On the finite-size imprints on waveforms of binary neutron star mergers

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MAX PLANCK INSTITUTE
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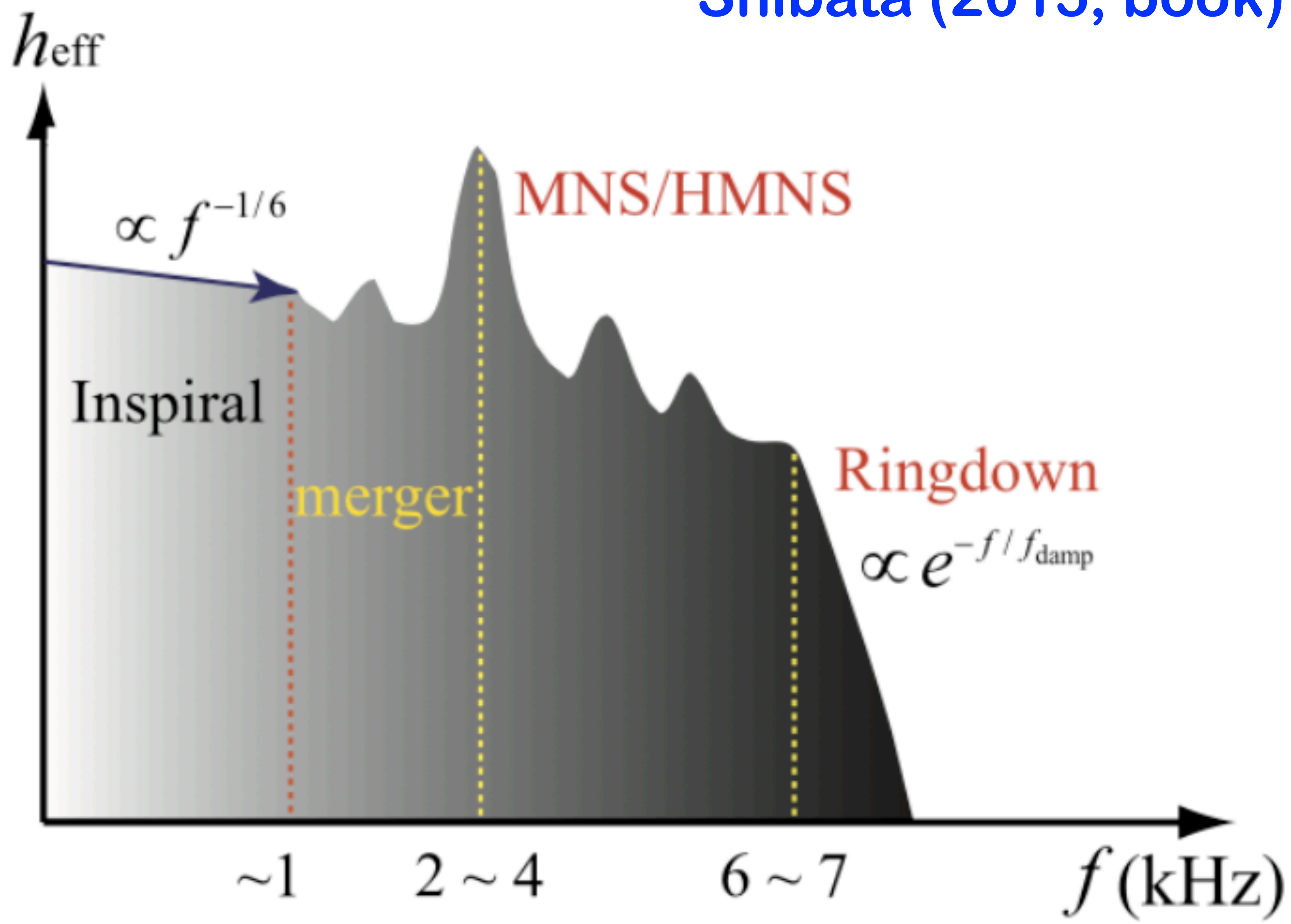
(Albert Einstein Institute)

Ondes gravitationnelles et objets compacts, October 10, 2024 @ Meudon

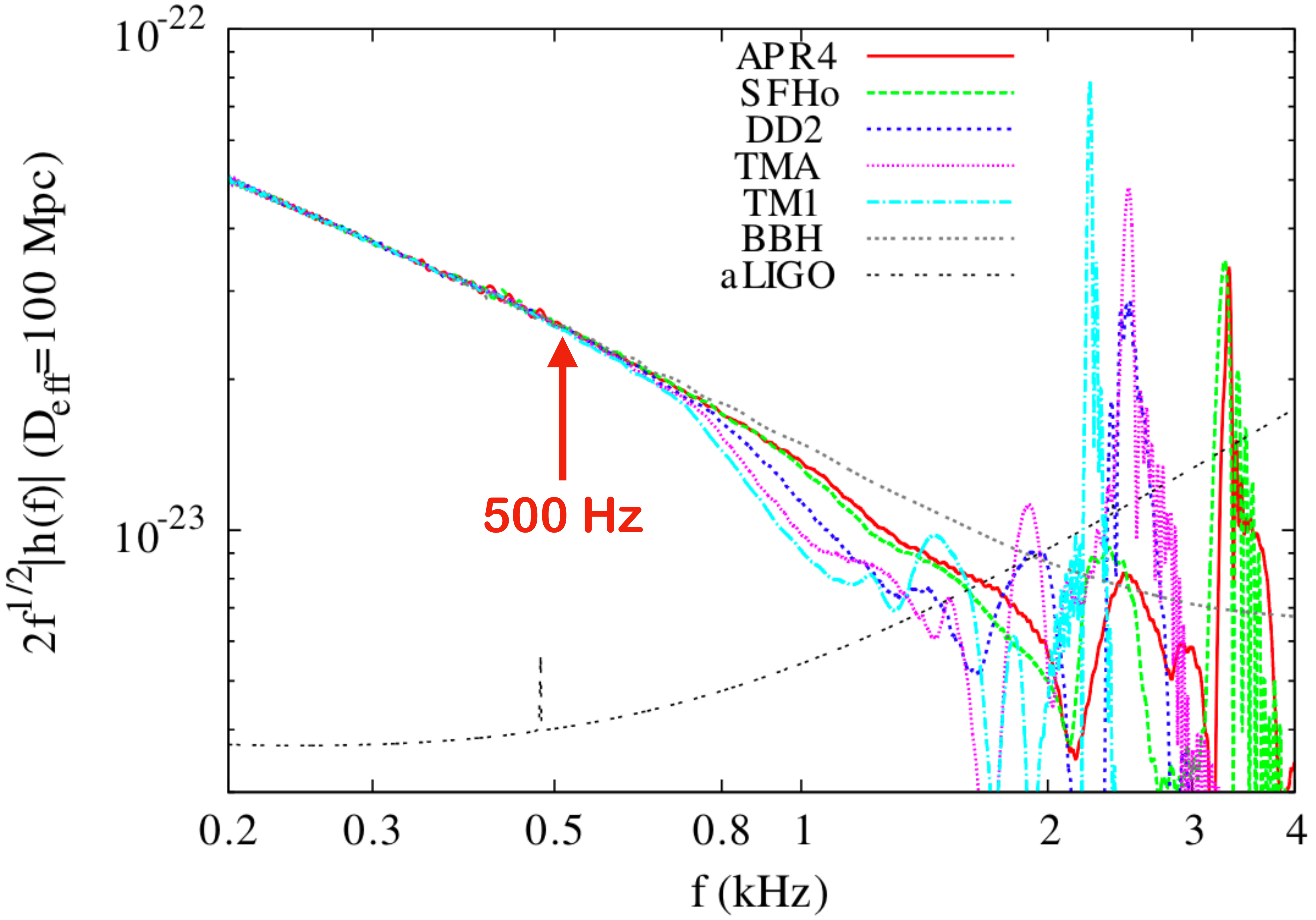
Outline

- **Finite-size imprints** on late-inspiral waveform
- **Scalar interaction** in the context of binaries
- Parameter space after pulsar timing observations
- **Quasi-equilibrium states** of binary neutron stars
- **Degeneracy between gravity theory and EOS**
- Possible scenarios for GW170817

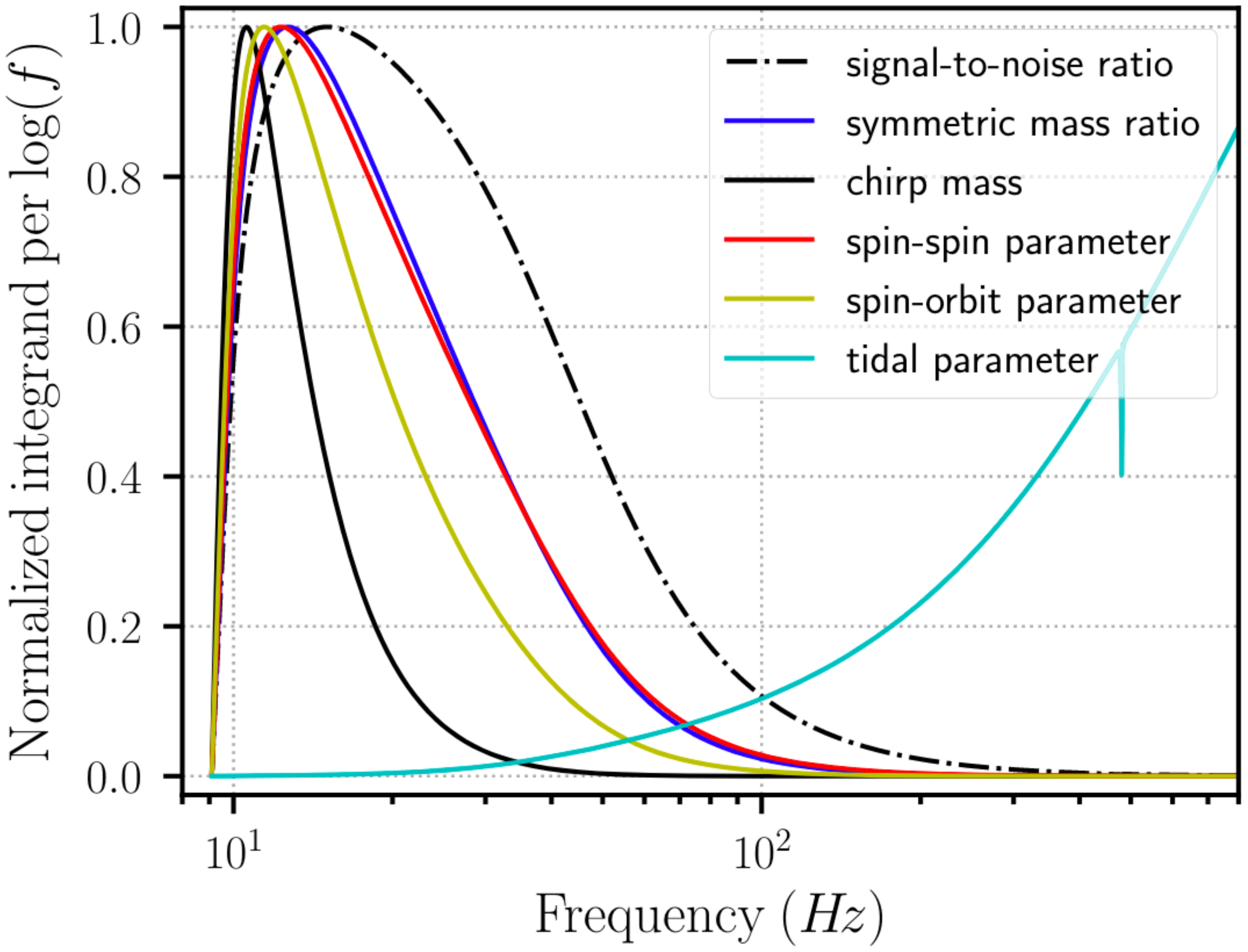
Shibata (2015; book)



Finite size effects in inspiral GW



Hotokezaka +, PRD (2013, 2016)



Harry & Hinderer, CQG (2018)

Scalar activity in binaries

Interplays of scalar in compact binaries

- Two bodies with scalar charges can interact such that they feel an effective gravitational constant

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

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

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

- Difference in the scalar charges can emit scalar waves

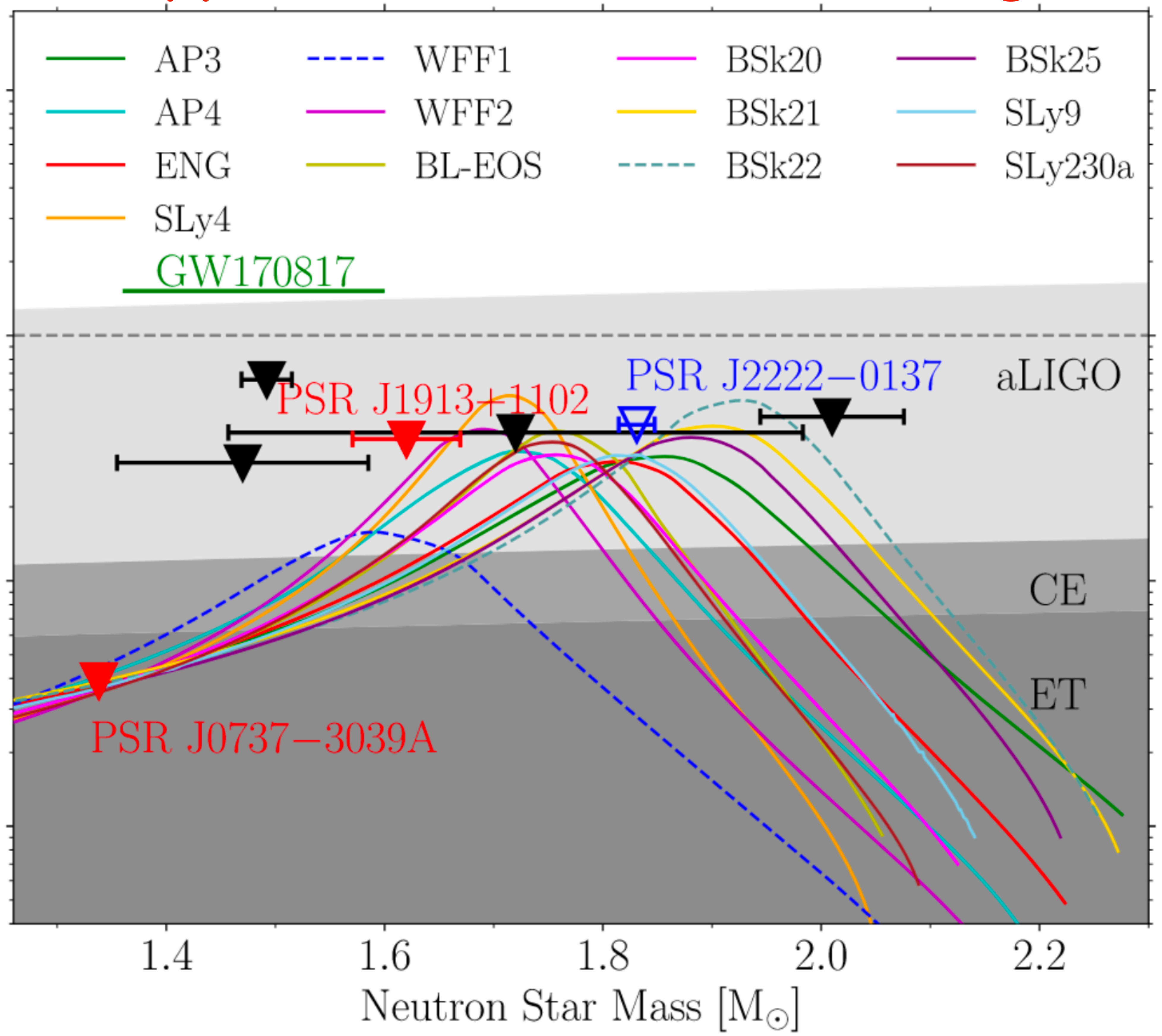
$$\dot{E}_{\rm quadrupole} = \frac{32G}{5c^3}\left(\frac{G_{\rm eff} m_1 m_2}{r^2}\right)^2 \left(\frac{v}{c}\right)^2$$

Damour & Esposito-Farese, CQG (1992)

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

A scalar mass is necessary

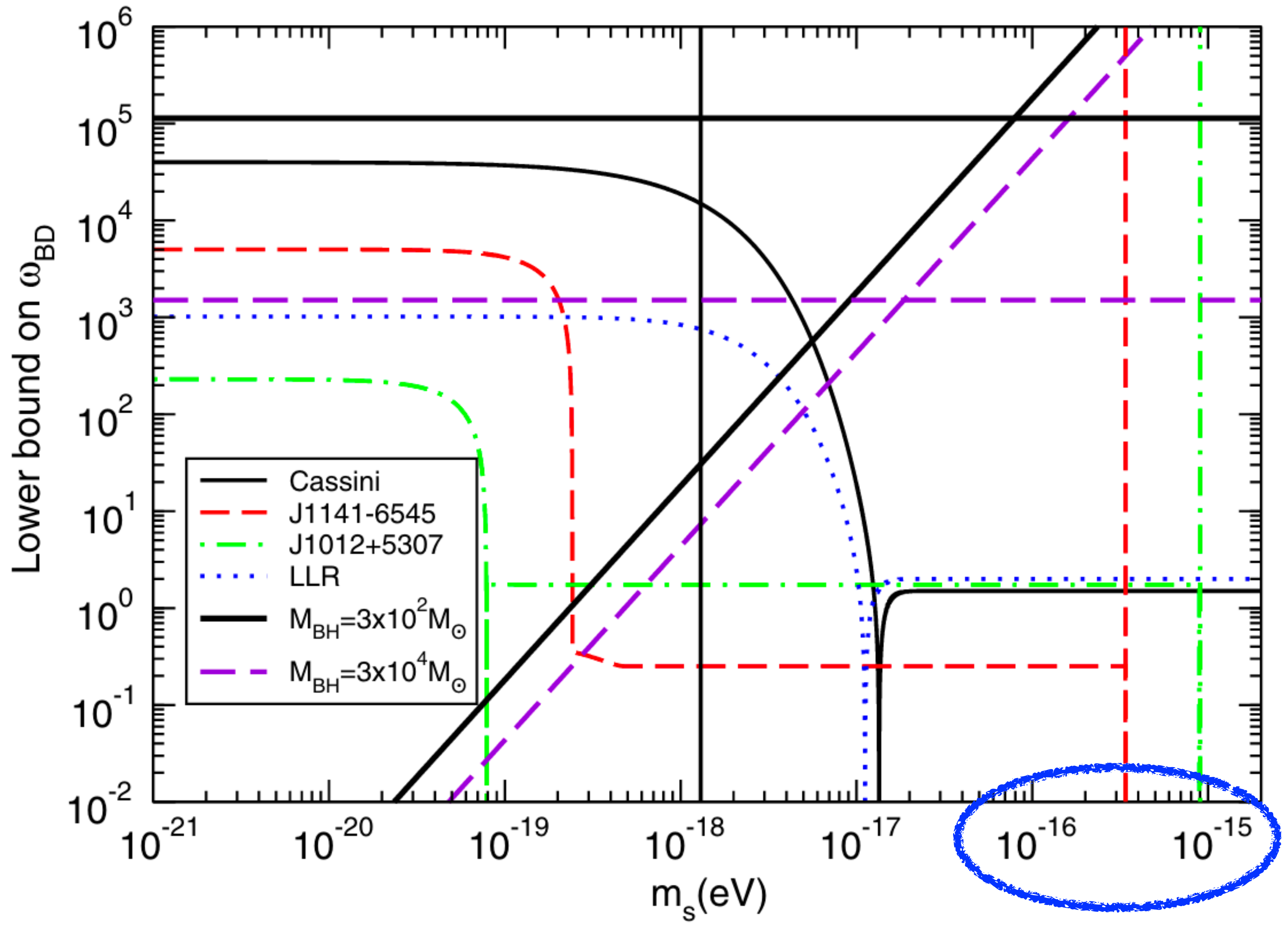
Upper bound on the scalar charge



Zhou +, 2022

- As of 2022, seven **pulsars almost exclude the scalarization** for all NS masses if the scalar is massless —> need mass, which gives **Compton length scale** $(10^{-11}\,\mathrm{eV} \simeq 20\,\mathrm{km})$

A scalar mass is necessary — II



Berti +, PRD (2013)

- To further constrain the scalar mass, closer binaries are necessary.
- In the LVK band, GWs can be used to measure the binary motion when orbital separation is **< a few 100 km, thus could probe up to** $\sim 10^{-11}$ eV

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 BNS initial data** for DEF **[Shibata +, PRD (2014); Taniguchi +, PRD (2015)]**
- Above efforts are in massless theory; nice way to gain intuition but need to go to the massive case. Starting from **constructing IDs**

Quasi-equilibrium states as IDs

focusing on the Damour-Esposito-Farese-type theory

Scalar mass effects

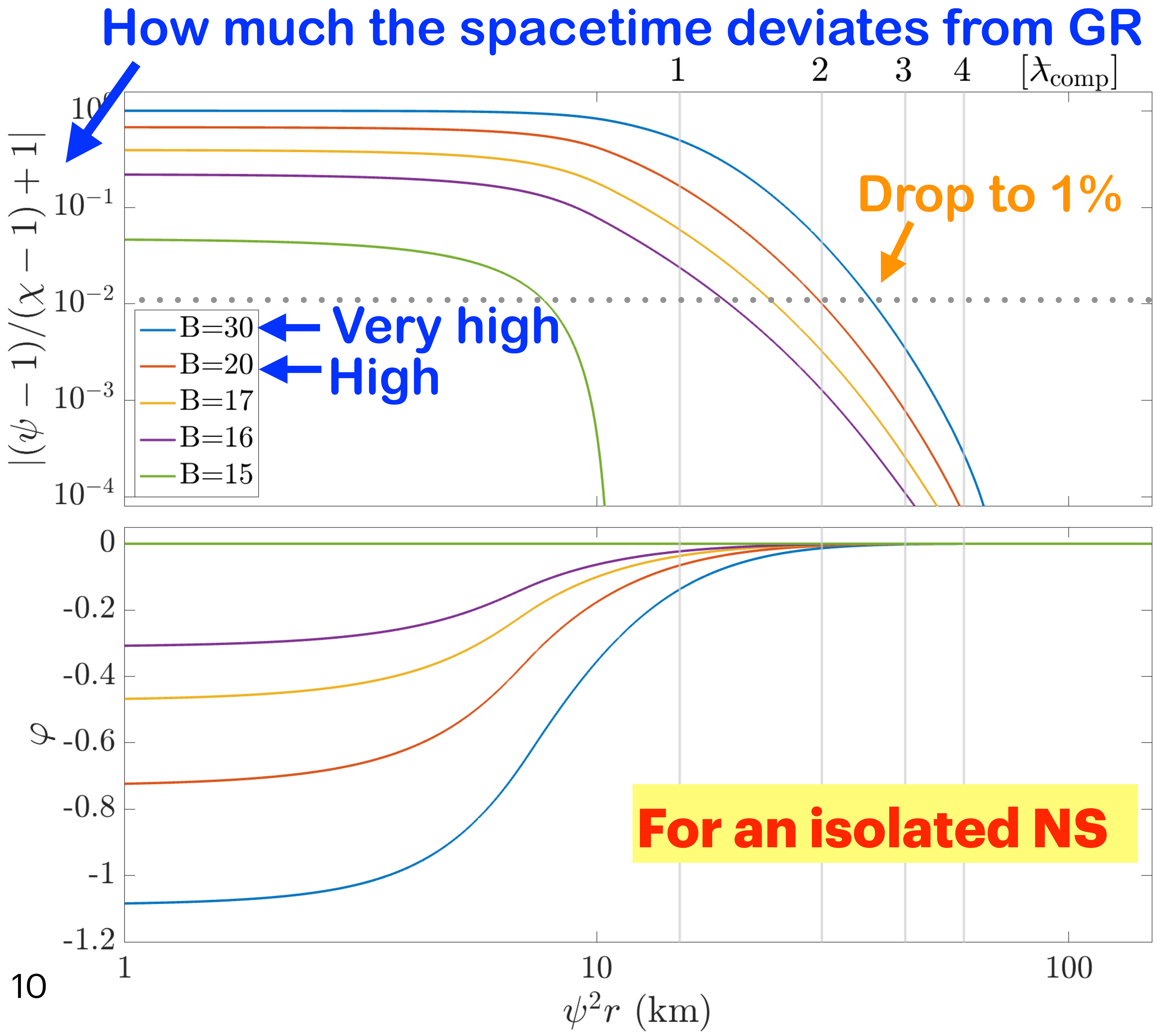
$$S = \frac{1}{16\pi}\int d^4x\sqrt{-g}\left[\phi\mathcal{R} - \frac{\omega(\phi)}{\phi}\nabla_a\phi\nabla^a\phi - \frac{2m_\phi^2\varphi^2\phi^2}{B}\right] - S_{\text{matter}},$$

Parameters:

- Coupling constant B
- Scalar mass m_ϕ

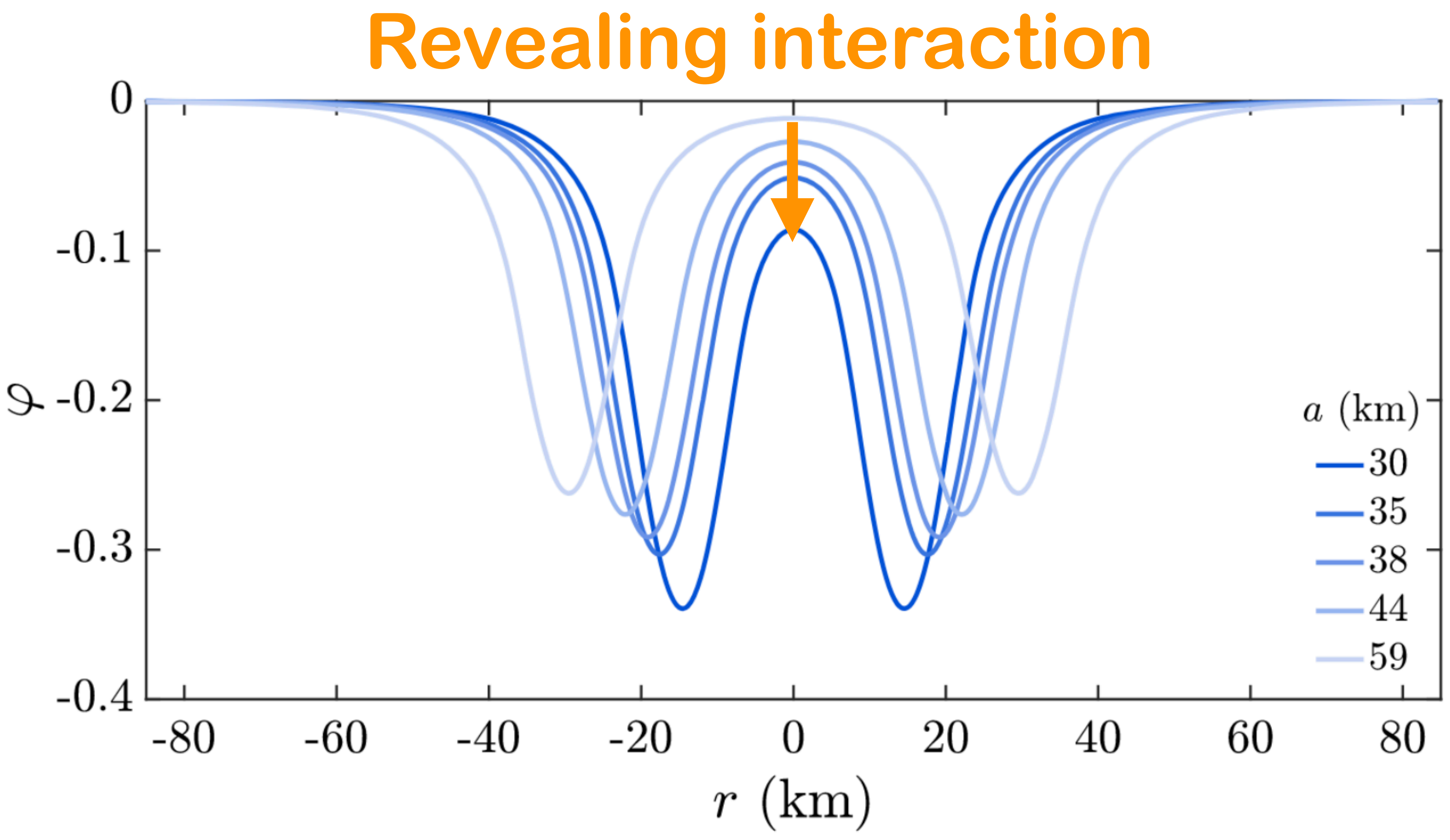
Scalar mass introduces:

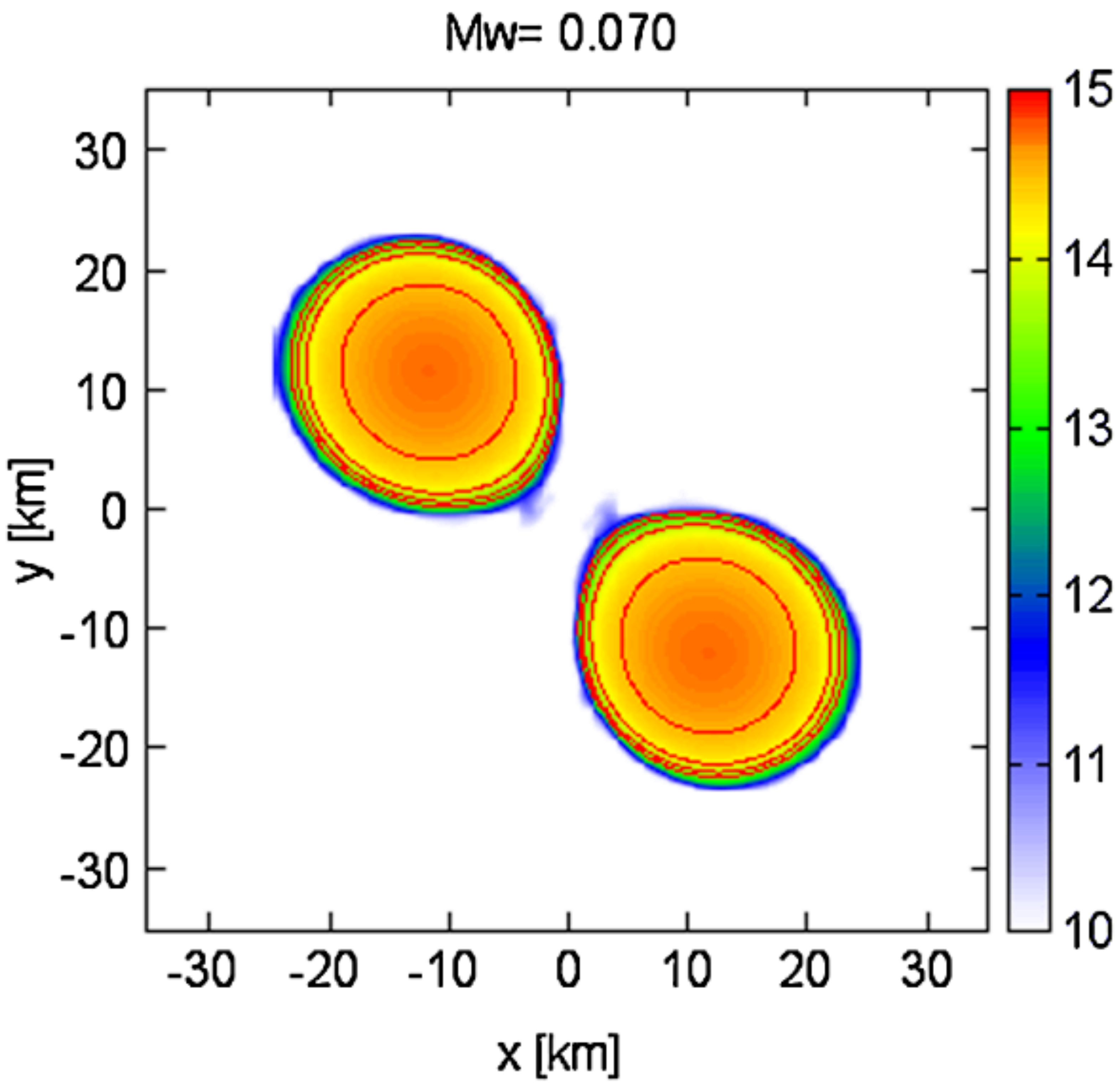
1. **a Yukawa-suppression to scalar interaction**
2. Cutoff frequency on the scalar emission



Development of scalar cloud

- Scalar cloud enhances as orbit shrinks—> providing “attractions”
- At the same time, tidal distortion is enhanced, which also accelerates the merger





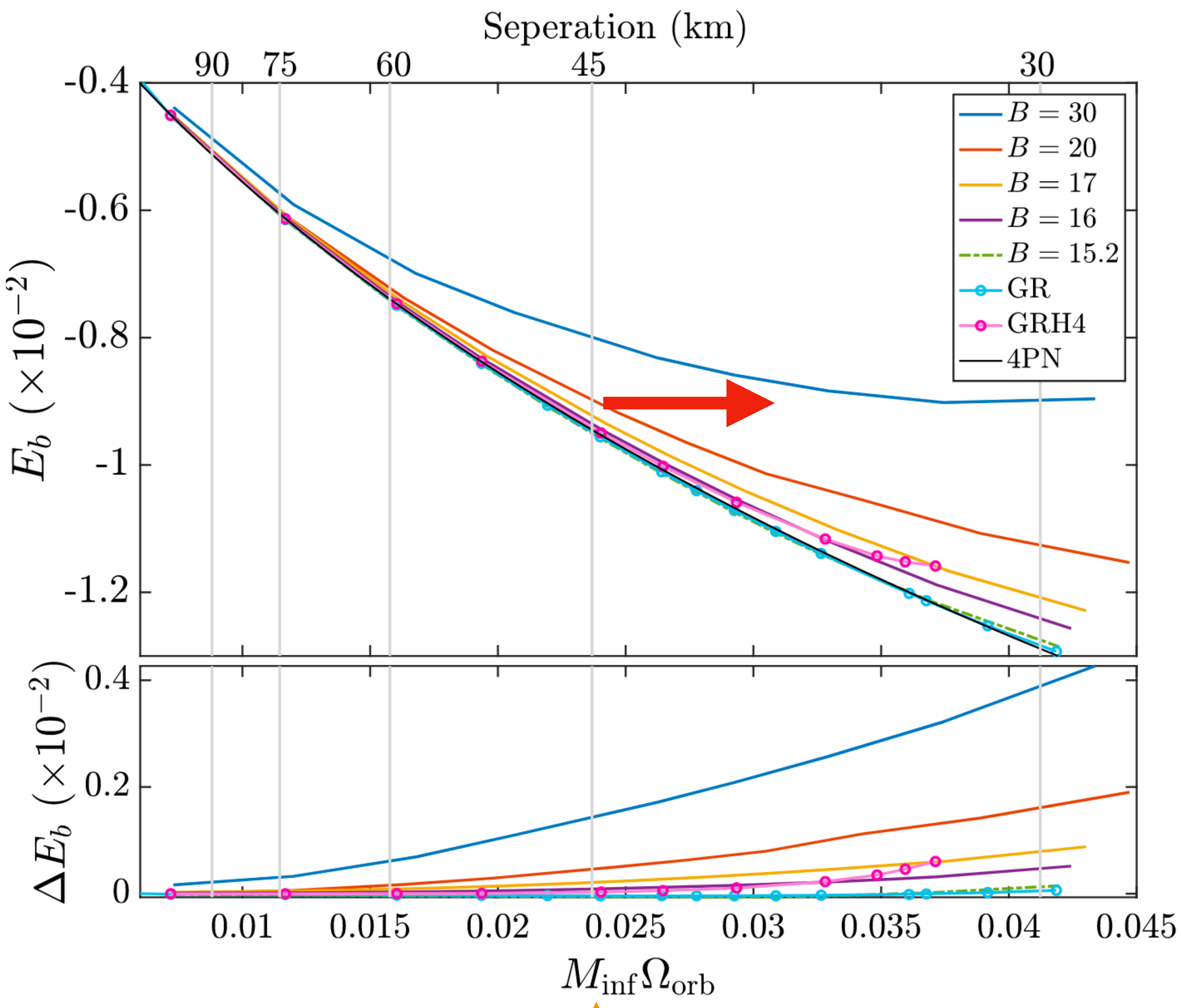
Hotokezaka +, PRD (2013, 2016)

Quasi-equilibrium states of BNS

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

Damour & Esposito-Farese, CQG (1992)

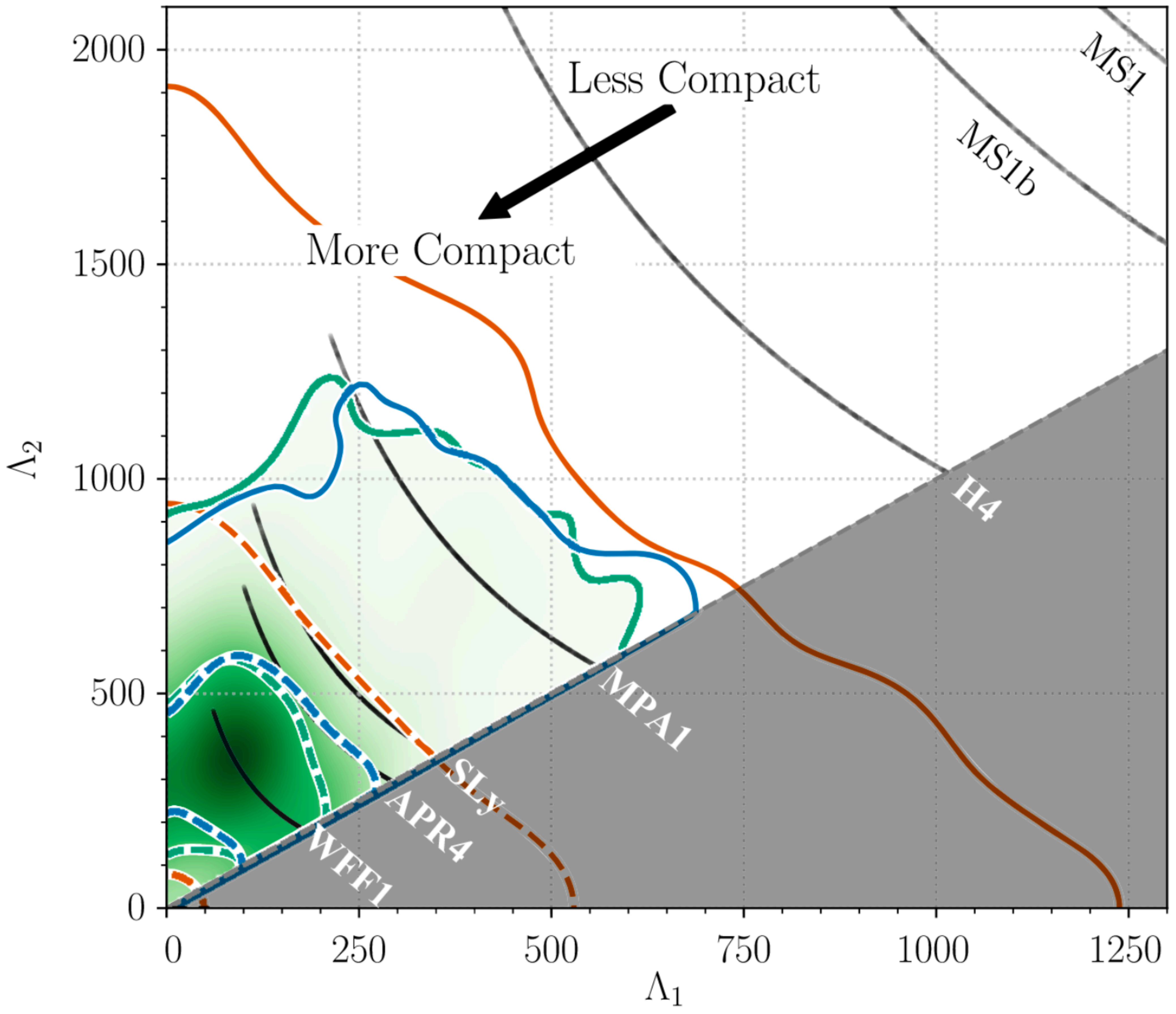
- The scalar interaction offers additional `attracting force' => higher orb. frequency for a given binding energy
- Tidal interaction can play a similar role as well (degeneracy)



Total mass of binary

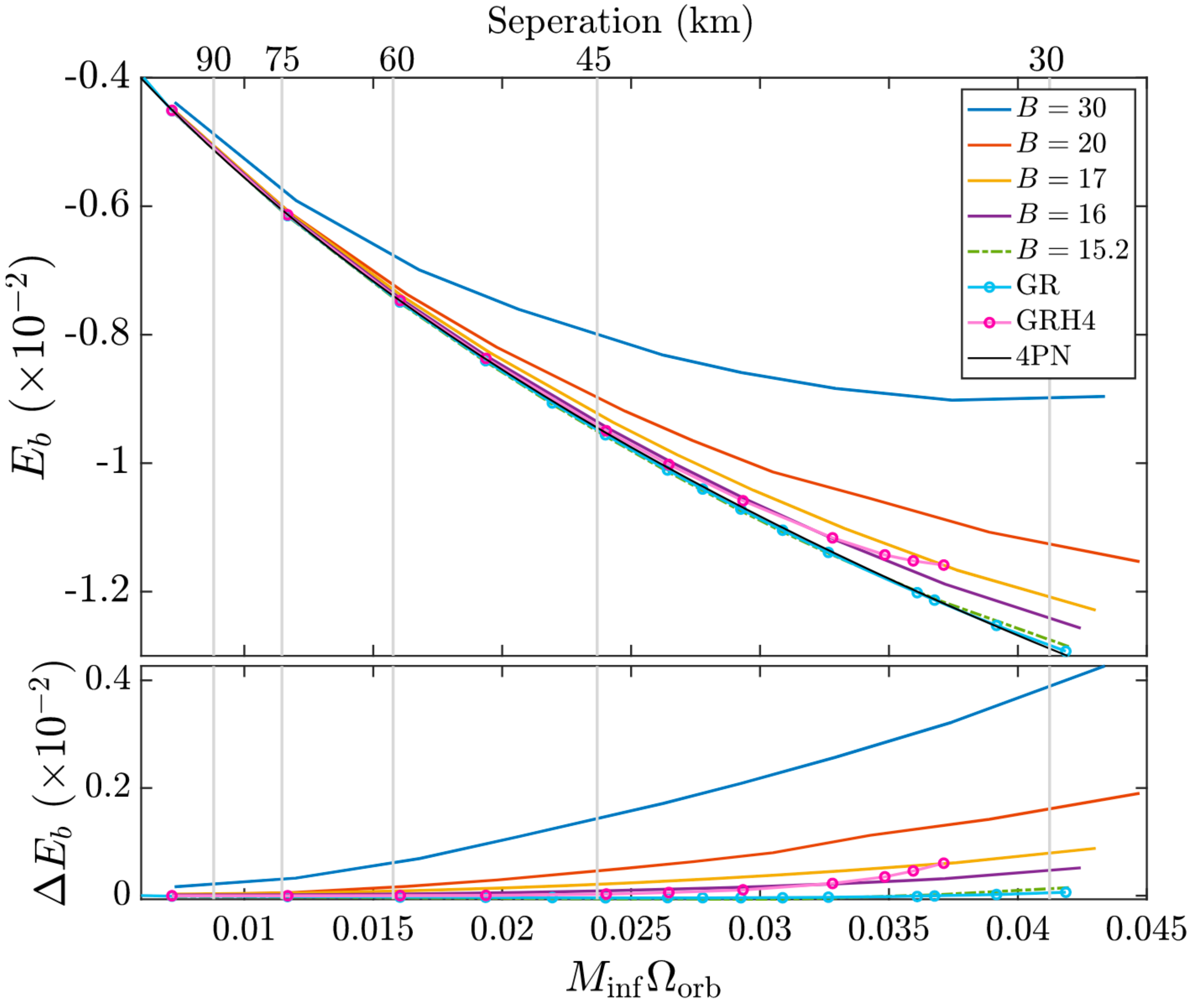
Potential in limiting scalar mass by BNS

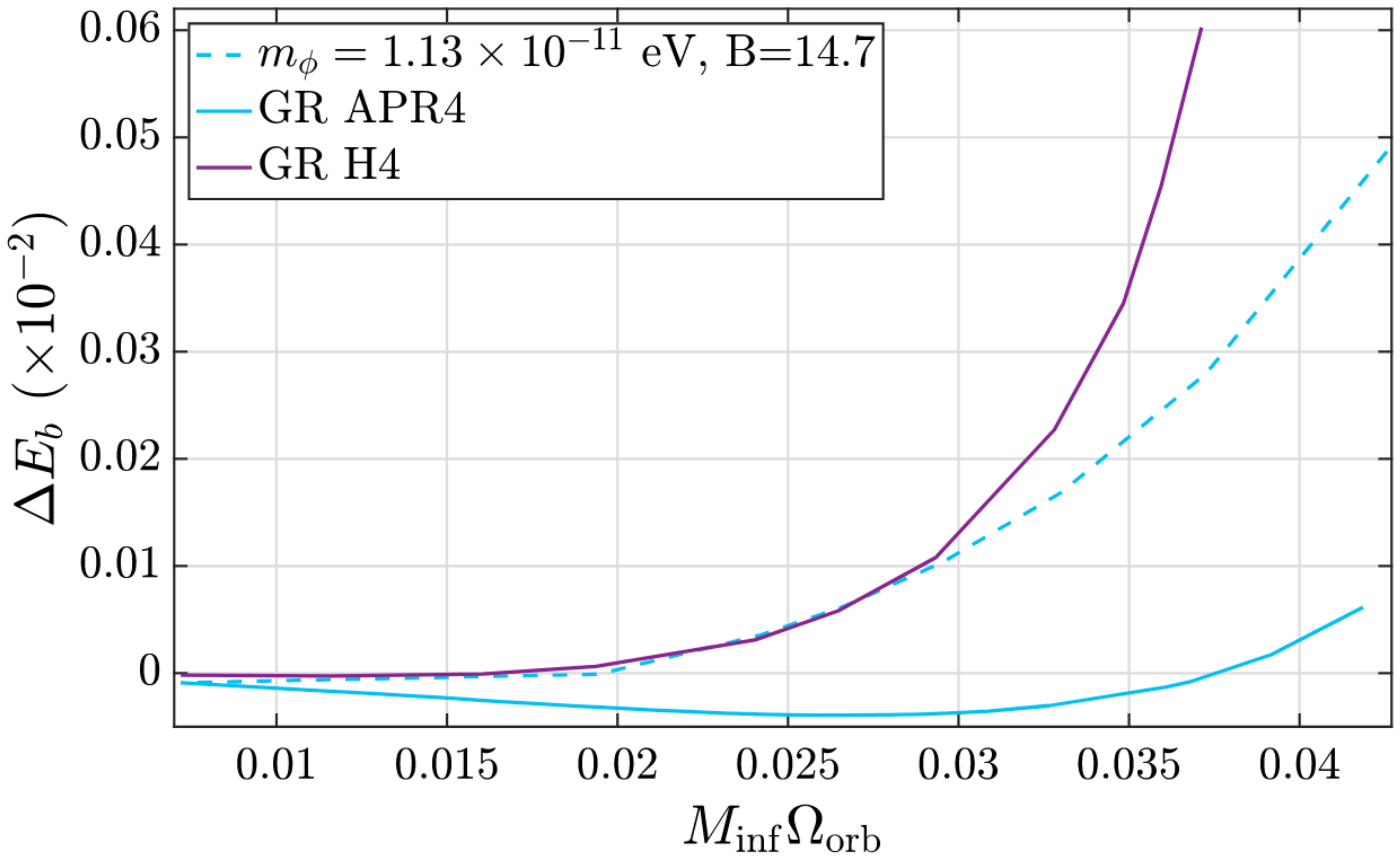
$$\delta\Psi_{\text{signal}} = \delta\Psi_{\text{EOS}} + \delta\Psi_{\text{gravity}}$$



Potential in limiting scalar mass by BNS — II

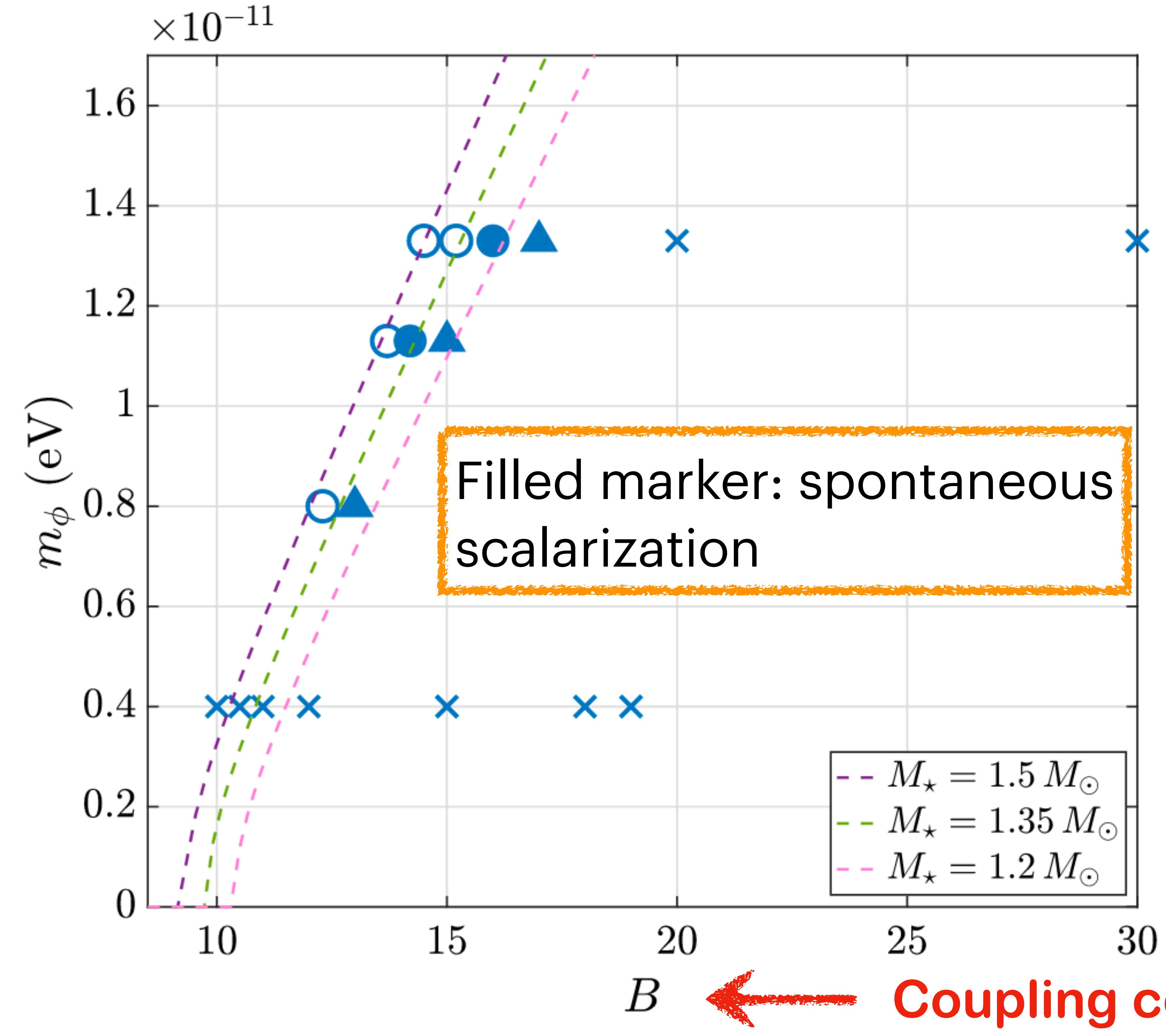
Assuming the 3.5 PN energy flux in GR **(Shibata +, 14')**, we can approximate # of cycles





Potential in limiting scalar mass by BNS — II

$\delta\Psi_{\text{signal}} = \delta\Psi_{\text{gravity}} + \delta\Psi_{\text{APR4}}$ → An m_ϕ-dep. upper bound on B



Coupling constant

Things after GW170817

- Possible scenarios for GW170817-like events:
    1. NS members are **not spontaneously scalarized while dynamically scalarized** after $f_{\rm gw} = 500$ Hz —> require late time precise modeling
    2. NS members are **spontaneously scalarized but scalar effects are suppressed** until $f_{\rm gw} = 500$ Hz
    3. Scalar effects can only kink in for higher energy physics in the post-merger phase **(Alan's talk)**
- Observation is consistent with GR but not necessarily excludes others **(Abbott +, 17' 18' 19')**; necessitating post-merger pheno. to probe the theory further

Summary

- The Compton length is shown to be less than 10^{6-7} km by pulsar observations
- Coalescing neutron stars could probe the Compton length down to $\lesssim 10^2$ km
- Strong degeneracy between finite size effects (i.e., tidal and scalar imprints on inspiral GWs)
- Post-merger evolution could be used to probe larger parameter space (e.g., weaker coupling and/or heavier scalar mass)

Thank you!