Lectures on quantum gravity phenomenology

Part 1: Theoretical models

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Short Course on: Theory and data analysis of Astroparticles

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- A historical description of quantum gravity can be seen in many books on the subject, for example from Rovelli's book "REALITY IS NOT WHAT IT SEEMS", which describes the birth of quantum gravity from Bronstein's work in 1936

Matvei Bronstein, "Republication of: Quantum theory of weak gravitational fields", Gen Relativ Gravit (2012) 44:267–283

Matvei Bronstein - One of the first researchers of quantum gravity in 1936

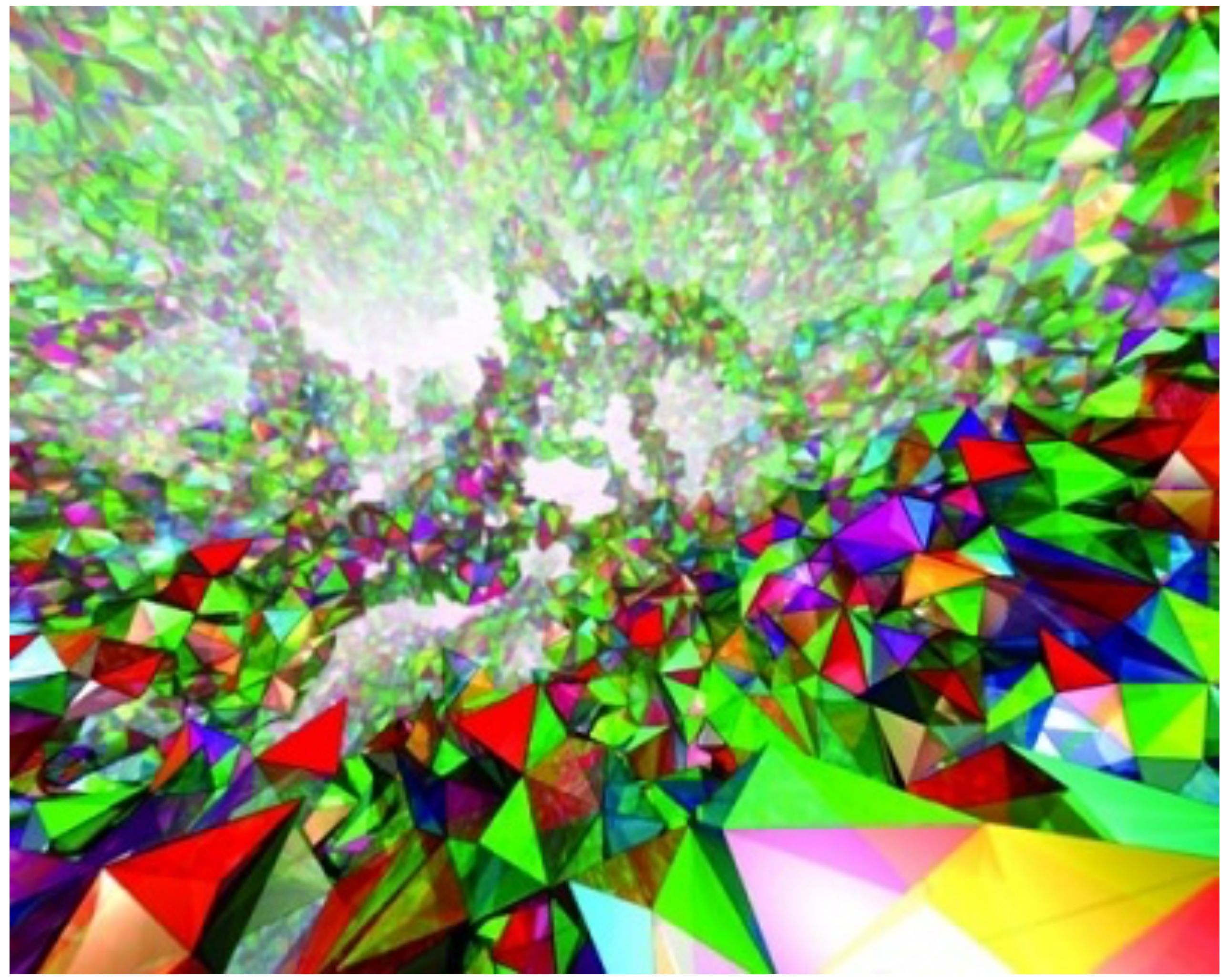
The quantization of the spacetime metric leads to an uncertainty in the determination of the trajectory probed by a test particle when gravity is "turned on".

Spacetime would no longer be Riemannian, but would need to be something else

$$\Delta[00,1] \gtrsim \frac{h^{2/3}G^{1/3}}{c^{1/3}\rho^{1/3}V^{2/3}T}.$$

Geometric uncertainty

This makes one suspect that quantum gravity leads to fundamental modifications in the geometrical nature of spacetime



Atoms of spacetime

One would also suspect that quantum mechanics postulates need to be modified.

$$\Delta p_x \approx \frac{h}{\Delta x} + G\rho^2 V \Delta x \Delta t.$$

The uncertainty in the connection is related to an uncertainty in the momentum of test particles.

This uncertainty sums up to the known Heisenberg uncertainty

Quantum Gravity corrections to known physics at an intermediate level

Riemannian Geometry + corrections

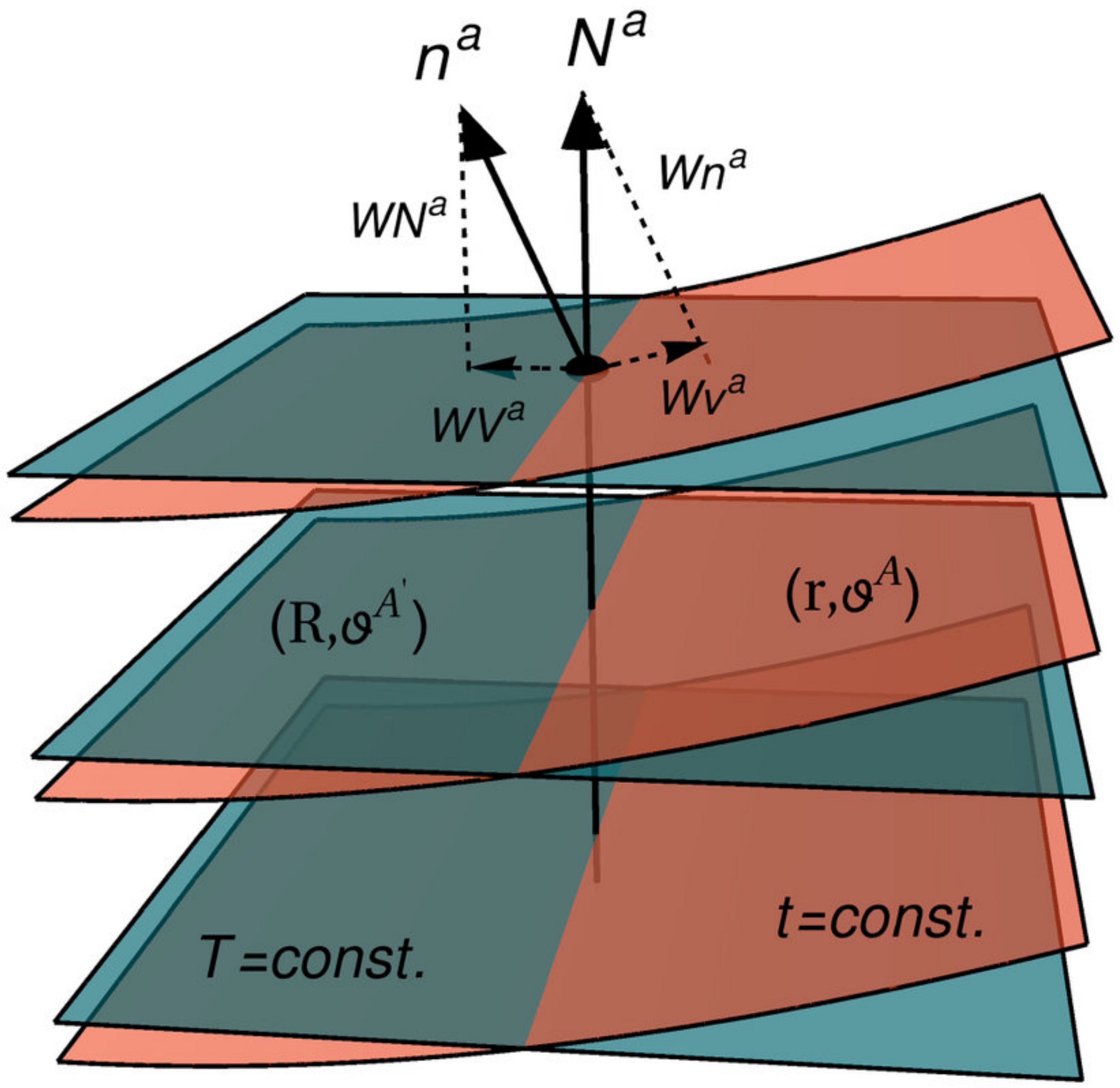
"Standard” Quantum Mechanics + corrections

There exist many other examples of approaches to quantum gravity that point to **departures of the Riemannian description of spacetime and its symmetries** or the **standard quantum mechanics/quantum field theory**

Examples:

- Loop Quantum Gravity
  [Amelino-Camelia, da Silva, Ronco, Cesarini, Lecian, PRD (2017)]
- Horava-Lifshitz gravity
  [P. Horava, PRL (2009)]
- Causal Dynamical Triangulation
  [Ambjorn, Jurkiewicz, Loll, PRL (2005)]
- Non-critical Lioville string theory
  [Amelino-Camelia, Ellis, Mavromatos, Nanopoulos, IJMPA (1997)]
- QG correction to Schrödinger equation
  [Kiefer, Singh, PRD (1991)]
- 3D Quantum Gravity
  [Freidel, Levine, PRL (2006)]

Example: Hypersurface Deformation Algebra from Loop Quantum Gravity



It's possible to write the equations of general relativity in terms of the algebra of generators of time evolution and space diffeomorphism

Effectively, one approaches Loop Quantum Gravity corrections of GR by deforming these generators

A linearization of this deformed algebra leads to a **modification of Poincaré algebra** with mass shell

$$m^2 \approx E^2 - P^2 - \lambda^2 P^4$$

Brahma, Ronco, Amelino-Camelia, Marciano, PRD (2017)

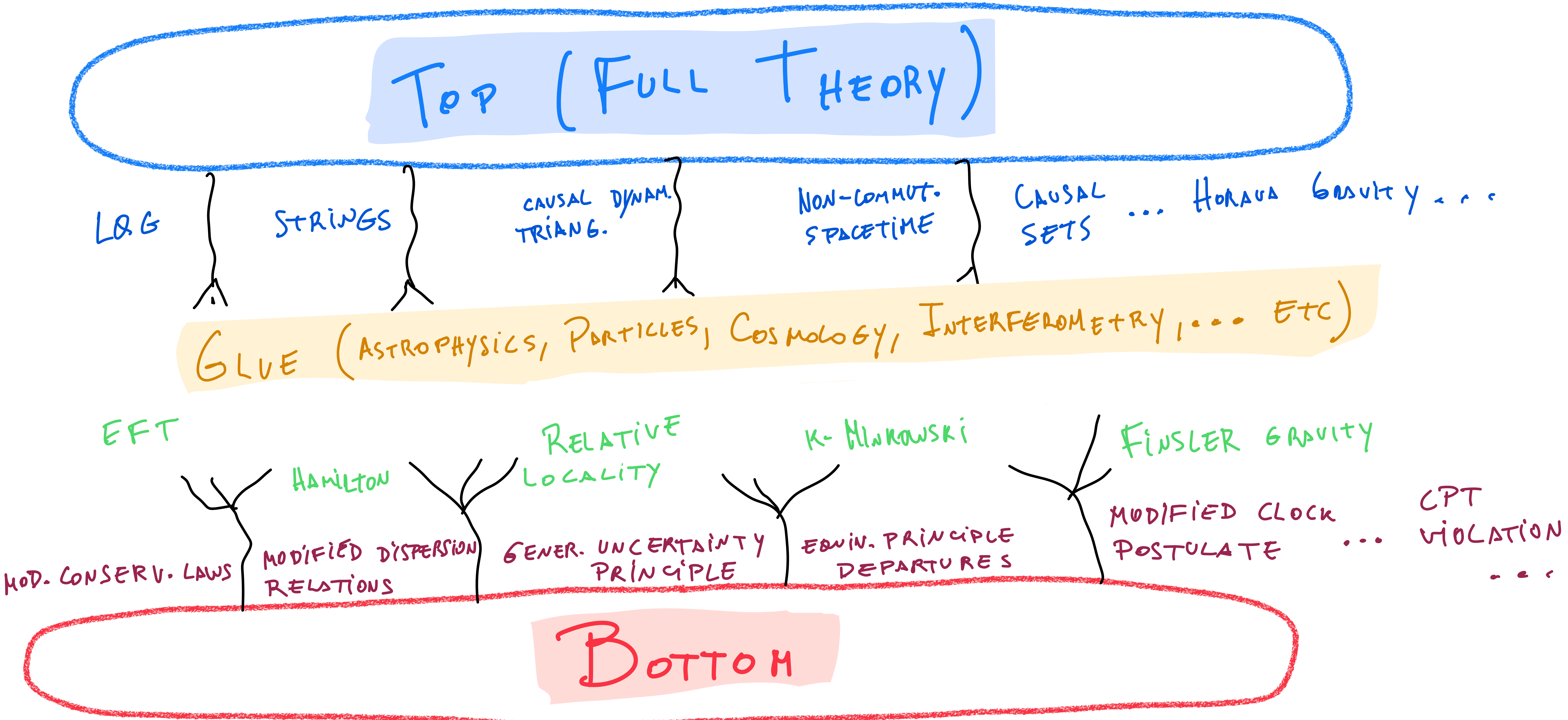
What is the correct approach to quantum gravity?

Is gravity really quantum?

What is a test of the quantum nature of spacetime?

Can we test these theories of QG?

Quantum gravitation phenomenology is a **bottom-up** proposal, in which the varied possibilities of **modifications of basic and well-established equations** of relativity are **parameterized** through corrections **inspired** by expectations of what **semi-classical limits would be like** or **lessons** from theories that quantize the gravitational field (or the geometry of space-time).



The advent of QG phenomenology

Quantum gravity needs experiments!

- Quantum gravity is a long-lived research area that has achieved enough maturity to be studied at a **phenomenological** level

- In the past 15 years, several effects predicted by approaches to quantum gravity have been **constrained** with **Planck scale sensitivity**

What is Planck scale sensitivity?

Planck scale sensitivity

- **Planck scale sensitivity**:
  Ability of an experimental setup or measurement technique to detect variations, **parametrized by Planckian units,** in the quantity or phenomenon being measured

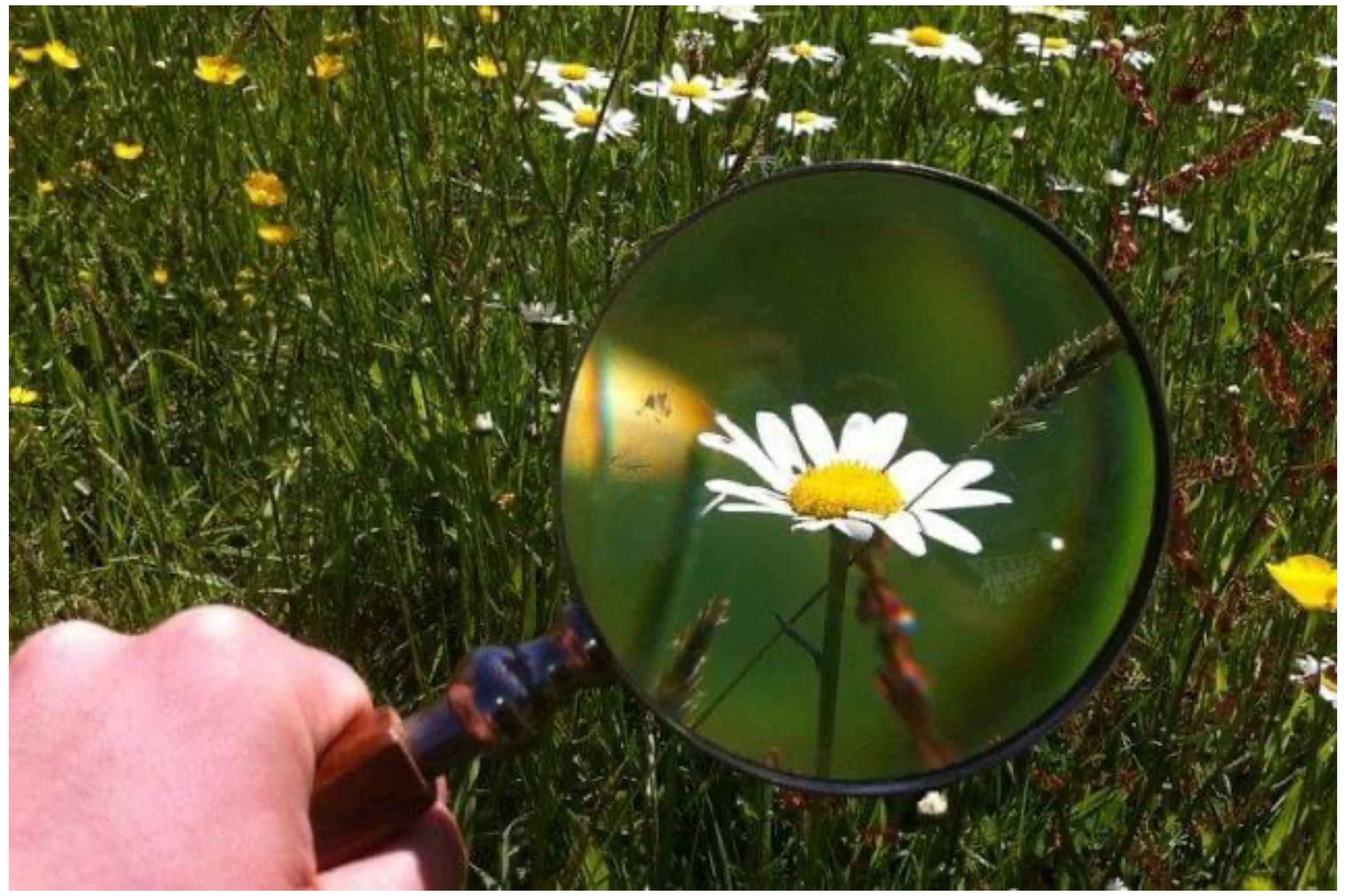
- Naively, one could expect that such variations would be simply given by powers of the product of Planck length or the inverse Planck energy and the energy scale of a particle $\ell_P E$.
  These corrections would be too tiny to be detected as $\ell_P^{-1} \sim 10^{28}\,\mathrm{eV}$

- For example, considering that the most energetic cosmic rays (UHECR) reach $10^{20} - 10^{21}\,\mathrm{eV}$, we would have the most optimistic corrections in particles interactions of the order 10^{-7}

Amplifiers

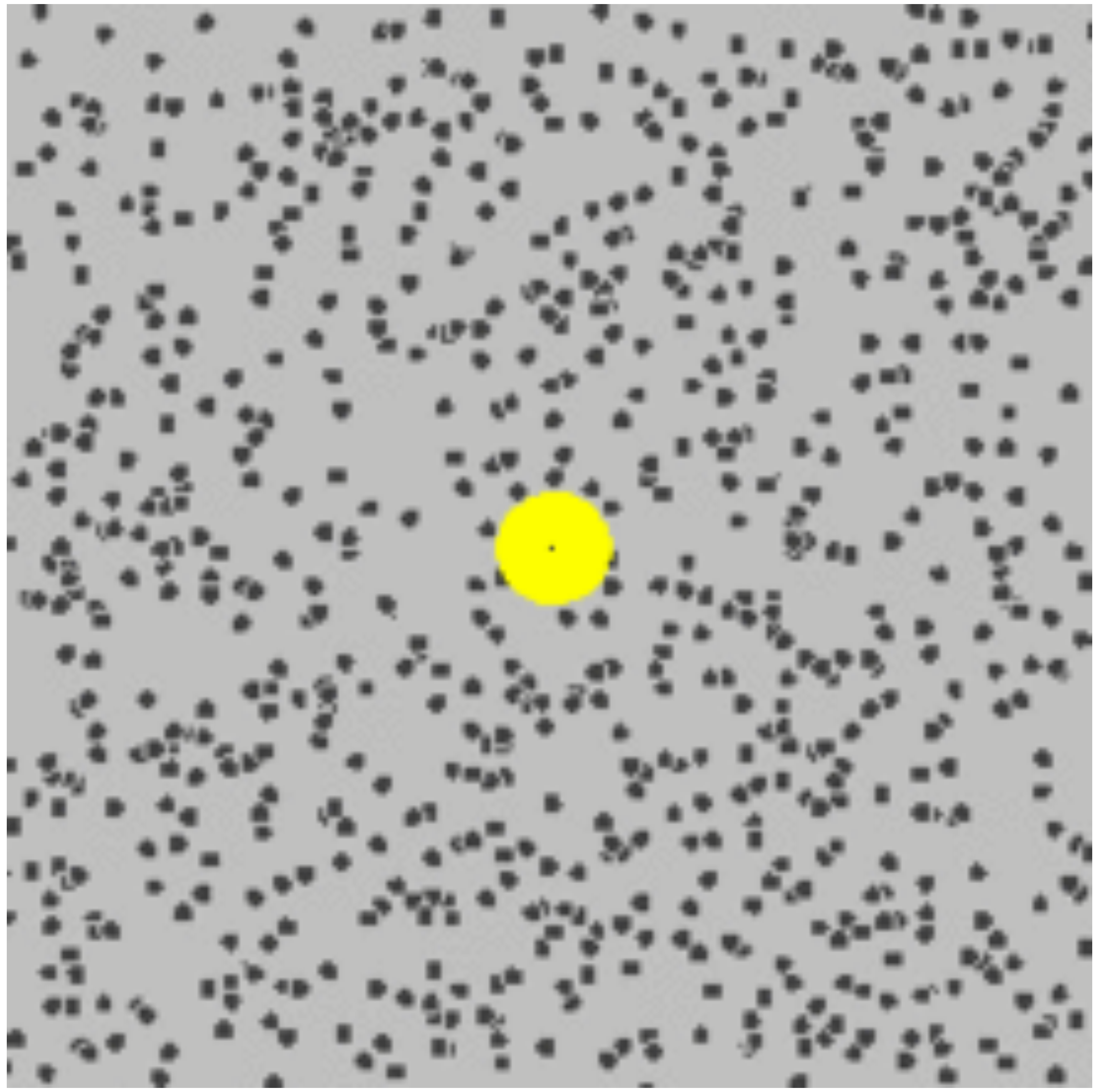
- Although this is correct for many observables, for a long time it was overlooked that phenomena could present **amplifiers** that would allow measurements with Planck scale sensitivity

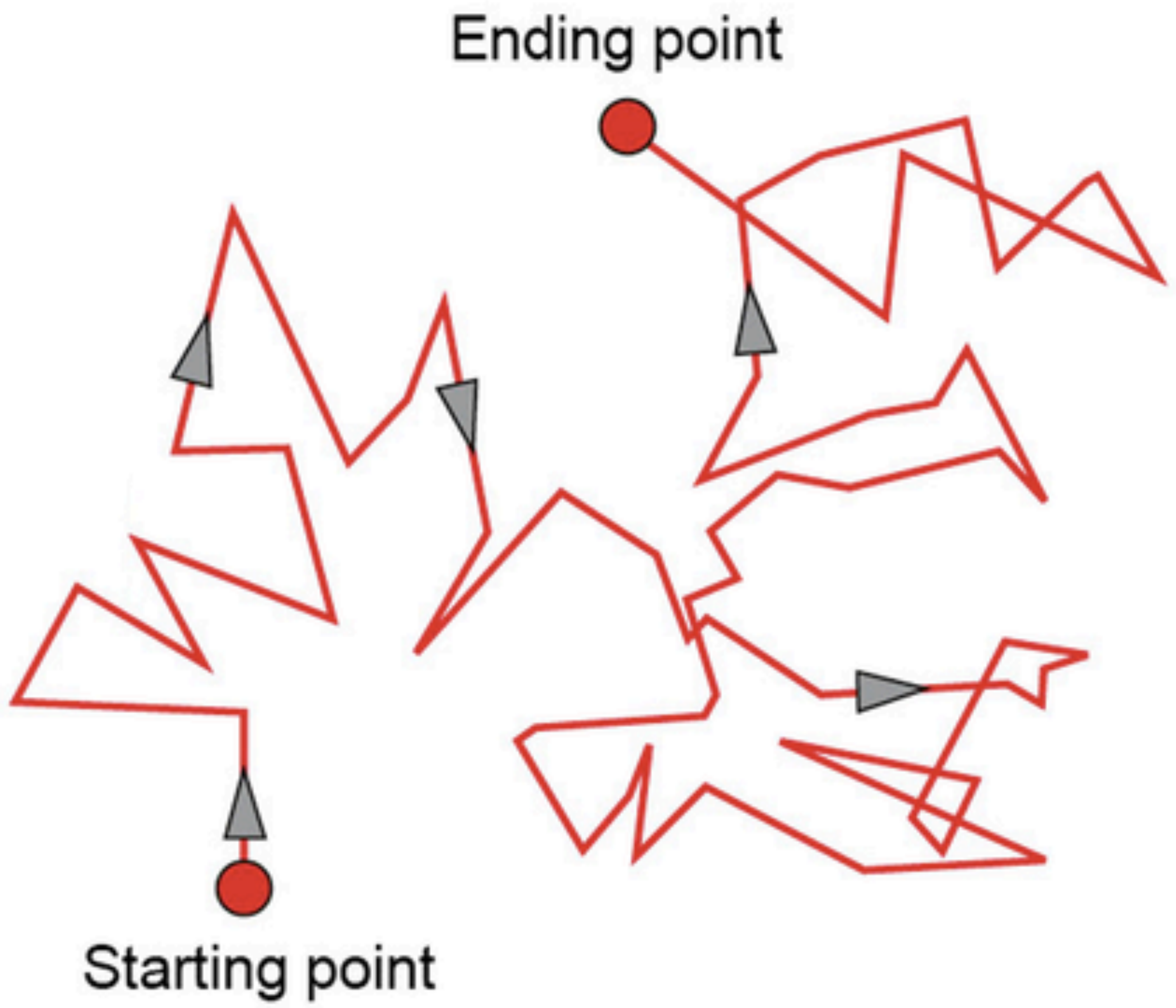
- Such amplifiers can appear both in the relativistic **ultraviolet** regime, from tens of GeV till beyond the PeV scale, or in the non-relativistic **infrared** regime.



- Amplifiers can come in **many forms** when coupled to the Planck length

Brownian motion

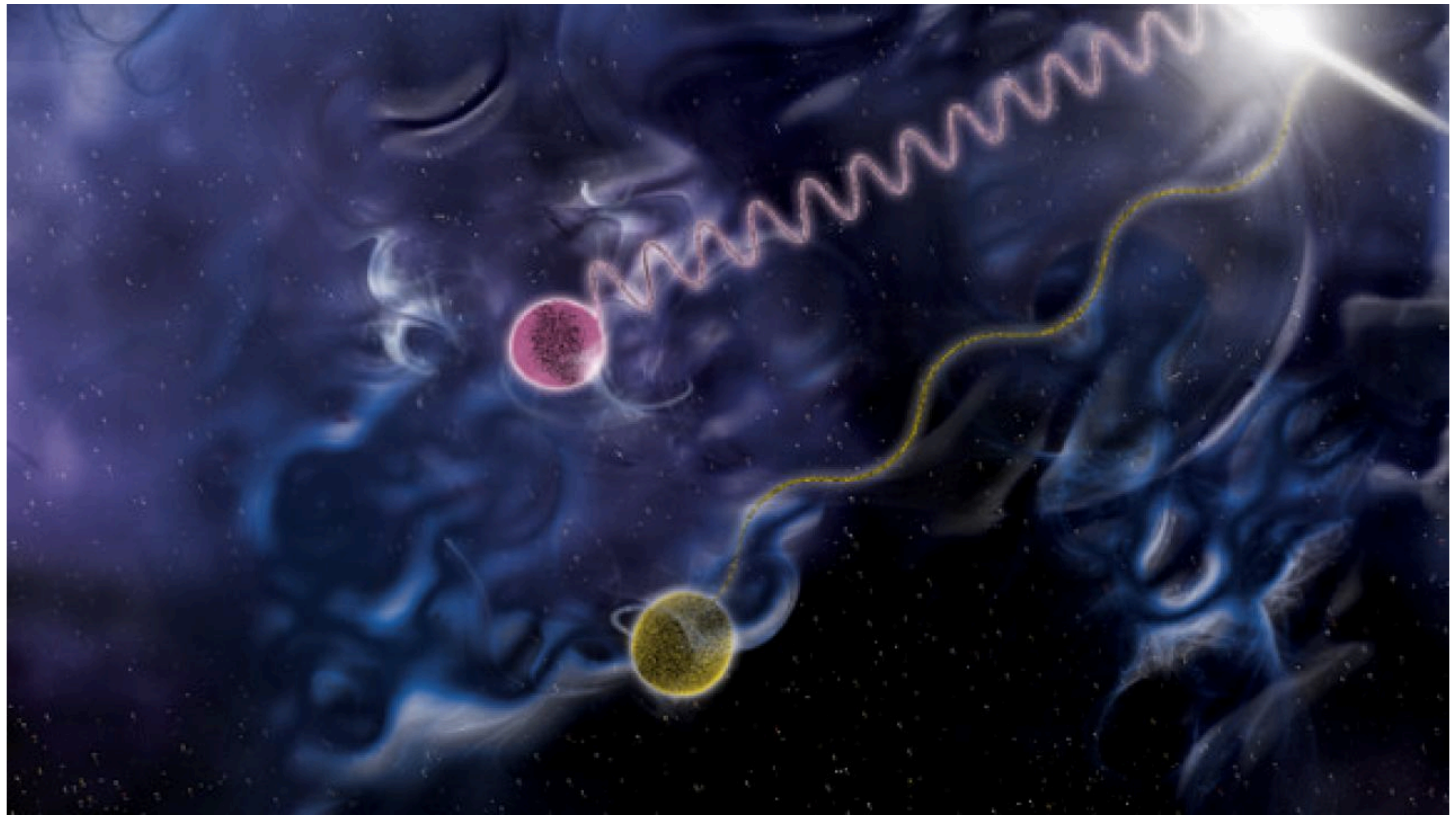




- small contributions add up to a measurable effect

Example: In-vacuo dispersion

- Around the beginning of the 21st century, technological advances (accuracy of experiments) allowed a different approach to be proposed
- If spacetime is discretized, one can **expect small corrections** in the kinematics of particles **propagating** in this background



- Effectively, it is possible to capture modifications of the kinematics of particles when they travel through a quantum spacetime

$$m^2 = E^2 - p^2 + \frac{1}{E_{Pl}}\left(\alpha E^3 + \beta E^2 p \dots\right) + \frac{1}{E_{Pl}^2}\left(\gamma E^4 + \lambda E^2 p^2 \dots\right) + \dots$$

Modified Dispersion Relations (MDR)

Inspired by

- LQG
  [Amelino-Camelia, da Silva, Ronco, Cesarini, Lecian, PRD (2017)]
- Horava-Lifshitz gravity
  [P. Horava, PRL (2009)]
- CDT
  [Ambjorn, Jurkiewicz, Loll, PRL (2005)]
- Non-critical Lioville string theory
  [Amelino-Camelia, Ellis, Mavromatos, Nanopoulos, IJMPA (1997)]

This idea gives rise to a wide phenomenology based on the modified trajectories that particles follow and modifications in processes involving fundamental particles in comparison to special relativity, which can be tested using cosmic messengers

Nontrivial Minkowski limit

Planck energy

$$E_{Pl} = \sqrt{\frac{\hbar c^5}{G}} \approx 1.2 \times 10^{28}\,\mathrm{eV}$$

$\hbar \to 0$

$G \to 0$

$\Rightarrow$ E_{Planck} remains finite

So, one would find a non-trivial local Minkowskian limit

Reminiscent of the Planck scale would remain at the Minkowskian limit

Modified dispersion relation is not invariant under the action of the Lorentz group

To violate Lorentz simmetry

- Different inertial frames measure different MDRs

To deform or to extend the Lorentz/Poincaré symmetry

- Energy and momentum, in each frame, are related by a deformation of the usual Poincaré transformation that preserves the MDR.

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c finite and invariant

Galileu → Lorentz (Special Relativity)

E_{Planck} finite and invariant

Lorentz (Special Relativity) → Doubly Special Relativity (DSR)

ℓ_{Planck} non-null

- MDR for elementary particles $\mathscr{H} = E^2 - p^2 + \ell E p^2 + \ldots = \mathscr{H}(E,p)$

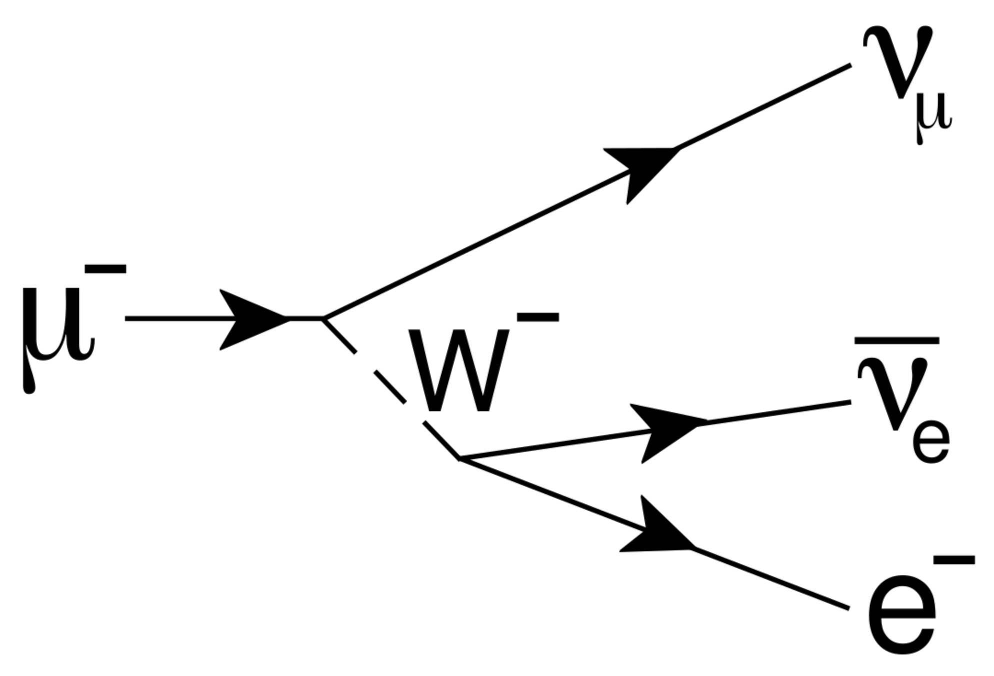
- Deformed Lorentz transformation

$$\begin{cases} E' = \Lambda_{0,\ell}(E,p) = \gamma(E + vp) + \mathcal{O}(\ell E) + \ldots \\ p_i' = \Lambda_{i,\ell}(E,p) = \gamma(p + vE) + \mathcal{O}(\ell E) + \ldots \end{cases}$$

- The invariance of the new dispersion relation under the new frame transformation is assured if

$$\Lambda[\mathscr{H}(E,p)] = \mathscr{H}(E',p')$$

Non-linear transformation



The nature of the vertices of interactions depend on the conservation of the 4-momentum

It is necessary to change the composition law non-linearly

$$\begin{cases} p_\mu \oplus q_\mu = p_\mu + q_\mu + \ell f_\mu(p,q) + \ldots \\ \Lambda_\ell(p \oplus q) = \Lambda_\ell(p) \oplus \Lambda_\ell(q) \end{cases}$$

Doubly Special Relativity

- Giovanni Amelino-Camelia, IJMPD (2002)
- João Magueijo, Lee Smolin, PRL (2002)

IN THE CONTEXT OF MODIFIED DISPERSION RELATIONS

LORENTZ INVARIANCE VIOLATION

MDR

$$E^2 = m^2 + p^2 + s\eta^{(n)}\frac{p^{n+2}}{E_{Pl}^n}$$

$s = 1 \Rightarrow$ Superluminal propagation

$s = -1 \Rightarrow$ Subluminal propagation

$\eta^{(n)}$ is the dimensionless parameter to be constrained

No symmetries

SR Composition law

$$p_\mu \oplus q_\mu = p_\mu + q_\mu$$

$$\Lambda_{SR}(p \oplus q) = \Lambda_{SR}(p) \oplus \Lambda_{SR}(q)$$

DEFORMED SPECIAL RELATIVITY

OR

LORENTZ INVARIANCE DEFORMATION

MDR

$$E^2 = m^2 + p^2 + s\eta^{(n)}\frac{p^{n+2}}{E_{Pl}^n}$$

Modified Symmetries and Composition Law

$$p_\mu \oplus q_\mu = p_\mu + q_\mu + \text{corrections}$$

$$\Lambda_\ell(p \oplus q) = \Lambda_\ell(p) \oplus \Lambda_\ell(q)$$

LIV (Lorentz Invariance Violation) has been explored in Humberto's lecture. It requires the introduction of new terms in the action of interactions with LIV contributions. But one proceeds using the standard Riemannian (Minkowski) geometrical language

Ex.: Standard Model Extension, by Kostelecký et al.

Lorentz-Violating Extension of the Standard Model

D. Colladay and V. Alan Kostelecký
Physics Department, Indiana University, Bloomington, IN 47405, U.S.A.
(preprint IUHET 359 (1997); accepted for publication in Phys. Rev. D)

Some entry points for SME:

Colladay, Kostelecky, PRD 1998

Kostelecky, Lane, PRD 1999

Kostelecky, Russell, Rev. Mod. Phys. 2011

Mattingly, Liv. Rev. Rel. 2005

For modeling a deformation of Lorentz symmetry, one needs to consider alternative mathematical frameworks

NONCOMMUTATIVE GEOMETRY

There are many mathematical languages to describe DSR models. Since the underlying symmetry is not broken, but deformed, this needs to be considered when modeling these effects.

Noncommutative geometry (κ-Minkowski spacetime)

Lukierski, Ruegg, Nowicki, Tolstoy, PLB 1991

$$[x_m, t] = \frac{i}{\kappa} x_m \ , \qquad [x_m, x_l] = 0 \ ,$$

Presents deformed generators of translations, boosts and rotations (κ-**Poincaré algebra**)

$$\begin{aligned}
&[J_a, J_b] = \epsilon_{abc} J_c \,, && [J_a, P_b] = \epsilon_{abc} P_c \,, && [J_a, K_b] = \epsilon_{abc} K_c \,, \\
&[K_a, P_0] = P_a \,, && [K_a, K_b] = -\epsilon_{abc} J_c \,, && \\
&[P_0, P_a] = 0 \,, && [P_a, P_b] = 0 \,, && [P_0, J_a] = 0 \,,
\end{aligned}$$

$$[K_a, P_b] = \delta_{ab} \left(\frac{\kappa}{2} \left(1 - \mathrm{e}^{-2P_0/\kappa} \right) + \frac{1}{2\kappa} \mathbf{P}^2 \right) - \frac{1}{\kappa} P_a P_b \,.$$

Mass Casimir or MDR

$$\mathcal{C}_\kappa = 4\kappa^2 \sinh^2(P_0/2\kappa) - e^{P_0/\kappa} \mathbf{P}^2 \,,$$

Coproduct of the algebra gives the modified composition law

$$P_0 \oplus Q_0 = P_0 + Q_0$$
$$P_1 \oplus Q_1 = P_1 + e^{-P_0/k} Q_1$$

Poincaré algebra ($\kappa \to \infty$)

$$[K_a, P_b] = \delta_{ab} P_0 \,,$$

$$\mathcal{C} = P_0^2 - \mathbf{P}^2 \,,$$

CURVED MOMENTUM SPACE

Curved momentum space

In Special Relativity, momentum space is flat. So, maybe the nontrivial structure of momentum space and interactions is related to a curvature of momentum space (Born Reciprocity Principle from 1938).

A suggestion for unifying quantum theory and relativity

By M. Born

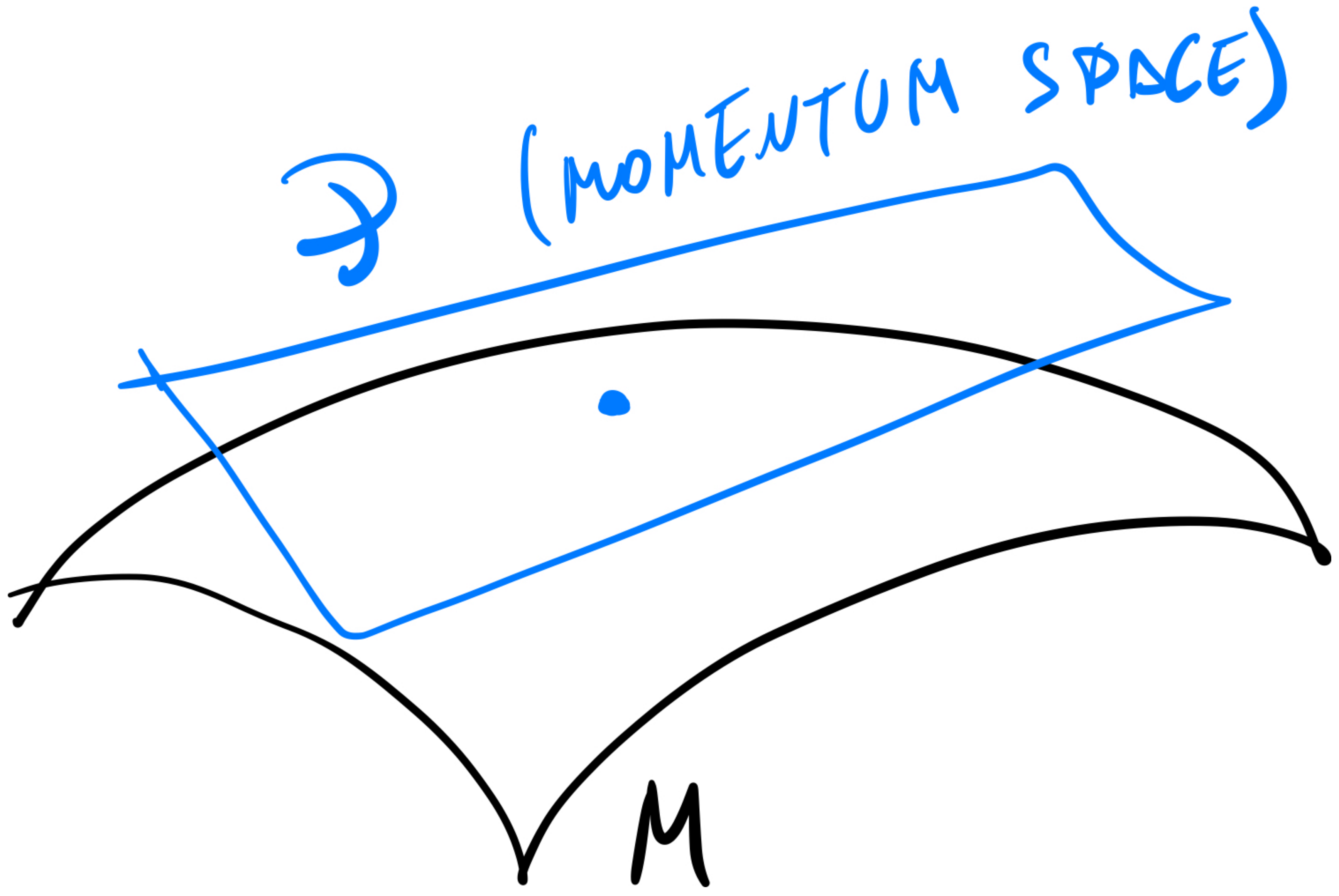
(*Communicated by E. T. Whittaker, F.R.S.—Received 5 January* 1938)

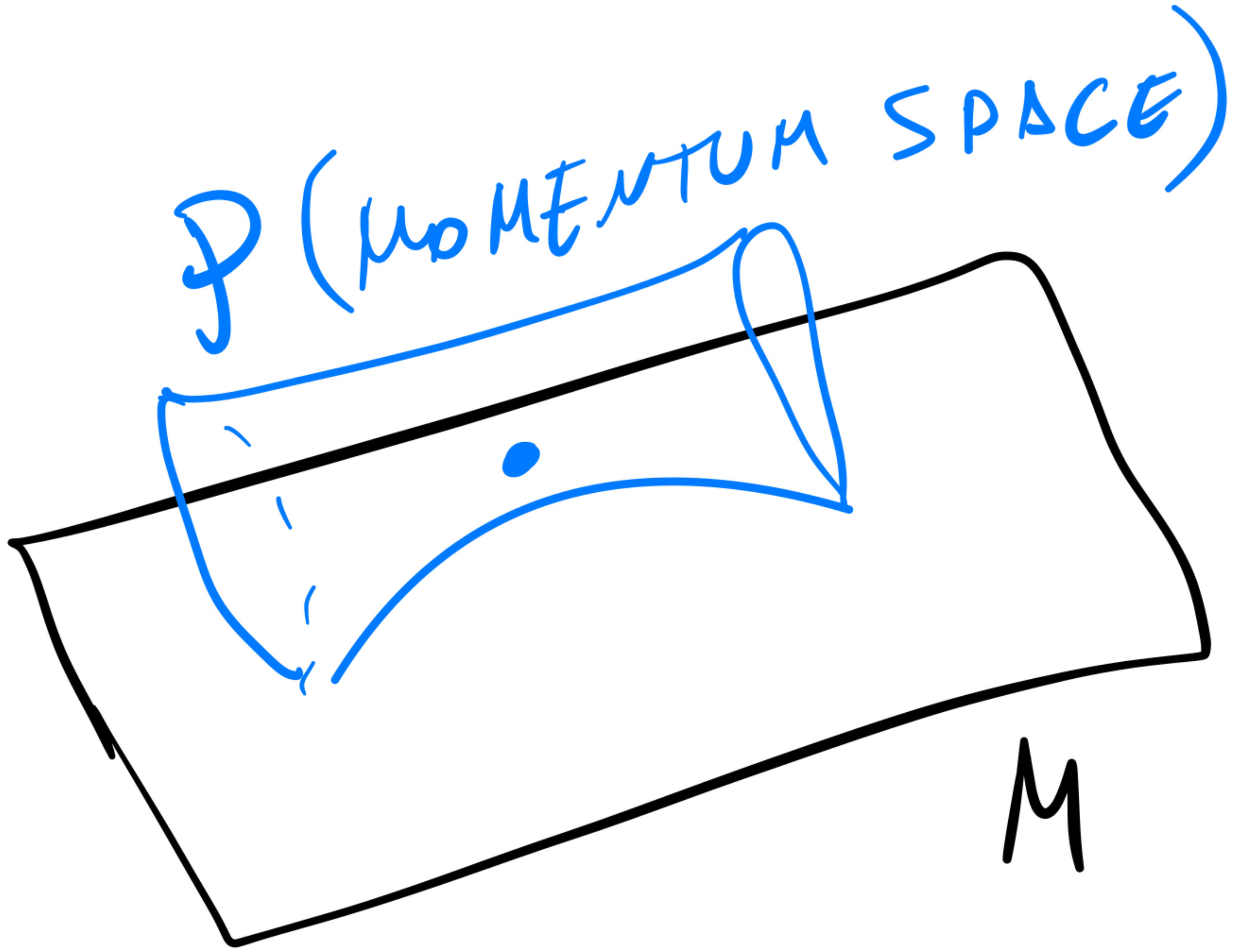
Quantized Space-Time

Hartland S. Snyder
Department of Physics, Northwestern University, Evanston, Illinois
(Received May 13, 1946)

Apparently independently discovered by Snyder and followed by Russian physicists from the 50's to the 80's

Amelino-Camelia, Freidel, Kowalski-Glikman, Smolin, PRD 2011



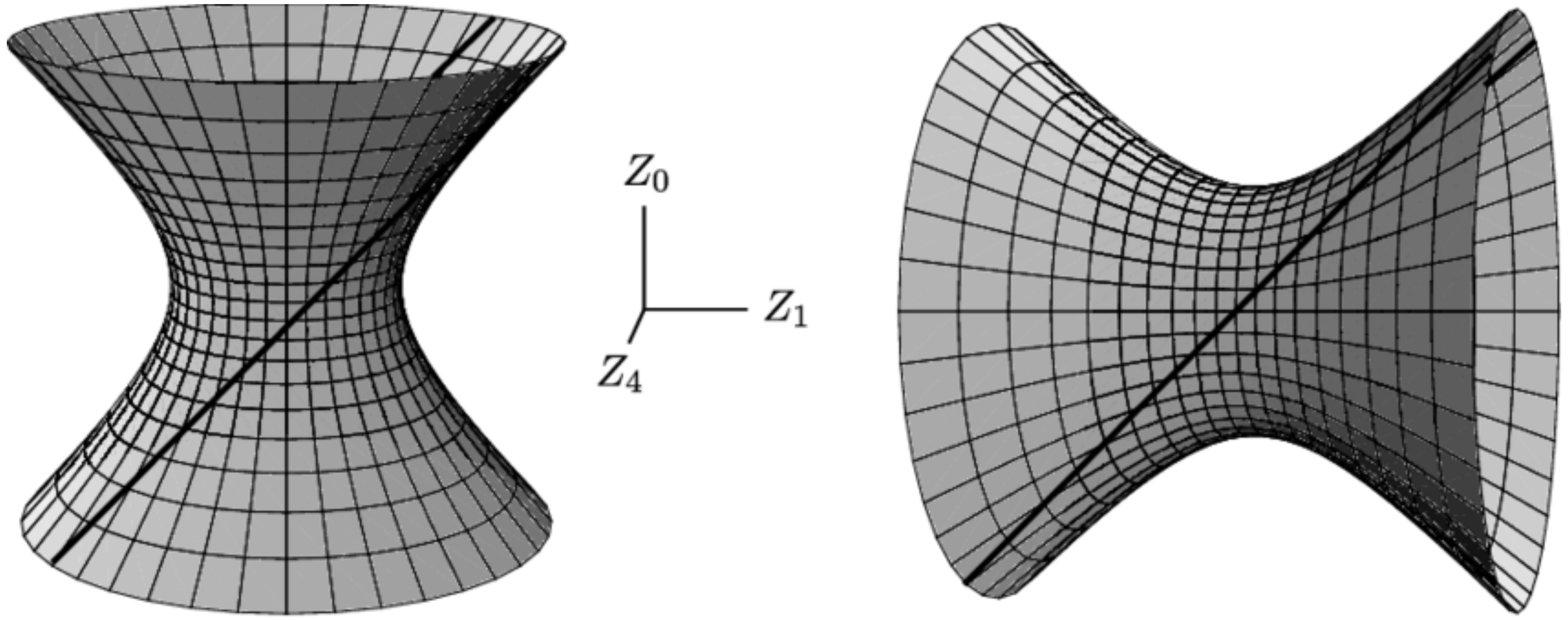


QG Phase space diagram

$$
\begin{array}{ccccc}
 & & \Gamma^{\mathrm{SR}} = \mathscr{M} \times \mathscr{P} & & \\
 & \nearrow & & \nwarrow & \\
\Gamma^{\mathrm{DSR}} = T^{*}\mathscr{P} & & & & \Gamma^{\mathrm{GR}} = T^{*}\mathscr{M} \\
 & \nwarrow & & \nearrow & \\
 & & \Gamma^{\mathrm{QG}} = ? & &
\end{array}
$$

The deformed Poincaré group is actually the group of symmetries in a maximally symmetric momentum space

De Sitter momentum space gives κ-Poincaré symmetries



Anti-de Sitter momentum space gives the momentum space of 2+1 QG

Gubitosi, Mercati, CQG (2013)

IPL, Amelino-Camelina, Palmisano, arXiv:2024.xxxx

Mass shell is defined from geodesic distance in momentum space

The curvature is the inverse of the Planck energy $R = E_{Pl}^{-2}$, such that when $E_{Pl} \to \infty$, we recover SR

Spacetime is given by the covectors in this momentum space

FINSLER GEOMETRY

Relativity was mostly clarified after Minkowski introduced the geometric description of spacetime

- **Relativity principle**
  Isometries are defined in a riemannian spacetime, since the dispersion relation is the norm of the 4-momentum

- **Equivalence principle (GR)**
  Free particles follow riemanniana geodesics

- **Clock postulate**
  Observers measure their proper time by the arc length function.

DSR Formalism

- **Relativity principle**
  Transformations that preserve the MDR $\mathscr{H}$

- **Trajectories**
  Defined by $dx/dt = \partial E/dp|_{\mathscr{H}=m^2}$

- **Proper time**
  ?

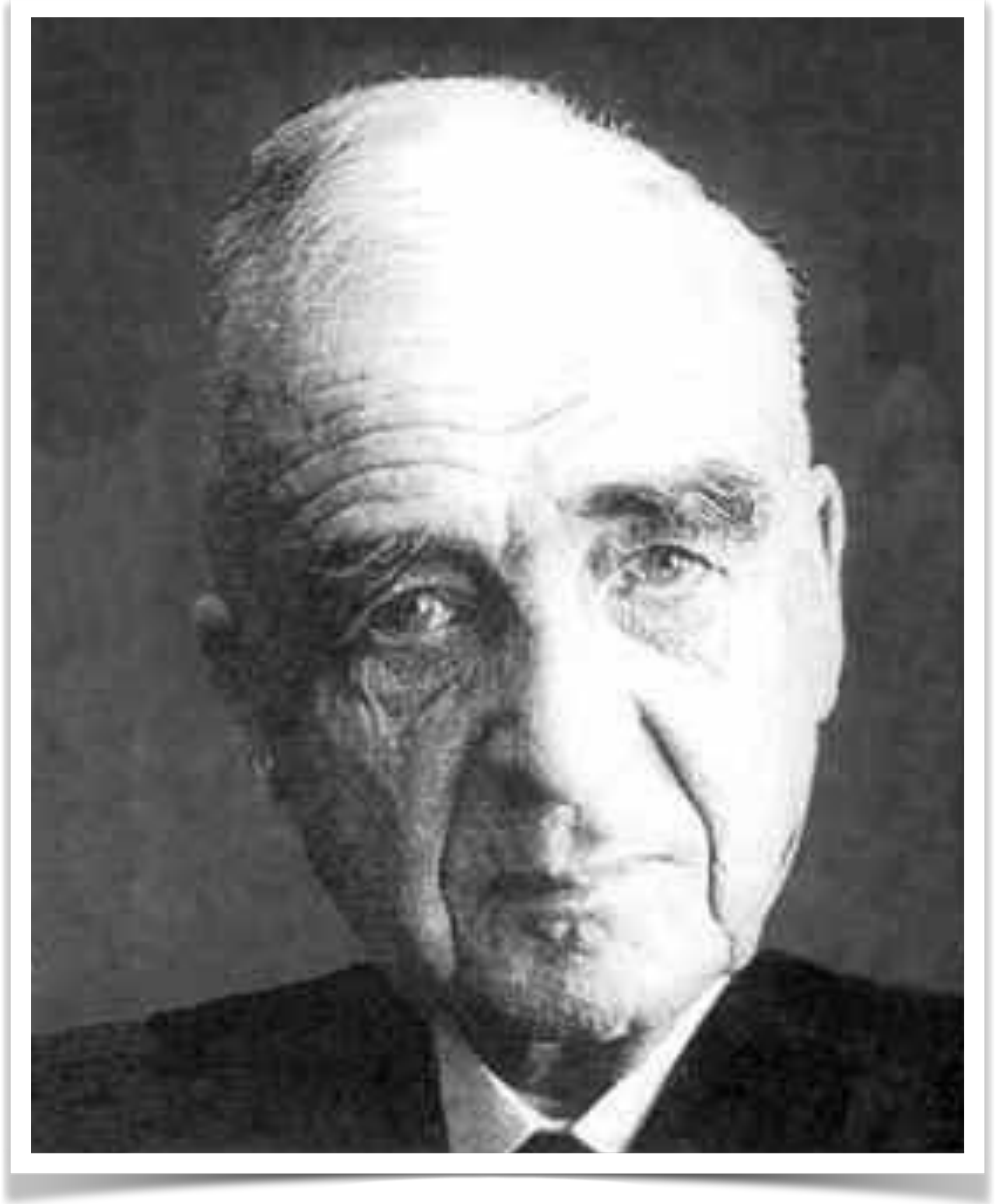
There exists a geometric formalism that can be to Doubly Special Relativity (DSR) what riemannian geometry is to Special Relativity (SR)?

Special relativity

Minkowski

Riemann

DSR



Paul Finsler

Algorith and general Finsler function

[Girelli, Liberati, Sindoni, PRD (2007)]
[**IPL**, Christian Pfeifer, PRD (2021)]

- The action of a free particle is of the form

$$S[x,p,\lambda]_H = \int d\mu(\dot{x}^\mu p_\mu - \lambda f(\mathcal{H}(x,p),m))$$

$$f = 0 \Leftrightarrow \mathcal{H}(x,p) = m^2$$

1) Variation with respect to λ enforces the dispersion relation.

2) Variation with respect to p_μ takes us to an equation $\dot{x}^a = \dot{x}^a(p,\lambda)$, which must be inverted to give $p_\mu(x,\dot{x},\lambda)$ and allow to eliminate the momenta p_μ of the action

3) Using $p_a(x,\dot{x},\lambda)$ on the MDR, one can find $\lambda(x,\dot{x})$ (this can only be done for massive particles).

4) Finally the equivalent action is obtained as $S[x] = S[x,p(x,\dot{x},\lambda(x,\dot{x})),\lambda(x,\dot{x})]_H$.

Constructing Finsler geometry

- Approximately, a modified hamiltonian has the form

$$H(x,p) = g(p,p) + \epsilon\, h(x,p) \qquad \text{where} \qquad h(x,p) = h^{\mu_1\mu_2\ldots\mu_n}(x)p_{\mu_1}p_{\mu_2}\ldots p_{\mu_n}$$

Perturbation parameter ← ϵ

- It gives the following action in spacetime

$$S[x] = m\int F(x,\dot{x})d\mu$$

$$F(x,\dot{x}) = \sqrt{g(\dot{x},\dot{x})} - \epsilon m^{n-2}\frac{h_{\mu_1\mu_2\ldots\mu_n}(x)\dot{x}^{\mu_1}\dot{x}^{\mu_2}\ldots\dot{x}^{\mu_n}}{2g(\dot{x},\dot{x})^{\frac{n-1}{2}}}$$

- The connection with Finsler geometry is realized by the identification of the arc length functional, $s[x]$, for massive observers, from which the Finsler metric $g_{\mu\nu} = \partial^2(F^2/2)/\partial\dot{x}^\mu\partial\dot{x}^\nu$ e $\mathscr{H} = g^{\mu\nu}p_\mu p_\nu$ can be found

$$s[x] \doteq m^{-1}S[x]$$

- Deformed trajectories are **geodesics** that extremize the Finsler arc-length

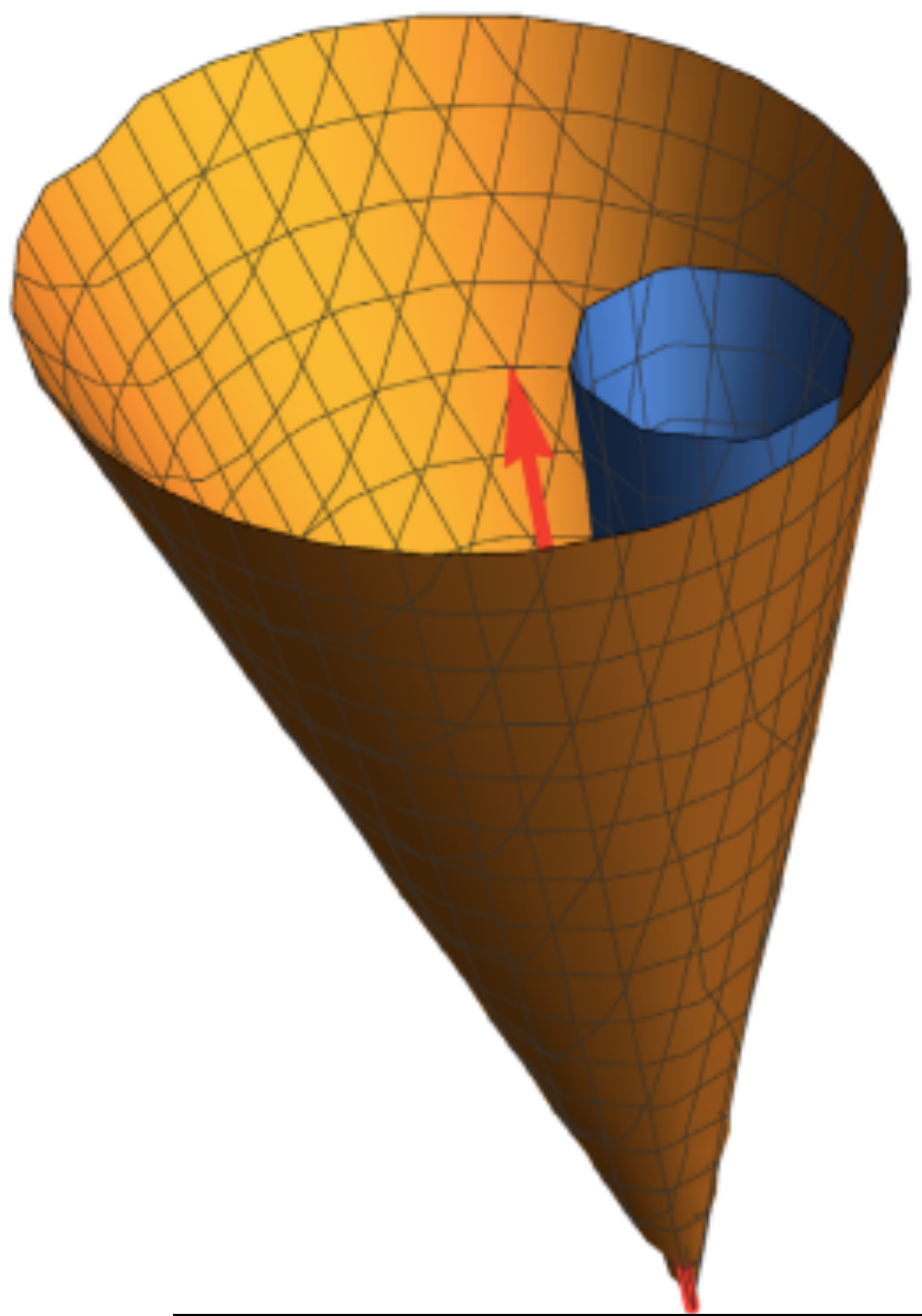
$$\ddot{x}^\mu + \Gamma(x,\dot{x})^\alpha_{\mu\nu}\dot{x}^\mu\dot{x}^\nu = \frac{\dot{F}}{F}\dot{x}^\mu$$

$$\Gamma^\alpha_{\mu\nu}(x,\dot{x}) = \frac{1}{2}g^{\alpha\beta}(x,\dot{x})\Big(g_{\beta\mu,\nu}(x,\dot{x}) + g_{\beta\nu,\mu}(x,\dot{x}) - g_{\mu\nu,\beta}(x,\dot{x})\Big)$$

Coincide with the trajectories found from $dx/dt = \partial E/dp\,|_{\mathscr{H}=m^2}$

$$\begin{cases} x(t) = \dfrac{p}{\sqrt{m^2+p^2}}\,t + \ell_{QG}\,p\,t + \ldots \\ x(t) = t + \ell_{QG}\,p\,t + \ldots \end{cases}$$

Time delay



Deformed light cone

[Amelino-Camelia, Barcaroli, Gubitosi, Liberati, Loret, PRD (2014)],

[**IPL**, Niccolò Loret, Francisco Nettel, PRD (2017)],

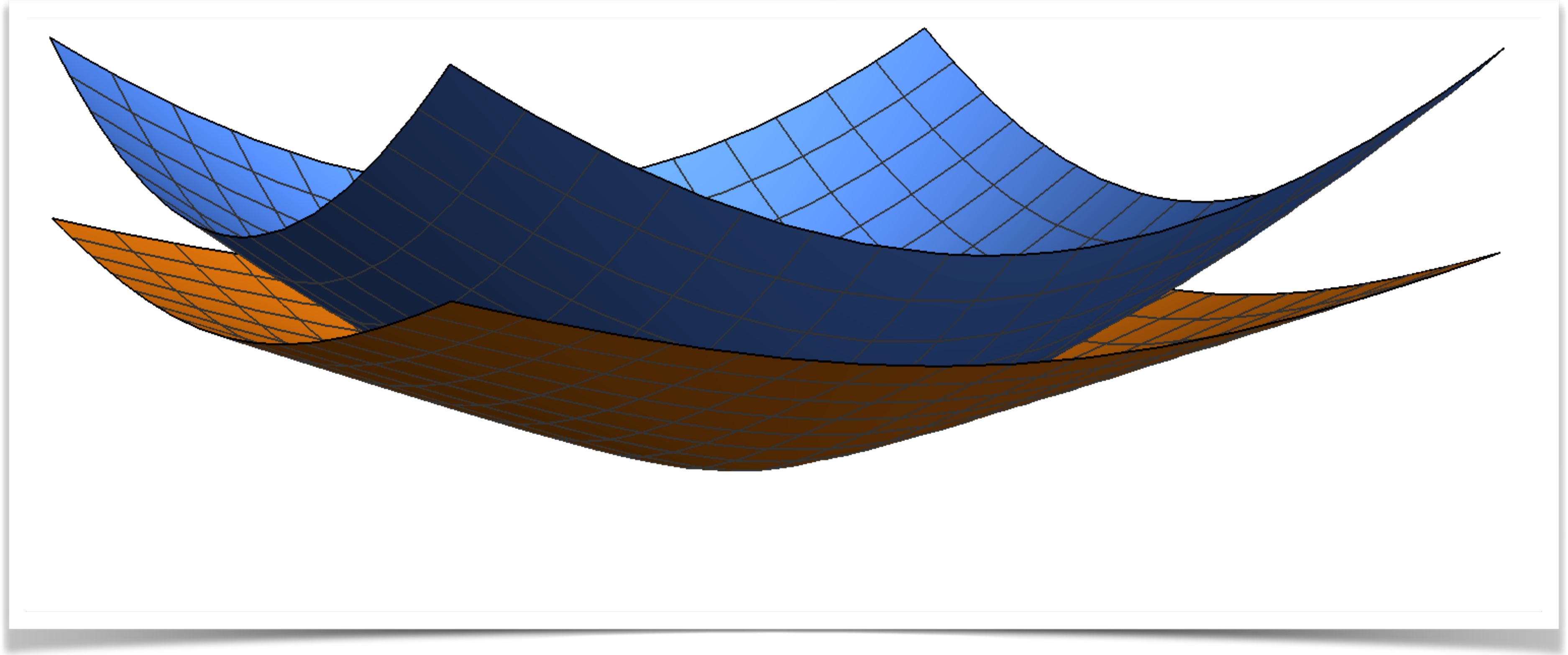
[Zhu, Ma, EPJC (2023)],

- **Symmetries are deformed** from **Killing vectors**

$$g_{(\mu\rho}\partial_{\nu)}\xi^\rho + \frac{\partial g_{\mu\nu}}{\partial x^\rho} + \frac{g_{\mu\nu}}{\partial \dot{x}^\rho}\frac{\partial \xi^\rho}{\partial x^\sigma}\dot{x}^\sigma = 0$$

$$\begin{cases} \tilde{E} \approx E + vp \\ \tilde{p} \approx p + vE - \ell_{QG} v \left(E^2 + \frac{p^2}{2} \right) \end{cases}$$

Symmetries that preserver the mass shell
$\mathscr{H} = g^{\mu\nu}(x, \dot{x}) p_\mu p_\nu$



[Amelino-Camelia, Barcaroli, Gubitosi, Liberati, Loret, PRD (2014)],

[**IPL**, Christian Pfeifer, Pedro H. Morais, Rafael Alves Batista, Valdir B. Bezerra, JHEP (2022)]

[Pedro H. Morais, **IPL**, Christian Pfeifer, Rafael Alves Batista, Valdir B. Bezerra, PLB (2023)]

HAMILTON GEOMETRY

MDR $m^2 = H(E, p)$

Barcaroli, Brunkhorst, Gubitosi, Loret, Pfeifer, PRD (2015)

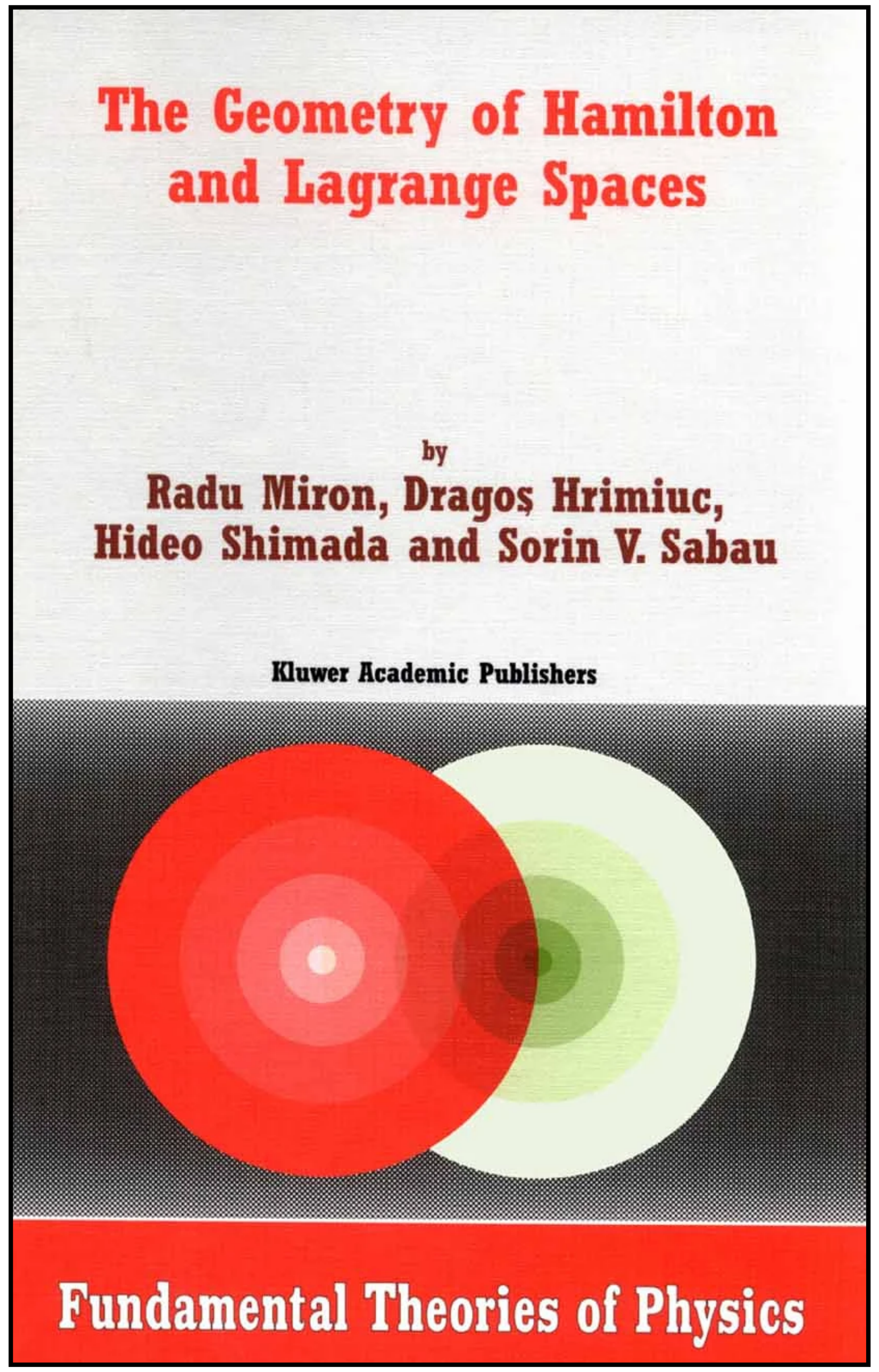
Metric $$g^{\mu\nu} = \frac{\partial^2 H}{\partial p_\mu \partial p_\nu}$$

- This metric is not invariant under reparametrizations, therefore it cannot define an arc-length
- I'm not sure if we can call this approach a geometry, since it can't be used to measure distances
- Nevertheless, the trajectories are found from the Hamilton equations.
- Symmetries can be defined as well from a Killing equation
- There is a canonical connection as well

It's possible to define connections, curvature, etc. All the known geometric quantities of riemannian geometry and beyond

Pedagogical book on Finsler and Hamilton geometries

Our review paper on applications to quantum gravity phenomenology



Quantum Configuration and Phase Spaces: Finsler and Hamilton Geometries

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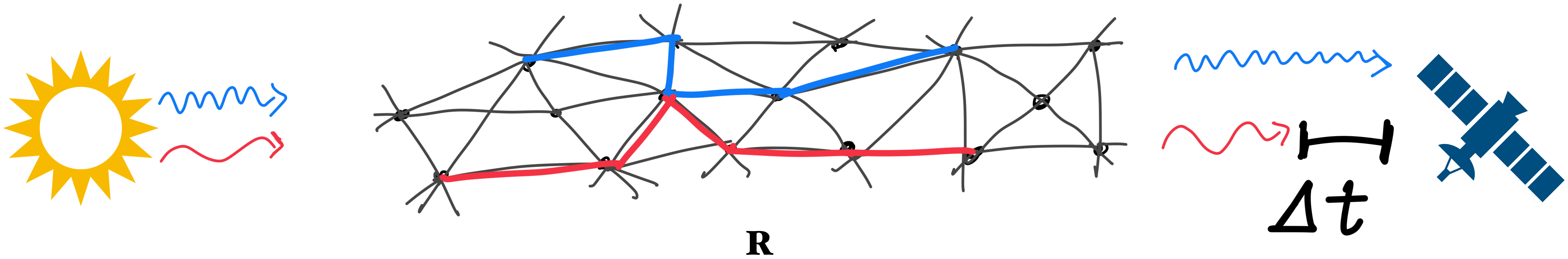
[3] *Physics Department, Federal University of Lavras, Caixa Postal 3037, 37200-000 Lavras-MG, Brazil.*
(Dated: January 24, 2023)

arXiv:2301.09448

SOME IMMEDIATE EFFECTS

Modified Trajectories

Considering a MDR $E^2 = m^2 + p^2 + s\eta^{(n)}\frac{p^{n+2}}{E_{Pl}^n}$ ⇒ $v = \frac{\partial E}{\partial p} = \frac{dx}{dt} = 1 + s\eta^{(n)}\frac{n+1}{2}\frac{p^n}{E_{Pl}^n}$



Time delay due to modified trajectories $\Delta t \sim \frac{\Delta E}{E_{QG}} R$ ← **Amplifies** the effect

This effect is present both in LIV and DSR

Modified interactions

Properties of interactions depend on the dispersion relation and on the conservation law

LIV

Processes that are forbidden in SR are allowed in LIV

The energy threshold of processes of SR are strongly modified in LIV

Ex.: Photon decay is allowed in LIV $\gamma \rightarrow e^+ e^-$

$$\cos(\theta) \simeq \frac{E_+(E_\gamma - E_+) + m_e^2 - \eta E_\gamma E_+(E_\gamma - E_+)/E_p}{E_+(E_\gamma - E_+)}$$

Opening angle between e^+ and e^- can be < 1

DSR

Processes that are forbidden in SR are still forbidden in DSR

The energy threshold of processes of SR are mildly modified in LIV

$$E_\gamma \simeq E_+ + E_- - \eta \vec{p}_+ \cdot \vec{p}_- \ ,$$

$$\vec{p}_\gamma \simeq \vec{p}_+ + \vec{p}_- - \eta E_+ \vec{p}_- - \eta E_- \vec{p}_+ \ .$$

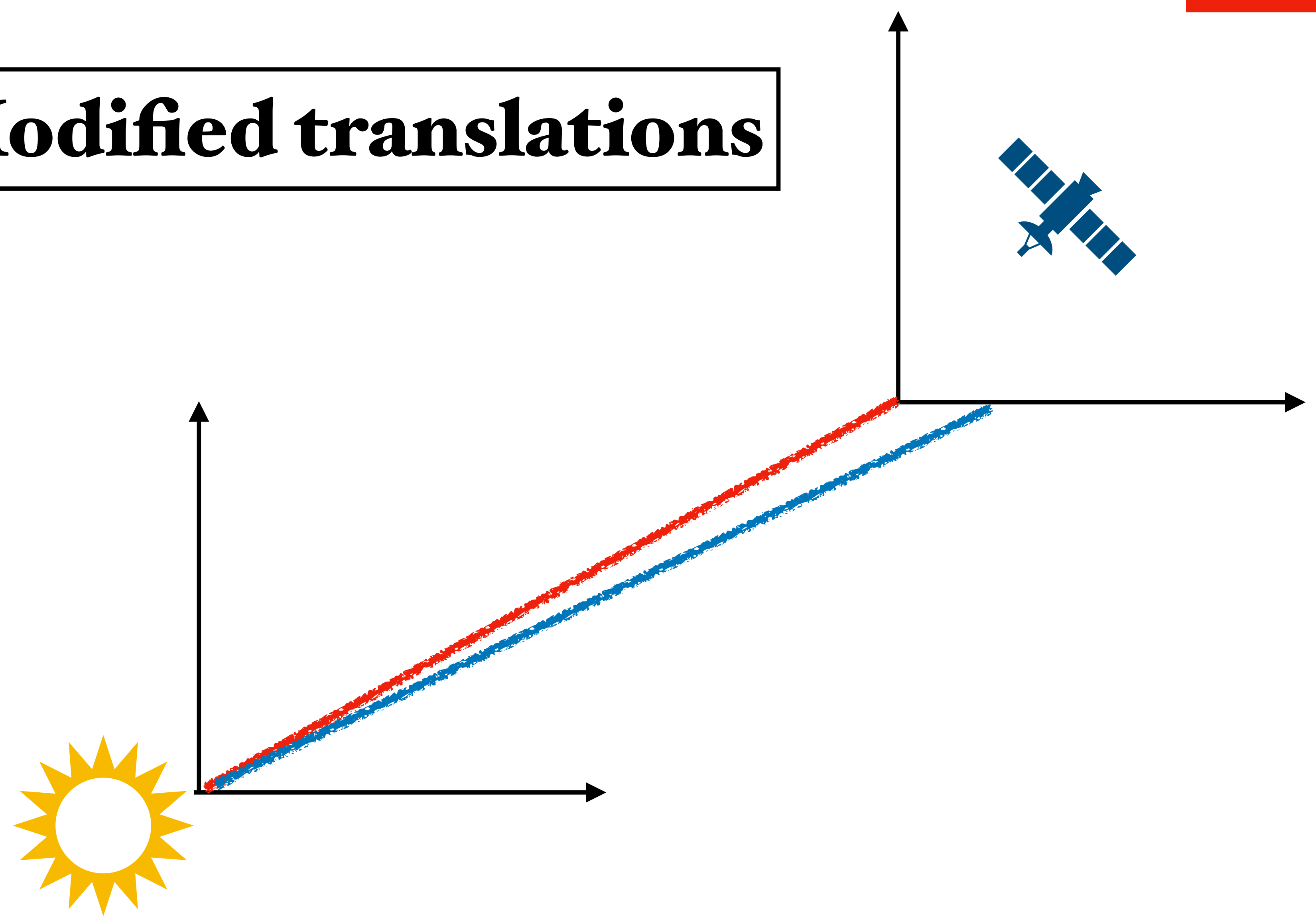
$$\cos(\theta) \simeq \frac{2E_+(E_\gamma - E_+) + \eta E_\gamma E_+(E_\gamma - E_+) + 2m_e^2}{2E_+(E_\gamma - E_+) + \eta E_\gamma E_+(E_\gamma - E_+)}$$

Always larger than 1

Amelino-Camelia, Liv. Rev. Rel. (2013)

Modified symmetries (absent in LIV)

Modified translations

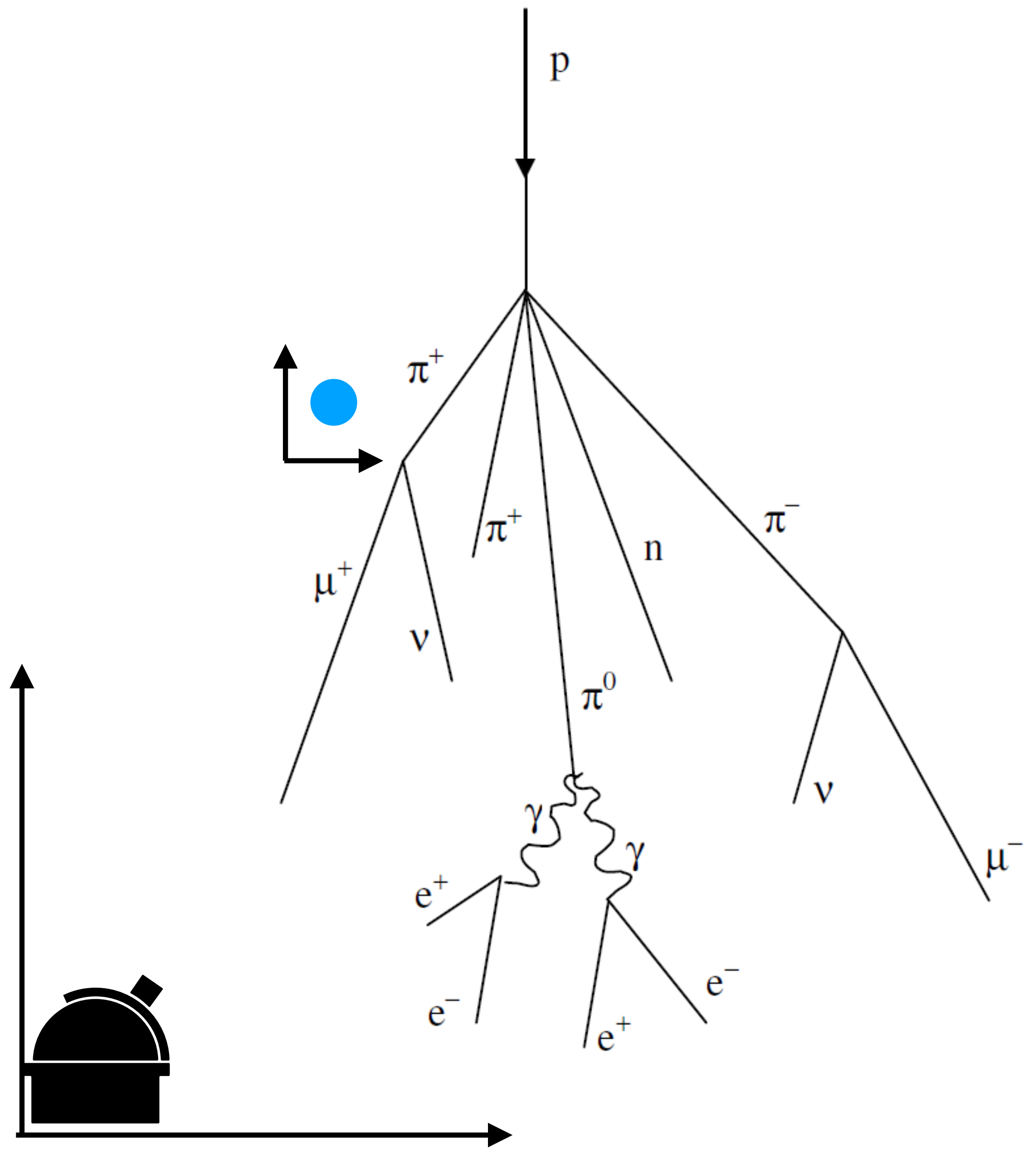


Not only trajectories are modified, but the emission and detection events are distant and differ by a translation, and depending on the emission event, the boost cannot be disregarded

This modifies the prediction for time delays

Modified boost

Modifies the lifetime of particles measured in the lab frame



Modified rotation

Usually rotations are not deformed due to the isotropic nature of the dispersion relation

Beyond Modified Dispersion Relations

Generalized Uncertainty Principle

Quantum gravity may introduce an extra degree of uncertainty in spacetime, beyond the usual Heisenberg principle

$$\Delta p_x \approx \frac{h}{\Delta x} + G\rho^2 V \Delta x \Delta t.$$

$$[\hat{x}^i, \hat{p}_j] = i \left[1 + \alpha \frac{\hat{p}}{E_{Pl}} + \beta \frac{\hat{p}^2}{E_{Pl}^2} + \dots \right] \delta^i_j$$

$$\hat{H} = \frac{\hat{p}^2}{2M} + V(\hat{x}),$$

It's possible to map this formalism into one that preserves the Heisenberg principle, but modifies the Schrödinger equation

$$[\hat{x}^i, \hat{k}_j] = i\delta^i_j,$$

$$\hat{H} = \frac{\hat{k}^2}{2M} + V(\hat{x}) + \delta H(\hat{k}).$$

Wagner, Varão, Lobo, Bezerra, PRD (2023)

This leads to several effects like violation of the equivalence principle, decoherence by a quantum spacetime, shift in energy levels, that **are being constrained nowadays with Planck scale sensitivity**.

Amelino-Camelia, Laemmerzahl, Mercati, Tino, PRL (2009)

Violation of Pauli Exclusion Principle (spin statistics) — Piscicchia et al., PRL (2022)

CPT violation and decoherence — Mavromatos, Lect. Not. Phys. (2005)

Spacetime fuzziness — Vasileiou, Granot, Piran, Amelino-Camelia, Nature Physics (2015)

Petruzziello, Illuminati, Nature Communications (2021)

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Please refer to

Giovanni Amelino-Camelia, "Quantum Spacetime Phenomenology", Living Reviews in Relativity 16 (2013) 5
arXiv:0806.0339

Andrea Addazzi et al., "Quantum gravity phenomenology at the dawn of the multi-messenger era -- A review", Progress in Particle and Nuclear Physics 125 (2022) 103948
arXiv:2111.05659

Rafael Alves Batista et al., "White Paper and Roadmap for Quantum Gravity Phenomenology in the Multi-Messenger Era", arXiv:2312.00409

As a continuation of the activities of a recent COST Action, called "Quantum Gravity Phenomenology in the Multimessenger Approach" (from which Humberto and myself are part of).

The members created a Network, called QGMM, intended to bring closer experimentalists and theoreticians to push forward this area.

We have a newsletter to be informed about relevant information for our community, like calls for positions, conferences, schools, etc...

https://sites.google.com/view/qgmm/newsletter/sign-up?authuser=0

Thank you!
Obrigado!