WG1: Quantum gravity and its phenomenology - theoretical perspectives from high energy

Alessia Platania

BridgeQG annual conference

Paris, 7 July 2025

The Niels Bohr International Academy

THE CENTER OF GRAVITY

UNIVERSITY OF COPENHAGEN

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WG1: Quantum gravity and its phenomenology - theoretical perspectives from high energy

BridgeQG working groups

- **WG1: HE th. of QG:** Christian Pfeifer, Alessia Platania
- **WG2: HE exp. searches for QG**: Tomislav Terzic, Alba Domi
- **WG3: LE th. of Gravity and QM**: Lin-Qing Chen, Tom Galley
- **WG4: LE exp. searches for QG**: Matteo Fadel, Catalina Curceanu
- **WG5: LE-HE combining results**: Flavio Mercati, Giacomo Rosati
- **WG6: Dissemination and Diversity**: Jelena Strišković, Denitsa Staicova

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- **WG1: HE th. of QG:** Christian Pfeifer, Alessia Platania

- **Outline**:

  HE QG: top-down high-energy QG

  HE QG: bottom-up parametrizations of some effects
  WG1: what we have done so far and what we will do in the future

Introduction to the problem

Two building blocks in Theoretical Physics:

General Relativity

- Based on Einstein Theory
- Classical theory
- Describes the gravitational interaction

Standard Model of particle physics

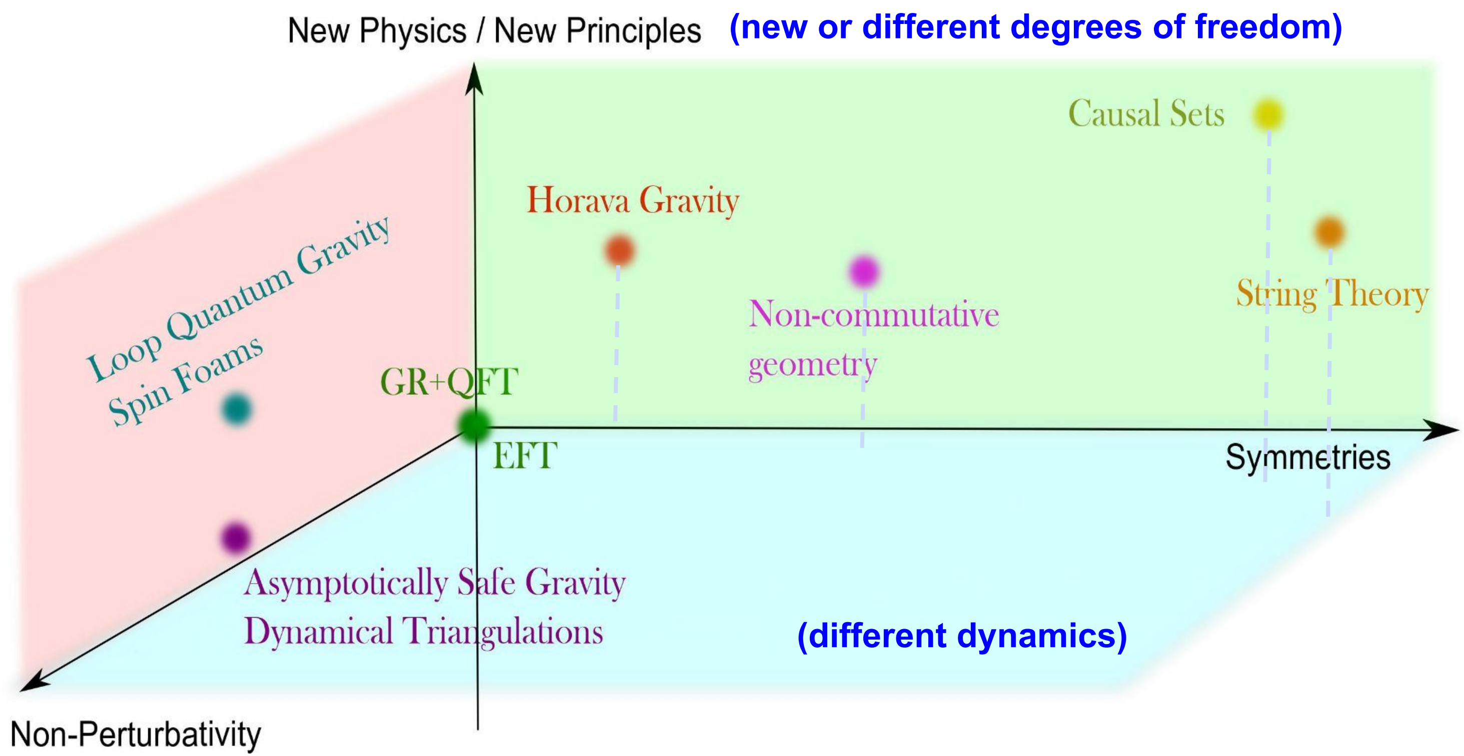
- Based on Quantum Field Theory
- Quantum Theory
- Describes electromagnetic, strong and weak interactions

How to define a **Quantum Theory of Gravity**, aka, **Quantum Gravity**?

Problem: a quantum field theory of gravity is inconsistent due to the appearance of at least one of the following problems:

- **Non-renormalizability**: infinities—integrals diverge
- **Non-unitarity**: probabilities do not sum up to one

The Realm of Quantum Gravity



Difficult to constrain:
QG *presumably* lives at the Planck scale!

State of the art in Quantum Gravity

SciPost Physics Lecture Notes Submission

Lectures in Quantum Gravity

Ivano Basile[1⋆], Luca Buoninfante[2†], Francesco Di Filippo[3‡],
Benjamin Knorr[4∘], Alessia Platania[5¶] and Anna Tokareva[6‖]

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∘ knorr@thphys.uni-heidelberg.de , ¶ alessia.platania@nbi.ku.dk , ‖ tokareva@ucas.ac.cn

Abstract

Formulating a quantum theory of gravity lies at the heart of fundamental theoretical physics. This collection of lecture notes encompasses a selection of topics that were covered in six mini-courses at the Nordita PhD school *"Towards Quantum Gravity"*. The scope was to provide a coherent picture, from its foundation to forefront research, emphasizing connections between different areas. The lectures begin with perturbative quantum gravity and effective field theory. Subsequently, two ultraviolet-complete approaches are presented: asymptotically safe gravity and string theory. Finally, elements of quantum effects in black hole spacetimes are discussed.

SciPost Physics Community Reports Submission

Visions in Quantum Gravity

Luca Buoninfante[1⋆], Benjamin Knorr[2†],
K. Sravan Kumar[3‡], Alessia Platania[4∘],

Damiano Anselmi[5], Ivano Basile[6], N. Emil J. Bjerrum-Bohr[4], Robert Brandenberger[7], Mariana Carrillo González[8], Anne-Christine Davis[9], Bianca Dittrich[10], Paolo Di Vecchia[11], John F. Donoghue[12], Fay Dowker[8, 10], Gia Dvali[13], Astrid Eichhorn[2], Steven B. Giddings[14], Alessandra Gnecchi[15], Giulia Gubitosi[16, 17], Lavinia Heisenberg[2], Renata Kallosh[18], Alexey S. Koshelev[19], Stefano Liberati[20, 21, 22], Leonardo Modesto[23], Paulo Moniz[24], Daniele Oriti[25, 26], Olga Papadoulaki[27], Jan M. Pawlowski[2], Roberto Percacci[20], Lesław Rachwał[28], Mairi Sakellariadou[29], Alberto Salvio[30, 31], Kellogg Stelle[8], Sumati Surya[32], Arkady Tseytlin[8], Neil Turok[33], Thomas Van Riet[34], and Richard P. Woodard[35]

⋆ luca.buoninfante@ru.nl , † knorr@thphys.uni-heidelberg.de ,
‡ sravan.kumar@port.ac.uk , ∘ alessia.platania@nbi.ku.dk

Abstract

To deepen our understanding of Quantum Gravity and its connections with black holes and cosmology, building a common language and exchanging ideas across different approaches is crucial. The Nordita Program *"Quantum Gravity: from gravitational effective field theories to ultraviolet complete approaches"* created a platform for extensive discussions, aimed at pinpointing both common grounds and sources of disagreements, with the hope of generating ideas and driving progress in the field. This contribution summarizes the twelve topical discussions held during the program and collects individual thoughts of speakers and panelists on the future of the field in light of these discussions.

Hot topics and important questions in fundamental QG research?

Short answer: we even disagree on which questions are important

Long answer: surely there are some hot topics in the community and some key open questions:

- ***What are the features of quantum gravity?*** Non-locality, holography, non-perturbativity, non-commutativity…
- ***What are the fundamental degrees of freedom?*** metric, strings, area metrics, torsion, holonomies…
- ***"Swampland program": universal features of quantum gravity at low energy?***
- ***Coupling with matter***: which quantum gravity theories are compatible with the Standard Model?
- ***Is quantum gravity a QFT or do we need to go beyond it?***
- …

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Key questions

How do we discriminate between different approaches?

How do we test different theories?

What are possible amplification effects and low-energy signatures of QG?

Intermediate Question

What do we expect from QG at high energy?

Intermediate Question

What do we expect from QG at high energy?

$\Downarrow$

How do we consistently go beyond GR?

The HE-theory side: concepts at the foundation of the main QG ideas

Approaches quantizing the gravitational interaction (idea: start from EFT/QFT)

Approaches quantizing the spacetime (idea: start from GR/geometry)

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***QFT-based**: keep QFT, give up on something else*:

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- **Asymptotically safe gravity / dynamical triangulations**: give up on perturbativity → dim reduction
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- **String Theory**: particles → extended objects, strings at weak coupling; reduces to QFT at low energies; extra dim

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- **Loop quantum gravity**: canonical quantization of GR in terms of new variables (holonomies), implement constraints
- **Spin foams**: inspired from loop quantum gravity, re-starts from path integral over “area metrics”
- **Group field theory**: quantum field theory on a group manifold
- **Causal sets**: fundamental principle is causal relations → fluctuating vacuum energy

From the HE-theory to potential observations: key features and effects

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Moreover:

- ***Scattering amplitudes to distinguish HE QG*** (testable signatures?)
- ***Non-commutativity as general feature?*** (Fröb, ‘23)
- ***Swampland program*: common features of consistent QGs?** (Palti, ‘19)
  → black holes & topology changes make a difference (Basile, Knorr, Platania, Schiffer, ‘25)
- ***Consistency with Standard Model*** (Eichhorn, Schiffer, ‘22)
  → postdictions as ways to rule out theories
- ***Quantum spacetime from first principles in Quantum Gravity?***

(Incomplete list of) **questions tackled by top-down HE QG community**

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Focus of BridgeQG

Next steps within BridgeQG:

- **Bottom-up HE theory**:
  parametrize effects
  (WG1 → C. Pfeiffer's talk)
- **LE theory**: QM+GR at low energies
- **Come up with experiments** (WG2, WG4)
- **Combine results** (WG5)

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Universität Bremen

QuantumFrontiers
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CENTER OF
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AND MICROGRAVITY
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Center for applied space science and microgravity (ZARM)

Fachbereich 04
Faculty of Production Engineering

Bridge-QG WG1

Quantum gravity and its phenomenology - theoretical perspectives from high energy

Alessia Platania, Christian Pfeifer

Dr. Christian Pfeifer
BridgeQG, first annual conference, July 2025 Paris

cost
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Quantum Gravity - Why and How?

Quantum Gravity

Quantum Gravity

LLI renormalizable QFT

Geometry of spacetime

Quantum Gravity

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Geometry of spacetime

Approaching QG from two perspectives

Quantum Gravity

LLI renormalizable QFT **Geometry of spacetime**

Approaching QG from two perspectives

Theoretical Construction Methods
Fundamental Approaches to QG
(Top-Down approach)

- Turn GR into a LLI renormalizable QFT
- Quantise the geometry of spacetime
- Quantise spacetime itself
- Unify Gravity and SM

[Kiefer 2012, Basile et. al 2025, Buoninfante et. al 2025]

Quantum Gravity

LLI renormalizable QFT

Geometry of spacetime

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[Kiefer 2012, Basile et. al 2025, Buoninfante et. al 2025]

Searching for observations
Phenomenological models for QG effects
(Bottom-Up approach)

- Determine effects on particles and fields propagating on and interacting with quantum spacetime
- Deviations from GR + SM predictions
- Give guidelines for low-energy / (semi)-classical limits of a fundamental theory of QG

[Addazi et. al 2021, Alves-Batista et. al 2023]

Quantum Gravity Phenomenology - Predicting and searching QG effects

Propagation of probe particles and fields on quantum spacetime

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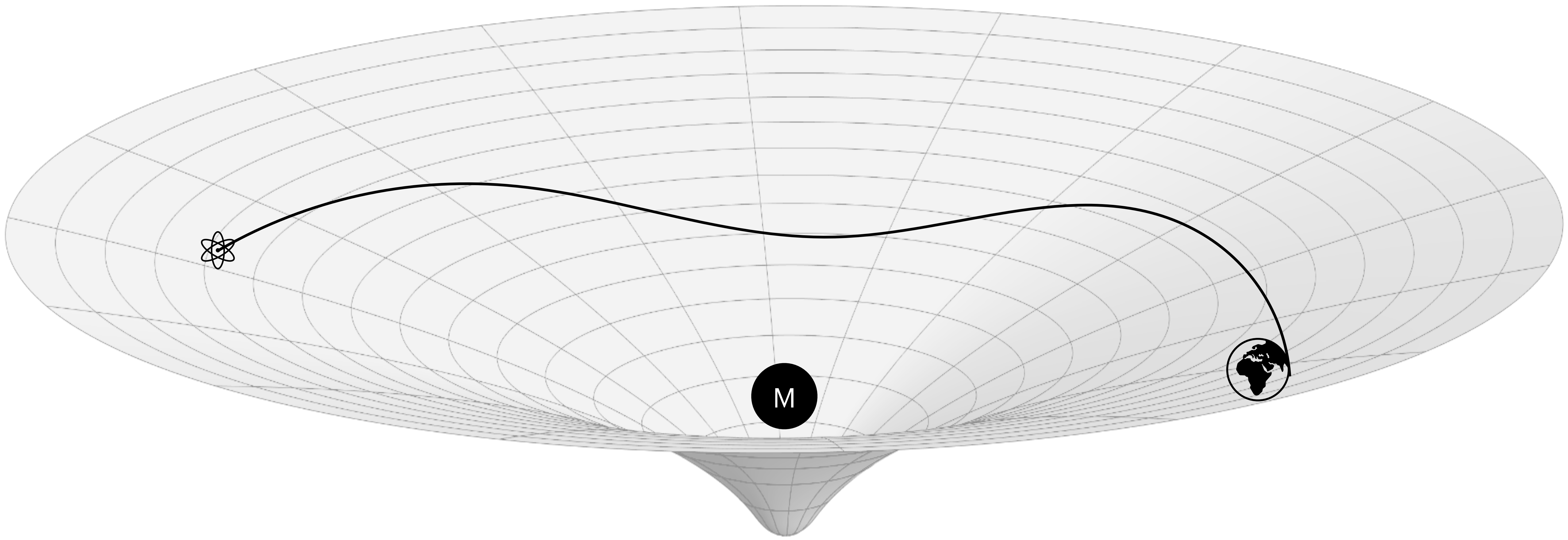
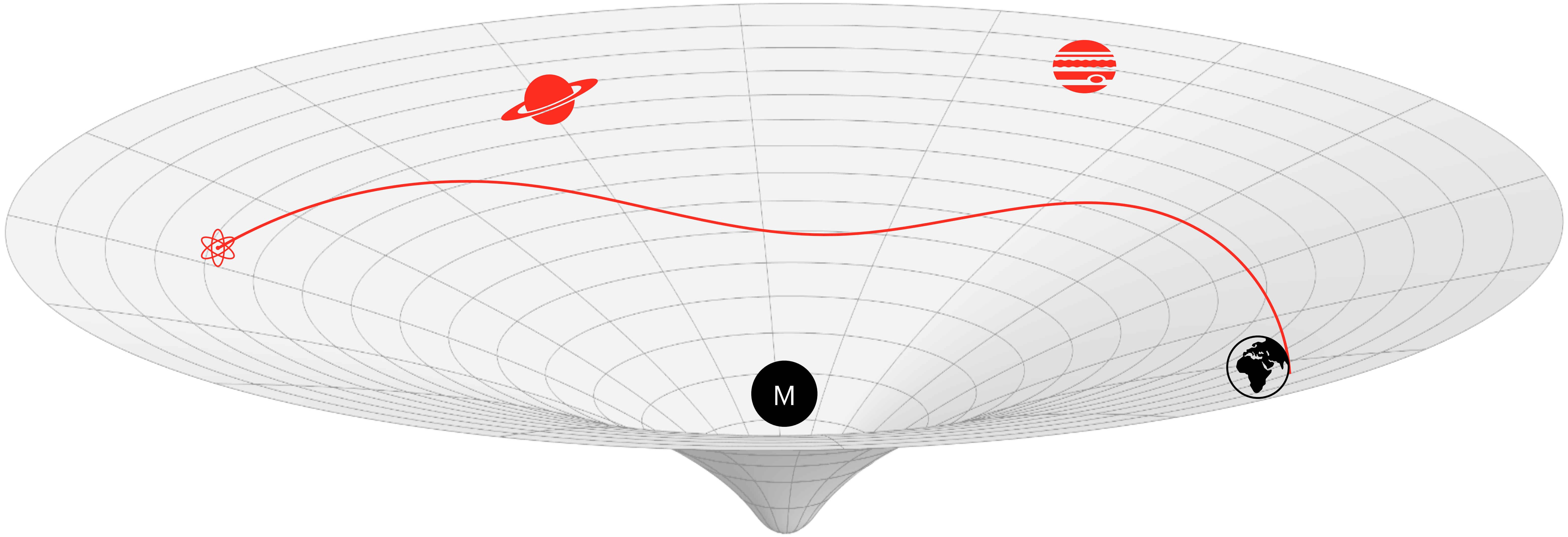


The idea

Propagation of probe particles and fields on quantum spacetime



The idea

- low energy particles see classical spacetime

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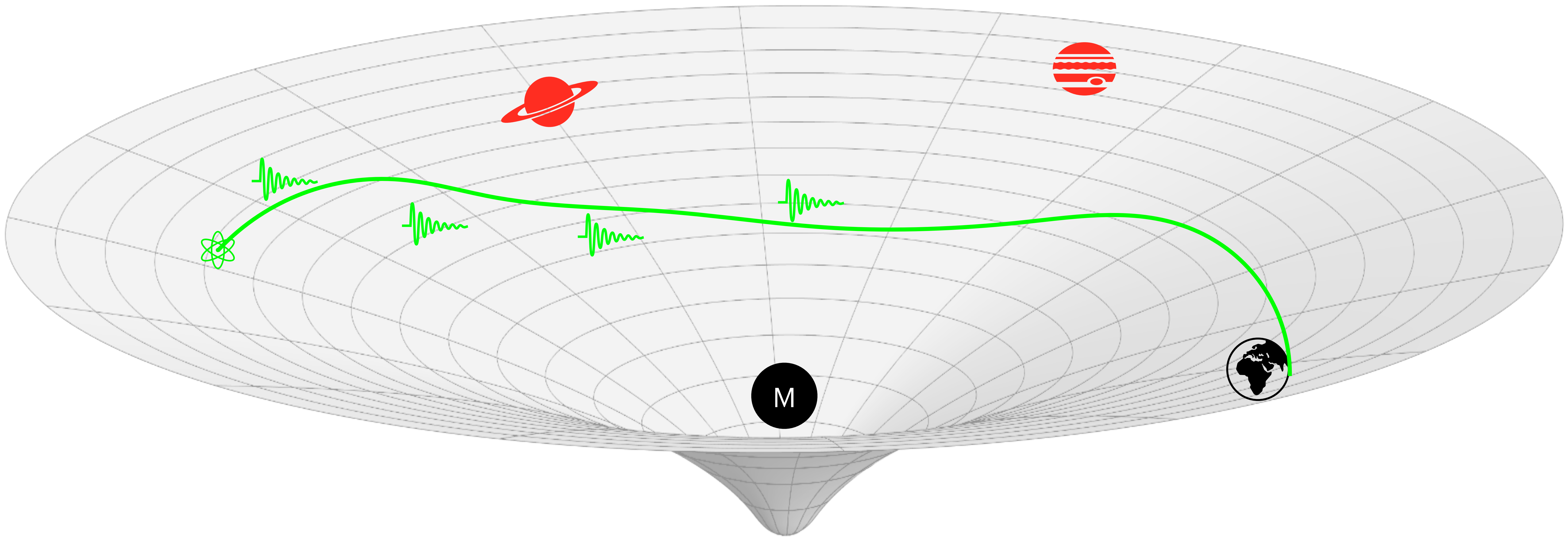

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- higher energetic particles see smaller scales

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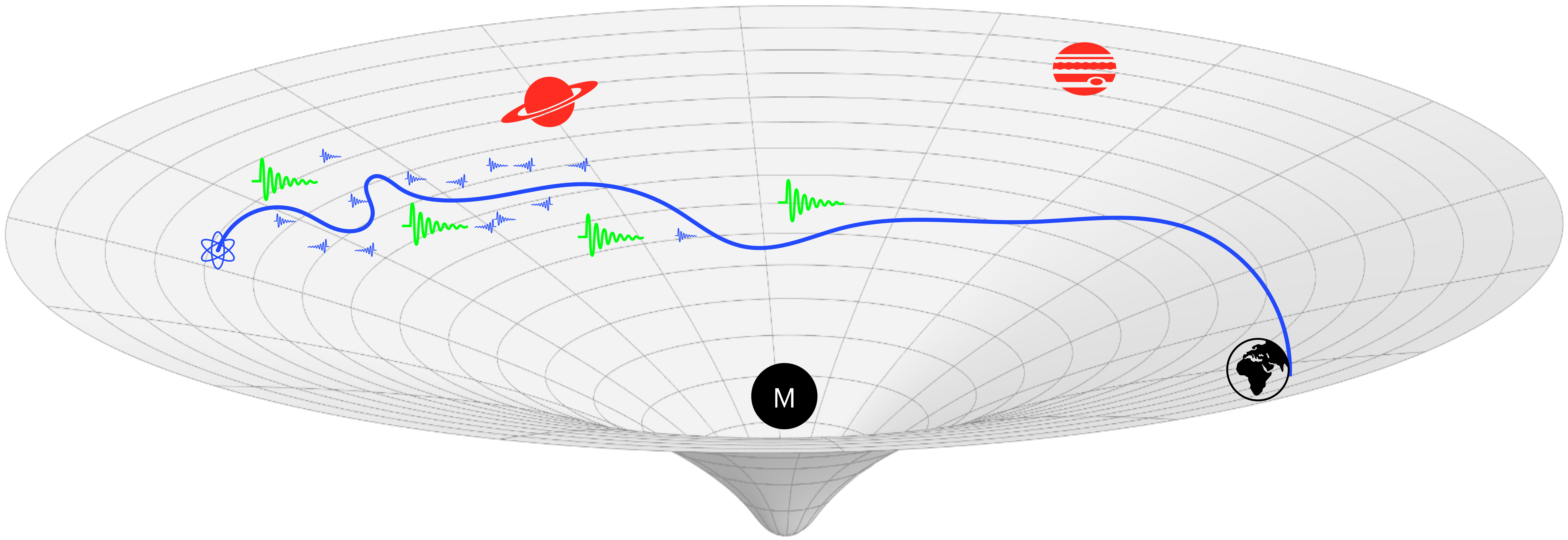
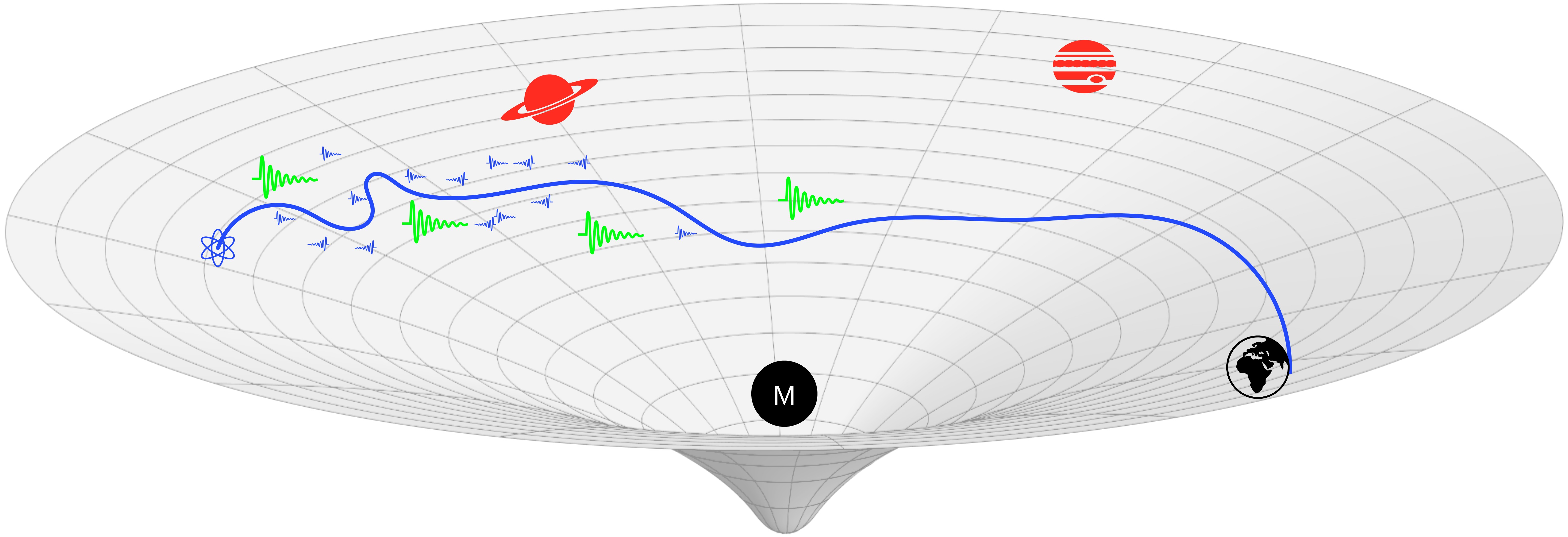


The idea

- low energy particles see classical spacetime
- higher energetic particles see smaller scales
- highest energetic particles see QG effects

Propagation of probe particles and fields on quantum spacetime



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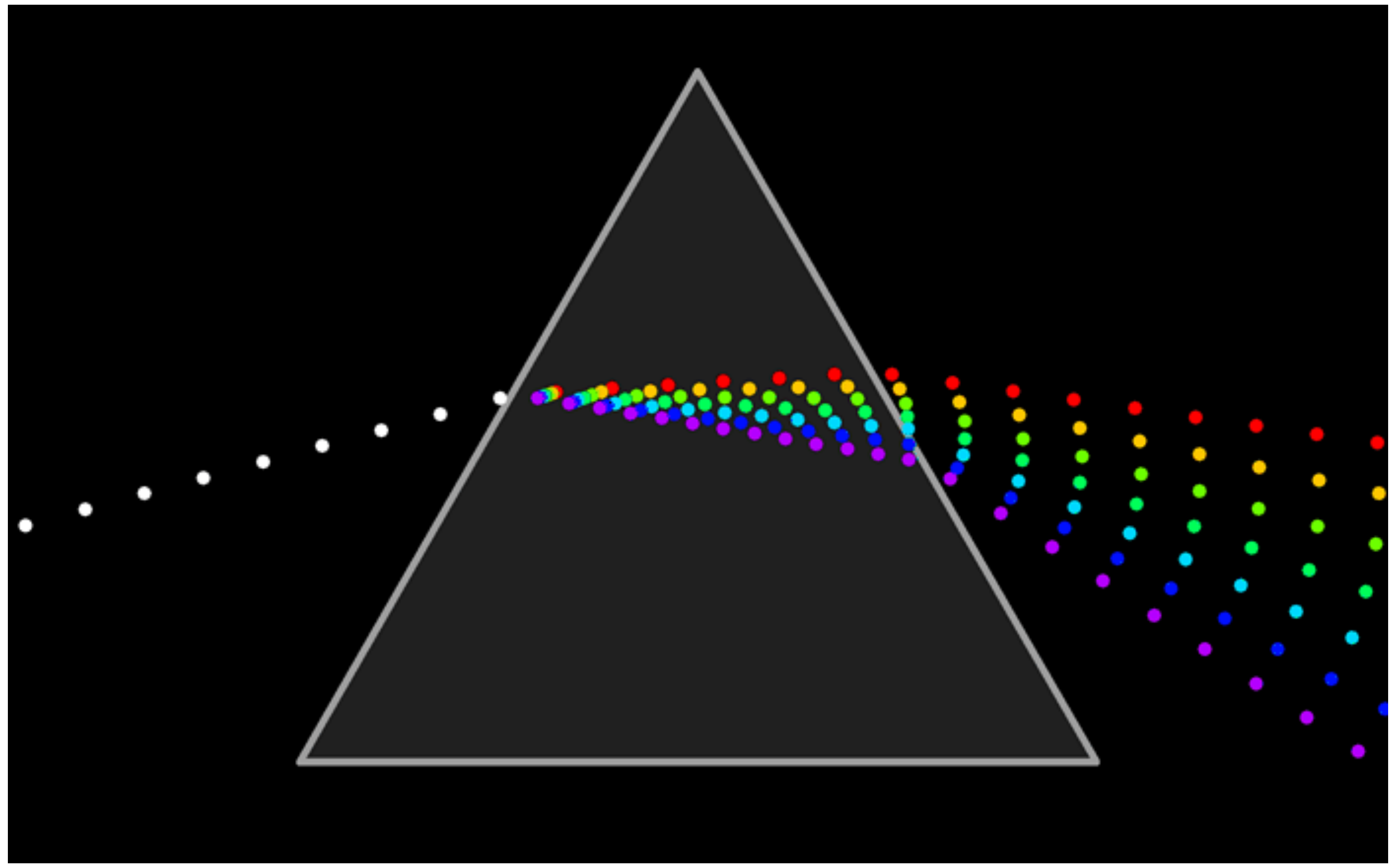
Consequences

- deviations from the GR predicted behaviour
- deviations in particles SM interactions
- deviations in the QM predicted behaviour

Analogy: Models of propagation of light though a medium



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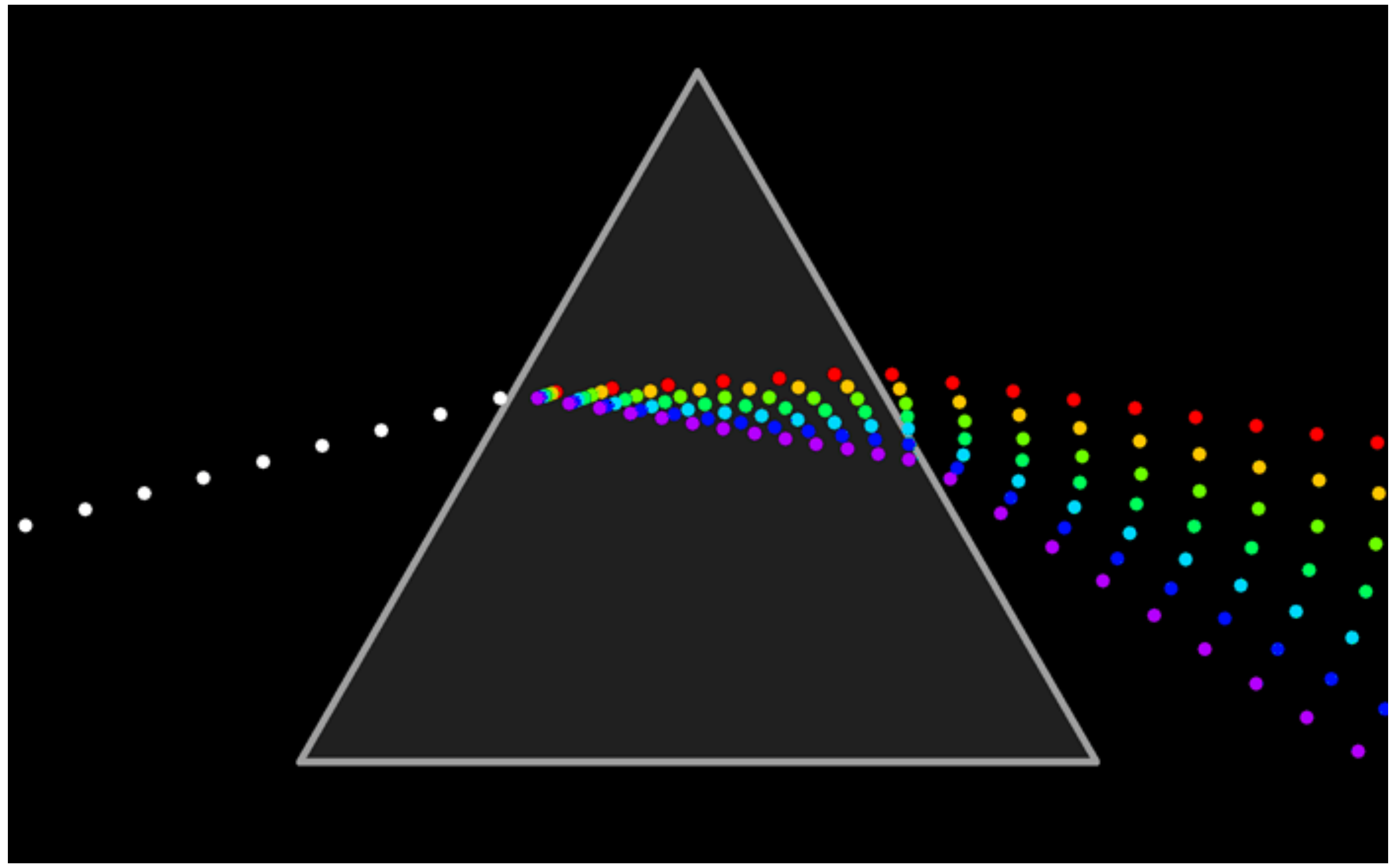

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- compared to higher energetic light
- or highest energetic light

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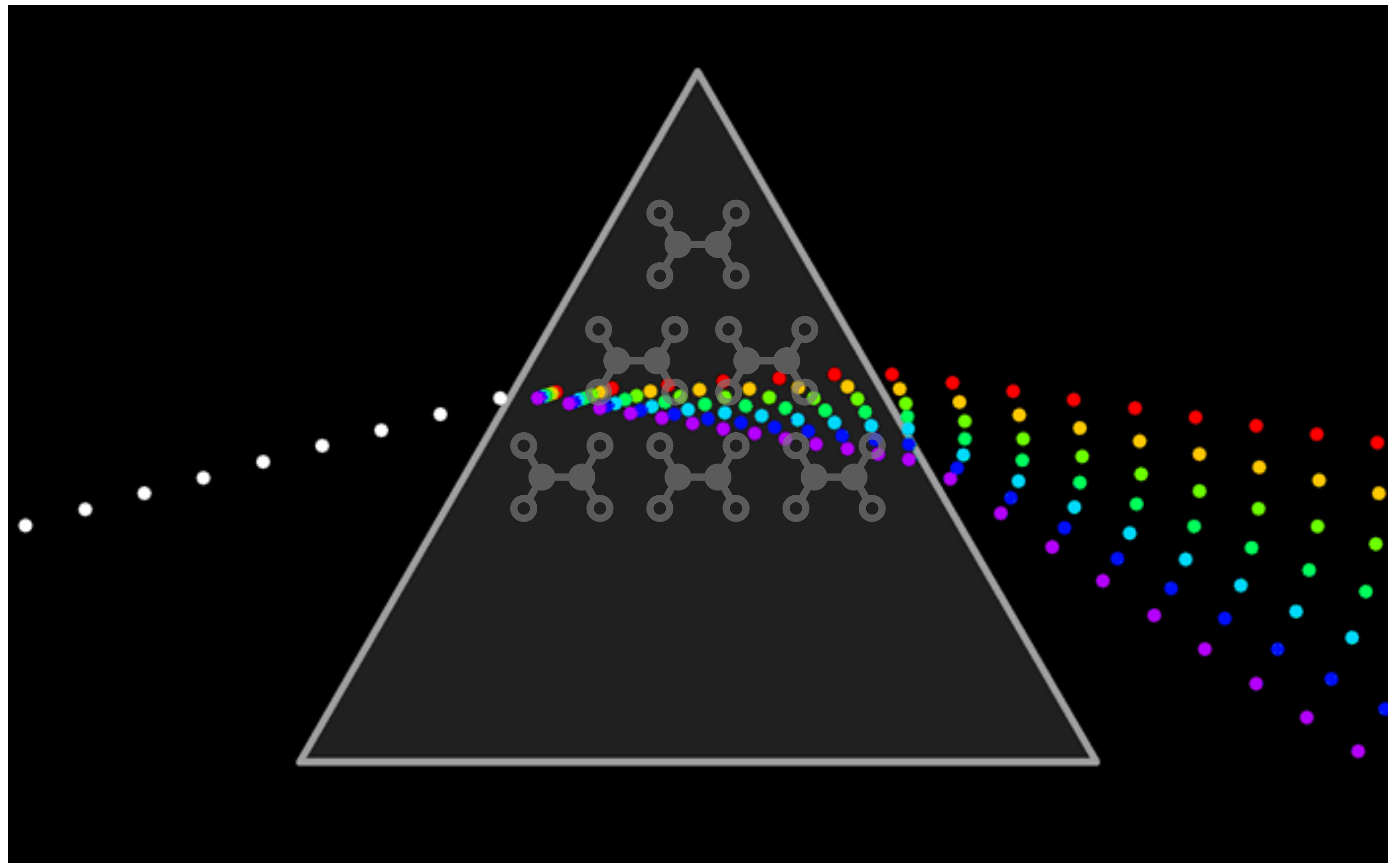

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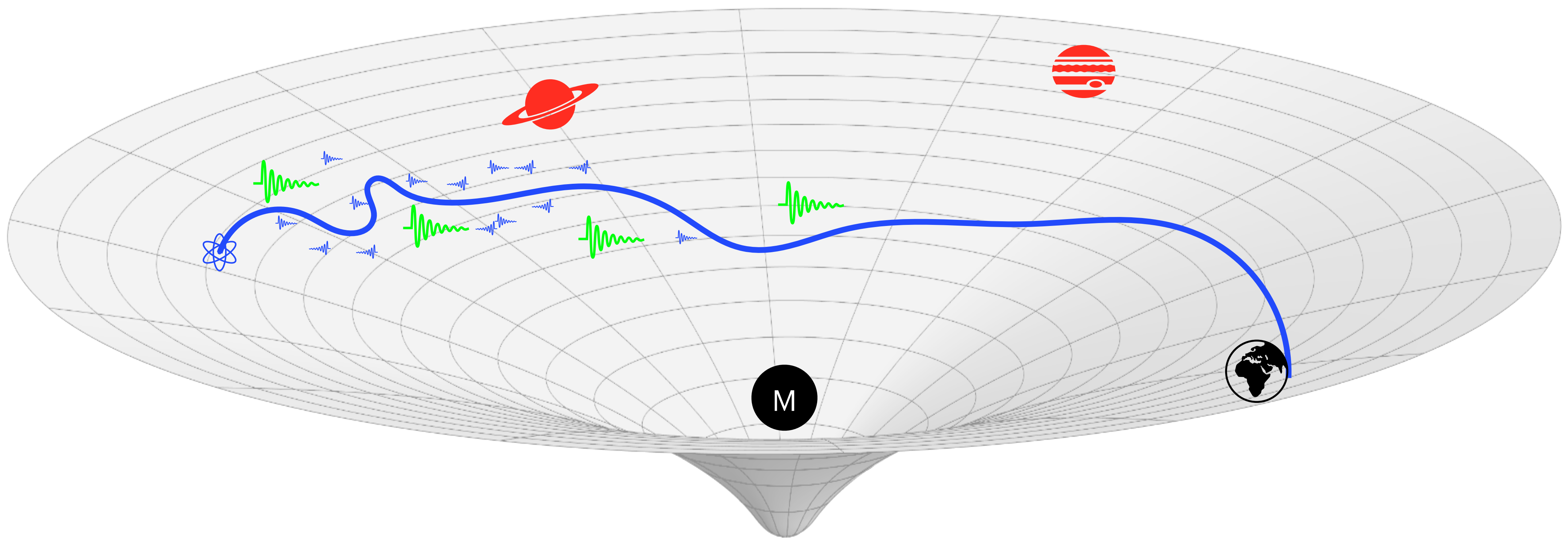
Understanding

- Fundamental theory: LLI standard model interaction between light and constituent of the prism
- effective description: modified light propagation, not necessarily LLI

Propagation of probe particles and fields on quantum spacetime



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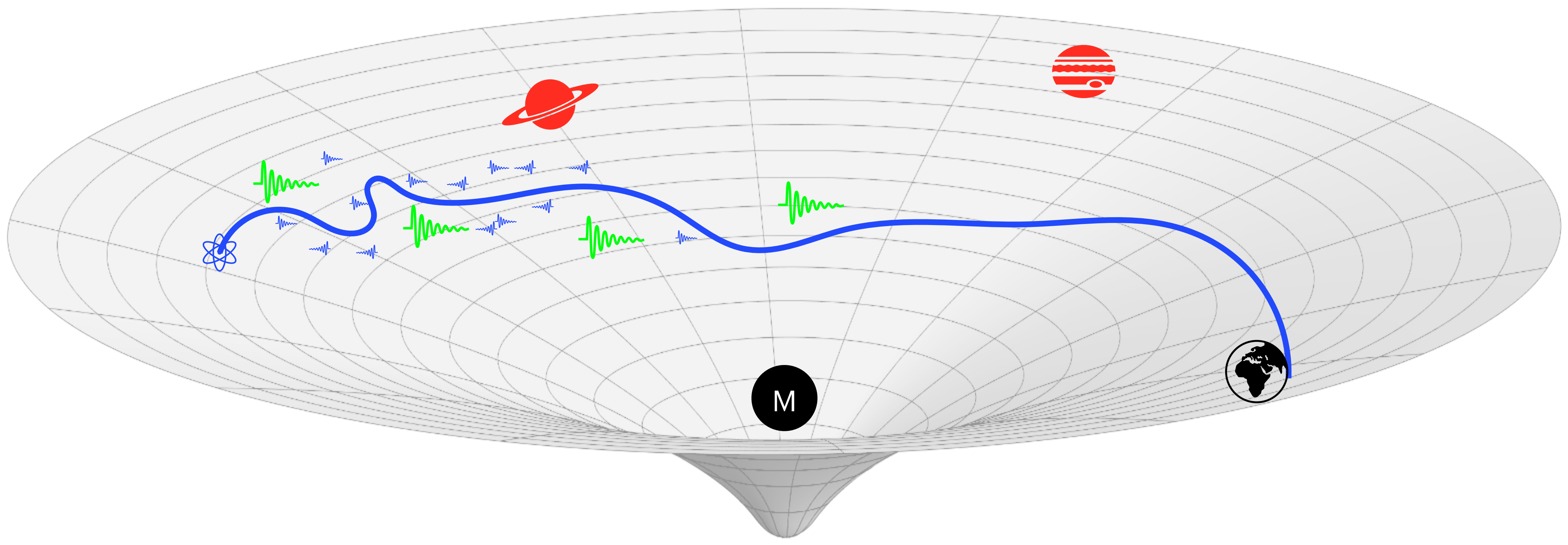

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Searching for observations

Deviations from GR + SM predictions: What kind of effects?

- Decoherence effects
- Deviations from CPT symmetry
- Anomalous, energy-momentum dependent time delays
- Optical and gravitational birefringence
- Modified interactions and threshold reactions
- …

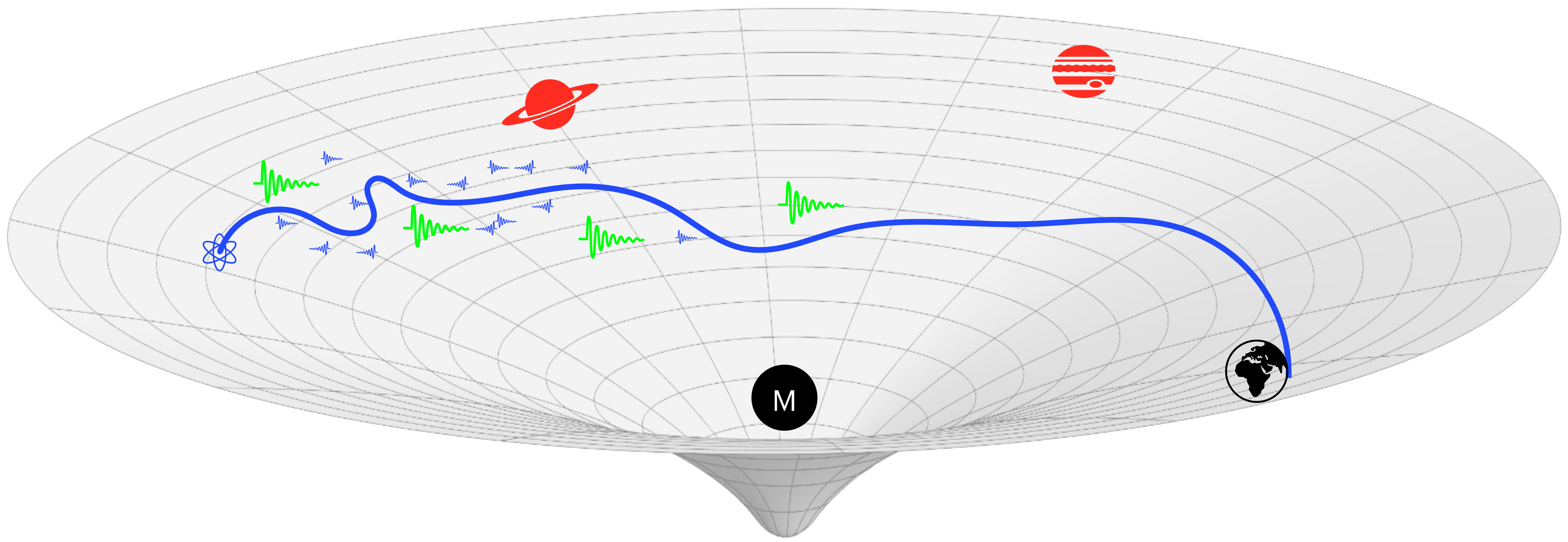
Phenomenological models

- Deformed/Doubly Special Relativity, Relative Locality
- Momentum/Velocity dependent spacetime geometries
- Generalised Uncertainty Principle
- Classical modified gravity as effective field theory for QG
- Non-commutative geometry
- Standard Model Extension
- …

[Addazi 2021, Alves-Batista 2023]

Quantum Gravity Phenomenology - Predicting and searching QG effects

Propagation of probe particles and fields on quantum spacetime



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Ask us everything you want to know!

Searching for observations

Deviations from GR + SM predictions: What kind of effects?

- Decoherence effects
- Deviations from CPT symmetry
- Anomalous, energy-momentum dependent time delays
- Optical and gravitational birefringence
- Modified interactions and threshold reactions
- …

Phenomenological models

- Deformed/Doubly Special Relativity, Relative Locality
- Momentum/Velocity dependent spacetime geometries
- Generalised Uncertainty Principle
- Classical modified gravity as effective field theory for QG
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[Addazi 2021, Alves-Batista 2023]

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Decoherence effects
Quantum systems interacting with an environment

- Described by the Lindblad equation

$$\dot{\rho} = -i[H,\rho] + D[\rho], \quad D[\rho] = \sum_j (\{\rho, D_j^\dagger, D_j\} - 2D_j\rho D_j^\dagger)$$

- Interaction of particles in coherent states with QG environment, leads to decoherence
- Examples study QG decoherence of mesons and neutrinos

[Studdard 2020, Lisi 2000, Vasileiou 2015, Mavromatos 2017, Giesel 2024, …]

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Deviations from CPT symmetry

- Standard Model Extension (SME) deformed Dirac matrices

$$\Gamma^\mu_{AB} = \gamma^\mu \delta_{AB} + c^{\mu\nu}_{AB}\gamma_\nu + d^{\mu\nu}_{AB}\gamma_\nu\gamma_5 + e^\mu_{AB} + if^\mu_{AB}\gamma_5 + g^{\mu\nu}_{AB}\gamma_\nu + \frac{1}{2}h^{\mu\alpha\beta}_{AB}\sigma_{\alpha\beta}$$

- CPT operator on non-commutative spacetime / DSR

$$CPT(\vec{p}) = -\vec{p}\frac{\kappa}{E+\sqrt{E^2-\vec{p}^2+\kappa^2}} = -\overrightarrow{S(P)}$$

[Kostelecky 2013, Arzano 2019, …]

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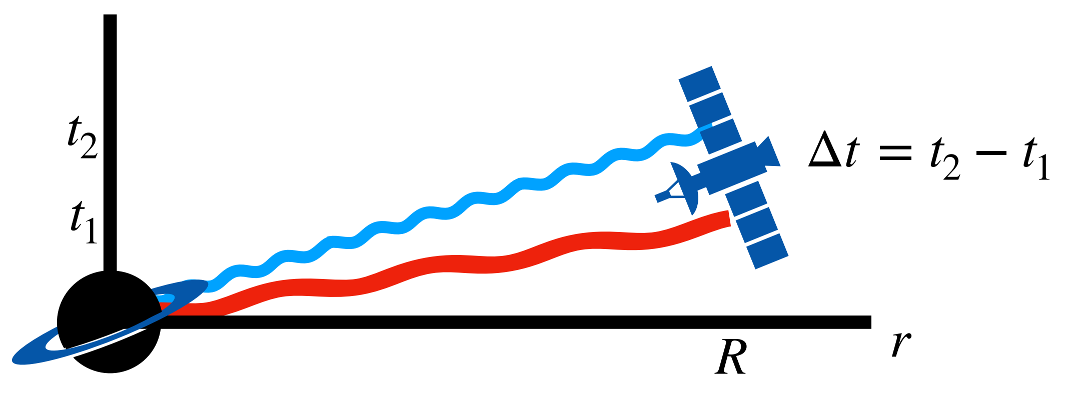
Time Delays



$$\Delta t = \frac{(E_1 - E_2)\kappa(z)}{\Lambda}$$

- Derived from modified dispersion relations

$$E = \frac{pc}{a}\left(1 - \frac{1}{2}\frac{1}{\Lambda}\left[B_m \frac{pc}{a(t)^m}\right]\right)$$

[Piran 2006; Rosati 2015; CP2018, Bolmont 2022, Amelino-Camelia 2024, Caroff 2025, ….]

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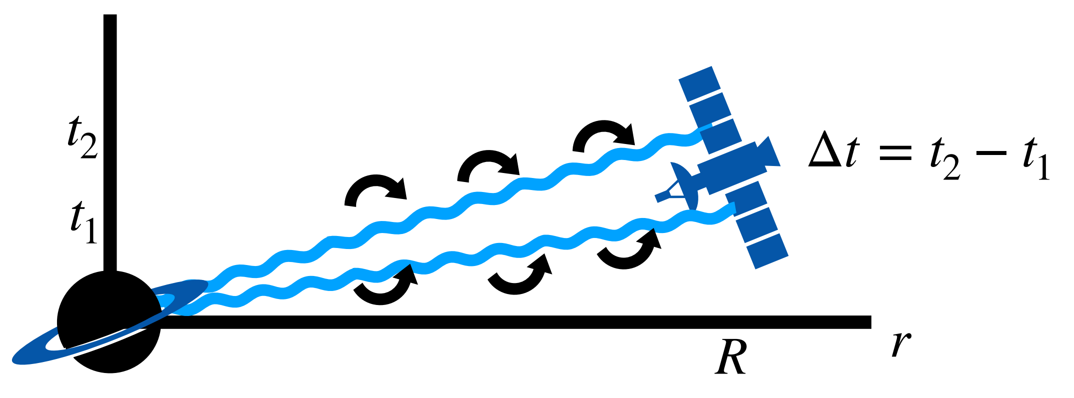
Birefringence effects



$$\Delta t = (c_+ - c_-) d(z)$$

- Derived from polarisation dependent dispersion relation

$$E = \frac{pc}{a}\left(1 - \frac{1}{2}\frac{1}{\Lambda}\left[B^{\pm}_{m} \frac{(pc)}{a(t)^m} \right]\right)$$

[Kostelecky 2016, Ezquiaga 2020, …]

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Quantum Gravity Phenomenology - Predicting and searching QG effects

Propagation of probe particles and fields on quantum spacetime

Modified interactions and threshold reactions

Example: $\gamma \to e^+ + e^-$

- Modified dispersion relation

$$E^2 - \vec{p}^2 c^2 + \ell_{DSR/LIV} E \vec{p} c = m^2 c^4$$

- Modified energy-momentum conservation law

$$E_\gamma = E_{e^+} + E_{e^-} \quad \vec{p}_\gamma = \vec{p}_{e^+} + \vec{p}_{e^-} - \ell_{DSR} E_{e^+} \vec{p}_{e^-}$$

- Angle between e^+ and e^-

$$\cos\theta \sim \frac{m^2 + E_{e^+}E_{e^-} - \ell_{LIV}(E_{e^+}E_{e^-}^2 + E_{e^-}E_{e^+}^2)}{\sqrt{(E_{e^+}^2 - m^2)(E_{e^-}^2 m^2)}} + \mathcal{O}(\ell_{DSR}^2) + \mathcal{O}(\ell_{LIV}^2)$$

[Jacobsen 2003, Carmona 2020, Lobo 2021, …]

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Quantum Gravity Phenomenology - Predicting and searching QG effects

Propagation of probe particles and fields on quantum spacetime

Relativity with an invariant minimal length

- Deformed Lorentz symmetry algebra (example)

$$[P_0, N_a] = -iP_a, \quad [P_a, N_b] = -i\delta_{ab}P_0 + \frac{1}{\kappa}h_{ab}(P_0, P_a)$$

- Modified dispersion relation

$$E^2 - \vec{p}^2 + \frac{1}{\kappa}f(E, \vec{p}) = m^2$$

- Modified energy-momentum conservation

$$p_\mu \oplus q_\mu = p_\mu + q_\mu + \frac{1}{\kappa}h_\mu(p, q)$$

- Geometrically: spacetime with curved momentum spaces
- Implies relativity of locality (in addition to relativity of simultaneity)

[Garay 1995, Amelino-Camelia 2001/2012, Kowalski-Glikman 2003, Hossenfelder 2013, …]

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Propagation of probe particles and fields on quantum spacetime

Modified dispersion relations on curved spacetime

- Hamilton functions $H(x,p)$ on the 1-particle phase space
- Dispersion relation and particle motion

$$H(x,p) = m^2, \quad \partial_{x^\mu} H = -\dot{p}_\mu, \quad \partial_{p_\mu} H = \dot{x}^\mu$$

- Spacetime and momentum space dependent metric

$$g^{\mu\nu}(x,p) = \frac{1}{2}\partial_{p_\mu}\partial_{p_\nu} H$$

- Velocity picture: $H(x,p) \to L(x,\dot{x})$
- Frameworks: Finsler and Hamilton geometry

[Girelli 2007, Barcaroli 2015, Pfeifer 2019, Relancio 2020, Lobo 2021, …]

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Propagation of probe particles and fields on quantum spacetime

Quantum mechanics with minimal length

- Modifying the uncertainty relation

$$\Delta x \Delta p \sim \frac{\hbar}{2}(1 + \beta p^2 + \mathcal{O}(p^4))$$

- GUP parameter β is not tightly constrained

$$\beta < 10^{16}$$

- Lead to a deformed Heisenberg Algebra

$$[x^i, p_j] = i\hbar\delta^i_j(1 + \beta^2 p^2), \quad [x^i, x_j] = 2i\hbar\theta(\vec{p}^2)p^{[i}x^{j]}, \quad [p_i, p_j] = 0$$

- Including non-commuting position operators

[Das 2008, Majhi 2013, Bosso 2023…]

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Propagation of probe particles and fields on quantum spacetime

Higher order curvature terms, and geometric features

- Beyond Einstein Hilbert, local term
- Higher dimensional classical gravity
- Non-local terms, add derivatives of the curvature tensor
- Additional geometric terms like torsion and non-metricity
- Lorentz invariance violating models like Horava gravity
- Non minimal coupling between geometry and matter fields
- …

[Dvali 2000, Sotiriou 2010, Cappoziello 2011, deRahm 2014, Mavromatos 2021 …]

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Propagation of probe particles and fields on quantum spacetime

Deforming the algebra of functions

- A non-commutative star product

$$f \star h = f \cdot h + \frac{1}{\kappa} D(f, h) + \dots$$

- Choosing the differential operator D defines the non-commutativity
- Many different implementations of non-commutative geometry exist
- Phenomenology from field theory on non-commutative spacetime

[Doplicher 1994, Connes 2007, Pachol 2017, Mignemi 2018, Franchino-Vinas 2020, …]

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Propagation of probe particles and fields on quantum spacetime

Adding Lorentz violating terms to the SM Lagangian

- Example electromagnetism

$$S = \int d^4x \sqrt{|\det g|}\,(F_{\mu\nu}F^{\mu\nu} + k^{\mu\nu\rho\sigma}F_{\mu\nu}F_{\rho\sigma} + \dots)$$

- Predicts birefringence in vacuum, constraints on k
- Developed for all sectors of the SM and Gravity
- Extensively tested in astrophysical observations (WG2)

[Colladay 1998, Kostelecky 2011, Lehnert 2016, Mewes 2019, …]

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- 24.12.17 WG1 action wide presentation
- 25.01.21 WG2 action wide presentation
- 25.02.25 WG3 action wide presentation
- 25.04.01 WG4 action wide presentation
- 25.05.27 WG5 action wide presentation
- WG1 - Show And Tell Slides and Recordings
- WG2 - Meetings and presentations

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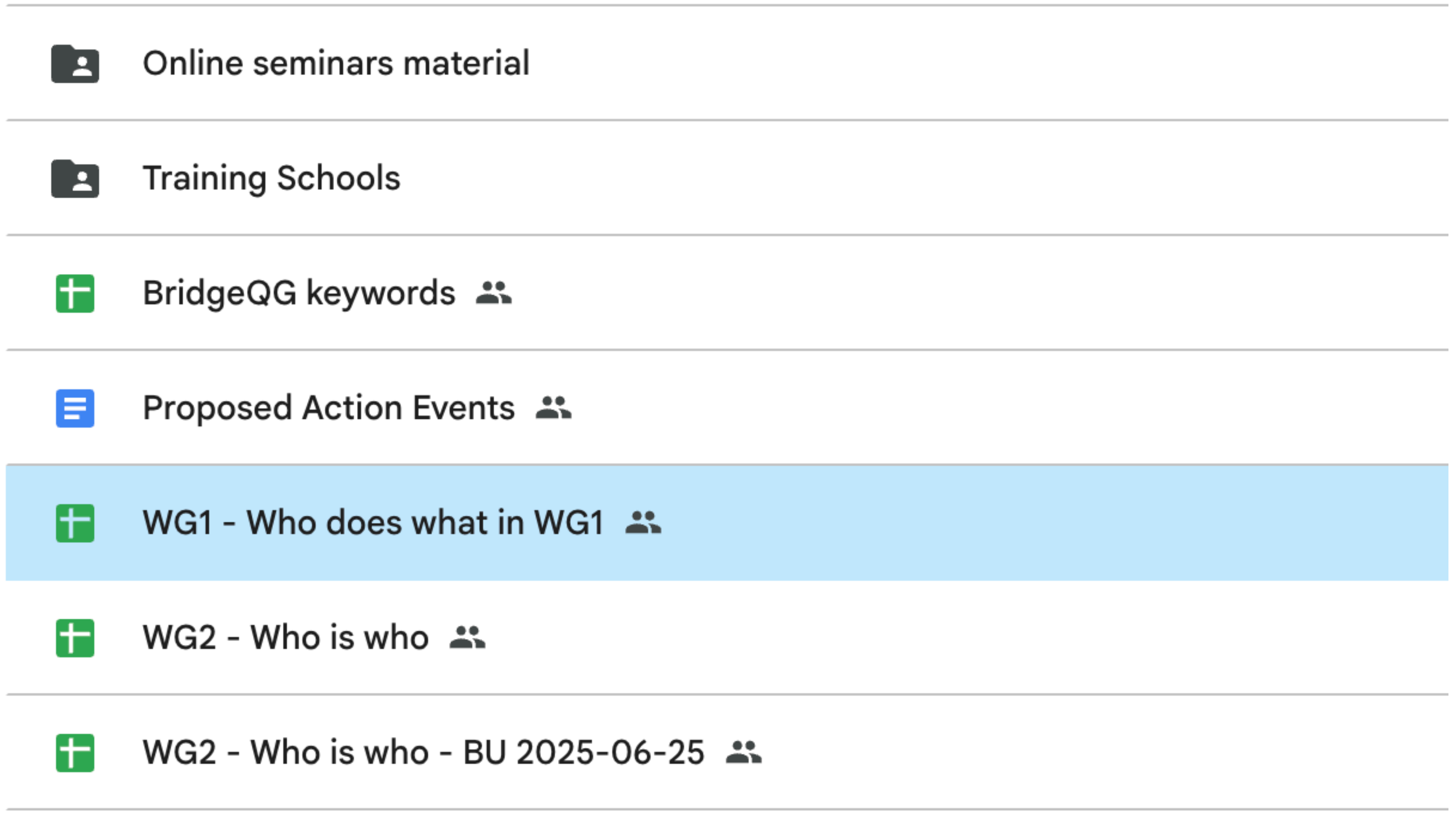

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    - Writing and coordinating the writing of the vademeicum
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- Coordinate collaboration with other COST actions (RQI)

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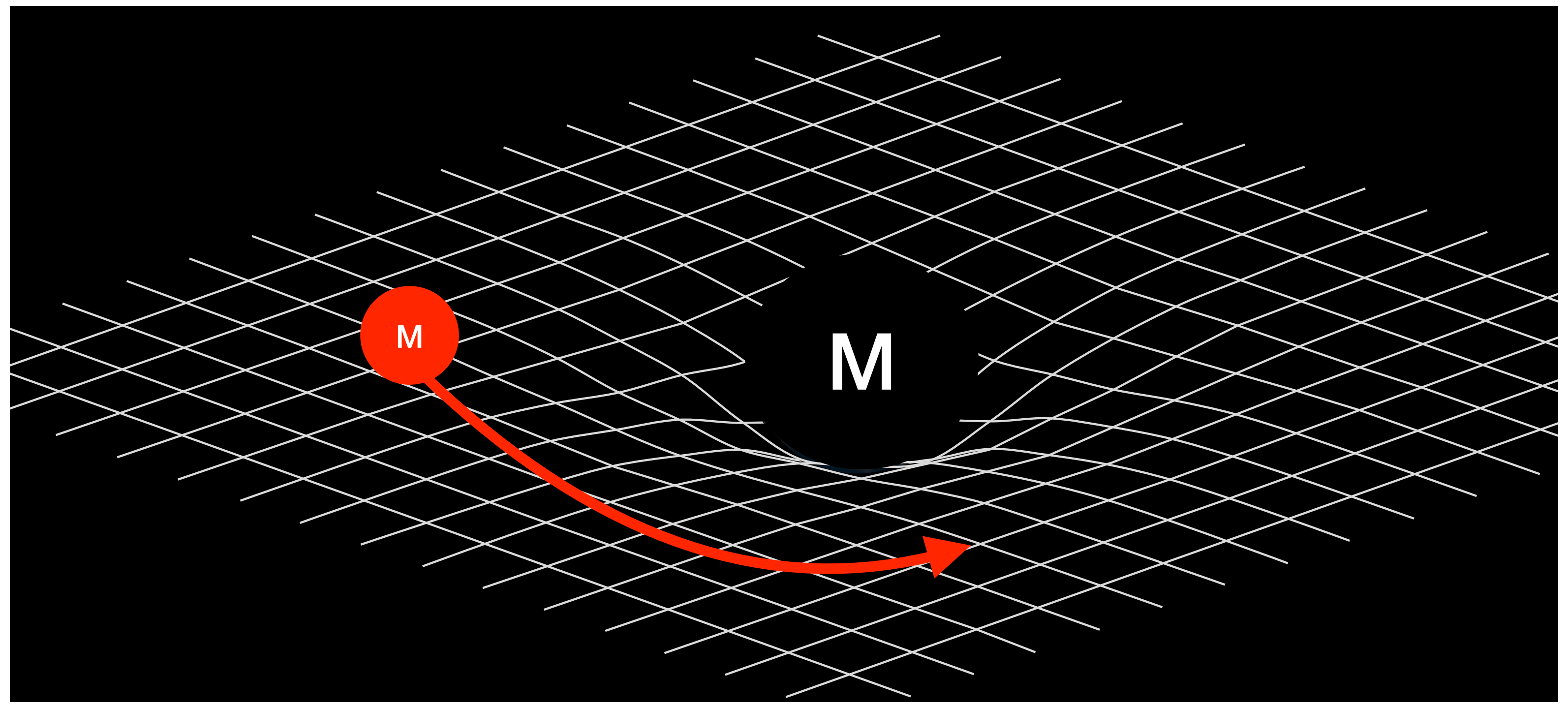
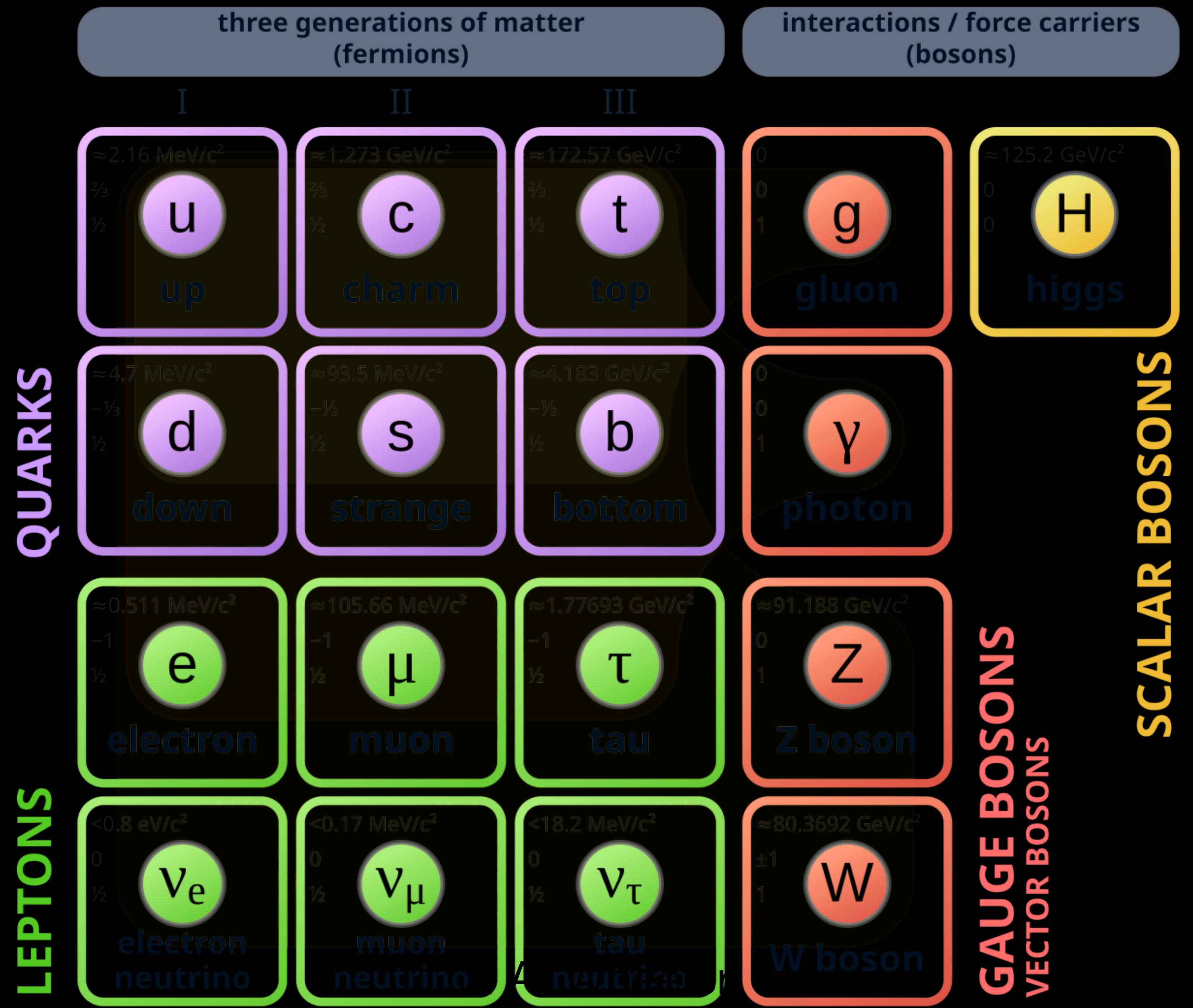
General Relativity (GR)



Standard model (SM)



Insufficient to explain our physical world

- Require the existence of Dark Matter and Dark Energy
  (rotation curves of galaxies, CMB observations, Hubble tension, …)
- Predict singularities
  (Big Bang, Black holes, infinite gravitational tidal forces, …)
- Do not treat all forces of nature on the same ground
  (unified model of the physical world, …)

Quantum Gravity

LLI renormalizable QFT

Geometry of spacetime

Approaching QG from two perspectives

Theoretical Construction Methods
Fundamental Approaches to QG
(Top-Down approach)

- Turn GR into a LLI renormalizable QFT
- Quantise the geometry of spacetime
- Quantise spacetime itself
- Unify Gravity and SM

[Kiefer 2012, Basile et. al 2025, Buoninfante et. al 2025]

Searching for observations
Phenomenological models for QG effects
(Bottom-Up approach)

- Determine effects on particles and fields propagating on and interacting with quantum spacetime
- Deviations from GR + SM predictions
- Give guidelines for low-energy / (semi)-classical limits of a fundamental theory of QG

[Addazi et. al 2021, Alves-Batista et. al 2023]

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