Matter effects on gravitational waves from binary inspirals

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YKIS conference

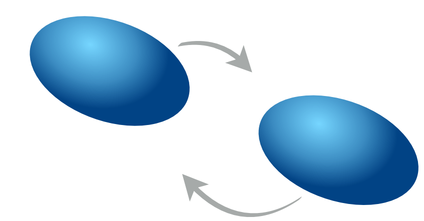
Oct 7, 2019

Outline of this talk

- Gravitational waves (GWs) now available for probing fundamental physics in unexplored regimes

- Interpretation of signals from binaries relies on theoretical models

- Dominant GW signatures of matter during an inspiral
    - Relatively clean regime
    - Small effects but cumulative
    - characteristic parameters



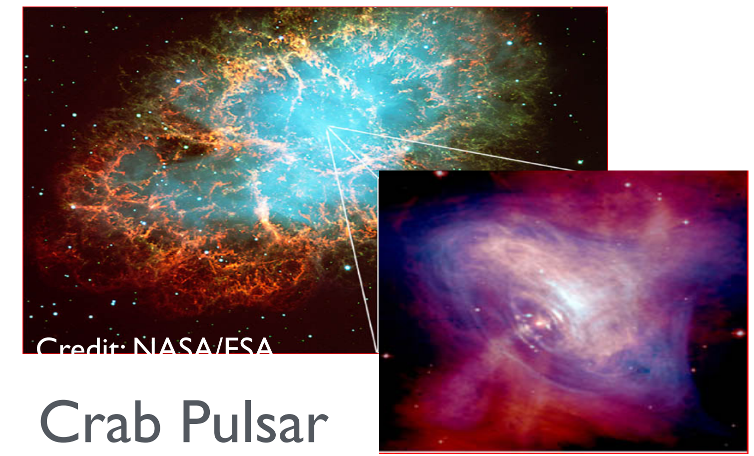
- Application to neutron stars

- Outlook

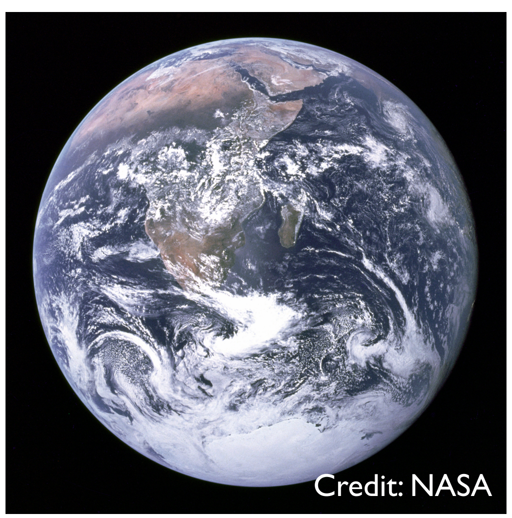
Neutron stars (NSs)

- densest stable material objects known in the universe
- 1939: theoretical description *[Oppenheimer & Volkoff]*
- thousands observed to date

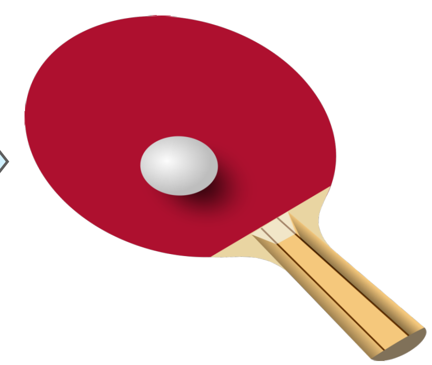
debris from a supernova explosion in 1054



Crab Pulsar
(NS rotating at 30 rev/sec)



crushed to NS compactness

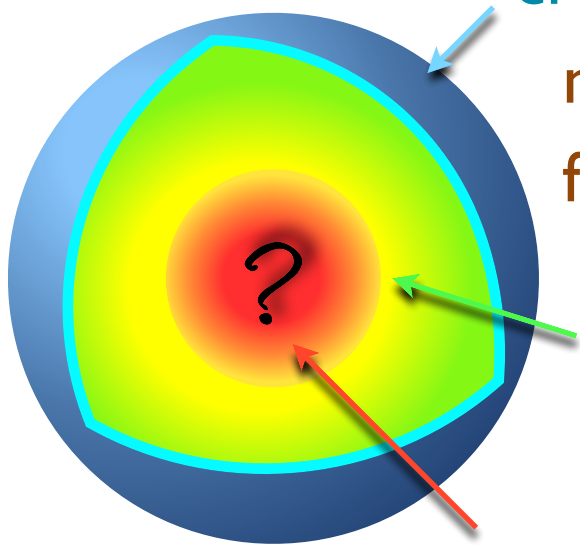


crushed

Black hole

What is the nature of matter in such extreme conditions?

Conjectured NS structure



crust ~ *km*

neutron rich ions,

free neutrons

outer core

uniform liquid

deep core

~2-10x nuclear density

exotic states of matter?

deconfined quarks?

signatures of BSM physics?

[iron ~ **10** g/cm^3]

~10^6 g/cm^3 inverse ***β***-decay

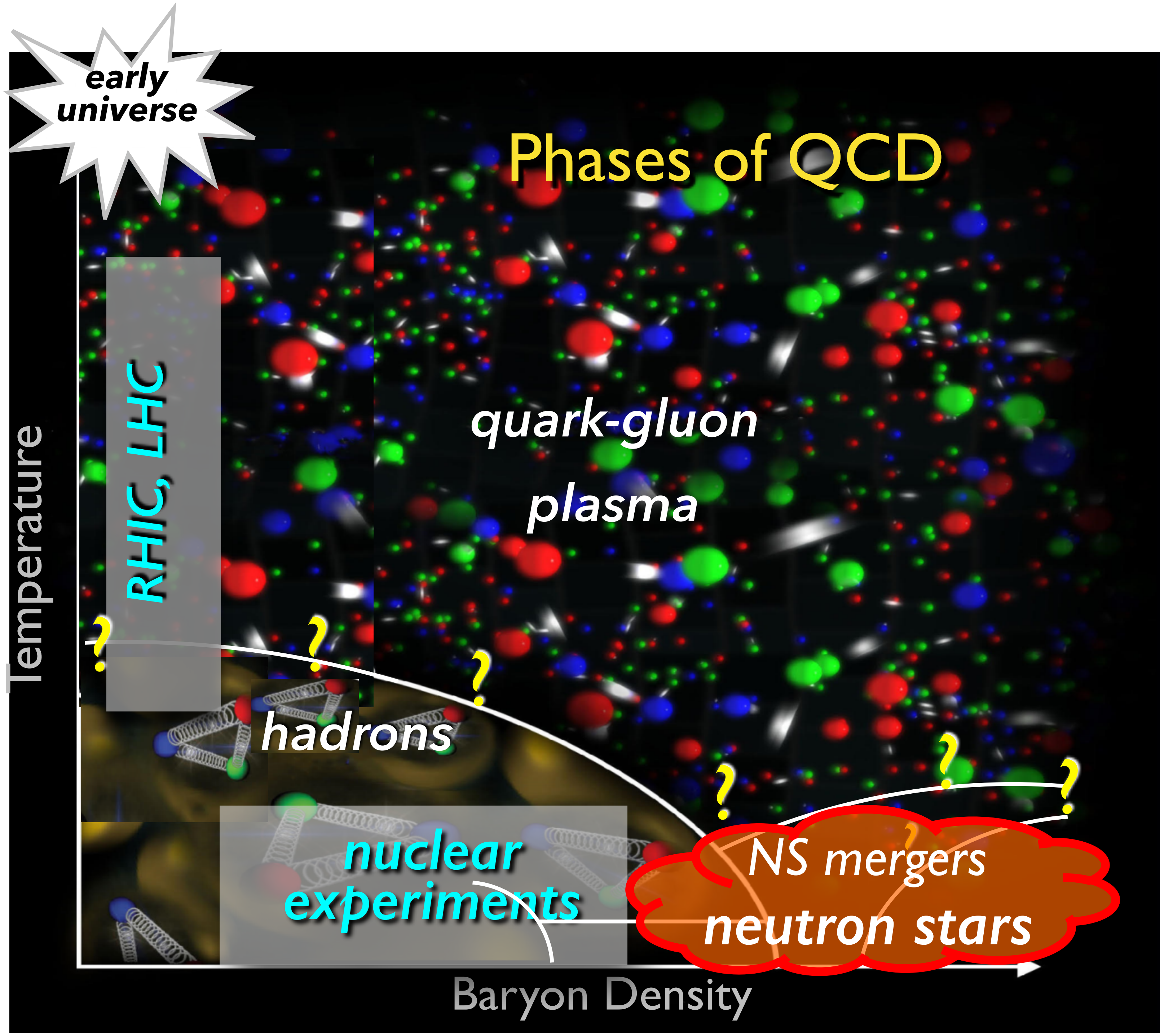
~10^{11} g/cm^3 neutron drip

~10^{15} g/cm^3

neutron wavefunctions overlap substantially - quark substructure expected to become important

- many theoretical difficulties
- far extrapolations from known physics

Key application: probing neutron star matter with GWs



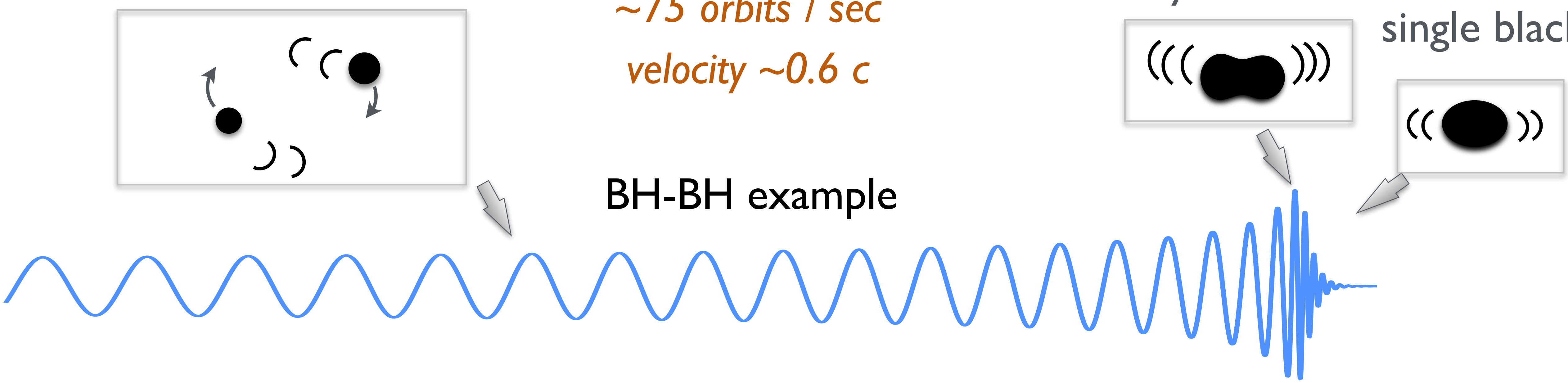
Credit: F. Linde

GW signals from binary systems

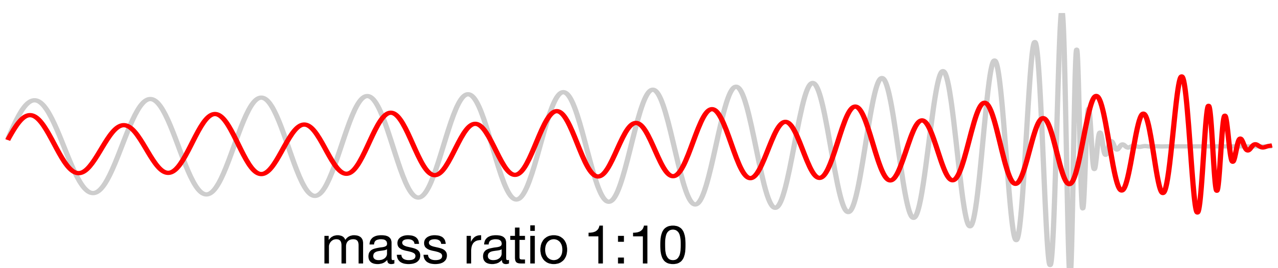
Inspiral — the orbit shrinks …

Merger — … until they collide

Ringdown — … and form a single black hole

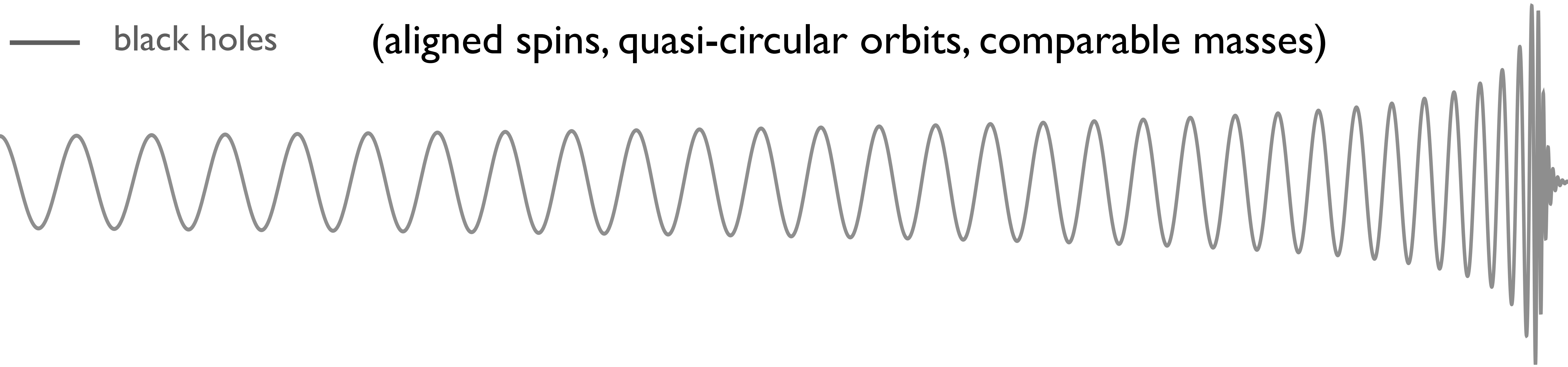


- Details of the waveform encode fundamental source properties



Interpretation of signals / measuring source physics requires accurate theoretical models (templates)

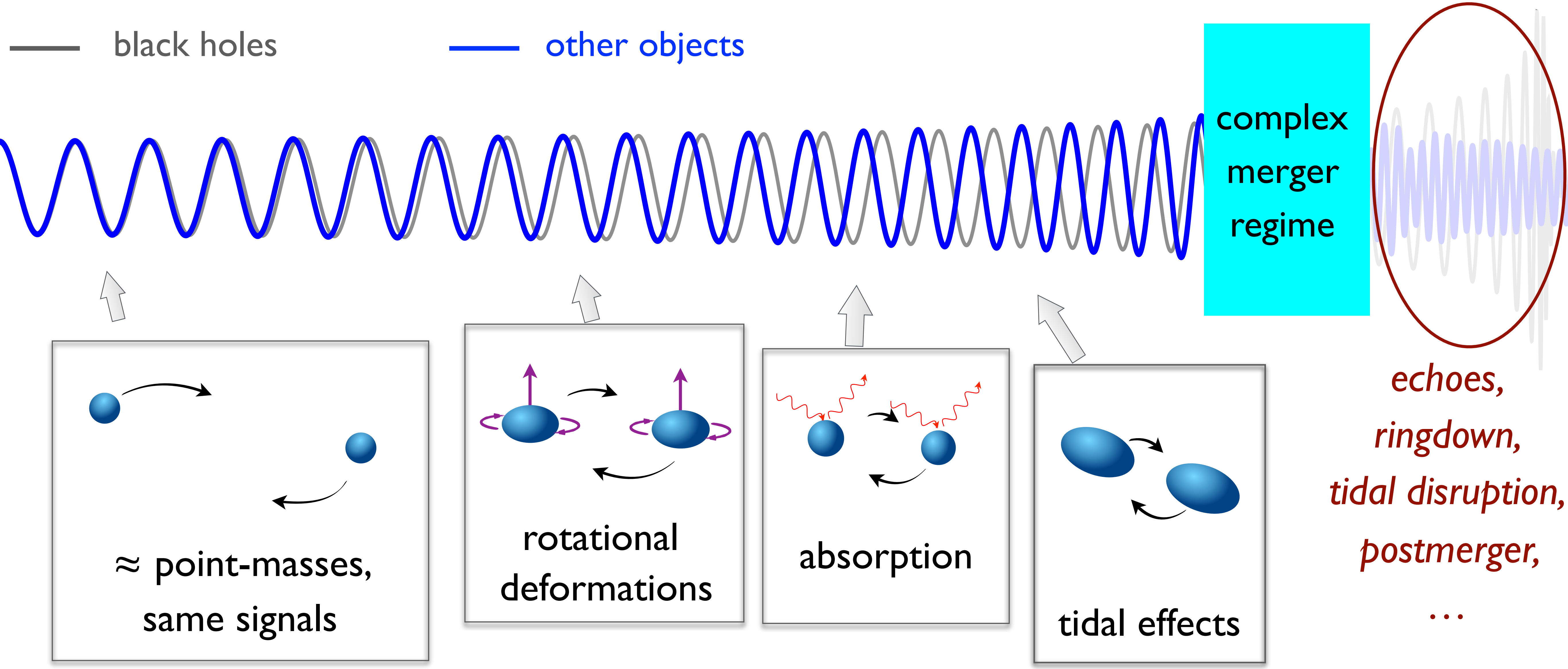
Matter effects on GWs



(aligned spins, quasi-circular orbits, comparable masses)

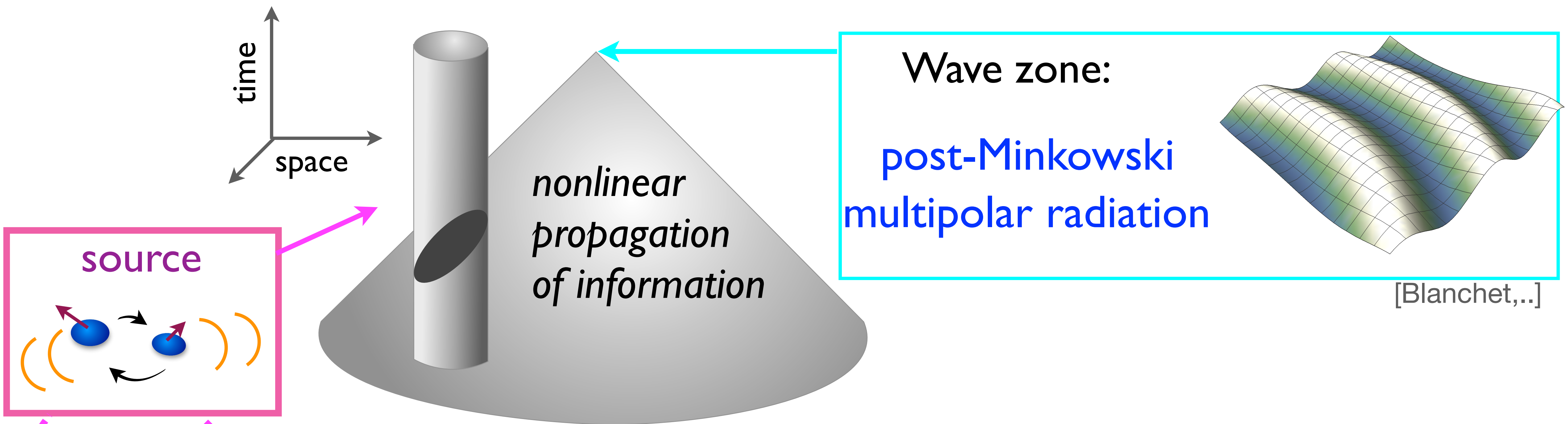
What changes for non-black hole objects (comparable masses)?

Matter effects on GWs



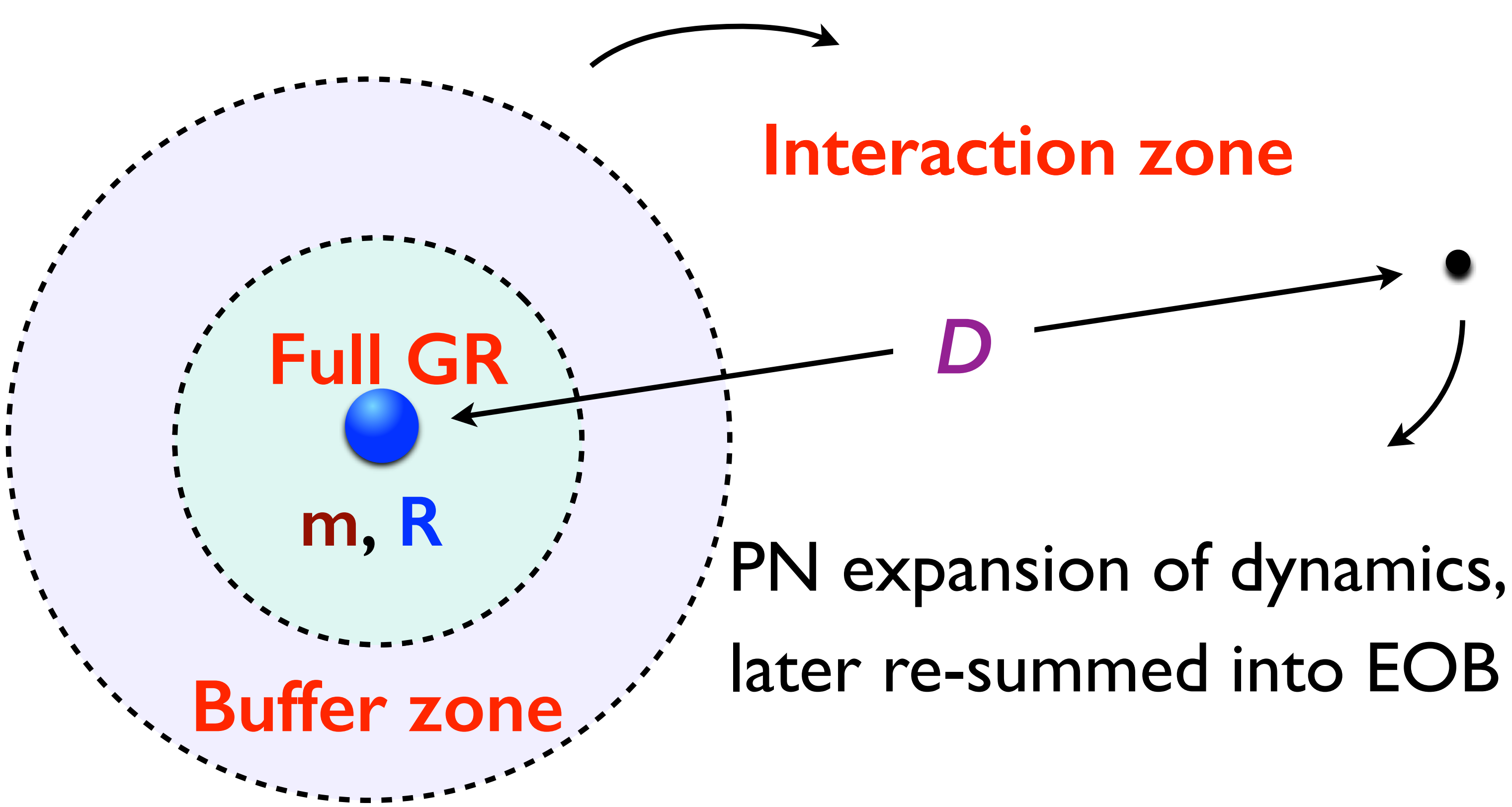
+ tidal excitation of oscillation modes

What specifically influences the GWs?



[Blanchet,..]

[Flanagan 1998, Racine, …]



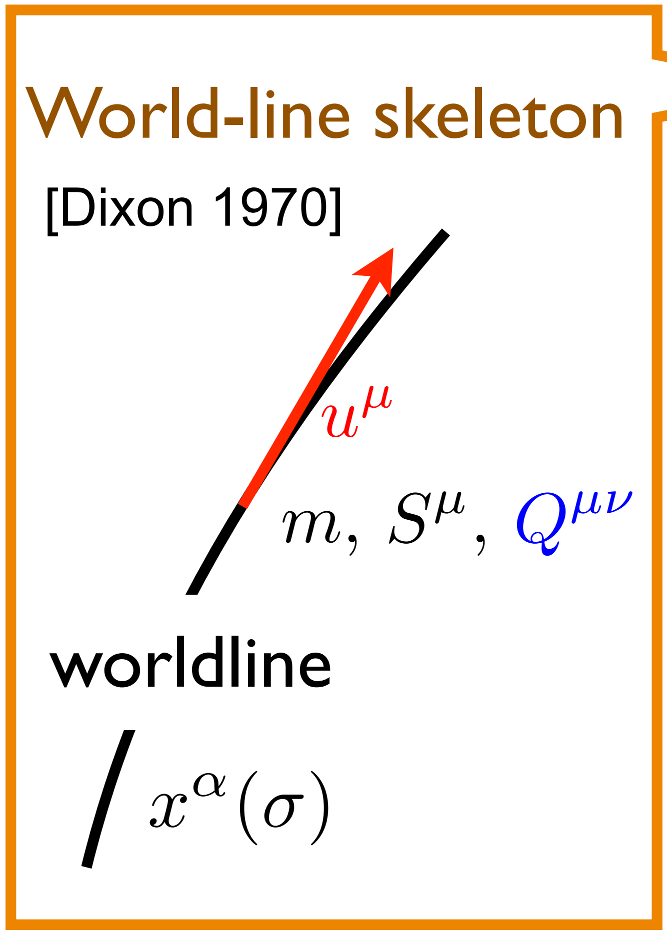
Dimensionless parameters:

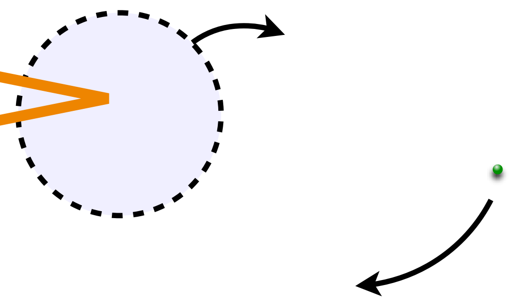
$$\delta = \frac{Gm}{Rc^2}$$ *NS's internal gravity* *(no approximation)*

$$\alpha = \frac{R}{D}$$ *Tidal expansion*

$$\epsilon = \frac{GM}{Dc^2}$$ *post-Newtonian expansion*

Interaction-zone dynamics





Buffer zone interior reduced to center-of-mass motion + multipoles

Dynamics described by an effective action:

$$S = S_{\rm pp} + \int d\sigma \left[-\frac{z}{2}\mathcal{E}_{\mu\nu} Q^{\mu\nu} + L_{\rm int} + \dots \right]$$

Point masses

Multipoles couple to companion's curvature

internal dynamics of $Q^{\mu\nu}$

$$z = \sqrt{-u_\mu u^\mu}$$

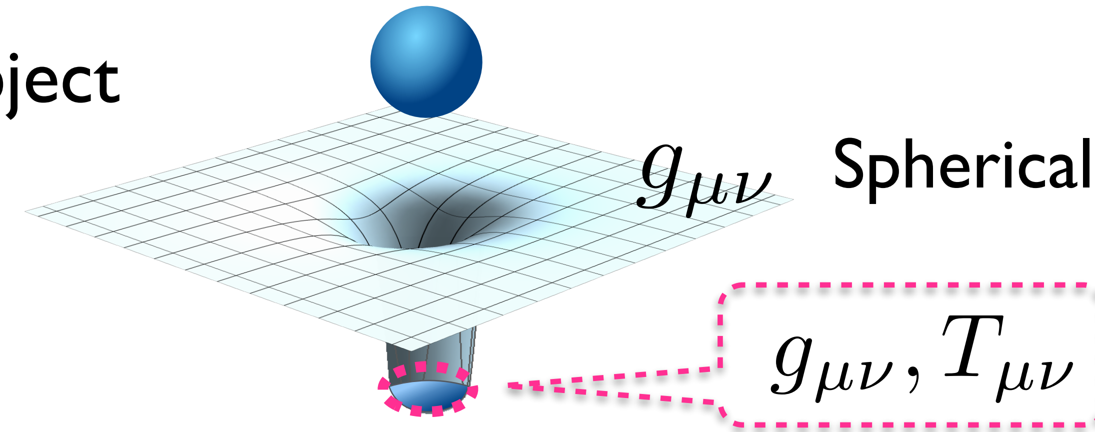
$$\mathcal{E}_{\mu\nu} = C_{\mu\alpha\nu\beta}\frac{u^\alpha u^\beta}{z^2}$$ *Weyl tensor (companion)*

Straightforward extension to higher multipoles

[Steinhoff, TH+ 2017; Pani, Vines, Landry, Poisson, Racine, +]

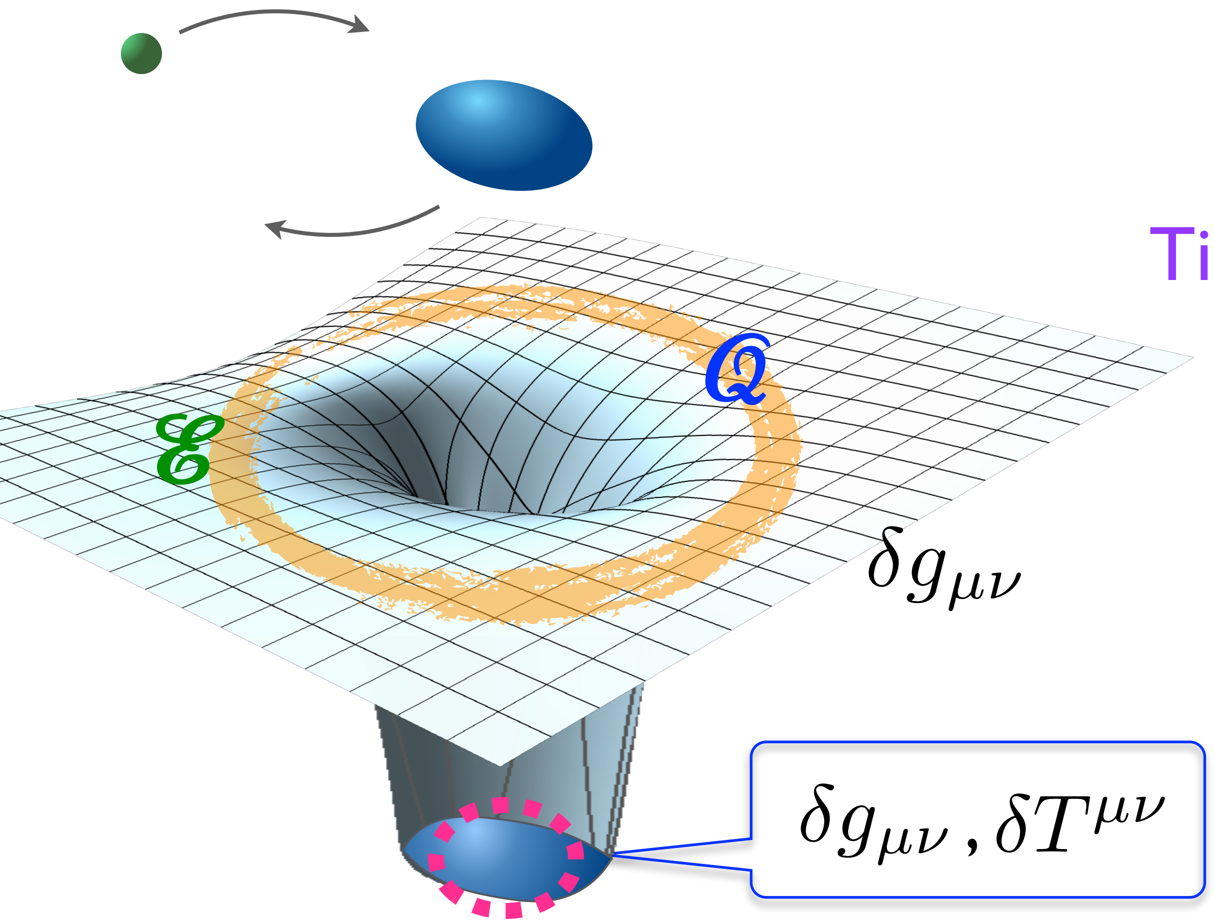
Body zone: example sources of multipole moments

- Isolated non-spinning compact object



Spherically symmetric

- **Tidal effects**



Tidally induced multipoles

- Adiabatic limit: $Q_{ij} = -\lambda \, \mathcal{E}_{ij}$

=0 for BHs in GR (in 4d)

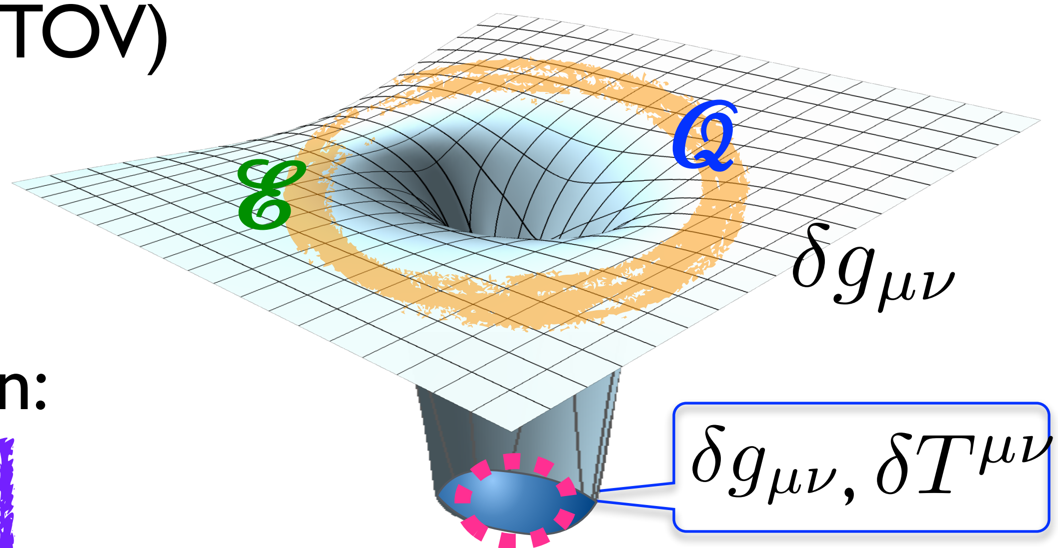
Characteristic tidal deformability parameter

[Flanagan, TH 2008, TH 2008, Damour,Nagar, Binnington, Poisson, Kol, Smolkin, Chakrabaty+,…]

Computation of tidal deformability (neutron stars)

- consider linear, static perturbations to equilibrium (TOV)

$$\delta g_{tt} \sim H(r) Y_{20}(\theta, \phi) e^{i0t}$$



- Linearized Einstein Eqs. + stress-energy conservation:

$$\boxed{H'' + a(r,\mathrm{TOV})\, H' + b(r,\mathrm{TOV})\, H = 0}$$

- **Interior** : numerical integration

practical computations: Need to solve this ODE, evaluate at the surface, substitute into

- **Exterior** : perturbed Schwarzschild with asymptotics:

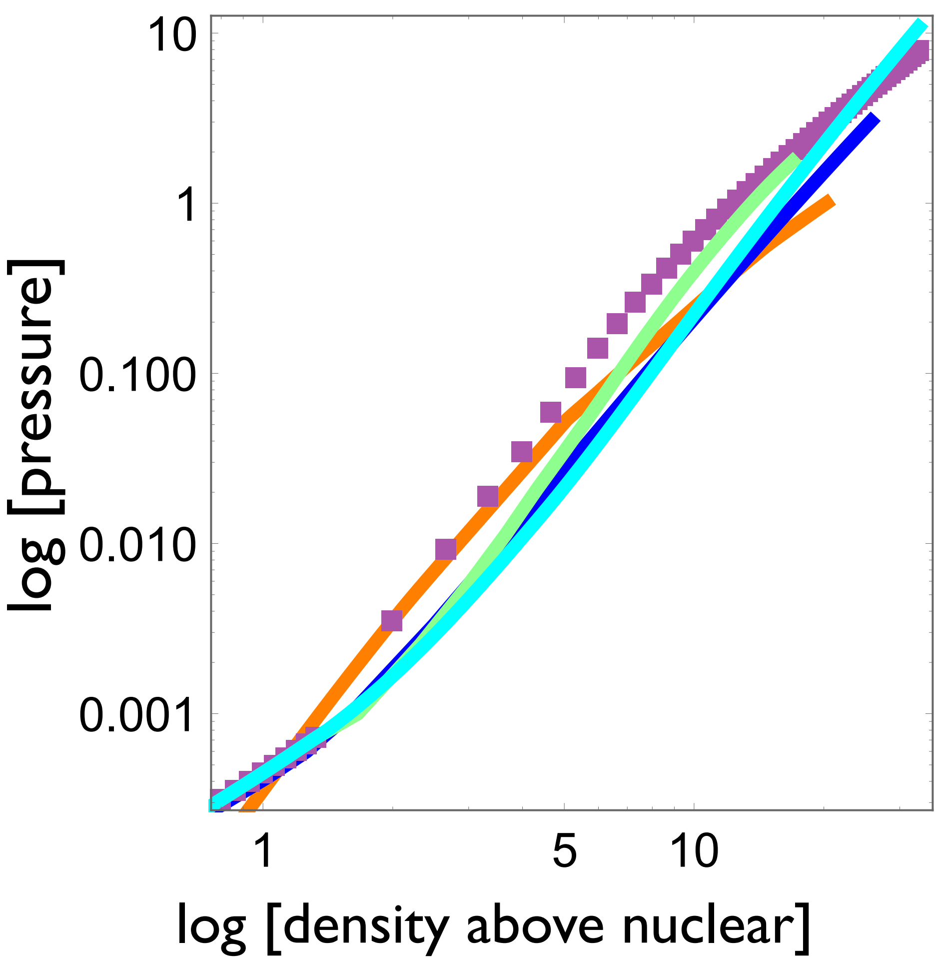
$$\frac{(1+g_{tt})}{2} = -\frac{\mathrm{M}}{r} + \frac{3\,\lambda\,\mathcal{E}\,Y_{20}(\theta,\phi)}{2\,r^3} + \ldots$$
$$+ \frac{1}{2}\mathcal{E}\, r^2 Y_{20}(\theta,\phi) + \ldots$$

- **Matching** interior & exterior solutions: explicit algebraic expression $\lambda(H, dH/dr)_{r=R}$

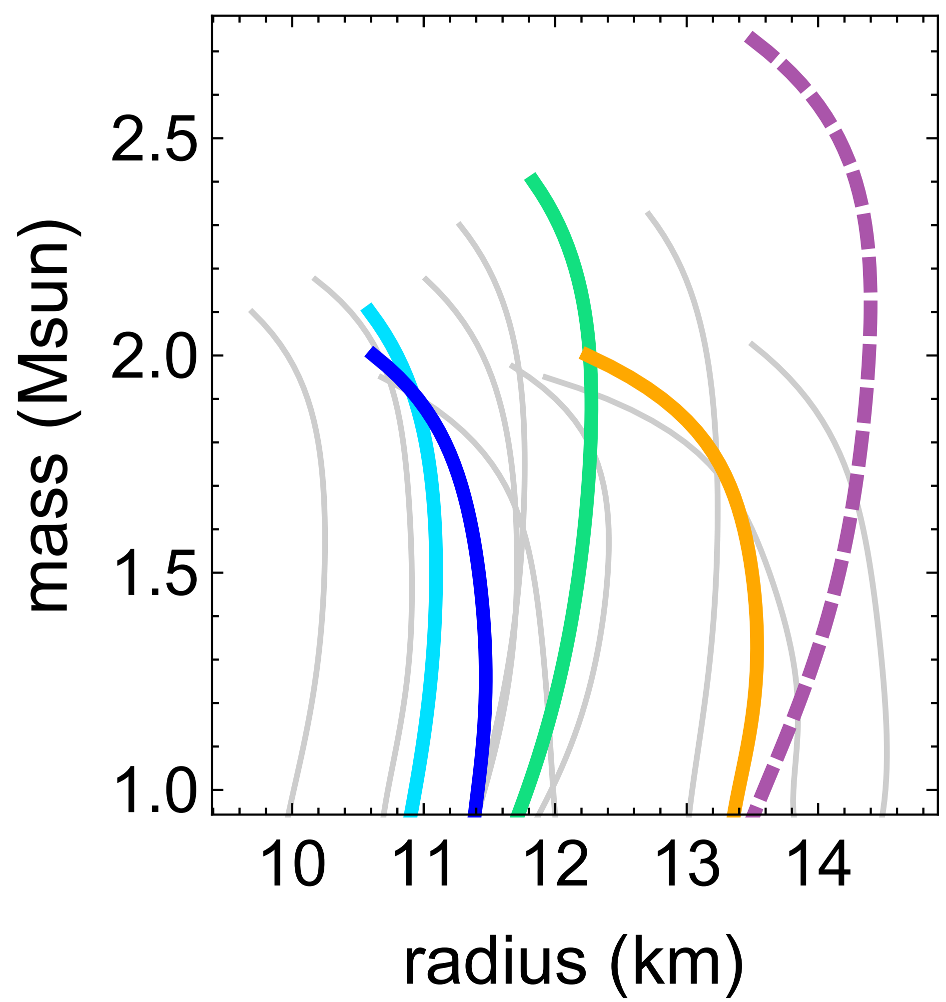
Properties of NS matter reflected in observables

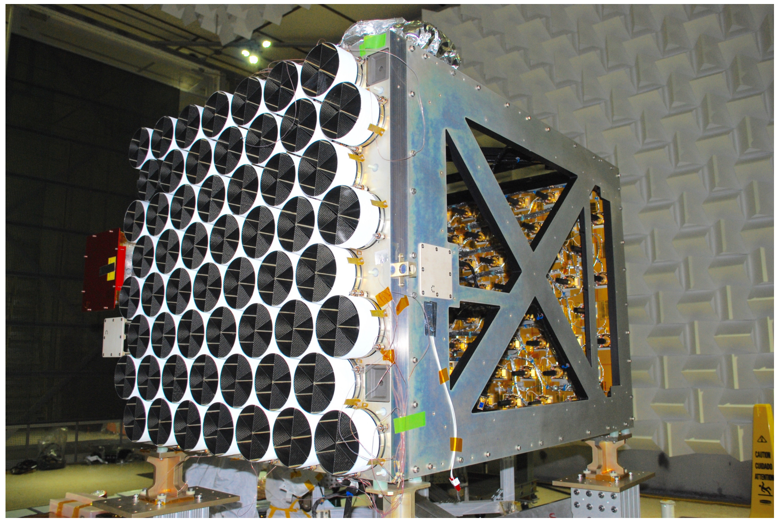
Equilibrium NS: radius

equation of state models



Mass vs. radius





NICER

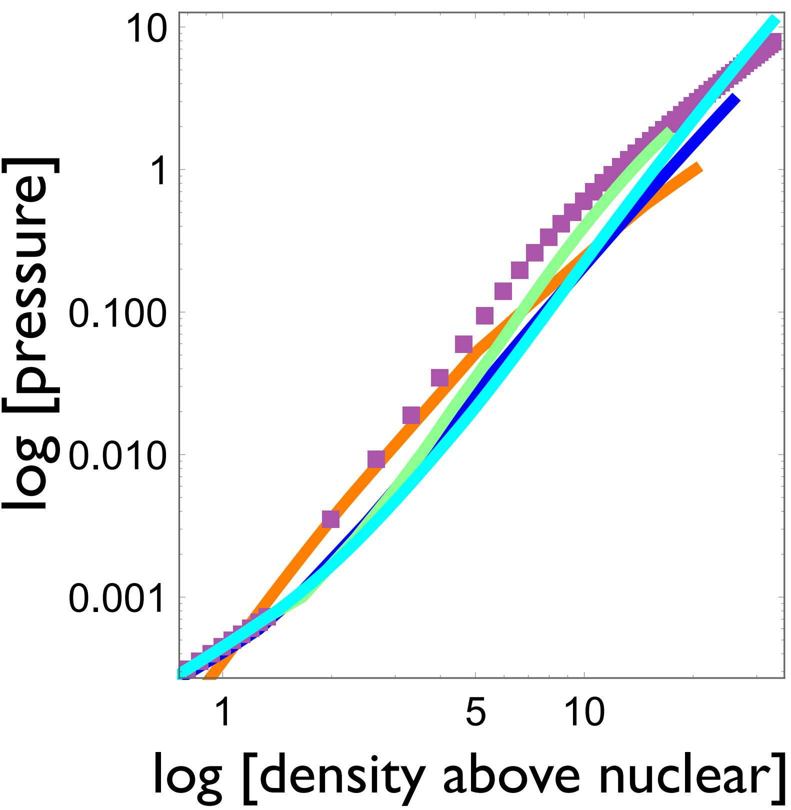
See poster by
Geert Raaijmakers

Properties of NS matter reflected in observables

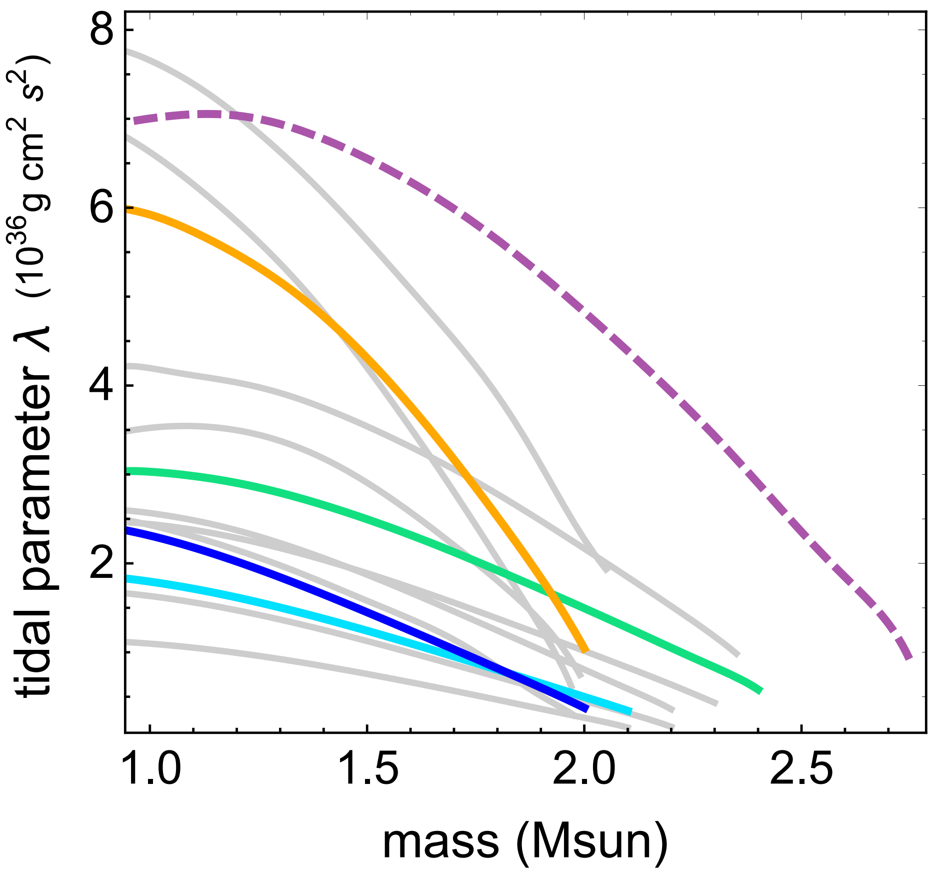
perturbed NS: tidal deformability

$$\Lambda = \frac{\lambda}{m_{\mathrm{NS}}^5}$$

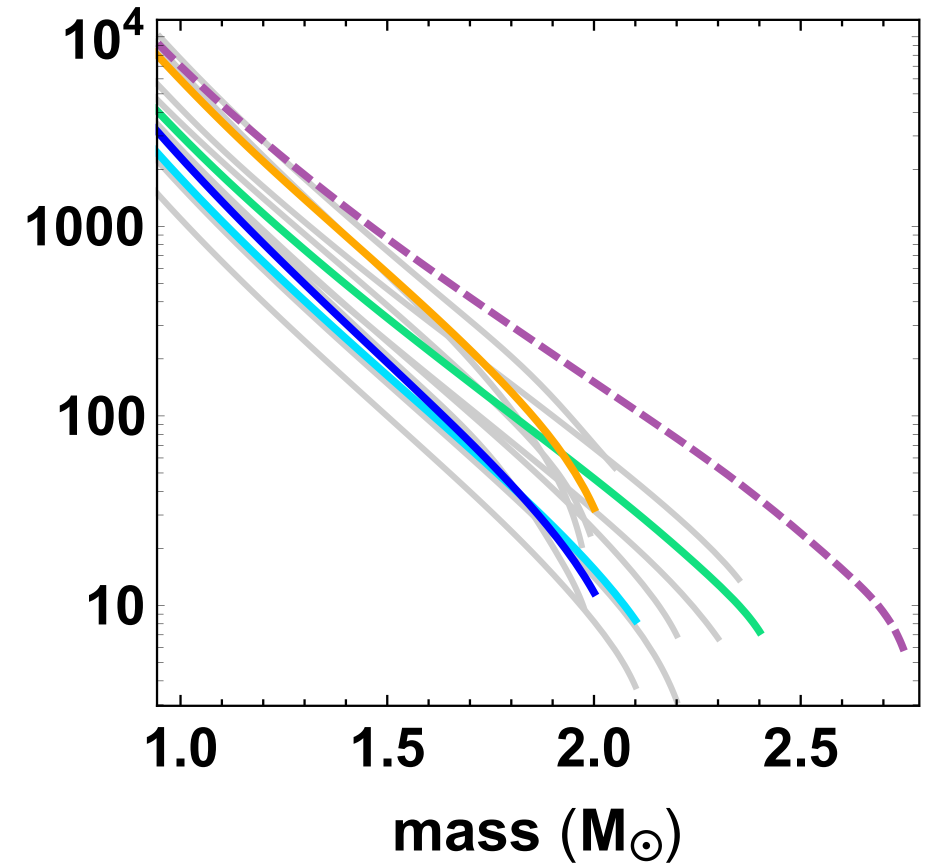
equation of state models



λ vs. mass



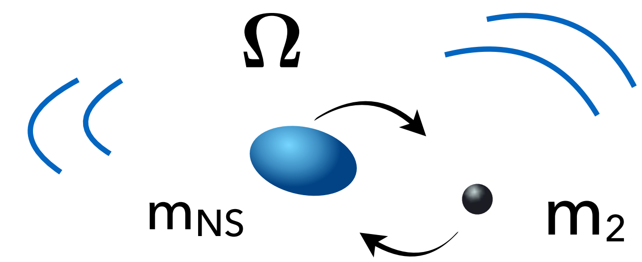
Λ vs. mass



[TH+ 2010]

Estimating the influence on GWs

- Energy goes into deforming the NS



$$E \sim E_{\mathrm{orbit}} + \frac{1}{4} \mathcal{Q}\, \mathcal{E}$$

$M = m_{NS} + m_2$

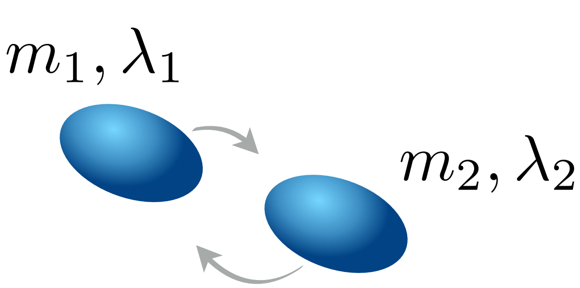
- moving multipoles contribute to gravitational radiation

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

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

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

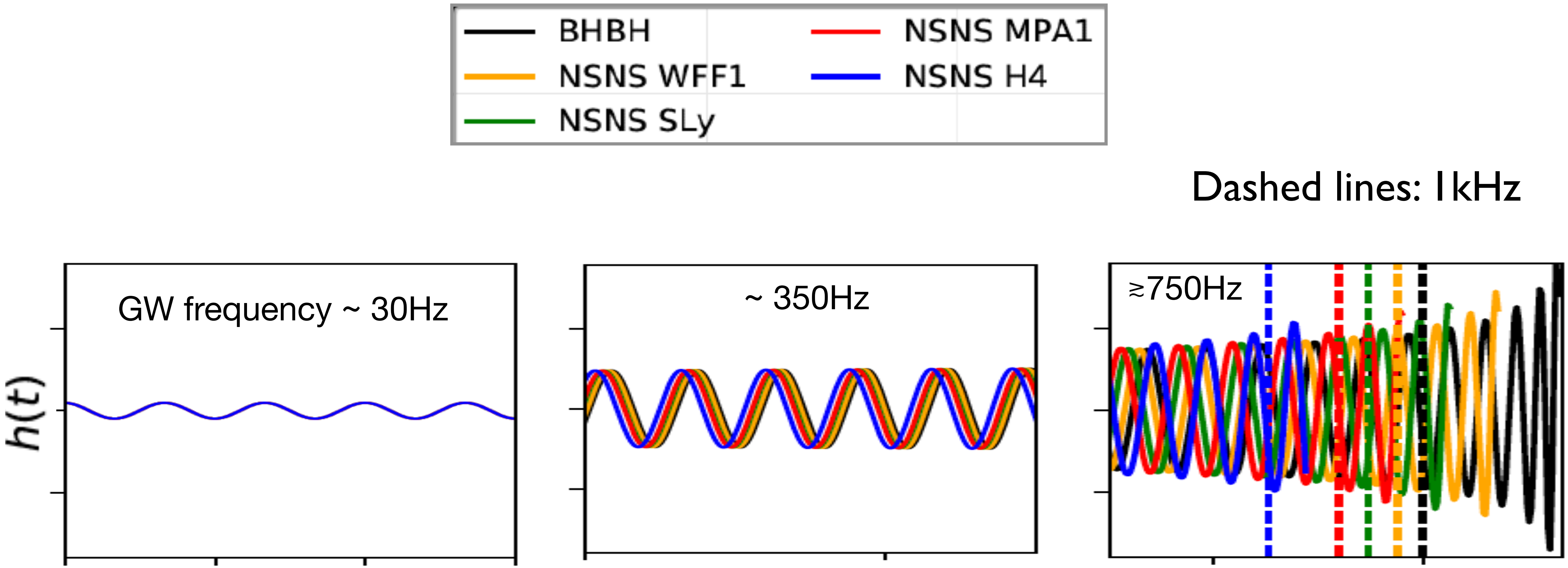
- for two NSs: most sensitive to:



$$\tilde{\Lambda} = \frac{13}{16\, M^5}\left[\left(1 + 12\frac{m_2}{m_1}\right)\lambda_1 + \left(1 + 12\frac{m_1}{m_2}\right)\lambda_2\right]$$

[Flanagan & TH, 2008, Vines+ 2011]

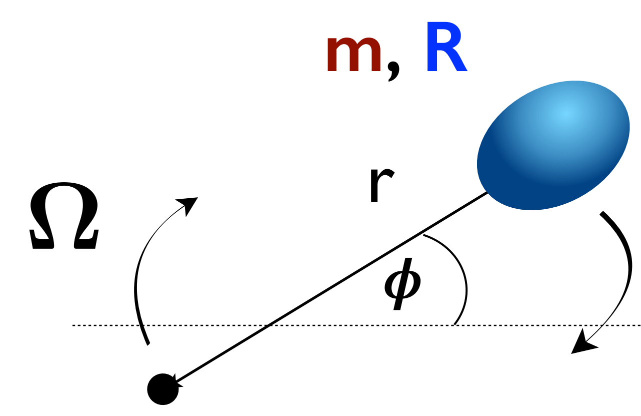
Example nonspinning inspirals starting from 30 Hz



[Guerra, TH 2019]

More realistic description of tidal response during inspiral

- $\mathcal{Q}$ is actually due to NS's quadrupolar (ℓ=2) oscillation modes



$$\mathcal{Q}_{ij} = \frac{2}{3}\sum_m \mathcal{Y}^{*2m}_{ij} \sum_n Q_{nm}$$

Converts to spherical harmonic decomposition

Overtone number

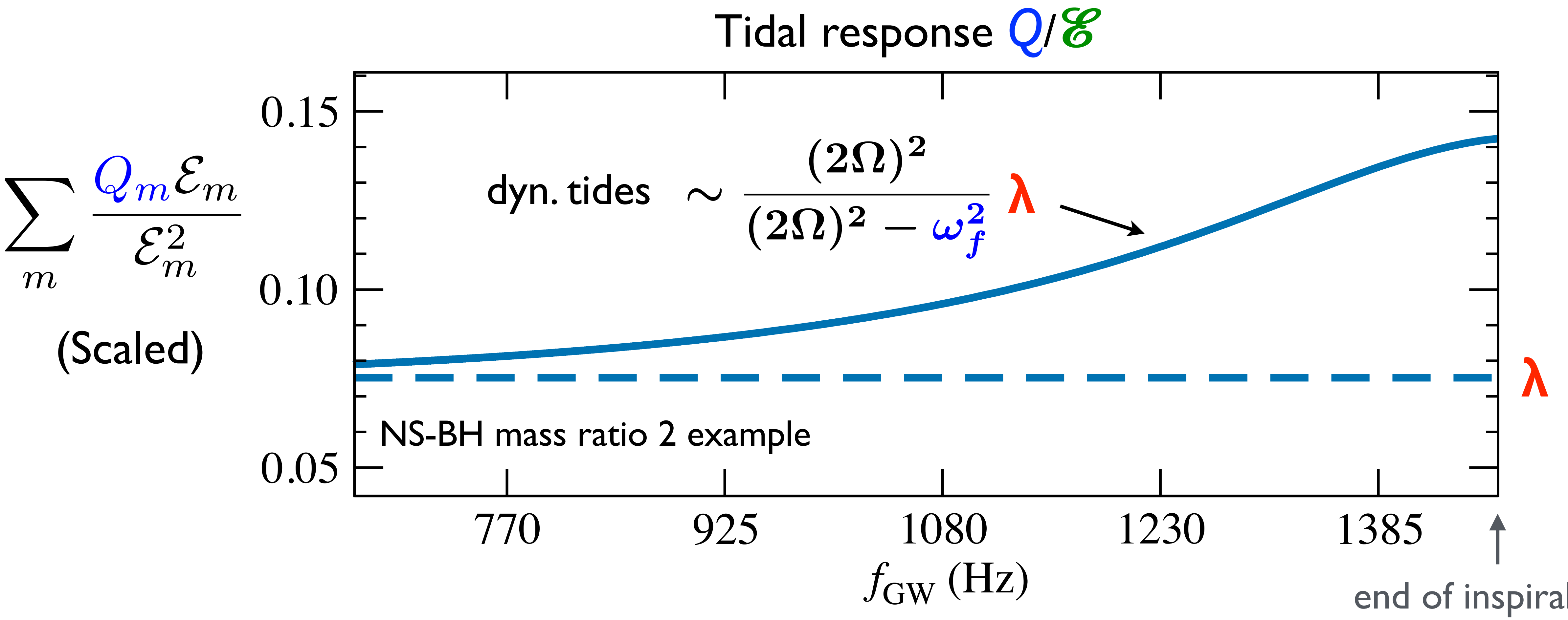
- Tidal couplings dominated (by ~order of magnitude) by fundamental f-mode (n=0)

[Kokkotas, Schaefer, Lai, Shibata]

- f-mode frequency: $\omega_f \sim \sqrt{m/R^3}$ (equation of state - dependent)
- tidal forcing frequency: $\sim 2\Omega \sim 2\sqrt{M/r^3}$
- adiabatic limit $2\Omega \ll \omega_f$: equilibrium solutions $Q_m = -\lambda\, \mathcal{E}_m e^{-im\phi}$

TH +(2016) , Steinhoff, TH+ (2016), Schmidt, TH (2019), Newtonian case: Lai, Kokkotas & Schaefer, Shibata, …

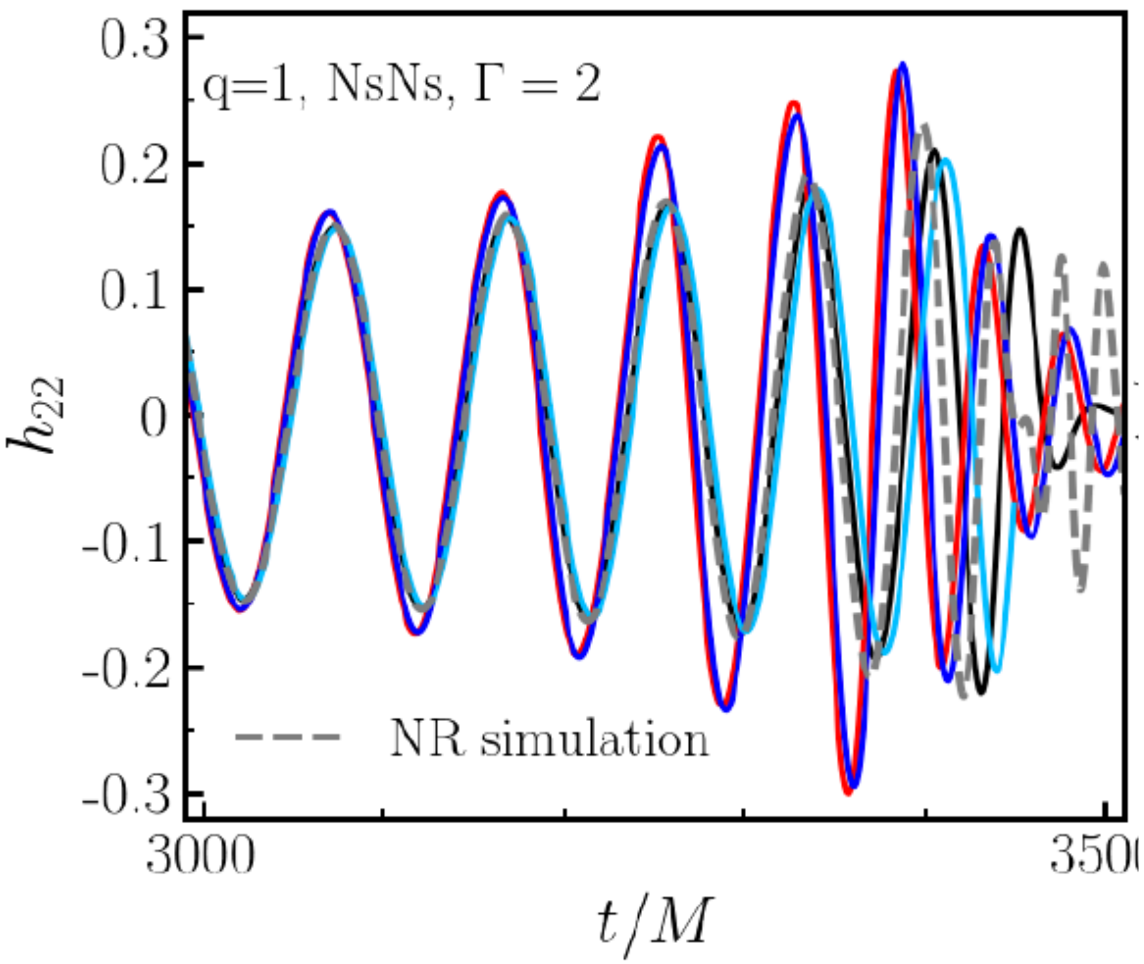
More realistic description of tidal response during an inspiral



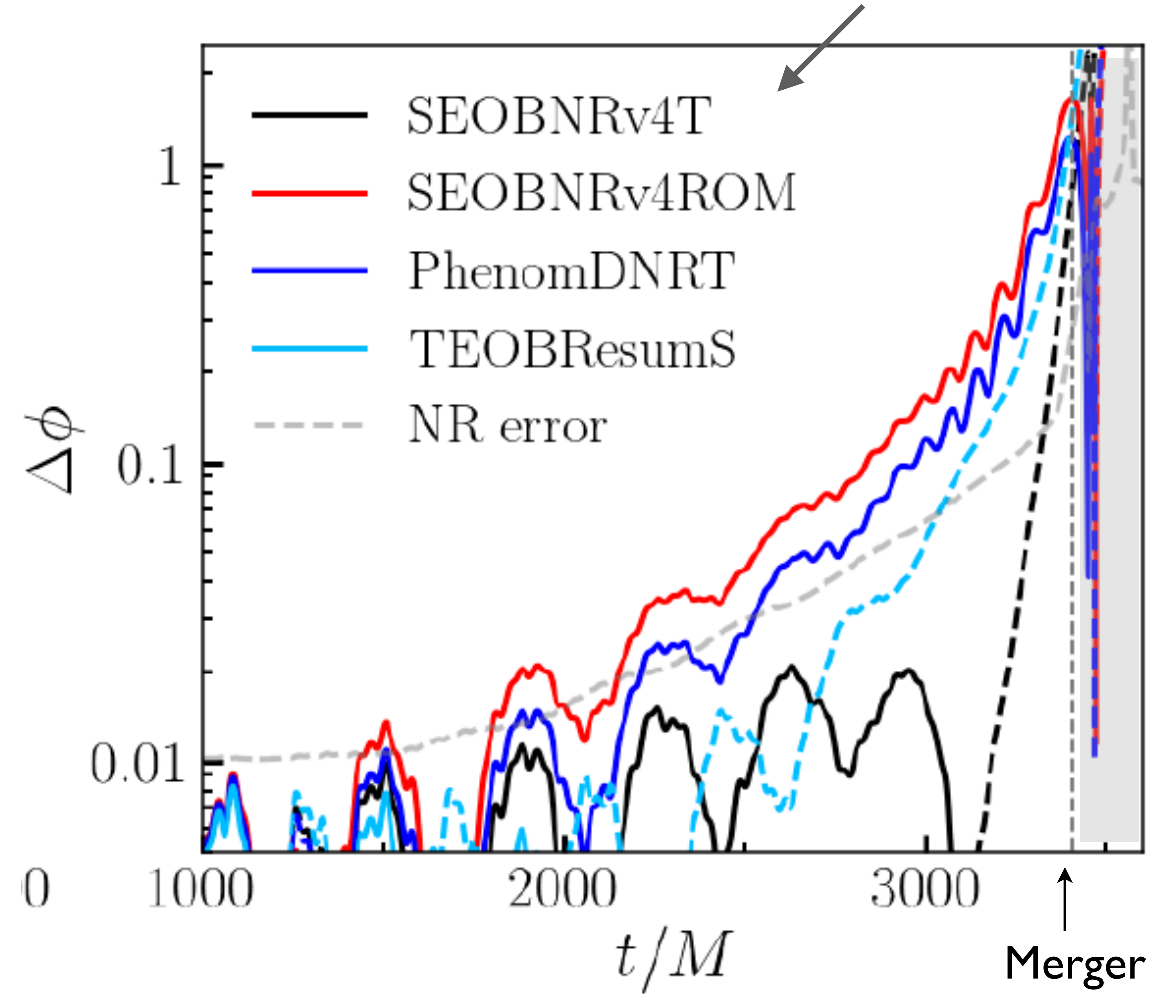
- For many EoSs: approximately universal relations between ω and λ [Leung & Lim]
- Enhancement of tidal effects also seen in ellipsoidal models and [Ferrari, Gualtieri, Maselli, + in tidal models calibrated to numerical relativity simulations [Dietrich+ Kawaguchi+]
- Effects included in EOB [TH+, Steinhoff, TH +]
- Efficient frequency-domain phase model also available [Schmidt, TH]

Performance of analytical models compared to NR

One example [Foucart+2019] representative of similar comparisons performed by other groups



Different tidal models with full BH-BH baseline

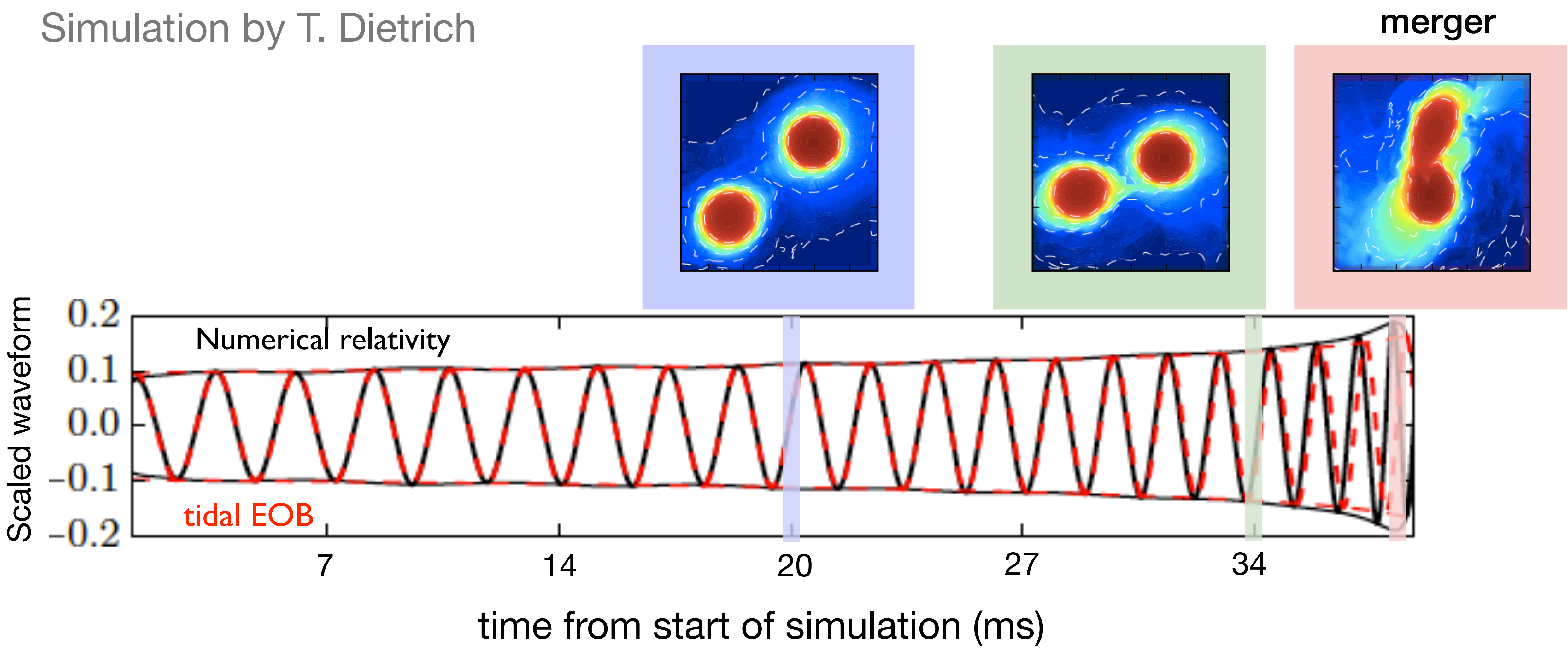


"merger": peak in GW amplitude ⇔ roughly: coalescence of NSs' high-density core parts

Note: robustness of state-of-the-art NR results among different codes has not been systematically quantified

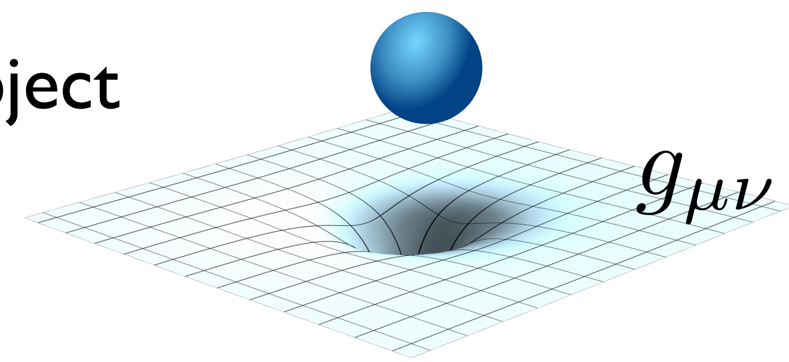
Comparisons to a different code

Simulation by T. Dietrich



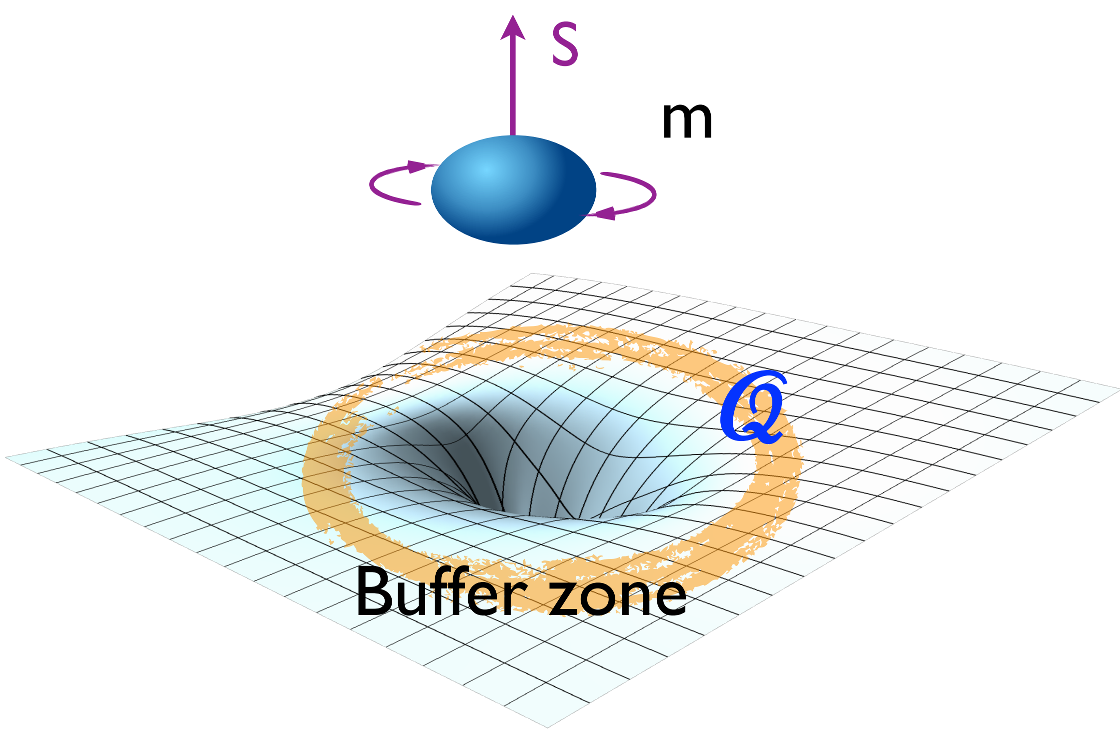
Body zone: example sources of multipole moments

- Isolated non-spinning compact object



Spherically symmetric

- **Rotation**



$$\chi = \frac{S}{m^2}$$

($\leq$1 for BHs
$\lesssim$0.4 for NSs)

Rotational multipoles

$$Q_{\rm spin} = -\kappa\, \chi^2 m^3$$

=1 for BHs

Characteristic spin-quadrupole parameter

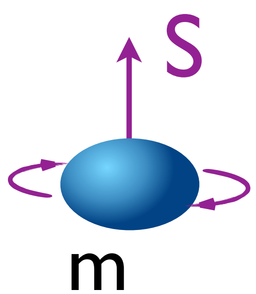
No-hair theorem: $M_\ell + i S_\ell = m(i\chi m)^\ell$

Mass moments

Current moments

[Poisson, Laraakers, 1999, …]

Properties of NS matter reflected in observables



Spin-quadrupole parameter

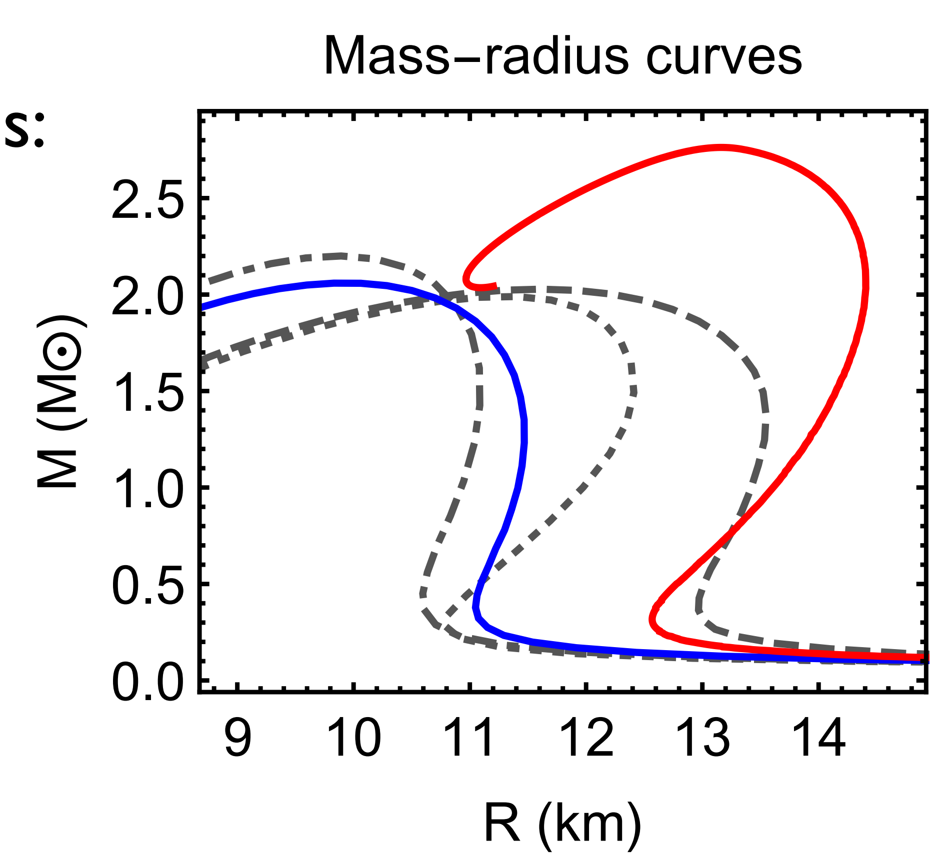
$$Q_{\rm spin} = -\kappa\, \chi^2 m^3$$

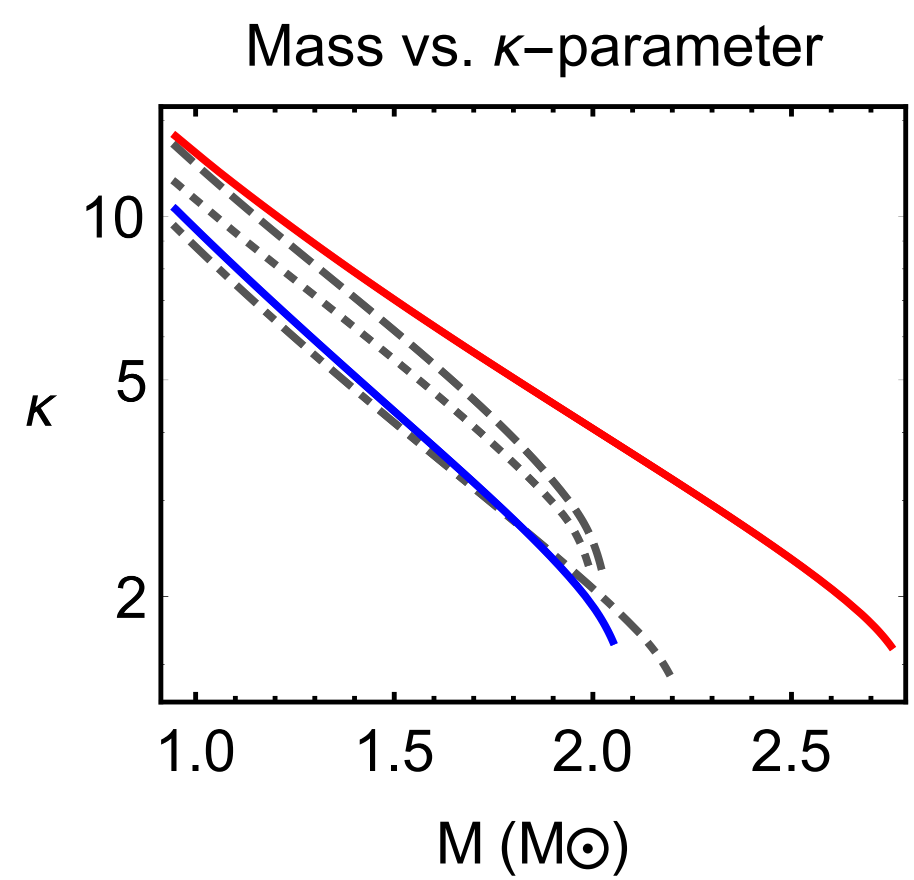
matter-dependent

spin parameter $\chi = \frac{S}{m^2}$ ≤ 1 for BHs

- For BHs: $\kappa = 1$ no-hair property $M_\ell + i S_\ell = m(i\chi m)^\ell$

- Examples for NSs:

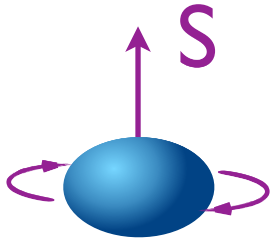




[Poisson 1997, Larakkers+1997, Mora, Berti, Will 2006, Arun+2017…]

Rotational quadrupole effect on GWs

$$Q_{\rm spin} = -\kappa\,\chi^2 m^3$$



matter-dependent

=1 for a black hole

$\lesssim$ 15 for neutron stars

dimensionless spin parameter

$\leq$1 for black holes

$\lesssim$ 0.4 for millisecond pulsars

- GW signature from post-Newtonian theory: $\Delta\phi^{\textit{spin-Q}} \sim \kappa\,\chi^2\,(M\Omega)^{4/3}$

[see Marsat and Arun+ 2017 for recent results and compilation of higher-order terms]

- also included in EOB and Phenom models
- Quasi-universal relations between κ and λ for many EoSs for NSs

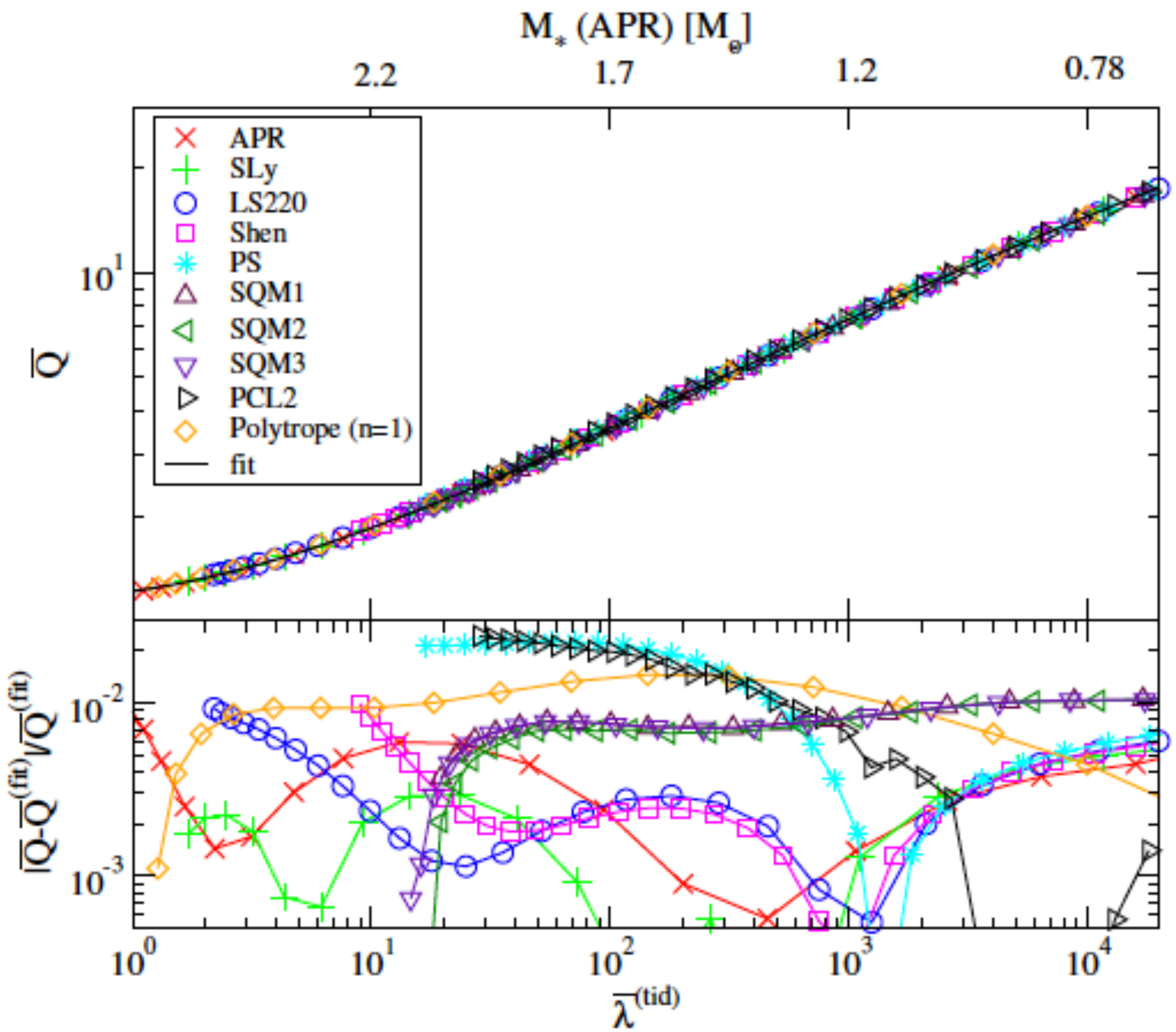
[Yagi & Yunes]

[EOB: Nagar+ 2017, Vines, Marsat+ 2017]

Quasi-Universal or EoS-insensitive relations

- Now found for many other quantities

Rotational quadrupole parameter

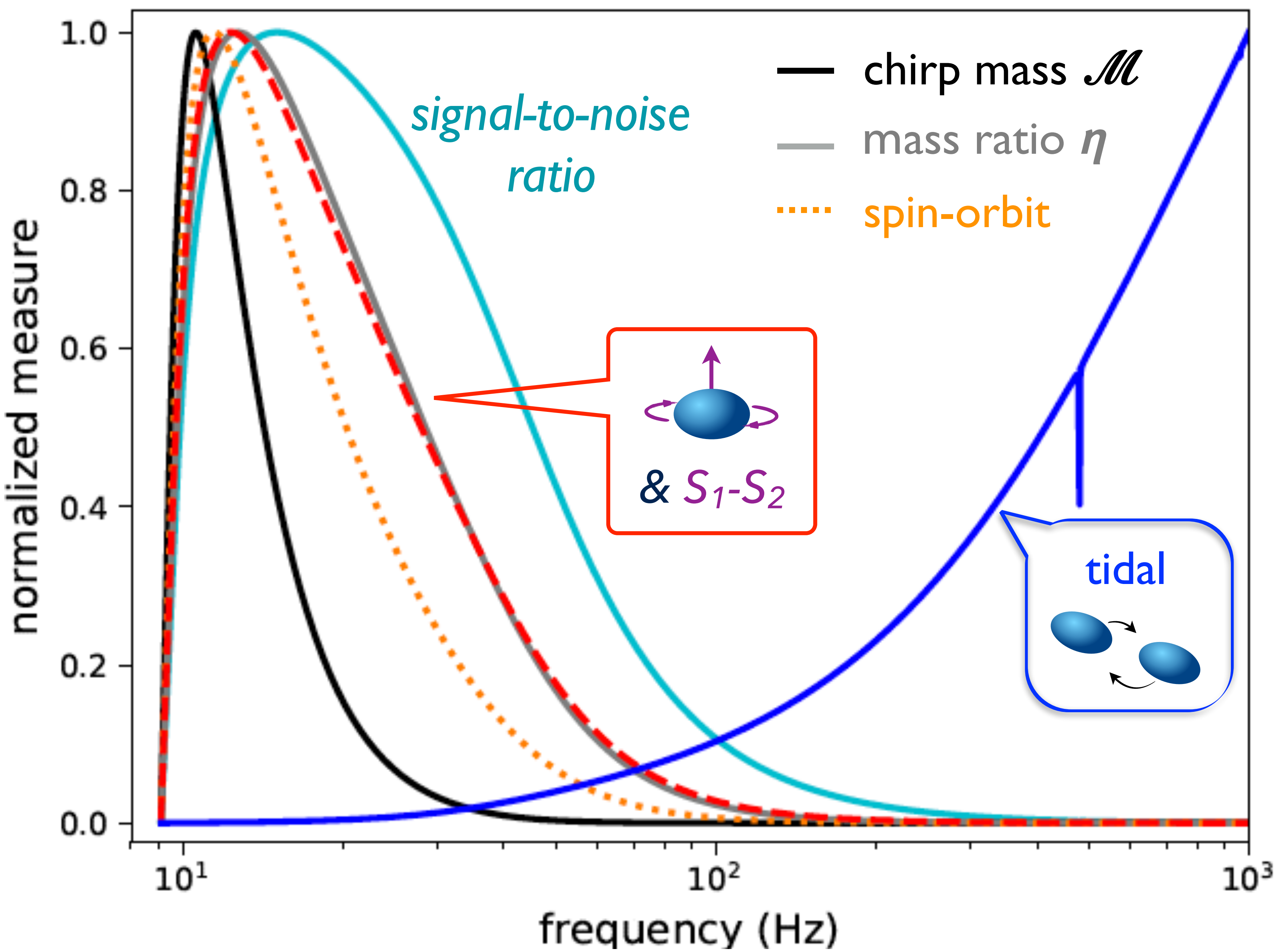


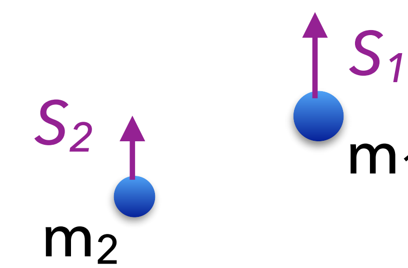
Tidal deformability parameter

[Yagi & Yunes 2013]

Accumulation of information about source properties

Approximately where in frequency does information about different source parameters come from [aLIGO]?





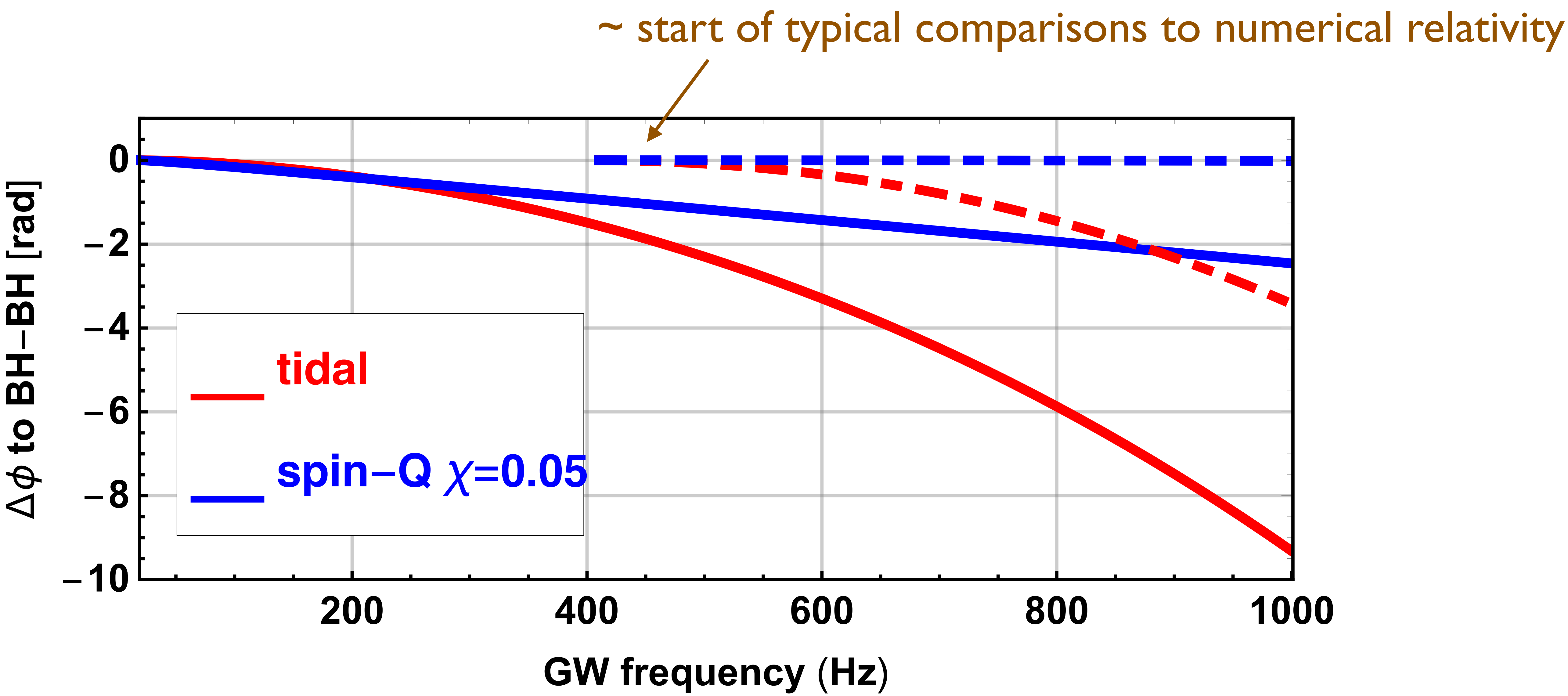
$$\mathcal{M} = \frac{(m_1 m_2)^{3/5}}{(m_1 + m_2)^{1/5}}$$

$$\eta = \frac{m_1 m_2}{(m_1 + m_2)^2}$$

I. Harry & TH arXiv:1801.09972

Numerical estimate of phase difference to BH-BH signal

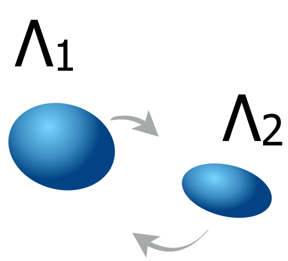
1.4+1.4Msun, identical NSs, DD2 EoS (Λ ~ 700, κ ~ 7)

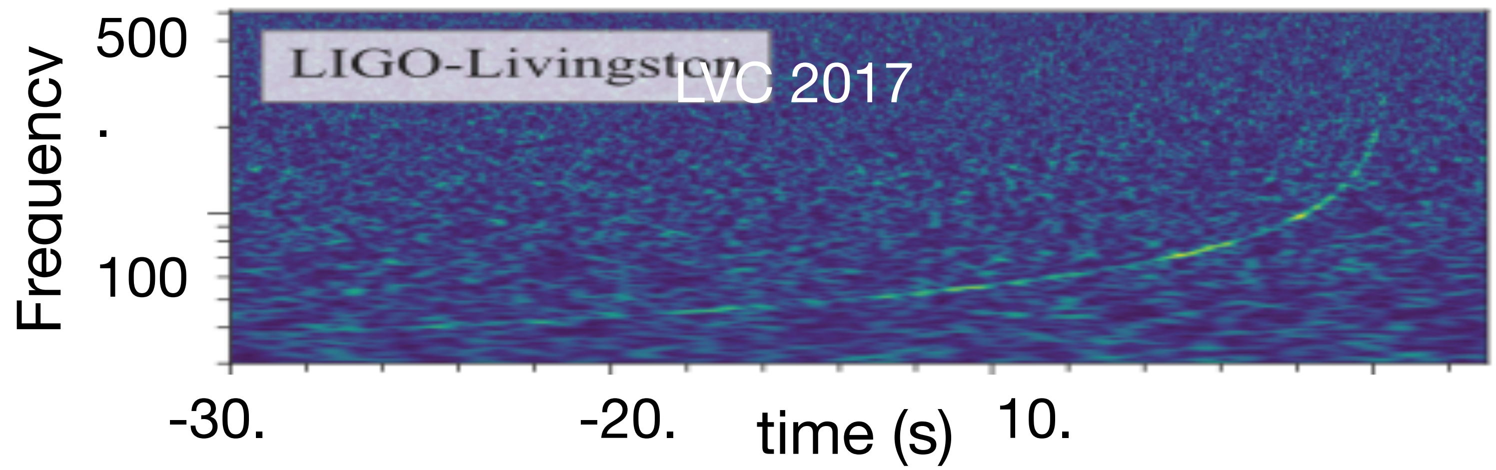


[depends on parameters and starting frequency]

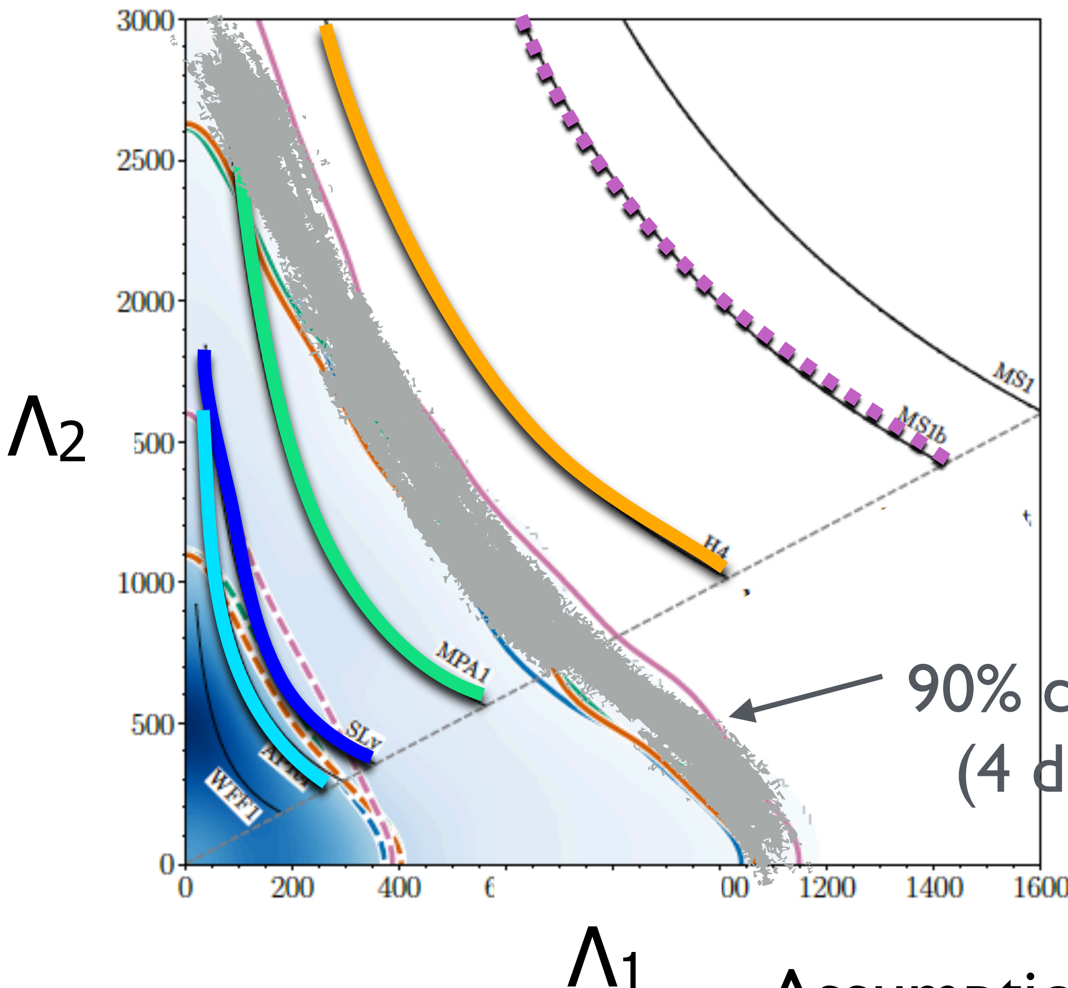
GW170817: NS binary inspiral measured in GWs

August 17, 2017:





Empirical constraints on tidal deformability

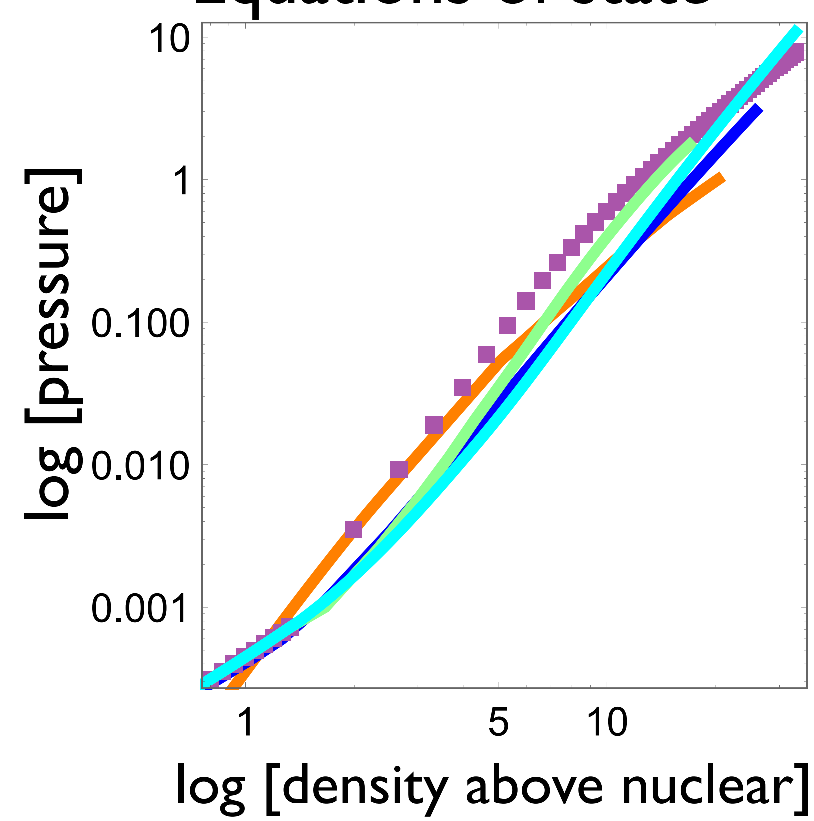


90% confidence upper limits
(4 different GW models)

LVC 2018

$$\Lambda = \frac{\lambda}{m_{\rm NS}^5}$$

Equations of state

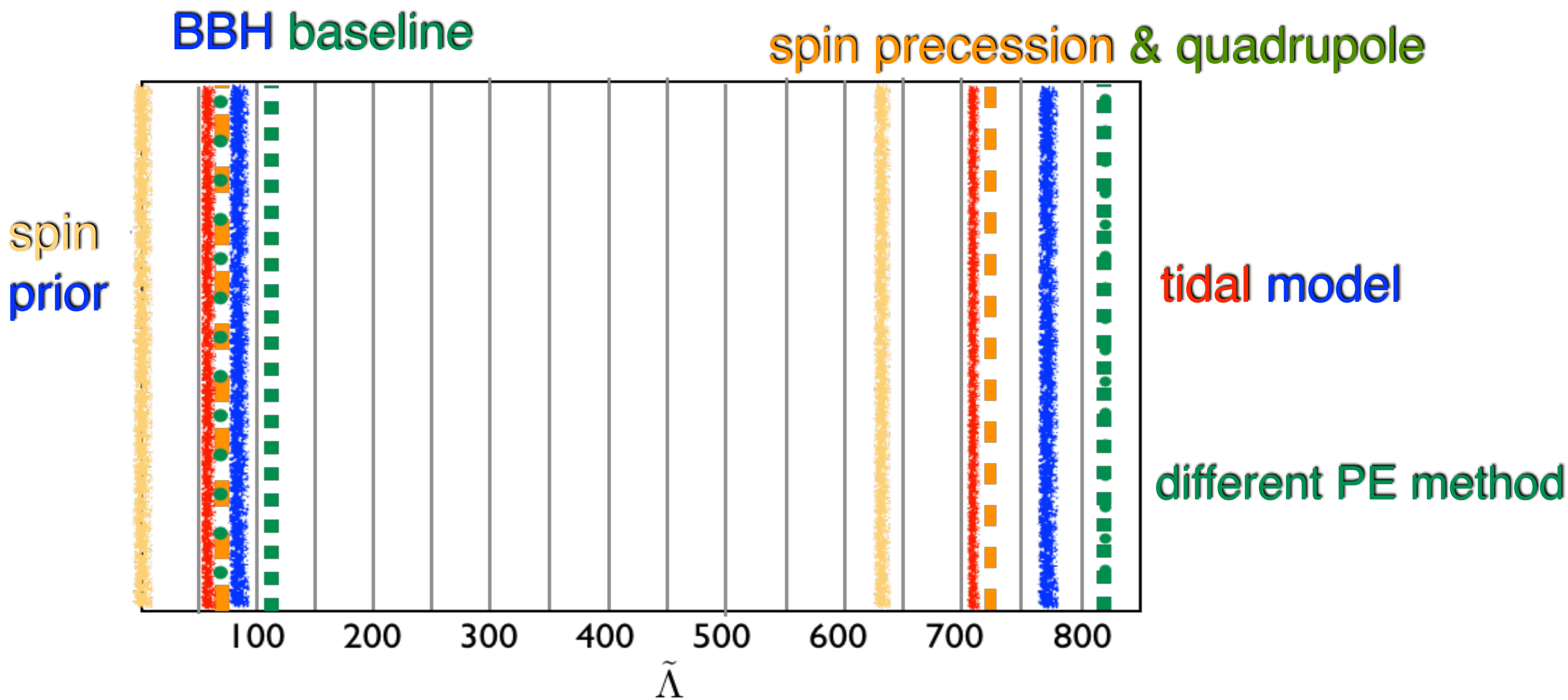


Assumption: quasi-universal relations
(all matter effects characterized by Λ)

GW170817: estimate of the size of systematic uncertainties

90% confidence intervals with a variety of currently available models in LAL

LVC 1805.11579 (appendix)

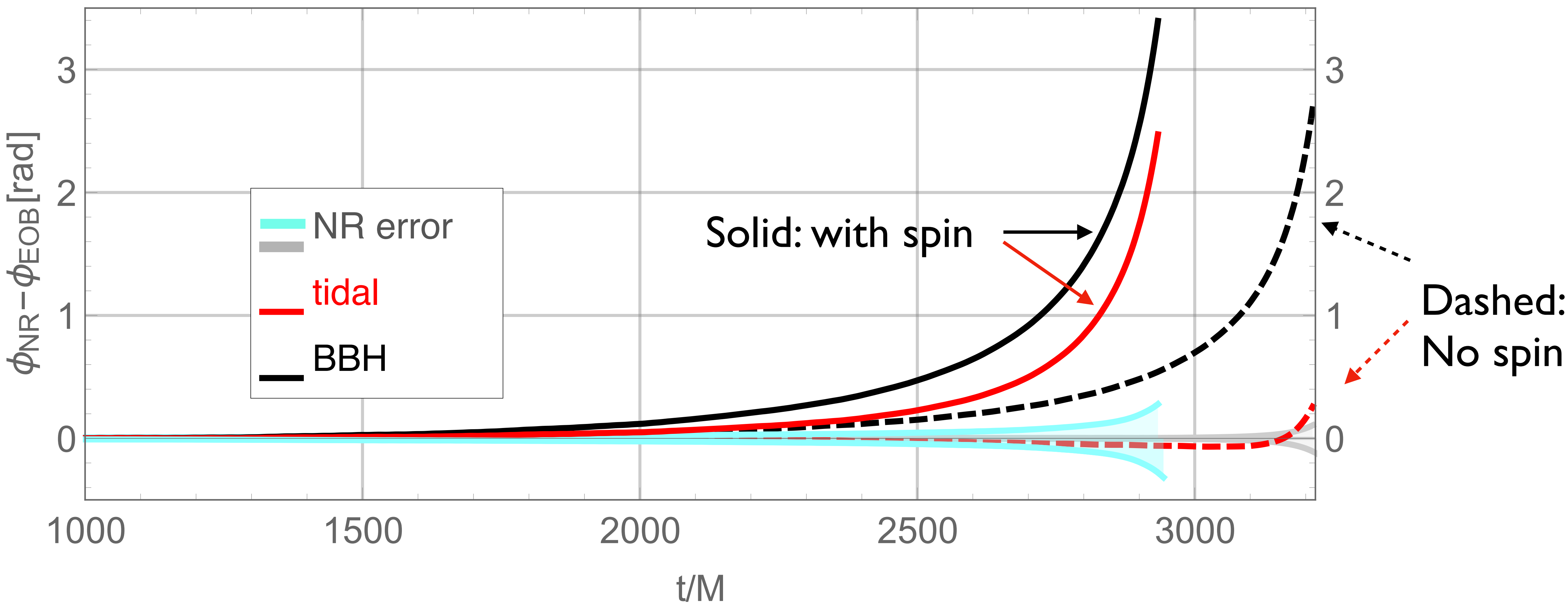


$$\tilde{\Lambda} = \frac{13}{16\,M^5}\left[\left(1+12\frac{m_2}{m_1}\right)\lambda_1 + \left(1+12\frac{m_1}{m_2}\right)\lambda_2\right]$$

+ detector calibration uncertainty not considered here

Effect of NS spin in late inspiral

Comparison to simulations by F. Foucart: mass ratio q=1 NS-BH with NS spin -0.2



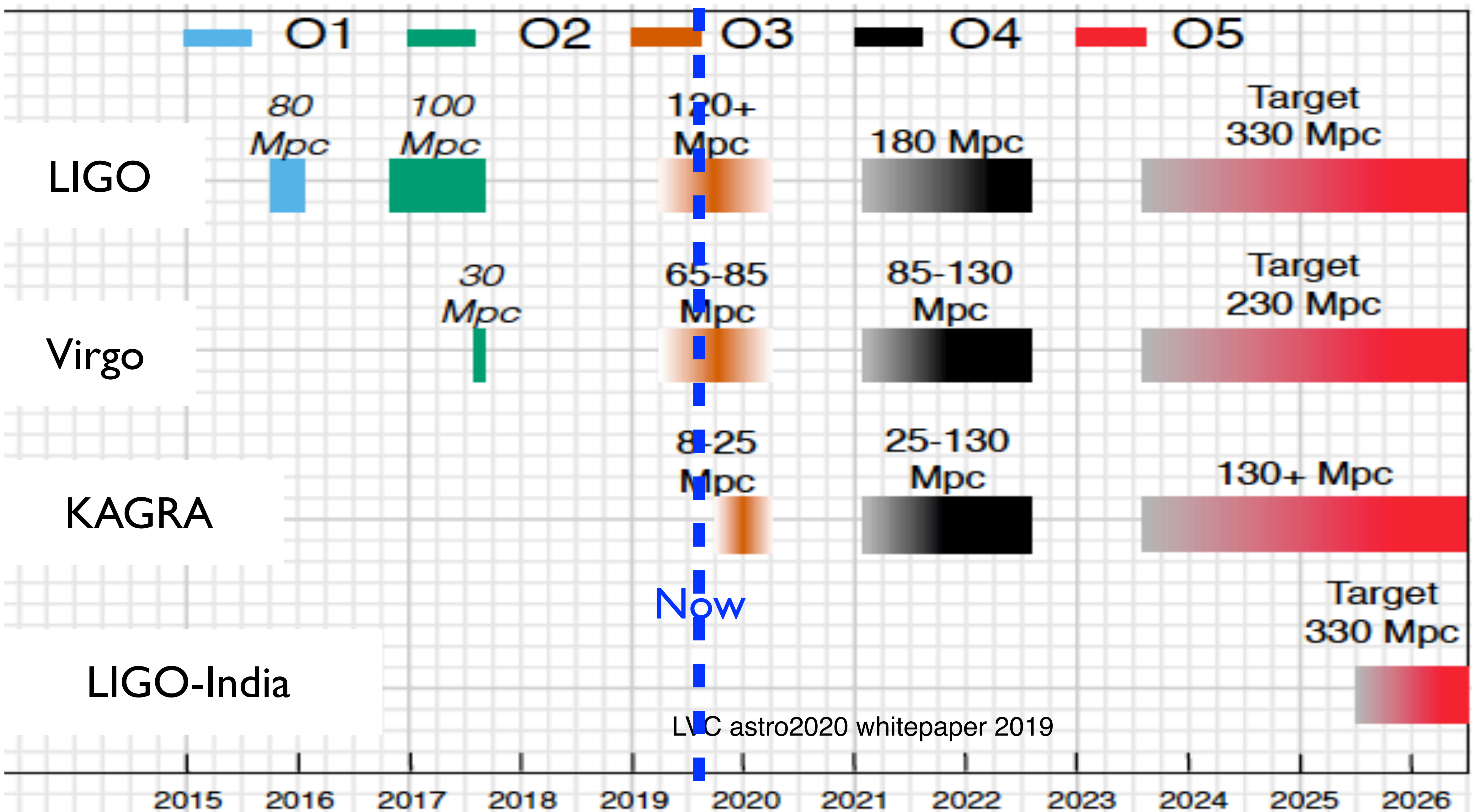
- expect effective shift of f-mode resonance, not yet included in models [ongoing work]

[Ho & Lai] [Steinhoff, TH+]

Examples of other finite size effects during the inspiral

- Tidal excitation of other modes
  - GW spectroscopy during inspiral
  - Need quasi-normal-mode frequencies + tidal excitation factors [Chakrabaty+]
- Spin-tidal interactions
  - shifts of mode resonances
  - new couplings
- Gravitomagnetic tidal interactions
- Late inspiral
- Tidal disruption in NS-BH (Alessandra's talk tomorrow)

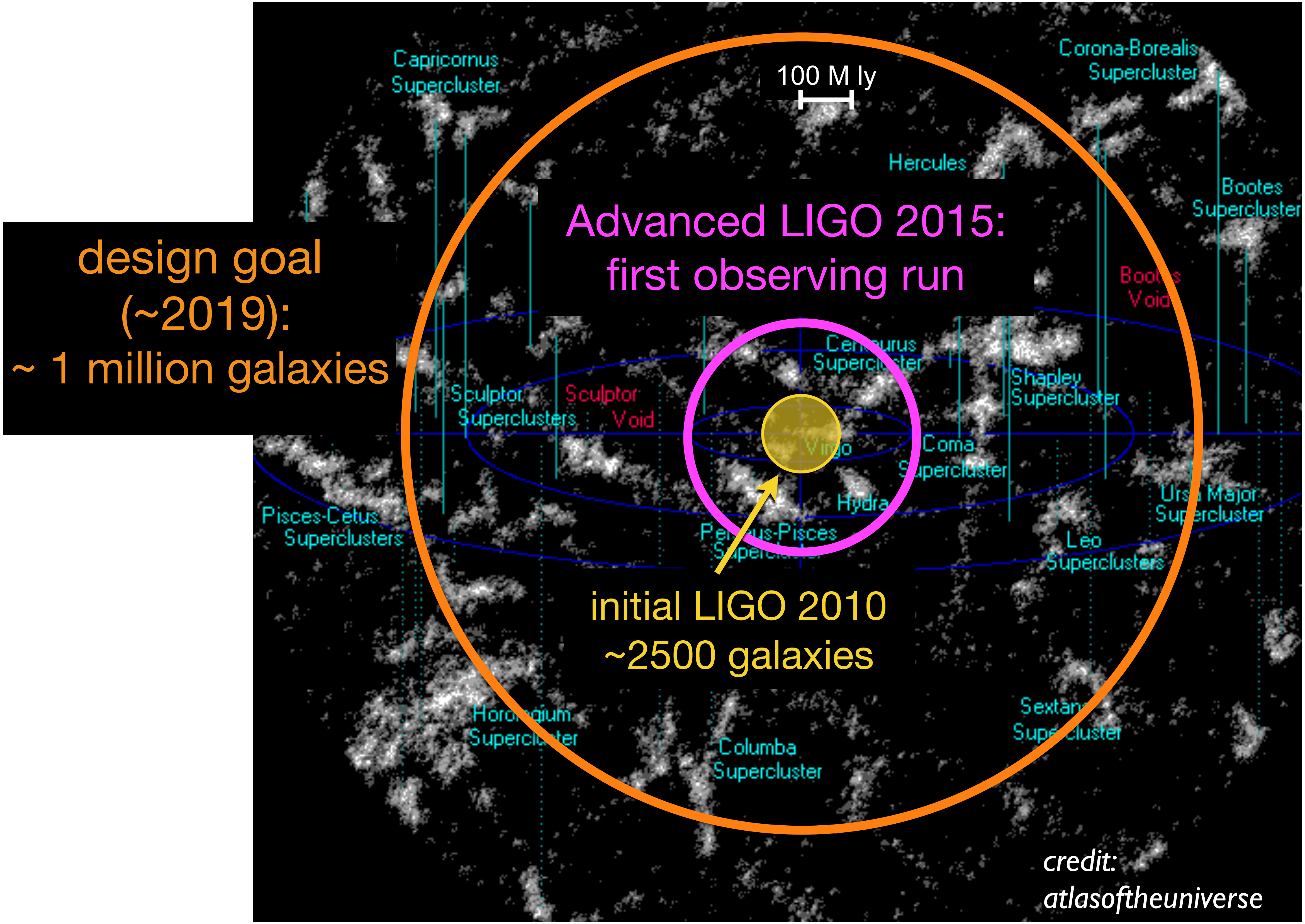
Planned detector developments



More accurate measurements of loud signals,

Greater number & diversity of events

Visible volume of the universe (for binary neutron stars)



Outlook

Much recent progress in modeling matter effects, application to GW170817

- GW detectors will improve in sensitivity over the next years, ~ 2030+: new detectors
  - Higher accuracy measurements of loud sources
  - populations, greater diversity of events

- Expect a wealth of new insights but requires advances in modeling
  - increasingly accurate NR simulations with robust error budget estimates
  - More realistic physics, improve accuracy, complete waveforms
  - detailed calculations of effects not discernible from NR

[more about this in Alessandra's talk tomorrow morning]