ECT* Apr 22–26, 2024, The physics of strongly interacting matter

Neutron star mergers in gravitational wave astronomy

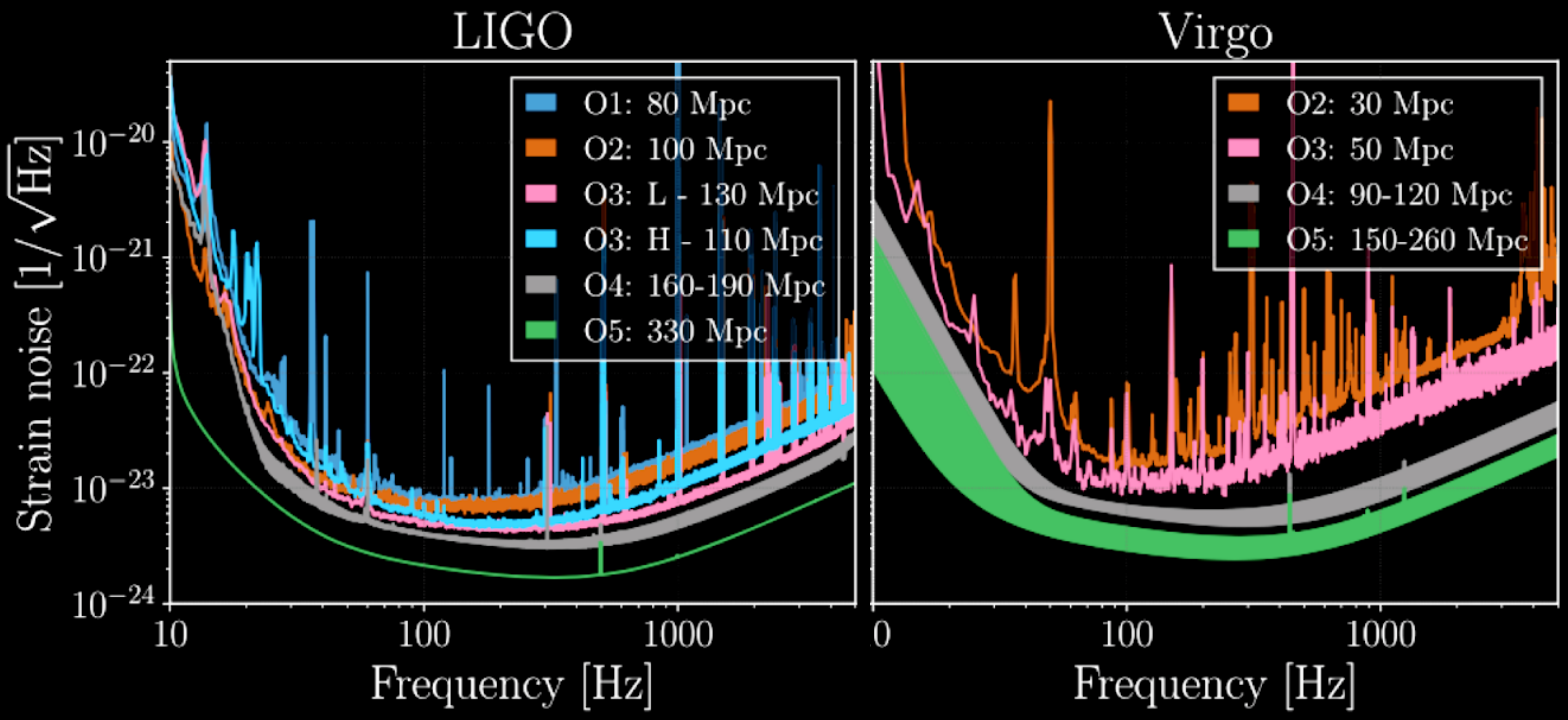
Jocelyn Read
Nicholas and Lee Begovich Center
for Gravitational-Wave Physics and Astronomy
California State University Fullerton

Neutron Stars Merging,
CSUF GWPAC Artist-in-Residence Eddie Anaya

Gravitational-wave astronomy in the Advanced Era

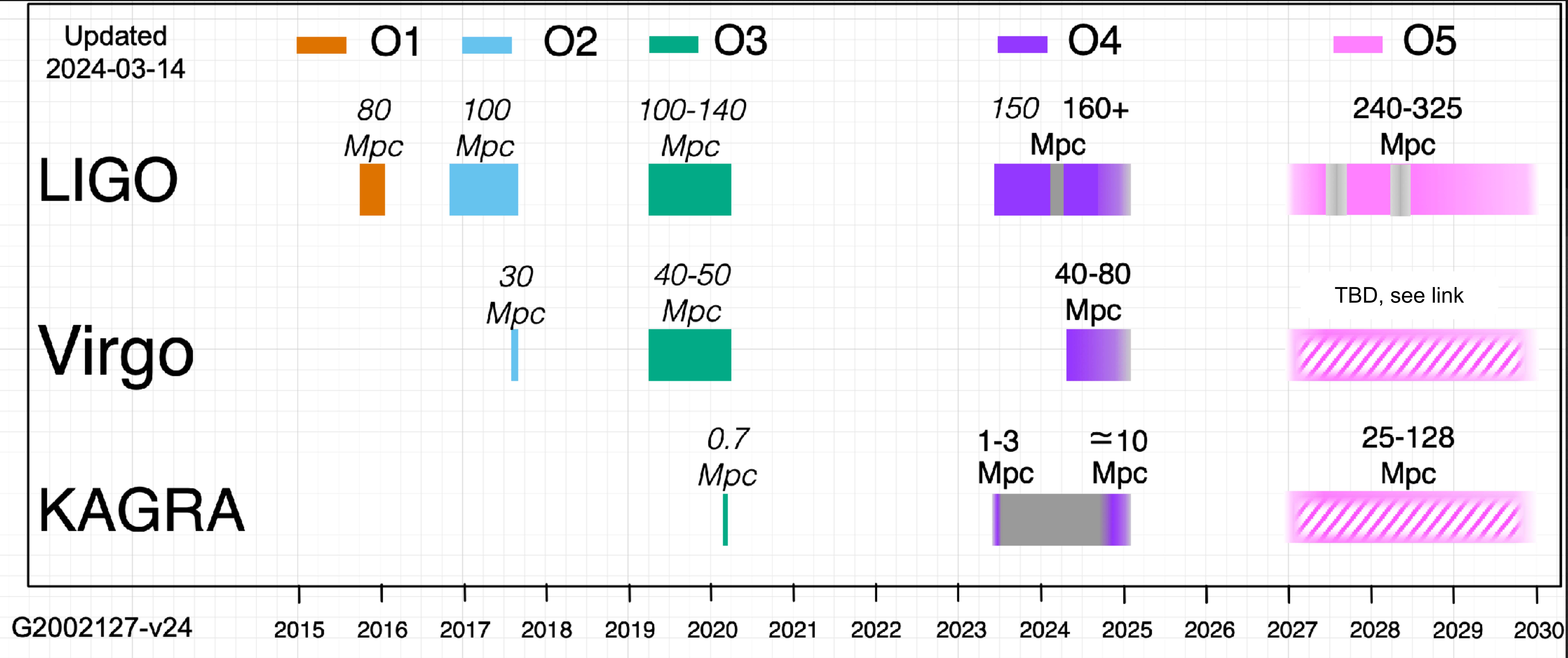
Ground-based gravitational-wave observatories

Strain noise: detector spectral density $\sqrt{S_n(f)}$



LIGO-Virgo-KAGRA Observing Scenarios Living Rev Relativ 23, 3[4](2020) https://observing.docs.ligo.org/plan/

Observing in the “Advanced” Era

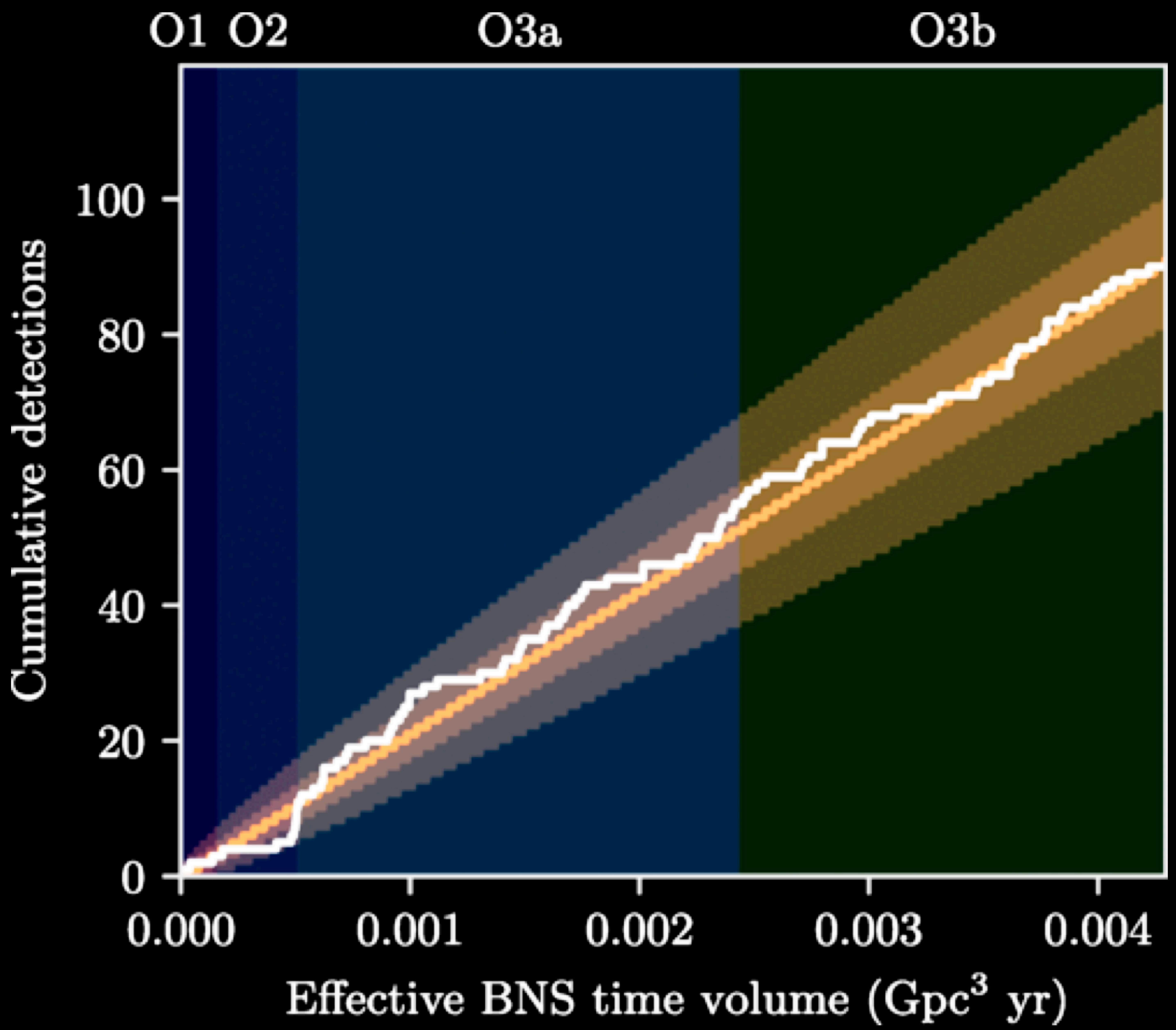


- Range: sky-average distance to a $1.4M_\odot - 1.4M_\odot$ binary that generates a single-detector signal-to-noise ratio $\rho = 8$.

Signals O1-O3

LIGO-Virgo-Kagra GWTC-3 Catalog, Phys. Rev. X **13**, 041039, arXiv:2111.03606, https://gwosc.org/GWTC-3/

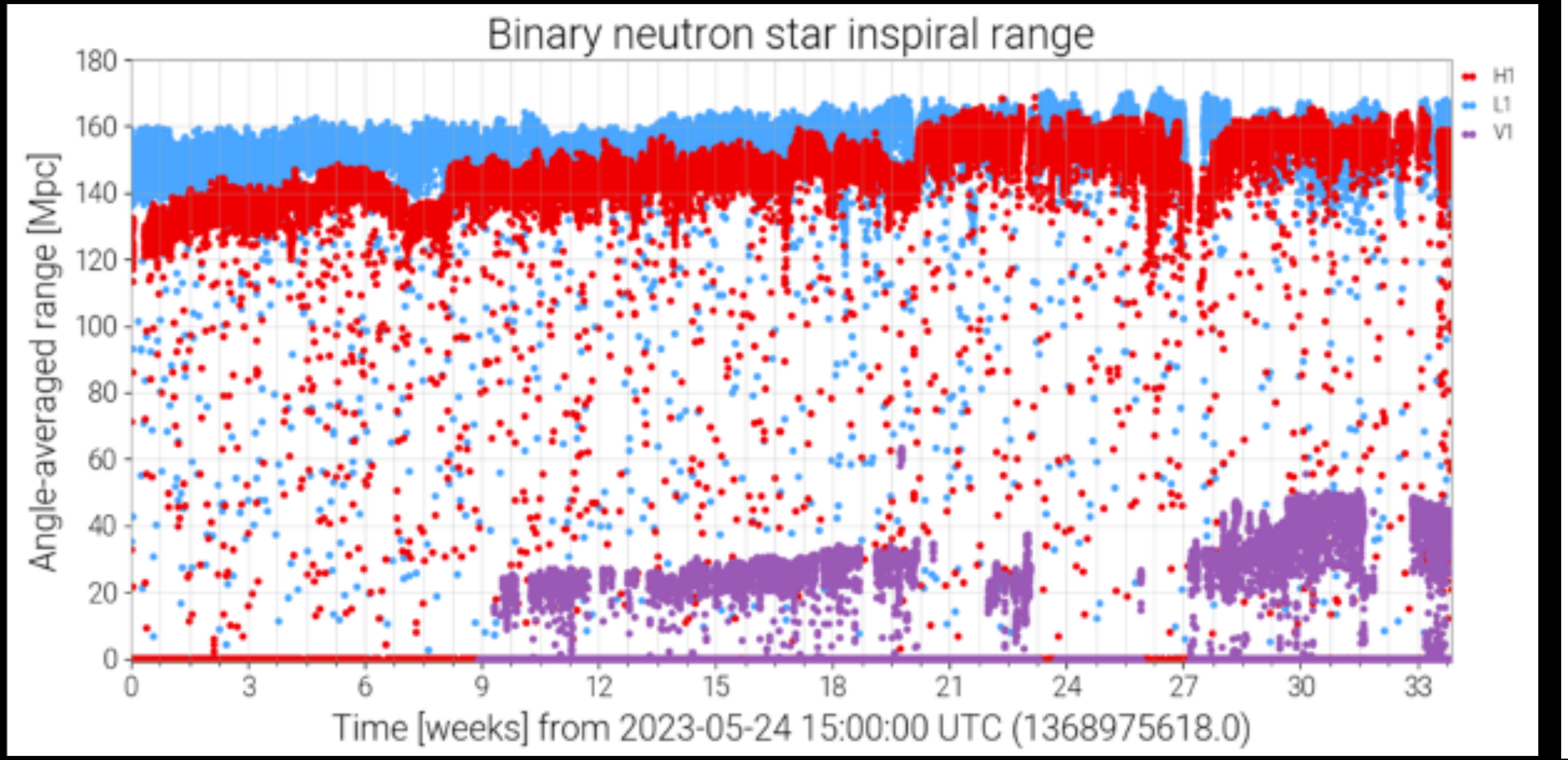
- Detections scale with observation time × estimated sensitive volume
- GW have a well-modeled selection function
- e.g. at low mass $V_{det} \propto (SNR)^3 \propto \mathscr{M}^{5/2}$



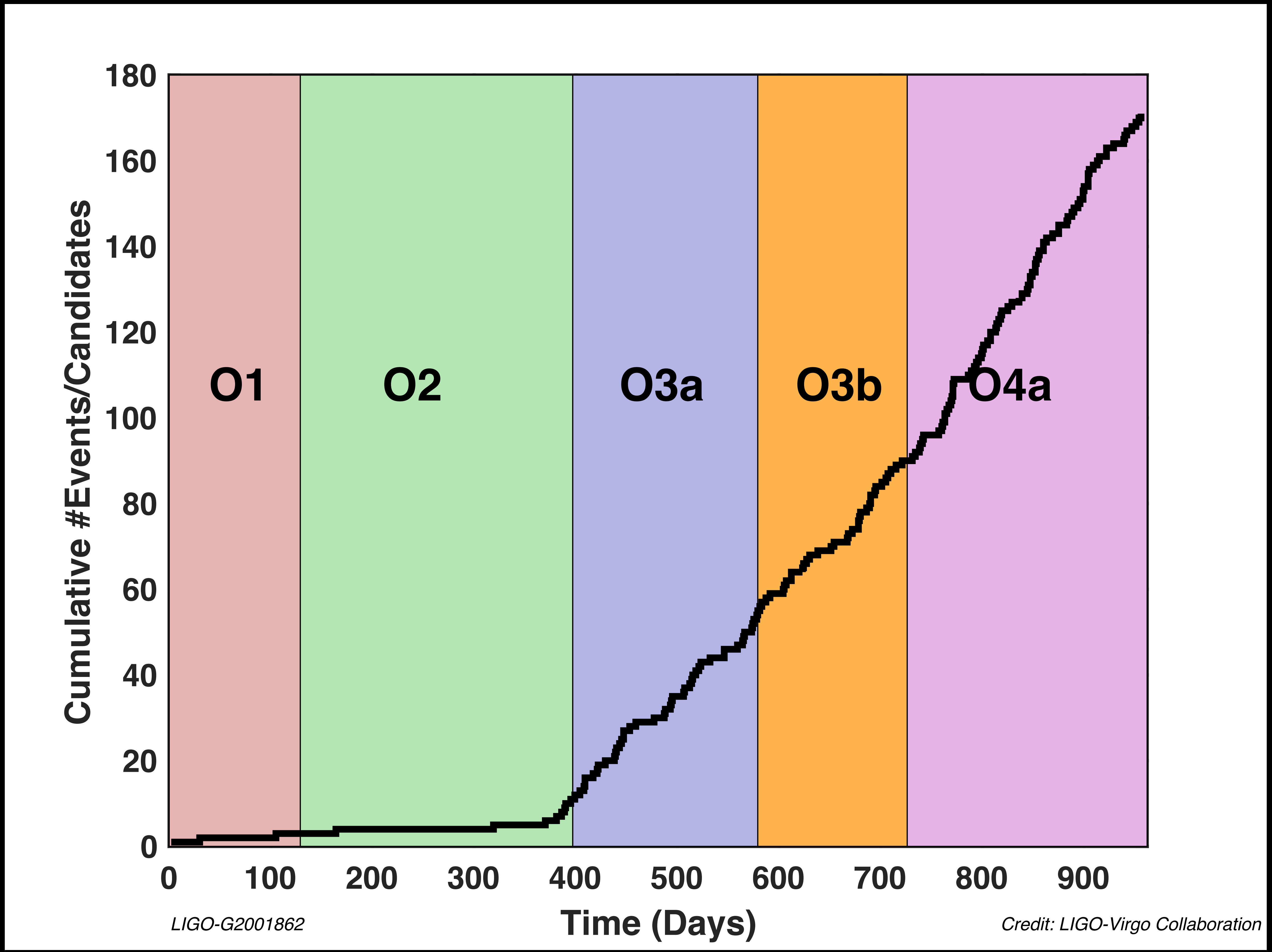
Observations: May 2023 - January 2024

Engineering run 15, Observing run 4a

- 4 “significant” alerts in ER15 and 85 so far in O4 (https://gracedb.ligo.org/superevents/public/O4/)



LIGO-G2400503



LIGO-G2001862

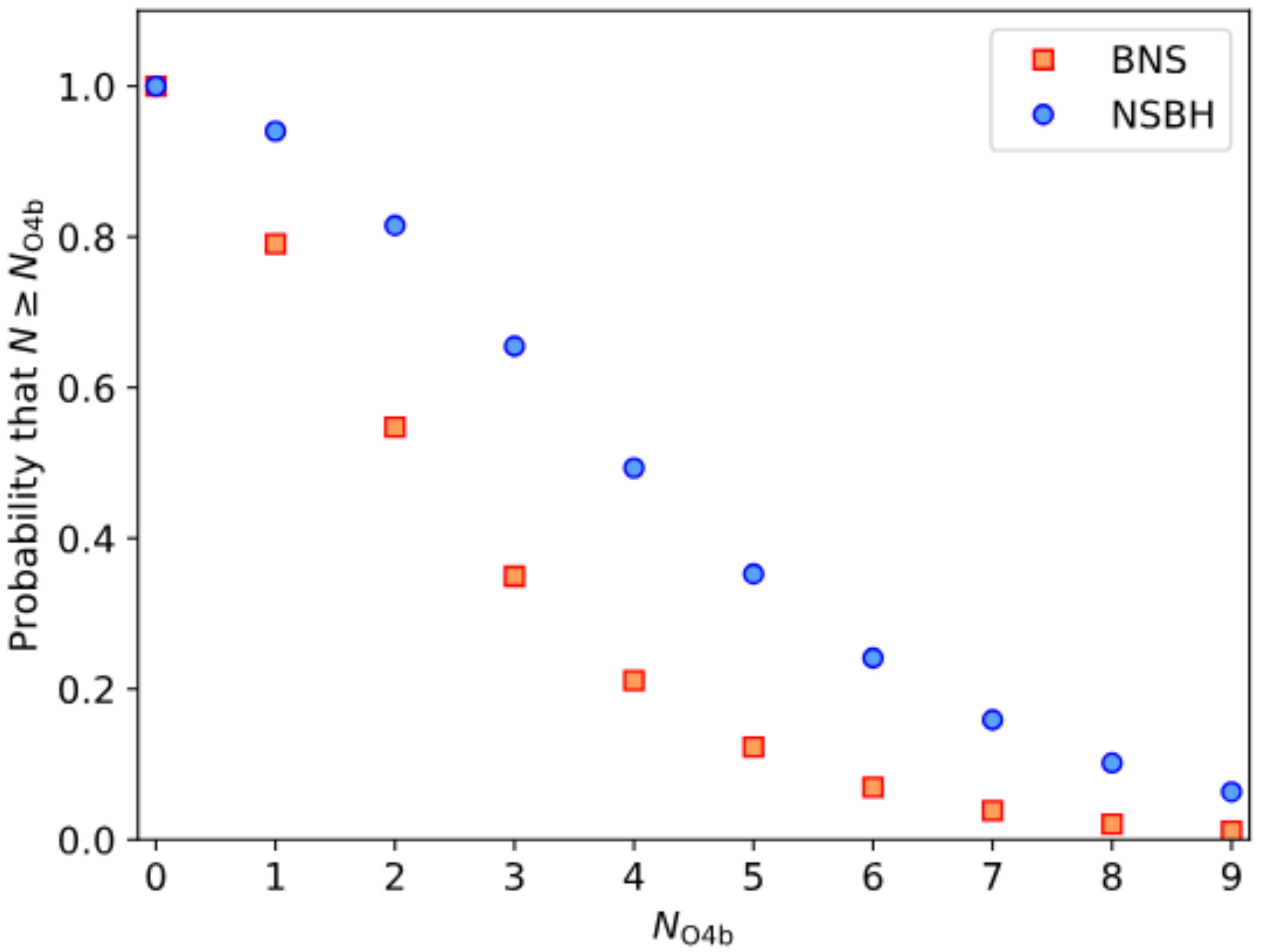
Expectations for this year

From O3; with O3 rates updated assuming no BNS in O4a time-volume

https://emfollow.docs.ligo.org/userguide/capabilities.html

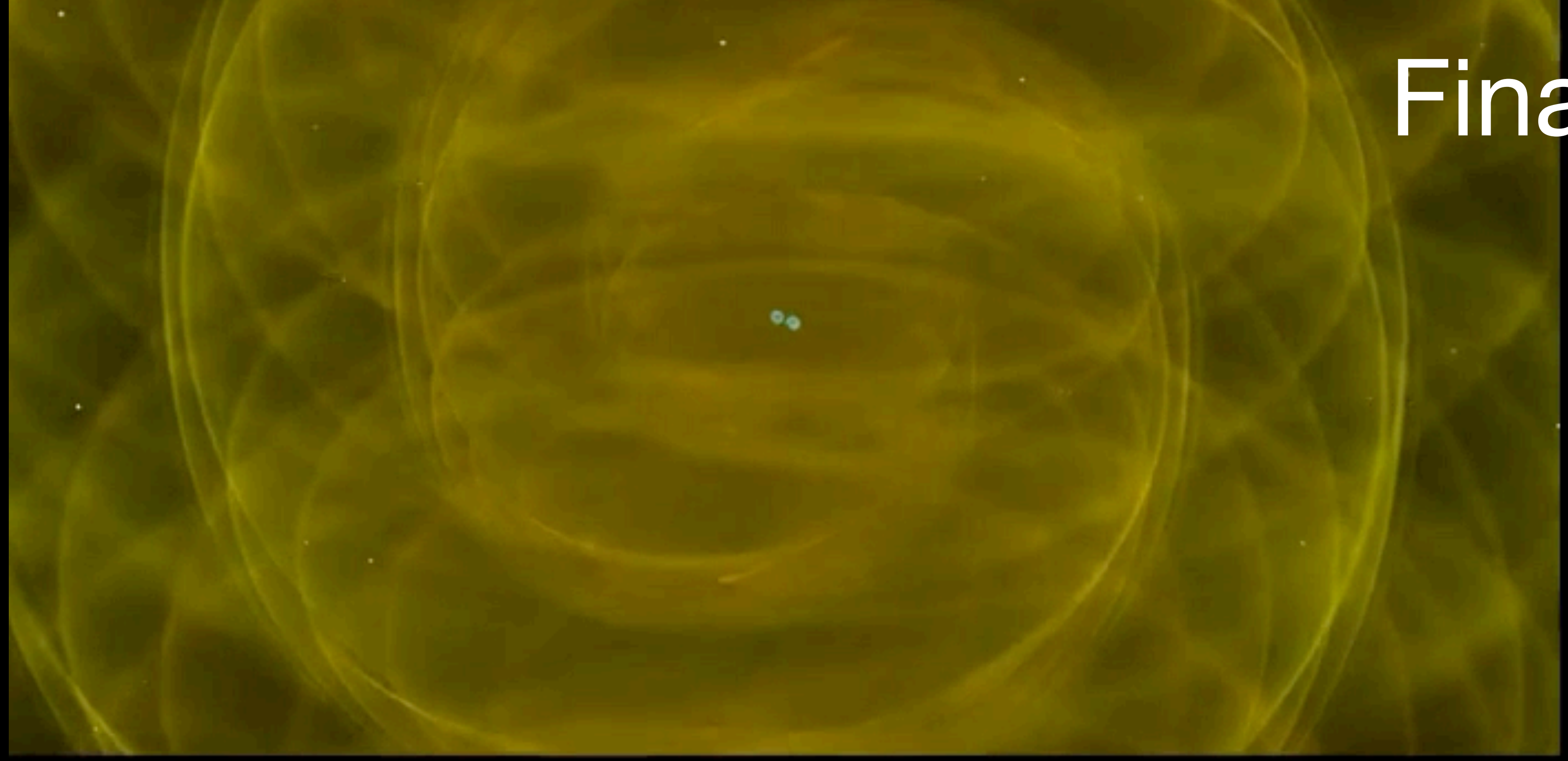
	BNS	NSBH	BBH
Merger rate per unit comoving volume per unit proper time (Gpc^{-3} year^{-1}, log-normal uncertainty)			
	210^{+240}_{-120}	$8.6^{+9.7}_{-5.0}$	$17.1^{+19.2}_{-10.0}$
Annual number of public alerts (log-normal merger rate uncertainty $\times$ Poisson counting uncertainty)			
O4	36^{+49}_{-22}	6^{+11}_{-5}	260^{+330}_{-150}
O5	180^{+220}_{-100}	31^{+42}_{-20}	870^{+1100}_{-480}

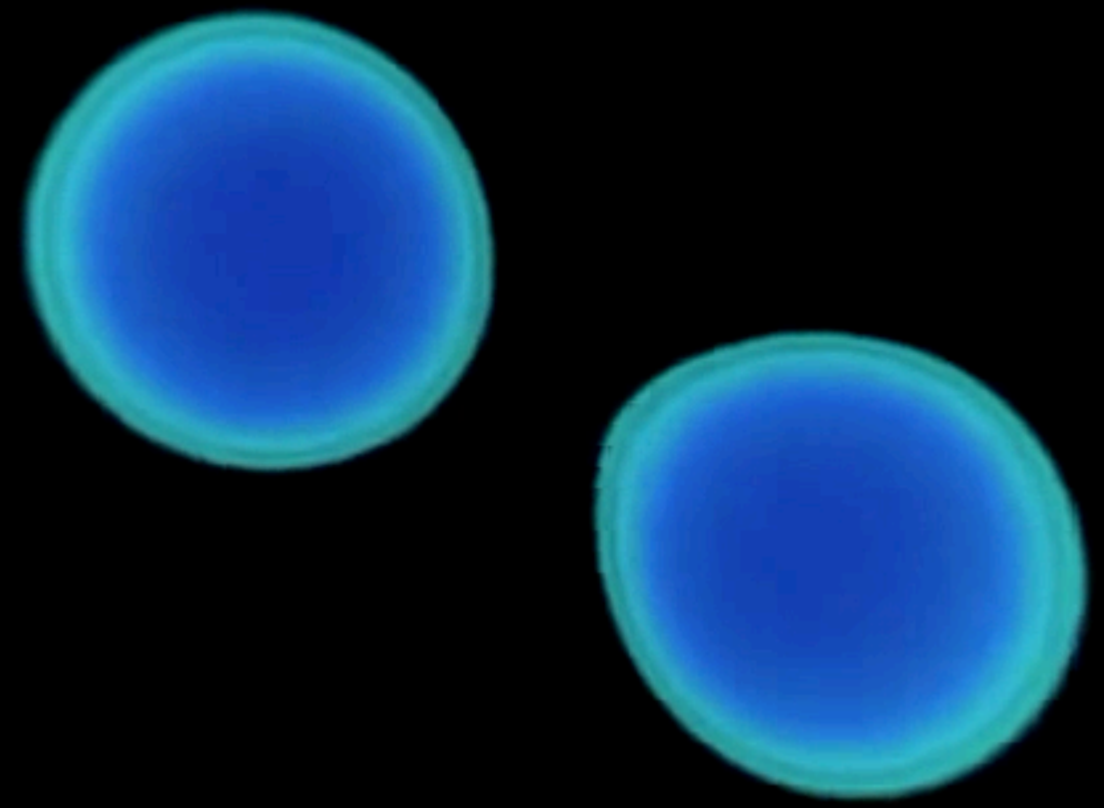
O4b projection: BNS updated to $5 - 920$ Gpc^{-3} yr^{-1}

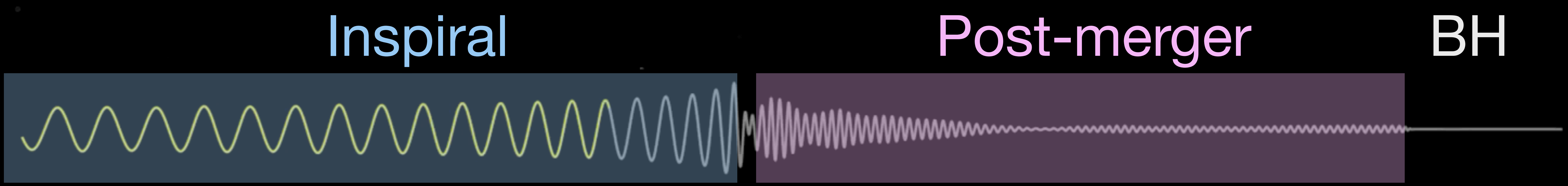


Interpreting observations

Final 40 milliseconds of inspiral





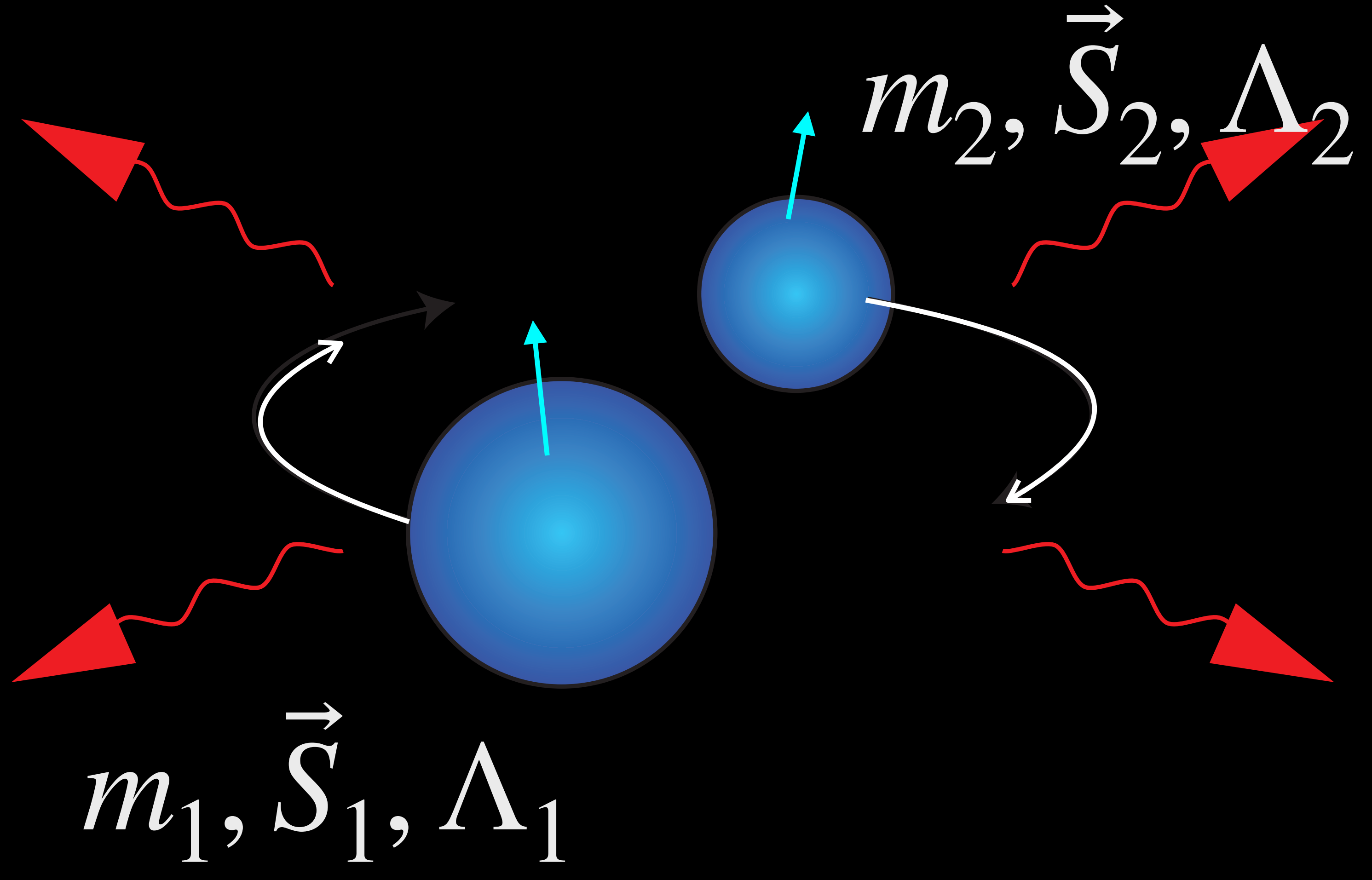


https://www.youtube.com/watch?v=V6cm-0bwJ98

T. Dietrich, S. Ossokine, H. Pfeiffer, A. Buonanno (AEI)

Source model

- Fourier domain $h(t) \rightarrow \tilde{h}(f)$



Sky location, orientation

Chirp mass $\frac{(m_1 m_2)^{3/5}}{(m_1 + m_2)^{1/5}}$

$$\tilde{h}(f) \sim Q(\alpha, \delta, \iota, \psi) \frac{\mathscr{M}}{d_L} f^{-7/6} (1 + \ldots) e^{i\phi(f)}$$

$\phi(f)$ is where the $(m, \vec{S}, \Lambda)$ magic happens!

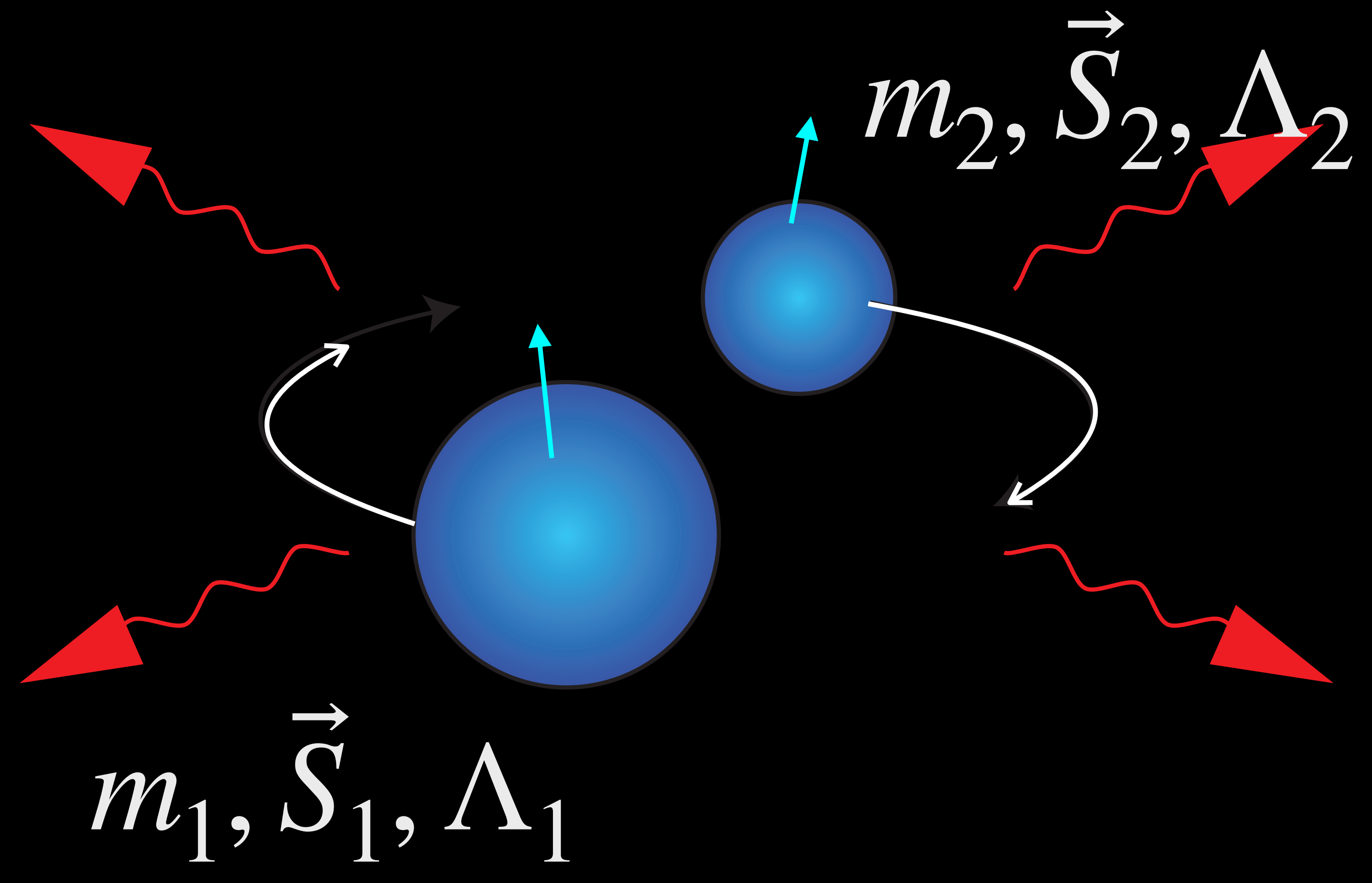
Luminosity distance

Amplitude fall-off in frequency domain

GW phase ↔ Orbital phase

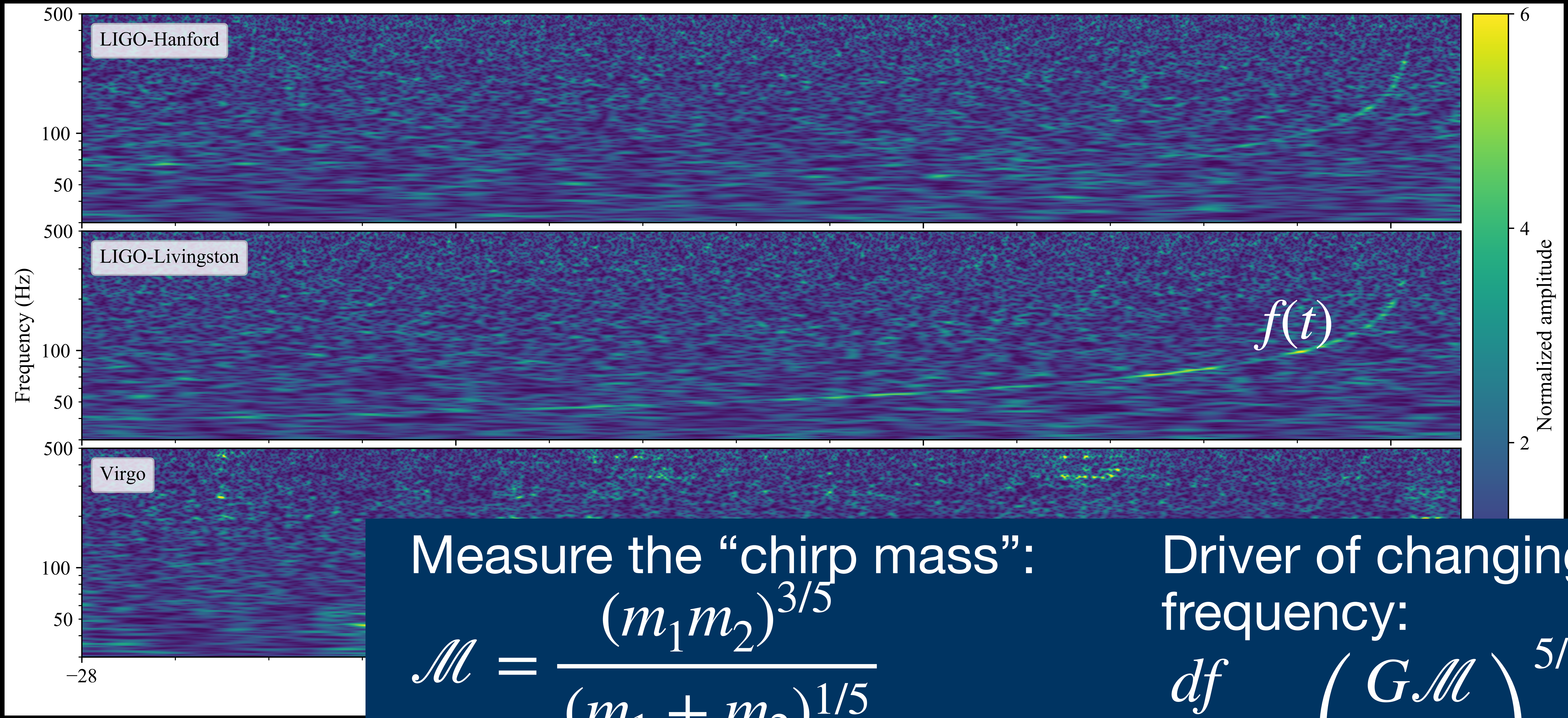
$$\phi(f) = 2\pi i f t_c + \phi_c + [\text{const}] \left(\mathcal{M} f\right)^{-5/3} + \ldots$$

for inspiral a function of leading-order combinations:



- Chirp mass: $\mathcal{M} = \dfrac{(m_1 m_2)^{3/5}}{(m_1 + m_2)^{1/5}}$
- Mass ratio: $q = m_2/m_1$
- Effective spin: $\chi_{\text{eff}} = \dfrac{\vec{S}_1/m_1 + \vec{S}_2/m_2}{m_1 + m_2} \cdot \overrightarrow{L}$
- Effective tide: $\tilde{\Lambda} = \dfrac{16}{13} \dfrac{(m_1 + 12 m_2) m_1^4 \Lambda_1 + (m_2 + 12 m_1) m_2^4 \Lambda_2}{(m_1 + m_2)^5}$

e.g. neutron-star merger GW170817



Measure the "chirp mass":

$$\mathscr{M} = \frac{(m_1 m_2)^{3/5}}{(m_1 + m_2)^{1/5}}$$

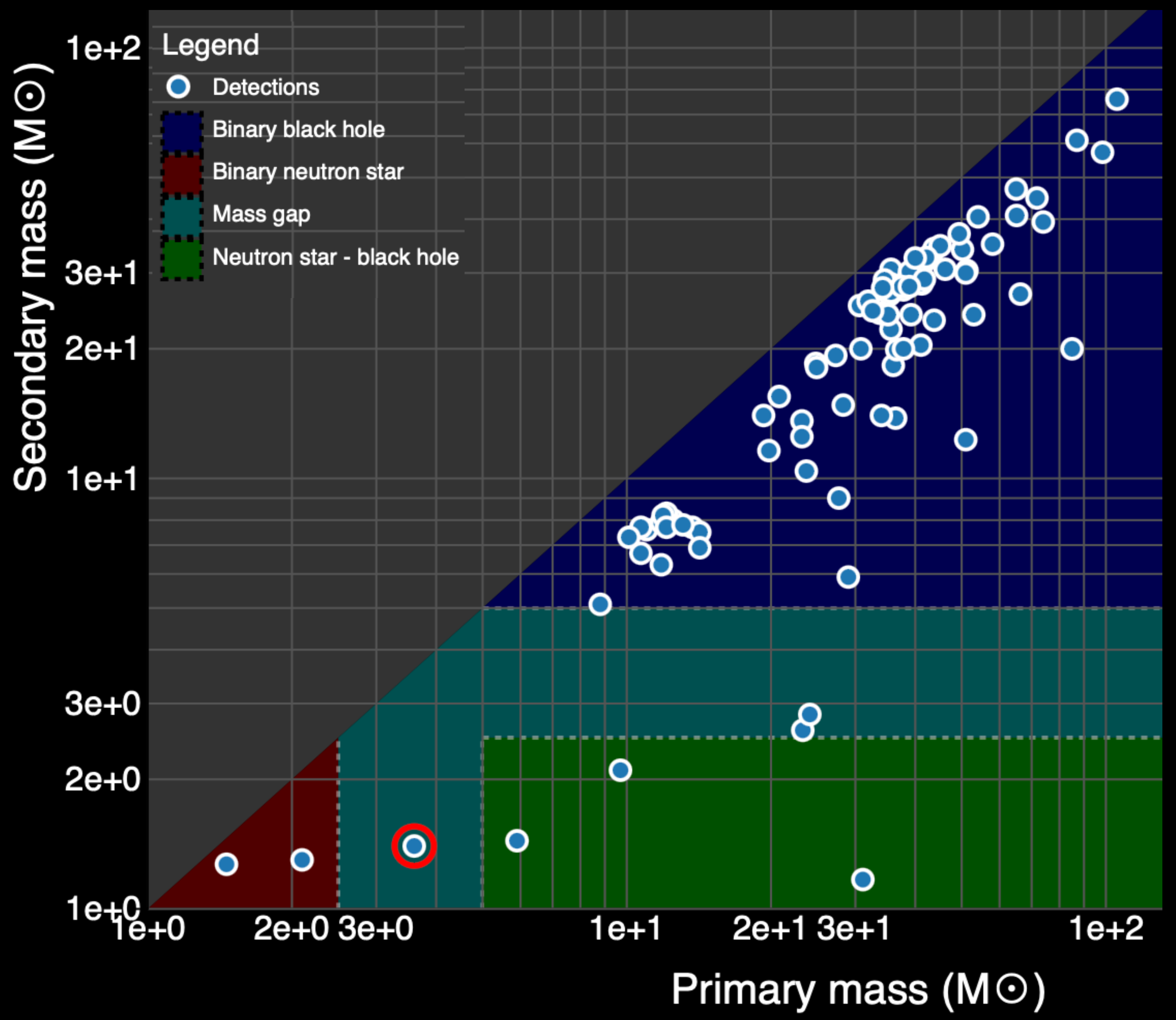
Driver of changing frequency:

$$\frac{df}{dt} \propto \left(\frac{G\mathscr{M}}{c^3}\right)^{5/3} f^{11/3} + \dots$$

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

Introducing GW230529

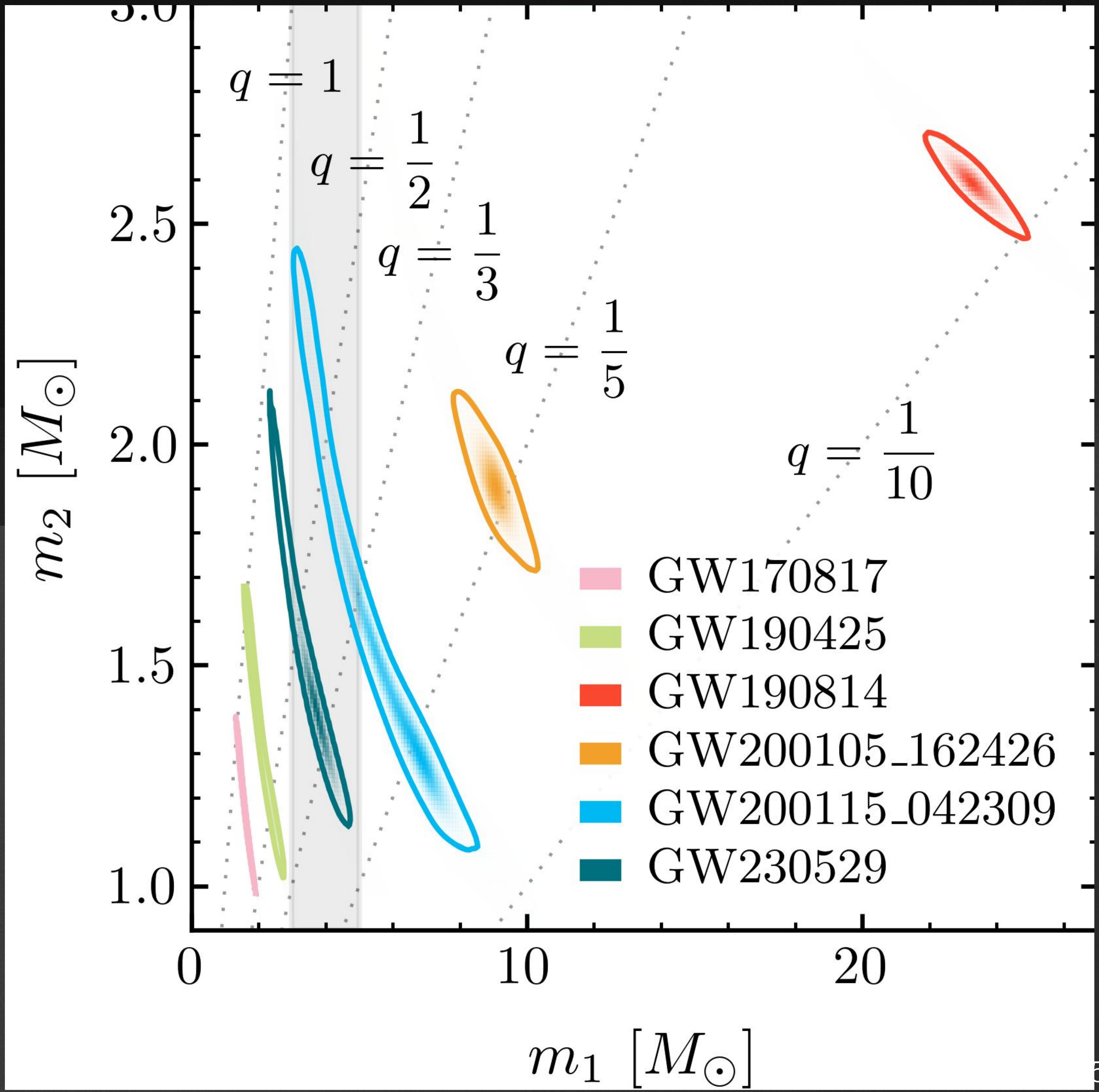
- First public event of the new observing run
- Filling the “mass gap” between neutron stars and previously-observed BBH



https://catalog.cardiffgravity.org/

Low-mass mergers ($m_i < 3.0 M_\odot$)

LIGO-Virgo-KAGRA GW230529
https://arxiv.org/abs/2404.04248v1

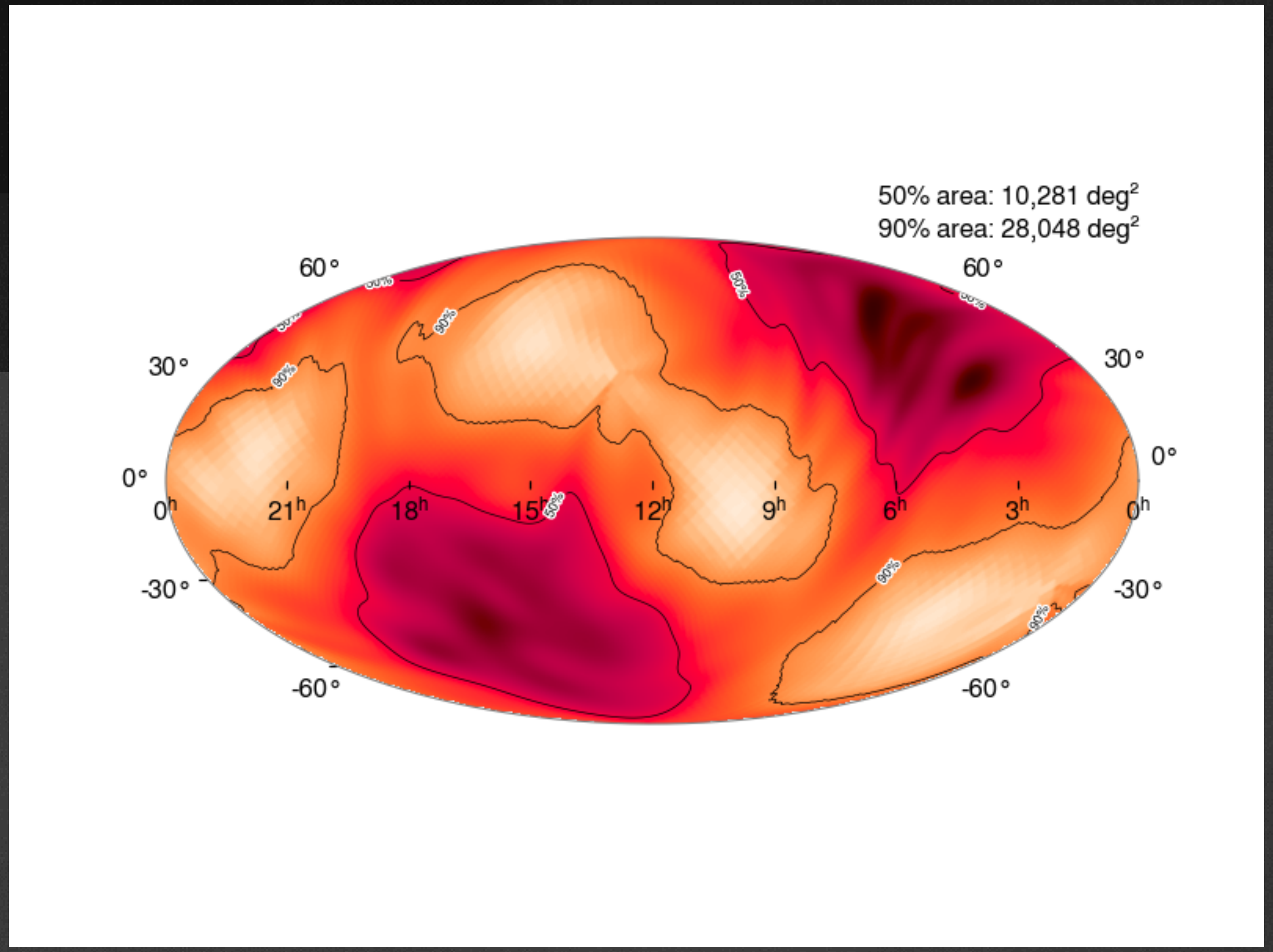


- Objects above the the **NS EOS-inferred maximum mass** are black holes
- Observation of orbits at high frequency requires compact object (NS or BH)
- Classification discussion: in GW190425: LSC/VSC ApJL, 892, L3 (2020), GW190814: LSC/VSC ApJL **896,** L44 (2020), NSBHs: LSC/VSC/KC ApJL, 915, L5 (2021), Essick & Landry ApJ 904 80 (2020)

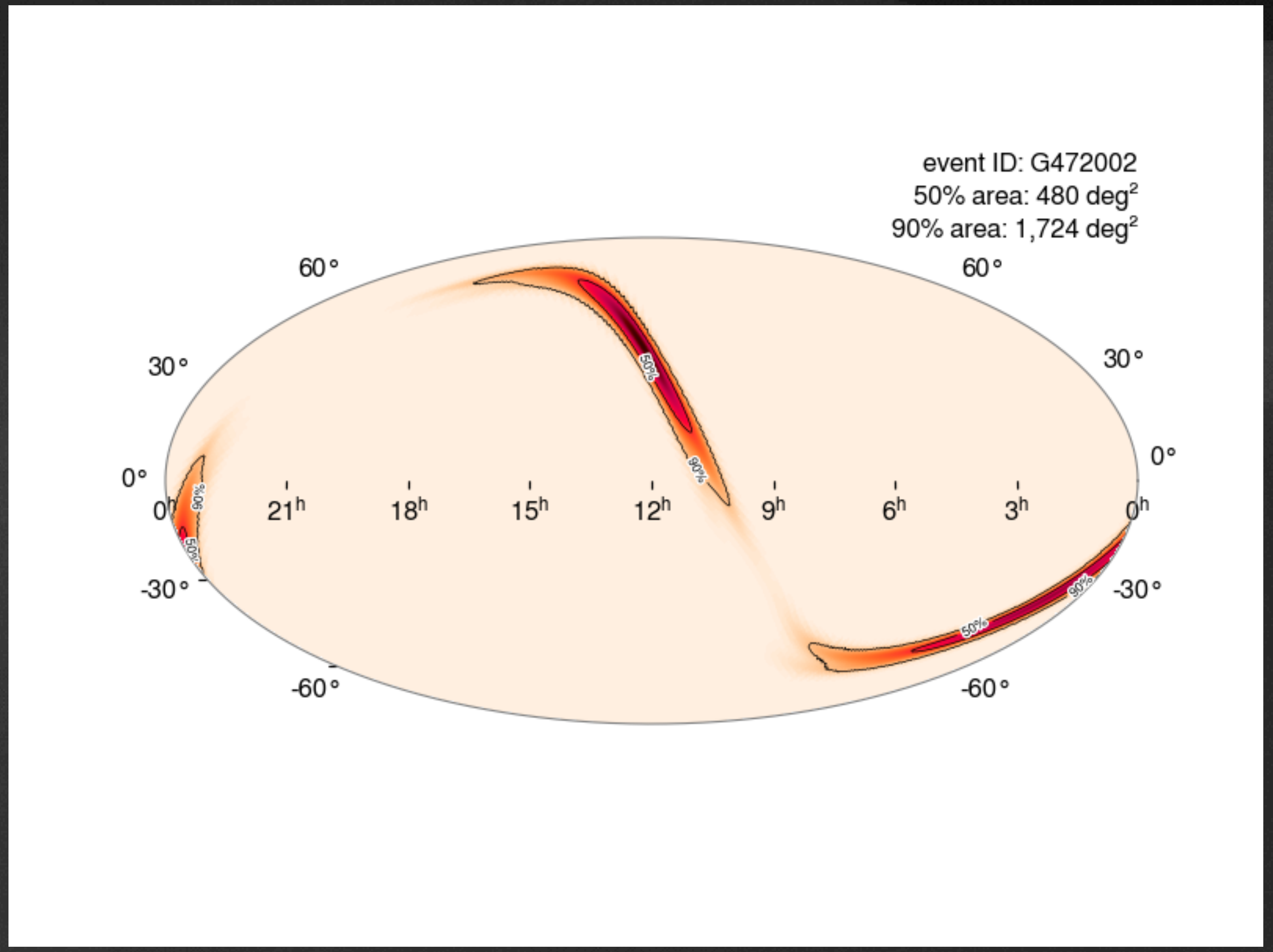
Virgo is back!

- https://gracedb.ligo.org/superevents/public/O4/

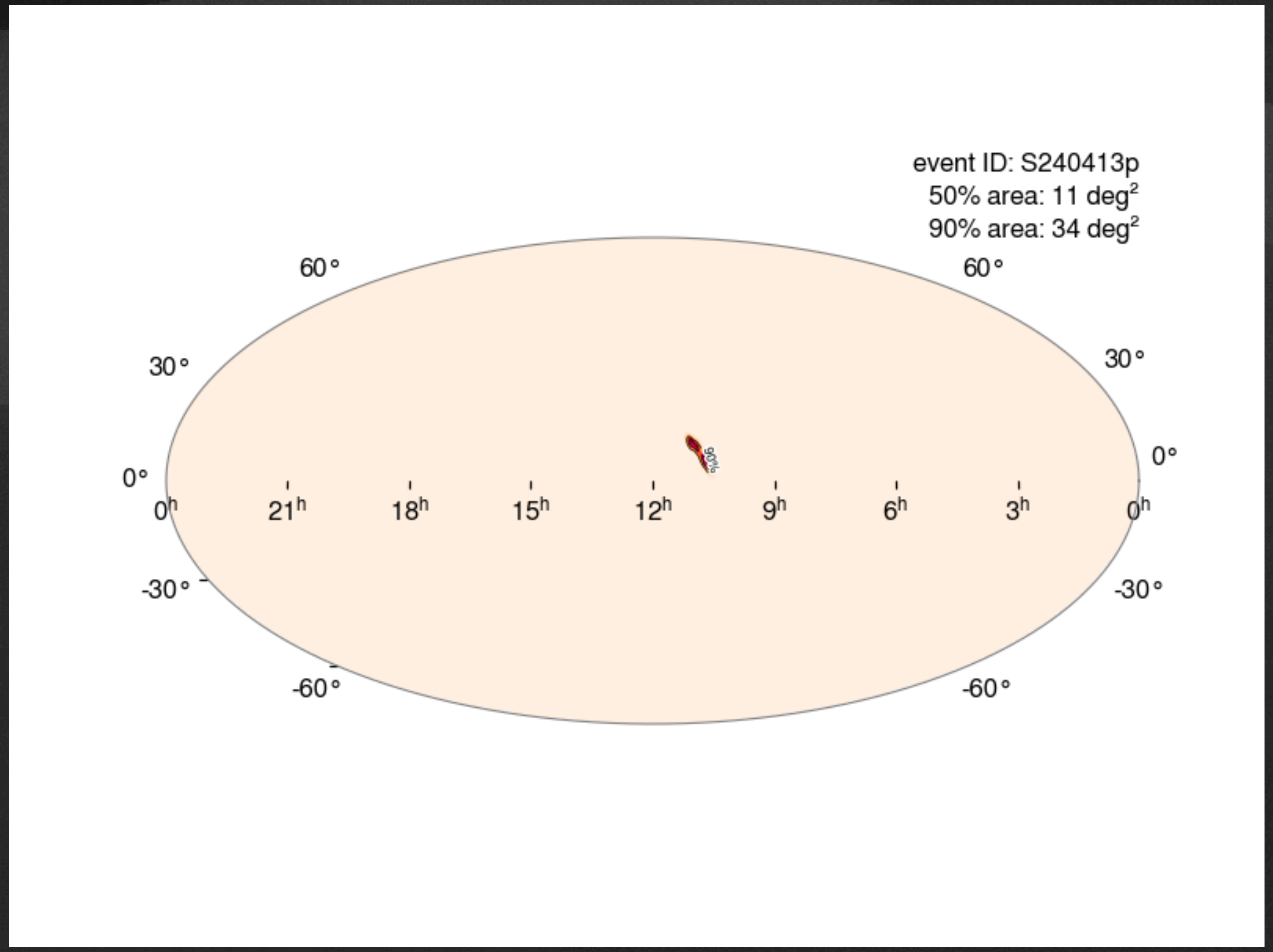
S240109a (H1)



S240406aj (H1,L1)

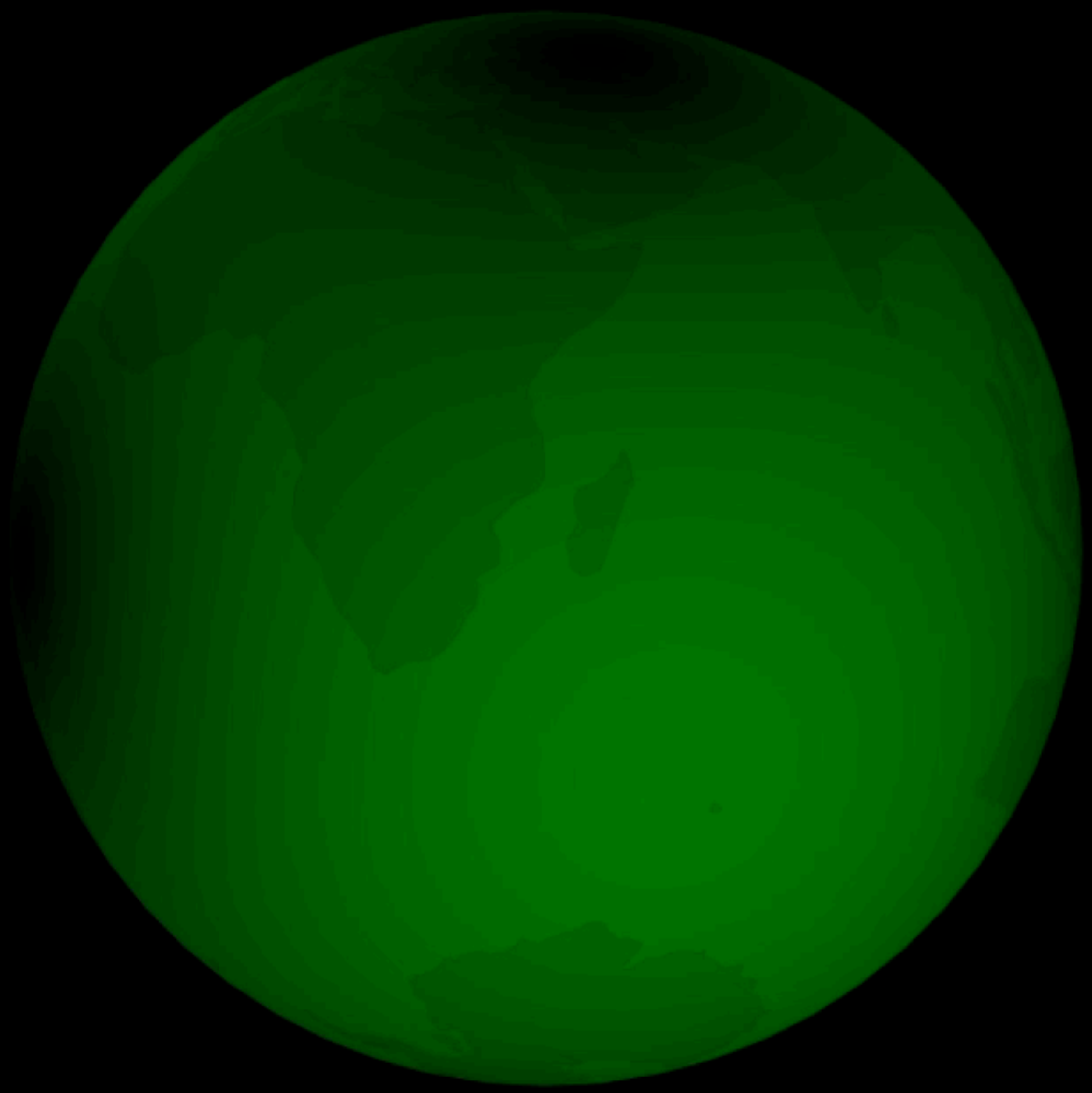


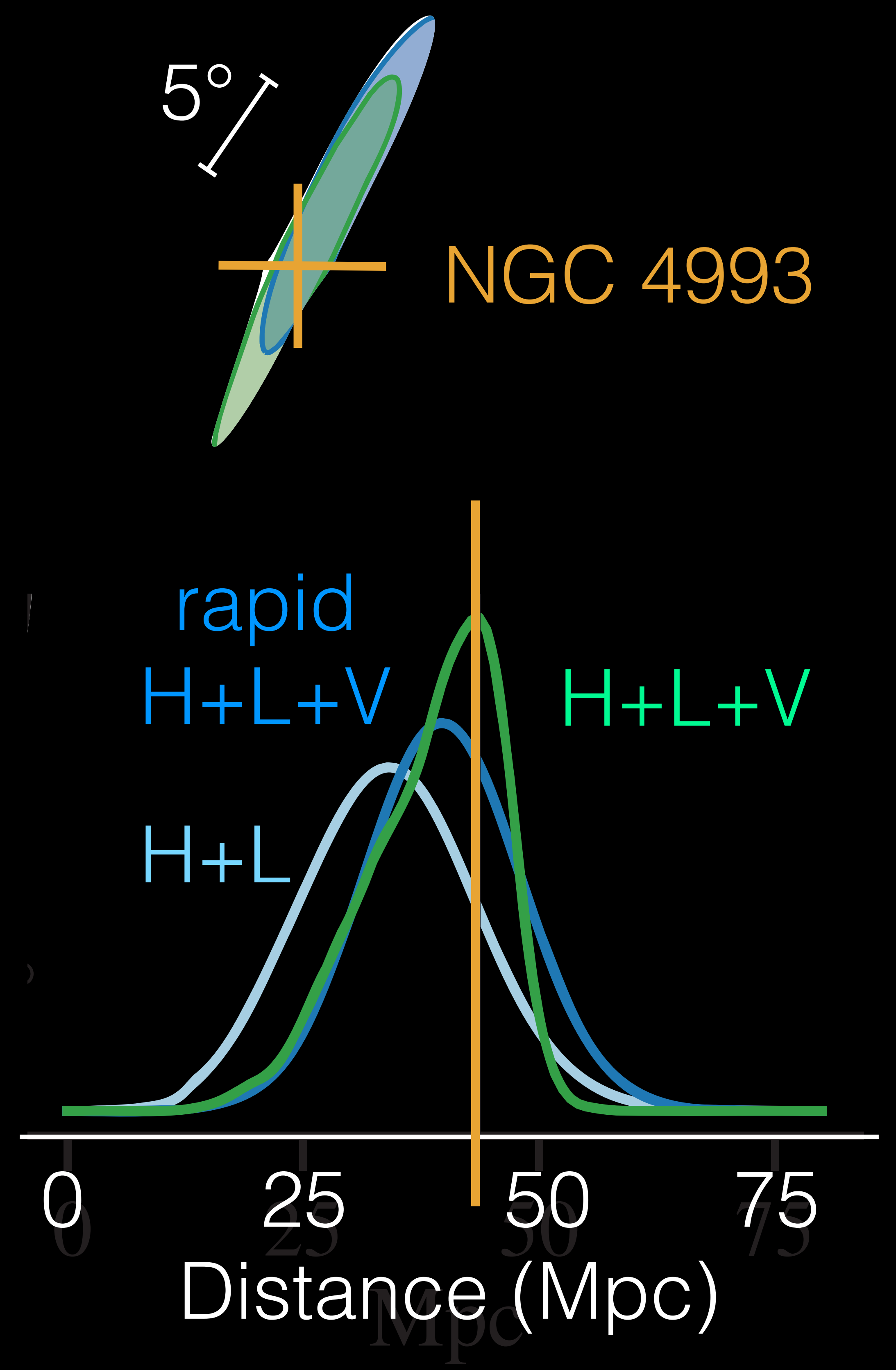
S240413p (H1,L1,V1)



- Three-detector network has much improved localization capability

Localization in GW170817:
Arrival time, amplitude, chirp mass

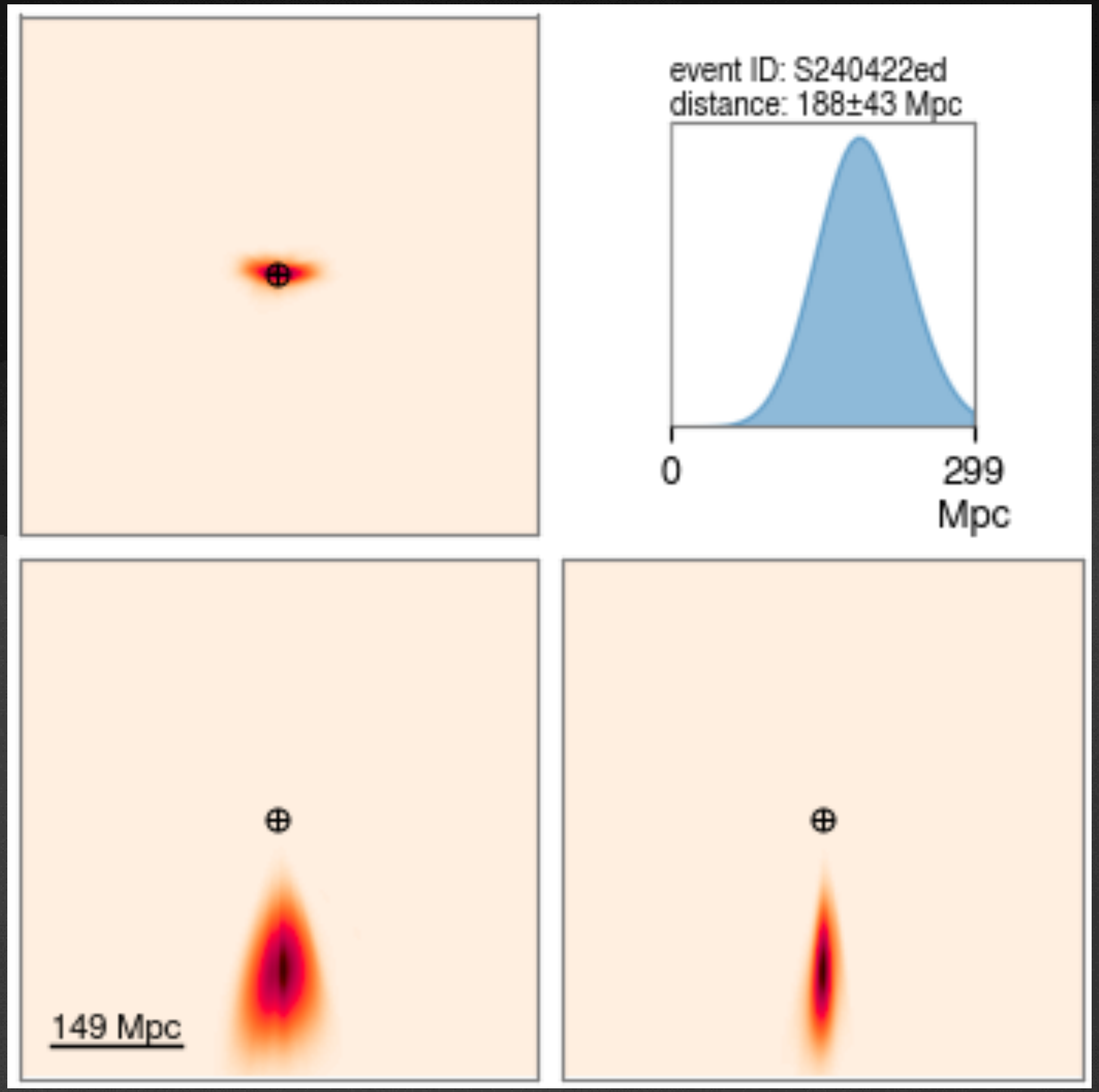


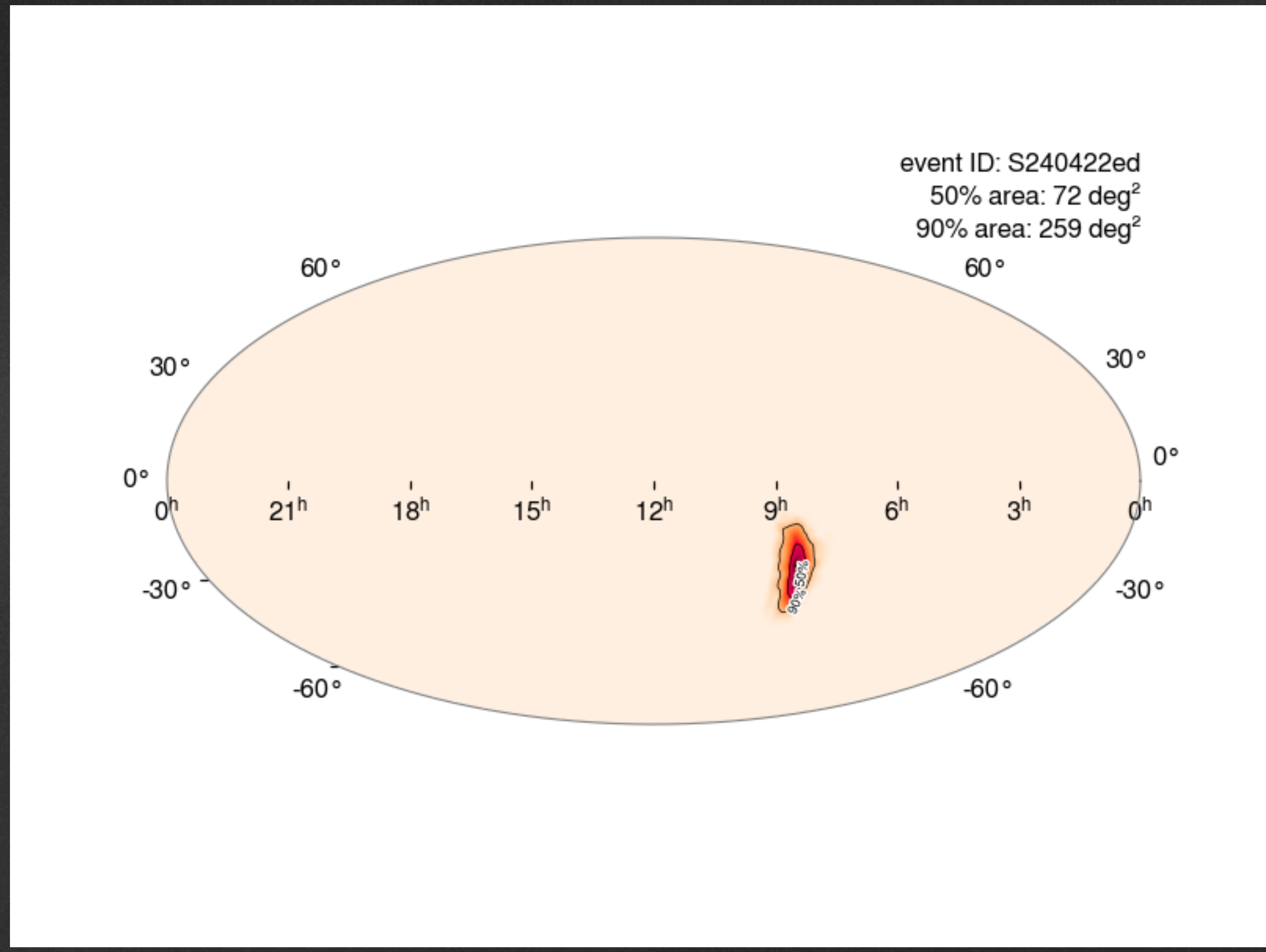


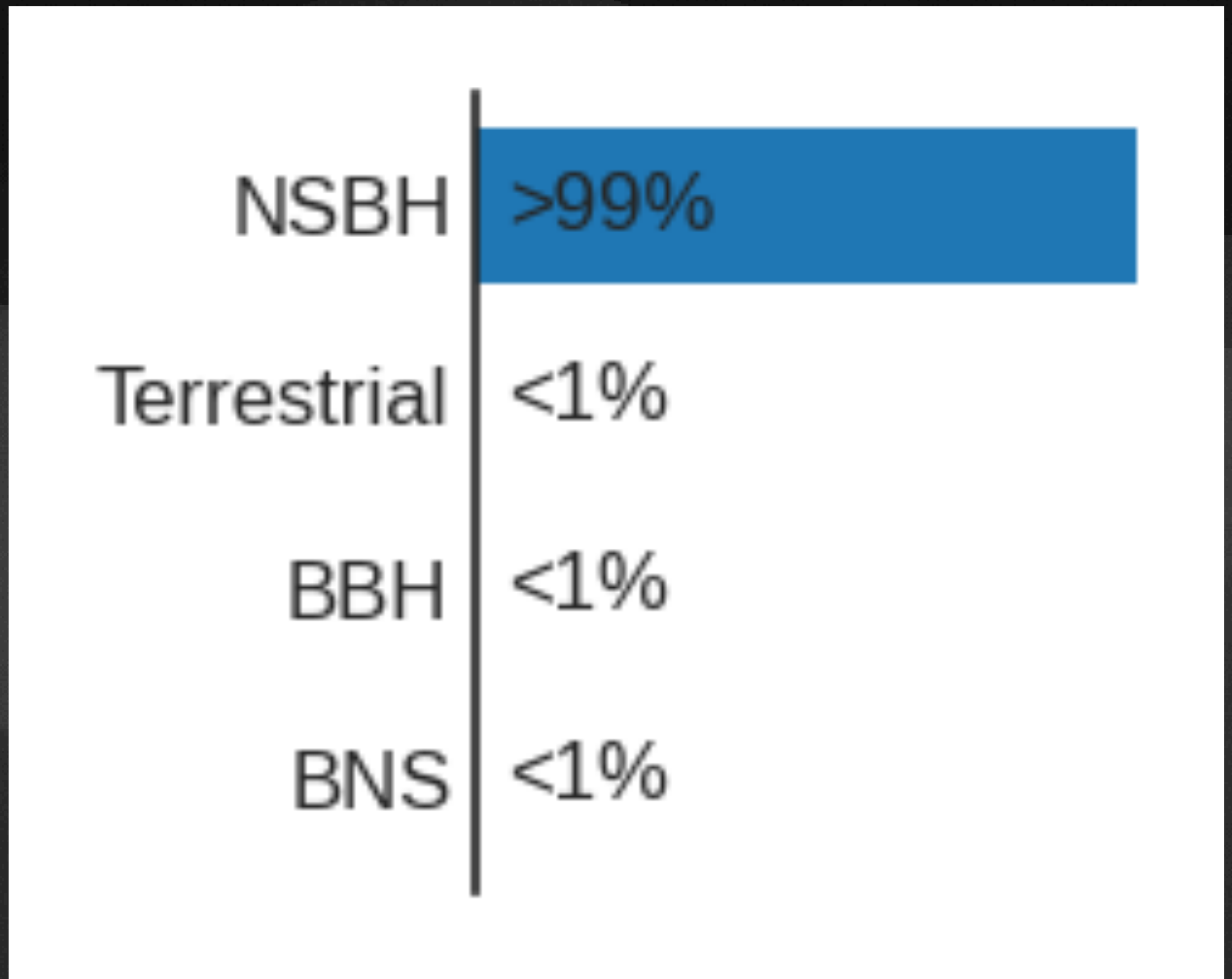
LIGO/Virgo/Leo Singer

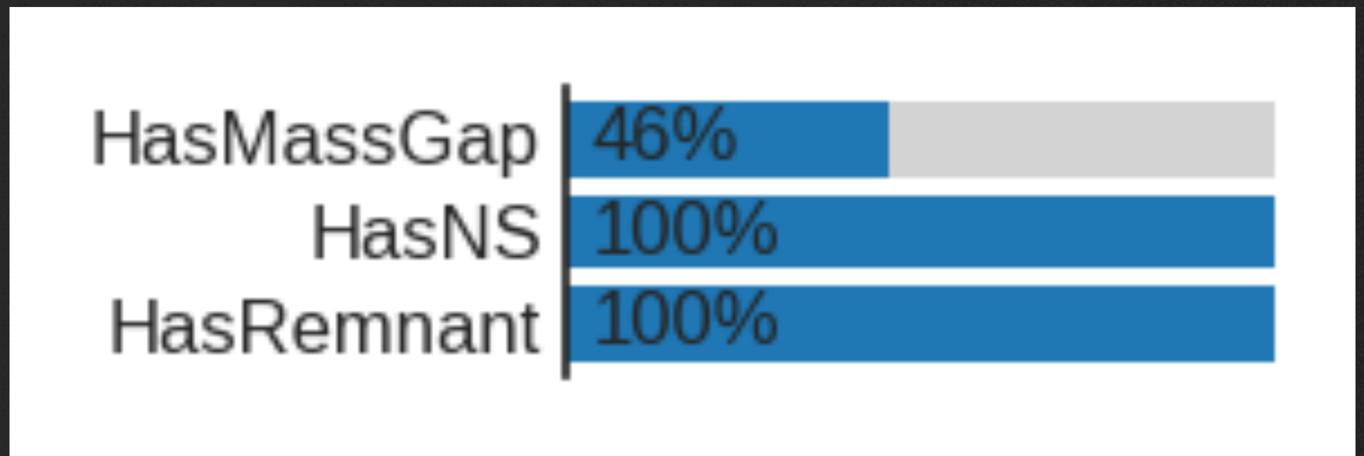
Last night: public alert

https://gracedb.ligo.org/superevents/S240422ed/view/





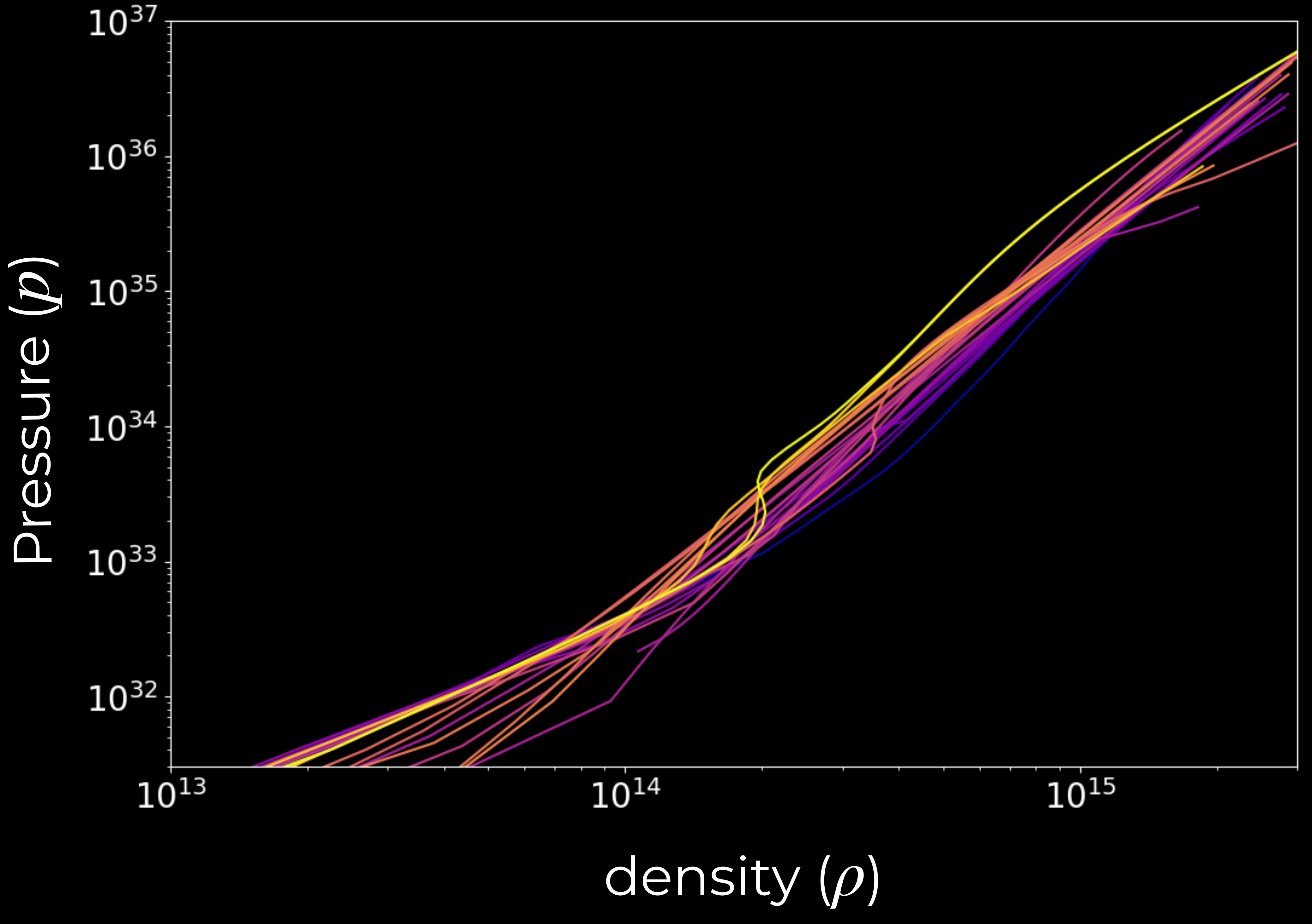




Matter in GW sources

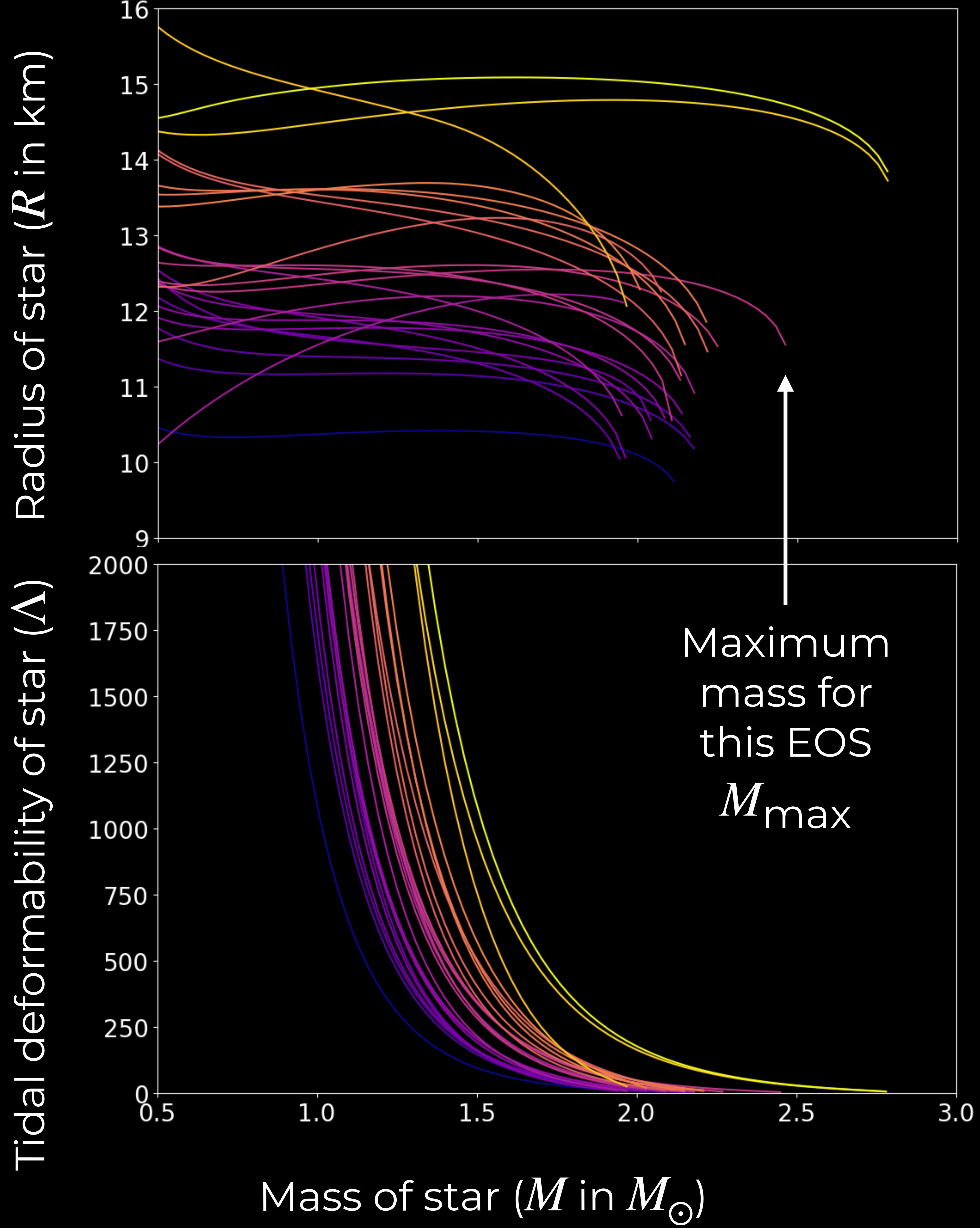
Dense matter imprint

Candidate NS equations of state: zero-temperature, beta equilibrium



Equilibrium models for range of central densities, giving range of masses M

Stable stars for a given EOS



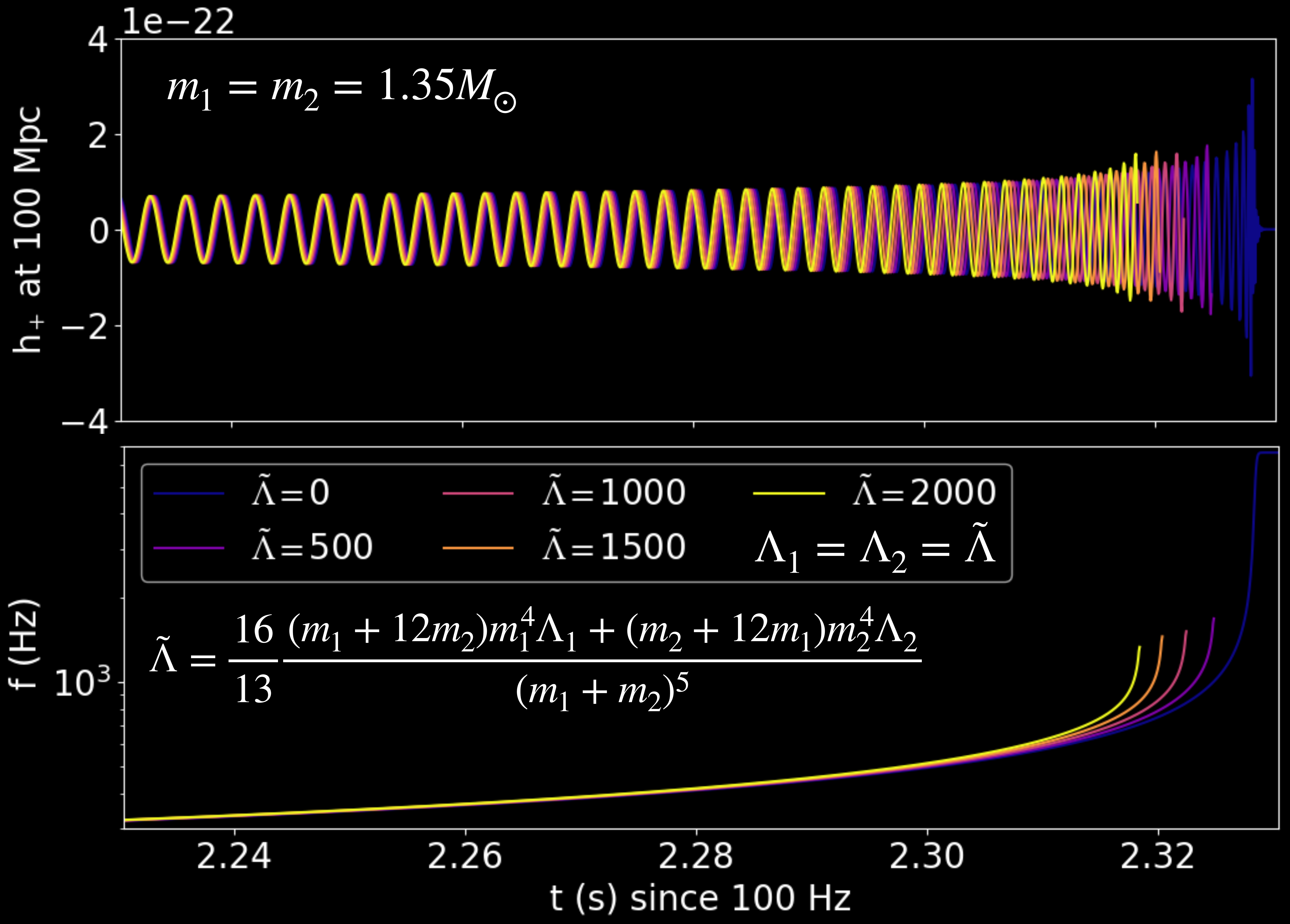
Plots made using LALSuite
https://github.com/jsread/APSPlots2024

Gravitational-wave signature

Model source binary with given $m_1, m_2, \Lambda_1, \Lambda_2$

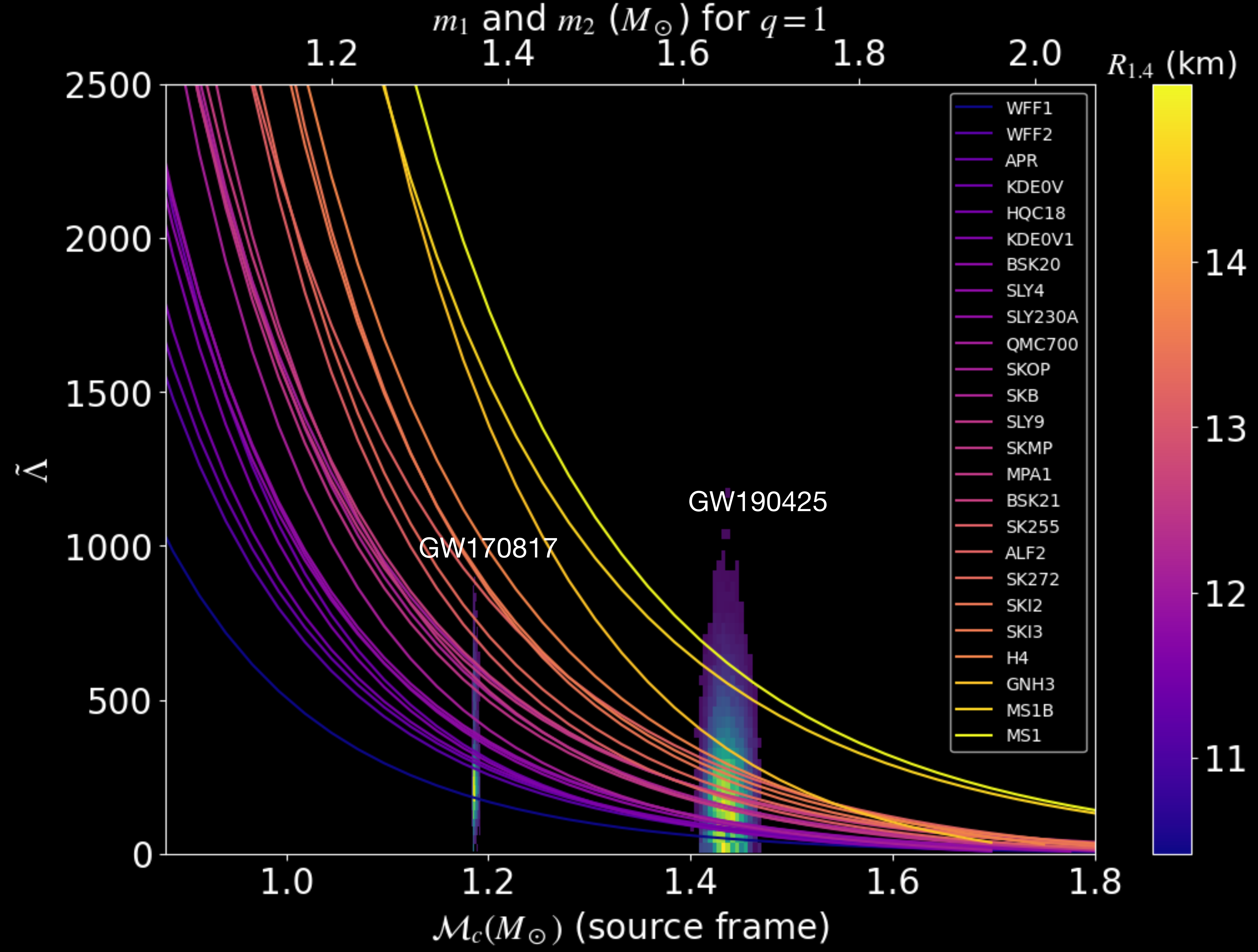
Leading order coefficient $\tilde{\Lambda}$, NR/theory calibrated contribution from higher order terms

At fixed mass, larger Λ means faster chirp (larger df/dt) as orbital separation approaches NS radius.



Plots made using pycbc, TEOBResumS
https://github.com/jsread/APSPlots2024

EOS from binary neutron star gravitational-wave observations



Chirp mass $\mathscr{M}$, Combined tidal parameter $\tilde{\Lambda}$: coefficients of leading-order waveform effects

Cold NS EOS:
$$\Lambda_i(m_i) \rightarrow \tilde{\Lambda}(\mathscr{M}, q)$$

GW170817 from LIGO/Virgo GWTC-1, Phys. Rev. X 9, 031040 (2019)

GW190425 from LIGO/Virgo GWTC-2, Phys. Rev. X 11, 021053 (2021)

Reweight to prior flat in $\tilde{\Lambda}$ following method of LIGO/ Virgo GW190425 ApjL 892 L3 (2020)

Formal EOS likelihood calculation: LIGO /Virgo Class. Quant. Gravity 37 4, 045006 (2020)

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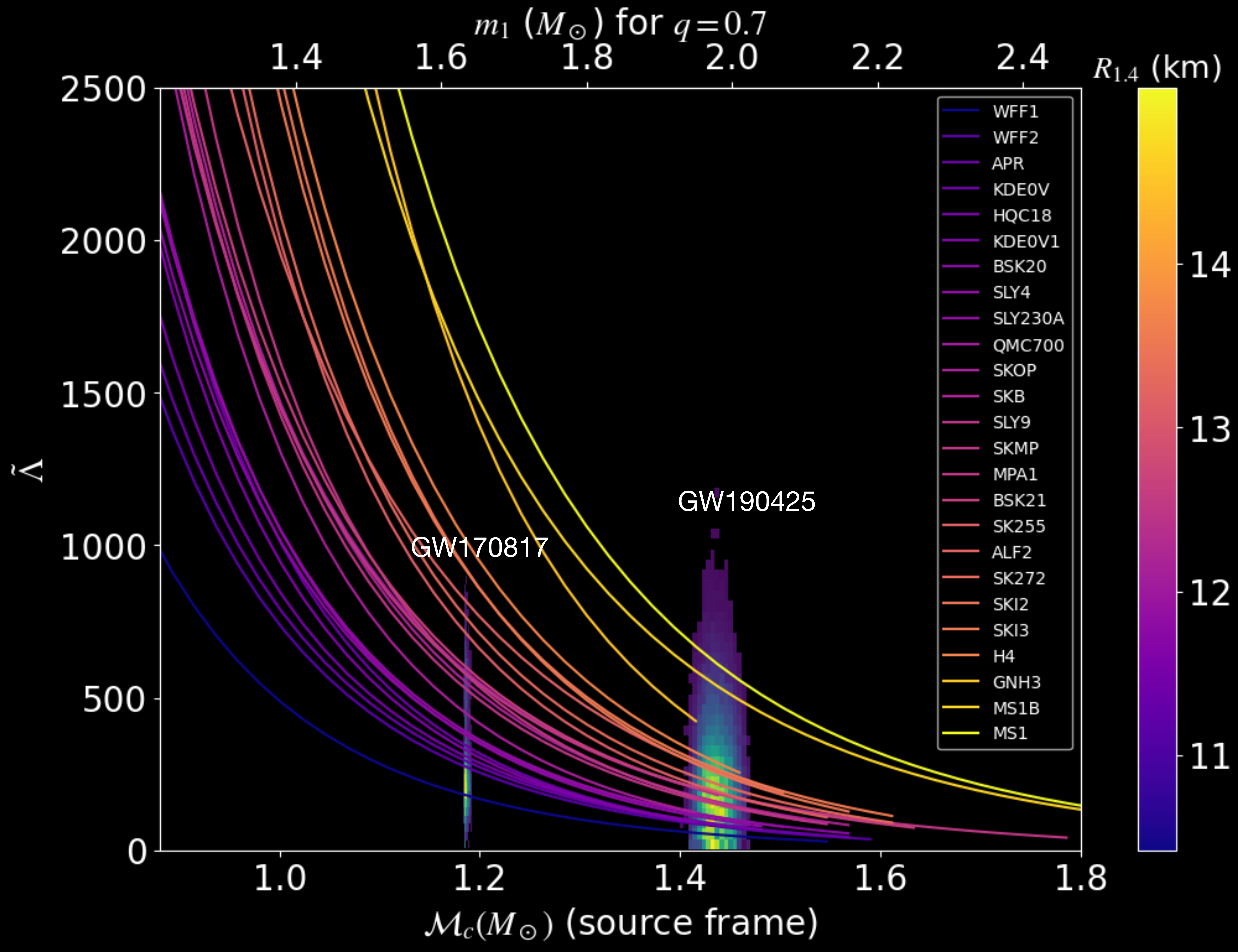

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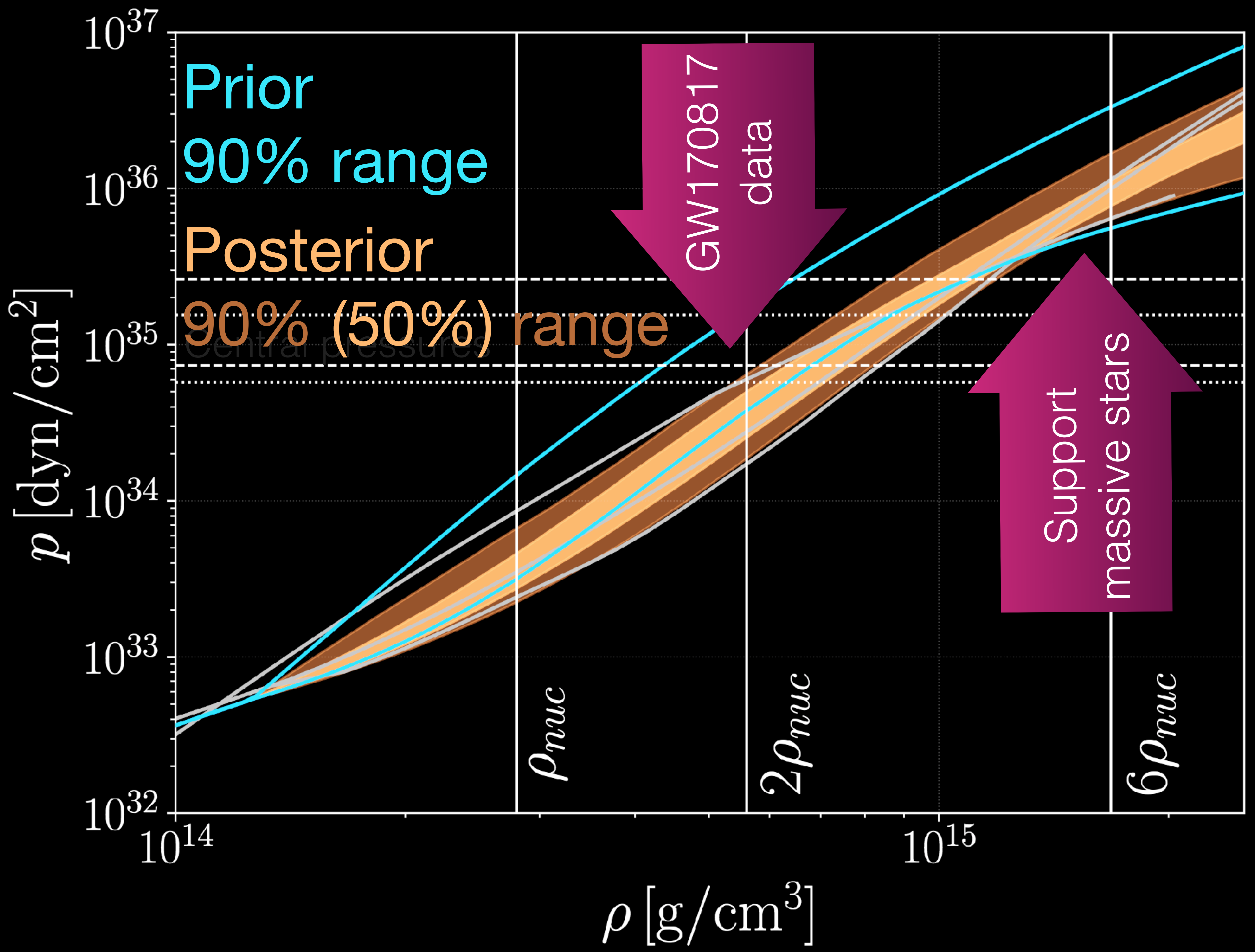
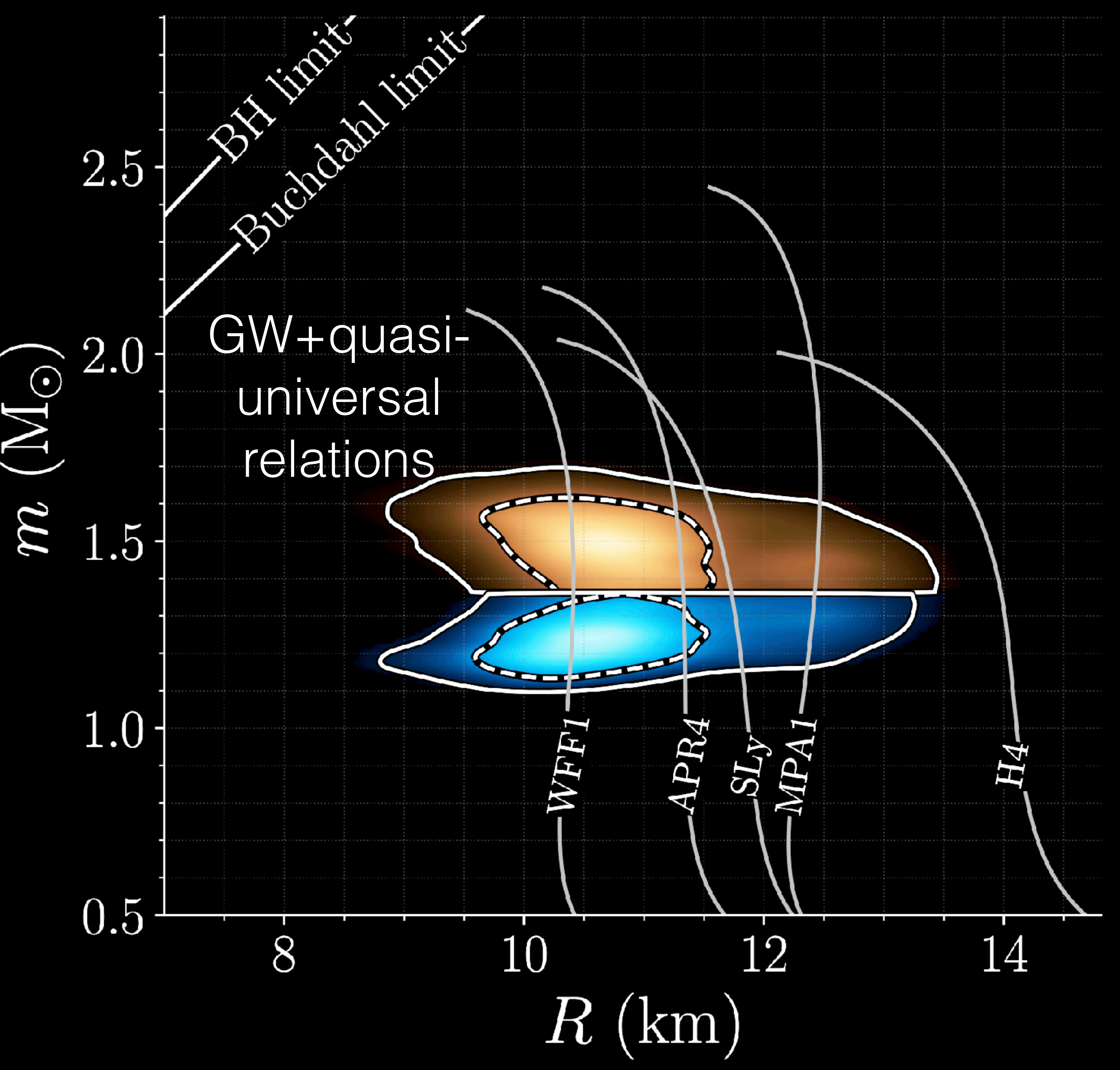
EOS+Radius implications in 2018: GW170817

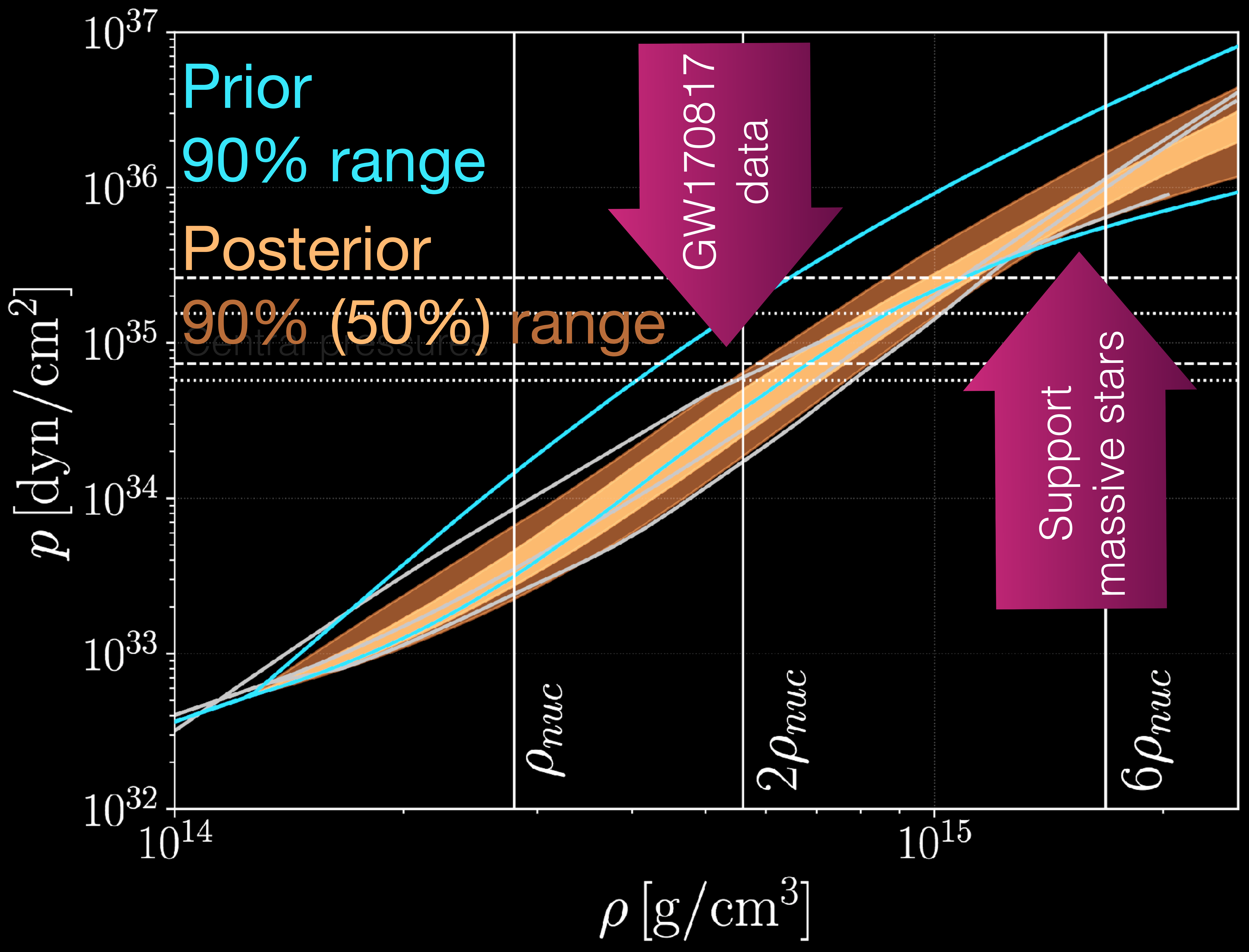


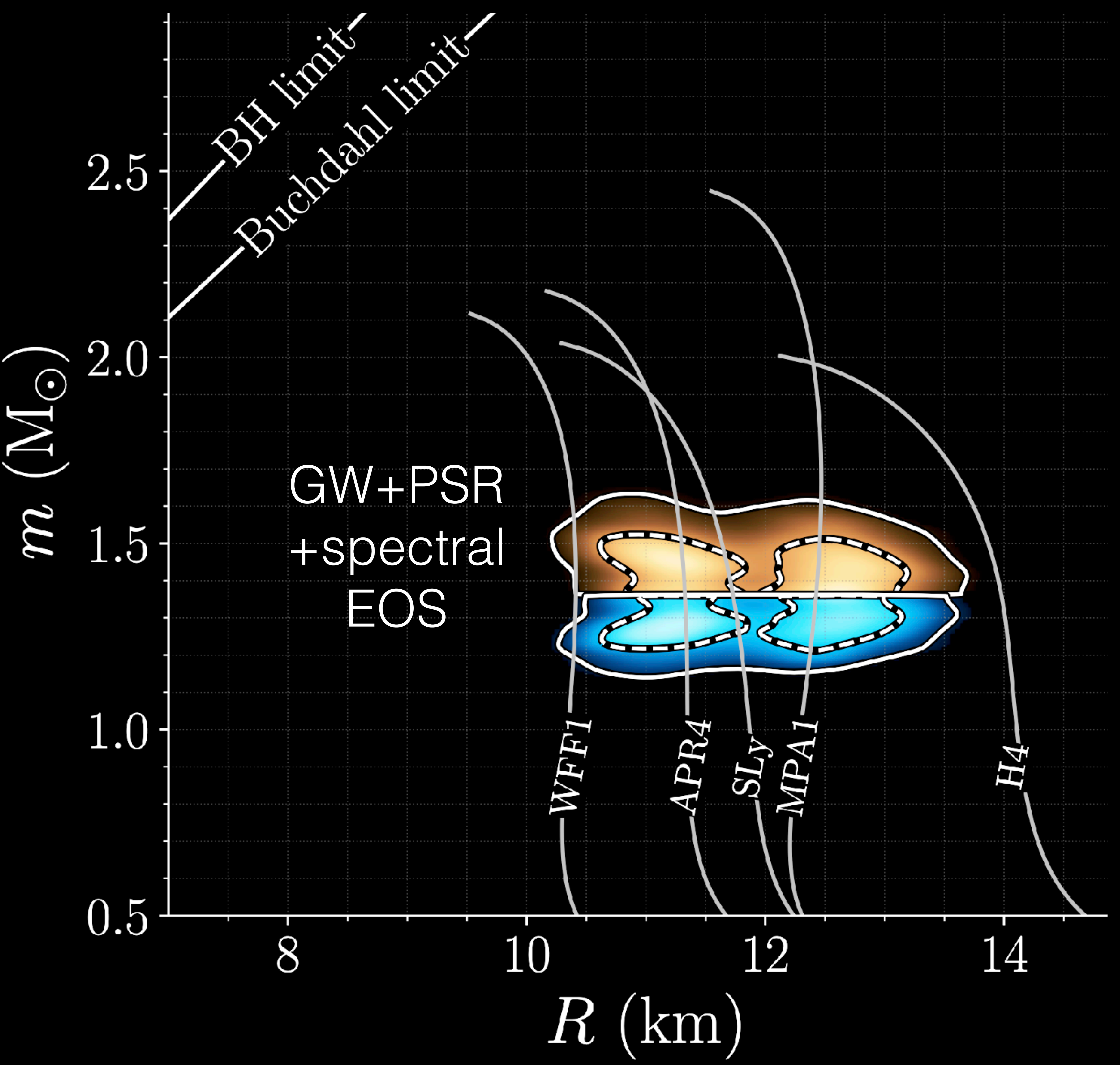


LIGO/Virgo Phys. Rev. Lett. 121, 161101 (2018)
Spectral EOS constraint: Carney & Wade
Phys. Rev. D 98, 063004 (2018)

LIGO/Virgo Phys. Rev. Lett. 121, 161101 (2018)
Quasi-universal relation radius inference:
Chatziioannou et al, Phys. Rev. D 97, 104036 (2018)

EOS+Radius implications in 2018: GW170817





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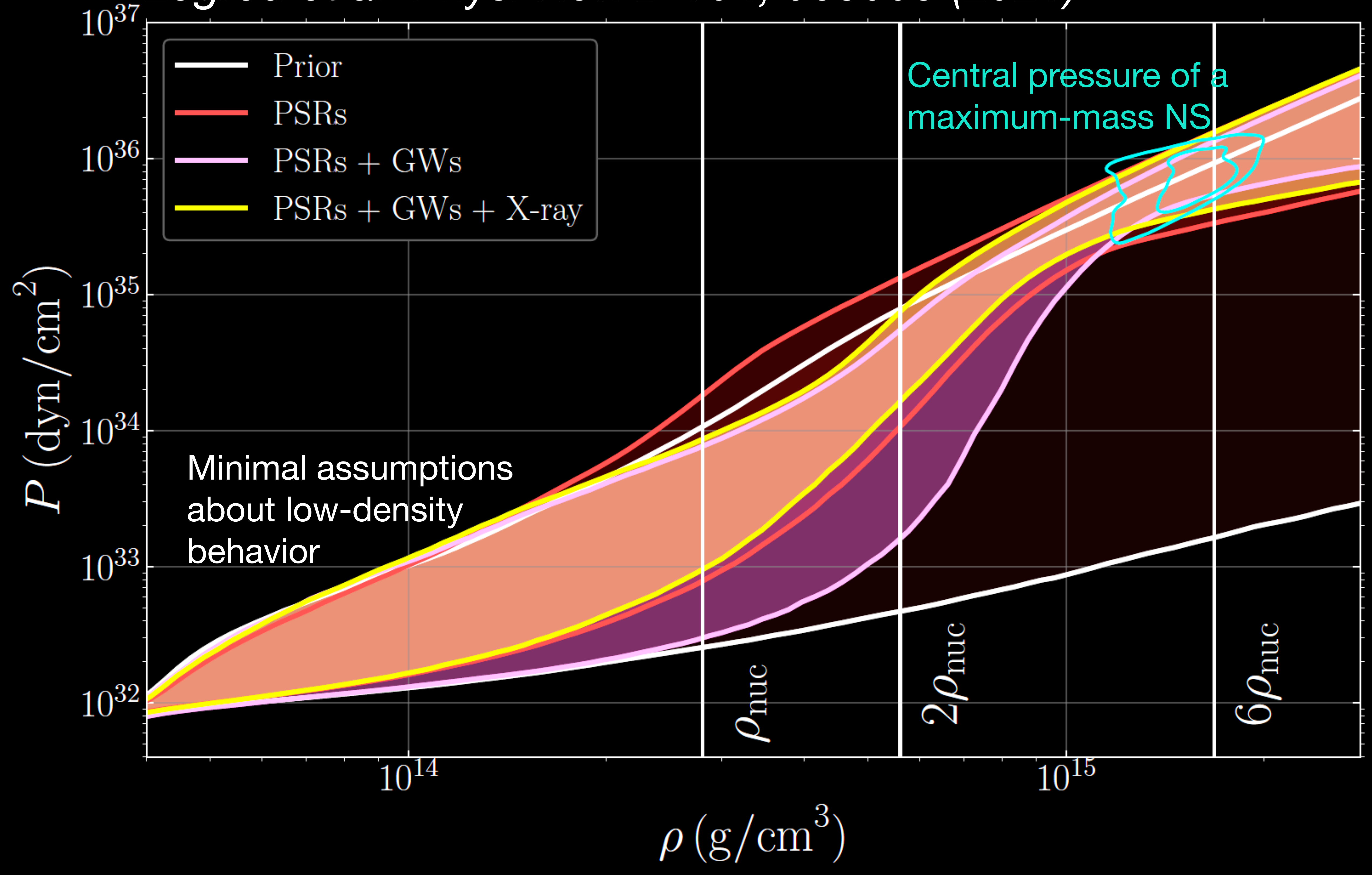
Spectral EOS constraint: Carney & Wade
Phys. Rev. D 98, 063004 (2018)

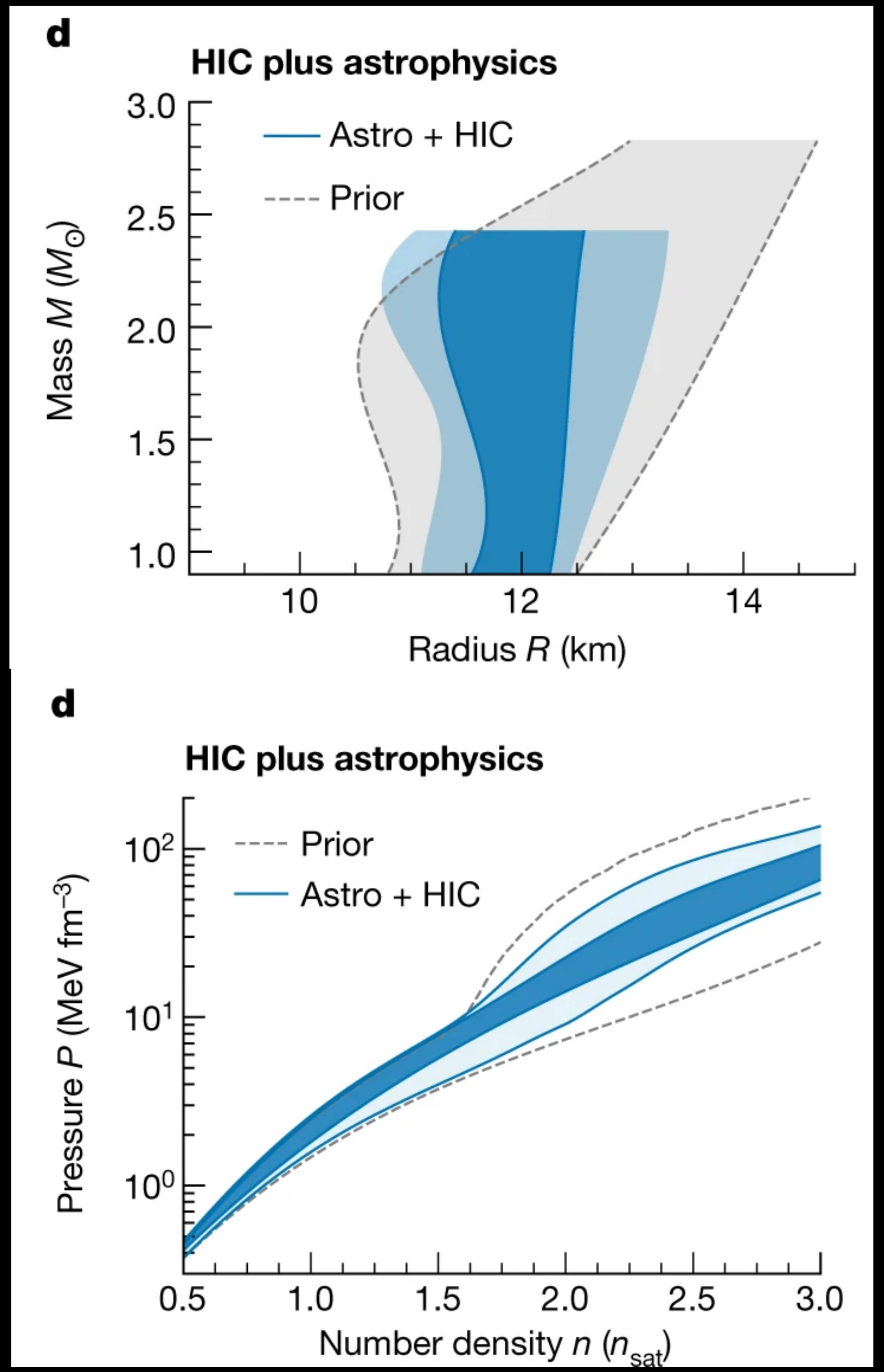
Modern Multimessenger inference: Pulsars, GW, NICER, Chiral EFT, heavy ion collison …

Astro-only constraint
Legred et al Phys. Rev. D 104, 063003 (2021)

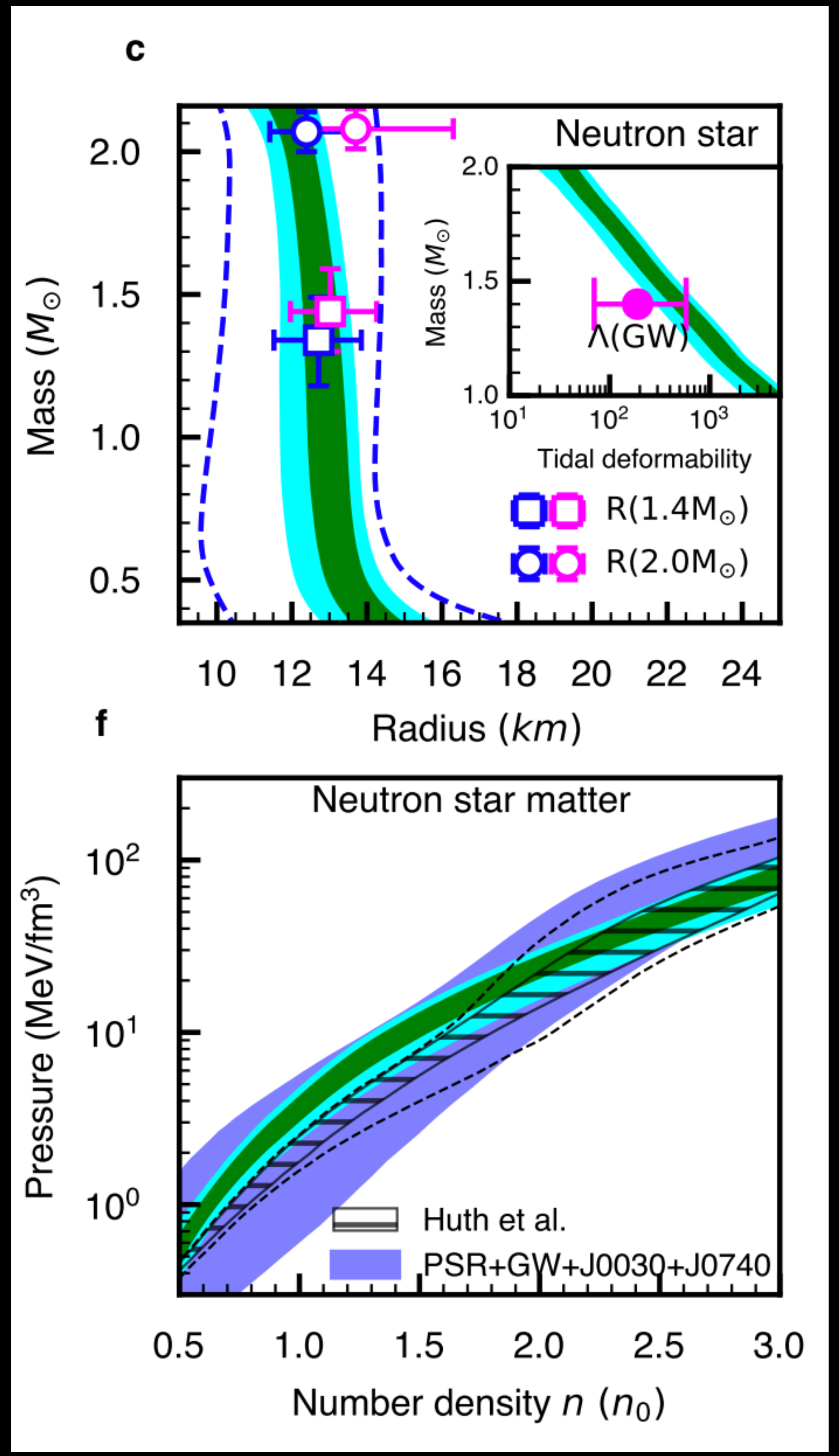


Gaussian-process-generated EOS posterior samples
https://zenodo.org/records/6502467

Huth et al
Nature 606, 276–280 (2022)



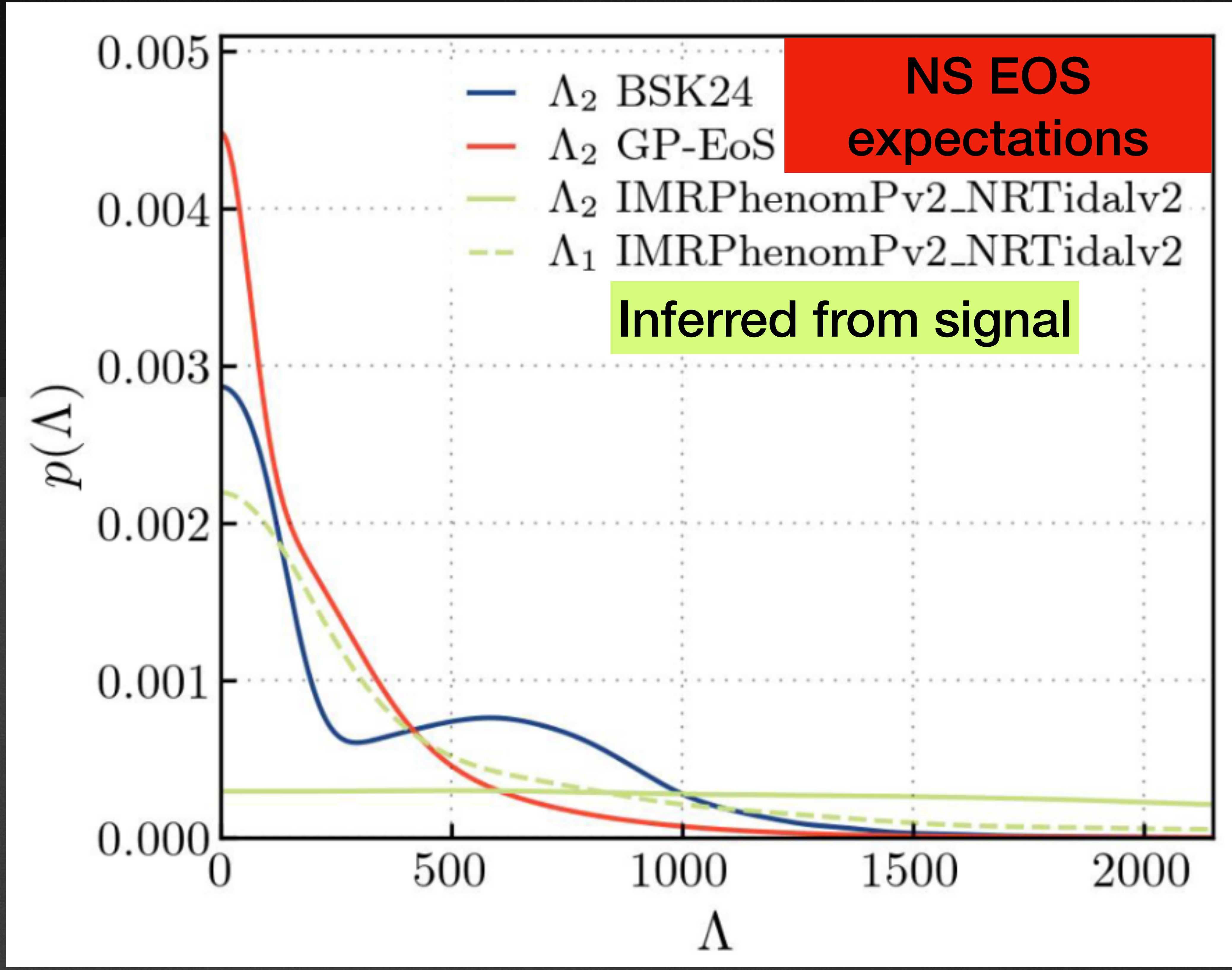
Tsang et al 2310.11588



LIGO-Virgo-KAGRA GW230529
https://arxiv.org/abs/2404.04248v1

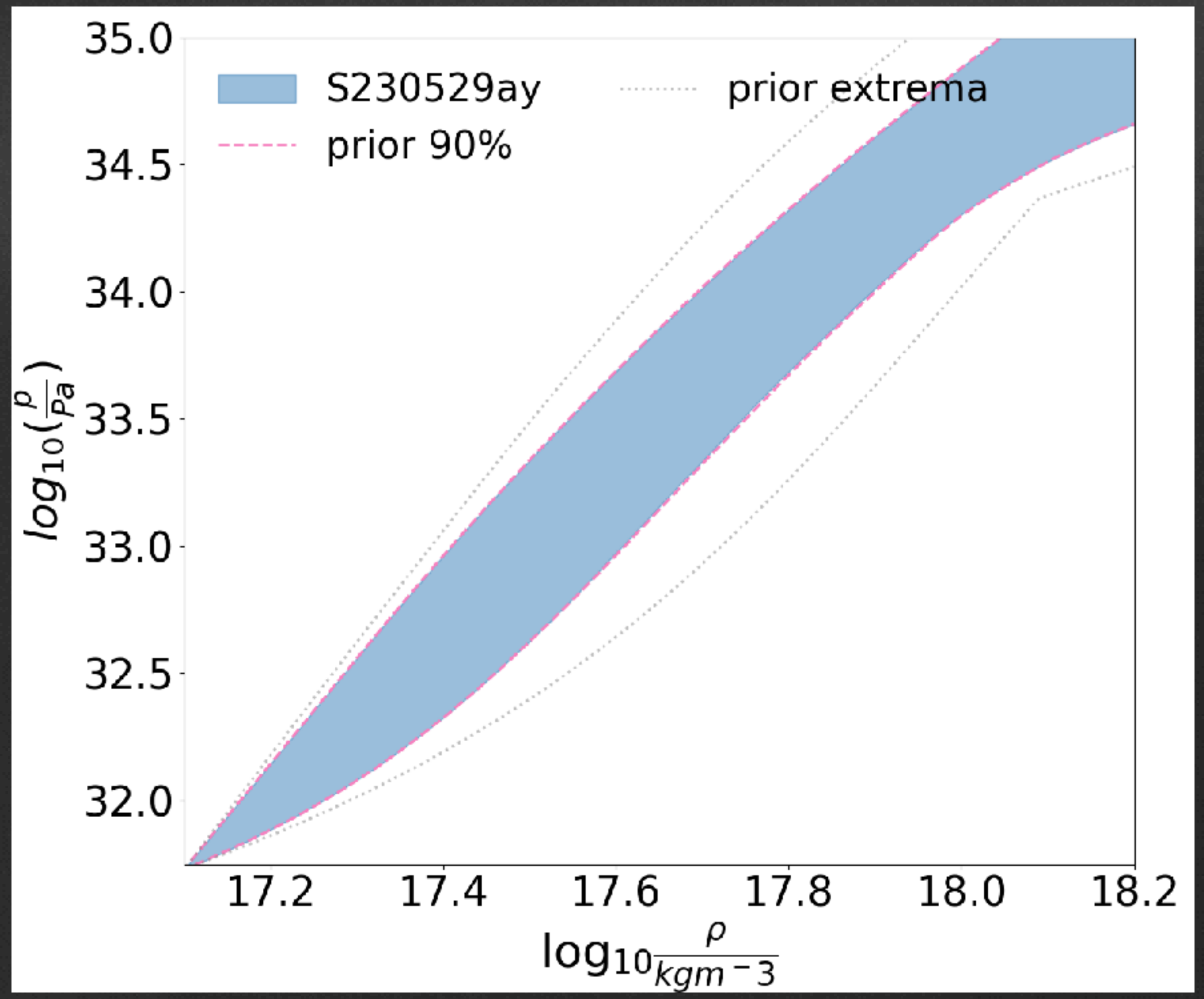
Observation of Gravitational Waves from the Coalescence of a $2.5\text{-}4.5\ M_\odot$ Compact Object and a Neutron Star

No implications for EOS

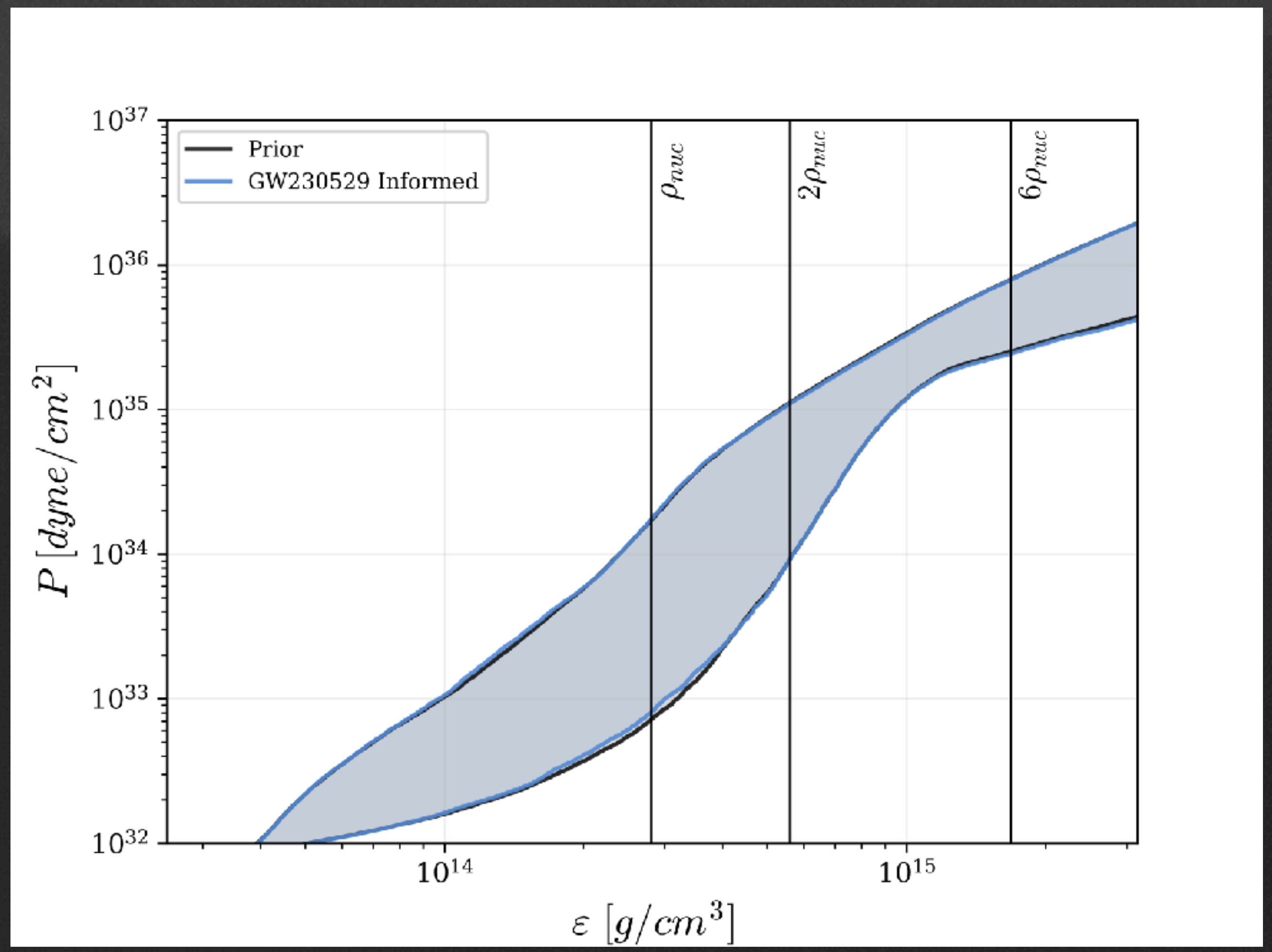


Estimate of tides are uninformative;

EOS inference recovers prior range



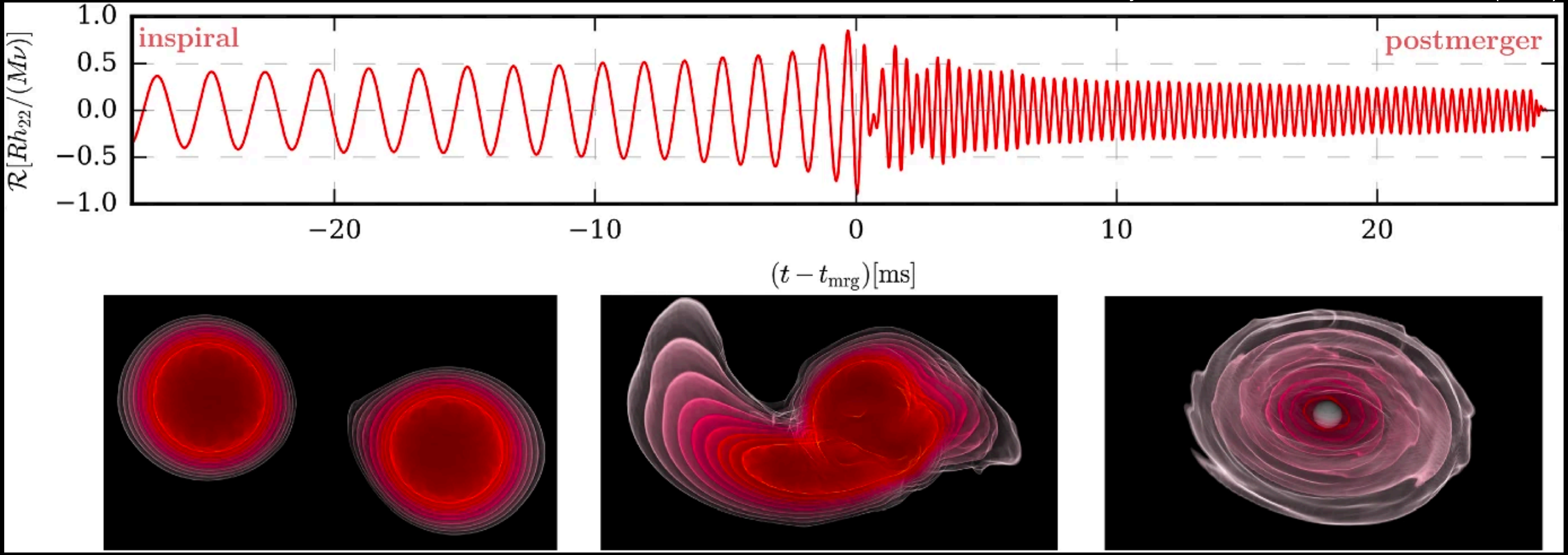
EOS inference using GWXtreme with spectral EOS prior
https://github.com/shaonghosh/GWXtreme



EOS inference using lwp from nonparametric Gaussian Process prior
https://git.ligo.org/reed.essick/lwp

An excursion into systematics, uncertainty, and unmodeled effects

Dietrich, T., Hinderer, T. & Samajdar, A. Gen Relativ Gravit 53, 27 (2021)



- We use a perturbative property of isolated stars (Λ_1, Λ_2) as an ***effective*** descriptor of matter effects in gravitational-wave models ***through to merger***
  (Based on GR+Hydro simulation: Read et al 1306.4065, Bernuzzi et al 1402.6244, Dietrich, & Tichy 1706.02969, …)
  (Empirical quasi-universal relation: Yagi Phys. Rev. D 89, 043011 (2014), Chan et al Phys.Rev.D90 (2014))

- **In XG era**: additional parameters needed to describe waveforms
  (e.g Carson et al Phys. Rev. D 99, 083016 (2019), Pratten et al Nat Commun 11, 2553 (2020).

How much can we trust the signal model?

- Source model $h_{22}(t) = \mathscr{A}(t)e^{i\psi(t)}$ has **instantaneous frequency**: $2\pi F(t) = \dot{\psi}(t)$
- Source masses, spins, tides: **encoded in characteristic functions** of F:

$$\mathscr{A}(F) \equiv \mathscr{A}(T(F)) \quad \text{and} \quad \dot{F}(F) \equiv dF/dT$$

Luminosity $\mathscr{L}$ and $\mathscr{A}$:

$\mathscr{A}(F)^2 = \frac{4}{\pi}\frac{1}{d^2}\frac{1}{F^2}\mathscr{L}_{\text{GW}}(F)$ from integration of $\left|\dot{h}_{\ell m}d\right|^2$

Energy balance and $\dot{F}$:

$\dot{F}(F) = -\frac{\mathscr{L}(F)}{E'(F)}$ from system energy $E(F)$ as function of emission frequency

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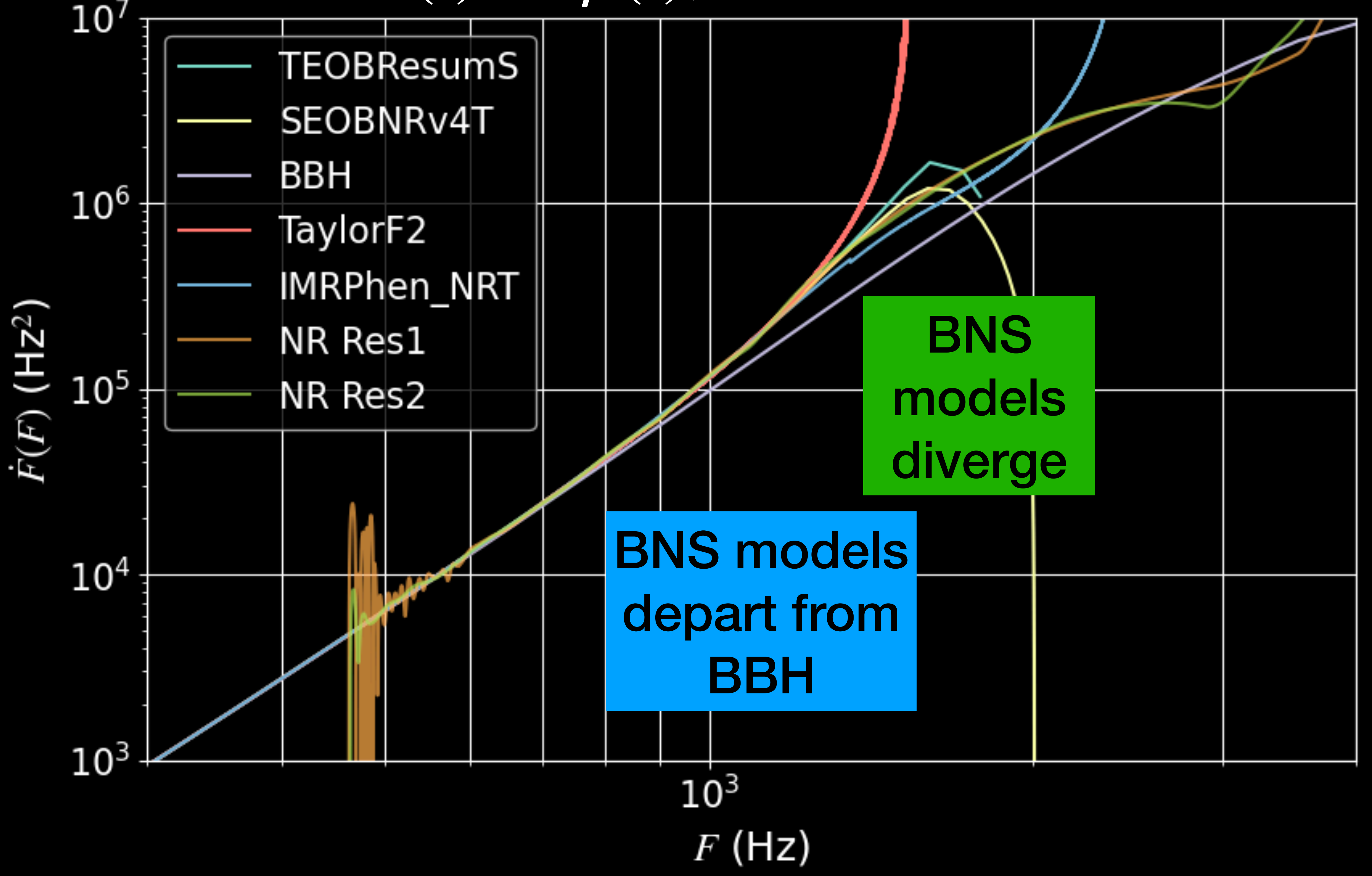
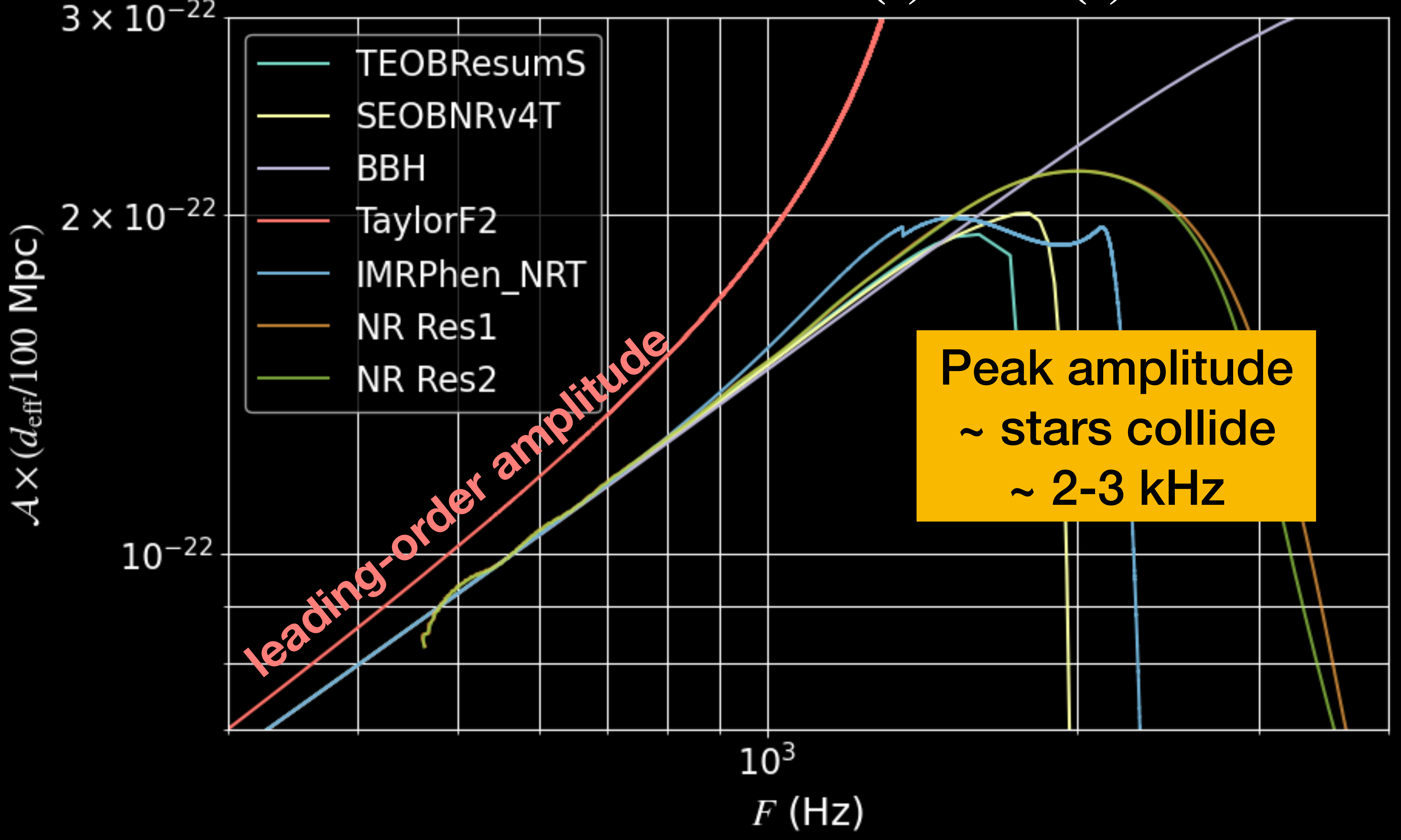
Comparison of waveform model frameworks

$2\pi F(t) = \dot{\psi}(t)$, $\dot{F} \propto \dot{\Omega}$ used in NR



NR - high-res CoRe sim 'BAM:0095' with SLy EOS
Spline smoothing for F before taking derivative
m_1 & m_2: 1.349998 for all waveforms shown

Time-domain $\mathscr{A}(t)$ vs $F(t)$



From Sly: Λ_1 & Λ_2 = 390.1104
used for TEOBResumS, SEOBNRv4T, TaylorF2, and IMRPhenomPv2_NRT

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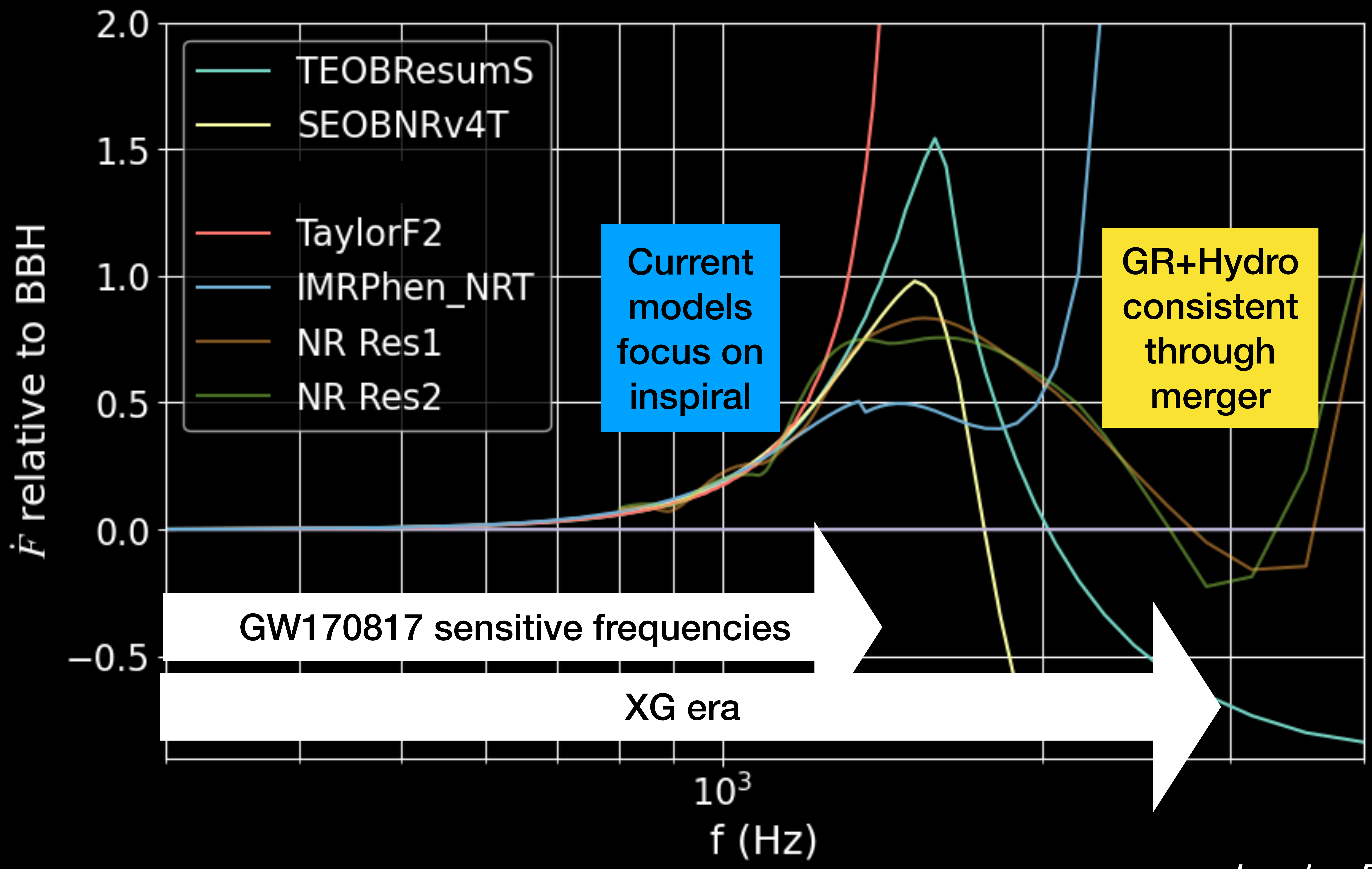
Systematic uncertainty from theoretical models

The tidal signature: modifying the $\dot{F}$ “chirp”



- Quantify difference when same physical system is modeled in variant frameworks
- Marginalize over uncertainties in future analyses

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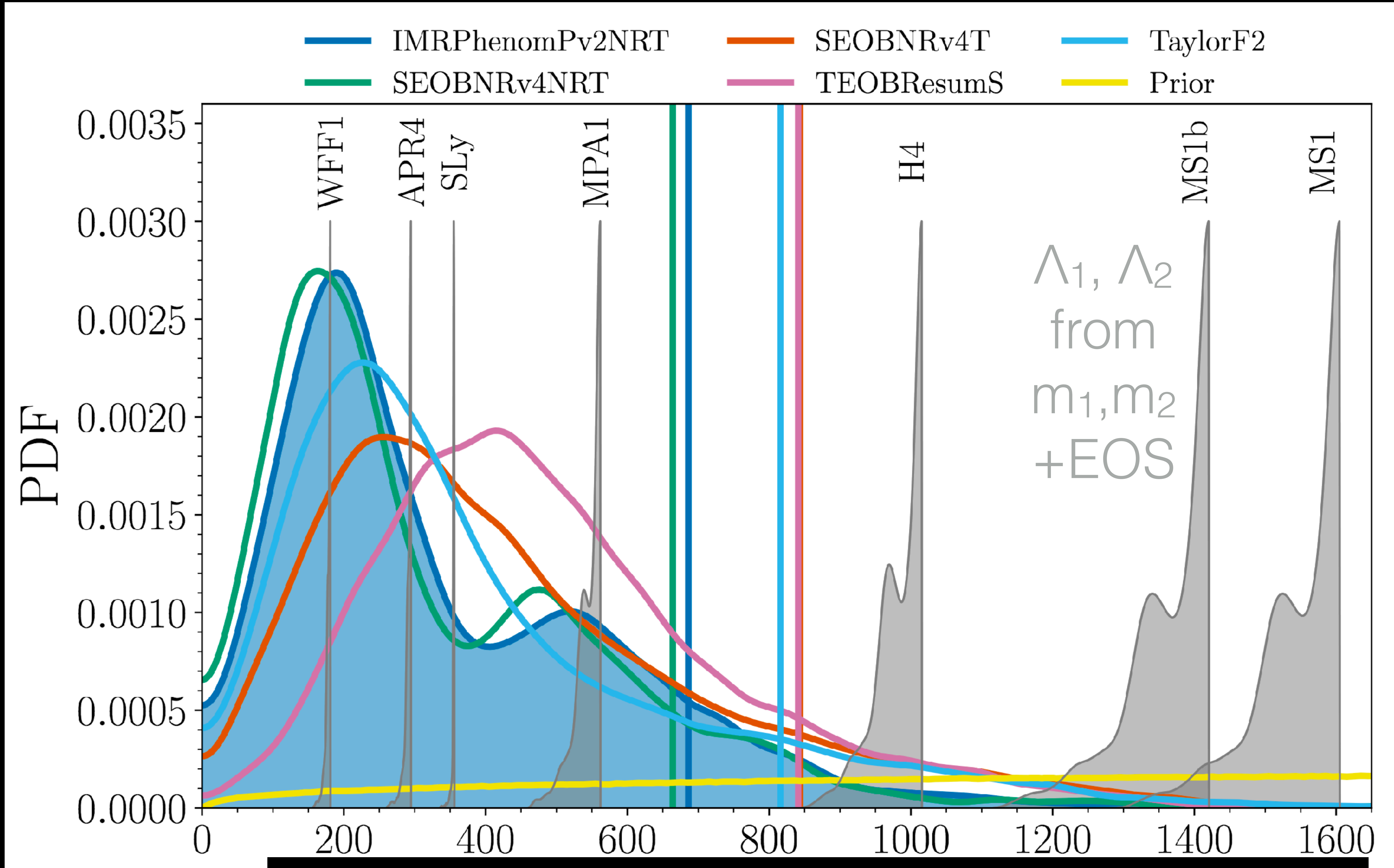
Model impact on recovering Λ for GW170817:



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

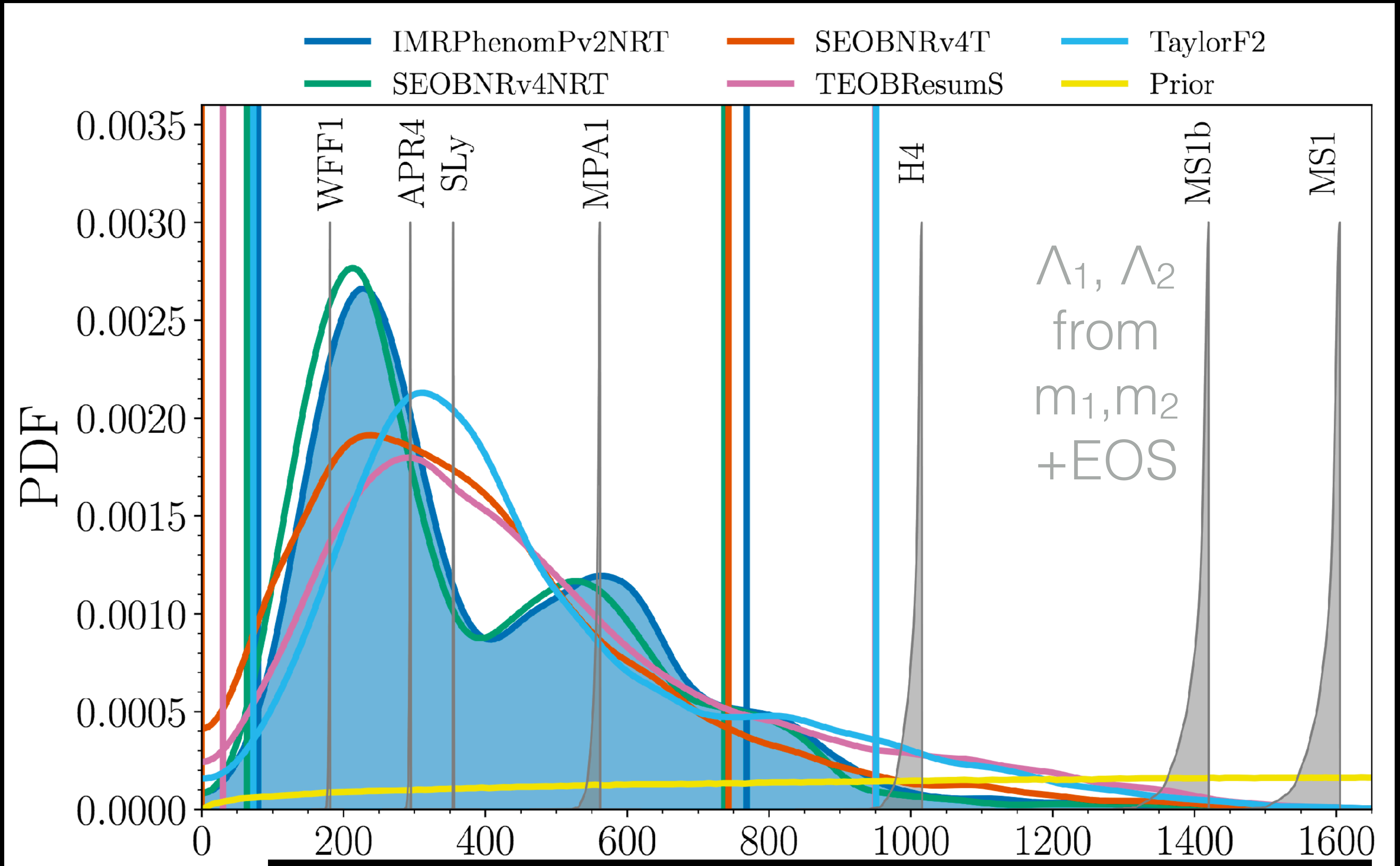
Fiducial waveform:

$\tilde{\Lambda} < 686$

Bars denote 90% highest probability density credible interval

LSC/Virgo GWTC-1 1811.12907, PRX

Model impact on recovering Λ for GW170817:



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

Assume low spin

($\chi < 0.05$)

Fiducial WF:

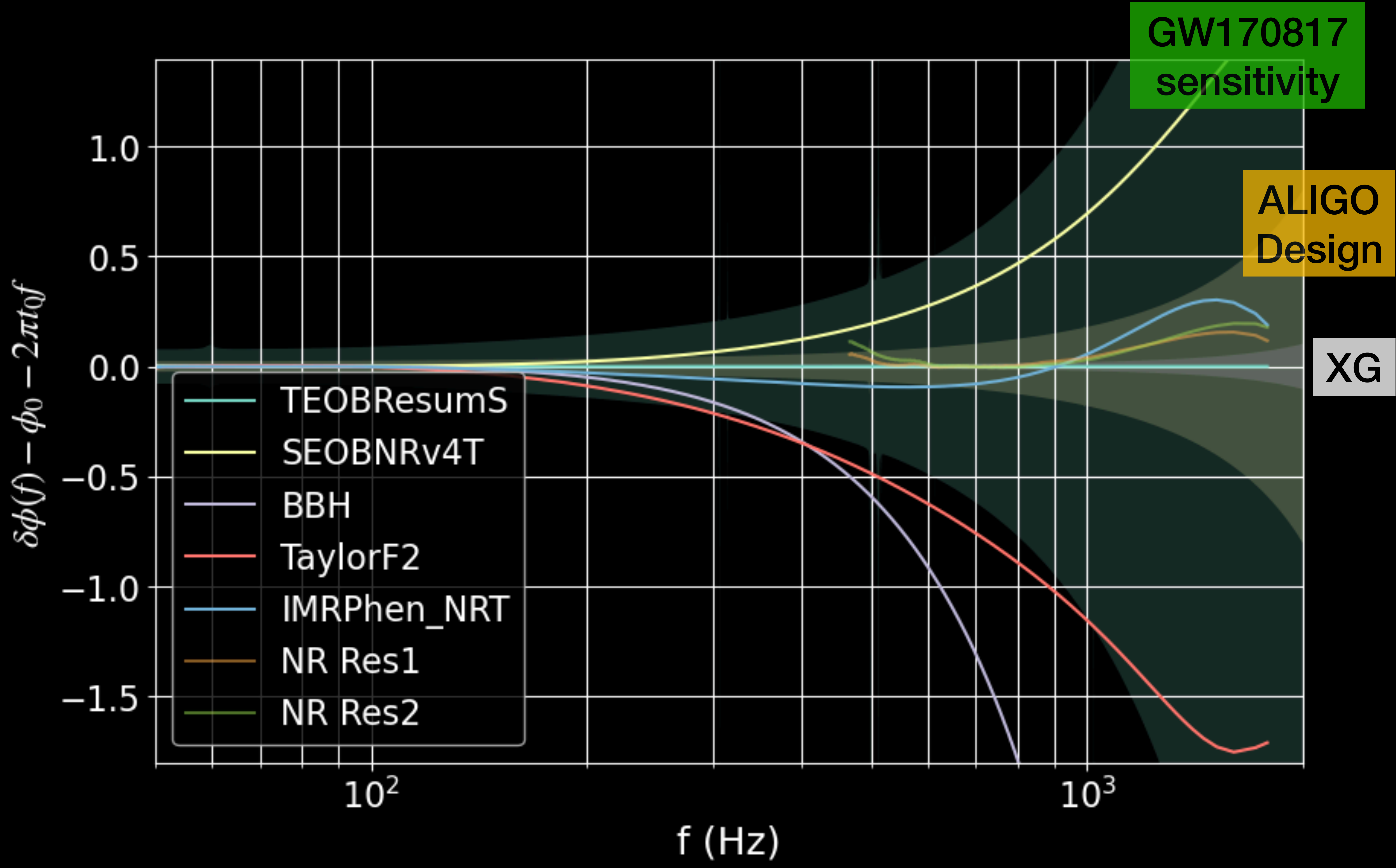
$\tilde{\Lambda} = 330^{+438}_{-251}$

Systematic uncertainty is coming from challenges of spin modeling!

LSC/Virgo GWTC-1 1811.12907, PRX

Systematic error in future observations

- Indistinguishability condition from characteristic strain: $2\sqrt{f}\,|\,\delta\tilde{h}(f)\,| < \sqrt{S_n(f)}$ sets shaded regions for reference detectors, signal $d_{\text{eff}} = 100$ Mpc
- Compare **residual phase** $\delta\phi_{\text{res}}$ after max likelihood fit $\phi_0 + 2\pi f t_0$ (weight by variance $S_n(f)/A(f)^2$)



NR waveforms: relative to 700 Hz for reference (not long enough to fit ϕ_0, t_0)

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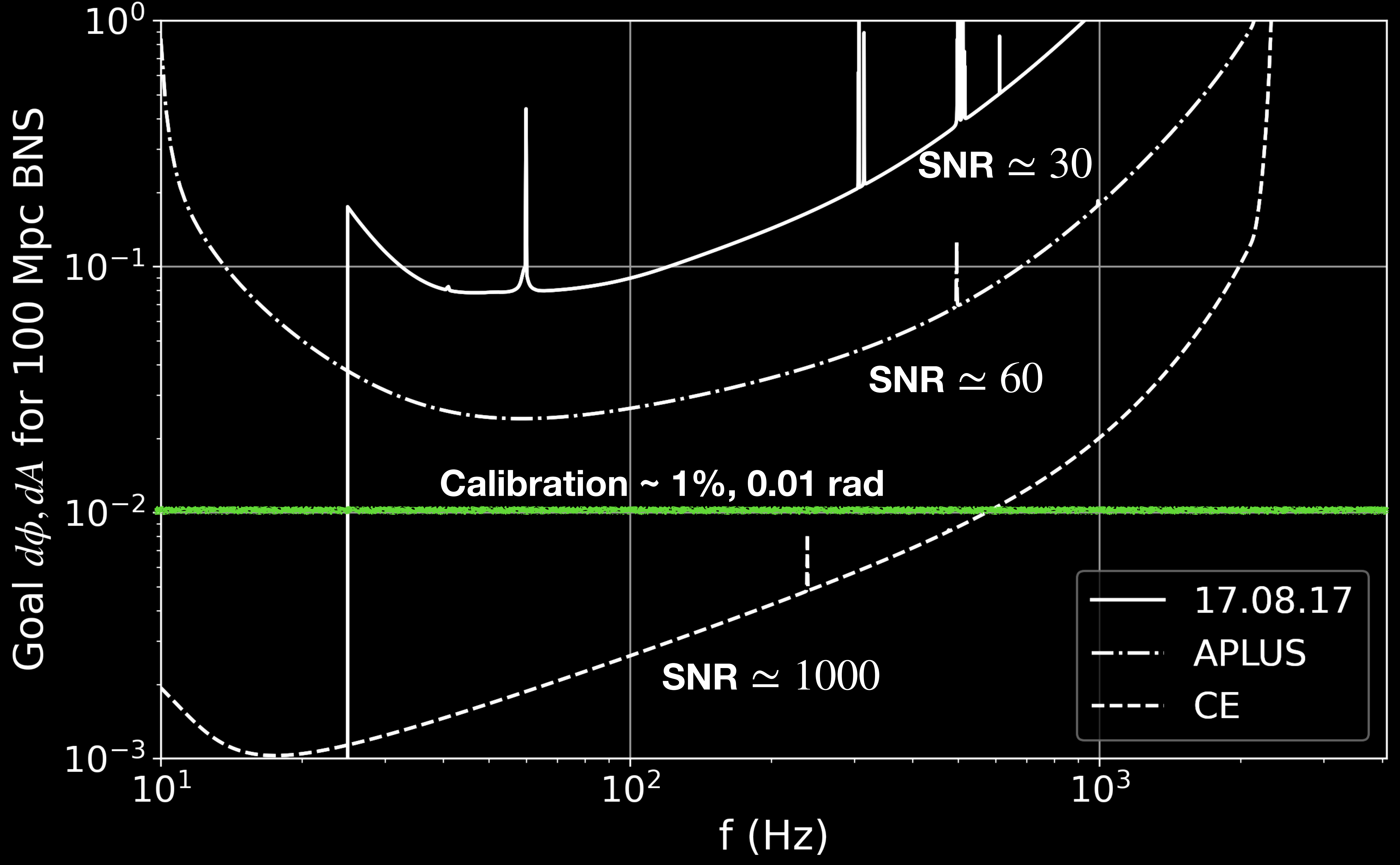
Future requirements / future capabilities

- 'Model' of detector (calibration) or source (waveform)
- May impact source analysis if $\delta h = h_{\text{true}} - h_{\text{model}}$ generates **characteristic strain larger than detector noise**
- Goal δA (fractional) and $\delta\phi$ (radians) shown

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



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Measuring beyond the model

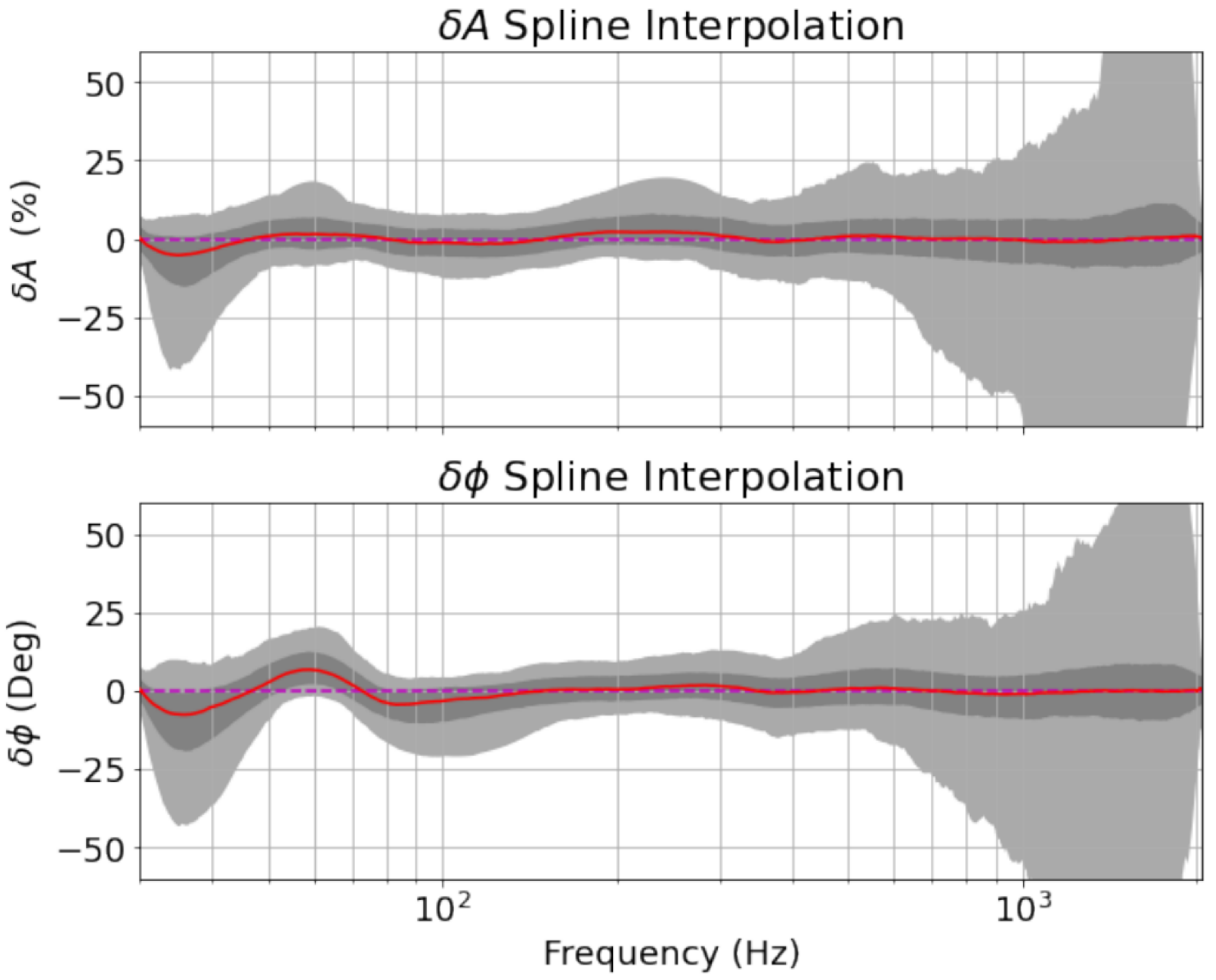


FIG. 12. Spline interpolation of GW170817 with 1 and 2 σ credible intervals (grey) and the median spline interpolant (red) shown.

- Edelman et al Phys. Rev. D 103, 042004 (2021): Constraint on coherent departures from waveform model
- Generic signal modification described with splines for $\delta A, \delta\phi$, constraint for GWTC-1

Interpreting unmodeled effects

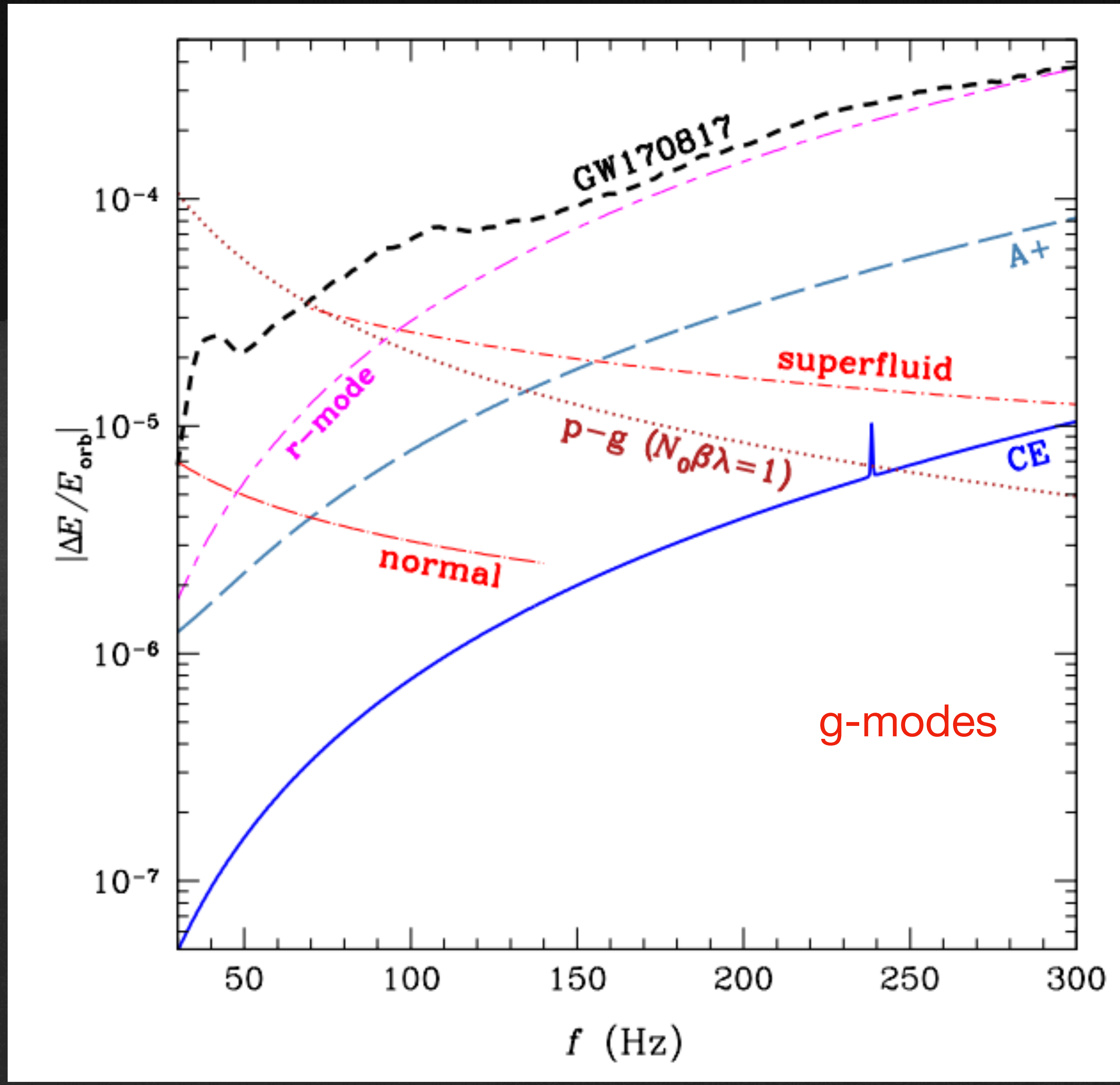
Sources of modification: Modification of system energy function $E(F)$, luminosity $\mathscr{L}(F)$

- Additional luminosity $\mathscr{L}(F)$: non-GW energy loss $\mathscr{L}_{MM}$ or $\mathscr{L}_{NR}$
- Internal energy transfers $\delta E_A, \delta E_D$ that modify how E changes with F:

$$\delta E' = \delta E_A + \frac{t_A}{t_D}\delta E_D$$ (A adiabatic, D dynamic, t timescales)

- Generically limit unmodeled *(not in PE waveform)* energy transfers in observed systems through constraints on $\delta A, \delta\phi$.
- Given a model of astrophysical energy transfer (**like resonant modes that depend on composition**), can augment *any* underlying waveform model
- Example application: Ho and Andersson, https://arxiv.org/abs/2307.10721

arXiv:2307.10721



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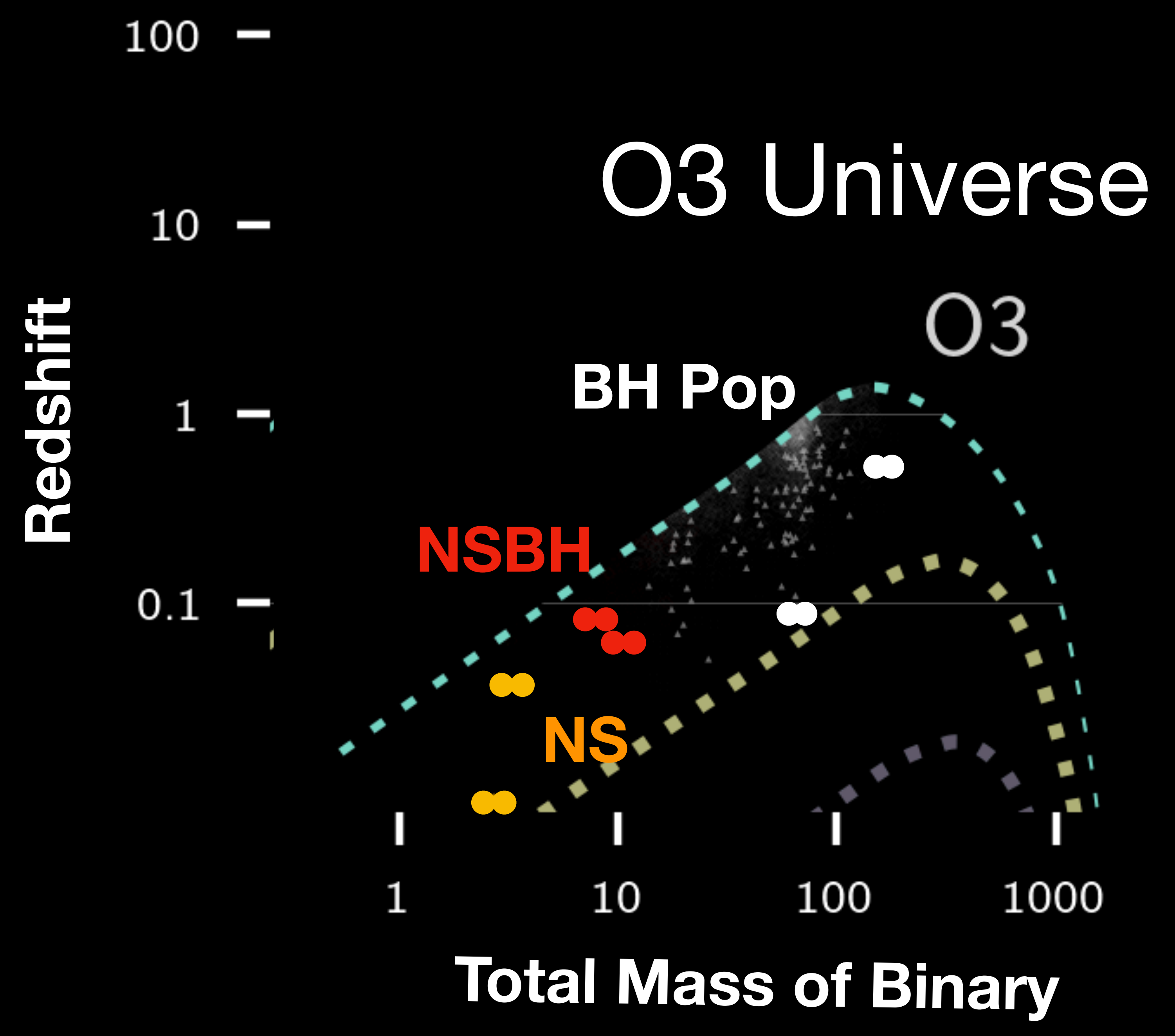
GW astronomy in the future

Unveiling the GW Universe



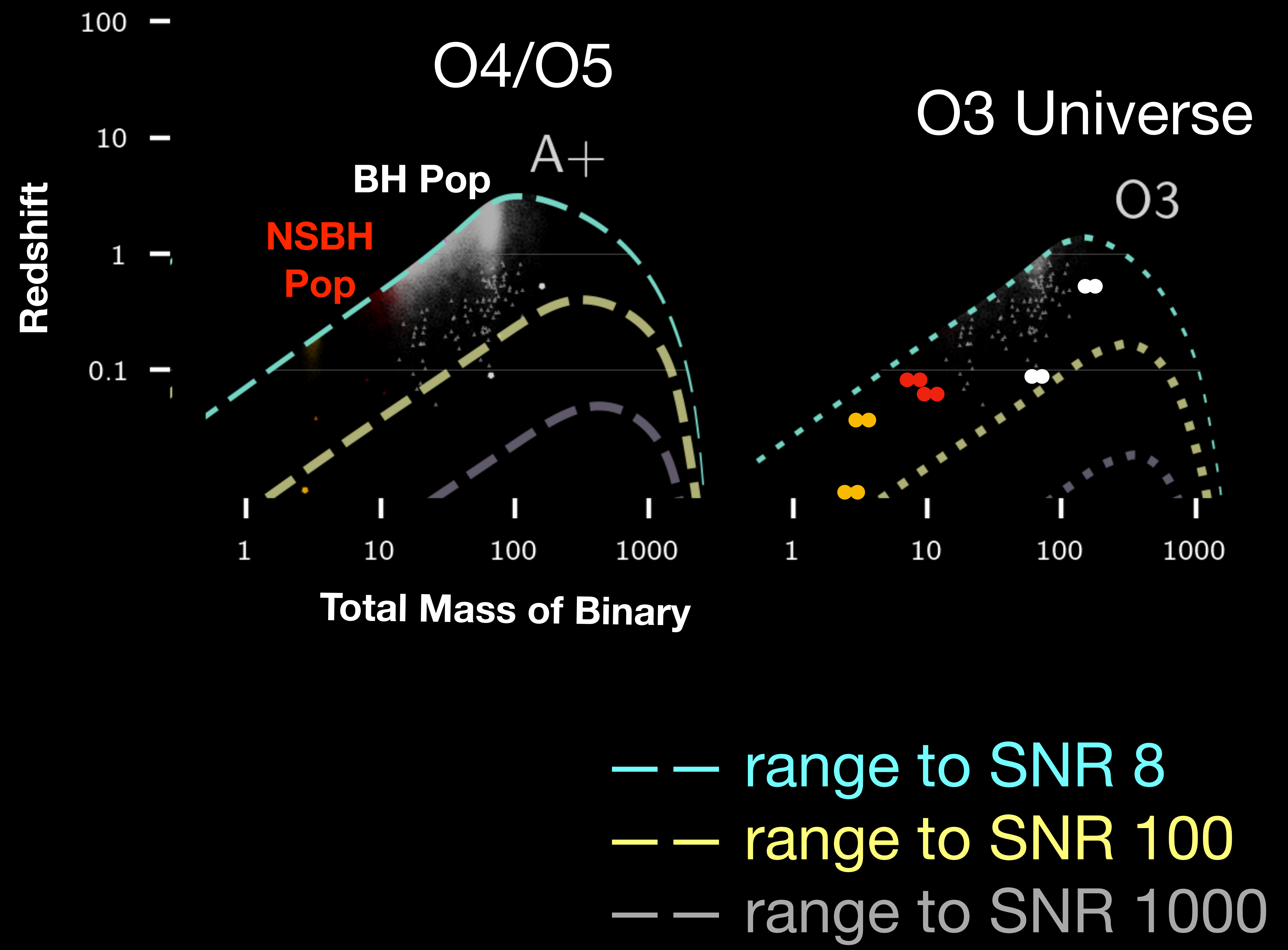
— — range to SNR 8

— — range to SNR 100

— — range to SNR 1000

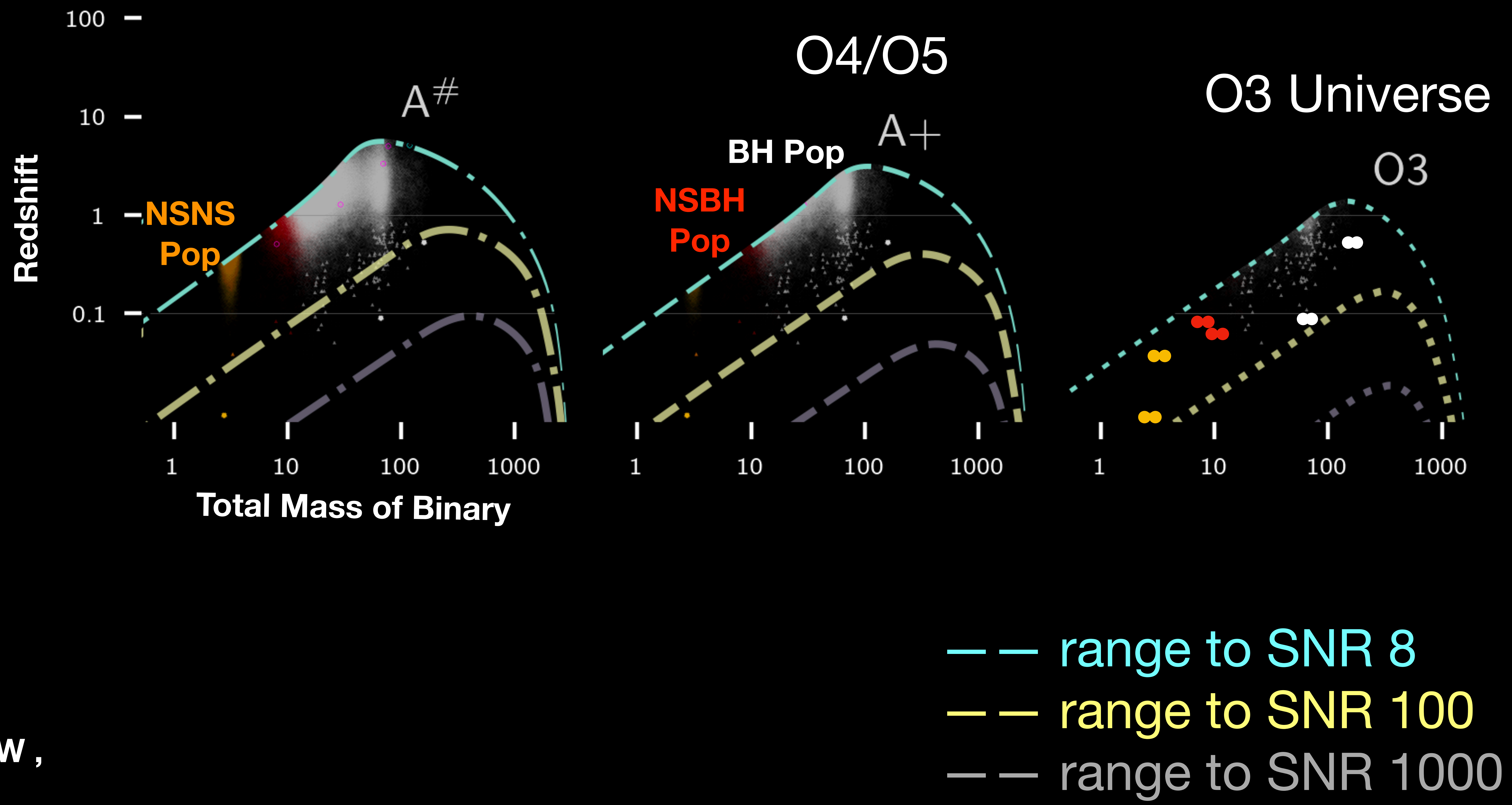
White Paper for NSF MSCAC ngGW ,
https://arxiv.org/abs/2306.13745

Unveiling the GW Universe



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

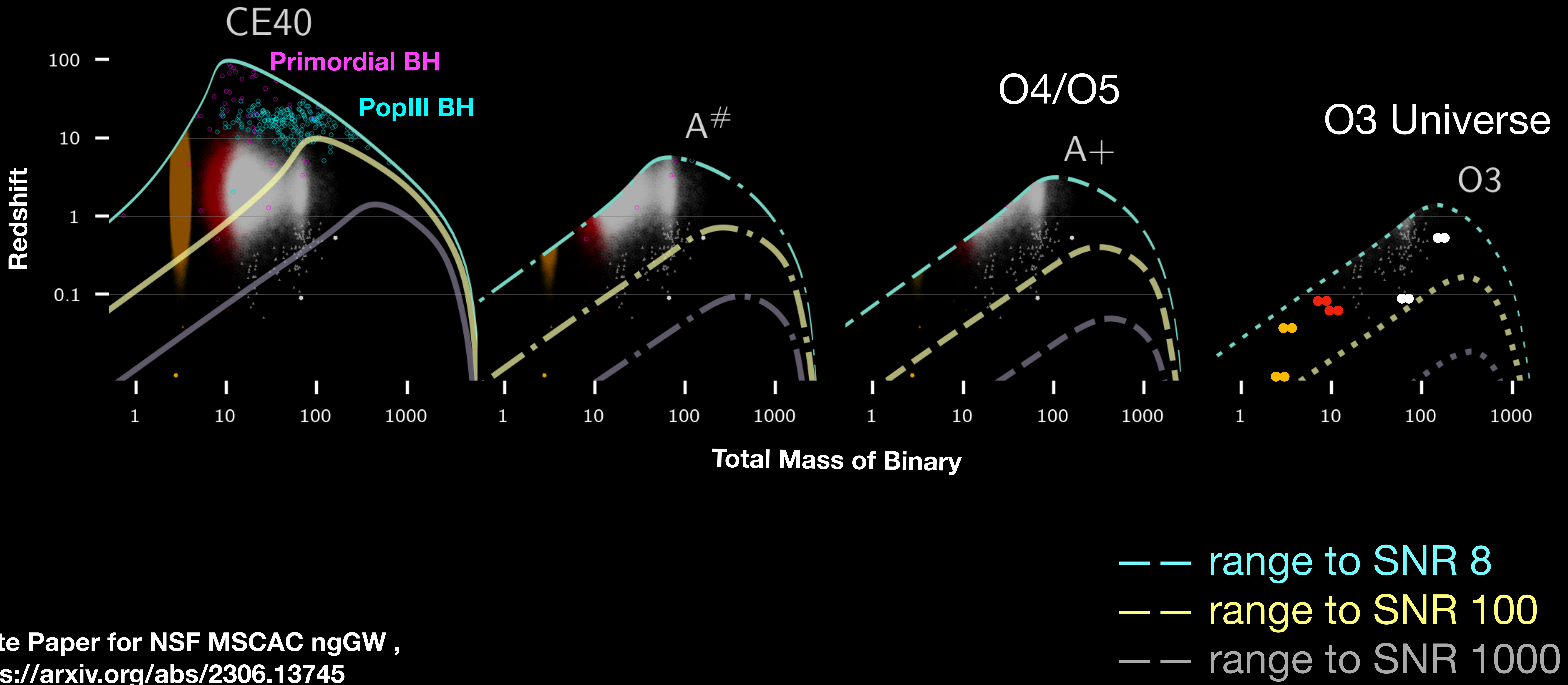
Unveiling the GW Universe



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

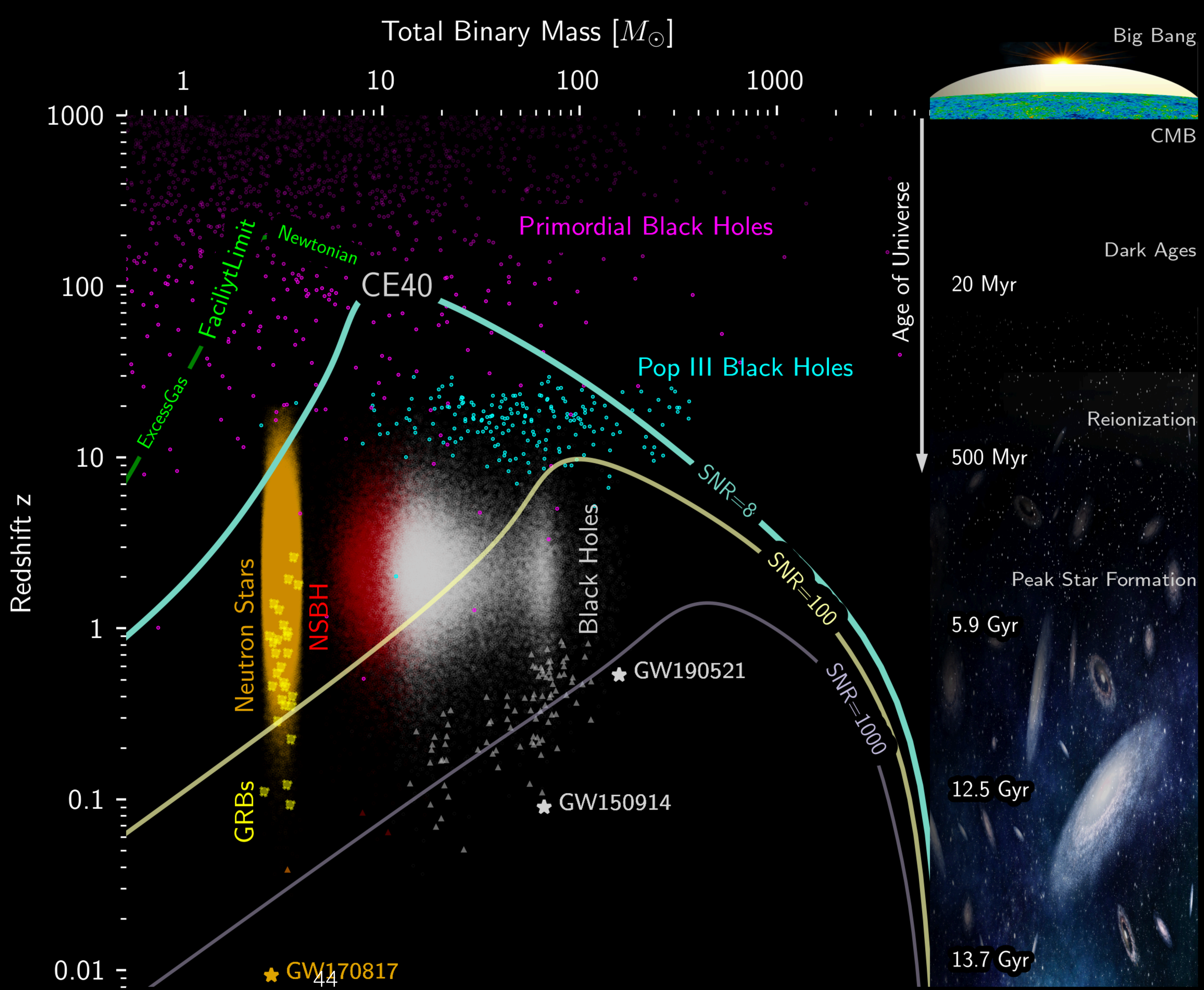
Unveiling the GW Universe

COSMIC EXPLORER



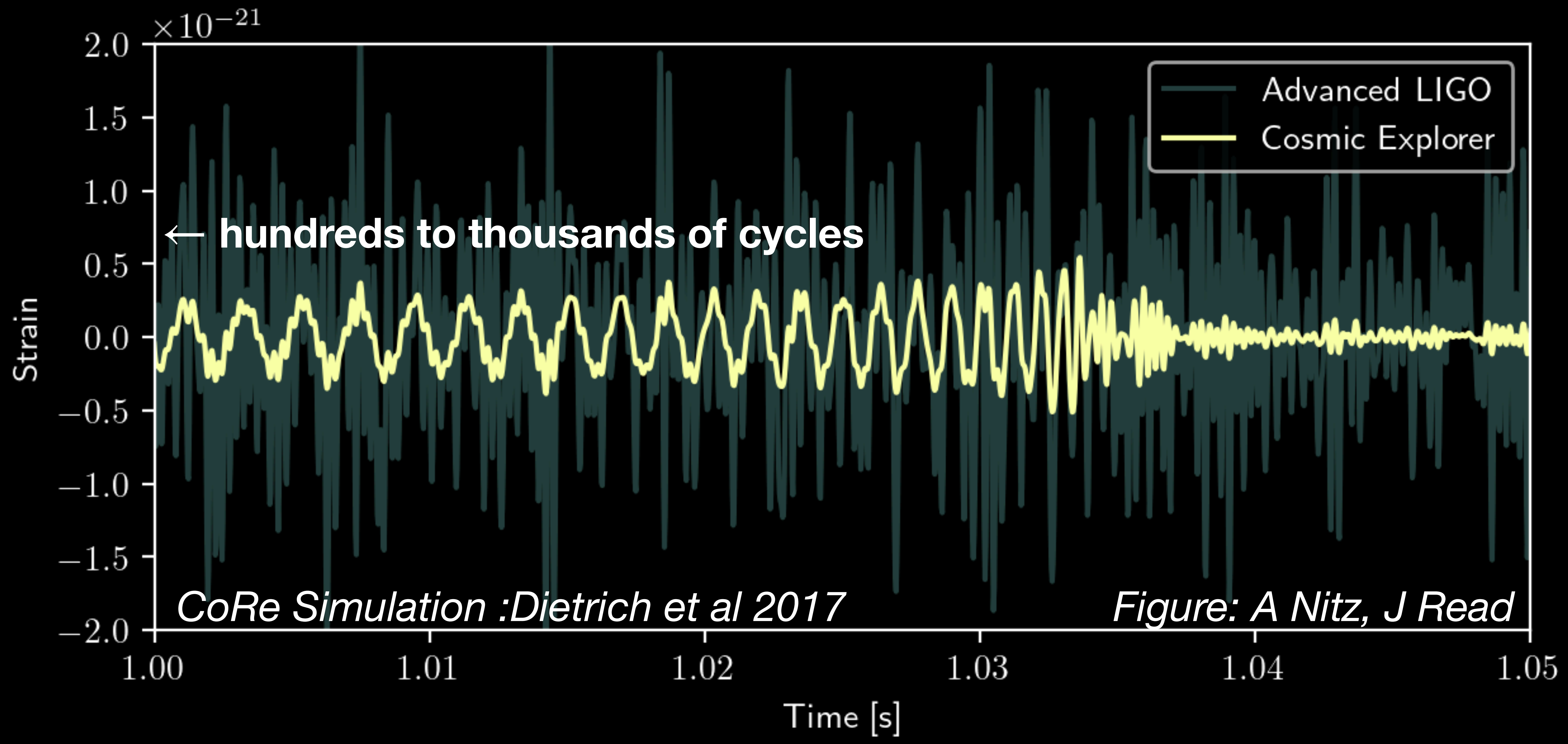
White Paper for NSF MSCAC ngGW ,
https://arxiv.org/abs/2306.13745

XG Universe



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

170817-like inspiral

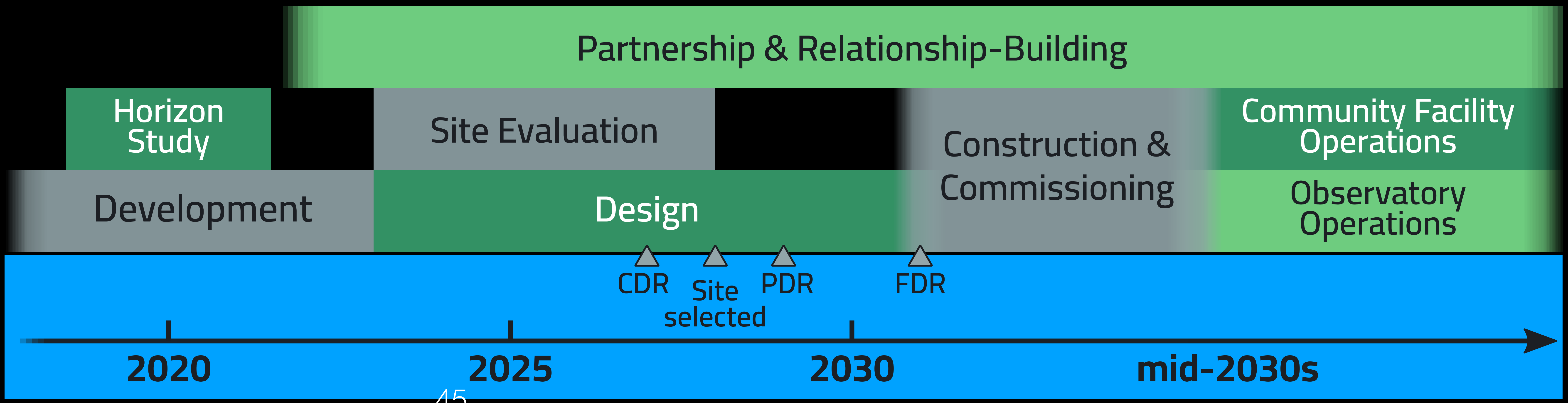


"Today's rare events are tomorrow's precision physics"

US Timeline

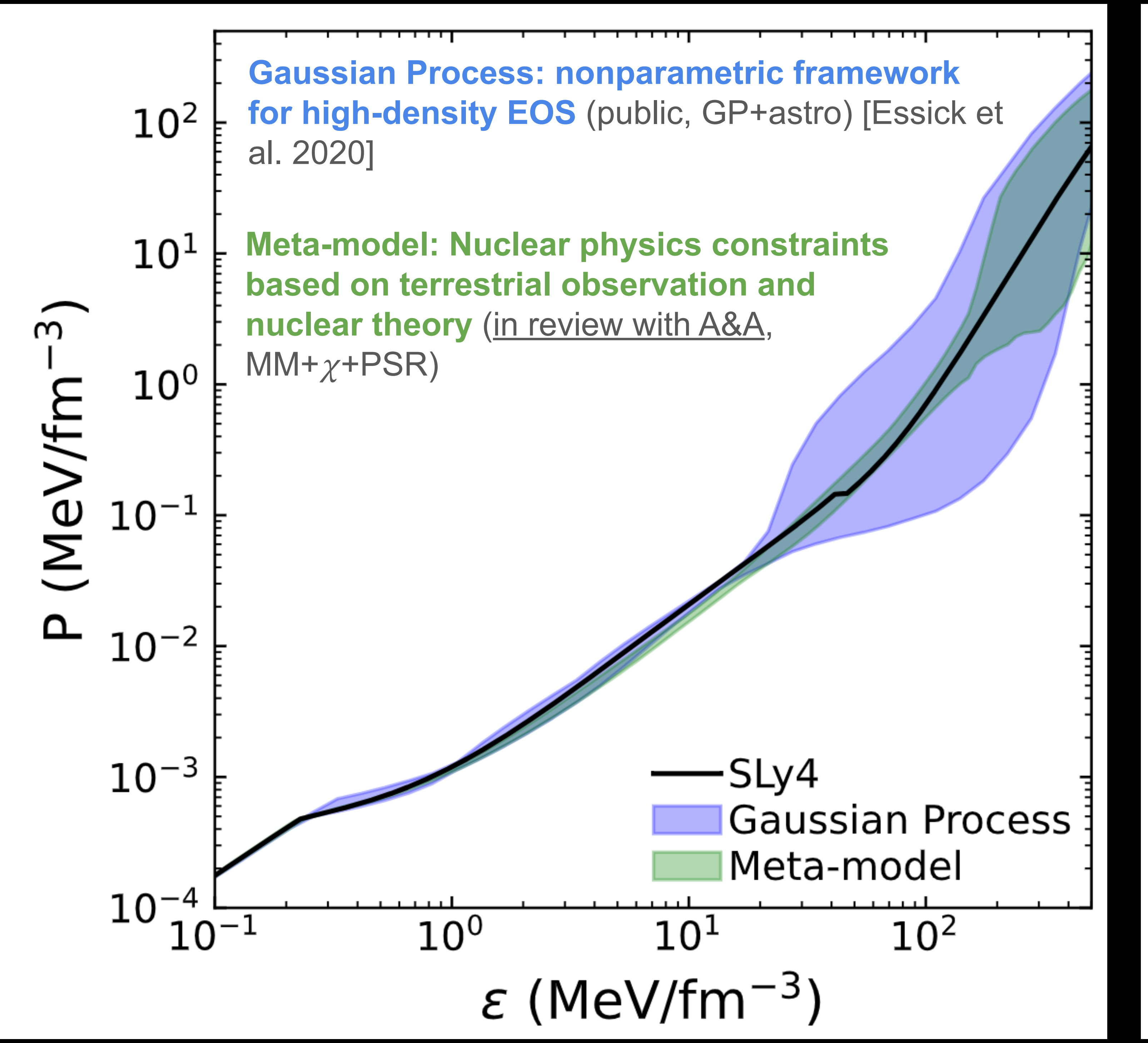
White Paper for NSF MSCAC ngGW , https://arxiv.org/abs/2306.13745

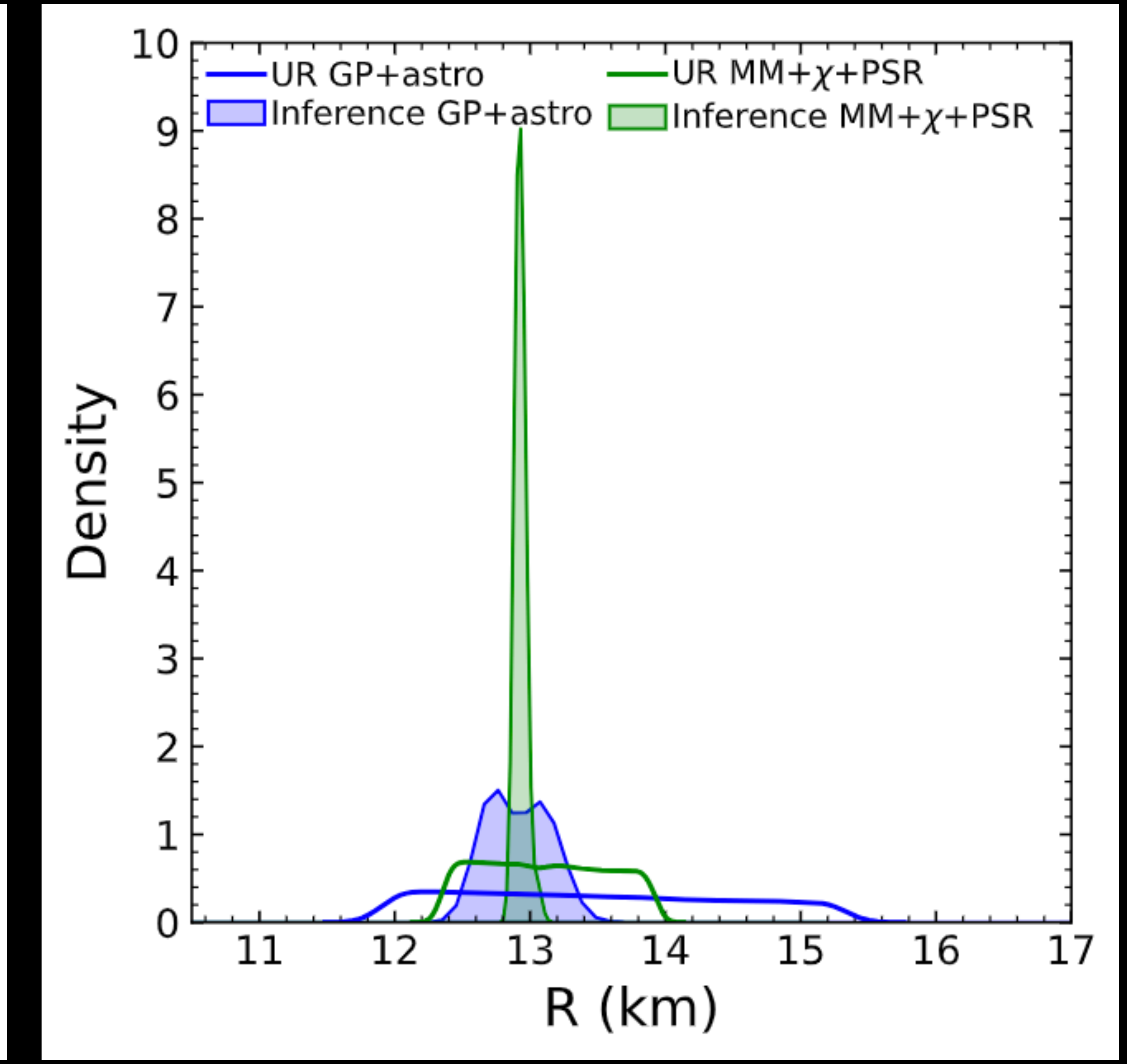
Site evaluation and design funded by NSF starting 2023



Using nuclear theory for next-generation GW interpretation

Connecting disparate observables: GW and the NS Radius

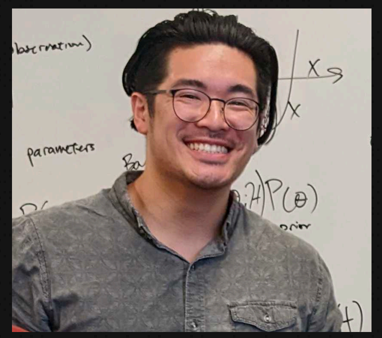


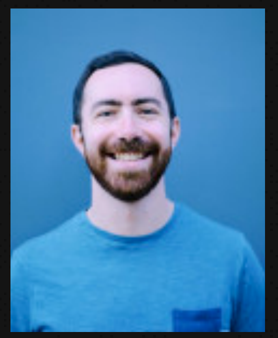


- Model observations with StrobeX, Cosmic Explorer
- Eg. observe Λ, compute R
- heirarchichally-inferred EOS + signal parameters (public library lwp).
- Challenge for quasi-universal relations

Suleiman & Read arXiv: 2402.01948

Ng, Suleiman, Landry, Read, in prep





Next-generation facilities

Cosmic Explorer and Einstein Telescope

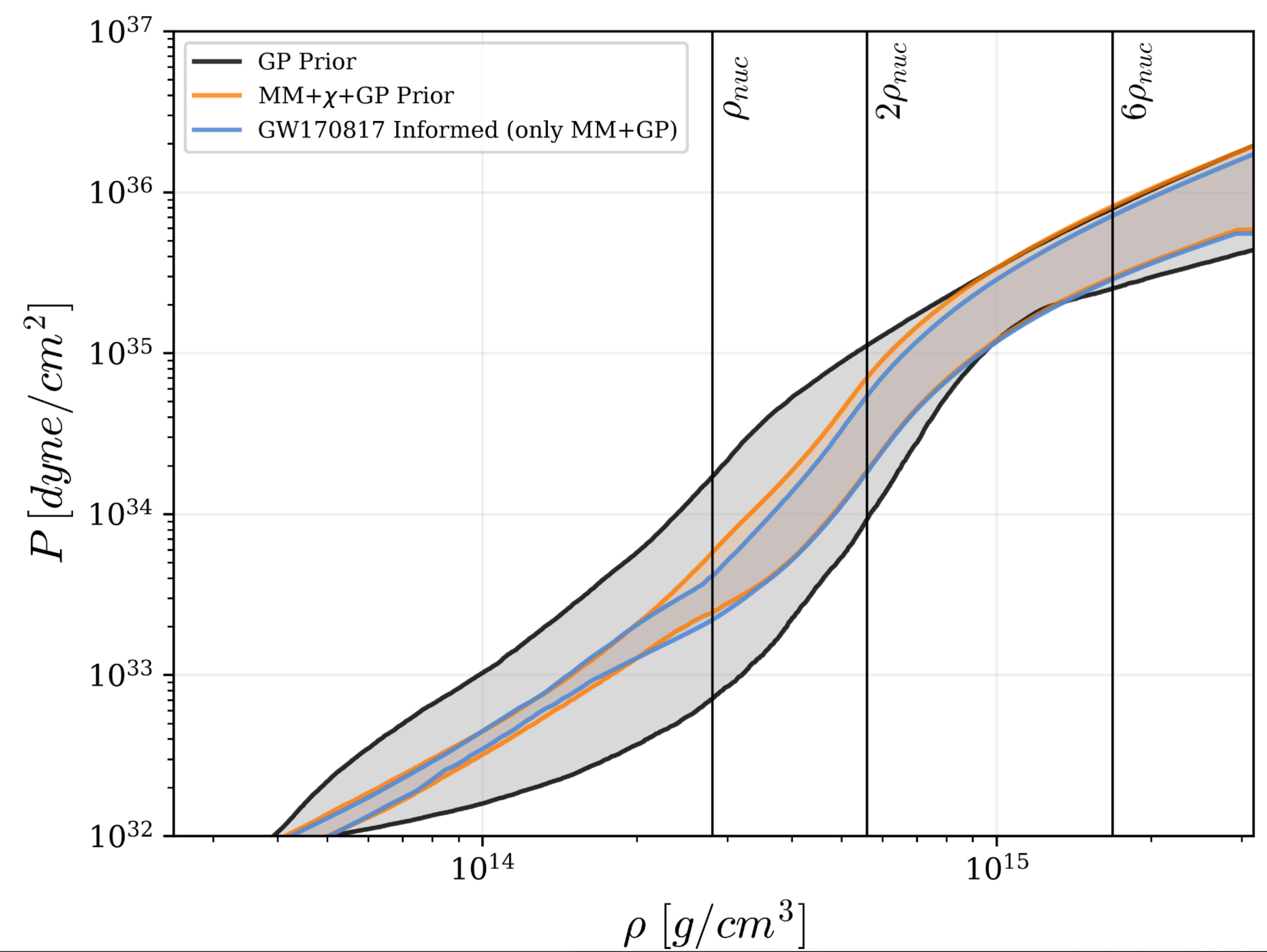
$\mathscr{M}_c = 0.96 M_\odot$ $\mathscr{M}_c = 1.28 M_\odot$ $\mathscr{M}_c = 1.64 M_\odot$

Density constrained varies with mass of binary

[Join inference is not possible due to lack of resolution of the EOS space: no candidates explain all three signals.]

Building effective models to explore the EOS

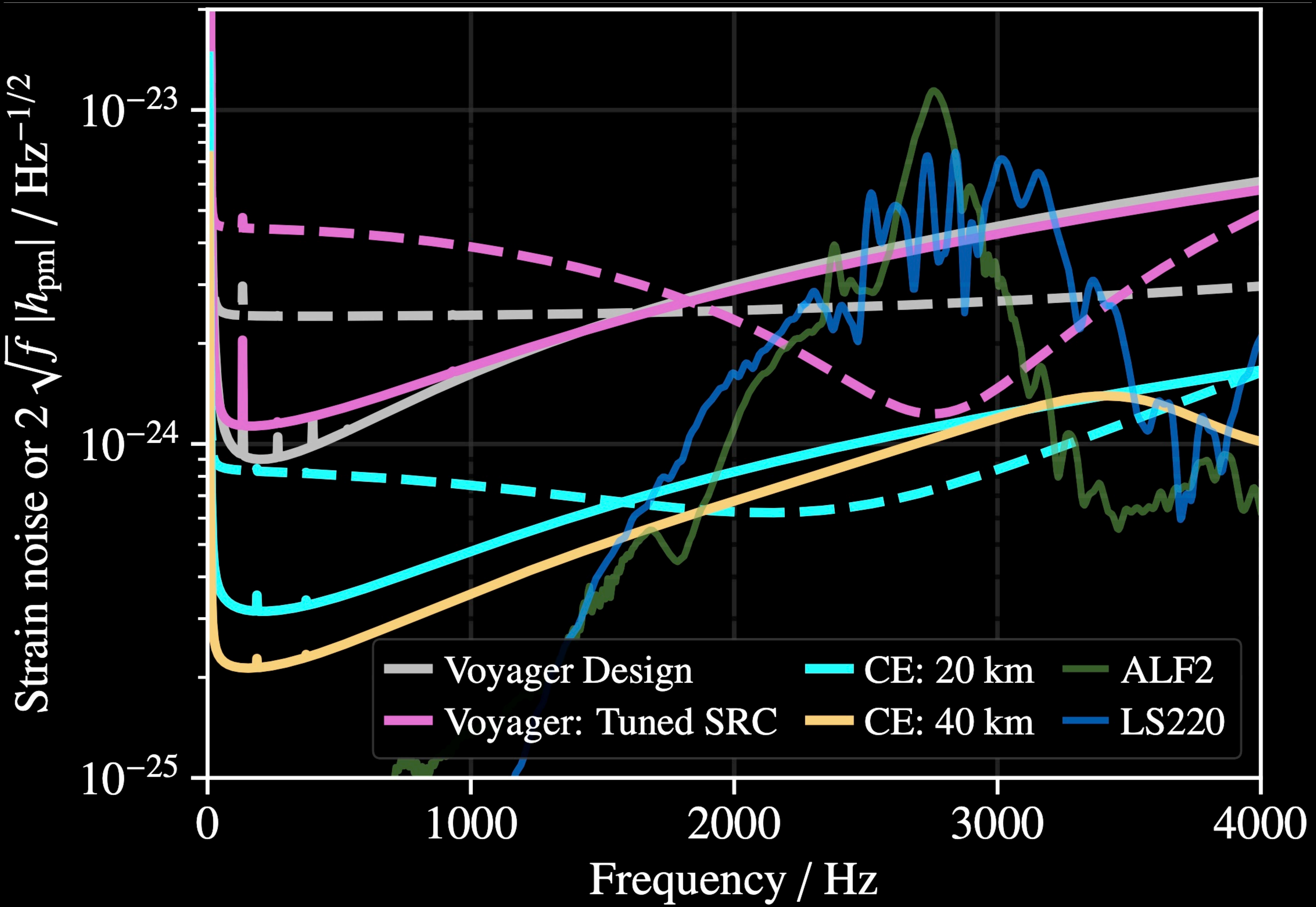
Connecting with low-density nuclear physics



- Meta-model: Nuclear physics constraints based on terrestrial observation and nuclear theory (MM+χ+PSR)
- Gaussian Process: nonparametric framework for high-density EOS (public, GP+astro) [Essick et al. 2020]
- Heirarchichally-inferred EOS + signal parameters (public library lwp).

Suleiman, Ng, Legred, Landry, Read

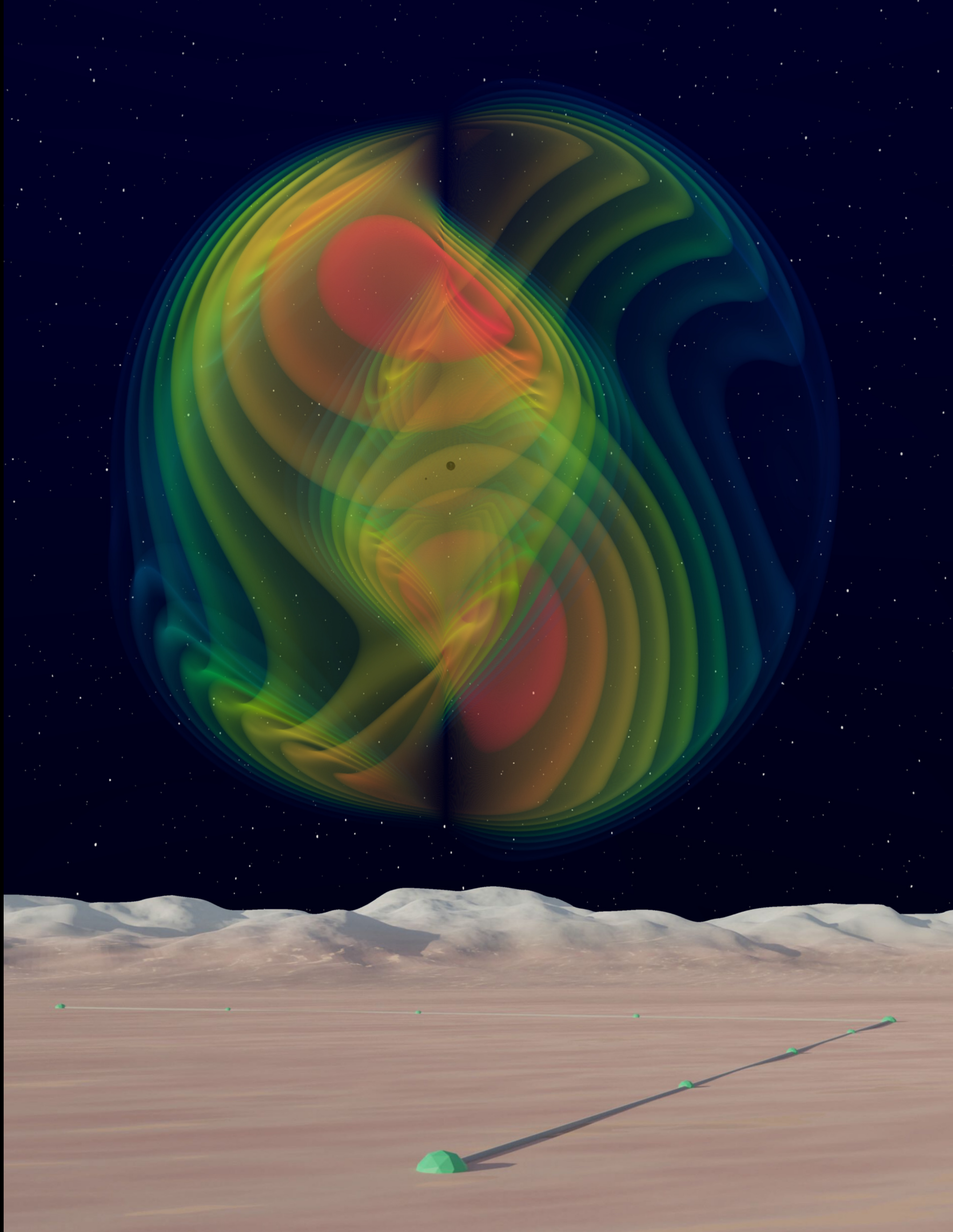
Post-merger GW?



Srivastava et al (incl J Read) 2022 *ApJ* **931** 22 arXiv:2201.10668

- burst follow-up to measure post-merger signals
- Clark et al 1509.08522: aLIGO measurement only for nearby ($\lesssim 30$ Mpc) sources
- Future observatories aim for ~1-100 post-merger GW detected / year

Join the Cosmic Explorer Consortium! Mailing list, joint meetings coming with Einstein Telescope working groups https://cosmicexplorer.org/consortium.html



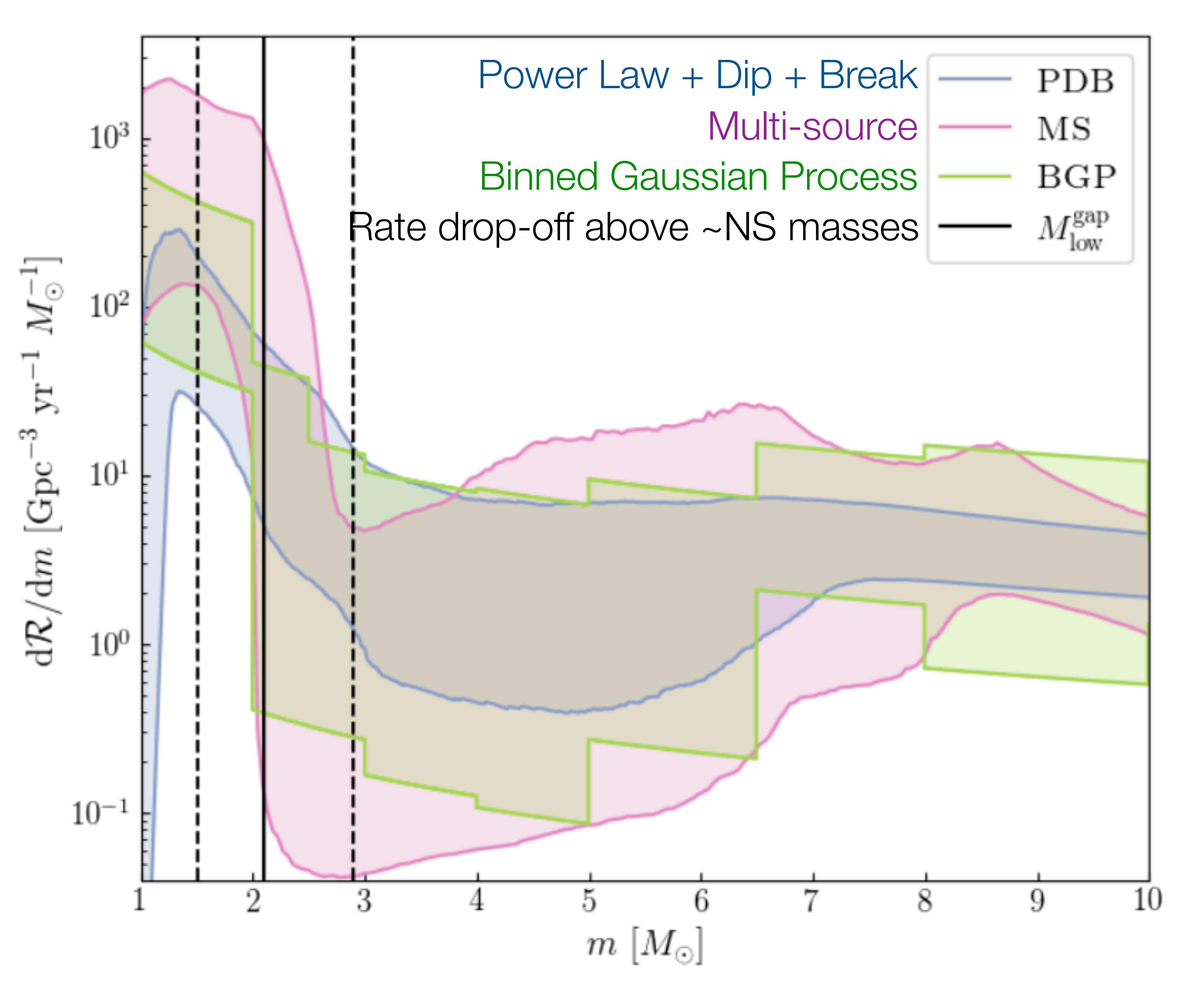
Horizon Study: arXiv:2109.09882

Extra Slides

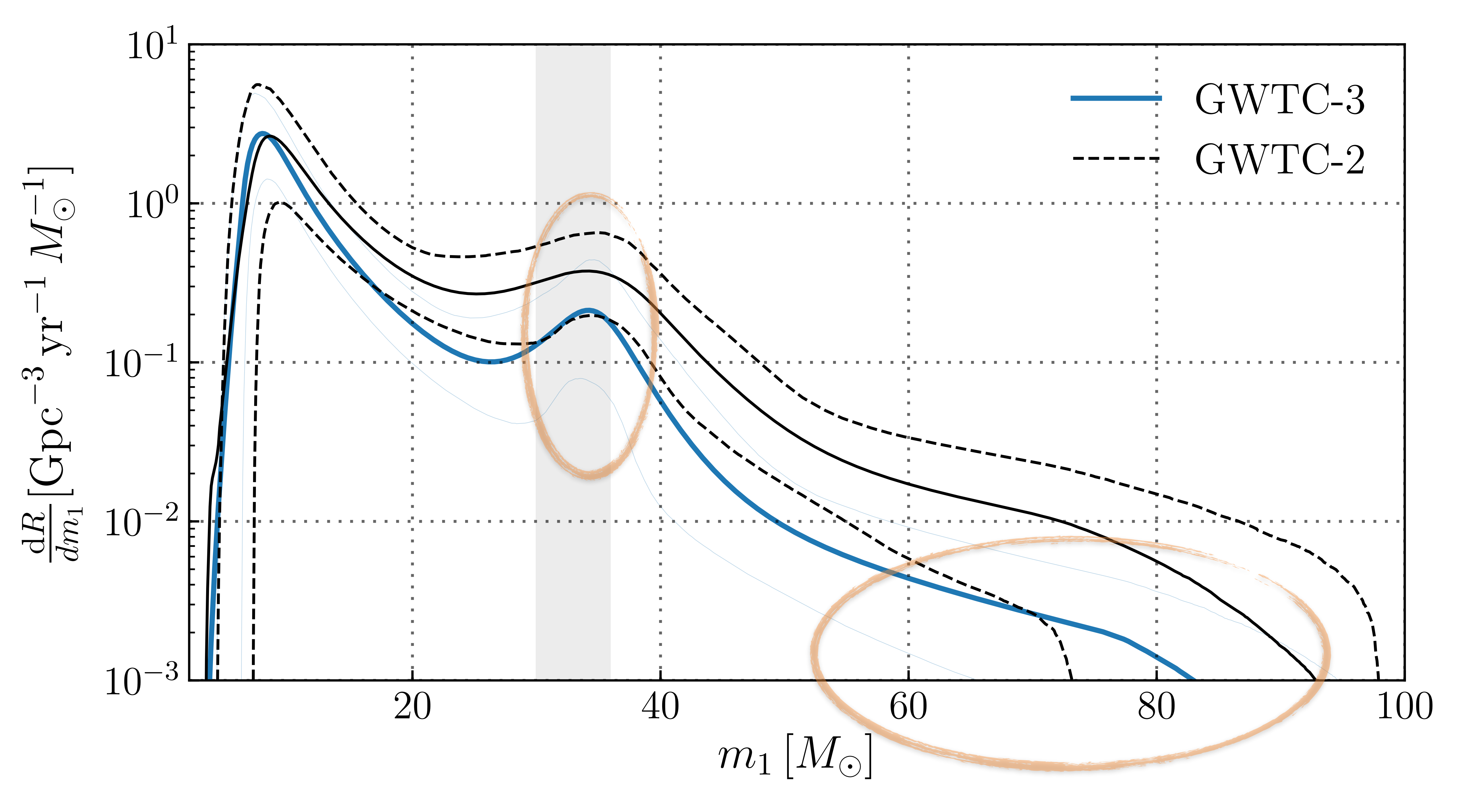
The population of merging compact binaries inferred using gravitational waves through GWTC-3

LIGO-Virgo-Kagra, Phys. Rev. X **13**, 011048
arXiv:2111.03634 (https://dcc.ligo.org/LIGO-P2100239/)

Lower mass gap above $\simeq 2.1 M_\odot$

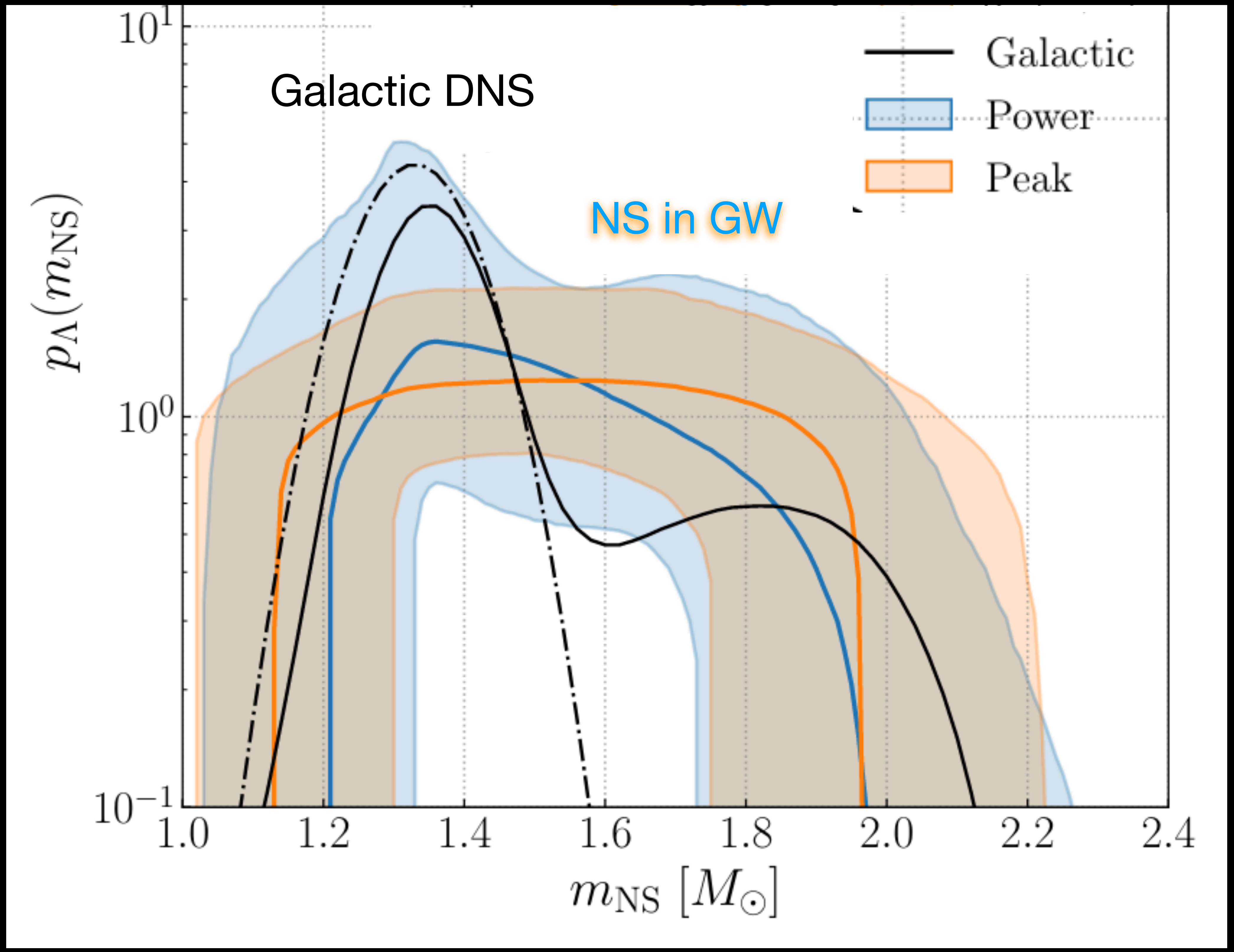


Structure in the BH mass spectrum



Upper mass gap above $> 60 M_\odot$

Neutron stars beyond the “typical” 1.4 $M_\odot$ in galactic binaries



LIGO-Virgo-Kagra O3 Population, Phys. Rev. X 13, 011048

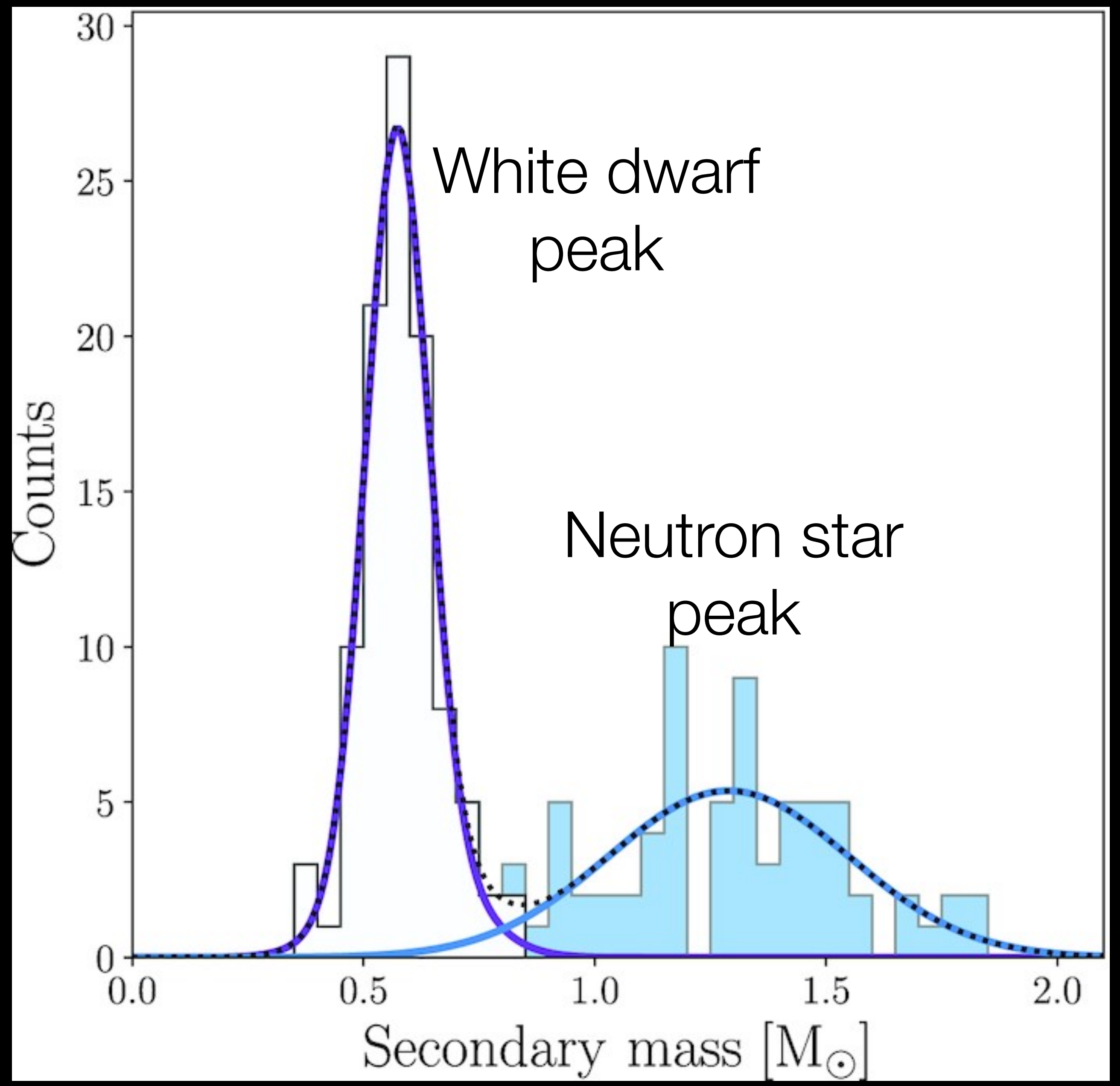
Method and related discussion: Landry and Read Astrophys. J. Lett. 921, L25 (2021)

High-mass NS in GW190425, GW200105, GW190917: GW show flatter mass distribution than galactic

(After removing GW190814, expected to be BH from EOS)

Broad low-mass distribution in Gaia companion NS candidates

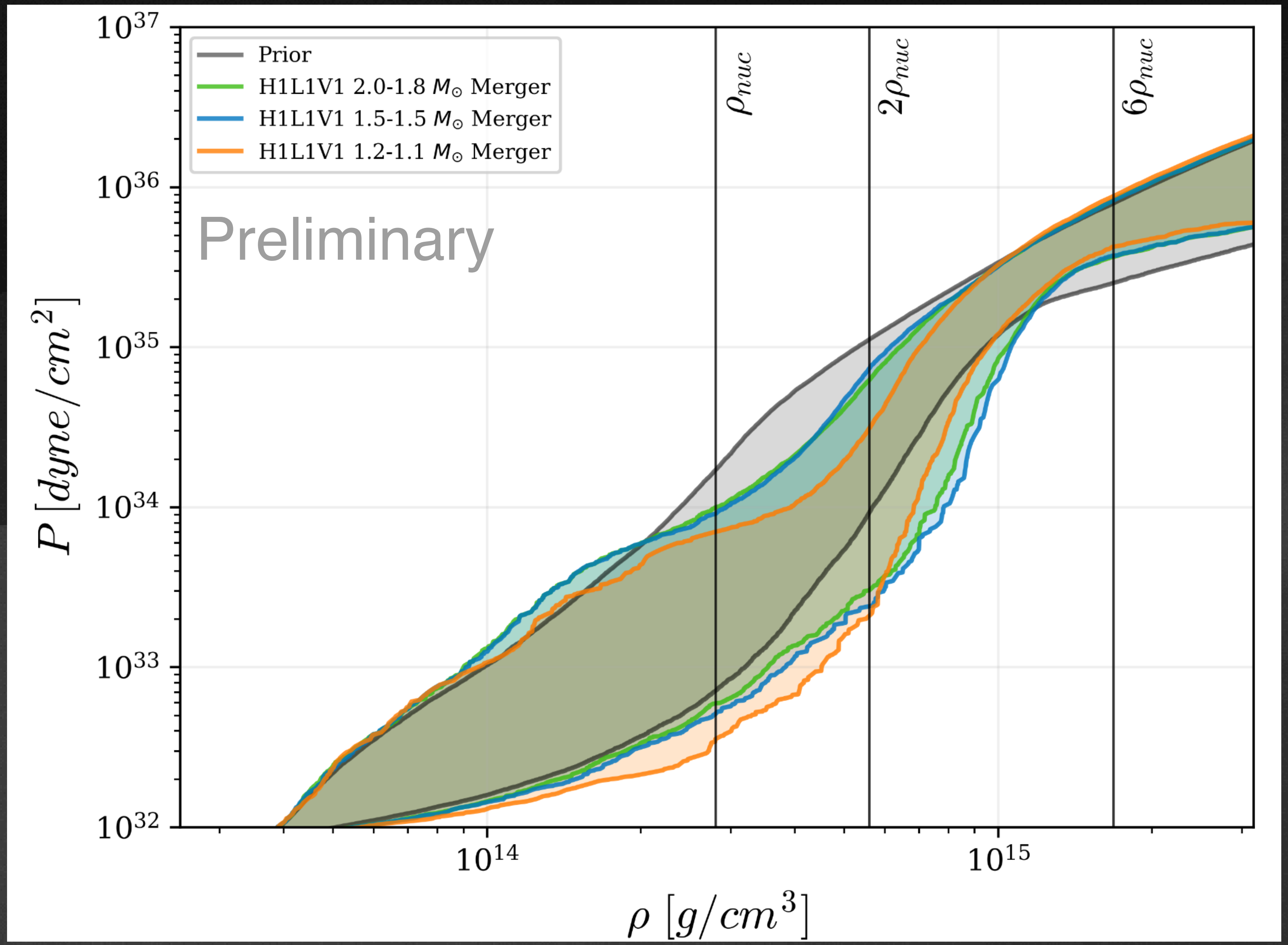
Shahaf et al, Triage of the Gaia DR3 astrometric orbits, MNRAS 518, 2, p2991–3003 (2023)



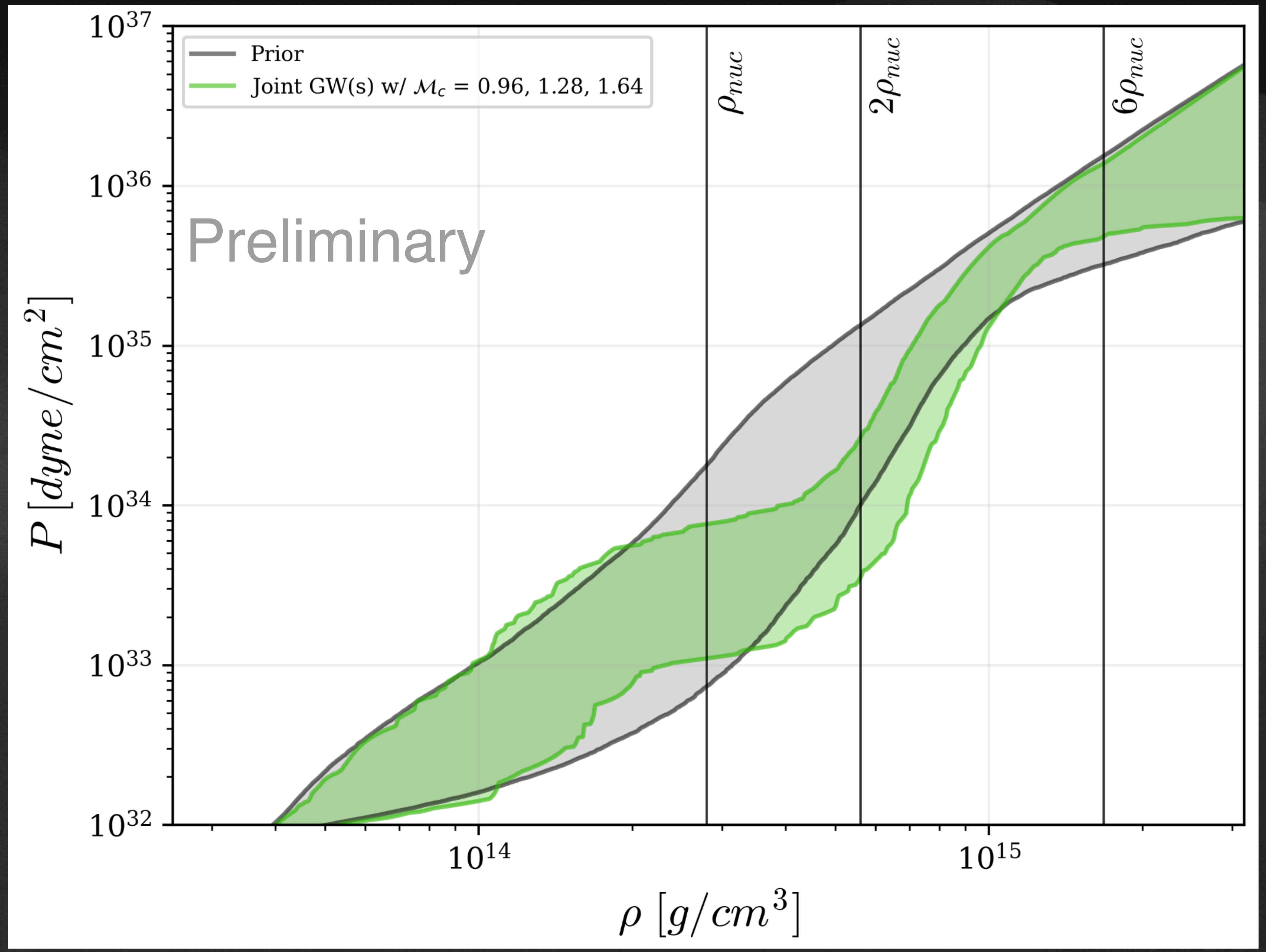
Plausible Constraints from LVK Network:

Simulated loud O4-O5 BNS events

Individual events



Joint constraint



Likelihood weighting with nonparametric, Gaussian Process EoS prior conditioned on heavy pulsar masses, 3 loud (SNR>13) GW events at O4 sensitivity

Wuchner, Ng, Landry, Read, in prep

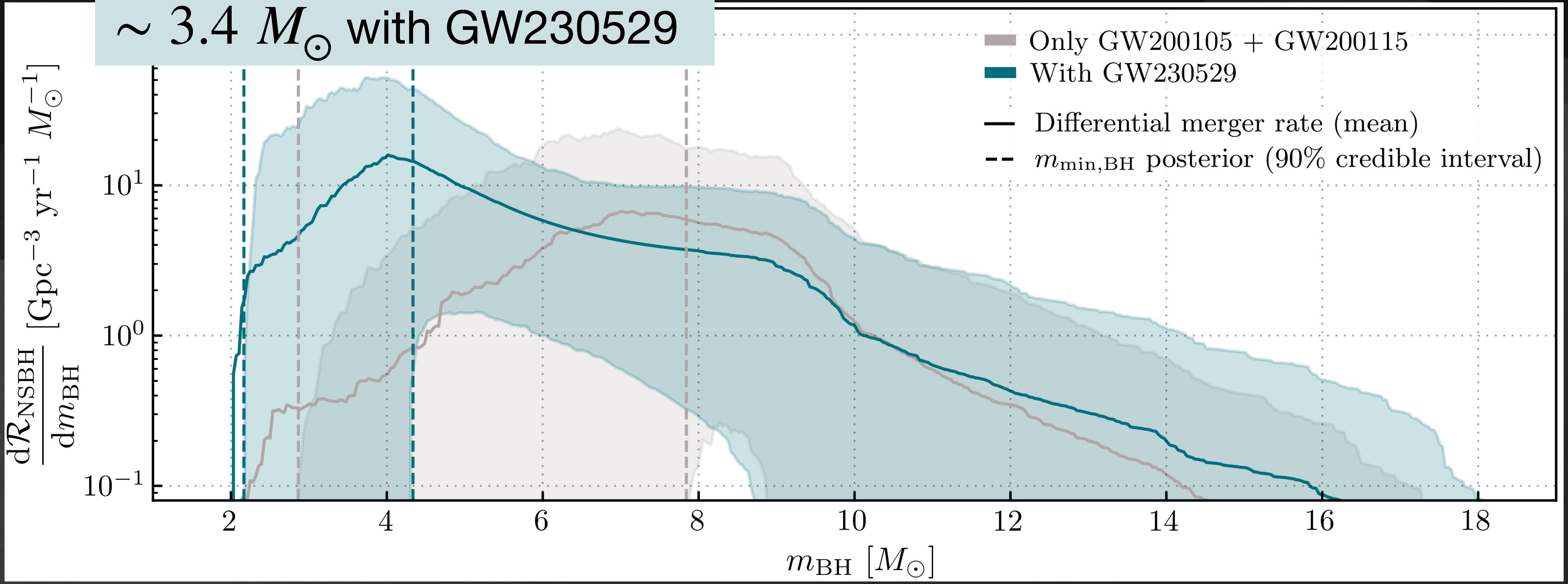
Impact of new “mass-gap” event

Minimum inferred BH mass in NSBH systems:

LIGO-Virgo-KAGRA GW230529
https://arxiv.org/abs/2404.04248v1

$\sim 6.0\ M_\odot$ without GW230529

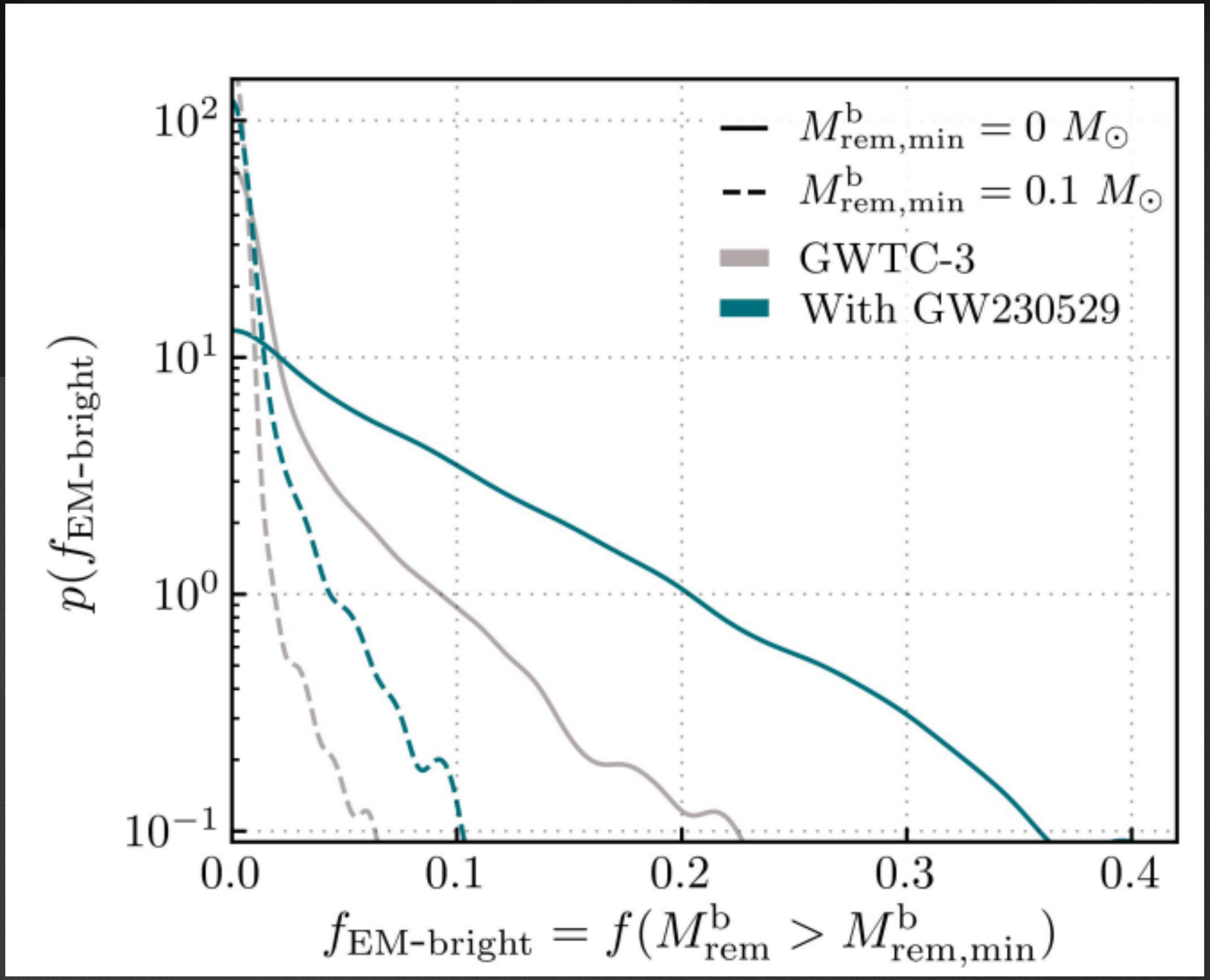
$\sim 3.4\ M_\odot$ with GW230529



- Updated local NSBH merger rate: **30-200** $\mathrm{Gpc}^{-3}\,\mathrm{yr}^{-1}$ (90% credible)

Observation of Gravitational Waves from the Coalescence of a 2.5-$4.5\ M_\odot$ Compact Object and a Neutron Star

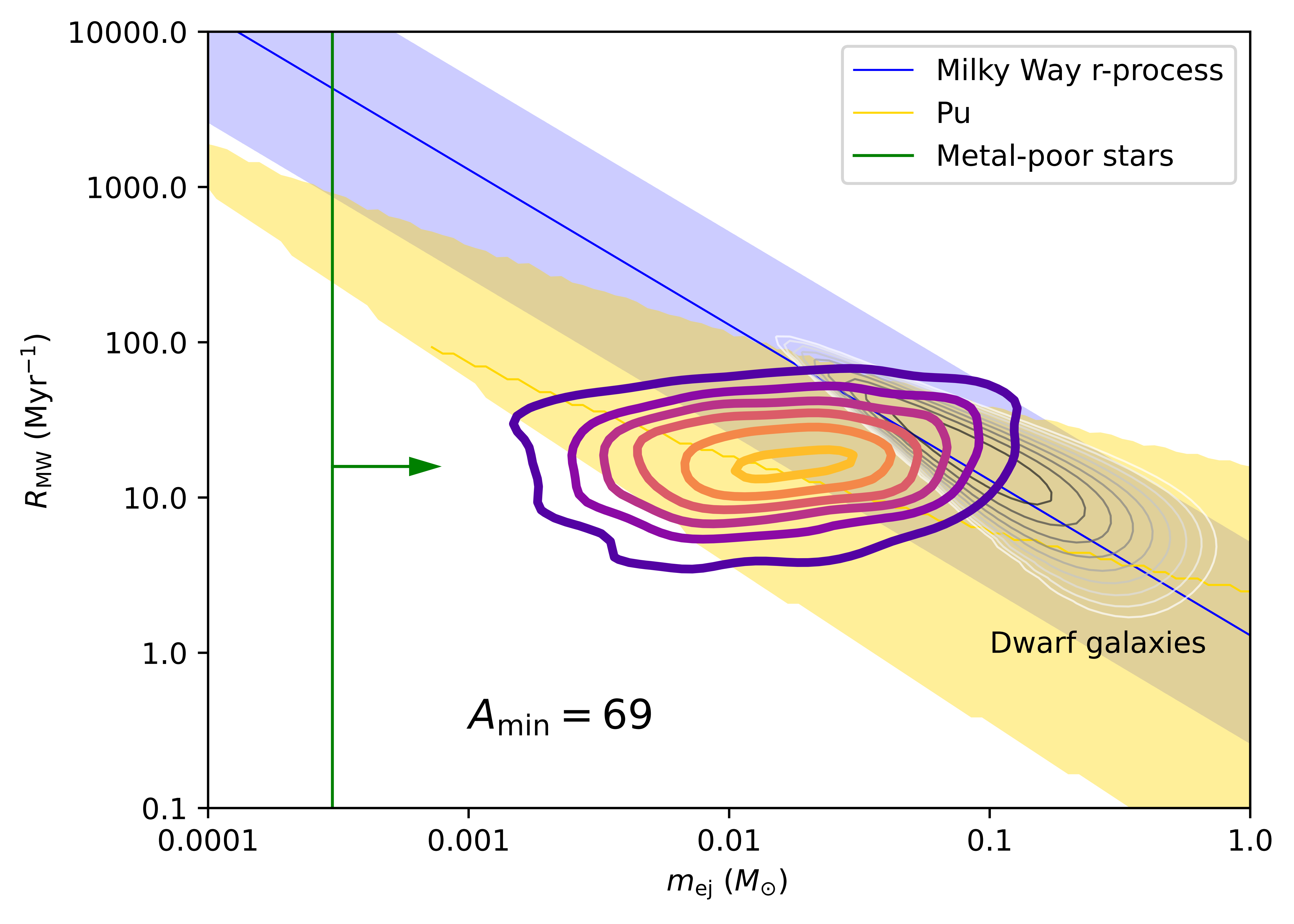
Neutron-star merger implications



- 10% disruption probability of the neutron star in GW230529 can be inferred based on the binary parameters
- Upper limit on the remnant baryon mass produced in the merger of 0.052 $M_\odot$ at 99% credibility
- Fraction of NSBH mergers with remnant matter ≤ 0.18 (or $0.13^{+0.19}_{-0.11}$ with NICER EOS info)
- NSBH mergers contribute at most 1.1 $M_\odot$ Gpc^{-3} yr^{-1} to the production of heavy elements
- Rate of NSBH progenitors for GRB < 23 Gpc^{-3} yr^{-1} at 90% credibility (small fraction of sGRB)

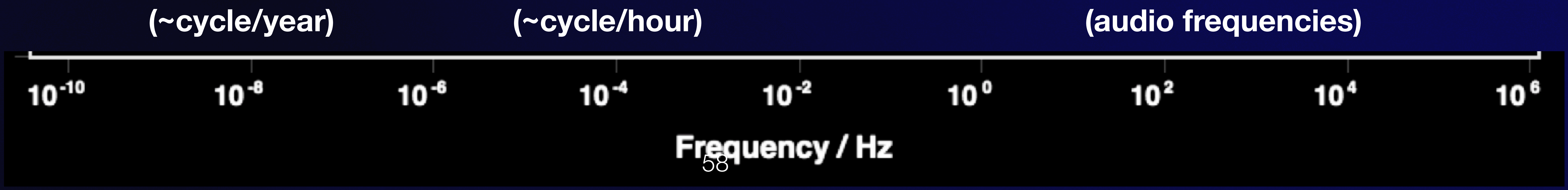
How much do BNS contribute to galactic nucleosynthesis?

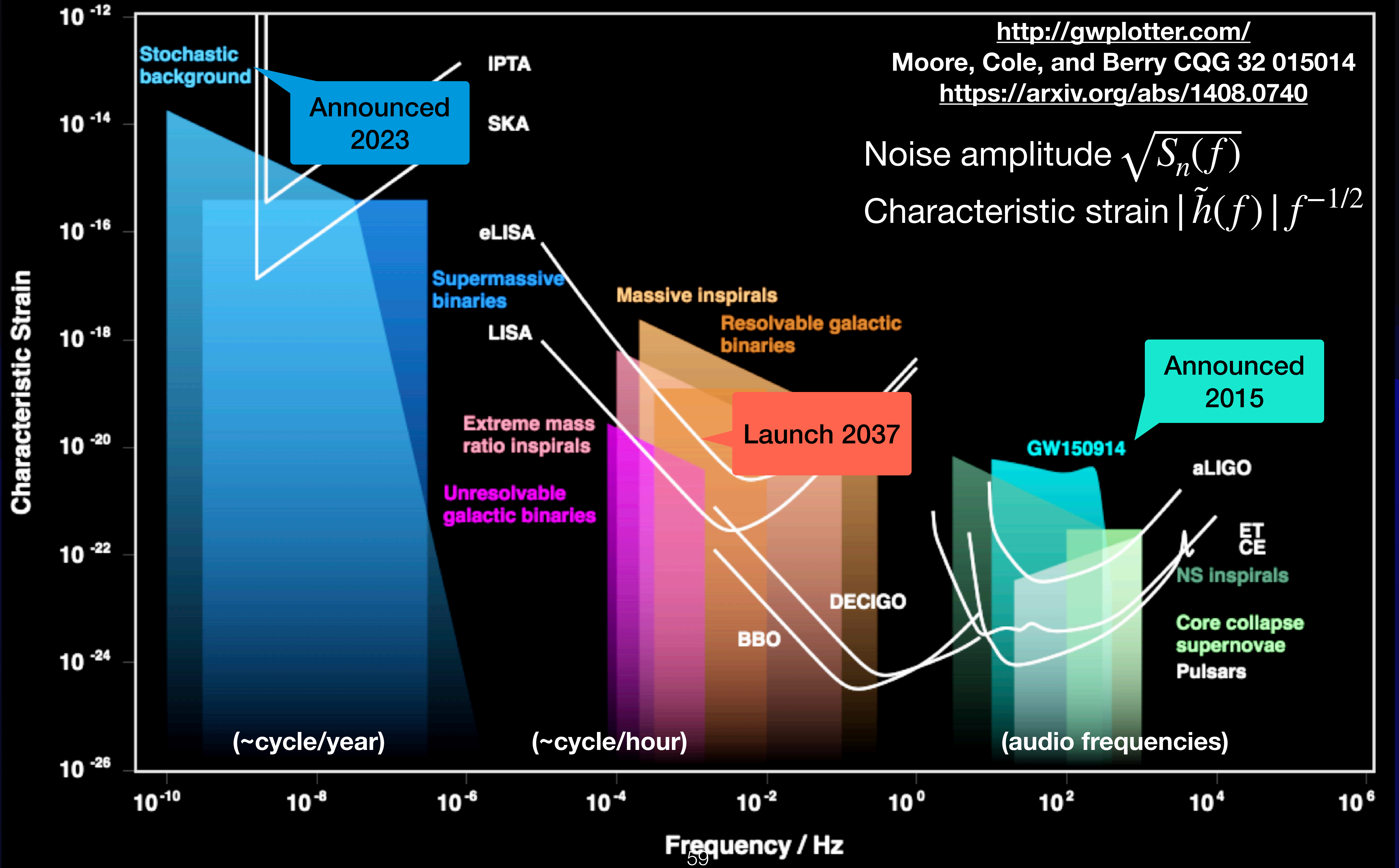
- **Merger rates and mass distribution from LVK O3 Populations public data**
- **EOS distribution from nonparametric inference using LVK/NICER/Pulsar masses**
- Ejecta mass per system from simulation-calibrated formulae (see Hsin-Yu Chen et al 2021 ApJL 920 L3)
- Compare rate of events, ejecta per event to other heavy-element observations



Chen, Landry, Read, Siegel arXiv 2402.03696
Also compares stellar abundance, GRB delay time to infer needed properties for non-delayed channel, ***with error bars!***

The Gravitational-wave Spectrum

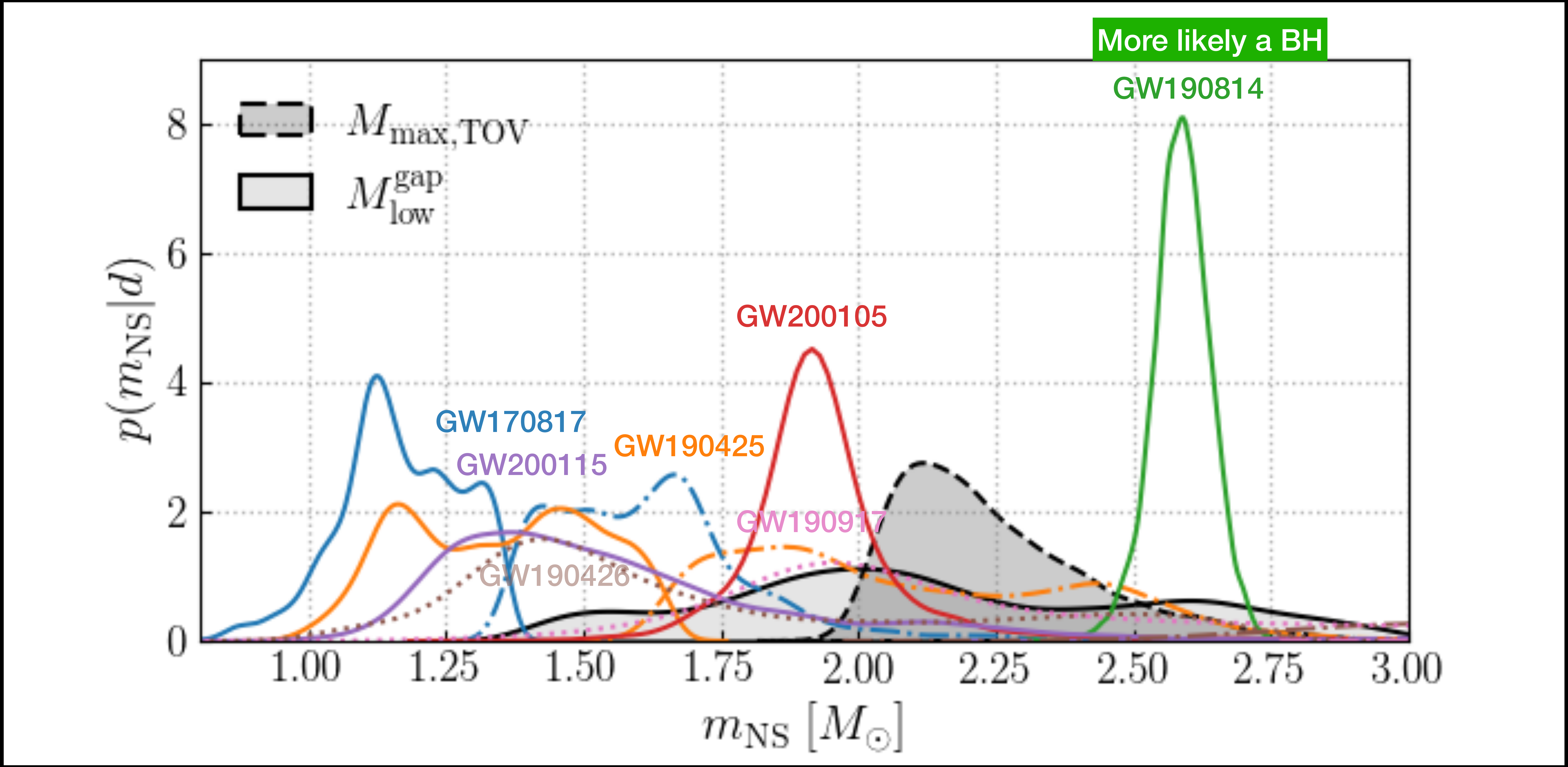


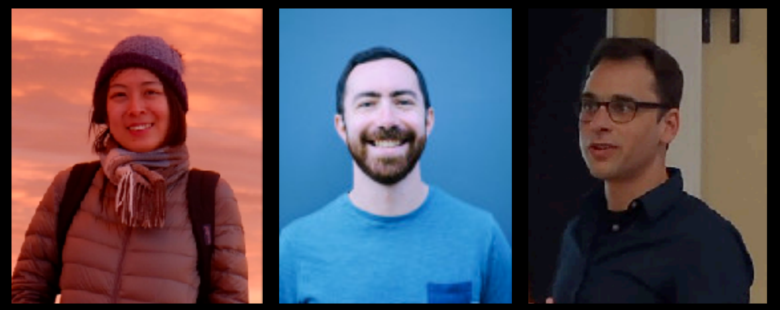


http://gwplotter.com/
Moore, Cole, and Berry CQG 32 015014
https://arxiv.org/abs/1408.0740
Noise amplitude $\sqrt{S_n(f)}$
Characteristic strain $|\tilde{h}(f)|f^{-1/2}$
Stochastic background
Announced 2023
IPTA
SKA
eLISA
Supermassive binaries
LISA
Massive inspirals
Resolvable galactic binaries
Extreme mass ratio inspirals
Unresolvable galactic binaries
Launch 2037
DECIGO
BBO
Announced 2015
GW150914
aLIGO
ET
CE
NS inspirals
Core collapse supernovae
Pulsars
(~cycle/year)
(~cycle/hour)
(audio frequencies)
Characteristic Strain
Frequency / Hz
10^{-12}
10^{-14}
10^{-16}
10^{-18}
10^{-20}
10^{-22}
10^{-24}
10^{-26}
10^{-10}
10^{-8}
10^{-6}
10^{-4}
10^{-2}
10^{0}
10^{2}
10^{4}
10^{6}

Neutron stars observed in GW

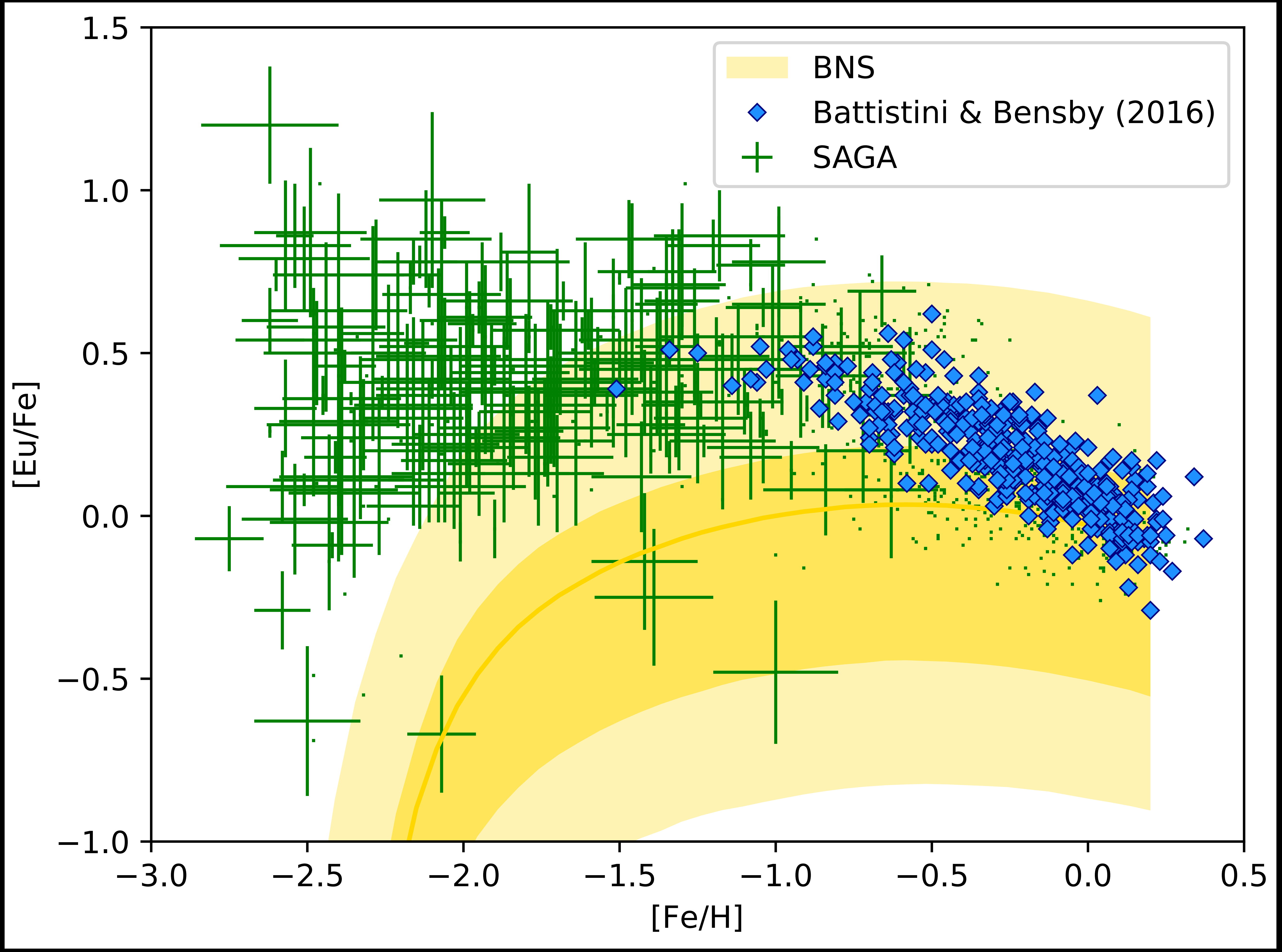
LIGO-Virgo-Kagra O3 Population, arXiv:2111.03634 ()





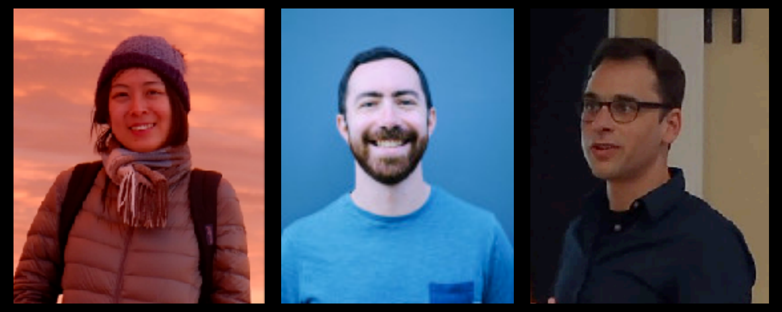
BNS contribution to stellar abundance

- Model rate of heavy-element production relative to rate of iron production with a one-zone galaxy model
- Delay BNS from star formation following sGRB (Michael Zevin et al 2022 ApJL 940 L18)
- Delayed BNS match solar abundance (0.0) well, but can't produce at low metallicity

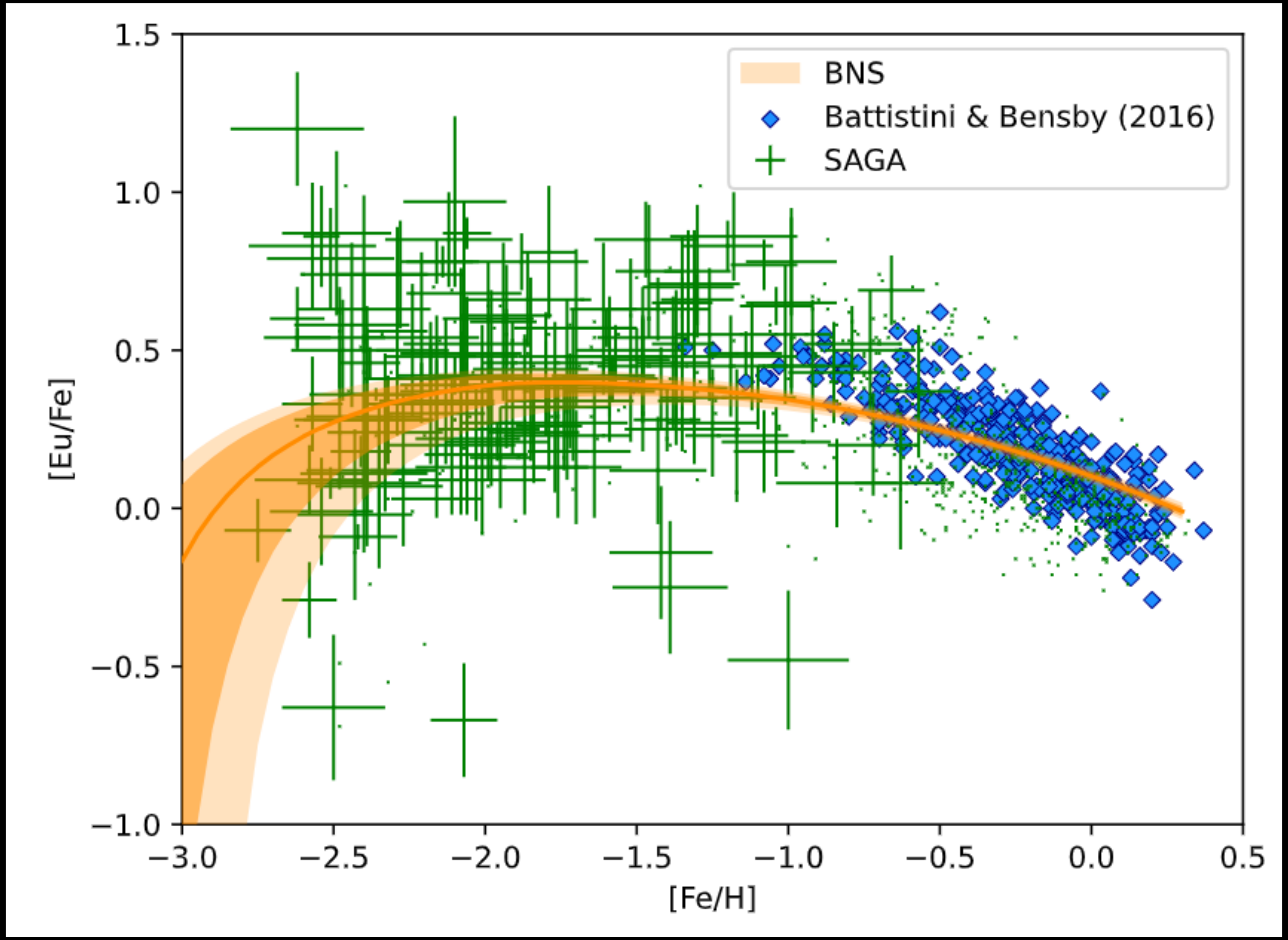


Chen, Landry, Read, Siegel arXiv 2402.03696

BNS contribution to stellar abundance

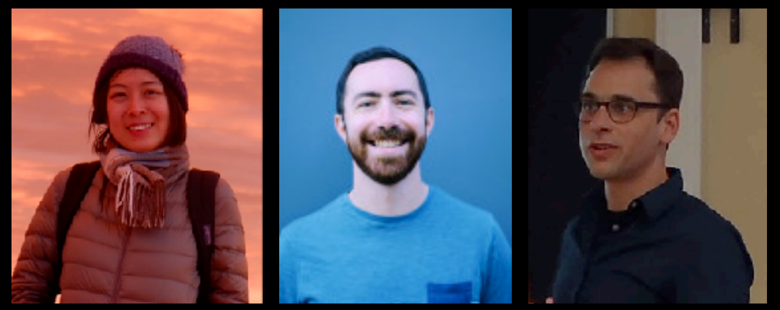


- Fit delay time to stellar abundance data
- Infer short delay time between star formation and merger, inconsistent with GRB observations

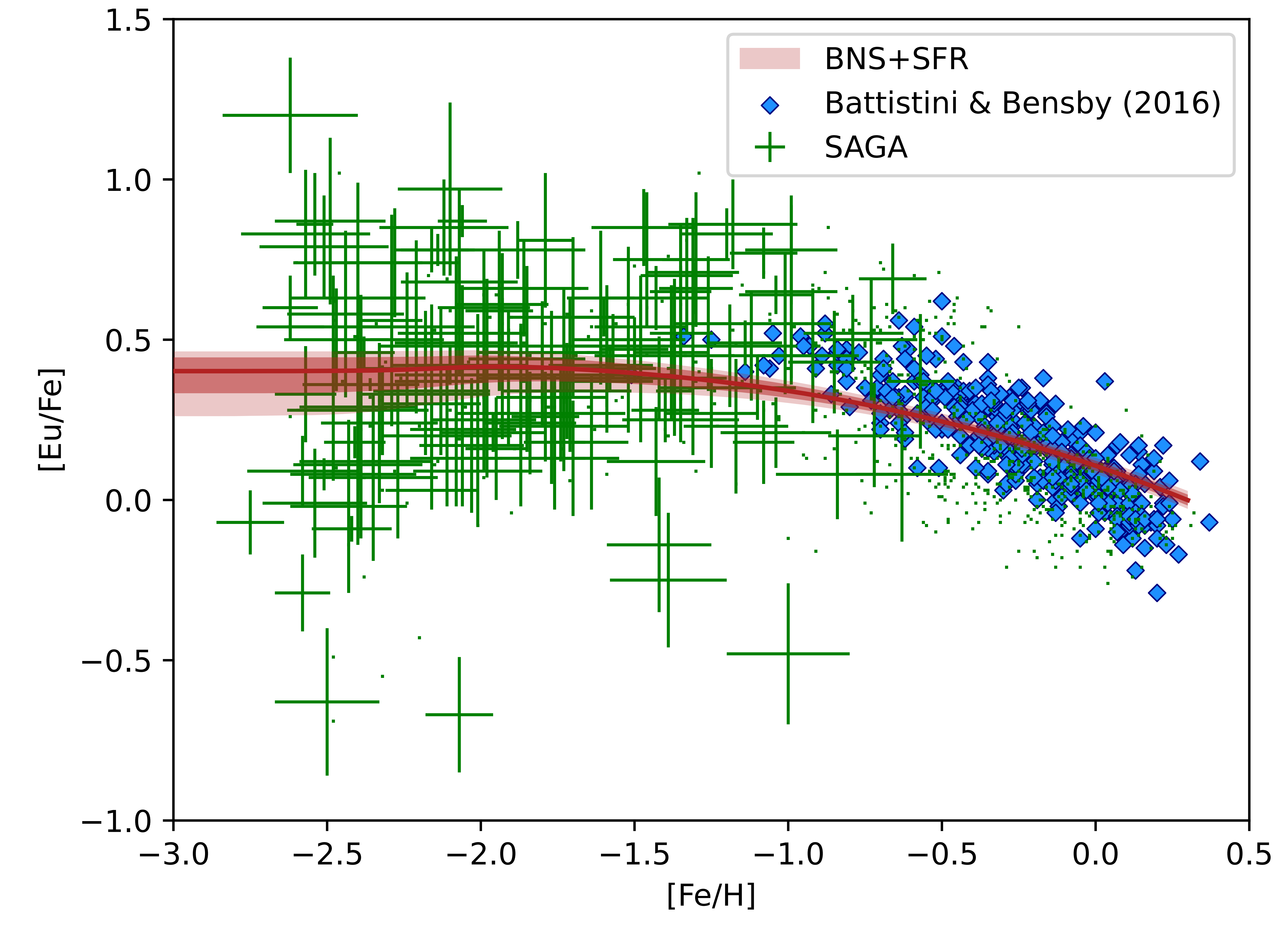


Chen, Landry, Read, Siegel arXiv 2402.03696

Inferring a second channel



- Model: Two sites of heavy-element formation
- Astronomical prior for slow BNS contribution
- Second rapid channel tracks star formation rate
- Constrain properties of second channel through fit to stellar abundances
- ~45-90% of all r-process from second channel



Chen, Landry, Read, Siegel arXiv 2402.03696