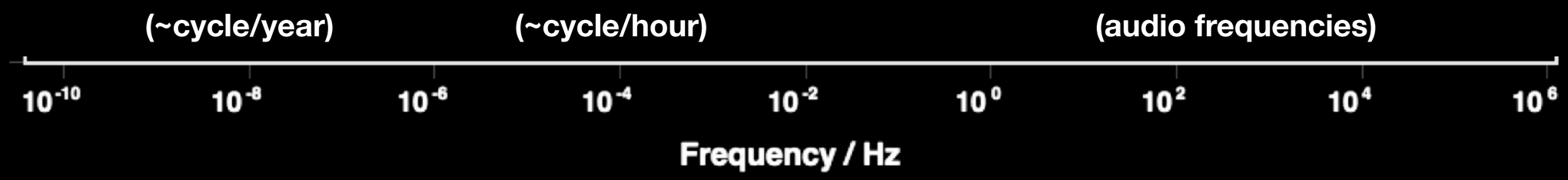
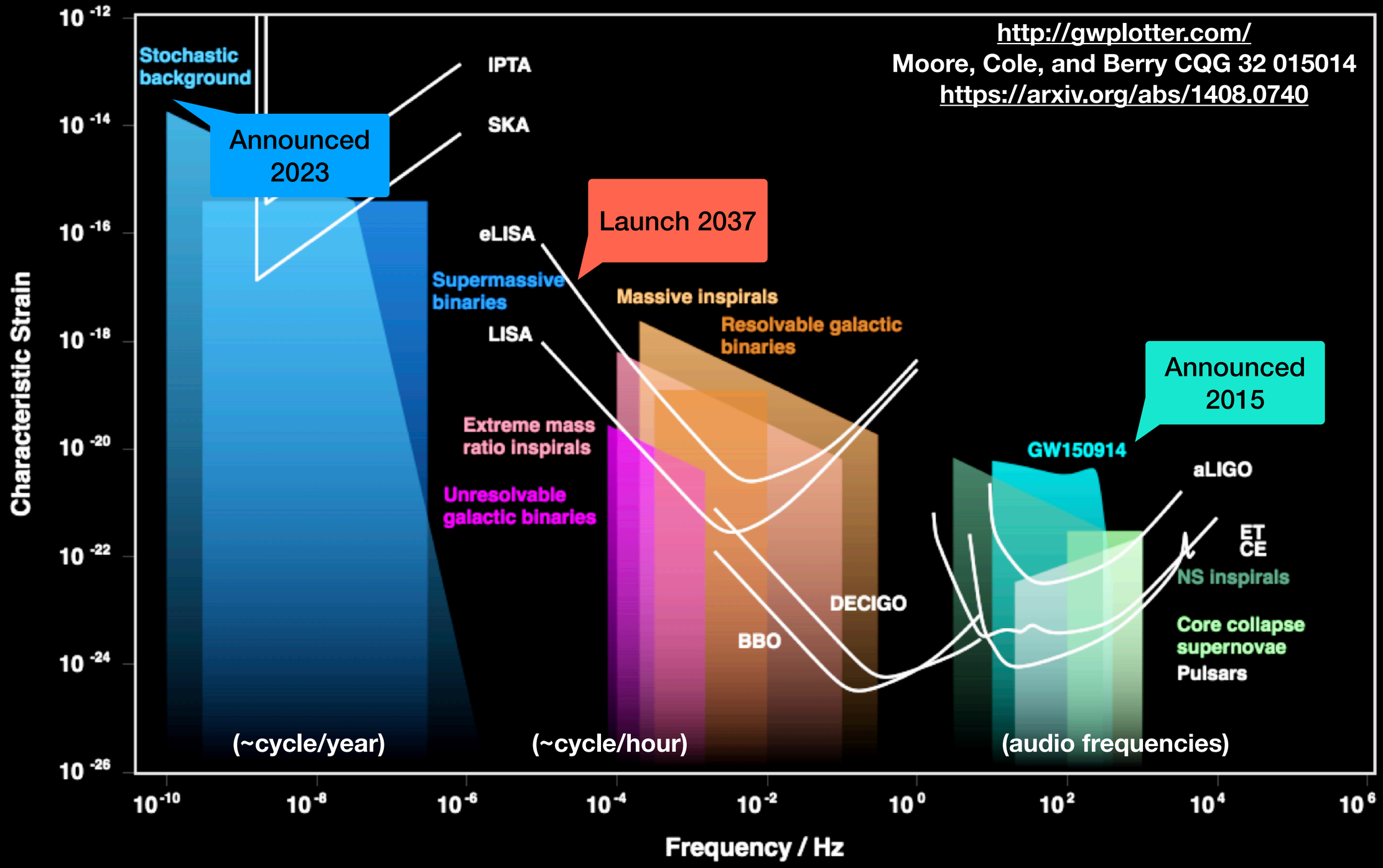
Extreme matter in gravitational waves

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

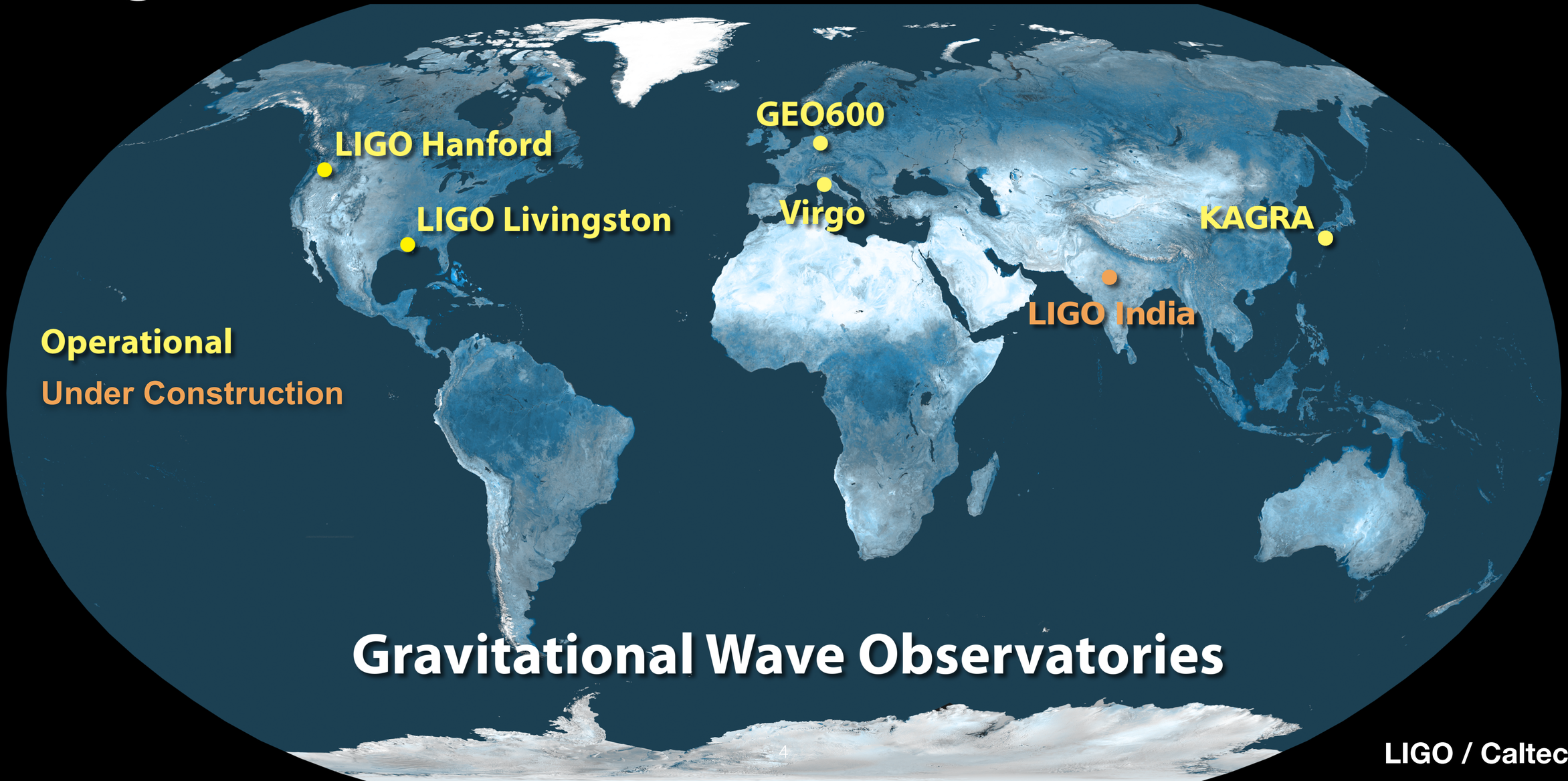
Neutron Stars Merging,
CSUF GWPAC Artist-in-Residence Eddie Anaya

The Gravitational-wave Spectrum




http://gwplotter.com/
Moore, Cole, and Berry CQG 32 015014
https://arxiv.org/abs/1408.0740
Stochastic background
IPTA
SKA
Announced 2023
Launch 2037
eLISA
Supermassive binaries
LISA
Massive inspirals
Resolvable galactic binaries
Extreme mass ratio inspirals
Unresolvable galactic binaries
Announced 2015
GW150914
aLIGO
ET
CE
NS inspirals
DECIGO
BBO
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

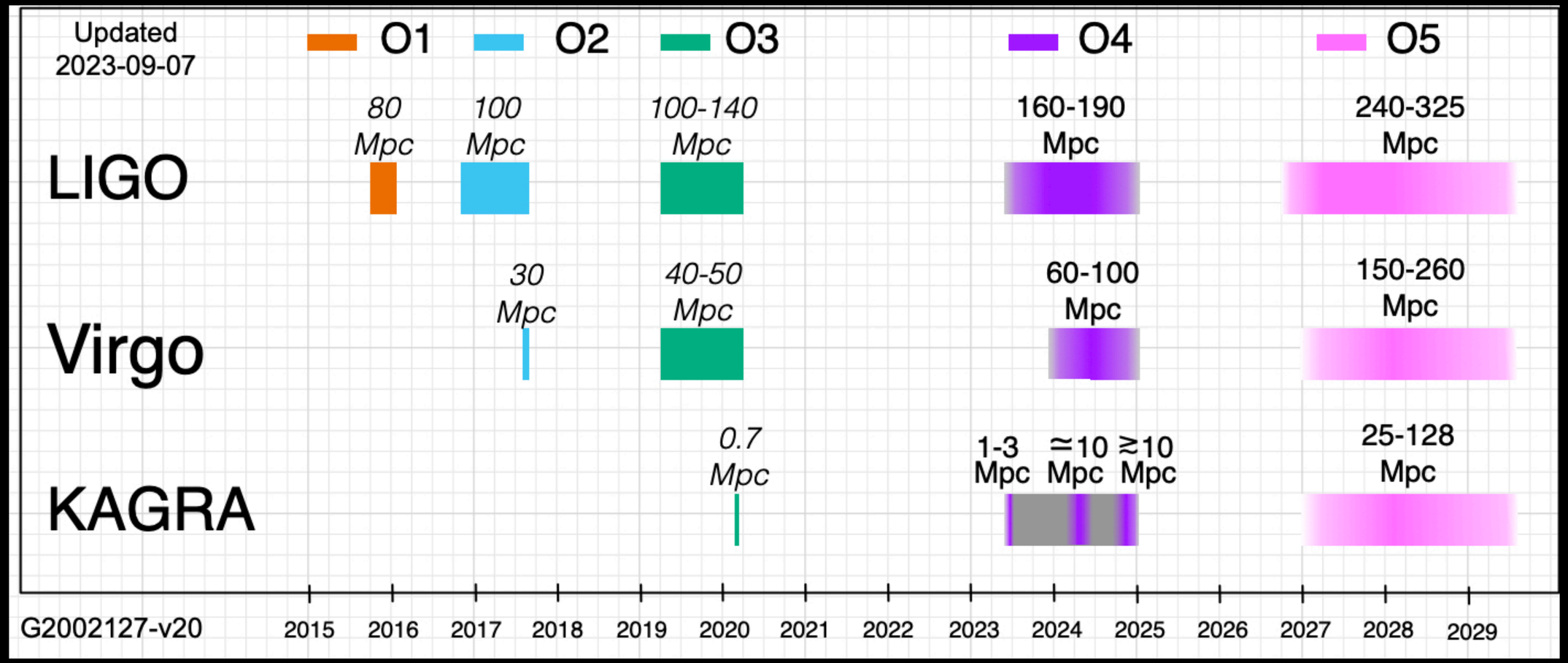
The current generation of audio-band gravitational-wave observatories



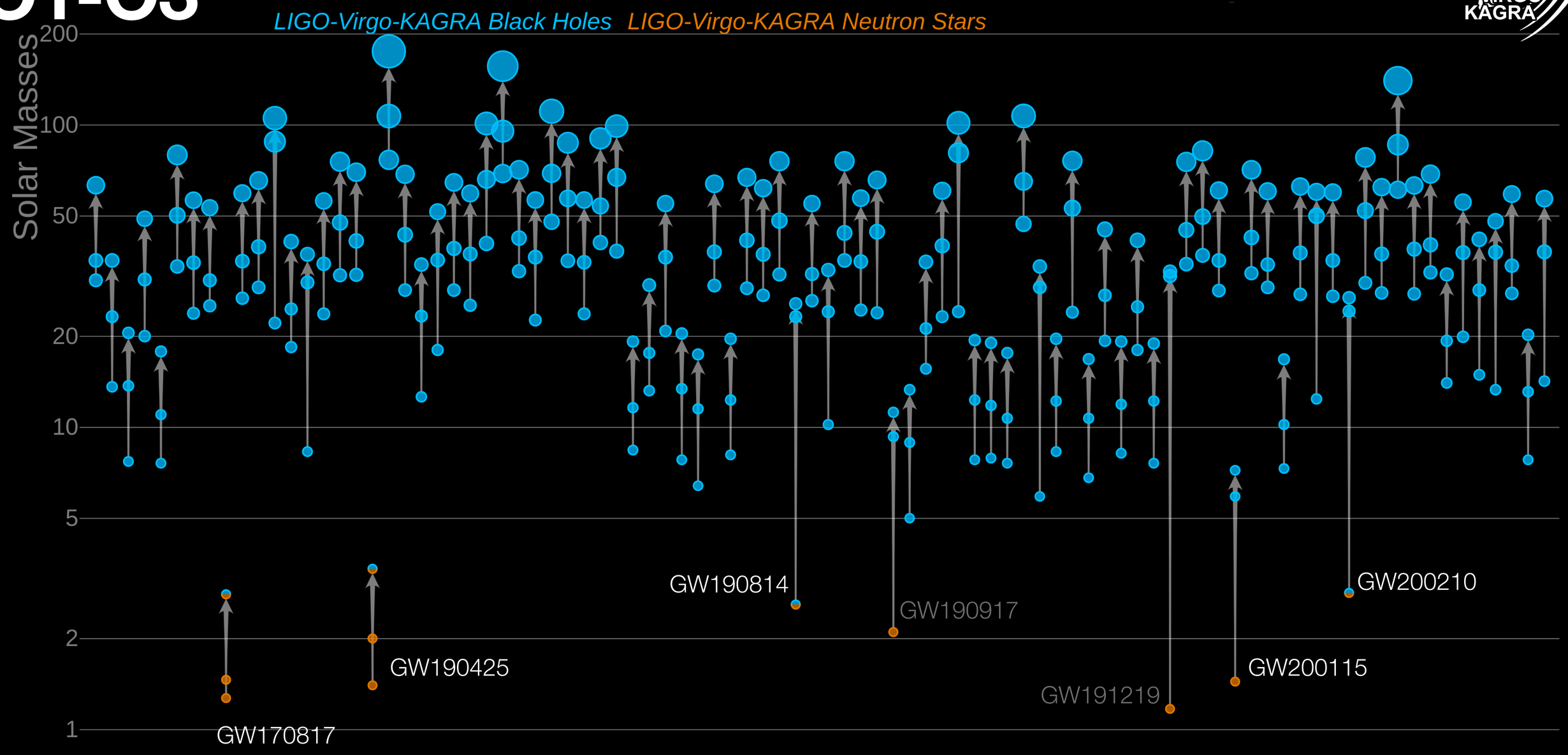
LIGO / Caltech

https://observing.docs.ligo.org/plan/

Observing in the “Advanced” Era



O1-O3

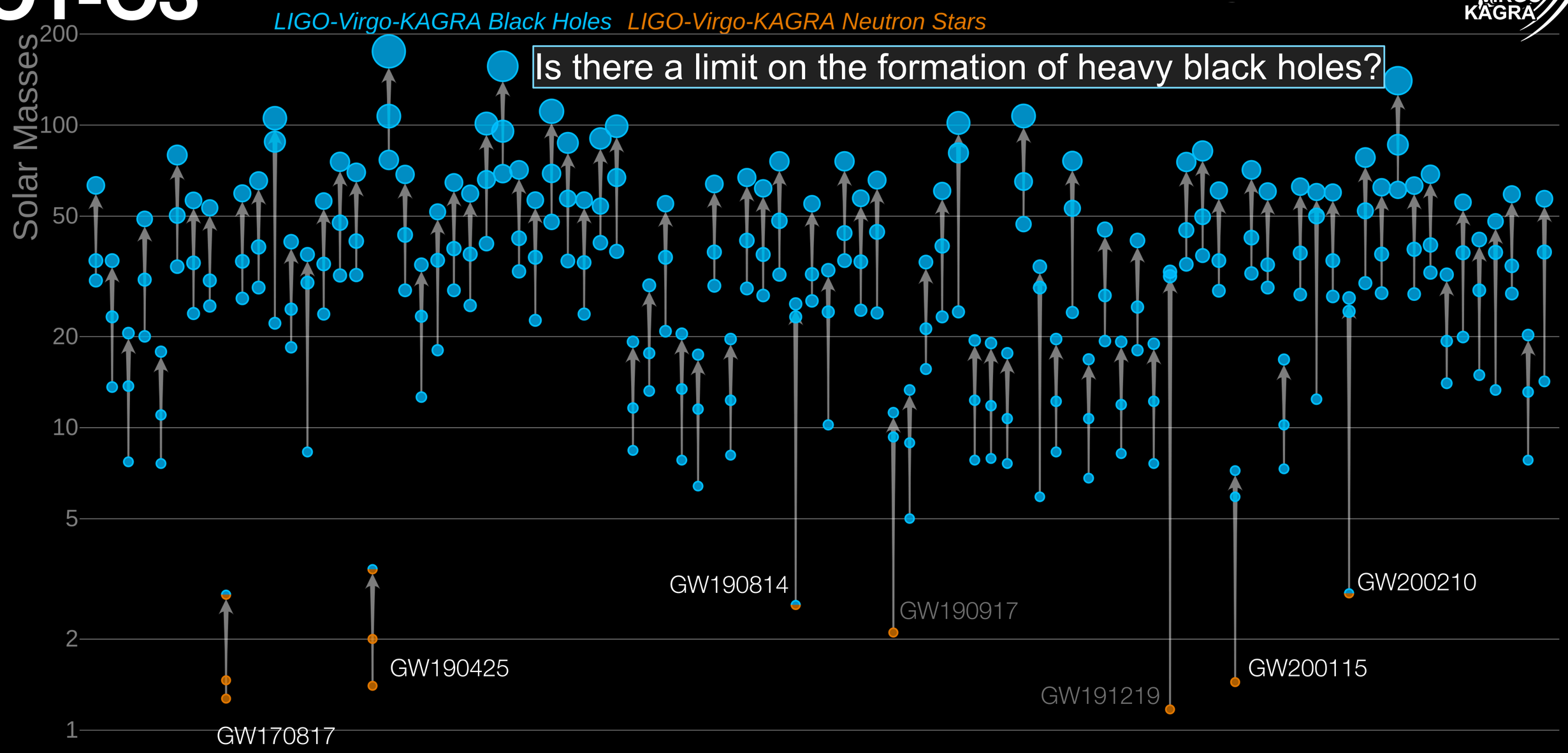


LIGO-Virgo-KAGRA | Aaron Geller | Northwestern

LIGO-Virgo-Kagra GWTC-3 Catalog LIGO-P2000318-v8, arXiv:2111.03606

LIGO-Virgo-Kagra O3 Population, arXiv:2111.03634 (LIGO-P2000318-v7)

O1-O3



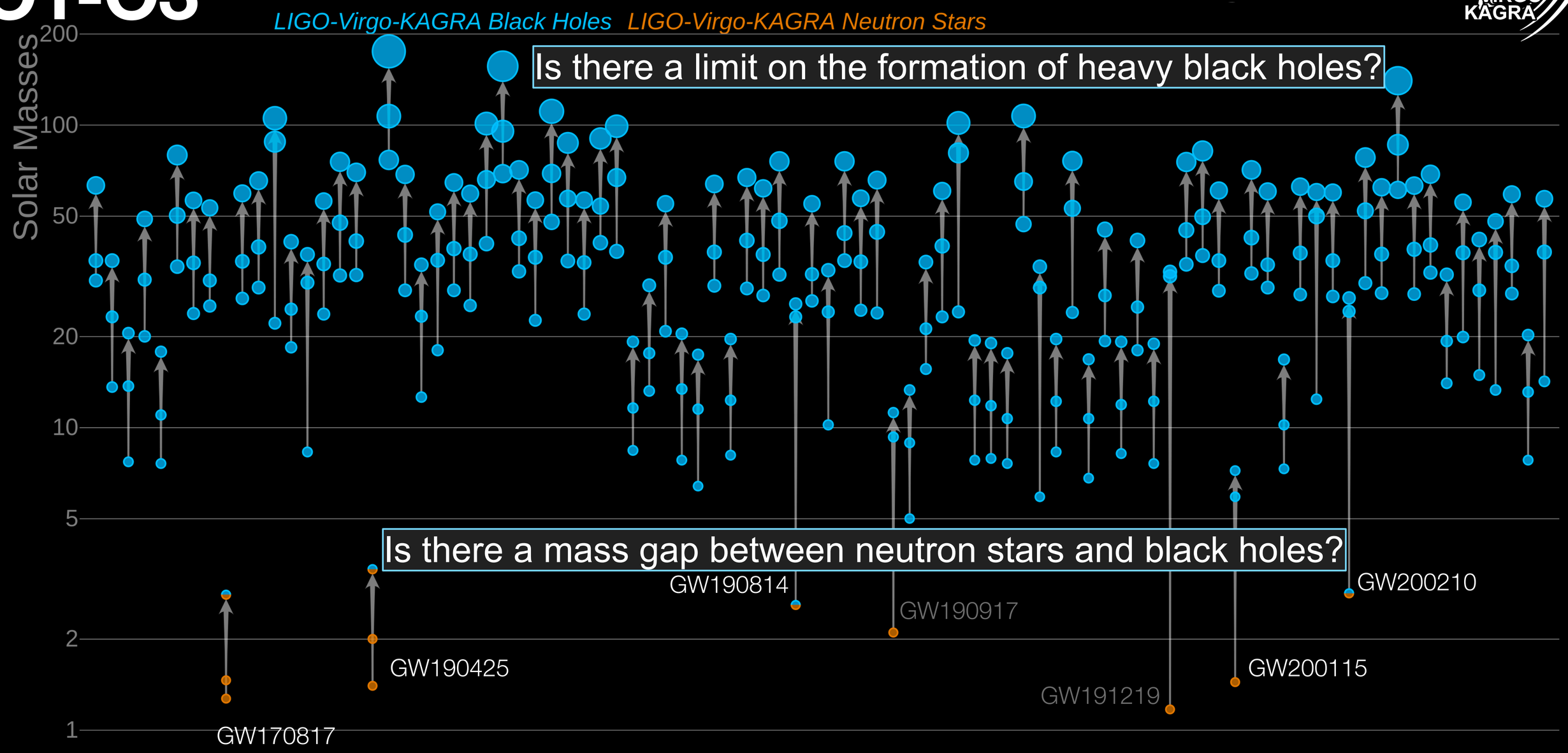
Is there a limit on the formation of heavy black holes?

LIGO-Virgo-KAGRA | Aaron Geller | Northwestern

LIGO-Virgo-Kagra GWTC-3 Catalog LIGO-P2000318-v8, arXiv:2111.03606

LIGO-Virgo-Kagra O3 Population, arXiv:2111.03634 (LIGO-P2000318-v7)

O1-O3

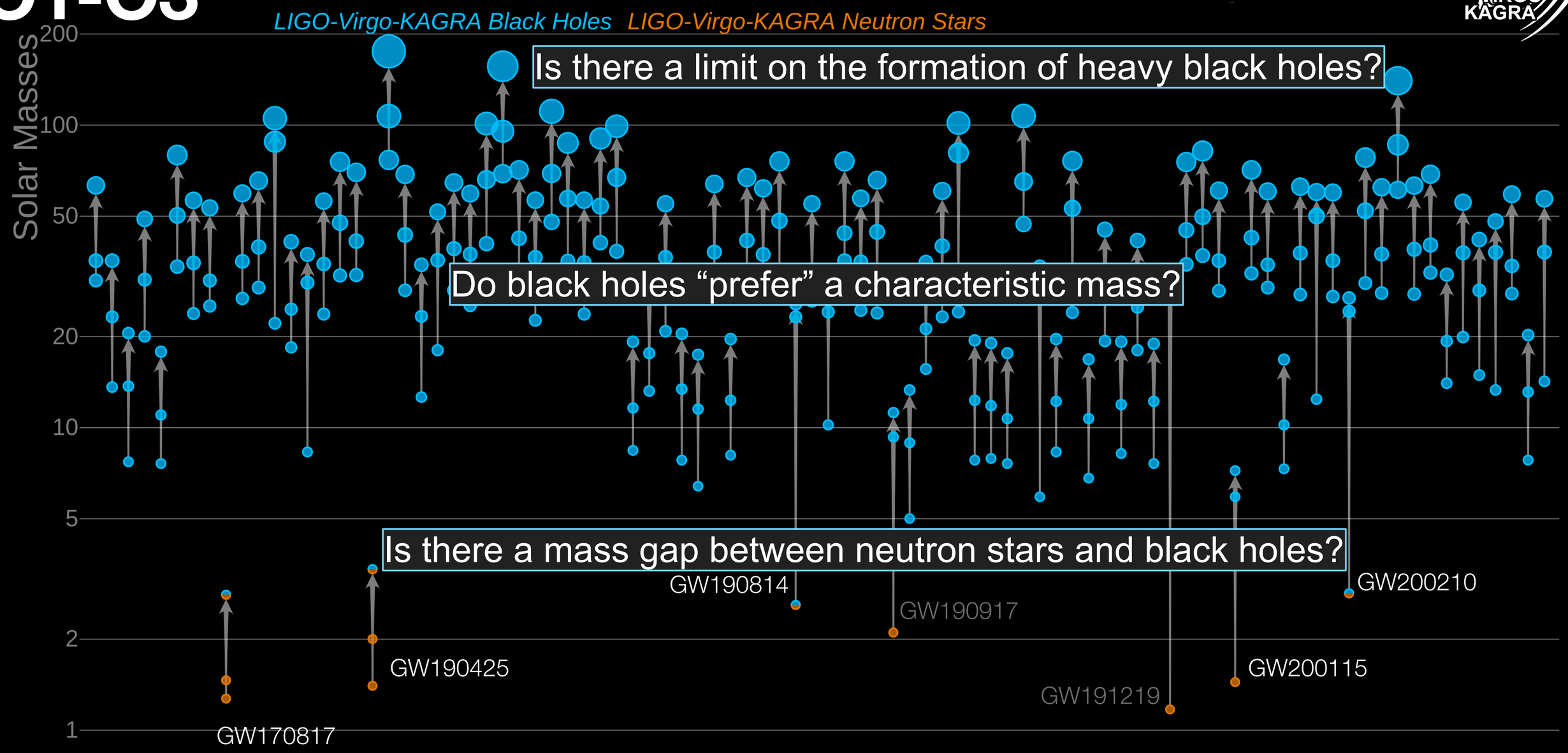


LIGO-Virgo-KAGRA | Aaron Geller | Northwestern

LIGO-Virgo-Kagra GWTC-3 Catalog LIGO-P2000318-v8, arXiv:2111.03606

LIGO-Virgo-Kagra O3 Population, arXiv:2111.03634 (LIGO-P2000318-v7)

O1-O3

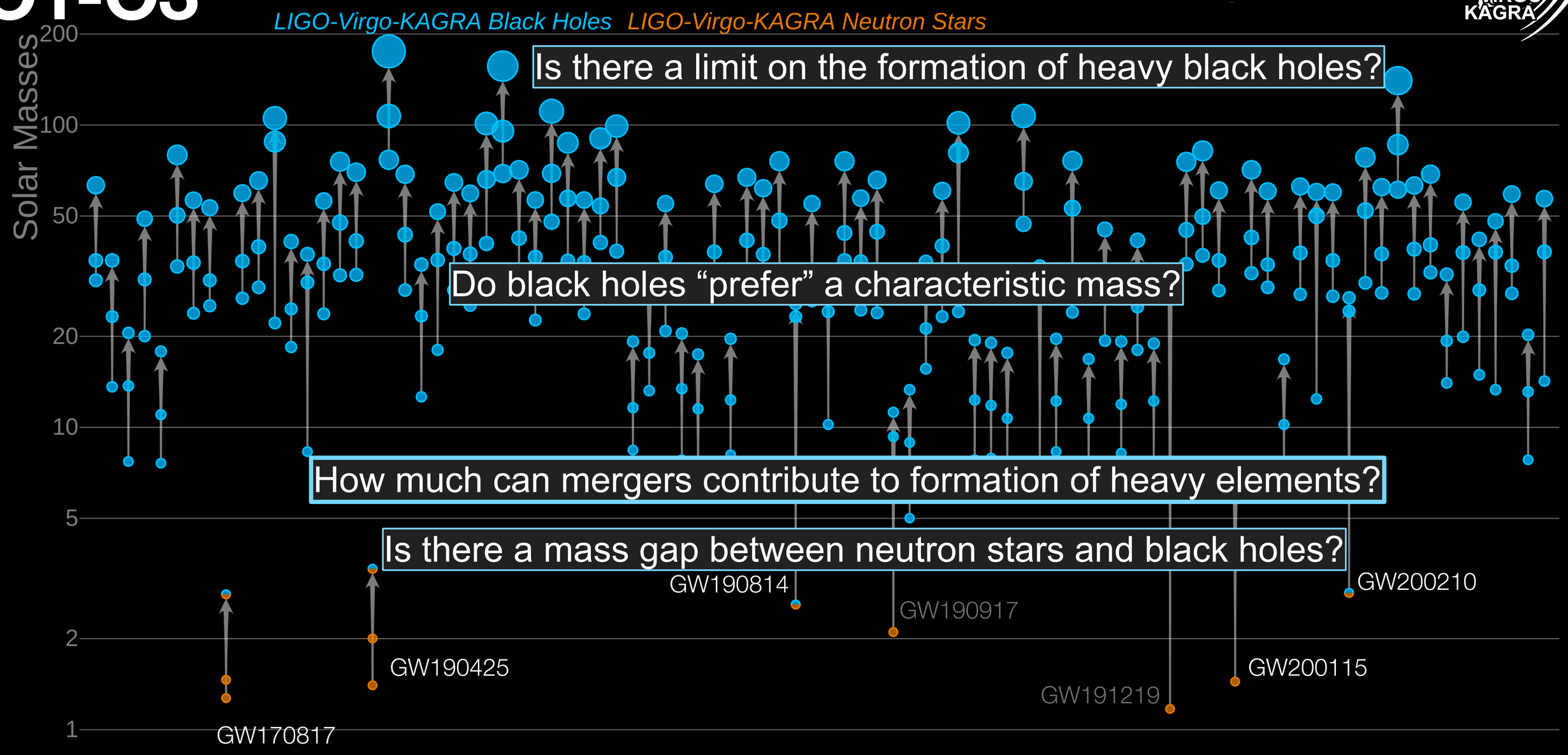


LIGO-Virgo-KAGRA | Aaron Geller | Northwestern

LIGO-Virgo-Kagra GWTC-3 Catalog LIGO-P2000318-v8, arXiv:2111.03606

LIGO-Virgo-Kagra O3 Population, arXiv:2111.03634 (LIGO-P2000318-v7)

O1-O3

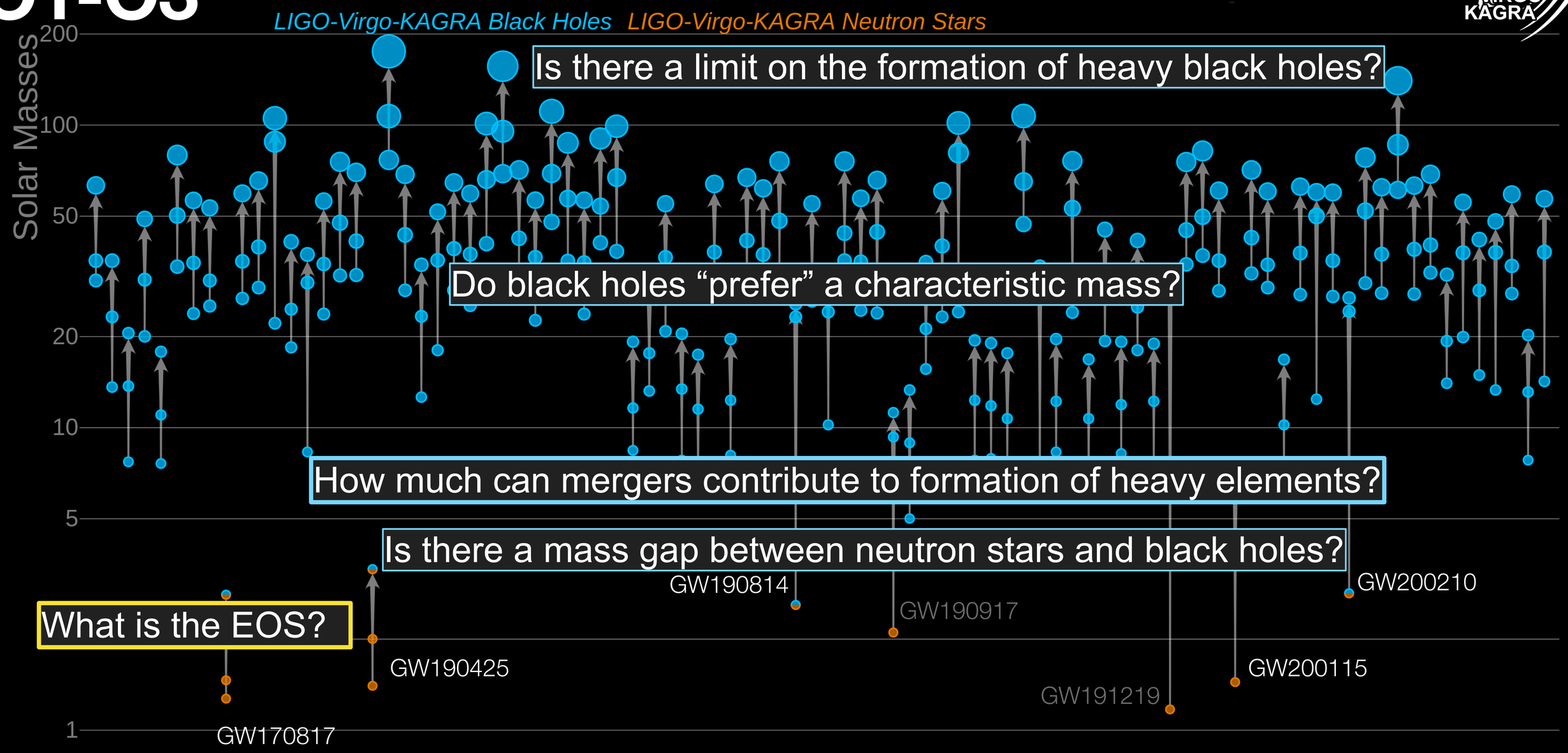


LIGO-Virgo-KAGRA | Aaron Geller | Northwestern

LIGO-Virgo-Kagra GWTC-3 Catalog LIGO-P2000318-v8, arXiv:2111.03606

LIGO-Virgo-Kagra O3 Population, arXiv:2111.03634 (LIGO-P2000318-v7)

O1-O3

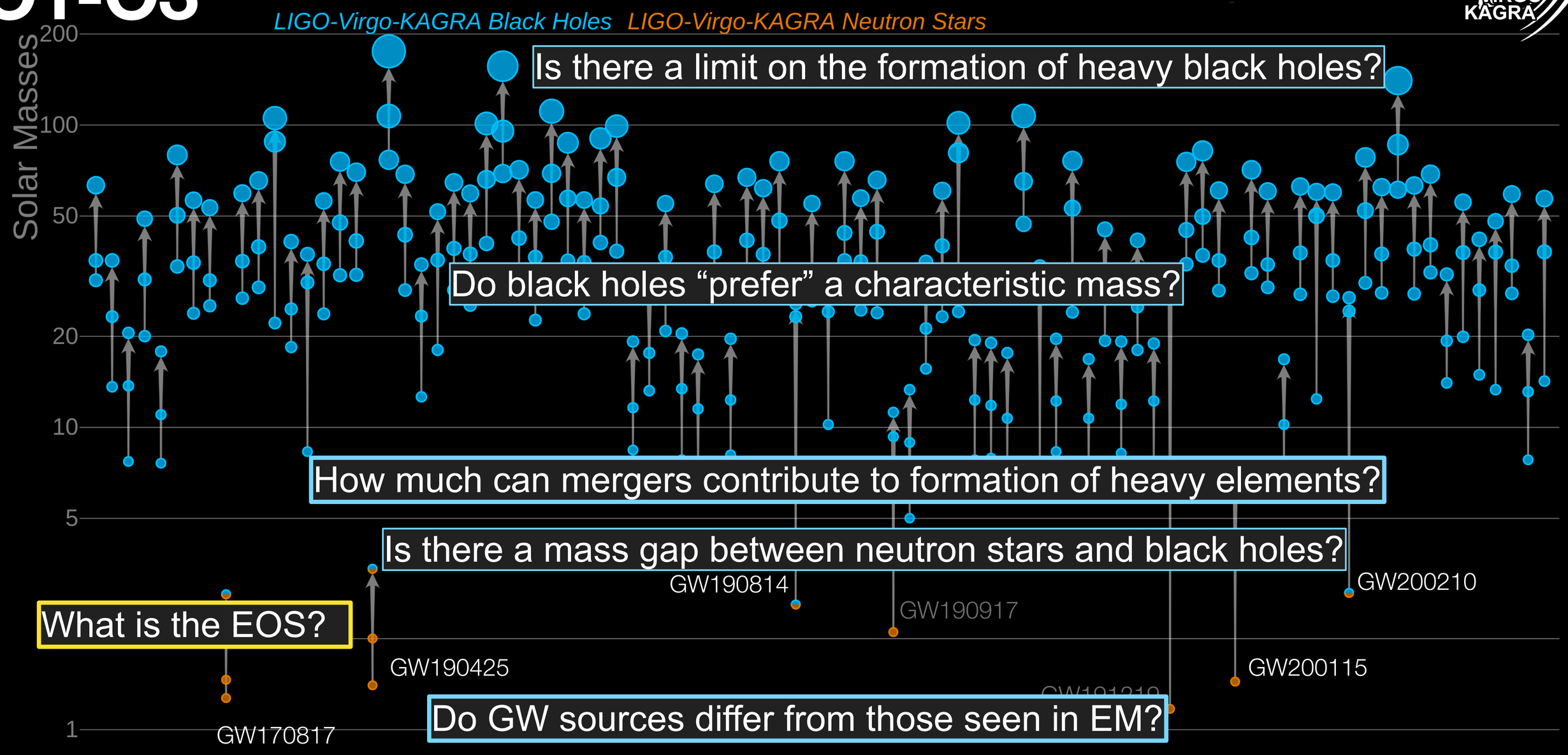


LIGO-Virgo-KAGRA | Aaron Geller | Northwestern

LIGO-Virgo-Kagra GWTC-3 Catalog LIGO-P2000318-v8, arXiv:2111.03606

LIGO-Virgo-Kagra O3 Population, arXiv:2111.03634 (LIGO-P2000318-v7)

O1-O3

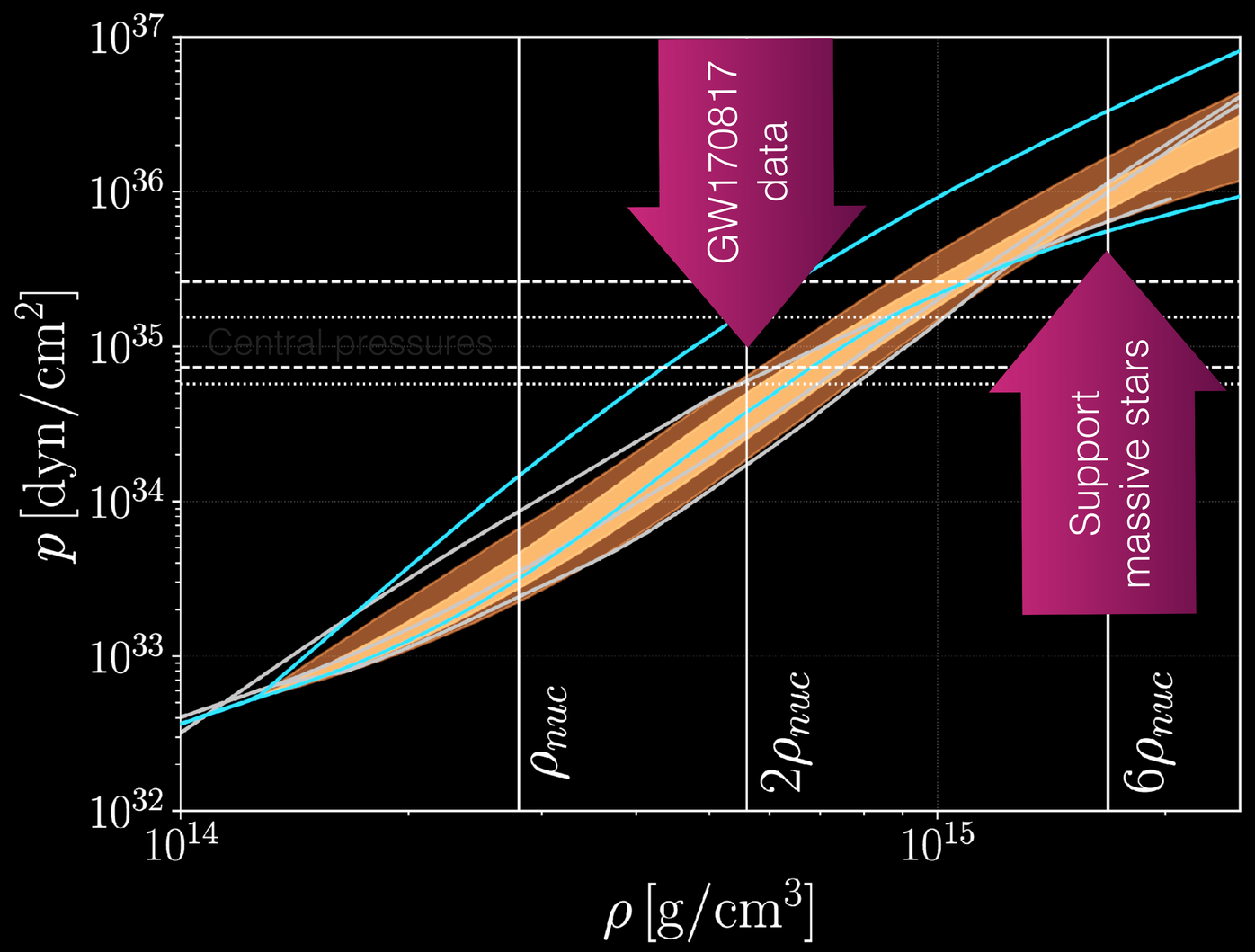


LIGO-Virgo-KAGRA | Aaron Geller | Northwestern

LIGO-Virgo-Kagra GWTC-3 Catalog LIGO-P2000318-v8, arXiv:2111.03606

LIGO-Virgo-Kagra O3 Population, arXiv:2111.03634 (LIGO-P2000318-v7)

Equation of state implications in 2017: GW170817



Prior
90% range

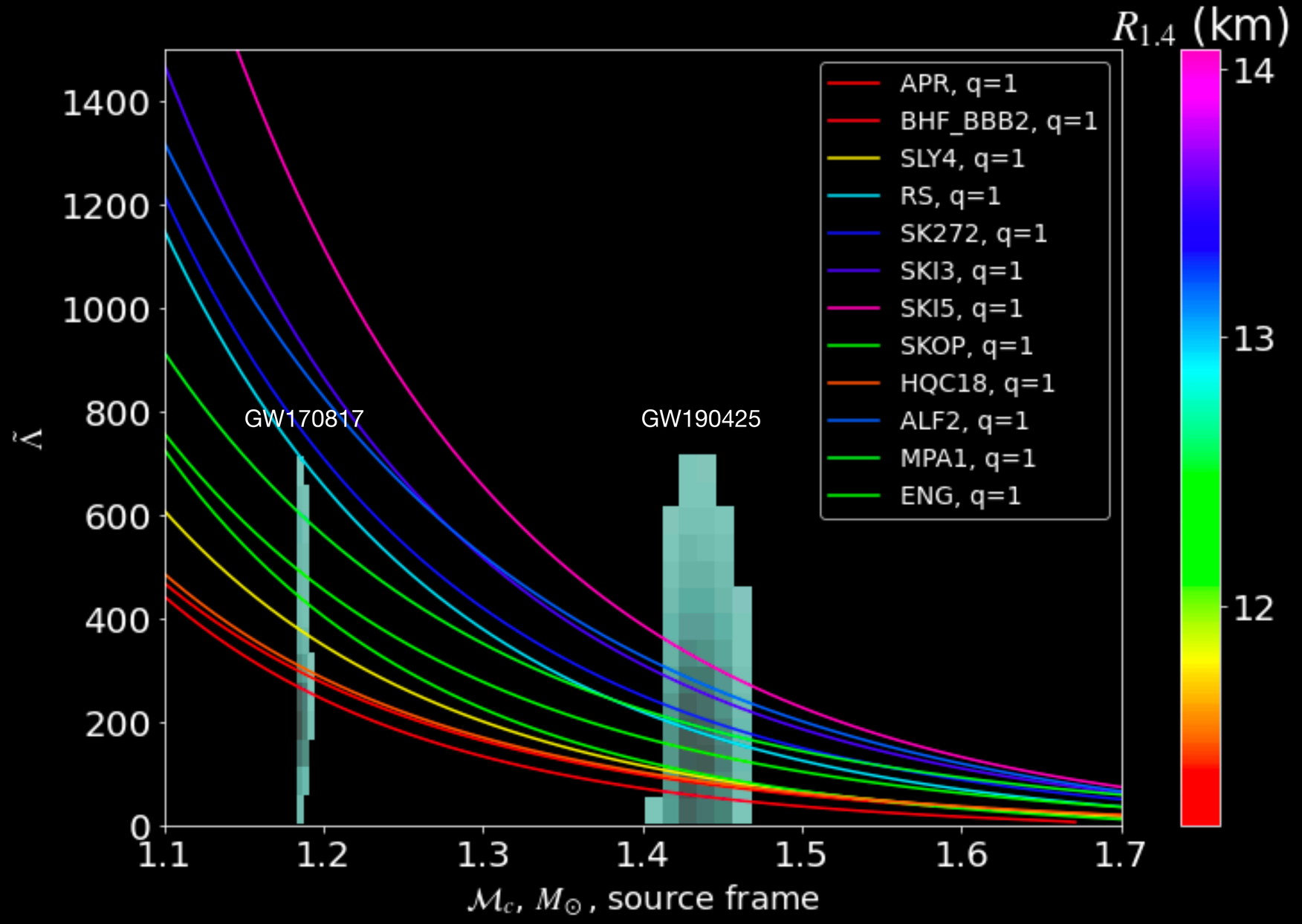
Posterior
90% (50%) range

For comparison:
H4 (top)
APR4
WFF1 (bottom)

Talks this morning: add GW190425, NICER, χEFT, AT2017gfo, GRB170817A, dark-GW190425, HIC, …

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

EOS from tides in binary neutron stars



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

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

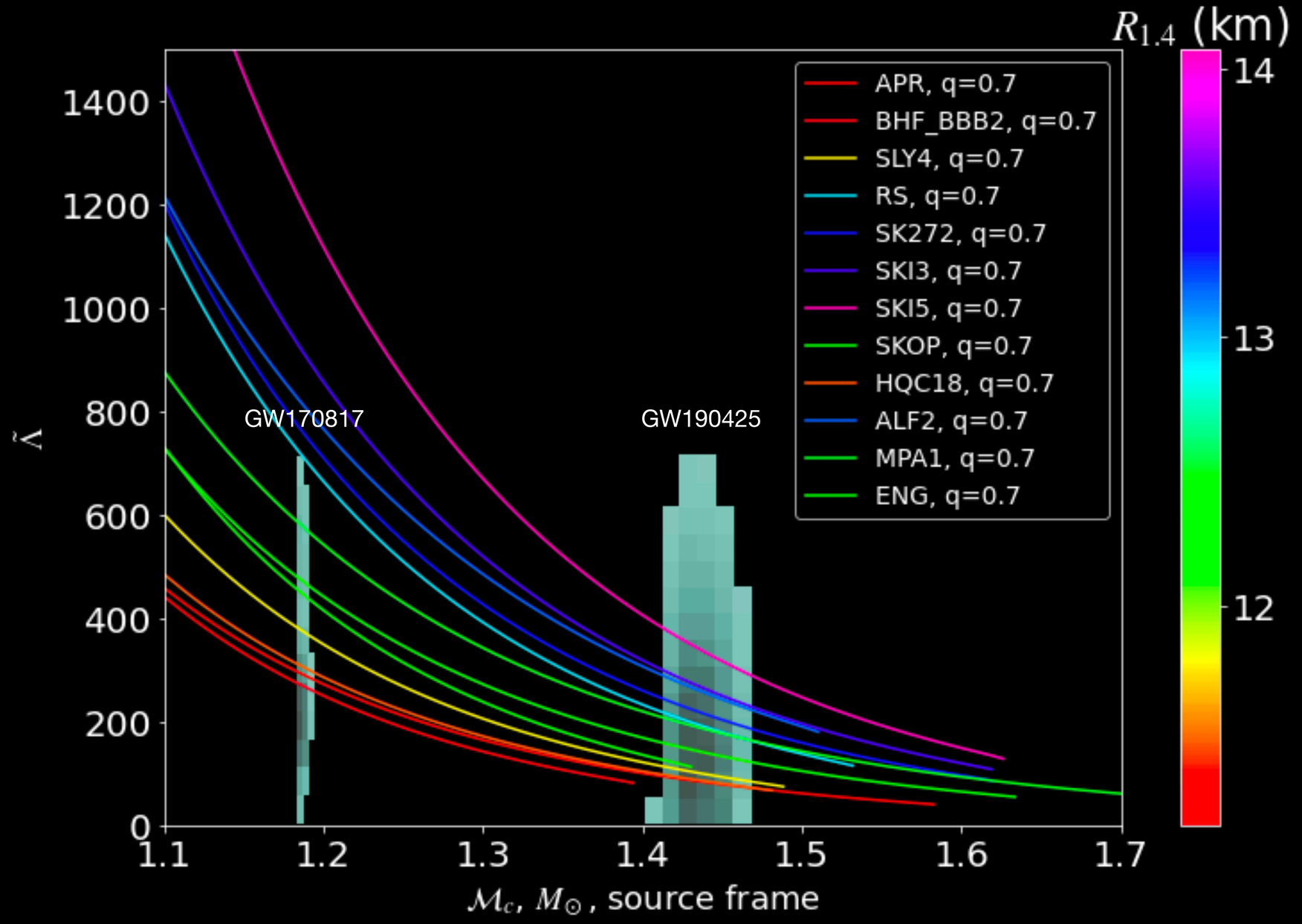
Weak dependence on mass ratio $q = m_2/m_1$

GW170817 from LIGO/Virgo GWTC-1 data release, P1800370, Phys. Rev. X 9, 031040 (2019)

GW190425 from LIGO/Virgo GWTC-2 data release, P2000223, Phys. Rev. X 11, 021053 (2021)

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

EOS from tides in binary neutron stars



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

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

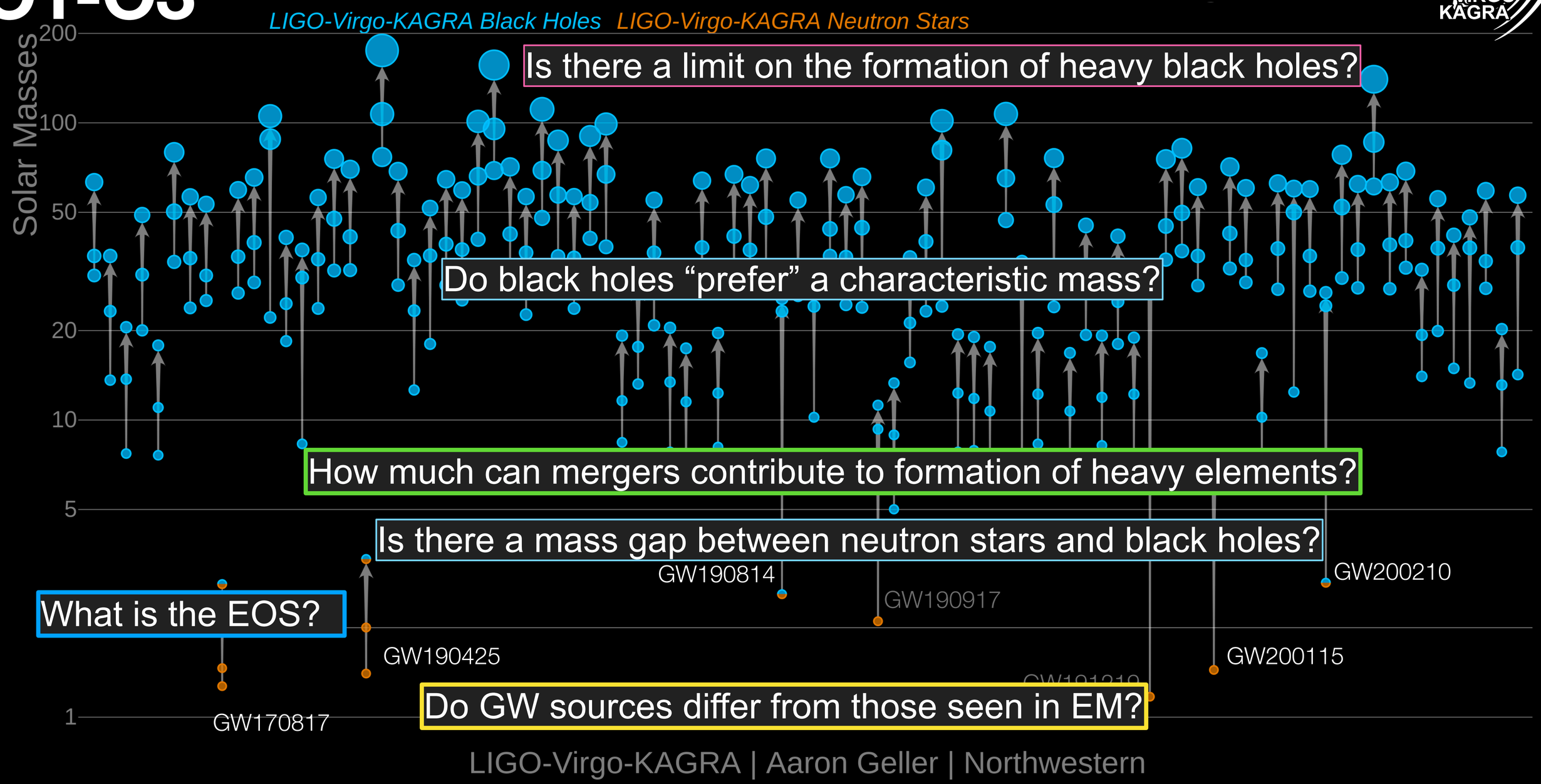
Weak dependence on mass ratio $q = m_2/m_1$

GW170817 from LIGO/Virgo GWTC-1 data release, P1800370, Phys. Rev. X 9, 031040 (2019)

GW190425 from LIGO/Virgo GWTC-2 data release, P2000223, Phys. Rev. X 11, 021053 (2021)

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

O1-O3

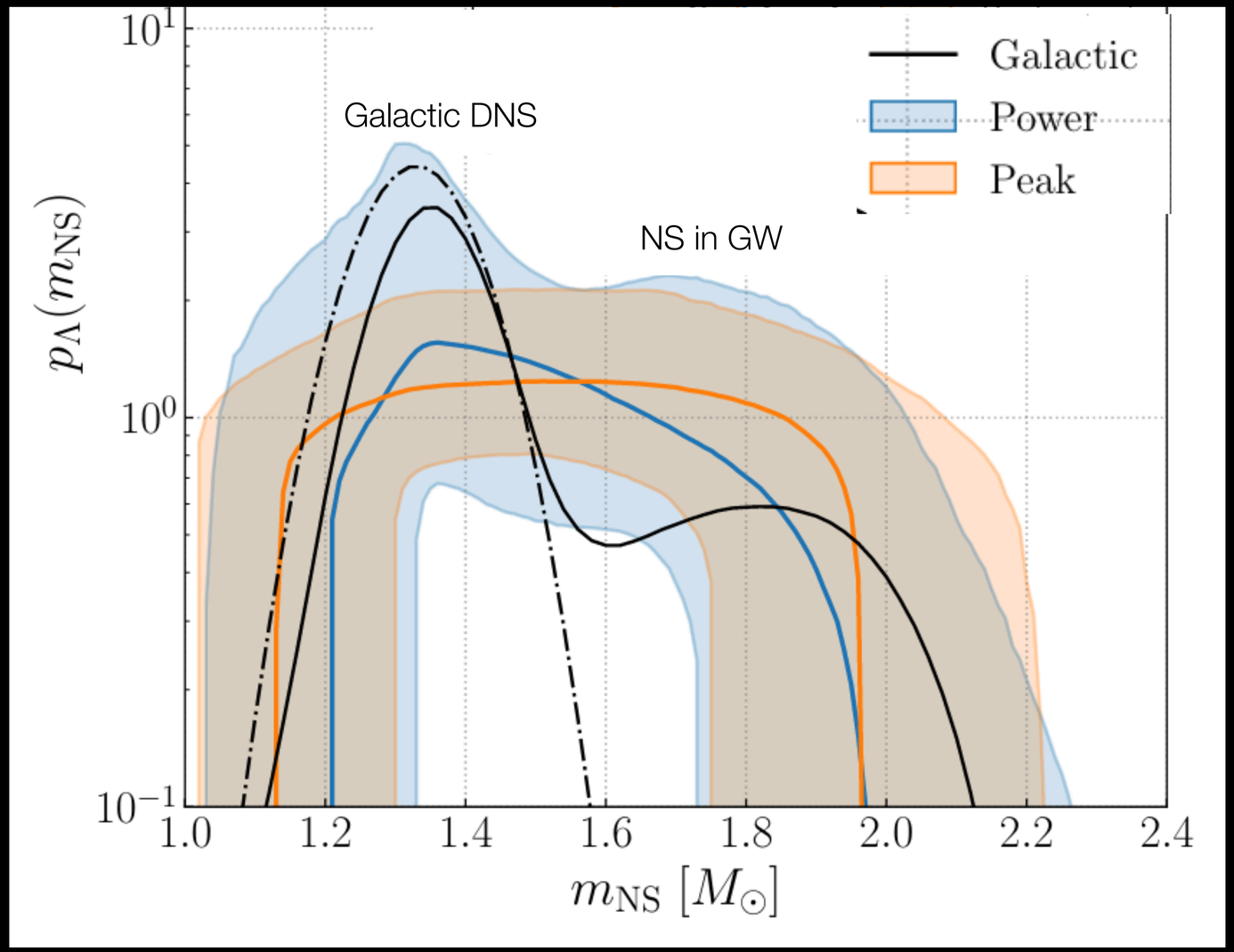


LIGO-Virgo-KAGRA | Aaron Geller | Northwestern

LIGO-Virgo-Kagra GWTC-3 Catalog LIGO-P2000318-v8, arXiv:2111.03606

LIGO-Virgo-Kagra O3 Population, arXiv:2111.03634 (LIGO-P2000318-v7)

Neutron star population in GW



GWTC-3 NS-NS 10-1700 Gpc^{-3} yr^{-1}

GWTC-3 BH-NS 7.8-140 Gpc^{-3} yr^{-1}

GWTC-3 BH-BH 17.9-44 Gpc^{-3} yr^{-1}

Flatter mass distribution than galactic: high-mass NS in GW190425, GW200105, GW190917.

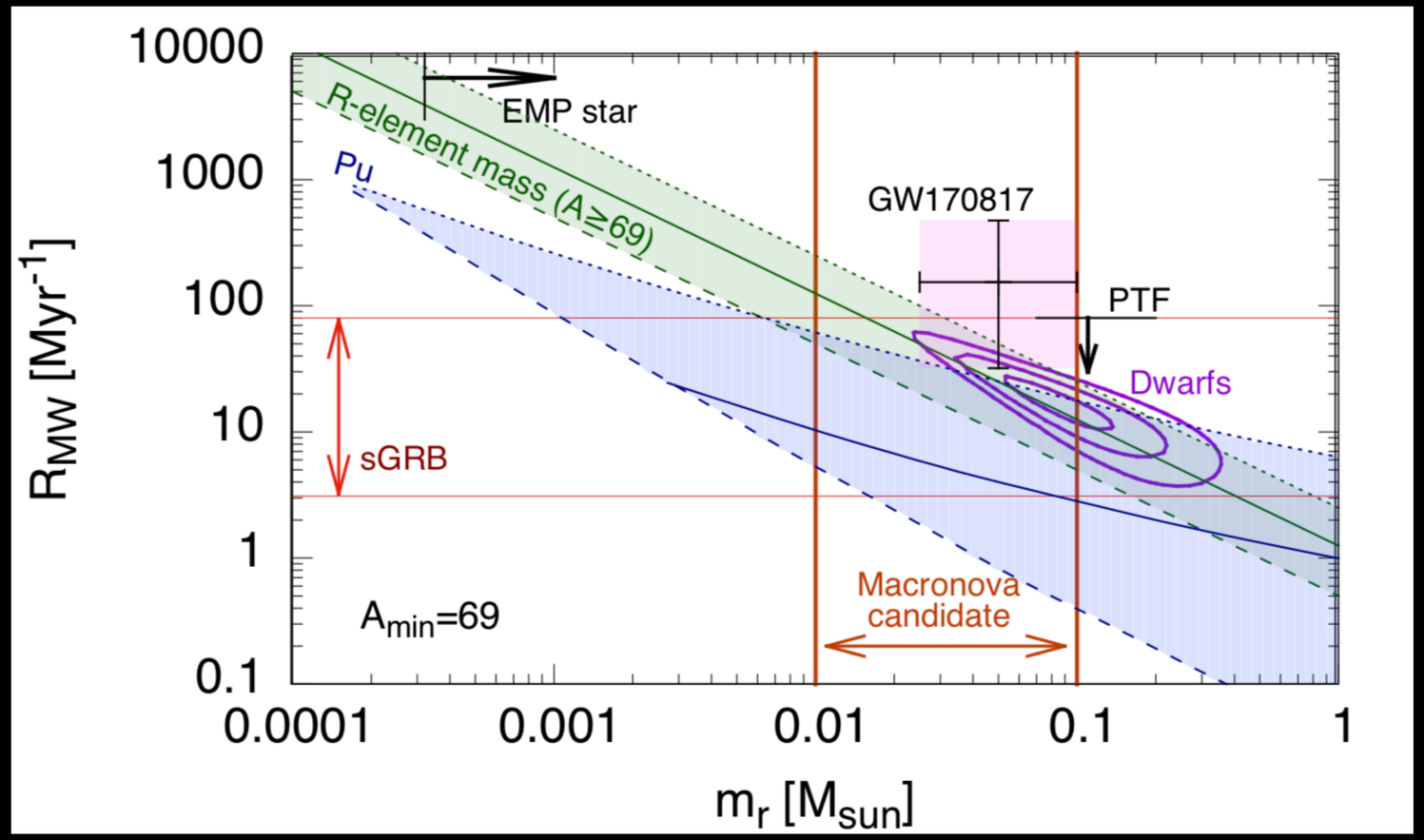
GW190814 expected to be BH from EOS

LIGO-Virgo-Kagra O3 Population, arXiv:2111.03634 (LIGO-P2000318-v7)

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

How much do BNS contribute to galactic nucleosynthesis?

- Merger rates and masses distributions from LVK O3
- 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)
- Delay from star formation following sGRB (Michael Zevin et al 2022 ApJL 940 L18)

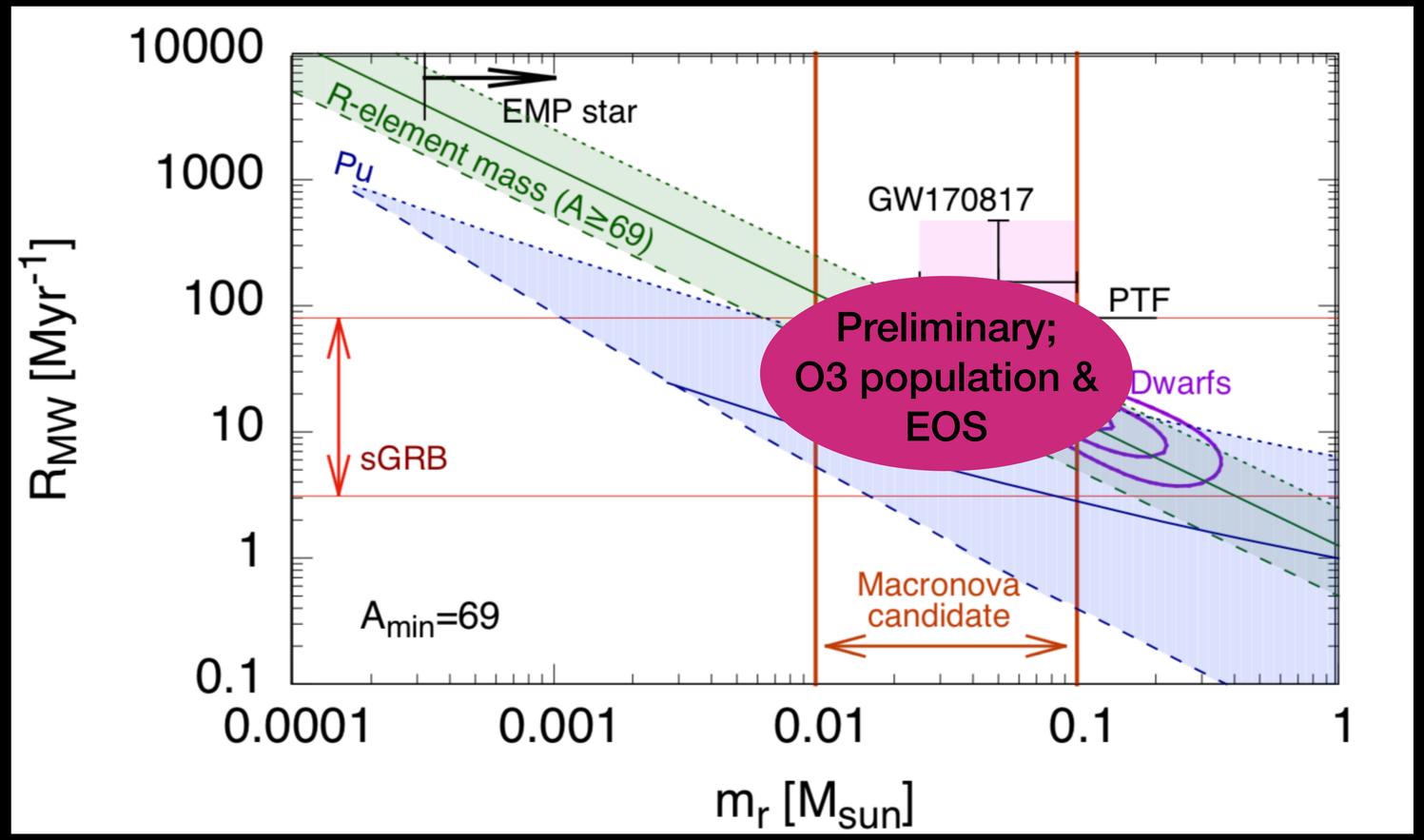


R/m_r plot: Hotokezaka, Beniamini, Piran 2018

Update NS contribution: Hsin-Yu Chen, Phil Landry, J Read, D. Siegel, in prep

How much do BNS contribute to galactic nucleosynthesis?

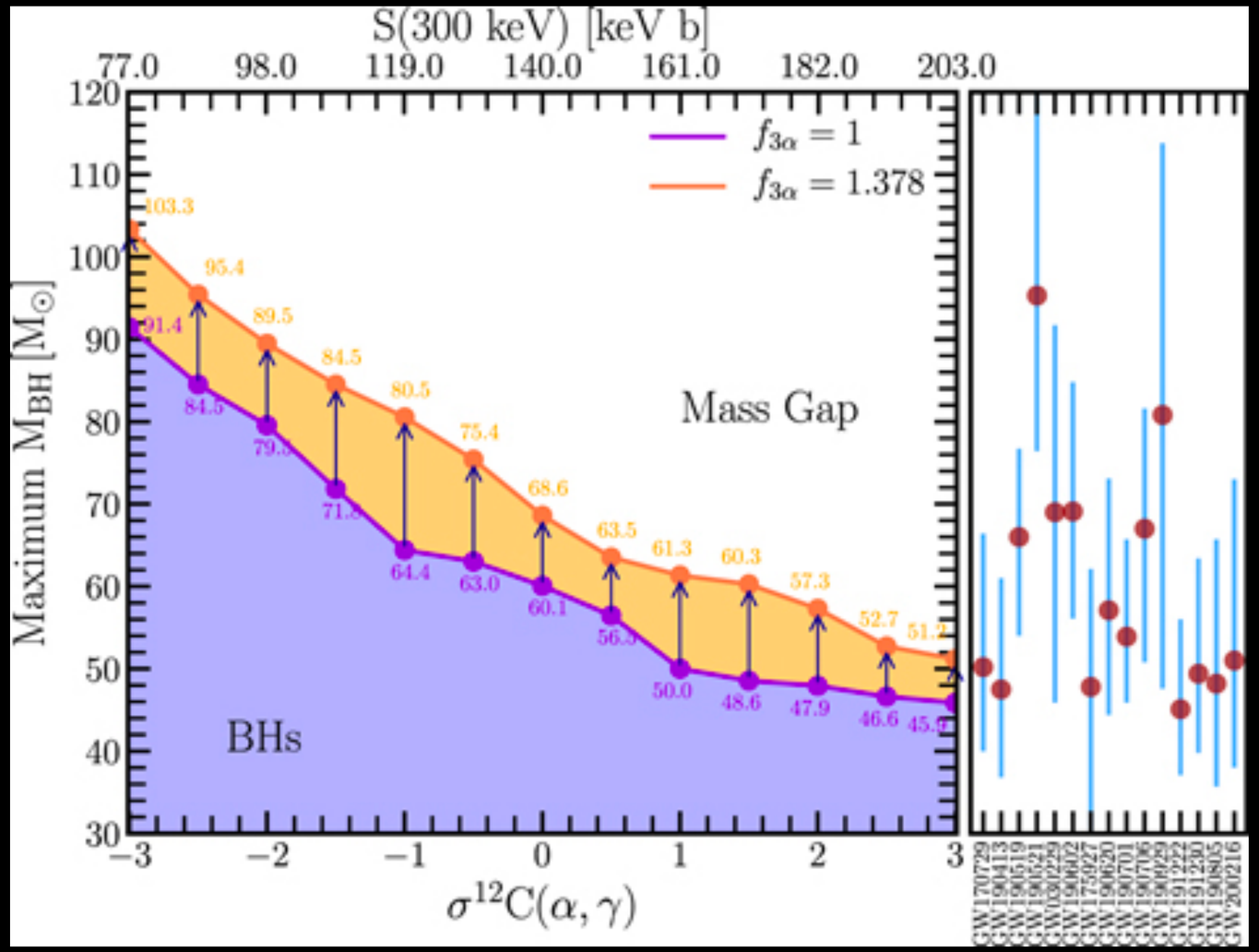
- Merger rates and masses distributions from LVK O3
- EOS distribution from nonparametric inference using LVK/NICER/Pulsar masses
- Ejecta mass per system from simulation-calibrated formulae (see Hsin-Yu Chen et al 2021 ApJL 920 L3)
- Delay from star formation following sGRB (Michael Zevin et al 2022 ApJL 940 L18)



R/m_r plot: Hotokezaka, Beniamini, Piran 2018

Update NS contribution: Hsin-Yu Chen, Phil Landry, J Read, D. Siegel, in prep

Black hole implications for nuclear physics: Supernovae depend on temperature-dependant uncertainty in $^{12}C(\alpha,\gamma)^{16}O$ reaction rate

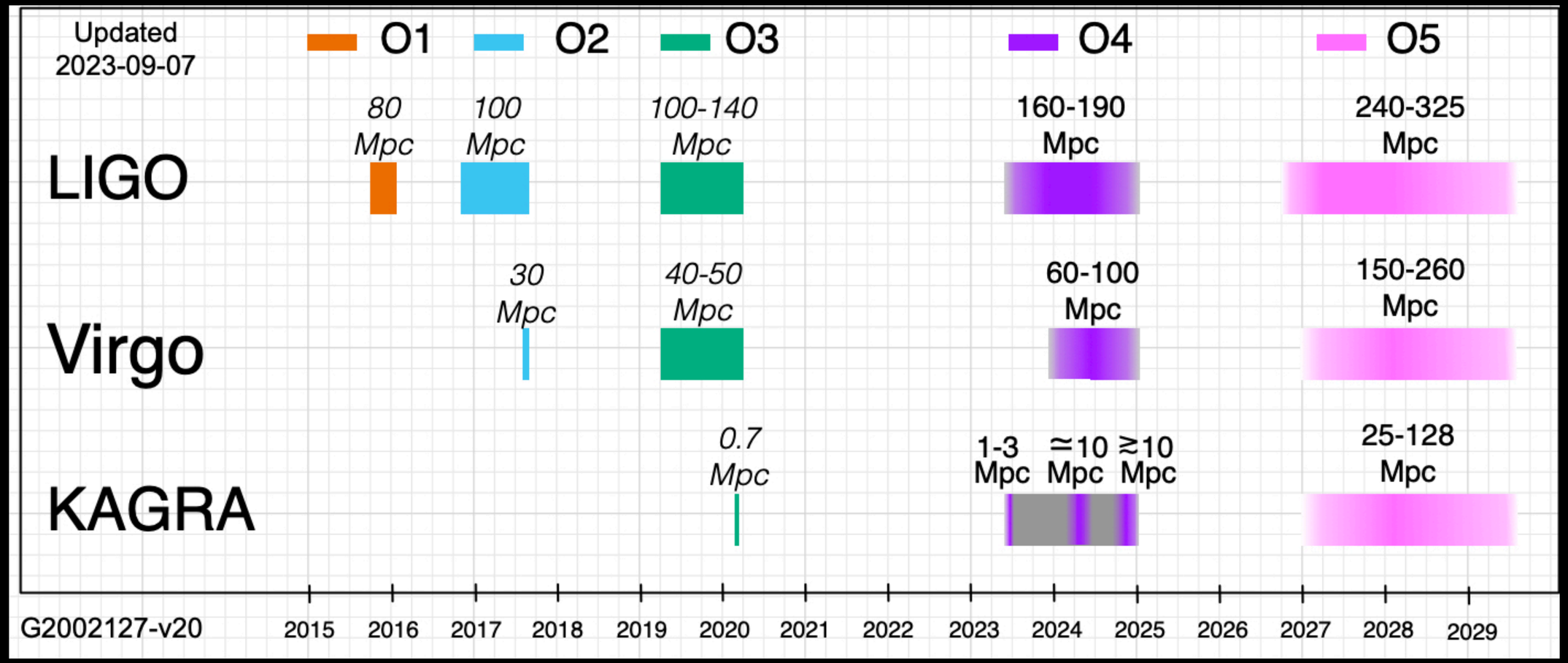


BH Masses from GWTC-3

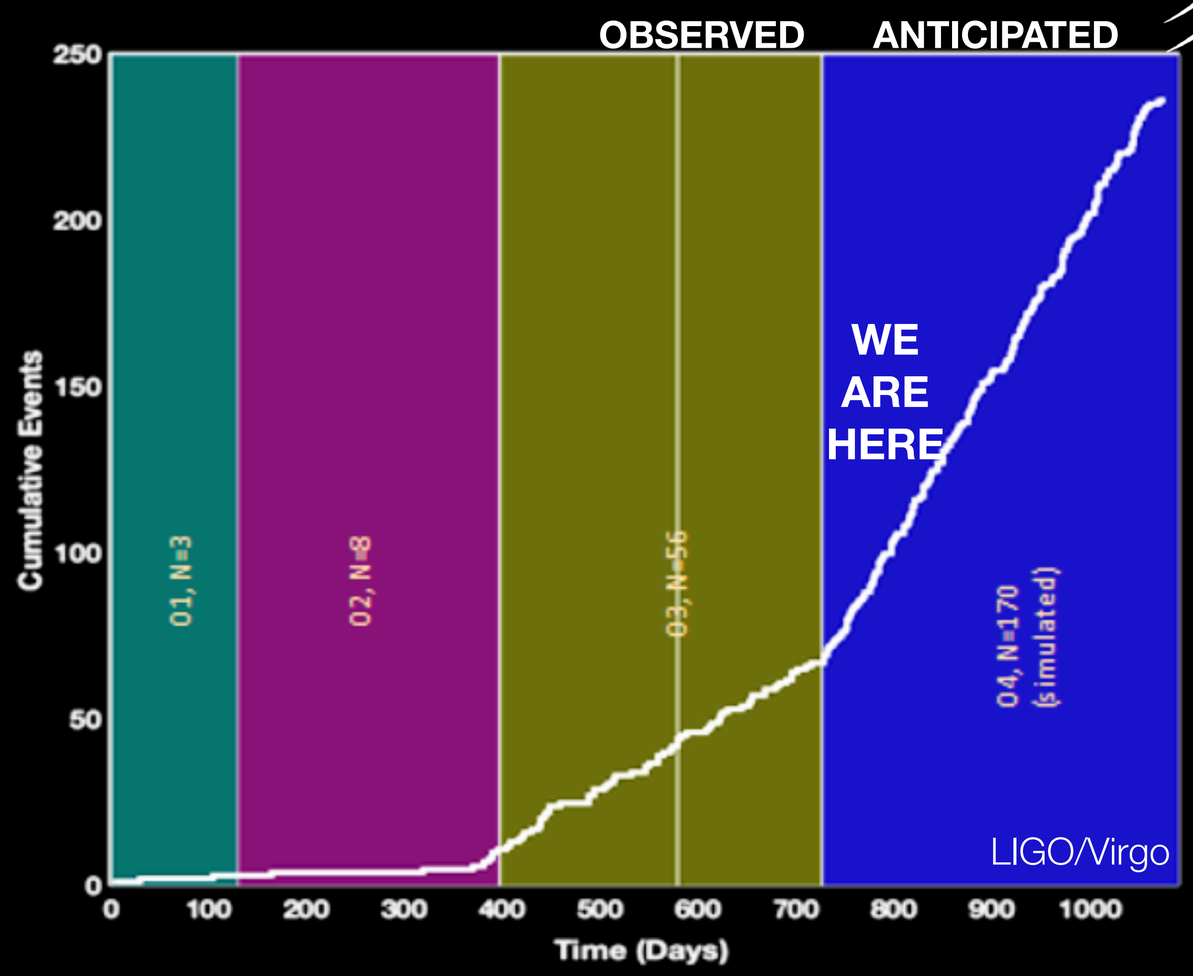
Ebraheem Farag *et al* 2022 *ApJ* **937** 112,
see also Michael Zevin et al 2020 ApJL 899 L1

https://observing.docs.ligo.org/plan/

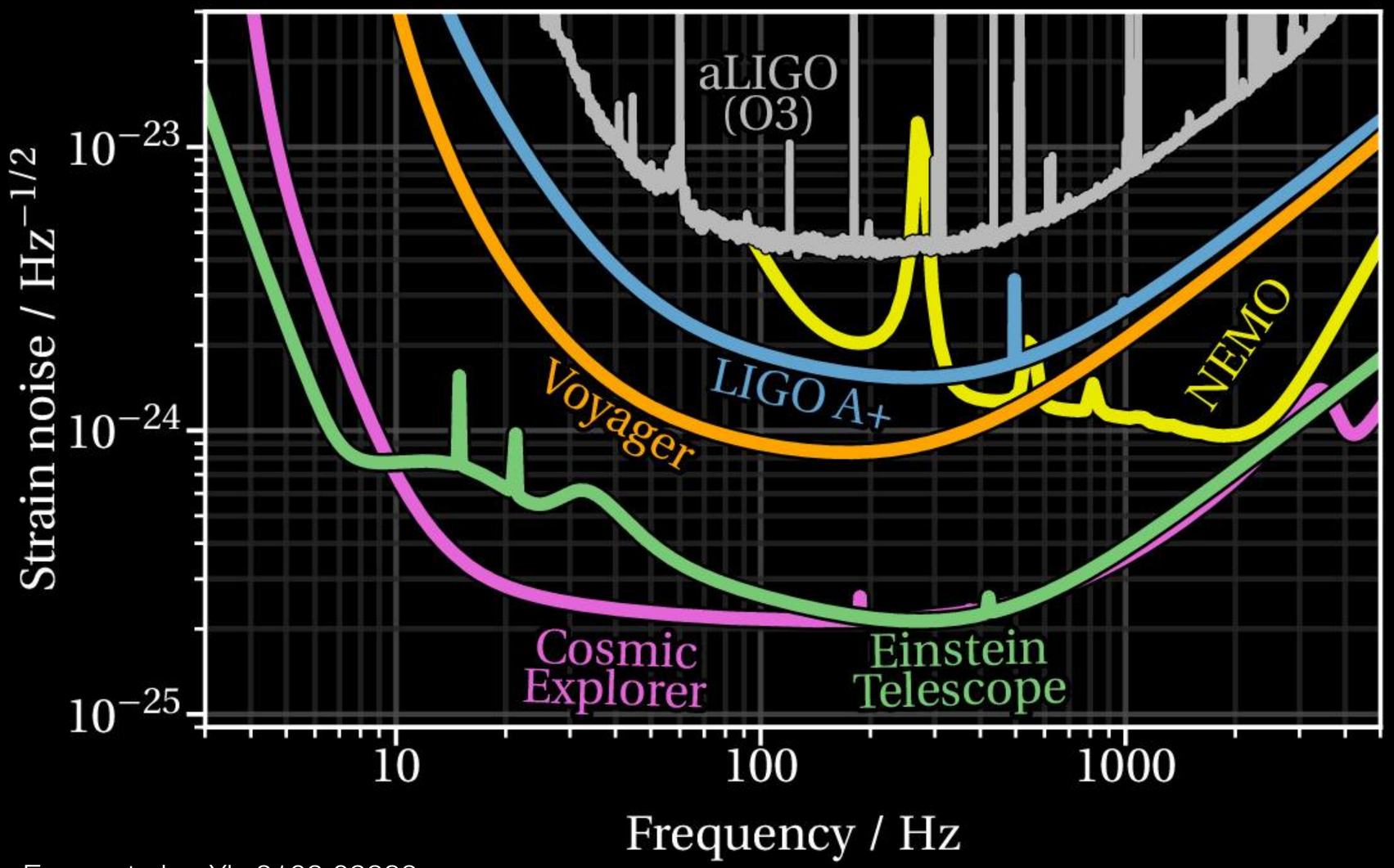
Observing in the “Advanced” Era



- 45 “significant” alerts in 2023 so far (https://gracedb.ligo.org/superevents/public/O4/)
- Which have a NS? S230518h, S230529ay, maybe S230627c (all NSBH)
- O4 target BNS search volume of 0.016 Gpc^3 yr (~4x previous total, LVK Observing Scenarios Document, LIGO-P1200087)
- “Offline” search may identify additional candidates

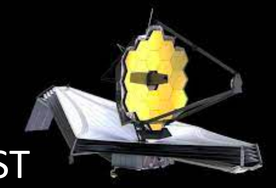


Audio-band GW Landscape

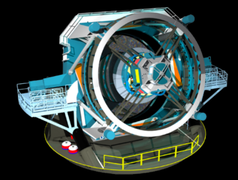


Current generation

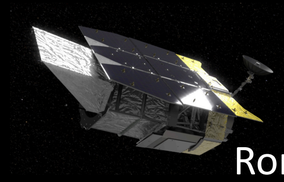
Next-generation (~2035)



JWST



Rubin

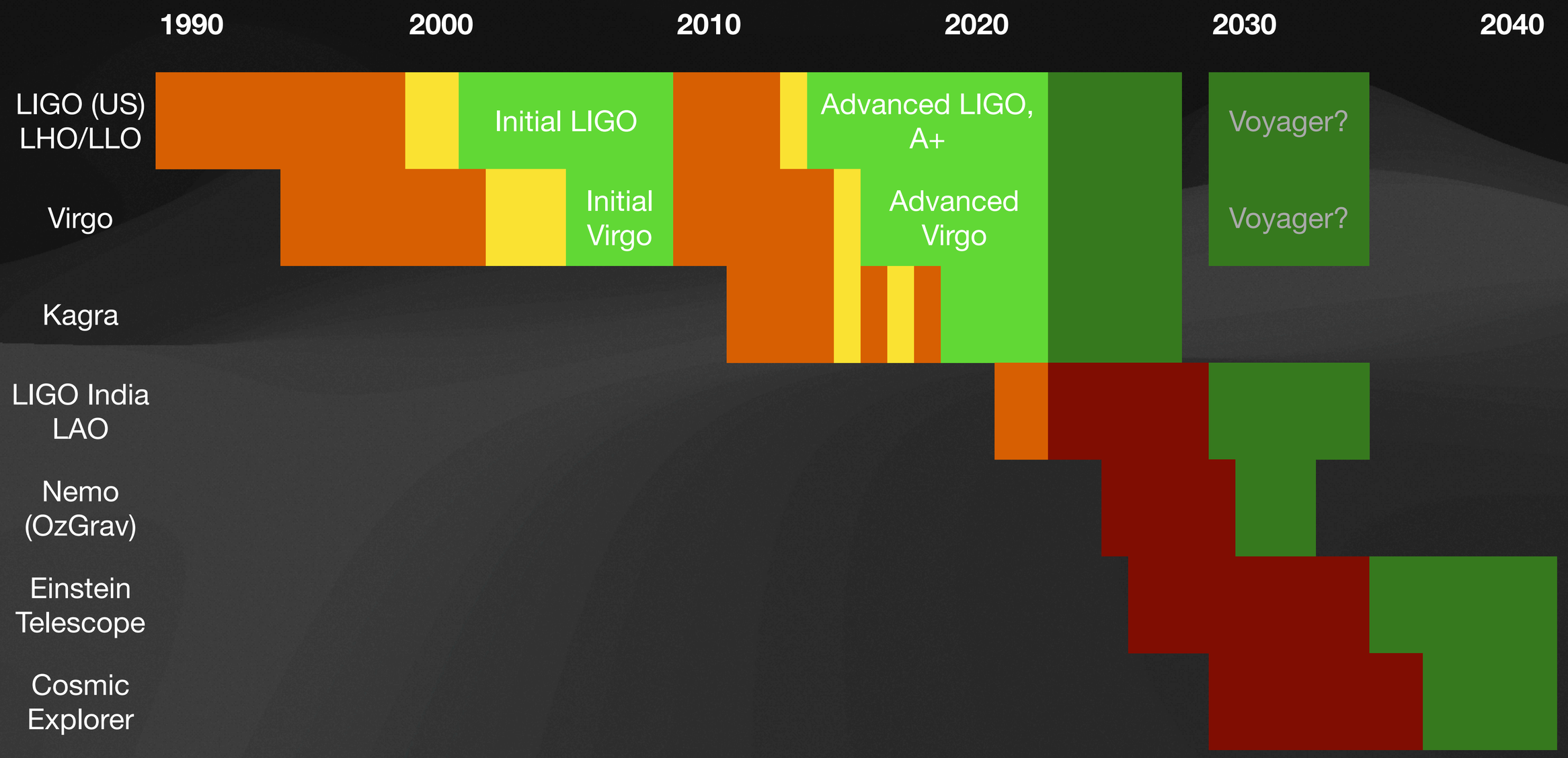


Roman

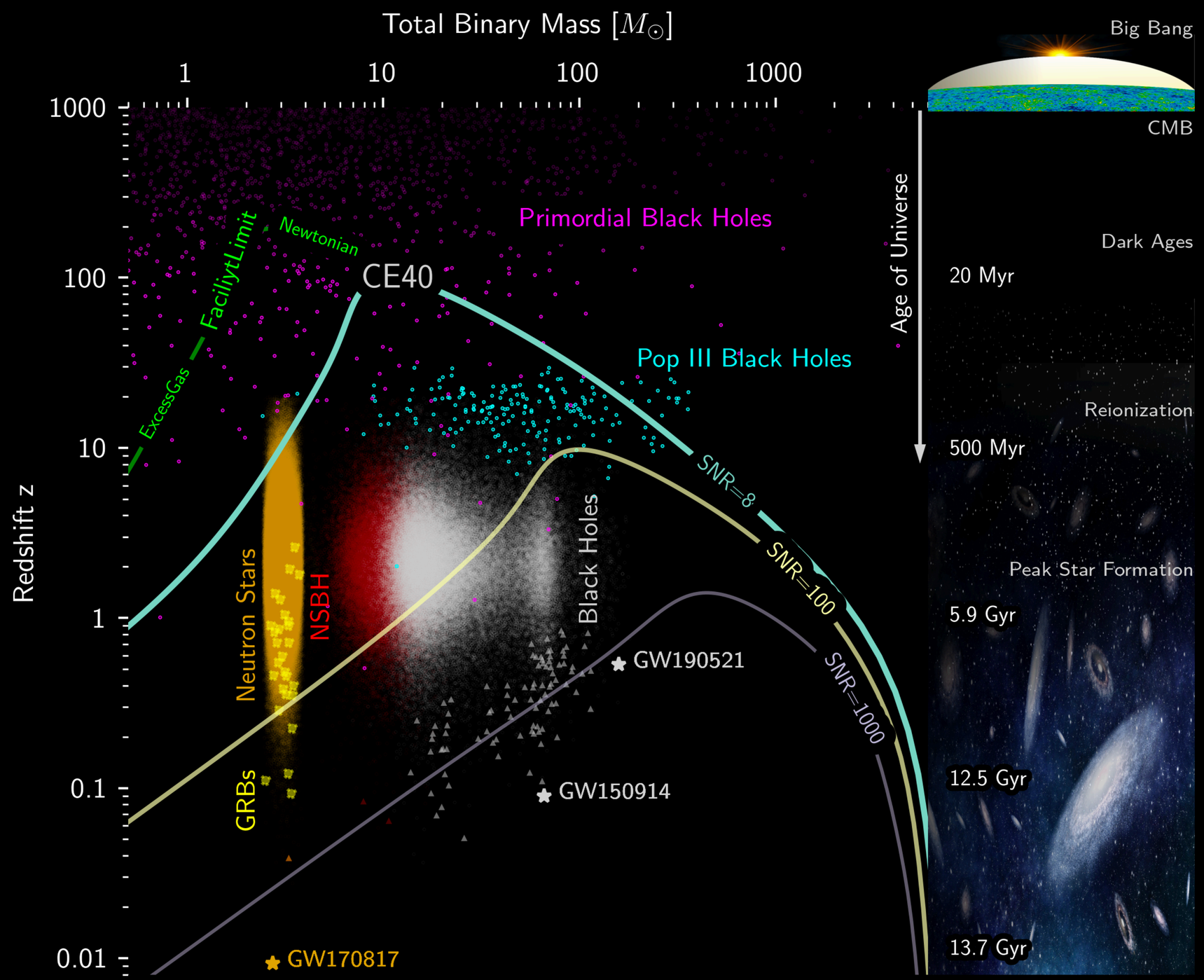
XG Design choices in coming years: What frequencies are important ?

Evans et al, arXiv:2109.09882

An *unofficial* compilation of timelines

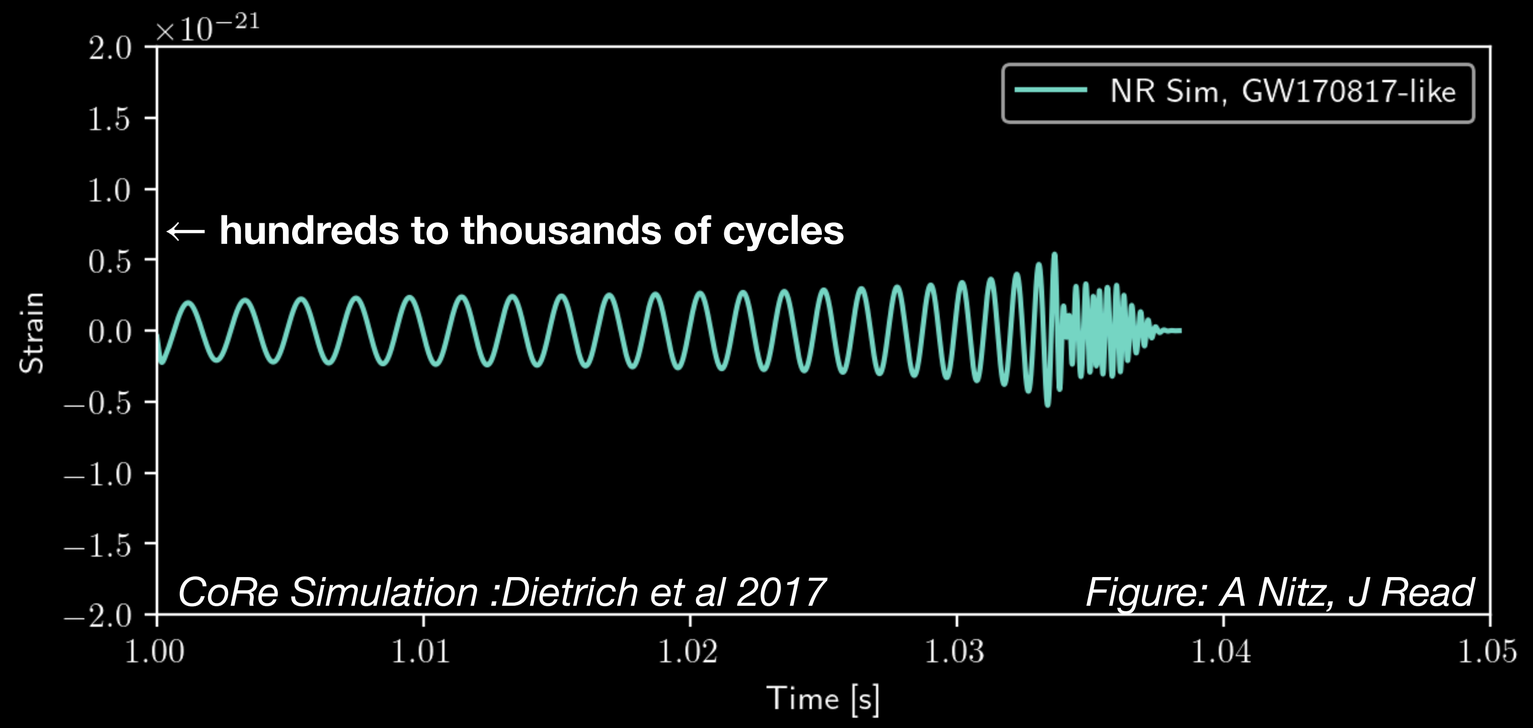


XG Universe



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

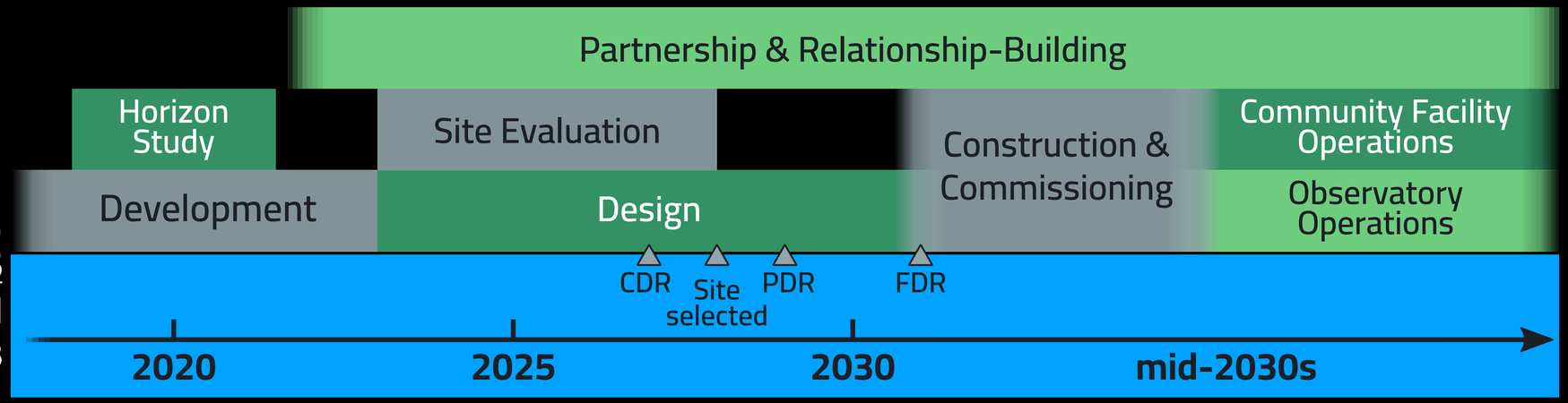
170817-like inspiral



From Monday:
"Today's rare events are tomorrow's precision physics"

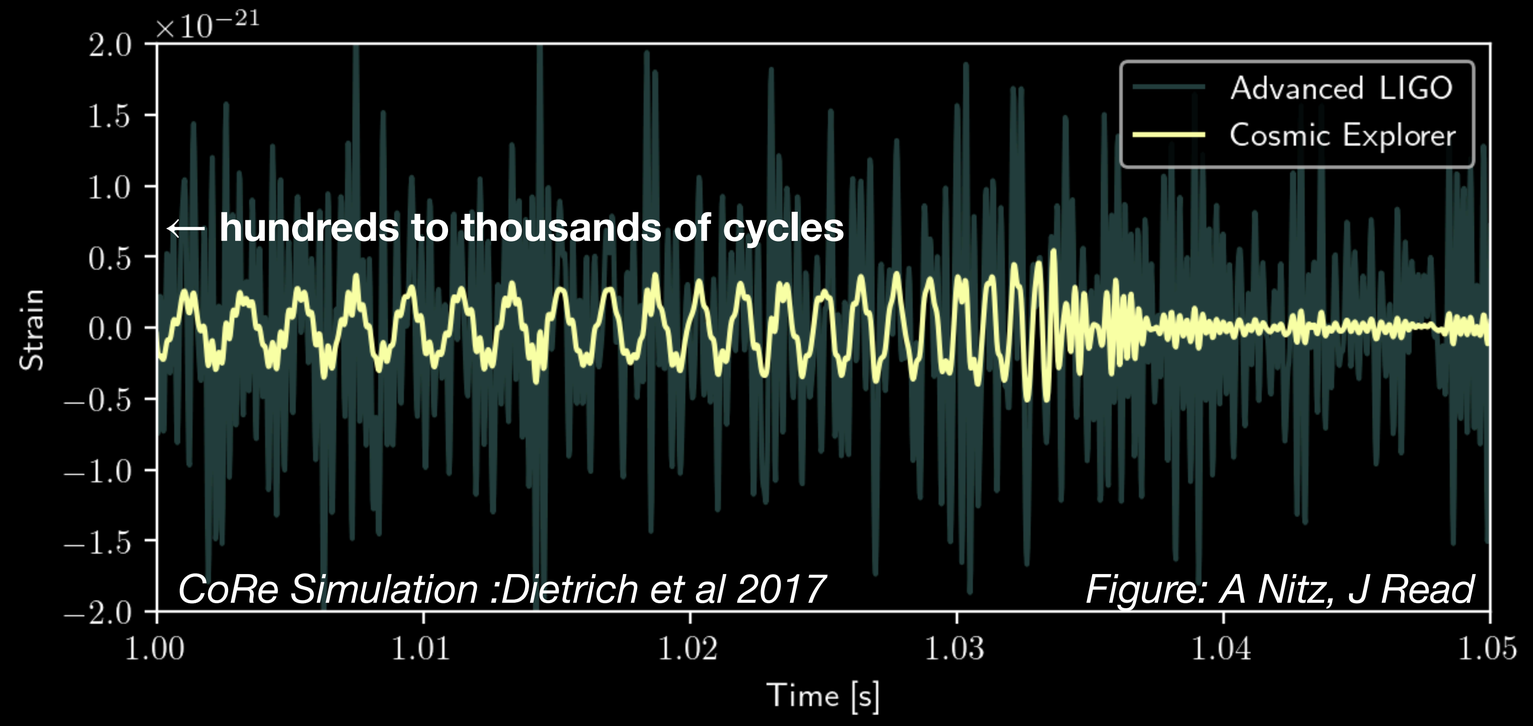
See coming talk from C. Raithel - what we learn after the merger

US Timeline



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

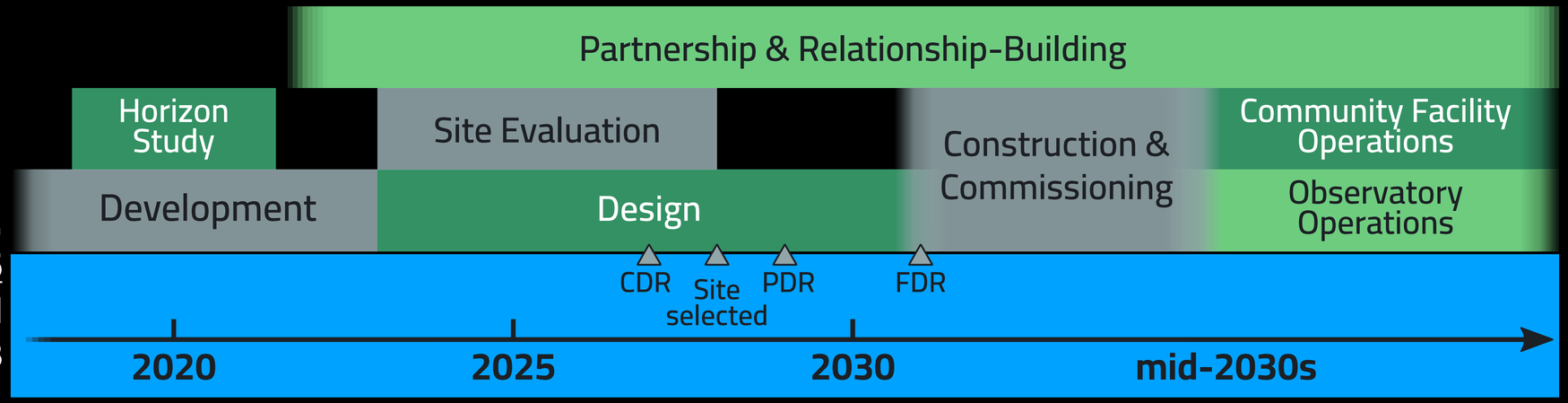
170817-like inspiral



From Monday:
"Today's rare events are tomorrow's precision physics"

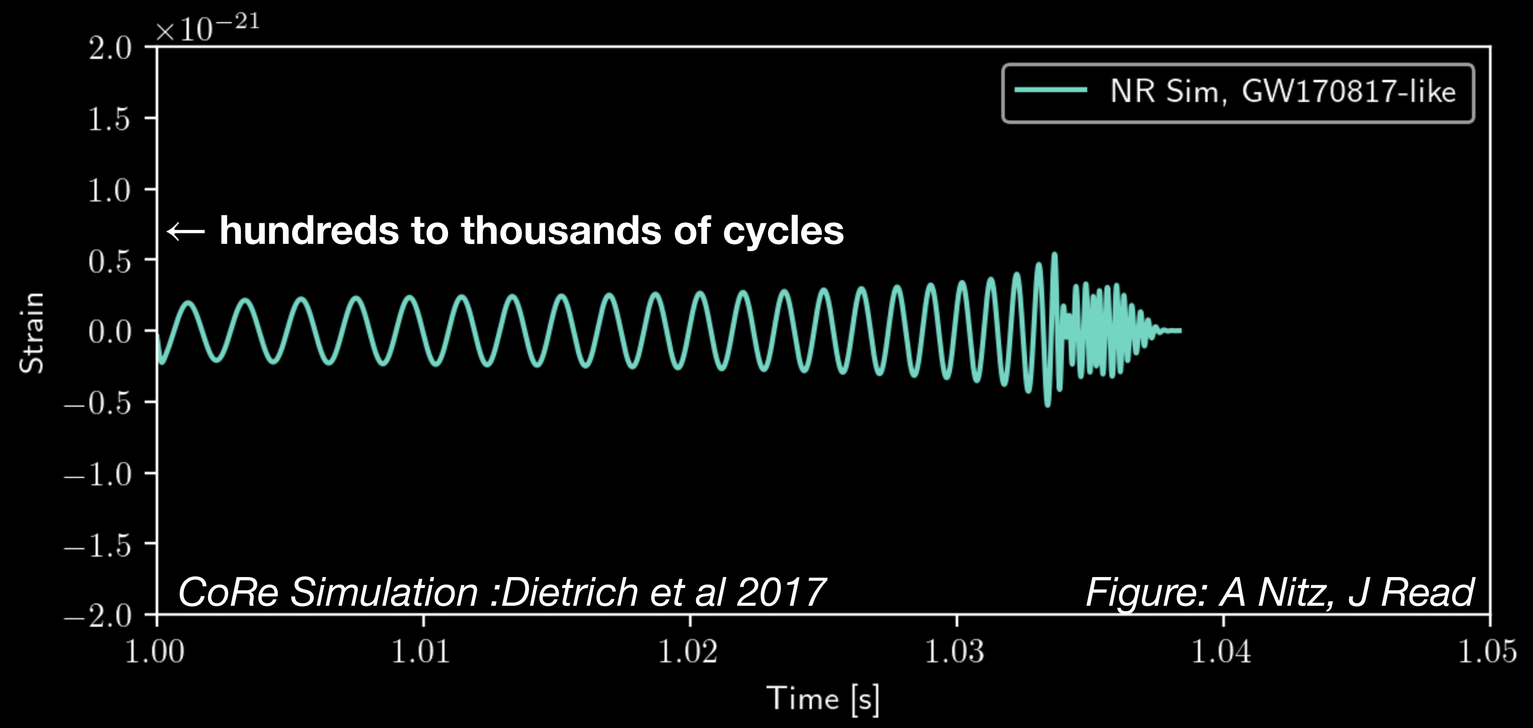
See coming talk from C. Raithel - what we learn after the merger

US Timeline



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

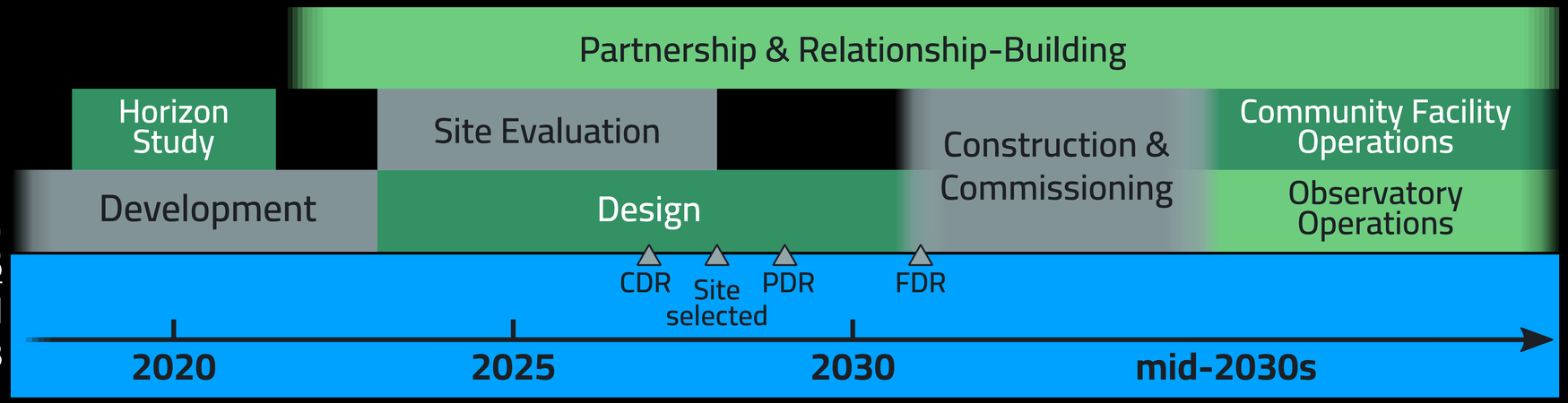
170817-like inspiral



From Monday:
"Today's rare events are tomorrow's precision physics"

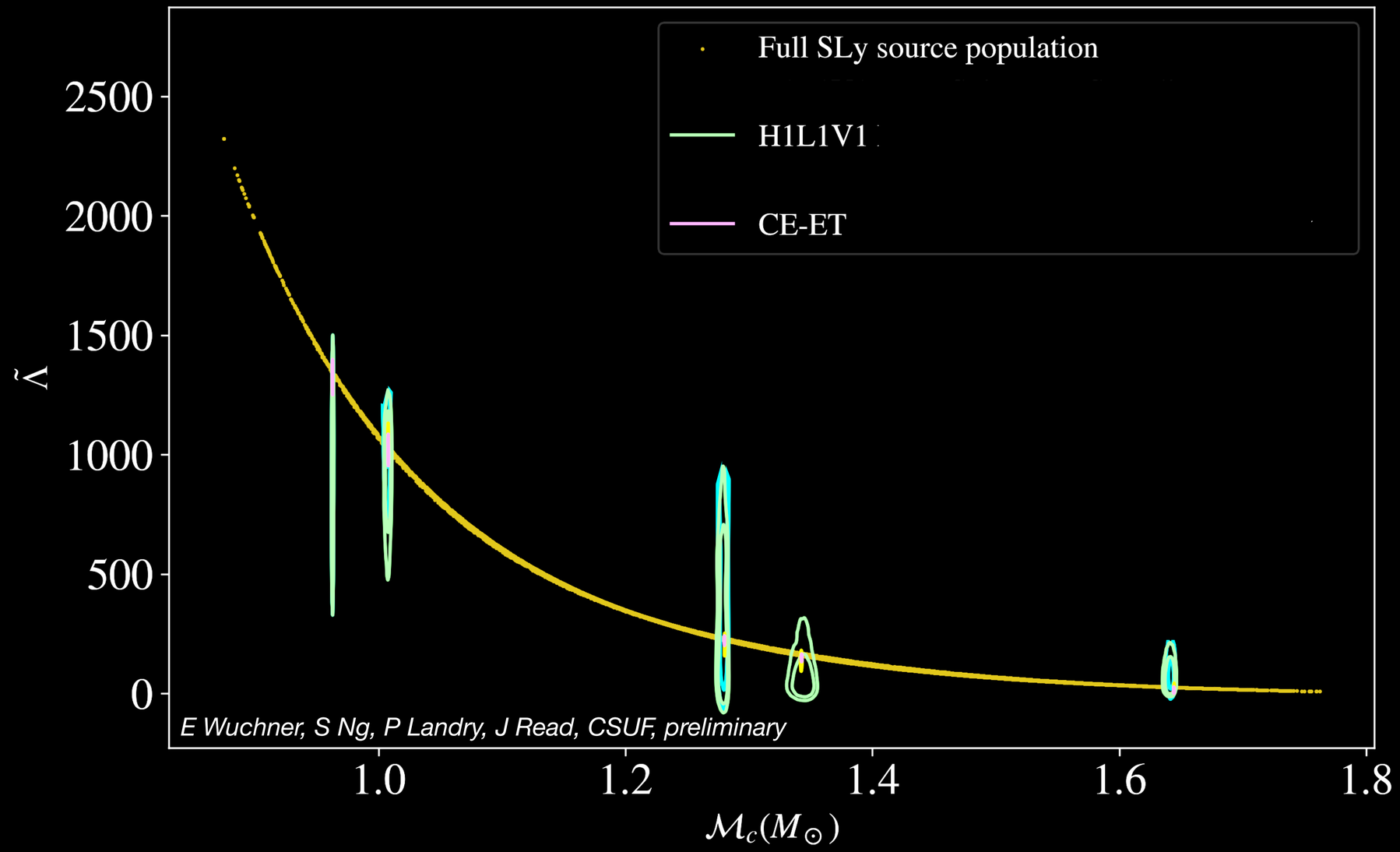
See coming talk from C. Raithel - what we learn after the merger

US Timeline



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

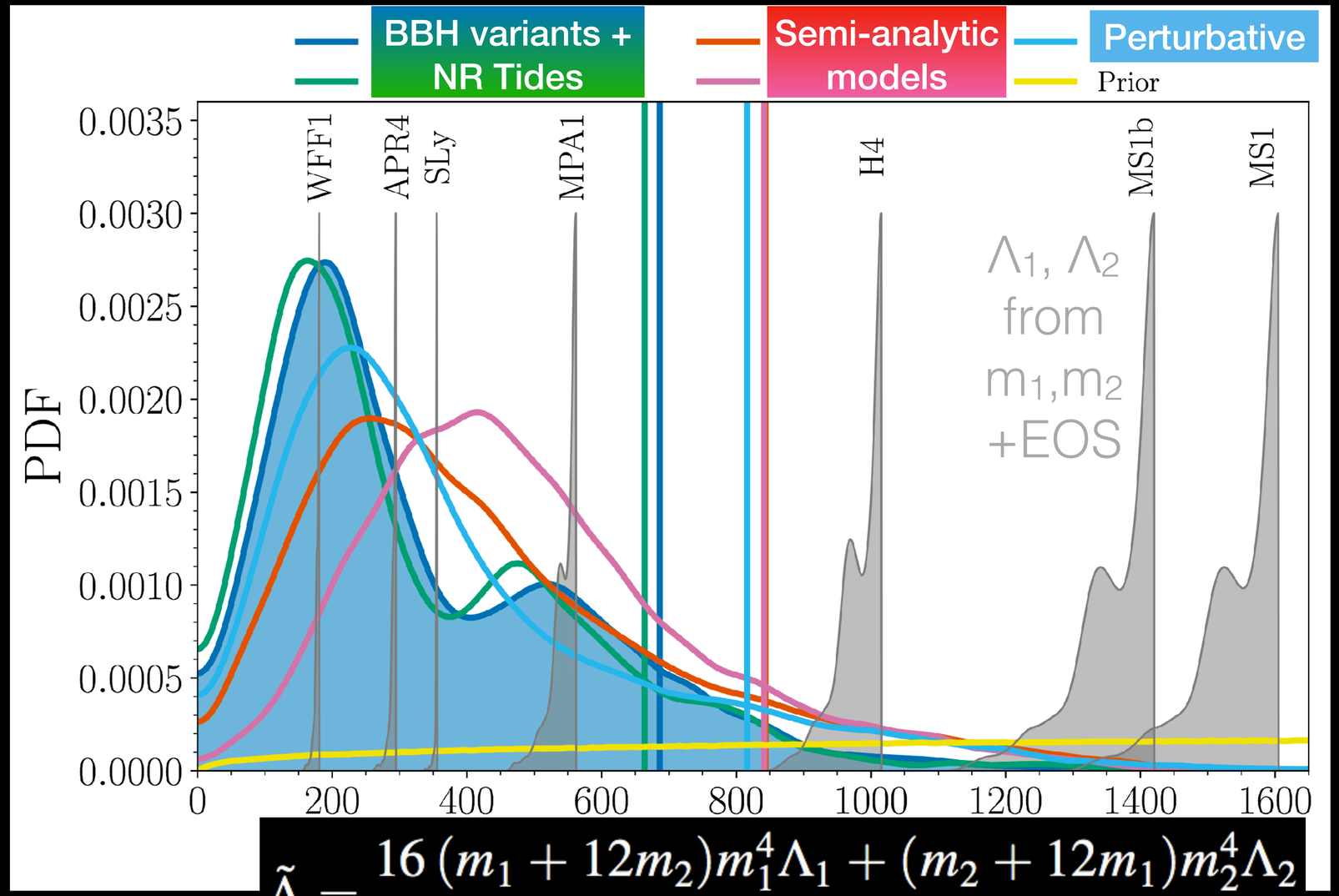
How much does EOS measurement improve?



- "Background population" with range of masses
- Strong signals in Advanced Network (SNR ~13-30) $\delta\tilde{\Lambda} \sim 100$s
- Same signals in CE+ET: $\delta\tilde{\Lambda} \sim 10$s
- See also Smith *et al* arXiv:2103.12274

EOS in XG observations: beyond Λ systematic uncertainty

Model systematics in GW170817:



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

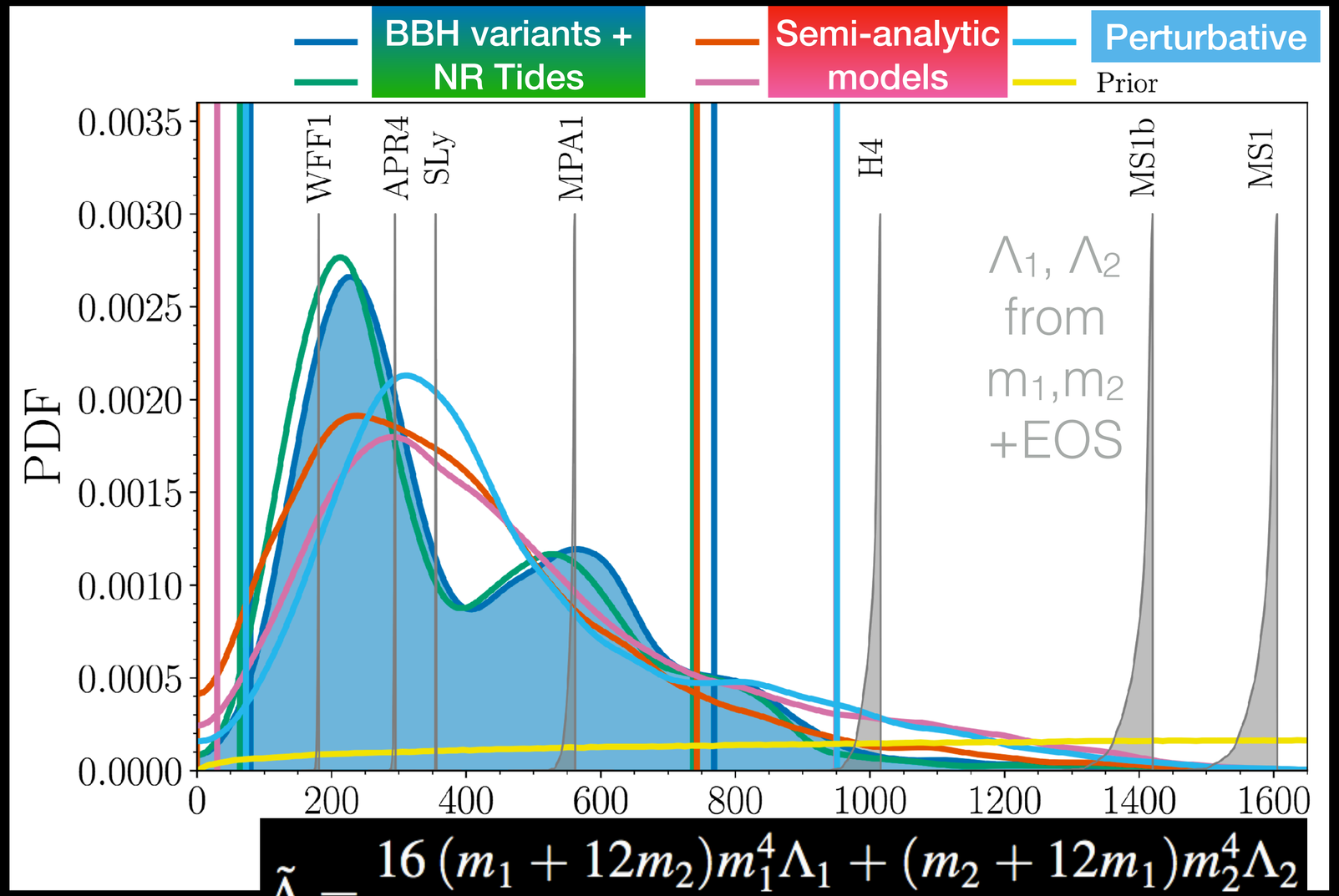
Fiducial WF:

$\tilde{\Lambda} < 686$

Bars denote 90% highest probability density credible interval

LSC/Virgo GWTC-1 1811.12907, PRX

Model systematics in 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 ($\chi < 0.05$)

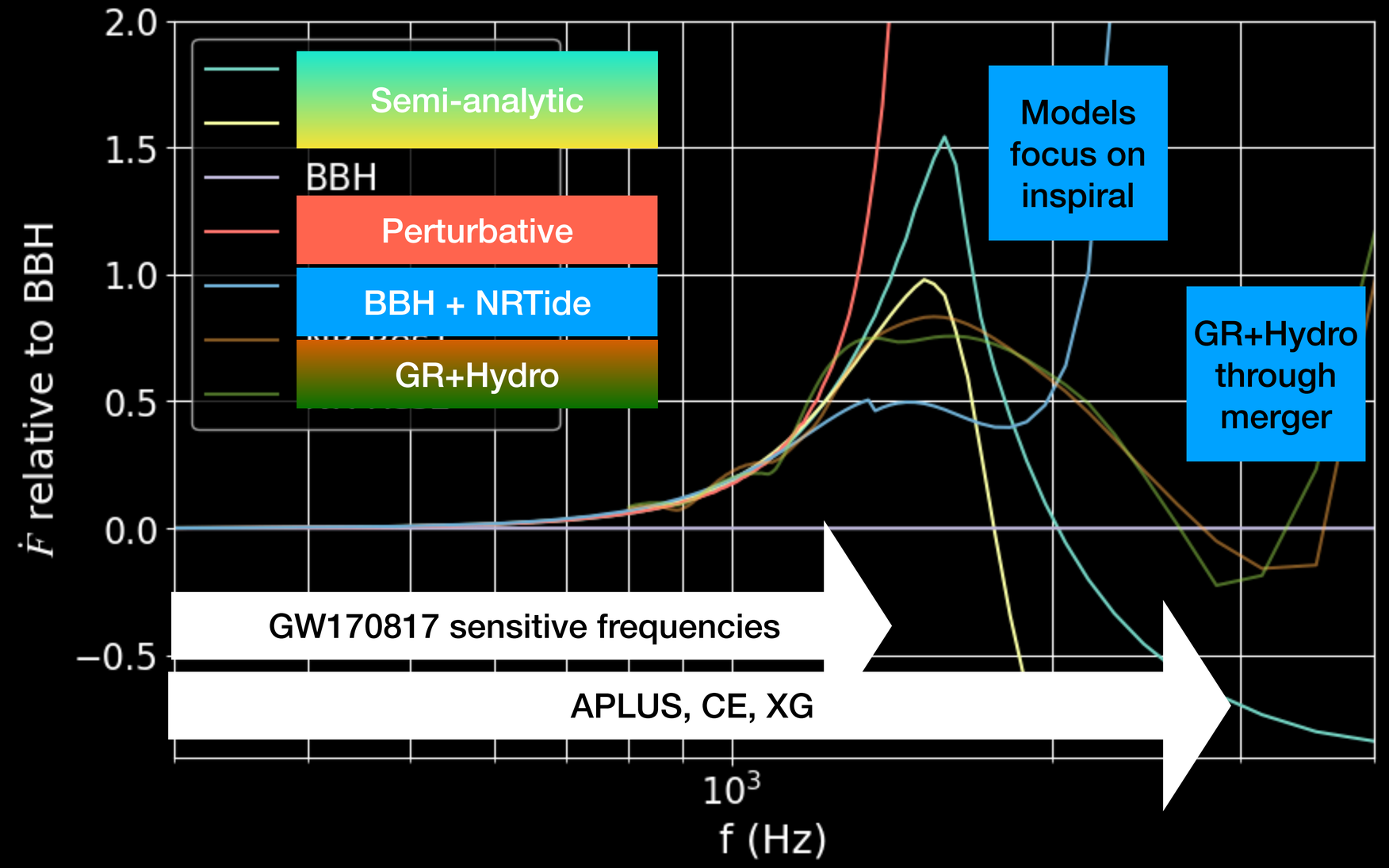
Fiducial WF:

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

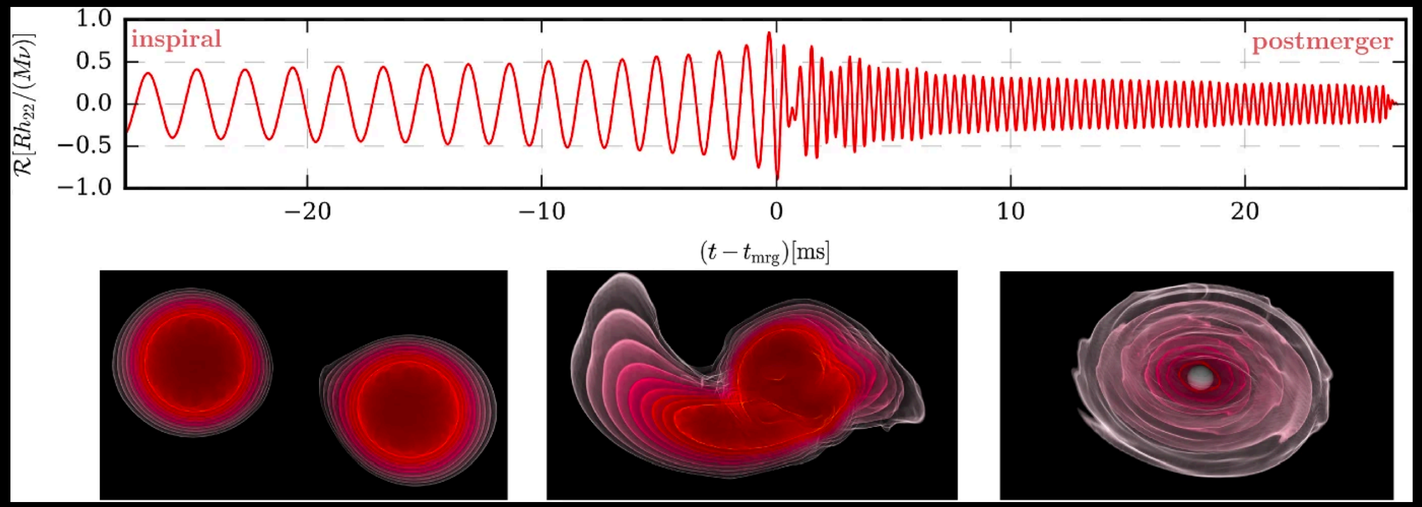
Bars denote 90% highest probability density credible interval

LSC/Virgo GWTC-1 1811.12907, PRX

Modeling the tidal signature



Jocelyn Read 2023 Class. Quantum Grav. 40 135002



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 ***effective*** descriptors 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 relations (Yagi Phys. Rev. D 89, 043011 (2014), Chan et al Phys.Rev.D90 (2014))* generate full EOS impact from Λ_i in semi-analytic models

- **This will break in XG era**: additional parameters to describe waveforms (e.g Carson et al Phys. Rev. D 99, 083016 (2019), Pratten et al Nat Commun 11, 2553 (2020). Additional opportunity for EOS constraint!

Waveform uncertainty

- A range of possible waveform model corrections can be inferred using observational data *(Edelman et al Phys. Rev. D 103, 042004 (2021).)*

- *JR 2023 Class. Quantum Grav. 40 135002:*

  - ***Interpretation***: Constraint on waveform corrections limits unmodeled energy transfers *(not in PE waveform)* within observed systems

  - ***Application to GW inference***: Marginalize over uncertainties in waveform modeling; recover data-informed waveform correction

  - ***Application to nuclear astrophysics:*** Given a model of astrophysical energy transfer (like a resonant mode that encodes transport properties), can imprint on *any* underlying waveform model

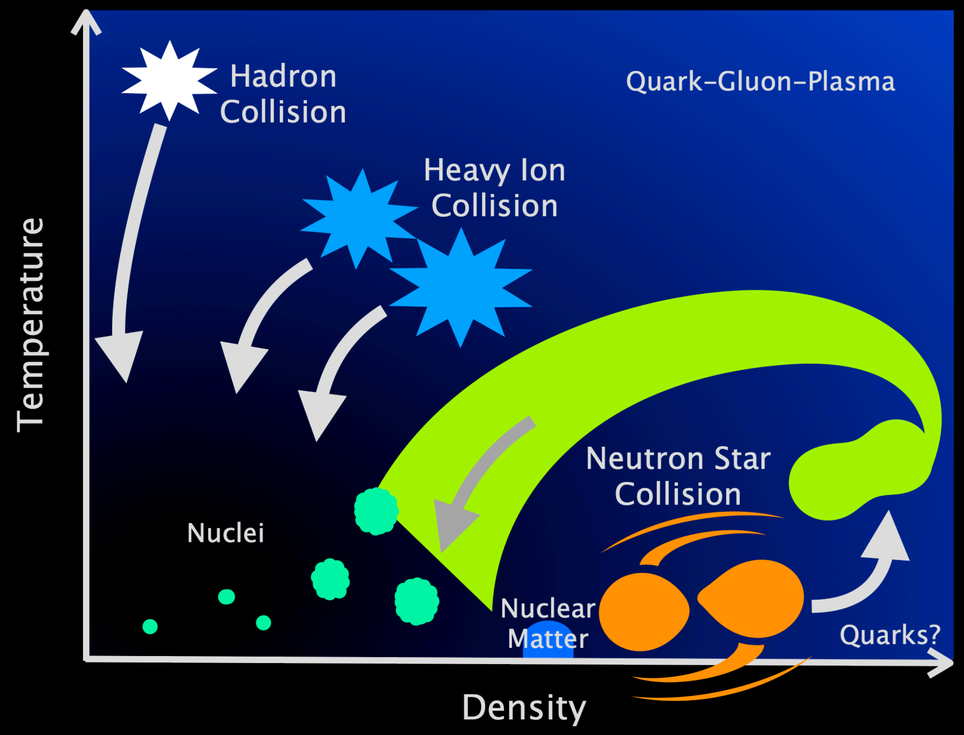
GW PAC NICHOLAS AND LEE BEGOVICH Center for Gravitational-Wave Physics and Astronomy

Cal State Fullerton

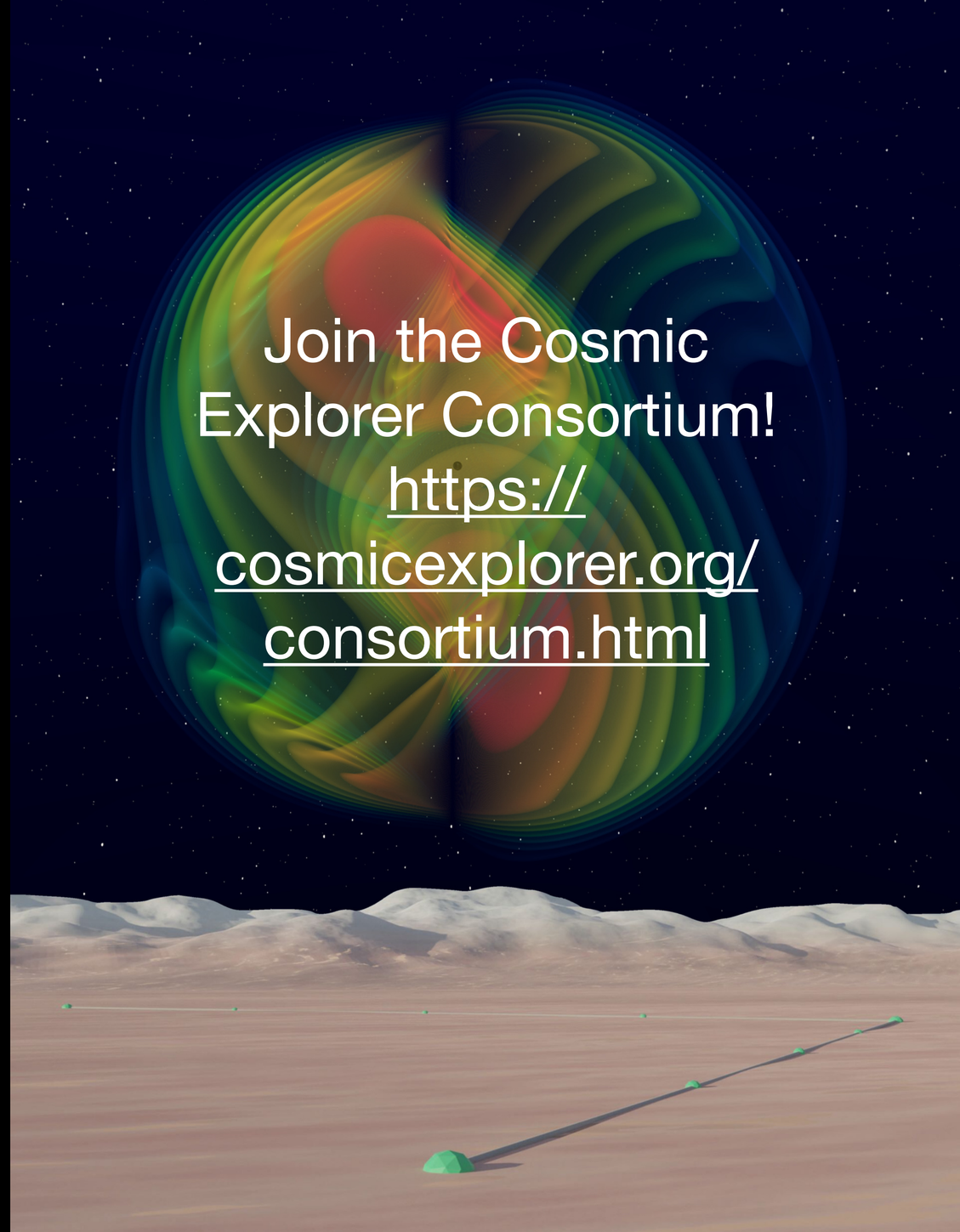
We are grateful to acknowledge: the National Science Foundation, the Research Corporation for Science Advancement, Dan Black and Family and Nancy Goodhue-McWilliams

RESEARCH CORPORATION for SCIENCE ADVANCEMENT

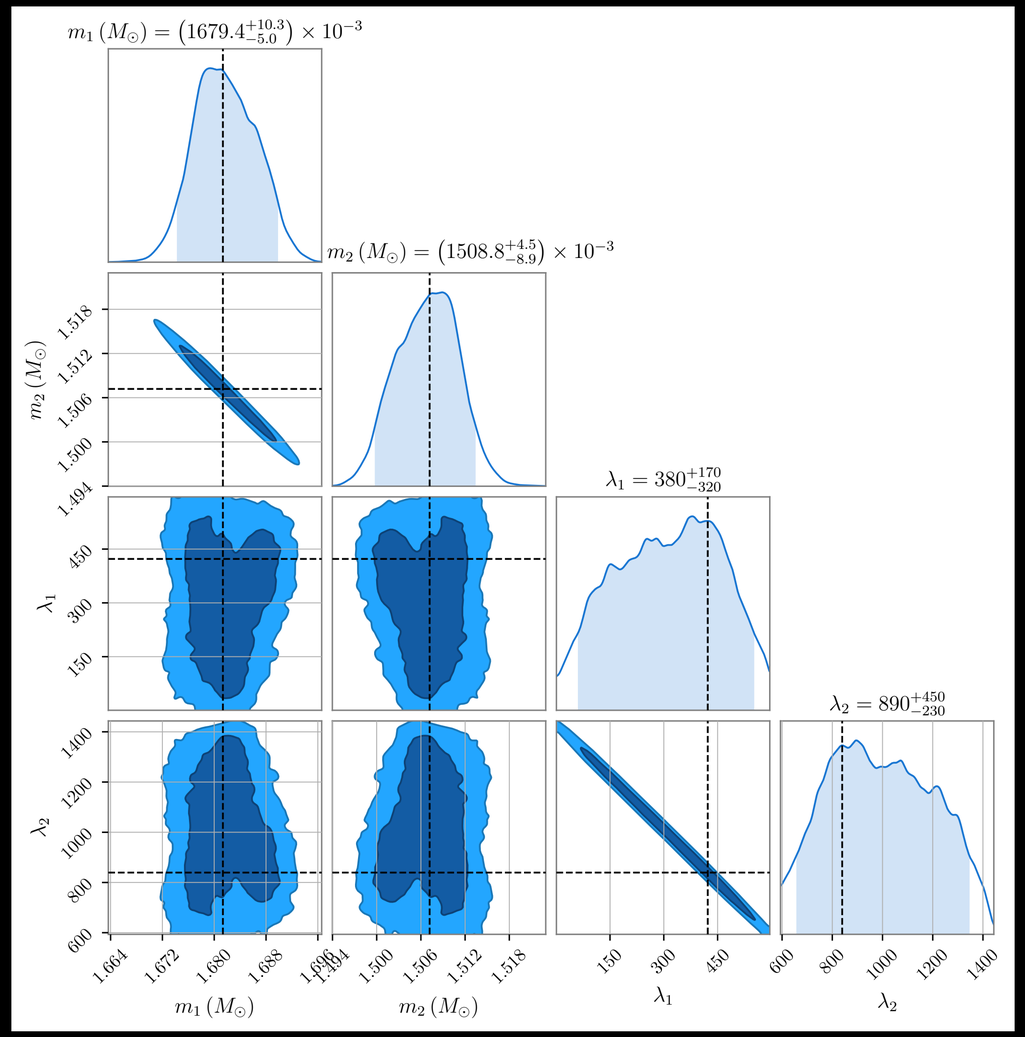
- ~1000s of neutron star mergers / year
- identify 80% of **all** ns mergers within z=1
- ~100 NS radii with error < ~0.1 km / year
- ~100 mergers with 10 minutes early warning
- ~100 post-merger GW detected / year
- ~10 / year SNR > 300



Horizon Study: arXiv:2109.09882



Next-gen observations: “GW370817”

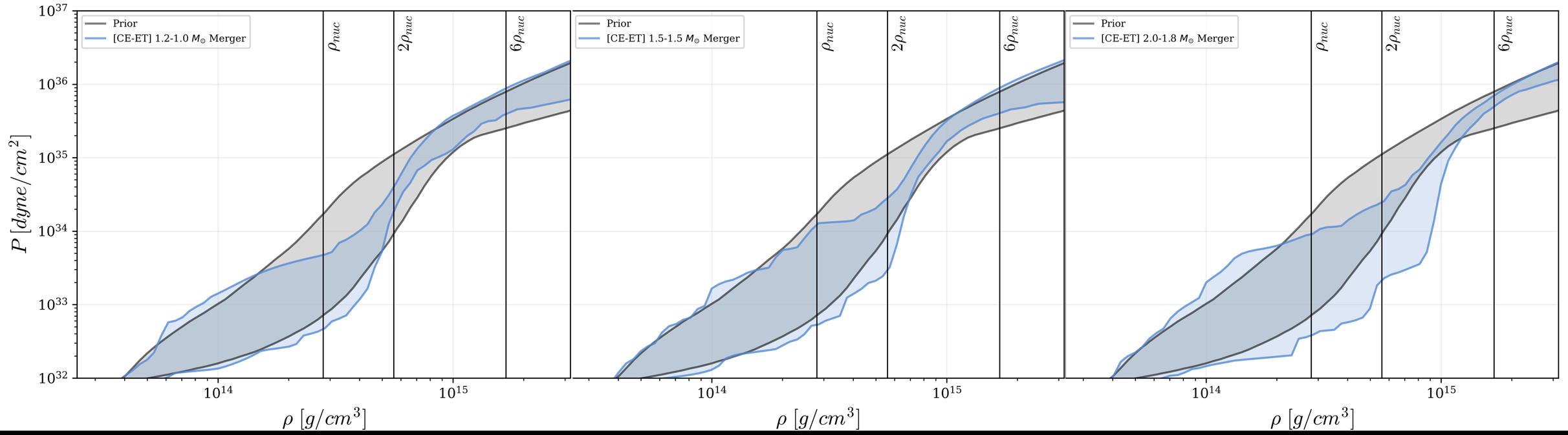


Smith *et al* arXiv:2103.12274

GW EOS implications

Low mass source | Intermediate mass | High mass source

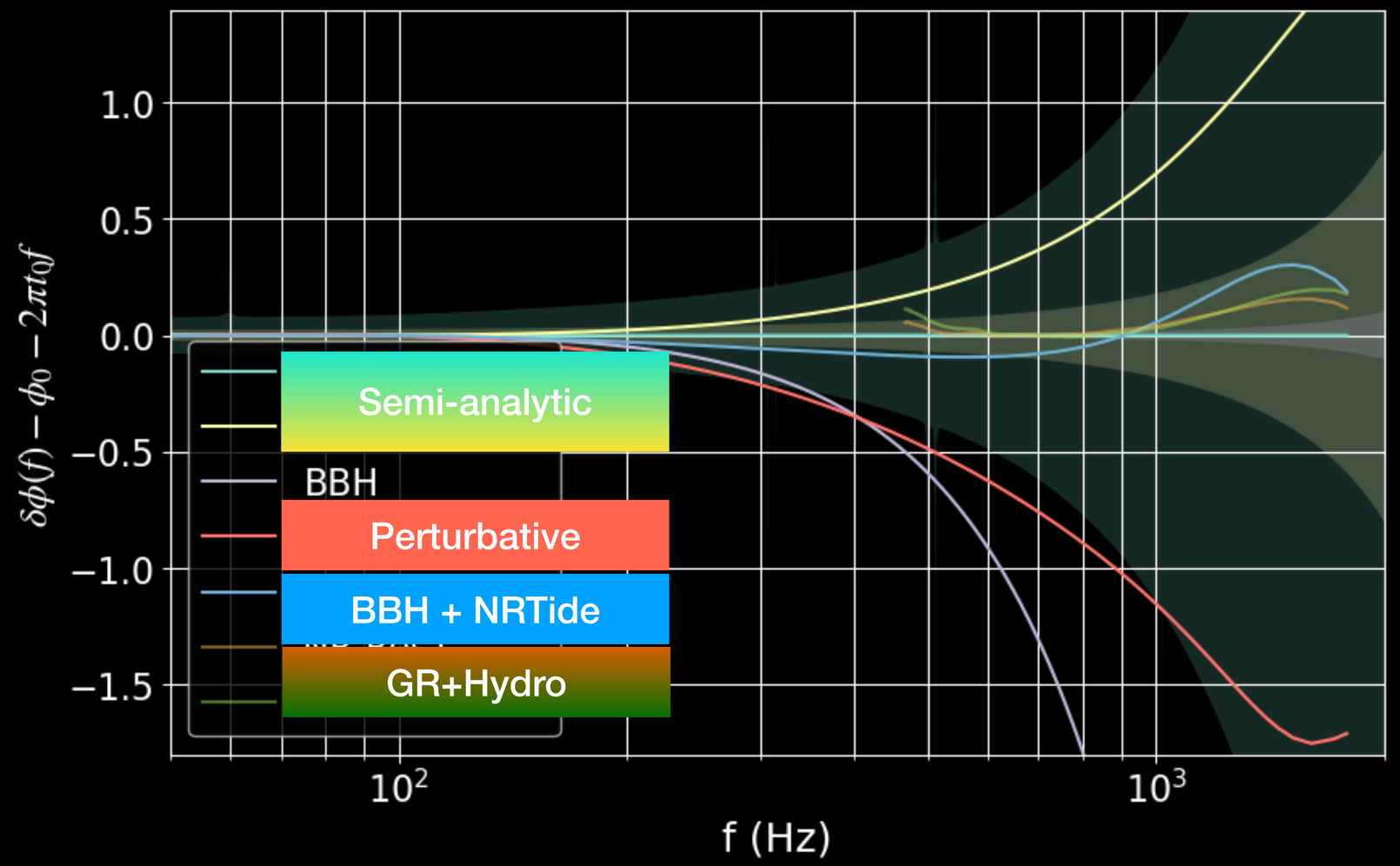
S Ng, E Wuchner, P Landry, J Read, CSUF, preliminary



Gaussian Process EOS constraint method developed by Landry & Essick, applied to multi messenger inference in Legred et al arXiv:2106.05313

Here: Range of EOS compatible with single observation;
joint constraint breaks the current resolution of EOS

XG Waveform requirements



- Waveform differences that remain in the shaded regions should be indistinguishable in that detector

- 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

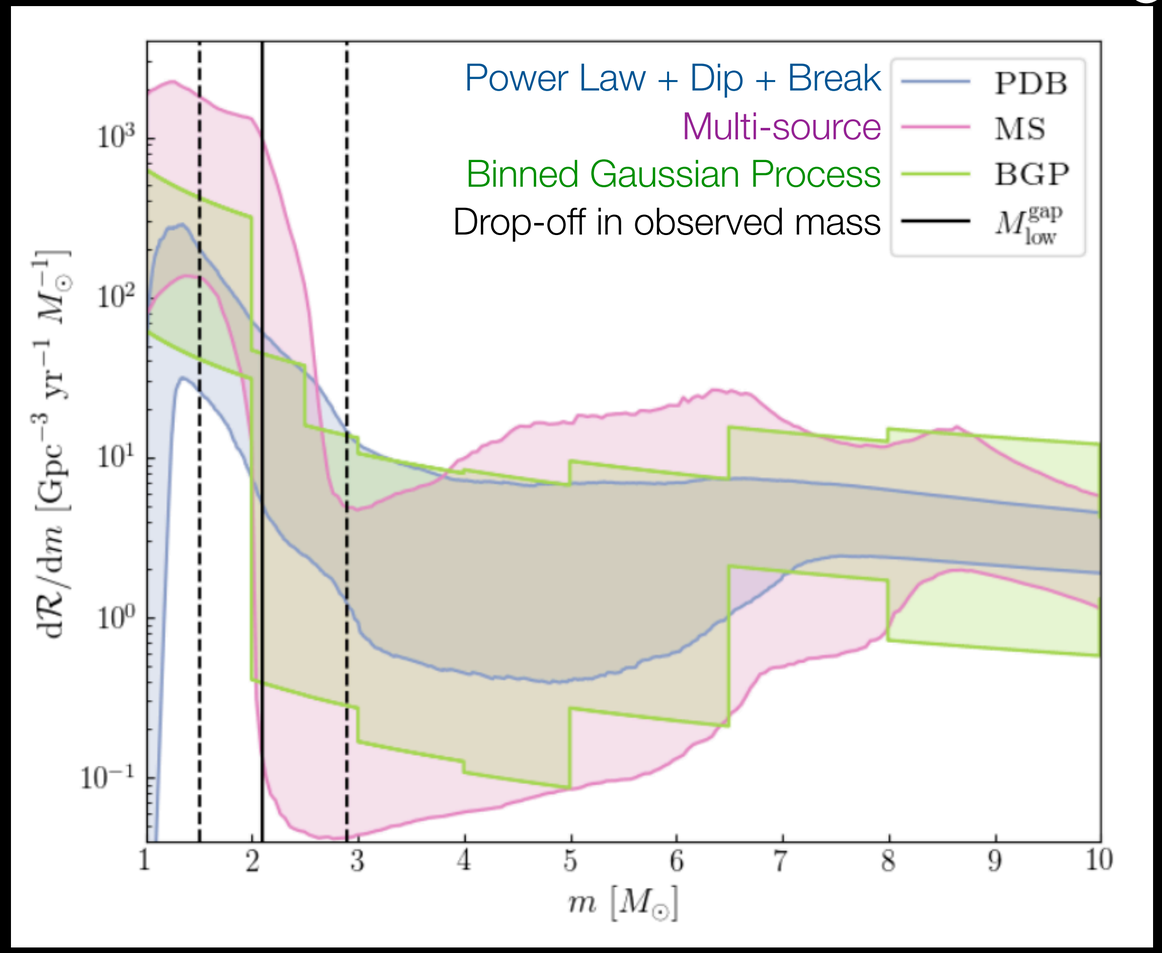
Jocelyn Read 2023 Class. Quantum Grav. 40 135002

Nuclear physics beyond Λ

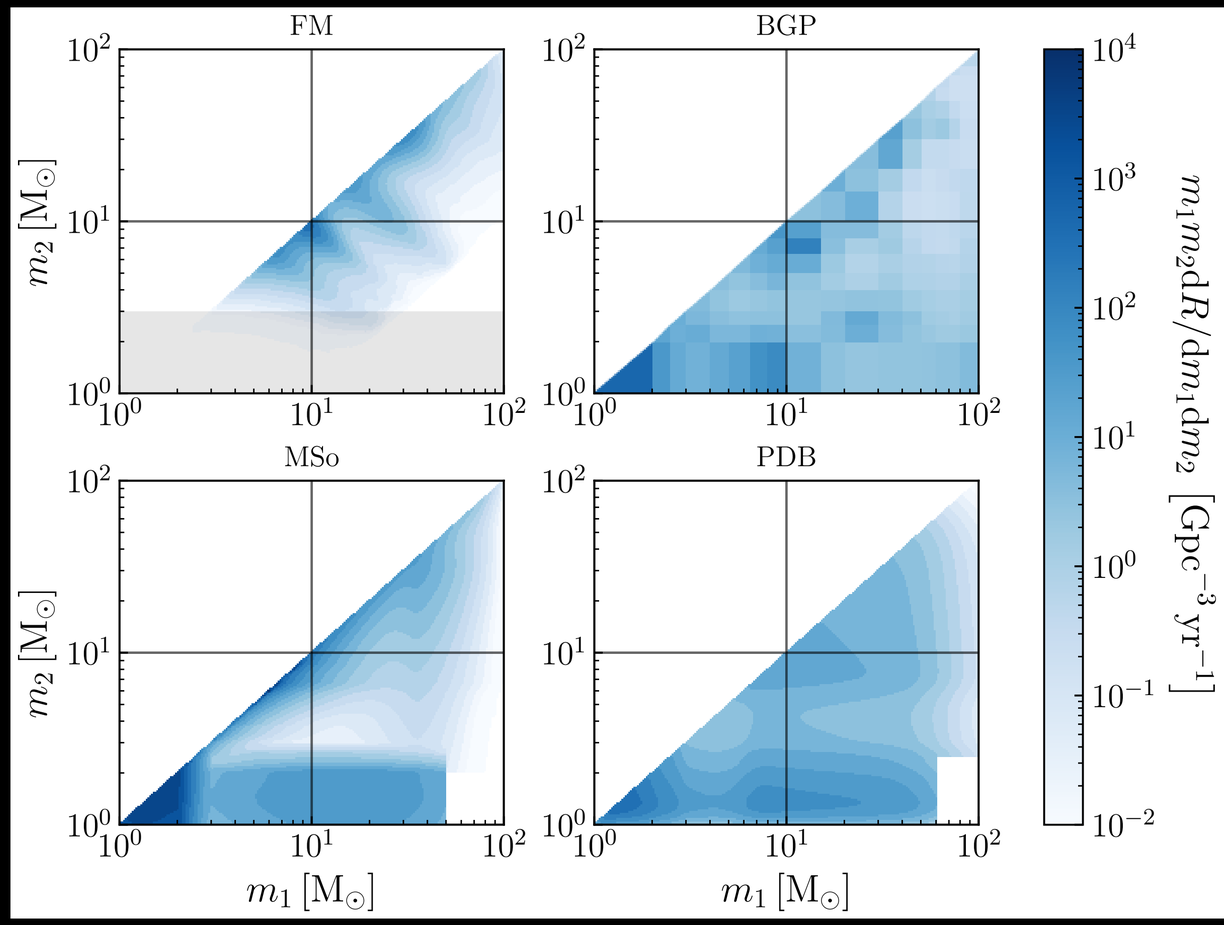
The population of merging compact binaries inferred using gravitational waves through GWTC-3

LIGO-Virgo-Kagra, arXiv:2111.03634 (LIGO-P2100239-v11)

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

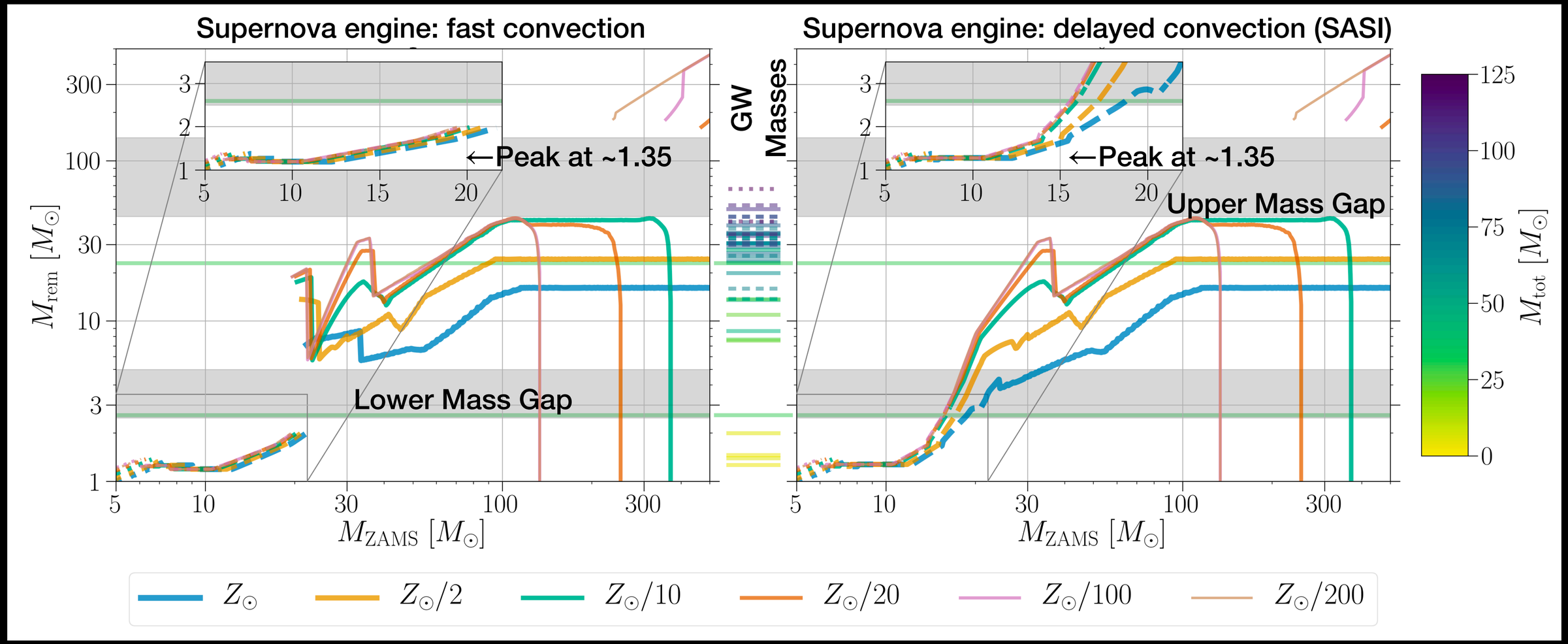


Rate varies across masses



What are the masses of merging objects?

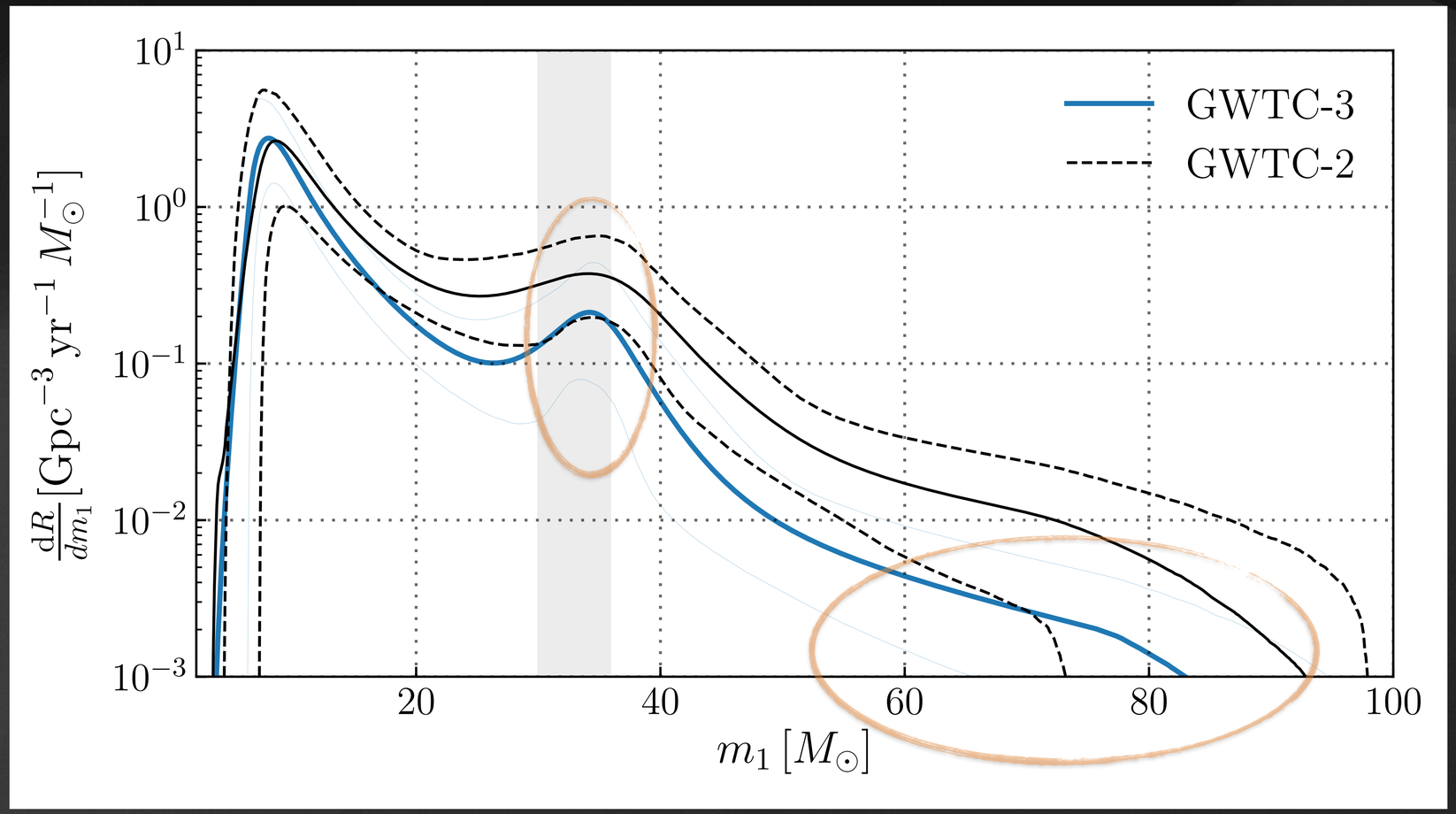
Fast/delayed scenarios from Chris Fryer *et al* 2012 *ApJ* 749 91



Michael Zevin *et al* 2020 *ApJL* 899 L1

Structure in the BH mass spectrum

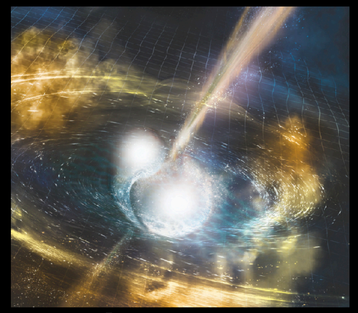
LIGO-Virgo-Kagra, arXiv:2111.03634 (LIGO-P2100239-v11)

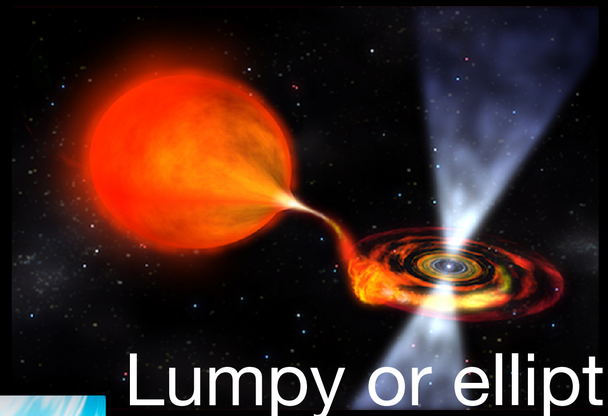


Potential sources of ~ 10 – 4000 Hz GW

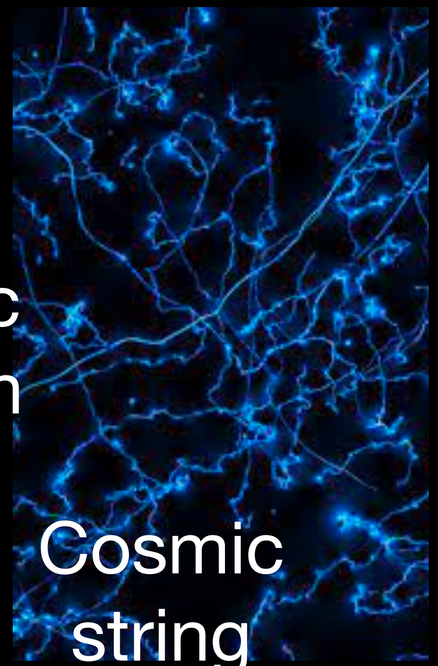
Black hole inspiral

Neutron star inspiral



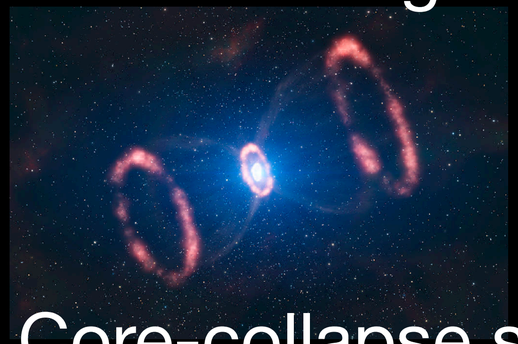


Lumpy or elliptic spinning neutron stars

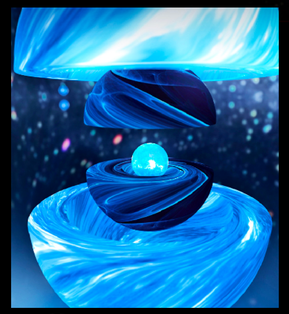


Cosmic string fluctuations

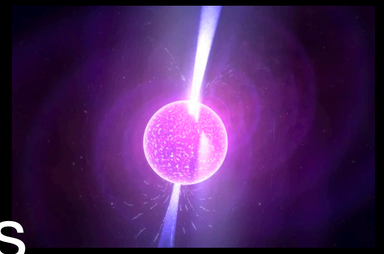
Black hole ringdown



Neutron star post-merger



Glitching neutron stars



Core-collapse supernovae

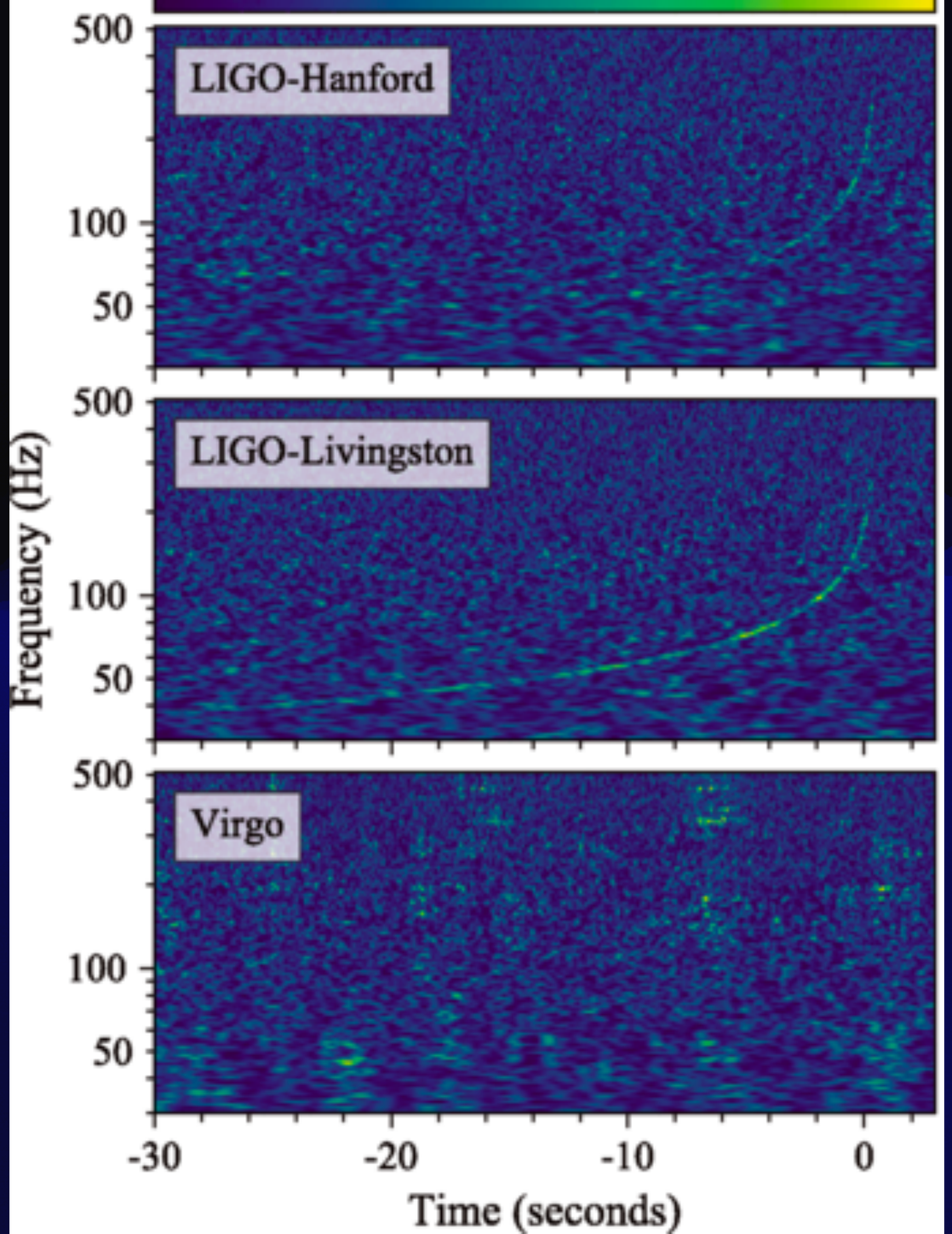
milliseconds minutes days years

Duration of in-band gravitational-wave emission

Images: A. Simonnet/Sonoma State/LIGO, ESO/L. Calçada

Images: Carl Knox/OzGrav, Kevin Gill Flickr (CC by 2.0)

How do we interpret observational data?



Source properties and signal parameters

- Fourier domain $h(t) \rightarrow \tilde{h}(f)$, project onto detector

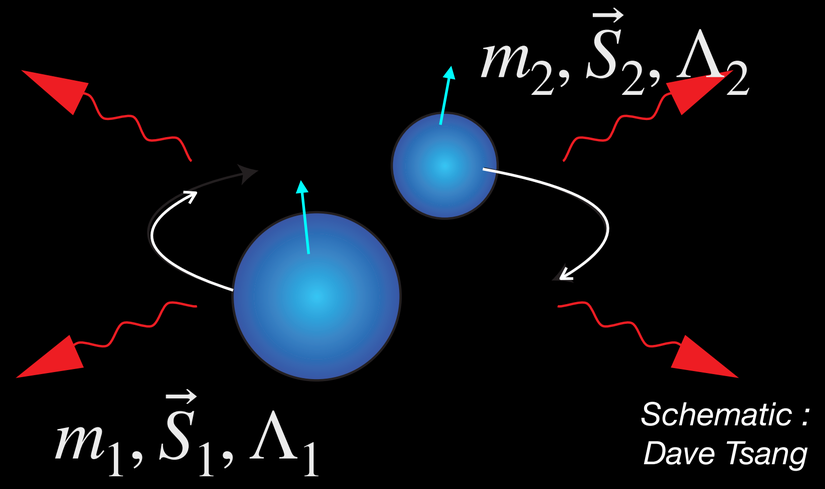
Chirp mass

Sky location, orientation

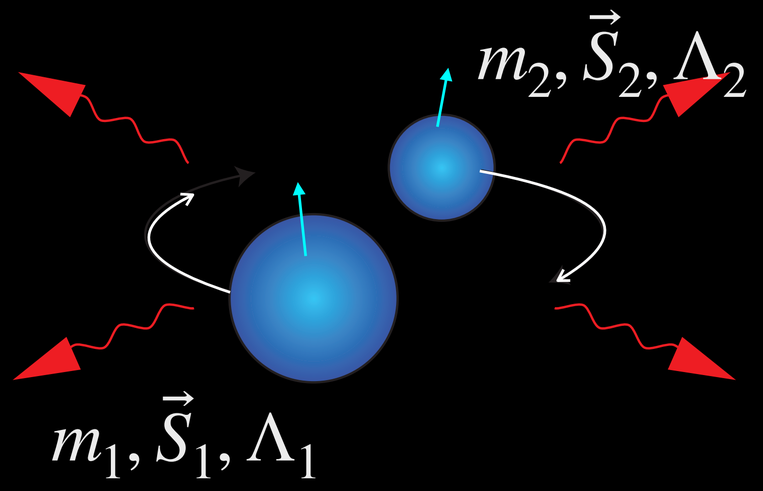
$$\tilde{h}(f) \sim \frac{\mathcal{M}}{d_L} Q(\alpha, \delta, \iota, \psi) f^{-7/6} e^{i\phi(f)}$$

Luminosity distance

Amplitude fall-off in frequency domain



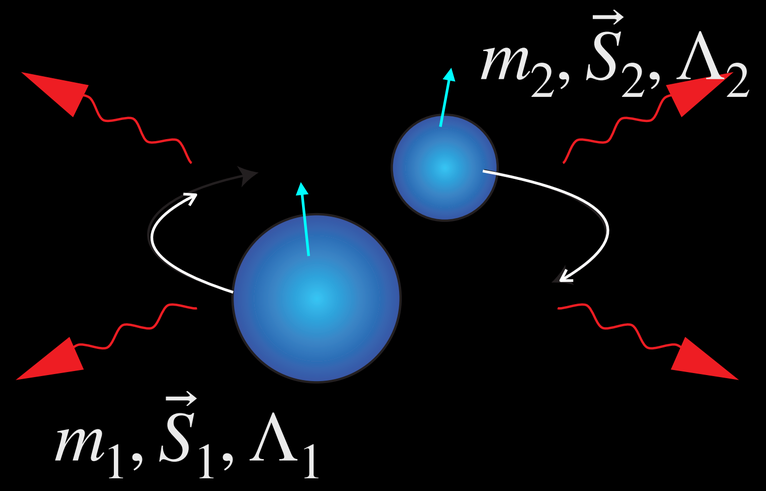
GW phase ↔ Orbital phase



GW phase ↔ Orbital phase

$$\phi(f) = 2\pi i f(1+z)t_c + \phi_c + [\text{const}]\left(\mathscr{M}f\right)^{-5/3} + \ldots$$

is a function of leading-order combinations:

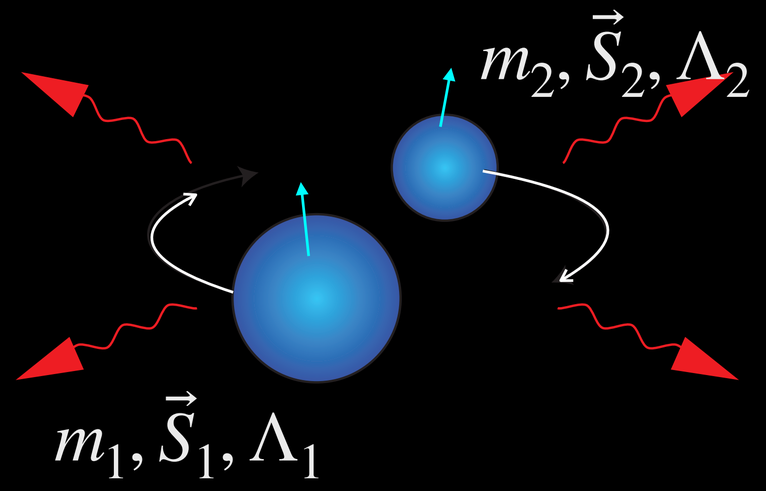


GW phase ↔ Orbital phase

$$\phi(f) = 2\pi i f(1+z)t_c + \phi_c + [\text{const}]\left(\mathscr{M}f\right)^{-5/3} + \ldots$$

is a function of leading-order combinations:

- "Chirp mass": $\mathscr{M} = \dfrac{(m_1 m_2)^{3/5}}{(m_1+m_2)^{1/5}}$

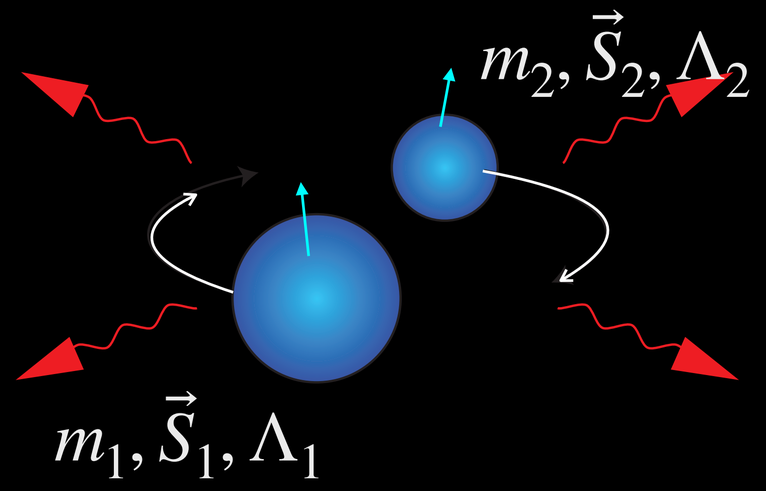


GW phase ↔ Orbital phase

$$\phi(f) = 2\pi i f(1+z)t_c + \phi_c + [\text{const}]\left(\mathscr{M}f\right)^{-5/3} + \ldots$$

is a function of leading-order combinations:

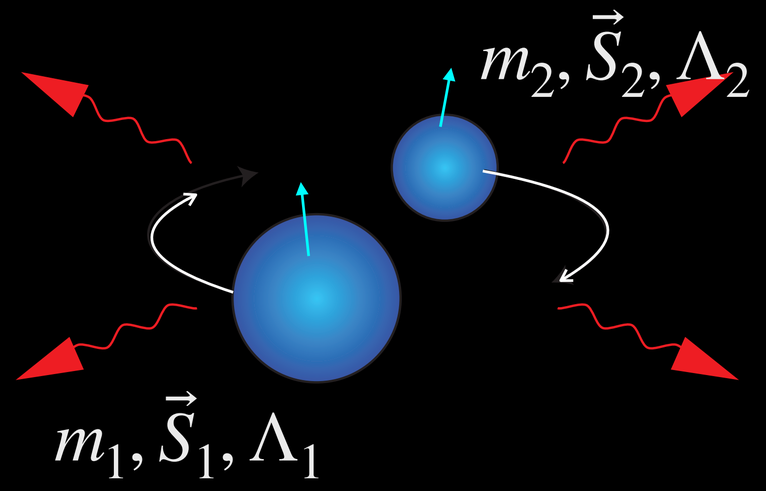
- "Chirp mass": $\mathscr{M} = \dfrac{(m_1 m_2)^{3/5}}{(m_1+m_2)^{1/5}}$
- Mass ratio: $q = m_2/m_1$



GW phase ↔ Orbital phase

$$\phi(f) = 2\pi i f(1+z)t_c + \phi_c + [\text{const}]\left(\mathscr{M}f\right)^{-5/3} + \ldots$$

is a function of leading-order combinations:

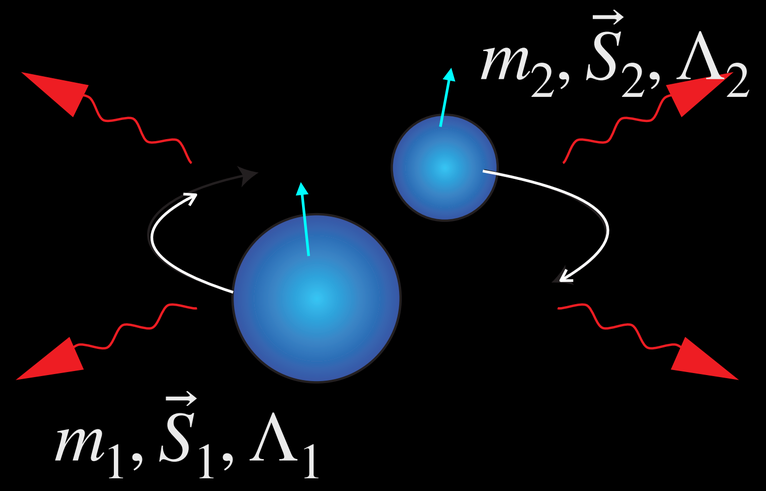


- "Chirp mass": $\mathscr{M} = \dfrac{(m_1 m_2)^{3/5}}{(m_1+m_2)^{1/5}}$
- Mass ratio: $q = m_2/m_1$
- Effective spin: $\chi_{\text{eff}} = \dfrac{\vec{S}_1/m_1 + \vec{S}_2/m_2}{m_1+m_2} \cdot \vec{L}$

GW phase ↔ Orbital phase

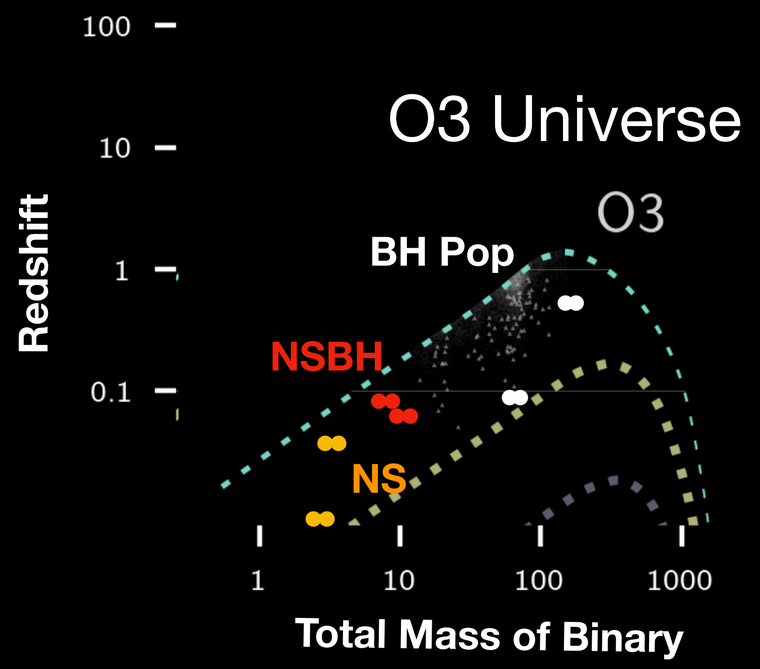
$$\phi(f) = 2\pi i f(1+z)t_c + \phi_c + [\text{const}]\left(\mathscr{M}f\right)^{-5/3} + \ldots$$

is a function of leading-order combinations:



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

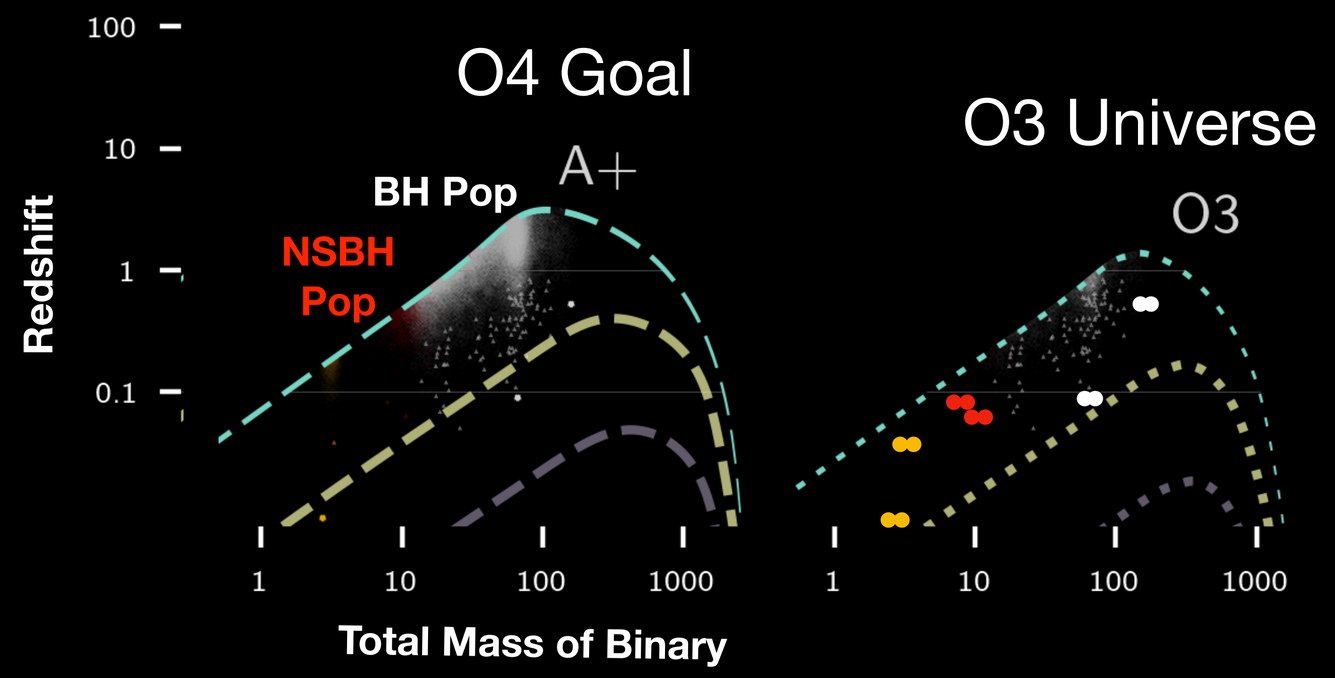
Unveiling the GW Universe



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

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

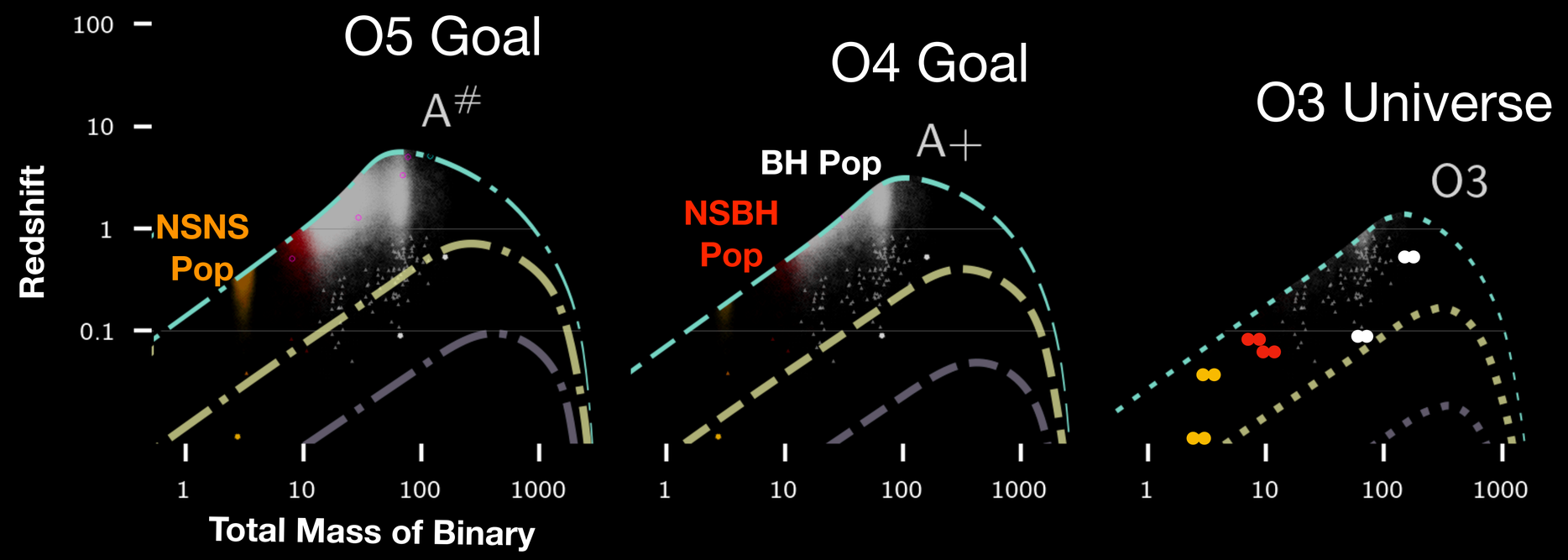
Unveiling the GW Universe



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

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

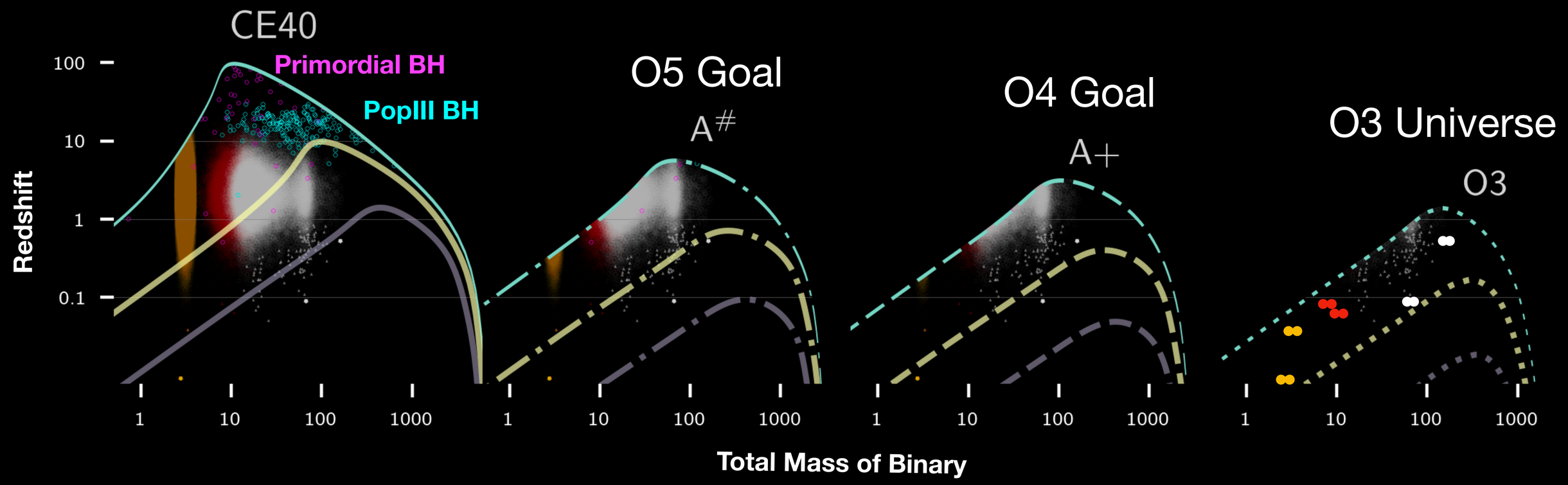
Unveiling the GW Universe



— — 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



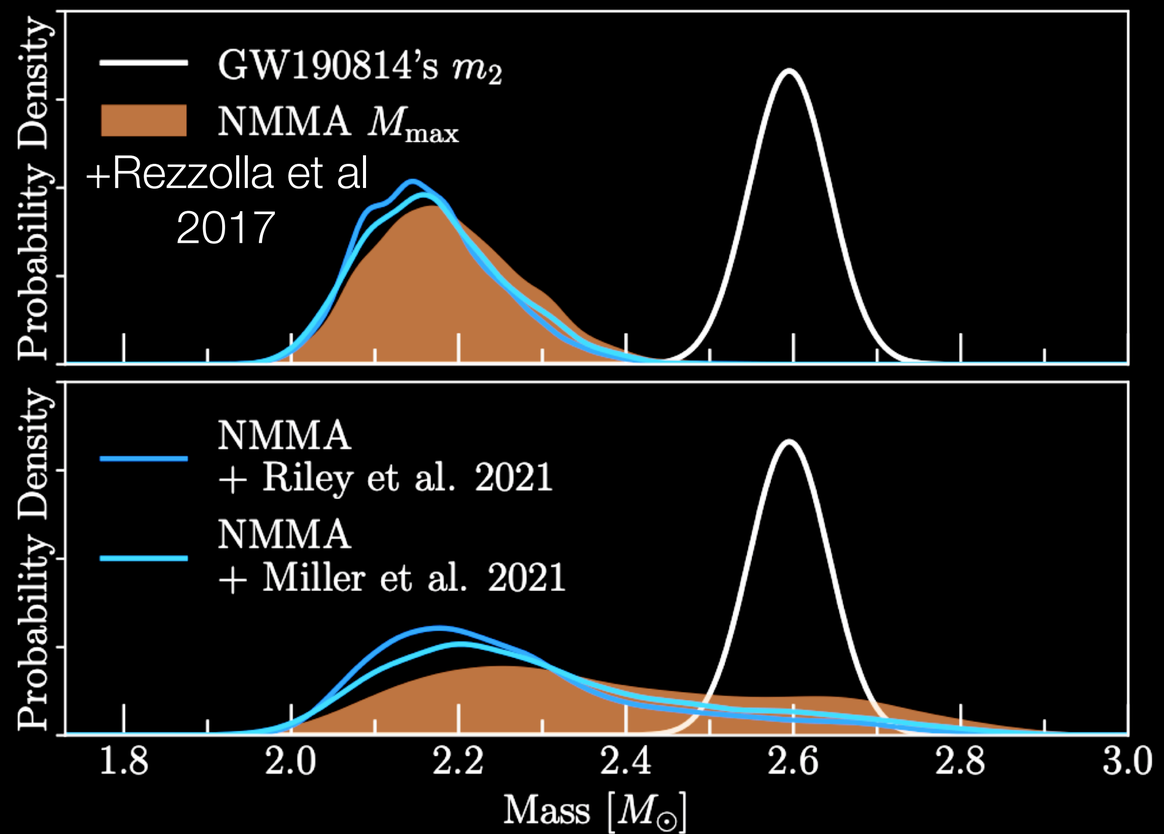
— — range to SNR 8
— — range to SNR 100
— — range to SNR 1000

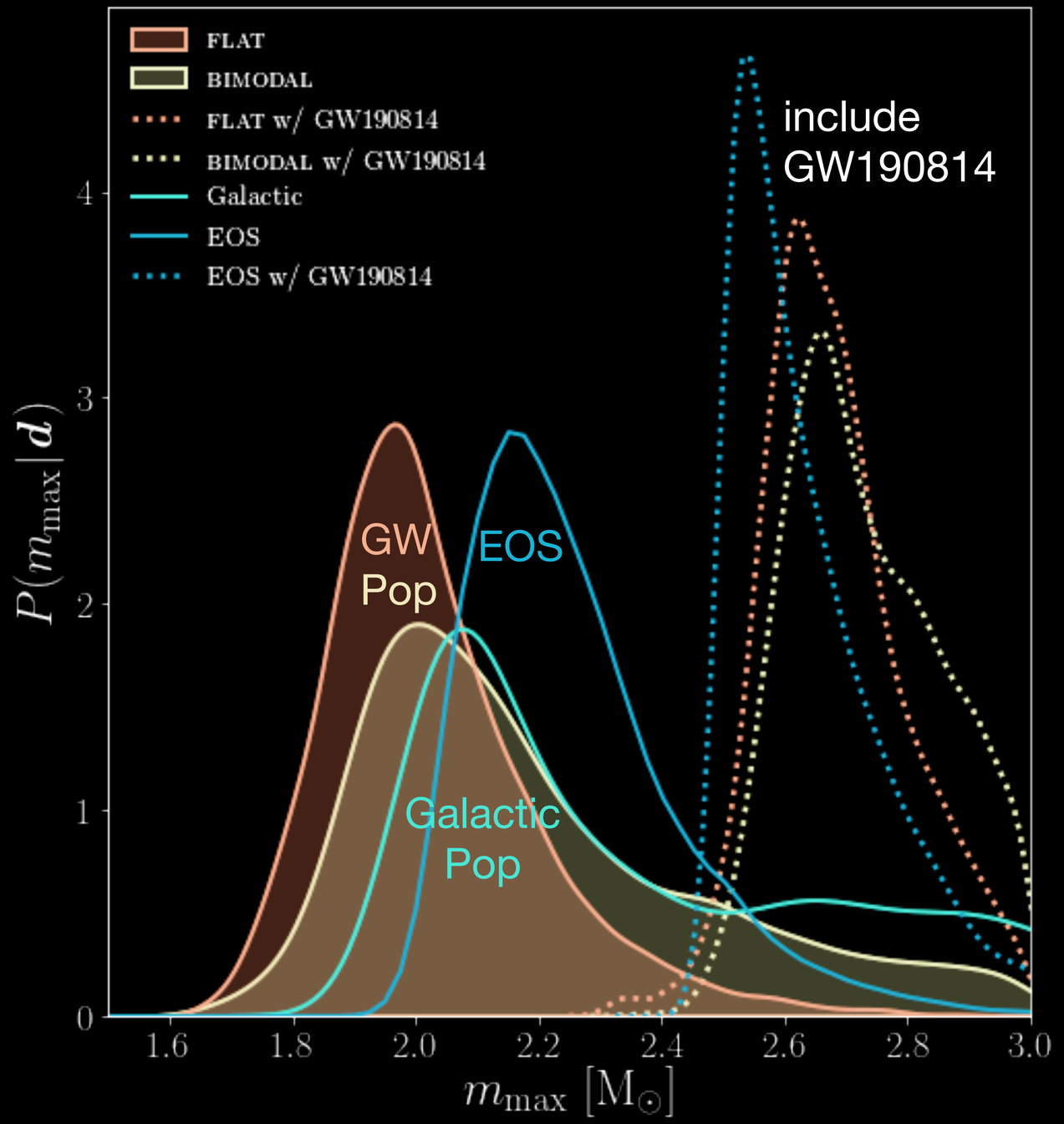
White Paper for NSF MSCAC ngGW ,
https://arxiv.org/abs/2306.13745

Maximum Mass

Informs classification of GW sources

Multimessenger GW170817, Pang et al 2105.08688

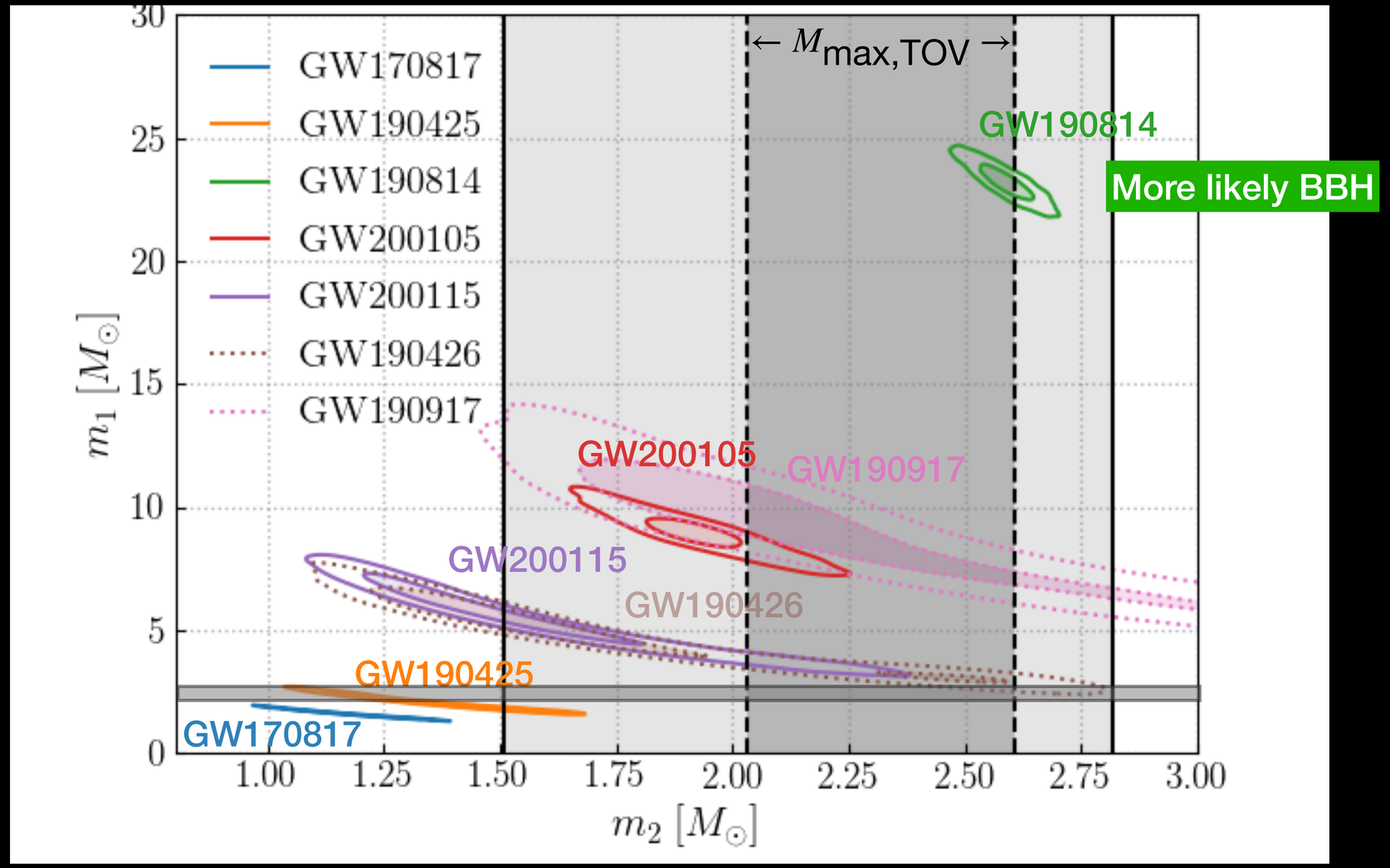




Landry and Read Astrophys. J. Lett. 921, L25 (2021)

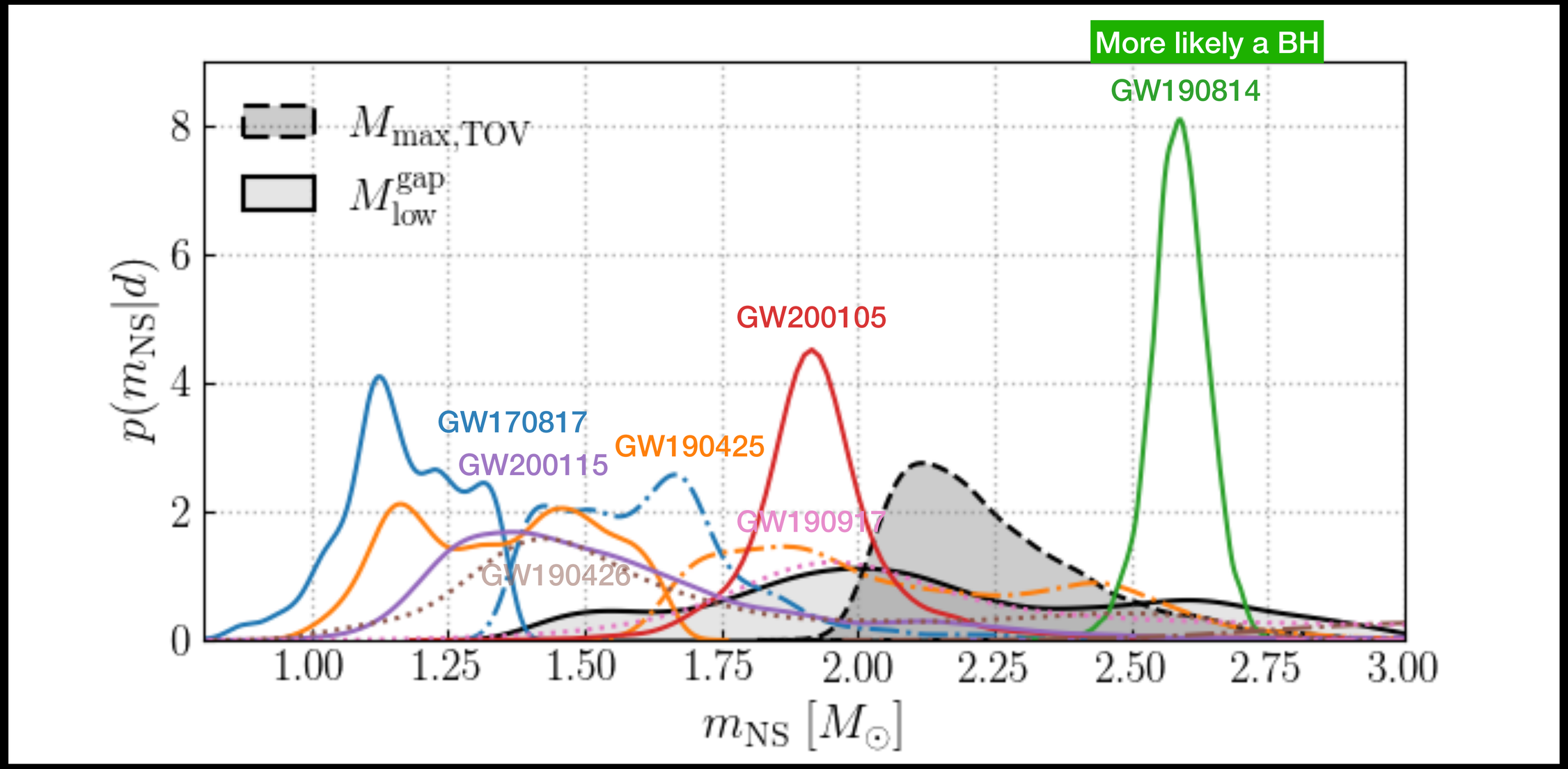
Low-mass mergers observed in GW

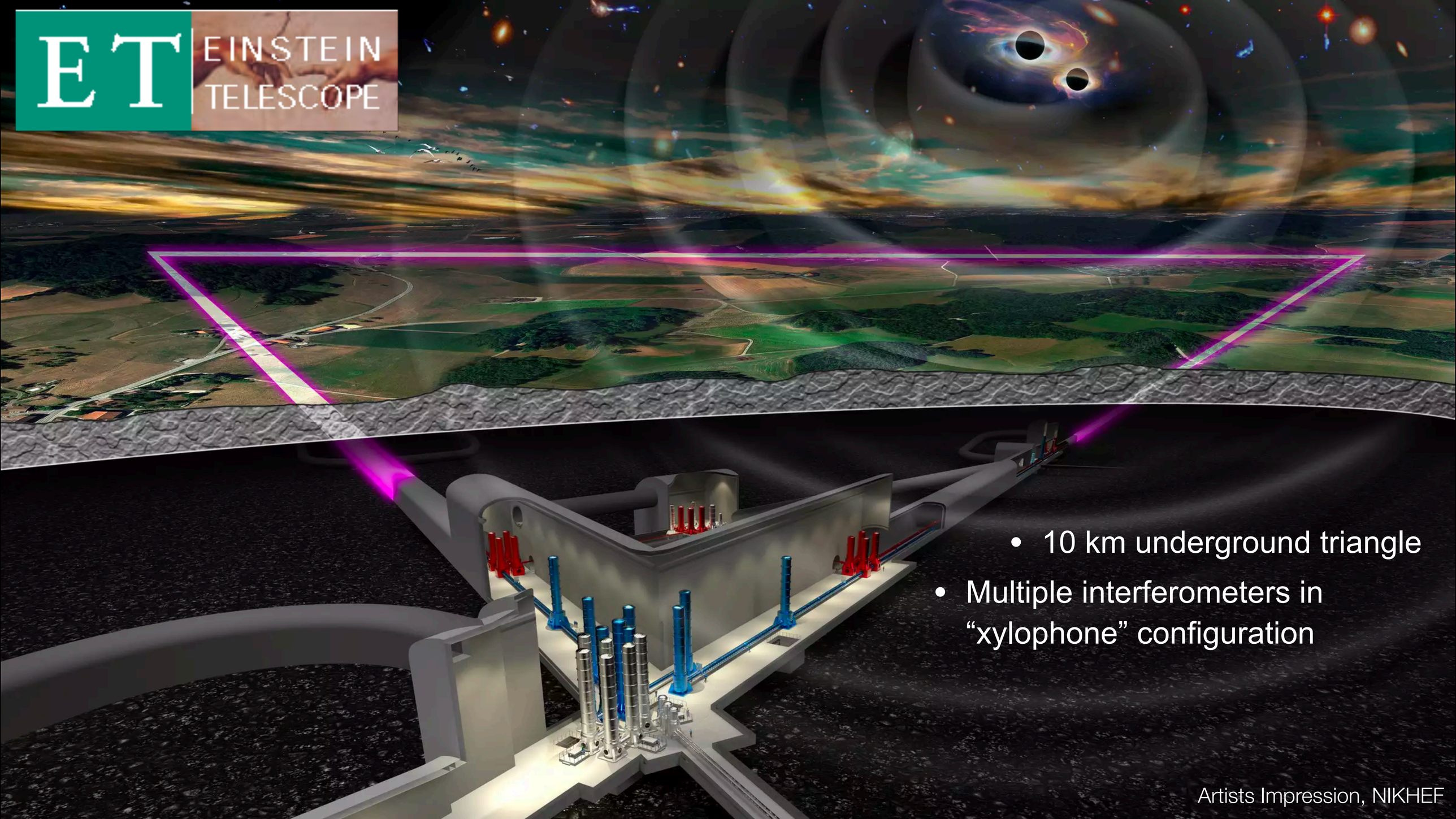
LIGO-Virgo-Kagra, arXiv:2111.03634 (LIGO-P2100239-v11)



Component stars observed in GW

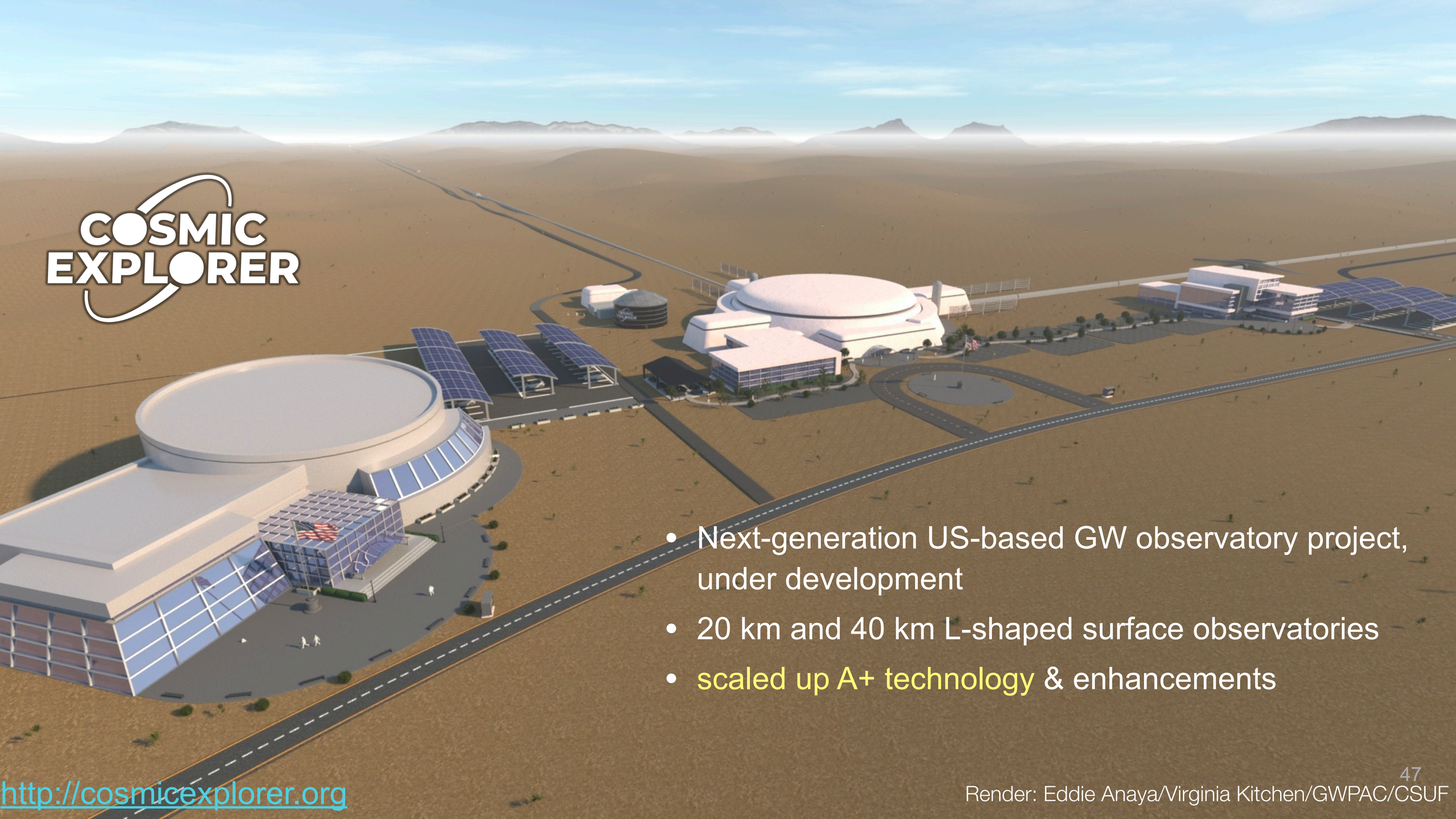
LIGO-Virgo-Kagra, arXiv:2111.03634 (LIGO-P2100239-v11)





- 10 km underground triangle
- Multiple interferometers in “xylophone” configuration

Artists Impression, NIKHEF



- Next-generation US-based GW observatory project, under development
- 20 km and 40 km L-shaped surface observatories
- scaled up A+ technology & enhancements

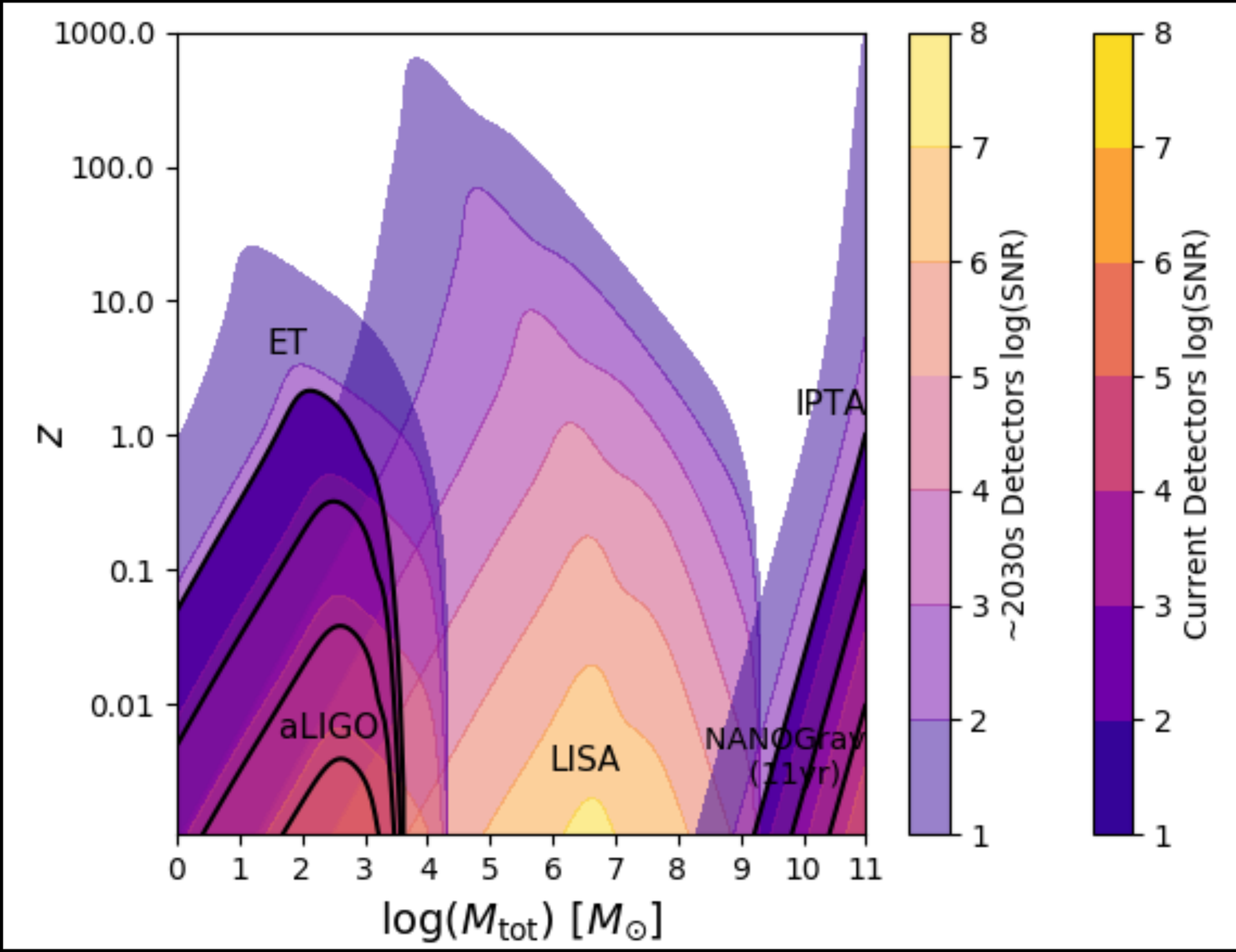
http://cosmicexplorer.org

Render: Eddie Anaya/Virginia Kitchen/GWPAC/CSUF

Individual binaries

- Multiband observation of given mass binary:
  - Continuous source at early times & low frequency ($t_{inspiral} \gg t_{observation}$)
  - Merger transient at late times & high frequencies ($t_{observation} \gg t_{inspiral}$)

Burke-Spolaor et al
arXiv:1811.08826



Key questions in nuclear astrophysics

- How does nuclear physics govern the lives and deaths of stars?

  Masses of black holes and neutron stars in binaries → signatures of nuclear physics in massive stars & supernovae

  e.g. $^{12}C(\alpha,\gamma)^{16}O$ rate sets largest **BH** mass (R. Farmer *et al* 2020 *ApJL* **902** L36)

- What is the origin of the elements?

  Rates of mergers, by source type → contribution of mergers to r-process: amount of ejecta per event, rate of events with nucleosynthesis

  EM counterparts → observation of elements in kilonovae, knowledge of progenitor

- What fundamental nuclear physics can we learn?

  Neutron-star tides → equation of state for cold dense matter

  ?Post-merger waves → hotter & denser regions of QCD phase diagram

  ?New physics → dark matter, beyond-Standard-model physics

Categories from Gail McLaughlin

Limit/recovery of model error

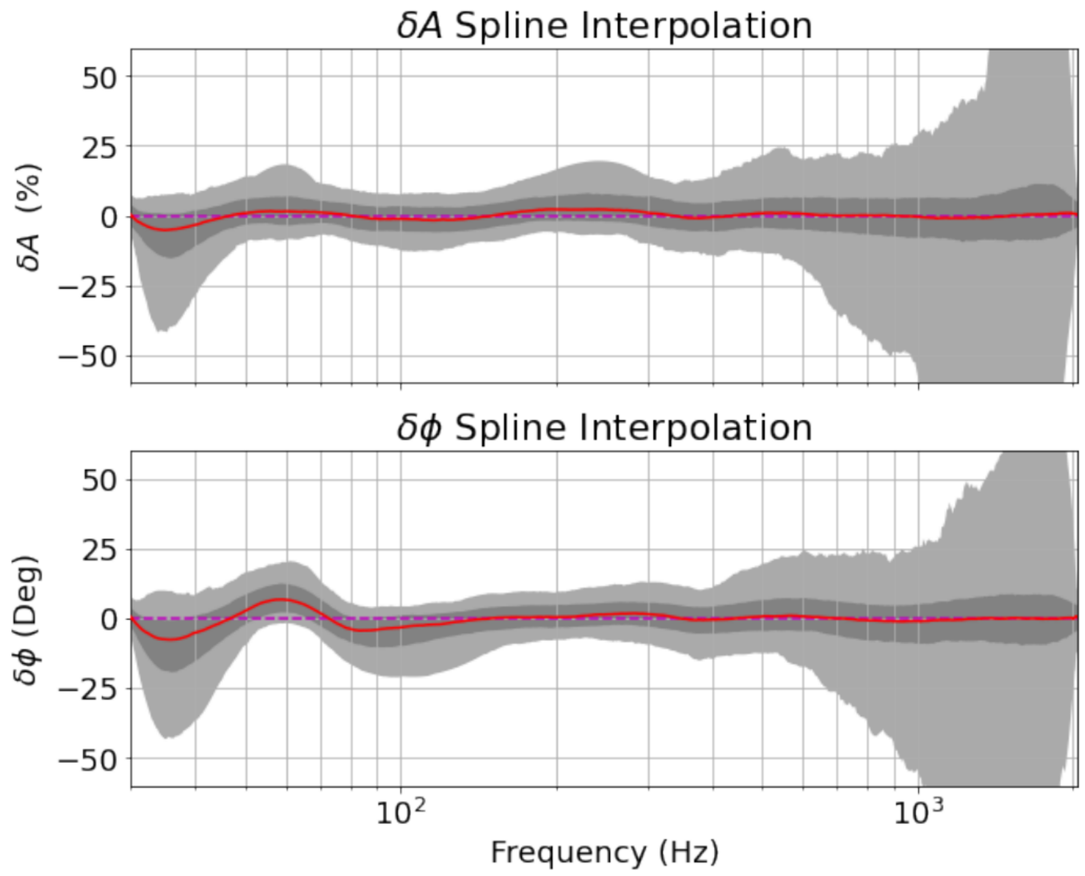
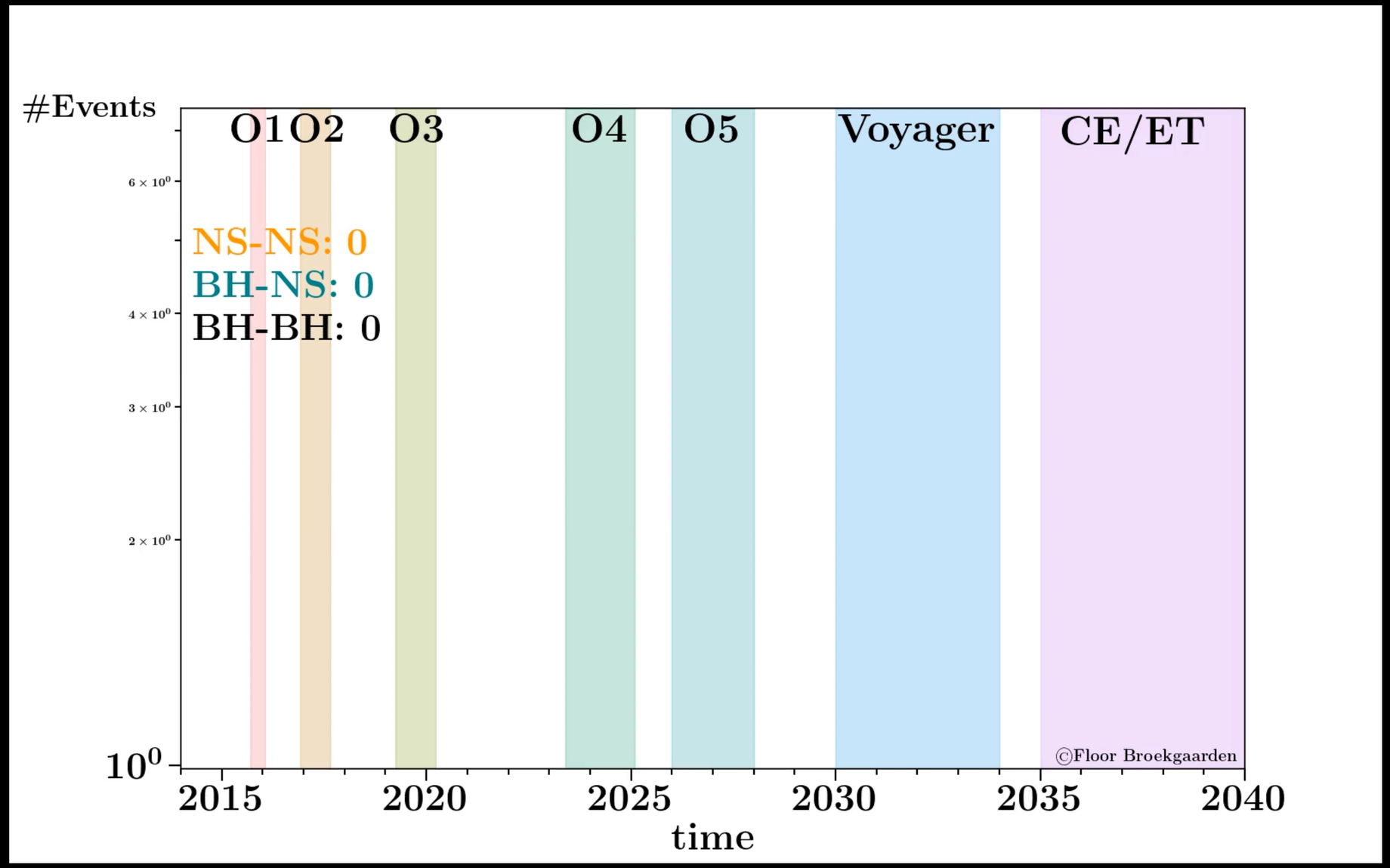


FIG. 12. Spline interpolation of GW170817 with 1 and 2 σ credible intervals (grey) and the median spline interpolant (red) shown.

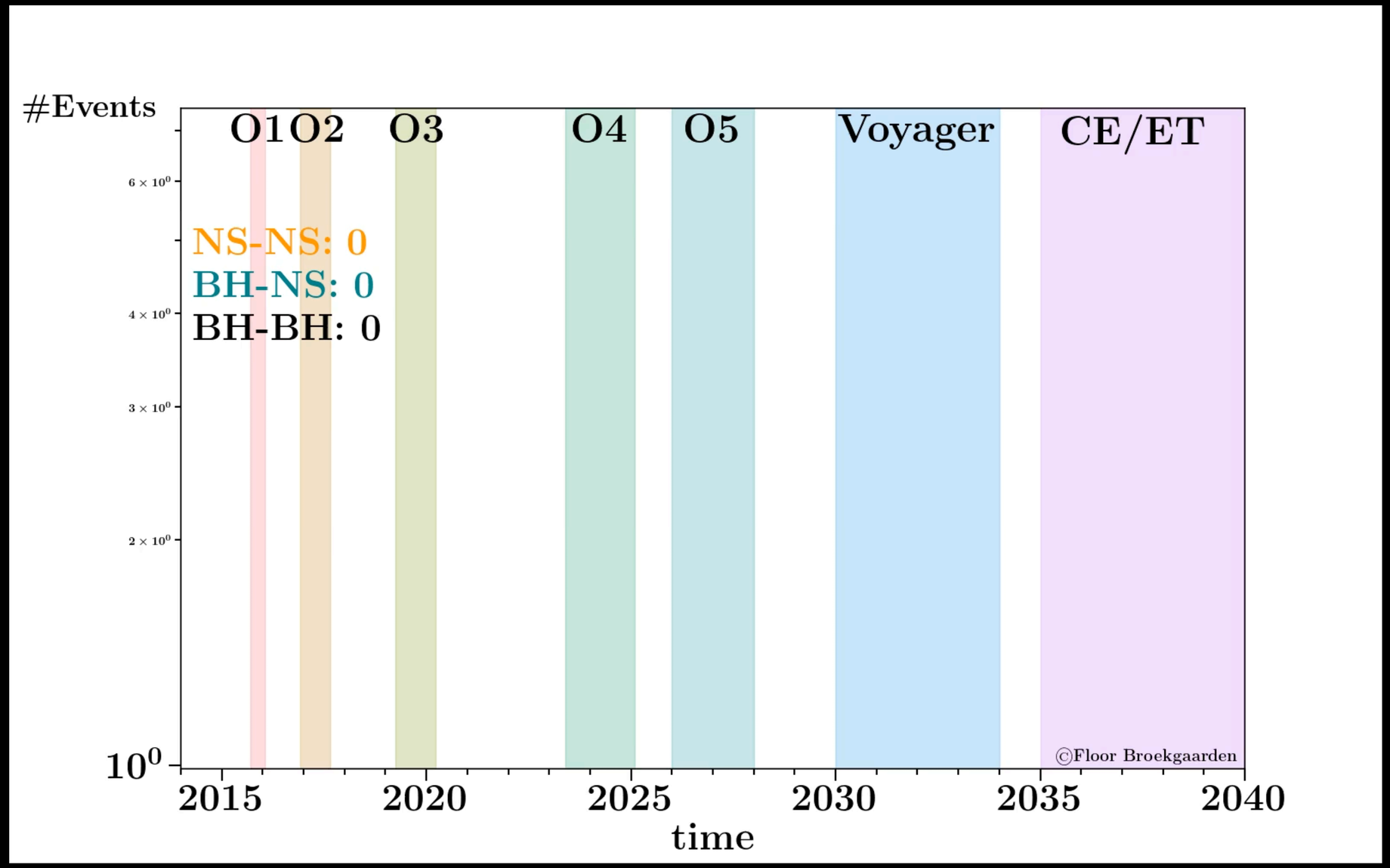
- Edelman et al Phys. Rev. D 103, 042004 (2021): Constraint on coherent departures from waveform model
- Generic signal modification described with splines for $\delta A, \delta\phi$, constraint for GWTC-1
- JR 2023: **Interpretation with waveform energetics:**
- **GW170817** phase shift $\delta\phi \sim 5$ 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)

Projected populations

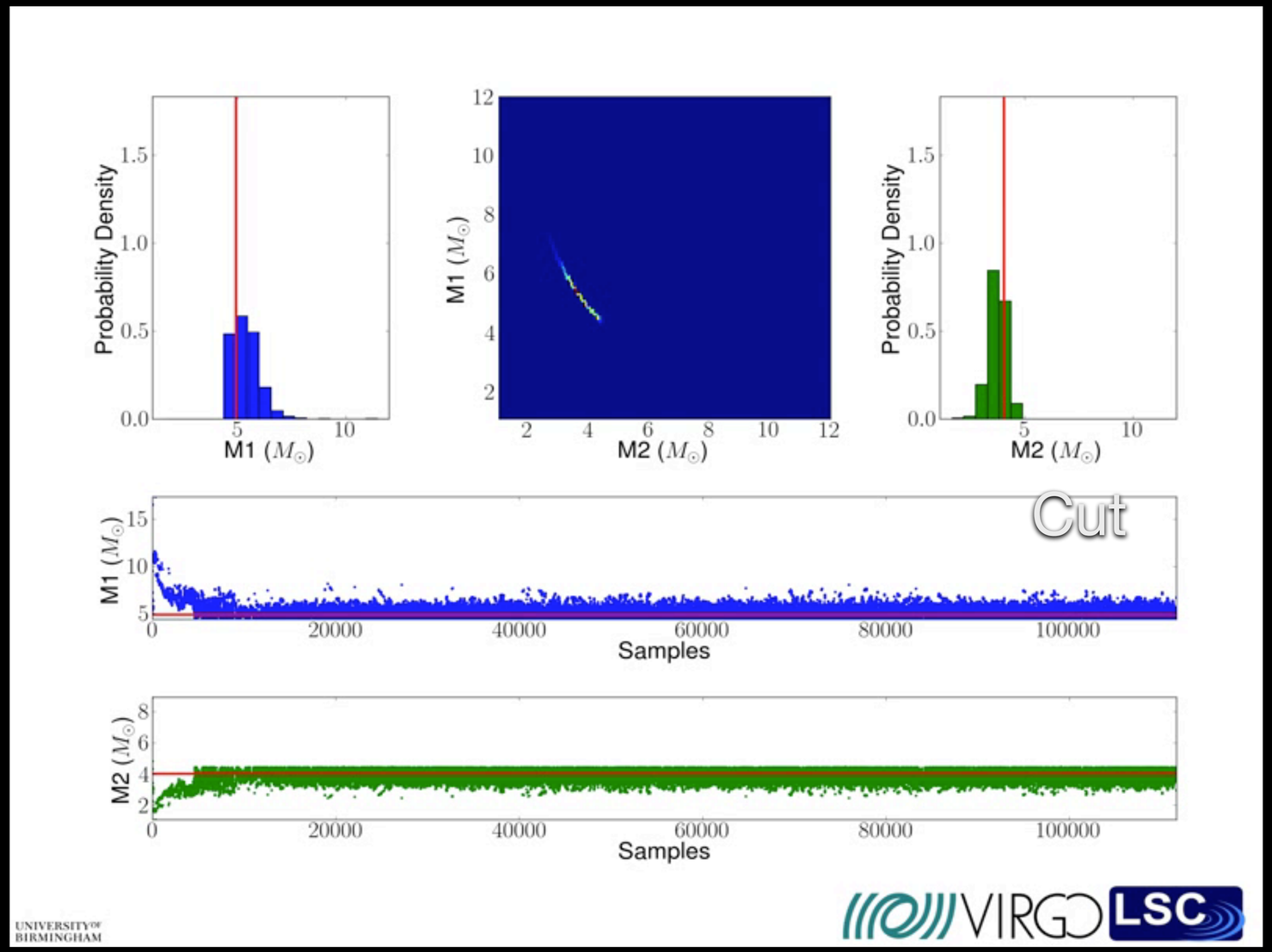


Visualization: Floor Broekgaarden

Projected populations



Visualization: Floor Broekgaarden



- LEFT: MCMC estimate of masses http://arxiv.org/abs/1304.1775

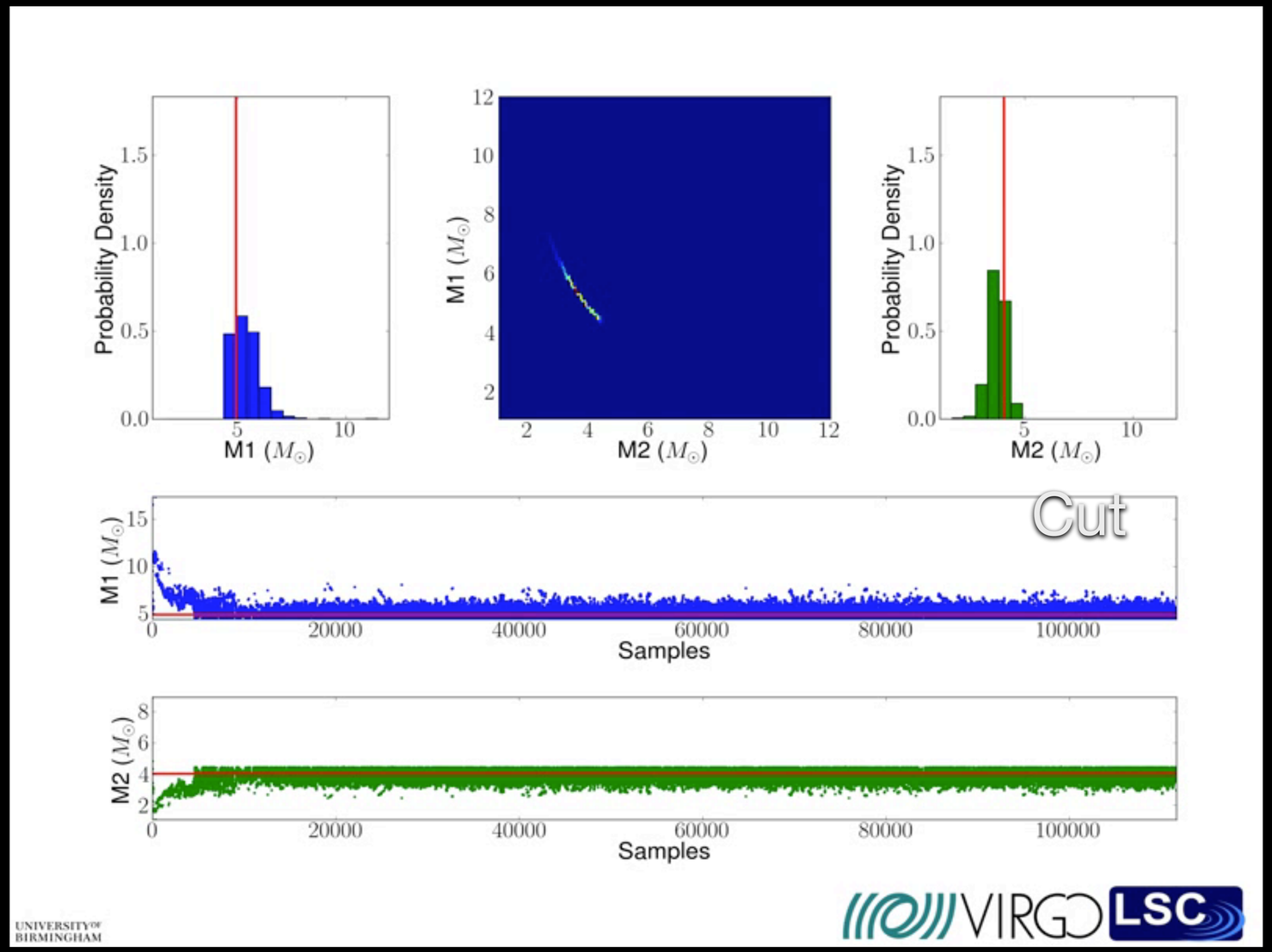
- Precision in the "chirp mass":

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

- Why?

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

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



- LEFT: MCMC estimate of masses http://arxiv.org/abs/1304.1775

- Precision in the "chirp mass":

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

- Why?

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

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