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Smoking guns of beyond-GR physics in binary mergers

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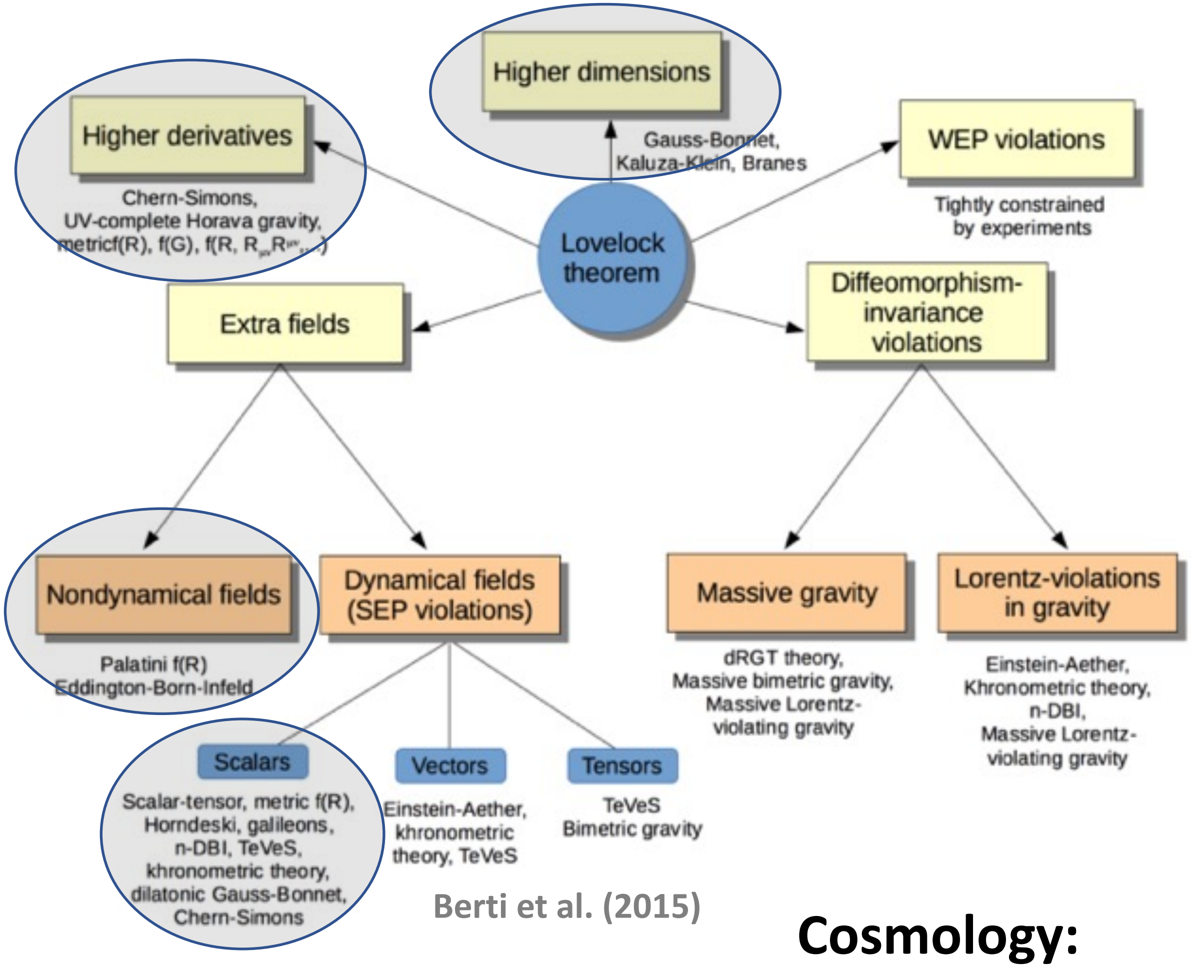
Extra scalar field(s)



Berti et al. (2015)

Cosmology:

- Ultralight axion dark matter
- Inflation scalar field
- f(R), Horndeski gravity

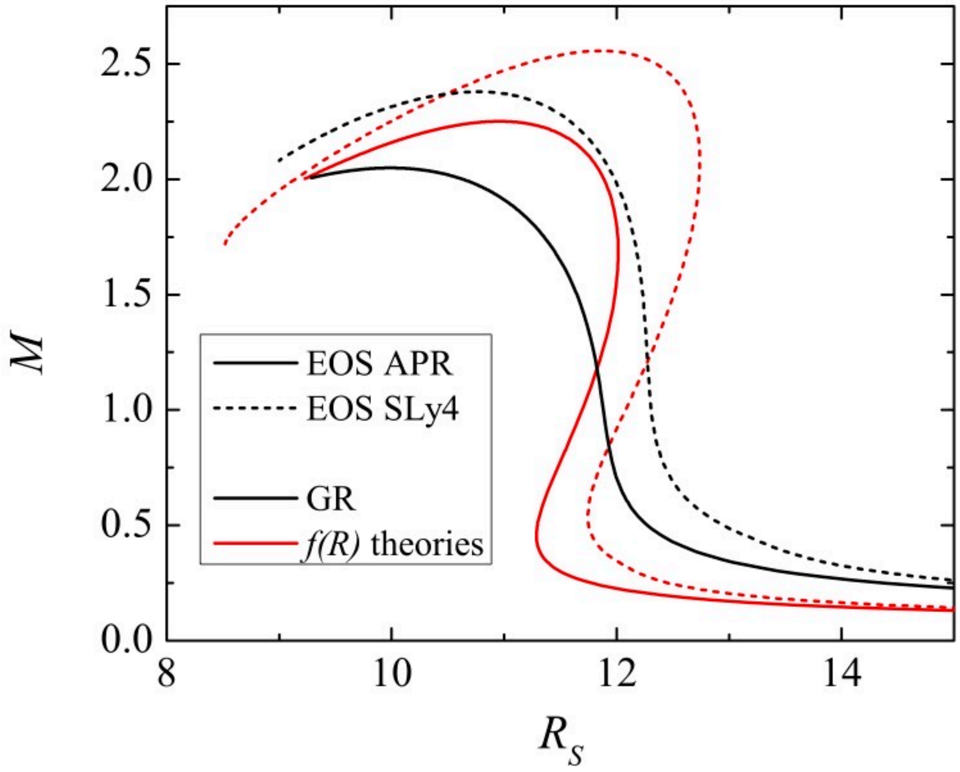
Quantum gravity motivated:

- Gauss-Bonnet gravity
- Chern-Simons gravity

Changes in the GW spectrum

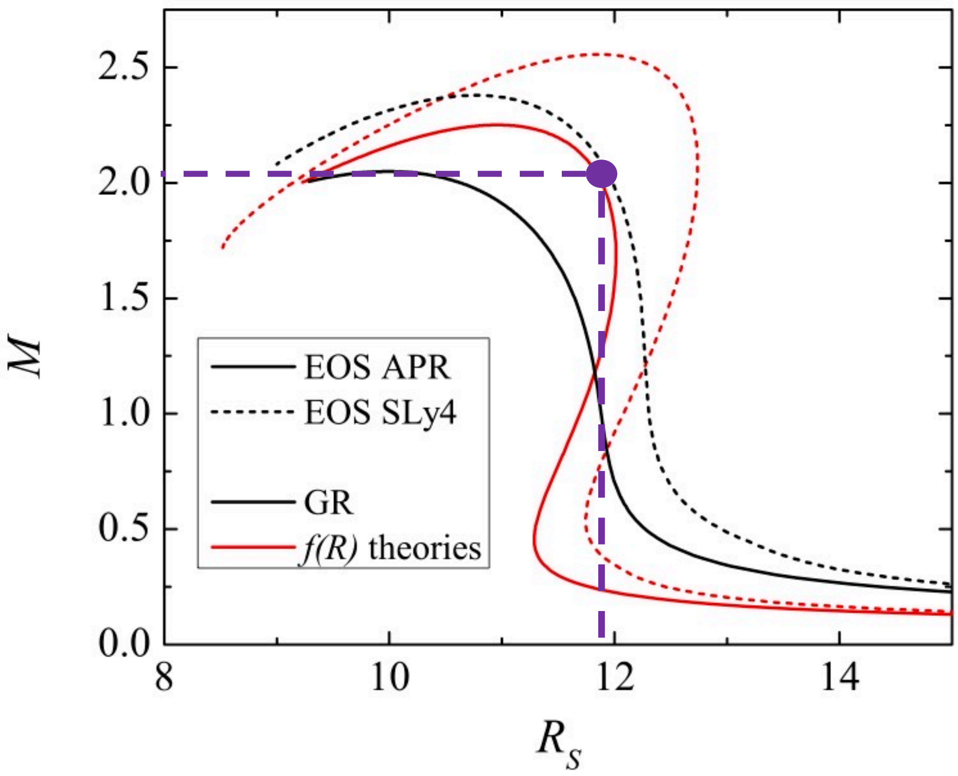
Quantitative vs. Qualitative

Quantitative changes



Modifying the theory of gravity ⟺ EOS uncertainty

Quantitative changes



Modifying the theory of gravity ⟺ EOS uncertainty

Changes in the GW spectrum

Quantitative vs. Qualitative

Jumps in GW emission during merger

Gauss-Bonnet gravity – Black Hole Scalarization

- **Gauss-Bonnet gravity –** the equations are of second order

$$S = \frac{1}{16\pi}\int d^4x\sqrt{-g}\left[R - 2\nabla_\mu\varphi\nabla^\mu\varphi - V(\varphi) + \lambda^2 f(\varphi)\boxed{\mathcal{R}^2_{GB}}\right].$$

Gauss-Bonnet invariant:

$$\boxed{\mathcal{R}^2_{GB} = R^2 - 4R_{\mu\nu}R^{\mu\nu} + R_{\mu\nu\alpha\beta}R^{\mu\nu\alpha\beta}}$$

- With a proper choice of $f(\varphi)$:
  - ✓ **Perturbatively equivalent to GR in the weak field**
  - ✓ Nonlinear effects for strong fields – **scalarization**

- Expand $f(\varphi)$ in series around $\varphi = 0$:

$$f(\varphi) = f_0 + f_1\varphi + f_2\varphi^2 + f_3\varphi^3 + f_4\varphi^4 + O(\varphi^5)$$

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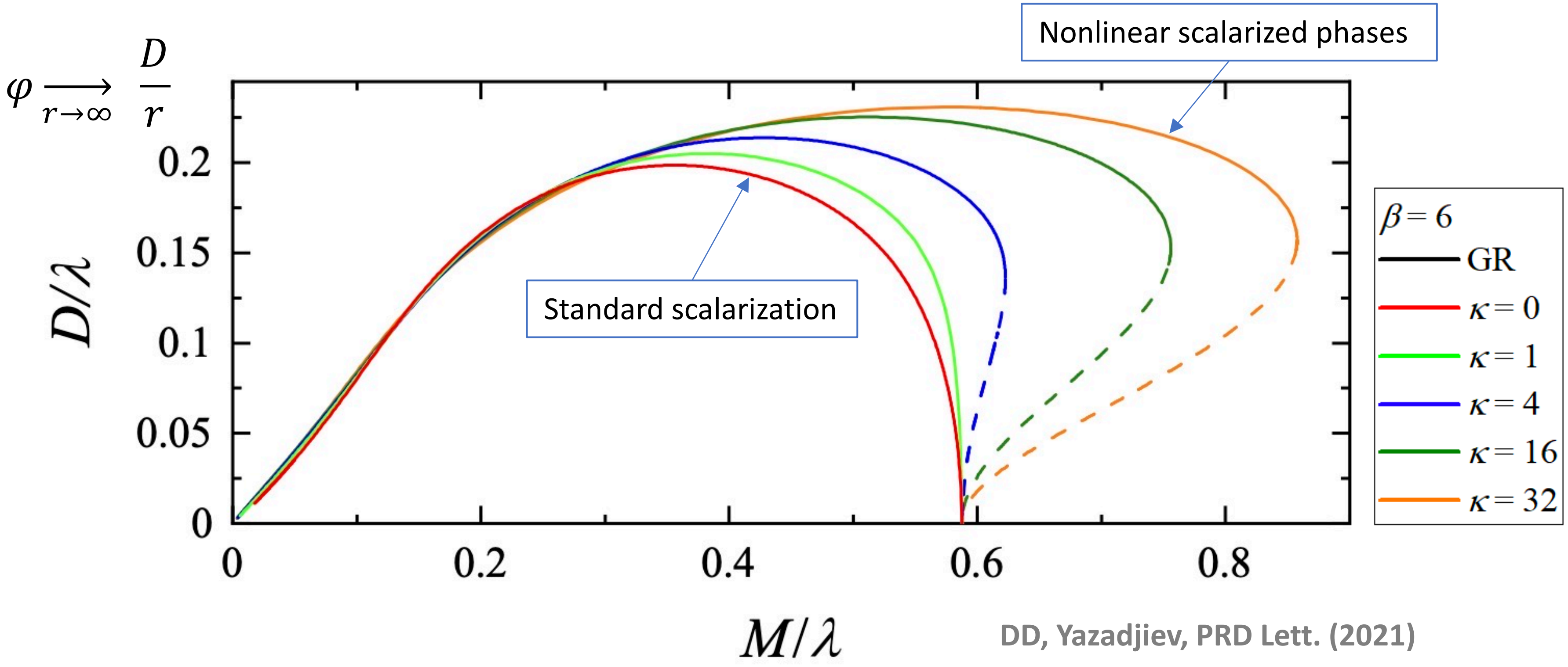
(De)scalarization with a jump during merger

$$f(\varphi) = \frac{1}{2\beta}\left(1 - e^{-\beta(\varphi^2+\kappa\varphi^4)}\right)$$



DD, Yazadjiev, PRD Lett. (2021)

- Transition from **stable scalarized to GR** happens with a **jump**
- For a similar effect for charged BH see Blázquez-Salcedo et al. PLB (2020)

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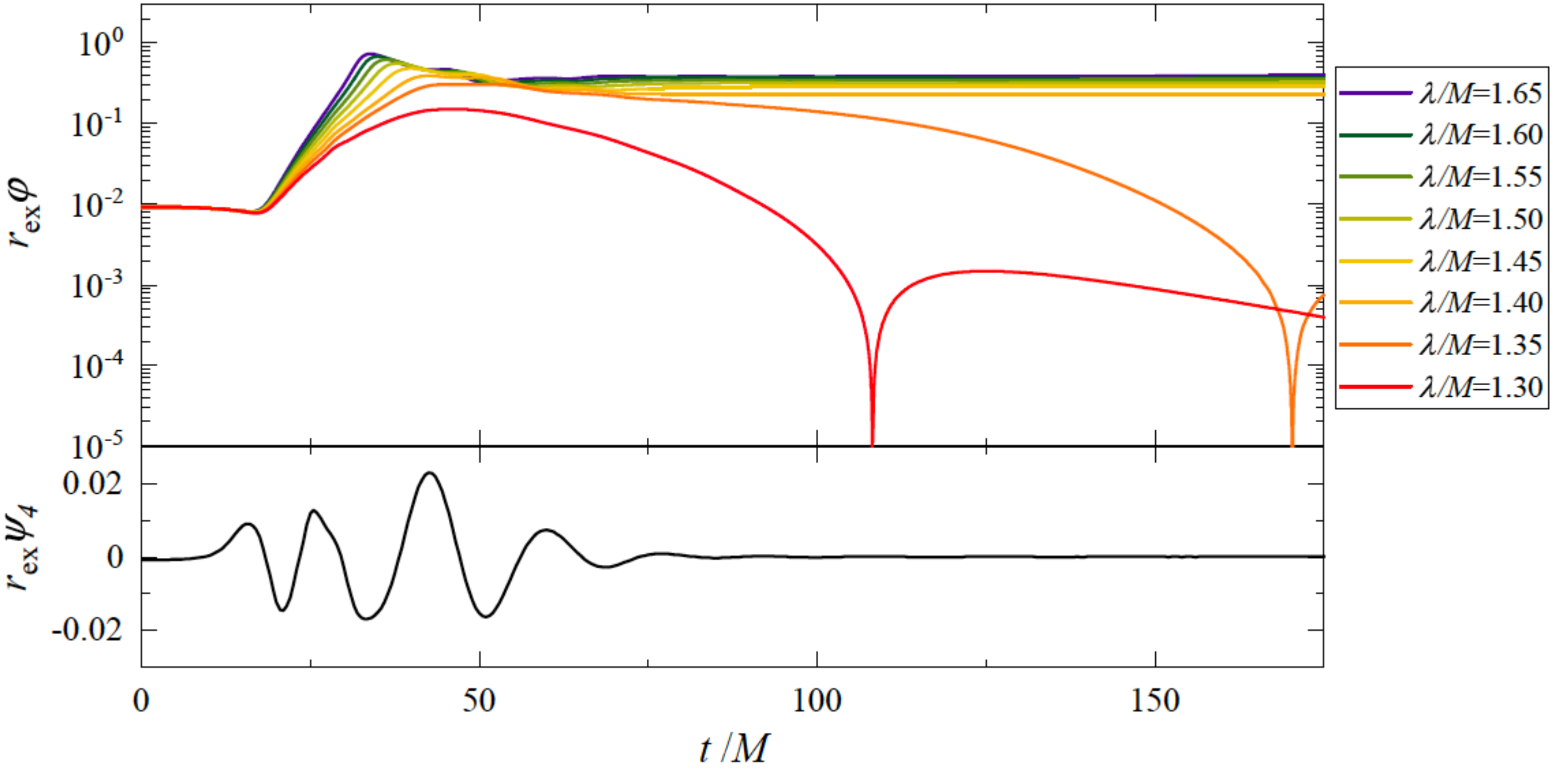
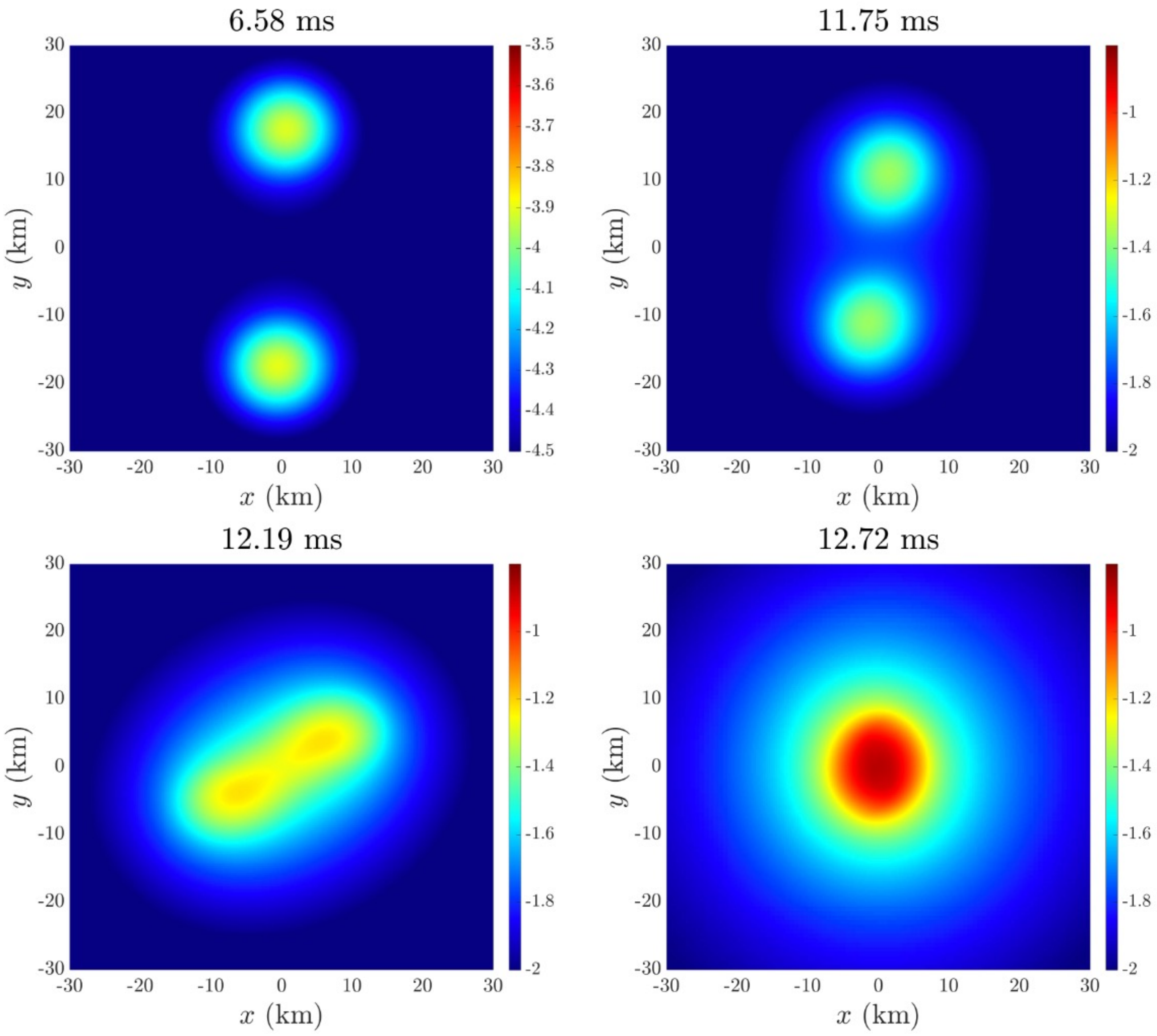


DD, Vano-Vinuales, Yazadjiev PRD (2022)

- **Similarities** with the **matter phase transitions** during neutron star binary mergers Most et al. PRL (2019), Bauswein et al. PRL (2019), Weih et al. (2020).

Binary neutron star mergers



Kuan, Lam, DD, Yazadjiev, Shibata, Kiuchi (2023)

EMRIs - inverse chirp signal

Supermassive black holes beyond GR

Kerr black holes with scalar hair

- A minimally coupled **complex massive scalar field** Φ

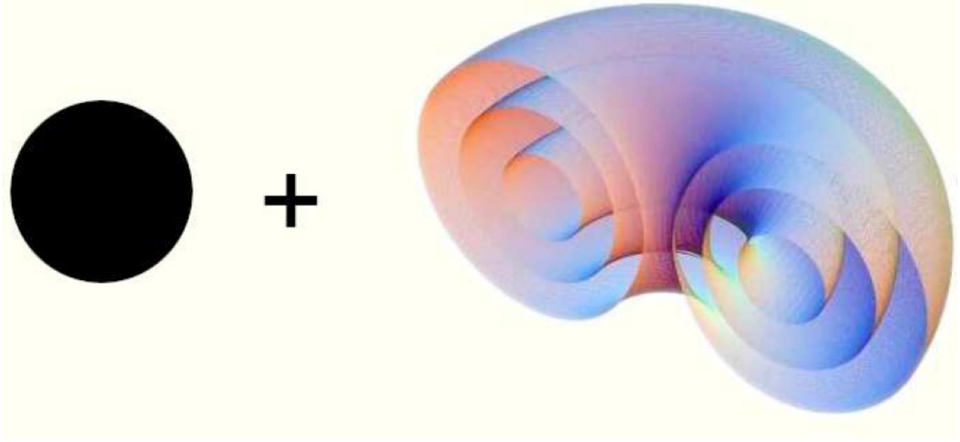
$$S = \int \left[\frac{R}{2} - g^{\mu\nu}\partial_\mu \Phi^* \partial_\nu \Phi - 2U(\Phi) \right] \sqrt{-g}\, d^4x \,, \quad \text{with} \quad U = \frac{1}{2}\mu^2 |\Phi|^2$$

- Scalar field **NOT** stationarity and axisymmetric (similar to boson start)

$$\Phi = \phi(r,\theta) e^{i(\omega t + m\varphi)}$$

- The **Noether charge -> number of particles**.

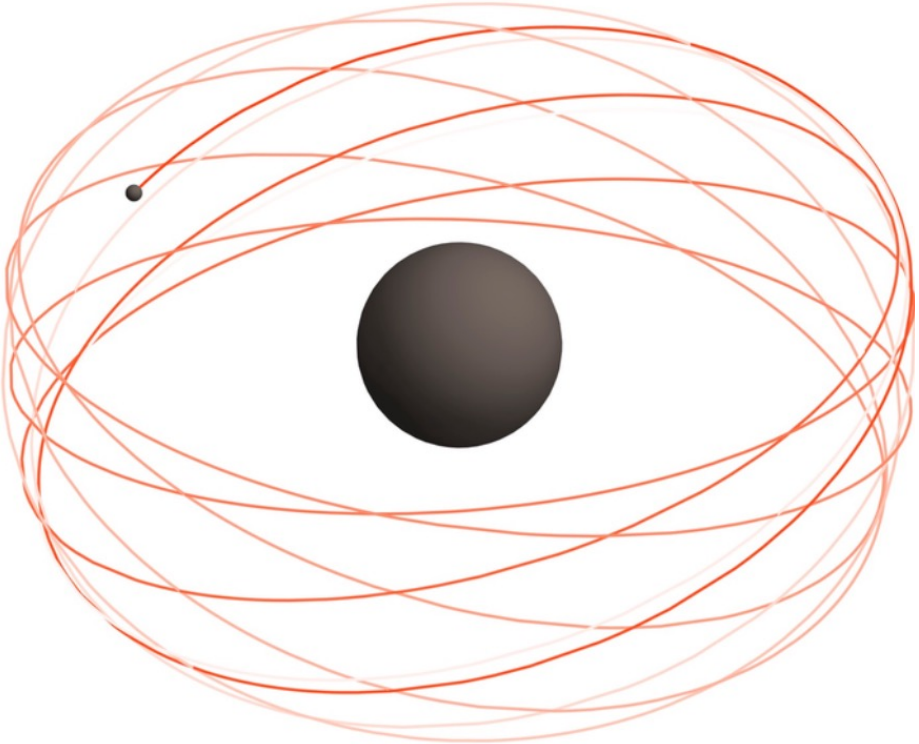
- The scalar field forms a **torus** (similar to rotating boson stars)



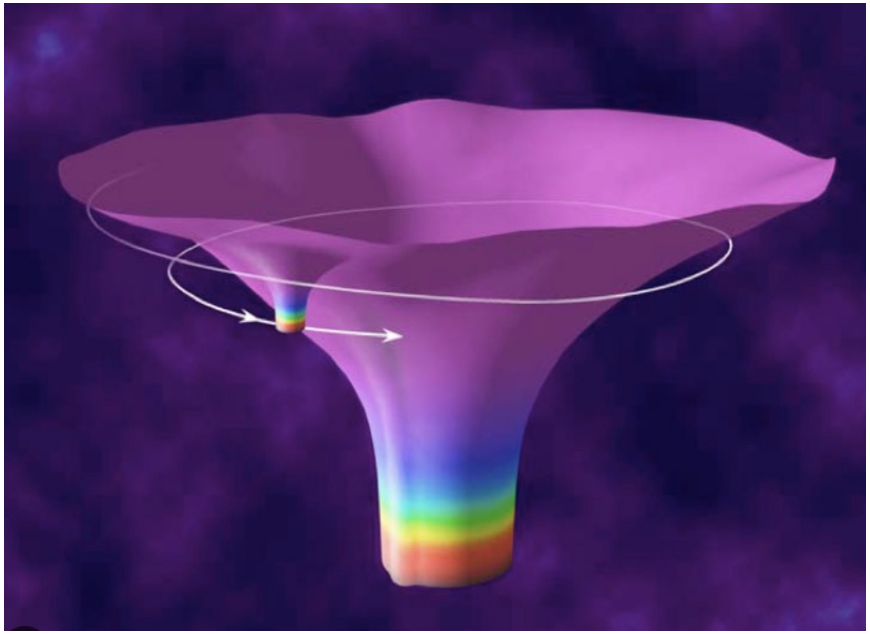
Herdeiro, Radu PRL (2015)

Extreme mass-ratio inspiral

- A small object (e.g. a black hole) orbiting a massive black
- Can be observed with LISA
- A perfect way to “feel” the geometry of spacetime

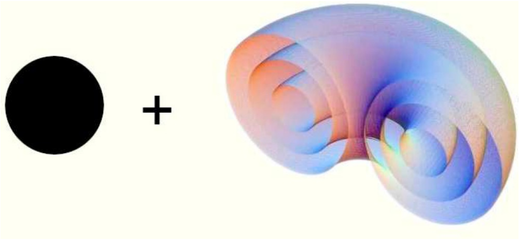


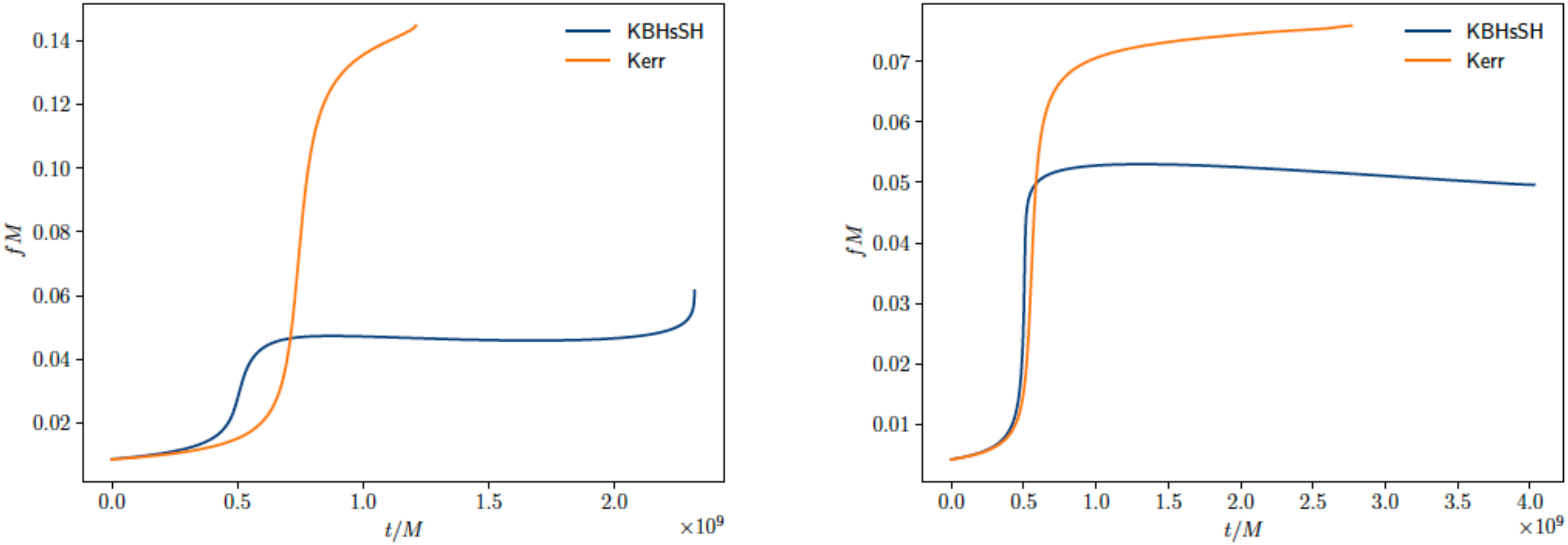
CREDIT: N. FRANCHINI



Extreme mass-ratio inspiral

Kerr BH + Rotating Boson Star





Collodel, DD, Yazadjiev PRD(2021)

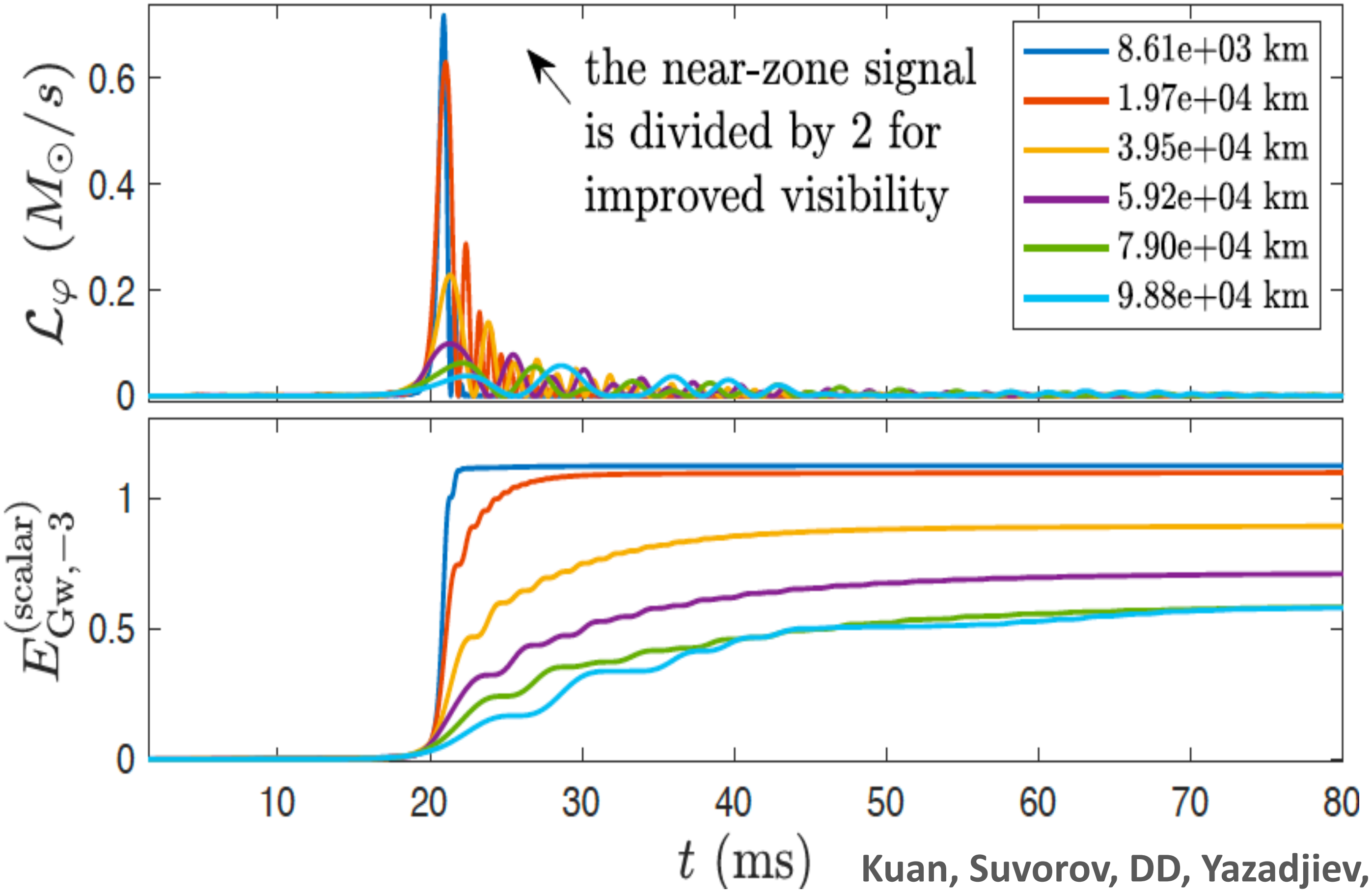
Conclusions

- GWs are among the ultimate tools to test beyond-GR physics
- Quantitative vs. Qualitative – tracing the smoking guns
- Jumps in the equilibrium properties ⇒ specifics in the GW signal
- **Final goal:** understand which exotics are physically motivated and constrain them via GWs.

THANK YOU!

Scalar radiation

- **Massive scalar field**: Modes with distinct frequencies propagate at **different subluminal velocities**
- A dispersively stretched burst



Kuan, Suvorov, DD, Yazadjiev, PRL (2022)