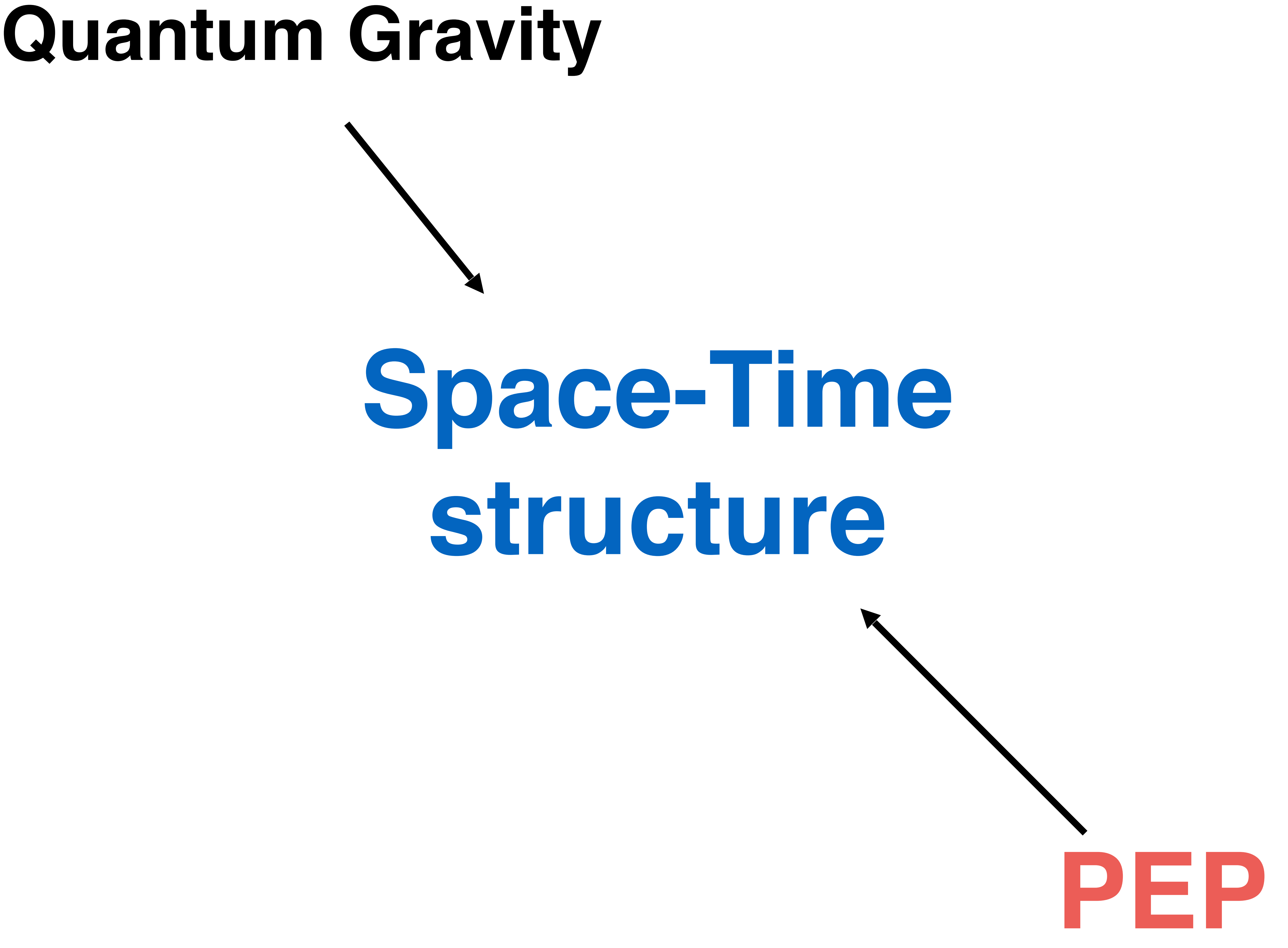
Direct tests elusive…

Indirect tests

Basic idea:

Statistical amplifier of indirect tiny tests

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, Marciano *et al* in a series of works 2017-2022

Non-linear Generalized Uncertainty Principle

Addazi, Bernabei, Belli, Marciano, Shababi
EPJC 2020

Underground experiments:

high statistics = amplifier

High controllability of the background nuclear and atomic processes.

High precision tests of transitions violating the PEP

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

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

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

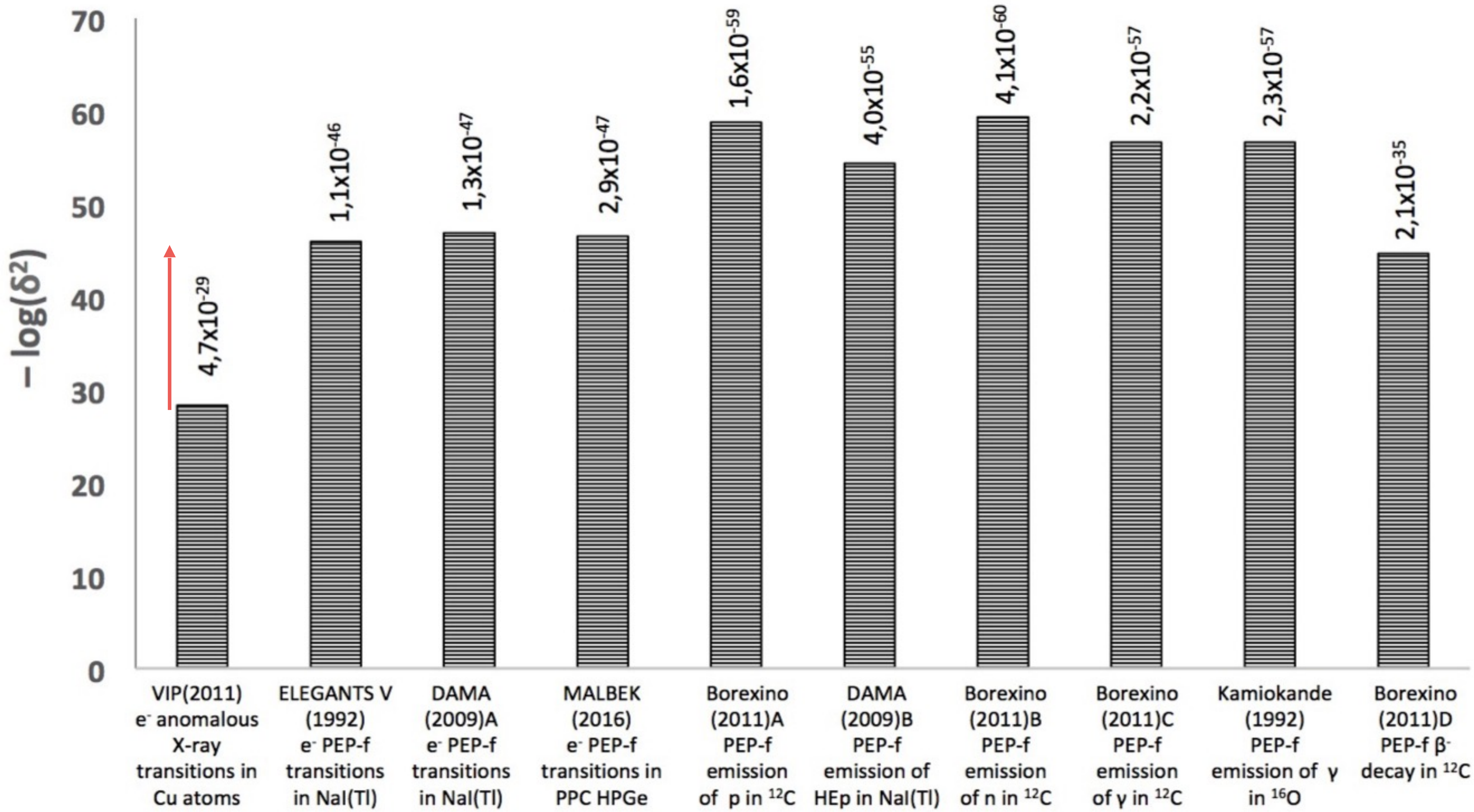
$$\delta^2(E) = c_k \frac{E^k}{\Lambda^k} + O(E^{k+1})$$

All possible PEPV transition rates. Nuclear or atomic transitions.

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

Here: (i) δ_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



PEP and
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

$$\mathbf{GM}: \ \mathfrak{so}(3,1) \to \text{noncommutative dual \ “deformed”} \ \mathfrak{so}(3,1)$$

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

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

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

Quantum fields as Groenwald-Moyal representations

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

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

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

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

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

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

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

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 trasformation 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

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

You can show that BS is violated! proof in
Addazi, Marciano IJMPA

UV/IR mixings
Mentioned by Amelino-Camelia in his talk

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

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

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

Related to the idea of
Double special relativity :
Fundamental invariant short scale, MDRs
and astrophysical pheno
G. Amelino-Camelia and J. Ellis talks

Around the UV pole super-uncertainty

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

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

$$\Delta L_i \Delta L_j \rightarrow \infty$$

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

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

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

Results from DAMA/LIBRA

From exclusions of Na a I PEPV transitions

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

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

$$n(\Lambda^{-2}P)^m < 4 \times 10^{-55} \text{ (90\% C.L.)}.$$

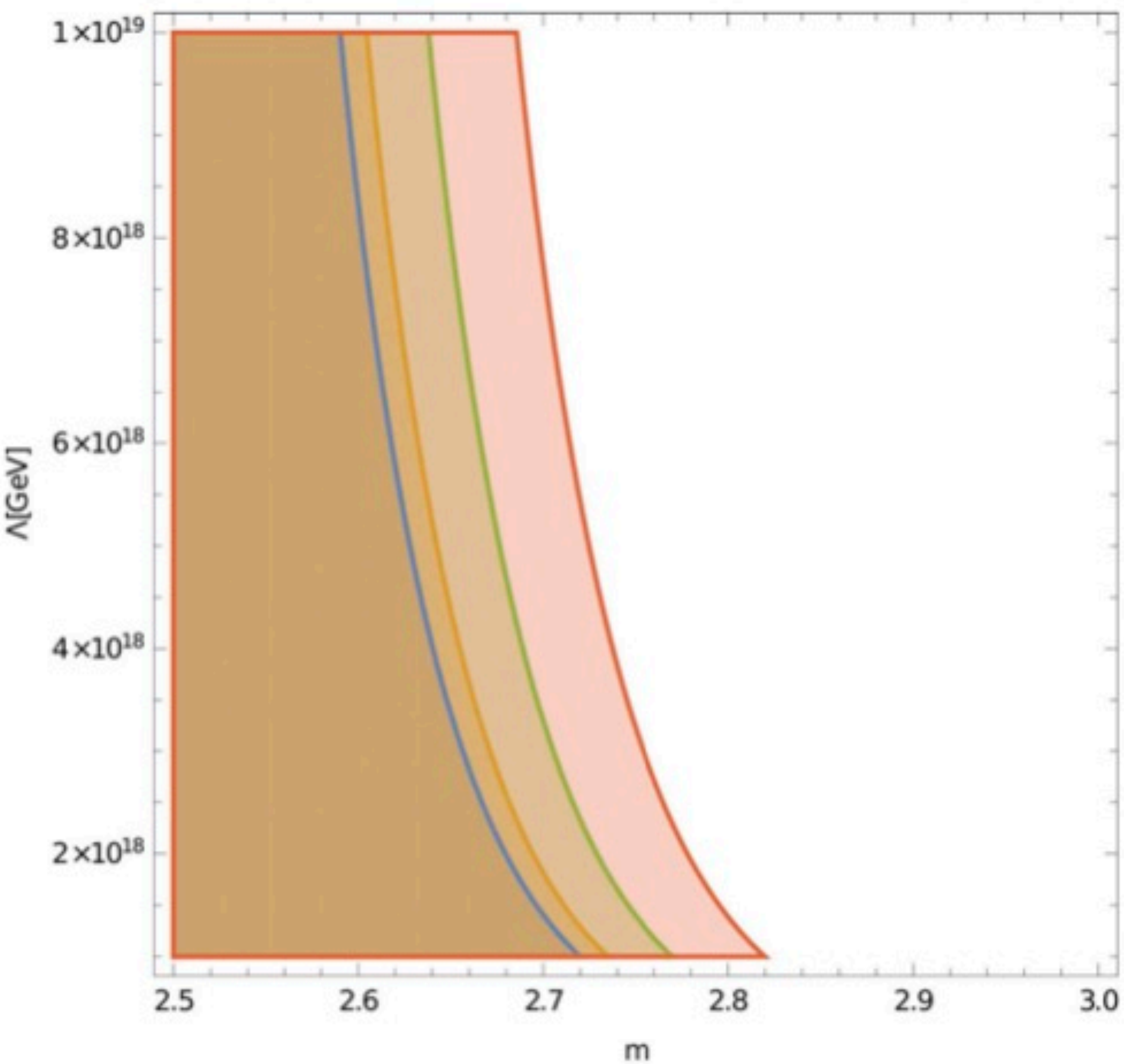


Fig. 1 Excluded parameter space (Λ, m) from DAMA experiment: the four contour limits correspond to fix $n = 1, 2, 10, 100$ respectively

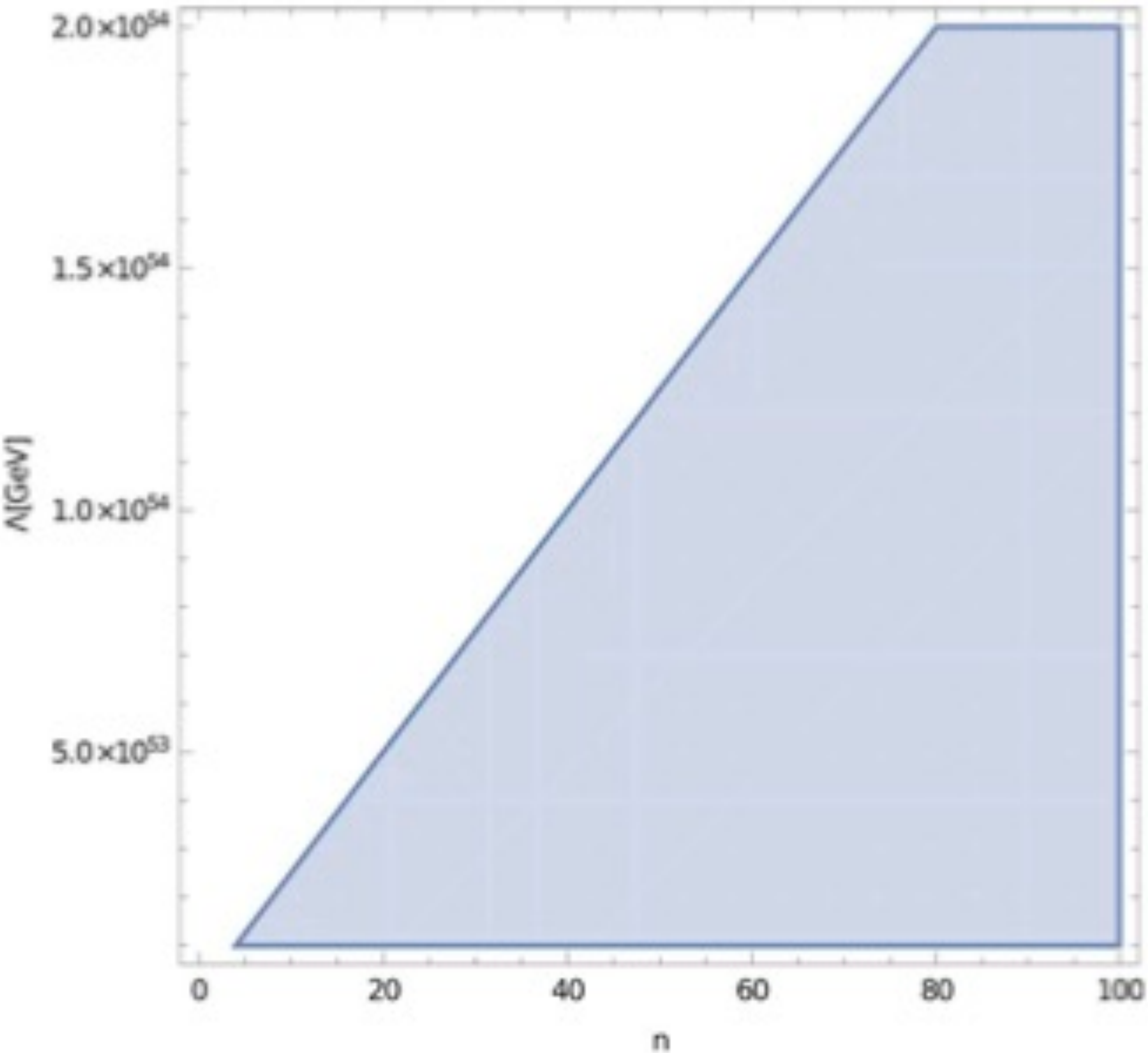
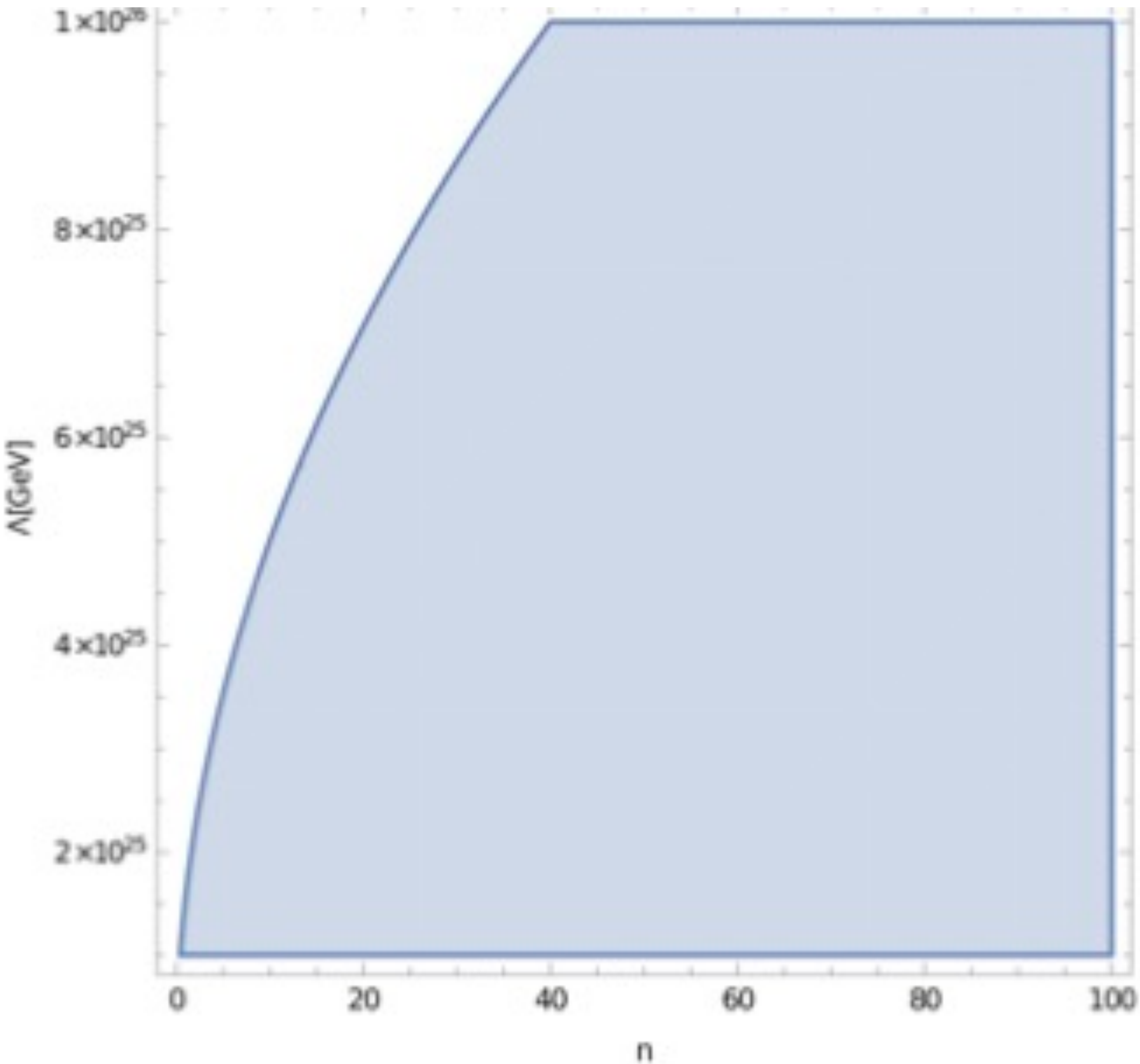


Fig. 2 Excluded parameter space (Λ, n) from DAMA experiment, fixing $m = 1$



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

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

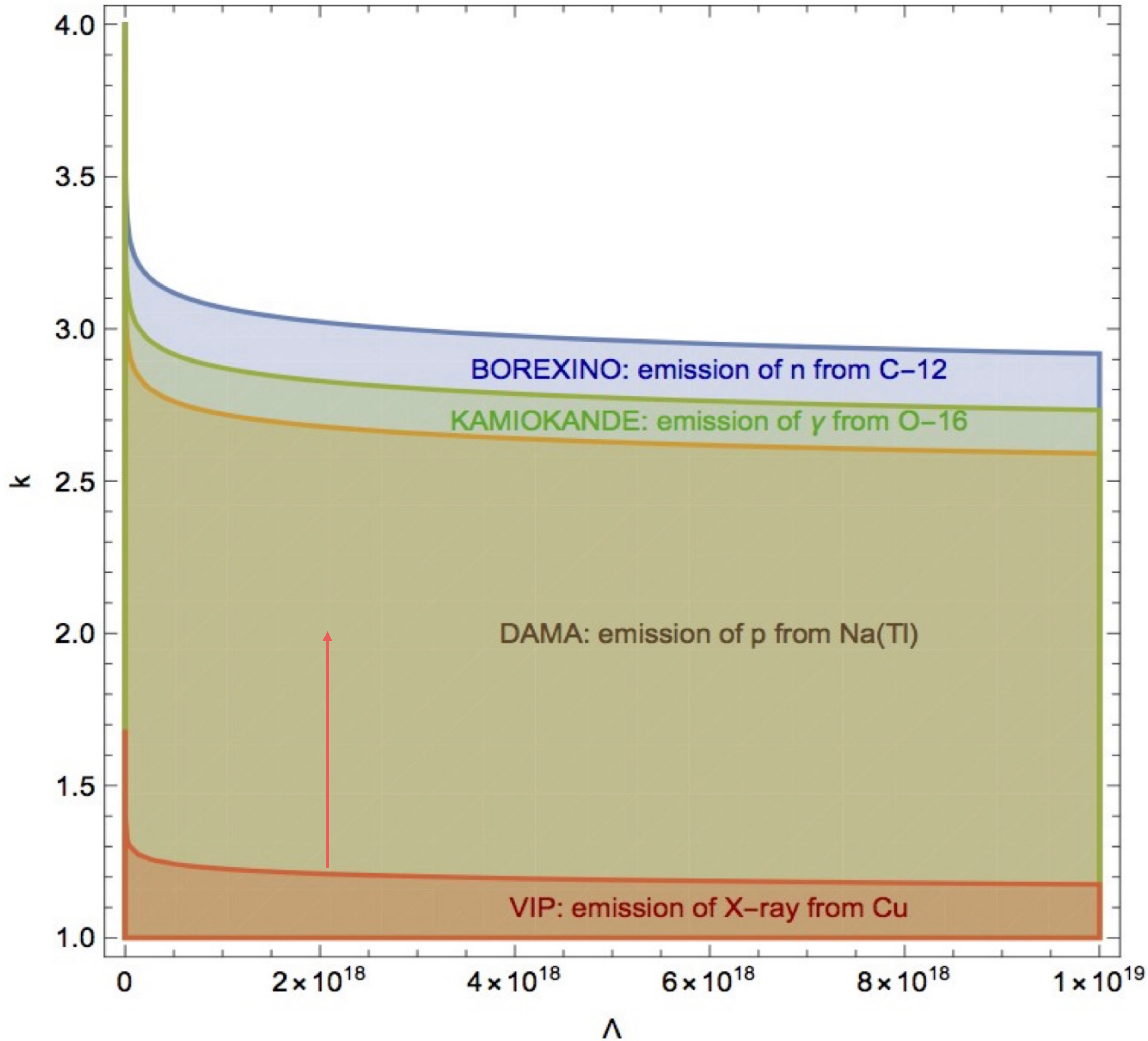
$$\delta^2(E) = \beta^2(E)/2.$$

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

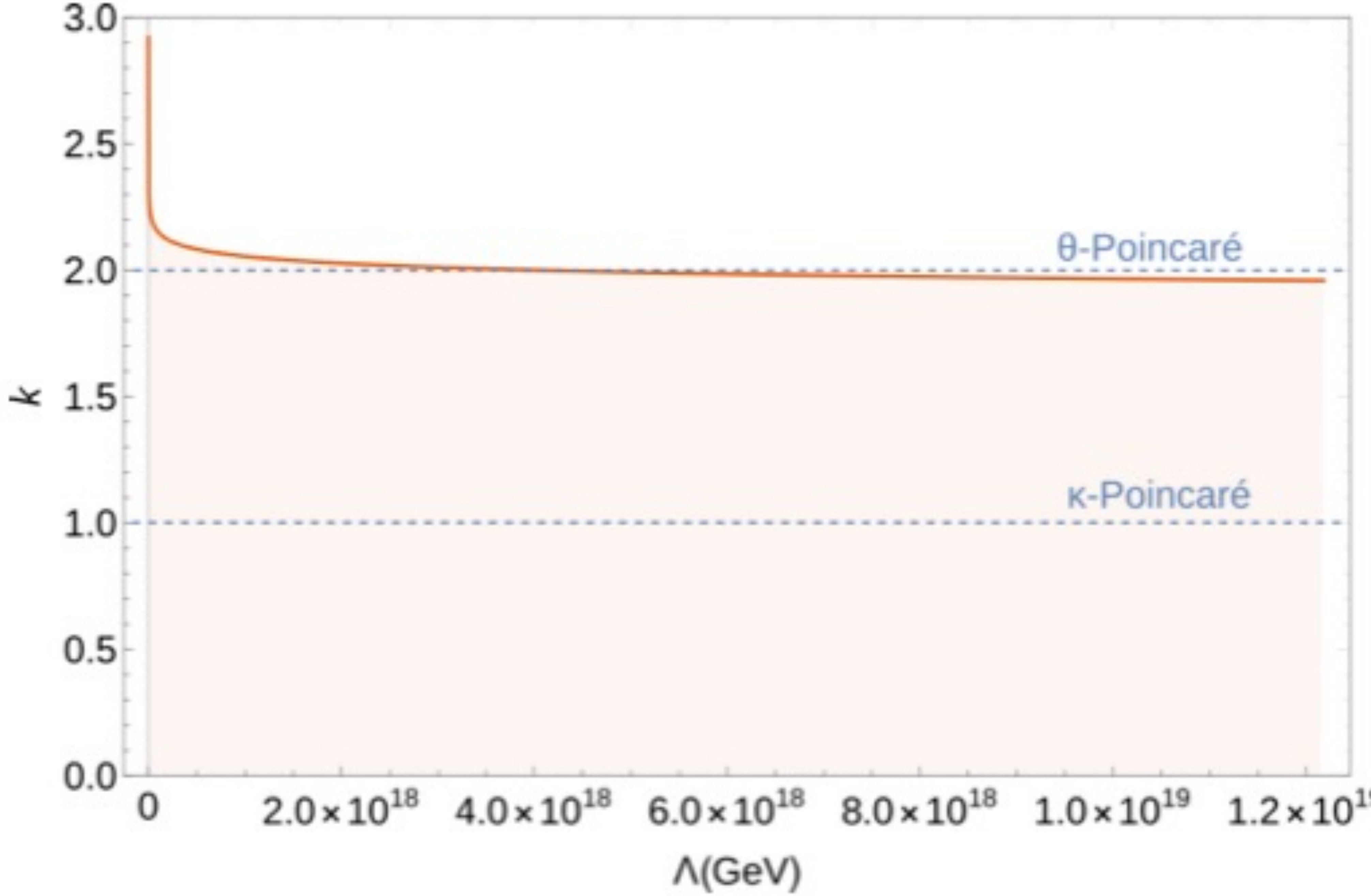
Results

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

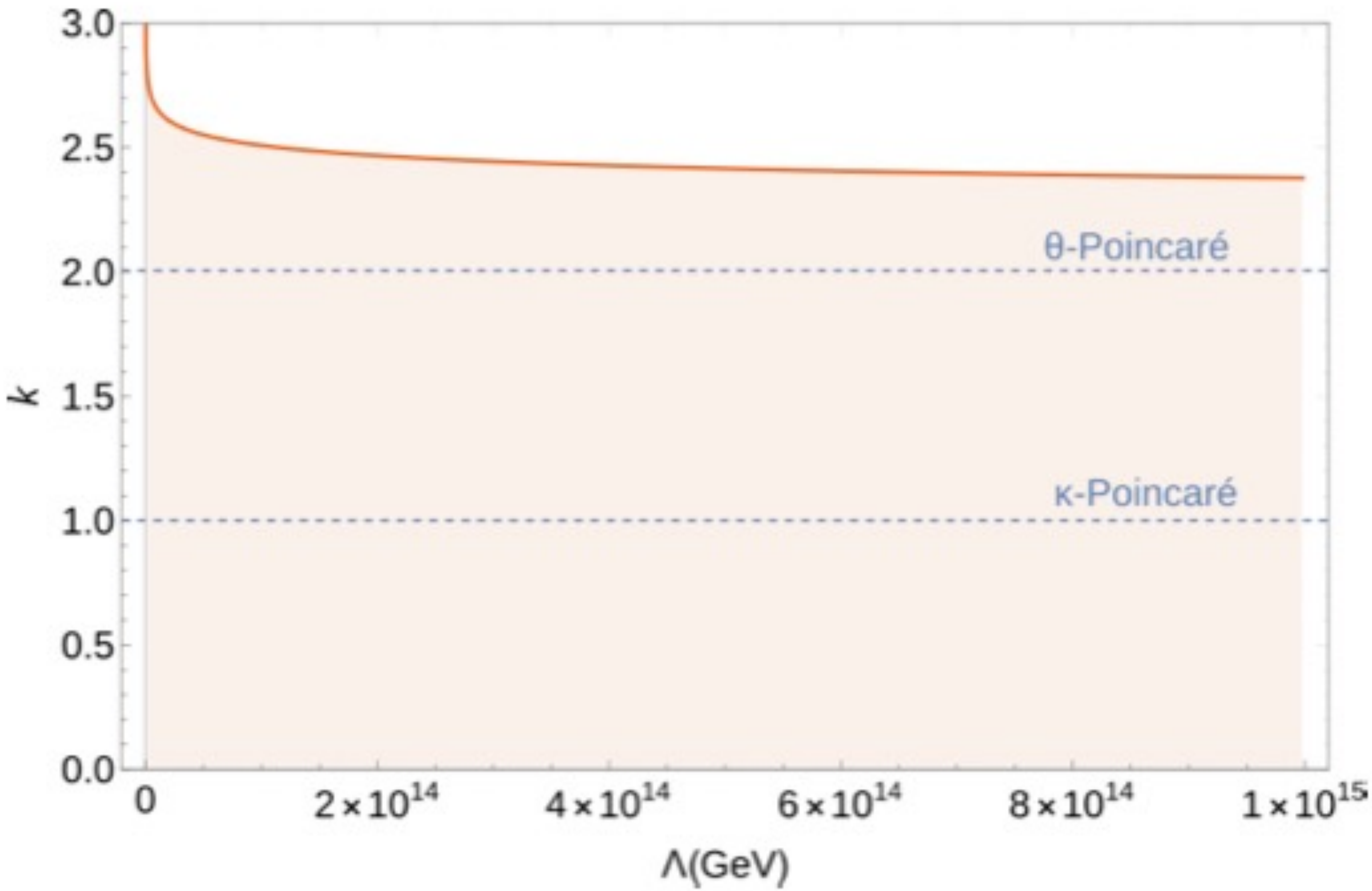
2017-2019



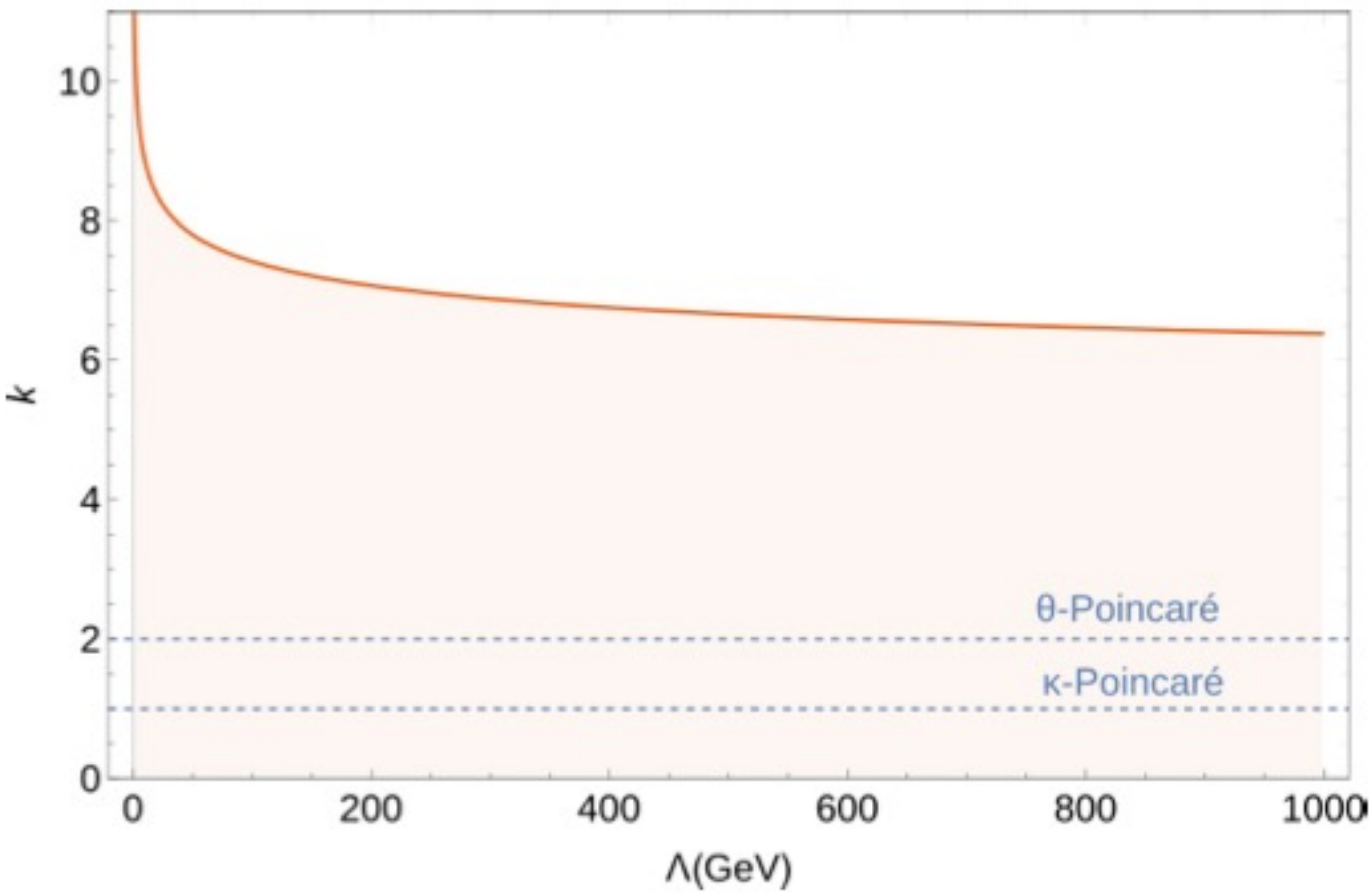
4.0
3.5
3.0
2.5
2.0
1.5
1.0
k
BOREXINO: emission of n from C–12
KAMIOKANDE: emission of γ from O–16
DAMA: emission of p from Na(Tl)
VIP: emission of X–ray from Cu
0
2×10^18
4×10^18
6×10^18
8×10^18
1×10^19
Λ



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)



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)



10
8
6
4
2
0
k
0
200
400
600
800
1000
Λ(GeV)
θ-Poincaré
κ-Poincaré

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

Two beautiful measurements in atomic transitions: DAMA and VIP

Belli’s talks today
And several about VIP in this meeting

47th digit of suppression from K-shell of Iodine, Belli, Bernabei et al EPJC 2019

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-Poncare from VIP

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

PRL result

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 until the Planck Scale regime.
Not all of them but a considerable 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, …

Grazie dell’attenzione