LISA and modified gravity III

i) Propagation effects

ii) GWs memory and MG

iii) Lorentz invariance

Diego Blas Temiño

Universitat Autònoma de Barcelona

IFAE

Excelencia Severo Ochoa

Barcelona Institute of Science and Technology

i) Propagating effects

Most of studies take (from the white paper)

$$\ddot{h}_{ij}(\mathbf{k},t) + [3H(t) + \Gamma(k,t)]\dot{h}_{ij}(\mathbf{k},t) + \left[c_{\mathrm{T}}^2(t)k^2 + D(k,t)\right] h_{ij}(\mathbf{k},t) = 0$$

in the optical (**eikonal** approx)

damping of the wave
cosmo/LV/Horndeski
$\phi(x,t) = \bar{\phi}(t)$

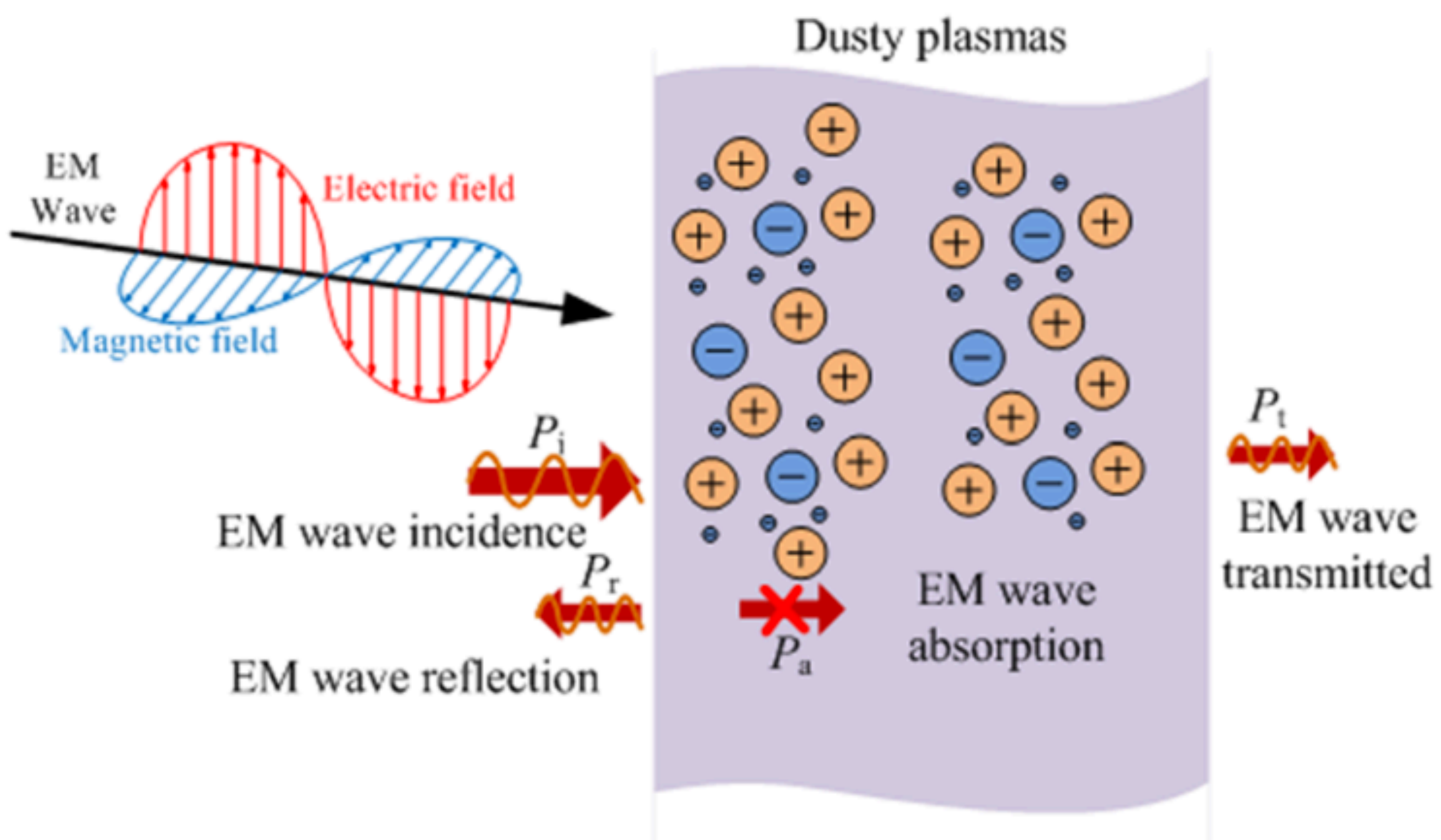
modified
group phase/velocity
$\phi(x,t) = \bar{\phi}(t)$

no sources

Cerenkov, GW170817 $\left\{ \begin{array}{l} \text{mass of the graviton} \quad D(k,t) \propto m^2 \\ \text{speed of propagation} \quad c_s \neq 1 \end{array} \right.$

i) Propagating effects   That's not all!!

Things that we know in GR, but not so much in MG



i) Plasma effects

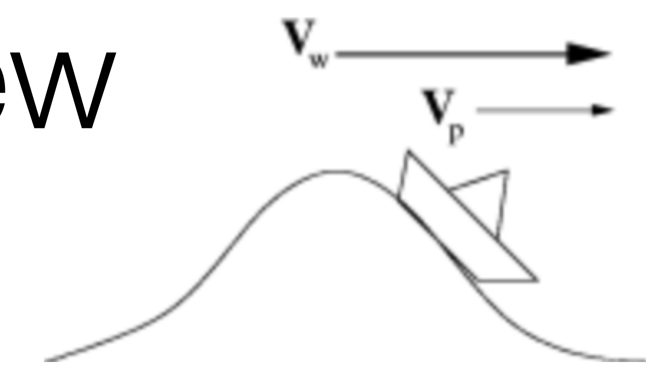
Flauger Weinberg 18&19

Baym Patil Pethick 17

$$\ddot{h}_{ij}(\mathbf{k},t) + k^2 h_{ij}(\mathbf{k},t) = 16\pi G \pi_{ij}$$

GR: The cosmological medium **NEVER** generates a visible effect :(

i) *MG*: The modification of the group/phase velocity allow for new **dramatic** effect (as Landau damping $v_{ph} \approx v_p$)



ii) π_{ij} may also correspond to something not LCDM

e.g. binaries of DM, ULDM,…anything **resonant!**

Bhupal Dev, Lindner, Ohmer 17

Watanabe Komatsu 06

new window on MG from cosmological sources (LISA)

????

i) Propagating effects

That's not all!!

Things that we know in GR, but not so much in MG

i) Plasma effects

ii) Beyond optical approximation

i) Propagating effects — That's not all!!

Things that we know in GR, but not so much in MG

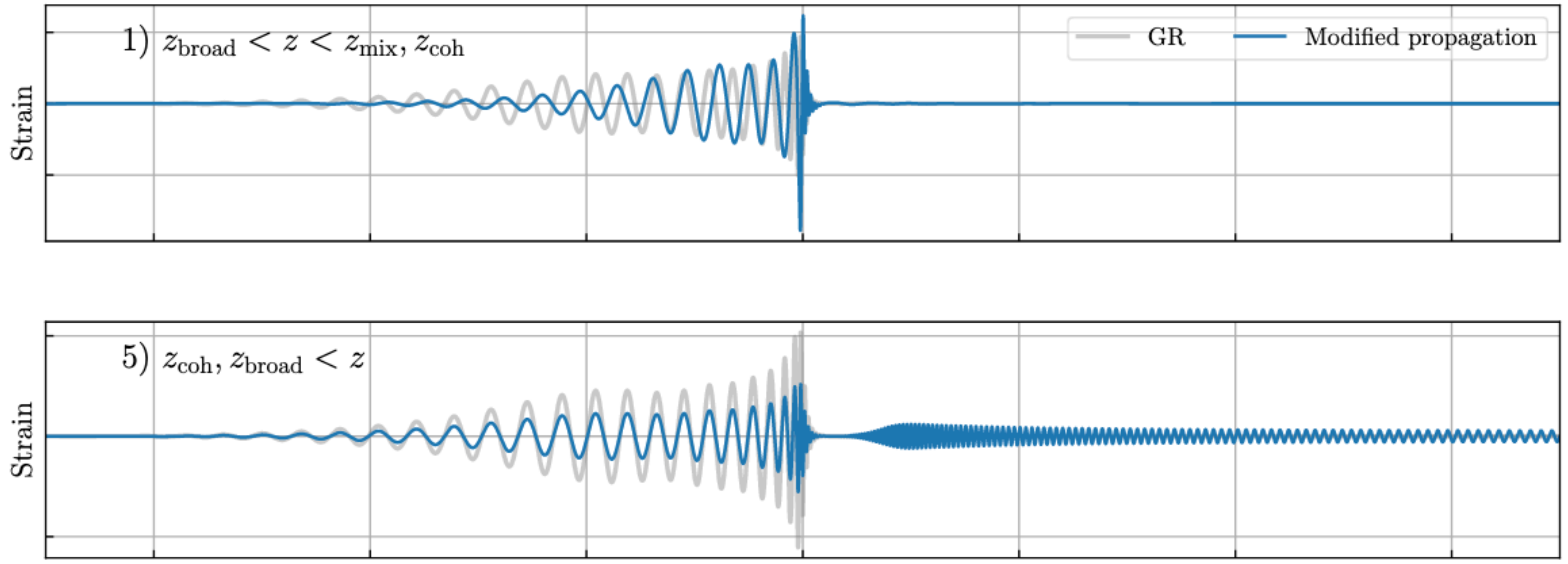
ii) Beyond optical approximation

Nakamura Takahashi 03
Cusin Lagos 19

GR: diffraction, interference patterns….

MG: The modification of the group/phase velocity allow for new **dramatic** effects

e..g Ezquiaga Zumalacarregui 20
e..g Ezquiaga et al 21

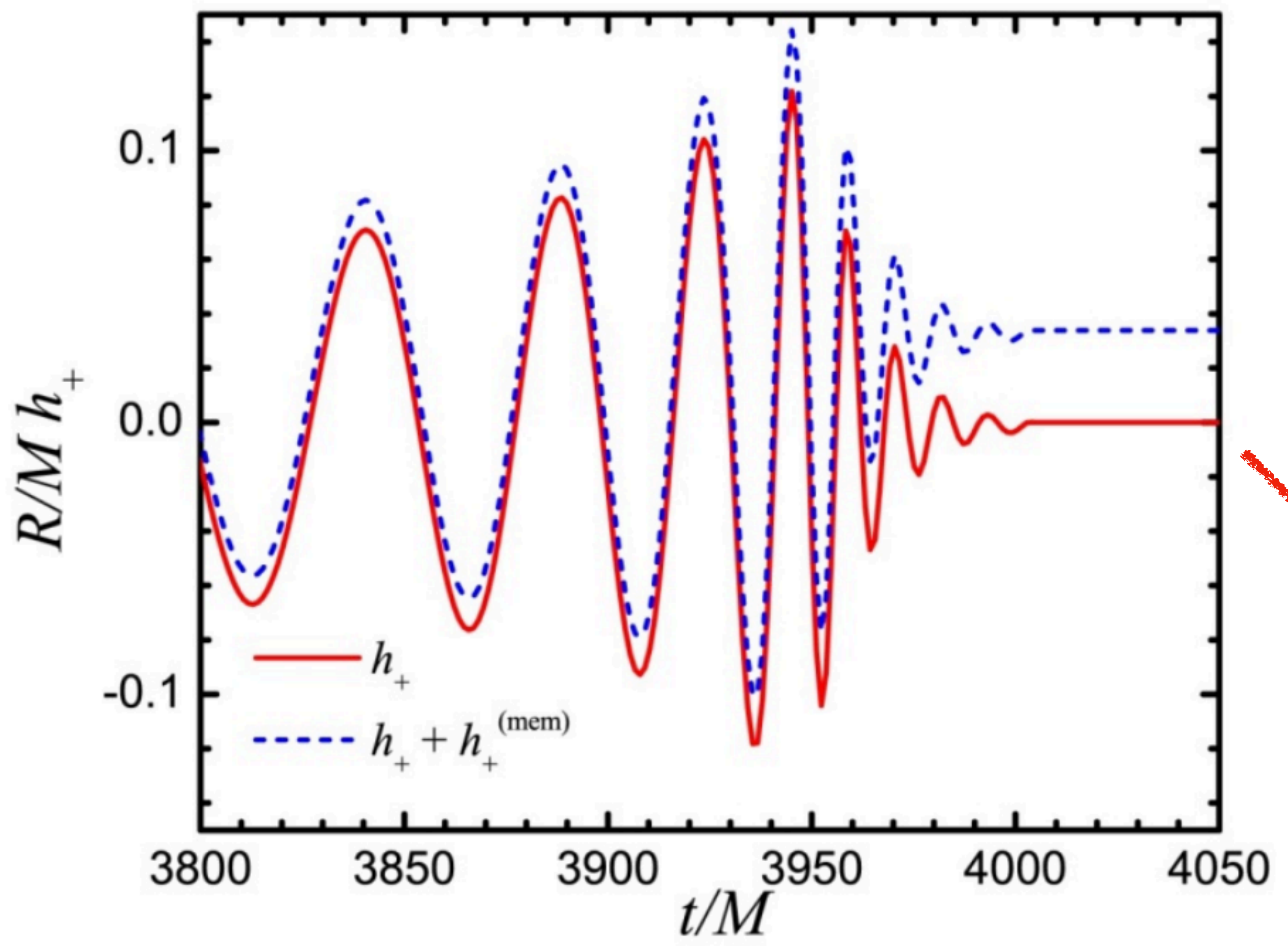


LISA ????

ii) Memory effects

Things that we know in GR, but not so much in MG

Favata 07 (and ‘classical references’)



EMT of the GWs backreacting

This is a *non-linear effect* connected to *‘propagation’* that WE WILL OBSERVE in LISA

Does it carry **new information about MG**? For sure and non-linear! But how? what? where?

????

iii) Apology of Lorentz breaking theories of MG

Einstein-aether and **Horava** theories

firstly motivated by quantum gravity and **can be tested!**

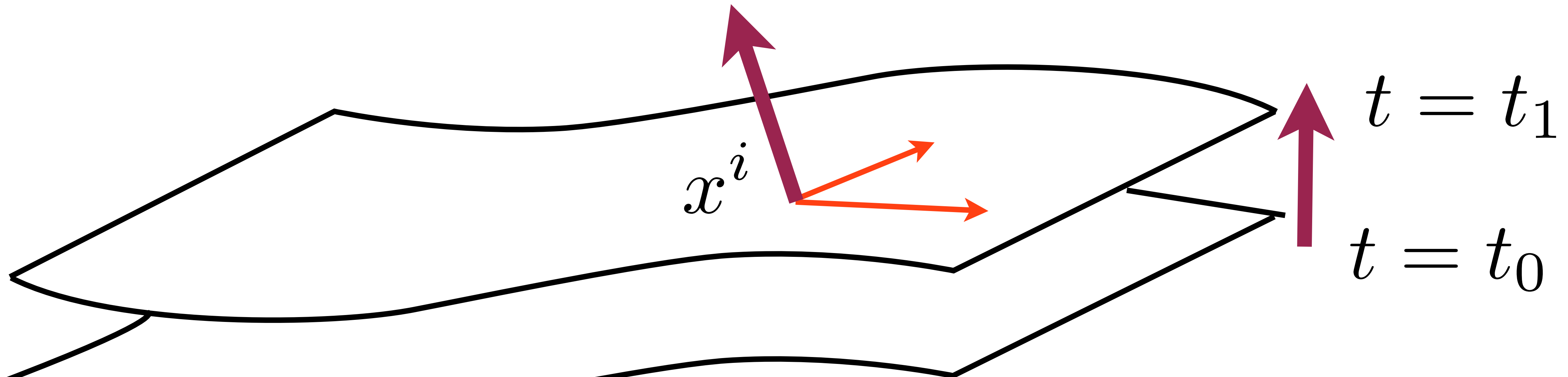
i) have new IR-dofs $g_{\mu\nu}$ & u^μ

with $u^\mu u_\mu = 1$ (Horava $u_\mu \equiv \dfrac{\partial_\mu \varphi}{\sqrt{\partial_\alpha \varphi \partial^\alpha \varphi}}$)

scalar tensor or *vector-scalar-tensor*

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

ii) and (sometimes) rigid-structure: foliation of space-time



iii) Apology of Lorentz breaking theories of MG

ii) and (sometimes) rigid-structure: foliation of space-time

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

$$u_\mu \equiv \frac{\partial_\mu \varphi}{\sqrt{\partial_\alpha \varphi \partial^\alpha \varphi}}$$

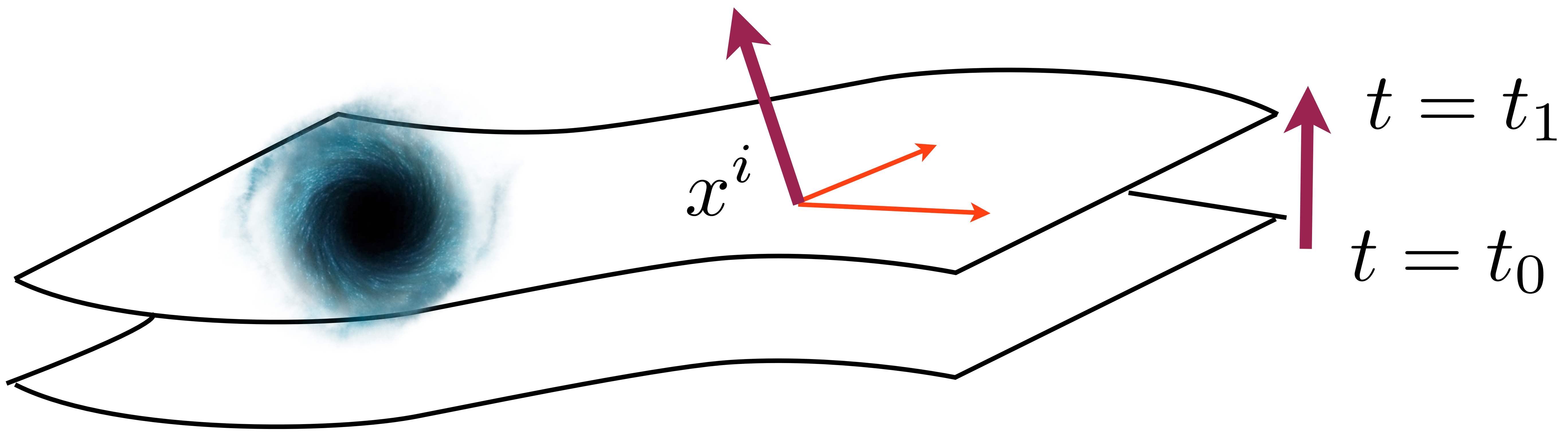
$$\bar{u}^\mu \neq 0$$

$$\bar{\varphi} = t$$

$$\omega^2 = c_t^2\, \mathrm{k}^2$$

$$\omega^2 = c_\varphi^2\, \mathrm{k}^2$$

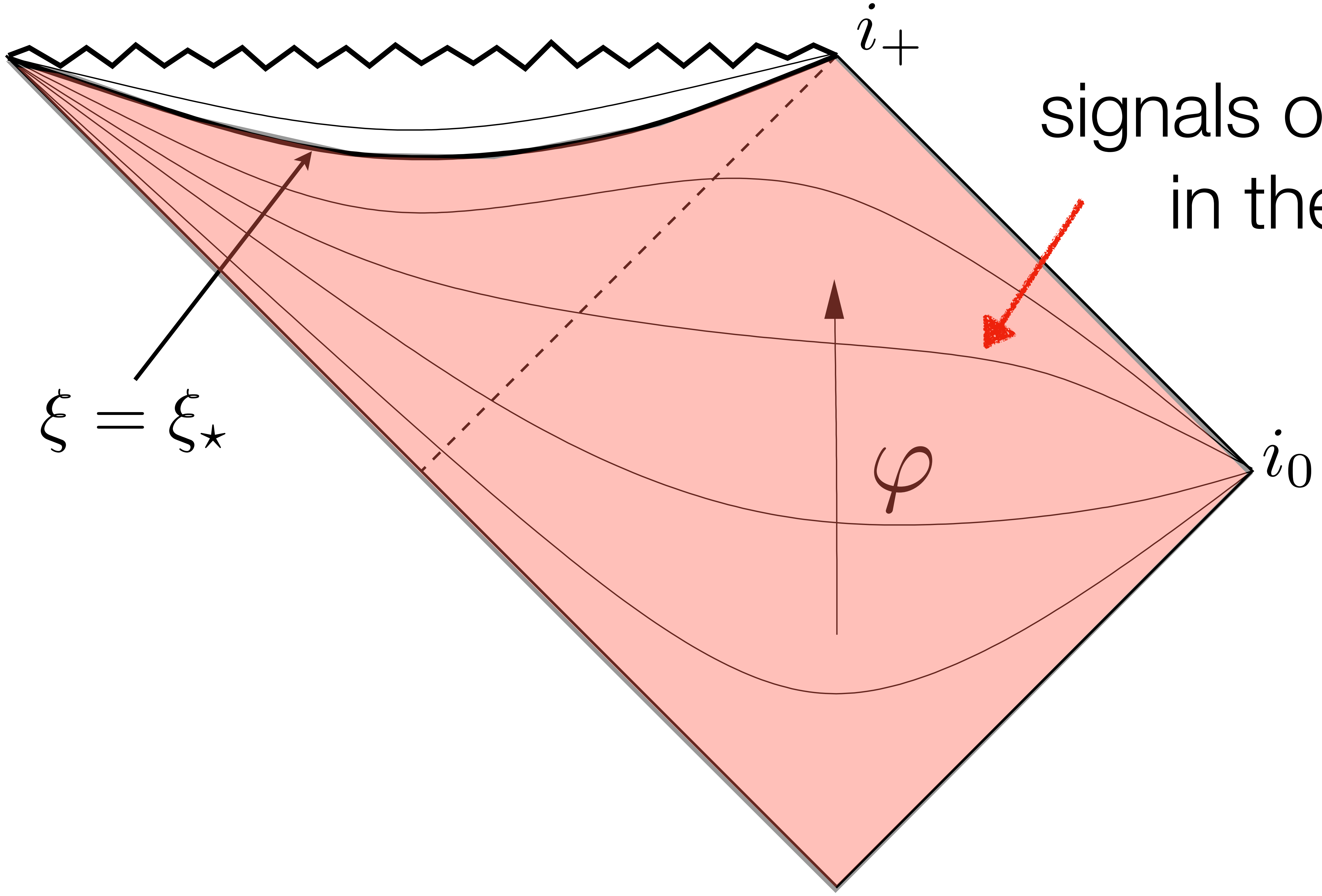
what happens for BH physics?



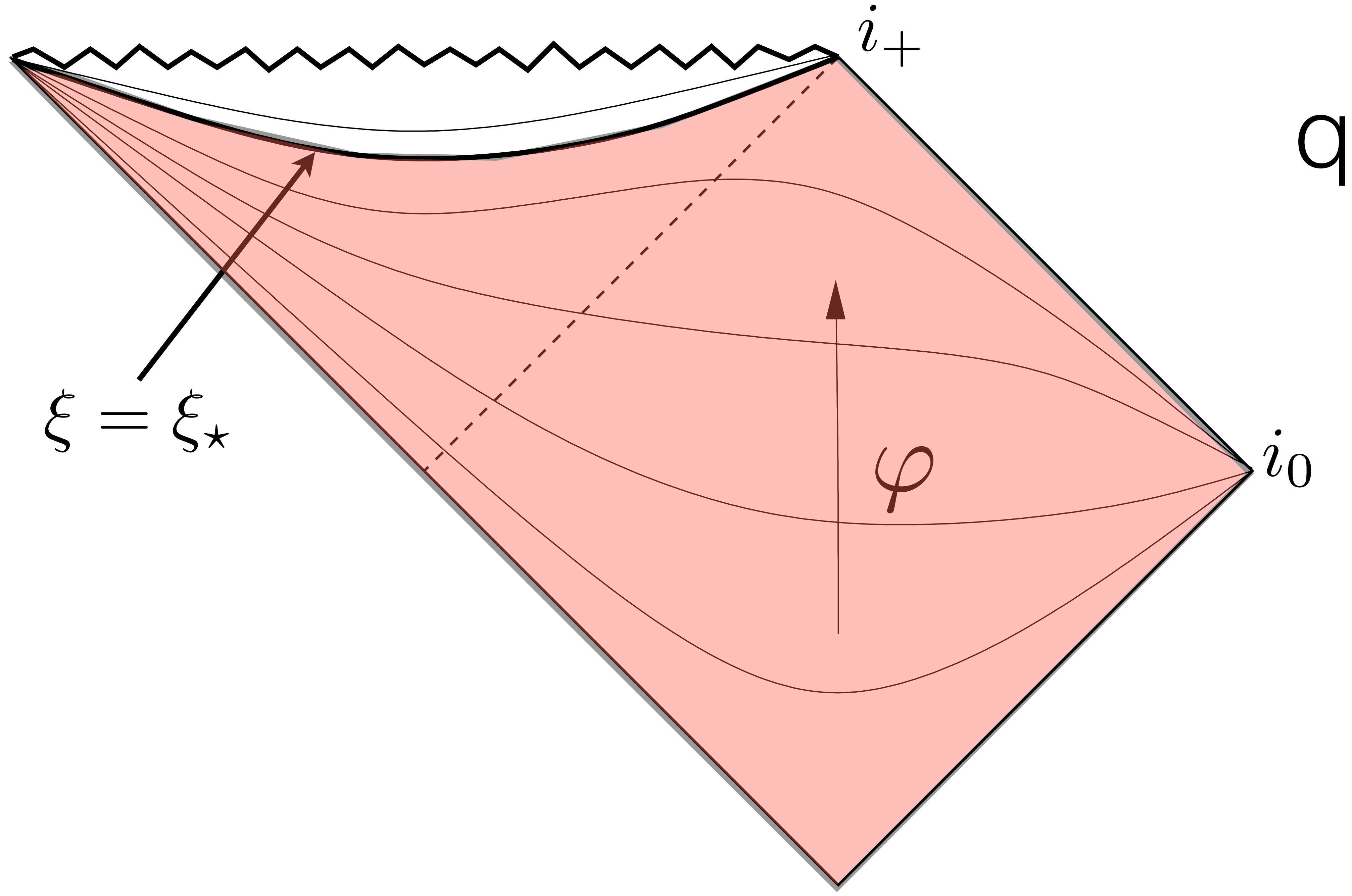
the foliation bends
(even if very rigid)

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

One can work in the small coupling limit: negligible $T^u_{\mu\nu} \sim O(\tilde{\alpha})$



$O(\tilde{\alpha}) \lesssim 10^{-4}$



quite ‘solid’ structure

LISA ????

i) How does it ring down? (QNM)

i) b) is the access to the interior playing any role (non-linear)

ii) $\delta\varphi$ also mediates a long-range force

(no hair still applies somehow)

iii) Rotation is still work in progress

iii) b) $\delta\varphi$ grow through super radiance?

$c_s < 1$

well-posed ✓

Connection to massive gravity

By adding 3 extra fields with symmetry

$$\phi_i \mapsto \phi_i + \xi_i(\varphi)$$

one generates a LV theory of massive gravity

$$\mathcal{L}^{(2)} = \frac{\mu_0^4}{8} h_{00}^2 - \frac{\mu^4 \kappa_0}{4} h_{00} h_{aa} - \frac{\mu^4}{8} h_{ab} h_{ab} + \frac{\mu^4 \kappa}{8} h_{aa}^2$$

Connection to massive gravity

By adding 3 extra fields with symmetry

$$\phi_i \mapsto \phi_i + \xi_i(\varphi)$$

one generates a LV theory of massive gravity

$$\mathcal{L}^{(2)} = \frac{\mu_0^4}{8} h_{00}^2 - \frac{\mu^4 \kappa_0}{4} h_{00} h_{aa} - \frac{\mu^4}{8} h_{ab} h_{ab} + \frac{\mu^4 \kappa}{8} h_{aa}^2$$

is this too much?

Massive gravity LV good points

Blas Sibiryakov 15

✓ Symmetry protected: it is a self-consistent well defined theory

✓ Cut-off scale remarkable for massive gravity!

$$\Lambda = \min(\mu_0, \mu) \leq \Lambda_2 = \sqrt{m_g M_P} \sim 10^3 \mathrm{eV} m_{-22}^{1/2}$$

can be completed to $\leq 10^{15}$ GeV

✓ Rich pheno to be explored! (some weird repulsive force at large distance)

LISA ????

i) Propagation effects

ii) GWs memory and MG

iii) BHs/SR…

LISA and modified gravity III

i) Propagation effects

ii) GWs memory and MG

iii) Lorentz invariance (including BHs & massive)

New Horizons for Fundamental Physics with LISA

white papers sets the stage

IMHO we should now make the full GR -> MG transition
(with LISA in mind)