What have we learned about binary neutron stars since the discovery of GW170817?

Duncan Brown
Syracuse University

GW170817

Abbott,..., DAB et al. PRL **119** 161101 (2017)

Basic Info

UID	Labels	Group	Pipeline	Search	Instruments	GPS Time / Event Time	FAR (Hz)	FAR (yr^{-1})	Links	UTC / Submitted
G298048	EM_COINC H1OK ADVOK L1OK V1OK	CBC	gstlal	O2VirgoTest	H1	1187008882.4457	3.478e-12	1 per 9111.7 years	Data	2017-08-17 12:47:18 UTC

Coinc Tables

End Time (GPS)	1187008882.4457 s
Total Mass	2.7693 $M_\odot$
Chirp Mass	
SNR	
False Alarm Proba	
Log Likelihood Ratio	32.3969

Single Inspiral Tables

IFO	H1

Low chirp mass

neutron star…

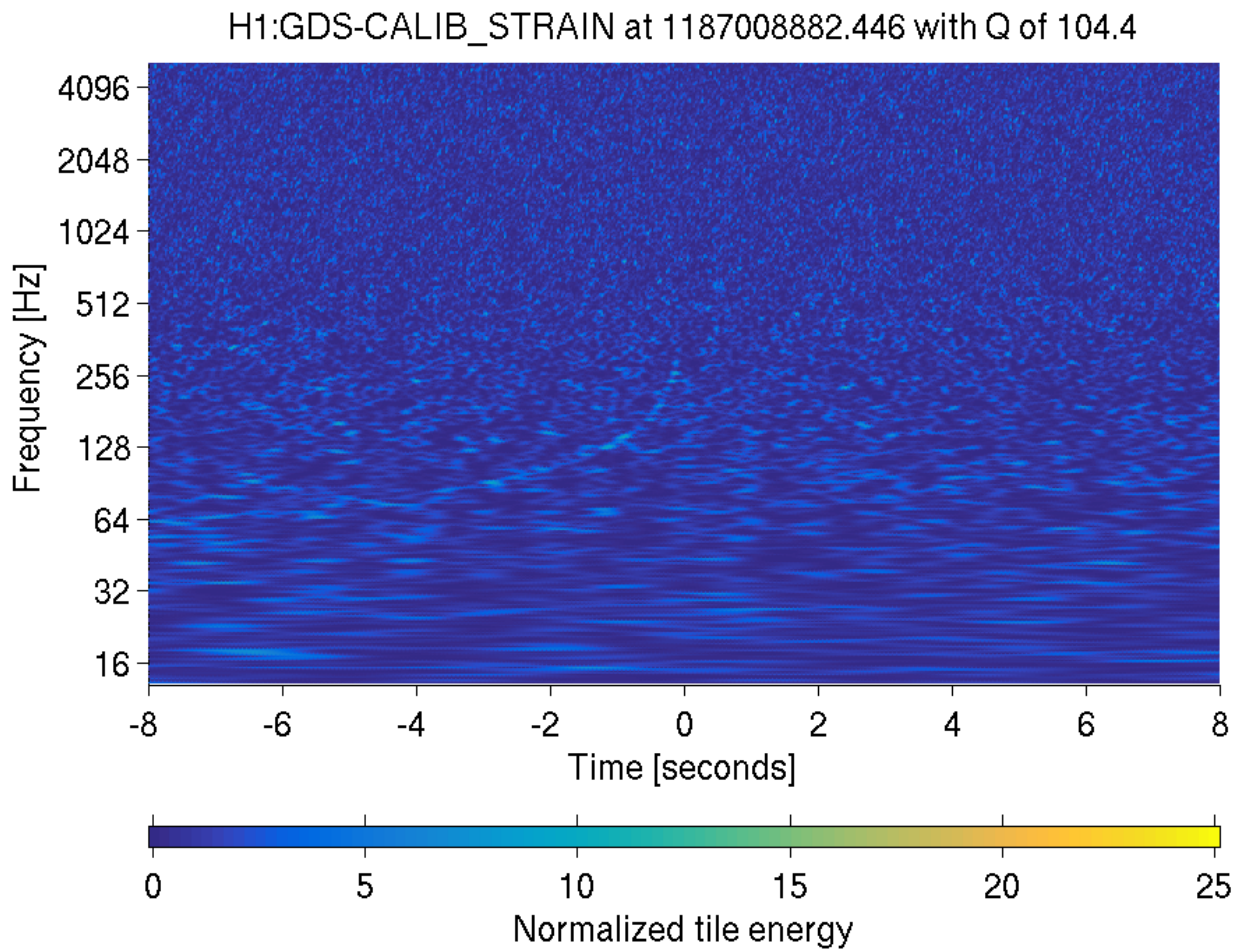
Fermi gamma-ray burst event ~ 2 second after merger!

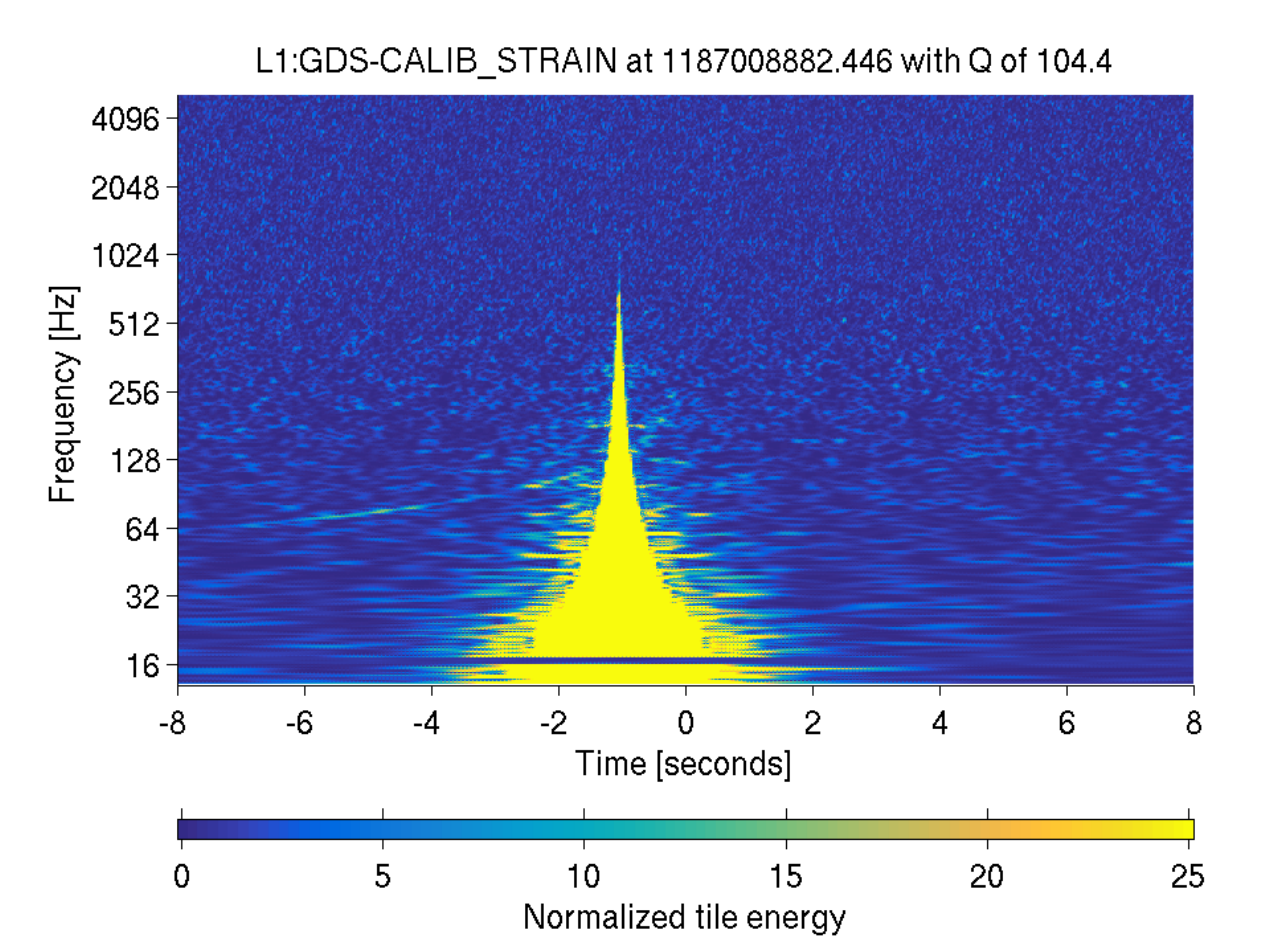
But only seen at Hanford, even though Livingston and Virgo were operating…

Neighbors [-5,+5]

UID	Labels	Group	Pipeline	Search	Instruments	GPS Time / Event Time	Δgpstime	FAR (Hz)	Links	UTC / Submitted
E298046	EM_COINC	External	Fermi	GRB		1187008884.4700	2.024290		Data	2017-08-17 12:41:45 UTC

Cannon et al. ApJ **748** 136 (2012)
Messick et al. PRD **95**, 042001 (2017)


H1:GDS-CALIB_STRAIN at 1187008882.446 with Q of 104.4
Frequency [Hz]
4096
2048
1024
512
256
128
64
32
16
-8
-6
-4
-2
0
2
4
6
8
Time [seconds]
0
5
10
15
20
25
Normalized tile energy


L1:GDS-CALIB_STRAIN at 1187008882.446 with Q of 104.4
Frequency [Hz]
4096
2048
1024
512
256
128
64
32
16
-8
-6
-4
-2
0
2
4
6
8
Time [seconds]
0
5
10
15
20
25
Normalized tile energy

GCN 21509 at 10:09 am EDT announcing significant BNS candidate coincident with the Fermi GBM trigger...

TITLE: GCN CIRCULAR
NUMBER: 21509
SUBJECT: LIGO/Virgo G298048: Identification of a binary neutron star candidate coincident with Fermi GBM trigger 524666471/170817529
DATE: 17/08/17 14:09:25 GMT
FROM: Reed Clasey Essick at MIT <ressick@mit.edu>

The LIGO Scientific Collaboration and the Virgo Collaboration report:

A binary neutron star candidate was identified in data from the LIGO Hanford detector at gps time 1187008882.4457 (Thu Aug 17 12:41:04 GMT 2017). The signal is clearly visible in time-frequency representations of the gravitational-wave strain in data from H1. The current significance estimate of ~1/10,000 years is based on data from H1 alone. Information about this candidate is available in GraceDb here

https://gracedb.ligo.org/events/view/G298048

The effective distance to this candidate is approximately 58 Mpc and the current localization estimate using gravitational-wave data alone is quite broad because it only makes use of data from H1. We note that this is only an estimate of the effective distance, and the actual luminosity distance to the source is likely larger.

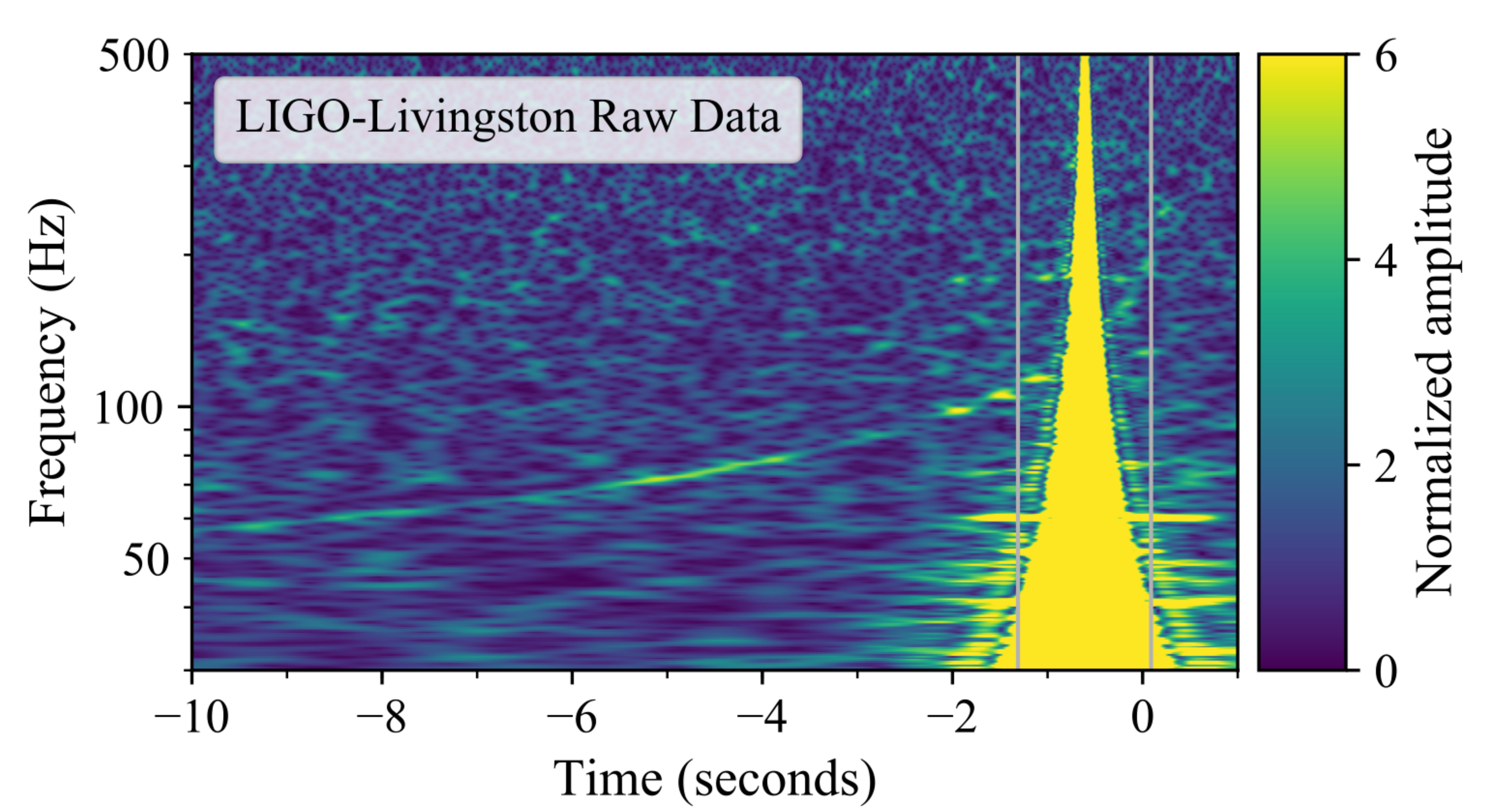
The neutron star coalescence candidate is also clearly visible in data from the LIGO Livingston detector, although there is a coincident noise artifact in the L1 data. To be clear, the binary neutron star candidate is clearly visible in the L1 data on top of the noise artifact. There is no evidence for any noise artifact at H1. Virgo was online at the time, although its data was not used to estimate the candidate's significance. It is expected to be visible in all detectors once the data has been analyzed.

The gravitational-wave candidate was found in coincidence with Fermi GBM trigger 524666471/170817529, which occurred at gps time 1187008884.47 (Thu Aug 17 12:41:06 GMT 2017). This is approximately 2 seconds after the gravitational-wave candidate's coalescence time. The Fermi trigger's localization estimate from Fermi data alone can be found here

https://heasarc.gsfc.nasa.gov/FTP/fermi/data/gbm/triggers/2017/bn170817529/quicklook/glg_locplot_all_bn170817529.png
https://heasarc.gsfc.nasa.gov/FTP/fermi/data/gbm/triggers/2017/bn170817529/quicklook/glg_locprob_all_bn170817529.fit

Analyses including data from H1, L1, and V1 are ongoing and a sky-map using gravitational-wave data will be made available as quickly as possible.

[GCN OPS NOTE(17aug17): Per author's request, the LIGO/VIRGO ID was added to the beginning of the Subject-line.]



Usman,... DAB, et al. Class. Quant. Grav.**33** 215004 (2016)

Abbott,..., DAB et al. PRL **119** 161101 (2017)

Nitz, Dent, Dal Canton, Fairhurst, DAB. Astrophys. J. **849** 118 (2017)

Laura Nuttall

Andy Lundgren

Tito Dal Canton

Ian Harry

Alex Nitz

TJ Massinger

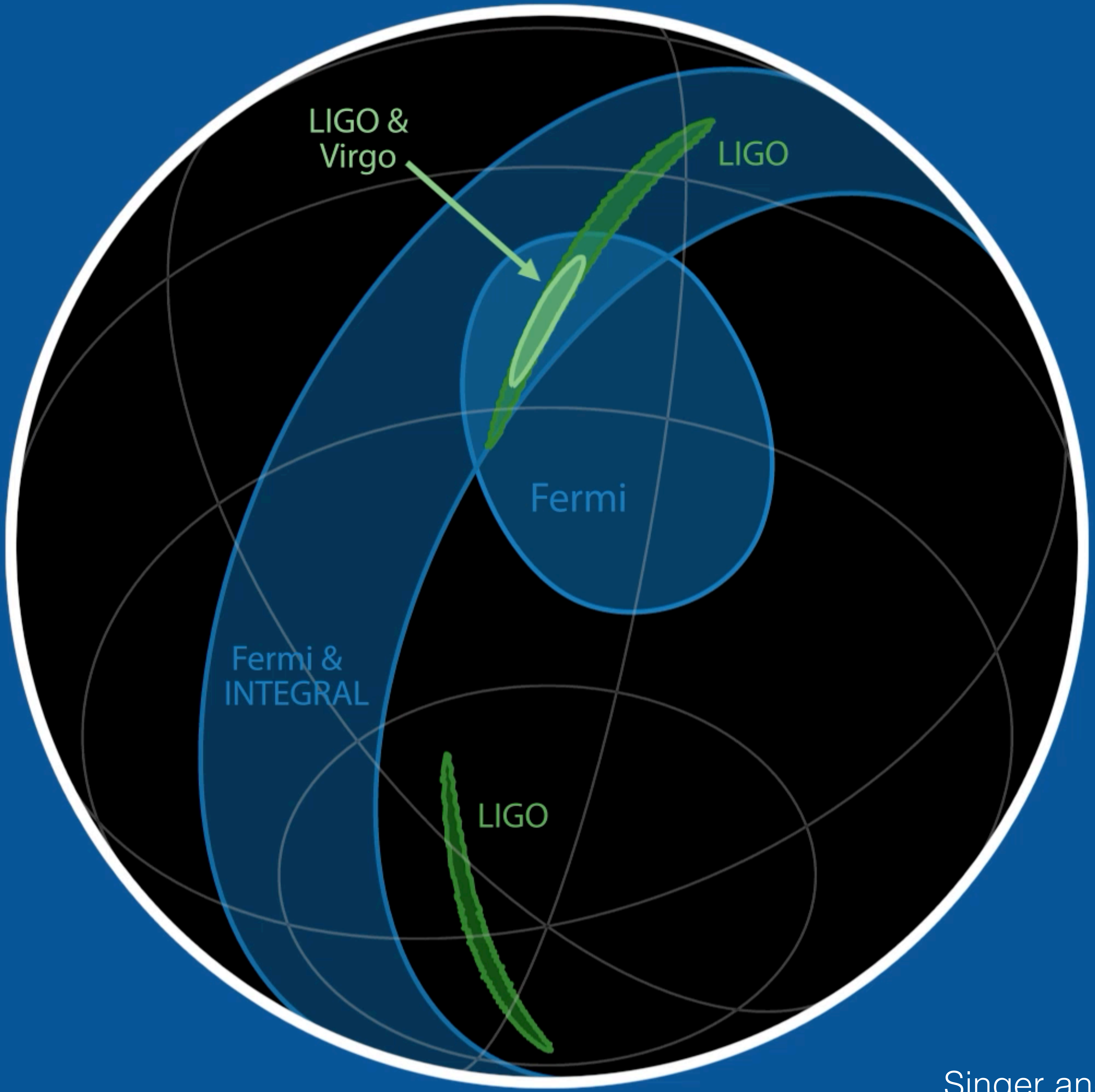
GCN 21513 at 1:54 pm EDT with localization...

TITLE: GCN CIRCULAR
NUMBER: 21513
SUBJECT: LIGO/Virgo G298048: Further analysis of a binary neutron star candidate
DATE: 17/08/17 17:54:51 GMT
FROM: Leo Singer at NASA/GSFC <leo.p.singer@nasa.gov>

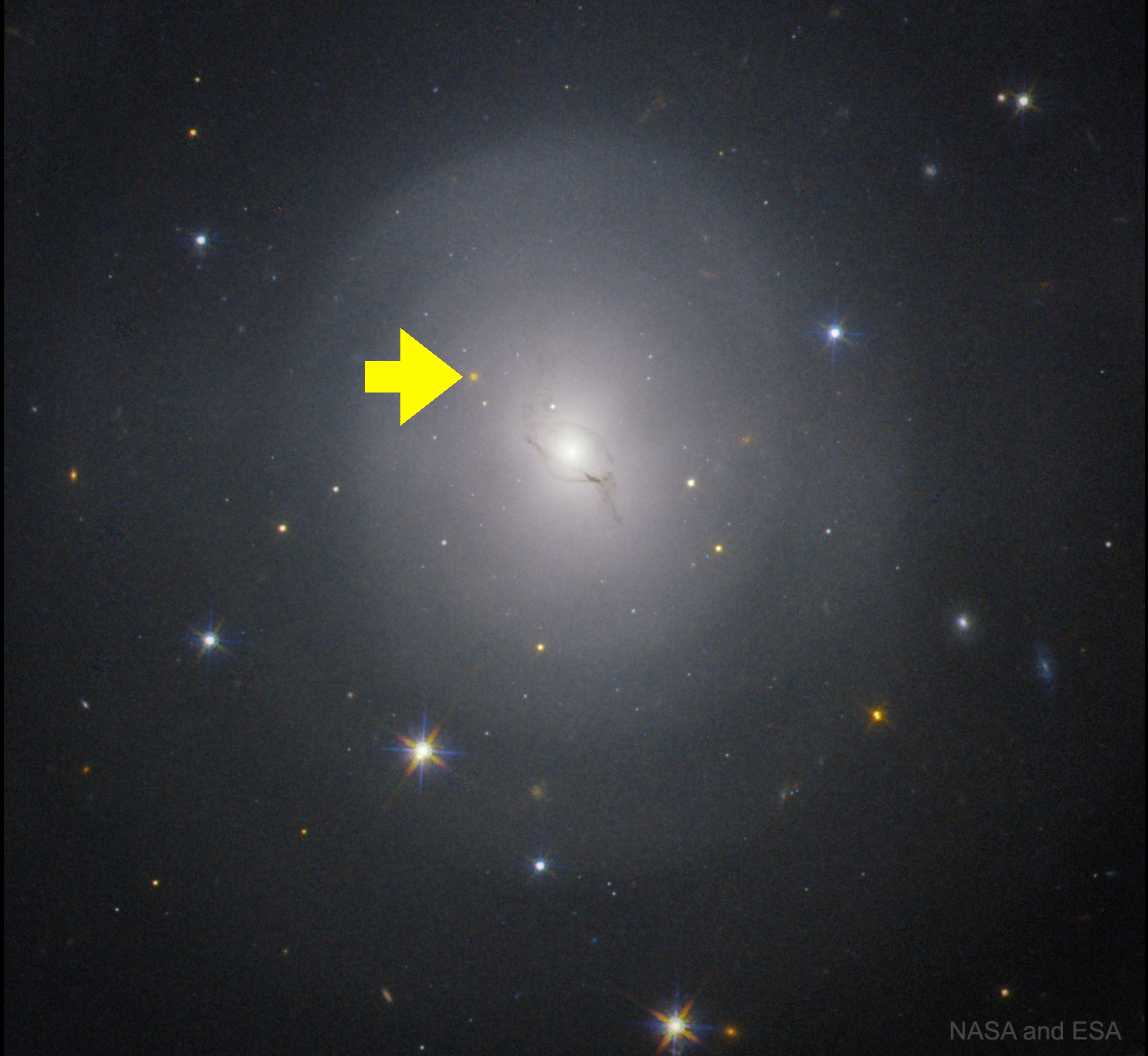
The LIGO Scientific Collaboration and the Virgo Collaboration report:

We performed a preliminary offline analysis using the PyCBC search (Nitz et al. arxiv:1705.01513, 2017) of the binary neutron star candidate G298048 (LSC and Virgo, GCN 21505, 21509, 21510) identified in low-latency by the gstlal online search (Messick et al. Phys. Rev. D 95, 042001, 2017).

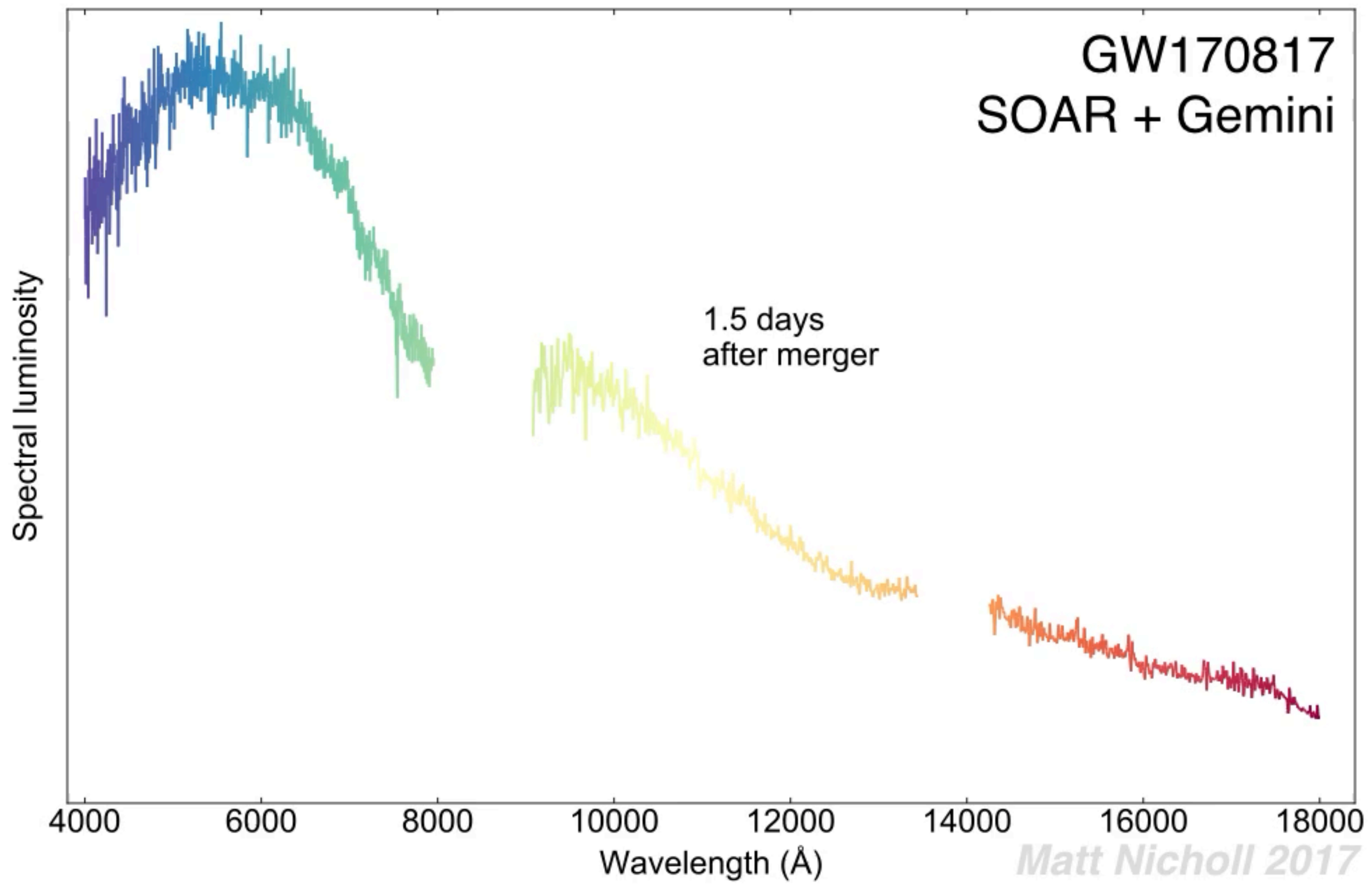
A trigger consistent with a binary neutron star merger is observed at GPS time 1187008882.443 (2017-08-17 12:41:04 UTC) in both the LIGO Livingston (L1) and LIGO Hanford (H1) detectors. The trigger is below threshold in Virgo because of the antenna pattern for Virgo (V1) at the time and location of this event, but the Virgo instrument contributes to the localization. The duration of the gravitational-wave signal is approximately 74 seconds from the searchâ€™s low-frequency cutoff of 27 Hz to the binary merger.



Singer and Price PRD **93**, 024013 (2016)

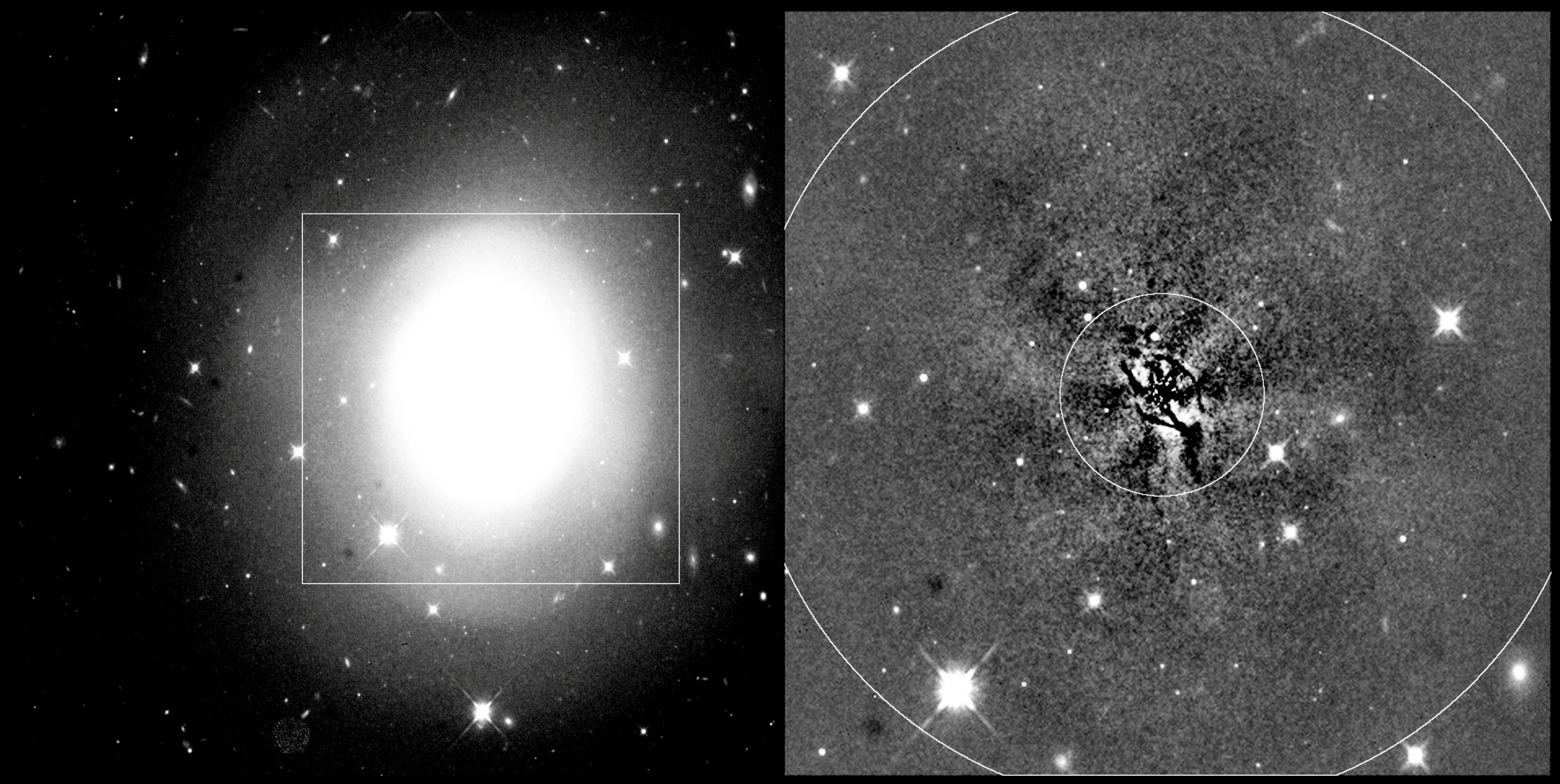

NASA and ESA

Soares-Santos,..., DAB, et al. ApJ **848** L16 (2017)


GW170817
SOAR + Gemini
1.5 days
after merger
Spectral luminosity
4000
6000
8000
10000
12000
14000
16000
18000
Wavelength (Å)
Matt Nicholl 2017

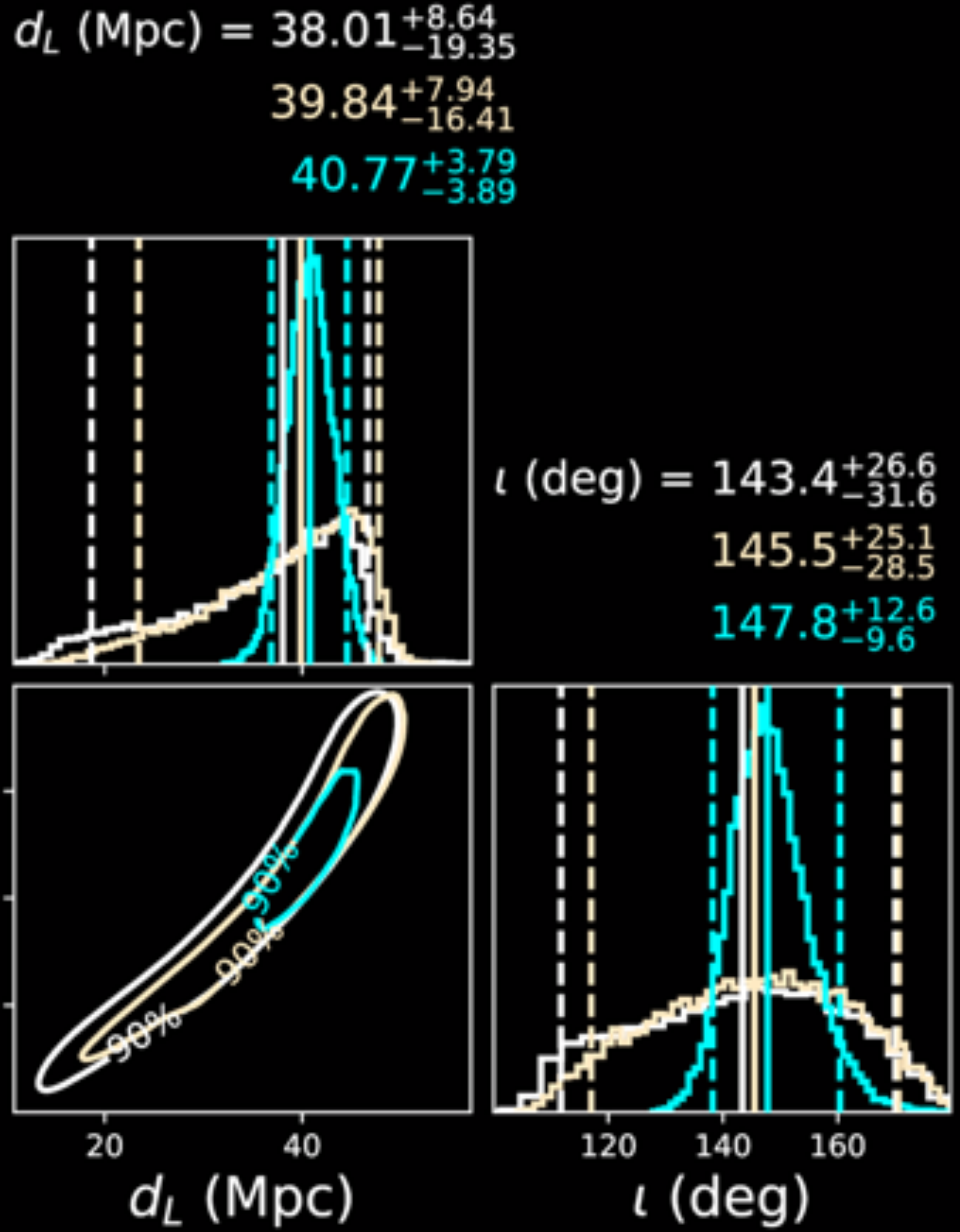
Inclination angle of the binary is degenerate with the distance

Can break this degeneracy with an accurate distance measure



Cantiello et al. Astrophys.J. **854** L31 (2018)

- Precise sky location measurement from Soares-Santos, et al.
- Prior on distance from Cantiello, et al. d_L = 40.7 ± 2.36 Mpc



Viewing angle is $32^{+10}_{-13} \pm 1.7$ deg

Lower limit of ≥ 13deg

robust to choice of prior

Daniel Finstad

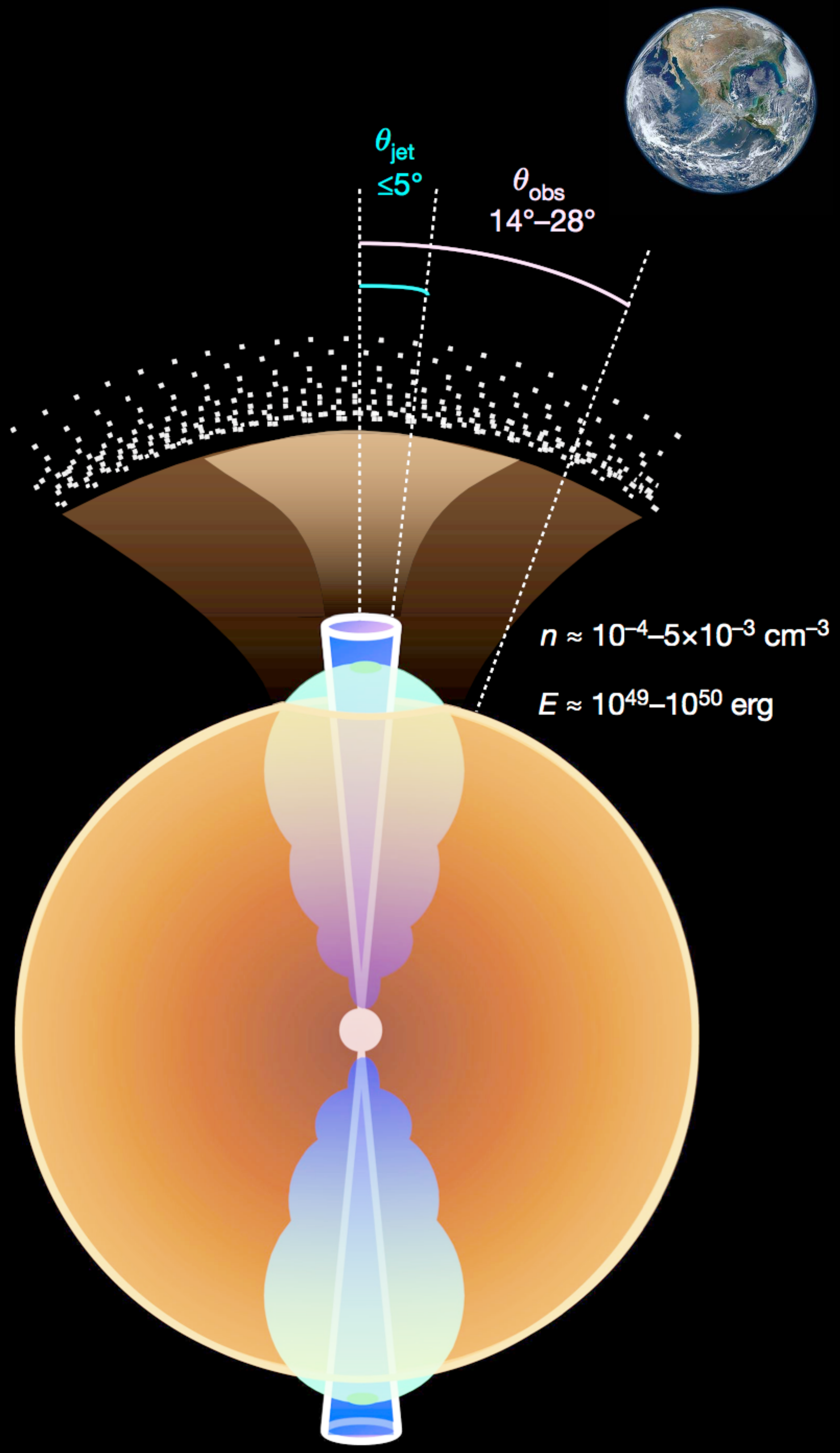
Finstad, De, DAB, Berger, Biwer ApJ **860** L2 (2018)

Distance-constrained GW observations of viewing angle are consistent with EM observations

Mooley et al. report 14 - 28 deg from radio

Troja et al. report 21 - 29 deg from broad band observations

GW and EM observations support successful-jet cocoon model (structured jet)



Mooley et al. Nature **561**, 355 (2018)

Troja et al. MNRAS arXiv:1808.06617

Abbott,..., DAB et al. PRL **119** 161101 (2017)

- The equation of state (EOS) of cold, ultra-dense matter remains poorly constrained at high densities

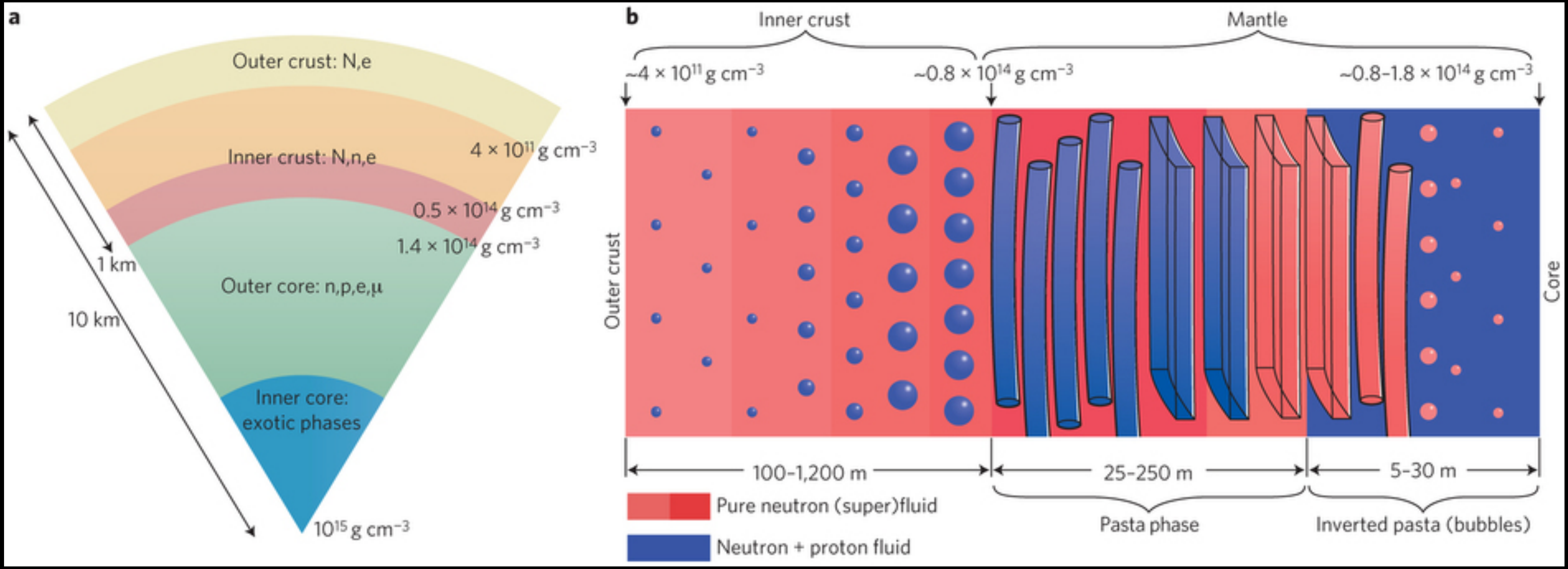
- At T = 0, the EOS relates pressure to density $P = P(\boldsymbol{\rho})$

- Nuclear experiments are only able to constrain EOS models up to the nuclear saturation density (2.7×10^{14} g / cm^3)

- Densities of the cores of neutron stars reach 8 - 10 times nuclear saturation density and so neutron stars allow us to explore the EOS at much higher densities

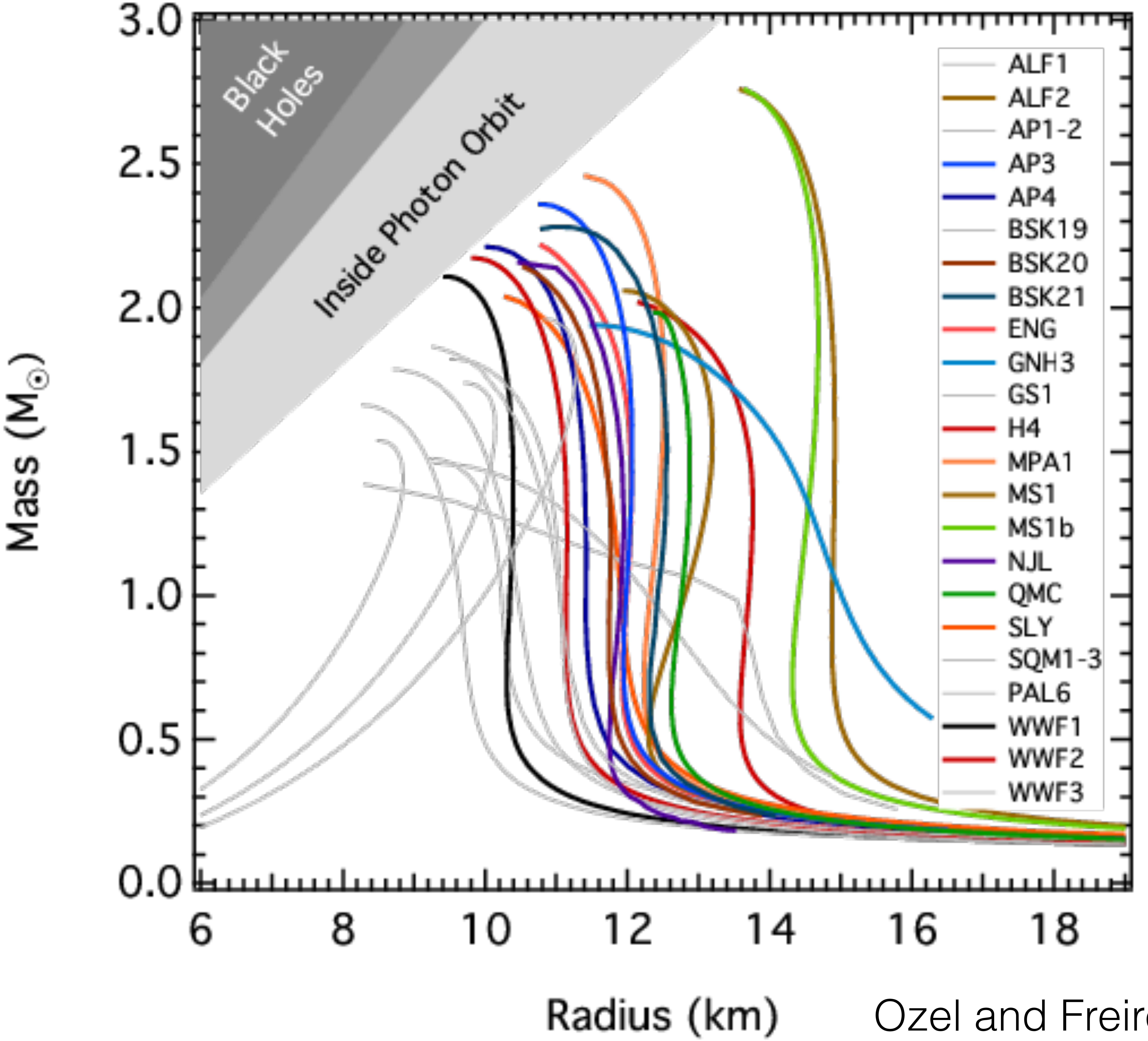
Pick an EOS and integrate the TOV equation, matching to Schwarzschild outside

$$\frac{dP(r)}{dr} = -\frac{G}{r^2}\left[\rho(r) + \frac{P(r)}{c^2}\right]\left[m(r) + \frac{4\pi r^3 P(r)}{c^2}\right]\left[1 - \frac{2Gm(r)}{rc^2}\right]^{-1}$$

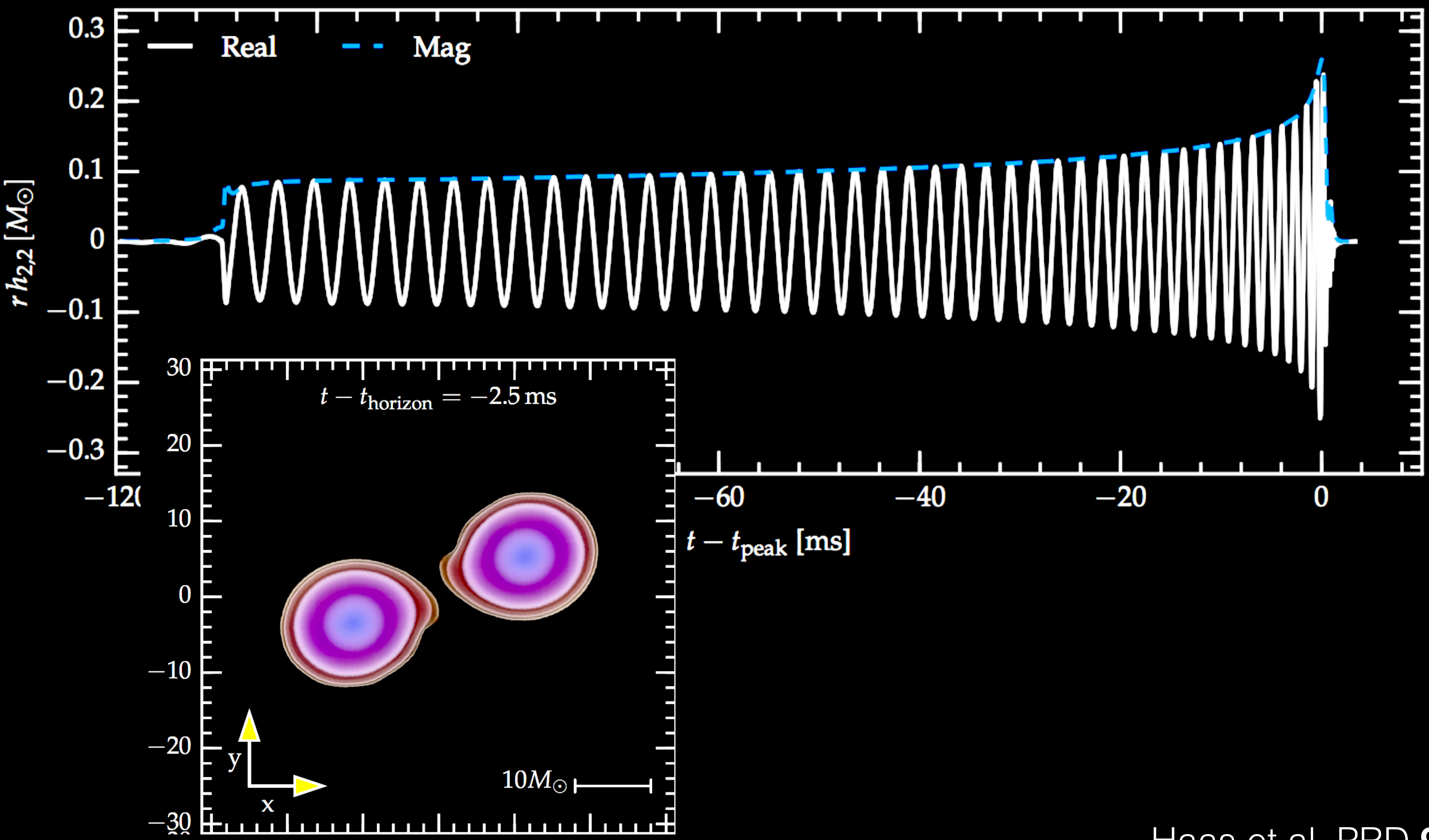


"Soft" EOS, low radius

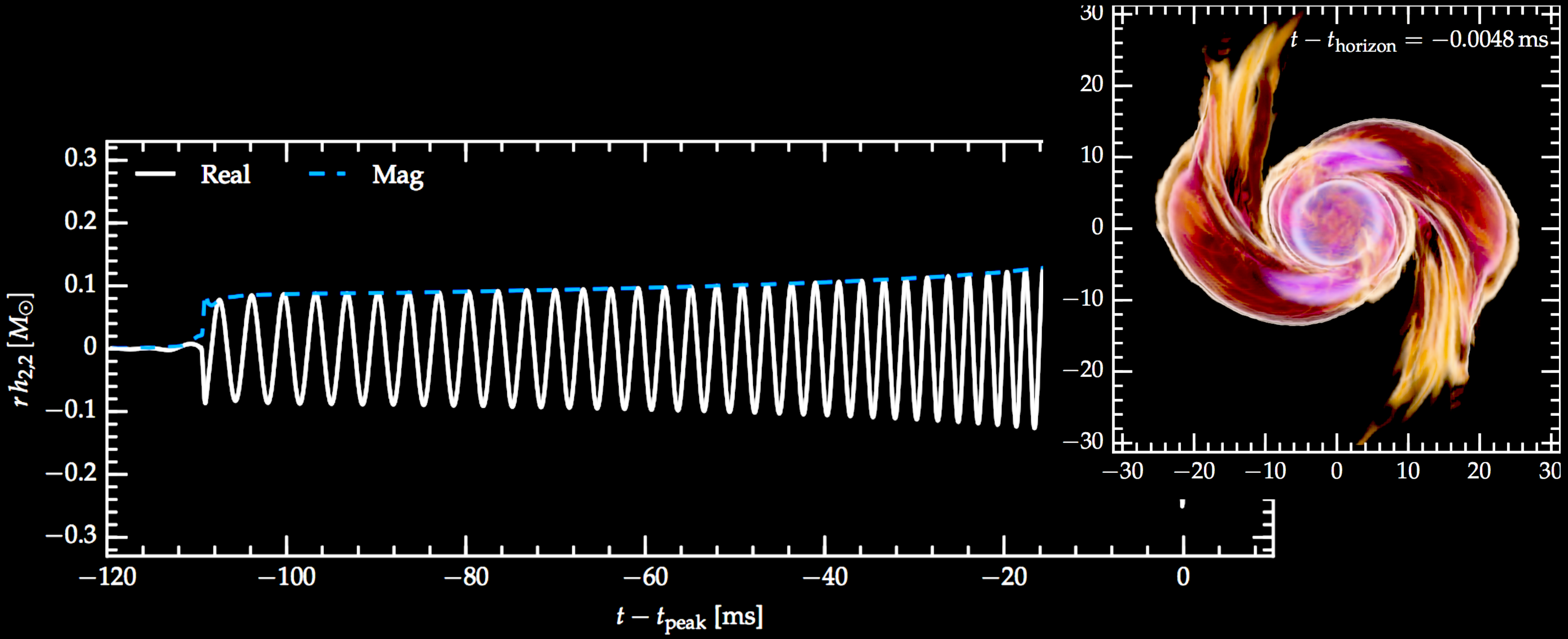
"Stiff" EOS, large radius



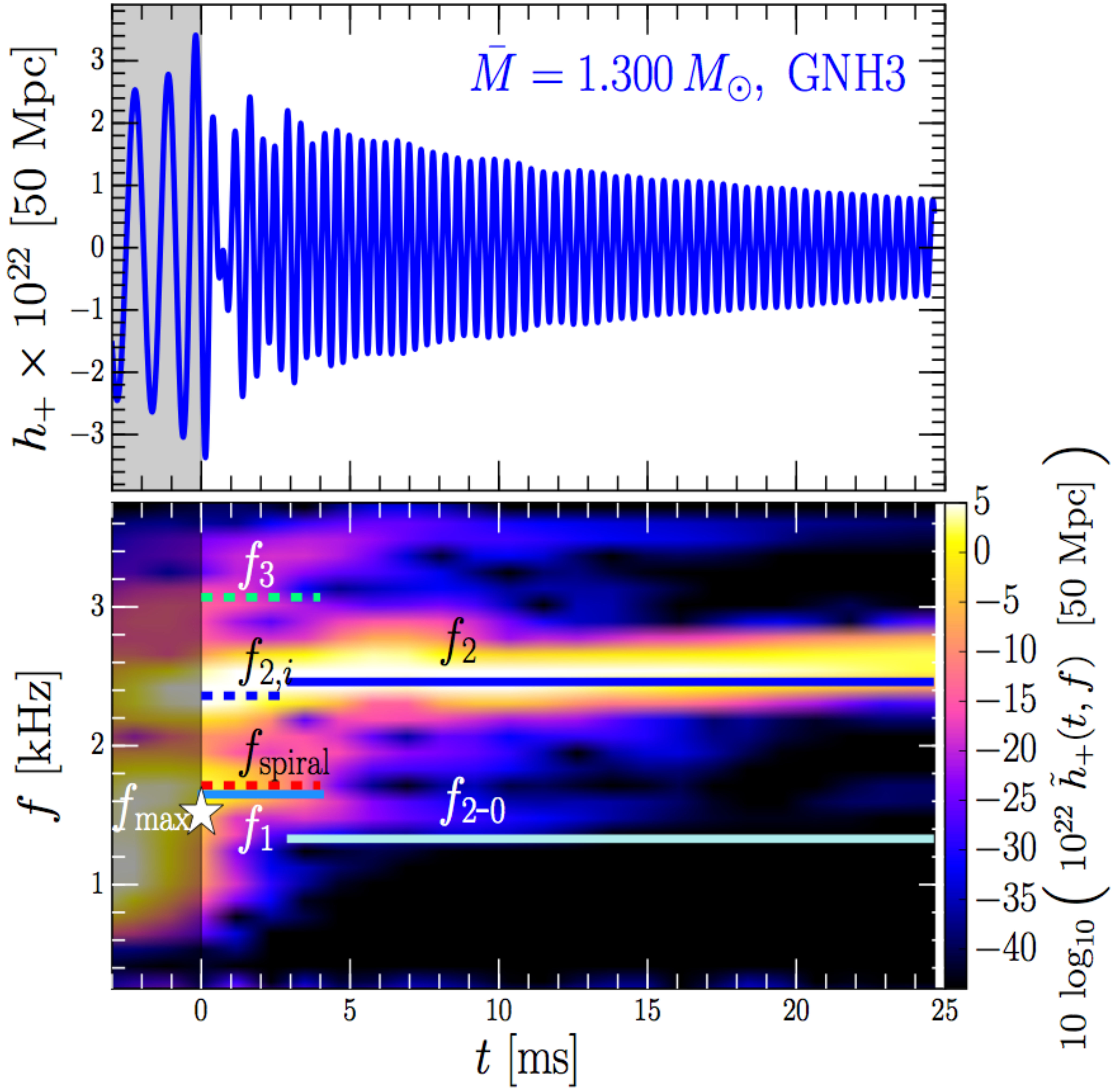
Ozel and Freire (2016)



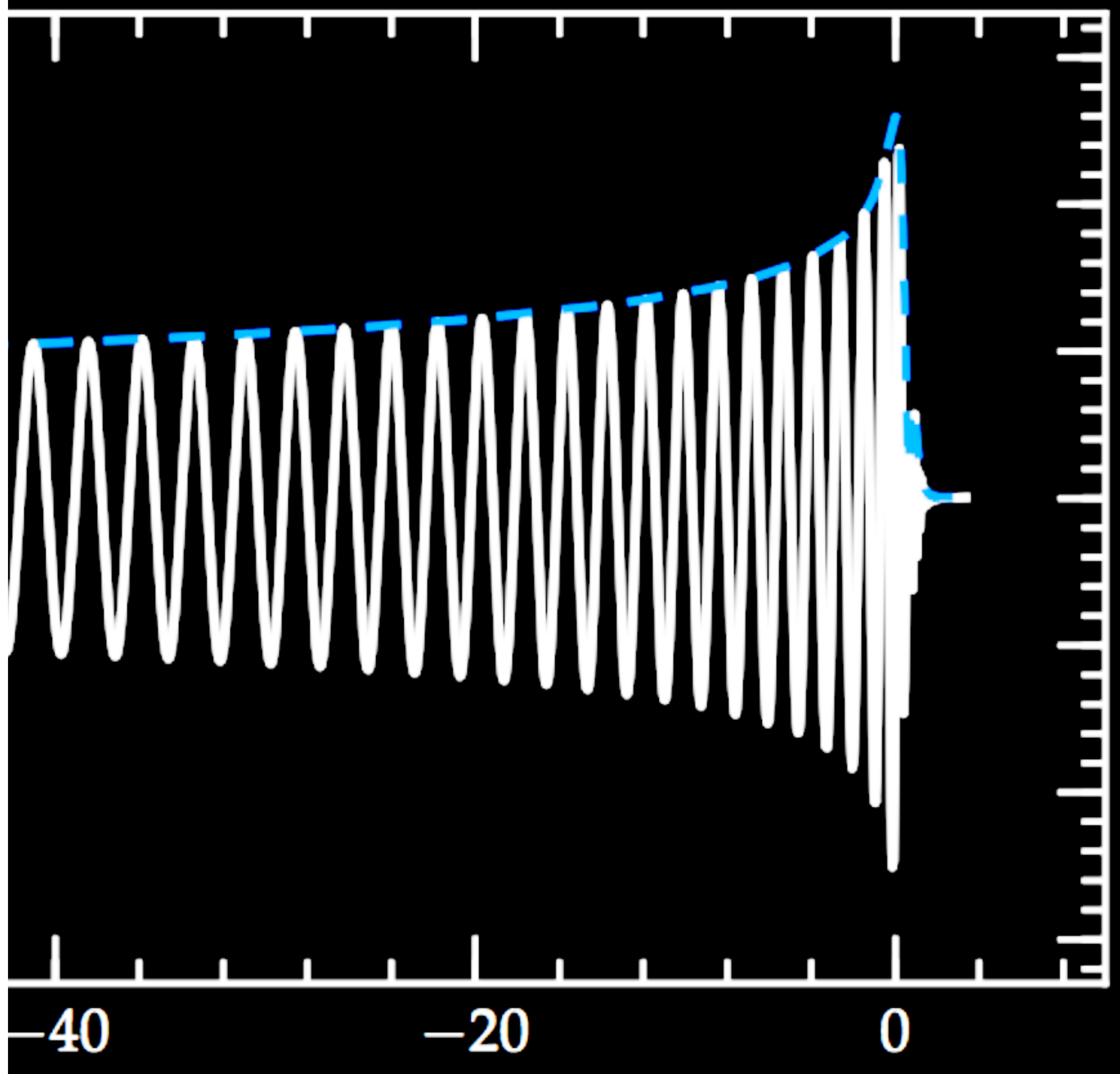
Haas et al. PRD **93**, 124062 (2016)



Haas et al. PRD **93**, 124062 (2016)



Rezzola and Takami Phys. Rev. D **93**, 124051 (2016)



Not detectable for GW170817
Abbott et al. ApJL **851** 16 (2017)

Haas et al. PRD **93**, 124062 (2016)

The information about the EOS is encoded in the gravitational-wave phase evolution

$$\Phi_{\mathrm{GW}}(t) = 0\mathrm{pN}(t; \mathcal{M}) \left[1 + 1\mathrm{pN}(t; \eta) + \cdots + 3.5\mathrm{pN}(t; \eta) + 5\mathrm{pN}(t; \mathrm{EOS})\right]$$

$$\mathcal{M} = \frac{(m_1 m_2)^{3/5}}{(m_1 + m_2)^{1/5}} \qquad \eta = \frac{(m_1 m_2)}{(m_1 + m_2)^2}$$

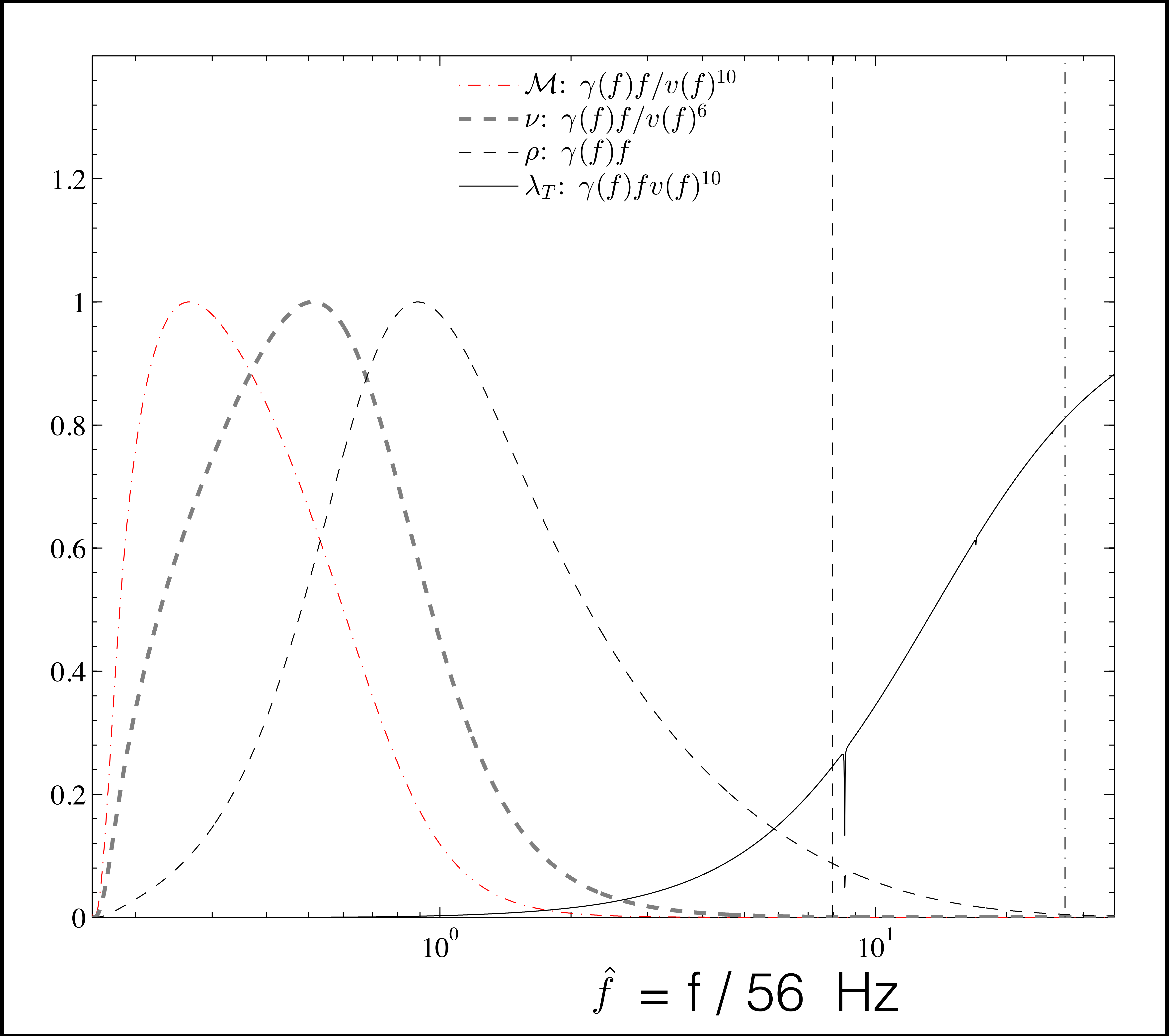
Tidal effects enter the post-Newtonian gravitational-wave phase as

$$\lambda \equiv -\frac{Q_{ij}}{\mathcal{E}_{ij}} \qquad \Lambda \equiv \frac{\lambda}{m^5} = \frac{2}{3} k_2 \left(\frac{Gm}{Rc^2} \right)^{-5}$$

$$\tilde{\Lambda} = \frac{16}{13} \frac{(12q+1)\Lambda_1 + (12+q)q^4 \Lambda_2}{(1+q)^5}$$

$$q = m_2/m_1 \leq 1$$

Flanagan and Hinderer PRD **77** 021502 (2008)



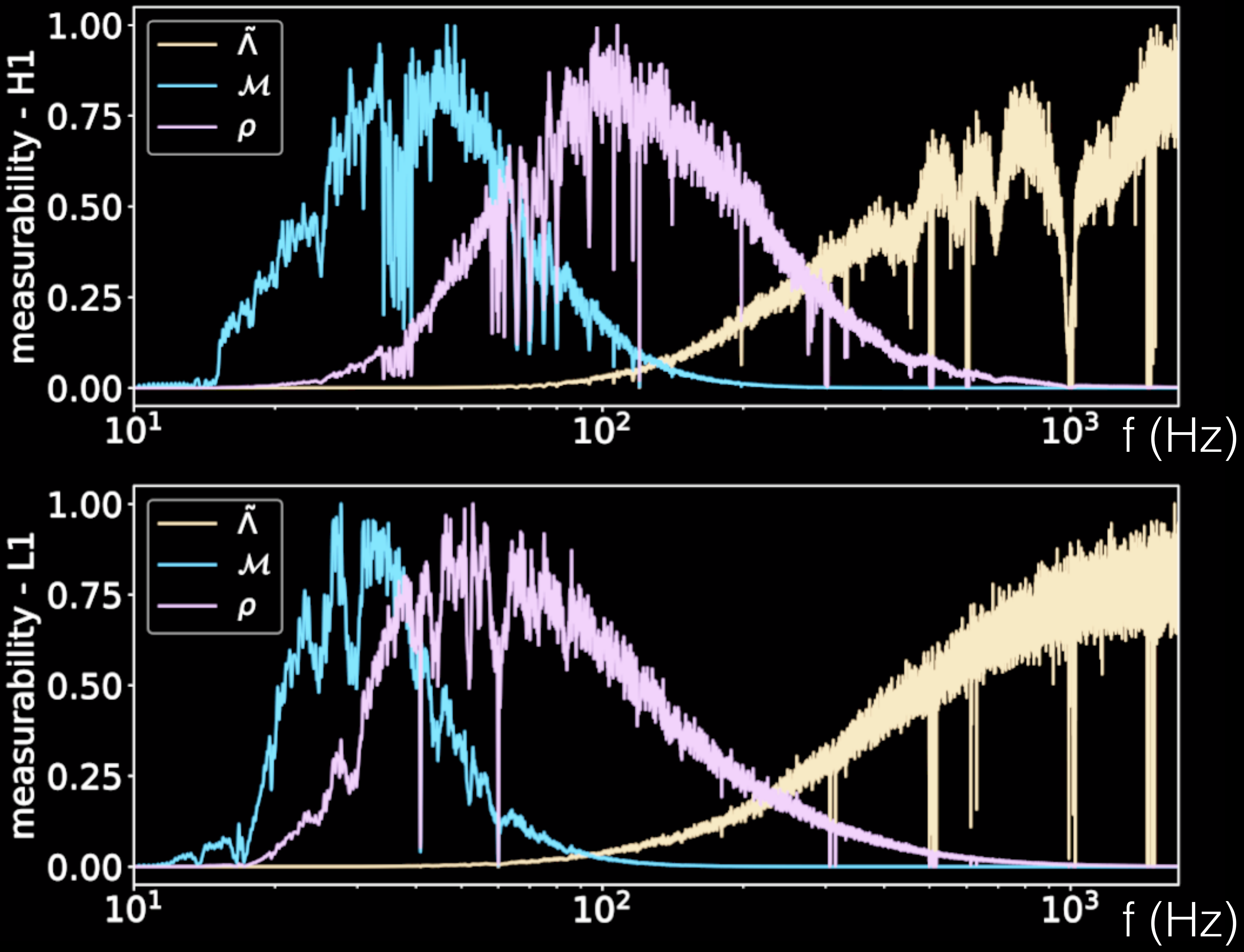
$$\gamma(f)\, df \equiv \frac{df\, f^{-7/3}/S_n(f)}{\int df\, f^{-7/3}/S_n(f)}$$

Information about chirp mass and mass ratio come from lower frequencies

Tidal information comes from late inspiral signal

Tidal information not strongly degenerate with other parameters

Damour, Nagar, Villain Phys. Rev. D **85**, 123007 (2012)



De, Finstad, Lattimer, DAB, Berger, Biwer, Phys. Rev. Lett. **121**, 091102 (2018)

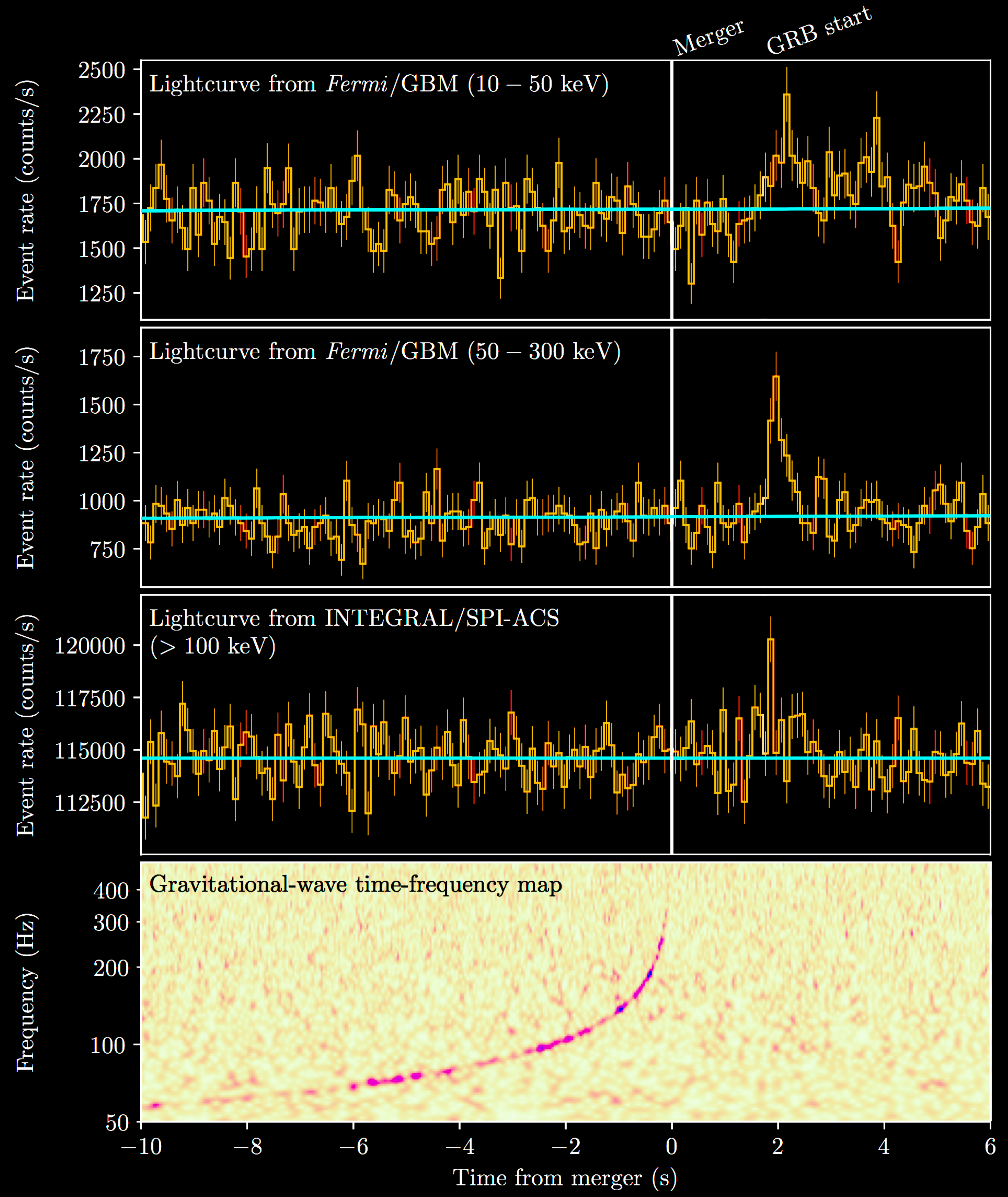
- Does the gravitational-wave signal show evidence for finite size effects?
- Use Bayesian inference to decide
- Model the waveform with and without the tidal deformability
- Compute the Bayes factor comparing these two models
- Evidence computed using MCMC and thermodynamic integration

Biwer, Capano, De, Cabero, DAB, Nitz Publ. Astron. Soc. Pac. **131** 024503 (2019)

Bayes factor comparing BNS to BBH = 0.3

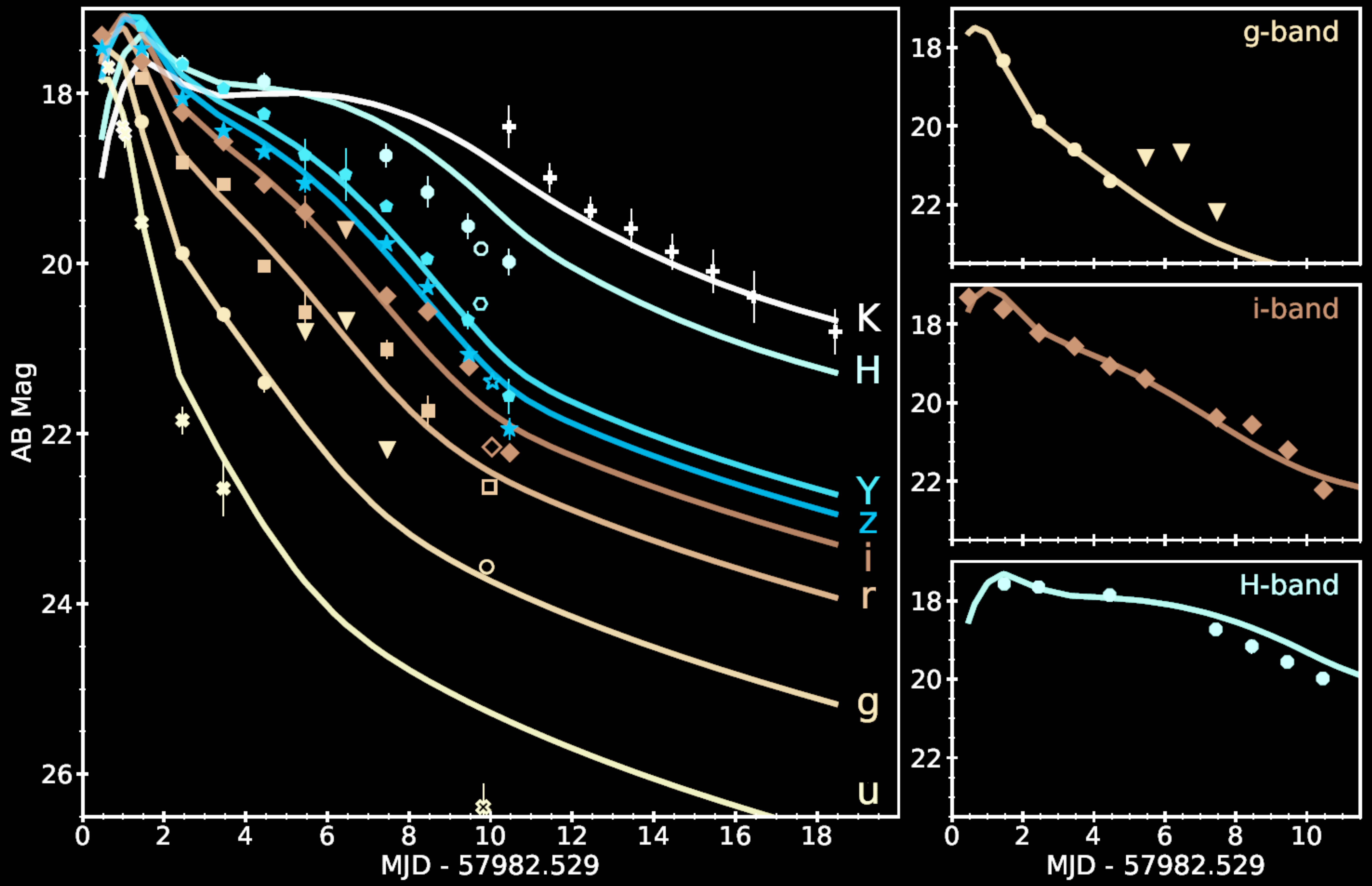
The gravitational wave data alone cannot say whether a model with tidal deformability is preferred over a binary black hole model

De, Finstad, Lattimer, DAB, Berger, Biwer, Phys. Rev. Lett. **121**, 091102 (2018)



- The probability of a chance temporal and spatial association of GW170817 and GRB170817A is 5.0×10^{-8}
- The time delay between the end of the gravitational-wave signal and the start of the gamma-ray burst is 1.74 (+/- 0.05) s

Abbott,..., DAB et al. ApJ **848** L13 (2017)



UV, optical, and near-IR spectra are well fit by a two-component kilonova

0.02 M_{sun} lanthanide-poor ejecta (blue) and 0.05 M_{sun} lanthanide rich ejecta (red)

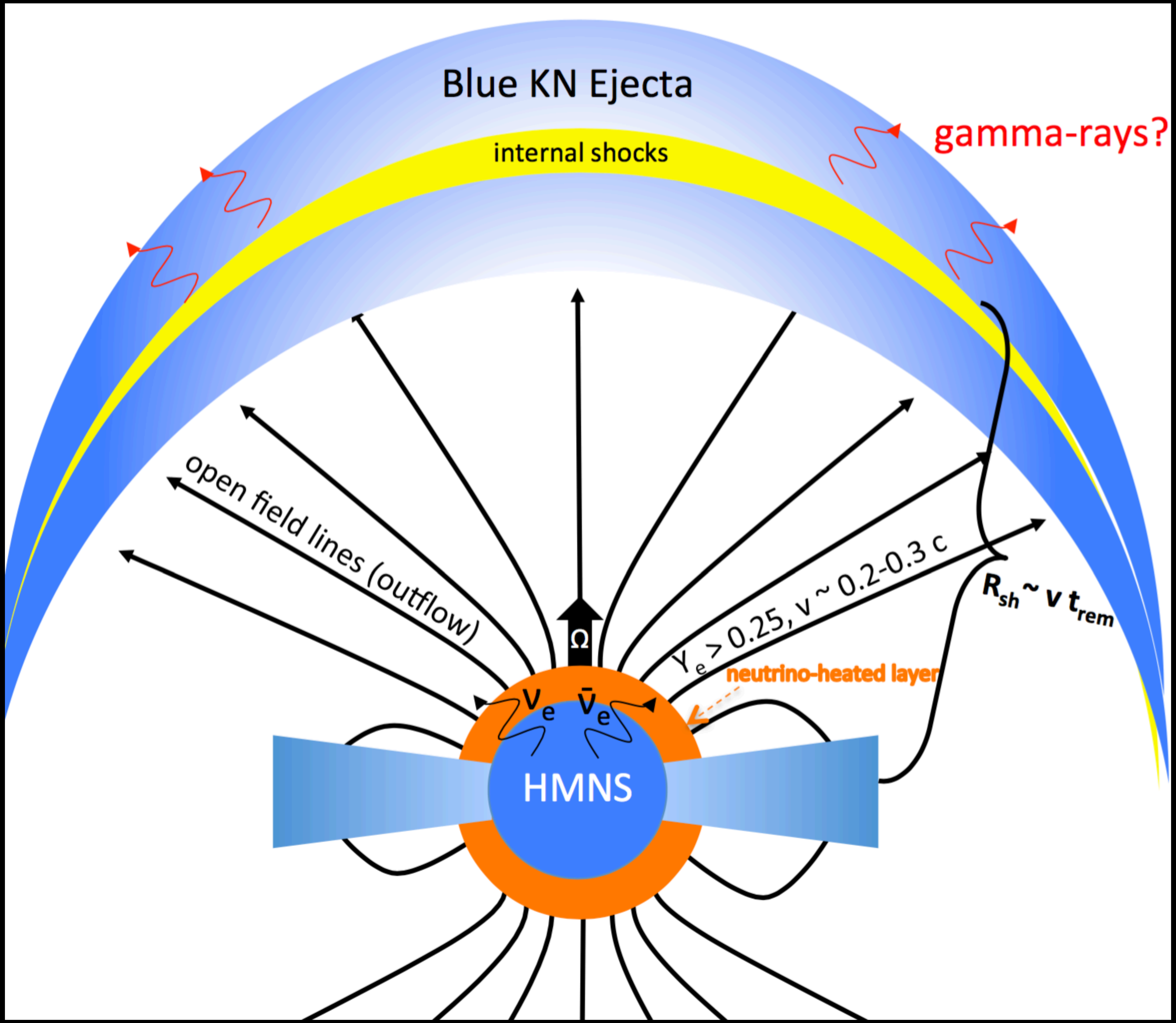
Cowperthwaite,..., DAB et al. ApJ **848** L17 (2017)

$v_{red} \sim 0.1$ c

$v_{blue} \sim 0.25$ c

Kilonova light curves suggest the existence of a hyper massive neutron star prior to collapse to a black hole

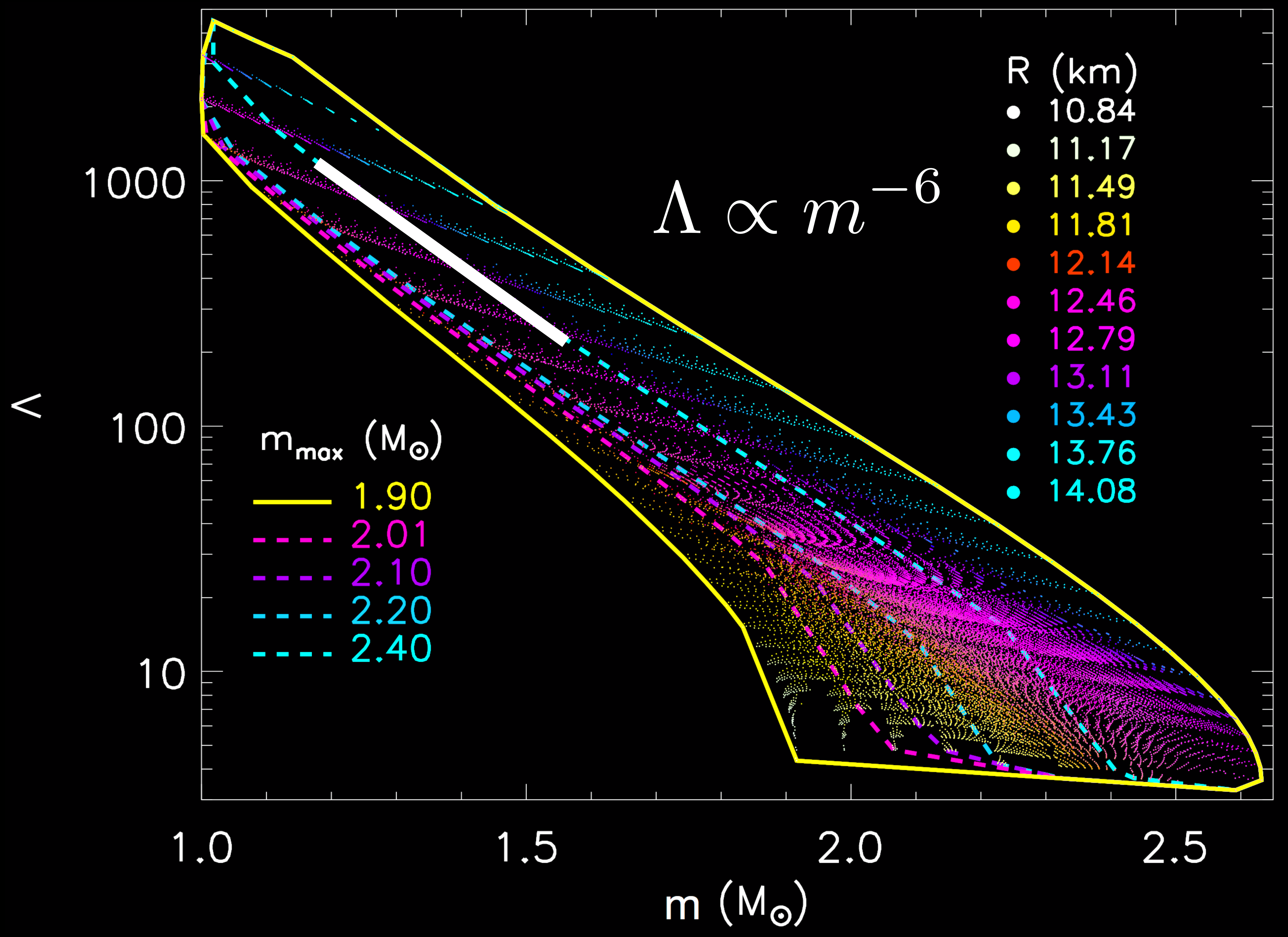
EM suggests neutron star merger



Metzger, Thompson, Quataert ApJL **856** 101 (2018)

Analyses of Gravitational-Wave Observations

- **Agnostic to neutron star's equation of state:**
  - Abbott et al. PRL **119,** 161101 (2017)
  - Abbott et al. PRX **9**, 011001 (2019)
  - Dai, Venumadhav, Zackay arXiv:1806.08793
- **Analyses with a constraint on the equation of state:**
  - De, Finstad, Lattimer, Brown, Berger, Biwer. PRL **121**, 091102 (2018)
  - Abbott et al. PRL **121**, 161101 (2018)
  - Radice and Dai. Eur. Phys. J. A **55** 50 (2019)



Results of TOV integrations for physically realistic polytopes

$$\Lambda = \alpha \left(\frac{Gm}{Rc^2} \right)^{-6}$$

De, Finstad, Lattimer, DAB, Berger, Biwer, Phys. Rev. Lett. **121**, 091102 (2018)

- For nearly every specific EOS in the mass range relevant to GW170817 [1.1,1.6] solar masses, range of radii is very small

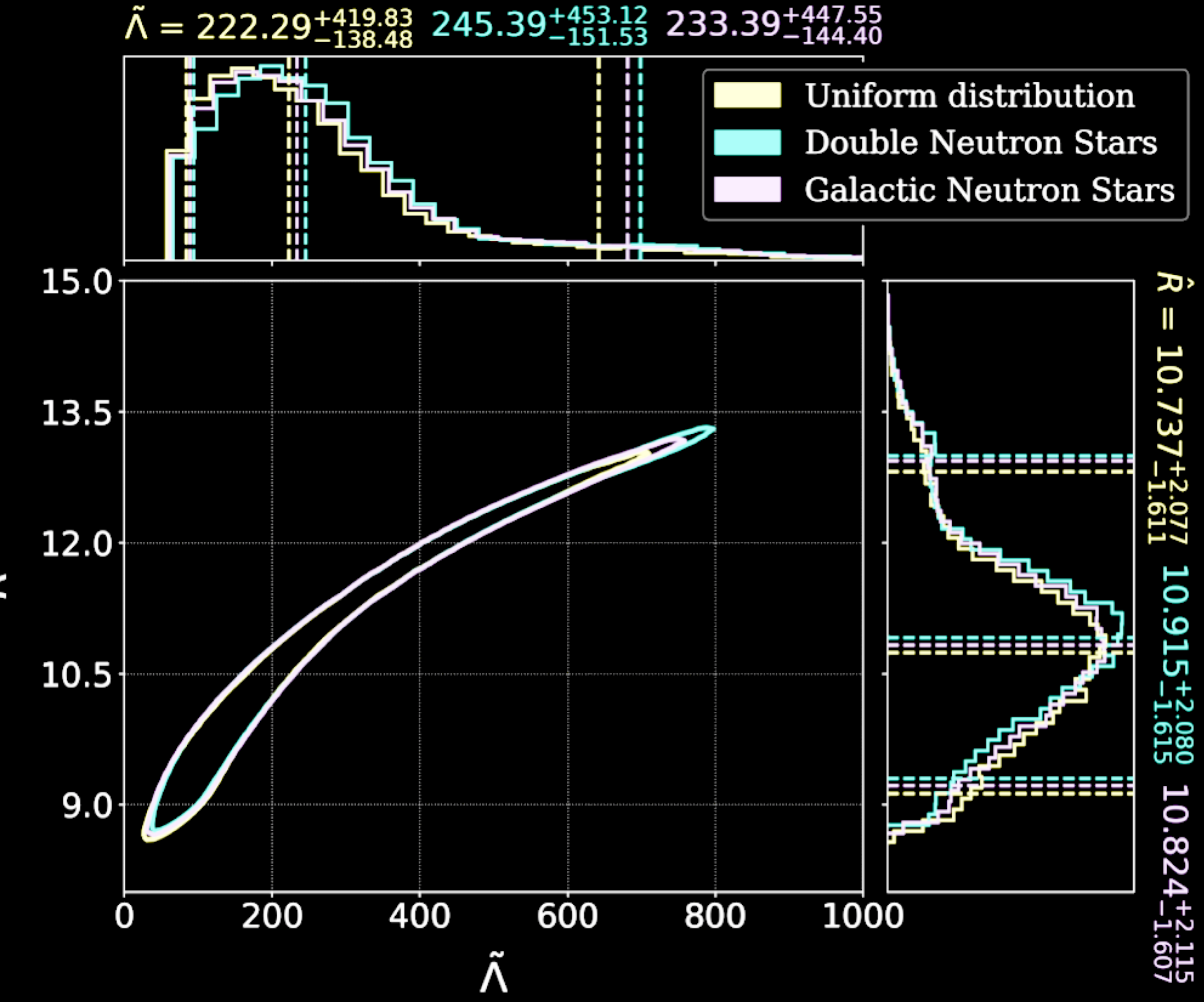
$$\langle \Delta R \rangle \equiv \langle R_{1.6} - R_{1.1} \rangle = -0.070 \text{ km}$$

$$\sqrt{\langle \Delta R \rangle^2} = 0.11 \text{ km}$$

- Common EOS constraint $\hat{R} \equiv R_1 \approx R_2$ $\Lambda_1 = q^6 \Lambda_2$

De, Finstad, Lattimer, DAB, Berger, Biwer, Phys. Rev. Lett. **121**, 091102 (2018)

- Explore three different mass priors:
  - Uniform [1,2] solar masses
  - Double neutron star masses from radio observations
  - All neutron star masses from radio observations
- Measure binary tidal deformability and compute radius



$$\langle \hat{R} \rangle = 10.8 \text{ km}$$

$$8.9 \leq \hat{R} \leq 13.2 \text{ km}$$

Soumi De

De, Finstad, Lattimer, DAB, Berger, Biwer, Phys. Rev. Lett. **121**, 091102 (2018)

Use EOS insensitive relations

$$\hat{\Lambda}_s = (\Lambda_1 + \Lambda_2)/2$$

$$\hat{\Lambda}_a = (\Lambda_1 - \Lambda_2)/2$$

Use MCMC to measure $\hat{\Lambda}_s$

$$\hat{\Lambda}_a(\hat{\Lambda}_s, q)$$

Analytical expression for an optimum fit using realistic EOSs, for physically reasonable mass

Yagi and Yunes (2016)

$$\Lambda_1, \Lambda_2$$

$$\Lambda(C)$$

Maselli et al. (2013)
Urbanec et al. (2013)

$$R_1, R_2$$

Abbott et al. PRL 121, 161101 (2018)

Use spectral parameterization of EOS

$$\Gamma(p;\gamma_i)$$

$$\gamma_i = \gamma_0, \gamma_1, \gamma_2, \gamma_4$$

Lindblom (2010)
Lindblom and Indik (2012+)

Use MCMC to measure

$$(\gamma_0, \gamma_1, \gamma_2, \gamma_4)$$

Integrate TOV equations using measured

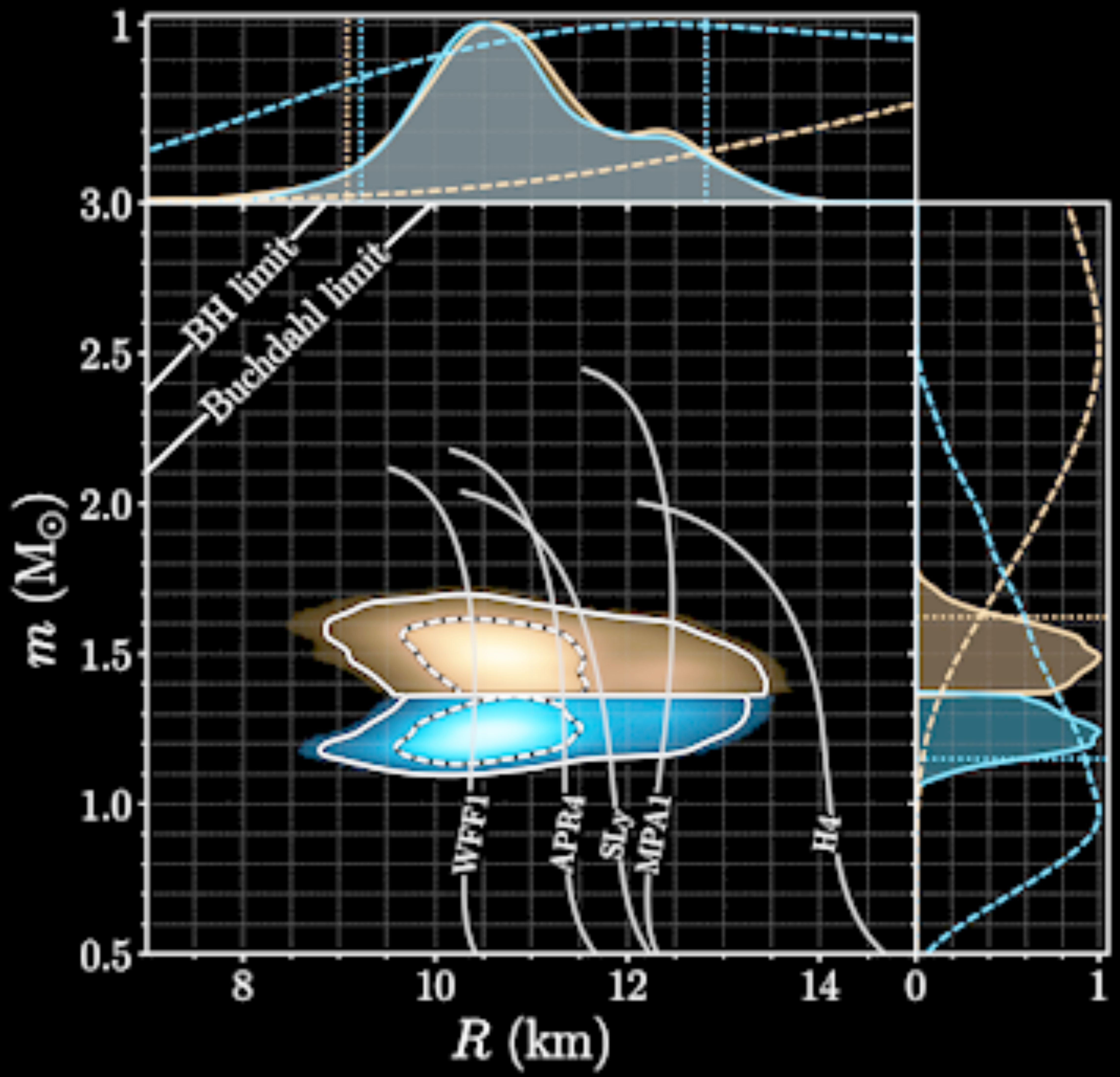
$$m_1, m_2$$

$$R_1, R_2$$

Abbott et al. PRL 121, 161101 (2018)

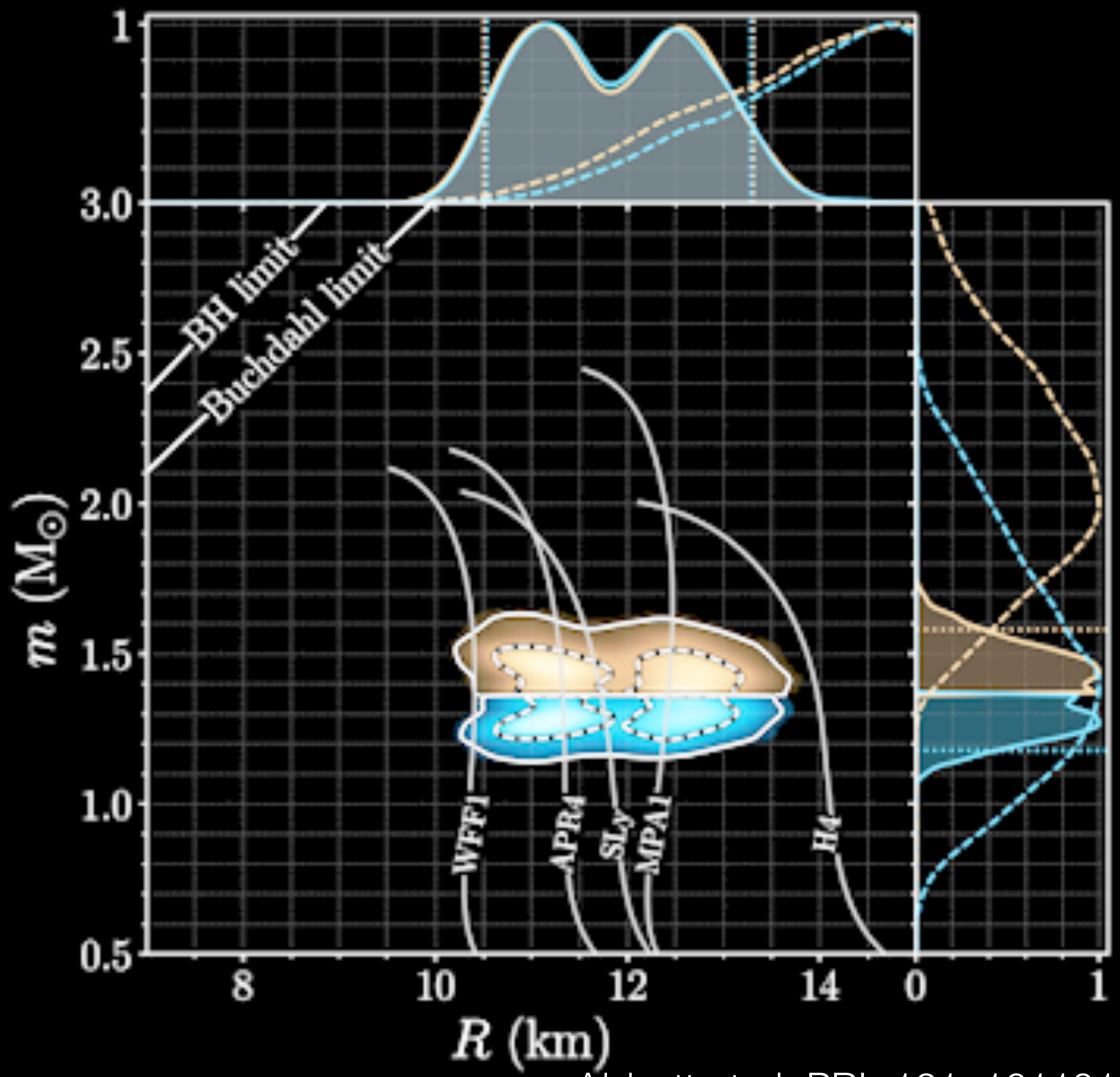
EOS Insensitive Relations

$$(R_1, R_2) = (10.8^{+2.0}_{-1.7}, 10.7^{+2.1}_{-1.5})$$

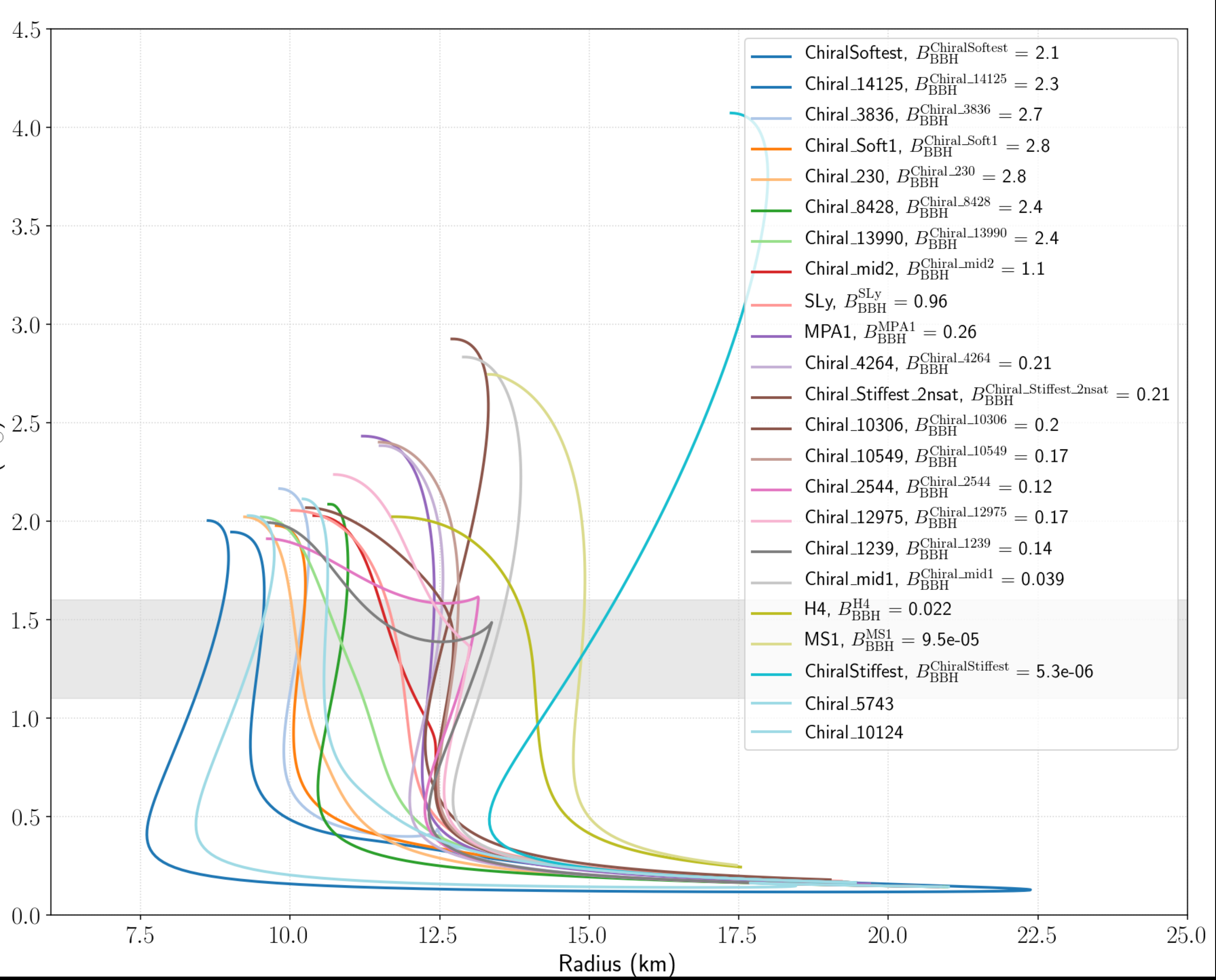


Parameterized EOS

$$(R_1, R_2) = (11.9^{+1.4}_{-1.4}, 11.9^{+1.4}_{-1.4})$$



Abbott et al. PRL 121, 161101 (2018)



Calculate Bayes factor for specific EOS vs BBH

Stiffest EOS ruled out at high confidence

Soft EOSes are all consistent with GW170817

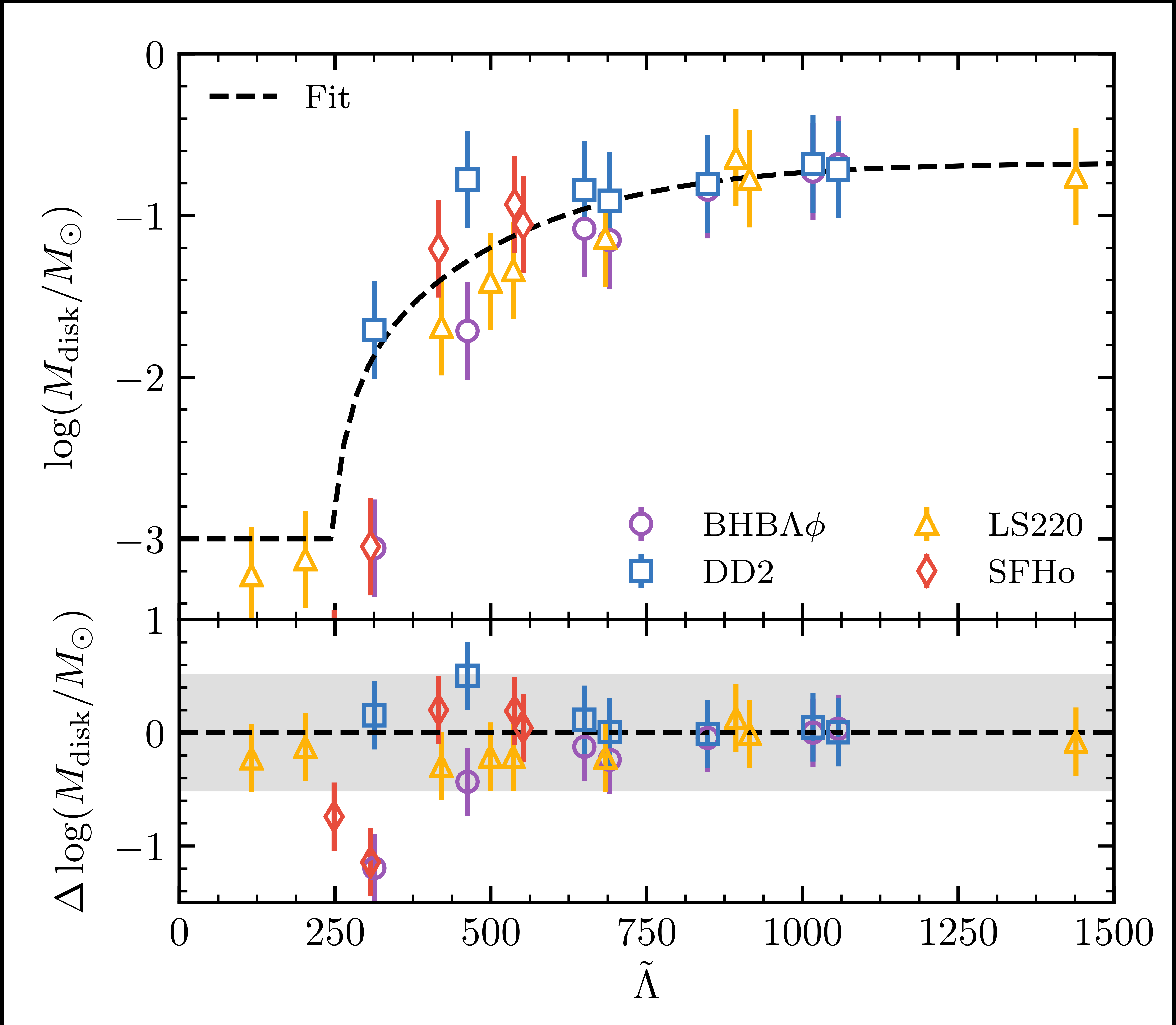
c.f. Abbott et al. arXiv:1908.01012

Tews, Capano, Brown, De, Margalit, Kumar, DAB, Krishnan, Reddy

Current best constraints on the soft end of the EOS space come from EM

Soft EOS undergo prompt collapse to black hole

Use numerical simulations of binary neutron stars to construct a relation between the tidal deformability and remnant disk mass



Radice and Dai. Eur. Phys. J. A **55** 50 (2019)

Use both GW and EM information

$$P[\{d_{\mathrm{GW}}, d_{\mathrm{EM}}\}|\theta] = P[d_{\mathrm{GW}}|\theta]\, P[d_{\mathrm{EM}}|\theta]$$

GW uses common radius constraint of De et al.

↓

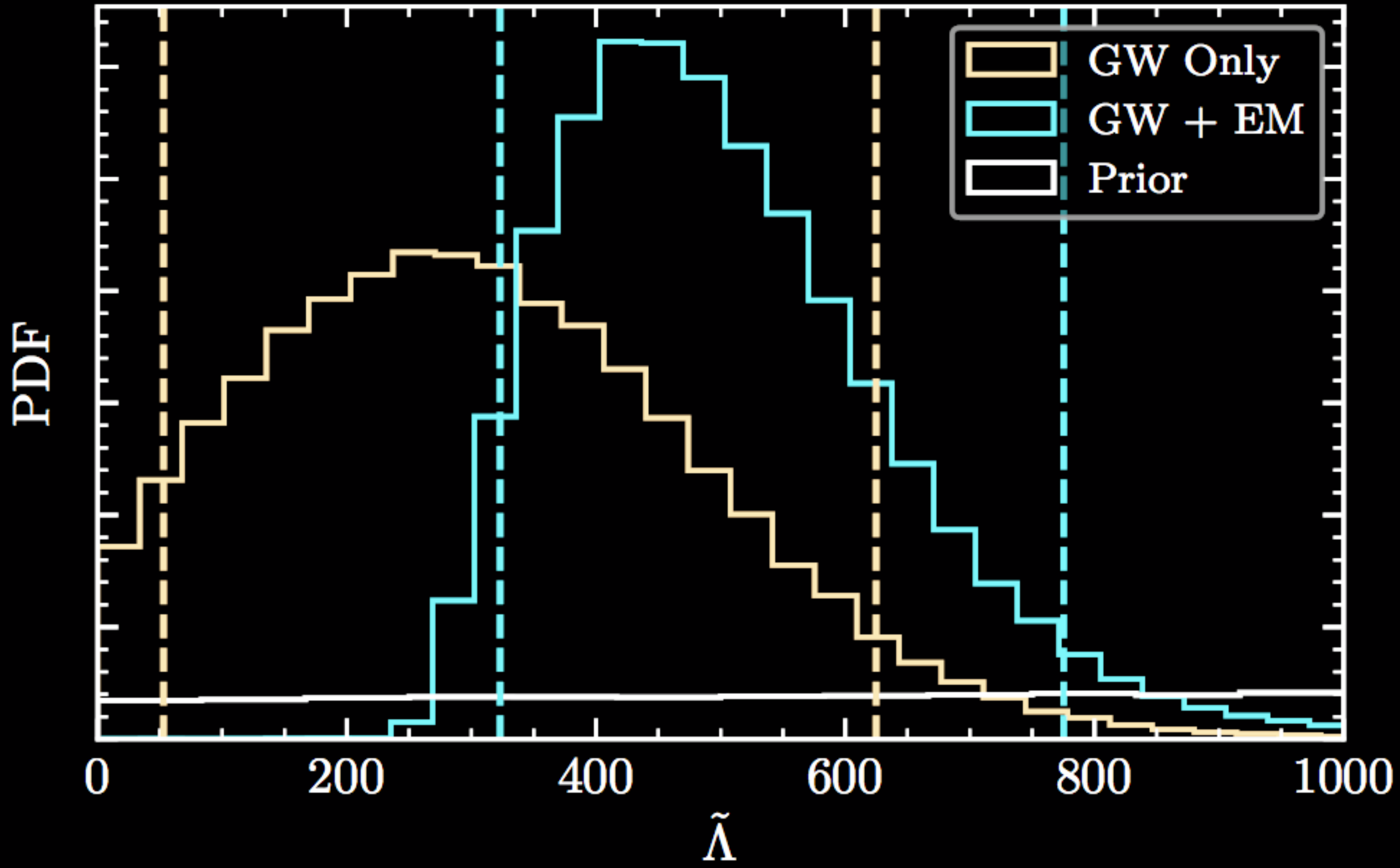
$$P[d_{\mathrm{EM}}|\theta] \simeq P[M_{\mathrm{disk}}(\theta) > 0.04\, M_\odot]$$

↓

$$P[M_{\mathrm{disk}} > 0.04\, M_\odot] = 1 - \frac{1}{2}\left[1 + \mathrm{erf}\left(\frac{\log(0.04) - \Phi(\tilde{\Lambda})}{\sqrt{2}\sigma}\right)\right]$$

Fit to numerical relativity simulations

Radice and Dai. Eur. Phys. J. A **55** 50 (2019)



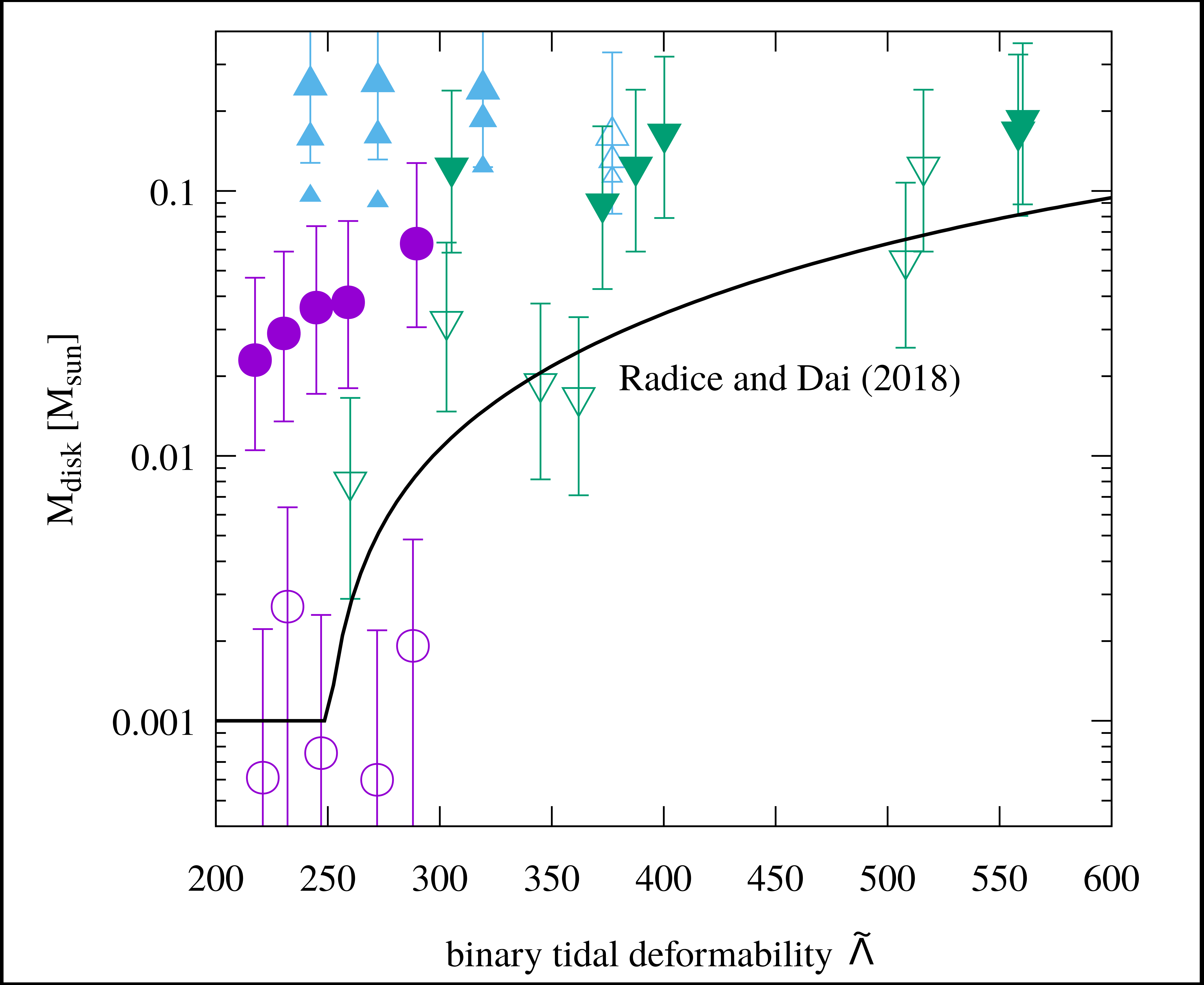
$$R_{1.4} = 12.2^{+1.0}_{-0.8} \pm 0.2 \text{ km}$$

Radice and Dai. Eur. Phys. J. A **55** 50 (2019)

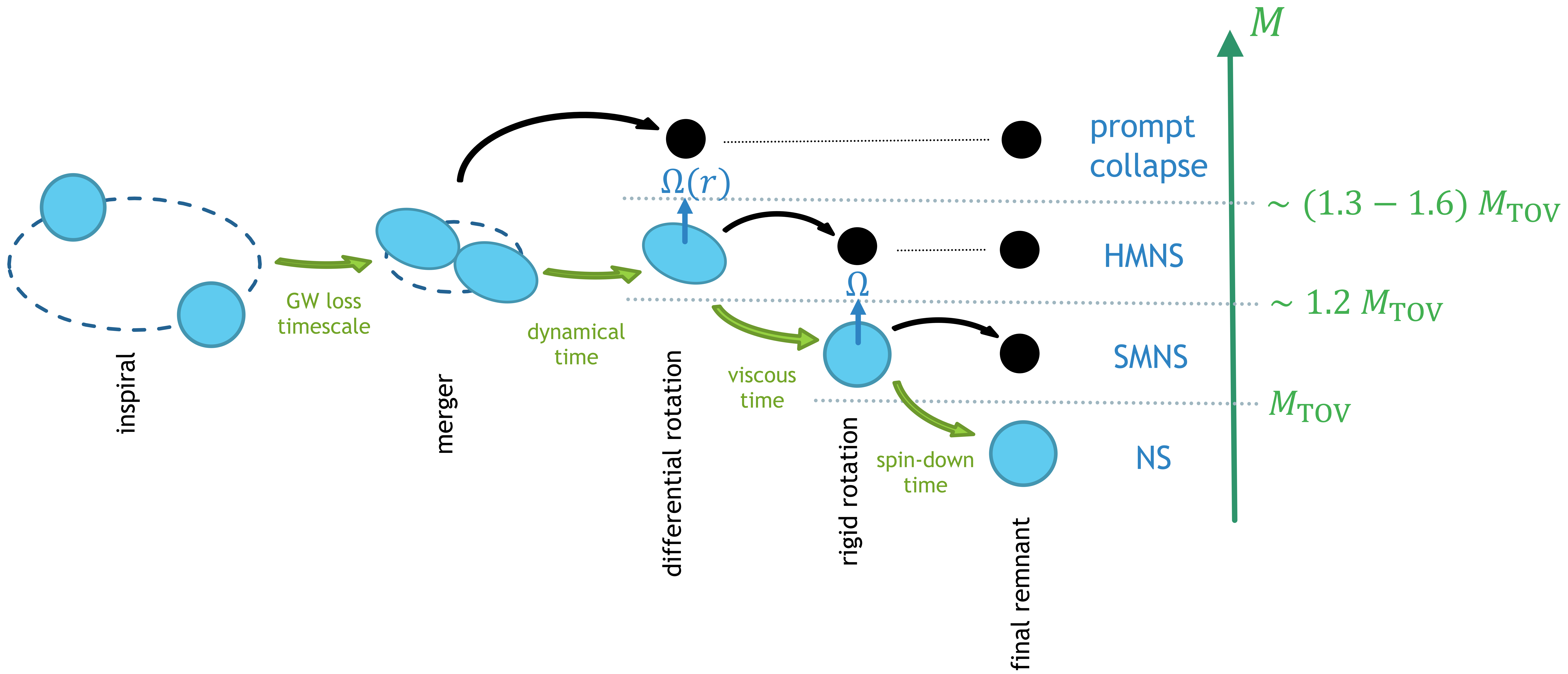
Radice assumed equal mass binary in simulations

GW posteriors include more unequal mass ratios

Kiuchi et al. can produce disk mass with softer EOS for higher mass ratios



Kiuchi et al Astrophys. J. 876, **L31** (2019)



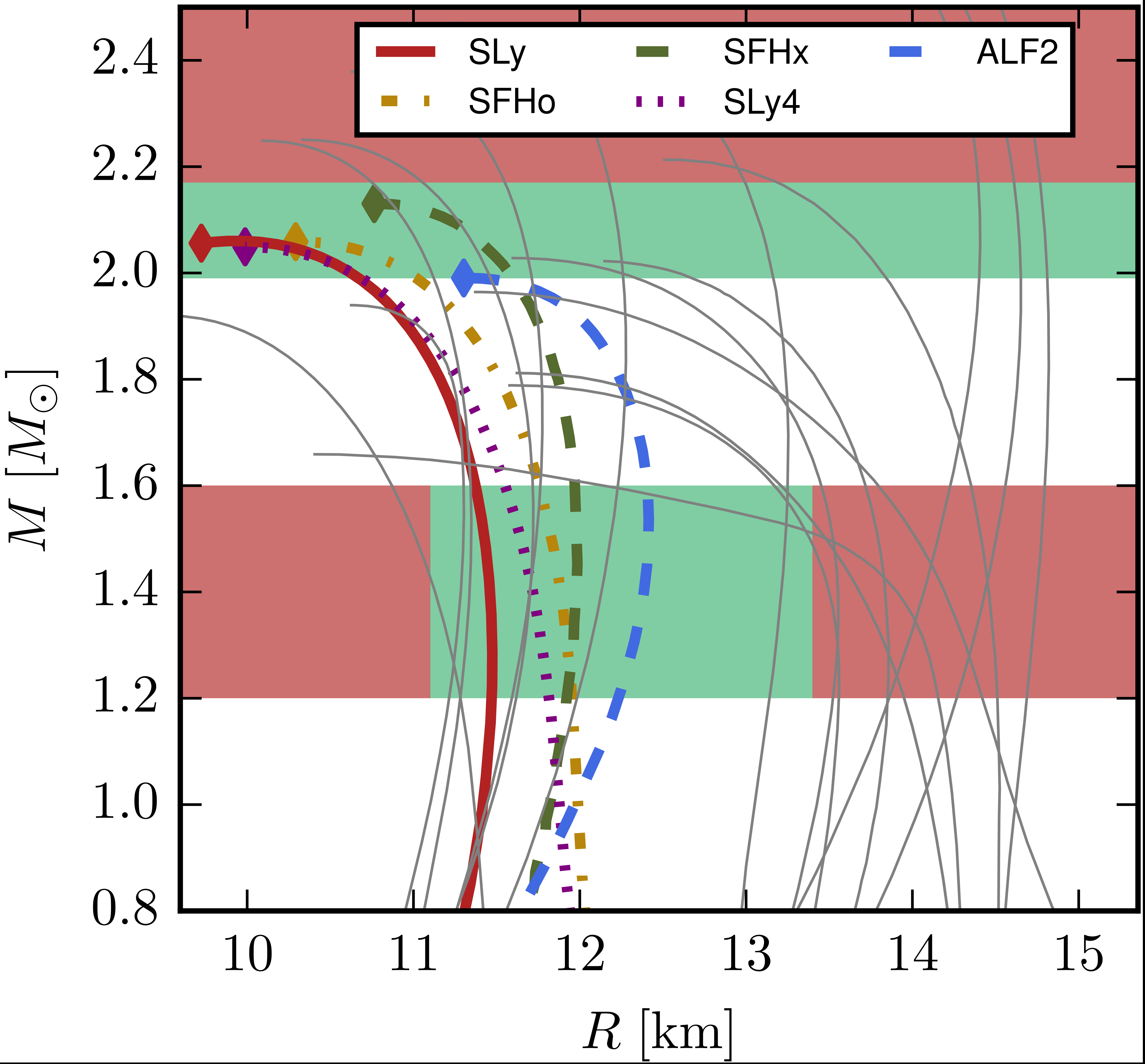
Ben Margalit

The merger remnant also places a constraint on the maximum neutron star mass

The remnant NS cannot be long lived, or there would be too much energy in the EM observantion

$$M_{\rm max} \leq 2.17 M_\odot \ (90\%)$$

Margalit and Metzger ApJL 850 19 (2018)



Coughlin, Dietrich, Margalit, Metzger arXiv:1812:04803

- Construct physically plausible EOS using Chiral Effective Field Theory calibrated against nuclear experiments

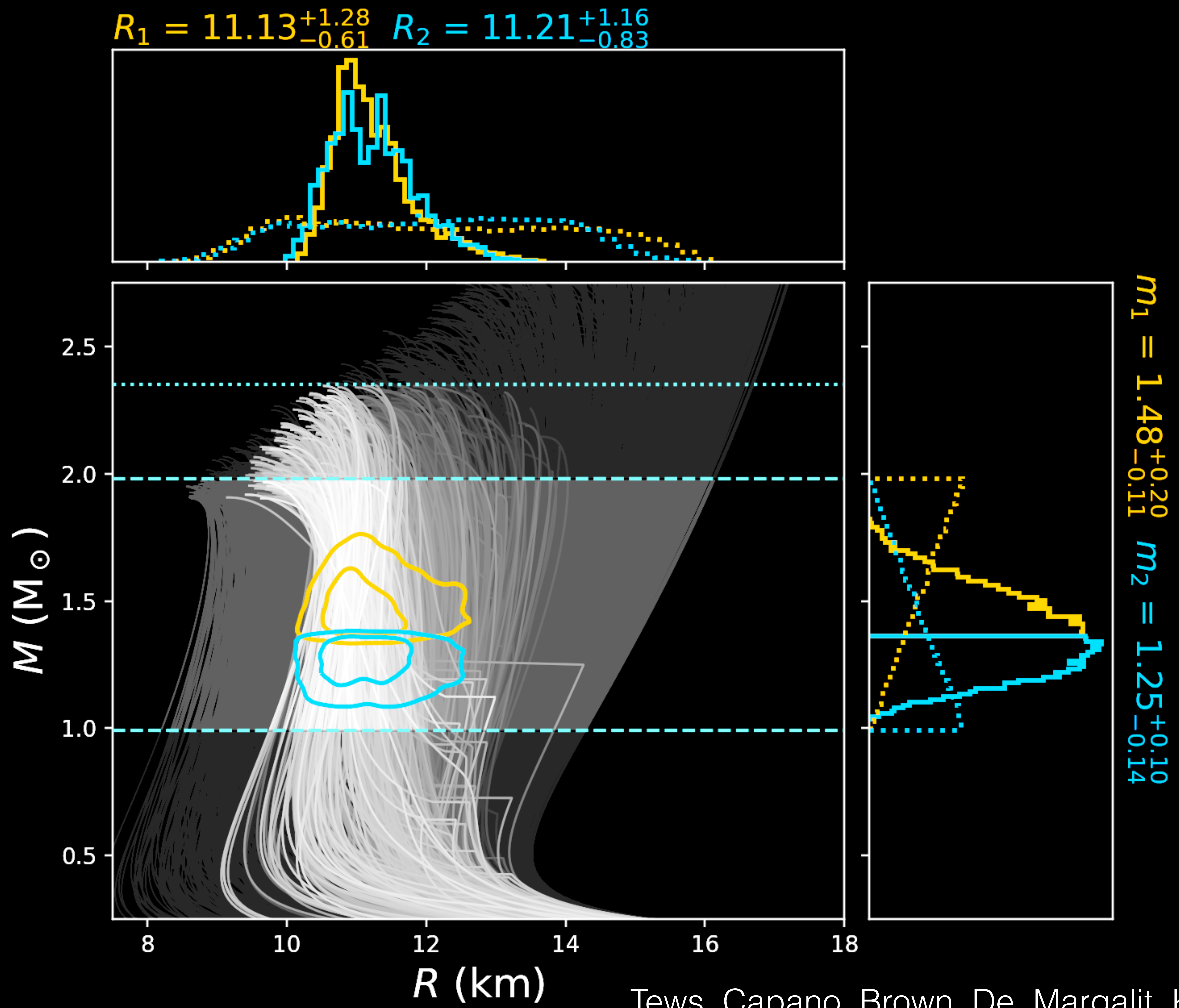
- Directly marginalize over EOS using GW observations

- Apply constraint that the merger remnant did not immediately collapse to black hole from Bauswin et al. PRL **111**,131101 (2013)

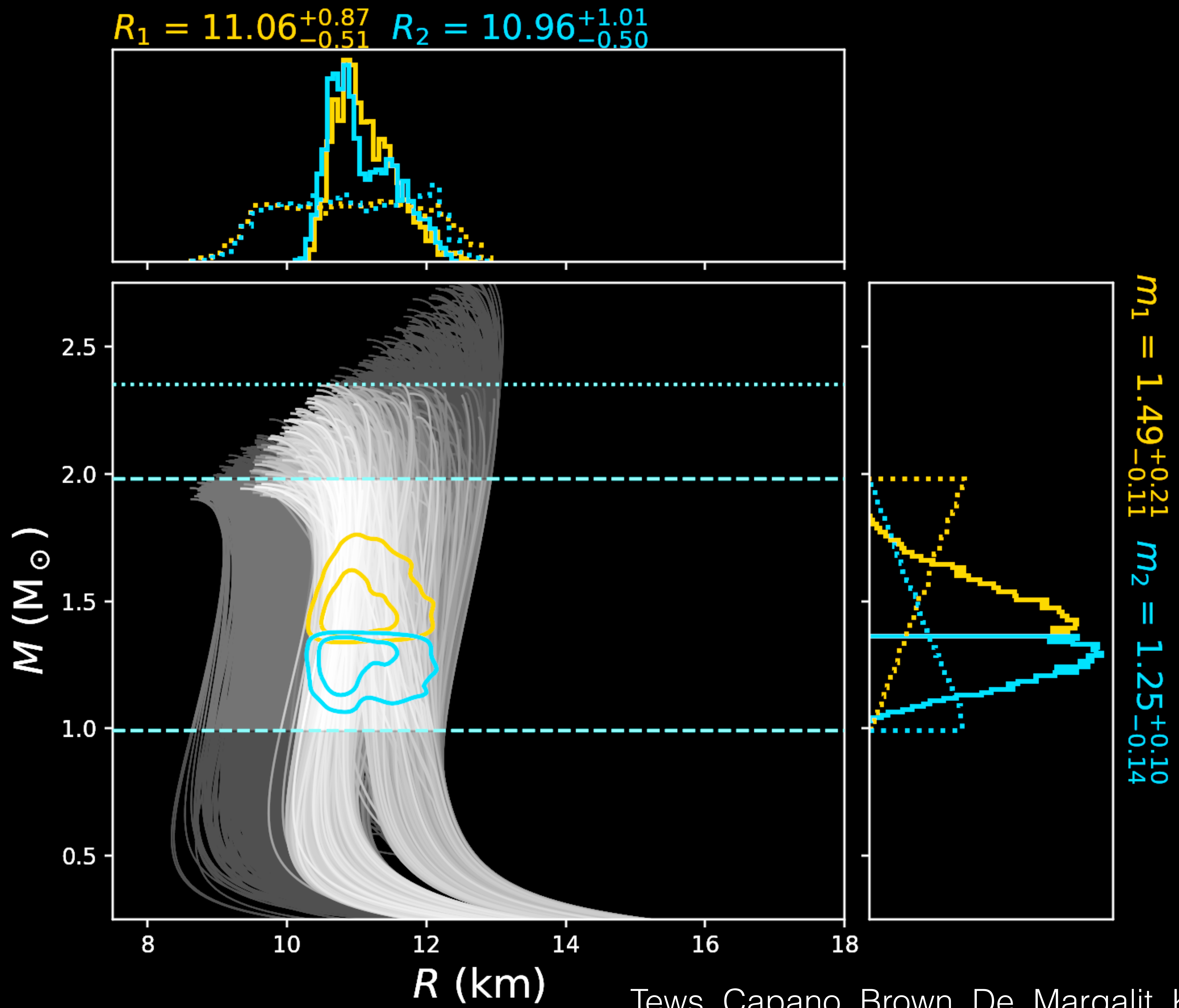
- Apply constraints on maximum neutron star mass from Rezzolla et al. ApJ Lett. **852**, L25 (2018)

Lynn et al. arXiv:1901.04868, Machleidt and Entem, Phys. Rept. **503** 1 (2011)

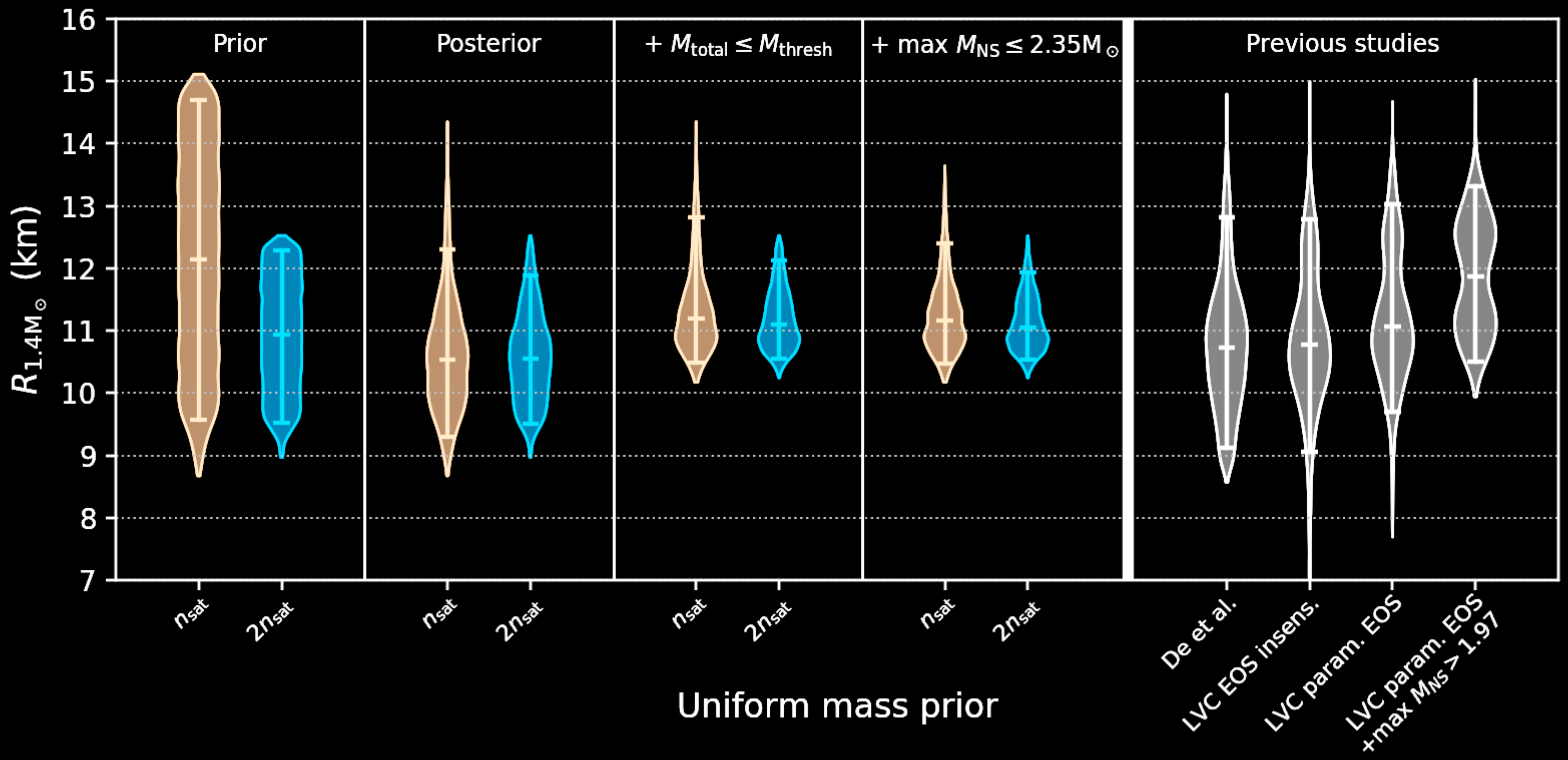
Tews, Capano, Brown, De, Margalit, Kumar, DAB, Krishnan, Reddy



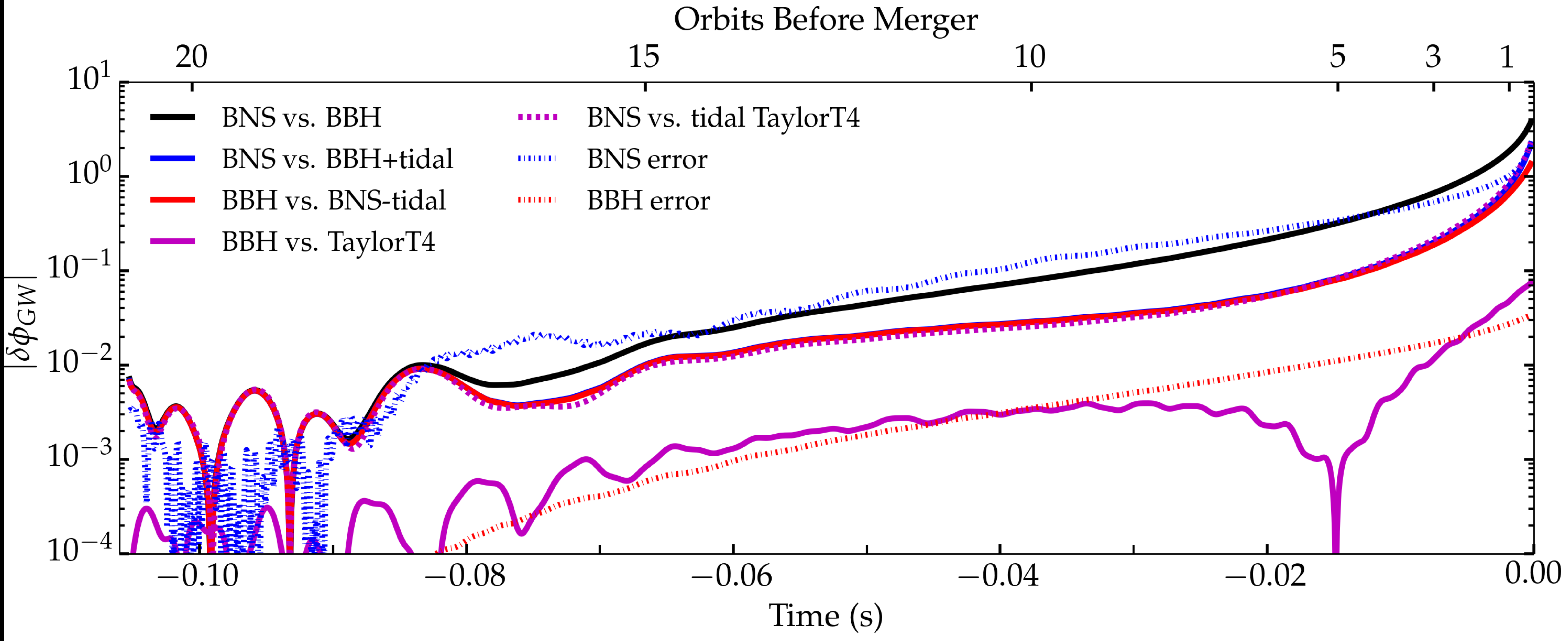
Tews, Capano, Brown, De, Margalit, Kumar, DAB, Krishnan, Reddy



Tews, Capano, Brown, De, Margalit, Kumar, DAB, Krishnan, Reddy

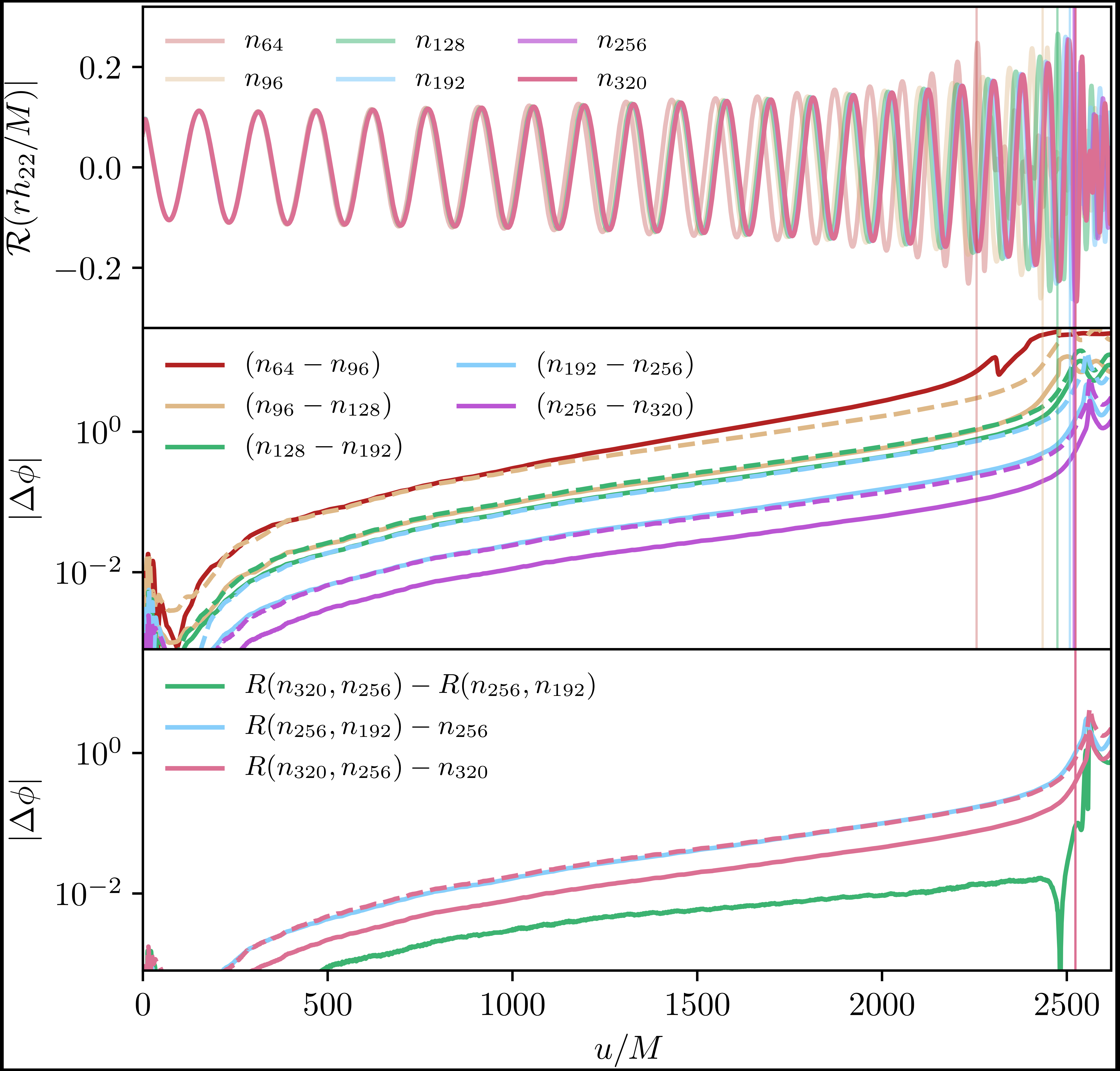


Tews, Capano, Brown, De, Margalit, Kumar, DAB, Krishnan, Reddy

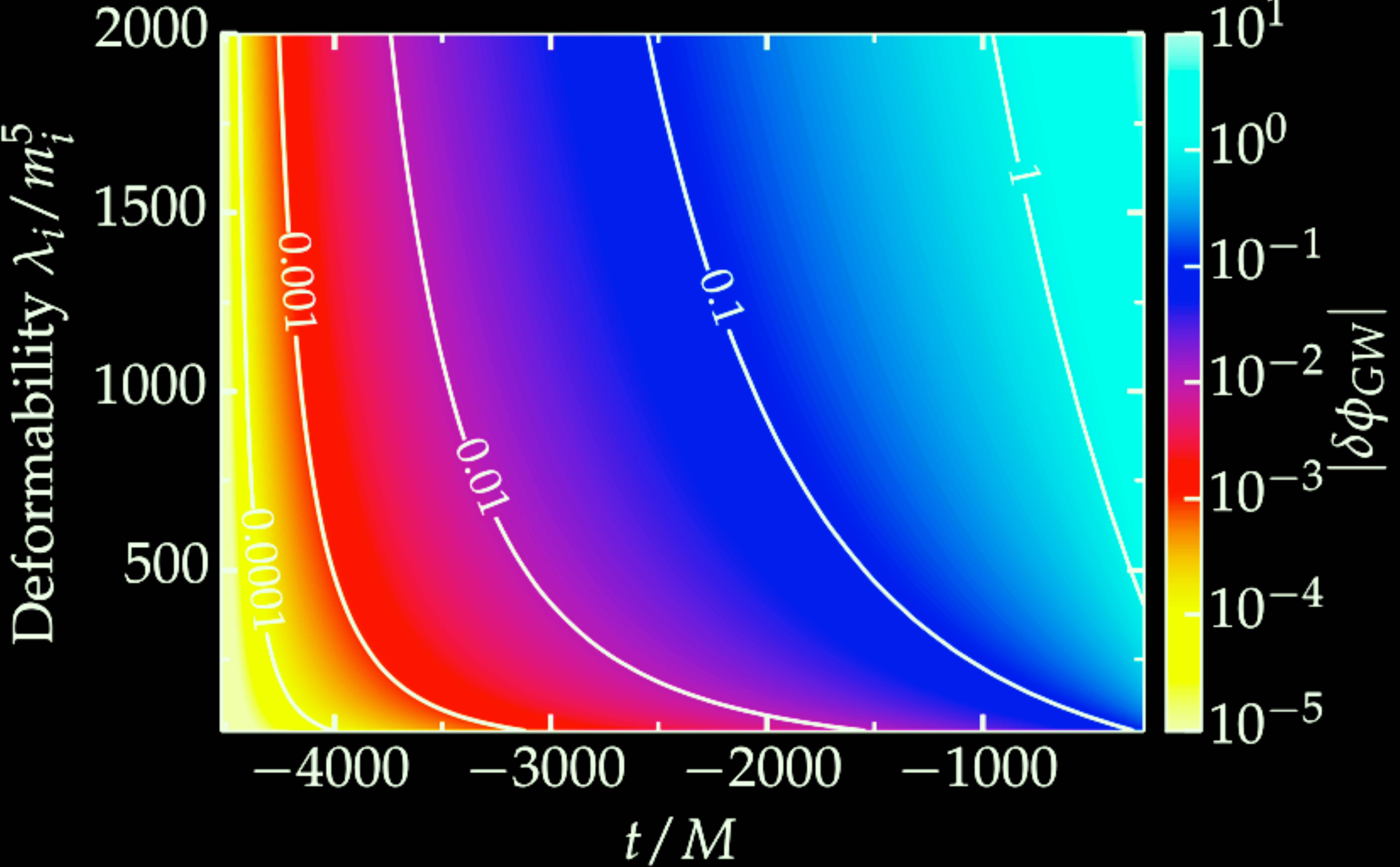


The difference between the point particle/BH and BNS waveform is comparable to the error in the BNS simulation

Barkett, Scheel, Haas, Ott, Bernuzzi, DAB, et al., Phys. Rev. D 93 044064 (2016)



Dietrich et al. arXiv:1905.06011



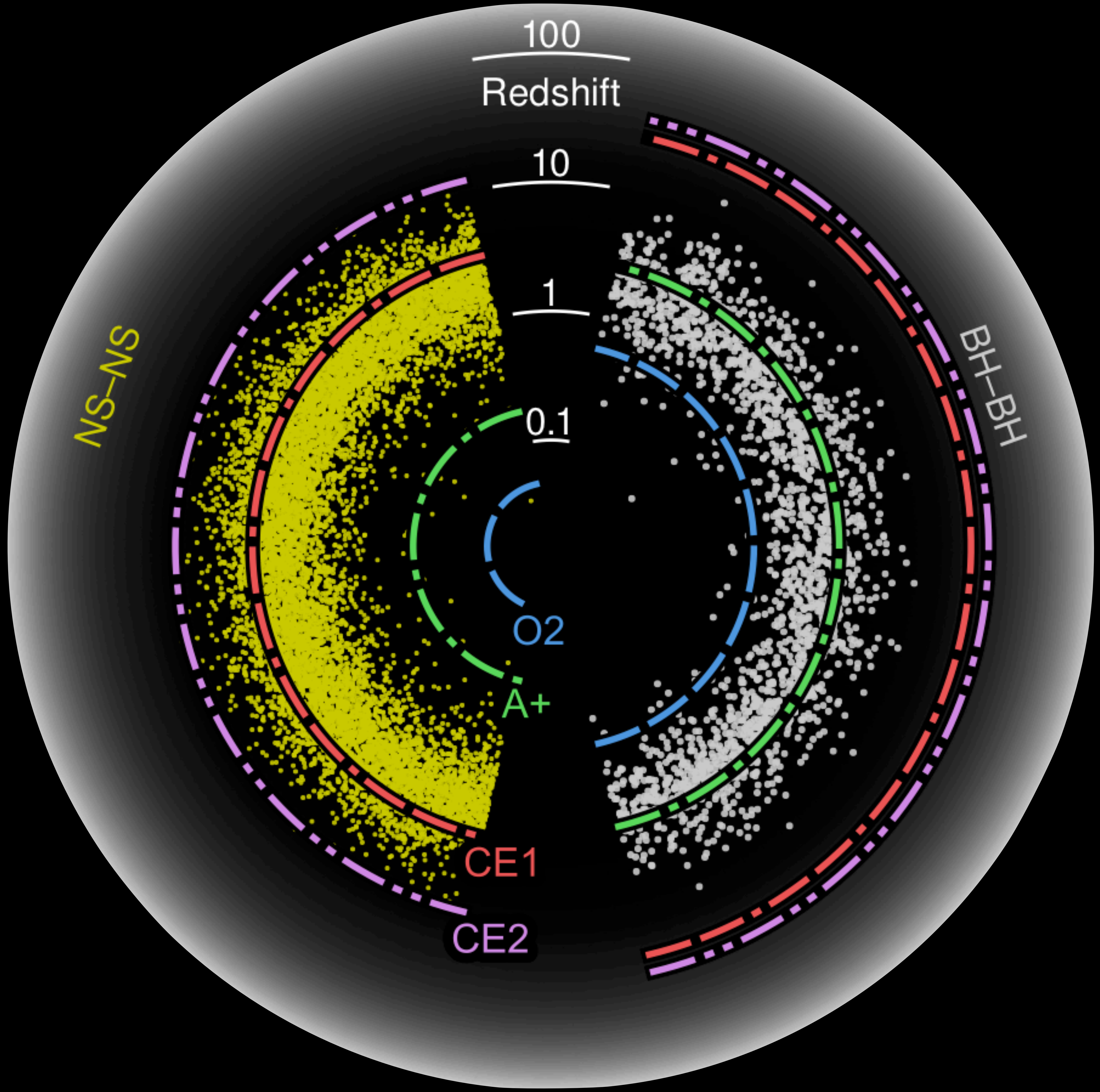
Barkett, Scheel, Haas, Ott, Bernuzzi, DAB, et al., Phys. Rev. D 93 044064 (2016)

Einstein Telescope

Cosmic Explorer

GWIC arXiv:1903.09260

Binary mergers throughout cosmic time



Hall/Vitale arXix:1903.04615

Einstein Telescope

- 2011 conceptual design, 10x range of advanced detectors, ~1B Euro cost
- Facility: 10.3km-long tunnels, 25m high vertex rooms, 100-200m underground, 20+year lifetime
- Three nested detectors, each with two interferometers
- Triangle geometry: equal sensitivity for both polarizations and more isotopic sensitivity

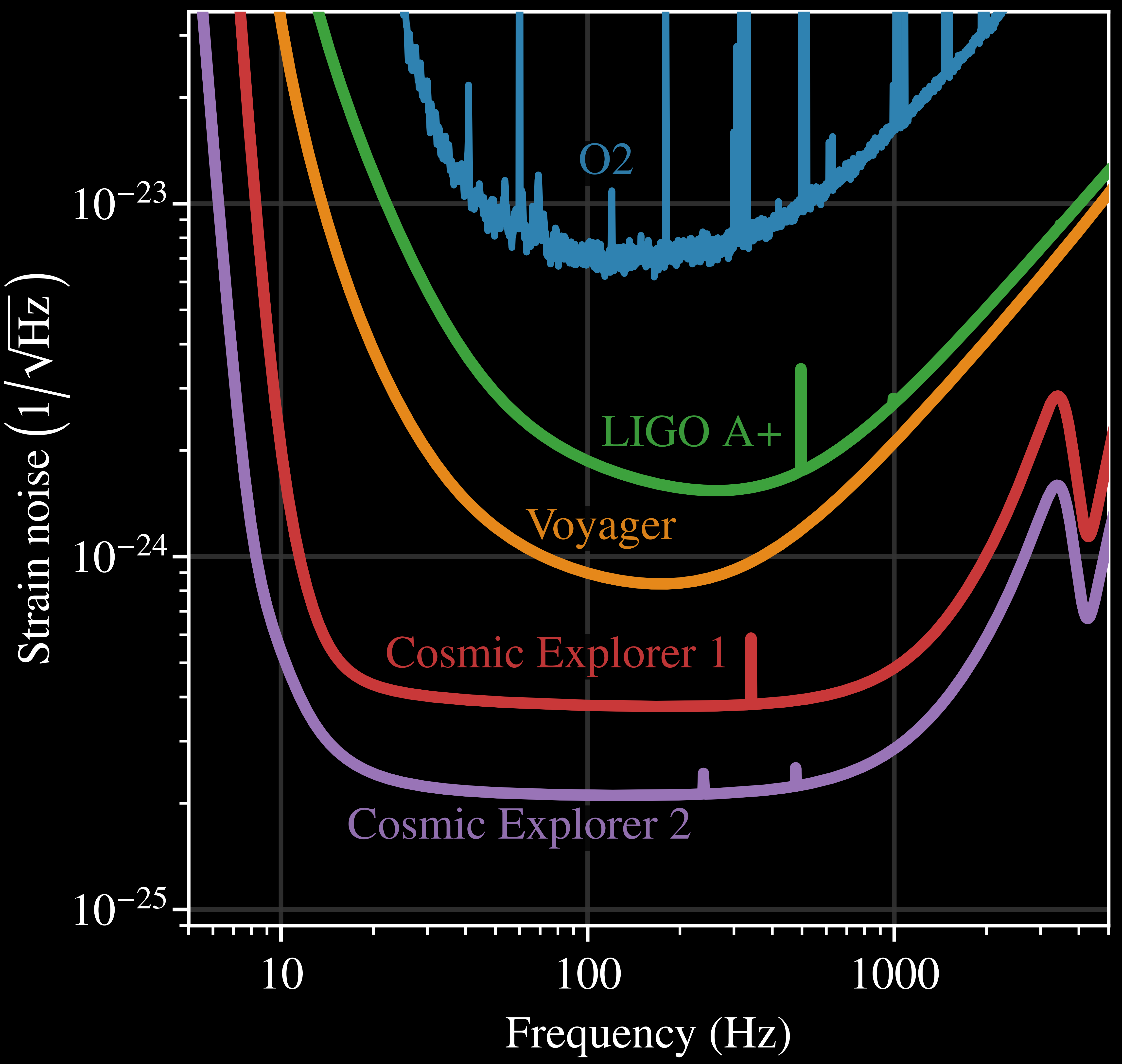
ET Design Study, ET-0106C-10

Cosmic Explorer

- Facility: 40km L-shaped detector on Earth's surface
- One interferometer in faculty
- 14cm wide laser beams, 2 MW laser
- R&D progress needed in optical coatings, quantum noise, thermal compensation
    - Year ~ 2030 and ~ 1B USD

CE1 and CE2: two-stage approach

	CE1 2030s, à la aLIGO	**CE2** 2040s, à la Voyager
Wavelength	1.0 μm	1.5 to 2.0 μm
Temp.	293 K	123 K
Material	glass	silicon
Mass	320 kg	
Coating	silica/tantala	silica/aSi
Spot size	12 cm	14 to 16 cm
Suspension	1.2 m fibers	1.2 m ribbons
Arm power	1.4 MW	2.0 to 2.3 MW
Squeezing	6 dB	10 dB



ET and CE are complimentary

- 1 x ET + 2 x CE would be awesome, but expensive
- Community is exploring the scientific benefits of various network configurations
- Other possible detectors:
  - OzGrav High Frequency Interferometer currently in conceptual design
  - Ignoring low-frequency simplifies things a lot, but still lots of physics

- GW170817 has opened up a new era of EOS constraints
- Upcoming detections will provide yet more information (both from GW and EM)
- More numerical modeling of sources is needed to interpret this information!
- Improvements to aLIGO and future detectors (Cosmic Explorer, ET) will give precision measurements and post-merger signatures

NSF