Tidal effects in the GWs from binary inspirals

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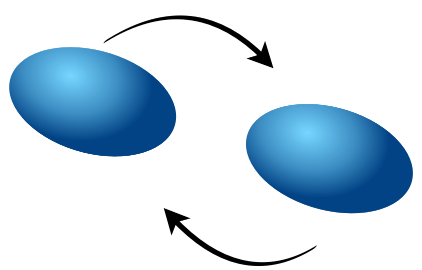
New frontiers in GW astrophysics workshop Sapienza U, Rome June 20, 2017

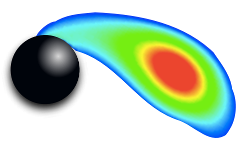
Overview

- Main influence of neutron star (NS) matter on the GW signals during the inspiral: adiabatic tidal effects



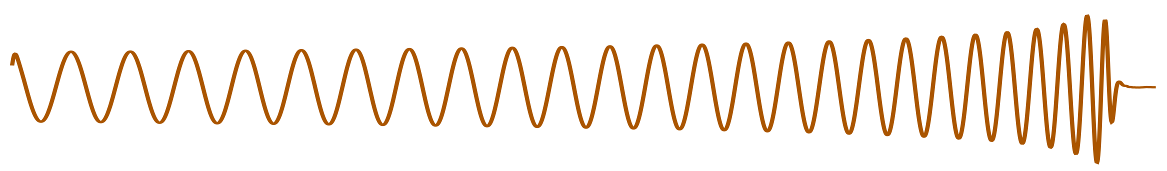
- Characteristic tidal deformability parameters

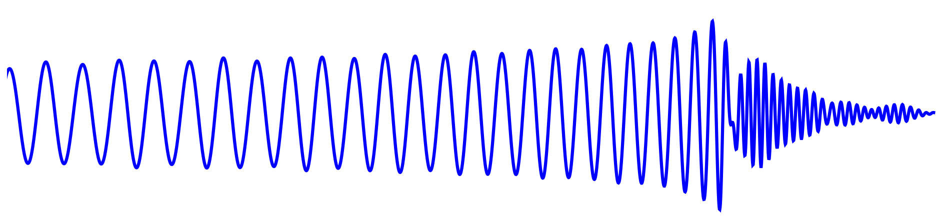
- Dynamical f-mode tides



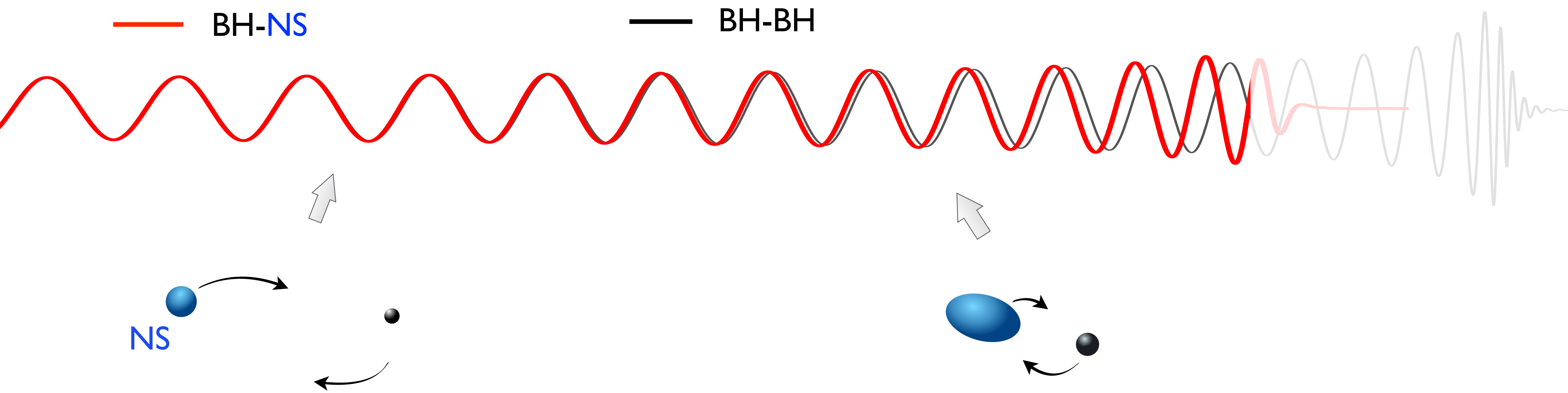
- Status of models, tests for NS-BH and NS-NS

- Outlook





Influence of NS matter on GWs (inspiral)



≈ point-masses

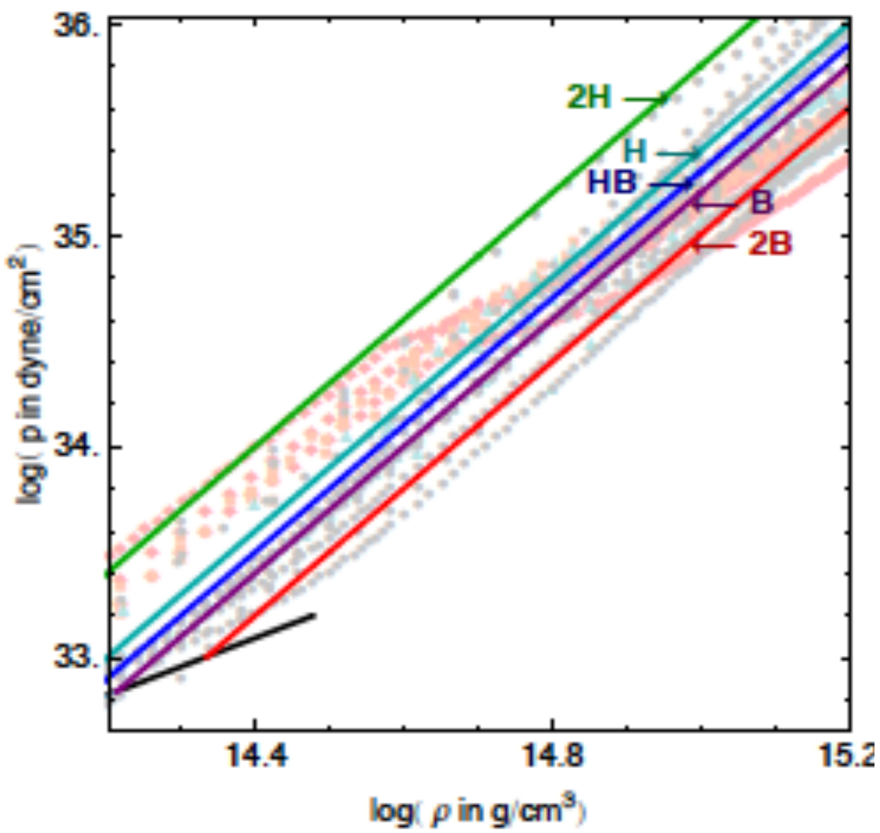
~ 10^3 cycles

dominant tidal effects: $Q_{\mathrm{NS}} = \boldsymbol{\lambda}\, \mathcal{E}_{\mathrm{tidal}}$

characteristic tidal deformability parameter

Tidal deformability / Love number parameter

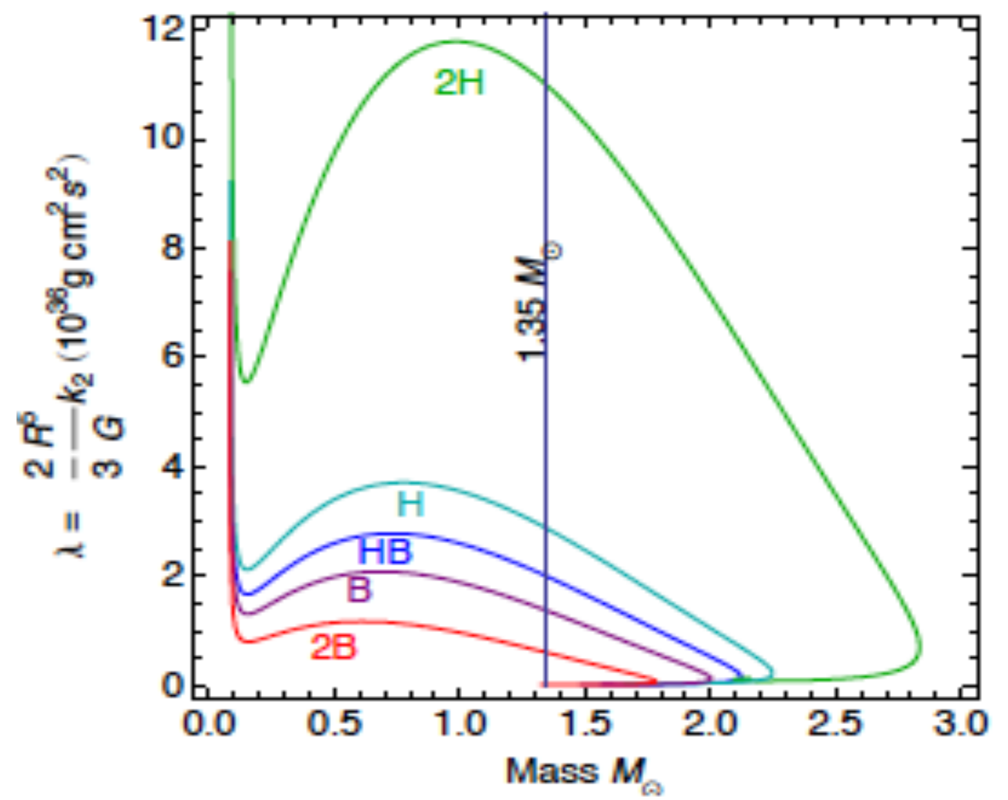
log (pressure - density)



Einstein's Eqs:
linear, static perturbations
to equilibrium sol.

$$\lambda_\ell = \frac{2}{(2\ell - 1)!!} k_\ell R^{2\ell+1}$$

λ- mass



credit: B. Lackey

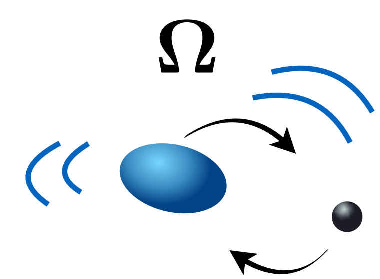
- λ=0 for a BH [Binnington+09, Kol+11]
- also characterizes exotic objects [Pani 15, Uchikata+16, Mendes+16, Cardoso+17, Sennett+17]
- similar treatment for higher multipoles and gravitomagnetic interactions

[Damour+09, Binnington+09, Landry+14]

Influence on the GWs

- Energy goes into deforming the NS

$$E \sim E_{\mathrm{orbit}} - \tfrac{1}{4} Q_{\mathrm{NS}} \mathcal{E}_{\mathrm{tidal}}$$



$$Q_{\mathrm{NS}} = \lambda \, \mathcal{E}_{\mathrm{tidal}}$$

- moving tidal bulges contribute to gravitational radiation

$$\dot{E}_{\mathrm{GW}} \sim \left[\frac{d^3}{dt^3} \left(Q_{\mathrm{orbit}} + Q_{\mathrm{NS}} \right) \right]^2$$

$$M = m_1 + m_2$$

- approx. GW phase: $\dfrac{d\phi_{\mathrm{GW}}}{dt} = 2\Omega, \quad \dfrac{d\Omega}{dt} = \dfrac{\dot{E}_{\mathrm{GW}}}{dE/d\Omega}$

$$\boxed{\Delta\phi_{\mathrm{GW}}^{\mathrm{tidal}} \sim \lambda \frac{(M\Omega)^{10/3}}{M^5}}$$

- for NS-NS: most sensitive to the weighted average:

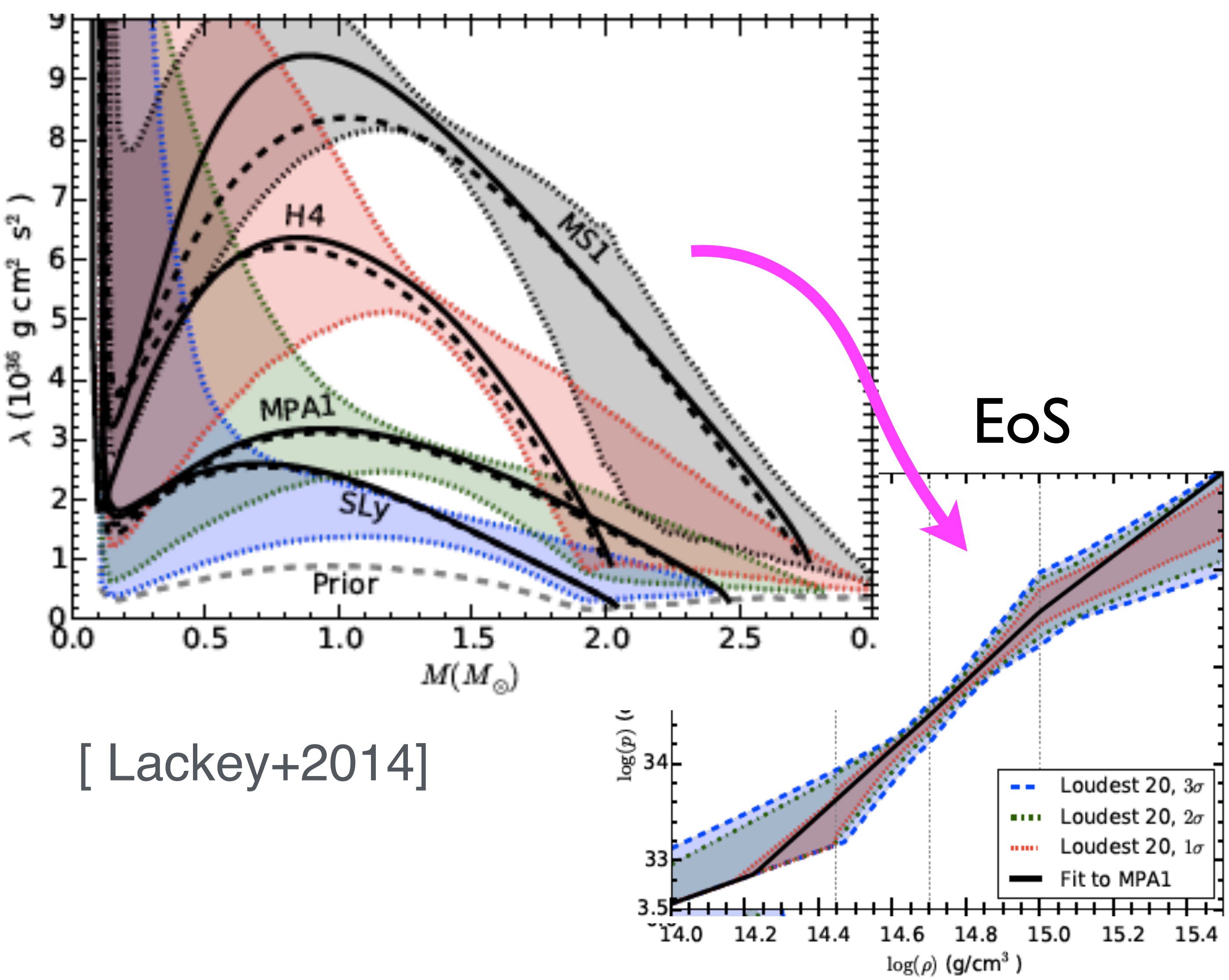
$$\tilde{\Lambda} = \frac{1}{26} \left[\left(1 + 12 \frac{m_2}{m_1} \right) \lambda_1 + \left(1 + 12 \frac{m_1}{m_2} \right) \lambda_2 \right]$$

Preliminary expectations with aLIGO+Virgo

- tens of NS-NS events could potentially give: [del Pozzo+2013, Lackey+2014, Agathos+2015]
  - λ to ~10-50 %, radius to ~1-2 km, pressure to ~ factor of 2
  - similar conclusions with hybrid NR waveforms [Shibata+2016]
- NS-BH systems: λ/m^5 to ~ 10-100 % [Lackey+ 13, Kumar+16 (full waveforms)]

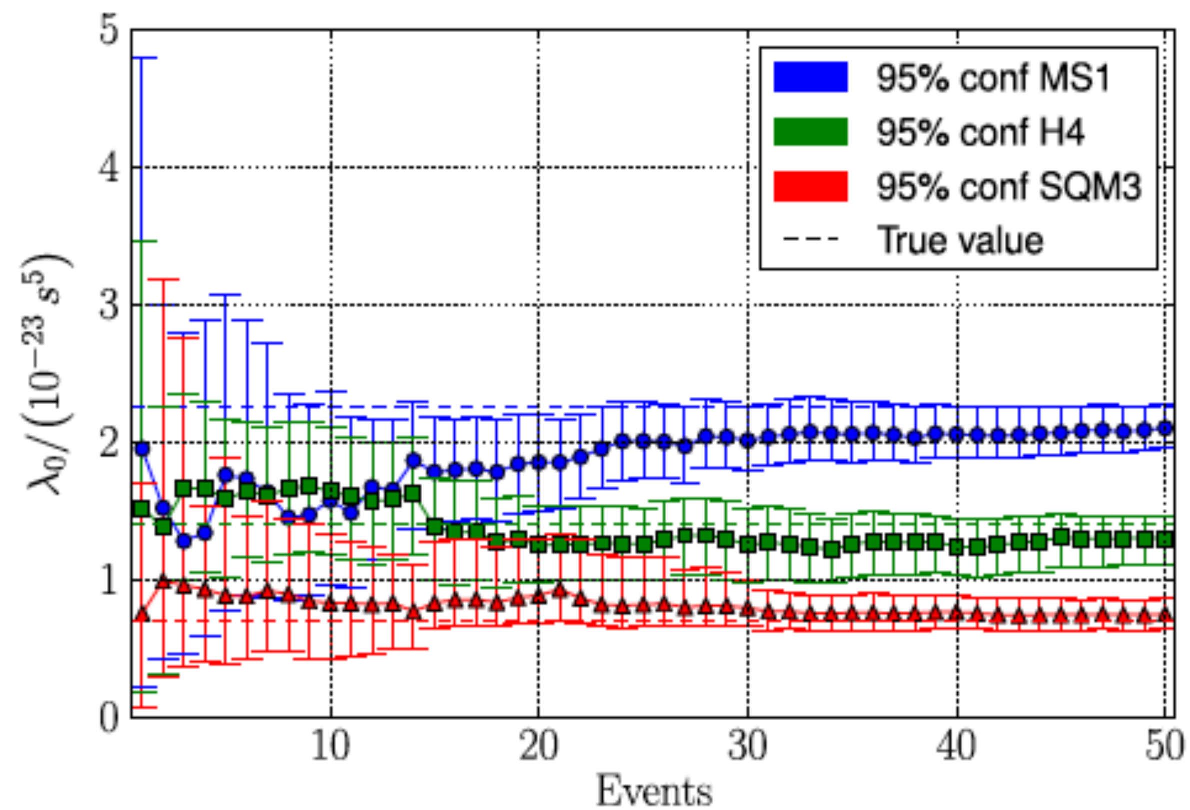
caveats

example results: λ



[Lackey+2014]

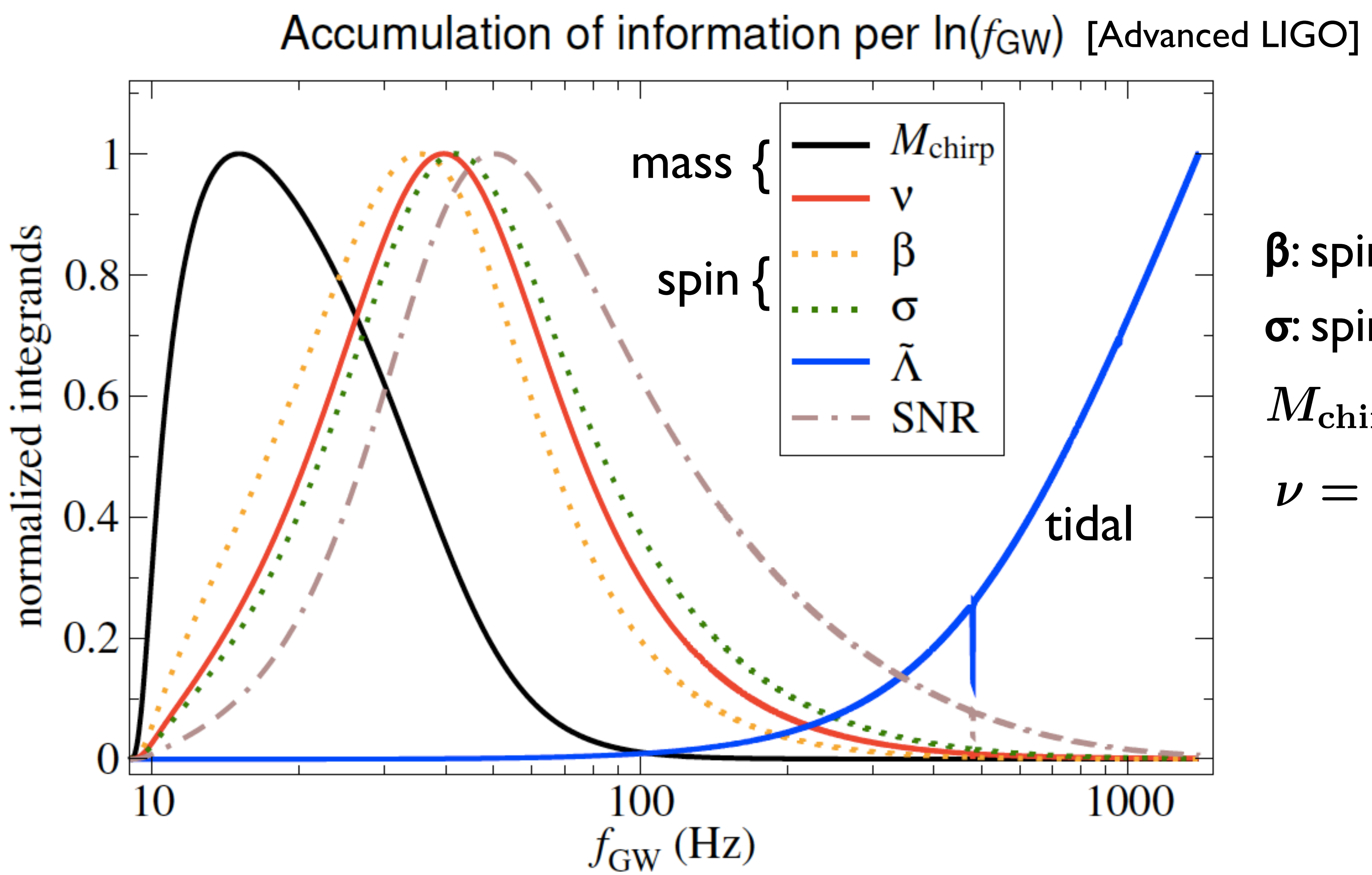
example results: λ(1.4Msun)



[delPozzo+2014]

Information on parameters in the GW signal

- Information about parameters is contained in different frequency ranges



β: spin-orbit parameter

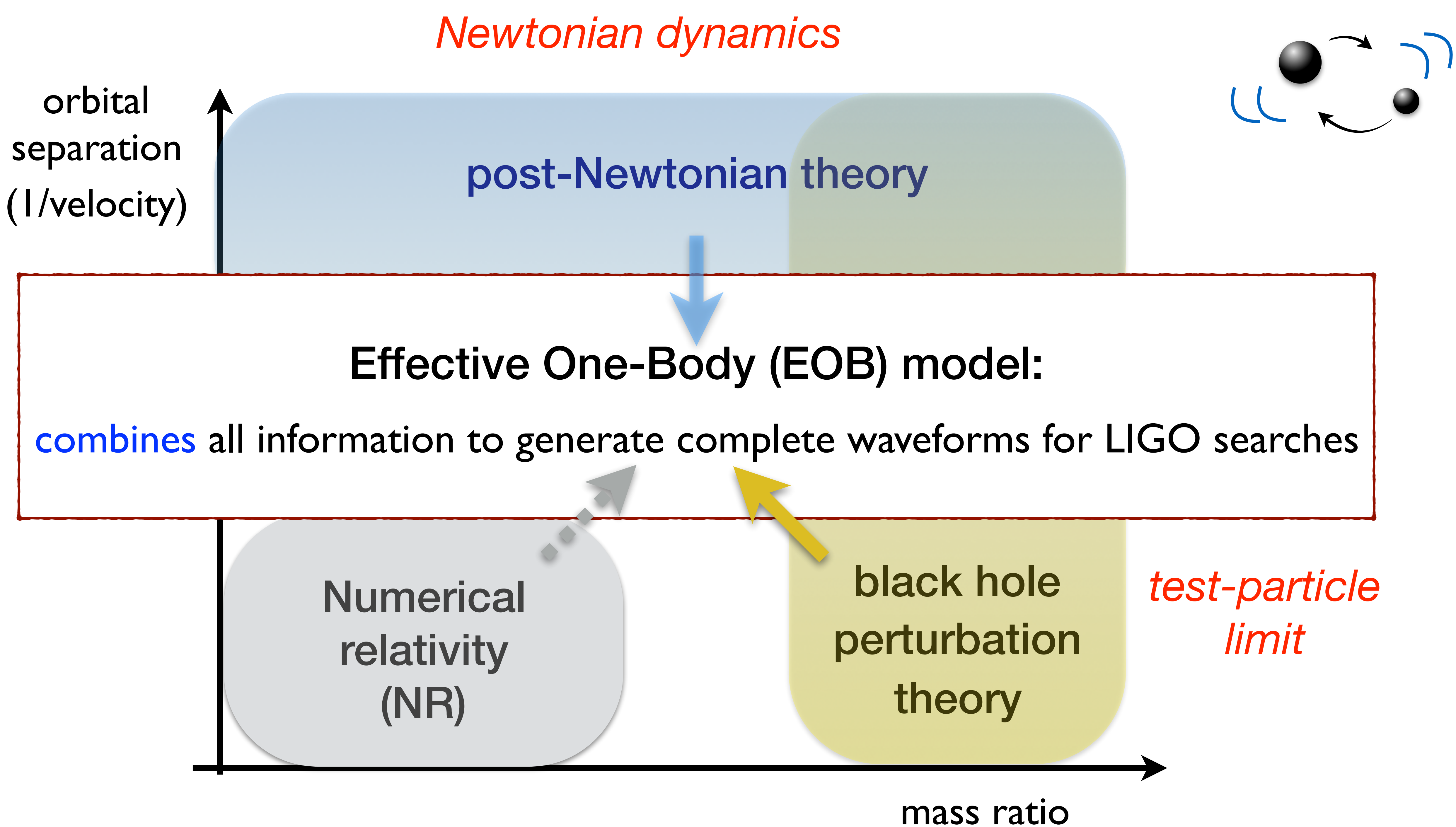
σ: spin-spin parameter

$M_{\mathbf{chirp}} = \nu^{3/5} M$

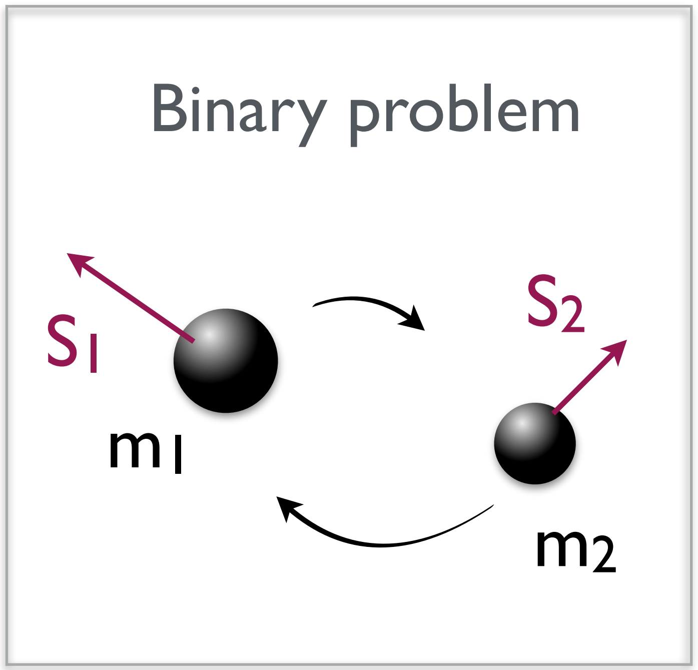
$\nu = \mu / M$

- to avoid large systematics in tidal parameter: need a good point-particle description

Approaches to the two-body problem



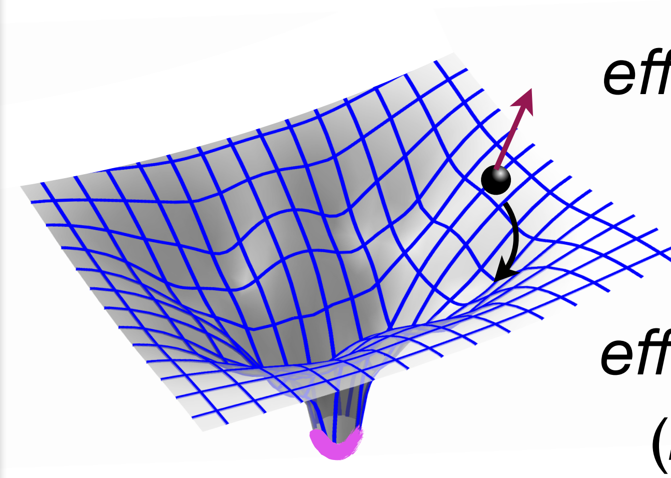
Effective One-Body (EOB) model



MAP

[Buonanno, Damour 1999, 2000; Barausse+]

Effective description



effective particle

($\boldsymbol{\mu}$, $S_{\rm eff}$)

effective spacetime

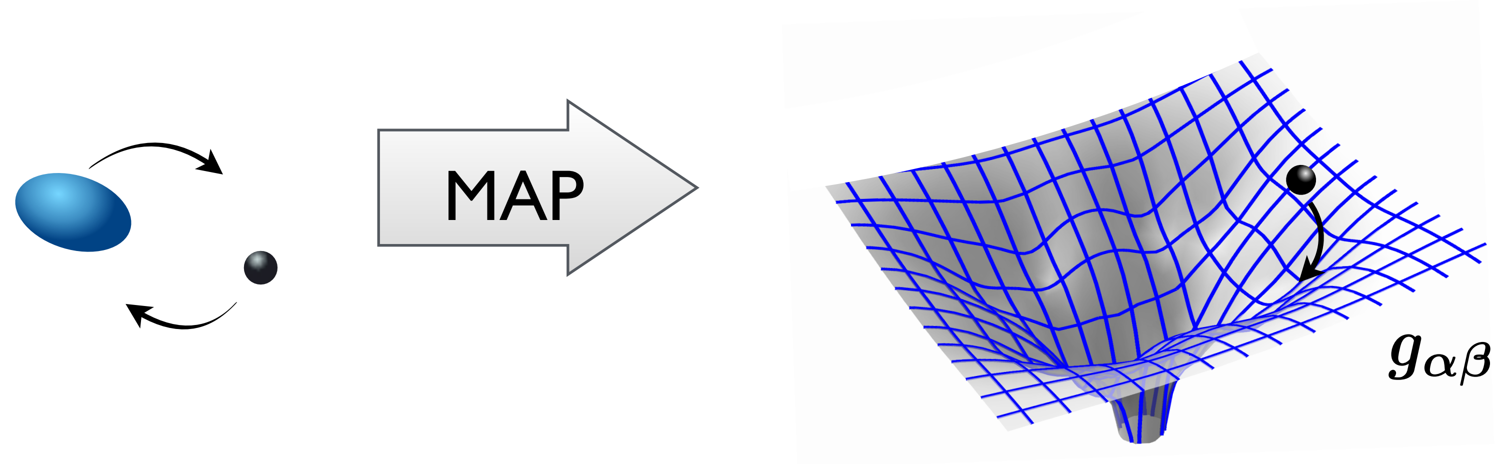
($\boldsymbol{M}$, $S_{\rm total}$, $\boldsymbol{\nu}=\boldsymbol{\mu}/M$)

$$g_{\alpha\beta} \sim g^{\rm Kerr}_{\alpha\beta} + \nu\, \delta g_{\alpha\beta}$$

$$M = m_1 + m_2 \qquad \mu = m_1 m_2 / M$$

EOB Hamiltonian + GW dissipation + wave generation + merger-ringdown

Adiabatic tidal effects in the EOB model



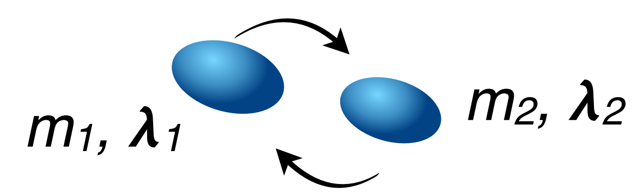
effective spacetime

$$g_{\alpha\beta} \sim g_{\alpha\beta}^{\mathrm{Kerr}} + \nu\, \delta g_{\alpha\beta} + \lambda\, \delta g_{\alpha\beta}^{\mathrm{Tidal}}$$

[Damour, Nagar, Bini, Faye, Bernuzzi+2009-2014]

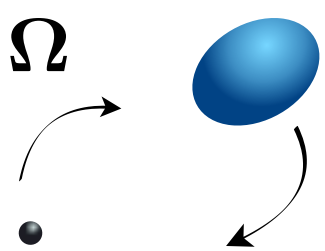
- for NS-NS: dominant tidal contribution in EOB Hamiltonian characterized by

$$\kappa_2^{\mathrm{T}} = 3\left(\frac{m_2}{m_1}\lambda_1 + \frac{m_1}{m_2}\lambda_2\right)$$

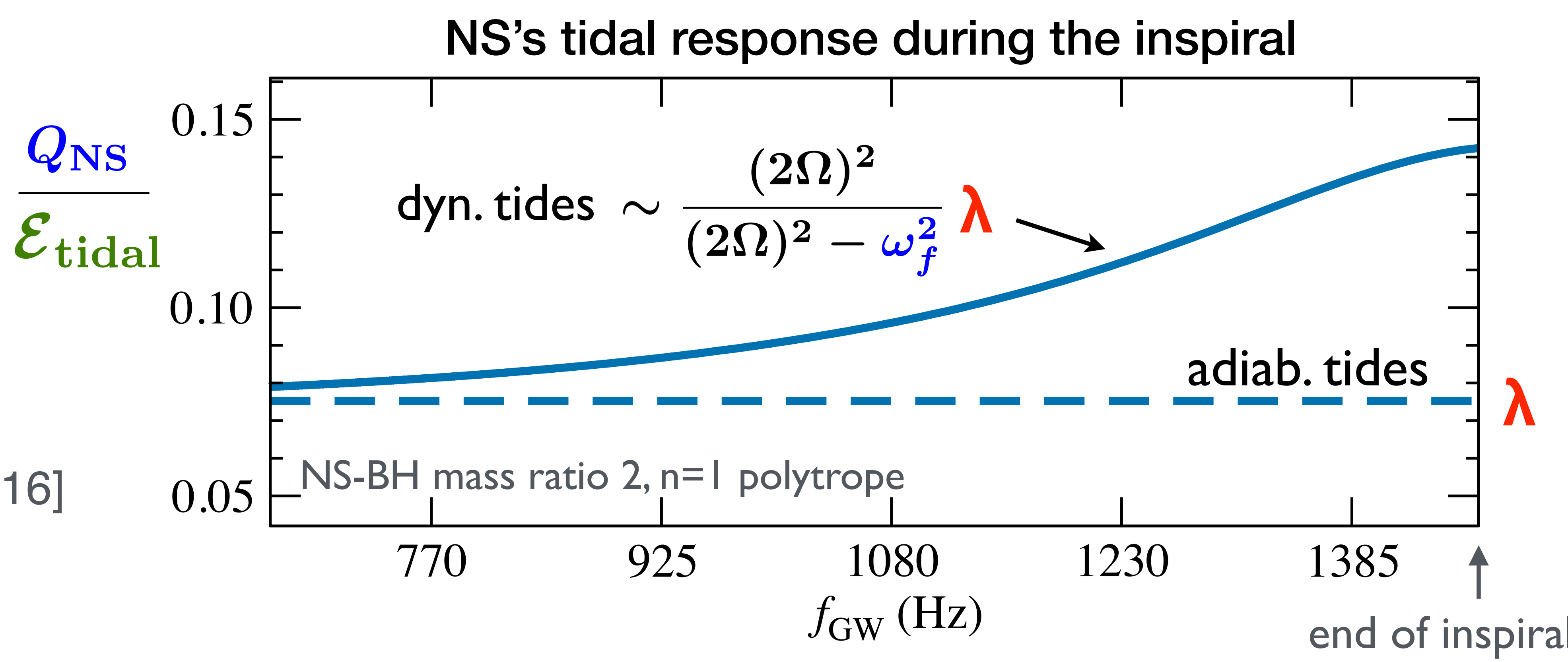


+ tidal correction to GW amplitude [Damour+2012]

Dynamic *f*-mode tides



- Q_{NS} corresponds (mainly) to the NS's *f*undamental oscillation modes
- *f*-mode frequency: $\omega_f \sim \sqrt{m_{\rm NS}/R^3}$ (internal structure - dependent)
- tidal forcing frequency: $\sim 2\Omega \sim 2\sqrt{M/r^3}$

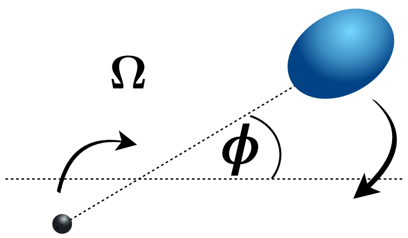


[Hinderer+16]

- separation-dependent tidal enhancement also found in affine approach

[Ferrari, Gualtieri, Maselli, Pannarale 11, 12]

Description of dynamic tides



- harmonic-oscillator-like Lagrangian:

f-mode frequency

$$L = L_{\rm orbit} + \sum_{\ell\geq 2}\sum_{m=-\ell}^{\ell}\left[-\frac{z}{2}\underbrace{Q_{\ell m}\mathcal{E}_{\ell m}e^{-im\phi}}_{\text{BH's tidal field (from Weyl tensor)}} + \frac{1}{4\lambda_\ell z^2\omega_{0\ell}^2}\left(\dot{Q}_{\ell m}^2 - z^2\omega_{0\ell}^2 Q_{\ell m}^2\right) + L_{\rm frame}\right]$$

redshift

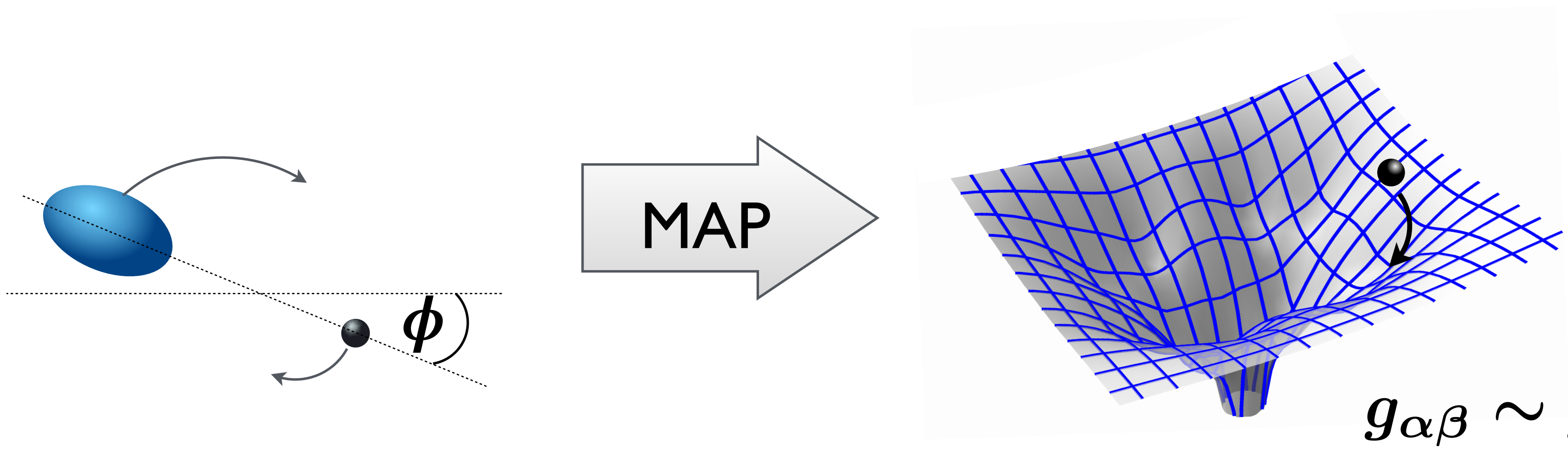
coupling of orbital and Q_{lm}'s angular momentum

- adiabatic limit:

$$L^{\rm AT} = L_{\rm orbit} + \sum_{\ell\geq 2}\sum_{m=-\ell}^{\ell}\frac{z}{4}\lambda_\ell\mathcal{E}_{\ell m}^2$$

tidal invariants computed from post-Newtonian or gravitational self-force

EOB with *approximate* dynamic tides



effective spacetime

$$g_{\alpha\beta} \sim g^{\mathrm{Kerr}}_{\alpha\beta} + \nu\, \delta g_{\alpha\beta} + \lambda^{\mathrm{eff}}\, \delta g^{\mathrm{Tidal}}_{\alpha\beta}$$

- effective tidal deformability encodes dynamical tides:

$$\frac{\lambda^{\mathrm{eff}}_{\ell}}{\lambda_{\ell}} \sim \frac{\omega_f^2}{\omega_f^2 - (m\Omega)^2} \ \& \ \frac{\omega_f^2}{(\phi - \phi_f)} \ \& \ \cos\left[(\phi - \phi_f)^2\right] \mathrm{FresnelS}(\phi - \phi_f)$$

before resonance

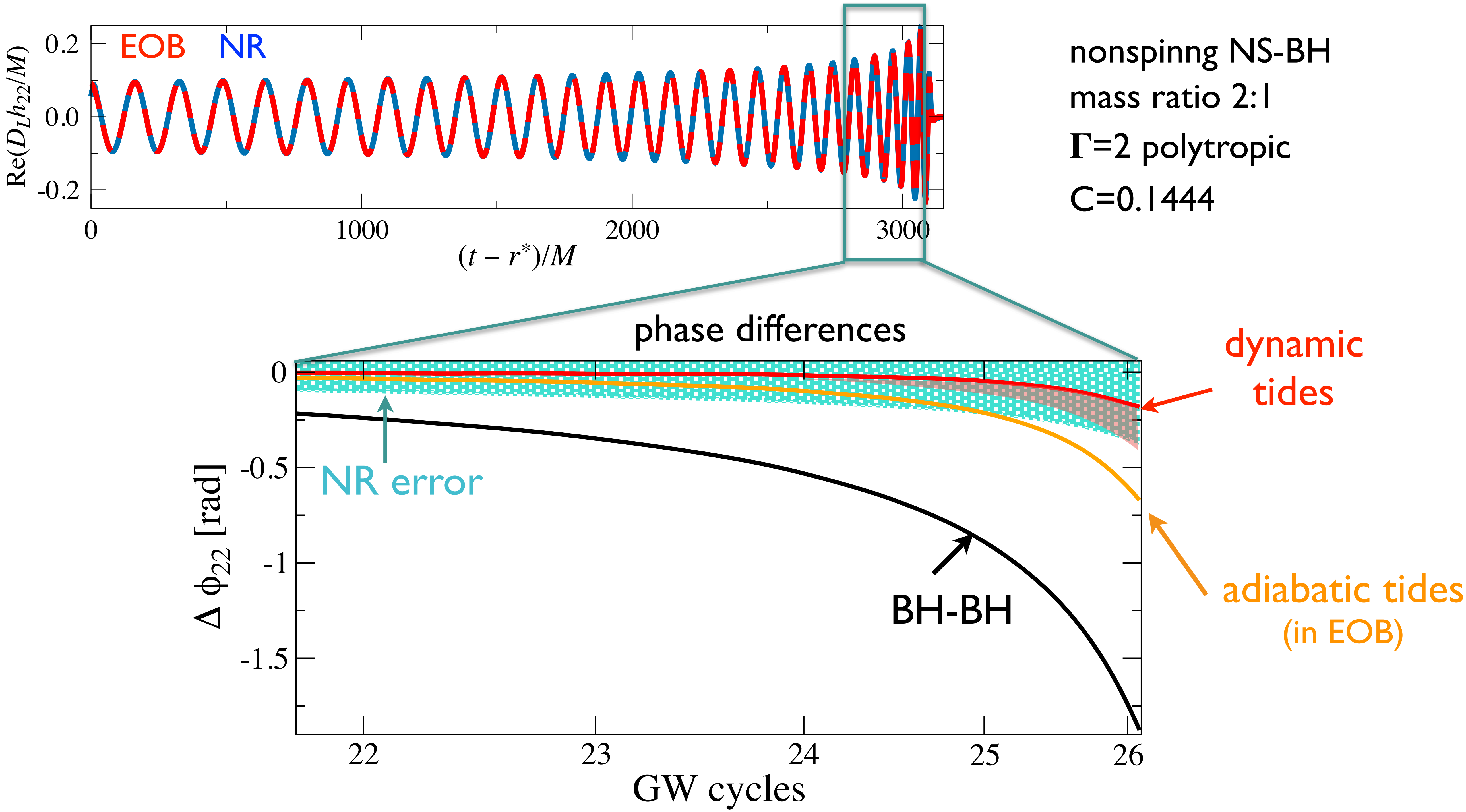
— common term

near resonance where $\phi \sim \phi_f$

all fns. of $\{M, \nu, \omega_f, r\}$

- analogous effective quantity for h_{lm} mode amplitudes

Comparison of EOB and NR for NS-BH

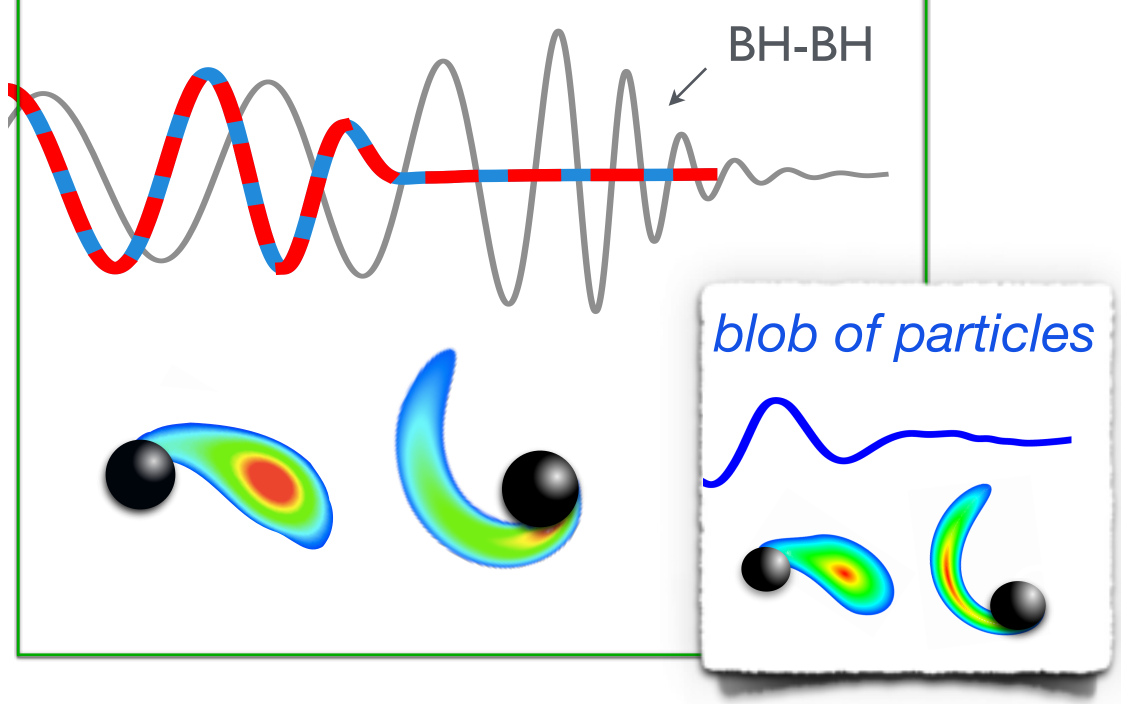


nonspinng NS-BH
mass ratio 2:1
Γ=2 polytropic
C=0.1444

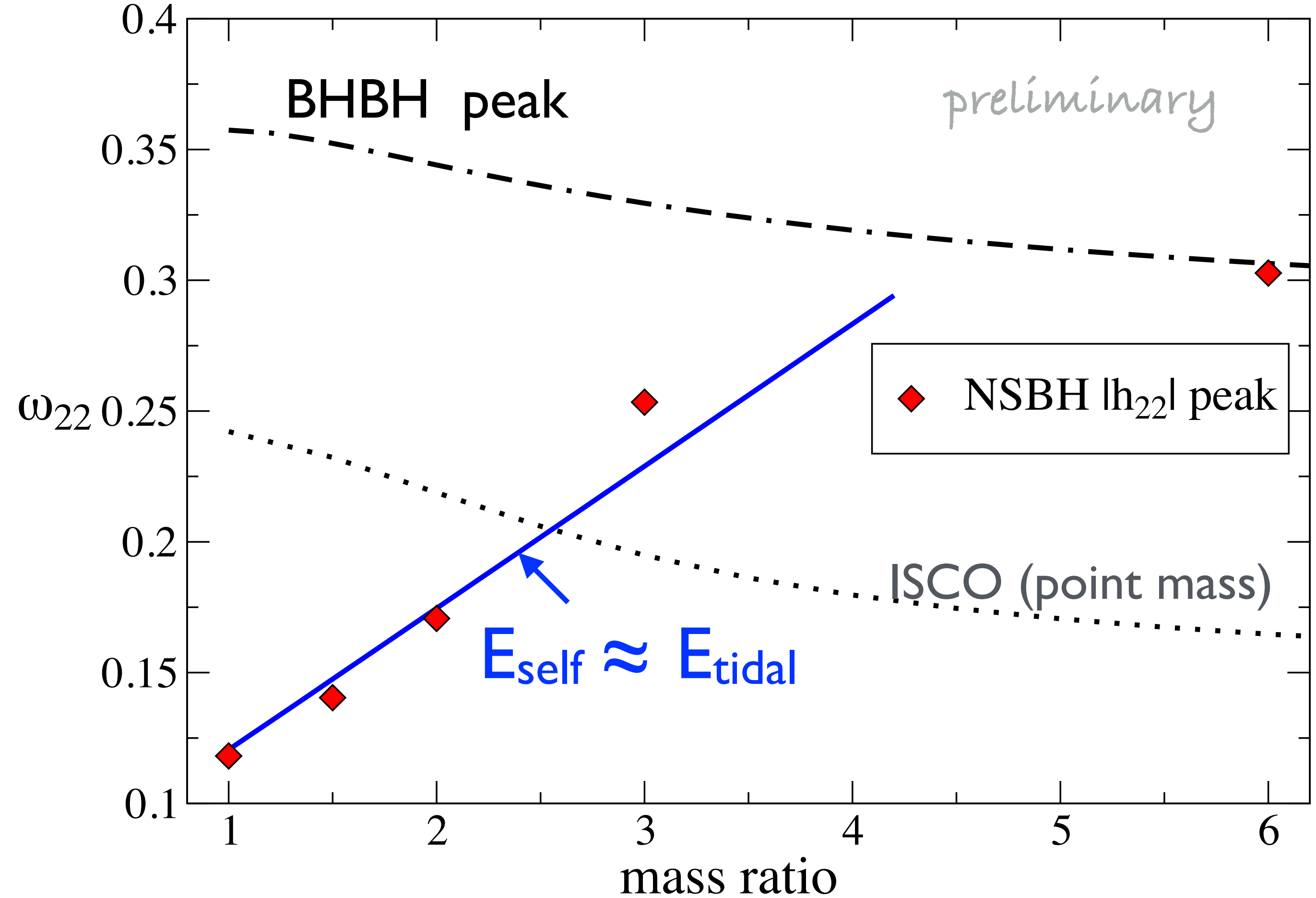
NR simulations by F. Foucart, SXS

Final fate of NS-BH binaries

Tidal disruption



simple prediction for disruption frequency

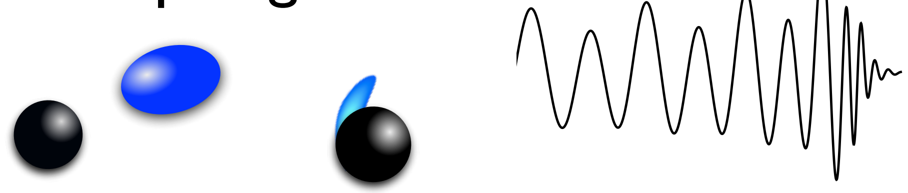


- GW shutoff frequency: depends also on Λ

$$\Lambda = \frac{\lambda}{m^5}$$

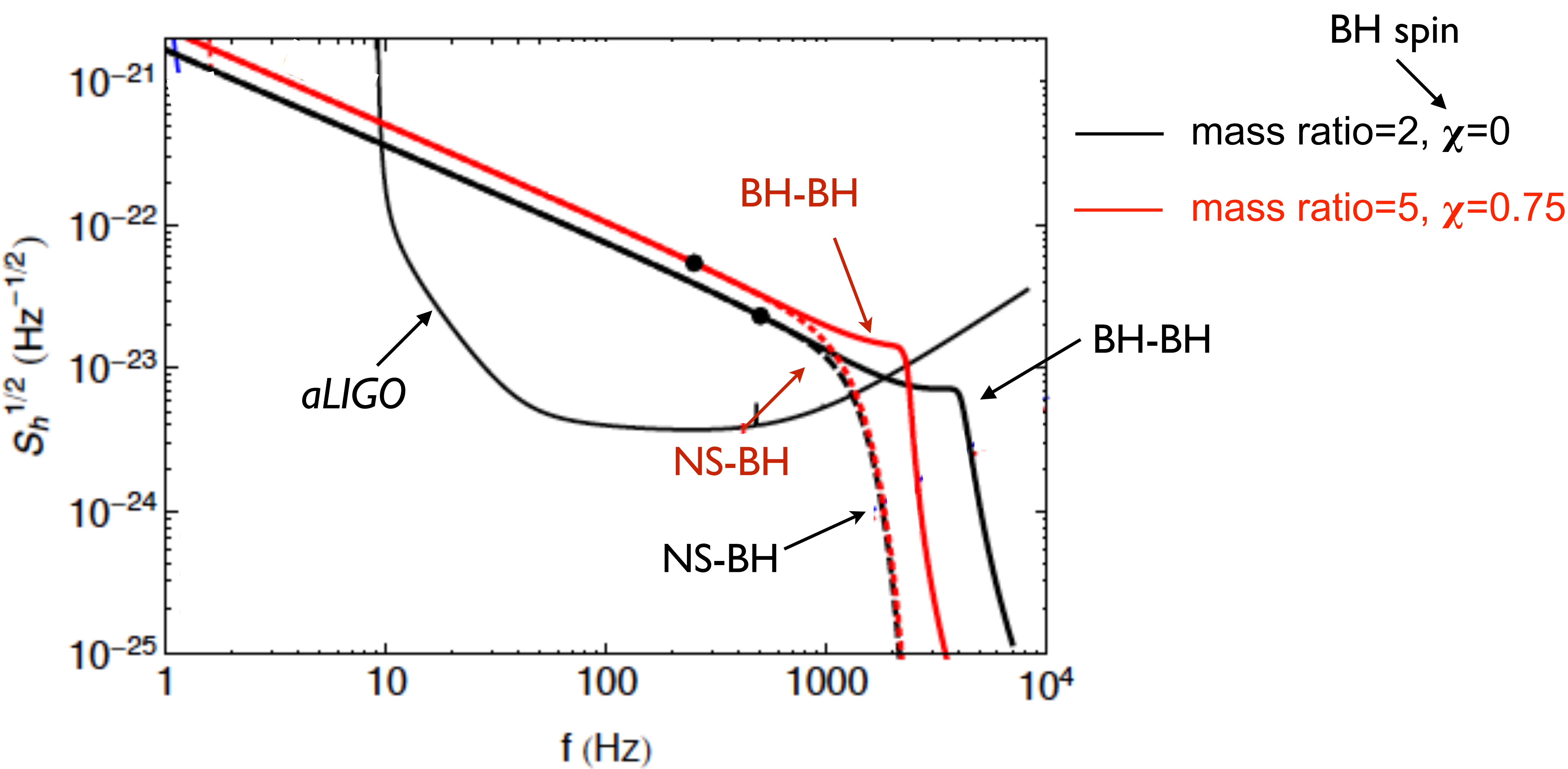
[Lackey+2013, Gualtieri+2014, Kyuotoku+2015]

plunge



- for large mass ratio, soft EoS, low BH spin

Frequency domain NS-BH signal

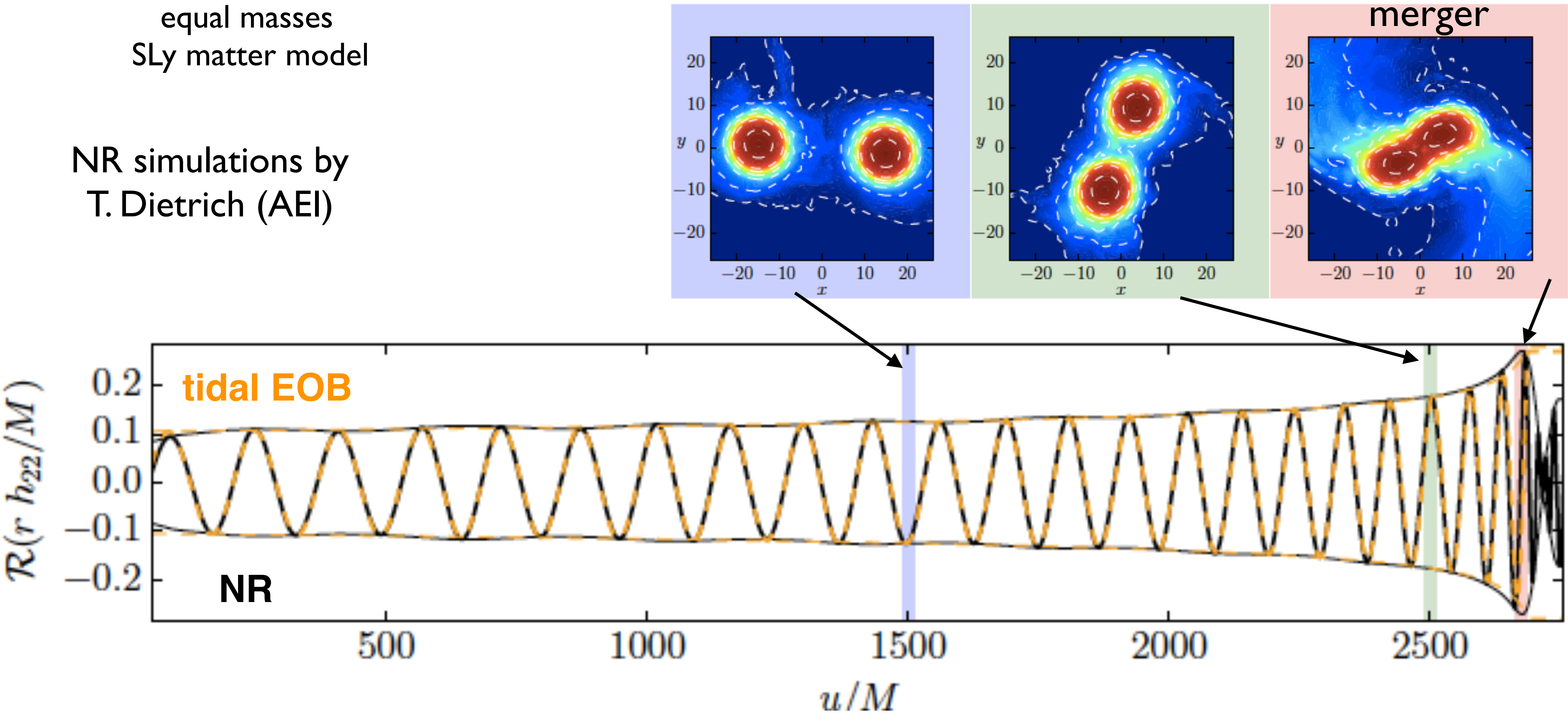


[Lackey+14]

NS-NS binary inspiral: soft EoS

equal masses
SLy matter model

NR simulations by
T. Dietrich (AEI)



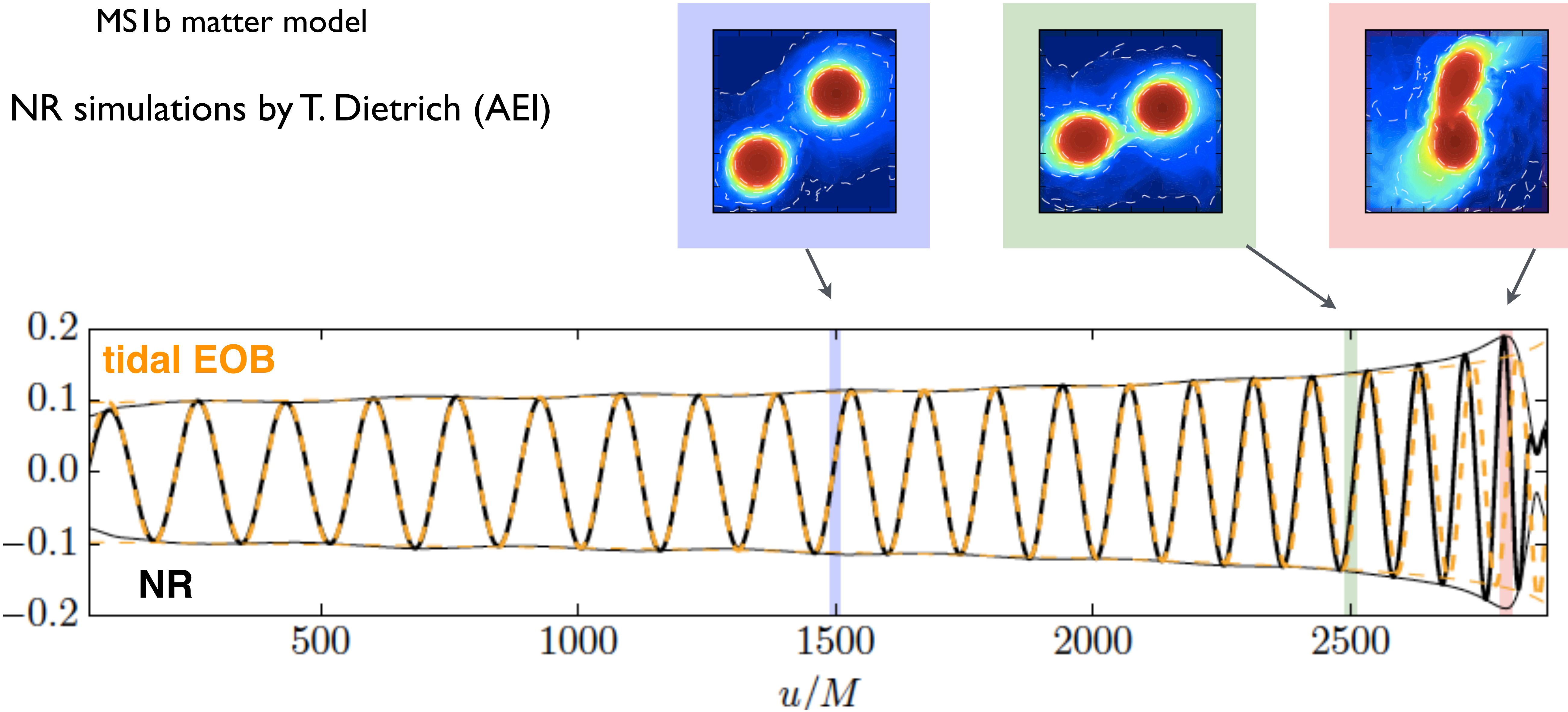
[Dietrich+17]

Comparison for NS-NS binary inspiral: stiff EoS

mass ratio 1.65:1.1
MS1b matter model

NR simulations by T. Dietrich (AEI)

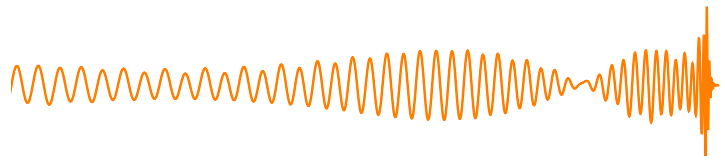
merger

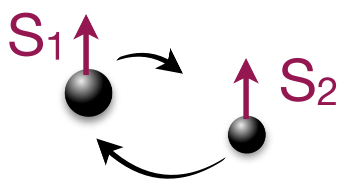


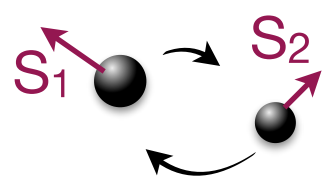
[Dietrich+ 17]

Physics included in current GW template models

spin effects (BHs)







most tests for mass ratio < 8

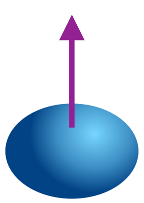
- EOB

  [Bohe+16, Nagar+17], [Babak+16]

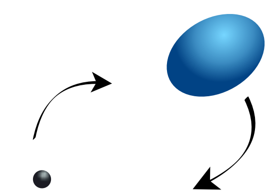
- PhenomX

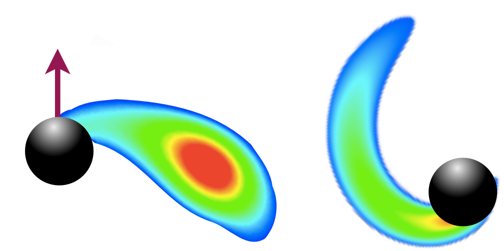
  [Ajith+ 08, Hannam+ 14, Khan+16]

matter effects



- tidally induced multipoles (ℓ=2,3,4) [post-Newtonian & EOB]
  - spin-induced deformation [post-Newtonian]
- dynamical f-mode tides [EOB]
- NSBH tidal disruption for moderate aligned BH spin [LEA+]
- tidal heating [Maselli+17]

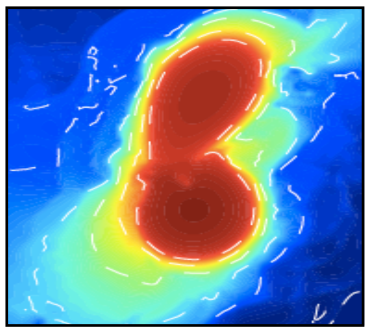




approx. universal relations used to reduce EoS parameters in surrogate GW templates to Λ_1, Λ_2

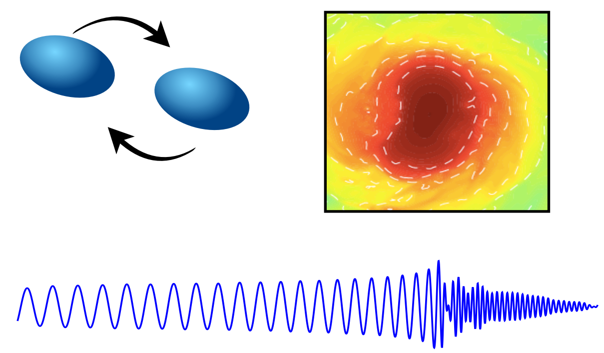
Remaining challenges

late inspiral

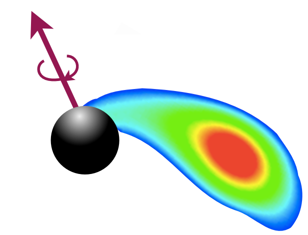


near disruption

complete model



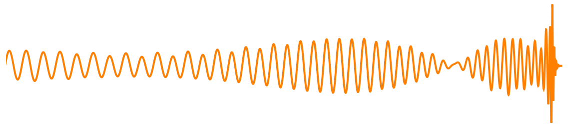
tidal disruption for arbitrary spins

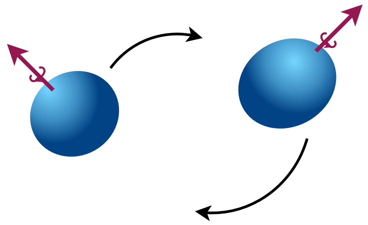


- continue to test, improve models — requires increasingly accurate NR simulations
- quantify systematic uncertainties
- optimize for data analysis
- choice of priors? best way to link constraints on Λ(m, EoS) to EoS?

Remaining challenges

spins: new phenomena





- spin-induced deformations [Poisson 1998]
- shifts of NS mode resonances [Ho & Lai 2000]
- new tidal interactions and Love numbers [Pani+ 2016, Landry 2017]
- gravitomagnetic effects: zero-frequency modes [Poisson, Landry 2015, 16]

tidally induced fluid velocity perturbation

$$\delta v \sim \frac{m_2}{M} R^2 \omega\, \Omega_{\rm orb}^{4/3}$$

NS spin frequency

- gravitomagnetic effects in general (expected to be small)

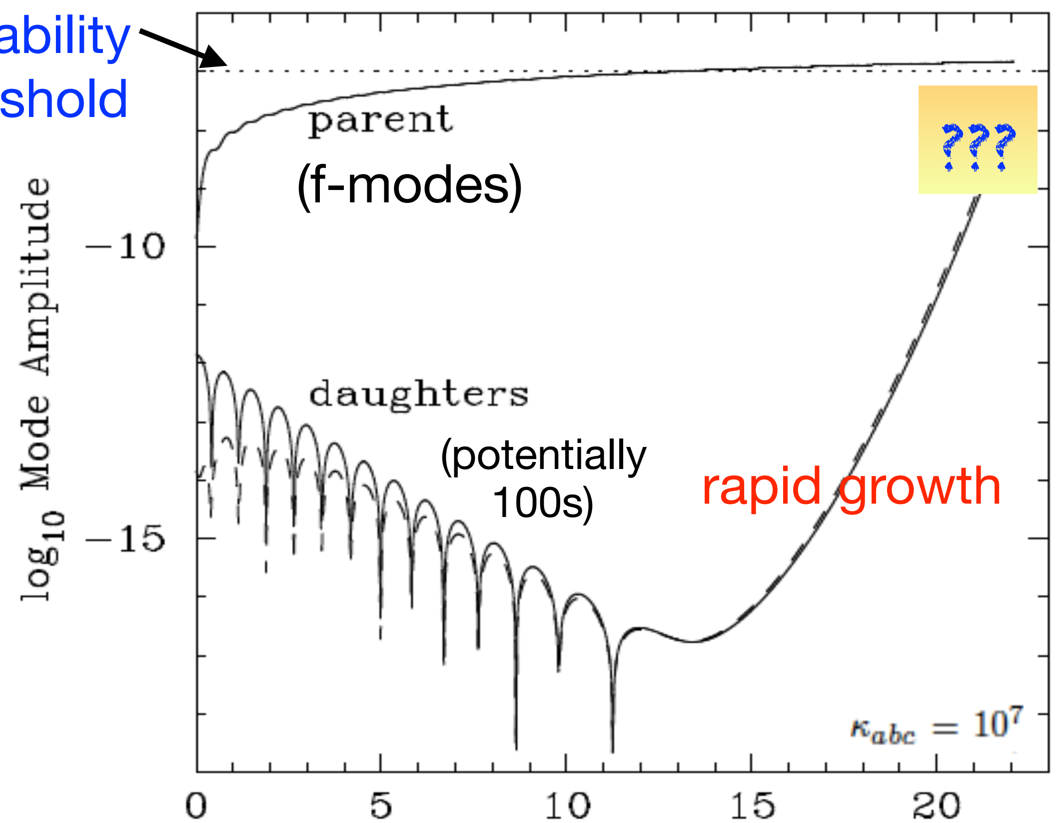
[different sign of Love numbers: Poisson, Landry 2014]

Remaining challenges

- quantify importance of nonlinear effects [Weinberg, Essick, Vitale+]

    3-mode coupling f, p, g modes

instability threshold



inspiral →

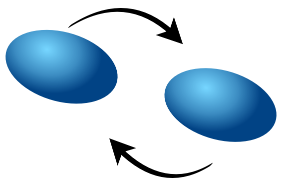
[Fig from Weinberg+13]

saturates at some point (nonlinear damping)

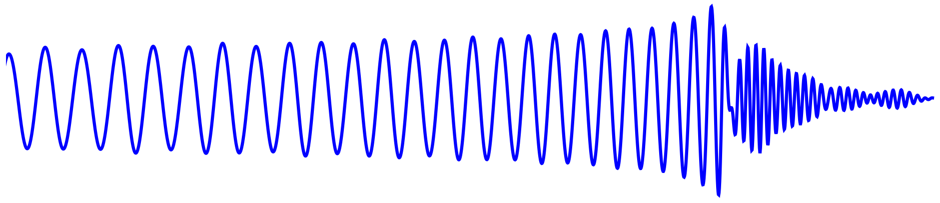
depending on saturation amplitude & frequency: imprint in GWs could be huge or negligible

- excitation of other oscillation modes for more realistic NSs during relativistic inspirals
- orbital eccentricity

Outlook



- GW detections of NS binaries expected in the coming years.
- Will yield a wealth of new insights into:
  - the properties of matter at extremes of density, astrophysics of NSs in binaries, the nature of gravity, and the central engines of powerful electromagnetic phenomena
  - most readily measurable information about NS matter: tidal parameters
- To take full advantage of this science potential requires increasingly accurate models
  - recent progress on including more realistic physics
  - tests against NR simulations
  - remaining work



- Further key goal: envision the science case for future instruments.