Observing neutron stars with gravitational waves

ECT* NEUTRON STARS AS MULTI-MESSENGER LABORATORIES FOR DENSE MATTER

Jocelyn Read
California State University Fullerton

June 2021

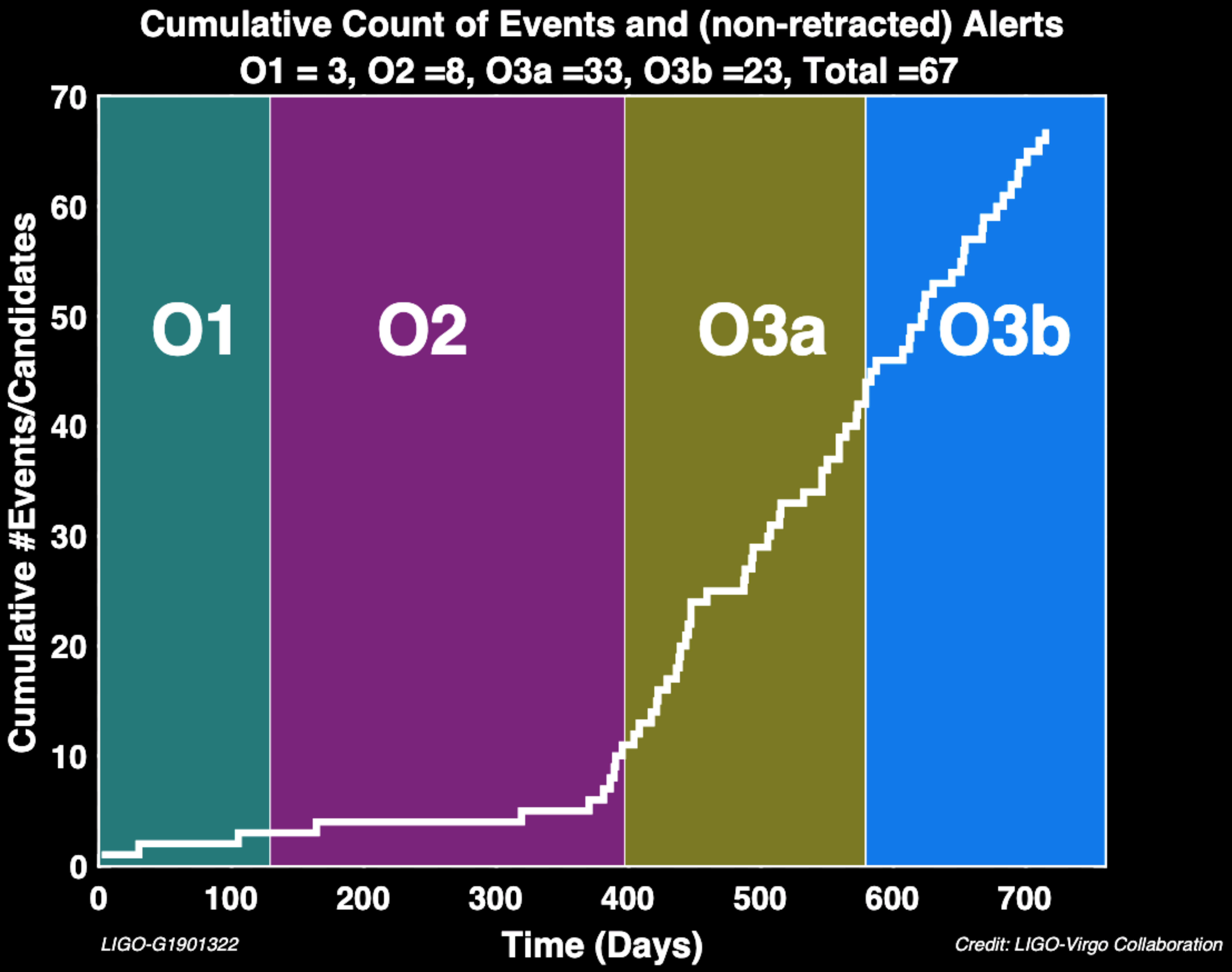
GW PAC

CALIFORNIA STATE UNIVERSITY
FULLERTON

LSC

NSF

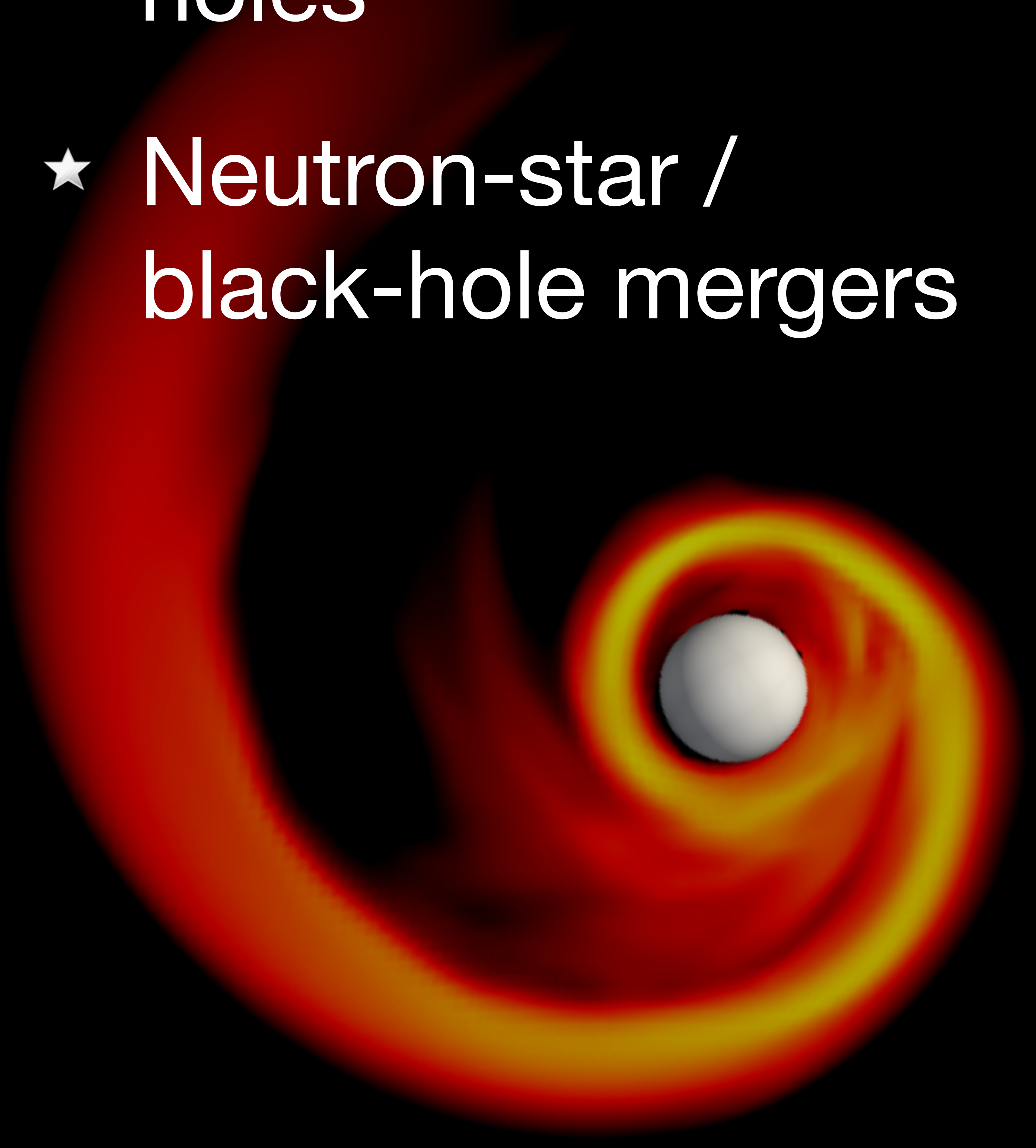
LSC/Virgo PRL 119, 161101 (2017), data visualization J. McIver M. Evans
simulation image: T. Dietrich(AEI/FSU)/BAM



https://dcc.ligo.org/LIGO-G1901322/public

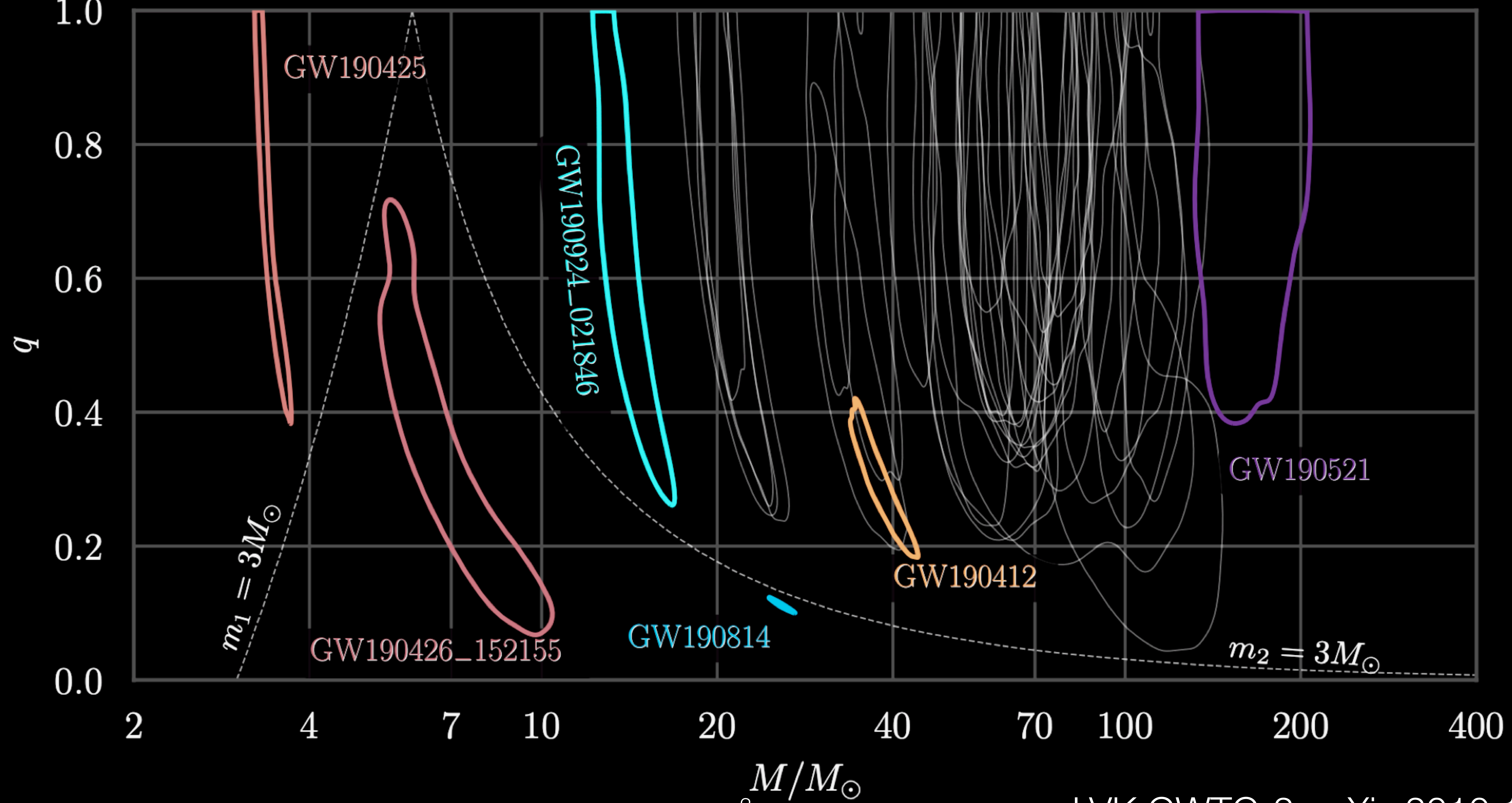
New alert classifications in O3:

- ⋆ “Mass-gap” black holes
- ⋆ Neutron-star / black-hole mergers



Neutron-star/black-hole simulation
Jennifer Sanchez, CSUF

O3a Events (April-September 2019)



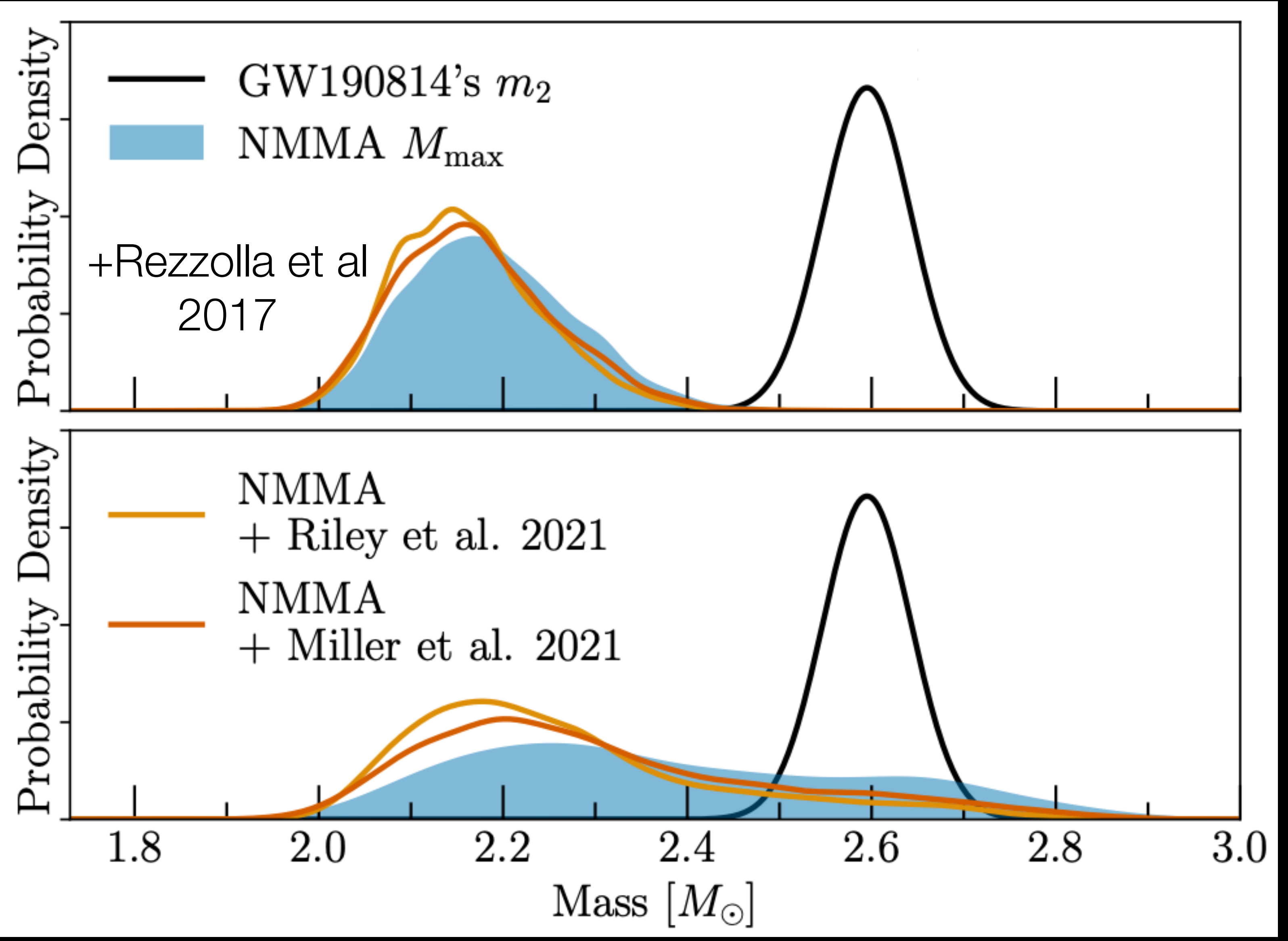
LVK GWTC-2, arXiv:2010.14527

Data released for low-mass LVK events

https://www.gw-openscience.org/eventapi/html/allevents/

Name	Mass 1 ($M_\odot$)	Mass 2 ($M_\odot$) ↑	Network SNR	Distance (Mpc)	Chirp Mass ($M_\odot$)
GW170817	$1.46^{+0.12}_{-0.10}$	$1.27^{+0.09}_{-0.09}$	33.0	40^{+7}_{-15}	$1.186^{+0.001}_{-0.001}$
GW190425	$2.0^{+0.6}_{-0.3}$	$1.4^{+0.3}_{-0.3}$	13.0	160^{+70}_{-70}	$1.44^{+0.02}_{-0.02}$
GW190426_152155	$5.7^{+3.9}_{-2.3}$	$1.5^{+0.8}_{-0.5}$	10.1	370^{+180}_{-160}	$2.4^{+8.0e-02}_{-8.0e-02}$
GW190814	$23.2^{+1.1}_{-1.0}$	$2.6^{+8.0e-02}_{-9.0e-02}$	22.2	240^{+40}_{-50}	$6.09^{+0.06}_{-0.06}$

- GWTC-2 (arXiv:2010.14527) added GW190426_152155 with FAR 1.4 yr^{-1}
- Direct tidal EOS constraints only from GW170817

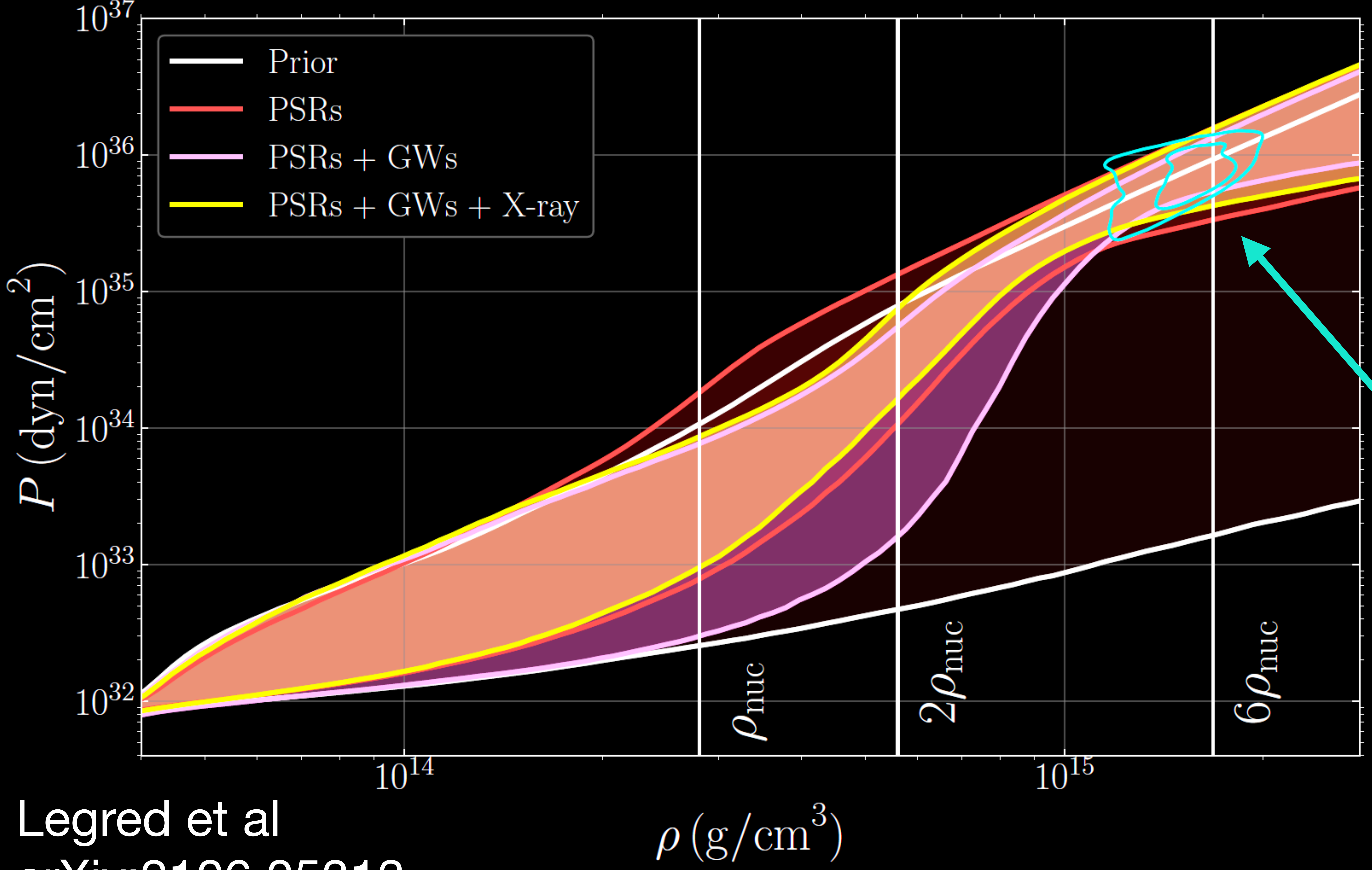


Pang et al 2105.08688

Gravitational-Wave Observations in Context

Beyond single-event analysis

GW + Pulse Profile EOS inference

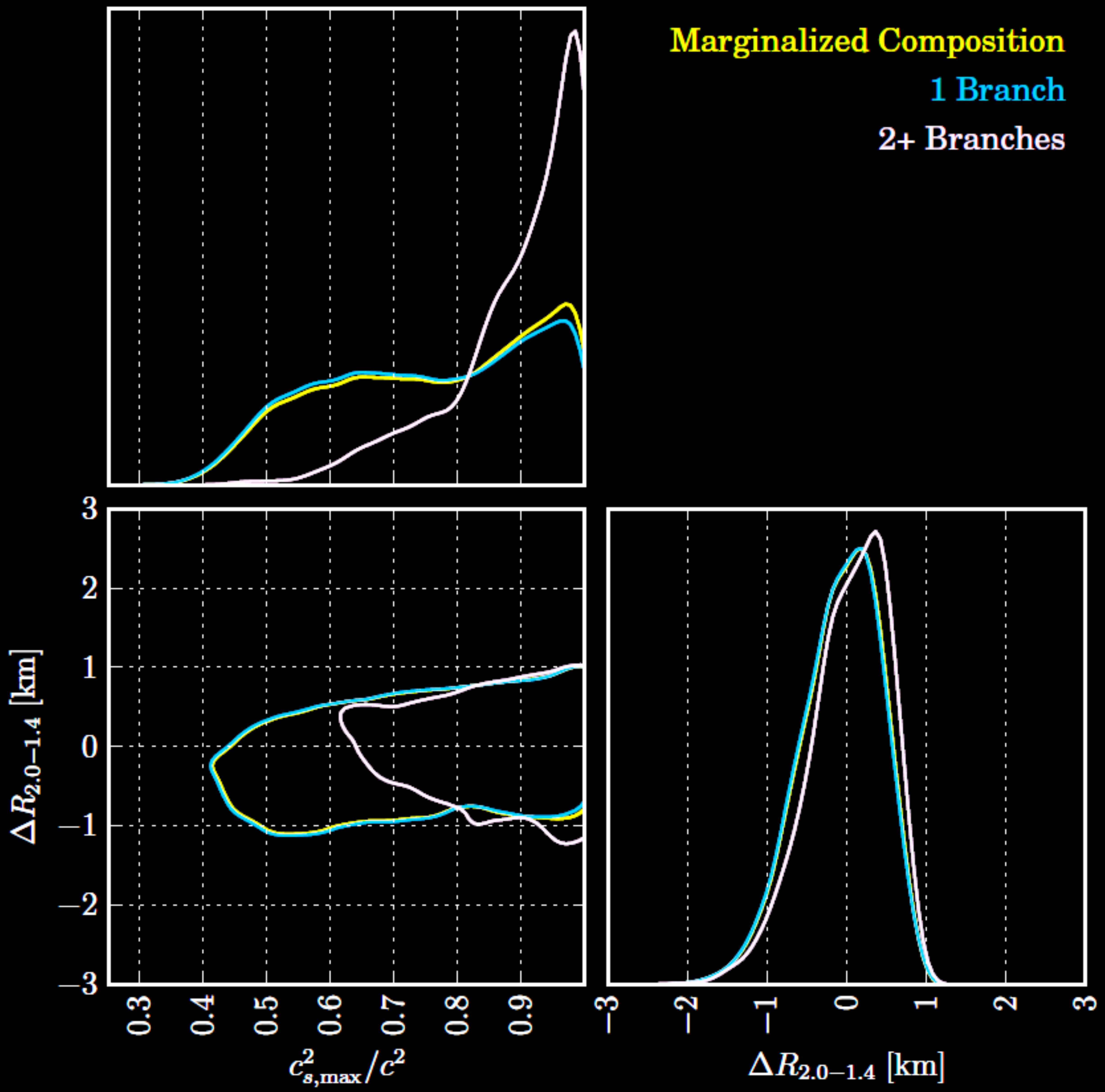


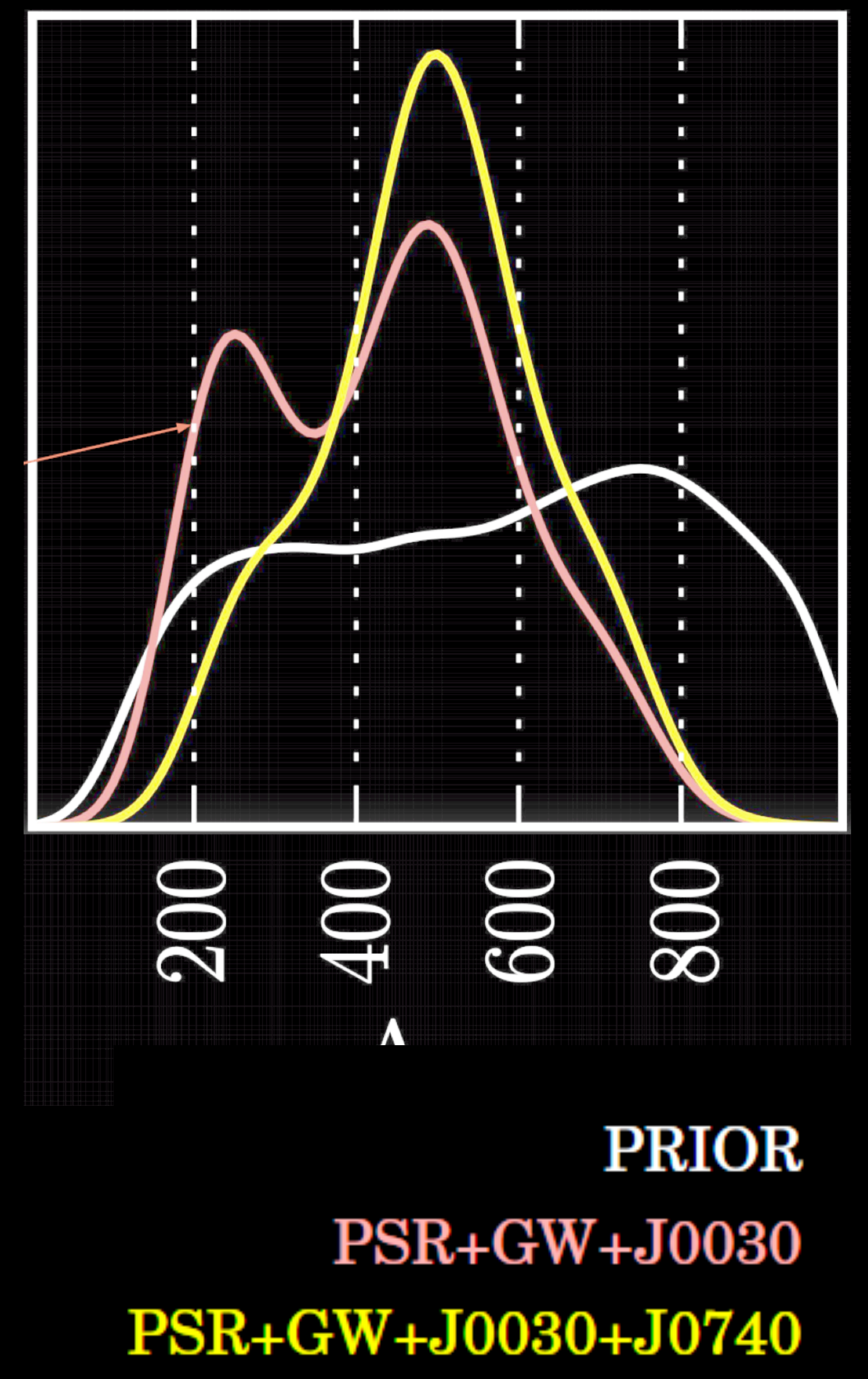
Methods of Essick et al & Landry et al, Phys. Rev. D 101 (2020) with addition of PSR J0740+6620

Central pressure of a maximum-mass NS

Legred et al arXiv:2106.05313

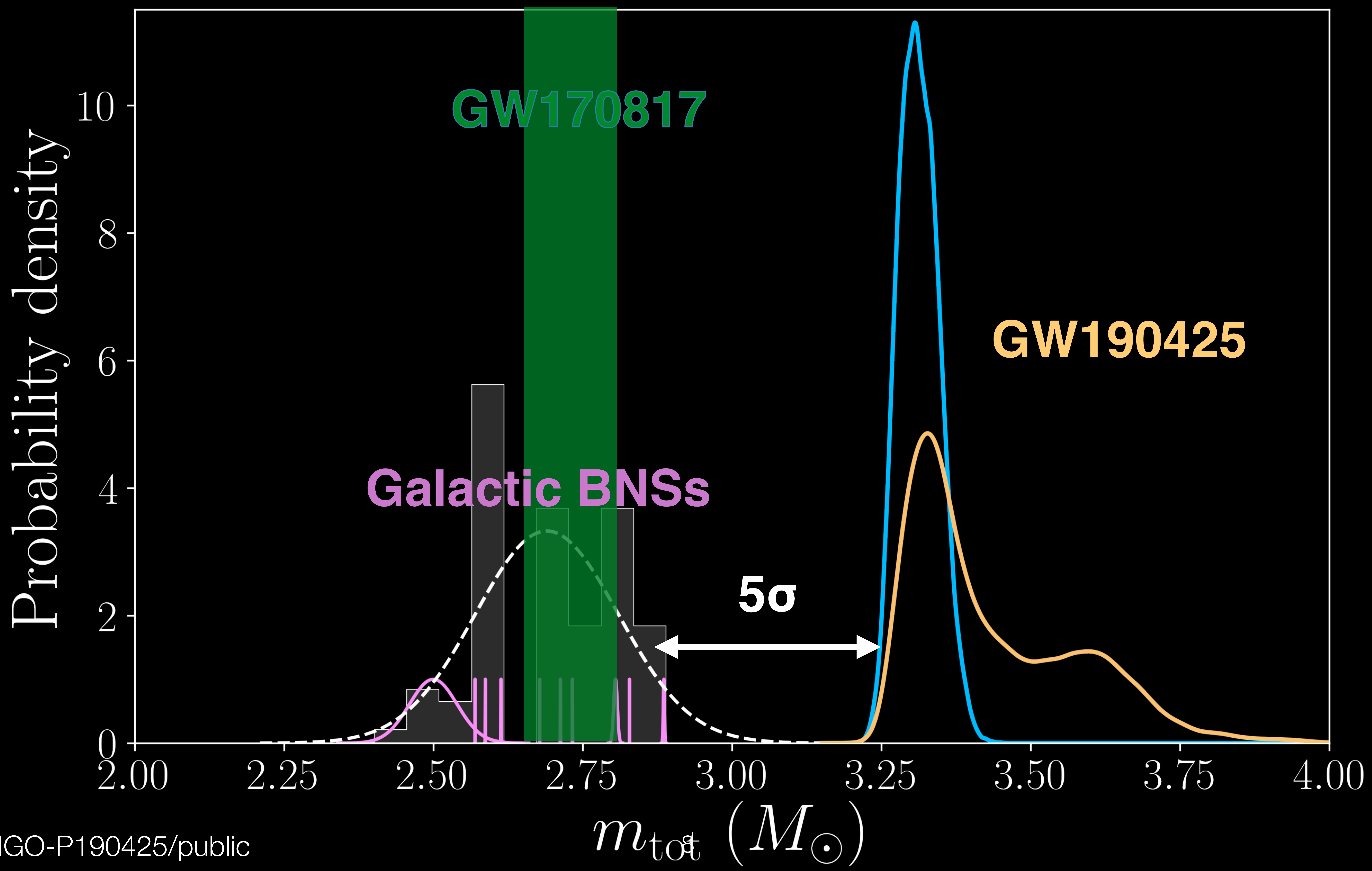
GW170817 in context: Joint analysis with J0740 breaks bimodality of tidal parameter





Legred et al
arXiv:2106.05313

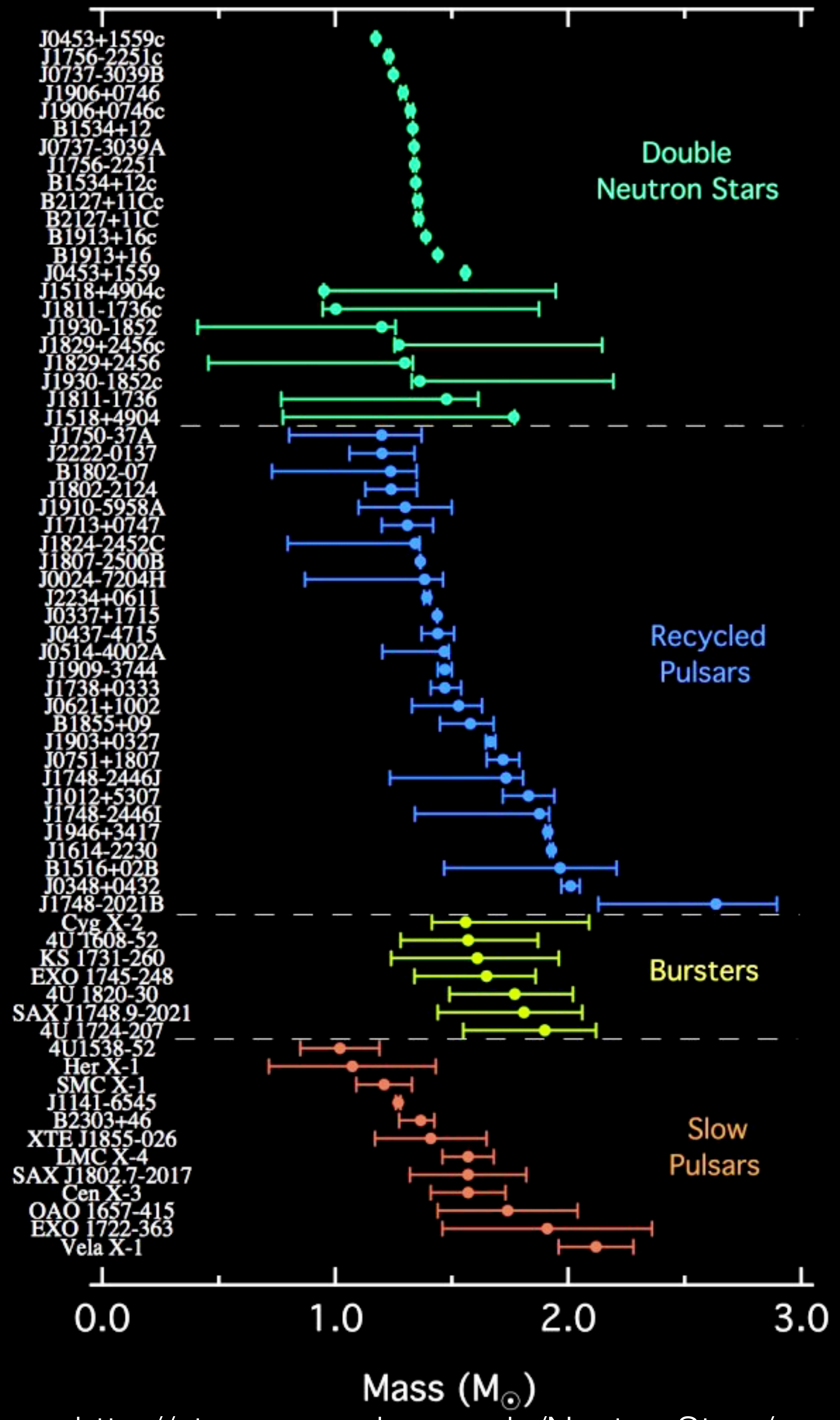
Neutron Star Masses



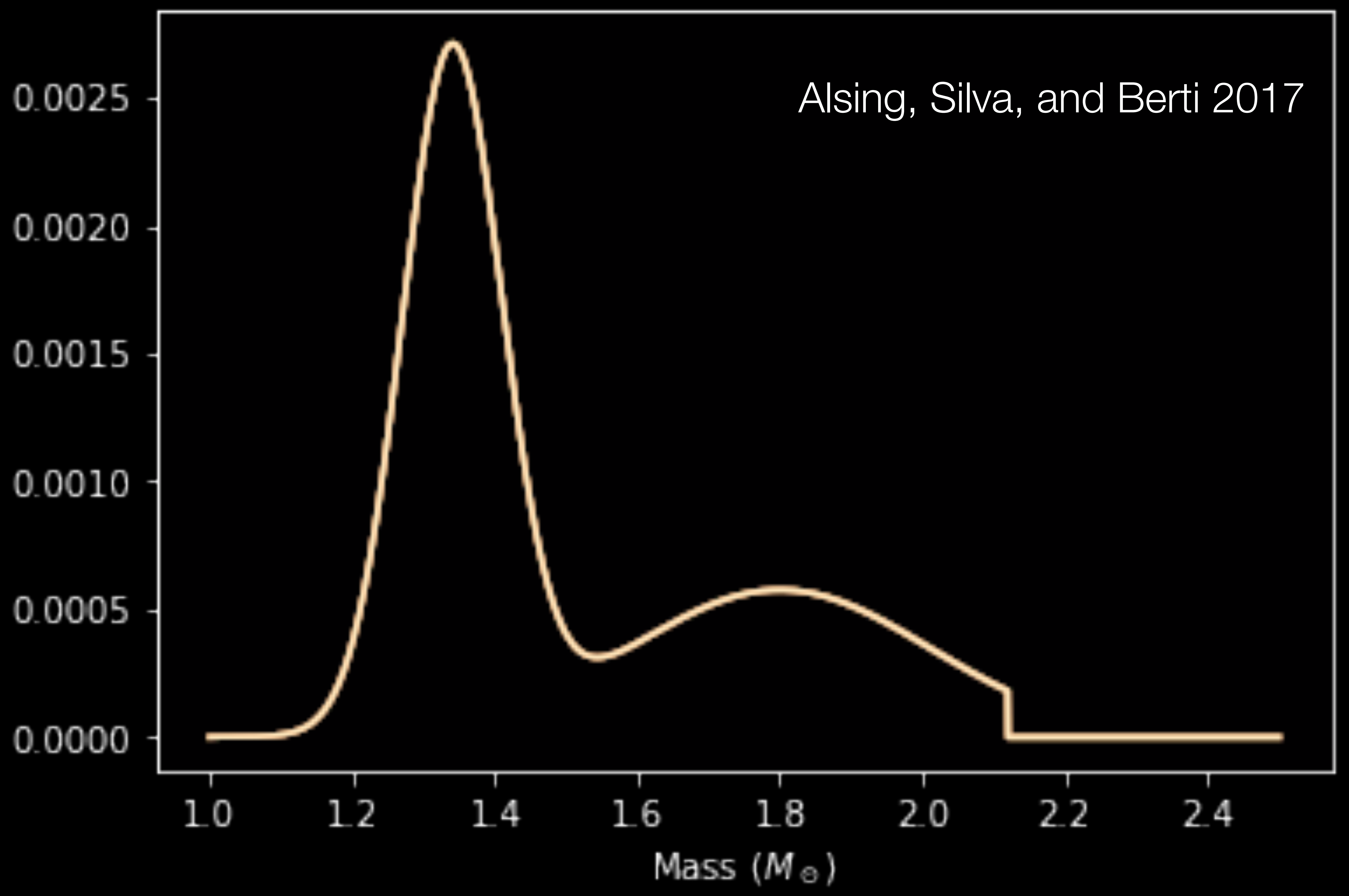
https://dcc.ligo.org/LIGO-P190425/public

Image: Rolf Olsen

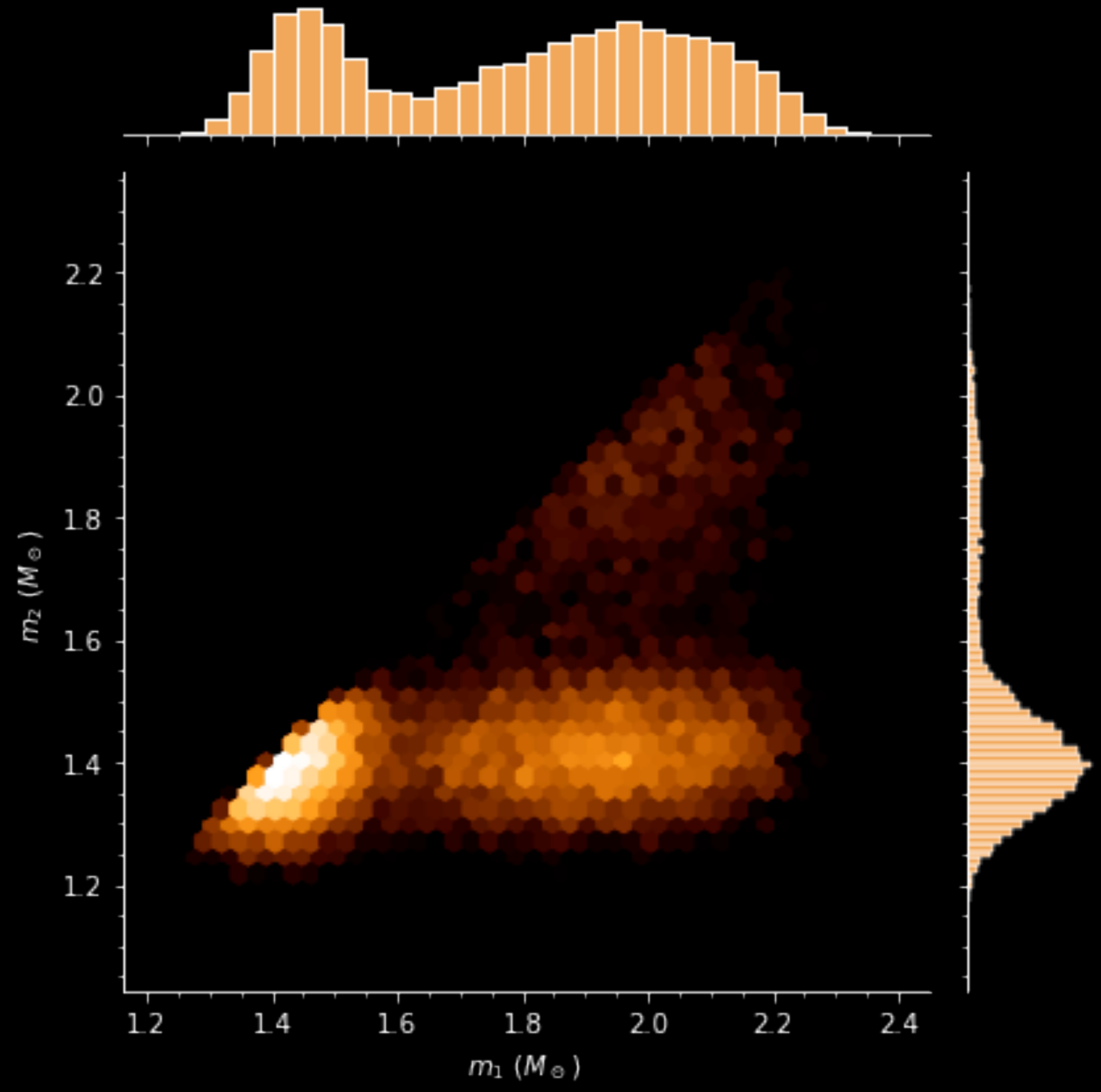
Galactic pulsar mass range



http://xtreme.as.arizona.edu/NeutronStars/



- Observations of all galactic neutron stars suggest a broad range of birth mass (Tauris et al 2016) and a double-peaked mass distribution (also Antoniadis et al 2016)



Implications for gravitational-wave observation

- independent components following the Alsing et al distribution

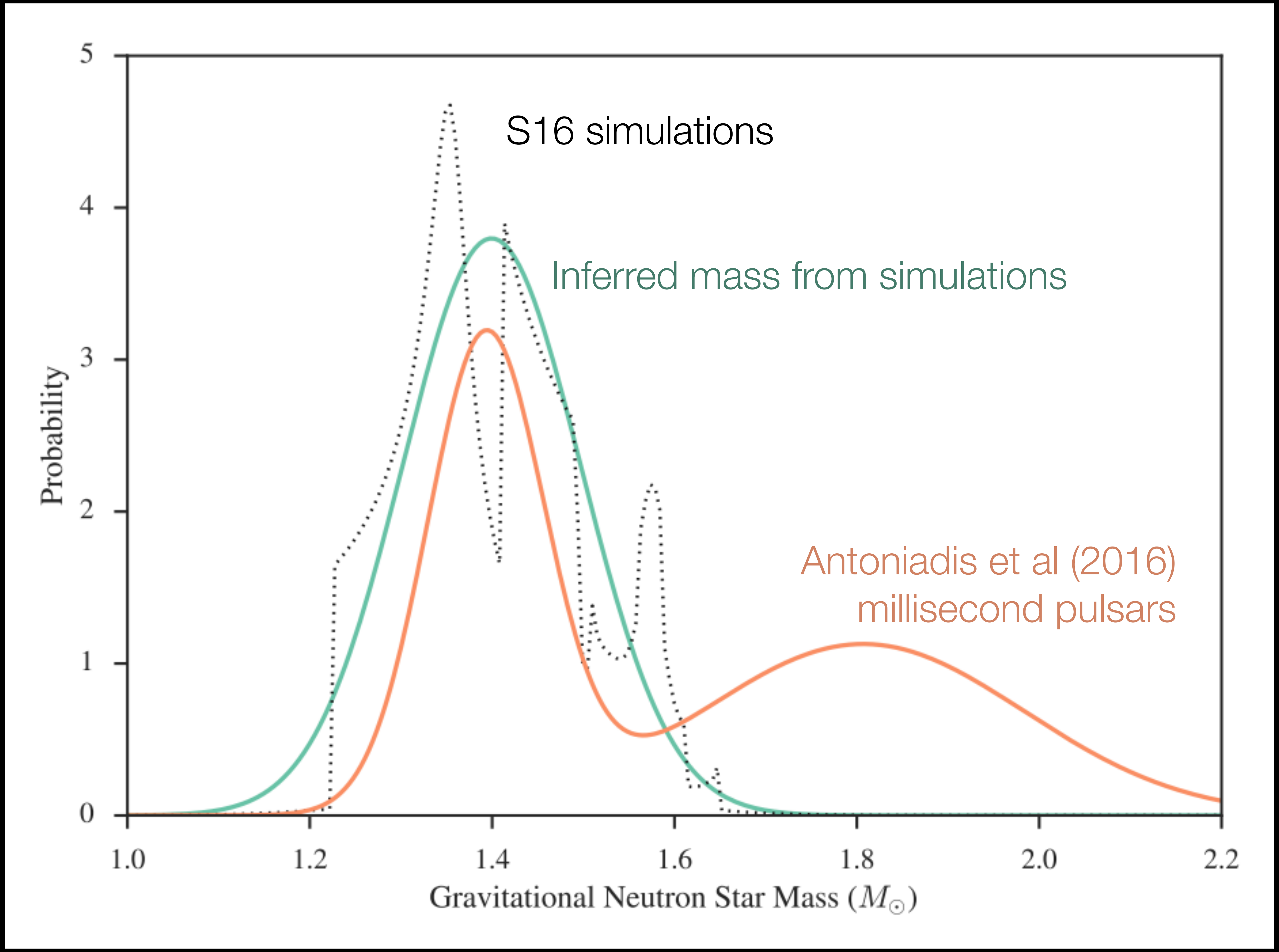
- selected by SNR for Advanced LIGO sensitivity (uniform in volume, random orientation, masses redshifted)

Ignores: recycling, binary interaction… see Farrow et al ApJ, 876, (2018)

Penuliar, Landry, Read, in prep

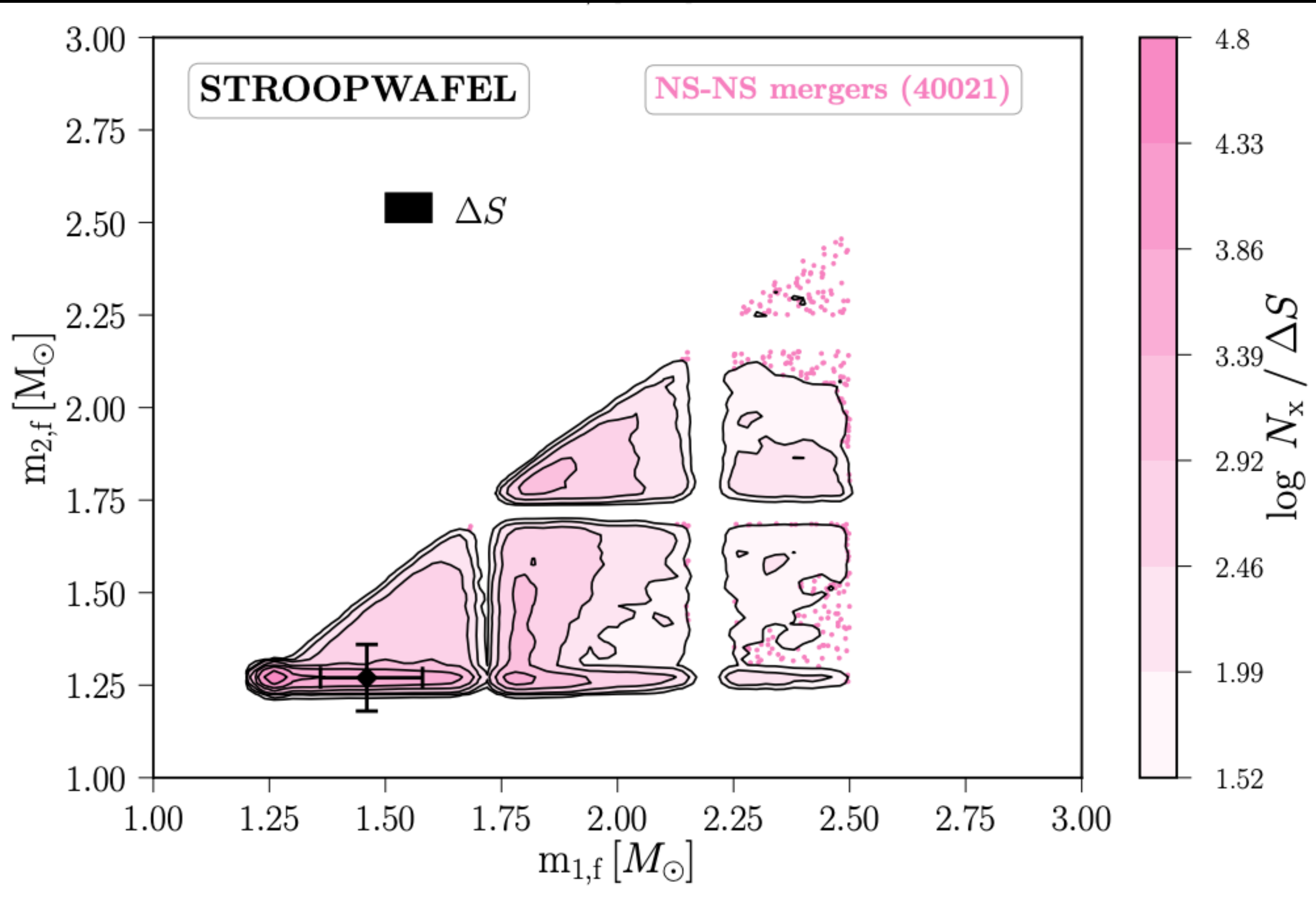
Connections to Stellar Evolution

What masses do supernovae produce?



Raithel et al ApJ V856 (2018)

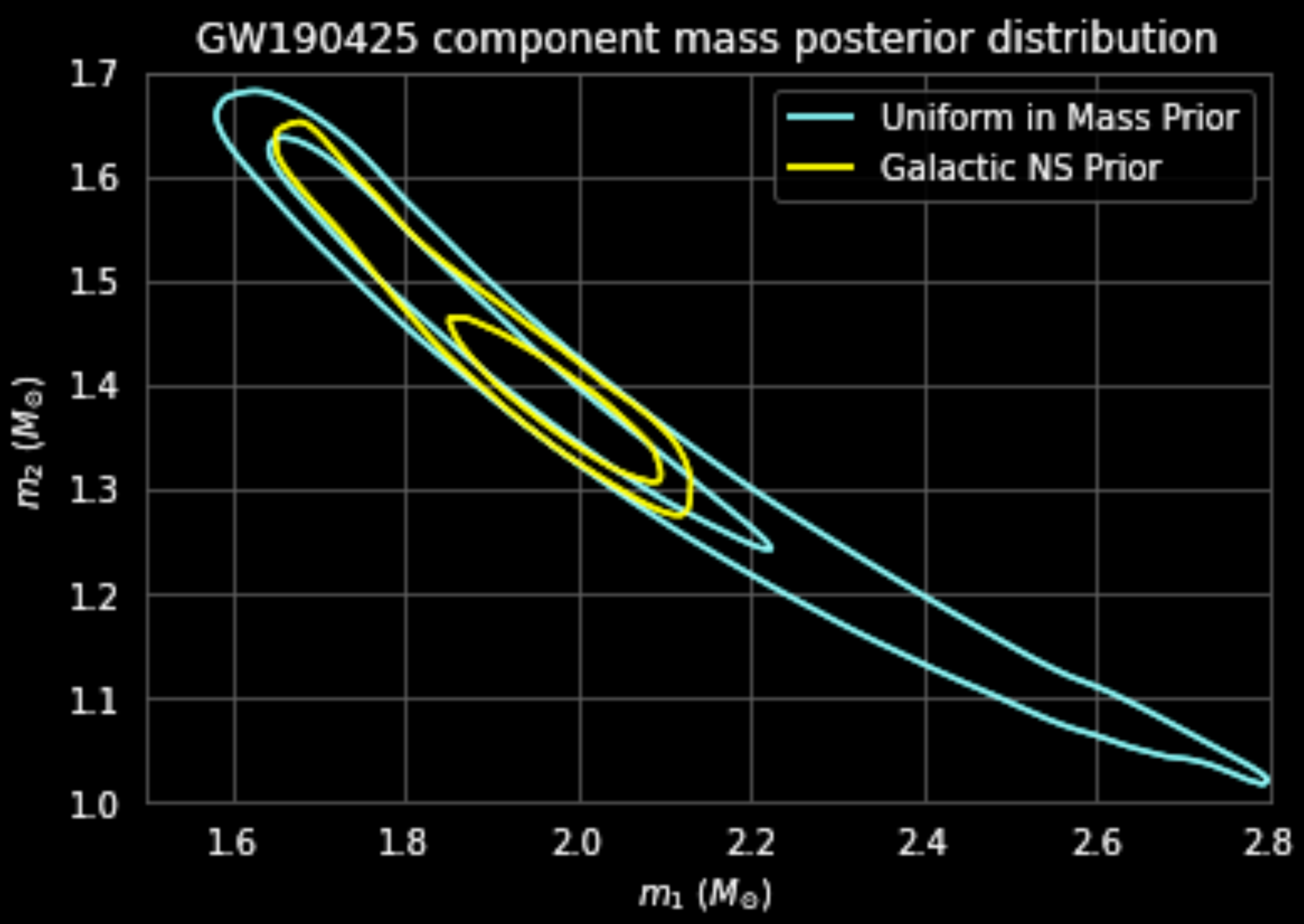
How do massive binaries interact and evolve?

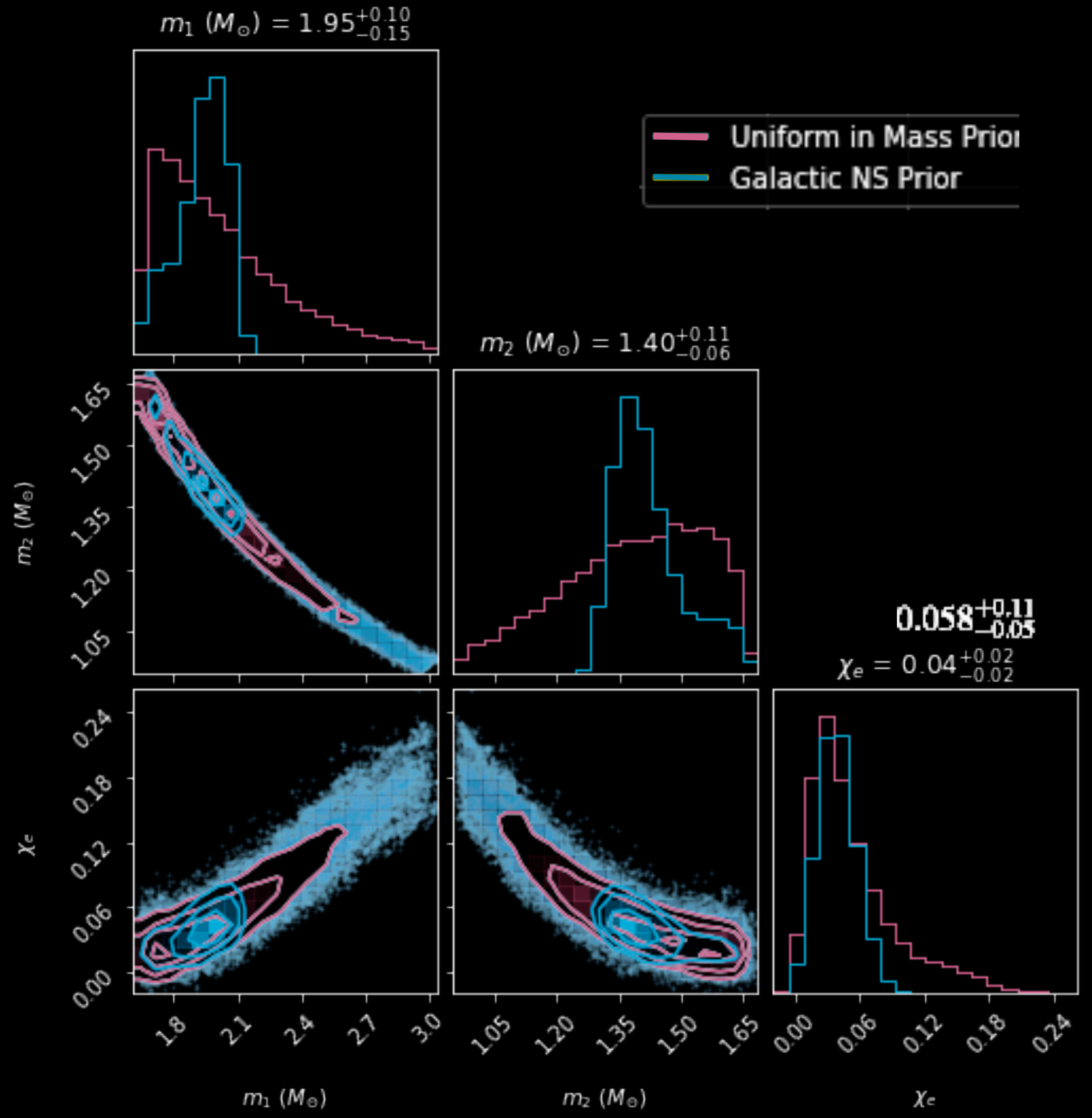


Broekgaarden et al MNRAS 490 (2019)
Population synthesis with COMPAS, STROOPWAFEL

GW190425 in context

- If GW190425 comes from a galactic-like population, it is an unequal-mass binary
- Spin and tidal contributions additionally constraint by this assumption. $\chi_e = 0.04^{+0.02}_{-0.02}$

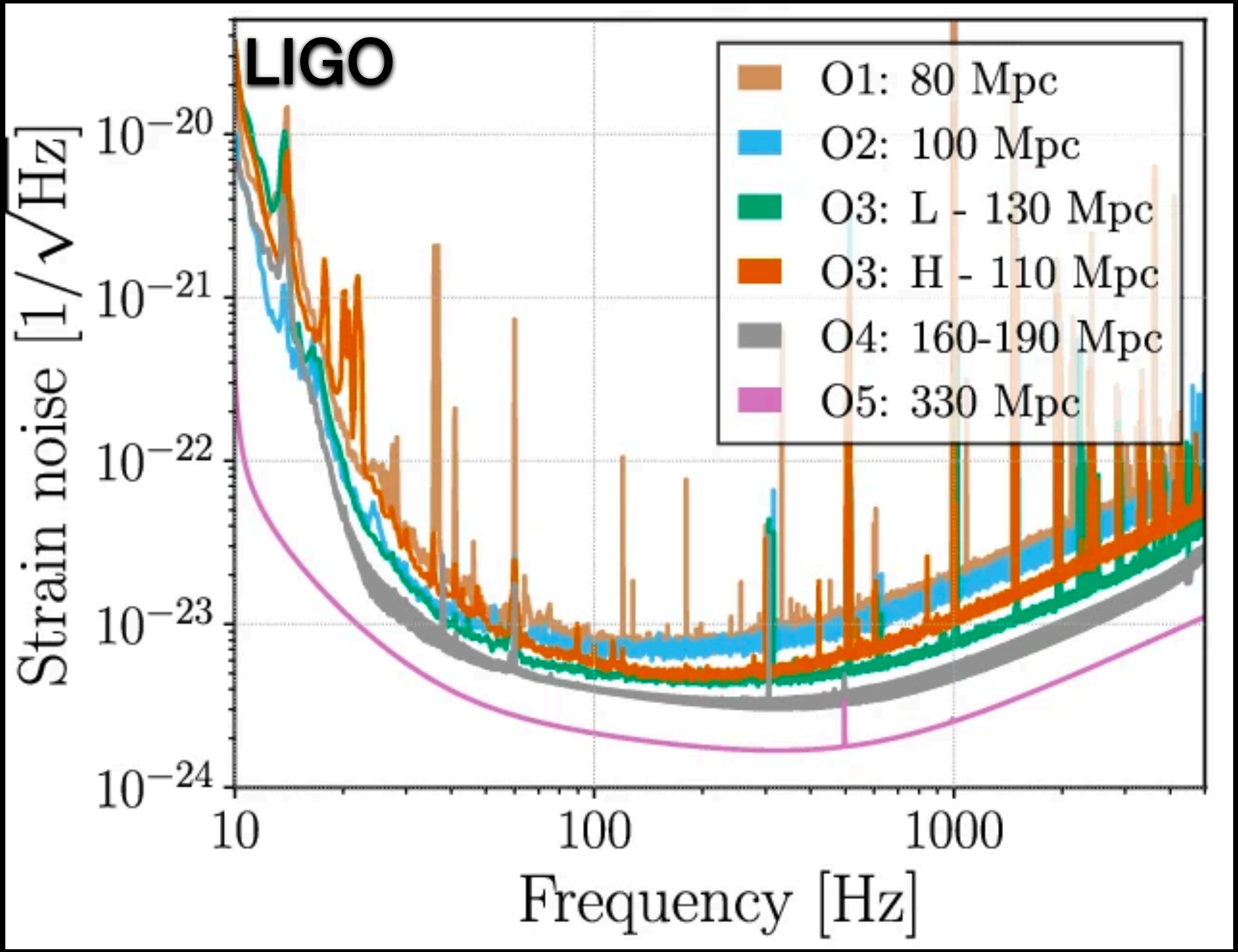




Penuliar, Landry, Read, in prep

Future Prospects

LVK Observing Plan (under development)



Double NS Merger rate

320^{+490}_{-240} Gpc^{-3} yr^{-1}

LIGO/Virgo arXiv:2010.14533

(was 250-2810 Gpc^{-3} yr^{-1})

Astrophys. J. Lett. 882, L24 (2019)

O4 predicted BNS detections:

10^{+52}_{-10} yr^{-1}

O4 predicted NS/BH detections:

1^{+91}_{-1} yr^{-1}

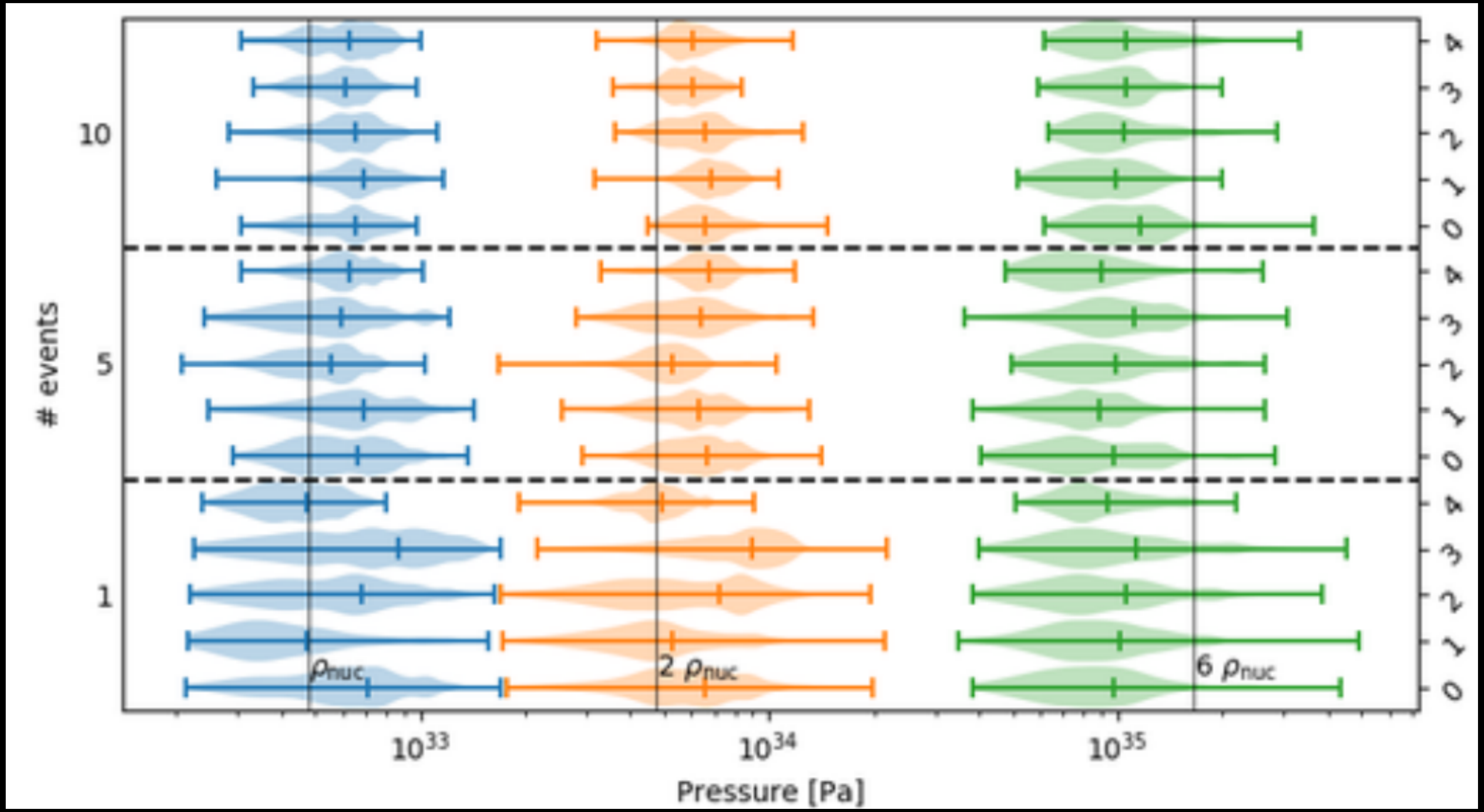
Living Reviews in Relativity; 21:3; (2020)

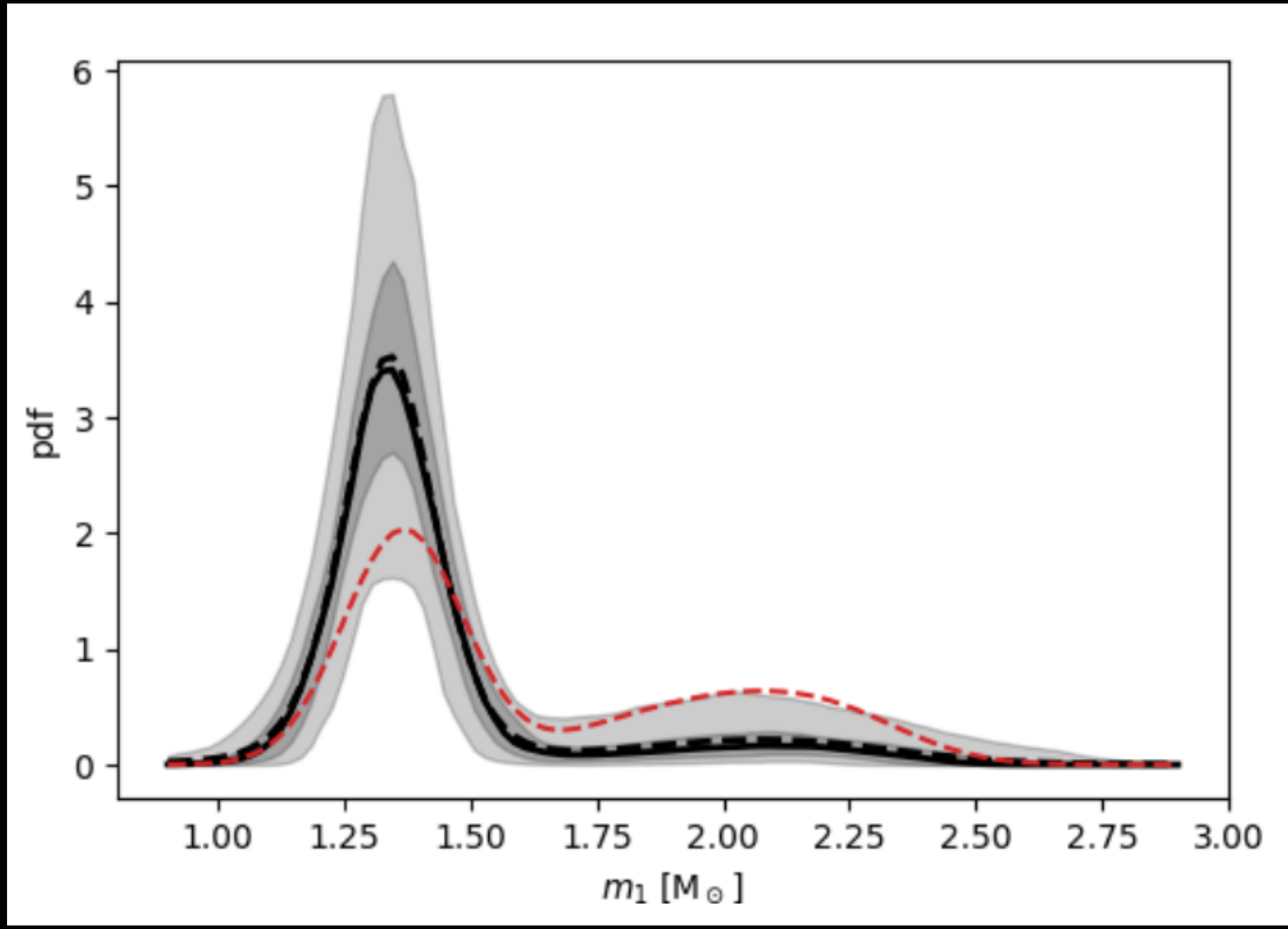
KAGRA/LIGO/Virgo Observing scenarios, Living Reviews in Relativity; 21:3; (2020)

Ten additional BNS observations?

Wysocki et al arXiv:2001.01747

Hierarchical inference; joint GW constraint on EOS and mass distribution





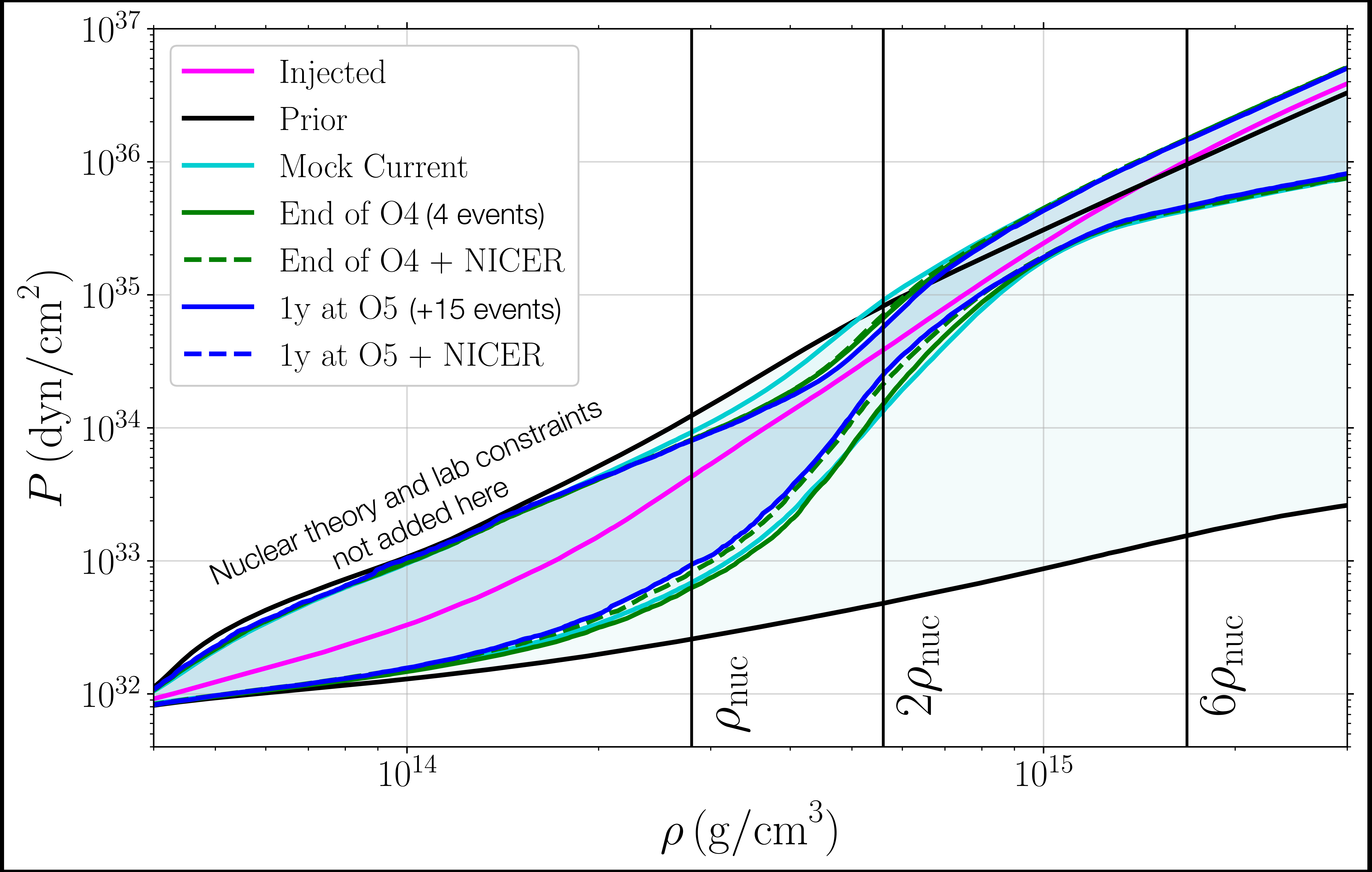
Prospects for Joint LVK and NICER analyses

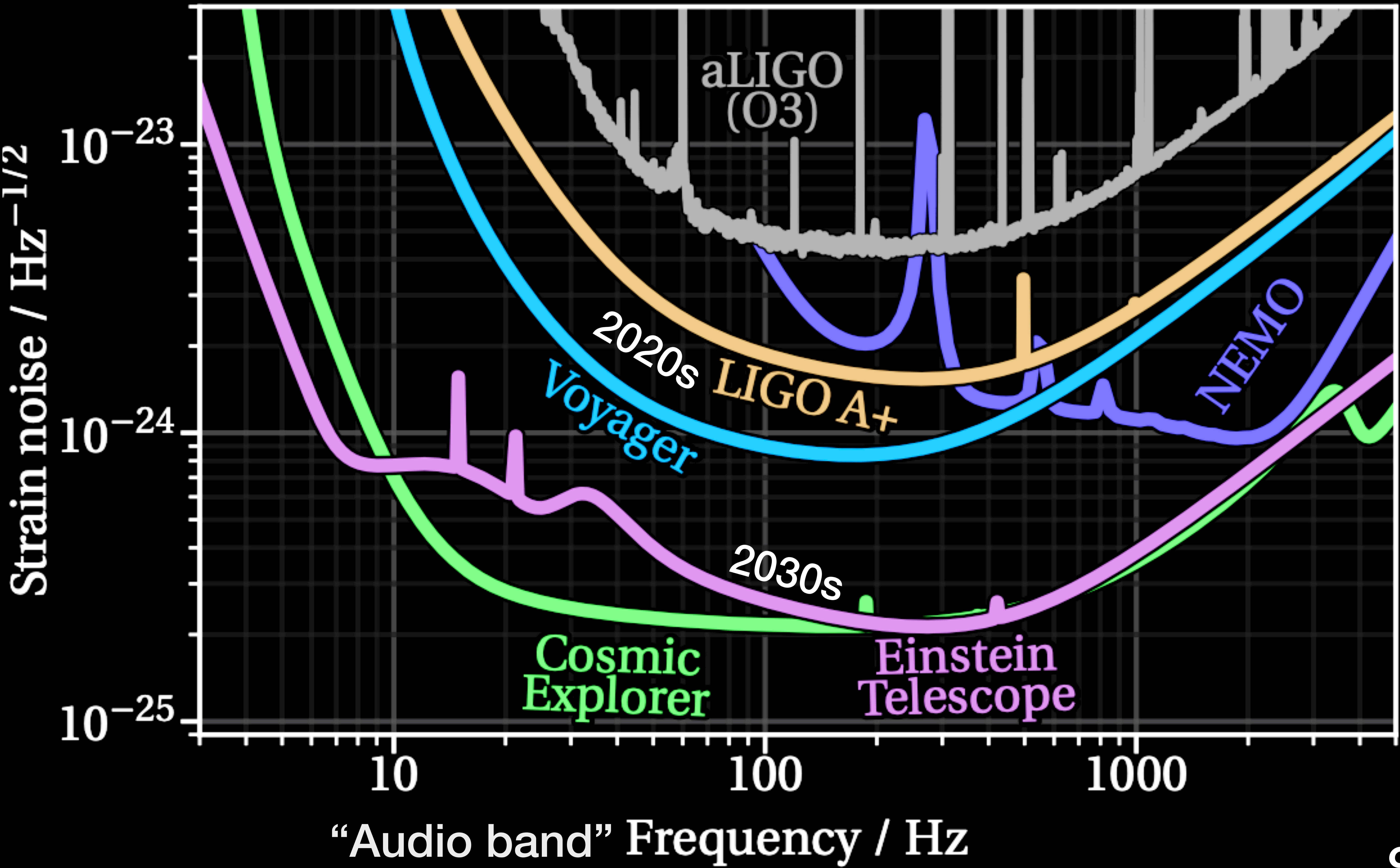
Landry, Essick, Chatziioannou Phys. Rev. D 101, 123007 (2020)

O4:
aLIGO 160 – 190 Mpc,
AdV 90 – 120 Mpc,
KAGRA 25 – 130 Mpc

O5:
aLIGO 330 Mpc,
AdV 150 – 260 Mpc,
KAGRA 130+ Mpc
(LIGO-India join in 2025)

Observing scenarios, Living Reviews in Relativity; 21:3; (2020)

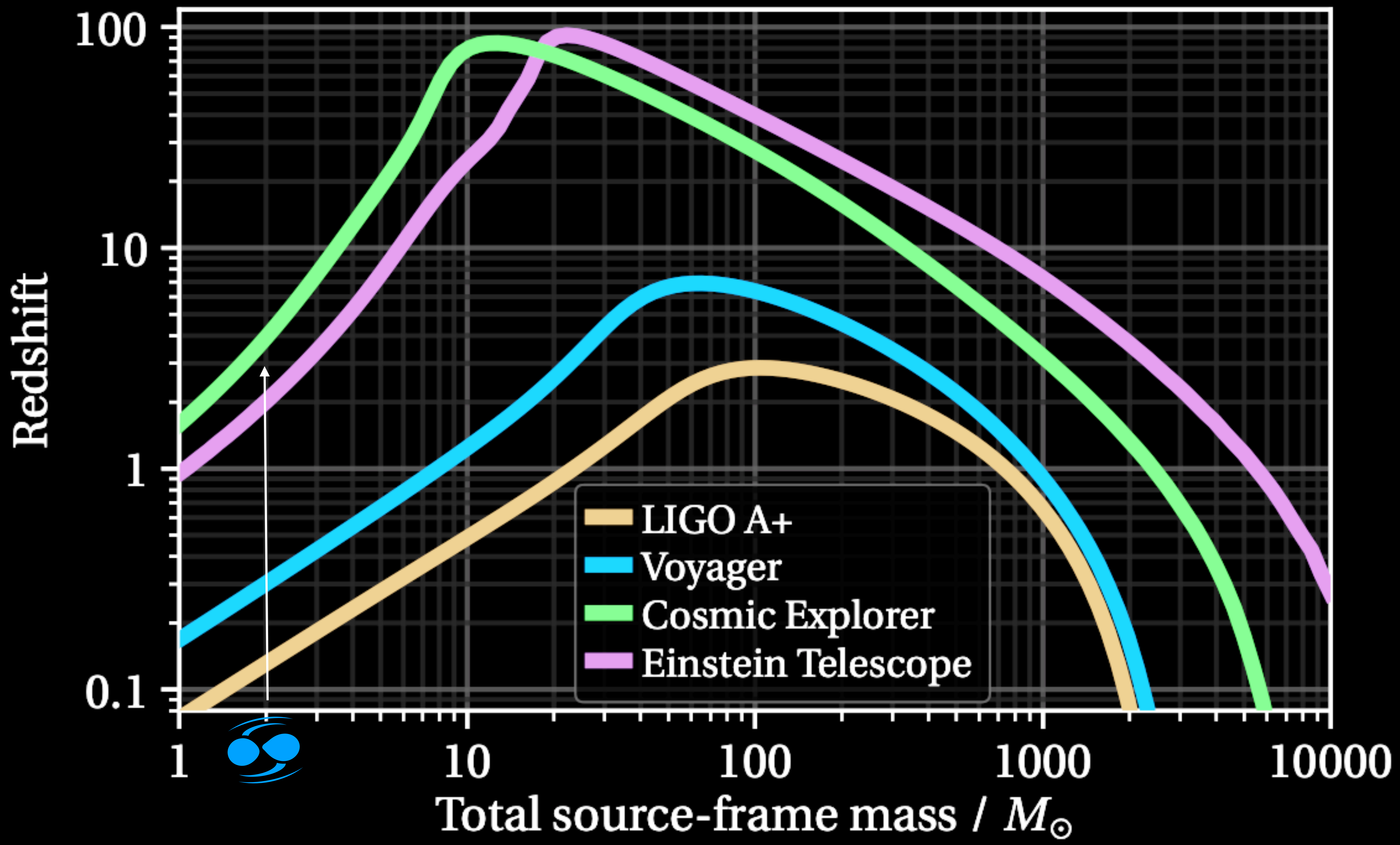




COSMIC EXPLORER

E. Hall, MIT

Observatory reach



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

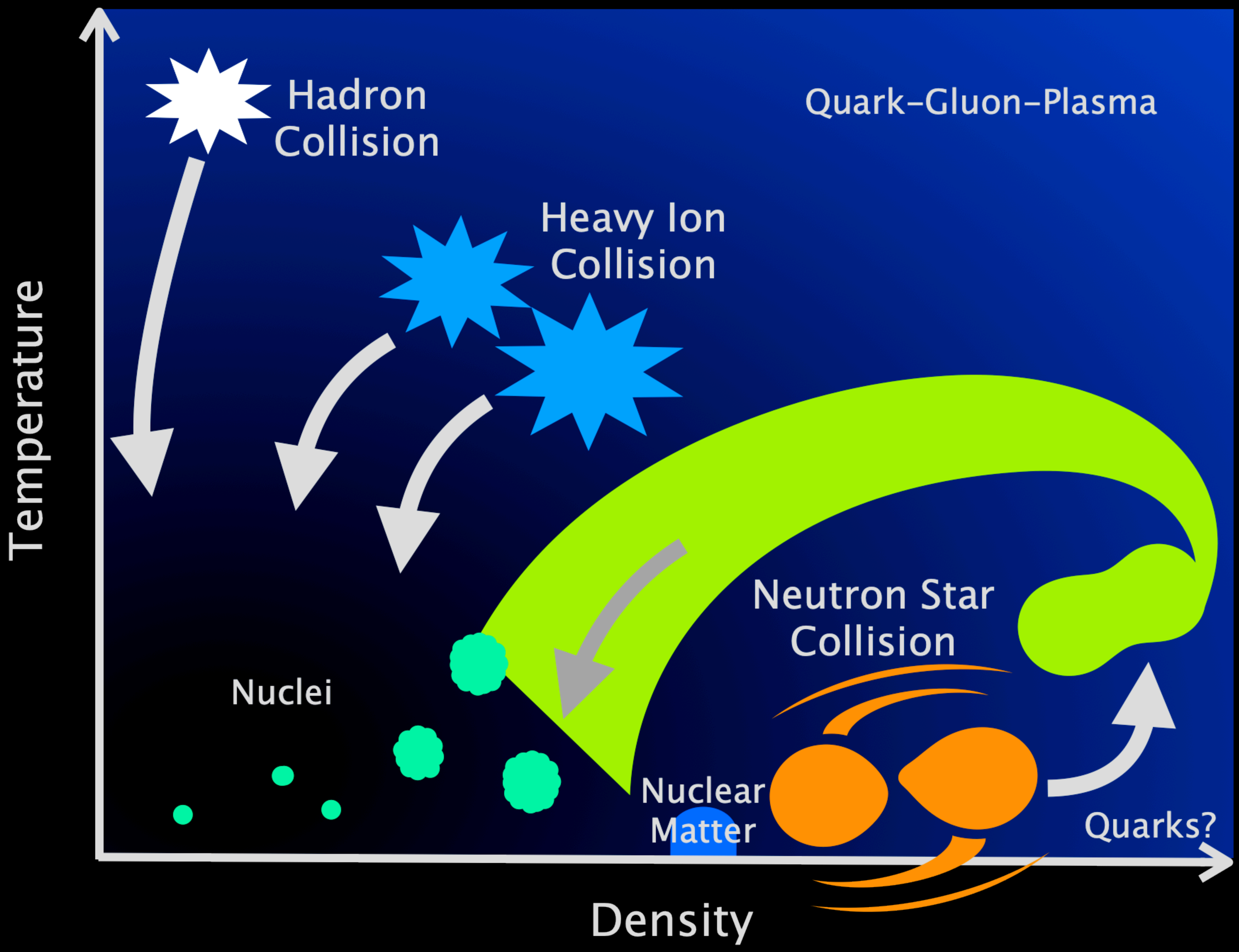
CE DCC document T2000035

Cosmic Explorer Science Goals

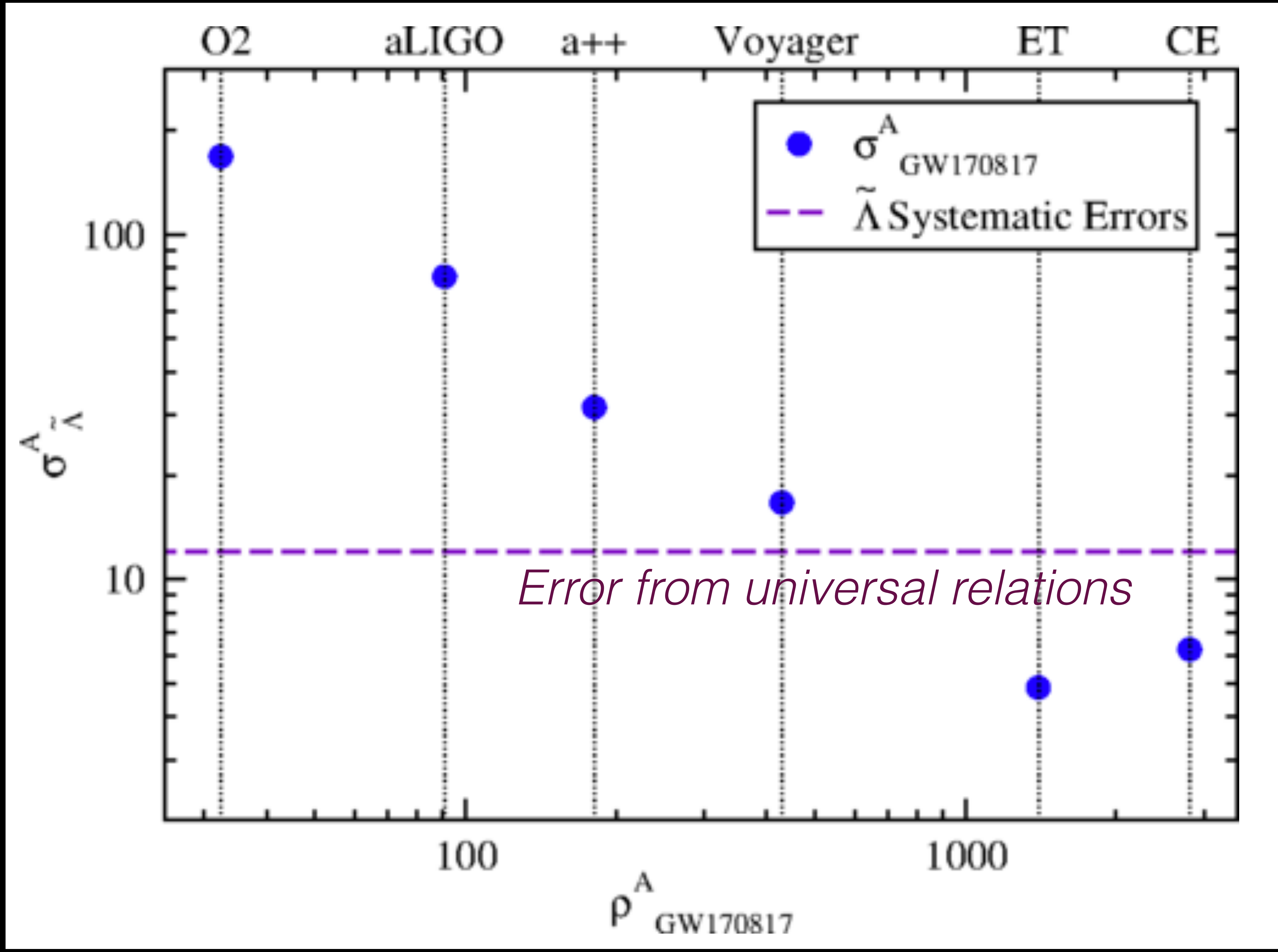
- Explore new regions in the phase diagram of quantum chromodynamics;

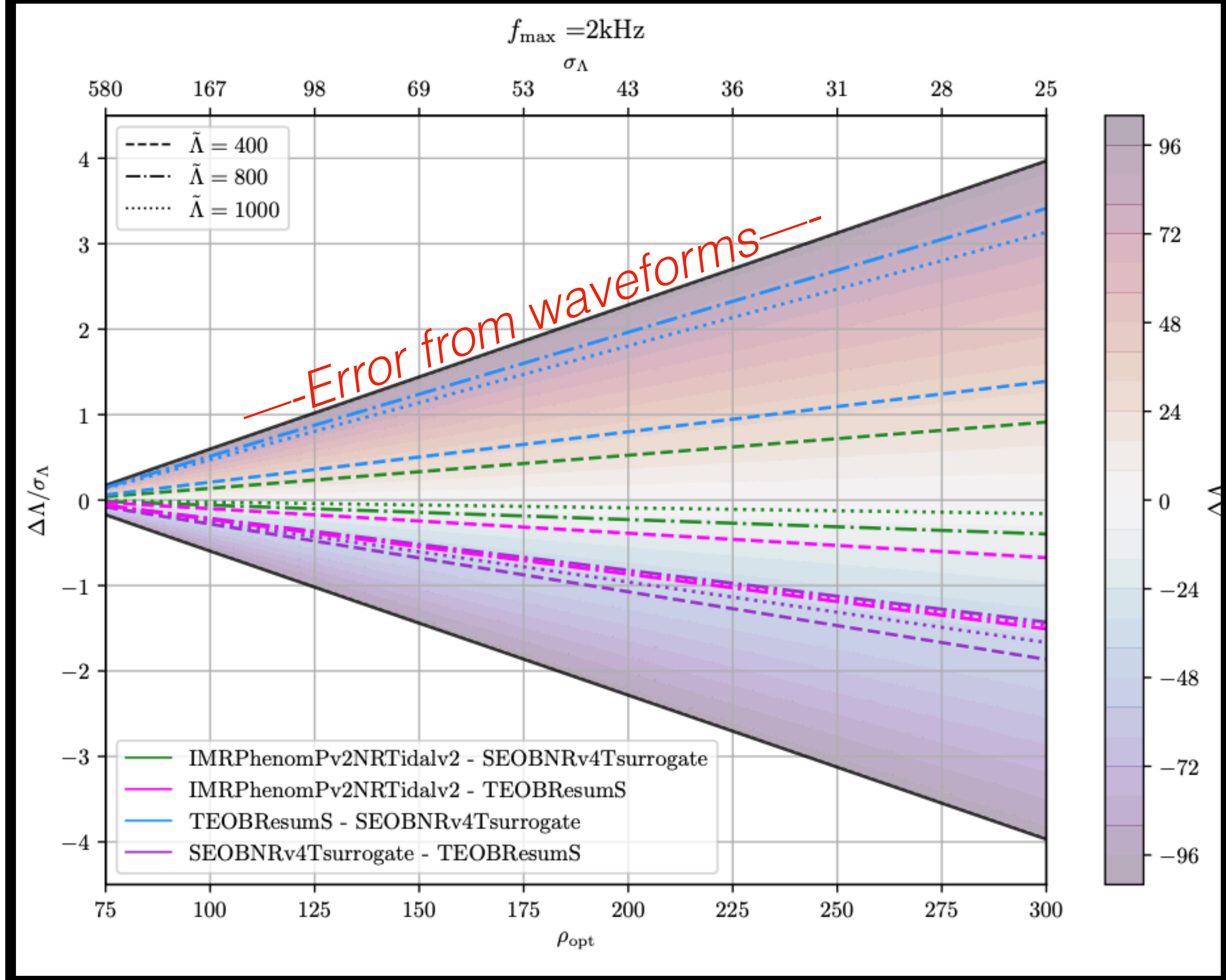
- Map heavy element nucleosynthesis in the universe through counterpart kilonovae and distant mergers;

- Reveal the central engine for the highly relativistic jets that power short gamma-ray bursts.



Modeling accuracy requirements





Carson et al Phys. Rev. D 99, 083016

*Gamba et al Phys. Rev. D **103**, 124015*

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

Cosmic Explorer Horizon Study Draft
https://dcc.cosmicexplorer.org/public/0163/P2100003/003/ce-horizon-study.pdf

https://tinyurl.com/cosmicexplorer