Probing gravity with gravitational waves from binary inspirals

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Overview

- Gravitational waves (GWs) from coalescing binary systems probe gravity in unexplored regimes

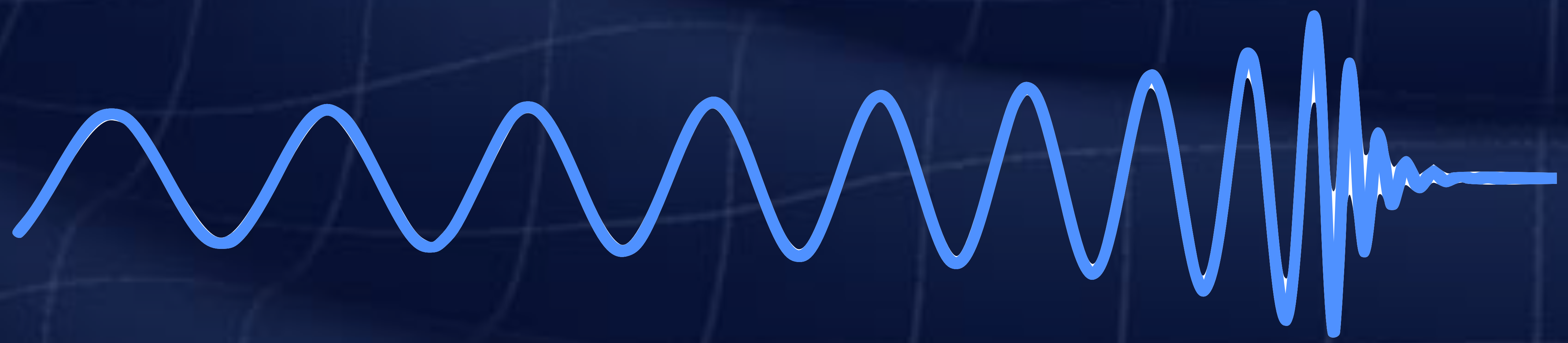
- Waveform models are essential to link GW data to fundamental theory

- Example *inspiral* GW signatures of phenomena arising in classes of gravity theories
  - *Black holes:* quadratic-curvature effects & scalar hair
  - *Neutron stars:* nonlinear interplay of dense matter, spacetime, scalar fields

- Outlook to upcoming future prospects and remaining challenges

Probing gravity with GWs

Consistency tests, e.g. parameterized deviations from GR waveforms



What do GWs tell us about fundamental properties of gravity?

theory-specific waveforms

Constraints on (classes of) gravity theories

Nonlinear link: features of gravity ↔ GWs signatures

different sectors of new physics

Example I: massless scalar-Gauss-Bonnet (sGB) gravity

Scalar field

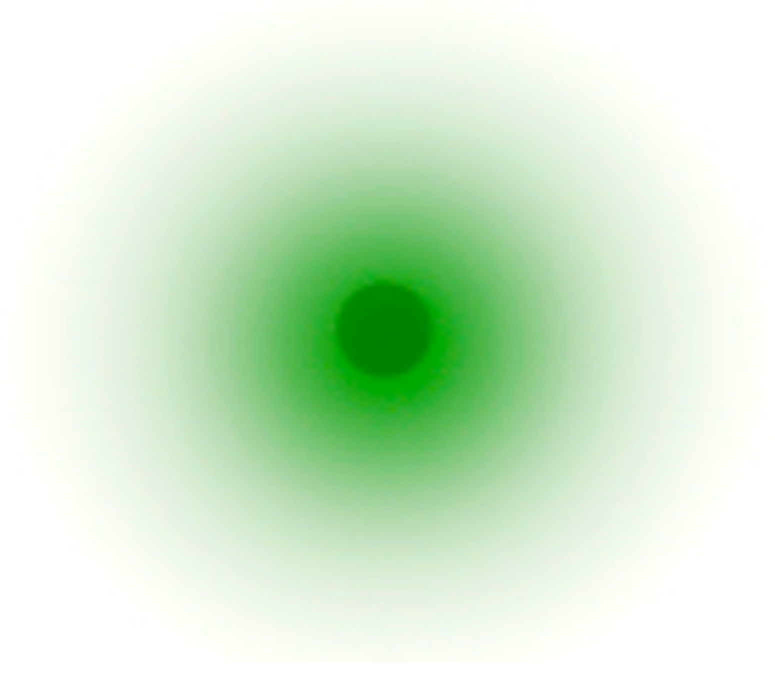
$$S_{\mathrm{sGB}} = \frac{c^3}{16\pi G}\int d^4x\sqrt{-g}\,\left[R + \alpha f(\phi)\,\mathscr{R}^2_{GB} - 2\nabla_\mu\phi\,\nabla^\mu\phi\right]$$

Coupling constant

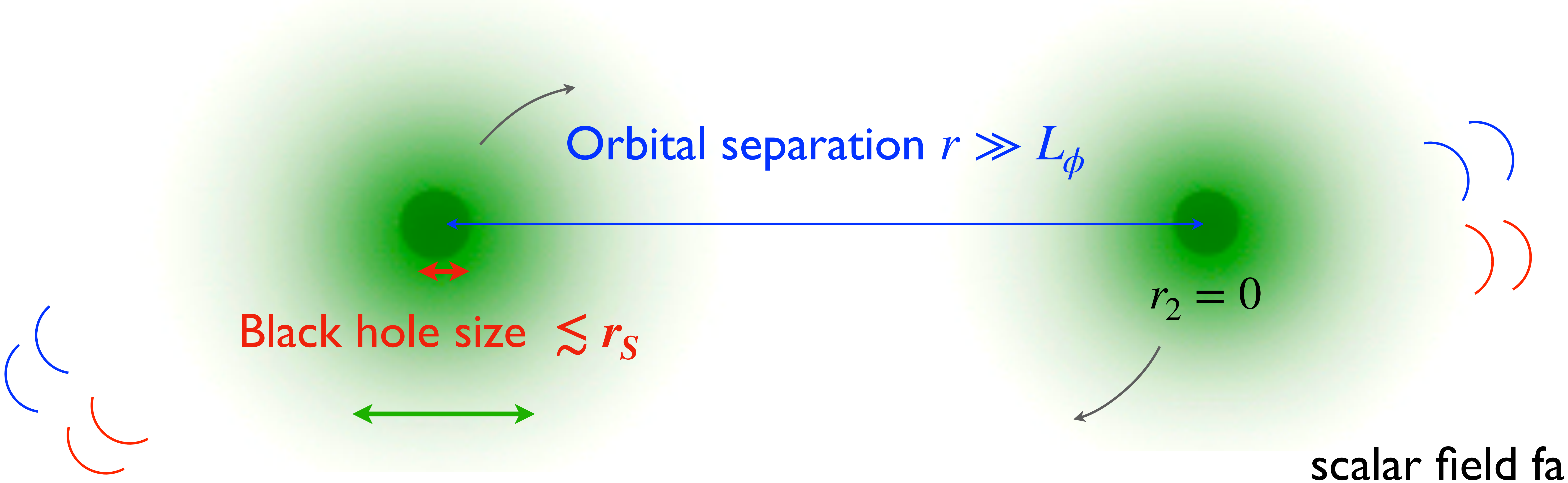
Coupling function

Gauss-Bonnet topological invariant: $\mathscr{R}^2_{GB} = R^2 - 4R^{\mu\nu}R_{\mu\nu} + R^{\mu\nu\rho\sigma}R_{\mu\nu\rho\sigma}$

- Quadratic-in-curvature corrections to GR
- Second-order equations of motion → dynamical system
- sGB black holes can acquire scalar hair



Leading-order scalar effects in sGB black hole binaries



Orbital separation $r \gg L_\phi$

Gravitational waves

Scalar waves

Black hole size $\lesssim r_S$

$r_2 = 0$

scalar field energy concentrated within $L_\phi \sim$ (few) r_S

scalar ‘charge’

scalar field falls off as: $\lim_{r_2 \to \infty} \phi \sim \frac{Q}{r_2}$

sGB: $Q = \frac{\alpha}{r_S} f'(0)$

Theory-dependent (matching to full compact-object - scalar condensate solutions)

Many effects of scalar charge are ‘universal’, e.g.

- Renormalized gravitational coupling $G_{\text{eff}} = G\left(1 + Q_1 Q_2 / M_1 M_2\right)$
- Scalar dipole radiation $\Phi^{\text{rad}}_{\text{dipole}} \sim \frac{4\mu}{d}\left(Q_1/M_1 - Q_2/M_2\right)(n \cdot v)$

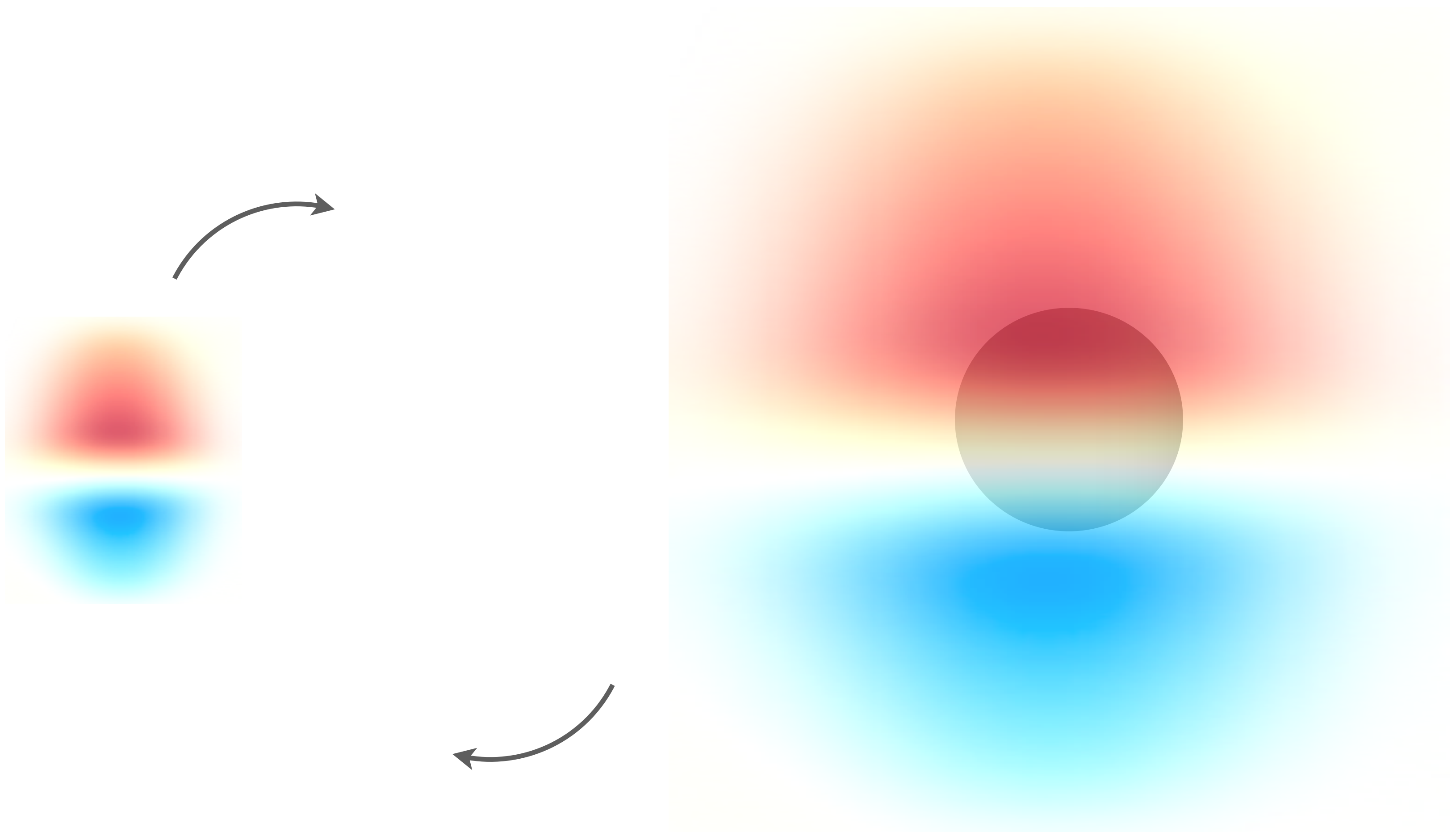
Damour & Esposito-Farese 1994, Yagi+ 2011 for sGB, Cliff Will’s book, …

Dominant interaction of the scalar clouds

- scalar dipolar tidal field $\mathscr{E}_i^s = -\nabla_i \phi$ due to companion
- scalar condensate responds: induced dipole moment $\mathcal{Q}_s^i$

Adiabatic limit: $\mathcal{Q}_s^i = -\lambda_s \, \mathscr{E}_s^i$

Scalar tidal deformability/Love number



ϕ sourced by companion varies across the condensate ⇒ tidal deformation

for sGB black holes:

$$\lambda_s = \frac{7}{12} \, \alpha \, r_S \, f''(0)$$

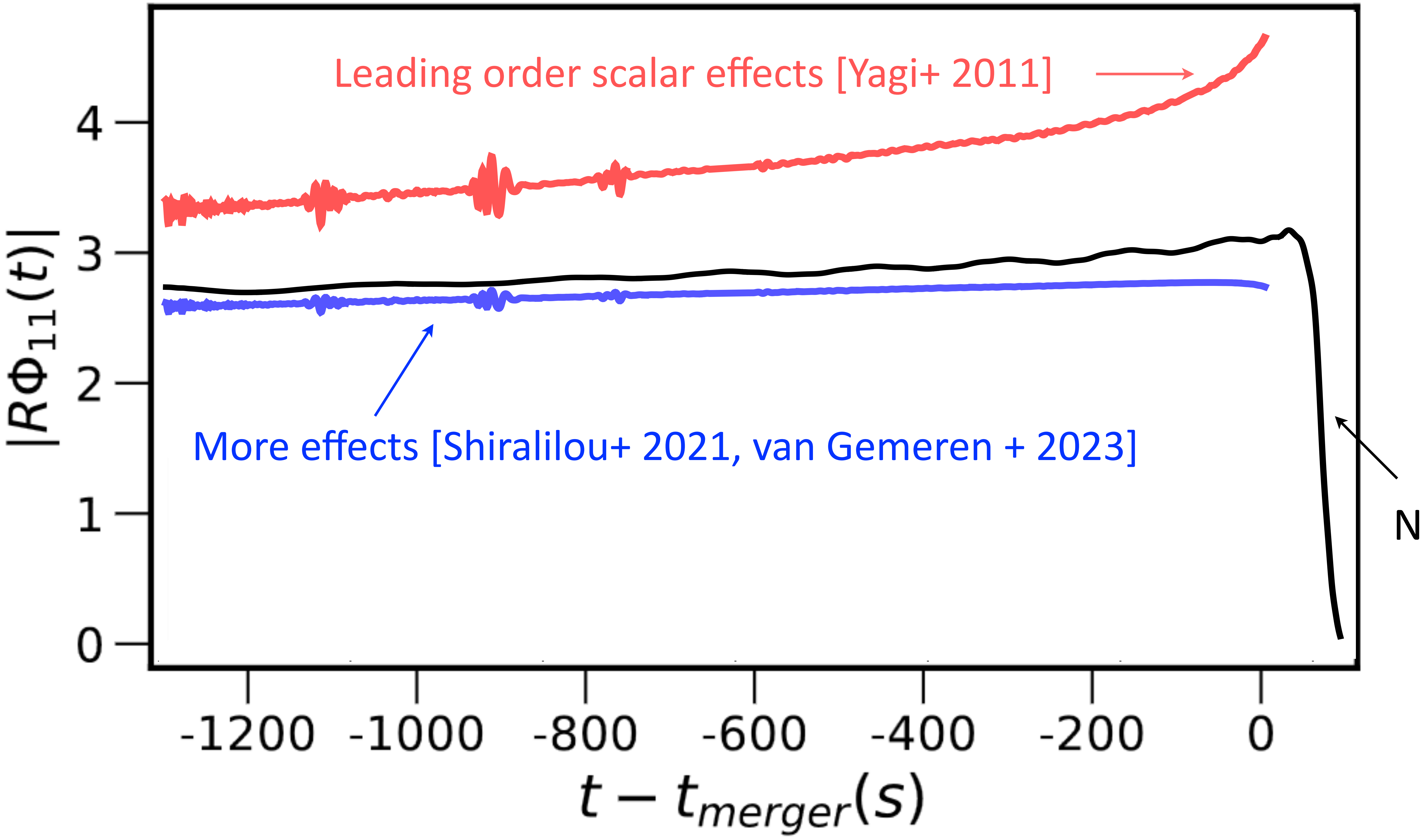
- In GWs: dipolar tidal effects lead to same scaling with frequency as the sGB higher-curvature corrections

Iris van Gemeren, Banafsheh Shiralilou, TH (2023)

Check: amplitude of scalar waves

- Test analytical results against numerical relativity simulations of scalar field dynamics

Amplitude of dipolar scalar waves (mass ratio 4)



Leading order scalar effects [Yagi+ 2011]

More effects [Shiralilou+ 2021, van Gemeren + 2023]

Numerical relativity

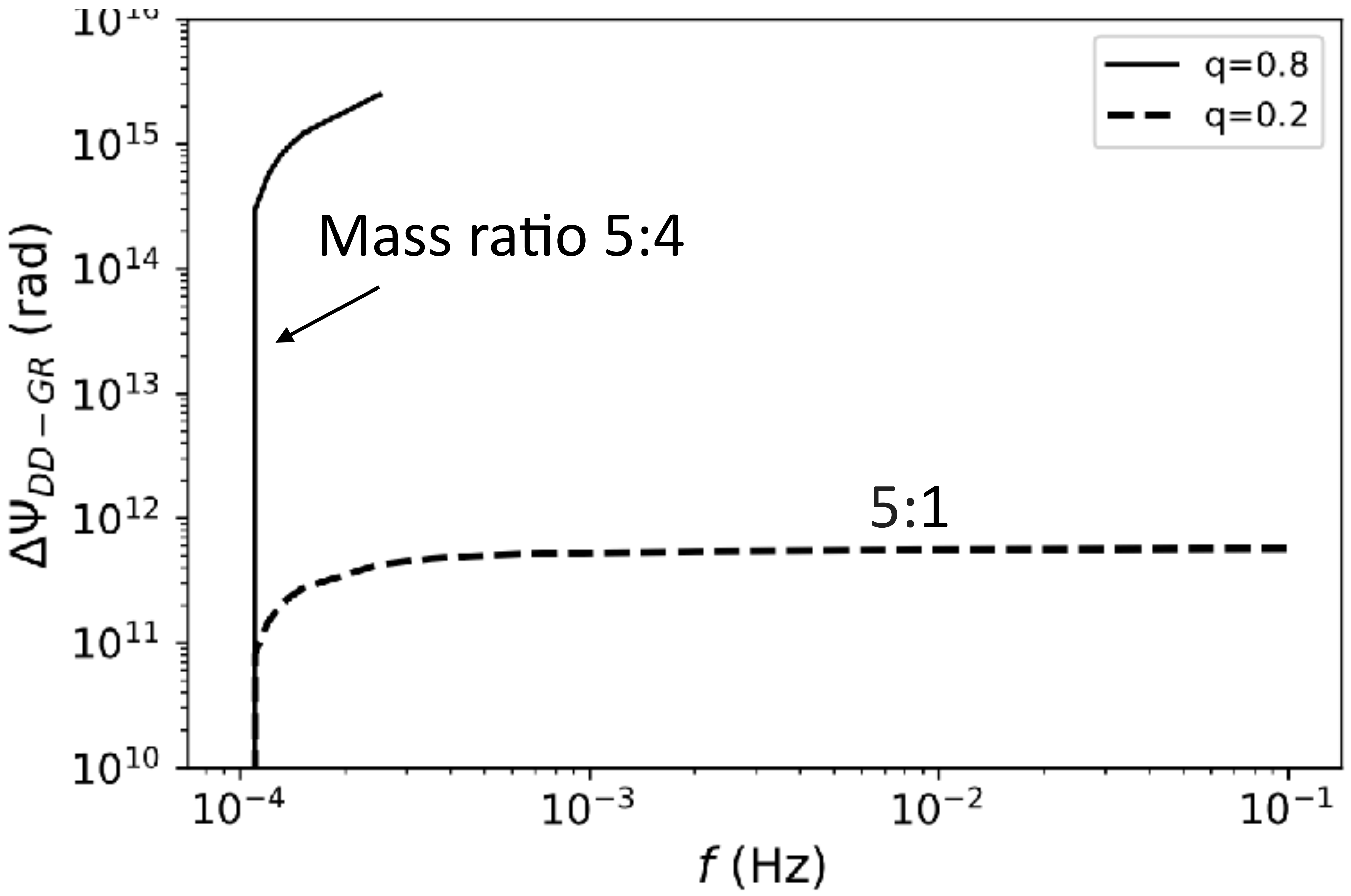
[Witek+2018]

GWs especially sensitive to the phase evolution

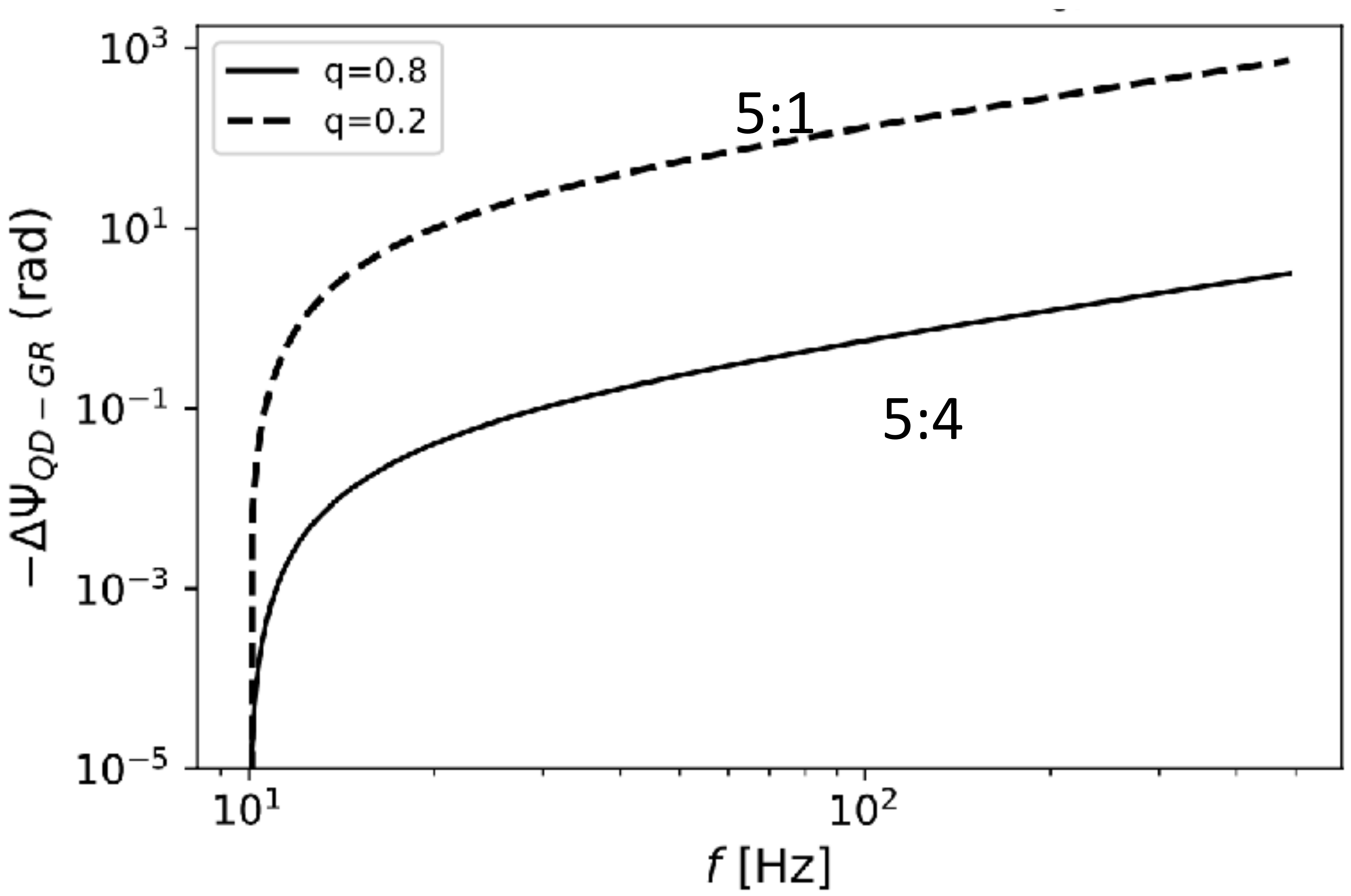
- Different parameter dependencies in the early (scalar losses dominate) and late (GW losses dominate) inspiral.

Example: mass ratio dependence

Early inspiral: phase difference from GR



Late inspiral: phase difference from GR



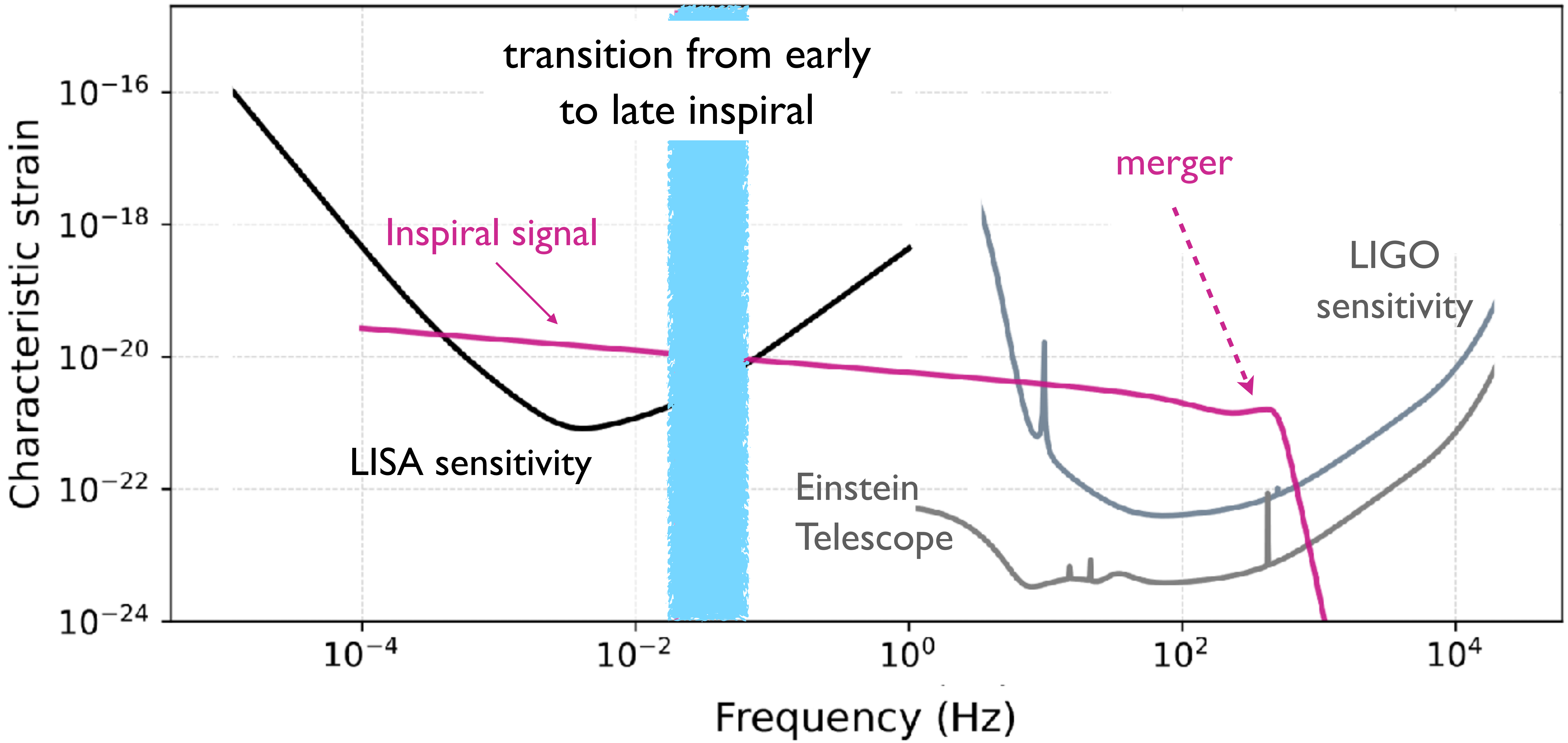
Example for $M = 18M_\odot, \sqrt{\alpha} = 1.7\mathrm{km}$

van Gemeren, Shiralilou, TH (2023)

Opportunities with future multi-band GW measurements

Some black hole binaries could be observed in both LISA and terrestrial detectors

Example binary with $M = 30M_\odot$, mass ratio 5:1 at 100 Mpc distance



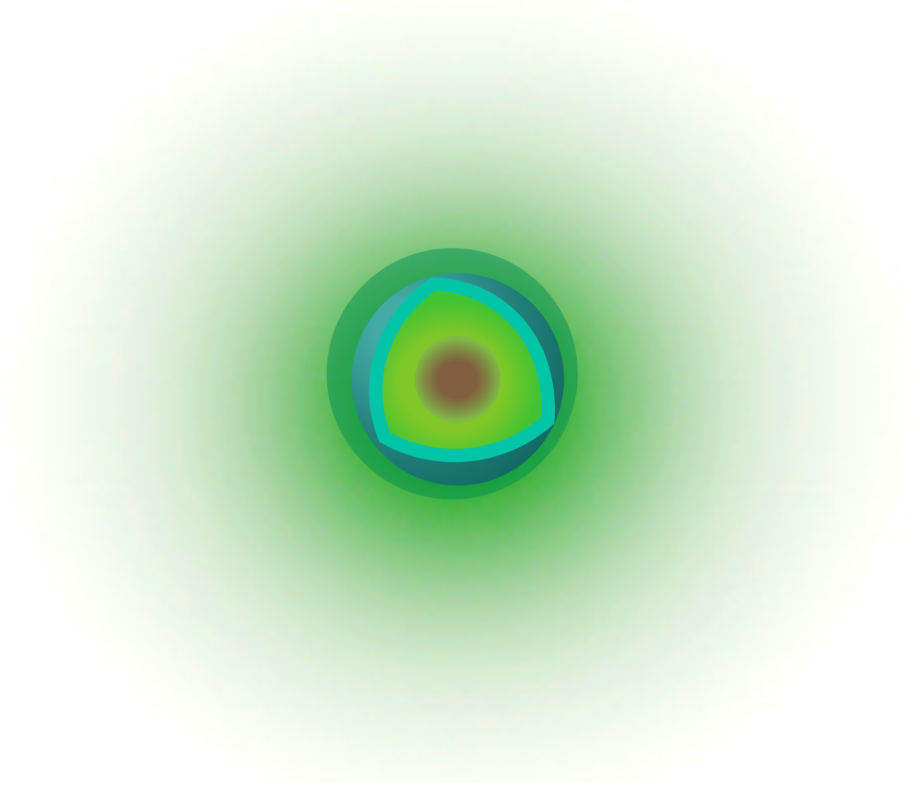
Shiralilou, TH+ (2021)

Neutron stars in scalar-tensor (ST) gravity

- Neutron stars: densest stable matter configurations, dominated by subatomic physics, collective phenomena
  - what do we learn from GWs about couplings of gravity to matter?
  - potential degeneracies between different sectors of 'unknown' physics?

- Consider a simpler class of scalar-tensor theories:

$$S_{\rm ST} \sim \int d^4x\sqrt{-g}\,\left[R - 2g^{\mu\nu}\,\nabla_\mu \underset{\text{Scalar field}}{\underset{\uparrow}{\varphi}}\,\nabla_\nu\varphi\right] + \overset{\text{Matter action}}{S_m}\left[\psi_m;\, \underbrace{A^2(\varphi)}_{\text{Coupling function}}\, g_{\mu\nu}\right]$$



- neutron stars can develop a 'scalarized' phase with large φ, very different from GR

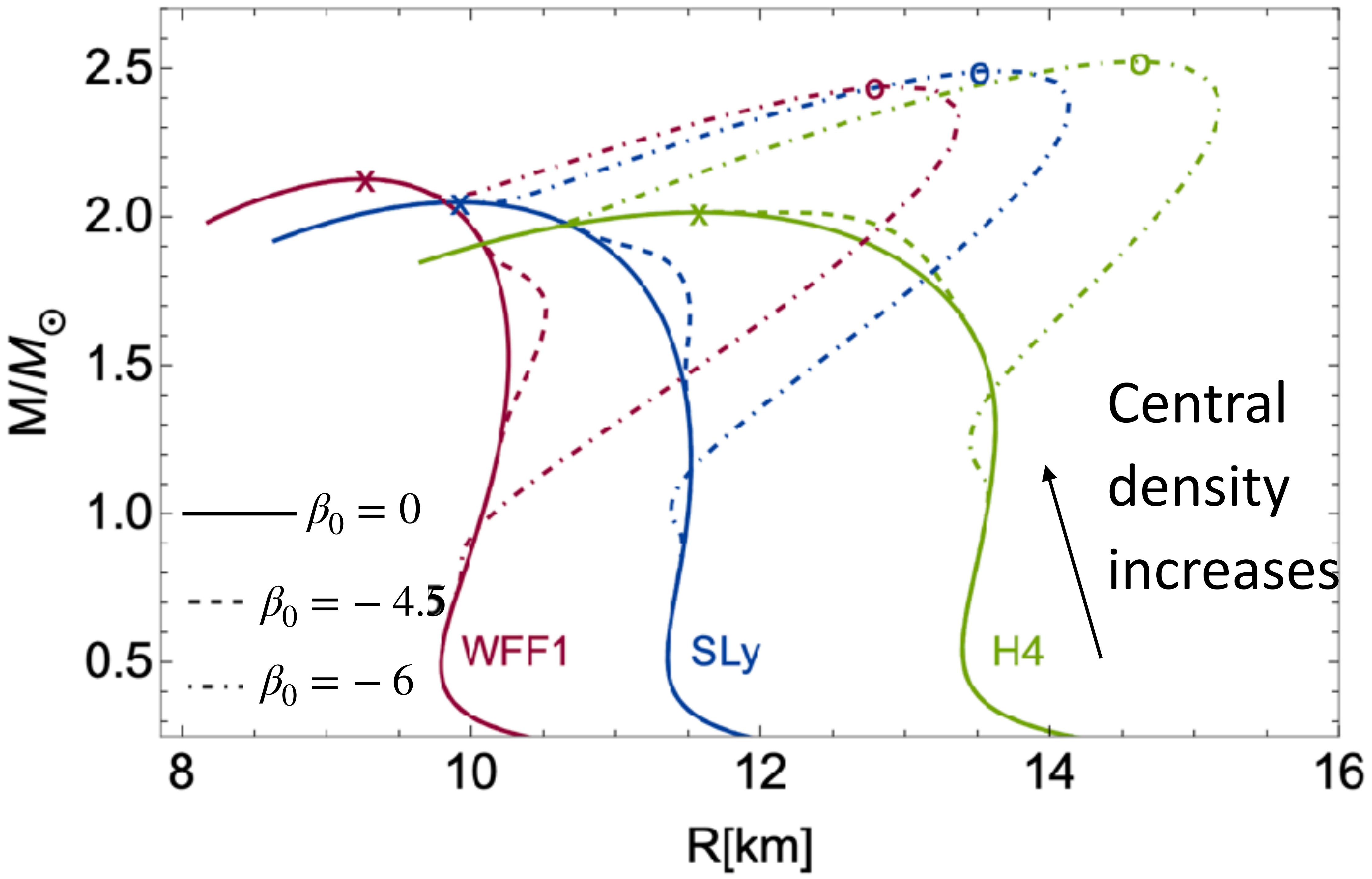
scalar field falls off as: $\lim\limits_{r_2\to\infty} \varphi \sim \varphi_\infty + \dfrac{Q}{r_2}$

Properties of isolated neutron star configurations

Example choice of coupling function: $\log[A(\varphi)] = \frac{1}{2}\,\beta_0\,\varphi^2$

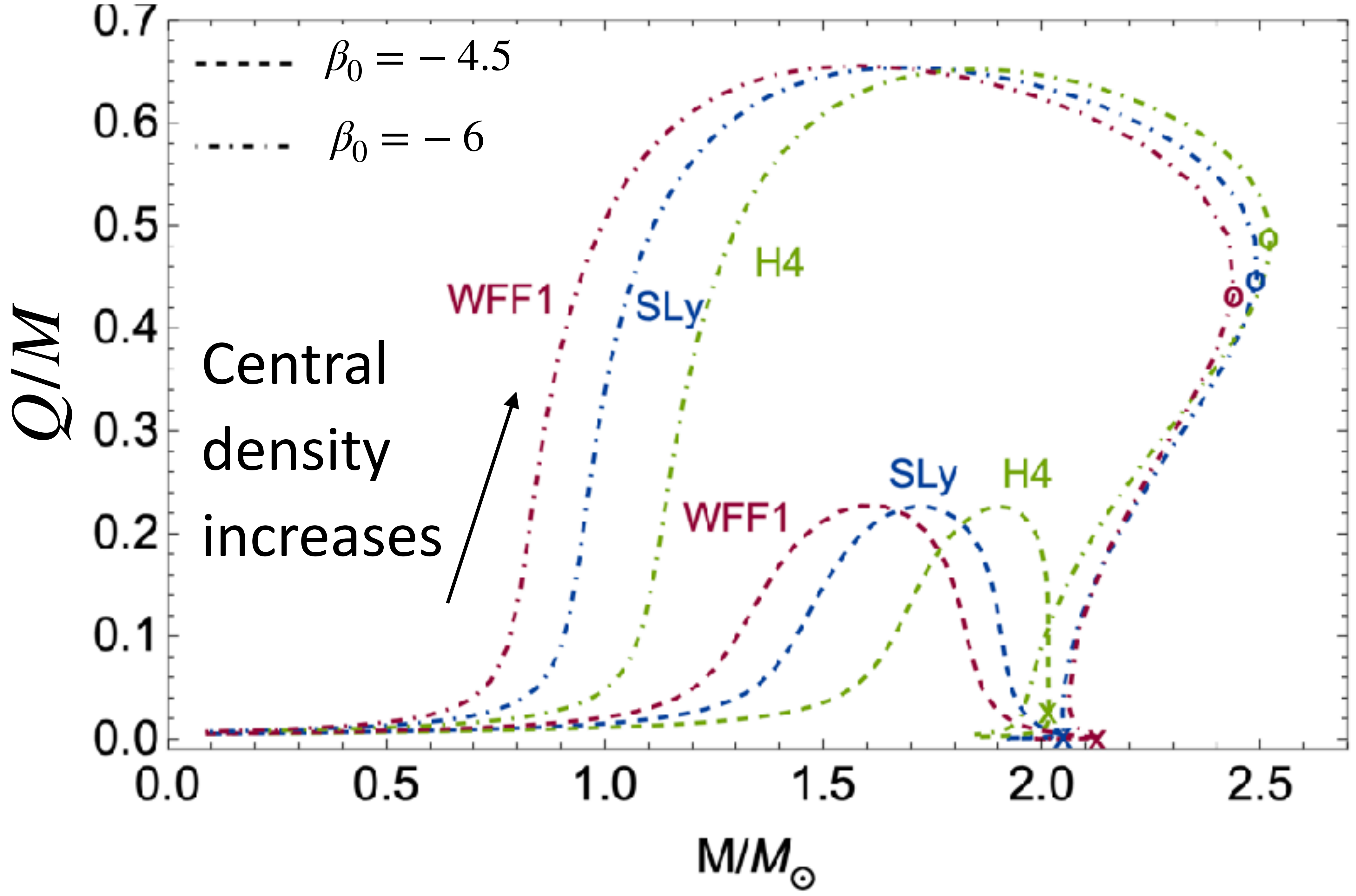
Damour & Esposito-Farese '94

NS mass & radius for $\varphi_\infty = 10^{-3}$



Central density increases

Scalar charge/mass for $\varphi_\infty = 10^{-3}$



Central density increases

Colors: different nuclear equations of state

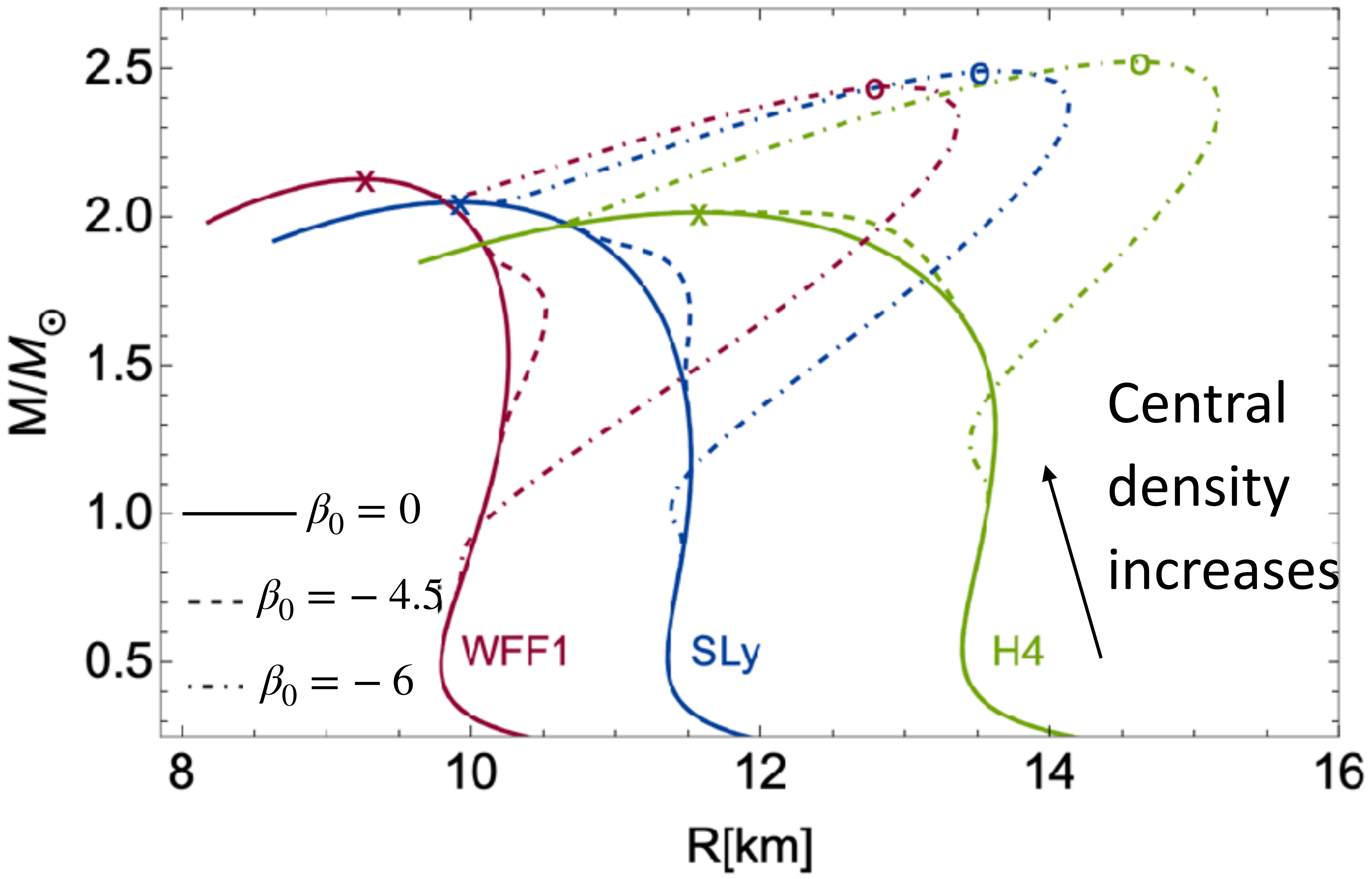
Properties of isolated neutron star configurations

scalarization threshold depends on: β_0, EoS, compactness ~ internal gravity GM/Rc^2

▷ non-perturbative phenomenon

Damour & Esposito-Farese '94

NS mass & radius for $\varphi_\infty = 10^{-3}$



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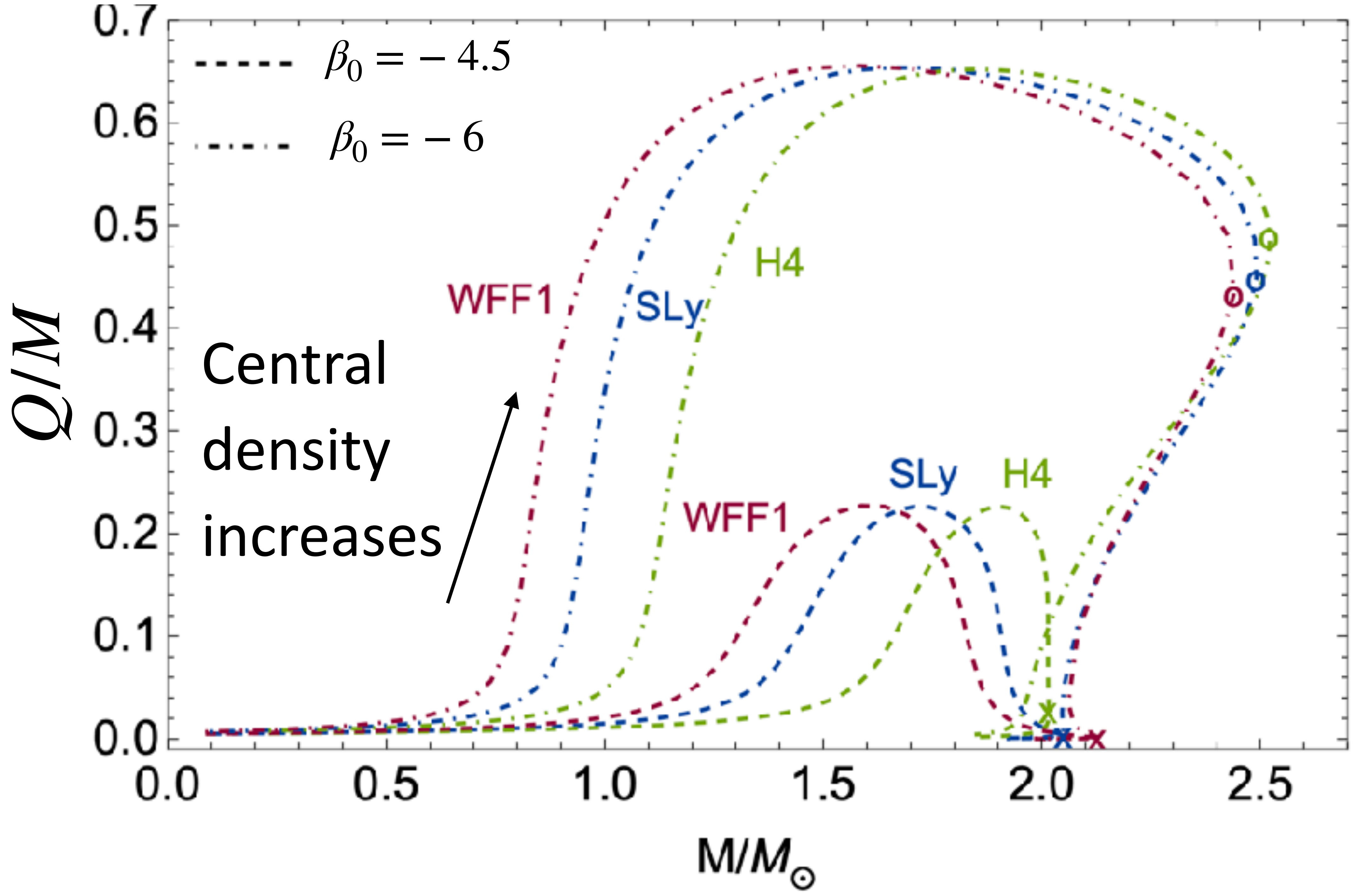

Colors: different nuclear equations of state

Properties of isolated neutron star configurations

scalarization threshold depends on: β_0, EoS, compactness ~ internal gravity GM/Rc^2

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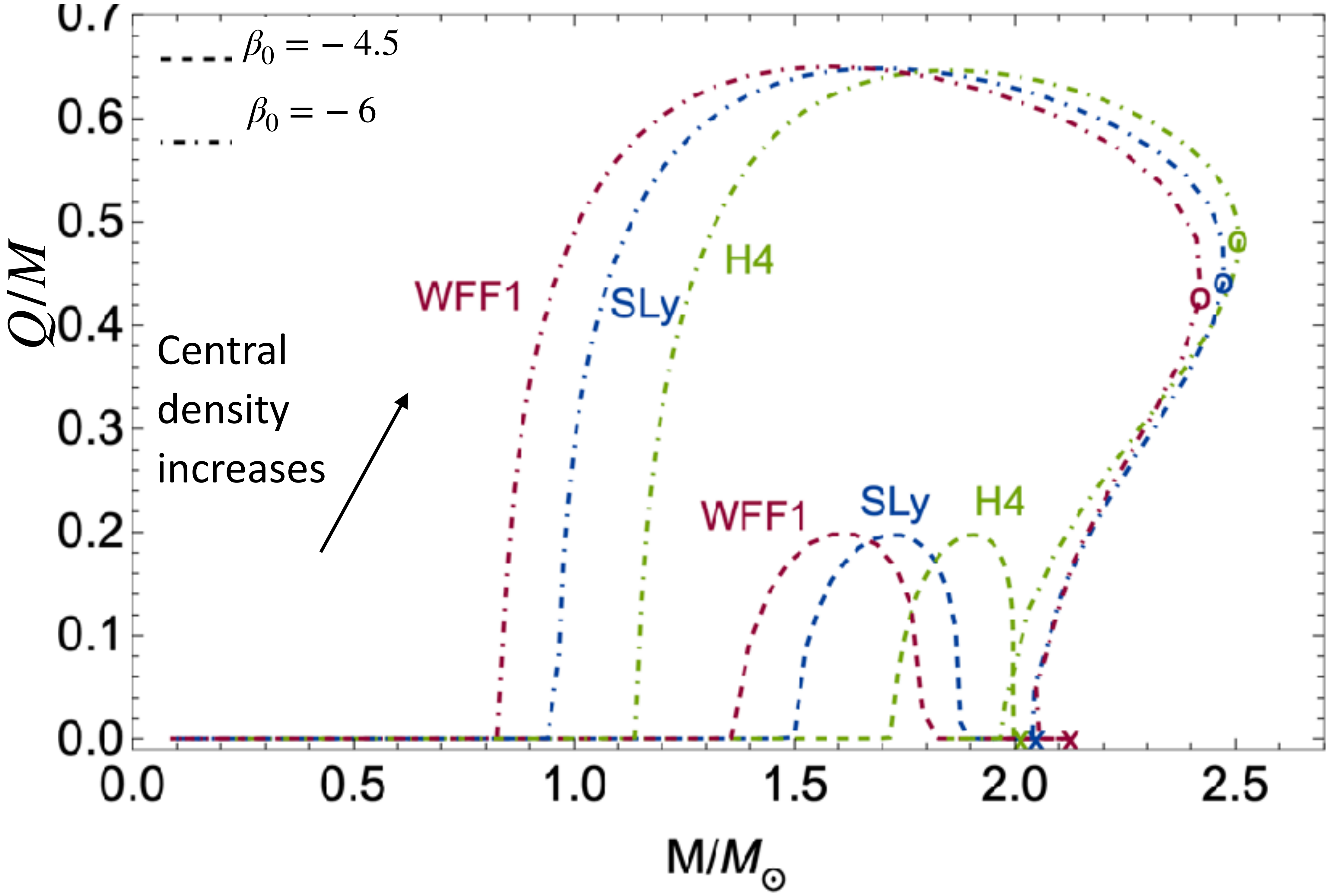
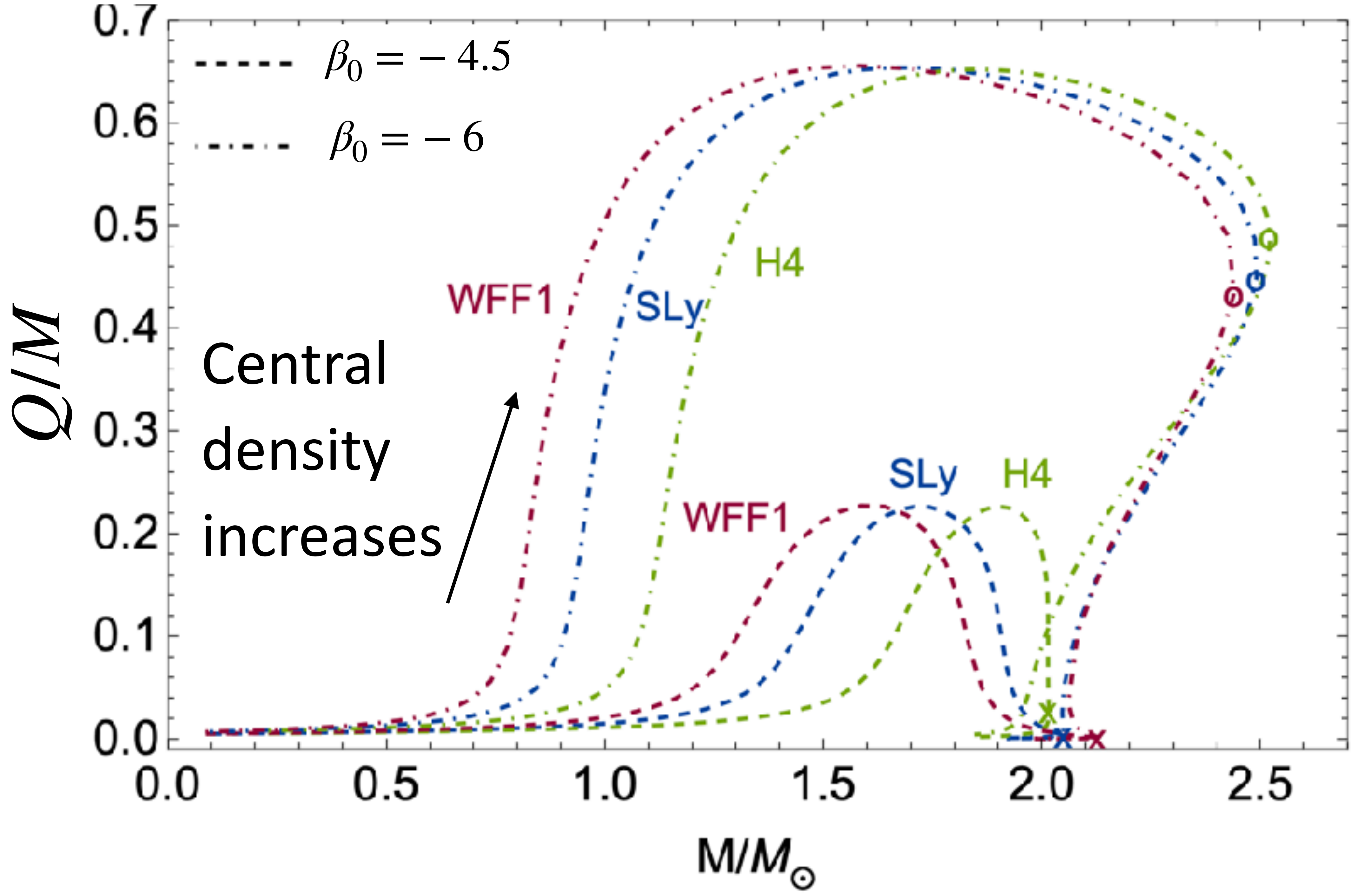
Smaller $\varphi_\infty = 10^{-6}$: sharper features

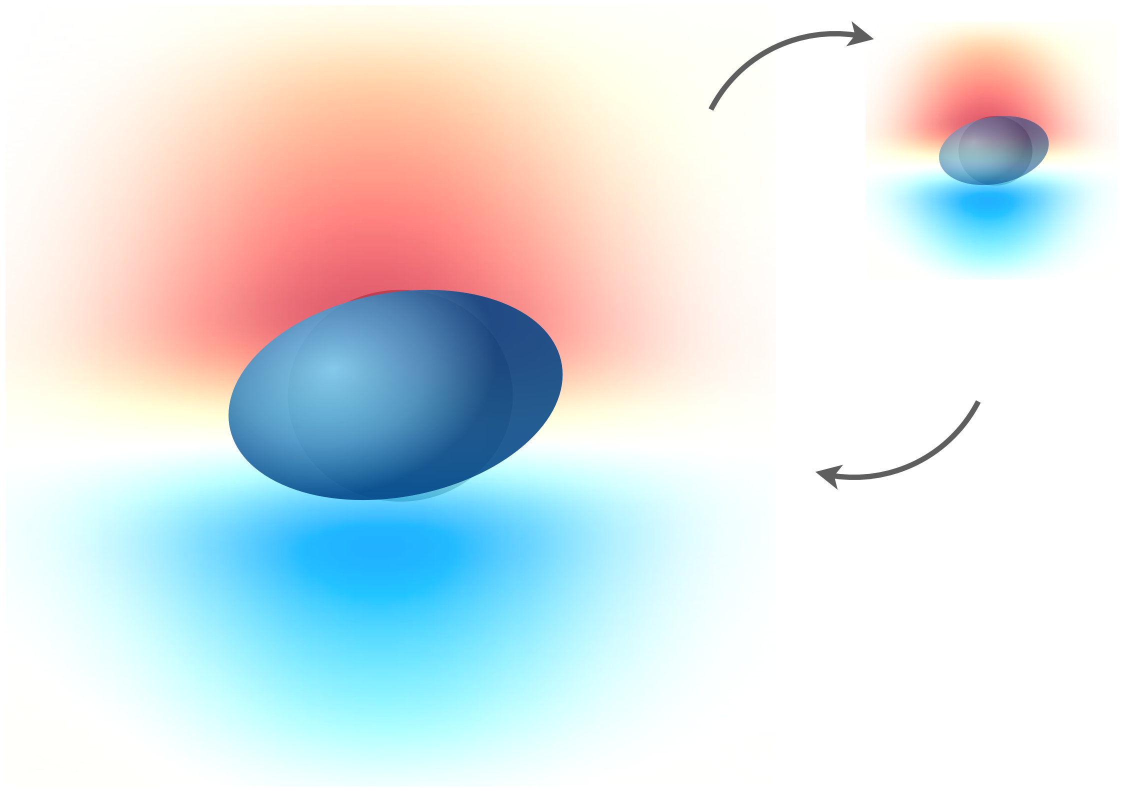


Scalar charge/mass for $\varphi_\infty = 10^{-3}$



Colors: different nuclear equations of state

Tidal effects (static, even-parity, up to quadrupole)



- Scalar (dipole, …) & tensor (quadrupole, …) tidal fields

configuration responds by deforming, here: *adiabatic* limit

- induced scalar dipole moment $\mathcal{Q}^i_S = -\lambda_S^{(\ell=1)}\,\mathcal{E}^i_S$

- Quadrupole moments affected by nonlinear interactions of scalar field, subatomic matter, metric

Induced *scalar* quadrupole $$\mathcal{Q}^{ij}_S = -\lambda_S\,\mathcal{E}^{ij}_S - \lambda_{ST}\,\mathcal{E}^{ij}$$

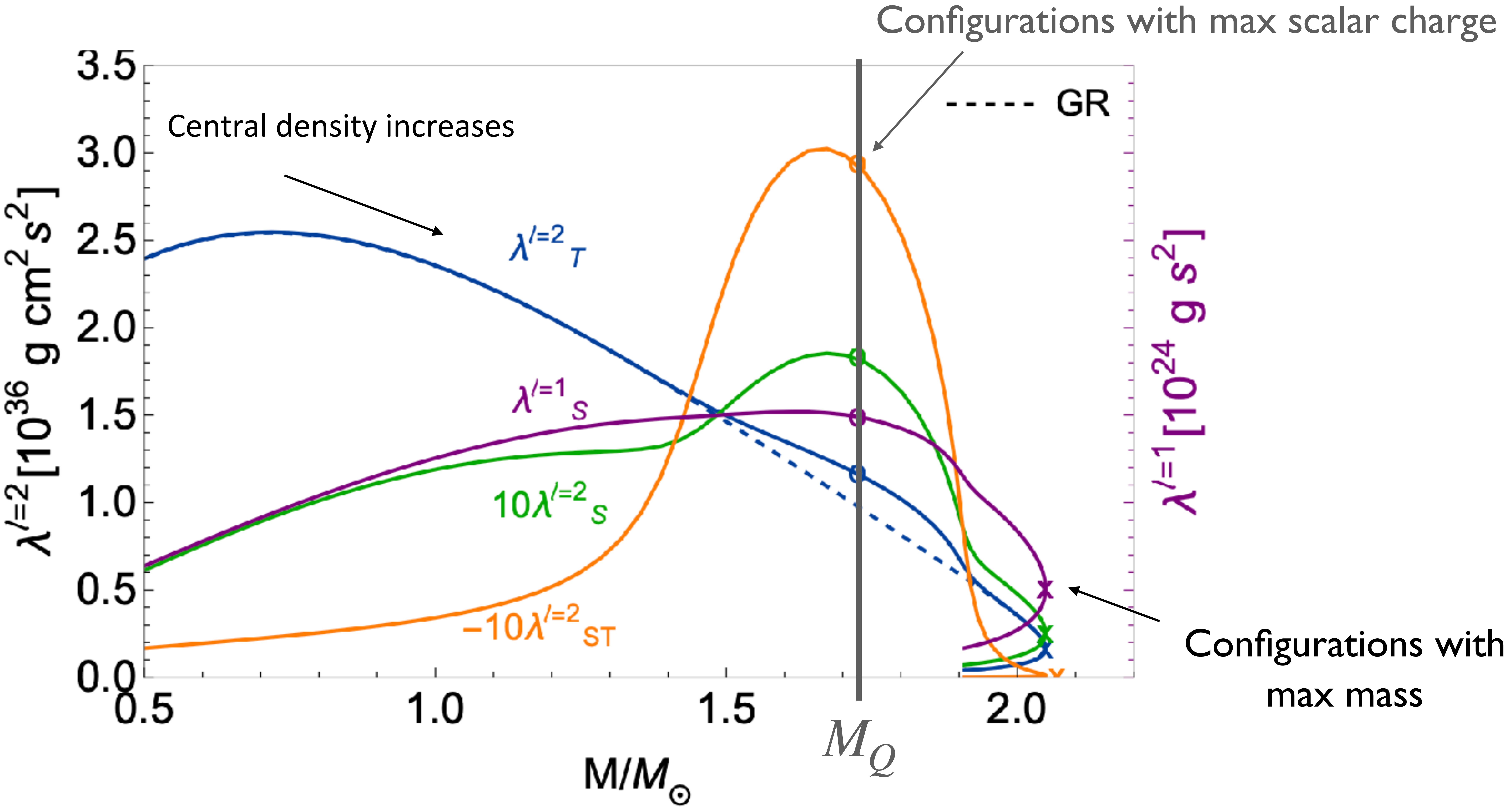
Induced *tensor* quadrupole $$\mathcal{Q}^{ij}_T = -\lambda_T\,\mathcal{E}^{ij} - \lambda_{ST}\,\mathcal{E}^{ij}_S$$

3 tidal deformabilities / Love numbers

Creci, TH, Steinhoff (2024)

Mass-dependence of tidal parameters

- Example: SLy EoS, $\beta_0 = -4.5$, $\varphi_\infty = 10^{-3}$



Analytical & numerical codes available at https://github.com/GastCre/Mathematica.codes/

Dominant tidal effects in the GW phase

frequency-parameter $x = \left(\frac{G_{\rm eff}\, M\, \pi f}{c^3}\right)^{2/3}$

dipolar scalar tides

$$\psi_{\rm tid} = -\frac{3}{128\eta x^{5/2}}\left[-c_2 S_- x^2 + c_3 x^3 + \overbrace{c_4 S_-^2 \left(\log x - \frac{2}{3}\right) x^4 + \left(\frac{39}{2\,\xi}\tilde{\Lambda} + c_5\right) x^5}^{\text{Quadrupolar tides}}\right]$$

$= 0$ for NS-BH

(No scalar $\mathscr{E}_S$)

tidal deformability enters in GR with $\xi = 1$

difference in scalar charges $S_- = 0$ for identical NSs

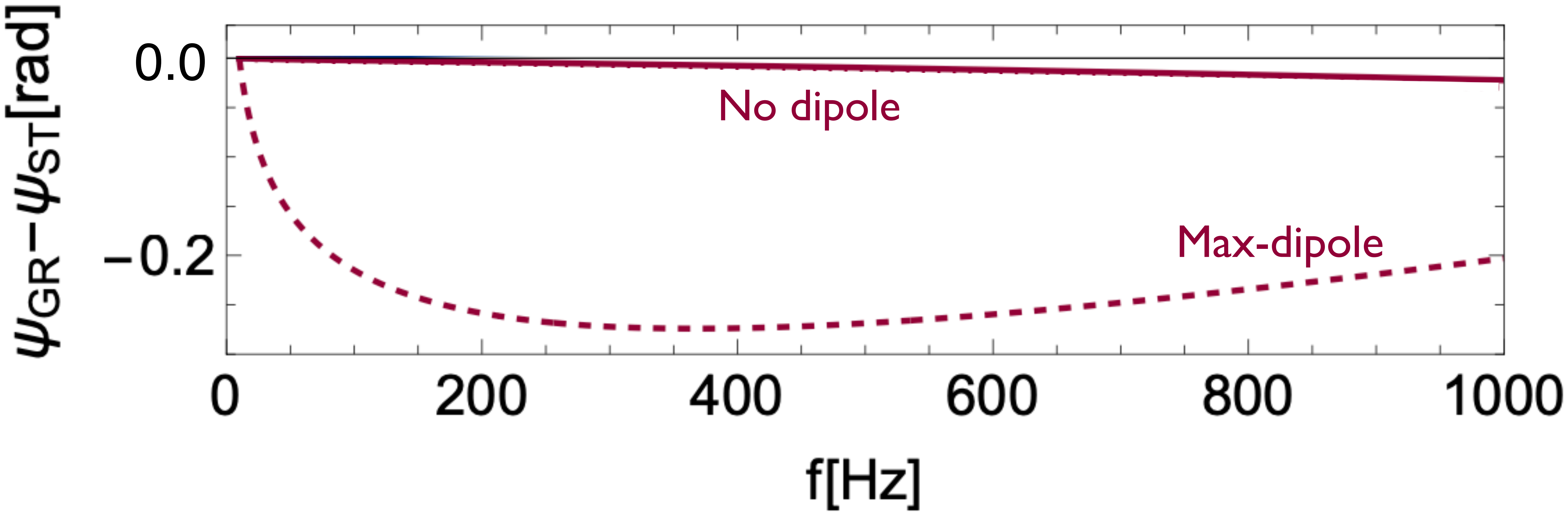
Coefficients $c_2, \ldots, c_5$ depend on various combinations of Love numbers, masses, scalar charges

Creci, van Gemeren, TH, Steinhoff (2025)

Total tidal effects smaller in ST than in GR

- Example cases cover extreme scenarios:
  - No dipole, large tensor tidal quadrupole $(1+1)M_\odot$
  - Largest dipole $(1+M_Q)M_\odot$

Phase differences from tidal phase in GR



Note: Tidal phase in GR is negative (accelerated inspiral) → smaller net tidal effects in ST

Creci, van Gemeren, TH, Steinhoff (2025)

Conclusions

- GWs are unprecedented probes of gravity: clean gravitational channel of information

- Exciting future ahead: larger, more precise GW datasets to come

- *In the future:* many discoveries & science payoffs expected to be limited by accuracy/physics included in theoretical models

- Useful to explore scenarios beyond GR to gain deeper understanding of what GW measurements imply for fundamentals of gravity, assess potential degeneracies

- More work needed to better capitalize on the science potential with GWs