EBERHARD KARLS
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Emmy Noether-Programm

DFG Deutsche Forschungsgemeinschaft

Tracing beyond GR physics with gravitational waves *qualitative vs quantitative*

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Approaches in testing strong gravity

Model independent
(e.g. PPN formalism)

- Much simpler
- No prior knowledge of the modified gravity theory is needed

- Mapping to a modified gravity models is not straightforward
- Performing dynamics is not possinle

Model dependent
(bounded to a given modified gravity theory)

- Observational implications predicted self consistently from a modified theory
- Gives intuition about what is physically relevant

- Much more involved

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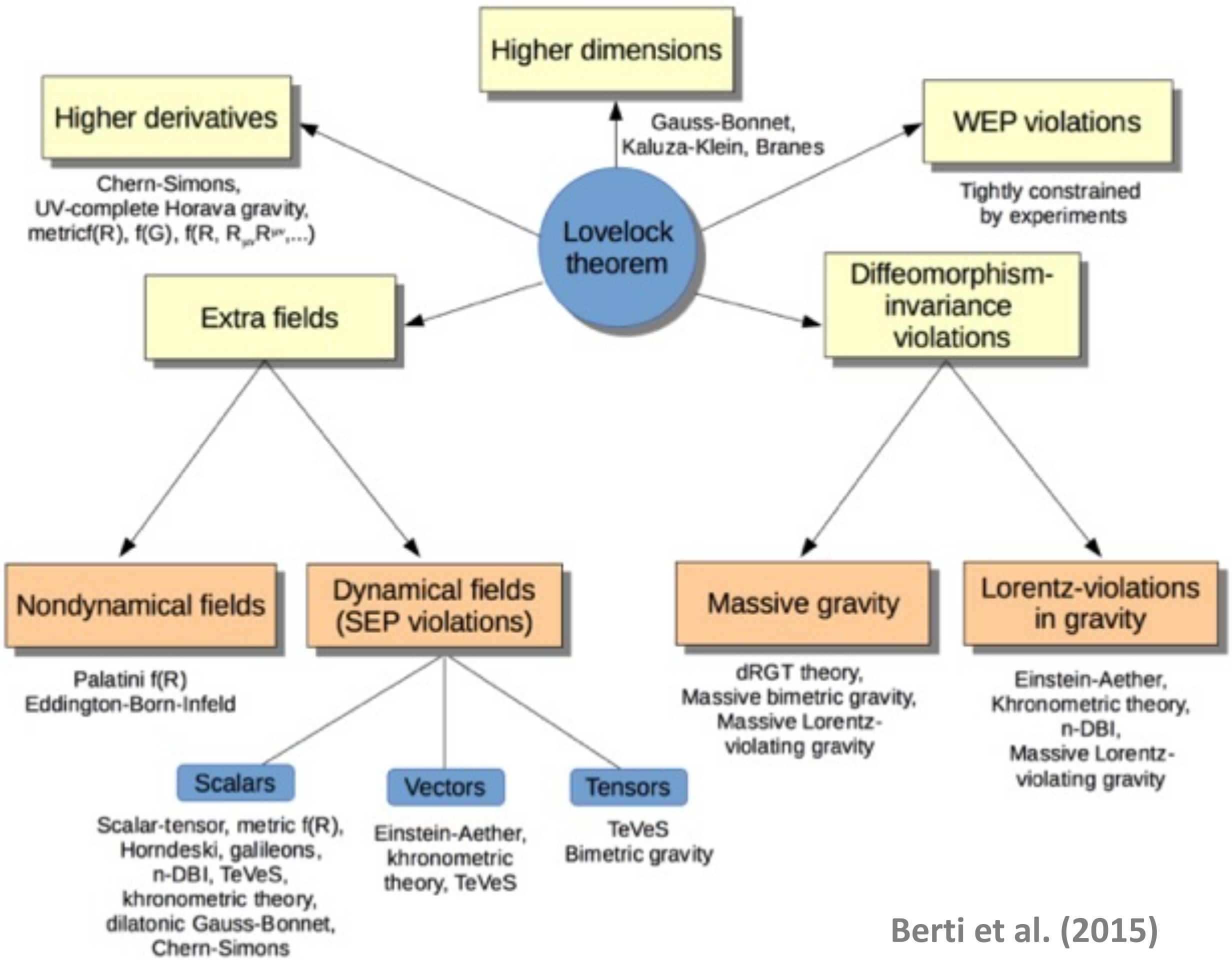
Lovelock's theorem

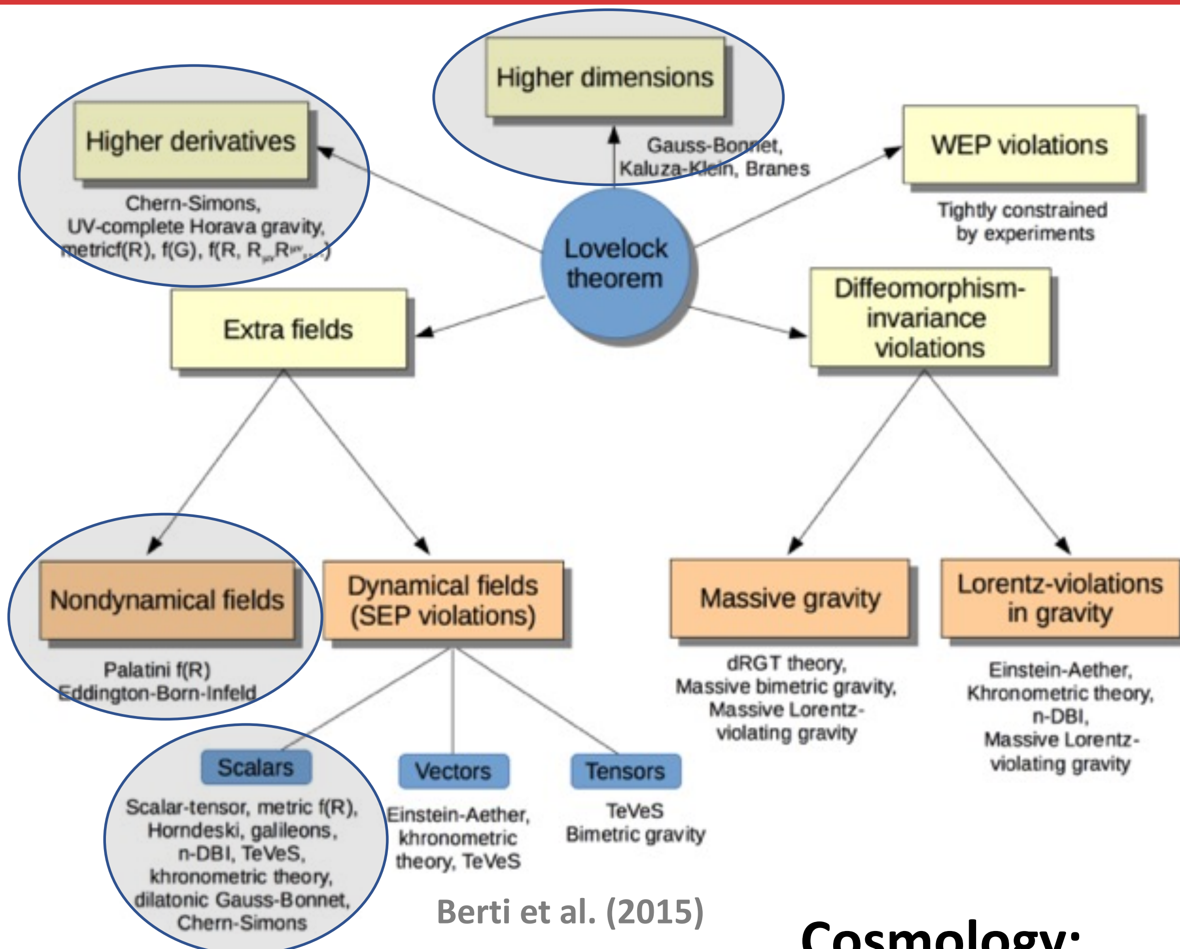
Einstein's field equations are **unique** if:

- ✓ we are working in **four dimensions**
- ✓ **diffeomorphism invariance** is respected
- ✓ the **metric** is the **only field** mediating gravity
- ✓ the equations are **second-order differential equations**.



Berti et al. (2015)

Extra scalar field(s)



Berti et al. (2015)

Quantum gravity motivated:

- Gauss-Bonnet gravity
- Chern-Simons gravity

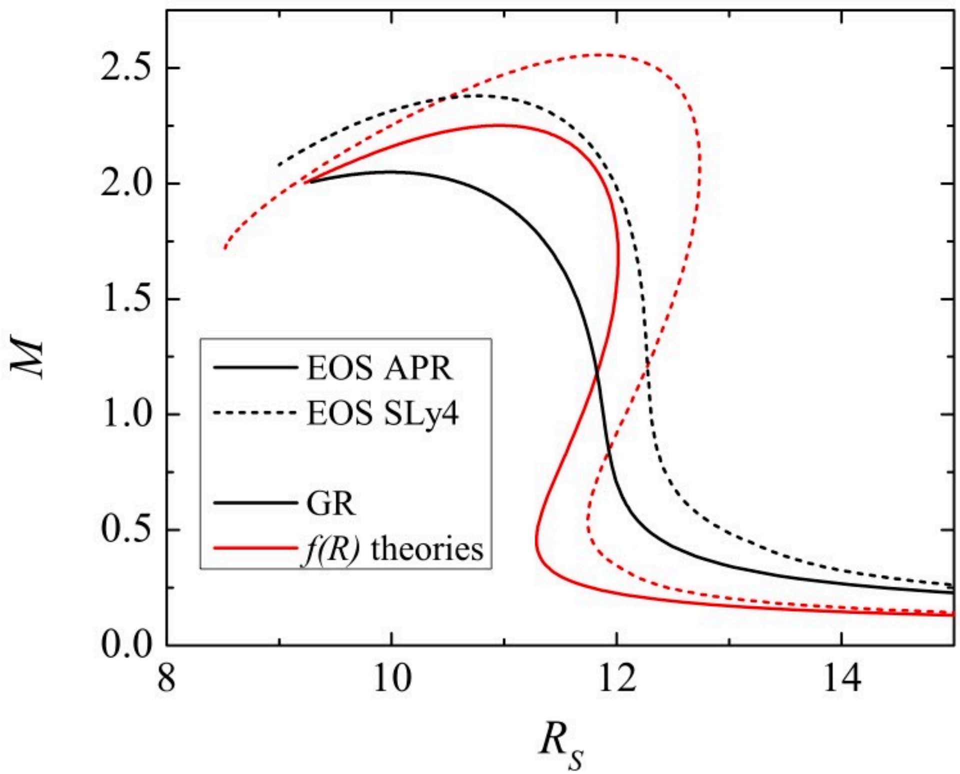
Cosmology:

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

Changes in the GW spectrum

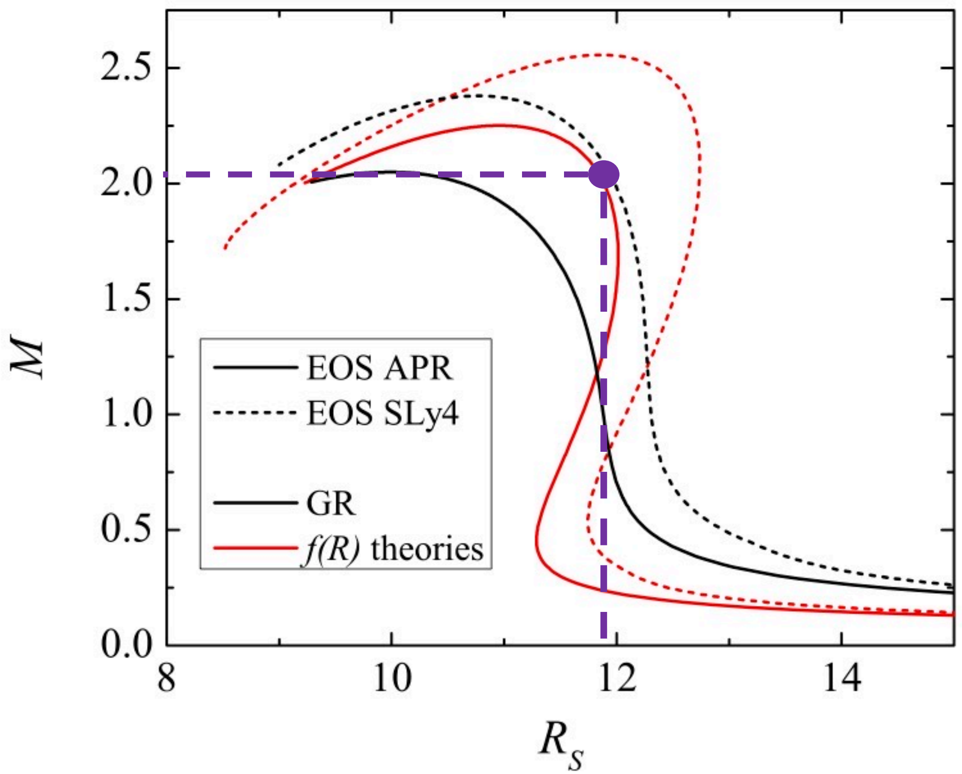
Quantitative vs. Qualitative

Quantitative changes



Modifying the theory of gravity $\Longleftrightarrow$ EOS uncertainty

Quantitative changes



Modifying the theory of gravity ⟺ EOS uncertainty

Quantitative vs. Qualitative

Jumps in GW emission during merger

Gauss-Bonnet gravity - Scalarization

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

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

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**

Gauss-Bonnet gravity - Scalarization

- **Scalar field equation :**

$$\nabla_\alpha \nabla^\alpha \varphi = \frac{1}{4}\frac{dV(\varphi)}{d\varphi} - \frac{\lambda^2}{4}\frac{df(\varphi)}{d\varphi}\mathcal{R}^2_{GB},$$

- **Conditions for the existence** of scalarized solutions

$$(\Box - \mu^2_{\text{eff}})\delta\varphi = 0 \text{ with } \mu^2_{\text{eff}} = -\frac{\lambda^2}{4}\frac{d^2 f}{d\varphi^2}(0) R^2_{GB} < 0$$

- If $\boldsymbol{\mu^2_{\text{eff}} < 0}$ a **tachyonic instability** is present leading to development of the scalar field. **DD, Yazadjiev PRL (2018), Antoniou et al. PRL (2018), Silva et al. PRL (2018)**

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- 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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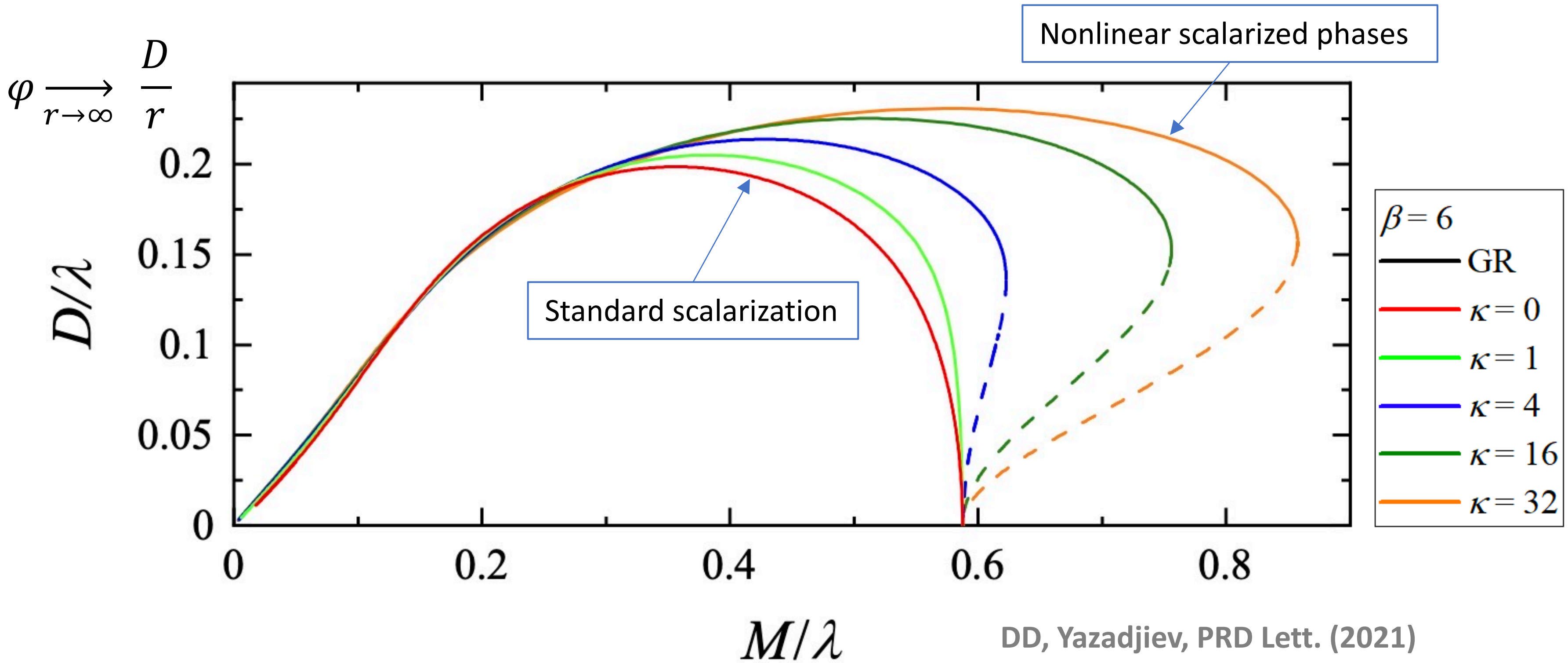
$$\boxed{\text{For scalarization } \frac{d^2 f}{d\varphi^2} \neq 0}$$

(De)scalarization with a jump during merger

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

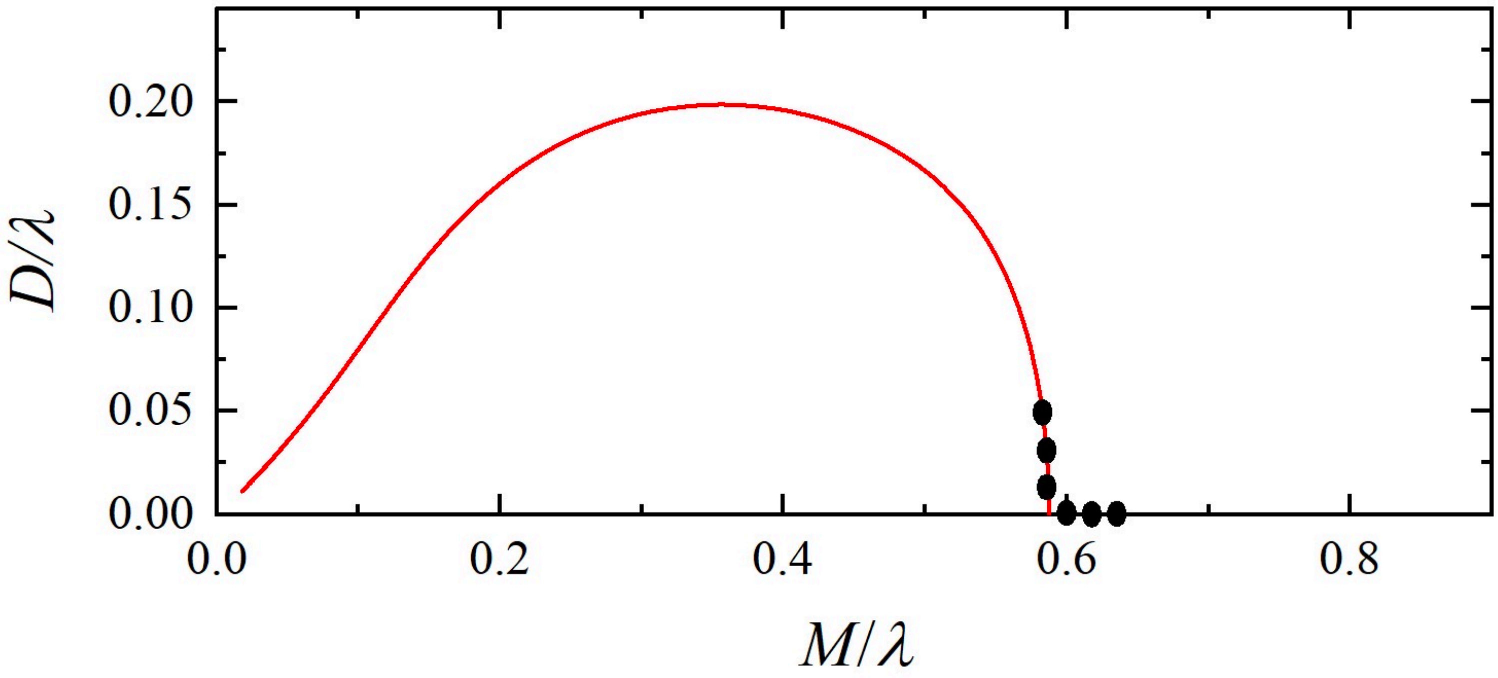


DD, Yazadjiev, PRD Lett. (2021)

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

(De)scalarization WITHOUT a jump during merger

$$f(\varphi) = \frac{1}{12}\left(1 - e^{-6\varphi^2}\right)\ (\beta = 6, \kappa = 0)$$



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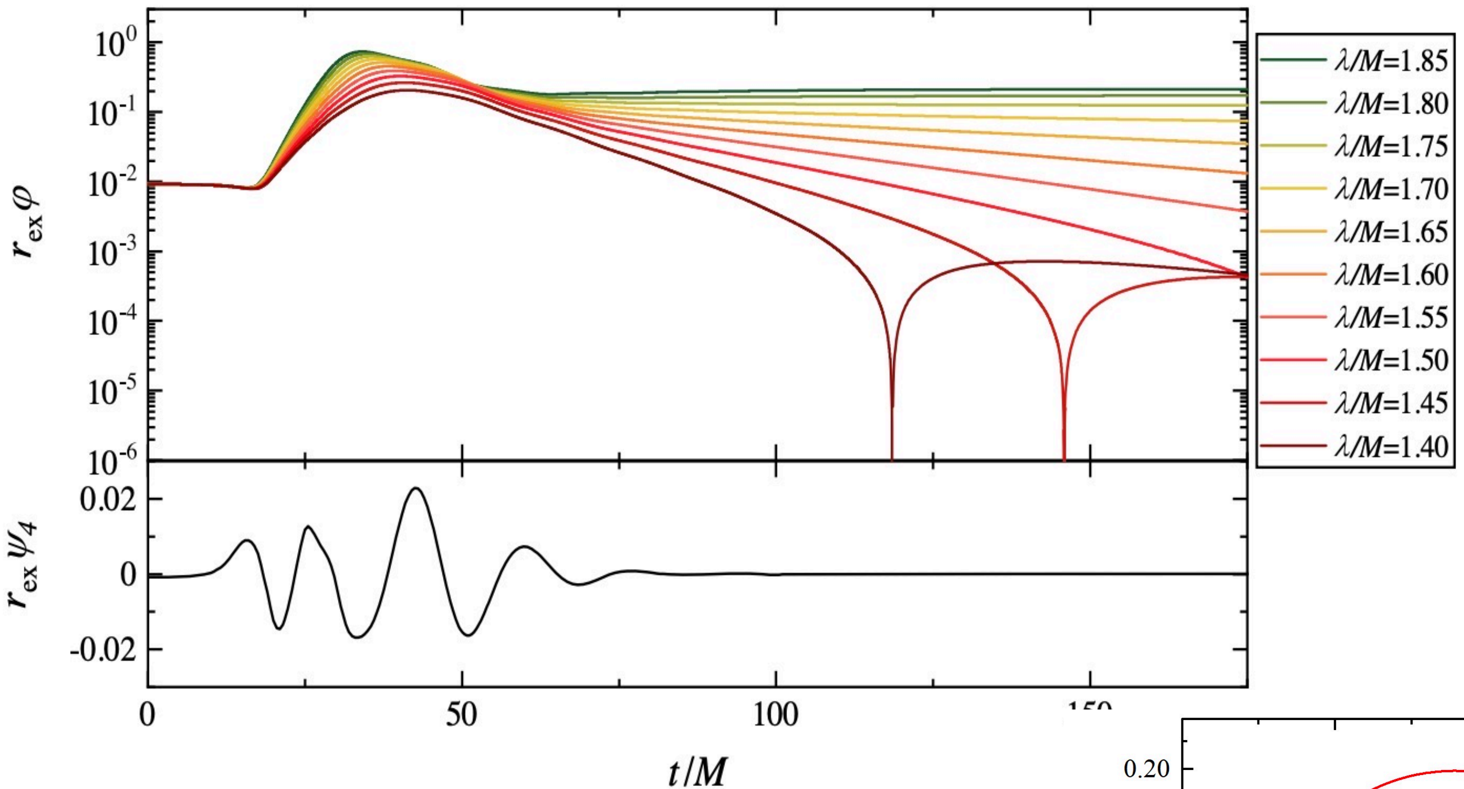
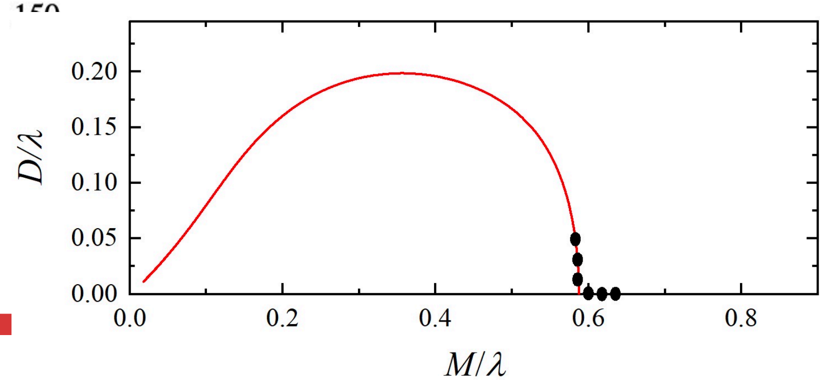
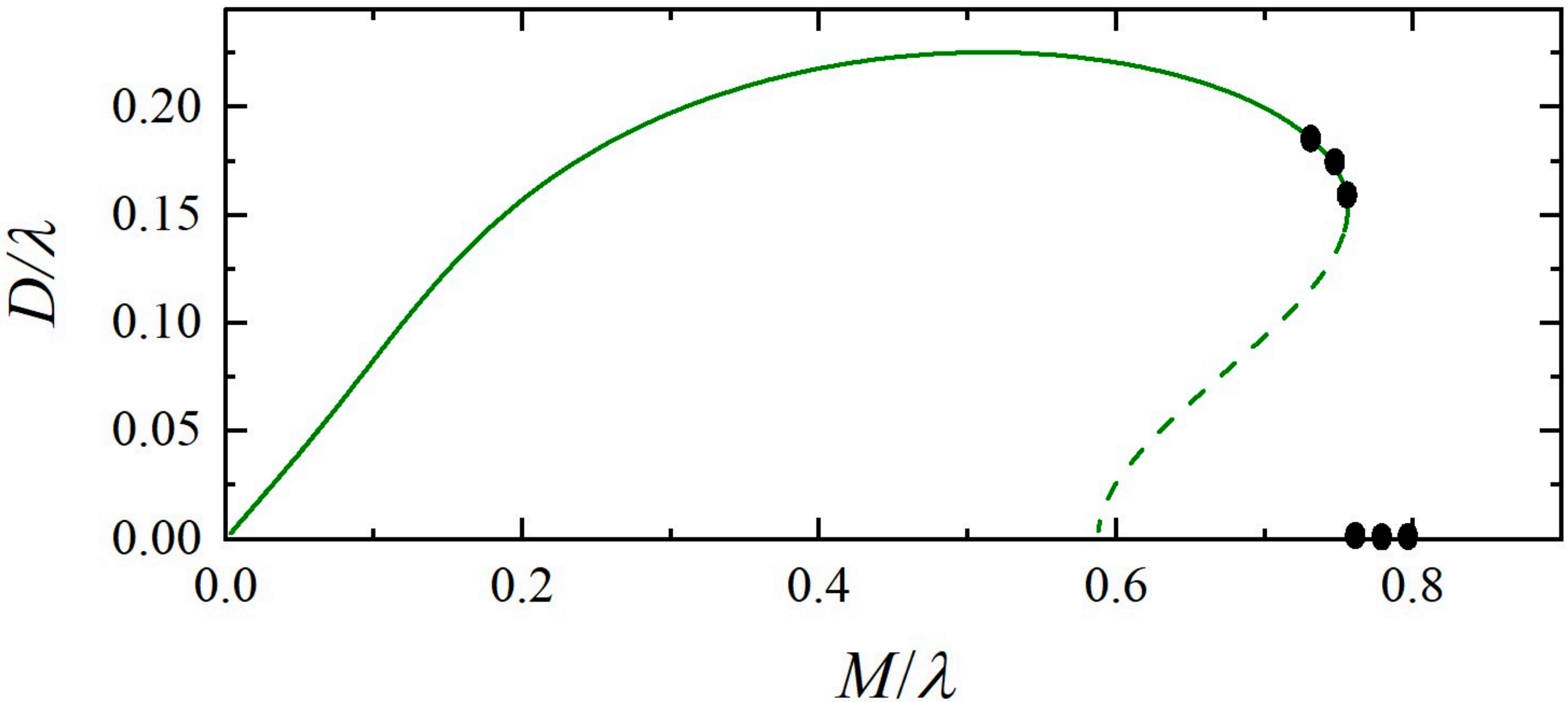


DD, Vano-Vinuales, Yazadjiev PRD (2022)



(De)scalarization WITH a jump during merger

$$f(\varphi) = \frac{1}{12}\left(1 - e^{-6\left(\varphi^2+16\varphi^4\right)}\right)\ (\beta = 6, \kappa = 16)$$



DD, Vano-Vinuales, Yazadjiev PRD (2022)

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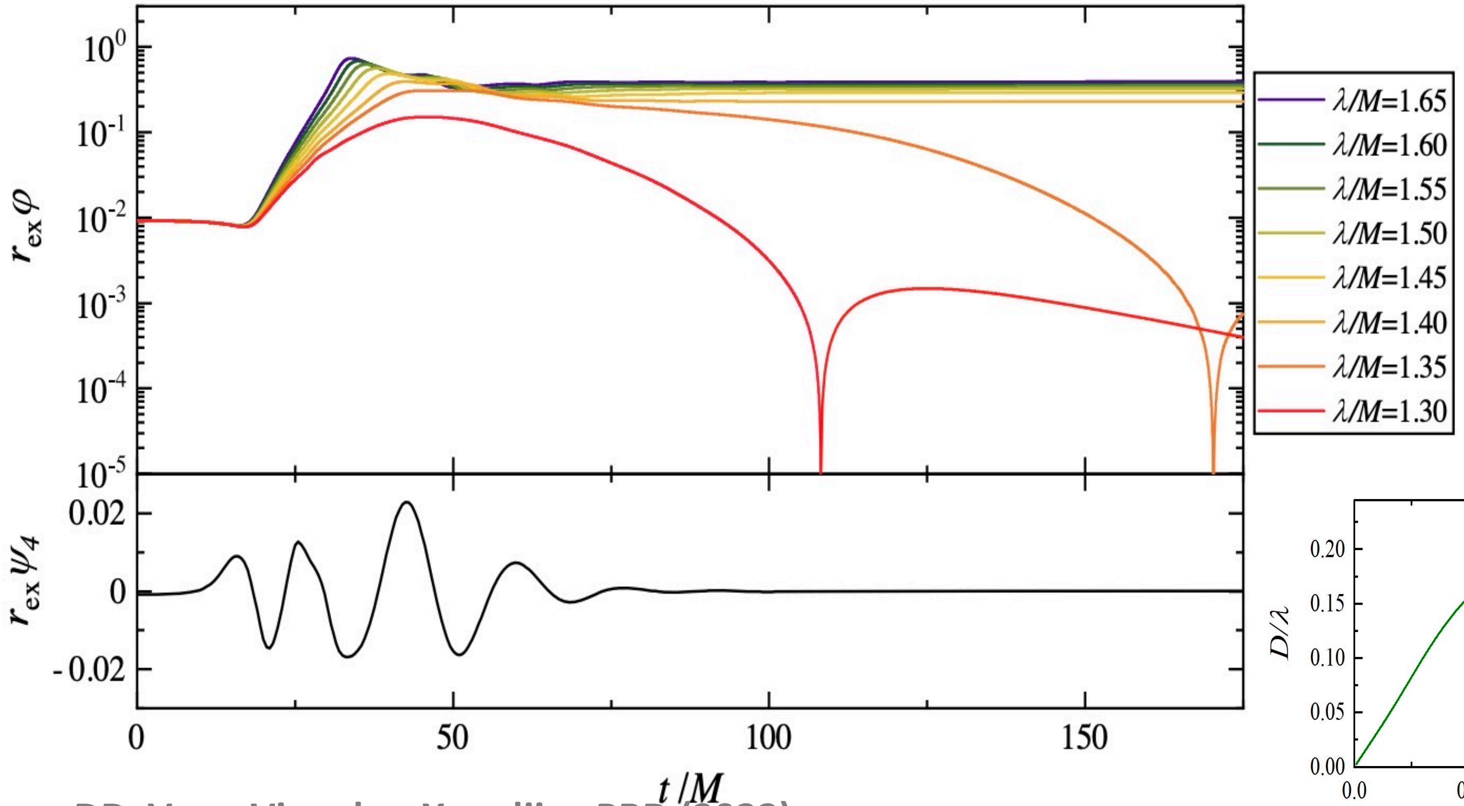
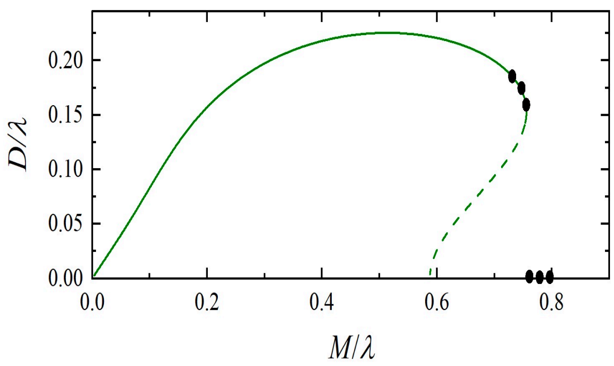




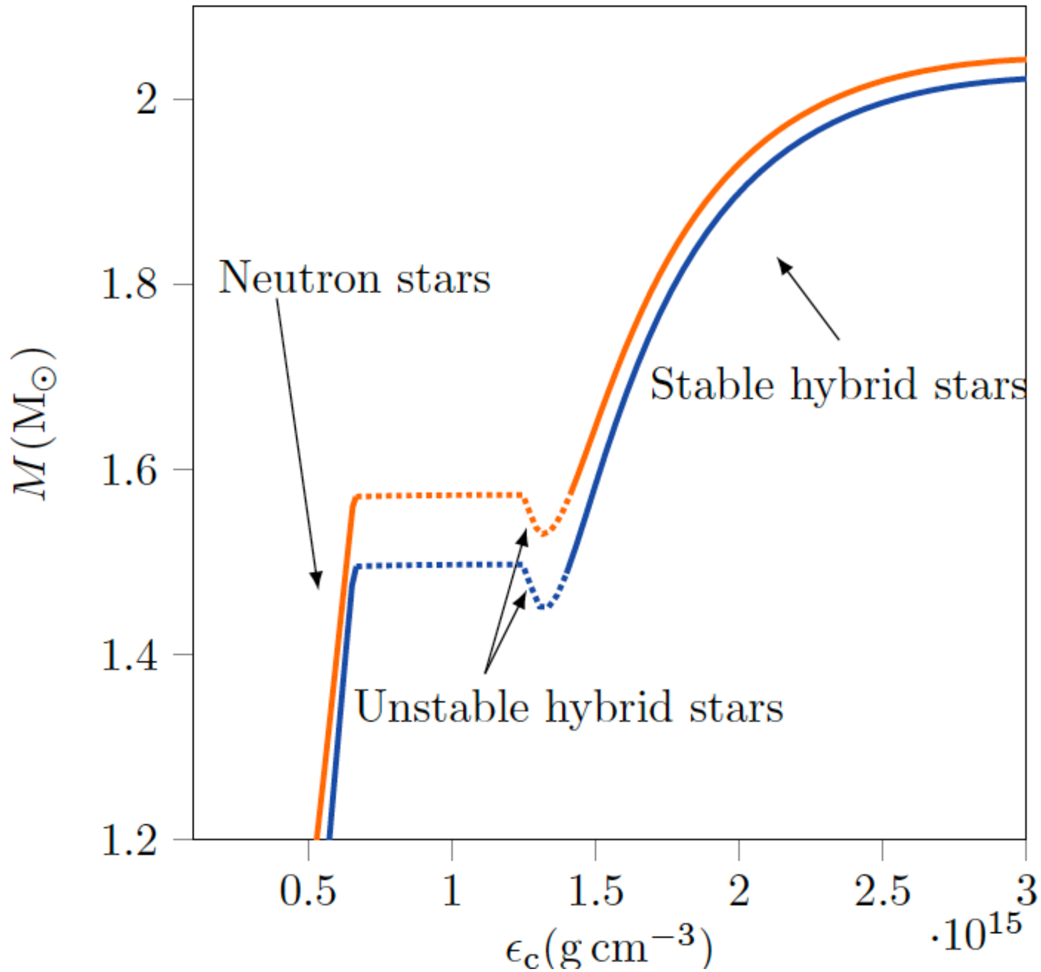
DD, Vano-Vinuales, Yazadjiev PRD (2022)

- **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).

Gravitational Phase Transitions

Matter phase transitions in GR: Twin Stars

- Matter phase transitions from nuclear matter to deconfined quark matter



Espino, Paschalidis (2021)

Scalarized neutron stars – DEF model

- **Scalarization of neutron stars** Damour&Esposito-Farese PRL (1993) due to a **nonzero trace** of the energy momentum tensor. **Energetically more favorable** over the GR solutions.

$$S = \frac{1}{16\pi G_*}\int d^4x\,\sqrt{g}\,[R - \underbrace{\boxed{2g^{\mu\nu}\partial_\mu\varphi\partial_\varphi\varphi}}_{\text{Kinetic term}} - \cancel{\boxed{4V(\varphi)}}] + S_m[\psi_m, \underbrace{\boxed{A^2(\varphi)}}_{\text{Coupling term}} g_{\mu\nu}]$$

- **Coupling function** – polynomial expansion in φ

$$\alpha(\varphi) = \frac{d\ln\big(A(\varphi)\big)}{d\varphi} = \alpha_0 + \beta_0\varphi$$

- Scalar field equation: $\Box\varphi = -4\pi G_*\alpha(\varphi)T$

(reminder in sGB gravity $\Box\varphi = -\frac{\lambda^2}{4}\frac{df(\varphi)}{d\varphi}R^2_{GB}$)

Scalarized neutron stars – DEF model

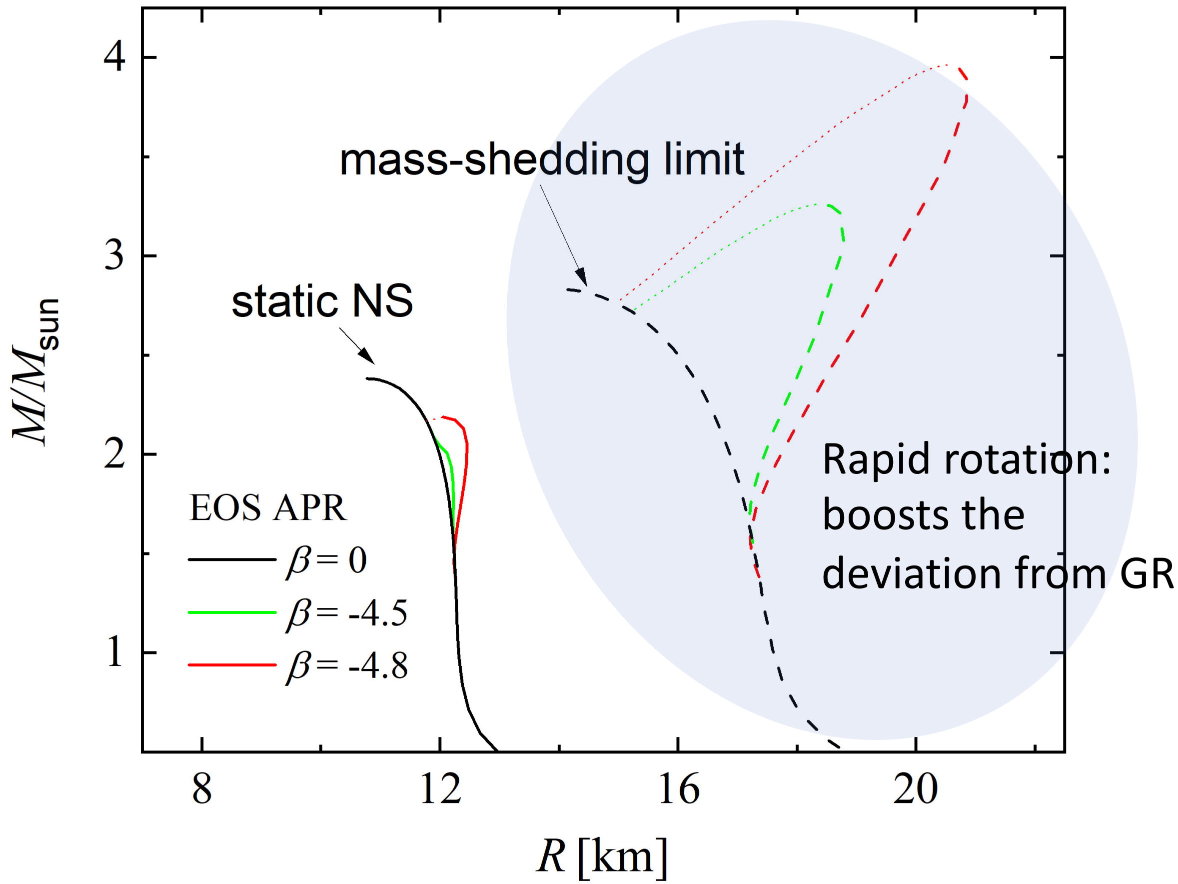
$$\alpha(\varphi) = \alpha_0 + \cancel{\beta_0 \varphi}$$

- **Brans-Dicke theory** – $\varphi = 0$ NOT a solutions, **ruled out** by weak field observations

Scalarized neutron stars – DEF model

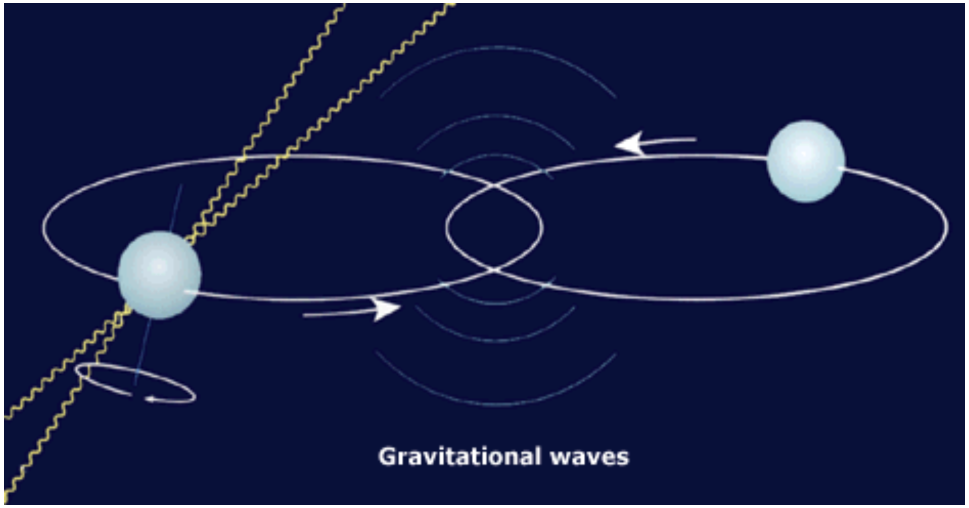
$$\alpha(\varphi) = \cancel{\alpha_0} + \beta_0\varphi \text{ (reminder } \mu_{\text{eff}}^2 = \frac{d\alpha}{d\varphi}|_{\varphi=0} 4\pi G_\star T<0)$$

- Original DEF model Damour&Esposito-Farese (1993)



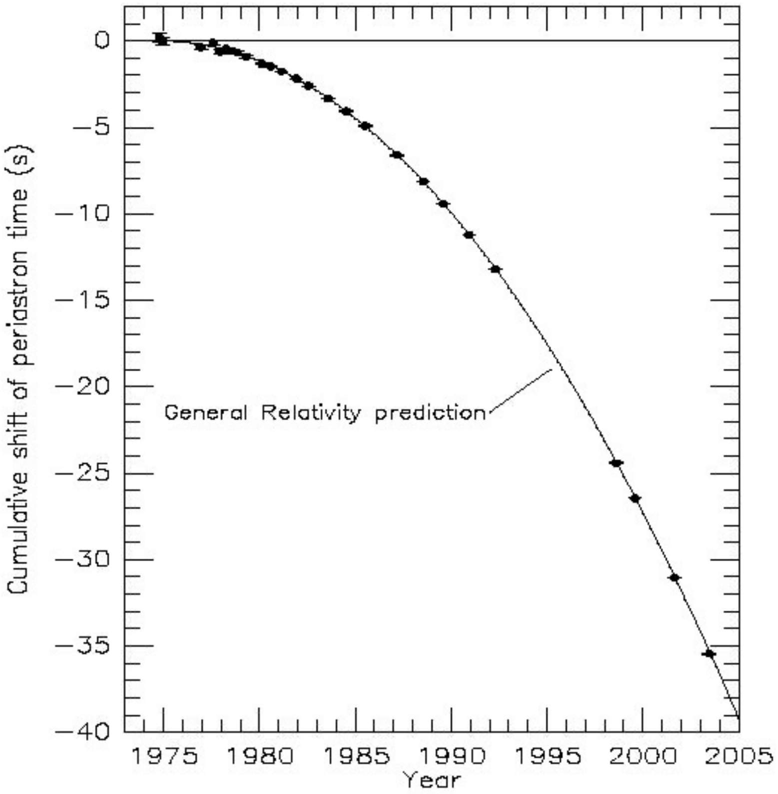
DD, Yazadjiev, Stergioulas, Kokkotas (2013,2014)

Observational constraints – binary pulsars

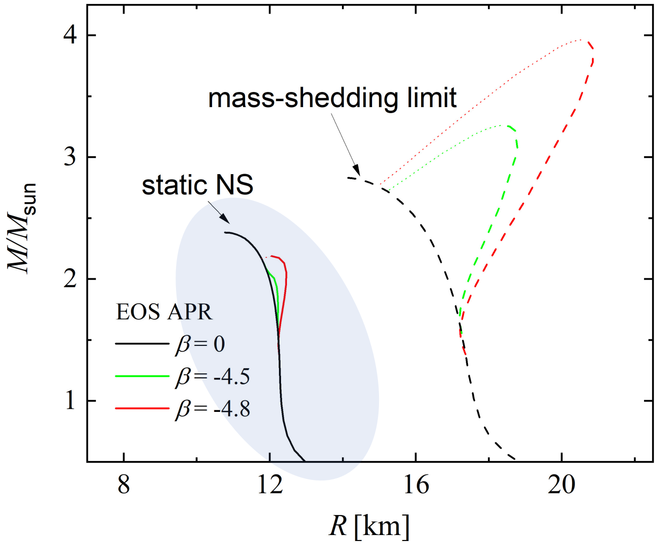


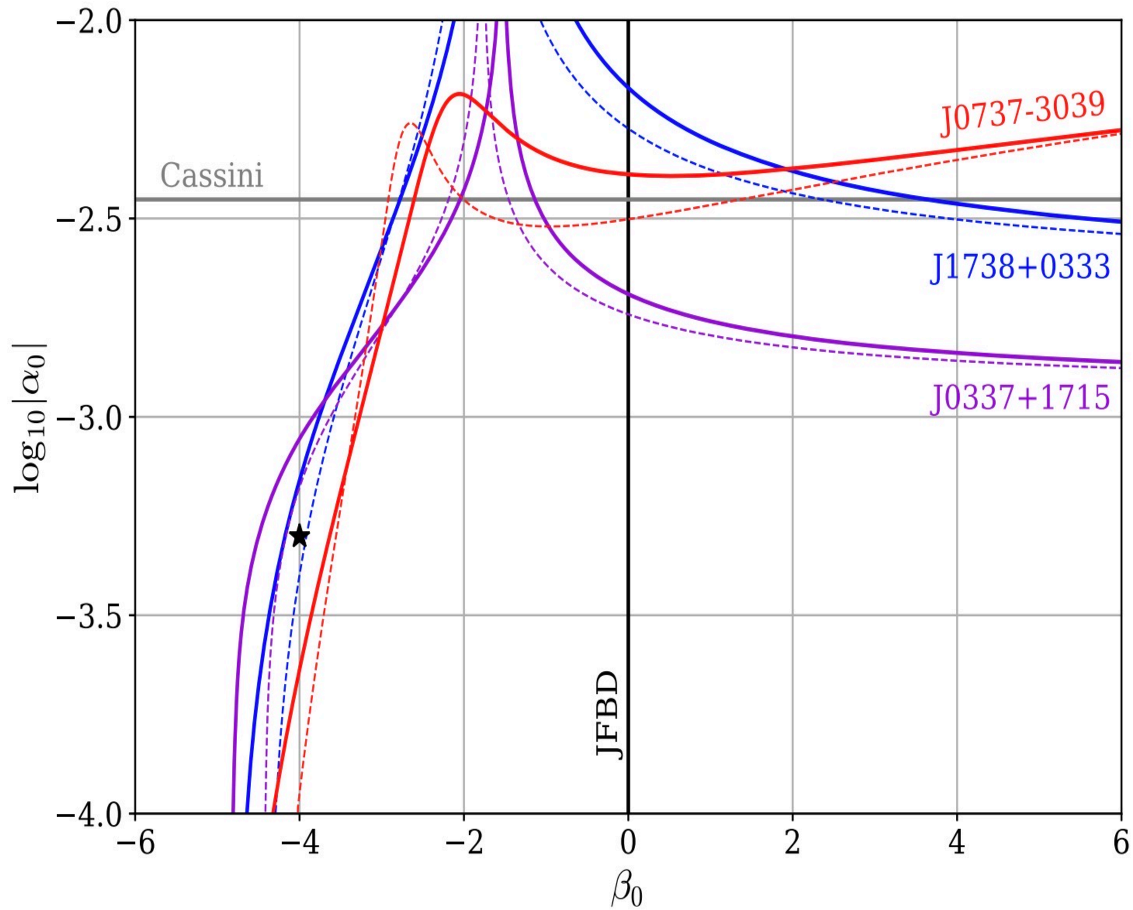
$$\frac{\dot{P}_{b,corrected}}{\dot{P}_{b,GR}} = 1.0013 \pm 0.0021$$

http://arxiv.org/abs/astro-ph/0407149



Original DEF model – Ruled out!





Kramer et al (2021), Zhao et al. (2022)

Evading the constraints – massive scalar field

Scalar field potential

$$V(\varphi) = \frac{1}{2} m_\varphi^2 \varphi^2 + \lambda \varphi^4$$

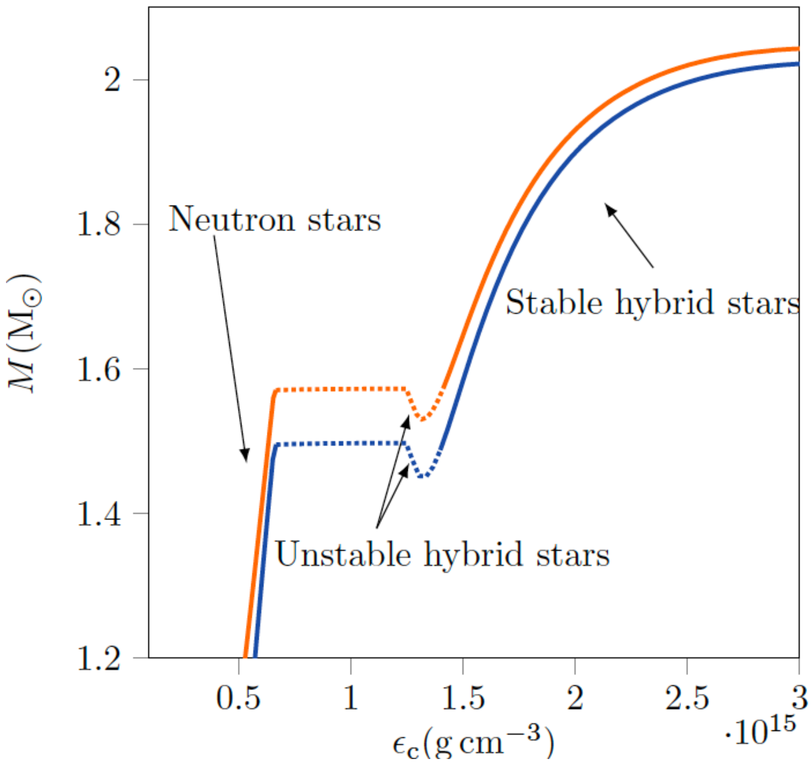
Scalar field mass

Self-interaction term

- Introduces an **effective range of the scalar field** connected to its **Compton wavelength** $\lambda_\varphi = \frac{2\pi}{m_\varphi}$
- For $\boldsymbol{r} \gg \boldsymbol{\lambda_\varphi}$ the scalar field drops exponentially.
- For $m_\varphi \gg 10^{-16}$eV : **not constraints on** $\boldsymbol{\beta_0}$ **Ramazanoglu,Pretorius(2016), Yazadjiev,DD(2016), Rosca-Mead et al. (2020)**

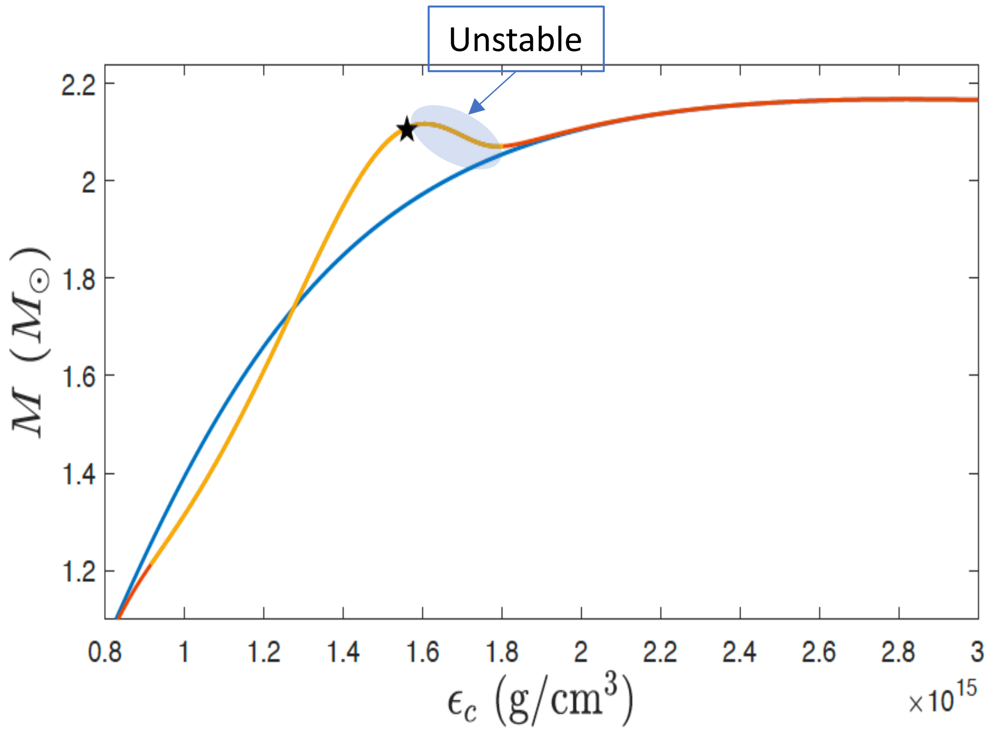
Twin Stars vs. Scalarization

Twin stars



Espino, Paschalidis (2021)

Gravitationally induced phase transition



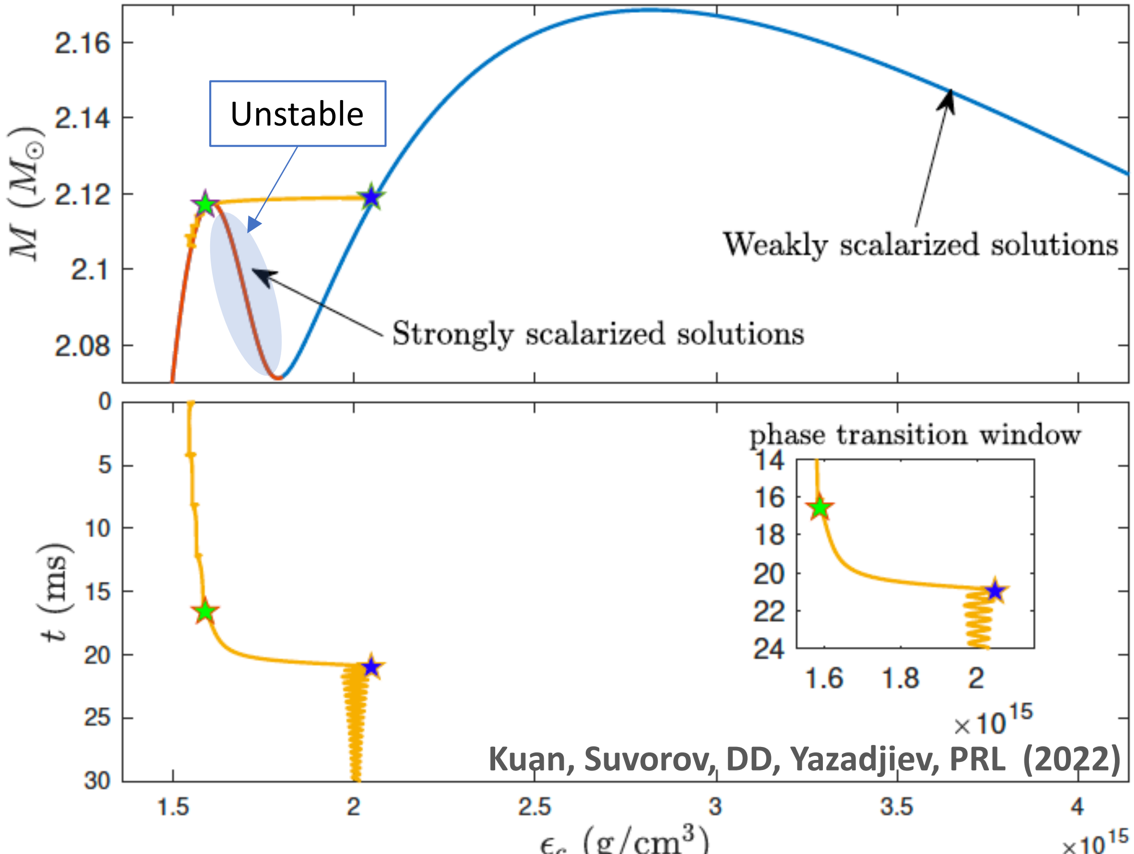
Kuan, Suvorov, DD, Yazadjiev, PRL (2022)

Gravitational phase transition

- **DEF model with a massive scalar field**

$$S = \frac{1}{16\pi G_*}\int d^4x\,\sqrt{g}\,[R - 2g^{\mu\nu}\partial_\mu\varphi\partial_\varphi\varphi - 4V(\varphi)] + S_m[\psi_m, A^2(\varphi)g_{\mu\nu}]$$

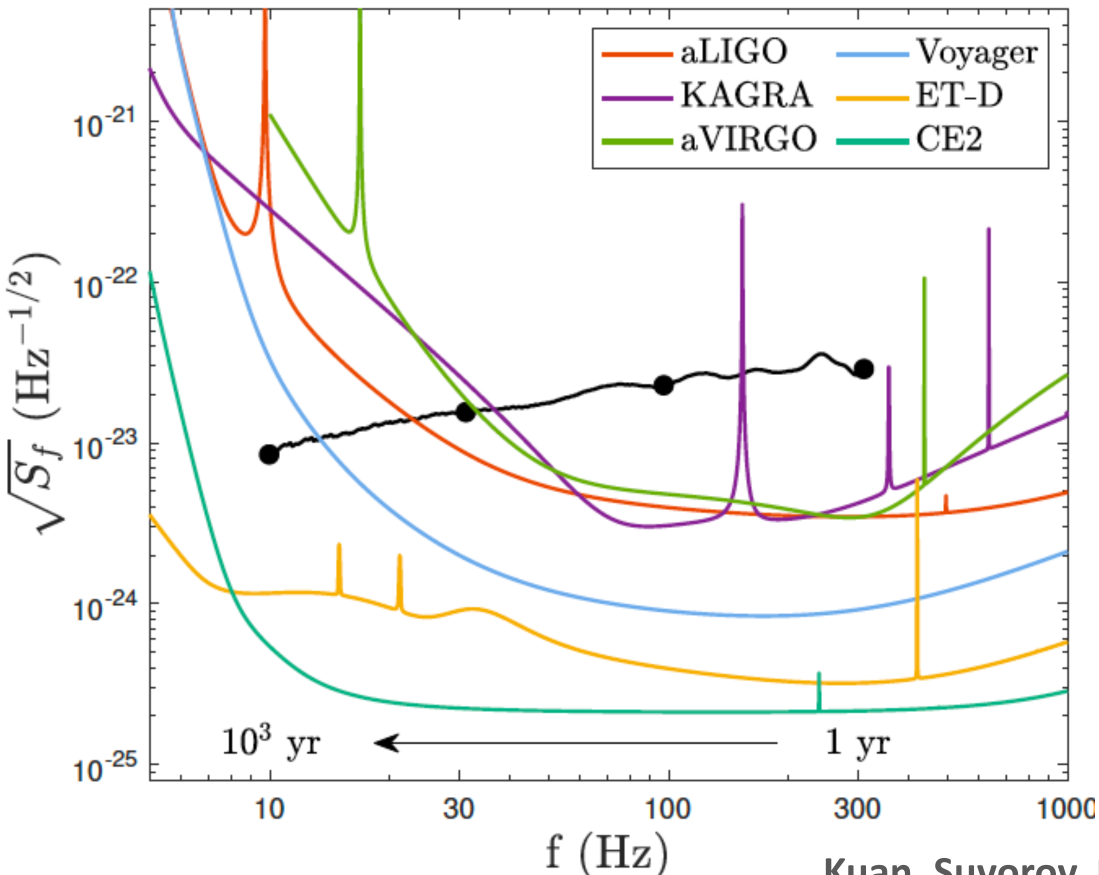
- $V(\varphi) \neq 0$ in order to **avoid binary pulsar constraints** Zhao et al. (2022)



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

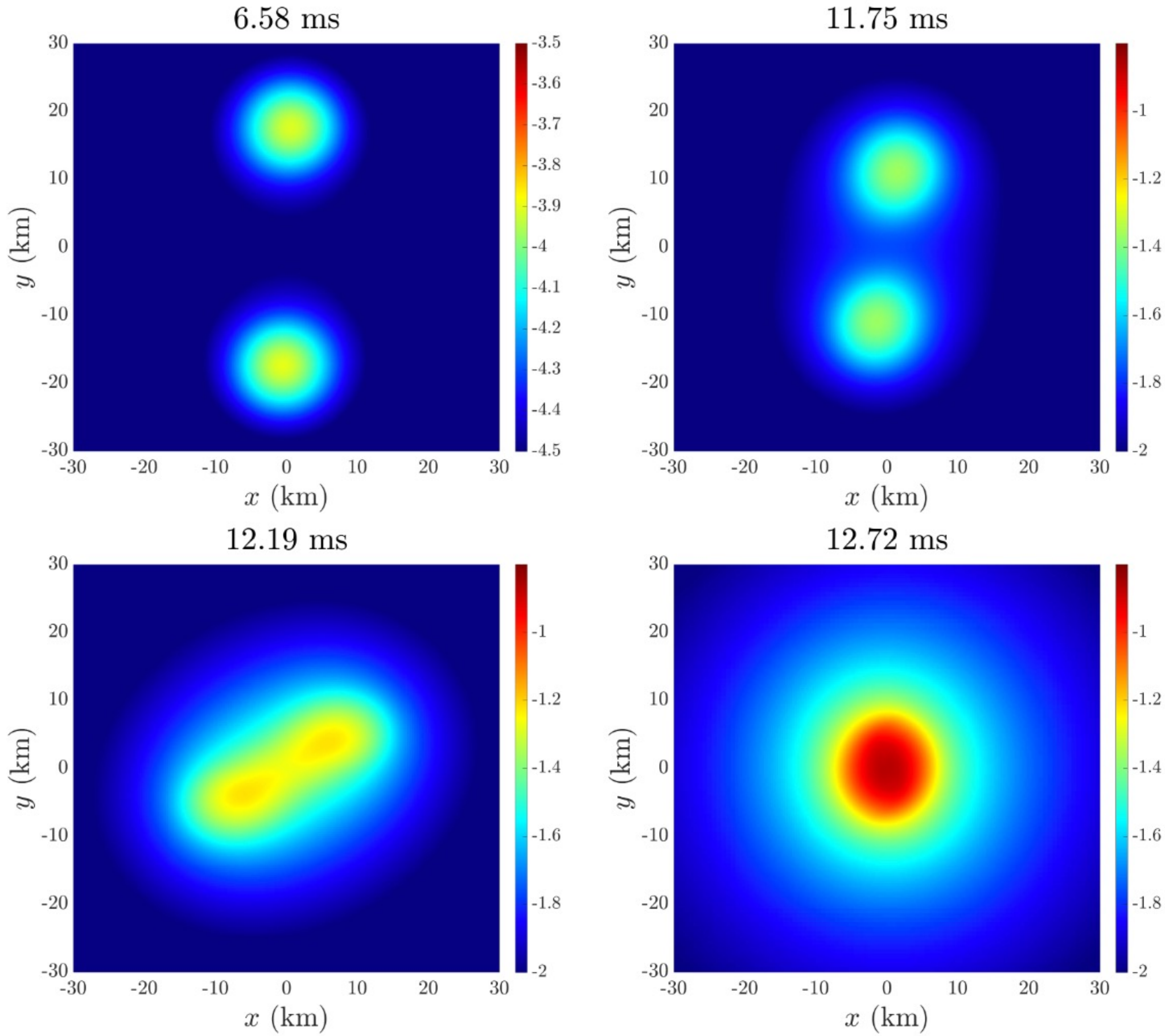
Effective power-spectral density

- Spherically symmetric perturbations ⇒ emission of **breathing modes**
- Observational period 2 months, distance 10kpc



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

Binary neutron star mergers

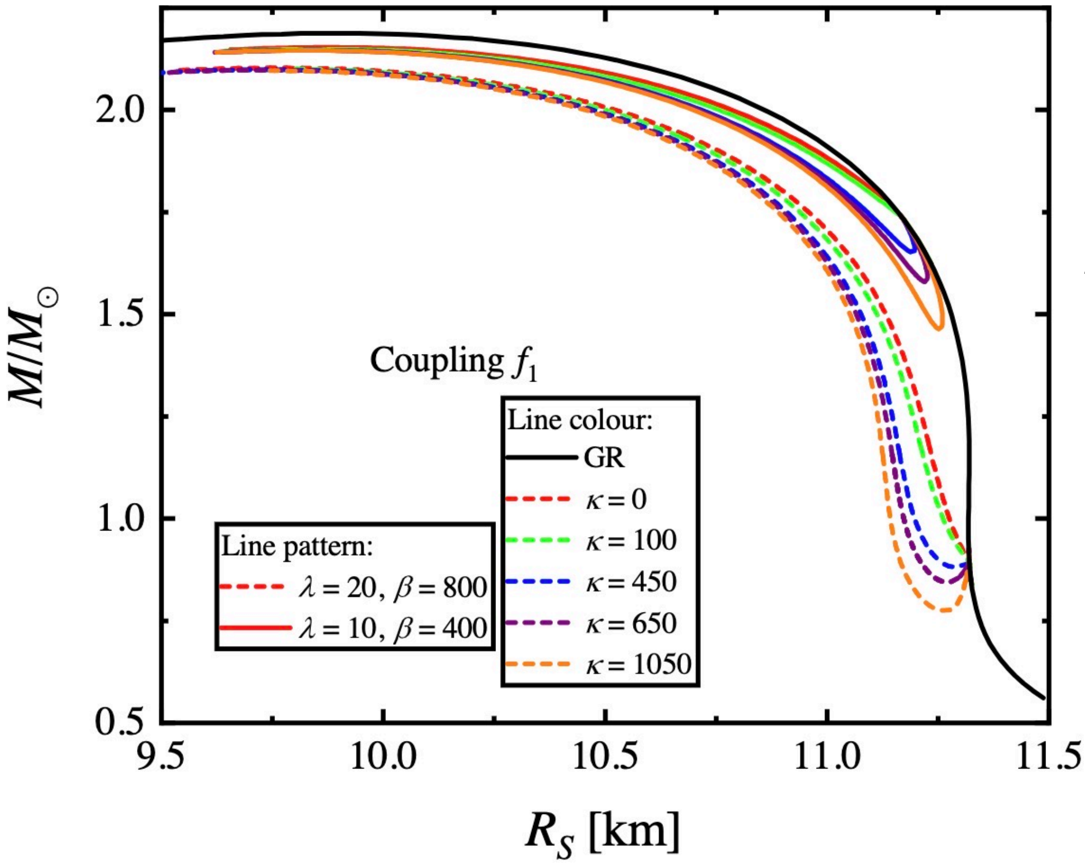


Kuan, Lam, DD, Yazadjiev, Shibata, Kiuchi (2023)

NS scalarization in Gauss-Bonnet gravity

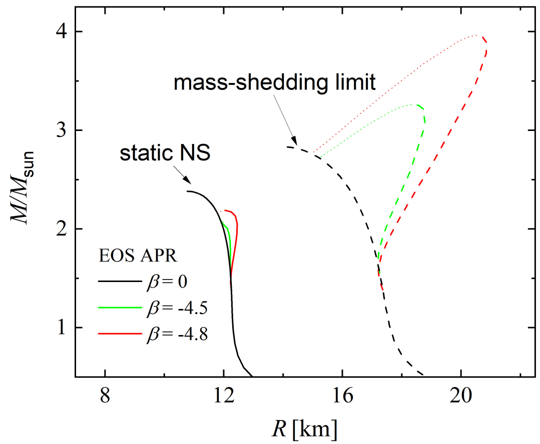
- Scalar field trigerred by the curvate itself through R_{GB}^2

$$S = \frac{1}{16\pi}\int d^4x\sqrt{-g}\left[R - 2\nabla_\mu\varphi\nabla^\mu\varphi + \lambda^2 f(\varphi)\mathcal{R}^2_{GB}\right] + S_{\rm matter}(g_{\mu\nu},\chi)$$



$$f_1(\varphi) = \frac{1}{2\beta}\left(1 - e^{-\beta(\varphi^2+\kappa\varphi^4)}\right)$$

DEF model



DD, Yazadjiev JCAP (2019), Staykov et al (in prep.)

EMRIs - inverse chirp signal

Kerr black holes with scalar hair

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

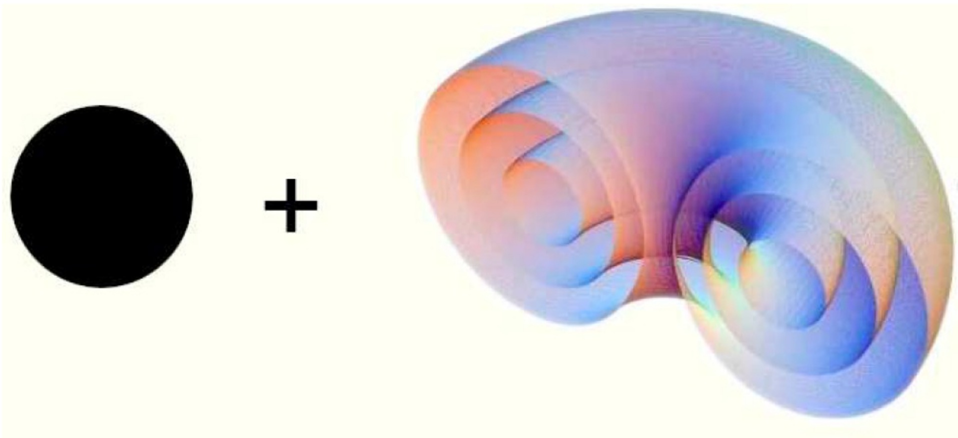
$$S = \int \left[\frac{R}{2} - g^{\mu\nu}\partial_\mu \Phi^* \partial_\nu \Phi - 2U(\Phi) \right] \sqrt{-g}\, d^4x \,, \quad \text{with} \quad U = \frac{1}{2}\mu^2 |\Phi|^2$$

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

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

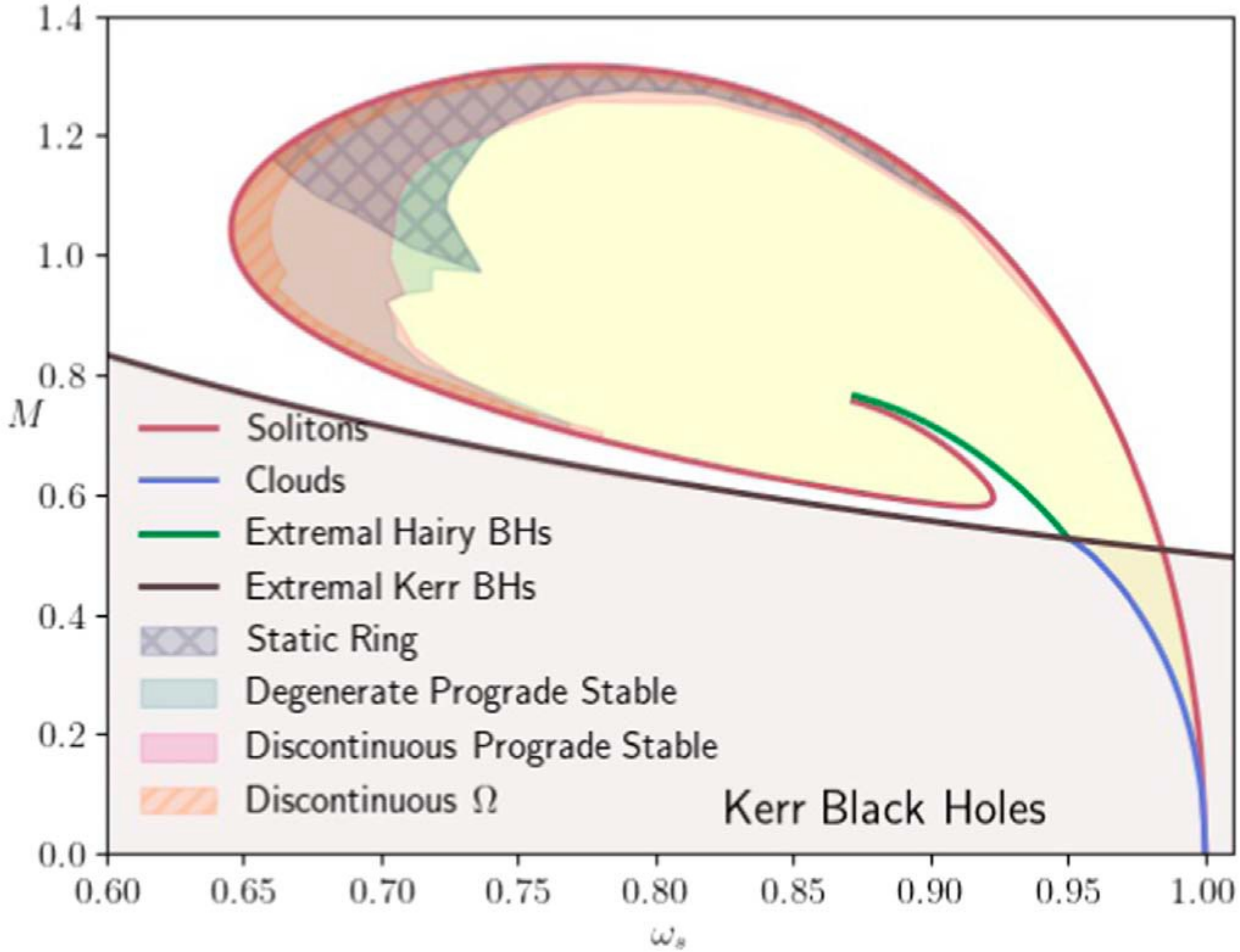
- The **Noether charge -> number of particles**.

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



Herdeiro, Radu PRL (2015)

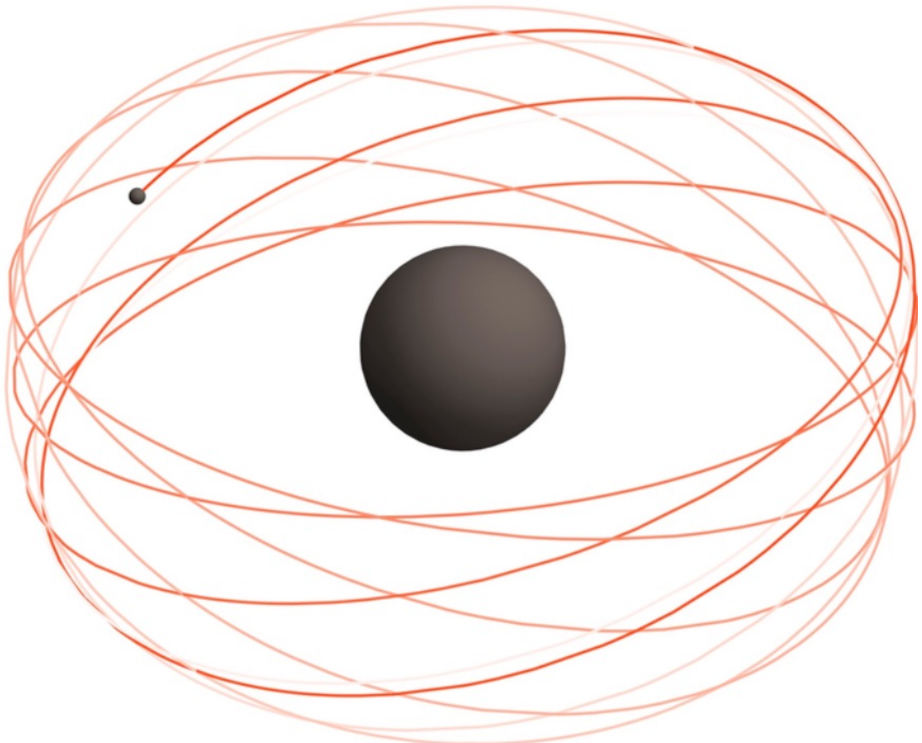
Circular orbits structure



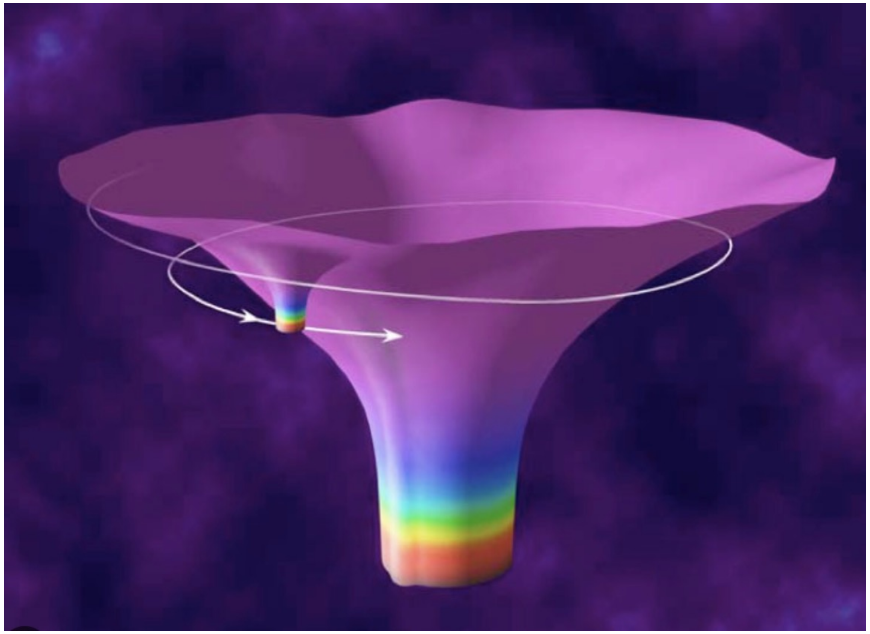
Collodel, DD, Yazadjiev PRD (2021, 2022)

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

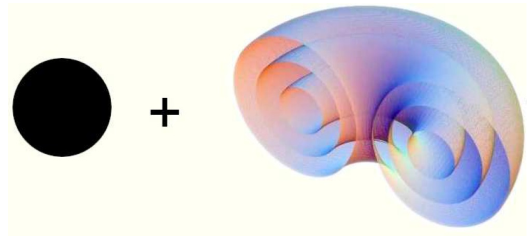


CREDIT: N. FRANCHINI

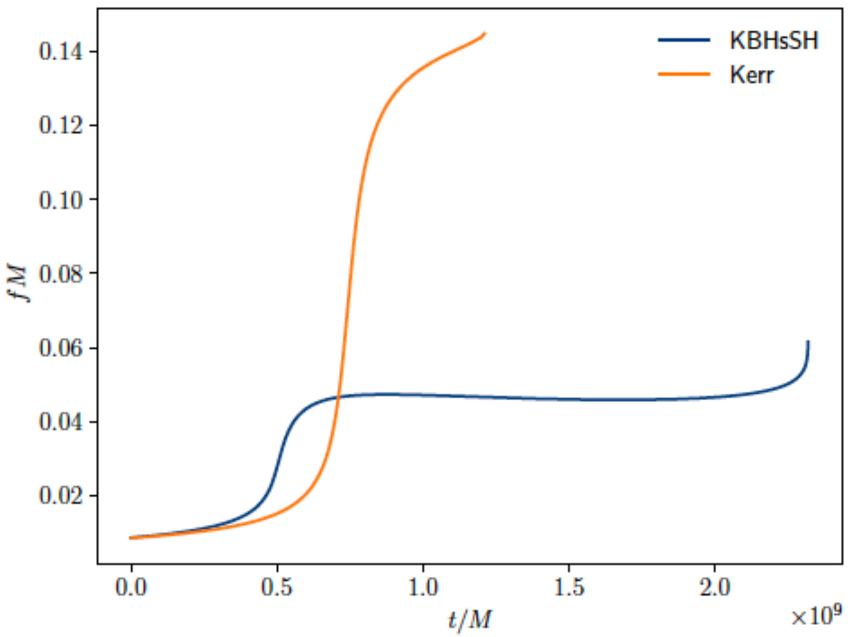


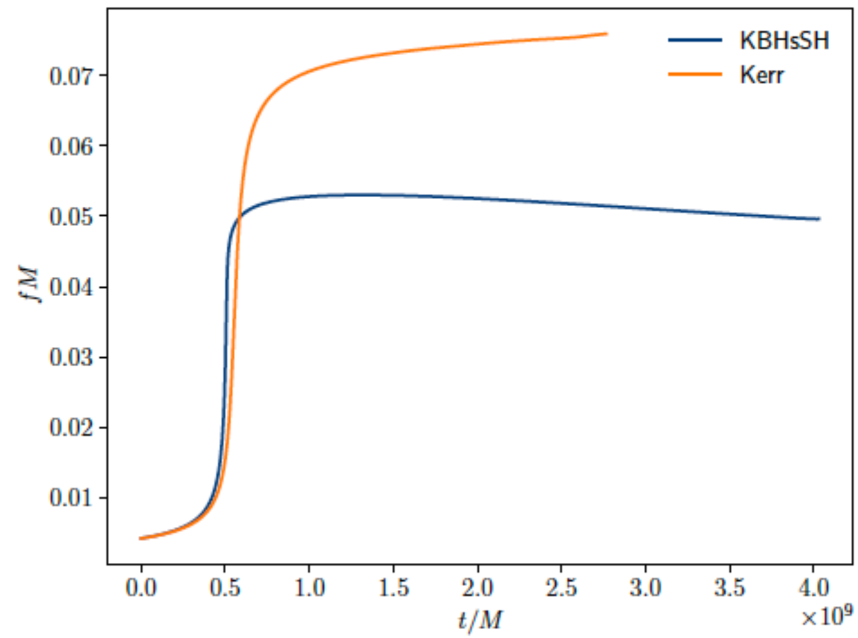
Extreme mass-ratio inspiral

Kerr BH + Rotating Boson Star



Herdeiro&Radu, RPL (2014)





Collodel, DD, Yazadjiev PRD(2021)

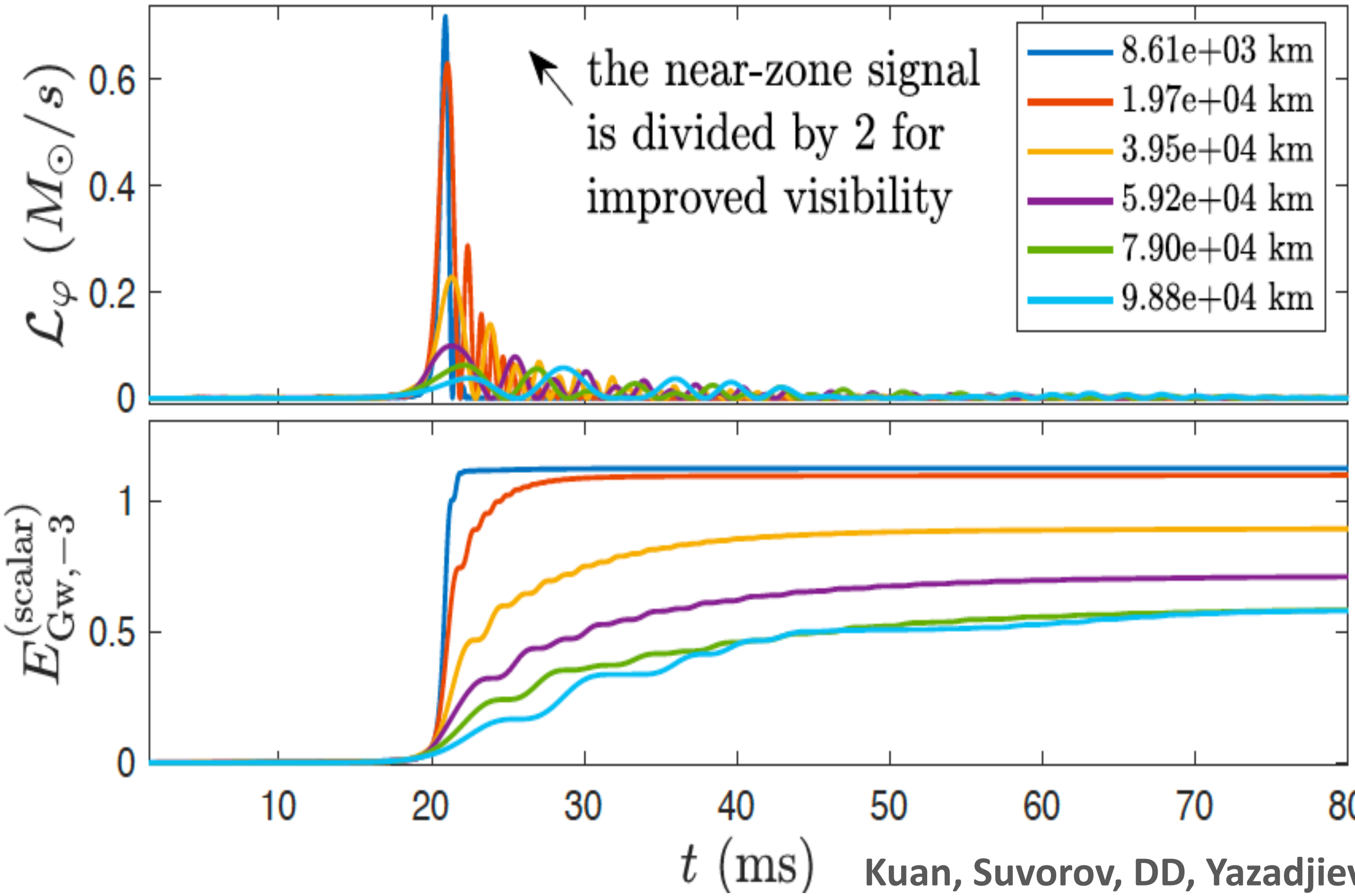
Conclusions

- GWs are among the ultimate tools to test beyond-GR physics
- **Quantitative vs. Qualitative** – tracing the smoking guns
- **Jumps (Gravitational phase transitions)** 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)