The Abdus Salam International Centre for Theoretical Physics

United Nations Educational, Scientific and Cultural Organization

IAEA International Atomic Energy Agency

2264-6

Workshop on Infrared Modifications of Gravity

26 - 30 September 2011

On the existence of black holes in Horava gravity

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Are there black holes in Hořava gravity?

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with Sergey Sibiryakov, arXiv:1109.xxxx

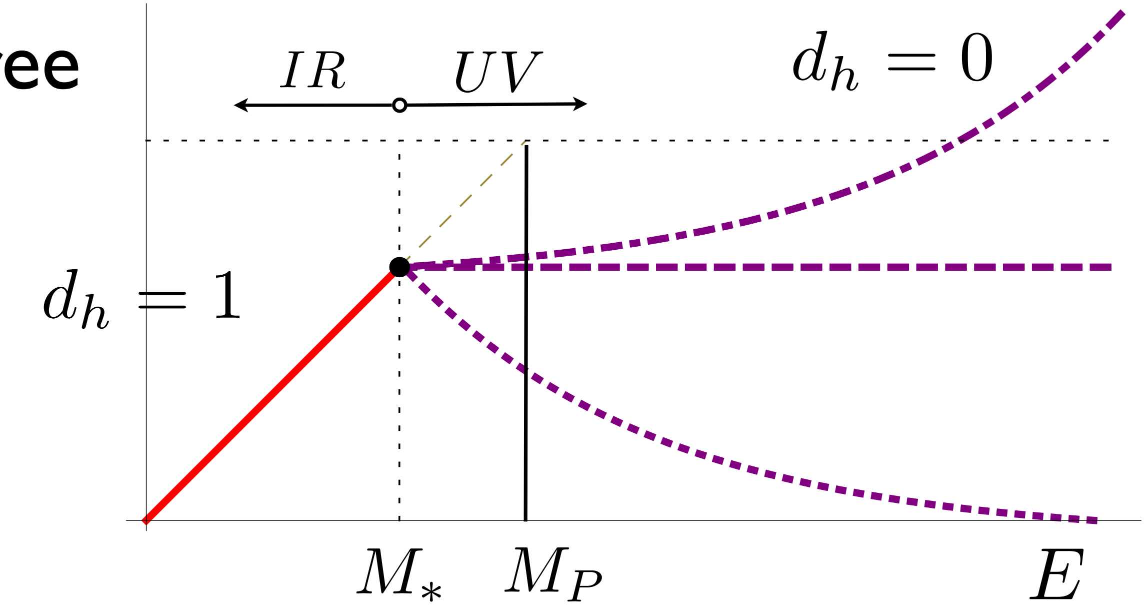
Outline

- Glimpse of Hořava gravity: low energy (khronon)
- Black holes: solution in the decoupled limit
- Universal horizon vs. instantaneous interaction
- No-hair and instabilities: no real BH
- Conclusions and Outlook

Hořava Gravity

UV completion
never leaving perturbative
QFT (always weak)

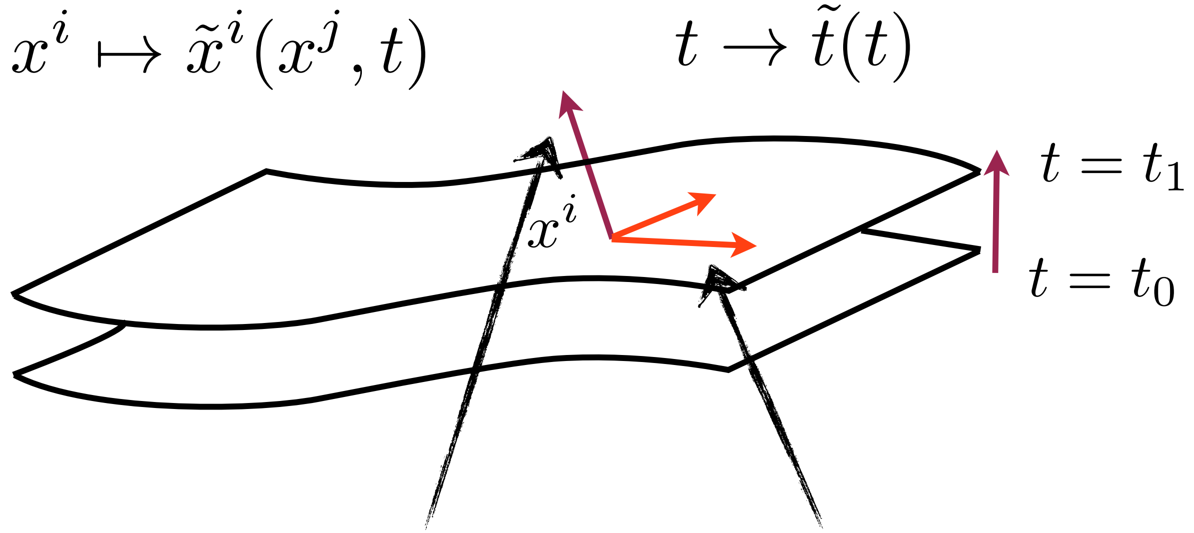
interaction/free



Hořava Gravity

- Breaking Lorentz invariance: Broken Diffeom.

New invariance: foliation preserving Diffeom.



Absolute **time** and **space** intervals

$$ds^2 = g_{\mu\nu}dx^\mu dx^\nu = N^2 dt^2 - \gamma_{ij}(dx^i + N^i dt)(dx^j + N^j dt)$$

Hořava Gravity

$$ds^2 = g_{\mu\nu}dx^\mu dx^\nu = N^2 dt^2 - \gamma_{ij}(dx^i + N^i dt)(dx^j + N^j dt)$$

$$K_{ij} \sim \frac{\partial \gamma_{ij}}{\partial t} \sim \omega\, \gamma_{ij} \qquad {}^{(3)}R^i{}_{jkl} \sim k^2 \gamma_{ij} \qquad \frac{\partial N}{\partial x^i} \sim k_i N$$

Healthy extension

$$\mathcal{L} = M_P^2 N \sqrt{\gamma} \Big(\underbrace{K_{ij}K^{ij} - \lambda' (\gamma_{ij}K^{ij})^2}_{\partial_0^2} - \xi' \, {}^{(3)}R - \alpha' (\partial_i \log(N))^2 +$$

Low energy

High energy (Renormalizable)

$$d_h = 0 \qquad \cdots + \frac{\Delta^{2\,(3)}R}{M_\star^4} \Big)$$

GR: $\lambda' = \xi' = 1, \quad \alpha' = 0$

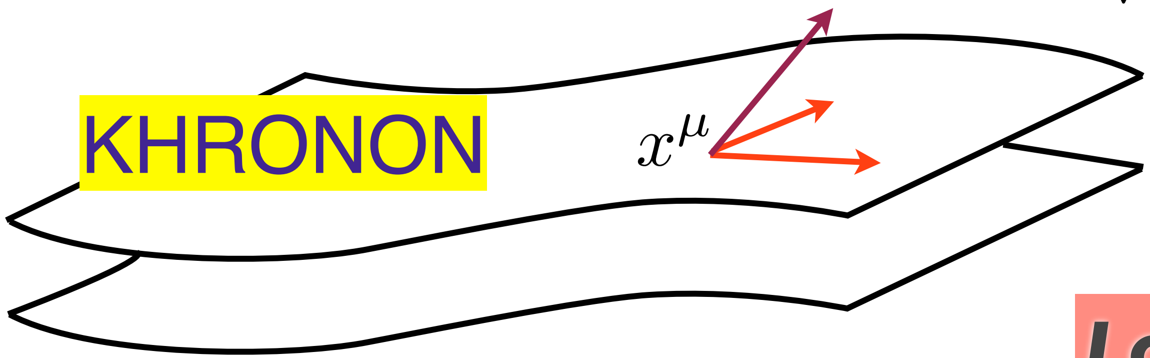
$$\omega^2 - \mathrm{k}^2 - \mathrm{k}^6 / M_*^4$$

Hořava Gravity: Covariant Form

- The same physics described by

$$\varphi \mapsto f(\varphi)$$

$$\bar{t} = (1,0,0,0) = \partial_\mu t \longleftrightarrow u_\mu \equiv \frac{\partial_\mu \varphi}{\sqrt{\partial_\alpha \varphi \partial^\alpha \varphi}}$$



$$\varphi = \varphi_1$$

$$\varphi = \varphi_0$$

Low energy

$$\mathcal{L} \underset{E < M_\star}{=} \mathcal{L}_{EH} + \sqrt{-g}\left(\lambda(\nabla^\mu u_\mu)^2 + \alpha\,(u^\nu \nabla_\nu u_\mu)^2 + \beta\,\nabla_\mu u_\nu \nabla^\nu u^\mu\right)$$

Scalar-tensor theory similar to Einstein-Aether!

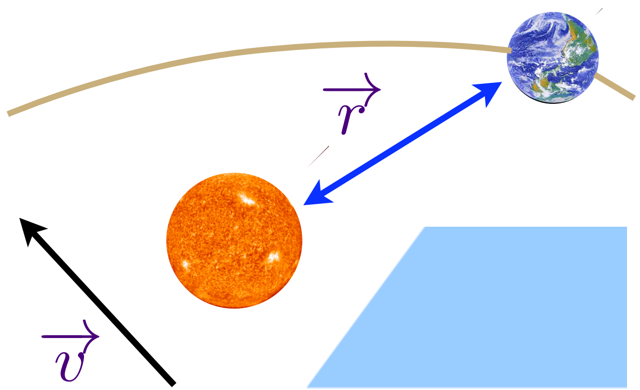
φ $g_{\mu\nu}$

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

Cut-off scale $\Lambda \sim M_P \sqrt{\alpha} > M_* > 10^{10}\ \mathrm{GeV}$

Hořava Gravity: Constraints

Assumption: Matter universally coupled to $g_{\mu\nu}$
(no L-violation, WEP-violation in matter sector)



$$h_{00} = -G_N \frac{M_\odot}{r}\left(1 - \frac{\alpha_2^{PPN}}{2}\frac{(x^i v^i)^2}{r^2}\right)$$

$$h_{0i} = \frac{\alpha_1^{PPN}}{2} G_N \frac{M_\odot}{r} v^i$$

Preferred frame effects $\vec{v} \sim 10^{-2}$

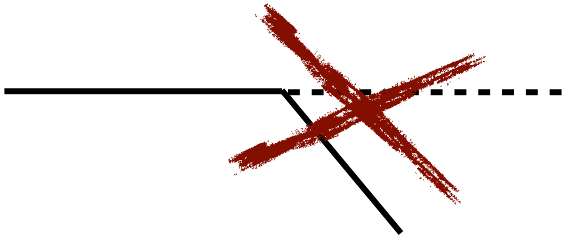
$$\alpha_1^{PPN} = -4(\alpha - 2\beta) \quad \sim 10^{-4}$$

$$\alpha_2^{PPN} = \frac{(\alpha - 2\beta)(\alpha - (\lambda - 1) + 3\beta)}{2(\lambda - 1 - \beta)} \quad \sim 10^{-7}$$

$\alpha = 2\beta$ Identical to GR at PN!

Hořava Gravity: Constraints II

No Gravitational Cerenkov: $c_t^2 > 1,\ c_s^2 > 1$



No ghosts or tachyons $0 < \alpha < 2$

Homogeneous cosmology $G_N/G_c = 1 + O(\alpha)$

BBN $G_N/G_c = 1 + O(10^{-2})$

Detour Adding a dilaton:
naturally small cosmological dark energy!!
Interesting phenom. as compared with ΛCDM

arXiv:1104.3579, JCAP

Hořava Gravity: GWs

Radiation damping in binaries

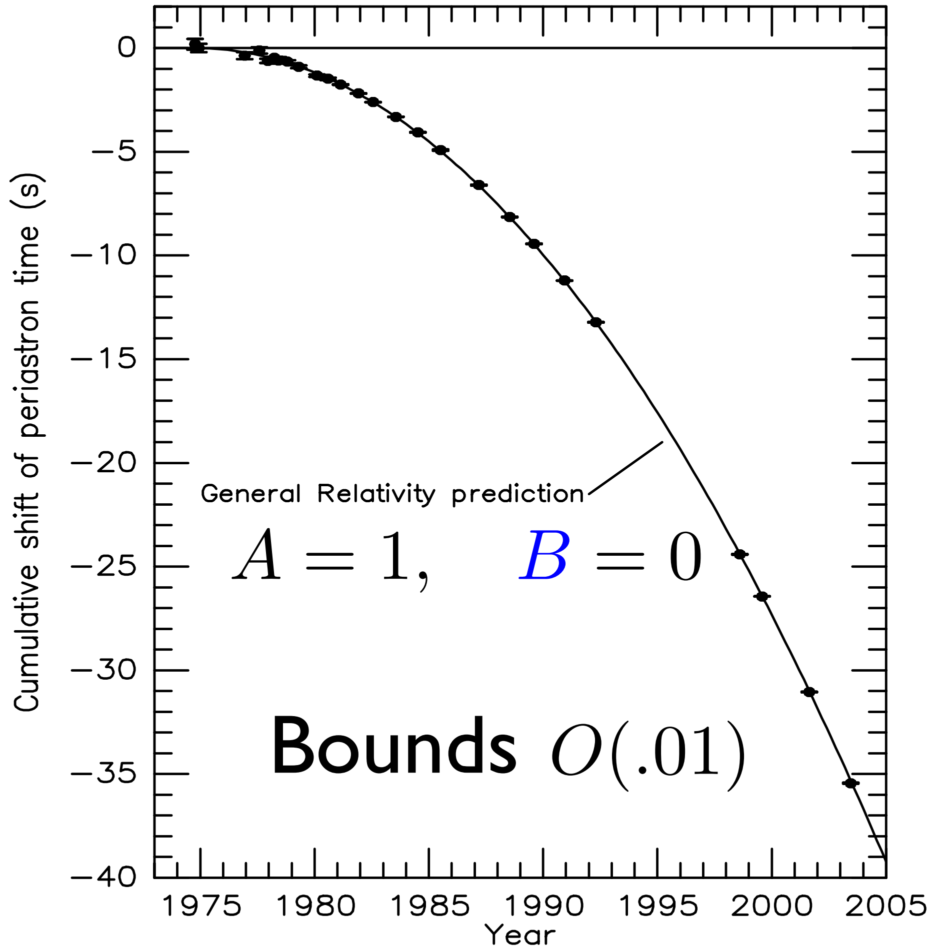
gravitational waves

$$\dot{E} = -G_N \left\langle \frac{A}{5} (\dddot{I}_{ij})^2 + B (\dddot{I}_{kk})^2 \right\rangle$$

$$I_{ij} = \int \mathrm{d}^4 x \, \rho \left(x^i x^j - \frac{1}{3} \delta_{ij} x^k x^k \right)$$

Quadrupole: $A = 1 + O(\alpha)$

Monopole: $B = O(\alpha)$



Hořava Gravity

Interesting and motivated theory of modified gravity
(in the IR and UV)

Healthy extension:
passes all **consistency** and **phenomenological** tests and provides interesting cosmological scenarios beyond GR
(even with natural DE)

Black holes

Motivations

Low energy

- Exploring strong fields regime
- BH thermodynamics

High energy

- Possible avoidance of singularities

Black holes

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Low energy

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Instantaneous propagation

A solution is Minkowski with $\bar{\varphi} = t$

For small perturbations for the khronon $\varphi = t + \chi$

$$S_{source} = \int d^4x \sqrt{-g}\, S^{\mu} u_{\mu}$$

$$c_{\chi} \equiv \frac{\beta + \lambda}{\alpha}$$

$$G_{ij}^{ret}(x) \supset \frac{\theta(t)\theta(|\mathbf{x}| - c_{\chi} t)}{4\pi\alpha} \left(\frac{3\mathbf{x}_i \mathbf{x}_j - \delta_{ij}|\mathbf{x}|^2}{|\mathbf{x}|^5} \right) t$$

Instantaneous propagation along surfaces of constant $\bar{\varphi}$

Are black holes possible at all? **YES!**

One needs to find $\bar{\varphi}$ in realistic backgrounds

Black holes: our approach

Low energy

$$\mathcal{L}_{E<M_\star} = \mathcal{L}_{EH} + \sqrt{-g}\left(\lambda(\nabla^\mu u_\mu)^2 + \alpha(u^\nu \nabla_\nu u_\mu)^2 + \beta \nabla_\mu u_\nu \nabla^\nu u^\mu\right)$$

- Limit $\lambda, \xi, \alpha \ll 1$ ⇒ $T^\varphi_{\mu\nu} \sim 0$
- Static, spherically symmetric

⇓

φ field equation in Schwarzschild $g_{\mu\nu}$

Note Also solutions for Einstein-aether! $u_\mu \equiv \dfrac{\partial_\mu \varphi}{\sqrt{\partial_\alpha \varphi \partial^\alpha \varphi}}$

Black holes: finding solutions

- Single ODE for u_t: new variable $\xi \equiv \frac{r_s}{r}$

$$u_t'' + \frac{c_\chi^2 u_t}{u_t^2(1-c_\chi^2) - 1 + \xi} F(u_t, u_t')$$

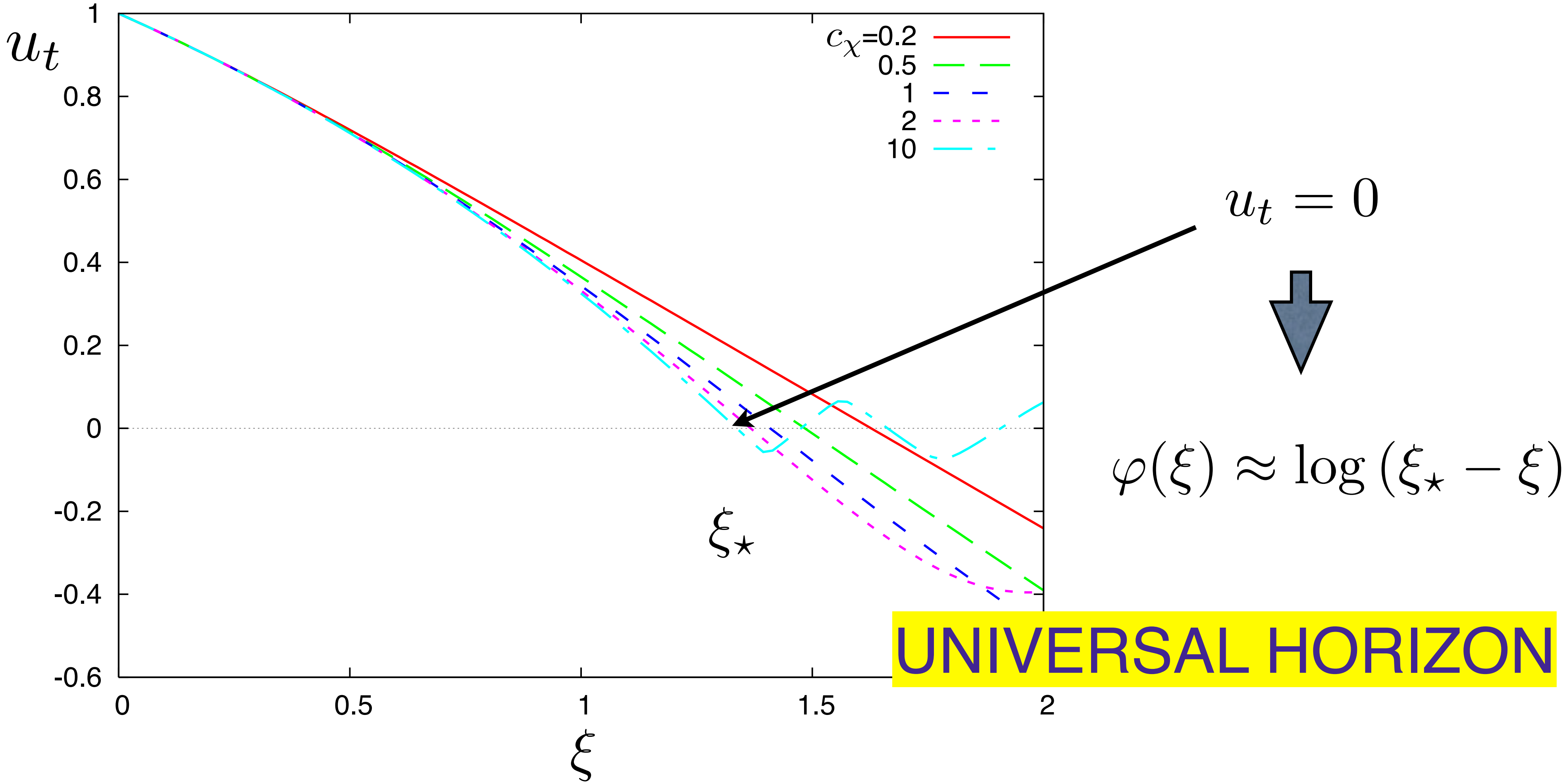
- Sound horizon ξ_c: $u_t^2(1-c_\chi^2) - 1 + \xi_c = 0$

- Boundary conditions:

$$u_t(\xi = 0) = 1$$

$$F(u_t, u_t')\big|_{\xi=\xi_c} = 0$$

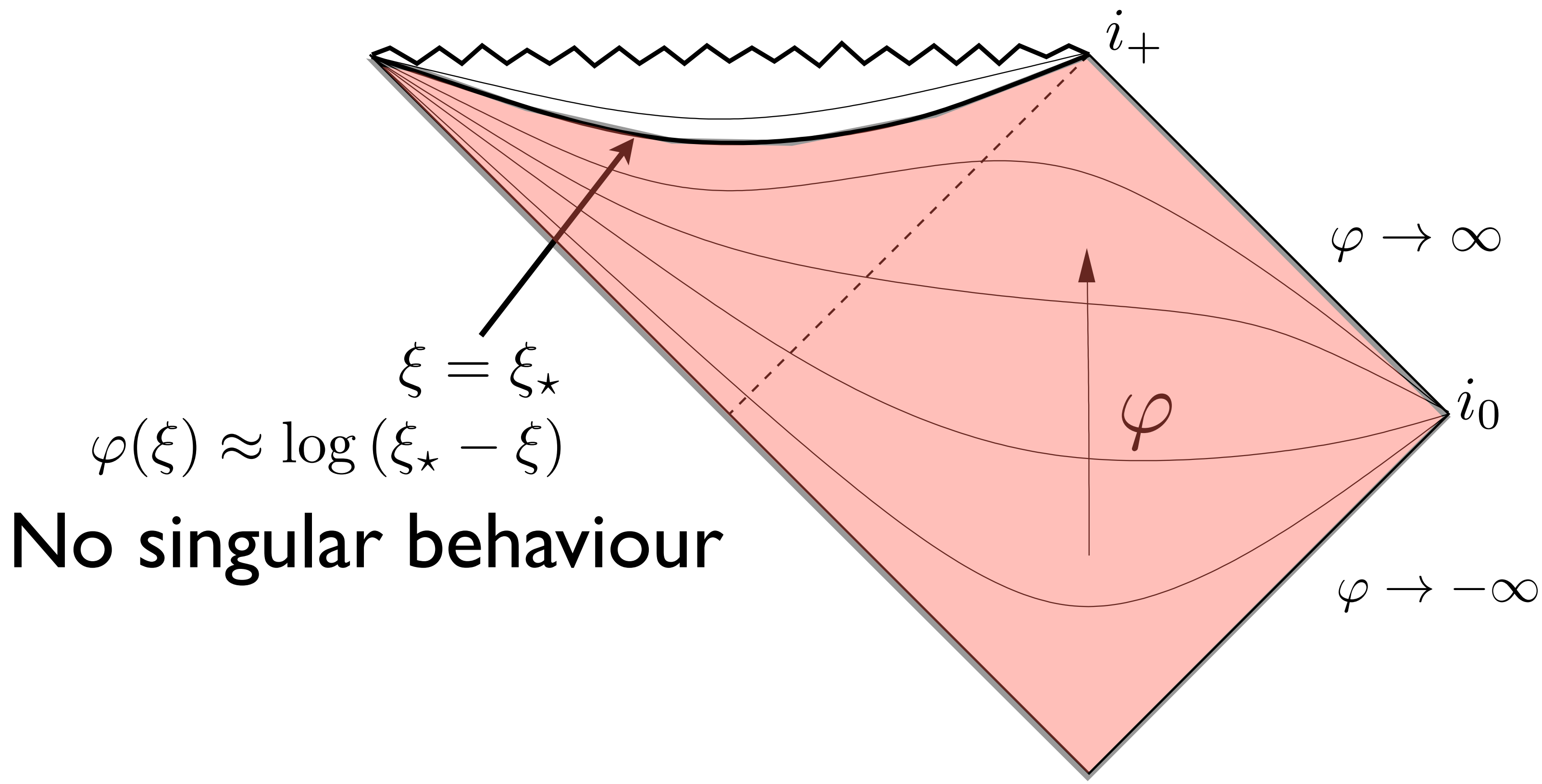
Black holes: finding solutions



Agreement with Barausse, Jacobson, Sotiriou

- In our approach: existence of $\xi_\star$ can be shown analytically

Universal horizon



- Similar to Cauchy horizon: two regions for b.c.
- Even the instantaneous interactions present horizons!
  Problems of information still present!

Absence of hair

- Perturbations around the background

$$\varphi = \bar{\varphi} + \chi$$

- Static case:

Imposing regularity at i_0, the **sound** horizon and **universal** horizon

$$\chi(\xi) = 0$$

NO HAIR!

Method:

i) Counting b.c. versus free parameters

ii) Solving for large angular momentum

Instabilities

- Time dependent perturbations (large l)
  - Stable ingoing and outgoing waves in Schwarzschild

$$\chi(t,\xi)_l{}^{\pm} \sim e^{i(\omega \pm \sqrt{l(l+1)/\xi})}$$

  - Instantaneous mode (absent in Einstein-aether)

$$\chi(t,\xi)_l \propto |\xi - \xi_\star|^{\gamma_+} f(t)$$

← Source

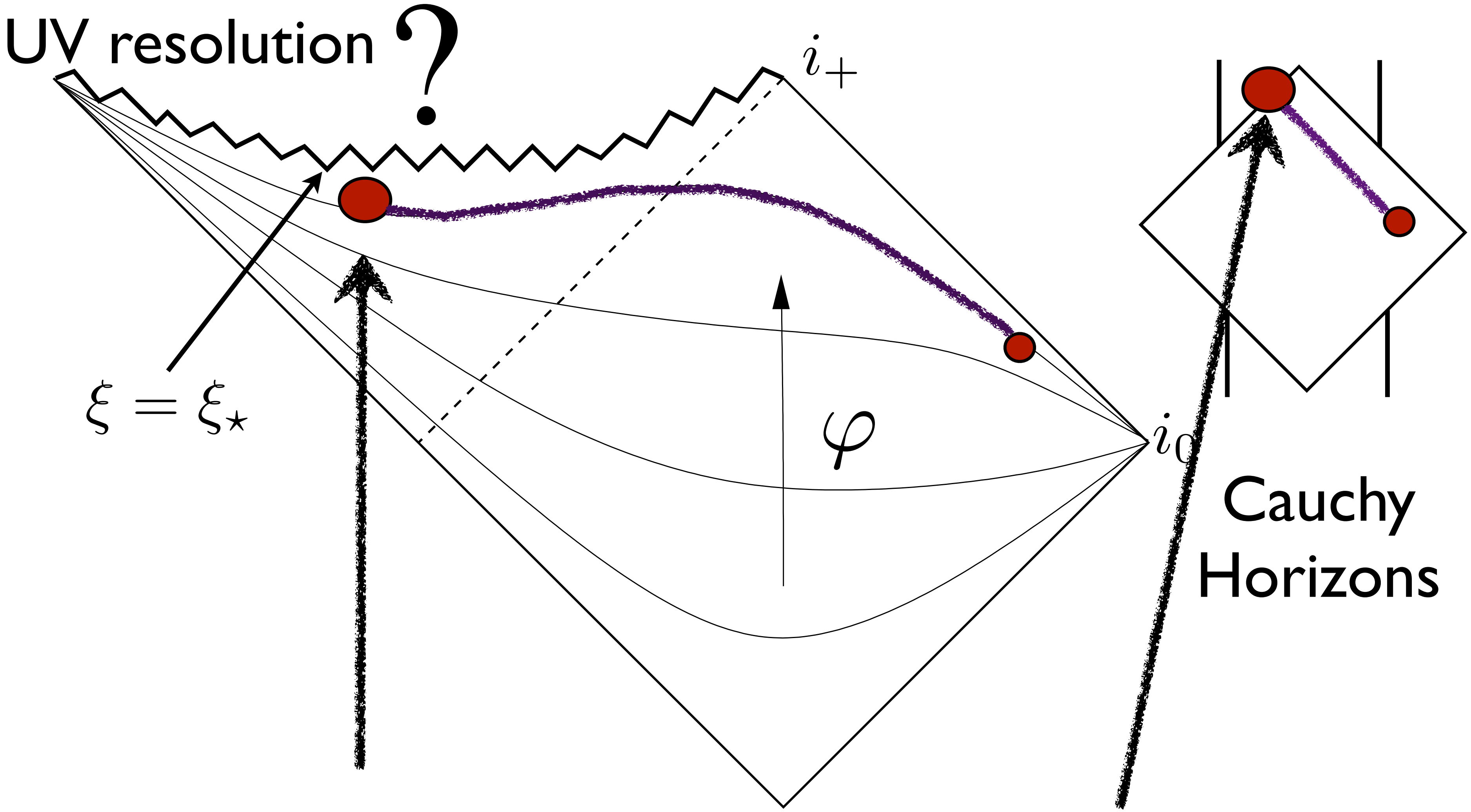
Non-analytic power!

$$\gamma_+ = -\frac{1}{2} + \sqrt{\frac{1}{4} + \frac{l(l+1)}{\xi_\star^2 {U'_\star}^2}}$$

$(u^\mu \partial_\mu)^l \chi$ diverges at $\xi_\star$ for big enough l

Enters in the non-linear e.o.m.: **physical singularity**

Real causal structure



Physically: perturbations pile up creating a huge backreaction (singularity of the low-energy)

Conclusions

- Low-energy Hořava gravity has **NO** physical black holes:

  Solutions with **universal horizon** are unstable

  (not for Einstein-aether!)

  The instantaneous modes can probe the whole geometry

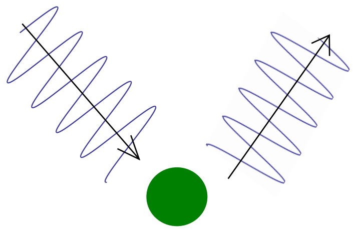
- We expect this to be **generic** (as for Cauchy horizons in GR)
- The physical solution has a geometry very different from GR inside (but close to) the Schwarzschild radius.

OUTLOOK

* Thermodynamics. Are these modes enough? How is Hawking radiation modified in this picture?

No Singularities?

NO MINIMAL LENGTH (?)



$$\Delta x_H \sim \hbar / \Delta p$$

$$\Delta x_G \sim \Delta a\, t^2 \sim \partial_r \phi\, t^2 \sim G_N \Delta p \left(\frac{M_*}{\Delta p}\right)^6$$

$$\Delta x > \min(\Delta x_H, \Delta x_G)$$

- l_P for GR
- No limit for Hořava

CHANDRASEKHAR LIMIT (?)

$$E_K \sim n\, r^3 \frac{p^3}{M_*^2} \sim \frac{\hbar^3\, n^2 r^3}{M_*^2} \sim \frac{\hbar^3\, M^2}{m^2 r^3 M_*^2}$$

$$p \sim \hbar\, n^{1/3}$$

$$E_V \lesssim -G_N \frac{M^2}{r}$$

Collapse stops at

$$r \sim \frac{\hbar^{3/2}}{m M_* G_N^{1/2}}$$