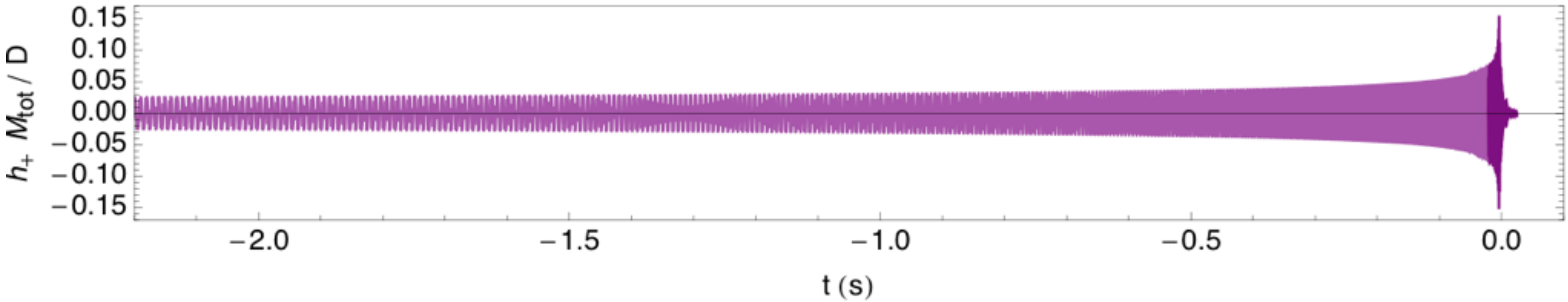

Dense matter in gravitational-wave sources: mergers involving neutron stars

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Jocelyn Read

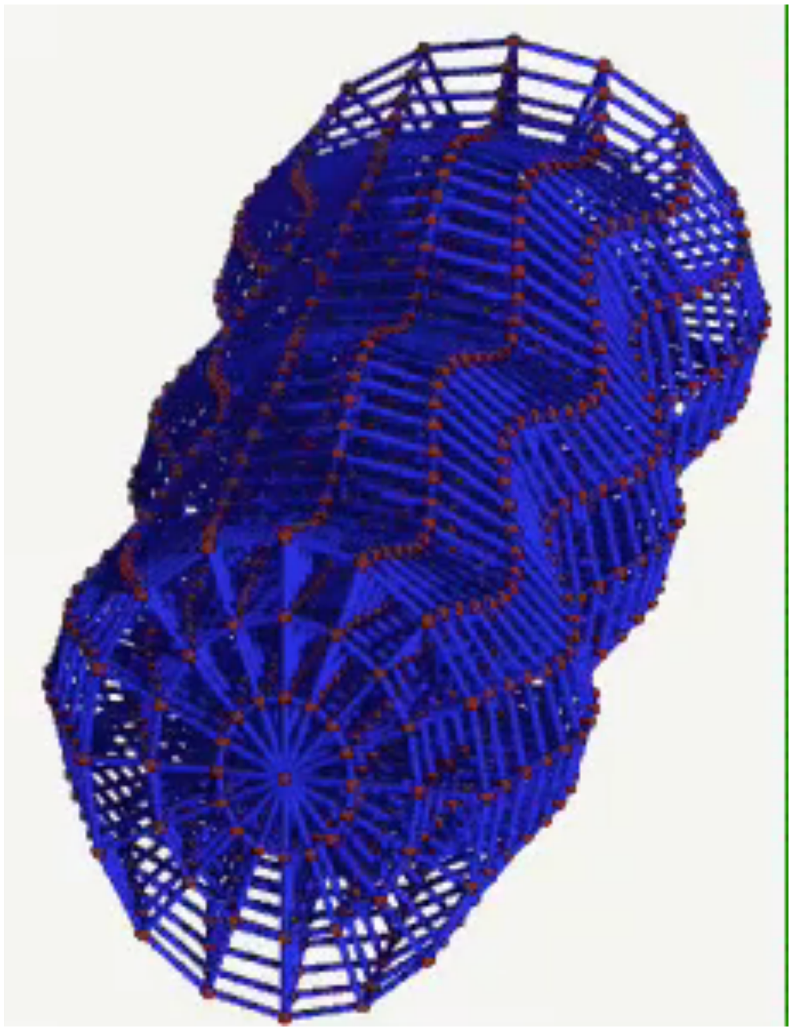
GW PAC GRAVITATIONAL WAVE Physics and Astronomy Center @ CALIFORNIA STATE UNIVERSITY FULLERTON

Gravitational waves

- Changing curvature of space around moving objects
- Information about change propagates outward at speed of light
- Linearized GR → wave equation
- GW stretch and squeeze the distance between freely-falling objects (Pirani 1957)
- Measure strain: $h \sim \Delta L/L$ (amplitude, not energy)

Two polarizations: + and x

Propagation



GW source: orbiting objects

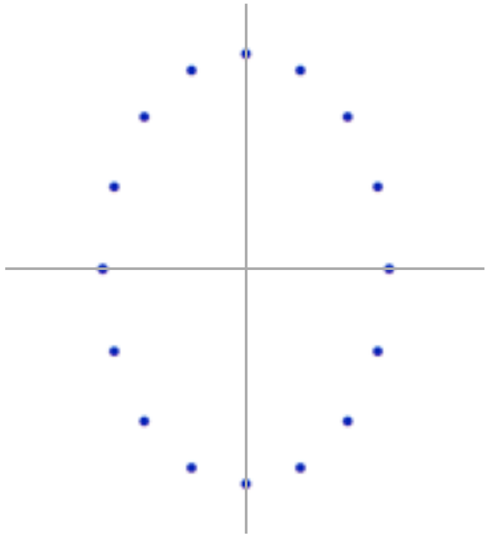
Massive objects orbit

$$L_{\mathrm{GW}} \sim \left(\frac{c^5}{G}\right)\left(\frac{v}{c}\right)^6\left(\frac{R_{\mathrm{S}}}{r}\right)^2$$

$$\sim 10^{59}\ \mathrm{erg/s}$$

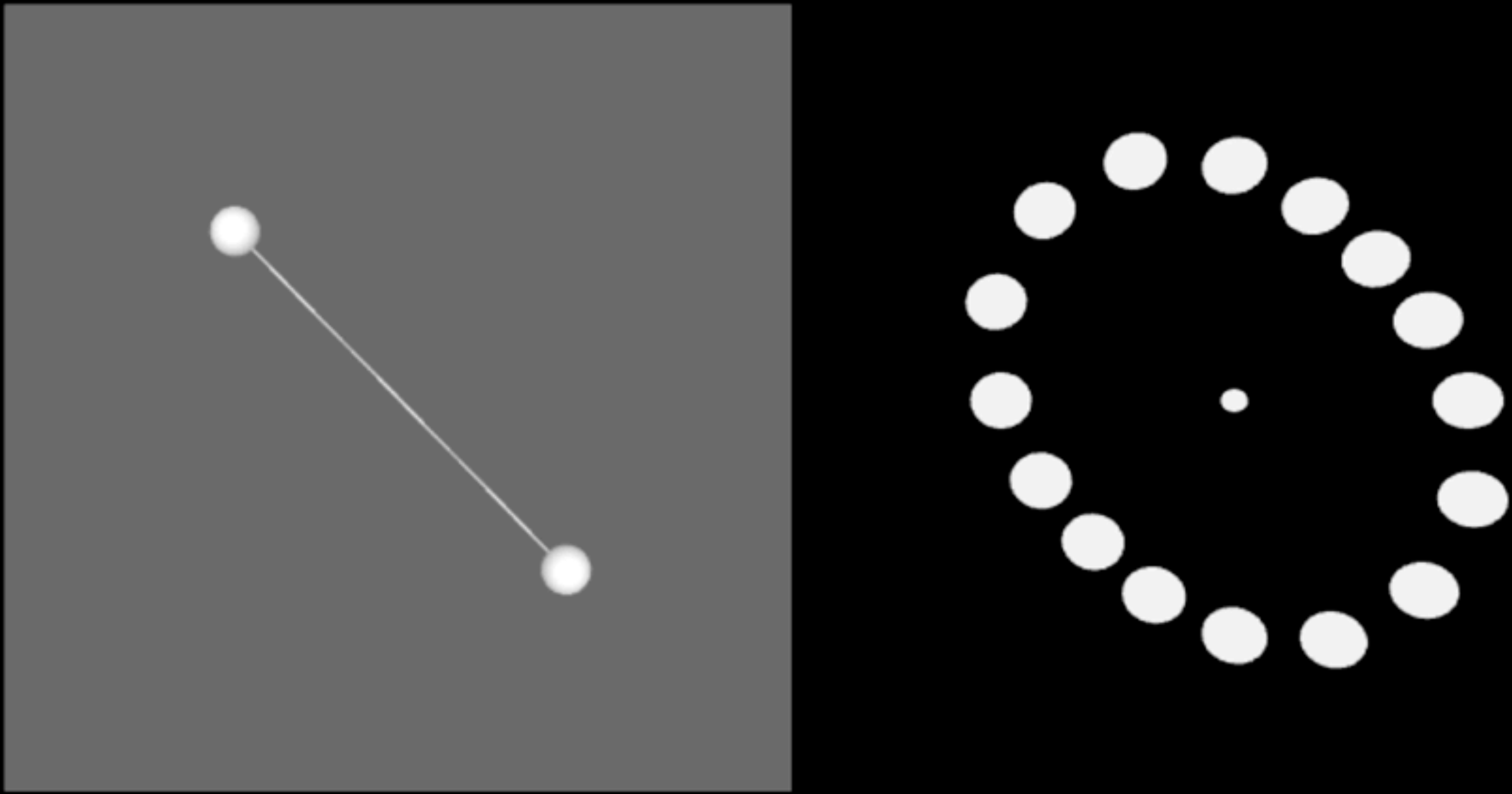
$$L_{\mathrm{GRB}} \sim 10^{49\text{-}52}\ \mathrm{erg/s}$$

Waves seen from above orbital plane



$$h \sim \frac{G}{c^4}\frac{E_{\mathrm{NS}}}{r} \sim 10^{-21}$$

Polarization vs. inclination



Demo by Eric Flynn, CSUF

Frequency of GW traces the frequency of orbits

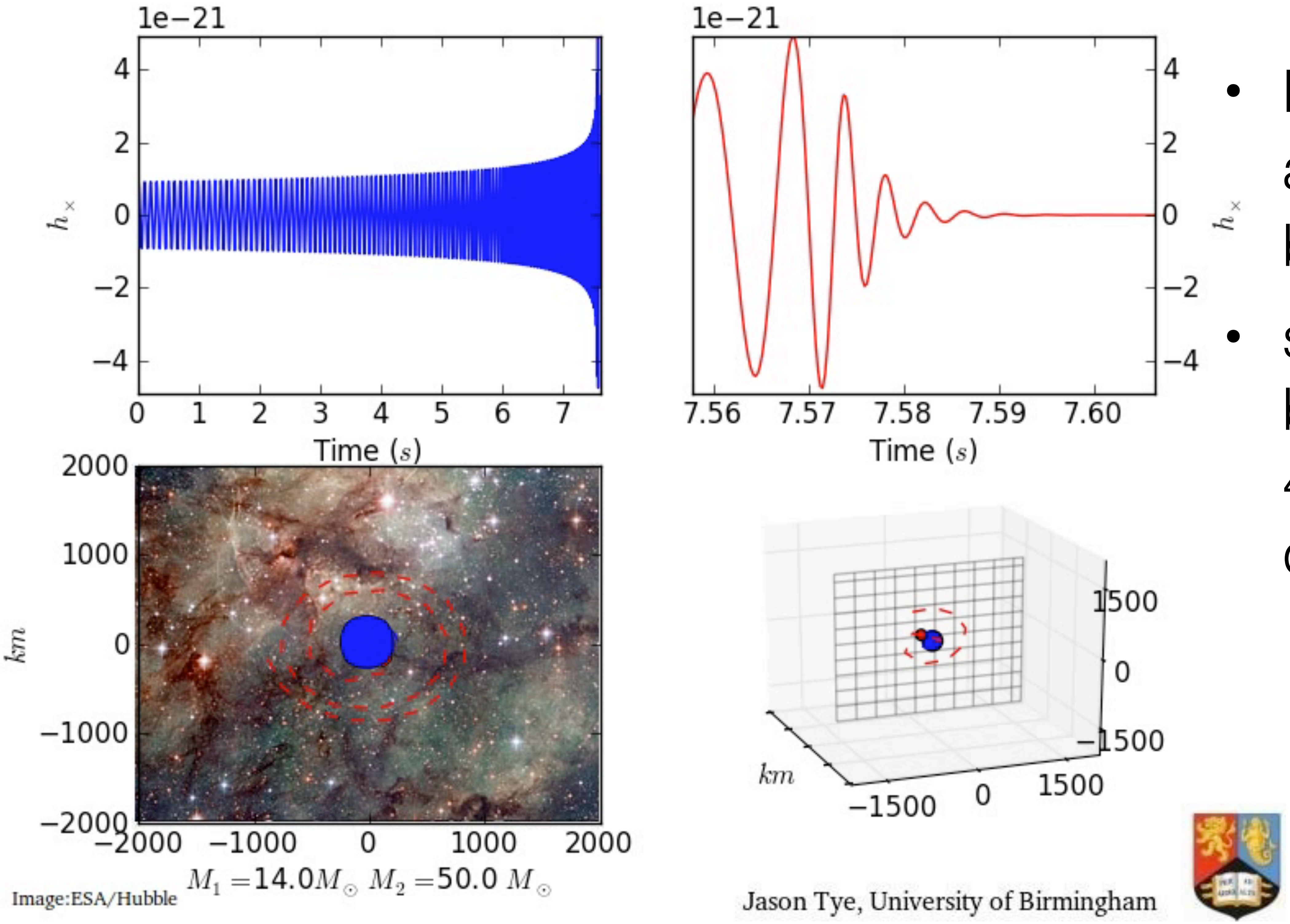


Image:ESA/Hubble

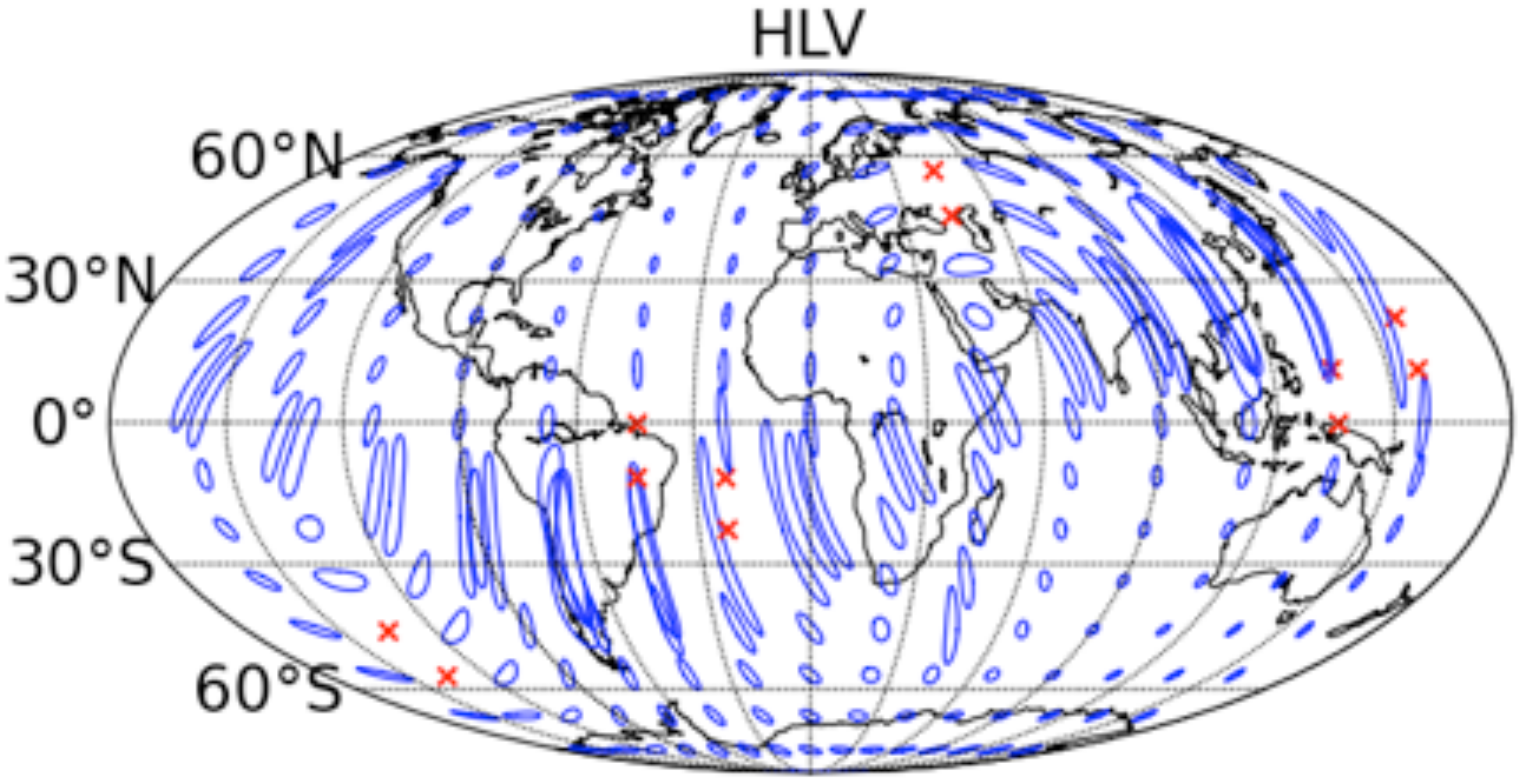
Jason Tye, University of Birmingham

- Movie:14 M⊙ and 50 M⊙ black holes
- slowed down by a factor of 4 to see/hear detail

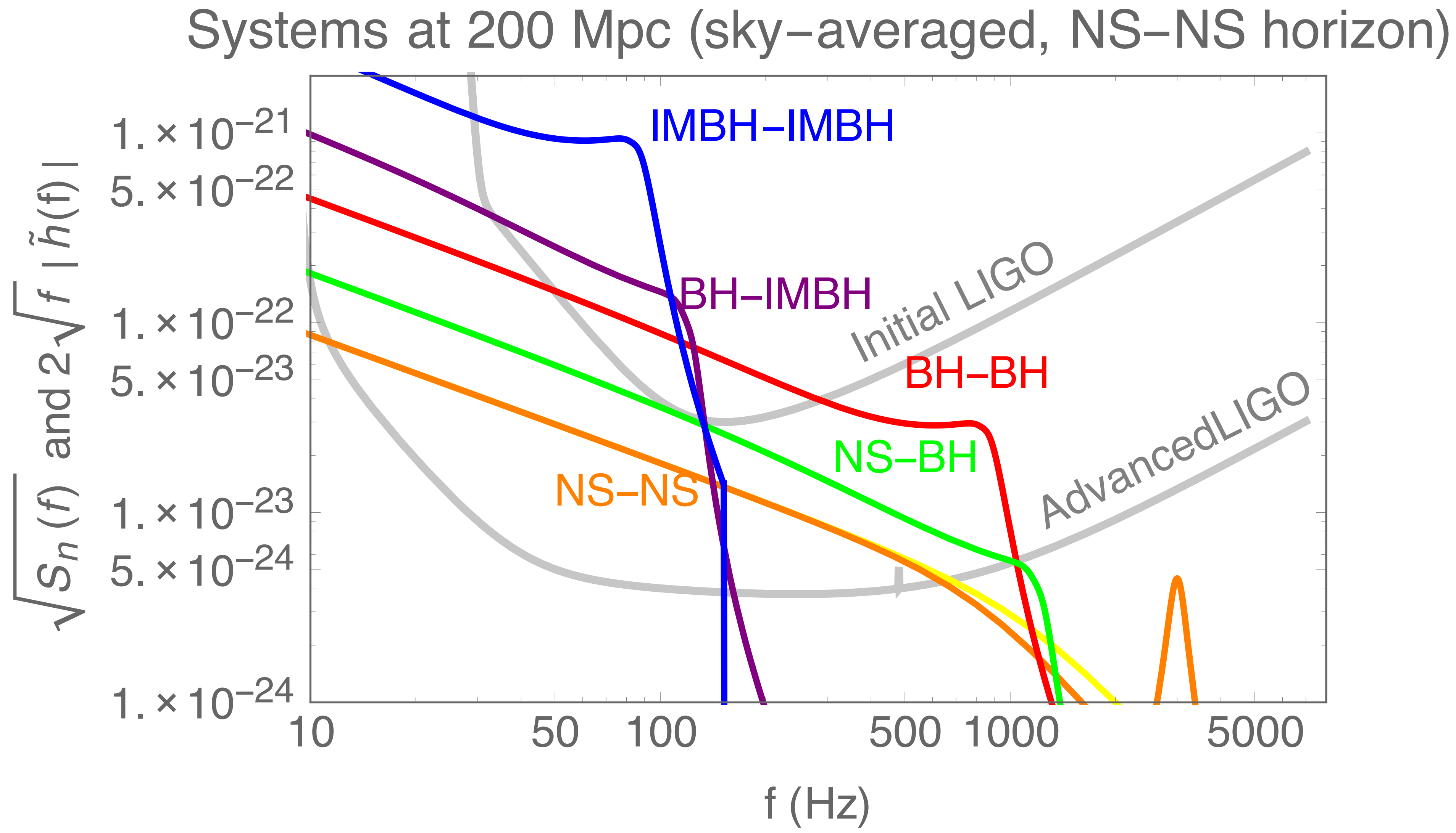
Parameters that modify the waveform (may be measurable)

- Masses
- Sky position
- Luminosity distance and orientation
- Spins
- Eccentricity
- Neutron-star EOS

Sky localization for source at 160 MPc with 3 detectors ~2019 (http://arxiv.org/abs/1304.0670)



Compact Binary Coalescence in LIGO



Assumptions:

NS at1.35 M⊙

BH at 10 M⊙

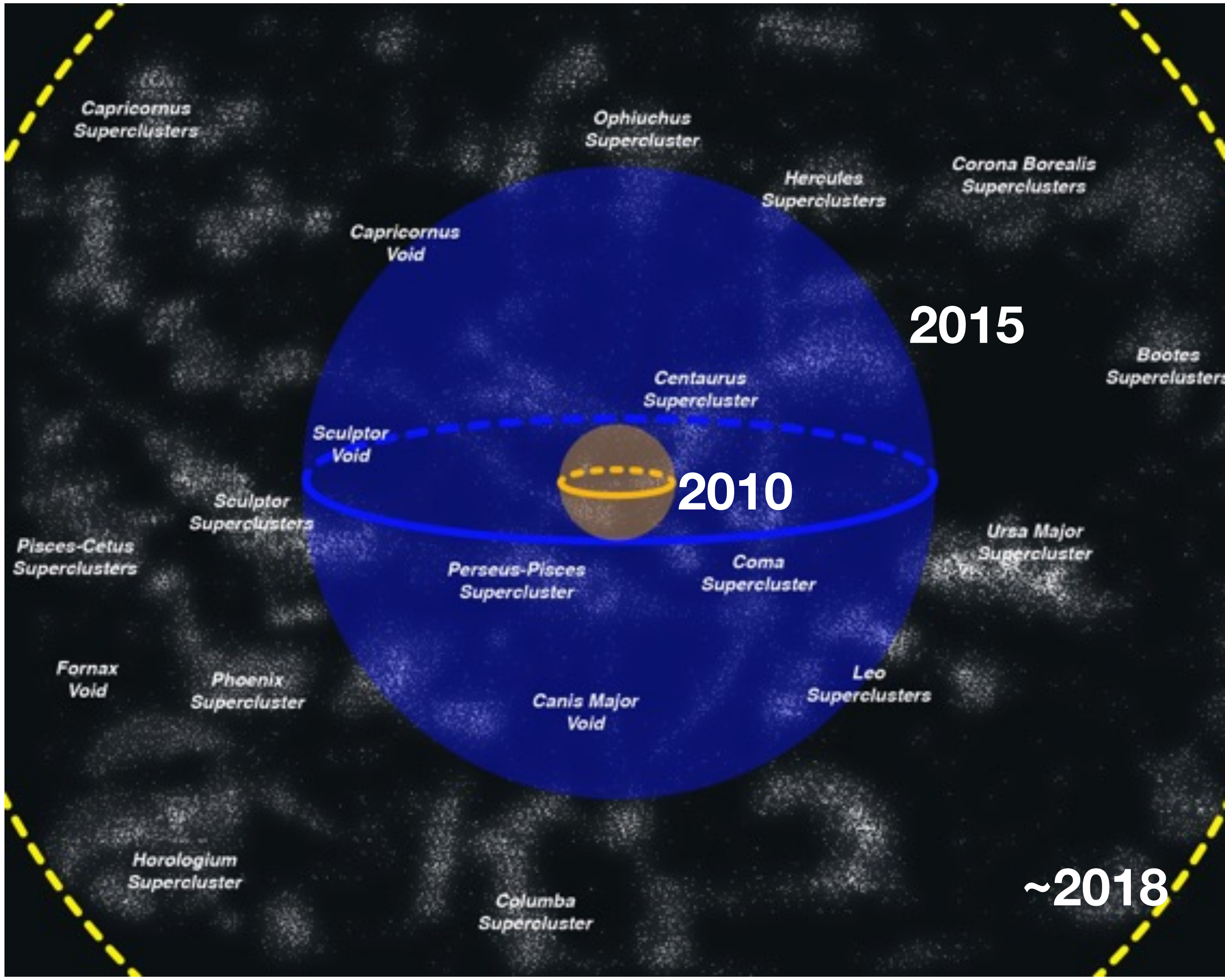
IMBH at 100 M⊙

Phenomenological waveform

Masses in detector frame

Detection prospects of Advanced LIGO design

- binary neutron star mergers to ~200 Mpc
- neutron star–black hole mergers to ~0.5 Gpc
- (10-10 M_{sun}) binary black hole mergers to ~1 Gpc
- unmodeled transients with energy of some galactic supernovae predictions
- (LIGO White Paper: https://dcc.ligo.org/LIGO-T1400054/public, rates above sky-averaged)



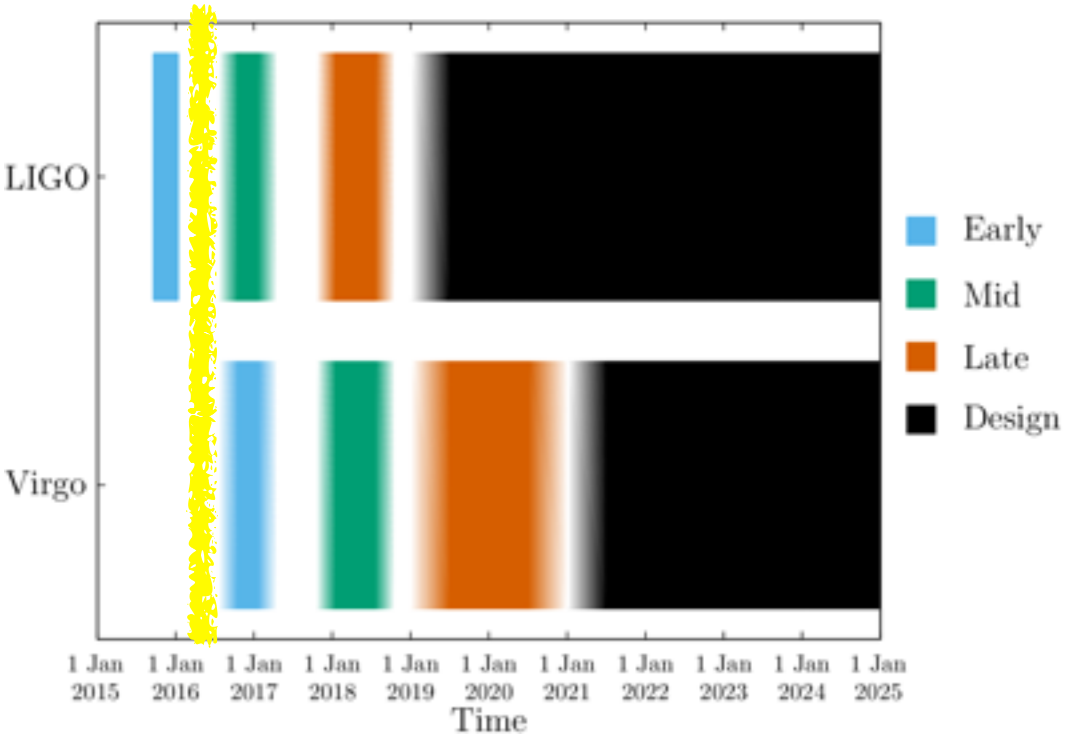
initial LIGO range: up to 20 Mpc
Shane Larson, Northwestern University

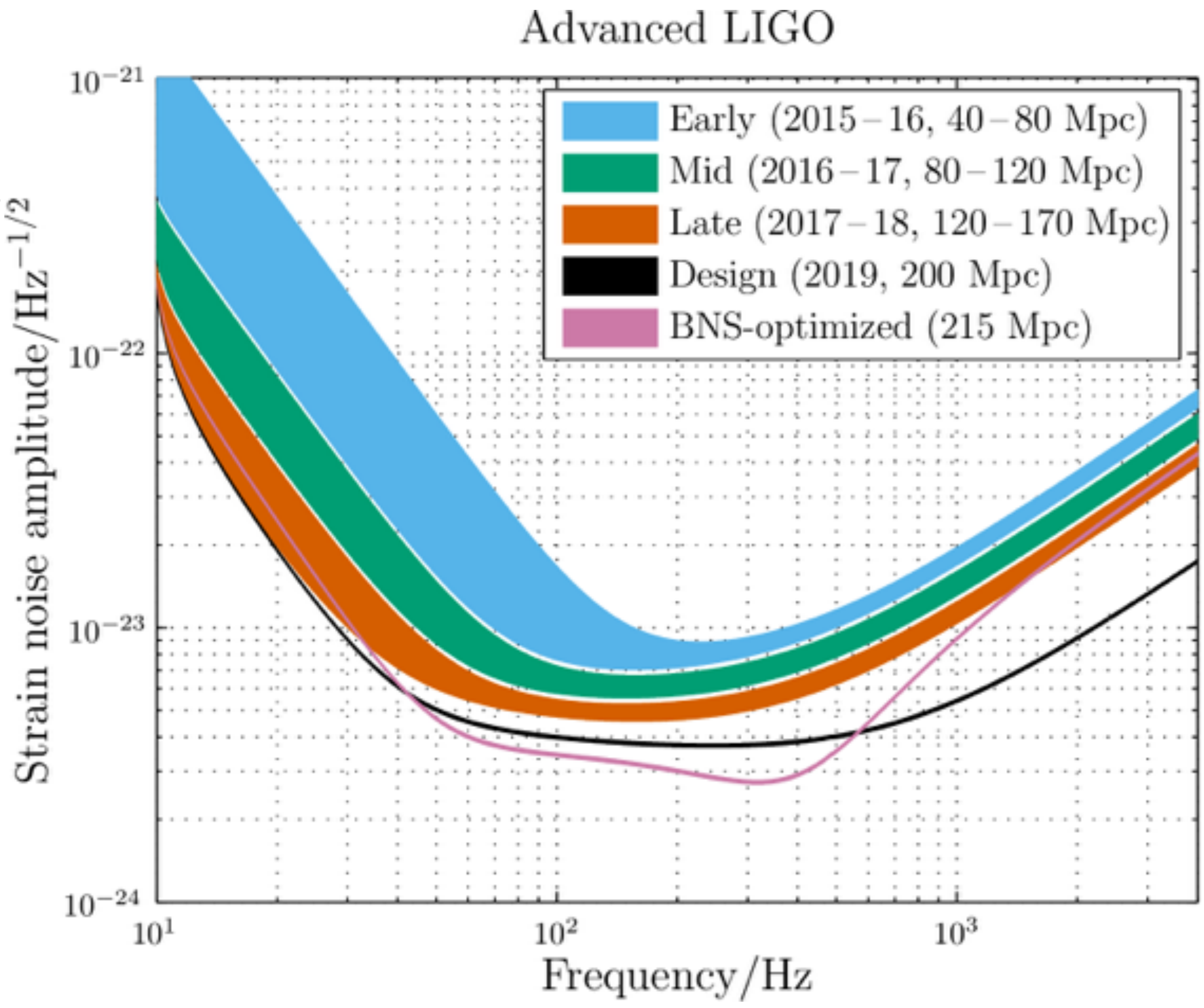
BNS detections 0.4 - 400 yr^{-1}
NSBH detections 0.2 - 300 yr^{-1}
LSC/VSC 1003.2480

BBH mergers 9 – 240 Gpc^{-3} yr^{-1}
LSC/VSC 1606.04856

GW Astronomy Roadmap

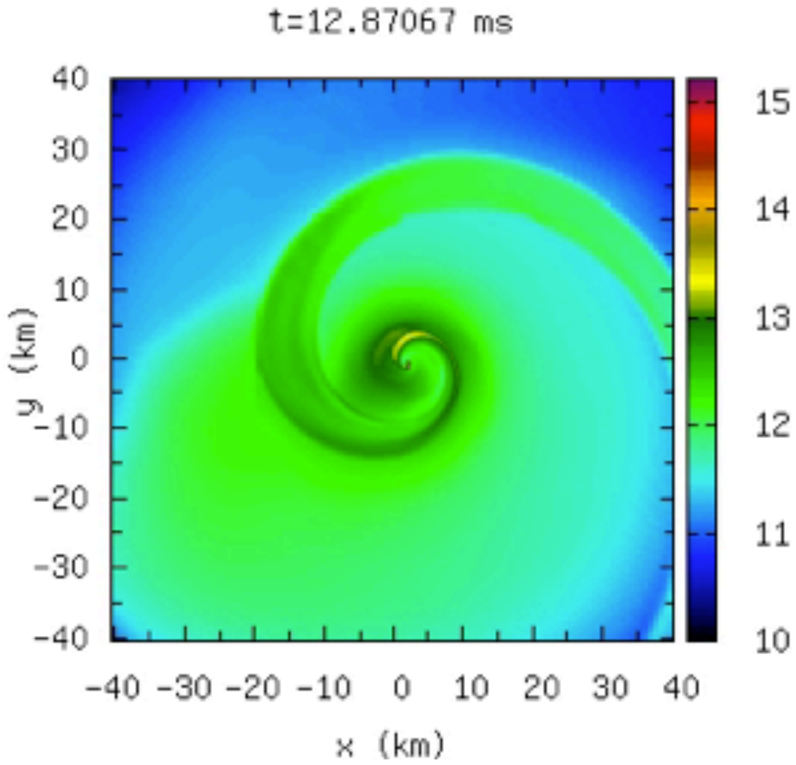
- LSC/VSC Living document at: http://arxiv.org/abs/1304.0670

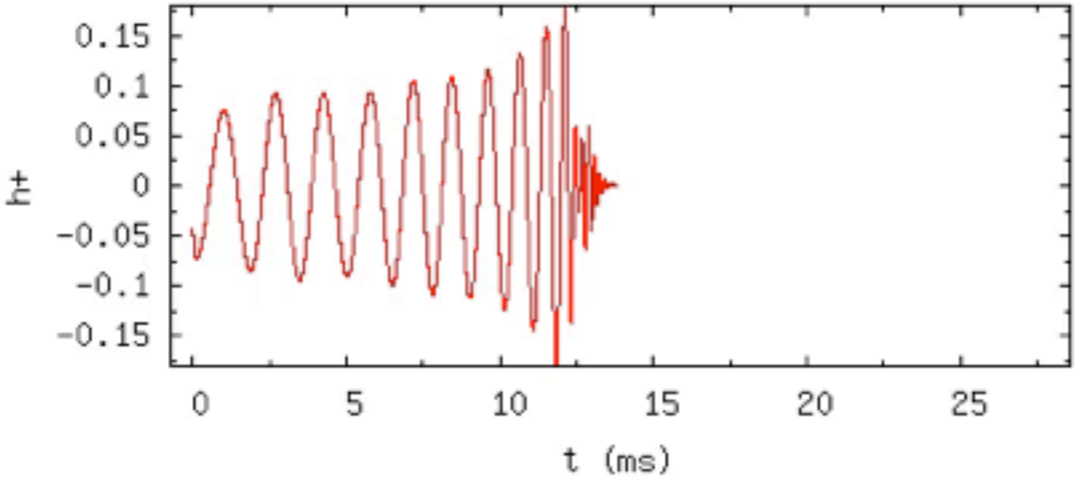




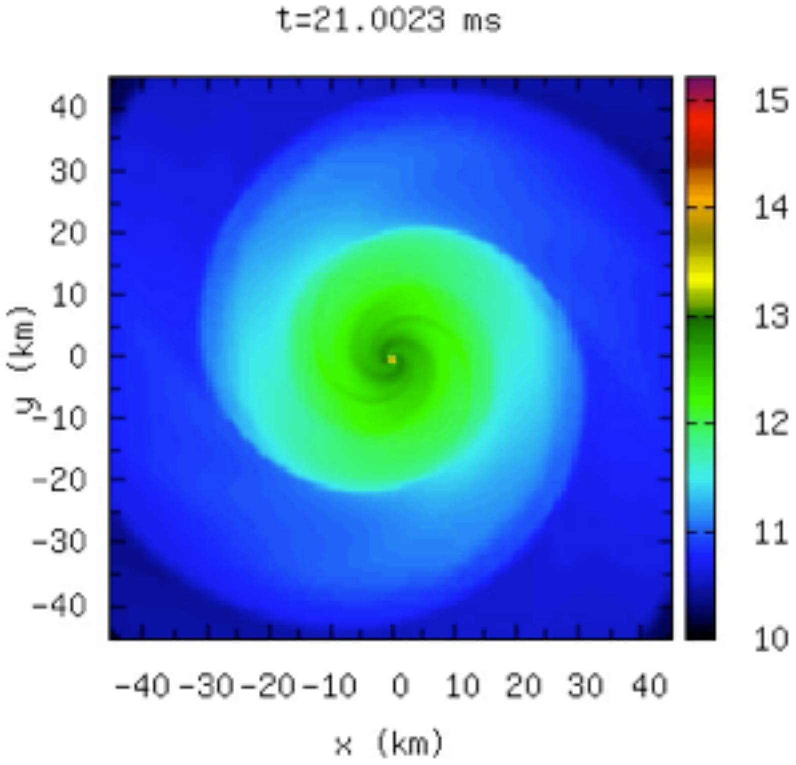
Epoch		2015 – 2016	2016 – 2017	2017 – 2018	2019+
Estimated run duration		4 months	6 months	9 months	(per year)
Burst range/Mpc	LIGO	40 – 60	60 – 75	75 – 90	105
	Virgo	—	20 – 40	40 – 50	40 – 80
BNS range/Mpc	LIGO	40 – 80	80 – 120	120 – 170	200
	Virgo	—	20 – 60	60 – 85	65 – 115
Estimated BNS detections		0.0005 – 4	0.006 – 20	0.04 – 100	0.2 – 200

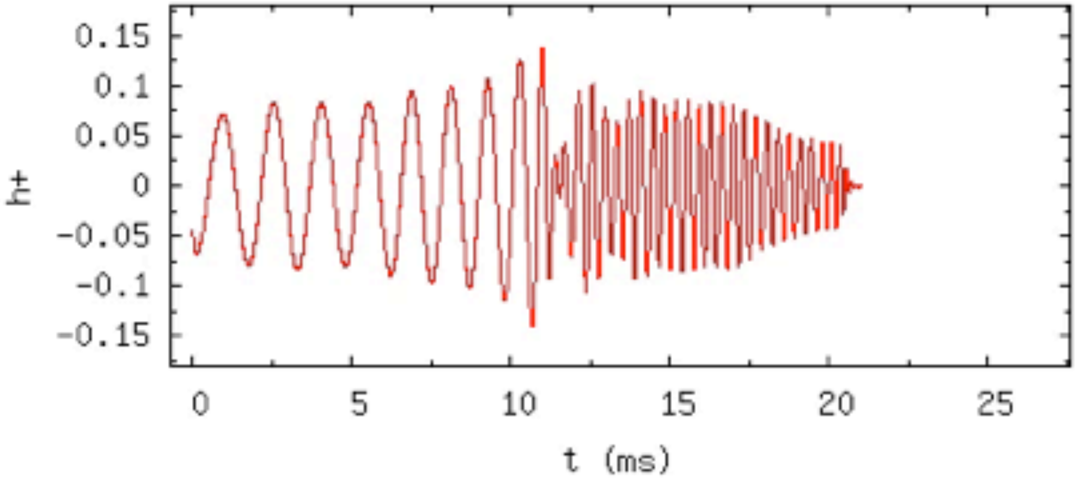
Merging
compact
stars





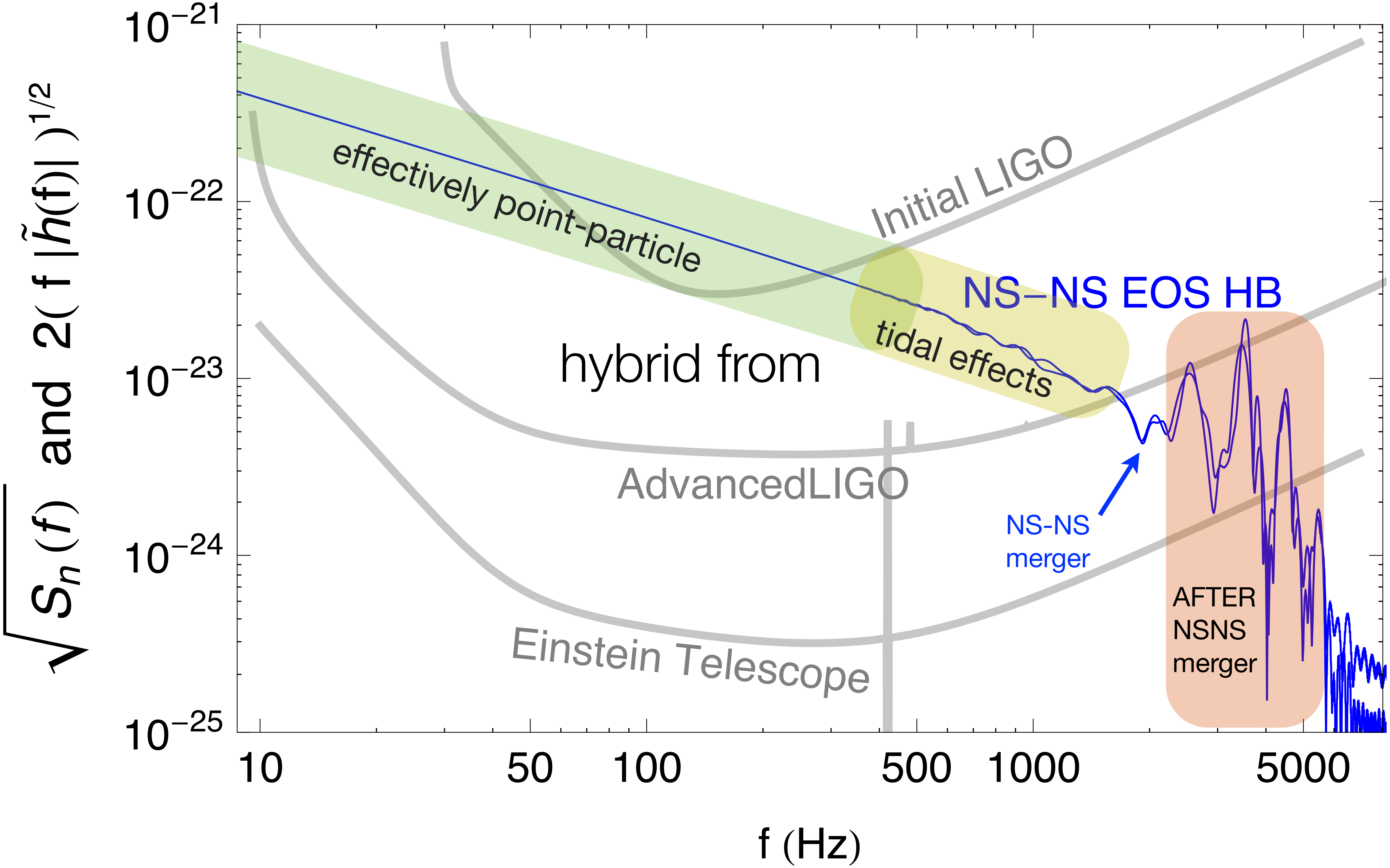
Merging
large
stars





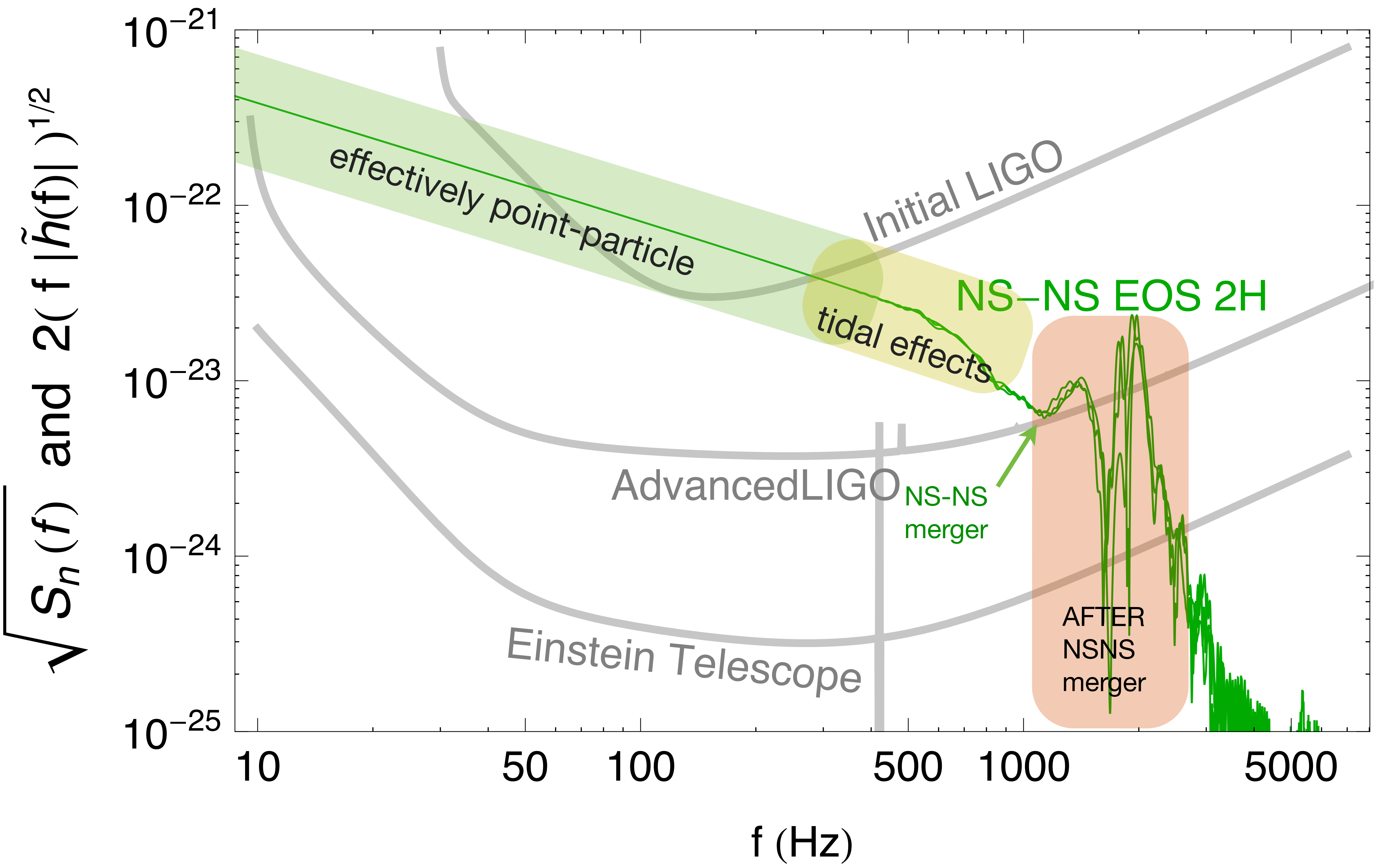
Numerical simulations: K. Hotokezaka, YITP

BNS spectrum (JR et al 1306.4065), 1.35-1.35, 100 Mpc



BNS spectrum (JR et al 1306.4065)

1.35-1.35, 100 Mpc



Dense matter in merging NS

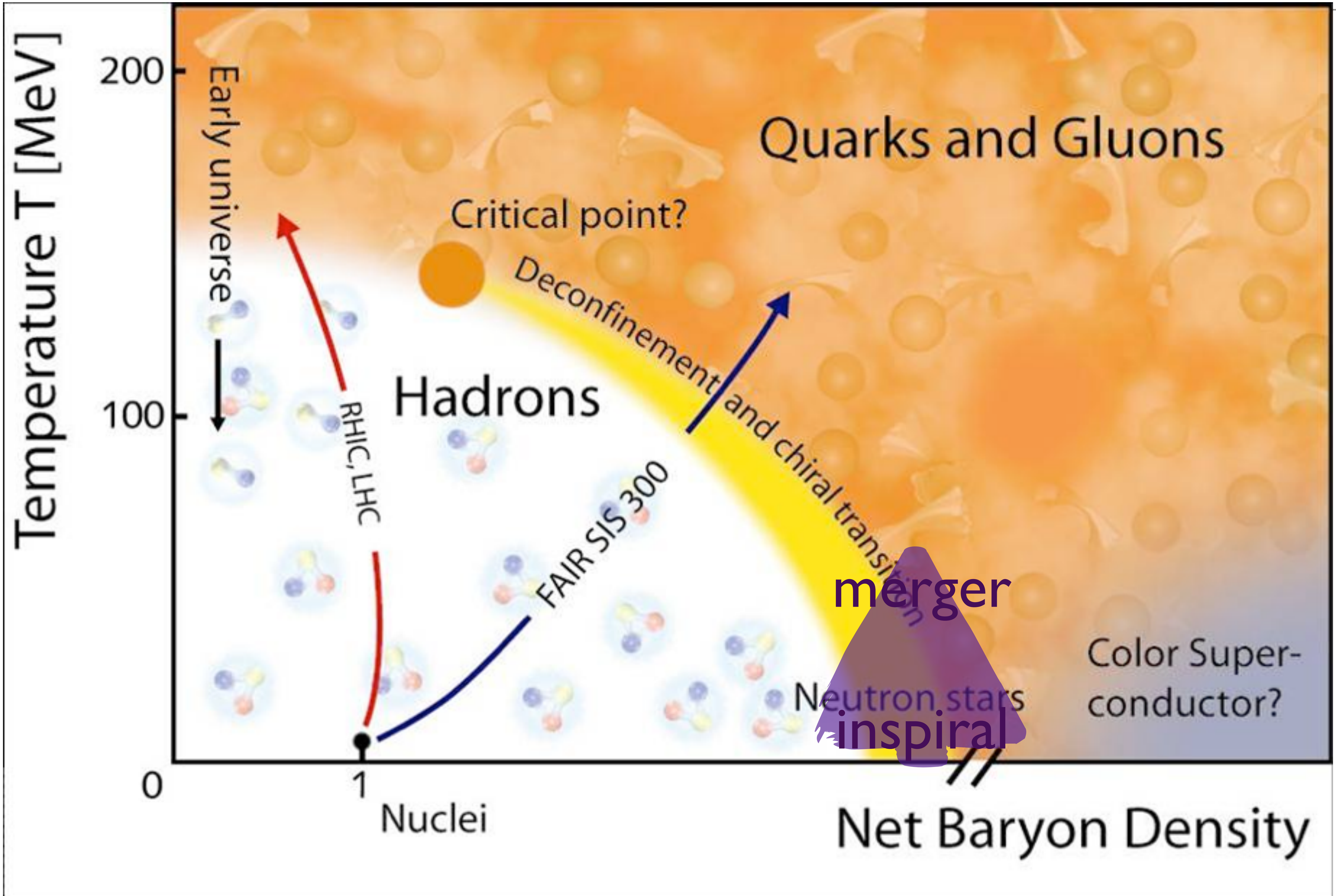
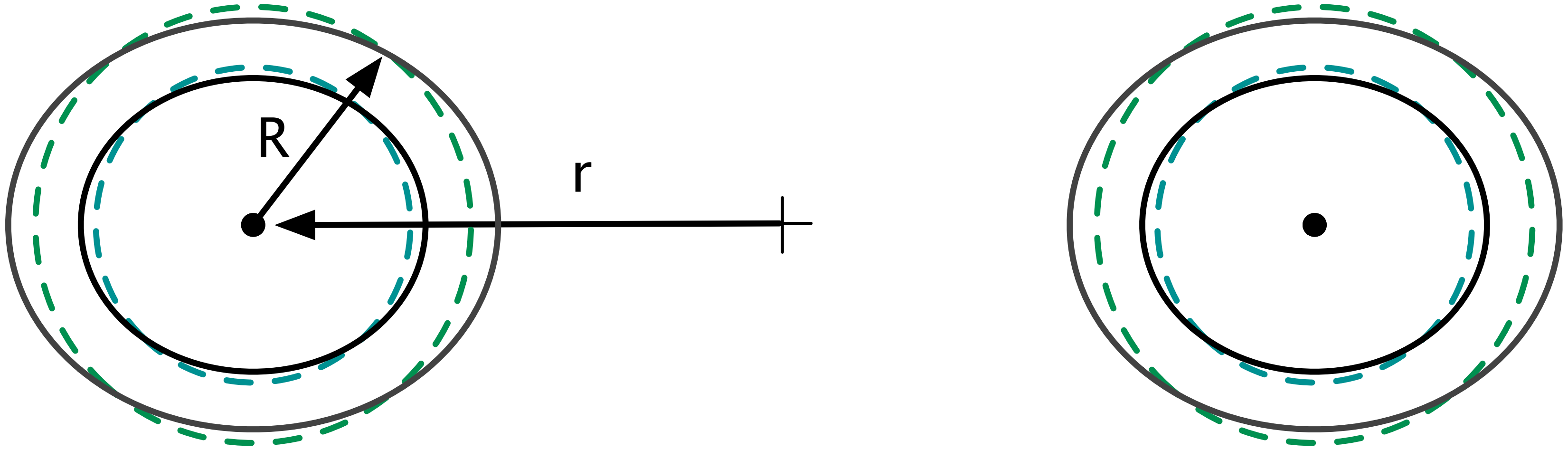


figure from FAIR CBM experiment

Hard to modify inspiral: e.g. transfer of ~10^{46} erg at ~100Hz modifies phase by 10^{-3} radians (Tsang et al 1110.0467) (but see e.g. Weinberg 1509.06975)

Tidal effects: Leading order modification of dynamics as stars approach each other



$$\lambda = \frac{Q}{\mathcal{E}} = \frac{\text{size of quadrupole deformation}}{\text{strength of external tidal field}}$$

Love number k_2

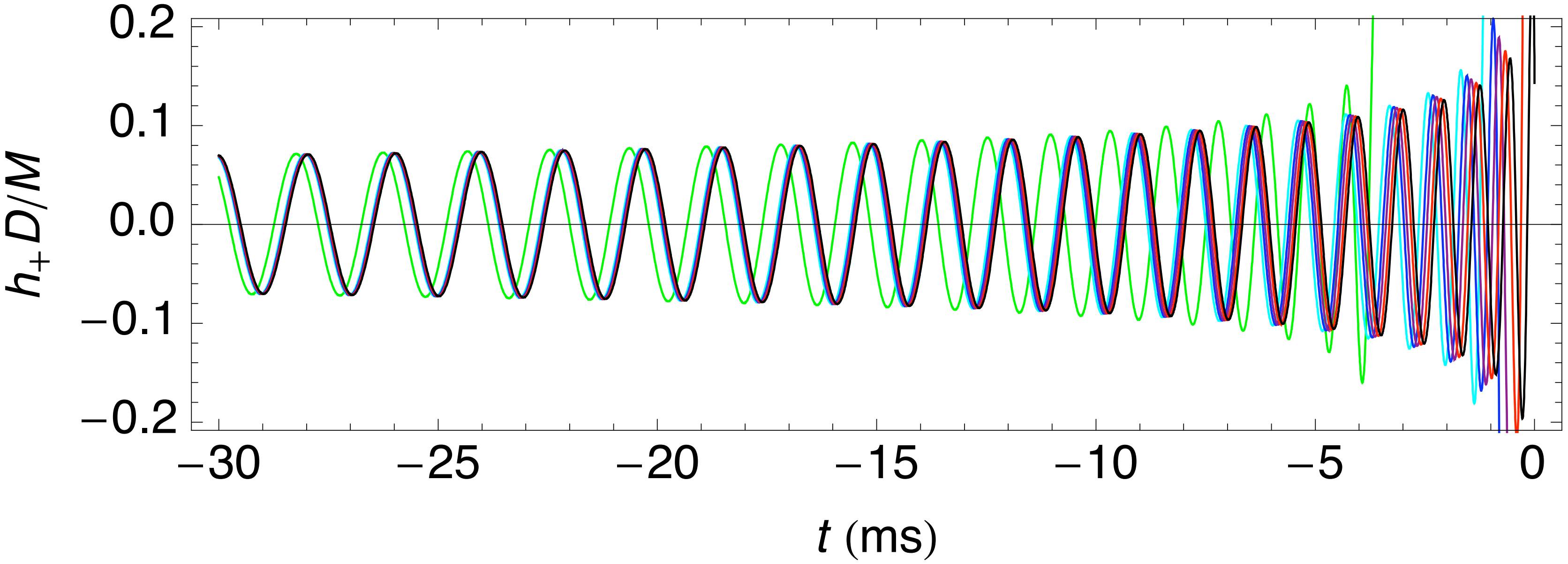
Radius R

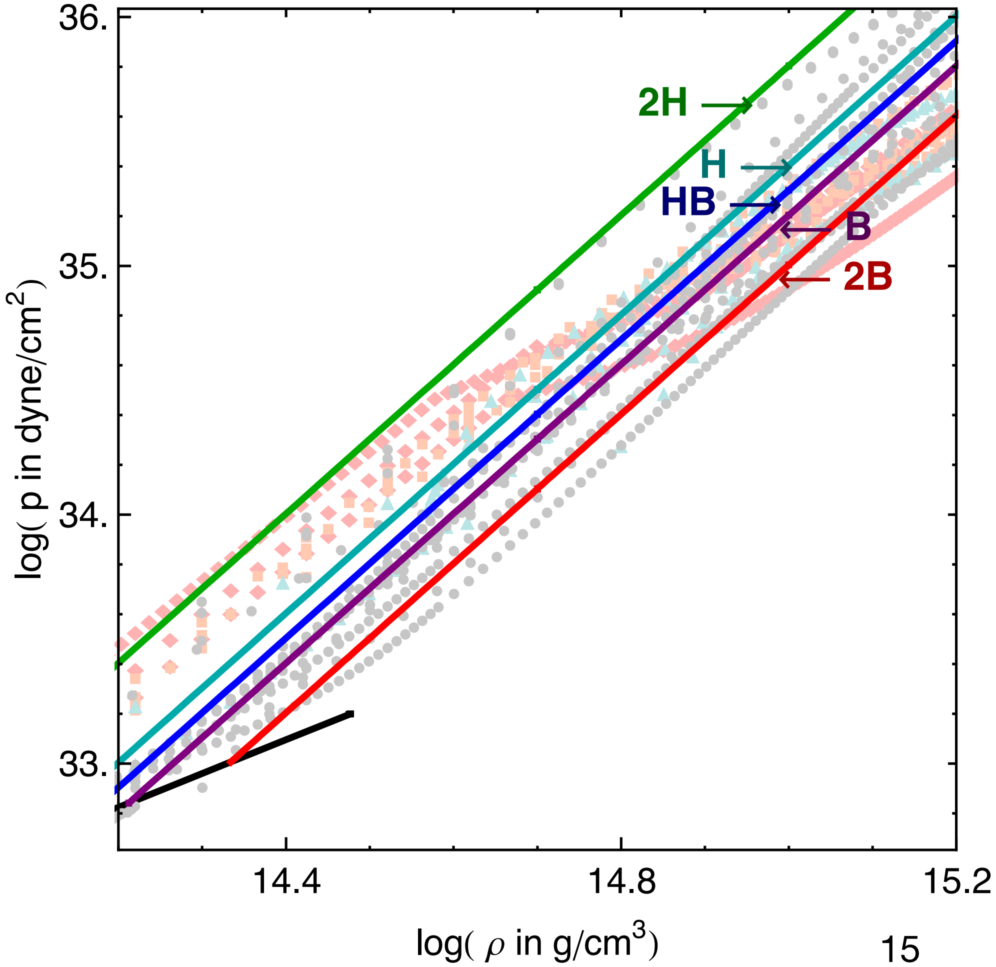
$$\lambda = \frac{2}{3} k_2 R^5 \quad (G = c = 1)$$

Tidal effects on waveforms

Energy goes into deforming the neutron star(s), tidal bulges add a bit to the gravitational radiation

Contribute to waveform formally at 5 and 6 PN - Vines et al (arXiv:1101.1673)

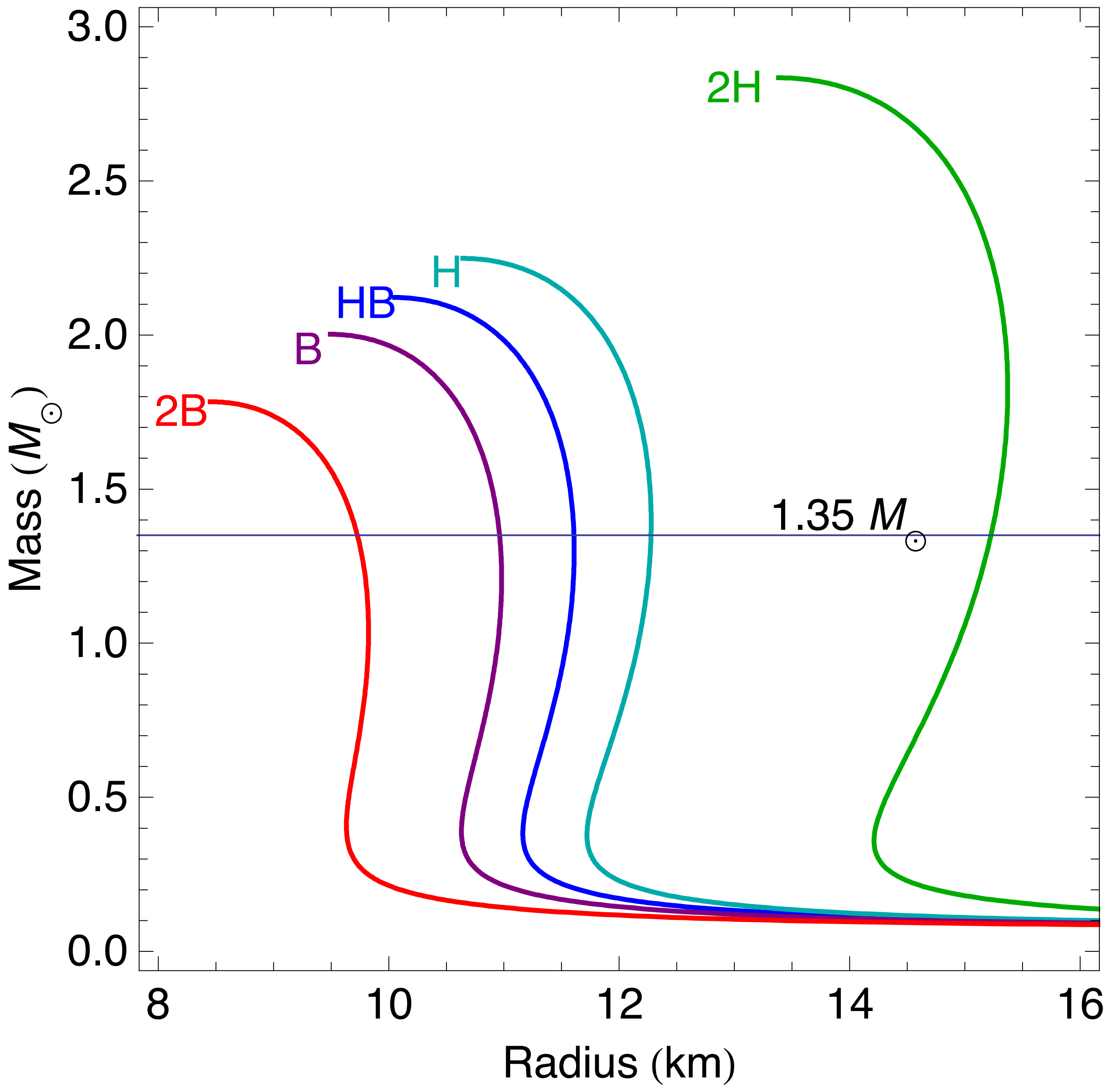


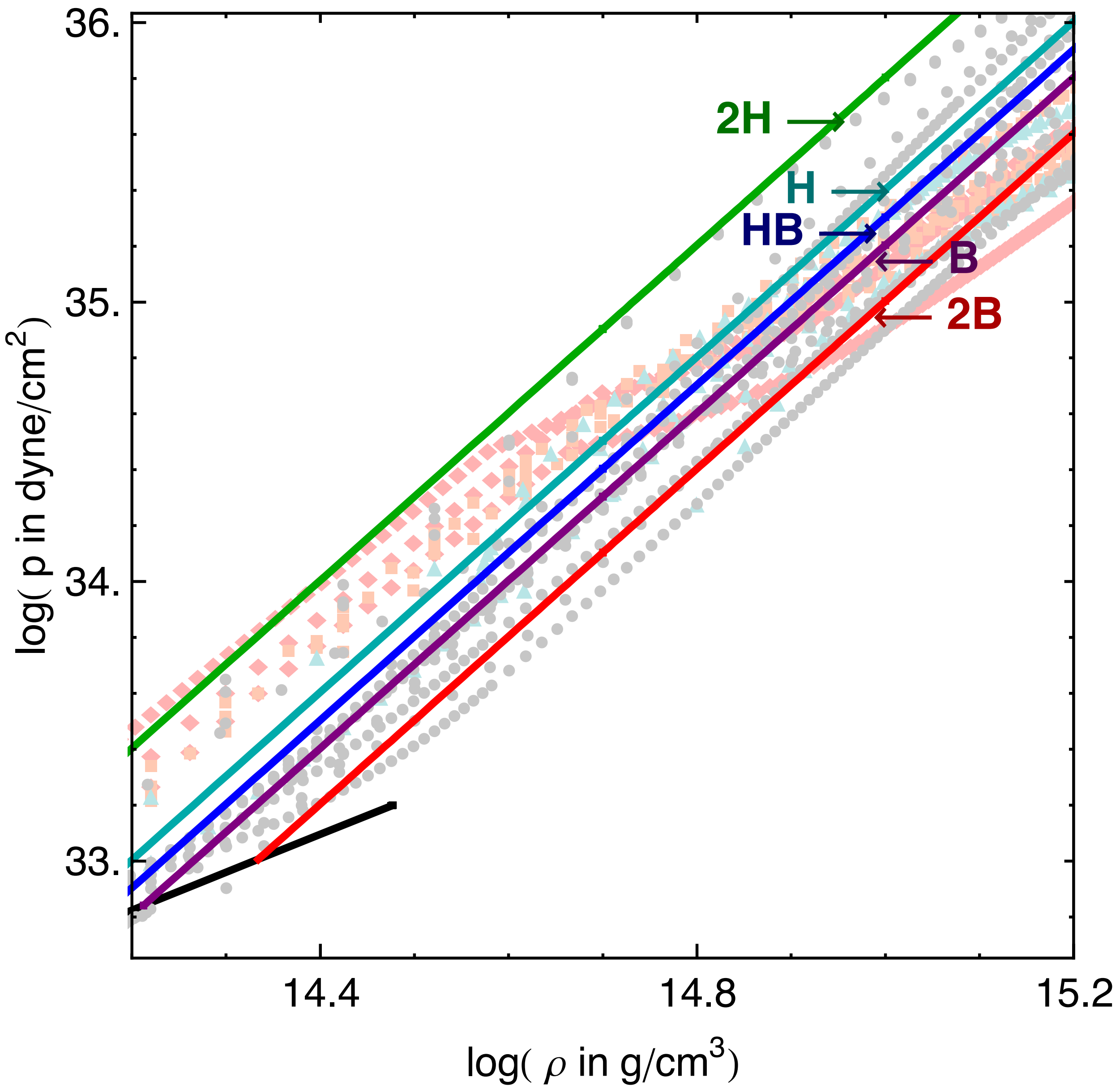


Write in terms of dimensionless parameter:

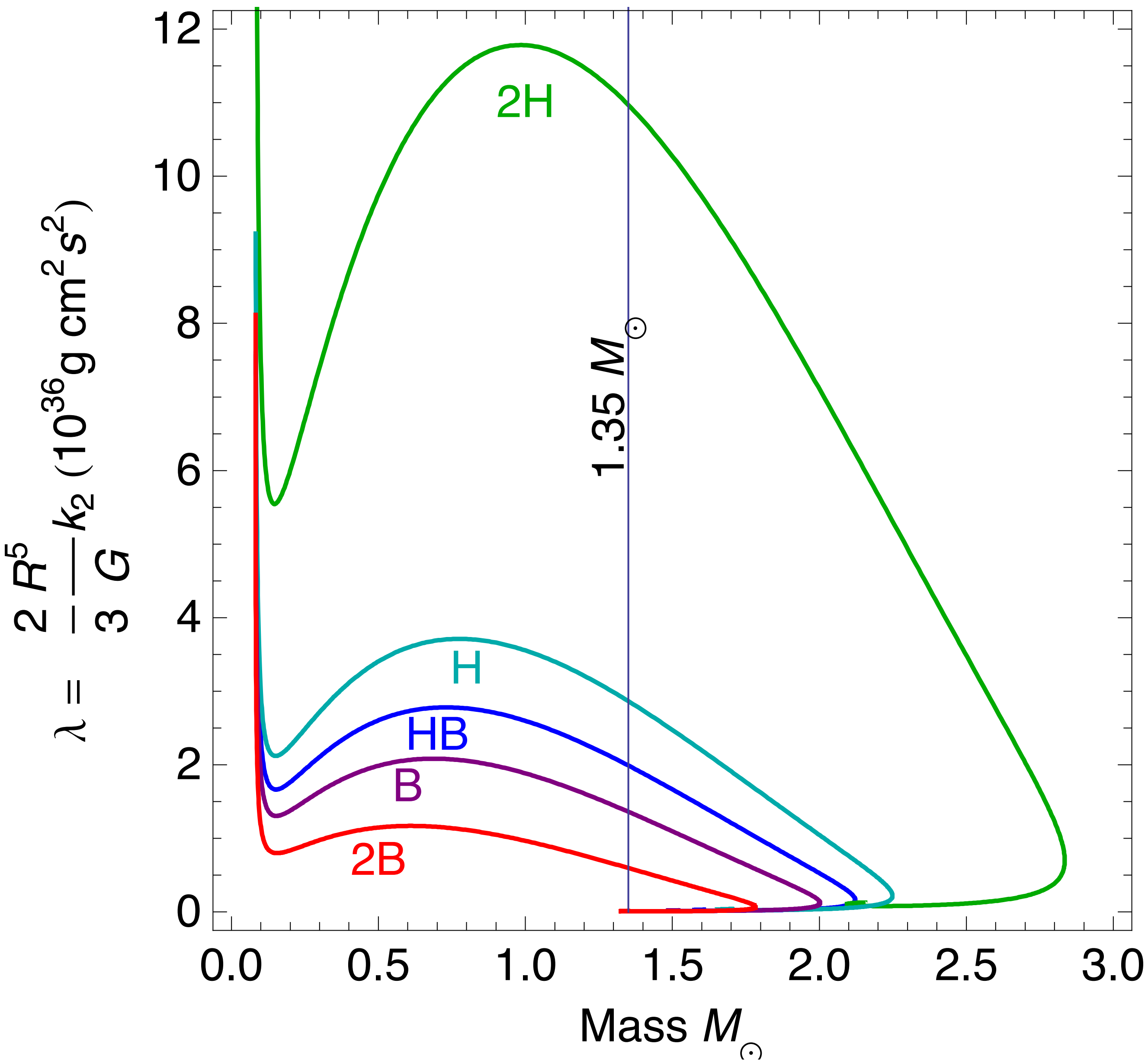
$$\Lambda = \frac{2}{3} k_2 \left(\frac{R}{M} \right)^5$$

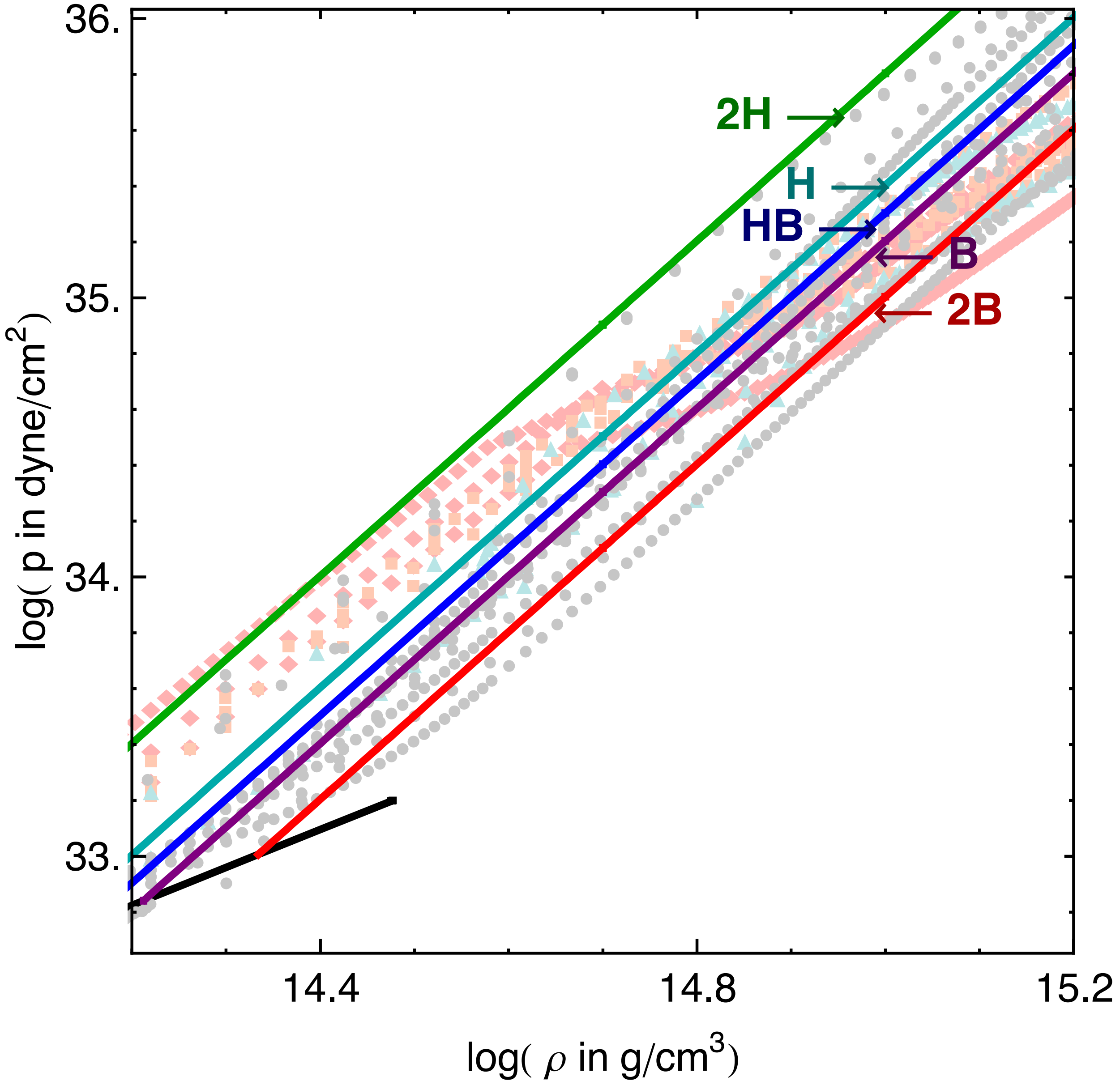
Equation of State: pressure and density



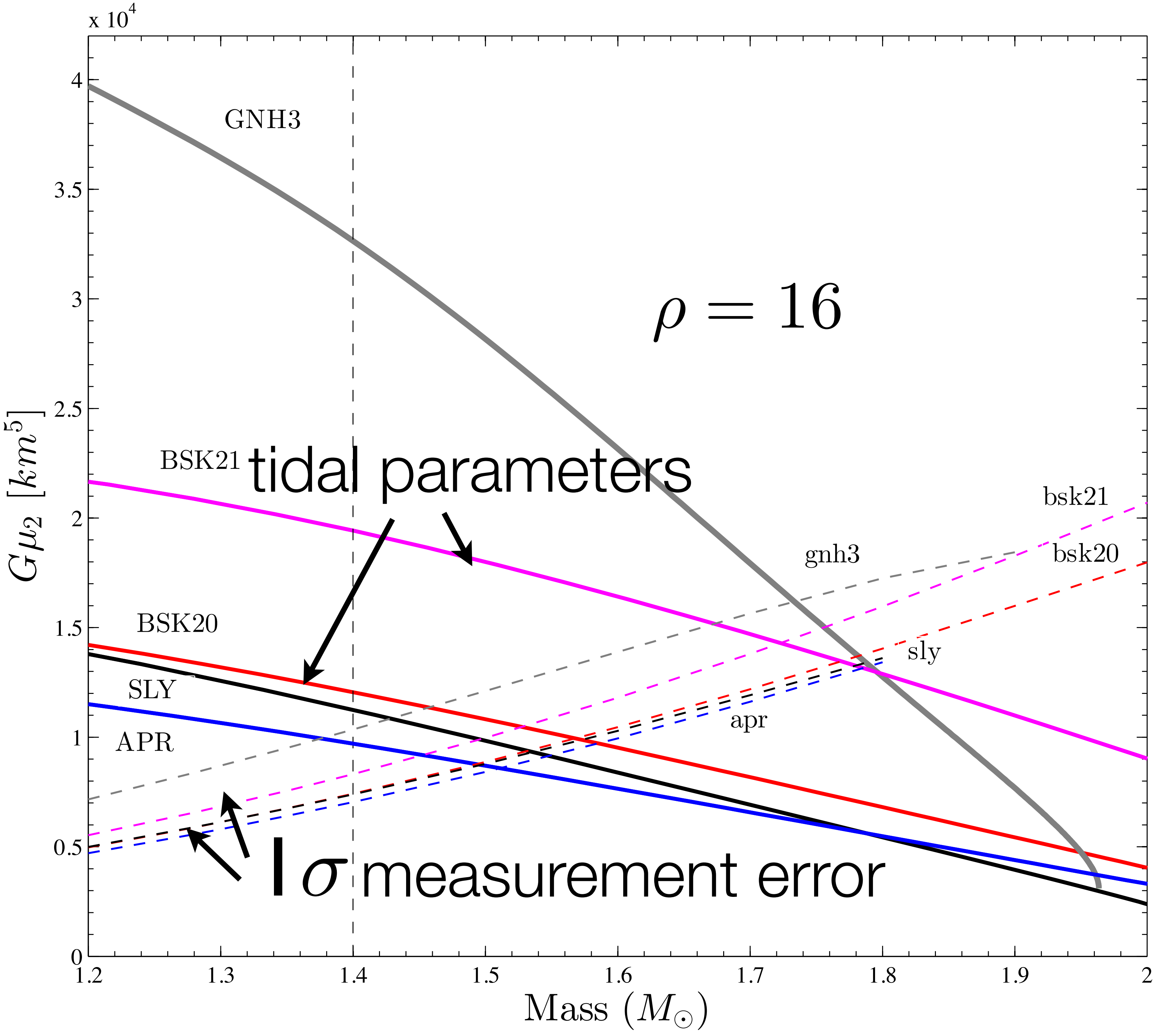


Equation of state determines λ(mass)





Extend leading-orders PN model to merger:



$\rho = 16$

tidal parameters

1σ measurement error

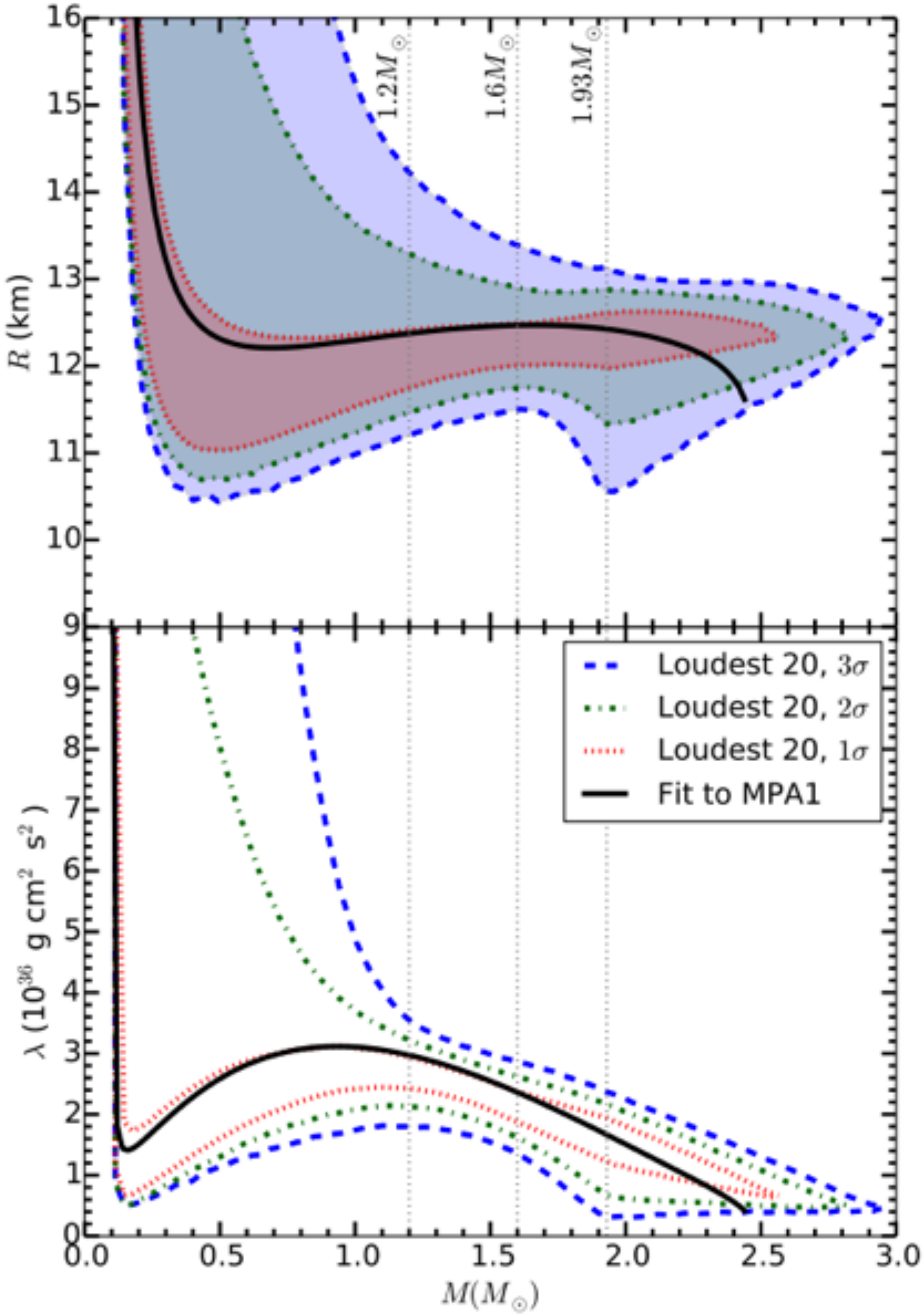
Damour, Nagar, Villain 2012

Use PN model up to 1704 Hz (estimate of contact)

spin marginalization

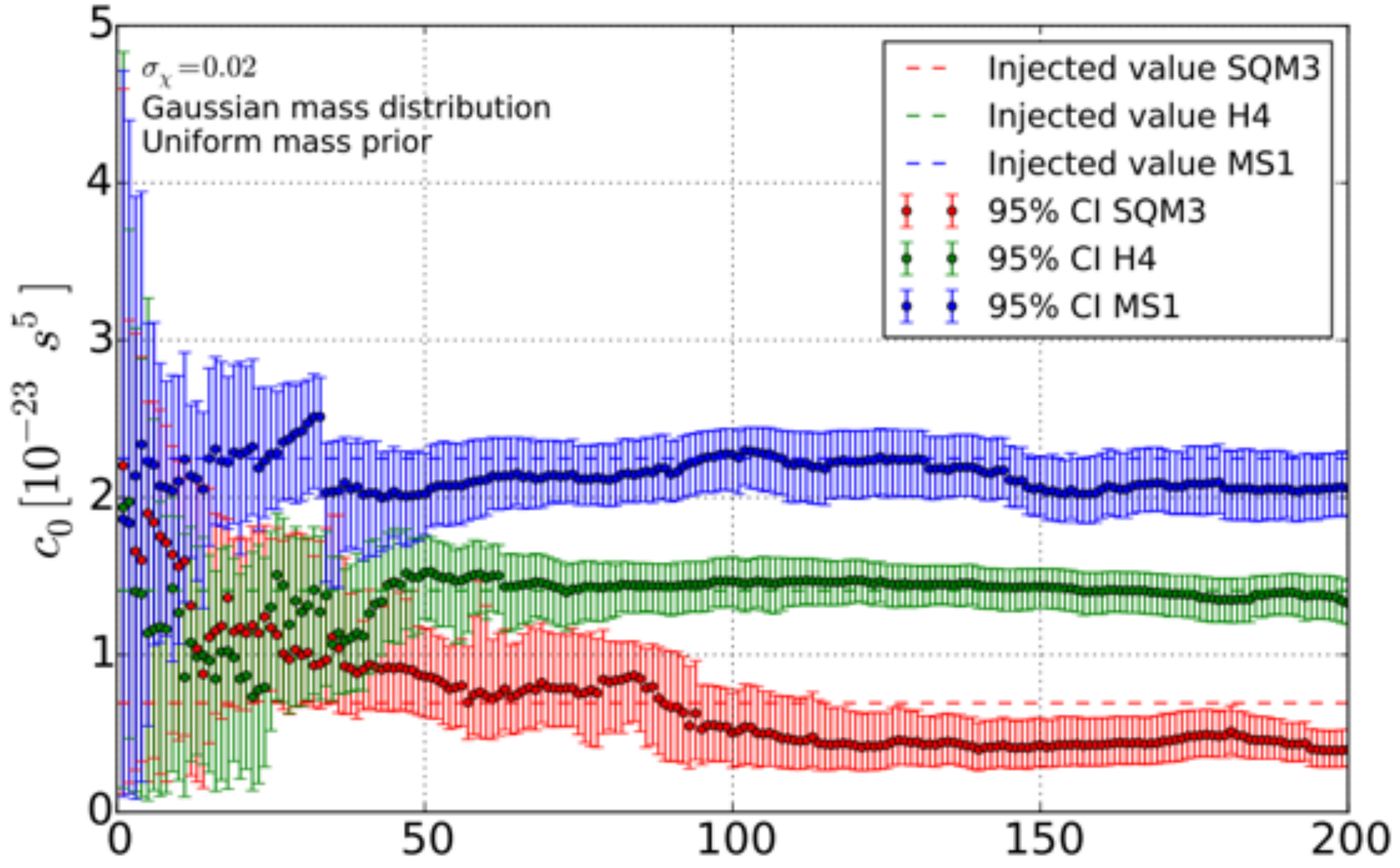
See also: Hinderer et al 0911.3535

Example implications for LIGO:
EOS constraint from multiple BNS detections



Lackey and Wade (40 signals)

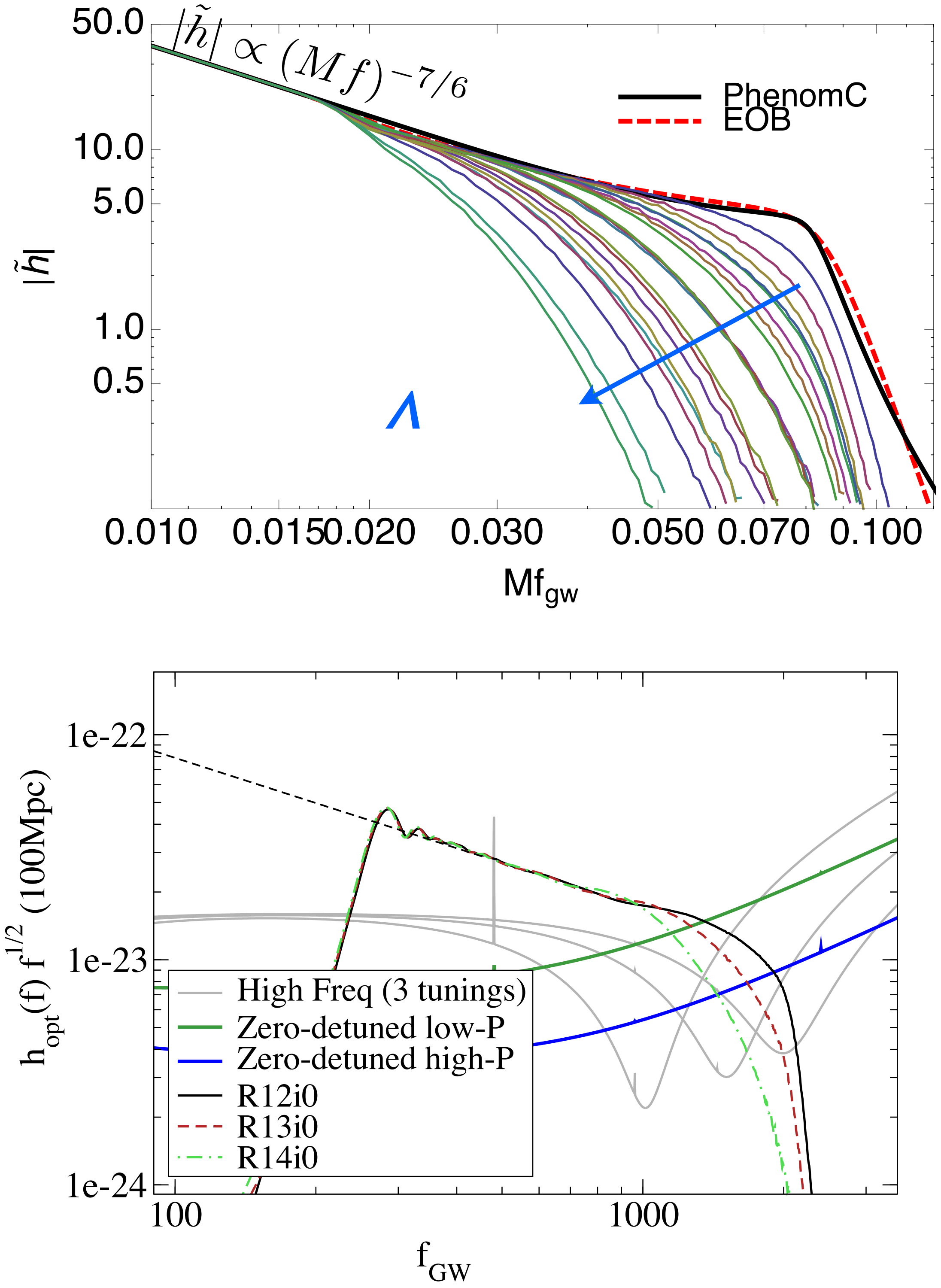
http://arxiv.org/abs/1410.8866



Agathos et al 2015

http://arxiv.org/abs/1503.05405

What about BHNS?

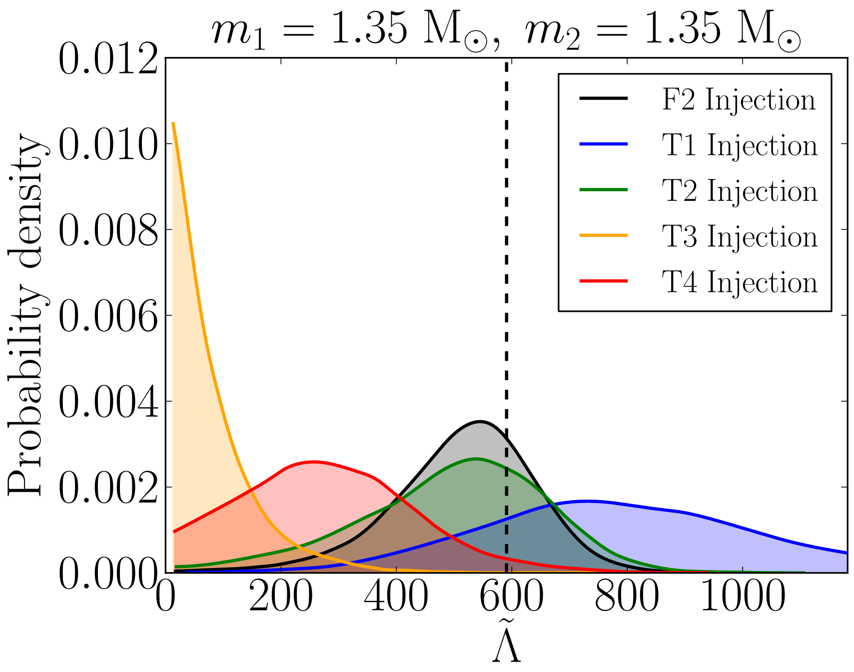


With aLIGO, tidal parameter can be measured to 10-100% error at 100 Mpc (Lackey et al 1303.6298)

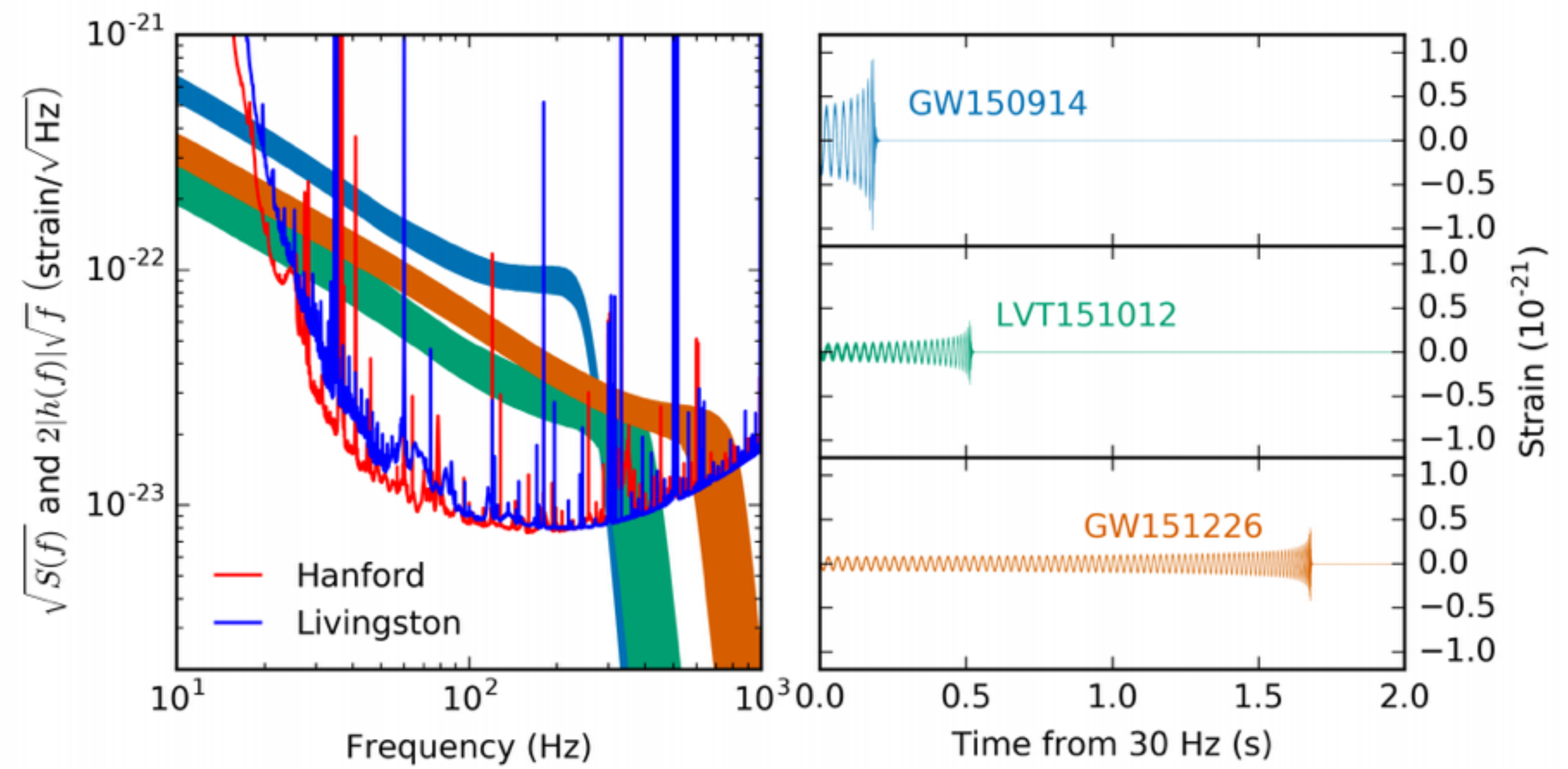
1:7 mass ratio: NS with radii of 12 and 14 are marginally distinguishable at 100 MPc (Foucart et al. 1212.4810)

(small fraction of ALIGO range)

- Leading order *parameter* (λ or Λ) is effective for describing full inspiral/merger for both BNS and BHNS (JR et al 1306.4065, Bernuzzi et al 1402.6244)
- Leading order PN waveforms give good estimates of EOS-dependent effect size/measurability (e.g. JR et al 1306.4065 compares PN to hybrid error estimates)
- Leading PN waveforms with tidal corrections are NOT sufficient for measuring EOS effects (Favata 1310.8288,Yagi/Yunes: 1310.8358, Wade et al. 1402.5156)

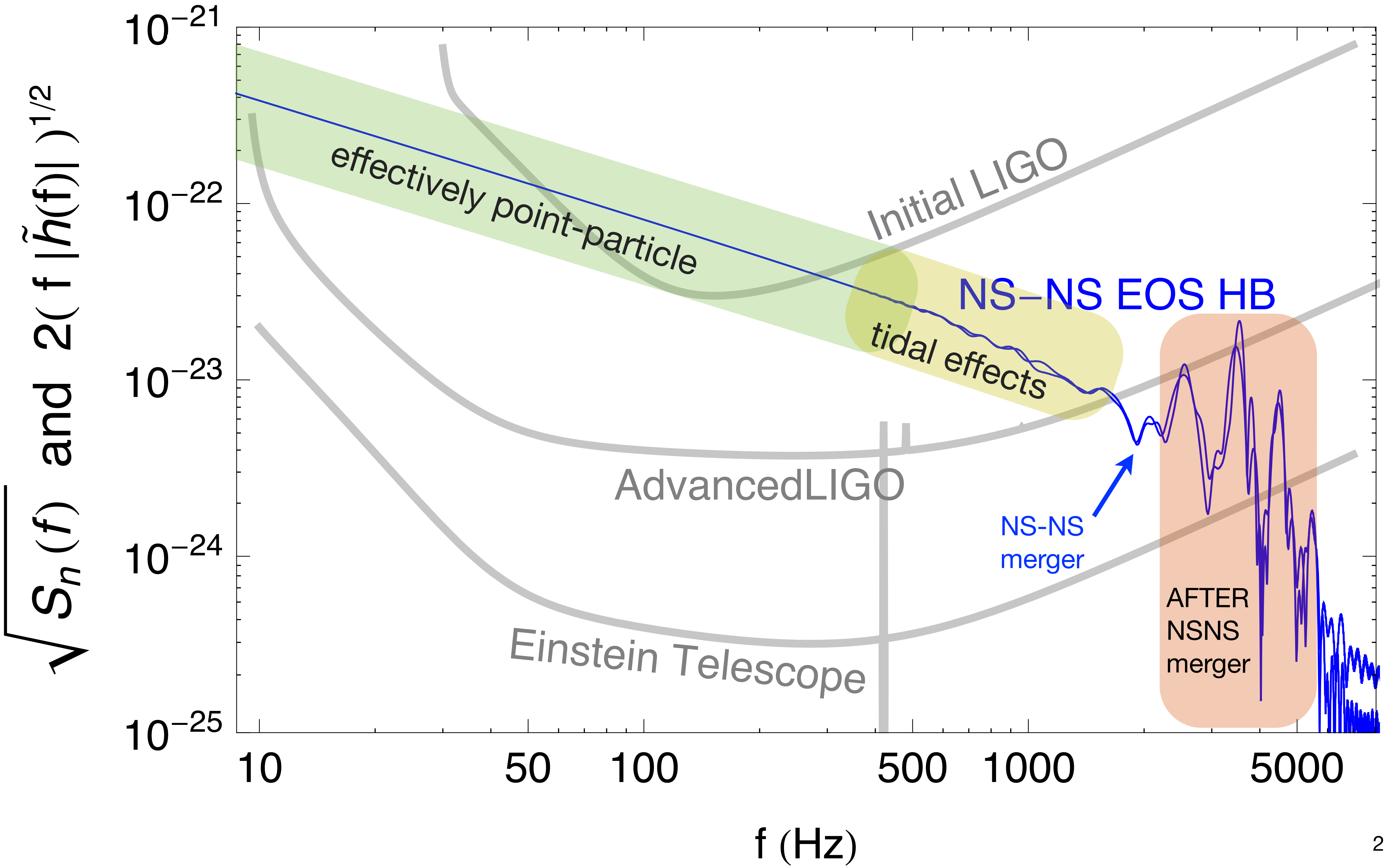


- We know more than PN! e.g. BBH analyses (LIGO/VIRGO 1602.03840,1606.04855,1606.04856 …) use Phenomenological and Effective-One-Body Inspiral+Merger waveform models calibrated to numerical simulation



"Binary Black Hole Mergers in the first Advanced LIGO Observing Run”
https://arxiv.org/abs/1606.04856

Focus on inspiral-to-merger for EOS measurement (post-merger? See e.g. Clark et al 1509.08522)



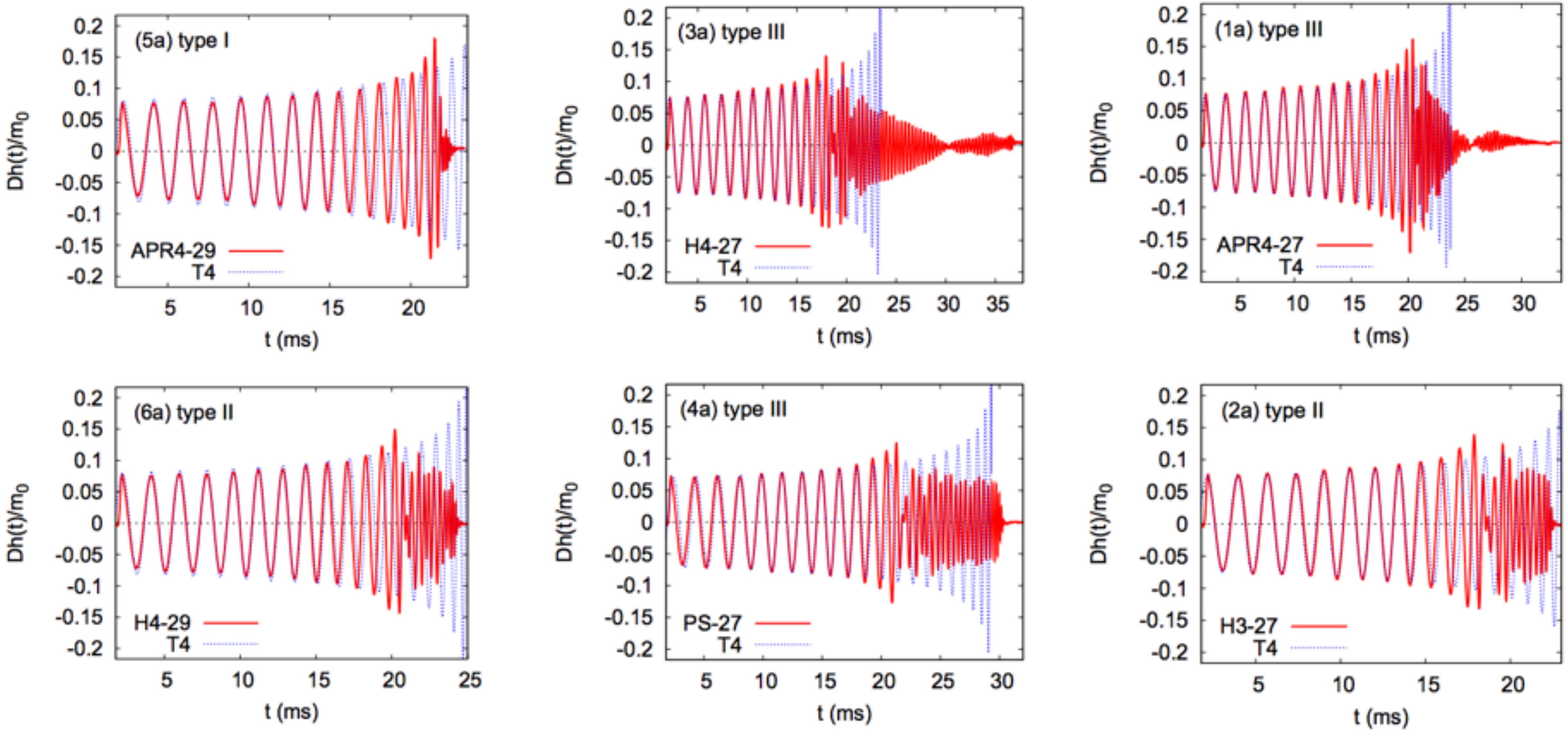
Frameworks for modeling gravitational waves for neutron-star mergers

- Effective-one-body (EOB)
  - PN maps to reduced-mass object orbiting Schwarzschild
  - + tidal corrections + high order effects (Bernuzzi et al 1412.4553, Hinderer et al 1602.00599, …)
- New: Phenomenological model based on modifying simple PN framework, fit to numerical merger (Park et al, in prep)
  - Useful to have two framework for systematics estimates!

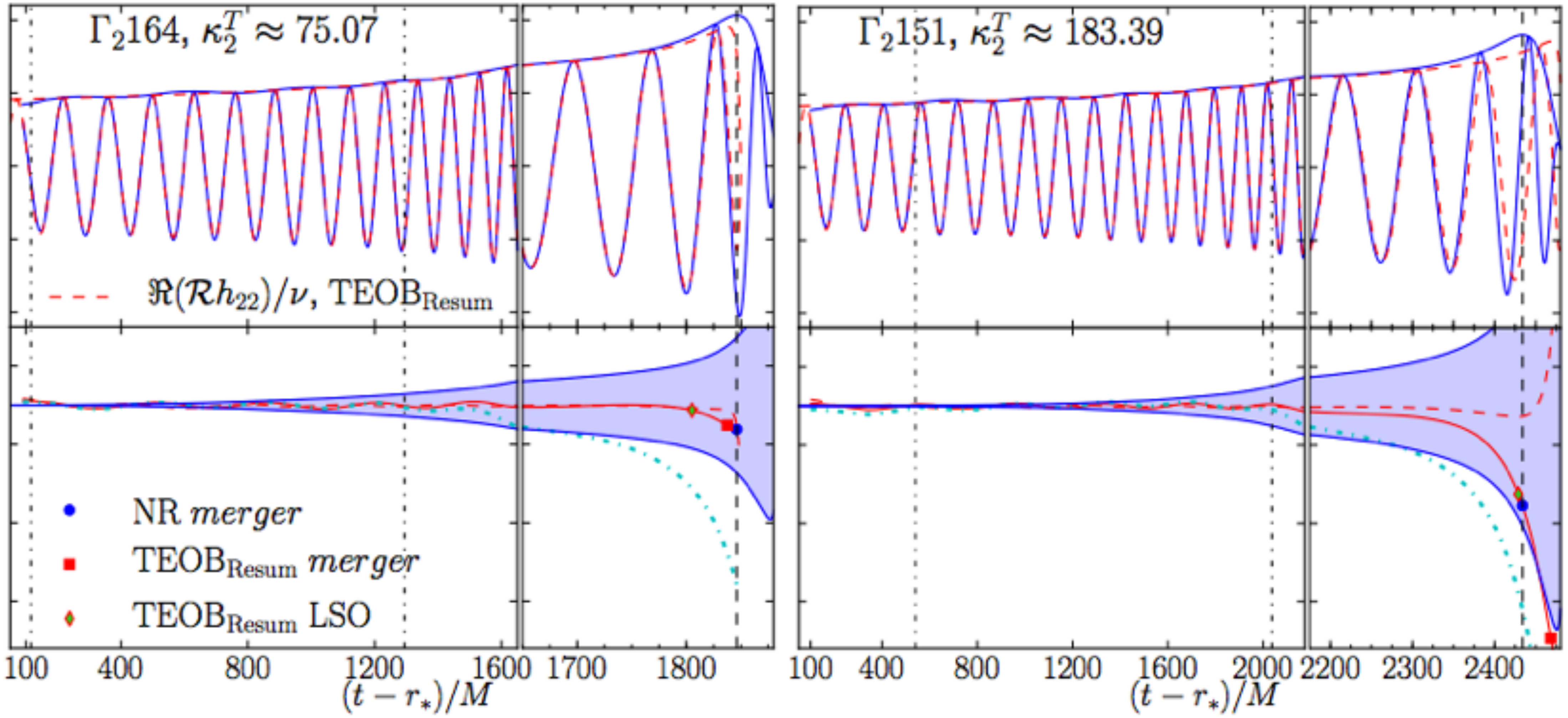
BNS merger waveforms?

6 examples from Hotokezaka *et al.* 1105.4370:

Numerical simulation Point-particle T4

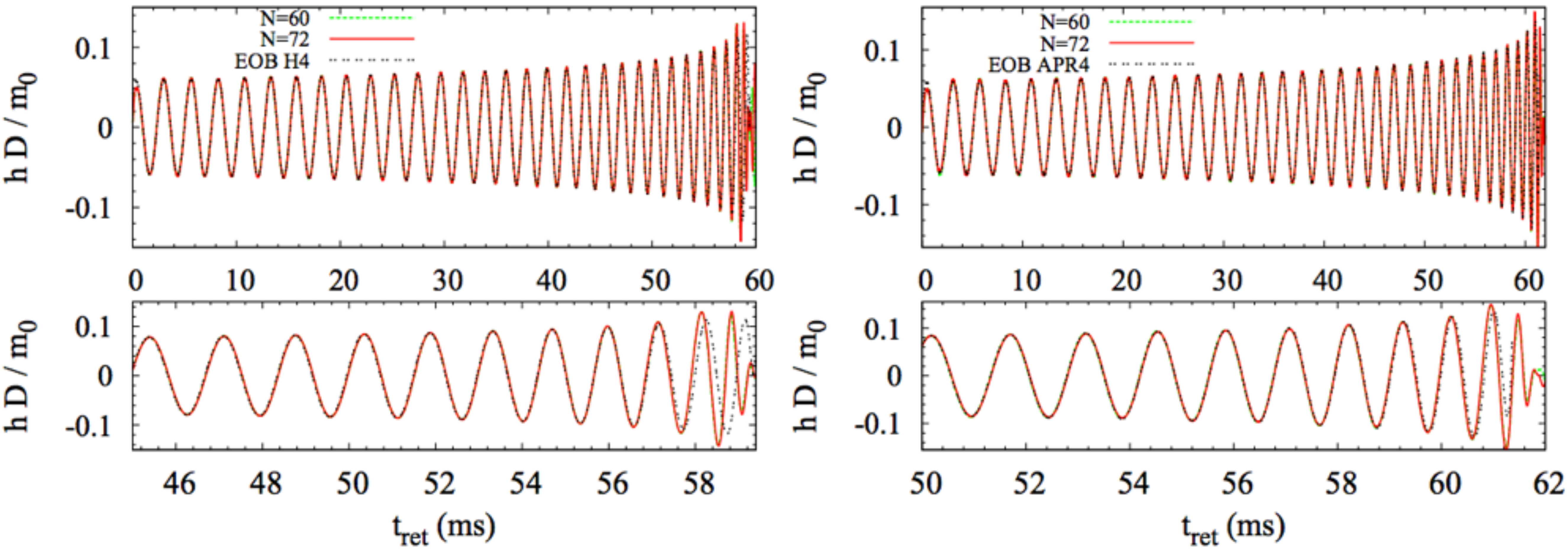


Tidal effects in EOB models: Bernuzzi et al 1412.4553



- EOB plus tidal corrections plus resummation procedure
- First semi-analytic model to capture merger phase

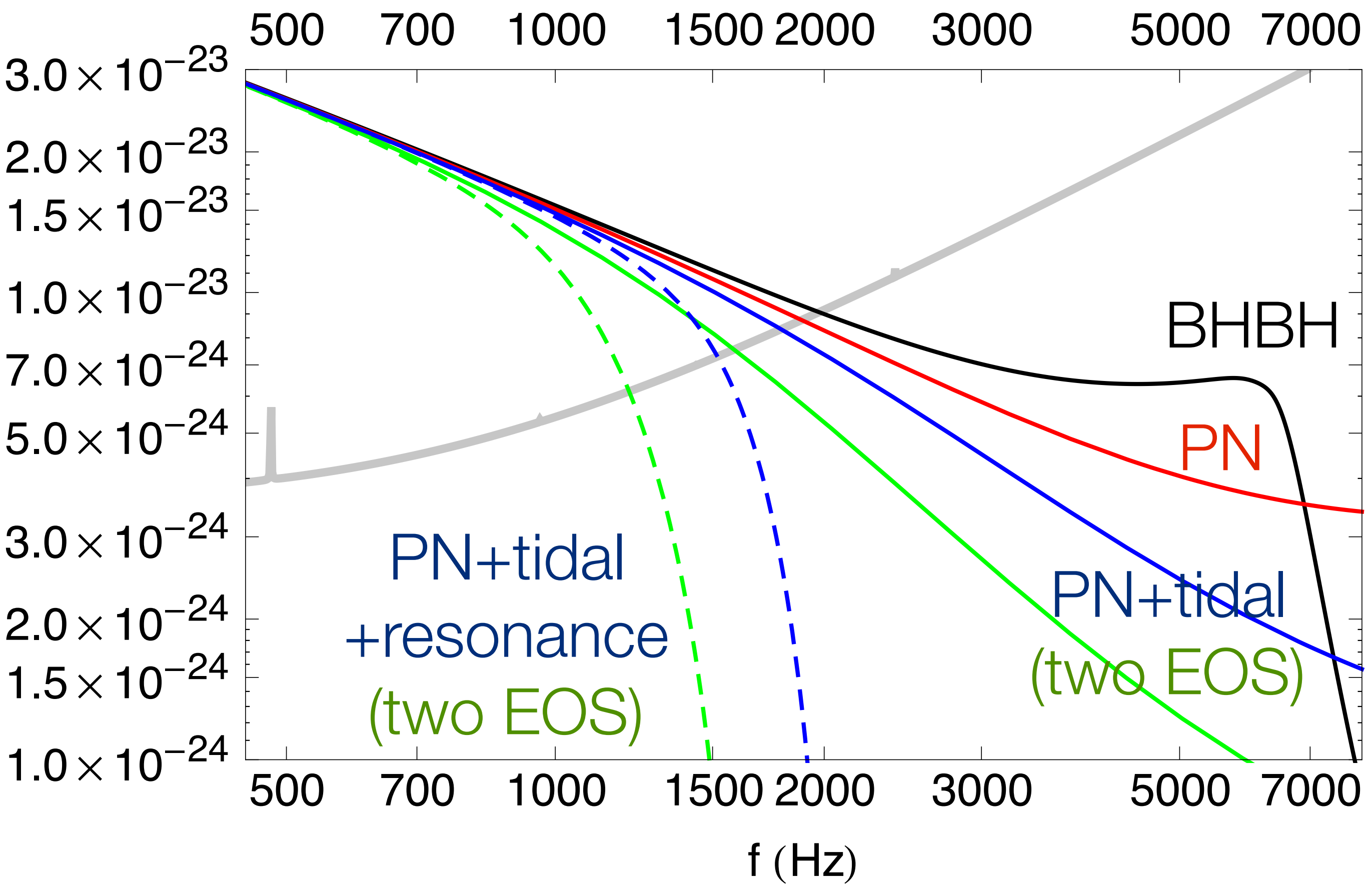
Comparison with long high-res BNS simulations Hotokezaka et al 1502.03457v1



- EOB model fits compact stars well, some additional tidal effect seen in simulations of larger stars (13km+).

Additional physical effects: dynamical tides?

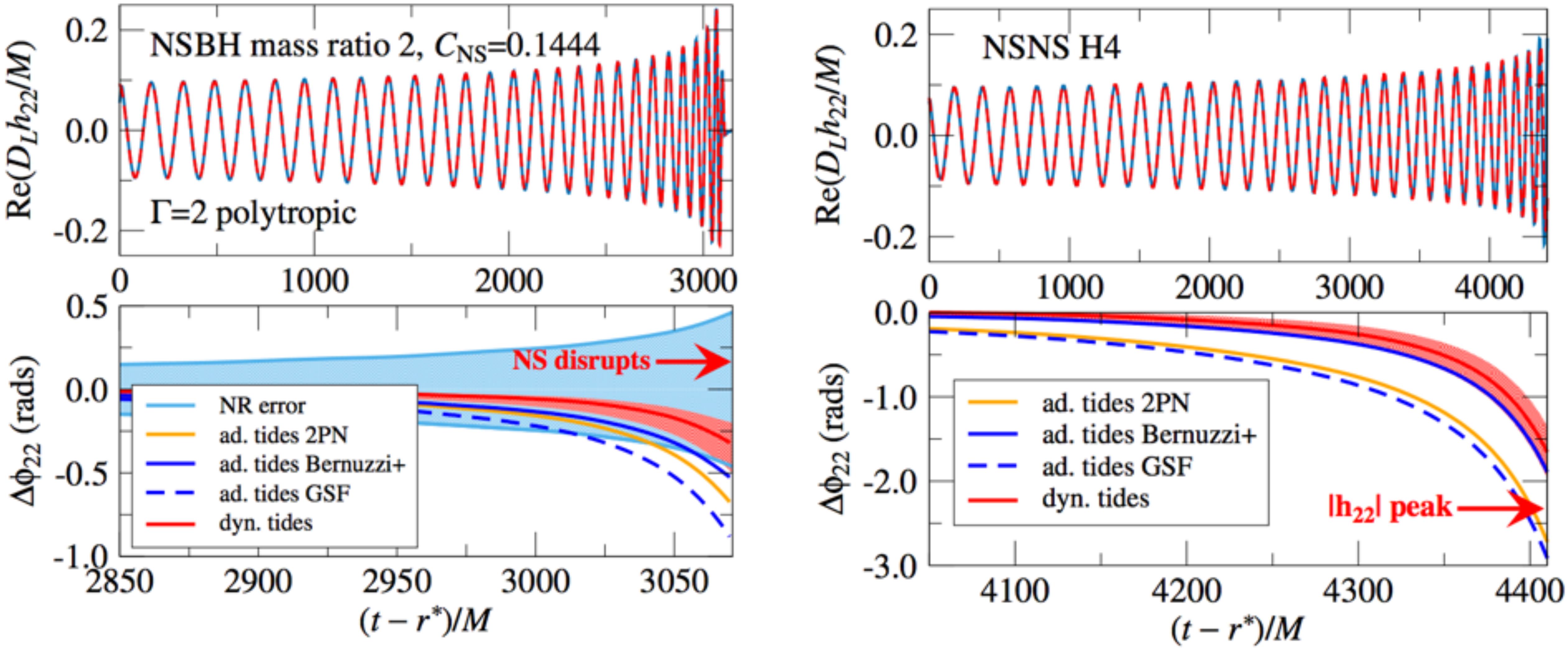
- Dynamical tide effects known, effects estimated in PN context (Kokkotas & Schaefer gr-qc/9502034, Flanagan & Hinderer 0709.1915)
  - Orbital tide approaches resonance with NS f-mode



- use universal relation between f-mode & tidal Λ (Chan et al 1408.3789)

JSR, Veronica Lockett-Ruiz

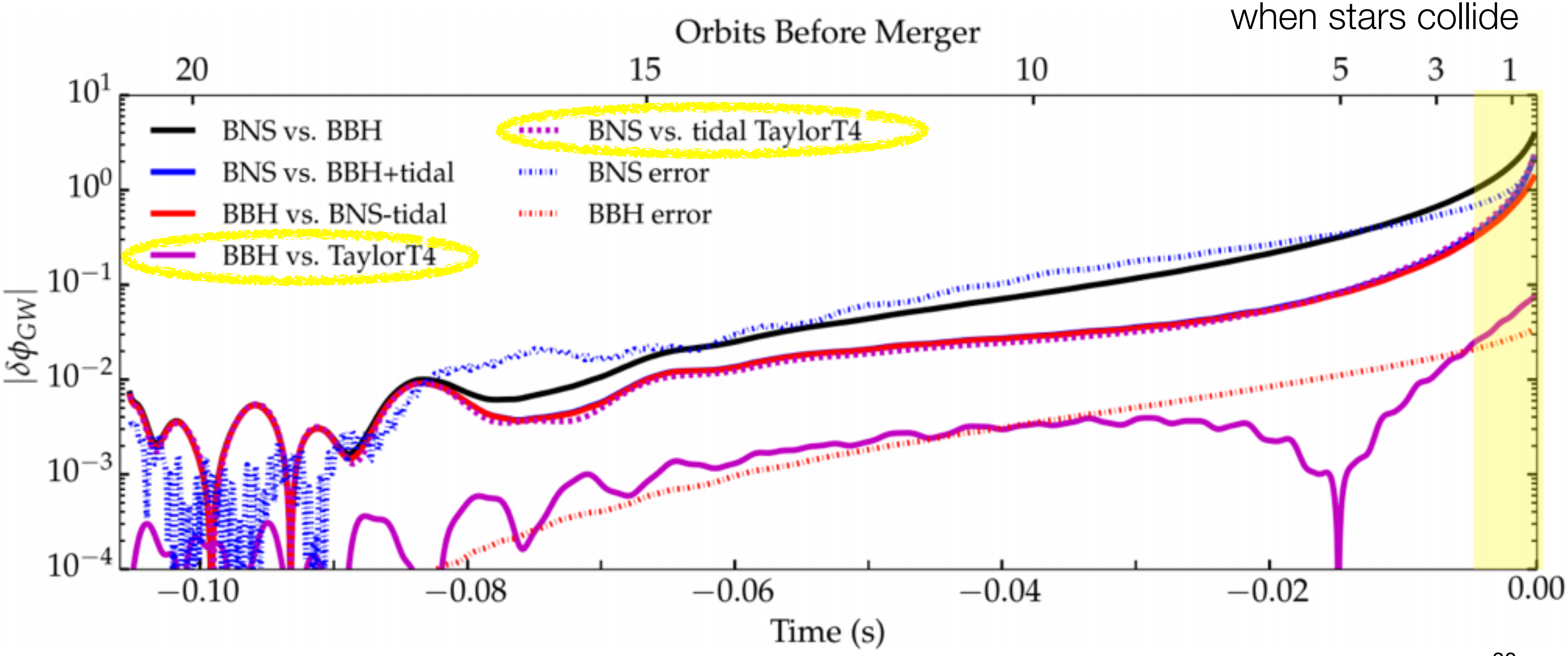
Add dynamic tides in EOB models (Hinderer et al 1602.00599)



- two key parameters: tidal deformability and fundamental oscillation frequency
- NR agreement mitigates systematic error concerns for GW obs

Are PN tidal contributions sufficient for inspiral?
Barkett *et al.*, 1509.05782

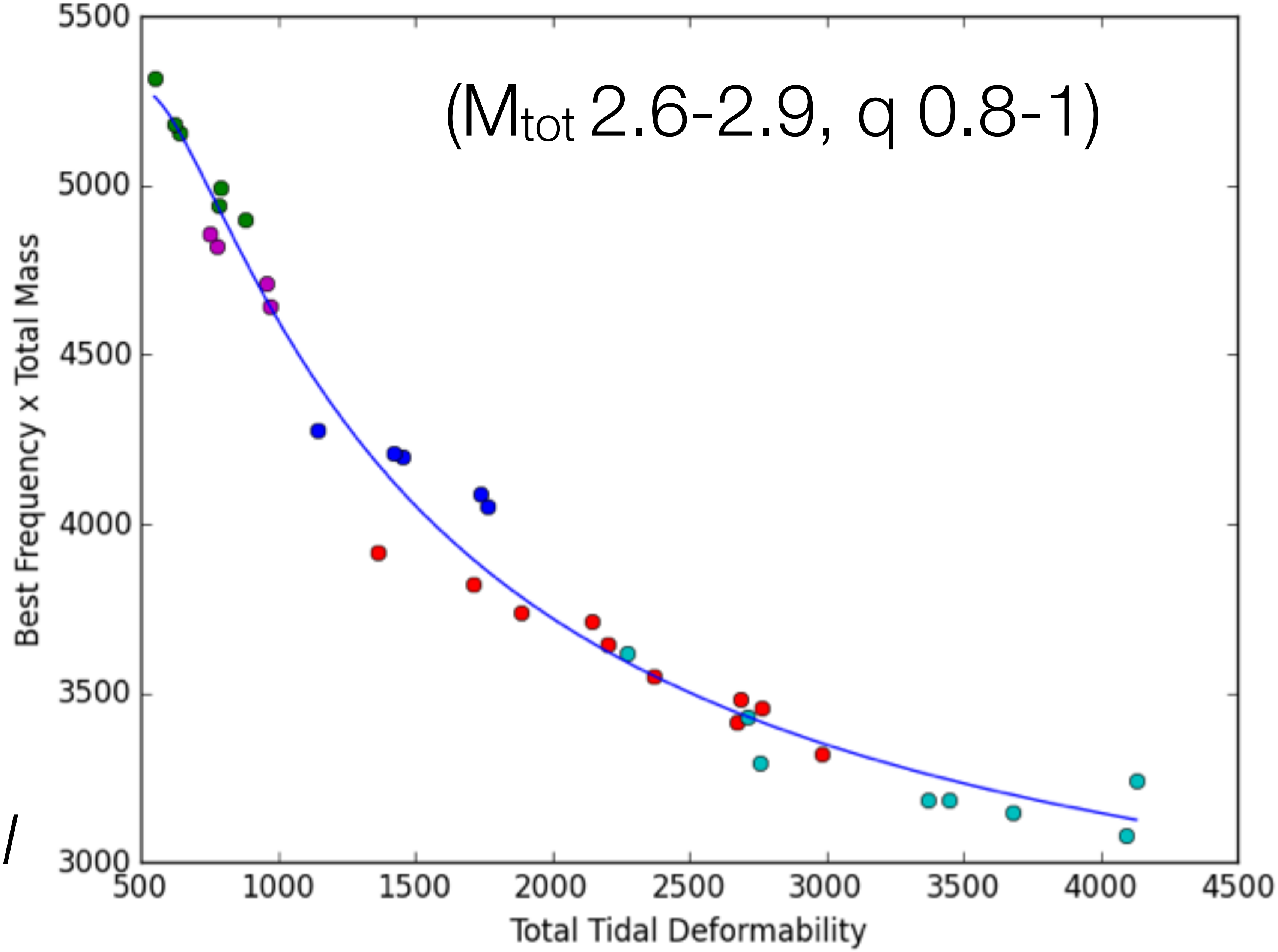
- BBH simulation + tidal corrections (and the particular PN choice T4+tidal) are *effective* model for (near) equal-mass systems *until last orbits*



Comparison ends when stars collide

New: phenomenological model

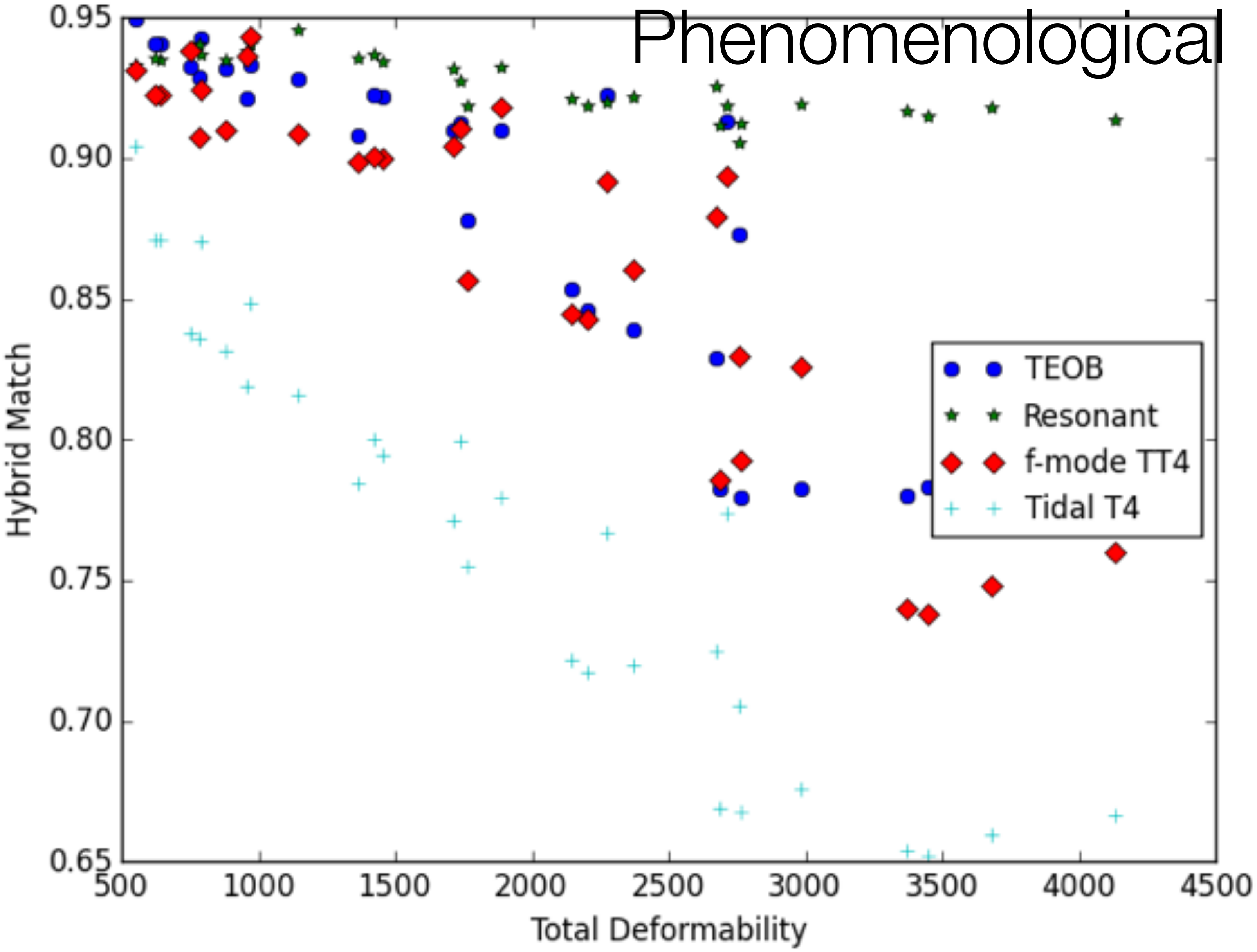
- Assume T4 inspiral,
- include dynamic tides, but fit effective frequency to drive merger
- Simple relation with Λ
- *Future: other parameters to improve fit? Physical motivation? Amplitude?*



Conner Park, Veronica Lockett-Ruiz, JR

Phenomenological modification of common PN model gives effective inspiral-to-merger waveform

- Waveform depends only on masses and Λs
- Phenom. coalescence fit to numerical merger
- *Future: Explicit error estimates. Test systematic error in parameter estimation.*



Conner Park, Veronica Lockett-Ruiz, JR

Conclusions

- Dense matter modifies end of inspiral/merger for BNS (cold EOS)
- Post-merger, BHNS harder to observe
- Favorable rates/signal strength required to constrain!