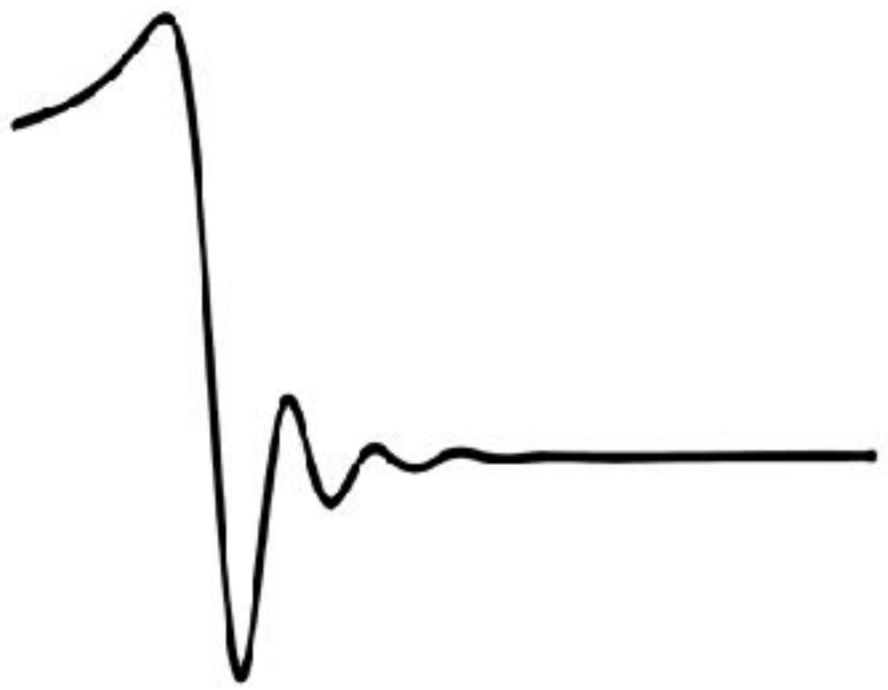
Gravitational wave observations of black hole mimickers: where do we look, and what do we look for

@ Black Hole Mimickers: From Theory to Observation

March 3, 2025



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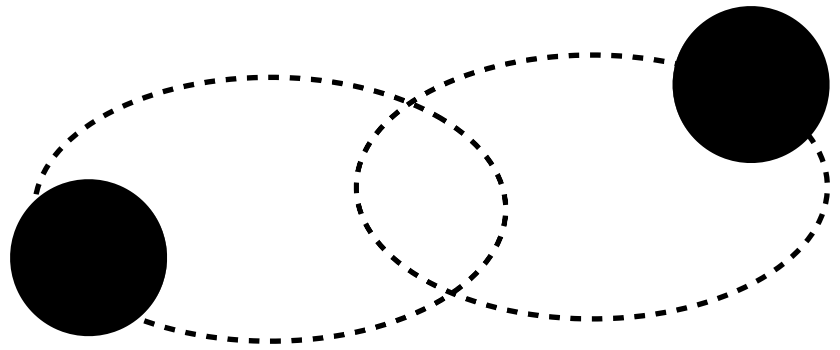
Where do we look for signatures

Different families of sources with different orbital setups, to potentially observe BH mimickers

- (some) common observables but: different approaches, simplifications, waveform models



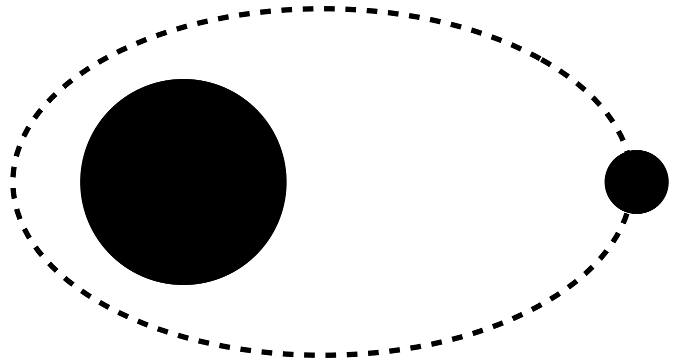
Comparable-mass binaries

post-Newtonian approach (inspiral)

Many observables and (some) waveform models already in "place"

Numerical Simulations

lessons from analogous sciences cases (neutron stars)



asymmetric bianries

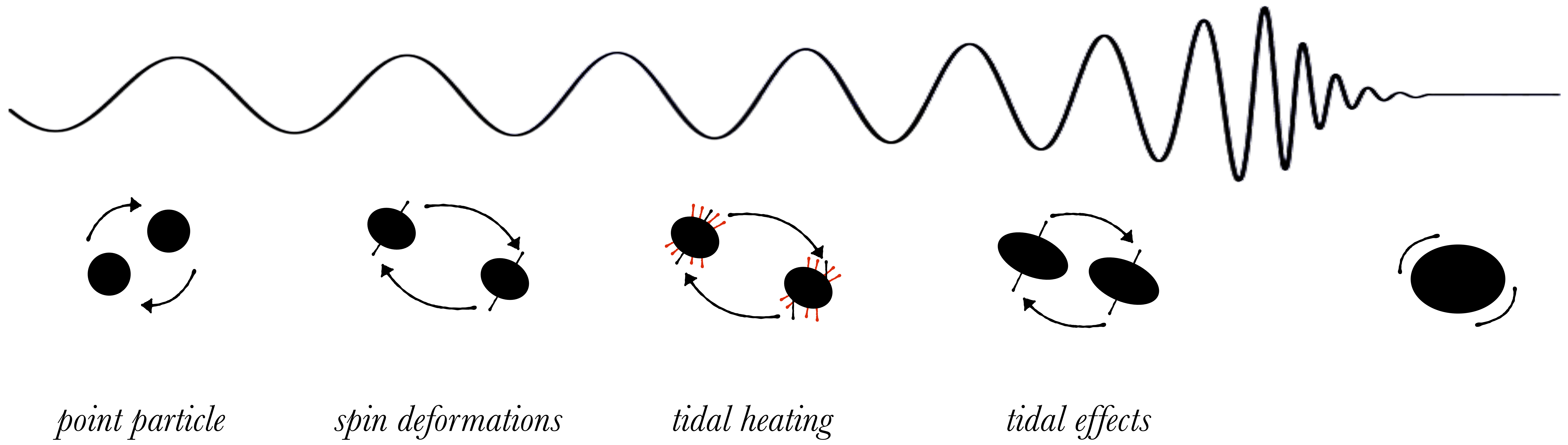
Self Force theory

Simplifications due to mass asymmetry

moving to the "microphysics" of the model

Where do we look for signatures

Through comparable-mass signals



post-Newtonian relevance $(v/c)^n$

- part of the "game" is already in place

What do we look for

Tidal interactions leave the footprint of the compact object structure on the GW signal

[T. Hinderer, 2008; T. Binnington & E. Poisson, 2009; T. Damour & A. Nagar, 200]

- Deformation properties of a compact object encoded within a set of Love numbers

body's quadrupole ⟵ $Q_{ij} = \frac{2}{3} k_2 R^5 \mathcal{E}_{ij} = \lambda \mathcal{E}_{ij}$ ⟶ *external tidal field*

<u>neutron stars</u>

$M_{\rm NS}/R_{\rm NS} \in [0.1 - 0.2]$

$\lambda \neq 0 \quad \lambda \sim \mathcal{O}(10^4)$

<u>BHs (in GR)</u>

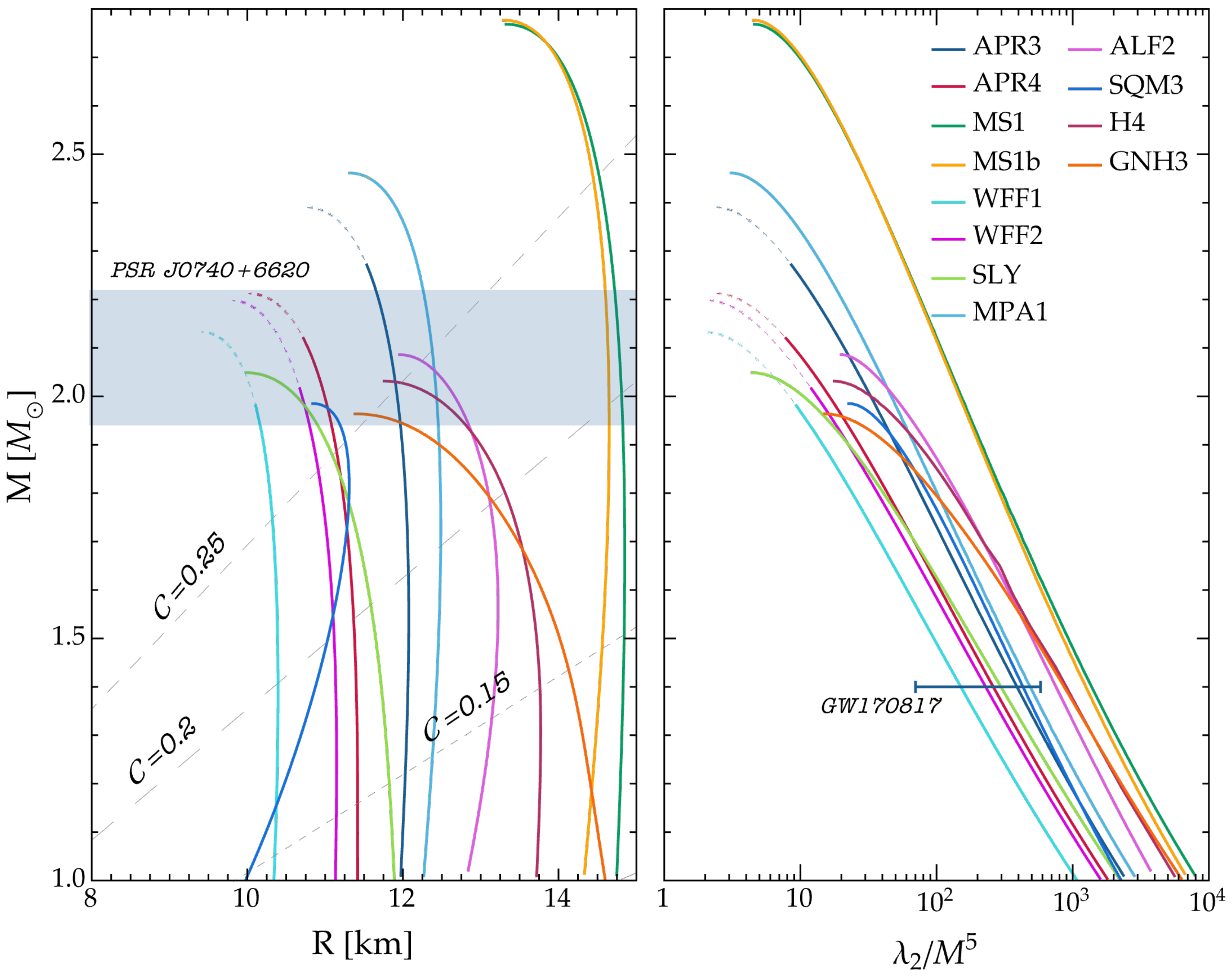
$\lambda = 0$ ⟵ *Schwarzschild* *Kerr*

[P. Landry & E. Poisson, 2015; P. Pani + incl. A. M., 2015; N. Gürlebeck, 2015; A. Le Tiec +, 2021]

<u>BHs non vacuum/ beyondGR ECOs</u>

$\lambda \neq 0$ ⟵ *generic tests of gravity*

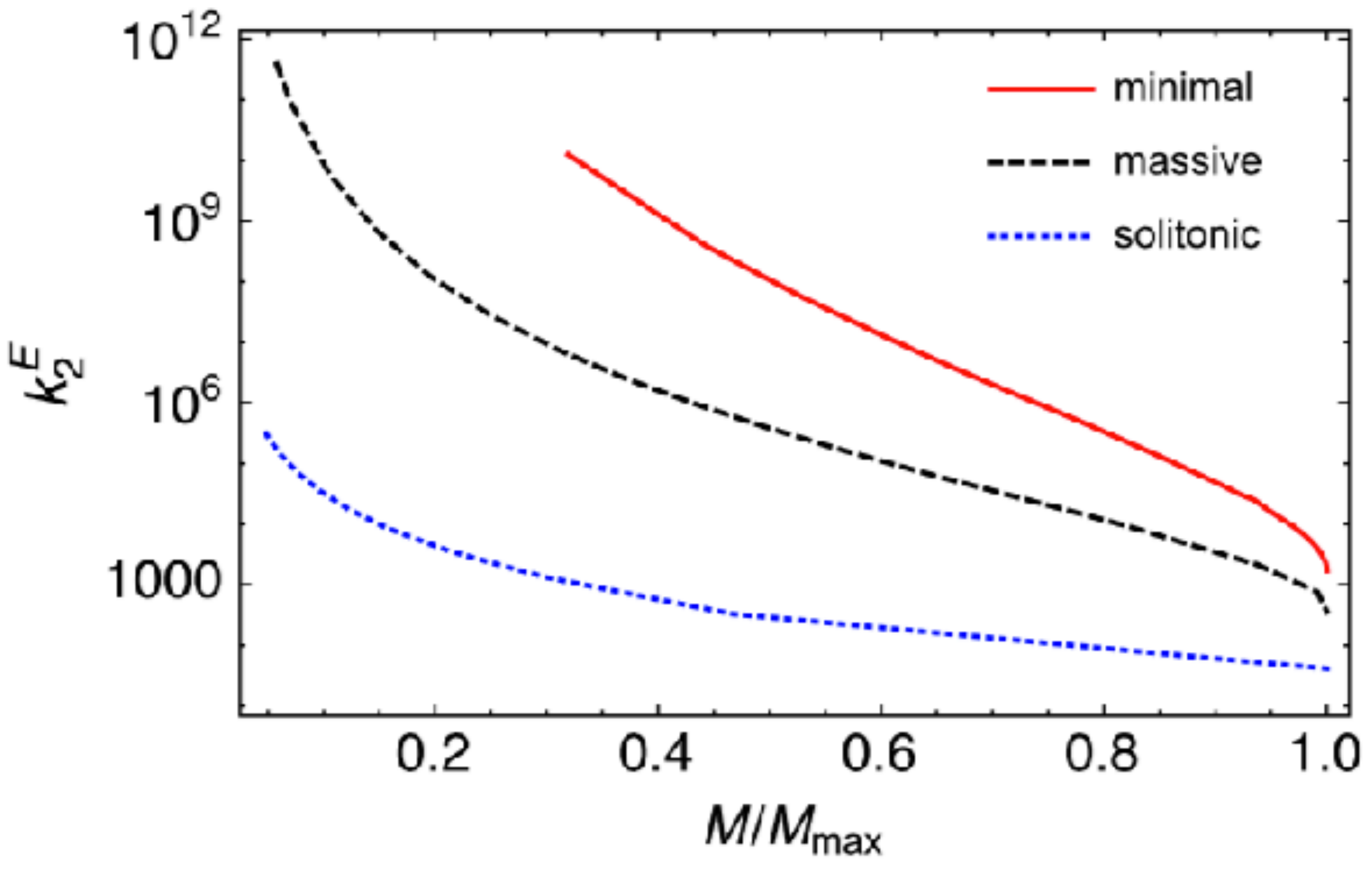
[V. Cardoso + incl. A. M., 2017; A. Maselli +, 2017]



Exotic Love numbers

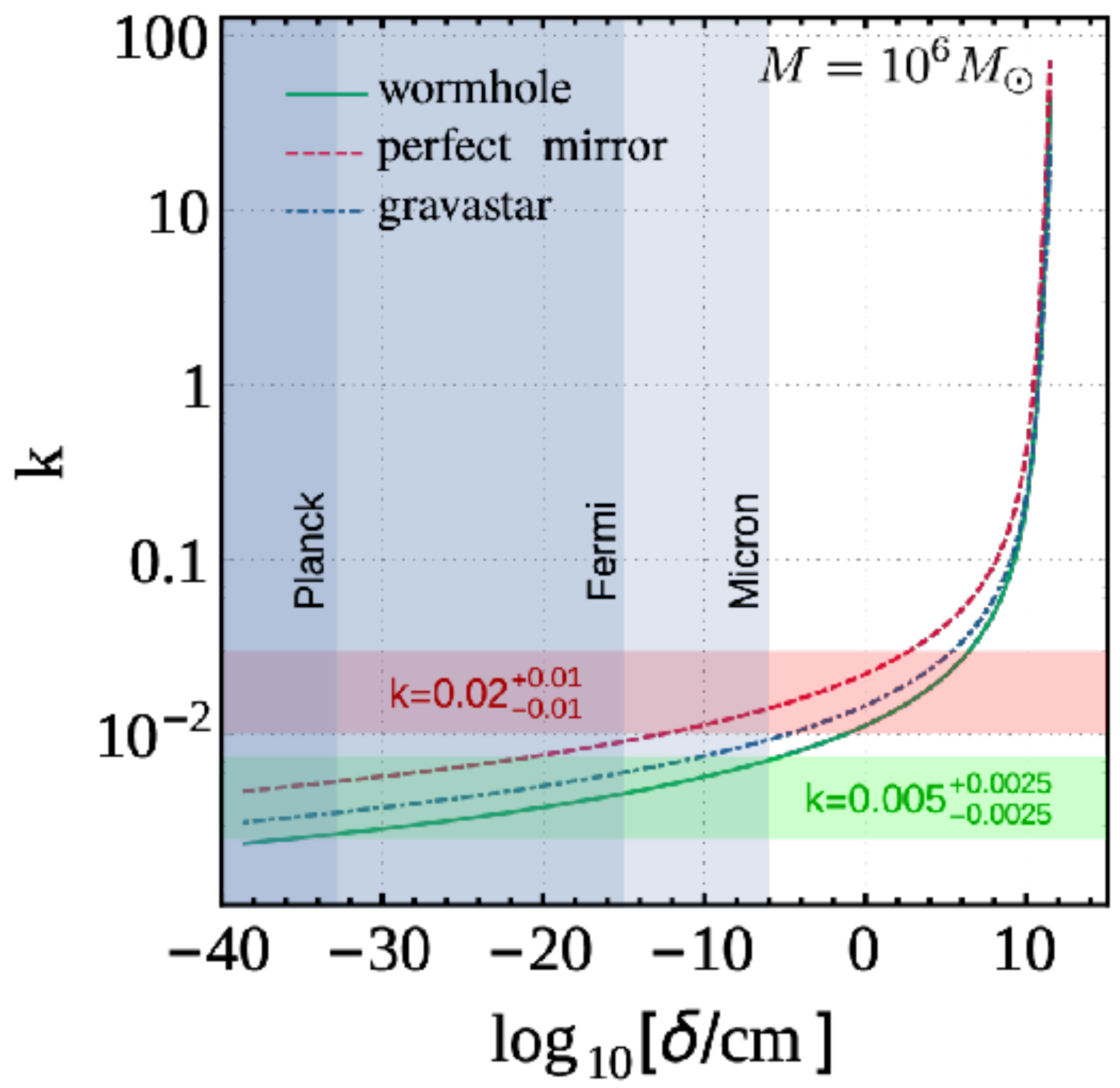
[V. Cardoso + incl. A. M., 2017]

Boson stars



Black hole mimickers

$R = R_{\rm horizon}(1+\delta)$



- Behaviour for BS in qualitative agreement with the neutron star case
- For mimickers Love numbers show a logarithmic dependence on δ

$\longrightarrow$ the Love number enters the waveform

What do we look for

Multipolar structure of Kerr black holes benefits from axial/equatorial symmetry [R. O. Hansen, 1974]

$$M_\ell^{\rm BH} + i S_\ell^{\rm BH} = M^{\ell+1}(i\chi)^\ell$$

$$M = M_{00} \qquad J = S_{10} \qquad M_\ell = M_{\ell 0} \qquad S_\ell = S_{\ell 0}$$

- Objects different from BHs can violate this relation and induce generic deviations [G. Raposo & P. Pani 2020; L. Bena & D.R. Mayrrson, 2020; M. Bianchi +, 2021; P. Cunha + 2022; N. Loutrel + inc. A.M, 2023, 2022]

$$M_{\ell m} = M_\ell^{\rm BH} + \delta M_{\ell m} \qquad\qquad S_{\ell m} = S_\ell^{\rm BH} + \delta S_{\ell m}$$

- $\delta M_{\ell m}, \delta S_{\ell m}$ depend on the structure of the compact object

- The leading contribution to the waveform is given by the mass moment $M_{20} = -M^3\chi^2$ at the 2pN order $(v/c)^2$

    - agnostic way to parametrize deviations from Kerr $M_{20} = -\kappa M^3\chi^2$ and $\kappa = 1 + \delta\kappa$

A coherent waveform model

[M. Vaglio + inc. A.M, 2023]

A waveform beyond minimal modelling (for inspiral) $\tilde{h}(f,\theta) = \mathcal{A}(f,\theta)e^{-i\varphi(f,\theta)}$

- post-Newtonian expanded waveform with finite size effects, $x = (\pi m f)^{2/3}$

$$\varphi = 2\pi f t_c - \varphi_c - \pi/4 + \frac{3}{128\eta x^{5/2}} \times \left(\underbrace{\sum_{i=0}^{7} \varphi_{\,\mathrm{pp},i/2} x^{i/2}}_{\text{point-particle}} + \underbrace{\varphi_{\kappa,2}x^2 + \varphi_{\kappa,3}x^3}_{\text{quadrupole}} + \underbrace{\varphi_{\mathrm{T},5}x^5 + \varphi_{\mathrm{T},6}x^6}_{\text{tidal}} \right)$$

- $\varphi_{\mathrm{T},5} = -12[(1+7\eta-31\eta^2)(\Lambda_1+\Lambda_2) + \delta(1+9\eta-11\eta^2)(\Lambda_1-\Lambda_2)]$

- $\varphi_{\kappa,2} = -\dfrac{50}{m^2}(\kappa_1 m_1^2\chi_1^2 + \kappa_2 m_2^2 \chi_2^2)$

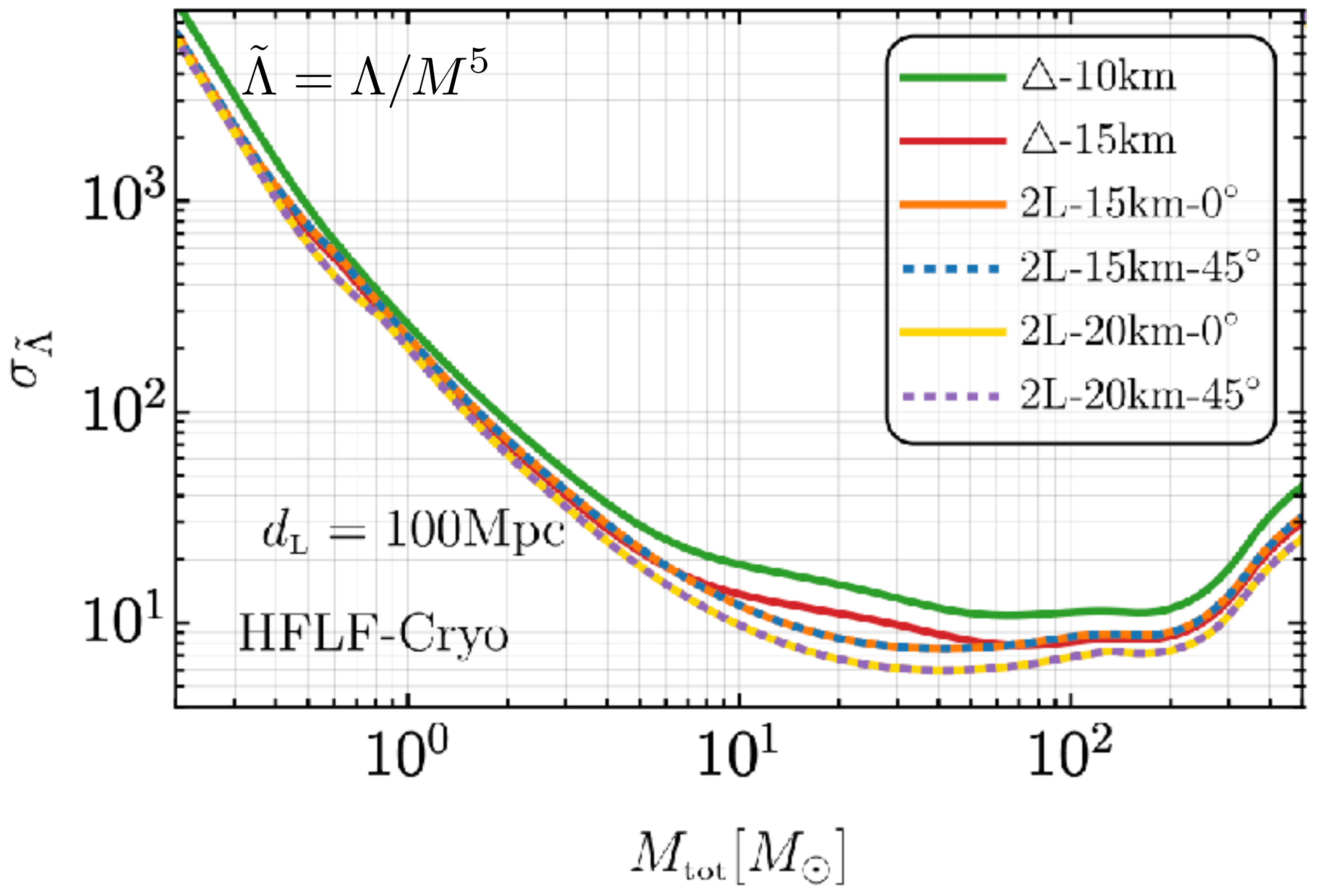
  - introduce Λ_i, κ_i (or combination of) as independent single or multiple parameters, and constrain deviations from zero

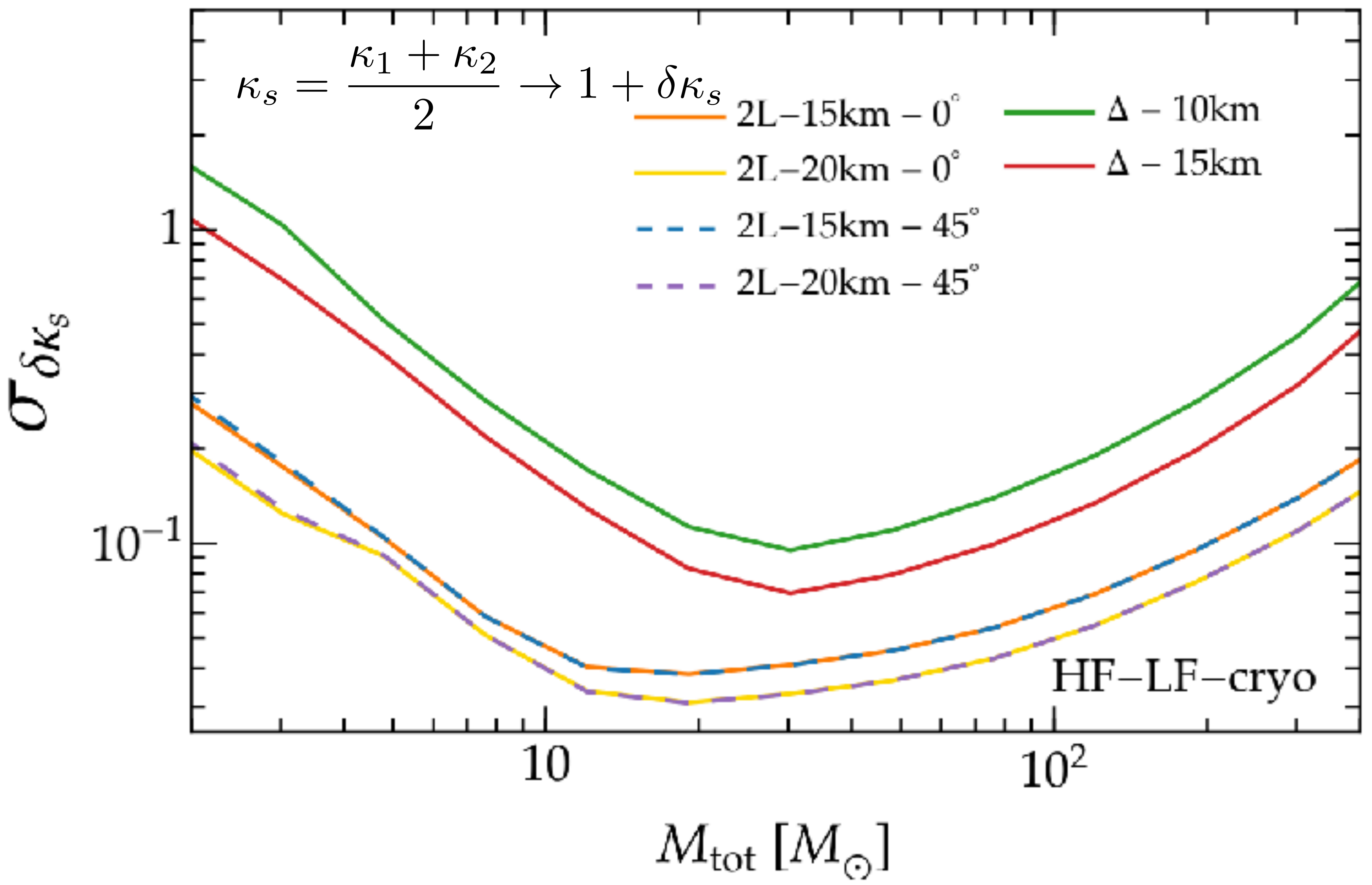
$$\theta = \{\mathcal{M}, \eta, \chi_1, \chi_2, \kappa_i, \Lambda_i, d_L, t_c, \phi_c\}$$

Forecasts with ET

[M. Branchesi +, 2023]

Constraints on the tidal deformability and quadrupole deviations from ET observations





$$\theta = \{\mathcal{M}, \eta, \chi_1, \chi_2, \Lambda_i, d_L, t_c, \phi_c\}$$

$$\theta = \{\mathcal{M}, \eta, \chi_1, \chi_2, \kappa_i, d_L, t_c, \phi_c\}$$

$\xrightarrow[\textit{NS mass}]{\textit{as a reference}}$ $\sigma_{\tilde{\Lambda}} \sim \mathcal{O}(10)$

$\sigma_{\tilde{\Lambda}}^{\mathrm{GW170817}} \sim \mathcal{O}(100)$

$\longrightarrow$ $\delta\kappa_s \sim 10^{-1} - 10^{-2}$

$\delta\kappa_s^{\mathrm{GW151226}} \lesssim 10 - 100$

[N. Khrishnendu +, 2019]

A coherent waveform model

[M. Vaglio + inc. A.M, 2023]

Or…introduce physics information to reduce the volume of the model

$$\mathcal{L}_\phi = -\frac{1}{2}g^{\mu\nu}\phi^*_{,\mu}\phi_{,\nu} - \frac{1}{2}\mu^2|\phi|^2 - \frac{1}{4}\sigma|\phi|^4$$

- In the limit $\sigma \gg \mu^2$ equilibrium solutions can be very compact
- Properties of equilibrium configurations depend only on the ratio $M_B = \sqrt{\sigma}/\mu^2$

Learning from the neutron star case, this allows to map *macroscopic* observables to *microscopic* fundamental parameters

[N. Sennet + 2017, ; C. Adams + 2023]

- Semi-analytic expression relating the static tidal deformability with $\beta = M/M_B$

$$\log_{10}\Lambda = \sum_{k=0}^{4}\alpha_k\beta^k$$

  - use this relation for spinning BS (but…[G. Castro + inc. A.M, 2020])

A coherent waveform model

- Quadrupole moment in terms of β and the dimensionless spin χ, $\kappa_2 = \kappa_2(\beta, \chi)$ [M. Vaglio + inc. A.M, 2022]

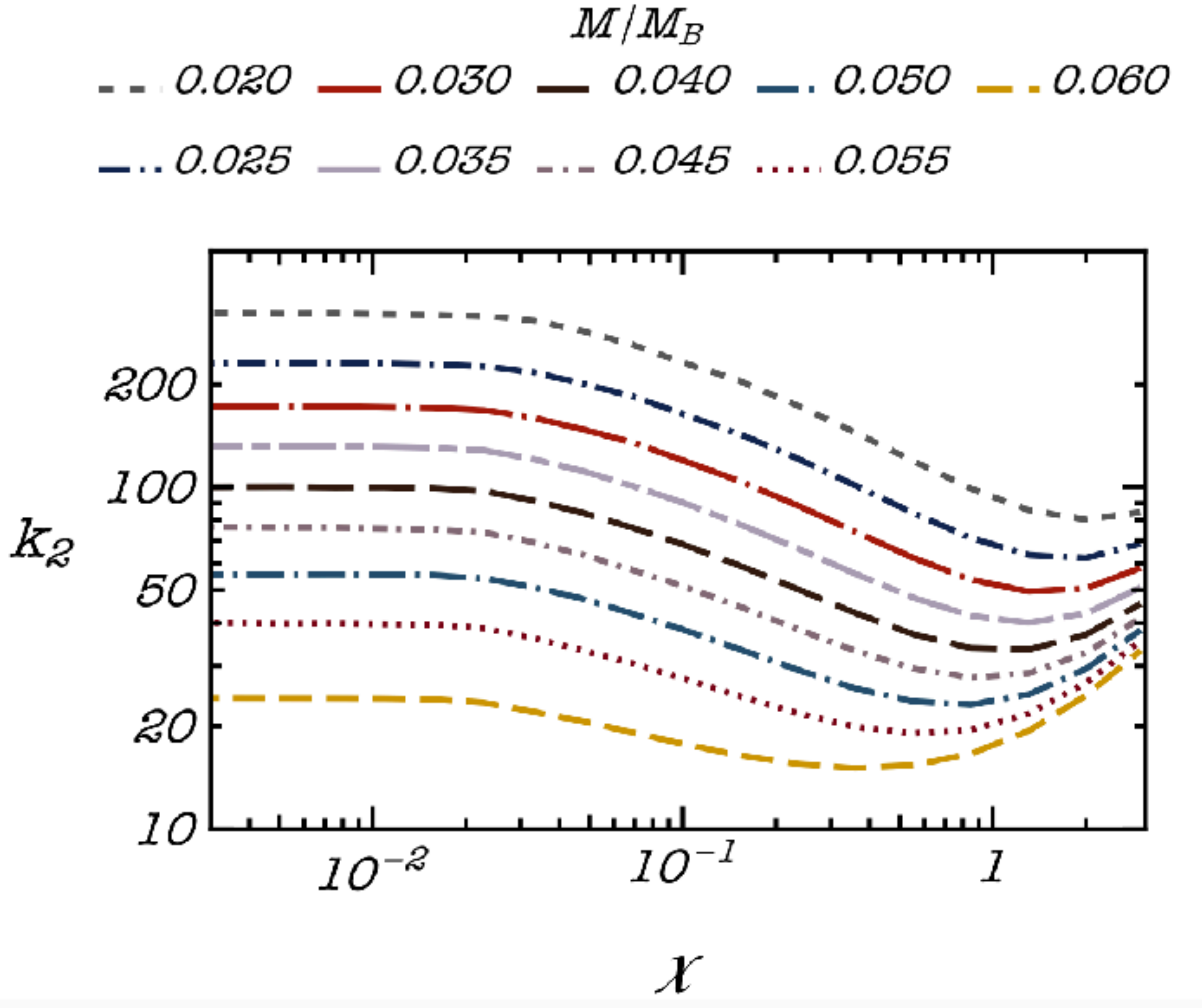
  - Interpolation of numerical data obtained from multipolar structure of spinning boson stars

  - $M_2 = -\kappa_2(\chi, \beta)\chi^2 M^3$, with $\kappa_2^{\rm BH} = 1$

    $\longrightarrow$ *universal relations among BS parameters*

- Deviations from BH evolution encoded within a single parameter

$$\theta = \{\mathcal{M}, \eta, \chi_1, \chi_2, M_B, d_L, t_c, \phi_c\}$$



$\kappa_2 \sim$ const only at low spin & has a minimum

Can we directly constrain M_B from GW observations ?

A coherent waveform model

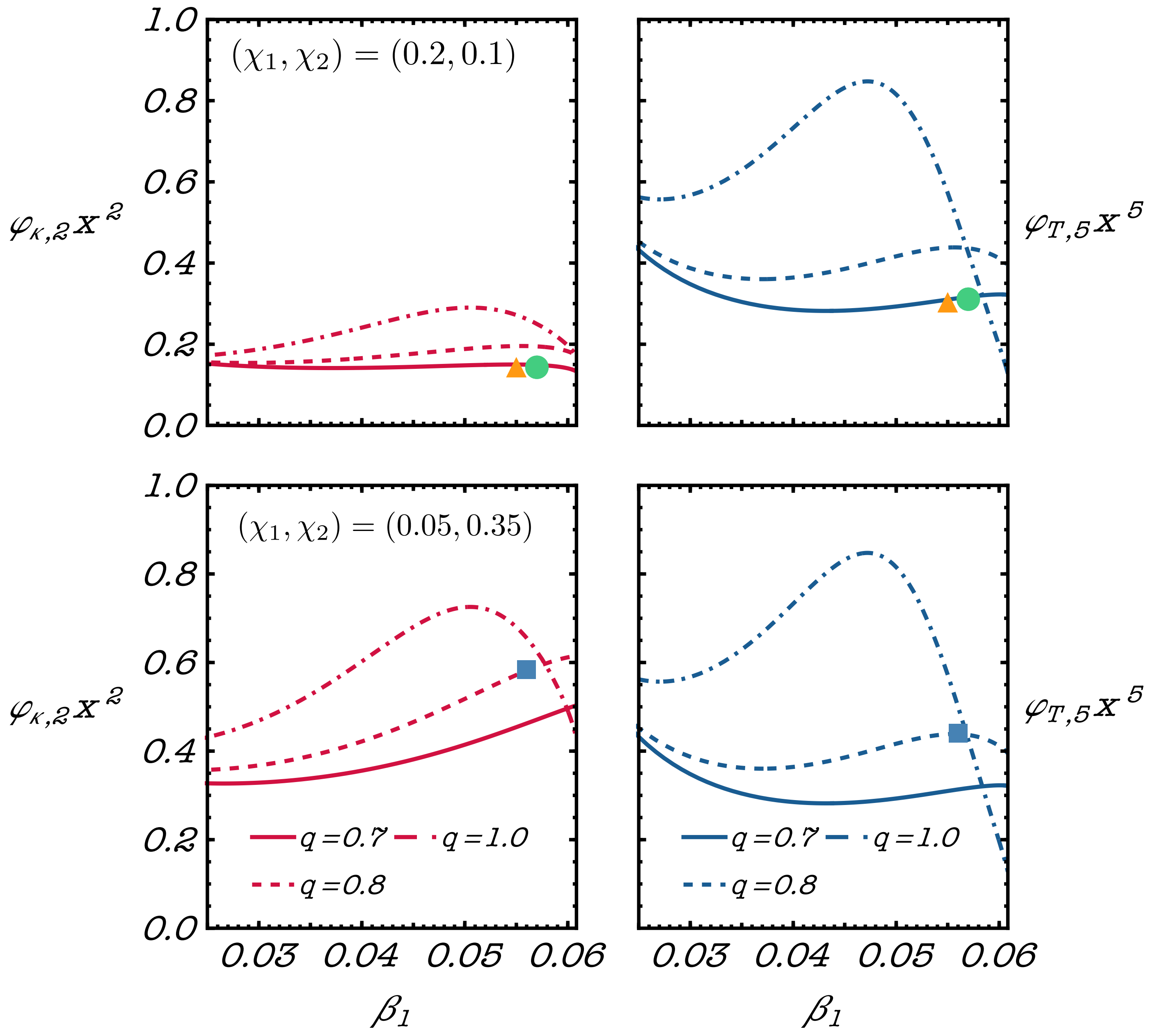
Bayesian study for 3g detectors (Einstein Telescope, Cosmic Explorer) [M. Vaglio + inc. A.M, 2023]

- Injection/recovery using inspiral only signals (TaylorF2) with different configurations
- Sampling on the waveform parameters up to mass shedding ($q = m_2/m_1 \leq 1$)

$$r_{\rm Roche} \sim \gamma r_2 \left(\frac{m_1}{m_2}\right)^{\frac{1}{3}} \longrightarrow f_{\rm Roche} = \frac{1}{\pi m}\sqrt{3+q+3q^{-1}+q^{-2}}\left(\frac{\mathcal{C}_2}{\gamma}\right)^{\frac{3}{2}}$$

$(m_1, m_2)\,[M_\odot]$	(β_1, β_2)	η	$M_B\,[M_\odot]$	χ_1	χ_2
$(6.9, 4.8)$	$(0.057, 0.040)$	0.242	120	0.20	0.10
$(6.4, 5.2)$	$(0.056, 0.045)$	0.247	115	0.05	0.35
$(13.8, 9.6)$	$(0.055, 0.039)$	0.242	250	0.20	0.10

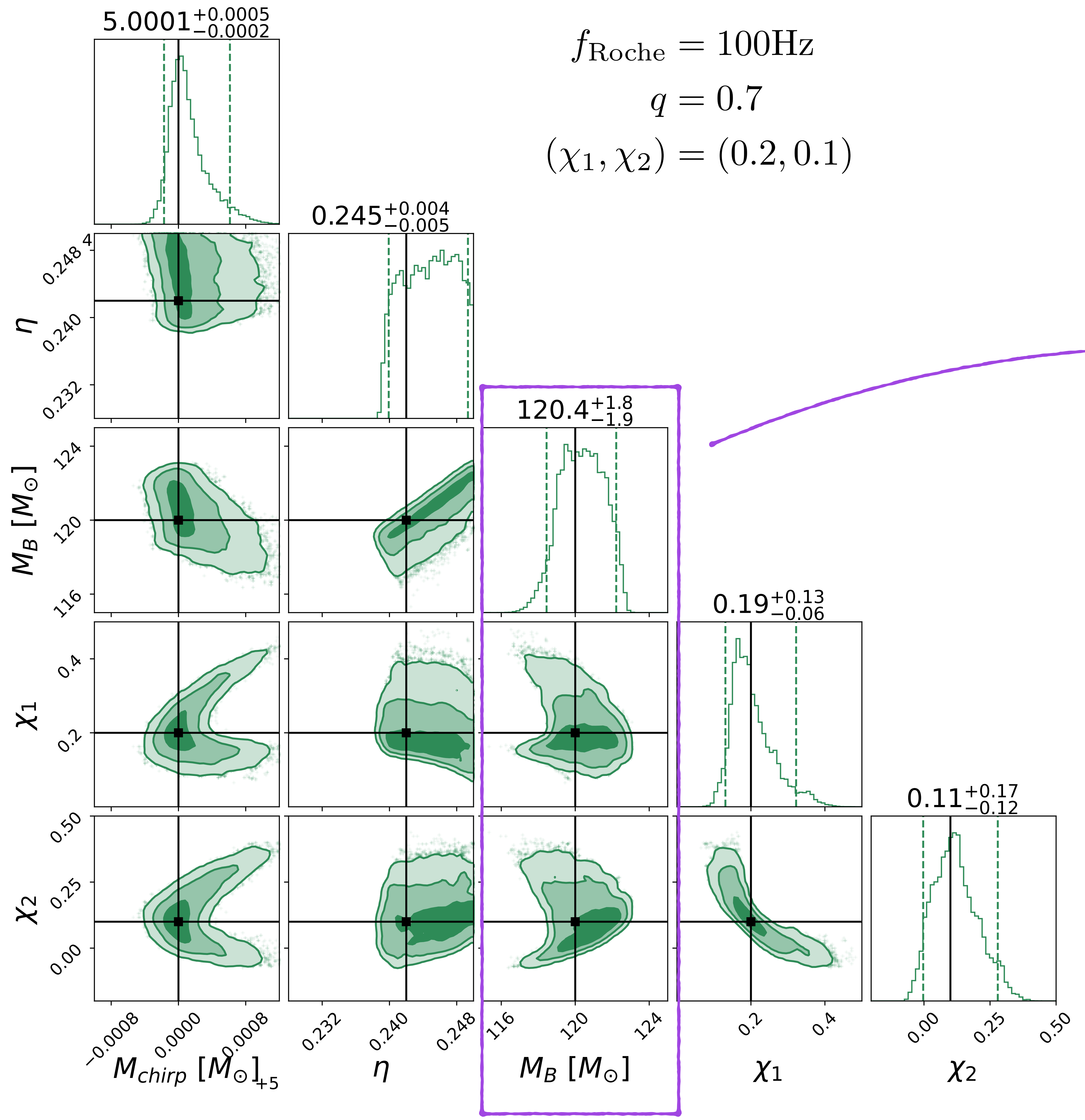
normalised phase contribution



A coherent waveform model

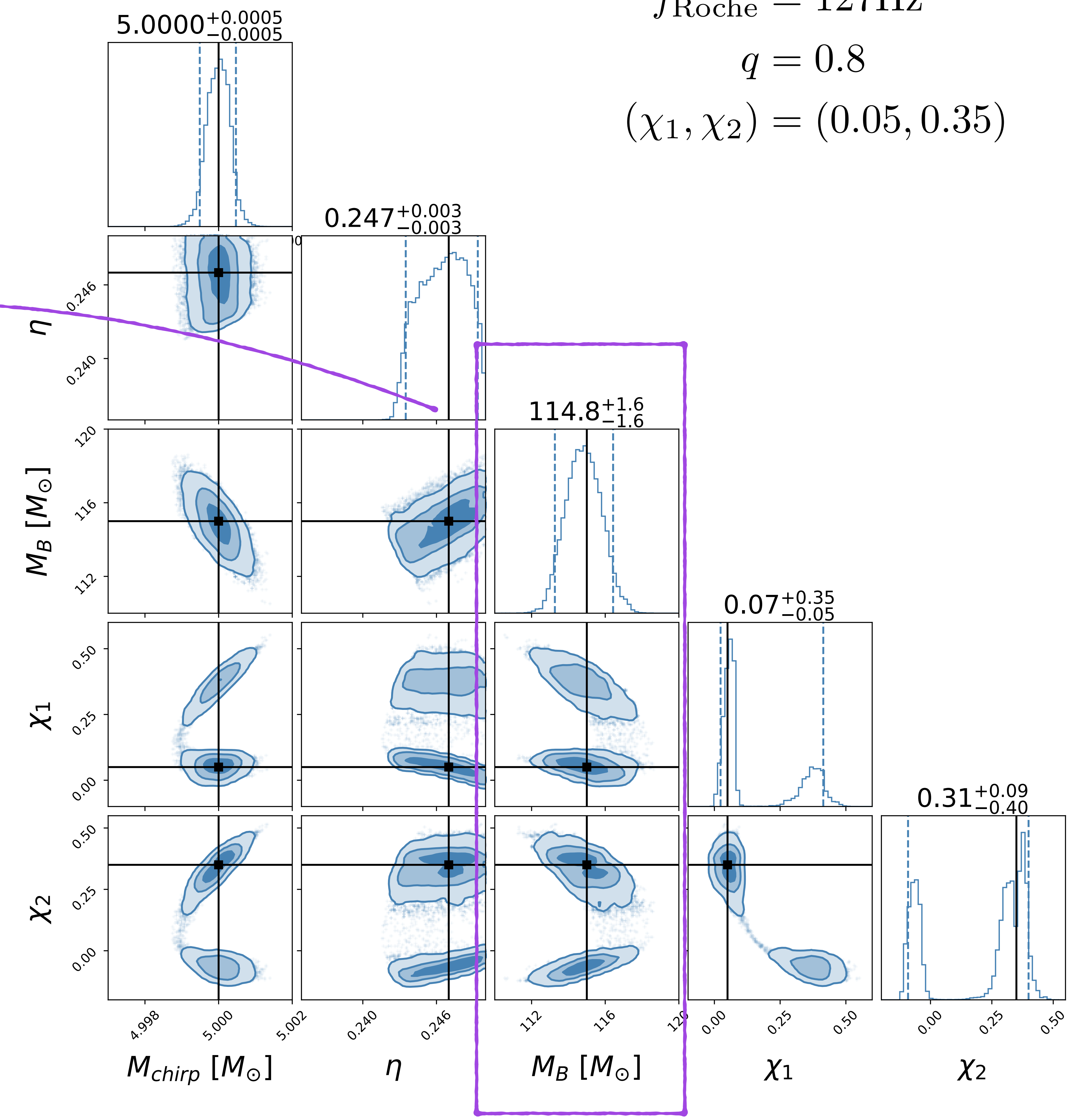
Reconstruction of the source parameters

$f_{\rm Roche} = 100{\rm Hz}$
$q = 0.7$
$(\chi_1, \chi_2) = (0.2, 0.1)$



% level

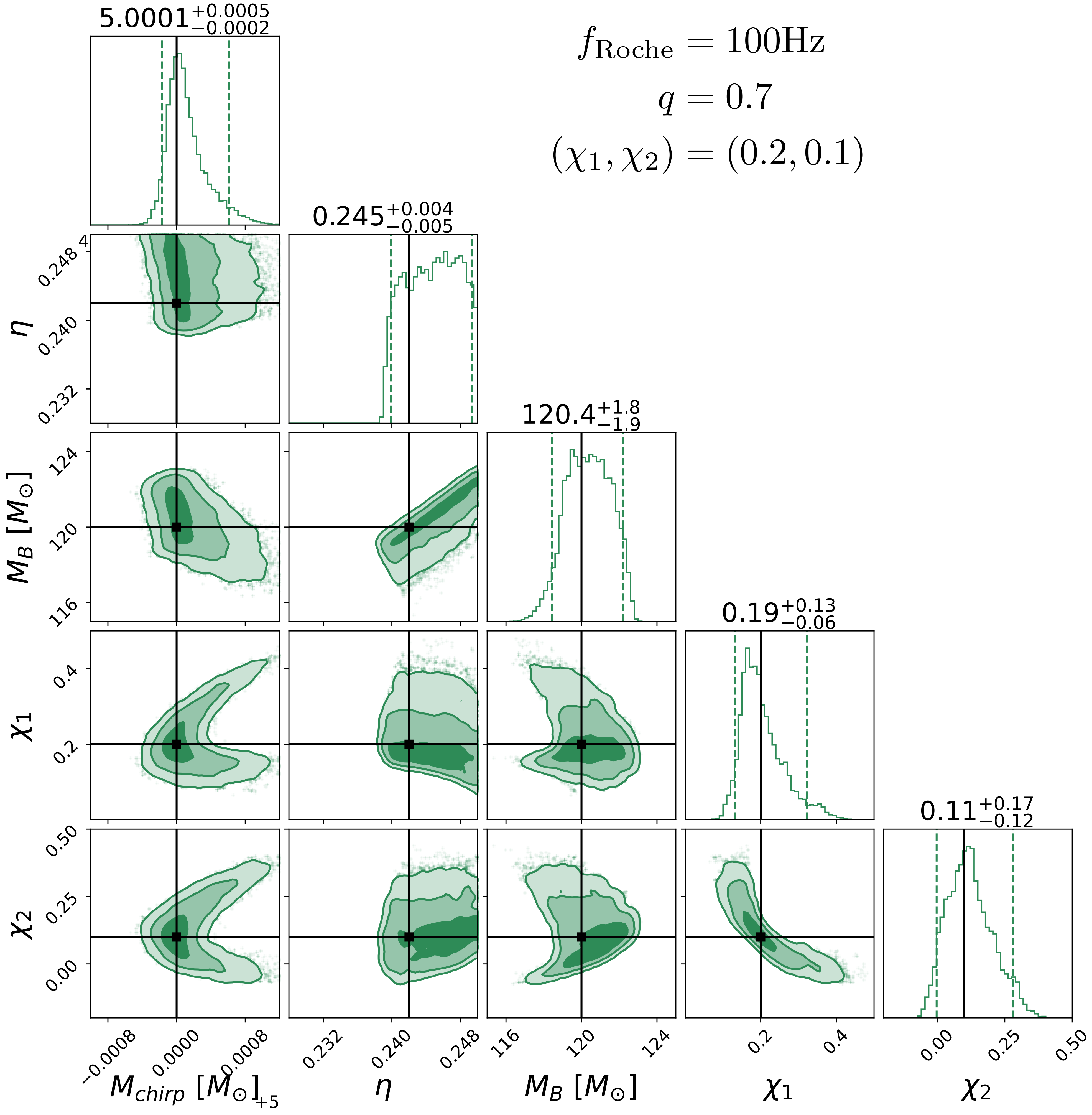
$f_{\rm Roche} = 127{\rm Hz}$
$q = 0.8$
$(\chi_1, \chi_2) = (0.05, 0.35)$



A coherent waveform model

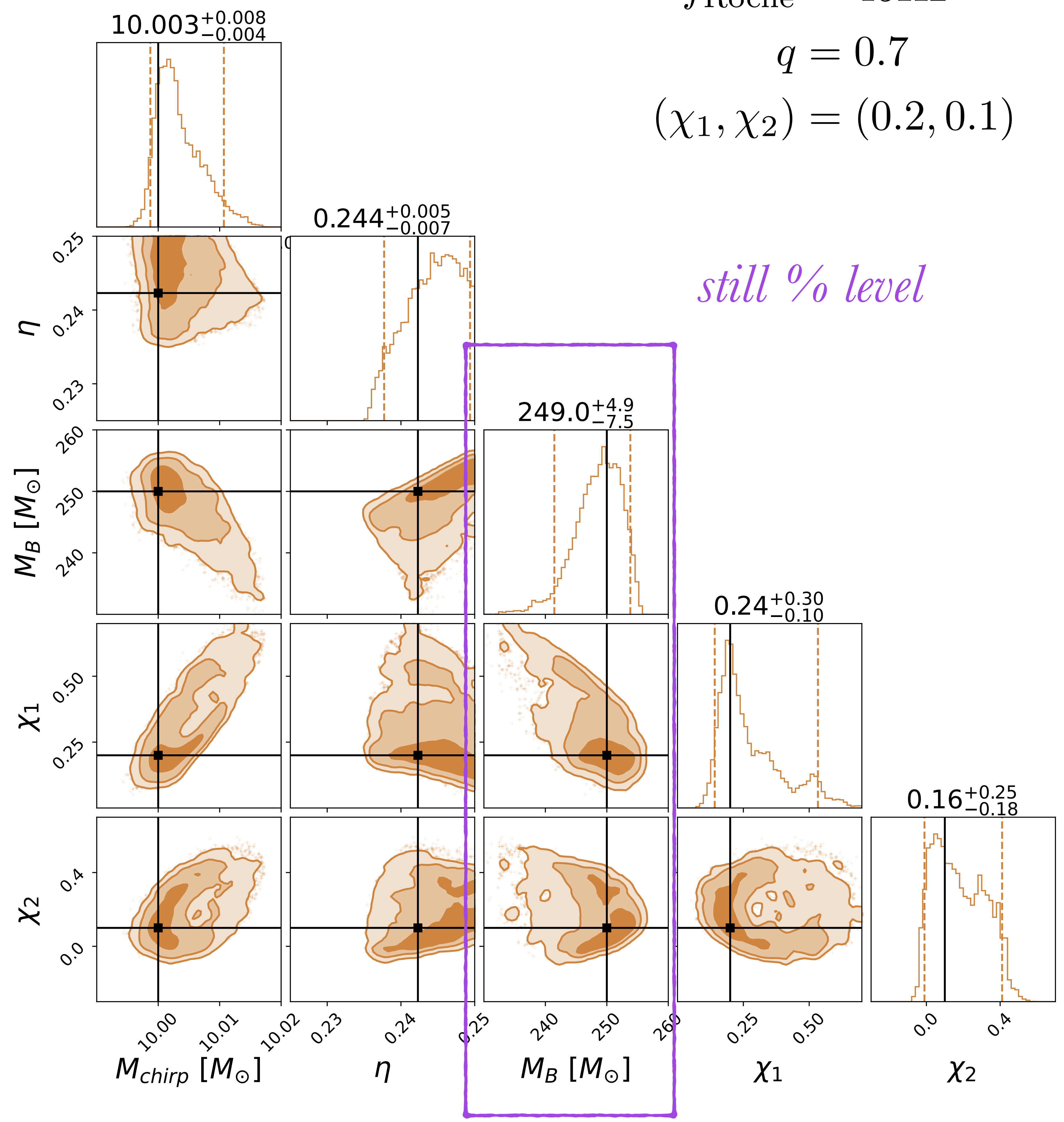
Reconstruction of the source parameters

$f_{\mathrm{Roche}} = 100\mathrm{Hz}$
$q = 0.7$
$(\chi_1, \chi_2) = (0.2, 0.1)$



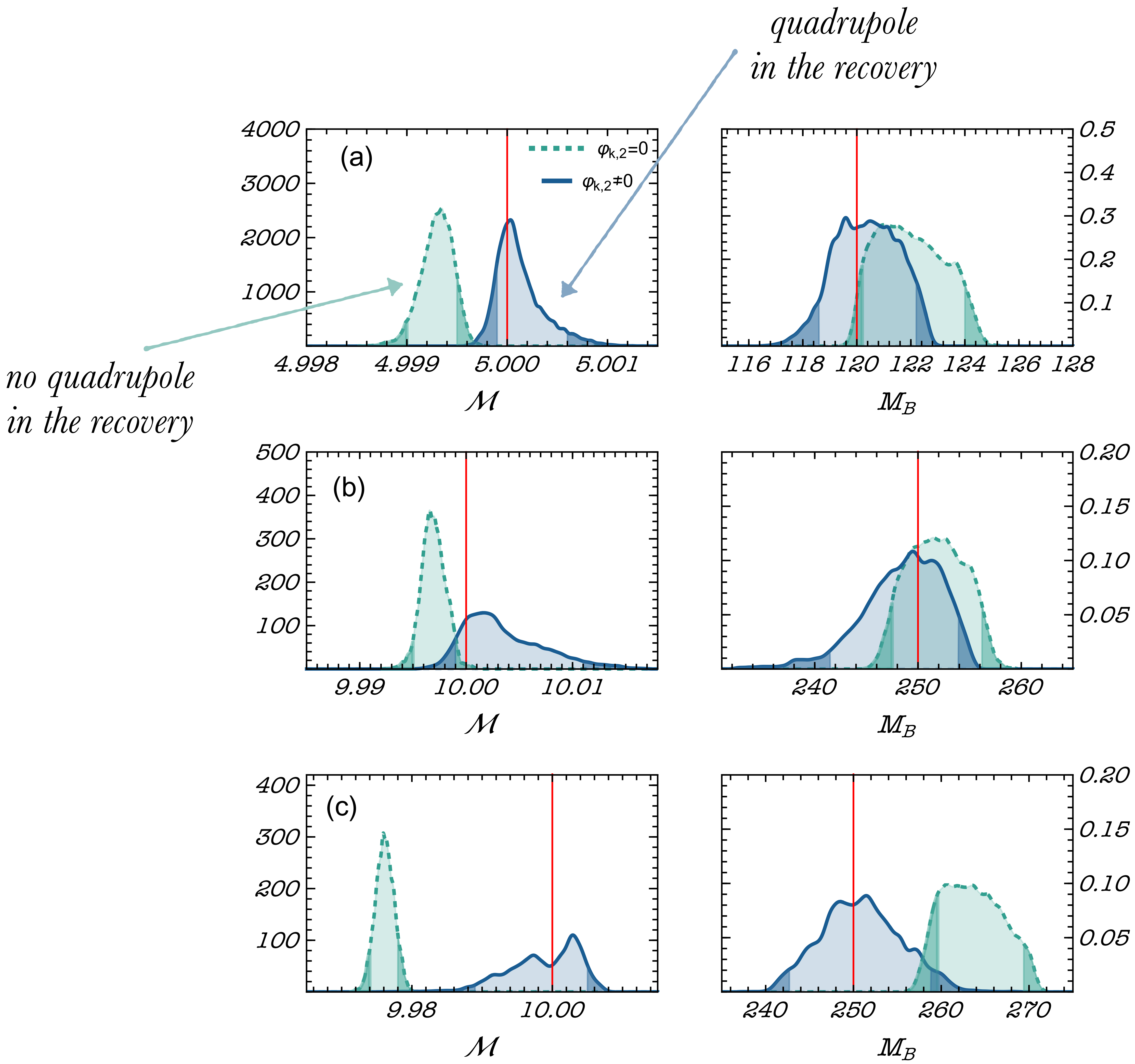
$f_{\mathrm{Roche}} = 45\mathrm{Hz}$
$q = 0.7$
$(\chi_1, \chi_2) = (0.2, 0.1)$

still % level



A coherent waveform model

Including the quadrupole matters



$\mathcal{M} = 5M_\odot$

$(\chi_1, \chi_2) = (0.2, 0.1)$

$\mathcal{M} = 10M_\odot$

$(\chi_1, \chi_2) = (0.2, 0.1)$

$\mathcal{M} = 10M_\odot$

$(\chi_1, \chi_2) = (0.4, 0.7)$

larger spins $\longrightarrow$ *larger quadrupolar effects*

$\longrightarrow$ *larger bias*

Speaking of the bias

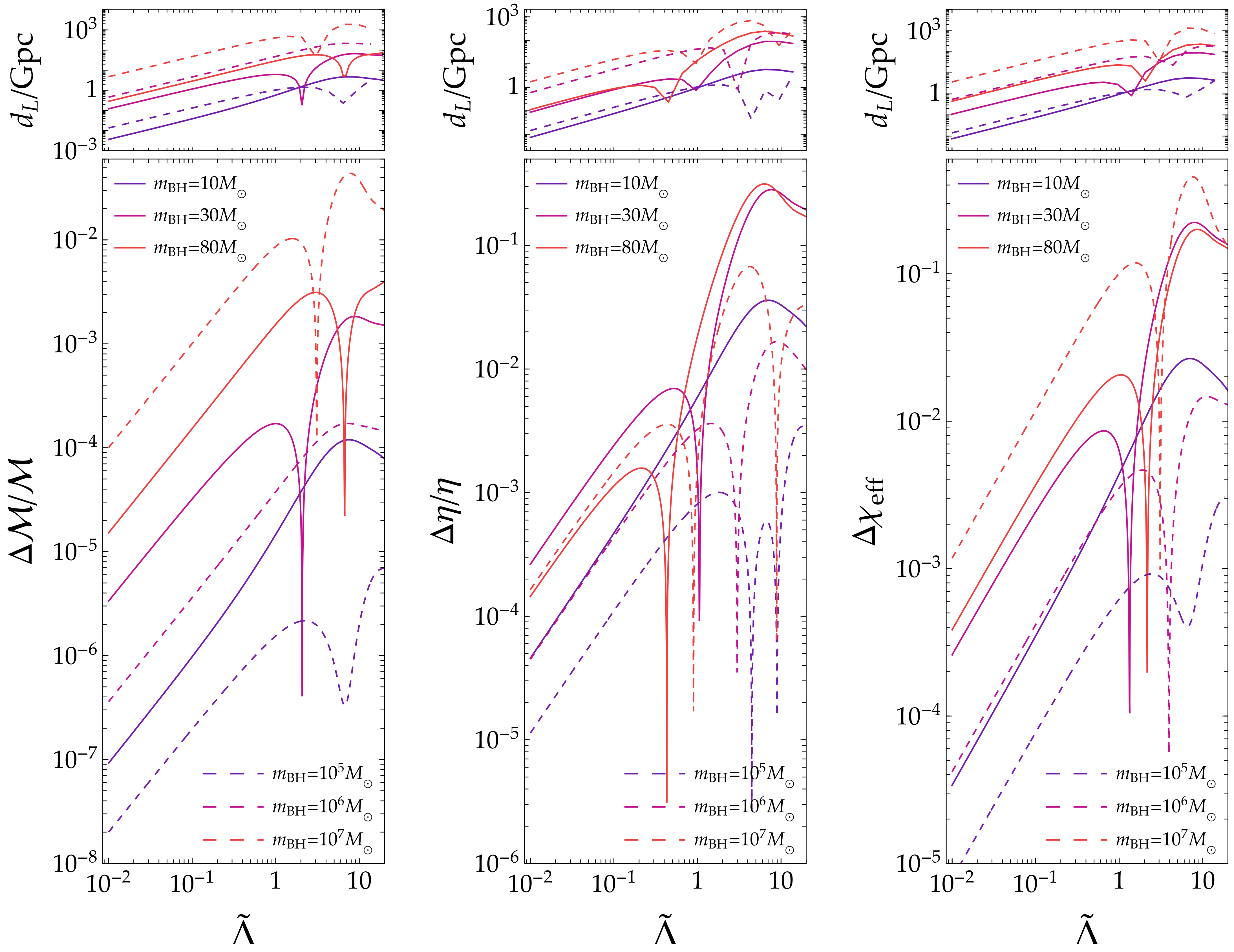
Is there any systematic error in the source parameters when using a <u>wrong</u> waveforms model?

[E. Berti + inc. A.M, 2025]

- Equal mass binaries observed by ET & LISA

Injection: GW signal with $\tilde{\Lambda} \neq 0$ ⟷ Recovery: GW signal with $\tilde{\Lambda} = 0$ → $\Delta\theta \propto \Lambda$

bias over injected value ←



→ *distance @ bias $\gtrsim$ statistical error*

Asymmetric binaries and next gen detectors

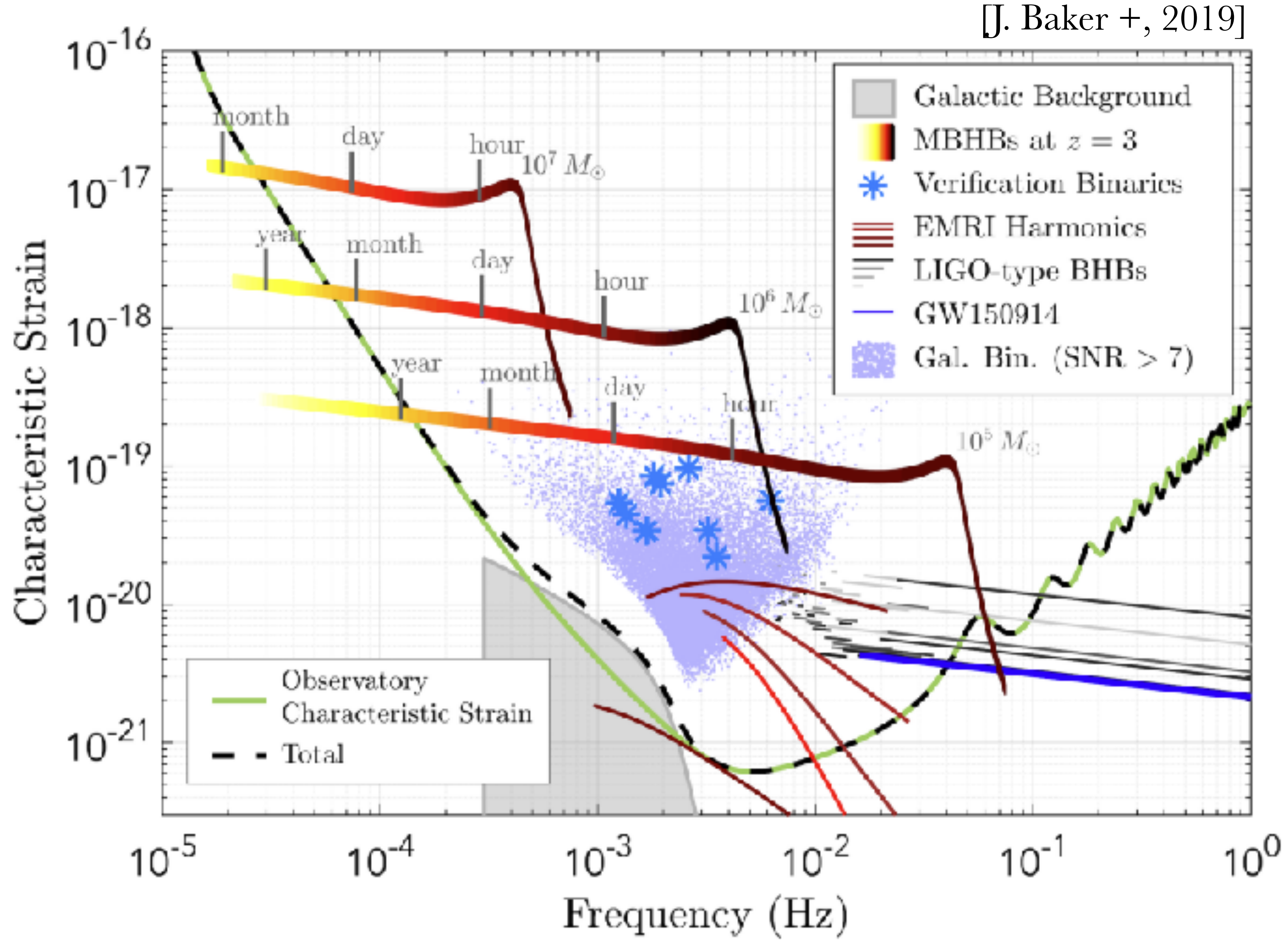
90+ events observed so far from LVK, spanning a relatively small interval of mass ratios $q \sim 1:30$

- Space and ground based detectors can beat down such value by several orders of magnitudes $m/M = q \sim 10^{-2} - 10^{-7}$

- Dynamics dictated by q, with the duration of the inspiral & number of cycles growing as q decreases

- E/IMRIs as golden sources for milli-Hz and deci-Hz detectors

[J. Baker +, 2019]



Discovery potential

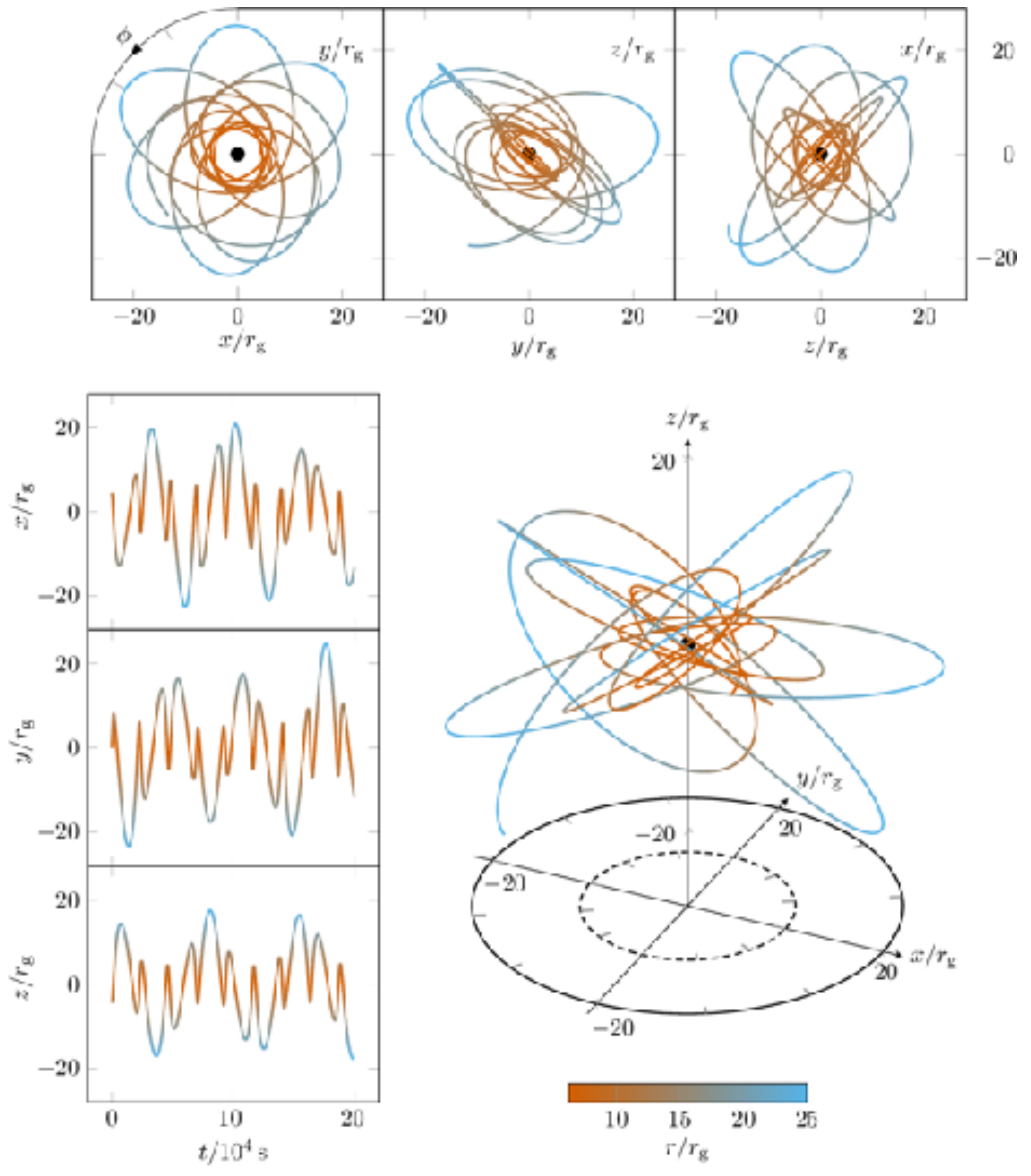
- Slow inspiral phase which could allow to continuously observe EMRI/IMRI for very long periods, from months to years

- Dynamical evolutions with an uncommon richness, with resonances, large eccentricities and off-equatorial orbits, etc.

- rich astro-fundamental physics science cases

EMRIs

EMRIs provide a rich phenomenology, due to their orbital features



Berry +, Astro2020 1903.03686 (2019)

- Non equatorial orbits
- Eccentric motion
- Resonances
- Complete $\sim 10^4 - 10^5$ cycles before the plunge

blessing in **disguise**

Tracking EMRIs for O(year) requires accurate templates

Precise space-time map and accurate binary parameters

Very appealing to test fundamental & astro-physics [A. Avendãno & C. Sopuerta, 2024]

- How do we include and test *new physics* with such sources?

EMRIs in nuce

The asymmetric character introduces a natural parameter to study the problem in perturbation theory $q = m_p/M \ll 1$

$$g_{\alpha\beta} = g^{(0)}_{\alpha\beta} + h_{\alpha\beta} + \dots$$

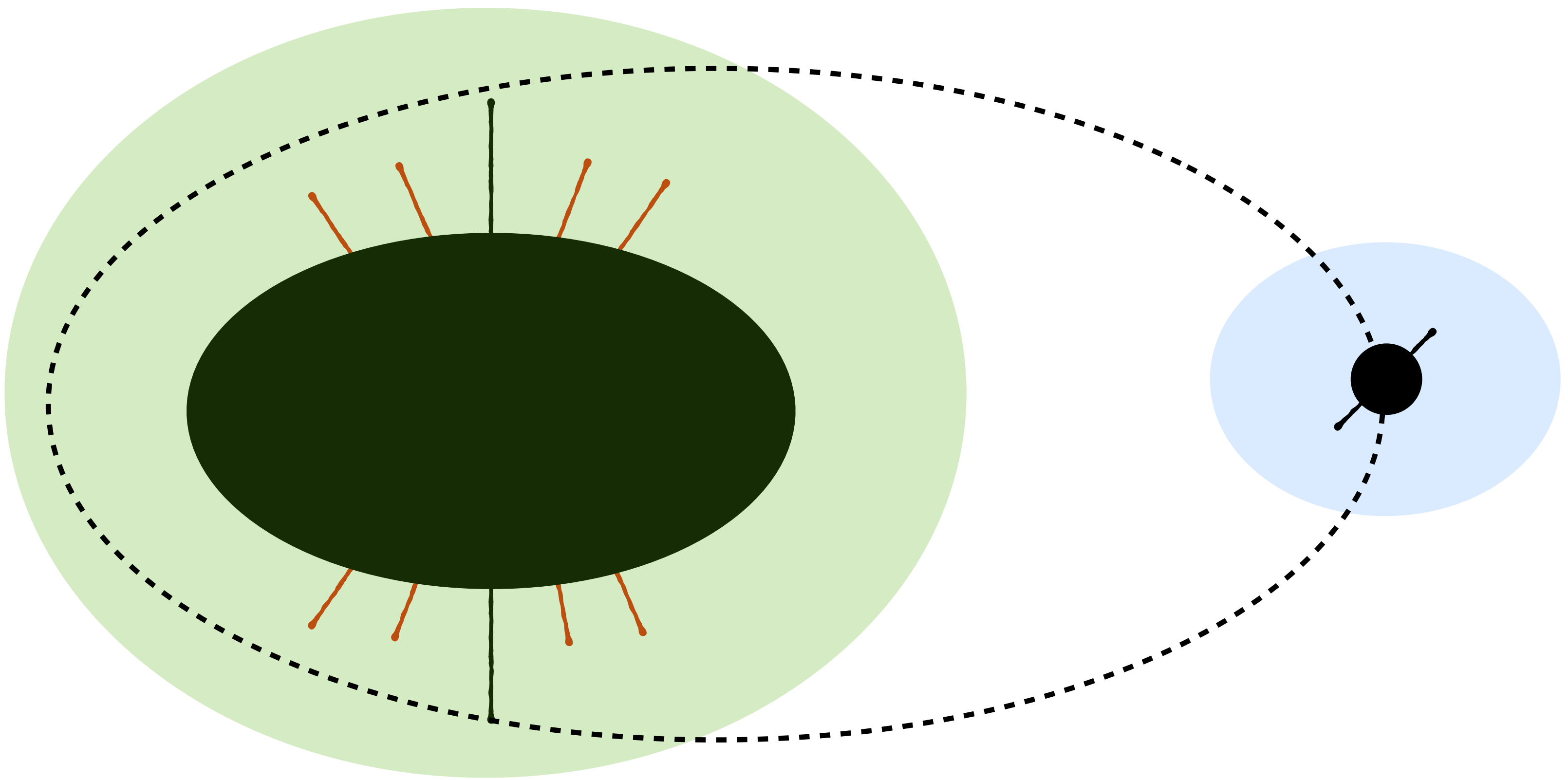
$$G_{\mu\nu} = T^{\rm p}_{\mu\nu} = 8\pi m_{\rm p} \int \frac{\delta^{(4)}(x - y_p(\lambda))}{\sqrt{-g}} \frac{dy_p^\alpha}{d\lambda} \frac{dy_p^\beta}{d\lambda} d\lambda \xrightarrow[\textit{adiabatic}]{\textit{leading}}$$

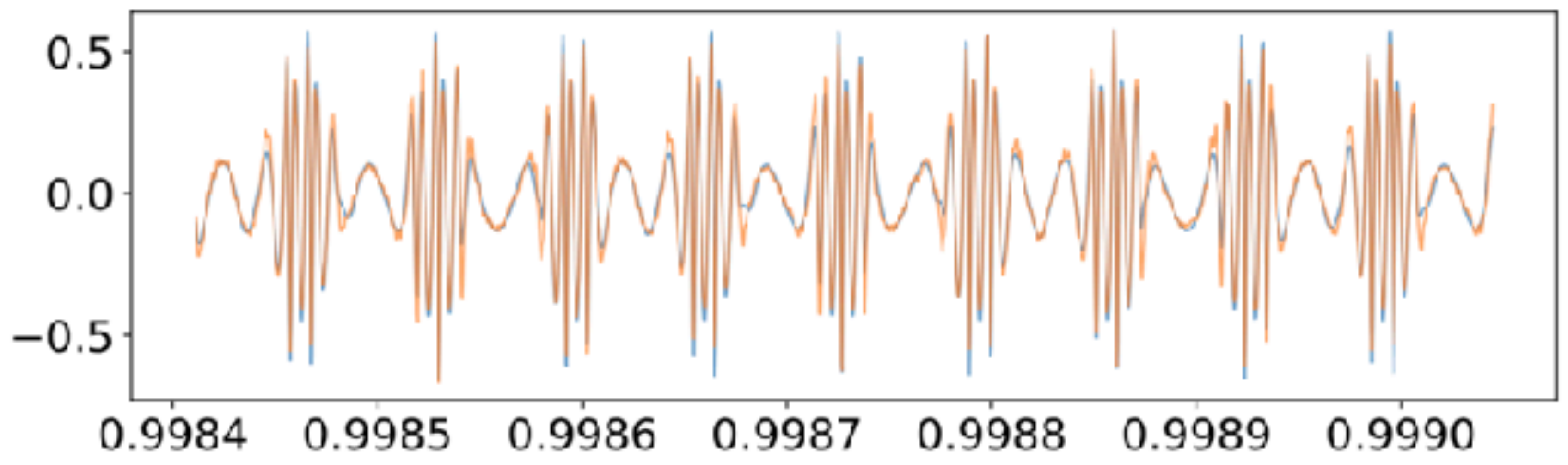
Regge-Wheeler-Zerilli (Schwarzschild)

Teukolsky (Kerr)

- The solution determines the phase evolution

$$\phi(t) = \underbrace{\overbrace{\phi_{\rm diss-1}}^{\textit{adiabatic}}}_{\mathcal{O}(1/q)} + \underbrace{\overbrace{\dots}^{\textit{first post-adiabatic}}}_{\mathcal{O}(1)}$$





EMRIs and tidal effects

Multipolar structure and absence of the horizon as signatures of non-Kerrness for the massive component

[F. Ryan, 1997, G. Raposo +, 2019, C. Herdeiro +, 2021, N. Loutrel +, 2022, K. Fransen & D. Mayerson 2022]

Tidal effects for asymmetric binaries. Learning some lesson from pN expansion (EMRIs are <u>not</u> pN binaries though….)

- Scaling of the pN tidal phase for binaries with $q \ll 1$.

$$\phi_{\rm tidal}(f) \propto [\underbrace{k_1 q^{-1}}_{\text{Love number primary}} + \underbrace{\cancel{q^3 k_2}}_{\text{Love number secondary}}] v^5$$

- Tidal deformability of the primary is naturally "promoted" within the phase hierarchy

- Same order in q of the leading point-particle contribution $\phi_N(f) \propto v^{-5} q^{-1}$

    - with $k_1 \gg q$ tidal effects become more important than conservative effects which are $\mathcal{O}(q)$

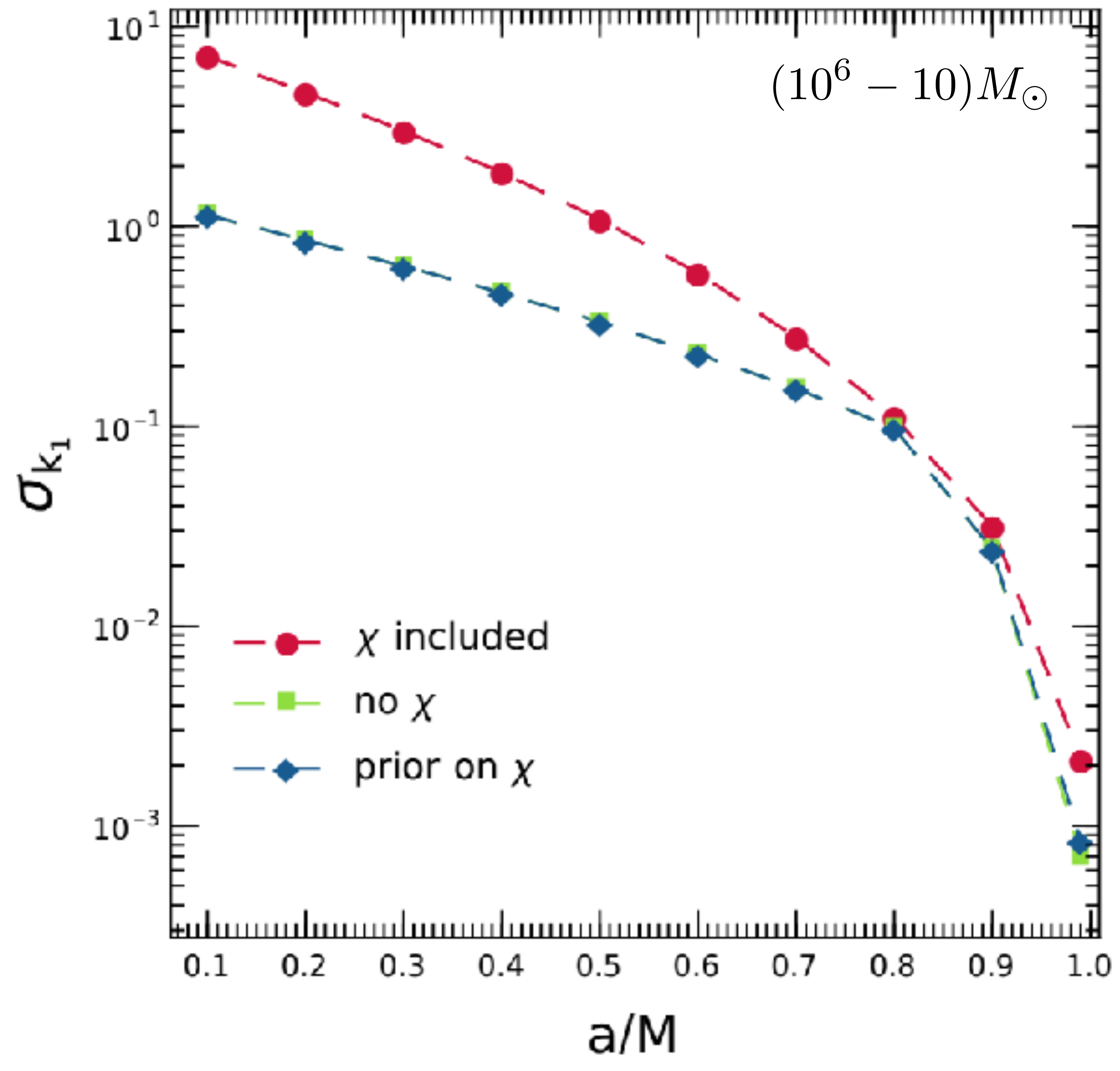
[P. Pani, A. M., 2019]

EMRIs and tidal effects

[G. Piovano, A. M., P. Pani 2023]

Uncertainties on the tidal Love number from EMRI observations by LISA

- Binary evolution with "kludge" waveforms
  - Relativistic amplitudes and mixed GW fluxes $\dot{\mathcal{E}} = \dot{\mathcal{E}}^{\rm Teuk} + \dot{\mathcal{E}}^{\rm tidal}_{\rm pN}$



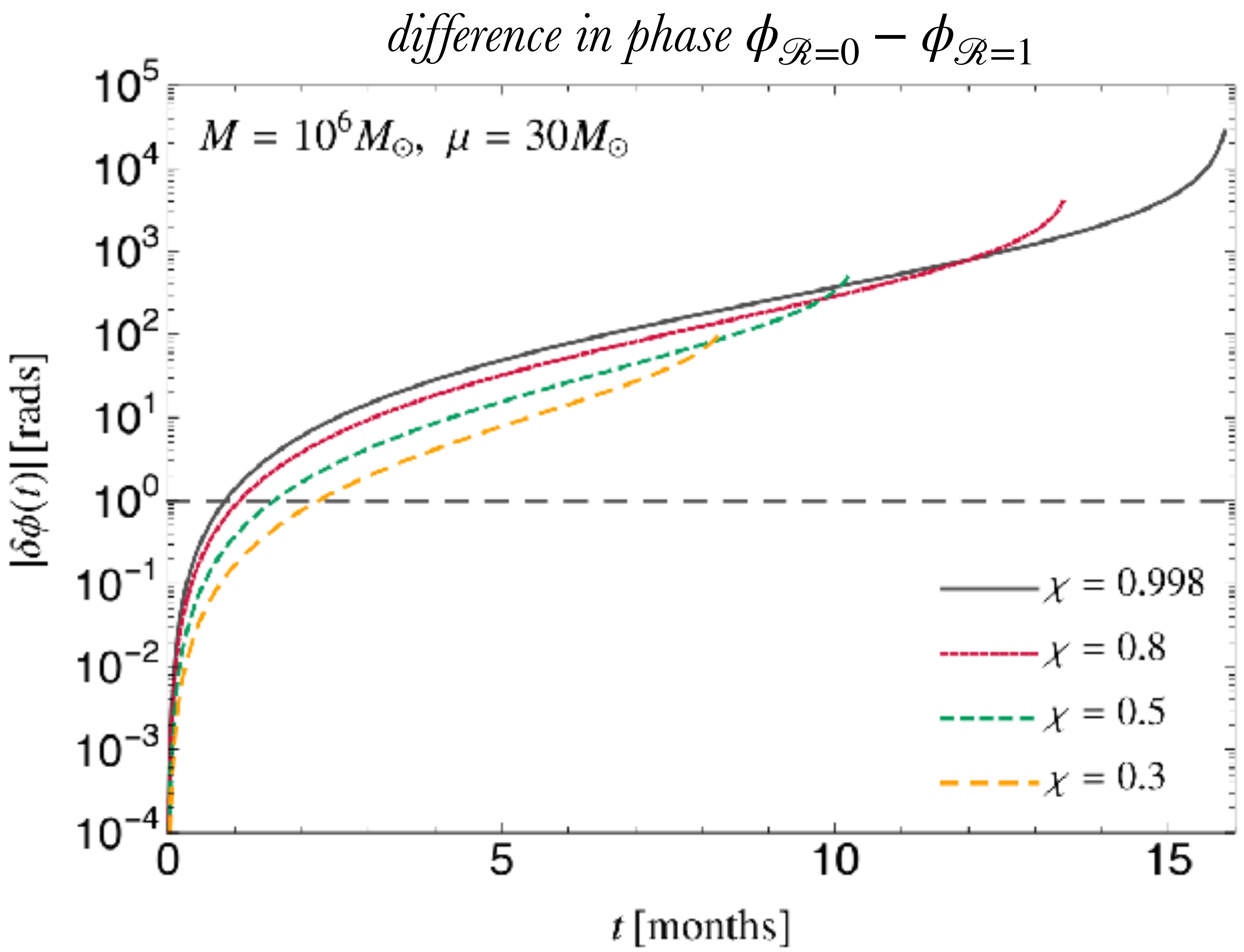
As reference, $\sigma_{k_1} \lesssim 10^3$
for constraints on tidal effects from
GW170817

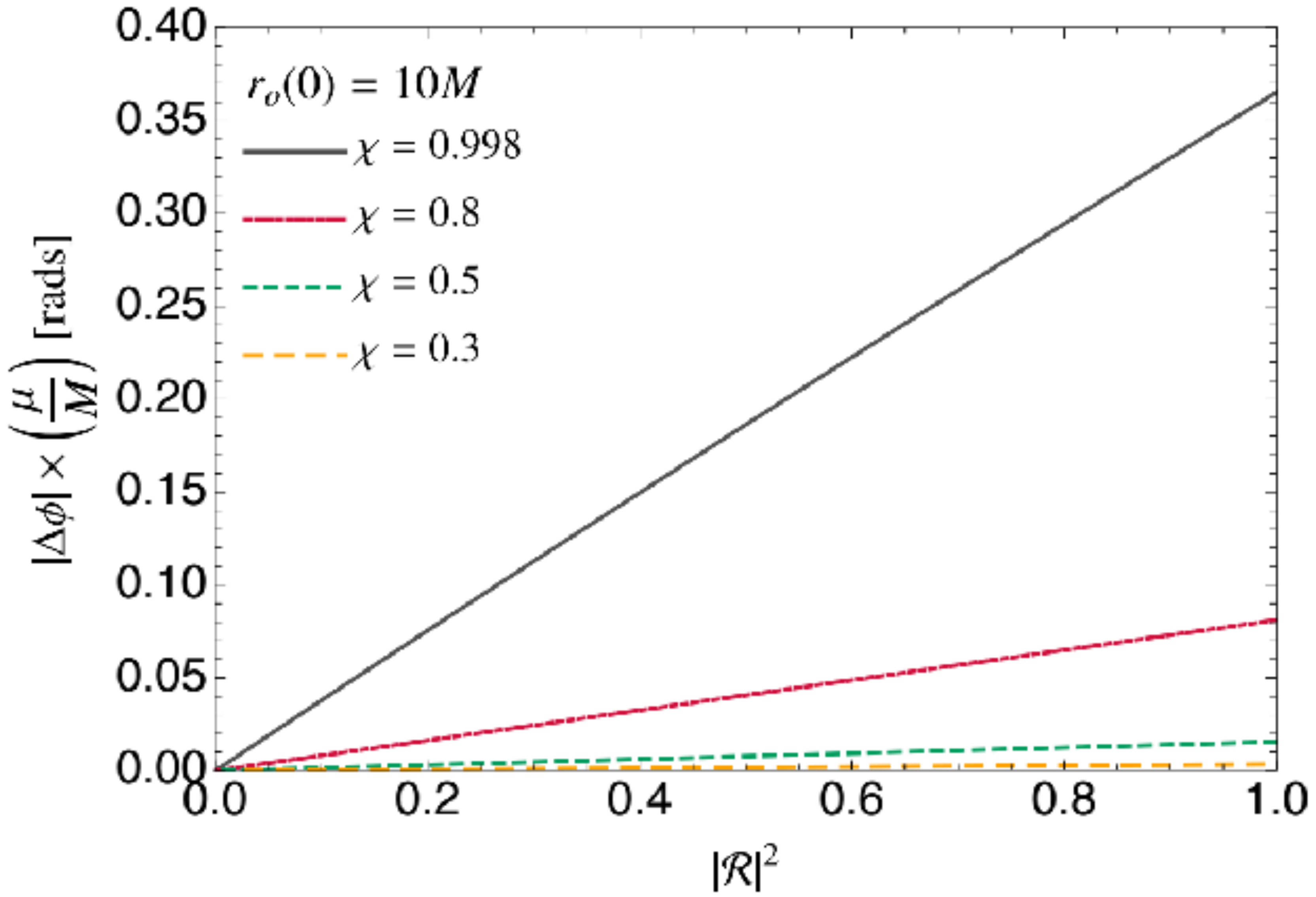
EMRIs and heating

Absence of horizon as potential discriminator for non - Kerrness

- Boundary conditions, QNMs, low frequency modes, partial absorption [S. Hughes 2001; S Bernuzzi +, 2012; P. Pani +, 2009; E. Maggio +, 2017; E. Maggio +, 2017; P. Pani +, 2010; C. Macedo +, 2013, A. M. +, 2018; V. Cardoso +, 2019]

  - (partial) reflection by surface $\dot{\mathcal{E}}^{\rm surf} = (1 - |\mathcal{R}|^2)\dot{\mathcal{E}}^H$ [S. Datta +, 2020]





EMRIs and heating

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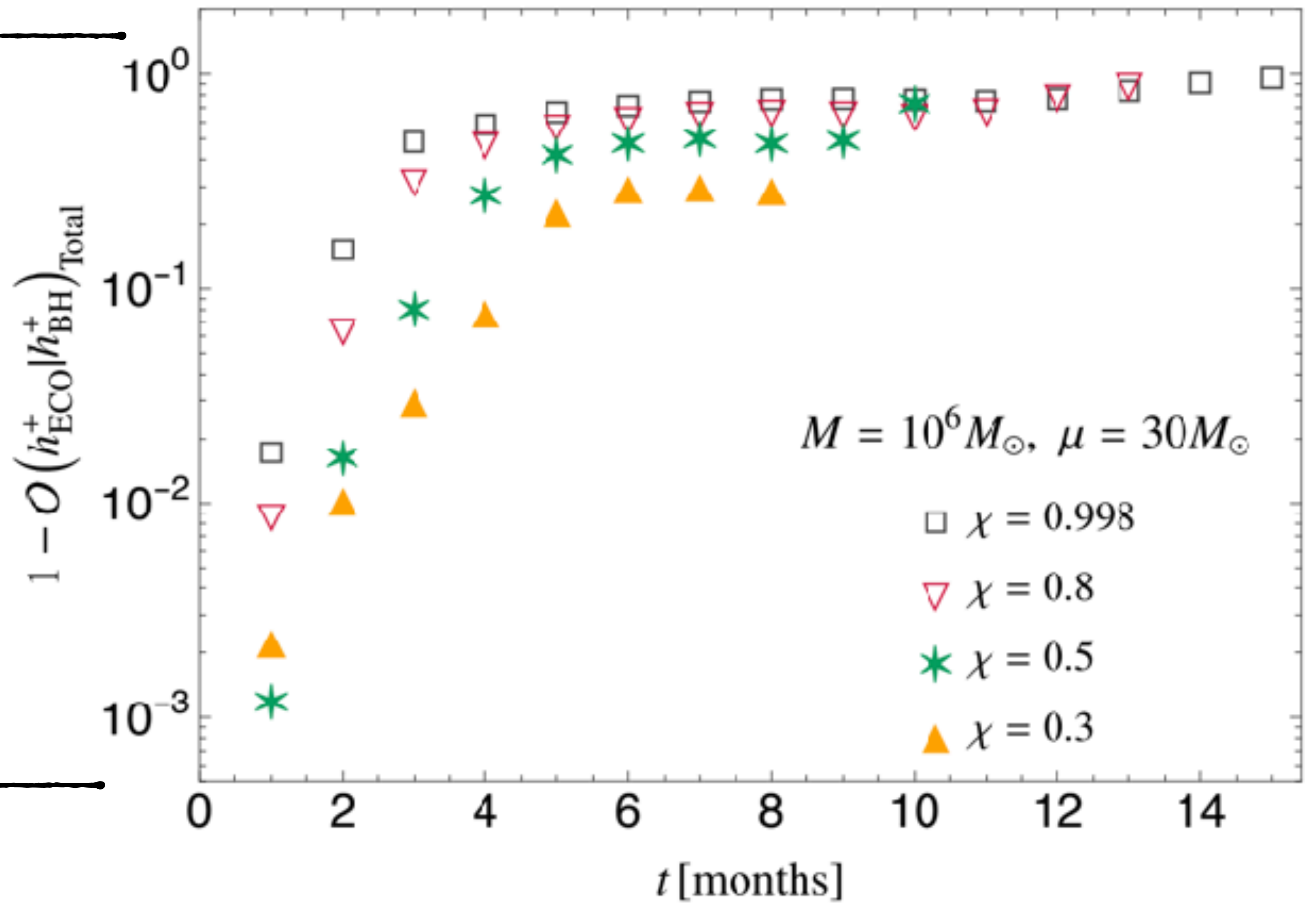
    - (partial) reflection by surface $\dot{\mathcal{E}}^{\rm surf} = (1 - |\mathcal{R}|^2)\dot{\mathcal{E}}^H$ [S. Datta +, 2020]

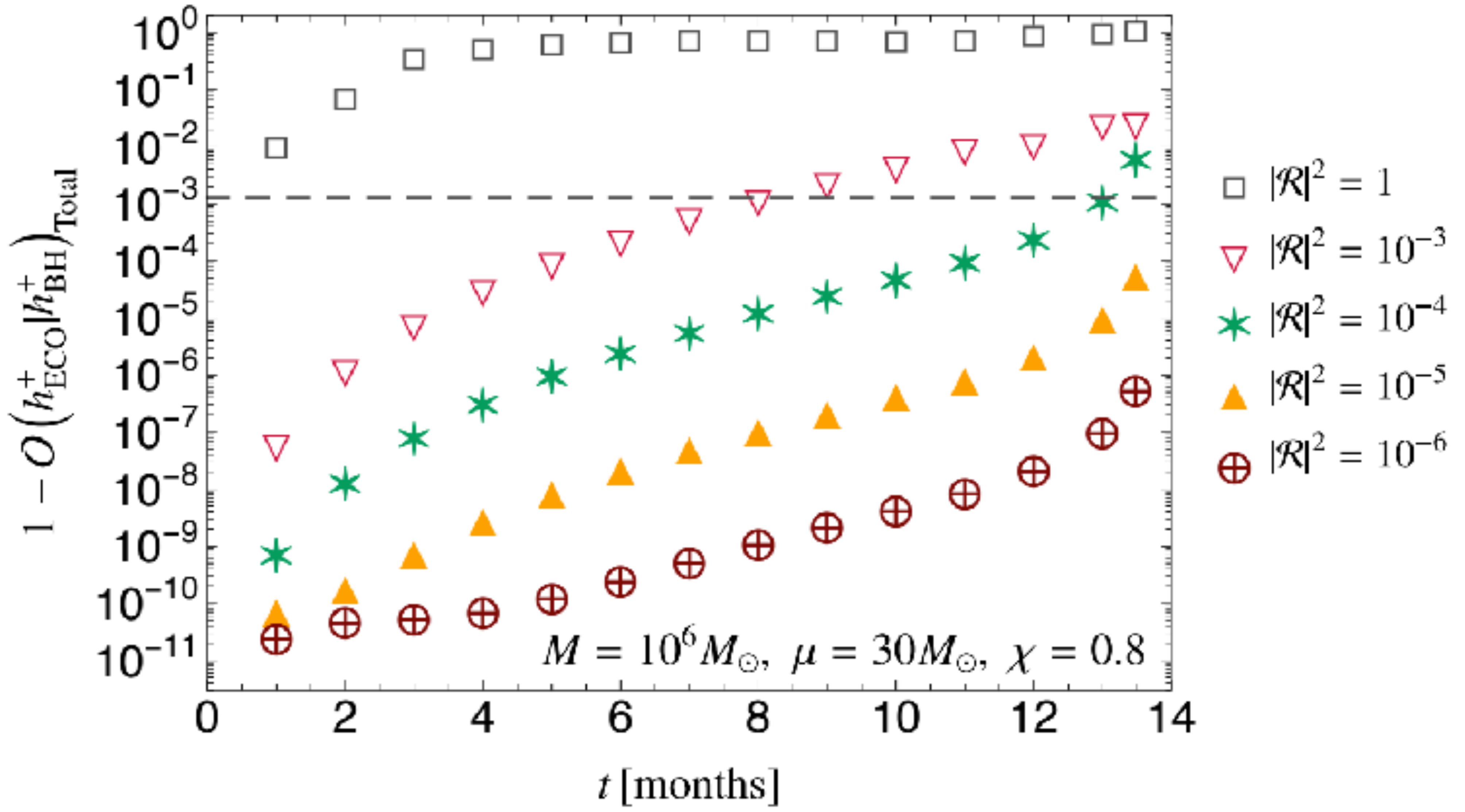
$$\mathcal{O}(h_1|h_2) = \max_{t_0, phi_0} \frac{\langle h_1|h_2\rangle}{\sqrt{\langle h_1|h_1\rangle\langle h_2|h_2\rangle}}$$

weighted by LISA sensitivity

very different

the same

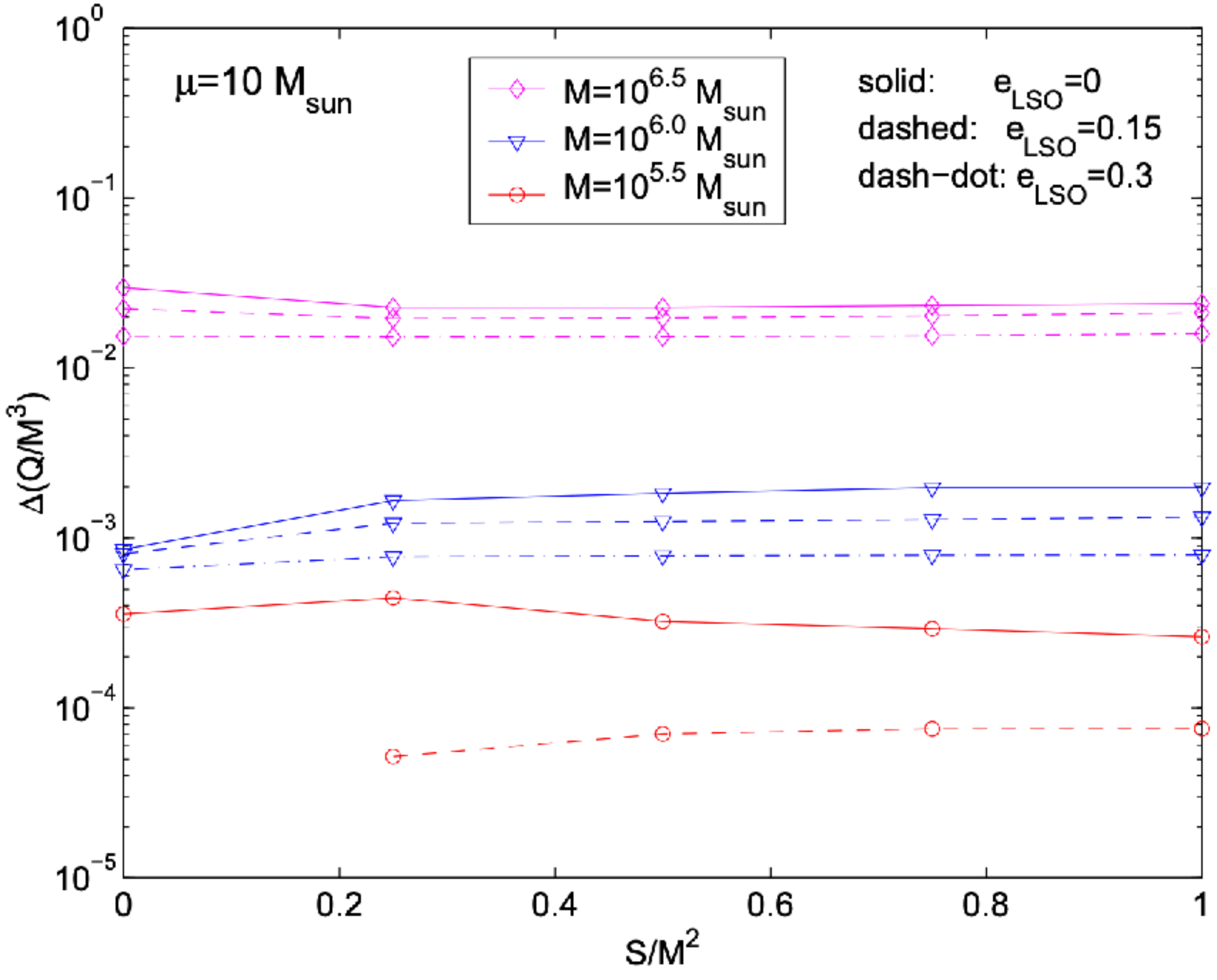




Other smoking guns? Quadrupole moment

Measuring the quadrupole moment of the massive EMRI component with LISA observations

[L. Barack & C. Cutler, 2006]



Thoughts

Using the inspiral phase of binary merger looks an appealing environment for searching new physics

- "recycle" theoretical developments, techniques, data analysis approaches…
- Do we have a faithful model for fundamental physics?

pN approaches

- Installed on BH/NS baseline models (theory still can and needs to inform the way we construct them)
- Goal to construct hybrid models. Few examples on realistic models [T. Evstafyeva + 2024; N, Siemonsen 2024; N. Siemonsen & W. East, 2023]
- ok for early (?) inspiral. When do we stop?

SF approaches

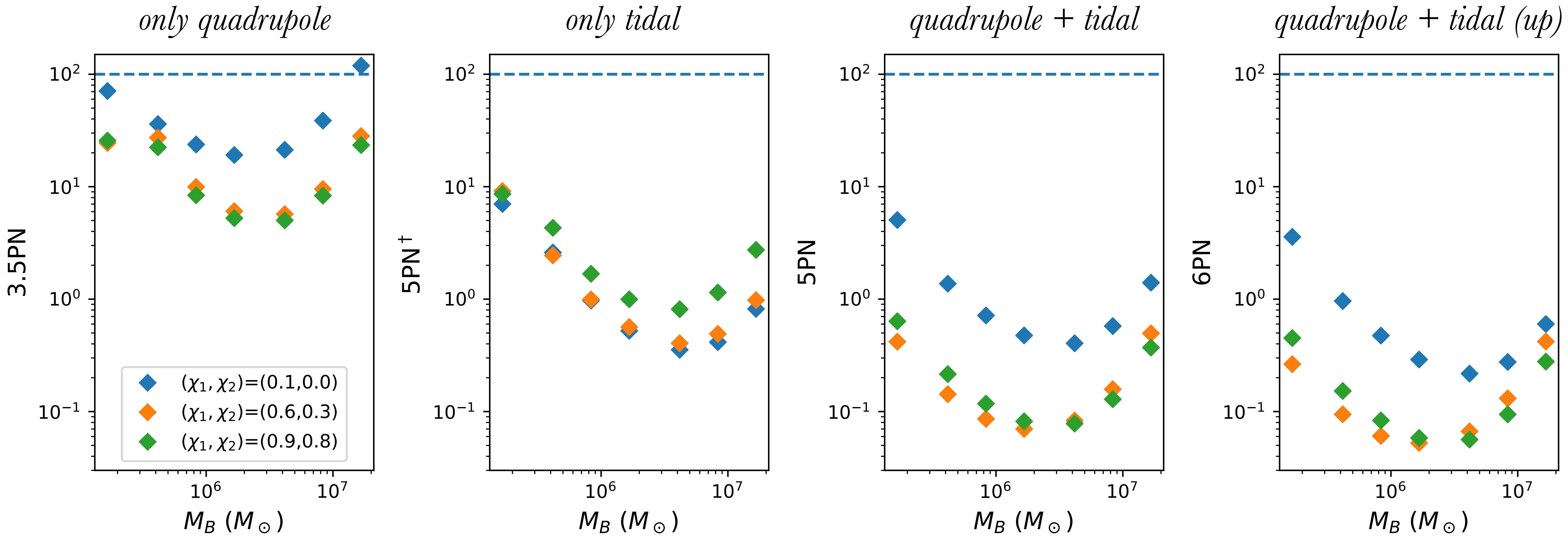
- Vast majority of works/analysis exploratory science
- At very best "kludge" waveform models mixing fully relativistic & pN results

Back up

A coherent waveform model

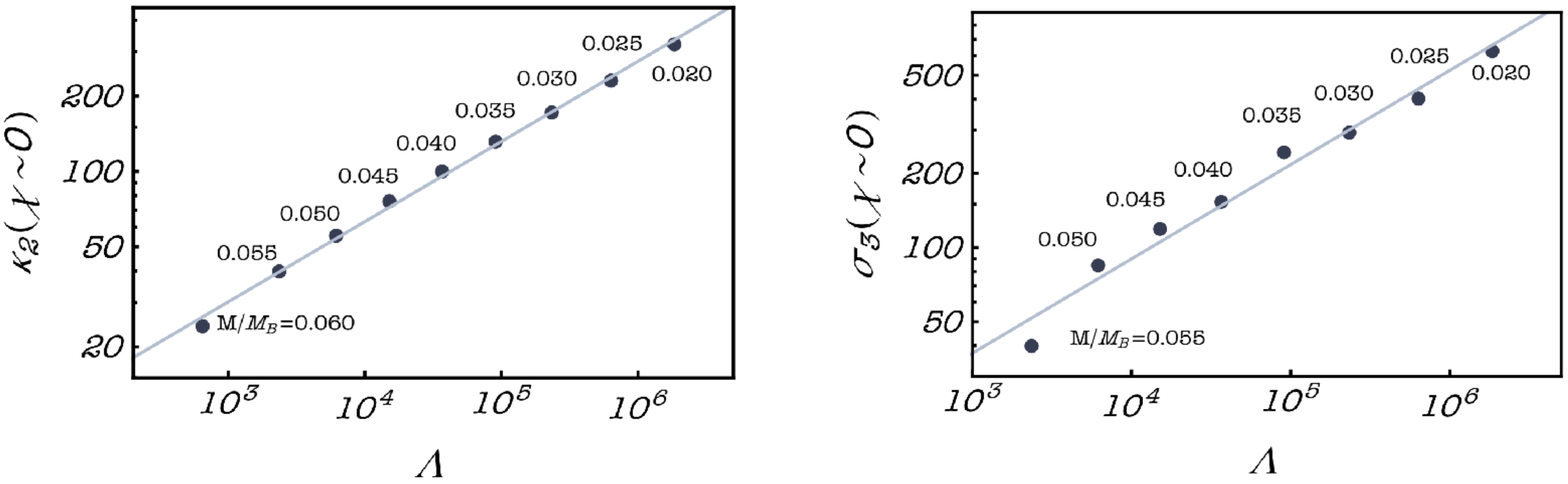
Constraining M_B with massive binaries evolving in the LISA band

- Fisher matrix analysis including different phase contributions



Universal relations among multipole moments

Semi-analytic relation between mass quadrupole and mass octupole and tidal deformability [M. Vaglio + inc. A.M, 2022]



- Can be used to break degeneracy among the source parameters

EMRIs in nuce

$$\mathbf{g}_{\alpha\beta} = g_{\alpha\beta} + q h_{\alpha\beta} + q^2 h^{(2)}_{\alpha\beta} + \mathcal{O}\left(q^3\right)$$

Contributions to the orbital trajectory

$$\frac{D^2 z^\alpha}{d\tau^2} = q f_1^\alpha + q^2 f_2^\alpha + \mathcal{O}(q^3)$$

Inspiral evolution on radiation-reaction time t_{rr}

$$t_{rr} = \mathcal{E}/\dot{\mathcal{E}} \sim M/q \quad \xrightarrow[\textit{of second order SF}]{\textit{cumulative shift}} \quad \delta z^\alpha \sim q^2 f_2^\alpha t_{rr}^2 \sim q^0$$

- Match filtering require error in phase << 1 radian: f_2^α ✓ f_3^α ✗

$$\Phi(t) = \frac{1}{q}\left[\Phi_0(t) + q\Phi_1(t) + \mathcal{O}(q^3)\right]$$

$\Phi_0(t) \rightarrow f^\alpha_{1,\mathrm{diss}}$

$\Phi_1(t) \rightarrow f^\alpha_{1,\mathrm{cons}}$, $f^\alpha_{2,\mathrm{diss}}$

[T. Hinderer & E. Flanagan, 2008]