Neutron stars in gravitational-wave astronomy

QNP 2022

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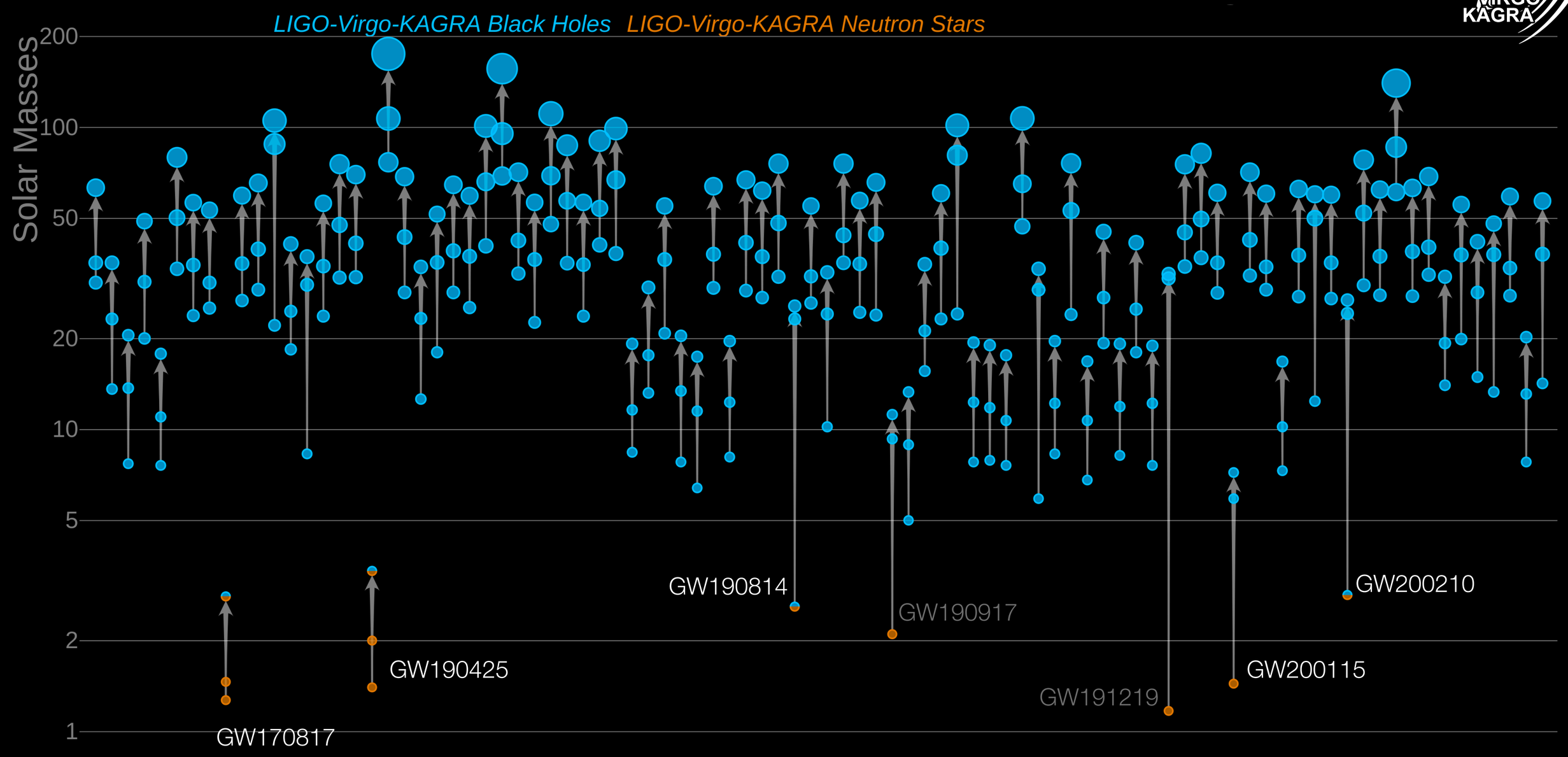
LIGO material is based upon work supported by NSF's LIGO Laboratory which is a major facility fully funded by the National Science Foundation.

LIGO VIRGO KAGRA

COSMIC EXPLORER

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



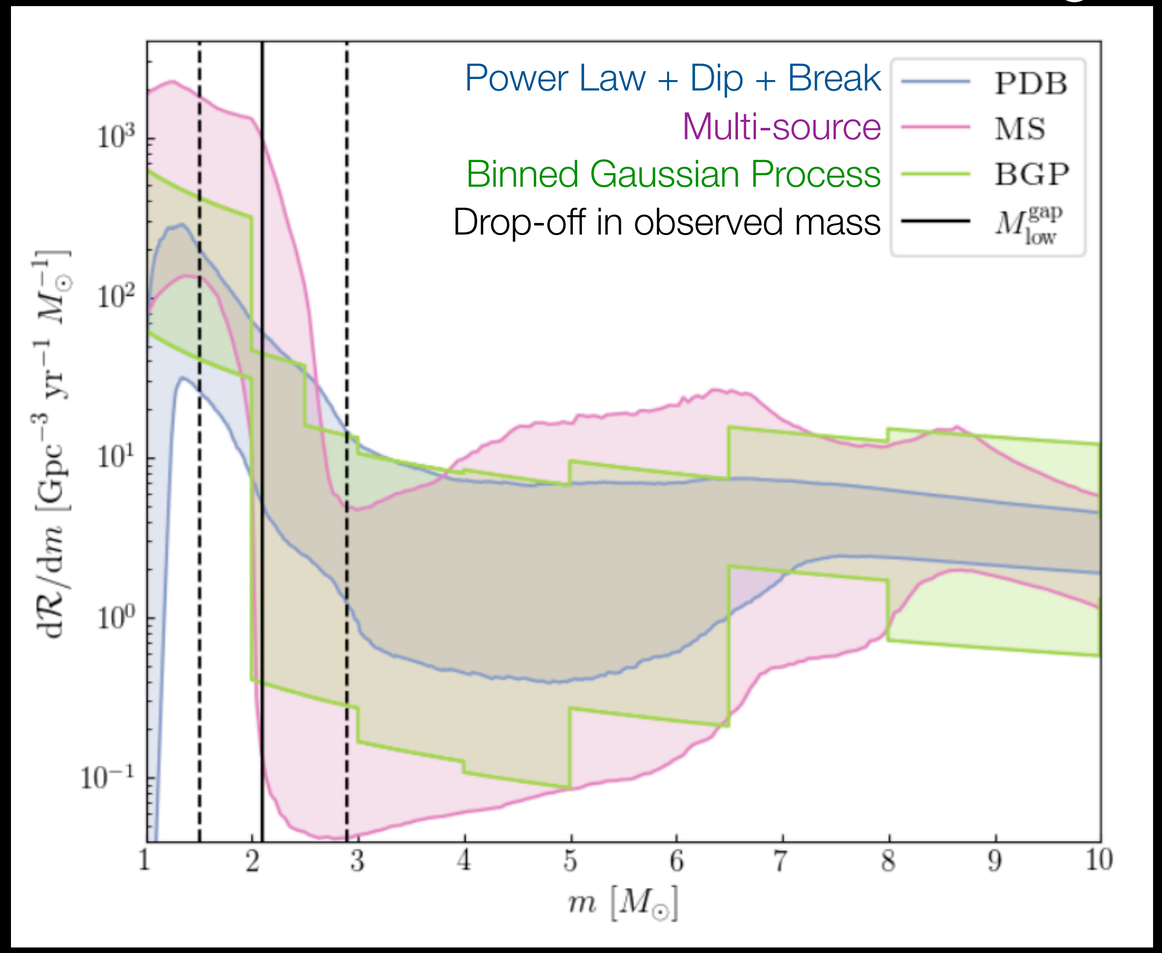
LIGO-Virgo-KAGRA | Aaron Geller | Northwestern

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

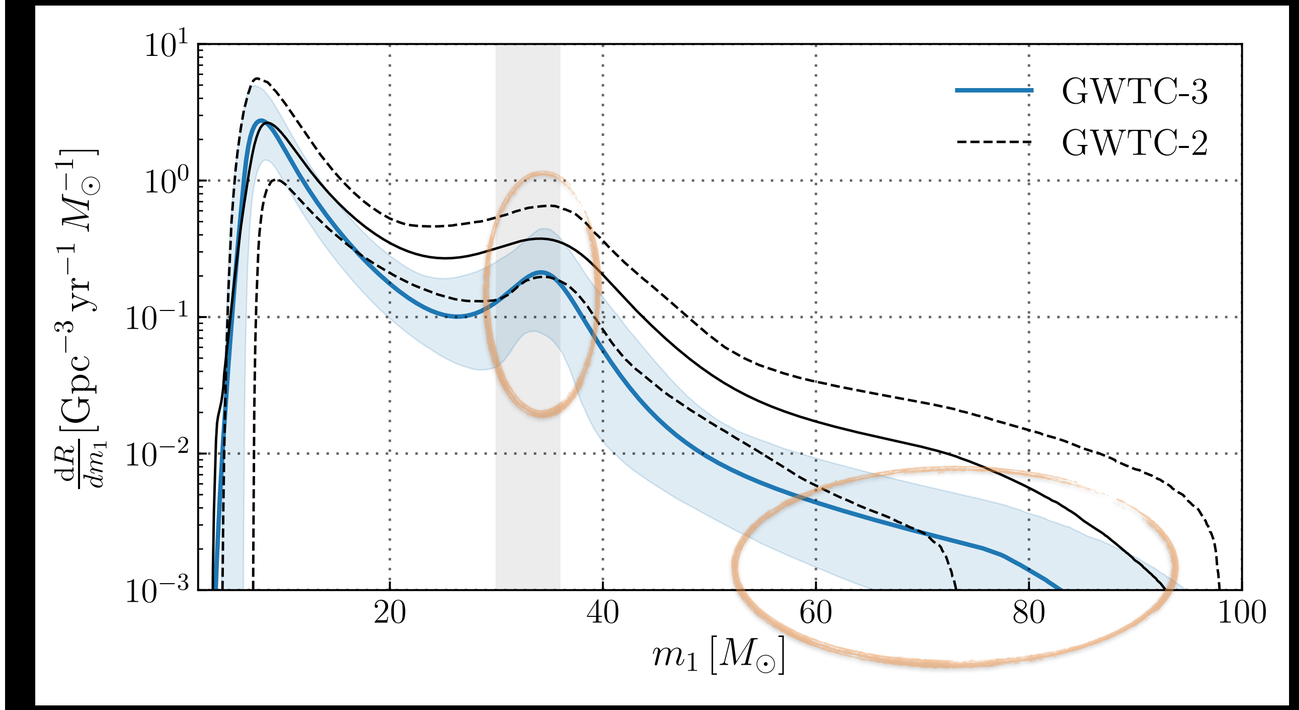
The population of merging compact binaries inferred using gravitational waves through GWTC-3

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

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

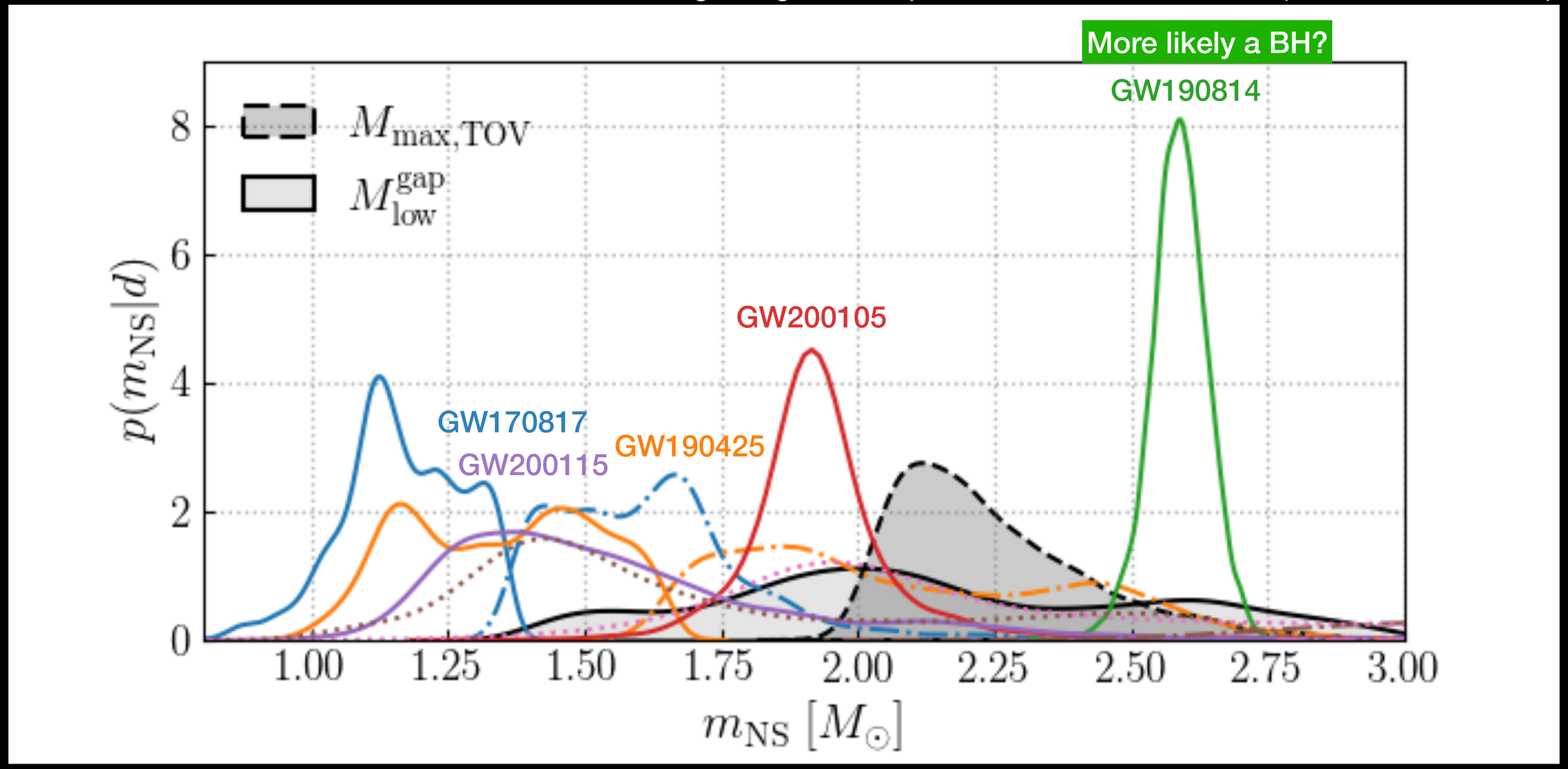


Structure in the BH mass spectrum



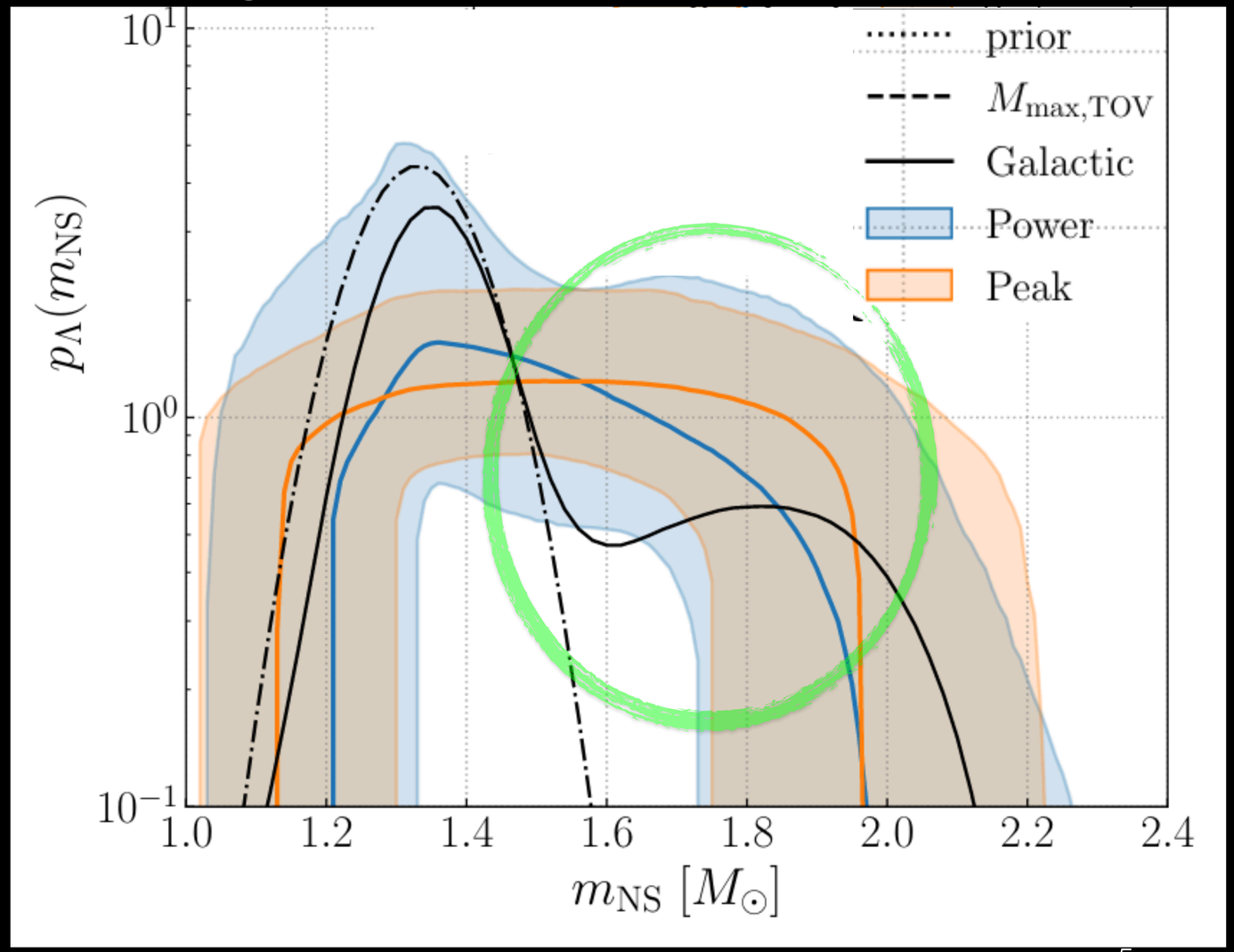
Neutron stars observed in GW

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

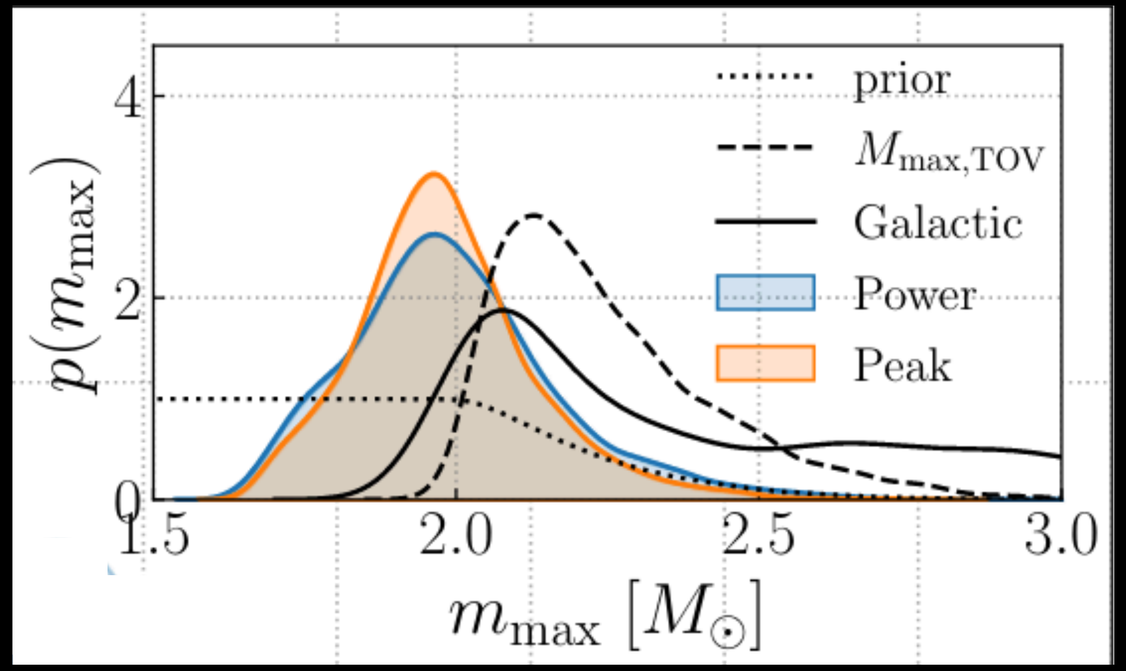


Neutron stars observed in GW

More high-mass observations



Maximum mass close to Galactic

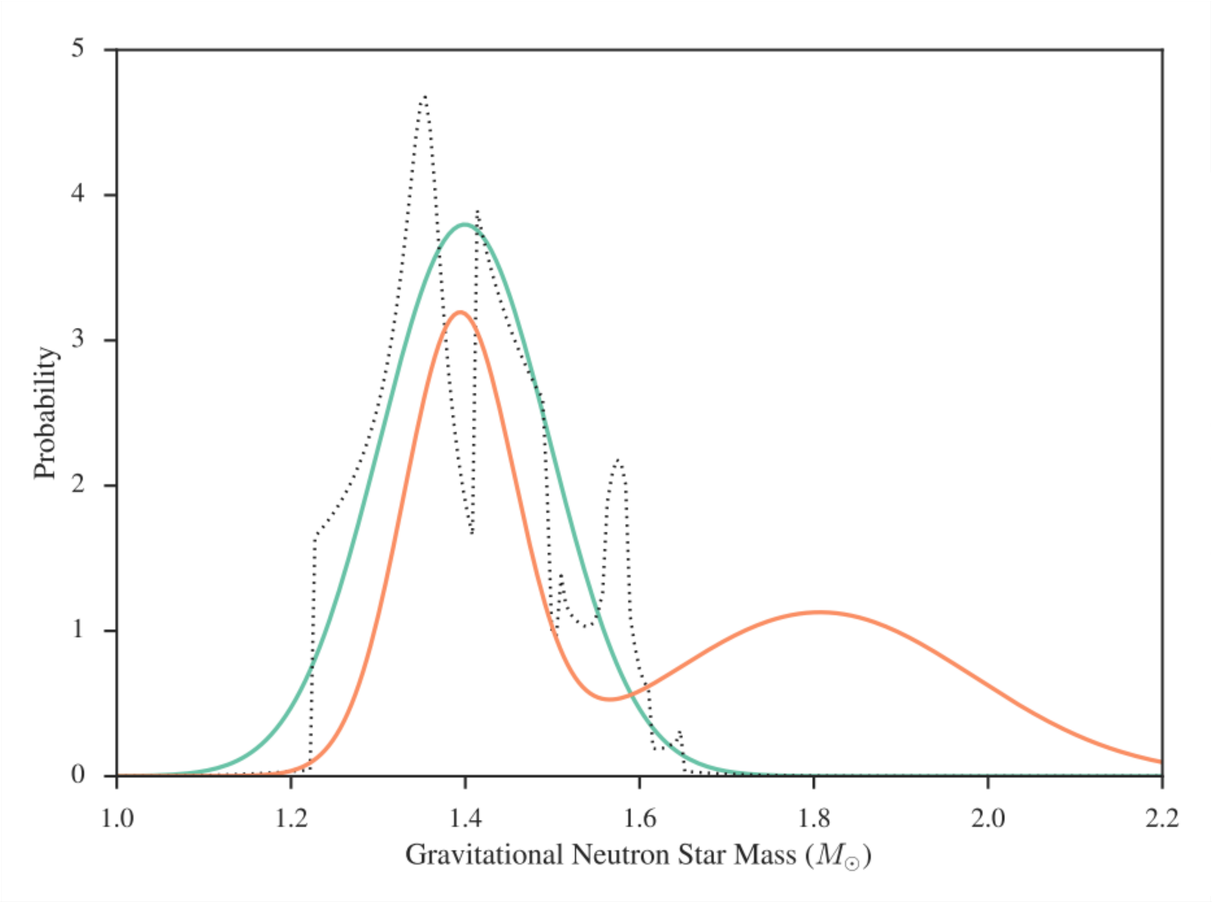


LIGO-Virgo-Kagra O3 Population, arXiv:2111.03634 (LIGO-P2000318-v7)

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

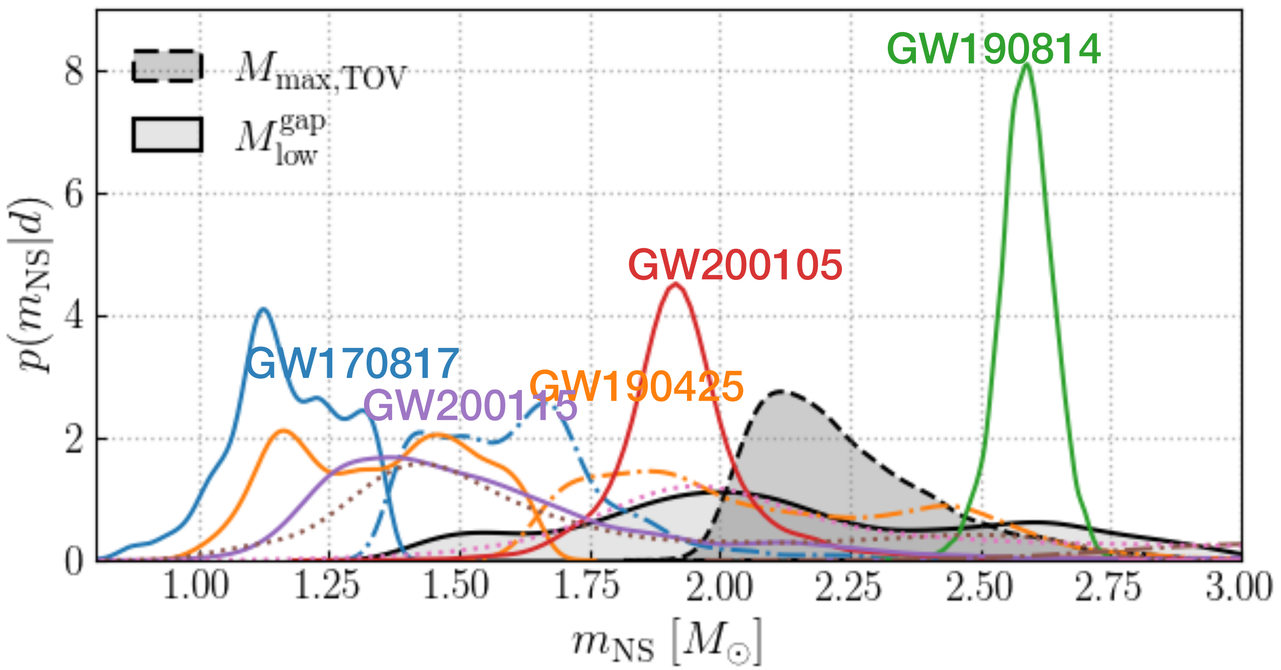
NS implications for stellar evolution: NS

What masses do supernovae produce?



Raithel et al ApJ V856 (2018)

What made this?



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

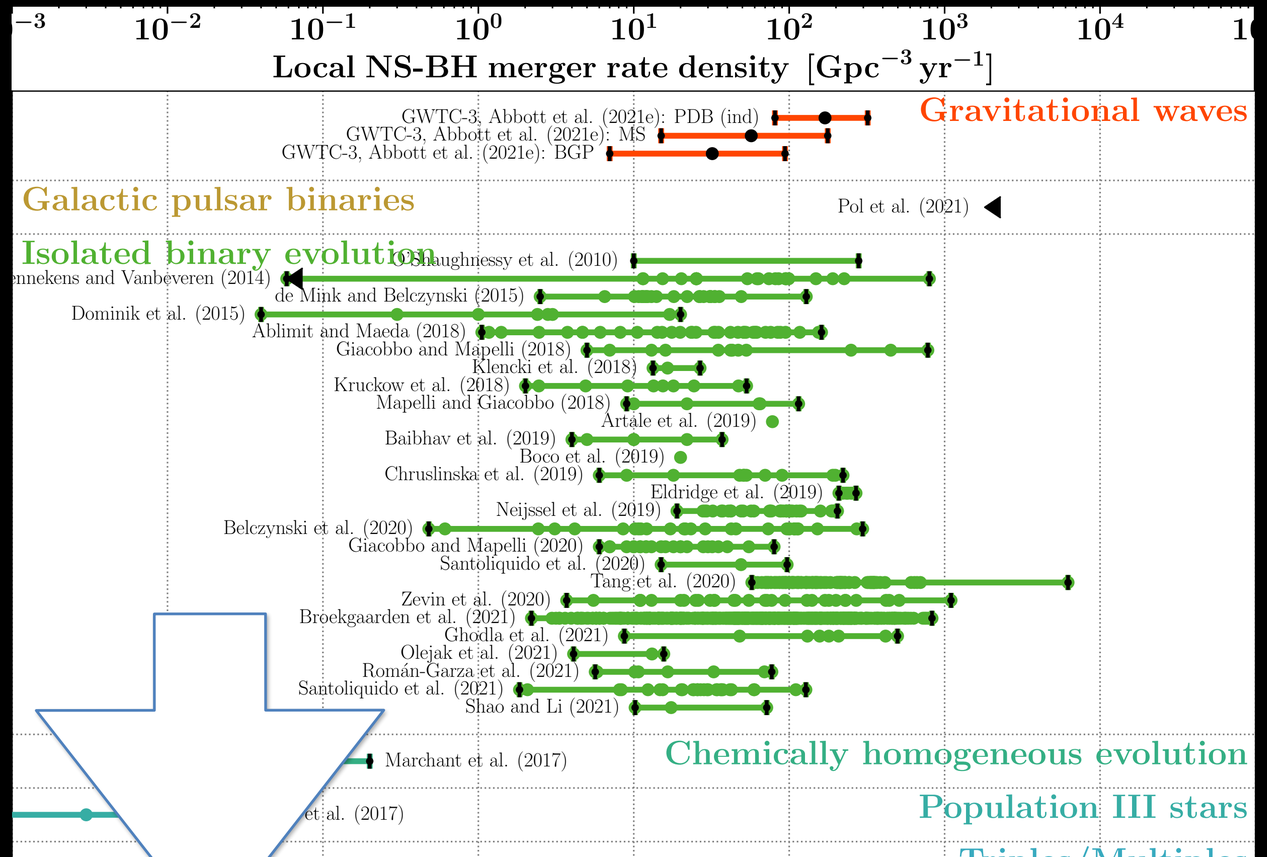
Merger rates

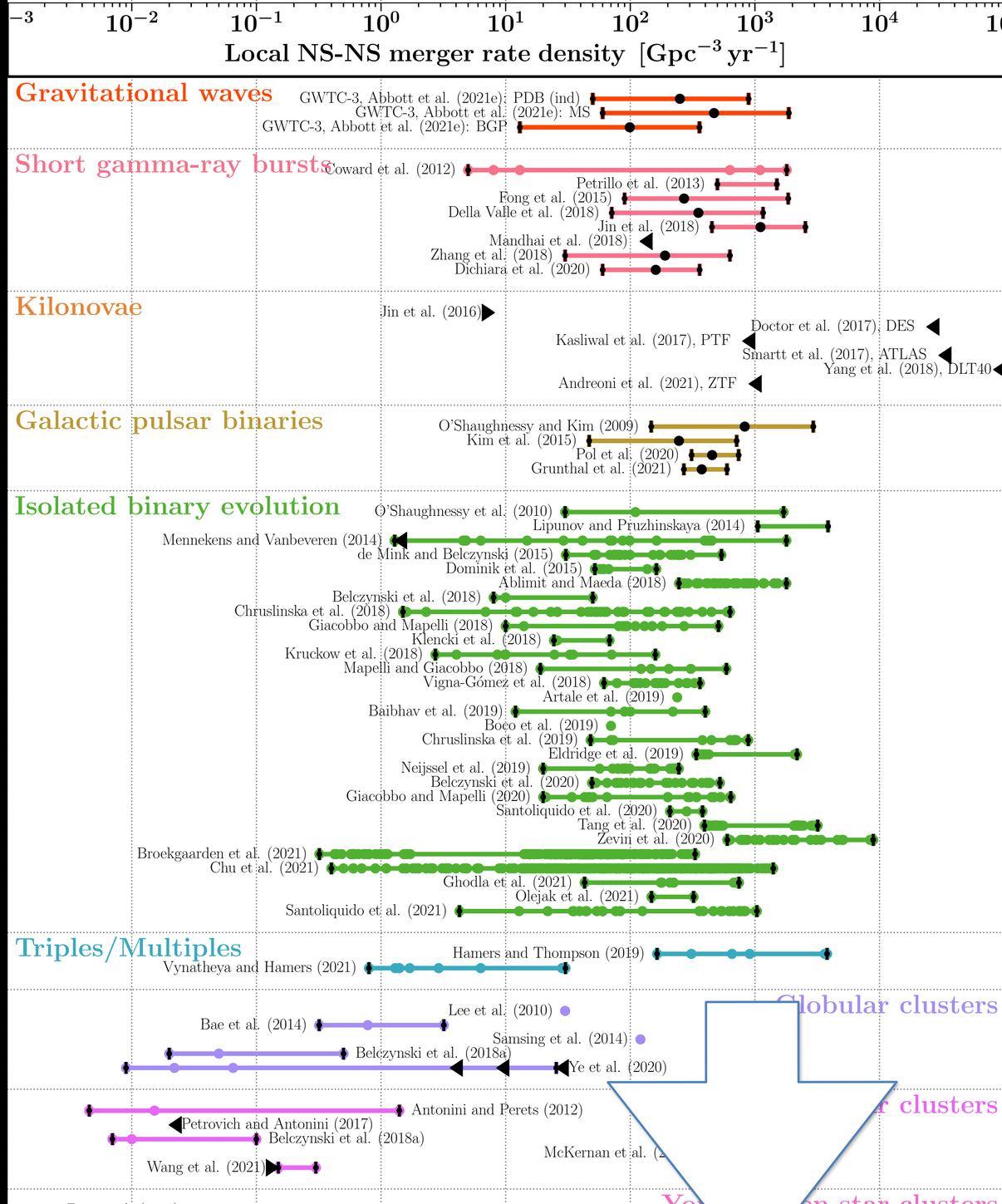
LIGO/Virgo arXiv:2111.03634:

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

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

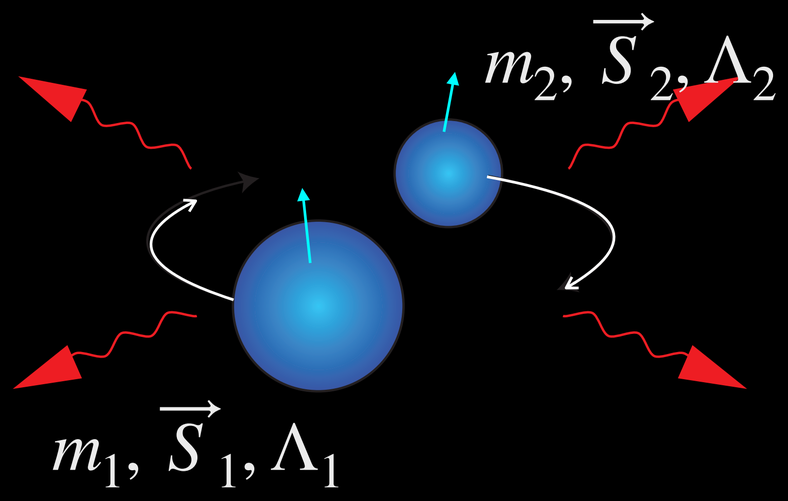
GWTC-3 BH-BH 17.9-44 $Gpc^{-3}\ yr^{-1}$





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

Source properties: Inspiral

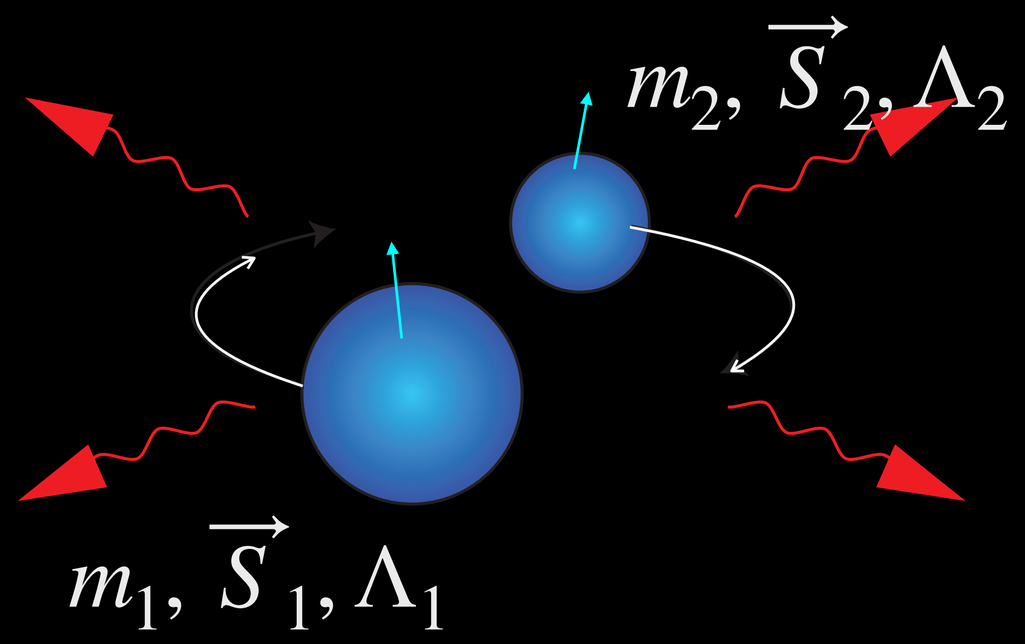


Wave pattern depends on (leading order terms):

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

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

Tides in GW binaries



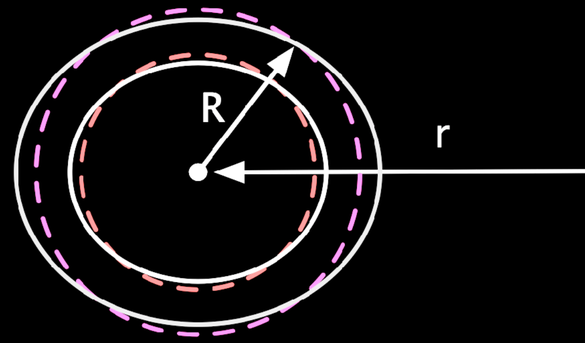
Λ_i characterizes the ratio
of mass quadrupole to external tidal field
for an isolated star

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

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
(distribution of mass within the surface

Tides add to energy loss

- Additional orbital energy lost to the deformation of the stars
- Tidal bulges add a little extra quadrupole, GW luminosity
- Energy scale required to modify orbit is LARGE: transfer of additional $\sim 10^{46}$ erg at ~ 100 Hz modifies phase by 10^{-3} radians (Tsang et al Phys. Rev. Lett. 108, 011102 (2012))



$$\frac{dr}{dt} = \frac{-\mathscr{L}_{GW} - \mathscr{L}_{GW,def}}{dE_{orb}(r)/dr + dE_{def}(r)/dr}$$

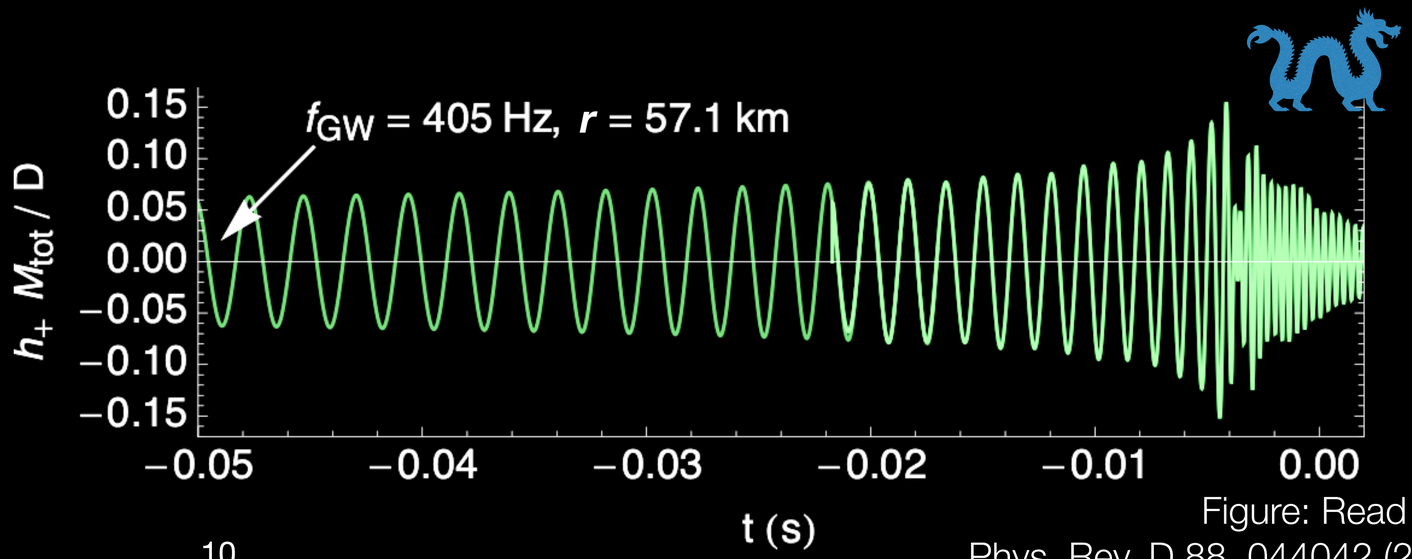
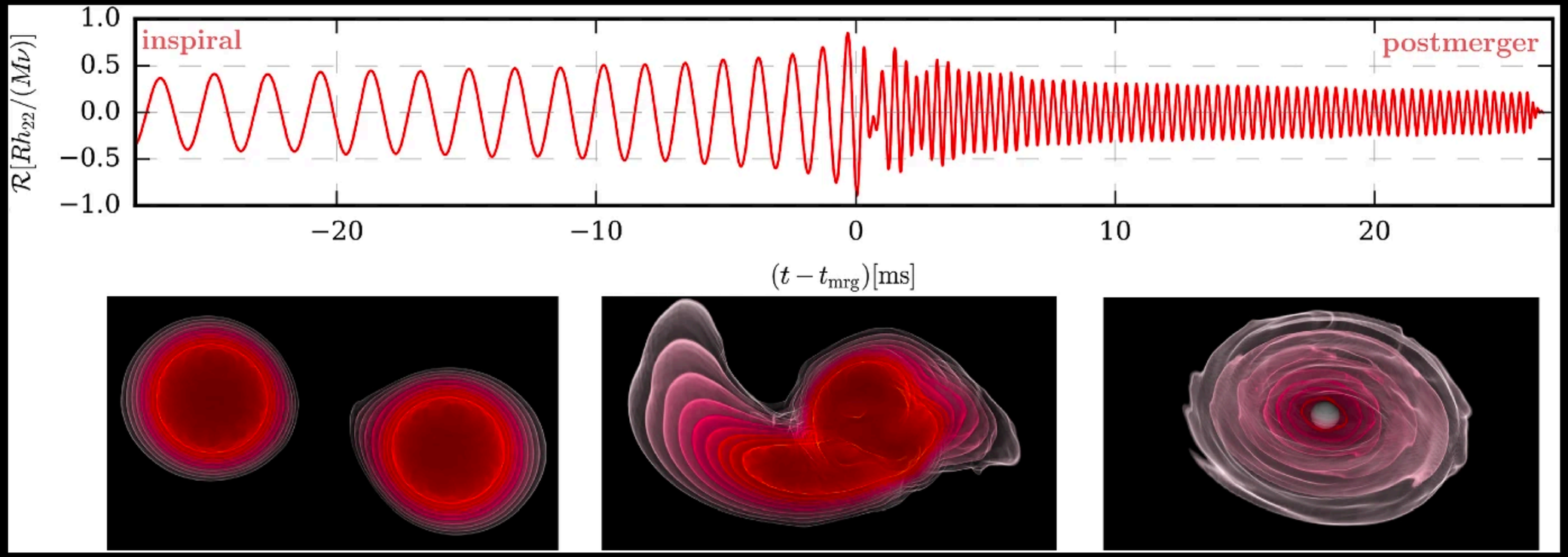
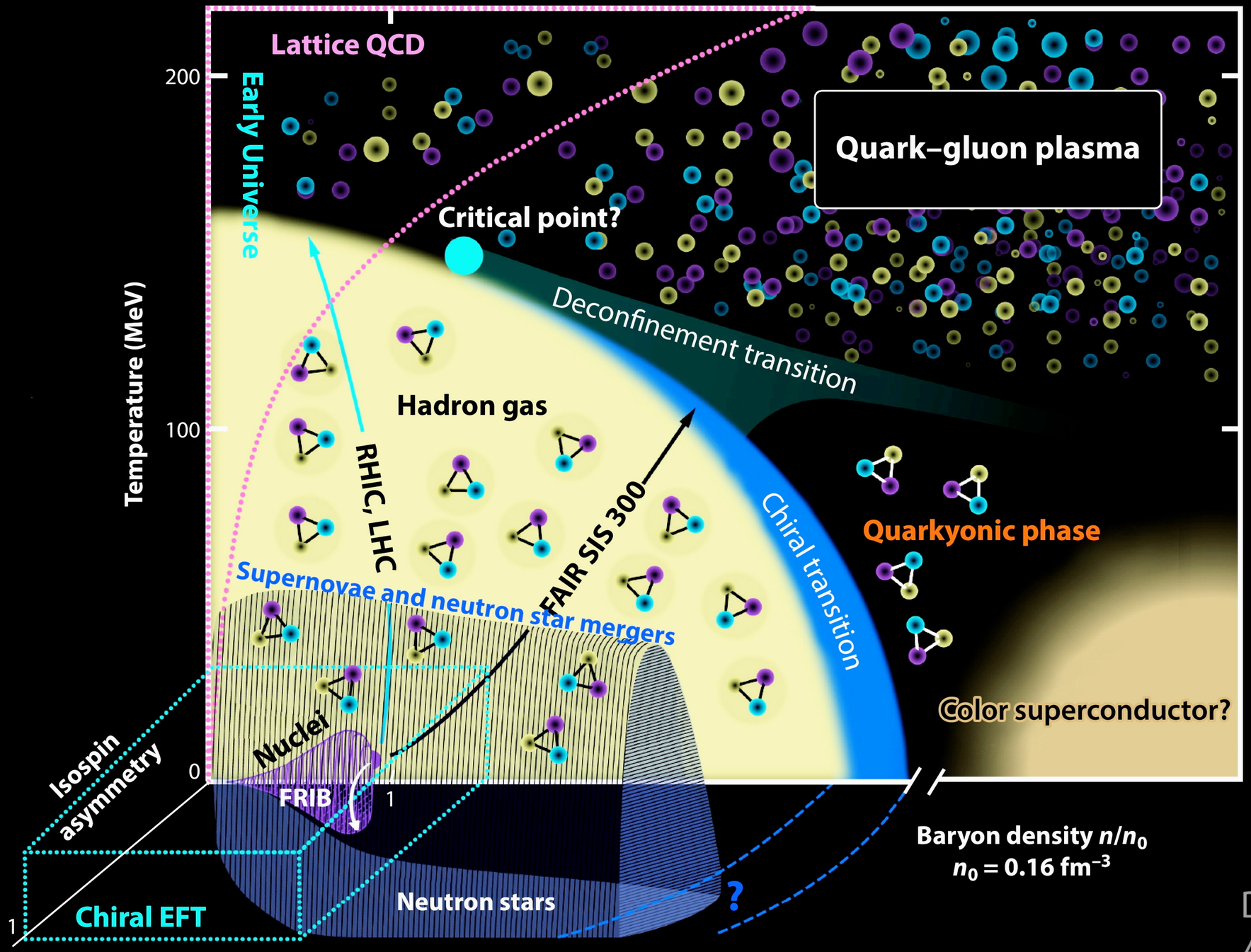


Figure: Read et al Phys. Rev. D 88, 044042 (2013)



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

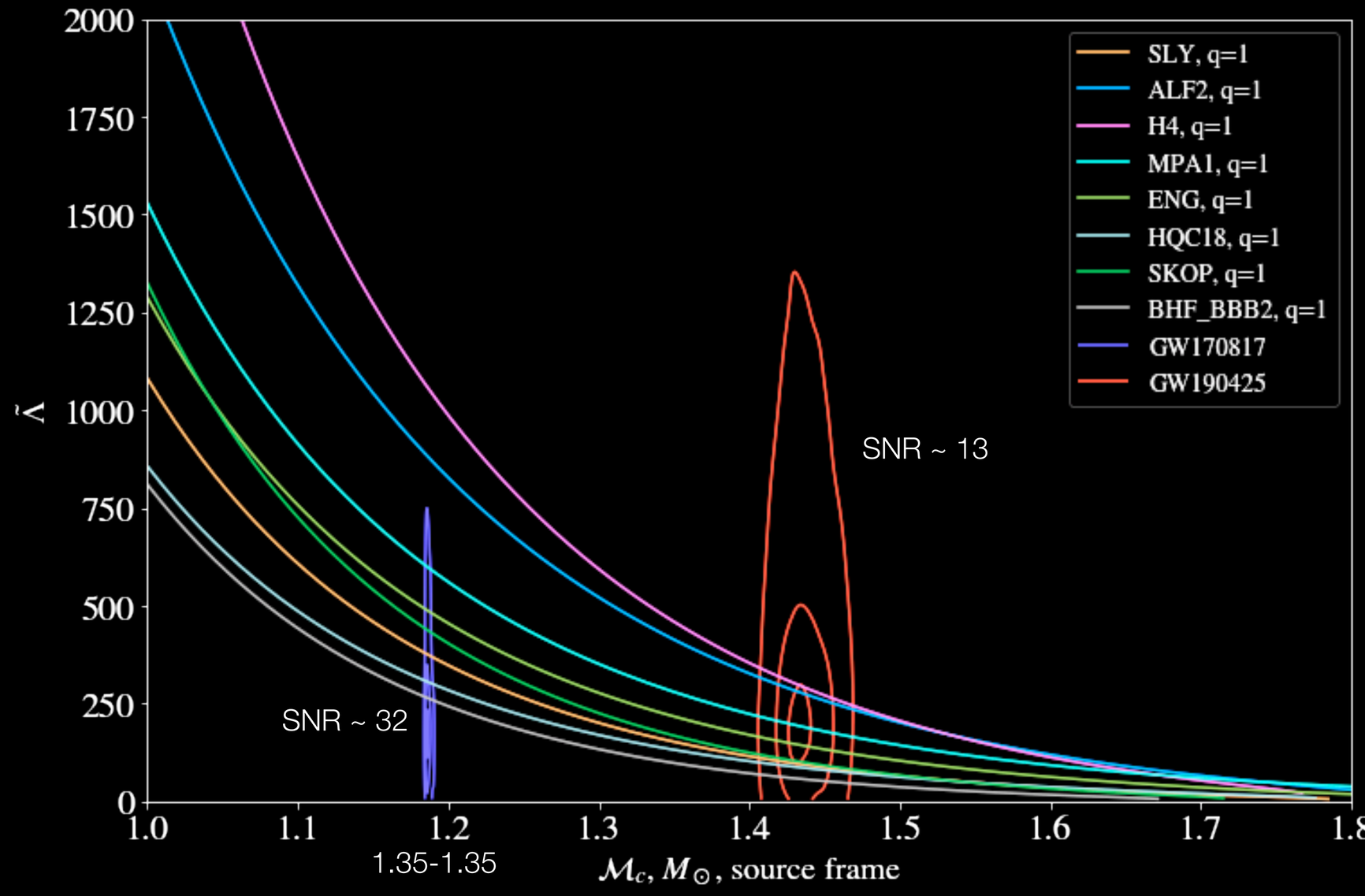
- Stars deform in complicated, close interactions:
  - stars are not isolated, deformations are not linear, deformations are not pure quadrupole
- GW waveform community uses (and test) Λ_1, Λ_2 as *effective* descriptors for gravitational-wave models from numerical simulation and higher-order analytical expressions



EOS for inspiral: cold beta-equlibrium matter

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

Observations so far: GW170817 & GW190425



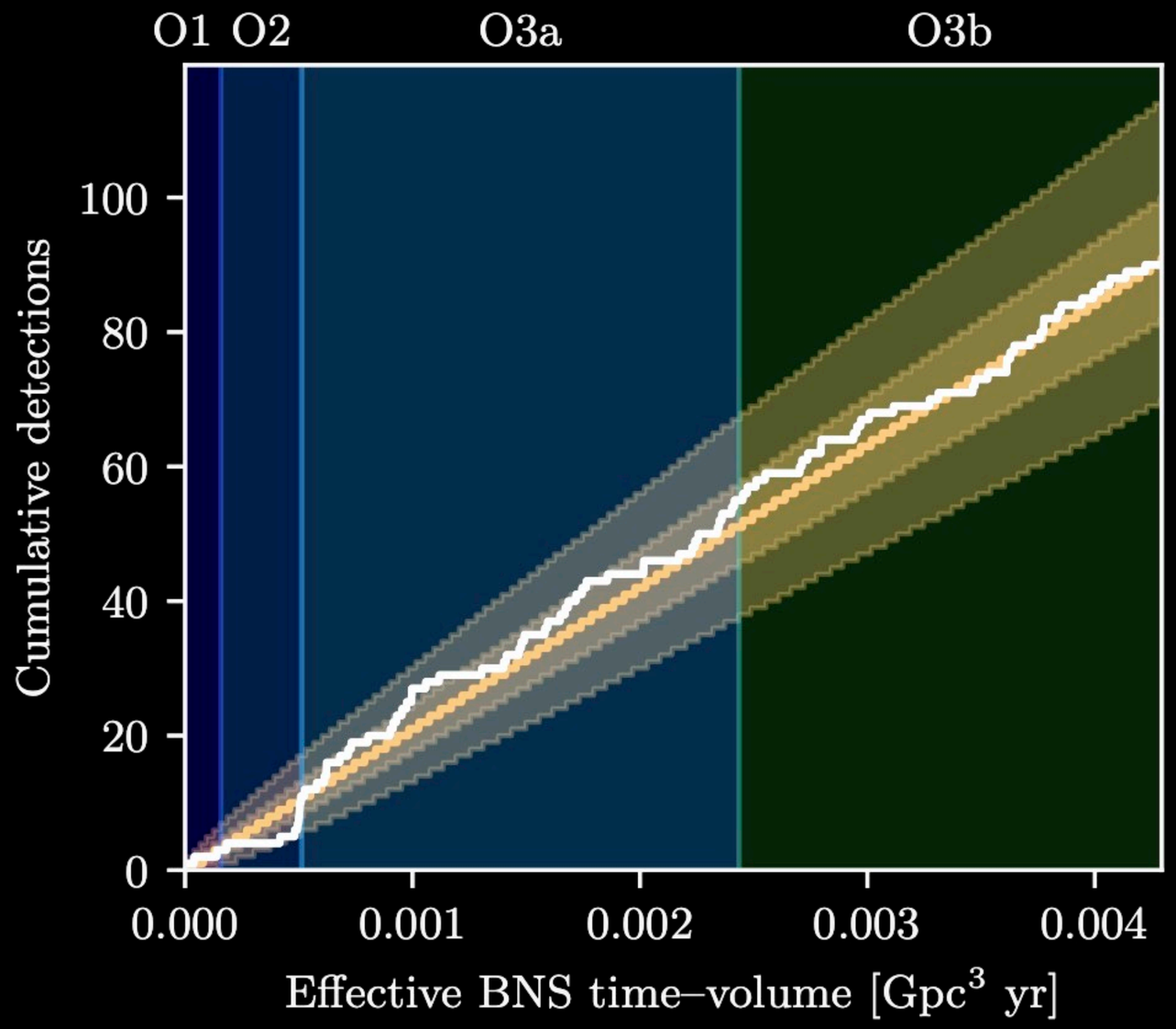
GW170817 from LIGO/Virgo GWTC-1 data release,
P1800370, Phys. Rev. X 9, 031040 (2019)

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)

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]



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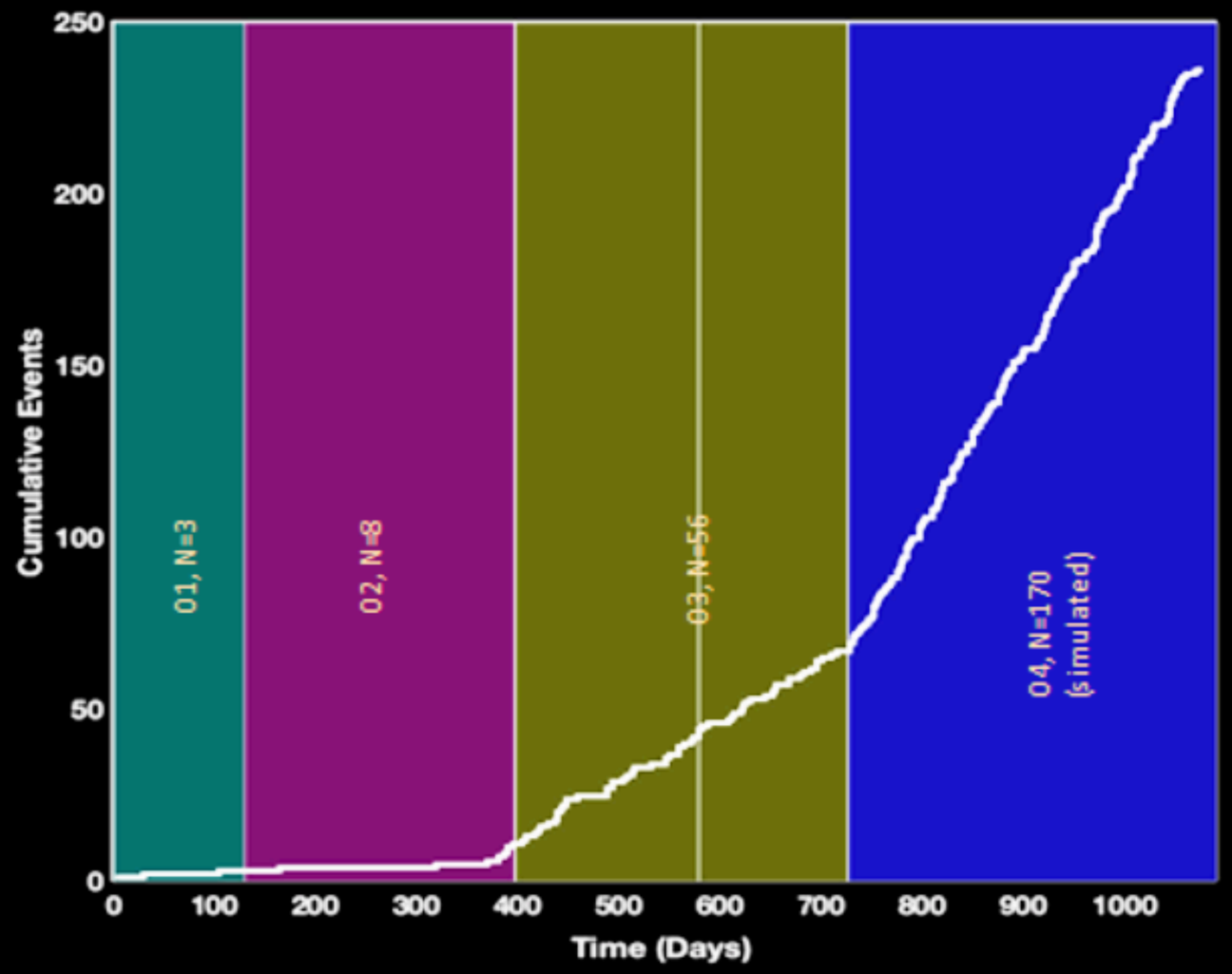
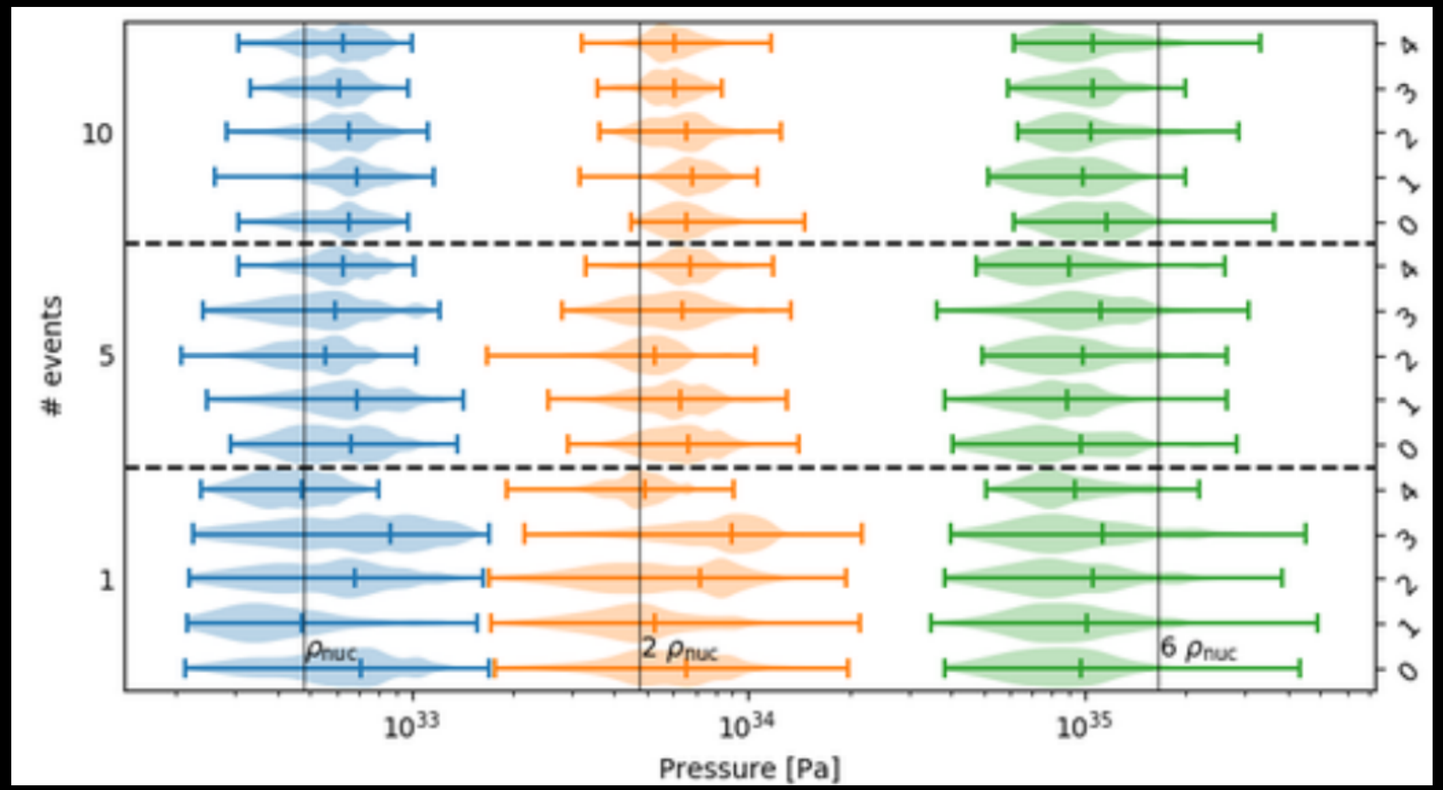
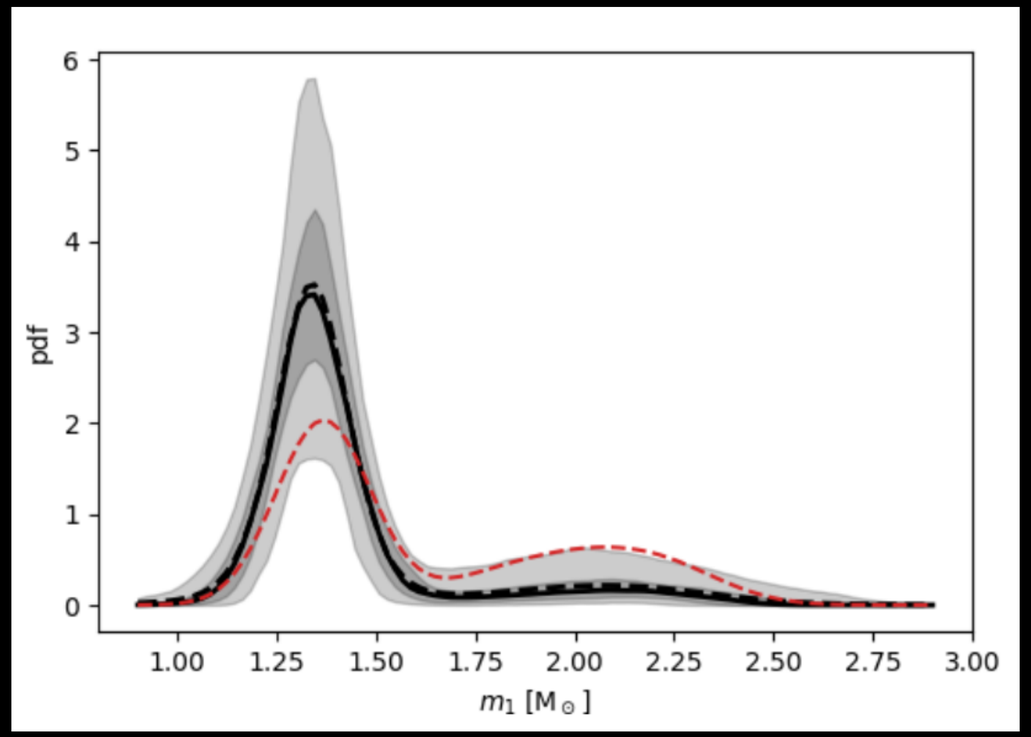


LIGO/Virgo

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

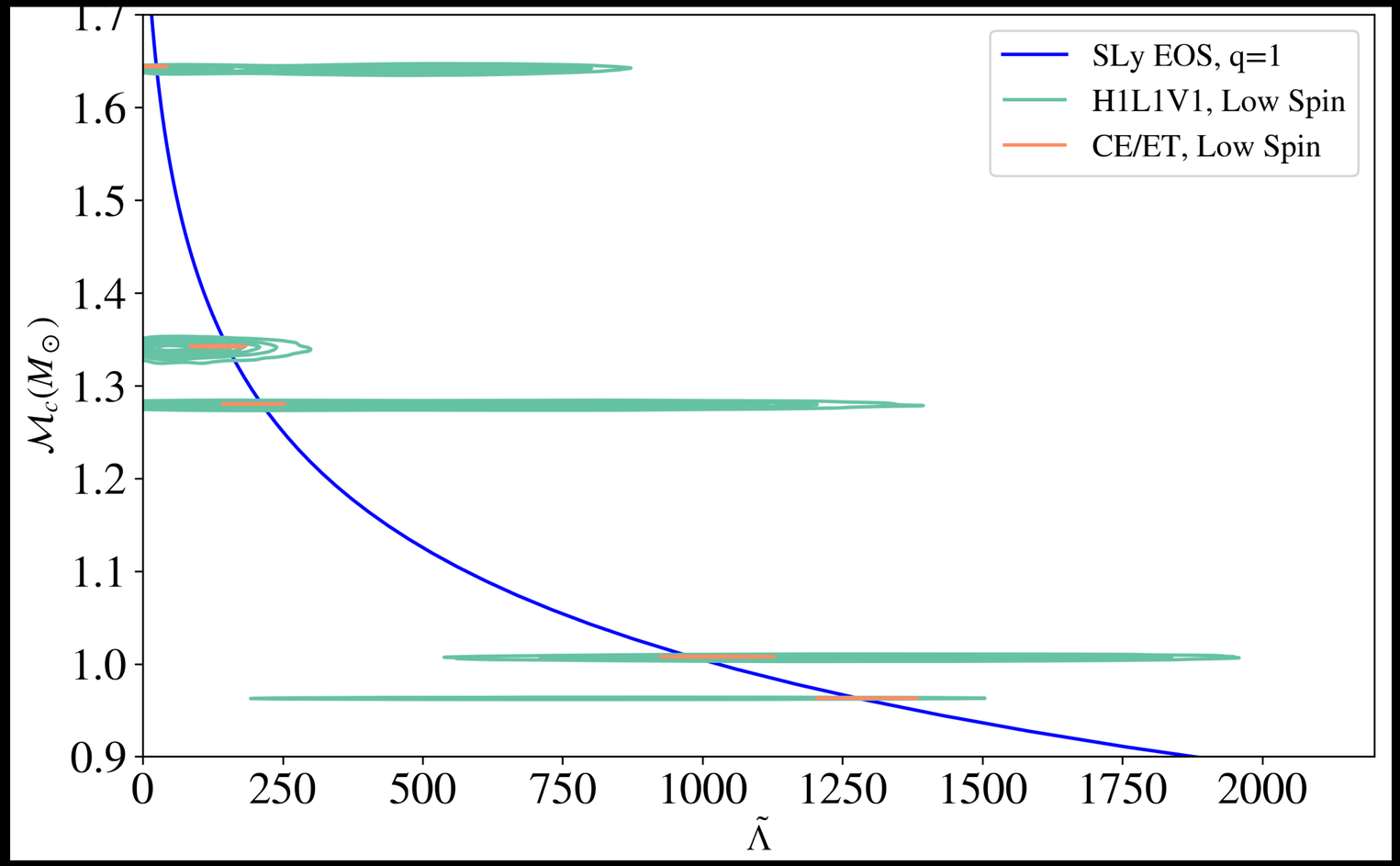




Wysocki et al arXiv:2001.01747

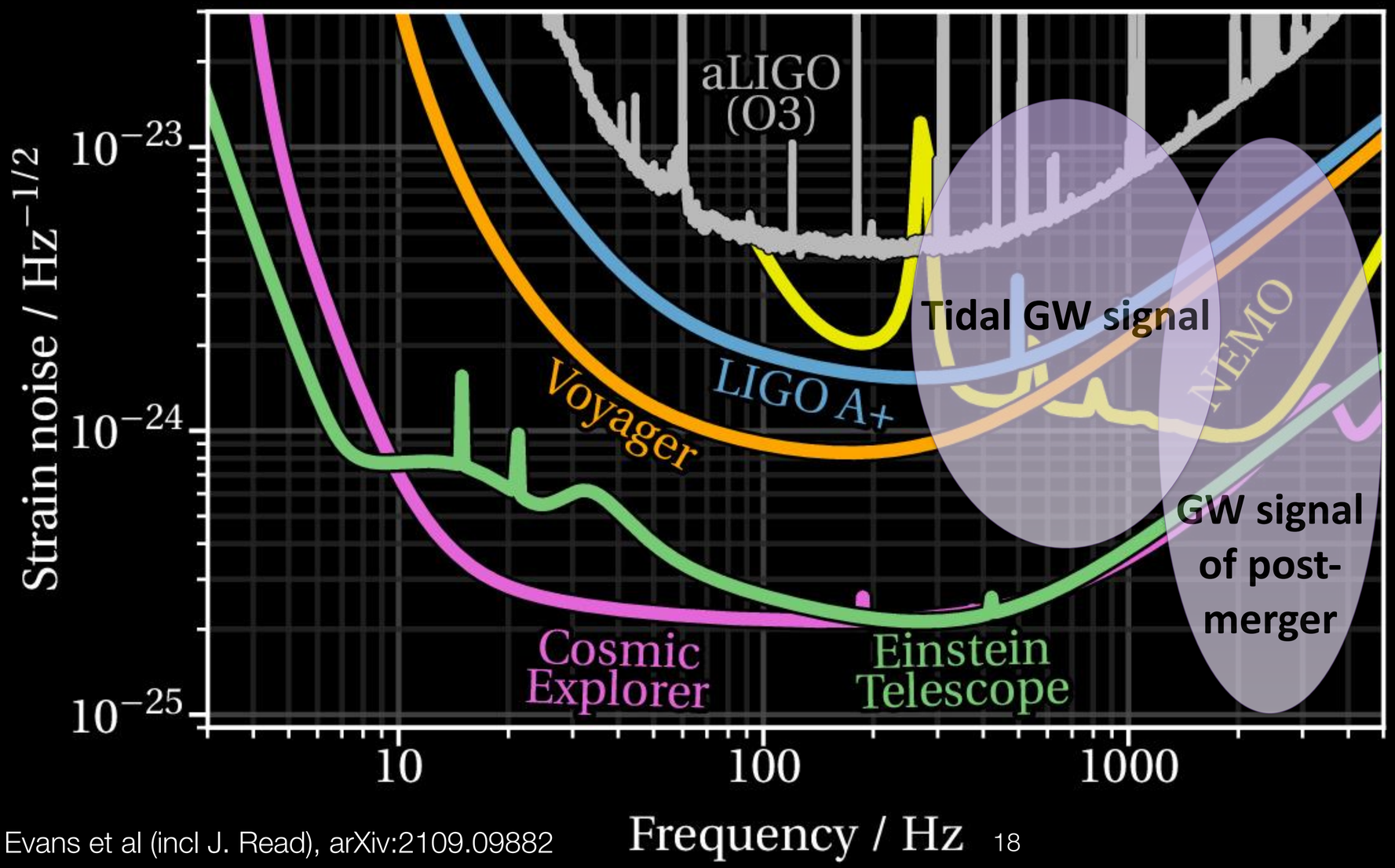
EOS constraint?

- Randomly drawn detected signals with SNR>13
- Masses from uniform distribution between 1.0 and EOS maximum mass
- 90% posterior recovery contours

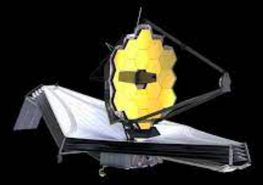


Wuchner Landry Read, in prep

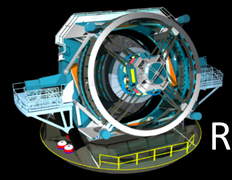
Landscape of GW Astronomy



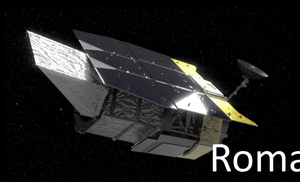
Current generation (now)



JWST



Rubin



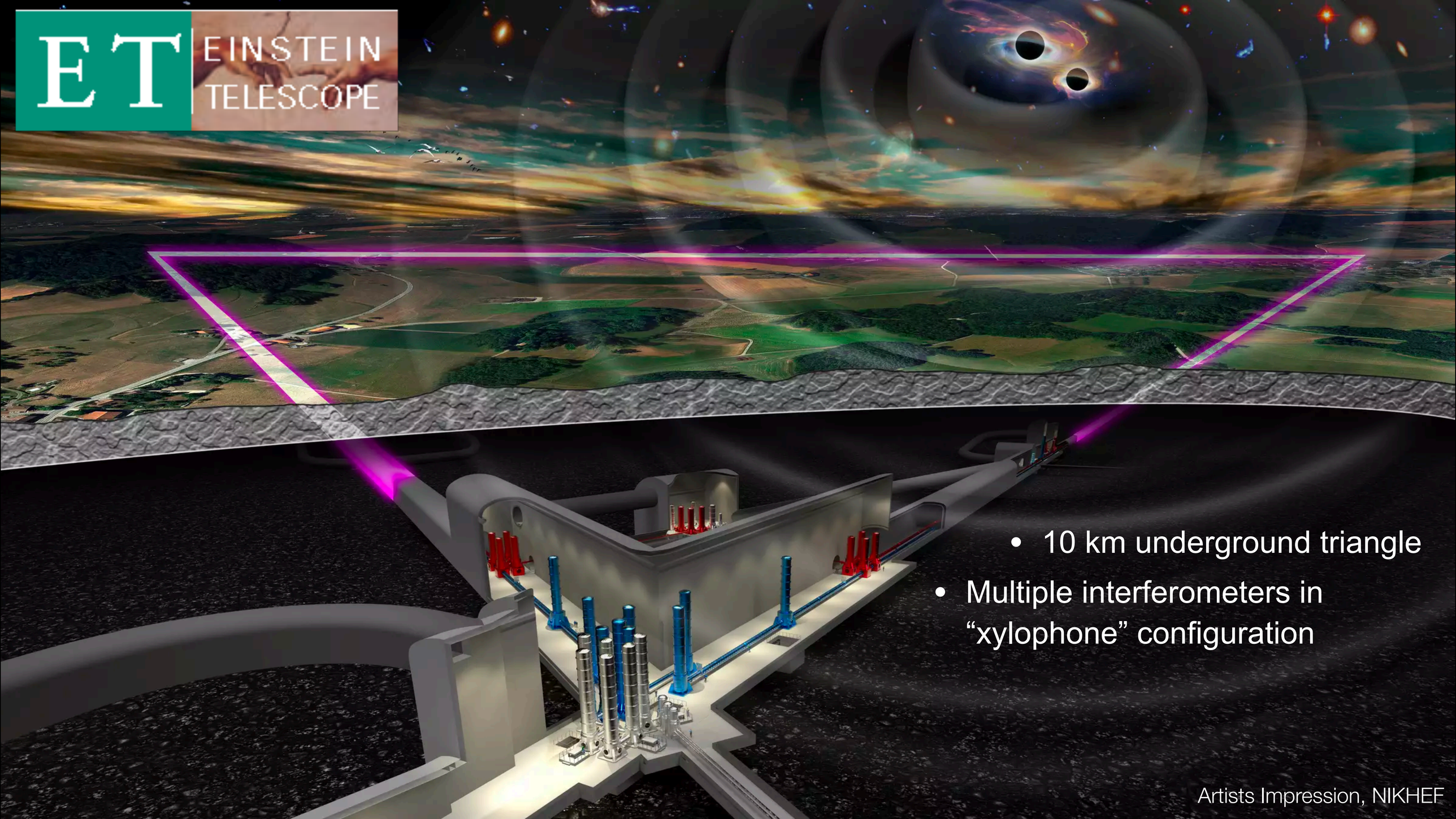
Roman

EM-survey merger identification?

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

Next-generation (ca. 2035+)

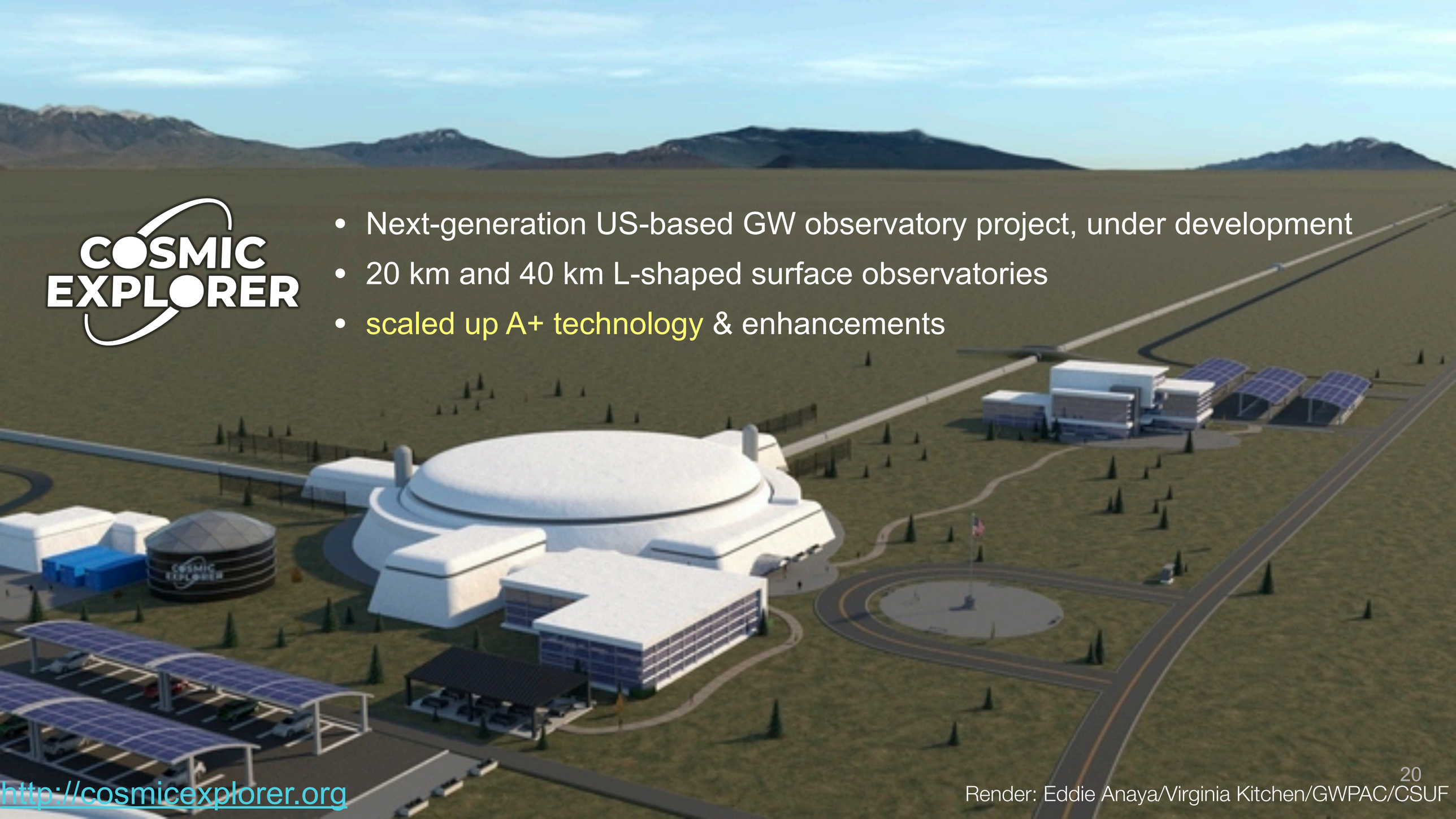
Evans et al (incl J. Read), arXiv:2109.09882



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

Artists Impression, NIKHEF

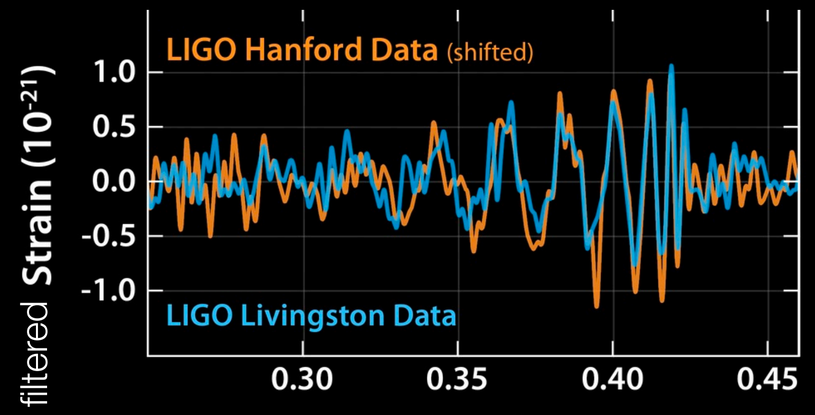
- Next-generation US-based GW observatory project, under development
- 20 km and 40 km L-shaped surface observatories
- scaled up A+ technology & enhancements

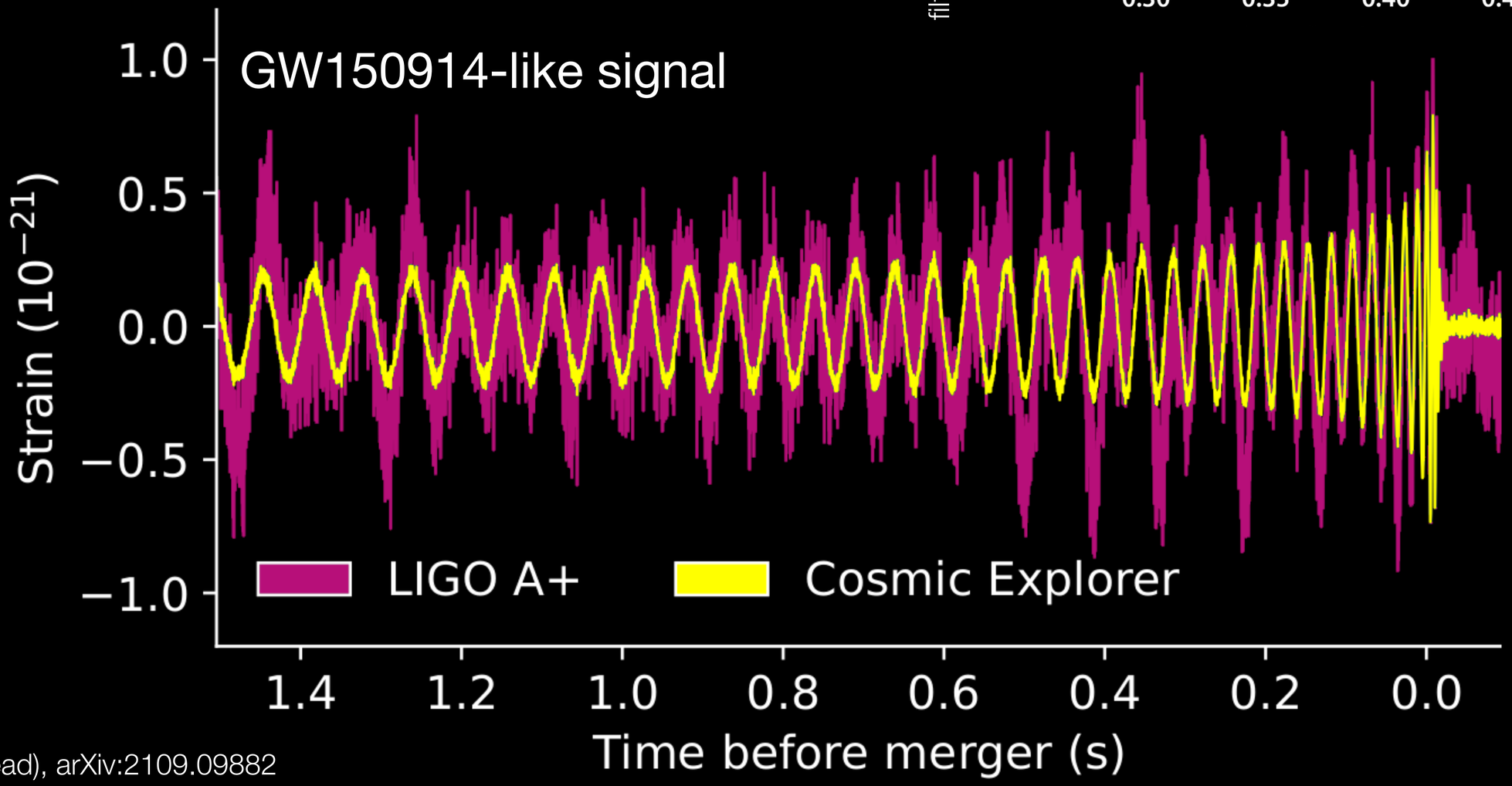


http://cosmicexplorer.org

Render: Eddie Anaya/Virginia Kitchen/GWPAC/CSUF

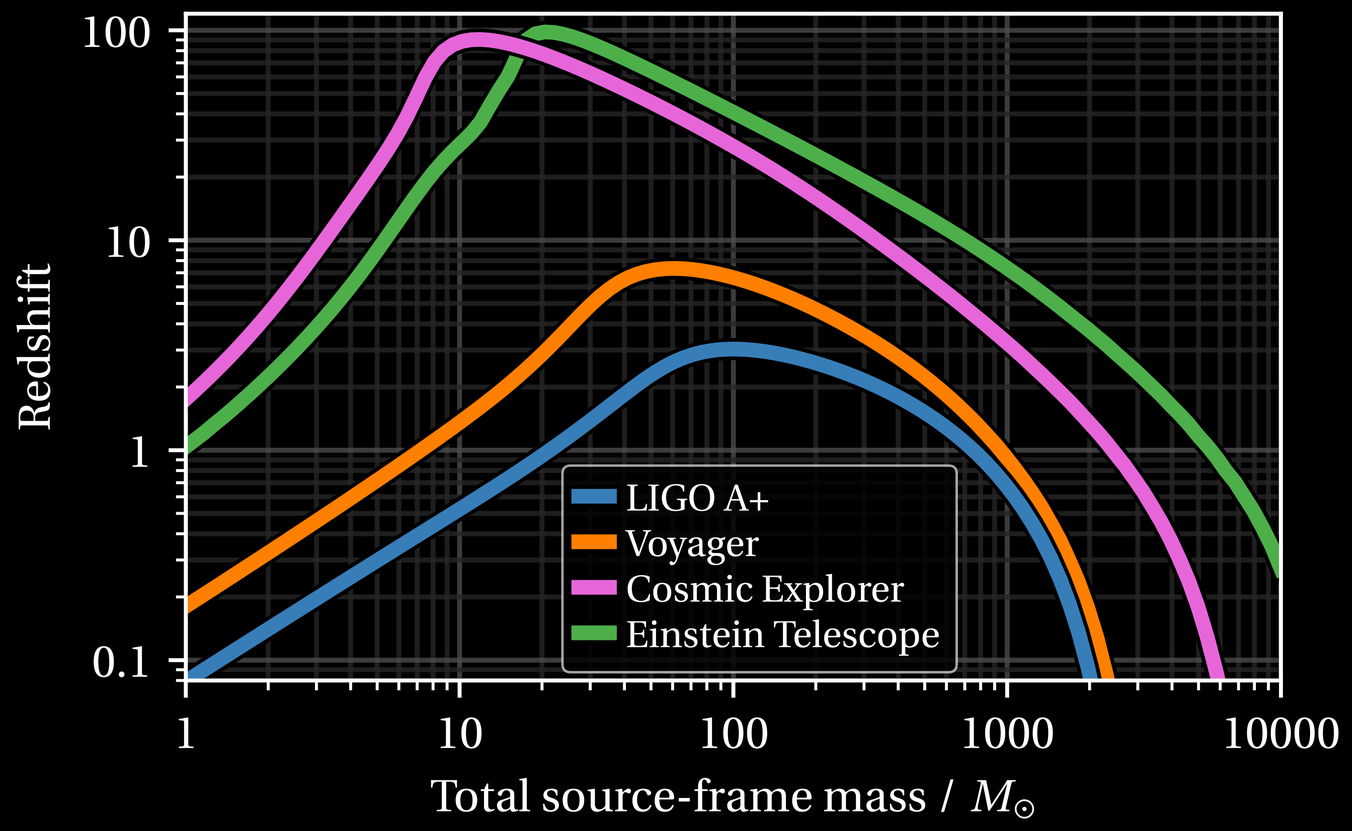
Next-generation capabilities: Precision measurement

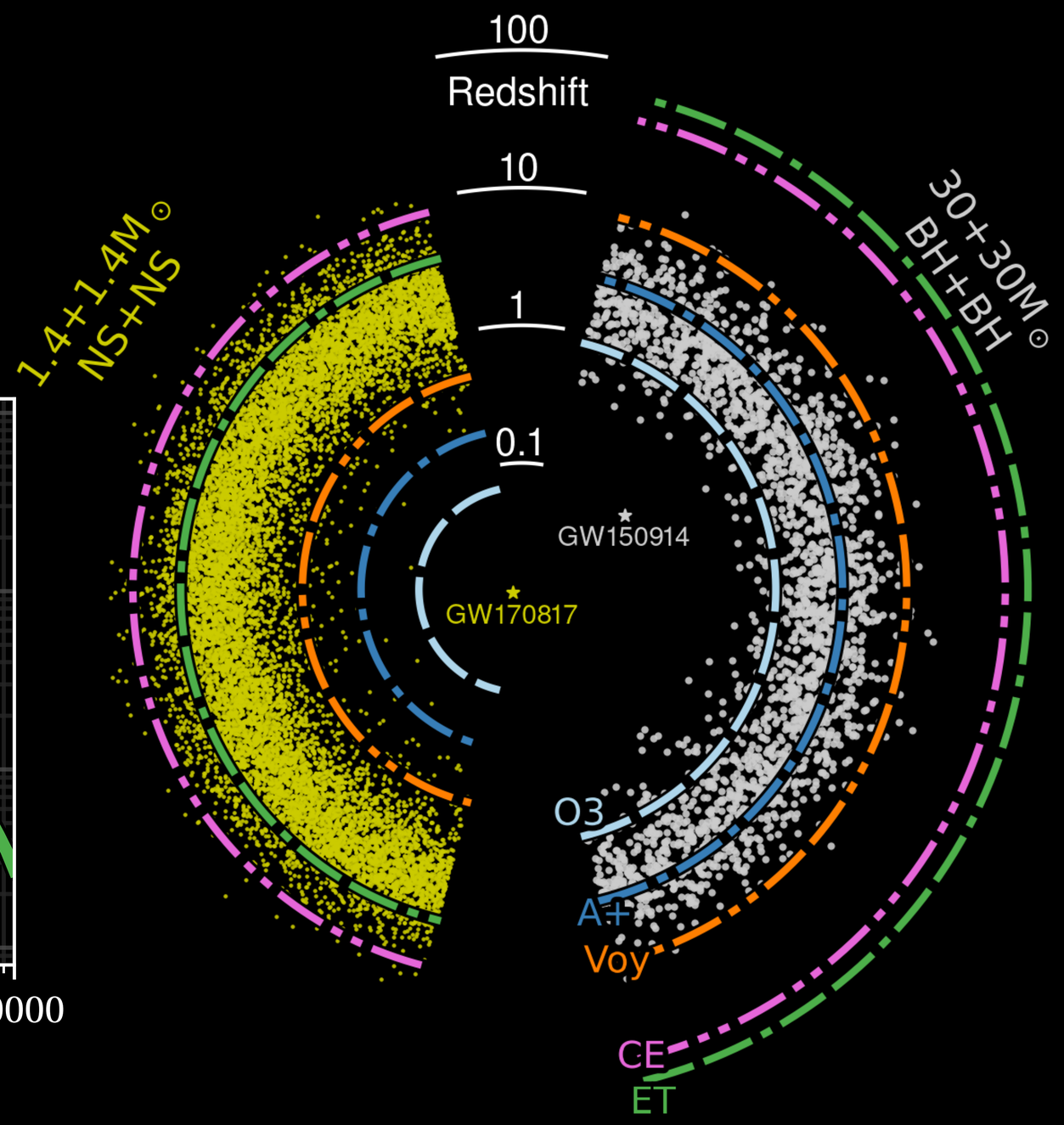




CEHS: Evans et al (incl J. Read), arXiv:2109.09882

Next-generation capabilities: Cosmic Reach





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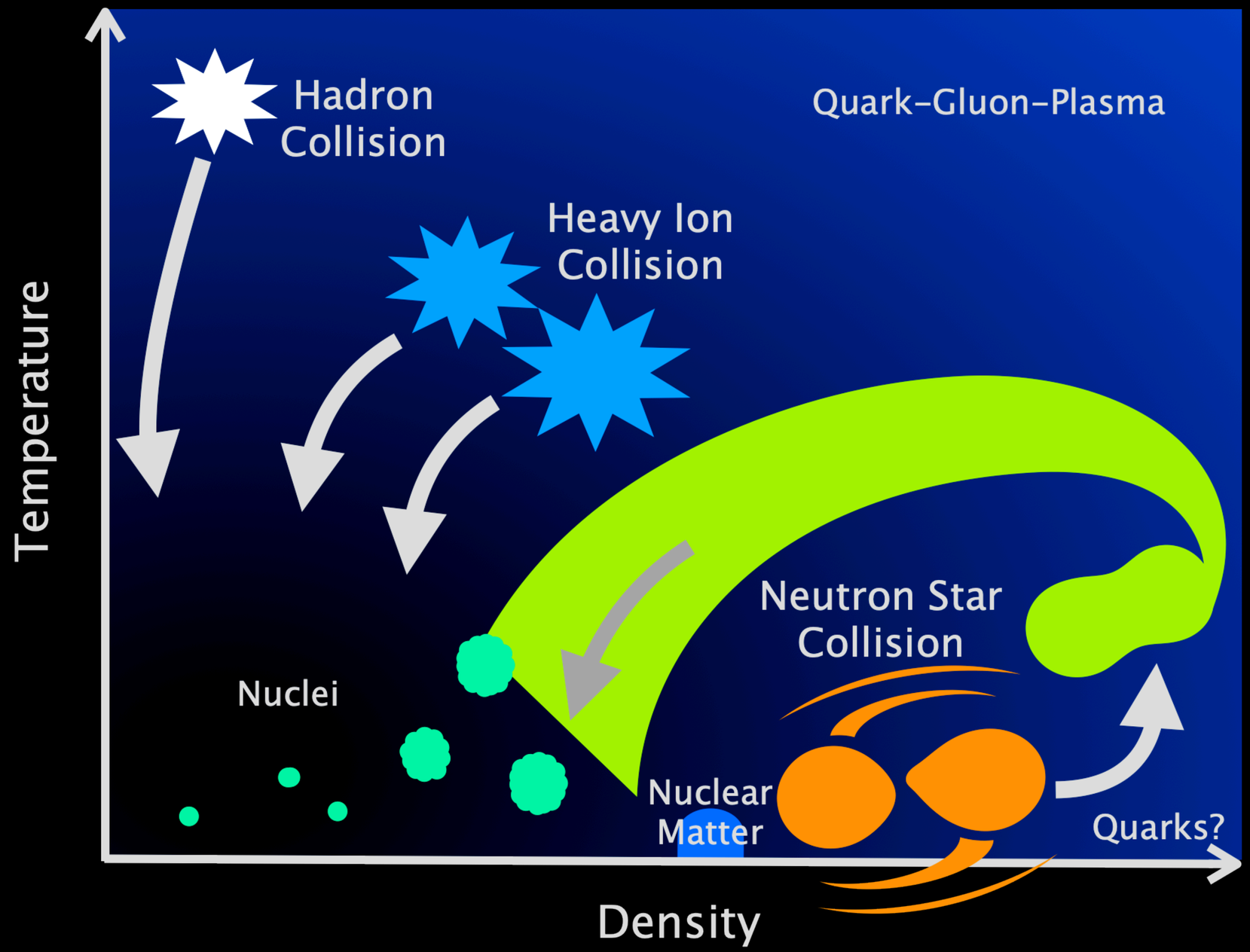
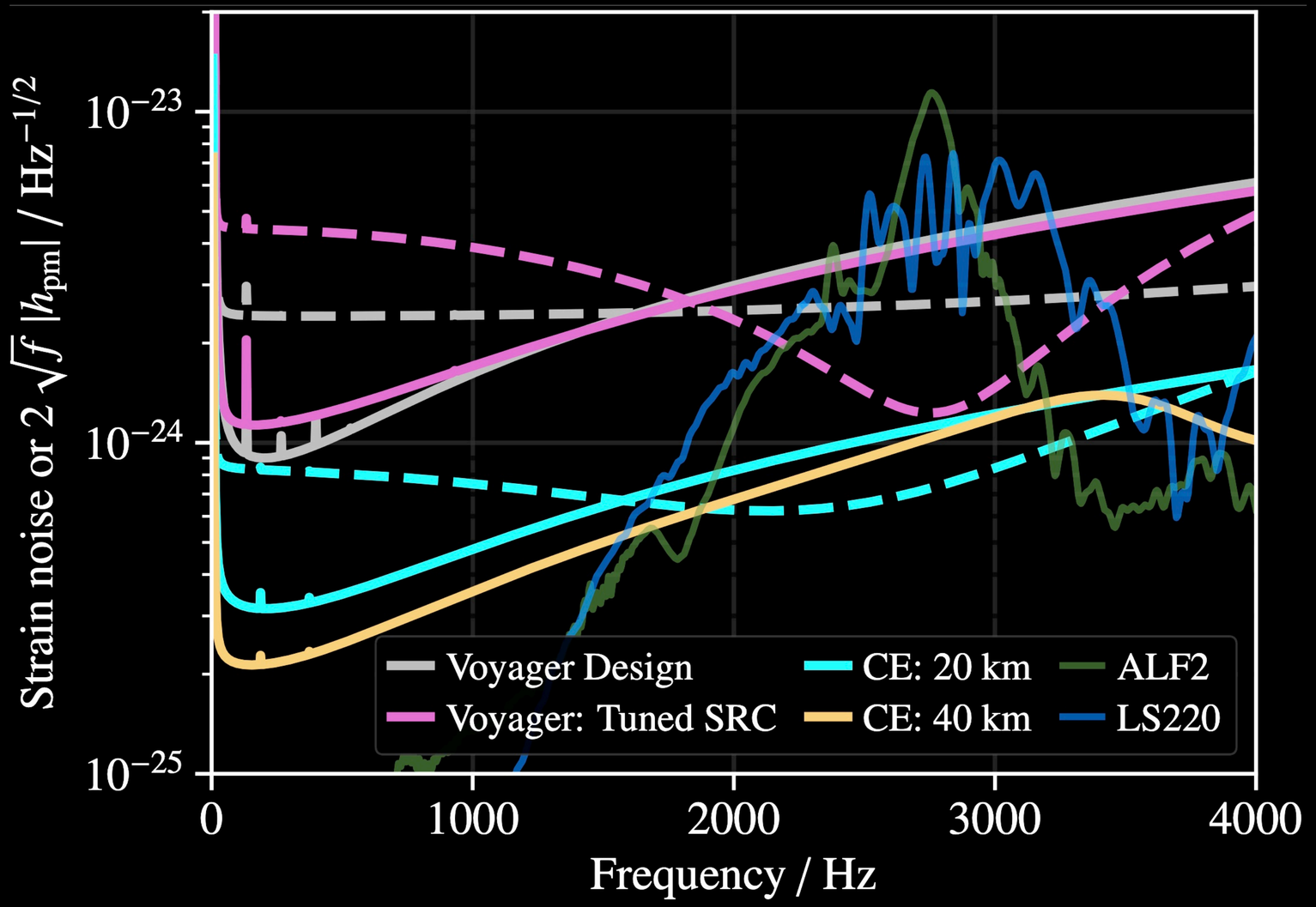


- ~1000s of neutron star mergers / year
- identify 80% of **all** mergers within z=1
- ~100 mergers with 10 minutes early warning
- ~100 NS radii with error < ~0.1 km / year
- ~10 / year SNR > 300
- ~100 post-merger GW detected / year

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

Post-merger GW?



- The only science target where smaller 20km detector may perform better than a larger 40km

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

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

CALIFORNIA STATE UNIVERSITY FULLERTON

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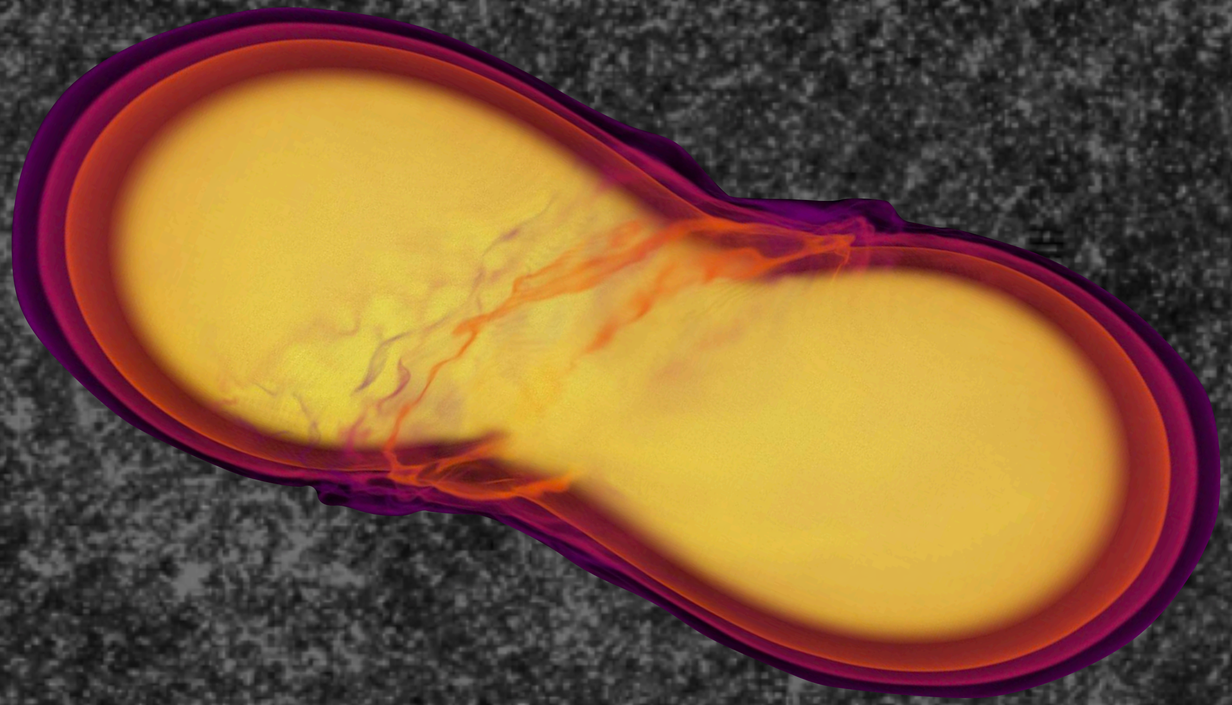
Nancy Goodhue-McWilliams

NSF

RESEARCH CORPORATION for SCIENCE ADVANCEMENT

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