Causality Constraints on Mergers beyond General Relativity

Francesco Serra

Scuola Normale Superiore, INFN Pisa

PONT – 03/05/2023

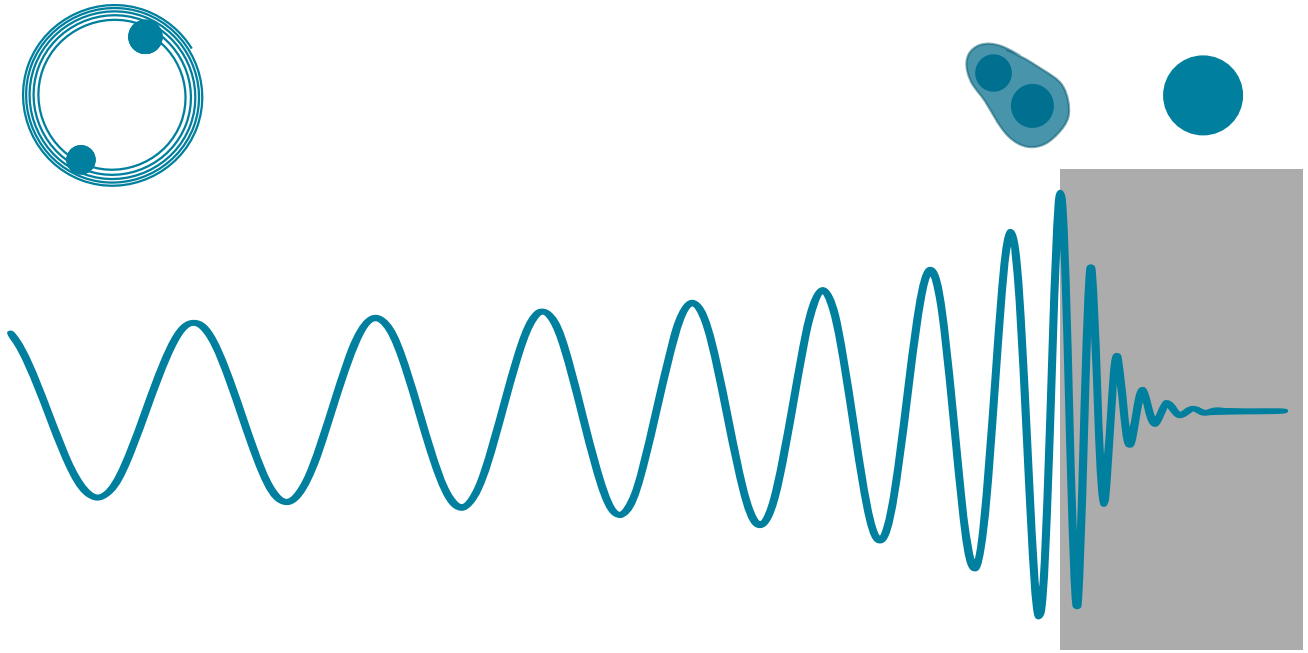
Based on:

FS, J. Serra, L.G. Trombetta, E. Trincherini – 2205.08551 + work in progress

A hidden scalar field?

- coupled only gravitationally
- shift-symmetric: $\phi \to \phi + c$

Test effects beyond GR with gravitational waves



How does the scalar field modify compact objects?

Black hole hair in scalar-tensor theories

The scalar Gauss-Bonnet exception

$$S = \int d^4x\sqrt{-g}\left(\frac{M_{\rm Pl}^2}{2}R - \frac{1}{2}(\partial\phi)^2 + \alpha M_{\rm Pl}\,\phi\mathcal{R}^2_{\rm GB}\right)$$

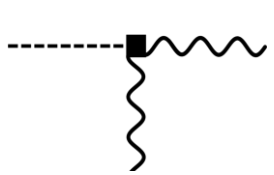
$$\mathcal{R}^2_{\rm GB} \equiv R^{\mu\nu\rho\sigma}R_{\mu\nu\rho\sigma} - 4R^{\mu\nu}R_{\mu\nu} + R^2$$

Detectable when $\sqrt{\alpha} \sim \mathrm{km}$

Black hole hair in scalar-tensor theories

The scalar Gauss-Bonnet exception

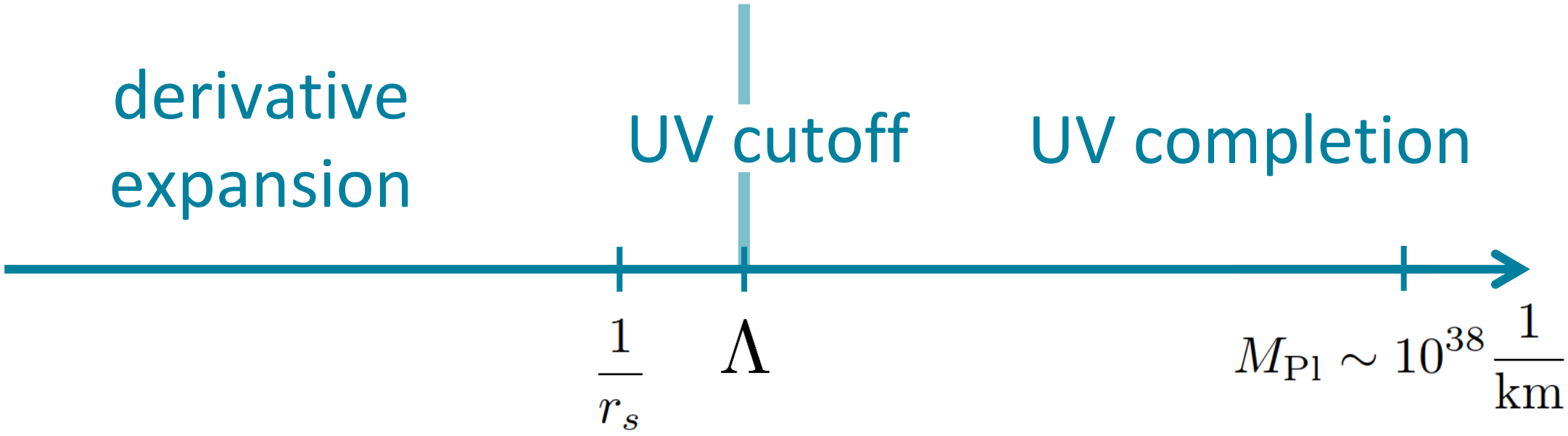
$$S = \int d^4x\sqrt{-g}\left(\frac{M_{\rm Pl}^2}{2}R - \frac{1}{2}(\partial\phi)^2 + \alpha M_{\rm Pl}\,\phi\mathcal{R}^2_{\rm GB}\right)$$



$$\frac{\partial^2\phi\,\partial h\partial h}{\Lambda_\alpha^3} \qquad \Lambda_\alpha = \left(\frac{M_{\rm Pl}}{\alpha}\right)^{1/3}$$

Detectable when $\sqrt{\alpha} \sim \mathrm{km}$

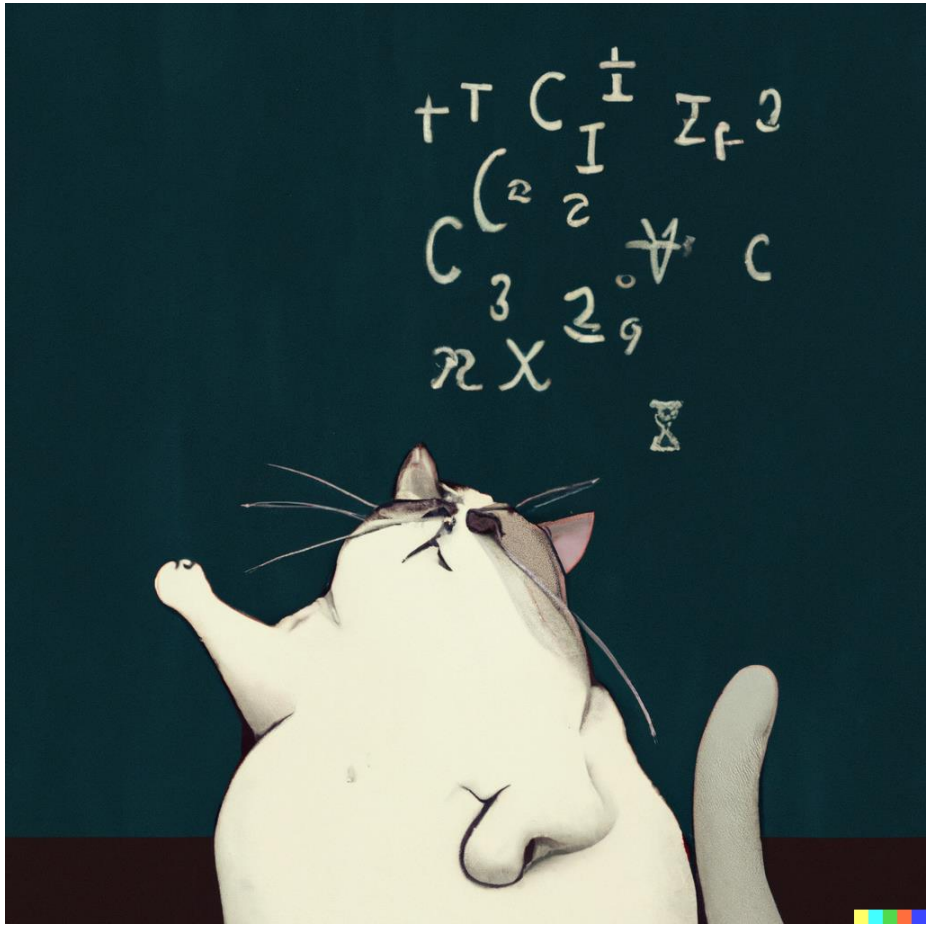
Is there a sensible UV completion?



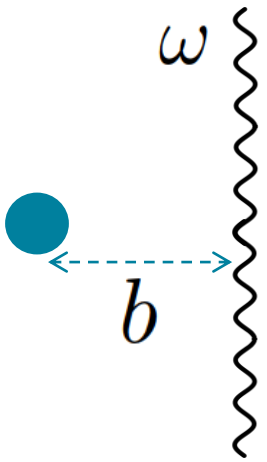
What are the consequences

of having a large coefficient α ?

Causality constraints



Time delays and time advances



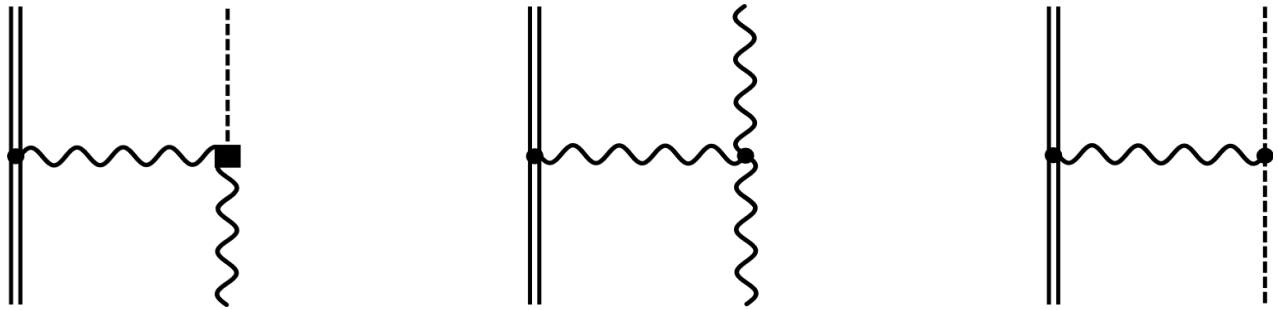
- GR : Shapiro time delay
- GR + scalar : ??

Classical superluminality if $\Delta t < 0$ & $|\Delta t| > \frac{1}{\omega}$

The case of scalar-GB

Time delay/advance from scattering

at impact parameter b



find eigenstates of propagation around massive source

Causality requires low UV cutoff

$$\Delta t_{\pm} = 2r_s \left(\log \frac{b_0}{b} \pm \sqrt{2} \frac{\alpha}{b^2} \right)$$

Shapiro scalar-GB

UV completion needed at small impact parameter

$$\Lambda \lesssim 1/\sqrt{\alpha}$$

Causality requires low UV cutoff

$$\Delta t_\pm = 2r_s \left(\log \frac{b_0}{b} \pm \sqrt{2} \frac{\alpha}{b^2} \right)$$

Shapiro scalar-GB

UV completion needed at small impact parameter

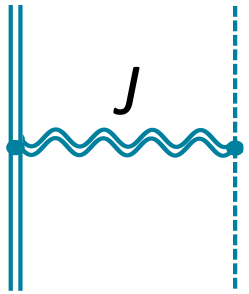
$$\Lambda \lesssim 1/\sqrt{\alpha} \ll \Lambda_\alpha = \left(\frac{M_{\rm Pl}}{\alpha} \right)^{1/3}$$

The EFT is still weakly coupled!

Which UV completion?

Only known cure for time advance at $b \lesssim \sqrt{\alpha}$

is a tower of spinning states (Camanho et al. 2014)



$\sqrt{\alpha} \sim \mathrm{km}$ ⇒ very light ~ 10^{-9} eV

Could such *dark* tower be hidden from detection?

Table top experiments – Newton law at μm

Adding other operators?

does not work

Moral of the story:

observing effects from a shift-symmetric scalar in BH mergers seems not at all likely

Diagnosis: Superluminality

Treatment: UV completion

Results: Narrow down space of testable deviations from GR

Next: Other compact objects?

francesco.serra@sns.it