Binary neutron star mergers in massive scalar-tensor theory

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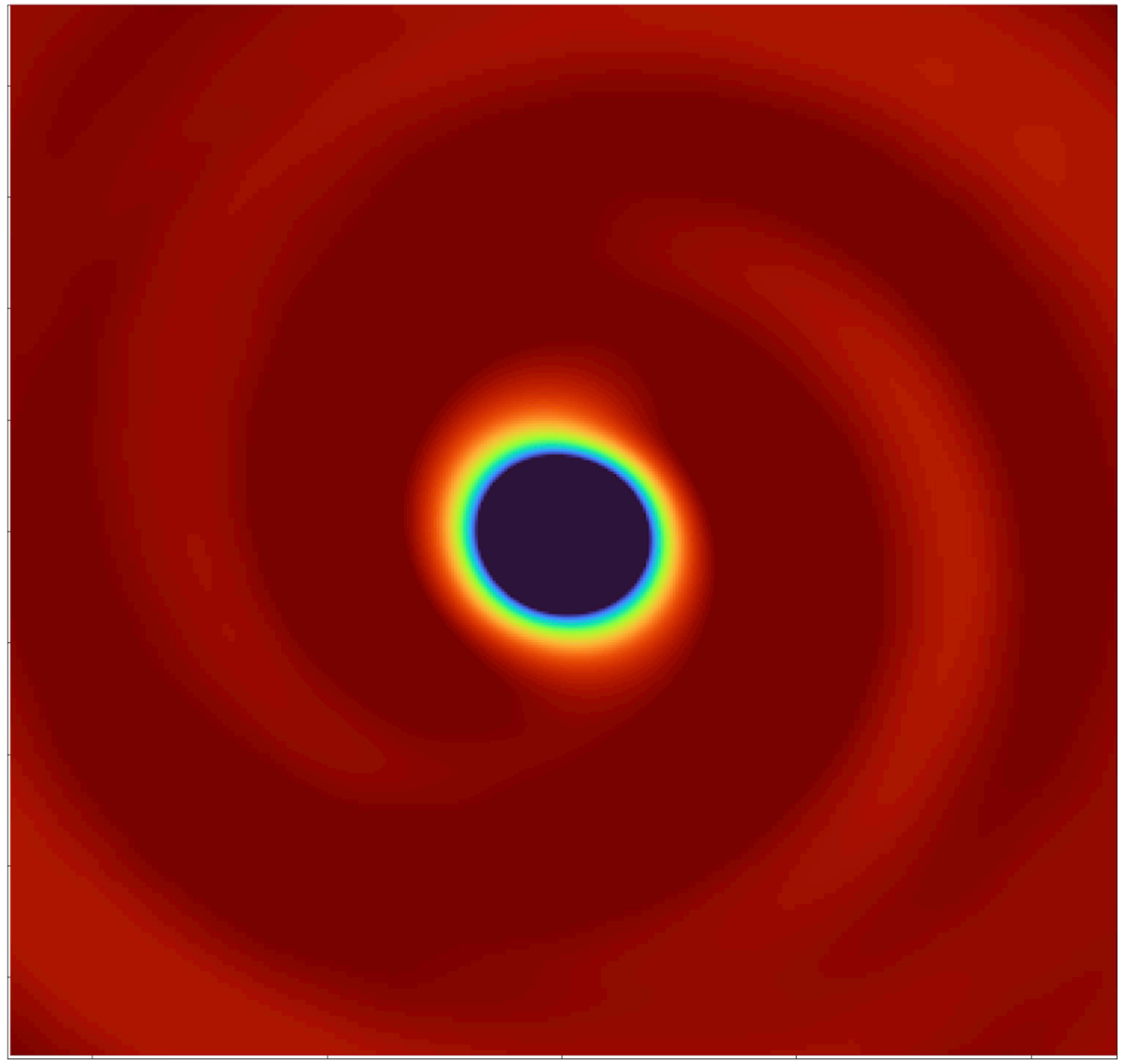


Gravity and Cosmology 2024, YITP, Kyoto, Japan (February 28)

Outline

- Scalar activities in compact binary systems
- Current valid parameter space for scalar-tensor theory
- Status on numerical simulations
- Adiabatic approximation to evolution — quasi-equilibrium states
- Parameters after GW170817 and how to proceed

DEF type of scalar-tensor theory throughout!!

$$\varphi \sim \alpha e^{-m_\phi r}/r$$

$$S = \frac{1}{16\pi}\int d^4x\sqrt{-g}\left[\phi\mathcal{R} - \underset{\uparrow}{\frac{\omega(\phi)}{\phi}}\nabla_a\phi\nabla^a\phi - \underset{\uparrow}{U(\phi)}\right] - \int d^4x\sqrt{-g}\rho(1+\varepsilon),$$

Scalar mass

Coupling const.

Interplays of scalar in compact binaries

- Two bodies with scalar charges can interact to feel an effective gravitational constant

Damour & Esposito-Farese, CQG (1992)

$$G_{\rm eff} = G(1 + \alpha_1 \alpha_2)$$

Bare grav. Const. **Charge of body 1** **Charge of body 2**

$$\boxed{F = \frac{G_{\rm eff} m_1 m_2}{r^2}}$$

- Difference in the scalar charges can emit scalar waves

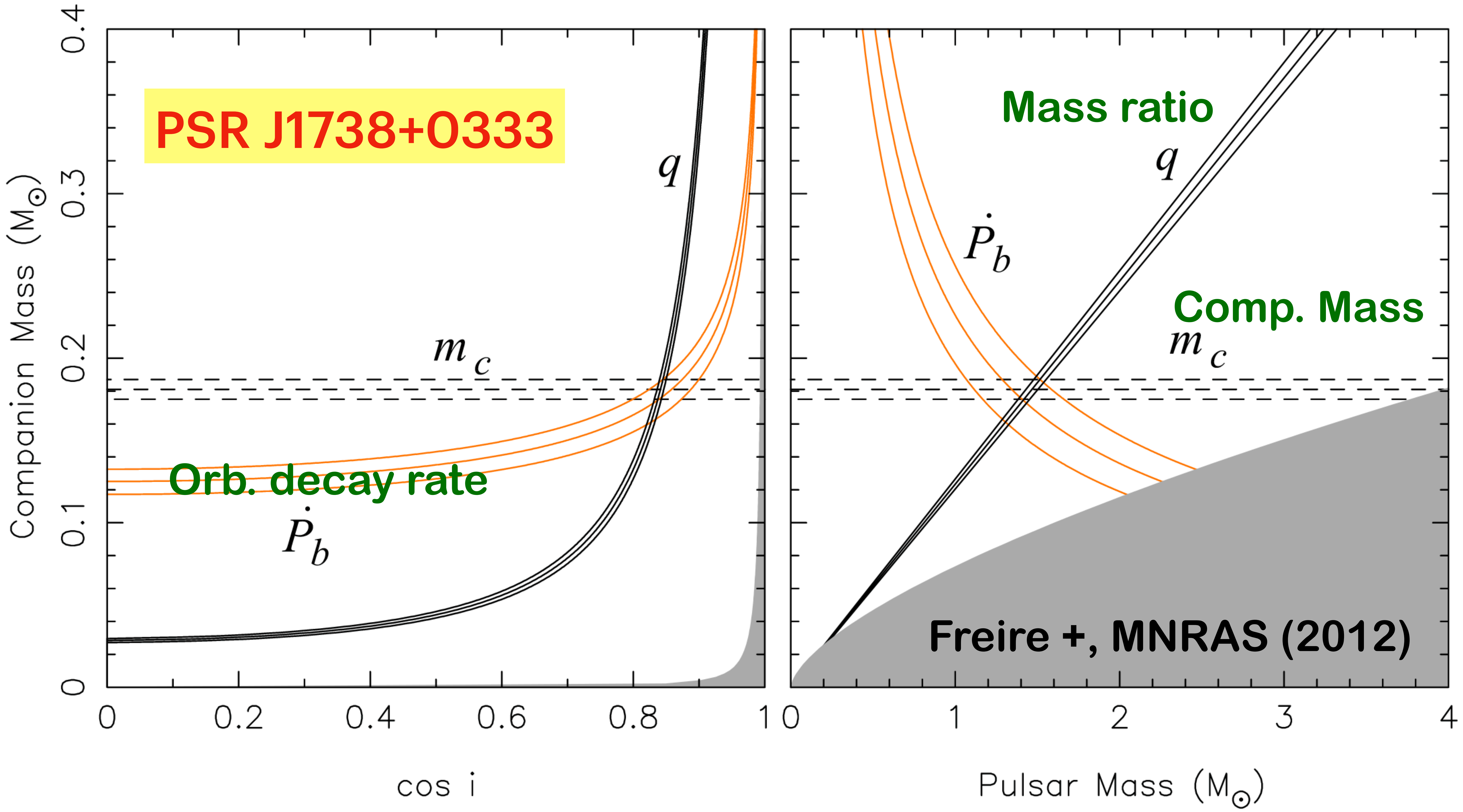
$$\boxed{\dot{E}_{\rm quadrupole} = \frac{32G}{5c^3}\left(\frac{G_{\rm eff} m_1 m_2}{r^2}\right)^2 \left(\frac{v}{c}\right)^2}$$

$$\dot{E}_{\rm dipole} = \frac{G}{3c^3}\left(\frac{G_{\rm eff} m_1 m_2}{r^2}\right)^2 (\alpha_1 - \alpha_2)^2$$

How pulsar binaries limit the theory?

Pulsar timing observation

By sizing the excess orbital decay when assuming GR



Freire +, MNRAS (2012)

Negligible for pulsar-WD binaries

Sources for the excess:

1. Mass loss from binary
2. Tidal effects
3. Dipolar GW
4. Varying G

Test of GR

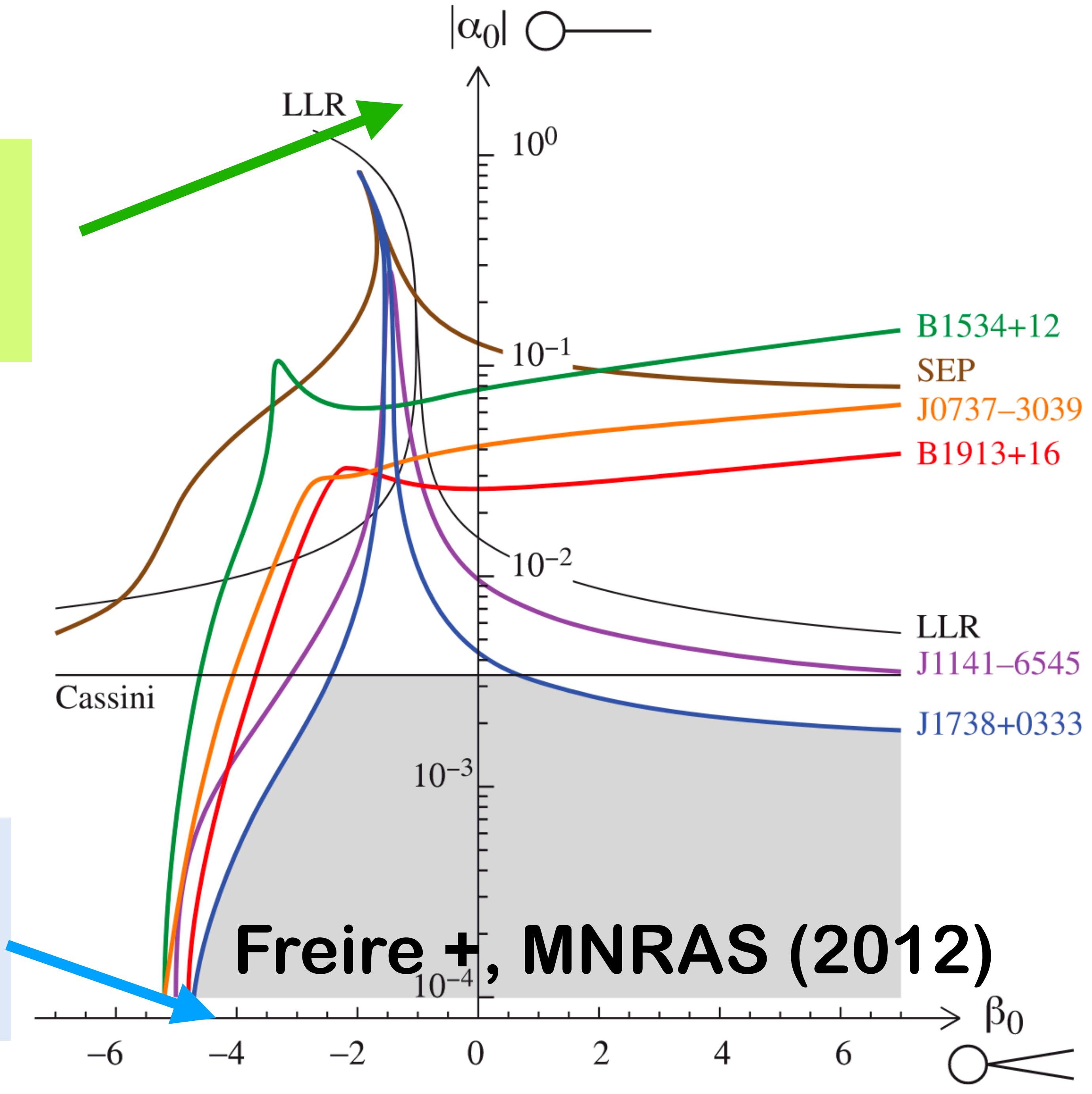
Damour & Taylor, ApJ (1991)

Pulsar timing observation (contd.)

… then inject to a specific theory — DEF ST here but massless scalar

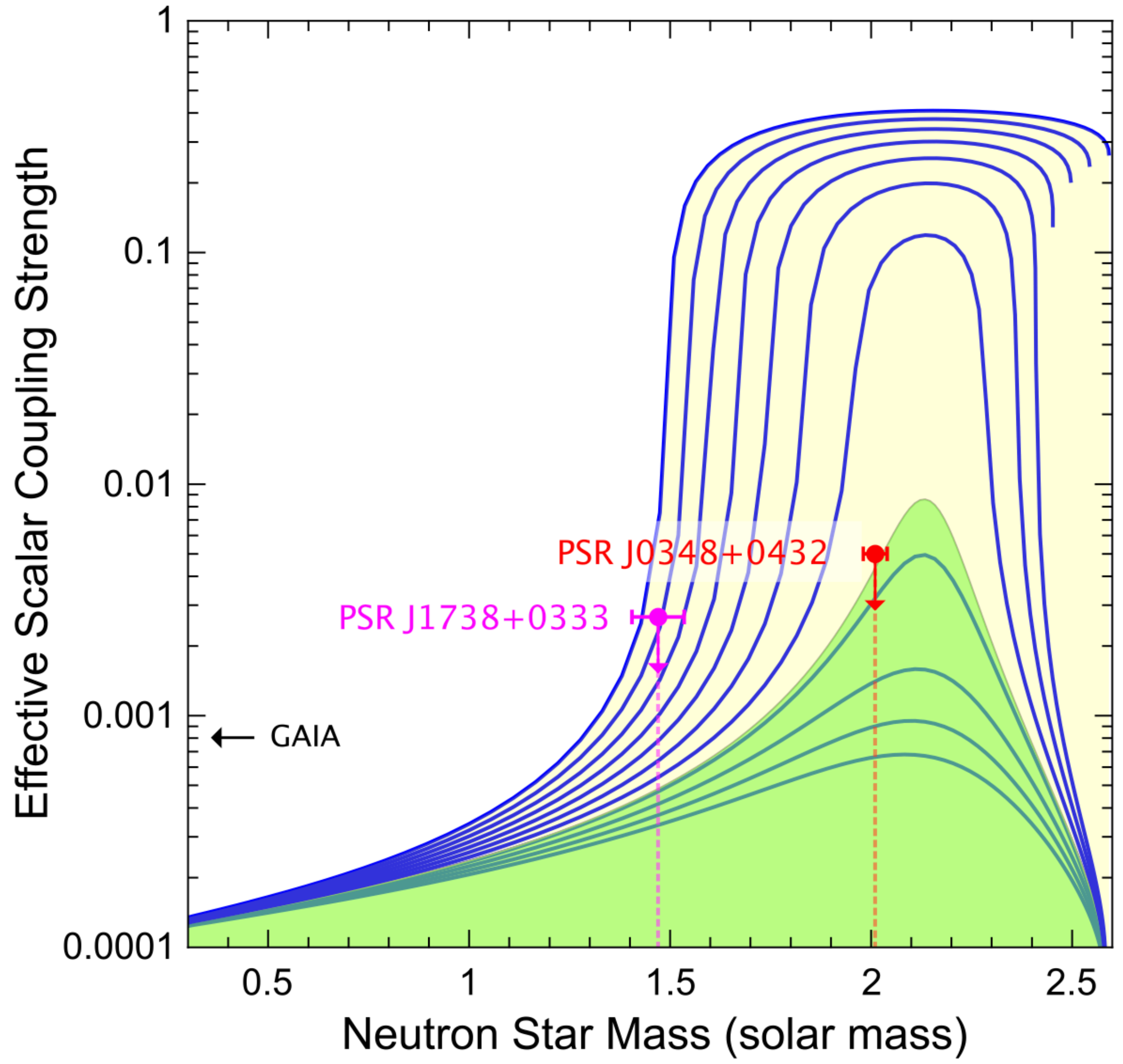
Cosmological value of scalar

Coupling strength of scalar to GR

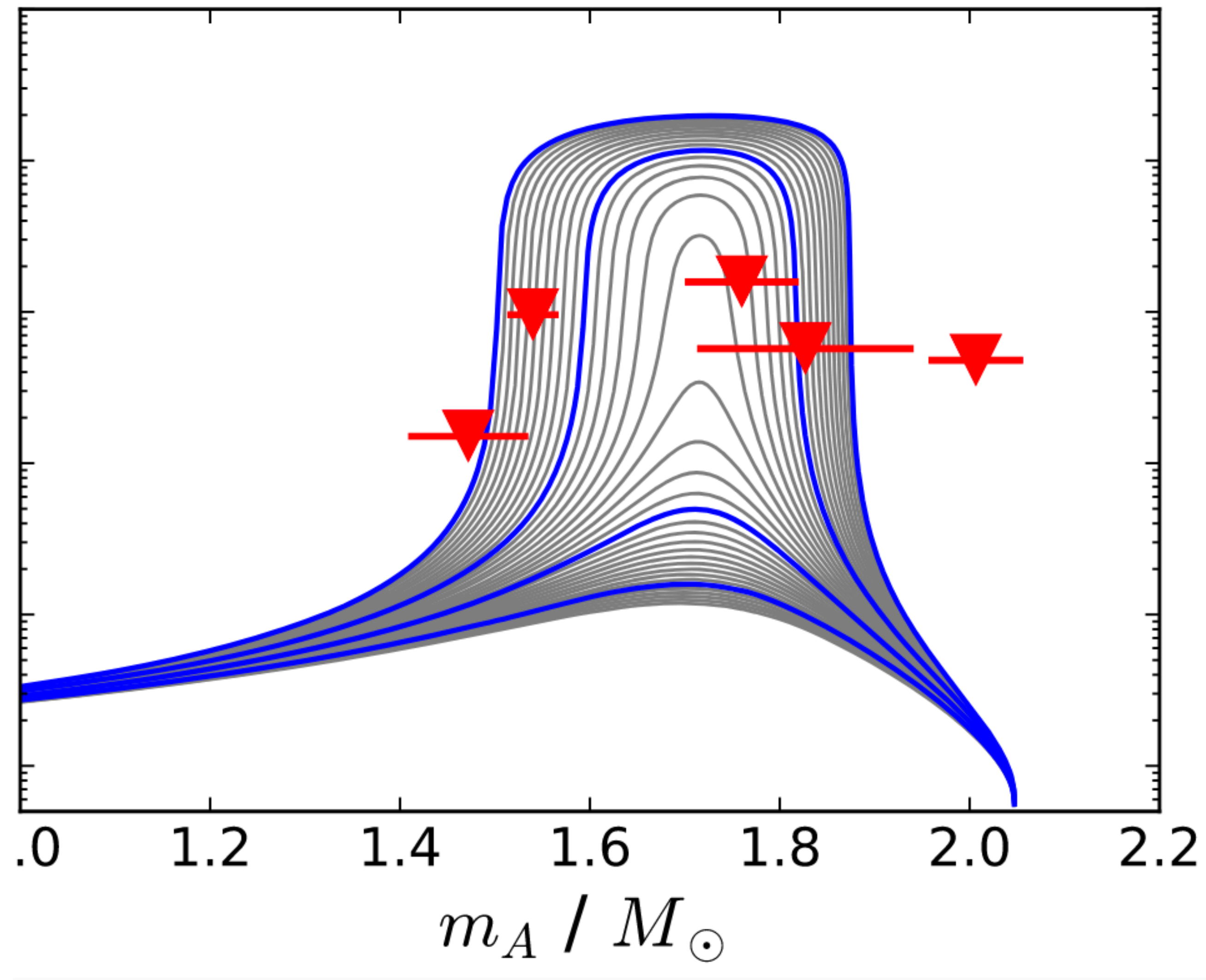


Freire +, MNRAS (2012)

Antoniadis +, Science (2013)



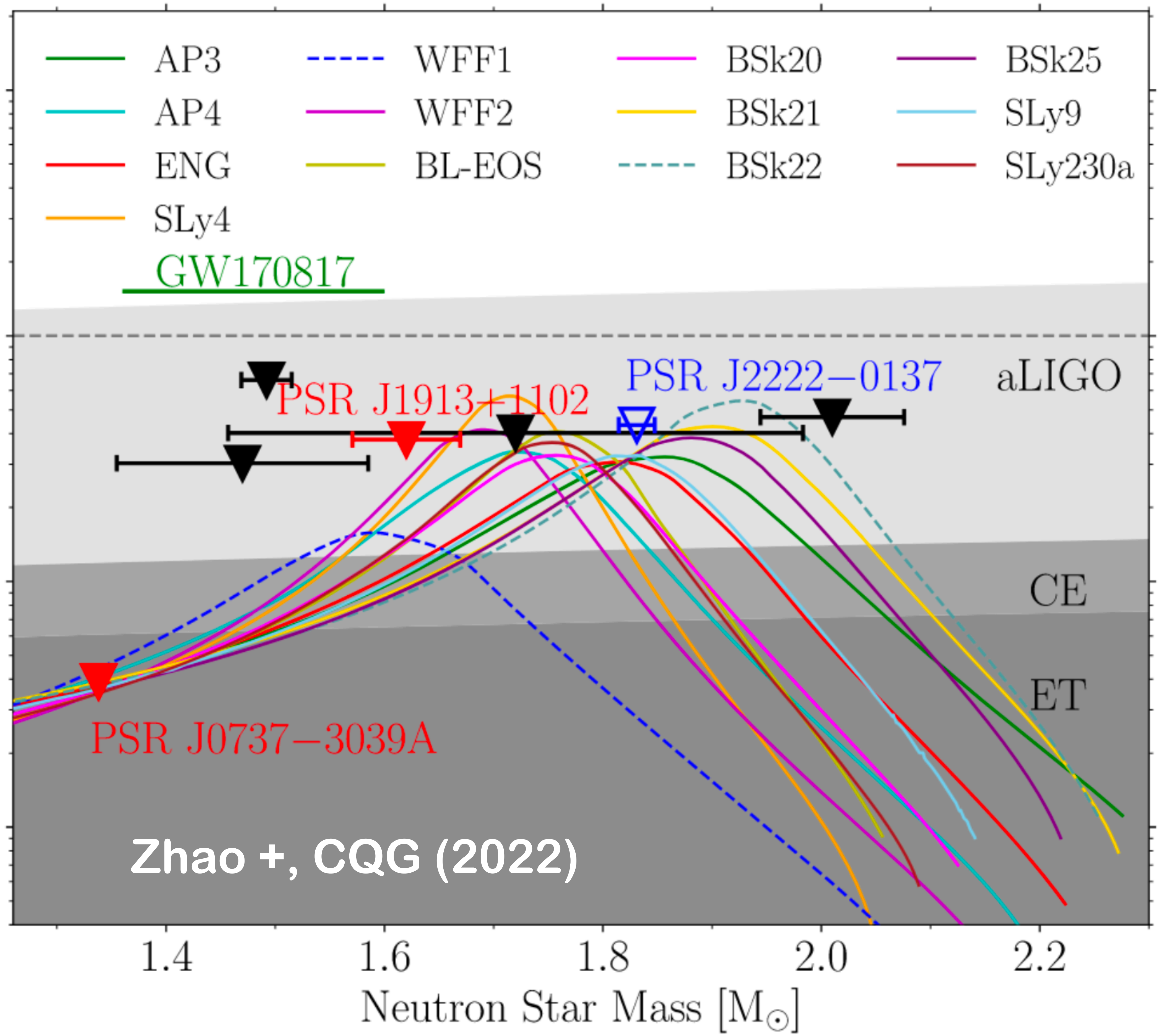
Shao +, PRX (2017)



The scheme: Damour & Esposito-Farèse, PRD (1996, 1998); Alsing +, PRD (2012); Anderson +, CQG (2019); Zhao +, CQG (2022) …

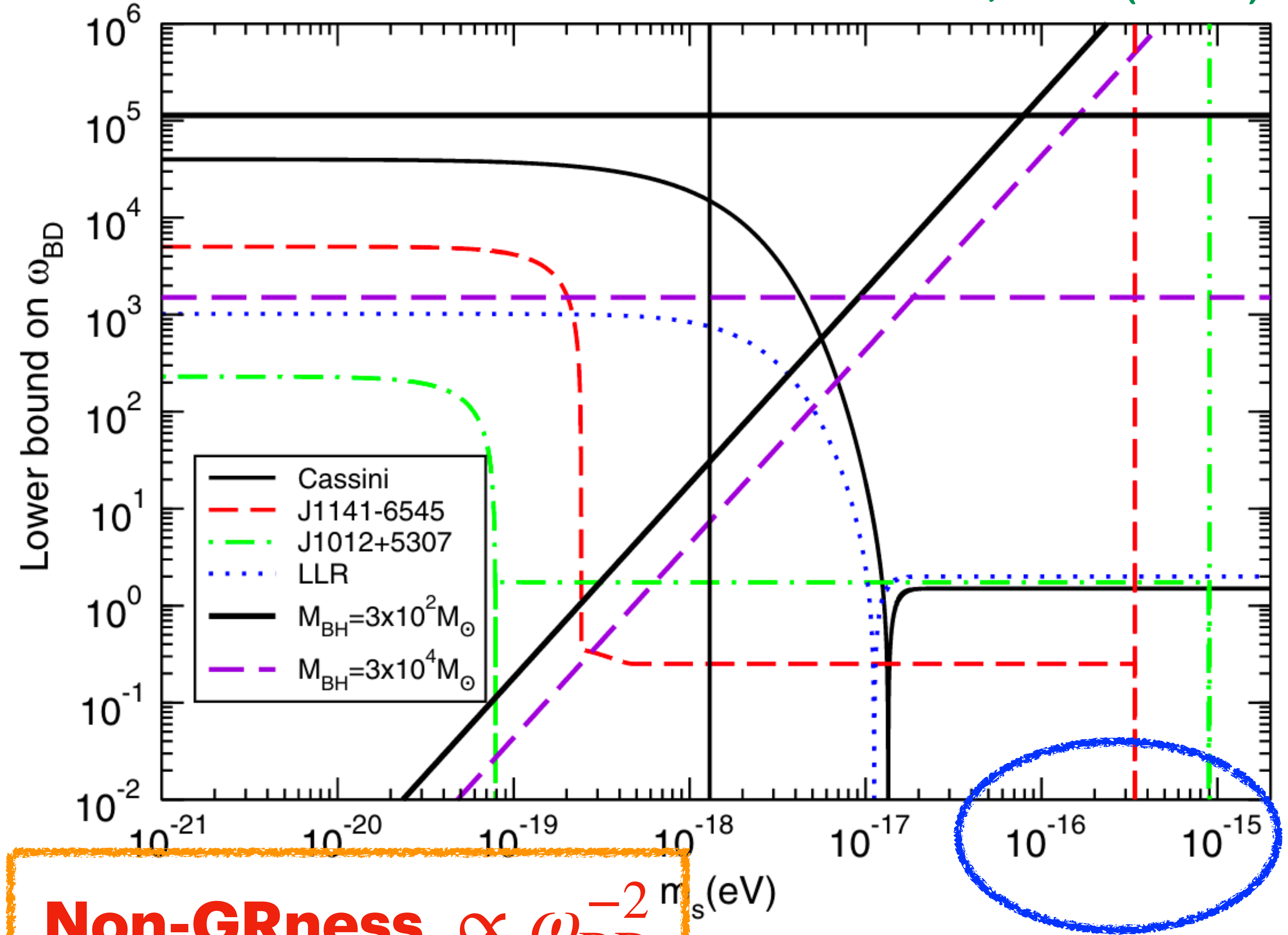
A scalar mass is necessary

As of 2022, seven pulsars almost exclude the scalarization for all NS masses if the scalar is massless —> need mass, which gives Compton L



Zhao +, CQG (2022)

Berti +, PRD (2013)



Non-GRness $\propto \omega_{\mathrm{BD}}^{-2}$

How can BNS improve the current knowledge?

Existing binary simulations in DEF ST

- Simulations from a GR binary data:
  - BNS: studies on dynamical scalarization **[Barausse +, PRD (2013); Palenzuela +, PRD (2014)]**
  - BHNS: comparison of waveforms from NR to AR **[Ma +, PRD (2023)]**
- BBH GR data with ad hoc scalar cloud: presence of dipolar emission **[Healy +, CQG (2011); Berti +, PRD (2013)]**
- Consistent initial data for DEF: for waveform modelling over larger parameter space **[Shibata +, PRD (2014); Taniguchi +, PRD (2015)]**
- Above efforts are **in massless theory;** nice way to gain intuition but need to go to massive case!

Initial data for massive ST

- Adding a module to the public code FUKA **[Jens Papenfort , PRD (2021)]**, which adopts spectral method solving PDEs

- A redefinition of scalar field to numerically solve is necessary

$$\varphi \propto e^{-m_\phi r}/r \quad \boxed{\xi = \varphi \cosh(m_\phi r)}$$

- **Simulation of BNS in massive ST** is now ready to be performed!

$$\begin{aligned}\Delta\varphi = {} & 2\pi B\psi^4\varphi\phi^{-1}T - \varphi f^{ij}(\partial_i\varphi)\partial_j\varphi \\ & - f^{ij}(\chi^{-1}\partial_i\chi + \psi^{-1}\partial_i\psi)(\partial_j\varphi) + m_\phi^2\psi^4\varphi\phi,\end{aligned}$$

$$\downarrow$$

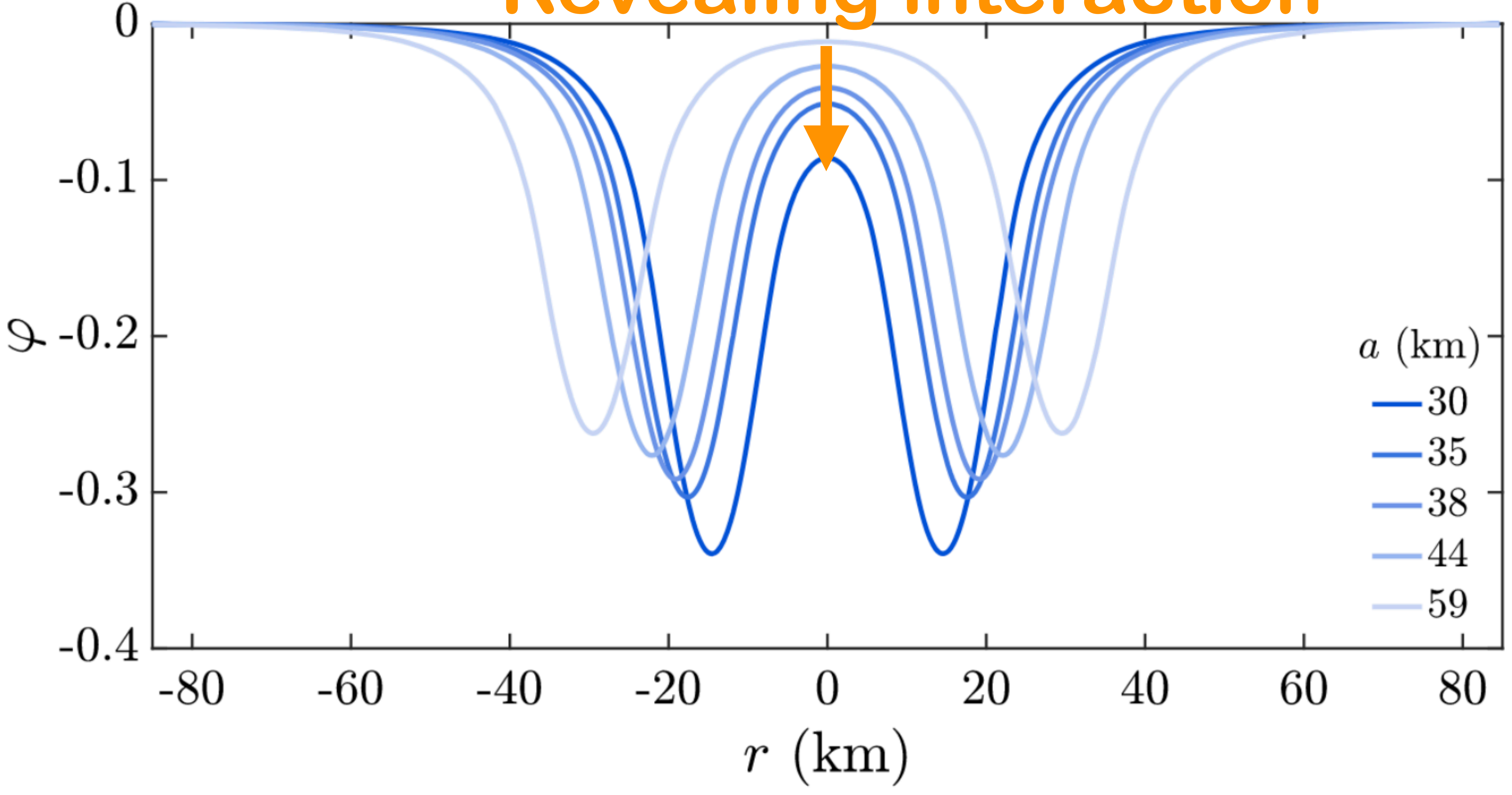
$$\begin{aligned}\Delta\xi = {} & m_\phi^2[2\cosh^{-2}(m_\phi r) + \psi^4\phi - 1]\xi \\ & + \frac{2m_\phi\tanh(m_\phi r)}{r}\xi + 2m_\phi\tanh(m_\phi r)\hat{r}^i\partial_i\xi \\ & + 2\pi B\psi^4\xi\phi^{-1}T - \cosh^{-2}(m_\phi r)\xi[f^{ij}\partial_i\xi\partial_j\xi \\ & - 2m_\phi\xi\tanh(m_\phi r)\hat{r}^i\partial_i\xi + m_\phi^2\xi^2\tanh^2(m_\phi r)] \\ & - (\chi^{-1}\partial_i\chi + \psi^{-1}\partial_i\psi)[f^{ij}\partial_j\xi - m_\phi\xi\tanh(m_\phi r)\hat{r}^i],\end{aligned}$$

Mass effects

Scalar mass introduces:

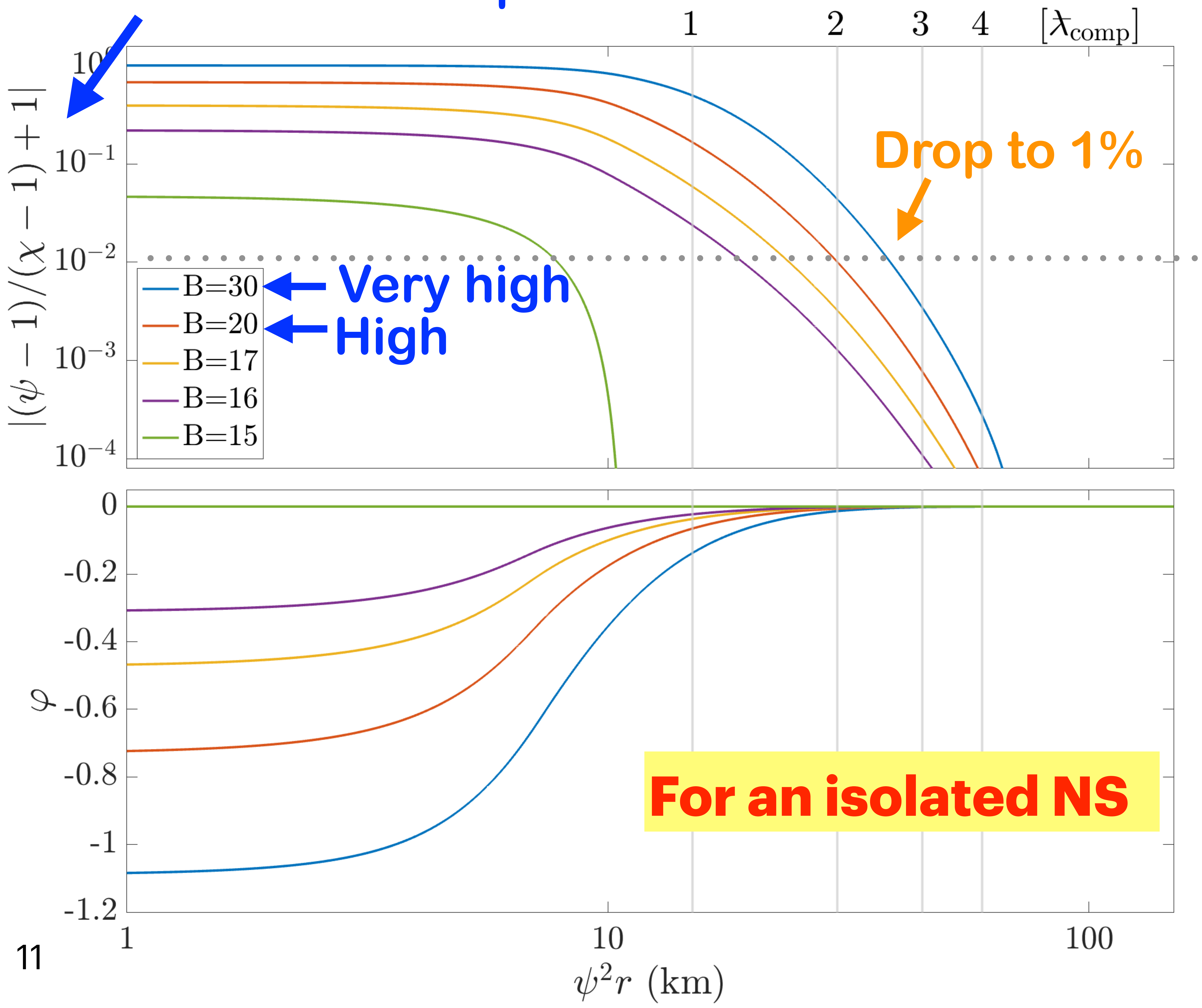
1. **a Yukawa-suppression to scalar interaction**
2. Cutoff frequency on the scalar emission

Revealing interaction



Scalar cloud enhances for less separation

How much the spacetime deviates from GR



Drop to 1%

Very high

High

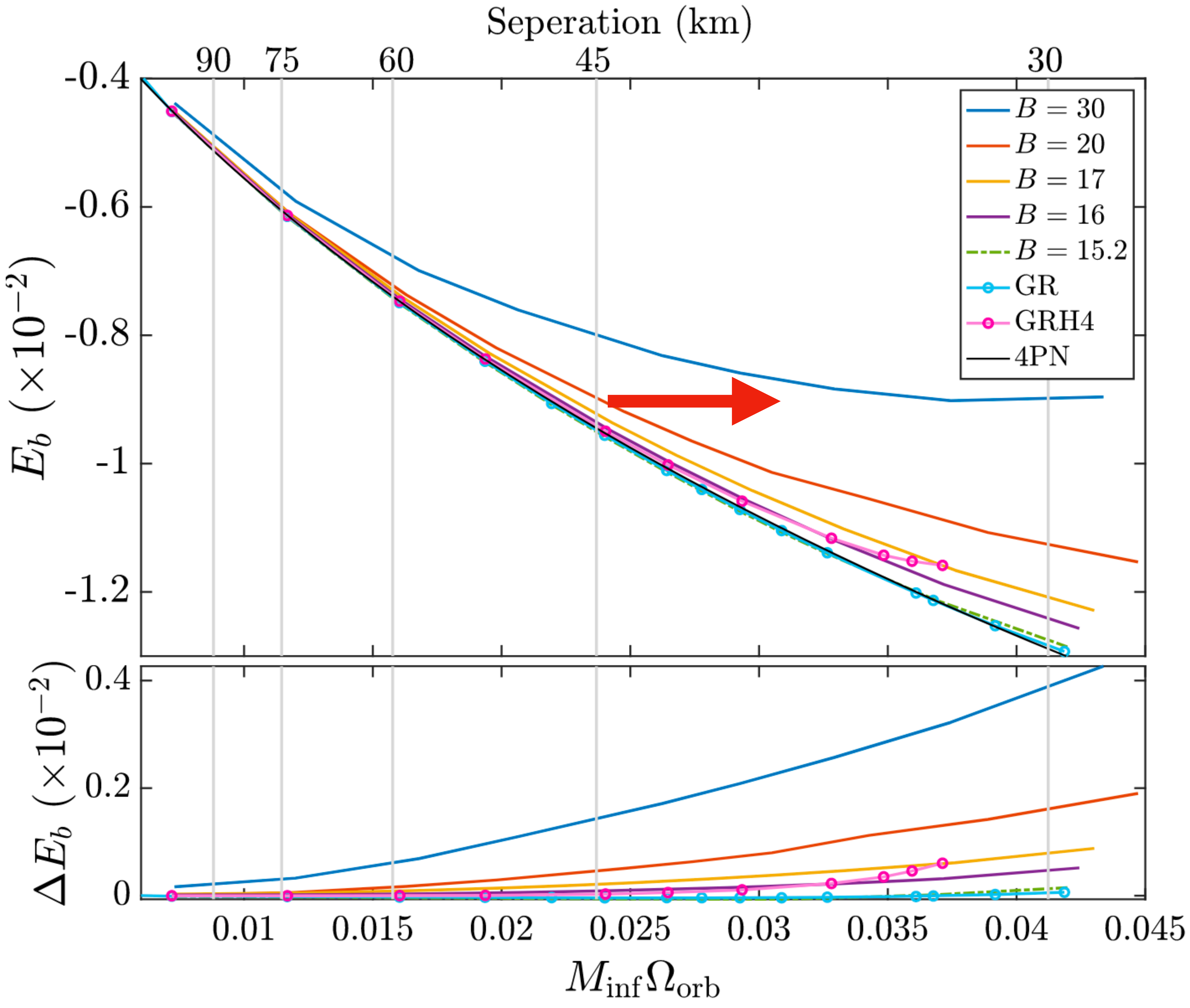
For an isolated NS

Quasi-equilibrium states of BNS

$$\boxed{F = \frac{G_{\text{eff}} m_1 m_2}{r^2}}$$

Damour & Esposito-Farese, CQG (1992)

- The scalar-type interaction offers additional ``attracting force'' => larger orb. frequency for a given binding energy (gravitational state)
- Tidal interaction can play the same role as well, however.

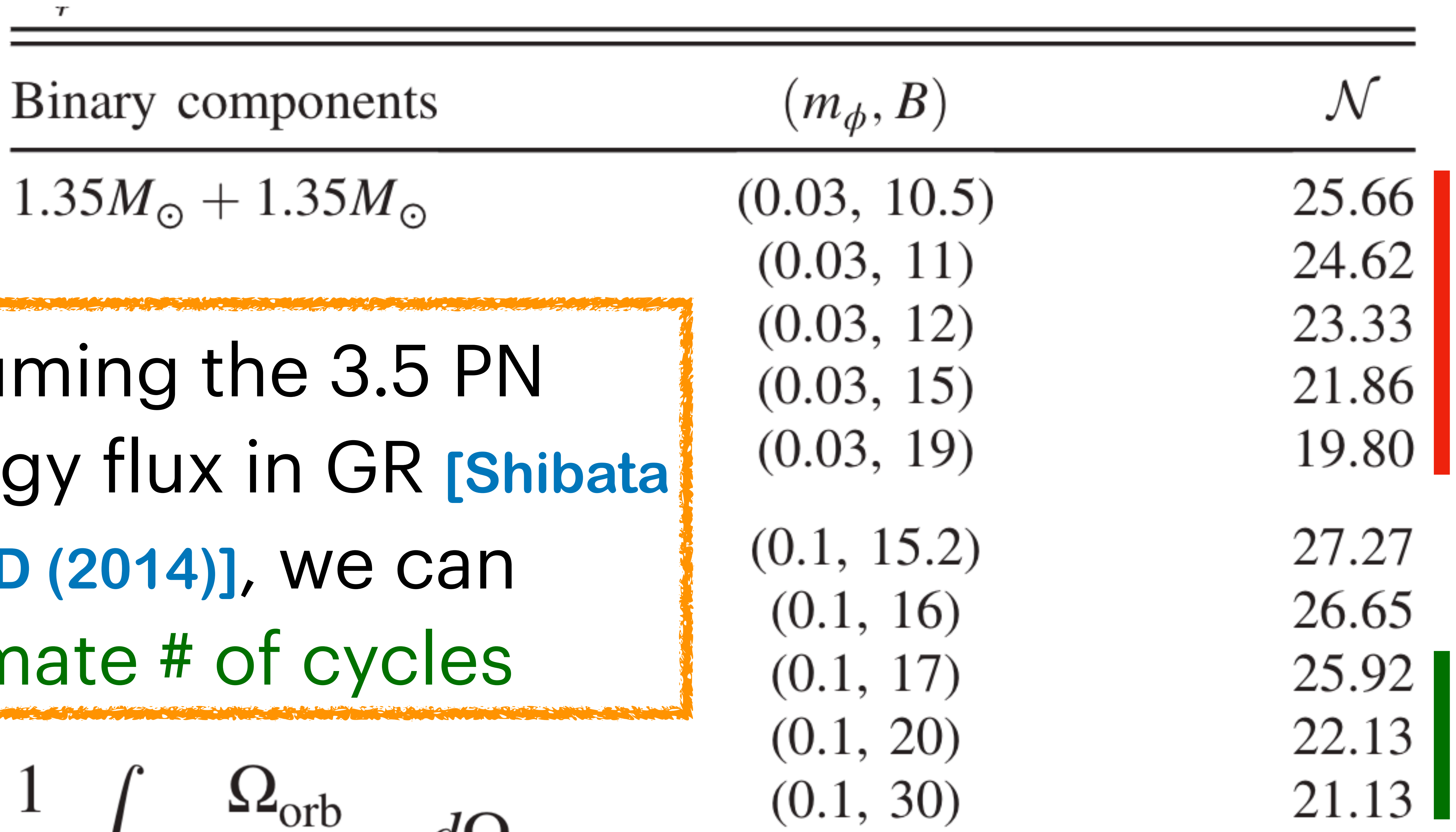


GW170817

- No clue of non-GR effects [Abbott +, PRL (2017,2018,2019)]
- Possible solutions to accommodate DEF with the observation:
  1. NS members are not spontaneously scalarized while dynamical scalarization after $f_{\rm gw} = 500$ Hz reveals
  2. NS members are spontaneously scalarized but scalar effects are smeared out until $f_{\rm gw} = 500$ Hz
  3. Scalar effects can only kink in for higher energy physics in the post-merger phase

New bound on the scalar mass by BNS

Bound can be updated by considering **adiabatic approximated coalescing BNS**



Binary components	(m_ϕ, B)	$\mathcal{N}$
$1.35M_\odot + 1.35M_\odot$	(0.03, 10.5)	25.66
	(0.03, 11)	24.62
	(0.03, 12)	23.33
	(0.03, 15)	21.86
	(0.03, 19)	19.80
	(0.1, 15.2)	27.27
	(0.1, 16)	26.65
	(0.1, 17)	25.92
	(0.1, 20)	22.13
	(0.1, 30)	21.13

Assuming the 3.5 PN energy flux in GR [Shibata +, PRD (2014)], we can estimate # of cycles

$$\mathcal{N} = \frac{1}{2\pi}\int \frac{\Omega_{\rm orb}}{d\Omega_{\rm orb}/dt}\, d\Omega_{\rm orb}$$

$$= -\frac{1}{2\pi M_{\rm inf}}\int \frac{x^{3/2}}{\mathcal{F}(x)}\frac{dE_{\rm b}}{dx}\, dx$$

$$x = (\overset{\uparrow}{M_{\rm inf}}\Omega_{\rm orb})^{2/3}$$

Total mass of binary

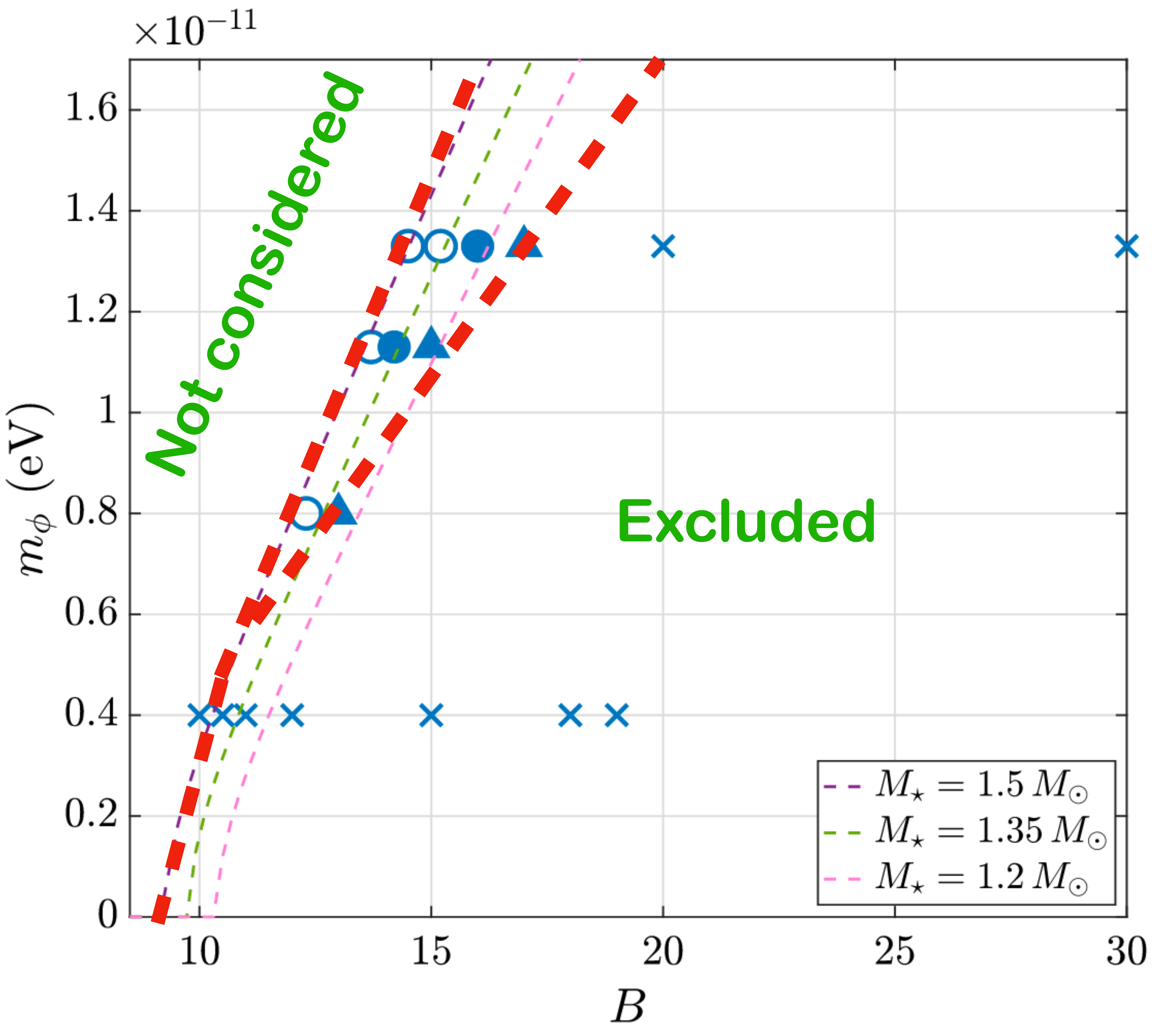
Within the accuracy of the detected waveform for GW170817, an uncertainty from APR4 to H4 remains.

The number of cycles obtained in GR are:

- 27.45 for APR4
- 26.24 for H4

=> Either small scalar mass or large coupling is disfavoured if spontaneous scalarization exists

New bound on the scalar mass by BNS (contd.)

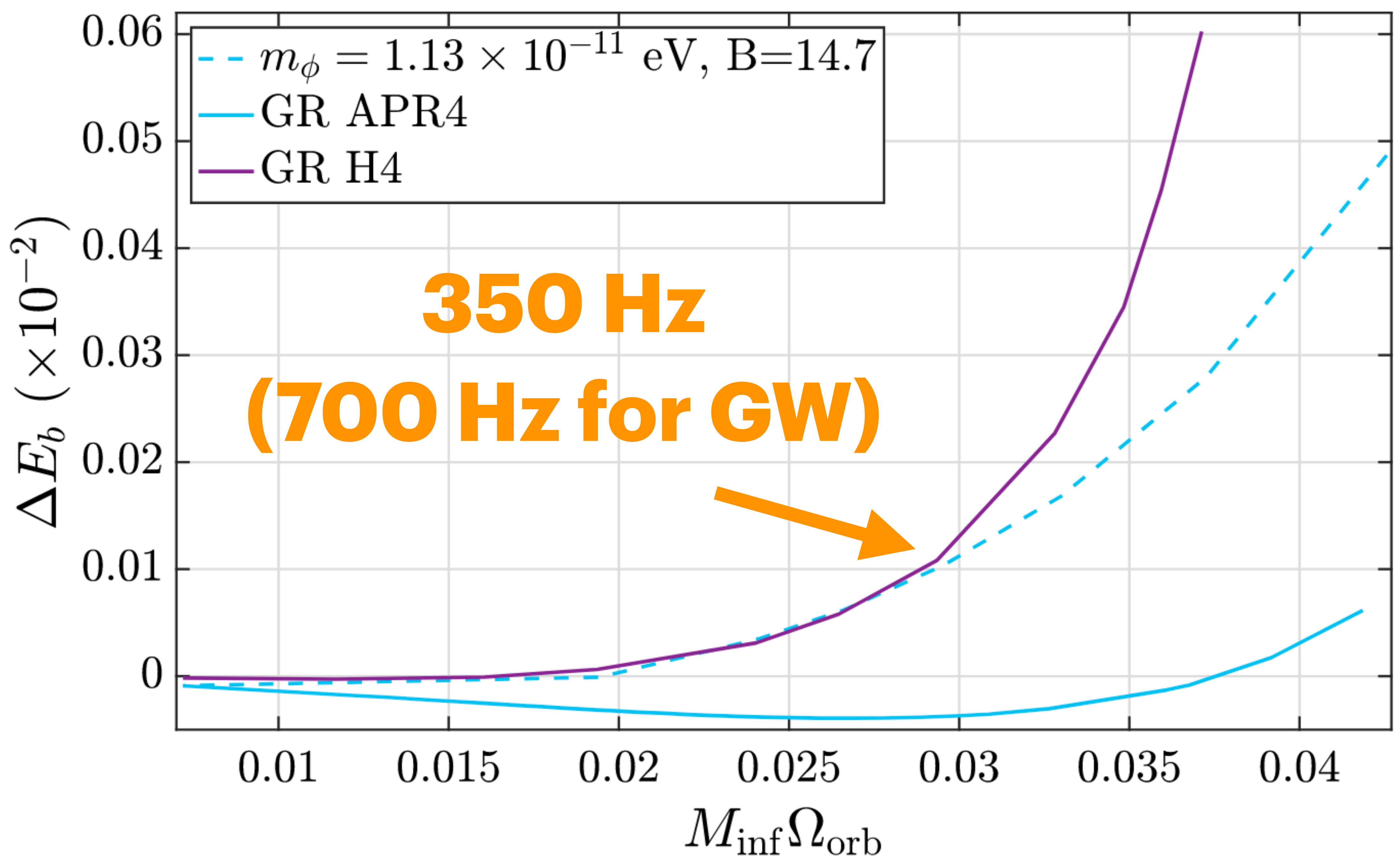


Not considered

Excluded

Issue for future study:

how to distinguish scalar and tidal effects?



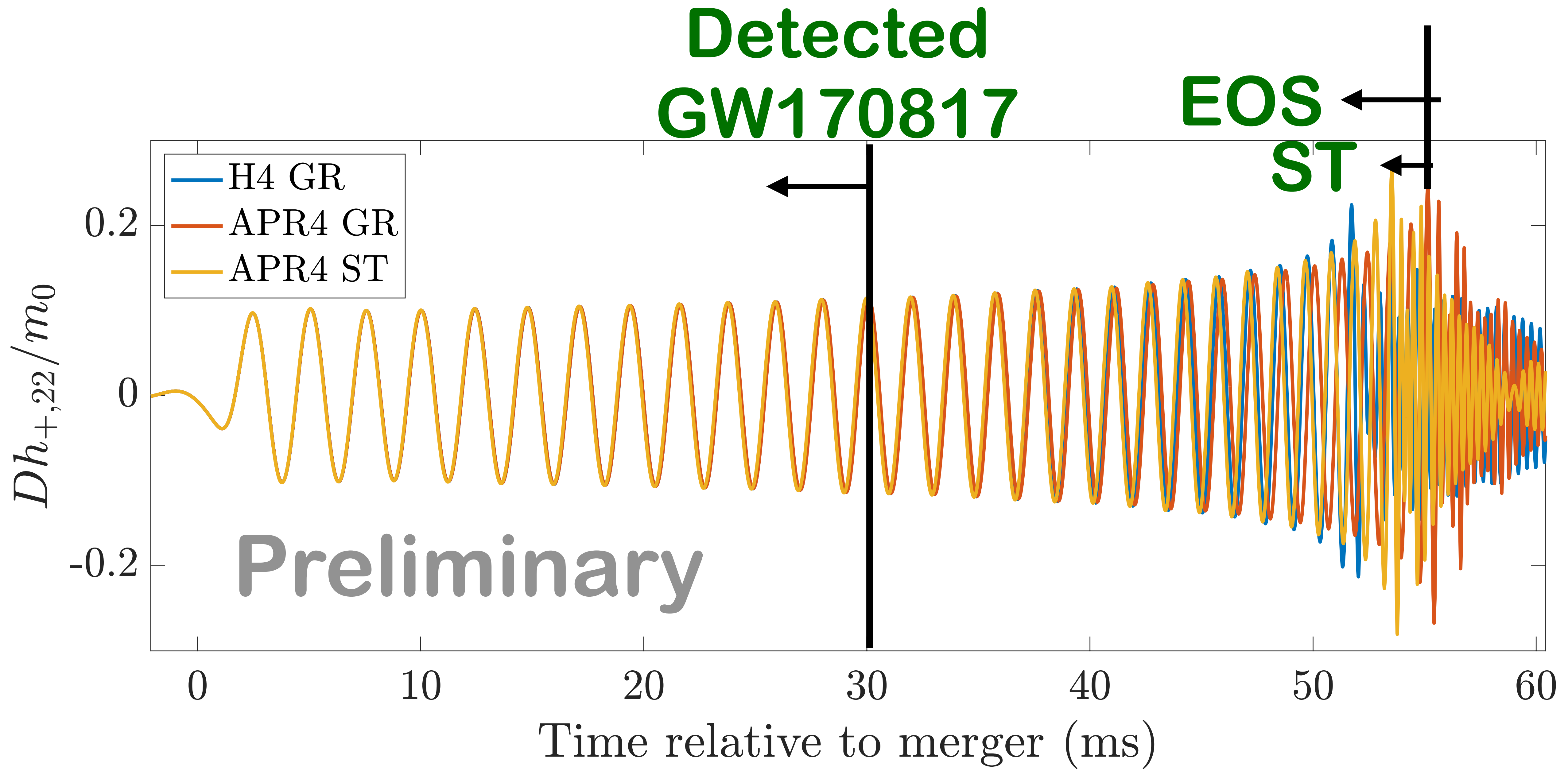
350 Hz

(700 Hz for GW)

Known where we stand! How to proceed with waveforms?

Waveforms as fingerprints of scalar field

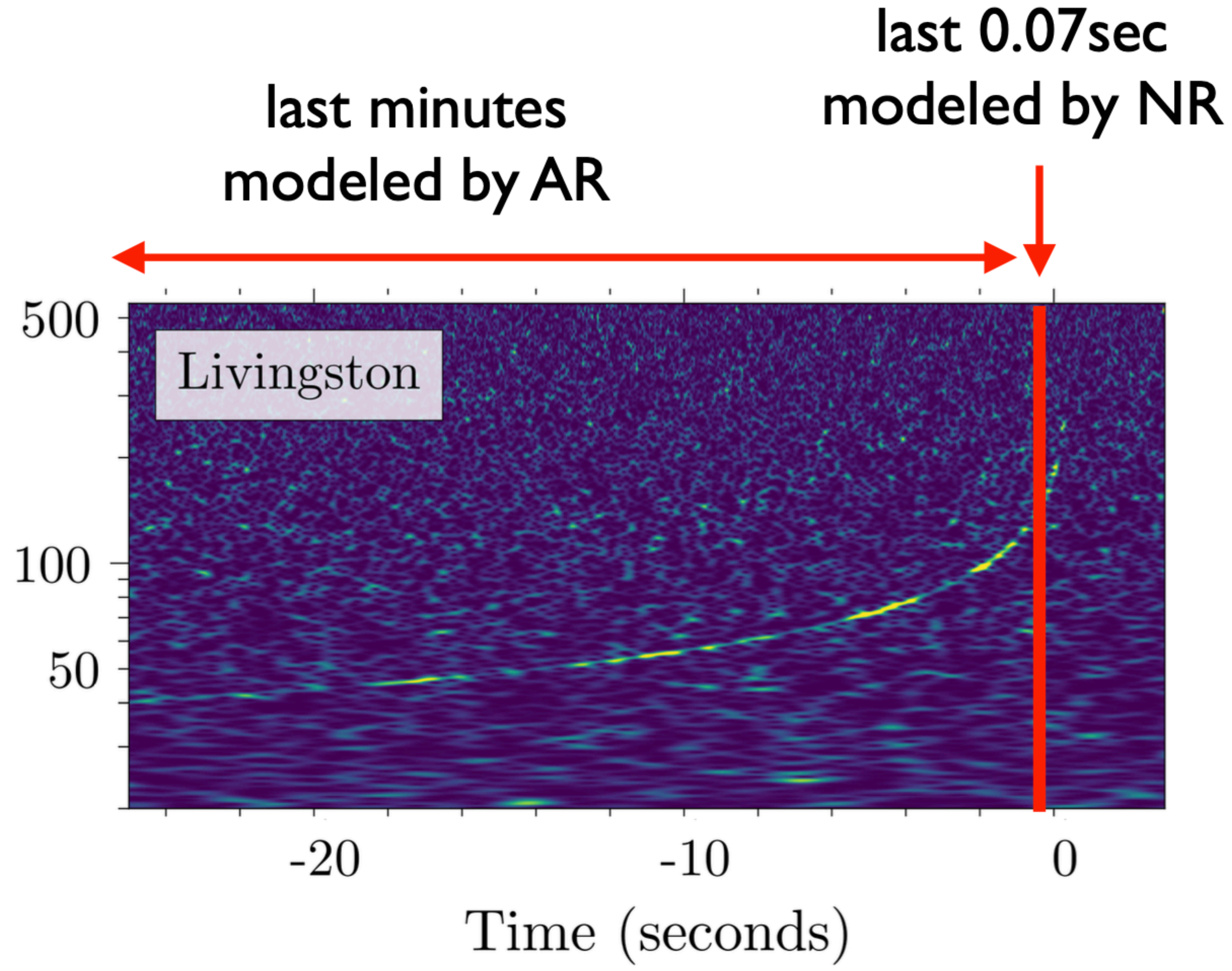
- Degeneracy to EOS, or tidal effects, need to be analysed [Bernard, PRD (R) (2020)]
- Synergy between analytic and numerical relativity is crucial



Detected GW170817

EOS

ST

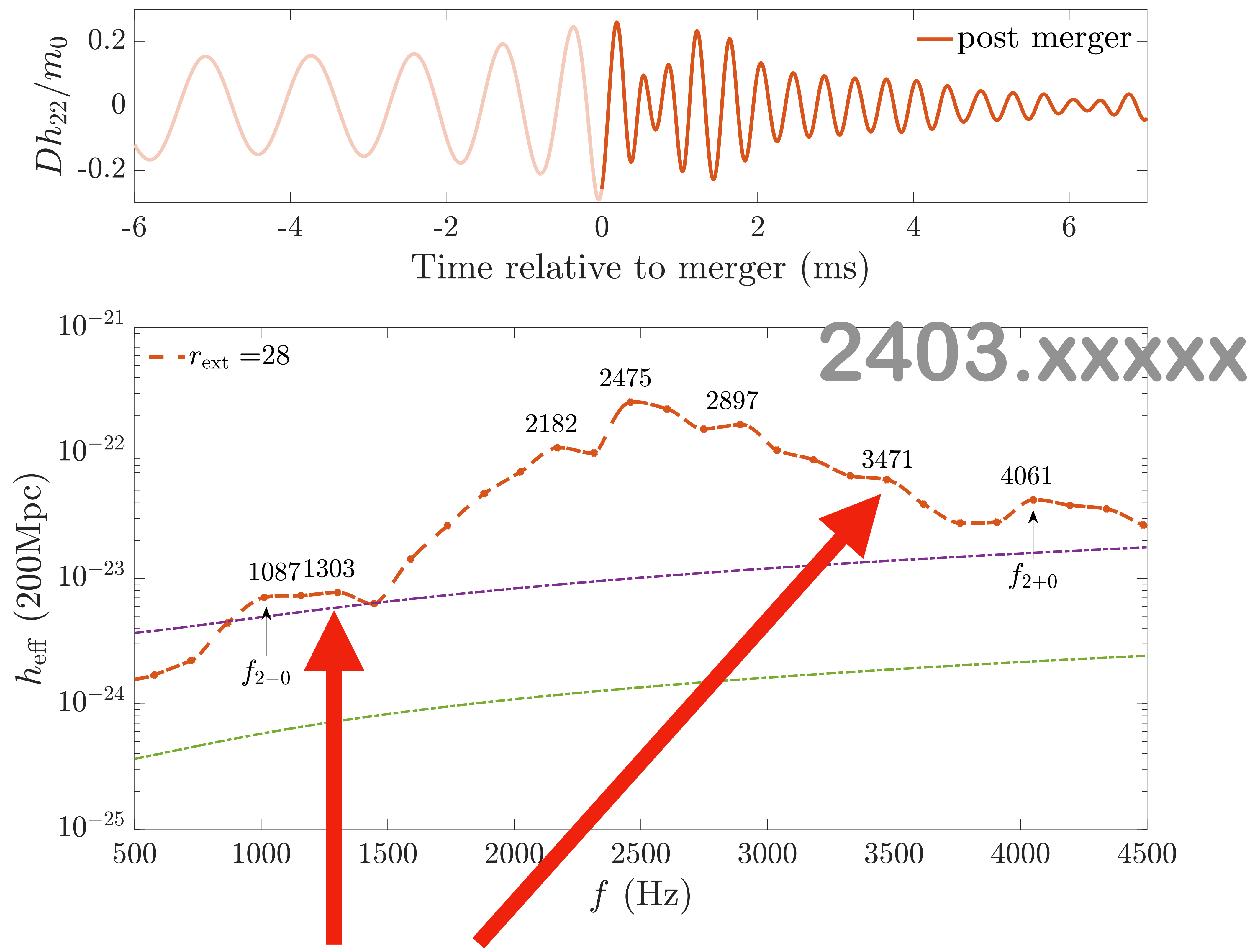


last minutes modeled by AR

last 0.07sec modeled by NR

Prospects of post-merger waveforms

- Complicated by the plethora outcomes of merger, while a pivotal channel to reveal the nature of remnants (Alan's talk)
- New features due to radial scalar mode
- Is pre- or post-merger waveform more promising channel? Universal relations connecting them?
- Superradiance in BH + torus remnant may fuel continuous waves — maybe year(s) long **[Brito +, PRD (2017)]**



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Additional non-linear peaks

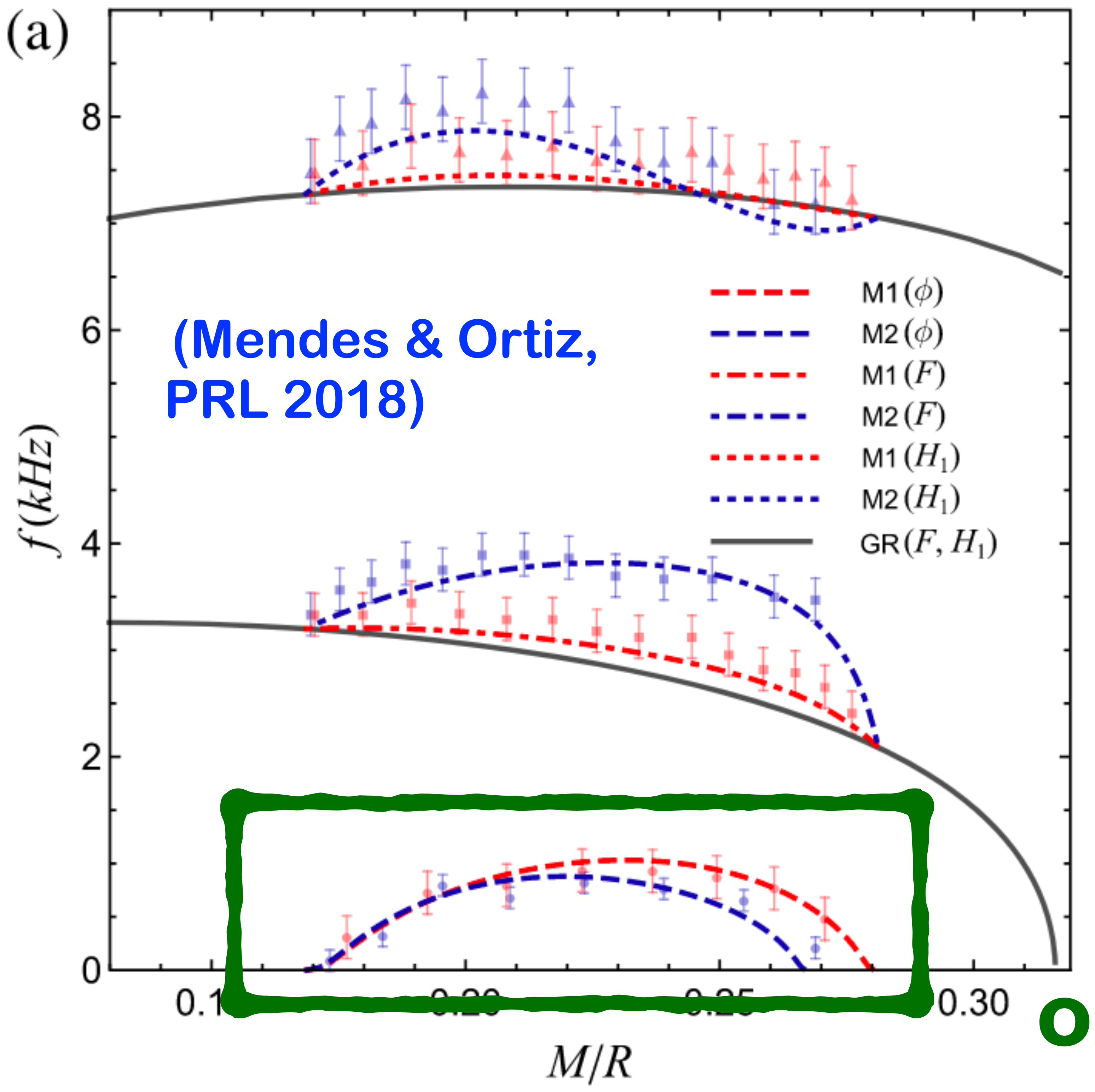
Thank you!

Backup

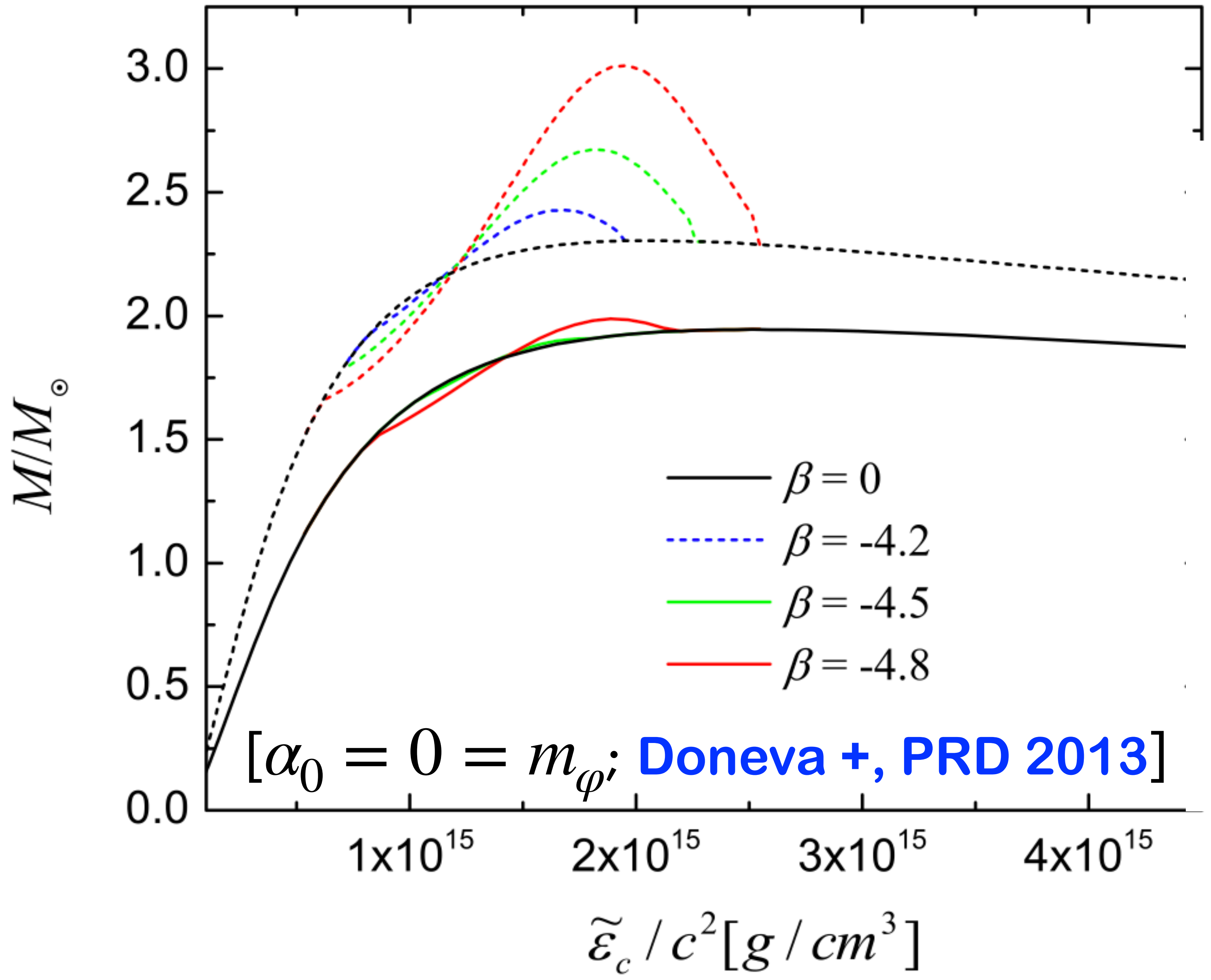
Spontaneous Scalarization

- The coupling between scalar field and matters becomes non-trivial over certain range of stellar equilibria.
- This range **coincides** with the range where the dynamics of the scalar field is unstable at the perturbative level; in particular, the tachyon instability operates where $m_\varphi^2 + 4\pi\beta_0 |T| < 0$ **(Ramazanoğlu & Pretorius, PRD 2016)**
- The extent to which a NS is ``scalarized'' can be quantified by scalar charge

$$m_{\rm eff} = \sqrt{m_\varphi^2 + 4\pi\beta_0|T|}$$



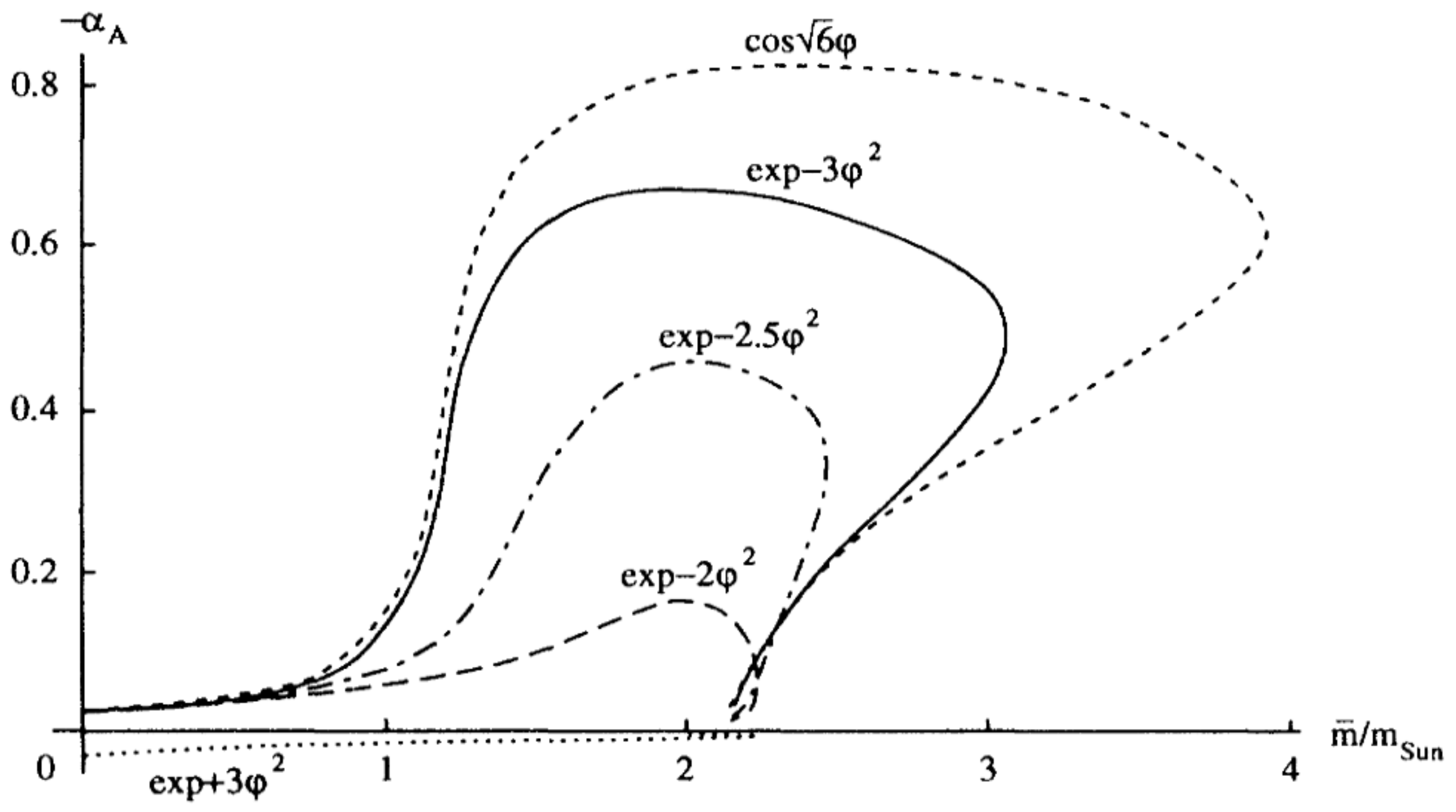
(Mendes & Ortiz, PRL 2018)



[$\alpha_0 = 0 = m_\varphi$; **Doneva +, PRD 2013**]

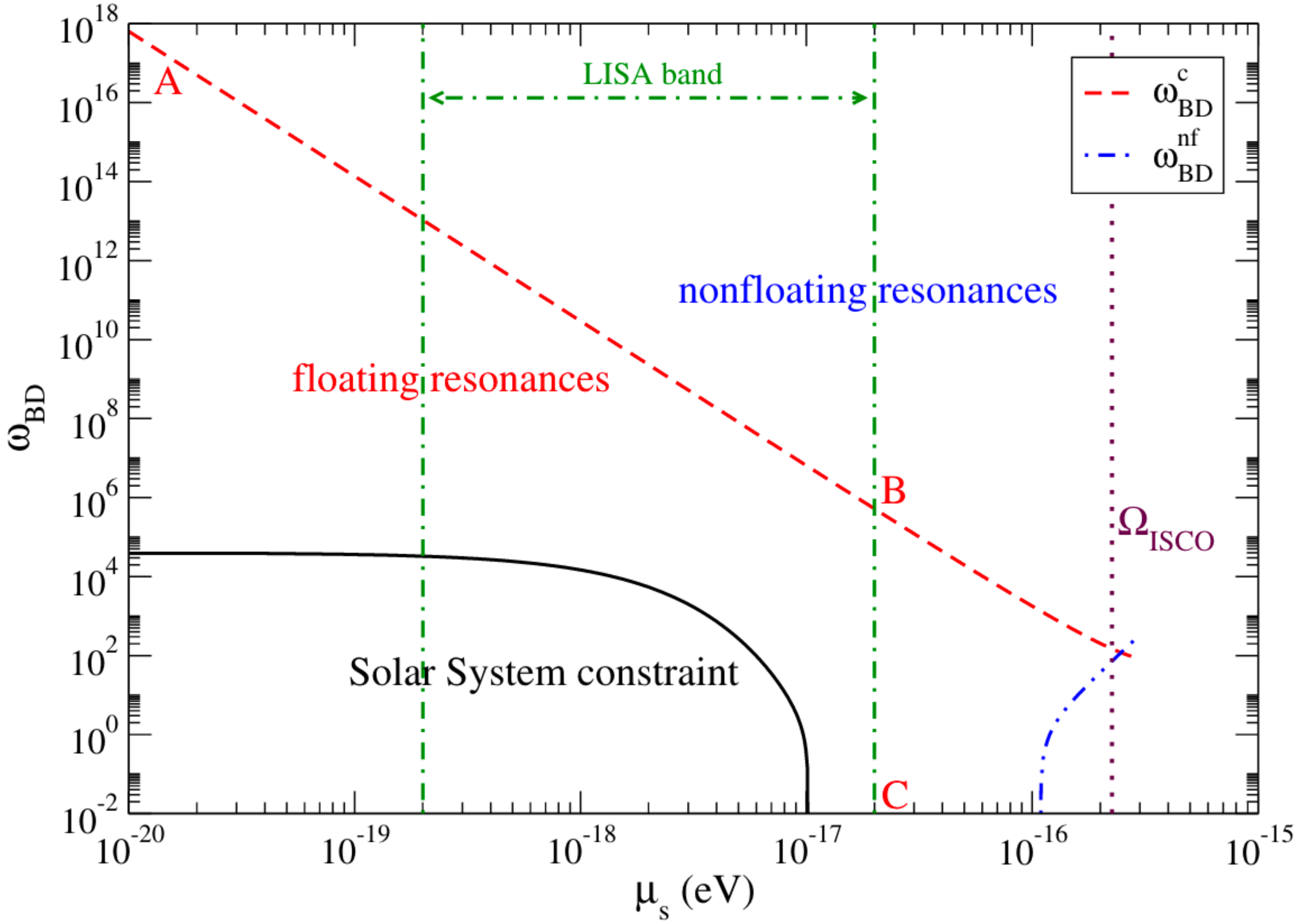
Only non-zero over certain range

(Damour & Esposito-Farèse, PRL 1993)



Lower bound on the scalar mass (contd.)

To which extent can EMRI probe the scalar mass?



Yunes +, PRD (2012)

Energy flux from binary

- Dipolar radiation is supported by the difference in scalar charges, which is the leading-order scalar flux

$$\begin{aligned}\begin{matrix}\text{Energy}\\ \text{flux}\end{matrix} &= \left\{\frac{\text{Quadrupole}}{c^5} + \mathcal{O}\left(\frac{1}{c^7}\right)\right\}_{\text{spin 2}} \\ &+ \left\{\frac{\text{Monopole}}{c}\left(0 + \frac{1}{c^2}\right)^2 + \frac{\text{Dipole}}{c^3} + \frac{\text{Quadrupole}}{c^5} + \mathcal{O}\left(\frac{1}{c^7}\right)\right\}_{\text{spin 0}},\end{aligned}$$

Esposito-Farèse, Fundam. Theor. Phys. (2011)

$$\frac{\dot{P}}{P} = -\frac{8}{5}\frac{\mu m^2}{r^4}\kappa_1 - \frac{\mu m}{r^3}\kappa_D \mathcal{S}^2,$$

where

$$\kappa_1 = \mathcal{G}^2\left[12 - 6\xi + \xi\Gamma^2\left(\frac{4\omega^2 - m_s^2}{4\omega^2}\right)^2 \Theta(2\omega - m_s)\right],$$

$$\kappa_D = 2\mathcal{G}\xi\frac{\omega^2 - m_s^2}{\omega^2}\Theta(\omega - m_s),$$

Alsing +, PRD (2012)

Dipolar scalar radiation in inspiral waveform

— stationary phase approximation —

For massive Brans-Dicke theory [Berti +, PRD (2012)]

0 PN (chirp mass)

1 PN

1.5 PN

$$\psi(f) = 2\pi f t_c - \phi_c - \frac{\pi}{4} + \frac{3}{128(\pi \mathcal{M} f)^{5/3}}\Big\{1 + \zeta + \frac{20}{9} A \eta^{-2/5}(\pi \mathcal{M} f)^{2/3} - 16\pi\eta^{-3/5}(\pi \mathcal{M} f) + \dots$$

Mass square

$$+ \xi \Gamma^2 \nu \left[\frac{5}{462}\eta^{6/5}(\pi \mathcal{M} f)^{-2} - \frac{\nu}{1632}\eta^{12/5}(\pi \mathcal{M} f)^{-4}\right]\Theta(2\pi f - m_s)$$

BD coupl.

$$+ \xi \mathcal{S}^2 \left[\frac{25\nu}{1248}\eta^{8/5}(\pi \mathcal{M} f)^{-8/3} - \frac{5}{84}\eta^{2/5}(\pi \mathcal{M} f)^{-2/3}\right]\Theta(\pi f - m_s)\Big\},$$

Scalar mass

-1 PN

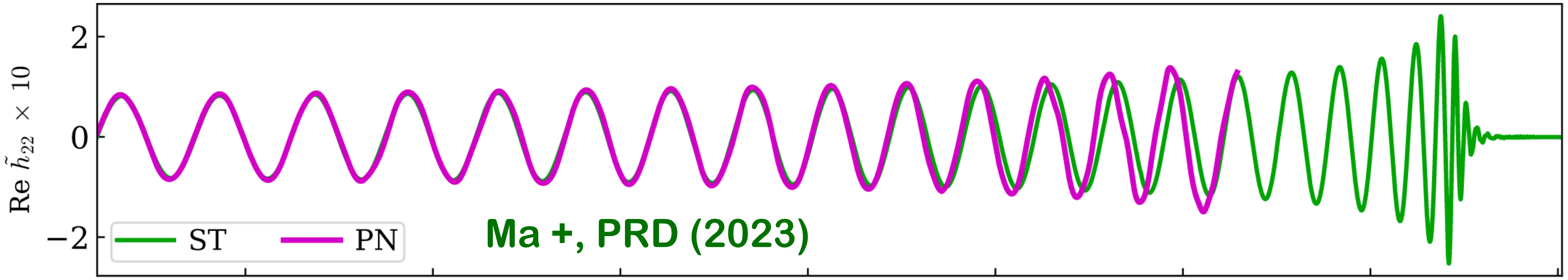
Charge diff.

Heaviside

Dipolar scalar radiation in inspiral waveform (contd.)

— stationary phase approximation —

For massless DEF theory **[Sennett +, PRD (2016); Bernard +, JCAP (2022)]**



Ma +, PRD (2023)

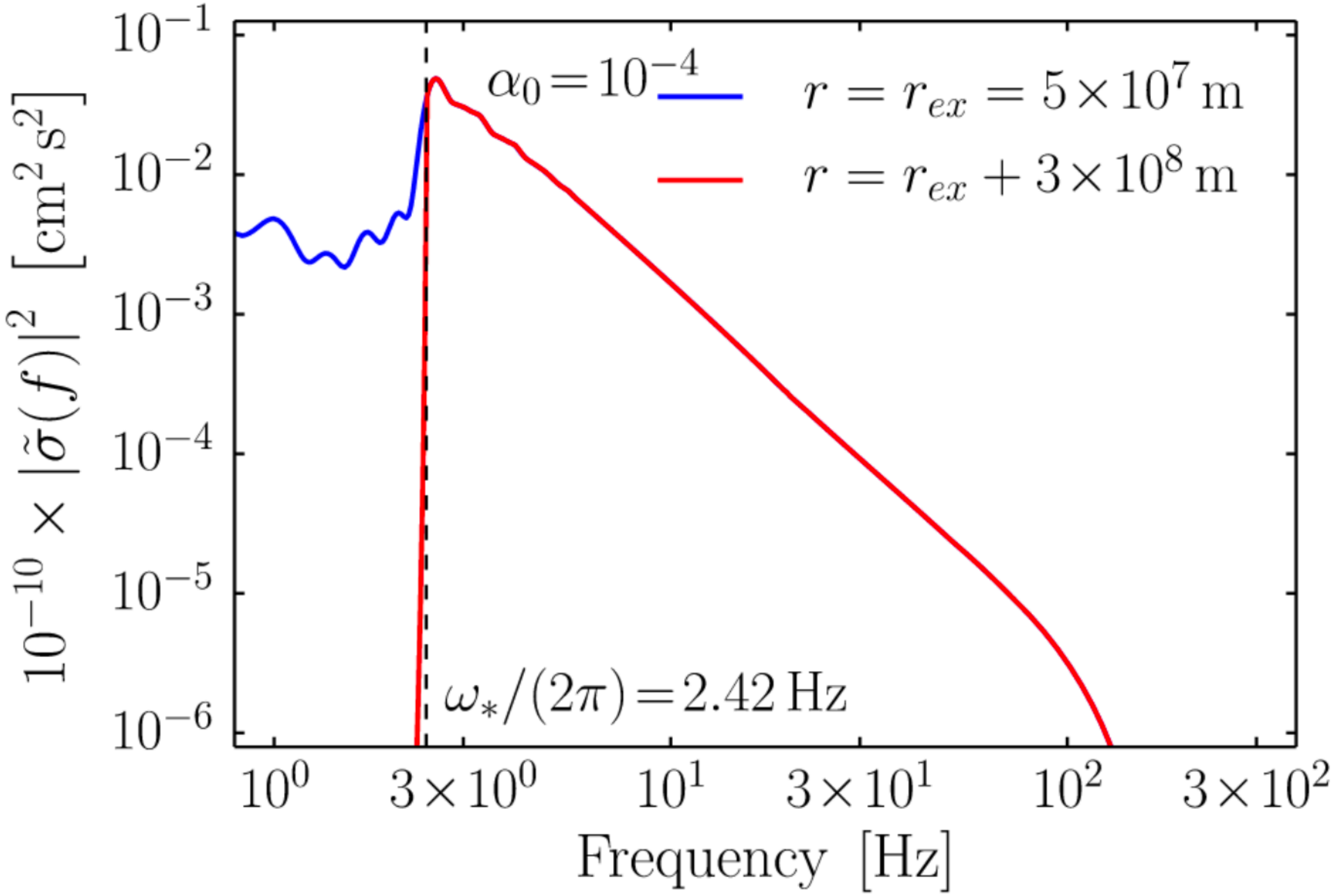
- In the presence of dynamical scalarization, the waveform can be divided into quadrupolar and dipolar emission dominant regions.
- In GW170817, it should be in the quad-dominant regime up to $f_{\rm gw} \gtrsim 500$ Hz
—> spontaneous scalarization is excluded unless roughly equal mass

Mass effects (contd.)

Scalar mass introduces:

1. a Yukawa-suppression to scalar interaction
2. **Cutoff frequency on scalar emission**

$$\tilde{\sigma}(\omega;r)=\tilde{\sigma}(\omega;r_{\rm ex})\begin{cases} e^{-i\sqrt{\omega^2-\omega_*^2}(r-r_{\rm ex})} & \text{for } \omega<-\omega_*, \\ e^{+i\sqrt{\omega^2-\omega_*^2}(r-r_{\rm ex})} & \text{for } \omega>-\omega_*. \end{cases}$$



Sperhake +, PRL (2017)