Source models and gravitational-wave signals:

Quantifying uncertainty and interpreting differences

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COSMIC EXPLORER

LIGO
VIRGO
KAGRA

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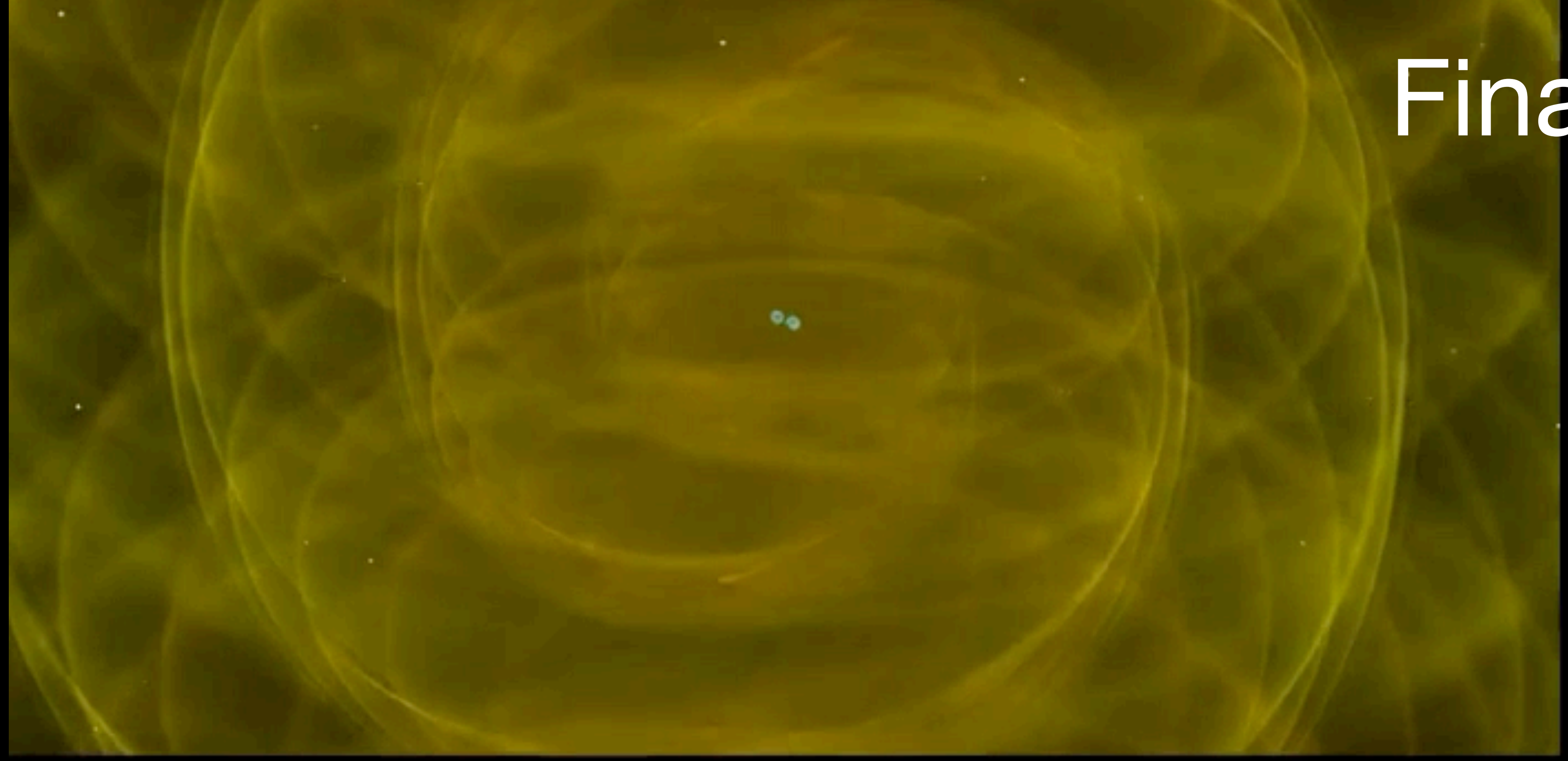
Center for Gravitational-Wave Physics and Astronomy

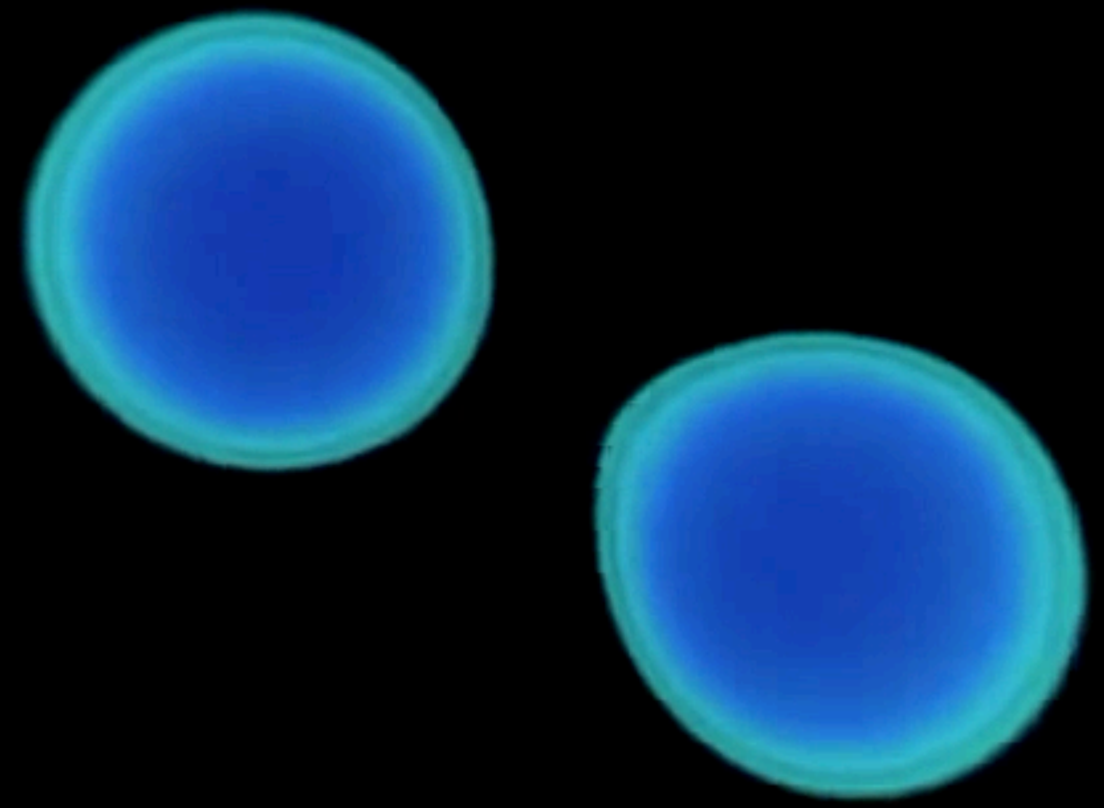
Neutron Stars Merging,
CSUF GWPAC Artist-in-Residence Eddie Anaya

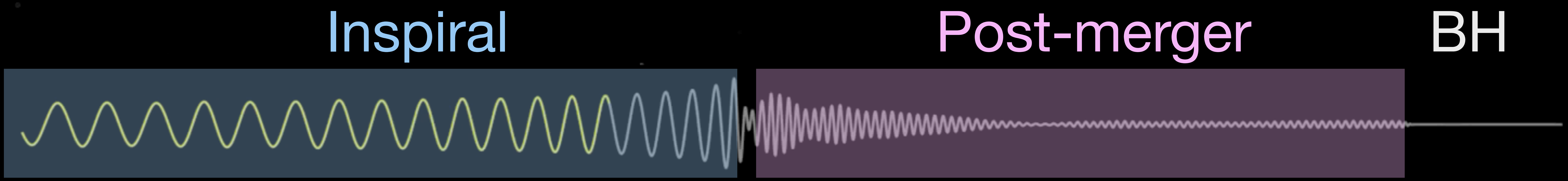
Part 1 - Context/Motivation:
What is the nature of matter in neutron stars?

Maciej Rebisz for Quanta Magazine

Final 40 milliseconds of inspiral

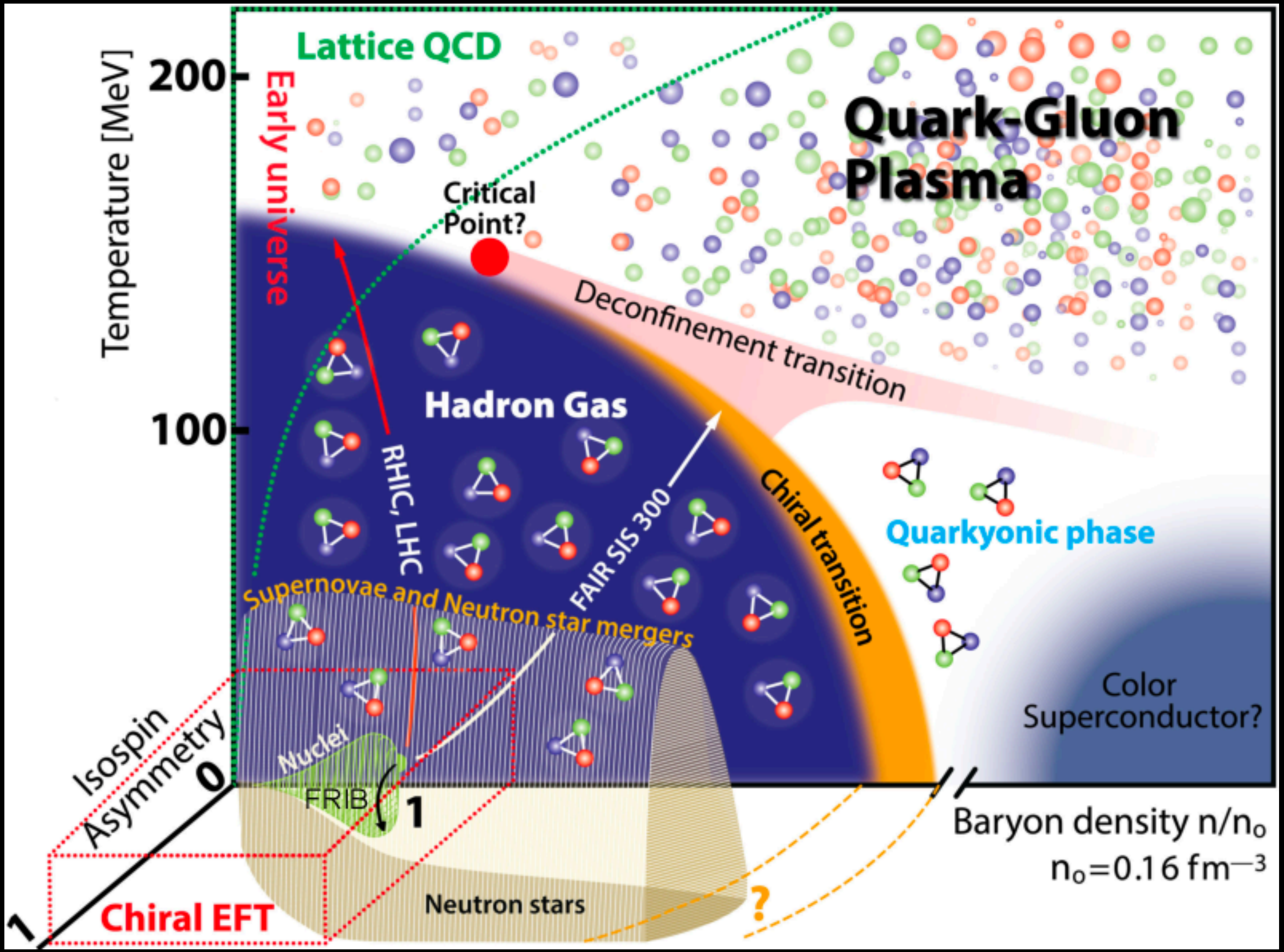






https://www.youtube.com/watch?v=V6cm-0bwJ98

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



Drischler, C., Holt, J.W., & Wellenhofer, C. Ann. Rev. Nucl. Part. Sci. 71:403-432 (2021)

Focus of this talk

Neutron star in inspiral:

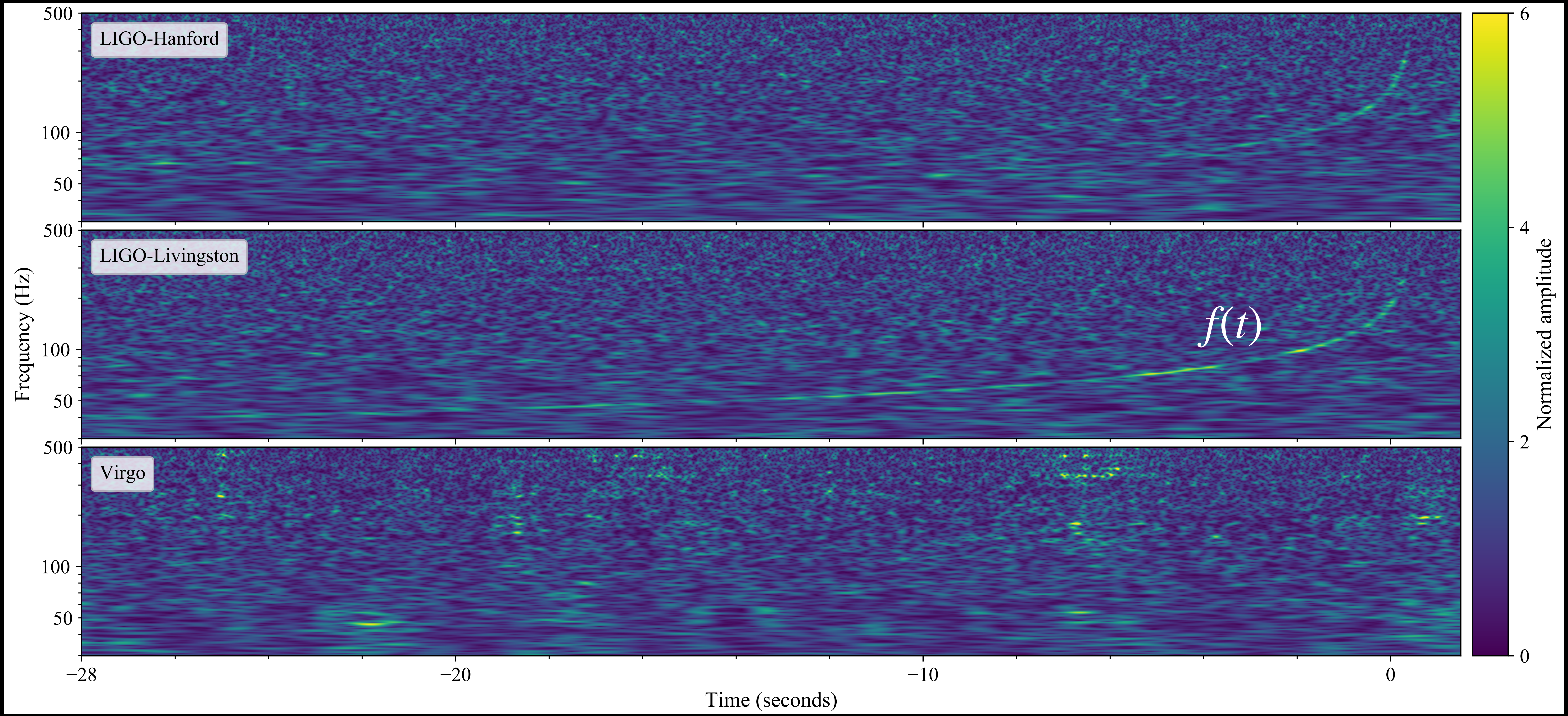
~ 2-6 times nuclear density, “cold,” neutron rich, beta-equlibrium matter

Post-merger:

Moderate increase in density, temperatures up to ~ 50 MeV

Outflows:

Site of r-process; return to nuclear density/symmetry



GW170817: Observation of Gravitational Waves from a Binary Neutron Star Inspiral

LIGO/Virgo Scientific Collaborations Phys. Rev. Lett. 119 161101 (2017)

- Easiest to measure the inspiral "chirp mass":

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

- Why? Driver of changing frequency

$$\frac{df}{dt} \propto \left(\frac{G\mathscr{M}}{c^3}\right)^{5/3} f^{11/3}\left[1 + \ldots\right]$$

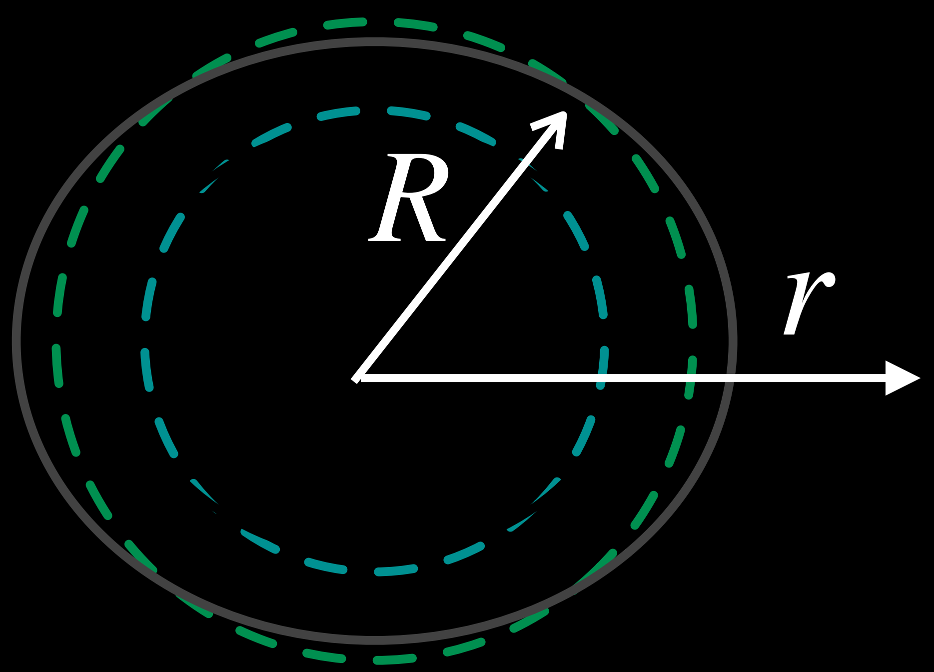
e.g. Cutler and Flangan, Phys. Rev. D 49, 2658 (1994)

Relativistic tides

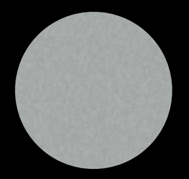
Leading order response of matter to a companion

- Deformability **defined** by linear perturbation of cold equilibrium star

  Ratio of quadrupole term $\sim \dfrac{1}{r^3}$ and external tidal term $\sim r^3$



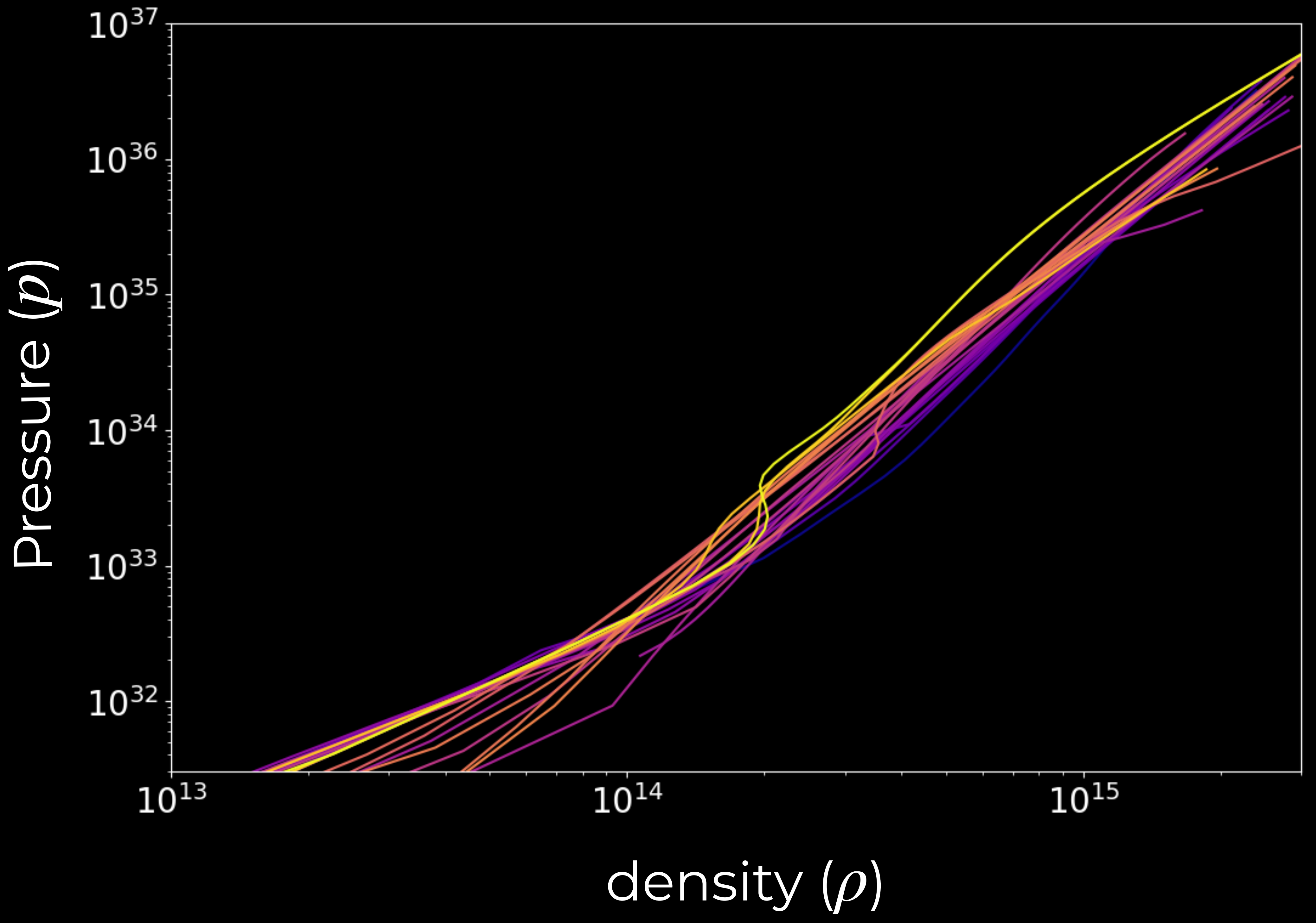
Dimensionless form: $$\Lambda_i = \frac{\lambda_i}{m_i^5} = \frac{2}{3} k_2 \left(\frac{R_i}{m_i} \right)^5$$



- *R* radius, *m* mass of star ⬅ *most EOS impact on tides*
- k_2 relativistic love number ≃ 0.05–0.15
  - Mass distribution inside the star (polarization), not surface deformation
  - $k_2 = 0$ for BH (discussion in literature)

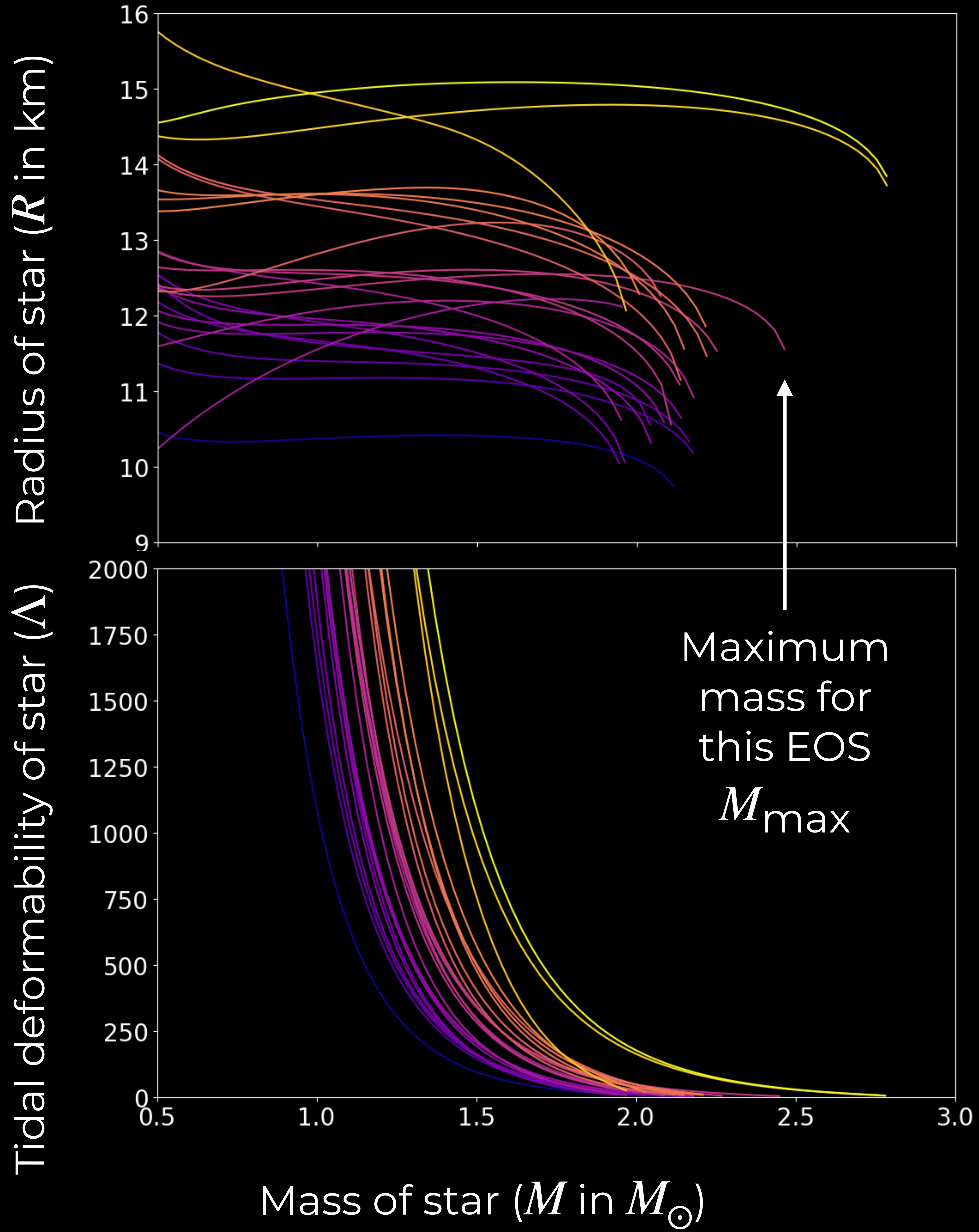
Dense matter imprint

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

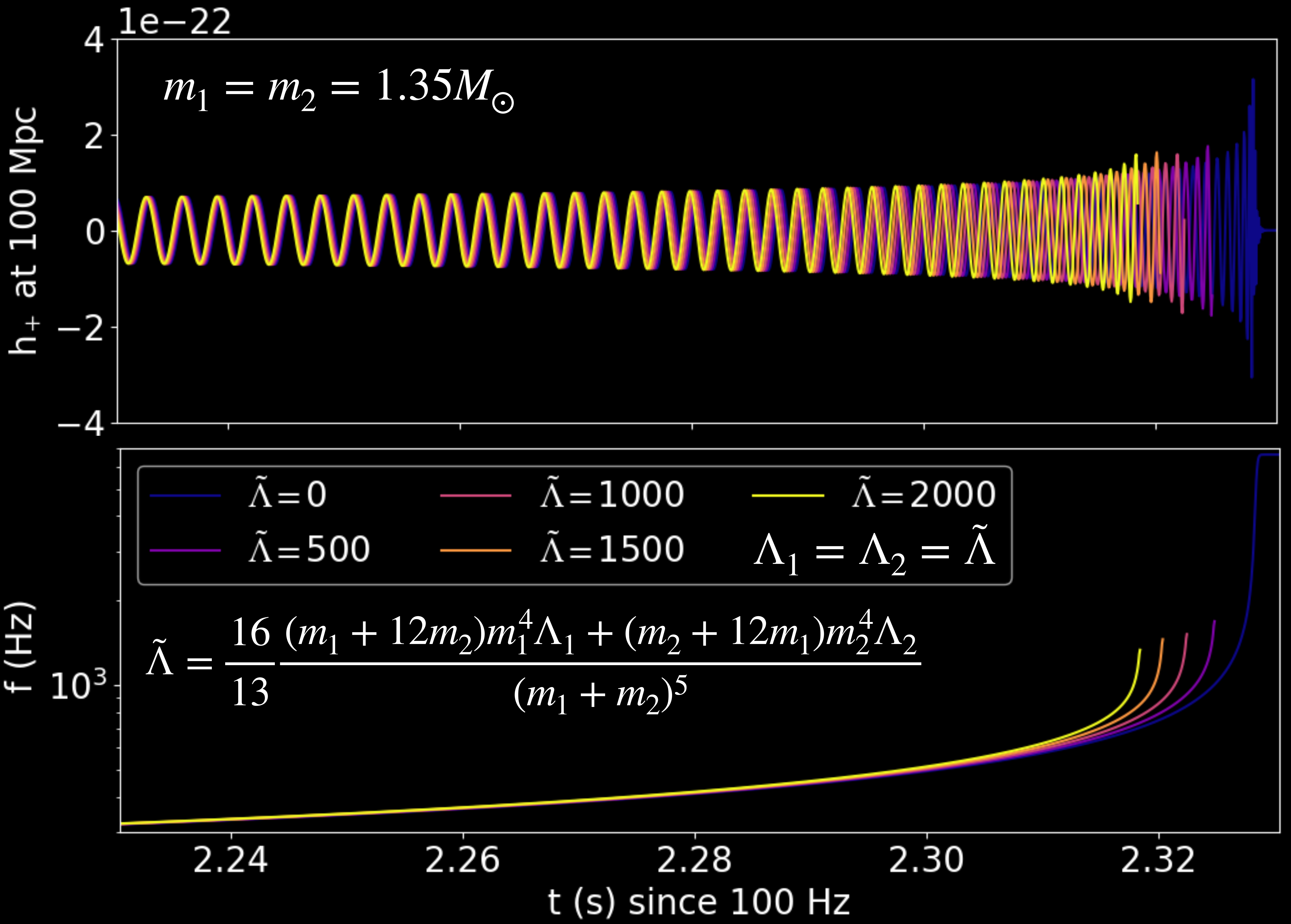
Matter signature in current models

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

Leading order coefficient $\tilde{\Lambda}$

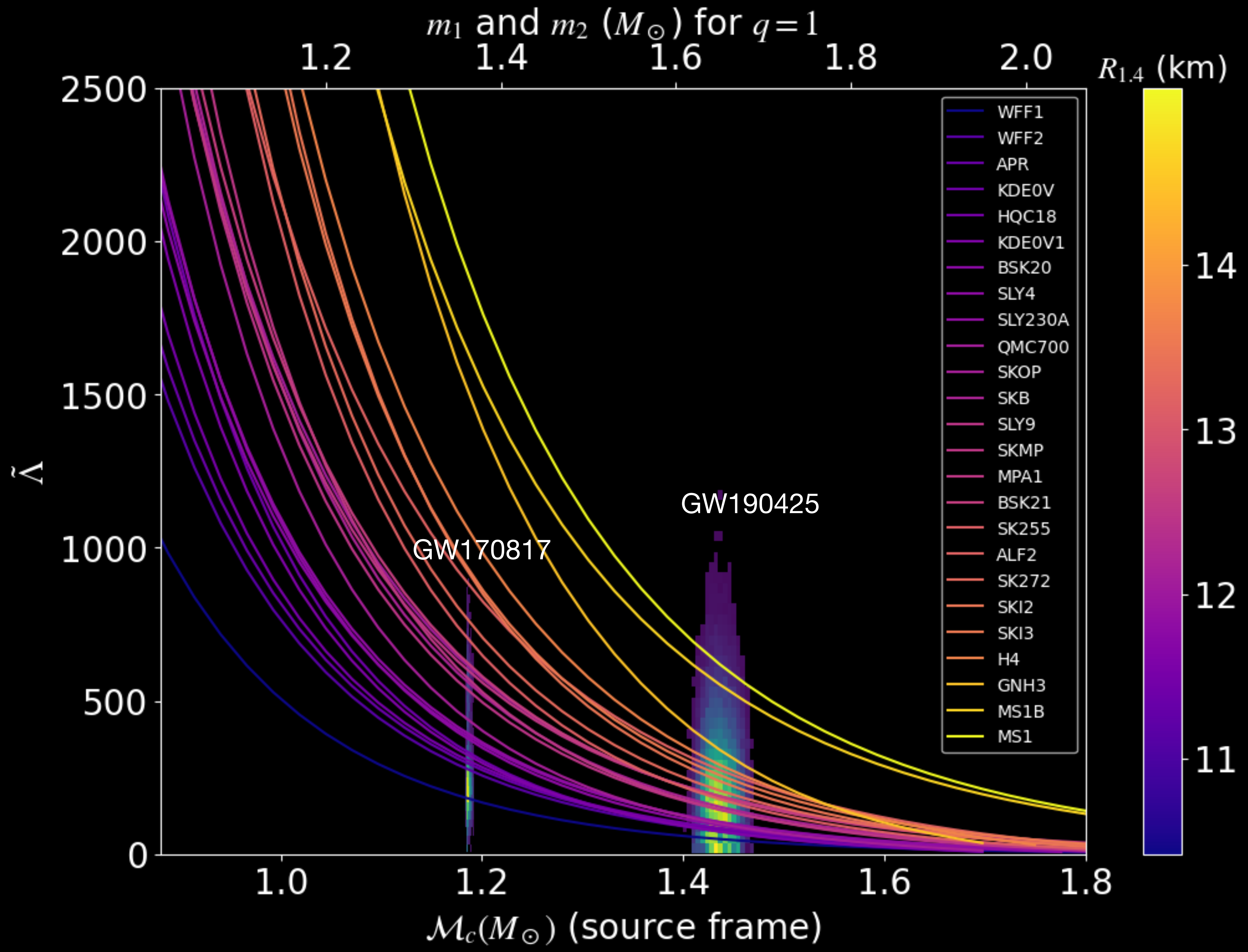
NR-calibrated/quasi-universal contributions from higher order terms, spin coupling, …

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 gravitational-wave observations



Joint constraint on chirp mass $\mathcal{M}$, combined tidal parameter $\tilde{\Lambda}$: coefficients of leading-order waveform effects

Cold NS EOS predictions:

$$\Lambda_i(m_i) \rightarrow \tilde{\Lambda}(\mathcal{M}, q)$$

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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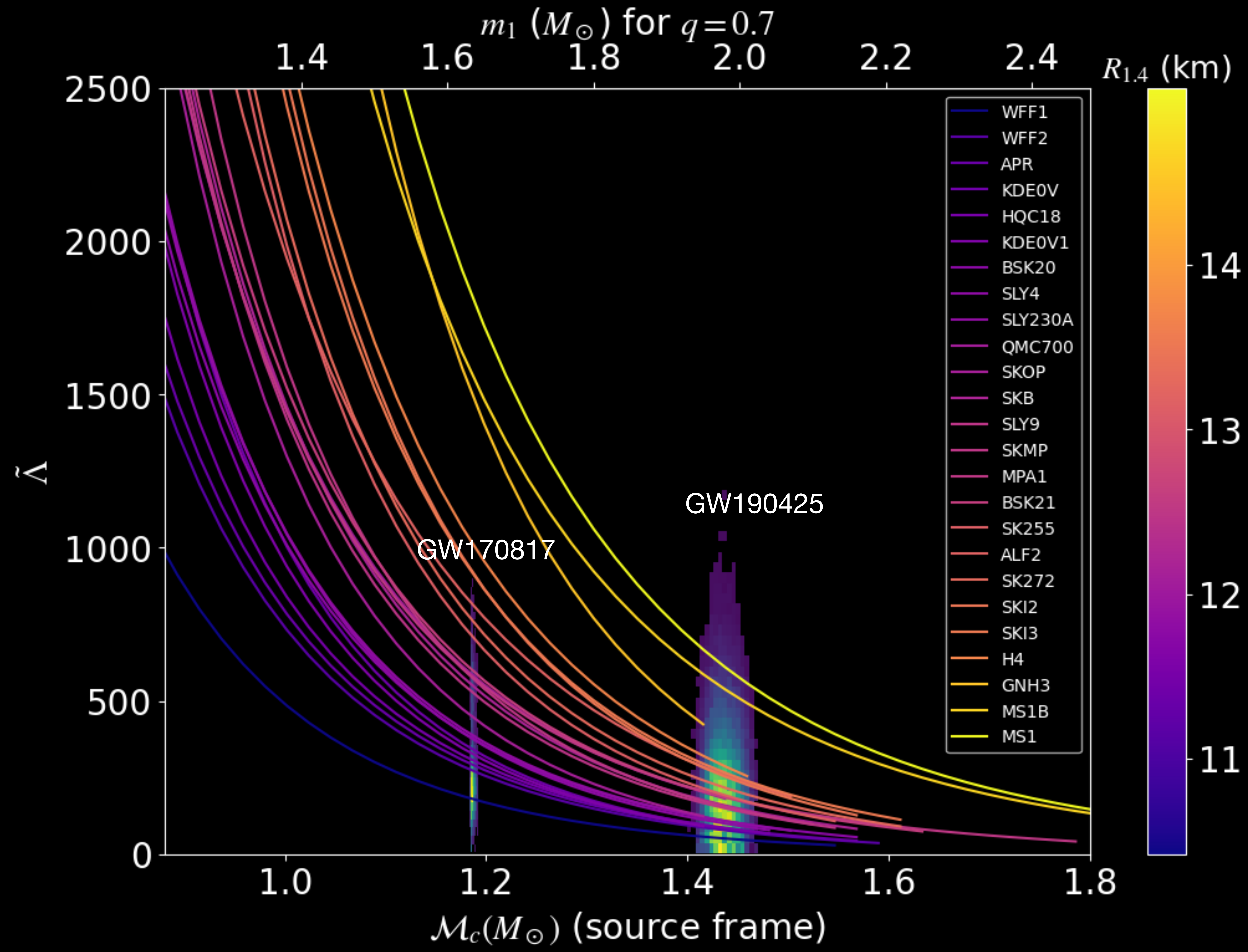

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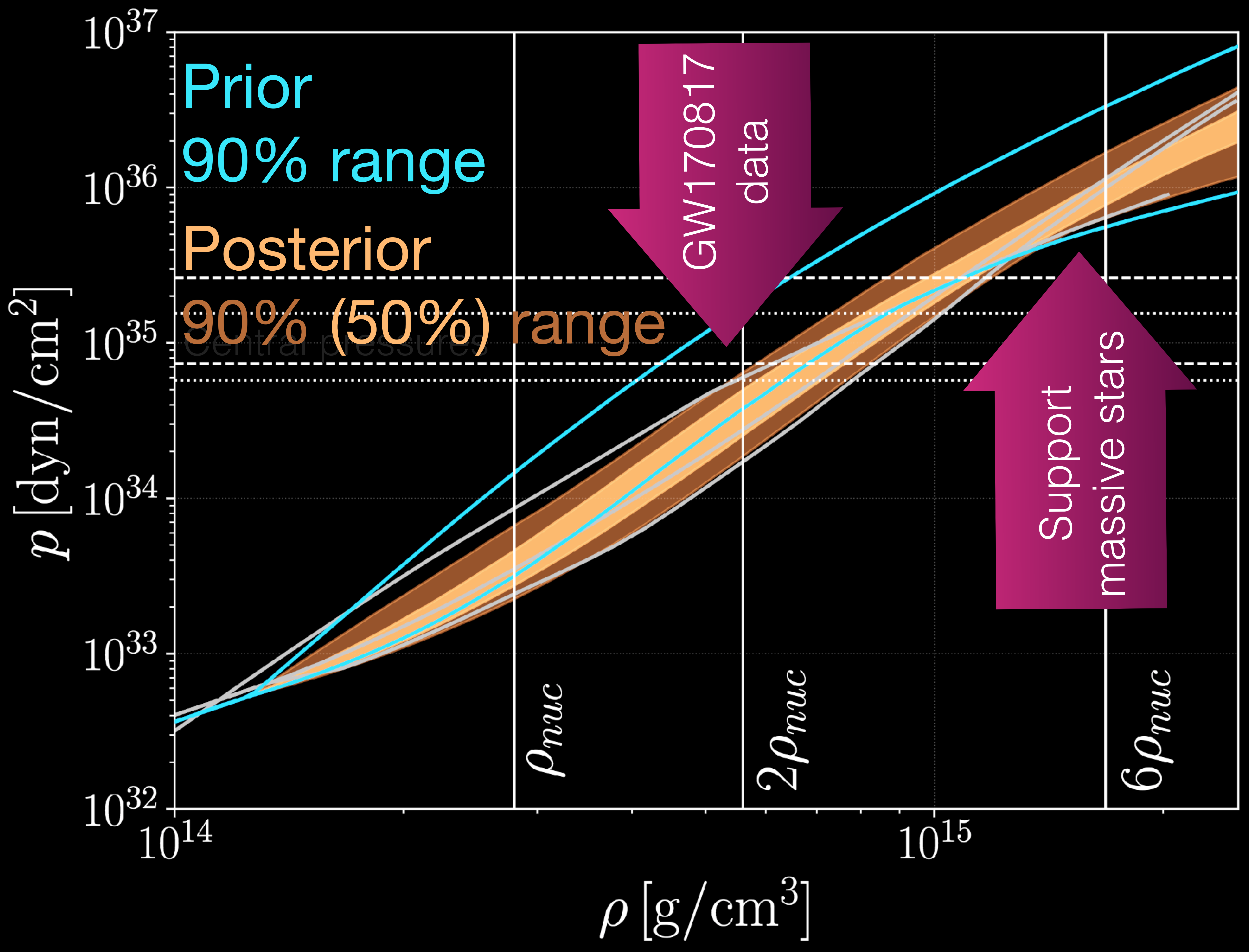
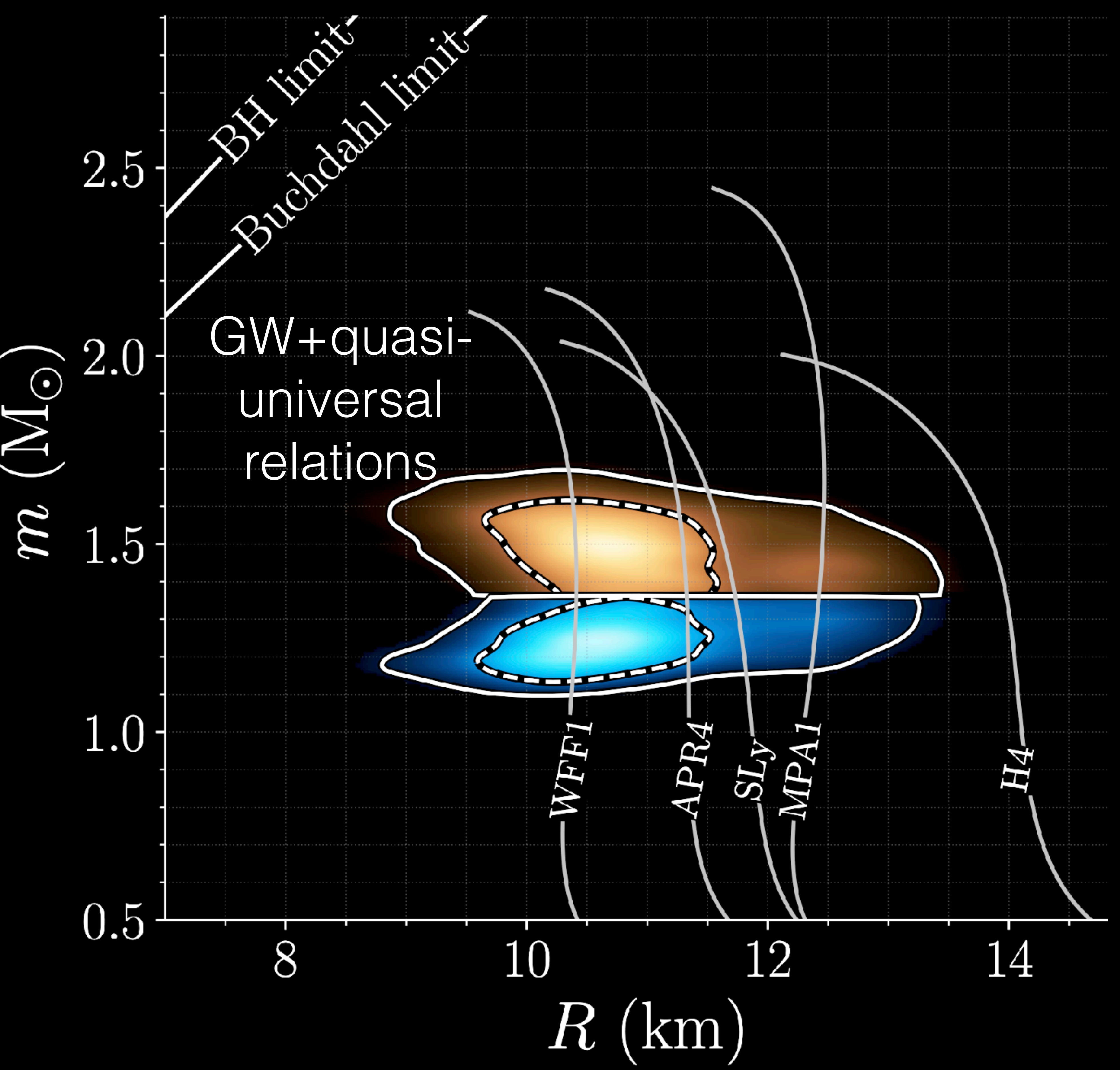
EOS+Radius implications in 2018: GW170817





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)

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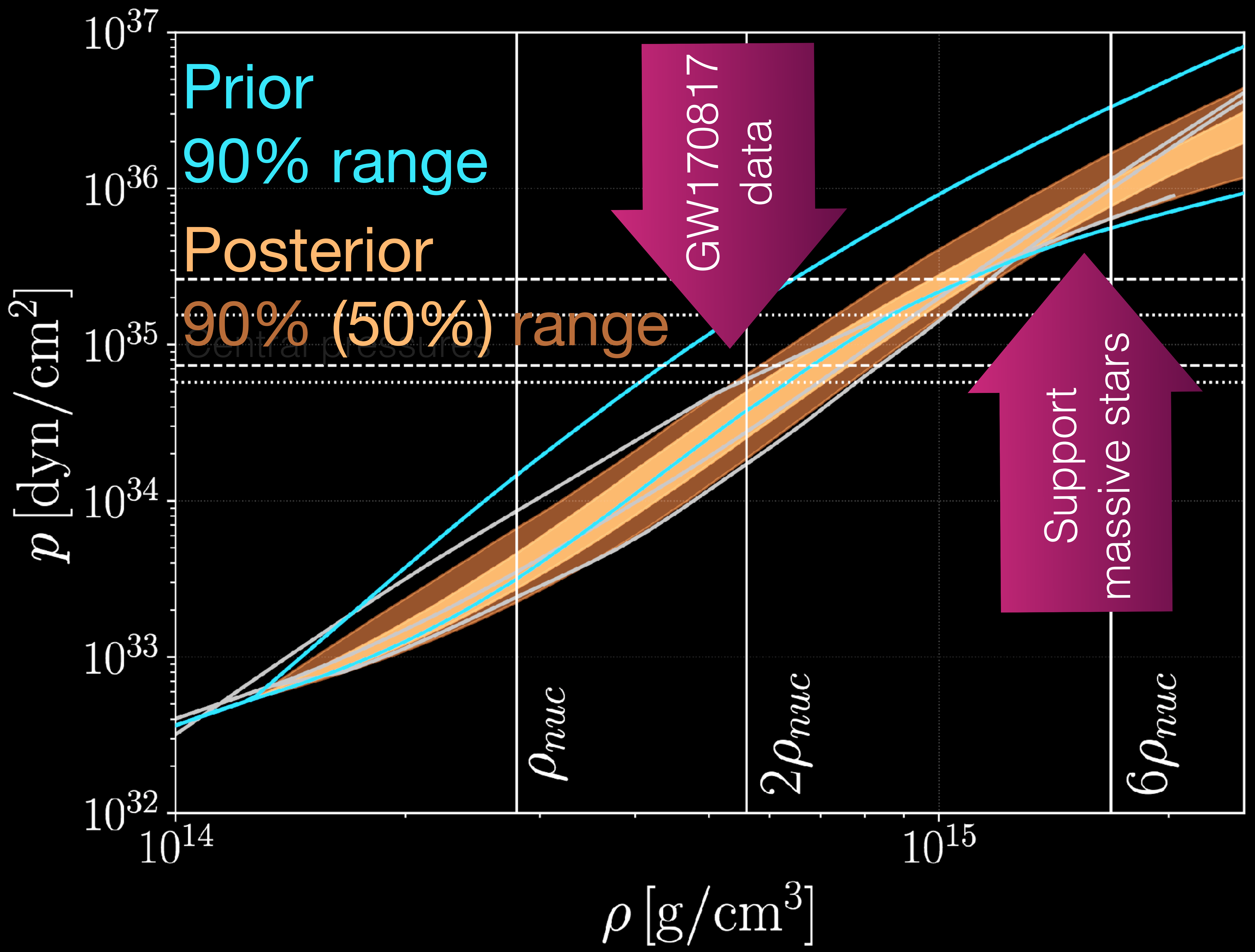

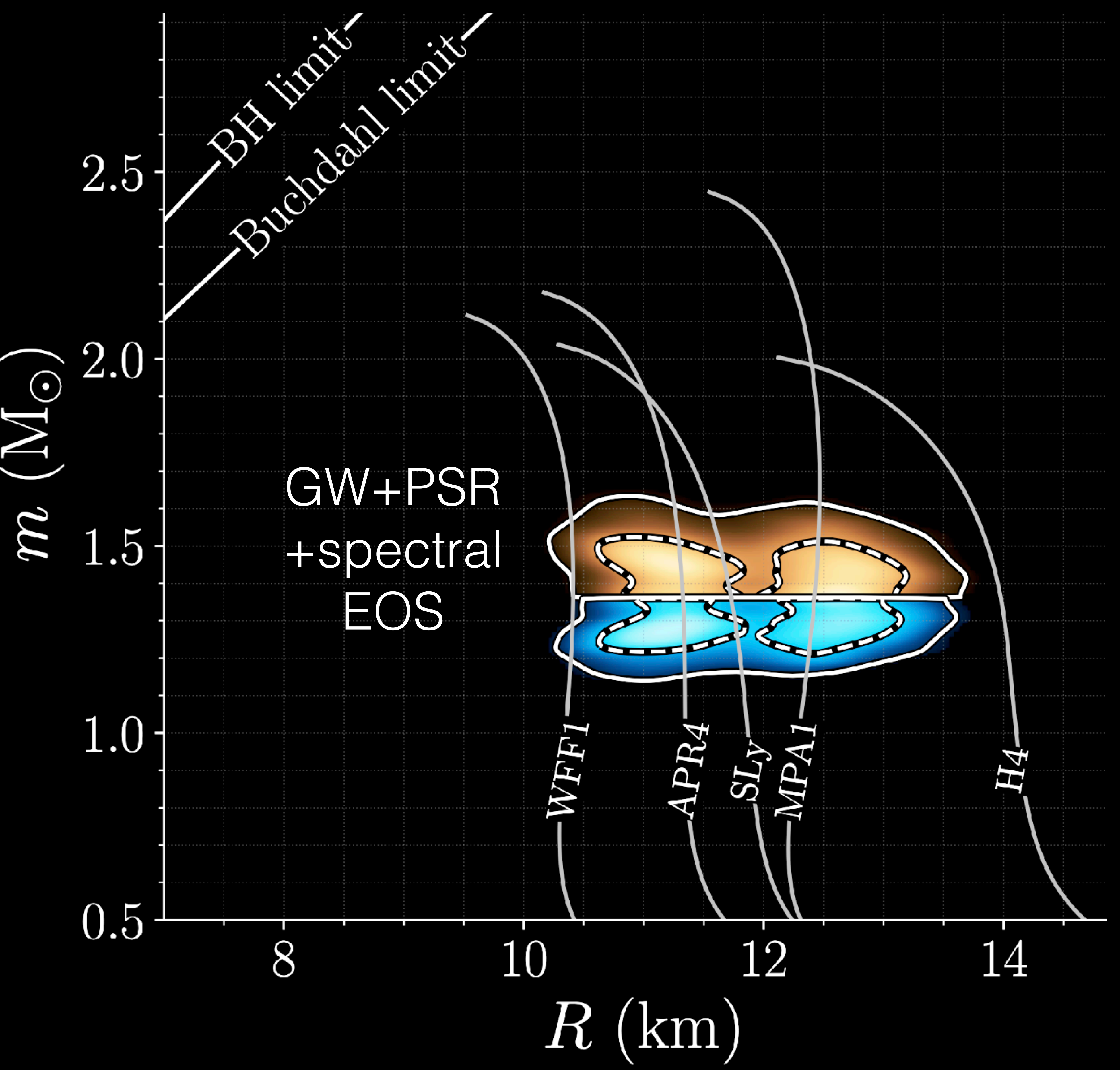

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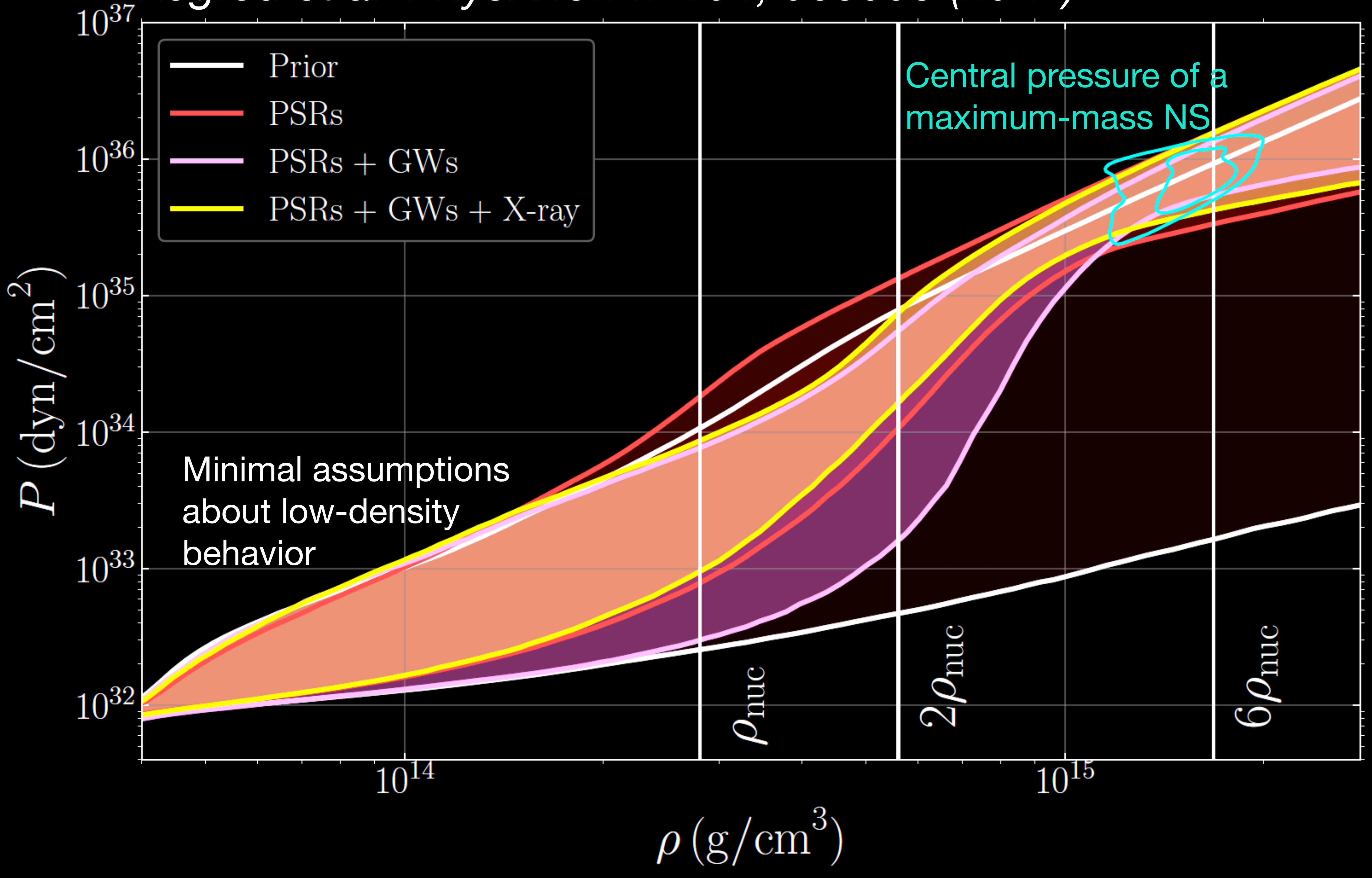
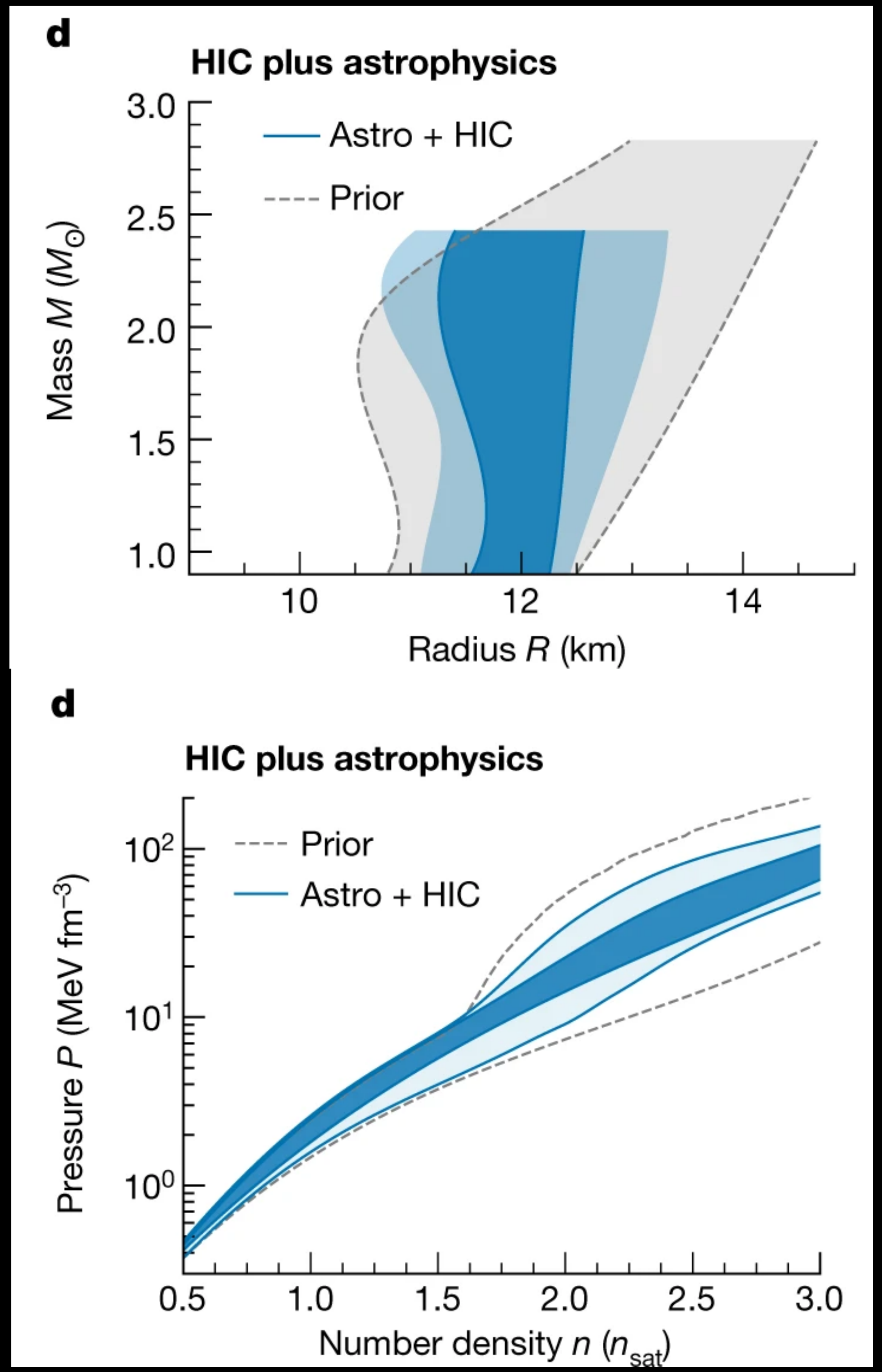
Modern Multimessenger inference: Combine Pulsars, GW, kilonova, NICER x-ray, Chiral EFT, heavy ion collison …

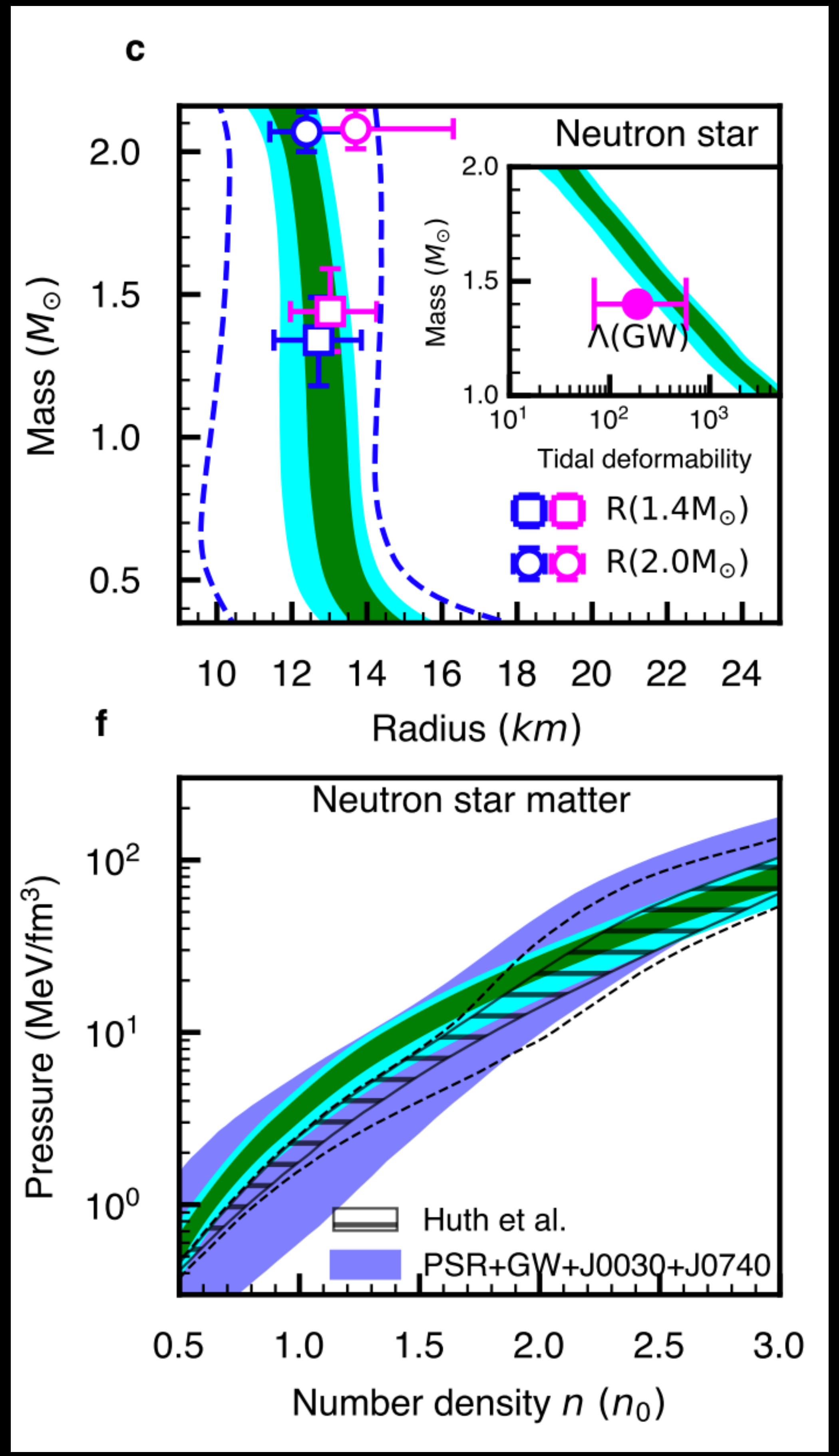
Astro-only constraint
Legred et al Phys. Rev. D 104, 063003 (2021)



Huth et al
Nature 606, 276–280 (2022)



Tsang et al 2310.11588

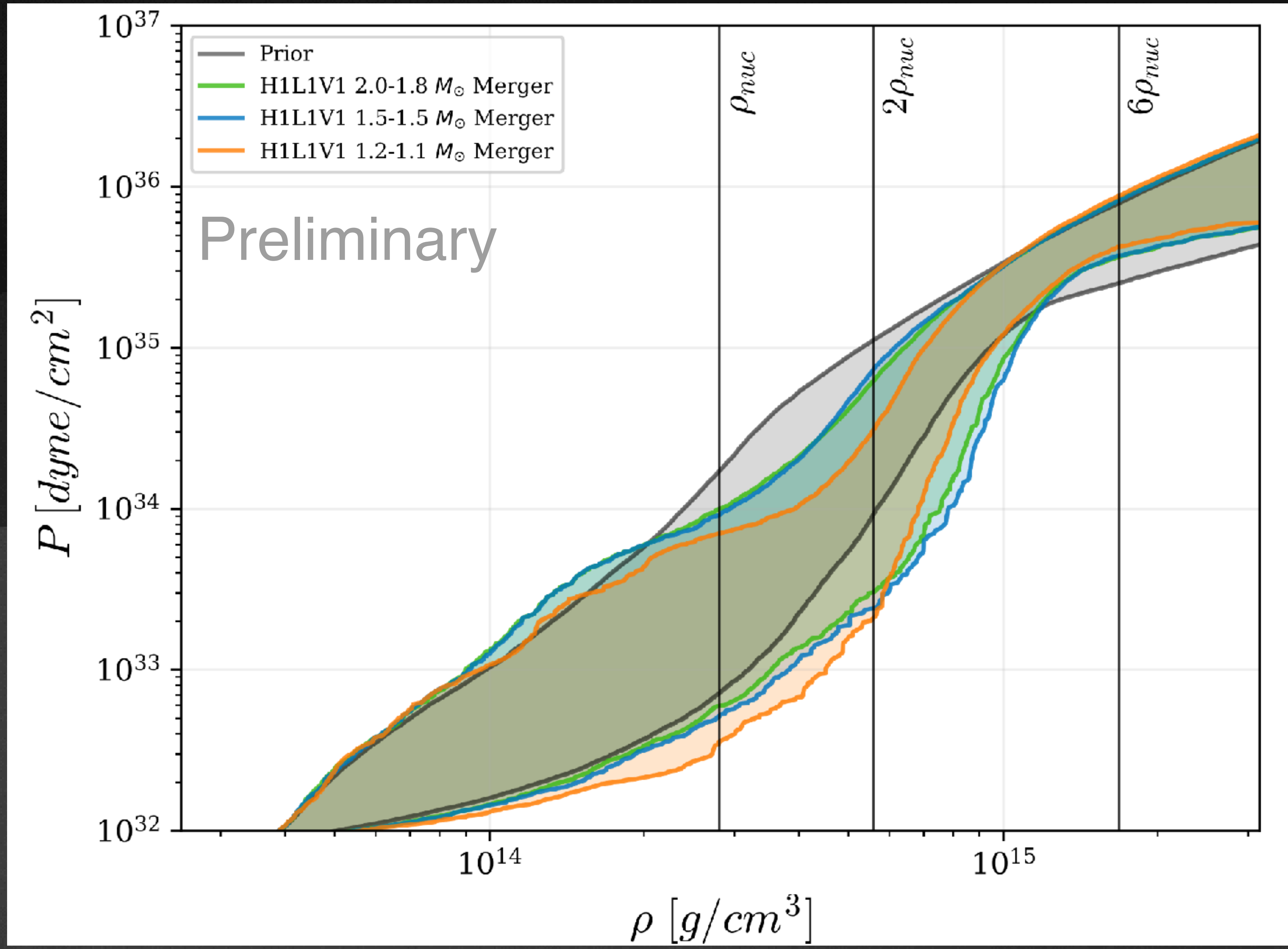


Gaussian-process-generated EOS posterior samples
https://zenodo.org/records/6502467

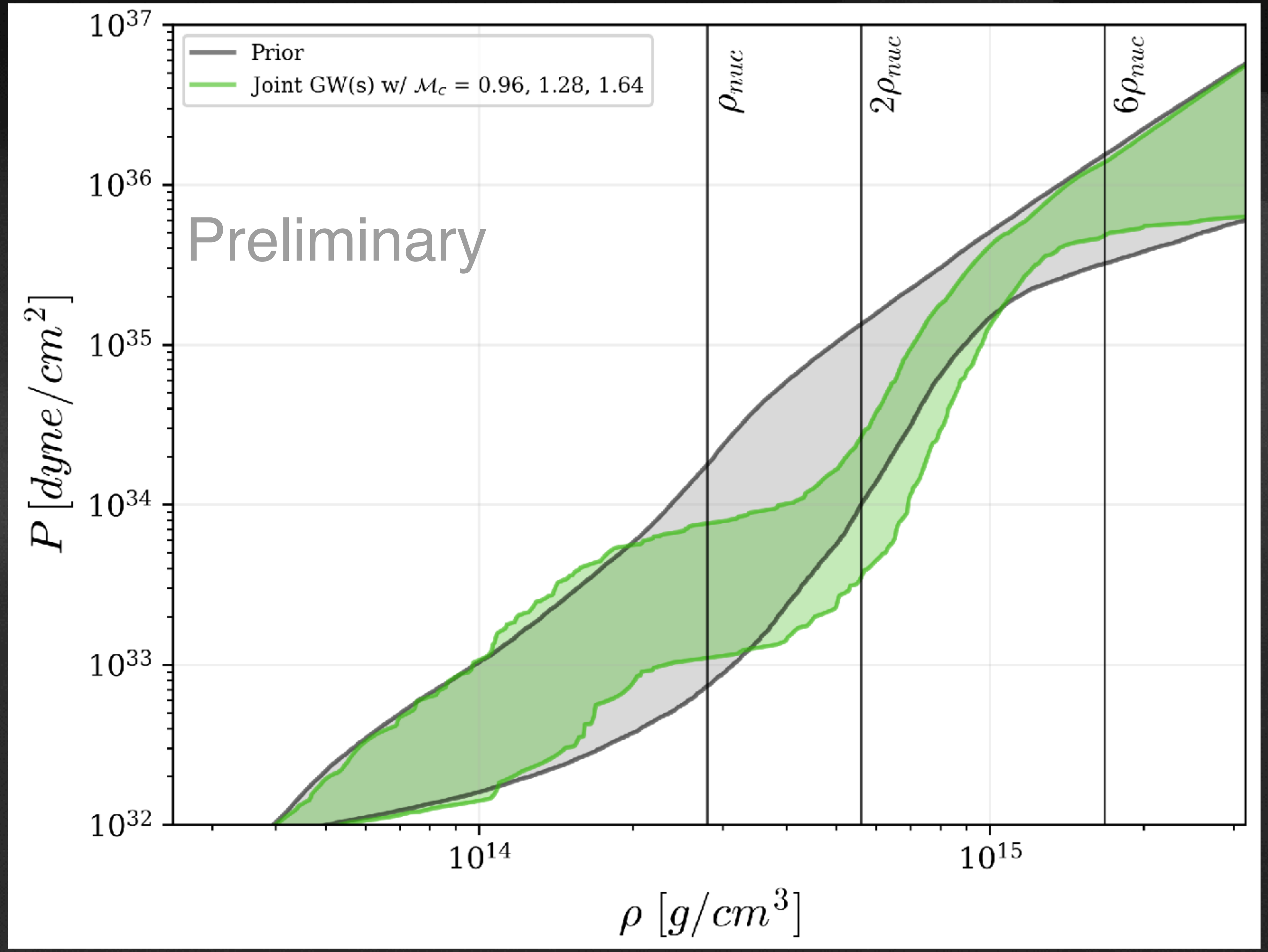
Plausible Constraints from LVK Network:

Simulated loud O4-O5 BNS events

Individual events

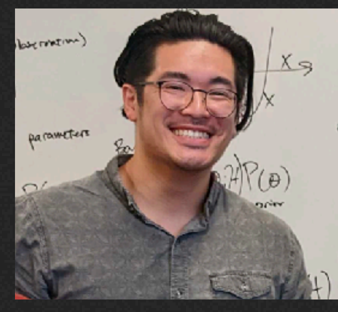


Joint constraint

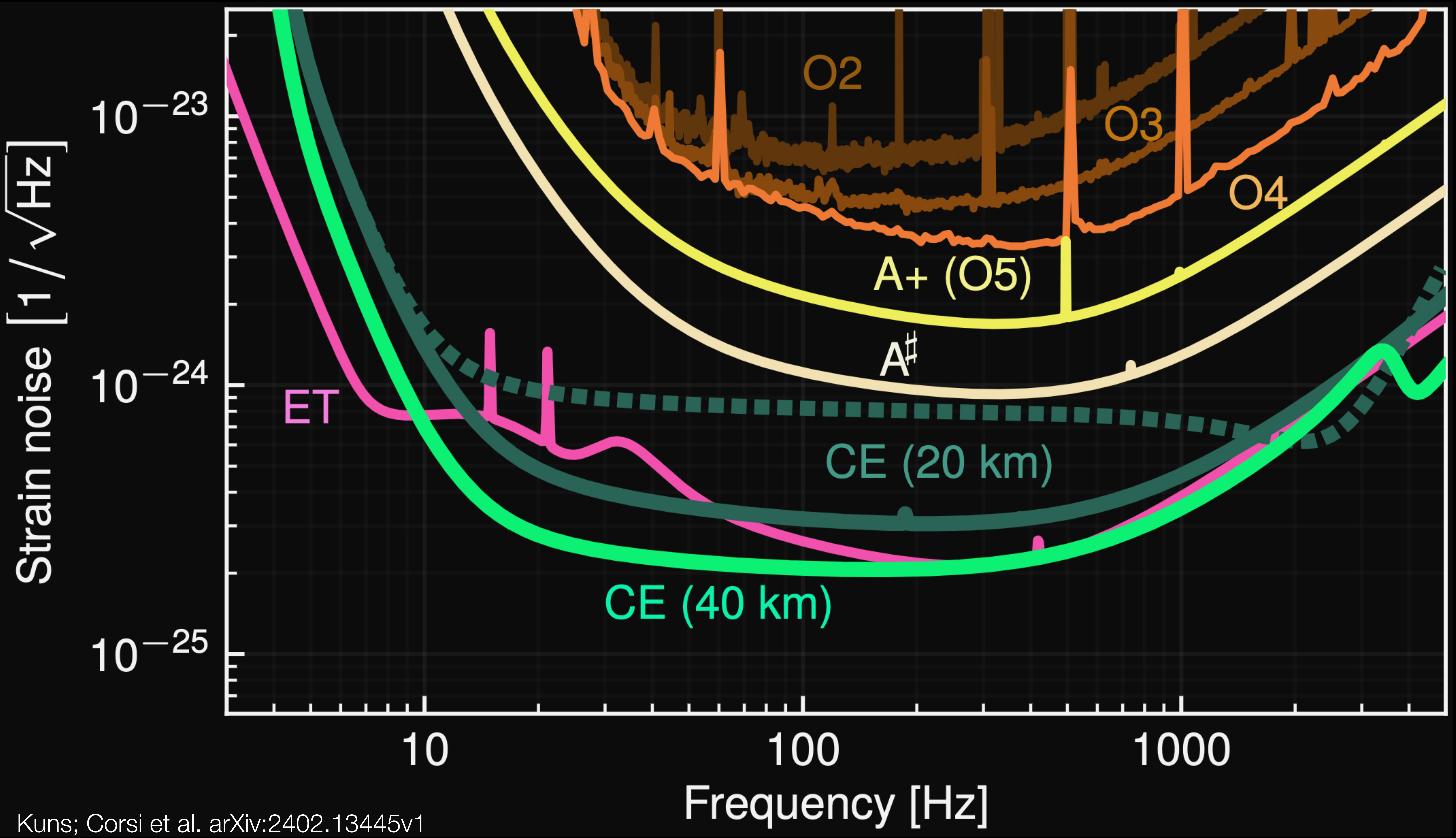


Likelihood weighting with nonparametric, Gaussian Process EoS prior conditioned on heavy pulsar masses, 3 loud (SNR>13) GW events at O4 sensitivity

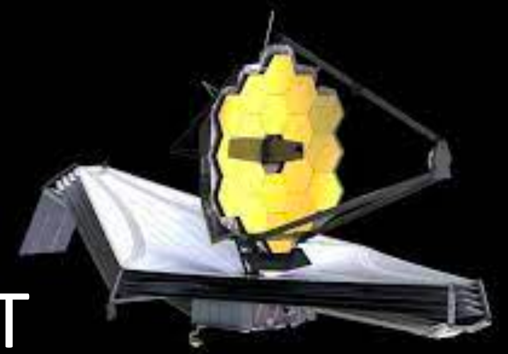
Wuchner, Ng, Landry, Read, in prep

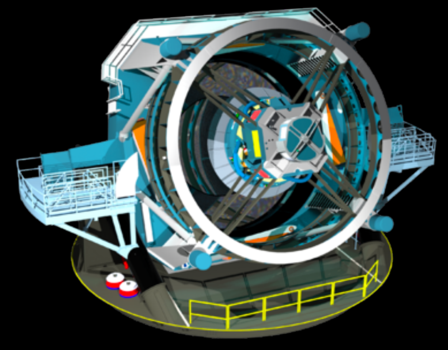


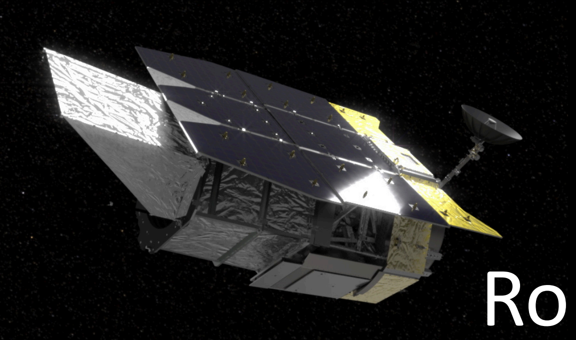
Towards the next generation



2023



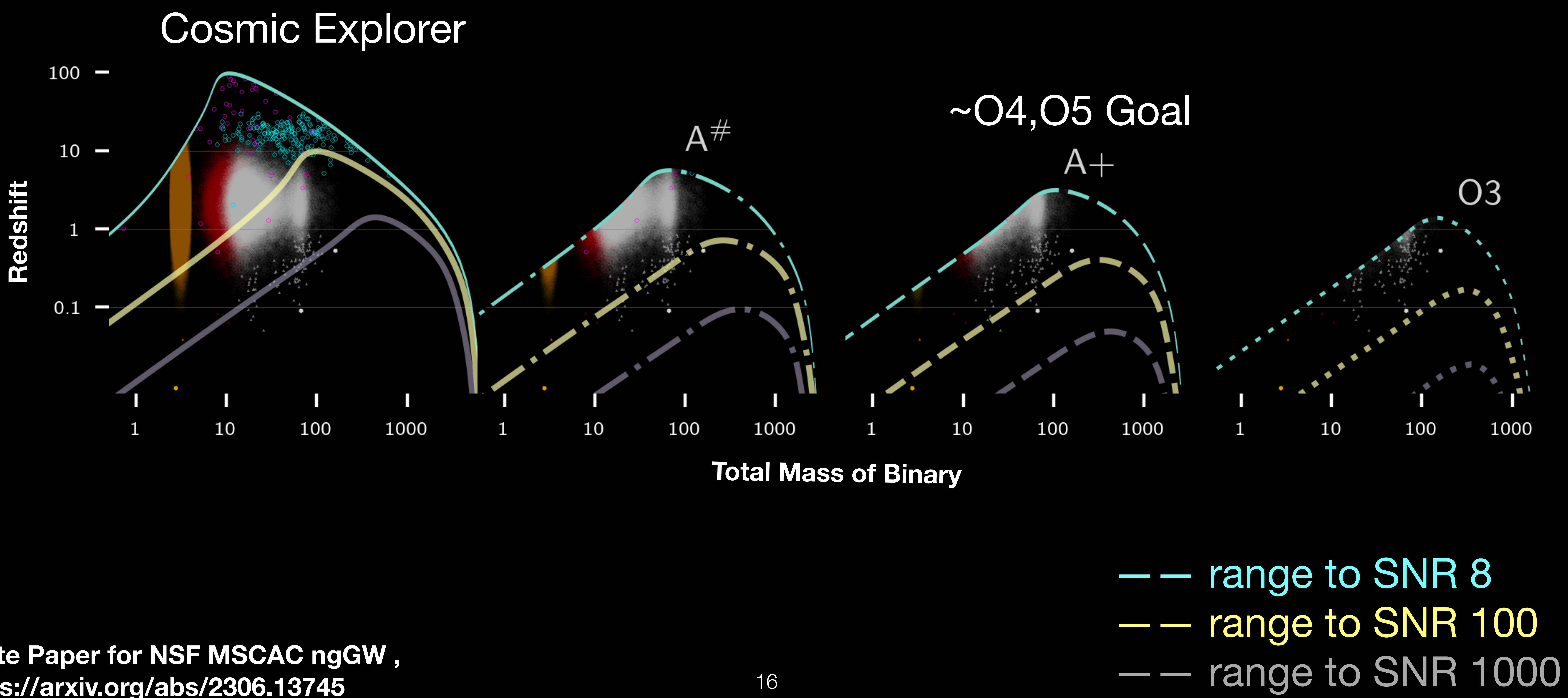




Next-generation (~2035)

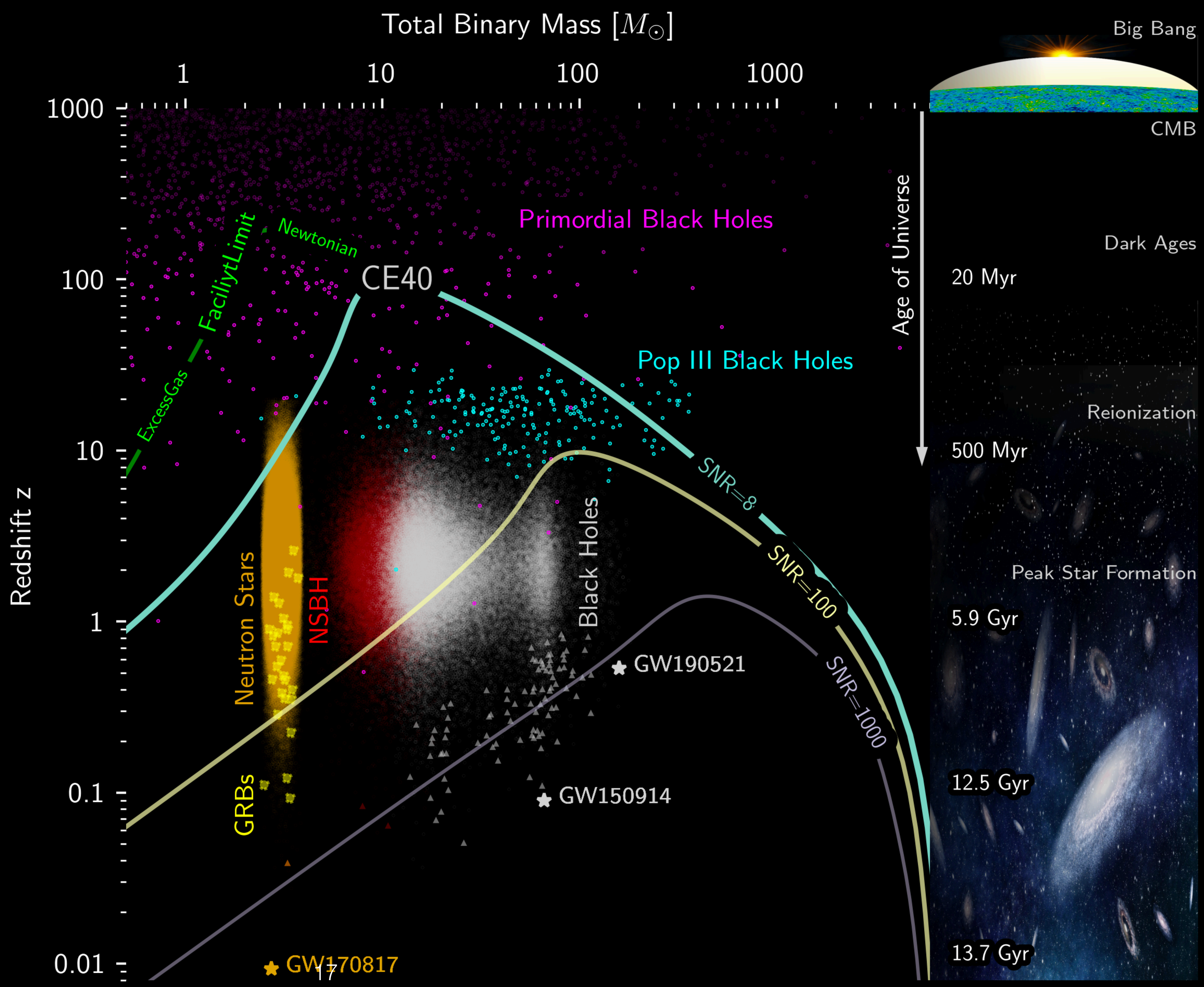
Kuns; Corsi et al. arXiv:2402.13445v1

Unveiling the GW Universe



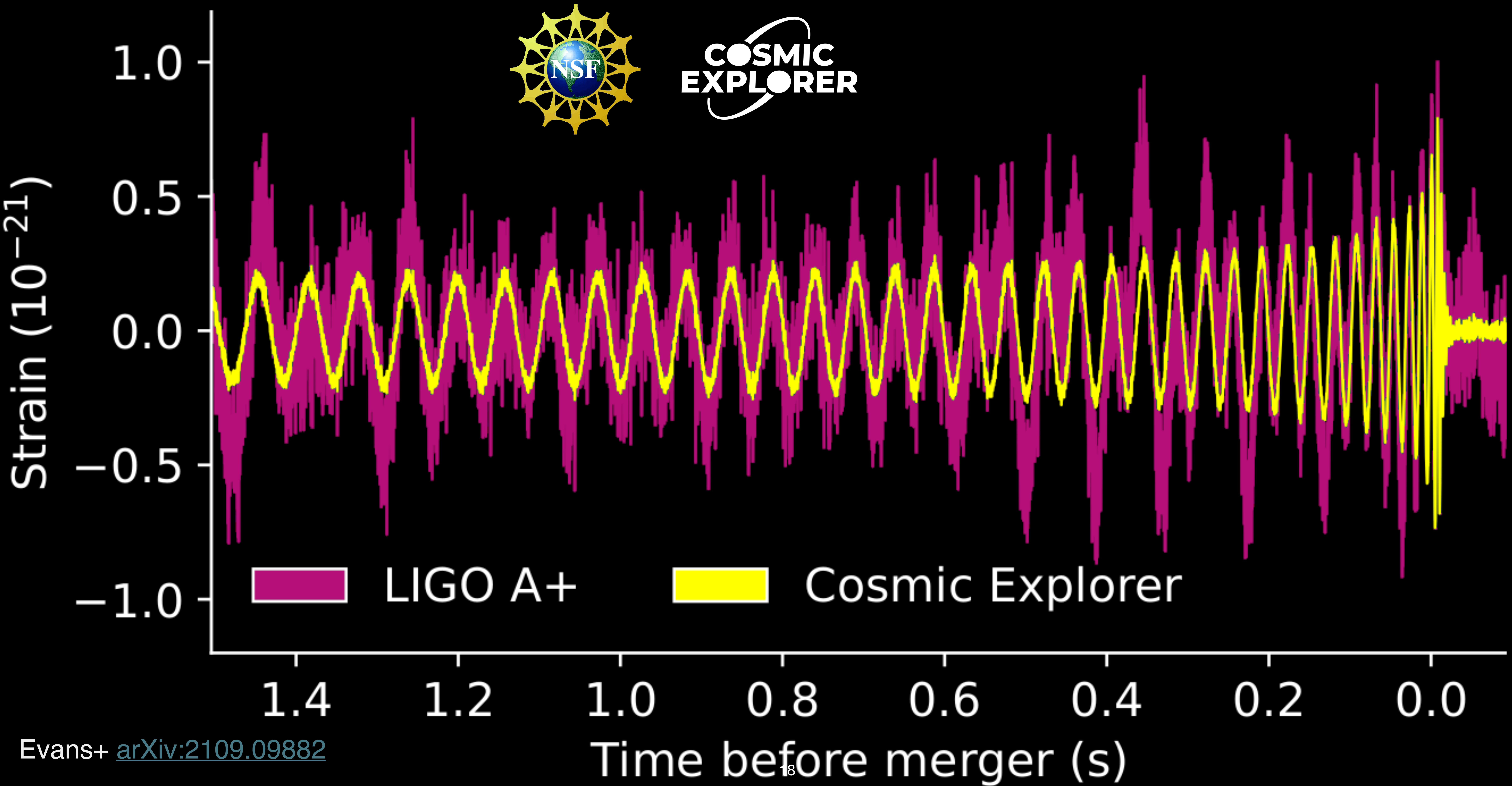
White Paper for NSF MSCAC ngGW ,
https://arxiv.org/abs/2306.13745

XG Universe



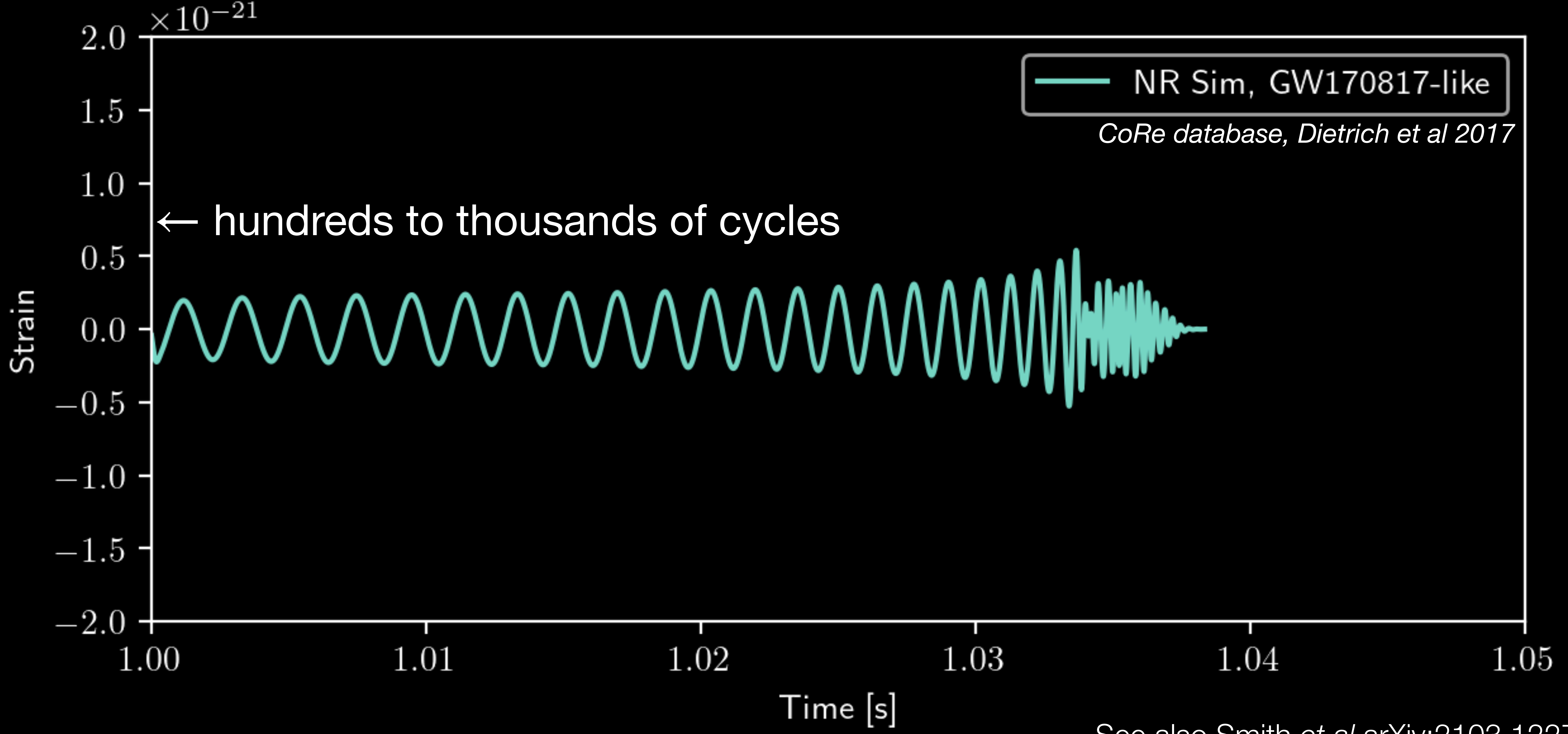
White Paper for NSF MSCAC ngGW , https://arxiv.org/abs/2306.13745
Site evaluation and design funded by NSF starting 2023

GW150914 as XG would record it



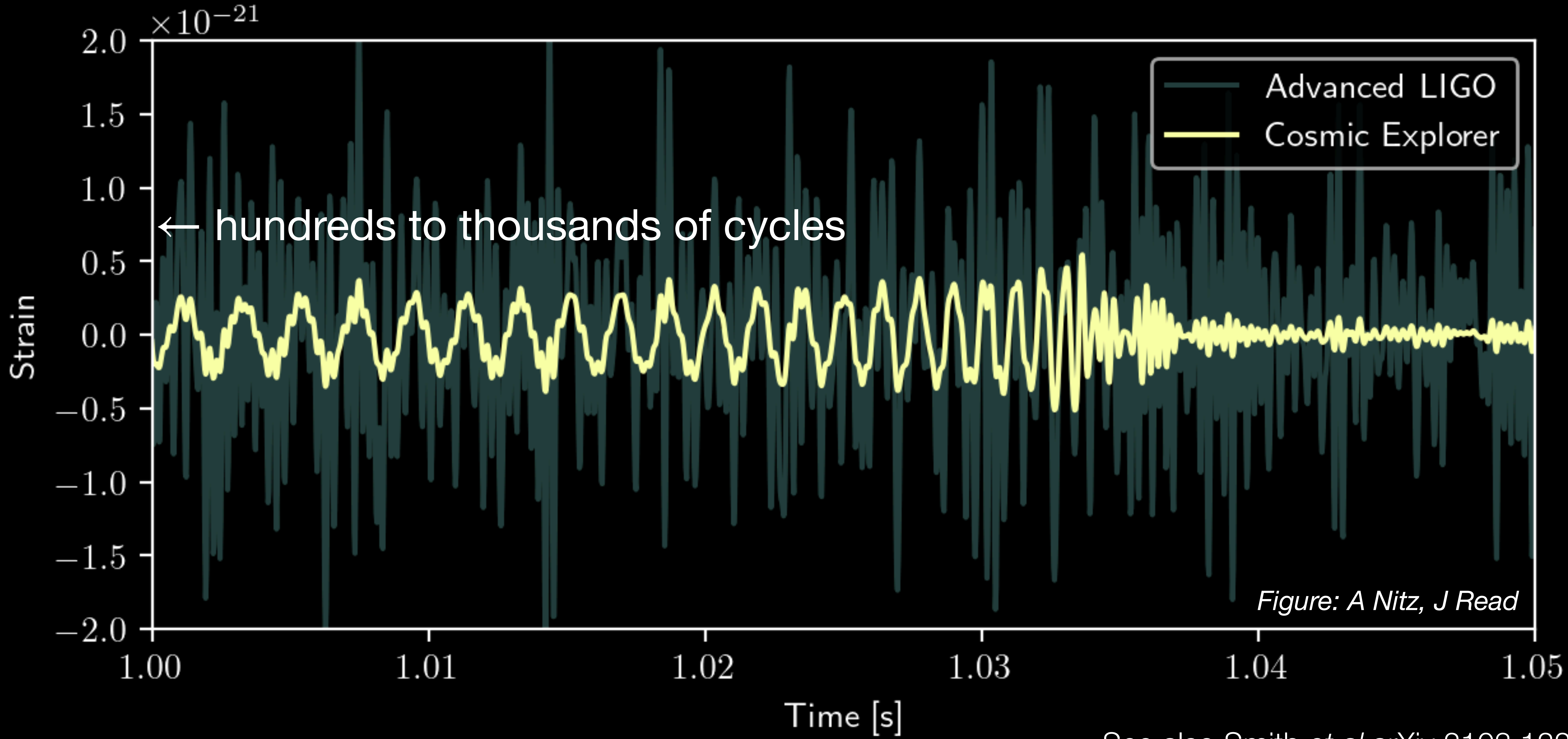
Evans+ arXiv:2109.09882

GW170817 as XG would record it



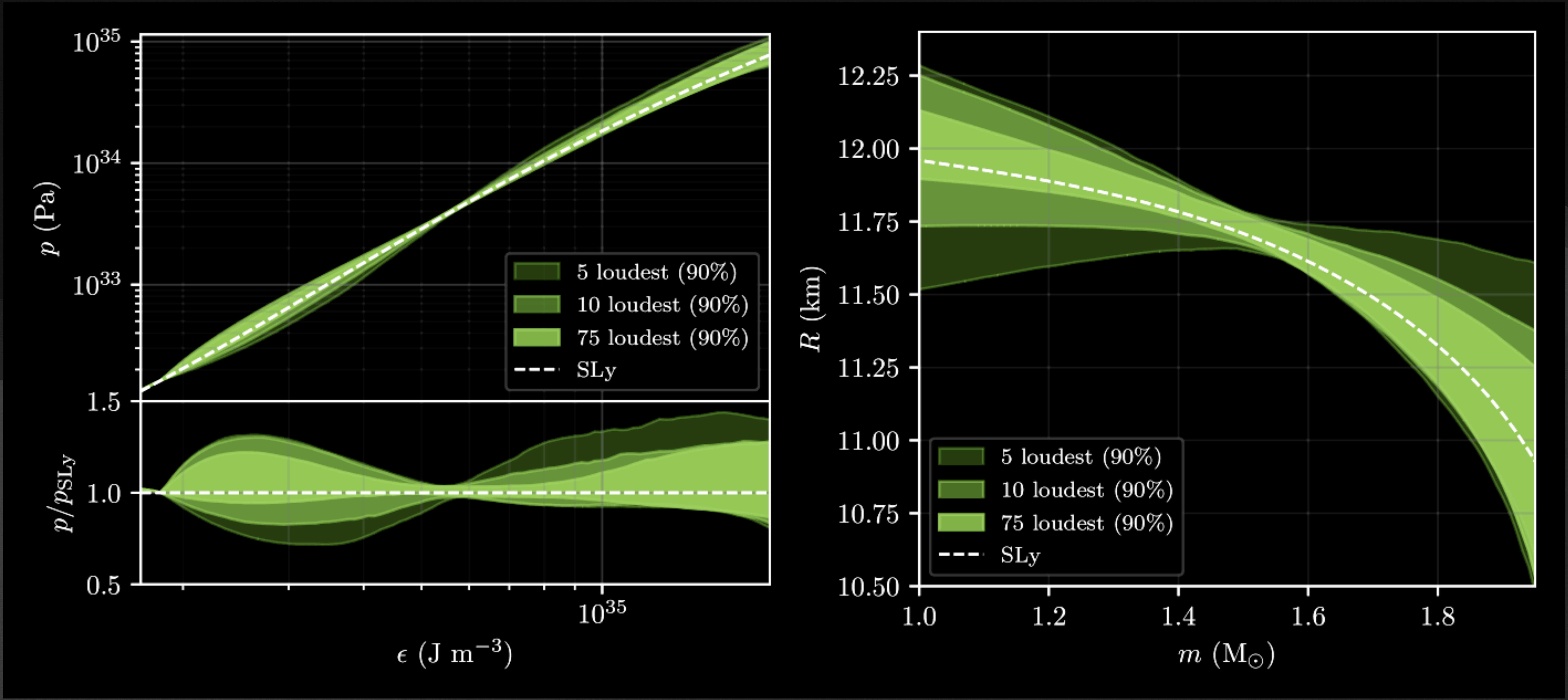
See also Smith *et al* arXiv:2103.12274

GW170817 as XG would record it



See also Smith *et al* arXiv:2103.12274

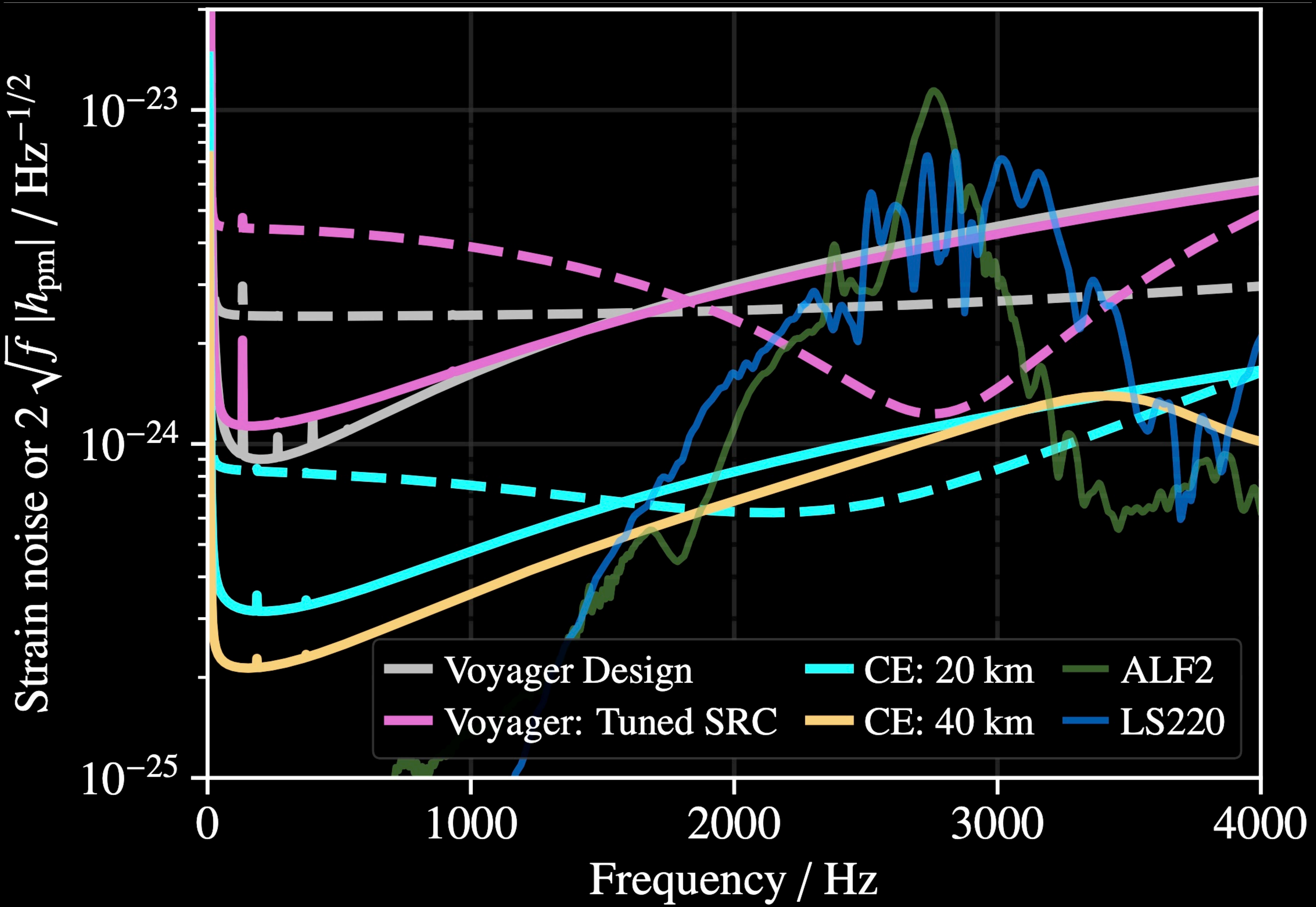
Potential XG EOS Constraint



NS masses ~ 1.4 $M_\odot$, spectral parameterized EOS with fixed crust

Walker et al arXiv:2401.02604

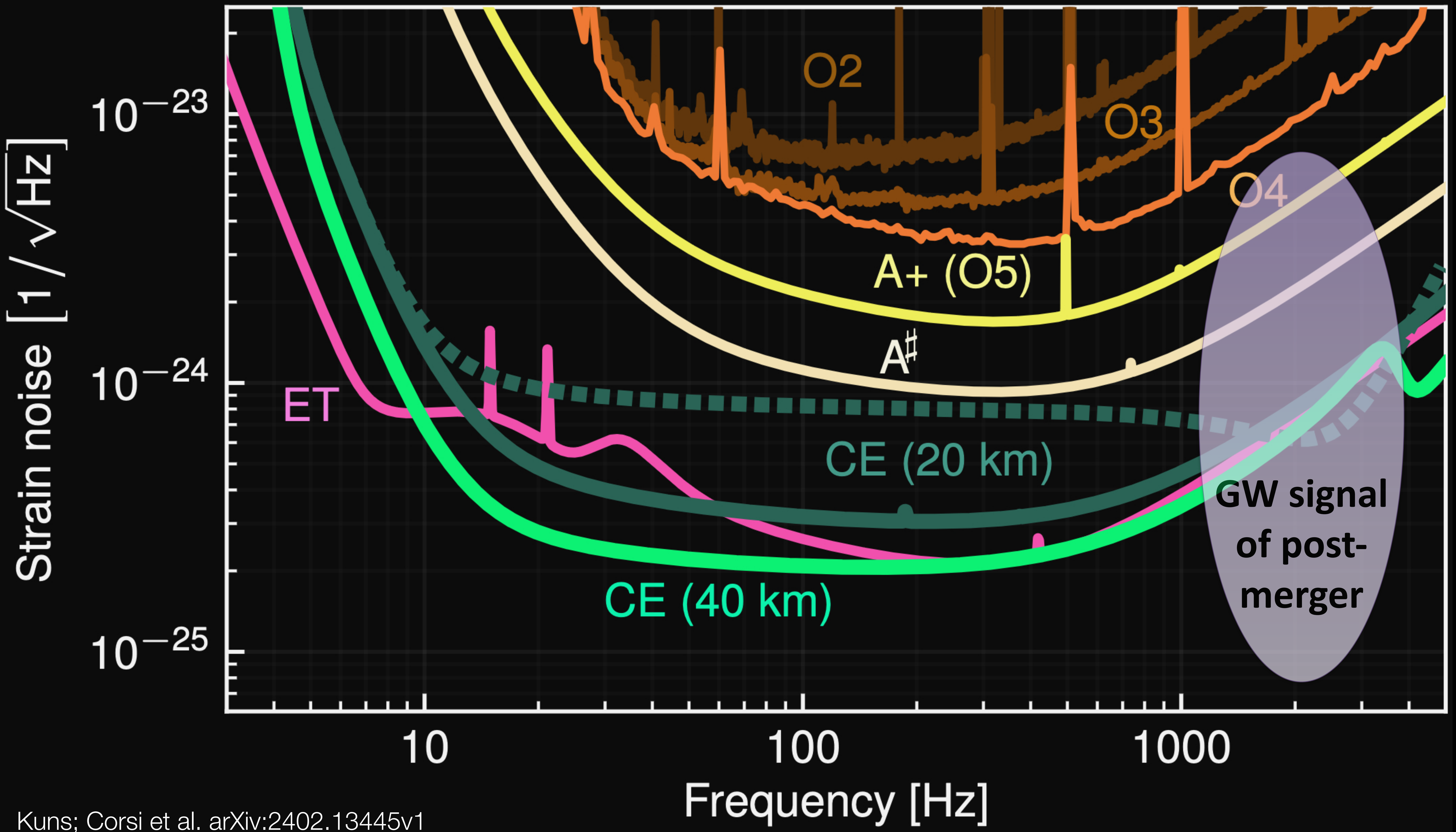
Post-merger GW?



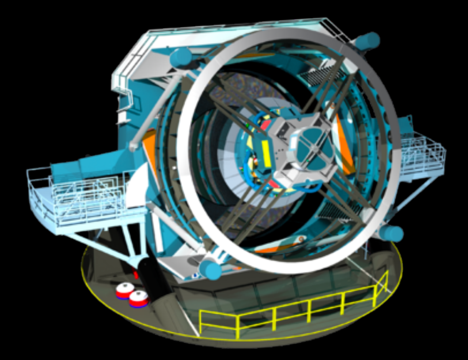
- burst follow-up to measure post-merger signals
- Future observatories aim for ~10s-100 post-merger GW detected / year

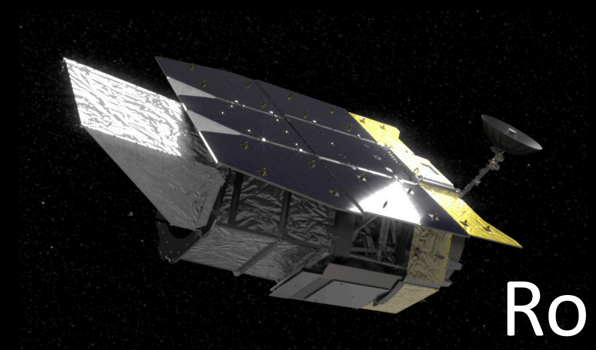
Srivastava et al (incl J Read) 2022 *ApJ* **931** 22 arXiv:2201.10668

Towards the next generation



2023



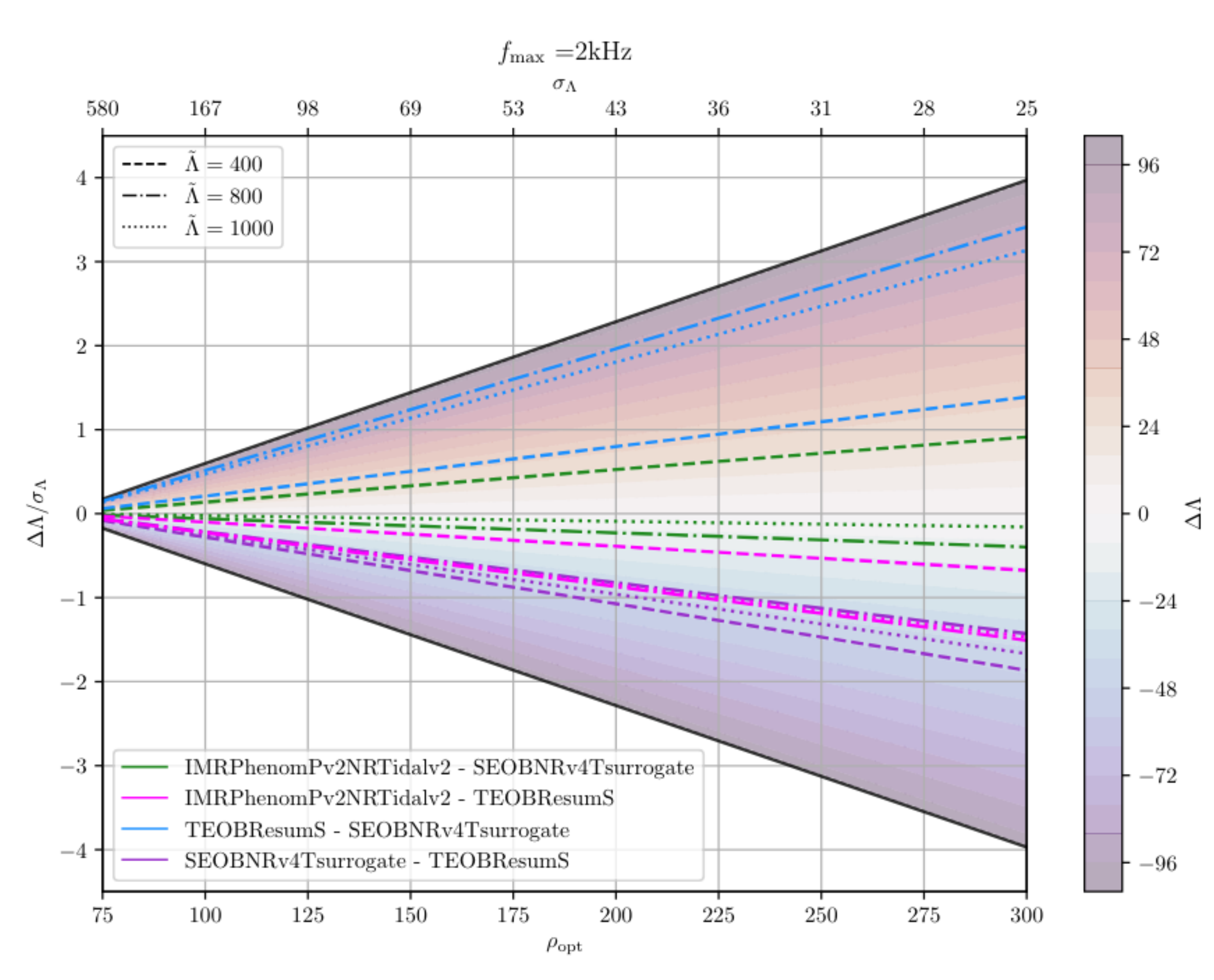


Next-generation (~2035)

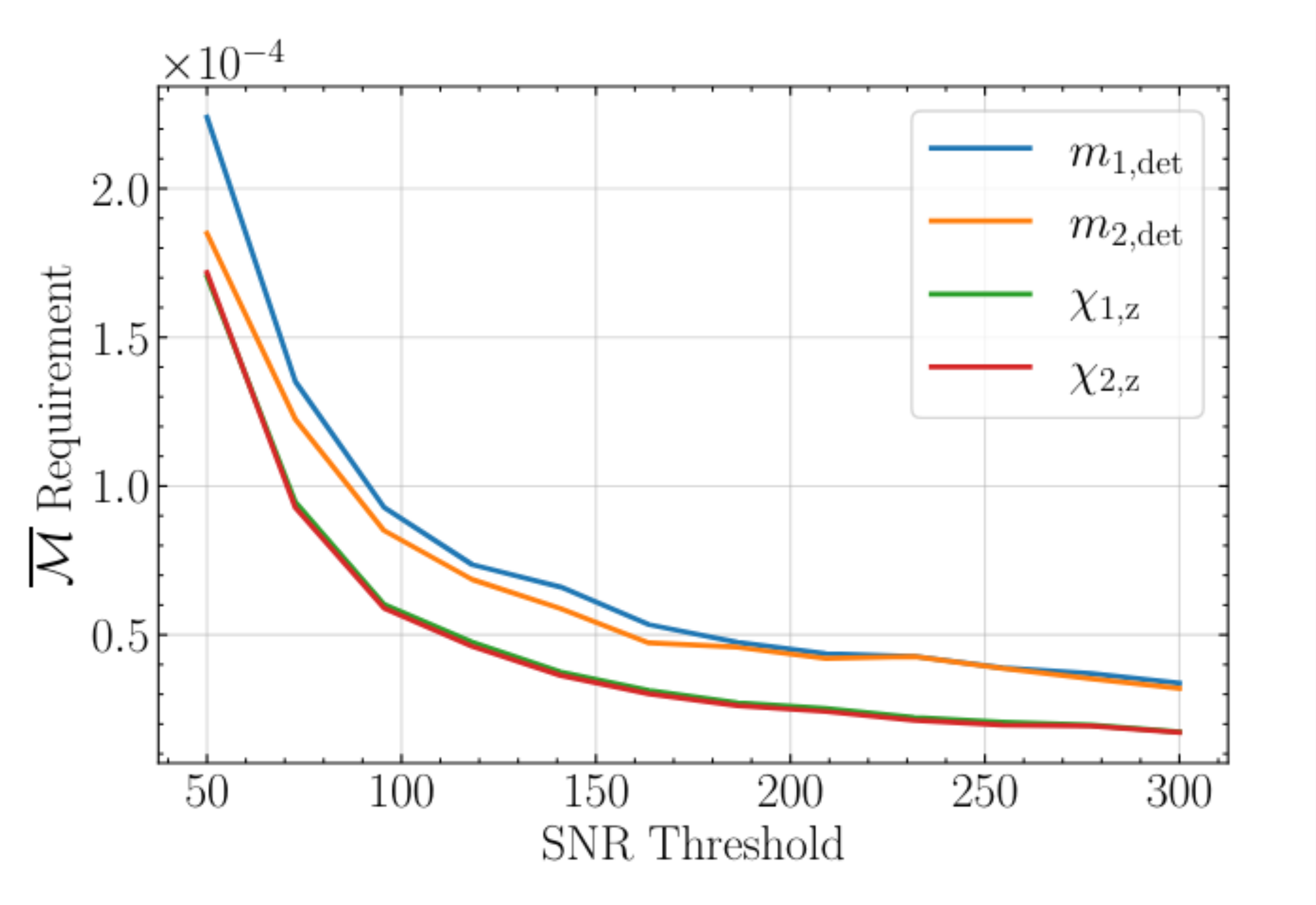
Kuns; Corsi et al. arXiv:2402.13445v1

Waveform systematics impact

A#/Virgo nEXT SNRs enter 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

Part 2. Quantifying and interpreting gravitational waveform error

Inference from GW observations

- $\boldsymbol{d}$ data $= \boldsymbol{h}$ signal $+ \boldsymbol{n}$ noise
- Power spectral density of noise $S_n(f)$:

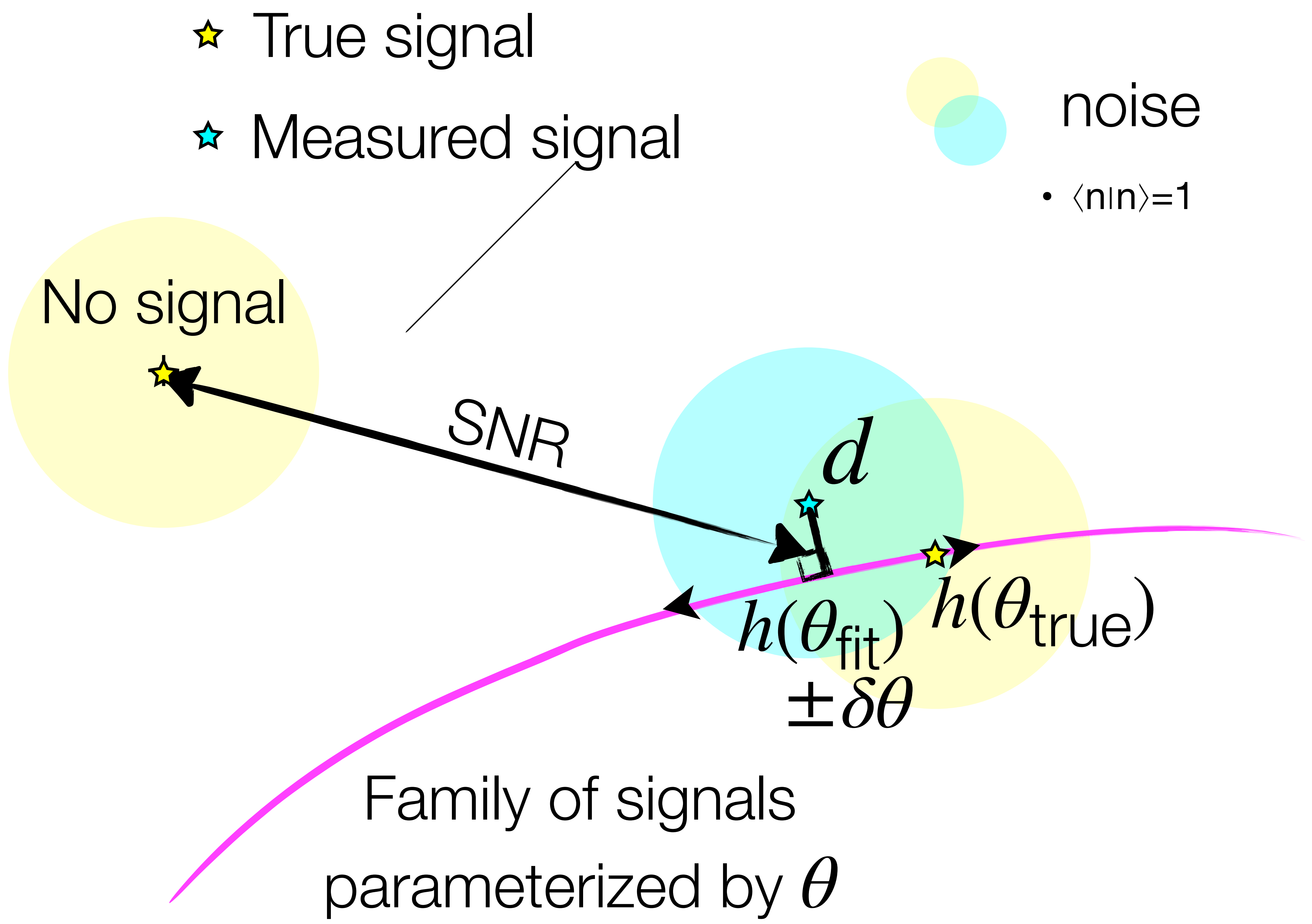
$$\mathscr{L}(\boldsymbol{n}) \propto \exp\left(-\sum_i 2\Delta f \frac{|n_i|^2}{S_n(f_i)}\right)$$

- Likelihood of data given a candidate signal :

$$\mathscr{L}(\boldsymbol{d}|\boldsymbol{h}) \propto \exp\left(-\sum_i 2\Delta f \frac{|d_i - h_i|^2}{S_n(f_i)}\right)$$

$$= \exp\left(-\langle \boldsymbol{d}-\boldsymbol{h}, \boldsymbol{d}-\boldsymbol{h}\rangle\right)$$

- Inner product in Fourier space; $\langle \boldsymbol{n}, \boldsymbol{n}\rangle = 1$



Sources of systematics

- e.g. Vitale et al 2012 Phys. Rev. D **85**, 064034, Ling Sun et al 2020 Class. Quantum Grav. 37 225008, Essick Phys. Rev. D 105, 082002

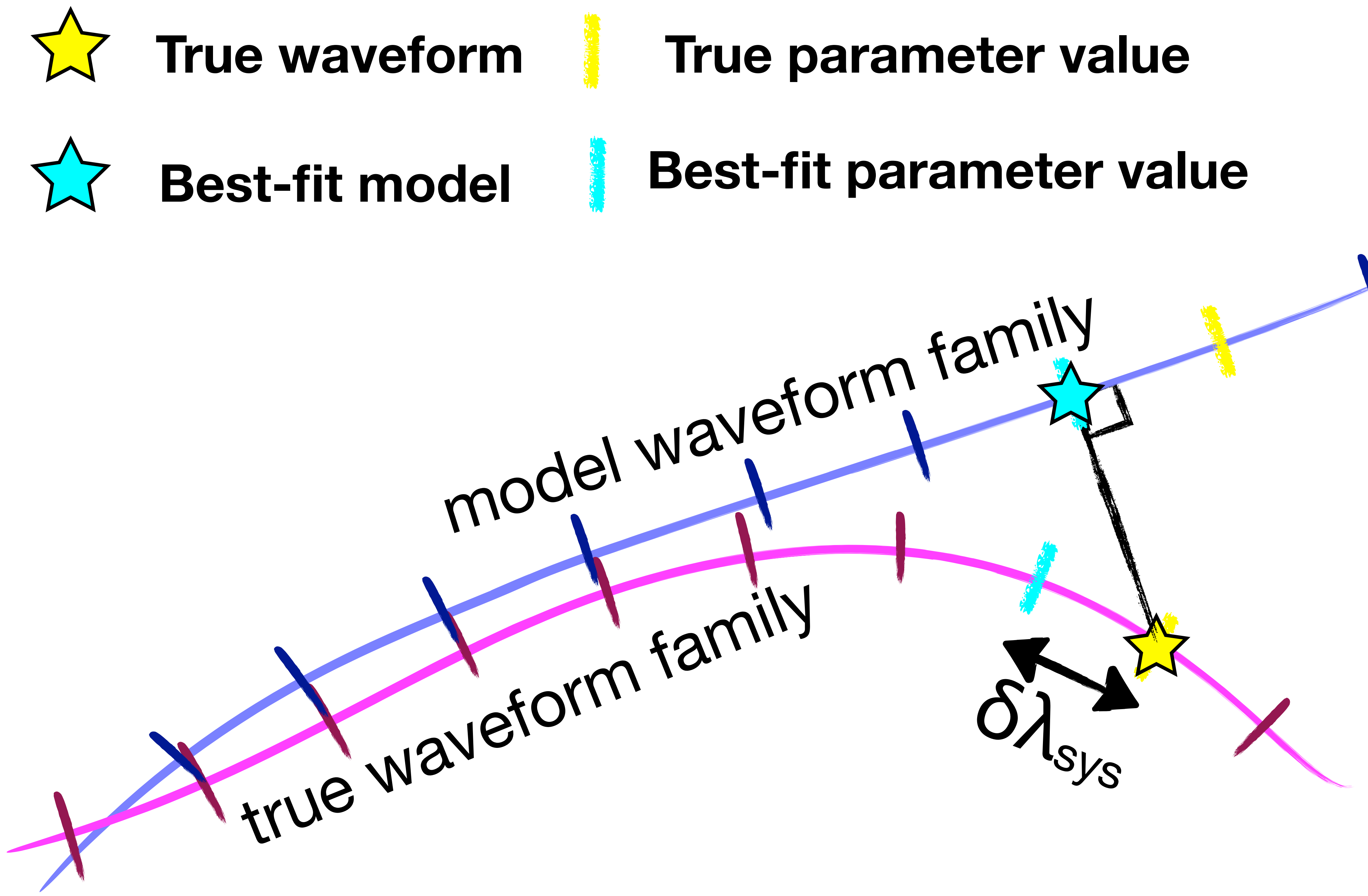
Detector Calibration

Source models

$$\mathscr{L}(d|\theta) \propto \exp\left(-\sum_i \frac{2\left|d_i - h_i(\theta)\right|}{S(f_i)}\right)$$

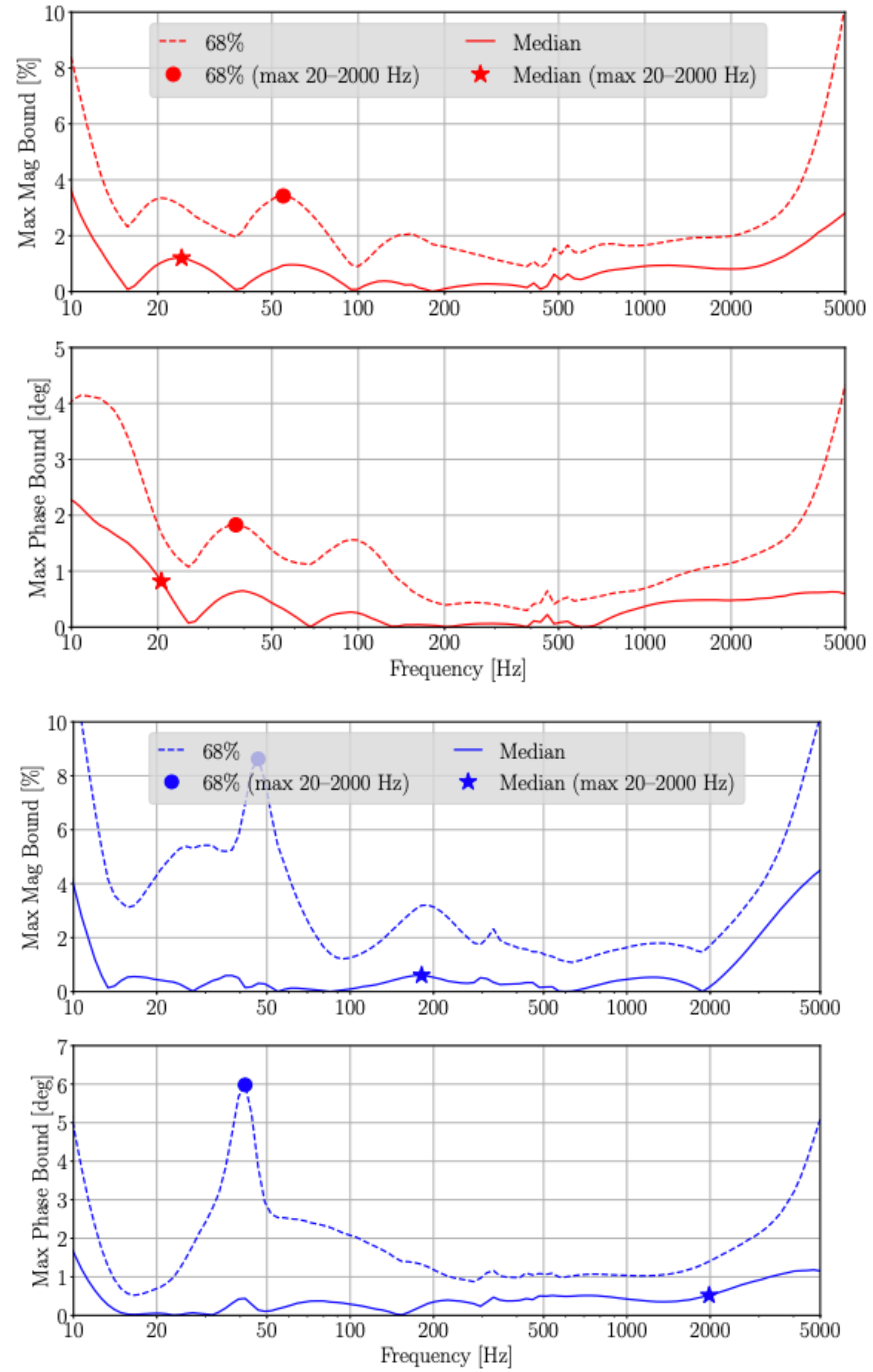
Non-Gaussian noise distribution

Noise amplitude estimation



e.g. "glitches"
Sophie Hourihane et al Phys. Rev. D **106**, 042006, Chris Panków et al, Phys. Rev. D 98, 084016 (2018)

e.g. Sylvia Biscoveanu et al Phys. Rev. D 102, 023008 2020, Talbot and Thrane Phys. Rev. Research **2**, 043298



Sun et al 2020

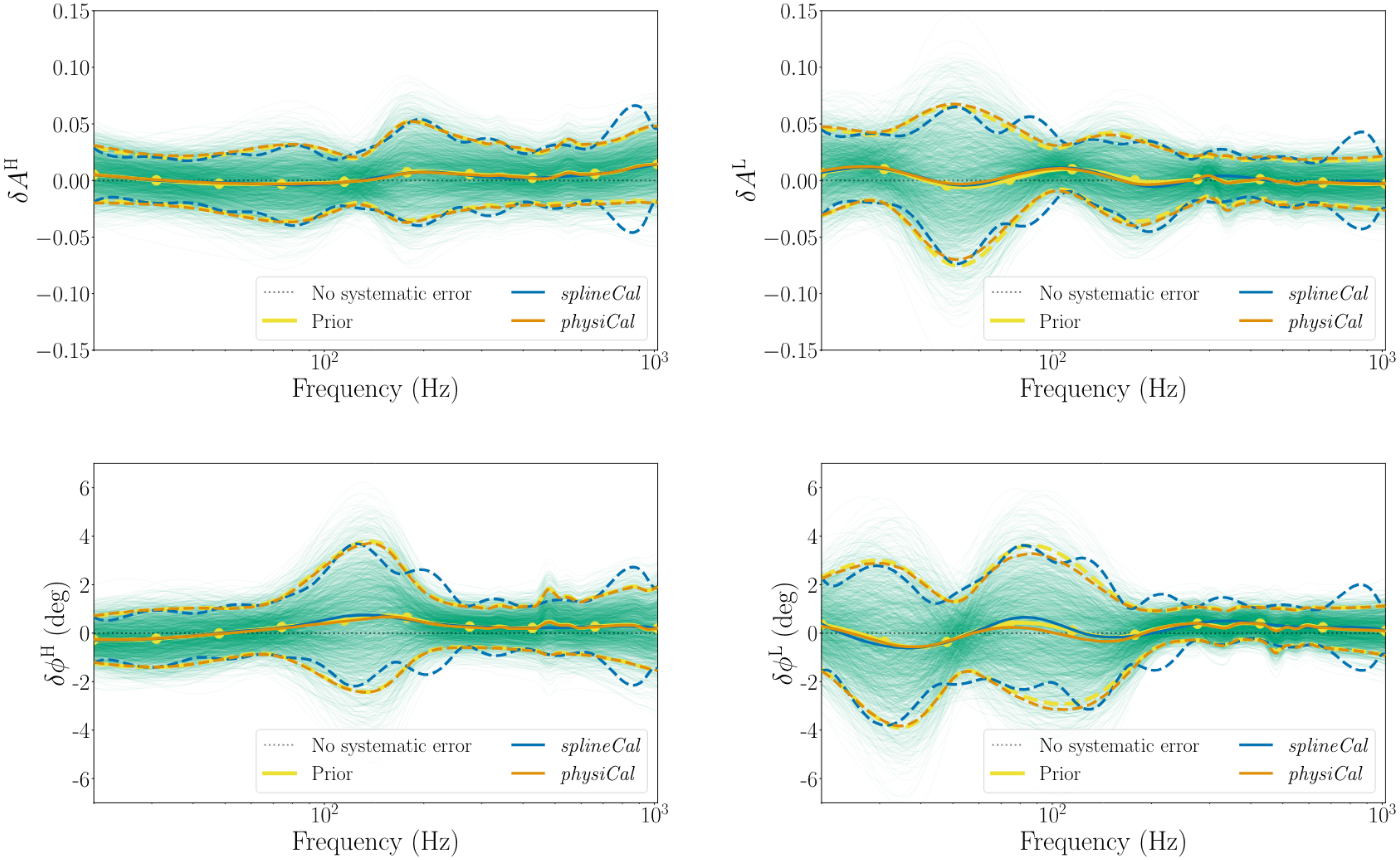
Calibration

- how well do we know instrument response?
- $h_{\text{obs}} = h(f)\big(1 + \delta A(f)\big) \exp\big(i\delta\phi(f)\big)$
- Calibration parameters: e.g. spline functions for $\delta A(f)$ and $\delta\phi(f)$ with priors calibrated to detector model e.g. Sun et al 2020 Class. Quantum Grav. **37** 225008
- Marginalize over calibration uncertainty during GW inference e.g. Vitale et al 2012 Phys. Rev. D **85**, 064034

Marginalizing over calibration (recovering prior)

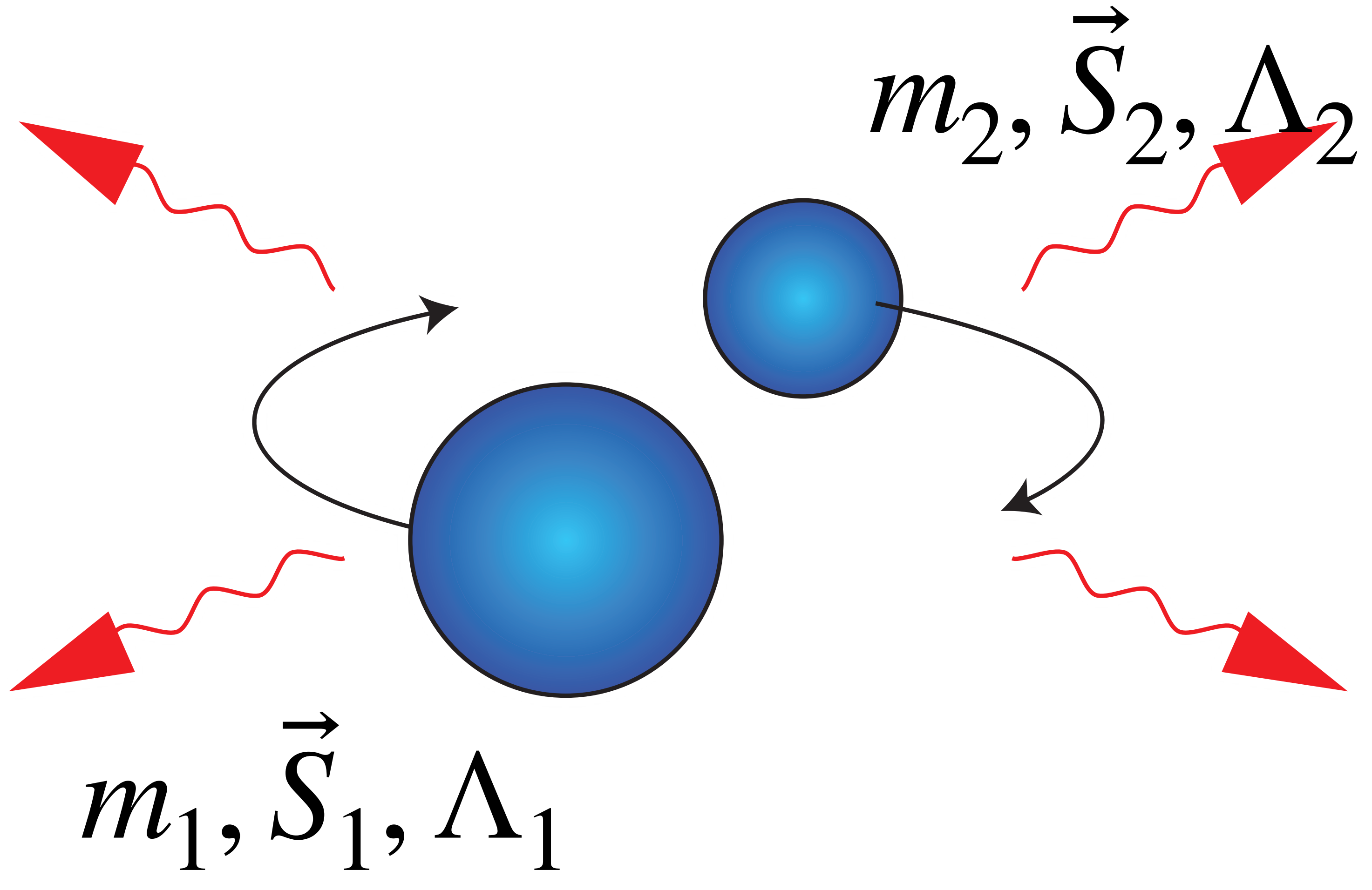
- Include calibration description in parameter space of inference

- Recover ~prior range of amplitude and phase errors in calibration of LIGO Hanford (left) and LIGO Livingston (right) during GW170814

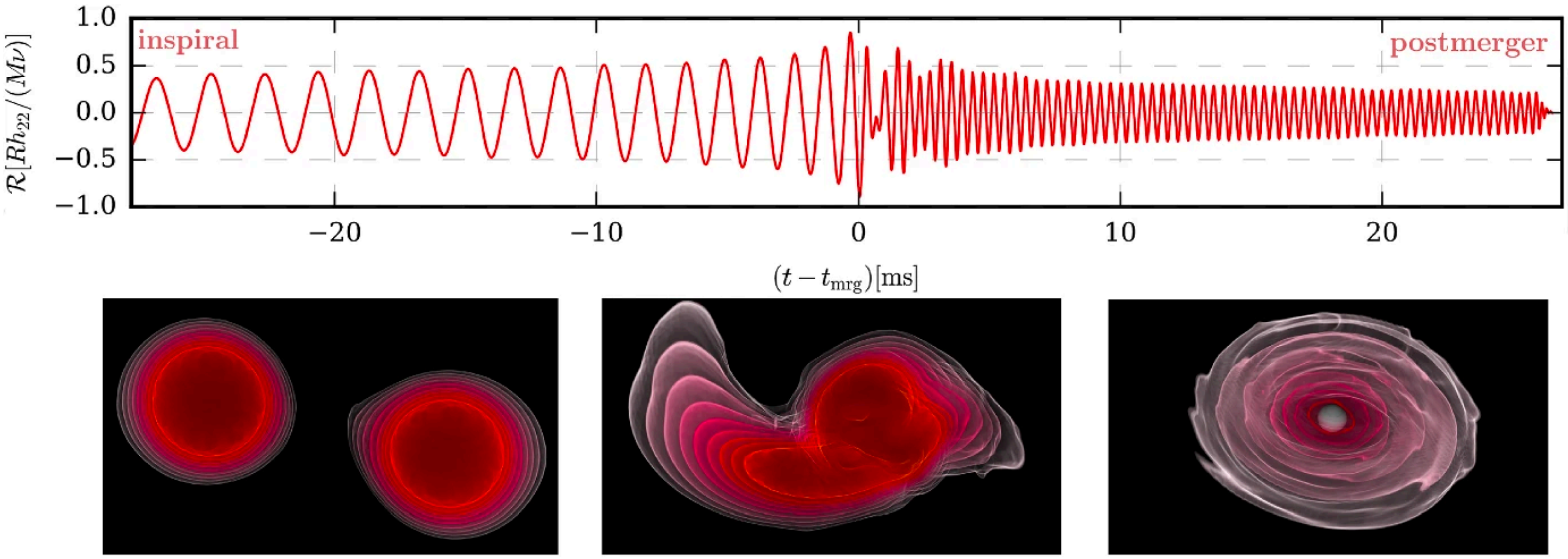


Vitale et al Phys. Rev. D 103, 063016 (2021)

Waveform variations



1. **Semi-analytic neutron-star component models**:
   Integrated effective-one-body (resummed) gravitational interactions w/ analytic tides
   - higher-order adiabatic tidal terms, dynamical tides & resonances, …
     (Nagar et al 1806.01772, Hinderer et al 1602.00599, …)
2. **Modify binary black hole models:**
   Take BBH model of choice, add tides into phaseing
   - Analytic tidal couplings to high order
   - Plus phenomenological corrections fit from numerical relativity
     (Dietrich et al 1706.02969 & 1905.06011)

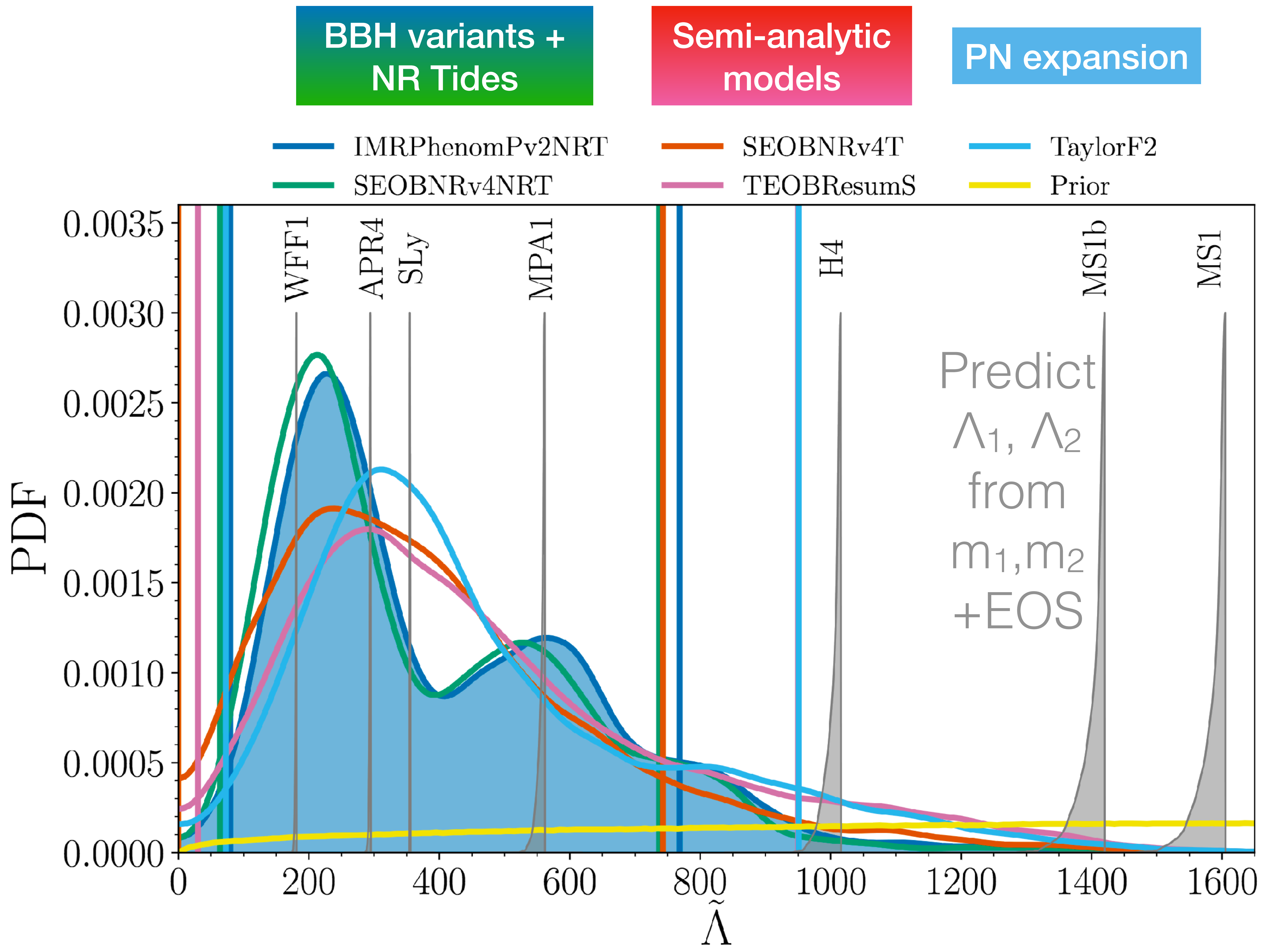


Dietrich, T., Hinderer, T. & Samajdar, A. Gen Relativ Gravit 53, 27 (2021)

- Note: Stars deform in complicated, close interactions:
  - stars are not isolated, deformations are not linear, deformations are not pure quadrupole, star response is dynamic …
- GW analysis currently uses Λ_1, Λ_2 as *effective* matter descriptors in gravitational-wave models

GW170817 waveforms:

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



Assume low spin ($\chi < 0.05$)

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

Bars denote 90% highest probability density credible interval

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

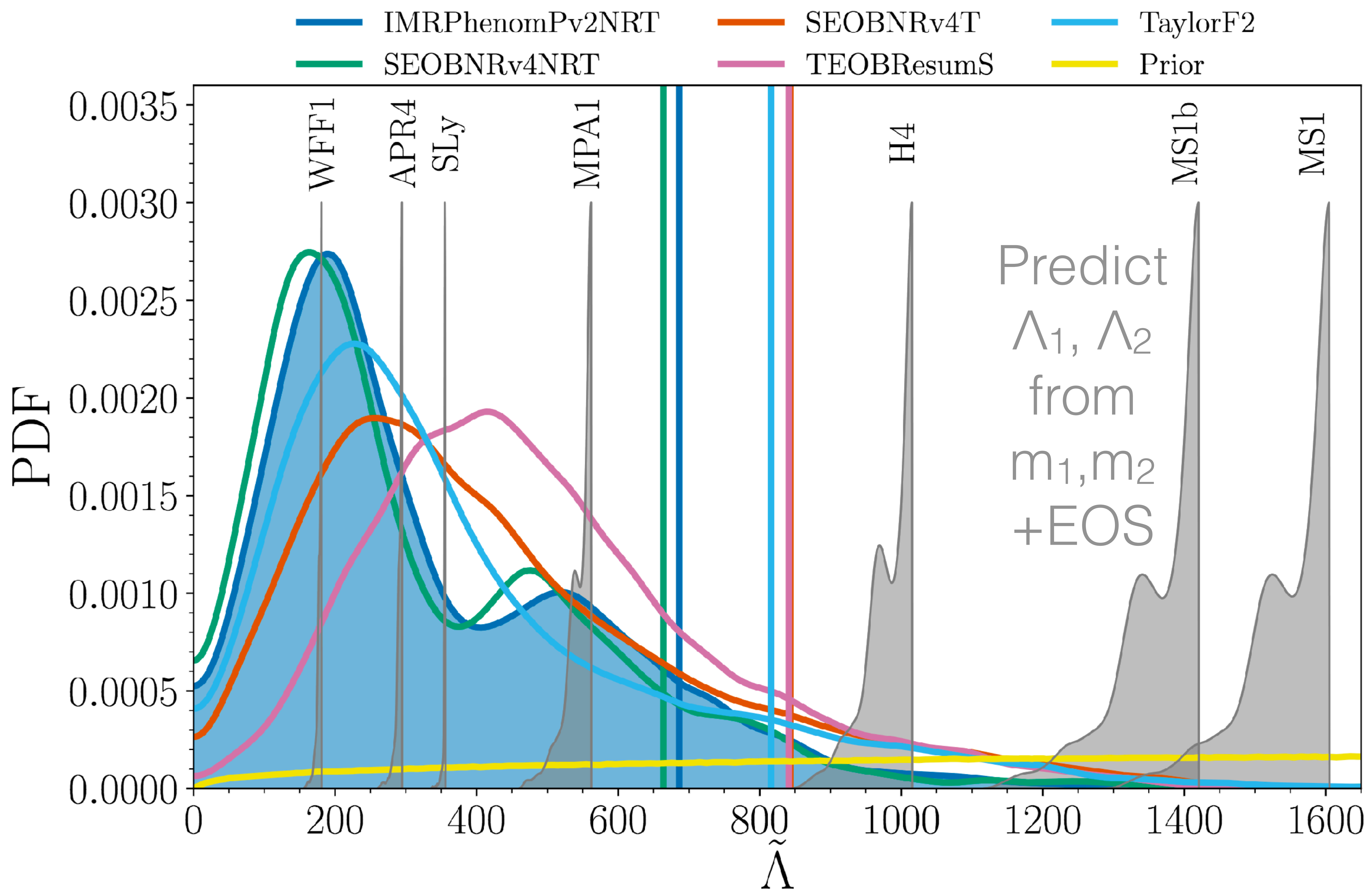
GW170817 waveforms:

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

BBH variants + NR Tides

Semi-analytic models

PN expansion



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

Bars denote 90% highest probability density credible interval

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

How to estimate and account for waveform model uncertainty?
How to interpret observed waveform differences?

From Source to Strain

- Source emission model: Multipole expansion

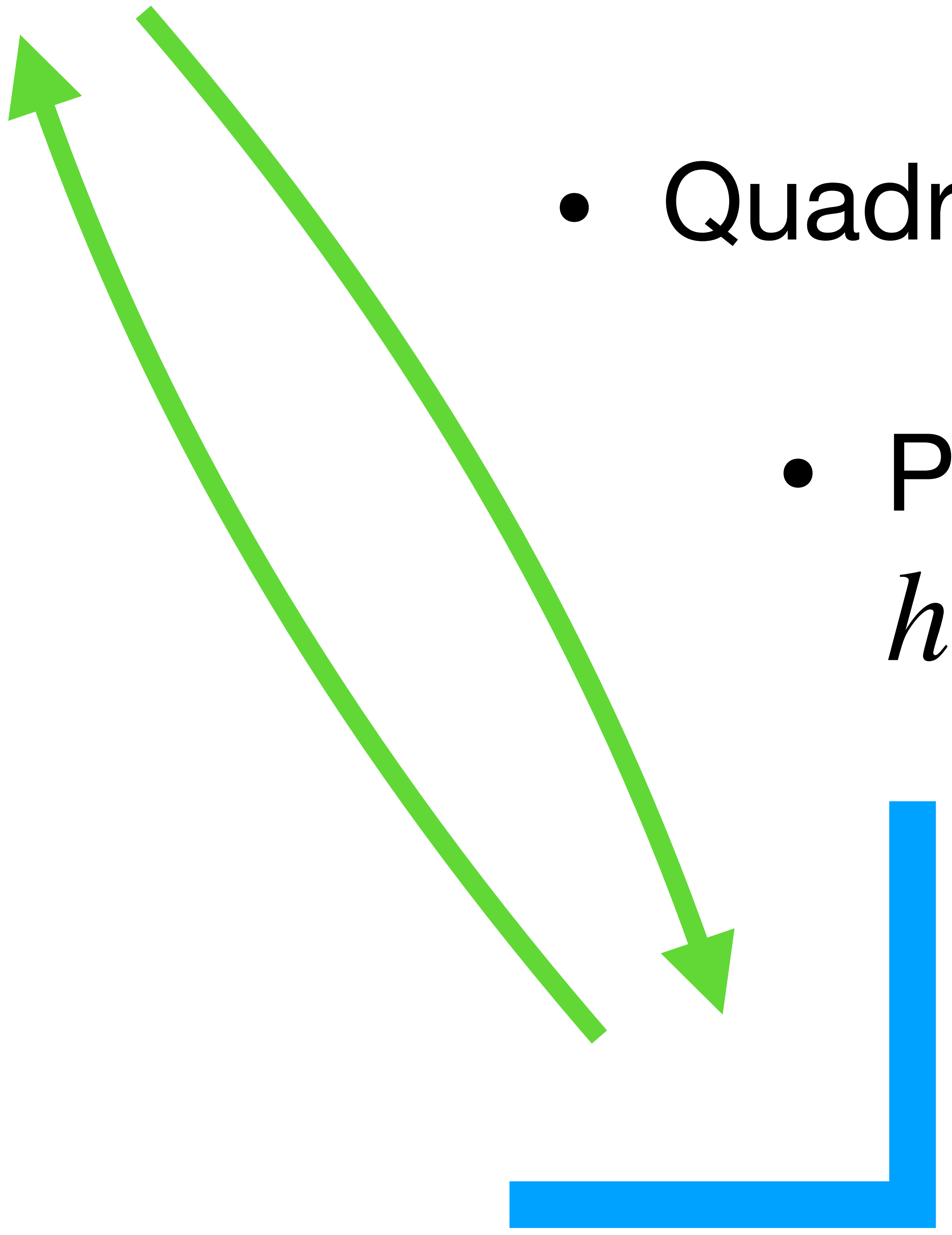
$$h_+(t) - ih_\times(t) = \sum_{\ell=2}^{\infty} \sum_{m=-\ell}^{\ell} h_{\ell m}(t) Y_{-2}^{\ell m}(\iota, \varphi)$$

Need **higher multipoles?**
SPA framework in Mezzasoma and Yunes 2022,
Hughes et al 2021

- Quadrupole-dominant: $h_{22}(t) = \mathscr{A}(t) e^{i\psi(t)}$

  - Projected onto detectors:
    $h(t) = F_+(\alpha, \delta, \psi_p) h_+(t) + F_\times(\alpha, \delta, \psi_p) h_\times(t)$

Sky location, orientation, inclination



- Resulting amplitudes: $h(t) = \dfrac{Q(\alpha, \delta, \iota, \psi)}{d_L} \mathscr{A}(t) e^{i\psi(t)}$

"Intrinsic properties"

Recovering coherent waveform modification

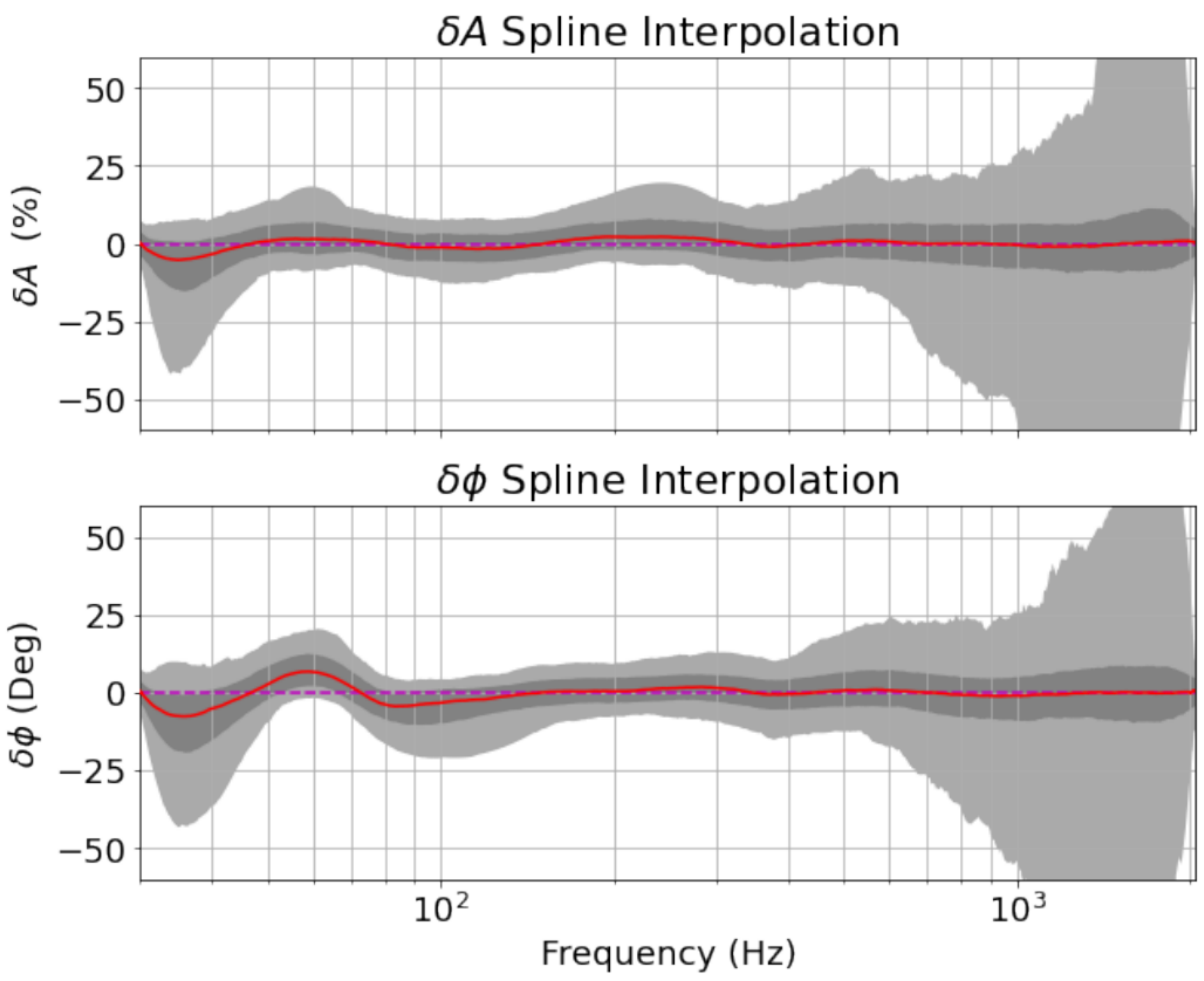


FIG. 12. Spline interpolation of GW170817 with 1 and 2 σ credible intervals (grey) and the median spline interpolant (red) shown.

$$h_{+,\times}(f) = h_{\mathrm{model},+,\times}(f)\,[1+\delta A(f)]\,\frac{2+i\delta\phi(f)}{2-i\delta\phi(f)} \quad (4)$$

- Edelman et al 2021: Search for coherent departures from waveform model
- Use splines for $\delta A, \delta\phi$ before projecting onto detector responses
- Recover credible range of potential differences from modeled waveform

Edelman et al Phys. Rev. D 103, 042004 (2021)

Physics of a GW inspiral

- Source model $h_{22}(t) = \mathscr{A}(t)e^{i\psi(t)}$ has **instantaneous frequency**: $2\pi F(t) = \dot{\psi}(t)$
- Define time-domain quantities relative to t_c and ϕ_c at **arbitrary reference** f_c:

time between f and f_c

$$T(f) = t_c - \int_f^{f_c} \frac{dF}{\dot{F}(F)}$$

phase accumulation between f and f_c

$$\psi(f) = \psi_c - 2\pi \int_f^{f_c} \frac{dF\, F}{\dot{F}(F)}$$

- Source masses, spins, tides: **encoded in characteristic functions** of F:

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

- Similar angular frequency derivatives used for guage invariant waveform comparison; here compared also to semi-analytic and fourier-domain waveforms used in signal analysis.

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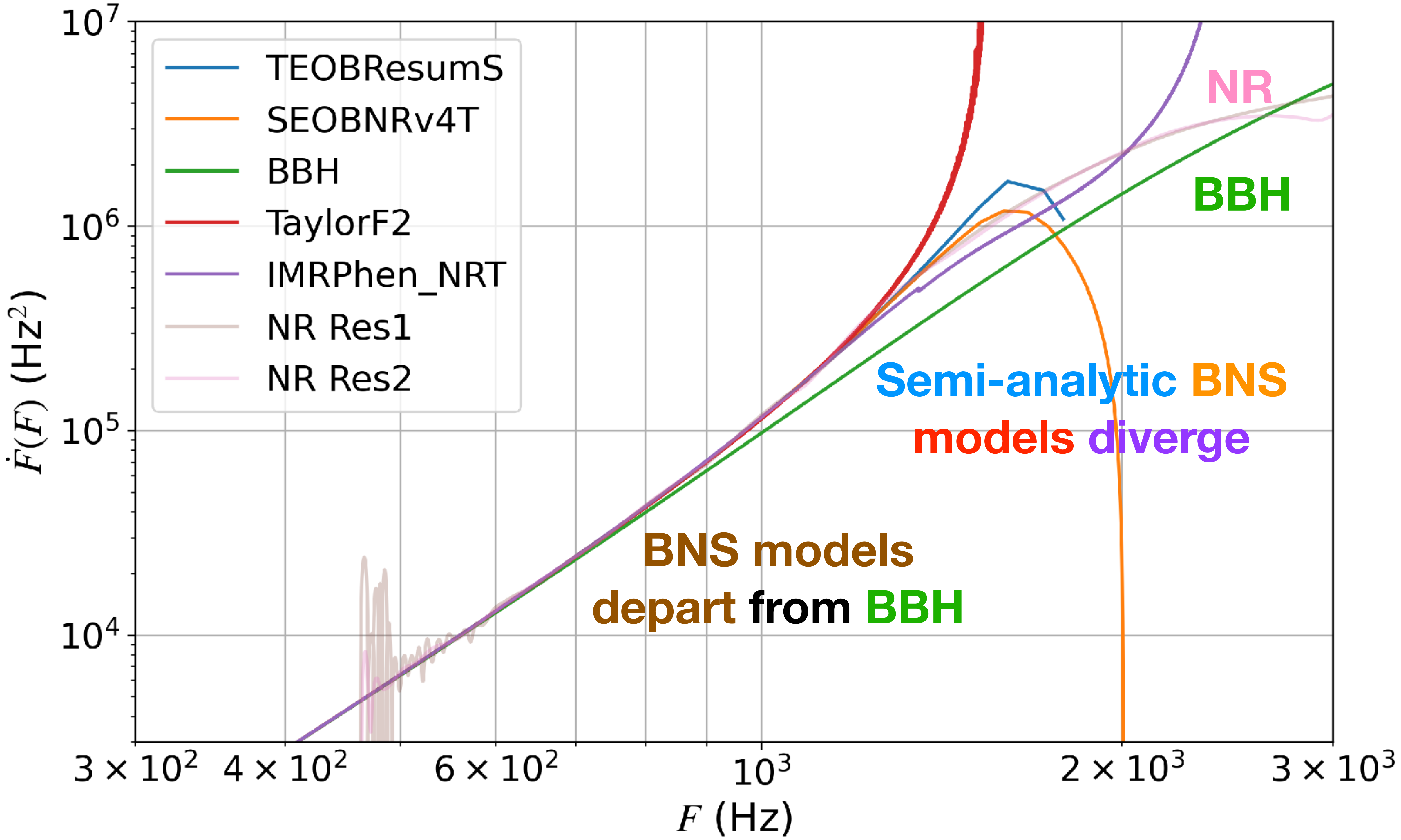
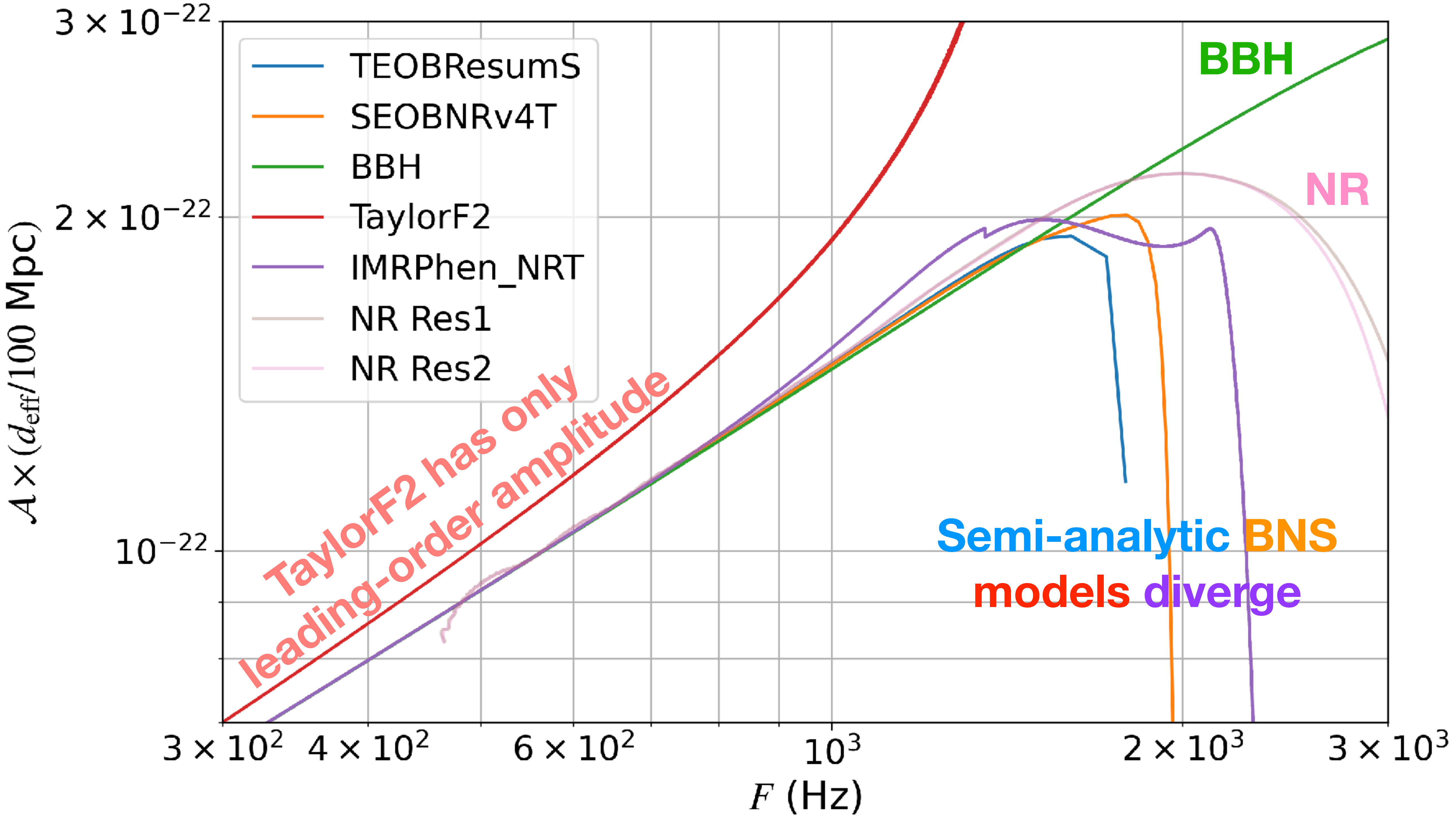
Characteristic functions allow waveform comparisons independent of alignment (overall shifts in time, phase)

$\dot{F} \propto \dot{\Omega}$ used in NR



NR - high-res CoRe sim ‘BAM:0095’ with SLy EOS
Spline smoothing for F before taking derivative
Semi-analytic models using same m_1, m_2 = 1.35

Time-domain $\mathscr{A}$ at F



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

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Adiabatic Energetics Interpretation

Luminosity 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 as function of emission frequency

Sources of modification: Variation of $E(F)$ or $\mathscr{L}(F)$ from GR source properties, plus

- 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)

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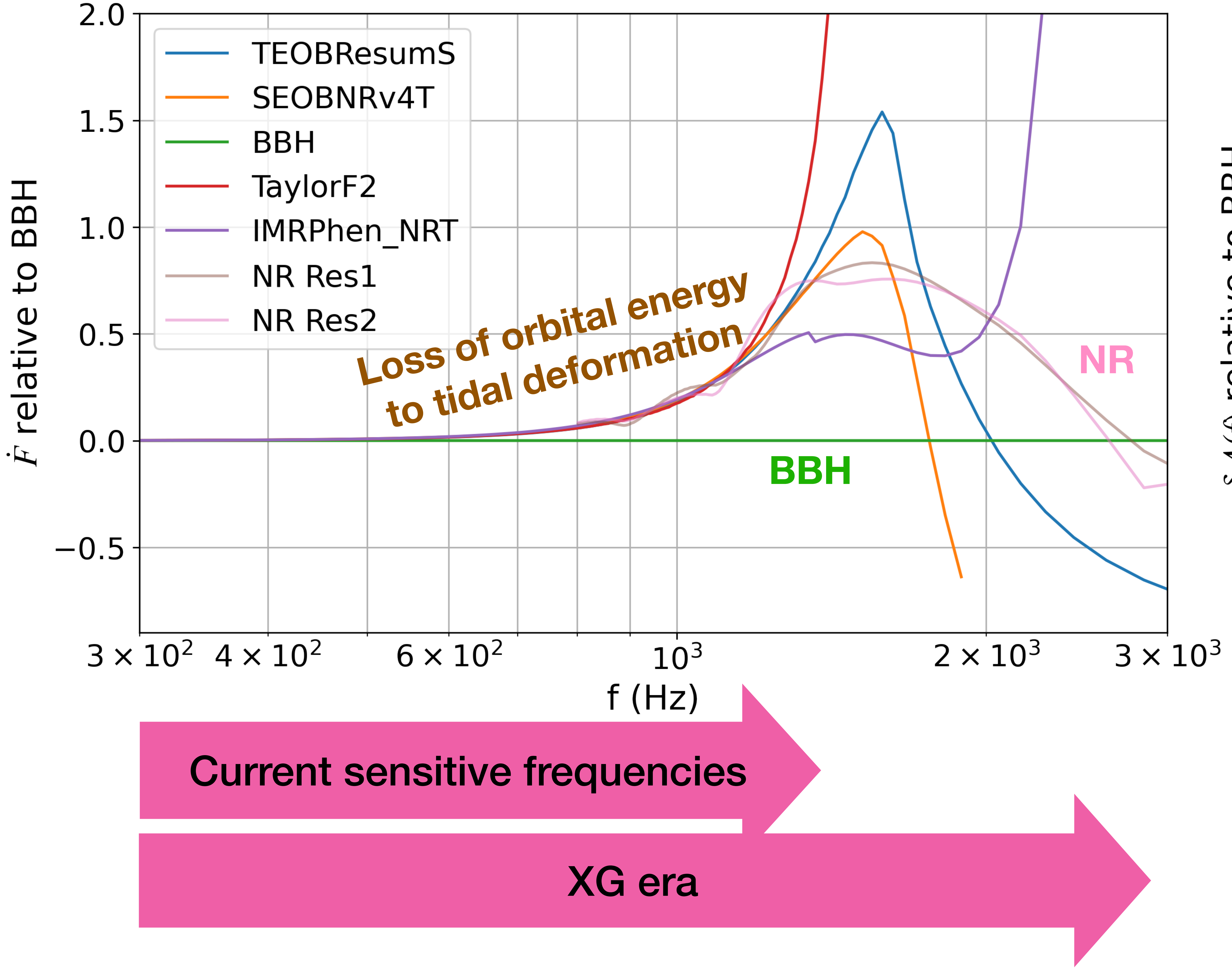
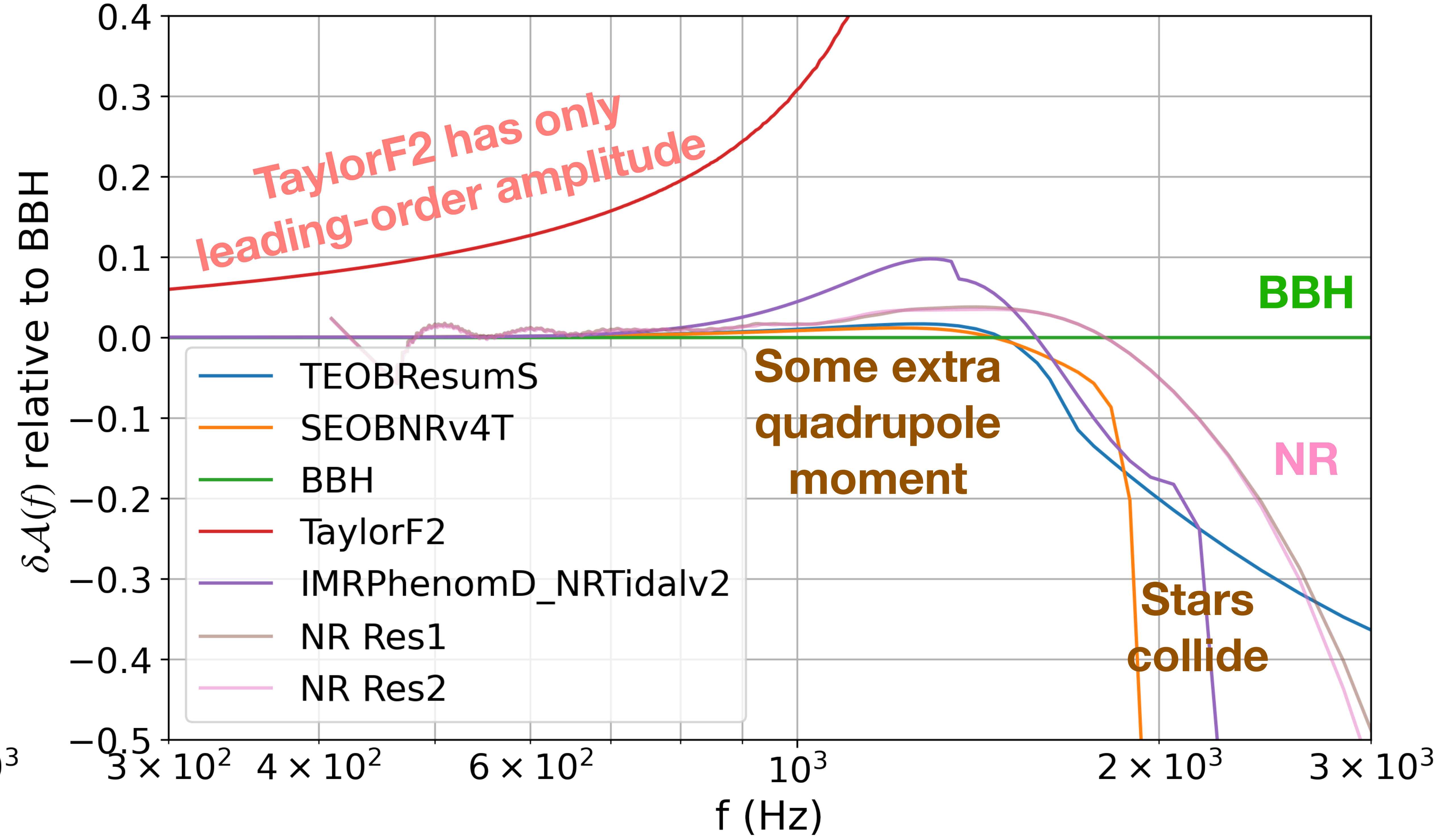
Matter: differences between BBH and BNS





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Fourier-domain signal

- Frequency domain signal $\tilde{h}(f) = A(f)e^{i\phi(f)}$ to compare with $S_n(f)$
- SPA from $\mathscr{A}$, ϕ_c, t_c and integration of dT/dF relative to f_c:
- $A(f) = Q(\boldsymbol{\theta}_{\text{ext}})\sqrt{T'(f)}\mathscr{A}(f)$

$$\phi(f) = \frac{\pi}{4} + \psi(f) - 2\pi f T(f) = \phi_c - 2\pi f t_c + 2\pi \int_f^{f_c} d\tilde{f} \int_{\tilde{f}}^{f_c} \frac{dF}{\dot{F}(F)}$$

Integrate dT/dF relative to f_c: one integration gives time, another gives phase

Time-domain phase $\psi(f)$ and time $T(f)$ differences (relative to f_c) are more robustly recovered from numerical simulation

Signal phase and time at f_c emerge as constants of integration

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SPA validity conditions for BNS

Extend framework to handle BBH, go past merger?
Will likely need higher-order SPA & non-monotonic frequency, as seen in Hughes et al Phys. Rev. D 103, 104014 (2021) arXiv:2102.02713

Indistinguishability

- Two waveform models have waveform difference $\delta \boldsymbol{h} = \boldsymbol{h}_1 - \boldsymbol{h}_2$
- $h_{\text{model}}(f) = h_{\text{true}}(f)\big(1 + \delta A(f)\big) \exp\big(i\delta\phi(f)\big)$
  - $\delta \boldsymbol{h}$ from δA is $A(f)\delta A(f)$
  - $\delta \boldsymbol{h}$ from $\delta\phi$ is $A(f)\Big(1 - \exp\big(i\delta\phi(f)\big)\Big)$
- "Indistinguishable" if $\langle \delta \boldsymbol{h} \,|\, \delta \boldsymbol{h} \rangle < 1$ "less than noise"
- In waveforms, distinguishability is often assessed via *mismatch*

$$\left(1 - \max_{\Delta t_c, \Delta\phi_c}\Big[\big\langle \mathbf{h_1}, \mathbf{h_2} \big\rangle\Big] / \sqrt{\big\langle \mathbf{h_1}, \mathbf{h_1} \big\rangle \big\langle \mathbf{h_2}, \mathbf{h_2} \big\rangle}\right) \lesssim \frac{min_{\Delta t_c, \Delta\phi_c}\left[\langle \delta\mathbf{h}, \delta\mathbf{h} \rangle\right]}{2\varrho^2}$$

when *SNR* $\varrho^2 = \langle \mathbf{h}, \mathbf{h} \rangle$ *is* approximately equal for each model

Model consistency: amplitude

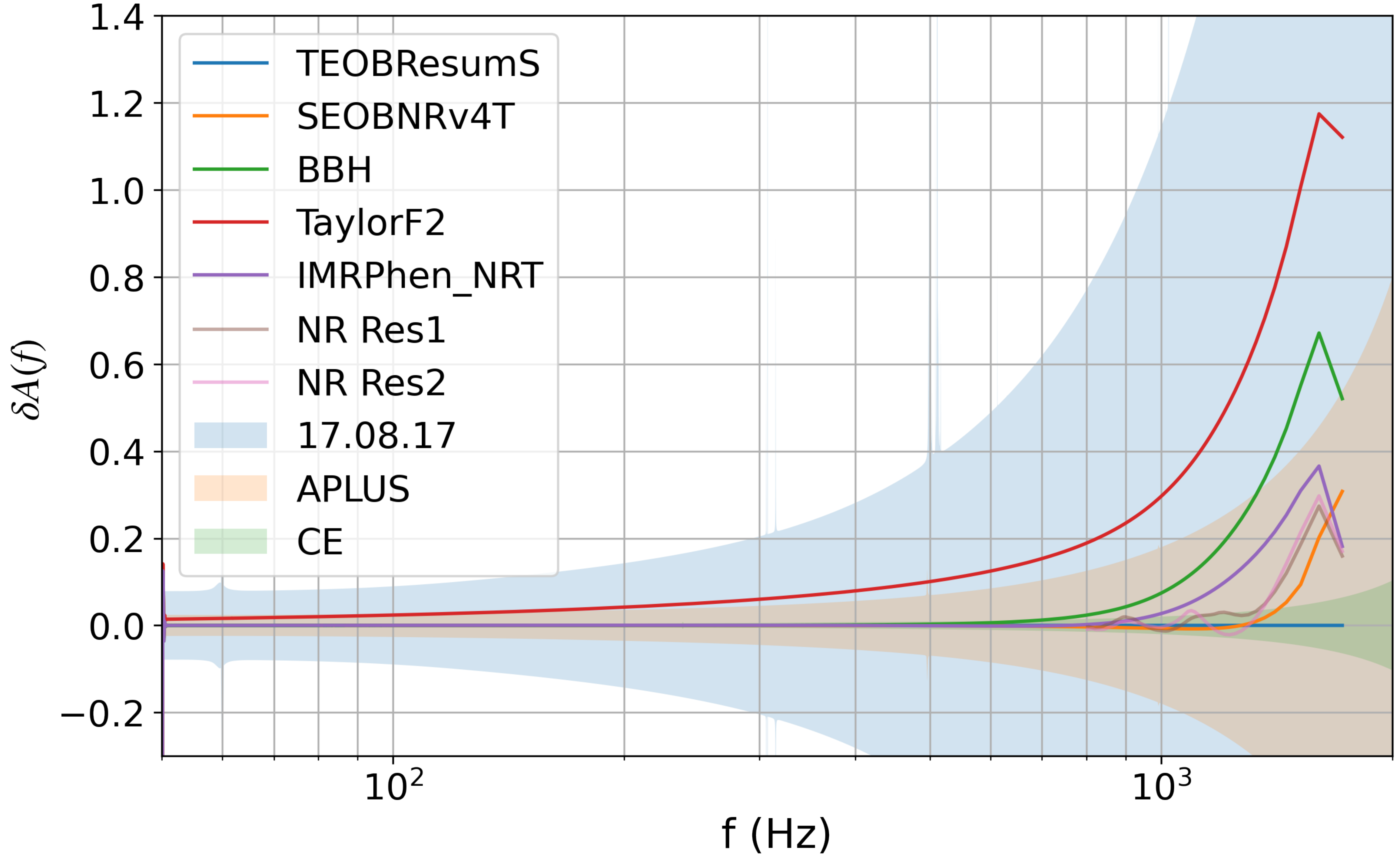
- $\tilde{h}(f) = A(f)e^{i\phi(f)}$
- in SPA:

$$A(f) = Q(\boldsymbol{\theta}_{\text{ext}})\left(T'(f)\right)^{1/2} \mathscr{A}(f)$$

$$\delta A(f) = \frac{A(f) - A_{\text{ref}}(f)}{A_{\text{ref}}(f)}$$

- PSD reference: condition for indistinguishability at 100 Mpc

δA relative to TEOBResumS



- TaylorF2 only has leading order amplitude
- Other differences in amplitude are small until merger (impact in CE only)

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Model consistency: phase?

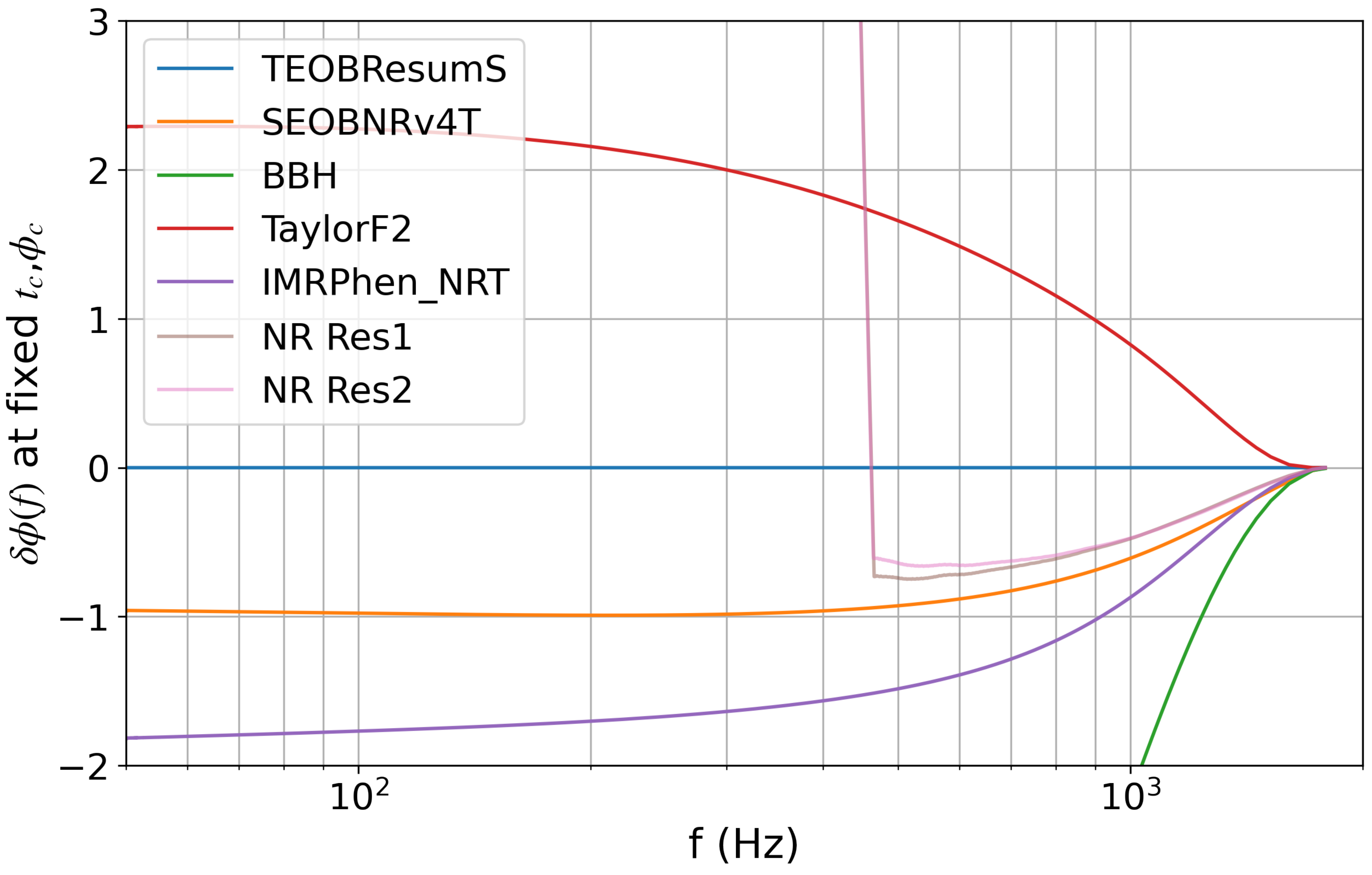
- With same t_c and ϕ_c for all signals, in SPA:

$$\phi(f) = \frac{\pi}{4} + \psi(f) - 2\pi f T(f)$$

$$= \phi_c - 2\pi f t_c + 2\pi \int_f^{f_c} d\tilde{f} \int_{\tilde{f}}^{f_c} dF\, T'(F)$$

- $\delta\phi(f) = \phi(f) - \phi_{\text{ref}}(f)$

- Can compute for NR from time and phase accumulation f to f_c



- Intrinsic model error relative to TEOB's f_c, as used in signal analysis
- other f_c [earlier] would give different alignment and potentially better NR/model agreement

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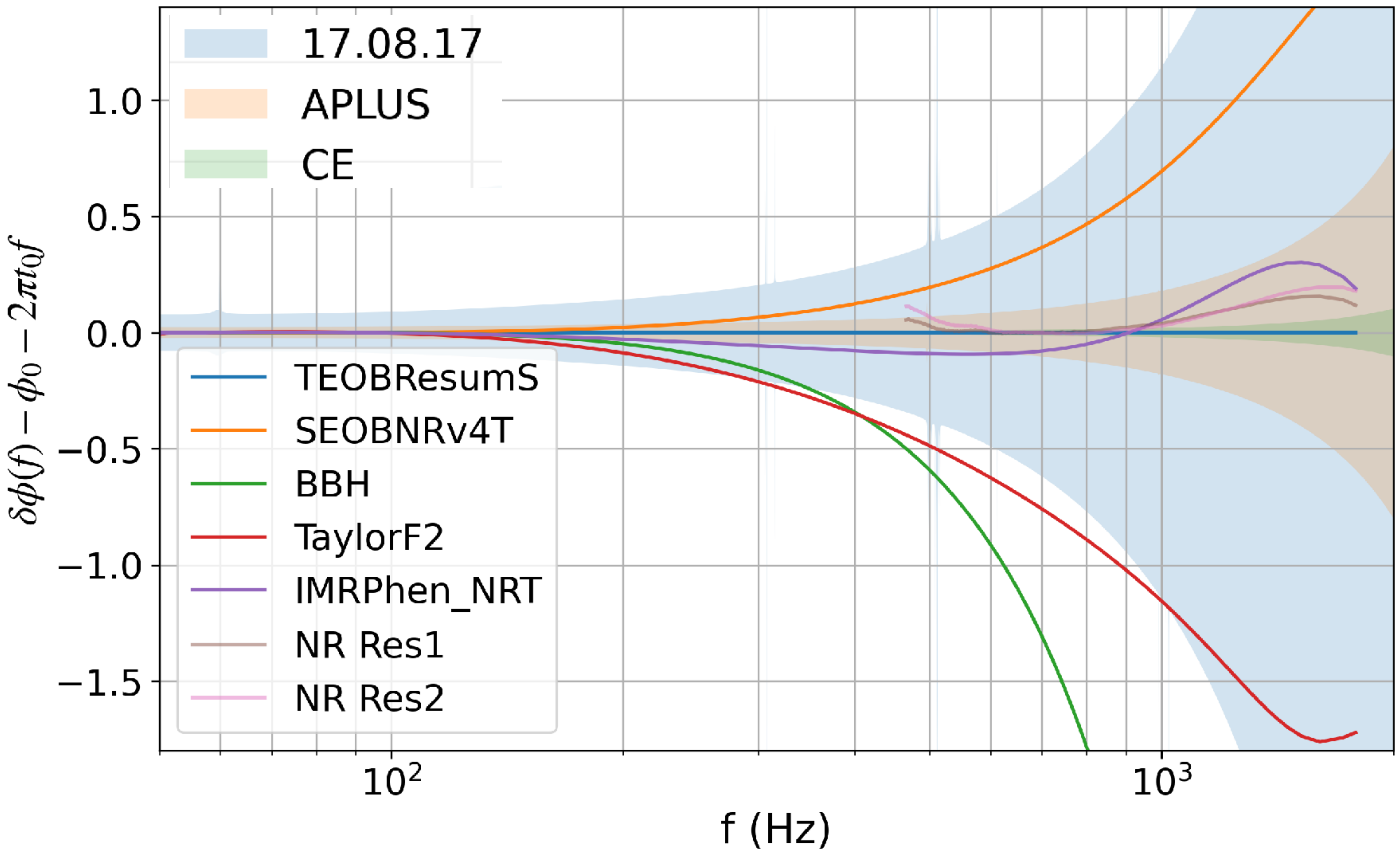
Residual phase

- Phase differences of $\phi_0 + 2\pi f t_0$ absorbed by marginalization over time and phase ϕ_c, t_c

- Compare **residual phase** $\delta\phi_{\rm res}$

- Subtract max likelihood fit of $\phi_0 + 2\pi f t_0$ (weight by variance $S_n(f)/A(f)^2$)

- Analogous to mismatch minimized over shifts in time and phase



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

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Indistinguishability

- Two waveform models have waveform difference $\delta \boldsymbol{h} = \boldsymbol{h}_1 - \boldsymbol{h}_2$
- $h_{\text{model}}(f) = h_{\text{true}}(f)\big(1 + \delta A(f)\big) \exp\big(i\delta\phi(f)\big)$
    - $\delta \boldsymbol{h}$ from δA is $A(f)\delta A(f)$
    - $\delta \boldsymbol{h}$ from $\delta\phi$ is $A(f)\Big(1 - \exp\big(i\delta\phi(f)\big)\Big)$
- "Indistinguishable" if $\langle \delta \boldsymbol{h} \,|\, \delta \boldsymbol{h} \rangle < 1$ "less than noise"
- In waveforms, distinguishability is often assessed via *mismatch*

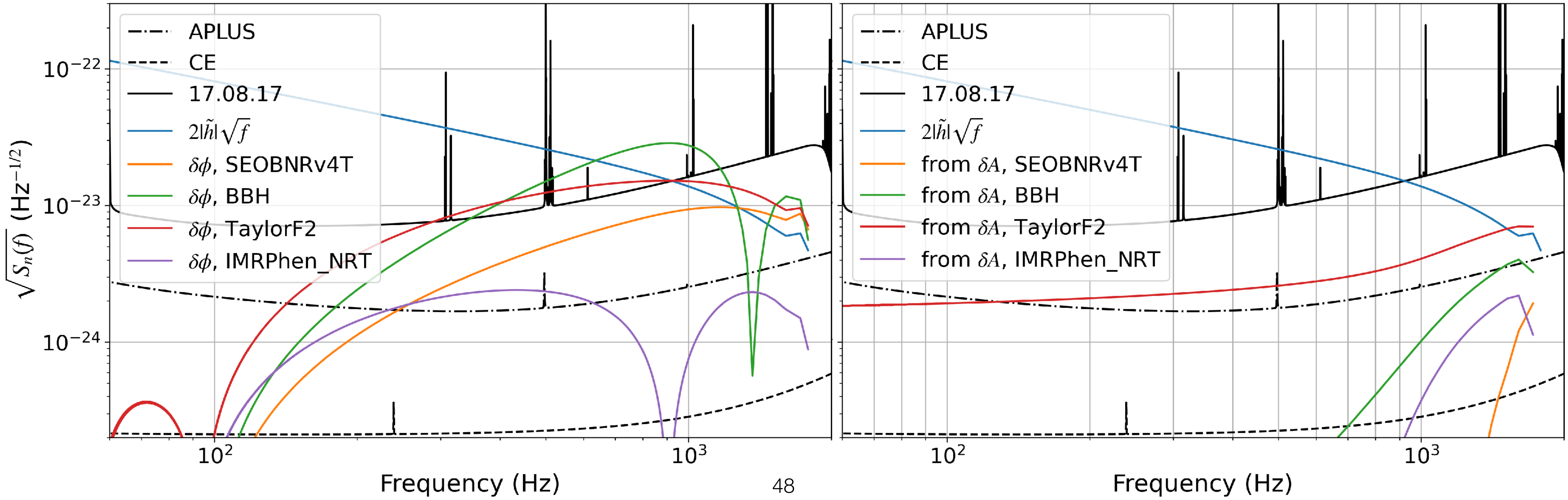
$$\left(1 - \max_{\Delta t_c, \Delta\phi_c}\left[\left\langle \mathbf{h_1}, \mathbf{h_2} \right\rangle\right] / \sqrt{\left\langle \mathbf{h_1}, \mathbf{h_1} \right\rangle \left\langle \mathbf{h_2}, \mathbf{h_2} \right\rangle}\right) \lesssim \frac{min_{\Delta t_c, \Delta\phi_c}\left[\langle \delta\mathbf{h}, \delta\mathbf{h} \rangle\right]}{2\varrho^2}$$

when *SNR* $\varrho^2 = \langle \mathbf{h}, \mathbf{h} \rangle$ *is* approximately equal for each model

Detector noise comparison

- Consider standard comparison of signal $\delta\mathbf{h}$ to amplitude spectral density curves for a 100 Mpc optimally-oriented merger, showing relevant frequencies for measurement

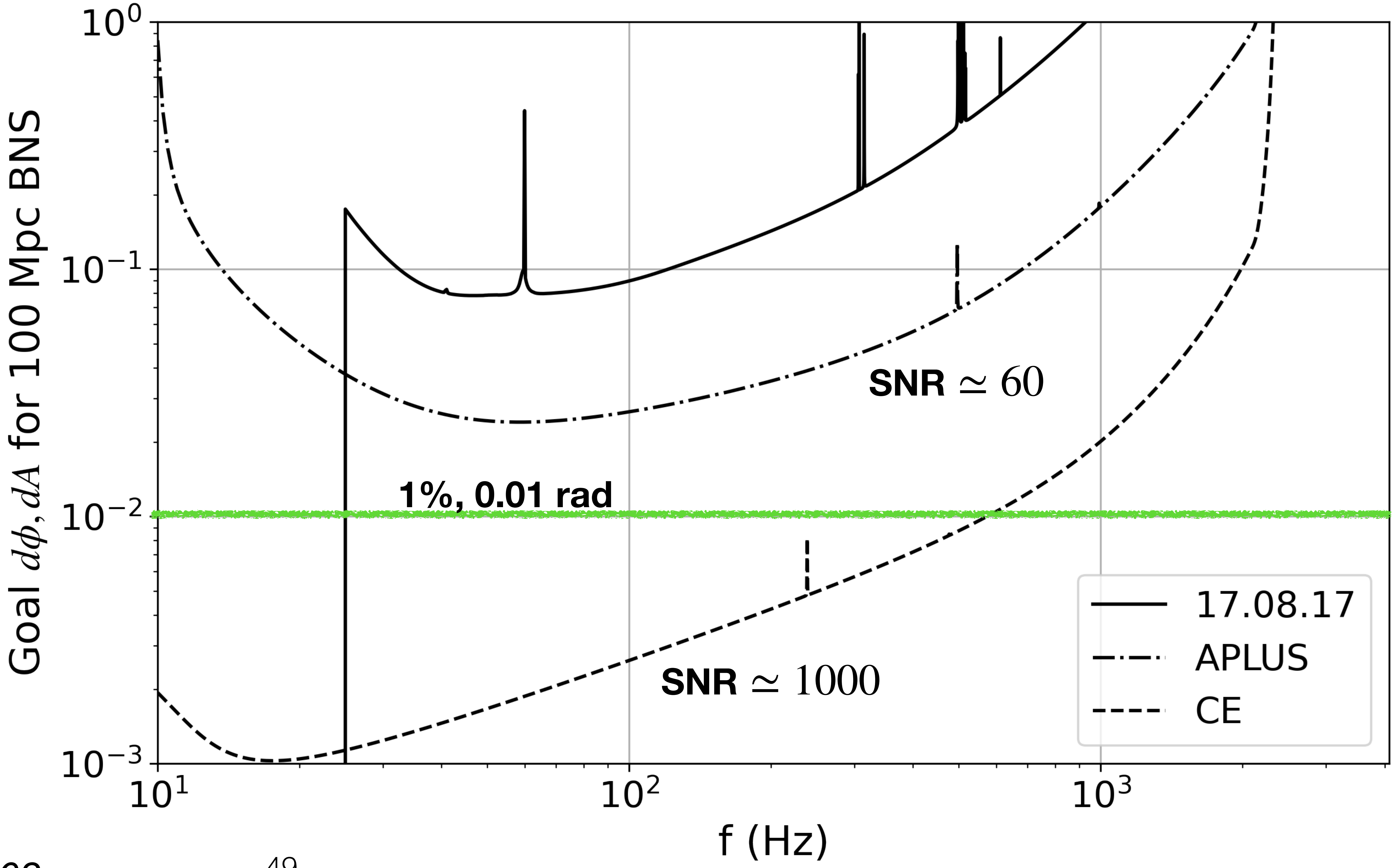
- Here, consider that error has potential to impact source analysis if $\delta h = h_{\text{true}} - h_{\text{model}}$ generates **characteristic strain larger than detector noise at a given frequency**



Goals for calibration & waveforms

- Indistinguishability condition from characteristic strain: $2\sqrt{f}\,|\,\delta\tilde{h}(f)\,| < \sqrt{S_n(f)}$ sets goal for reference detectors
- Here: BNS signal at $d_{\text{eff}} = 100$ Mpc
- Goal δA (fractional) and $\delta\phi$ (radians) shown
- 'Model' of detector (calibration) or source (waveform)
- Significance of model differences depends on frequency (obscured in integrated mismatch)

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



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Energy transfers and the Fourier signal

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

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

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

- **Applications:**
  - 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

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Application: Interpret observed $\delta\phi, \delta A$

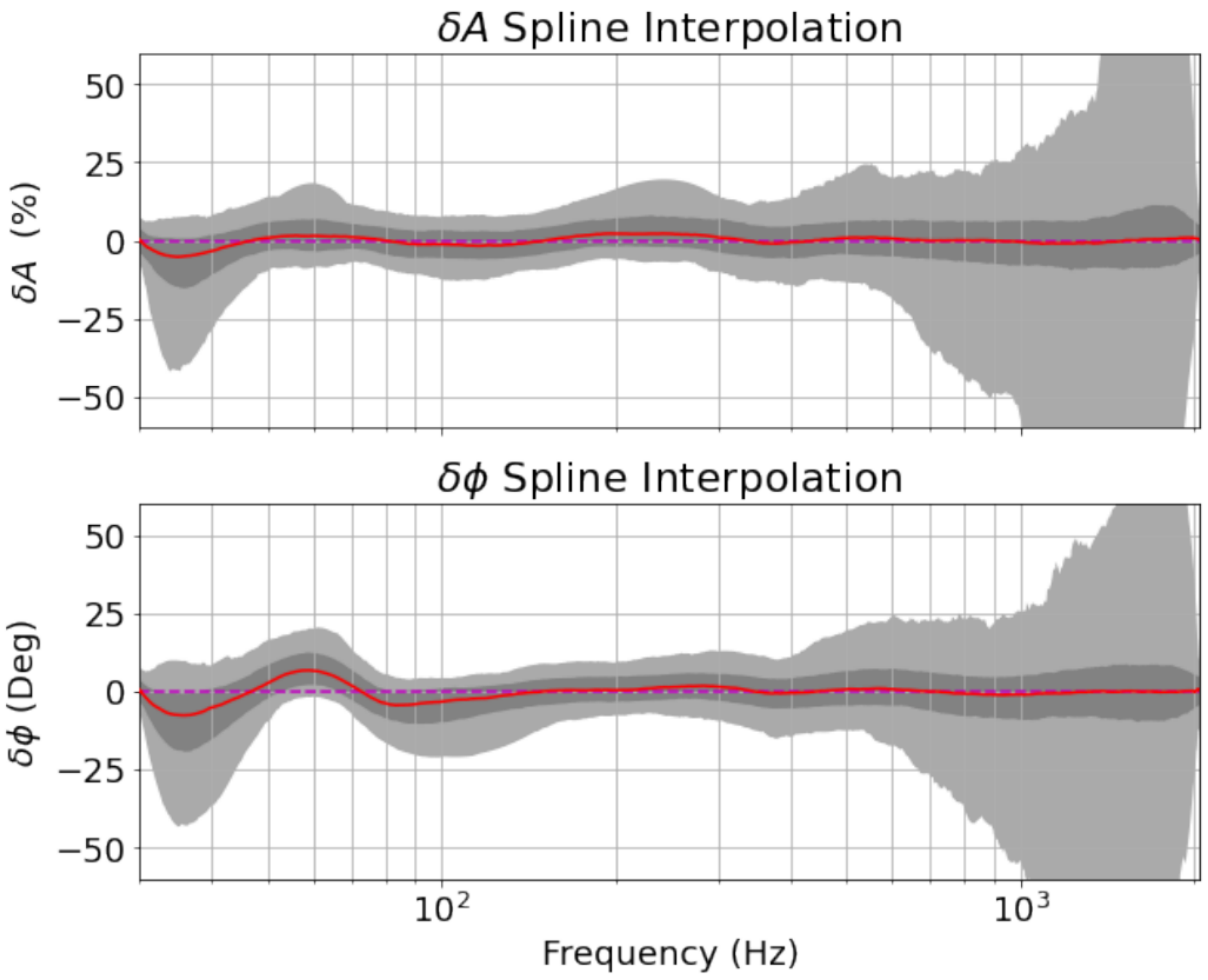
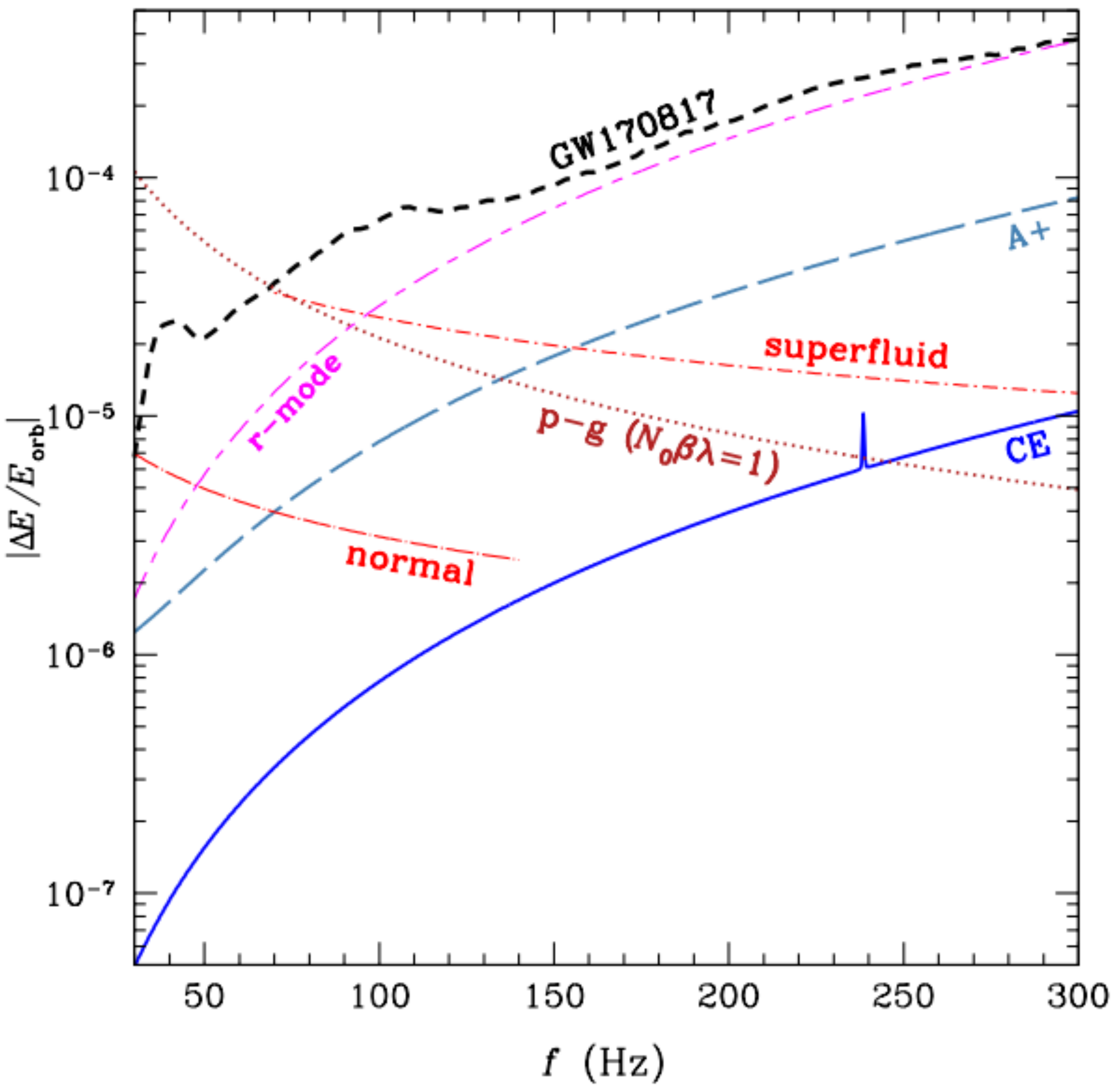


FIG. 12. Spline interpolation of GW170817 with 1 and 2 σ credible intervals (grey) and the median spline interpolant (red) shown.

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

- **Interpretation with waveform energetics: GW170817** phase shift $\delta\phi \sim$ 5 deg at 60 Hz is compatible with a **resonant energy transfer** of $\delta E = \Delta E/E \sim 0.001$ relative to the orbital energy $E(60\text{ Hz}) \simeq -0.006 M_{\odot}c^2$ (Scale of $\Delta E \sim 10^{49}$ erg)

Implications for observing resonant modes



- Ho and Andersson Phys. Rev. D 108, 043003 (2023) arXiv:2307.10721
- Use the Edelman *et al* 2021 constraint, energetics framework from Read 2023
- Limit the amount of orbital energy that is transferred to the neutron star to $< 2 \times 10^{47}$ erg and the g-mode tidal coupling to $Q_{\text{mode}} < 10^{-3}$ at 50 Hz (5×10^{48} erg and 4×10^{-3} at 200 Hz) (1- σ)
- Estimated improvement with A+, XG compares to plausible resonant energy transfer to neutron star modes in inspiral

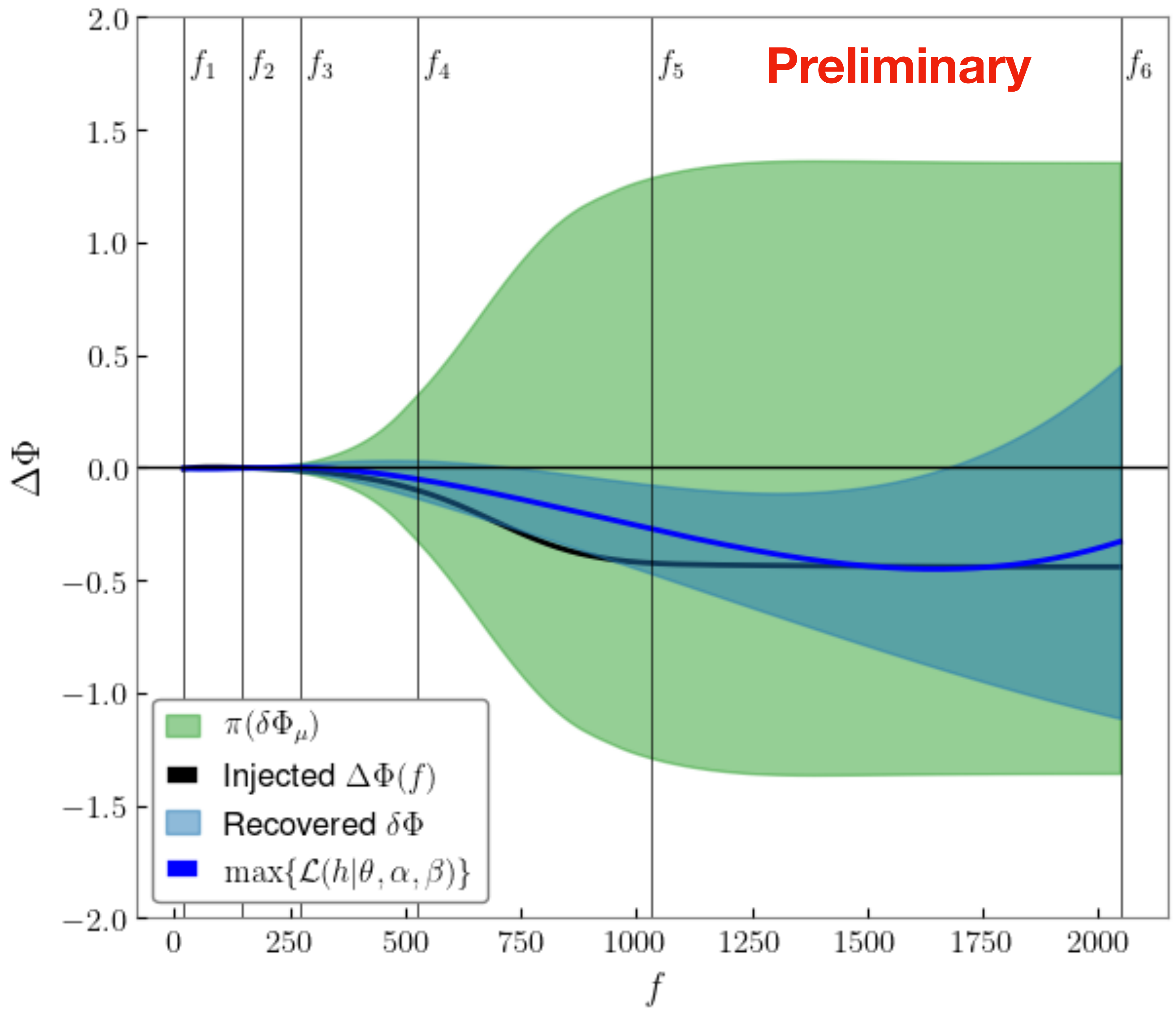
Measurement in `bilby`

- Goal: Marginalize over $\delta A, \delta\phi$ with prior set by waveform model differences (Similar to calibration process)

- If data allows, *recover* best-fit $\delta A, \delta\phi$ from observation (as done in Edelman et al)

- First steps: Spline model of $\delta A, \delta\phi$; modified `WaveformGenerator`

Ryan Johnson, CSUF



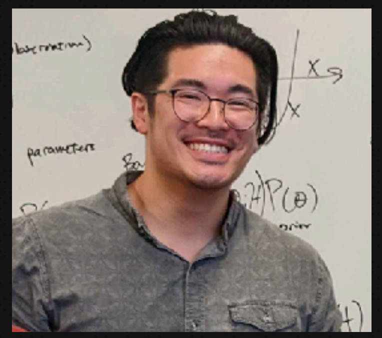
$$\mathcal{L}(h(f_j)|\theta,\alpha,\beta) = \frac{1}{2\pi P(f_j)} \exp\left(-2\Delta f \frac{|h(f_j) - \mu(f_j;\theta)(1+\delta A(f_j;\alpha)) \exp[i\delta\phi_R(f_j;\beta)]|^2}{P(f_j)}\right)$$

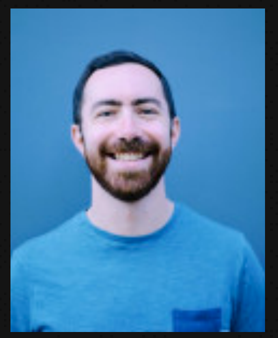
Thank you!

Join the Cosmic Explorer Consortium!
https://cosmicexplorer.org/consortium.html

Angela Nguyen, Eddie Anaya, and Virginia Kitchen, Cal State Fullerton

Ng, Suleiman, Landry, Read, in prep

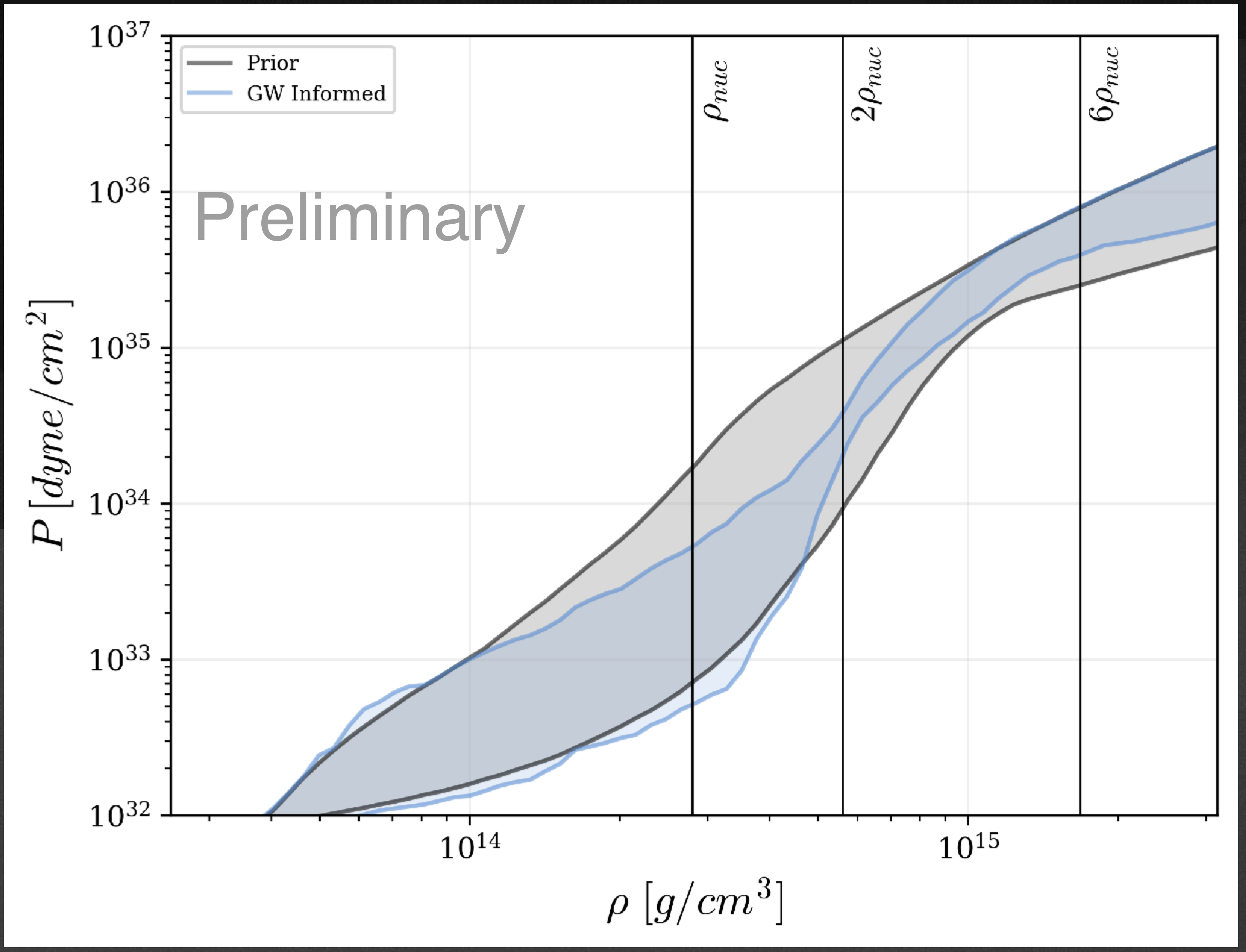




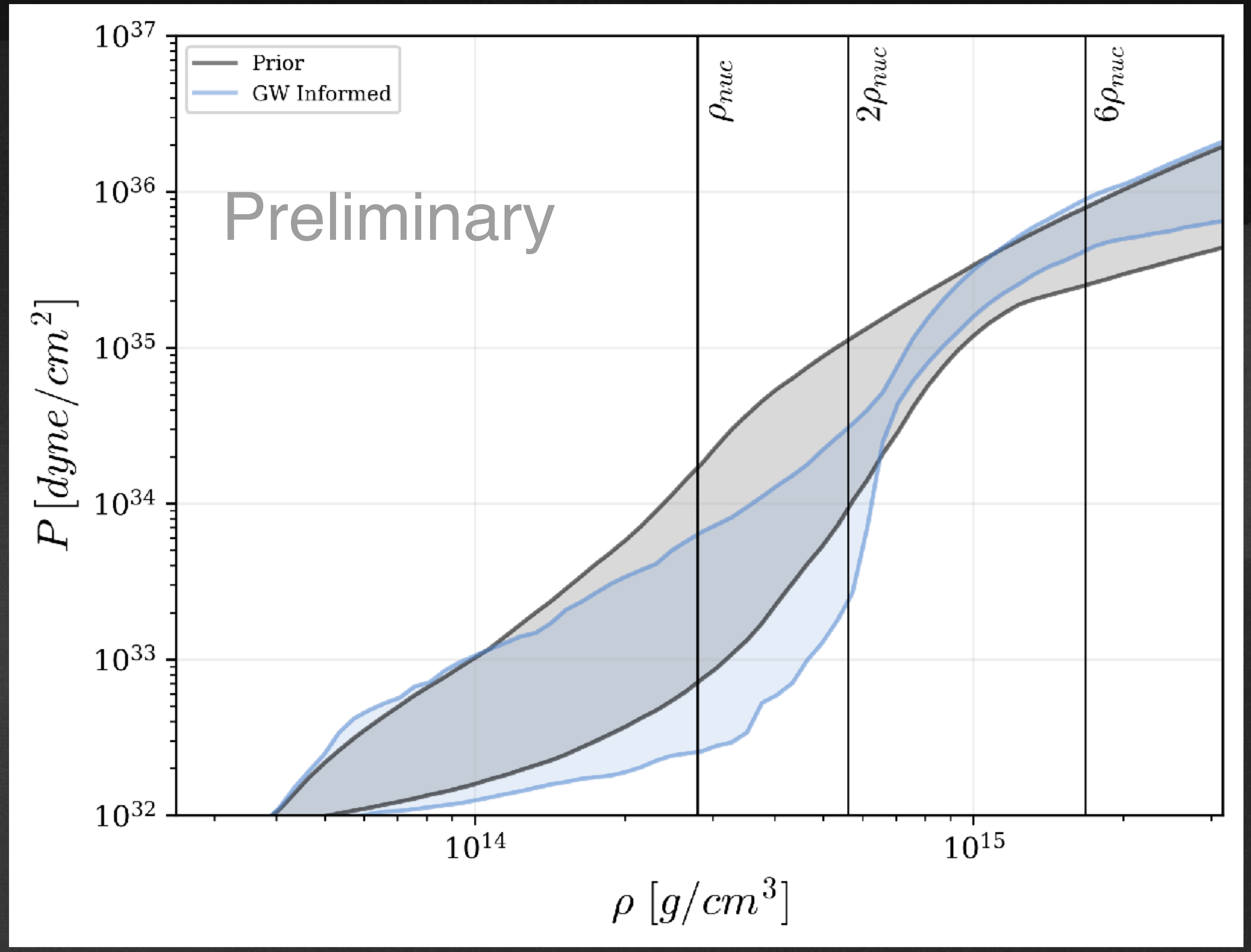
Next-generation facilities

Cosmic Explorer and Einstein Telescope

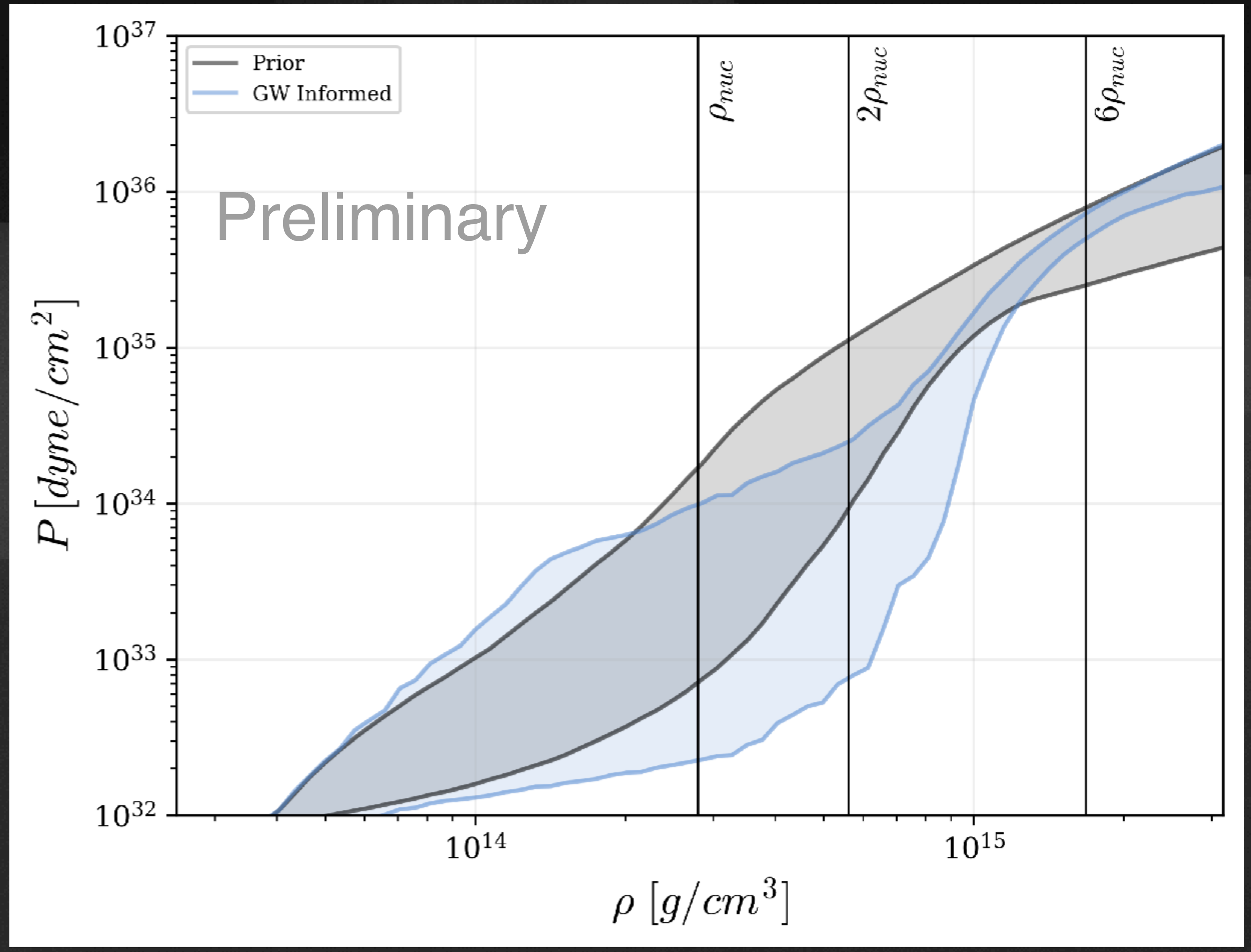
$\mathscr{M}_c = 0.96 M_\odot$



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



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

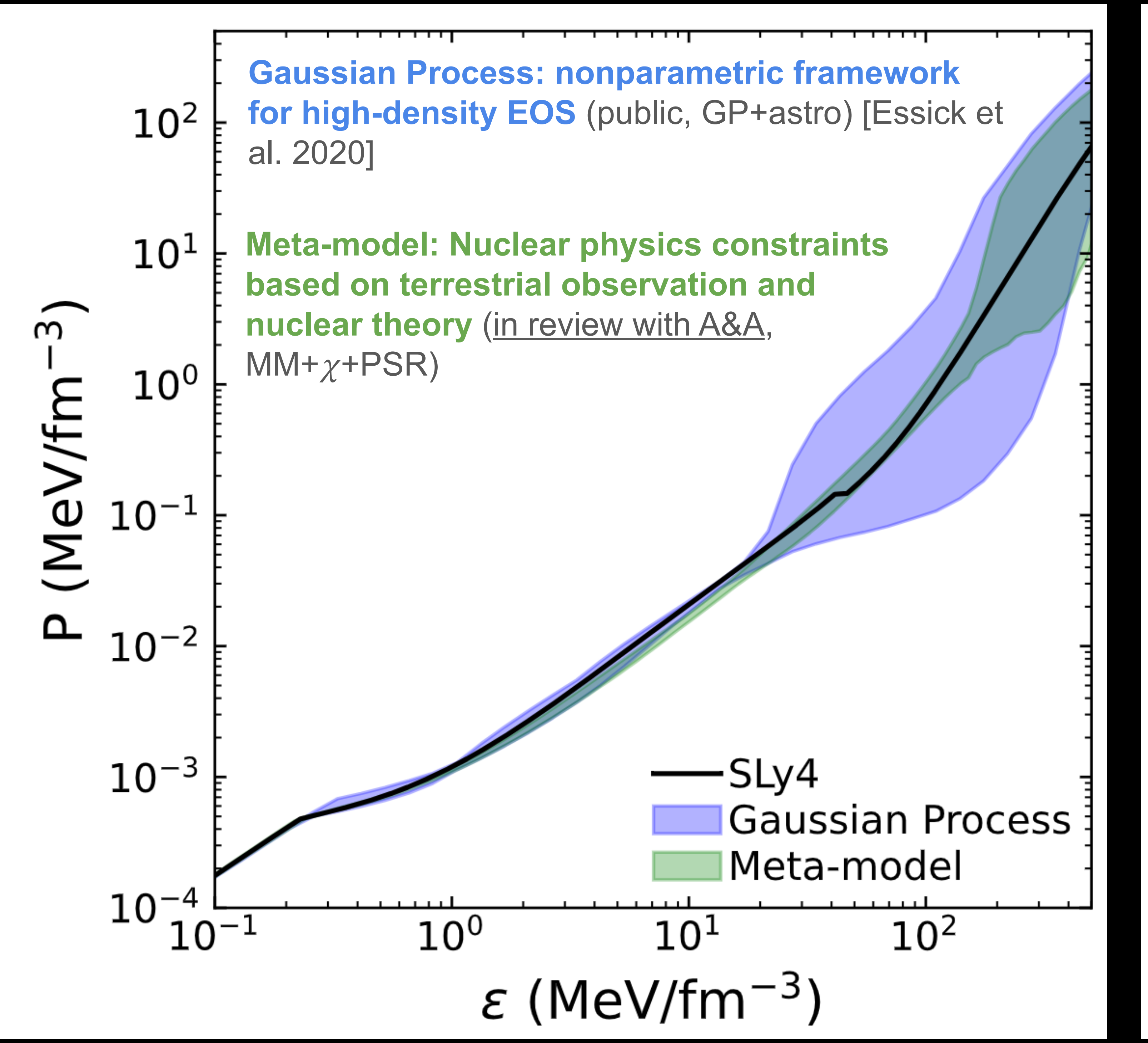


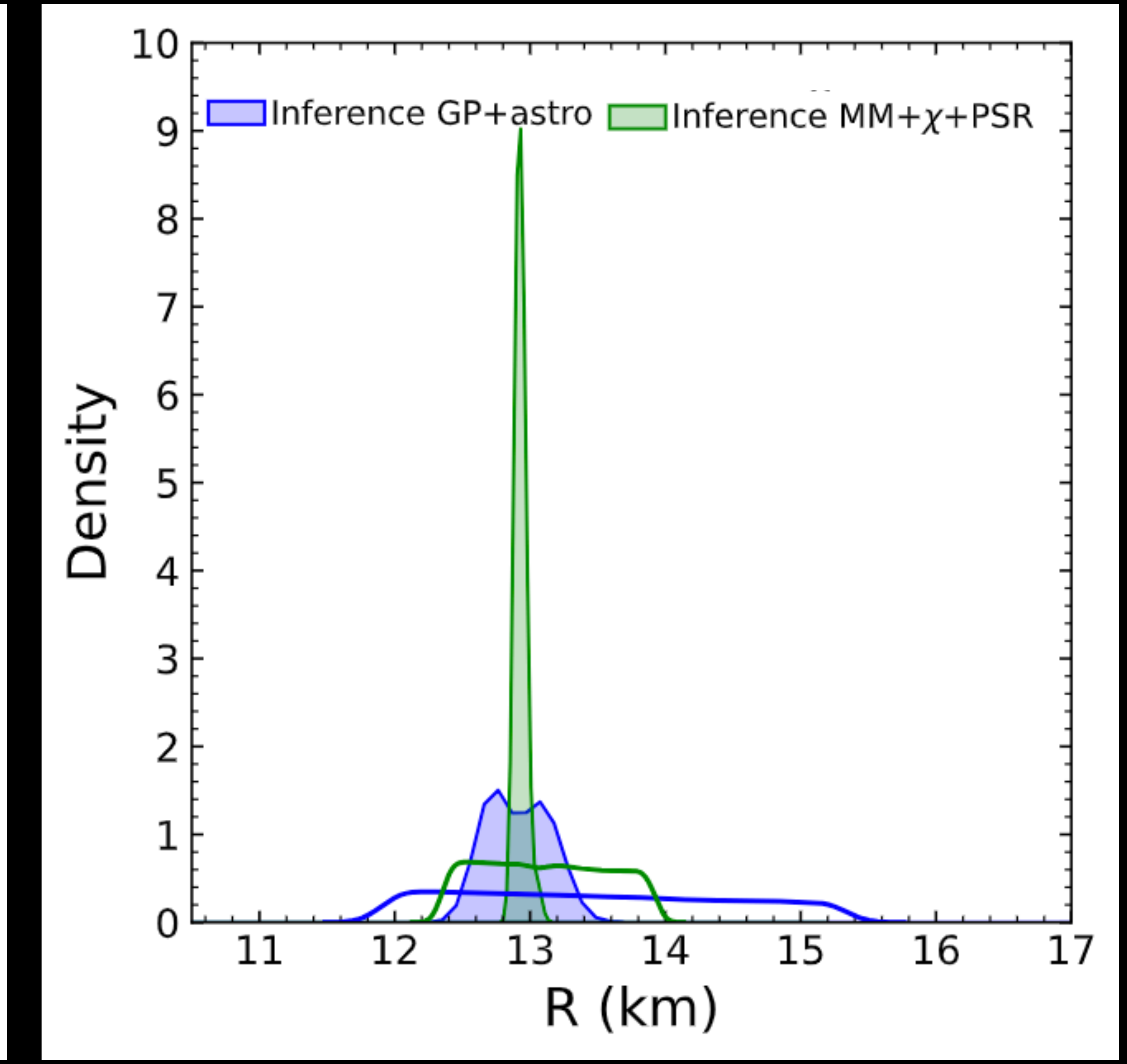
Density constrained varies with mass of binary;
single observation decimates candidate EOS

Using nuclear theory for next-generation GW interpretation

Connecting disparate observables: GW and the NS Radius

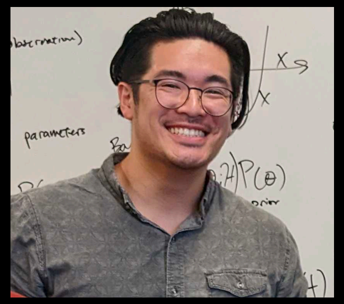
w/ Lami Suleiman





- GW recover M, Λ at the sensitivity of 3G detectors

- Compute R from heirarchichally-inferred EOS + signal parameters (public library lwp).



- Challenge for quasi-universal relations (Suleiman & Read arXiv: 2402.01948, Penuliar et al in prep)

Jocelyn Read

Cal State Fullerton

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

- Some things I've worked on:
  - Piecewise polytrope EOS, NR-based estimates of EOS measurement with LIGO, Crust shattering flares, Neutron star search config and rates for Advanced LIGO/Virgo, led LVK extreme matter analysis for GW170817, nuclear astrophysics with LVK, XG science case and design goals
- Some current projects:
  - waveform uncertainty, r-process contributions of NS mergers (with Hsin-yu Chen, Phil Landry, Daniel Siegal), EOS families and inference (with Lami Suleiman, Richard O'Shaughnessy), quasi-universal relations in XG (with Lami Suleiman)
- I'm here with my family, kids are 7 & 9, we're interested in (easier) hikes and activities and seeing a castle!