# QUANTUM GRAVITY-INDUCED VIOLATIONS OF LORENTZ INVARIANCE

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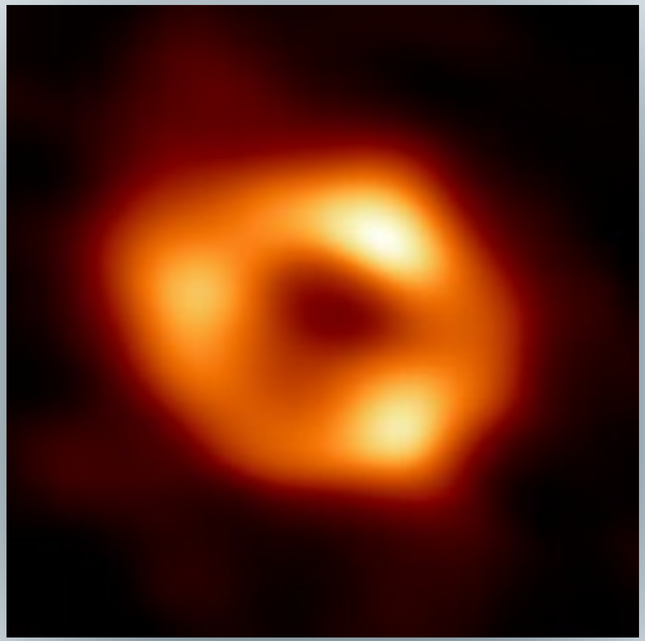
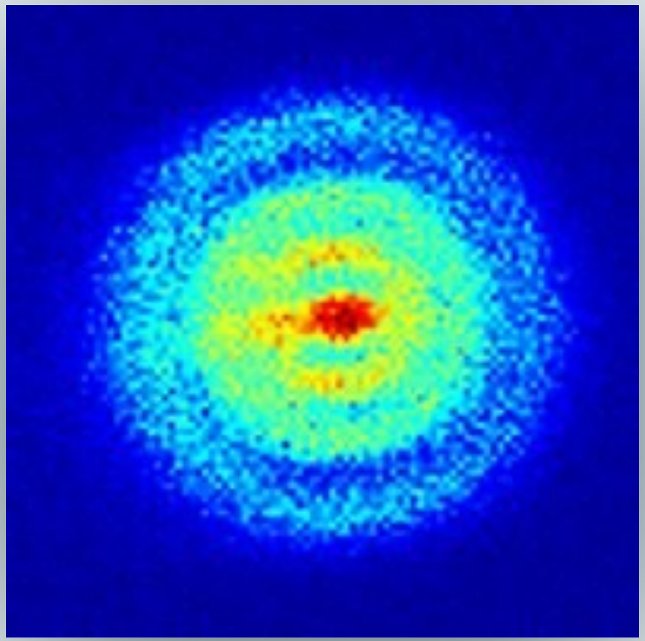
# Quantum Gravity - why, what, where?





| General Relativity | Quantum mechanics |
|---|---|
| Macroscopic realm | Microscopic realm |
| Dynamical spacetime | Fixed spacetime |
| Classical matter | Quantum matter |

General Relativity describes spacetime dynamics and its interaction with classical 'matter'

Quantum Mechanics (and relativistic Quantum Field Theory) is a theory of quantum 'matter' on a fixed background spacetime

## Quantum Gravity - why, what, where?

While both GR and QFT use a **classical spacetime**, they define its points in **incompatible ways**

### General Relativity

Schwarzschild radius:

$$r_S = \frac{2Gm}{c^2}$$

fundamental obstruction to packing
a mass m into too small regions:
beyond the Schwarzschild radius
GR predicts the formation of horizons

Localization: low mass probe
(minimise back-reaction on geometry)

### Quantum mechanics

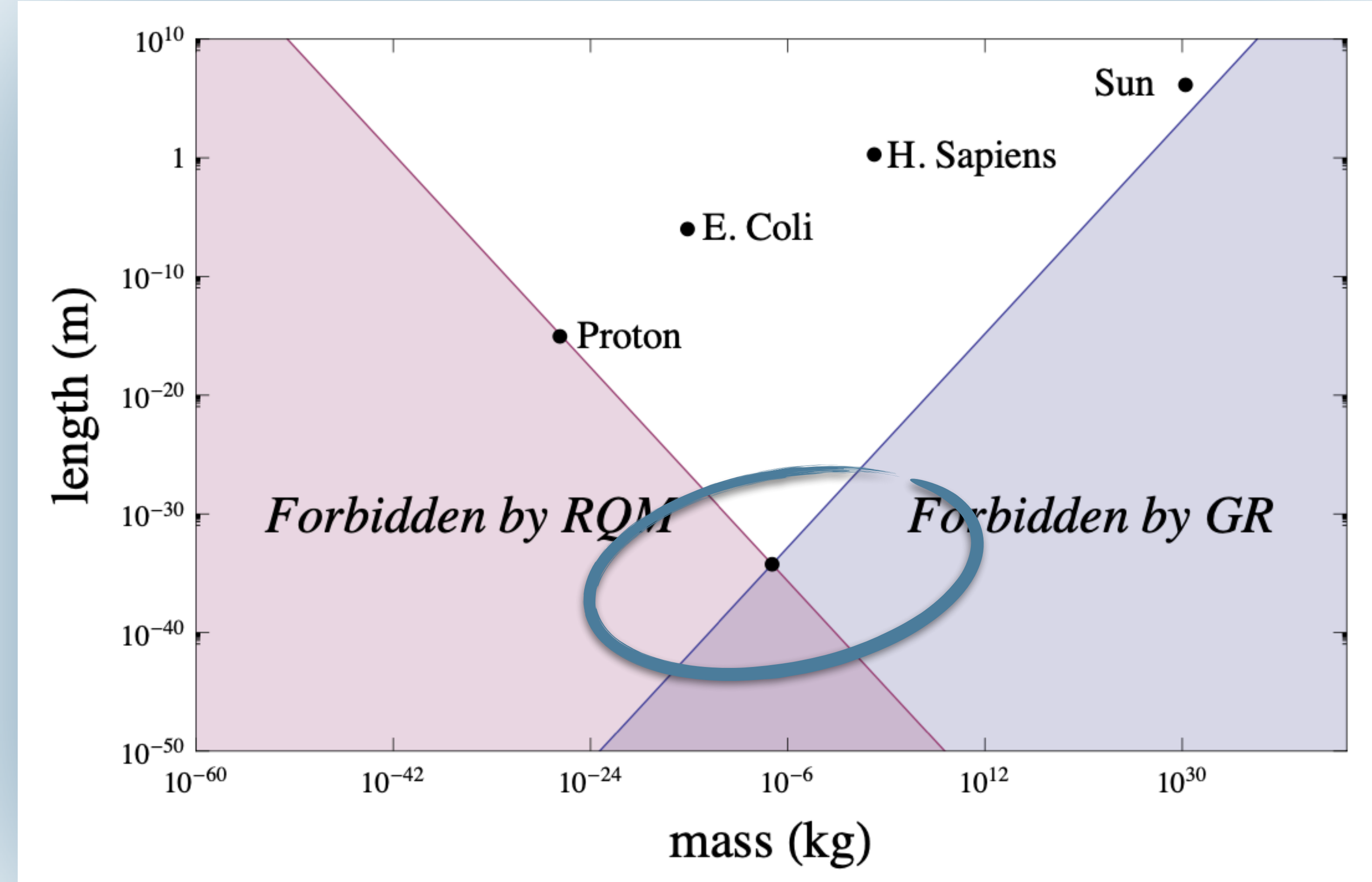
Compton radius:

$$r_C = \frac{2\pi\hbar}{mc}$$

fundamental limitation to measuring
the position of a particle:
beyond the Compton radius
QM predicts the creation of particles

Localization: high mass probe
(minimise quantum uncertainty)

# Quantum Gravity - why, what, where?




Adapted from S. Majid 2007

## The Planck scale

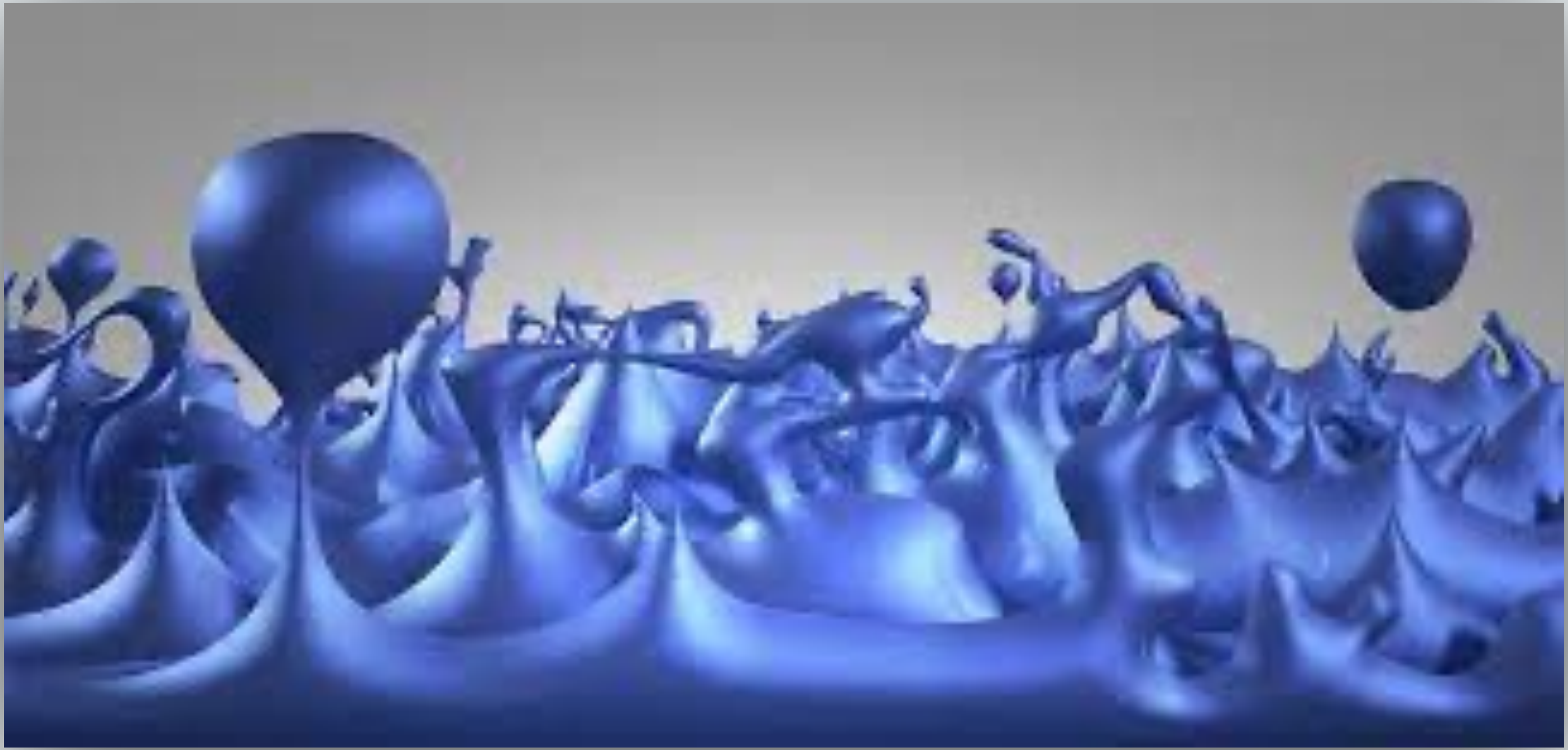
$$M_P = \sqrt{\frac{\hbar c}{G}} \sim 10^{19}\,\mathrm{GeV}/c^2$$

$$\ell_P = \sqrt{\frac{\hbar G}{c^3}} \sim 10^{-35}\,\mathrm{m}$$

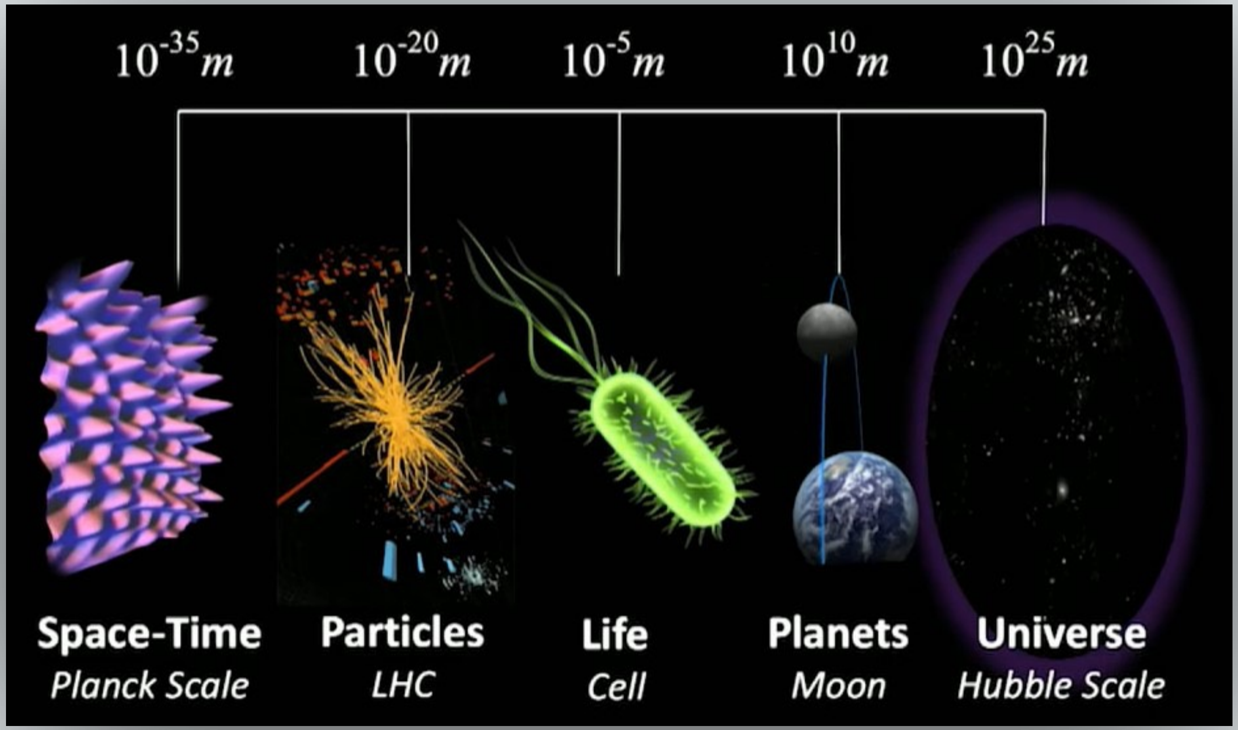
NB: QG scale might be a few orders of magnitude away (see e.g. large extra dimensions theories)

## Quantum spacetime

In quantum gravity research it is expected that spacetime shows quantum properties when tested at length scales of the order of the Planck length



# Testing spacetime properties at the Planck scale?




For a long time QG was considered a **purely theoretical/conceptual problem**: a direct measurement of QG effects would require observing collisions of particles with Planckian energy, or the shrinking of a black hole from macroscopic size to Planckian size — scenarios that in practice are of limited interest

## Lorentz symmetries at the Planck scale

A way to experimentally investigate the properties of spacetime at the Planck scale is by testing its symmetries: Local Lorentz symmetries, CPT invariance…

QG research foresees different options concerning the fate of Lorentz symmetries*

- Relativistic models which ***preserve*** Lorentz invariance
- Non-relativistic models which ***break*** Lorentz invariance (LIV)
- Relativistic models where Lorentz transformations are ***deformed*** (DSR)

The effects associated to each option have observational consequences that depend on the theoretical framework in which they are embedded, e.g. kinematical assumptions, dynamical assumptions, assumptions on the validity of a Hamiltonian description, etc…

*it is not always straightforward to identify which of these options applies to a given fundamental QG theory

## Lorentz breaking (LIV) vs. Lorentz deformation (DSR)

✦ Lorentz **breaking** theories:

Everything transforms as usual under the Lorentz group.
Lorentz non-invariant fields (e.g. fixed background tensors) are introduced, that identify a **preferred frame of reference** and so manifestly break the symmetry.

For example: $$S \propto \int d^4x\sqrt{-g}\left[g^{\alpha\beta}\partial_\alpha\phi\partial_\beta\phi + \left(g^{\alpha\beta}+\tau^{\alpha\beta}\right)\partial_\alpha\psi\partial_\beta\psi\right]$$

Deformations of particles energy-momentum dispersion relations are a typical manifestation

e.g. for photons: $$E^2 = |\vec{p}|^2 \pm \frac{\xi}{E_P}|\vec{p}|^3$$

However such features will take **different forms for different observers**

✦ Theories with Lorentz **deformations:**

The action of the Lorentz group is modified to allow for a **relativistically invariant energy scale**
Inertial observers agree on the physics , because the laws of transformations between them are modified w.r.t. special relativity. Also in this scenario the on-shell relation of particles can be modified

e.g.: the relation $m^2 = E^2 - |\vec{p}|^2 - \lambda E|\vec{p}|^2$ is invariant under the deformed transformations

$$\begin{array}{lll} E & \rightarrow & E + \xi p_j \\ p_i & \rightarrow & p_i + \xi\left[E\delta_{ij} + \frac{\lambda}{2}|\vec{p}|^2\delta_{ij} - \lambda E^2\delta_{ij} - \lambda p_j \sum_k p_k\delta_{ik}\right] \end{array}$$

# Implications for astrophysical messengers - time-of-flight anomalies

A **common implication of LIV and DSR** models is that the dispersion relation of particles is modified, with **Planck-scale suppressed** corrections

This kind of effect can be tested by looking at the **propagation of high energy particles** (photons, neutrinos) from astrophysical sources, since it induces a **modified propagation time**

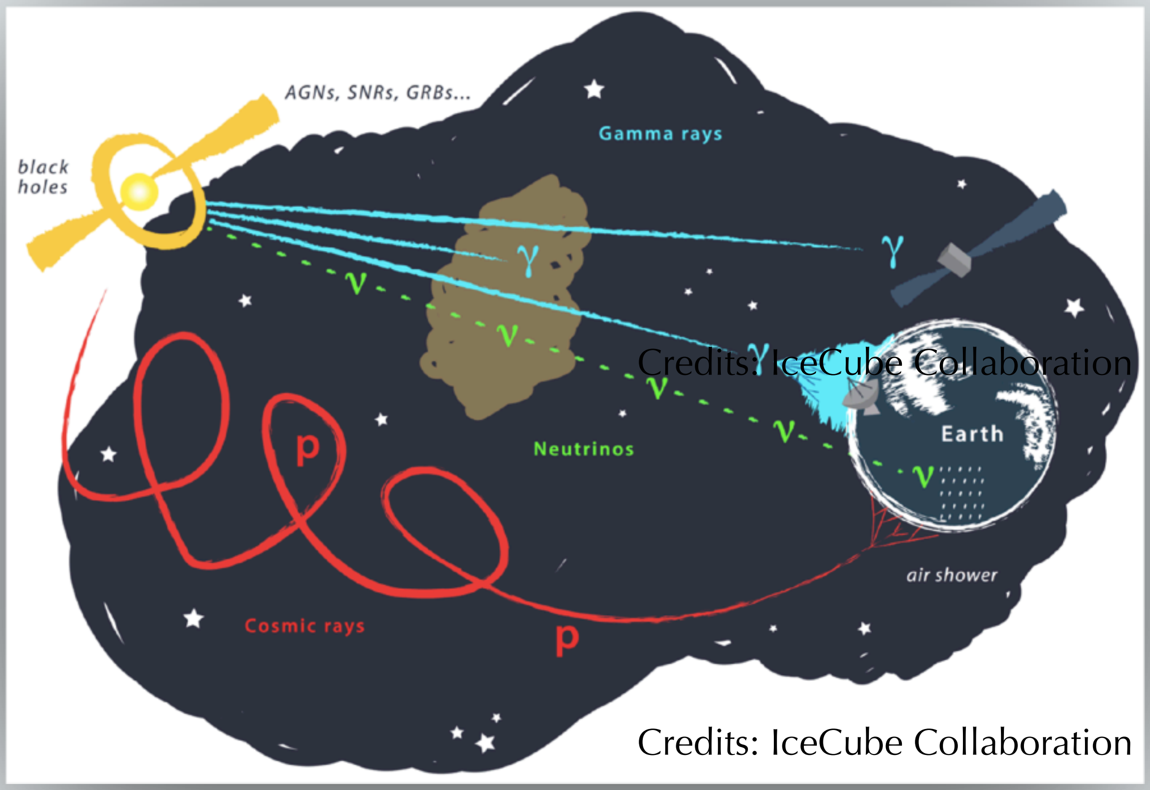
The very long travel time of these particles can amplify tiny residual propagation effects that are present at energies much lower than the Planck scale

flat spacetime: $$\Delta t = \eta L \frac{\Delta E}{E_P}$$

FRW spacetime: $$\Delta t = \eta \frac{\Delta E}{E_P} D(z)$$

Jacob, Piran, JCAP 2008

$$D(z) = \int_0^z d\zeta \frac{1+\zeta}{H_0\sqrt{\Omega_\Lambda + (1+\zeta)^3\Omega_m}}$$



Credits: IceCube Collaboration

→ Search for a correlation between energy, distance of the source and arrival time

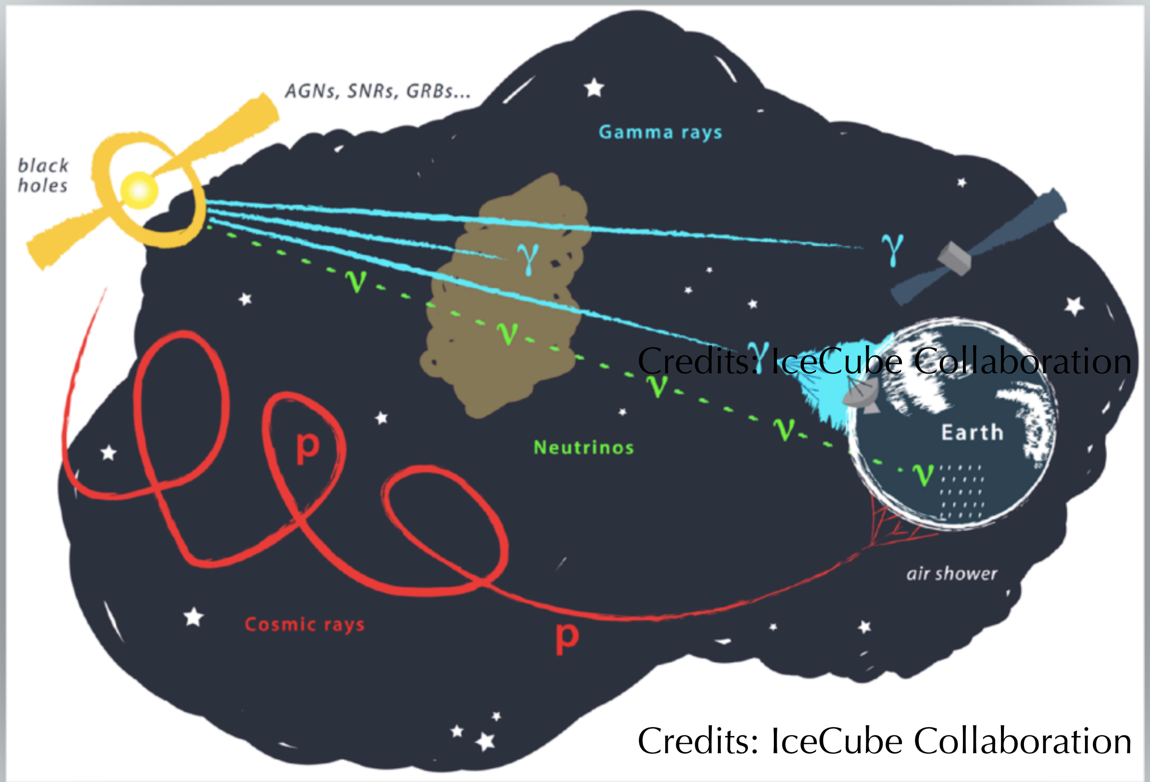
## Implications for astrophysical messengers - time-of-flight anomalies

Using the FRW Jacob+Piran formula for time delays, assuming $\eta = 1$ and a source at redshift $z = 1$

One might expect that particles with energy ~10 GeV from z~1 arrive with a time difference $\Delta t \sim 10^{-1} s$ w.r.t. lower energy particles

For particles of energy ~ few 100 TeV, one might expect a time difference $\Delta t \sim 1$ day

Challenges: intrinsic emission mechanisms at the source; identification of the source and its redshift; energy resolution



Credits: IceCube Collaboration
Credits: IceCube Collaboration

# Astrophysical tests of time-of-flight anomalies

See the review *“Quantum gravity phenomenology in the multi-messenger approach”* by the COST Action CA18108, Prog. Part. Nucl. Phys. 125 (2022) 103948
arXiv: 2111.05659 [hep-ph]

letters to nature

**Tests of quantum gravity from observations of $\gamma$-ray bursts**

G. Amelino-Camelia, John Ellis, N. E. Mavromatos, D. V. Nanopoulos & Subir Sarkar

*Nature* **393**, 763–765 (1998)

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Bounds on Lorentz Invariance Violation from MAGIC Observation of GRB 190114C

V. A. Acciari *et al.* (MAGIC Collaboration)
Phys. Rev. Lett. **125**, 021301 – Published 9 July 2020

nature astronomy — ARTICLES

PUBLISHED: 5 JUNE 2017 | VOLUME: 1 | ARTICLE NUMBER: 0139

***In vacuo*** **dispersion features for gamma-ray-burst neutrinos and photons**

Giovanni Amelino-Camelia[1,2]*, Giacomo D'Amico[1,2], Giacomo Rosati[3] and Niccoló Loret[4]

Over the past 15 years there has been considerable interest in the possibility of quantum-gravity-induced *in vacuo* dispersion, the possibility that spacetime itself might behave essentially like a dispersive medium for particle propagation. Two recent studies have exposed what might be *in vacuo* dispersion features for gamma-ray-burst (GRB) neutrinos of energy in the range of 100 TeV and for GRB photons with energy in the range of 10 GeV. We here show that these two features are roughly compatible with a description such that the same effects apply over four orders of magnitude in energy. We also show that it should not happen so frequently that such pronounced features arise accidentally, as a result of (still unknown) aspects of the mechanisms producing photons at GRBs or as a result of background neutrinos accidentally fitting the profile of a GRB neutrino affected by *in vacuo* dispersion.

nature

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Published: 28 October 2009

**A limit on the variation of the speed of light arising from quantum gravity effects**

A. A. Abdo, M. Ackermann, [...] M. Ziegler

*Nature* **462**, 331–334 (2009) | Cite this ar

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**Lorentz violation from gamma-ray burst neutrinos**

Yanqi Huang & Bo-Qiang Ma

*Communications Physics* **1**, Article number: 62 (2018) | Cite this article

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Limits on an Energy Dependence of the Speed of Light from a Flare of the Active Galaxy PKS 2155-304

F. Aharonian *et al.* (H.E.S.S. Collaboration)
Phys. Rev. Lett. **101**, 170402 – Published 22 October 2008

## Additional consequences of time-of-flight anomalies

Time-of-flight anomalies can be associated to either LIV or DSR — the theoretical implications and further observational signals to look for are very different in the two scenarios

### Lorentz breaking

There is a ***preferred frame of reference*** where the propagation law takes the given form.

The most natural assumption is that energy and spatial momenta are conserved as usual. E.g. in a process $a + b \to c + d$

$$\begin{aligned} E_a + E_b &= E_c + E_d \\ \vec{p}_a + \vec{p}_b &= \vec{p}_c + \vec{p}_d \end{aligned}$$

The combination of modified dispersion relation and standard interaction produces strong ***implications for threshold reactions***, e.g. they allow for photon decay.

Carroll, Field, Jackiw, PRD 1990
Kostelecky, Mewes, PRD 2009

### Lorentz deformation

The propagation law is the same in all reference frames, linked by ***deformed transformations.***

Conservation law are modified to be invariant under the deformed transformations. E.g. in a process $a + b \to c$

$$\begin{aligned} E_a &= E_b + E_c - \eta \vec{p}_b \cdot \vec{p}_c \\ \vec{p}_a &= \vec{p}_b + \vec{p}_c - \eta E_b \vec{p}_c - \eta E_c \vec{p}_b \end{aligned}$$

The interplay between MDR and modified conservation rules ***weakens the effects on threshold reactions,*** e.g. photon decay is forbidden.

Amelino-Camelia, IJMPD 2002, PLB 2001
Kowalski-Glikman, IJMPA 2001; Magueijo, Smolin, PRL 2002

## MDR in a Lorentz breaking scenario

The combination of MDR and standard energy and momentum conservation law have strong implications for **threshold reactions**

e.g. they allow for photon decay $\gamma \to e^+ e^-$

$$0 = E^2 - |\vec{p}|^2 - \eta \frac{E}{E_P} |\vec{p}|^2 \longrightarrow E_\gamma^{th} = \left(4 m_e^2 E_P / \eta\right)^{1/3}$$

strongly constrained by observations of gamma-rays up to 1.4 PeV and ultra-high energy cosmic rays

Galaverni, Sigl PRL 2008
Jacobson, Liberati, Mattingly, PRD 2003
LHAASO coll., Nature 2021

NB. if a reaction is kinematically allowed, it can still be dynamically forbidden, so not seeing it does not rule out the kinematical model

or they significantly change the threshold for pair production on the Extragalactic Background Light (EBL) $\gamma\gamma \to e^+ e^-$

$$0 = E^2 - |\vec{p}|^2 - \eta \frac{E}{E_P} |\vec{p}|^2 \longrightarrow \epsilon_{th} = \frac{m_e^2}{E_\gamma} + \frac{\eta}{4} \frac{E_\gamma^2}{E_P}$$

Also constrained (in the subliminal case) by observations of gamma-rays and cosmic rays

HESS coll, ApJ 2019
Biteau, Williams, ApJ 2015
Lang, Martínez-Huerta, de Souza, PRD 2019

## MDR in a DSR scenario

The interplay between MDR and modified conservation rules **weakens the effects on threshold reactions** (e.g. in the case of photon pair production on the EBL)

Typically modifications of the threshold are significant only for particle with Planck-scale energy

Moreover the reactions that would be forbidden in special relativity (such as **photon decay**) are also **forbidden in DSR**, since this framework does not allow to identify preferred reference frames

Note that, if a reaction is forbidden at the kinematical level, it will be so regardless of the dynamics — conversely, a reaction allowed kinematically might be forbidden by dynamics, or have a very low probability of happening

## Back to modelling the time-of-flight anomaly — the LIV case

The commonly used formula by Jacob+Piran (the one we also used in the analysis described before) assumes that the energy of the signal scales as usual with the redshift:

$$E_{source} = E_0(1+z) \longrightarrow \Delta t = \eta \frac{\Delta E}{E_p} \int_0^z d\zeta \frac{1+\zeta}{H_0\sqrt{\Omega_\Lambda + (1+\zeta)^3\Omega_m}}$$

However, once Lorentz invariance is broken, this does not need to be the case. For example

$$E_{source} = E_0(1+z) - \eta' \frac{E_0}{E_P}\frac{1}{1+z} \longrightarrow \Delta t = \frac{\Delta E}{E_p} \int_0^z d\zeta \frac{\eta(1+\zeta) + \frac{\eta'}{(1+\zeta)}}{H_0\sqrt{\Omega_\Lambda + (1+\zeta)^3\Omega_m}}$$

(In this example, when $\eta = -\eta'$ no time delay is expected for signals coming from sources at small redshifts)

In general, there is an **infinite array of possibilities** for the redshift dependence of the time delay

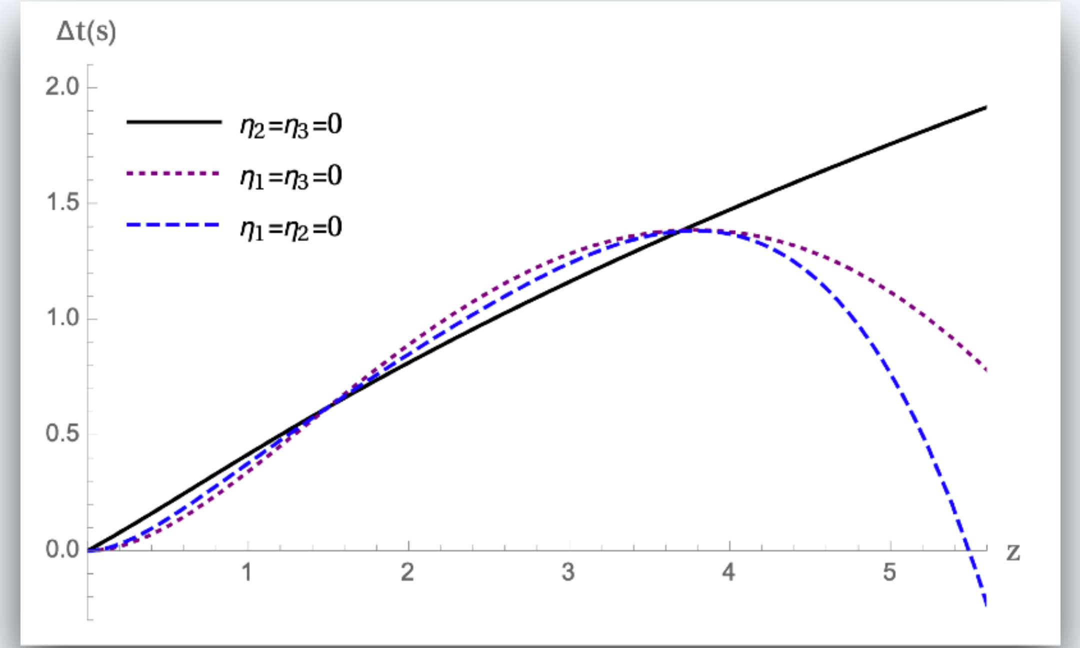
Amelino-Camelia, Bedic, Rosati, PLB 2021

# Back to modelling the time-of-flight anomaly — the DSR case

Relativistic invariance constrains the possible forms of the redshift dependence of the time delay, limiting it to just three free parameters:

$$\Delta t = \frac{\Delta E}{E_p}\int_0^z d\zeta \frac{(1+\zeta)}{H(\zeta)}\left[\eta_1 + \eta_2\left(1-\left(1-\frac{H(\zeta)}{1+\zeta}\int_0^\zeta \frac{d\zeta'}{H(\zeta')}\right)^2\right) + \eta_3\left(1-\left(1-\frac{H(\zeta)}{1+\zeta}\int_0^\zeta \frac{d\zeta'}{H(z')}\right)^4\right)\right]$$

The case $\eta_2 = \eta_3 = 0$ reproduces the Jacob+Piran formula




Time delay as function of redshift z of the source, assuming $\Delta E$ = 10 GeV and fixing the parameters so that the time delays match at z = 1.5

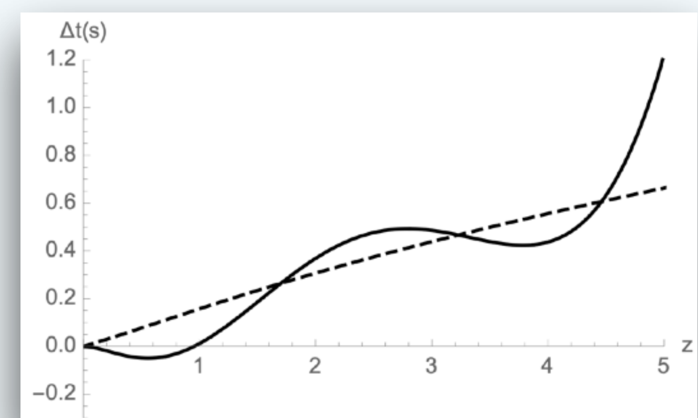
Amelino-Camelia, Frattulillo, Gubitosi, Rosati, Bedic, JCAP 2024

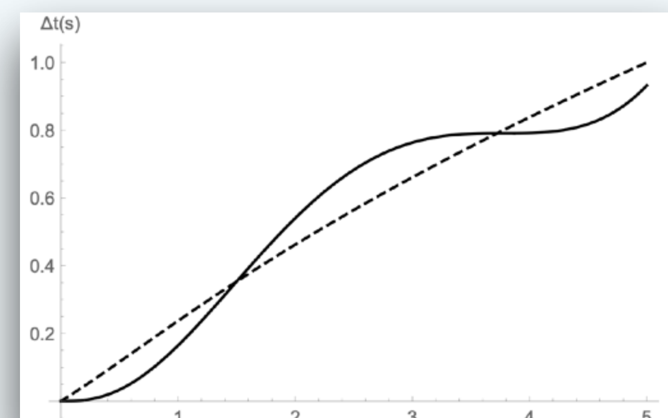
# Back to modelling the time-of-flight anomaly — the DSR case

Relativistic invariance constrains the possible forms of the redshift dependence of the time delay, limiting it to just three free parameters:

$$\Delta t = \frac{\Delta E}{E_p} \int_0^z d\zeta \frac{(1+\zeta)}{H(\zeta)} \left[ \eta_1 + \eta_2 \left( 1 - \left( 1 - \frac{H(\zeta)}{1+\zeta} \int_0^\zeta \frac{d\zeta'}{H(\zeta')} \right)^2 \right) + \eta_3 \left( 1 - \left( 1 - \frac{H(\zeta)}{1+\zeta} \int_0^\zeta \frac{d\zeta'}{H(z')} \right)^4 \right) \right]$$

Different combinations of the three parameters can produce a variety of different behaviours




Continuous line: ΔE = 10 GeV, $\eta_2 = 4$, $\eta_3 = -3$. Dashed line: ΔE = 10 GeV, $\eta_1$ fixed so that the time delays match at z = 1.5

Continuous line: ΔE = 10 GeV, $\eta_3 = -1$. Dashed line: ΔE = 10 GeV, $\eta_1$ fixed so that the time delays match at z = 1.5

Amelino-Camelia, Frattulillo, Gubitosi, Rosati, Bedic, JCAP 2024

## BridgeQG COST Action

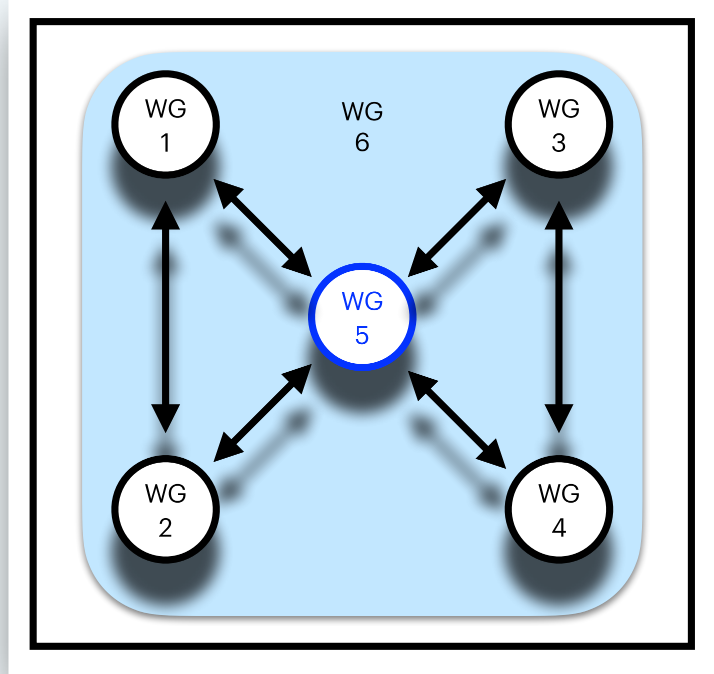
**Main aim:**

To investigate the ***interface between high-energy quantum gravity and quantum aspects of gravity in the low-energy regime***, using both theoretical and experimental tools, in order to construct a phenomenologically viable theory of quantum gravity.

**Research questions:**

- ***Is gravity quantised***, and what constitutes a quantum signature of gravity? [Entanglement, …]
- What are the ***symmetries*** at the Planck scale?
- Is there a ***separation of scales*** in gravitational interactions, or shall we expect ultraviolet effects to percolate to low energies?
- How are observers & ***reference frames*** defined in QG?
- How does gravity (both classical and quantum) affect the ***dynamics of quantum systems***? [Decoherence, modified Schoroedinger equation,…]

- WG1: HE theory
- WG2: HE experiment
- WG3: LE theory
- WG4: LE experiment
- WG5: LE-HE interplay
- WG6: Dissemination




https://www.cost.eu/actions/CA23130

# The quantum-spacetime regime of quantum gravity

Behaviour of **high-energy/small wavelength particles** in a quantum spacetime:

- propagation effects (in-vacuo dispersion, birefringence)
- interaction effects (anomalous threshold reactions )
- violations of CPT symmetries [Mavromatos, Lec. Not. Phys. 2005]
- fundamental decoherence [Mavromatos, Lec. Not. Phys. 2005]

Behaviour of **table-top quantum systems** in a quantum spacetime:

- Modified uncertainty relations (e.g. in optomechanical oscillators [Marin et al. Nat. Phys. 2013])
- violations of CPT symmetries
- fundamental decoherence
- Pauli exclusion principle

Possibility of **IR/UV mixing**: quantum spacetime effects are introduced in the ultraviolet, but some counterpart effects might show up in the infrared regime, e.g.

- non commutative field theory
- GUP: $\Delta x \geq \frac{\hbar}{2\Delta p} + \beta^2 \Delta p$

  UV momentum induces IR fuzziness in position

non-planar contributions to one-loop propagator of $\lambda\varphi^4$ theory:

$$\int d^4k \, \frac{e^{i\,k_\mu\,\theta^{\mu\nu}\,p_\nu}}{k^2+m^2} \propto \frac{m}{\sqrt{p\cdot\theta^2\cdot p}} K_1(m\sqrt{p\cdot\theta^2\cdot p}),$$

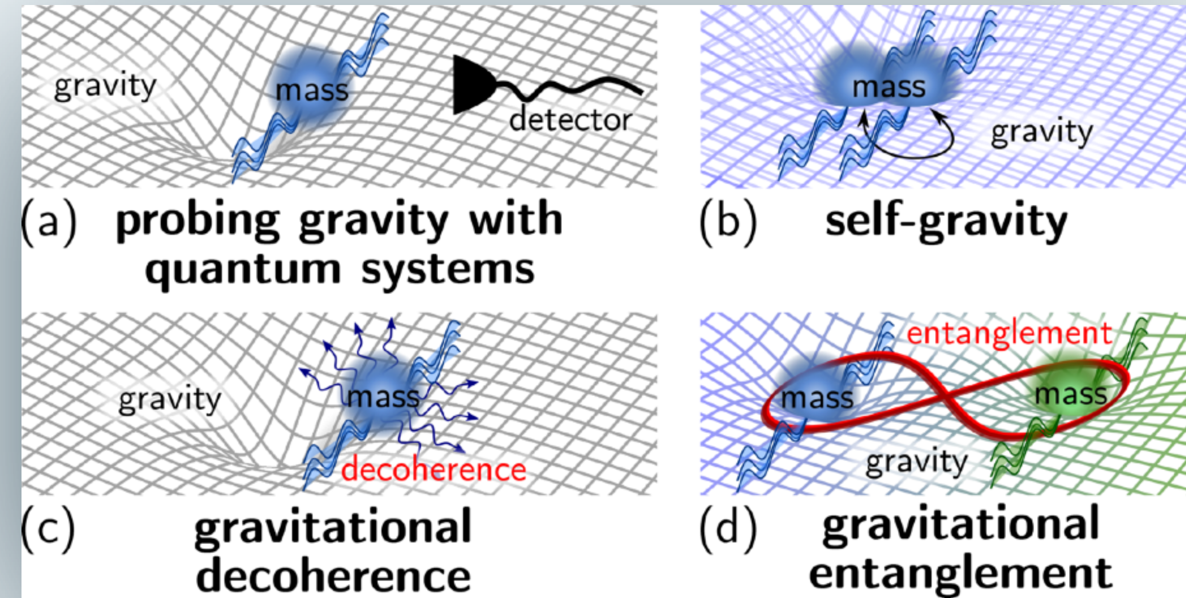
where $p\cdot\theta^2\cdot p = p_\mu \theta^\mu{}_\rho \theta^{\rho\nu} p_\nu$. UV-finite, but IR-divergent:

$$\sim p^2 + m^2 + \frac{1}{p\cdot\theta^2\cdot p} + \frac{m^2}{2}\log\left(p\cdot\theta^2\cdot p\right) + \ldots .$$

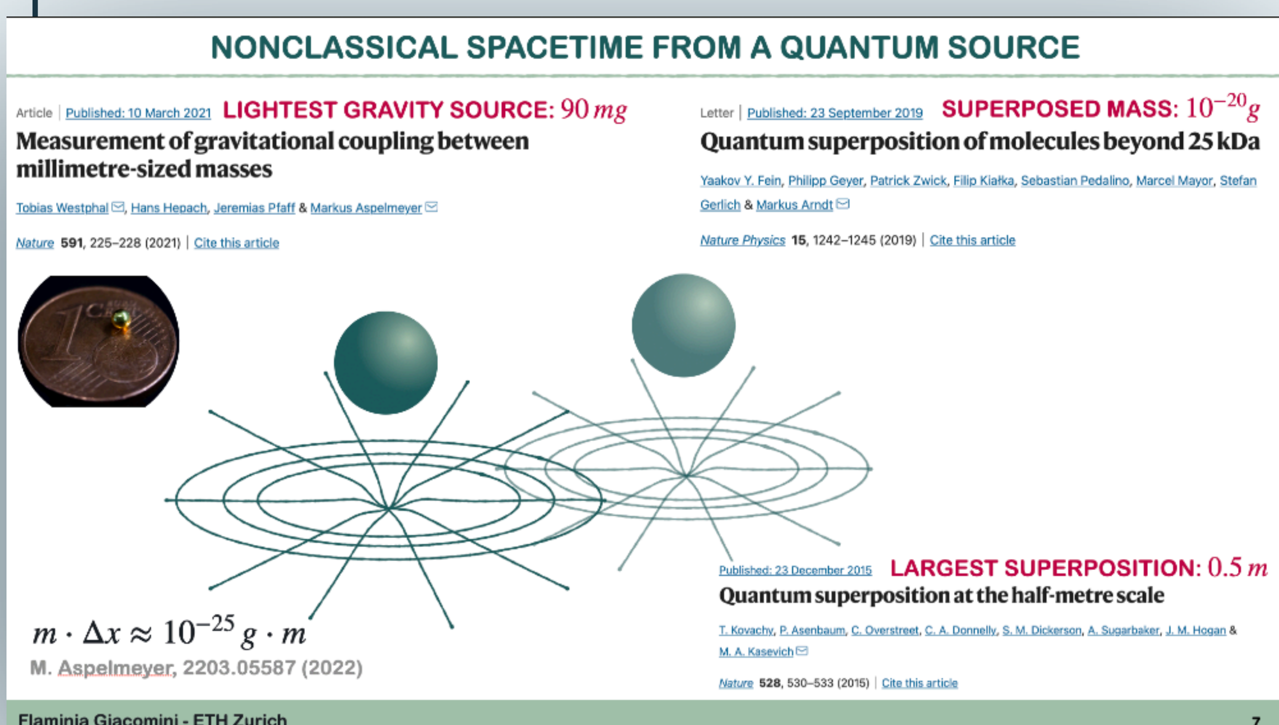
# The interface between quantum mechanics and gravity

**Behaviour of quantum systems in gravity:**

- Schroedinger-Newton equation for quantum systems in a gravitational field - gravitational phase shift [Colella, Overhauser, Werner, 1975]
- Gravitational decoherence
  [Diosi-Penrose 1987, Anastopoulos+Hu, Blencowe 2013]
- Quantum equivalence principle
  [Zych,Brukner, 2018]
- Quantum field theory in curved spacetime




Credits: Bose et al. Rev. Mod. Phys. 2025




**Gravitational field generated by quantum systems:**

- Self-gravitating Bose Einstein condensates
- Gravity-induced entanglement
  [Bose+Mazumdar,Marletto+Vedral 2017]
- Semiclassical Einstein equations

$$G_{\mu\nu} = \frac{8\pi G}{c^4} < \hat{T}_{\mu\nu} >$$