Dense matter inference: promises and challenges with next-generation observations

Nuclear Physics in Mergers - Going Beyond the Equation of State

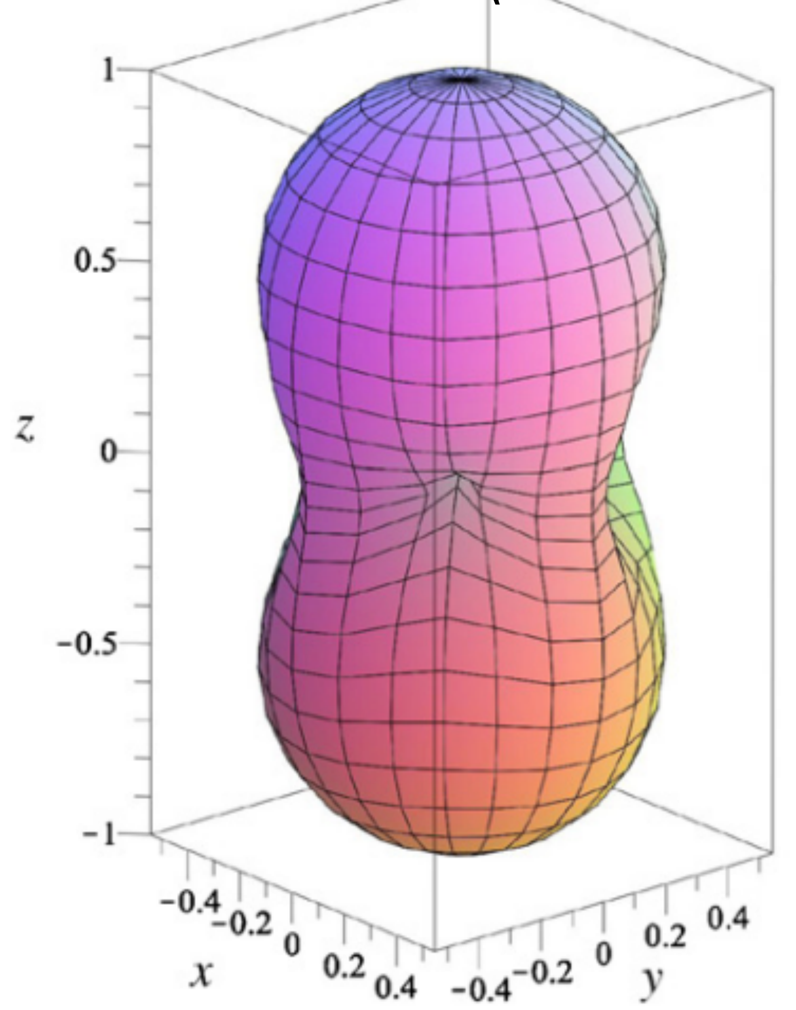
Jocelyn Read, Sept 8 2025

NICHOLAS AND LEE BEGOVICH GW PAC Center for Gravitational-Wave Physics and Astronomy

LIGO VIRGO KAGRA

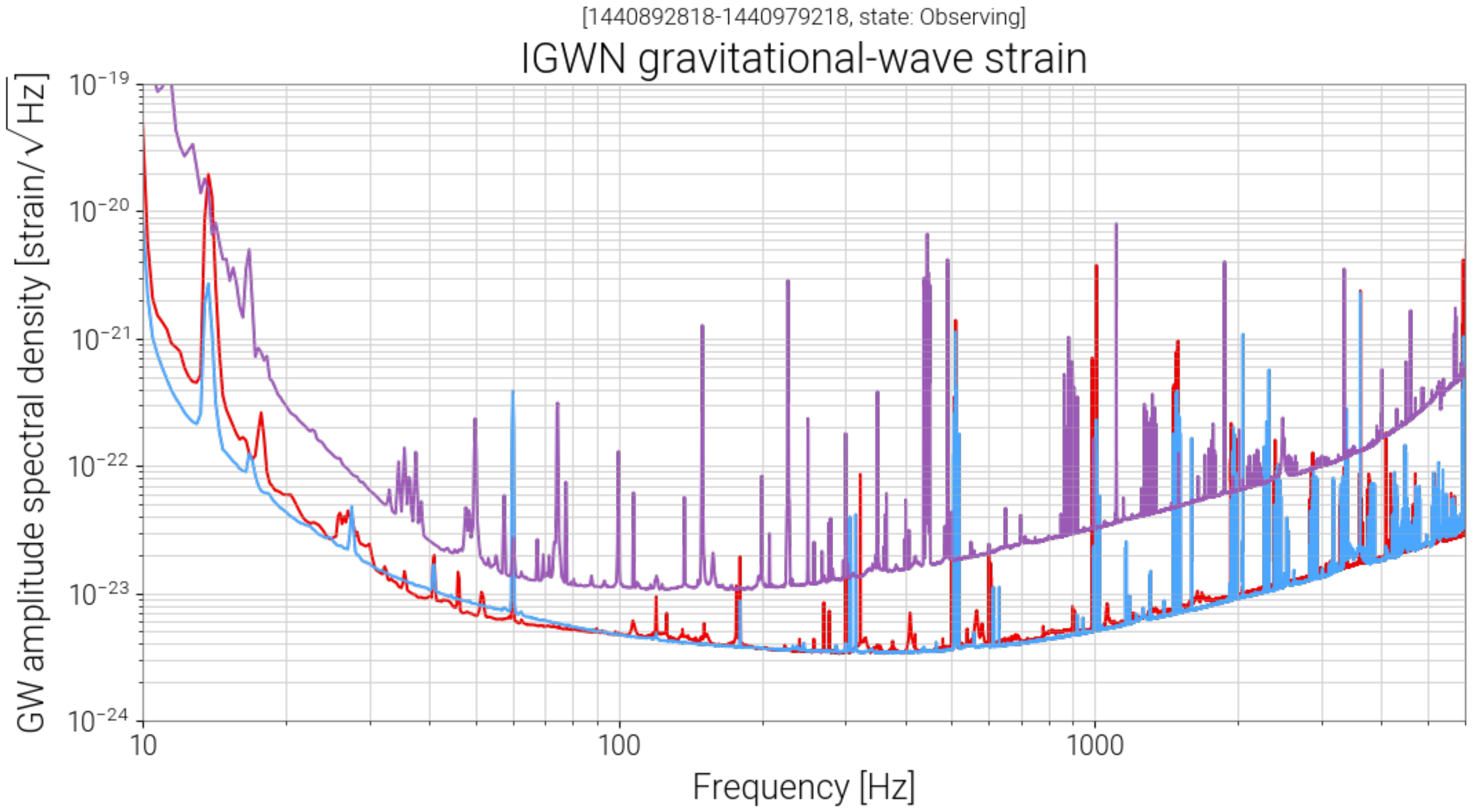
COSMIC EXPLORER

Single-detector antenna amplitude pattern (Schutz 2011)

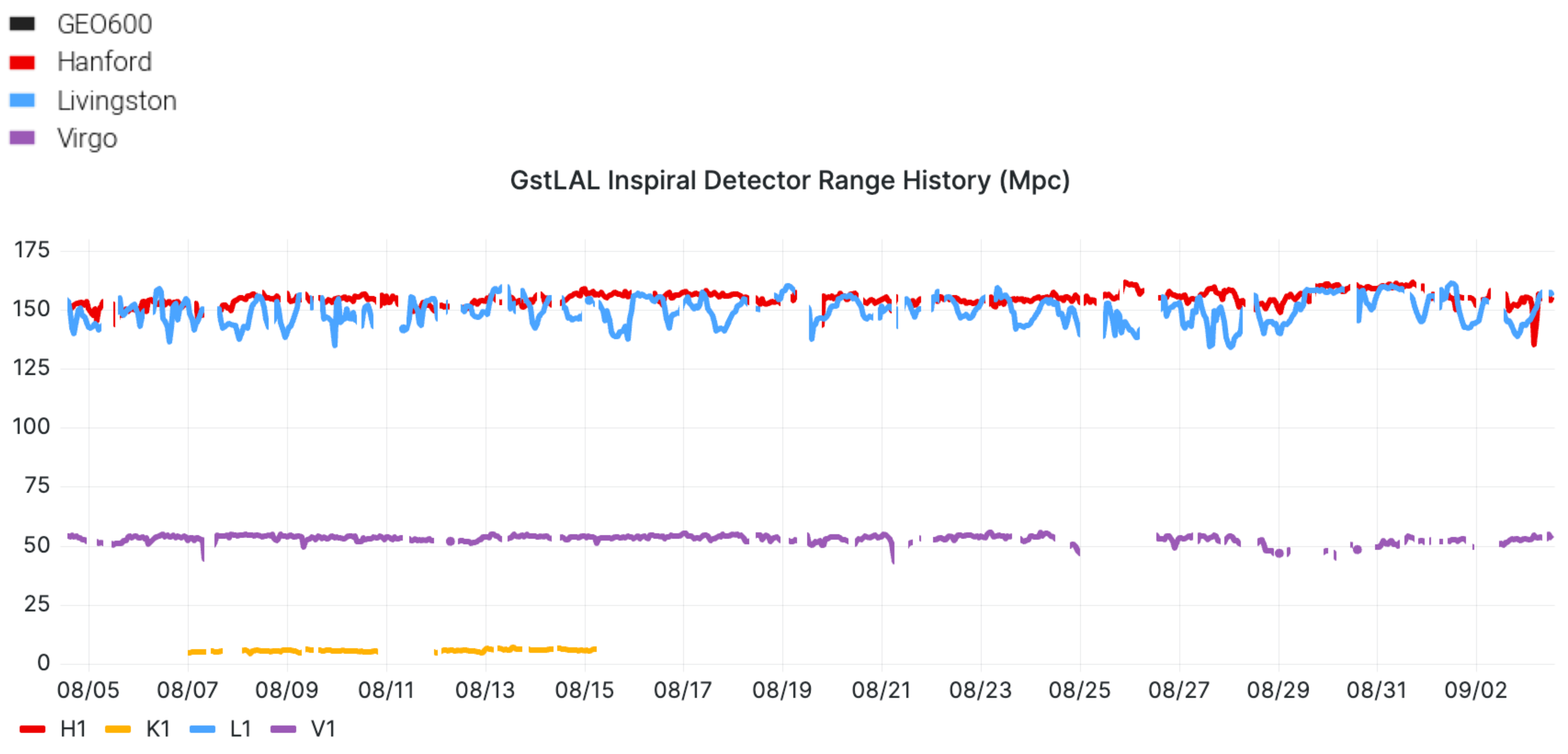


Detector Sensitivity and Reach

- Spectral density $S_n(f)$: steady signal at f has SNR $\propto h_0\sqrt{T}/\sqrt{S_n(f)}$
- Range: distance to a 1.4-1.4 $M_\odot$ binary merger with single-detector SNR 8, averaged over sky location and orientation relative to detector



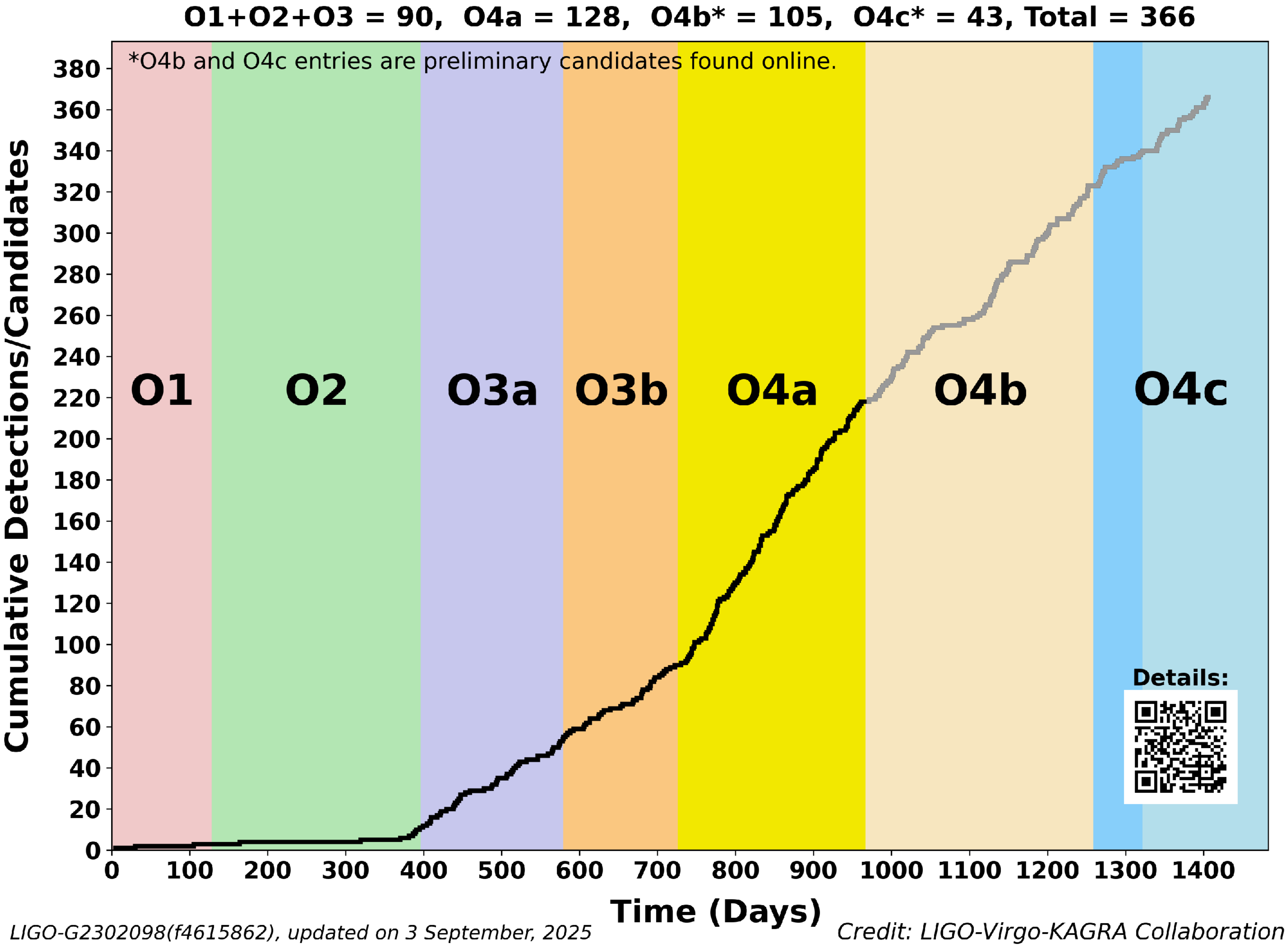
https://gwosc.org/detector_status/20250903/



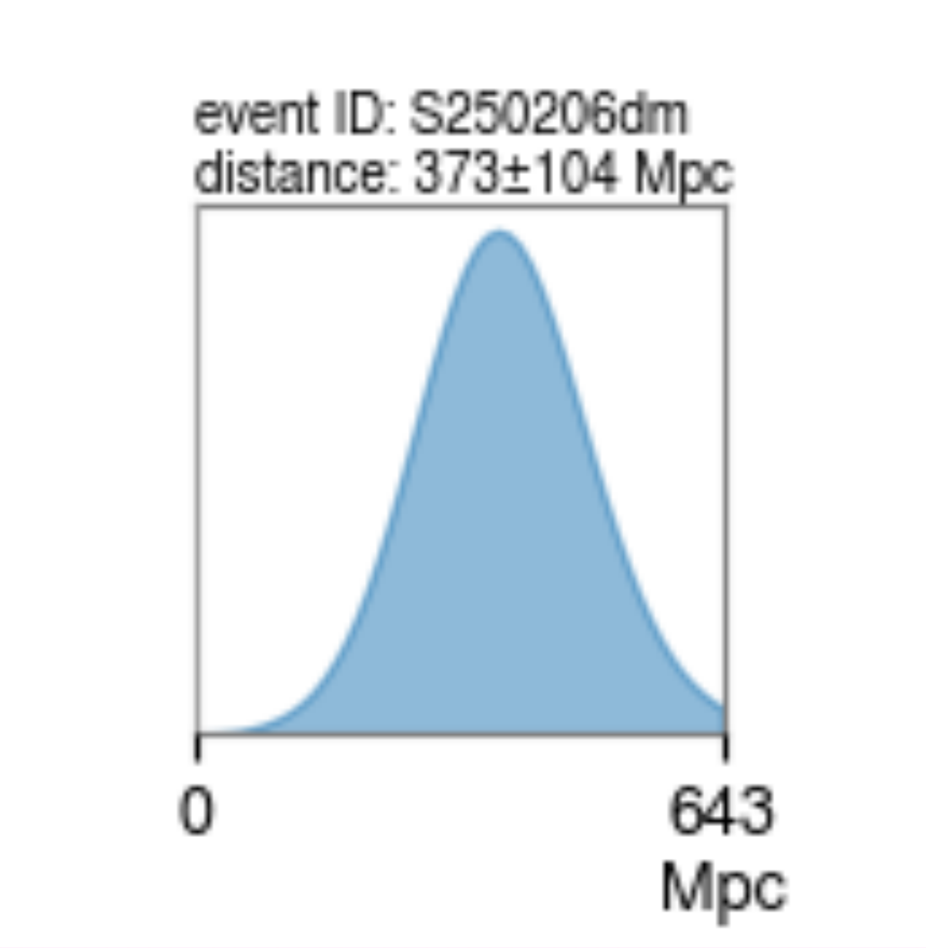
Hanford & Livingston ~ 160 Mpc, Virgo ~ 50 Mpc
Kagra: K1 coming it at ~ 5 Mpc since 2025-06-10
https://online.igwn.org/

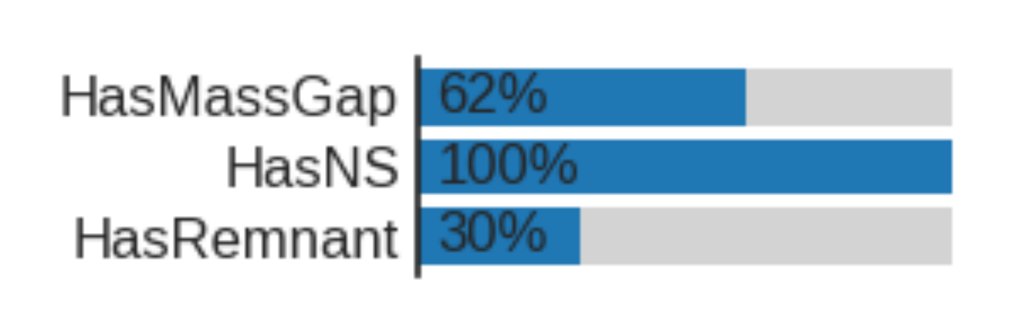
Observing Scenarios

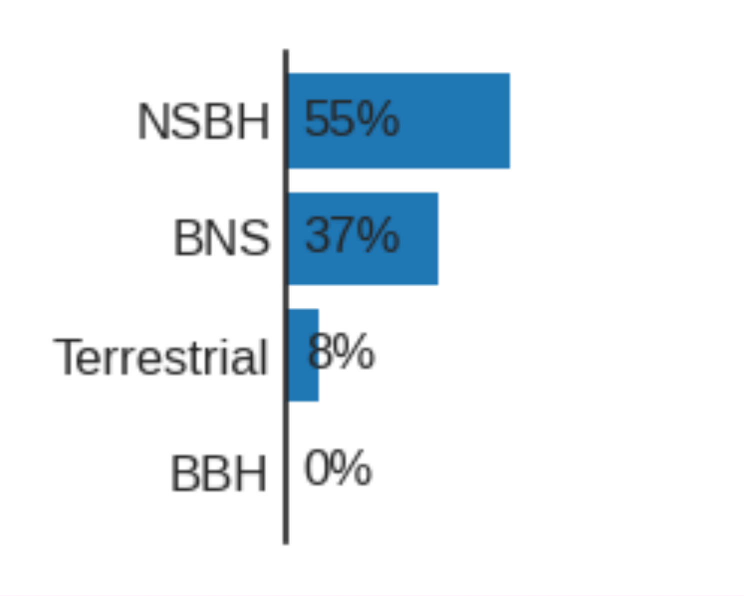
O4 continues through to November 2025

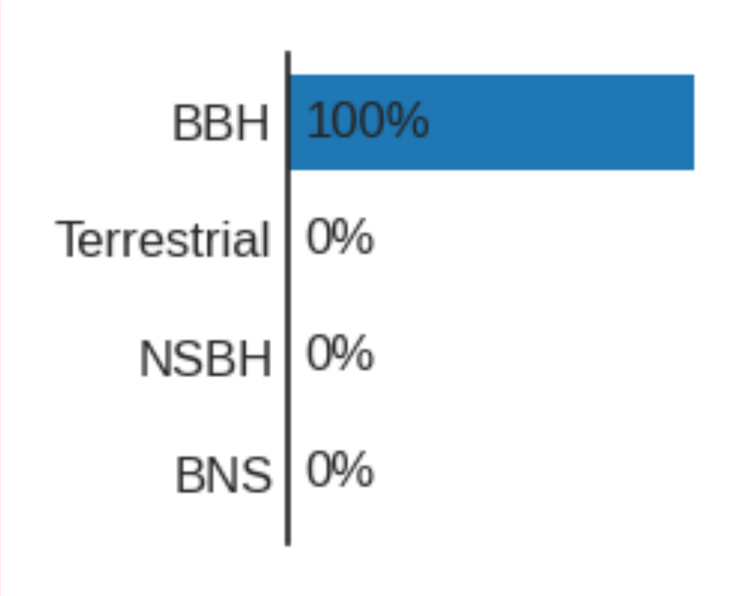

O1+O2+O3 = 90, O4a = 128, O4b* = 105, O4c* = 43, Total = 366
*O4b and O4c entries are preliminary candidates found online.
O1
O2
O3a
O3b
O4a
O4b
O4c
Details:
Cumulative Detections/Candidates
0
20
40
60
80
100
120
140
160
180
200
220
240
260
280
300
320
340
360
380
0
100
200
300
400
500
600
700
800
900
1000
1100
1200
1300
1400
Time (Days)
LIGO-G2302098(f4615862), updated on 3 September, 2025
Credit: LIGO-Virgo-KAGRA Collaboration

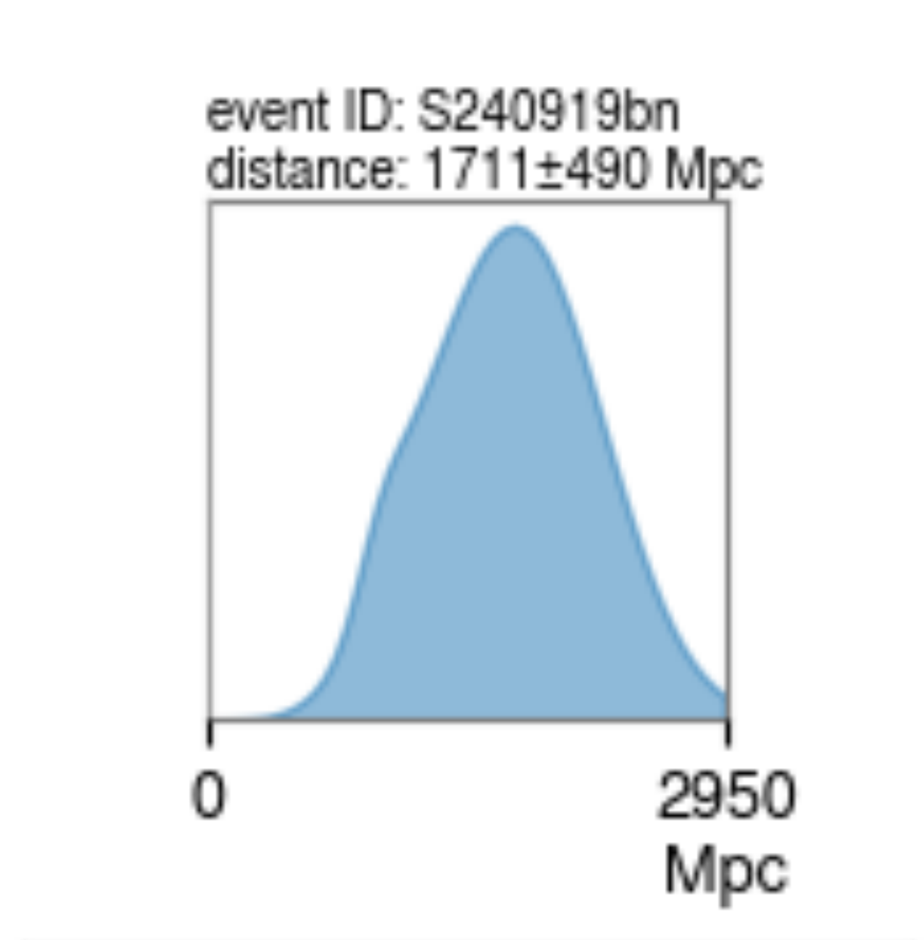
O4b& O4c: Well-localized 3-detector events

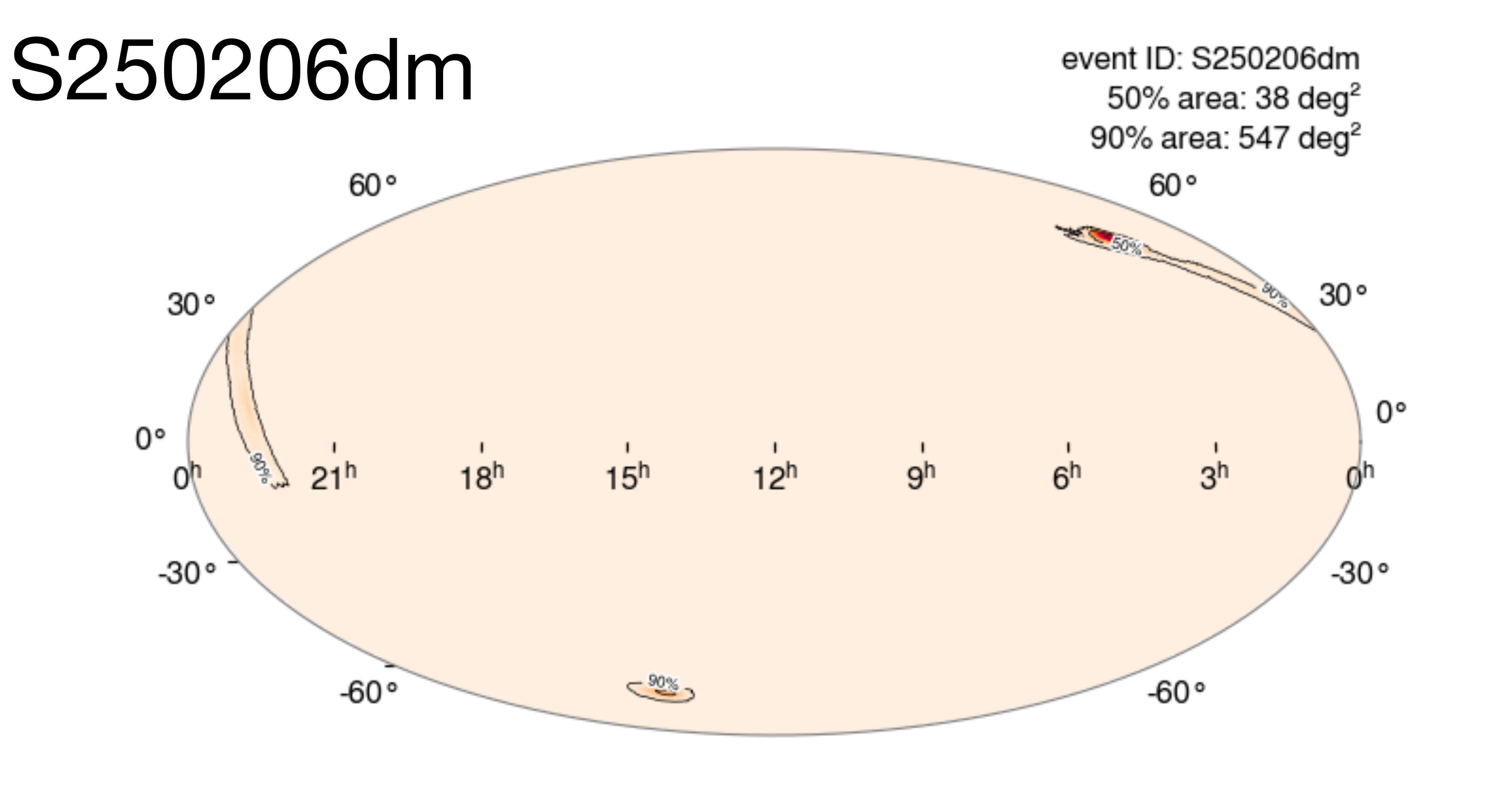




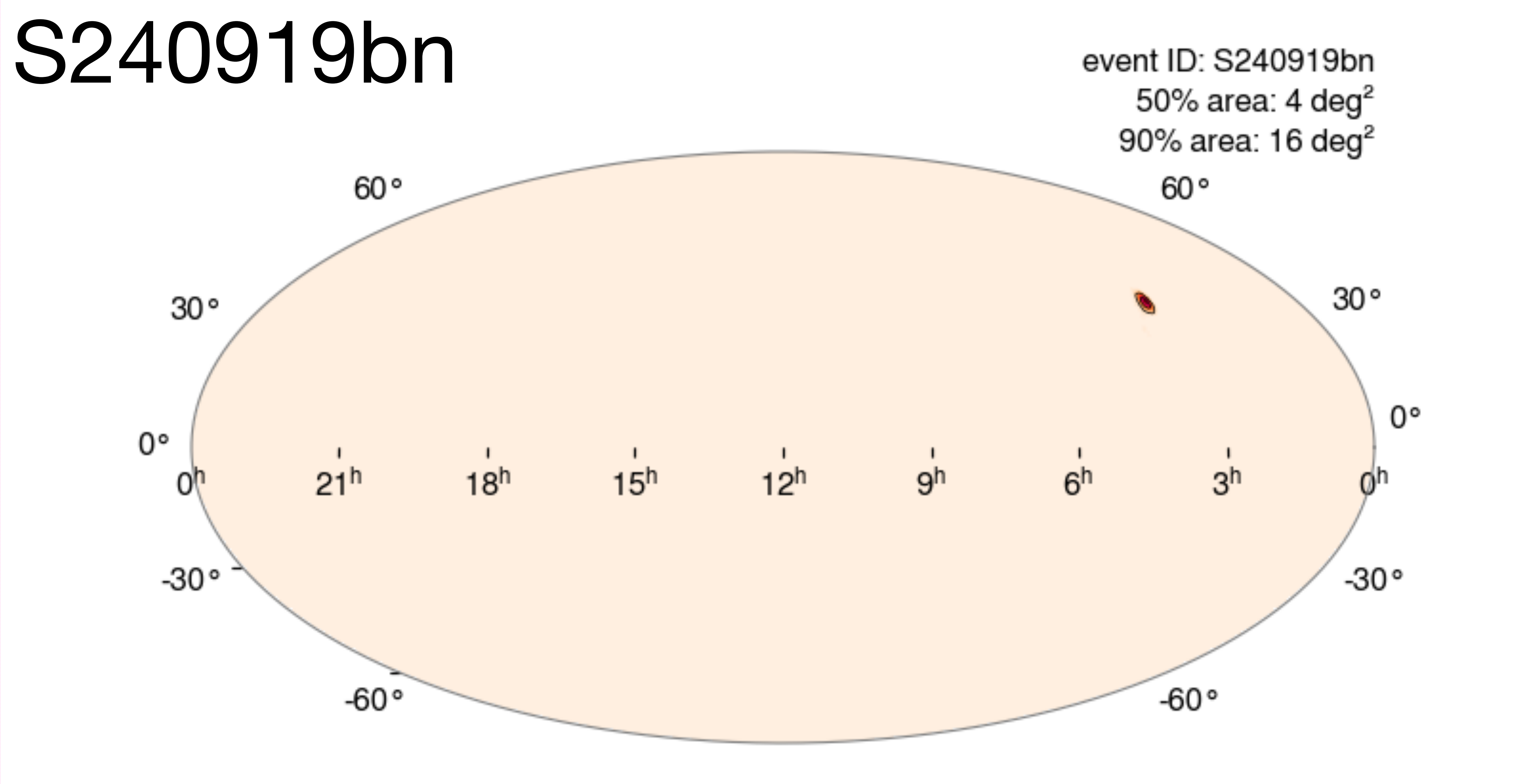








https://gracedb.ligo.org/superevents/S250206dm/view/

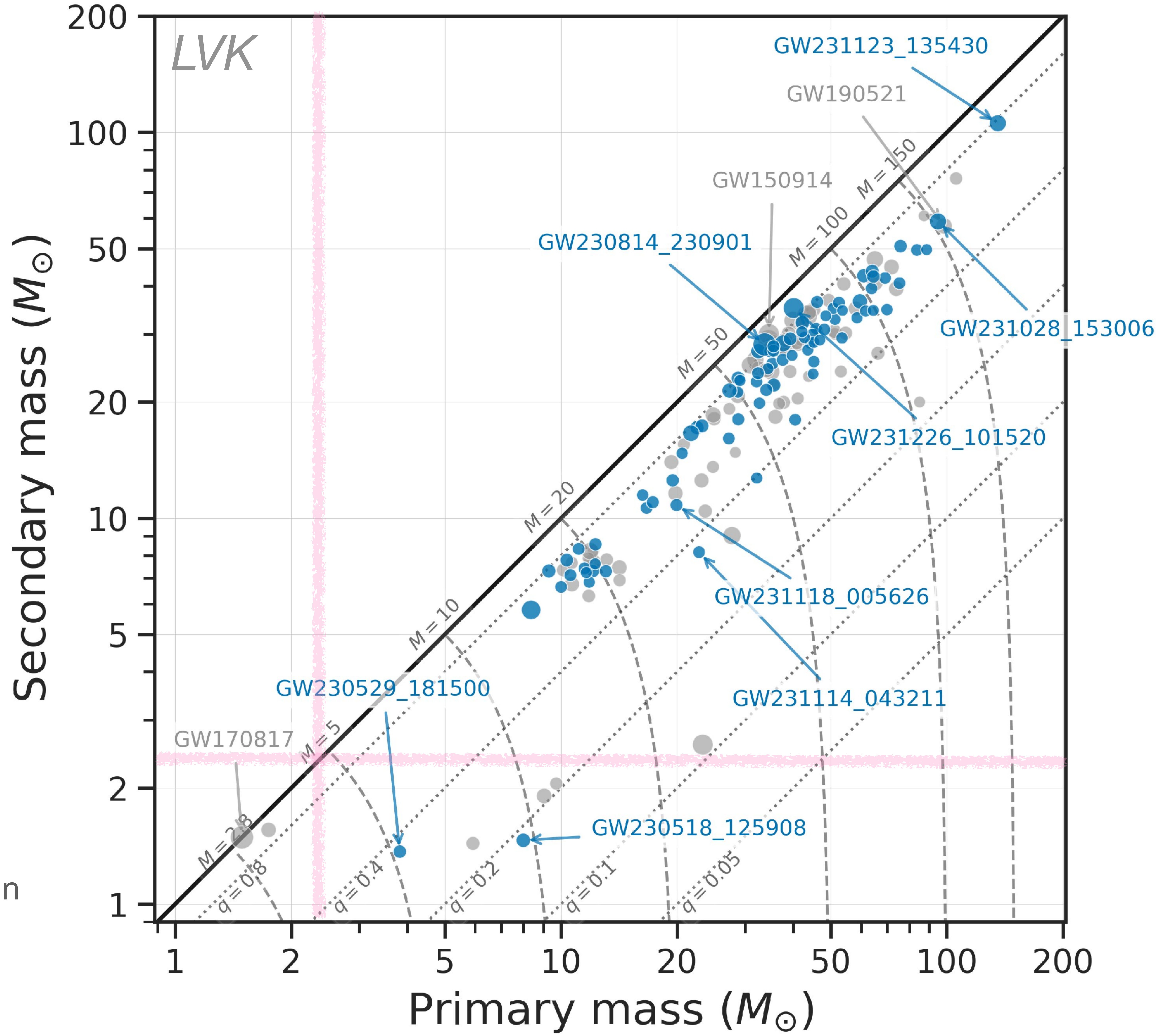


https://gracedb.ligo.org/superevents/S240919bn/view/

Observations

Compact binary mergers with public data

- O1+O2+O3+O4a:
  GWTC-4
  218 published events
  PE samples on
  https://gwosc.org/eventapi/
  & Zenodo



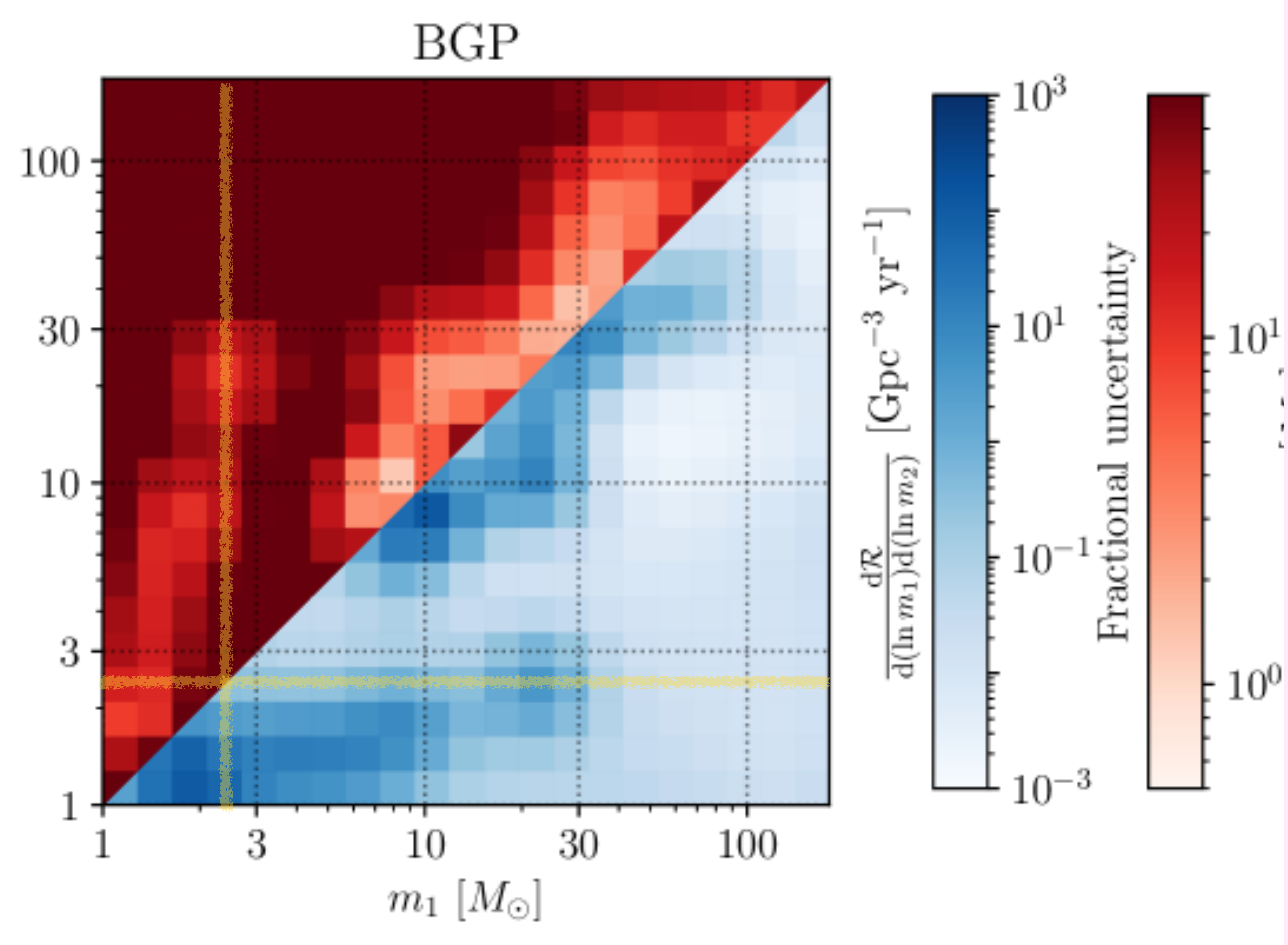
GWTC-4.0: Updating the Gravitational-Wave Transient Catalog with Observations from the First Part of the Fourth LIGO-Virgo-KAGRA Observing Run
LVK, arXiv:2508.18082

https://dcc.ligo.org/LIGO-G2302098-v15/public

Populations

Local source rates

- Well-measured BBH rates, peaks at $9M_\odot$ and $30M_\odot$
- BNS
  $7.6 - 260$ Gpc^{-3} yr^{-1}
- NSBH
  $9.1 - 84$ Gpc^{-3} yr^{-1}
- BBH
  $14 - 26$ Gpc^{-3} yr^{-1}

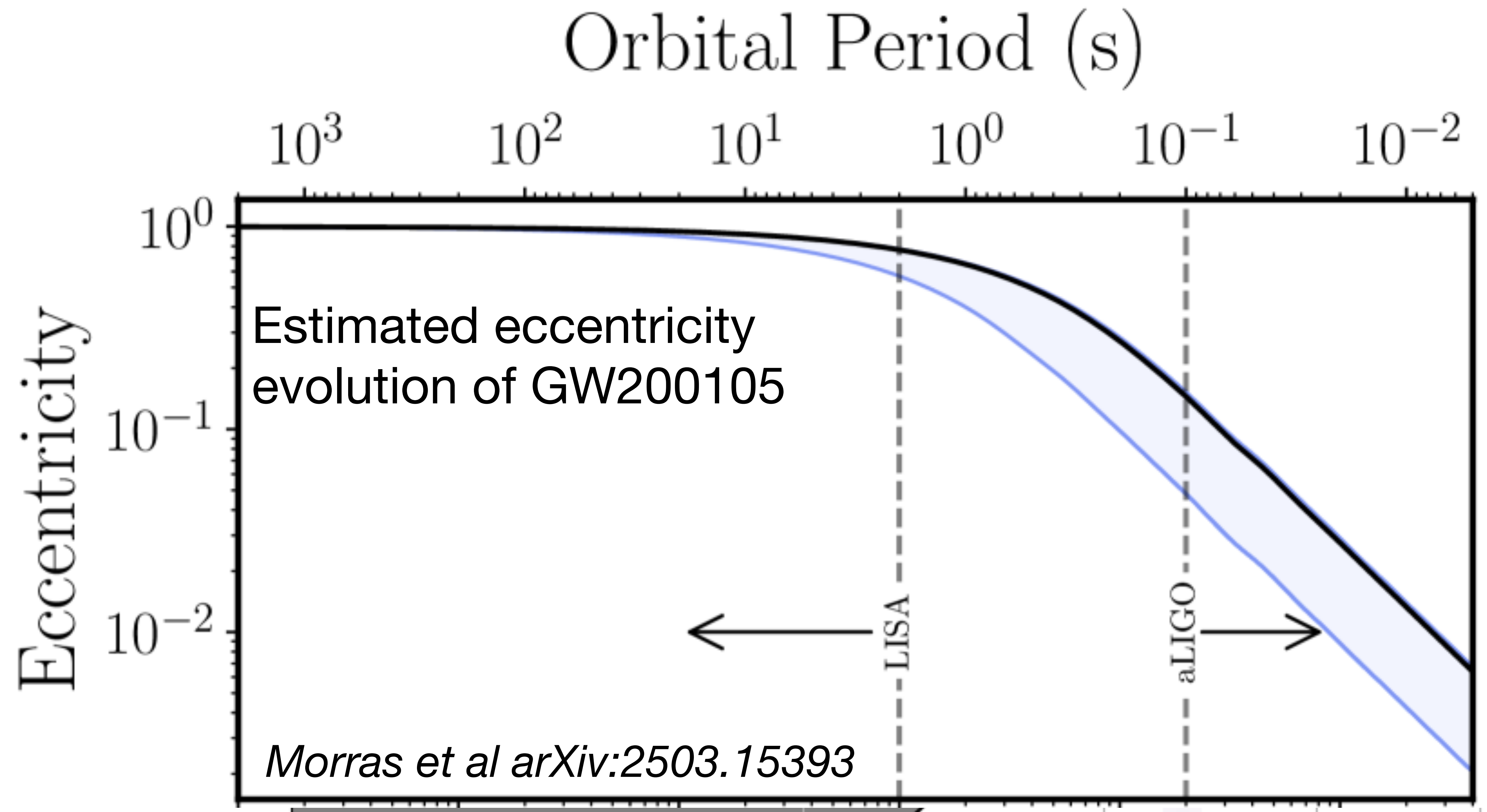


GWTC-4.0: Population Properties of Merging Compact Binaries, LVK, arXiv:2508.18083

Low-mass gravitational-wave observations

https://gwosc.org/

al-wave observations



with eccentricity?

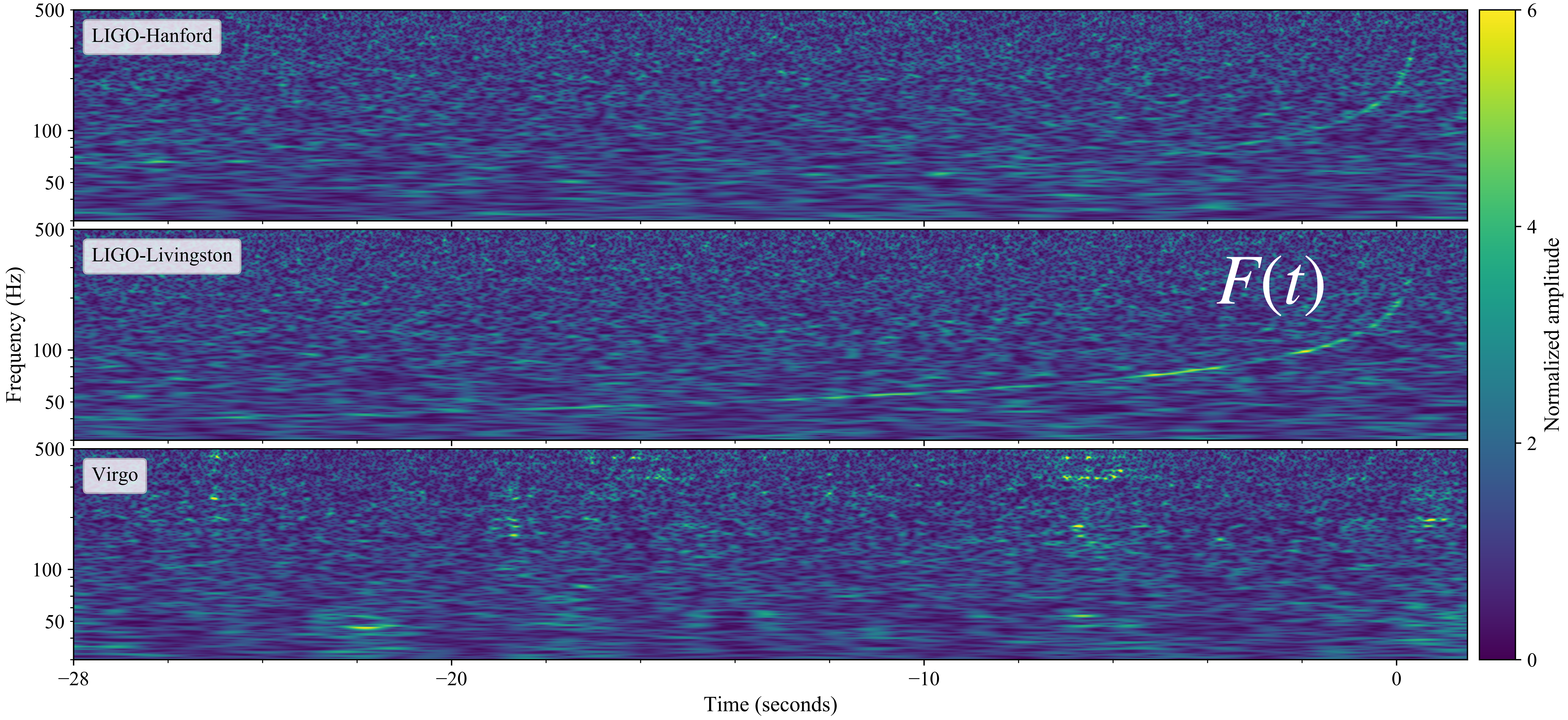
Morras et al arXiv:2503.15393

Planas et al arXiv:2506.01760

but Jan et al arXiv 2508.12460

Using GW to understand extreme matter

First neutron-star merger: GW170817



$$\mathscr{L}_{GW} \sim \frac{c^5}{G}\left(\frac{R_S}{s}\right)^2\left(\frac{v}{c}\right)^6$$

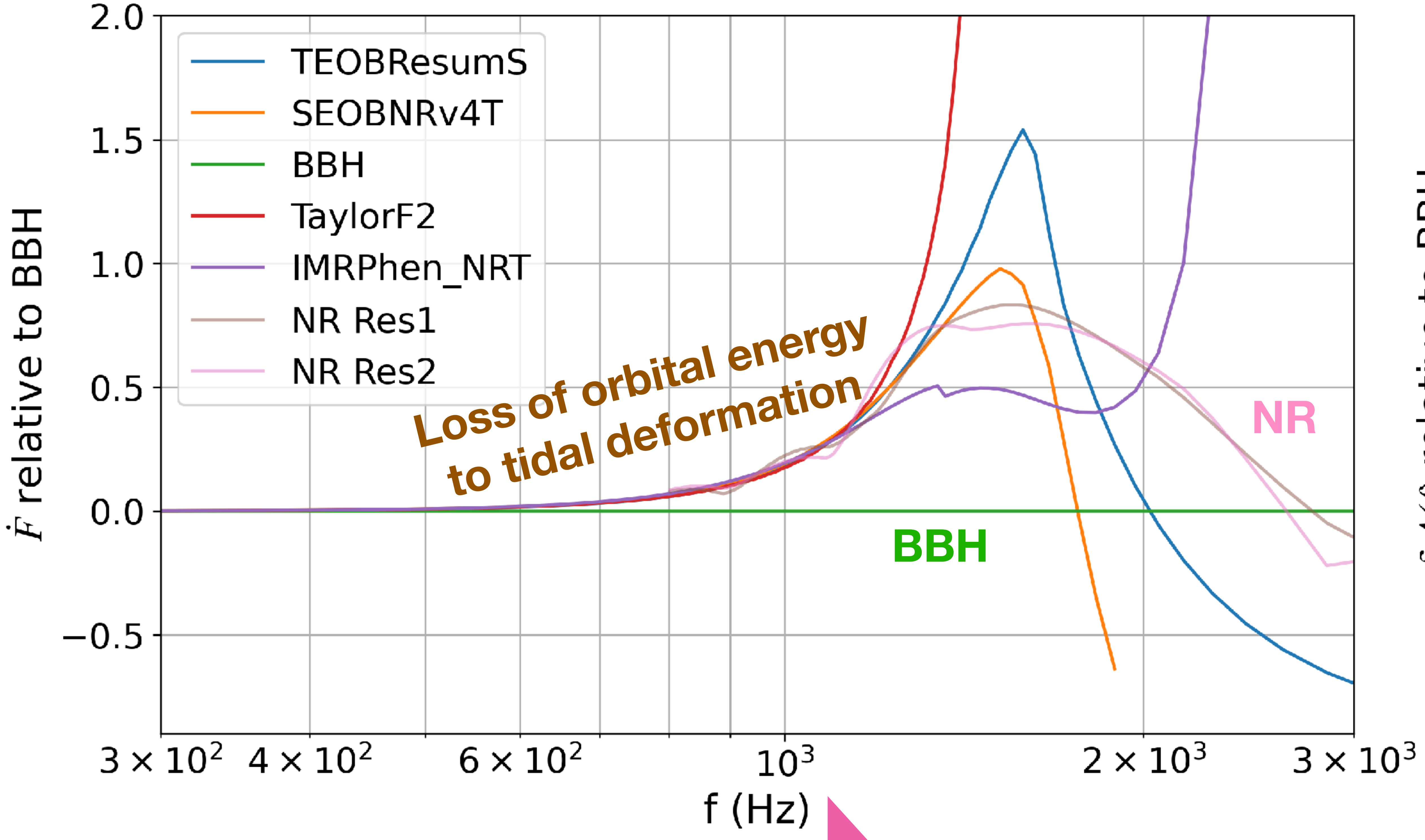
$$\sim 10^{59}\ \text{erg s}^{-1}\frac{R_S}{s}$$

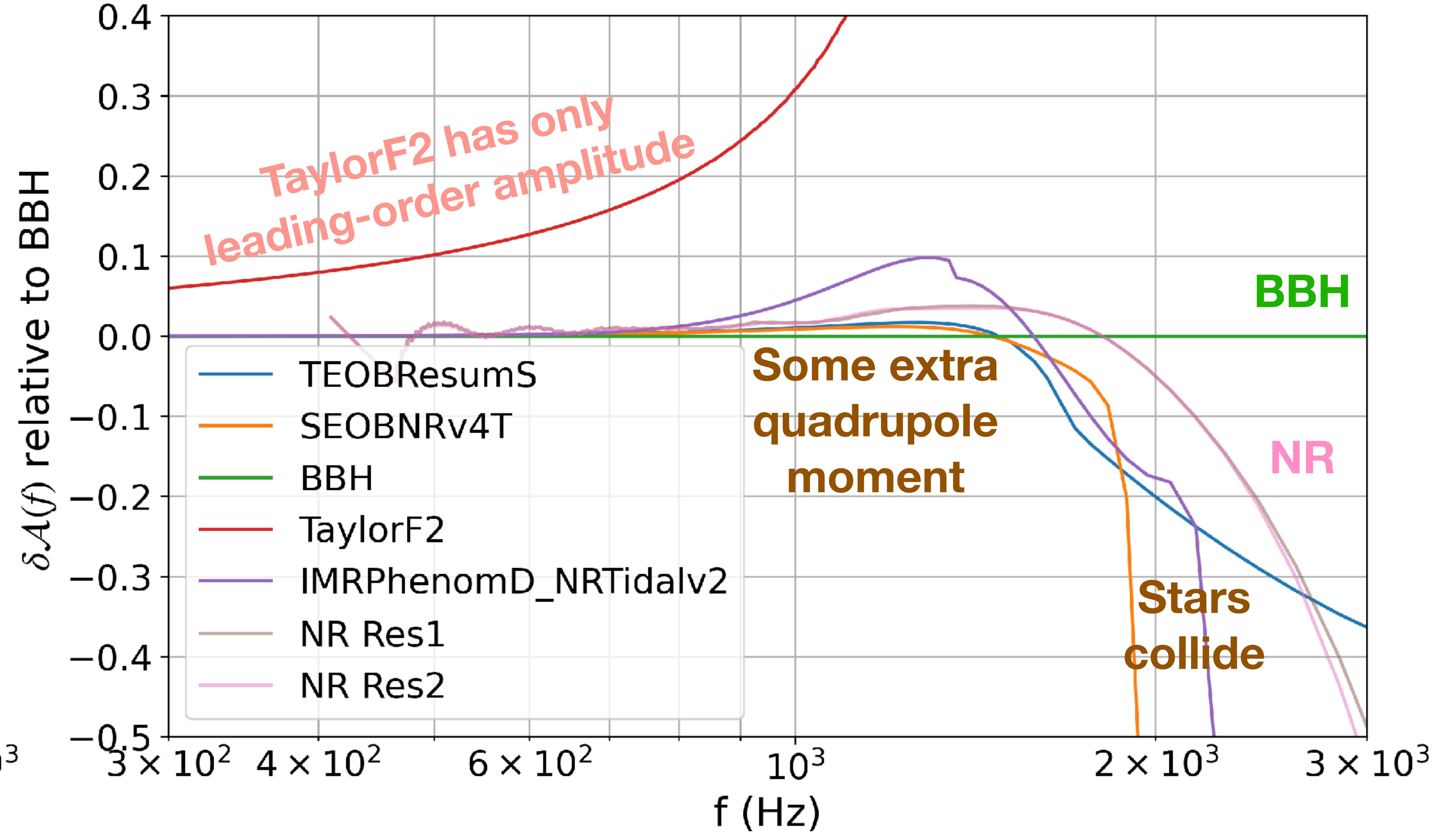
$$\dot{F}(F) = -\frac{\mathscr{L}(F)}{E'(F)}$$

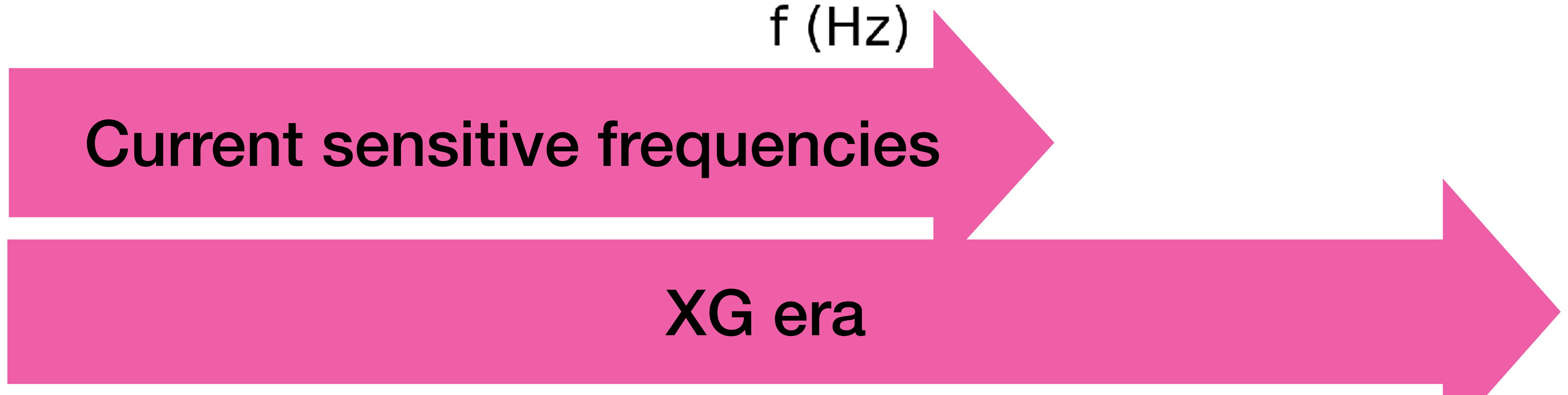
GW170817: Observation of Gravitational Waves from a Binary Neutron Star Inspiral, LIGO & Virgo Scientific Collaborations, Phys. Rev. Lett. 119 161101 (2017)

How matter modifies the "chirp"

At fixed masses, EOS: $\dot{F}(F) = -\frac{\mathscr{L}(F)}{E'(F)}$ $\mathscr{A}(F)^2 = \frac{4}{\pi}\frac{1}{d^2}\frac{1}{F^2}\mathscr{L}_{\mathrm{GW}}(F)$



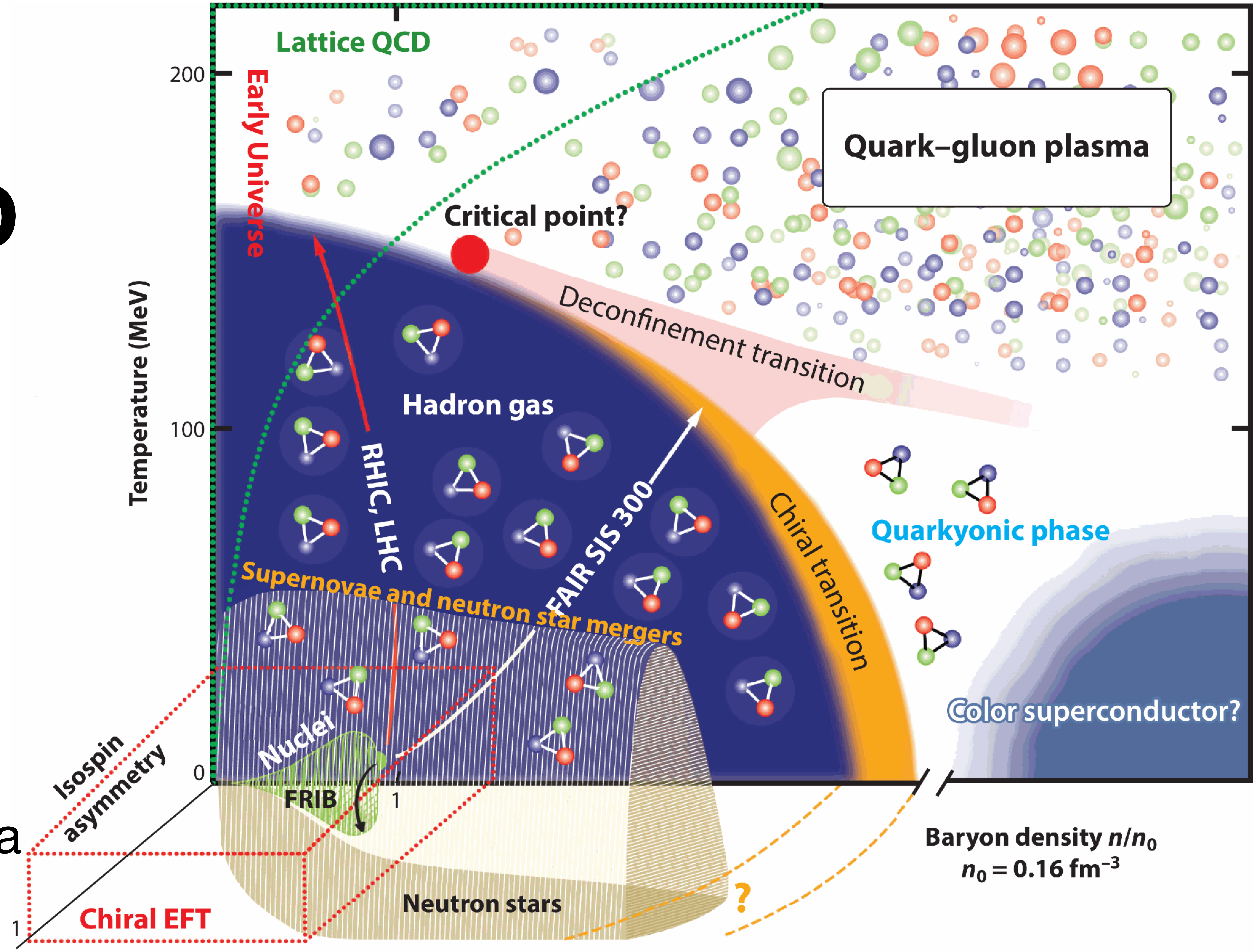




Read 2023 Class. Quantum Grav. 40 135002

The phase diagram of QCD

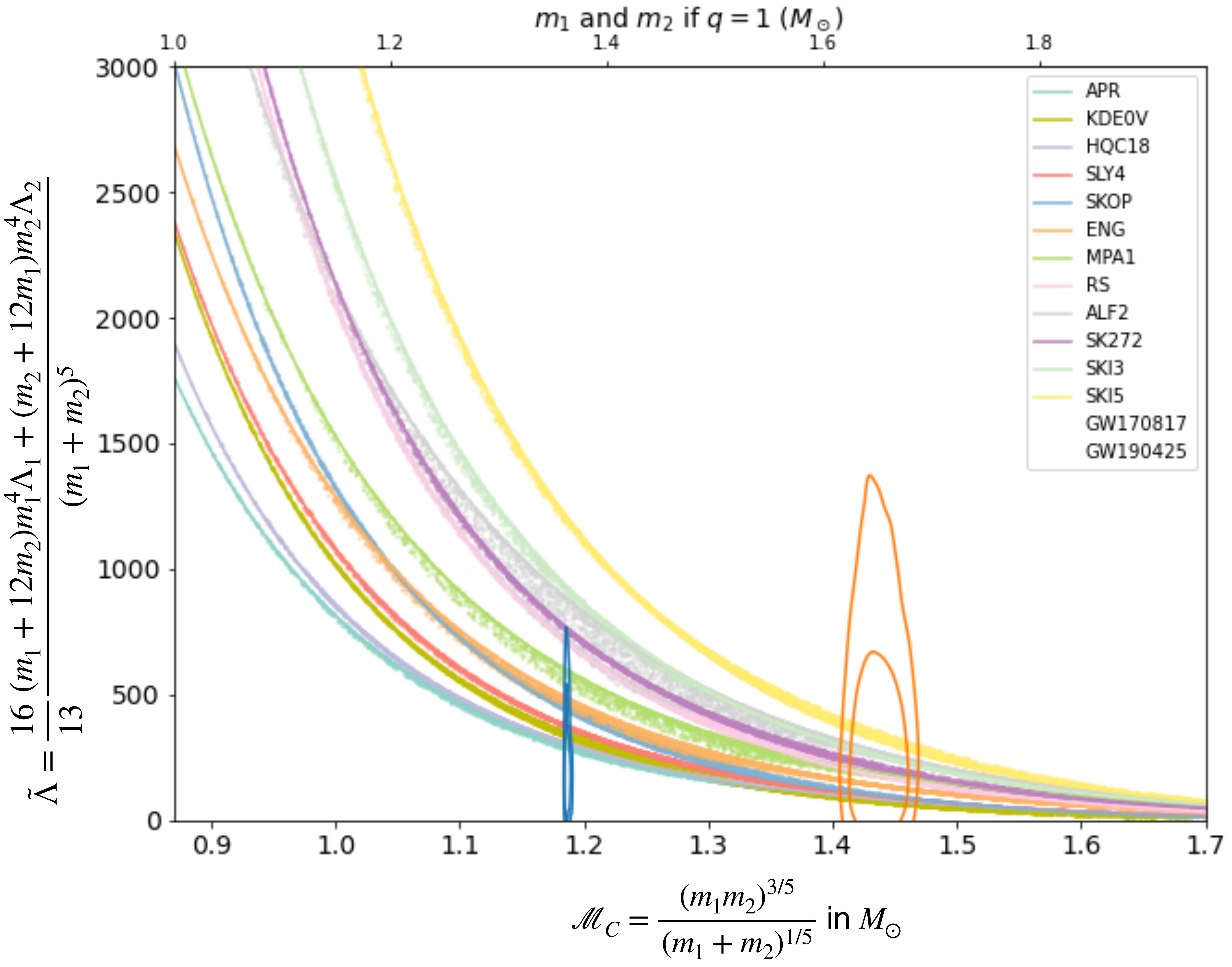
- Neutron star equation of state:
  - isospin asymmetry
  - above-nuclear density
- Inspiral - Cold equation of state: pressure vs density along a track set by beta equilibrium



Drischler C, et al. 2021
Annu. Rev. Nucl. Part. Sci. 71:403–32

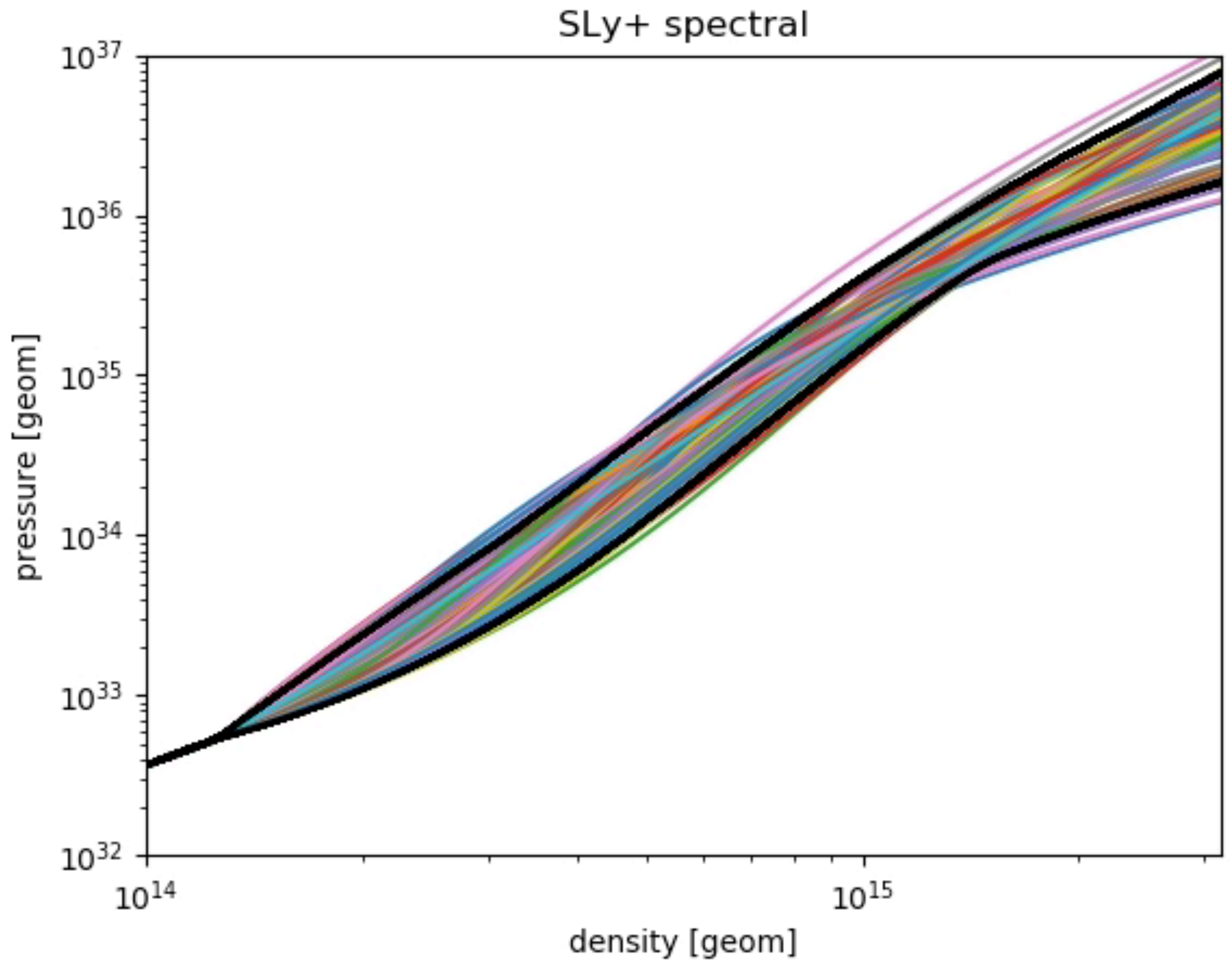
EoS GW implications

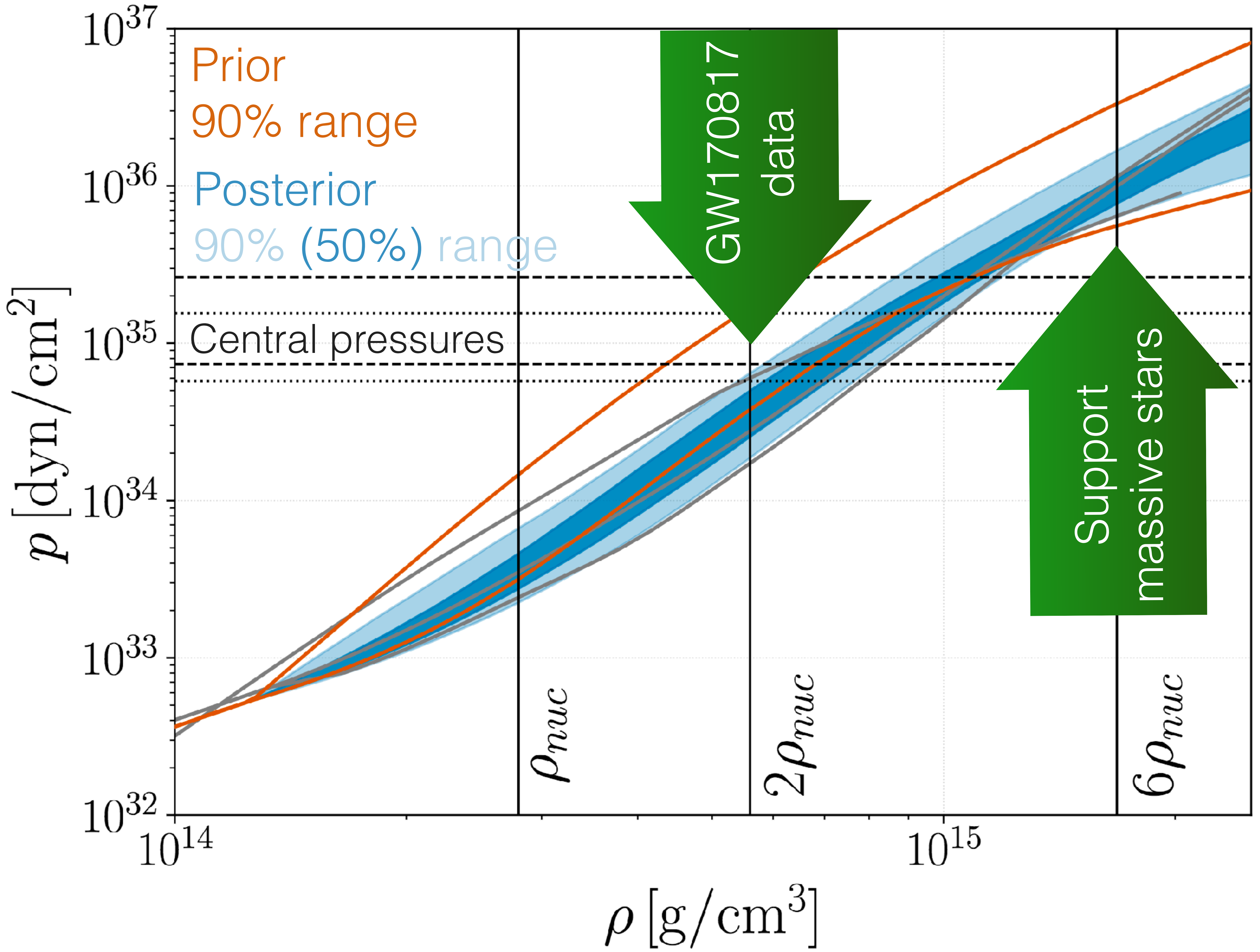
- Use EOS to model spherical star; linear tidal perturbation gives $\Lambda(m)$ for both components
- Compare predicted binaries with parameters recovered from GW



2018: Spectral EOS sampling

Animation: Rossella Gamba, LSC/Virgo
Based on LSC/Virgo EOS 1805.11581





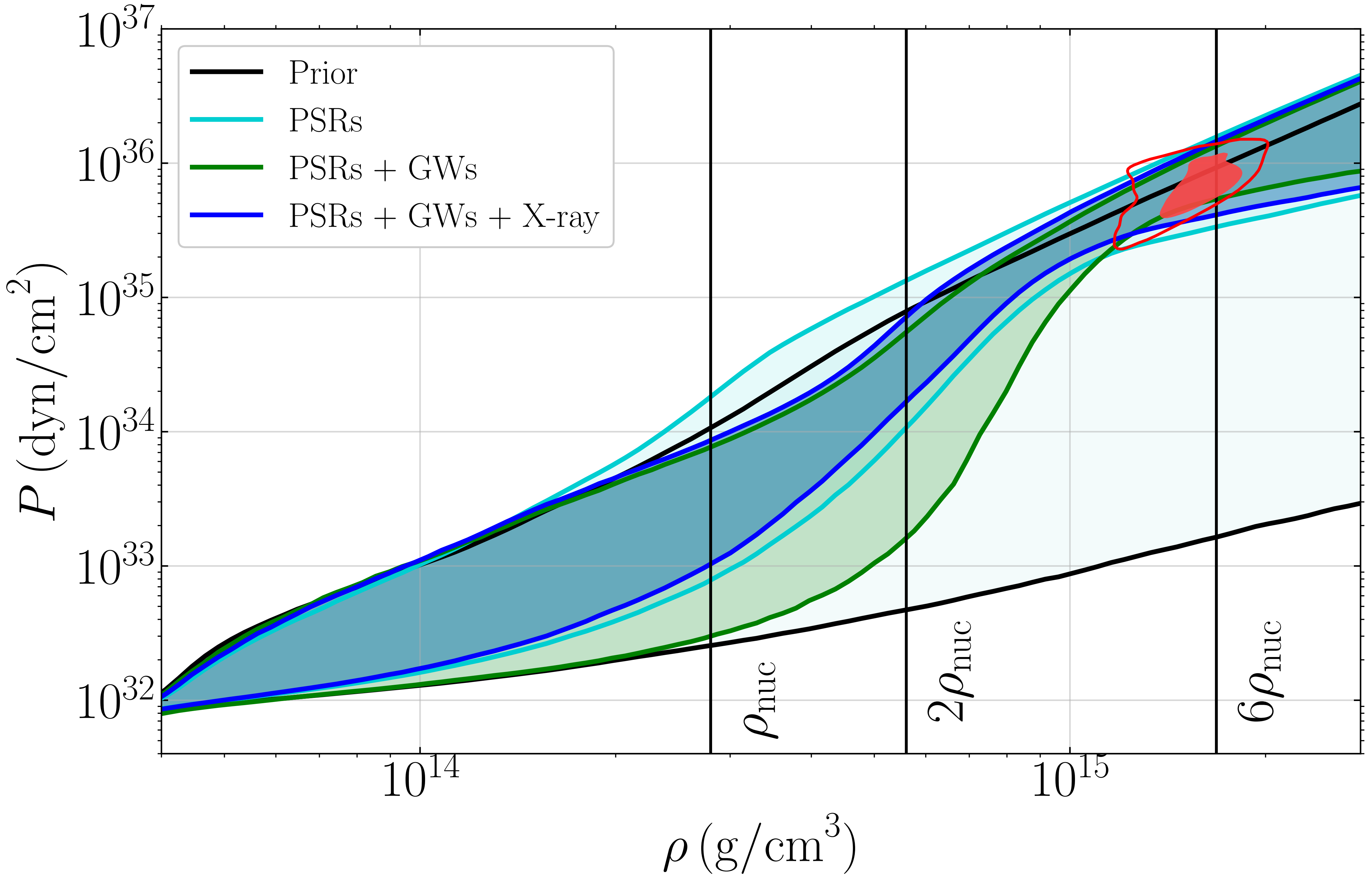
Method developed in Carney et al Phys. Rev. D 98, 063004 (2018)
LIGO/Virgo Phys. Rev. Lett. 121, 161101 (2018)

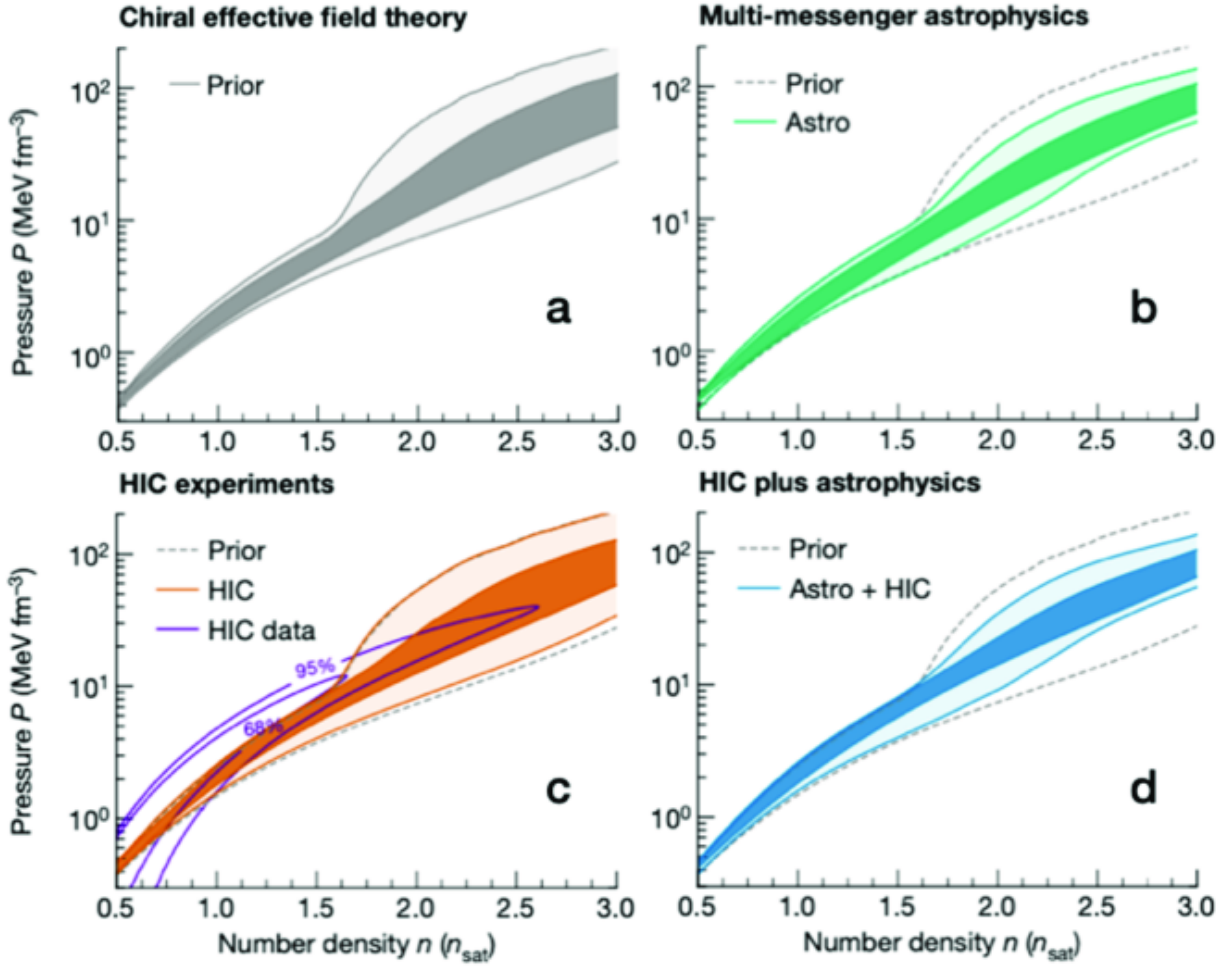
GW in multi-messenger EOS constraint

Variation in EOS model, incorporating additional observations

Le Fevre et al 2023

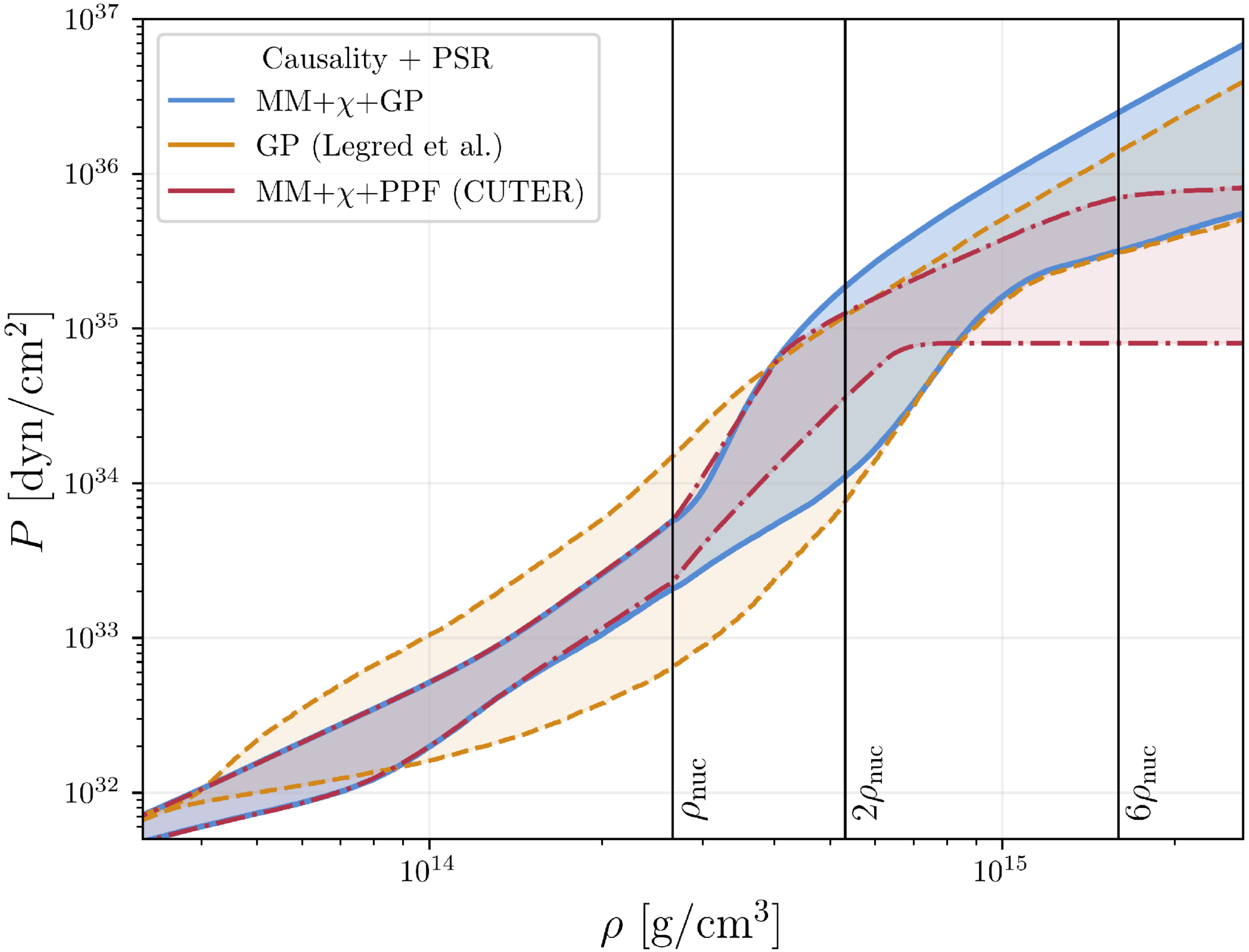
Legred et al 2021





Building an effective EOS prior

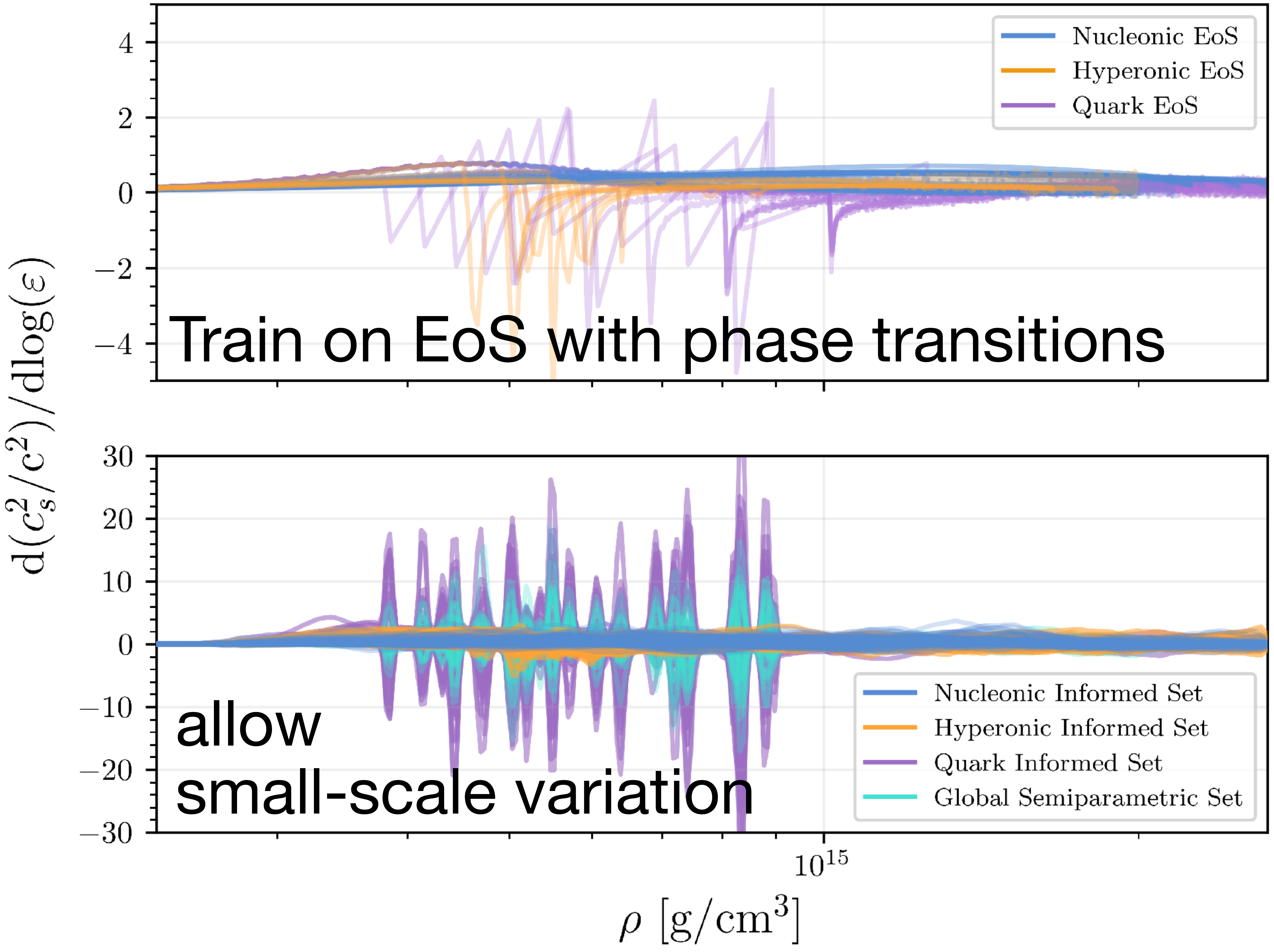
Ng et al arXiv:2507.03232v1

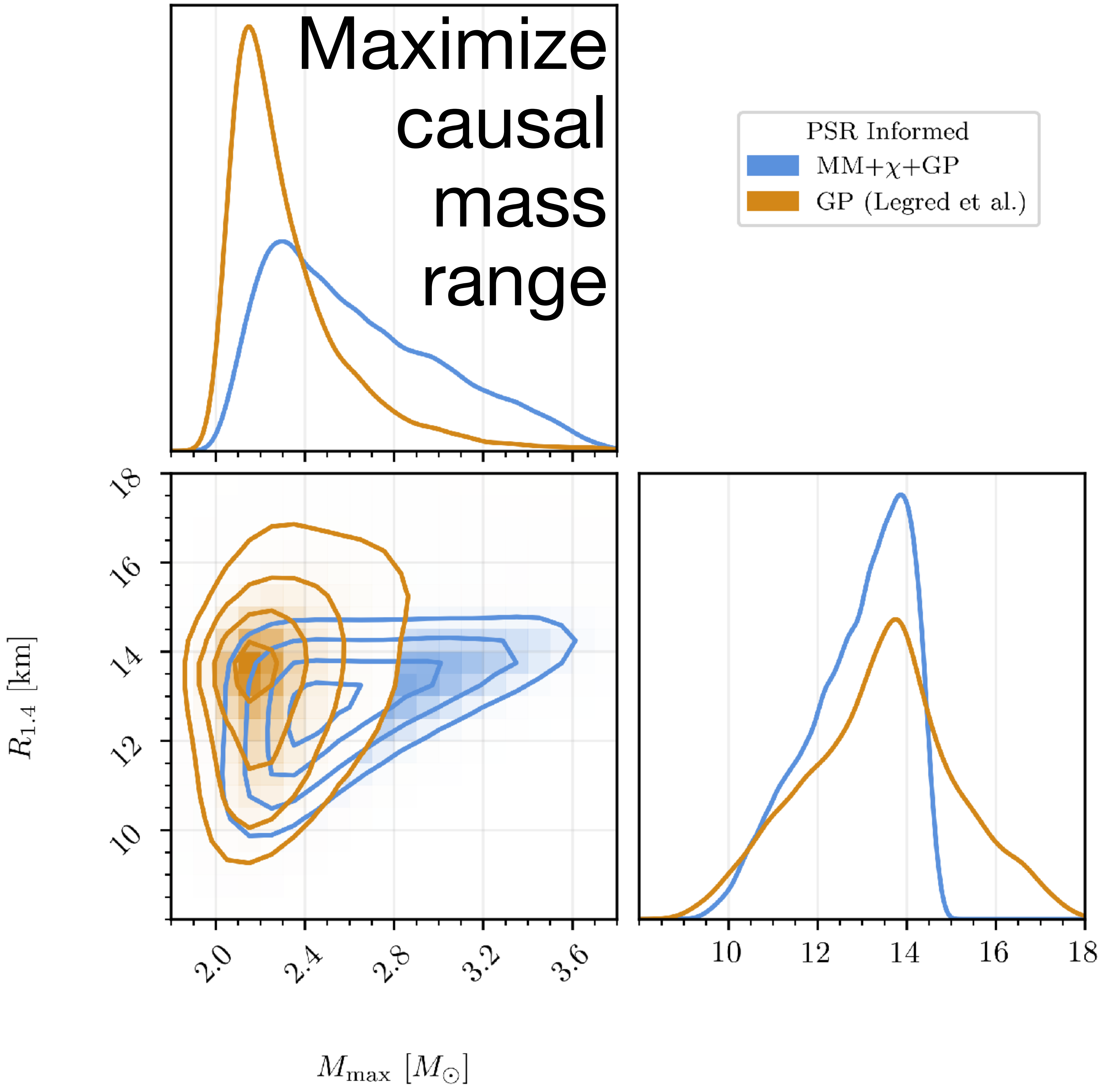


- 1D Gaussian-process for high density [introduced by Landry & Essick (2018)]
- "metamodel" at low density [Margueron et al 2018]
  - informed by terrestrial experiements, χEFT [Davis et al 2023]
- Sunny Ng, Lyla Traylor @ CSUF: exploring hyperperameter and kernel impacts on high density, ability to resolve phase transitions

Maximizing the range compatible with nuclear physics

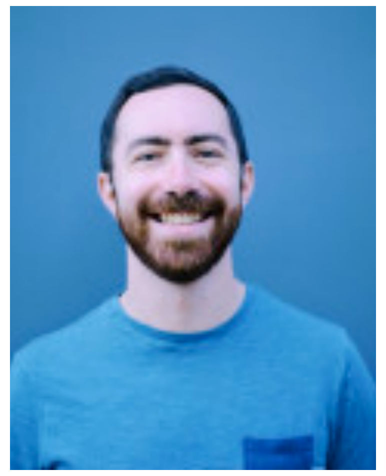
Ng et al arXiv:2507.03232v1





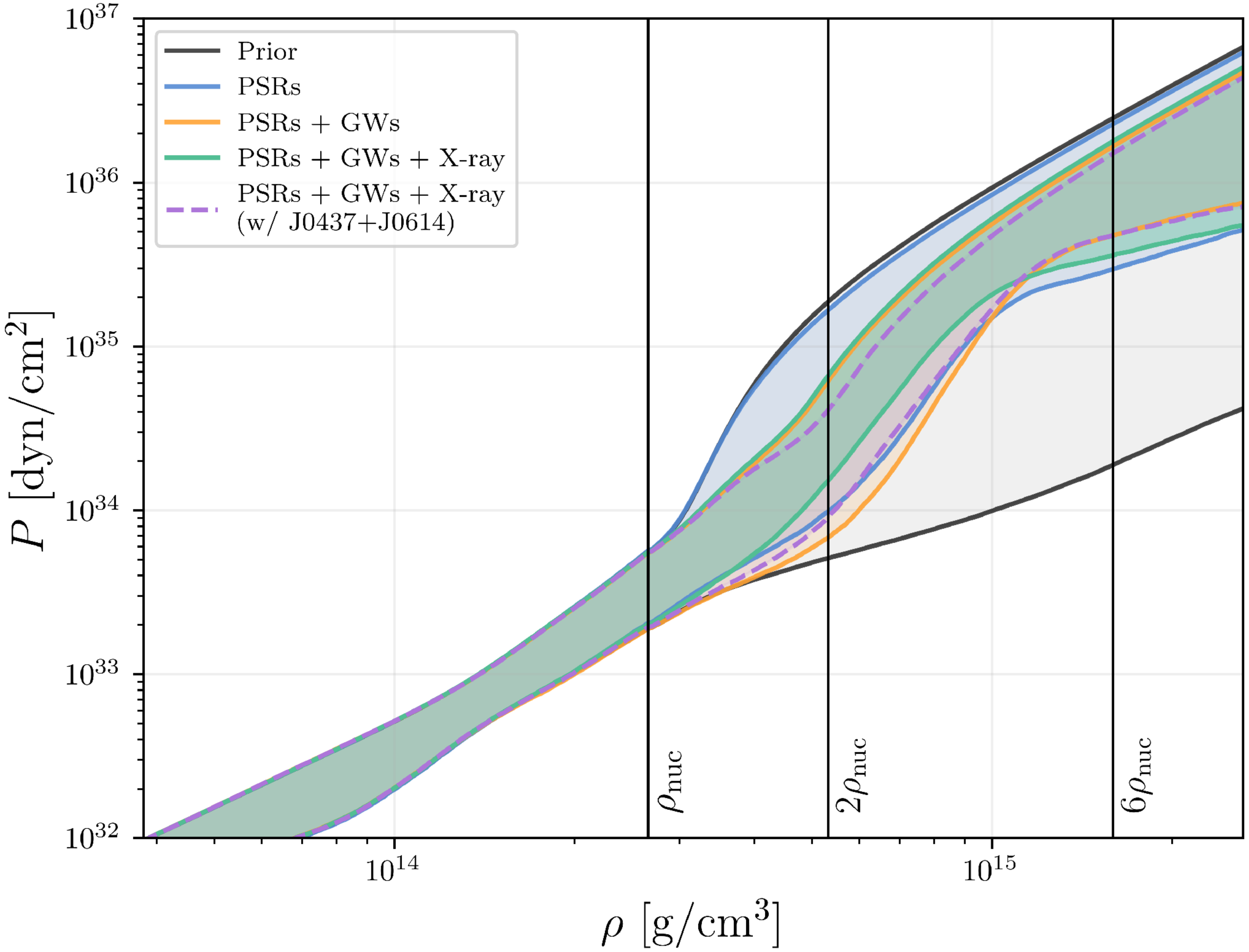
Informing the EOS with observation




Ng et al arXiv:2507.03232v1

- Astrophysical info from:
  - high-mass pulsars J1614, J0740
  - GW170817
  - Nicer: PSR-J0740, PSR-J003, *Add*: PSR-J0437, PSR-J0614
- Feed back into the interpretation of new signals [e.g. Vilka et al 2407.15753]



Informing the EOS with observation

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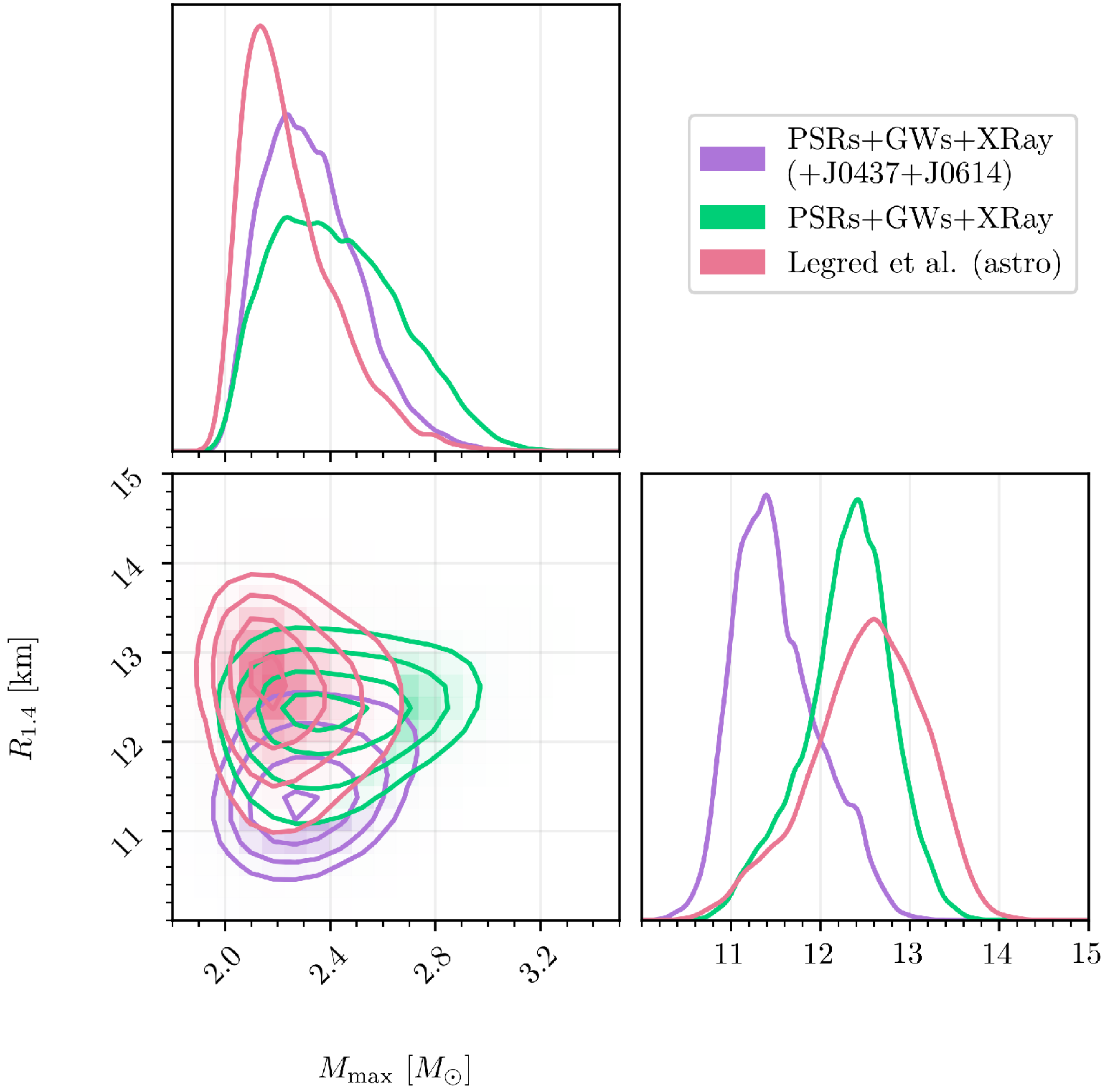
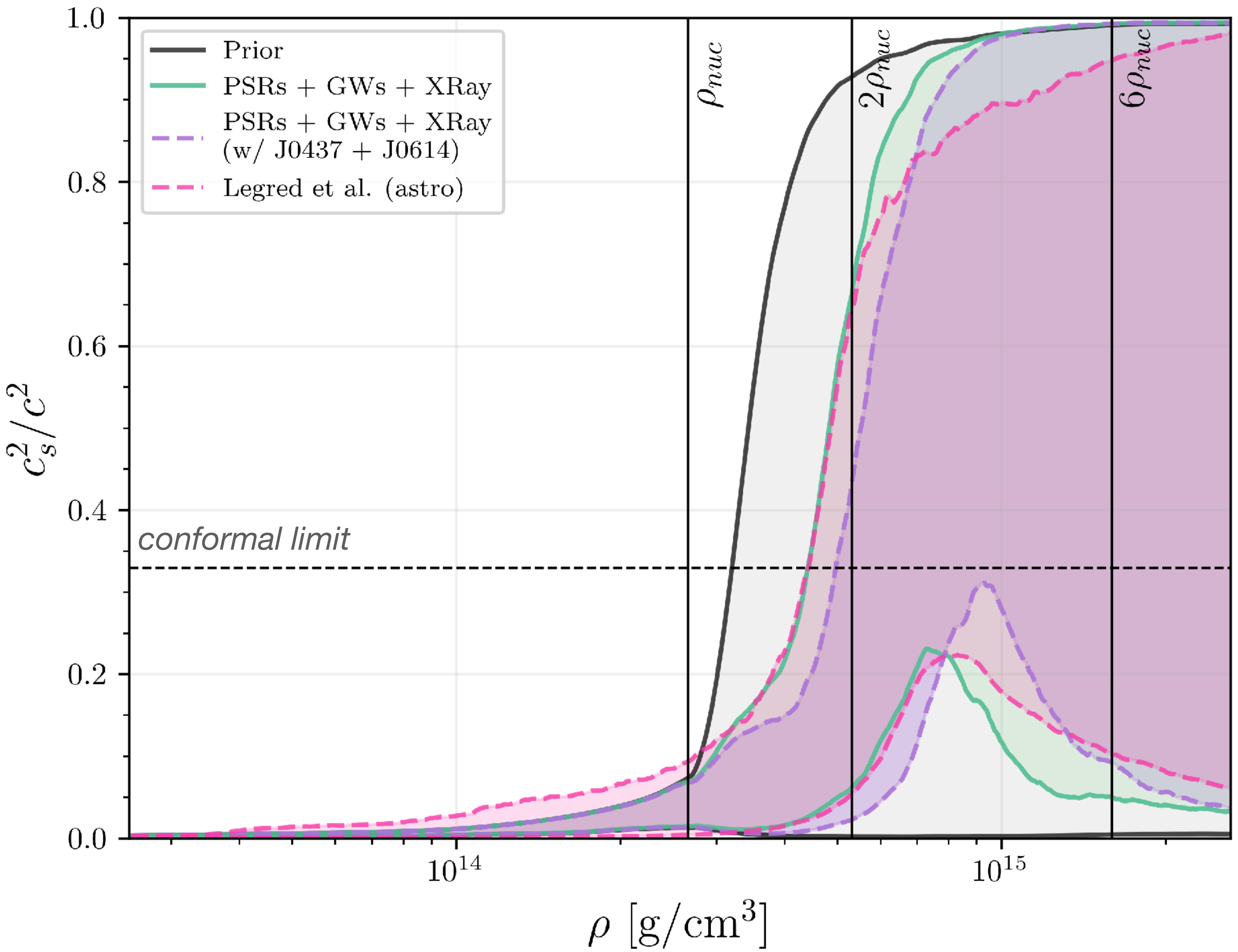
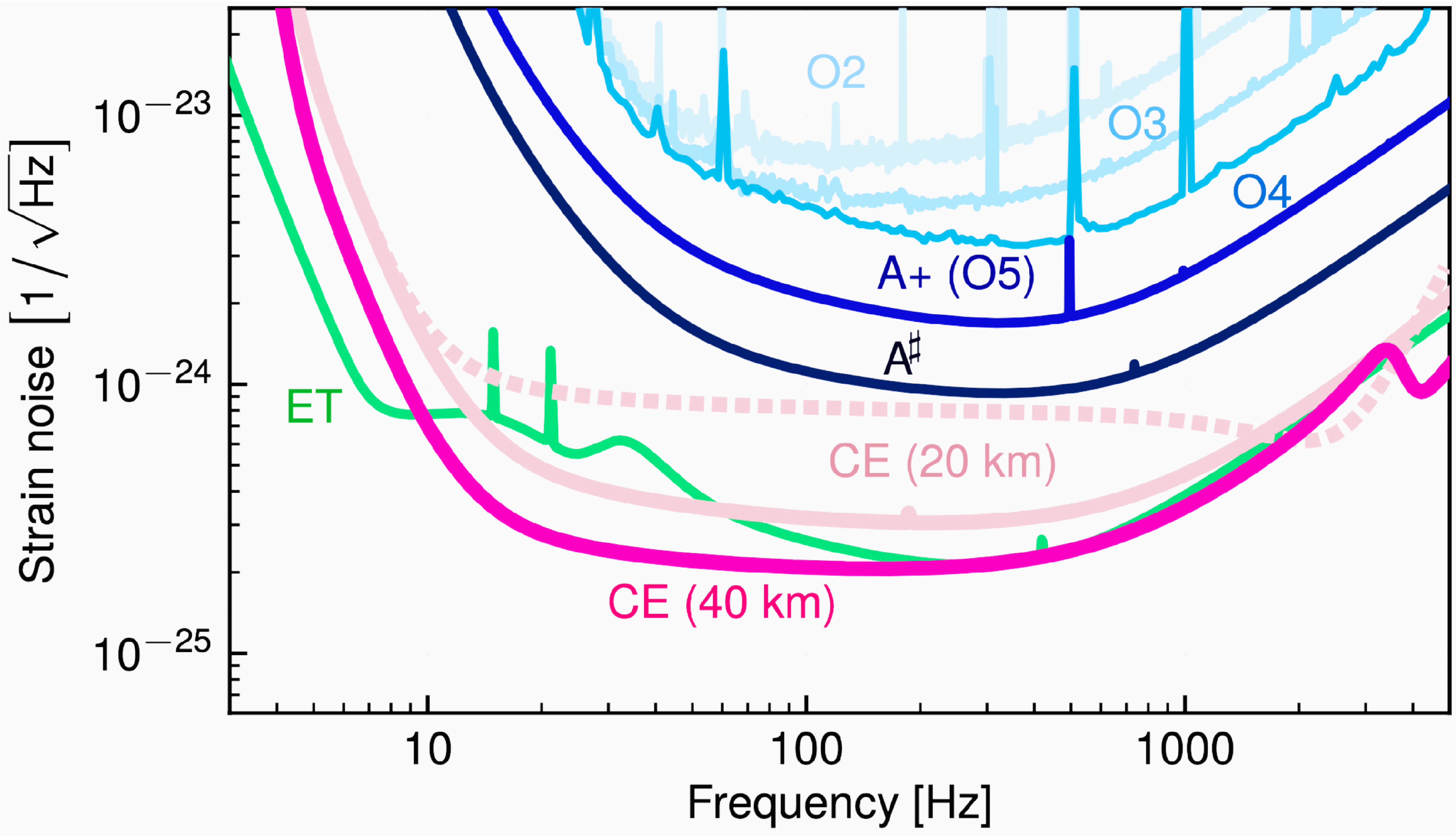




Improving detector sensitivity

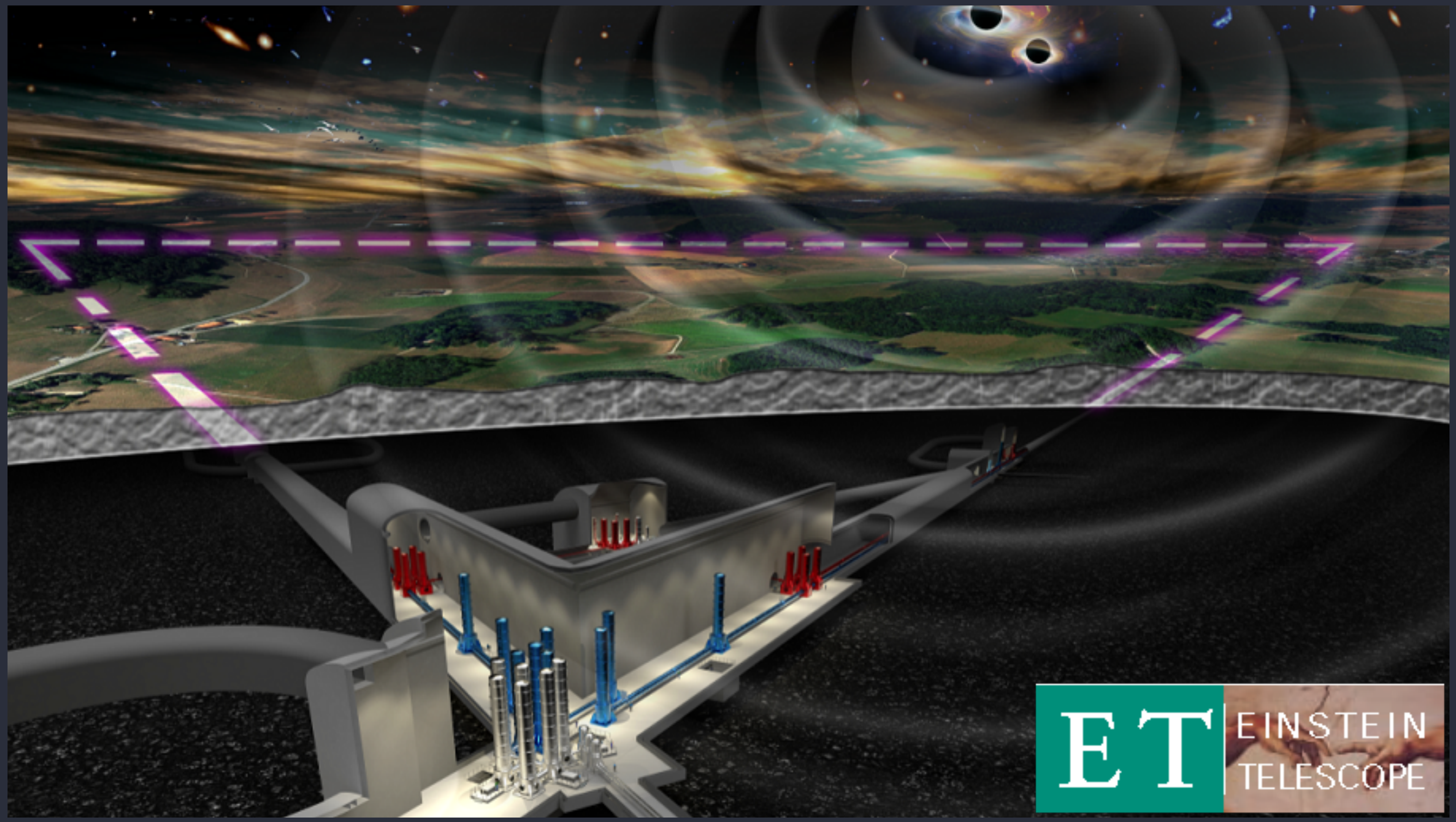


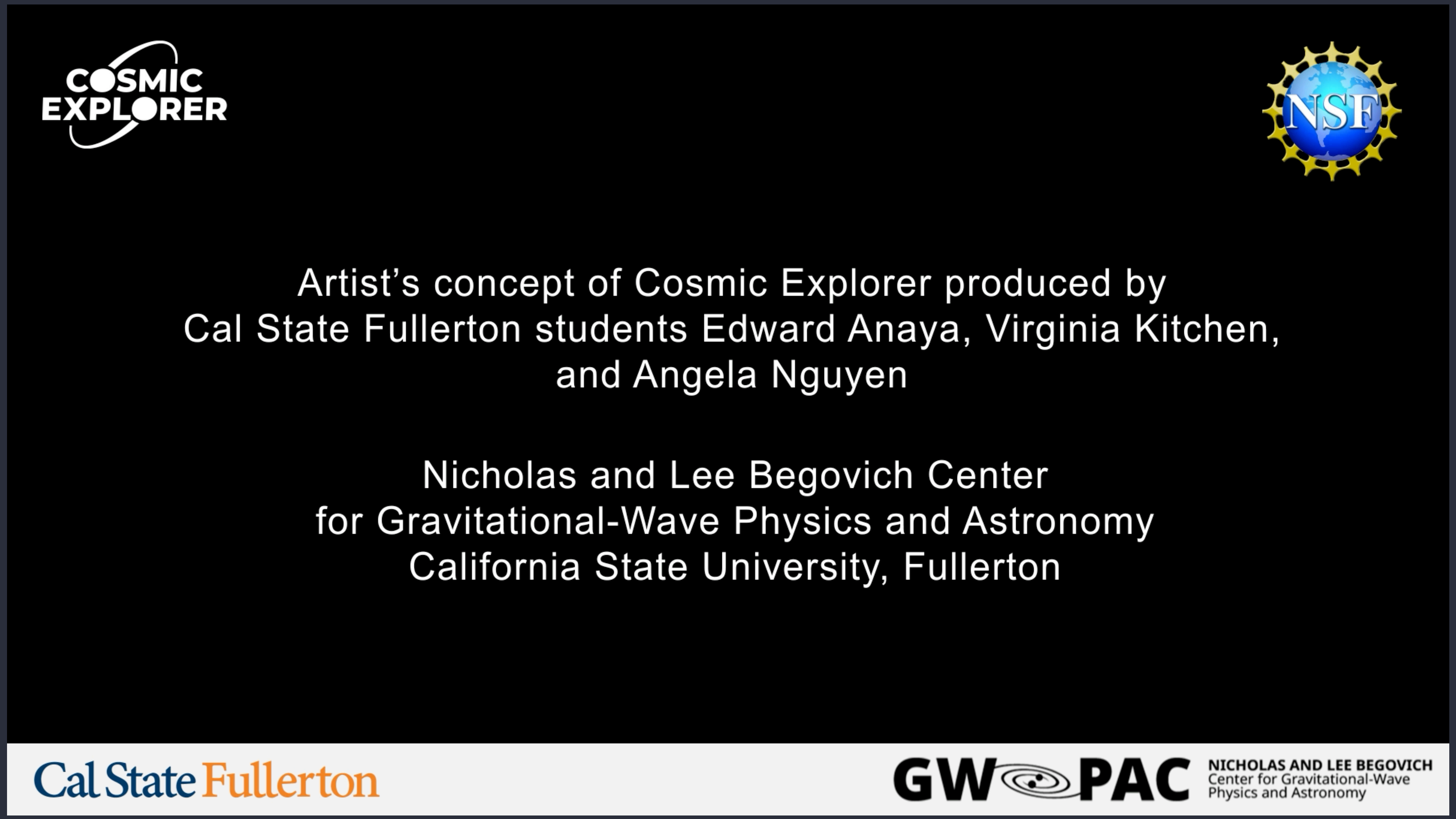
2017

Next-generation (~2035)

Kuns; Corsi et al. arXiv:2402.13445v1

“XG”: new facilities for ground-based GW





Einstein Telescope (ET)

- 10 km underground triangle
- Cryogenic low frequency, high power high frequency interferometers in “xylophone” configuration
- ESFRI Roadmap 2021
- Site procedure in progress, decision 2025/26
- Construction goal 2028

Cosmic Explorer (CE)

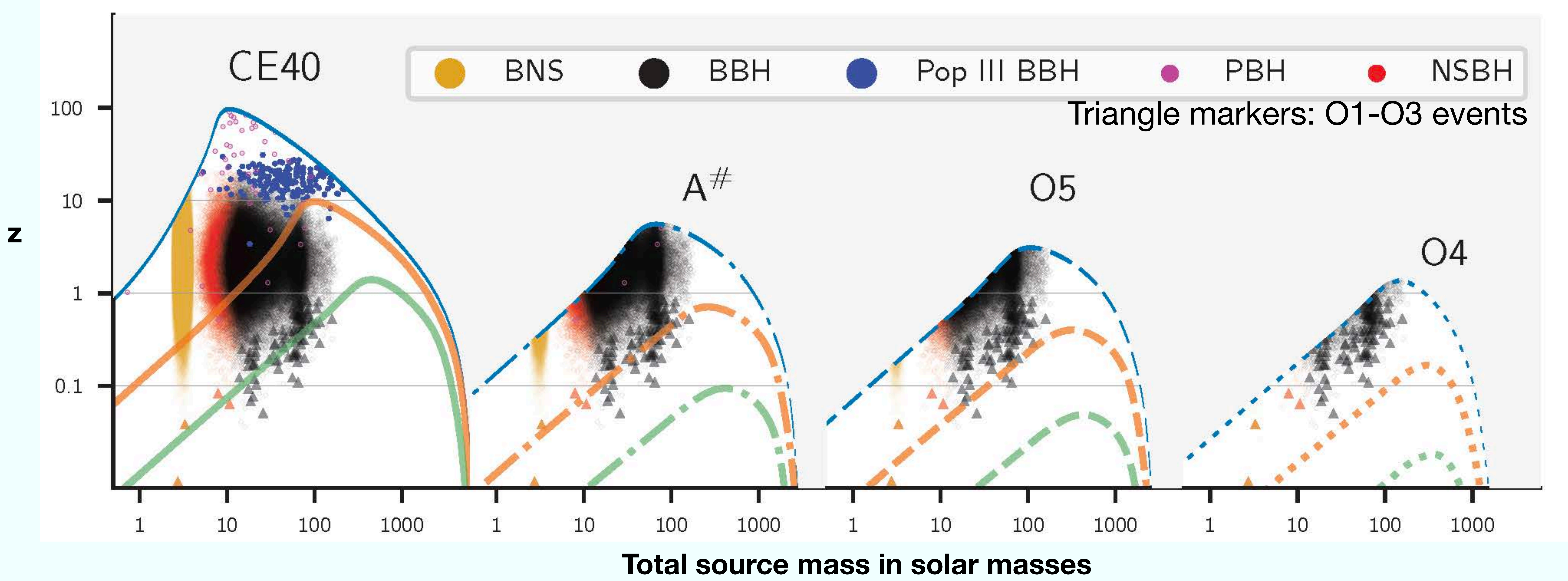
- 20 km and 40 km L-shaped surface observatories
- scaled up A+ technology & enhancements
- NSF ngGW recommendation in 2024
- Site procedure in progress, complete 2028
- Construction goal early 2030s

Images courtesy Einstein Telescope, Cosmic Explorer

Future Reach

White Paper for NSF MSCAC ngGW , https://arxiv.org/abs/2306.13745

— — range to SNR 1000
— — range to SNR 100
— — range to SNR 8



Current sGRB distances
z~0.01-1.5

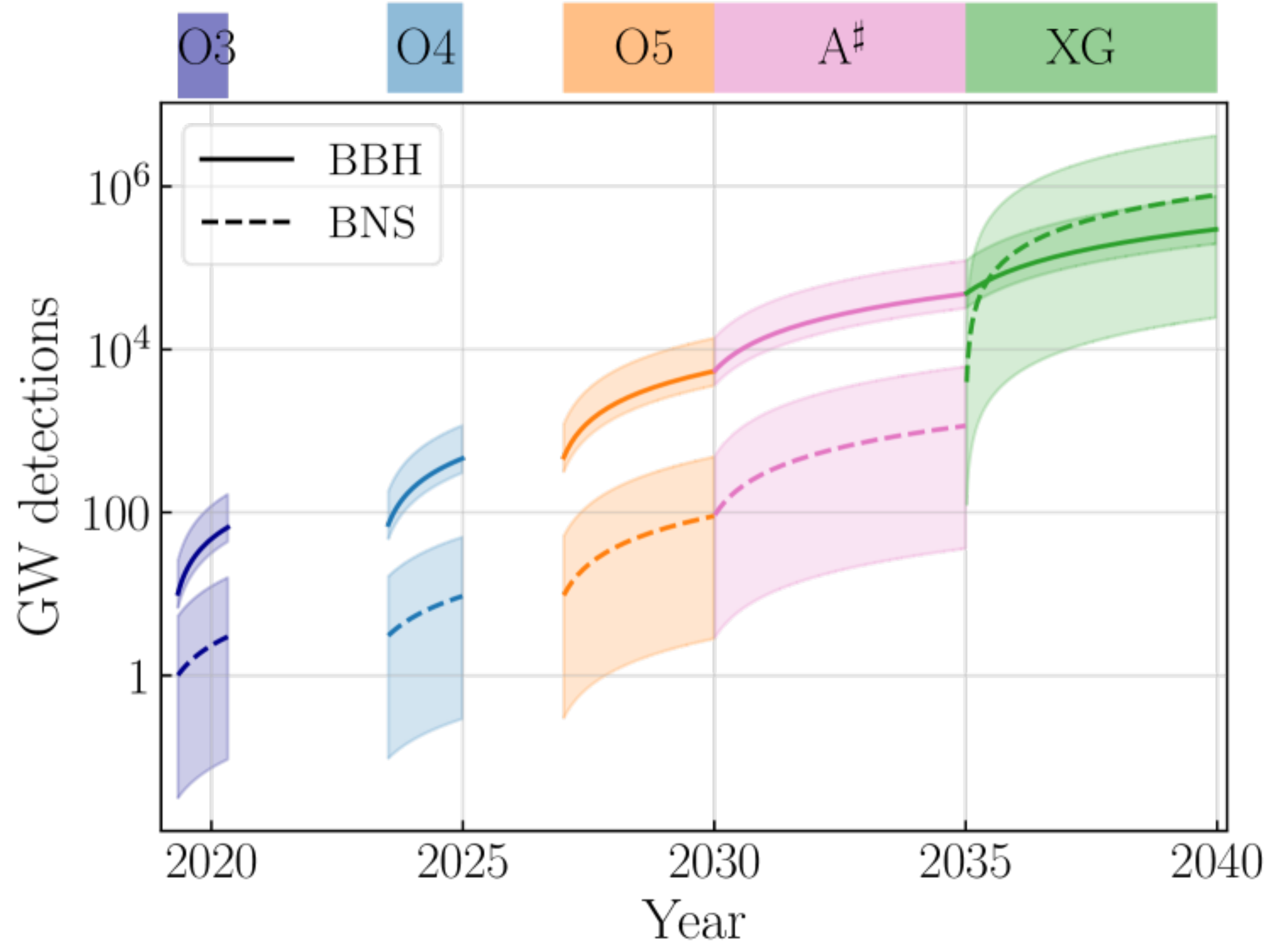
Kilonova identification
to z~0.02-0.5 for LSST
to z~1 for Roman

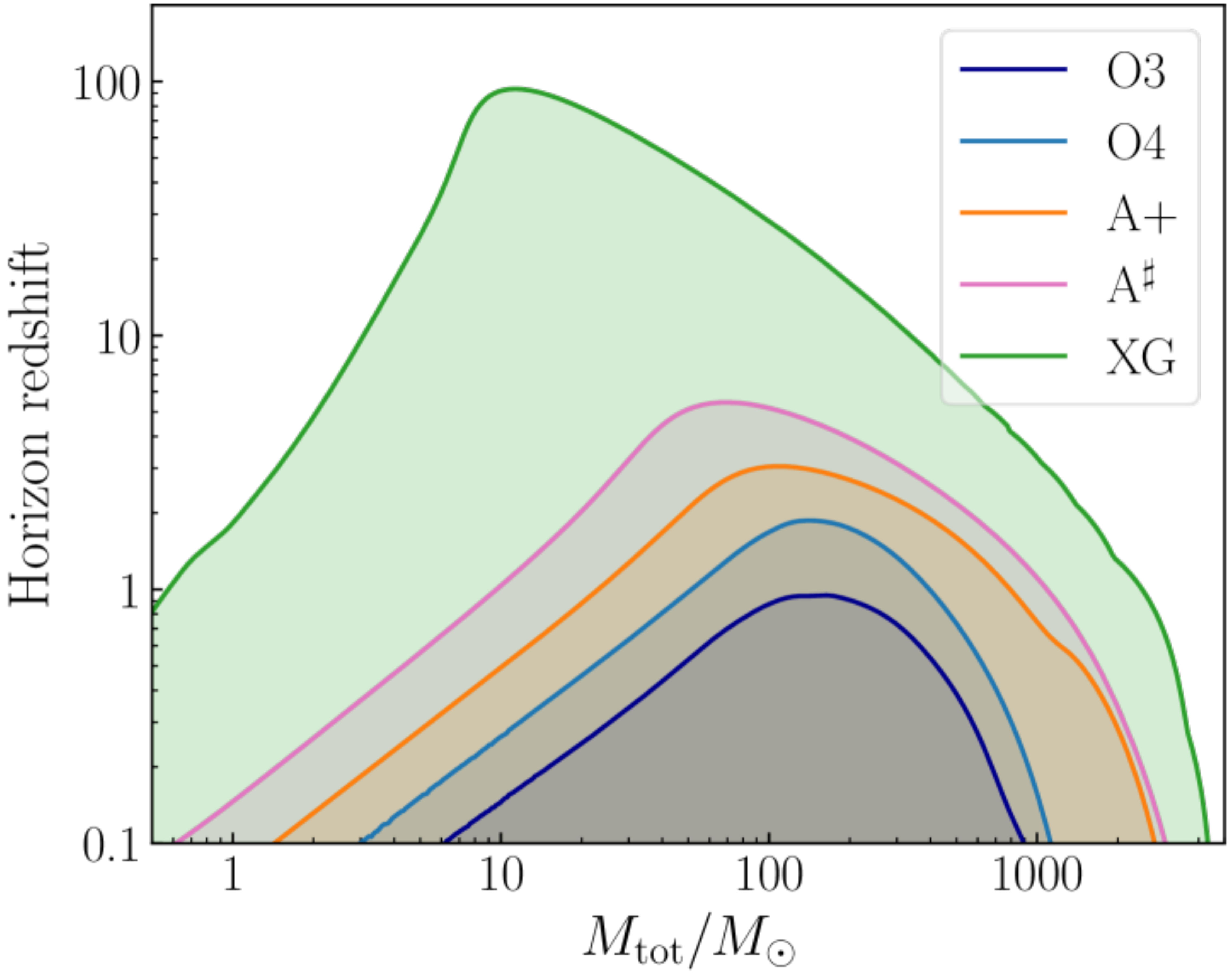
Chase et al 2022 ApJ 927 163

FRB distances ~100-1000 Mpc
O3 Exclusions ~ 60-600 Mpc

R. Abbott et al 2023 ApJ 955 155

Populations of mergers across the universe

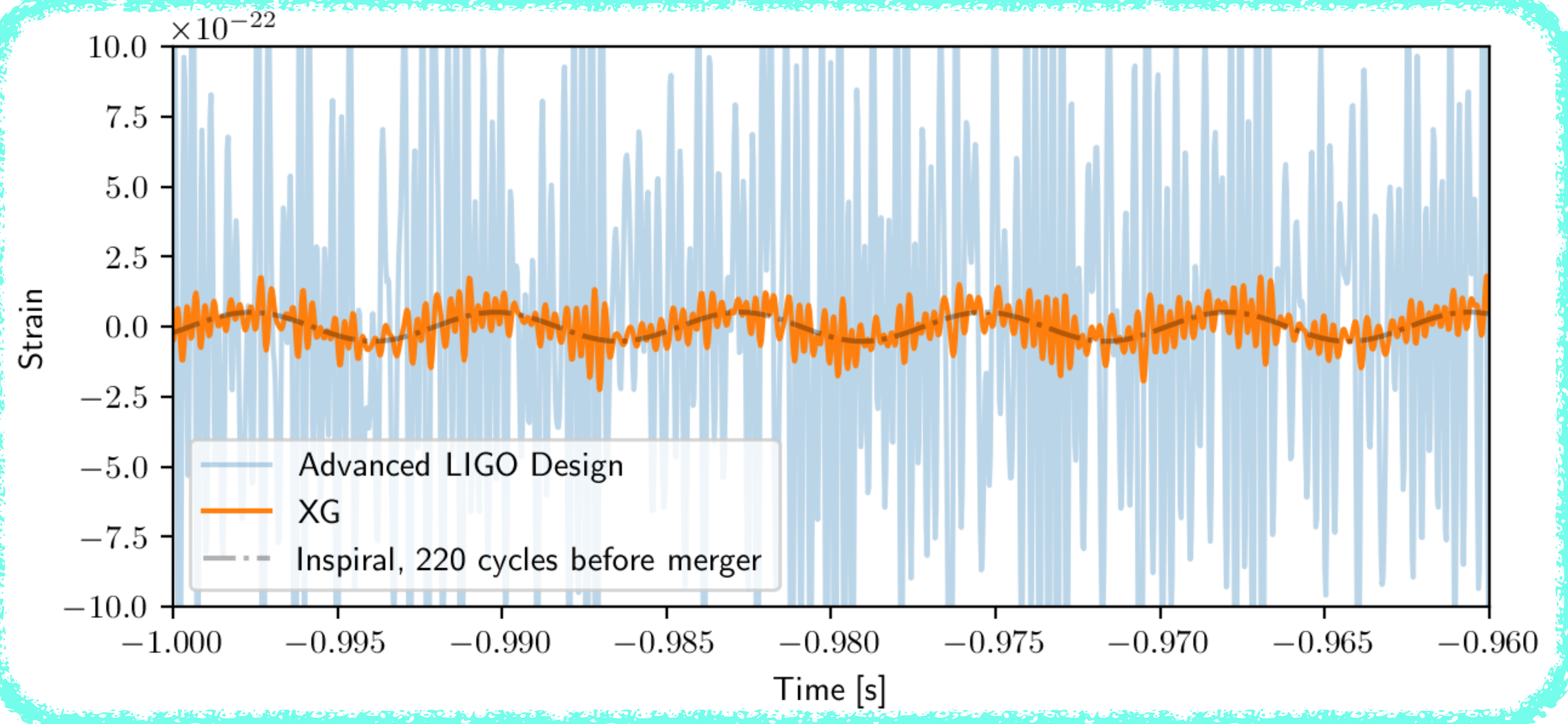


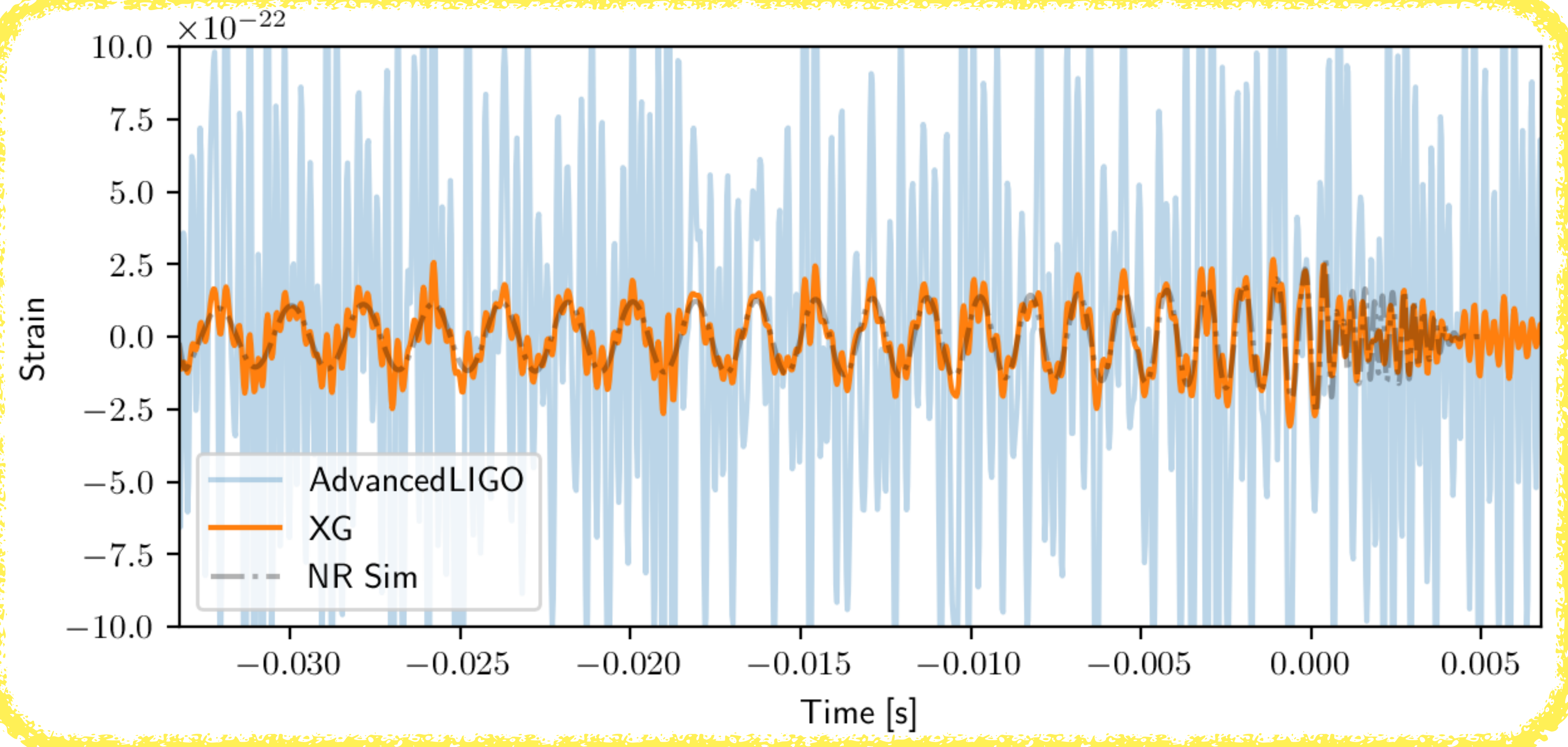


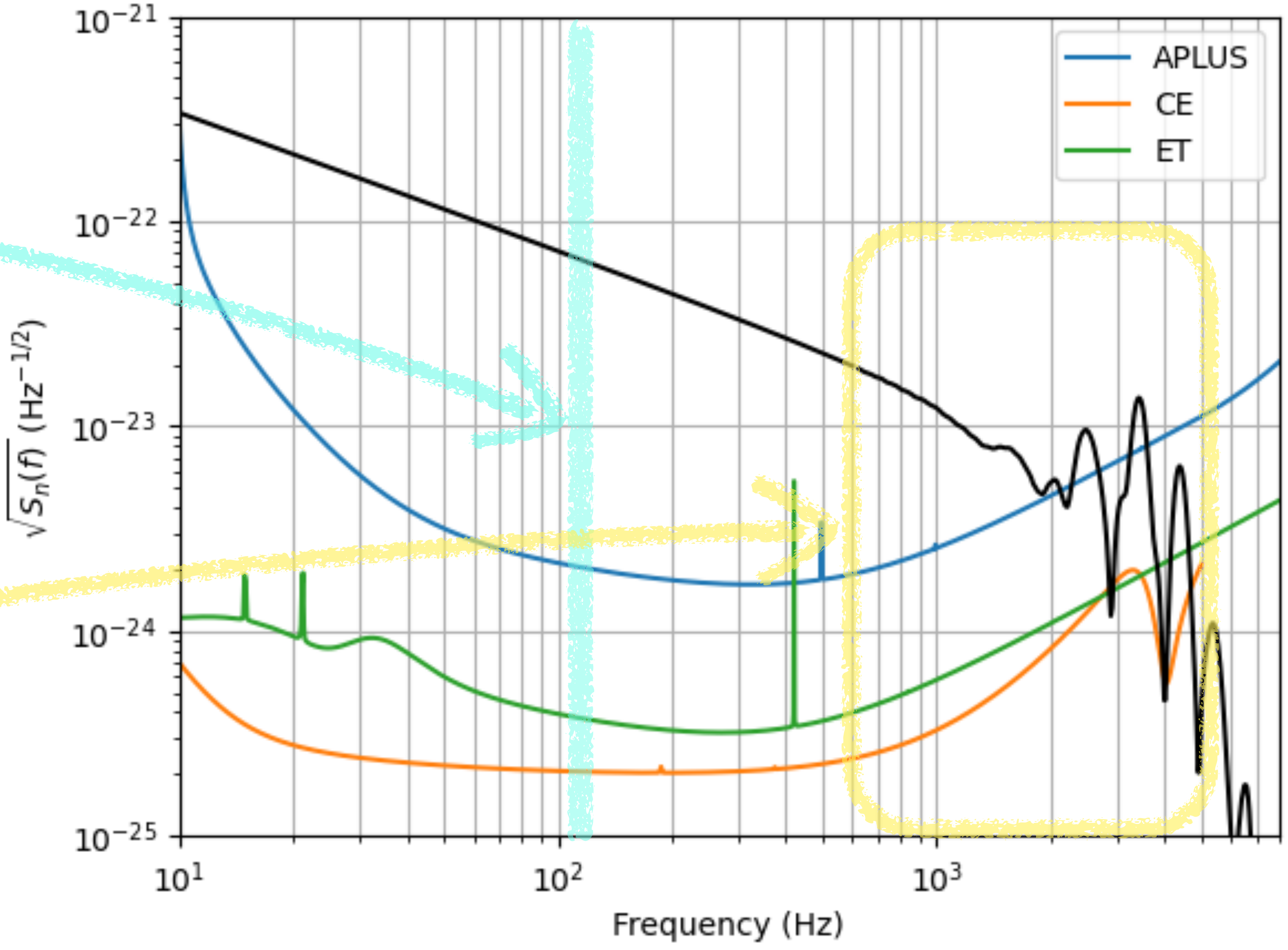
Hsin-Yu Chen et al 2024 Class. Quantum Grav. 41 125004
Source rates from O3 - lack of observations in O4 reduces expectations for BNS

GW170817 as a future observatory could see it

Hundreds of individually resolvable cycles





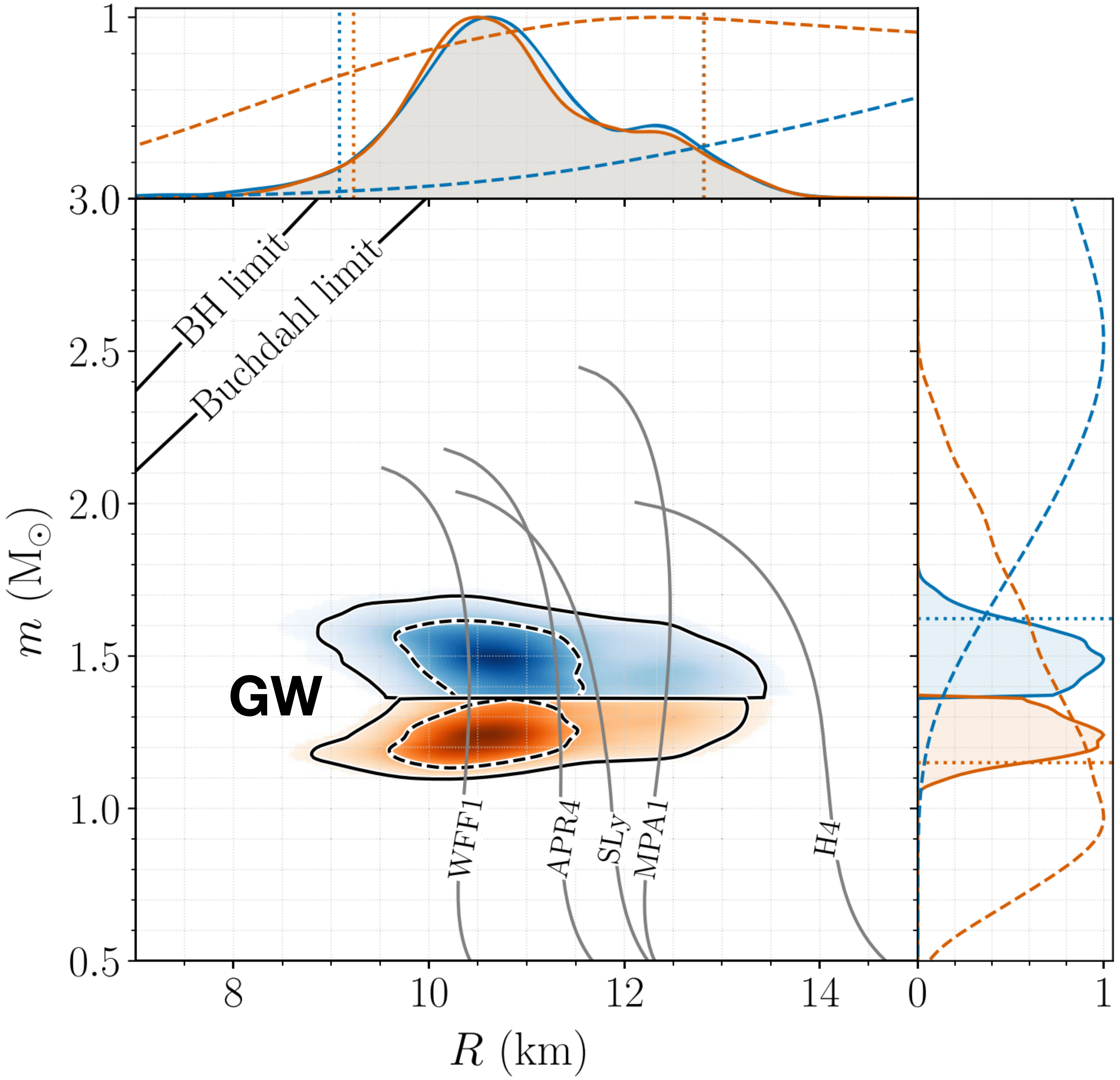


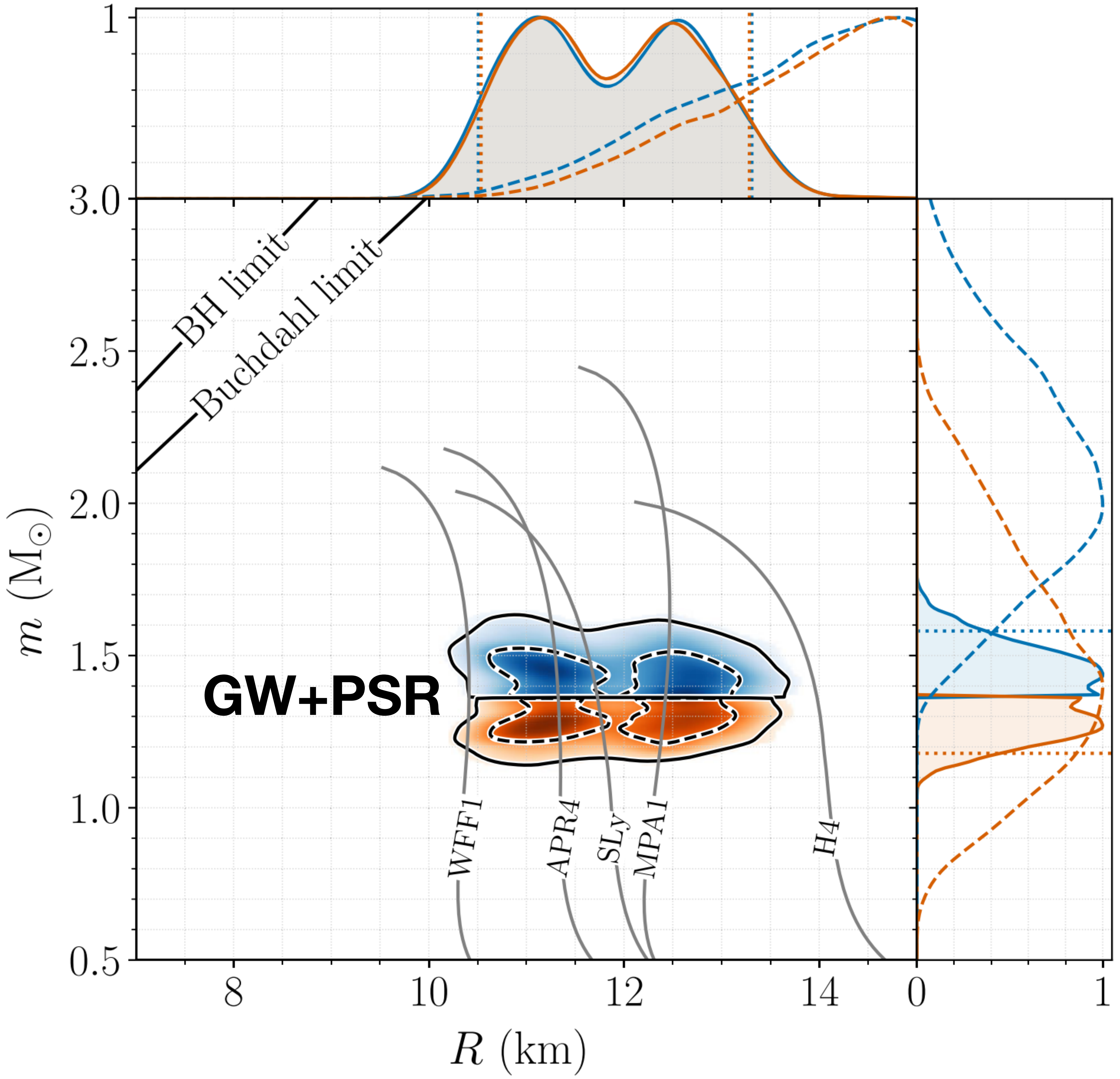
J. Read, A. Nitz (pycbc/lalsimulation + NR from CoRe database)

High-precision observations: Systematics challenges, beyond Λ_i opportunities

2018: Inferring the neutron-star radius

LIGO/Virgo Phys. Rev. Lett. 121, 161101 (2018)



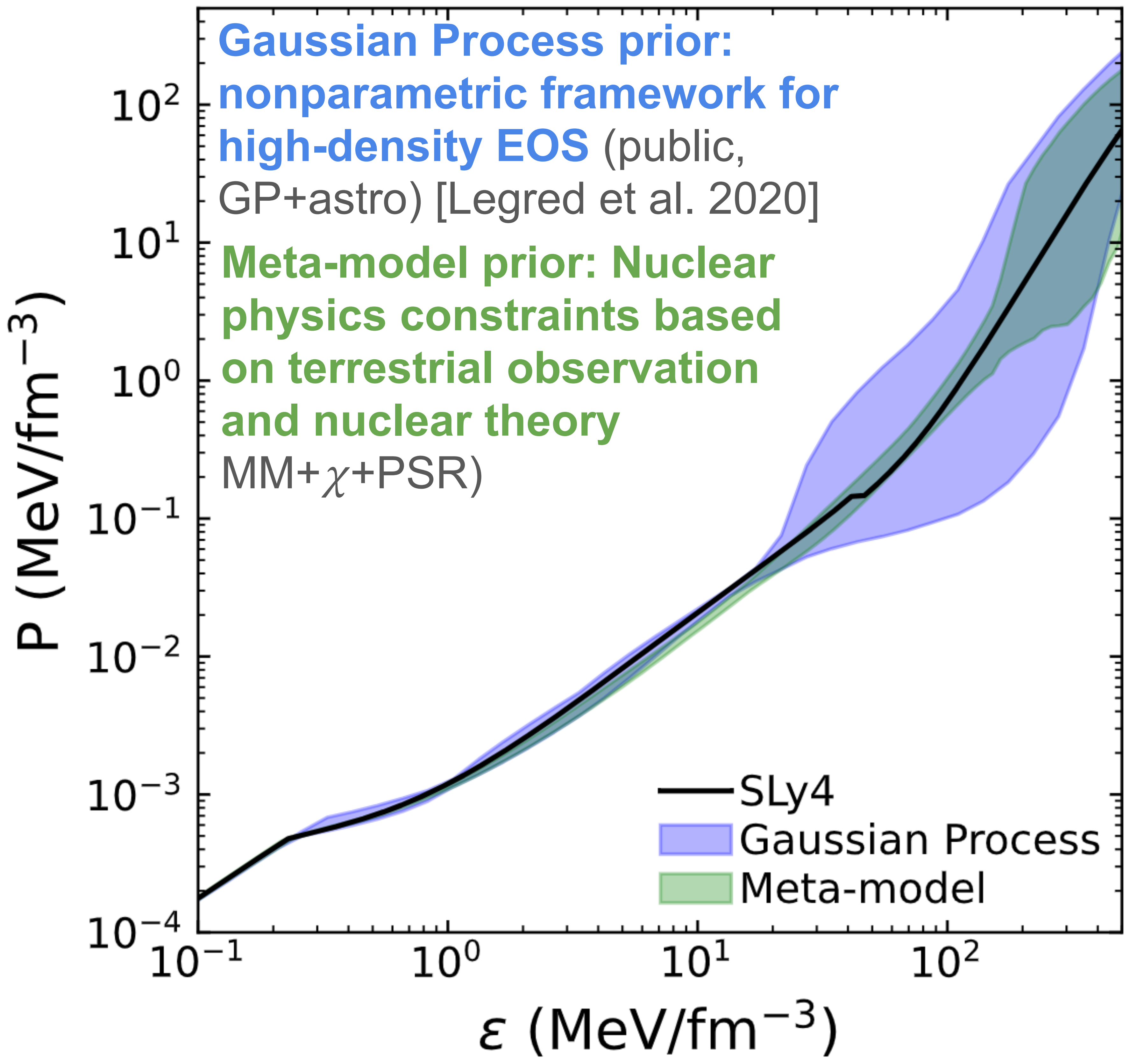


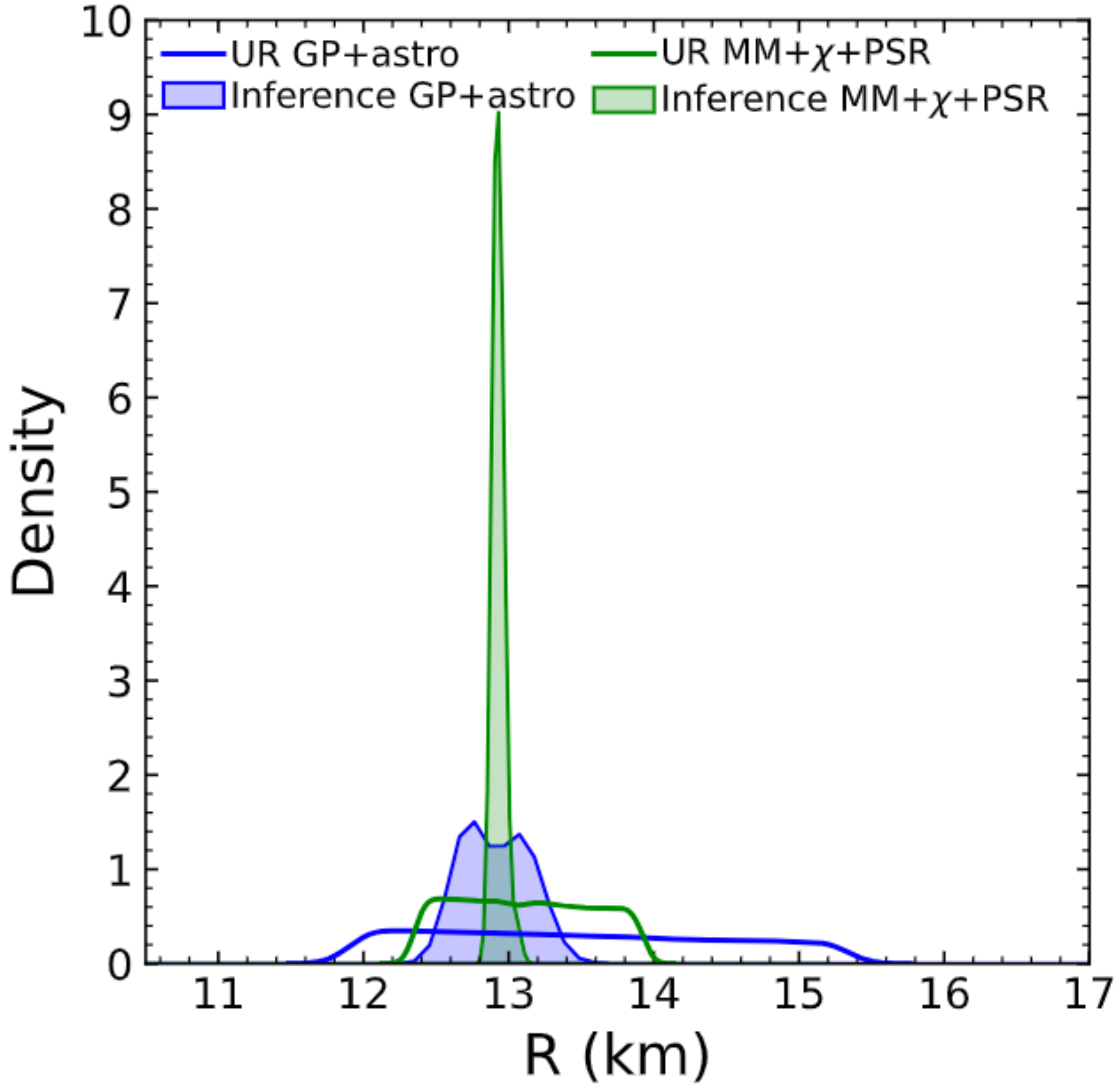
Quasi-universal relation radius inference methods: Chatziioannou et al, Phys. Rev. D 97, 104036 (2018)

Spectral EOS constraint methods: Carney & Wade Phys. Rev. D 98, 063004 (2018)

Radius implications from high-precision observations

Full EOS modeling needed; low-density modeling impact



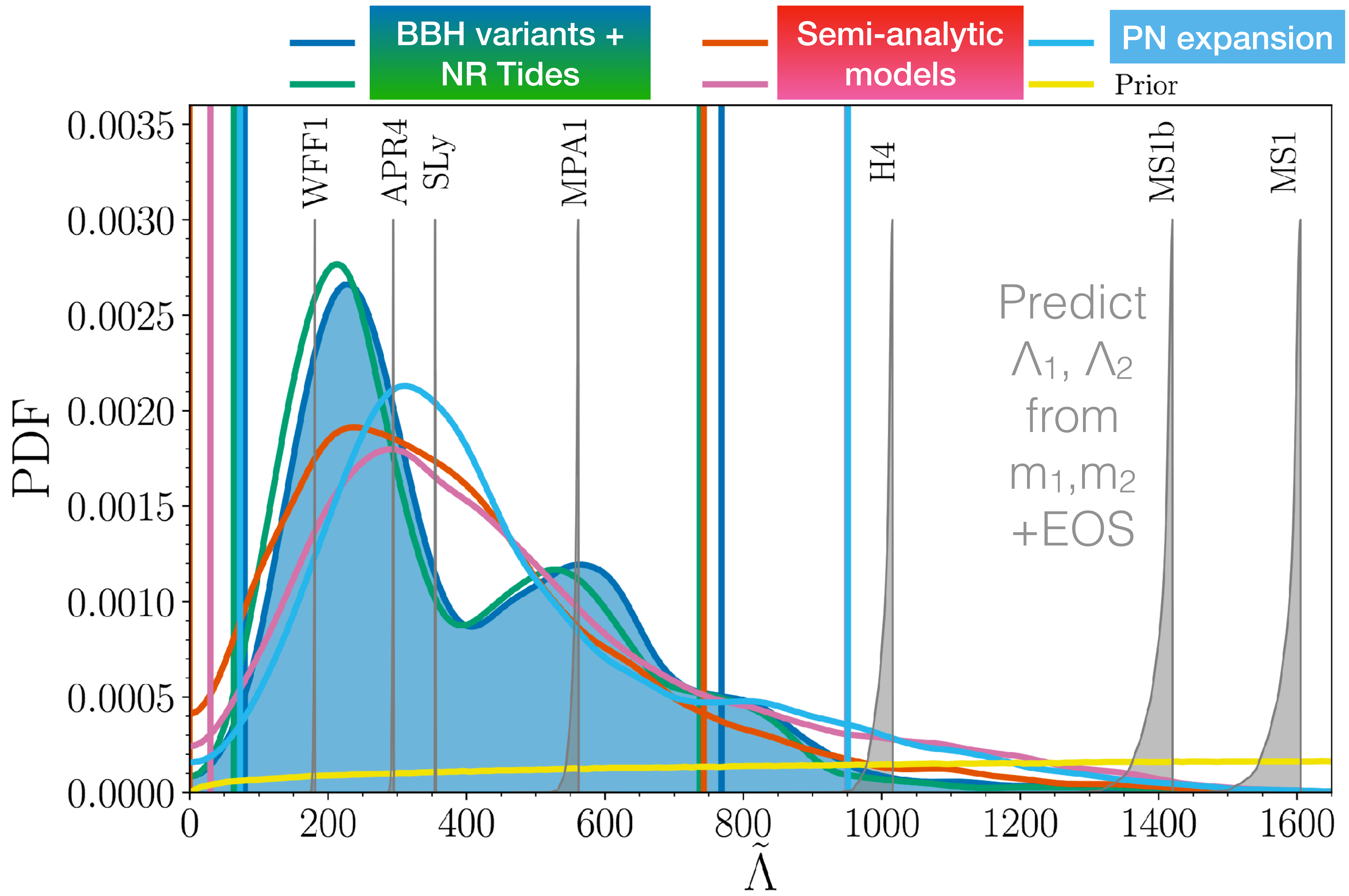


- Model observations with StrobeX, Cosmic Explorer
  - Eg. observe Λ, compute R
- heirarchichally-inferred EOS (public library lwp).
- **Challenge for quasi-universal relations in XG**

Suleiman & Read Phys. Rev. D 109, 103029 (2024)

Waveform/prior systematics:

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



Assume low spin (χ < 0.05)

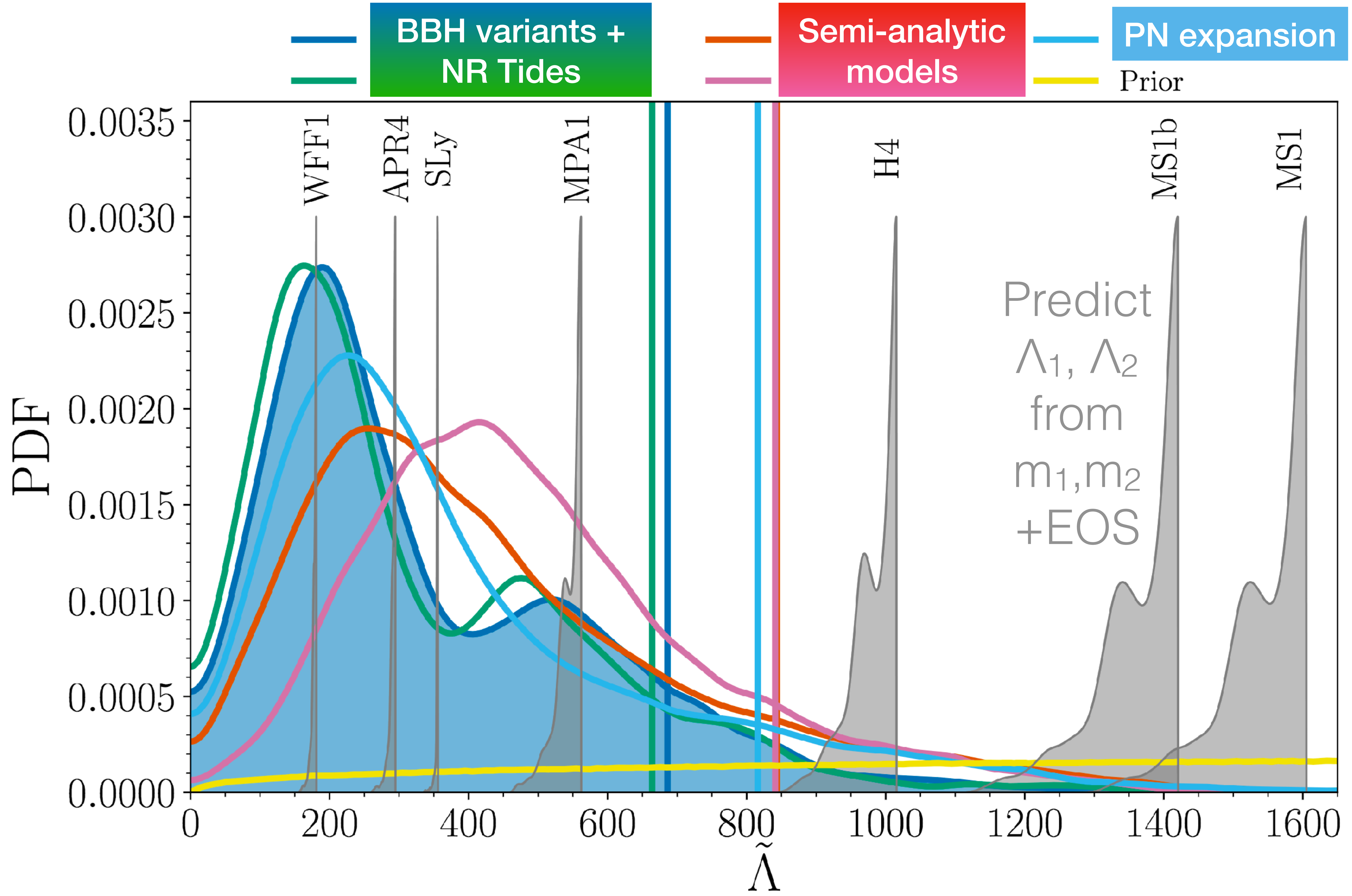
Fiducial WF:
$\tilde{\Lambda} = 330^{+438}_{-251}$

Bars denote 90% highest probability density credible interval

LSC/Virgo GWTC-1 Phys. Rev. X 9, 031040 (2019)

Waveform/prior systematics:

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



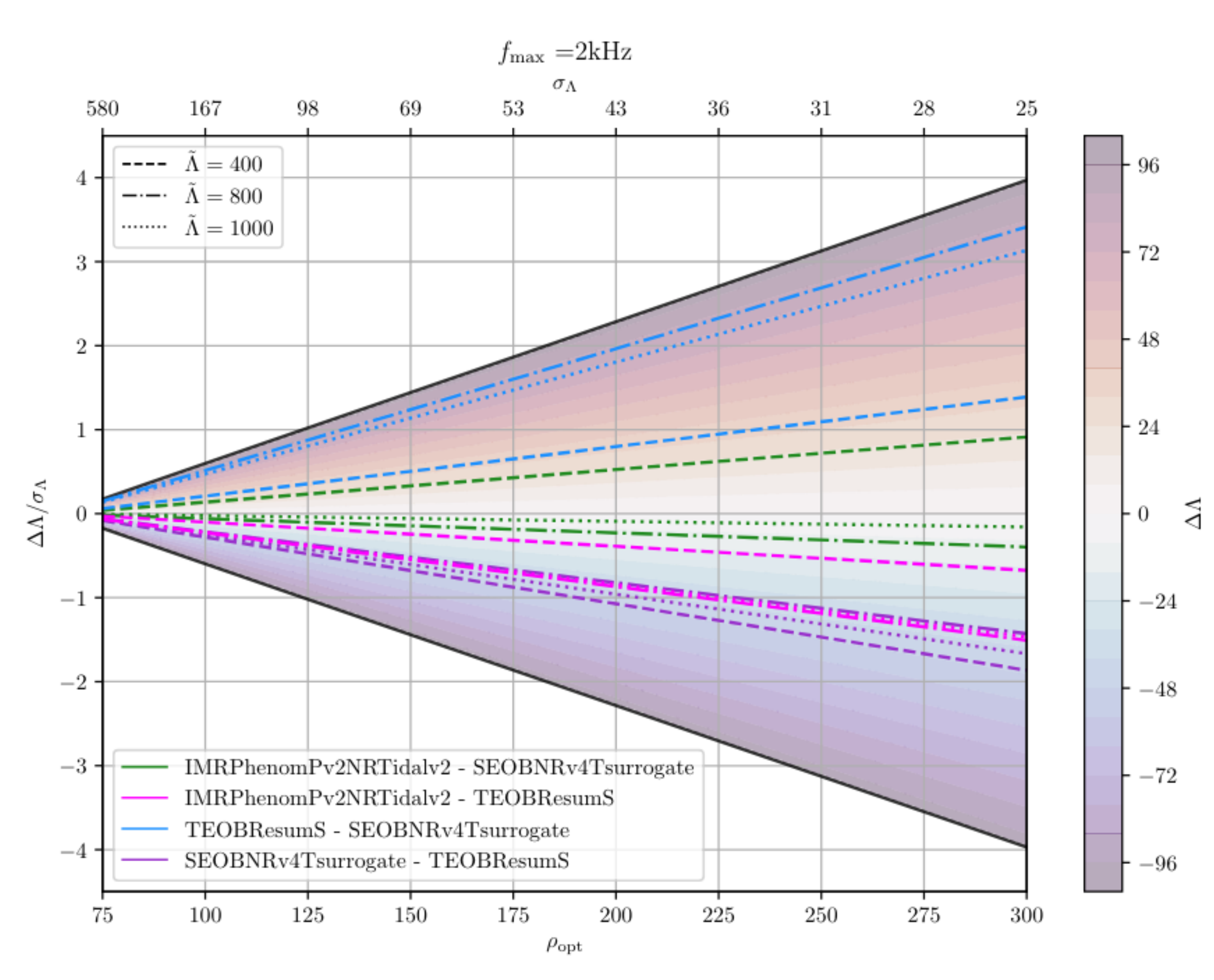
Fiducial WF: $\tilde{\Lambda} < 686$

Bars denote 90% highest probability density credible interval

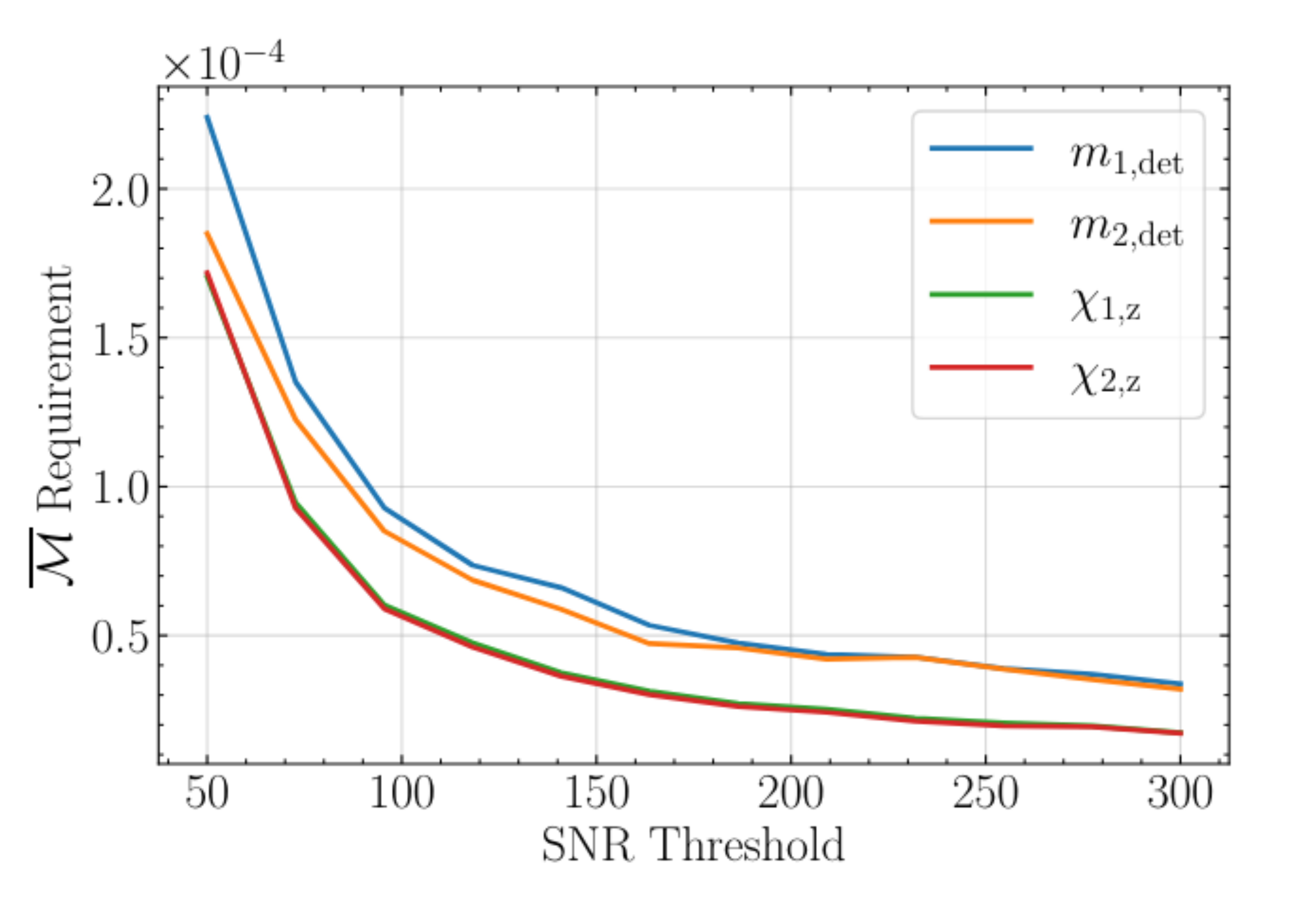
LSC/Virgo GWTC-1 Phys. Rev. X 9, 031040 (2019)

Waveform systematics impact

A#/Virgo nEXT SNRs into the 100s, loudest XG in the 1000s



Gamba, Breschi, Bernuzzi, Agathos, and Nagar
Phys. Rev. D 103, 124015



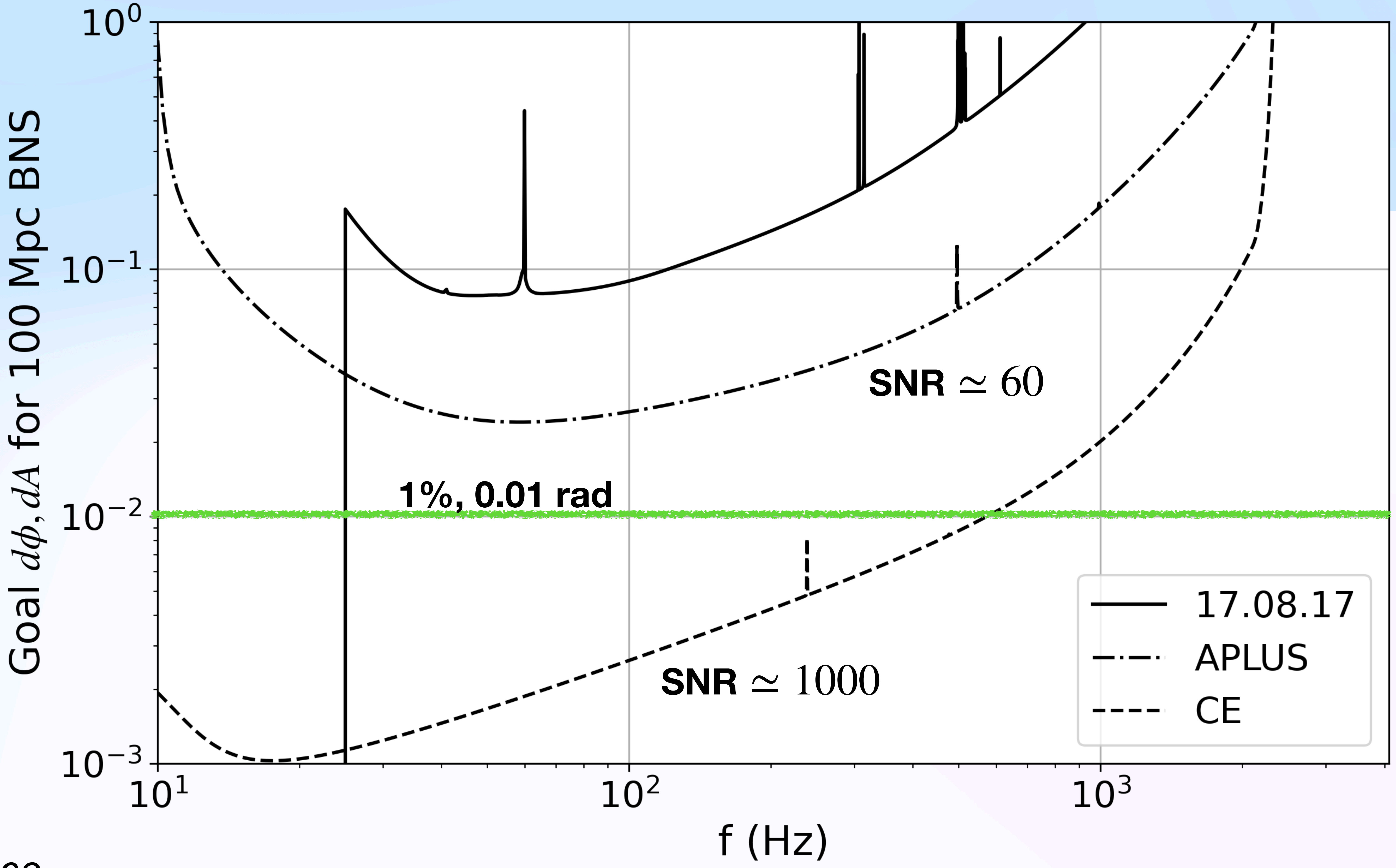
Kapil, Reali, Cotesta, and Berti
Phys. Rev. D 109, 104043

Goals for calibration & waveforms

BNS signal at $d_{\text{eff}} = 100$ Mpc

- Goal δA (fractional) and $\delta\phi$ (radians) shown
- Difference from model of detector (calibration) or source (waveform)

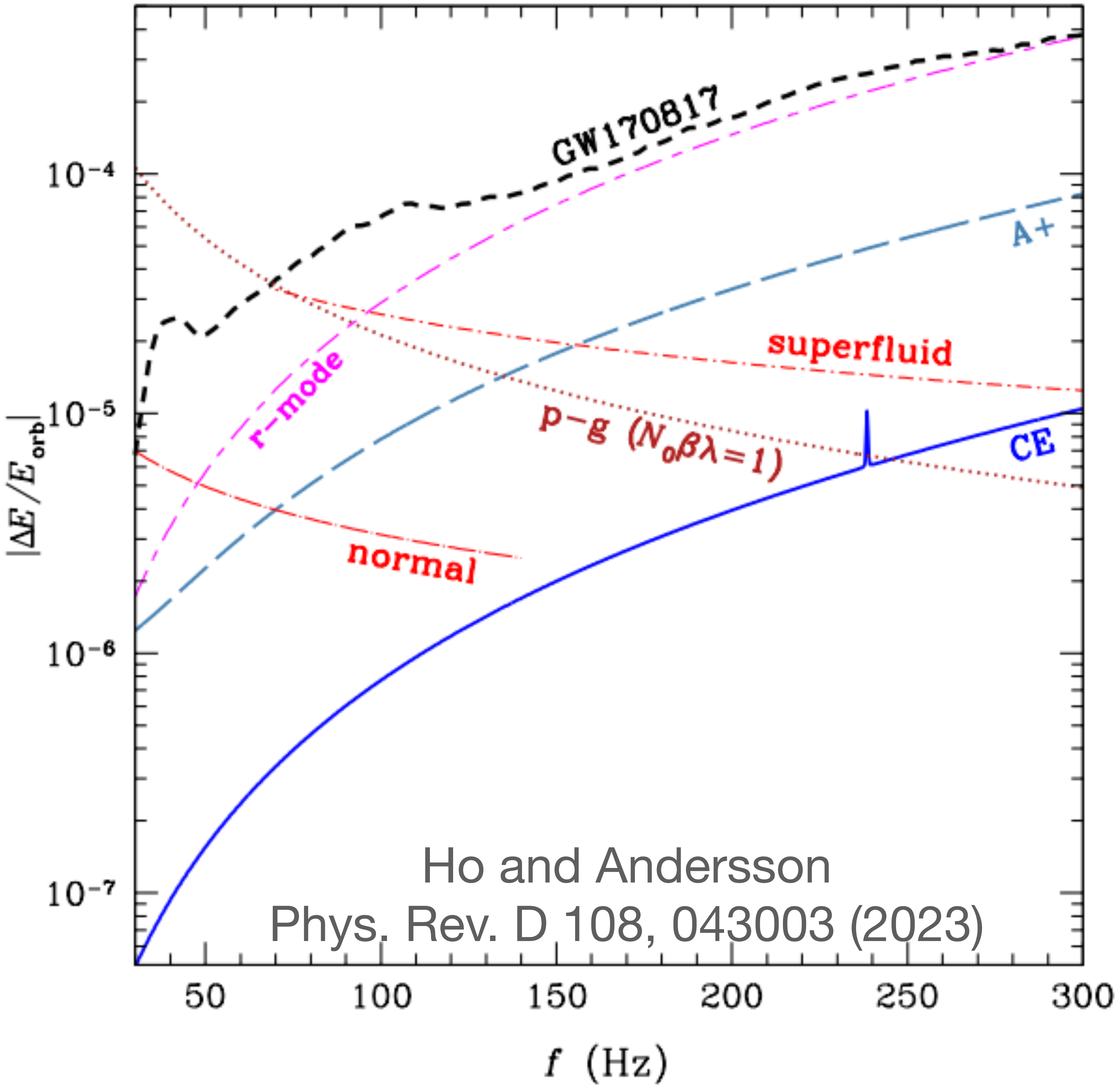
$$h_{\text{model}}(f) = h_{\text{true}}(f)\big(1 + \delta A(f)\big)\exp\big(i\delta\phi(f)\big)$$



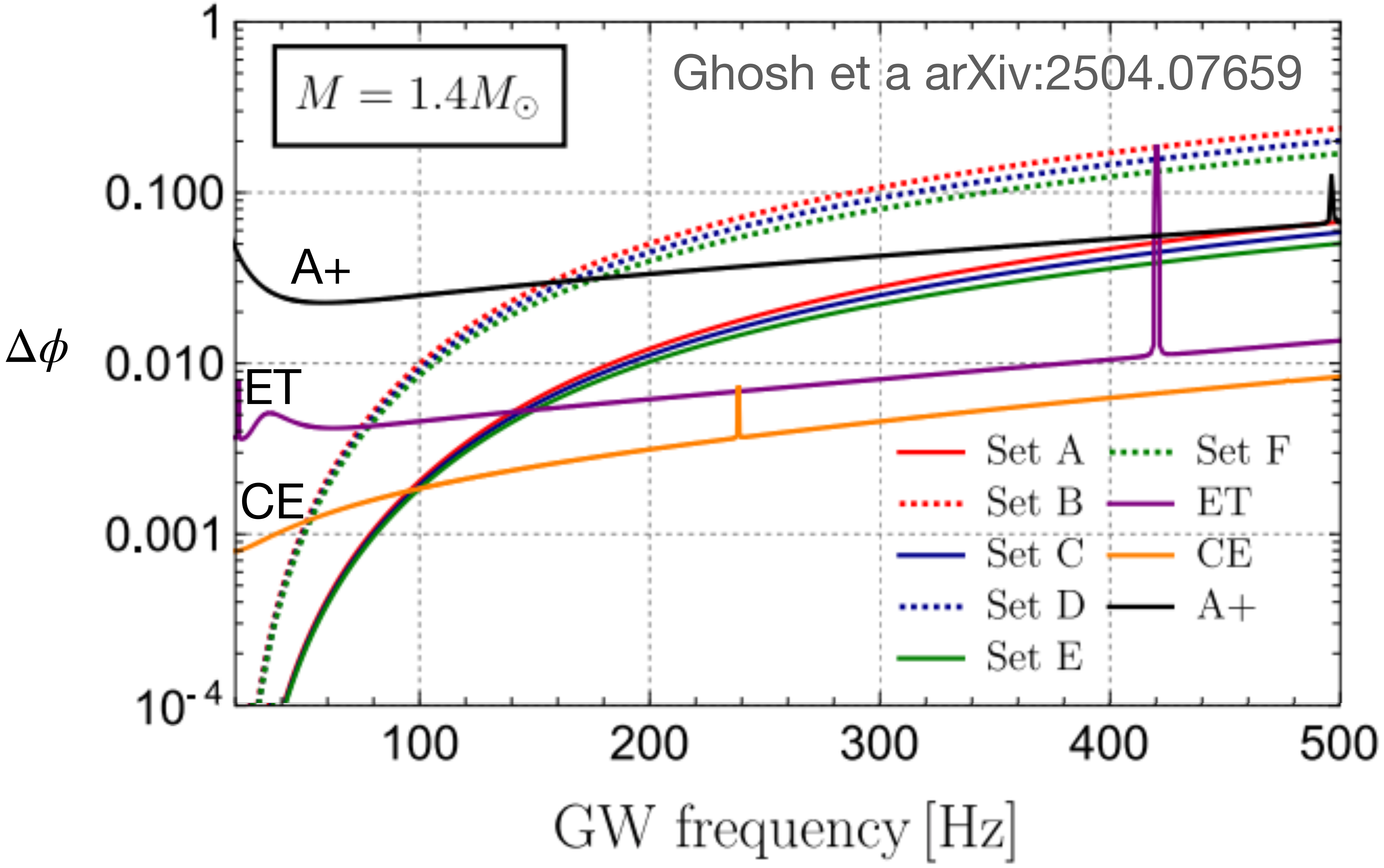
Jocelyn Read 2023 Class. Quantum Grav. 40 135002

XG phase accuracy: beyond Λ

resonant modes, viscous tidal heating



Ho and Andersson
Phys. Rev. D 108, 043003 (2023)



Ghosh et a arXiv:2504.07659

WaveformUncertainty package

Extension of bilby to add and infer waveform corrections

- Include corrections $\delta A, \delta\phi$ in generation of source model

  Marginalize over $\delta A, \delta\phi$ with prior set by waveform model uncertainty, *recover* best-fit $\delta A, \delta\phi$ from high-SNR observation

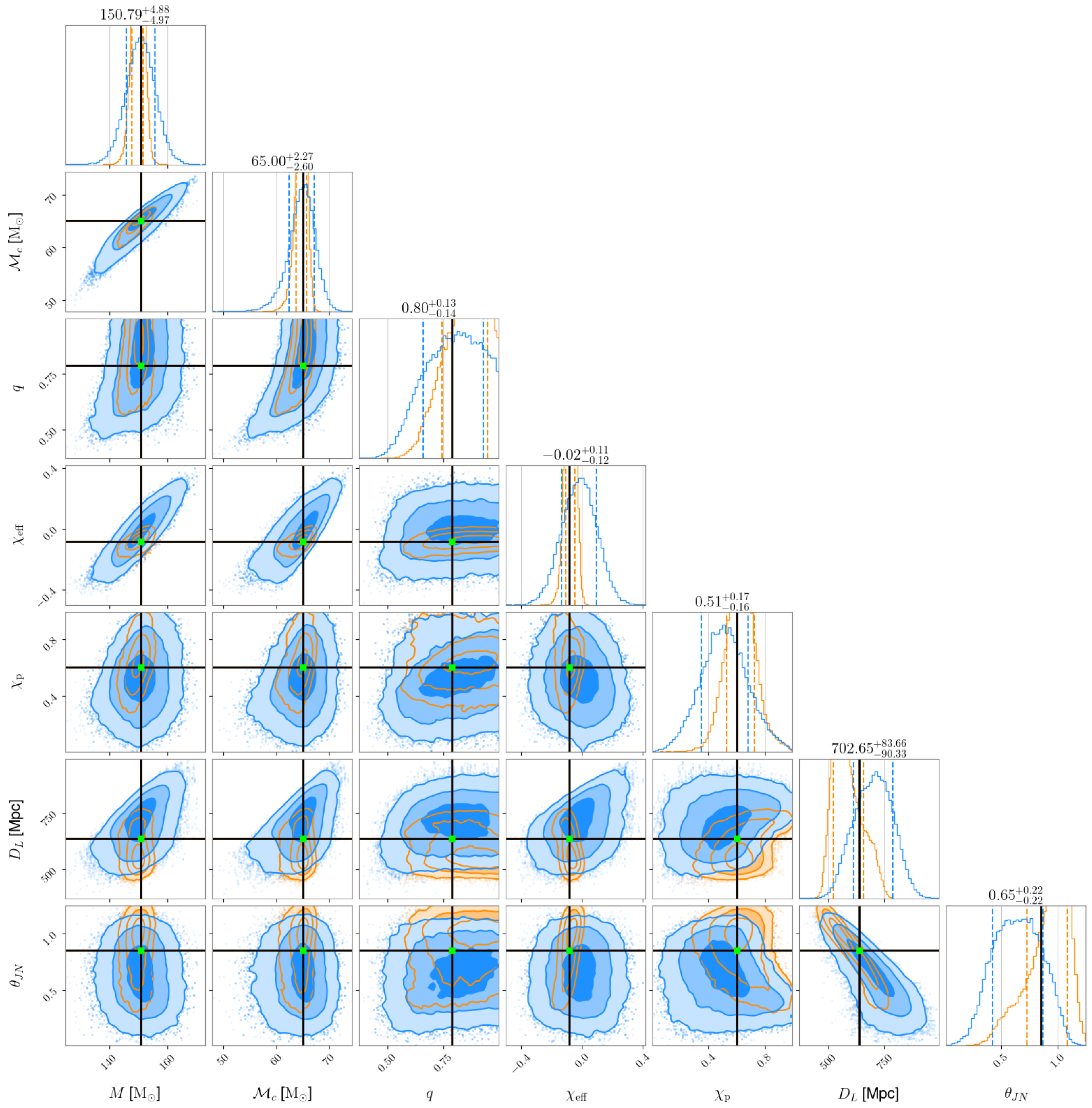
- Ryan Johnson, CSUF: Spline model of $\delta A, \delta\phi$; modified `WaveformGenerator`

$$\mathcal{L}(h(f_j)|\theta, \alpha, \beta) = \frac{1}{2\pi P(f_j)} \exp\left(-2\Delta f \frac{|h(f_j) - \mu(f_j;\theta)(1+\delta A(f_j;\alpha)) \exp[i\delta\phi_R(f_j;\beta)]|^2}{P(f_j)}\right)$$

- Builds on lalinference work by Edelman et al Phys. Rev. D 103, 042004 (2021): Constraint on coherent departures from waveform model

BBH Test: marginalize systematics

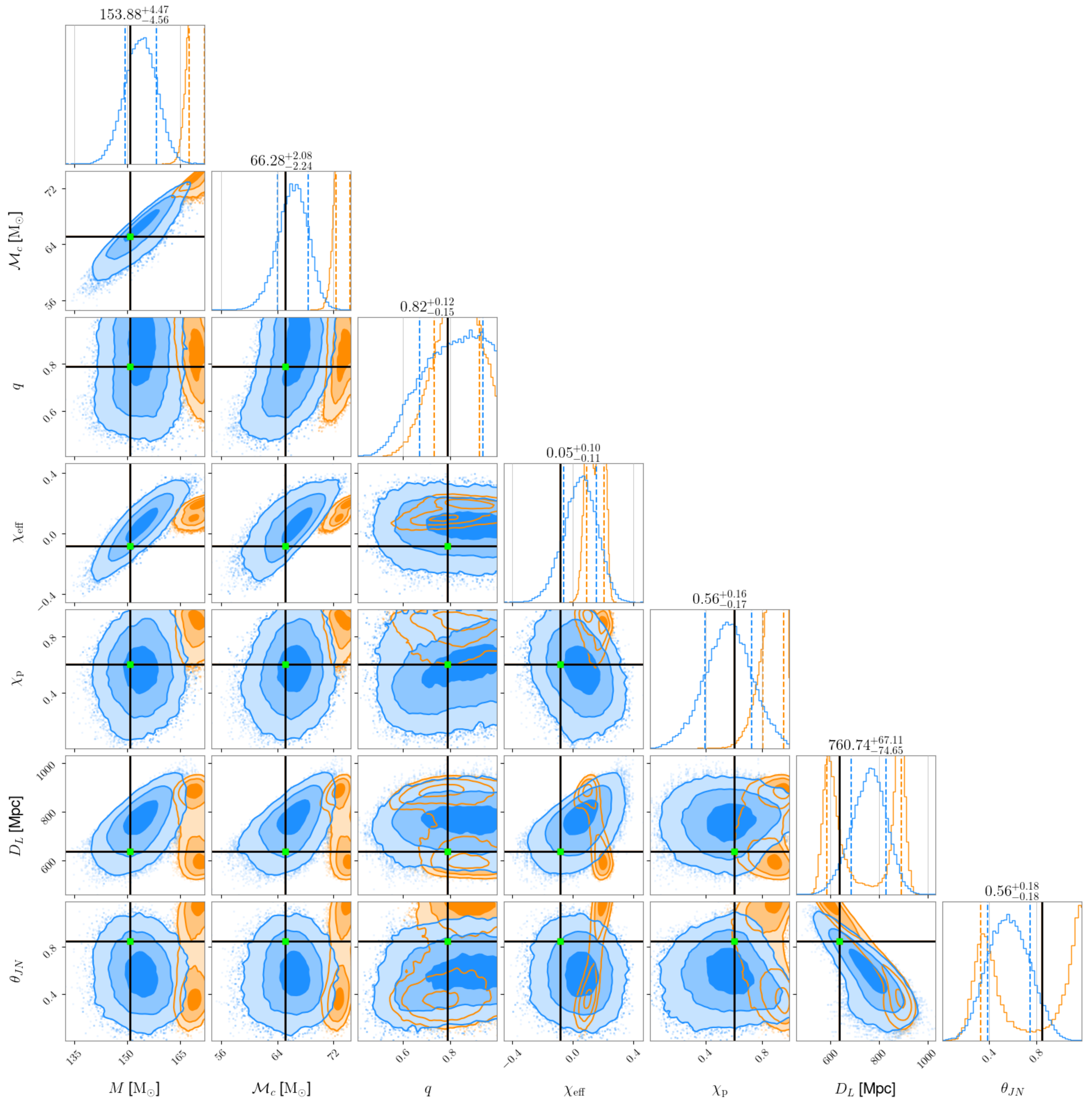
Prior range of waveform differences set by model comparison



- Inject/recovery with same model; marginalize over waveform uncertainty
- No uncertainty marginalization: recover injected parameters
- Uncertainty marginalization: recover injected parameters, with some increased error bars

BBH Test: marginalize systematics

Prior range of waveform differences set by model comparison



- Inject a model with added phase correction within range spanned by current models
- No uncertainty marginalization: systematic error in recovered parameters
- Uncertainty marginalization: Recover injected parameters, with some increased error bars
- Also recover best fit correction to $\delta\phi$

Energy transfers and the Fourier signal

- If there are small, linearizable corrections to the model used for PE:

$$\delta A(f) = \frac{1}{2}\left(\delta E' + \delta \mathscr{L}_{\text{GW}} - \delta \mathscr{L}_{\text{MM}}\right)$$

$$\delta \phi(f) = 2\pi \int_{f}^{f_c} d\tilde{f} \int_{\tilde{f}}^{f_c} dF\, T'(F)\left(\delta E' - \delta \mathscr{L}_{GW} - \delta \mathscr{L}_{MM}\right)$$

  - Generically limit unmodeled energy transfers *(not in PE waveform)* in observed systems through constraints on $\delta A, \delta \phi$.
  - Given a model of astrophysical energy transfer (like a resonant mode), can imprint on *any* underlying waveform model

Jocelyn Read 2023 Class. Quantum Grav. 40 135002