Quantum gravity Phenomenology
Where do we stand?

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What is Quantum gravity Phenomenology?

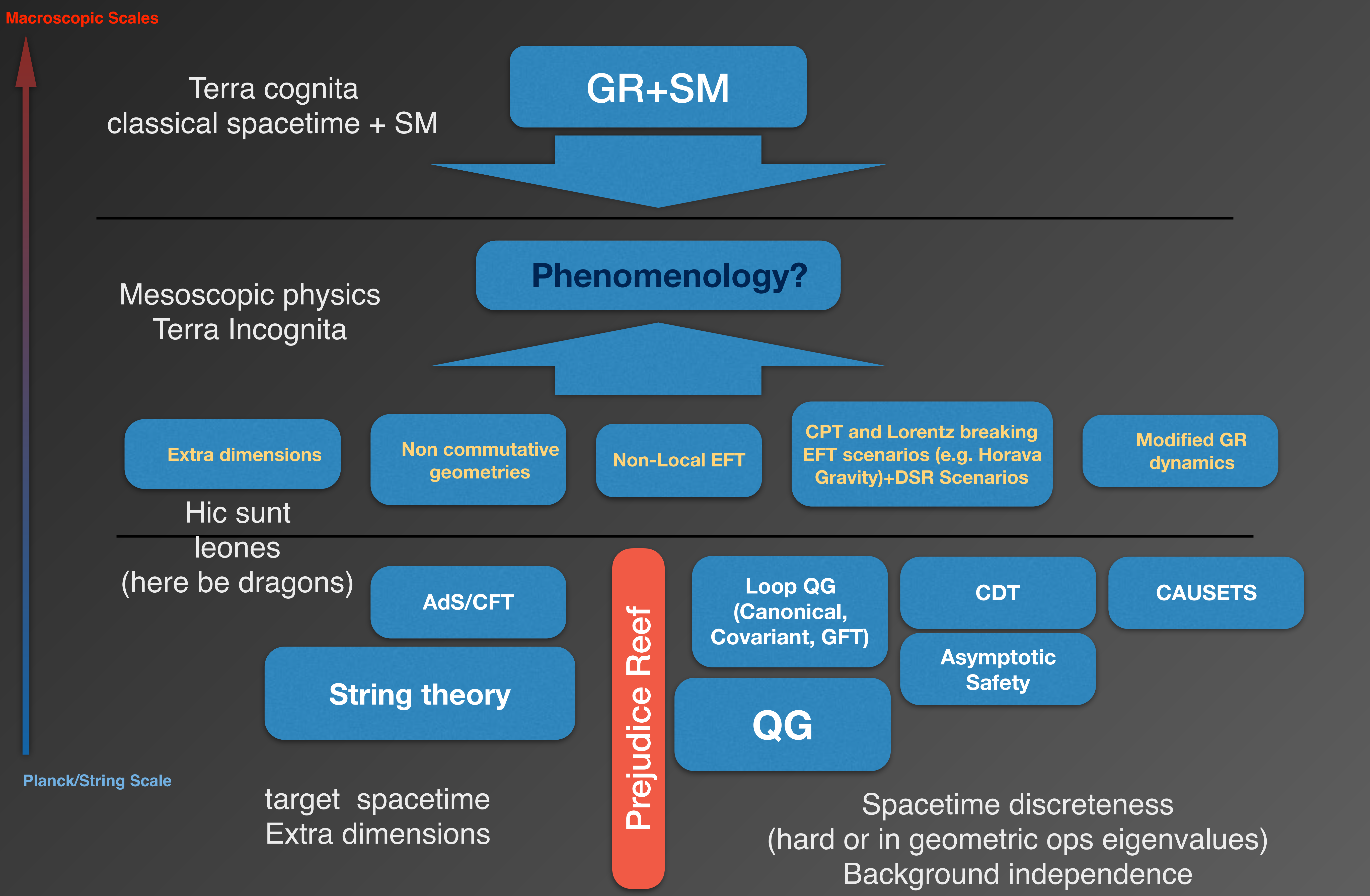
Old “dogma”: you shall not access any quantum gravity effect as this would require experiments at the Planck scale!

This has changed in the last decade, as several proposal for QG effects have been proposed.

- We have nowadays several workable quantum gravity theories and various scenarios for how the continuous and semi-classical limit are reached within them
- I.e. we have for the first time a chance to ask the hard questions about how and what we can probe of the fabric of spacetime.
- Missing a definitive scenario for the continuum limit of QG I will explore here some lines of research and their outcomes and lessons…

Let’s see where this goes…

Between a rock and a hard place
(The world for a QG phenomenologist)



QG phenomenology a la carte

ex pluribus quattuor

Broken or deformed Symmetries

- Lorentz
- Translations
- Diffeomorphism (strong bounds from pulsar timing Donoghue et al. PhysRevD.81.084059)

QG Modified gravitational dynamics

- E.g. Bouncing Universes
- Regular Black holes.

Locality

- QG induced non-locality
- Uncertainty Principle->GUP
- (no strong constraints)
- Non-commutative geometries

Dimensions

- Extra dimensions
- (still missing obs. evidence so far)
- Dimensional reduction in QG
- (early universe?)

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Let's start with the PULP stuff..

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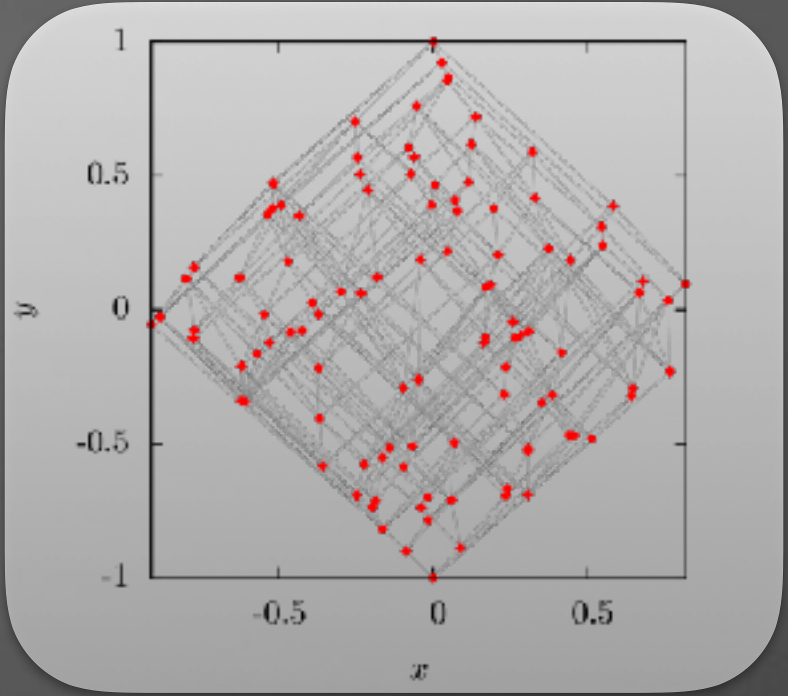
Symmetries Violations

Spacetime locally Poincaré invariant...
Translations Breaking (CAUSETS)
Lorentz breaking (several QG scenarios)

Breakdown of translations in discrete QG: The CAUSET case study



The causal sets program: spacetime is fundamentally discrete and spacetime events are related by a partial order given by the causality relations between spacetime events. So CAUSET encode causality and, by counting points, provide a notion of volume. This is enough to reconstruct the metric (Malament): "Order + Number = Geometry". A CAUSET on average preserves LI but violates translation invariance.

Then Phenomenology exercise

1. Treat massive particles as point particles
2. Particle can only hop from point to point on a causal set. LIKE A SPACETIME PACHINKO!
3. Lorentz-invariant momentum space diffusion of initial probability distribution $\rho(p,x,\tau)$:

F. Dowker, J. Henson and R. D. Sorkin, Quantum gravity phenomenology, Lorentz invariance and discreteness, Mod. Phys. Lett. A 19, 1829 (2004).

$$\frac{\partial\rho}{\partial\tau} = k\nabla_p^2\rho - \frac{1}{mc^2}p^\mu\frac{\partial}{\partial x^\mu}\rho$$

See also similar ideas by S. Hossenfelder, Phys.Rev. D88 (2013) no.12, 124031 Phys.Rev. D88 (2013) no.12, 124030

The problem with this diffusion in momentum space is basically that cold stuff becomes rapidly hot. Even assuming this applies only to elementary particles you get strong bounds from cosmology.

N.Kaloper and D.Mattingly, Low energy bounds on Poincare violation in causal set theory, Phys. Rev. D 74, 106001 (2006).

STRONG BOUNDS FROM RELIC NEUTRINOS NOT VIOLATING BOUNDS ON HOT DM.

Similar bounds also for photons w.r.t. CMB (Philipot, Dowker, Sorkin, Phys. Rev. D 79, 124047 (2009).)

$$k < 10^{-61}\,\mathrm{GeV}^3$$

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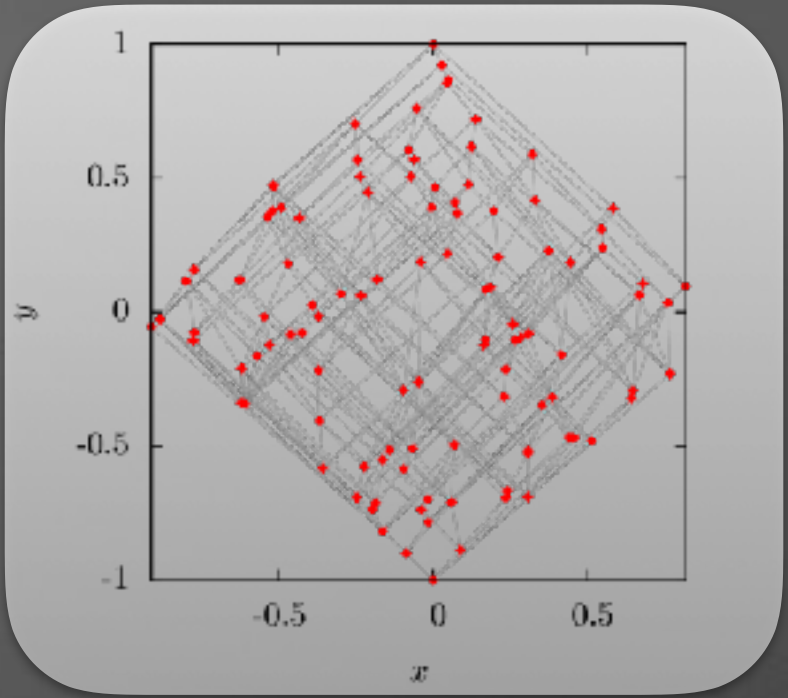

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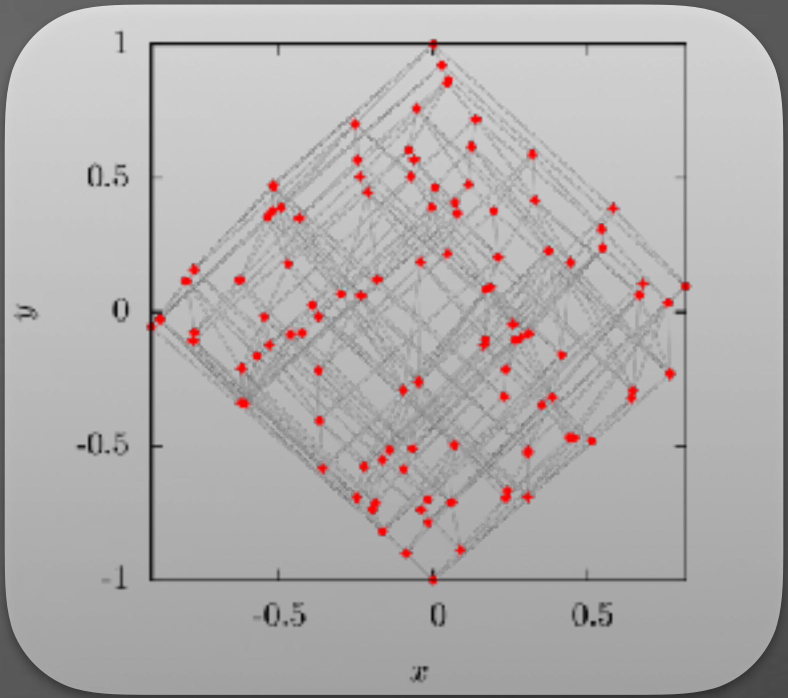

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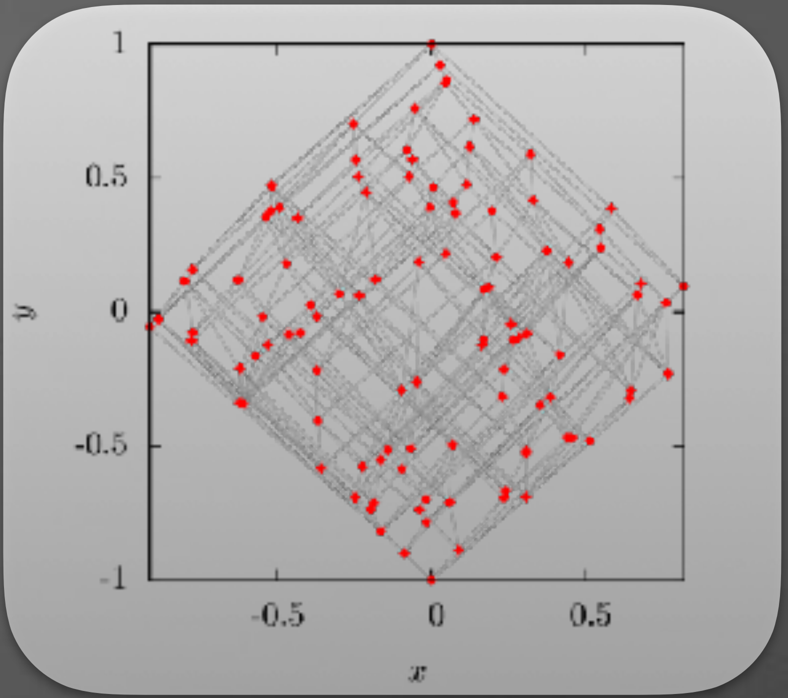

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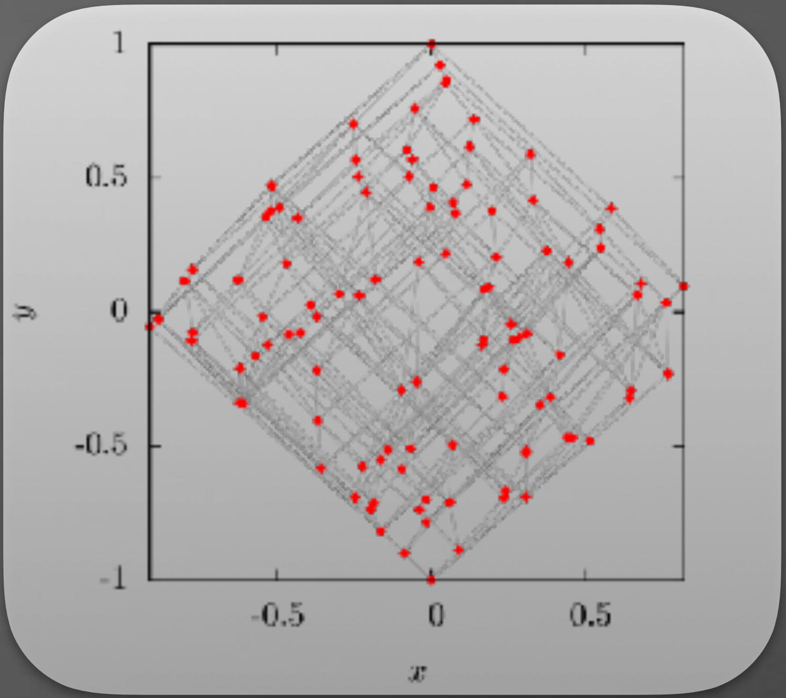

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Teaser: We shall come back to this later…

Lorentz violation: a possible first glimpse of QG?

Suggestions for Lorentz violation searches (at low or high energies) were not inspired only by Analogue models of emergent gravity. They came also from several QG models

- String theory tensor VEVs (Kostelecky-Samuel 1989, ...)
- Cosmological varying moduli (Damour-Polyakov 1994)
- Spacetime foam scenarios (Ellis, Mavromatos, Nanopoulos 1992, Amelino-Camelia et al. 1997-1998)
- Some semiclassical spin-network calculations in Loop QG (Gambini-Pullin 1999)
- Einstein-Aether Gravity (Gasperini 1987, Jacobson-Mattingly 2000, …)
- Some non-commutative geometry calculations (Carroll et al. 2001)
- Some brane-world backgrounds (Burgess et al. 2002)
- Ghost condensate in EFT (Cheng, Luty, Mukohyama, Thaler 2006)
- Horava-Lifshiftz Gravity (Horava 2009, …)

Quote: "How you dare to Violate Lorenz Invariance?"

- Lorentz invariance is rooted via Einstein equivalence principle in GR and it is a fundamental pillar of the SM. The more fundamental is an ingredient of your theory the more needs to be tested observationally!
- You do not need Planck scale observations to constraint Planck suppressed Lorentz violations.
- In any quantum/Discrete gravity model it is a non-trivial task to recover exact Local Lorentz Invariance and/or background independence. Hence it is very important to understand what is needed in order to conciliate LLI and forms of hard or quantum discreteness at the Planck scale.

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But what we mean by Lorentz Invariance violation?

Breaking of Local Lorentz Invariance

von Ignatowsky theorem (1911): Axiomatic Special Relativity

PRINCIPLE OF RELATIVITY → GROUP STRUCTURE
HOMOGENEITY → LINEARITY OF THE TRANSFORMATIONS
ISOTROPY OF SPACE → ROTATIONAL INVARIANCE AND RIEMANNIAN STRUCTURE
PRECAUSALITY → OBSERVER INDEPENDENCE OF CO-LOCAL TIME ORDERING

⇒

LORENTZ TRANSFORMATIONS WITH UNFIXED LIMIT SPEED C
$C=\infty$ → GALILEO
$C=C_{LIGHT}$ → LORENTZ
EXPERIMENTS DETERMINE C!

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Lorentz breaking does not necessarily mean to have a preferred frame!

BREAK PRECAUSALITY → HELL BREAKS LOOSE, BETTER NOT!

BREAK PRINCIPLE OF RELATIVITY → PREFERRED FRAME EFFECTS

BREAK KINEMATICAL ISOTROPY → FINSLER GEOMETRIES. E.G. VERY SPECIAL RELATIVITY (GLASHOW, GIBBONS ET AL.).

BREAK HOMOGENEITY → NO MORE LINEAR TRANSFORMATIONS → NO LOCALLY EUCLIDEAN SPACE. → TANTAMOUNT TO GIVE UP OPERATIVE MEANING OF COORDINATES

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Breaking of Local Lorentz Invariance

von Ignatowsky theorem (1911): Axiomatic Special Relativity

Principle of relativity → group structure
Homogeneity → linearity of the transformations
Isotropy of Space → rotational invariance and Riemannian structure
Precausality → observer independence of co-local time ordering

⇒

Lorentz transformations with unfixed limit speed C
C=∞ → Galileo
$C=C_{light}$ → Lorentz
Experiments determine C!

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Lorentz breaking does not necessarily mean to have a preferred frame!

Break Precausality → Hell breaks loose, better not!

Break Principle of relativity → Preferred frame effects

Break kinematical Isotropy → Finsler geometries. E.g. Very Special Relativity (Glashow, Gibbons et al.).

Break Homogeneity → no more linear transformations → No Locally Euclidean Space. → tantamount to give up operative meaning of coordinates

Let's relax the Relativity Principle first and study the phenomenology. To do this we need a framework…

Dynamical frameworks for LIV

Frameworks for preferred frame effects

See e.g. SL. CQG Topic Review (2013)

Generally assumed rotational invariance

- simpler and boost w.r.t. CMB frame small
- cutoff idea only implies boosts are broken, rotations maybe not
- boost violation constraints likely also boost + rotation violation constraints

EFT+LV

See e.g. Amelino-Camelia. Living Reviews of Relativity

Non EFT proposals:
Spacetime foam models (Ellis et al.)
DSR/Relative Locality

local EFT with LIV
Non-renormalizable ops,
CPT ever or odd
(no anisotropic scaling),
(UV LIV – QG inspired LIV)

Minimal Standard Model Extension
Renormalizable ops.
(IR LIV - LI SSB)

NOTE: CPT violation implies Lorentz violation but LV <u>does not</u> imply CPT violation in local EFT. "Anti-CPT" theorem (Greenberg 2002). So one can catalogue LIV by behaviour under CPT

E.g. QED, rot. Inv. dim 3,4 operators

electrons $E^2 = m^2 + p^2 + f_e^{(1)} p + f_e^{(2)} p^2$

photons $\omega^2 = \left(1 + f_\gamma^{(2)}\right) k^2$

(Colladay-Kosteleky 1998, Colemann-Glashow 1998)

E.g. QED, dim 5 operators

electrons $E^2 = m^2 + p^2 + \eta_\pm^{(3)} (E^3/M_{\rm Pl})$

photons $\omega^2 = k^2 \pm \xi(\omega^3/M_{\rm Pl})$

(Myers-Pospelov 2003)

Dynamical frameworks for LIV

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EFT with Lorentz breaking Ops.
Matter Sector Constraints

Terrestrial tests:

Penning traps
Clock comparison experiments
Cavity experiments
Spin polarised torsion balance
Neutral mesons
Slow atoms recoils

Astrophysical tests:

Cosmological variation of couplings, CMB
Cumulative effects in astrophysics
Anomalous threshold reactions
Shift of standard thresholds reactions with new threshold phenomenology
LV induced decays not characterised by a threshold
Reactions affected by "speeds limits"

$$E_\gamma^2 = k^2 + \xi_\pm^{(n)} \frac{k^n}{M_{pl}^{n-2}} \qquad \text{photons}$$

$$E_{matter}^2 = m^2 + p^2 + \eta_\pm^{(n)} \frac{p^n}{M_{pl}^{n-2}} \qquad \text{leptons/hadrons} ,$$

where, in EFT, $\xi^{(n)} \equiv \xi_+^{(n)} = (-)^n \xi_-^{(n)}$ and $\eta^{(n)} \equiv \eta_+^{(n)} = (-)^n \eta_-^{(n)}$.

Table 2 Summary of typical strengths of the available constrains on the SME at different orders.

Order	photon	e^-/e^+	Hadrons	Neutrinos[a]
n=2	N.A.	$O(10^{-13})$	$O(10^{-27})$	$O(10^{-8})$
n=3	$O(10^{-14})$ (GRB)	$O(10^{-16})$ (CR)	$O(10^{-14})$ (CR)	$O(30)$
n=4	$O(10^{-8})$ (CR)	$O(10^{-8})$ (CR)	$O(10^{-6})$ (CR)	$O(10^{-4})^*$ (CR)

GRB=gamma rays burst, CR=cosmic rays
[a] From neutrino oscillations we have constraints on the difference of LV coefficients of different flavors up to $O(10^{-28})$ on dim 4, $O(10^{-8})$ and expected up to $O(10^{-14})$ on dim 5 (ICE3), expected up to $O(10^{-4})$ on dim 6 op. * Expected constraint from future experiments.

SL, CQG Topic Review 2013

Example: Constraints on QED with dim 5 CPT Odd

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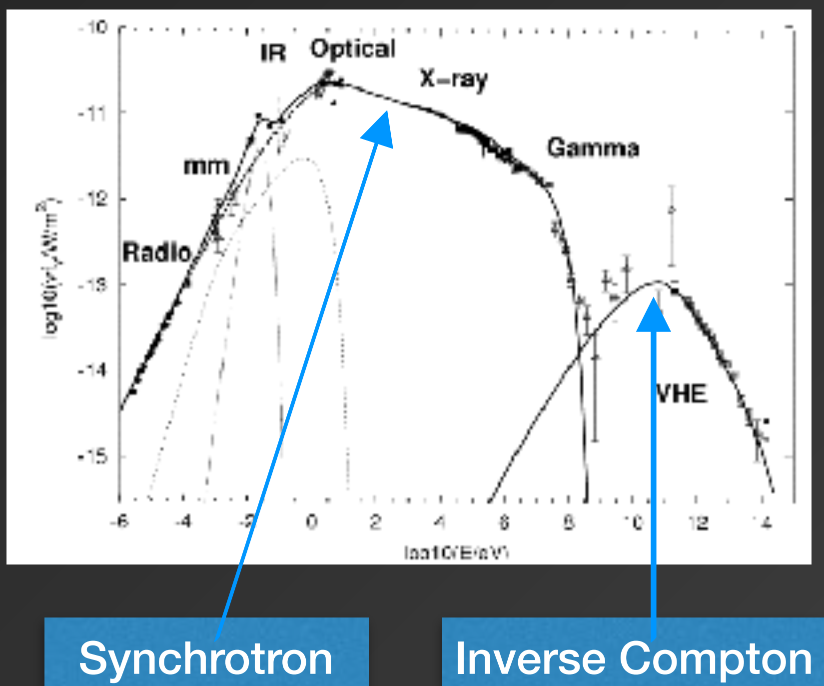

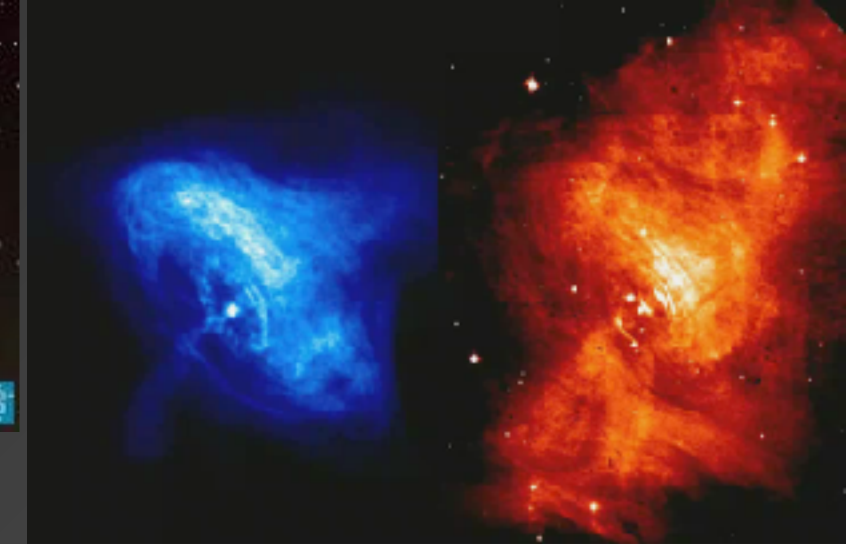

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The Crab nebula a supernova remnant (1054 A.D.) distance ~1.9 kpc from Earth.
Spectrum (and other SNR) well explained by synchrotron self-Compton (SSC)
Electrons are accelerated to very high energies at pulsar: in LI QED $\gamma_e \approx 10^9 \div 10^{10}$
High energy electrons emit synchrotron radiation
Synchrotron photons undergo inverse Compton with the high energy electrons

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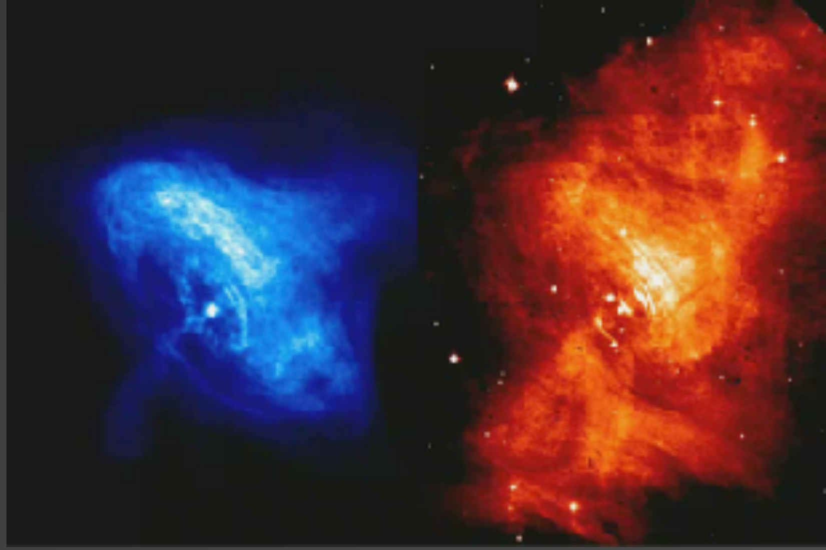

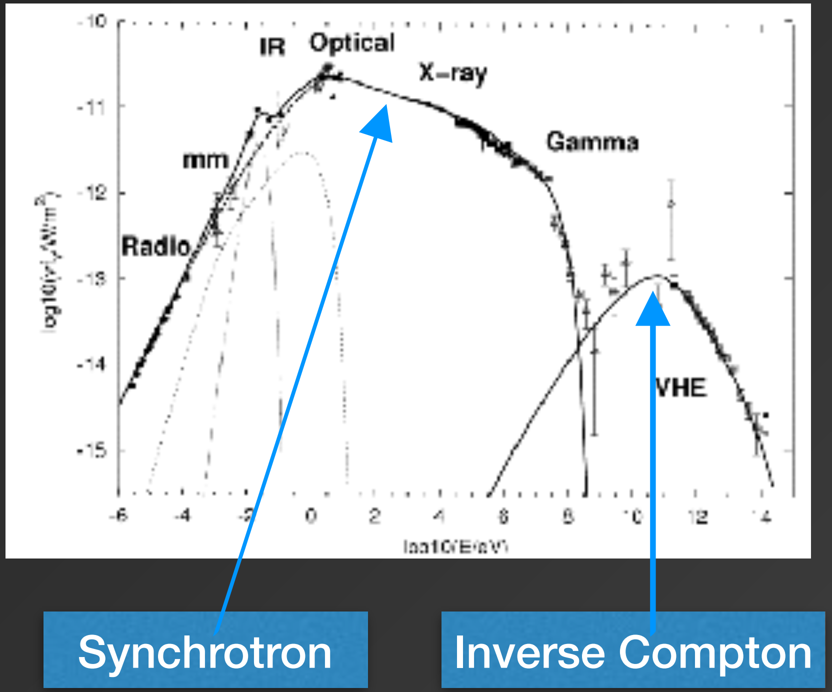

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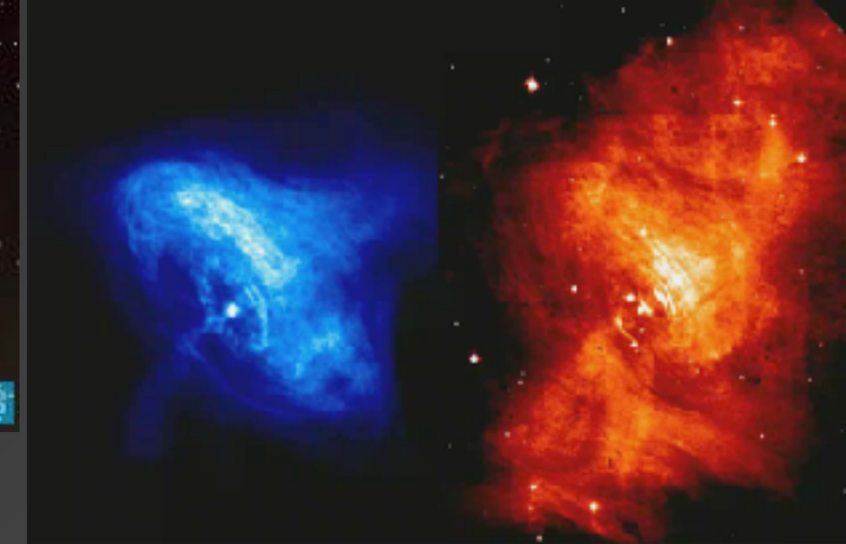

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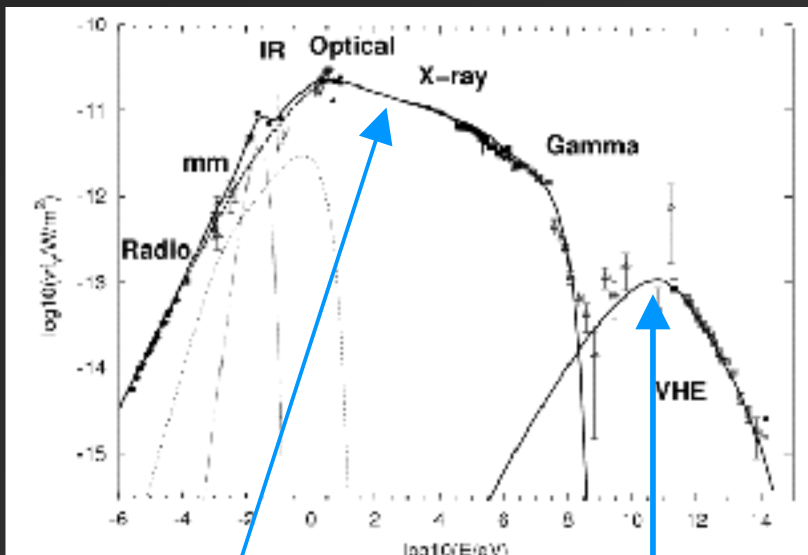

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Inverse Compton

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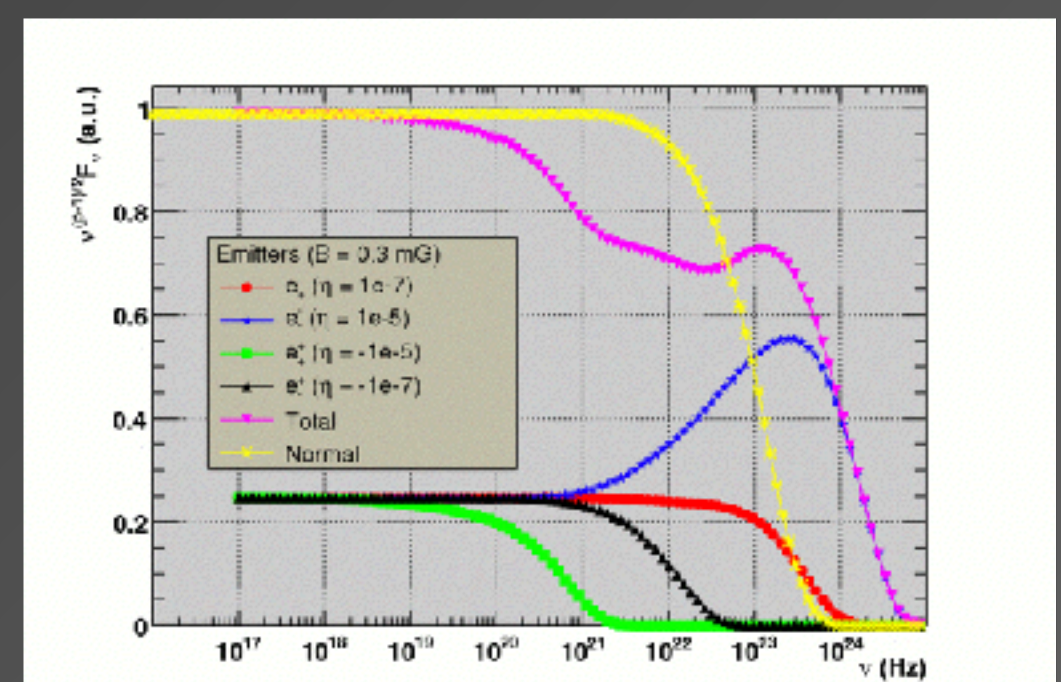
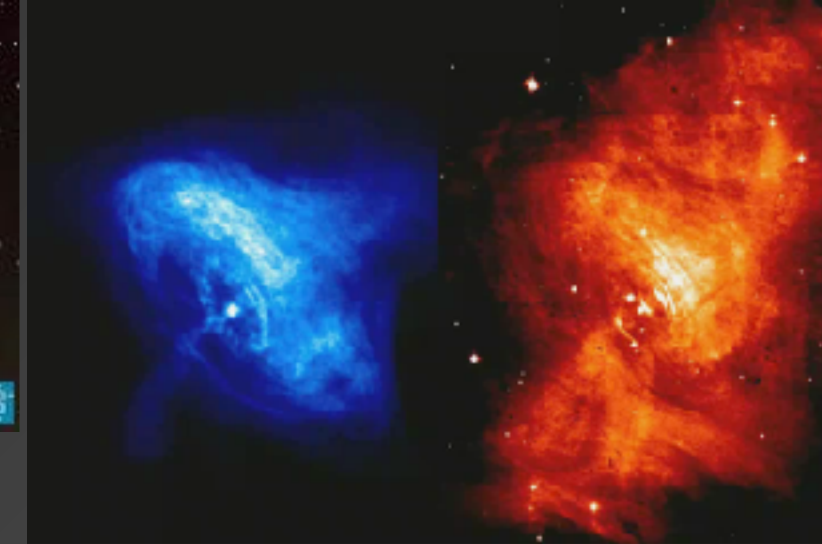


Example: Constraints on QED with dim 5 CPT Odd



electrons $E^2 = m^2 + p^2 + \eta_\pm (p^3/M_{\rm Pl})$

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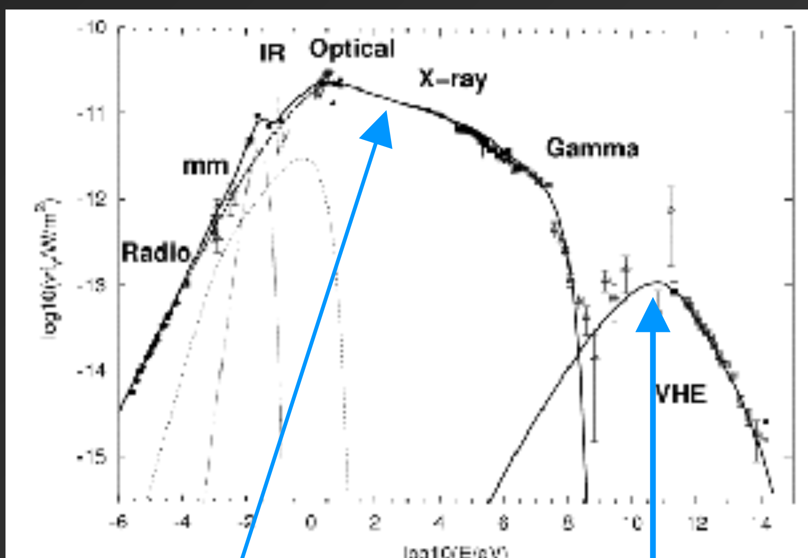

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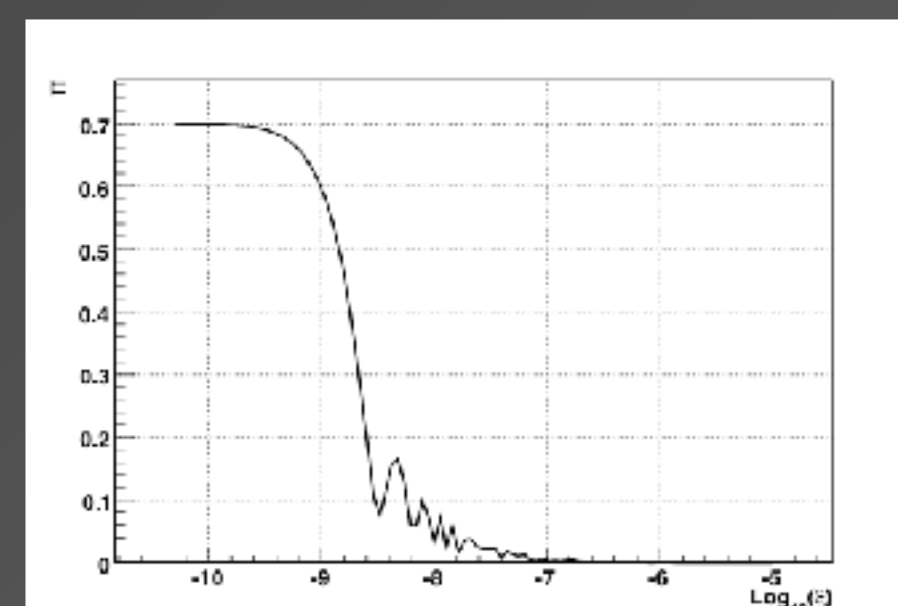
$$\Delta\theta = \xi\,(k_2^2 - k_1^2)\,d/2M, \quad \text{(where } d = \text{distance source-detector)}$$

Polarization recently accurately measured by INTEGRAL mission: 40±3% linear polarization in the 100 keV - 1 MeV band + angle θ_{obs}= (123±1.5)° from the North



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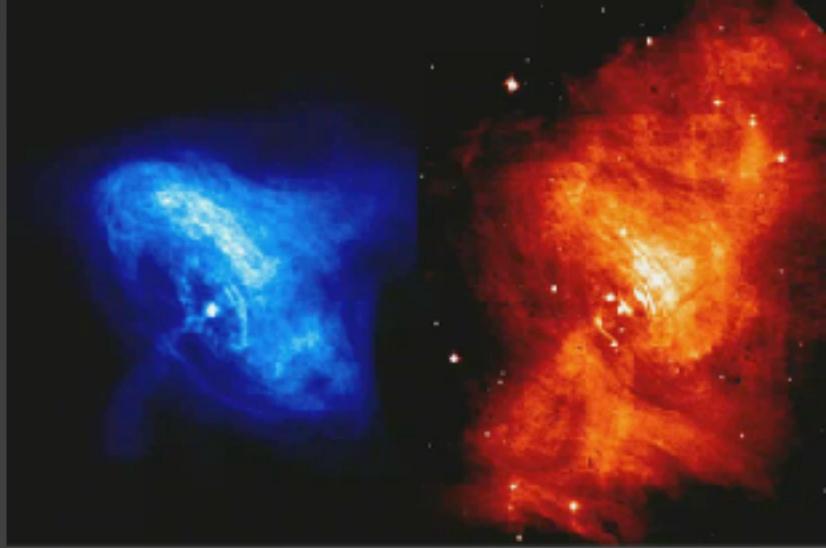

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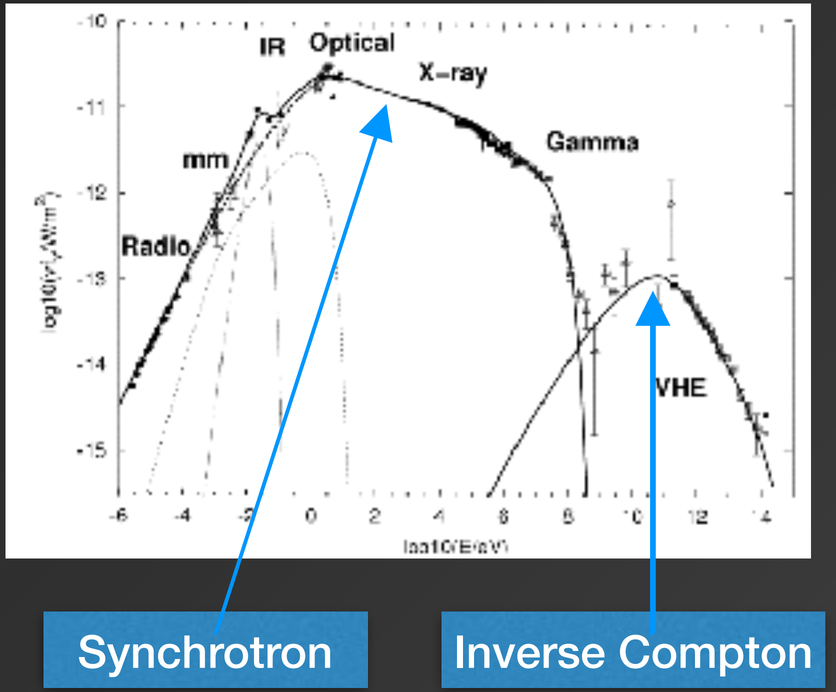

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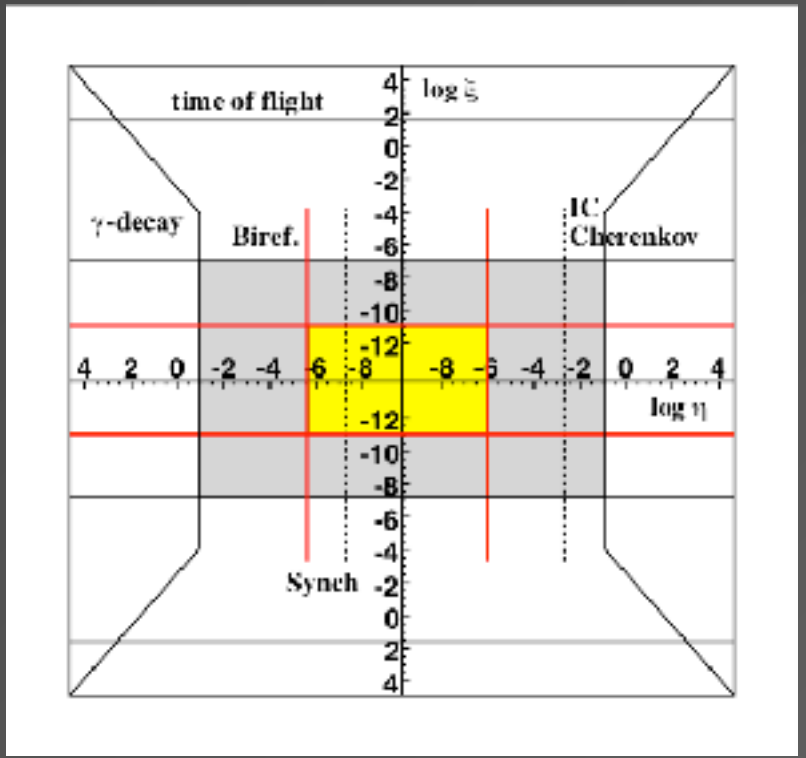

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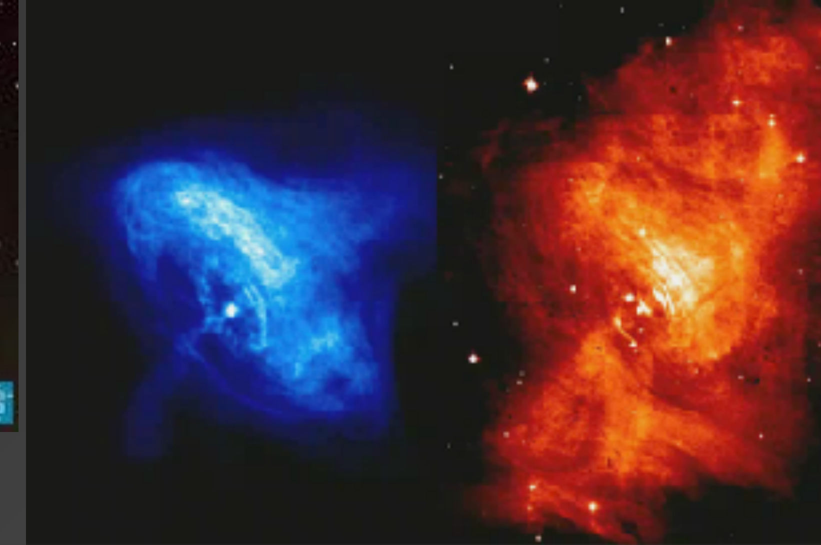

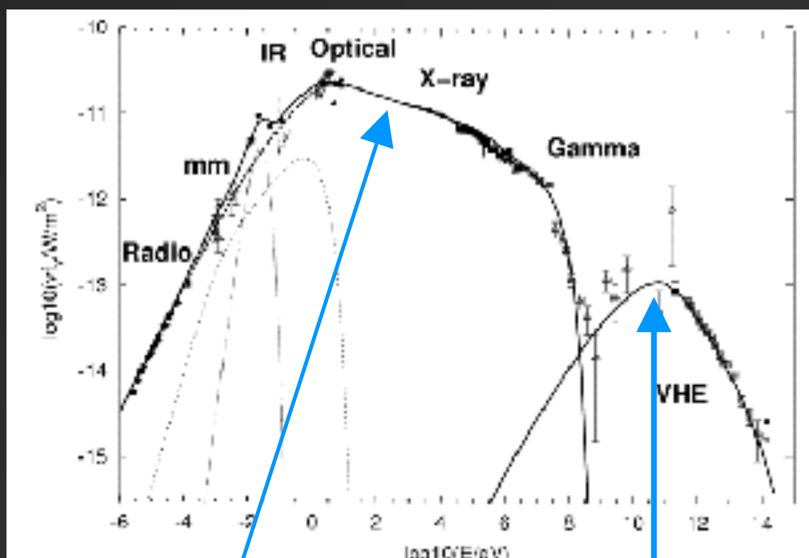

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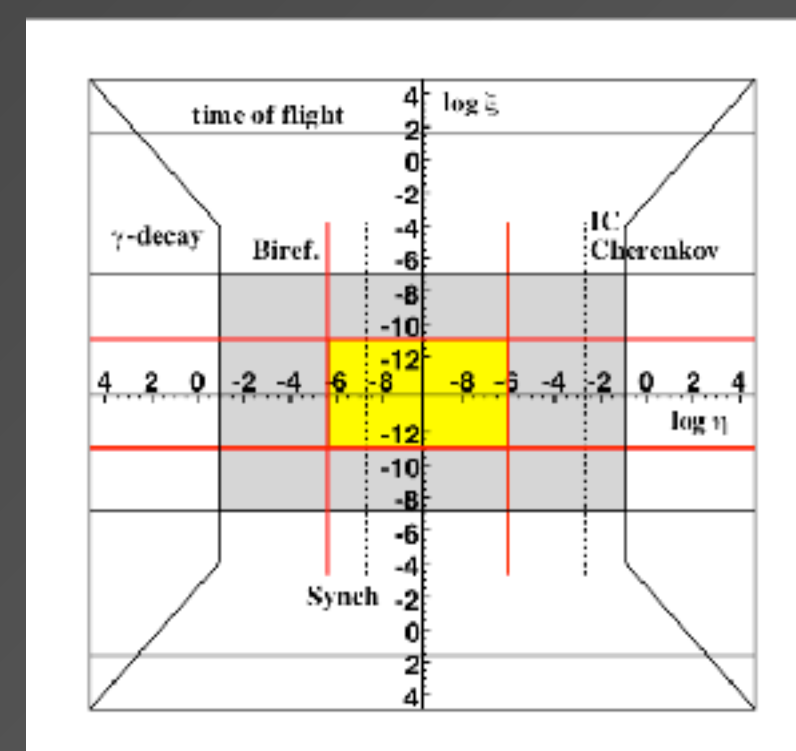

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In this case we need ultra high energies:
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Cosmic Rays Photo pion production:
The Greisen-Zatsepin-Kuzmin effect

$$p + \gamma \to p + \pi^0 (n + \pi^+) \qquad E_{\rm th} = \frac{2 m_p m_\pi + m_\pi^2}{4\epsilon} \sim 4 \cdot 10^{19}\ \text{eV}$$

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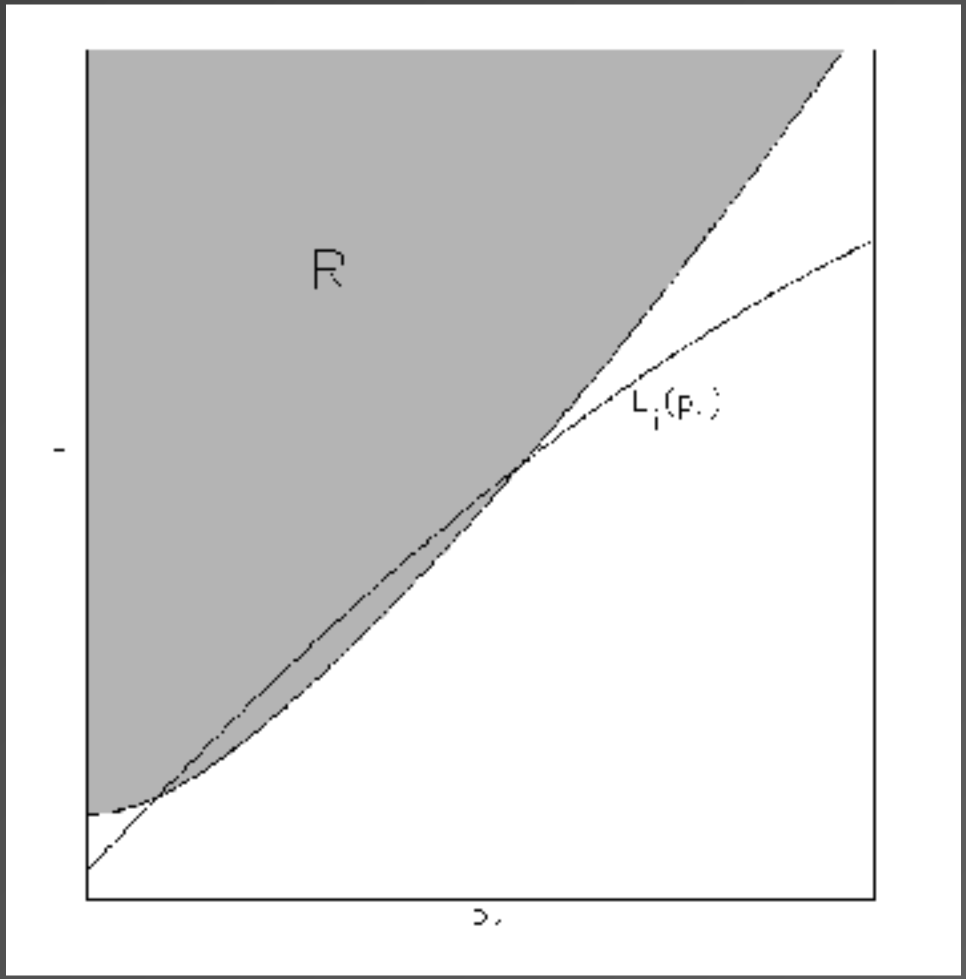

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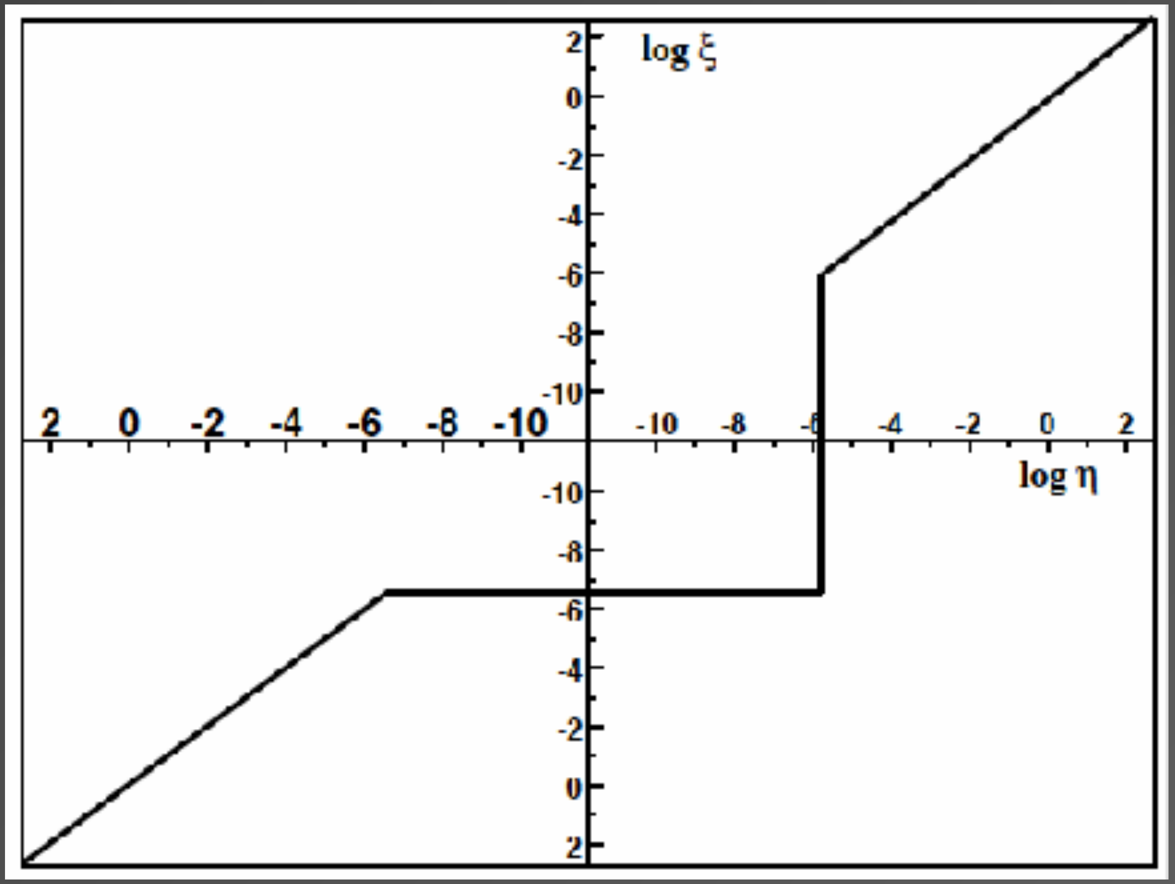

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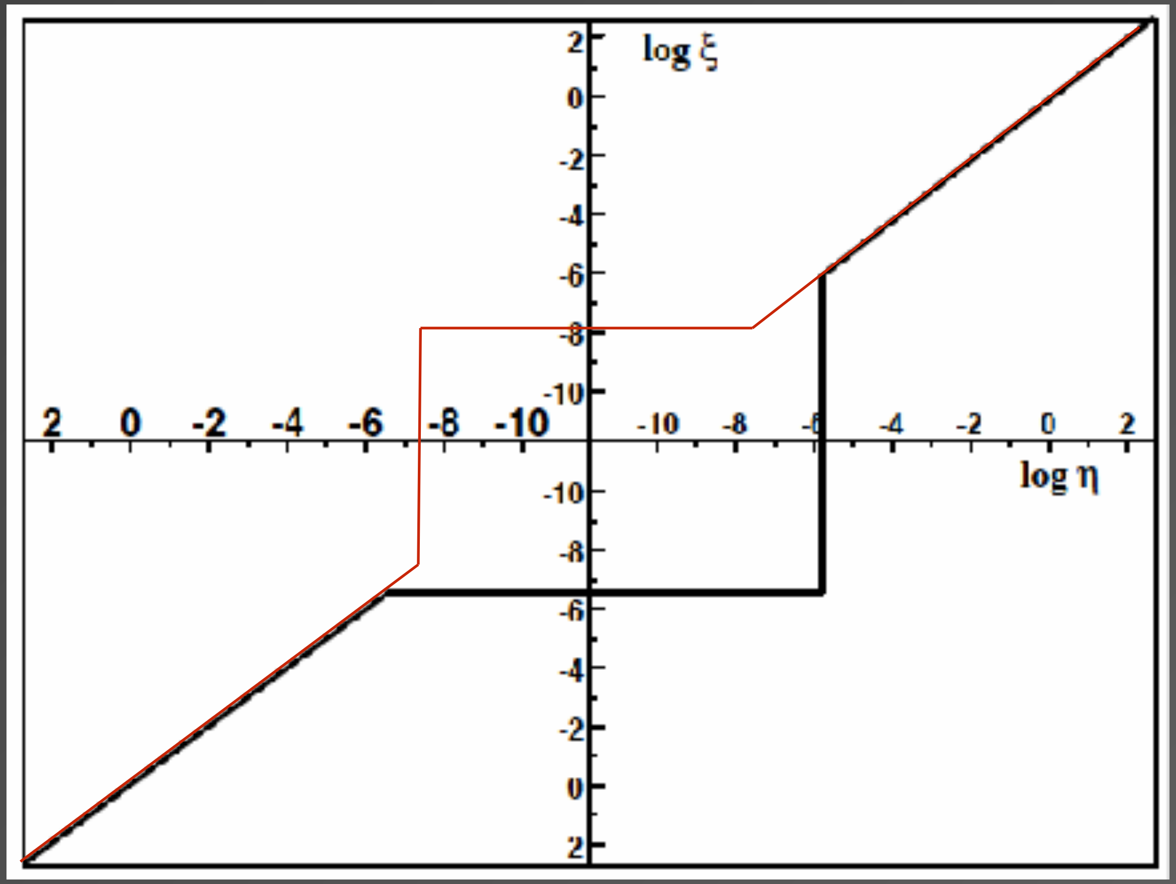

LIV strongly affects the threshold of this process: lower and also upper thresholds.
If $k_{up} < 10^{20}$ eV then photon fraction in UHECR much larger than present upper limits
LIV also introduces competitive processes: γ-decay
If photons above 10^{19} eV are detected then γ-decay threshold > 10^{19} eV

Caveat: A potential problem with the UHECR data?

- With increased statistics the composition of UHECR beyond 10^{19} eV seems more and more dominated by iron ions rather than protons at AUGER.
- With improved statistic the correlated AUGER UHECR-AGN events has been lost: large deflections? i.e. heavy (high Z) ions?
- Ions do photodisintegration rather than the GZK reaction, this may generate much less protons which are able to create pions via GZK and hence UHE photons.
- Have we really seen the GZK cutoff or sources exhaustion? See e.g. arXiv:1408.5213.
- If not all the constraints on dim 6 CPT even operators would not be robust…
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At the moment we cannot anymore deem the dim 6 ops constraints robust.

What about Lorentz breaking by dissipative effects?

By Kramers-Kronig one would naturally expect also dissipative effects.

SL, L. Maccione
Phys.Rev.Lett. 112 (2014) 151301

Analogue gravity describes spacetime emergence in hydrodynamics. Dissipation->Viscosity. Using the analogy one expects a generalised Navier-Stokes equations describing the propagation of perturbations of the velocity potential ψ_1

$$\partial_t^2 \psi_1 = c^2 \nabla^2 \psi_1 + \sum_{n=2}^{\infty} \frac{4}{3} \nu_n \, \partial_t \nabla^n \psi_1$$

Using the Planck scale as the natural scale of the new physics and so define at lowest order a dimensionless coefficient $\sigma=(4\nu_2 M_{Pl})/3c$

$$\omega^2 = c^2 k^2 - i\sigma c^2 \frac{k^3}{M_{\rm Pl}}$$

The energy loss rate Γ can be computed a la Breit-Wigner $\sigma c^2 \frac{k^3}{M_{\rm Pl}} \equiv 2\omega\Gamma$

For an ultra-relativistic particle with momentum k traveling over a long distance D, a constraint is obtained by requiring its lifetime τ to be larger than the propagation time D/c, that is $\tau>D/c$ or $c\hbar/\Gamma>D$.

Let us consider the observed 80 TeV photons from the Crab nebula, $D_{Crab} \approx 1.9$ Kparsec. We get

$$\sigma \leq \frac{2c\hbar}{D_{\rm Crab}(80\ \text{TeV})^2} M_{\rm Pl} \approx 1.3 \times 10^{-26}$$

Similar considerations leads to
Electron/positron $\sigma < 10^{-23}$ (From Crab and 1 pc traveled)
Neutrinos $\sigma < 10^{-27}$
(detection of a bunch of extraterrestrial neutrinos with energies between 30 and 250 TeV by Ice-Cube)
Gravitational waves could in principle provide constraints. Unfortunately, current experiments are sensitive to waves which are far too low energy (1-10^3 Hz) for providing meaningful constraints.

Next order would be $\omega^2 = c^2 k^2 \pm i|\sigma_4| c^2 k^5 / M_{\rm pl}^3 \,, \quad \text{where} \quad \sigma_4 \equiv (4\nu_4 M_{\rm pl}^3)/3c$

Noticeably we do not have constraints better than O(1). But if indeed spacetime would behave like a superfluid phase of fundamental constituents this would be the first non-zero terms. Worth keep looking…

Conceptual issues with Lorentz breaking? The flies in the Ointment…

Lorentz breaking theories suffers two main theoretical problems

- Naturalness problem
- Possible breakdown of black hole thermodynamics

The "un-naturalness" of small LV in EFT

[Collins et al. PRL93 (2004), Lifshitz theories (anisotropic scaling): Iengo, Russo, Serone (2009)]
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Dim>4 LiV Operators + **No new physics up to E_{LIV}** + **Radiative Corrections** = **Unsuppressed corrections to dim 4 operators (low energy propagators)**

Given the strong constraints on dim 3,4 LIV operators (low energy effects) this is BAD

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Three main Ways out

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Custodial symmetry

One needs EFT range to be bonded by $E_{EFT}<E_{LIV}$
[which we have so far assumed $O(M_{Pl})$].
So far main candidate SUSY but needs E_{SUSY} not too high
(requires $E_{SUSY}<100$ TeV to protect percolation of dim 6 ops.
With current bounds at ~950 GeV no hope to protect
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E.g. gr-qc/0402028 (Myers-Pospelov) or hep-ph/0404271 (Nibblink-Pospelov) or gr-qc/0504019 (Jain-Ralston),
SUSY QED:hep-ph/0505029 (Bolokhov, Nibblink-Pospelov). See also Pujolas-Sibiryakov (arXiv:1109.4495) for SUSY Einstein-Aether gravity.

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Gravitational confinement

Assume only gravity LIV with $M_*<<M_{PL}$, then percolation into the (constrained) matter sector is suppressed by smallness of coupling constant G_N.

E.g. Horava gravity coupled to LI Standard Model: Pospelov & Shang arXiv.org/1010.5249v2

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Dim>4 LiV Operators + **No new physics up to E_{LIV}** + **Radiative Corrections** = **Unsuppressed corrections to dim 4 operators (low energy propagators)**

GIVEN THE STRONG CONSTRAINTS ON DIM 3,4 LIV OPERATORS (LOW ENERGY EFFECTS) THIS IS BAD

THREE MAIN WAYS OUT

Gravitational confinement

Assume only gravity LIV with $M_* << M_{PL}$, then percolation into the (constrained) matter sector is suppressed by smallness of coupling constant G_N.

E.g. Horava gravity coupled to LI Standard Model: Pospelov & Shang arXiv.org/1010.5249v2

Custodial symmetry

One needs EFT range to be bonded by $E_{EFT}<E_{LIV}$ [which we have so far assumed $O(M_{Pl})$].
So far main candidate SUSY but needs E_{SUSY} not too high (requires $E_{SUSY}<100$ TeV to protect percolation of dim 6 ops.
With current bounds at ~950 GeV no hope to protect percolation of dim 5 ops).

E.g. gr-qc/0402028 (Myers-Pospelov) or hep-ph/0404271 (Nibblink-Pospelov) or gr-qc/0504019 (Jain-Ralston),
SUSY QED:hep-ph/0505029 (Bolokhov, Nibblink-Pospelov). See also Pujolas-Sibiryakov (arXiv:1109.4495) for SUSY Einstein-Aether gravity.

Improved RG flow at HE

Models with strong coupling at high energies improving RG flow a la Nielsen
[G.Bednik, O.Pujolàs, S.Sibiryakov, JHEP 1311 (2013) 064]

Violations of the Generalised Second Law in Lorentz breaking scenarios

S.L.Dubovsky, S.M.Sibiryakov, Phys. Lett. B 638 (2006) 509.
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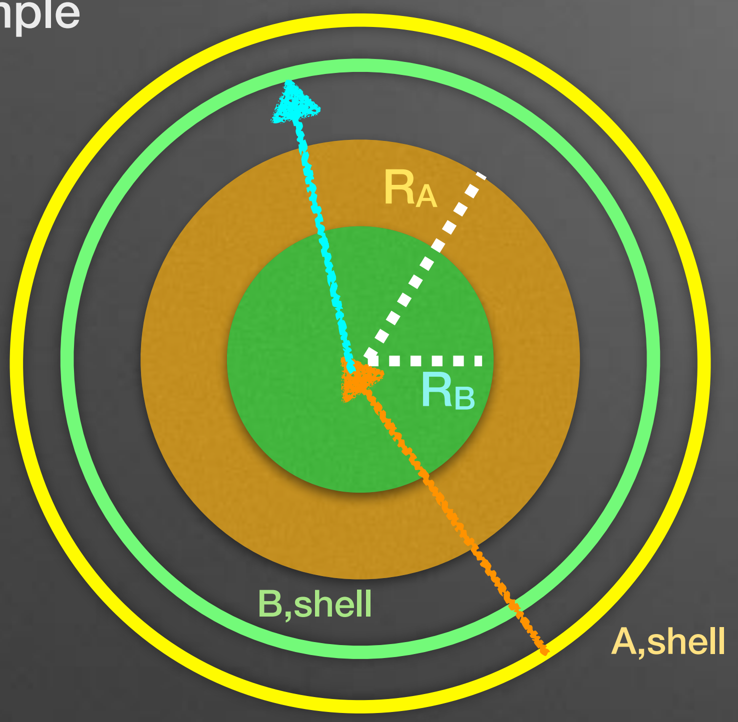
Example



A and B fields interacts only gravitationally

$c_B > c_A \longrightarrow R_B < R_A \longrightarrow T_{B,Haw} > T_{A,Haw}$

Surround the BH with two shells of A and B fields

It is possible to choose the temperatures of the shells such that
$T_{B,Haw} > T_{B,shell} > T_{A,shell} > T_{A,Haw}$

and still get flux from Shell A to Shell B!

Conclusion: Violation of LLI seems to lead to violation of the Generalized Second Law (GSL).

But is it consistent to consider Lorentz breaking matter without breaking Lorentz also in the gravitational sector?

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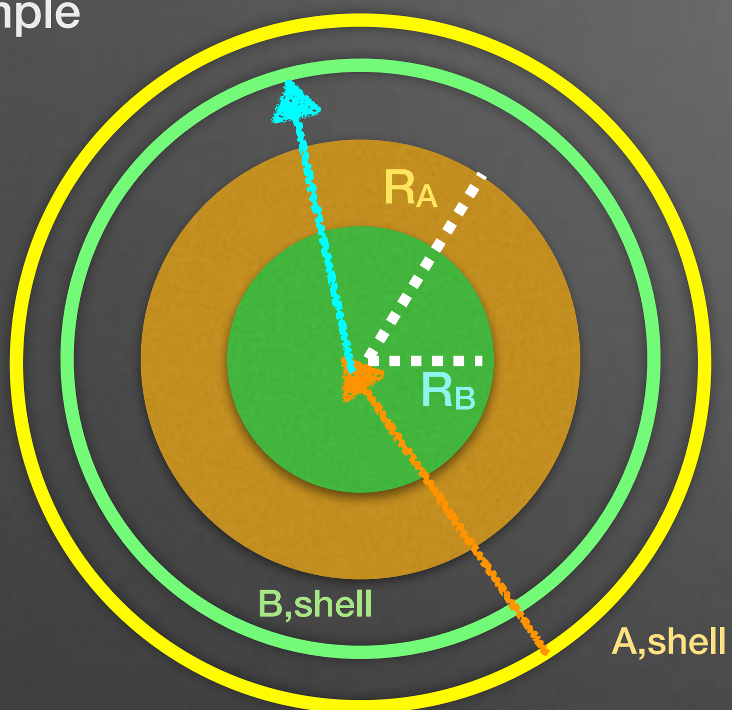

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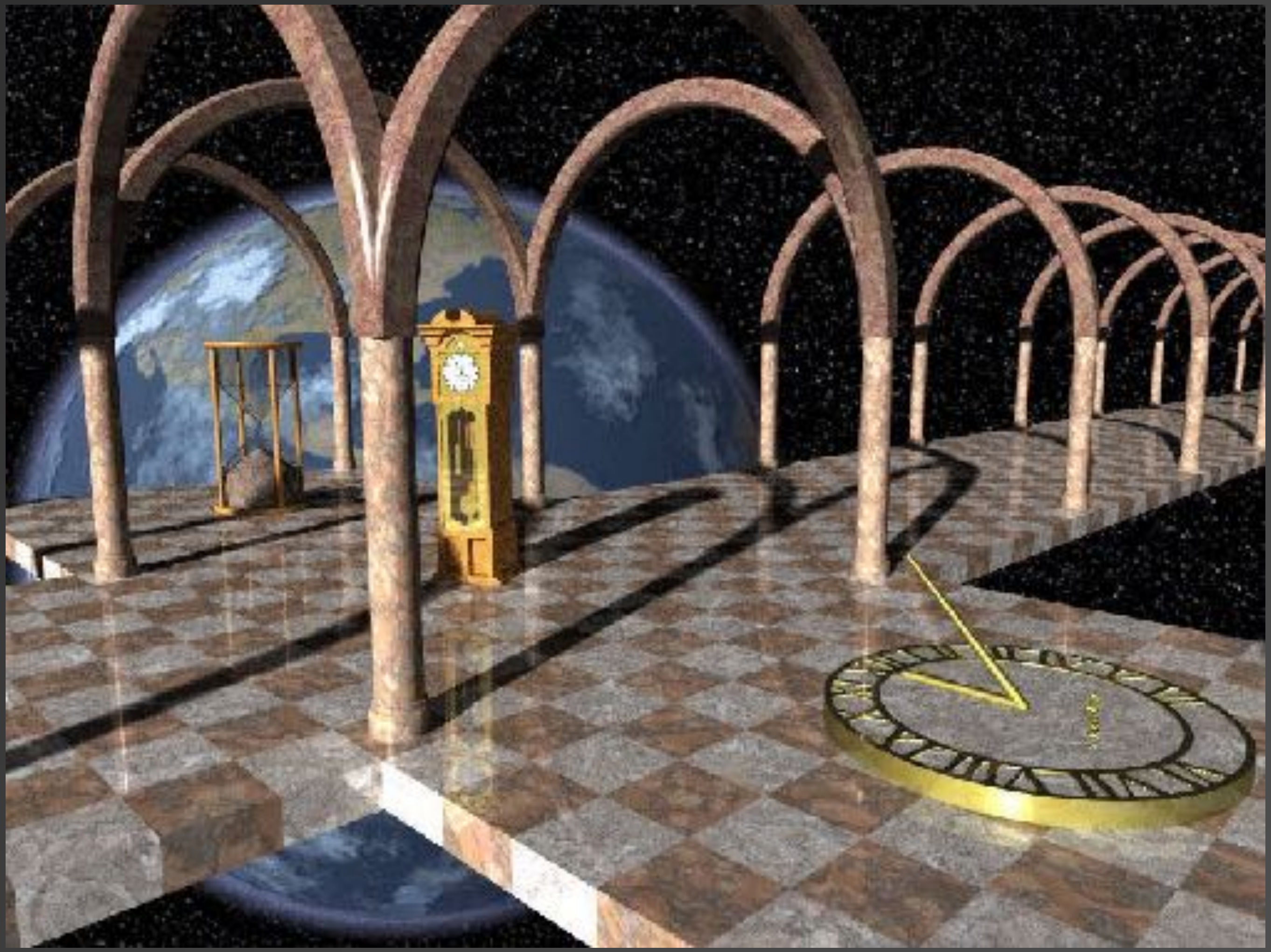
What can we say about Lorentz breaking in the gravitational sector?



Gravity VS Local Lorentz invariance

(what does not kill you makes you stronger)

LIV constraints with Gravitational Waves

A first crude test of IR LIV in the gravity sector is to check for GW speed vs Light or Neutrino speed measurement (e.g. supernova, GRB, neutron binaries merging). Presently we know from binary pulsars $\Delta c/c<1\%$ for GW vs light.

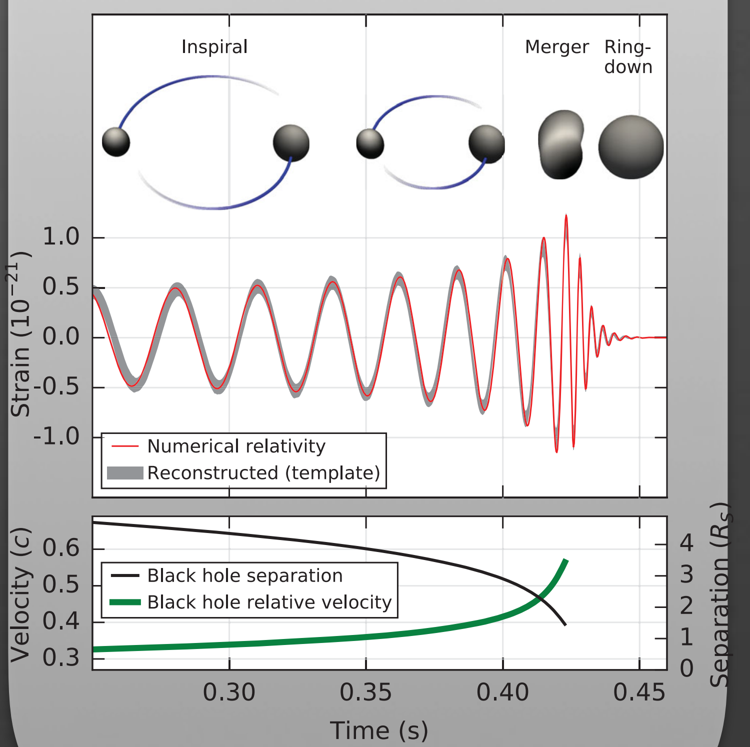
- Gravitational theories with LIV need $c_{grav}>c_{light}$ to avoid gravy-Cherenkov: from UHECR this implies the conservative bound $(c_{light}-c_{grav})/c_{light}<10^{-15}$

- Using a Bayesian approach that combines the first three gravitational wave detections reported by the LIGO collaboration arXiv.org:1707.06101 constrains $-0.45 < (c_{grav}-c_{light})/c_{light}< 0.42$

- E.g. if faint GRB detection almost simultaneous and co-local to GW150914 would be robust then $(c_{grav}-c_{light})/c_{light}<10^{-17}$ (Ellis et al. arXiv:1602.04764).

- Future Tests: polarisation constraints extra DOF in GW (e.g.associated to preferred foliation), test nature of Horizon via ringdown

- GW indirect detection via B-modes of CMB could confirm need to quantise gravity (but just gravitons) plus would tell us about possible modified gravitational dynamics.



This is the dawn of a new channel also for QG phenomenology!

Lorentz breaking gravity

Einstein-Aether
(Jacobson-Mattingly 2000)

Rotationally invariant Lorentz violation in the gravity sector via a vector field.
Take the most general theory for a unit timelike vector field coupled to gravity which is second order in derivatives.

$$\mathcal{S} = \mathcal{S}_{EH} + \mathcal{S}_u = \frac{1}{16\pi G_{\rm ae}} \int dx4\sqrt{-g}\ (R + \mathcal{L}_u)\,.$$

$$\mathcal{L}_u = -Z^{\alpha\beta}_{\gamma\delta}(\nabla_\alpha u^\gamma)(\nabla_\beta u^\delta) + \lambda(u^2+1). \qquad Z^{\alpha\beta}_{\gamma\delta} = c_1 g^{\alpha\beta} g_{\gamma\delta} + c_2 \delta^\alpha_\gamma \delta^\beta_\delta + c_3 \delta^\alpha_\delta \delta^\beta_\gamma - c_4 u^\alpha u^\beta g_{\gamma\delta}\,,$$

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IR Constraints (pure gravity-aether)

$$\alpha_1 = \frac{-8(c_3^2 + c_1 c_4)}{2c_1 - c_1^2 + c_3^2}$$

$$\alpha_2 = \frac{\alpha_1}{2} - \frac{(c_1 + 2c_3 - c_4)(2c_1 + 3c_2 + c_3 + c_4)}{(c_1 + c_2 + c_3)(2 - c_1 - c_4)}.$$

All the PPN parameters vanish except for α_1,α_2 which describe preferred frame effects.

Current solar system constraints imply $\alpha_1 < 10^{-4}$ and $\alpha_2 < 10^{-7}$ which can be used to reduce the parameter space to 2 parameters, c_1 and c_3.

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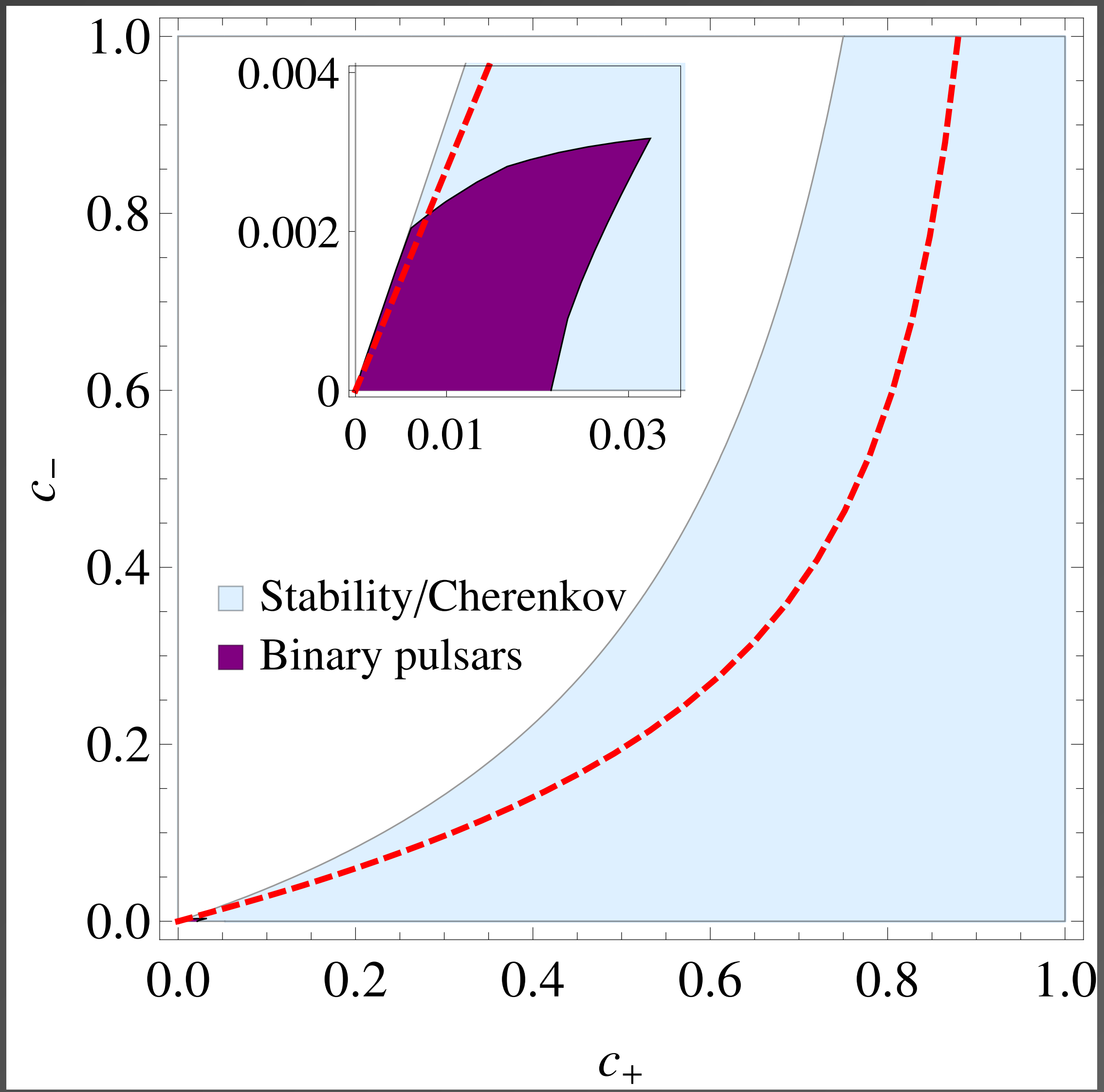

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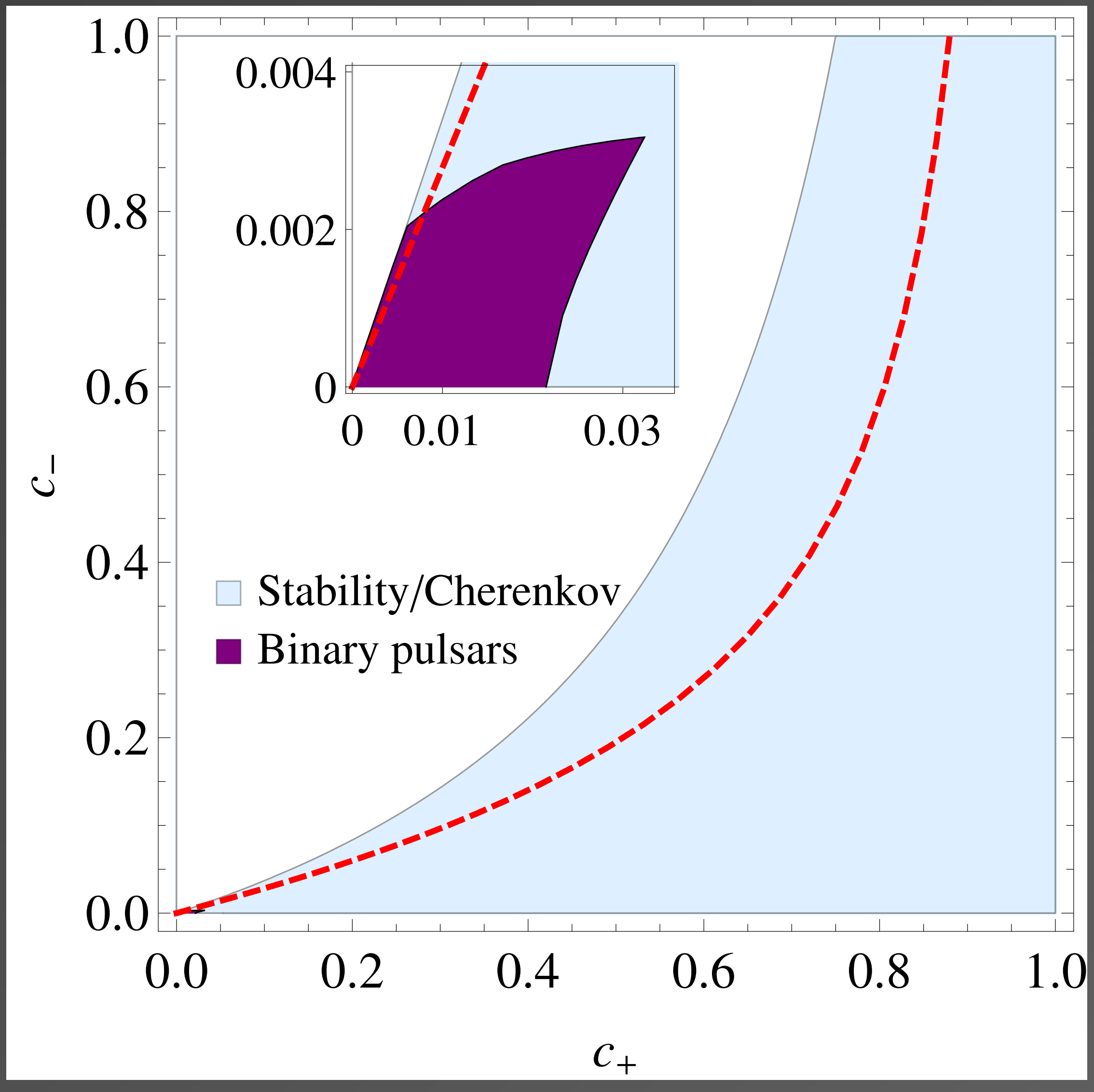

WHAT ABOUT THE UV OPS IN LORENTZ BREAKING GRAVITY?

UV Lorentz breaking Gravity with a preferred foliation: Horava gravity

$$S_{HL} = \frac{M_{\rm Pl}^2}{2} \int dt d^3x \, N\sqrt{h} \left(L_2 + \frac{1}{M_\star^2} L_4 + \frac{1}{M_\star^4} L_6 \right),$$

where h is the determinant of the induced metric h_{ij} on the spacelike hypersurfaces, and $L_2 = K_{ij}K^{ij} - \lambda K^2 + \xi {}^{(3)}R + \eta a_i a^i$ with K is the trace of the extrinsic curvature. K_{ij}, ${}^{(3)}R$ is the Ricci scalar of h_{ij}. N is the lapse function, and $a_i = \partial_i \ln N$.

$\lambda=1$, $\xi=1$, $\eta=0$ in General Relativity (GR).

IR limit: L_2 is Einstein-Aether (Jacobson-Mattingly) with hypersurface orthogonal aether field.

Observationally constrained but not ruled out: similar strength constraints on L_2

$$M_{\rm obs} < M_\star < 10^{16}\ \mathrm{GeV} \qquad M_{\rm obs} \approx \text{few meV} \quad \text{(from sub mm tests)}$$

Blas,Pujolas,Sibiryakov,
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The condition $M_* < 10^{16}$ GeV

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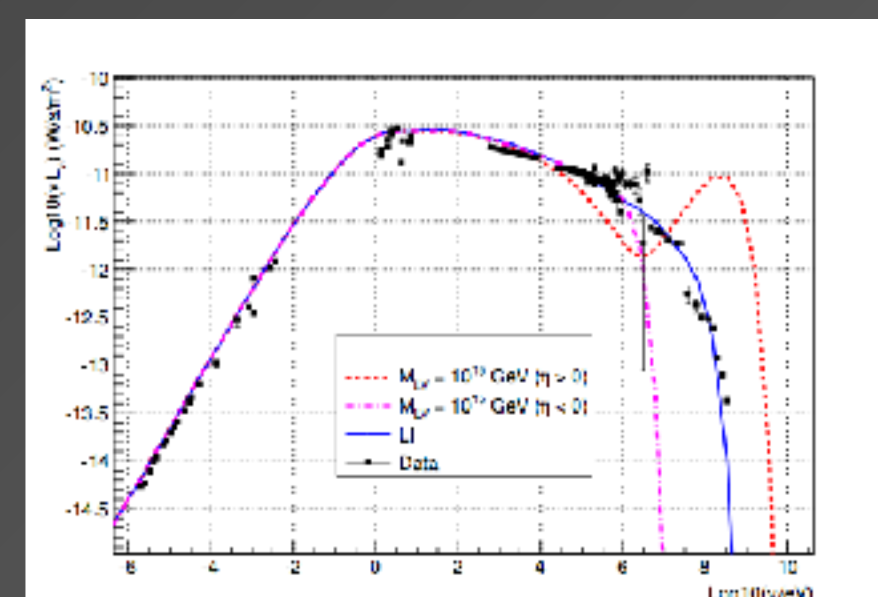
HOWEVER: EVEN IF CONFINED TO MASS DIMENSION 6 OPERATORS ONE CANNOT ACCEPT THAT LIV IN GRAVITY INDUCES SUCH A LOW LORENTZ BREAKING SCALE M_{LIV} IN MATTER DUE TO SYNCHROTRON CRAB NEBULA CONSTRAINTS.

I.E. EVEN IF ELECTRON INDUCED MDR IS JUST

$$E^2 = m^2 + p^2 + \eta\frac{p^4}{M_{\rm LV}^2} + O\left(\frac{p^6}{M_{\rm LV}^4}\right).$$

THEN



SL, Maccione, Sotiriou. Phys.Rev.Lett. 109 (2012) 151602

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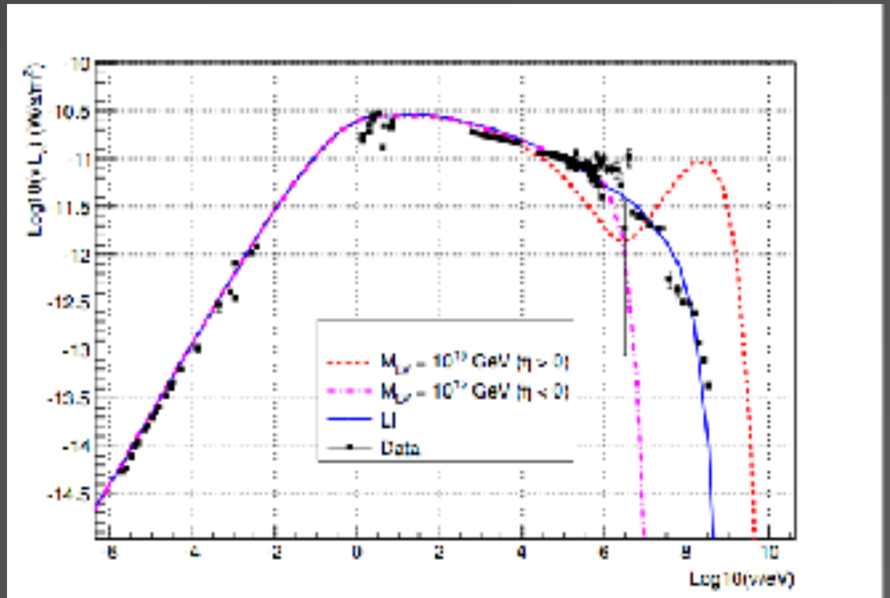
Mass scales $M_{LV} \cong 2 \times 10^{16}$ GeV are excluded at 95% CL.
The window for $M_{LV} \sim M_*$ is closed.

Therefore a mechanism, suppressing the percolation of LV in the matter sector, must be present in HL models, and such mechanism should not only protect lower order operators but also UV ones.
Pospelov's Gravitational confinement? Low M_*? GW opportunity?



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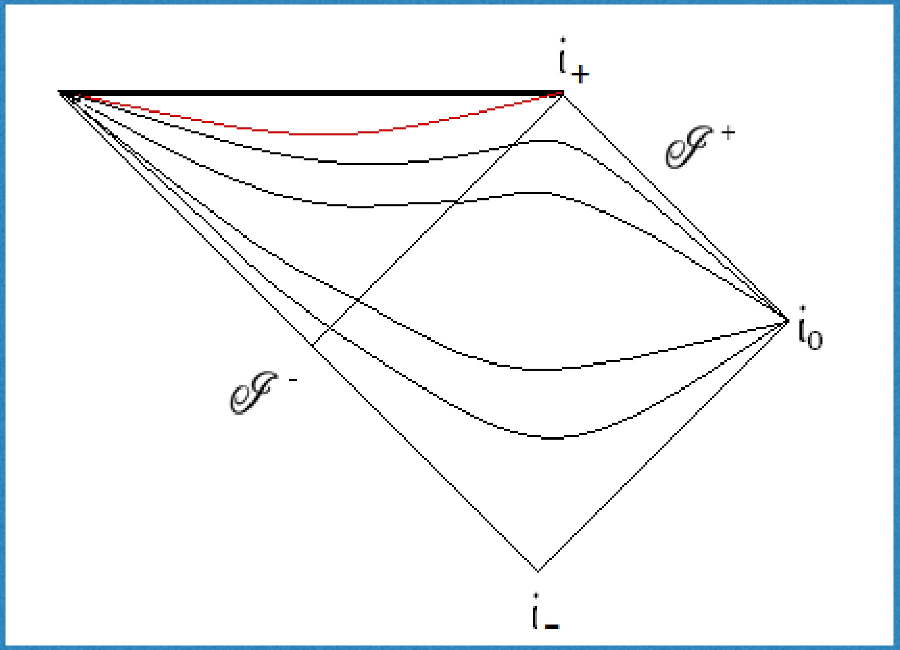
What about LIV BH thermodynamics?

Let’s playing Jenga with BH thermodynamics.
What is really at the root of it?

A new hope: Universal horizons



Conformal diagram of black hole with Universal horizon, showing lines of constant khronon field, with the Universal horizon shown in red.

Eternal BH: D. Blas and S. Sibiryakov (2011), E. Barausse, T. Jacobson, T. P. Sotiriou (2011)
Collapse solutions: M.Saravani, N. Afshordi, Robert B. Mann., (2014).
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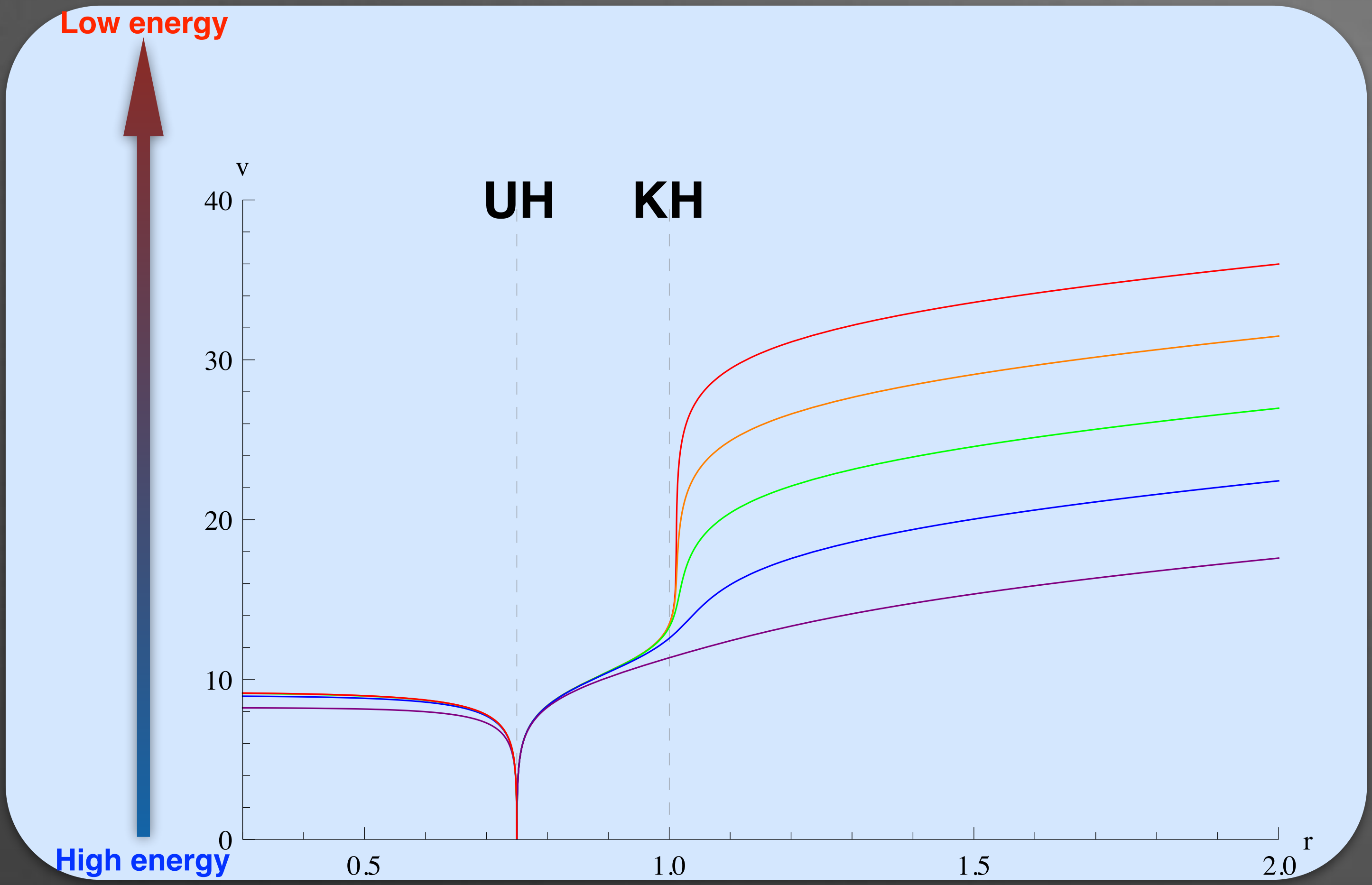

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$$\bar{\kappa}_{\rm UH} \equiv \frac{1}{2} u^a \nabla_a (u \cdot \chi) \Big|_{\rm UH}$$

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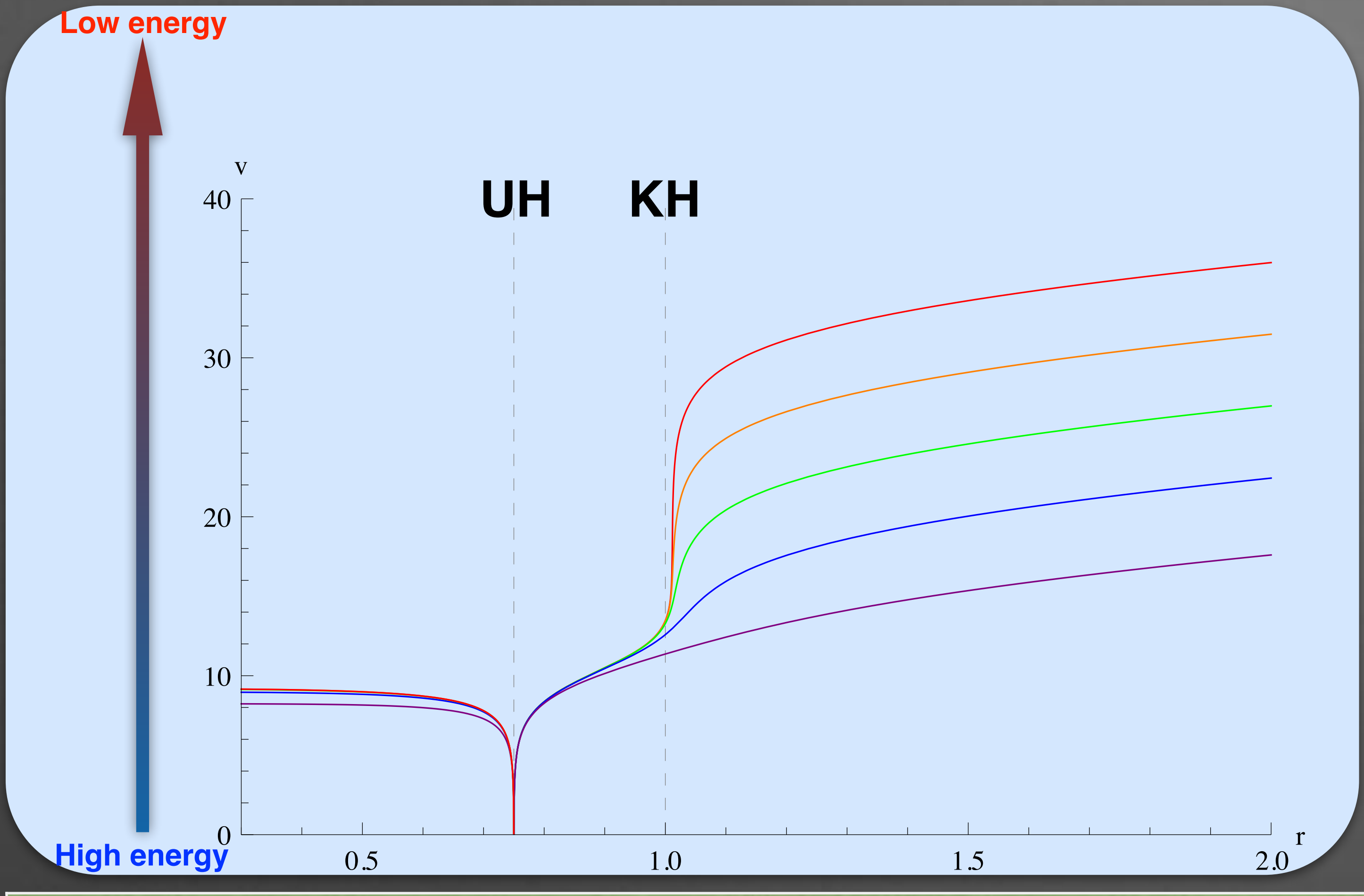

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$$\bar{\kappa}_{\rm UH} \equiv \frac{1}{2} u^a \nabla_a (u \cdot \chi)\Big|_{\rm UH}$$

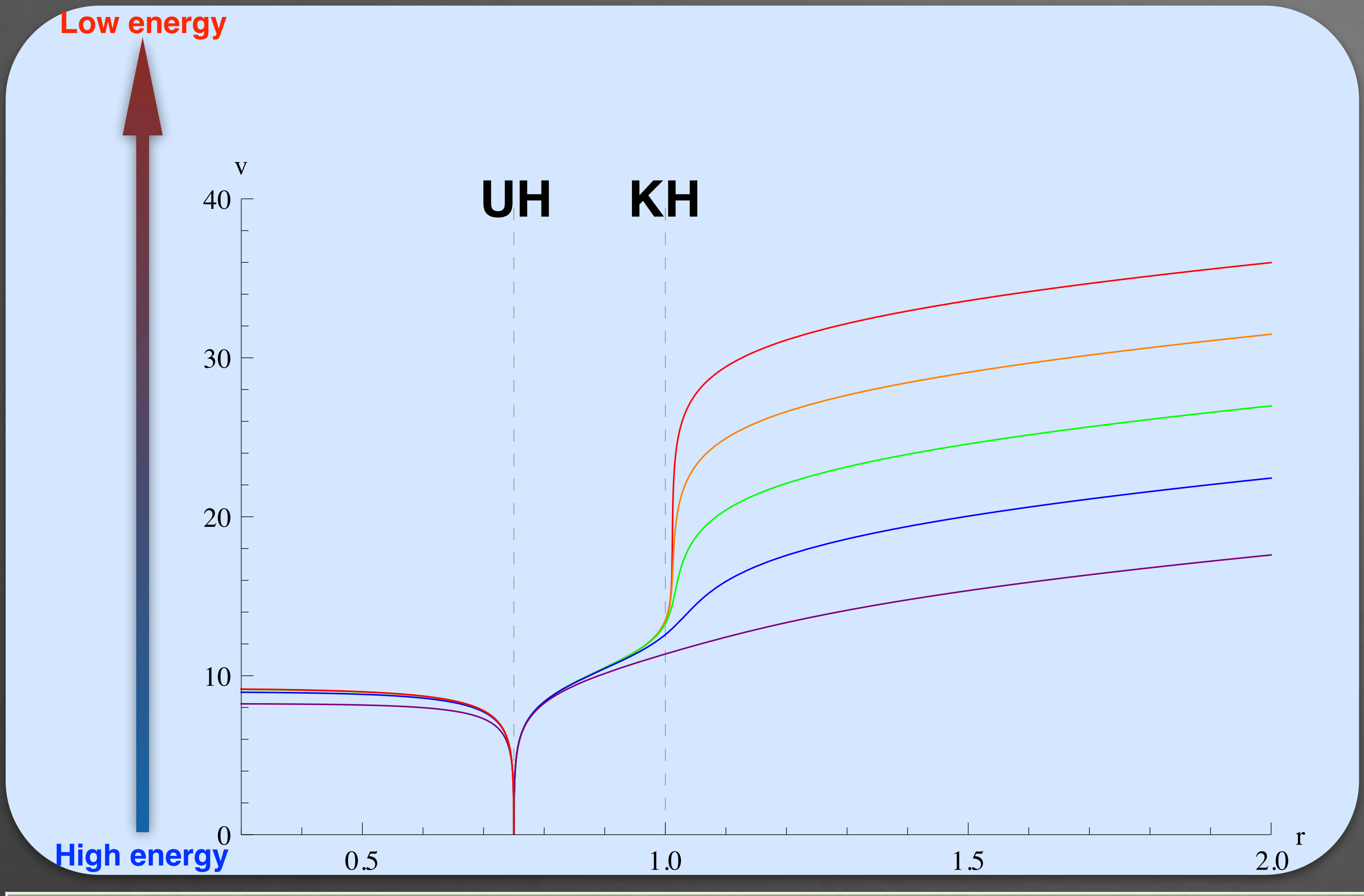
If $\omega \sim p^N$ for large p

Preliminary calculations (tunnelling) seems to suggest

$$T_{\rm UH} = \frac{(N-1)}{N} \frac{\kappa_{\rm UH}}{\pi}$$

UH THERMODYNAMICS LAWS			
	Gist	Status	Math
OTH	surface gravity is constant on UH	✔	$\chi^\mu \nabla_\mu \kappa\|_{UH} = 0$
1ST	Energy conservation	✔ But See Pacilio,SL arXiv:1709.05802	$\delta M_{æ} = \frac{q_{\rm UH}\delta A_{\rm UH}}{8\pi G_{æ}}$ $\delta A_{\rm UH} \geq 0$
2ND	Non decreasing entropy	✔?	
3RD	Unattainability of T=0 state	?	?

A new hope: Universal horizons



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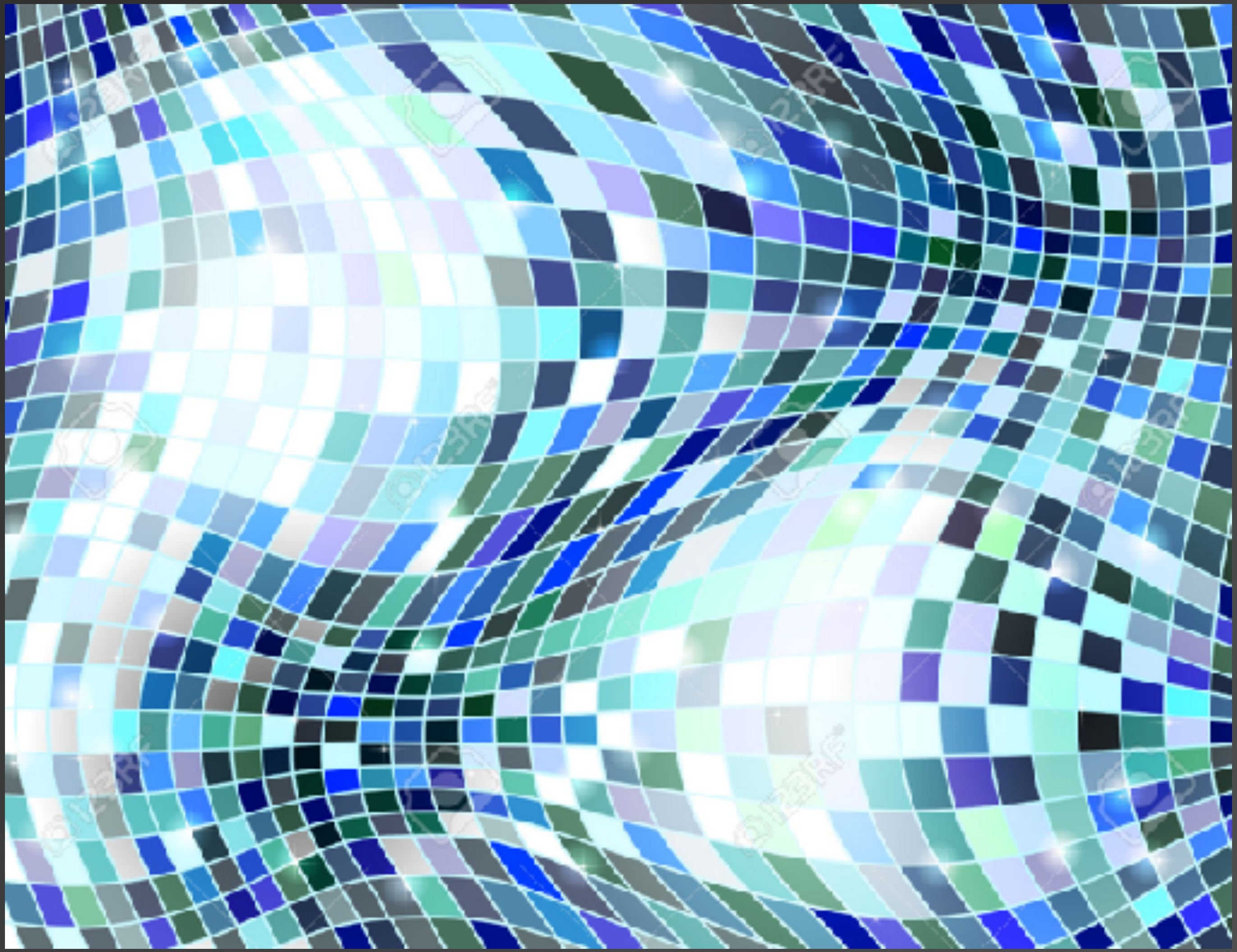
But still open issues about UH stability and Effective Temperature at infinity (see e.g. Florent & Parentani PRD91 (2015)) and Thermodynamics law also due to lack so far of complete rotating BH solutions (also needed for GW constrains).

Work in progress…



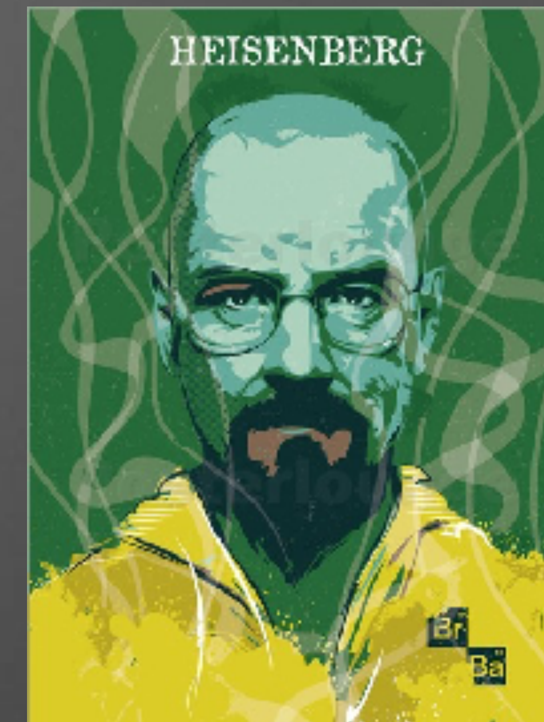
Deformed QM? Alternative relativity groups?

(If you can’t break it, can you deform it?)

Deformed Heisenberg Uncertainty Principle
Aka: Generalised Uncertainty Principle (GUP)

Garay, gr-qc/9403008,
Hossenfelder 1203.6191

$$[x,p] = i\hbar\left(1 - \gamma_0 \frac{p}{M_P c} + \beta_0 \left(\frac{p}{M_P}\right)^2\right)$$



Planck scale test requires constraint of O(1)

system/ experiment	$\beta_{0,max}$	$\gamma_{0,max}$
Position measurement	10^{34}	10^{17}
Hydrogen Lamb shift	10^{36}	10^{10}
Electron tunneling	10^{33}	10^{11}

Pikovski et. al. 1111.1979

Recently further improved via macroscopic harmonic opto-mechanical oscillators

Mass (kg)	Frequency (Hz)	Max. ampl. (nm)	Max. Q_0	Max. $\Delta\omega/\omega_0$	β	β_0	indicator
					$\beta = \beta_0\,(\hbar m\omega_0/m_P^2c^2)$		
3.3×10^{-5}	5.64×10^{3}	600	6×10^{10}	4×10^{-7}	7×10^{-29}	3×10^{7}	$\Delta\omega$
"	"				7×10^{-25}	2×10^{11}	3rd harmonic
7.7×10^{-8}	1.29×10^{5}				8×10^{-24}	5×10^{13}	$\Delta\omega$
"	"				2×10^{-19}	2×10^{18}	3rd harmonic
2×10^{-8}	1.42×10^{5}	55	7×10^{8}	6×10^{-8}	3×10^{-25}	6×10^{12}	$\Delta\omega$
2×10^{-11}	7.47×10^{5}	7.5	7×10^{6}	4×10^{-8}	4×10^{-21}	2×10^{19}	$\Delta\omega$
"	"	47	4×10^{7}	3×10^{-6}	"	"	$\Delta\omega$
"	"				2×10^{-14}	1×10^{26}	3rd harmonic

Bawaj et al. arXiv:1411.6410

Nature Communications 6, 7503 (2015).

We need to do better…

Local Lorentz Invariance Deformations?

Doubly/Deformed Special Relativity

Amelino-Camelia, Int.J.Mod.Phys. D11 (2002) 35-60
C.Rovelli, arXiv:0808.3505. L.Smolin, arXiv:0808.3765.

Hossenfelder, Phys.Rev.Lett. 104 (2010) 140402

Relative Locality (curved momentum space)

Amelino-Camelia, Freidel, Kowalski-Glikman, Smolin. Phys.Rev. D84 (2011) 084010

$$\{P_0, P_1\} = 0$$
$$\{\mathcal{N}, P_0\} = P_1$$
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Often linked to quantum groups like κ-Minkowski
Possibly linked to Finsler or Finsler-like structures?
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Aletrnatively, let's look back at von Ignatowsky theorem (1911):
Axiomatic Special Relativity

W. von Ignatowsky
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Aletrnatively, let's look back at von Ignatowsky theorem (1911): Axiomatic Special Relativity

Break Precausality → Hell breaks loose, better not!

Break Principle of relativity → Preferred frame, Modified dispersion relations

Break kinematical Isotropy → Finsler geometries. True geometry on the phase space. E.g. Very Special Relativity (Glashow, Gibbons et al.).

Break Homogeneity → no more linear transformations → No Locally Euclidean Space. → tantamount to give up operative meaning of coordinates → Physics only on Phase space?

W. von Ignatowsky
(Tiblisi 1875-Leningrad 1942)

Tests of Deformed Relativity

Consequences

- Particles travel at observer energy dependent speeds (Rosati et. al. 1203.4677)

- Modified dispersion
- Modified energy/momentum conservation
- No new anomalous particle reactions necessarily. HUGE benefit.

Upshot: Toss any constraints that rely on interactions and only use time of flight

Constraint on the photon LIV coefficient ξ by using the fact that different colours will travel at different speeds. Given current data we can cast constrains only on O(E/M) LIV…

E.g. if

$$v_\gamma = \frac{\partial E}{\partial p} = 1 + \xi \frac{E}{E_{Pl}}$$

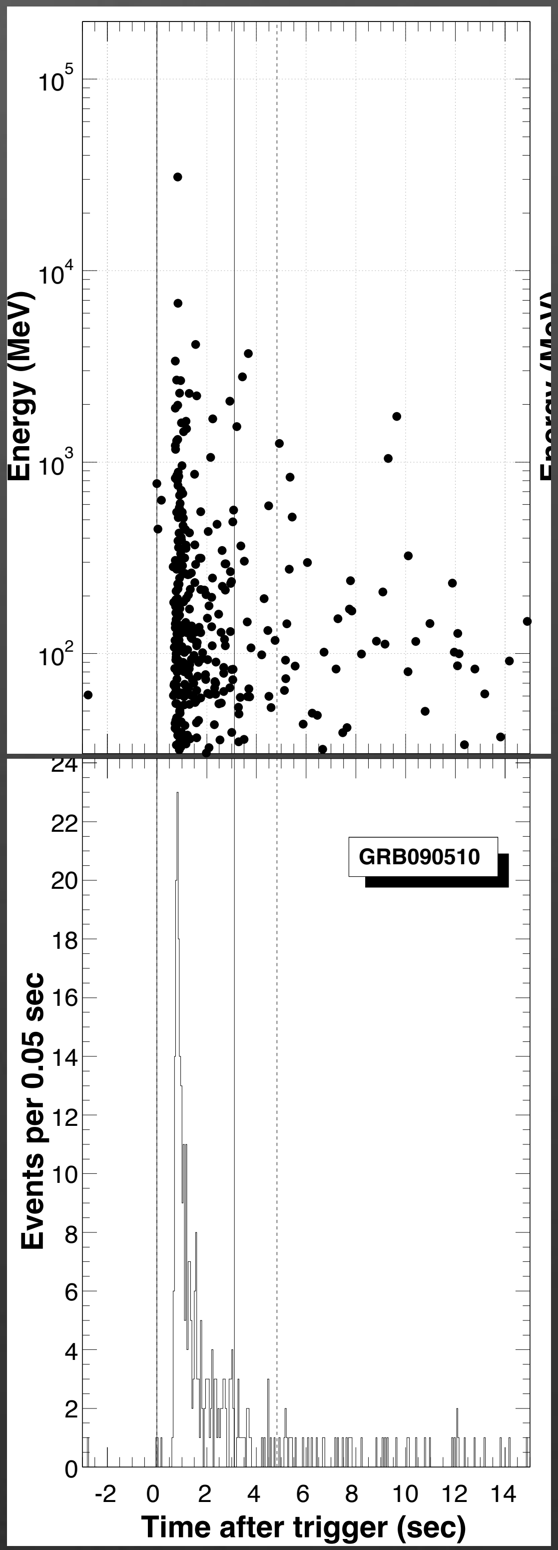
$$\Delta t = \Delta v T = \xi \frac{E_2 - E_1}{M} T$$

$$\Delta t \approx 10\,\text{msec}\,\xi\, d_{Gpc}\, E_{GeV}$$

Constraints of $\xi \sim O(10^{-1})$ on O(E/M) LIV have been cast using time of arrival measurements on beams of light from distant sources like GRBs and AGN (FERMI,MAGIC,HESS).

FERMI-LAT measurements of GRB 090510. (Vasileiou et. al. 1305.3463)

GRB 090510: z=0.9
Peak E: 30 GeV



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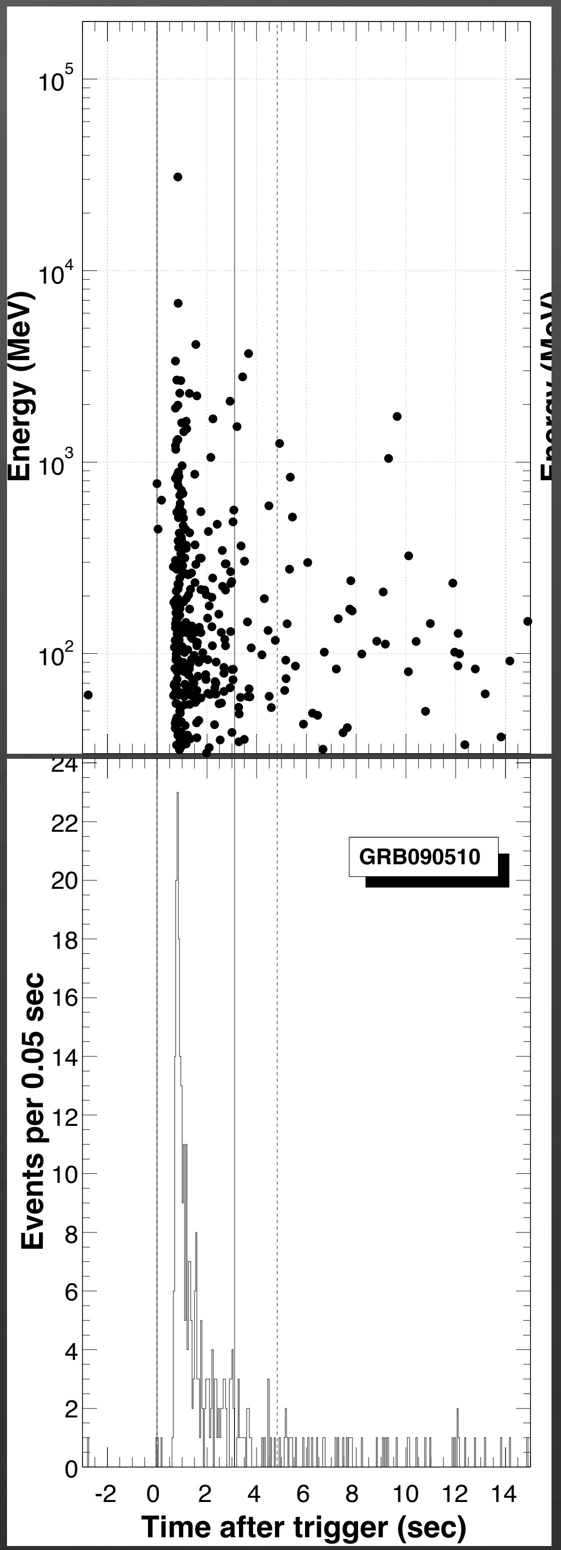
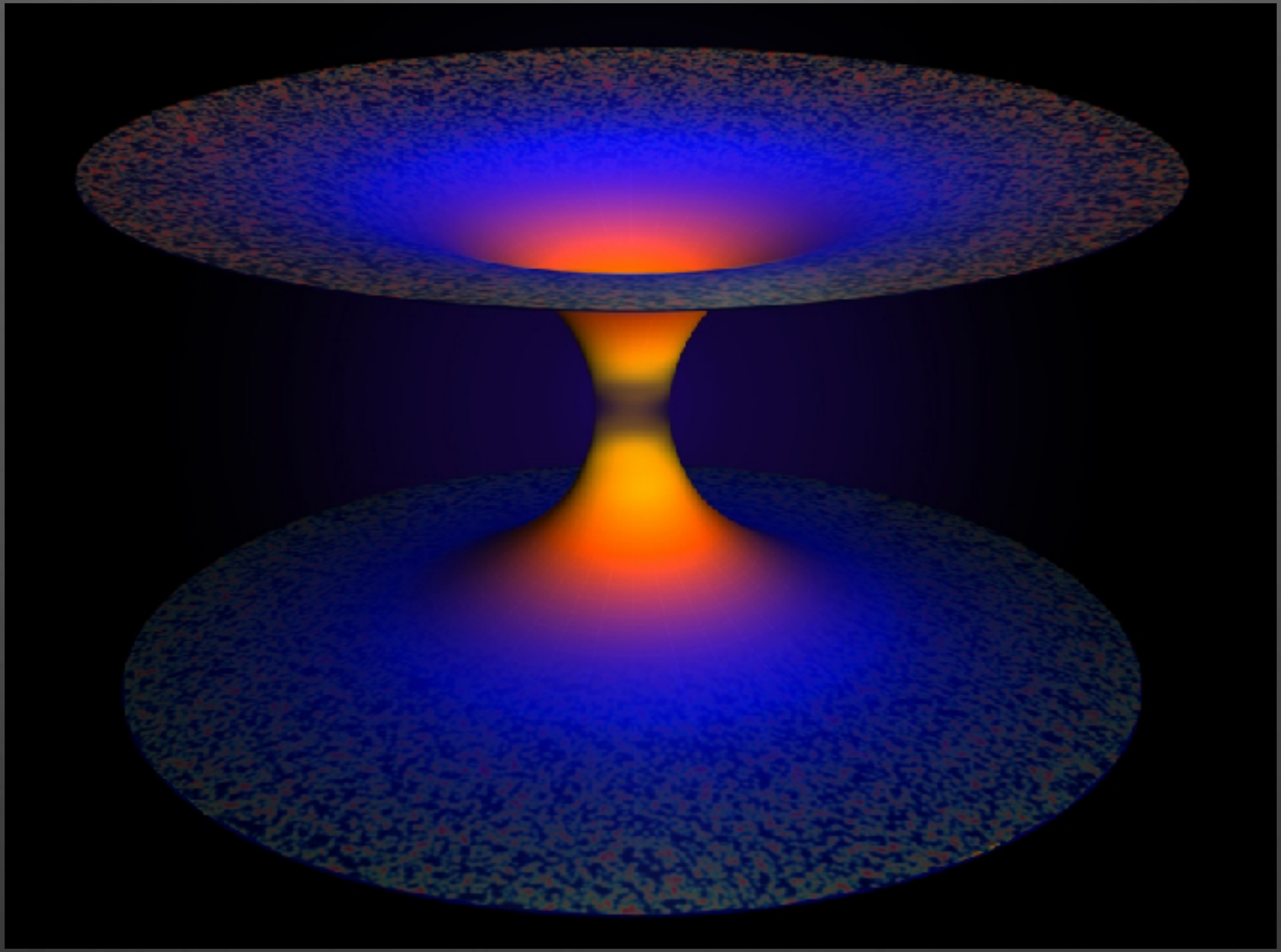


Enough with the breaking and deforming?

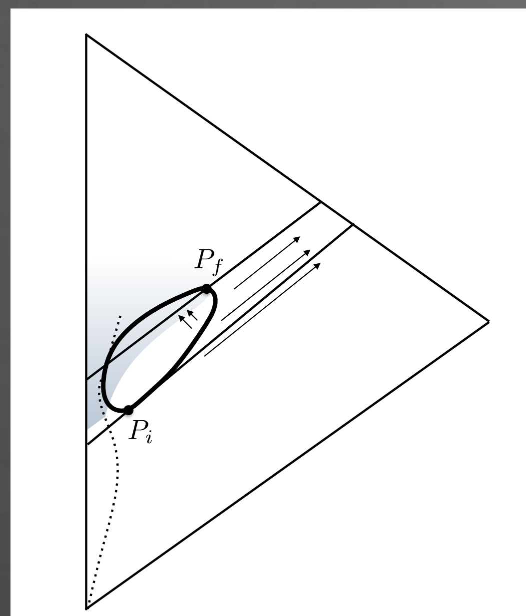


QG modified effective dynamics?
Extra dimensions?

Testing modified dynamics? The regular BH case study

Many incarnations of the idea… let's pick the two most recent ones

Planck stars



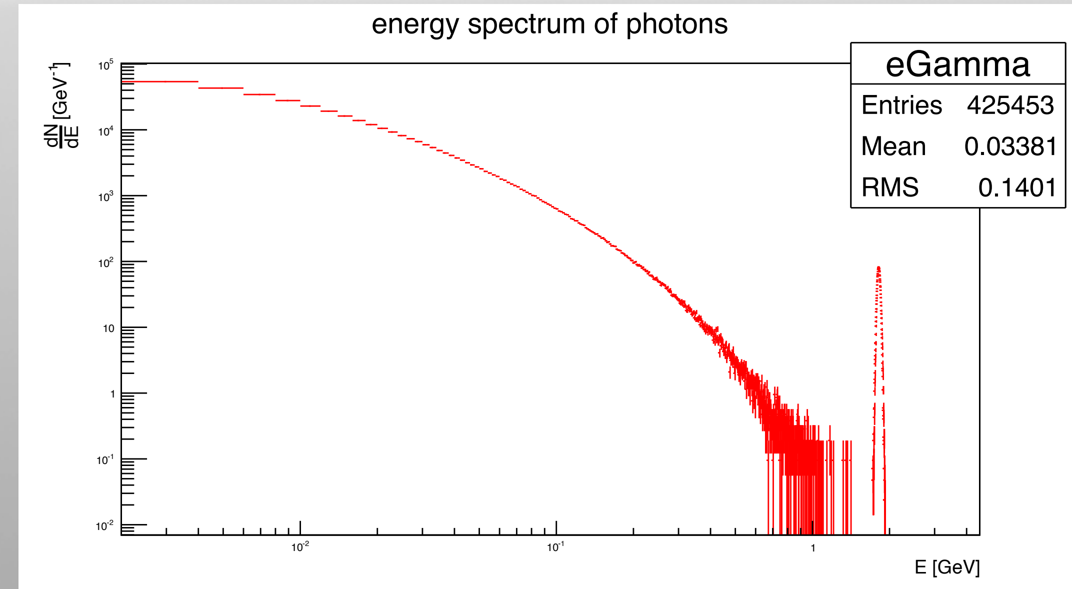
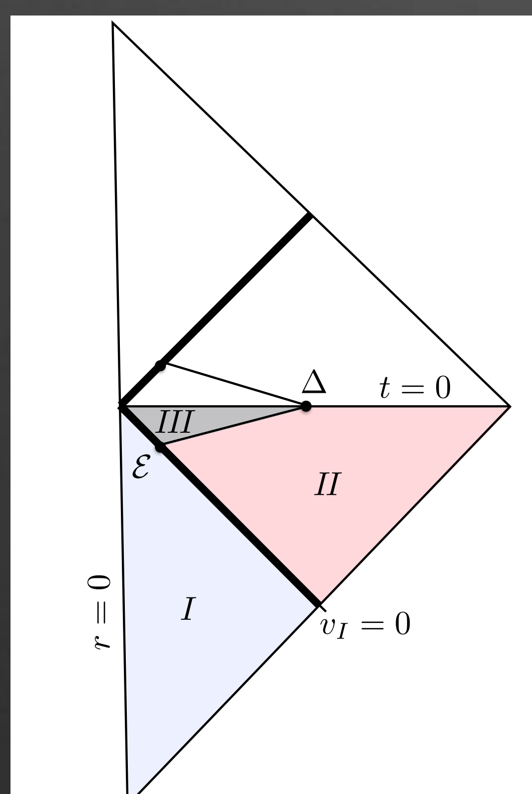


FIG. 4: Full spectrum of gamma-rays emitted by a decaying Planck star at $z = 3$ (log scales).

A.Barrau and C.Rovelli, "Planck star phenomenology" Phys.Lett.B 739, 405 (2014)

BH-WH solutions

See also M. Christodoulou, C. Rovelli, S. Speziale and I. Vilensky, ``Realistic Observable in Background-Free Quantum Gravity: the Planck-Star Tunnelling-Time," arXiv:1605.05268



A.Barrau, C.Rovelli and F.Vidotto, "Fast Radio Bursts and White Hole Signals" Phys. Rev. D 90, no. 12, 127503 (2014)

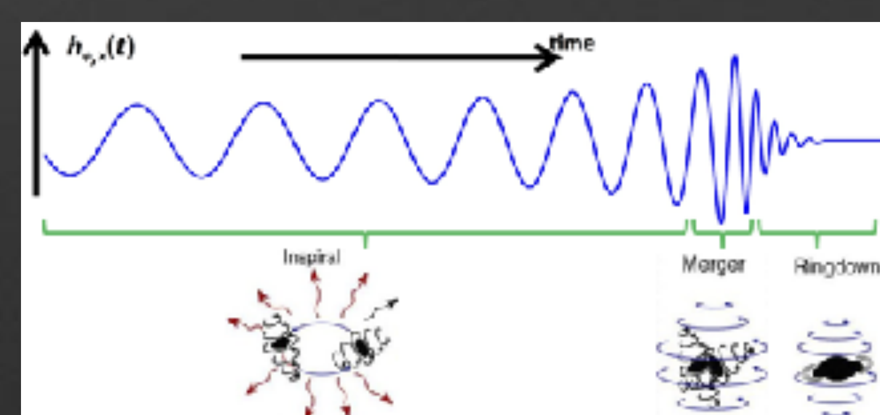
Radio Burst?

$\lambda_{predicted} \gtrsim .02$ cm.

$\lambda_{observed} \sim 20$ cm.

GW?

A generic prediction of regular black hole solutions like this seems to be the presence of a non-classical region beyond the trapping horizon. Can we test it by accurate measurement of BH mergers? (e.g. modified ringdown?)



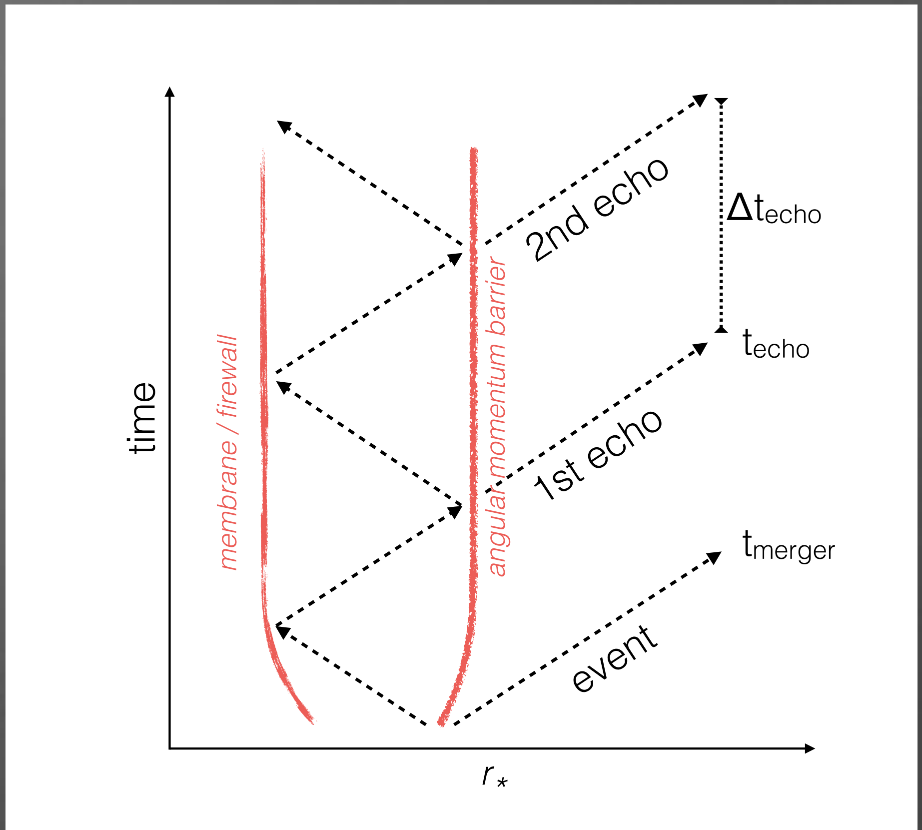
Black hole echoes from near horizon structure

Objects with near horizon structure sat at l ≪ M are characterised by peaks in the effective potential felt by perturbations.

Key point: If we consider a microscopic correction at the horizon scale (l ≪ M), then the main contribution to the time delay comes near the radius of the star and scales with the Log of (M/l). So for l~M_P and LIGO observed BH

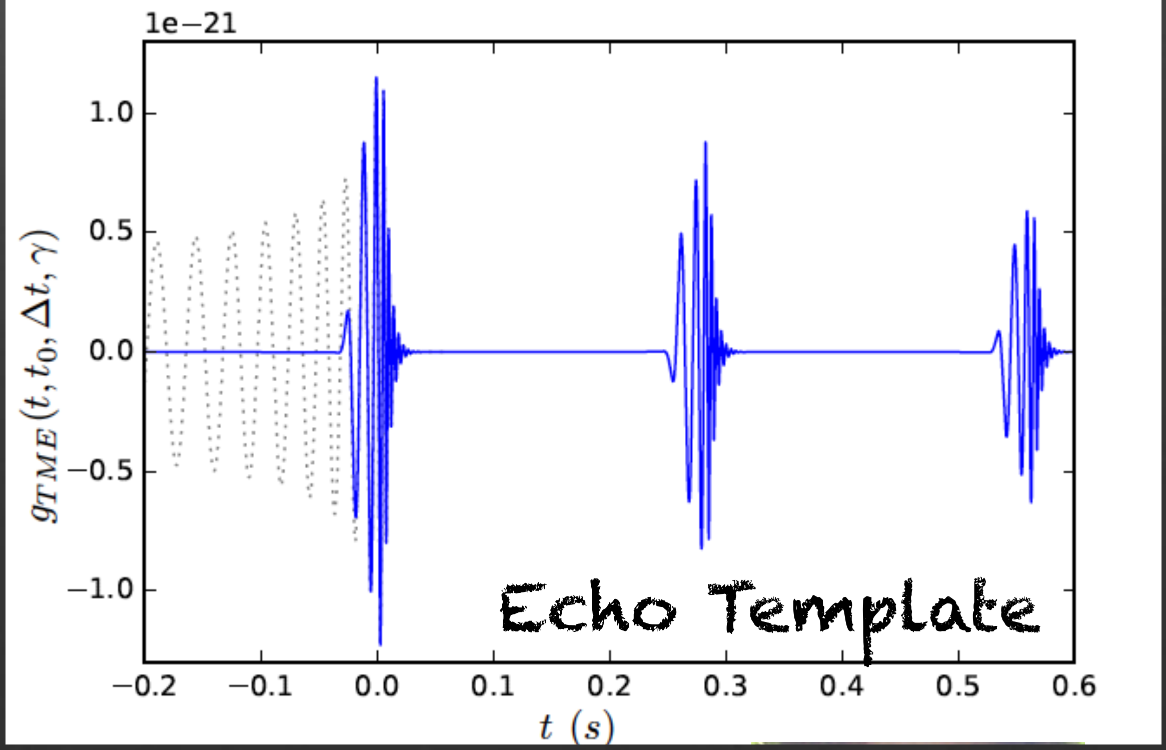
$$\Delta t \simeq 8M_{BH} \log\left(\frac{M_{BH}}{M_P}\right) \simeq 0.25 \text{ sec}$$

Cardoso et al. PRD94, 2016
Afshordi et al 2016, 2017



the logarithmic dependence implies that even Planckian corrections (l ≈M_P= 2 × 10^{-33} cm) appear relatively soon after the main burst of radiation, so they might leave an observable imprint in the GW signal observed at late times.

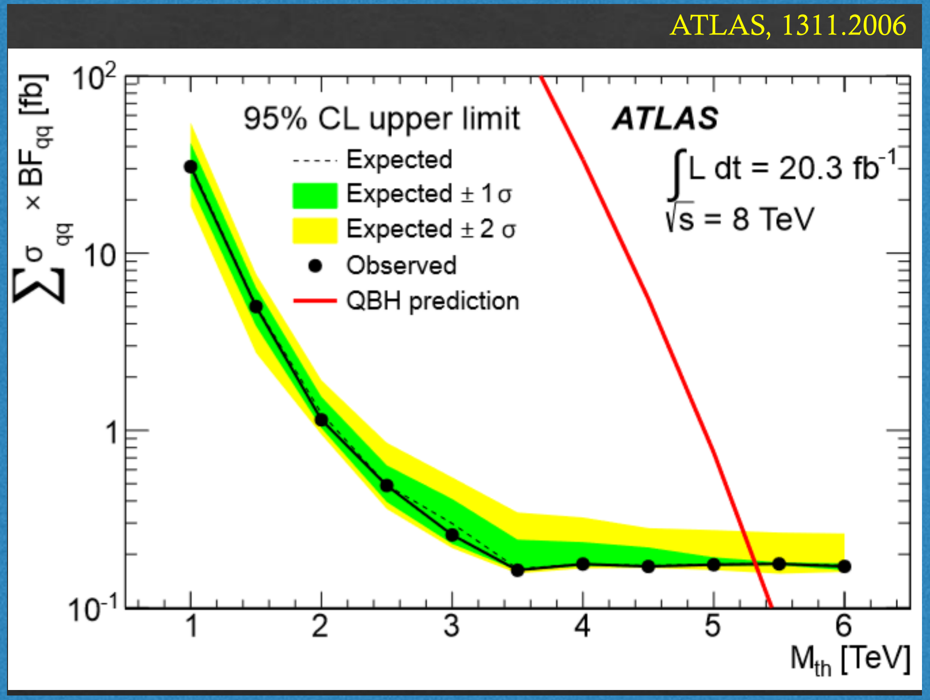
This implies that generically one should expect Late echoes after merging from near horizon Planck scale structure e.g. firewall, fuzzball. Afshordi 2016 claims detection in LIGO events at 2.9σ but more statistics needed…



Extra Dimensions

So far no evidence of large extra dimensions at LHC or micro-gravity experiments

short scale precision tests of gravity confirm the inverse square law down to 56 μm



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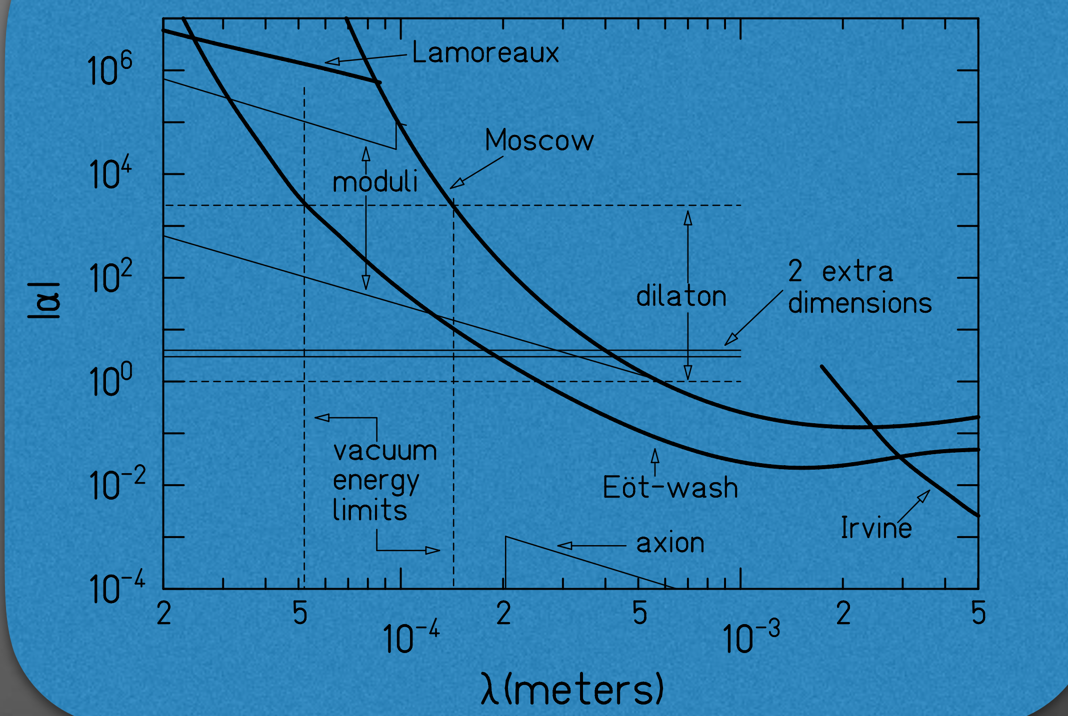

$$V(r) = -G_N \frac{m_1 m_2}{r}\left(1 + \alpha e^{-r/\lambda}\right)$$

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What about testing dimensional reduction in QG?
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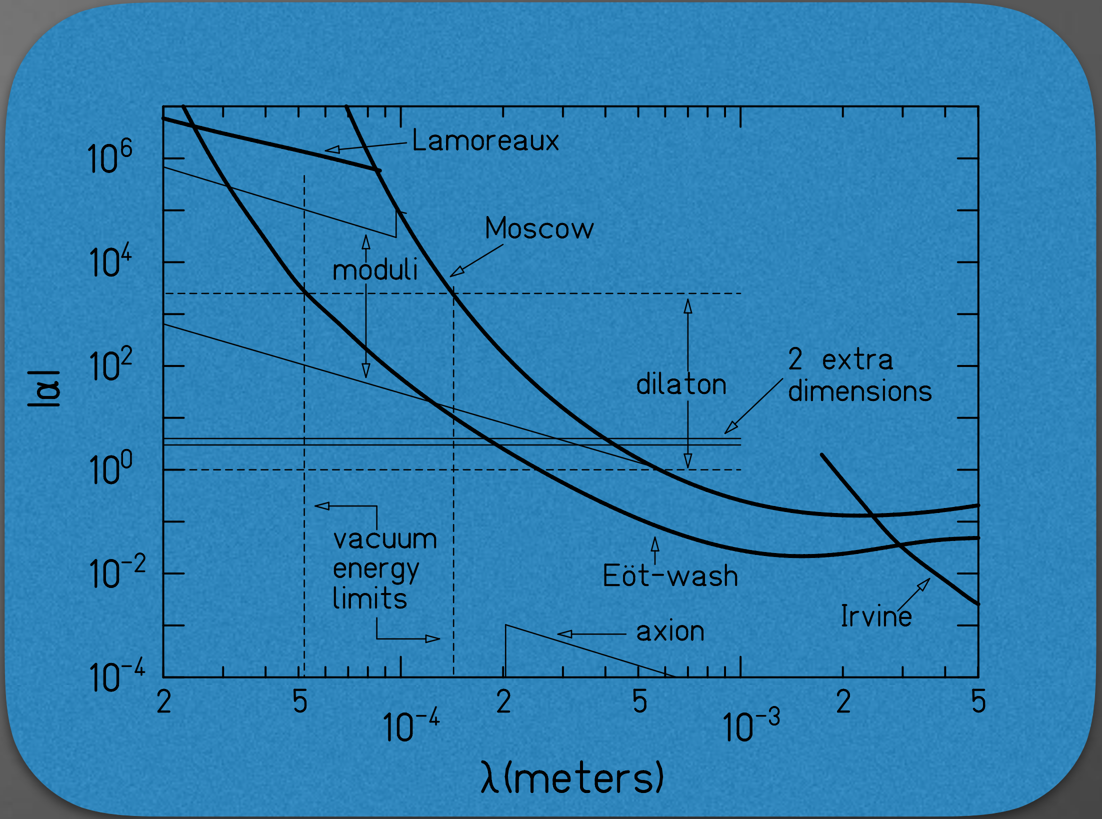

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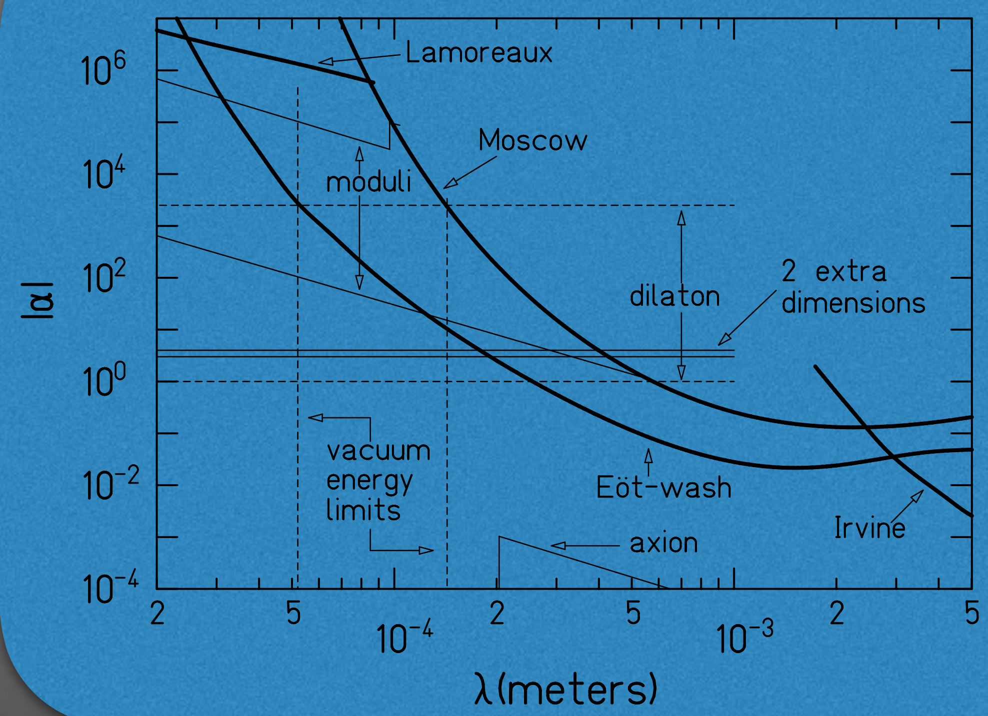

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- Causal dynamical triangulations (Ambjorn et. al. hep-th/0505113)
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- Loop quantum gravity (Modesto, 0812.2214, but not in GFT Calcagni 1311.3340)
- Causal Sets (Belenchia, Benincasa, Marcianò and Modesto, Phys. Rev. D 93, no. 4, 044017 (2016). (but see also Eichhorn, Mizera 1311.2530)
- Dimensional reduction has further been argued from WDW equation (Carlip 1009.1136) and general grounds (‘t Hooft 9310026)

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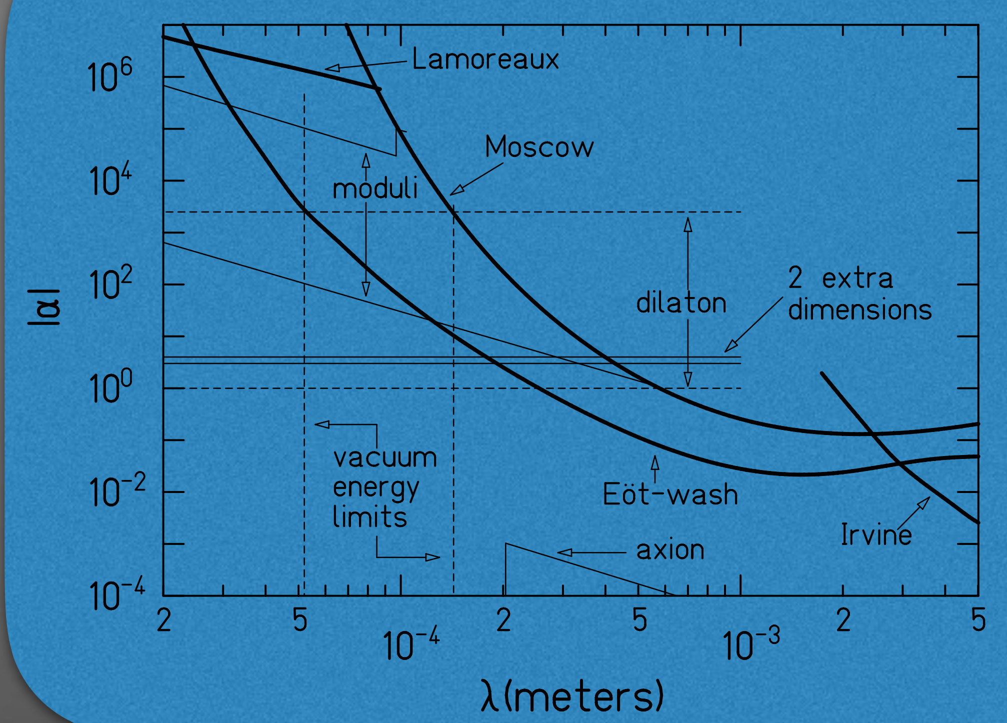

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However, it looks like we need to get back to the very early universe to test this.
We need a better strategy…

Fifty shades of non-locality?

Non-locality as an alternative to symmetry breaking?

What about other mesoscopic physics without Lorentz violation?

- We do have concrete QG models of emergent gravity like Causal Sets or String Field Theory or Loop Quantum Gravity which generically seem to predict exact Lorentz invariance below the Planck scale in spite of (fundamental or quantum) discreteness at the price to introduce non-local EFT.
  Conjecture: Discreetness + Lorentz Invariance = Non-Locality

Several forms of non-locality

- Non-local kinetic terms
- Non-local interactions
- DSR-like non-locality
- Disordered locality in LQG
- ...

These theories involve a very subtle phenomenology very hard to constraint, still they do show novelties.
Differently from UV Lorentz breaking physics it will be here a matter of PRECISION instead of HIGH ENERGIES…

Non-local D'Alambertians

$$\Box \to f(\Box)$$

Generic expectation if you want to introduce length or energy scale in flat spacetime KG equation without giving up Lorentz invariance.

CONCRETE EXAMPLES OF KINEMATICAL NON-LOCALITY
RESPECTIVELY WITH NON-ANALYTIC OR ANALYTIC FUNCTION.
ALSO IN CAUSET CLEAR EXAMPLE THAT A CORRECT CONTINUOUS LIMIT IMPLIES AVERAGING AND $\ell_{nl} \gg \ell_{\mathrm{discr}}$

Causal Set Theory
$$\Box_\rho \approx \Box + \frac{\alpha}{\sqrt{\rho}}\Box^2 + \frac{\beta}{\sqrt{\rho}}\Box^2 \ln\left(\frac{\gamma}{\rho}\Box^2\right) + \dots \qquad \rho = 1/\ell_{nl}^4$$

String Field Theory
$$\Box \to (\Box + m^2)\exp^{\frac{\Box + m^2}{\Lambda^2}} \qquad \Lambda = 1/\ell_{\mathrm{nl}}$$

Belenchia, Benincasa, SL and Martin-Martinez,
``Transmission of Information in Non-Local Field Theories,'' arXiv:1707.0165

Non-local D'Alambertians

$$\Box \to f(\Box)$$

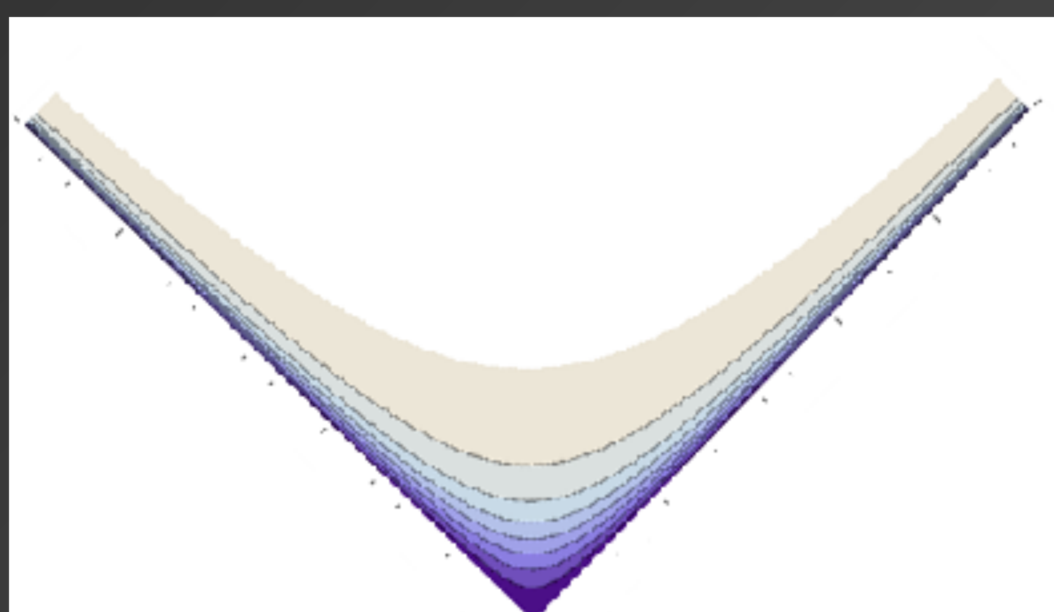
Generic expectation if you want to introduce length or energy scale in flat spacetime KG equation without giving up Lorentz invariance.

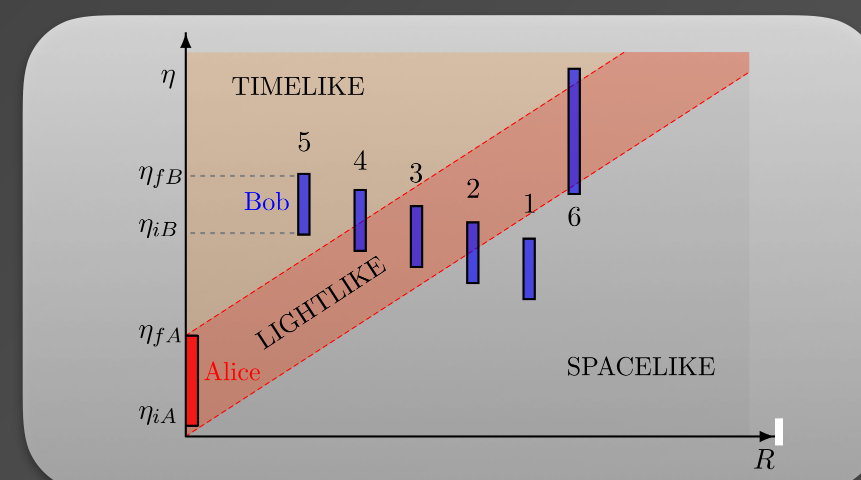
Concrete examples of kinematical non-locality respectively with non-analytic or analytic function.
Also in CAUSET clear example that a correct continuous limit implies averaging and $\ell_{nl} \gg \ell_{\rm discr}$

Causal Set Theory $$\Box_\rho \approx \Box + \frac{\alpha}{\sqrt{\rho}}\Box^2 + \frac{\beta}{\sqrt{\rho}}\Box^2 \ln\left(\frac{\gamma}{\rho}\Box^2\right) + \dots \qquad \rho = 1/\ell_{nl}^4$$

String Field Theory $$\Box \to (\Box + m^2)\exp\frac{\Box + m^2}{\Lambda^2} \qquad \Lambda = 1/\ell_{\rm nl}$$

A typical signature of <u>non-analytical</u> non-local propagators are violations of the Huygen principle: The propagator of massless particles can have support inside the light cone in 3+1





Possibly very relevant for relativistic quantum information tests as detectors can influence each other at timelike separations

Opportunity for Phenomenology

R. H. Jonsson, E. Martin-Martinez, and A. Kempf, Phys.Rev.Lett. 114, 110505 (2015).

Ana Blasco, Luis J. Garay, Mercedes Martin-Benito, Eduardo Martin-Martinez. Phys.Rev.Lett. 114 (2015) 14, 141103

Belenchia, Benincasa, SL and Martin-Martinez, ``Transmission of Information in Non-Local Field Theories,'' arXiv:1707.0165

Testing non-local EFT with optomechanical oscillators

E.g. let's consider its non-relativistic limit of a non-local KG with <u>analytic</u> f(□).

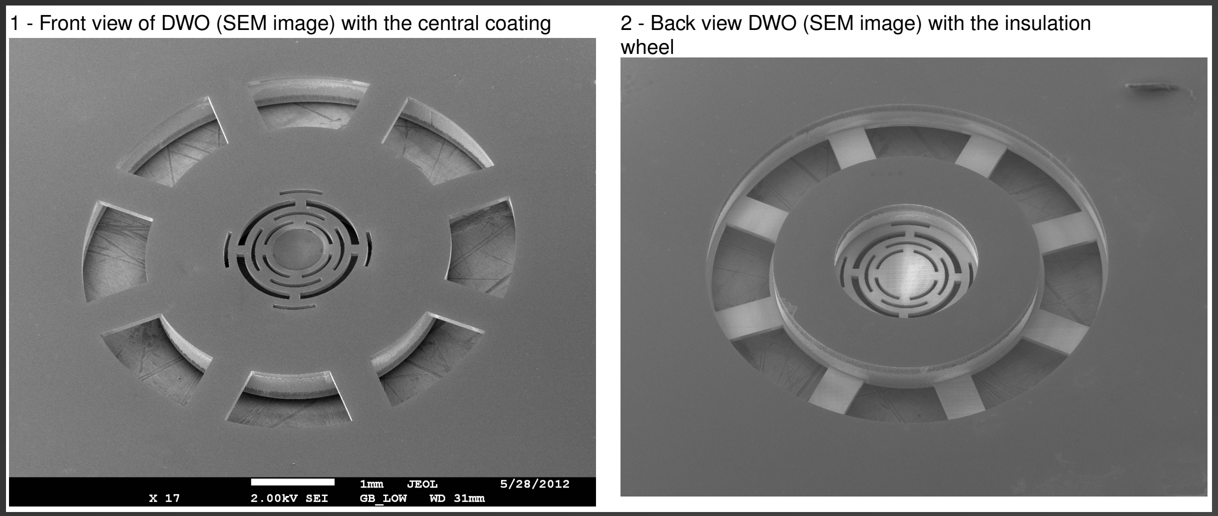
$$\sum_{n=0}^{\infty} \underbrace{\frac{1}{n!}\left(-\frac{2m}{\hbar^2}\right)^n \frac{1}{\Lambda^{2(n-1)}}}_{a_n} \frac{1}{\Lambda^2}\mathcal{S}^{n+1} \equiv \mathcal{S}_{NL}.$$

So we get $$(\mathcal{S}_{NL} - V)\,\phi(t,x) = 0.$$

Where can we test this?

HUMOR

Heisenberg Uncertainty Measured with Opto-mechanical Resonators



1 - Front view of DWO (SEM image) with the central coating

2 - Back view DWO (SEM image) with the insulation wheel

Designed to determine evolution of <x>, <p> and variances.

In order to solve this, one needs to adopt a perturbative expansion around a "local" Sch. solution

$$\phi = \phi_0 + \sum_{n=1}^{\infty} \epsilon^n \psi_n$$

With ϵ the small dimensionless parameter for this problem.

$$\epsilon = \frac{m\omega}{\hbar\Lambda^2}$$

A. Belenchia, D. Benincasa, SL, F. Marin, F. Marino, A. Ortolan.
Phys.Rev.Lett. 116 (2016) no.16, 161303
Phys.Rev. D95 (2017) no.2, 026012

And at the lowest order we can solve

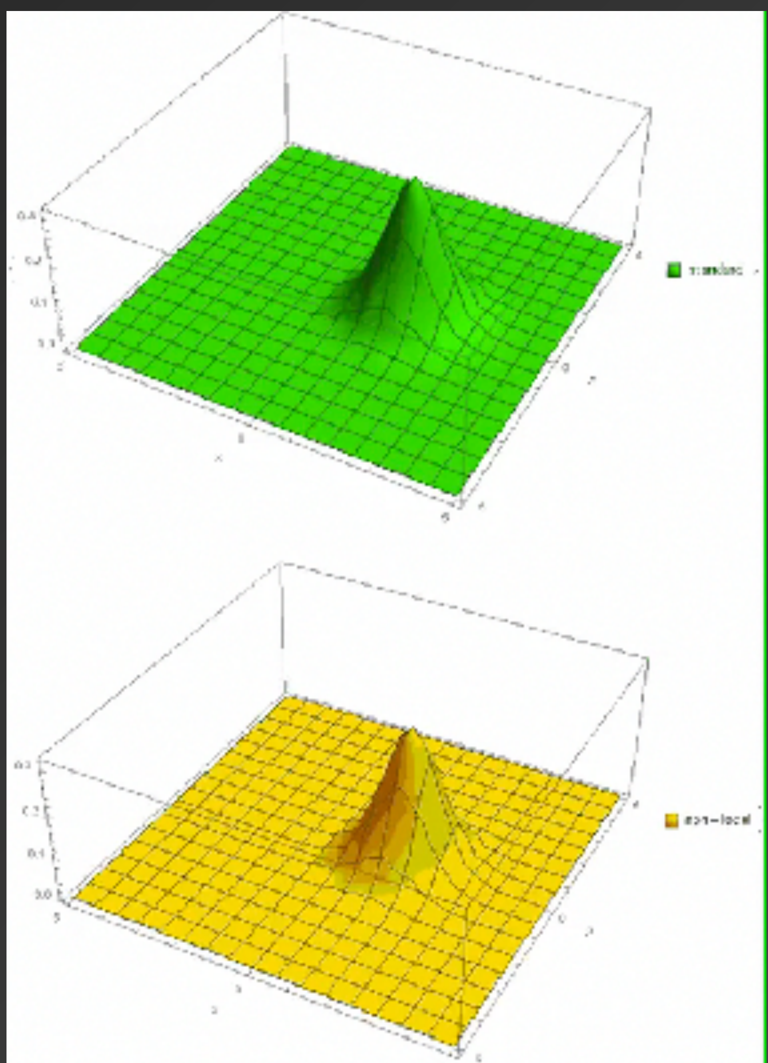
$$\left(i\hbar\partial_t + \frac{\hbar^2}{2m}\partial^2_{xx}\right)\psi + \epsilon a_2\left(\frac{-2}{\hbar\omega}\right)\mathcal{S}^2\psi = \frac{1}{2}m\omega^2x^2\psi.$$

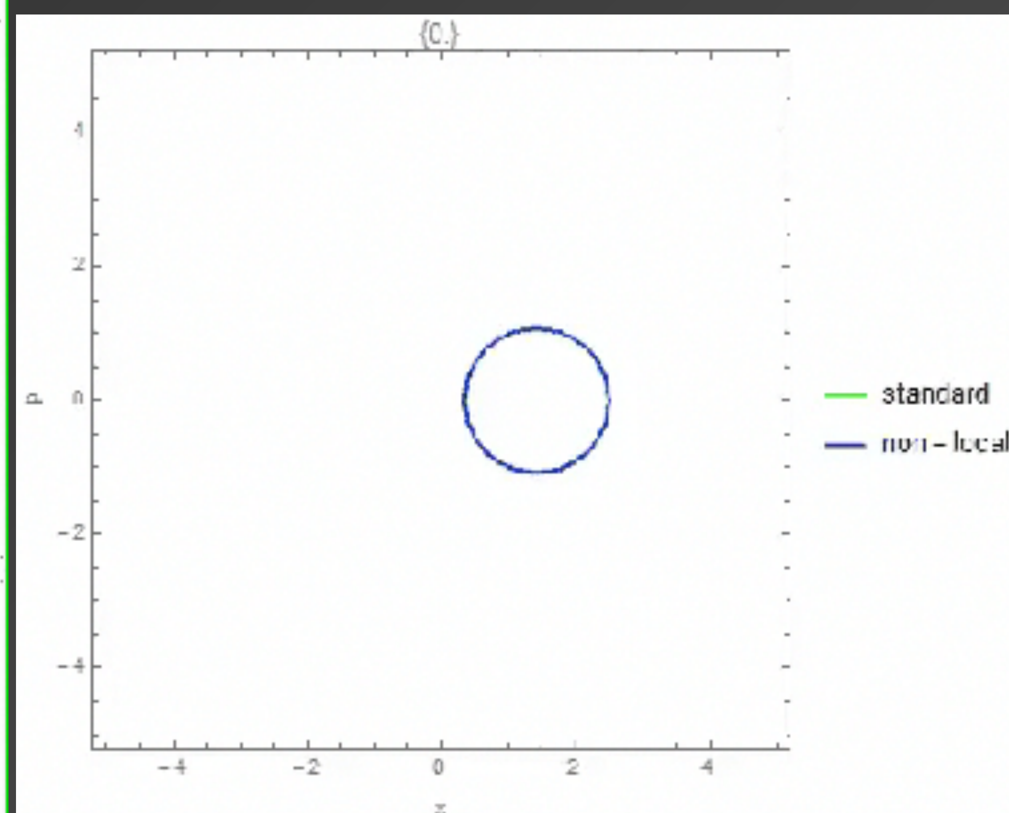
Spontaneous squeezing from non-locality

Let's consider Wigner quasi probability distribution for a coherent state of our quantum harmonic oscillator,

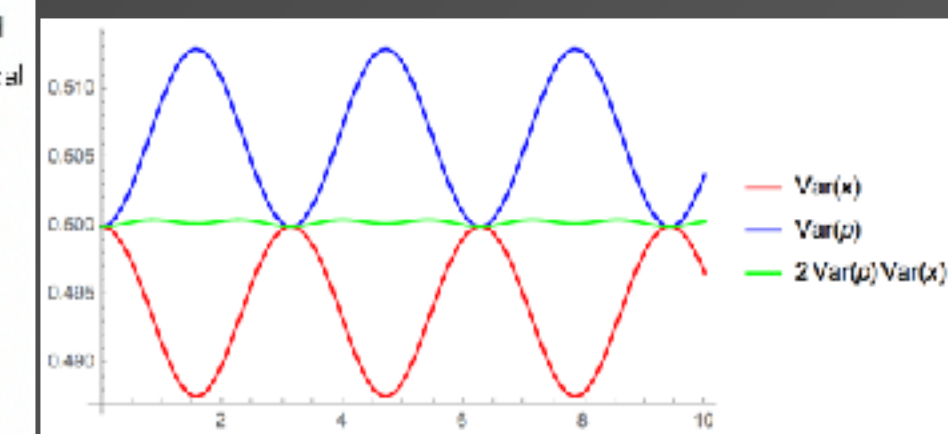
$$P(x,p;t)\frac{1}{\pi}\int_{-\infty}^{\infty}\mathrm{dy}\ \phi(x+y,t)^*\phi(x-y,t)\ e^{2ipy}$$

and confront its evolution for a coherent state (easier to experimental realise than the ground state) in the case of ***S*** and ***S***+ε***S***^{2}





The Coherent state Wigner function shows a periodic almost perfect squeezing.
Very difficult to produce spontaneously…



Current best bounds on the non-locality scale by comparing nonlocal relativistic EFTs to the 8 TeV LHC data $l_{nl} \leq 10^{-19}$m

Forecast: with experiment in preparation (in absence of periodic squeezing) imply $l_{nl} \leq 10^{-29}$m !

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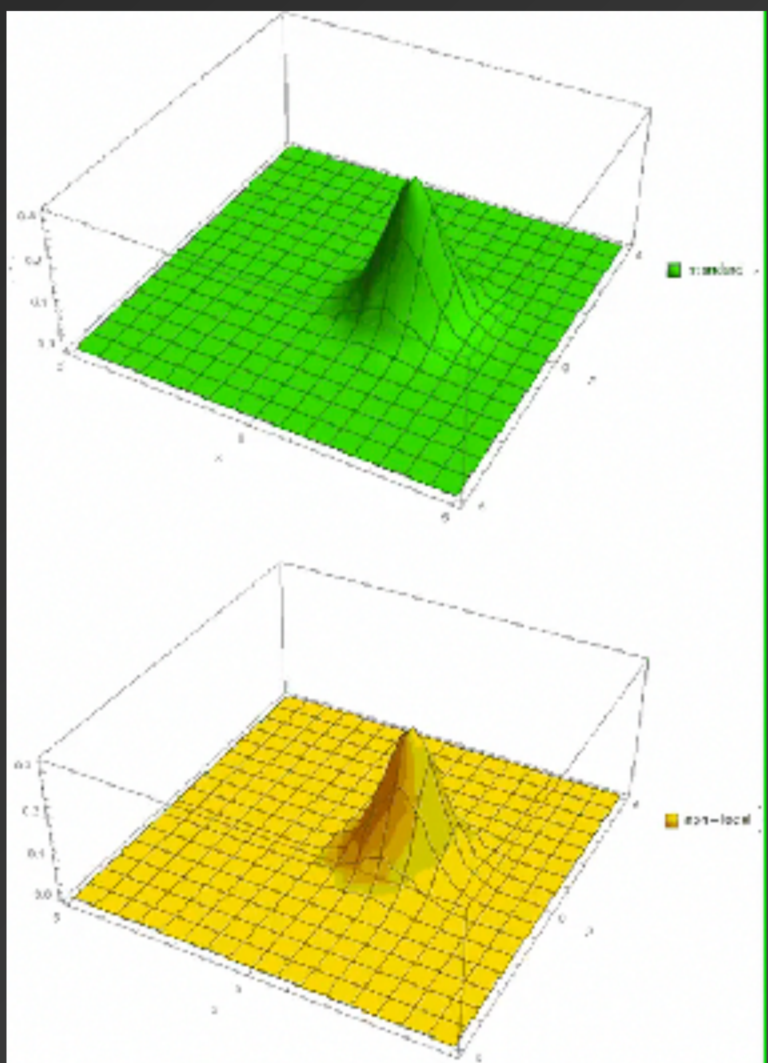

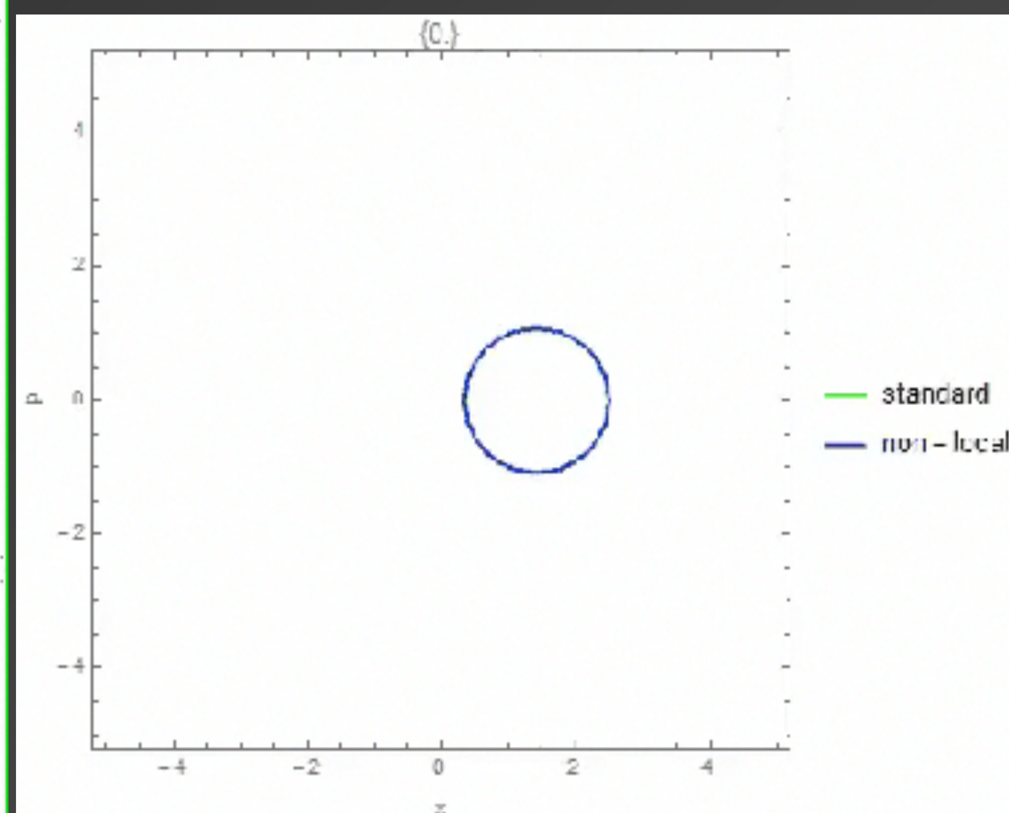

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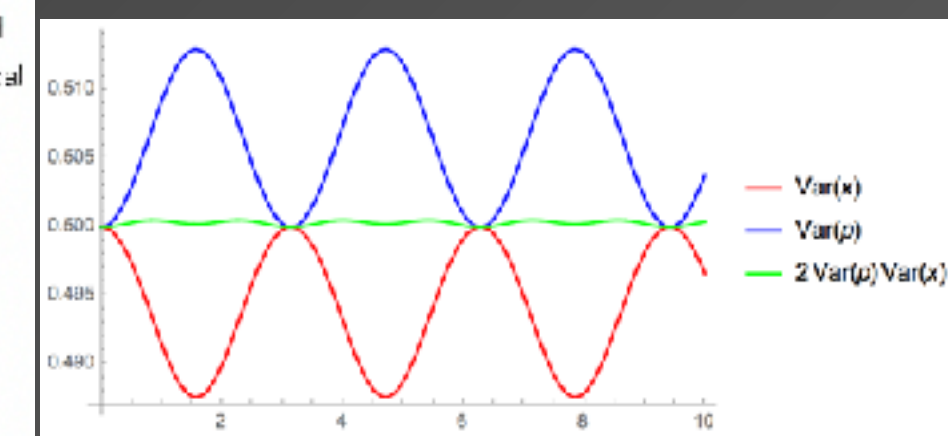

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Wrapping up

Broken or deformed Symmetries

- SUSY- So far no evidence at LHC
- Lorentz - Ok Matter but n=4 needs GZK, more to do on Gravitational sector. Good perspectives
- Translations - Done
- GUP-Deformed Relativity? We need to understand it better!

Modified gravitational dynamics

- Bouncing Universes
- Regular Black holes.

Much work in progress especially on GW

Locality

- QG induced non-locality

Much work in progress.

Dimensions

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- Dimensional reduction in QG - Only early Universe test? We need better ideas.

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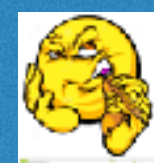

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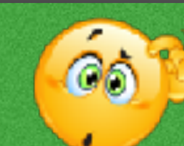

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THESE ARE REALLY EXCITING TIMES FOR QG PHENOMENOLOGY!

MAYBE THE BEST HAS TO COME YET...