# Neutron stars observed With gravitational-wave astronomy

ECT* 2022

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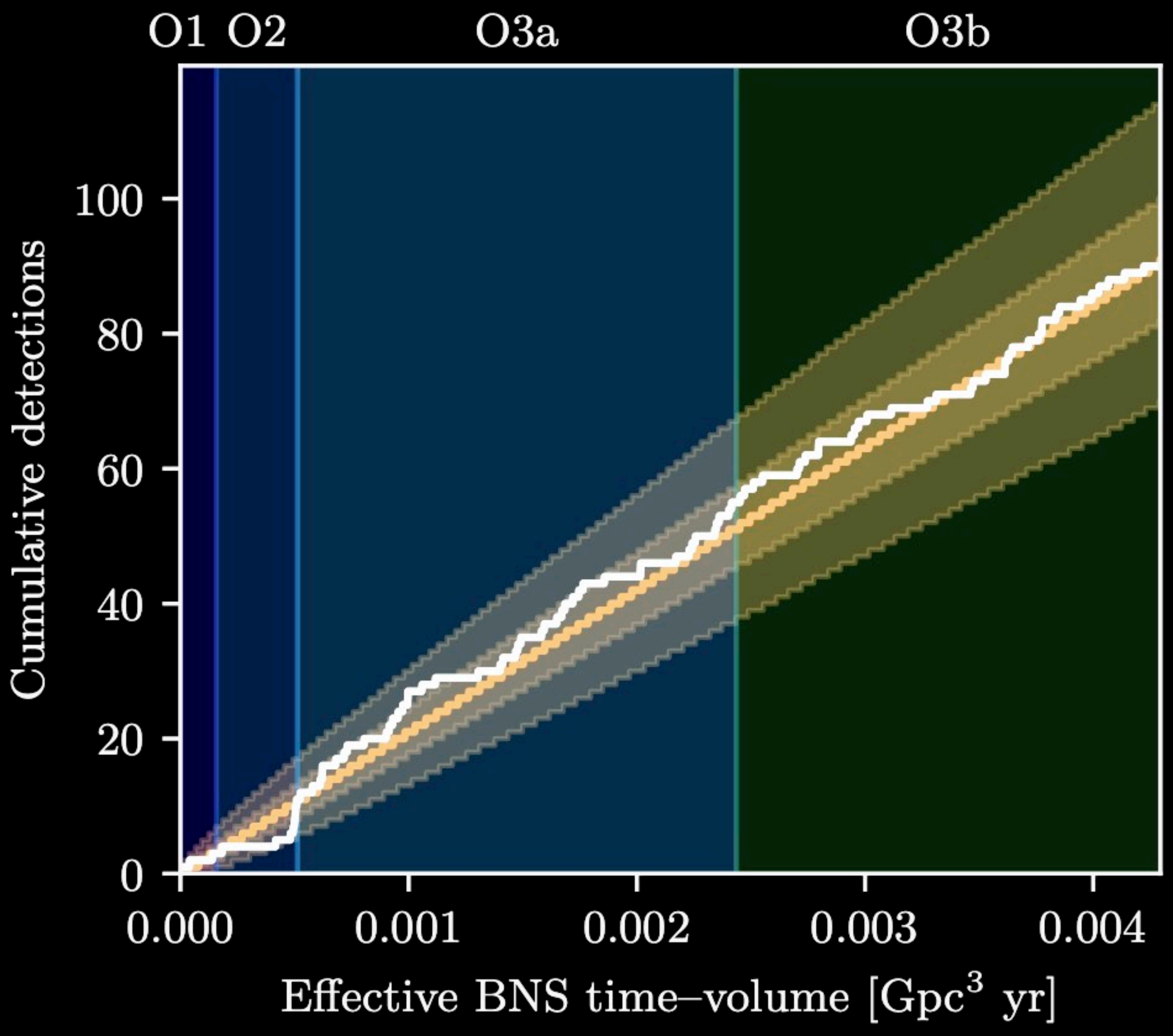
Neutron Stars Merging,
CSUF GWPAC Artist-in-Residence Eddie Anaya

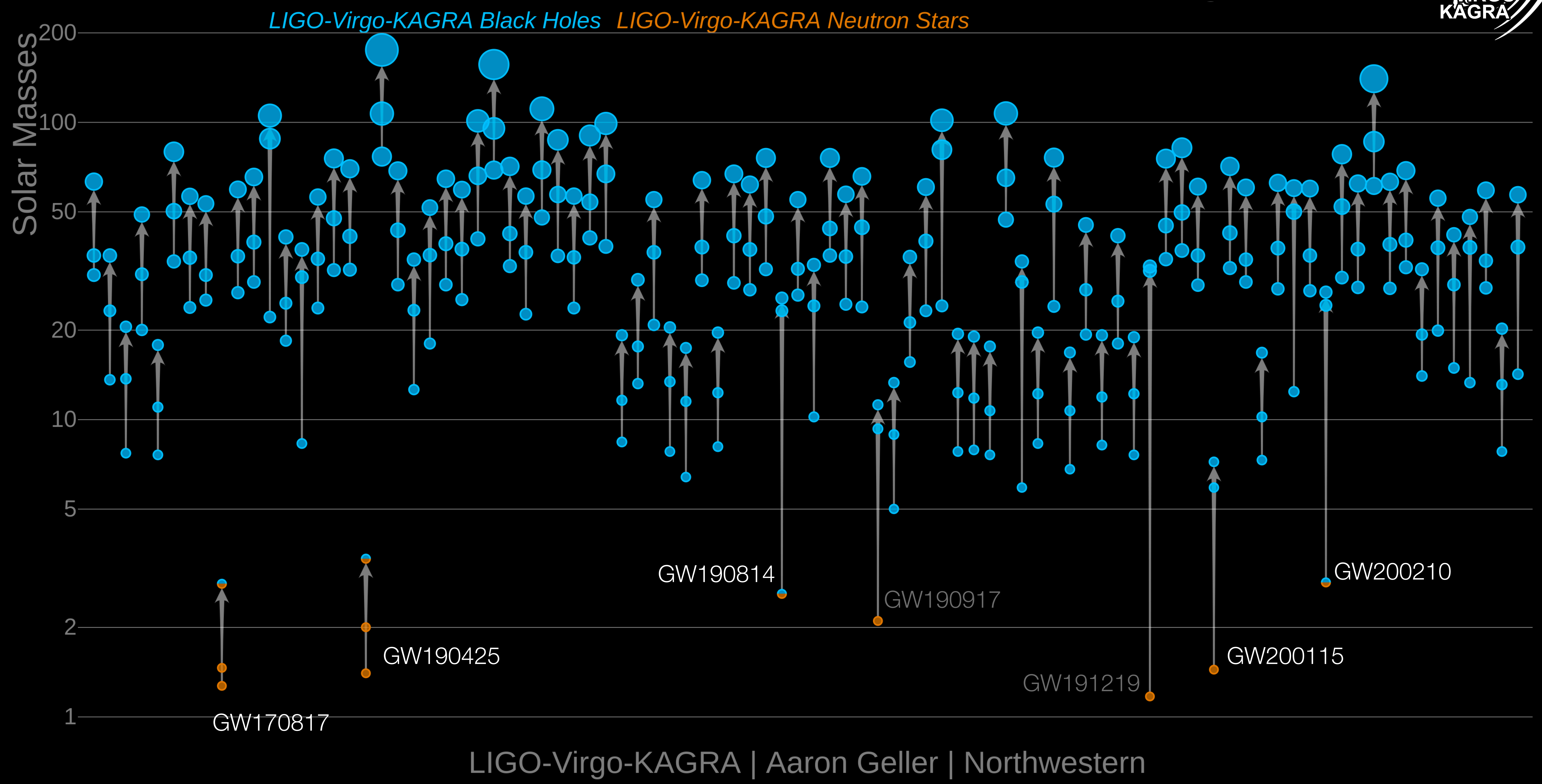
O1-O3:

- 90 compact binary systems [LVK GWTC-3 Catalog, LIGO-P2000318, arXiv:2111.03606]
- O4:
  - One year duration from early 2023,
  - anticipated BNS search volume of 0.016 $Gpc^3$ yr (~4x previous total, range ~190 Mpc)
  - [LVK Observing Scenarios Document, LIGO-P1200087]






LVK GWTC-3 Catalog, LIGO-P2000318

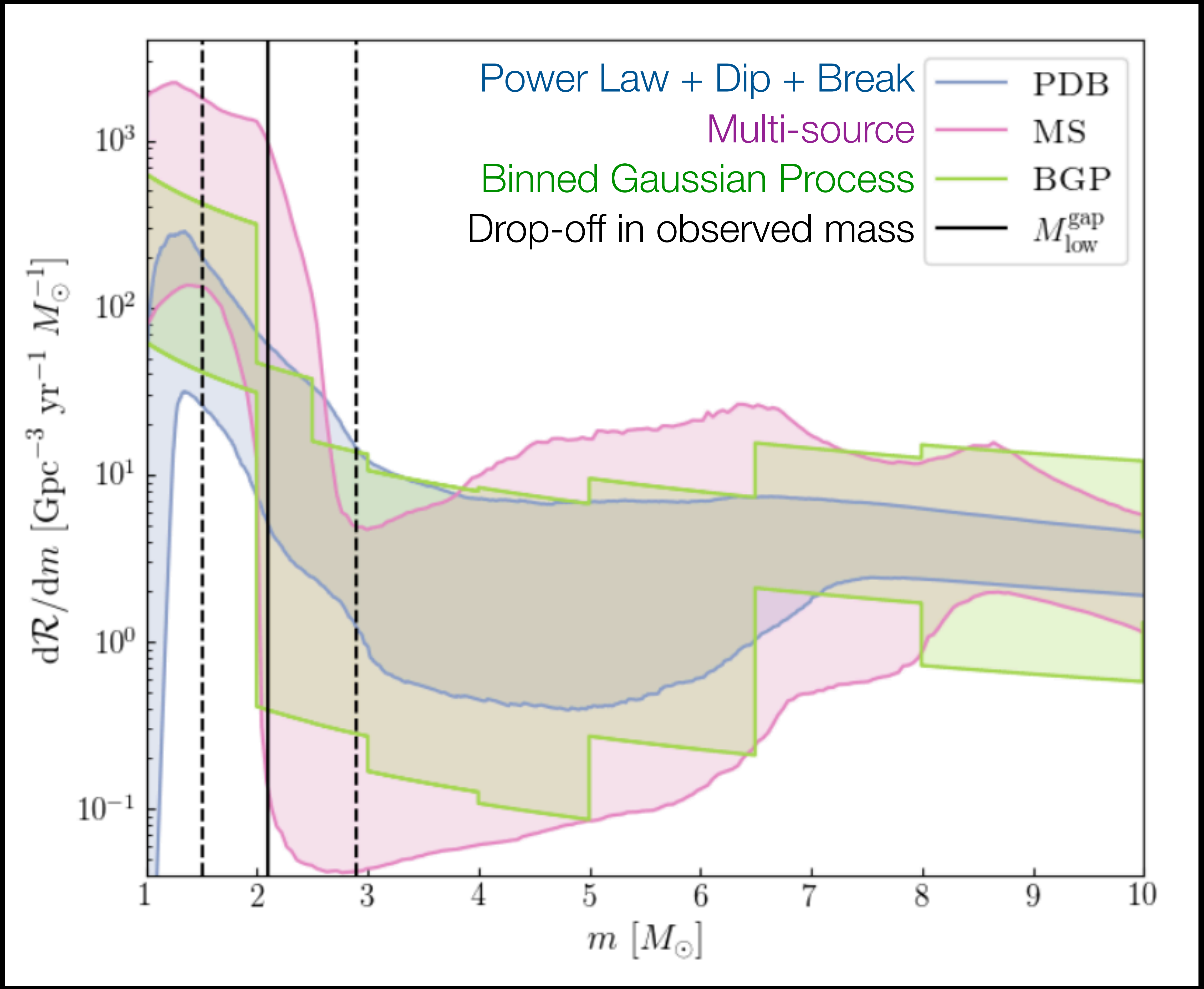



 LIGO-Virgo-Kagra GWTC-3 Catalog LIGO-P2000318-v8, arXiv:2111.03606

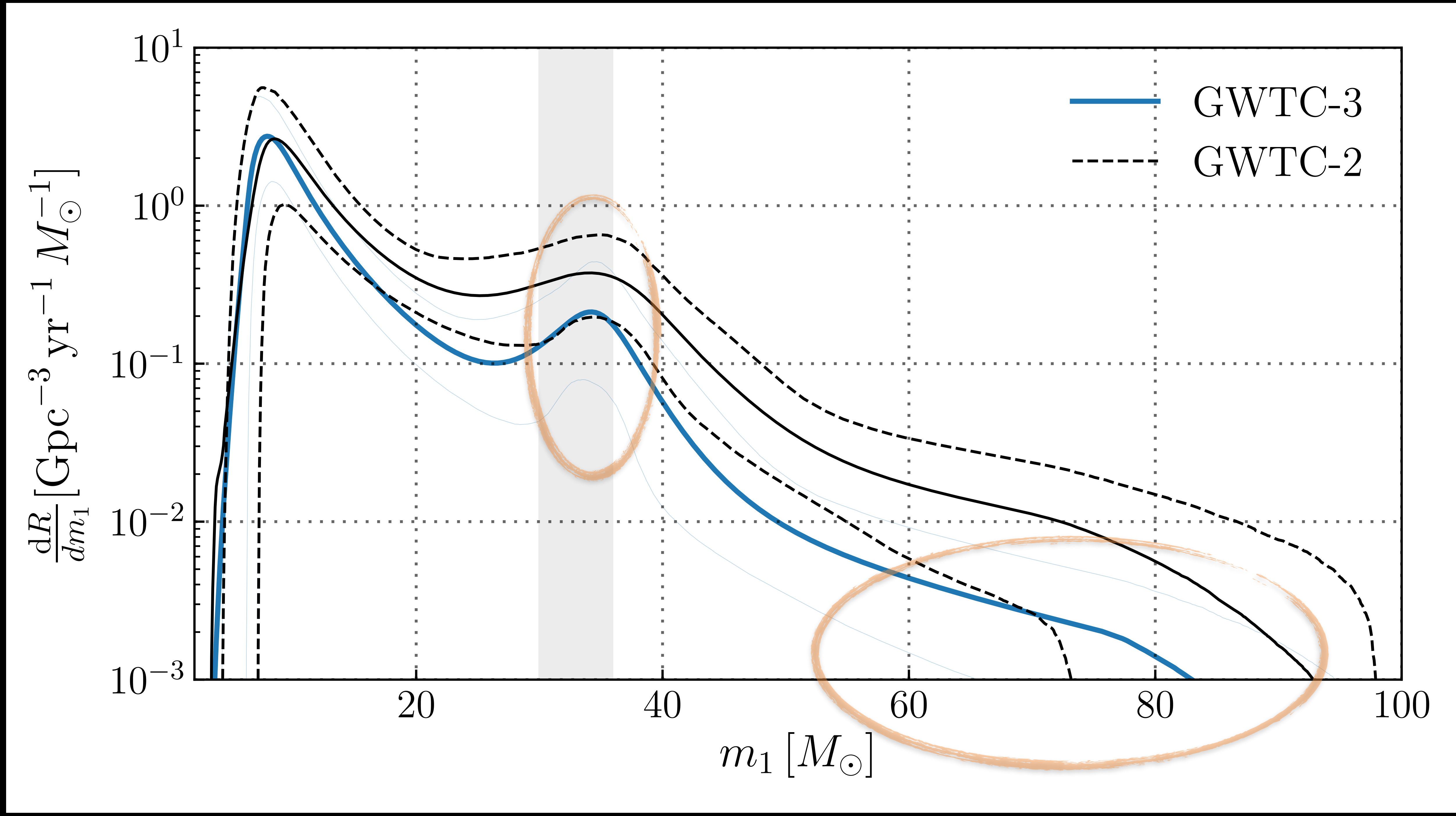
# The population of merging compact binaries inferred using gravitational waves through GWTC-3

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

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

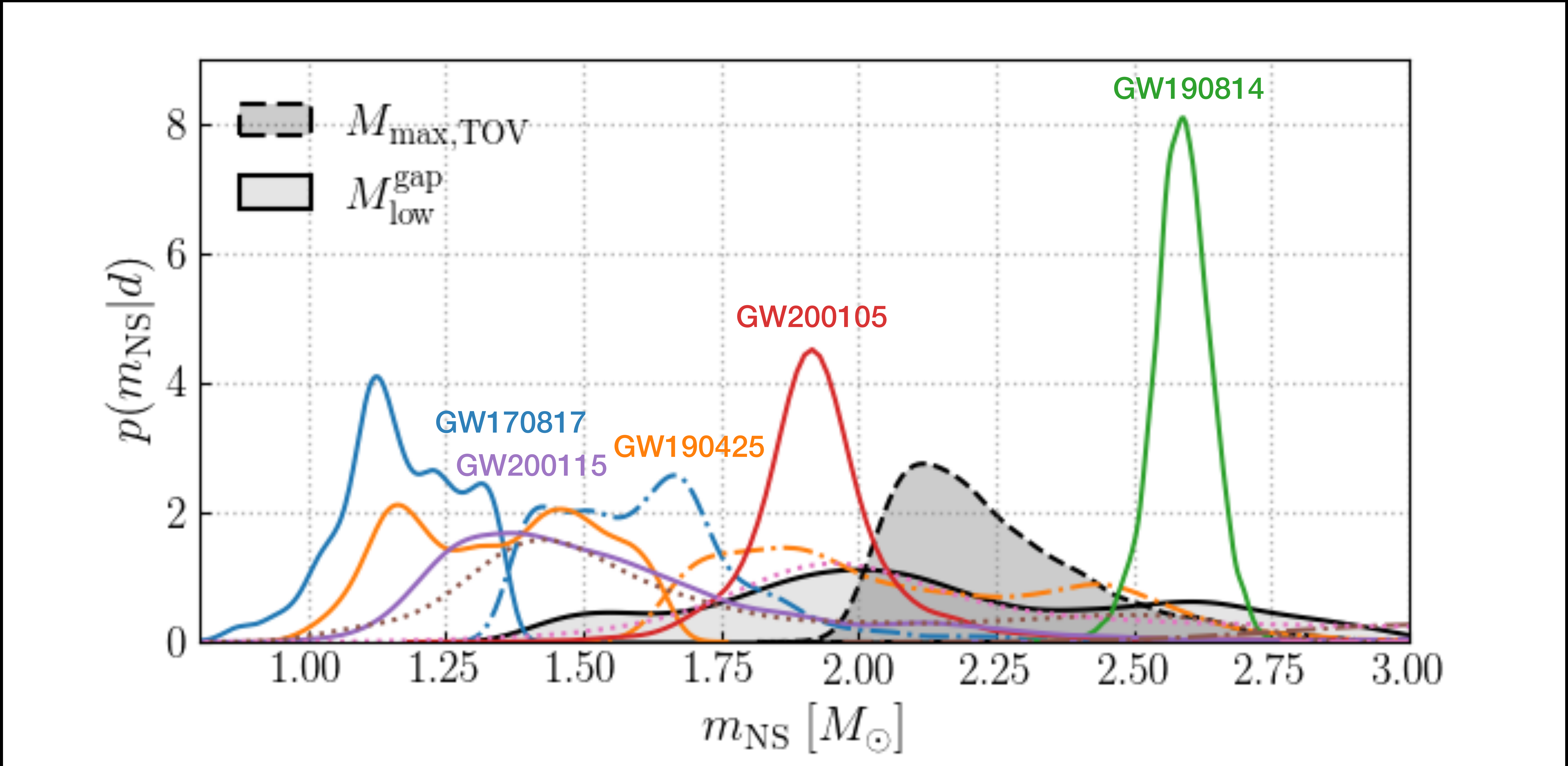



## Structure in the BH mass spectrum



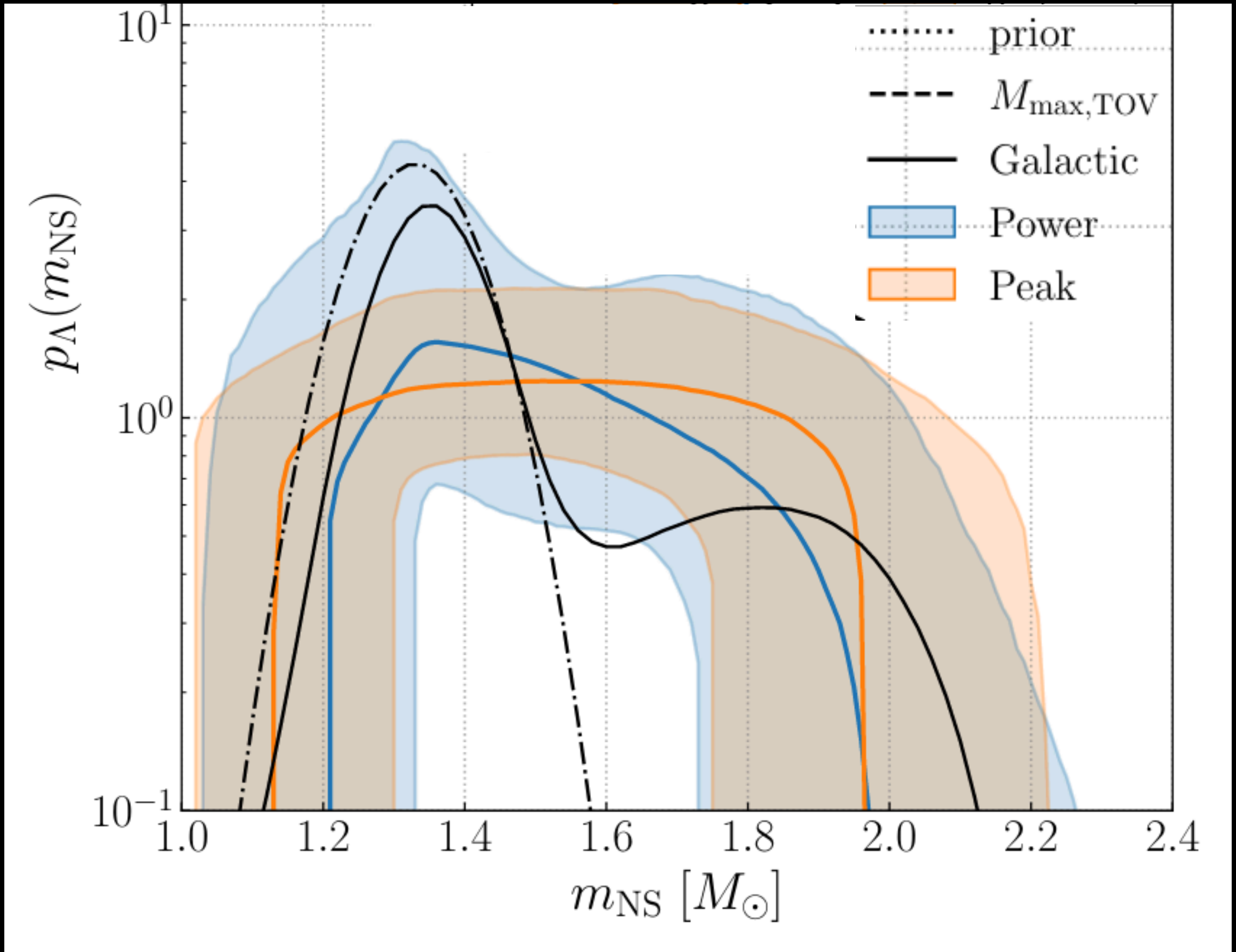
# Neutron stars observed in GW

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

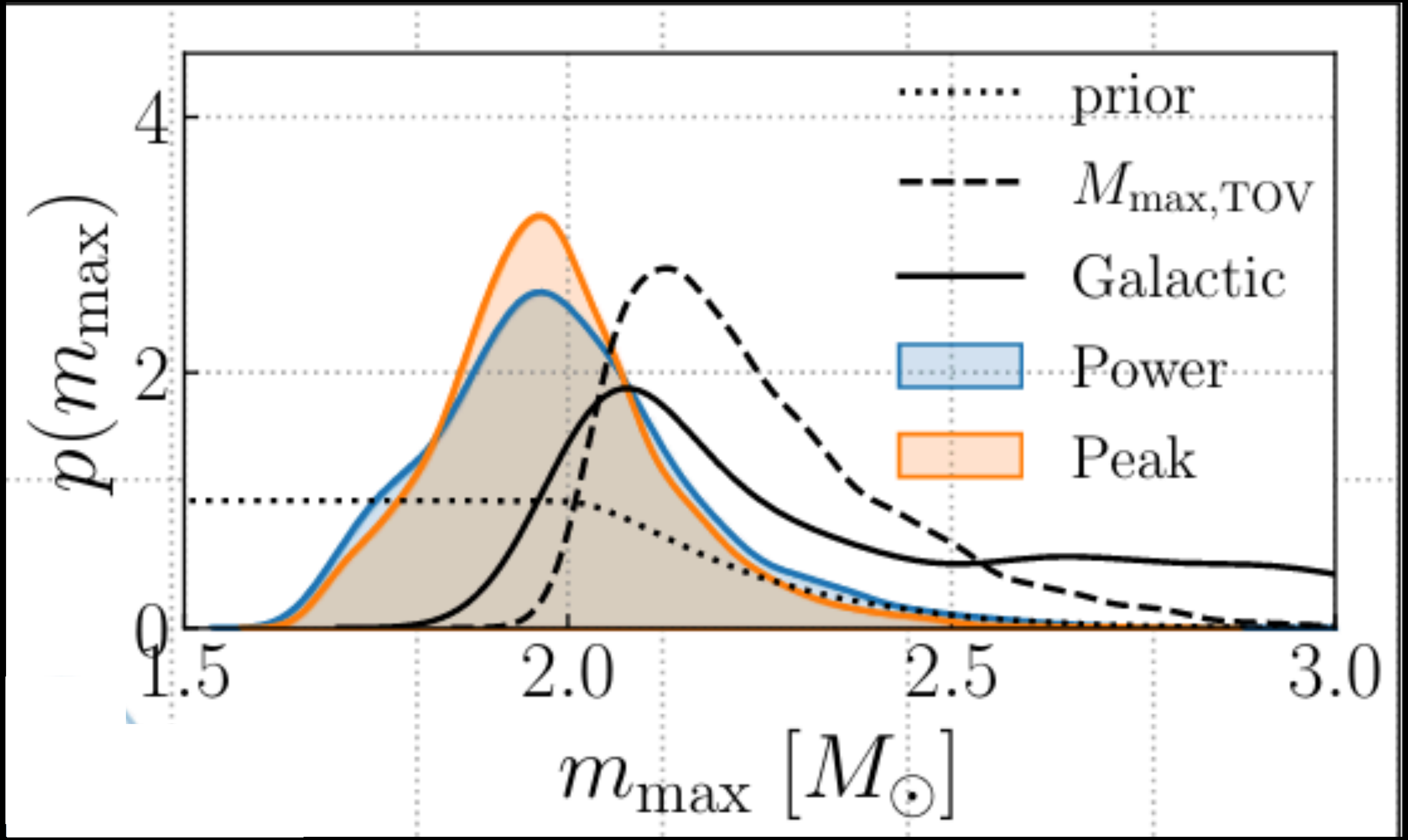


# Neutron stars observed in GW

More high-mass observations




Maximum mass observed in GW




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

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

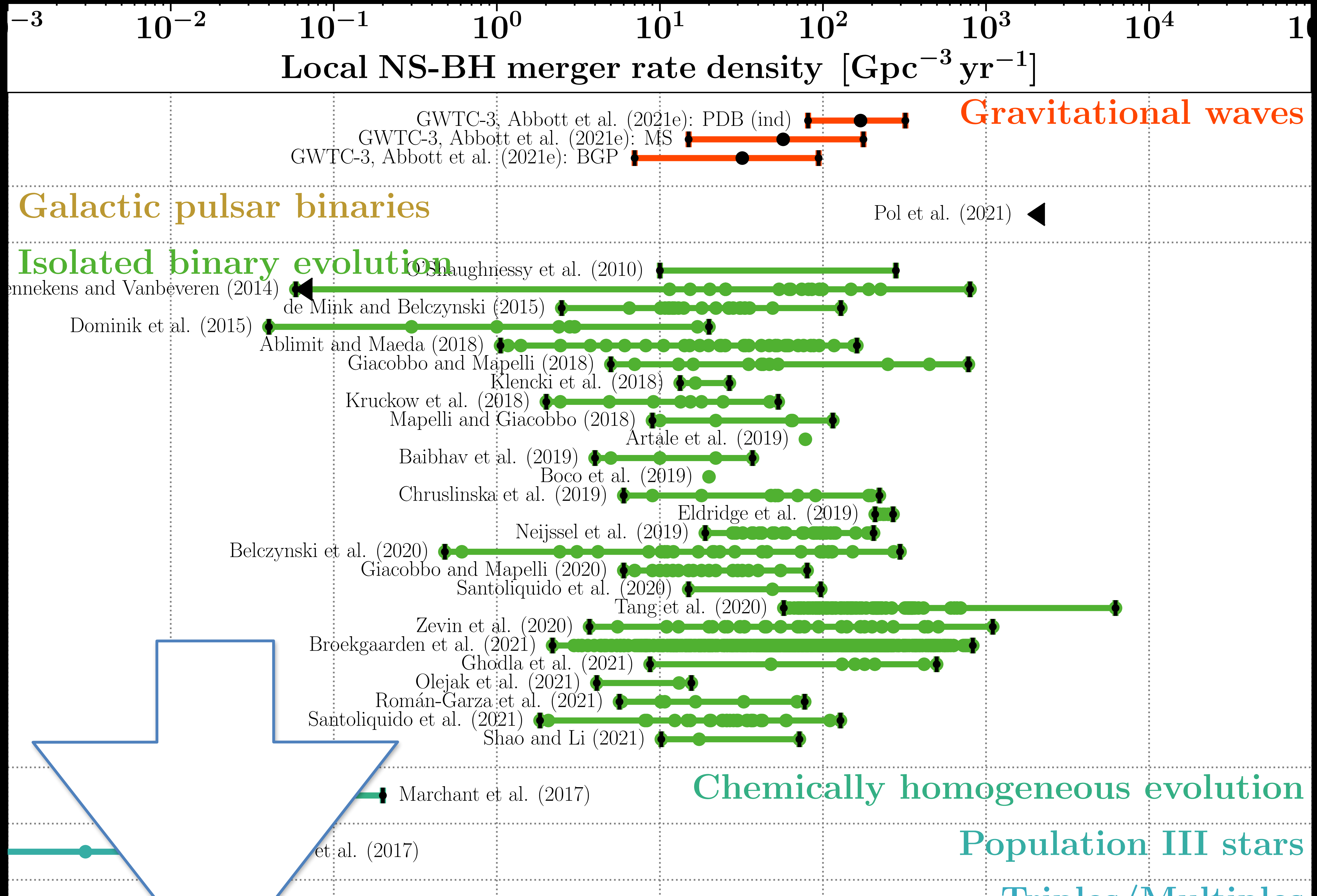
# Merger rates

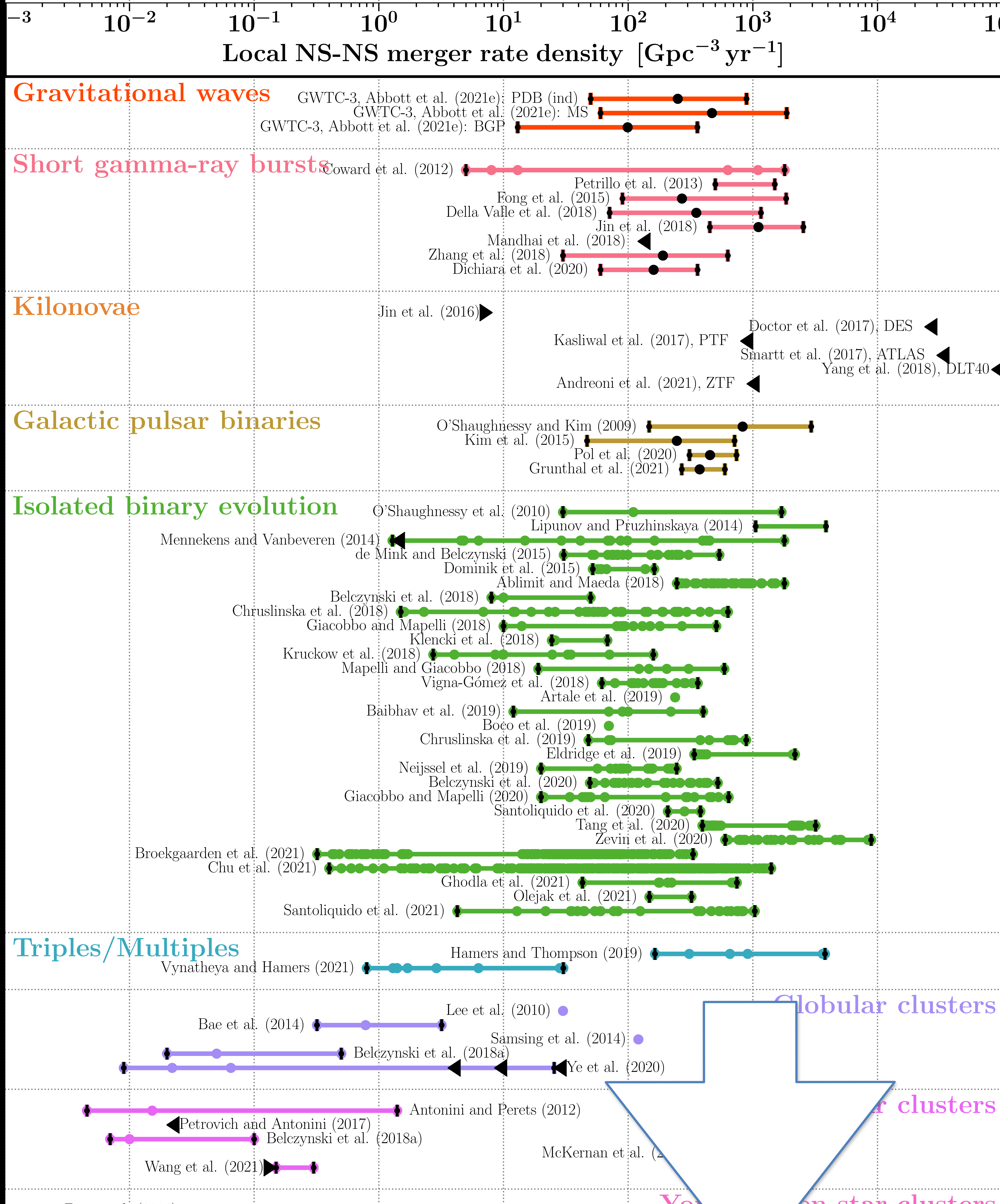
*LIGO/Virgo arXiv:2111.03634:*

*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 $Gpc^{-3}\ yr^{-1}$



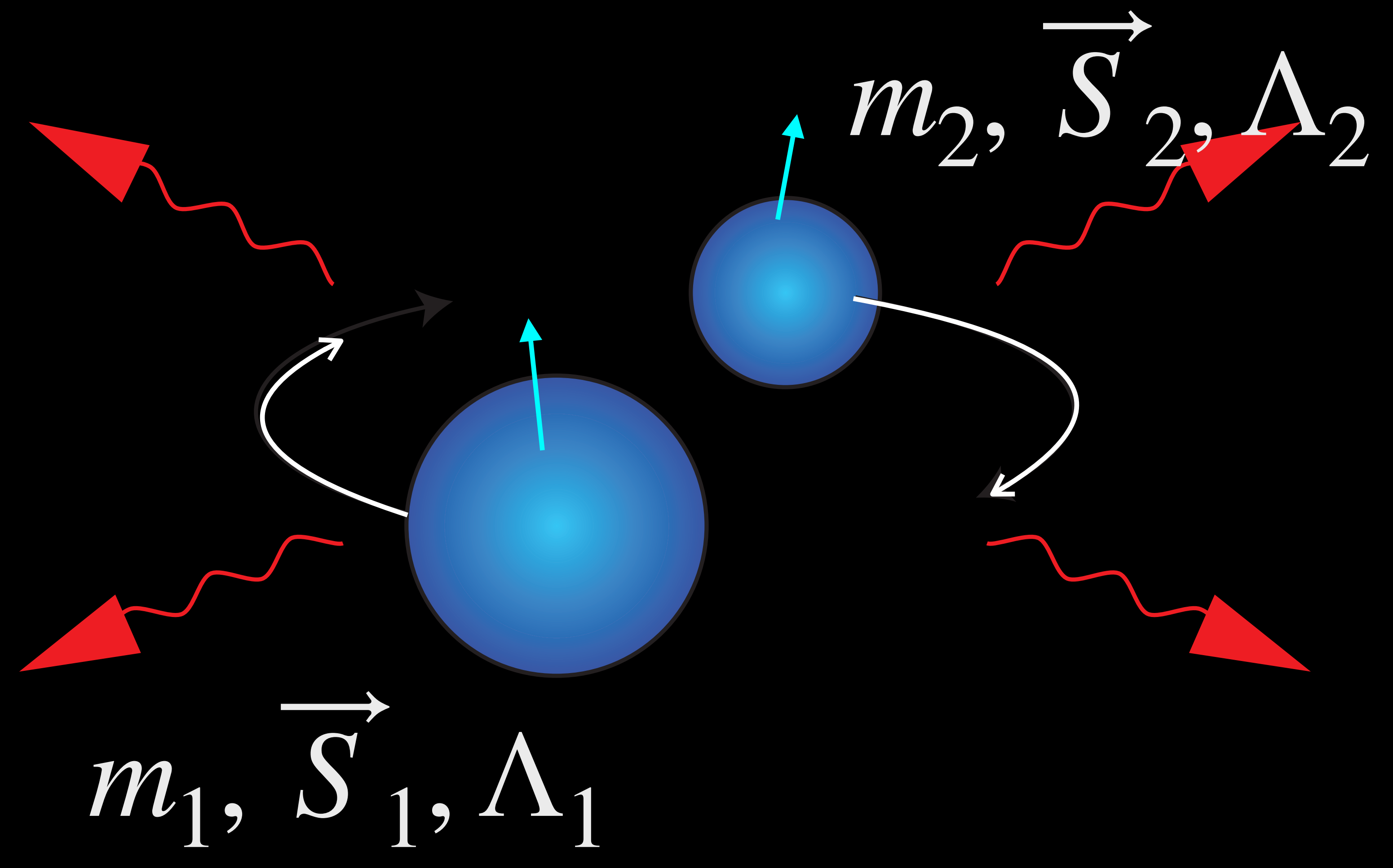




Mandel & Broekgaarden, Living Reviews in Relativity, arXiv:2107.14239

# Direct impact of neutron-star matter on gravitational waves

# Source properties and signal parameters

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




Chirp mass

Sky location, orientation

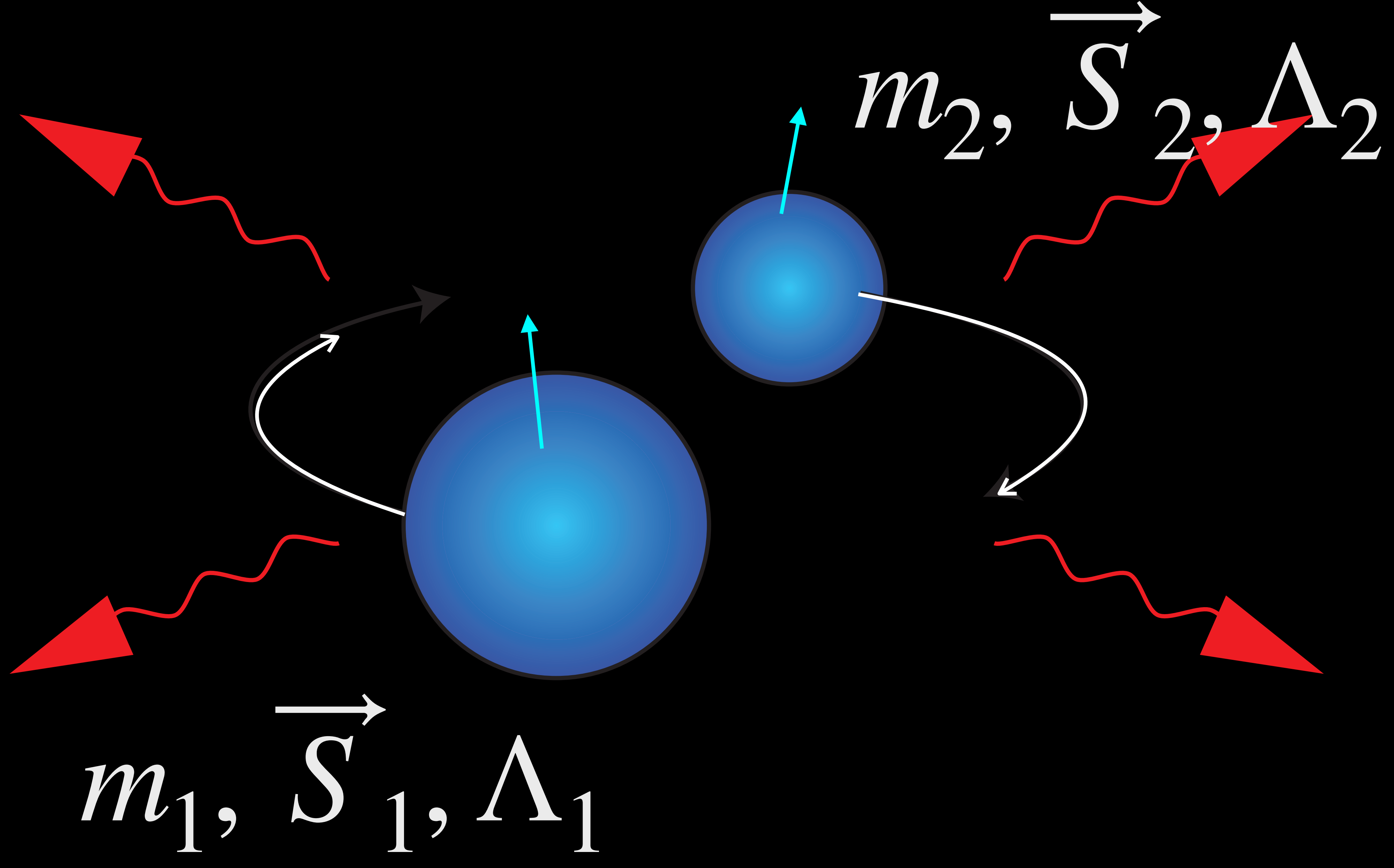
$$\tilde{h}(f) \sim \frac{\mathscr{M}}{d_L} Q(\alpha, \delta, \iota, \psi) f^{-7/6} e^{i\Psi(f)}$$

Luminosity distance

Amplitude fall-off in frequency domain

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

# Tides in GW binaries




See also: talk by Bernuzzi today

$\Lambda_i$ characterizes the ratio of mass quadrupole to external tidal field for an isolated star

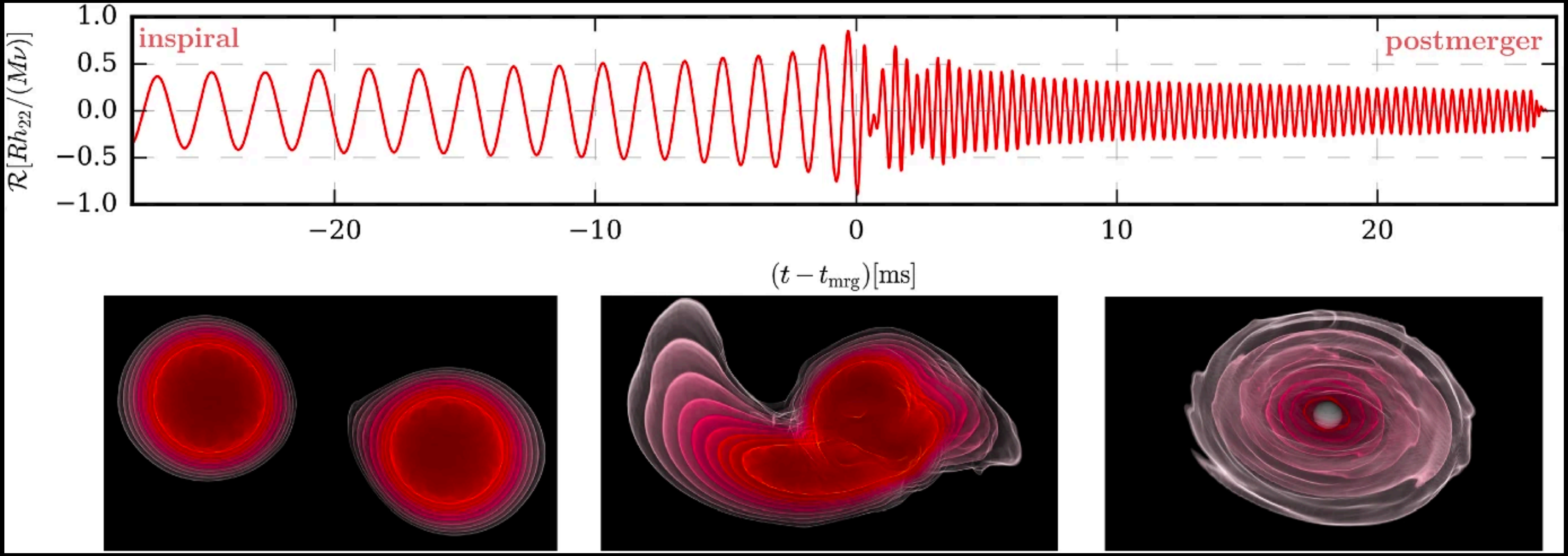
$$\Lambda_i = \frac{2}{3} k_2 \left( \frac{R_i}{m_i} \right)^5$$

$R$ radius, $m$ mass of star

$k_2$ relativistic Love number

$k_2 = 0$ for BH

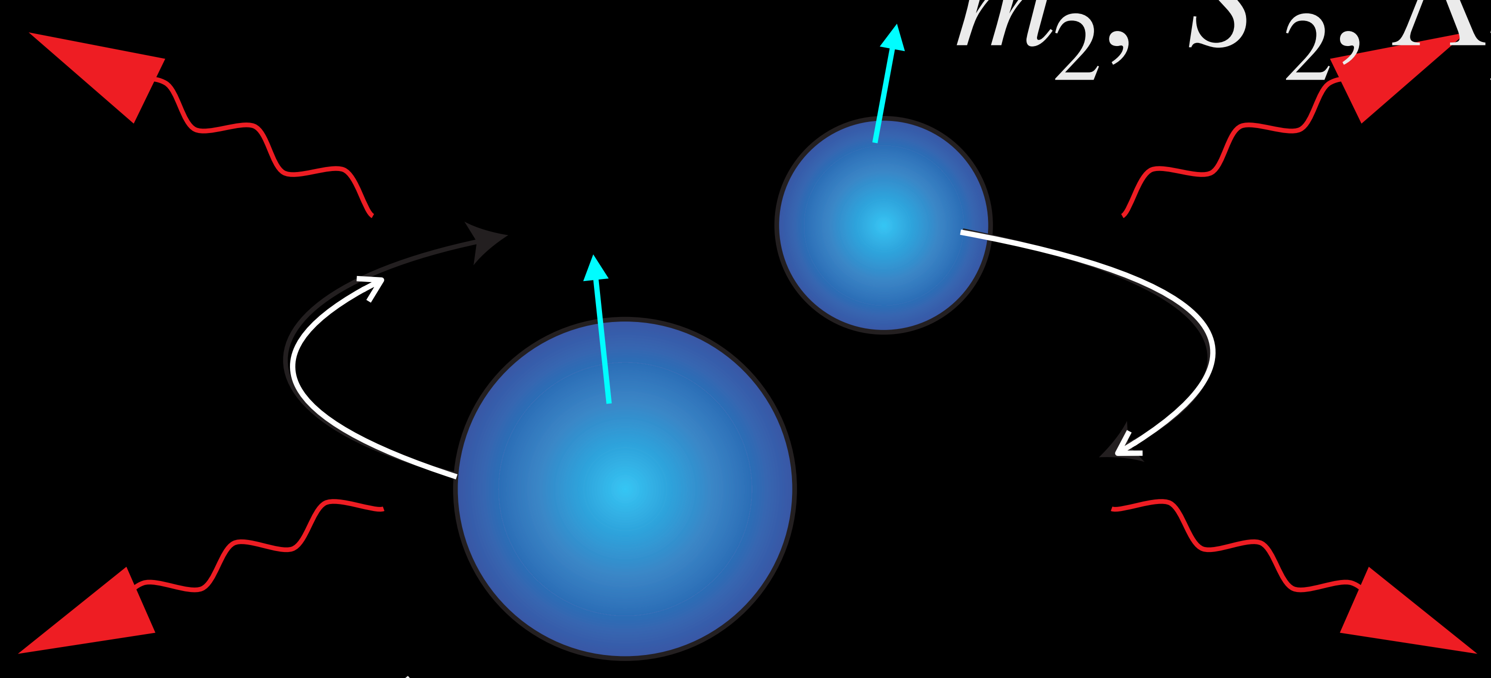
$k_2 \simeq 0.05 - 0.15$ for NS




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

- Stars deform in complicated, close interactions:
    - stars are not isolated, deformations are not linear, deformations are not pure quadrupole
- We use (and test) $\Lambda_1, \Lambda_2$ as *effective* descriptors in gravitational-wave models

# Source properties: Inspiral

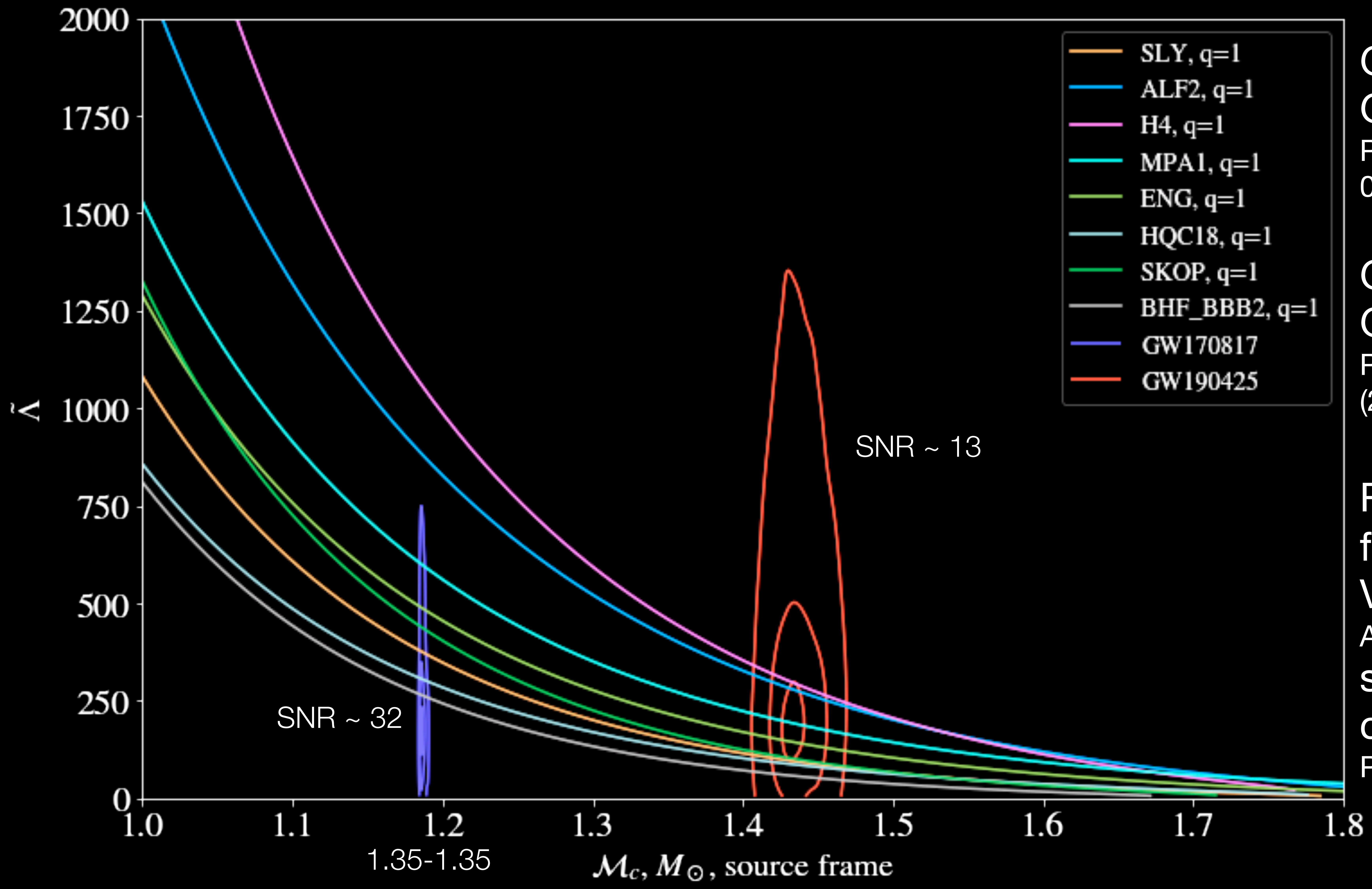



$\Psi(f)$ depends on (leading order combinations):

- 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: $\chi_{\text{eff}} = \dfrac{\boldsymbol{S}_1/m_1 + \boldsymbol{S}_2/m_2}{m_1 + m_2} \cdot \boldsymbol{L}$
- Effective tide:

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

# Observations so far: GW170817 & GW190425



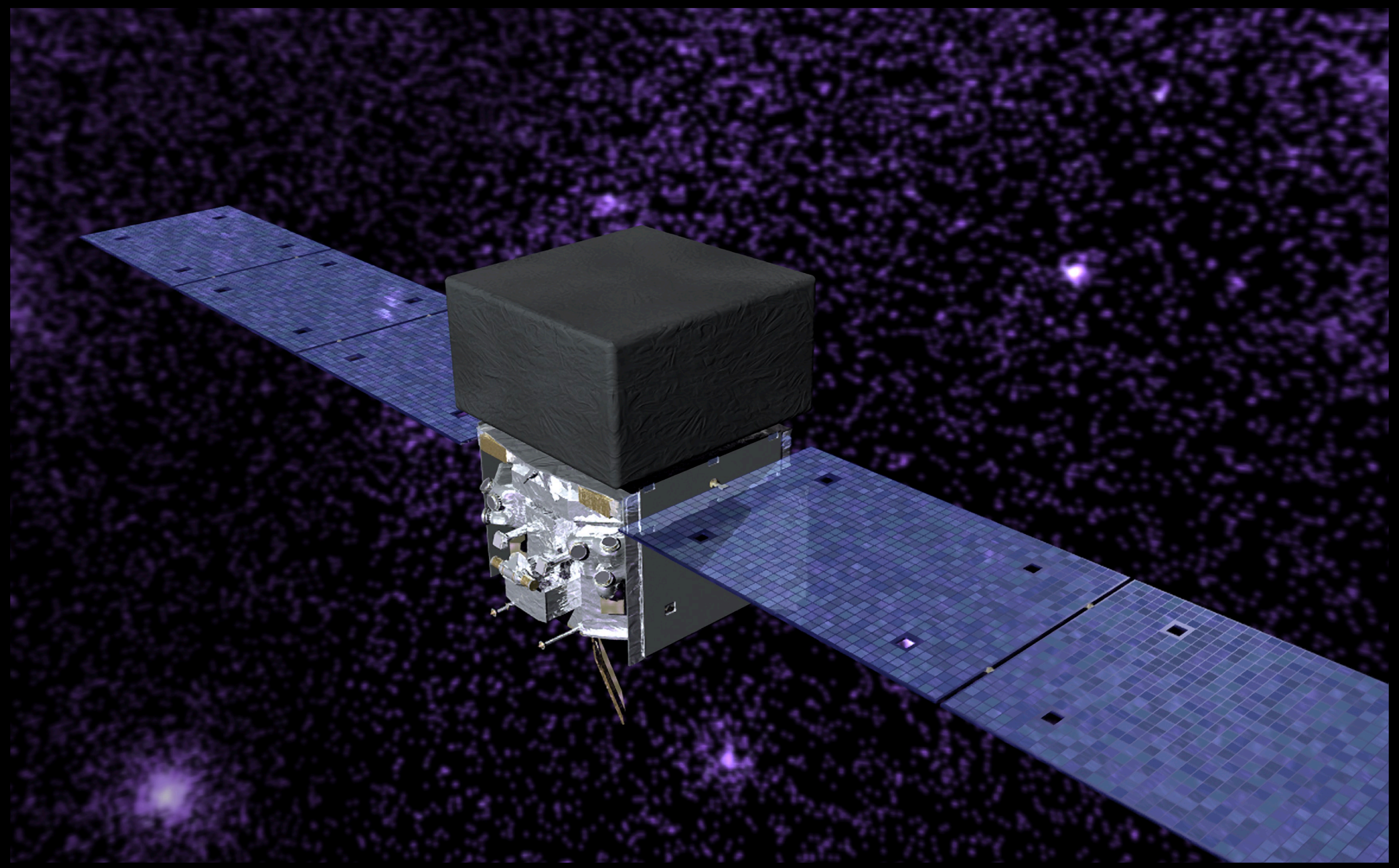
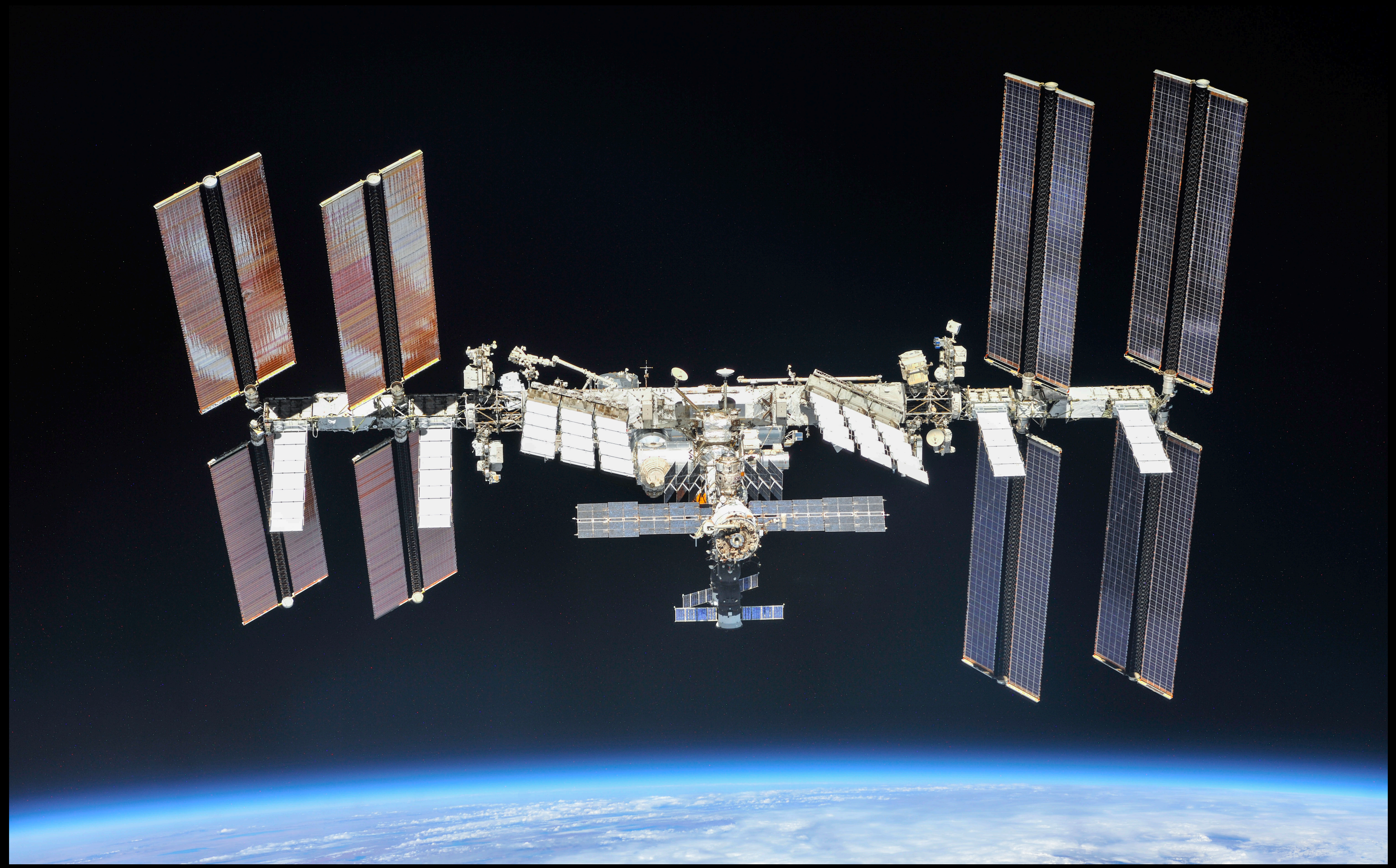

GW170817 from LIGO/Virgo GWTC-1 data release,
P1800370, Phys. Rev. X 9, 031040 (2019)

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
similar to assumption of common EOS in De et al
Phys. Rev. Lett. 121, 091102 (2018)

# Multimessenger EOS inference:

Talks by Bernuzzi, Miller, Nattila, Dietrich, Capano, Raaijmakers …

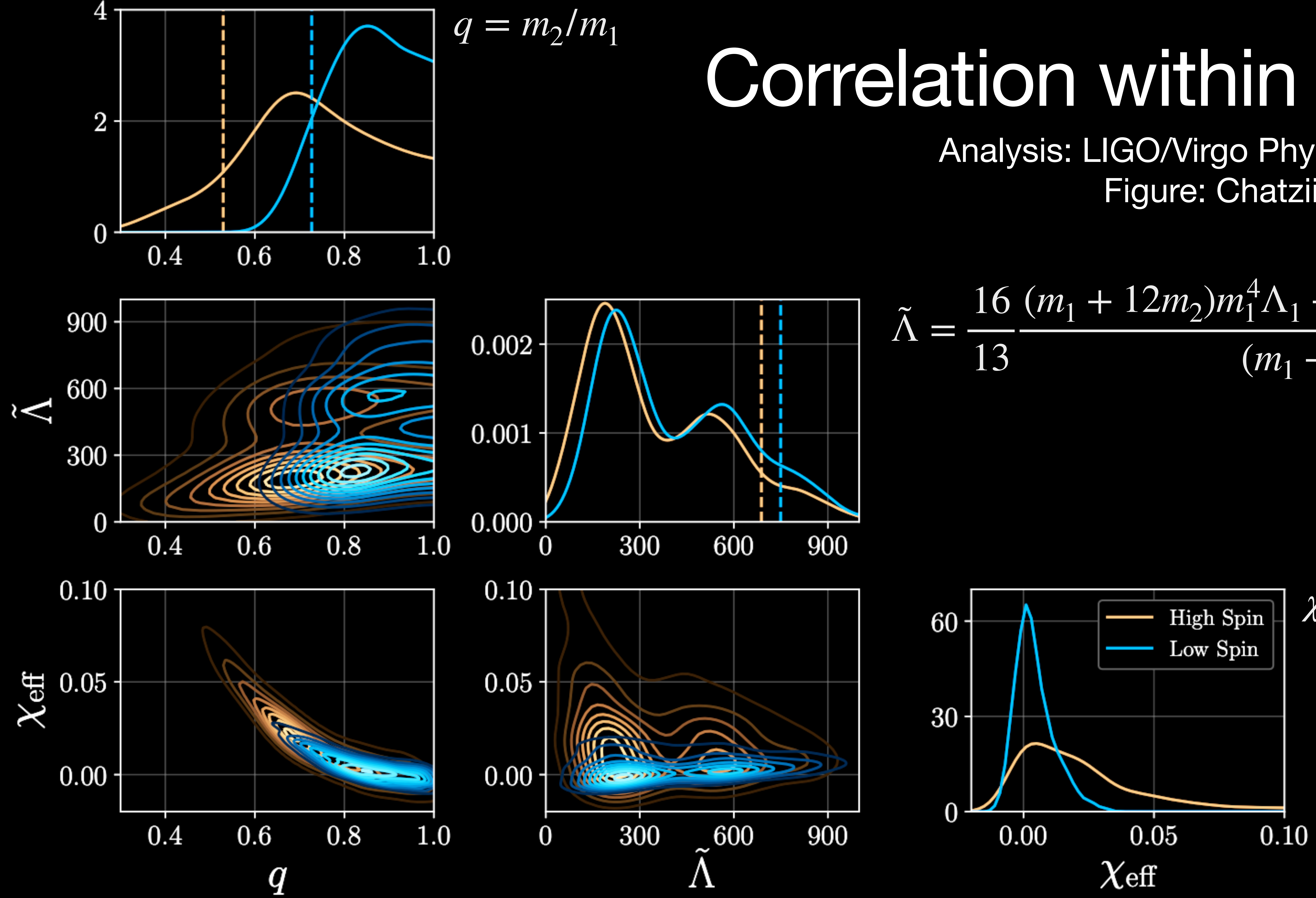

# Correlation within GW170817

Analysis: LIGO/Virgo Phys. Rev. X 9, 011001 (2019)
Figure: Chatziioannou ArXiv:2006.03168

$q = m_2/m_1$

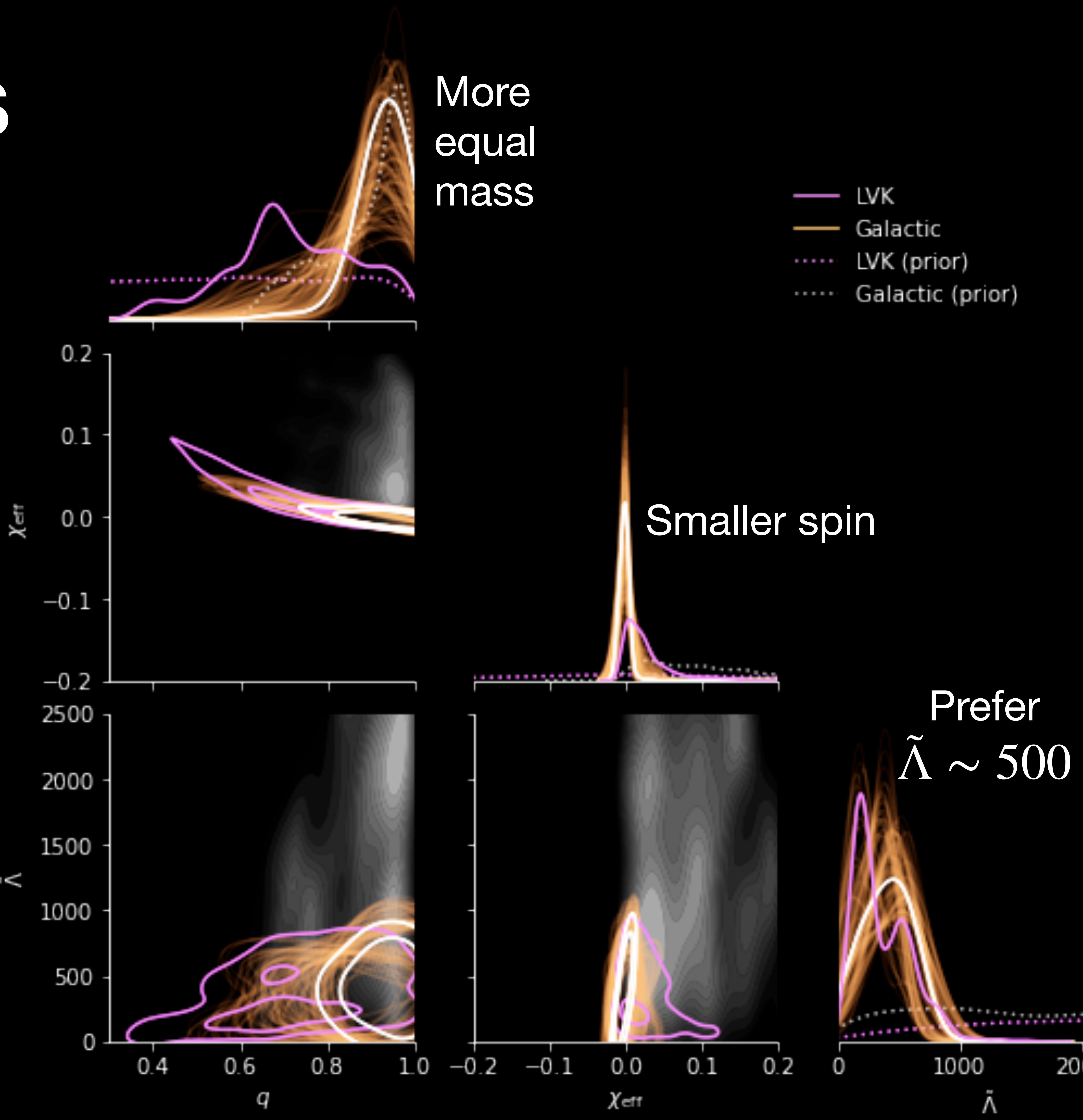
$$\tilde{\Lambda} = \frac{16}{13}\frac{(m_1 + 12m_2)m_1^4\Lambda_1 + (m_2 + 12m_1)m_2^4\Lambda_2}{(m_1+m_2)^5}$$

$$\chi_{\rm eff} = \frac{S_1/m_1 + S_2/m_2}{m_1+m_2}\cdot L$$



# Population affects interpretation

- Assuming GW170817 contains:
  - GW source masses that individually follow double-peak galactic mass observations
  - Spins more aligned
  - NS have a 'common' EOS ($k_2$ scaling like 1/m, $R$ within 10% tolerance)






Penuliar, Landry, Read, in prep

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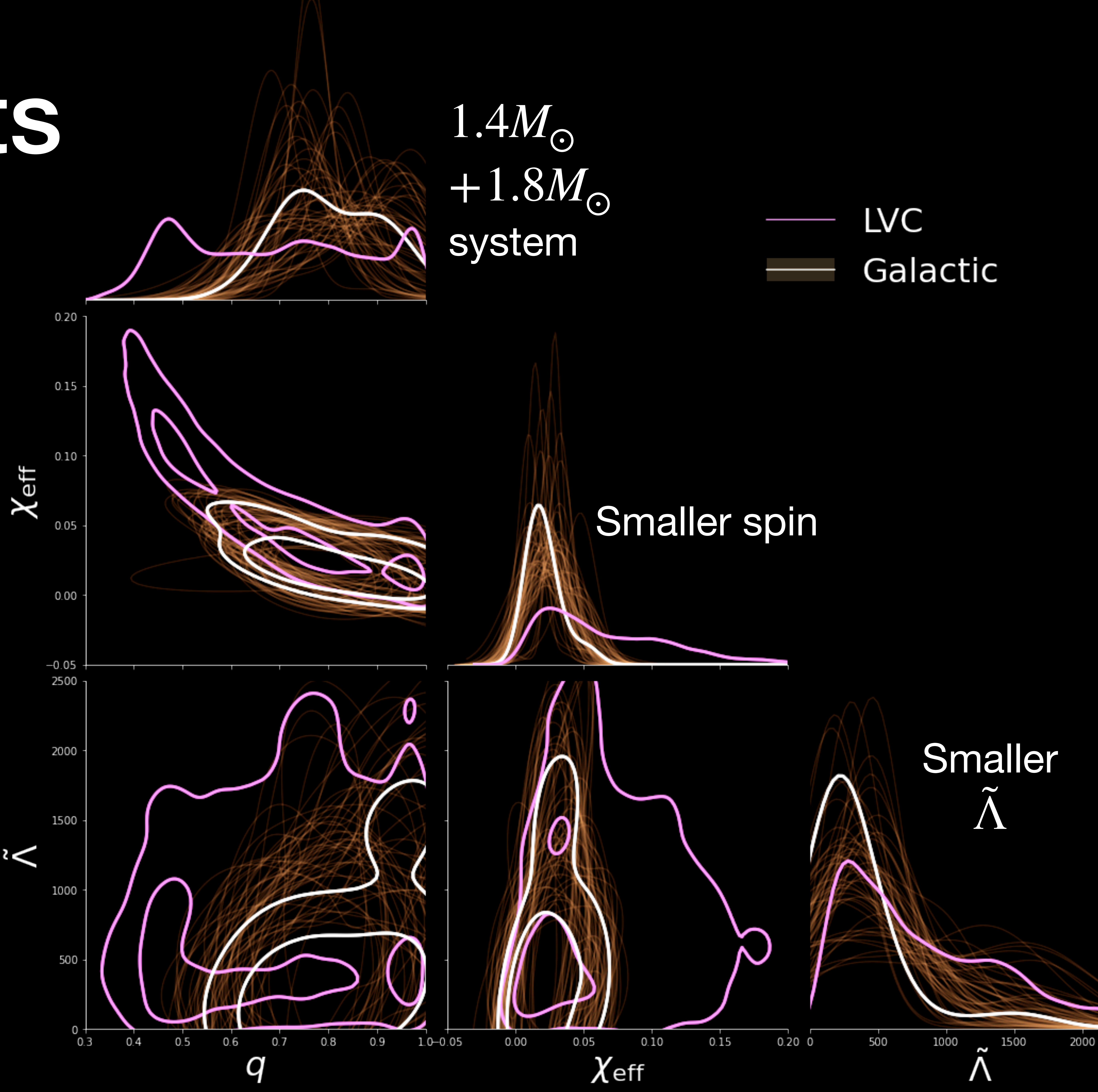


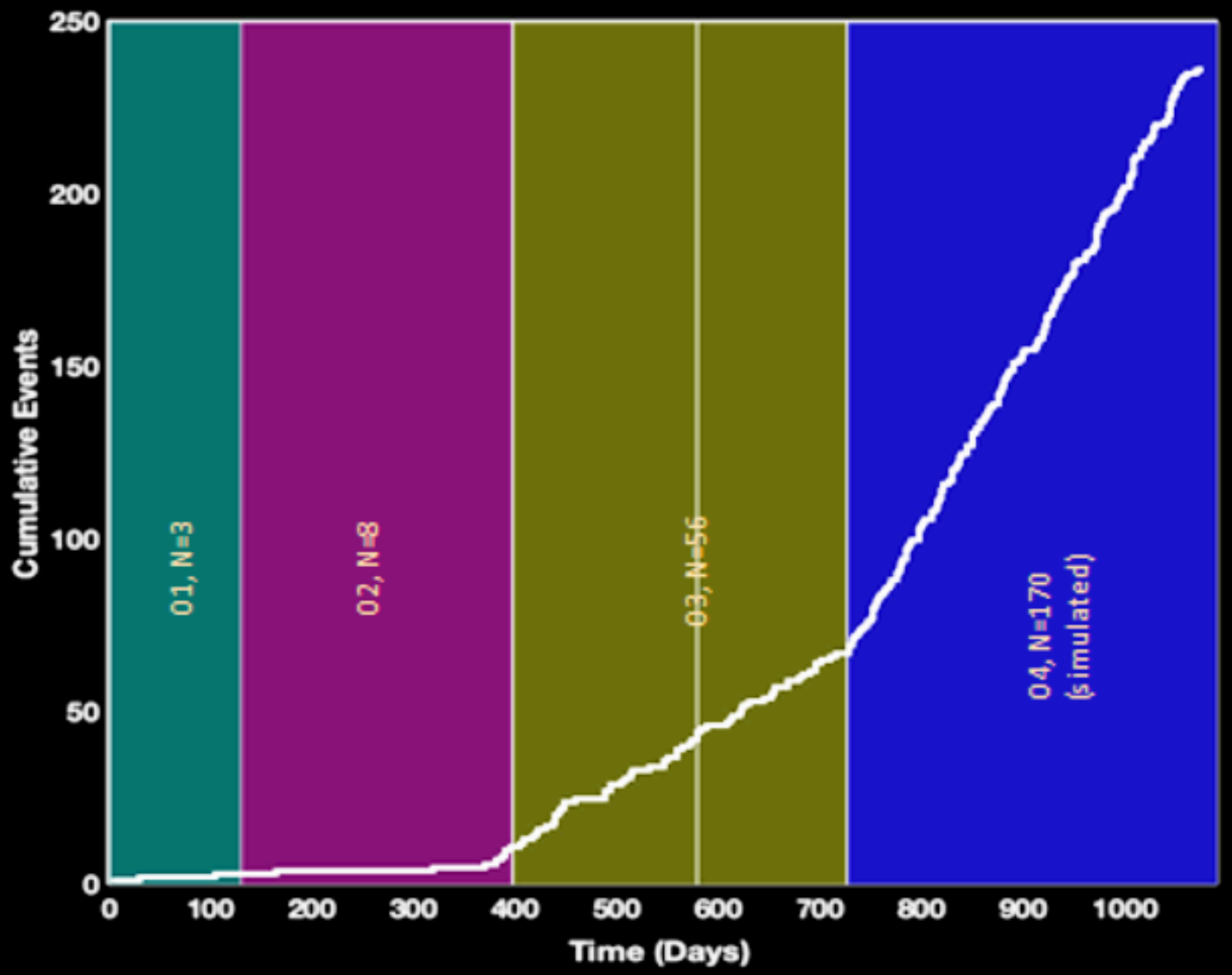



Penuliar, Landry, Read, in prep

# O4:

- One year duration from early 2023, anticipated BNS search volume of 0.016 $Gpc^3$ yr (~4x previous total, range ~190 Mpc)

- ~10 NS-NS & NS-BH,
  ~100s BH-BH
  [LVK Observing Scenarios Document, LIGO-P1200087]

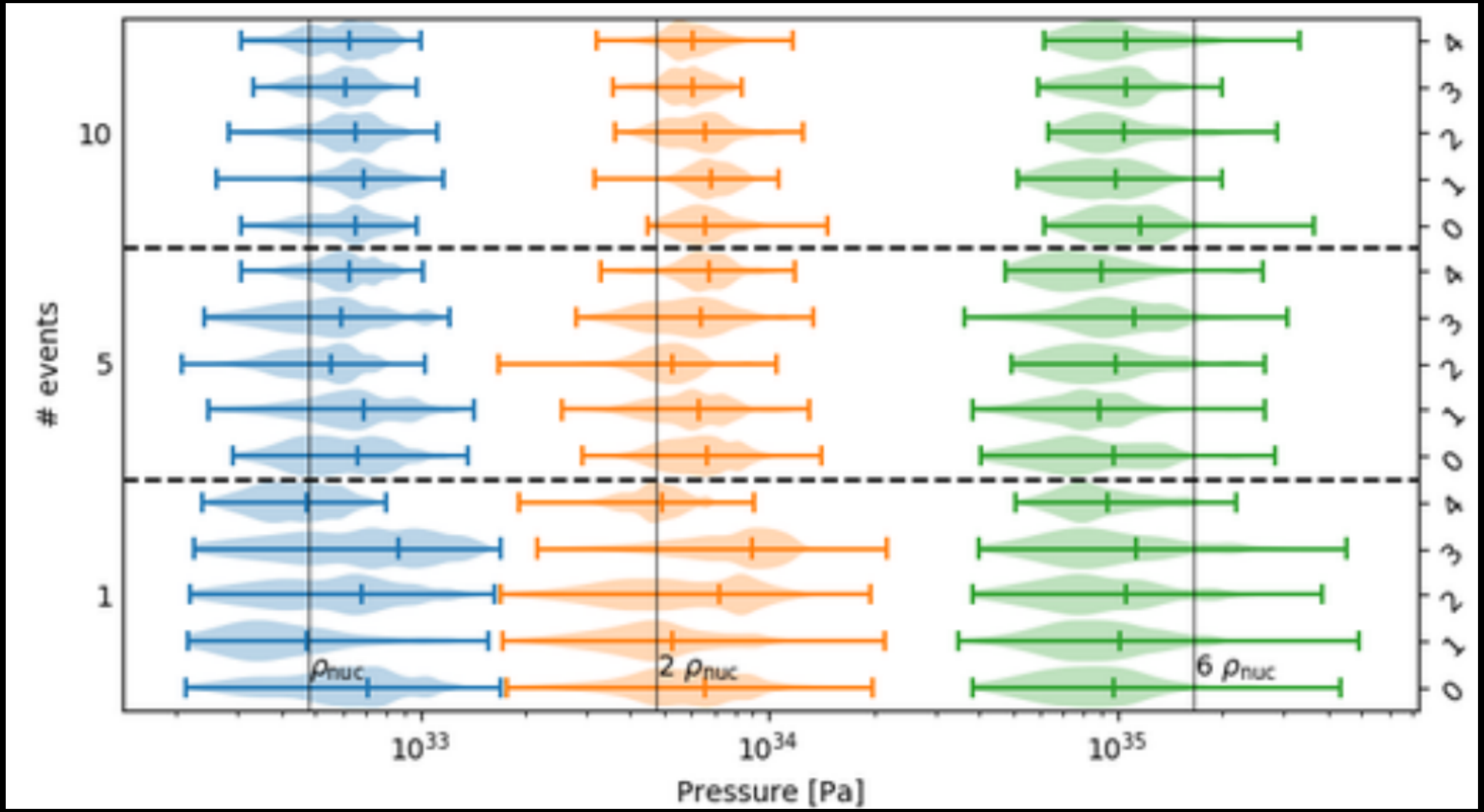


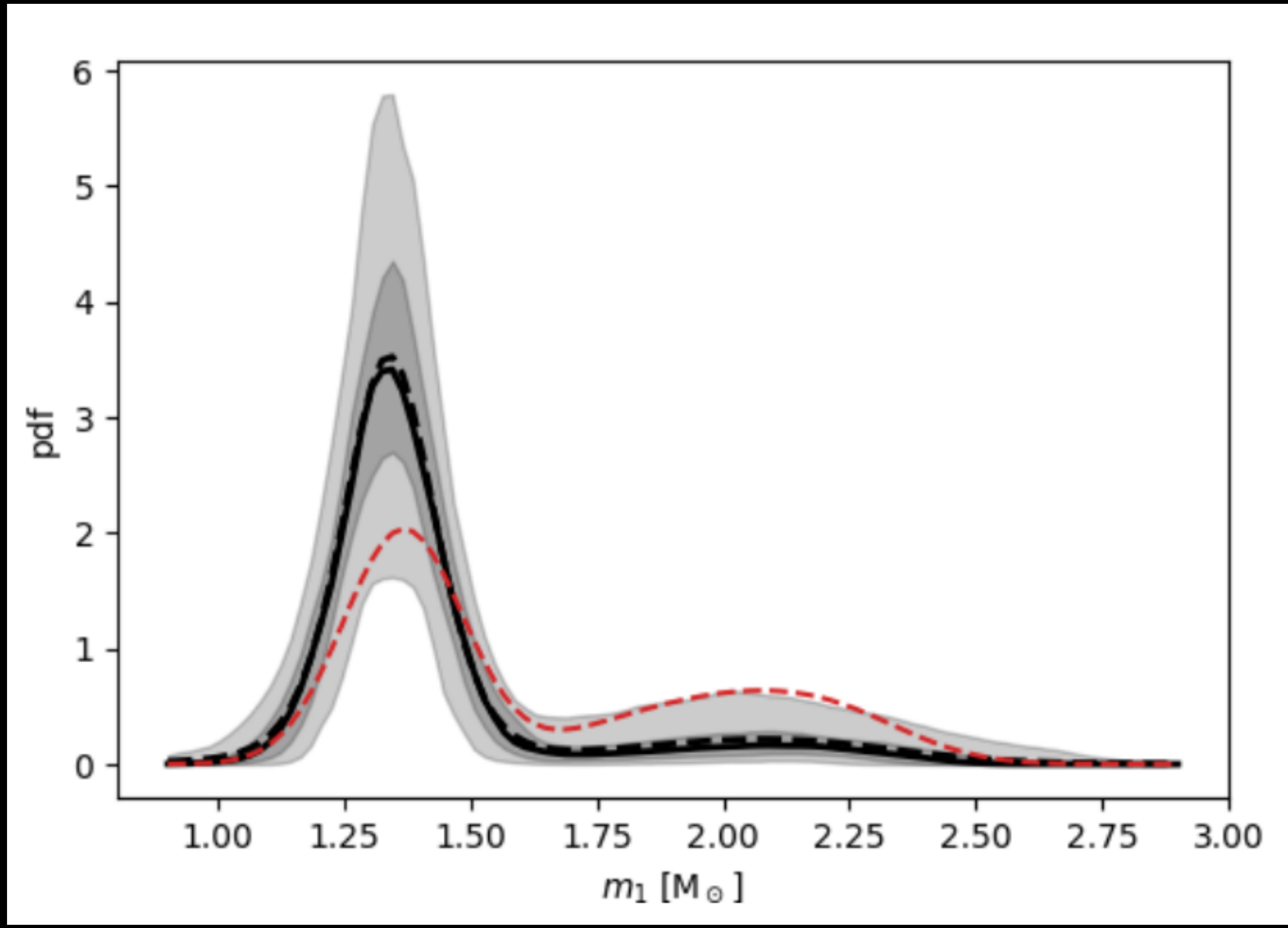



LIGO/Virgo

# Expected impact of O4?

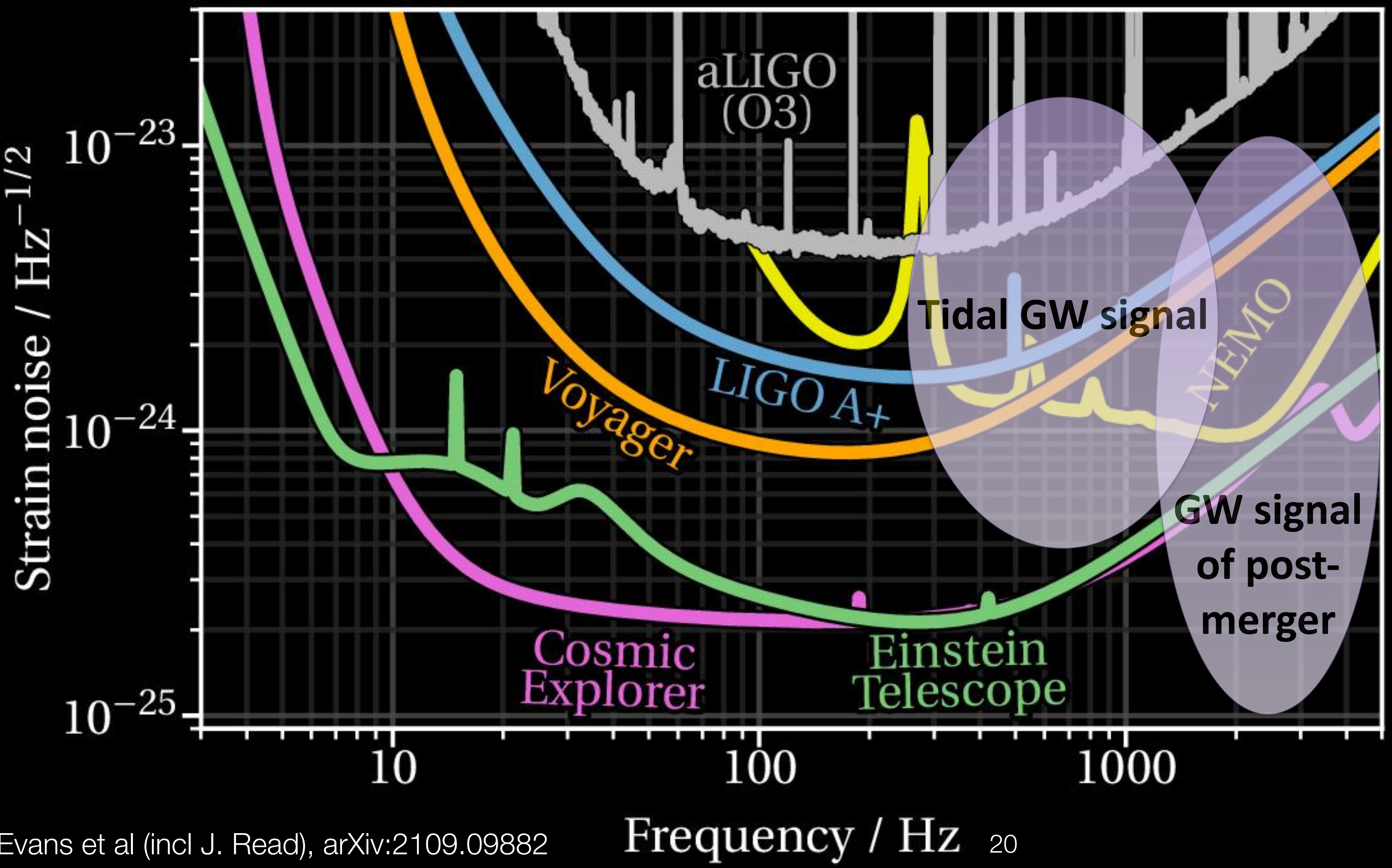
Wysocki et al arXiv:2001.01747
Simultaneous heirarchical GW constraint on EOS and mass distribution
Joint analysis required to avoid bias after ~10 events, see also Golomb+Talbot ApJ 2022



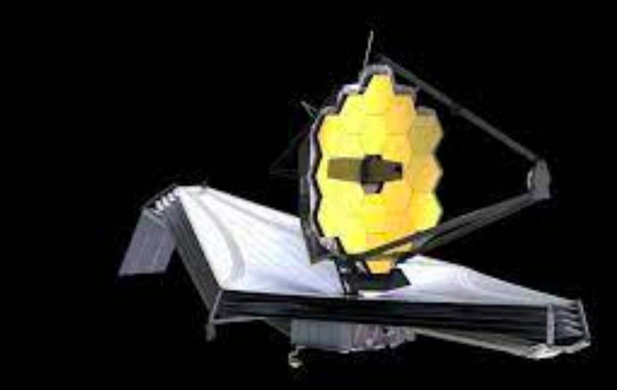

*Wysocki et al arXiv:2001.01747*

# Landscape of GW Astronomy

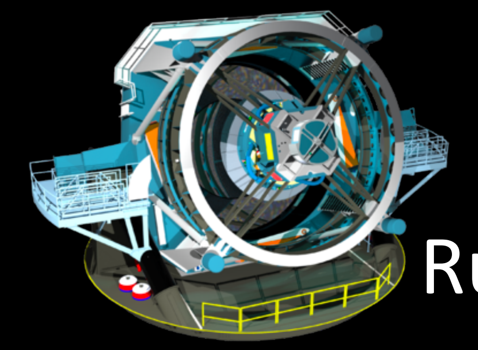



Current generation (now)

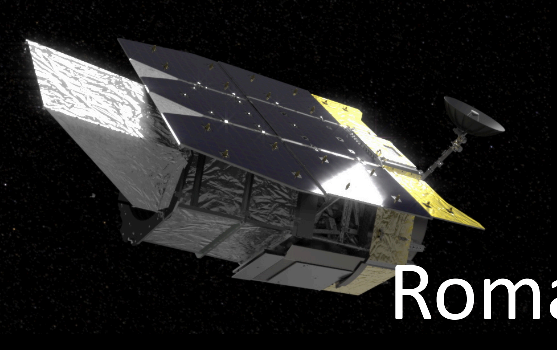
Next-generation (ca. 2035+)



JWST



Rubin



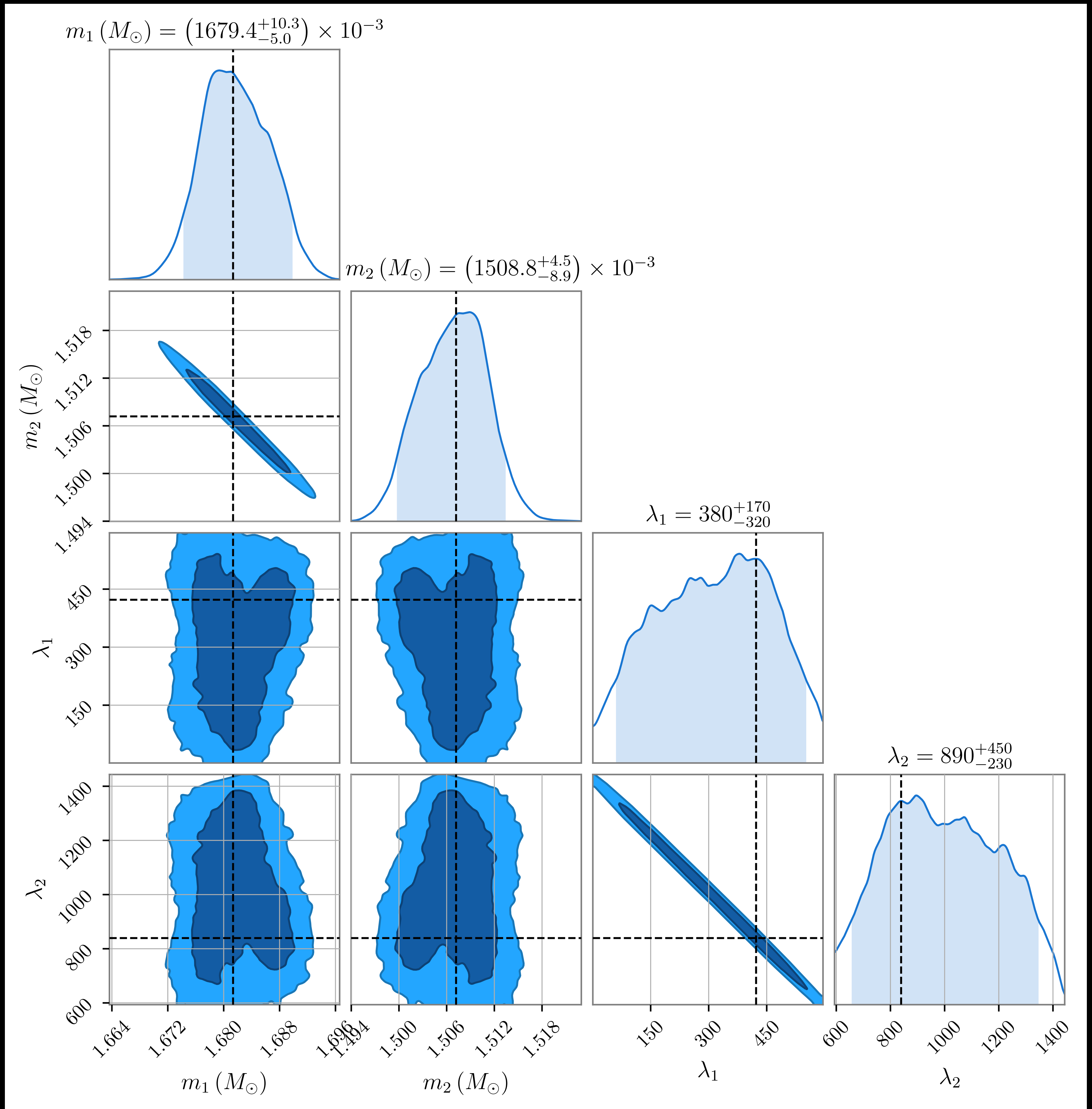
Roman

EM-survey merger identification?

D. Scolnic *et al* 2018 *ApJL* **852** L3

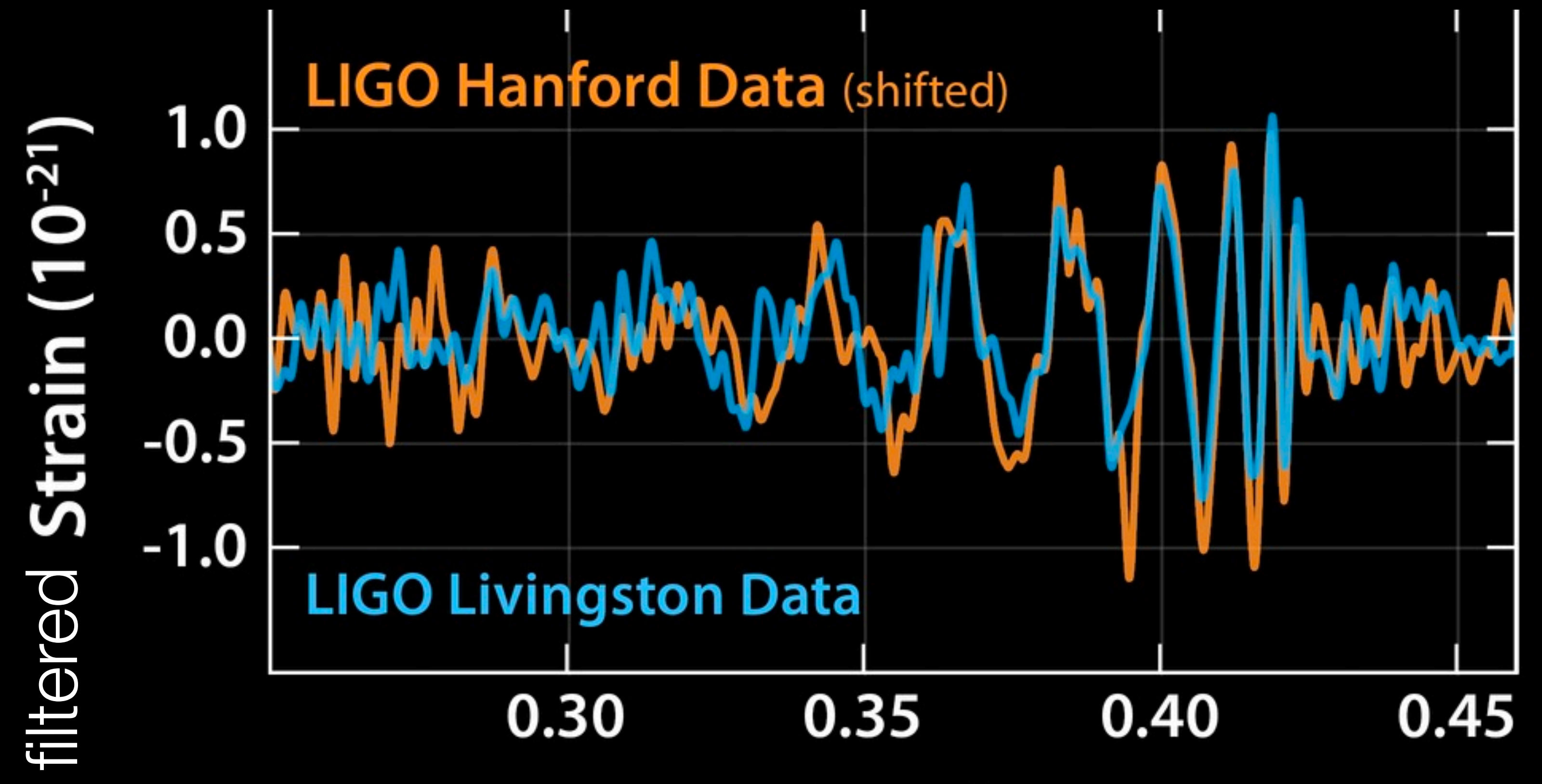
Evans et al (incl J. Read), arXiv:2109.09882

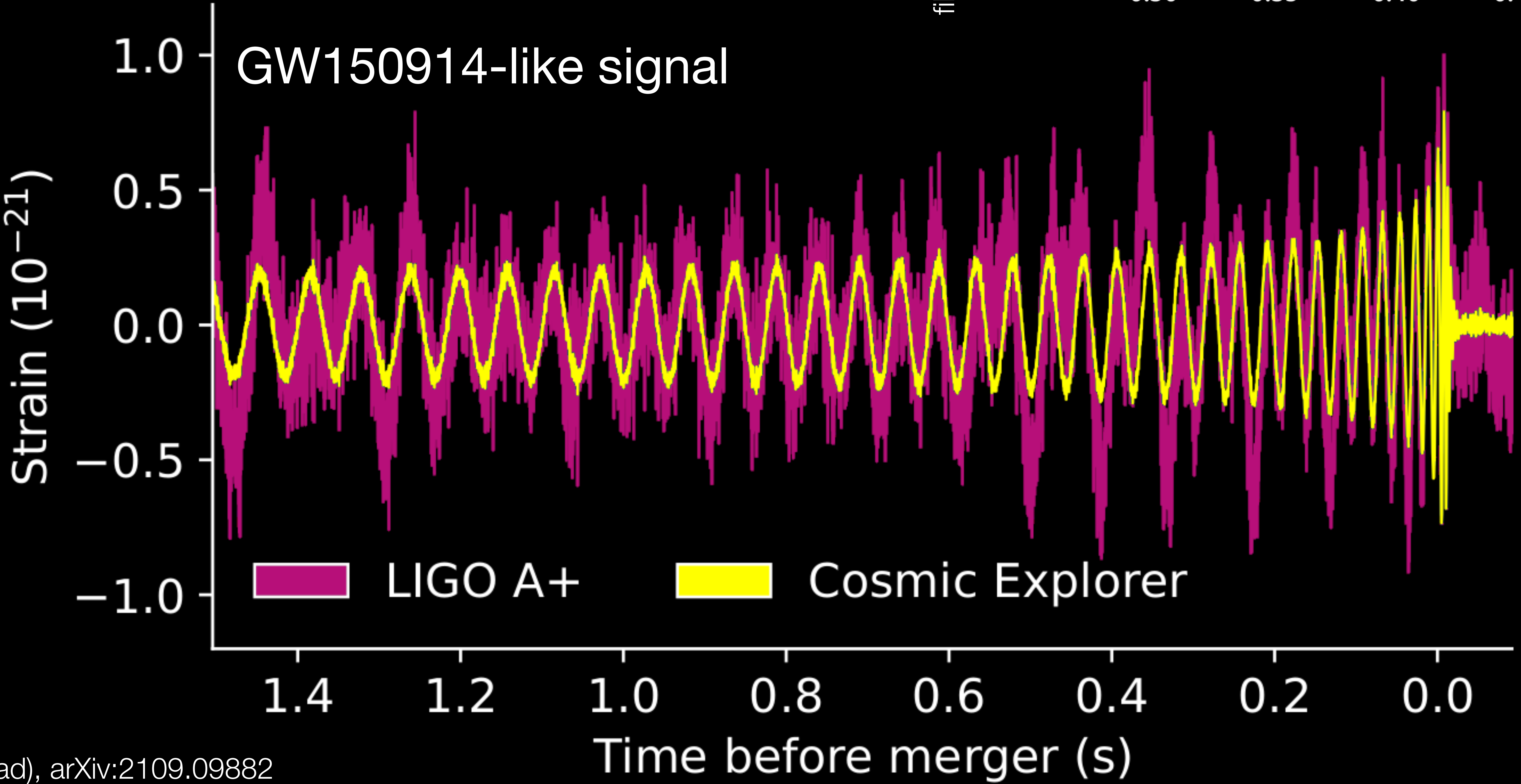
# Next-gen observations: “GW370817”




Smith *et al* Phys. Rev. Lett. 127, 081102 (2021)

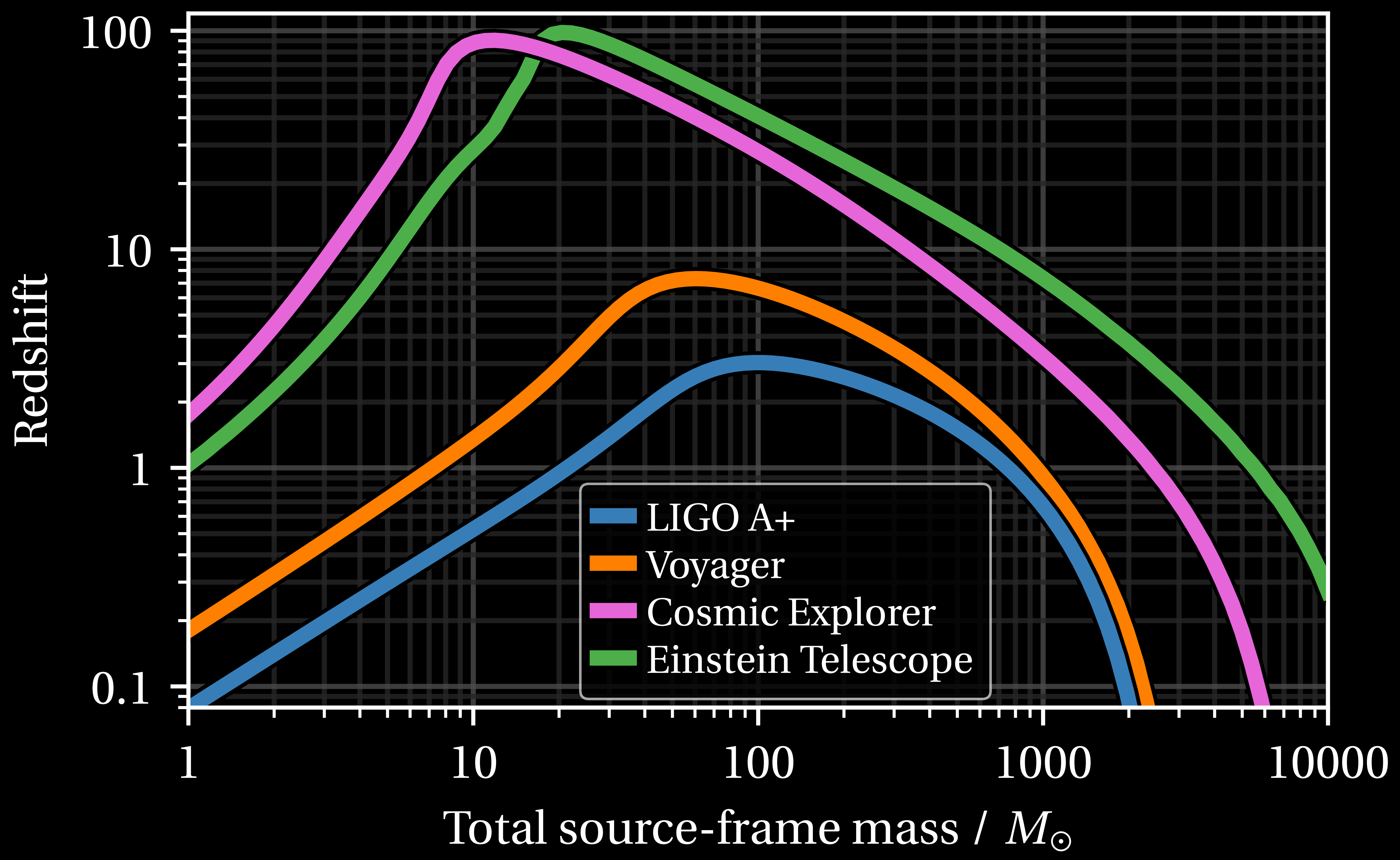
# Next-generation capabilities: Precision measurement

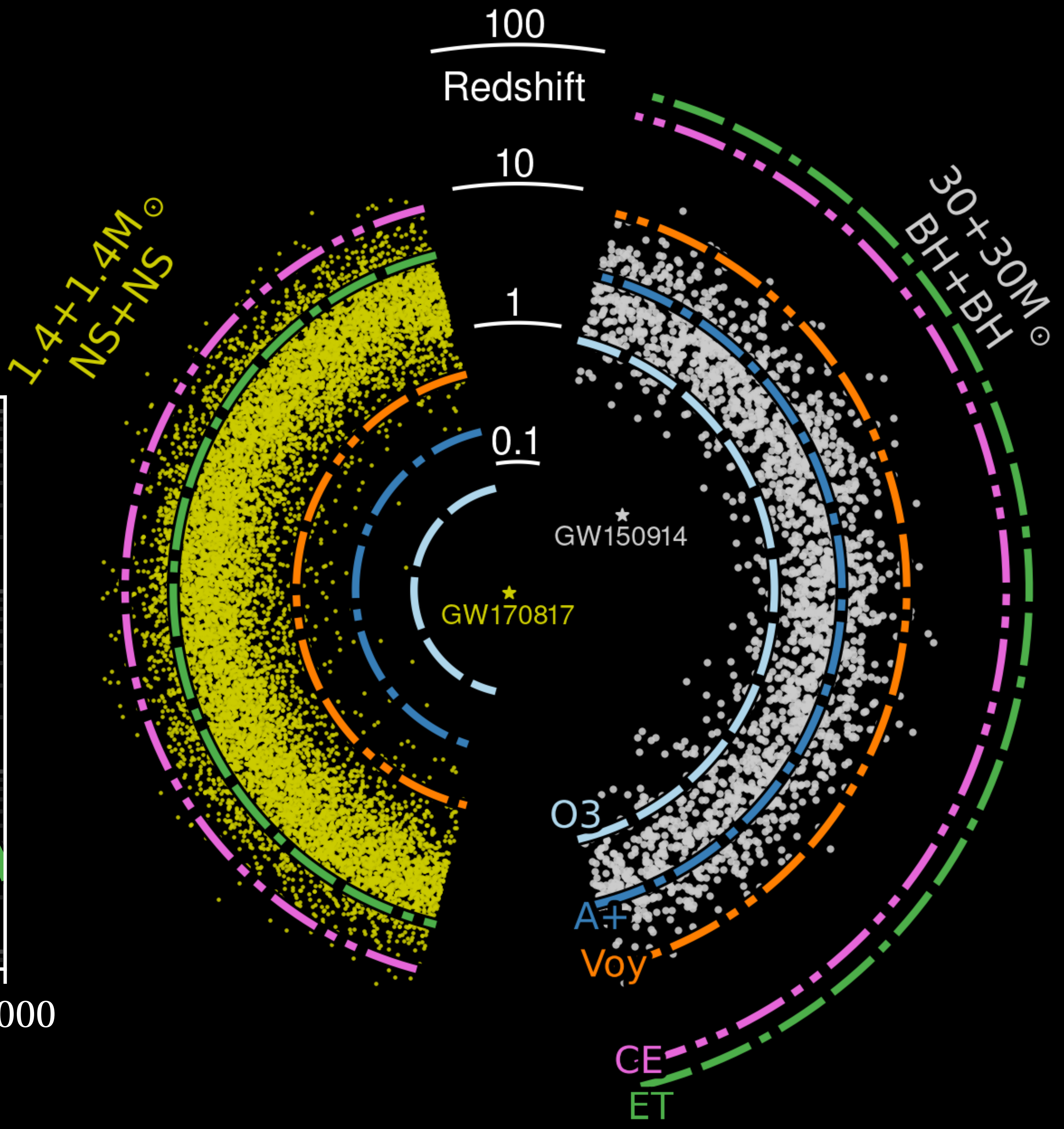



CEHS: Evans et al (incl J. Read), arXiv:2109.09882

# Next-generation capabilities: Cosmic Reach



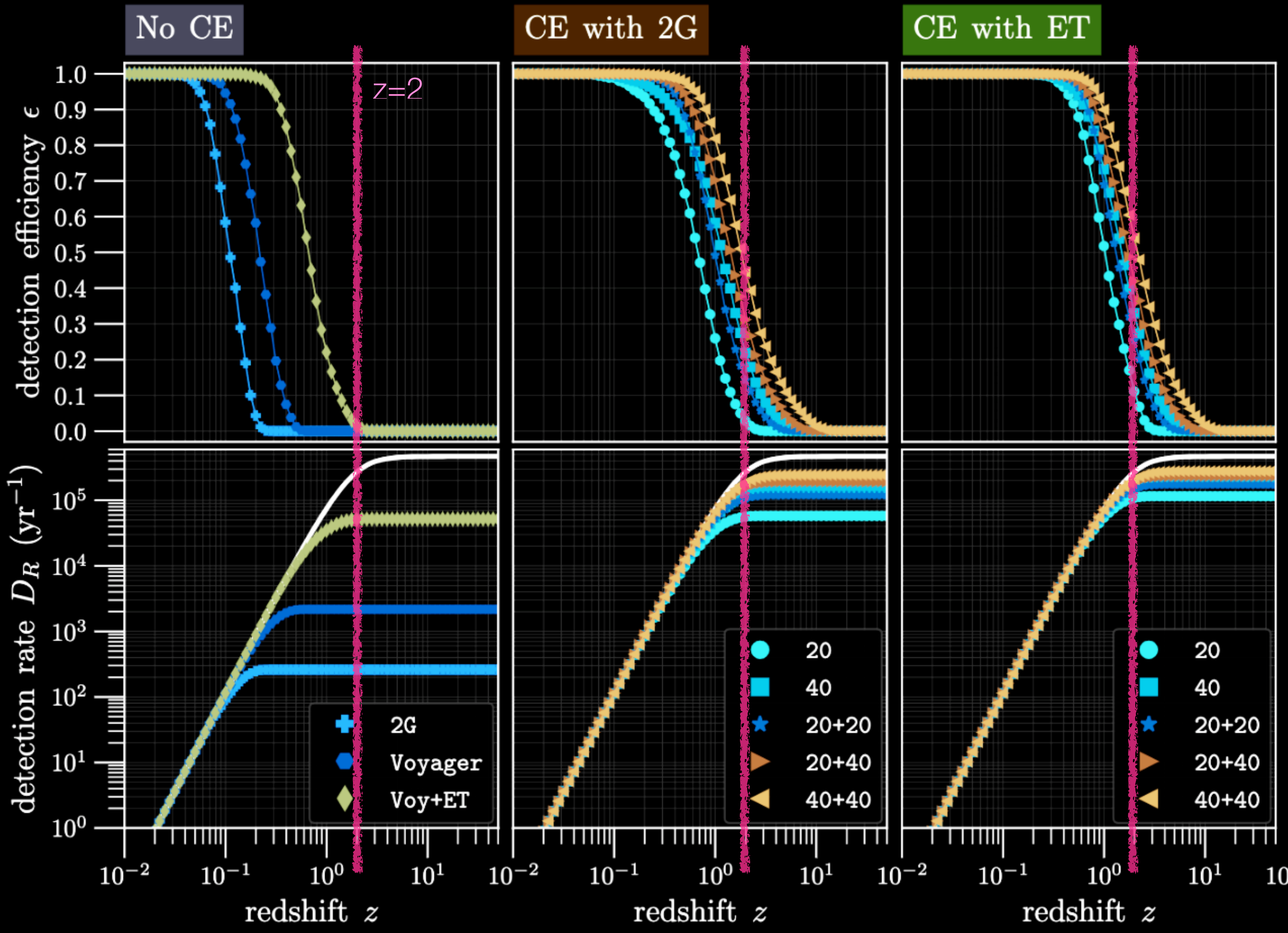






CEHS: Evans et al (incl J. Read), arXiv:2109.09882

# NS-NS detection

- Cosmic Explorer goal  / year
- ~1000s of neutron star mergers
- identify 80% of **all** mergers within z=1
- ~100 mergers 10 minutes early
- ~100 NS radii to ≲ 0.1 km
- ~10 SNR > 300

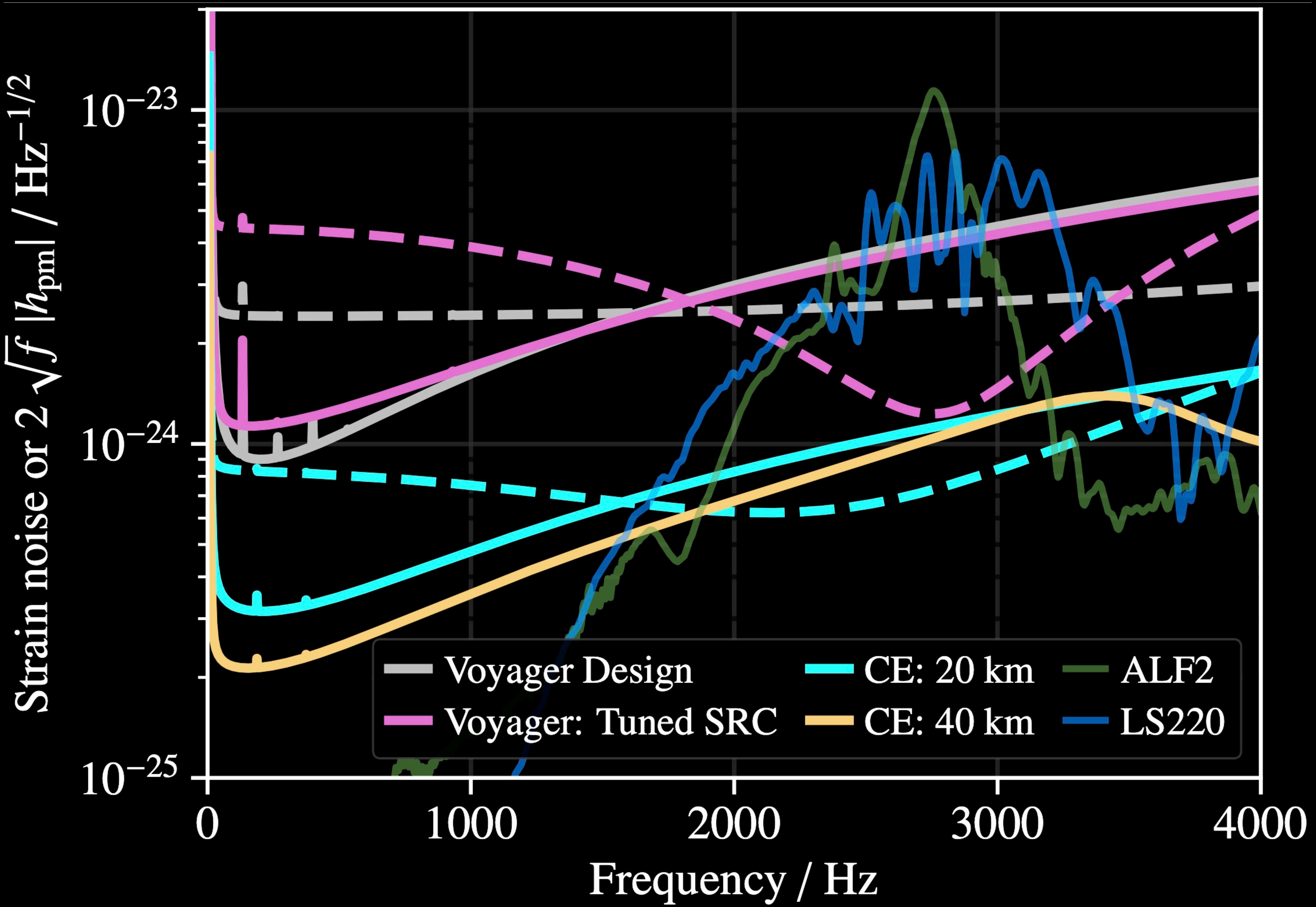



CEHS: Evans et al (incl J. Read), arXiv:2109.09882



https://dcc.cosmicexplorer.org/CE-P2100003/public

# Post-merger GW?

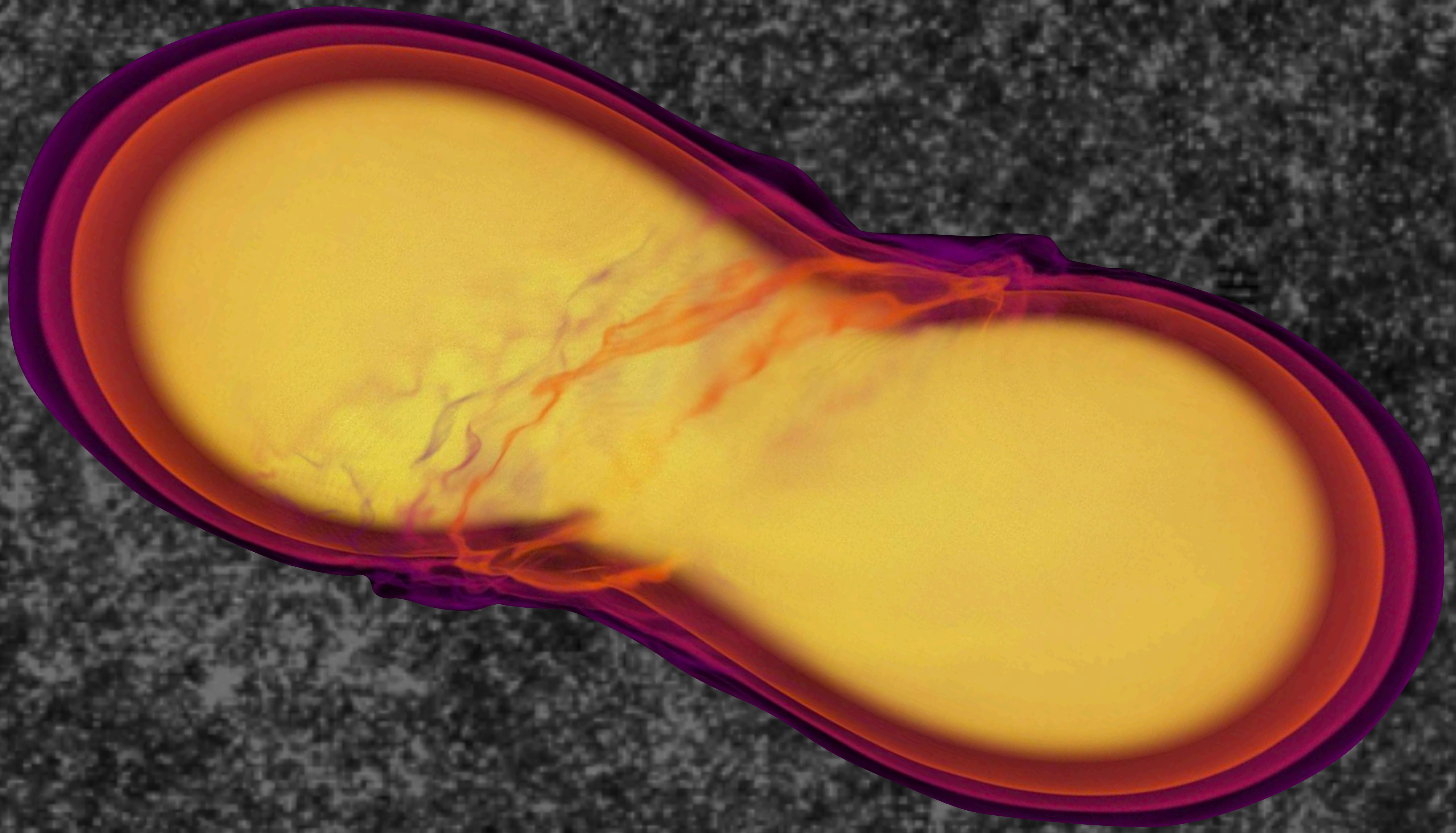



- Only science target where 20km detector can be better than 40km, with tuning



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

# Thank you!



*sky: SDSS III galaxy distribution*

Neutron-star merger: Radice et al. 2018

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

**LIGO/VIRGO**

https://www.gw-openscience.org