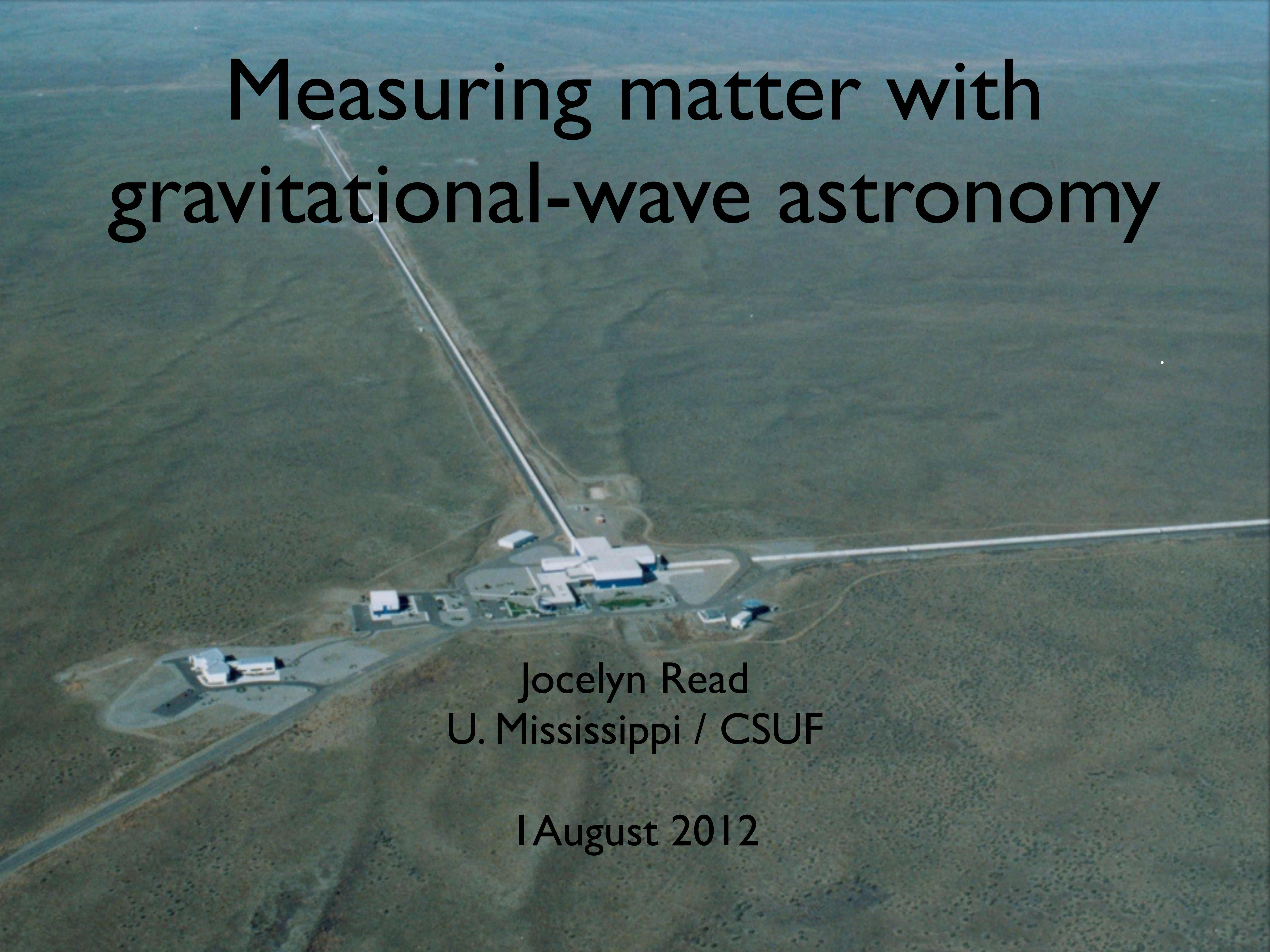


Measuring matter with gravitational-wave astronomy

Jocelyn Read
U. Mississippi / CSUF

1 August 2012

Tidal deformation in PN

NSNS: Tanja Hinderer (Maryland), Ben Lackey (Wisconsin–Milwaukee), and Ryan Lang (NASA Goddard)

BHNS: Francesco Panaralle (AEI), Frank Ohme (AEI), Luciano Rezzolla (AEI)

Numerical simulations and analysis

L. Baiotti (Osaka), J. Creighton (Wisconsin–Milwaukee), J. Friedman(Wisconsin–Milwaukee), B. Giacomazzo(JILA), K. Kyutoku (YITP), C. Markakis(Wisconsin–Milwaukee), L. Rezzolla(AEI), M. Shibata (YITP), and K. Taniguchi (Tokyo),

QCD phase diagram

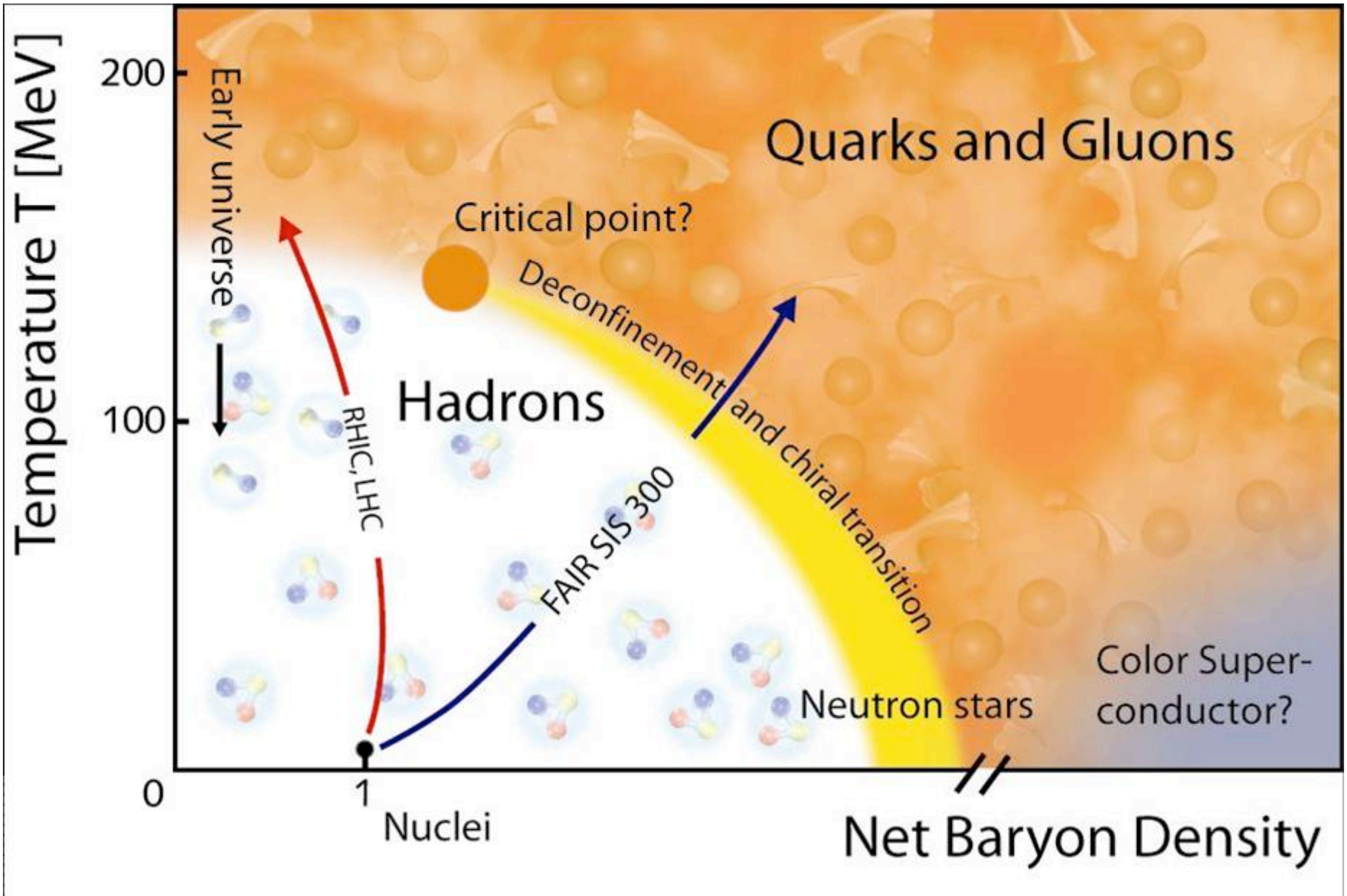


figure from FAIR CBM experiment

QCD phase diagram

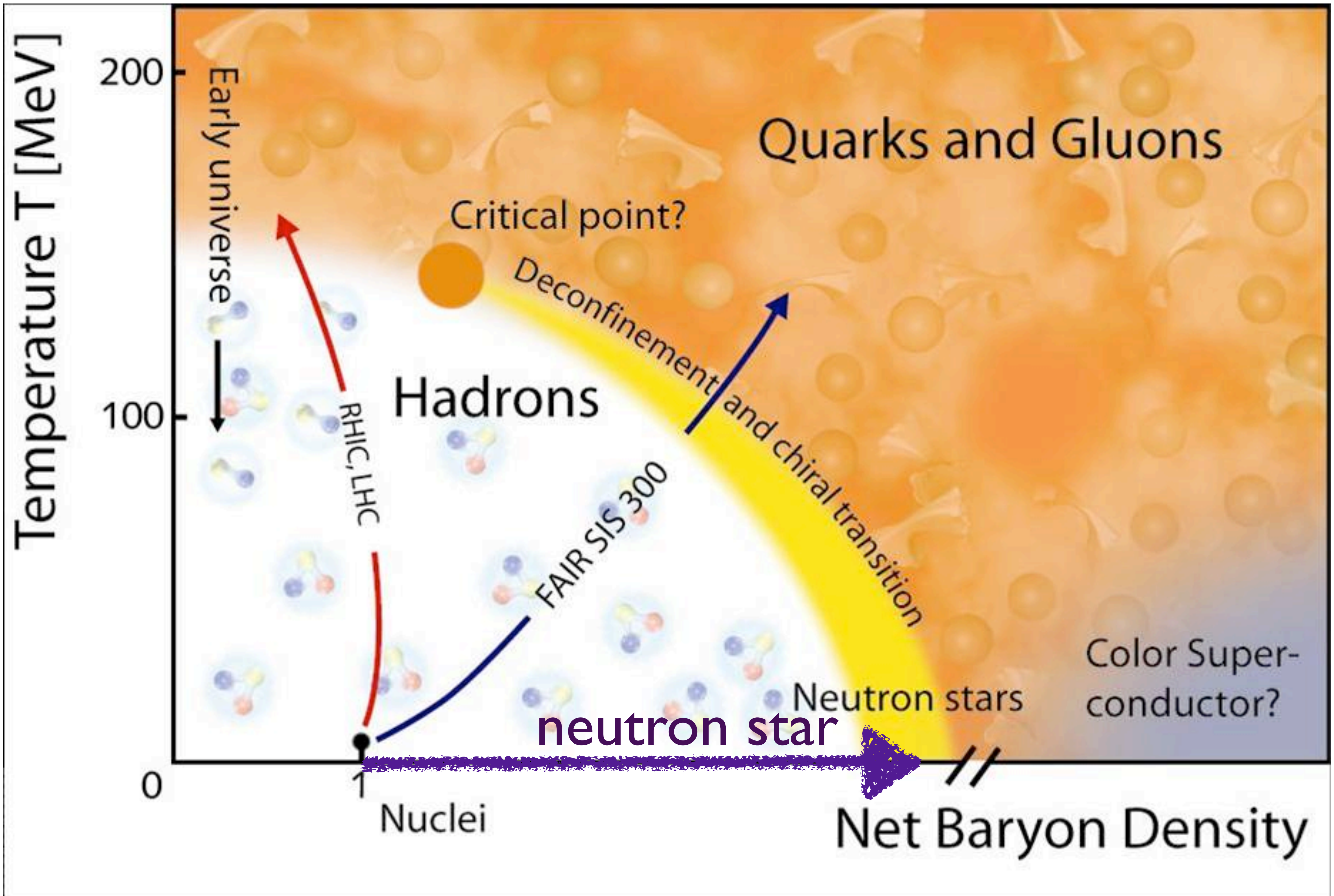


figure from FAIR CBM experiment

QCD phase diagram

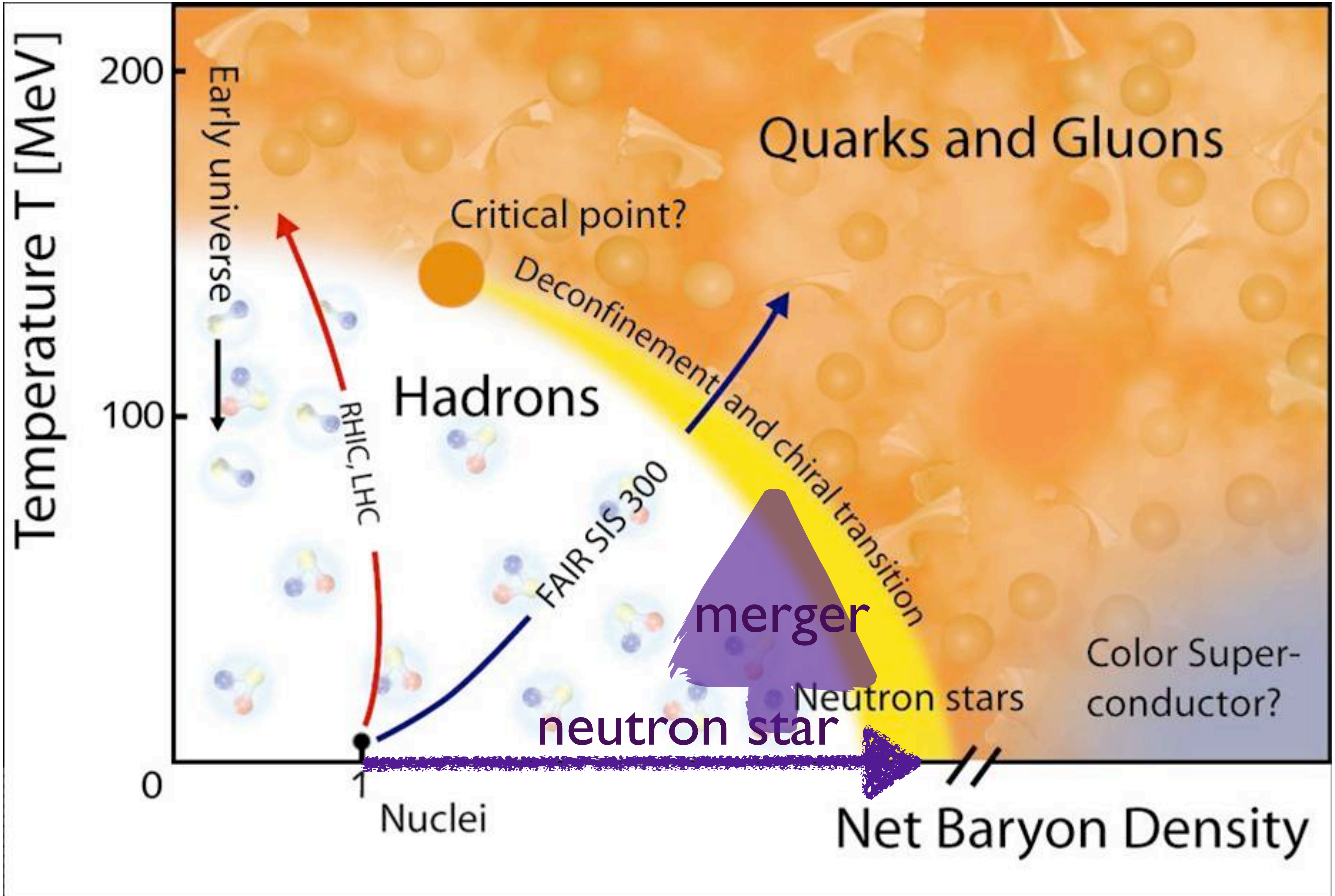
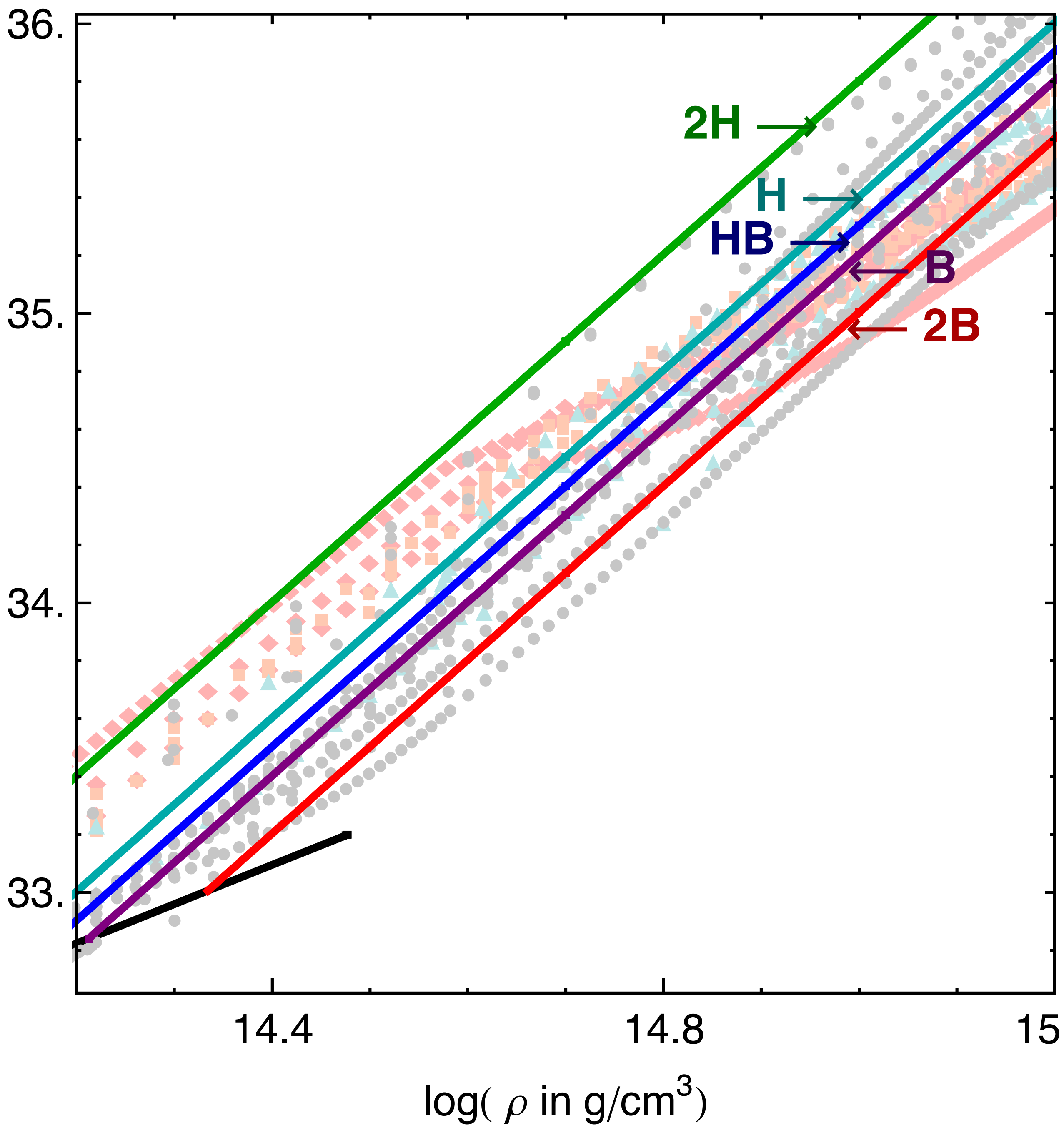
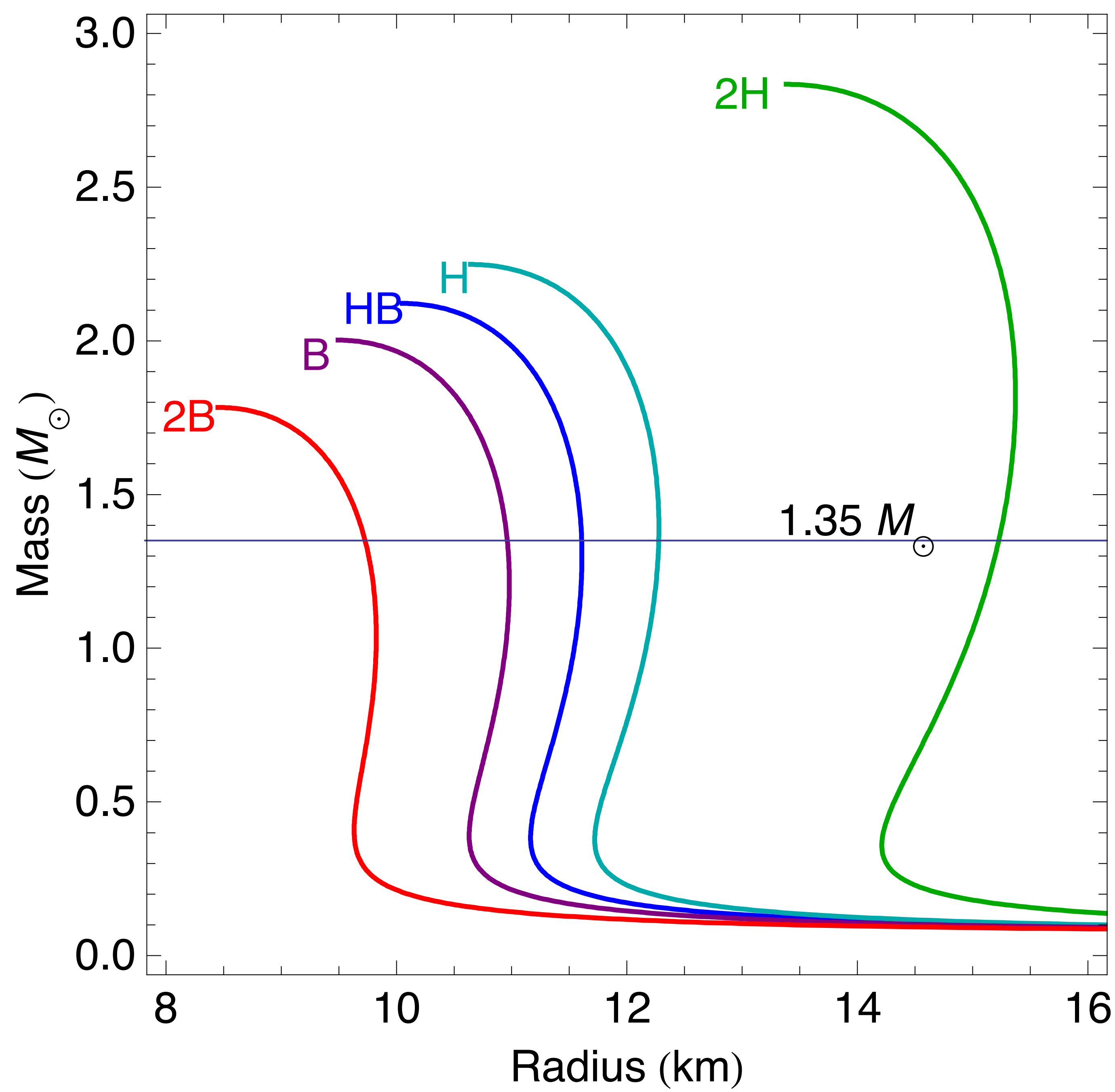


figure from FAIR CBM experiment

Equation of state above nuclear density determines NS structure





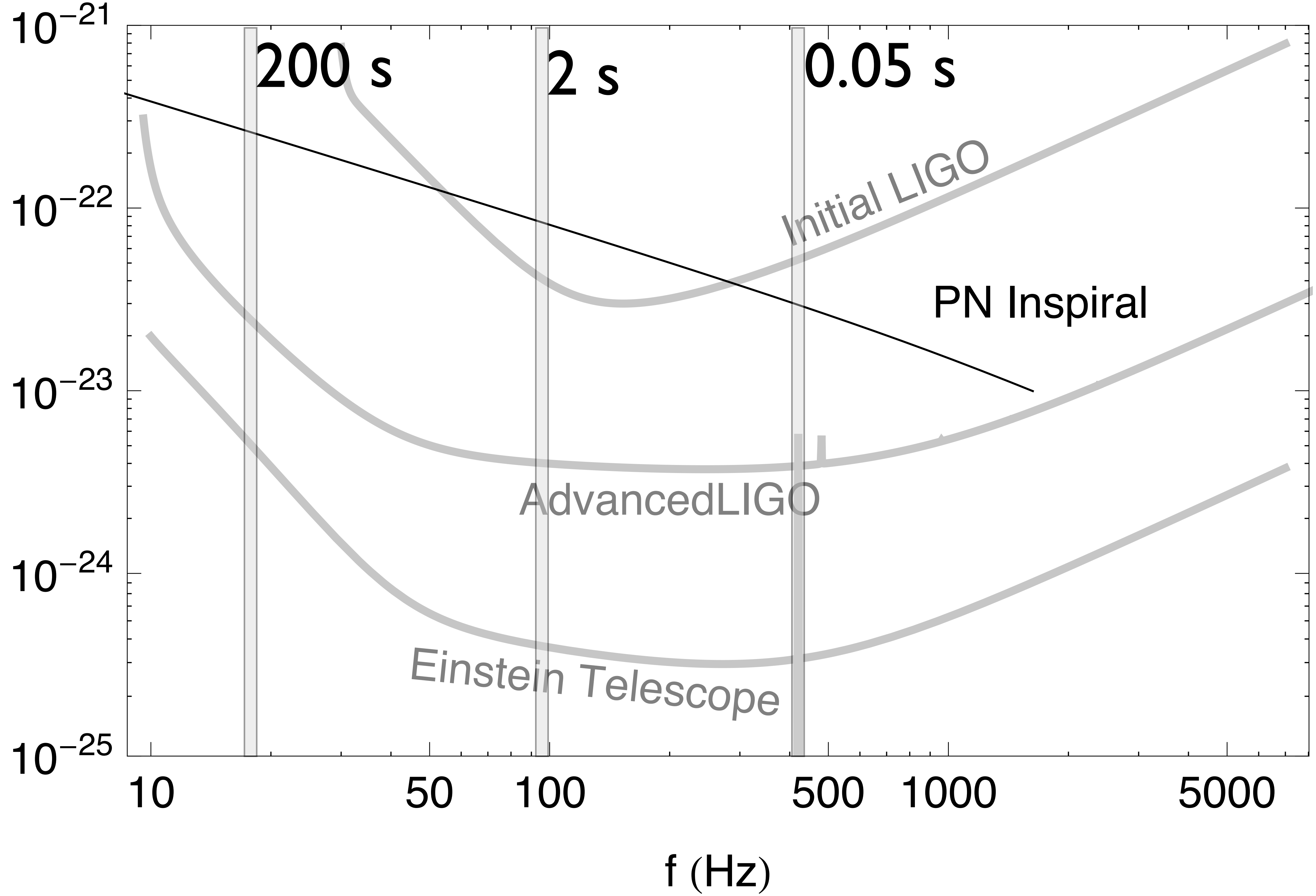
Constraint on EOS from neutron-star observations

Observed masses, spin frequencies, and oscillation frequencies must be possible with given EOS.

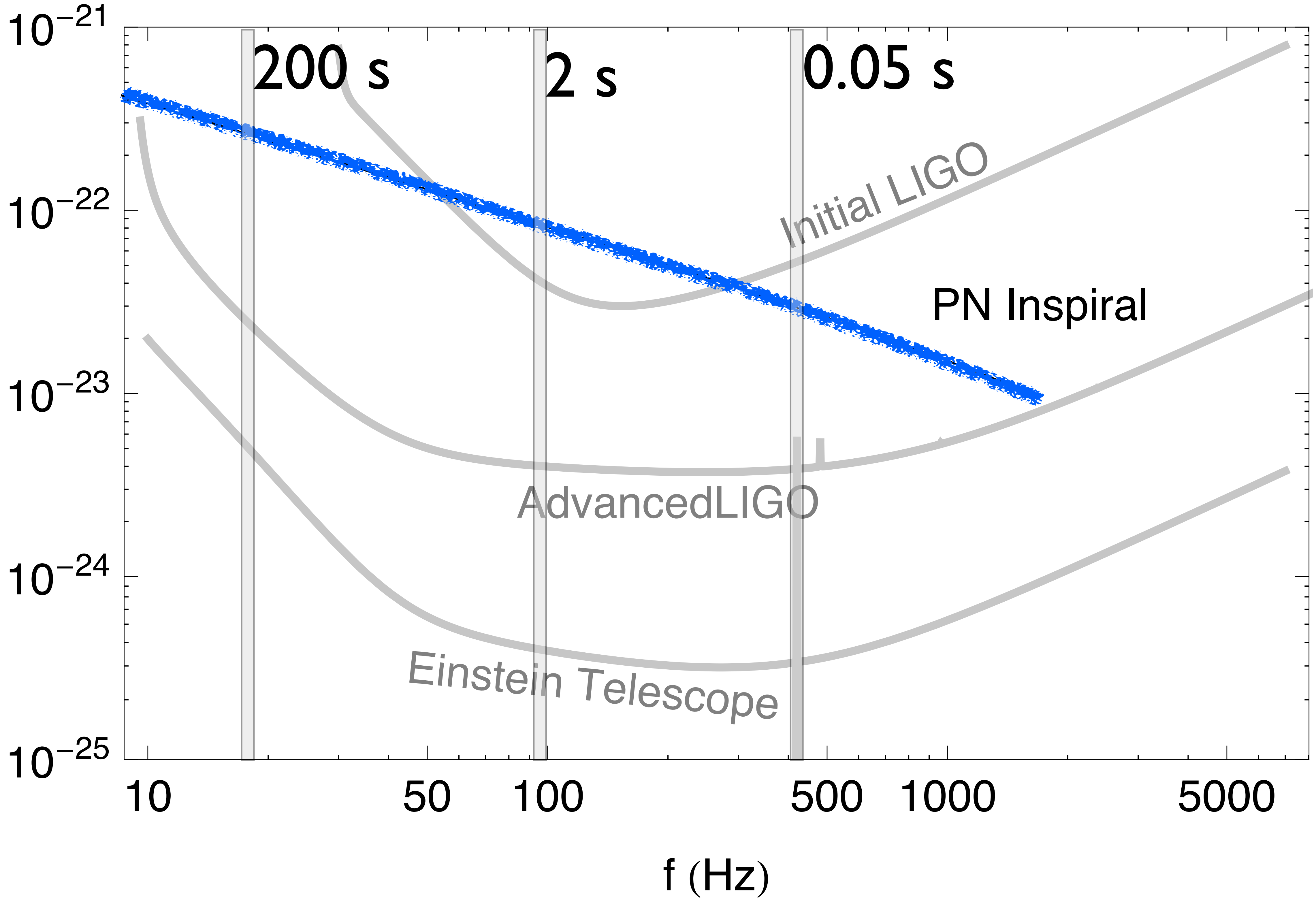
If one can measure multiple properties: observationally implied radius, moment of inertia, or tidal deformability must be predicted by given EOS at observed mass.

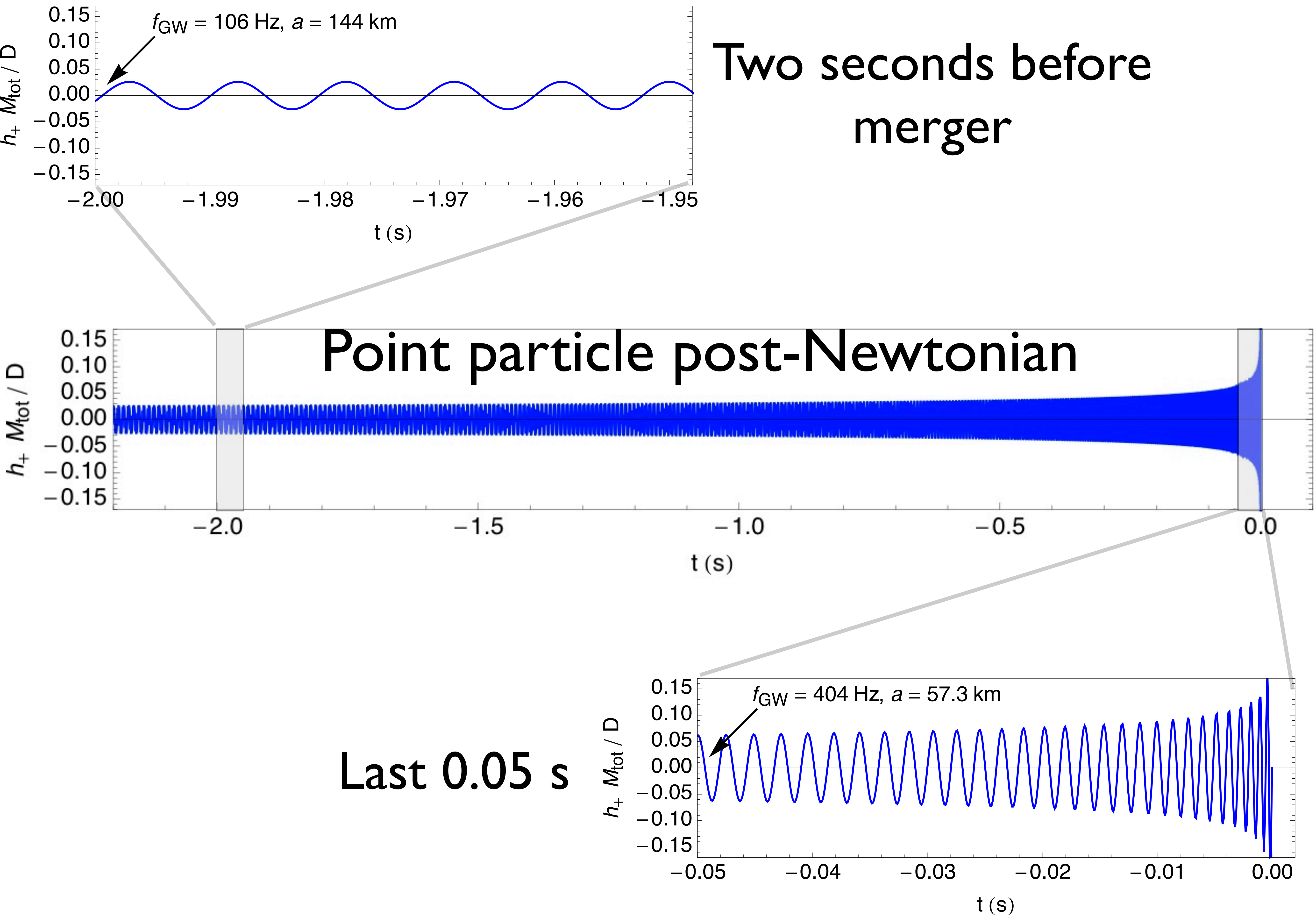
Gravitational dynamics

The path of an inspiraling double neutron star

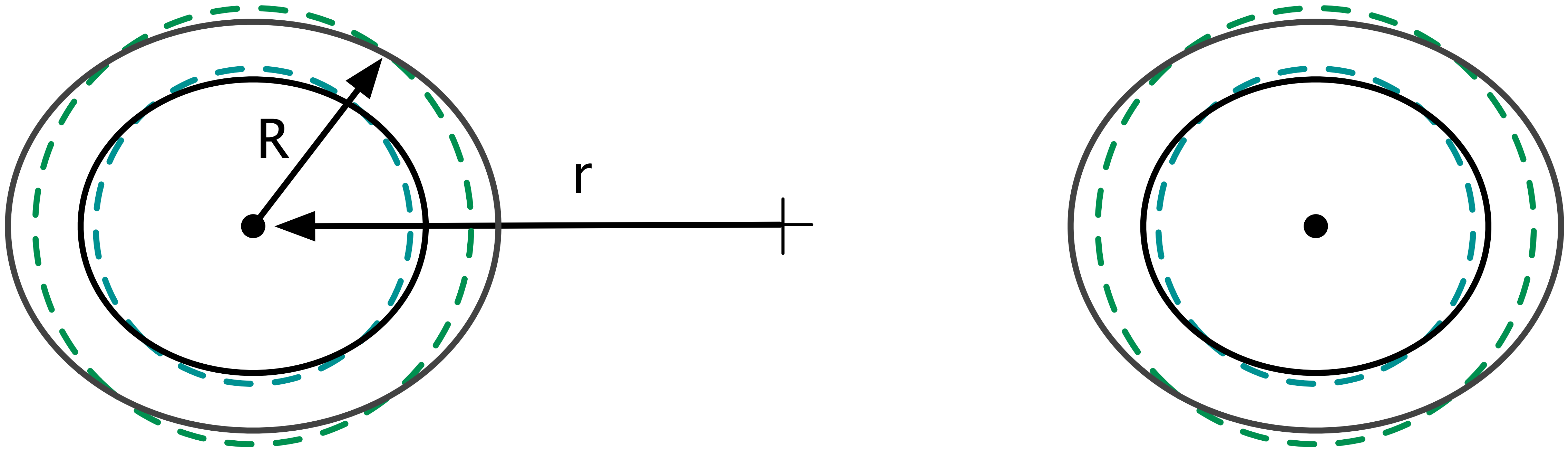


The path of an inspiraling double neutron star




Two seconds before merger
Point particle post-Newtonian
Last 0.05 s
f_{GW} = 106 Hz, a = 144 km
f_{GW} = 404 Hz, a = 57.3 km
$h_+ M_{tot}$ / D
t (s)
0.15
0.10
0.05
0.00
−0.05
−0.10
−0.15
−2.00
−1.99
−1.98
−1.97
−1.96
−1.95
−2.0
−1.5
−1.0
−0.5
0.0
−0.05
−0.04
−0.03
−0.02
−0.01
0.00

What changes the waveform?



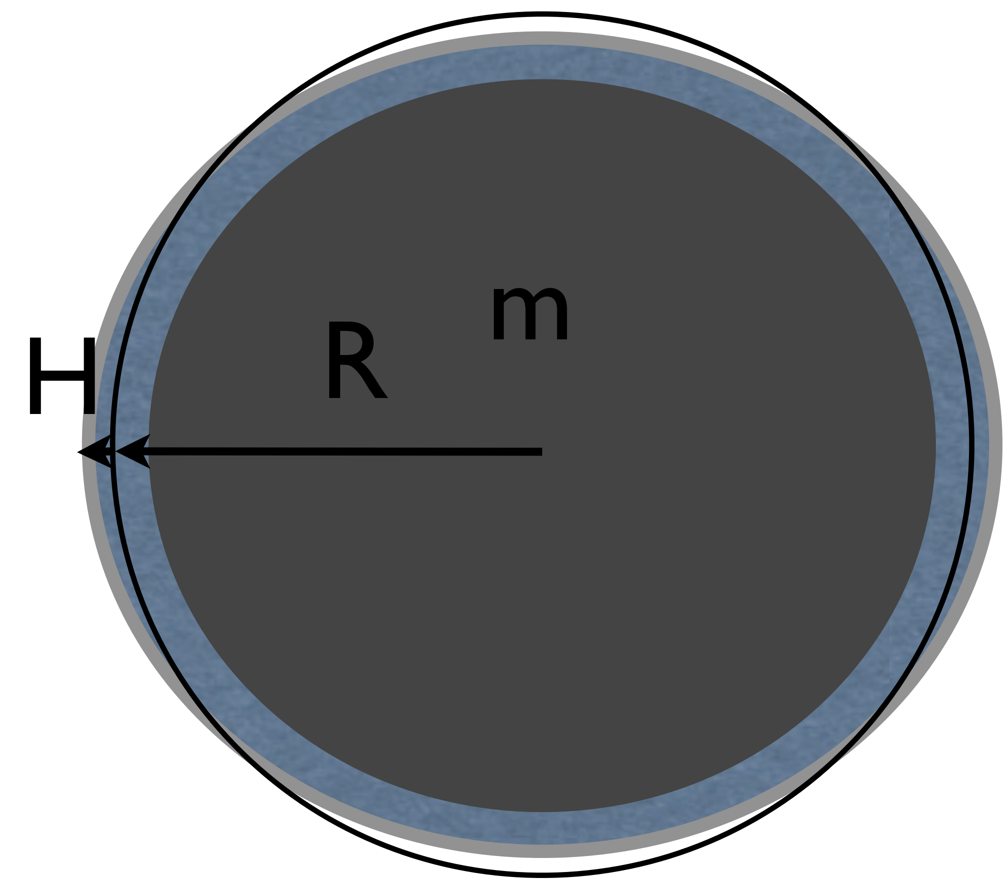
For an object following it's orbit, the leading residual effect of gravity is felt in tides.

Surface deformation Love number h:

Love number h determines deformation of surface.
larger h deforms more easily (e.g. ocean vs. rock)

$$H = h\left(\frac{M}{m}\right)\left(\frac{R}{a}\right)^3 R\frac{(3\cos^2\theta - 1)}{2}$$

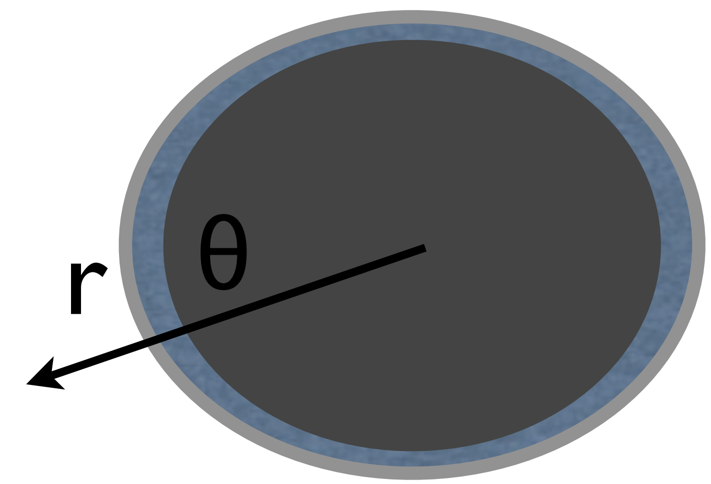
M mass of Jupiter
m mass of Enceladus
R radius of Enceladus
a distance to Jupiter



Gravitational potential Love number k

Love number k determines quadrupole moment Q of deformed body

$$Q = km\frac{R^5}{a^3}$$



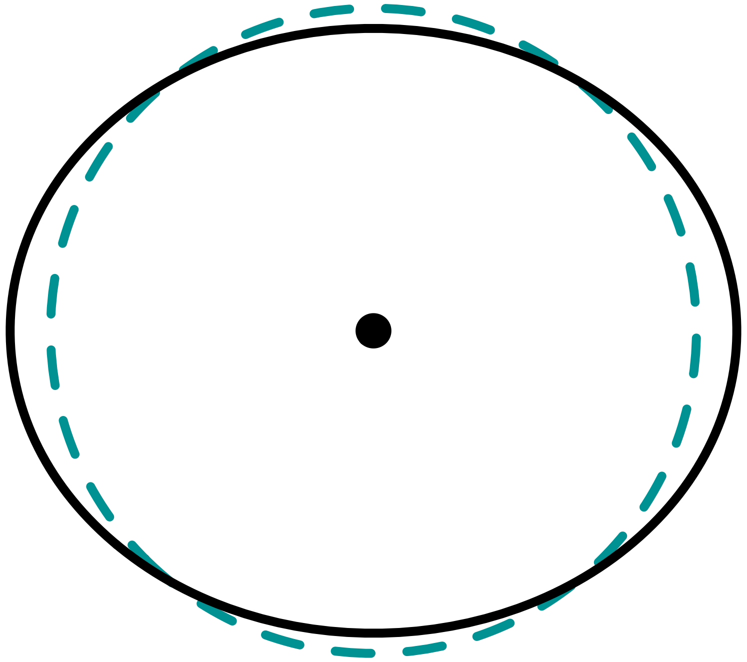
Q determines the gravitational potential around the deformed body

$$U = -\frac{M}{r} - \frac{3}{2}\frac{Q(\cos^2\theta - 1)}{r^3}$$

e.g.
M mass of moon
m mass of Earth
R radius of moon
a distance to Earth

This tells us about things like satellite movement around the body, tidal locking ("back-reaction" on bulges), and **orbital dynamics in binary systems**

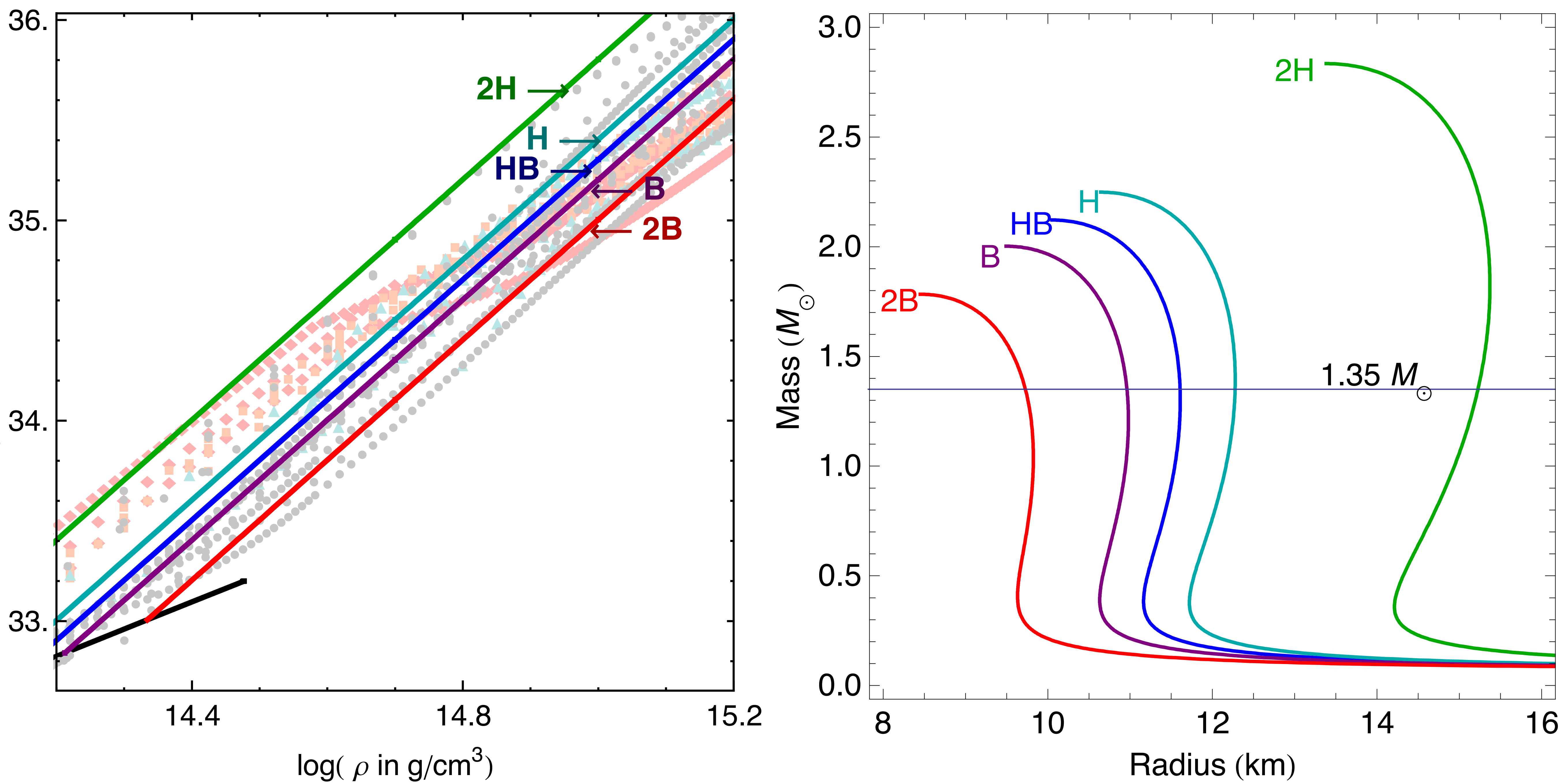
Calculate to leading order:



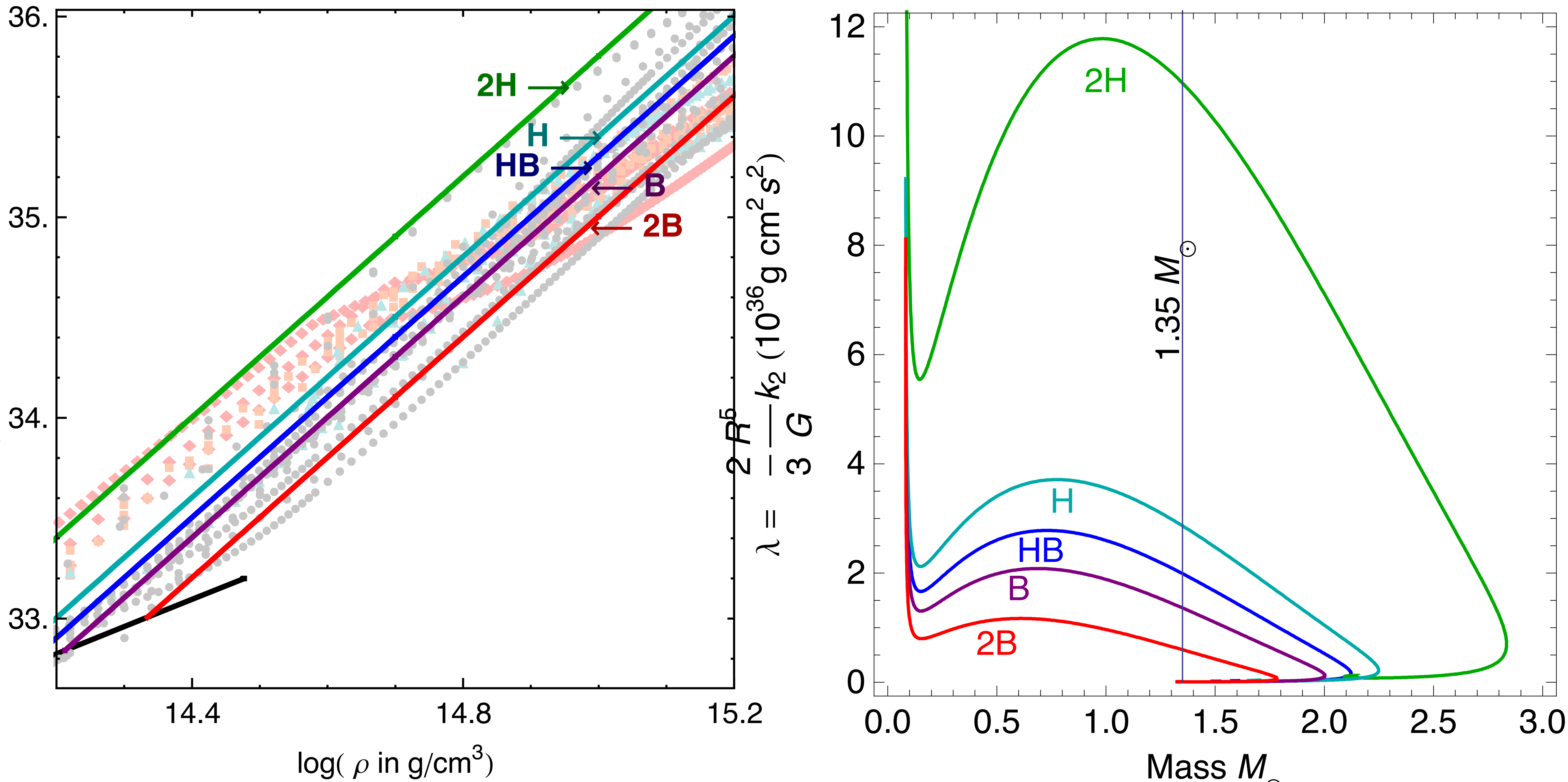
Perturb a spherically symmetric star with given EOS

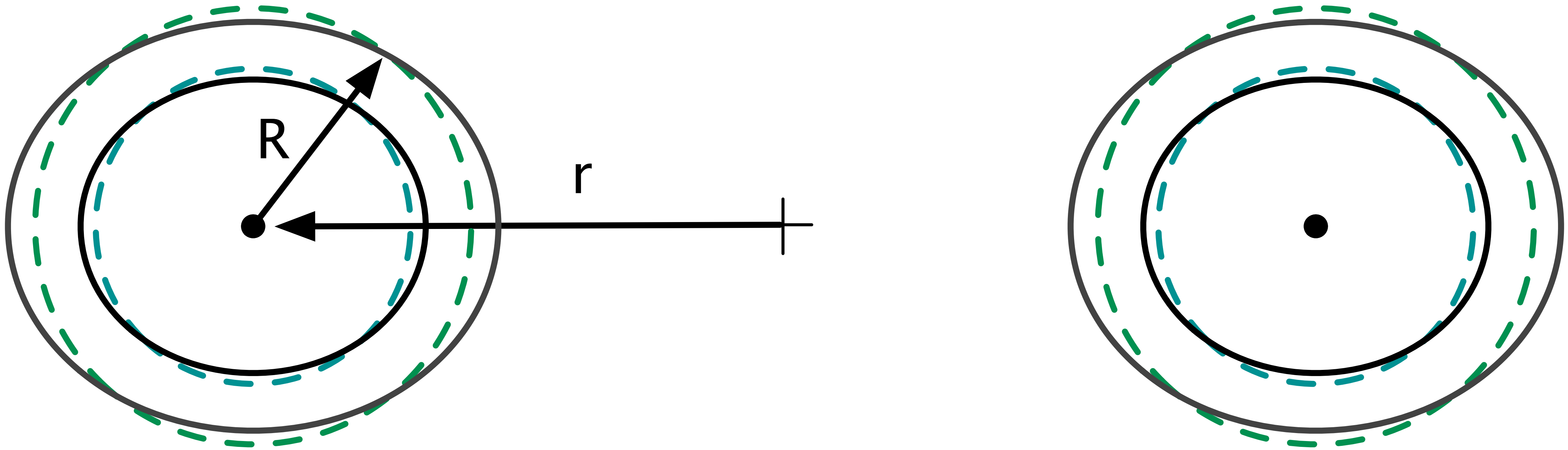
$$\lambda = \frac{Q}{\mathcal{E}} = \frac{\text{size of quadrupole deformation}}{\text{strength of external tidal field}}$$

Equation of state determines NS structure



Equation of state determines NS structure



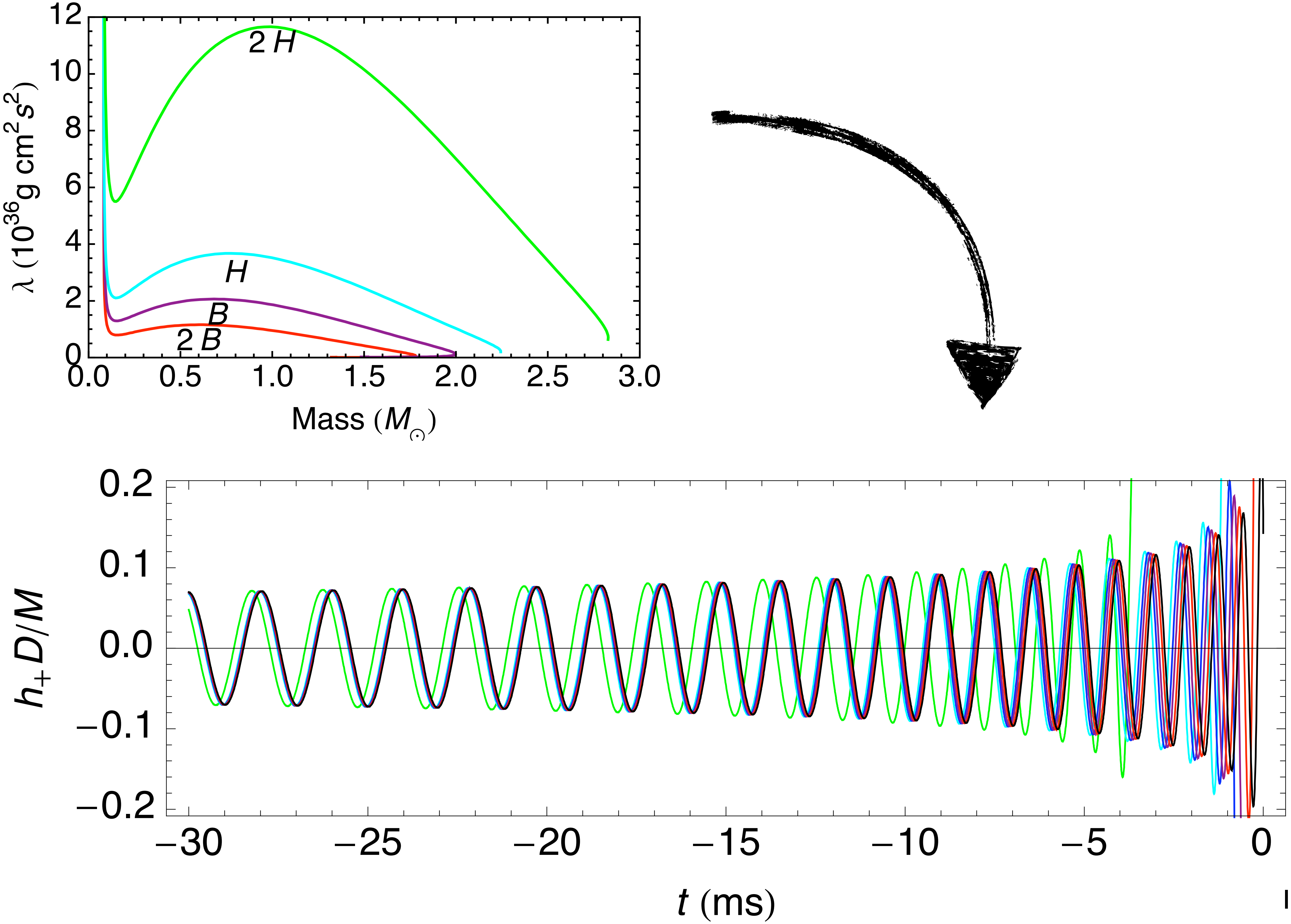


Early tidal interactions:

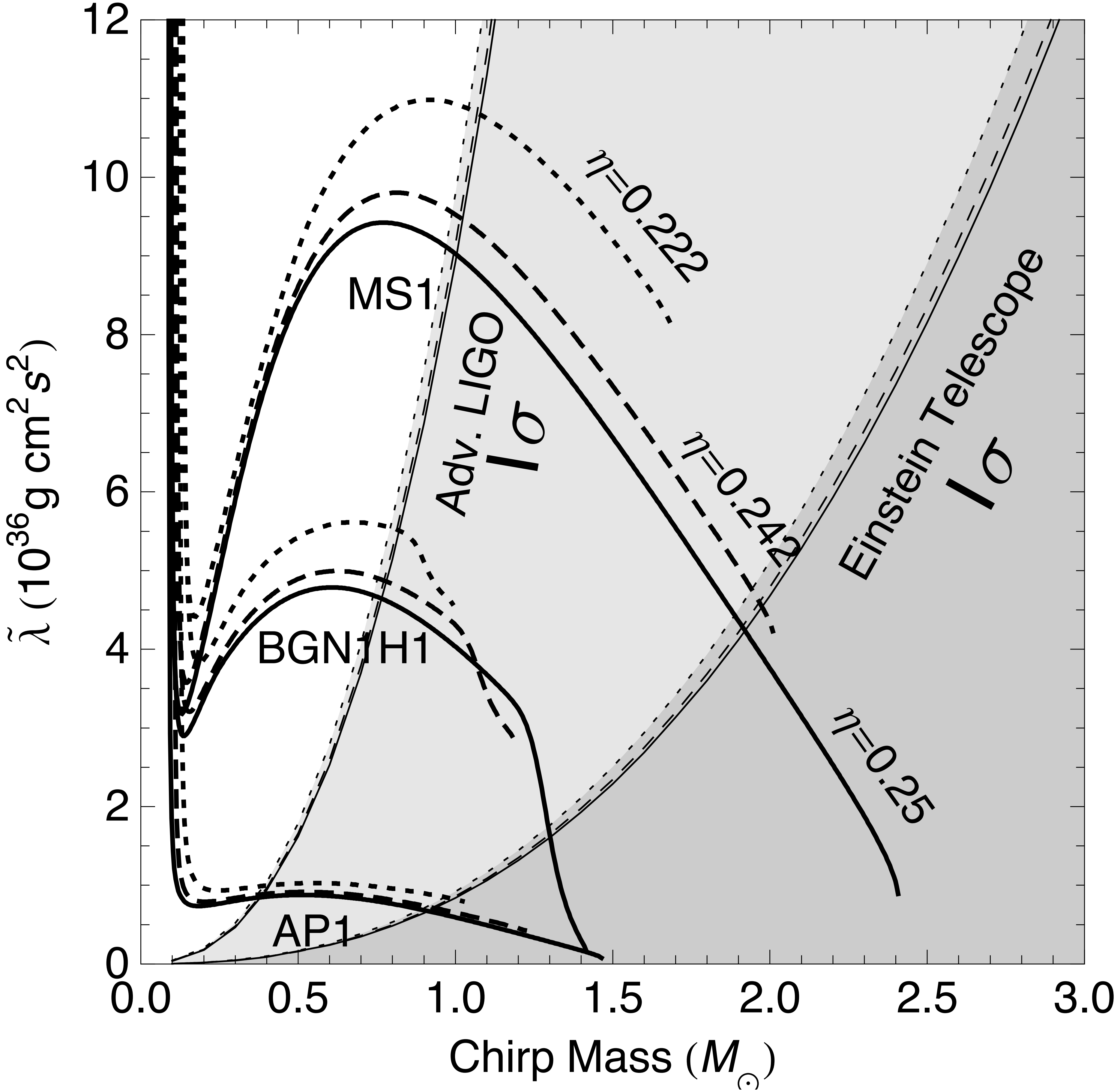
Some energy goes into deforming the stars

Moving tidal bulges add a bit to the gravitational radiation

Effect on waveforms from different EOS



Analytic estimates of measurability



Limit to signal before 450 Hz

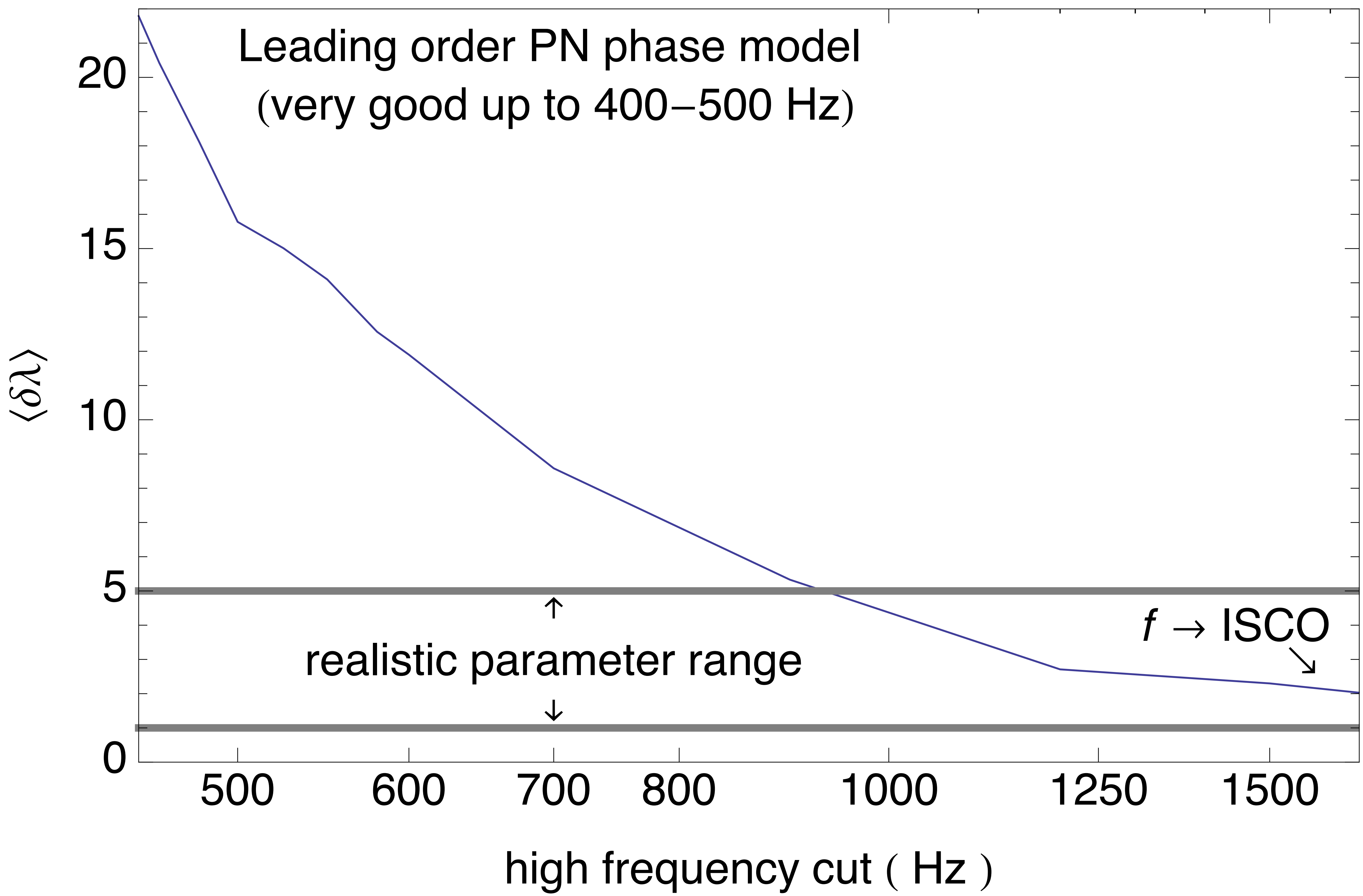
Expect "clean" signal

marginalize over spin, mass ratio

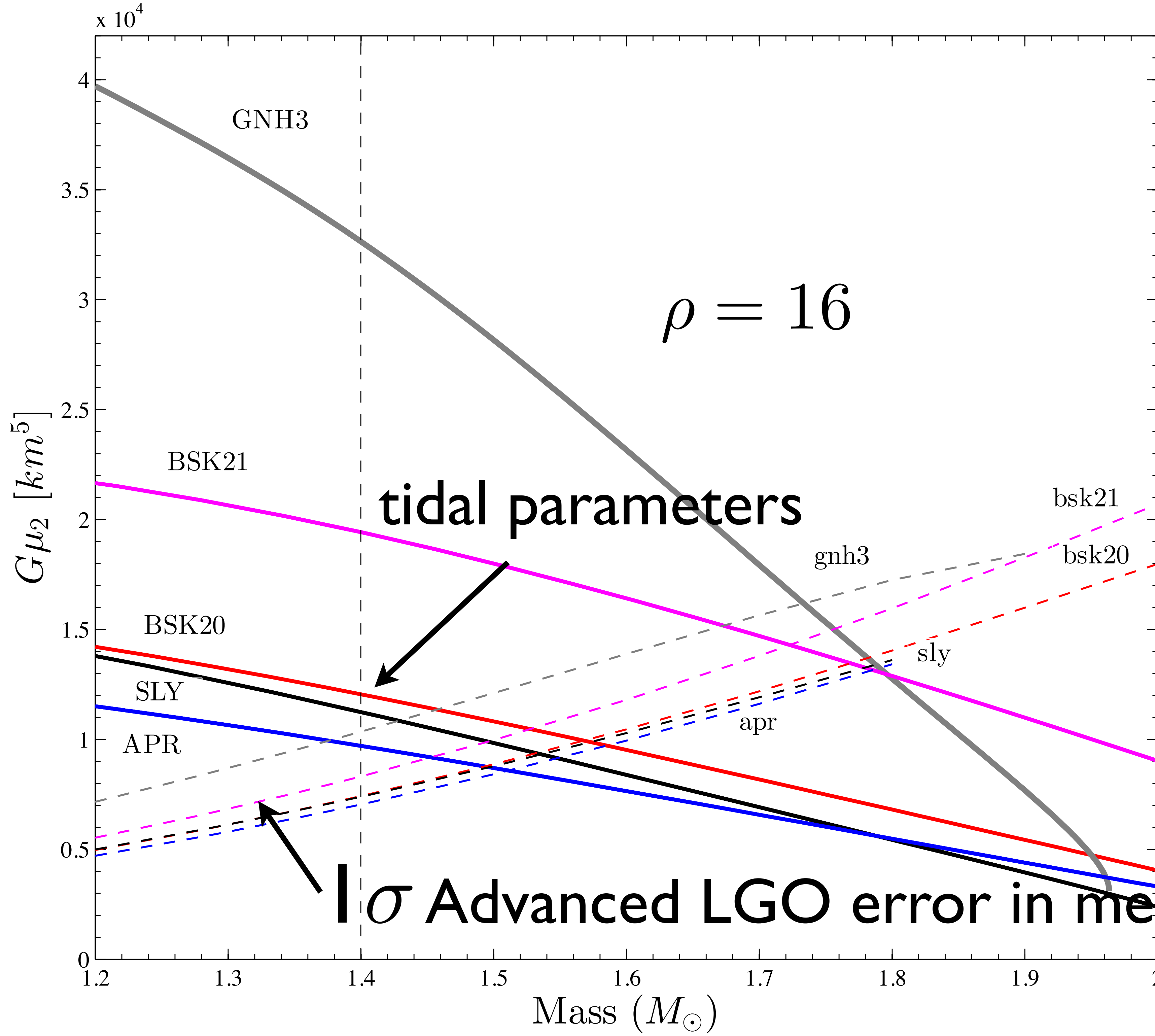
CAVEAT: see poster by M. Favata; need to understand comparable order point dynamics

arXiv: 0911.3535

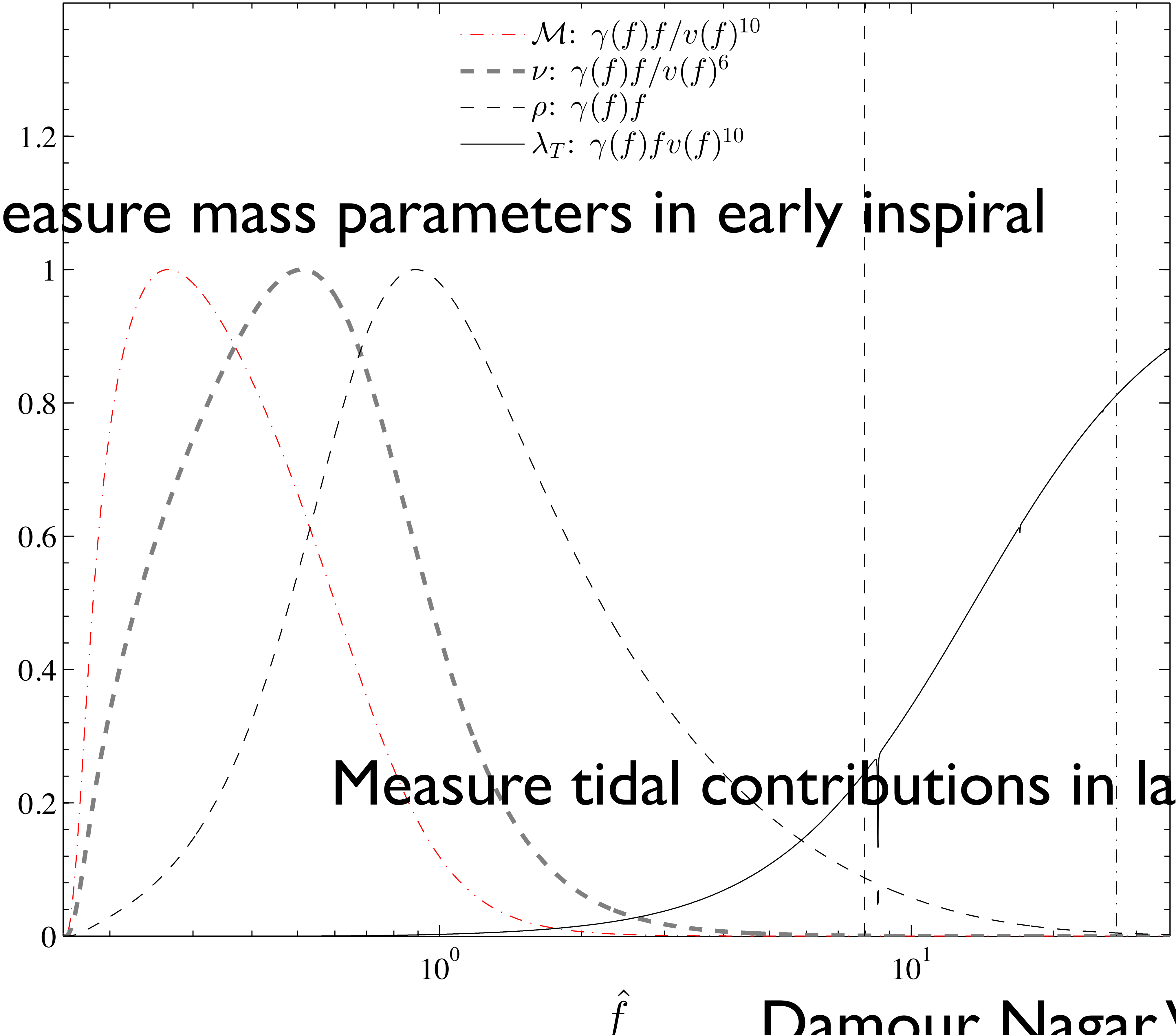
Fisher matrix estimate of measurability in AdLIGO high power configuration



Damour, Nagar, Villain have a much stronger estimate of measurability



assume inspiral waveform known through to 1704 Hz (estimate of radius contact), neglect spin

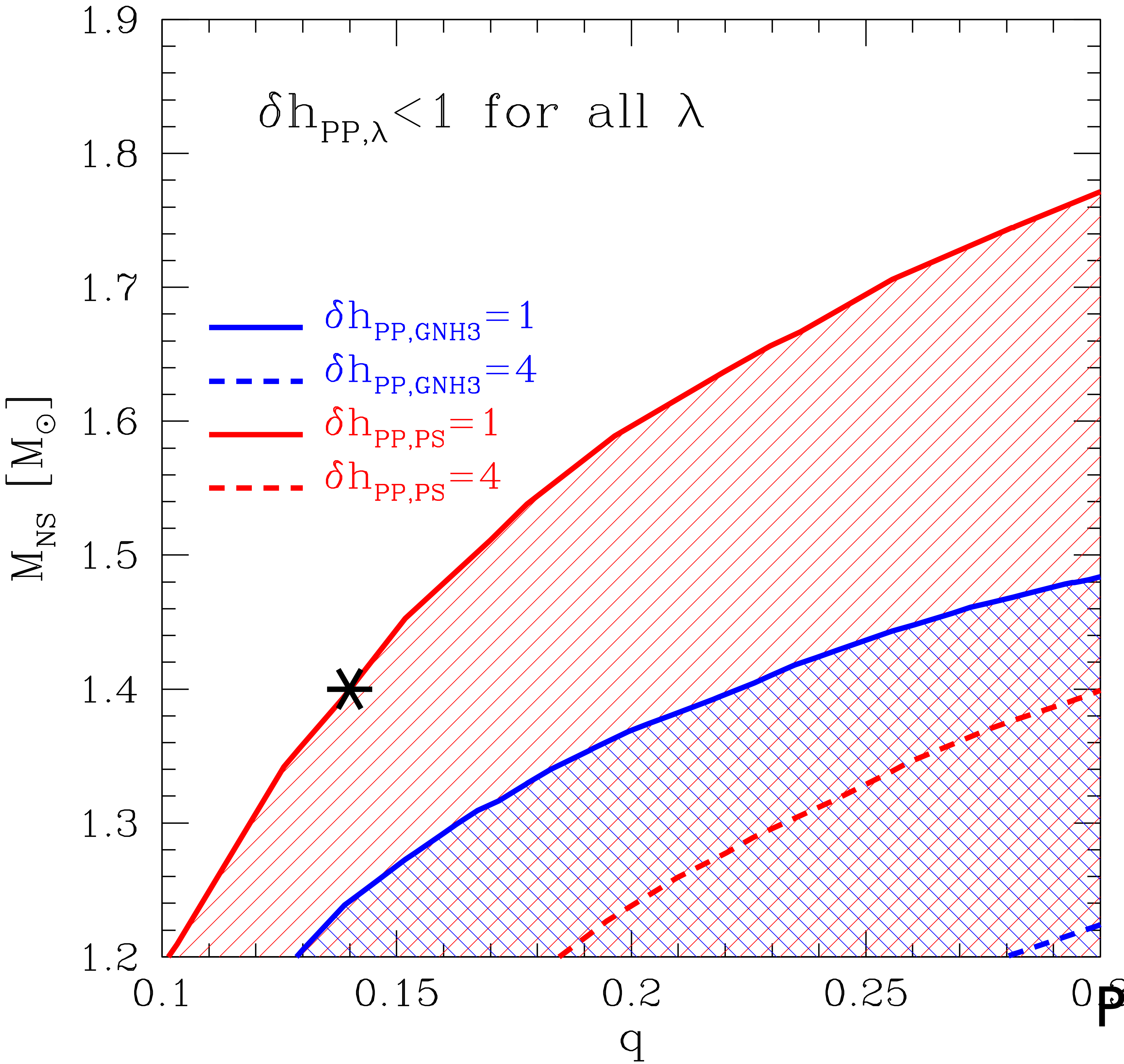


Measure mass parameters in early inspiral

Measure tidal contributions in late inspiral

Damour Nagar Villain 2012

Similar extrapolation in BHNS is less promising

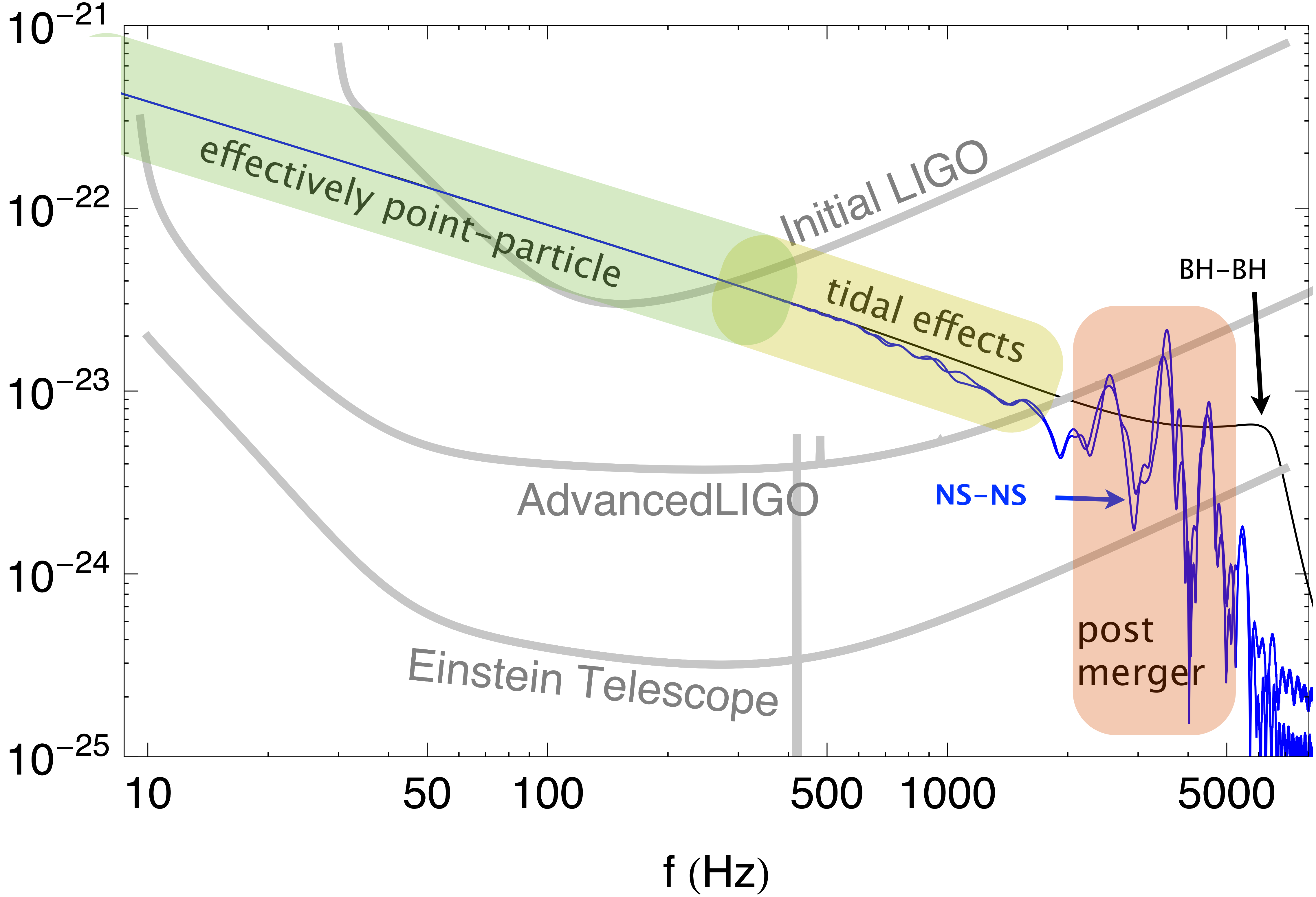


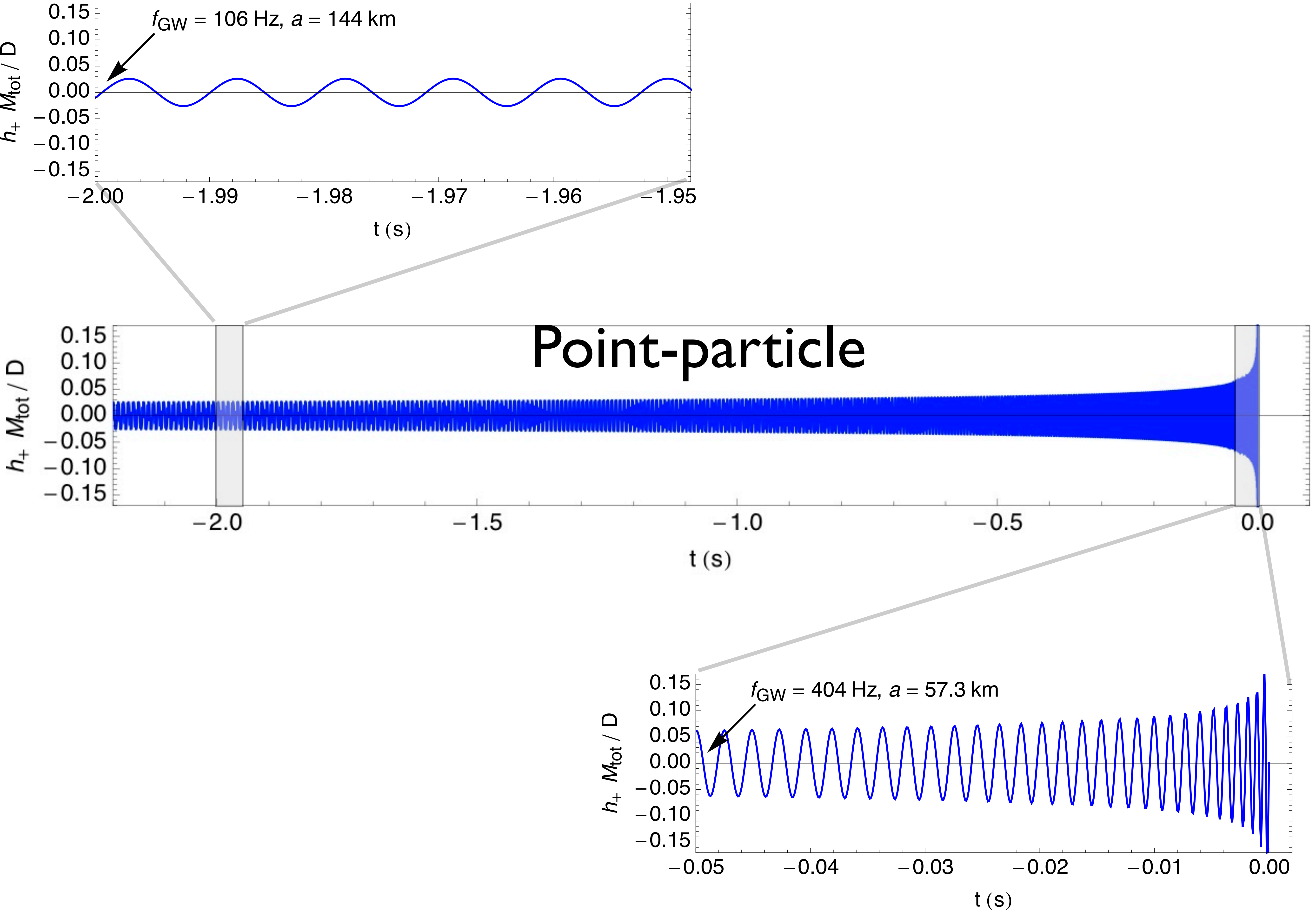
@100 Mpc distinguishing very stiff EOS only in low mass ratio systems

Pannarale et al arXiv: 1103.3526

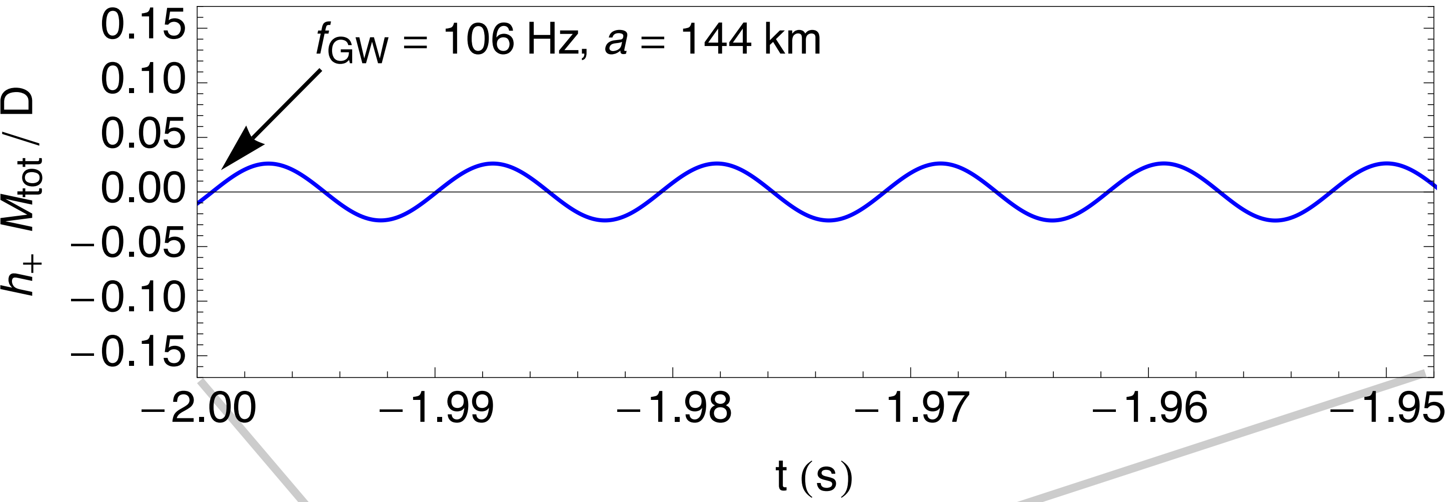
Numerical only estimates

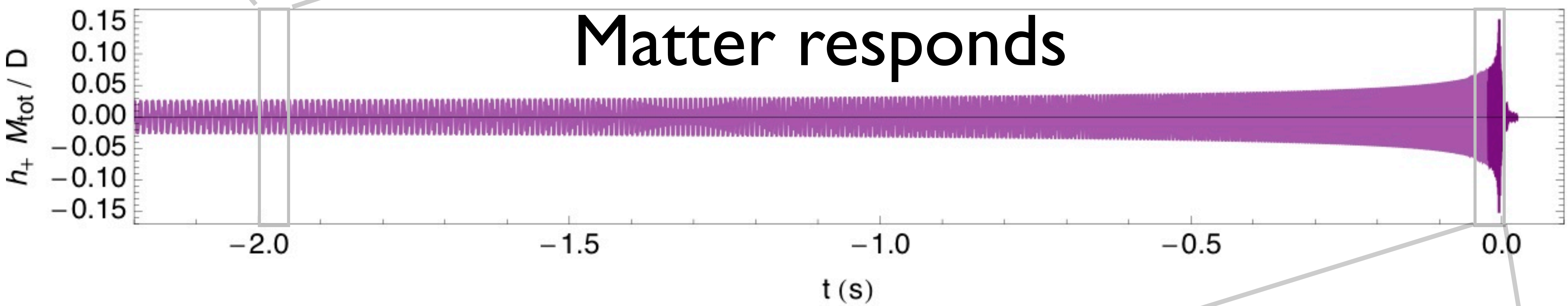
NS NS waveforms



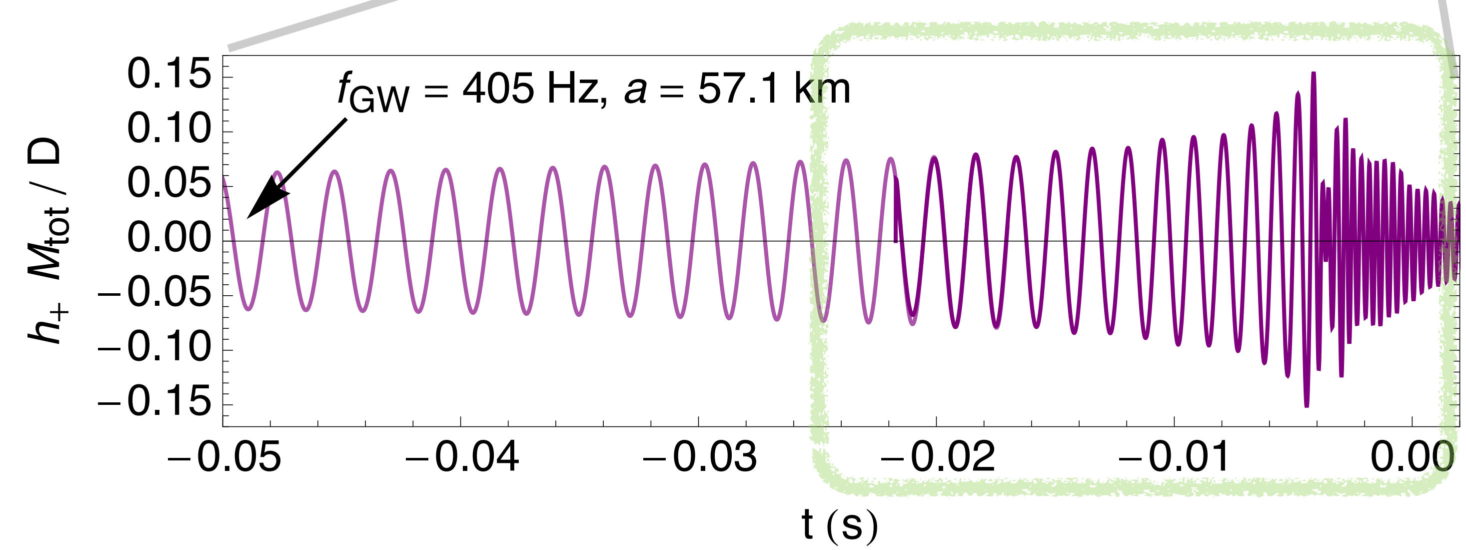

Point-particle
f_{GW} = 106 Hz, a = 144 km
f_{GW} = 404 Hz, a = 57.3 km
$h_+ M_{tot}$ / D
t (s)
0.15
0.10
0.05
0.00
−0.05
−0.10
−0.15
−2.00
−1.99
−1.98
−1.97
−1.96
−1.95
−2.0
−1.5
−1.0
−0.5
0.0
−0.05
−0.04
−0.03
−0.02
−0.01
0.00

Matter responds

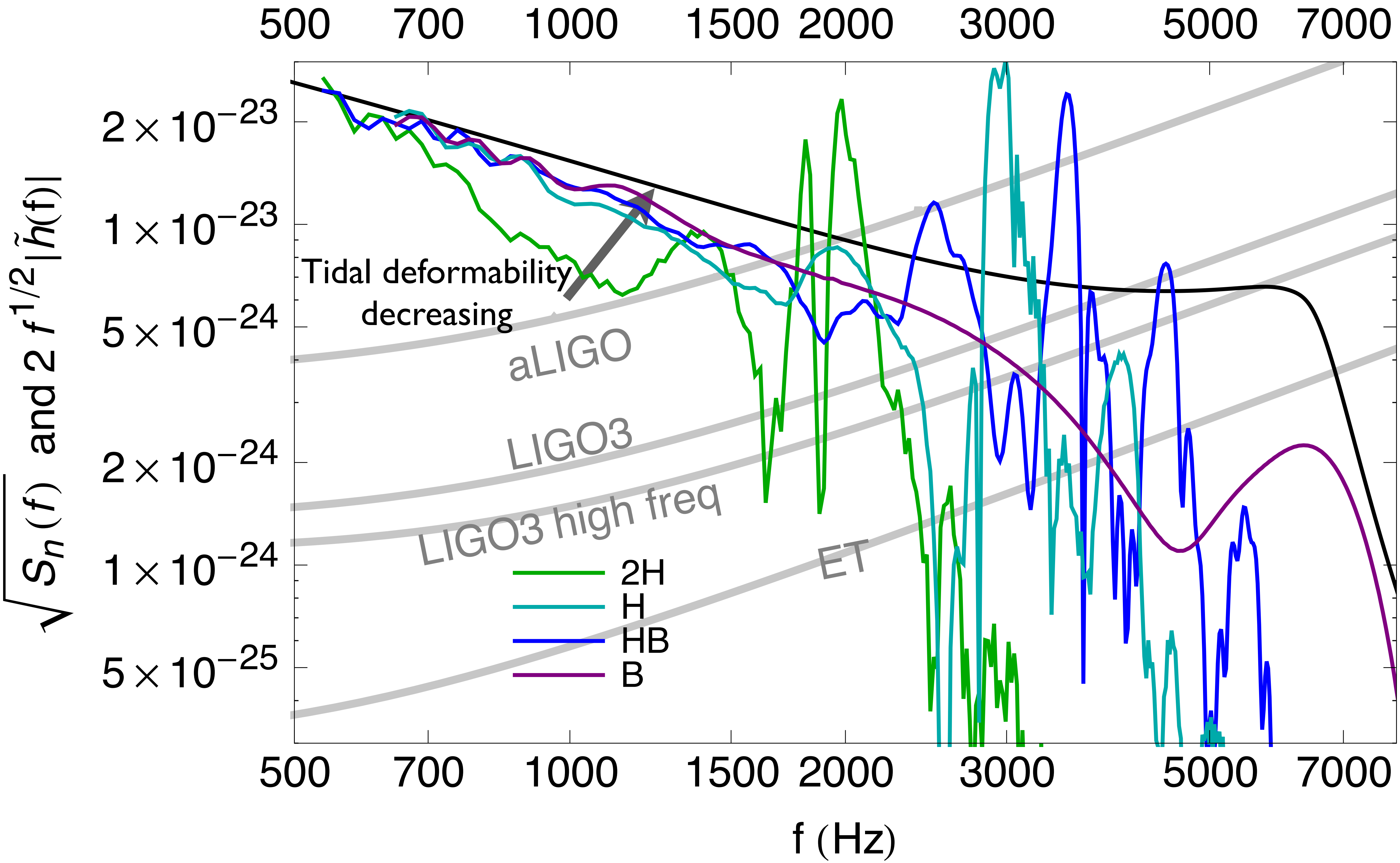




For the final coalescence, numerical simulation required



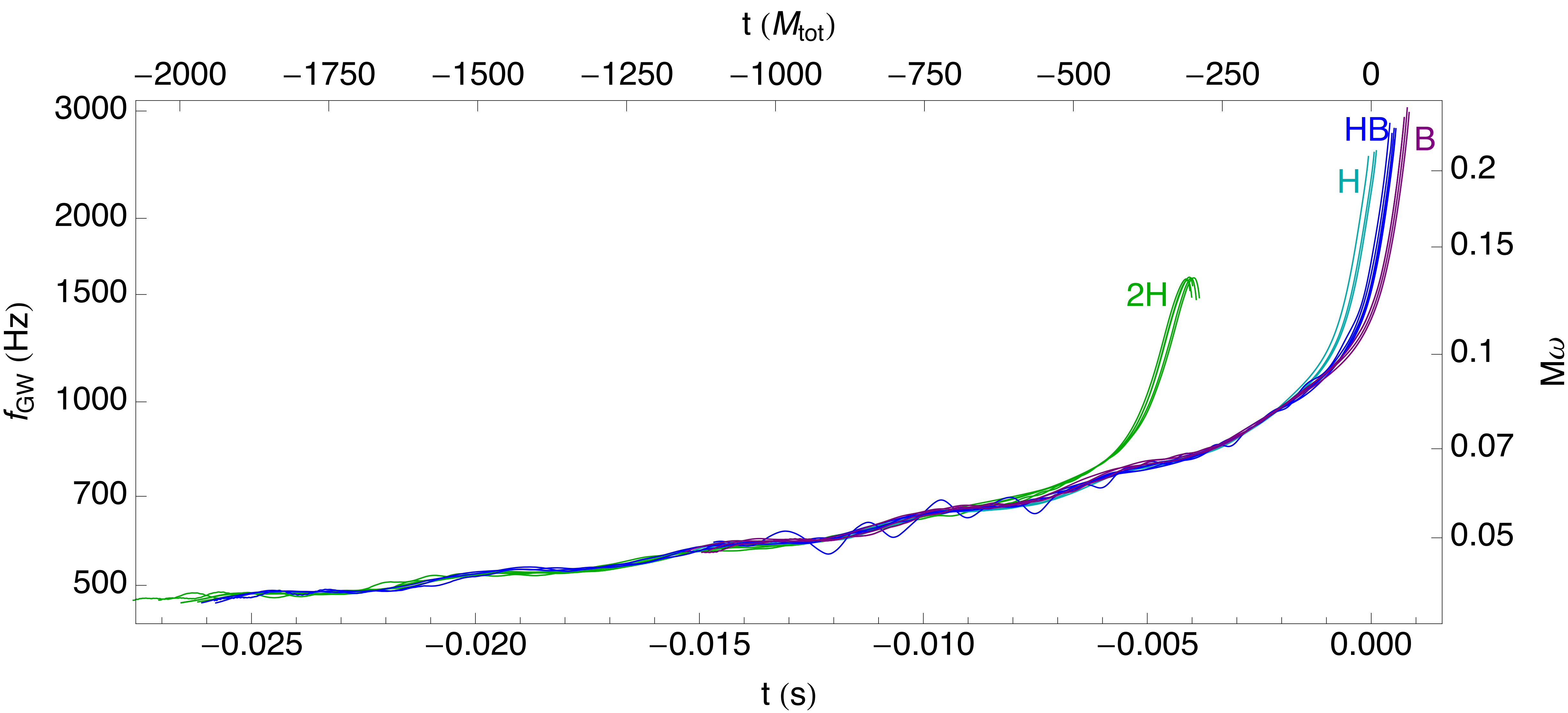
NS-NS: What can we extract?



Measurable?

Avoid high PN systematics; use numerical simulations only.

Minimized differences between noise weighted inspirals with different EOS



SNR of differences between waveforms

Advanced LIGO high-power detuned

EOS	H	HB	B
2H	2.162 ± 0.030	2.210 ± 0.036	2.234 ± 0.035
H	-	0.896 ± 0.099	1.0452 ± 0.087
HB	-	-	0.580 ± 0.168

Einstein Telescope configuration D

EOS	H	HB	B
2H	20.352 ± 0.314	20.739 ± 0.369	20.890 ± 0.360
H	-	7.740 ± 0.914	9.130 ± 0.866
HB	-	-	5.095 ± 1.490

$$\langle \delta R \rangle \Big|_{R_{avg}} \simeq \frac{R_1 - R_2}{\big\langle h(R_1) - h(R_2) \big| h(R_1) - h(R_2) \big\rangle^{1/2}}$$

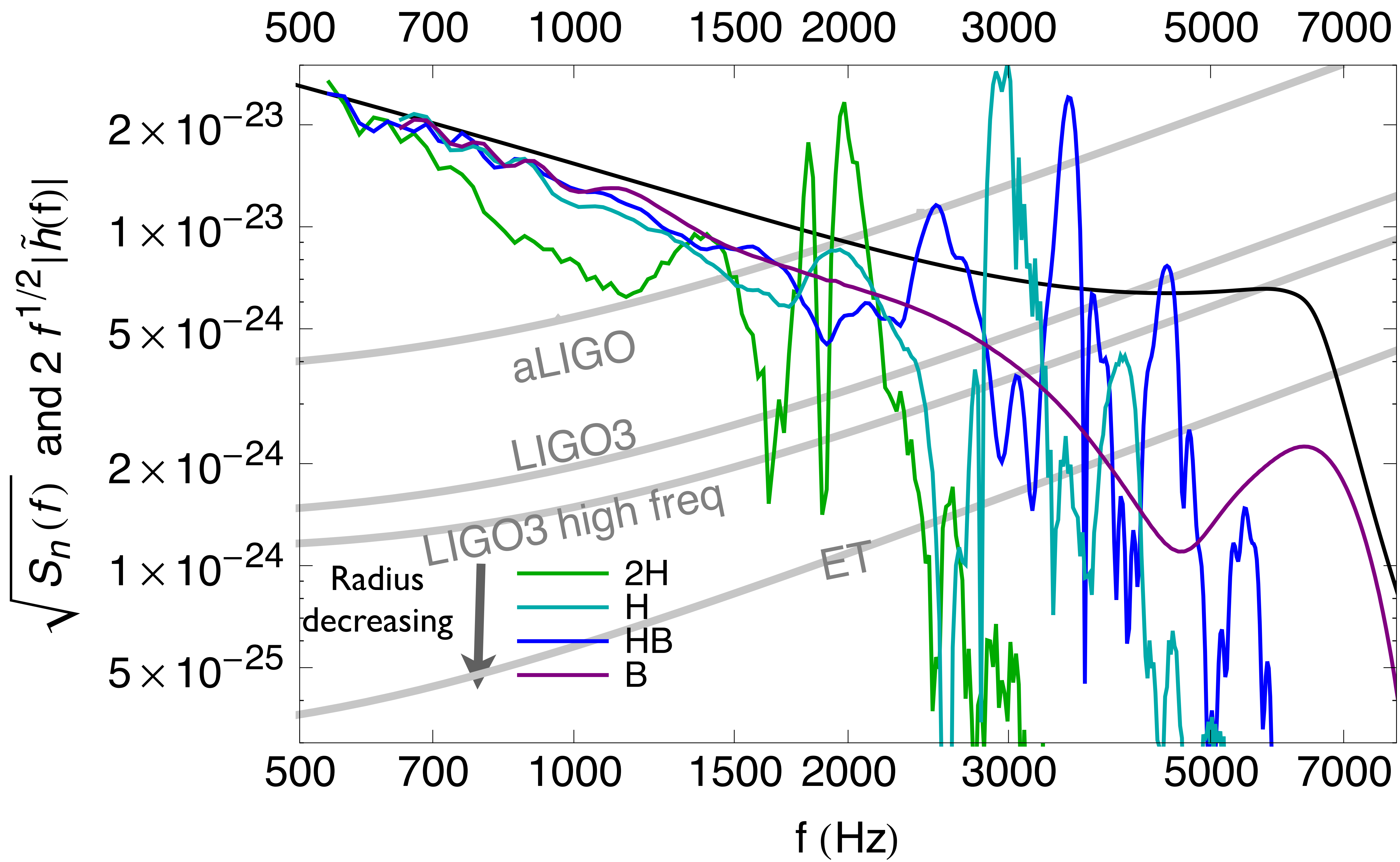
$\langle \delta R \rangle$, R is radius of isolated neutron star

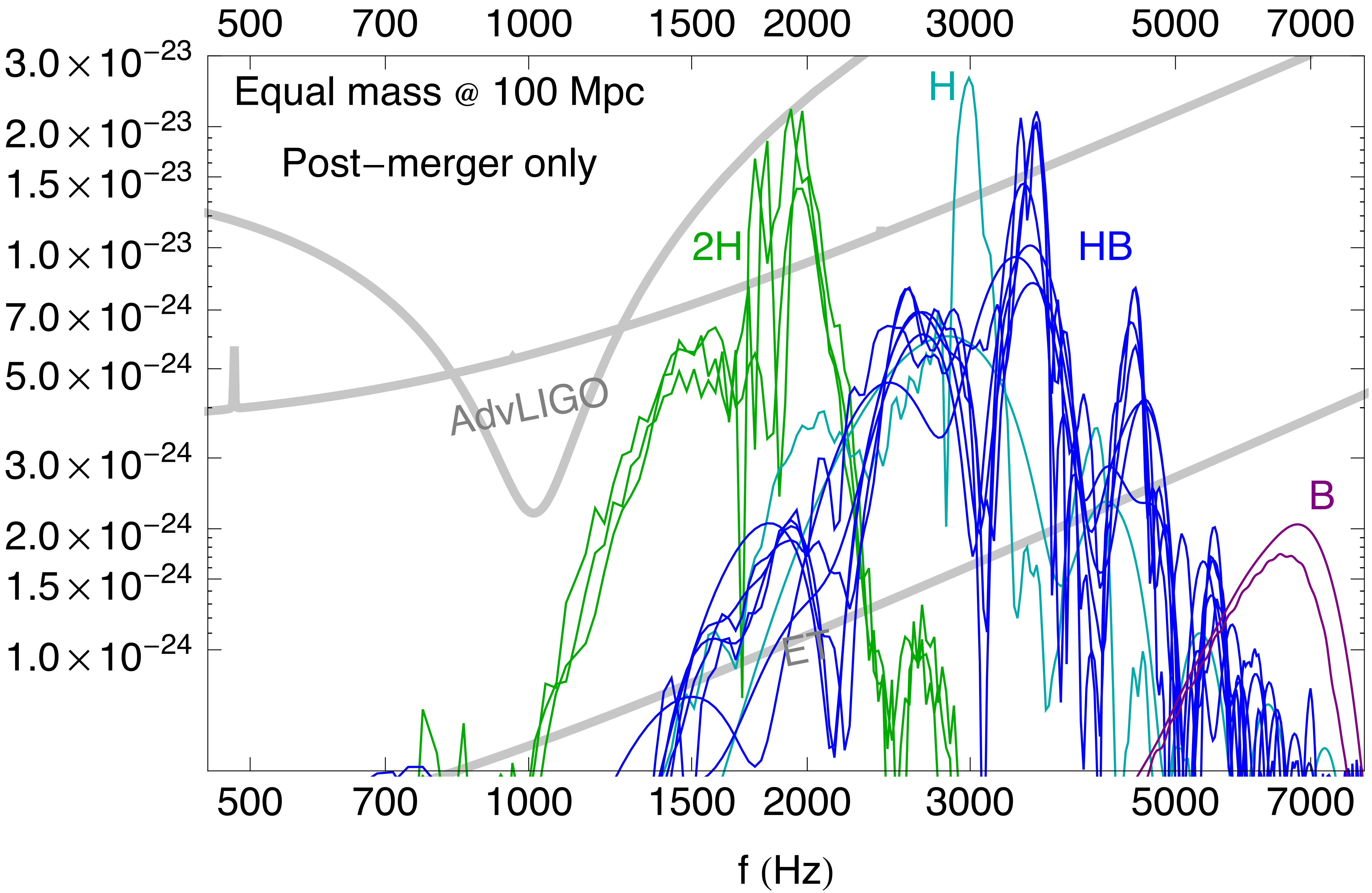
	Broadband AdLIGO	ET-D
$R = 10.8$	± 0.9 km	± 0.09 km
$R = 11.9$	± 0.8 km	± 0.10 km

Radius can be constrained with a strong Advanced LIGO signal
(in high-power detuned configuration)
based on numerical waveform alone.

Systematics from different numerical simulations with same EOS ~ 0.1 km
Other sources: parameterization choice, discrete parameter sampling

Effect of matter post-merger





Equal mass @ 100 Mpc
Post−merger only
AdvLIGO
ET
2H
H
HB
B
f (Hz)
500
700
1000
1500
2000
3000
5000
7000
3.0 × 10−23
2.0 × 10−23
1.5 × 10−23
1.0 × 10−23
7.0 × 10−24
5.0 × 10−24
3.0 × 10−24
2.0 × 10−24
1.5 × 10−24
1.0 × 10−24

It is harder to measure the post-merger than the (extrapolated) inspiral

	SNR $\times (100\,\mathrm{Mpc}/D_{\mathrm{eff}})$		f_p
EOS	aLIGO Broadband	ET-D	(kHz)
2H	0.83	6.1+	2
H	0.54	5.6+	3
HB	0.47	3.3+	3.5
B	0.07	0.7	6.5–7
Bs	0.07	0.7	6.5–7
Bss	0.03	0.3	6.5–7
HBs	0.06	0.4	6.5–7
HBss	0.05	0.7	6.5–7

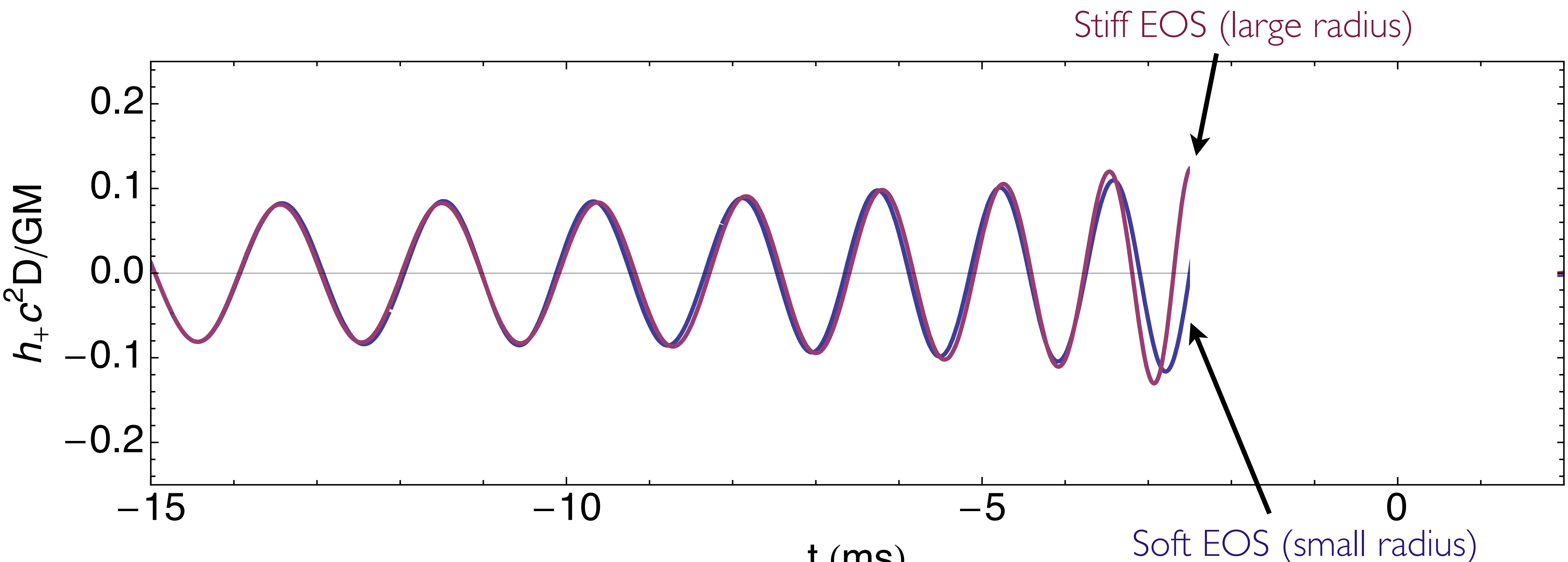
Hybrid estimates

NSBH: What can we extract?

- Phase shift $\delta\Phi$ during inspiral
  - Much smaller than for BNS systems because

$$\delta\Phi \propto \frac{\lambda}{(1+q)^5 M_{\rm NS}^5} = \frac{\Lambda}{(1+q)^5}$$

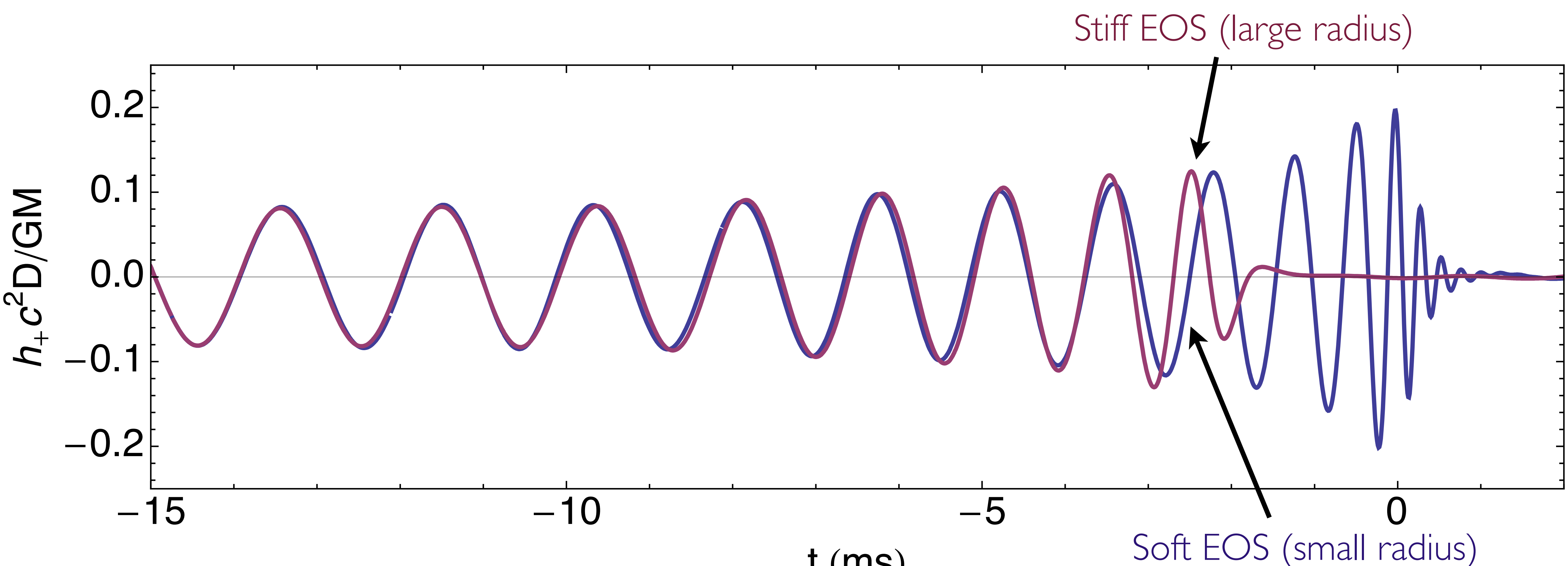
  - Only marginally observable with Advanced LIGO (Pannarale et al. arXiv:1103.3526)



Slide from Ben Lackey

NSBH: What can we extract?

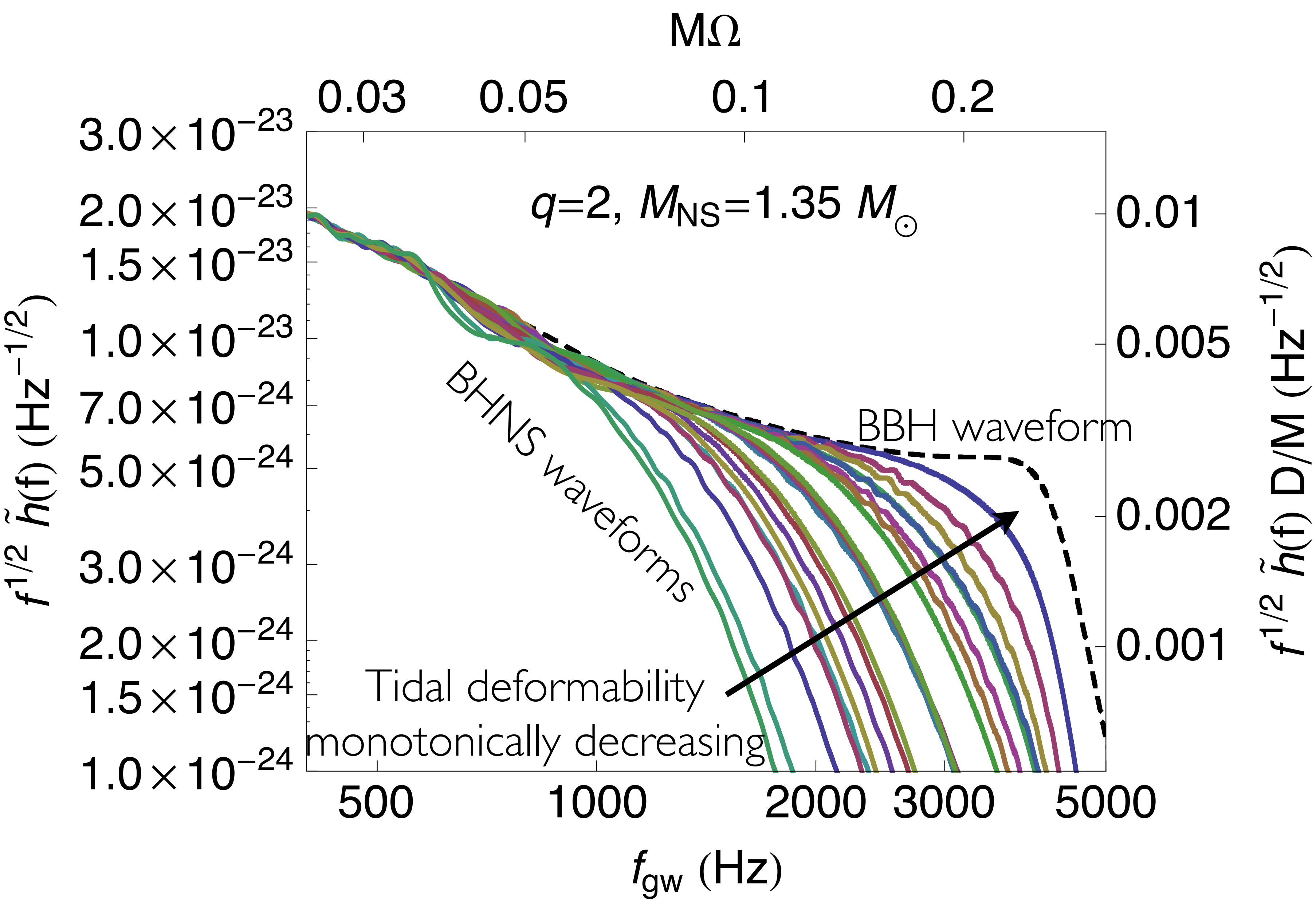
- Cutoff in amplitude from tidal disruption
  - Occurs earlier (lower frequency) for larger stars
  - Much larger effect than phase shift



Slide from Ben Lackey

NSBH: What can we extract?

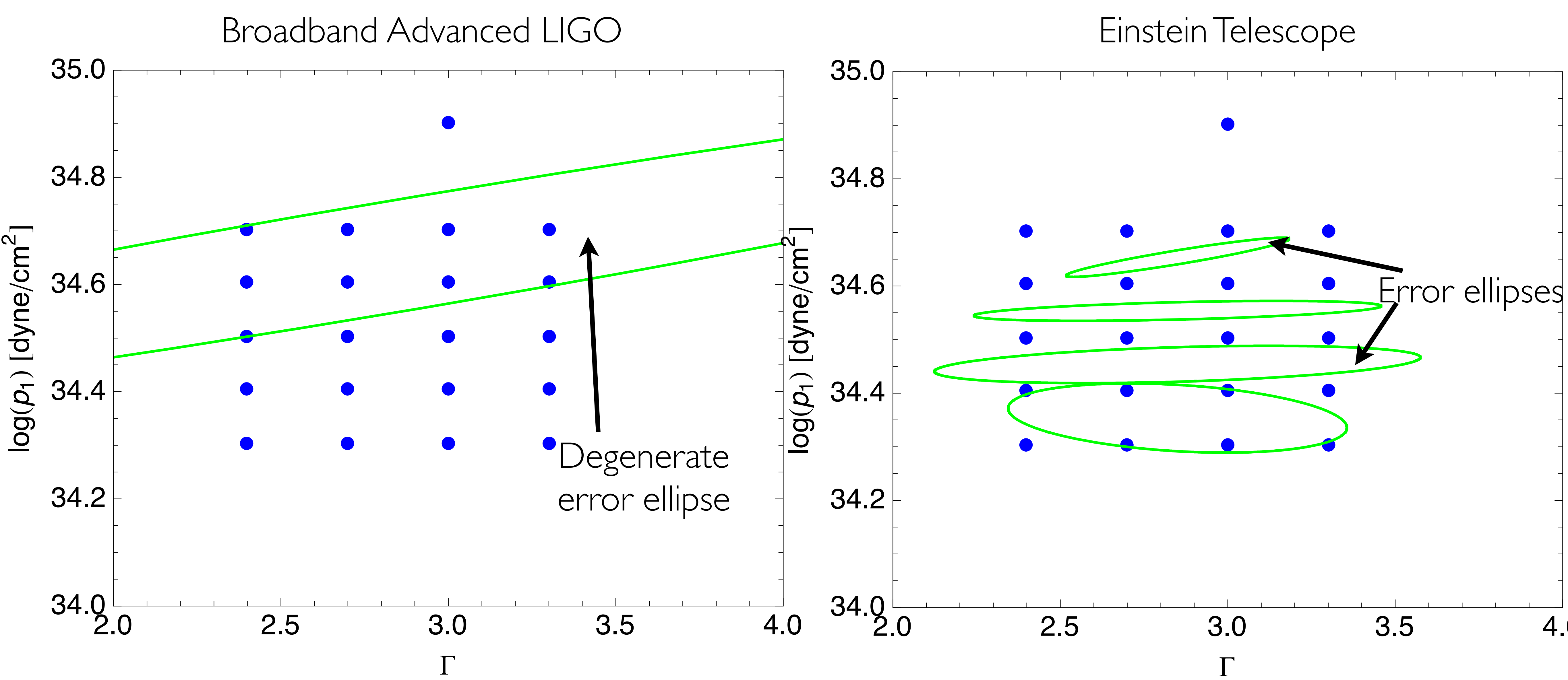
- Cutoff frequency depends on tidal deformability parameter Λ



Slide from Ben Lackey

EOS parameter estimates

- 1-sigma errors shown for single binary optimally oriented at 100Mpc
- Errors for proposed Einstein Telescope 5-10 times smaller than for Advanced LIGO



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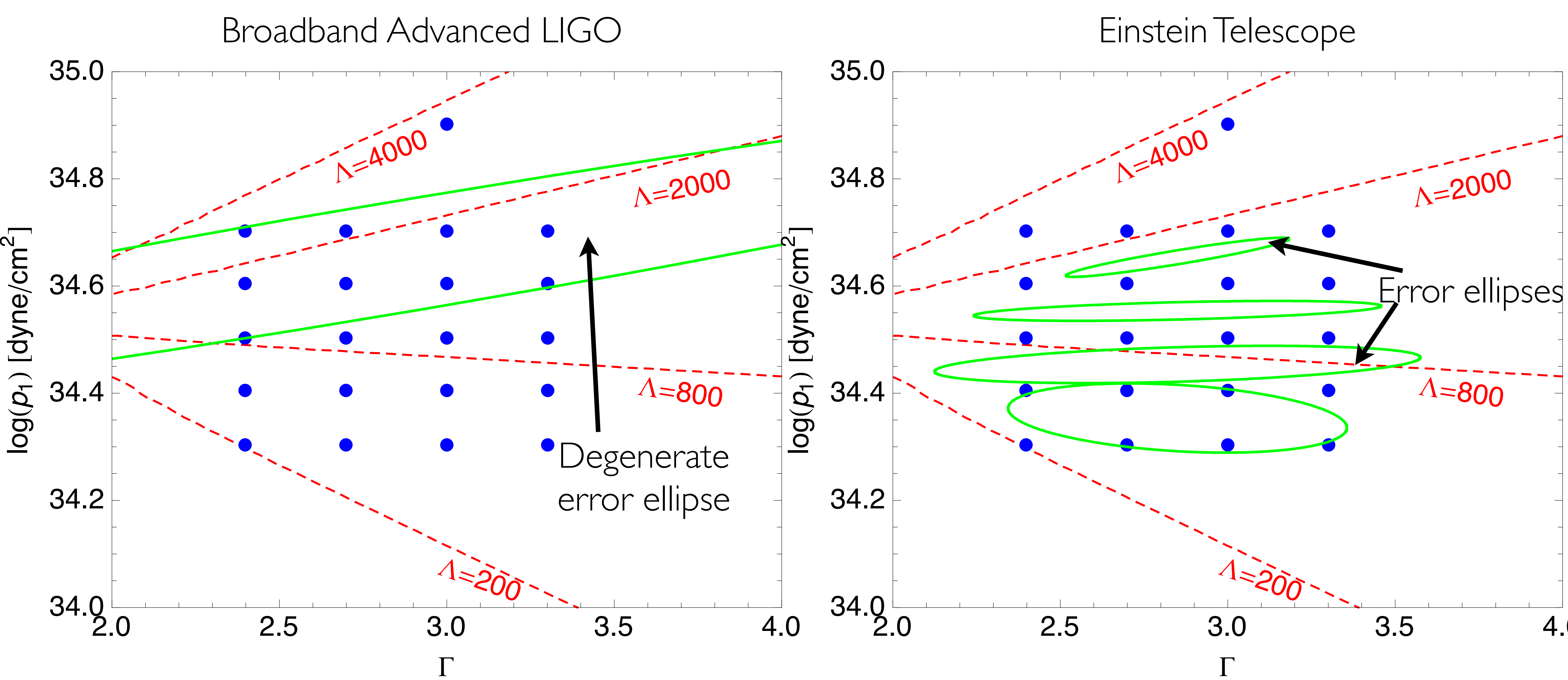

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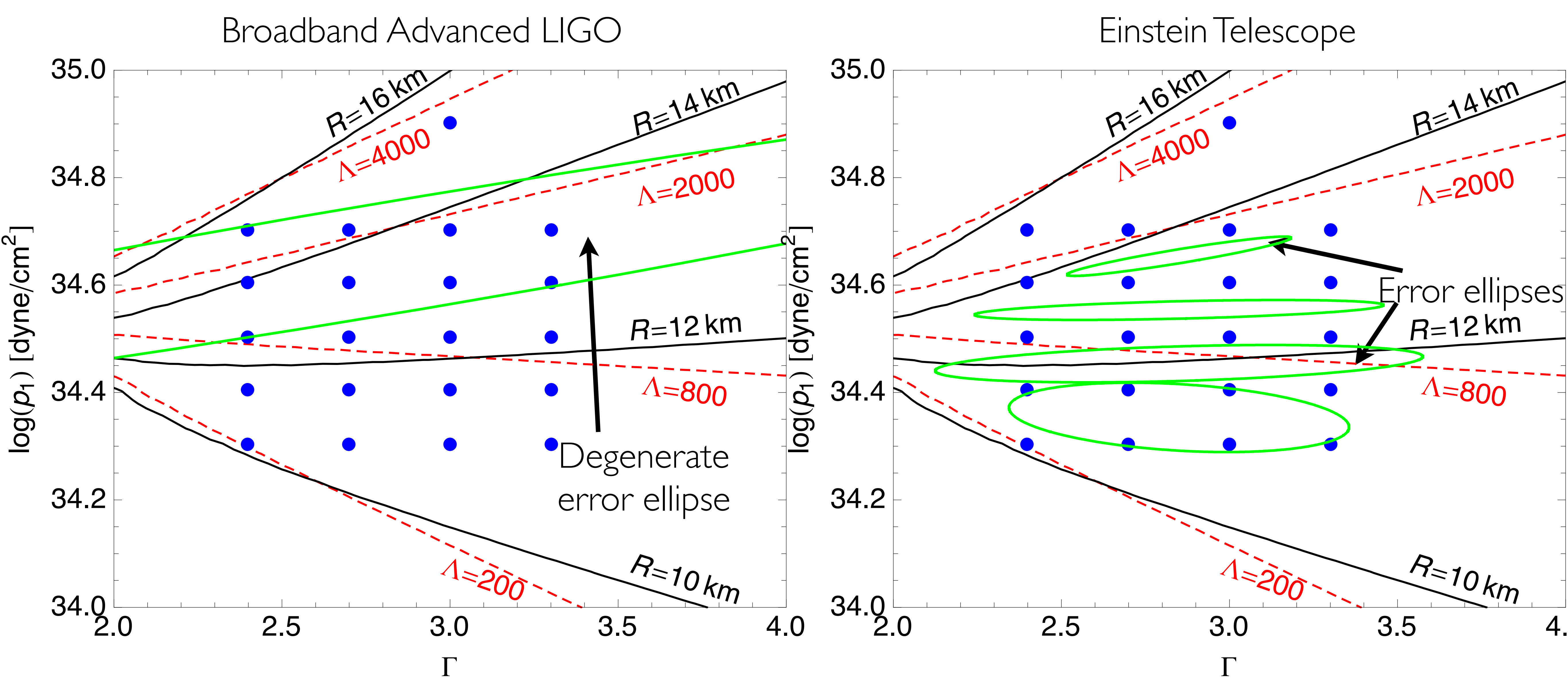
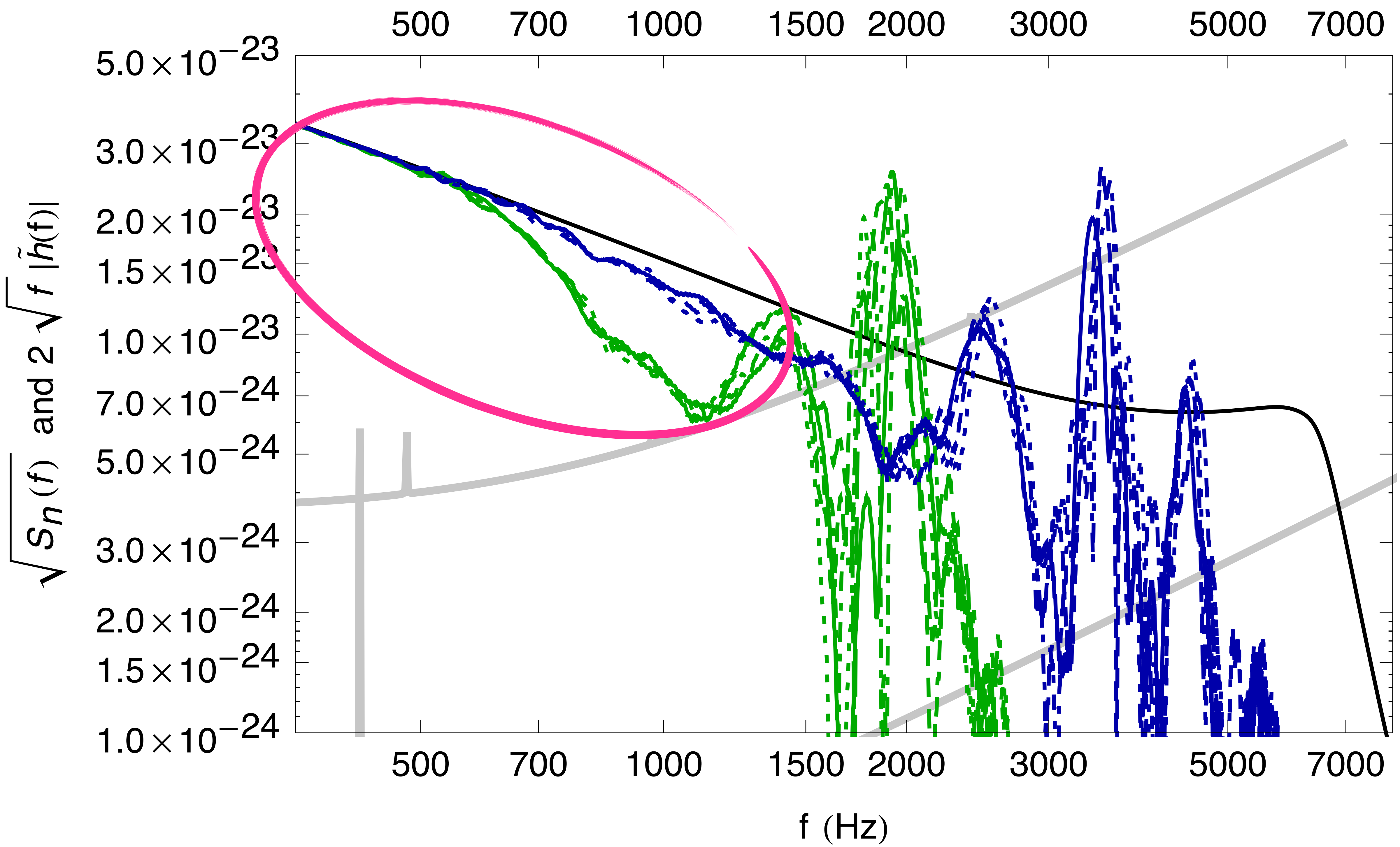
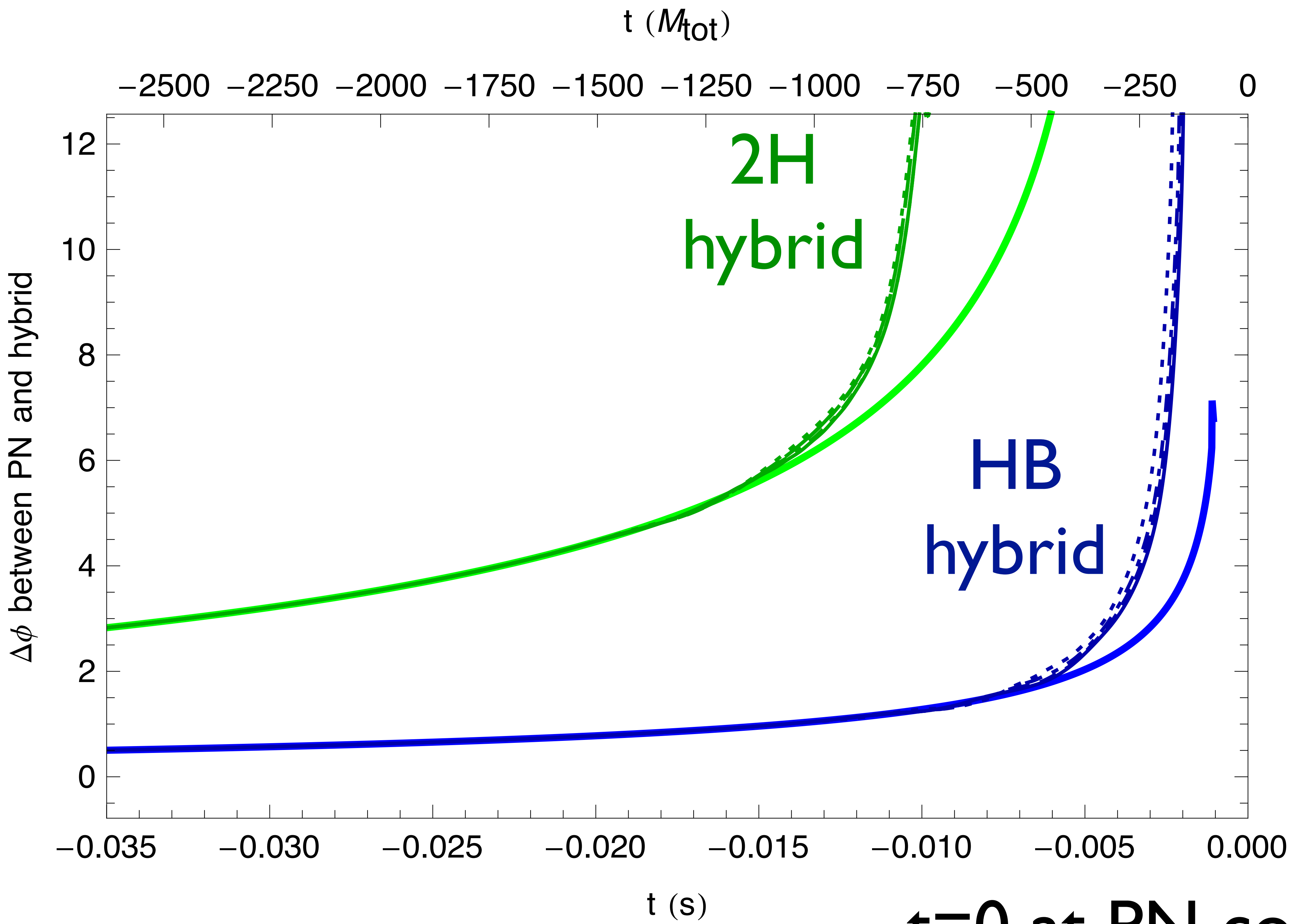


- The same EOS parameter that determines behavior during inspiral also accurately describes behavior during merger/ringdown

NSNS: Hybrid construction improves inspiral measurability

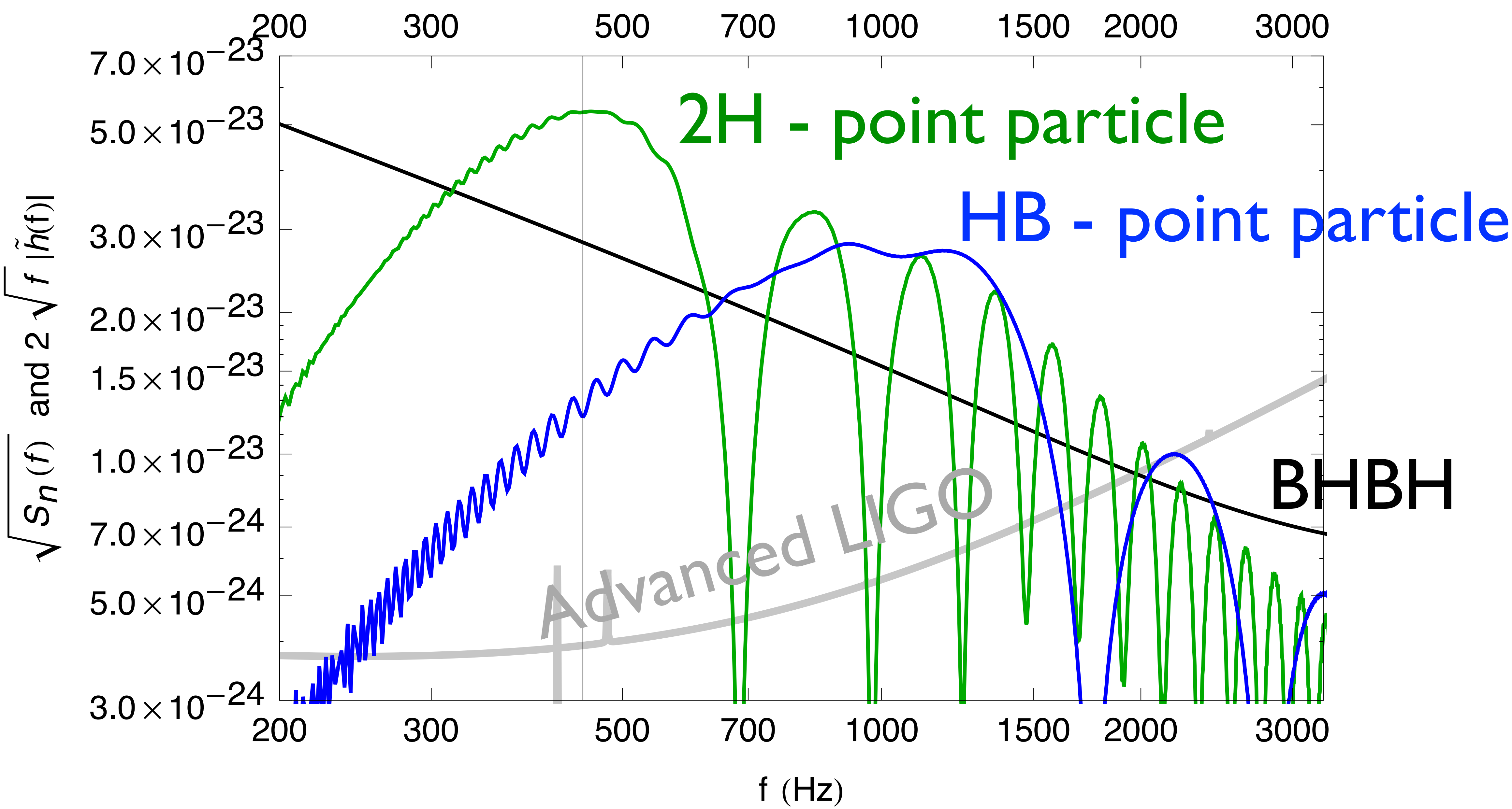


Transition hybrid to numerical merger in late inspiral, resolution does not significantly modify phase evolution



t=0 at PN coalescence

Amplitude spectrum of difference between NSNS waveforms and waveforms with no matter
(This better encodes the accumulated phase differences)



	Broadband aLIGO	ET-D
EOS 2H to EOS HB		
$R = 13.42$	± 0.50 km	± 0.05 km
$(\Lambda)^{1/5} = 2.02$	± 0.07	± 0.01
EOS 2H to unmodified PN		
$(\Lambda)^{1/5} = 1.18$	± 0.20	± 0.02
EOS HB to unmodified PN		
$(\Lambda)^{1/5} = 0.84$	± 0.28	± 0.03

Some systematics: 3% from change in numerical simulation of same system, 5% variation in hybridization region, 1% neglecting higher order tidal terms