Measuring the neutron-star equation of state with GW170817

Jocelyn Read
California State University, Fullerton

LSC/Virgo PRL 119, 161101 (2017), data
simulation image: T. Dietrich(AEI/FSU

Neutron-star mergers: An astrophysical collider

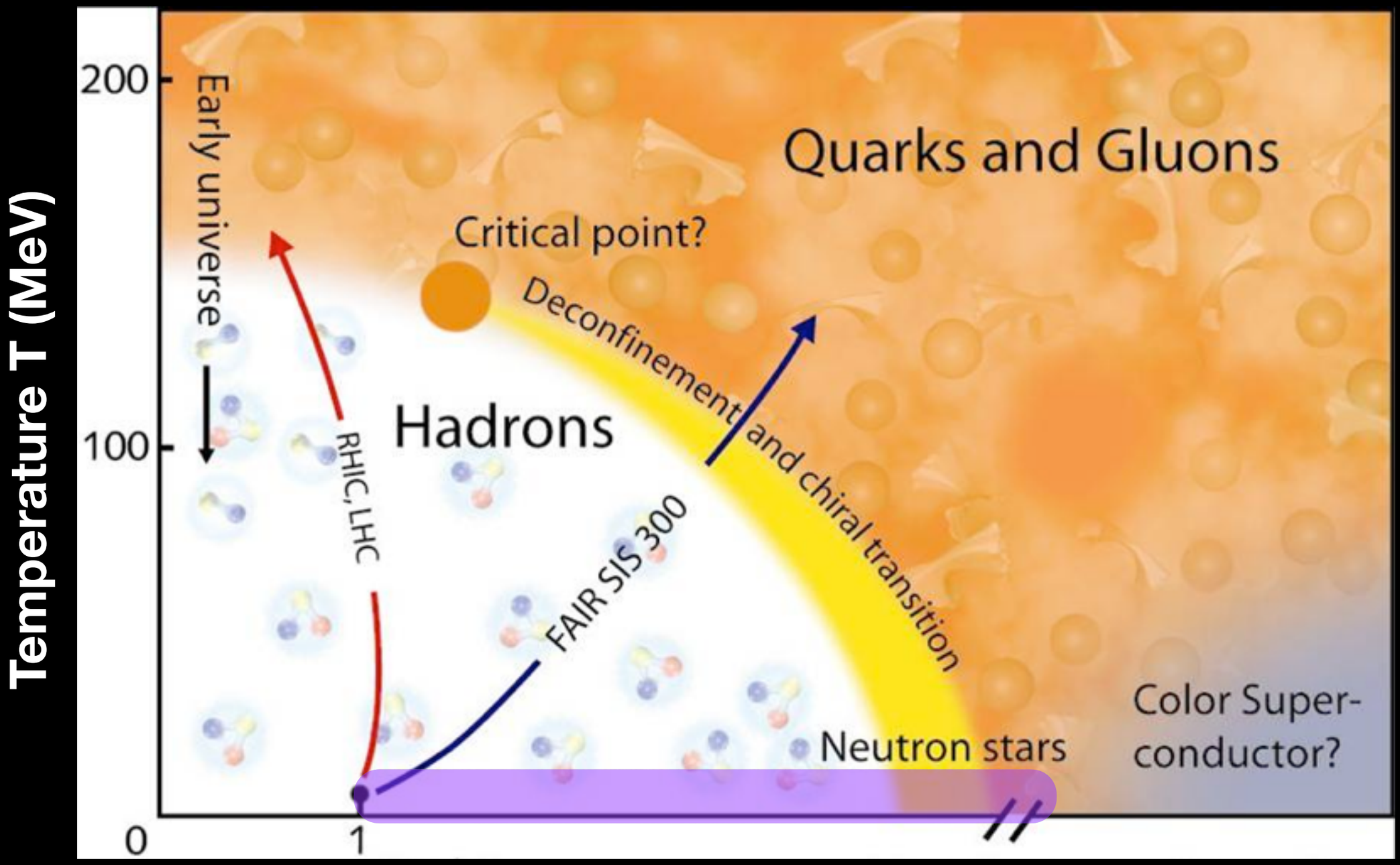

figure from FAIR CBM experiment

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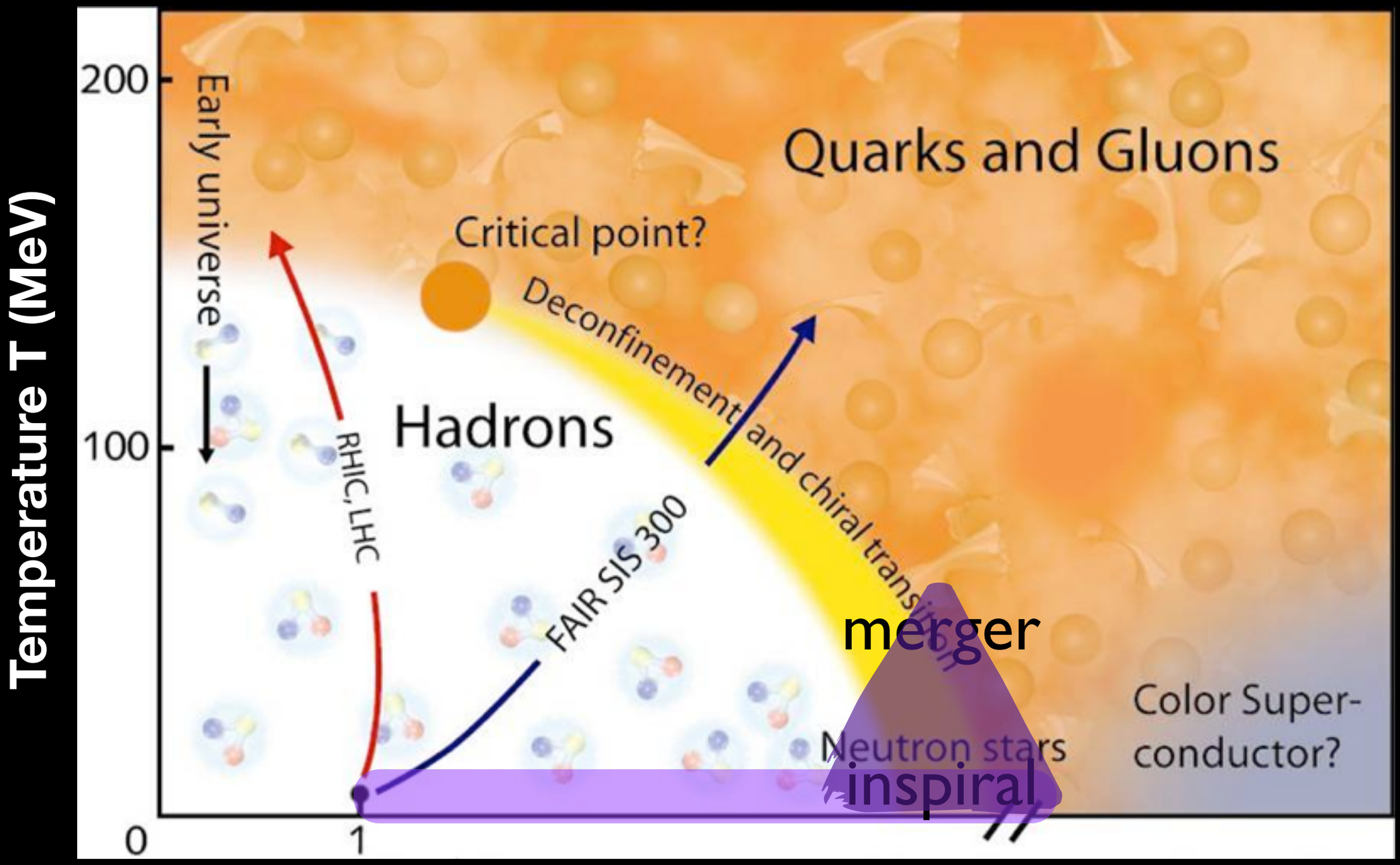


figure from FAIR CBM experiment

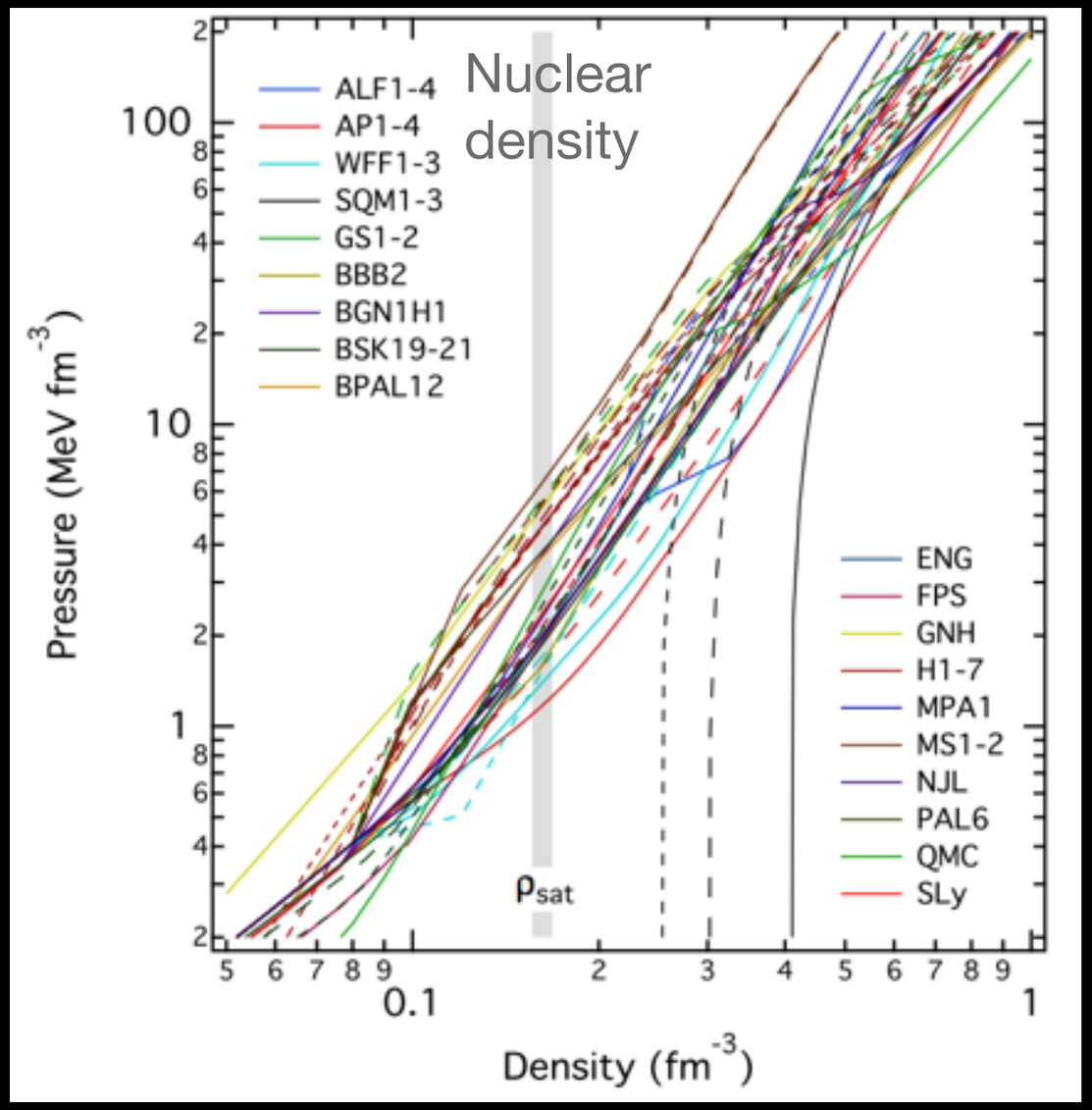
Properties of dense matter

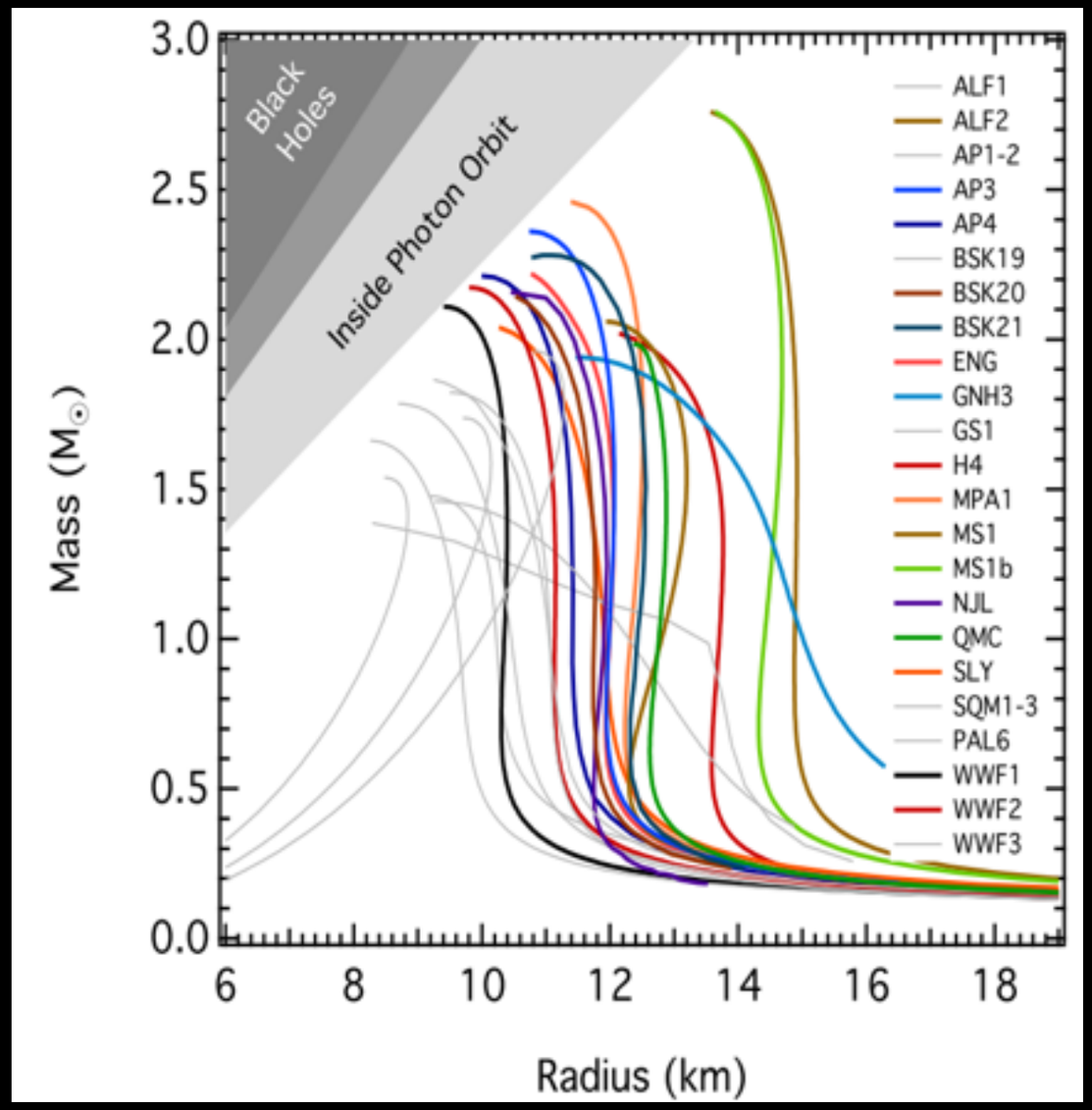
↔

Neutron star properties

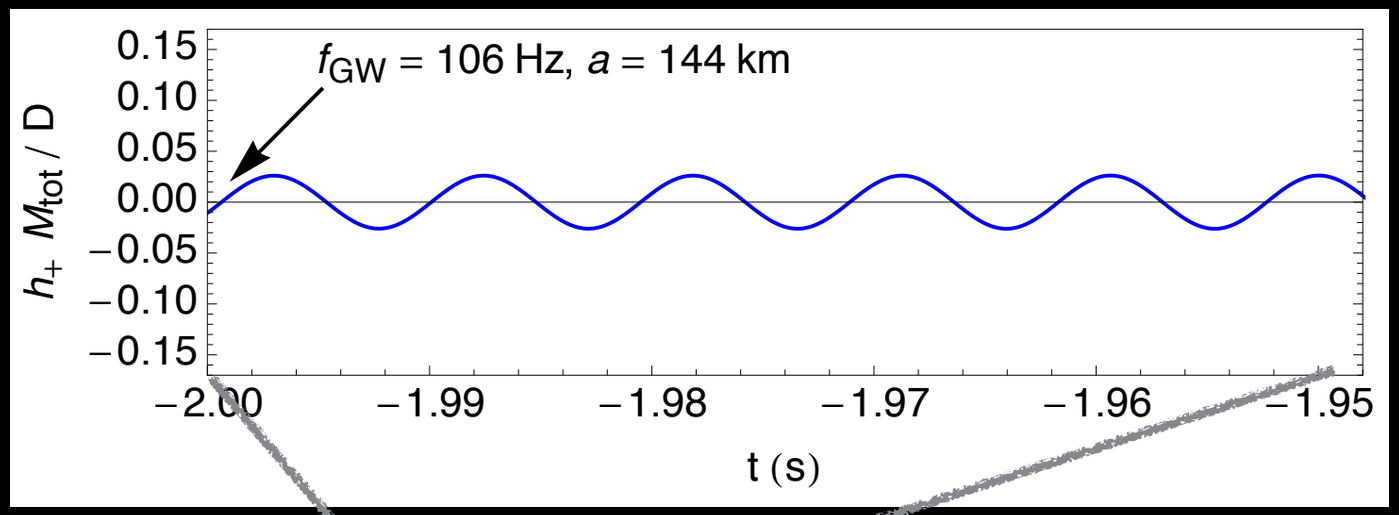
Equation of state in beta equilibrium

Mass-radius relation, max mass, deformability

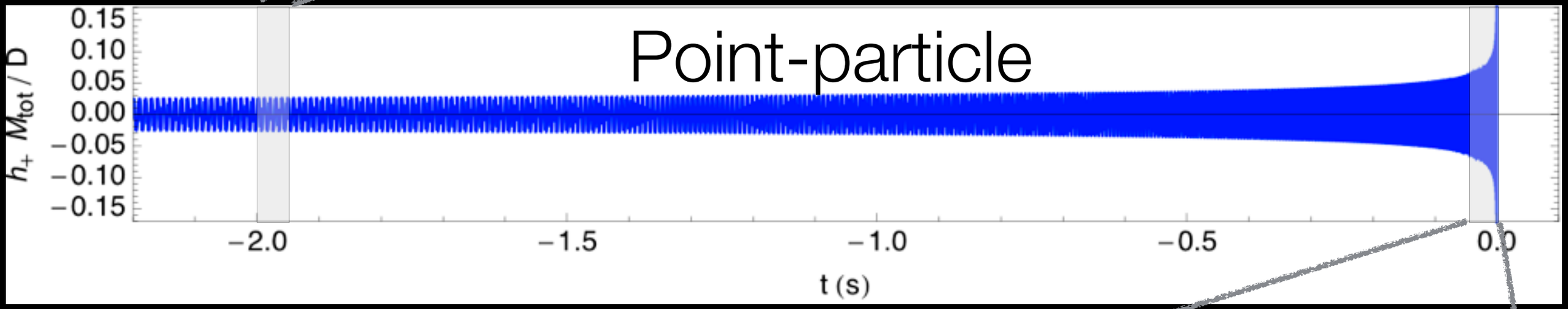


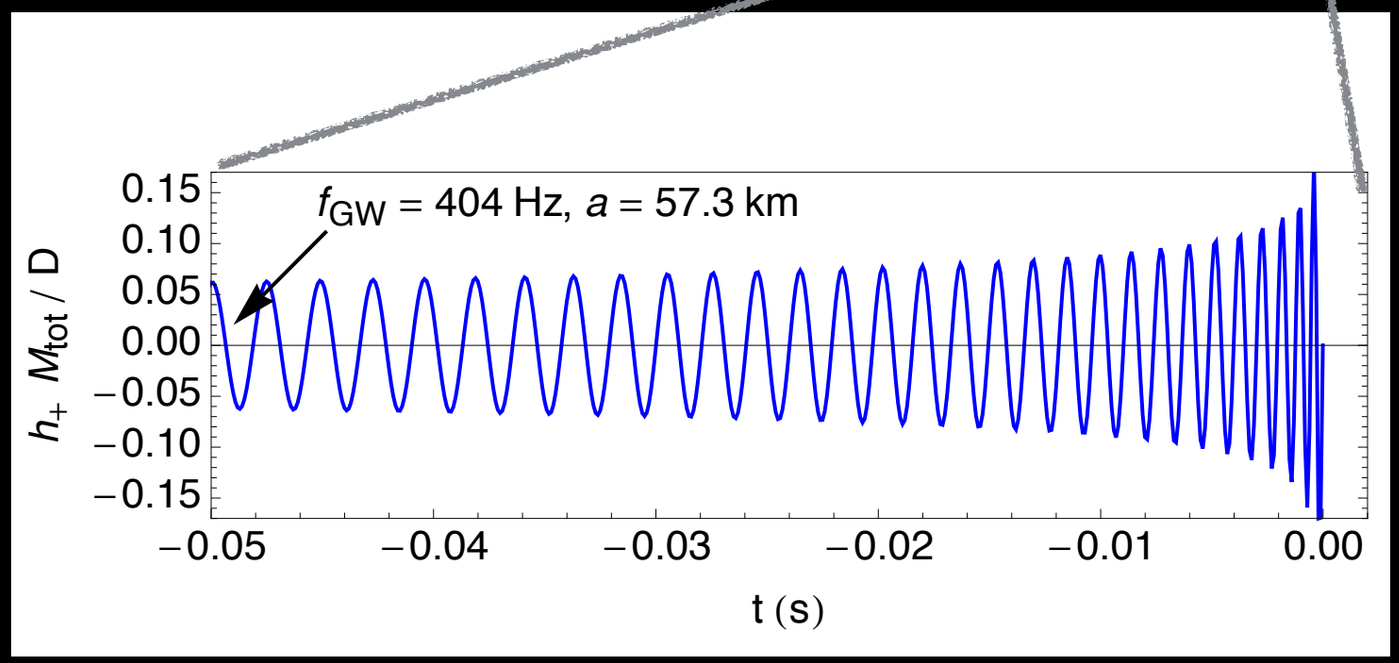


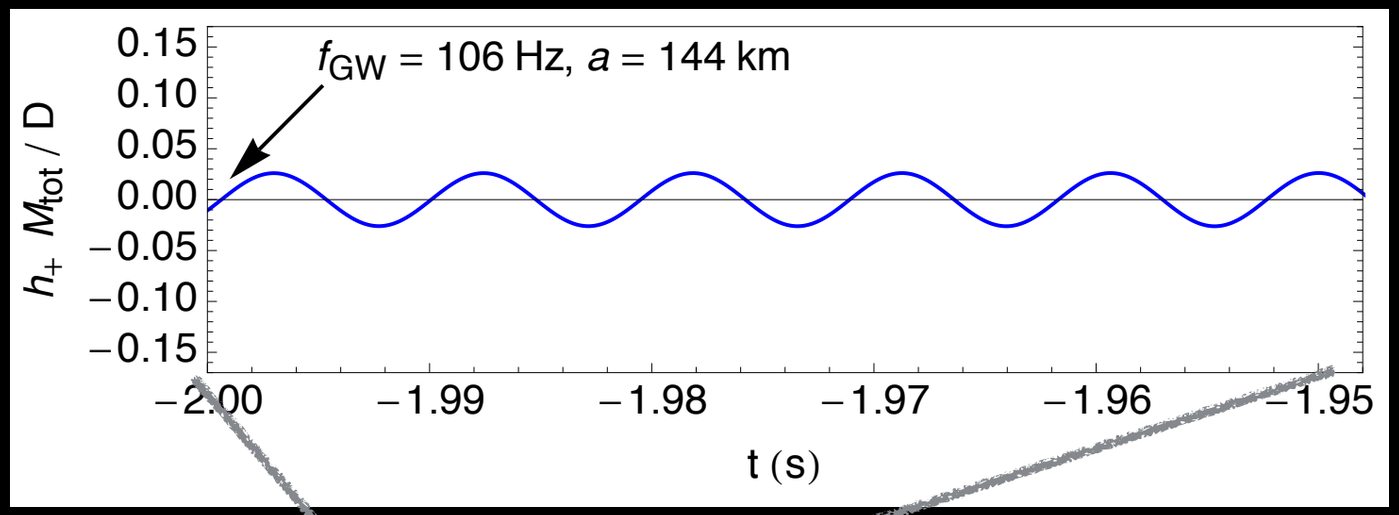
Ozel and Friere 2016

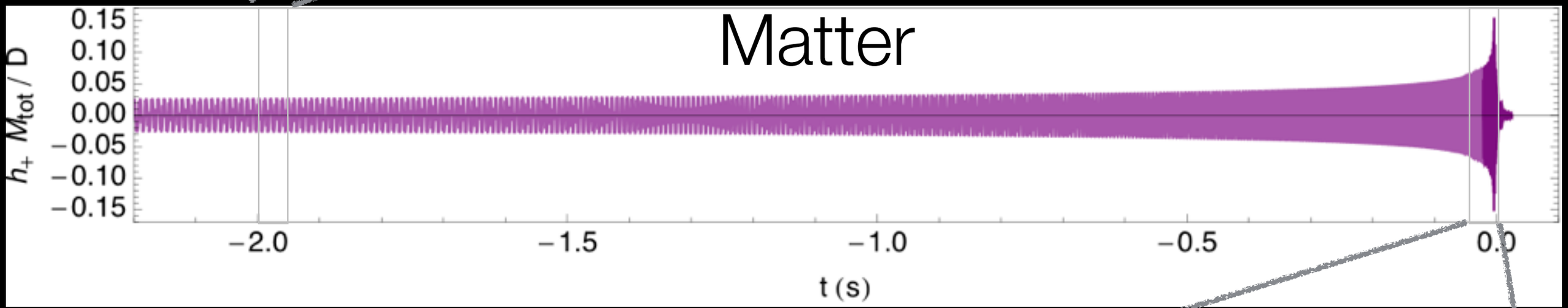


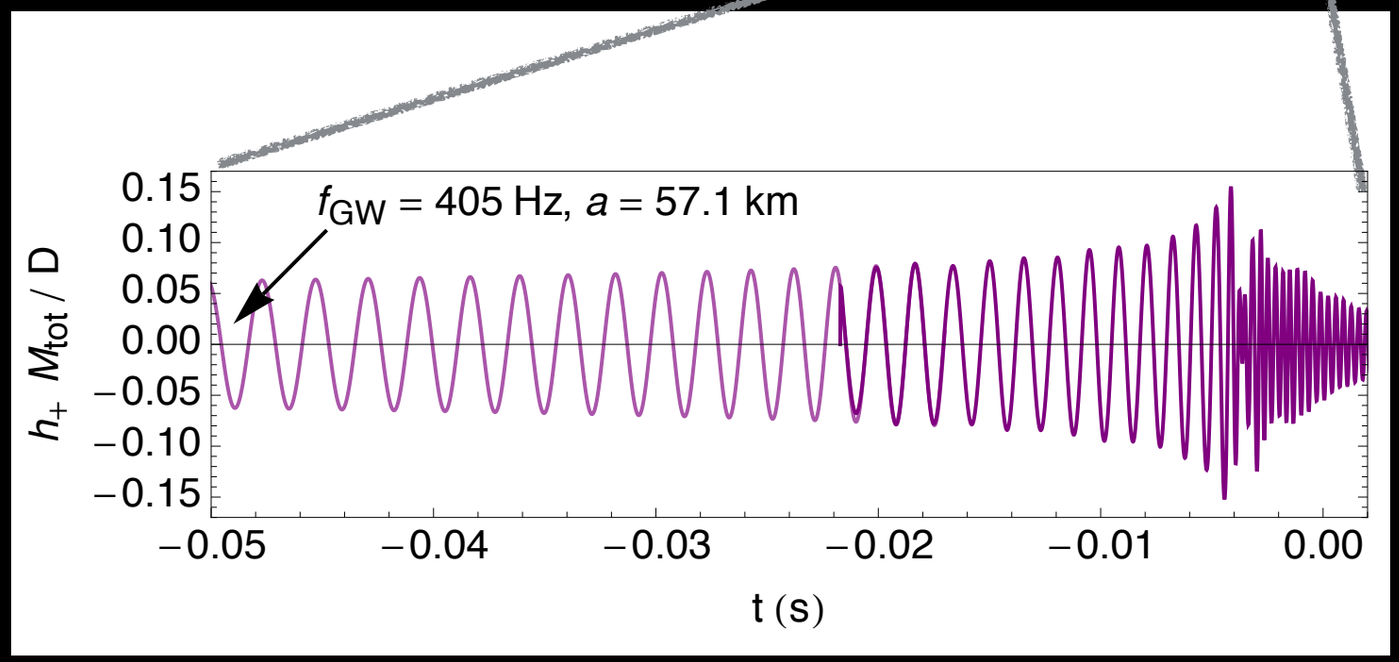
Hard to modify early inspiral: transfer of ~10^{46} erg at ~100Hz modifies phase by 10^{-3} radians (crust shattering, Tsang et al 1110.0467)

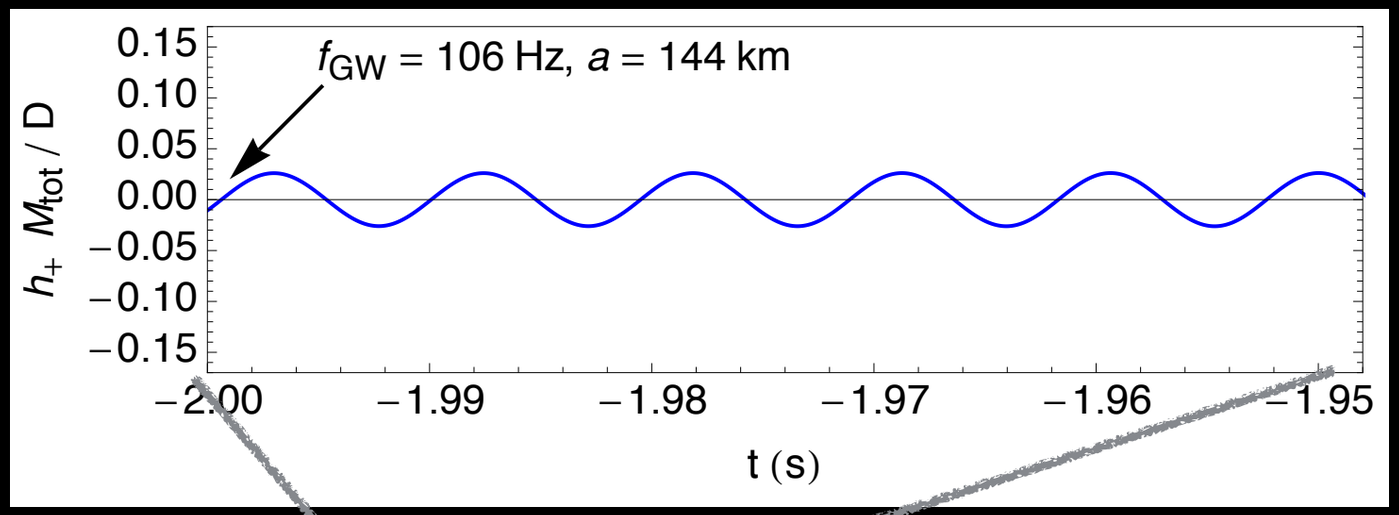


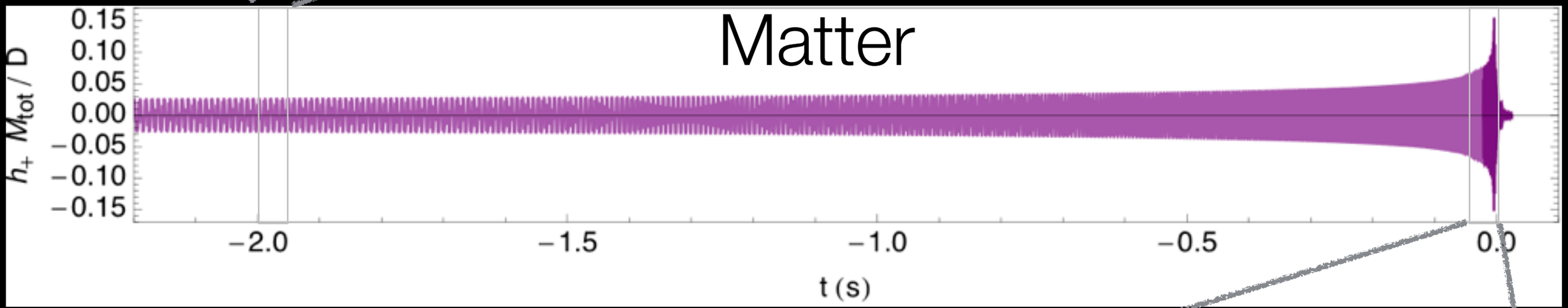



f_{GW} = 106 Hz, a = 144 km
h_+ M_{tot} / D
0.15
0.10
0.05
0.00
−0.05
−0.10
−0.15
−2.00
−1.99
−1.98
−1.97
−1.96
−1.95
t (s)

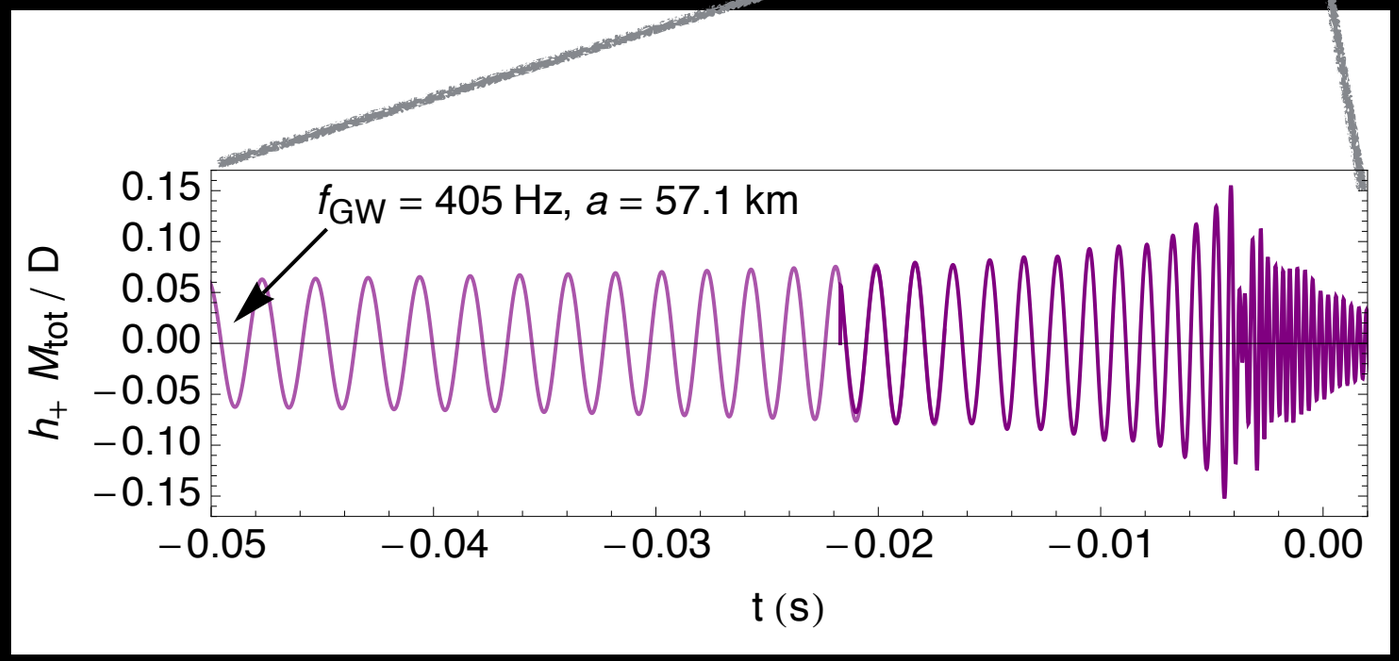

Matter
h_+ M_{tot} / D
0.15
0.10
0.05
0.00
−0.05
−0.10
−0.15
−2.0
−1.5
−1.0
−0.5
0.0
t (s)

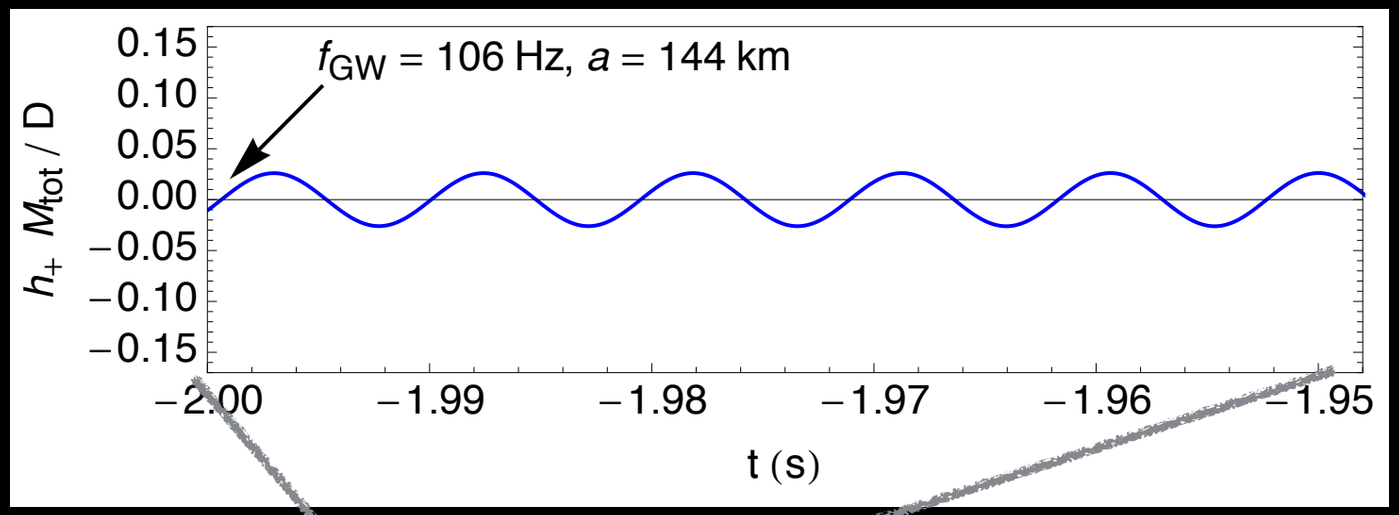

f_{GW} = 405 Hz, a = 57.1 km
h_+ M_{tot} / D
0.15
0.10
0.05
0.00
−0.05
−0.10
−0.15
−0.05
−0.04
−0.03
−0.02
−0.01
0.00
t (s)

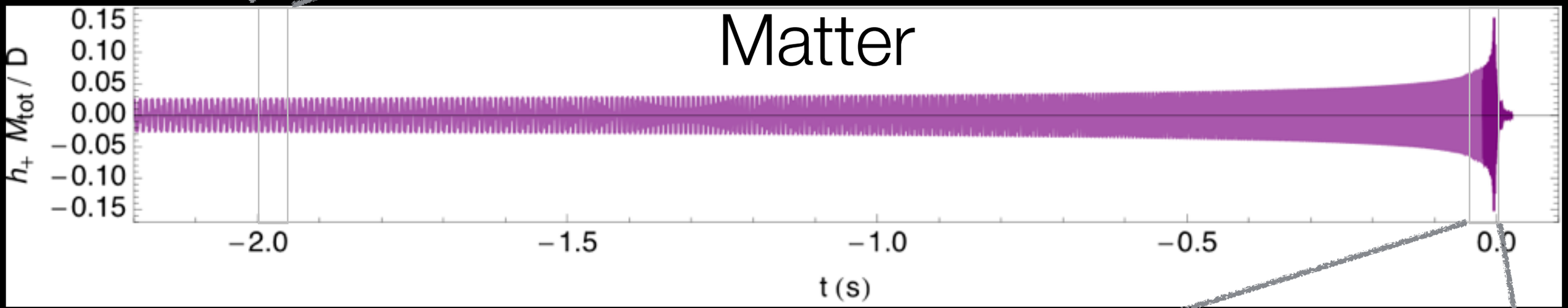




Tidal interactions lead to accumulated phase shift at higher frequencies.







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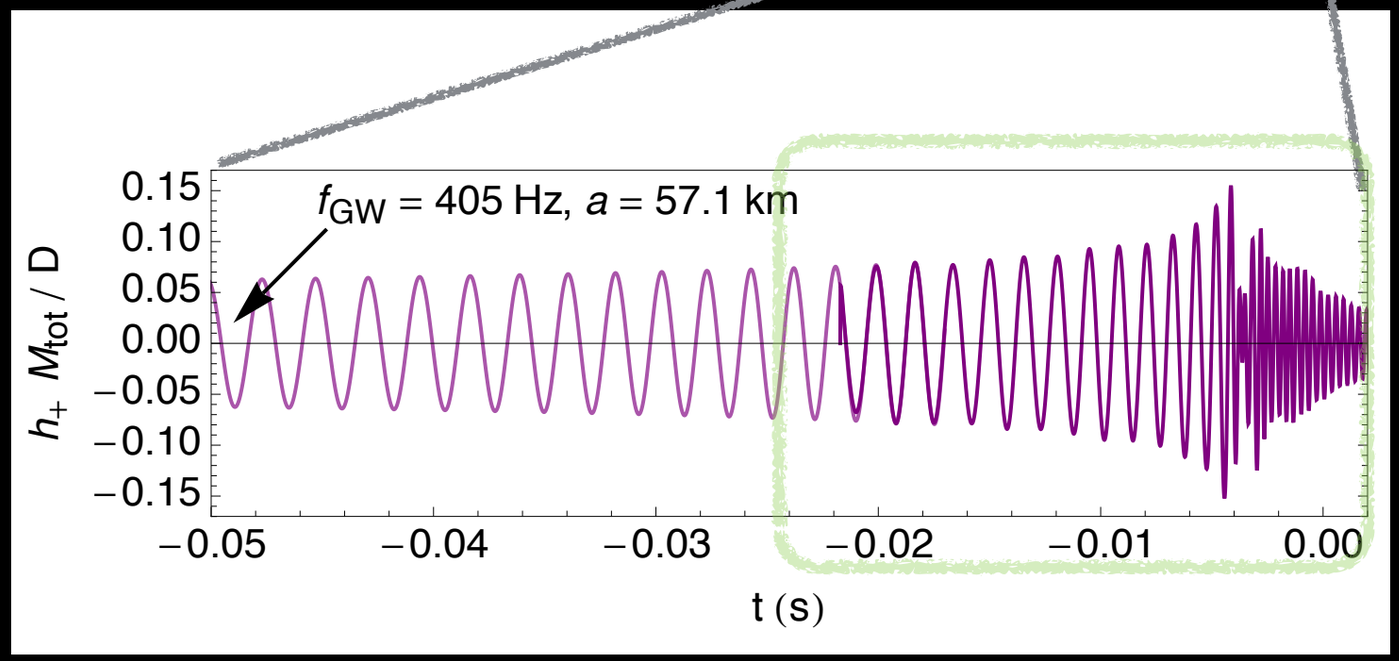
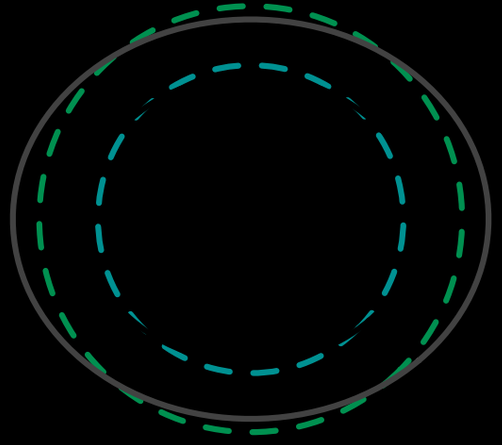
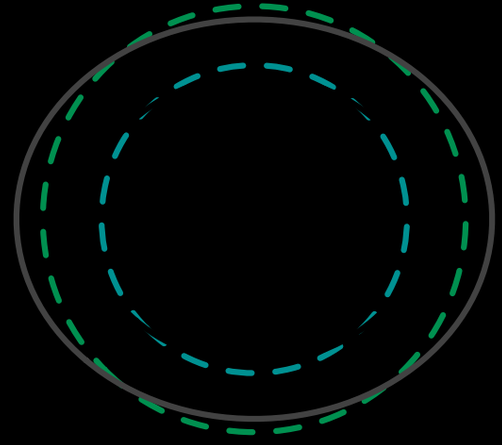
For the final coalescence, numerical simulations required



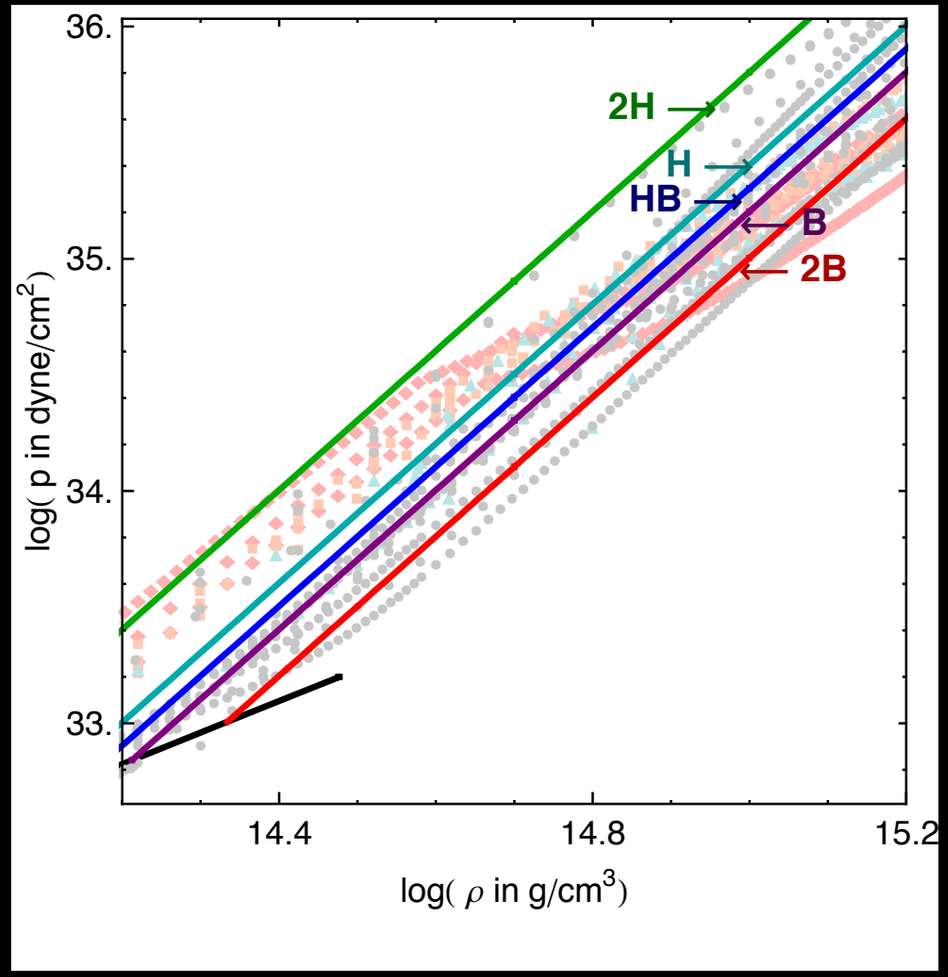


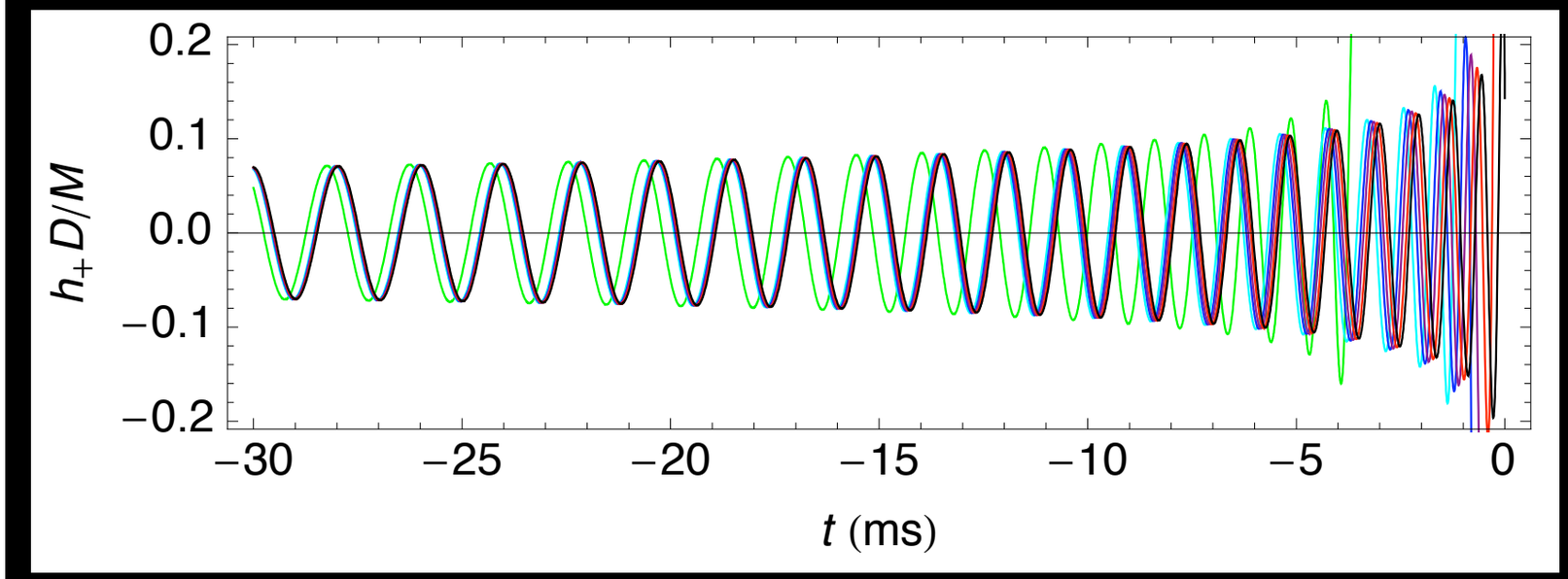
Inspiral matter dependence



- Deformation accelerates inspiral - extra energy into deforming stars.
- Size of effect on waveform determined by **tidal deformability**:

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



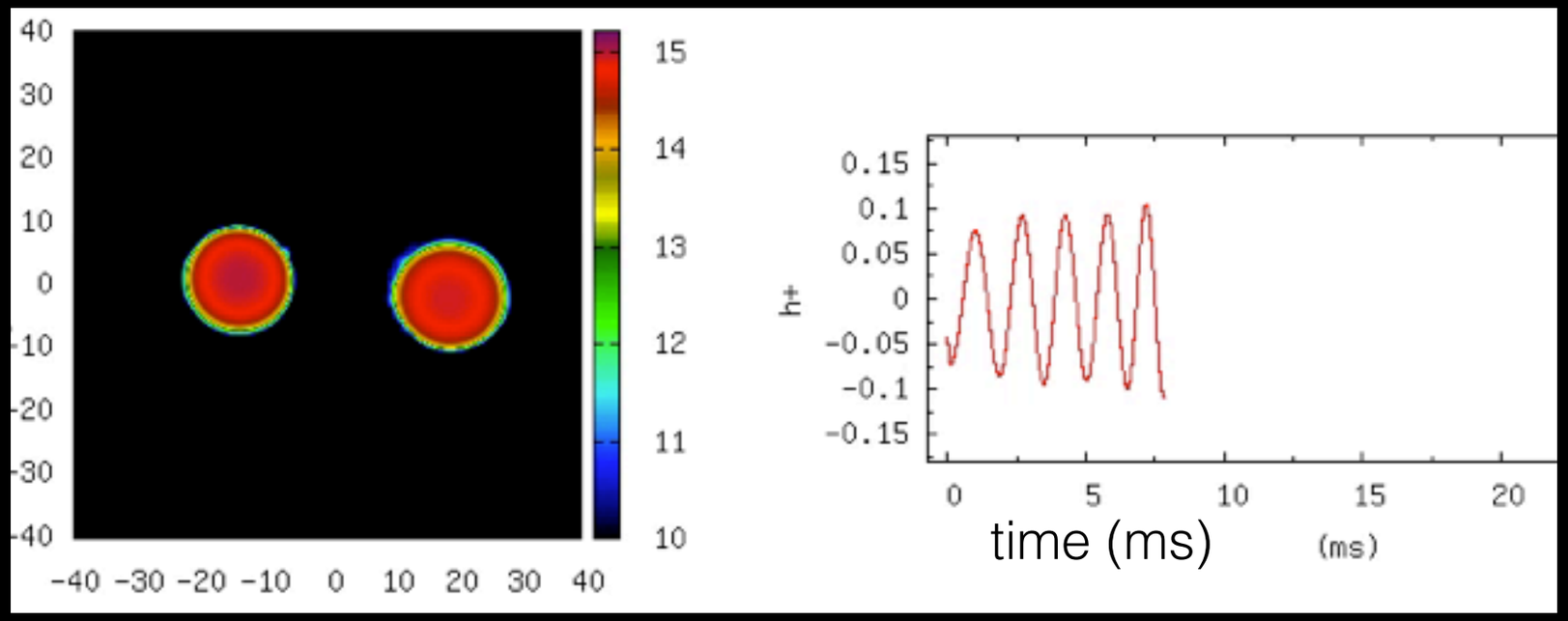


extreme radius like 2H disfavored by GW170817

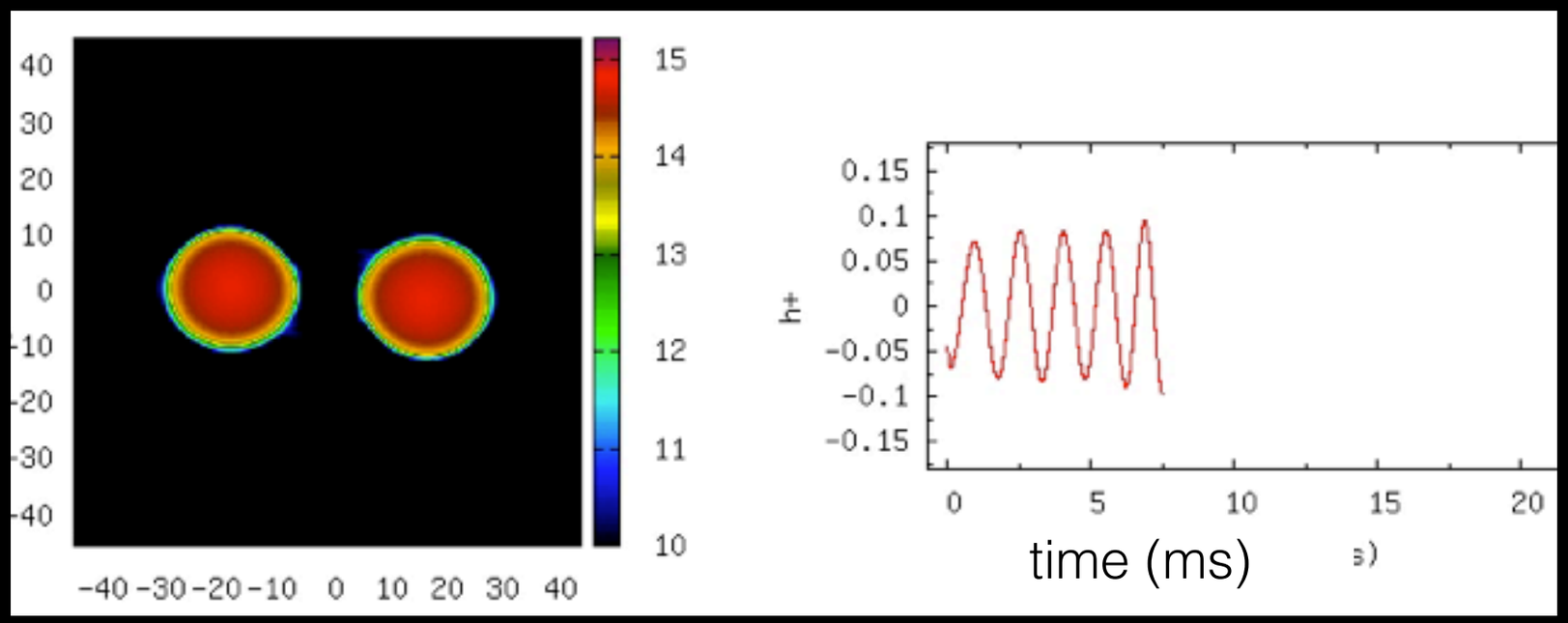
Flanagan and Hinderer 2008,

Merger matter dependence

Compact stars: merge at higher frequency, more similar to BBH



Large-radius stars: collide earlier, merge at lower frequency



Numerical simulations: K. Hotokezaka, YITP, Audio: J. Read

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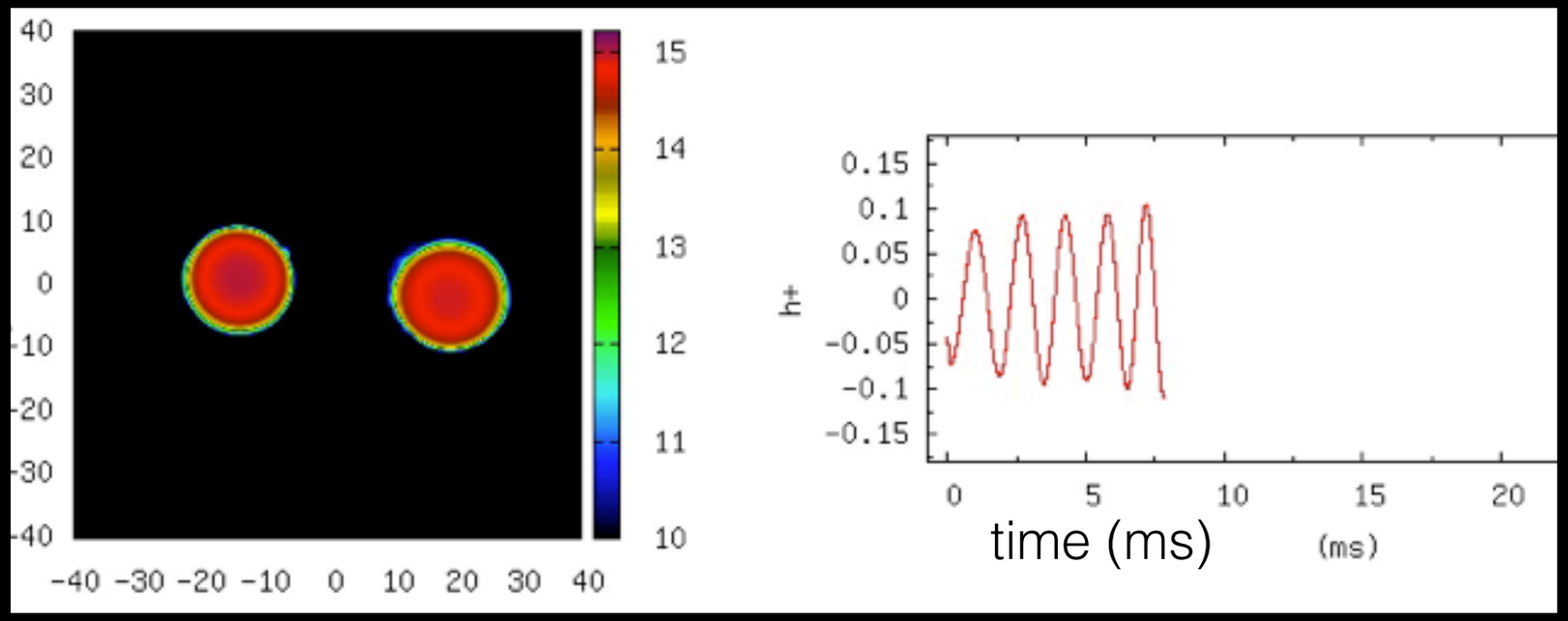

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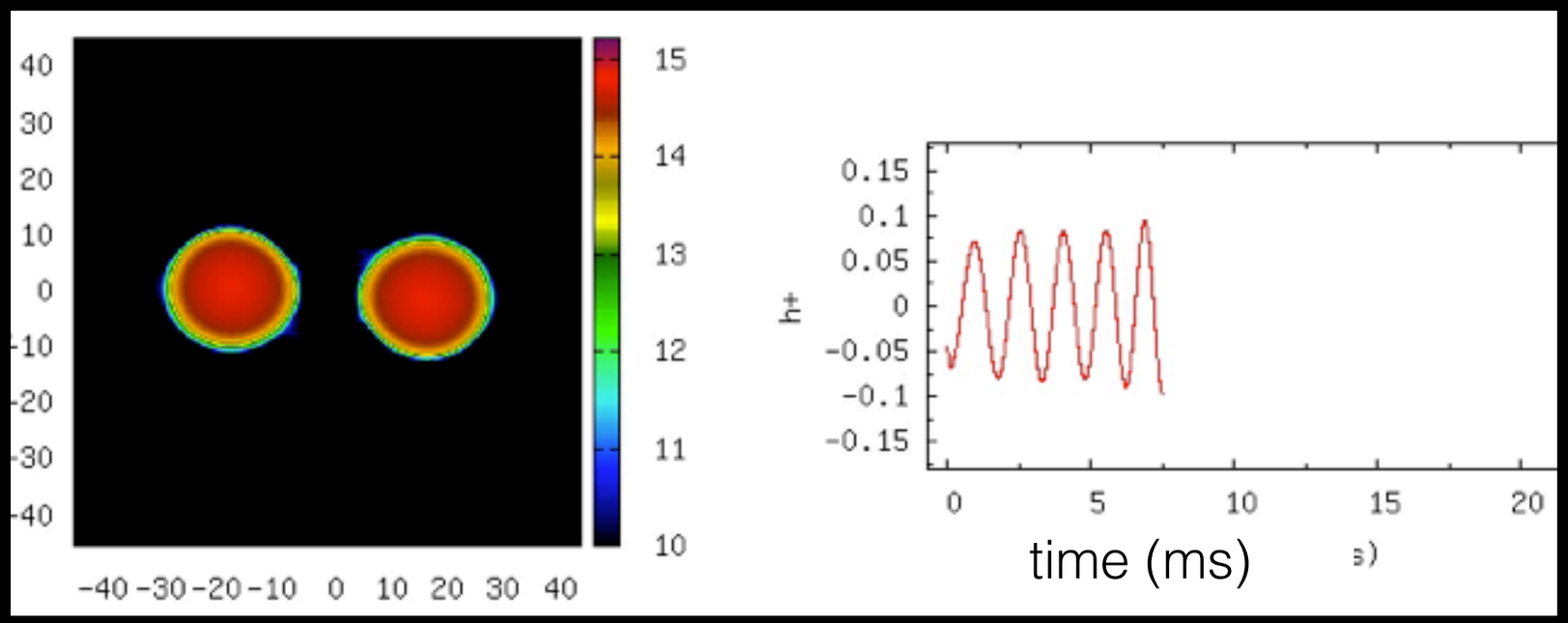

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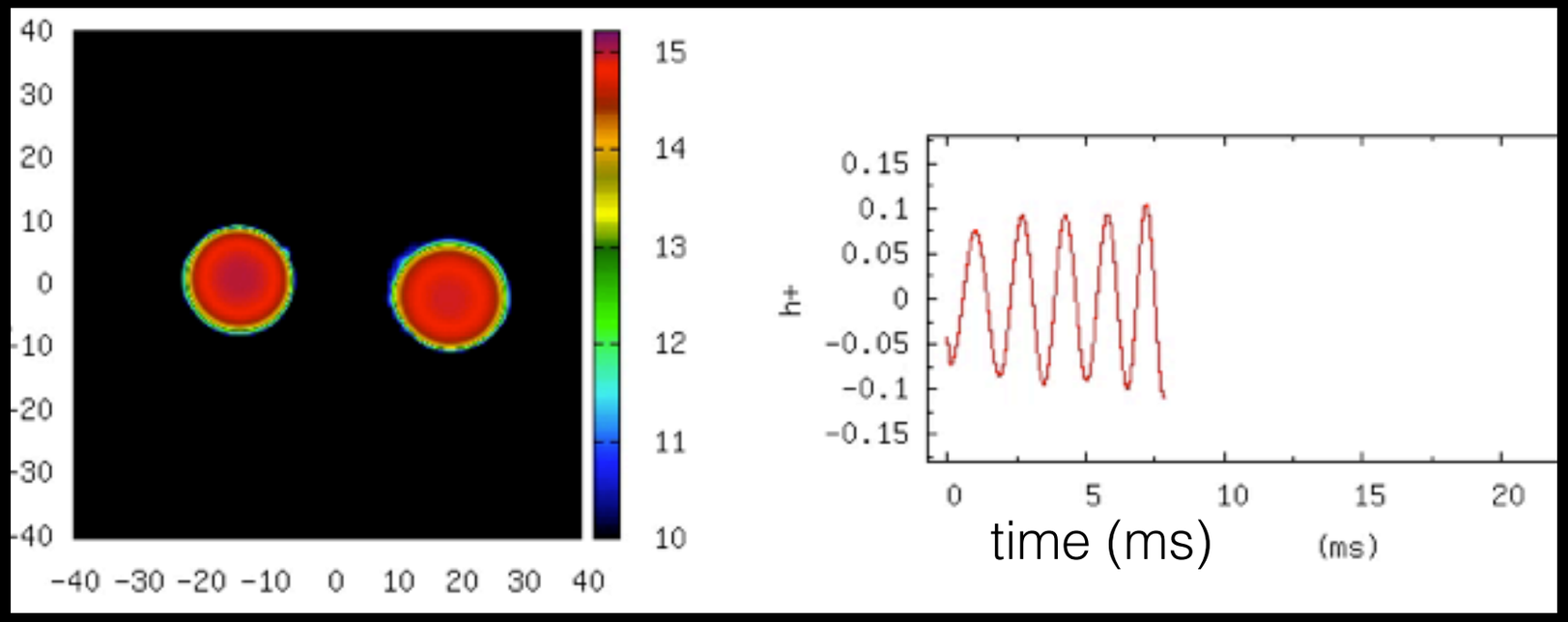

GW170817 post-merger
hidden by detector noise
https://arxiv.org/abs/1710.09320

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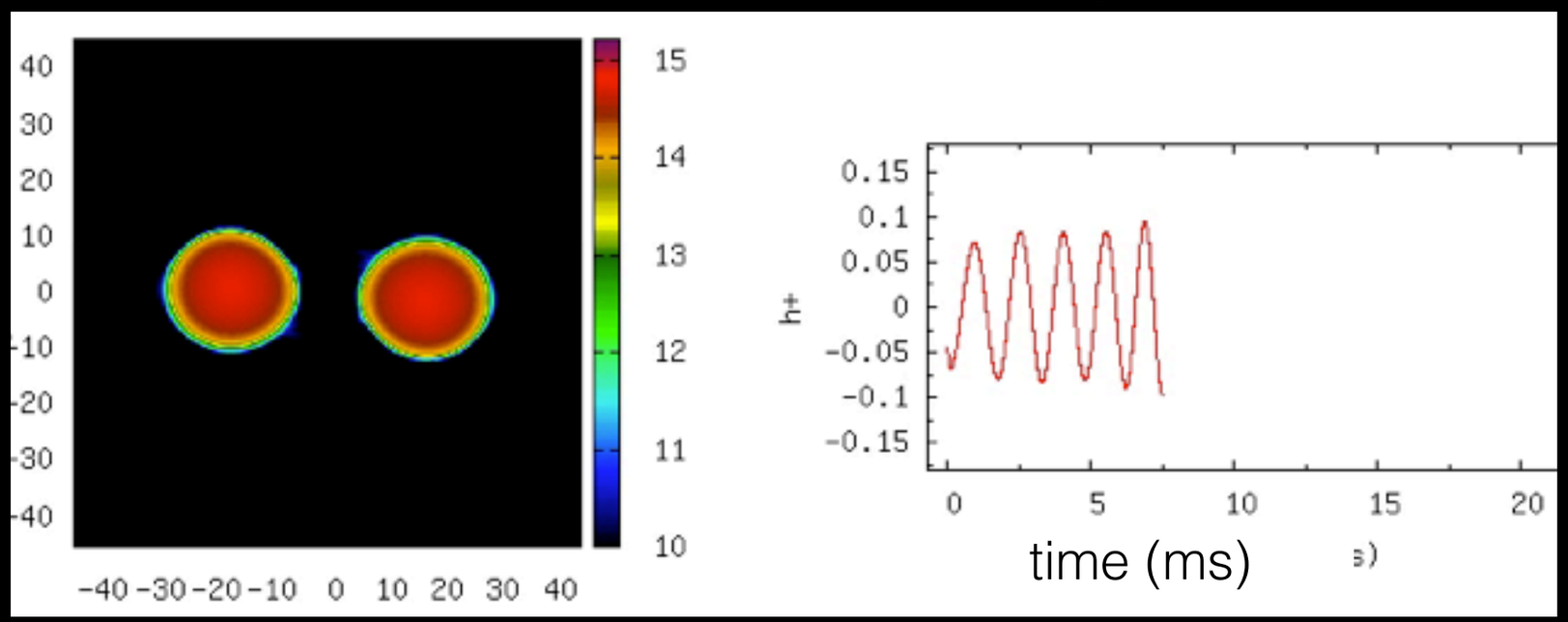

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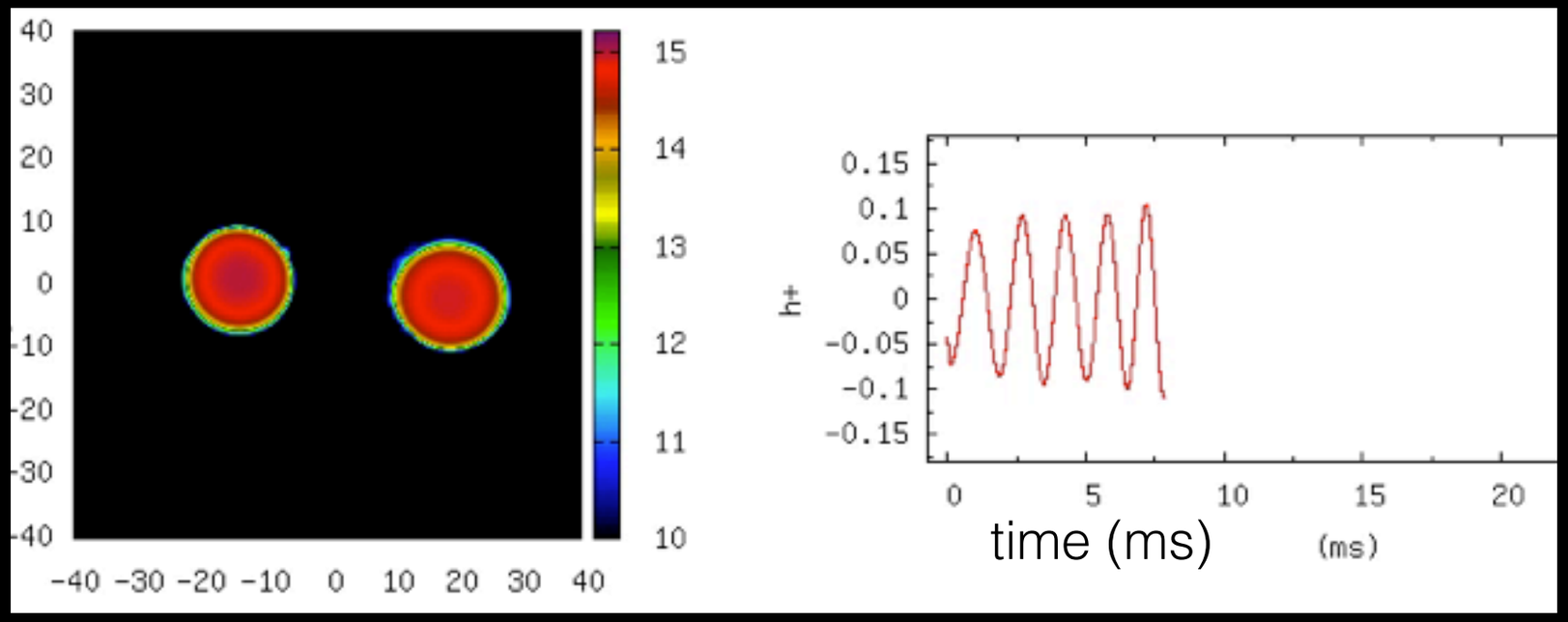

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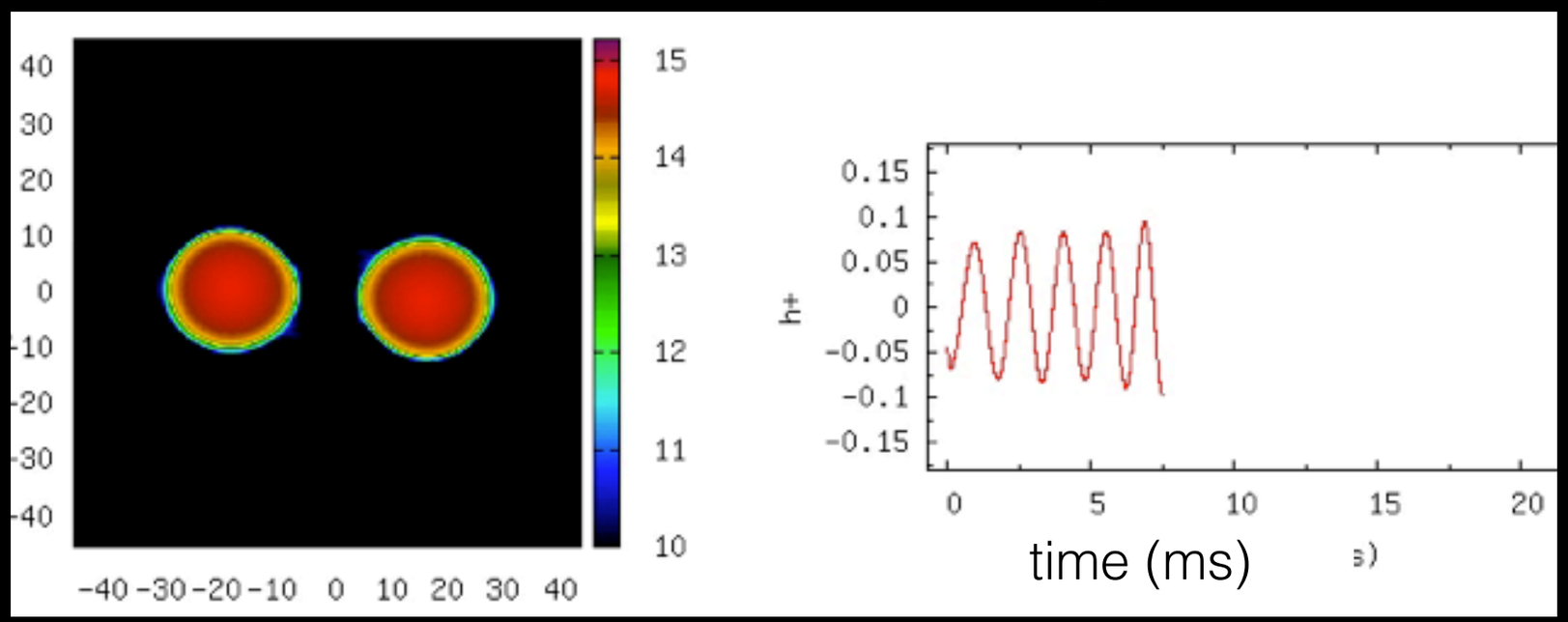

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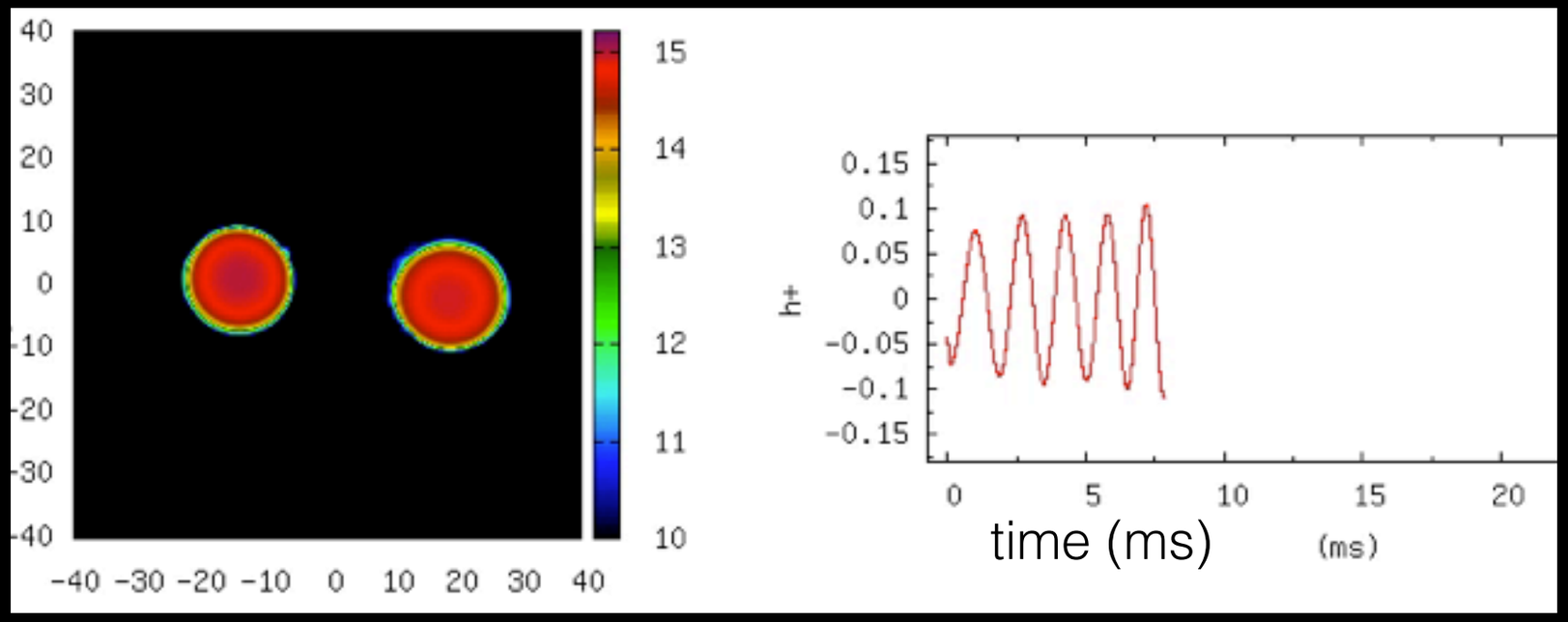

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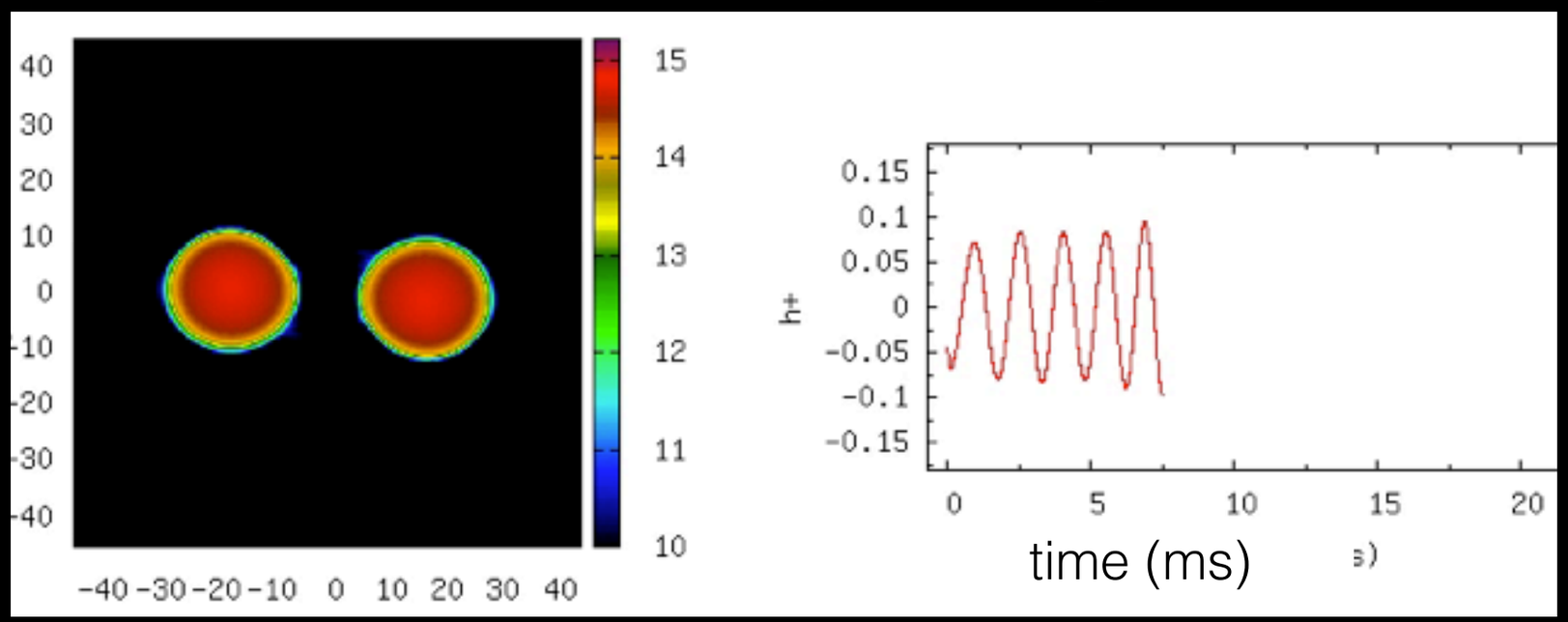

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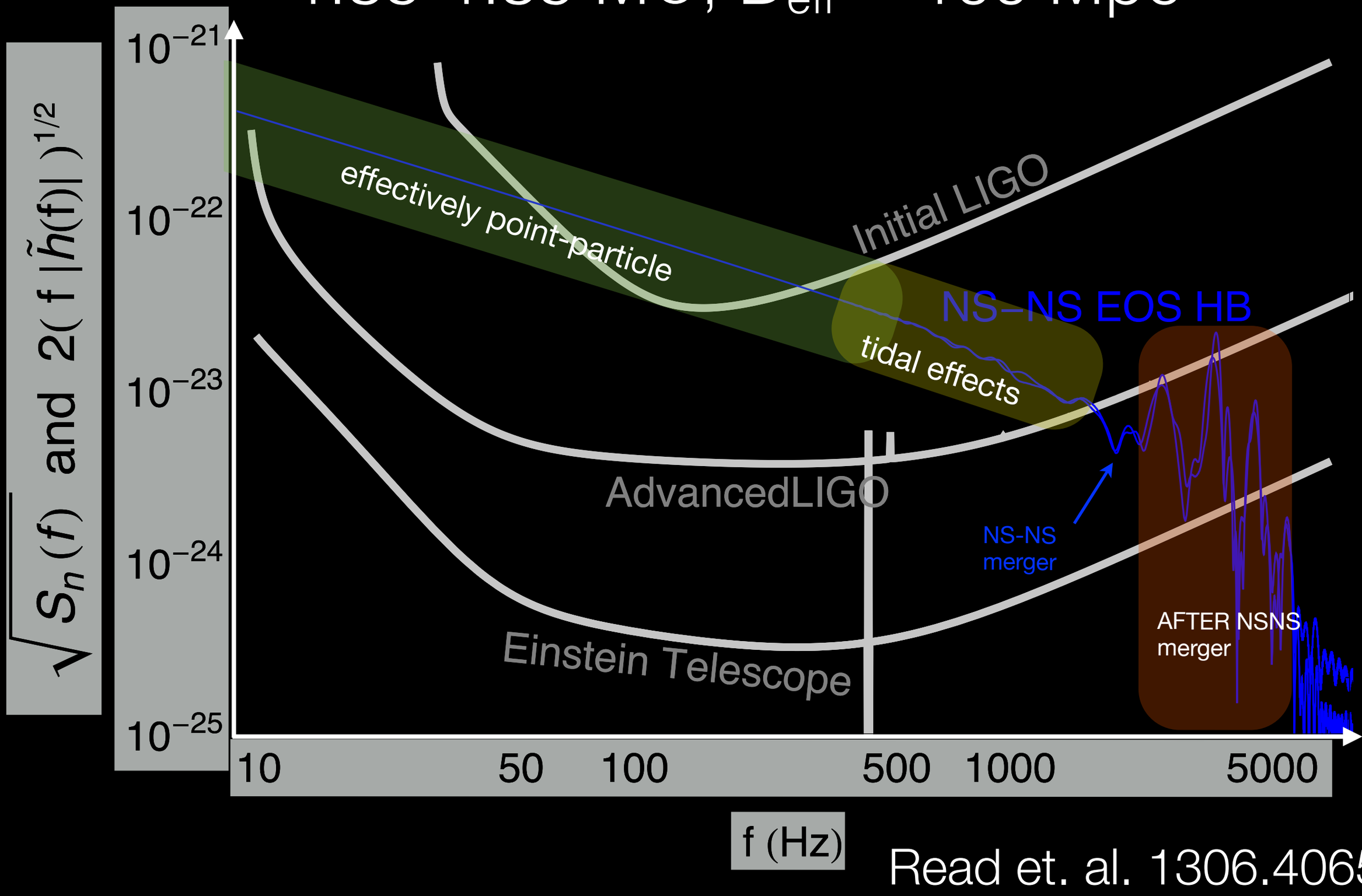
EOS impact on BNS Spectrum:

1.35-1.35 M⊙, D_{eff} = 100 Mpc



Read et. al. 1306.4065

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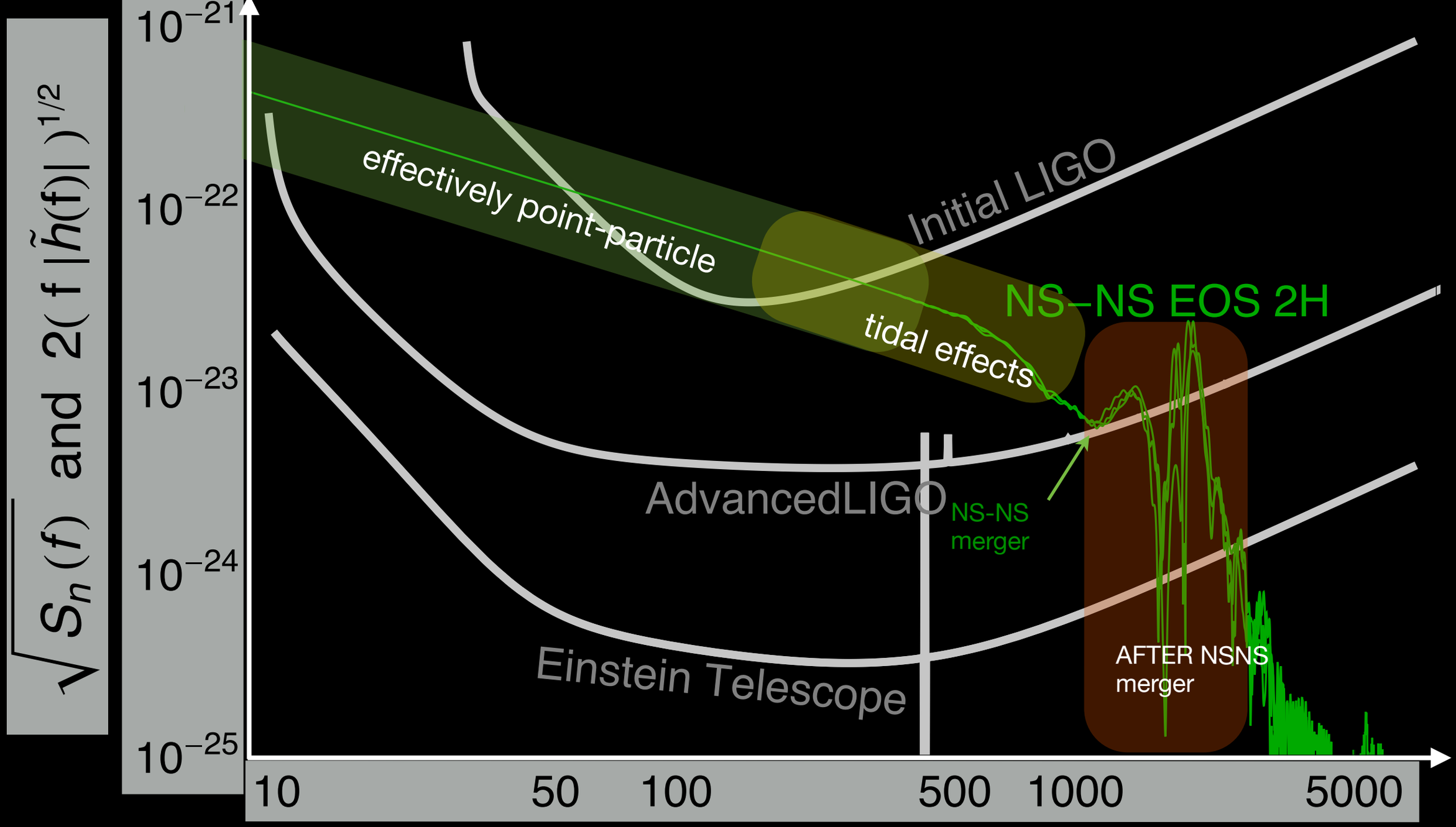
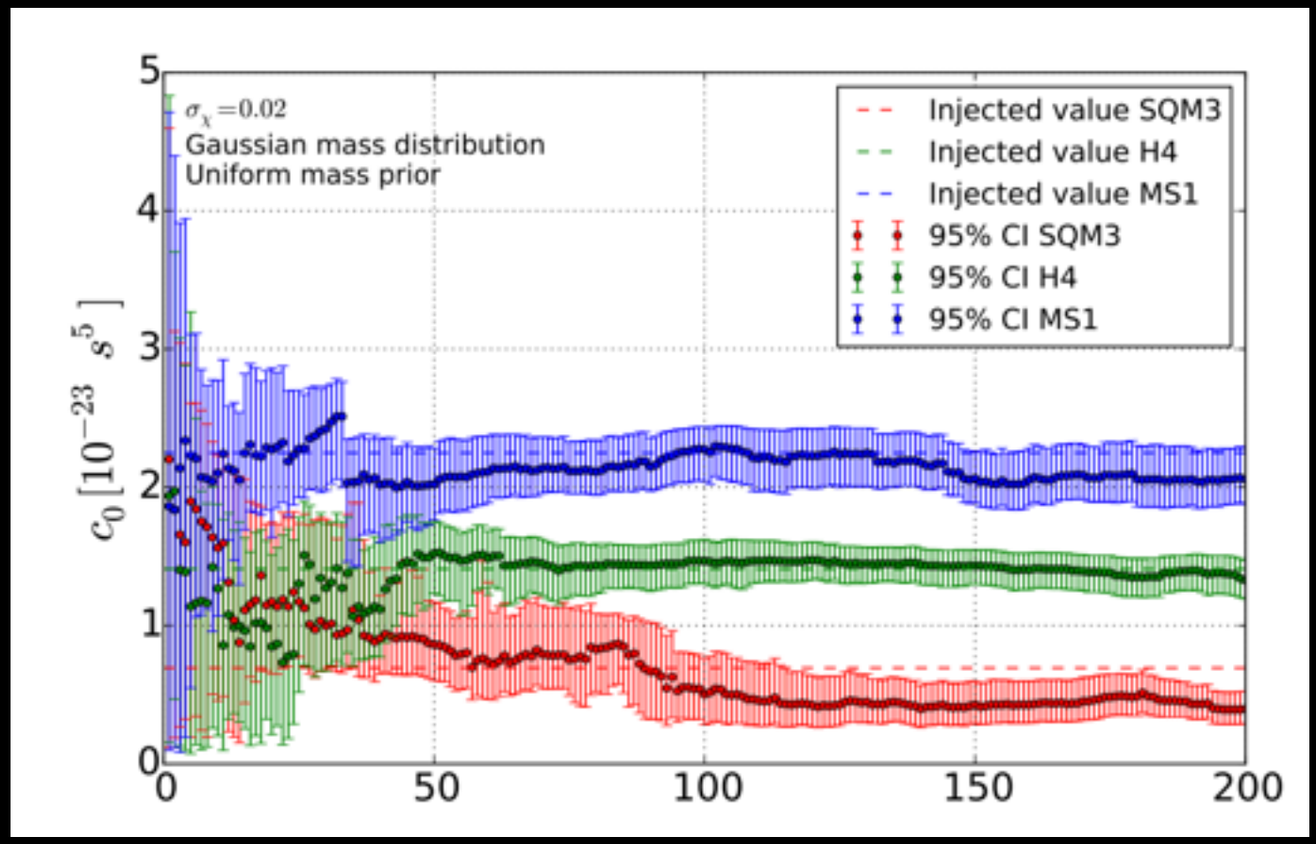


Read et. al. 1306.4065

Learning about neutron-star matter from a population of GW signals

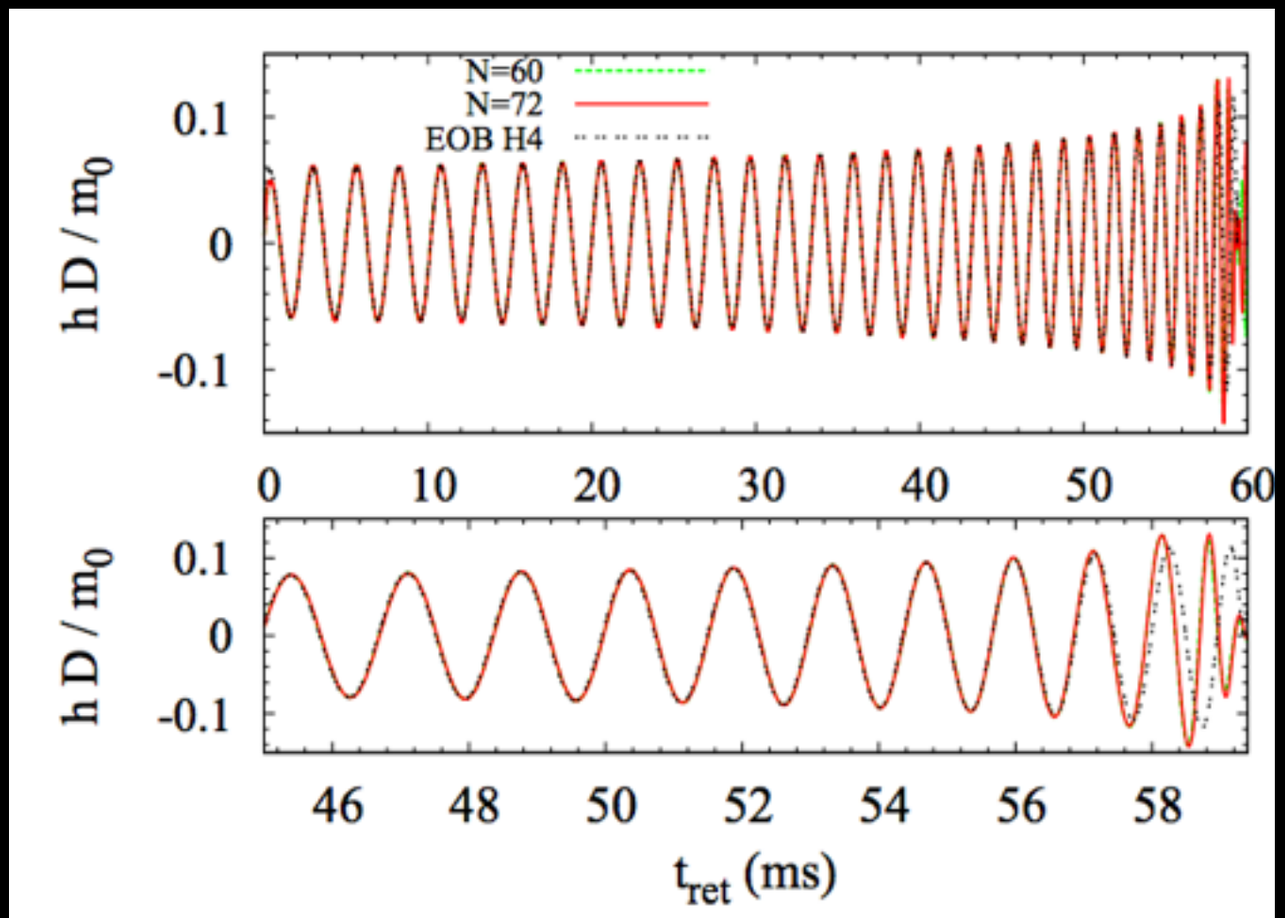
- Neutron-star mergers give useful information about the NS EOS
- Relies on accurate waveform modeling (PN models give signficant systematic error: Favata 1310.8288,Yagi/Yunes: 1310.8358, Wade et al. 1402.5156)



Agathos et al arXiv:1503.05405

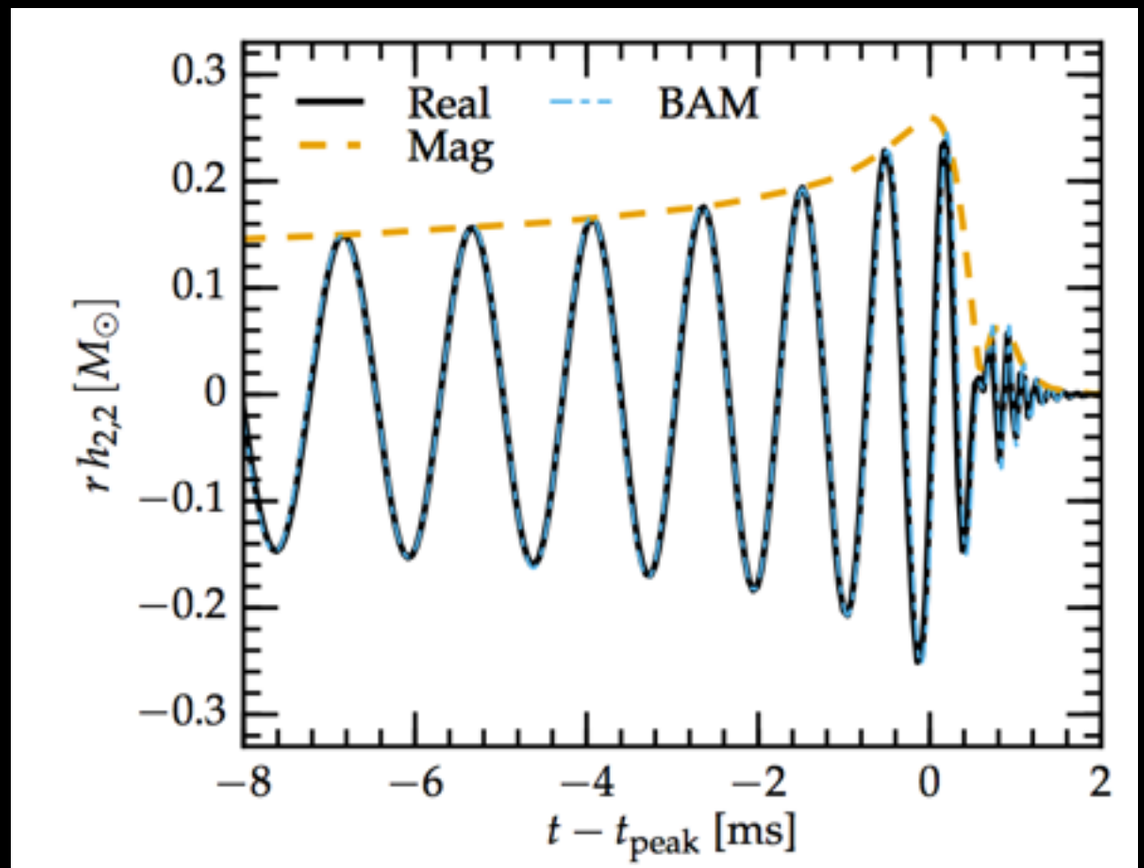
Accurate Merger Simulations

Hotokezaka et al 1502.03457



estimated total phase error
<1 radian over ~200 radians

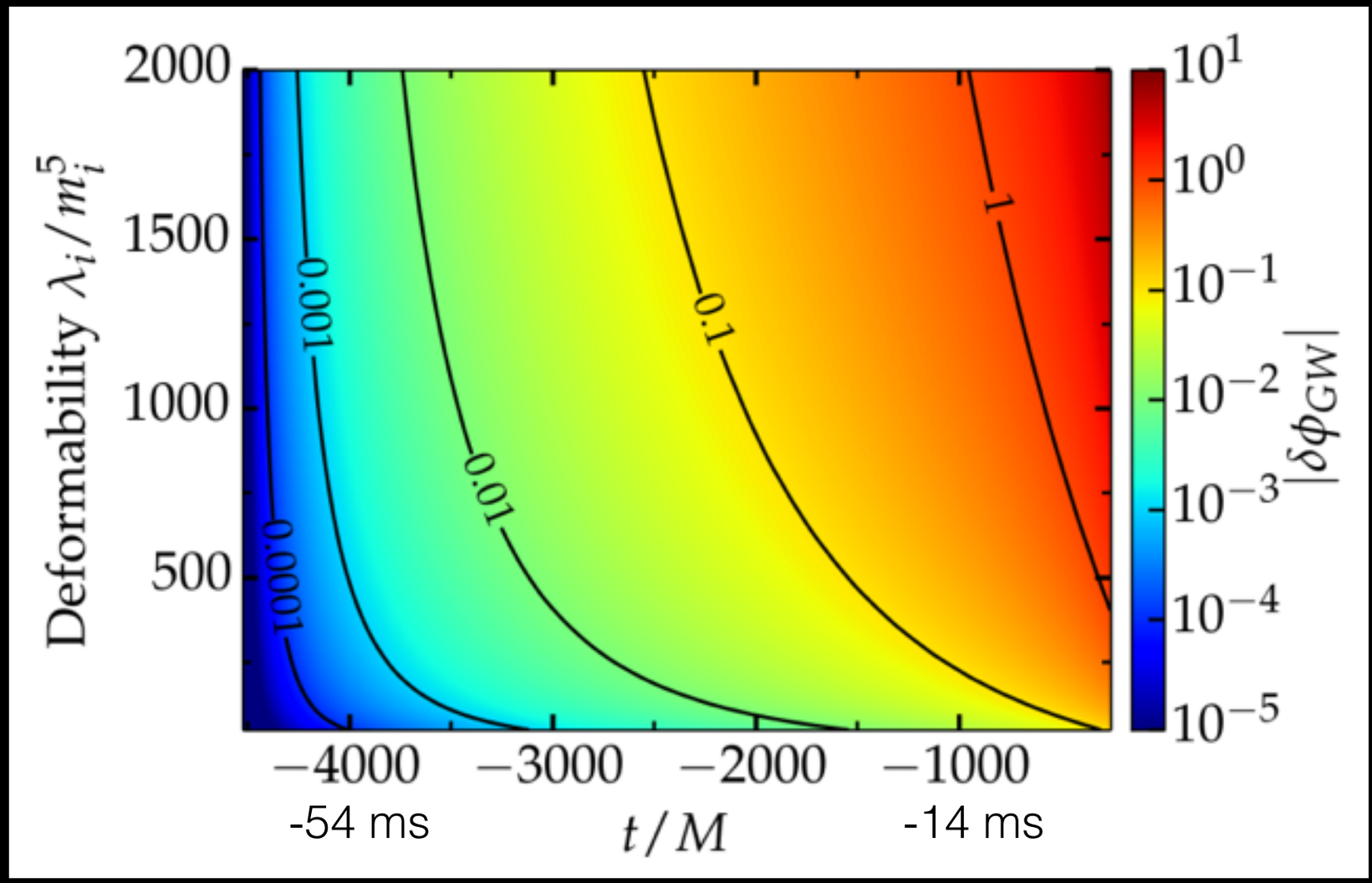
Haas et al 1604.00782 (22 orbits!) comparison to Bernuzzi et al 1412.4553



Waveforms aligned
before -13.3 ms

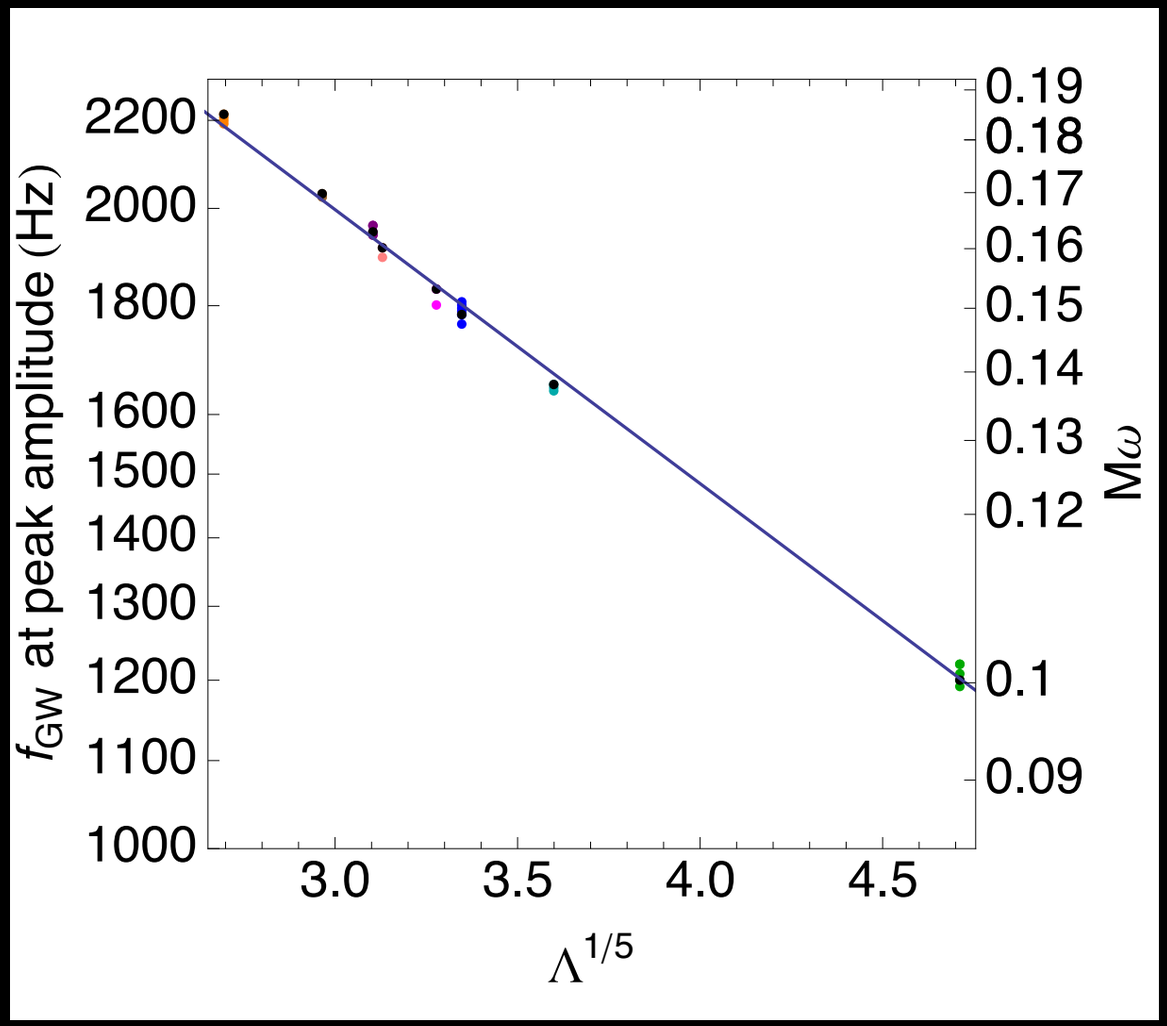
Note: Early inspiral tidal effects challenging to resolve numerically

Phase differences between BBH and BNS



Barkett et al 1509.05782

Perturbative tidal deformability also characterizes merger



- Read et al 1306.4065 Bernuzzi et al 1402.6244

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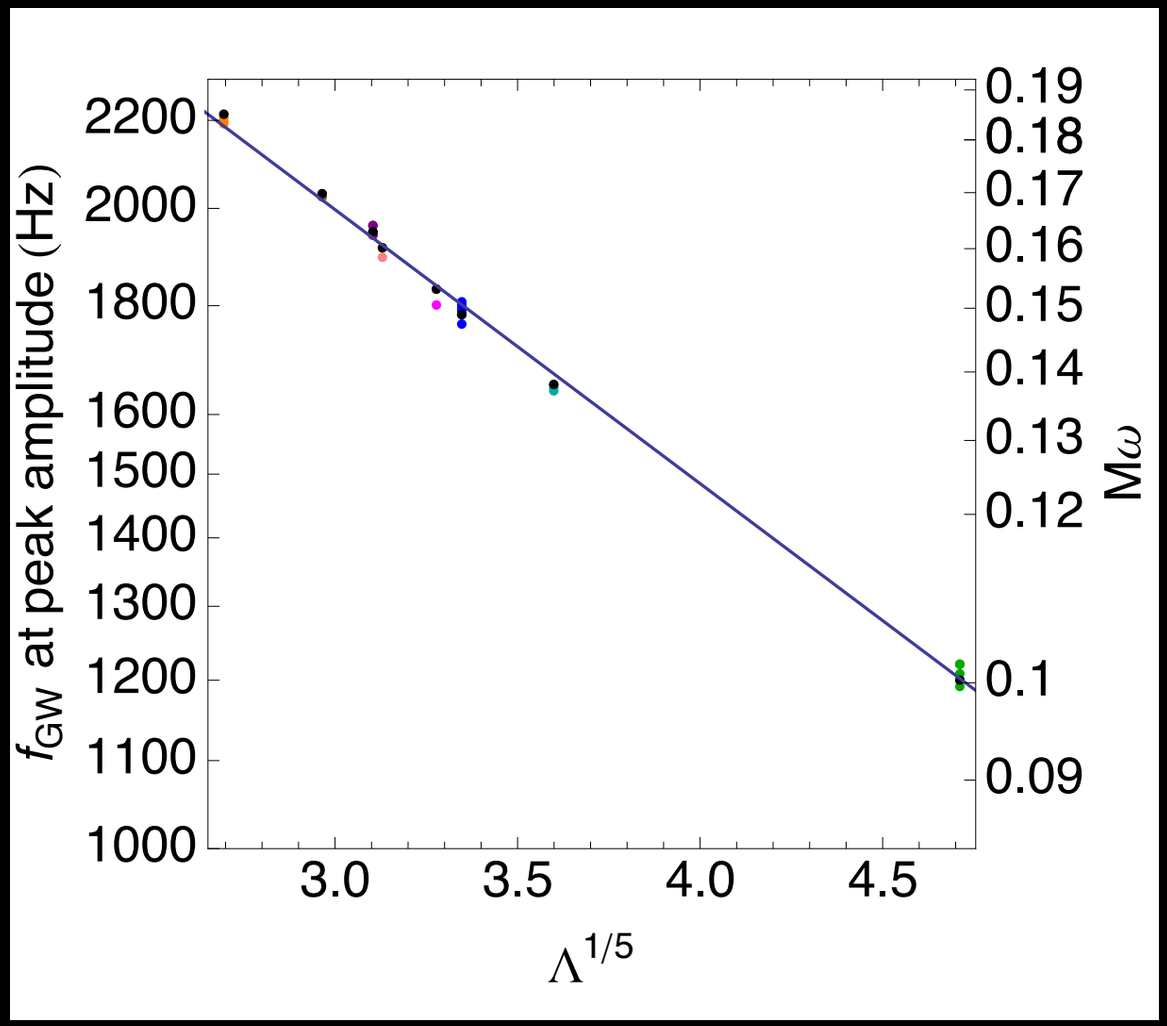

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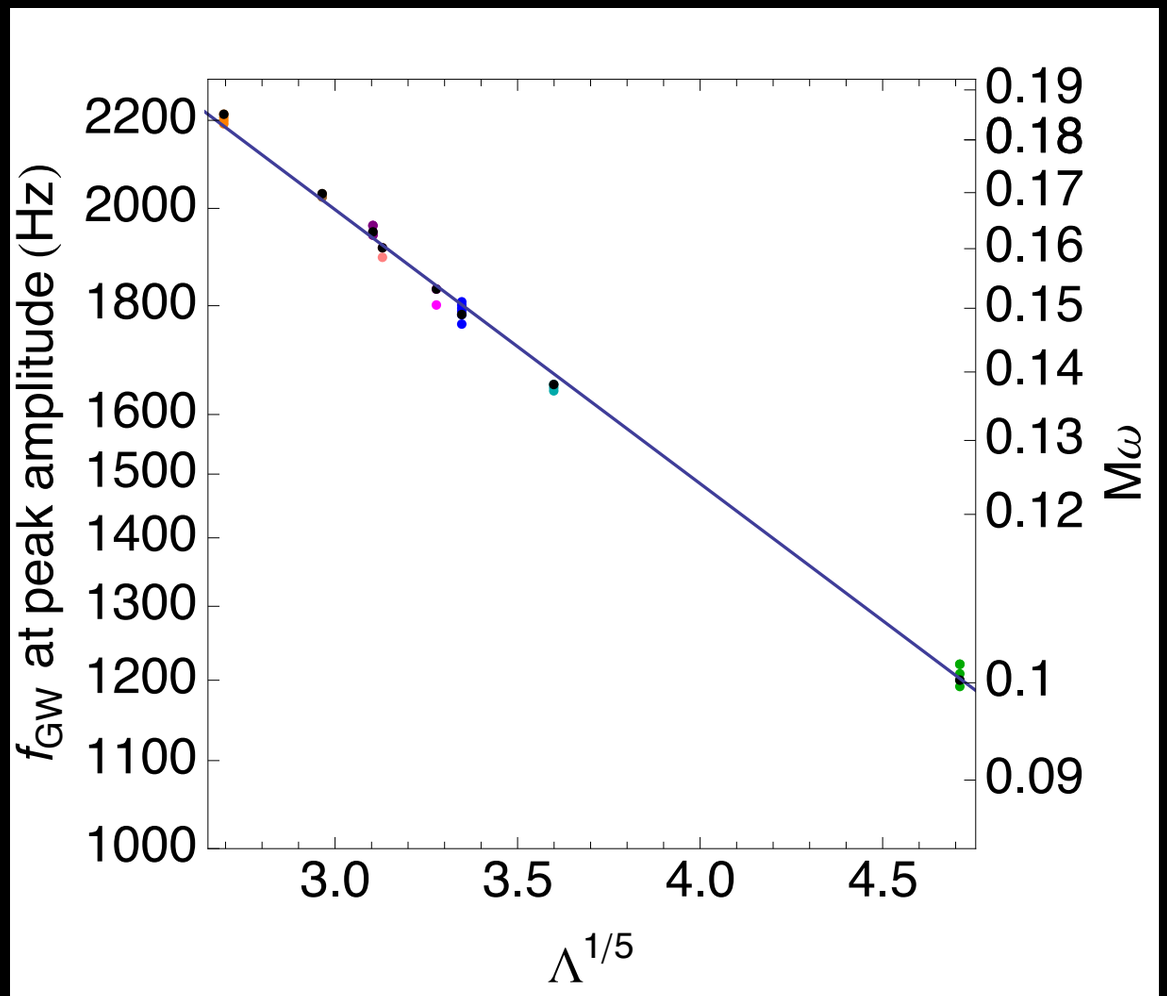

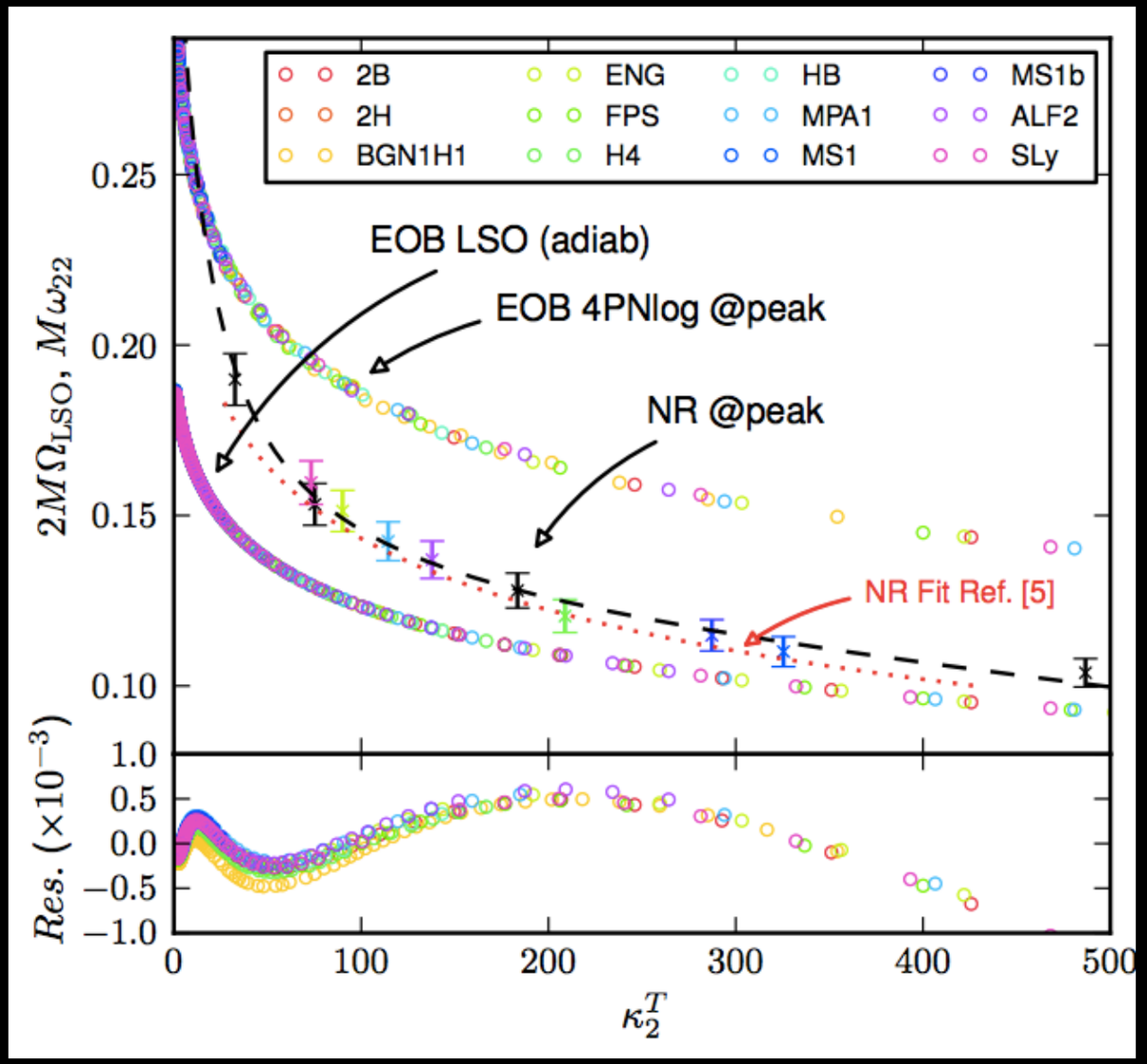

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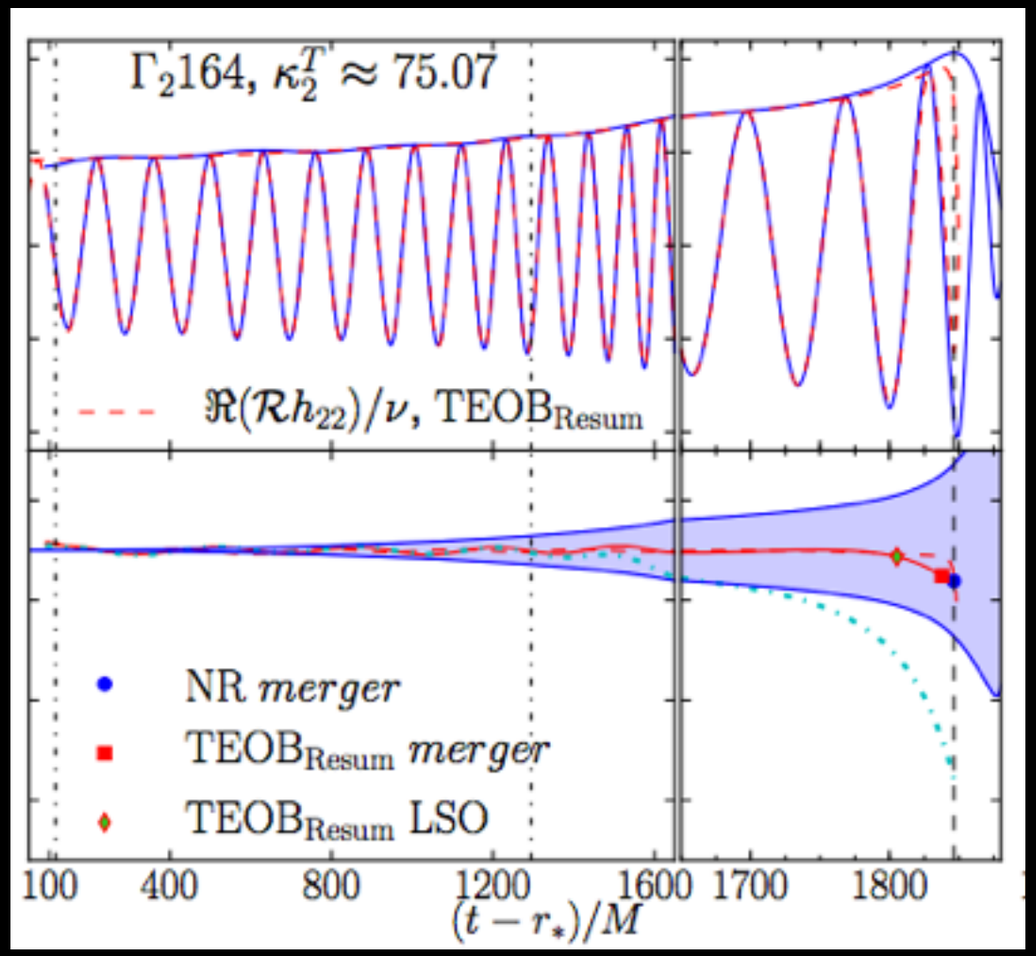
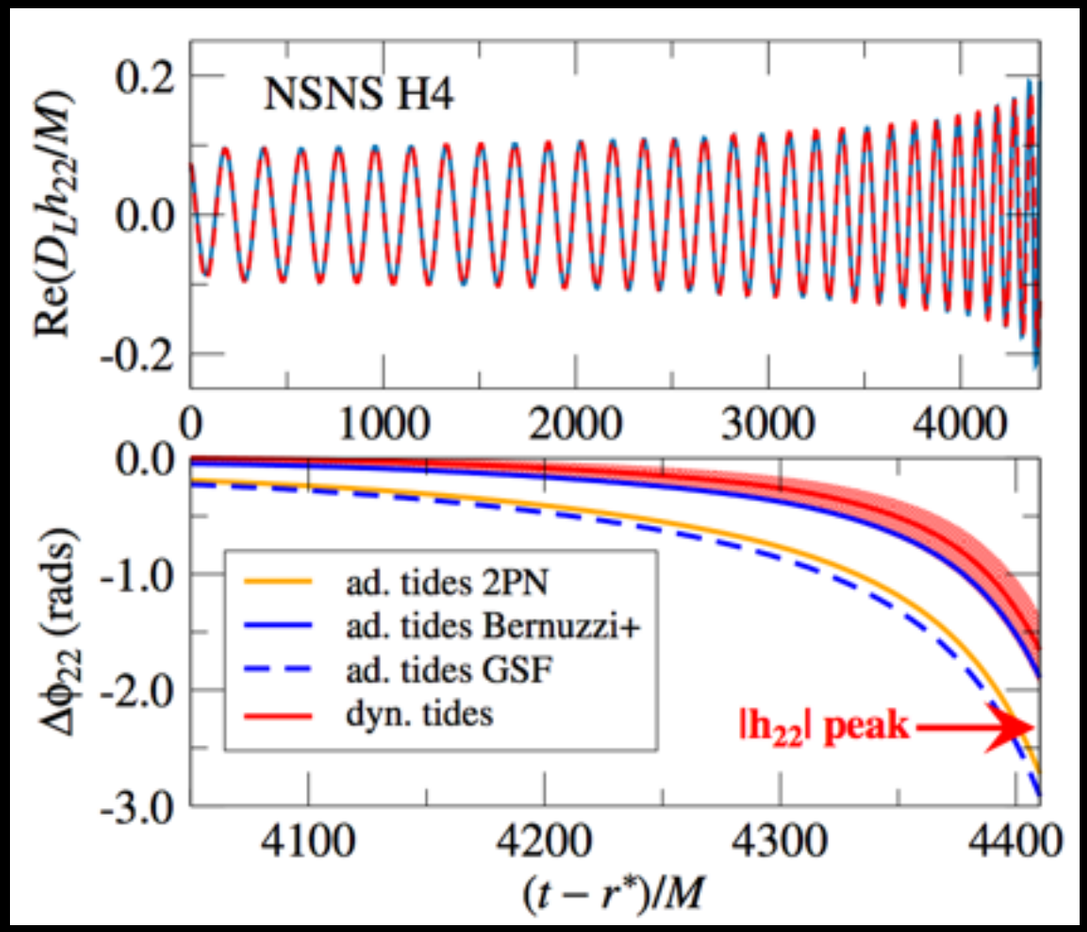
Tidal effects in EOB models:

- Bernuzzi et al 1412.4553



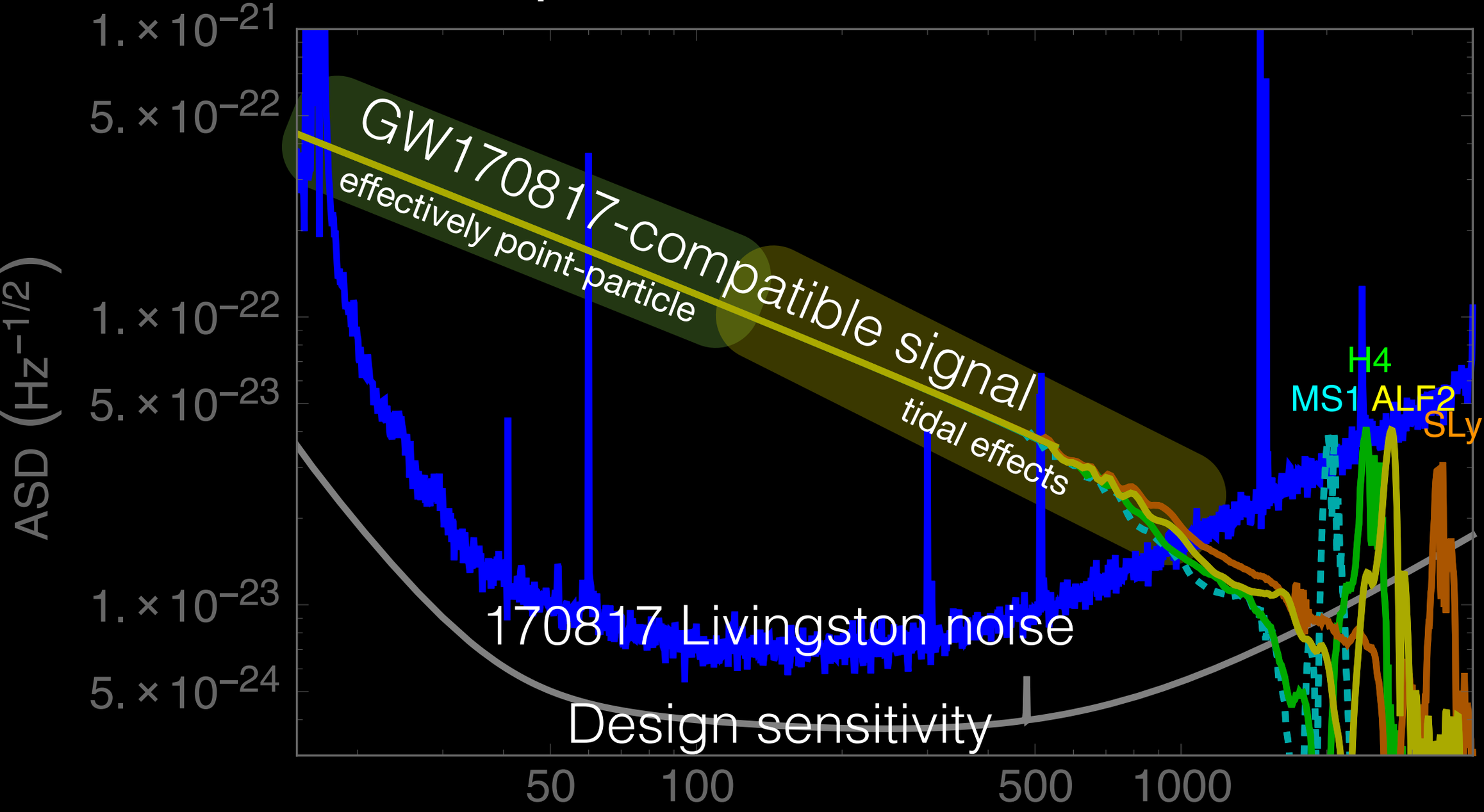
- Hinderer et al 1602.00599



- EOB plus tidal corrections plus higher-order effects: semi-analytic models capture inspiral-to-merger phase

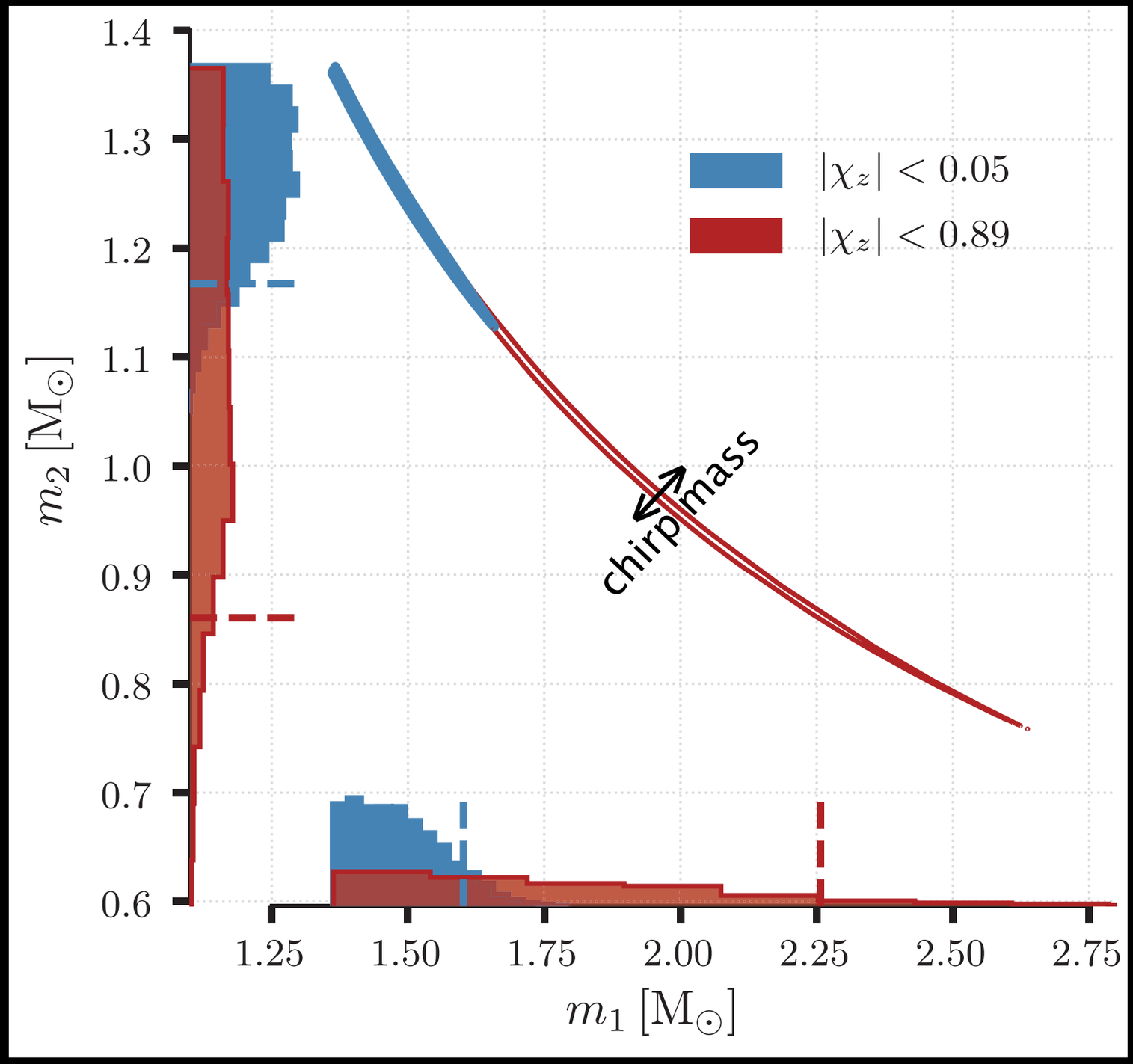
- Phenomenological extensions to improve agreement with NR (Bernuzzi, Dietrich, & Tichy 2017 NRTides + SEOB used for GW170817 systematics in LSC/Virgo PRL 119, 161101 (2017))

EOS Impact on GW170817



Above 500Hz: amplitude from simulation data
Tim Dietrich (AEI/FSU/BAM Collaboration)
Phys. Rev. D95(12):124006 and Phys. Rev. D95(2):024029, used for NRTides

Recall: GW170817 Masses and Spin



$$\chi = \frac{J}{m^2} \approx 0.4 \left(\frac{1\,\mathrm{ms}}{T} \right)$$

LSC/Virgo PRL 119, 161101 (2017)

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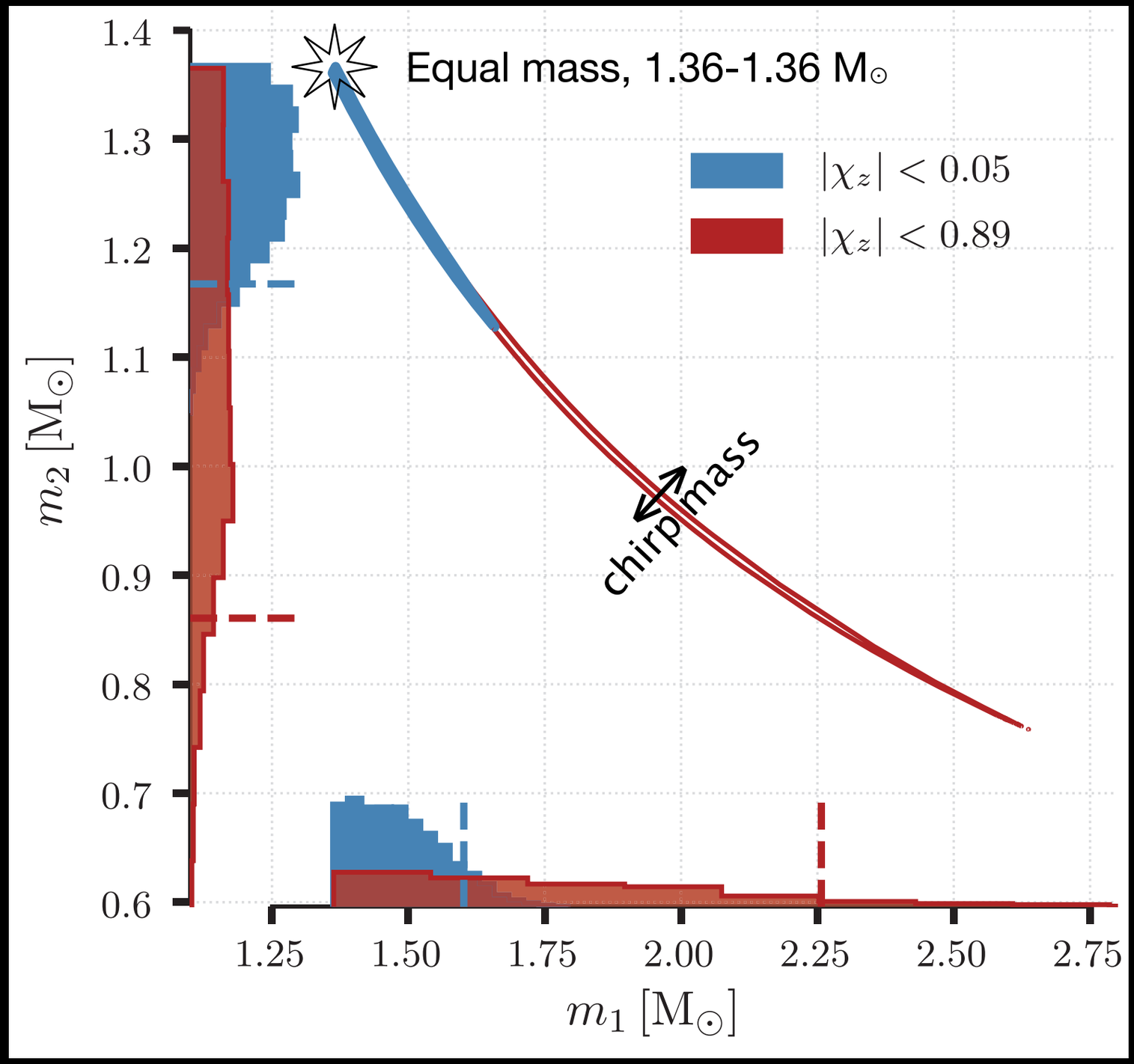

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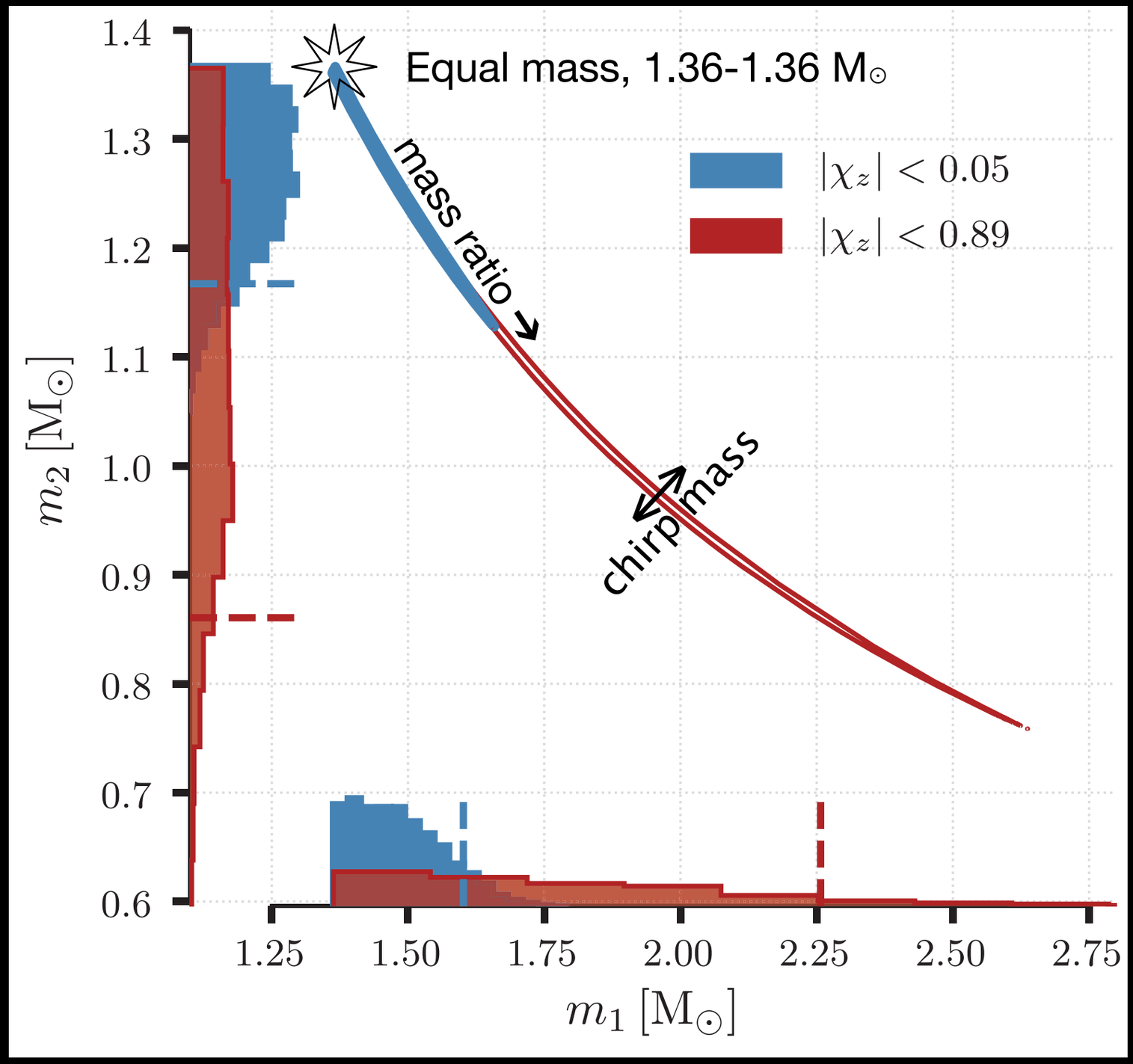

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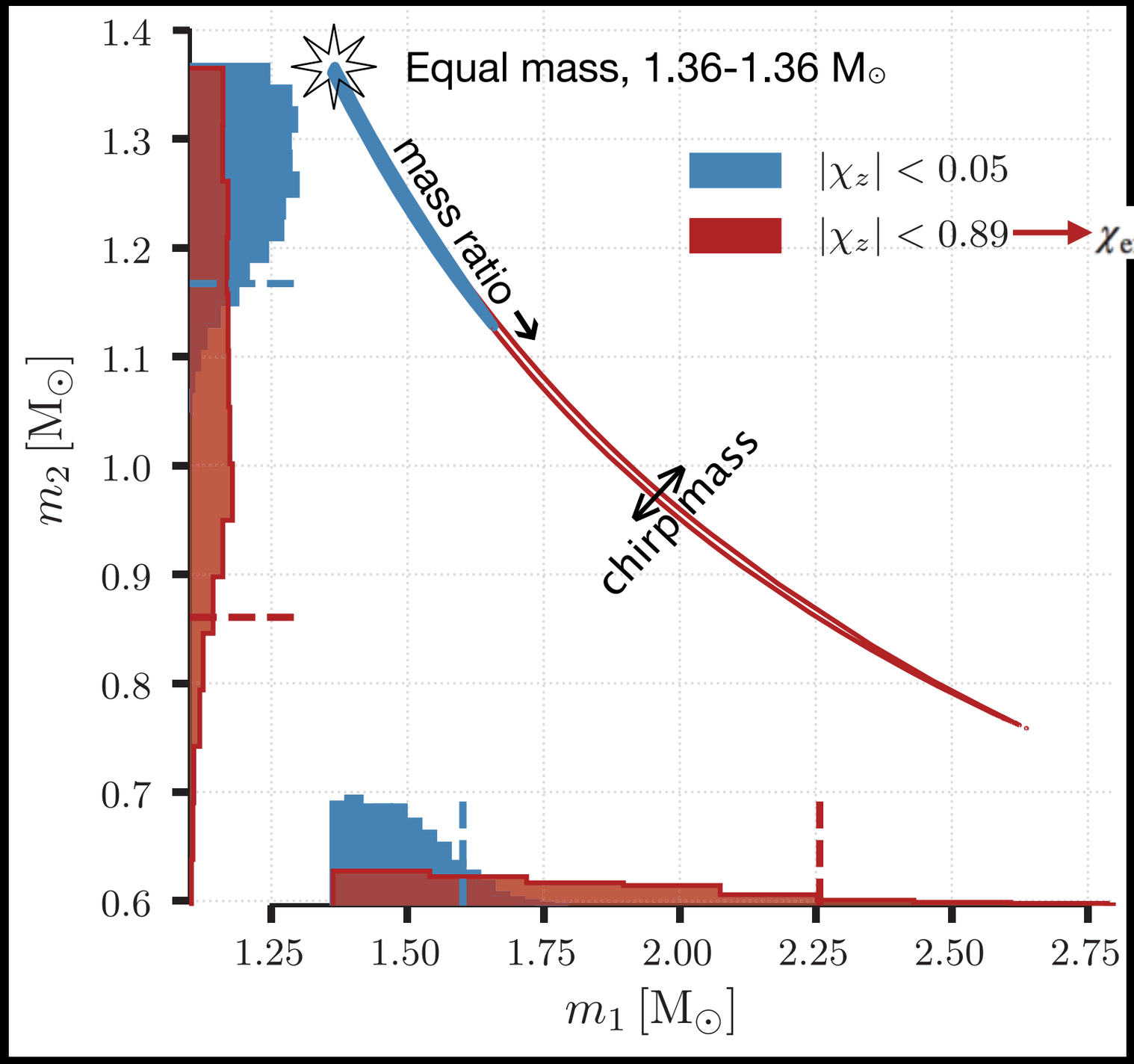

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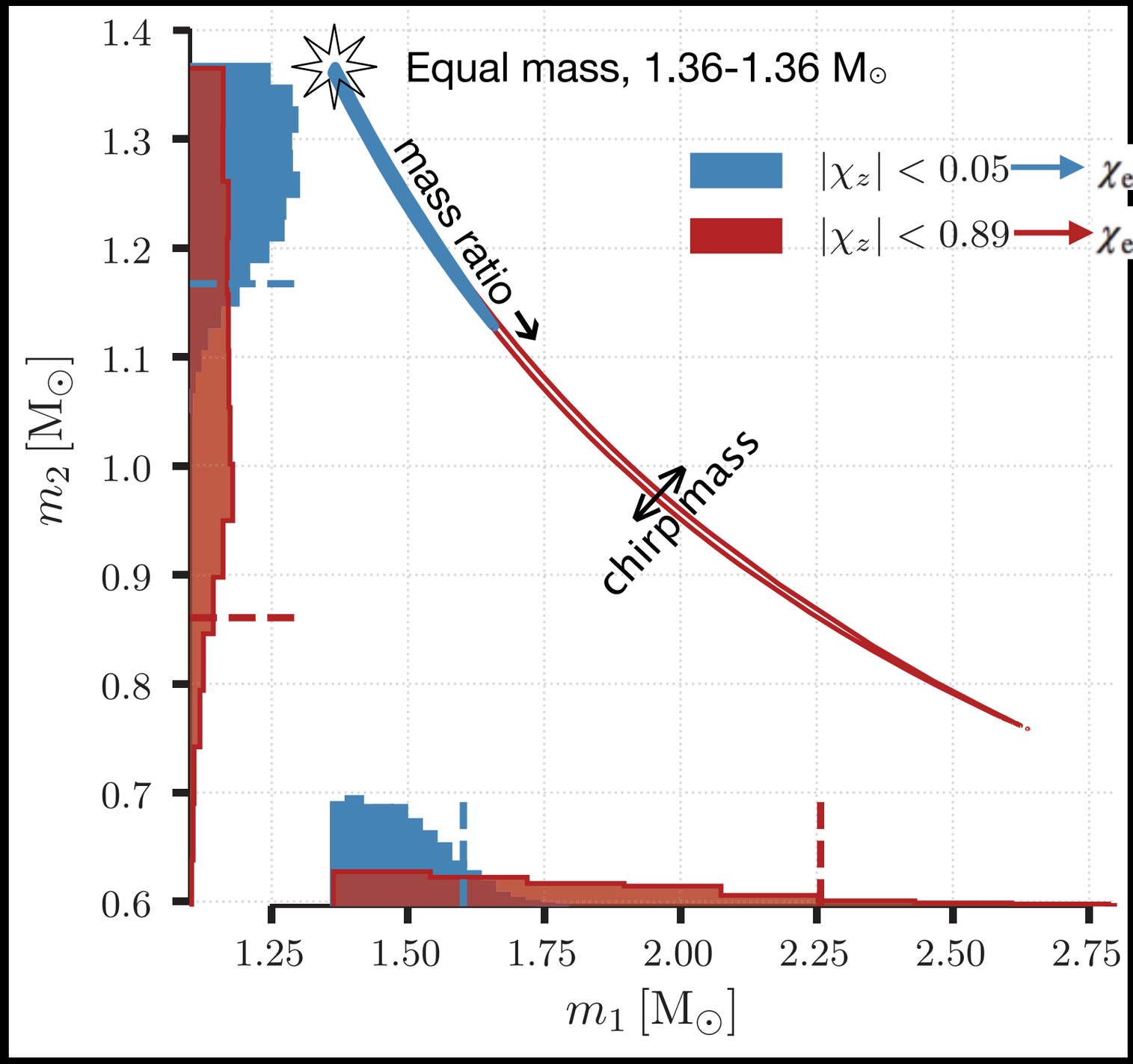

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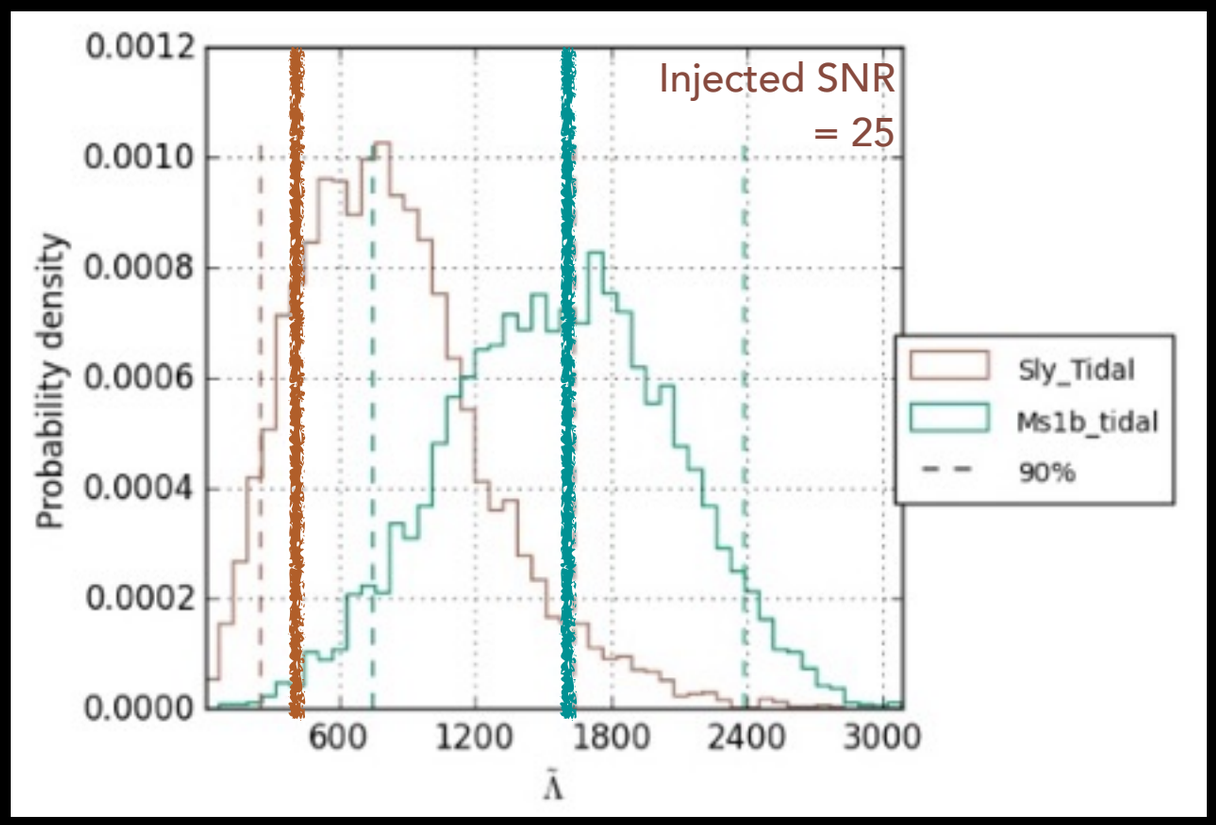
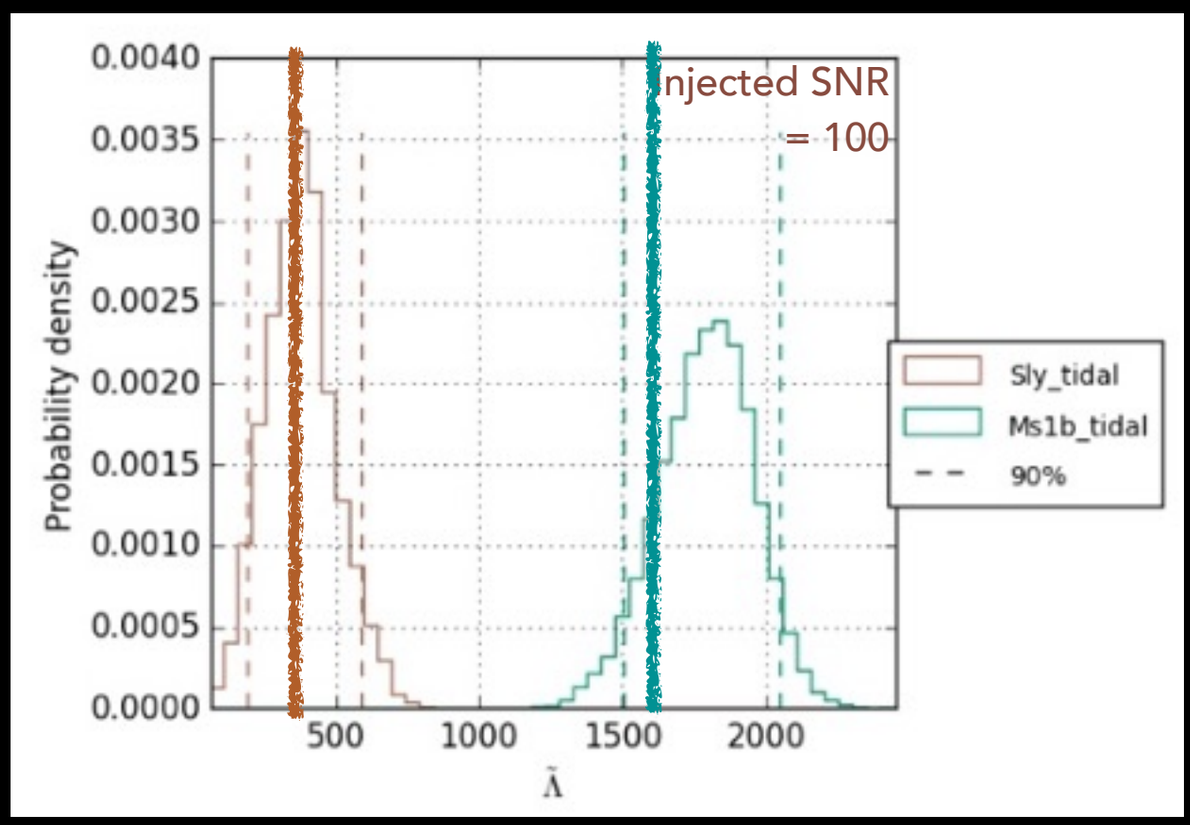
A lucky break for initial LIGO analysis

Injection/Recovery with $TEOB_{Resum}$+NR test signals

Injected Λ value for SLy= 392, MS1b = 1596

Recover reasonable values with TaylorF2



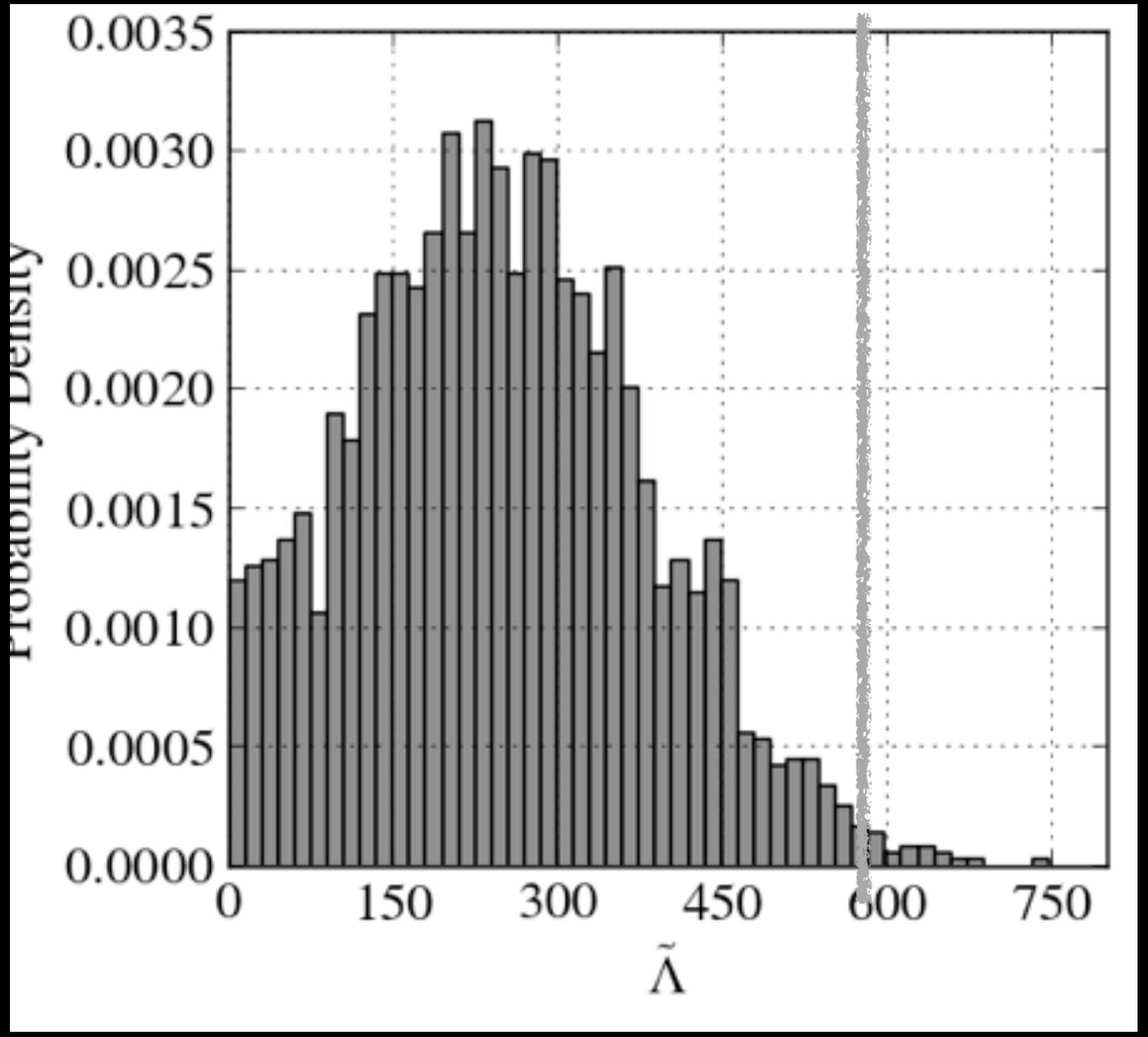


Reetika Dudi, Francesco Pannarale, et. al., Cardiff

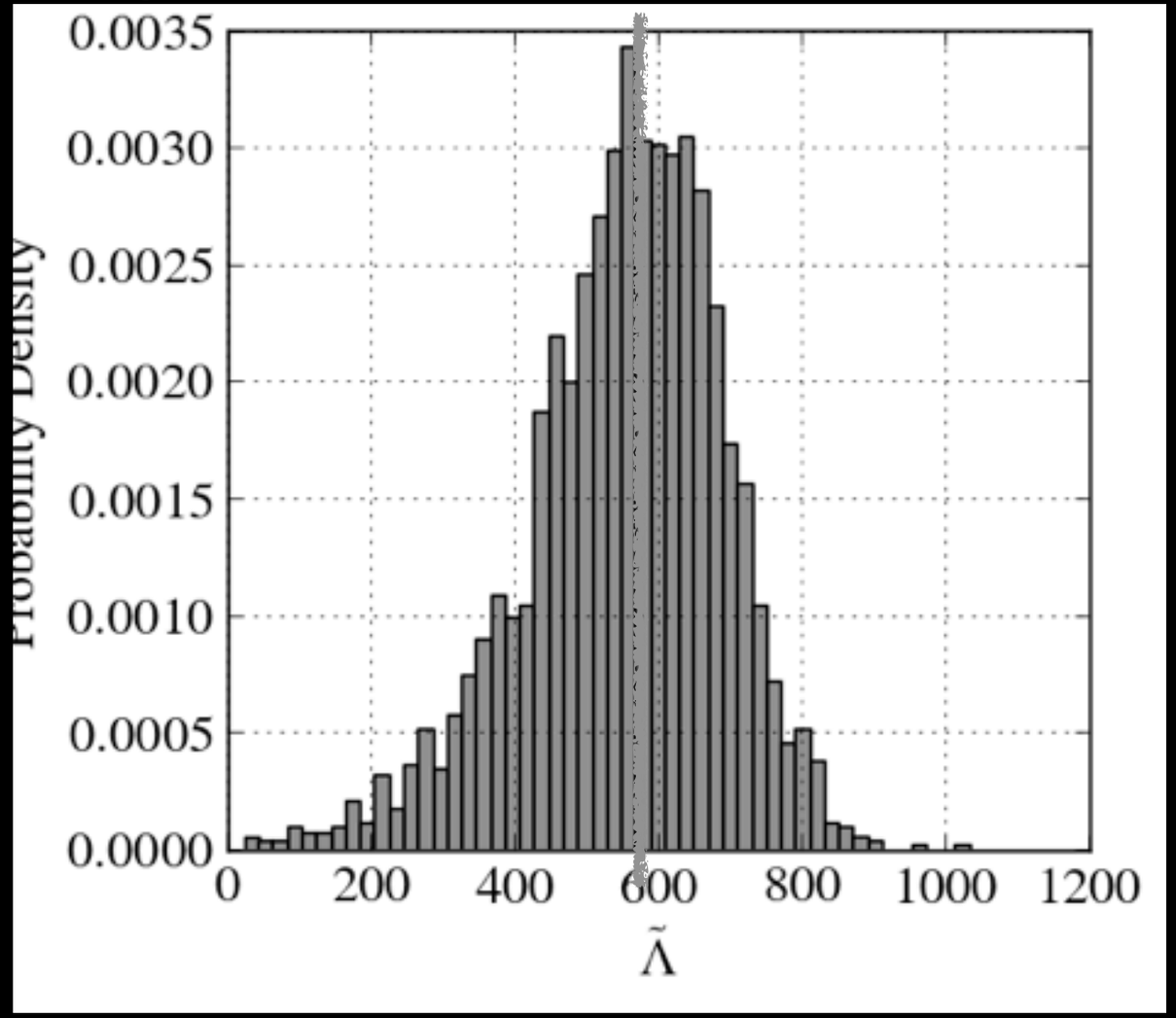
Independent recovery test

- Semi-analytic waveforms for equal mass system
  $\Lambda = 591$

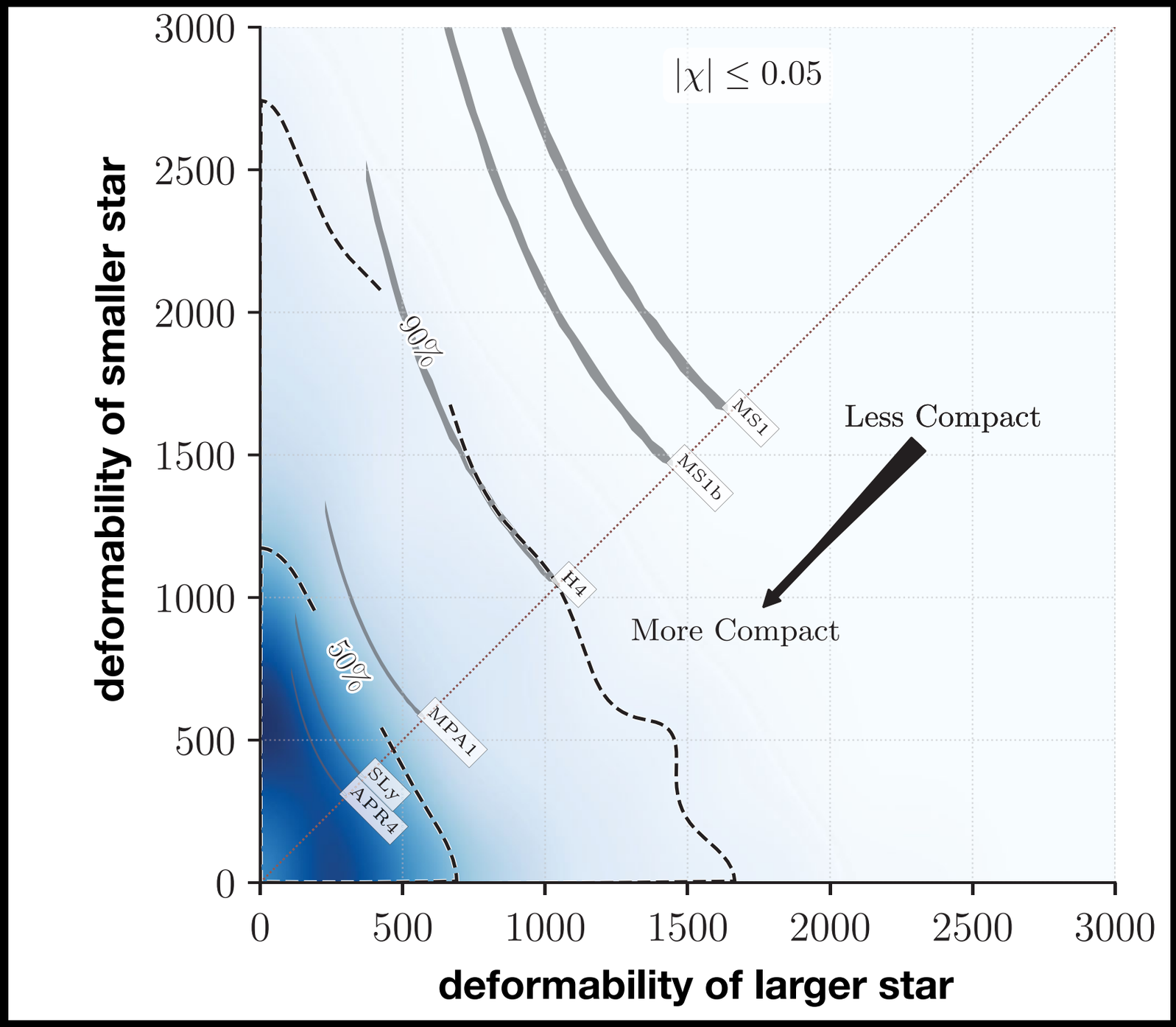
Inject PN T4/ Recover PN F2



Inject TEOB/ Recover PN F2



Dense matter in GW170817



TaylorF2 model, low-spin prior

Independent deformabilities (no assumption that both are NS w/same EOS)

In progress: waveform systematics, direct EOS constraint, possible improved bounds with better waveform models.

LSC/Virgo PRL 119, 161101 (2017)

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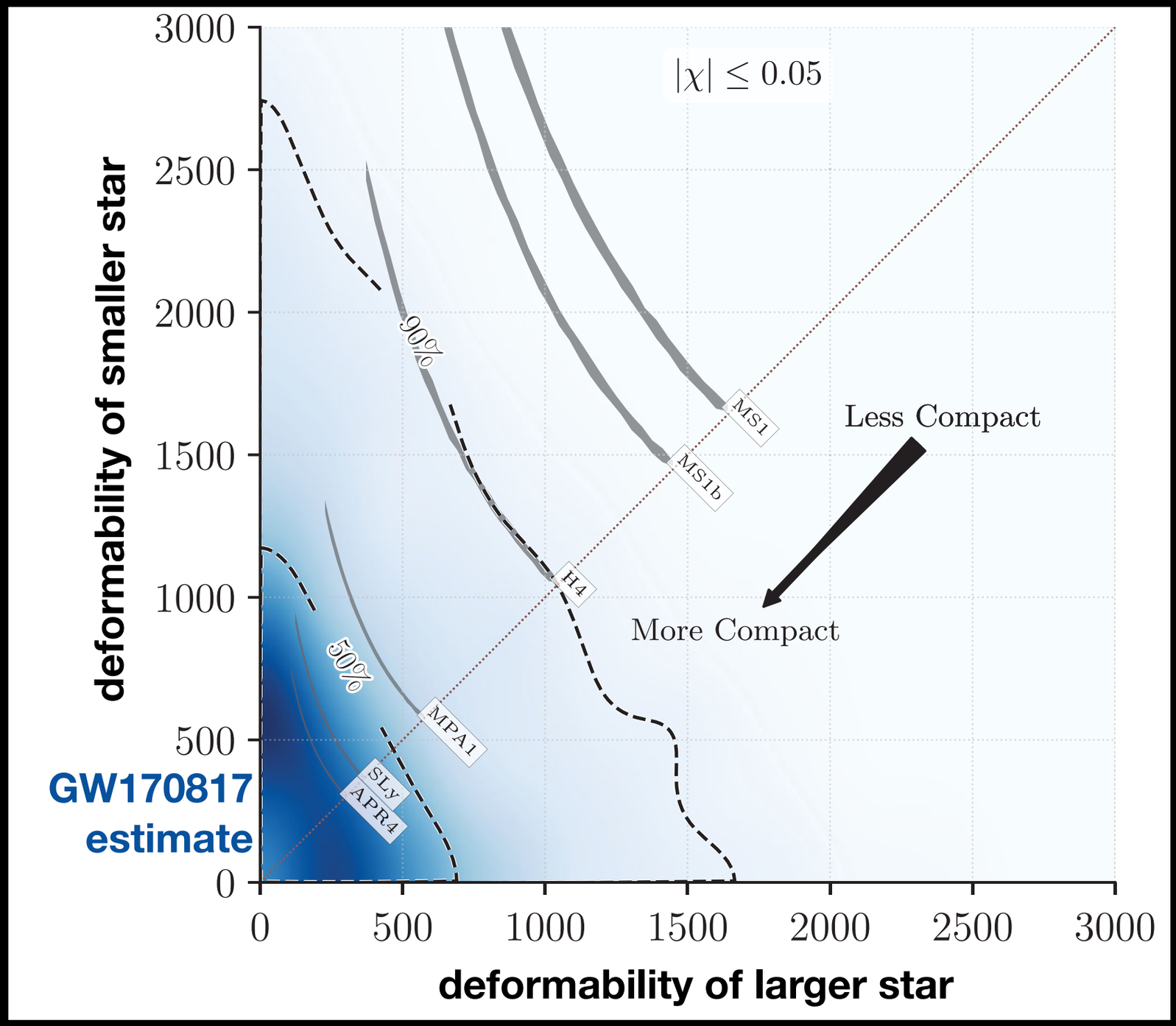

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LSC/Virgo PRL 119, 161101 (2017)

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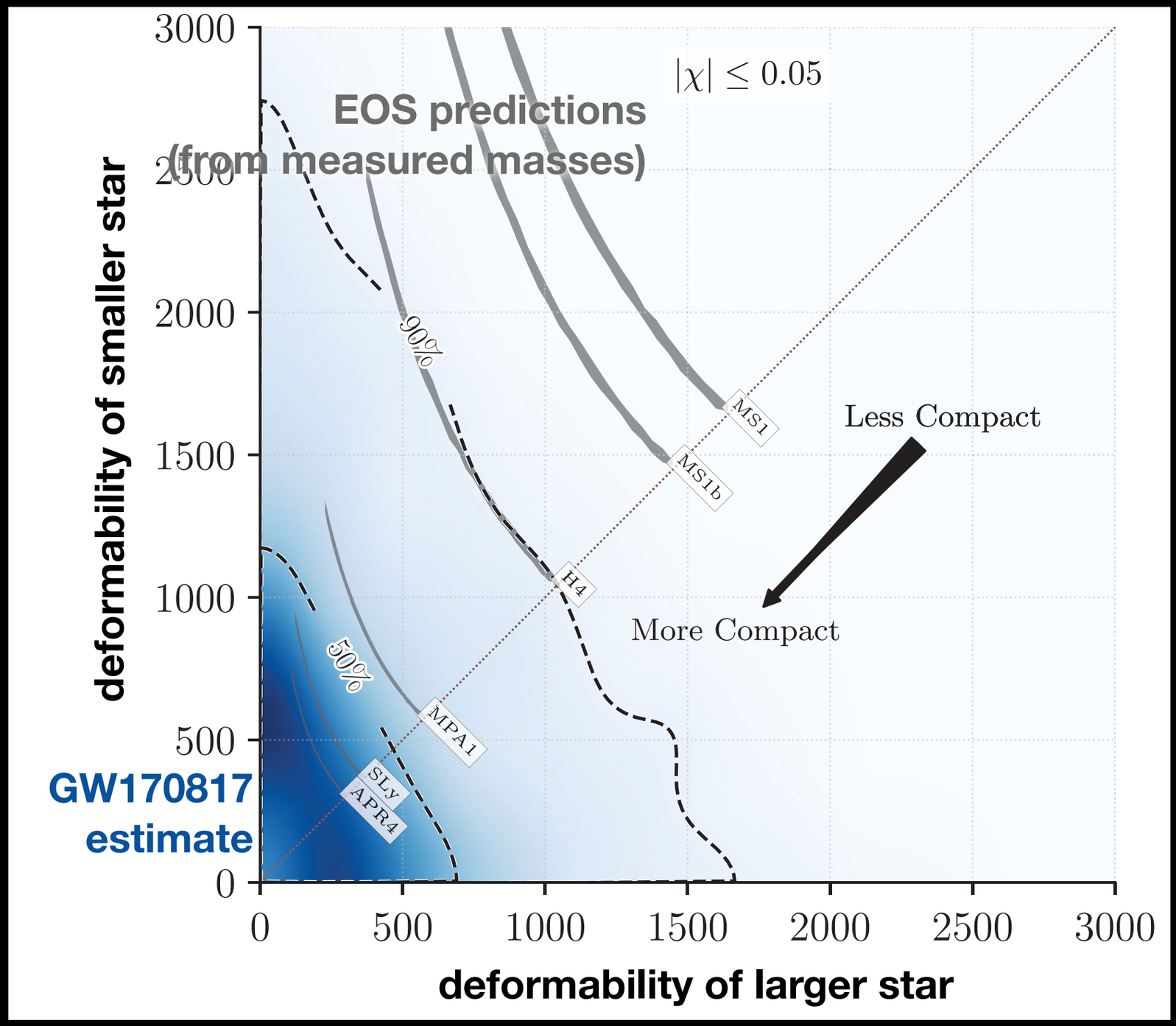

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LSC/Virgo PRL 119, 161101 (2017)

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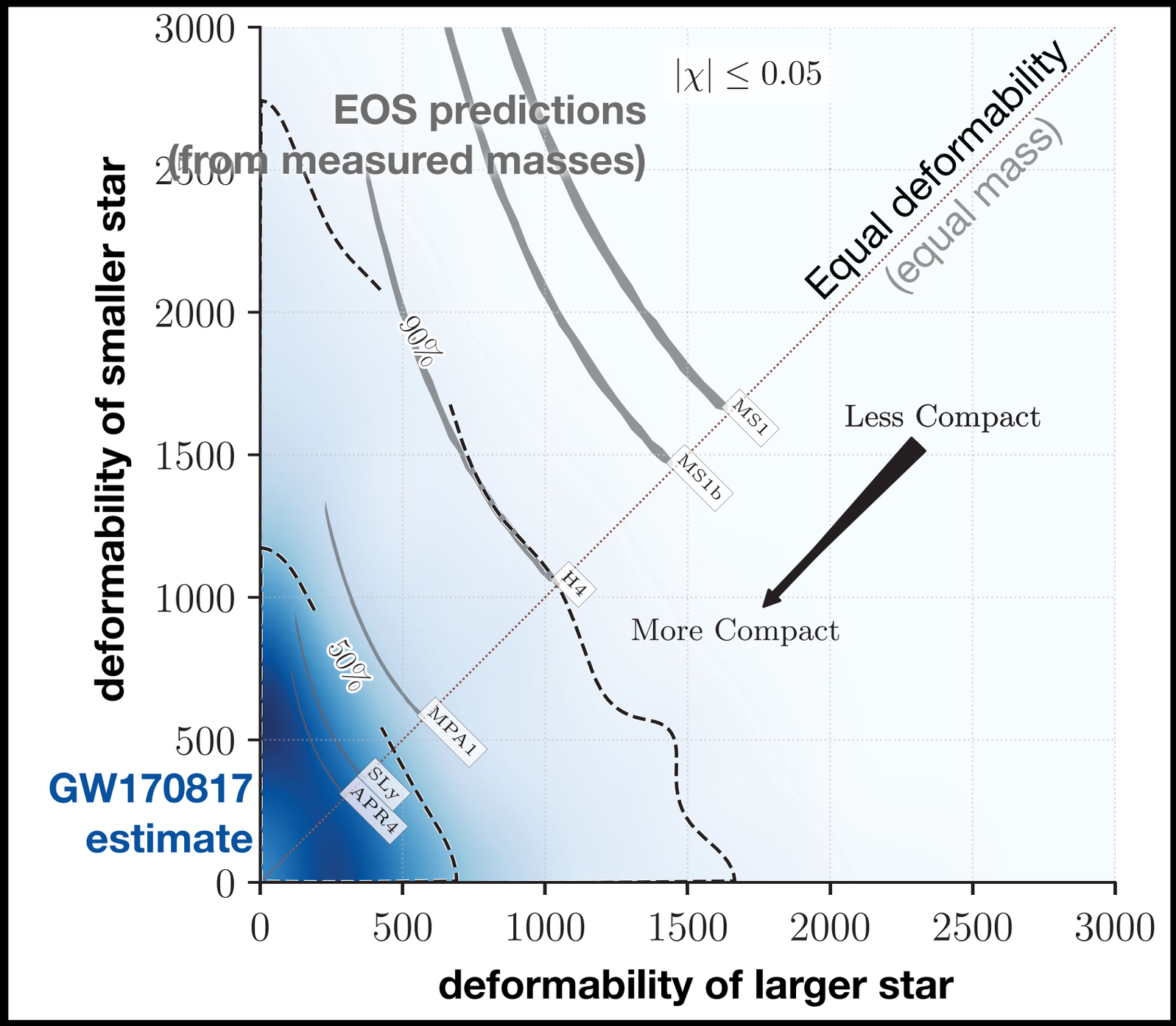

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LSC/Virgo PRL 119, 161101 (2017)

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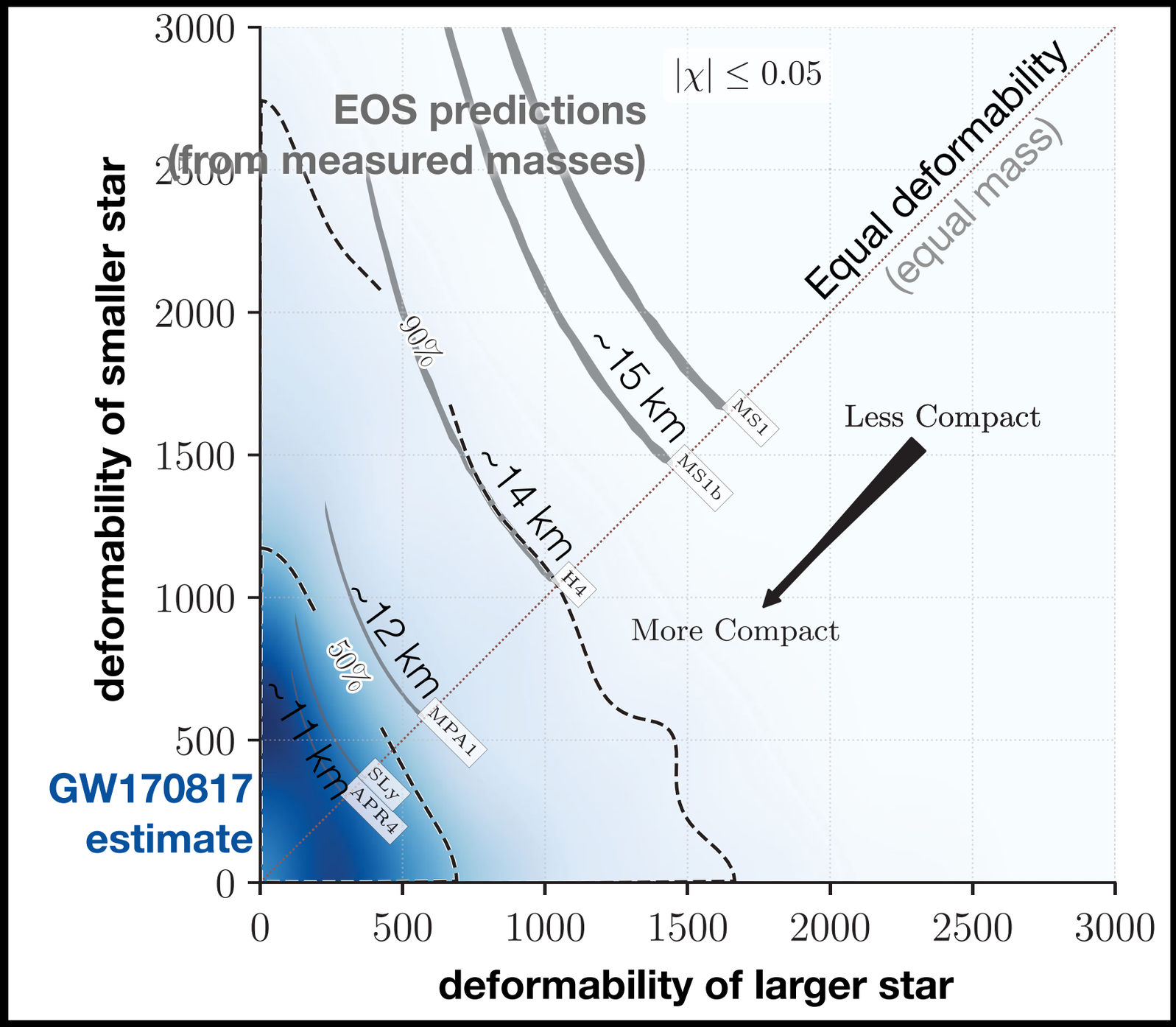

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LSC/Virgo PRL 119, 161101 (2017)

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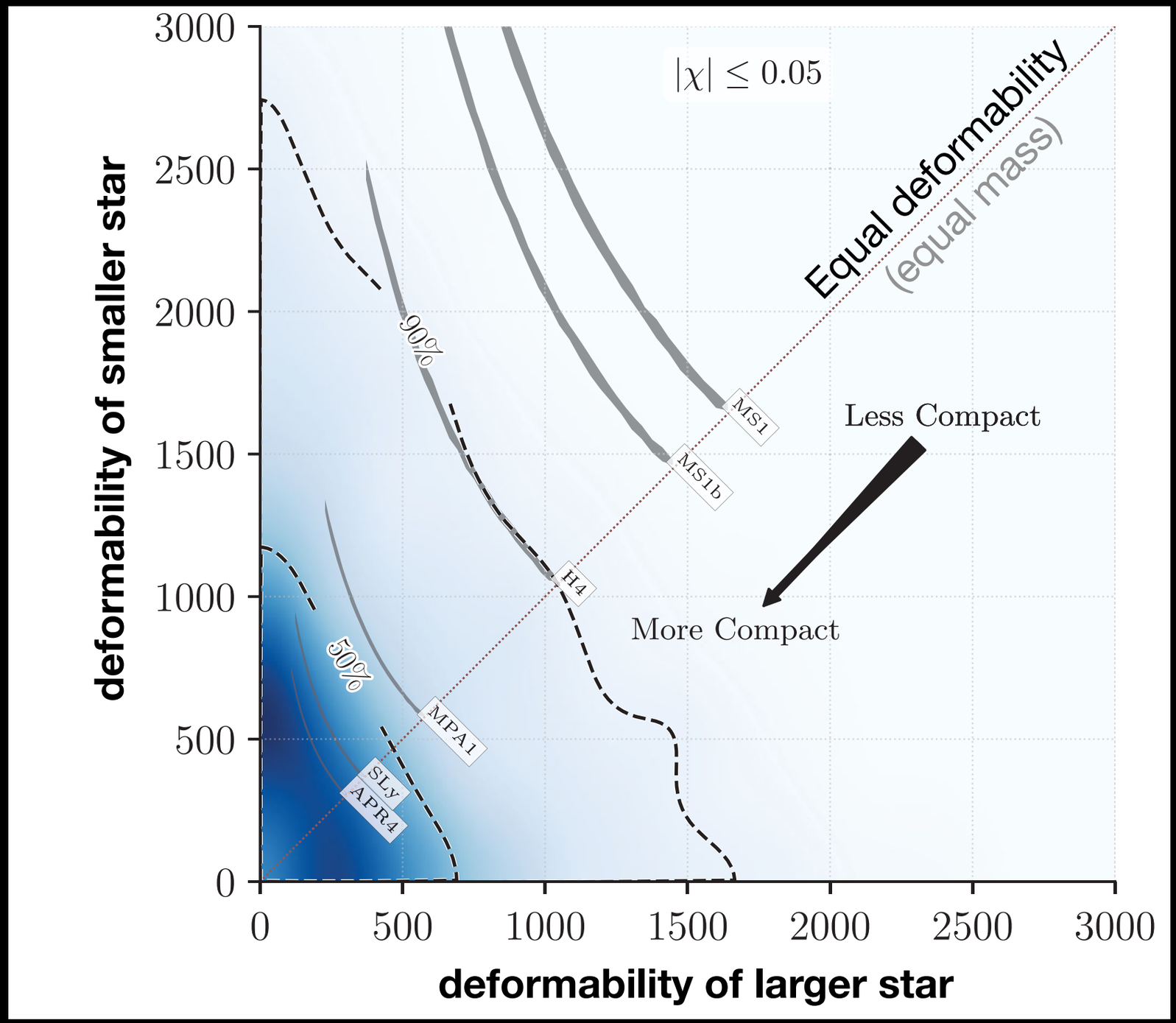


Effective "chirp deformability" is measured

$$\tilde{\Lambda} = \frac{16}{13}\frac{(m_1 + 12m_2)m_1^4\Lambda_1 + (m_2 + 12m_1)m_2^4\Lambda_2}{(m_1 + m_2)^5}$$

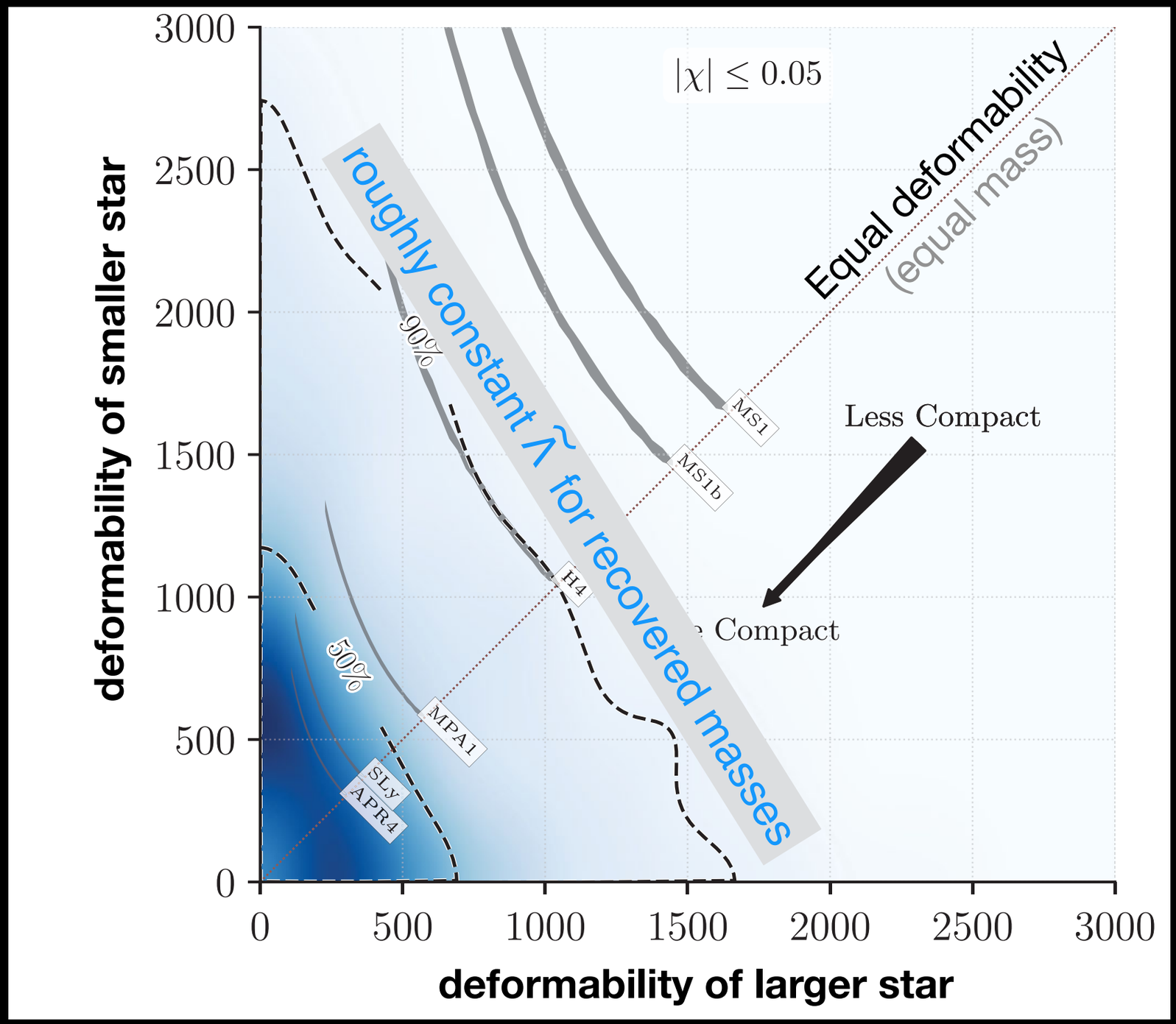
reweigh samples to uniform prior on this measured parameter:

$\tilde{\Lambda} \leqq 800$

each EOS has *distribution* of $\tilde{\Lambda}$ from mass samples

LSC/Virgo PRL 119, 161101 (2017)

Dense matter in GW170817



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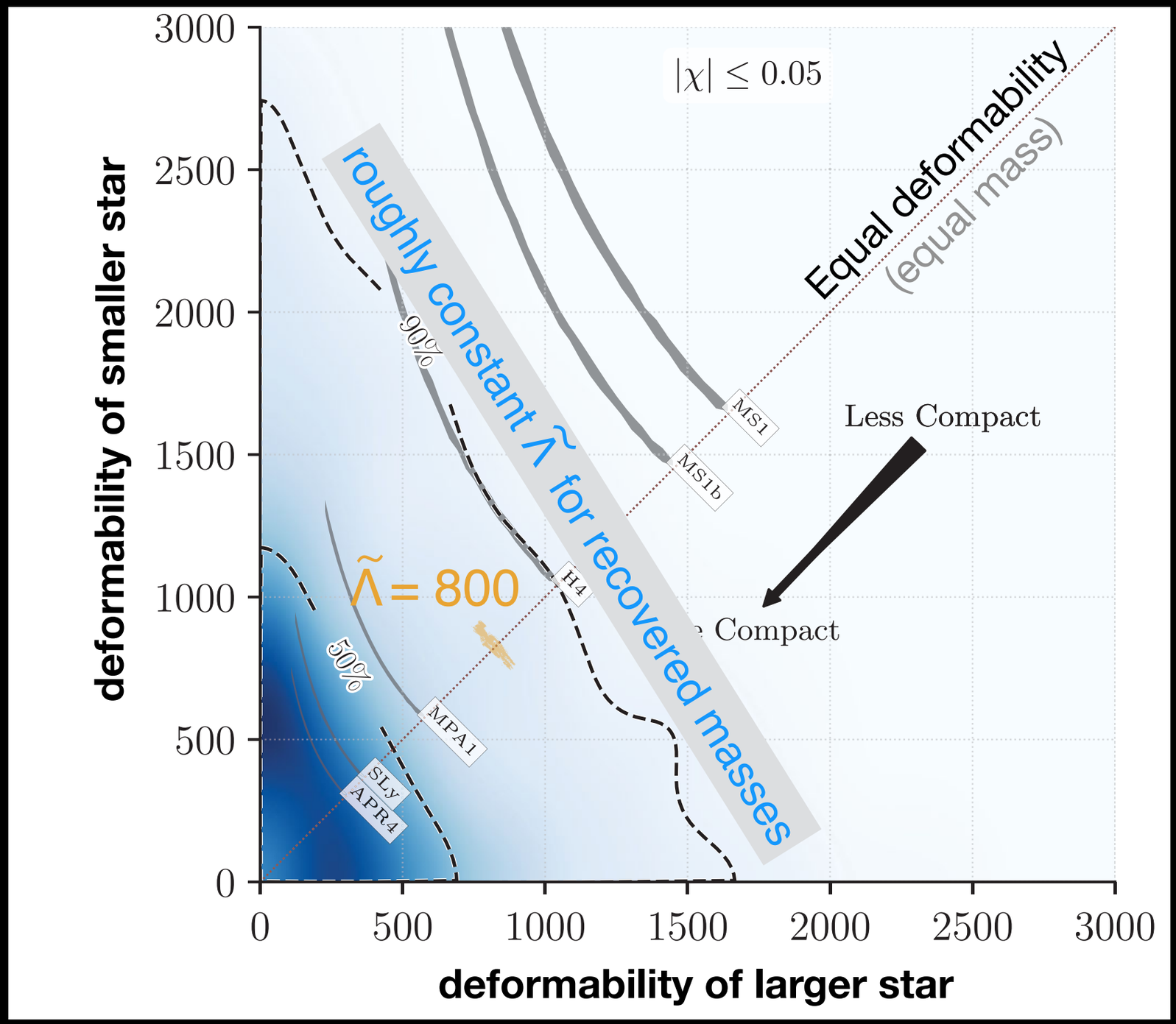
LSC/Virgo PRL 119, 161101 (2017)

Dense matter in GW170817



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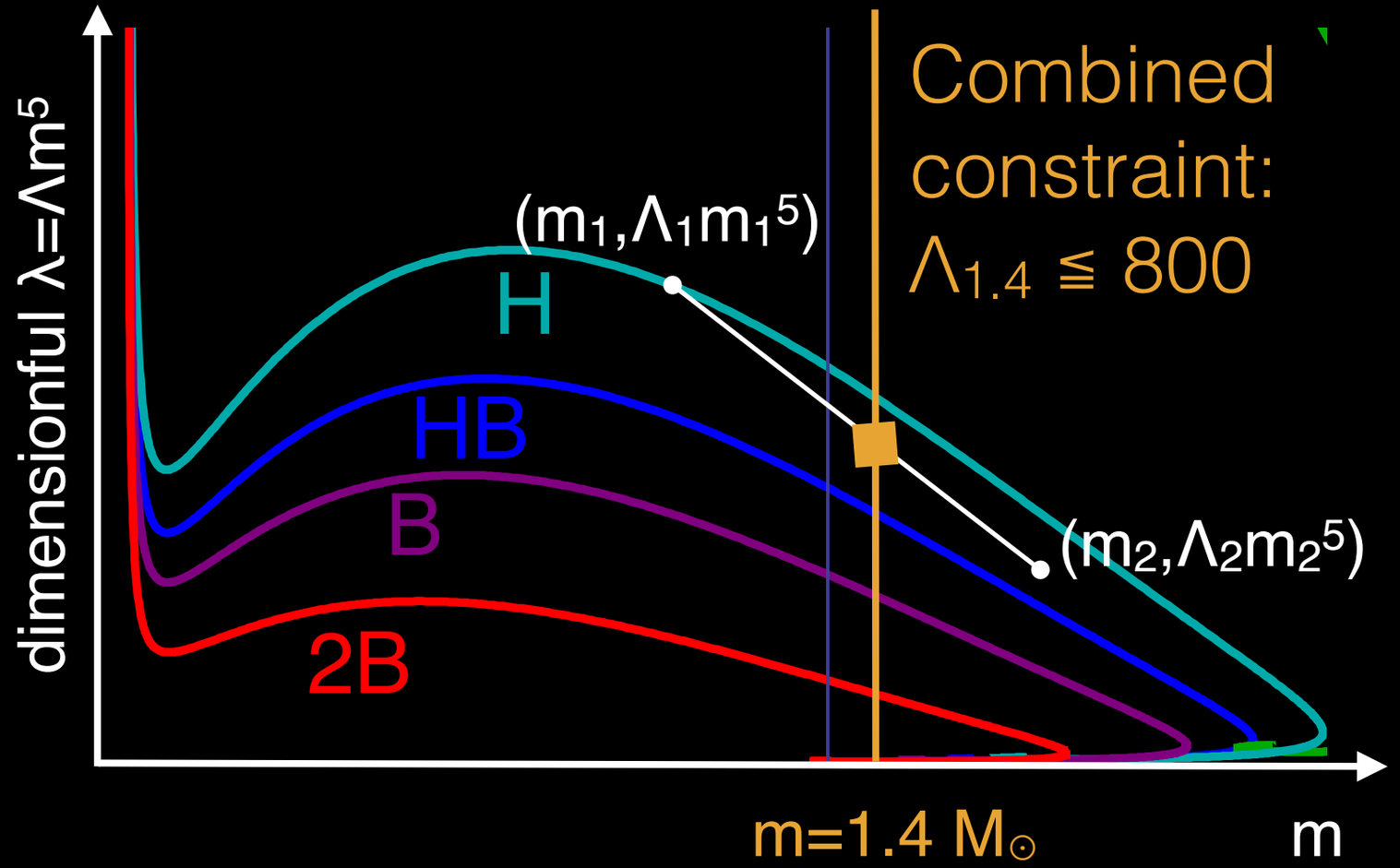
LSC/Virgo PRL 119, 161101 (2017)

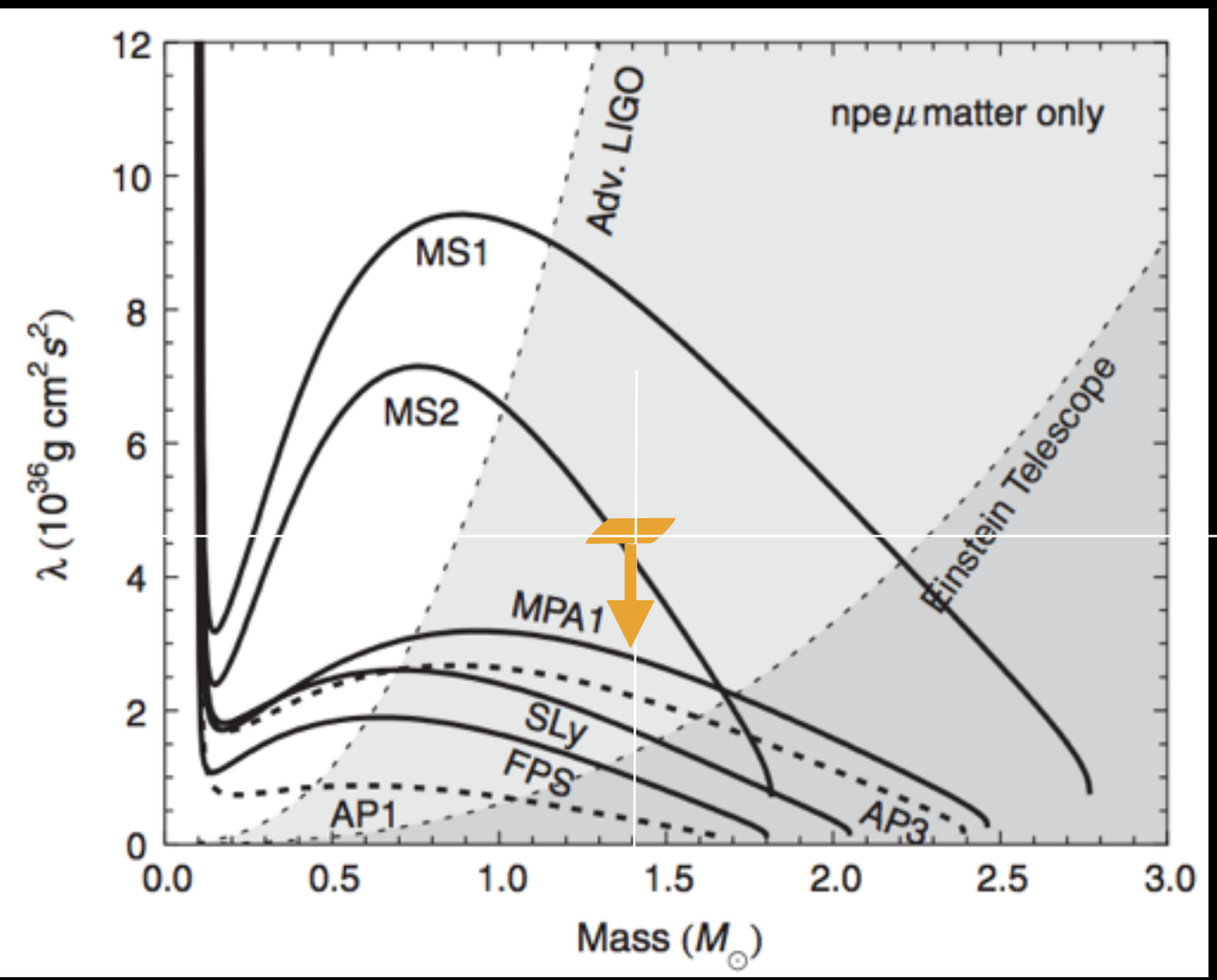
Constraints on underlying EOS:

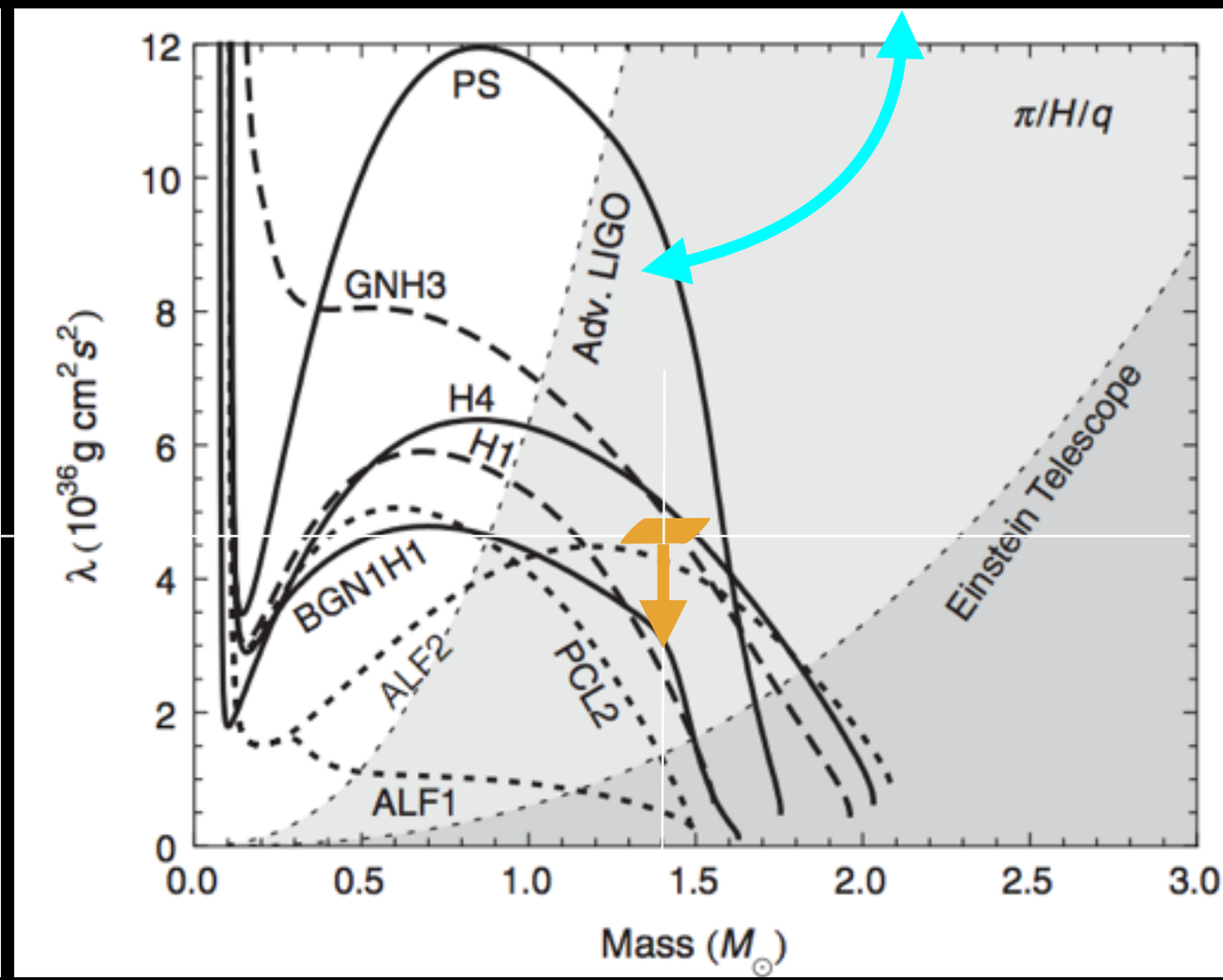
- combine tidal deformation information for each sample assuming a single (linear) EOS function (del Pozzo et al Phys. Rev. Lett. 111, 071101 (2013))
- Result matches upper bound from X-ray constraints (Steiner et al Phys. Rev. C 91, 015804)



- With fixed mass, can compare to dimensionful tidal deformability:
  - $\lambda_{1.4} \leqq 4.6 * 10^{36}$ g cm^2 s^2

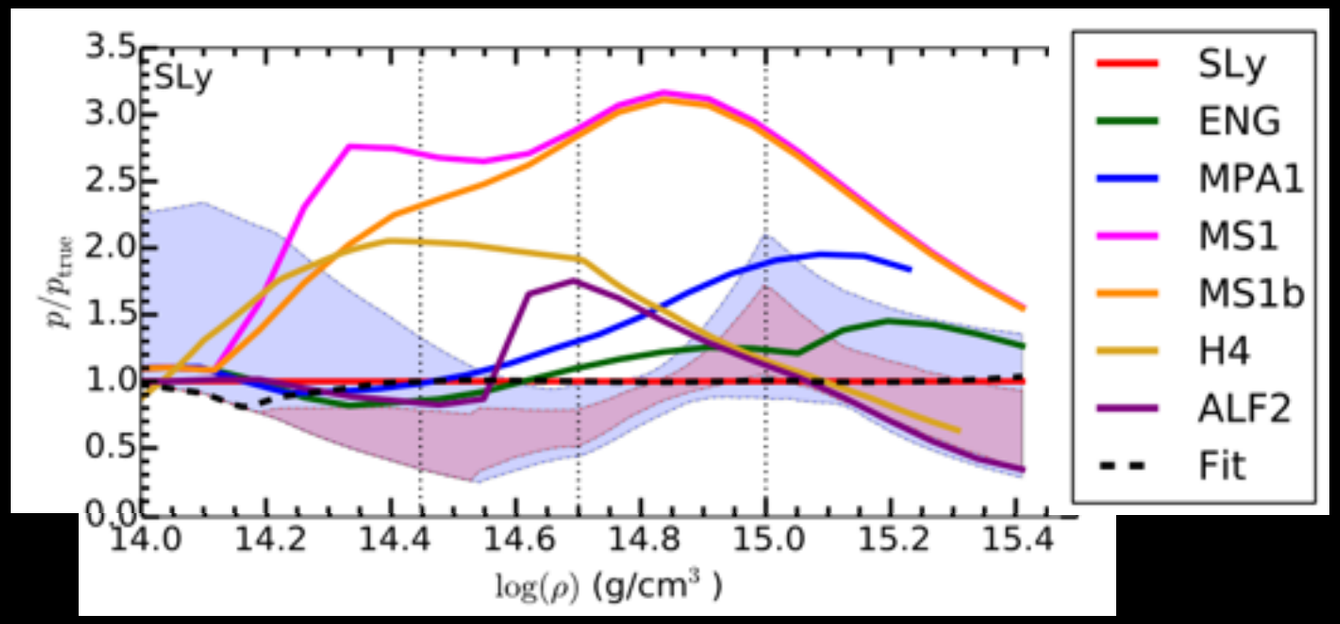
paper considered < 450 Hz only,
approx error ~ $f_{end}^{-2.2}$
GW170817 analyses to to 2048 Hz
"However, a rare nearby event could allow more interesting constraints, as the uncertainty scales as the distance to the source"



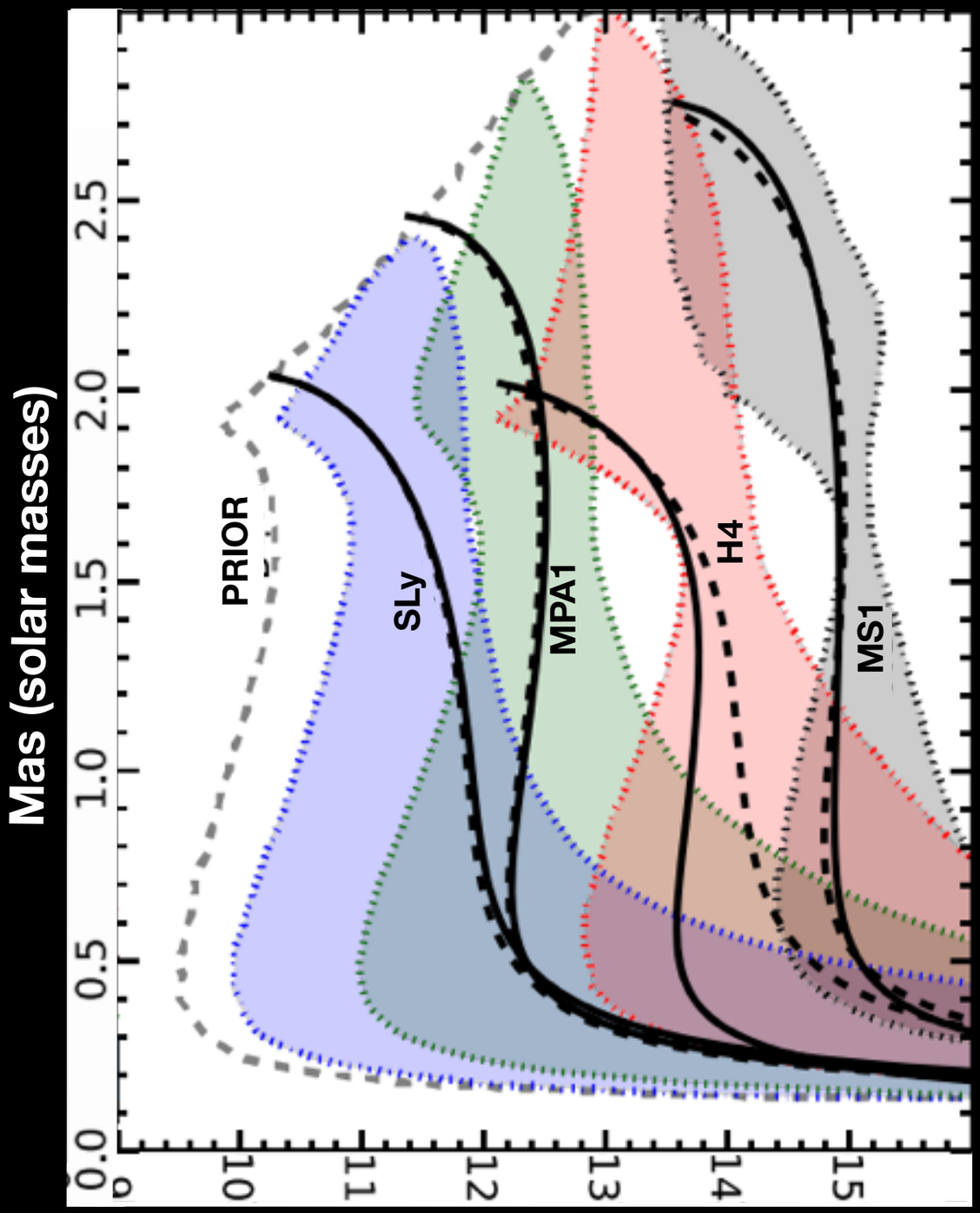


EOS in Hinderer et al PRD 81, 123016 (2010)

Future possibilities for EOS/NS radius



- 95% regions
- Direct EOS constraint; implications for radius
- Combined information from 40 events (~ 1 yr)
- Advanced LIGO design



Lackey & Wade 2014 arxiv:1410.8866