Title: Gravity, an unexpected journey: from thermodynamics to emergent gravity, Lorentz breaking and back...

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Abstract: Thermodynamical aspects of gravity have been a tantalising puzzle for more than forty years now and are still at the center of much activity in semiclassical and quantum gravity. We shall explore the possibility that they might hint toward an emergent nature of gravity exploring the possible implications of such hypothesis. Among these we shall focus on the possibility that Lorentz invariance might be only a low energy/emergent feature by discussing viable theoretical frameworks, present constraints and open issues which make this path problematic. In the end we shall focus on black hole thermodynamics in Lorentz breaking gravity by presenting some recent results that seems to hint towards a surprising resilience of thermodynamics aspect of gravity even in these scenarios.

The quest for Quantum gravity

In spite of decades of attempts we are still lacking a workable and falsifiable QG theory.

We do have accumulated however many candidate theories and many insights...

These are mainly coming from "critical" points in the current theory of gravitation...

I will explore today the possibility and consistency of emergent gravity scenarios with emergent spacetime symmetries, more specifically with accidental (IR) Lorentz symmetry

The idea is not only to verify the viability of these scenarios but also to uncover the role of Lorentz symmetry in important aspect of gravitational physics

A weird theory...

Why emergence?
Tantalising features of Gravity

- Singularities
- Critical phenomena in gravitational collapse
- Horizon thermodynamics
- Spacetime thermodynamics: Einstein equations as equations of state.
- The cosmological constant problem
- Faster than light and Time travel solutions
- AdS/CFT duality, holographic behaviour
- Gravity/fluid duality

Spacetime thermodynamics (Jacobson, 1995)

Gravity as thermodynamics

In standard thermodynamics one can recover a system equation of state from the first law and the Clausius relation: can we do the same starting from horizon properties?

- Use the fact that spacetime is locally flat around any chosen point
- Then at each point of spacetime one can locally consider a local Rindler horizon as the boundary of the causal past of a space-like 2-surface patch B including p. This horizon will have Unruh temperature $T=1/2\pi$.
- Assume that the Clausius relation holds for the horizon Energy-Entropy balance: $\delta Q=TdS$
- Assume that $dS=\alpha dA$ (EE) where dA is the infinitesimal variation of the horizon area (α=const by SEP).
- δQ=matter energy-momentum flux
- Assume energy-momentum conservation.
- Then one derives the Einstein equations of General Relativity (with an arbitrary cosmological constant) as an Equation of State for spacetime with $\alpha=1/4$ IF the shear at B is taken to be zero at p.

$$dS = \alpha \int_H \tilde{\epsilon}\, d\lambda \left[\theta - \lambda\left(\frac{1}{2}\theta^2 + \|\sigma\|^2 + R_{ab}\ell^a\ell^b\right)\right]_p .$$

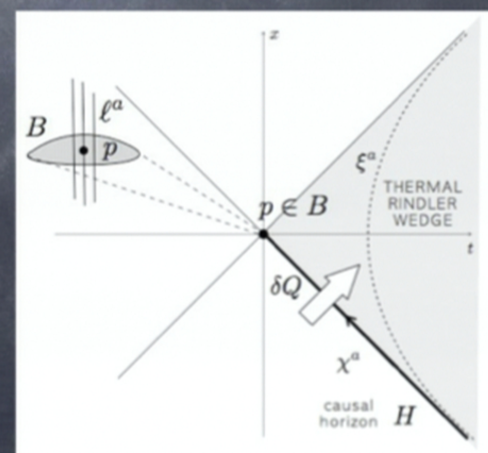
$$\delta Q = \int_H \tilde{\epsilon}\, d\lambda\, (-\lambda\kappa)\, T_{ab}\ell^a\ell^b .$$

l^a = affinely parametrized tangent vector to the horizon

λ = affine parameter

χ^a = Horizon generating Killing vector

$\chi^a = -\lambda l^a$



$$dS = \frac{\delta Q}{T} \quad + \quad \nabla^b T_{ab} = 0,$$

$$\frac{2\pi}{\hbar\alpha} T_{ab} = R_{ab} - \frac{1}{2} R\, g_{ab} - \Lambda\, g_{ab}$$

Einstein eq. with $\alpha = \frac{1}{4\hbar G}$

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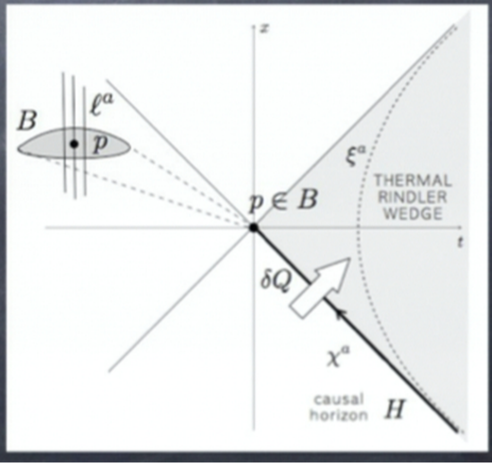

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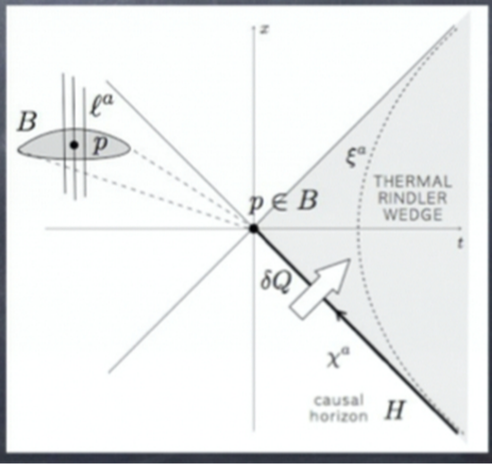

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Eling, Guedens,Jacobson (2006) - Eling (2008) - Chirco, SL (2009)

Near equilibrium thermodynamics:

"if you can heat it, it has microstructure"

Loophole in the previous derivation: the expansion has to be zero at order $O(\lambda)$ if Clausius holds but the shear can be arbitrary.

Suggestion: in order to account for these terms and be able to recover the Einst. Eq.
One has to generalize the Clausius equation for a near-equilibrium thermodynamics situation

$$d_e S + d_i S = \frac{\delta Q}{T} + \delta N$$

$d_e S$= external entropy production: entropy exchange rate with the surroundings

$d_i S$= internal entropy production term (due to internal d.o.f. of the system and zero for eversible processes)

δQ= compensated heat (heat transfer between system and environment)

δN= uncompensated heat (heat transfer to internal d.o.f)

- $d_e S = \delta Q/T$, at the reversible level, → Einstein Equations
- $d_i S = \delta N$, at the irreversible level. → Dissipative terms: what are they?

$$(d_i S)^{\mathrm{vis}} = \frac{1}{T}\int_H \widetilde{\epsilon}\, dv\, \zeta\, \hat{\theta}^2 + 2\eta\, \|\hat{\sigma}\|^2.$$

KSS bound

$$T\,\delta N = \frac{\alpha T}{\kappa}\int_H \widetilde{\epsilon}\, dv\, \|\hat{\sigma}\|_p^2.$$

= Hartle-Hawking tidal heating!

$$\frac{2\eta}{T} = \frac{\alpha}{\kappa}, \longrightarrow \frac{\eta}{\alpha} = \frac{\hbar}{4\pi}$$

Gravitational fluxes appears as dissipative terms for the system (the Rindler wedge)!
They are IN the spacetime not ON the spacetime.
Like heat fluxes thought a medium cannot be localized via phonon fluxes but can nonetheless transfer energy via the microscopic excitation of the fundamental constituents

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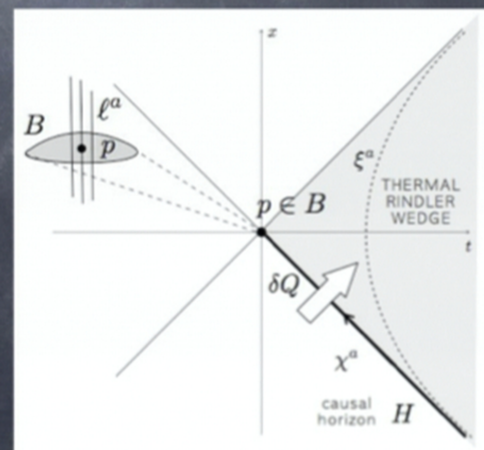

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Emerging manifolds and gravity

- Many models are nowadays resorting to emergent gravity scenarios (albeit sometimes through very different routes). An incomplete list could include
  - Causal sets
  - Quantum graphity models
  - Group field theories
  - AdS/CFT scenarios where the CFT is considered primary
  - Gravity as an entropic force
  - Condensed matter analogues of gravity

Analogue models in particular played an important inspirational role

- These are condensed matter systems which have provided toy models showing how at least the concept of a pseudo-Riemannian metric and Lorentz invariance of matter equations of motion can be emergent.

- For example, non-relativistic systems which admit some hydrodynamics description can be shown to have perturbations (phonons) whose propagation is described, at low energies, by hyperbolic wave equations on an effective Lorentzian geometry.

See e.g. Barcelo', SL, Visser: Living Rev.Rel. 8 (2005) 12, Living Rev.Rel. 14 (2011) 3

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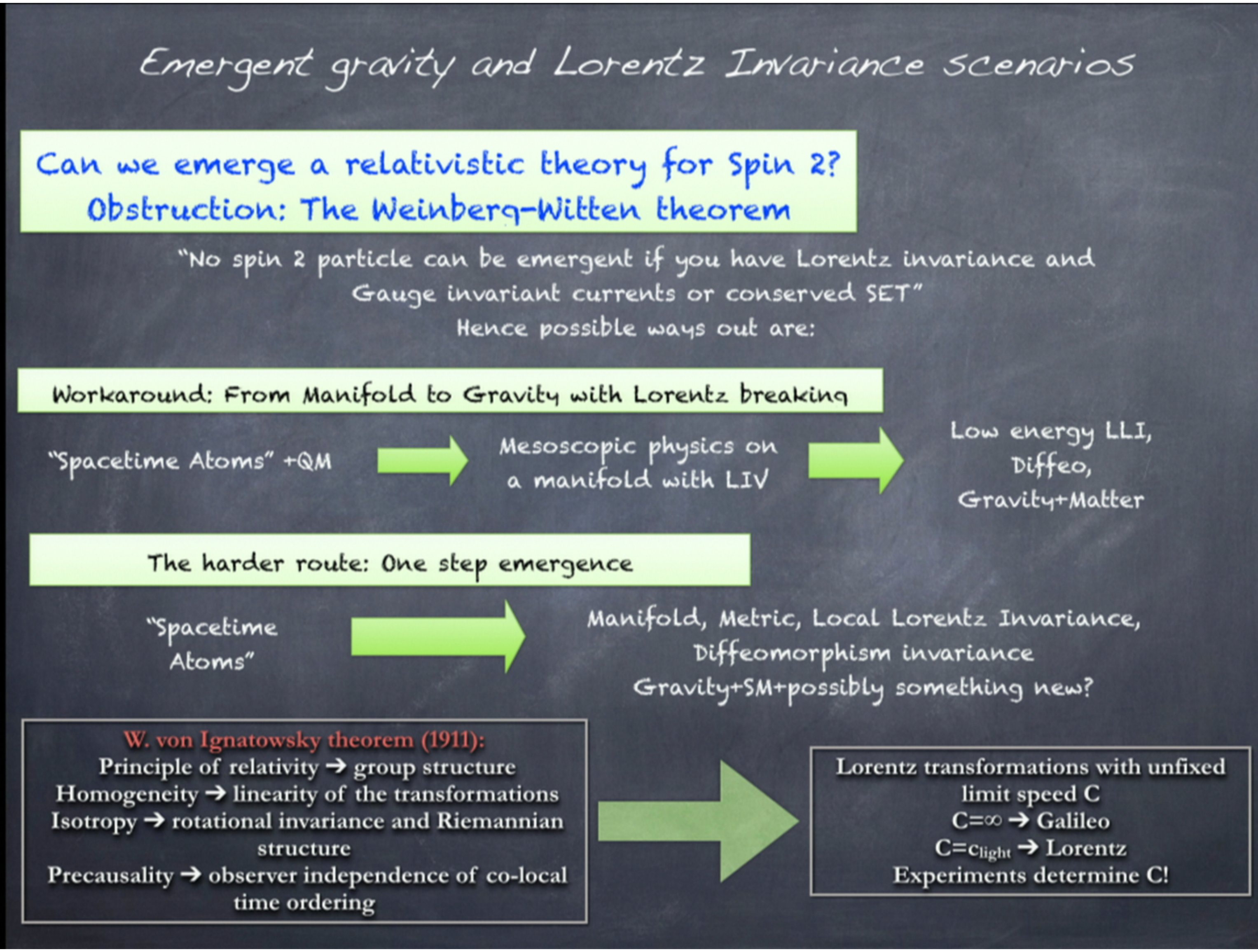
Emergent gravity and Lorentz Invariance scenarios
Can we emerge a relativistic theory for Spin 2?
Obstruction: The Weinberg-Witten theorem
"No spin 2 particle can be emergent if you have Lorentz invariance and
Gauge invariant currents or conserved SET"
Hence possible ways out are:
Workaround: From Manifold to Gravity with Lorentz breaking
"Spacetime Atoms" +QM
Mesoscopic physics on a manifold with LIV
Low energy LLI, Diffeo, Gravity+Matter
The harder route: One step emergence
"Spacetime Atoms"
Manifold, Metric, Local Lorentz Invariance, Diffeomorphism invariance
Gravity+SM+possibly something new?
W. von Ignatowsky theorem (1911):
Principle of relativity → group structure
Homogeneity → linearity of the transformations
Isotropy → 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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A digression: how hard it is the hard route?

Other mesoscopic physics without Lorentz violation?

One might try to relax other principles rather than the relativity one... but nothing seems to work...

Break Precausality ➔ Hell breaks loose, better not!

Break Principle of relativity ➔ Preferred frame, Modified dispersion relations

Break kinematical Isotropy ➔ Finsler geometries.
E.g. Very Special Relativity (Glashow, Gibbons et al.) but reduced symmetry group… already very constrained.

Break Homogeneity ➔ tantamount to give up operative meaning of coordinates. Breaking the underlying assumption of euclidean space locally used to start posing von Ingnatovski theorem.

- **Nonetheless we do have concrete QG models of emergent gravity like Causal Sets which predict exact Lorentz invariance below the Planck scale in spite of discreteness. There the key point is that spacetime comes from a statistical averaging over many microscopic configurations. This produces Lorentz invariance physics which however has non-locality (EFT with infinite series of higher order derivatives).**

$$\Box_\rho \approx \Box + \frac{\alpha}{\sqrt{\rho}}\Box^2 + \frac{\beta}{\sqrt{\rho}}\Box^2 \ln\left(\frac{\gamma}{\rho}\Box^2\right) + \dots$$

- **Similarly integrating out transplanckian d.o.f in Loop Quantum gravity seem to give non-Local EFT. Also Deformed Special Relativity attempt led to Non-Locality (Relative Locality).**

- **Conjecture: Discreetness + Lorentz Invariance = Non-Locality. Can we test this kind of EFT?**
  More soon... Let's consider LIV emergence instead...

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Let's start with the bad news...

UV LIV in the matter sector, current constraints

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

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

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

So it seems that if LIV is part of the emergent gravity scenarios, it must be somehow confined at tree level in the gravitational sector...

Lorentz breaking gravity

Einstein-Aether **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 (but not to matter), 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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Constraints (pure gravity-aether)

All the PPN parameters vanish except for α_1, α_2 which describe

PPN

Current constraints are $\alpha_1 < 10^{-4}$ and $\alpha_2 < 4\times10^{-7}$ and so there is still a large 2-d region of parameter space that remains consistent with available tests of GR.
(see also arXiv:1311.7144 [gr-qc] Yagi et al. for more complete analysis and improved constraints)

$$\alpha_2 = \frac{\alpha_1}{2} - \frac{(c_1 + \ldots}{\ldots}$$

...elike hyper- ...e trace of the ...lapse function,

...spectively and ...s. ...parameters that take the values $\lambda=1$, ...ogonal aether field.

Gravity-aether waves

If we denote the speeds of the spin-2, spin-1 and spin-0 modes by s_2, s_1, s_0 then the requirement that all these speeds are greater than unity puts constraints on a combination of the c_i coefficients. However, even after imposing all of the above constraints there is still a large region of parameter space allowed.

(~10^2) and so have been proposed several ...m. In particular ...ailed balance ...e shall not deal with them here

UV Lorentz breaking Gravity with a preferred foliation: Horava gravity

Idea: achieve power-counting renormalizability by modifying the graviton propagator in the UV by adding to the action terms containing higher order spatial derivatives of the metric, but not higher order time derivatives, so to preserve unitarity (anistotropic scaling). This procedure naturally leads to a space-time foliation into spacelike surfaces, labeled by the t coordinate and with xi being the coordinates on each surface.

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

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 $a_i = \partial_i \ln N$.

L_4 and L_6 denote a collection of 4th and 6th order operators respectively and M* is the scale that suppresses these operators.

These Infrared (IR) Lorentz violations are controlled by three dimensionless parameters that take the values $\lambda=1$, $\xi=1$, $\eta=0$ in General Relativity (GR).

IR limit L_2 is Einstein-Aether with hypersurface orthogonal aether field.

Unfortunately L_4 and L_6 contain a very large number of operators ($\sim 10^2$) and so have been proposed several restrictions to the theory to limit them. In particular

Projectability; N=N(t) | Detailed balance

There is still debate about these constraints, we shall not deal with them here

A Digression:

Constraints on Horava-Lifshitz Gravity

How much can be M*? **It is indeed bounded from below and above**

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

Due to the reduced symmetry with respect to GR, the theory propagates an extra scalar mode. If one chooses to restore diffeomorphism invariance, then this mode manifests as a foliation-defining scalar.

Blas, Pujolas, Sibiryakov,
Phys. Lett. B 688, 350 (2010).

The condition $M^* < 10^{16}$ GeV
is a consequence of the need to protect perturbative renormalizability by assuring that the mass scale of the Horava scalar mode $M_{sc} > M^*$ (ie. strong coupling only when UV terms become non negligible)
Plus Solar System constraints on L_2 that generically imply $M_{sc} < 10^{16}$ GeV.

So is $M_{LIV} \sim M^*$ or $M_{LIV} \gg M^*$?

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However LIV cannot be confined to gravity!

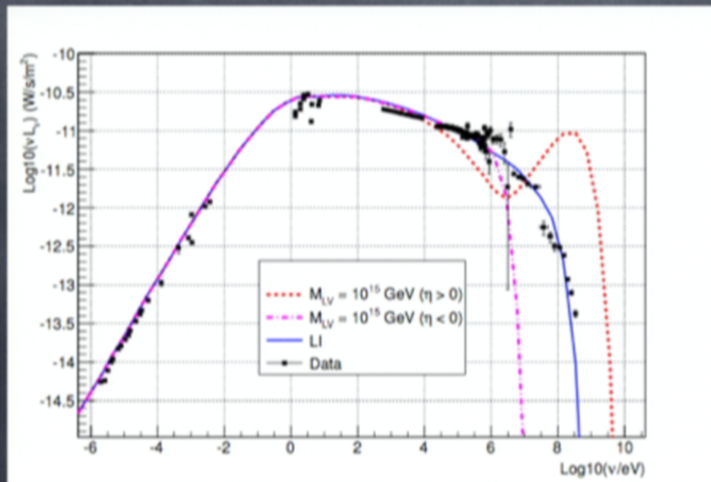
Higher order operators will always induce lower order ones by radiative corrections!
[Collins et al. PRL93 (2004), Iengo, Russo, Serone 2009]
So in general even starting with a Lorentz invariant matter sector at tree level one expects that matter LIV operators will be generated via graviton radiative corrections
Let us assume that some protective mechanism can be envisaged to protect the lowest order operators (universal coefficient of p_2 in MDR c=1), i.e Horava gravity IR viable.
Then the symmetries of the LIV operators in Hořava-Lifshitz action naturally leads MDR for matter (we assume no LIV at three level in matter and that CPT, P even nature of LIV in gravity sector is maintained in the LIV terms induced in matter)

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

So is $M_{LIV} \sim M^*$ or $M_{LIV} \gg M^*$?

Using time delay from GRB one can infer $M_{LV} > 10^{11}$ GeV. Can we improve this without using UHECR?

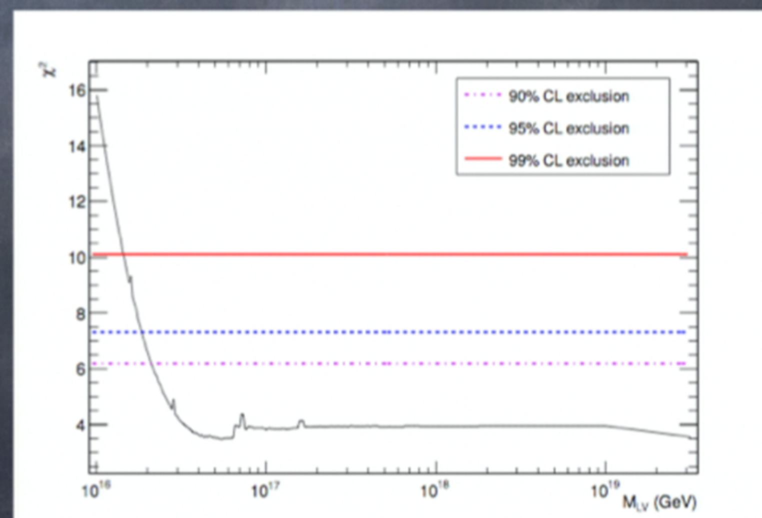
Synchrotron radiation constraint for Horava-Lifshitz Gravity



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

Crab Nebula spectrum for the LI case (blue, solid curve), for the LV case n=4, with $M_{LV} = 10^{15}$ GeV and $\eta>0$ (red, dashed curve), and for the case with same parameters but $\eta<0$ (magenta, dot-dashed curve). While, as discussed, the $\eta<0$ case would lead to premature fall off of the synchrotron spectrum, we see here that for $\eta>0$ there is a sudden surge of emission at high frequencies, followed by a dramatic drop due to the onset of vacuum Čerenkov emission at the characteristic threshold energy $E_{th} \cong [mM_{LV}]^{1/2}/\eta^{1/4}$.

Dependence of the reduced χ^2 on MLV.
By considering the offset from the minimum of the reduced χ^2 we set exclusion limits at 90%, 95% and 99% Confidence Level (CL).
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.

An open problem: the un-naturalness of small LV in EFT

[Collins et al. PRL93 (2004), Lifshitz theories (anisotropic scaling): Iengo, Russo, Serone (2009)]

In the matter sector Dim 3,4 operators are tightly constrained: $O(10^{-46})$, $O(10^{-27})$.
This is why much attention was focused on dim 5 and higher operators (which are already Planck suppressed).

However
if one postulates classically a dispersion relation with only naively (no anisotropic scaling) non-renormalizable operators (i.e. terms $\eta^{(n)}p^n/M_{Pl}^{n-2}$ with $n\geq 3$ and $\eta^{(n)}\approx O(1)$ in disp.rel.) then

Radiative (loop) corrections involve integration up to the natural cutoff M_{Pl} will generate the terms associated to renormalizable operators ($\eta^{(1)}pM_{Pl}$,$\eta^{(2)}p^2$) which are unacceptable observationally if $\eta^{(1,2)}\approx O(1)$.

Three main Ways out

Gravitational confinement

Assume only gravity LIV with $M_* \ll M_{PL}$, 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 another scale other from E_{LIV} [which we have so far assumed $O(M_{Pl})$]. So far main candidate SUSY but needs E_{SUSY} not too high.

E.g. gr-qc/0402028 (Myers-Pospelov) or hep-ph/0404271 (Nibblink-Pospelov) or gr-qc/0504019 (Jain-Ralston),
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Improved RG flow at HE

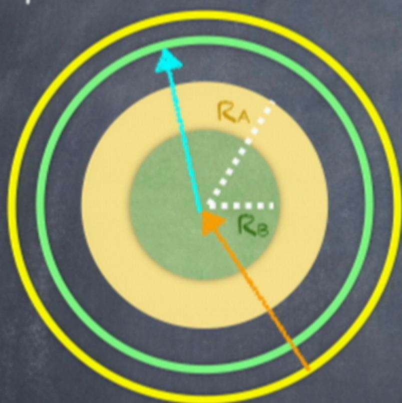
Models with strong coupling at high energies improving RG flow a la Nielsen [G.Bednik, O.Pujolàs, S.Sibiryakov, JHEP 1311 (2013) 064]

Violations of the Generalised Second Law in Lorentz breaking scenarios

If someone points out to you that your pet theory of the universe is in disagreement with Maxwell's equations – then so much the worse for Maxwell's equations. If it is found to be contradicted by observation – well, these experimentalists do bungle things sometimes. But if your theory is found to be against the second law of thermodynamics I can give you no hope; there is nothing for it but to collapse in deepest humiliation."

Sir Arthur Stanley Eddington. The Nature of the Physical World (1915), chapter 4

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

$$T_{B,Haw} > T_{B,shell} > T_{A,shell} > T_{A,Haw}$$

Then $T_{A,shell} > T_{A,Haw}$ implies flux from Shell A to BH

But $T_{B,Haw} > T_{B,shell}$ implies flux from BH to shell B

One can choose the temperatures of the shells in such a way that the two energy fluxes compensate each other.

So BH mass, radius, entropy stay constant.

But $T_{B,shell} > T_{A,shell}$ hence the net effect is to bring heat from cooler shell to hotter one!

Note: split in horizons can be used also to generate classical violation of GSL (region between radii is like ergoregion for B field: possible energy extraction)

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

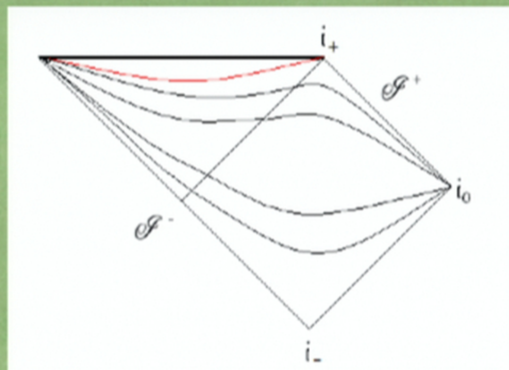
Possible way out: UV completion might imply "no BH interior" so that GSL goes in Ordinary Second law, which should still hold for non-relativistic fields.

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

C. Eling, B. Z. Foster, T. Jacobson and A. C. Wall, "Lorentz violation and perpetual motion", Phys. Rev. D 75 (2007) 101502.

T. Jacobson and A. C. Wall, "Black hole thermodynamics and Lorentz symmetry", Found. Phys. 40 (2010) 1076.

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.

In the previous picture one has just different limit speeds for different fields

$$E_i^2 = c_i^2 \left(c_i^2 m^2 + p^2 \right)$$

But in general one expect some sort of UV completion which would lead to energy dependent propagation speeds.

$$E_i^2 = c_i^2 \left(c_i^2 m^2 + p^2 + \xi_i \frac{p^n}{M^{n-2}} \right)$$

Black holes in LIV gravity

ingredients $g_{\mu\nu}$ and hypersurface orthogonal aether field $u^\mu \propto \nabla^\mu \phi$

In BH thermodynamics gravity is treated classically (IR physics) while matter reaches deep UV regime as traced back to the horizon.

So one can treat BH solution in Einstein-Aether considering them IR limit of Horava but take matter with UV completed dispersion relations (UV infinite speed).

An Universal Horizon occurs when a surface of constant Kronon field becomes compact. These are surfaces of instantaneous propagation hence nothing can move outwards from them. Alternatively the UH occurs when the Killing field χ associated to energy at infinity becomes orthogonal to the aether field: $(\chi u)=0$.

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

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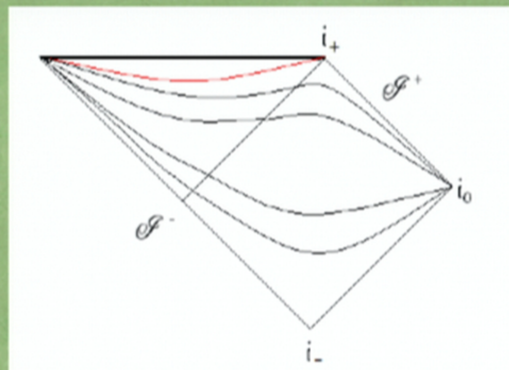

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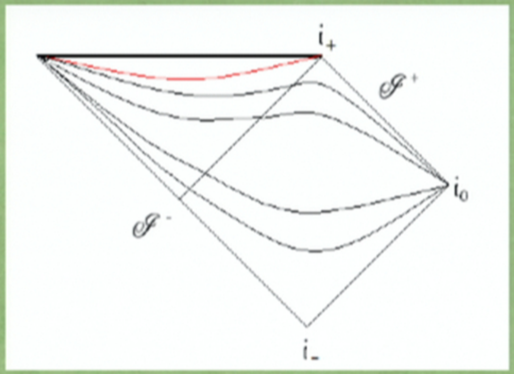

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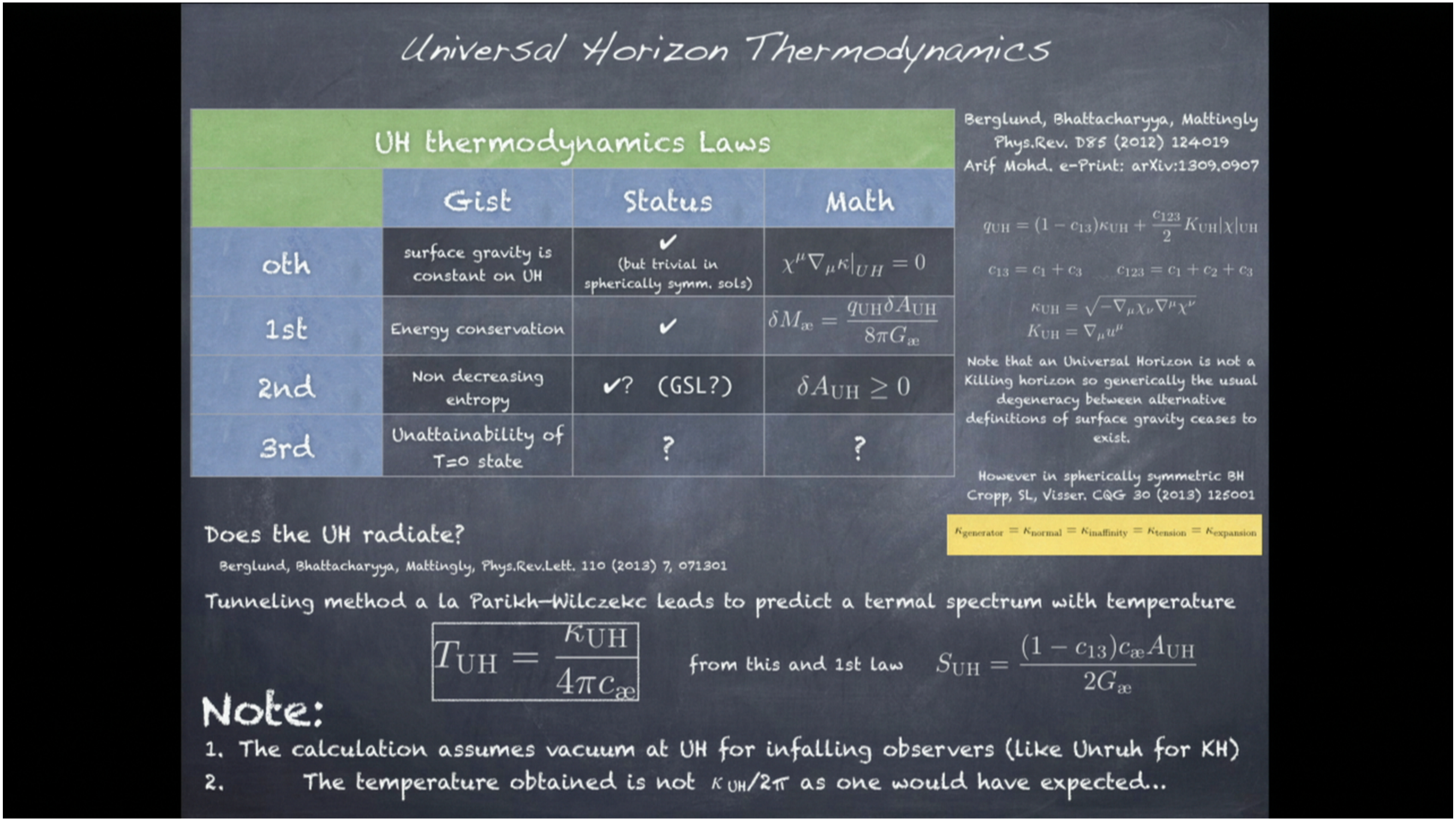
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1. The calculation assumes vacuum at UH for infalling observers (like Unruh for KH)
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AE-Black holes

$$\mathrm{d}s^2 = -e(r)\,\mathrm{d}v^2 + 2\,\mathrm{d}v\,\mathrm{d}r + r^2\,\mathrm{d}\Omega^2.$$

- Solution 1: $c_{123} = 0$.

$$e(r) = 1 - \frac{r_0}{r} - \frac{r_u(r_0 + r_u)}{r^2}; \qquad \text{where} \qquad r_u = \left[\sqrt{\frac{2 - c_{14}}{2(1 - c_{13})}} - 1\right]\frac{r_0}{2}.$$

For this particular exact solution, the Killing horizon is located at $r_{\text{KH}} = r_0 + r_u$, and the Universal horizon at $r_{\text{UH}} = r_0/2$.

- Solution 2: $c_{14} = 0$.

$$e(r) = 1 - \frac{r_0}{r} - \frac{c_{13} r_{\text{æ}}^4}{r^4}; \qquad r_{\text{æ}} = \frac{r_0}{4}\left[\frac{27}{1 - c_{13}}\right]^{1/4};$$

The Universal horizon is located at $r_{\text{UH}} = 3\,r_0/4$.

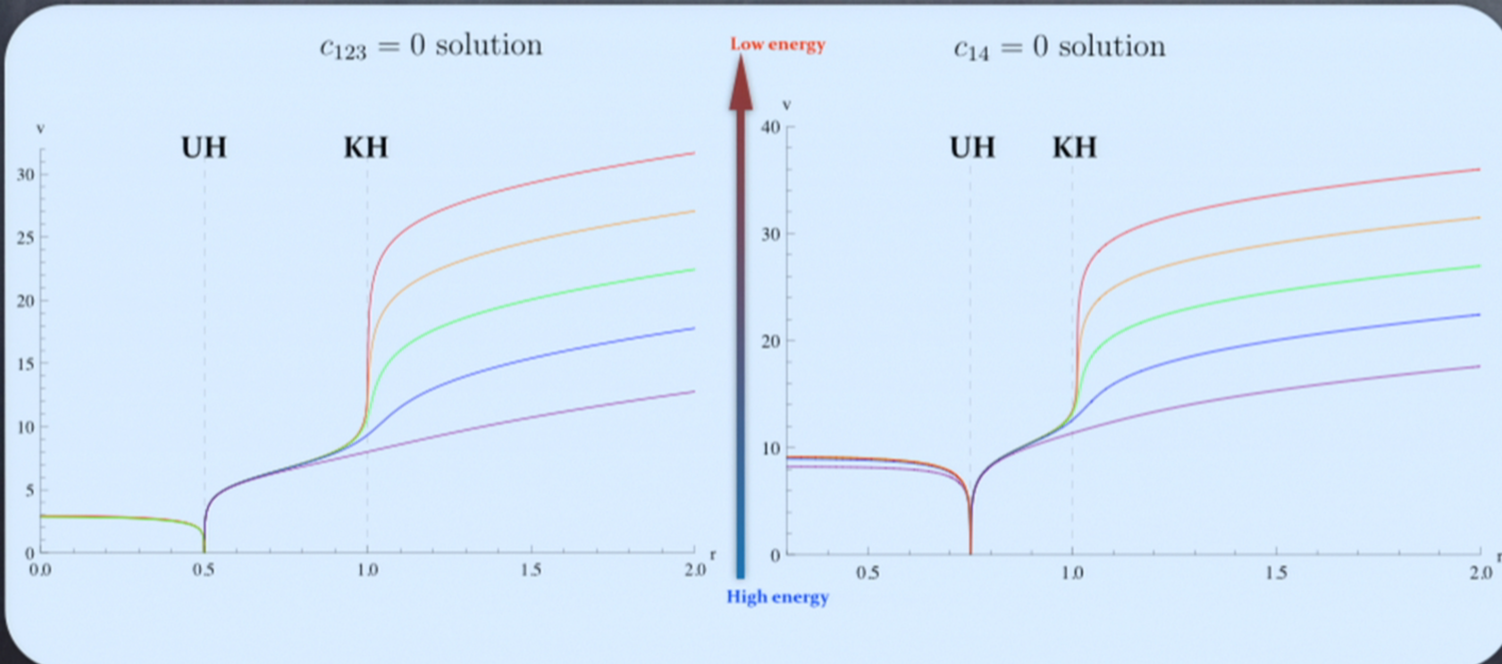
Aether field assumed to be a unit time-like vector everywhere

Raytracing in LV Black holes

Ingredients

- UV Modified dispersion relation $$\omega = c\,k_s + \frac{1}{2c}\ell^2\,k_s^3.$$
  $\omega \equiv -(k\cdot u) \qquad k_s \equiv (k\cdot s) \quad [s\perp u,\ u^2=1,\ (u,s)$ aether frame$]$
- Identify a conserved energy
  $\nabla_\mu (k_\nu \chi^\nu) = \nabla_\mu \Omega = 0 \quad \Omega =$ Killing energy as observed at infinity
- Use conserved quantity to go from spacetime and momentum dependent trajectory to purely spacetime trajectory

Results



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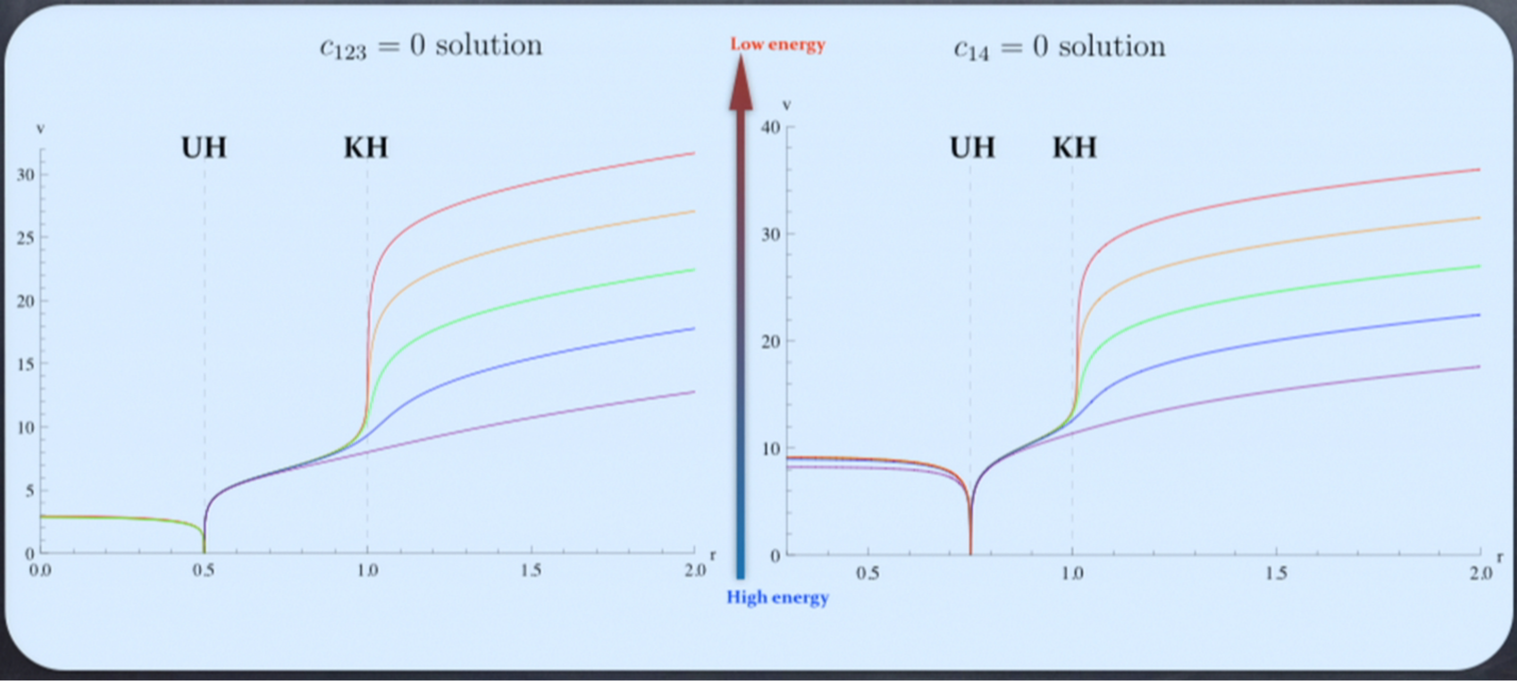

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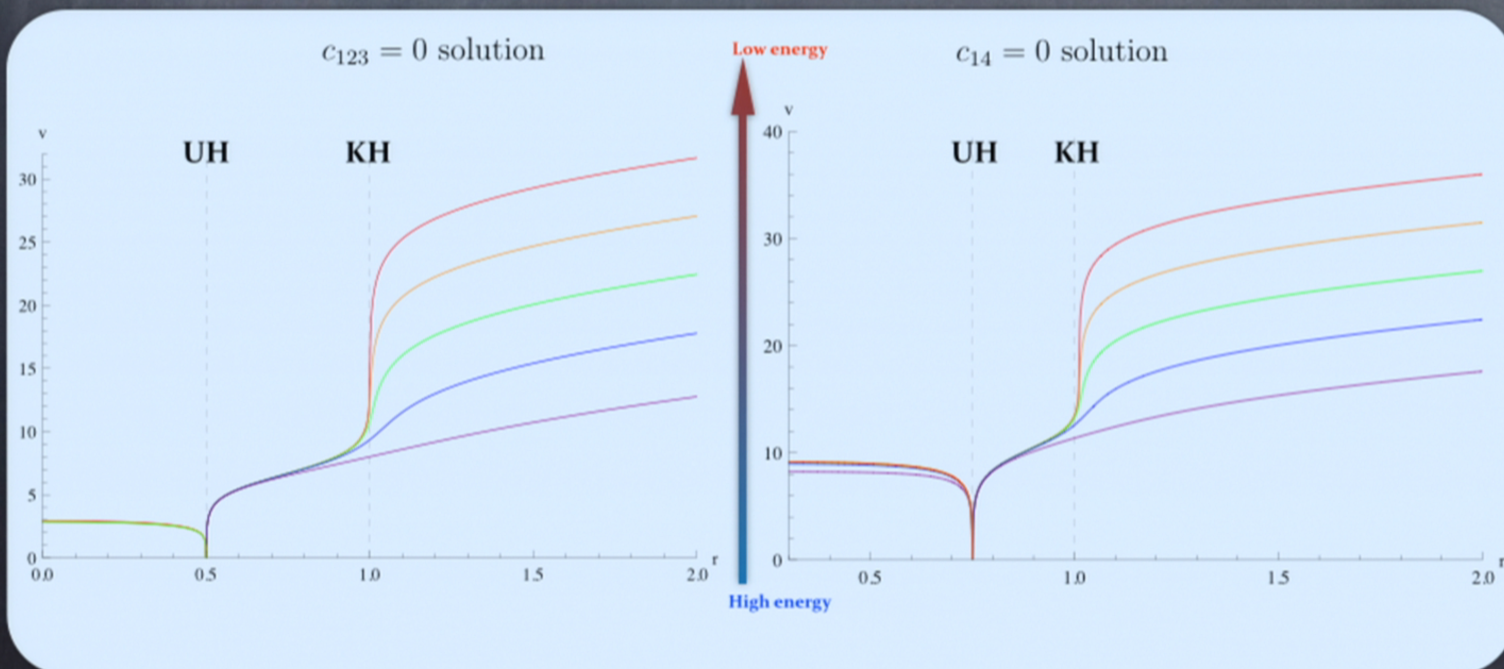

Vacuum state and Surface gravity

Vacuum state: The presence of a vacuum state for free falling observers at horizon is strongly linked to exponential peel-off. This is now exact only at UH. Hint that Unruh state might be fixed there?

Surface gravity: We take the UH surface gravity to be the parameter controlling the exponential "peeling-off" of light rays at the UH.

$$\bar{\kappa}_{\rm UH} \equiv \frac{1}{2}\frac{\mathrm{d}}{\mathrm{d}r}\frac{\mathrm{d}r}{\mathrm{d}v}\bigg|_{\rm UH}$$

The surface gravity for the two exact solutions at hand is given by

$$\bar{\kappa}_{c_{14}=0} = \frac{1}{2r_{\rm UH}}\sqrt{\frac{2}{3(1-c_{13})}}, \qquad \bar{\kappa}_{c_{123}=0} = \frac{1}{2r_{\rm UH}}\sqrt{\frac{2-c_{14}}{2(1-c_{13})}}$$

- These surface gravities **do not coincide** with the one calculated purely from the metric.
- However, the temperature calculated in {Mattingly et al, Phys.Rev.Lett. 110 (2013) 7, 071301}, can be expressed as these peeling $\kappa/2\pi$!
- While at the leading order we use the same dispersion relation as Mattingly et al., we stress that our analysis shows that the peeling surface gravity of the Universal horizon is indeed universal, i.e., independent of the specific form of the superluminal dispersion relation!
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Reprocessing at the Killing horizon?

One can generically expect that an outgoing ray of low Omega can be significantly be affected by the Killing horizon if it sticks to it long enough in terms of its "intrinsic time"

$$\tau_{\text{intrinsic}} = 1/\omega|_{\text{KH}}$$

This should be compared with its "lingering time" that we can define as

$$\tau_{\text{linger}} = 1/\varkappa$$

where we took as the characteristic scale of the lingering the difference between the peeling and metric surface gravity of the Killing horizon

$$\varkappa \equiv |\kappa_{\text{KH}} - \kappa_{\text{KH,metric}}| = \frac{[2(r_0+2r_u)]^{1/3}\,(5r_0+3r_u)\,\ell^{2/3}\Omega^{2/3}}{2\,(r_0+r_u)^{7/3}} + \mathcal{O}(\Omega^{4/3}), \qquad \kappa_{\text{KH}} = \frac{1}{2}\,\frac{\mathrm{d}}{\mathrm{d}r}\frac{\mathrm{d}r}{\mathrm{d}v}\bigg|_{\text{KH}}.$$

Note that this τ_{linger} goes to zero for large Ω, and becomes infinite as Ω goes to zero.

Finally, for small Ω one gets

$$\mathcal{R} = \frac{\tau_{\text{linger}}}{\tau_{\text{intrinsic}}} = \frac{\omega}{\varkappa} \approx \frac{2(r_0+r_u)^{8/3}}{(r_0+2r_u)^{2/3}(5r_0+3r_u)}\frac{1}{\ell^{4/3}\Omega^{1/3}}.$$

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Conclusions

- Non-equilibrium Spacetime thermodynamics is a tantalising feature that may hint towards emergent/induced gravity scenarios (but see Chirco, Haggard, Riello, Rovelli, arXiv:1401.5262 for alternative point of view)
- Emergent gravity scenarios have the problem to explain the accurate Lorentz invariance of the low energy world
- While discrete gravity scenarios like CAUSETS can avoid problems at the cost of introducing non-localities we have explored UV Lorentz scenarios.
- Constraints on the matter sector seem to imply a Pospelov-Shang like solution to the Naturalness problem of LIV in EFT.
- Another problem linked to LIV is violation of GSL.
- LIV BH however have Universal horizons
- Apparently Killing horizons thermodynamics becomes Universal Horizons thermodynamics in this setting.

- Open issues: stability of UH? what is the spectrum at infinity? what is the natural vacuum state for a these BH when formed by a collapse?

Universal Horizon Thermodynamics

UH thermodynamics Laws	Gist	Status	Math
0th	surface gravity is constant on UH	✔ (but trivial in spherically symm. sols)	$\chi^{\mu}\nabla_{\mu}\kappa\vert_{UH}=0$
1st	Energy conservation	✔	$\delta M_{æ}=\dfrac{q_{\rm UH}\delta A_{\rm UH}}{8\pi G_{æ}}$
2nd	Non decreasing entropy	✔? (GSL?)	$\delta A_{\rm UH}\geq 0$
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Berglund, Bhattacharyya, Mattingly Phys.Rev. D85 (2012) 124019
Arif Mohd. e-Print: arXiv:1309.0907

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Lorentz breaking gravity

Einstein-Aether **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 (but not to matter), which is second order in derivatives.**

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

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