Regular Black Holes in Lorentz-Violating Gravity

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Based on:

JM, S. Liberati, JHEP 03 (2023) 199 [2301.04697]

“Regular Black Holes and Ultra-Compact Obejects in Lorentz-Violating Gravity”

?

Why
Lorentz Invariance Violations (**LIV**) in gravity?

- LI well tested in matter, not so much in gravity
- Many QG scenarios point to LIV
  [LIV cornerstone of QG phenomenolgy]
- LIV can help build QG theories

Hořava gravity

Framework: (non-projectable) **Hořava gravity**

QFT of gravity

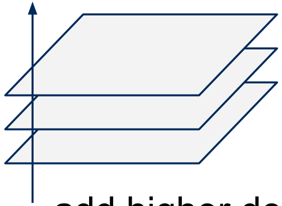
with higher derivatives

power-counting renormalisable

(probably perturbatively renormalisable)

no ghosts

how?



fundamental split between space & time

add higher derivatives only in space (not time)

Focus on low-energy limit: **Khronometric theory** — scalar-tensor theory, related to Einstein–æther theory

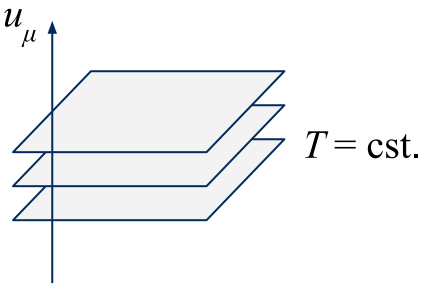
Building blocks

Basic ingredients

metric
$$g_{\mu\nu}$$

$$T(x) \quad \text{or} \quad u_\mu = N\nabla_\mu T$$

khronon — æther



coupling with æther gives LIV

constraint

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

æther everywhere timelike

there can be superluminal causal signals

æther determines causal structure

Black Holes

Surprisingly,
BHs exist!

Killing horizons (**KHs**)
not causal horizons

new kind of horizons:
universal horizon (UHs)

compact leaf of preferred foliation

Static and spherically symmetric IR solution (in corner of parameter space):
Schwarzschild + “painted on” æther

$$ds^2 = F(r)\mathrm{d}v^2 - \mathrm{d}v\mathrm{d}r - r^2\mathrm{d}\Omega^2$$

$$F(r) = 1 - \frac{2M}{r}$$

M mass

$$u^\mu \partial_\mu = A(r)\partial_v + y(r)\partial_r$$

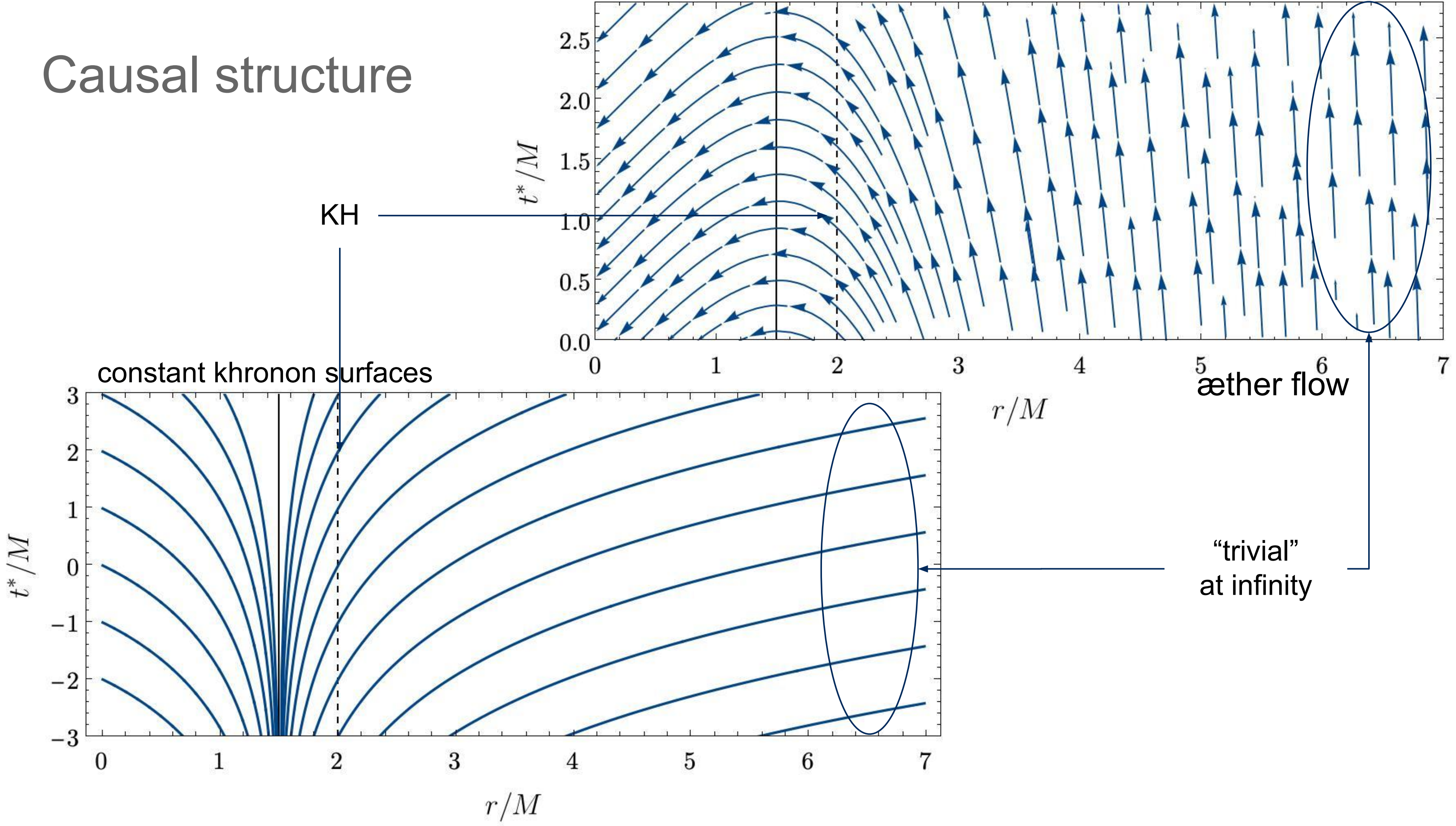
$$y(r) = -\frac{r_{\mathrm{ae}}^2}{r^2}$$

$$r_{\mathrm{ae}} = M\left[\tfrac{27}{16}\right]^{1/4}$$

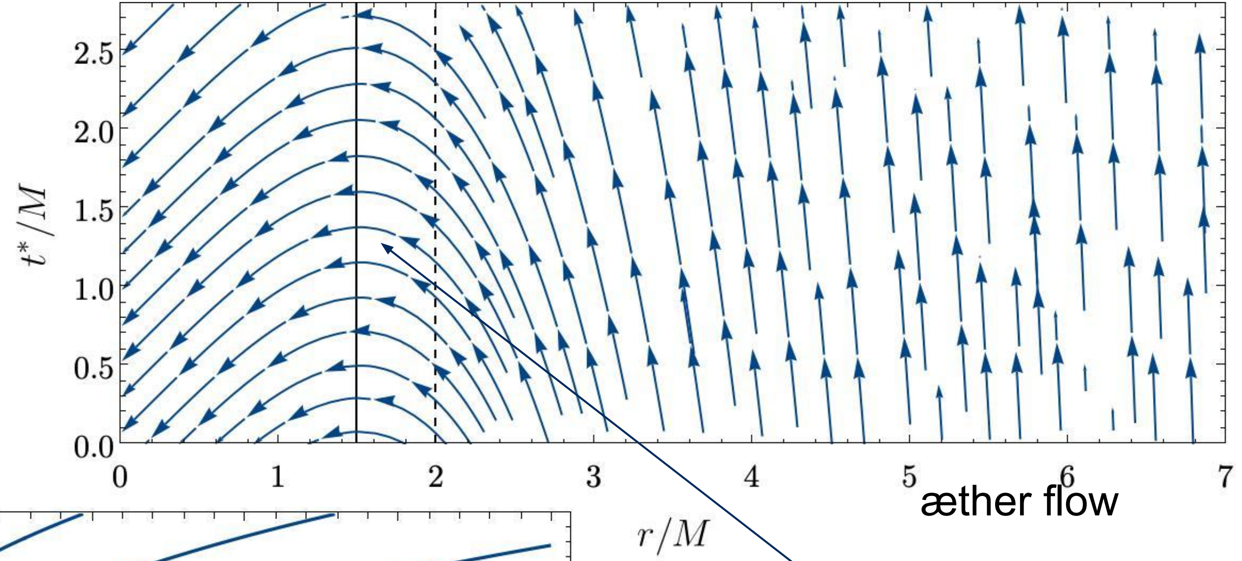
(choice)

spacetime singularity at $r = 0$

Causal structure

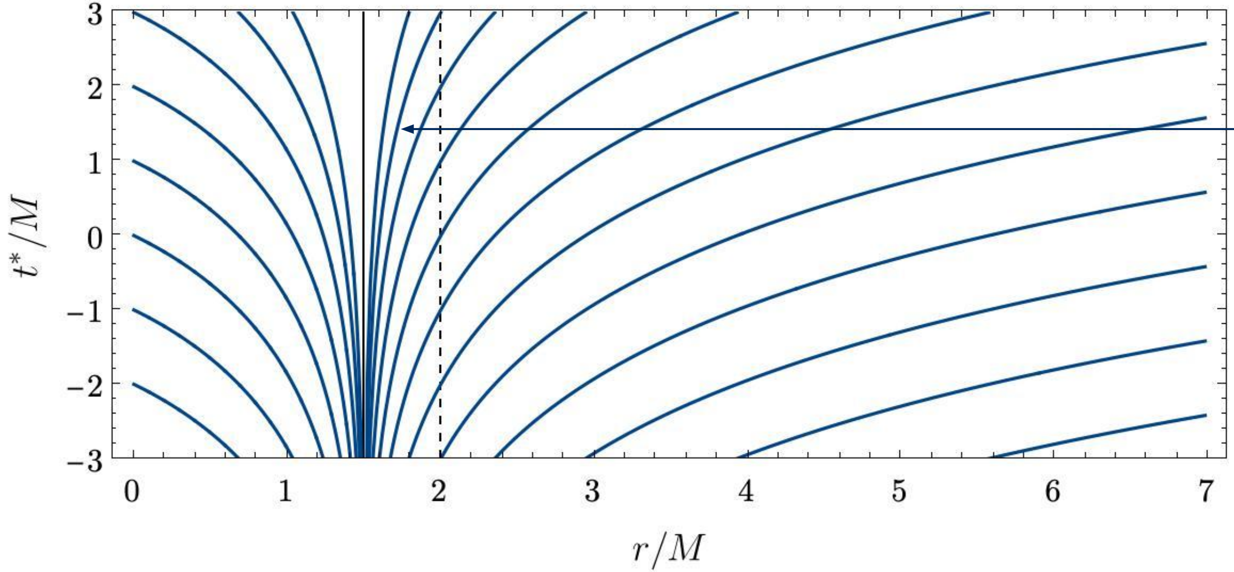


Causal structure



æther flow

constant khronon surfaces



UH

universal horizon:
æther ⊥ Killing vector

- traps modes of any speed
- some BH mechanics
- seems to have thermal properties

Goal

If Hořava is UV-complete QG, its BHs might be non-singular.

What would they look like?

Build (effective) models of non-singular BHs
[“regularisations” of low-energy singular solution]

Equations are hard, so not looking for solutions

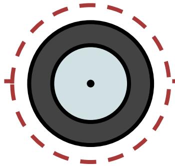
Models quantitatively wrong, but qualitatively good

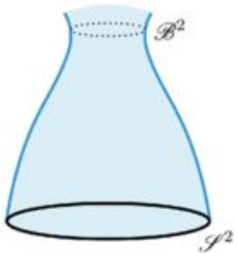
Two classes

Qualitatively, two classes of RBHs

Simply Connected (SC)

regular centre
multiple horizons
(“proper” RBHs)

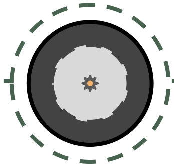




Carballo-Rubio, Di Filippo, Liberati, and Visser, PRD **101**, 084047 [1911.11200]

Multiply Connected (MC)

wormholes
hidden by horizon
require topology change



Regularising BHs

Start from singular solution and replace

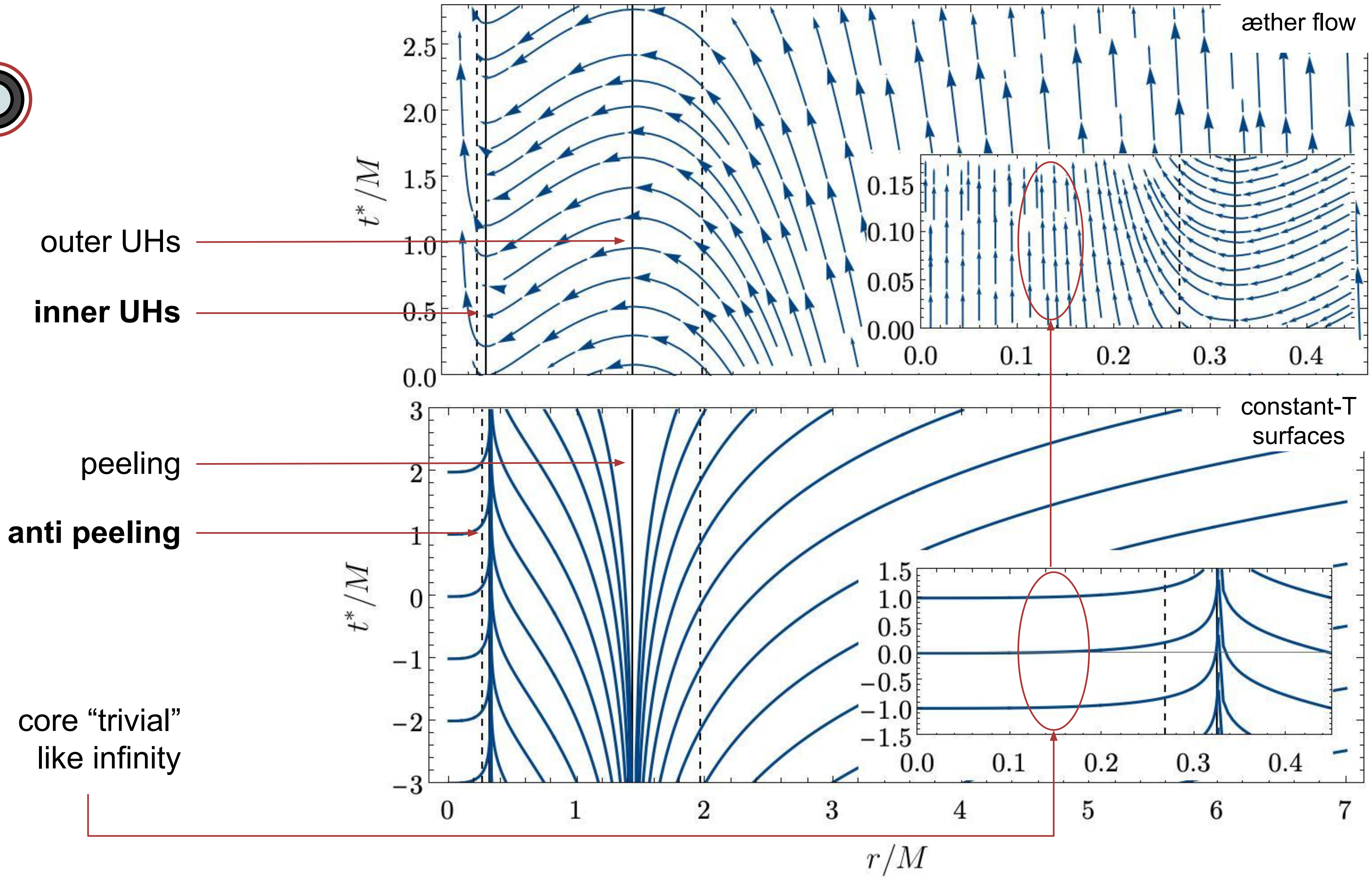
SC		**MC**
$$M \mapsto m(r)$$		$$r \mapsto R(r)$$
$$m(r) = c\,\ell^{-2} r^3 + \mathcal{O}\left(r^4\right)$$	for $r \to 0$	$$R(r) = \ell + \mathcal{O}(r)$$
e.g. Hayward $$m(r) = M \frac{r^3}{r^3 + 2M\ell^2}$$		e.g. Simpson–Visser $$R(r) = \sqrt{r^2 + \ell^2}$$

in metric *and* æther

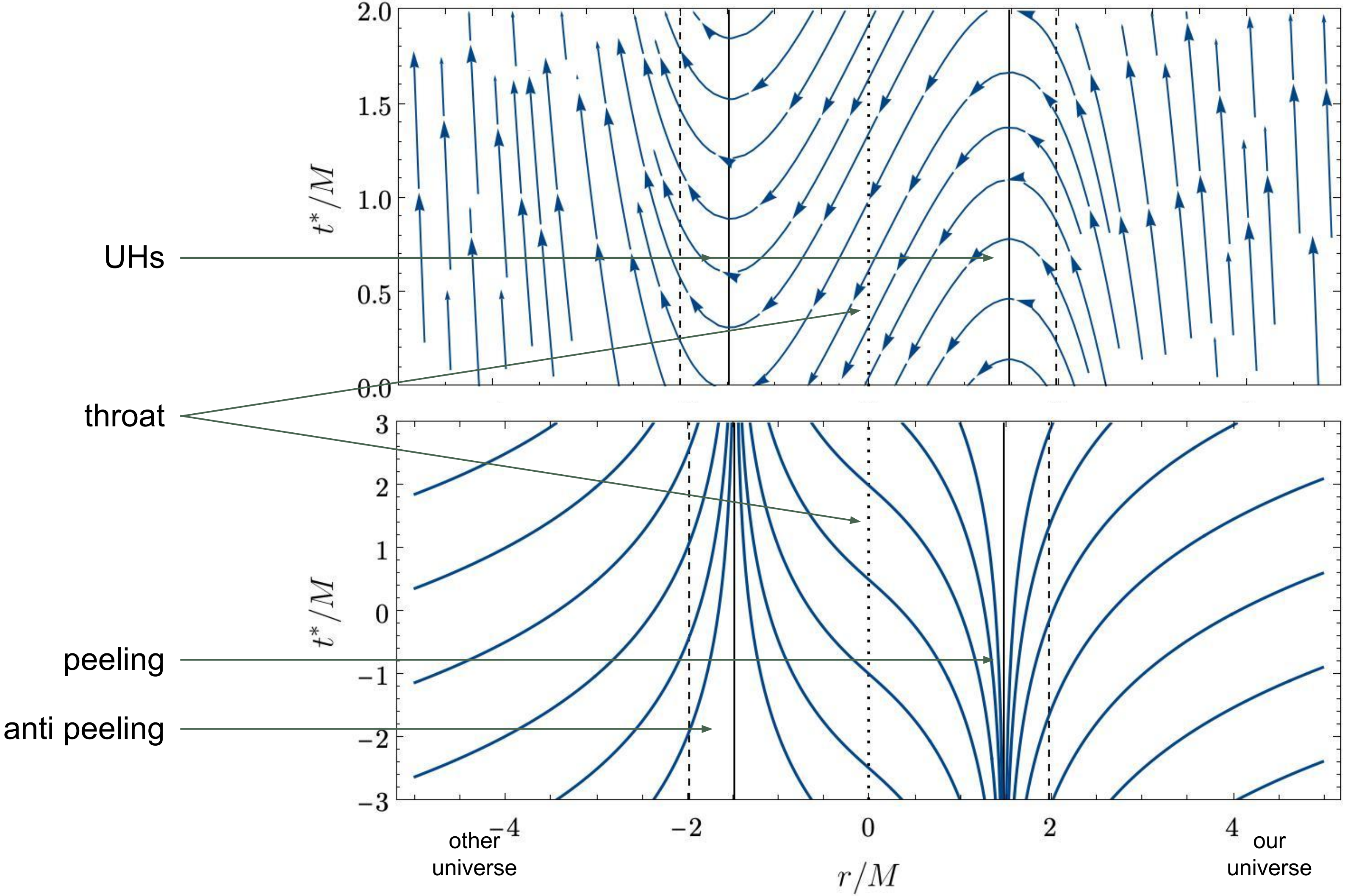
$$y_{\rm SC}(r) = -\frac{r_{\rm ae}^2(r)}{r^2}$$

$$r_{\rm ae}(r) = m(r) \left[\frac{27}{16}\right]^{1/4}$$

$$y_{\rm MC}(r) = -\frac{r_{\rm ae}^2}{R(r)^2}$$

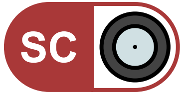


SC
æther flow
constant-T surfaces
outer UHs
inner UHs
peeling
anti peeling
core “trivial” like infinity
t^*/M
r/M


UHs
throat
peeling
anti peeling
other universe
our universe
t^*/M
r/M
2.0
1.5
1.0
0.5
0.0
3
2
1
0
−1
−2
−3
−4
−2
0
2
4

Recap & Outlook

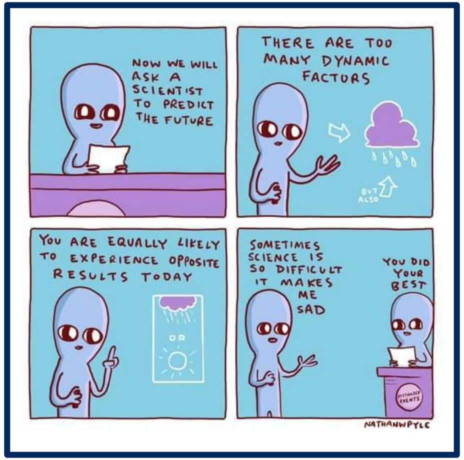
Effective models of RBHs in Lorentz-violating gravity



- outer *and* inner horizons (KH/UH)
- wormhole throat hidden by horizons (KH/UH)

Common features:

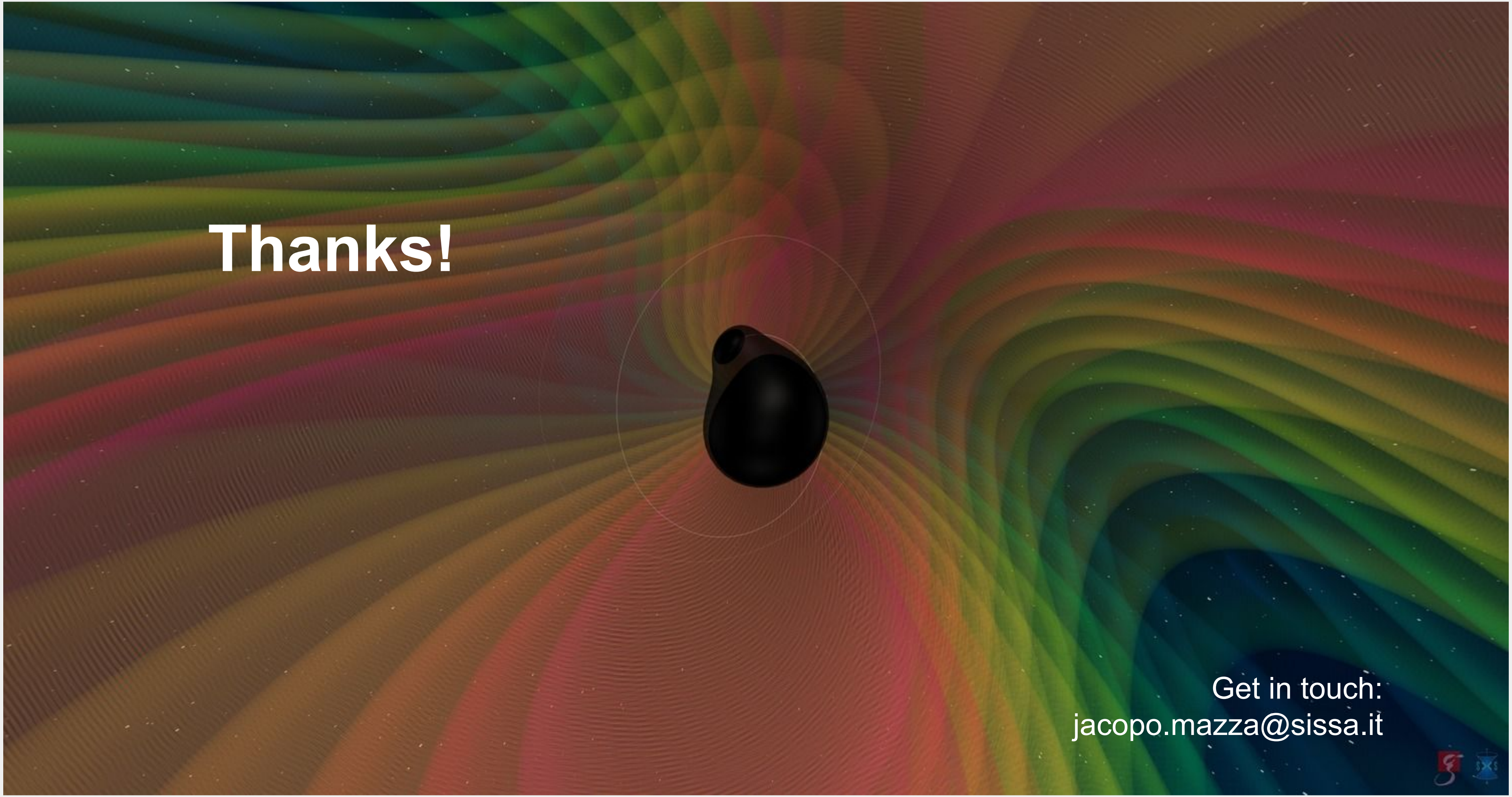
- BHs *and* horizonless objects
- metric+æther simple
  - horizons' features (location, surface gravity, etc.) are tunable



Several open questions:

- Do RBHs really exist in Hořava?
- Are UHs stable?
  - mass inflation?
- How much of familiar BH physics translate to LIV gravity?
  - thermodynamics?
  - rotation, dynamics?

Thanks!



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N. Fischer, H. Pfeiffer, A. Buonanno (Max Planck Institute for Gravitational Physics), Simulating eXtreme Spacetimes (SXS) Collaboration.

BckUp: T-theory

$$S = -\frac{1}{16\pi G}\int \mathrm{d}^4x\sqrt{-g}\left[R + \lambda(\nabla_\mu u^\mu)^2 + \beta\nabla_\mu u^\nu \nabla_\nu u_\mu + \alpha a_\mu a^\mu\right]$$

$$a^\mu = u^\nu \nabla_\nu u^\mu$$

Constraints

$$|\beta| \leq 10^{-15}$$

either

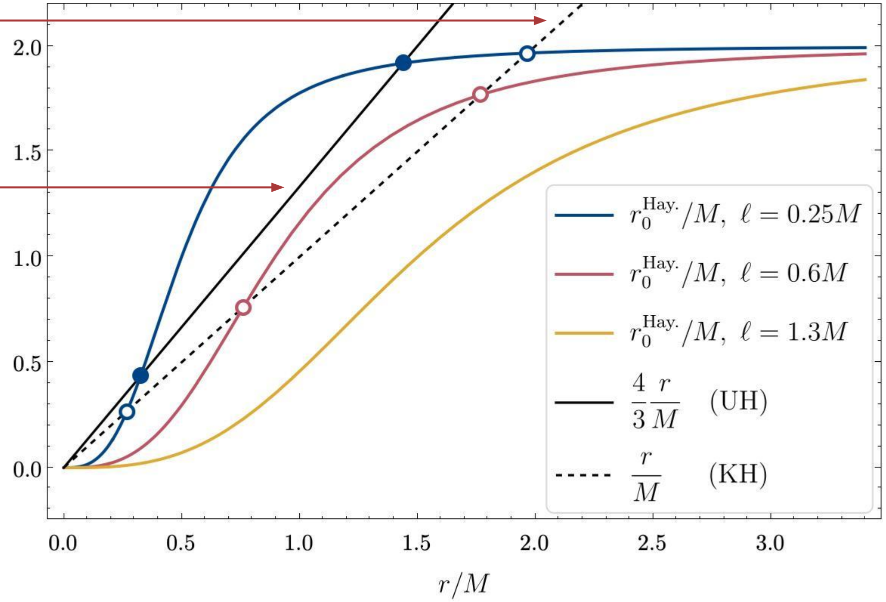
$$\begin{cases} |\alpha| \leq 10^{-7} & \lambda \text{ unconstrained} \\ |\alpha| \leq 0.25\times 10^{-4} & \lambda \approx \alpha/(1-2\alpha) \end{cases}$$

BckUp: Hayward

A common choice: Hayward $m(r) = M\frac{r^3}{r^3+2M\ell^2}$

intersections: KHs

intersections UHs



shape of $m(r)$ changes with ℓ so do horizons

horizons come in pairs (outer/inner)

UHs always in trapped region

BckUp: SV

Simpson-Visser regularisation
a.k.a. black bounce

$$r \mapsto \sqrt{r^2 + \ell^2}$$

$$ds^2 = -\left(1 - \frac{2M}{\sqrt{r^2+\ell^2}}\right) \mathrm{d}t^2 + \frac{\mathrm{d}r^2}{1-\frac{2M}{\sqrt{r^2+\ell^2}}} + \left(r^2 + \ell^2\right) \mathrm{d}\Omega^2$$

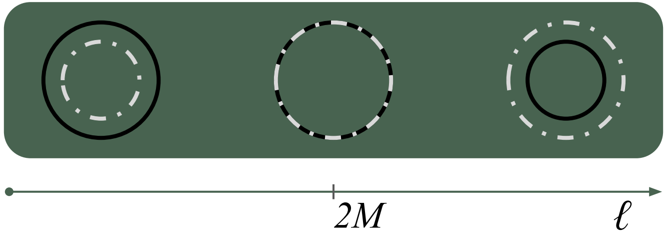
reflection symmetry
$r \to -r$

$r = 0$ sphere of area
$4\pi\ell^2$

$r \in (-\infty, +\infty)$

two identical “universes”, glued at $r = 0$

horizon(s): Y/N depending on ℓ



BkcUp: Effective Sources

$$G_{\mu\nu} - T^{\text{ae}}_{\mu\nu} = T^{\text{eff}}_{\mu\nu} \neq 0$$

measure in preferred frame

$$(c_a = c_\sigma = 0)$$

SC

$$\rho_G^{(u)} = -p_G^{(s)} = \frac{12M^2\ell^2}{(r^3+12M\ell^2)^2}\,, \qquad \rho_\theta^{(u)} = \frac{243M^6\ell^4r^6}{6(r^3+2M\ell^2)^6}\,,$$

$$p_G^{\perp} = -\frac{24M^2\ell^2(M\ell^2-r^3)}{(r^3+2M\ell^2)^3}\,, \qquad p_\theta^{(s)} = p_\theta^{\perp} = \frac{243M^5\ell^2r^6(r^3-2M\ell^2)}{6(r^3+2M\ell^2)^6}\,,$$

MC

$$\rho_G^{(u)} = -\frac{\ell^2}{8\varrho^8}(8\varrho^4 - 32\varrho^3M + 27M^4)\,, \qquad \rho_\theta^{(u)} = 0\,,$$

$$p_G^{(s)} = -\frac{\ell^2}{8\varrho^8}(8\varrho^4 + 27M^4)\,, \qquad p_\theta^{(s)} = 0\,,$$

$$p_G^{\perp} = \frac{\ell^2(\varrho - M)}{\varrho^5}\,, \qquad p_\theta^{\perp} = 0\,,$$

$$(\varrho = \sqrt{r^2+\ell^2})$$

at infinity

SC: $\mathcal{O}\left(r^{-6}\right)$

$\left[\mathcal{O}\left(r^{-4}\right)\ \text{with}\ c_a\right]$

MC: $\mathcal{O}\left(r^{-4}\right)$