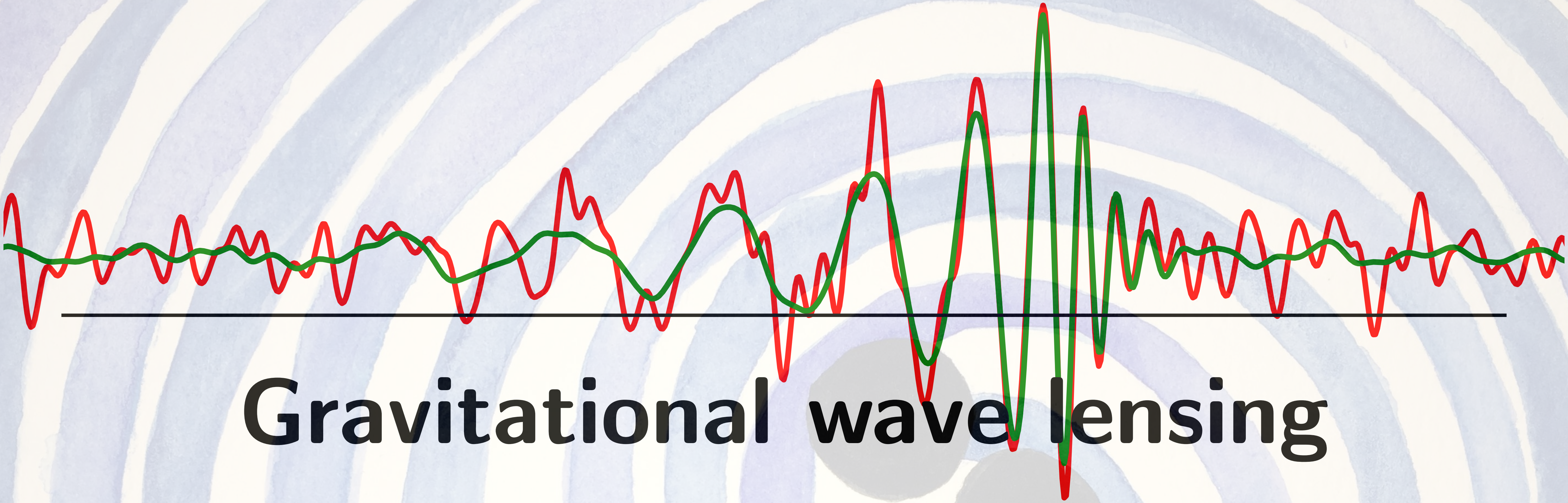

Gravitational wave lensing beyond General Relativity

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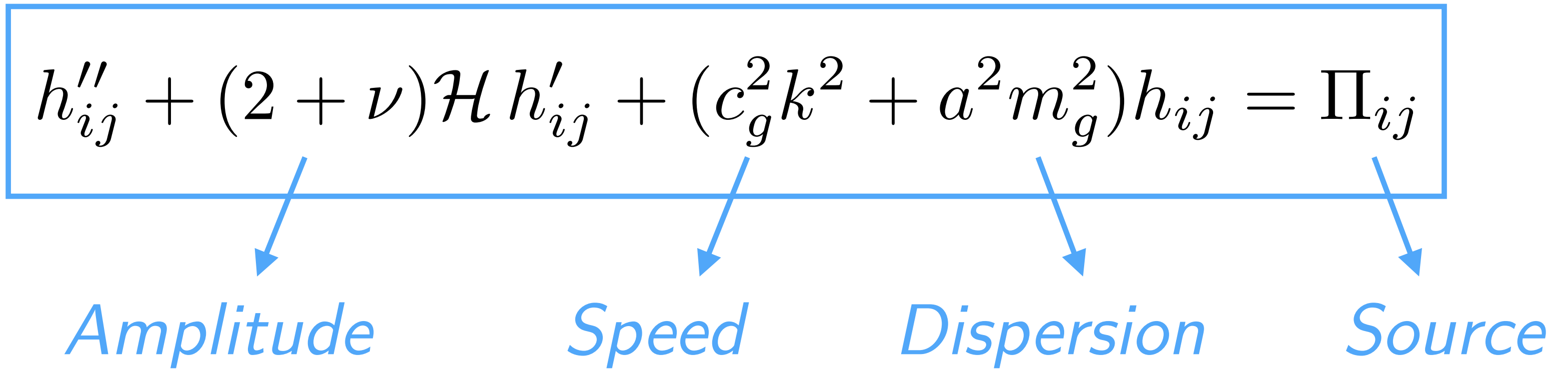
Testing cosmo GW propagation

- Around FRW background, parametrized modified GW propagation



$$\boxed{h''_{ij} + (2+\nu)\mathcal{H}\, h'_{ij} + (c_g^2 k^2 + a^2 m_g^2) h_{ij} = \Pi_{ij}}$$

Amplitude *Speed* *Dispersion* *Source*

[review Ezquiaga&Zumalacárregui'18] [see also Beltran, Ezquiaga, Heisenberg'19]

Pros

- Decoupling of scalar, vector and tensor modes
- Simple evolution equations
- Tight constrains on cosmological modifications. E.g. GW170817 $|\alpha_T| < 10^{-16}$

Cons

- Only probes GW mixing with tensor modes
- Only reduced sector of the gravity theory is tested
- Most tests require EM counterparts

GW lensing in GR

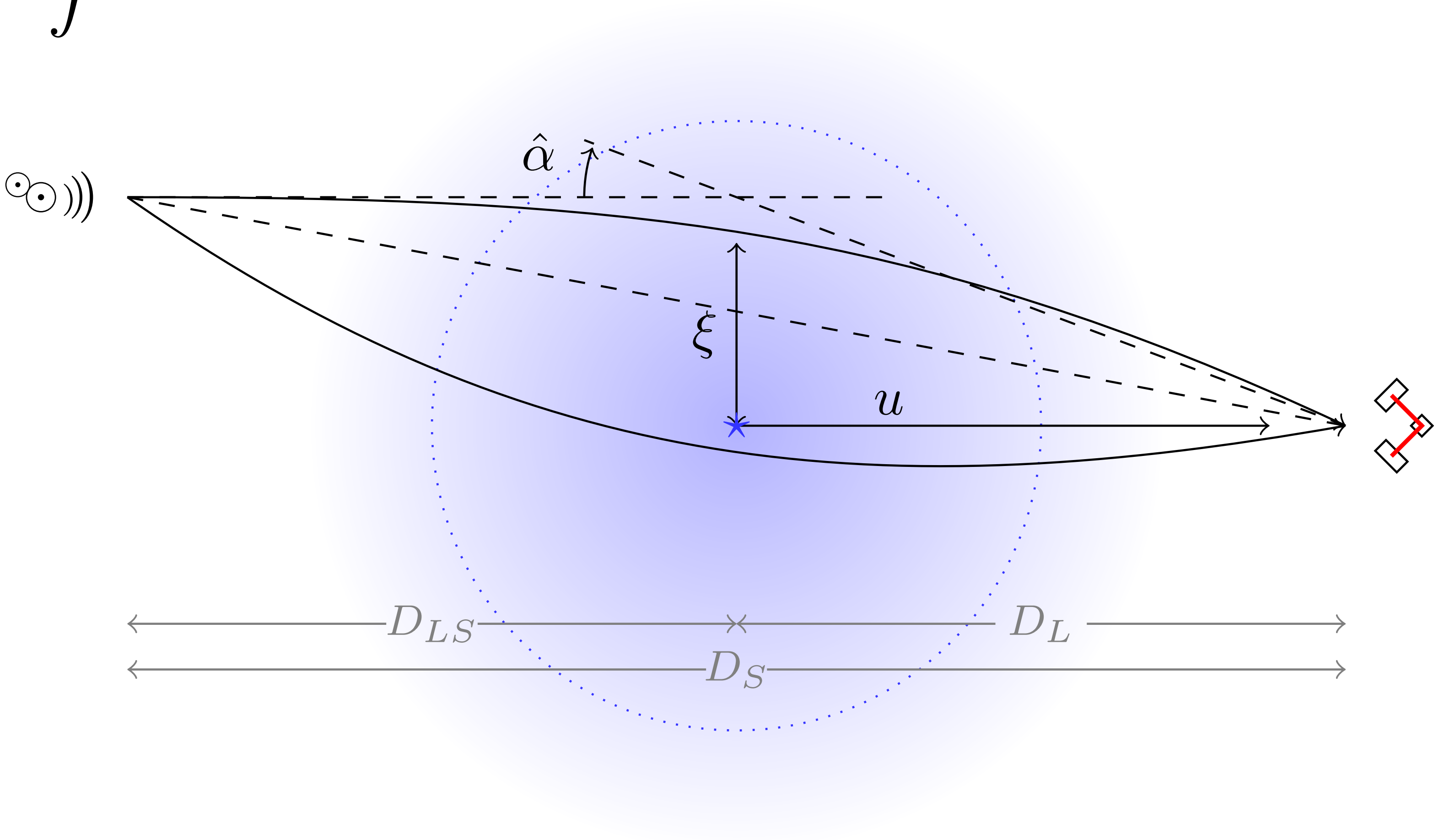
- Local gravitational potential modifies GW trajectory

$$\vec{\hat{\alpha}} \approx -\frac{1}{2}\int du\,\vec{\nabla}_\perp c^2_{\rm gw}(\vec{x}) \approx 2\int du\vec{\nabla}_\perp\Phi(\vec{x})$$

- And arrival time

$$\Delta t = \Delta t_{\rm Shapiro} + \Delta t_{\rm geom}$$

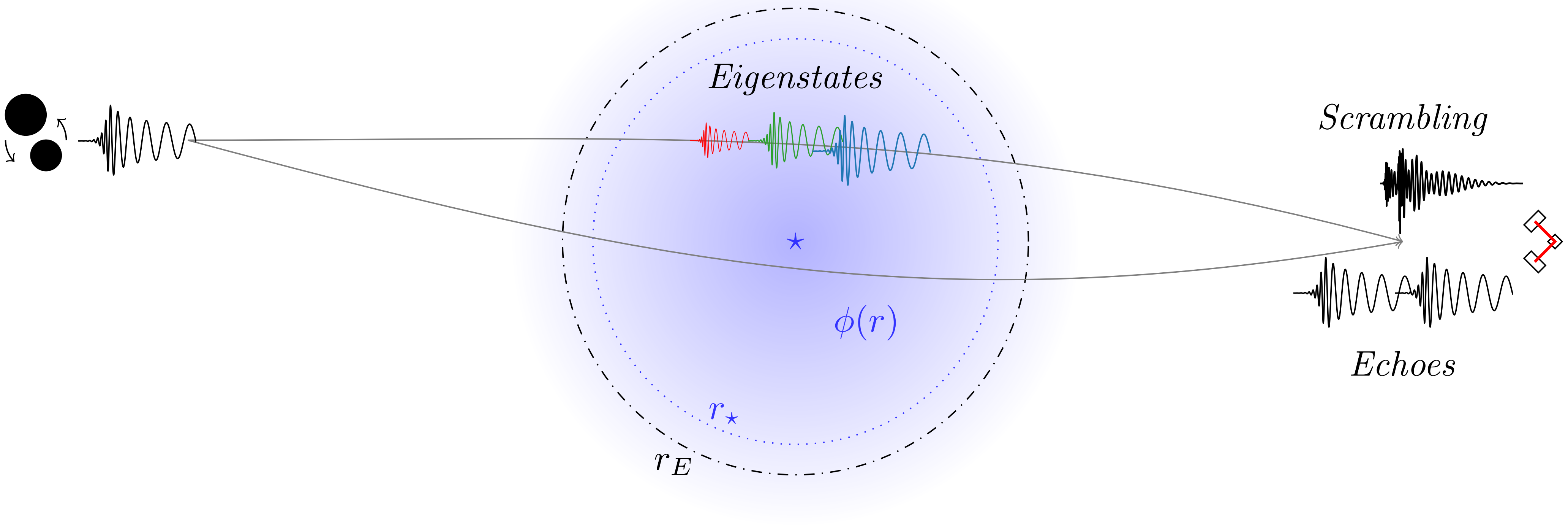
$$\Delta t_{\rm Shapiro} \approx \int du\, c^{-1}_{\rm gw}(x)$$



In strong lensing regime, multiple images of the same source arrive at the detector with different time delays

GW lensing beyond GR

- Beyond GR the background of the additional fields $\phi(r)$ modify propagation (besides the change in gravitational potential)
- The relevant scale for the modifications $r_\star$ might be different from the Einstein radius r_E



GWs can mix with the additional fields. The propagation eigenstates may have different speeds, splitting or distorting each image

Diagonalizing the propagation

- We will concentrate in scalar-tensor theories

$$g_{\mu\nu}^{\text{tot}} = g_{\mu\nu} + h_{\mu\nu} \qquad\qquad \phi^{\text{tot}} = \phi + \varphi$$

- Solving the propagation implies diagonalizing an 11x11 set of equations

$$\mathcal{D}_{ab} V_b = 0\,, \quad V_b = (h_{\mu\nu}, \varphi)$$

- Locally one can solve the constraint equations to arrive at 3x3 system

Leading derivative eqs.

Mixing matrix

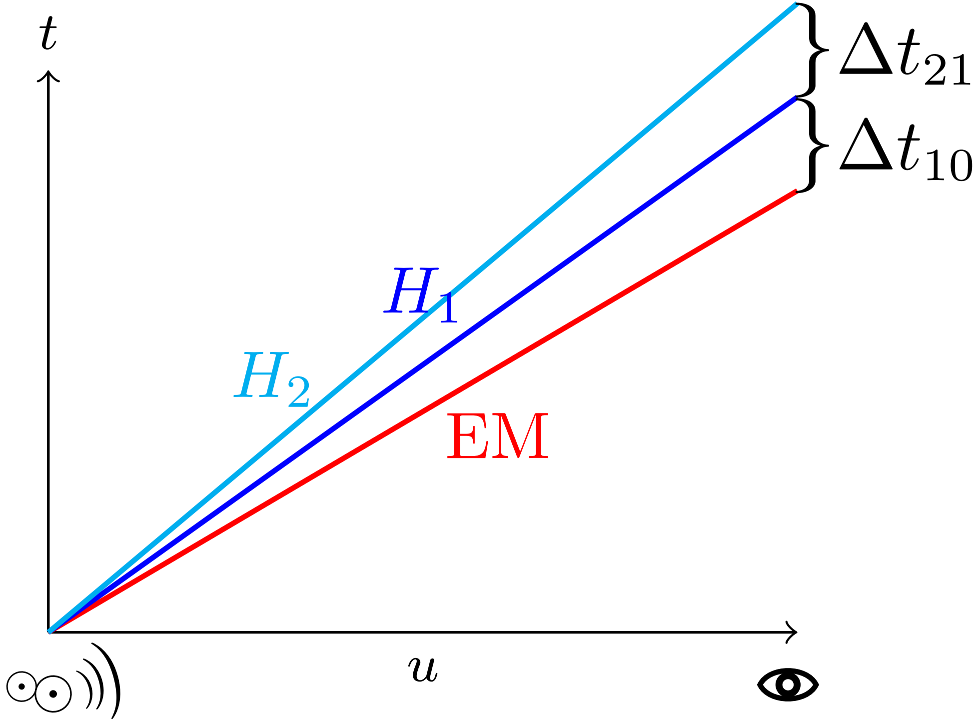
$$\boxed{\begin{pmatrix} G_{hh} & 0 & G_{+s} \\ 0 & G_{hh} & G_{\times s} \\ G_{+s} & G_{\times s} & G_{ss} \end{pmatrix} \begin{pmatrix} h_+ \\ h_\times \\ \varphi \end{pmatrix} = 0 \qquad \begin{pmatrix} H_1 \\ H_2 \\ H_3 \end{pmatrix} = \hat{\mathcal{M}} \begin{pmatrix} h_+ \\ h_\times \\ \varphi \end{pmatrix}}$$

Propagation basis

Interaction basis

Diagonalizing the propagation

- Mixing terms: $G_{+s} = M_\phi \cos(2\beta)\Box\,, \quad G_{\times s} = M_\phi \sin(2\beta)\Box$



- *Pure metric:*

$$\vec{v}_1 = \begin{pmatrix} -\sin(2\beta) \\ \cos(2\beta) \\ 0 \end{pmatrix}\,, \qquad c_1^2 = c_h^2$$

- *Mostly-metric:*

$$\vec{v}_2 \approx \begin{pmatrix} \cos(2\beta) \\ \sin(2\beta) \\ M_\phi \frac{c^2 - c_h^2}{c_h^2 - c_s^2} \end{pmatrix}\,, \qquad c_2^2 \approx c_h^2 + M_\phi^2 \frac{(c_h^2 - c^2)^2}{c_h^2 - c_s^2}$$

- *Mostly-scalar:*

$$\vec{v}_3 \approx \begin{pmatrix} M_\phi \cos(2\beta) \\ M_\phi \sin(2\beta) \\ \frac{c_s^2 - c_h^2}{c^2 - c_s^2} \end{pmatrix}\,, \qquad c_3^2 \approx c_s^2 - M_\phi^2 \frac{(c_s^2 - c^2)^2}{c_h^2 - c_s^2}$$

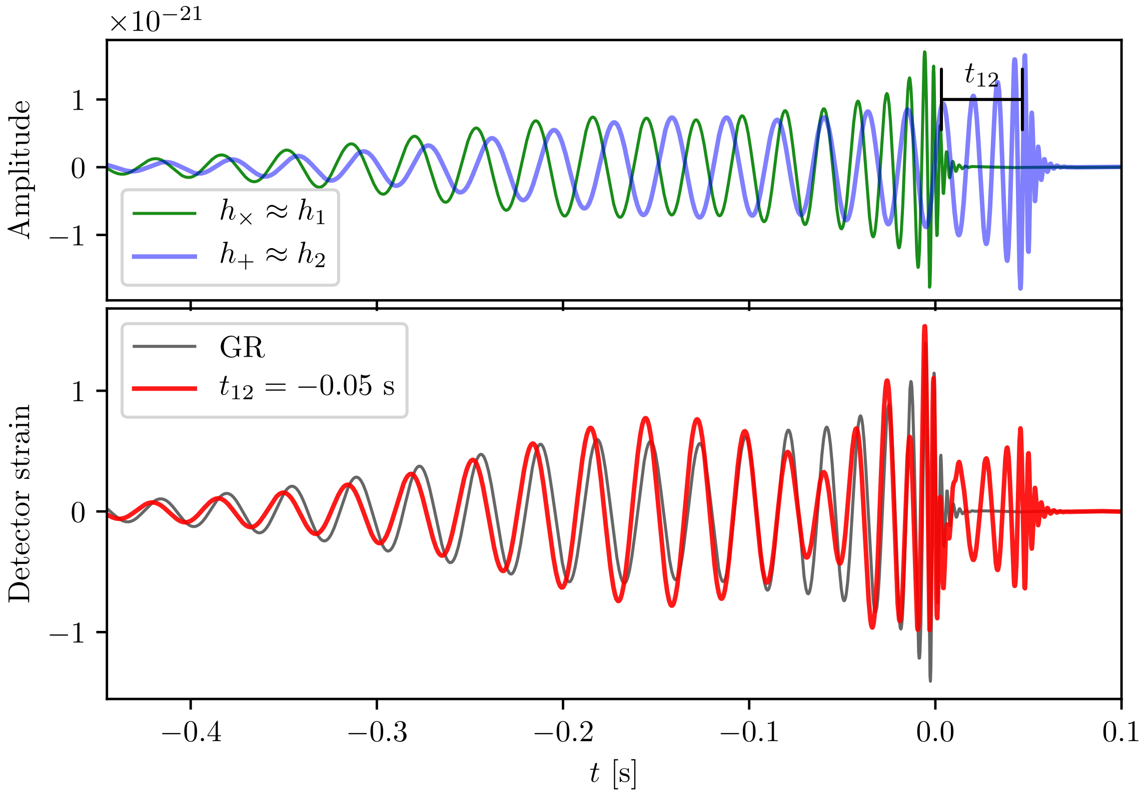
Main effects

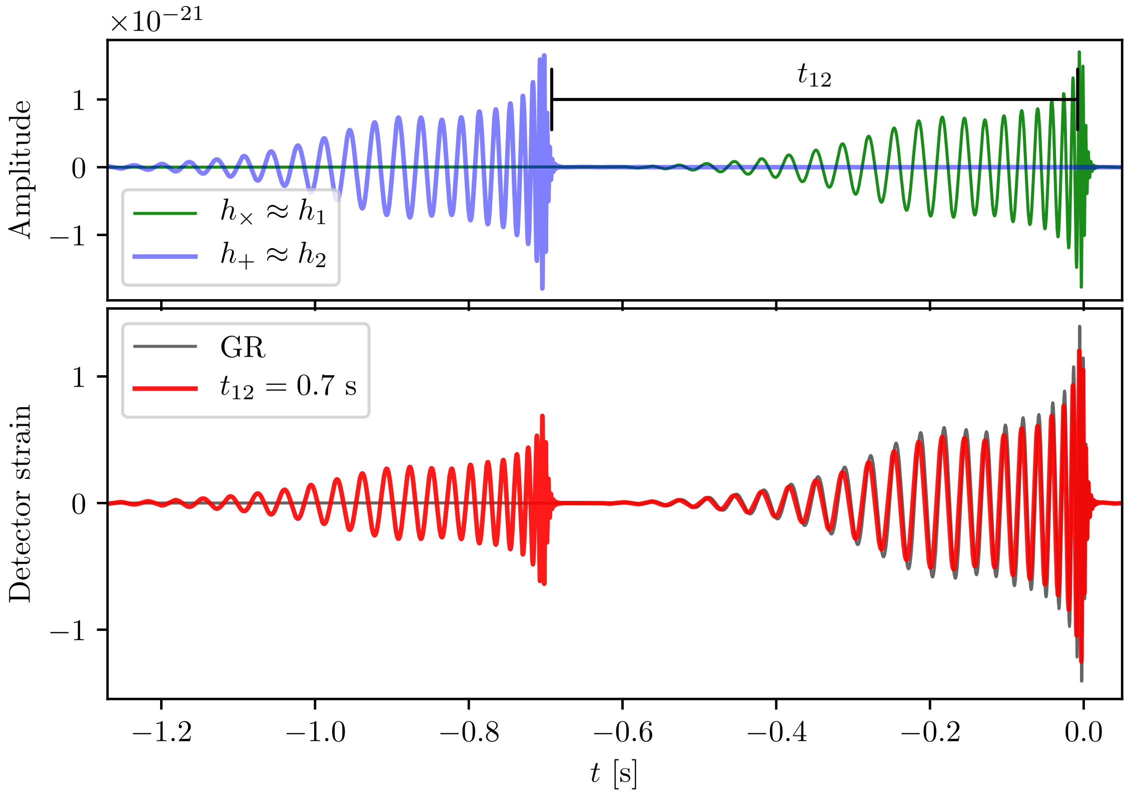
Modified effective metric for each eigenstate and polarization mixing

Time delays

Birefringence

- For each lensed image there could be <u>scrambling</u> or <u>echoes</u>
- No need of EM counterpart!





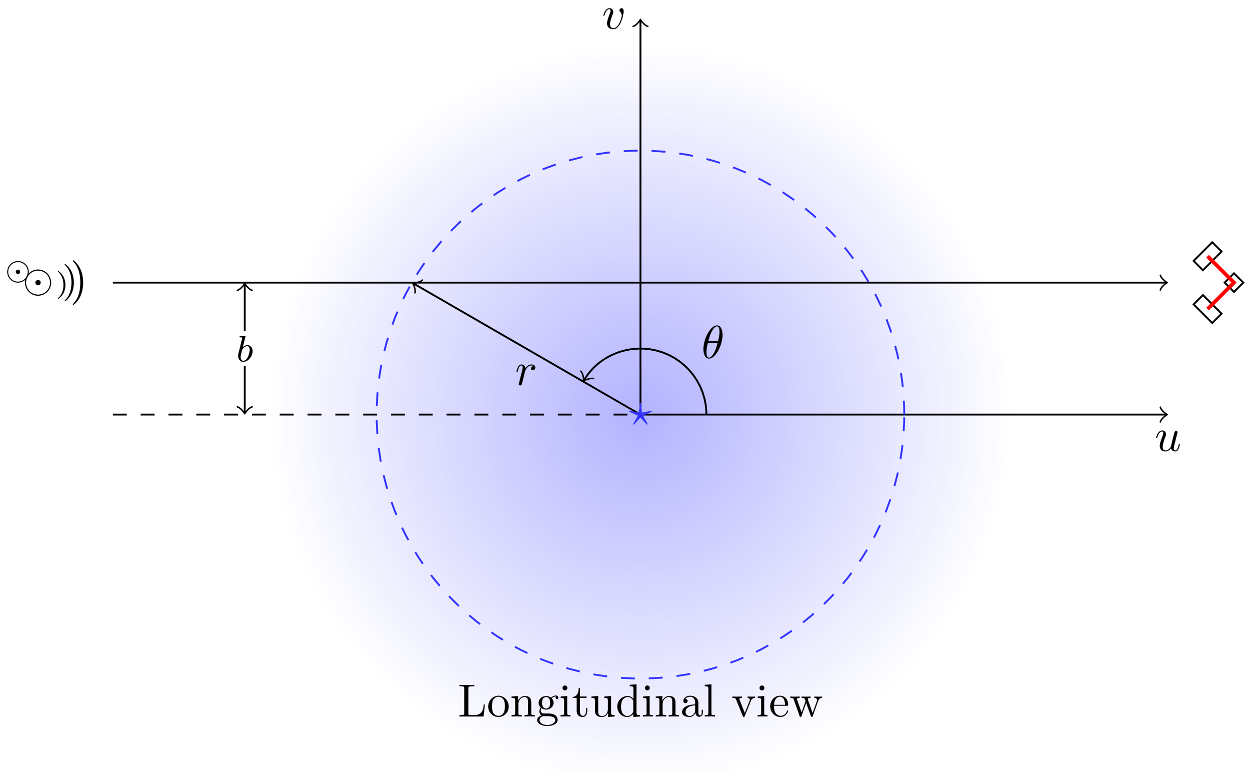
Screening in Horndeski

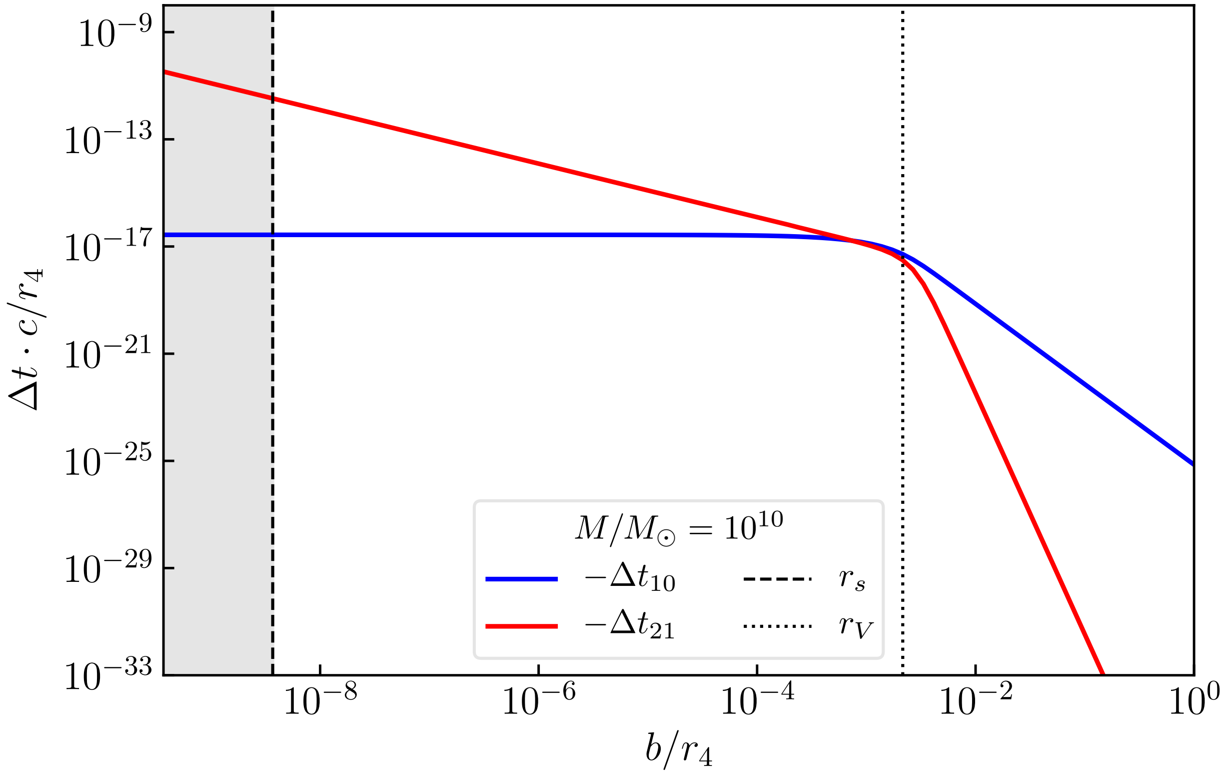
- Let us consider the effect of screening in the GW propagation for a quartic Horndeski theory

$$\mathcal{L} \sim \mathcal{L}_{\text{shift-sym}} + p_{4\phi}\phi M_{\text{Pl}} R \qquad G_4 \sim \frac{M_{\text{Pl}}^2}{2}\left(1 + p_{4X}\frac{(\partial\phi)^2}{M_{\text{Pl}}^2\Lambda_4^2}\right)$$

- Relevant scales: quartic term length scale and Vainshtein radius

$$(r_4)^3 = \frac{r_s}{2\Lambda_4^2} \qquad r_V = p_{4\phi}^{1/3} r_4$$



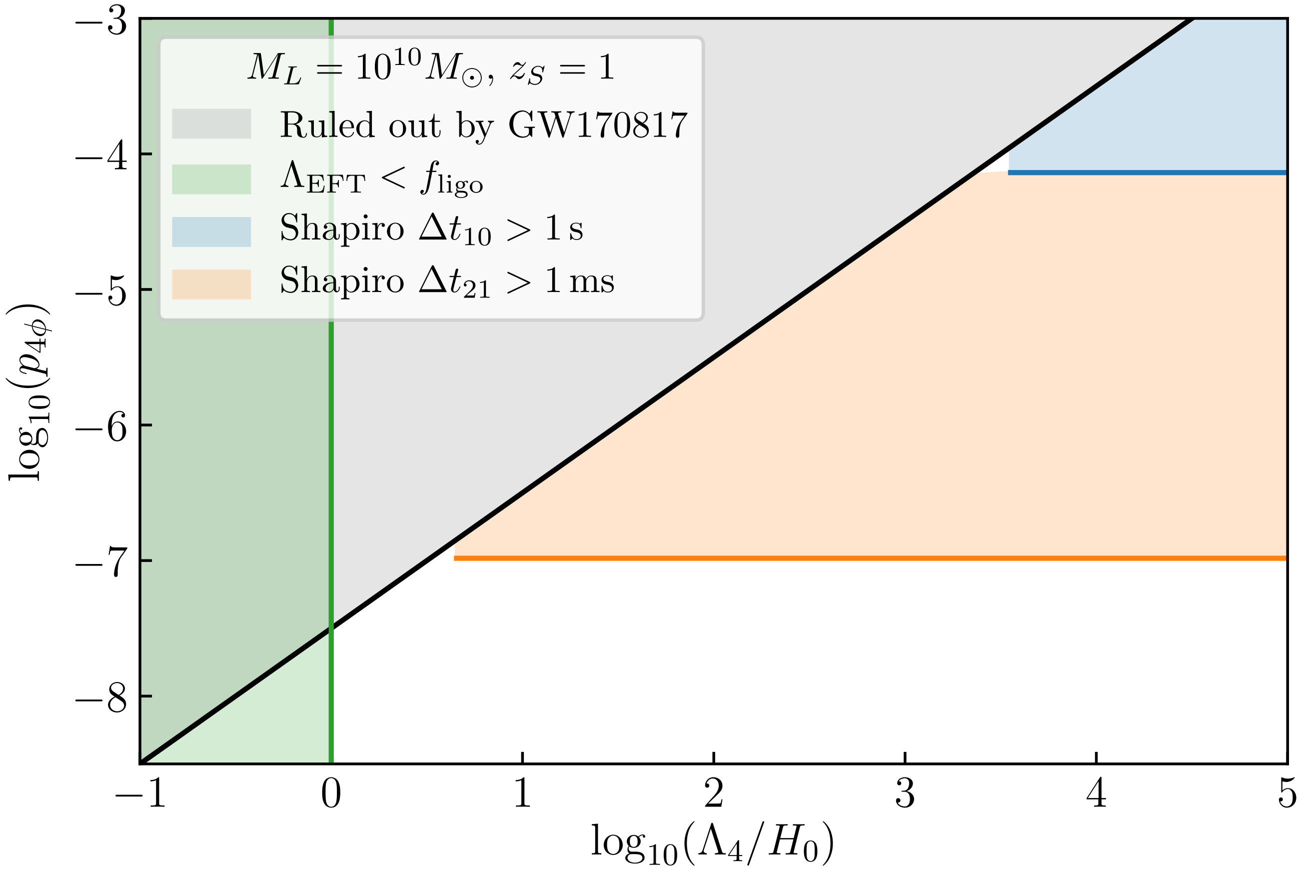


Screening in Horndeski

- Screening can be probed through the multi-messenger time delay Δt_{10} or the birefringent time delay Δt_{21}

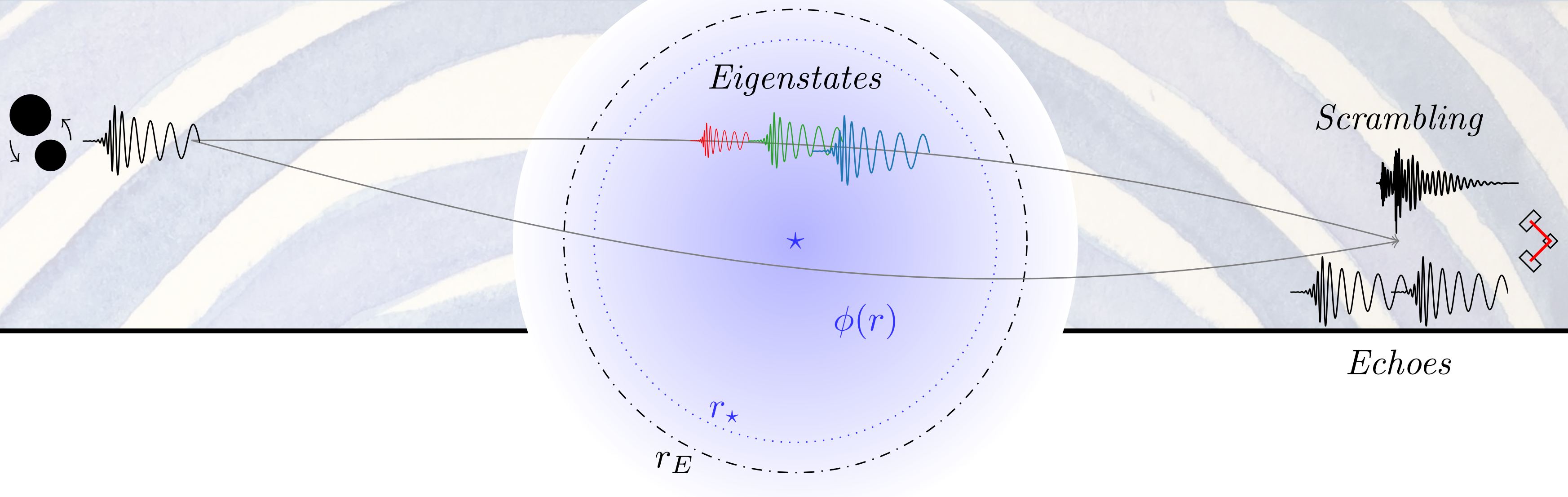
- Shapiro delay is independent of the source-lens distances

- Most probable, largest delay occurs for impact parameters around the Vainshtein



GW lensing beyond GR can probe regions of the parameter space unconstrained by GW170817

Summary



- Beyond General Relativity additional fields may mix with GWs while they propagate near a gravitational lens: new effects beyond FRW!

- Diagonalizing the evolution at leading order in derivatives one can obtain the propagation eigenstates, their velocities and polarization composition

- Without EM counterparts, birefringent time delay could probe models with screening and unconstrained by GW170817

- Plenty of room for future work: beyond leading order, prob. crossing multiple lenses, additional polarizations constraints, other theories...

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