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Causality and black holes in spacetimes with a preferred foliation

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Based on: arXiv:1509.01558 (w/ M. Colombo & T. P. Sotiriou)

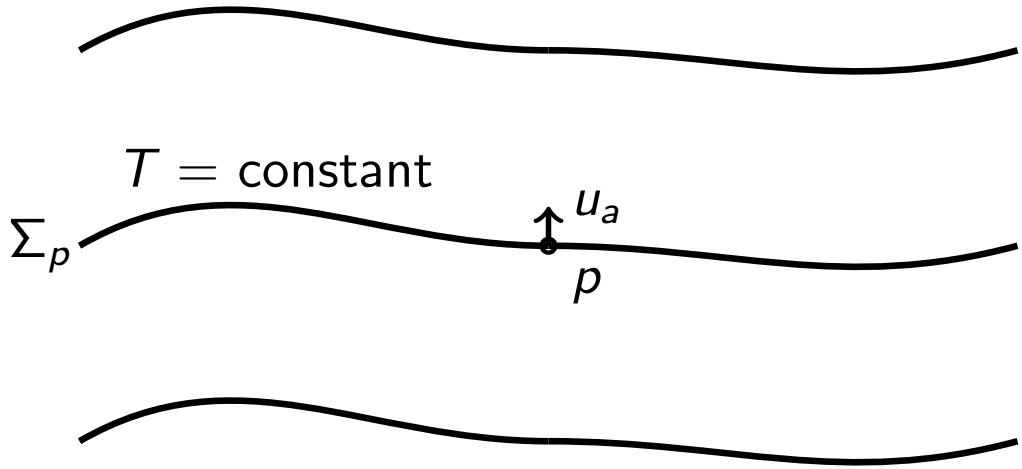
Entertaining LLV theories of gravity

- quantitatively parametrize deviations from local Lorentz invariance in the gravitational sector,
- possibility to construct renormalizable QFT of gravity (*e.g.* Hořava gravity).

Theories with a preferred foliation

Characteristics of theories (*e.g.* Hořava gravity) with a *preferred foliation*:

- solutions admit a *special* foliation Σ (*e.g.* a scalar field T has timelike gradient everywhere)

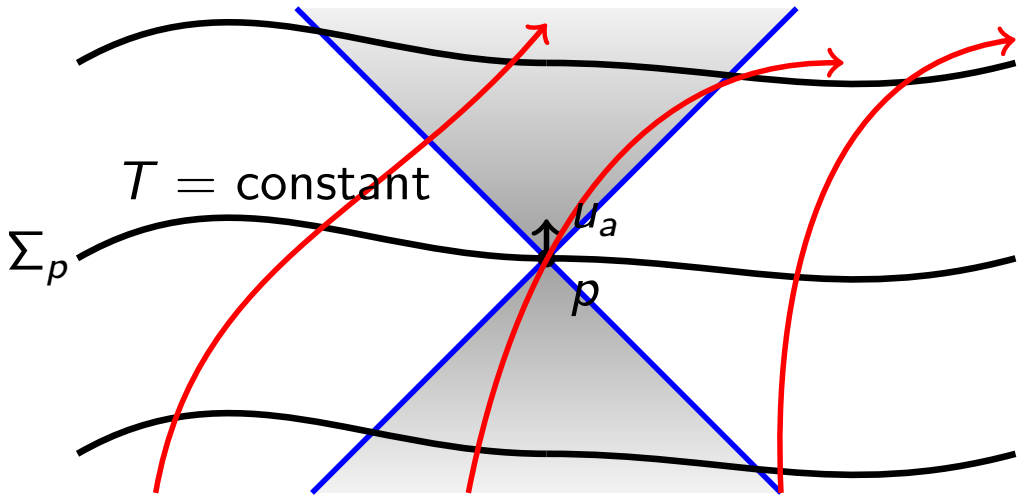


$$u_a \propto -\nabla_a T, \qquad g^{ab} u_a u_b = -1\,.$$

Theories with a preferred foliation

Characteristics of theories (*e.g.* Hořava gravity) with a *preferred foliation*:

- equations of motion 2nd order in 'time' *only* w.r.t Σ



- modes have *higher order dispersion relations* w.r.t Σ

$$\omega^2 \propto k^6 \,, \qquad k \to \infty \,.$$

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Theories with a preferred foliation

Characteristics of theories (*e.g.* Hořava gravity) with a *preferred foliation*:

- even at the lowest order (IR), there is an *elliptic* equation which is not preserved under time evolution (*i.e.* $\neq$ constraint) – *instantaneous mode*.

* * * *

Theories with special foliations but *without* the above properties *do not admit a preferred foliation* – *e.g.* hypersurface orthogonal Einstein-æther theory.

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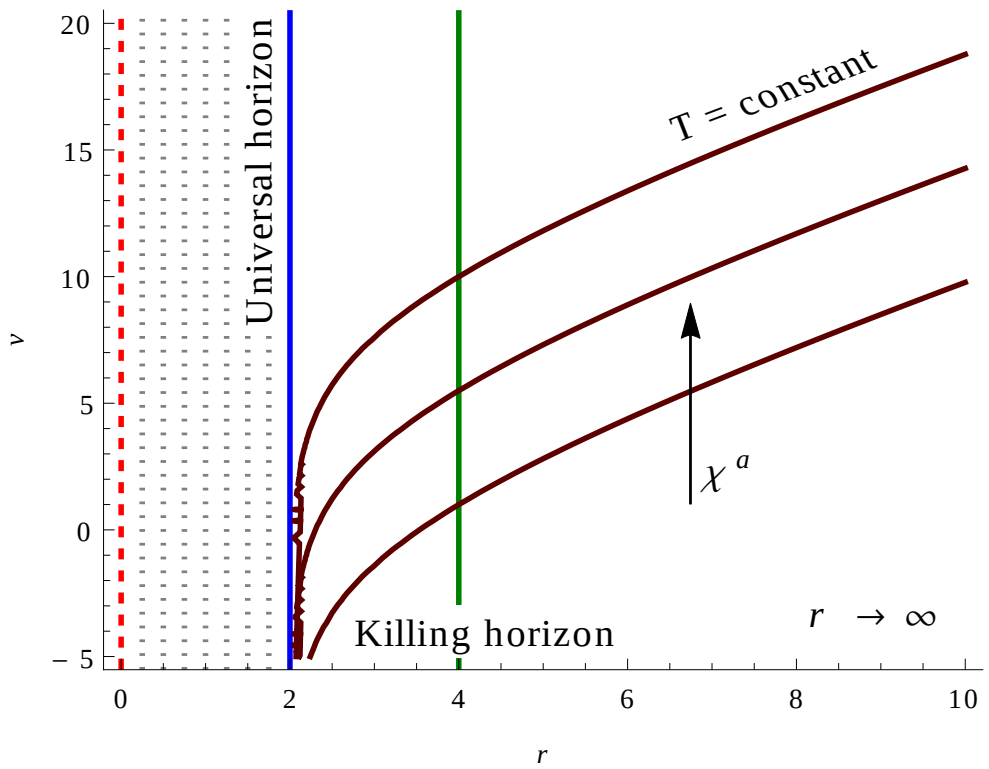
Causal stucture of LLV spacetimes: why?

- ensure no conflict with the basic principles of causality;
- existence of 'out of the lightcone' propagations and 'instantaneous mode' *consistent* with the problem of *well-posed causal development*?
- can black holes exist?

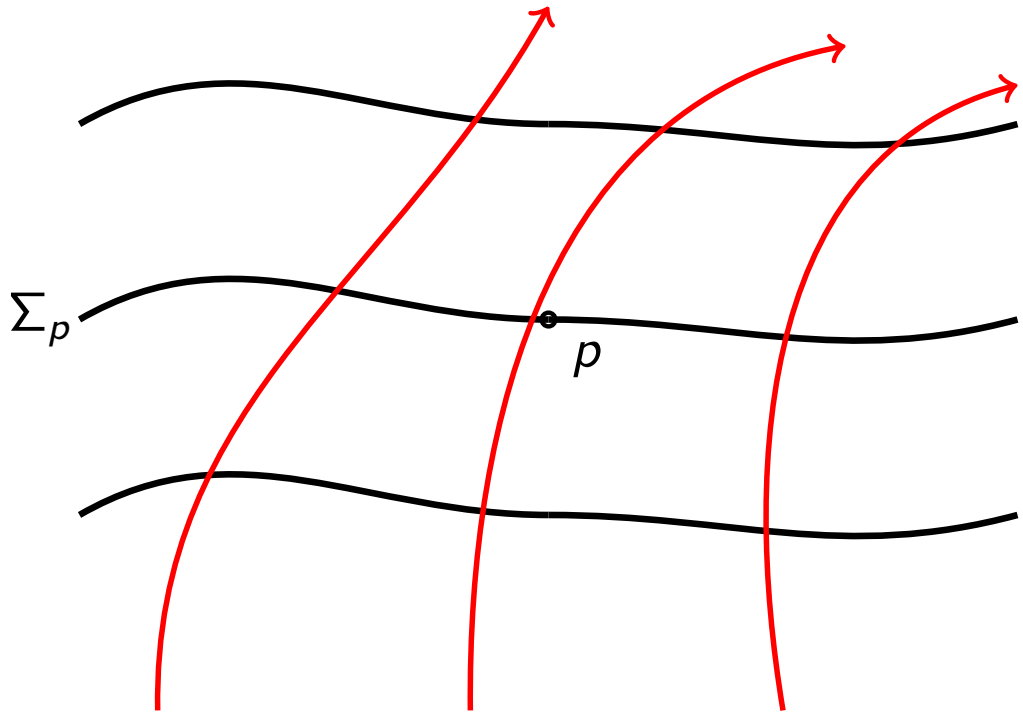
The universal horizon: lots of symmetries



Eling, Jacobson 2006; Barausse, Jacobson, Sotiriou 2011; Blas, Sibiryakov 2011; Barausse, Sotiriou 2013; Sotiriou, Vega, Vernieri 2014; Berglund, JB, Mattingly 2012; JB, Mattingly 2014.

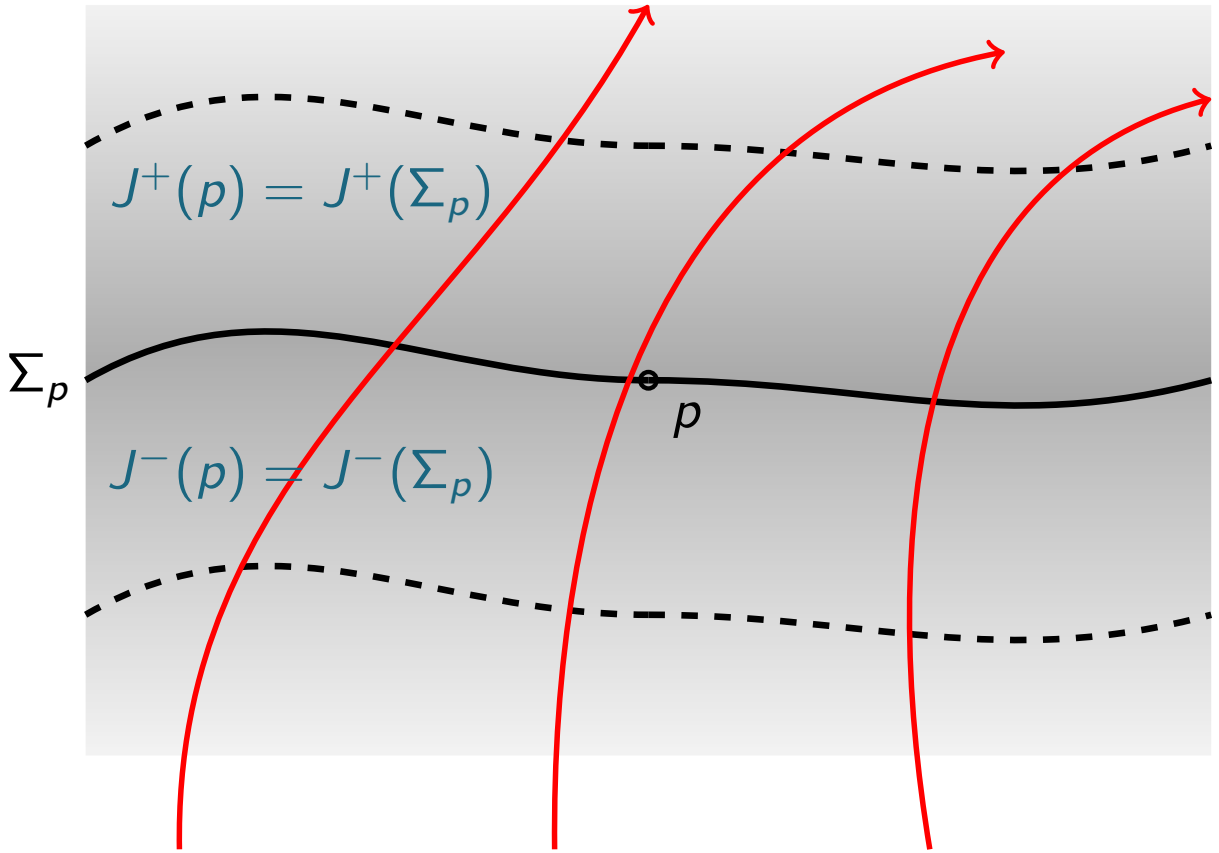
Preferred foliation $\equiv$ preferred simultaneity

- spacetime with a preferred foliation $= (\mathscr{M}, \Sigma, g_{ab})$

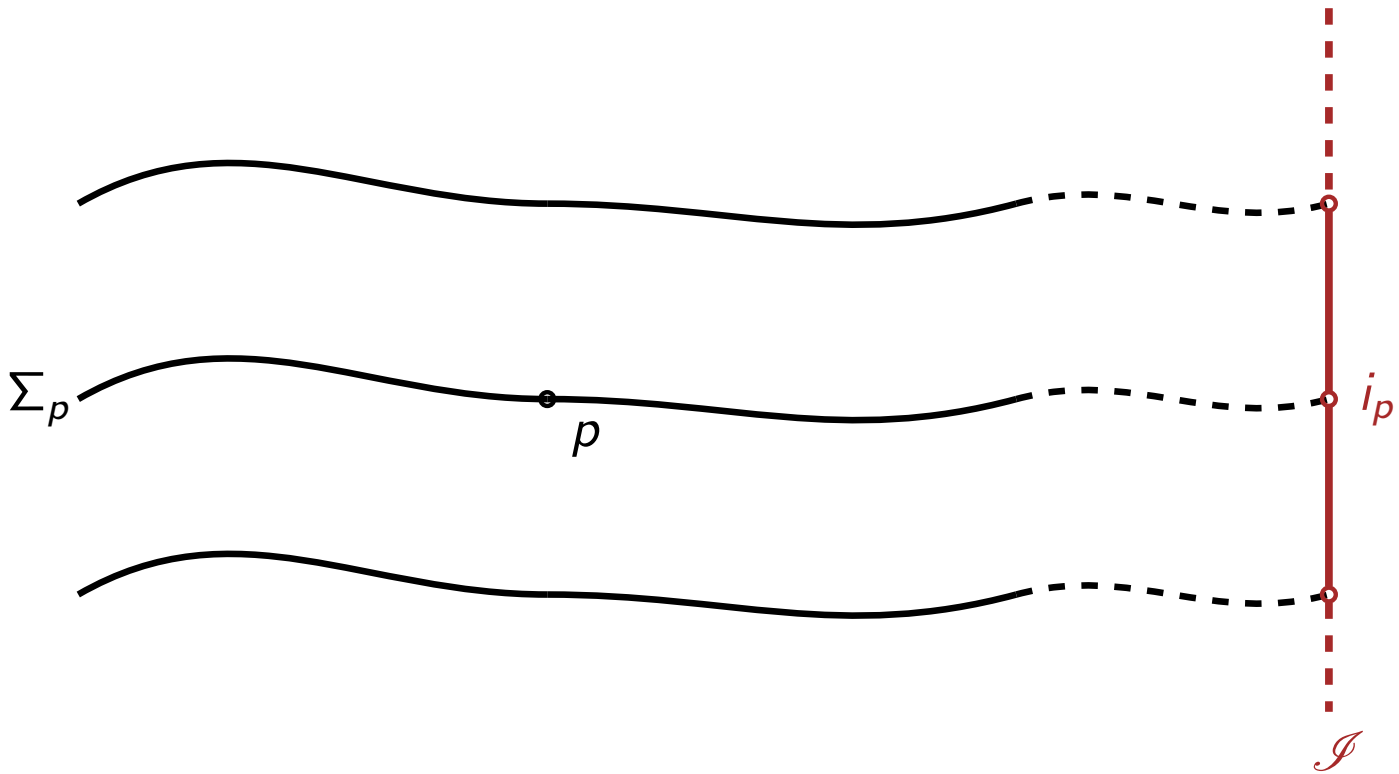


- preferred foliation is *ordered*: (i) $p \leftrightarrow \Sigma_p$, (ii) $p \neq q$ have *unique* causal relationship.

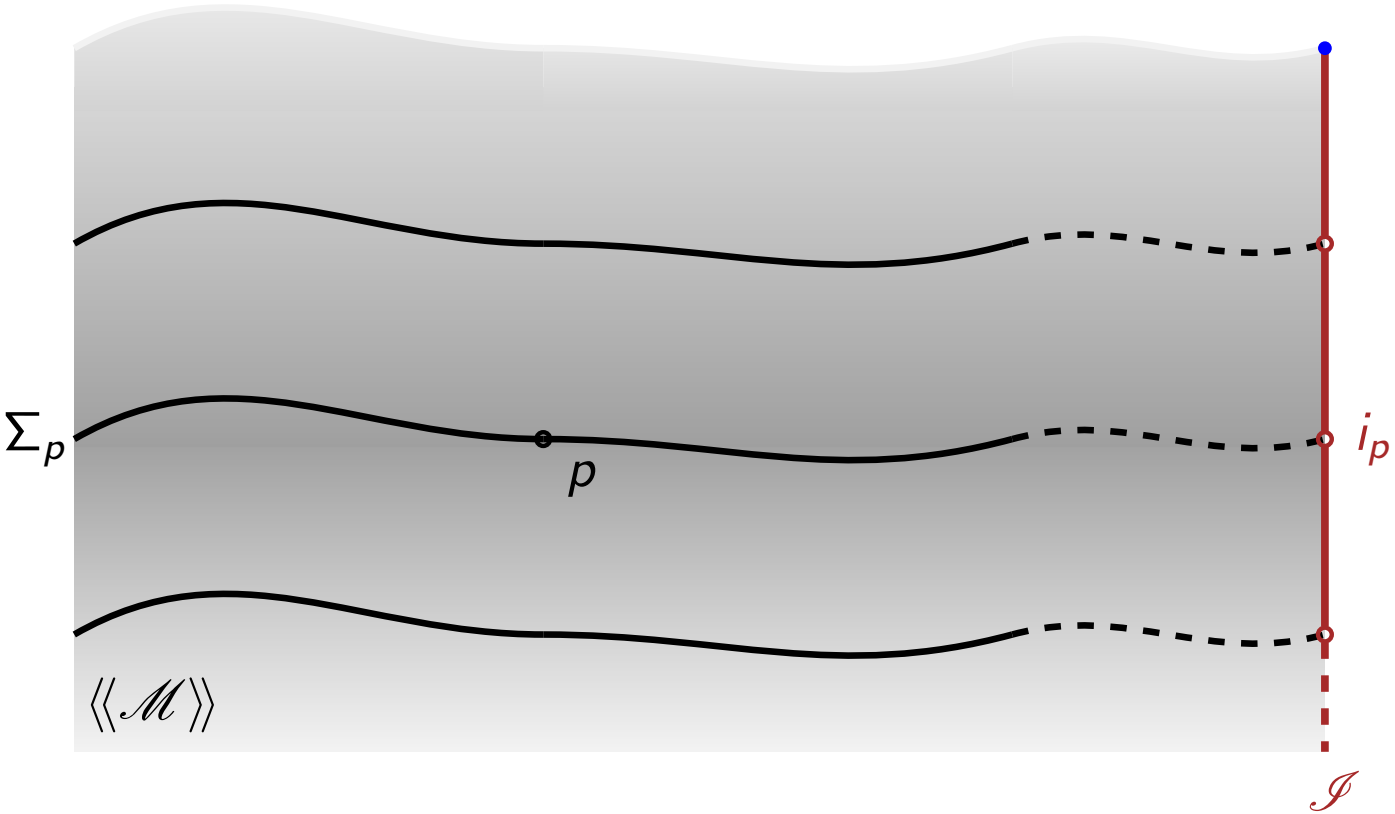
Past and future



Asymptotic boundary: $\mathscr{I}$

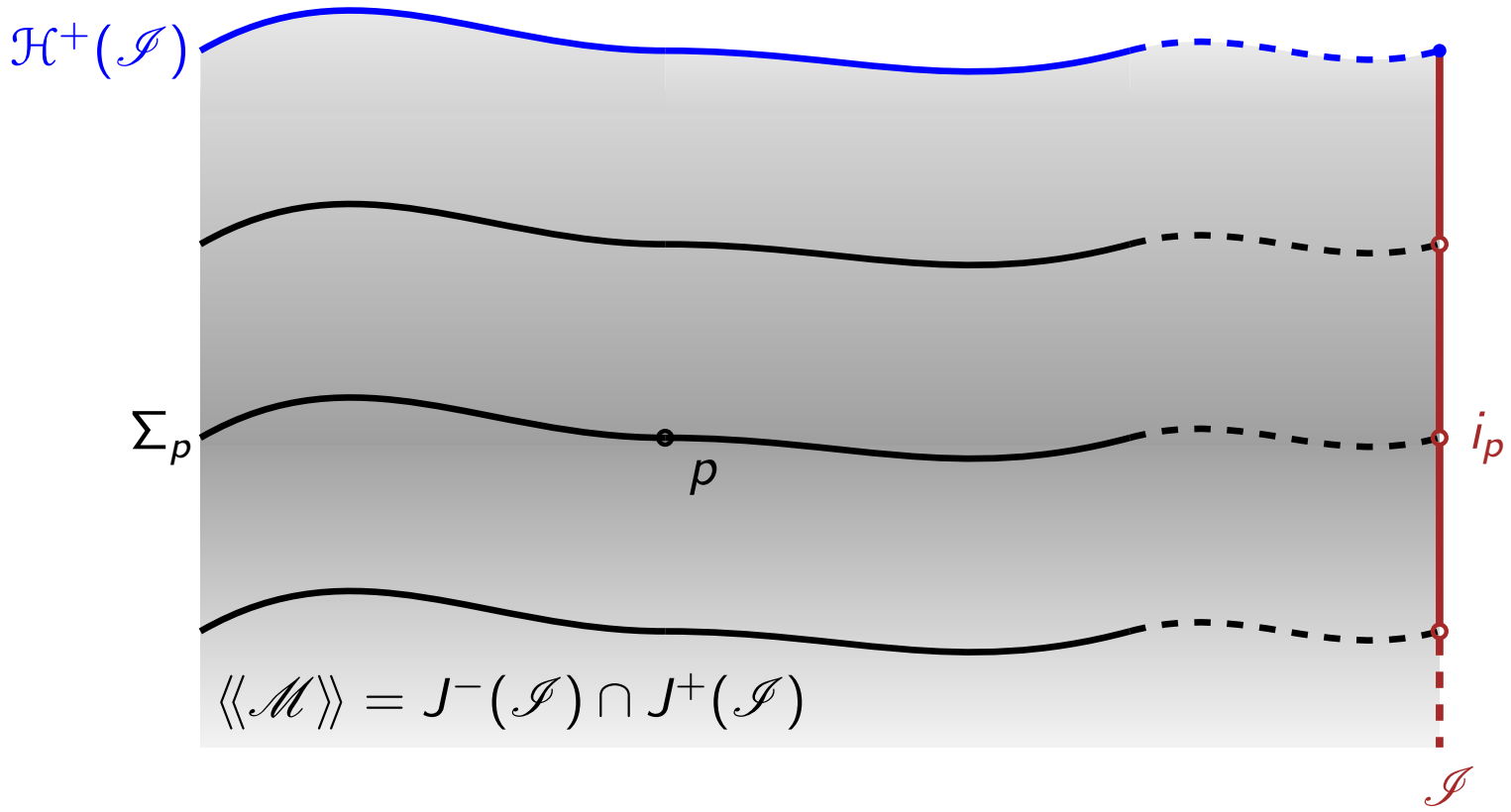


'Outside region': $\langle\langle \mathscr{M} \rangle\rangle$



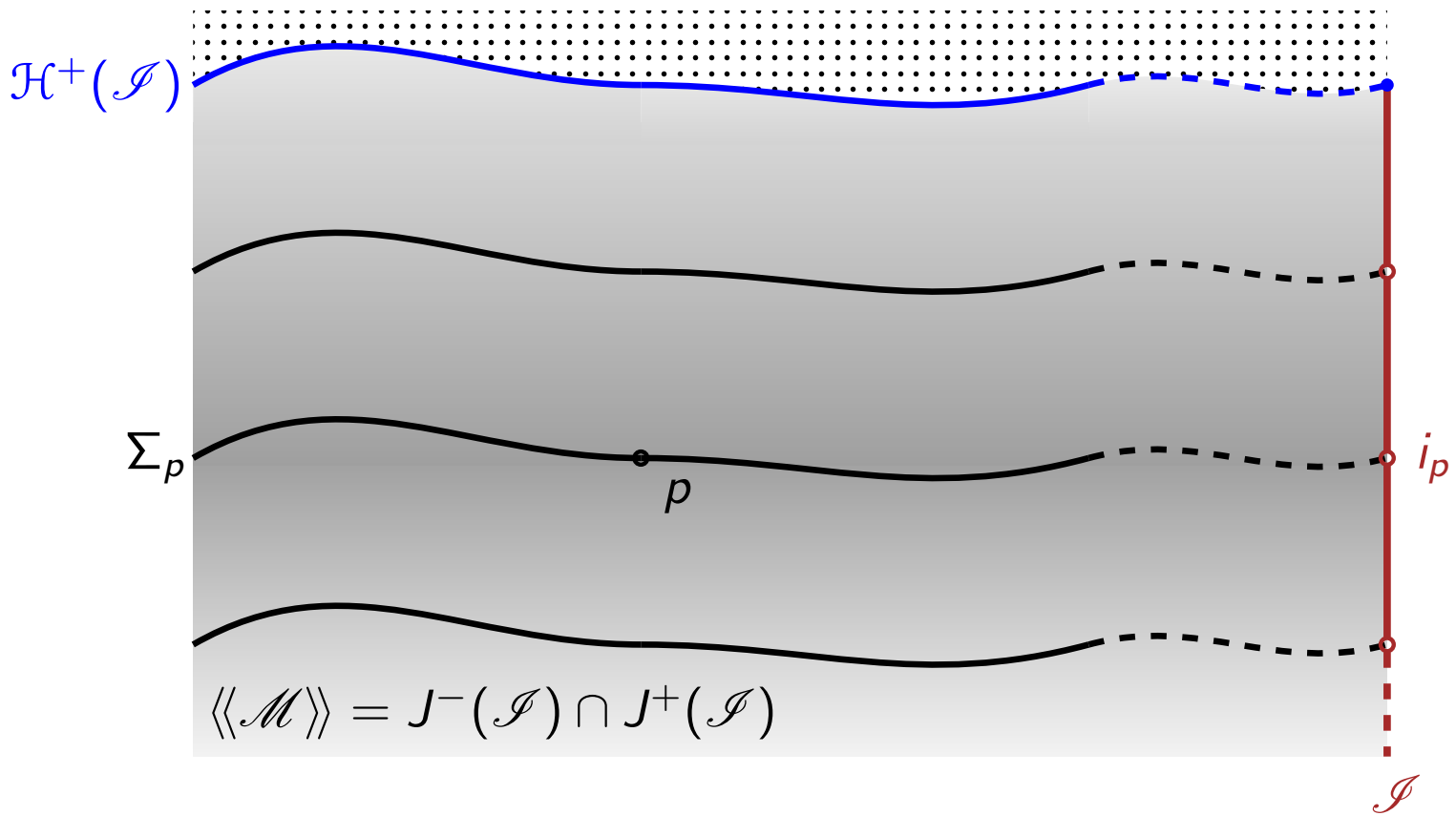
$$\langle\langle \mathscr{M} \rangle\rangle = J^-(\mathscr{I}) \cap J^+(\mathscr{I})$$

Universal horizon as an event horizon



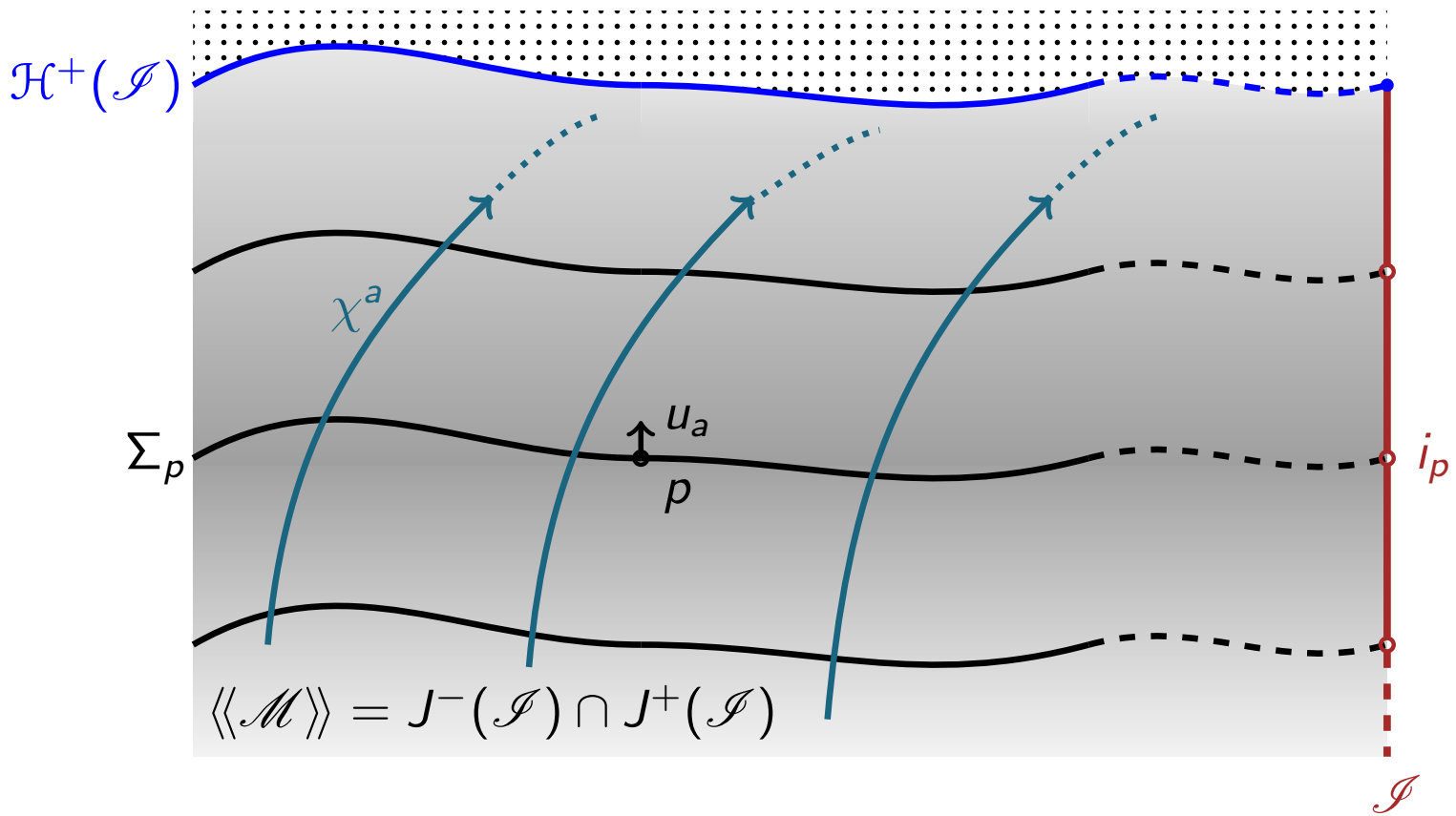
$$\mathcal{H}^+(\mathscr{I}) = \partial J^+(\mathscr{I})$$

Universal horizon as a Cauchy horizon



$$\mathcal{H}^+(\mathscr{I}) = \text{Cauchy horizon}(\Sigma_p, \mathscr{I})$$

Universal horizon: local characterization



$$\mathcal{H}^+(\mathscr{I}) \quad \Leftrightarrow \quad u_a \chi^a = 0$$

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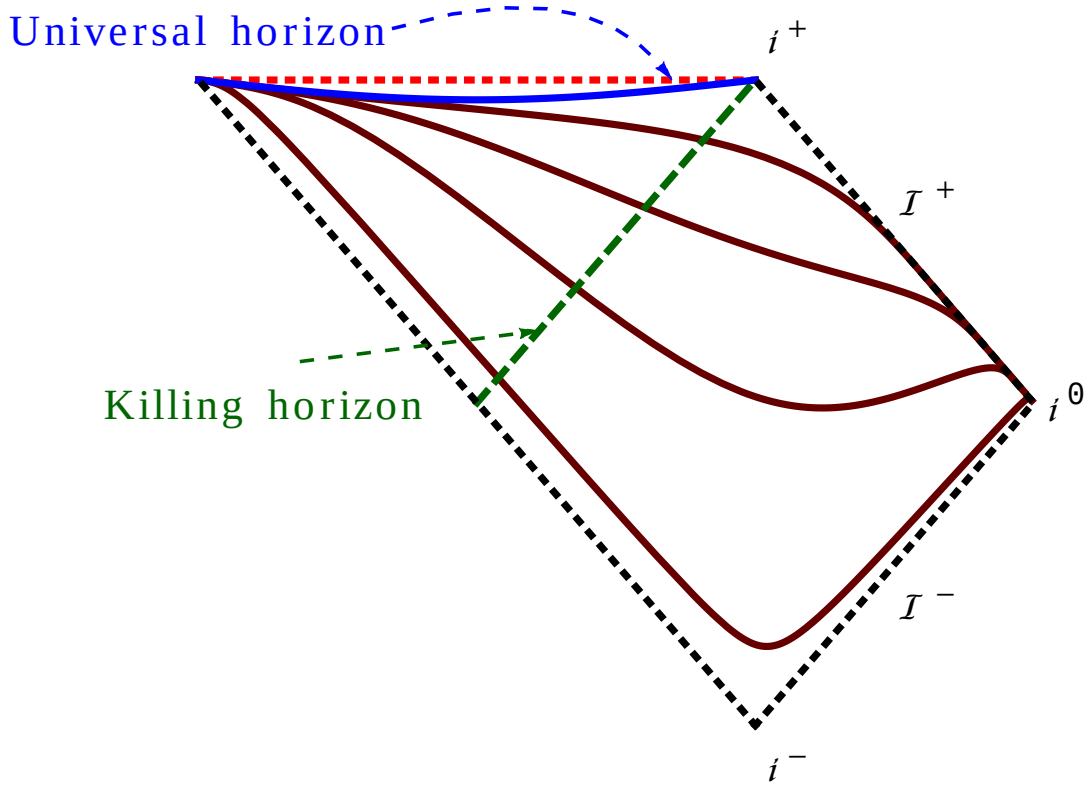
To summarize · · ·

- spacetimes with a *preferred foliation* has a *consistent causal structure*,
- black holes can exist even though Lorentz invariance is not respected; *event horizon* $\equiv$ *universal horizon*,
- *universal horizon* $\equiv$ *Cauchy horizon* for the 'outside region',
- in stationary spacetimes with Killing vector χ^a, *local characterization* of universal horizon: $u_a \chi^a = 0$.

Extra slide


Universal horizon
Killing horizon
i^+
$\mathcal{I}^+$
i^0
$\mathcal{I}^-$
i^-