Syracuse University

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

Duncan Brown

As massive objects move around, the curvature of space changes

The strength of the gravitational waves radiated is given by their strain

$h(t)$ = change in length / length

Typical strains from astrophysical sources when the waves arrive at the Earth are

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

However, the energy radiated is enormous

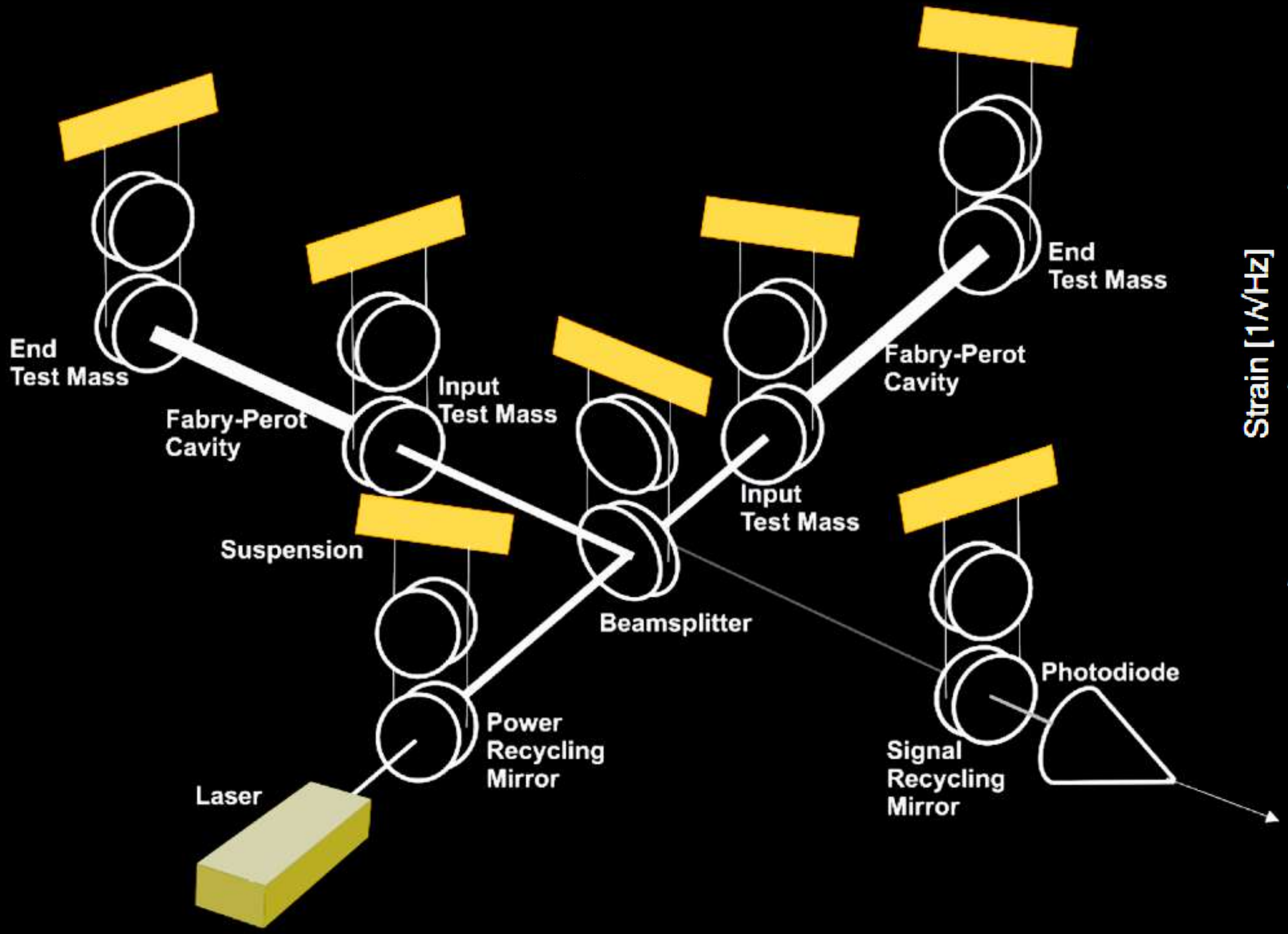
$$L_{\rm GW} \sim \left(\frac{c^5}{G}\right)\left(\frac{v}{c}\right)^6\left(\frac{R_{\rm S}}{r}\right)^2 \sim 10^{59}{\rm erg/s}$$

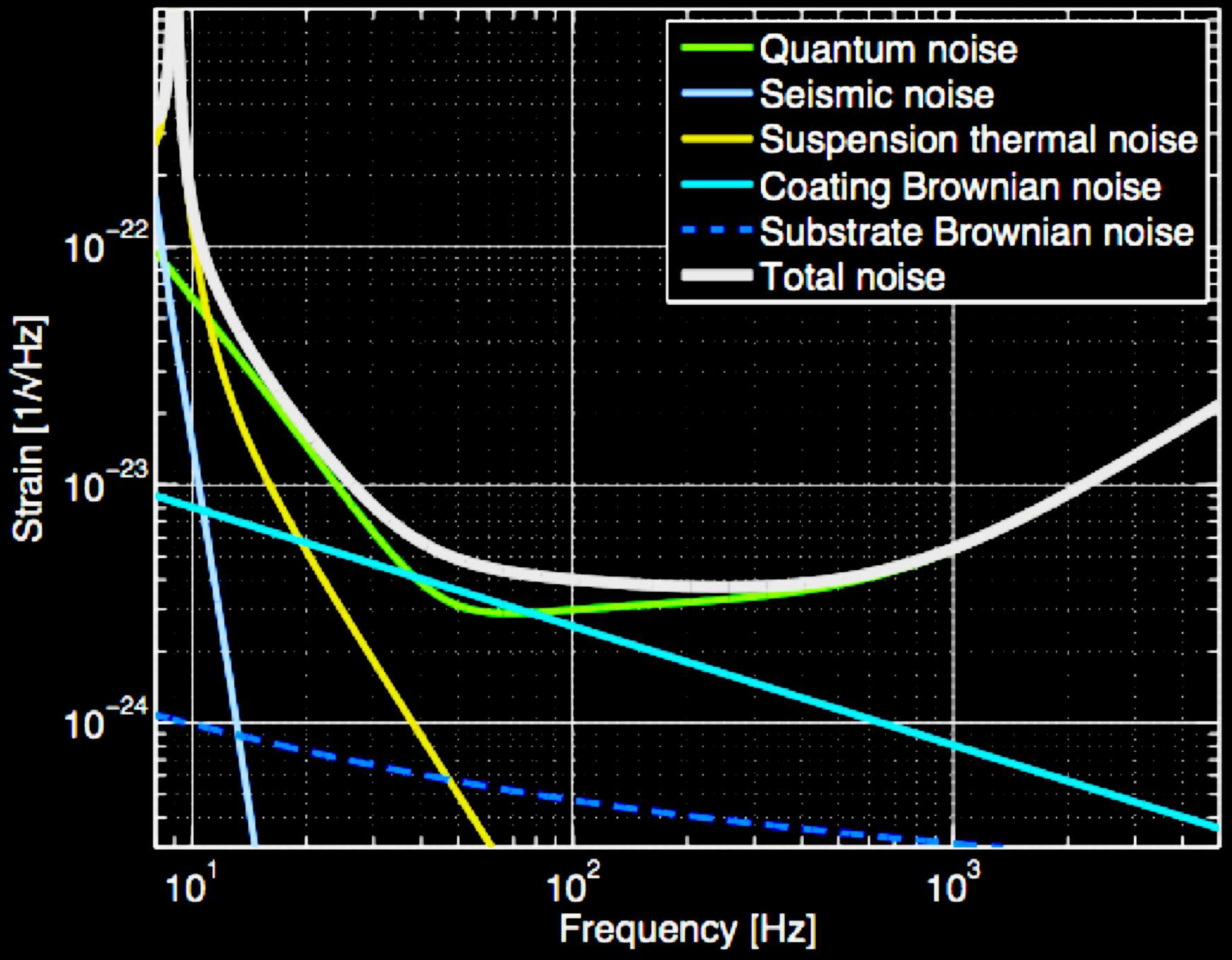
Solar luminosity L ~ 10^{33} erg/s

Gamma Ray Bursts L ~ $10^{49\text{-}52}$ erg/s

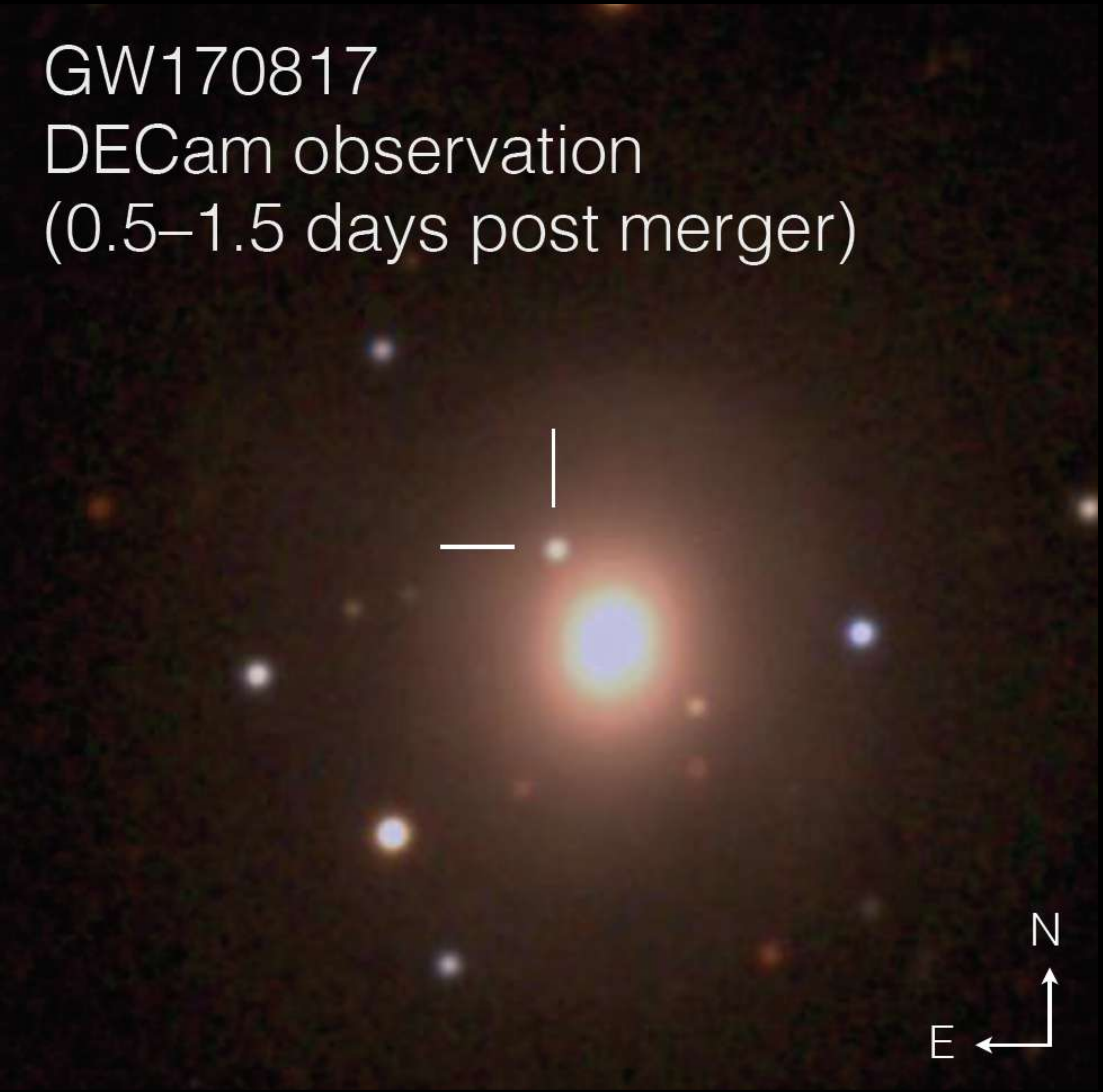
Imagine measuring this distance to a precision of ten microns

Advanced LIGO

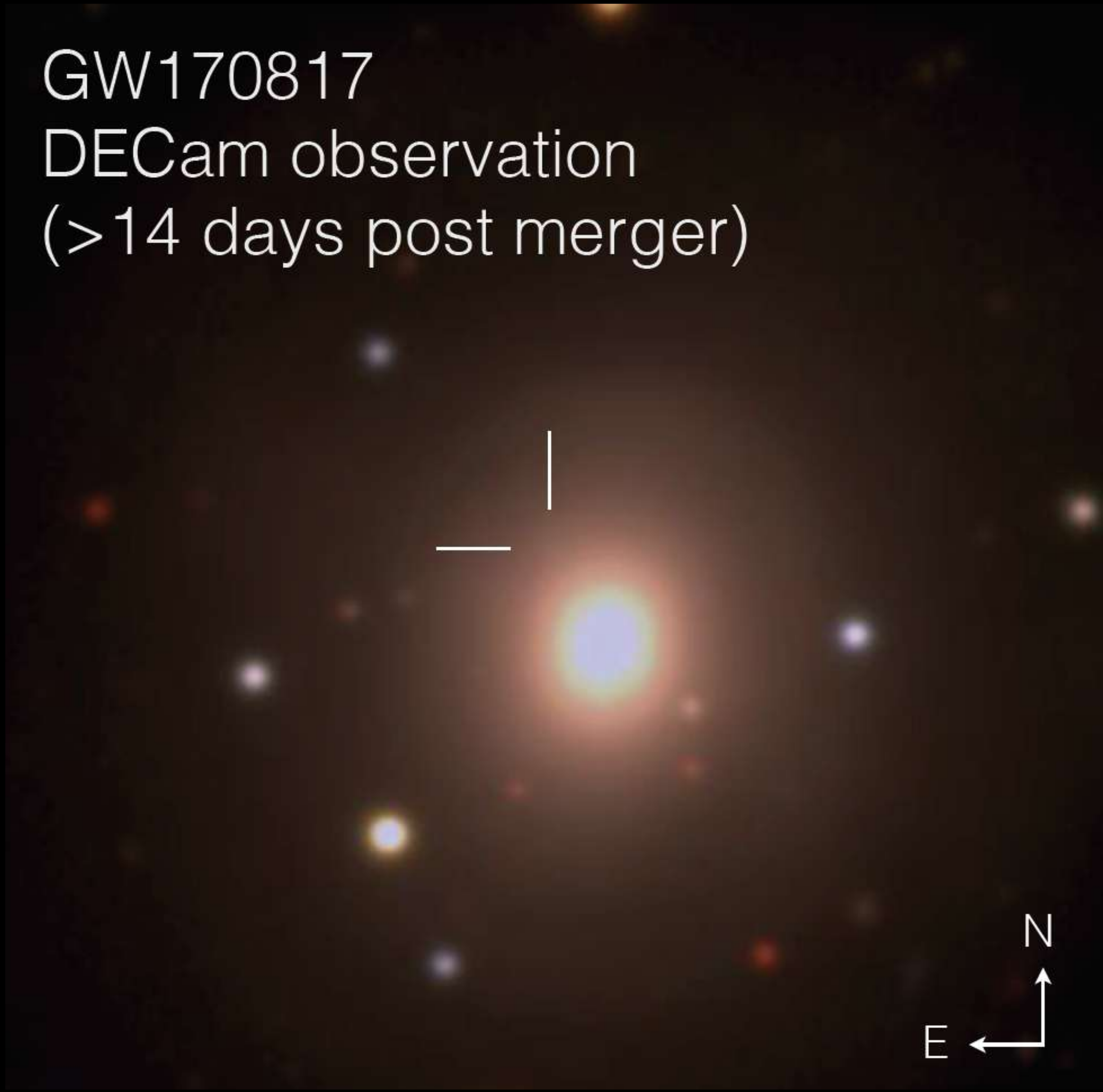




Abbott,..., DAB et al. PRL **119** 161101 (2017)



GW170817
DECam observation
(0.5–1.5 days post merger)



GW170817
DECam observation
(>14 days post merger)

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

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

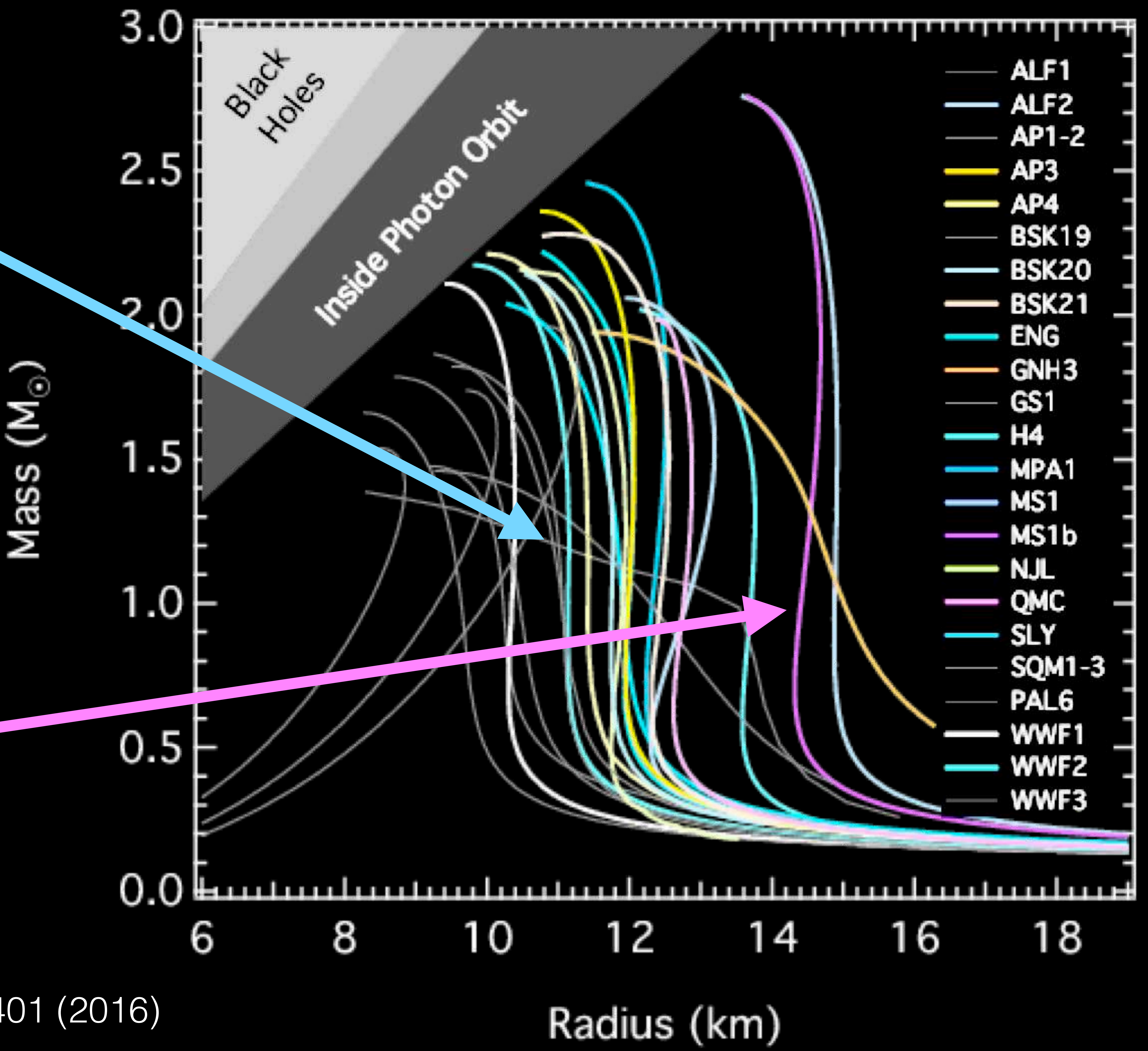
- At $T = 0$, the EOS relates pressure to density $P = P(\boldsymbol{\rho})$

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

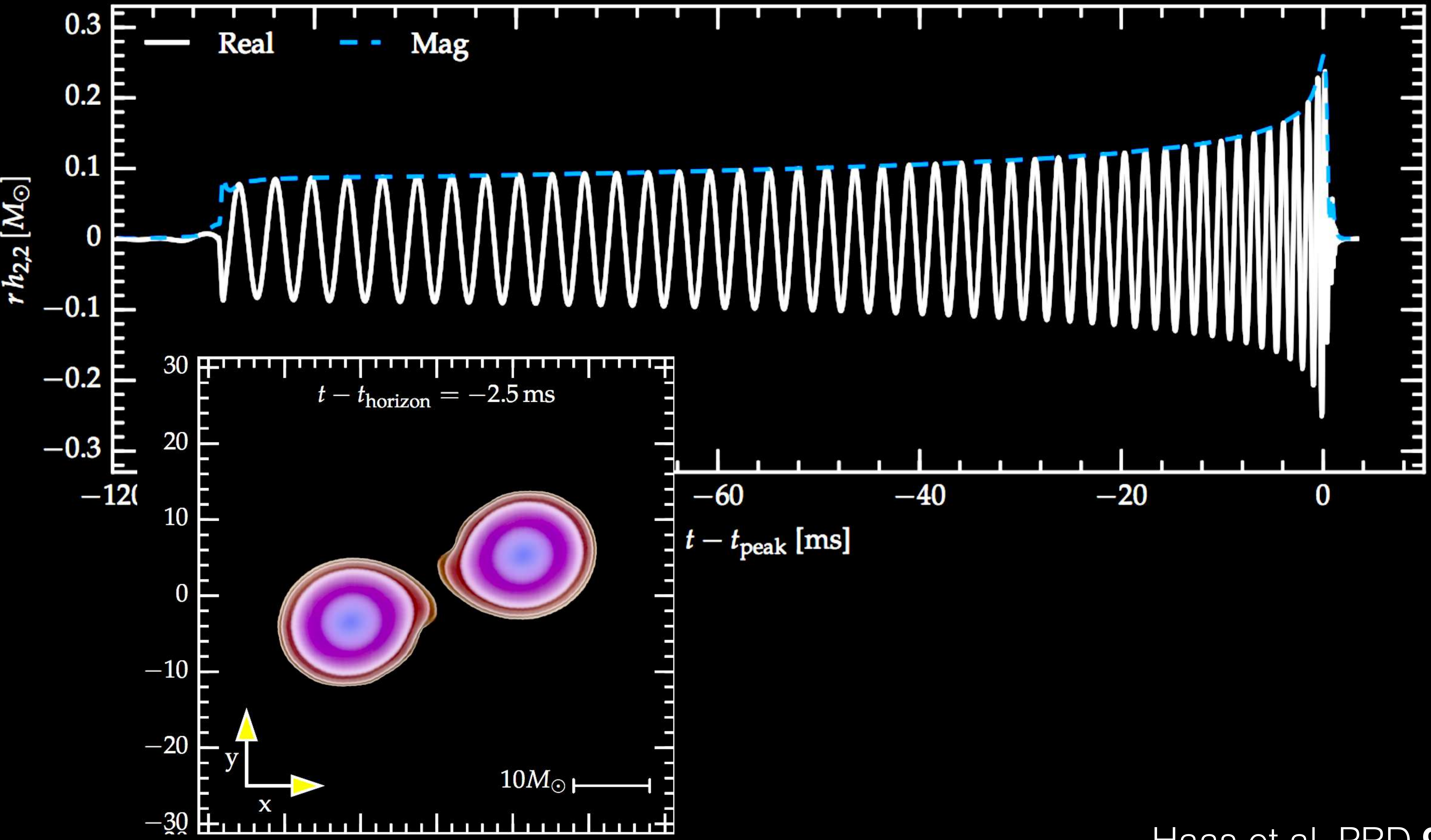
- Densities of the cores of neutron stars reach 8 - 10 times nuclear saturation density and so neutron stars allow us to explore the EOS at much higher densities

"Soft" EOS, low radius

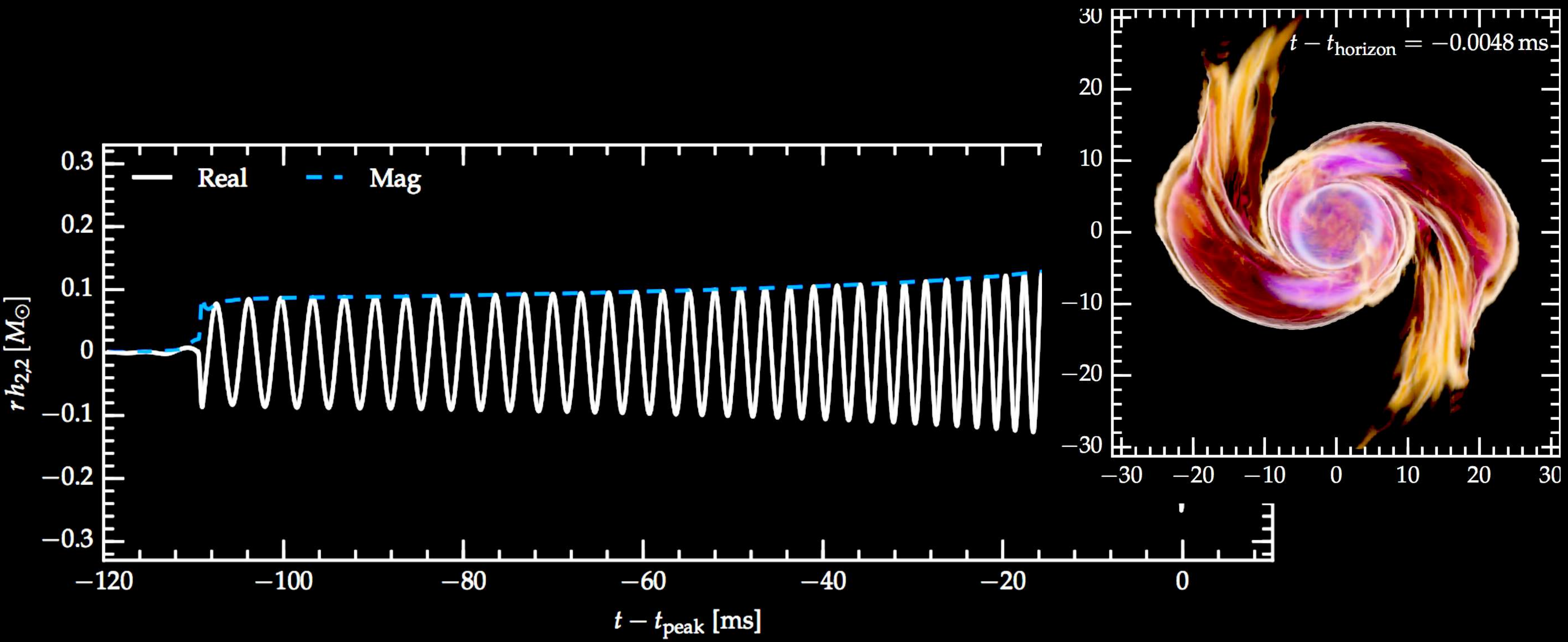
"Stiff" EOS, large radius



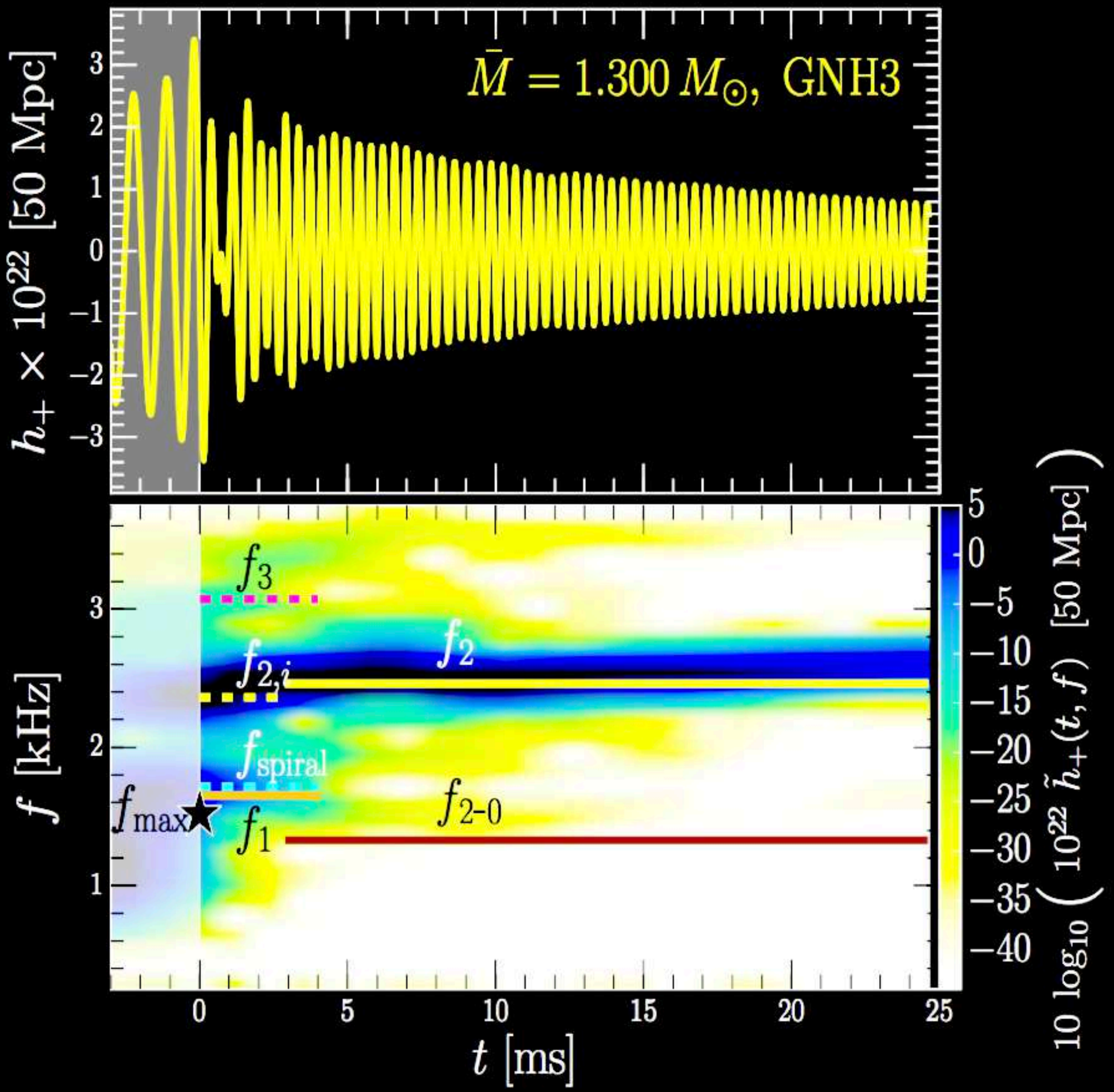
Ozel and Freire Ann. Rev. Astron. Astro. **54** 401 (2016)

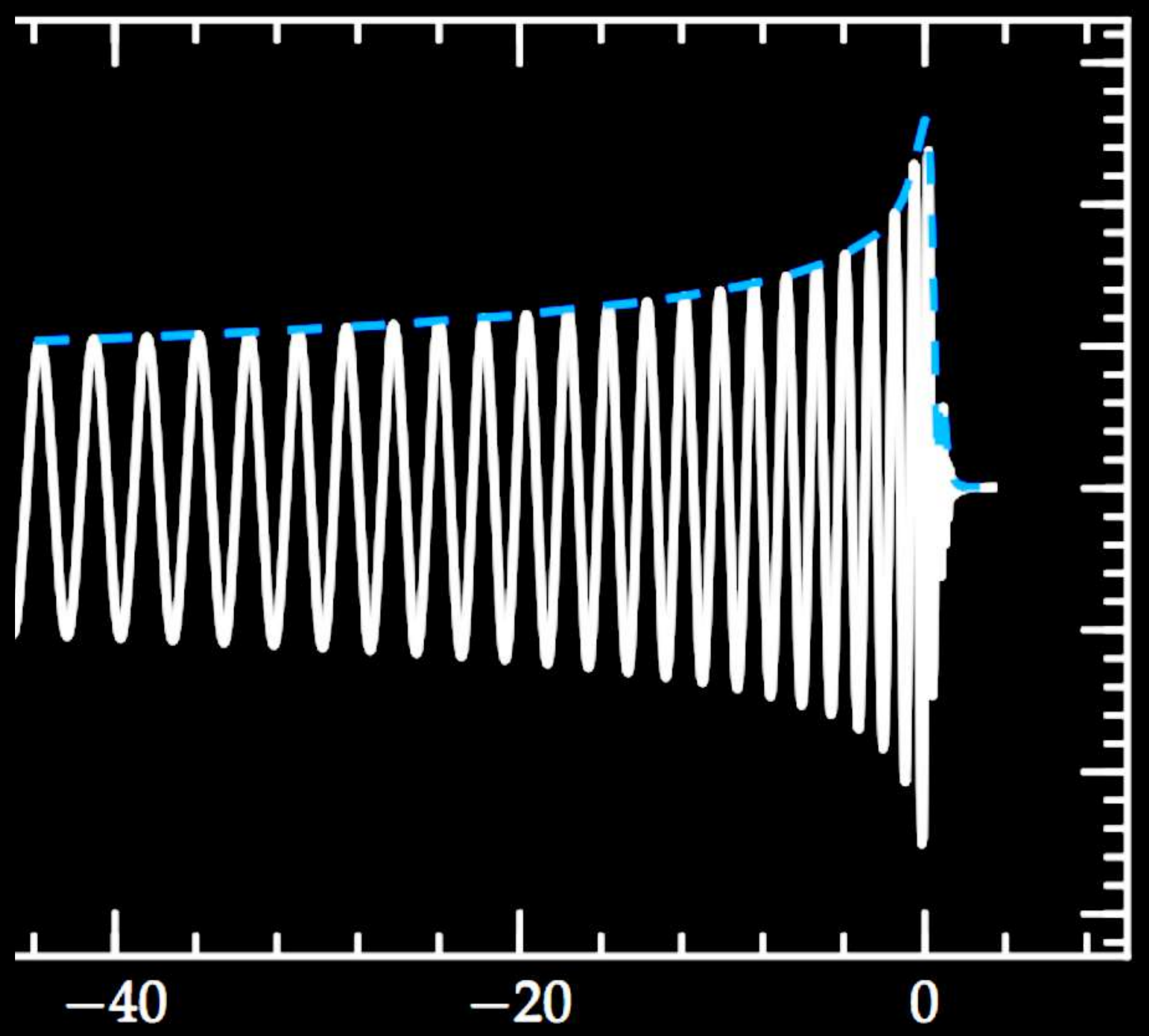


Haas et al. PRD **93**, 124062 (2016)



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





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

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

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

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

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

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

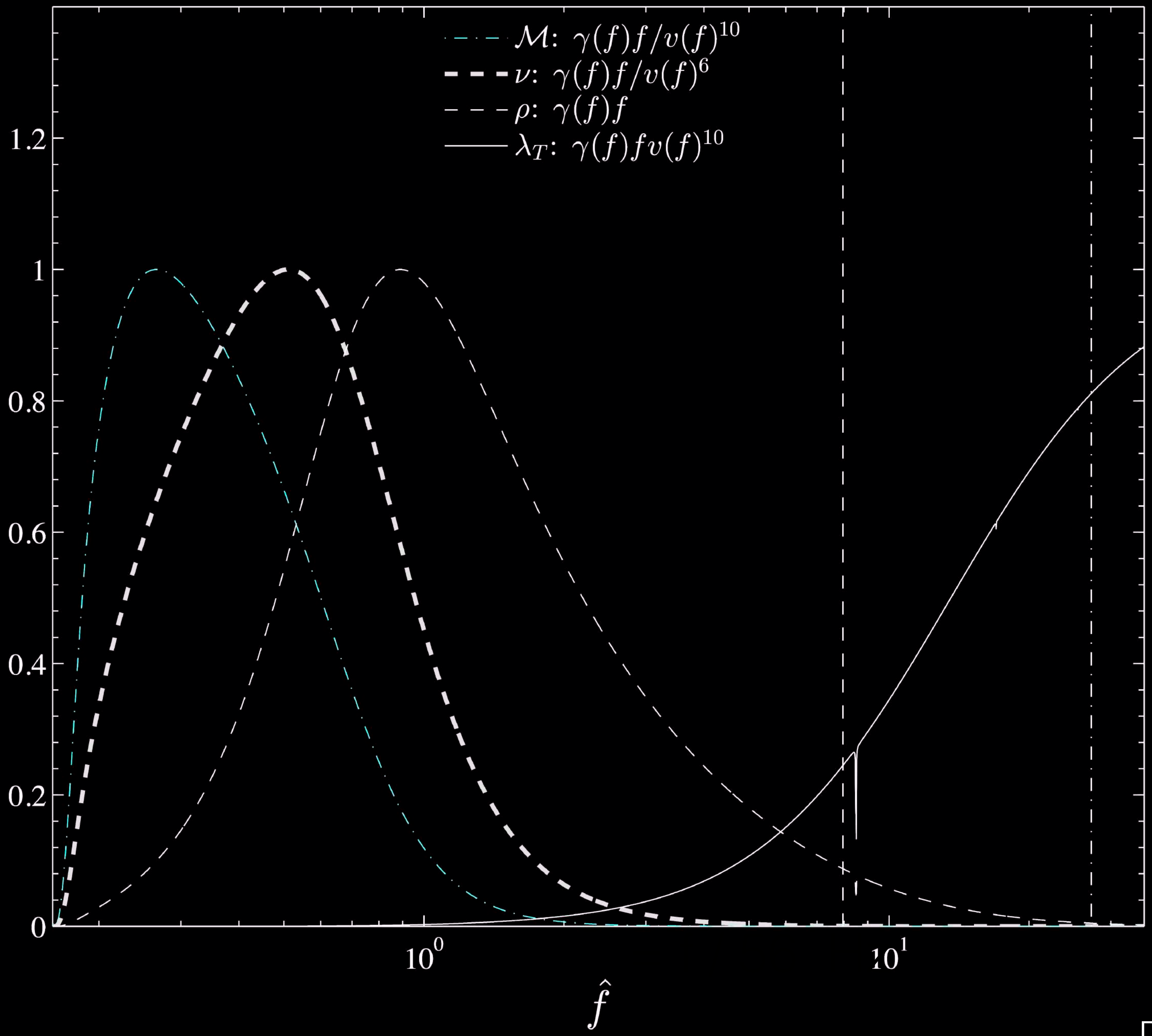
Tidal effects enter the post-Newtonian gravitational-wave phase as

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

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

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

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

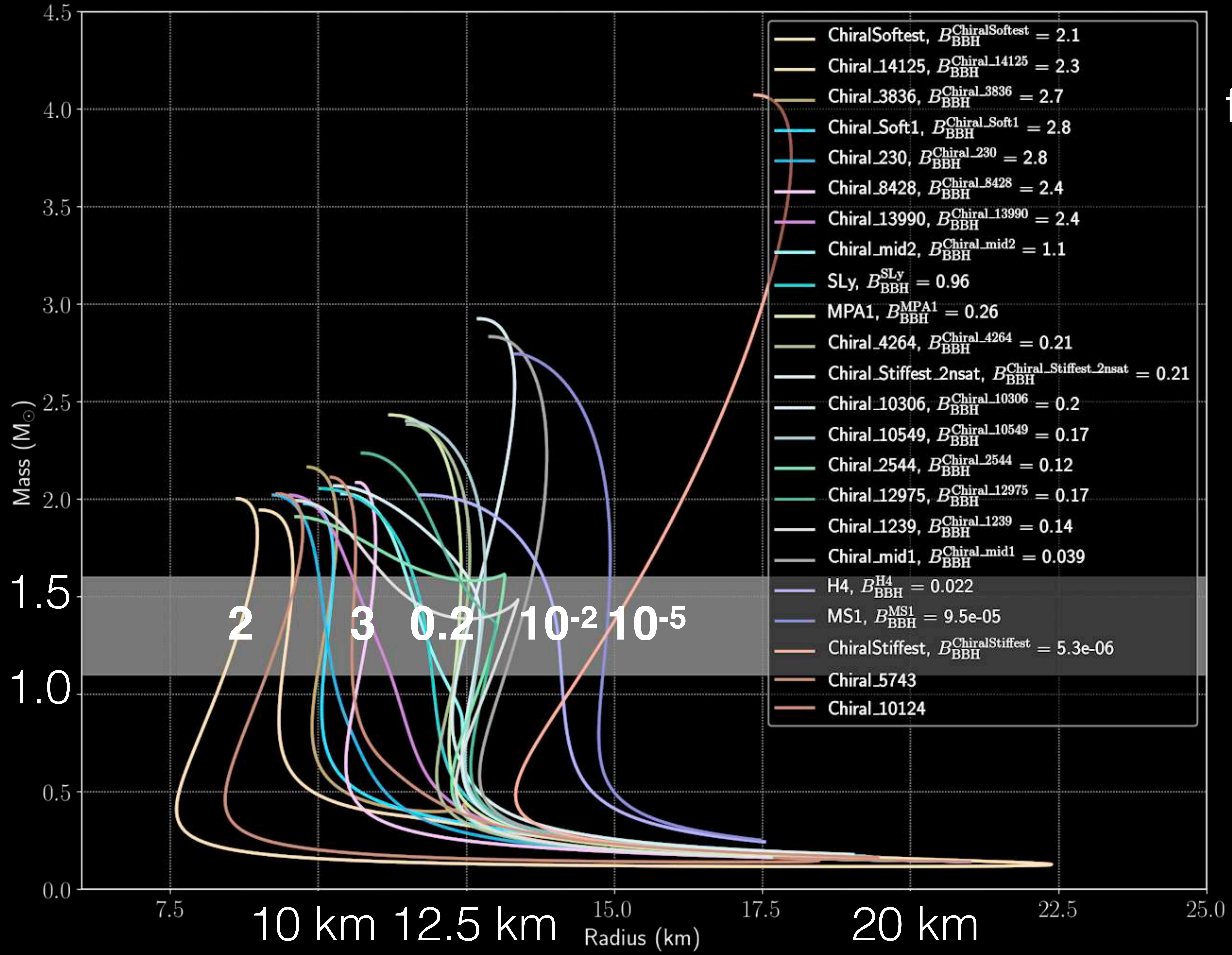
Tidal information comes from late inspiral signal

Tidal information not strongly degenerate with other parameters

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

- 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 GW170817 against two models (BBH and BNS)

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



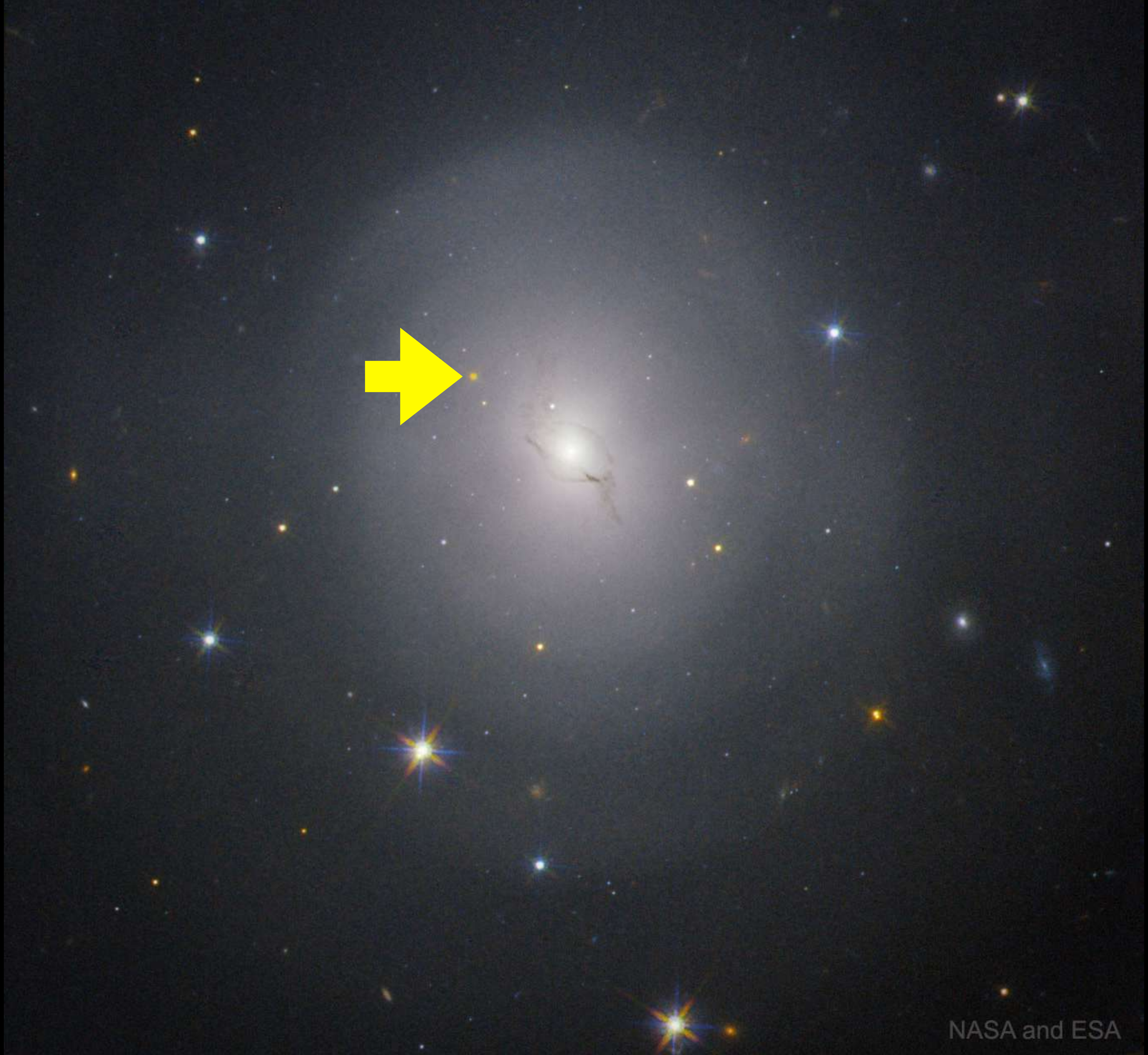
Calculate Bayes factor for specific EOS vs BBH

Only the stiffest EOS
are ruled out
at high confidence

Soft EOSes
and black holes
are all consistent with
GW170817

c.f. Abbott et al.
CQG **37** 045006 (2020)

But black holes are... black!

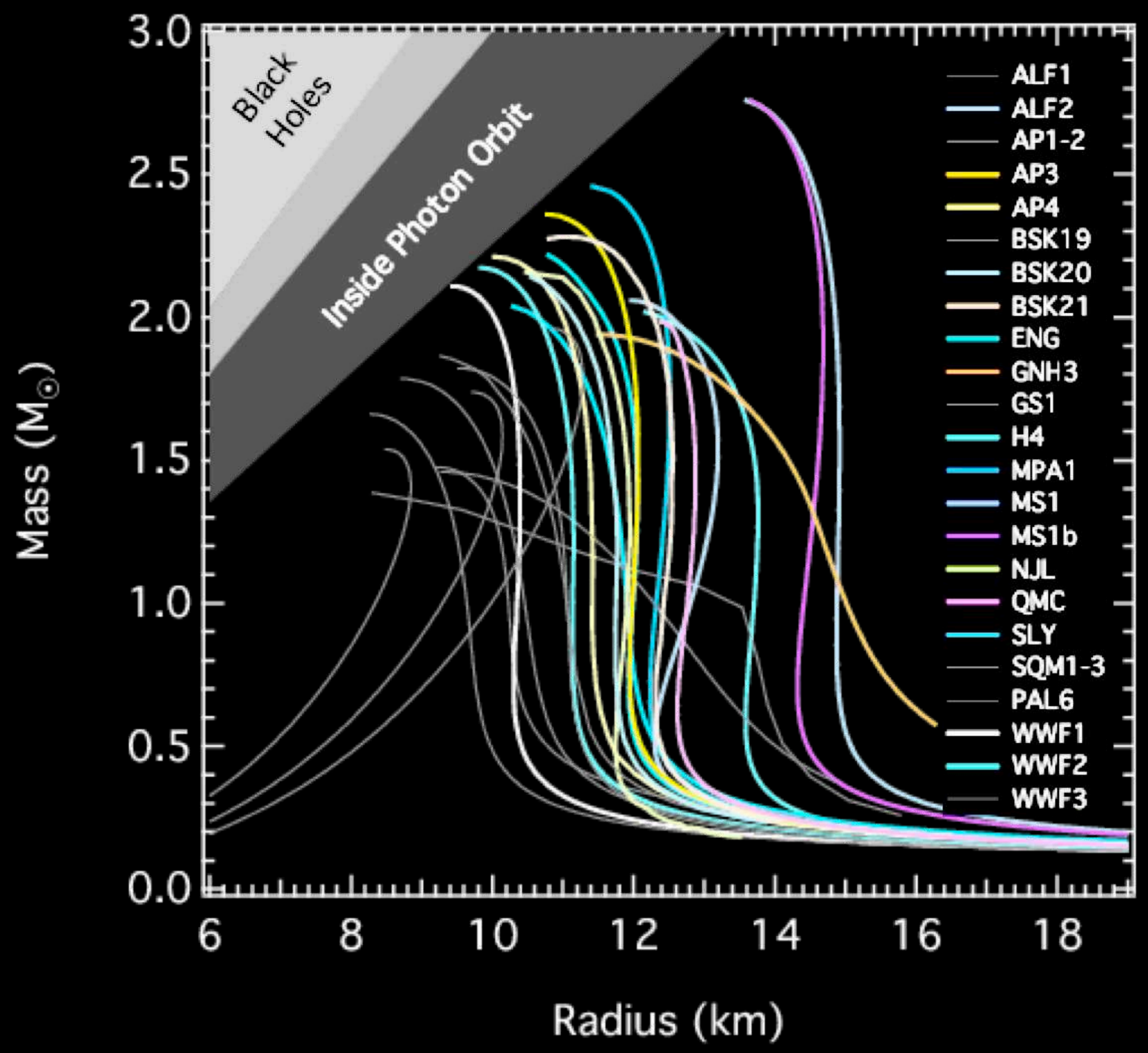

NASA and ESA

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, DAB, Berger, Biwer. PRL **121**, 091102 (2018)
  - Abbott et al. PRL **121**, 161101 (2018)
  - Radice and Dai. Eur. Phys. J. A **55** 50 (2019)
  - Capano, ..., DAB, et al. Nature Astronomy **4**, 625 (2020)

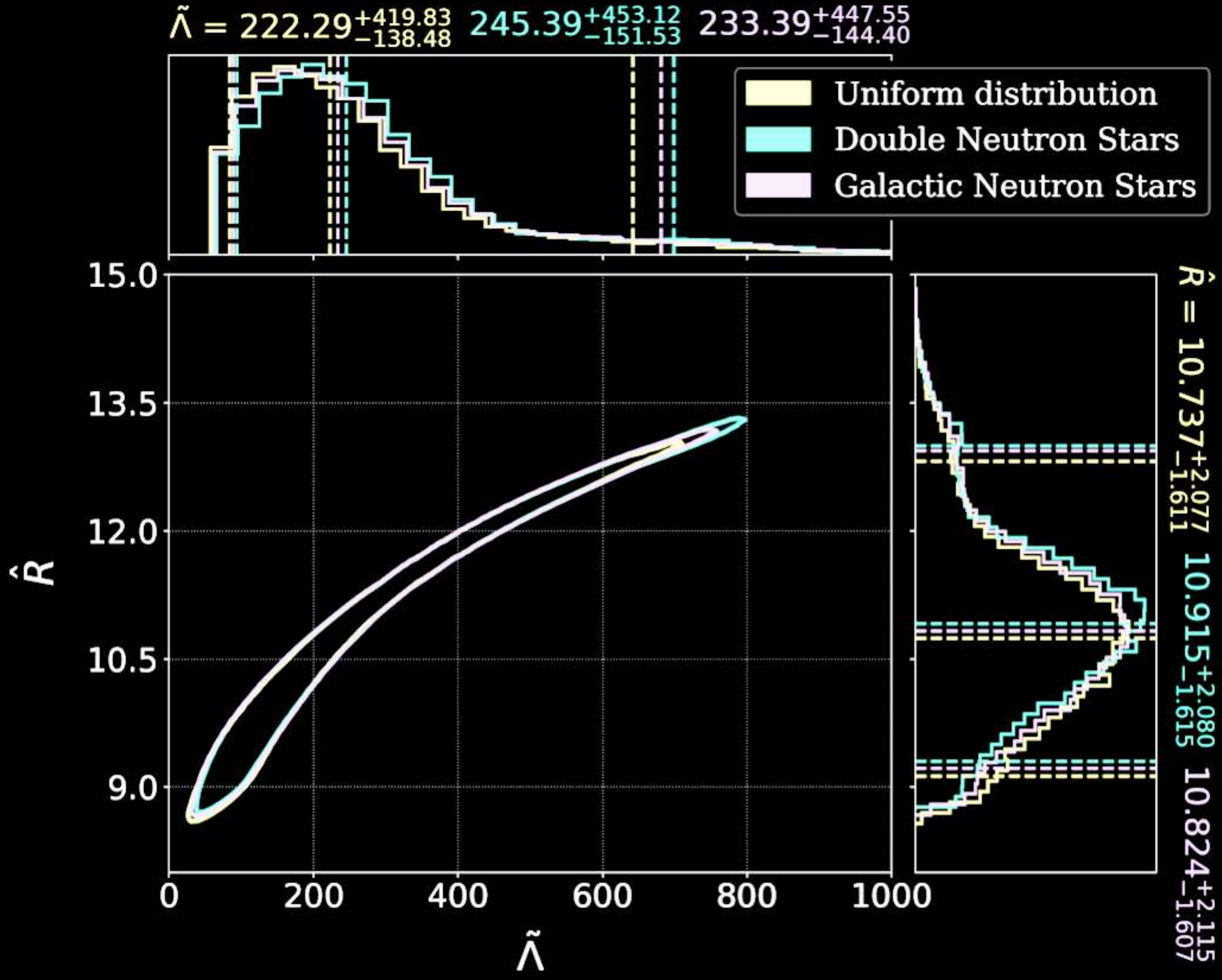
- For nearly every specific EOS in the mass range relevant to GW170817 [1.1,1.6] solar masses, change in radius is very small

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



- 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)

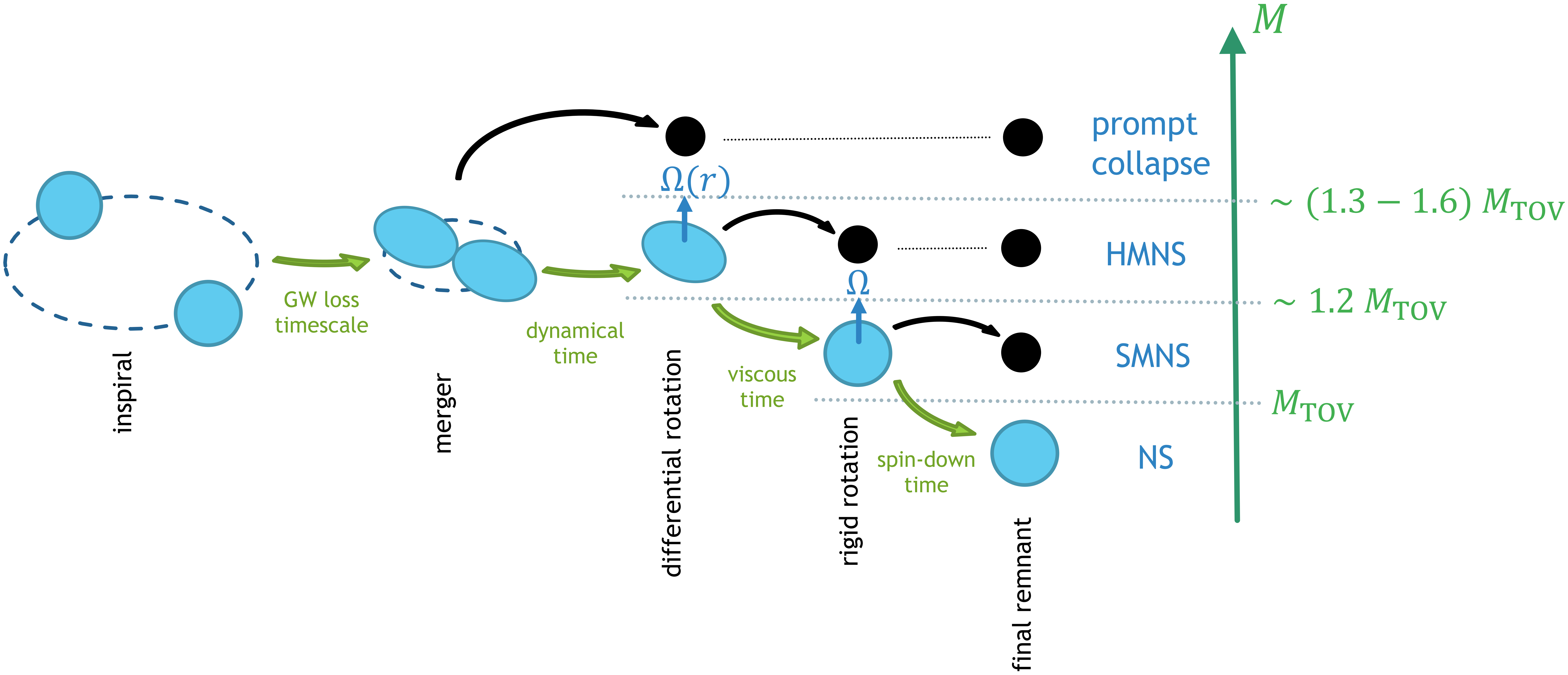


$$\langle \hat{R} \rangle = 10.8 \text{ km}$$

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

Soumi De

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



inspiral

GW loss timescale

merger

dynamical time

differential rotation

$\Omega(r)$

viscous time

rigid rotation

Ω

spin-down time

final remnant

prompt collapse

HMNS

SMNS

NS

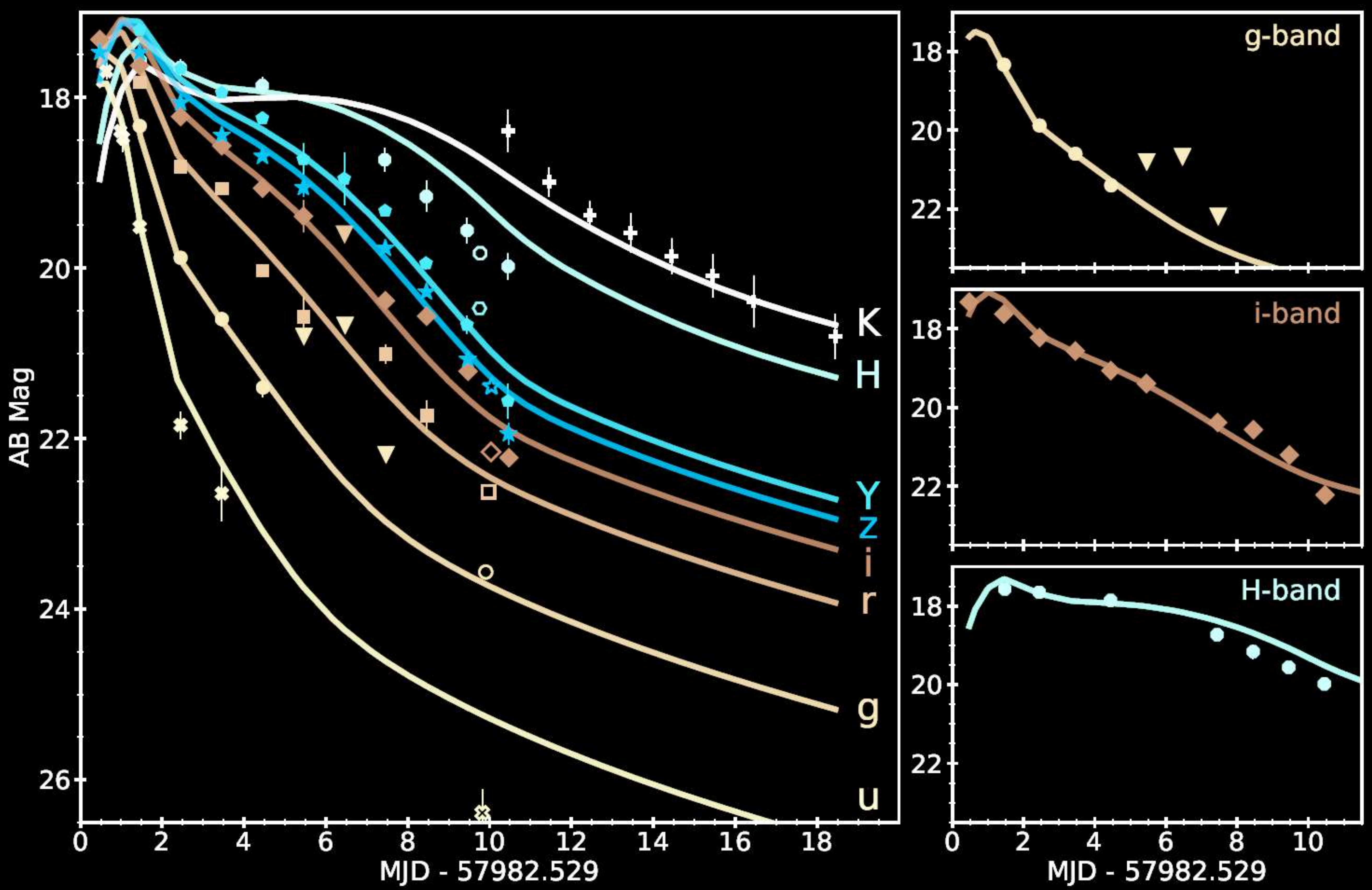
M

$\sim (1.3 - 1.6)\ M_{\mathrm{TOV}}$

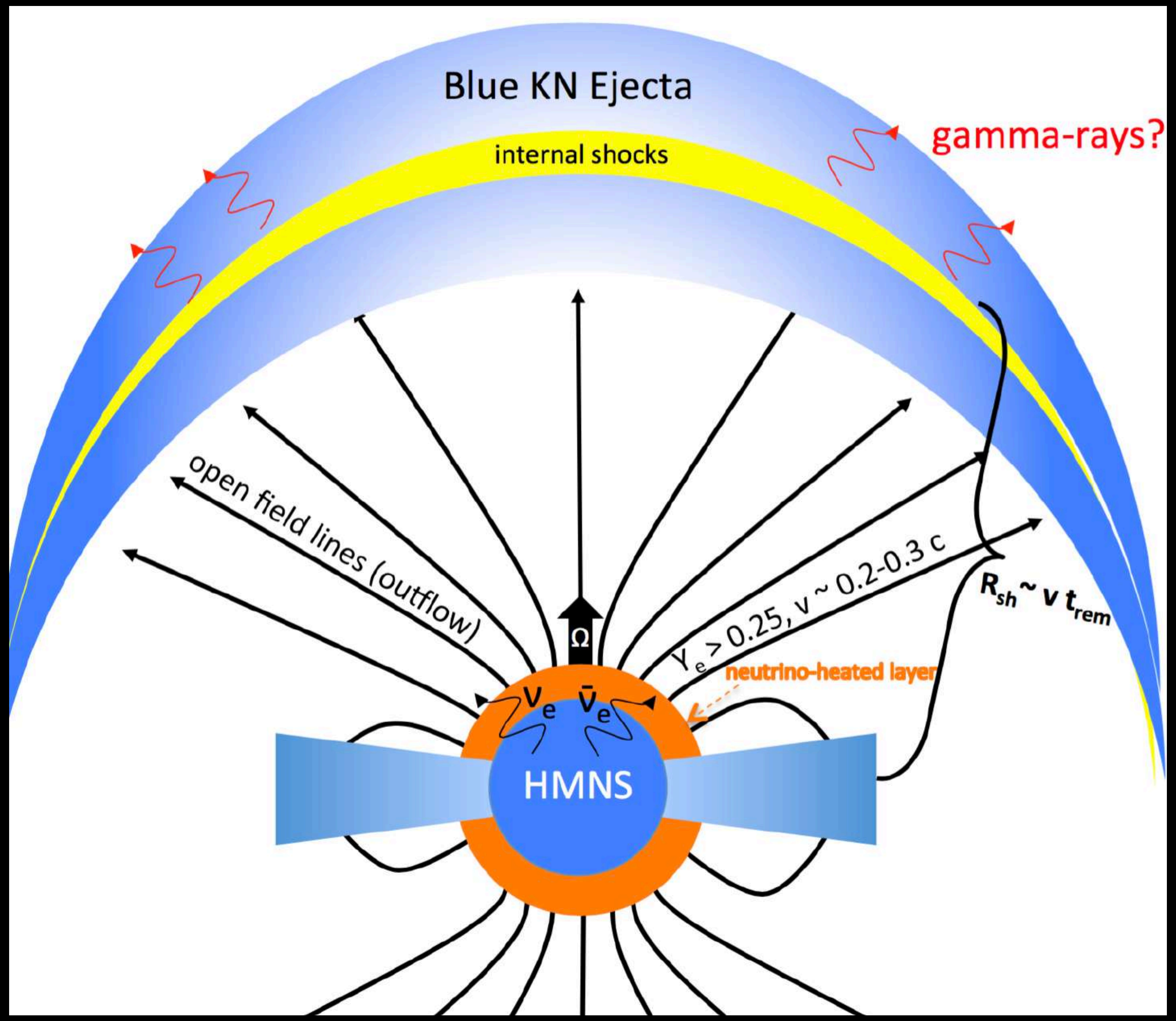
$\sim 1.2\ M_{\mathrm{TOV}}$

M_{TOV}

Ben Margalit



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



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

Kilonova light curves suggest the existence of a hyper massive neutron star

Remnant cannot be massive enough to directly collapse to black hole

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

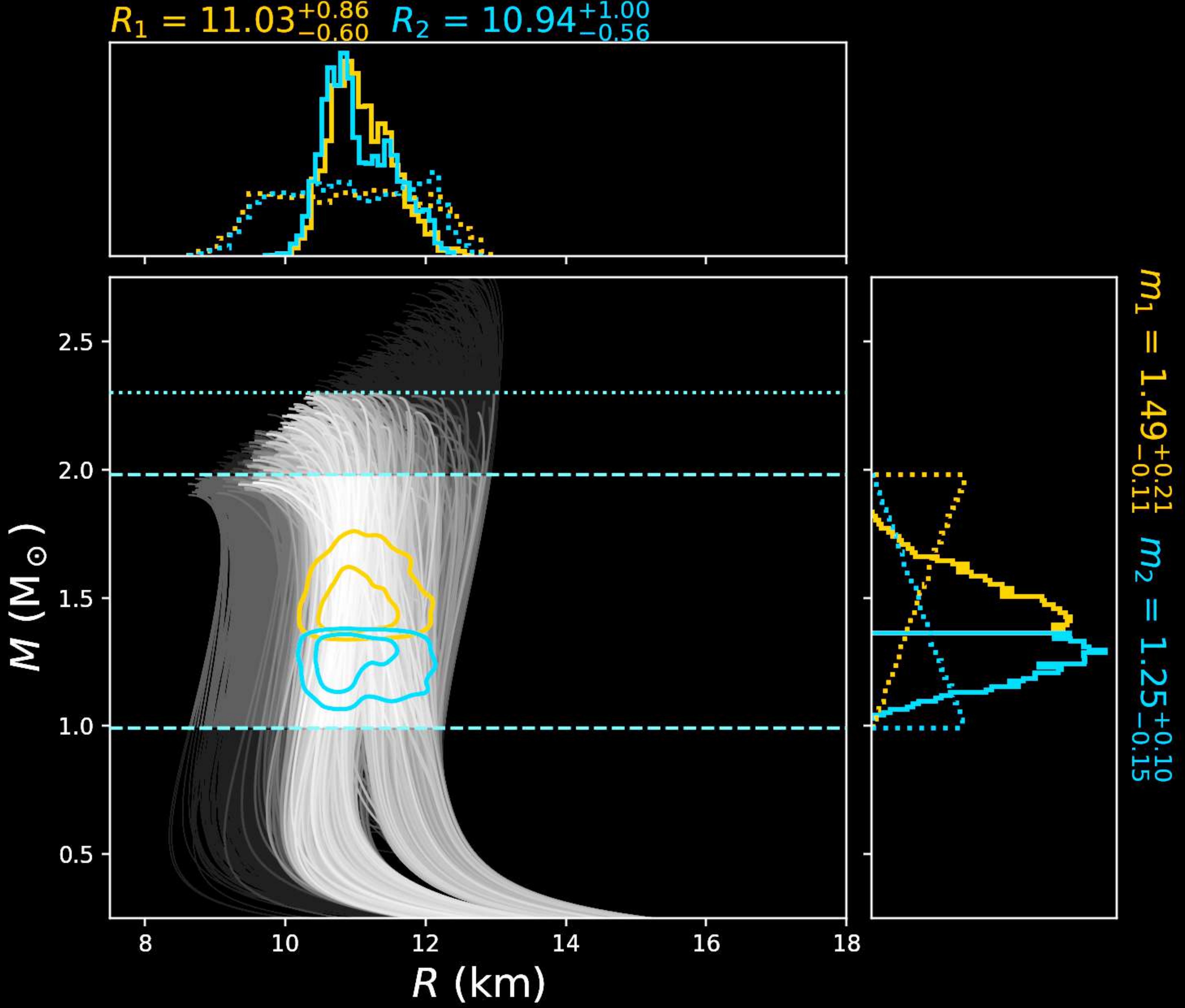
$$M_{\max} \leq 2.17 M_{\odot}\ (90\%)$$

Margalit and Metzger ApJL 850 19 (2018)

- 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)

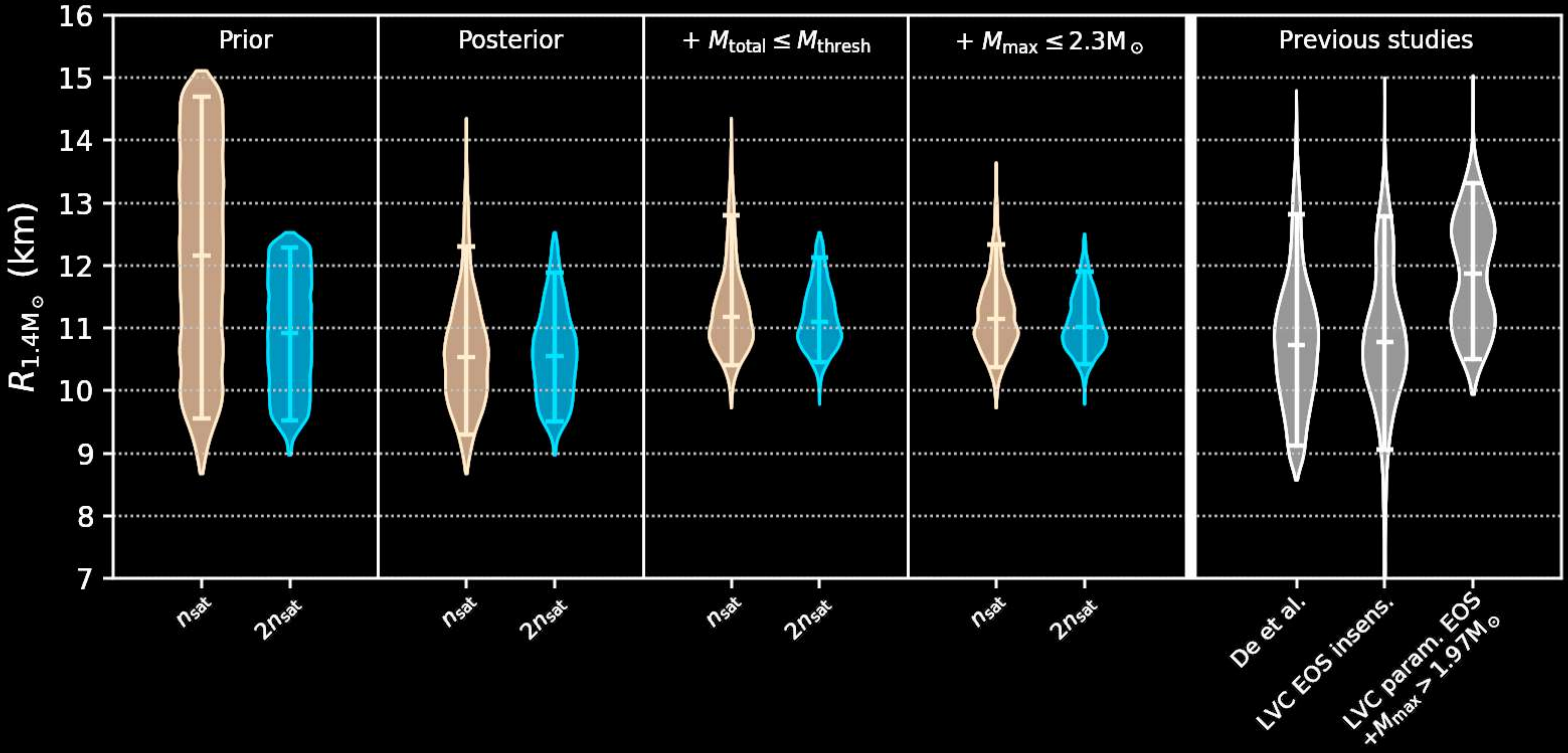
Lynn et al. arXiv:1901.04868, Machleidt and Entem, Phys. Rept. **503** 1 (2011)

Capano, Tews, Brown, De, Margalit, Kumar, DAB, Krishnan, Reddy, Nature Astron. **4**, 625 (2020)



Collin Capano

Capano, Tews, Brown, De, Margalit, Kumar, DAB, Krishnan, Reddy, Nature Astron. **4**, 625 (2020)

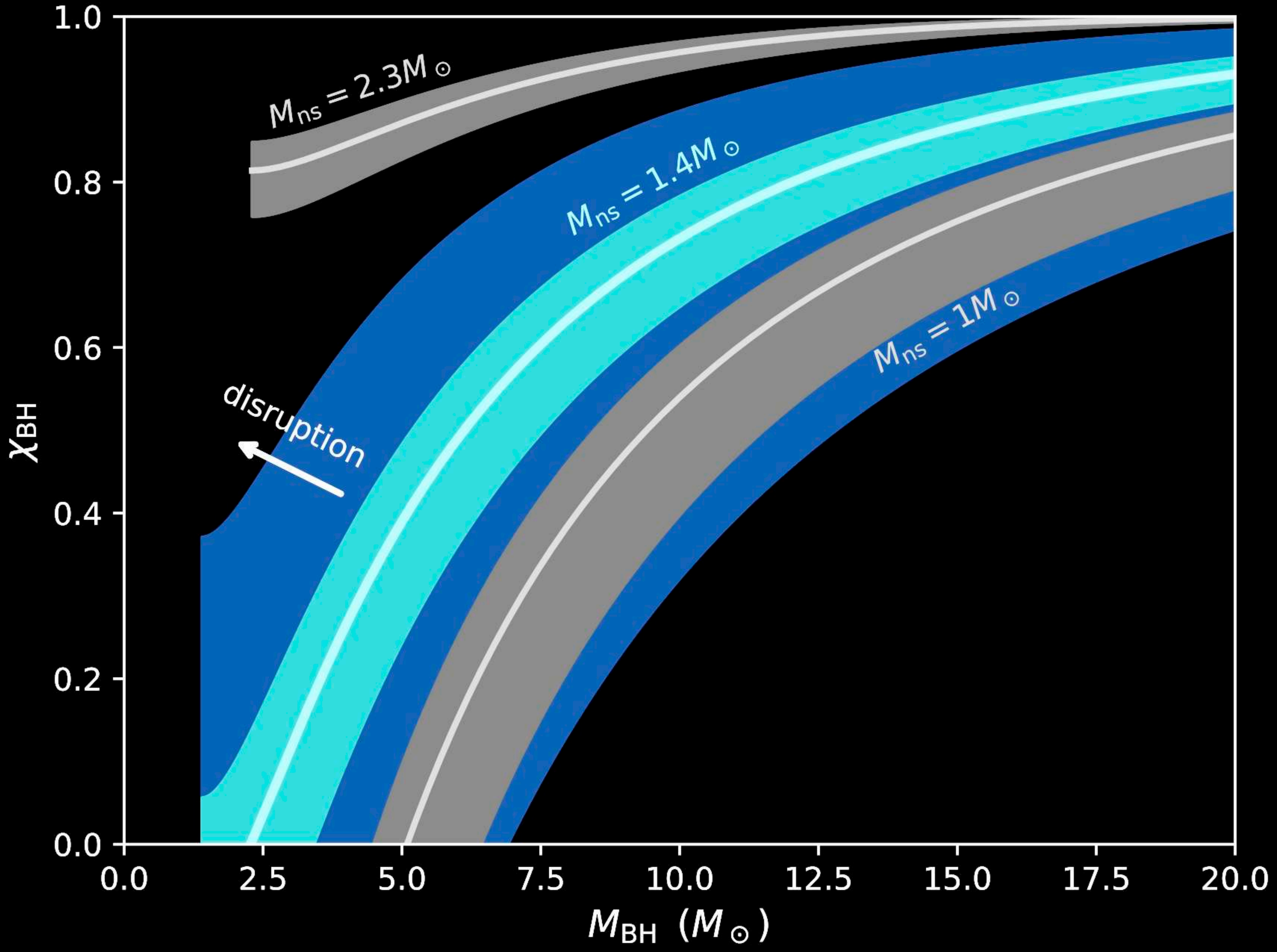


Capano, Tews, Brown, De, Margalit, Kumar, DAB, Krishnan, Reddy, Nature Astron. **4**, 625 (2020)

- Use the constraints on the neutron star radius to determine tidal disruption in a neutron-star black-hole merger

- Electromagnetic counterpart is only expected if the neutron star disrupts before merger

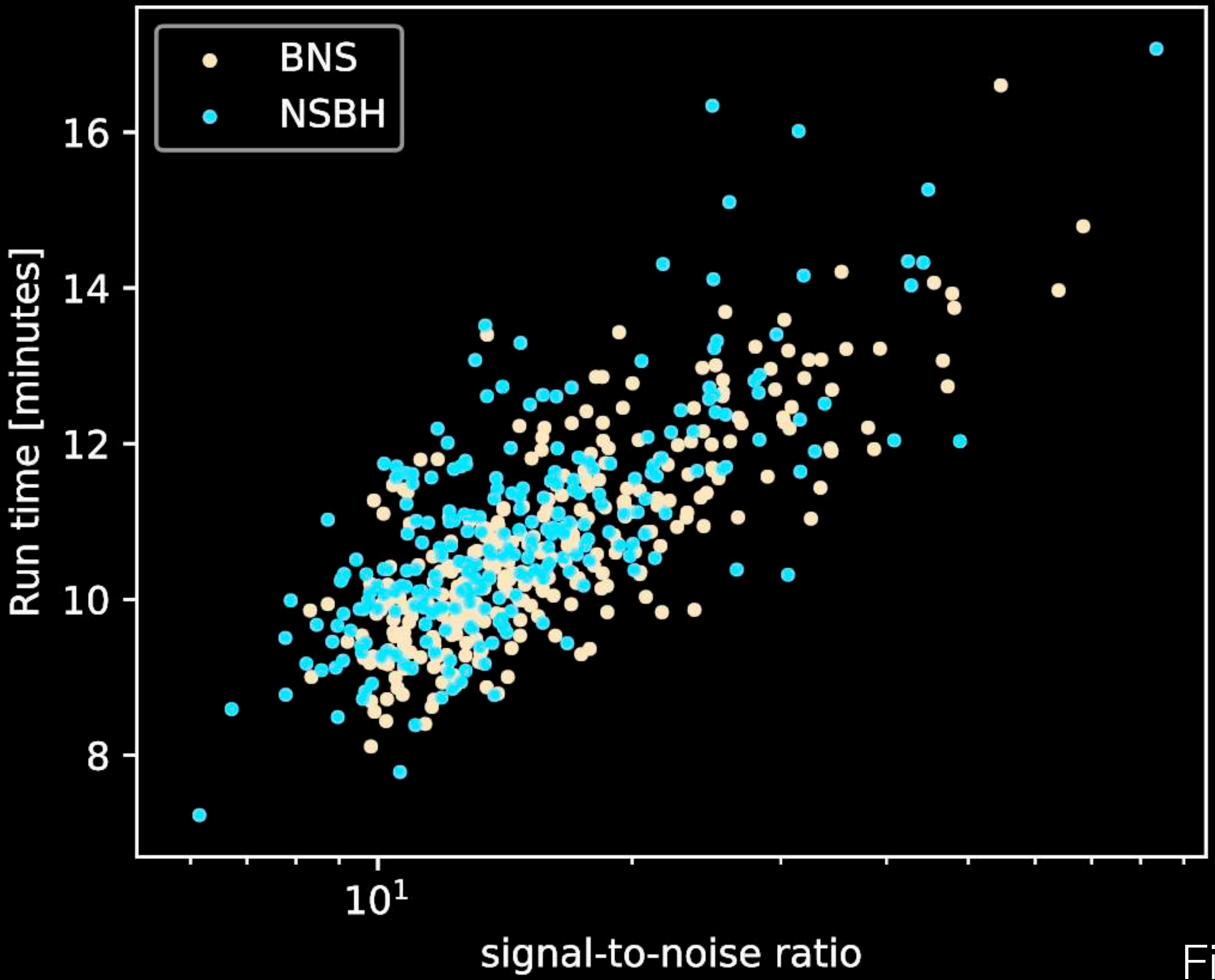
Foucart et al. Phys. Rev. D **98** 081501 (2018)



NSBH mergers are unlikely to produce EM counterparts

Capano, Tews, Brown, De, Margalit, Kumar, DAB, Krishnan, Reddy, Nature Astron. **4**, 625 (2020)

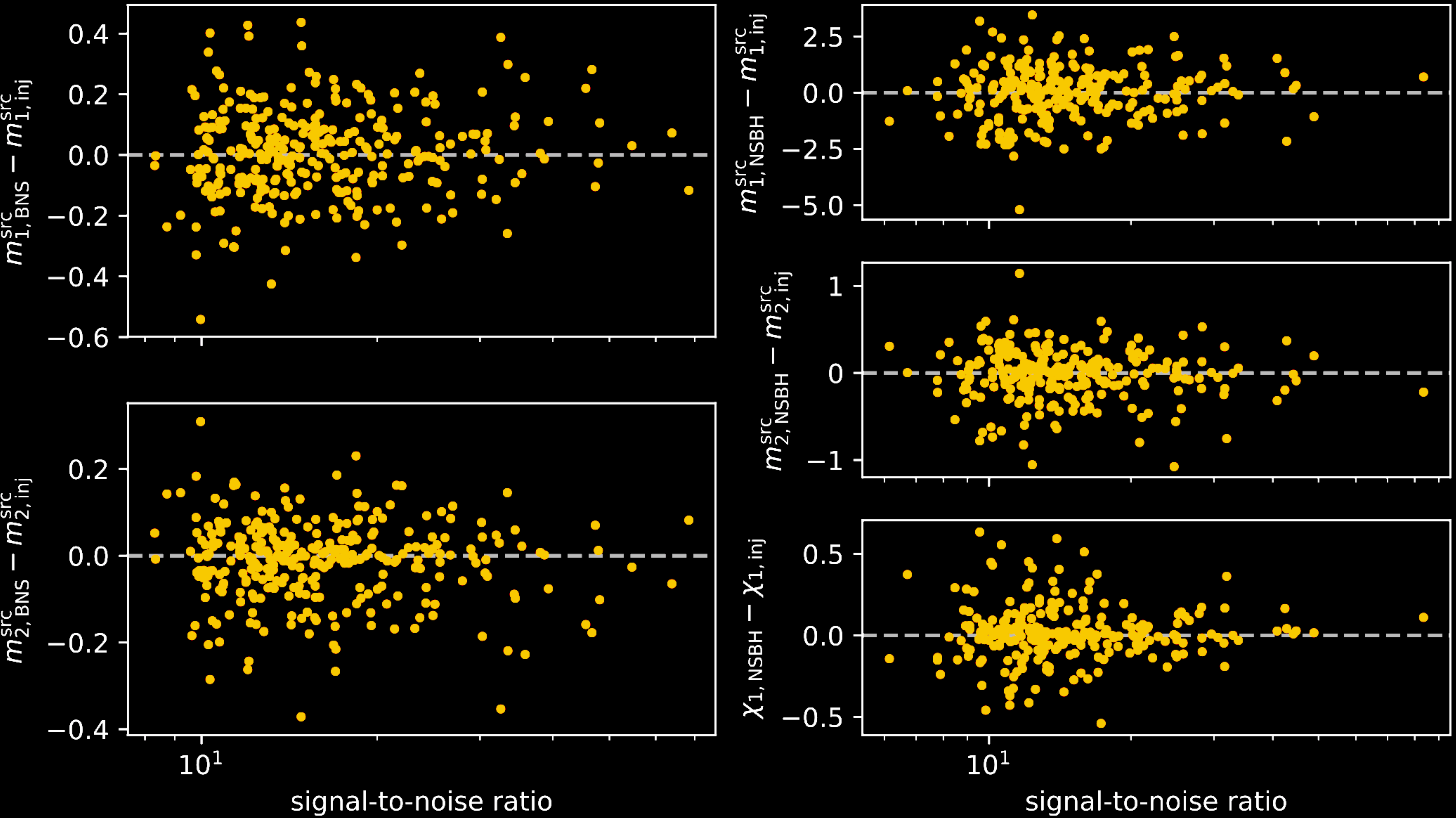
Generalize rapid parameter measurement method of Zackay et al. (2018) (originally proposed by Cornish) to coherent network statistic



Possible to run full parameter
estimation for BNS and NSBH
in less than 20 mins from detection

Daniel Finstad

Finstad and DAB arXiv:2009.13759 to appear in ApJ Letters

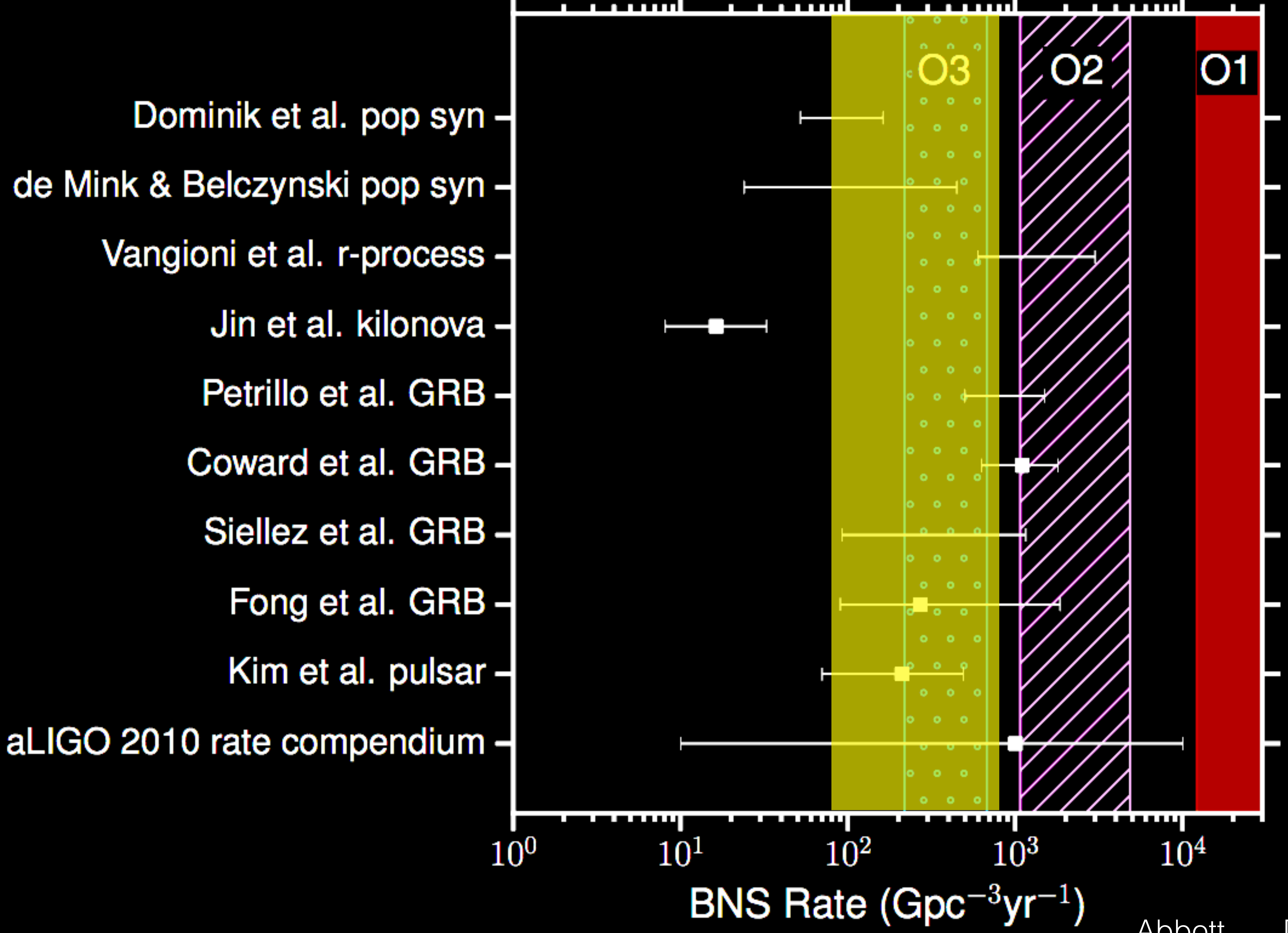


Finstad and DAB arXiv:2009.13759 to appear in ApJ Letters

GW190425

- Single detector event, so no EM counterpart
- Total mass ~ 3.4 M_{sun} is much larger than GW170817
- D ~ 160 Mpc
- However, GW signal is weaker than GW170817...consistent with BNS, NSBH, and BBH models

Abbott et al. ApJ **892** L3 (2020)
Han et al. ApJ **891** L5 (2020)



🟨 GWTC-2

LIGO/Virgo O3a

Abbott, et al. arXiv:2010.14527

Abbott, ..., DAB, et al. ApJ **832** L21 (2016)
Abbott,..., DAB et al. PRL **119** 161101 (2017)

Non-linear tides

- Energy from the inspiral can couple into interior stellar oscillation modes in neutron stars.

- This can excite a nonlinear, non-resonant instability of p and g modes Weinberg et al. (2013).

- Essick et al. (2016) developed a parametric model for examining p-g mode instabilities in gravitational wave data.

- Abbott et al. [Phys. Rev. Lett. 122, 061104 (2019)] show that the GW170817 is consistent with a signal that neglects p-g mode tides.

Consistency of GW170817 with non-linear tide model is due entirely to degeneracy of model with standard waveforms. Any **measurable** effects are ruled out.

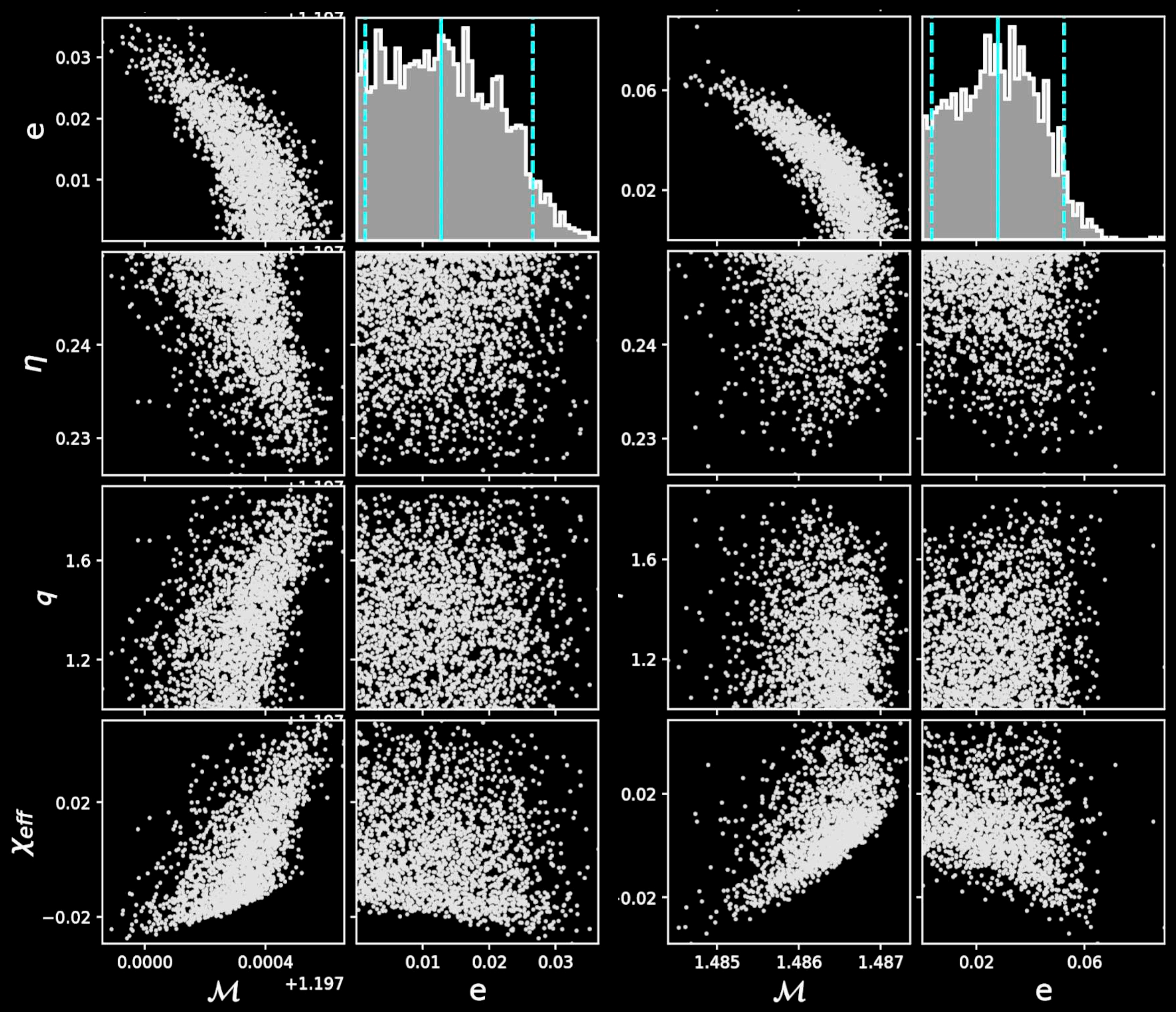
Steven Reyes

Reyes and DAB ApJ **894**, 41 (2020)

Eccentric Binaries

If the binary's orbit is eccentric rather than circular then this will change the gravitational waves radiated. See e.g. Moore and Yunes GQG **36** 185003 (2019)

Use GW170817 and GW190425 to constrain eccentricity



$e \leq 0.024$ (GW170817)
$e \leq 0.048$ (GW190425)

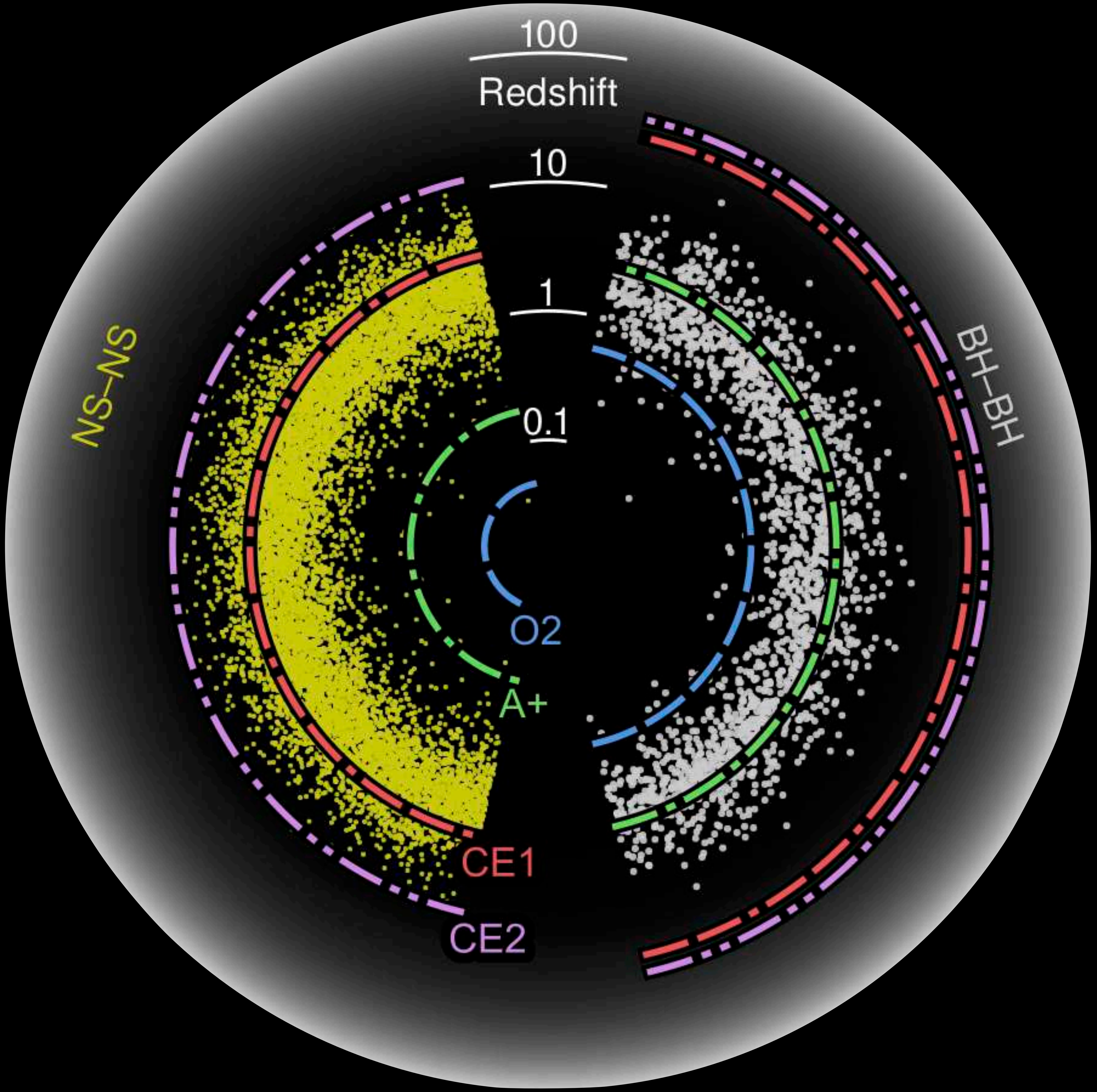
90% confidence

Amber Lenon

Lenon, Nitz, DAB MNRAS **497**, 1966 (2020)

Cosmic Explorer

Binary mergers throughout cosmic time



Reitze, ..., DAB, et al. arXiv:1907.04833

Cosmic Explorer

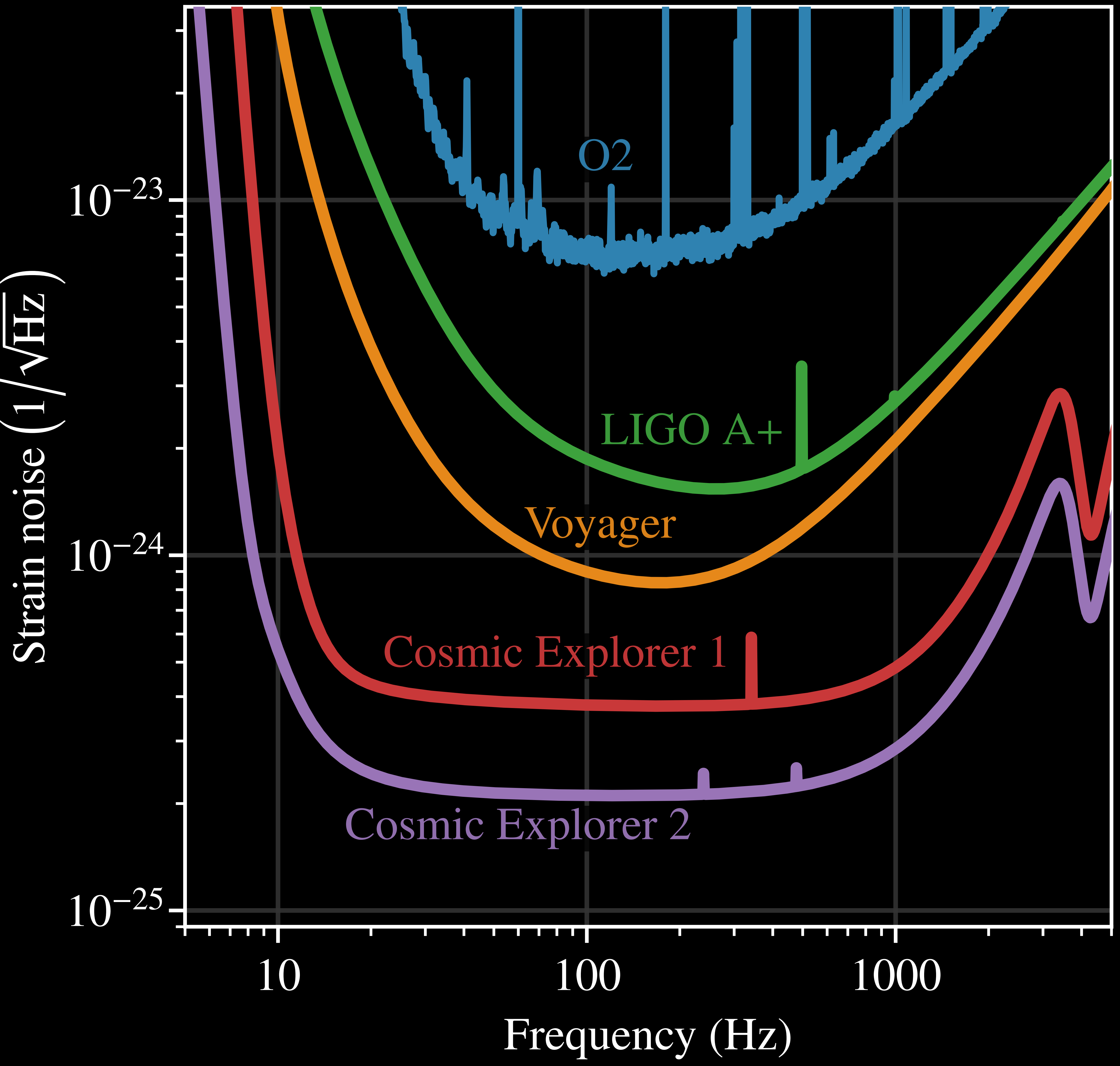
- Facility: 40km L-shaped detector on Earth's surface
- 14cm wide laser beams, 2 MW laser
- R&D progress needed in optical coatings, quantum noise, thermal compensation
    - Year ~ 2030 and ~ 1B USD

Reitze, ..., DAB, et al. arXiv:1907.04833

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

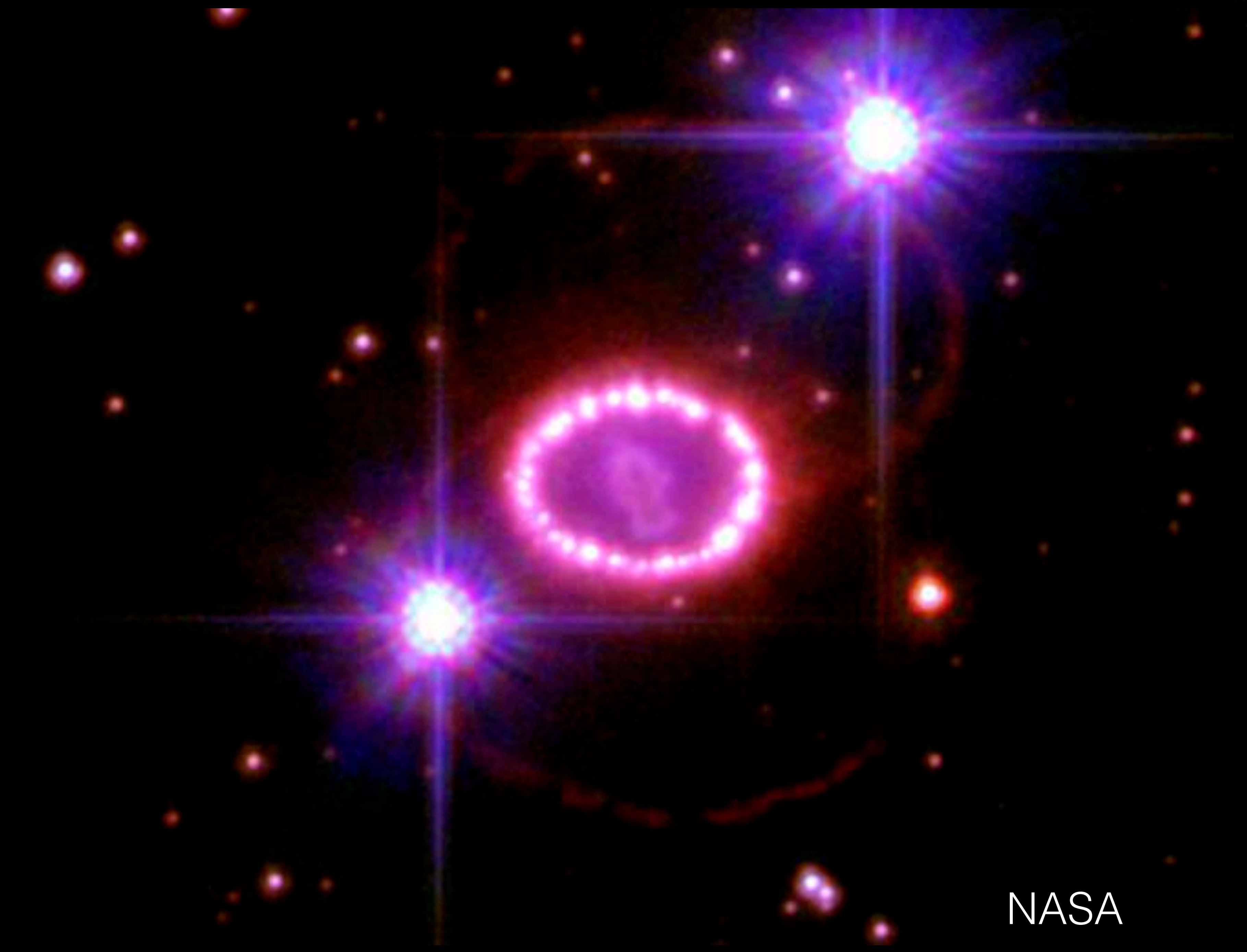
Reitze, ..., DAB, et al. arXiv:1907.04833

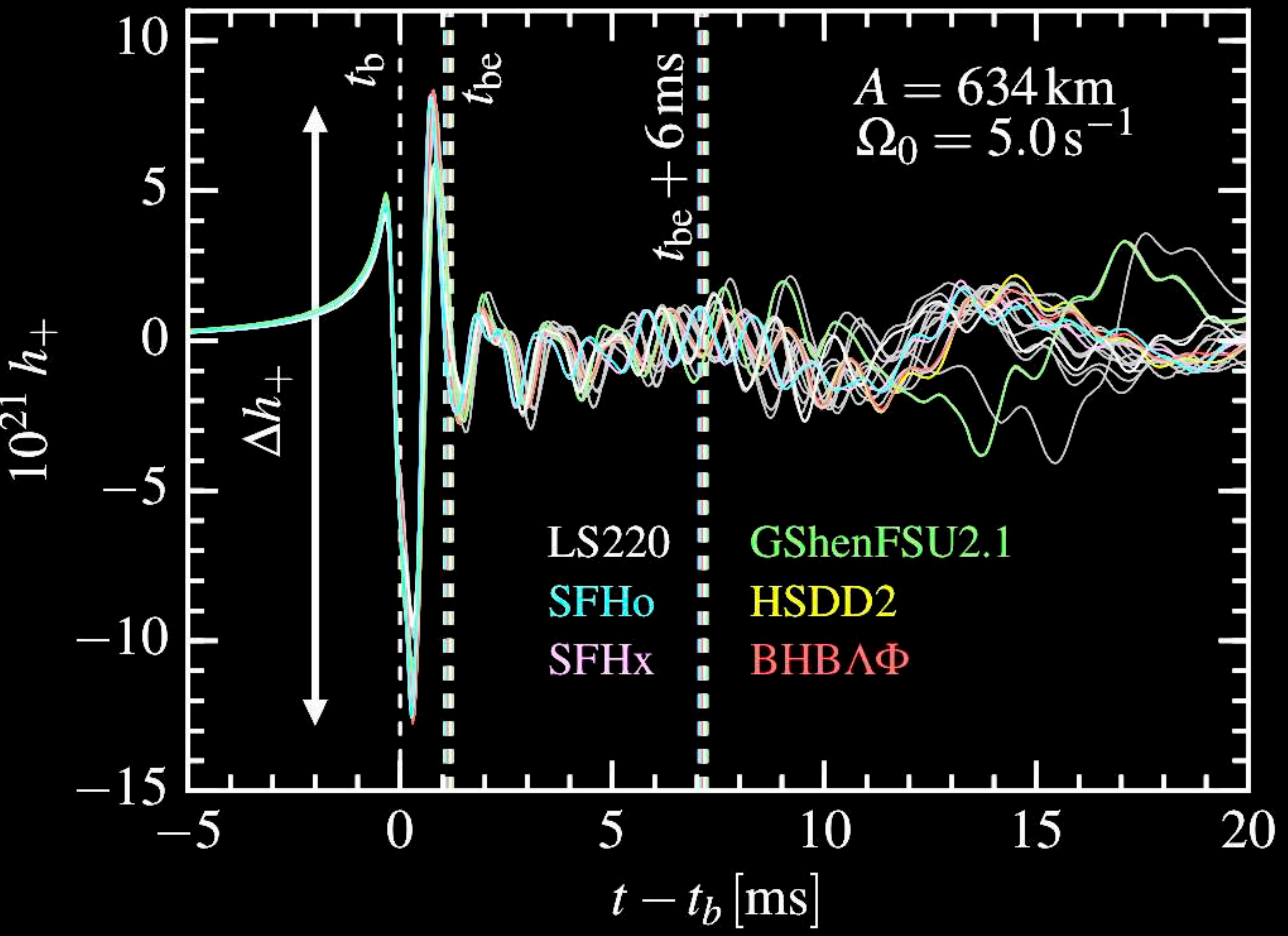


Interested in Cosmic Explorer?

https://cosmicexplorer.org/consortium.html

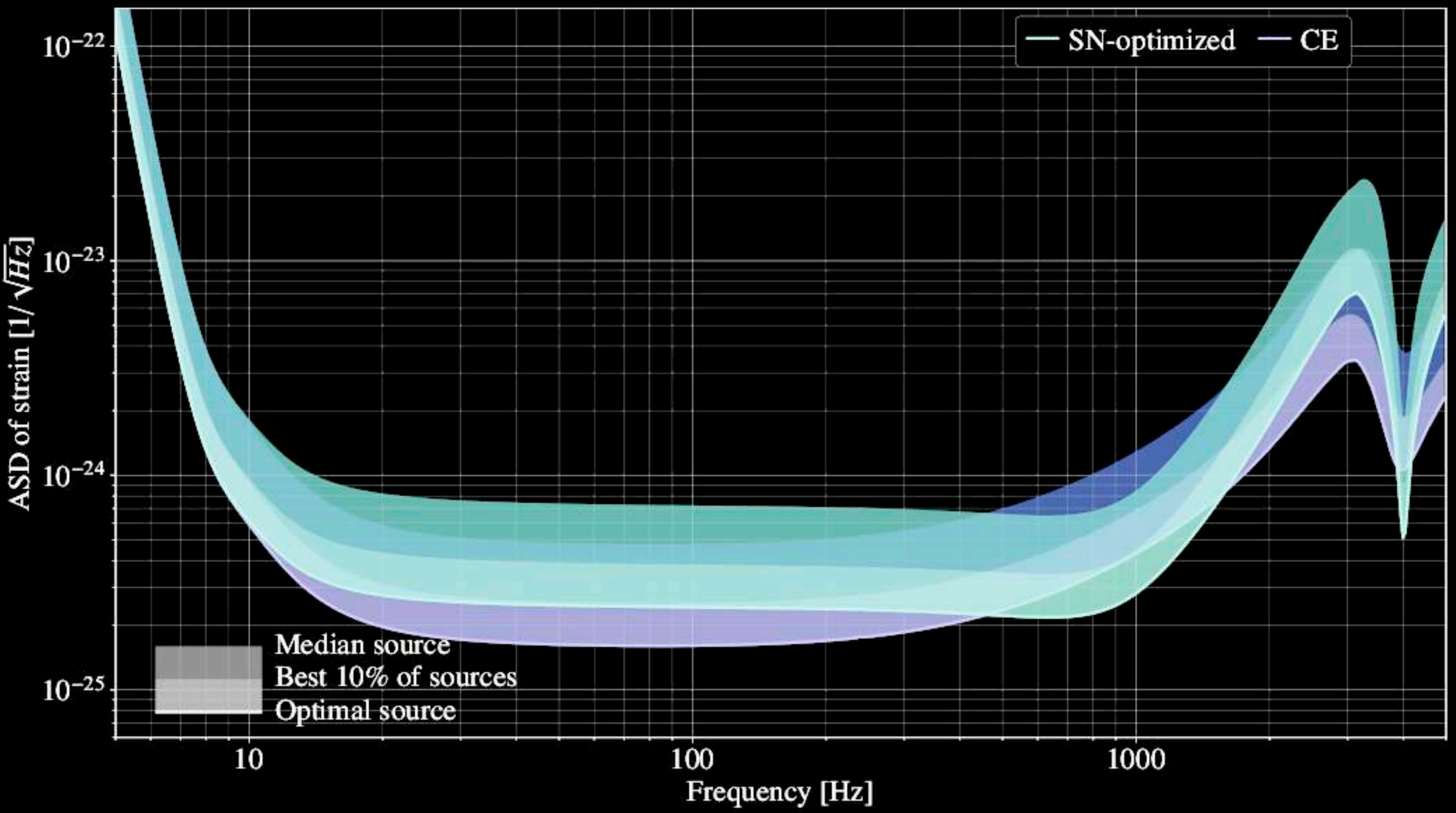
Can we optimize Cosmic Explorer to detect gravitational waves from core collapse supernovae?


NASA



Richers et al. PRD **95** 063019 (2017)

Supernovae in Cosmic Explorer



70 kpc at SNR 8

95 kpc at SNR 8

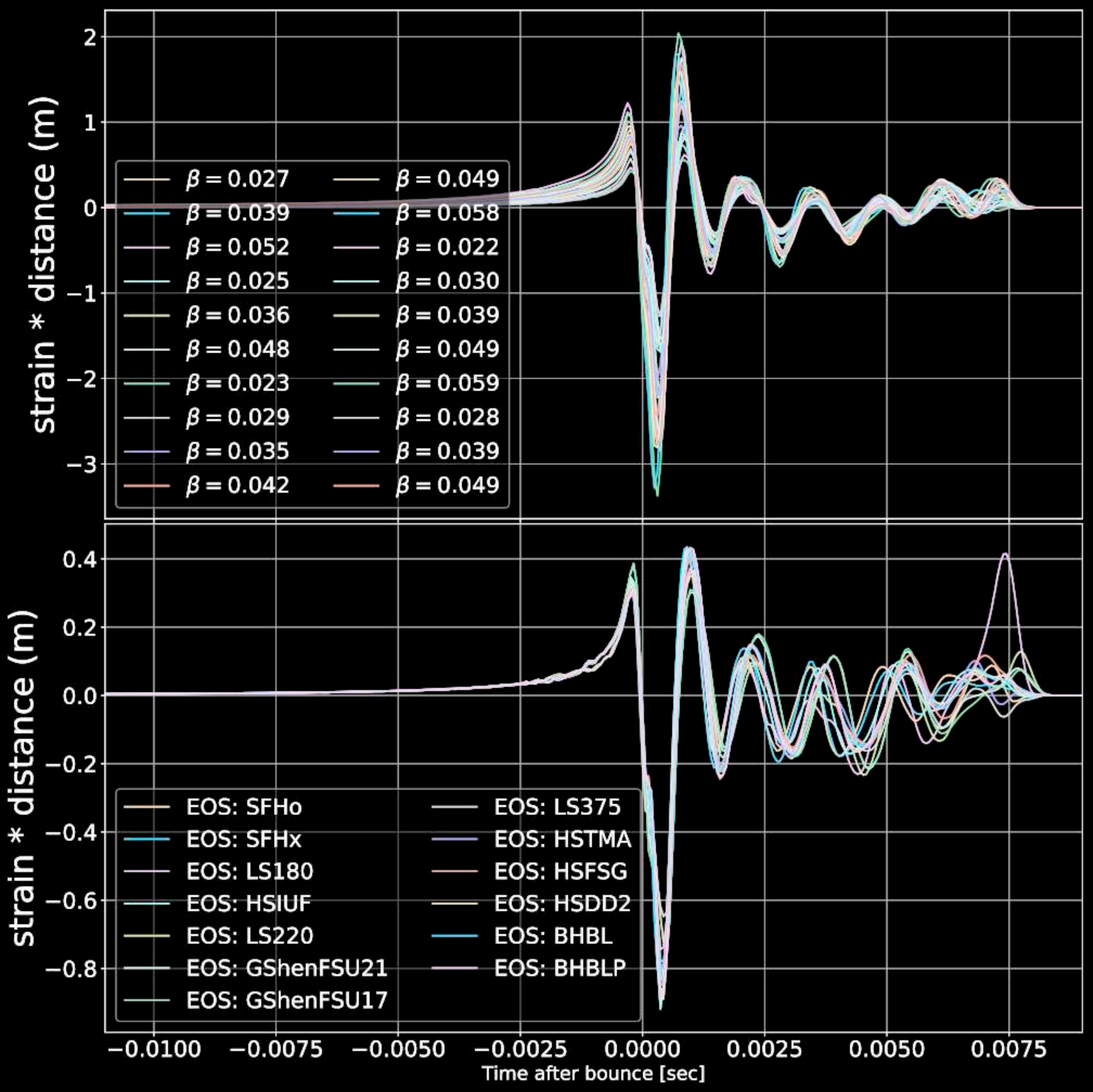
c.f. DUNE

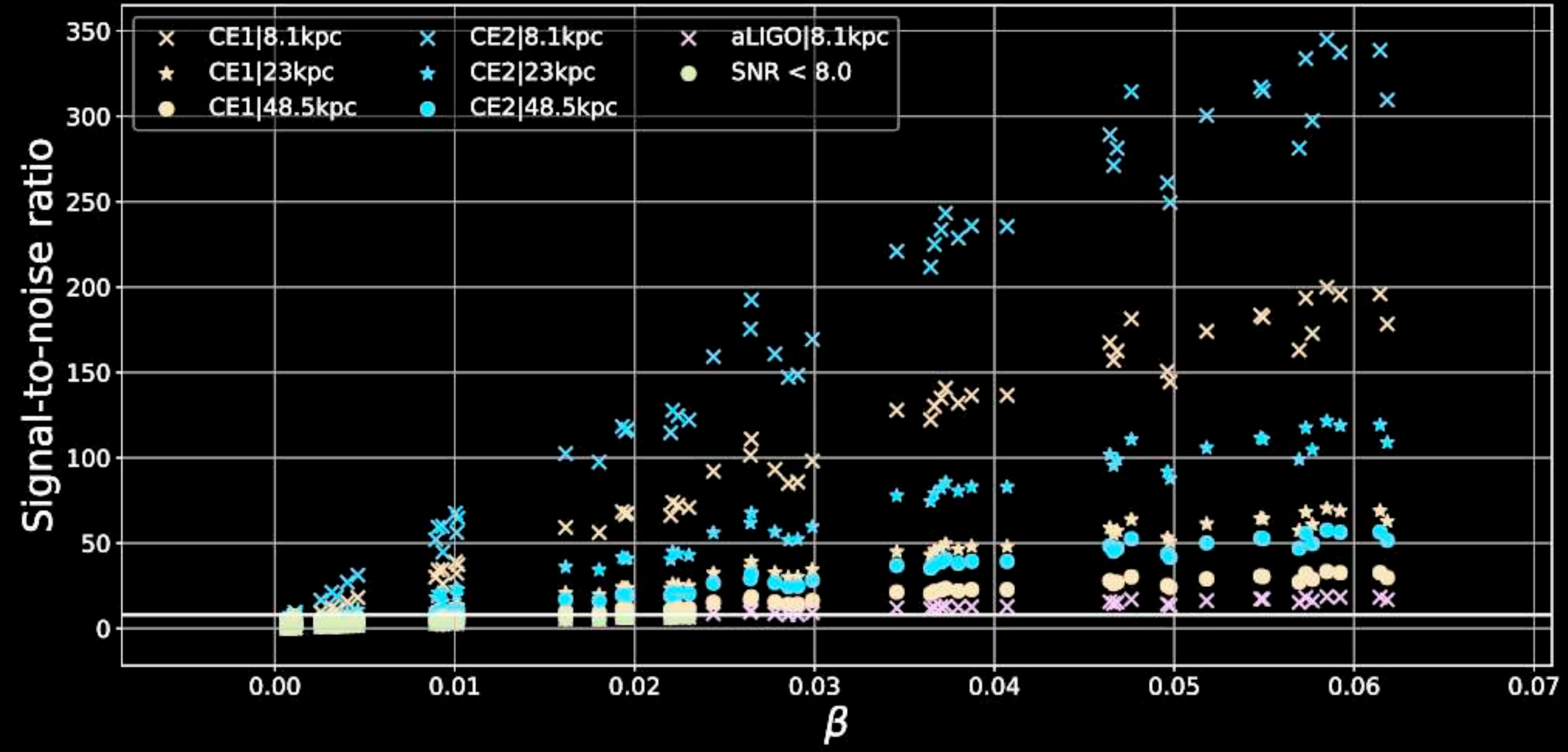
Srivastava, Ballmer, DAB, Afle, Burrows, Radice, Vartanyan PRD **100**, 043026 (2019)

- Can we measure the parameters of the progenitor star?
- Try to extract ratio of core's rotational kinetic energy to gravitational potential energy β (primarily from the bounce)
- Try to extract the equation of state (primarily from the post merger ringing of the protoneutron star)
- Use Richers et al. catalog of supernovae waveforms to constrict a principal component basis to extract physical parameters

Afle and DAB arXiv:2010.00719 to appear in PRD

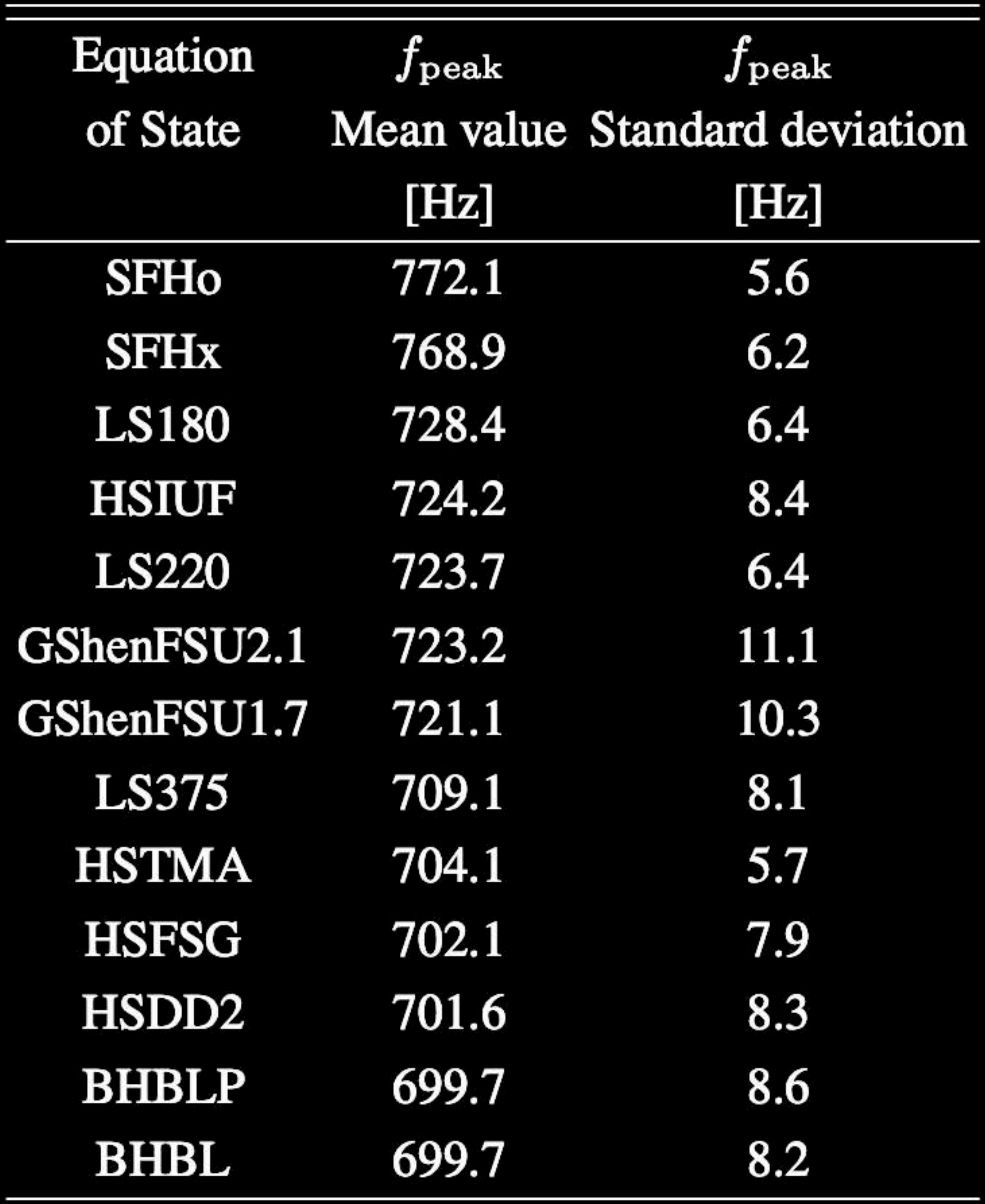
Build a Bayesian measurement algorithm using PCA and test with simulations





Generate posteriors on β and f_{peak}

Afle and DAB arXiv:2010.00719 to appear in PRD



Equation of State	f_{peak} Mean value [Hz]	f_{peak} Standard deviation [Hz]
SFHo	772.1	5.6
SFHx	768.9	6.2
LS180	728.4	6.4
HSIUF	724.2	8.4
LS220	723.7	6.4
GShenFSU2.1	723.2	11.1
GShenFSU1.7	721.1	10.3
LS375	709.1	8.1
HSTMA	704.1	5.7
HSFSG	702.1	7.9
HSDD2	701.6	8.3
BHBLP	699.7	8.6
BHBL	699.7	8.2

For a galactic progenitor with β = 0.02,
90 % credible interval is
0.02 (aLIGO), 0.002 (CE)

A galactic supernova observed by
Cosmic Explorer could constrain
f_{peak} to within 10 Hz

Chaitanya Afle

Afle and DAB arXiv:2010.00719 to appear in PRD

- GW170817 has opened up a new era of EOS constraints
- Upcoming detections will provide yet more information (both from GW and EM)
- Improvements to aLIGO and future detectors (Cosmic Explorer) will give precision measurements of neutron stars, post-merger signatures, and possibly supernovae!


NSF