Gravitational waveform from binary neutron star mergers: Numerical Relativity & Effective one body

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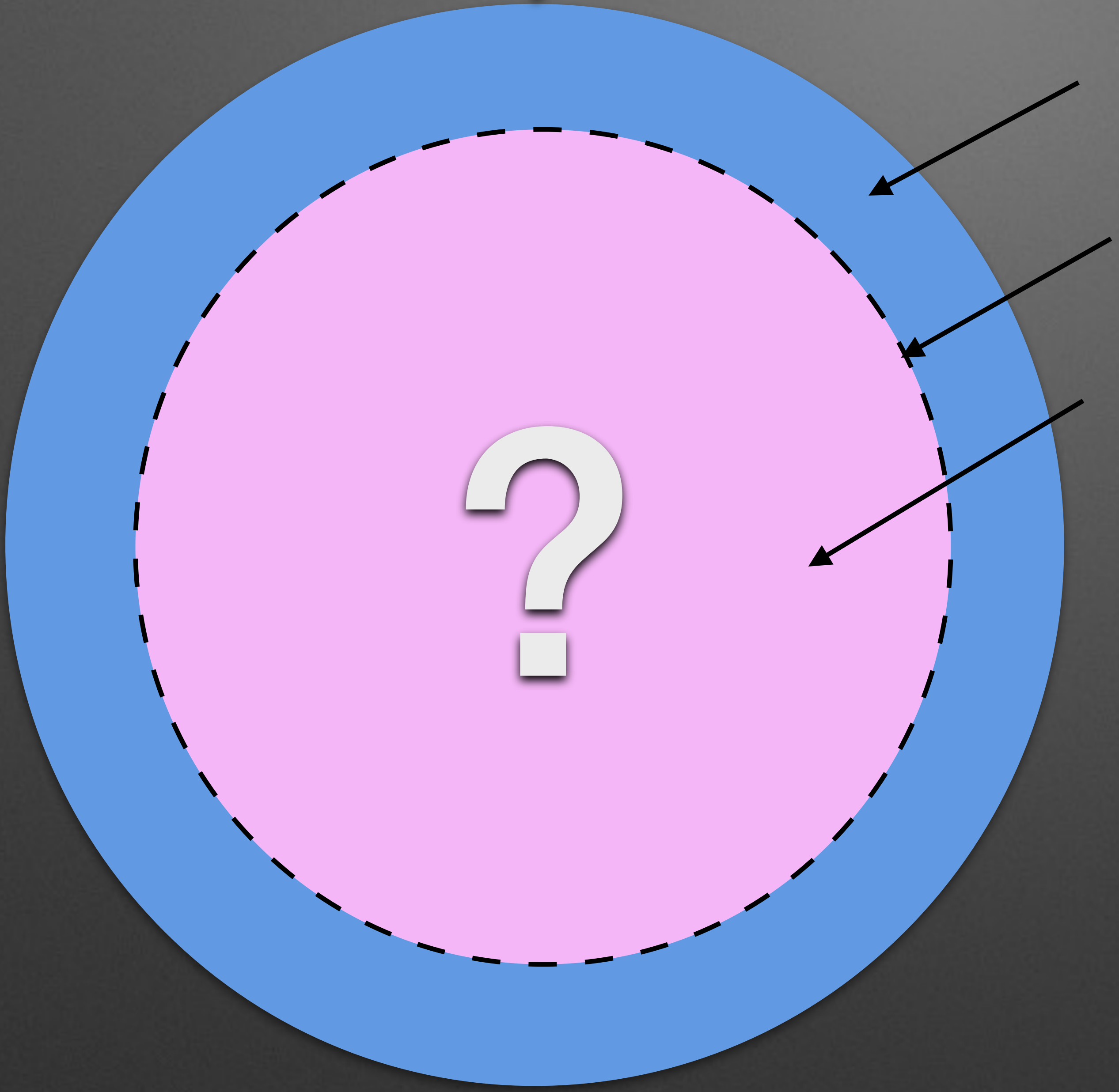
Introduction: Neutron Star

Mass ~ 1.4 Msun, Radius ~ 10km



Crust

Nuclear density

Core

Composition ?

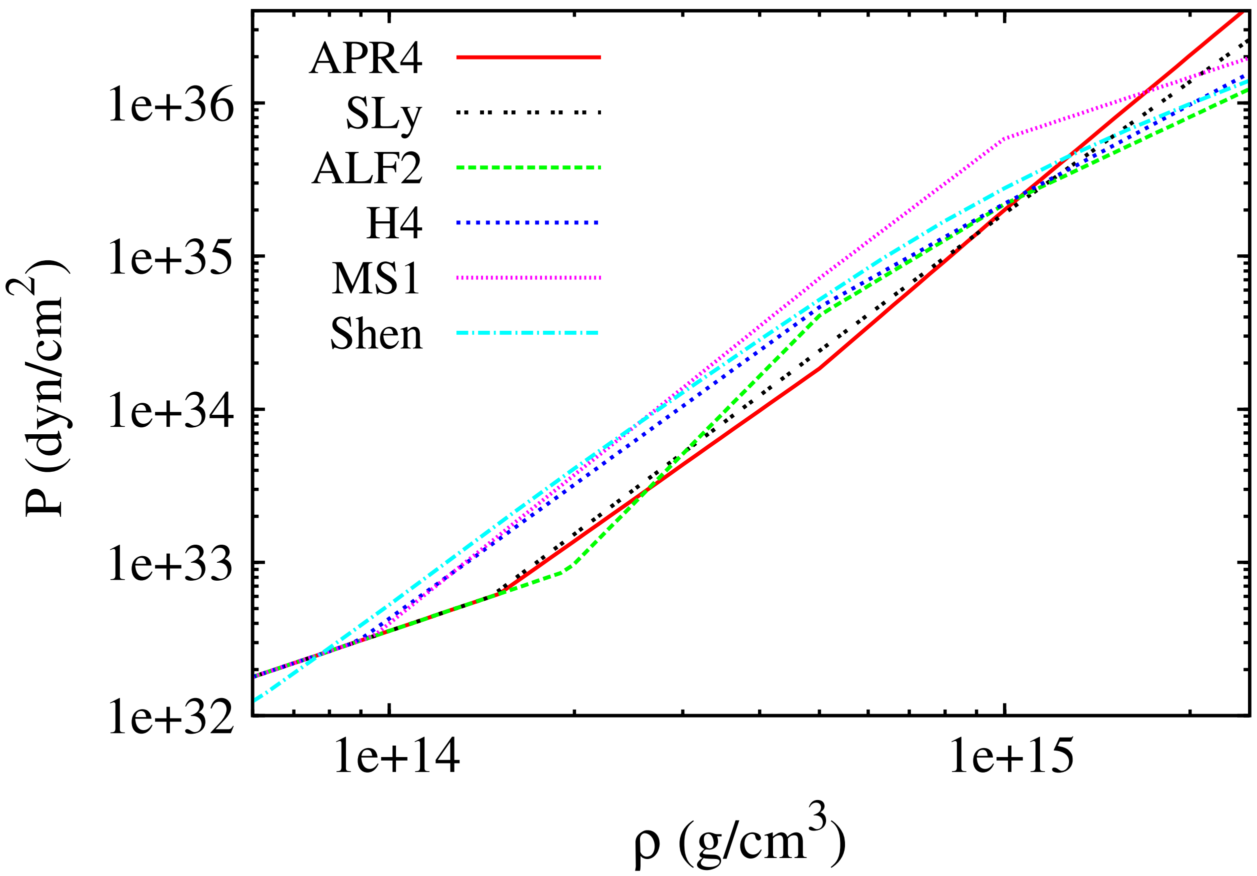
(neutron, hyperon, quark)

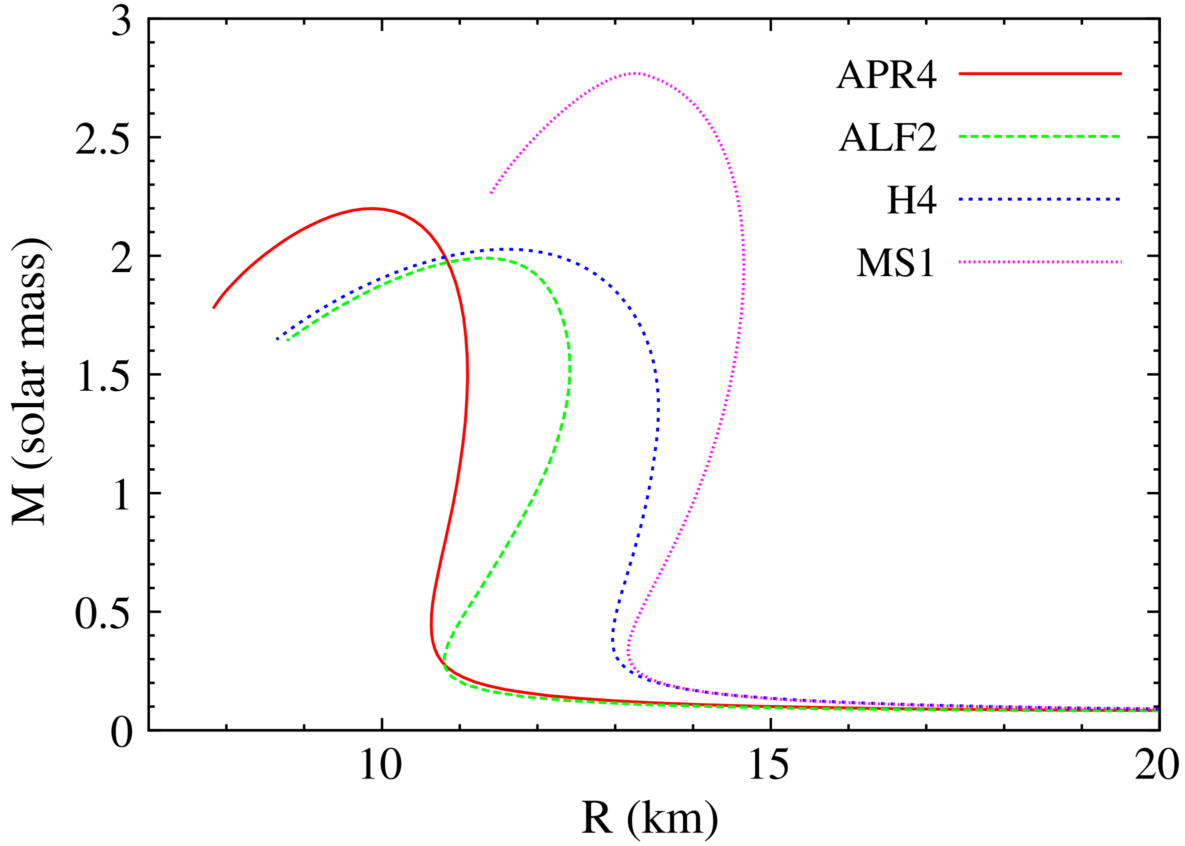
Interaction?

etc

Many mysteries in deep inside of neutron stars.

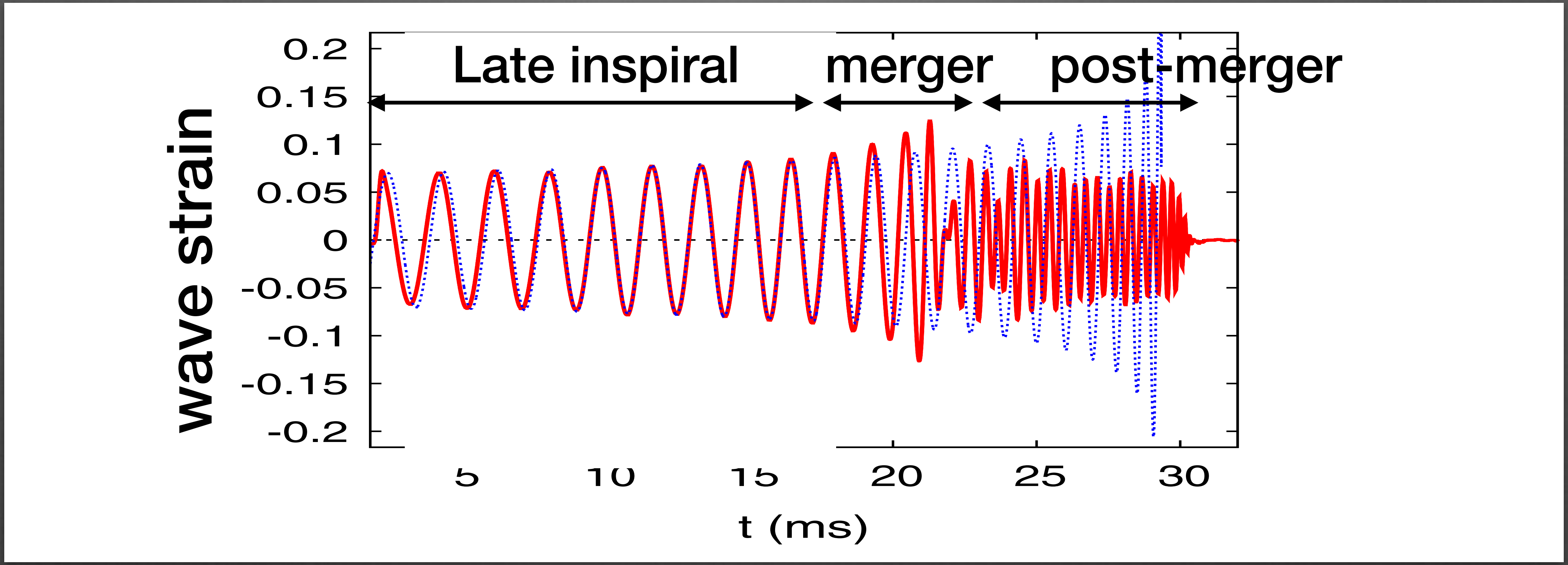
Introduction: Neutron Star EoS & M-R


EOS


Mass & Radius

1 to 1 correspondence between EOS and M-R relation.
Measurements of Mass & Radius => High-dense material.

GWs as a probe of NSs



- The masses can be measured using the chirp signal
- Neutron Star’s size affects gravitational-waves of mergers

Tidal effect in pre-mergers:

  Flanagan & Hinderer 2008
  Hinderer et al 2010
  Damour, Nagar, & Villain 2012
  Agathos et al 2015

Post-merger:

  Bauswein & Janka 2012
  Baustein et al 2014
  Hotokezaka et al 2013

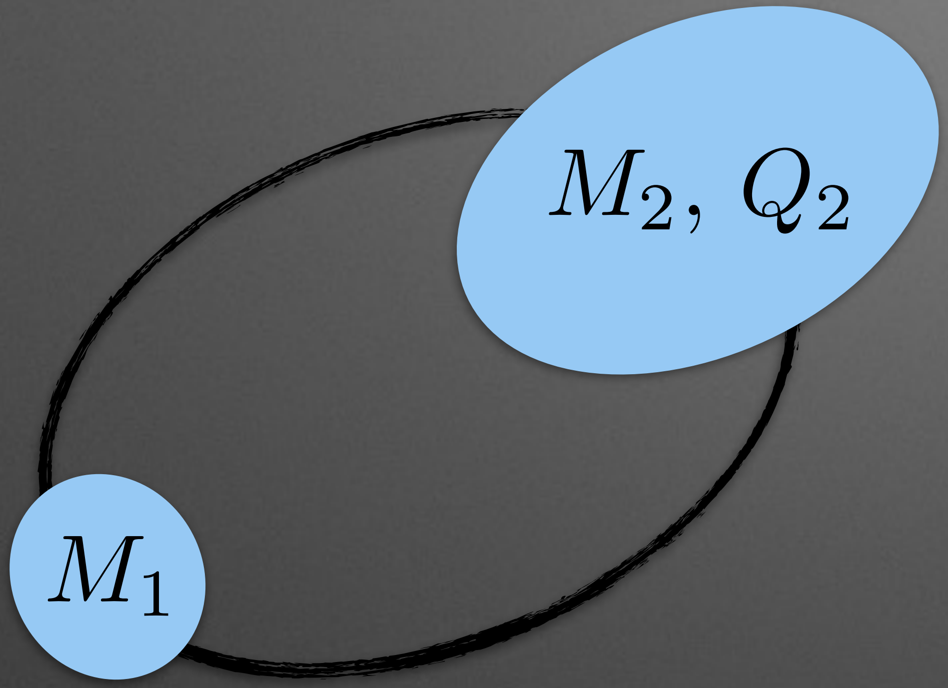
Inspiral-merger-post merger:

  Read et al 2010, 2013

Cut off at the merger:

  Kiuchi et al 2010, Lackey et al 2014

Tidal interaction in binaries



Binary inspiral

$$E_{\rm int} \approx -\frac{M_1}{r}\left(M_2 + \frac{3Q_2}{2r^2}\right)$$

$$Q_2 \sim \Lambda_2 \frac{GM_1}{r^3}$$

Tidal deformability parameter

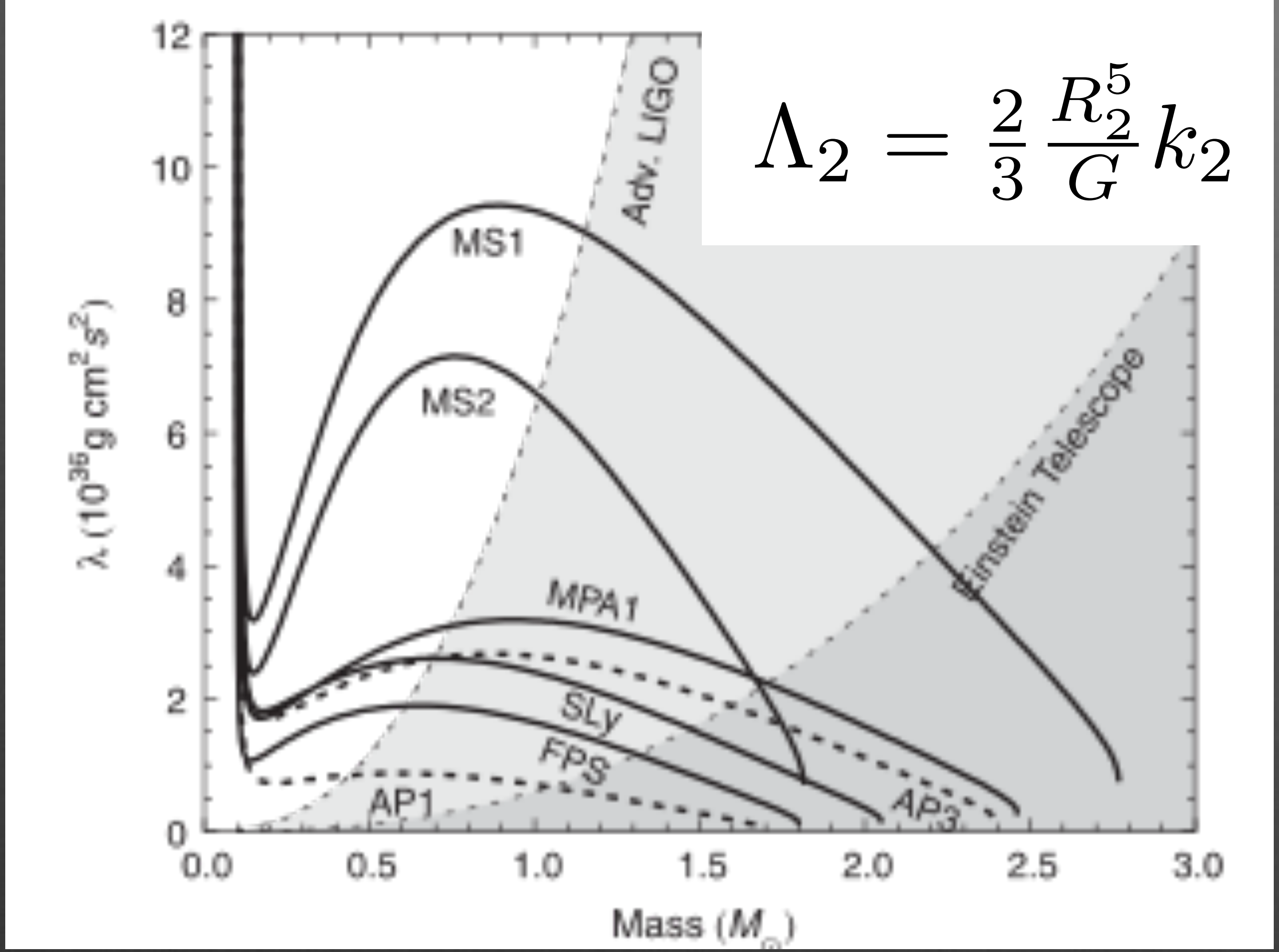
$$\Lambda_2 = \frac{2}{3}\frac{R_2^5}{G}k_2$$

Dimensionless tidal Love number

The orbital motion is affected by the tidal effect.
The leading of the tidal effect is 5PN order.

Tidal deformability of neutron stars

Hinderer et al 2010, see also Damour and Nagar 2009



$$\Lambda_2 = \frac{2}{3}\frac{R_2^5}{G}k_2$$

Questions:
What is the measurability of tidal deformability parameters?

Can we distinguish a BNS merger from a BBH with the same mass ?

Waveform

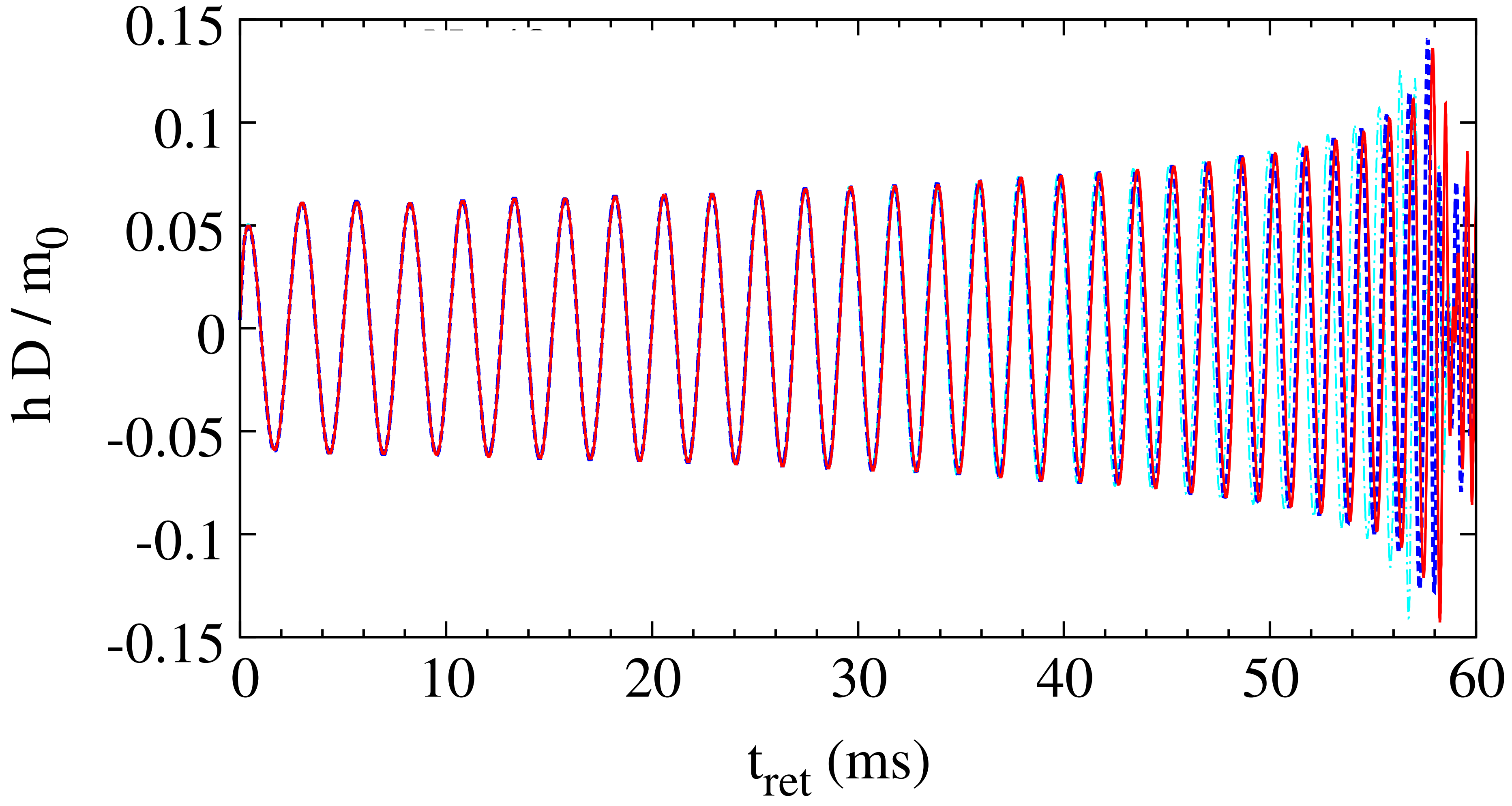
The tidal effect is stronger in later times of inspiral.
=> We want to use the information up to the merger.

In fact, Read et al 2014 show that hybrid waveforms of analytic and NR waveforms improve the measurability of tidal deformability parameters.

But, the truncation error of post-Newtonian causes parameter estimation biases.
(Favata 2014, Yagi & Yunes 2014, Wade et al 2014)

Motivated by this, we compute late-inspiral waveforms using numerical relativity

High accuracy Numerical Relativity

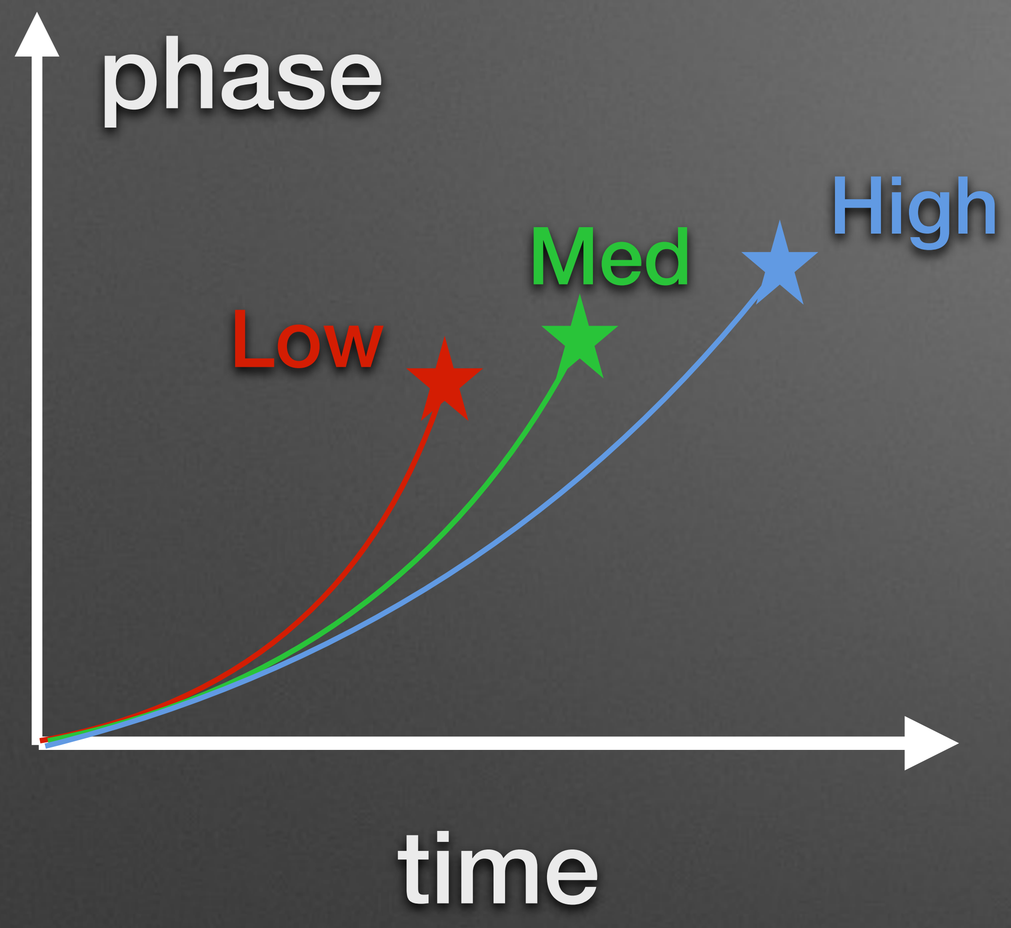


Hotokezaka et al 2015

Long-term : ~15 orbits

Low eccentricity : e < 0.001 see Kyutoku et al 2014 for a method

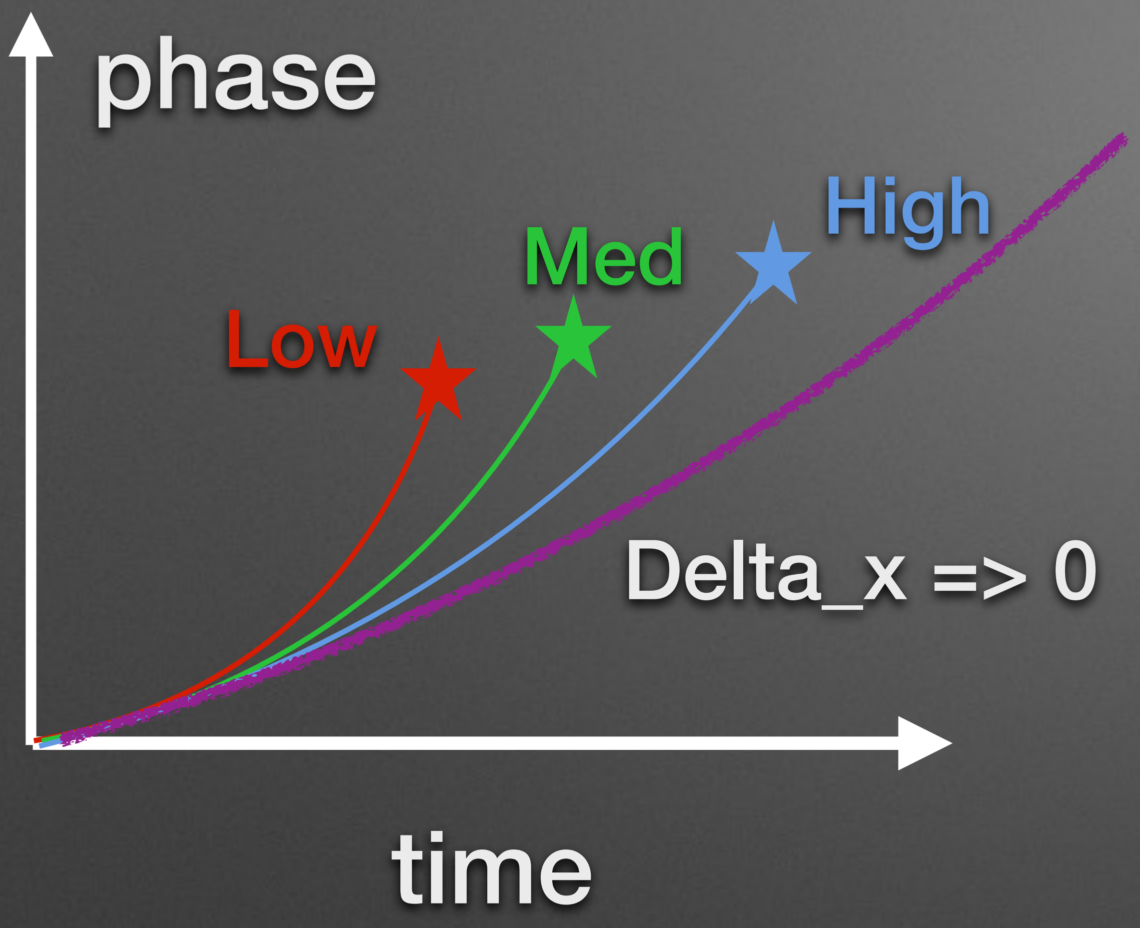
Resolution Extrapolation



The finite resolution effects systematically cause overestimates of the tidal effects.

=> A extrapolation procedure is needed.

Resolution Extrapolation



$$h^{2,2}(t_{\rm ret}) = A^{2,2}(t_{\rm ret})\,\exp\left[i\Phi(t_{\rm ret})\right].$$

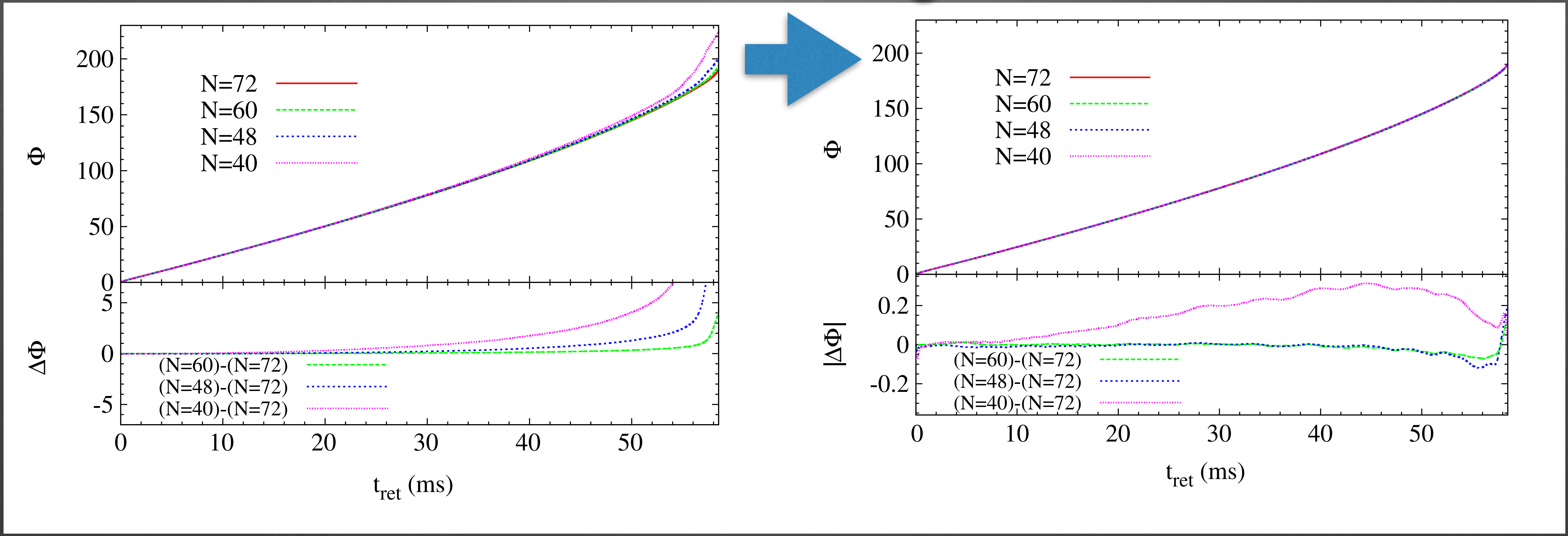
$t_{\rm ret} \to \eta t_{\rm ret}$ and $\Phi \to \eta\Phi$. **Uniformly stretching**

$$I = \min_{\eta',\phi} \int_{t_i}^{t_f} dt_{\rm ret} |A_2^{2,2}(\eta' t_{\rm ret})\exp[i\eta'\Phi_2(\eta' t_{\rm ret}) + i\phi] - A_1^{2,2}(t_{\rm ret})\exp[i\Phi_1(t_{\rm ret})]|^2$$

taking a limit Delta_x -> 0.

Resolution Extrapolation

stretching



Difference between
the extrapolated and highest

Merger time: ~ 0.3 ms

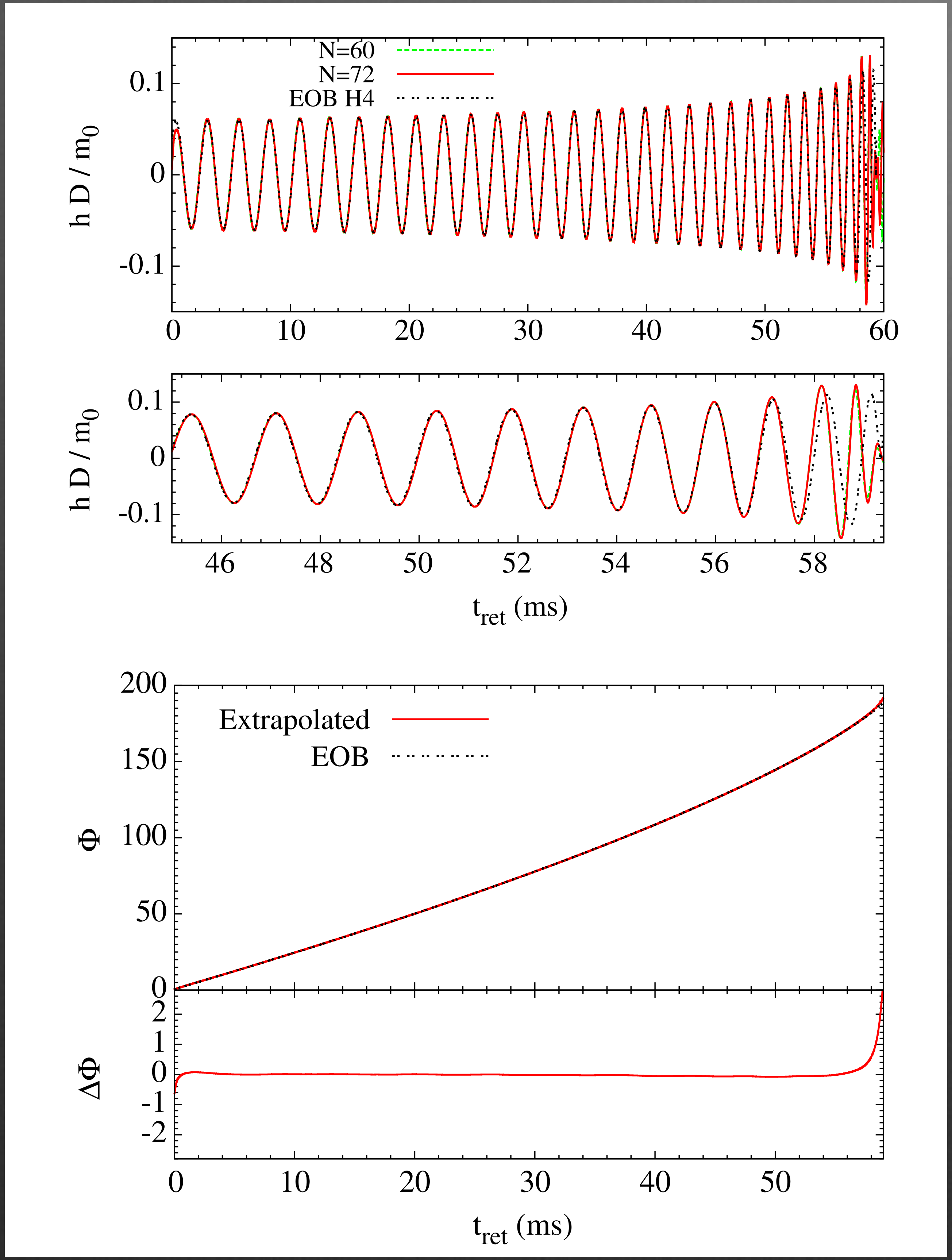
Total phase : ~ 1 radian

the two extrapolated

Merger time: ~ 0.1 ms

Total phase : ~ 0.5 radian

Comparison with Effective-one body

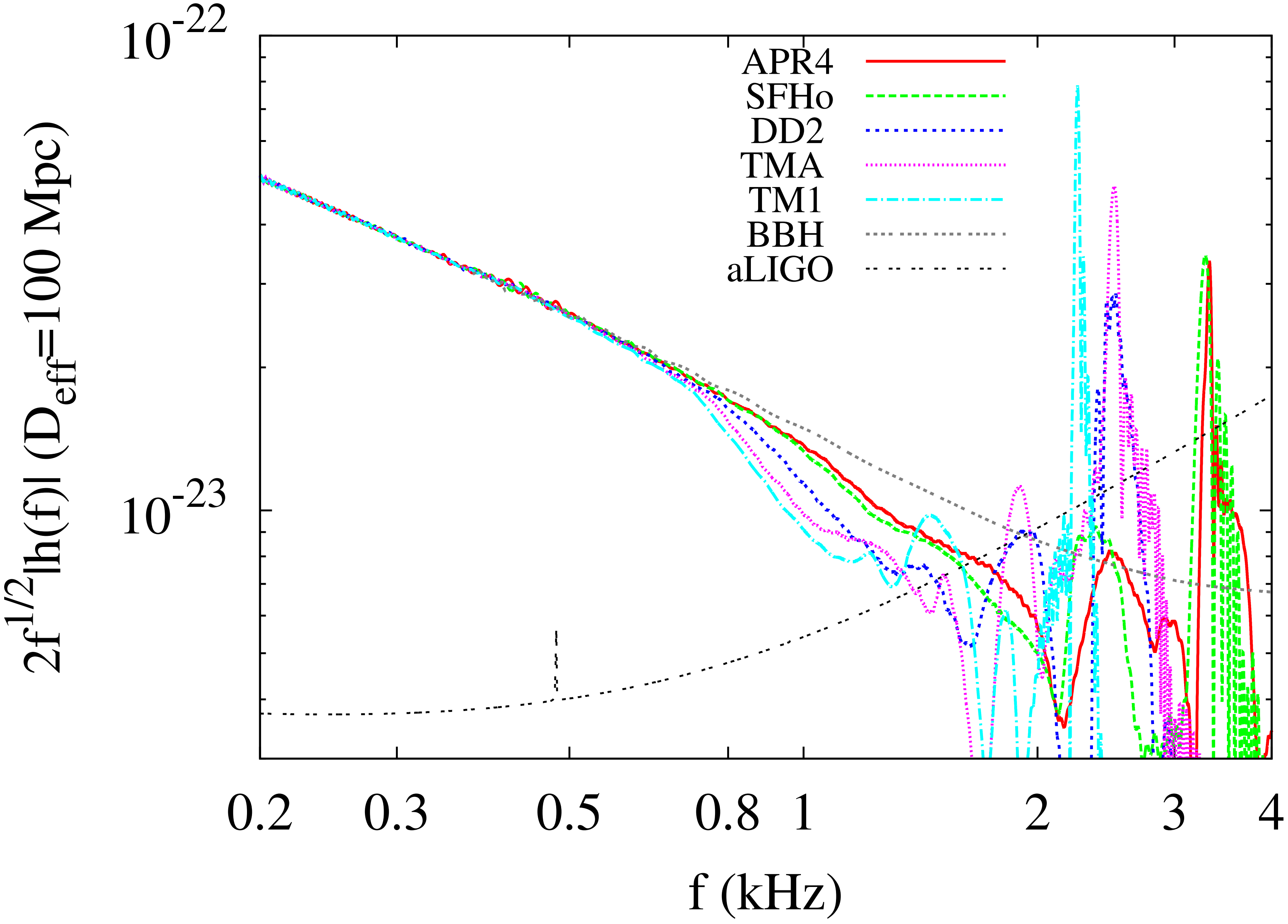


Effective one body waveforms with tidal (Bernuzzi et al 2015) agree very well with NR ones up to a last few cycles.

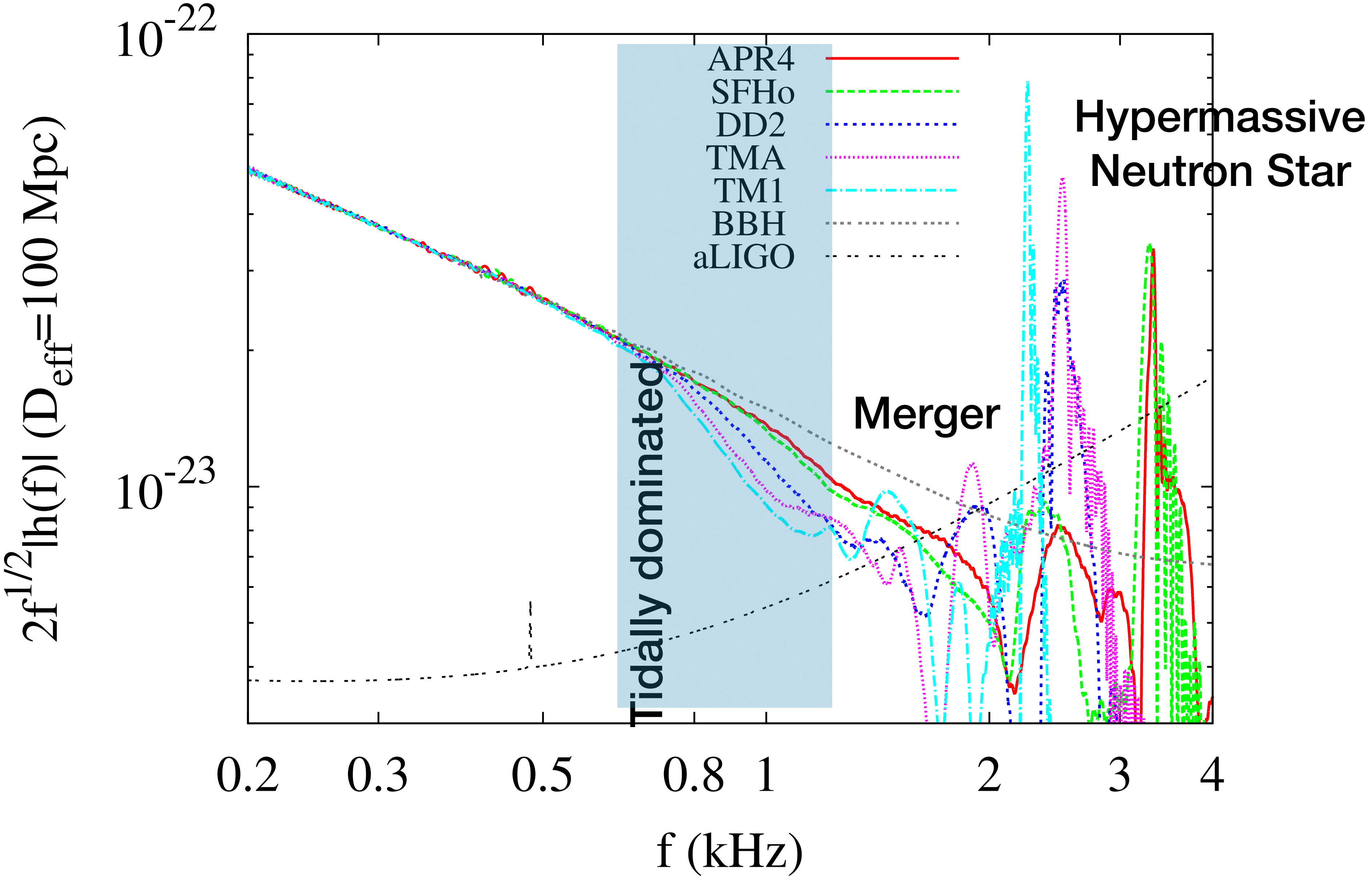
In a last few cycle,
Phase difference: 0.5 ~ 1 rad
(Better for Smaller NS)

Hybridize these waveforms

Hybrid waveform



Hybrid waveform



Measurability (Distinguishability)

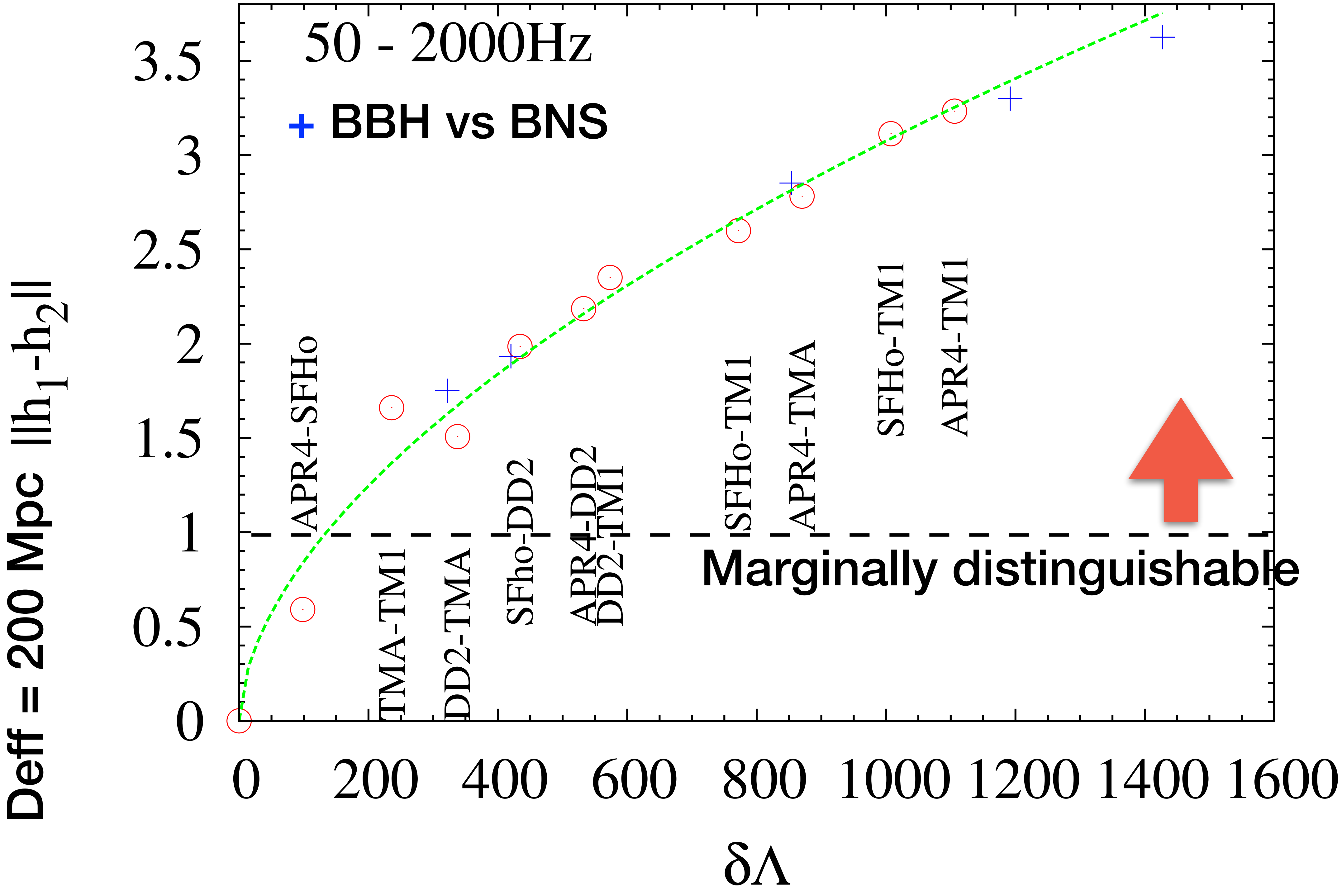
$$||h_1 - h_2||^2 := \min_{\Delta t, \Delta\phi} \left[4 \int_{f_i}^{f_f} \frac{\left| \tilde{h}_1(f) - \tilde{h}_2(f) e^{i(2\pi f \Delta t + \Delta\phi)} \right|^2}{S_n(f)} df \right]$$

$||h_1 - h_2|| > 1$ **Marginally distinguishable**

$$\delta\Lambda_{\mathrm{rand}} = \frac{|\Lambda_1 - \Lambda_2|}{||h_1 - h_2||}$$

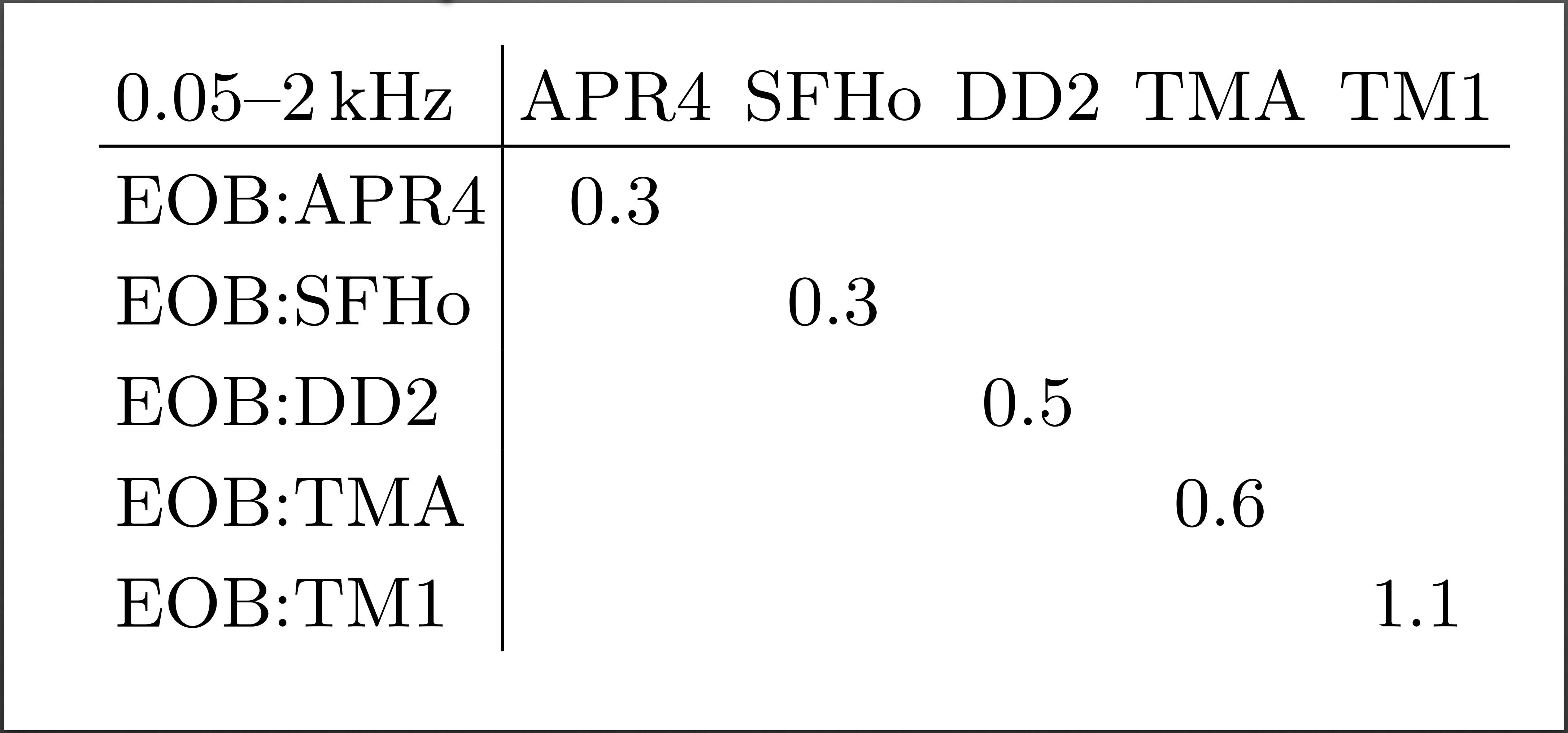
see Lindblom et al 2009
Read et al 2013

Measurability of tidal deformability



EOB vs NR

Deff = 200 Mpc



0.05–2 kHz	APR4	SFHo	DD2	TMA	TM1
EOB:APR4	0.3				
EOB:SFHo		0.3			
EOB:DD2			0.5		
EOB:TMA				0.6	
EOB:TM1					1.1

EOB is working quite well for Deff > 200 Mpc

Conclusion

We compute long-term (15 orbit) gravitational waveforms with errors of ~0.5 rad.

Current tidal Effective one body formalism is good to describe NS-NS inspirals up to the merger. (indistinguishable to NR waveforms for SNR<20)

For a NSNS merger event Deff~200Mpc (SNR~17),
we can distinguish between BBH and BNS
NSs with R<12km and R>13 km