Strong gravity and fundamental physics: the 4 challenges

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Lovelock and GR

$$S = \int d^4x \sqrt{-g}\,(R - 2\Lambda) + S_M(g_{\mu\nu}, \psi)$$

Lovelock's theorem leads to GR under assumptions:

- 4 dimensions
- Diffeomorphism invariance
- No extra fields
- Locality

Brans-Dicke theory

The action of the theory is

$$S_{\rm BD} = \int d^4x\sqrt{-g}\Big(\varphi R - \frac{\omega_0}{\varphi}\nabla^\mu\varphi\nabla_\mu\varphi - V(\varphi) + L_m(g_{\mu\nu},\psi)\Big)$$

and the corresponding field equations are

$$G_{\mu\nu} = \frac{\omega_0}{\varphi^2}\left(\nabla_\mu\varphi\nabla_\nu\varphi - \frac{1}{2}g_{\mu\nu}\nabla^\lambda\varphi\nabla_\lambda\varphi\right) + \frac{1}{\varphi}\left(\nabla_\mu\nabla_\nu\varphi - g_{\mu\nu}\Box\varphi\right) - \frac{V(\varphi)}{2\varphi}g_{\mu\nu}$$

$$(2\omega_0+3)\Box\varphi = \varphi V' - 2V$$

Solutions with constant φ are admissible and are GR solutions.

Brans-Dicke theory

However, they are not the only ones. E.g. for

$$V = m^2\left(\varphi - \varphi_0\right)^2$$

around static, spherically symmetric stars a nontrivial configuration is necessary and

$$\gamma \equiv \frac{h_{ii}|_{i=j}}{h_{00}} = \frac{2\omega_0 + 3 - exp[-\sqrt{\frac{2\varphi_0}{2\omega_0+3}}mr]}{2\omega_0 + 3 + exp[-\sqrt{\frac{2\varphi_0}{2\omega_0+3}}mr]}$$

So, hiding the scalar requires, either a very large mass (short range) or a very large Brans-Dicke parameter

Scalar-tensor theory

Jordan frame action:

$$S_{\rm st} = \int d^4x\sqrt{-g}\Big(\varphi R - \frac{\omega(\varphi)}{\varphi}\nabla^\mu\varphi\nabla_\mu\varphi - V(\varphi) + L_m(g_{\mu\nu},\psi)\Big)$$

Redefinitions:

$$\hat{g}_{\mu\nu} = \varphi g_{\mu\nu} = A^2(\phi)g_{\mu\nu} \qquad\qquad 4\sqrt{\pi}\varphi d\phi = \sqrt{2\omega(\varphi)+3}\,d\varphi$$

Einstein frame action:

$$S_{\rm st} = \int d^4x\sqrt{-\hat{g}}\Big(\frac{\hat{R}}{16\pi} - \frac{1}{2}\hat{g}^{\nu\mu}\partial_\nu\phi\partial_\mu\phi - U(\phi)\Big) + S_m(g_{\mu\nu},\psi)$$

Spontaneous scalarization

Assume you have a theory without a potential which admits solutions such that

$$\omega(\phi_0) \to \infty$$

- Then the theory will admit GR solutions around matter!
- However they will not necessarily be the only ones...
- The non-GR configuration is preferred for sufficiently large central density

T. Damour and G. Esposito-Farese, Phys. Rev. Lett. 70, 2220 (1993)

Celebrated demonstration that strong field effects can be very important...

Scalars and Neutron stars

- Large ambiguity in the EOS
- Degeneracy with modifications of gravity
- Fundamental Physics "laboratories"

But there is notable progress…

- I-Love-Q and 3-moment relations

K. Yagi and N. Yunes, Science 341, 365-368 (2013)
G. Pappas and T. Apostolatos, Phys. Rev. Lett. 112, 121101 (2014)

- Moments related to observables in scalar-tensor

G. Pappas and T.P.S., Phys. Rev. D 91, 044011 (2015);
Mon. Not. Roy. Astron. Soc. 453, 2862-2876 (2015)

Scalarization and Higgs-like effects

- Usually the scalar is assumed to not couple to matter
- This is sufficient to guarantee the WEP
- It is not necessary though!

One can construct models where the coupling to matter is absent in the unscalarized phase and present in the scalarized phase.

This can change the microphysics in the interior of the star in a Higgs-like fashion!

A. Coates, M. Horbatsch and T.P.S., arXiv:1606.03981 [gr-qc]

Scalar fields in BH spacetimes

The equation

$$\Box\phi = 0$$

admits only the trivial solution in a BH spacetime that is

- stationary, as the endpoint of collapse
- asymptotically flat, i.e. isolated

S.W. Hawking, Comm. Math. Phys. 25, 152 (1972).

The same is true for the equation

$$\Box\phi = U'(\phi)$$

with the additional assumption of local stability

$$U''(\phi_0) > 0$$

T. P. S. and V. Faraoni, Phys. Rev. Lett. 108, 081103 (2012)

No difference from GR?

Actually there is...

- Perturbations are different!

  E. Barausse and T.P.S., Phys. Rev. Lett. 101, 099001 (2008).

- They even lead to new effects, e.g. floating orbits

  V. Cardoso et al., Phys. Rev. Lett. 107, 241101 (2011).

- Cosmic evolution or matter could also lead to scalar "hair"

  T. Jacobson, Phys. Rev. Lett. 83, 2699 (1999);
  M. W. Horbatsch and C. P. Burgess, JCAP 1205, 010 (2012).
  V. Cardoso, I. P. Carucci, P. Pani and T. P. S., Phys. Rev. Lett. 111, 111101 (2013)

- In general, relaxing the symmetries of the scalar can lead to "hairy" solutions.

  C. A. R. Herdeiro and E. Radu, Phys. Rev. Lett. 112, 221101 (2014).

A simple exception

T.P.S. and S.-Y. Zhou, Phys. Rev. Lett. 112, 251102 (2014);
Phys. Rev. D 90, 124063 (2014).

Consider the action

$$S = \frac{m_P^2}{8\pi}\int d^4x\sqrt{-g}\left(\frac{R}{2} - \frac{1}{2}\partial_\mu\phi\partial^\mu\phi + \alpha\phi\mathcal{G}\right)$$

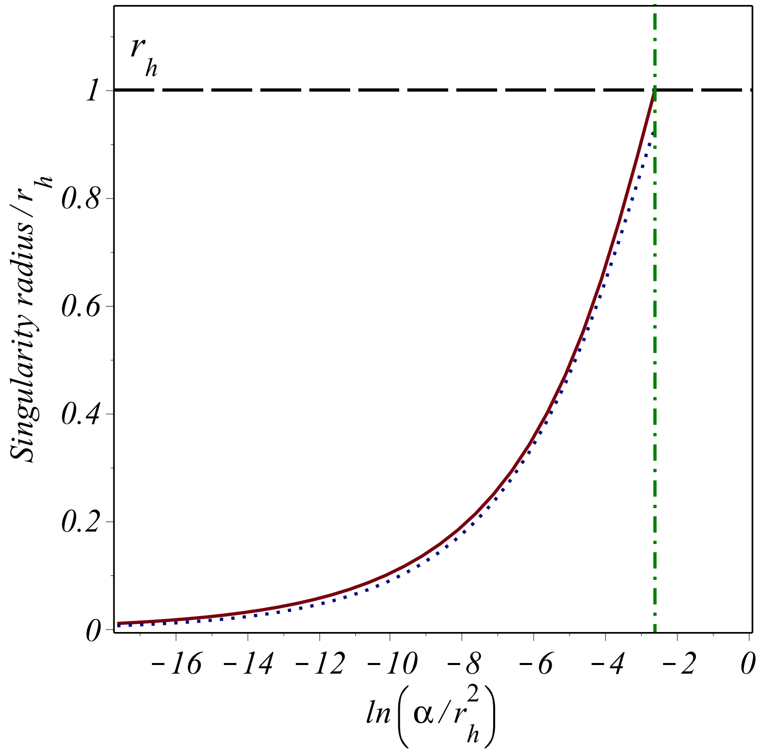
The corresponding scalar equation is

$$\Box\phi + \alpha\mathcal{G} = 0$$

The Gauss-Bonnet term does not vanish in BH spacetimes!

Non-perturbative effects

- The finite area singularity is not present in the perturbative solution



- Black holes have a minimum size!

- Perturbative treatments breaks down at roughly the radius of the naked singularity

GR without SR?

General Relativity taught us that:

- general covariance
- dynamical metric describes the gravitational field
- universality of free fall
- Local flatness

Local Lorentz symmetry
& minimal coupling

Field theories taught us that:

- Symmetries can be broken!

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

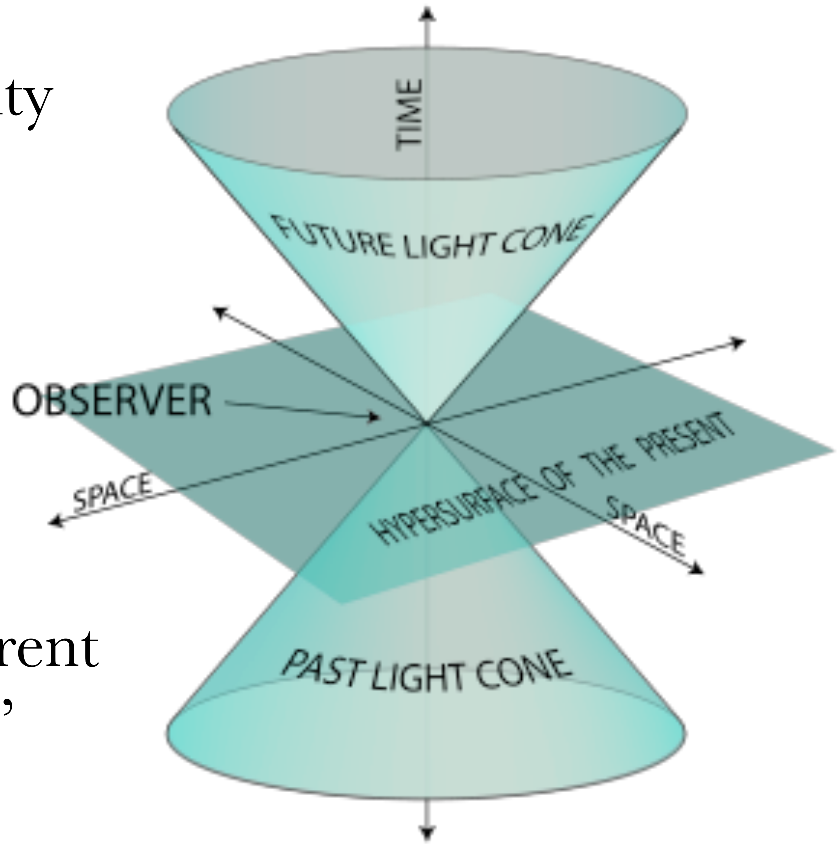
$$u^\mu u_\mu = 1$$

- 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).

LV and light cones

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!

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).

Causal structure

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

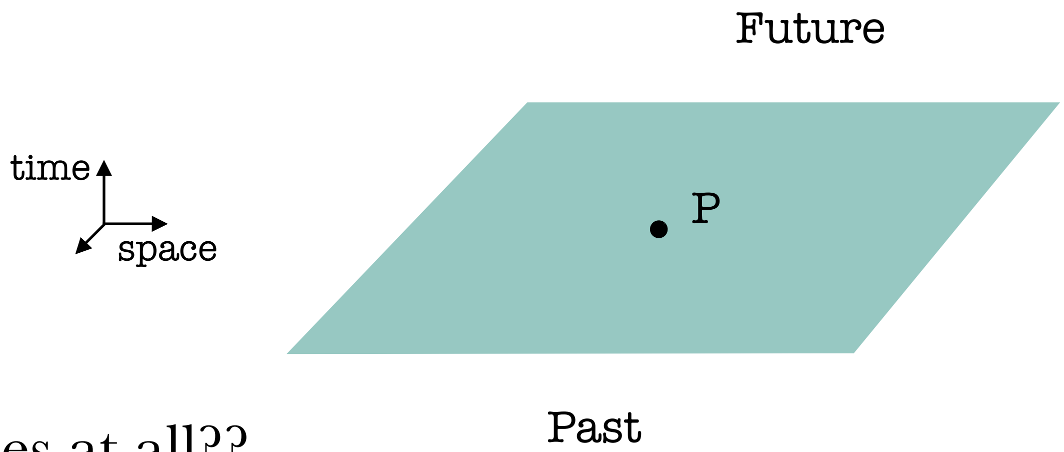
One can make the ansatz

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

and then the "T-equation" takes the form

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

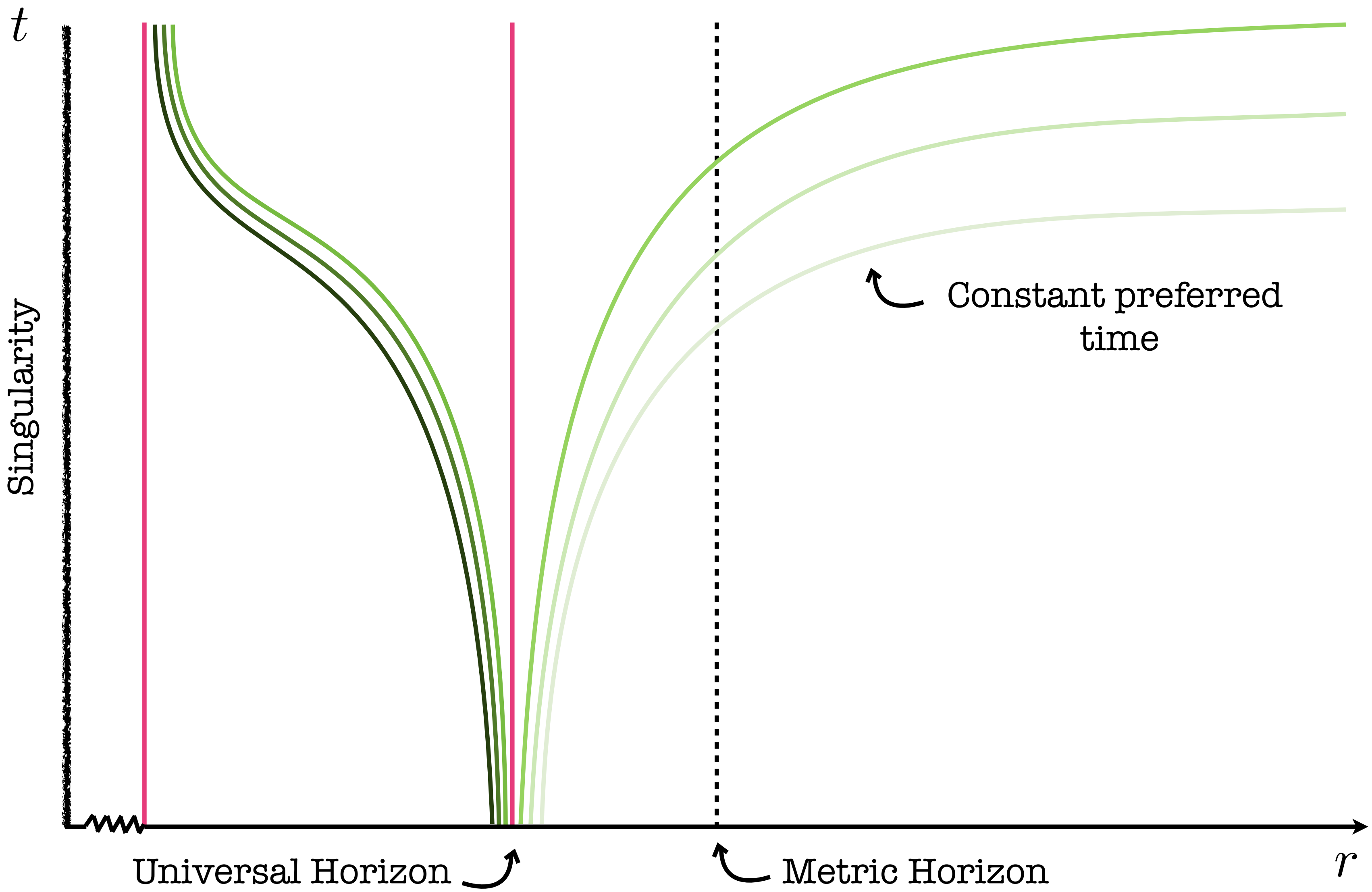
- There is an instantaneous mode!



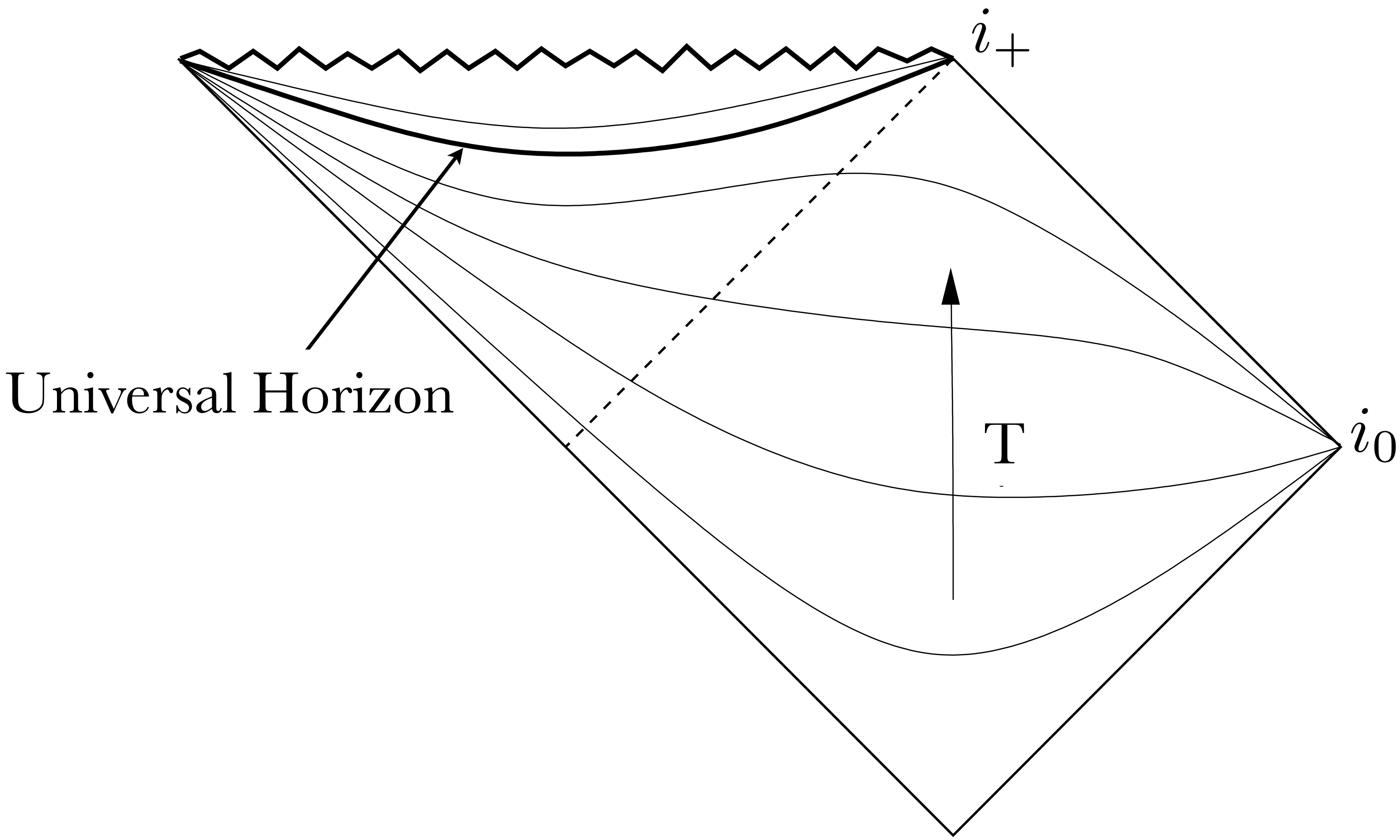
No black holes at all??

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)

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

Perspectives

- Major challenges: screening, NS microstructure and degeneracies, no-hair theorems all lead to more elaborate models
- New degrees of freedom that are screened on weak-field might couple to matter in the strong field!
- If this is true we are grossly underestimating our ignorance regarding the microphysics on neutron stars.
- Lorentz symmetry might be a symmetry of the standard model but not of gravity
- Remarkably black holes survive anyway!
- Perhaps we should be asking why new fields do not couple to matter!