Lorentz violations: from quantum gravity to black holes

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Motivation

Test Lorentz symmetry!

Motivation

Old problem: Can we make gravity renormalizable?

Possible solution: Add higher-order curvature invariants

- Higher order term contain higher order time derivatives
- This introduces ghosts!

Simple solution: give up Lorentz invariance. Then

- Higher order spatial derivatives without higher order time derivatives, i.e. no ghosts
- Renormalizable theory (at the power counting level)

Well, maybe not that simple...

Lifshitz scalar

Consider the action

$$S = \int dt dx^d \left(\dot{\phi}^2 - a_m \phi (-\Delta)^m \phi + g_n \phi^n \right)$$

It is then natural to choose the scaling dimensions

$$[dt] = [\kappa]^{-z} \qquad\qquad [dx] = [\kappa]^{-1}$$

which implies that

$$[\phi] = [\kappa]^{(d-z)/2} \quad [a_m] = [\kappa]^{2(z-m)} \quad [g_n] = [\kappa]^{d+z-n(d-z)/2}$$

So long as

$$z \geq d$$

the theory is power counting renormalizable.

Lifshitz gravity

We first need to split spacetime into space and time by introducing a preferred foliation

$$ds^2 = -N^2c^2dt^2 + g_{ij}(dx^i - N^i dt)(dx^j - N^j dt)$$

Remaining symmetry: "foliation preserving diffeomorphisms"

- Time reparametrization: $t \longrightarrow \tilde{t}(t)$
- Spacetime-dependent 3-diffeos: $x^i \longrightarrow \tilde{x}^i(t, x^i)$

Most general action

$$S = \frac{M_{\rm pl}^2}{2} \int d^3x dt N \sqrt{g} \left\{ K^{ij}K_{ij} - \lambda K^2 - V(g_{ij}, N) \right\}$$

P. Hořava, Phys. Rev. D 79, 084008 (2009)

General features

- The potential should be at least 6th order in spatial derivatives

$$V = -\xi R - \eta\, a_i a^i + \frac{1}{M_\star^2} L_4 + \frac{1}{M_\star^4} L_6 \qquad a_i = \partial_i \ln N$$

- There are 2 types of Lorentz-violating terms: those that come at lower order and those that come at higher order
- The theory propagates a scalar mode
- Generically there will be more than 60 couplings!
- So far perfectly consistent and viable theory (with certain assumptions about matter coupling)

D. Blas, O. Pujolas and S. Sibiryakov, Phys. Rev. Let. 104, 181302 (2010)

Projectable version

P. Hořava, Phys. Rev. D 79, 084008 (2009)
T.P.S., M. Visser, S. Weinfurtner, PRL 102, 064035 (2009)
JHEP 0910, 033 (2009)

- The lapse is space-independent
- Drastic simplification - 9 couplings only
- Same degrees of freedom
- Severe infrared viability issues

T.P.S., M. Visser, S. Weinfurtner, JHEP 0910, 033 (2009)
D. Blas, O. Pujolas, S. Sibiryakov, JHEP 0910, 029 (2009)
K.Koyama, F. Arroja, JHEP 1003, 061 (2010)

- Shown to be renormalizable!

A. O. Barvinsky et al., PRD 93, 064022 (2016)

- Shown to be asymptotically free in 2+1 dimensions

A. O. Barvinsky et al., arXiv:1706.06809

Einstein-aether theory

The action of the theory is

$$S_{æ} = \frac{1}{16\pi G_{æ}} \int d^4x \sqrt{-g}(-R - M^{\alpha\beta\mu\nu}\nabla_\alpha u_\mu \nabla_\beta u_\nu)$$

where

$$M^{\alpha\beta\mu\nu} = c_1 g^{\alpha\beta} g^{\mu\nu} + c_2 g^{\alpha\mu} g^{\beta\nu} + c_3 g^{\alpha\nu} g^{\beta\mu} + c_4 u^\alpha u^\beta g_{\mu\nu}$$

and the aether is implicitly assumed to satisfy the constraint

$$u^\mu u_\mu = 1$$

- Most general theory with a unit timelike vector field which is second order in derivatives

T. Jacobson and D. Mattingly, Phys. Rev. D 64, 024028 (2001).

Hypersurface orthogonality

Now assume $$u_\alpha = \frac{\partial_\alpha T}{\sqrt{g^{\mu\nu}\partial_\mu T \partial_\nu T}}$$

and choose T as the time coordinate

$$u_\alpha = \delta_{\alpha T}(g^{TT})^{-1/2} = N\delta_{\alpha T}$$

Replacing in the action and defining one gets

$$S_{æ}^{ho} = \frac{1}{16\pi G_H}\int dT d^3x N\sqrt{h}\left(K_{ij}K^{ij} - \lambda K^2 + \xi^{(3)}R + \eta a^i a_i\right)$$

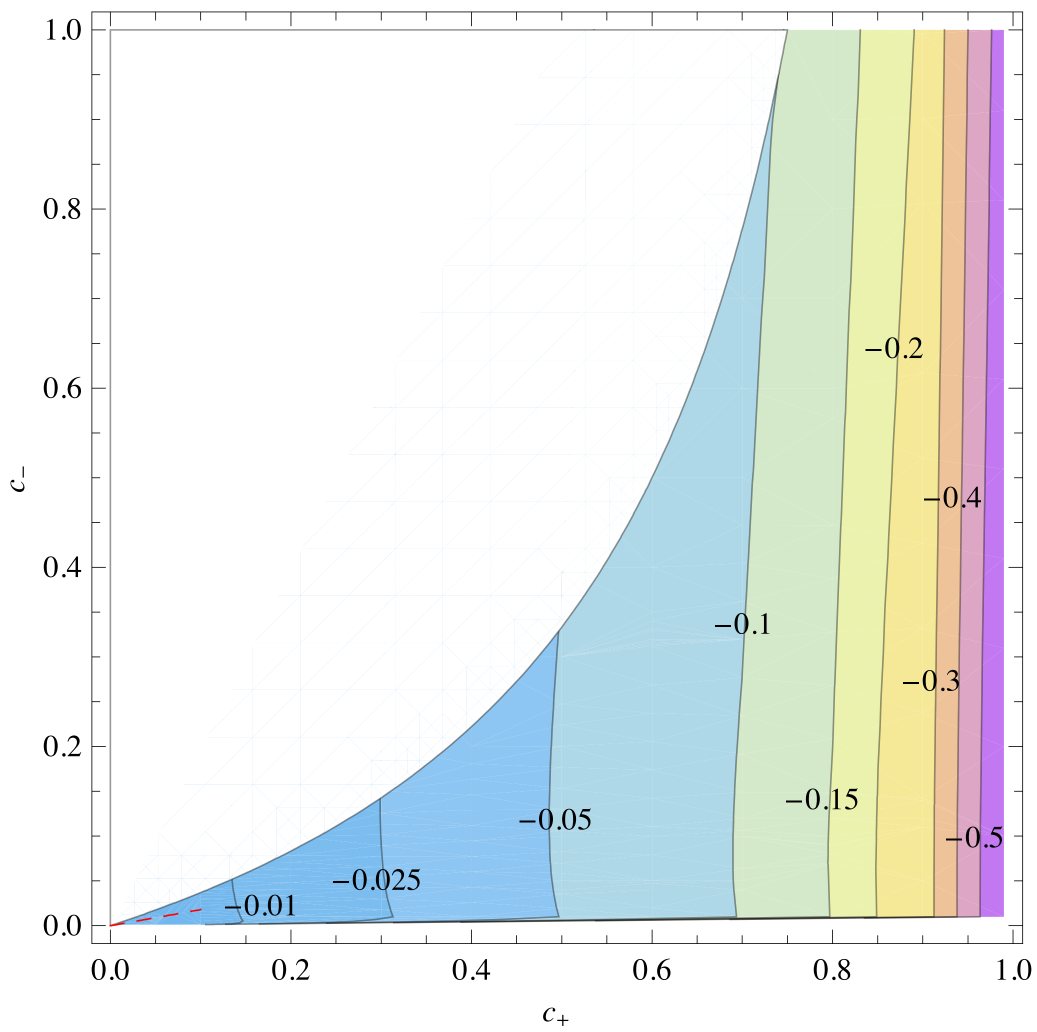
with $a_i = \partial_i \ln N$ and the parameter correspondence

$$\frac{G_H}{G_æ} = \xi = \frac{1}{1-c_{13}} \qquad \lambda = \frac{1+c_2}{1-c_{13}} \qquad \eta = \frac{c_{14}}{1-c_{13}}$$

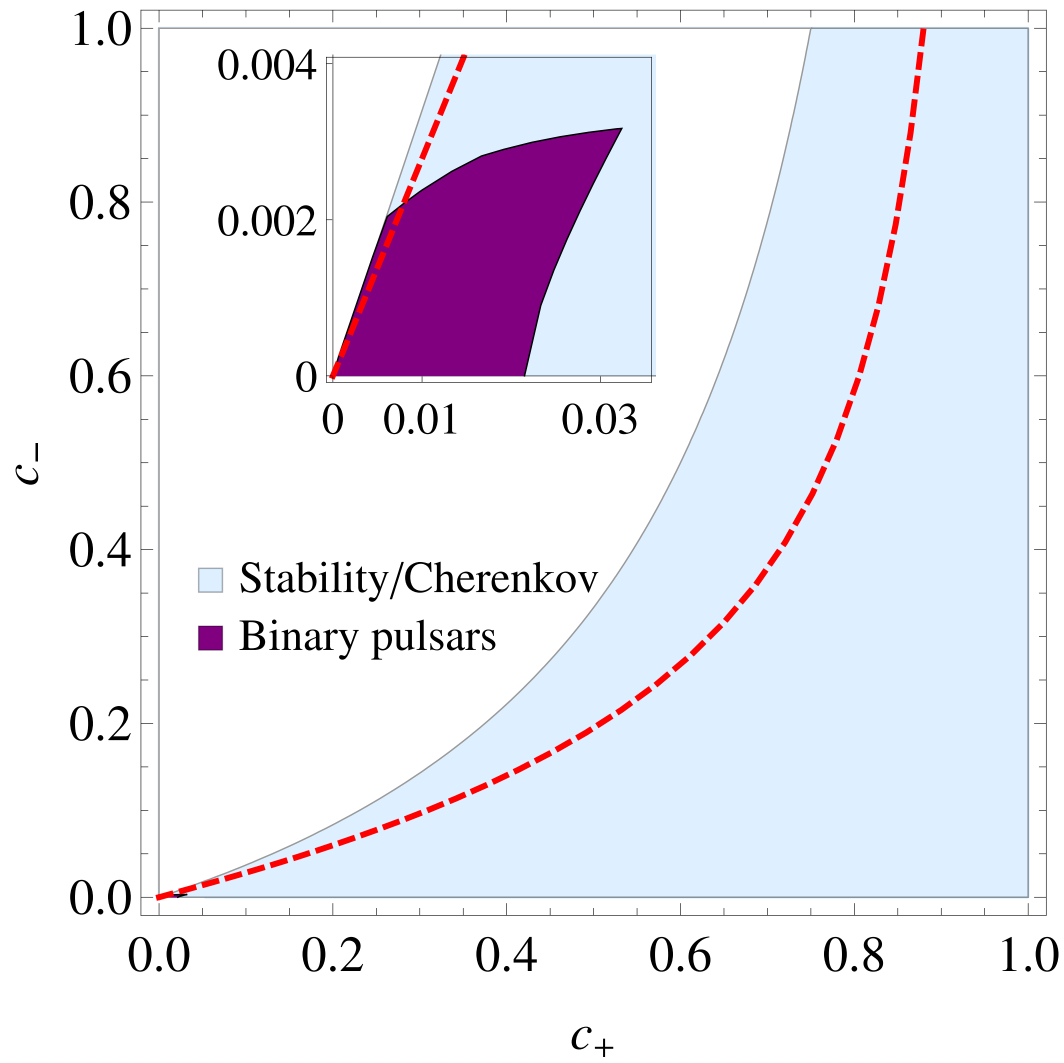
T. Jacobson, Phys. Rev. D 81, 101502 (2010).

Combined Constraints

Einstein-aether theory



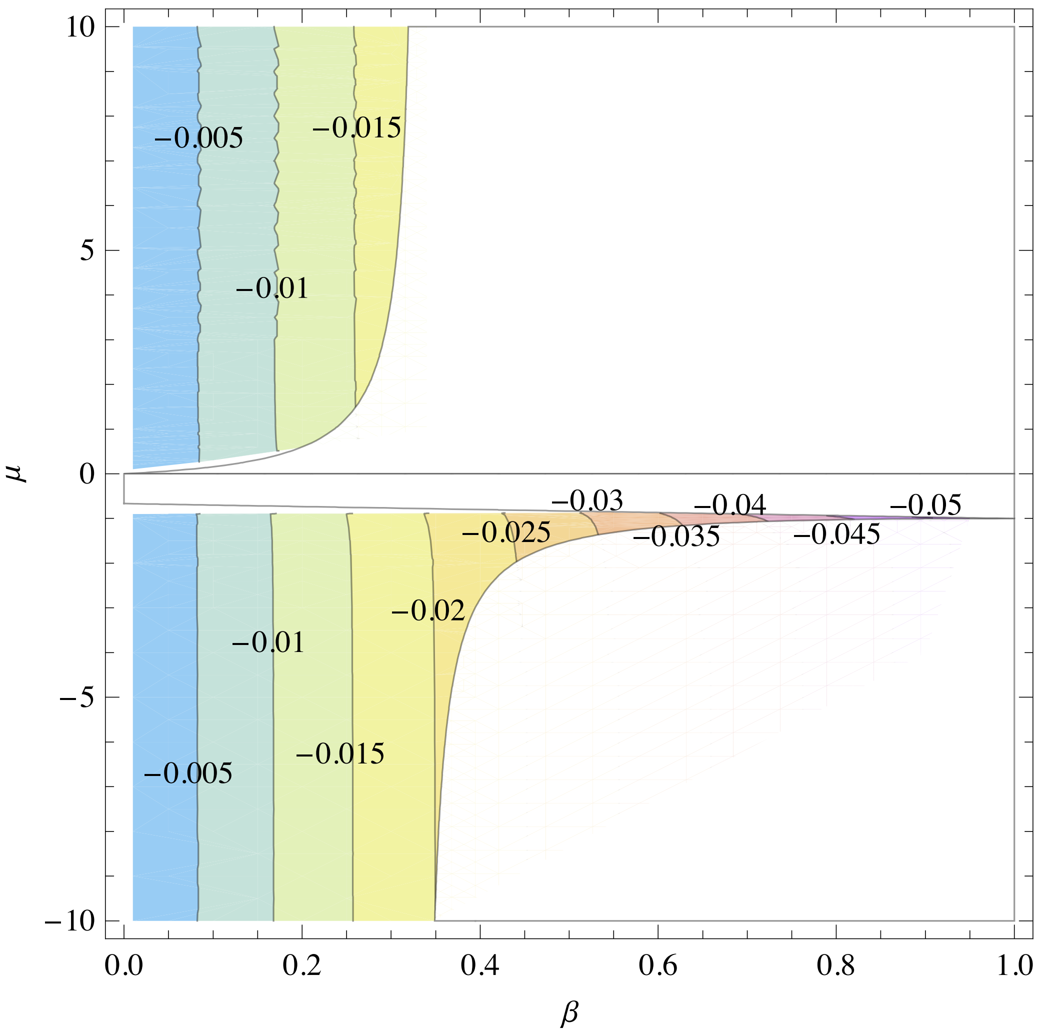
$\omega_{\text{ISCO}}\, r_g$



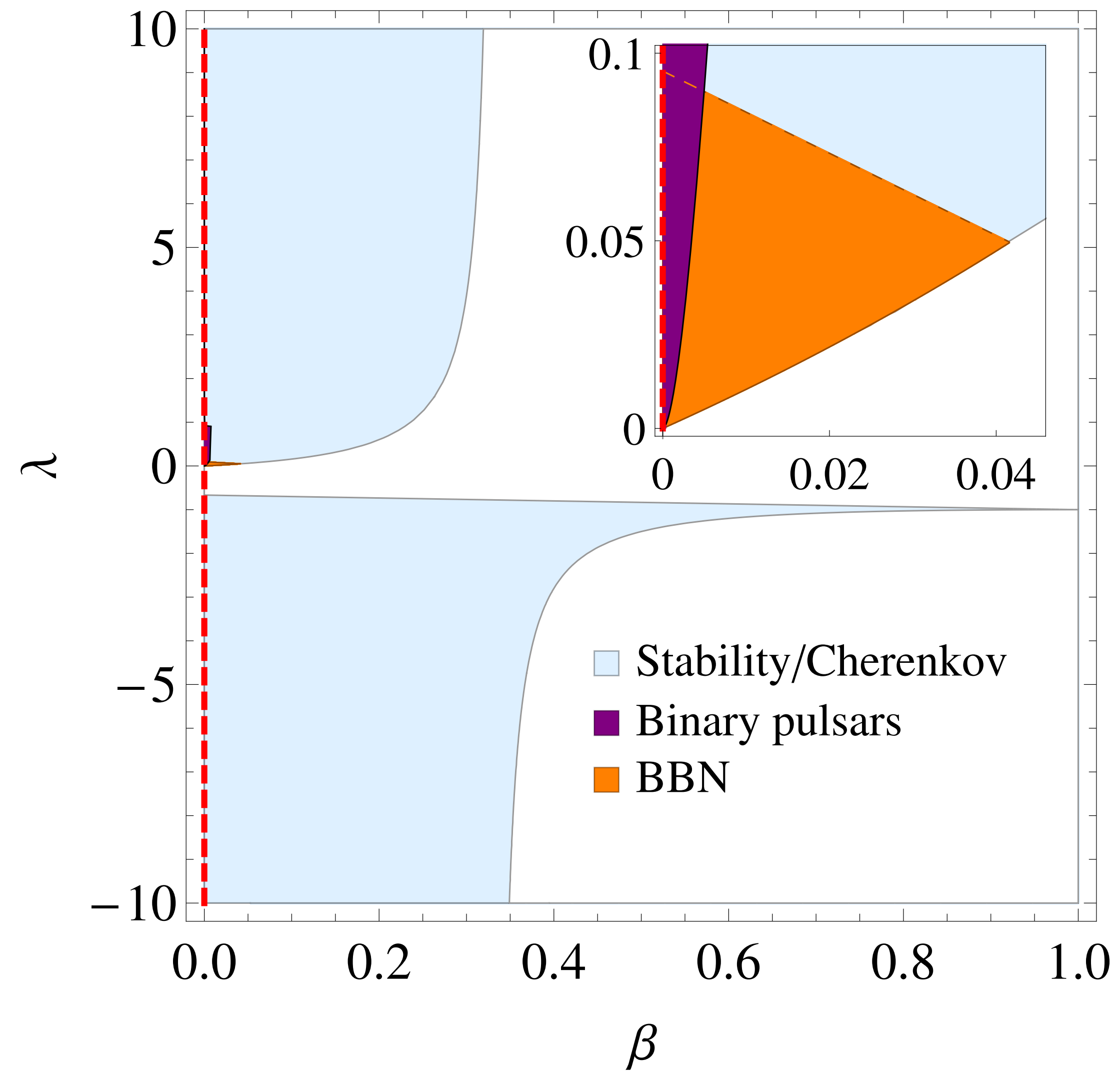
E. Barausse, T. Jacobson and T.P.S., Phys. Rev. D 83, 124043 (2011)
K. Yagi, D. Blas, N. Yunes and E. Barausse Phys. Rev. Lett. 112, 161101 (2014)

Combined Constraints

Horava gravity



$\omega_{\rm ISCO}\, r_g$



E. Barausse, T. Jacobson and T.P.S., Phys. Rev. D 83, 124043 (2011)
K. Yagi, D. Blas, N. Yunes and E. Barausse Phys. Rev. Lett. 112, 161101 (2014)

Strong coupling

The low energy action exhibits strong coupling at energy

$$M_{\rm sc} = f(|\lambda - 1|, \eta) M_{\rm pl}$$

Can be a large scale, but problem with renormalizability!

A. Papazoglou and T. P. S., Phys. Lett. B 685, 197 (2010)
I. Kimpton and A. Padilla, JHEP 1007, 014 (2010)

Strong coupling problem can be circumvented if

$$M_{\rm sc} > M_\star$$

D. Blas, O. Pujolas and S. Sibiryakov, Phys.Lett. B 688, 350 (2010)

But then potential tension with observations!

$$10^{16}{\rm GeV} > M_\star > M_{\rm obs}$$

A. Papazoglou and T. P. S., Phys. Lett. B 685, 197 (2010)

Hierarchy of scales

Consider the dispersion relation

$$E^2 = m^2 + p^2 + \eta_4 \frac{p^4}{M_{LV}^2} + \mathcal{O}(\frac{p^6}{M_{LV}^4})$$

Assume that there is a universal LV scale, so

$$M_{LV} \sim M_\star$$

Constraint from synchrotron radiation from the Crab Nebula:

$$M_{\rm obs} > 2 \times 10^{16} \mathrm{GeV}$$

$M_\star$ cannot be a universal scale!

S. Liberati, L. Maccione and T. P. S., Phys. Rev. Lett. 109, 151602 (2012)

Percolations of LV

But what about the matter sector and lower order operators?

- Different speeds for different fields in the IR, with logarithmic running!

R. Iengo, J. G. Russo and M. Serone, JHEP 0911, 020 (2009)

Possible ways out:

- Some extra symmetry, e.g. supersymmetry

S. Groot Nibbelink and M. Pospelov, Phys. Rev. Lett. 94, 081601 (2005)

- Assume Lorentz symmetry in matter and let the weak coupling to gravity (the Lorentz-violating sector) do the rest

M. Pospelov and Y. Shang, Phys. Rev. D 85, 105001 (2012)

Pertinent questions

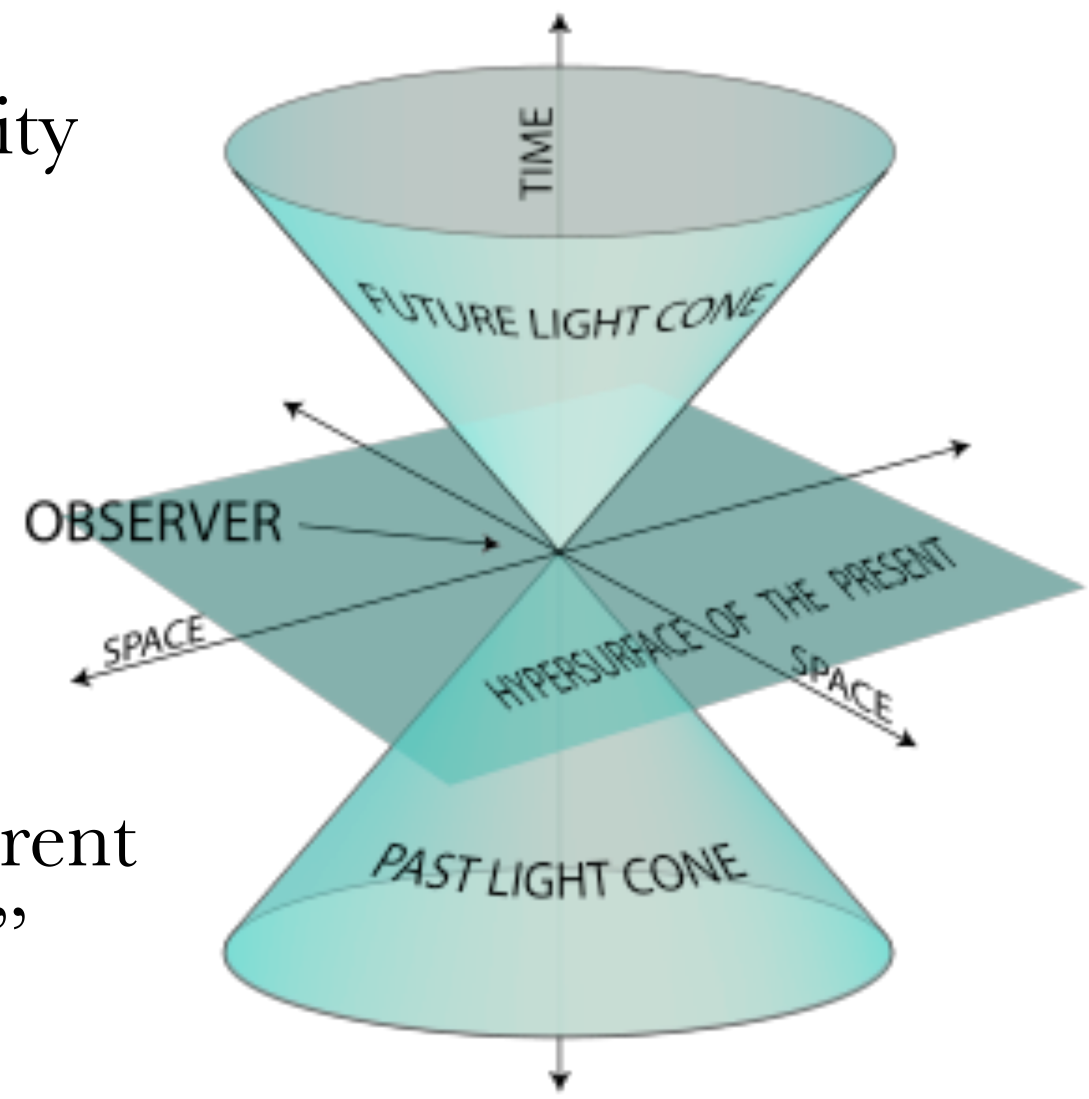
- Renormalization group flow: Do couplings get the values we want them to get?
- Quantization: some real quantum gravity predictions
- Matter coupling and relevant (possibly worrisome) phenomenology

I. Kimpton and A. Padilla, JHEP 1304, 133 (2013)
M. Colombo, A. E. Gumrukcuoglu, and T.P.S., Phys. Rev. D 91, 044021 (2015);
Phys. Rev. D 92, 064037 (2015)
A. Coates, M. Colombo, A. E. Gumrukcuoglu, and T.P.S., Phys. Rev. D 94, 084014 (2016)

- Vacuum energy
- Causal structure: do we understand it?
- Black holes and singularities: are there black holes? Are singularities resolved?

LV and causal structure

Causal structure in special relativity



- LV with linear dispersion relations

$$\omega \propto k$$

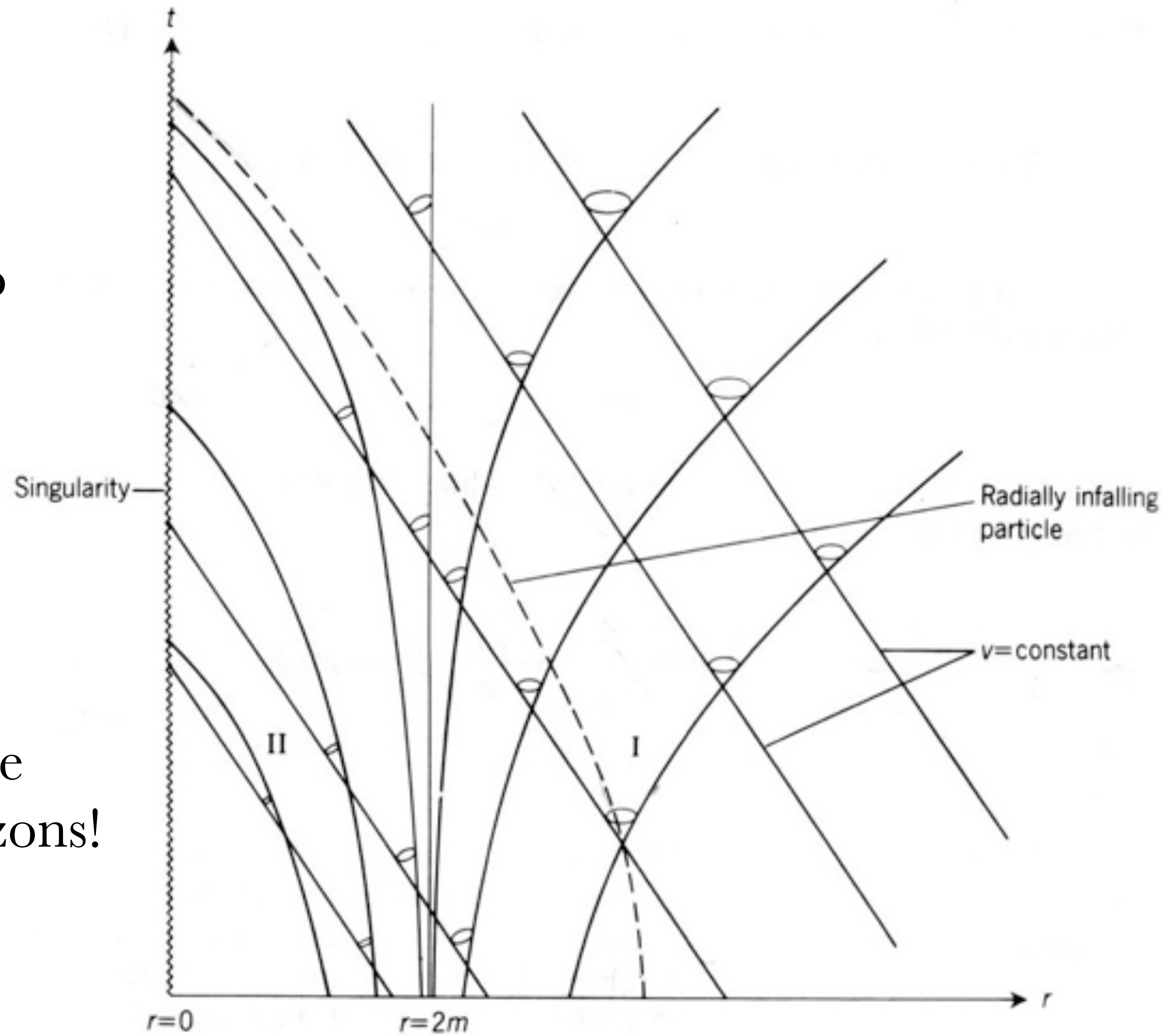
- Different modes have different speeds and different “light” cones

- But there are still “light” cones!

LV and black hole structure

What happens to black holes?

- They will have multiple horizons!



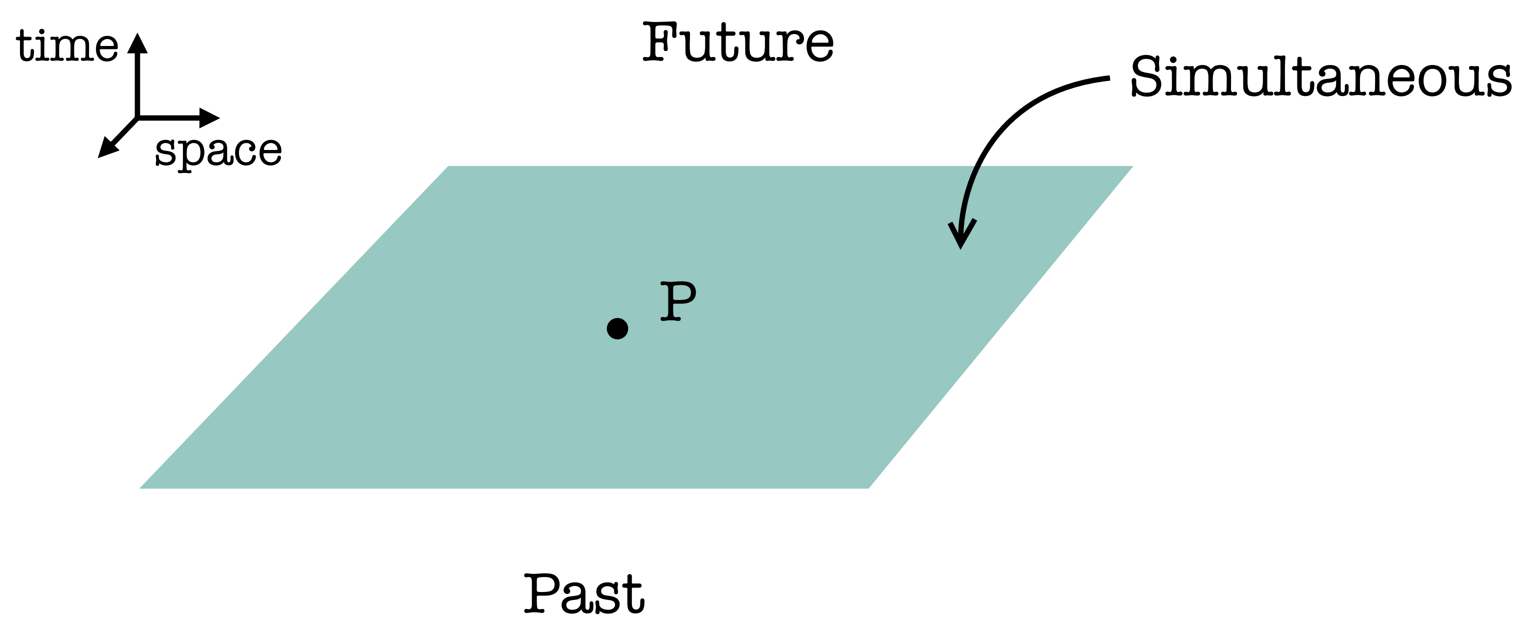
LV and black hole structure

- LV with non-linear dispersion relations

$$\omega^2 \propto k^2 + ak^4 + \ldots$$

- No light cones!

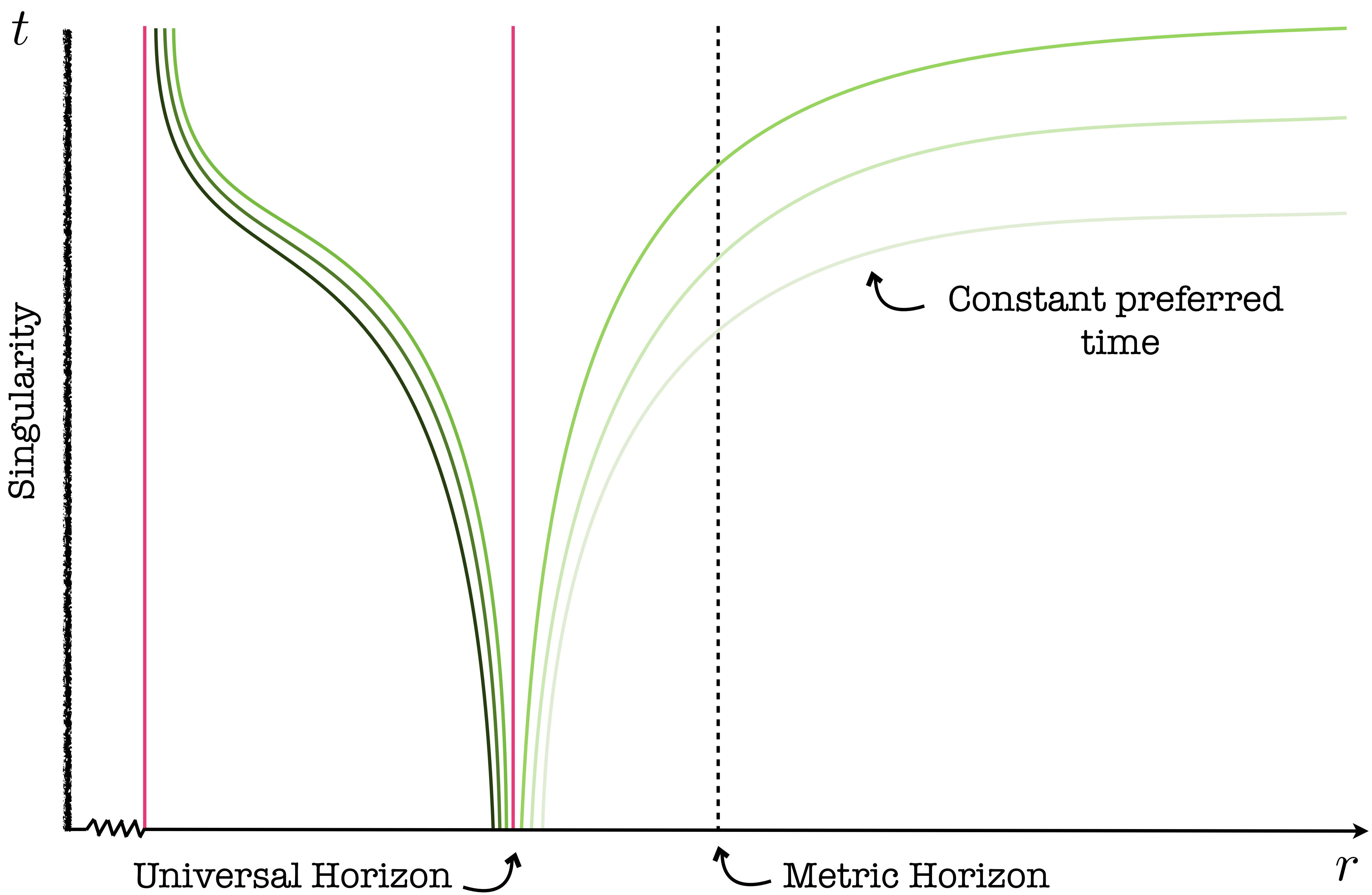
Causal structure without relativity



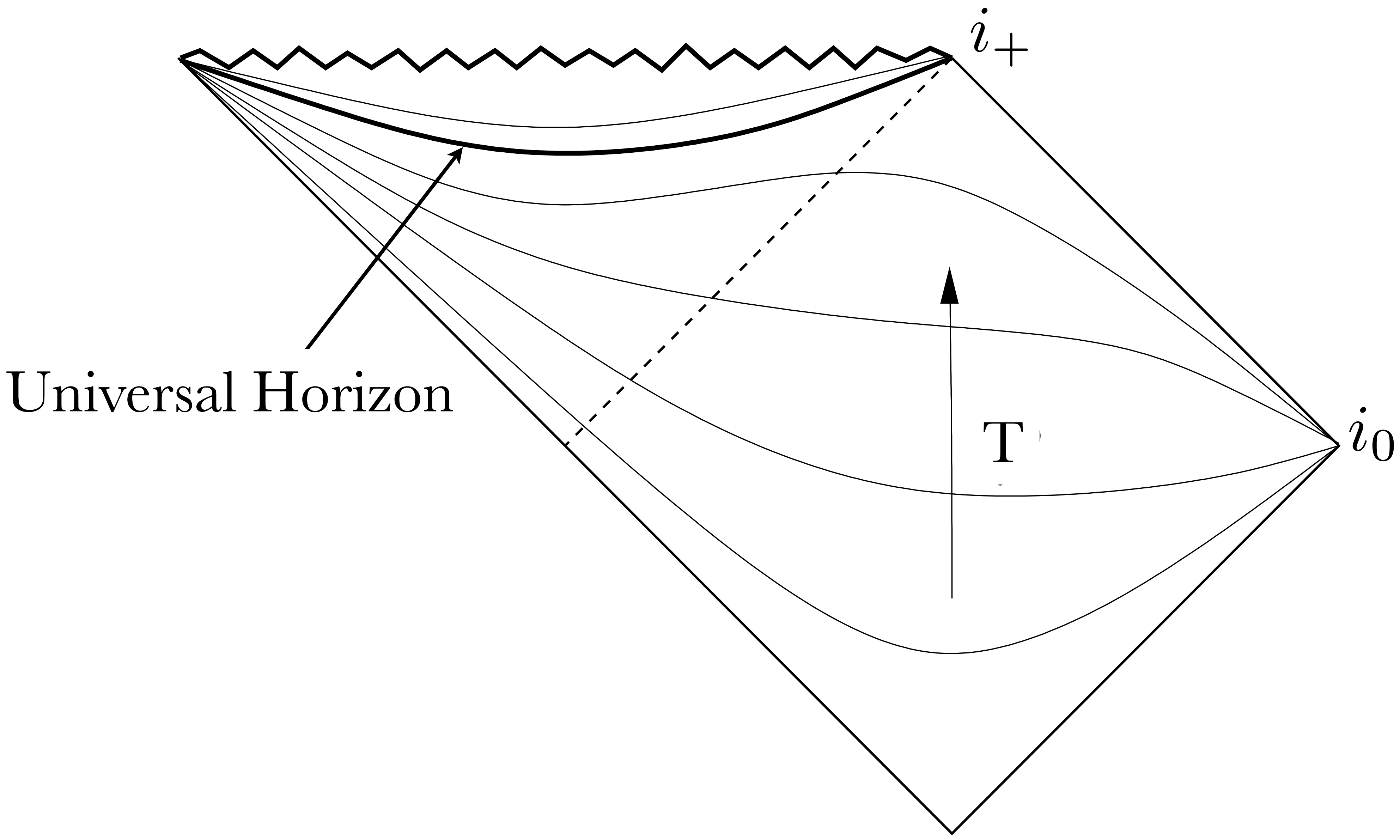
No black holes at all??

Spacetime diagram

E. Barausse, T. Jacobson and T.P.S., Phys. Rev. D 83, 124043 (2011)



Penrose diagram



Taken from D. Blas and S. Sibiryakov, Phys. Rev. D 84, 124043 (2011)

Rotating black holes

- Slowly rotating BHs in Einstein-aether theory do not have a preferred foliation.
- Slowly rotating BHs in Horava gravity have universal horizons.

E. Barausse and T.P.S., Phys. Rev. Lett. 109, 181101 (2012)
E. Barausse and T.P.S., Phys. Rev. D 87, 087504 (2013)
E. Barausse and T.P.S., Class. Quant. Grav 30, 244010 (2013)
E. Barausse, I. Vega and T.P.S., Phys. Rev. D 93, 044044 (2016)

- 3d rotating black holes can have universal horizons even with flat asymptotics.
- Universal horizons can lie “outside” de Sitter horizons.

T.P.S., I. Vega and D. Vernieri, Phys. Rev. D 90, 044046 (2014)

Beyond exact solutions

- A new "toolkit" is needed

  M. Colombo, J. Bhattacharyya, and T.P.S., Class. Quant. Grav. 33, 235003 (2016).

- Can we define this horizon in full generality?

  Yes!

- Can we have a local definition when we have less symmetry?

  Theorem

  $(u \cdot \chi) = 0, \quad (a \cdot \chi) \neq 0$ form a set of necessary and sufficient conditions for a hypersurface to be a universal horizon

- Is the universal horizon relevant to astrophysics?

  No, it lies always behind the usual horizon

Spherical collapse

J. Bhattacharyya, A. Coates, M. Colombo, and T.P.S., Phys. Rev. D 93, 064056 (2016).

One can make the ansatz

$$ds^2 = -N^2 dT^2 + S^2(N^R dT + dR)^2 + r^2(d\theta^2 + \sin^2\theta d\phi^2)$$

and then the "T-equation" takes the form

$$\partial_R \left[r^2 S N^2 \vec{\text{Æ}}^R \right] = 0 \qquad \Leftrightarrow \qquad (s \cdot \vec{\text{Æ}}) = \frac{f_{IM}(T)}{r^2 N^2}$$

- Horava gravity has an instantaneous mode!
- The universal horizon corresponds to $N \to \infty$
- This foliation was used for simulations

D. Garfinkle, C. Eling and T. Jacobson, Phys. Rev. D 76, 024003 (2007)

- It does not penetrate the horizon!

LV and GW propagation

$$E^2 = m_g^2 + a_1 M_\star p + c_g^2 p^2 + a_3 \frac{p^3}{M_\star} + a_4 \frac{p^4}{M_\star} + \dots$$

- GWs constrain significantly only the mass, p and p^3
- Constraining the speed of GW requires knowing distance AND time of travel, or to have EM counterpart
- Weak constraints on speed from time delays between detectors

D. Blas et al., JETP Lett 103, 624 (2016)
N. Cornish, D. Blas and G. Nardini, arXiv: 1707.06101 [gr-qc]

- Smoking-gun detection: scalar mode with time delay!
(but hard to detect)

T.P.S., arXiv:1709.00940 [gr-qc]

Perspectives

- LV QG: Well-defined candidate, testable predictions
- Major IR viability issues resolved (in some versions)
- Some very interesting predictions. I did not mention:
  - Cosmology: scale invariant spectrum, no horizon problem, novel dark energy model, …

    S. Mukohyama, Class. Quant. Grav. 27, 223101 (2010)
    D. Blas and S. Sibiryakov, JCAP 1107, 026 (2011)
  - Possible contact with discrete QG (CDT)

    P. Hořava, Phys. Rev. Lett. 102, 161301 (2009)
    T. P. Sotiriou, M. Visser and S. Weinfurtner, Phys. Rev. Lett. 107, 131303 (2011)
- Major challenges ahead: renormalization group flow, quantization
- What about quantum predictions?

Perspectives

- Black holes are of great interest in Lorentz-violating theories. New notion: "universal horizon"
- Non-trivial causal structure
- Is this horizon stable?
- Does it form from collapse?

D. Blas and S. Sibiryakov, Phys. Rev. D 84, 124043 (2011)

M. Saravani, N. Afshordi and R. B. Mann, Phys. Rev. D 89, 084029 (2014)

J. Bhattacharyya, A. Coates, M. Colombo, and T.P.S., Phys. Rev. D 93, 064056 (2016).

- Testing LV with GW observations?