Studying neutron stars with gravitational waves

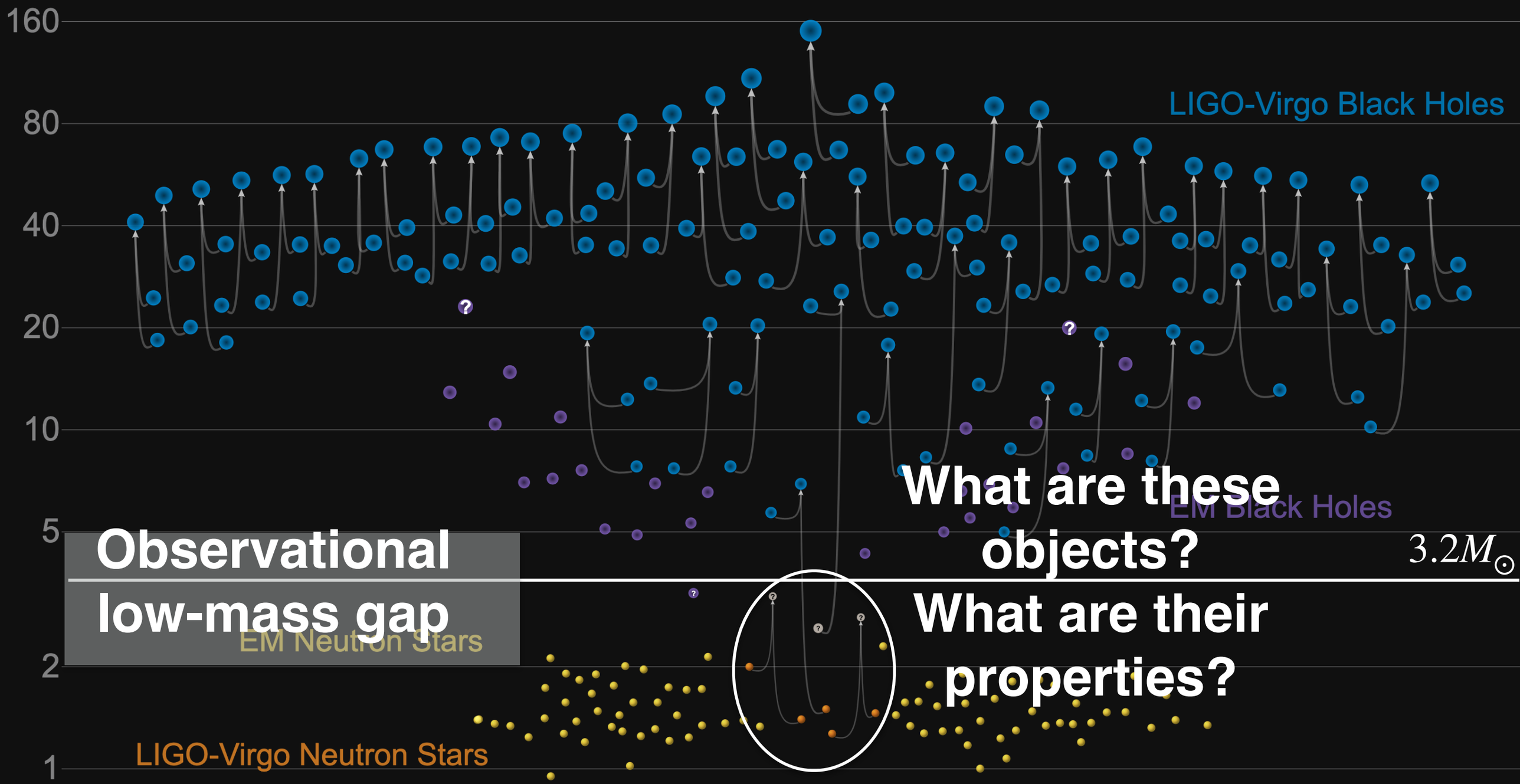
Katerina Chatziioannou
Caltech

FAIRness 2022
May 24, 2022

Image: Aurore Simonnet

Masses in the Stellar Graveyard

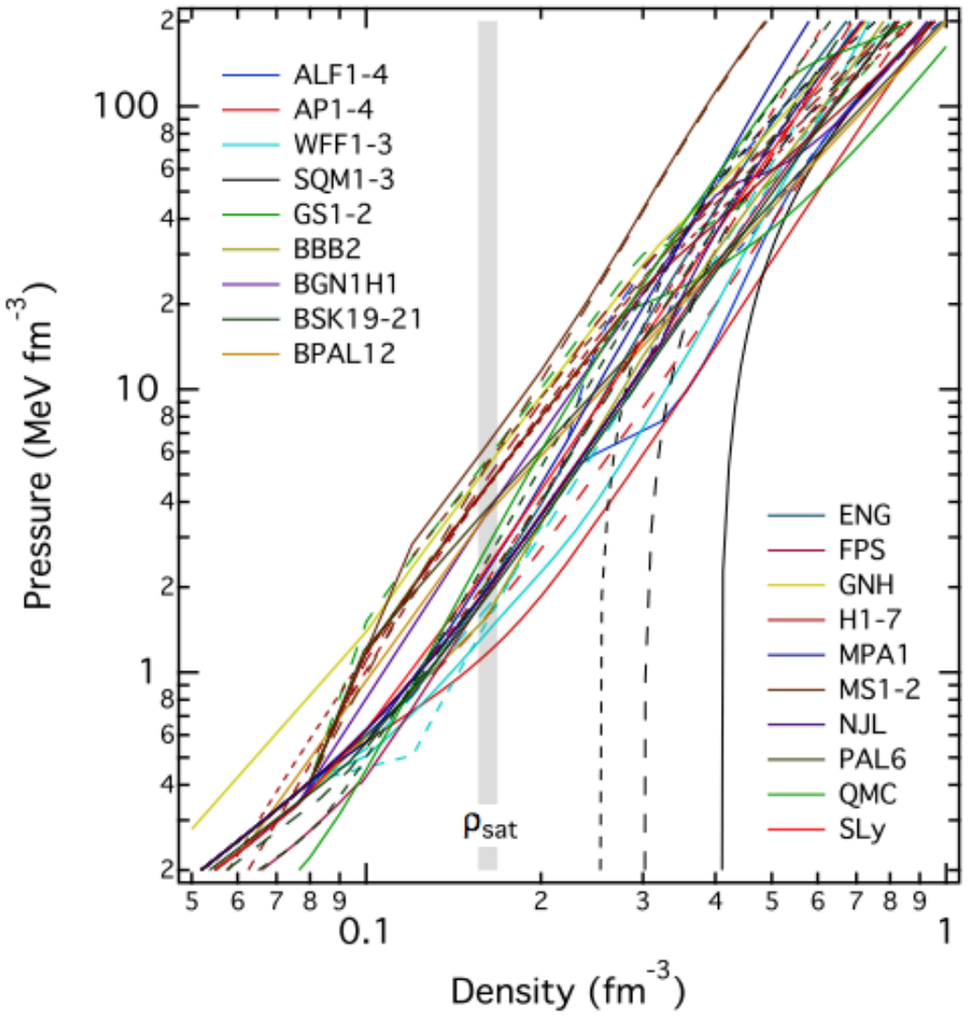
in Solar Masses



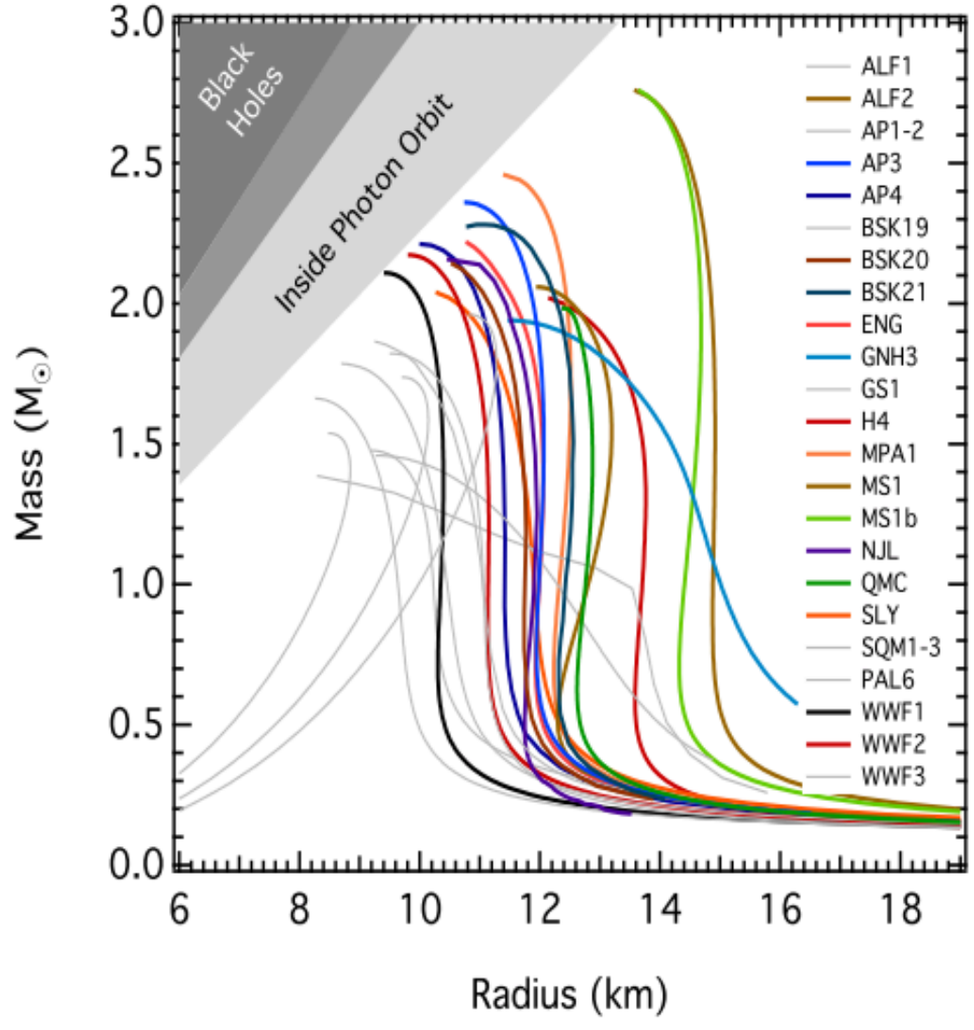
LIGO-Virgo | Frank Elavsky, Aaron Geller | Northwestern

Unique equation of state

Microscopic **properties of dense matter in beta equilibrium**

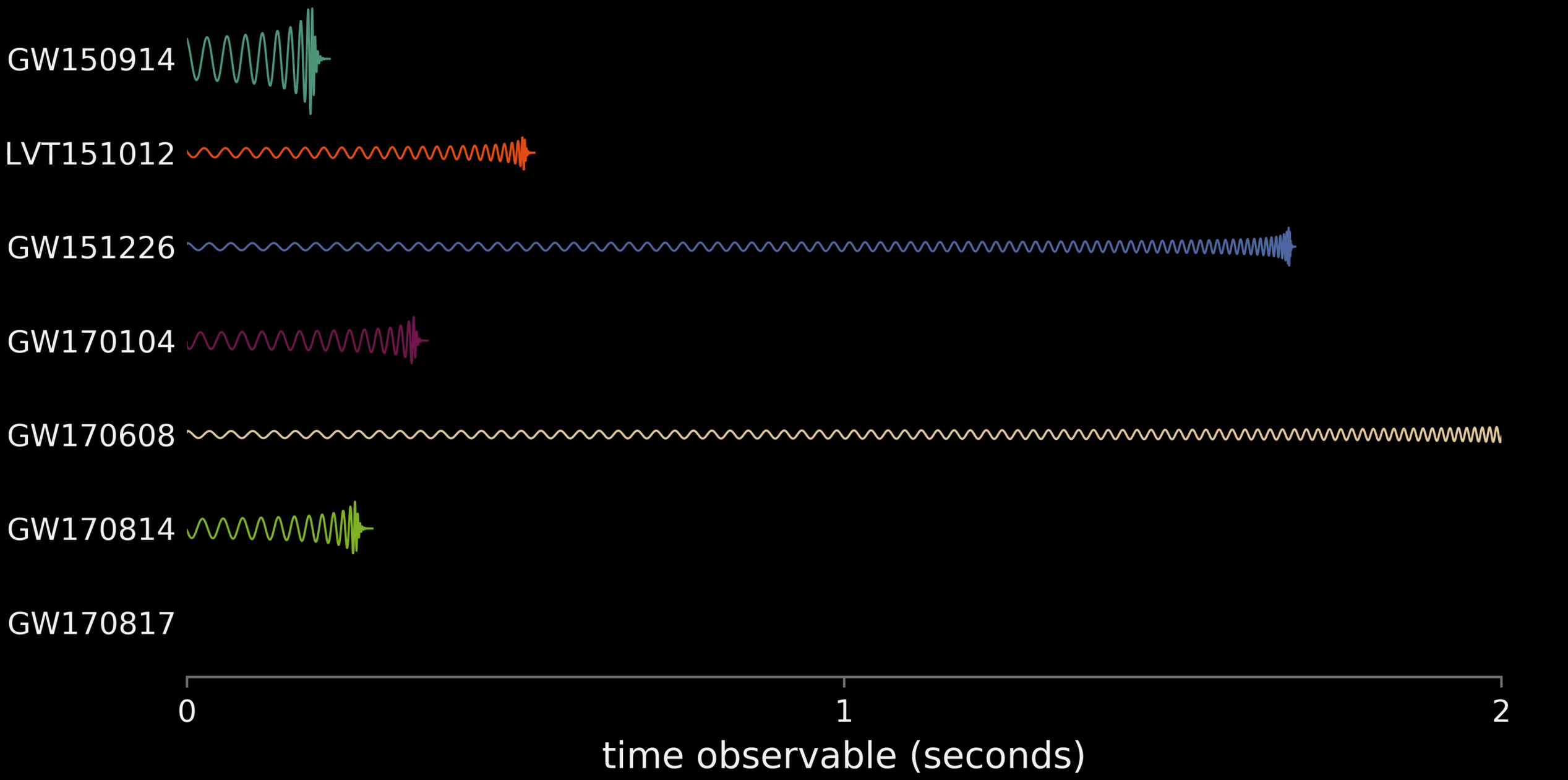


Macroscopic **properties of compact objects**

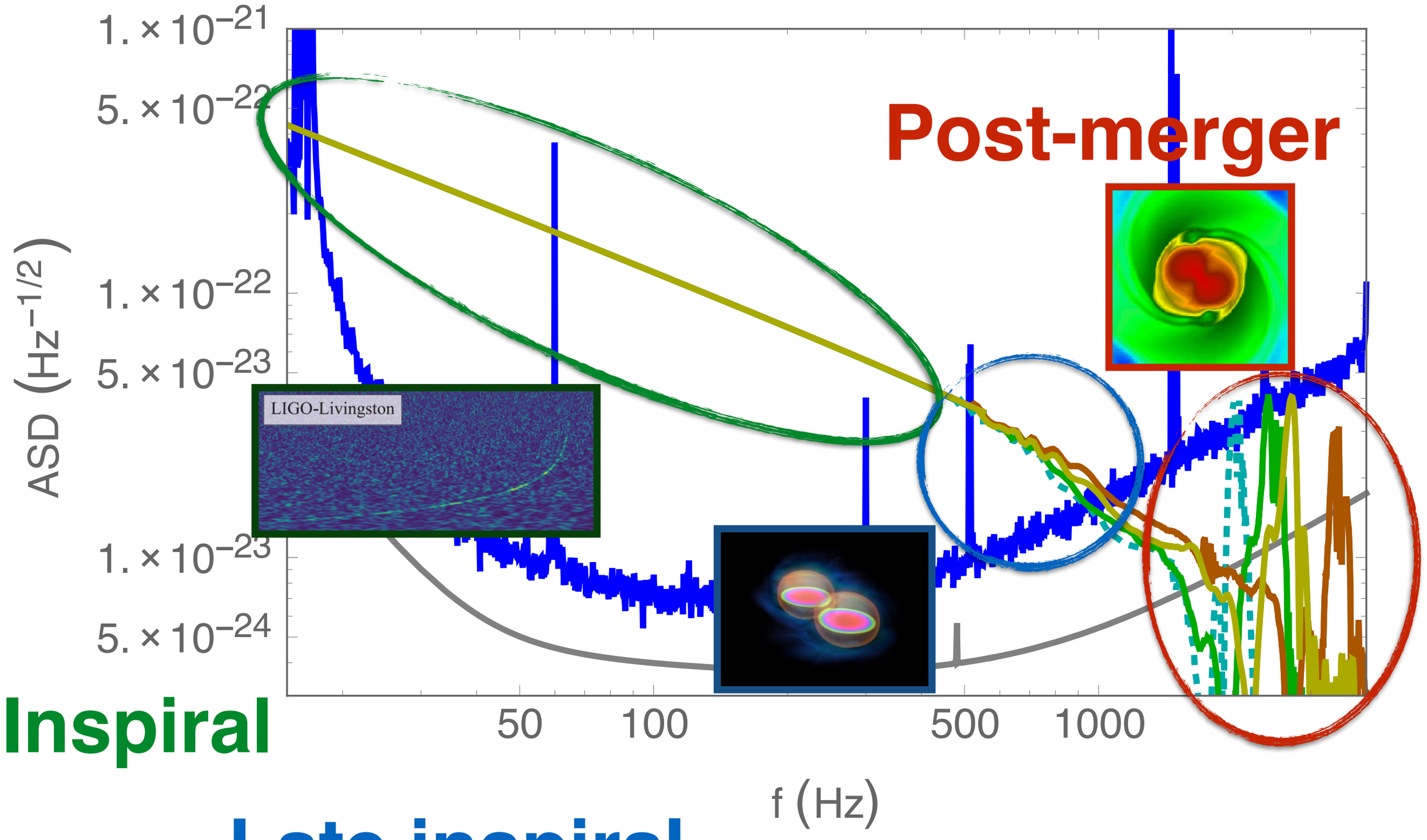


Joint study over 18 orders of magnitude

Ozel, Freire (arxiv:1603.02698)

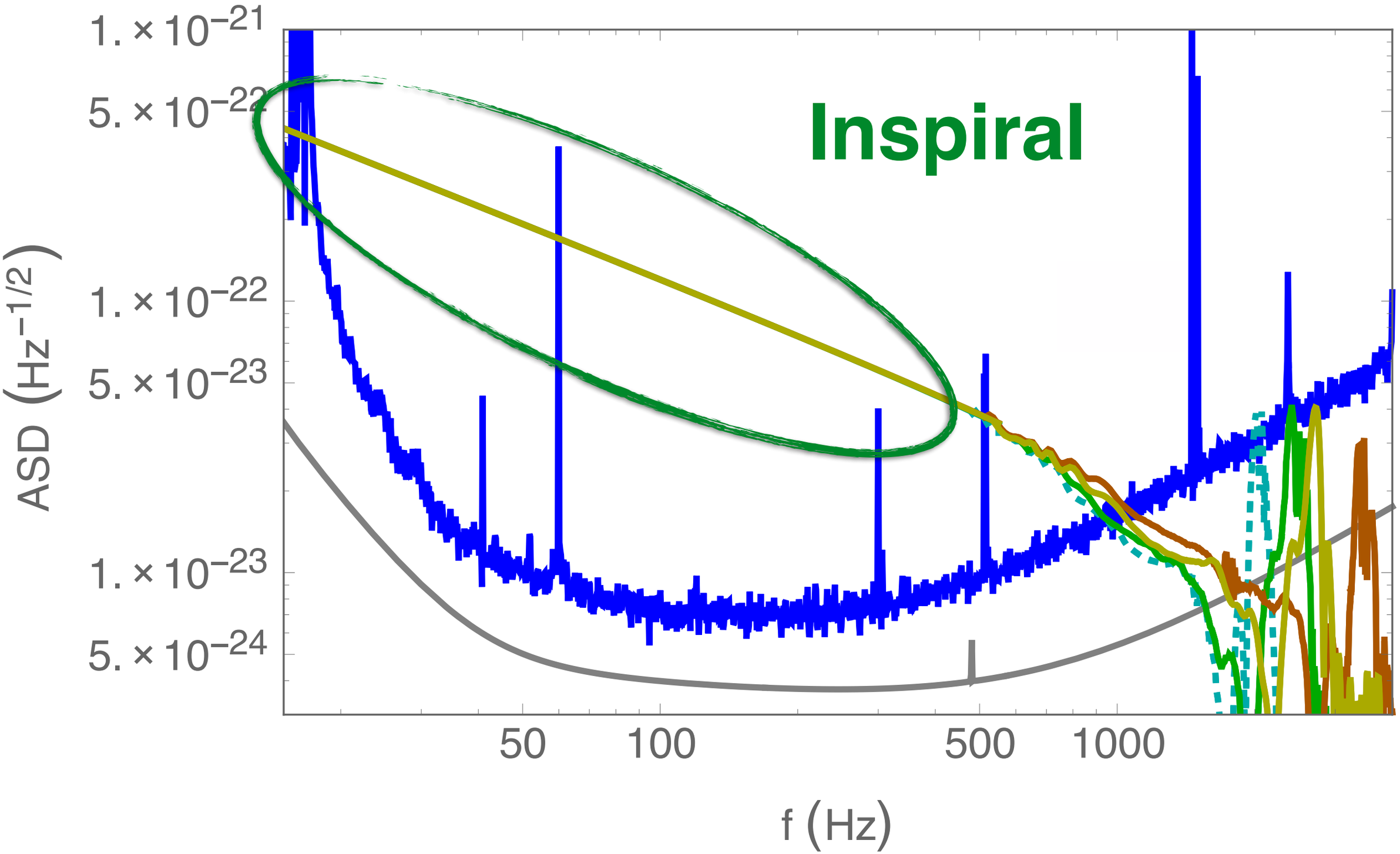

GW150914
LVT151012
GW151226
GW170104
GW170608
GW170814
GW170817
0
1
2
time observable (seconds)
LIGO/University of Oregon/Ben Farr

Anatomy of a BNS coalescence



Data Visualization by J. Read
Numerical data by Tim Dietrich (AEI/FSU/BAM Collaboration)
PRD 95 124006, PRD 95 024029

Anatomy of a BNS coalescence: Inspiral

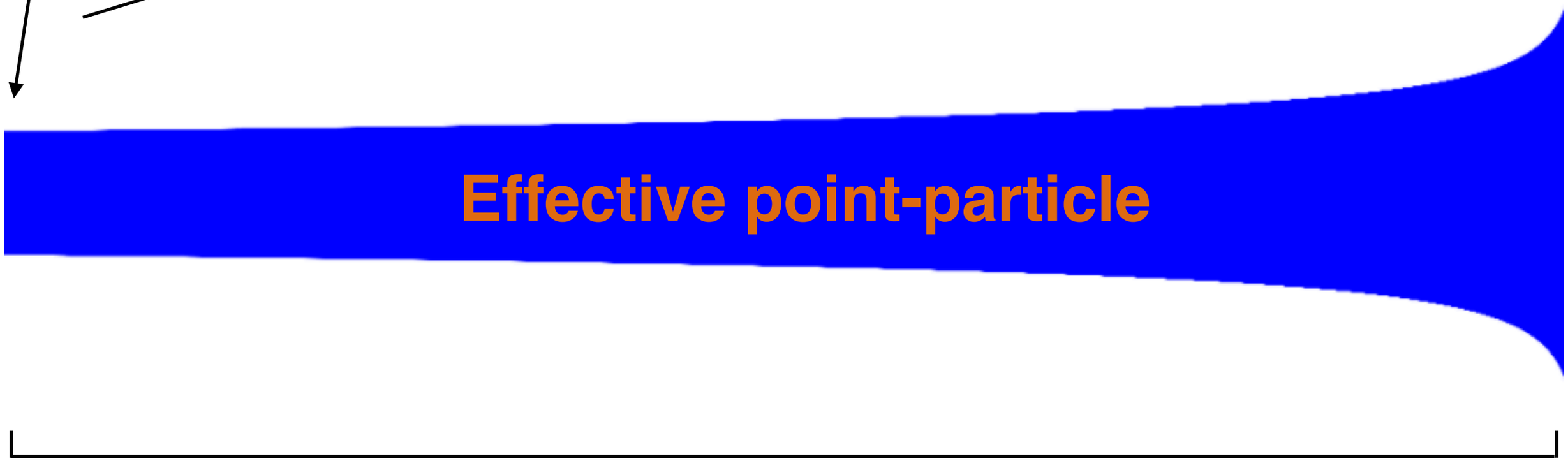


Data Visualization by J. Read
Numerical data by Tim Dietrich (AEI/FSU/BAM Collaboration)
Phys. Rev. D95(12):124006 and Phys. Rev. D95(2):024029

Inspiral

~400km apart

10,000 cycles

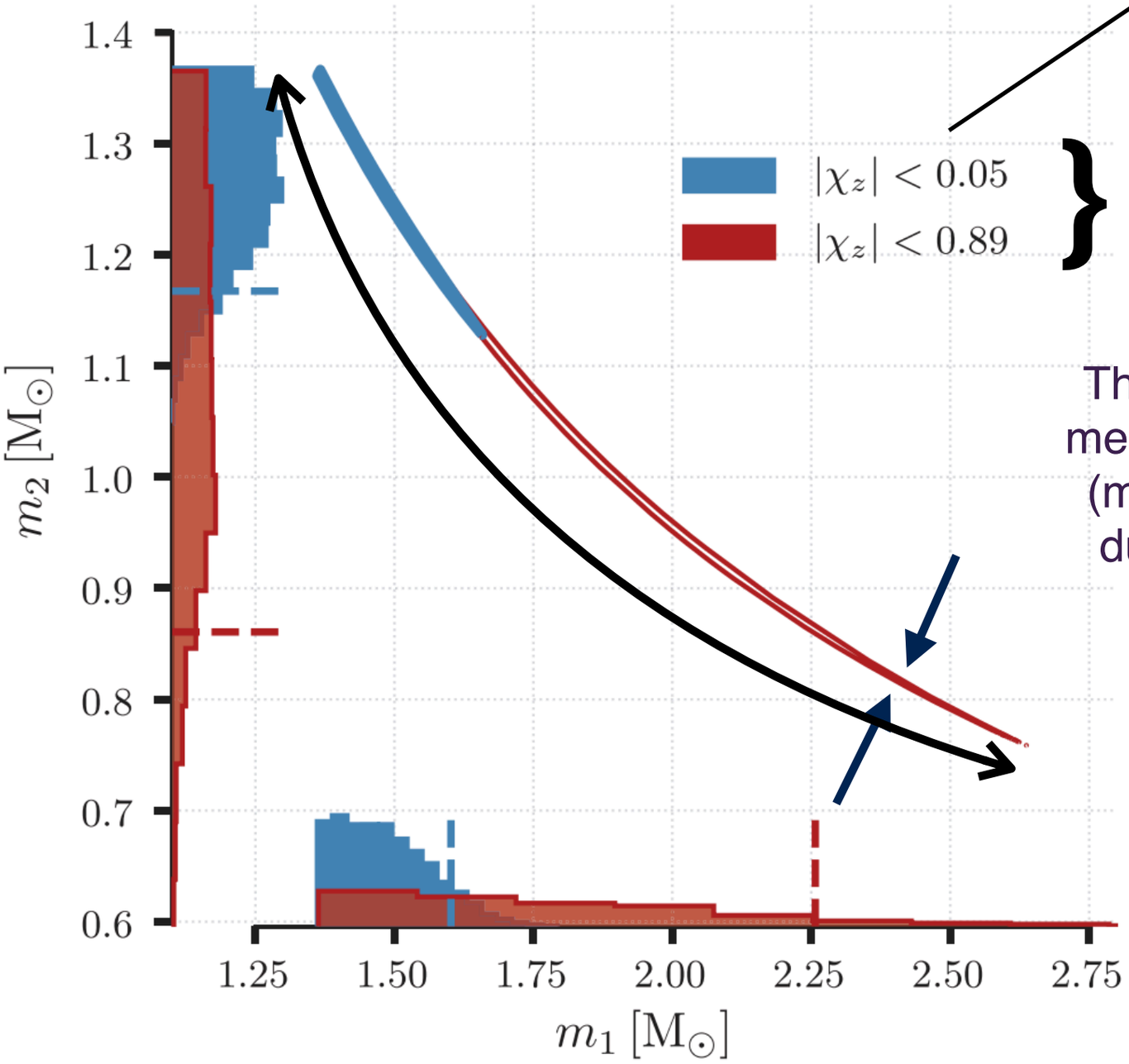


10 mins

GW170817 masses

The mass ratio is measured less well

$$\chi \sim 0.4 \frac{1\mathrm{ms}}{T}$$



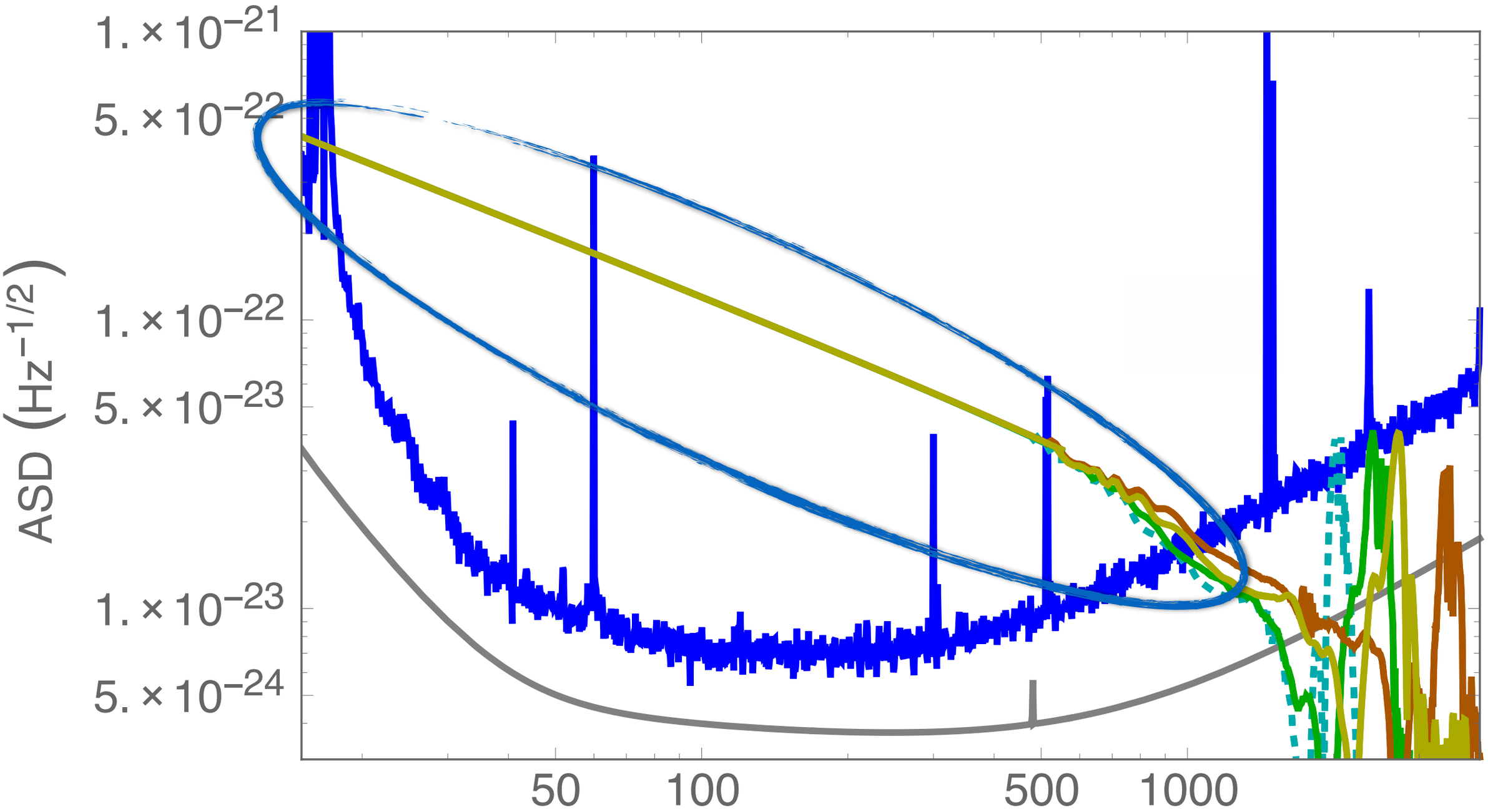
The mass ratio is correlated with the spin

The chirp mass is measured very well (main uncertainty due to distance)

LVC (arxiv:1710.05832)

PE: Veitch+ (arxiv:1409.7215)

Anatomy of a BNS coalescence: Late Inspiral



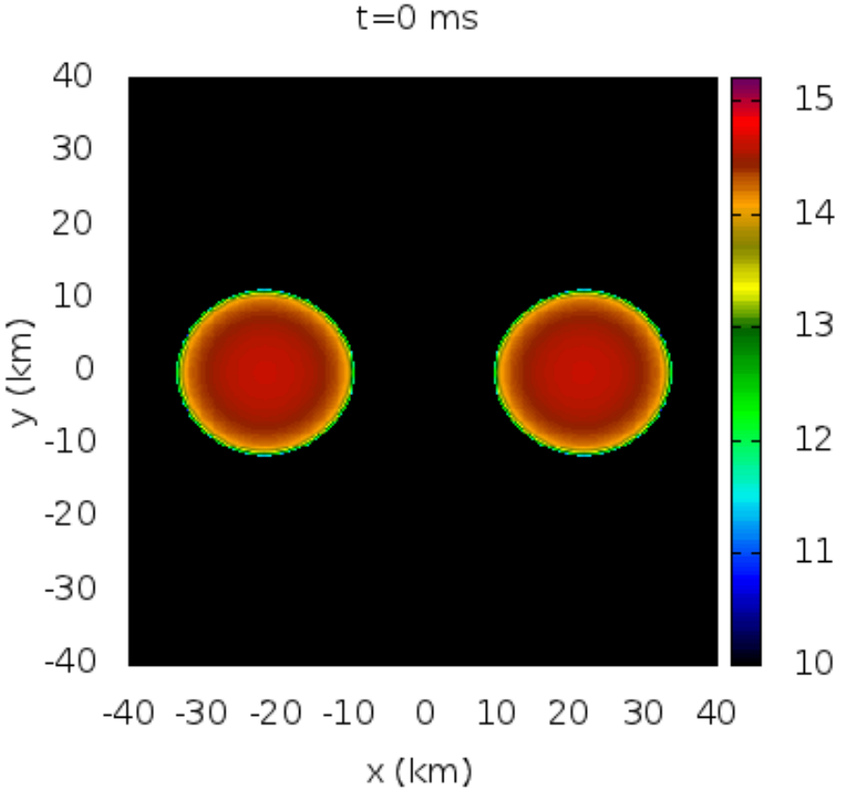
Inspiral+Late inspiral

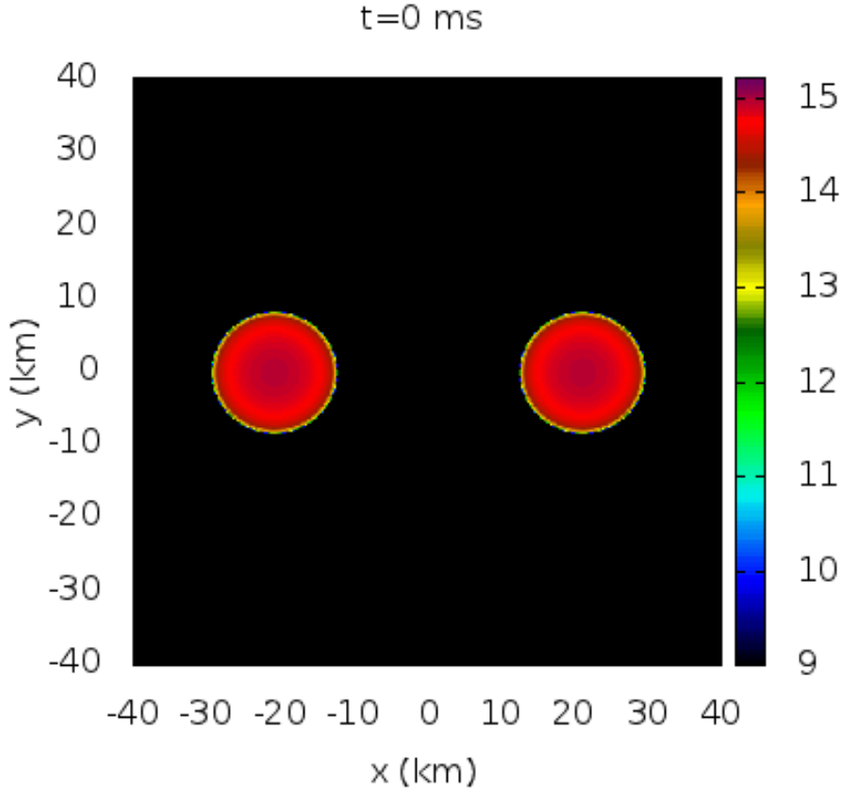
Data Visualization by J. Read
Numerical data by Tim Dietrich (AEI/FSU/BAM Collaboration)
PRD 95 124006, PRD 95 024029

Effect of equation of state

Larger NSs emit energy faster, accelerating the inspiral

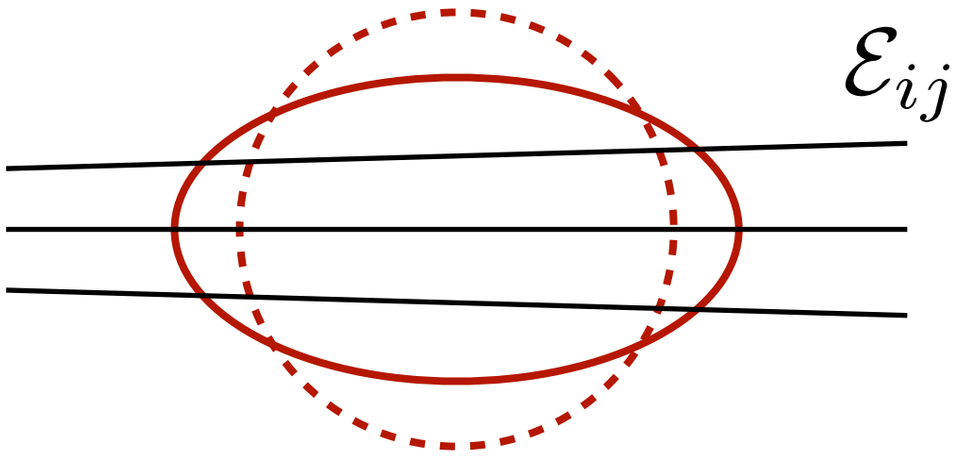
Smaller NSs take longer to merge





Simulations by Kenta Hotokezaka

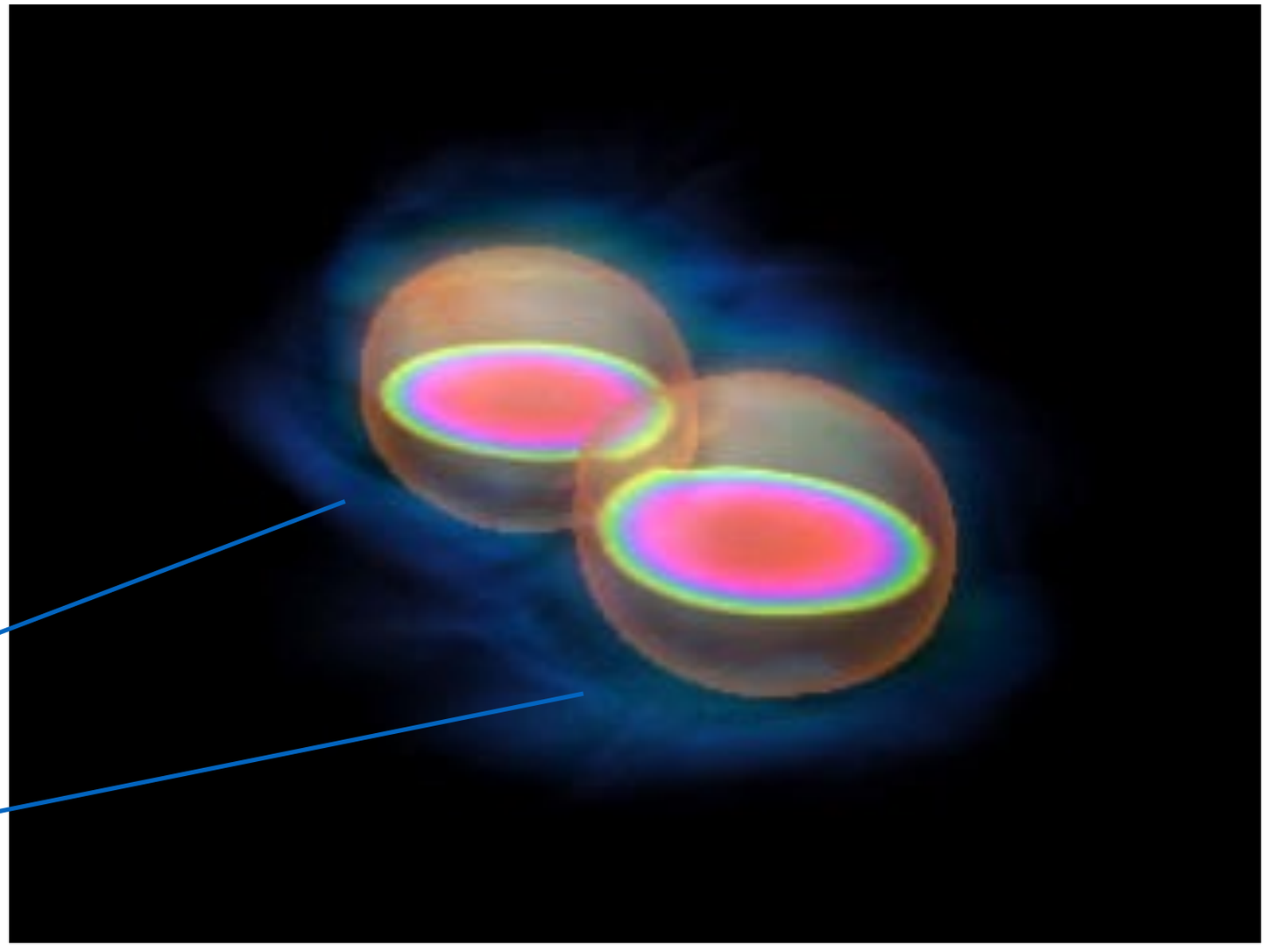
Tidal interactions



Credit: Aaron Zimmerman

Tidal deformability

$$Q_{ij} = -\lambda \mathcal{E}_{ij}$$



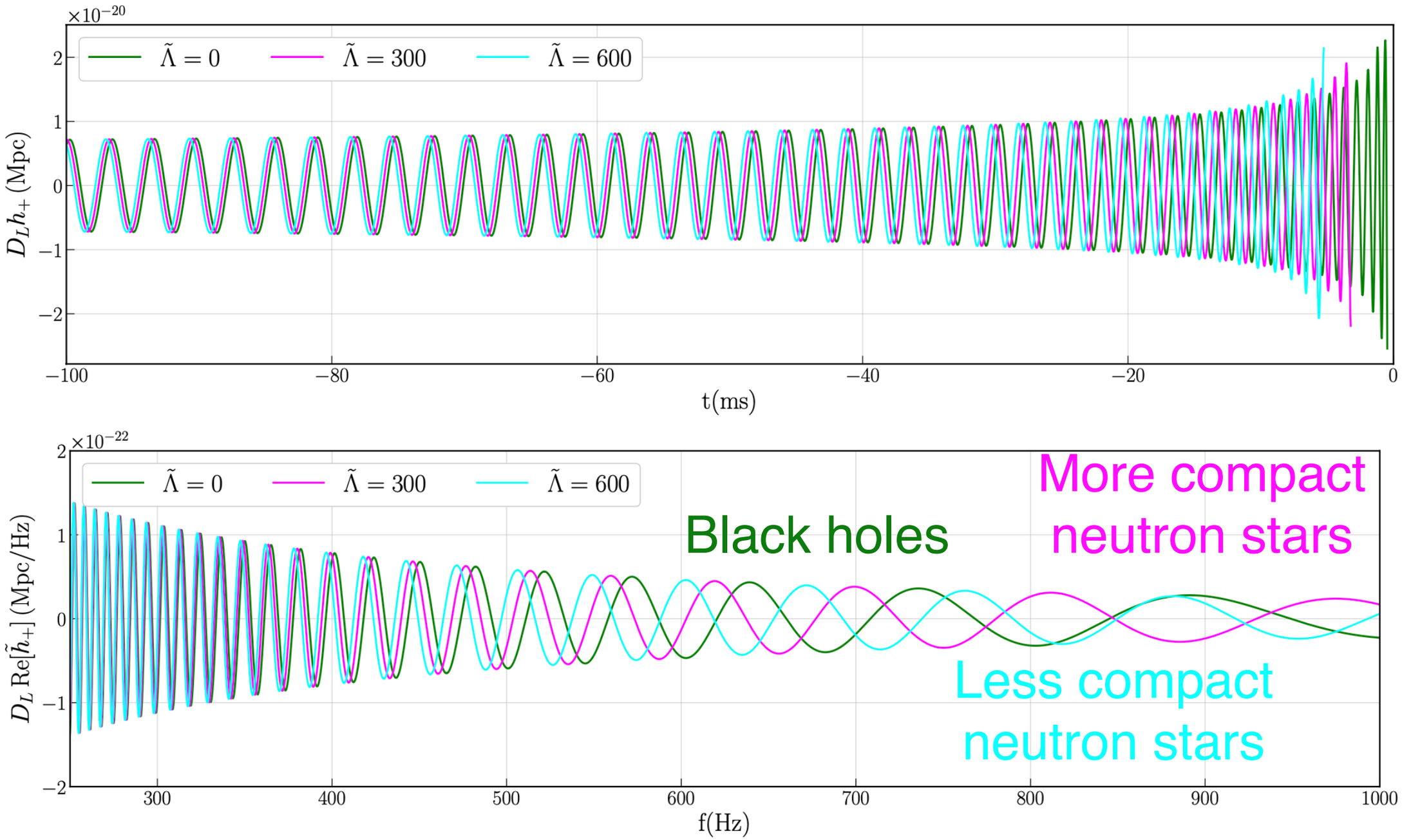
Calder

The tidal deformation speeds up the inspiral (observable) and it depends on the equation of state

Waveform

In practice with current sensitivity we only measure:

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

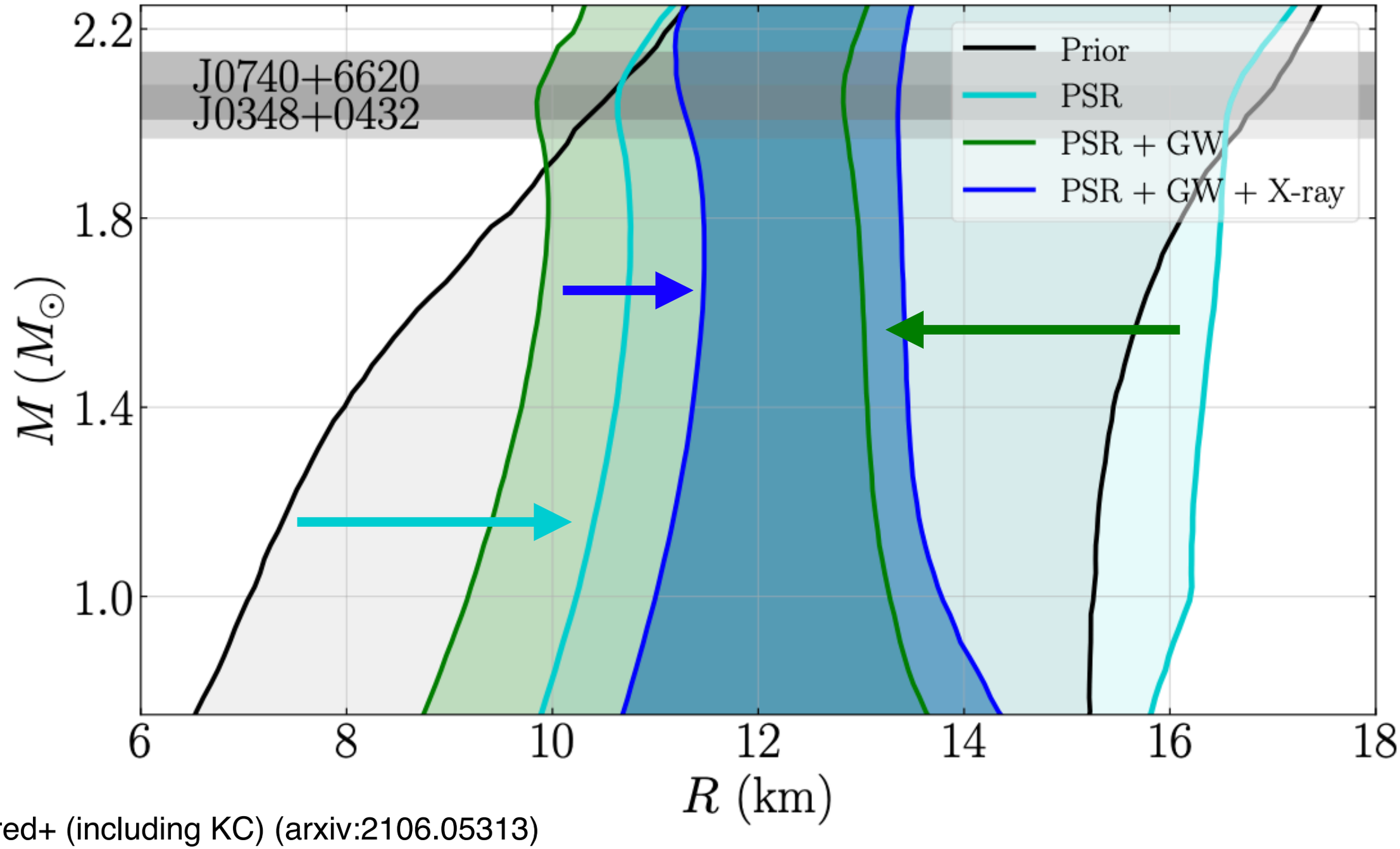


Chatziioannou (arxiv:2006.03168)

Waveform: Dietrich+ (arxiv:1804.02235)

Constraints on neutron star sizes

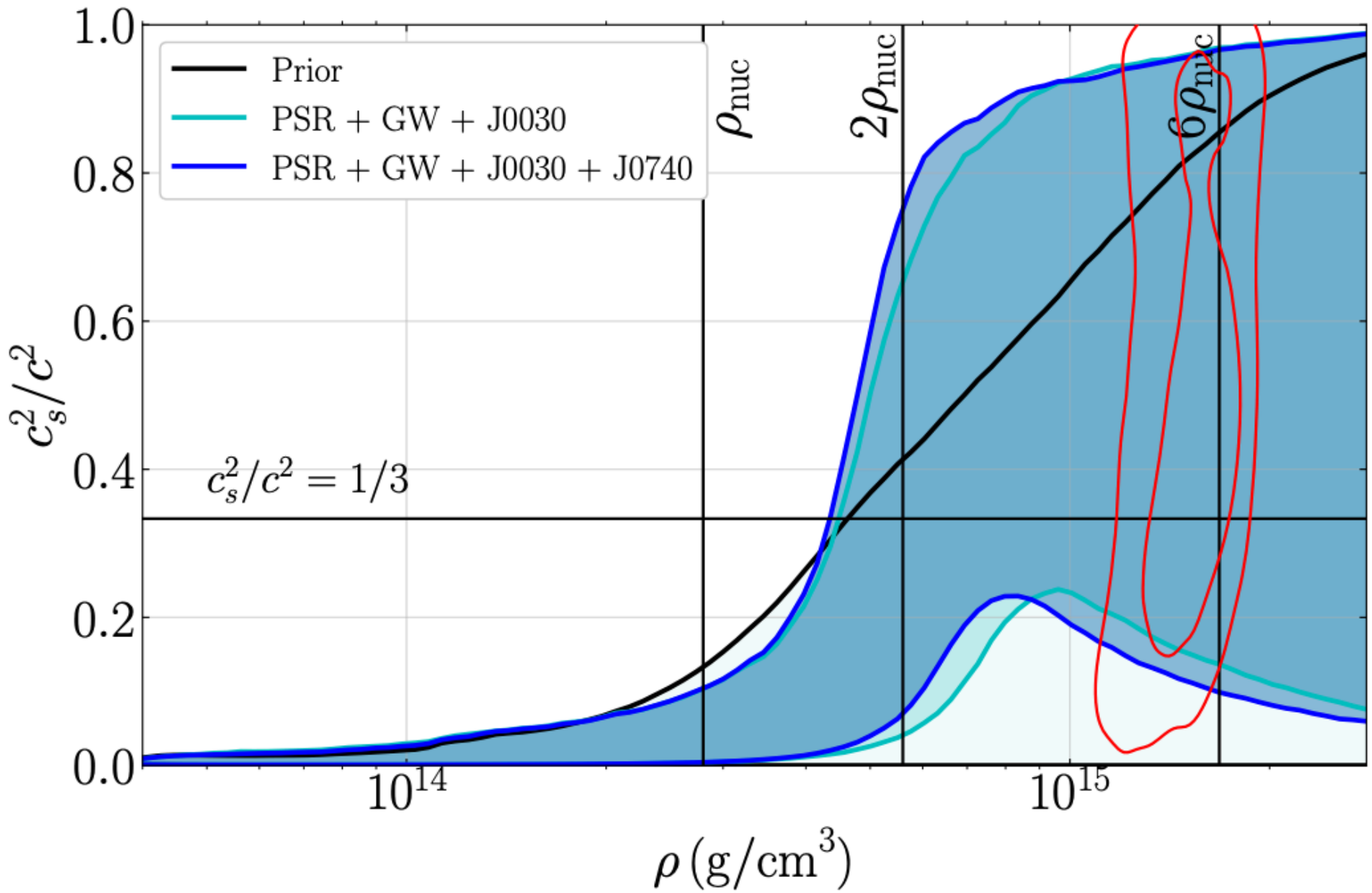
GWs constrain the high side ($\Lambda \sim R^6$),
X-rays constrain the low side ($C \sim R^{-1}$)



Legred+ (including KC) (arxiv:2106.05313)
Landry+ (including KC) (arxiv:2003.04880)

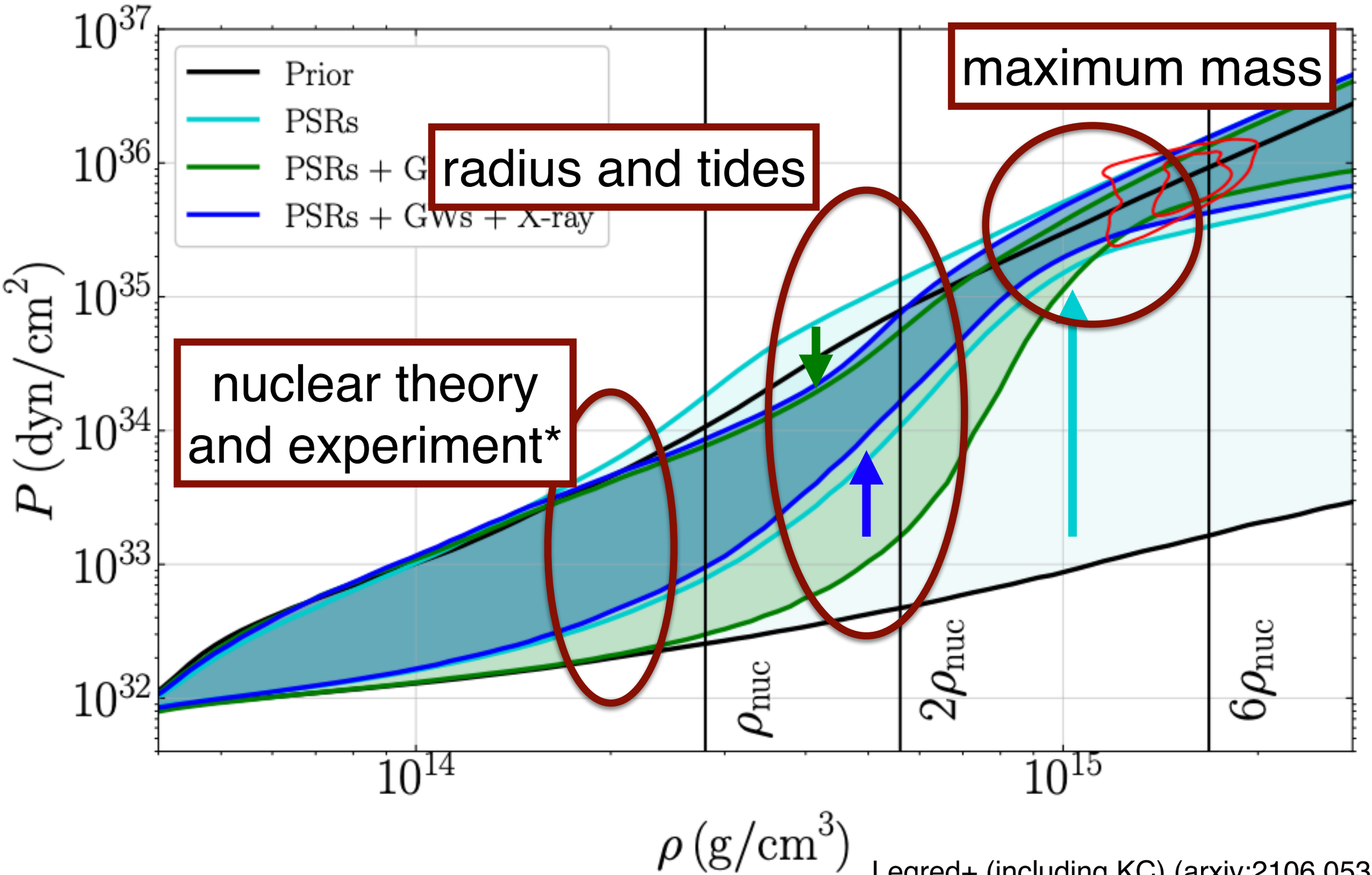
Speed of sound

soft at low densities (GW170817) +
stiff at high densities (Heavy PSRs) =
$c_s^2 > 1/3$



Legred+ (including KC) (arxiv:2106.05313)
Landry+ (including KC) (arxiv:2003.04880)

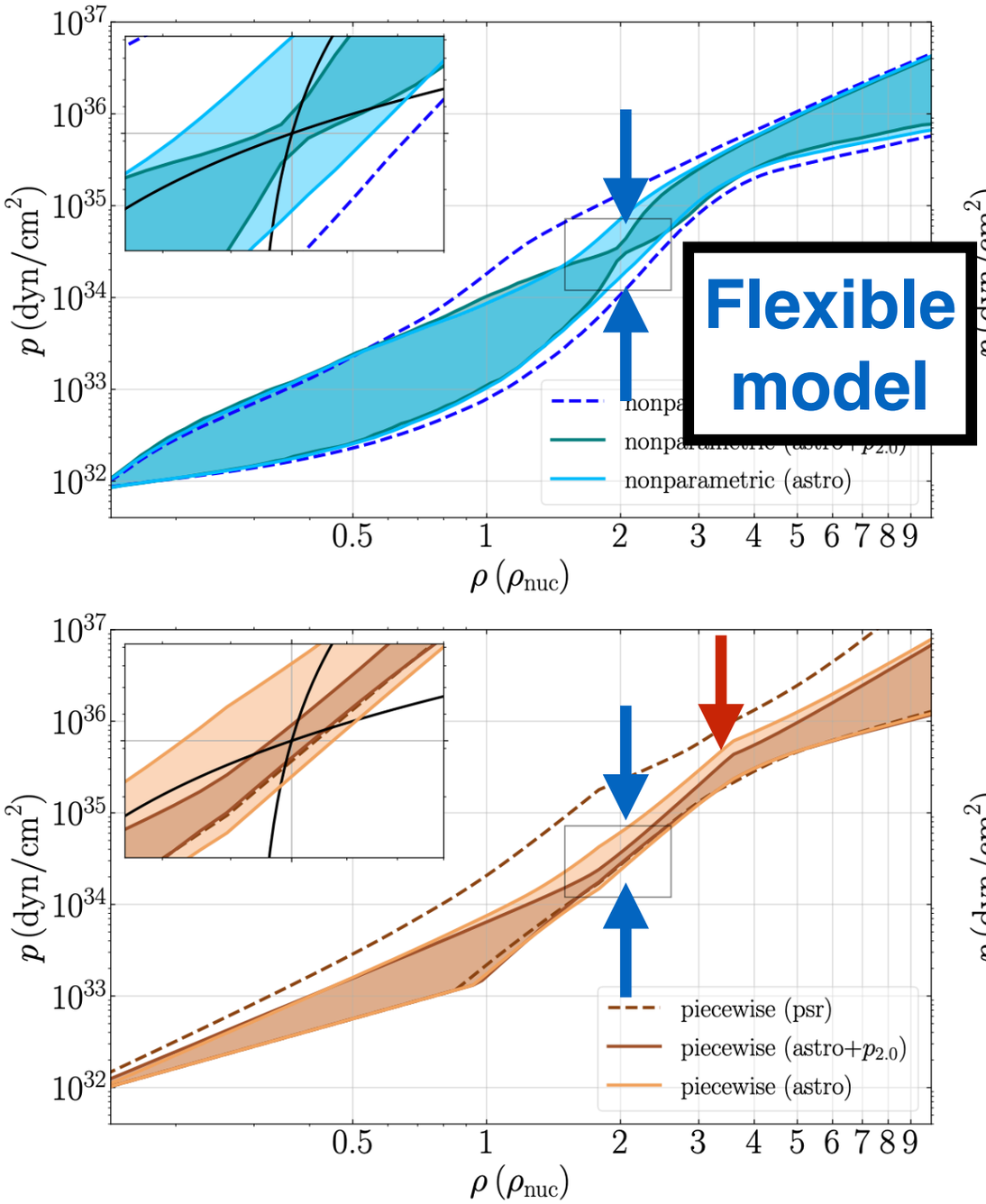
Constraints on the full equation of state



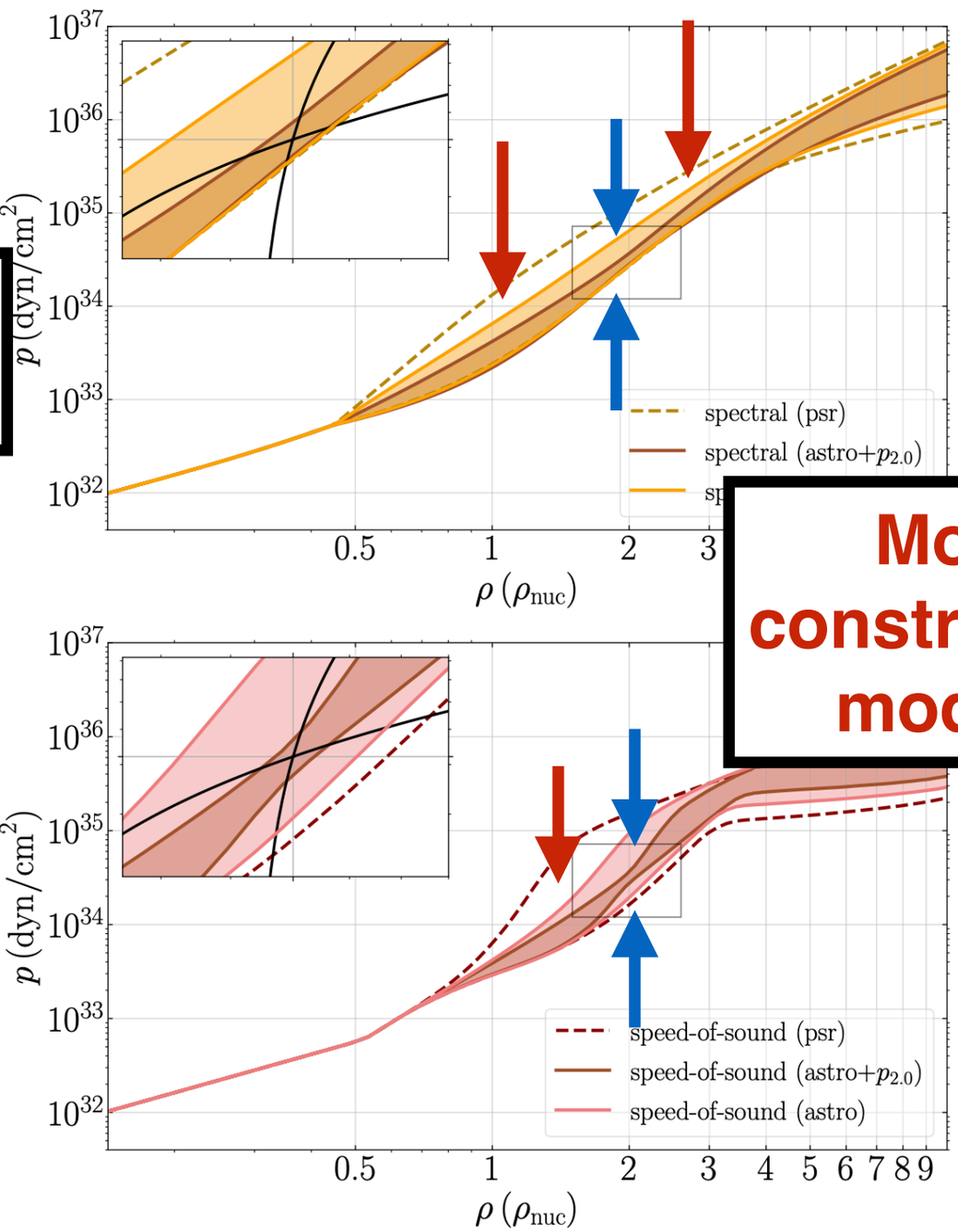
Legred+ (including KC) (arxiv:2106.05313)
Landry+ (including KC) (arxiv:2003.04880)

Intra-density correlations

Models might introduce unphysical (or at least unjustified) correlations



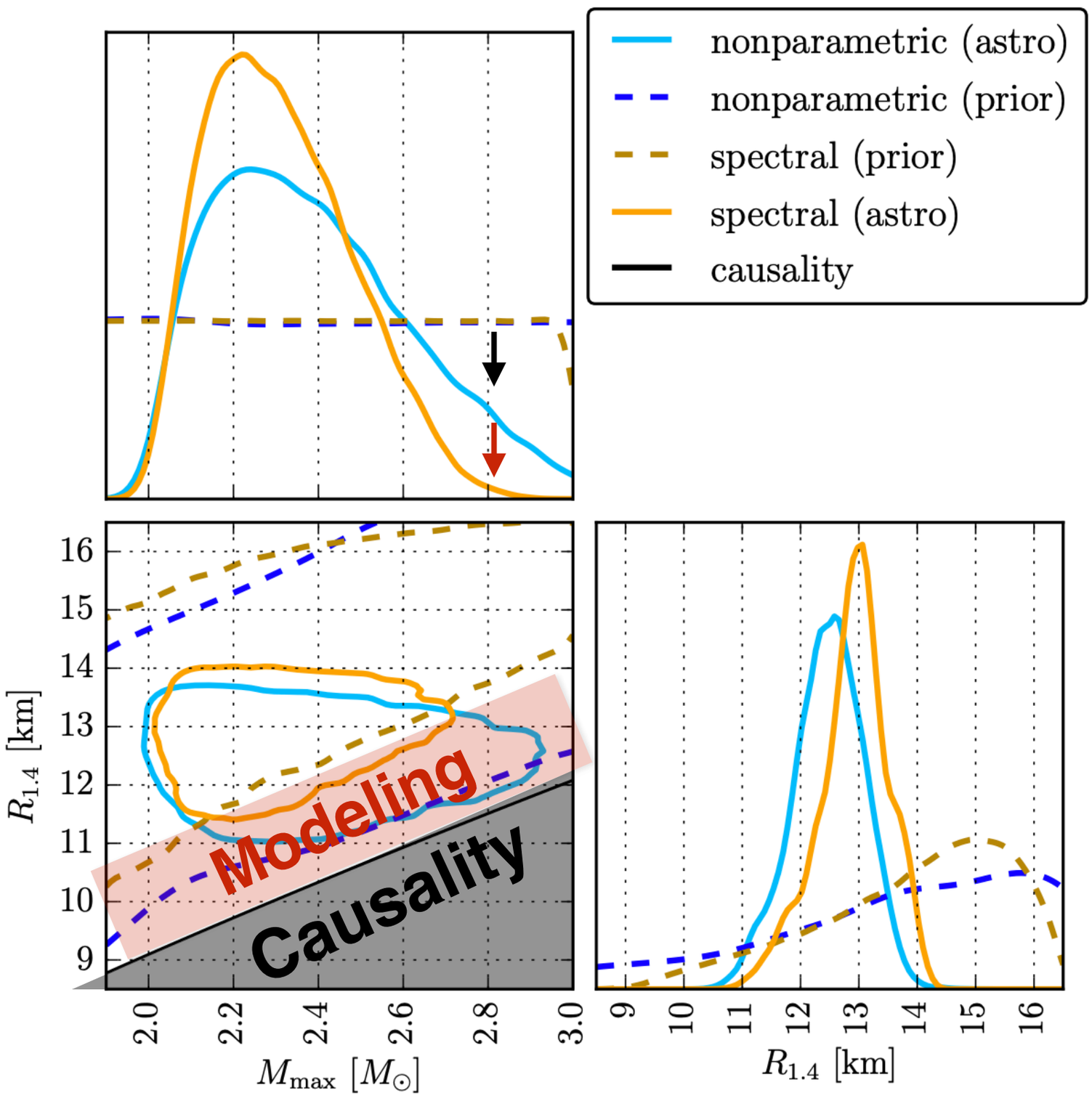
Flexible model



More constraining models

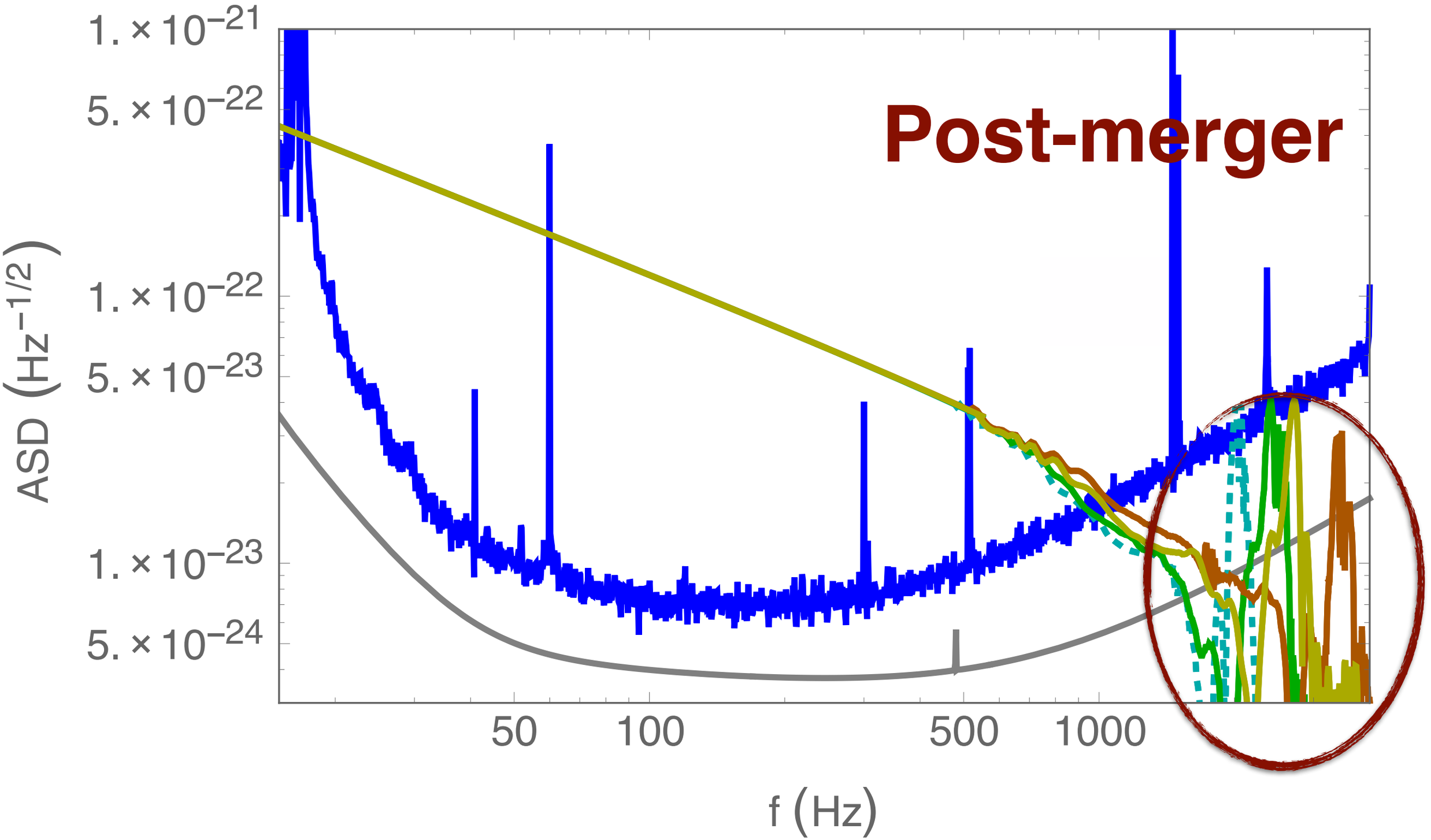
Legred+ (including KC) (arxiv:2201.06791)

The maximum mass from the EoS



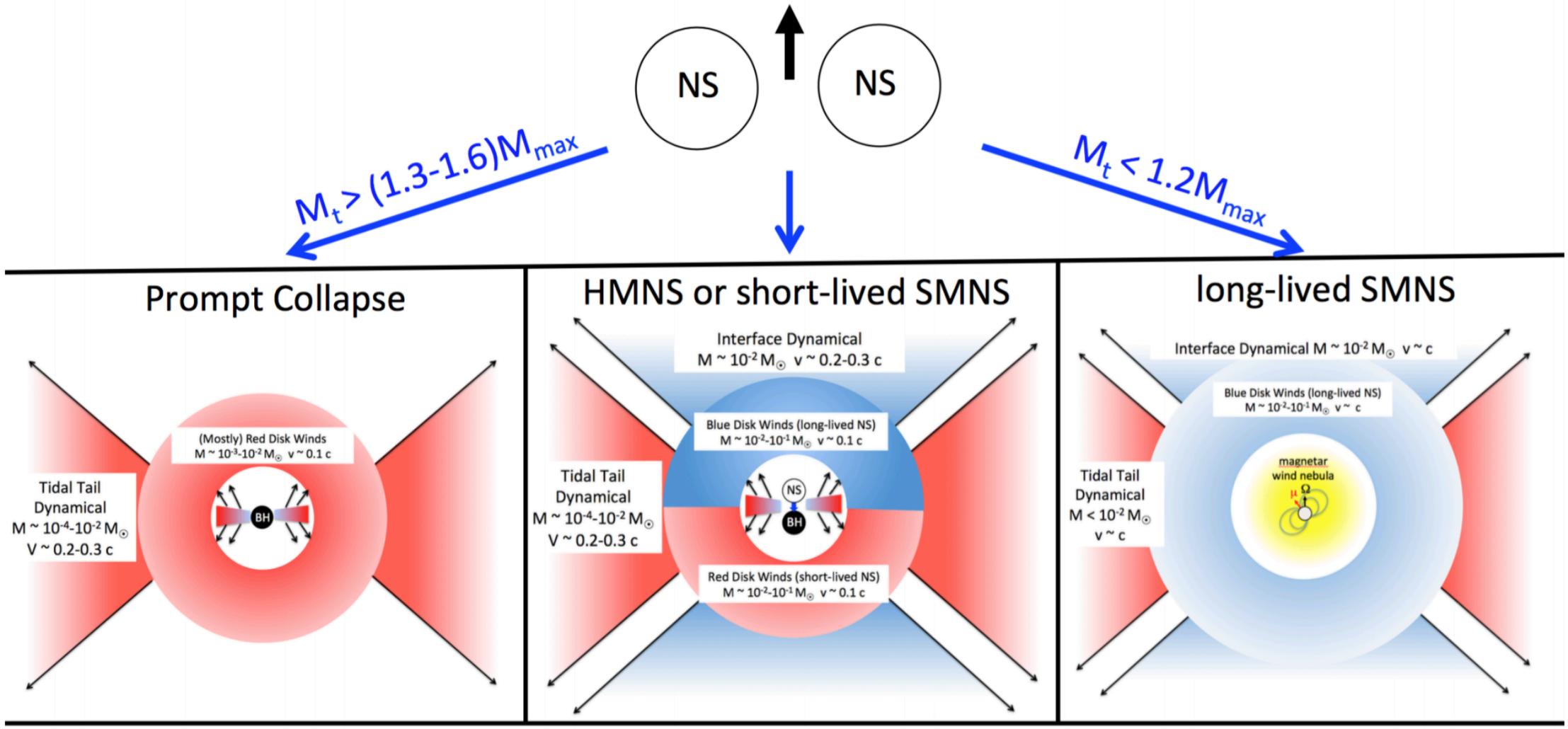
Legred+ (including KC) (arxiv:2201.06791)

Anatomy of a BNS coalescence: post-merger



Data Visualization by J. Read
Numerical data by Tim Dietrich (AEI/FSU/BAM Collaboration)
PRD 95 124006, PRD 95 024029

Remnant star



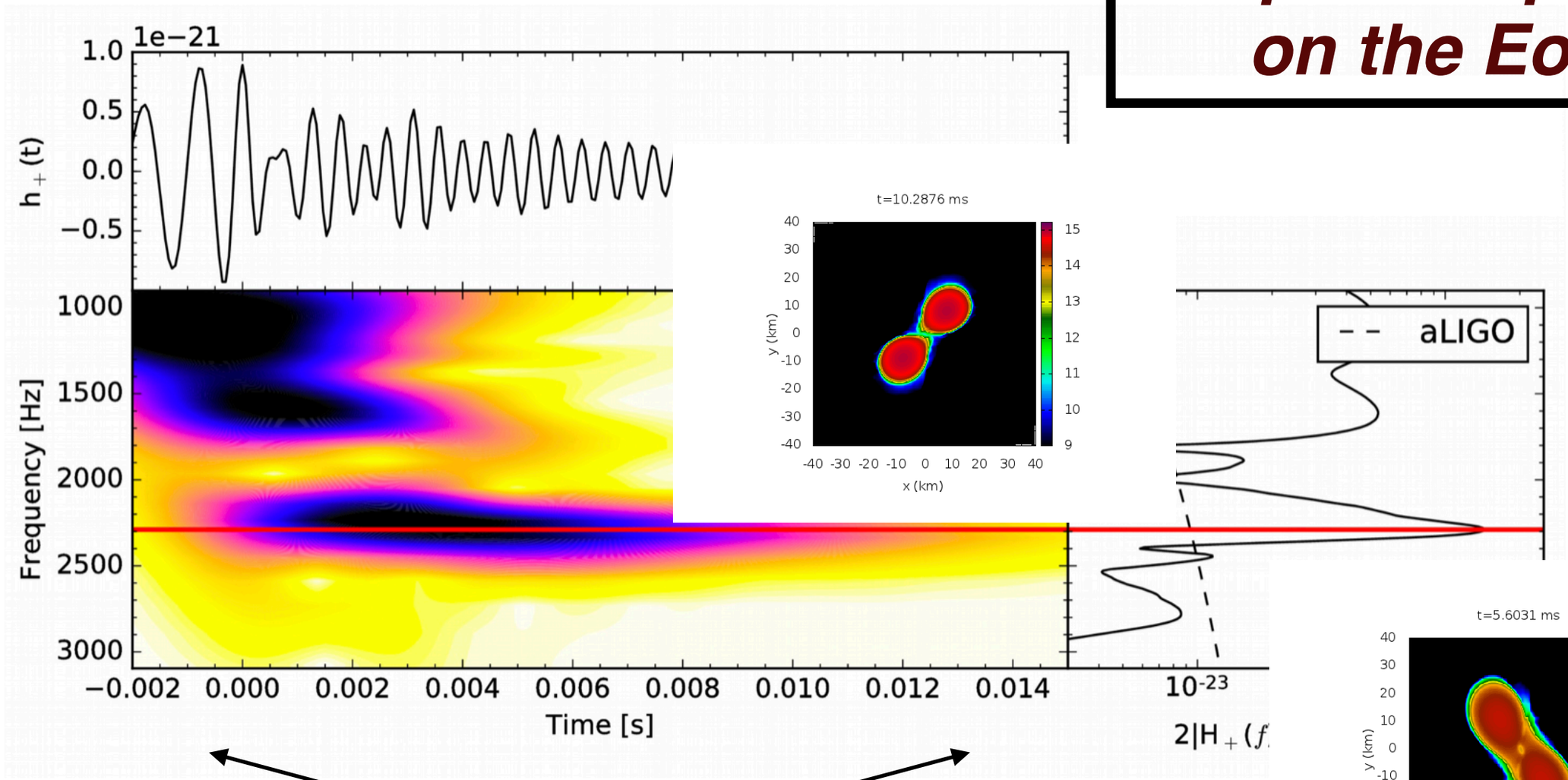
Margalit, Metzger (arxiv:1710.05938)

~6kHz ringdown | **Short duration signal at ~2-4kHz** | **Long duration signal**

Post-merger signal

complicated morphology

The location of the peak depends on the EoS



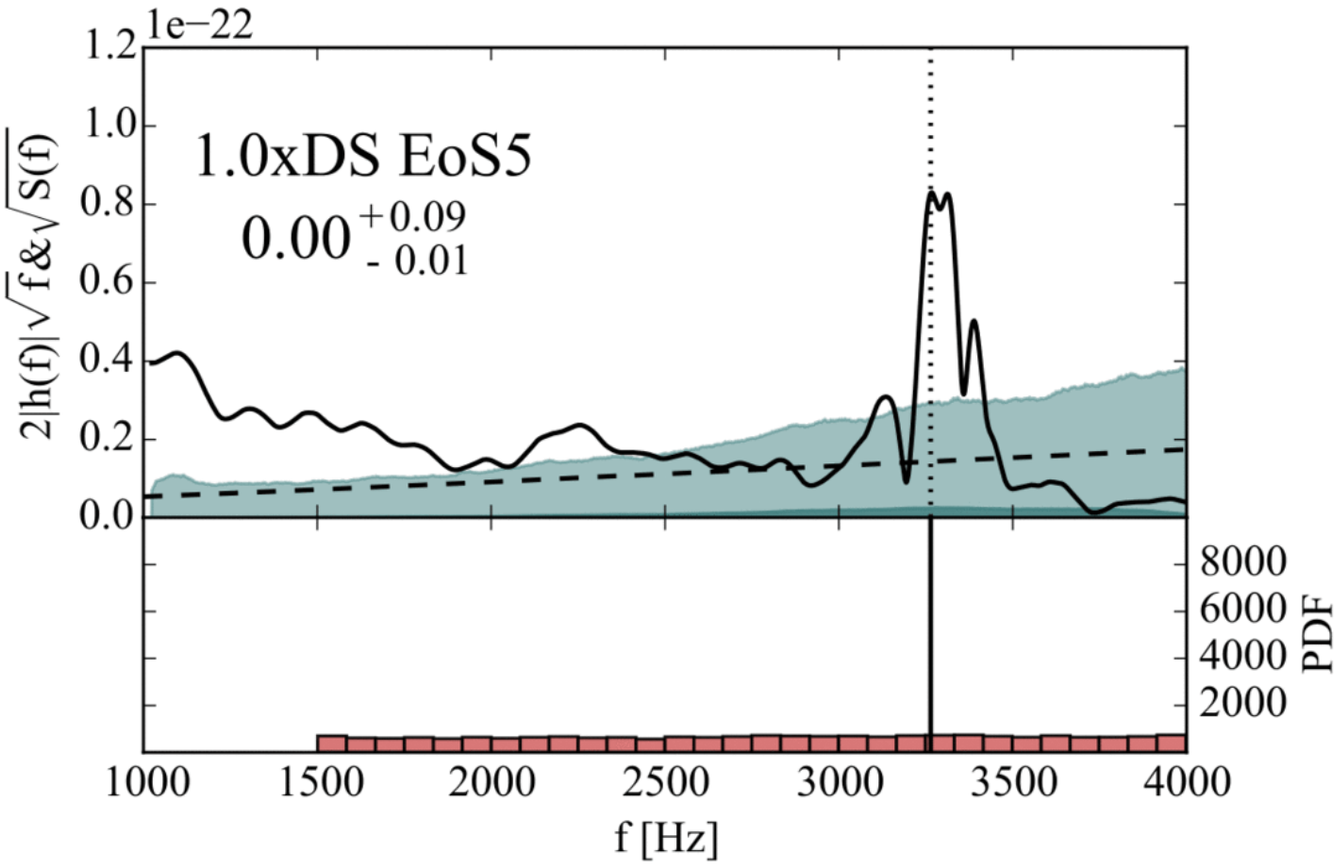
high frequency

characteristic

short duration

Clark+ (arxiv:1509.08522)

Instrumental upgrades

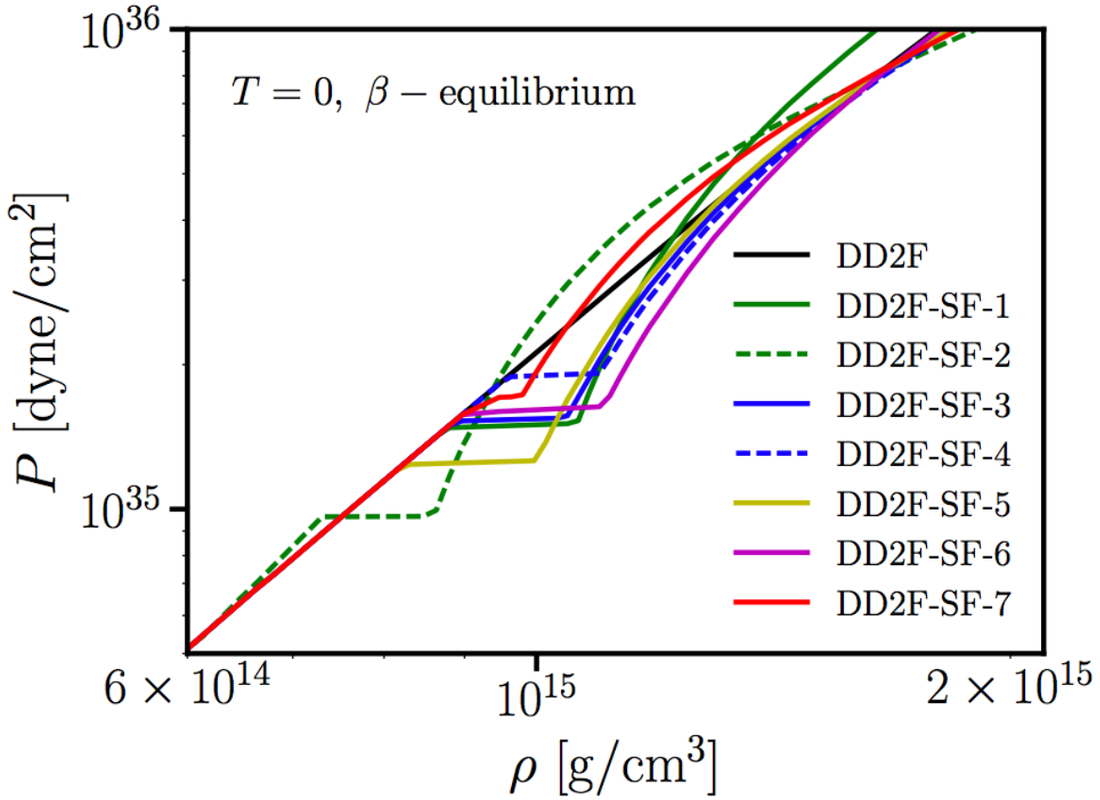


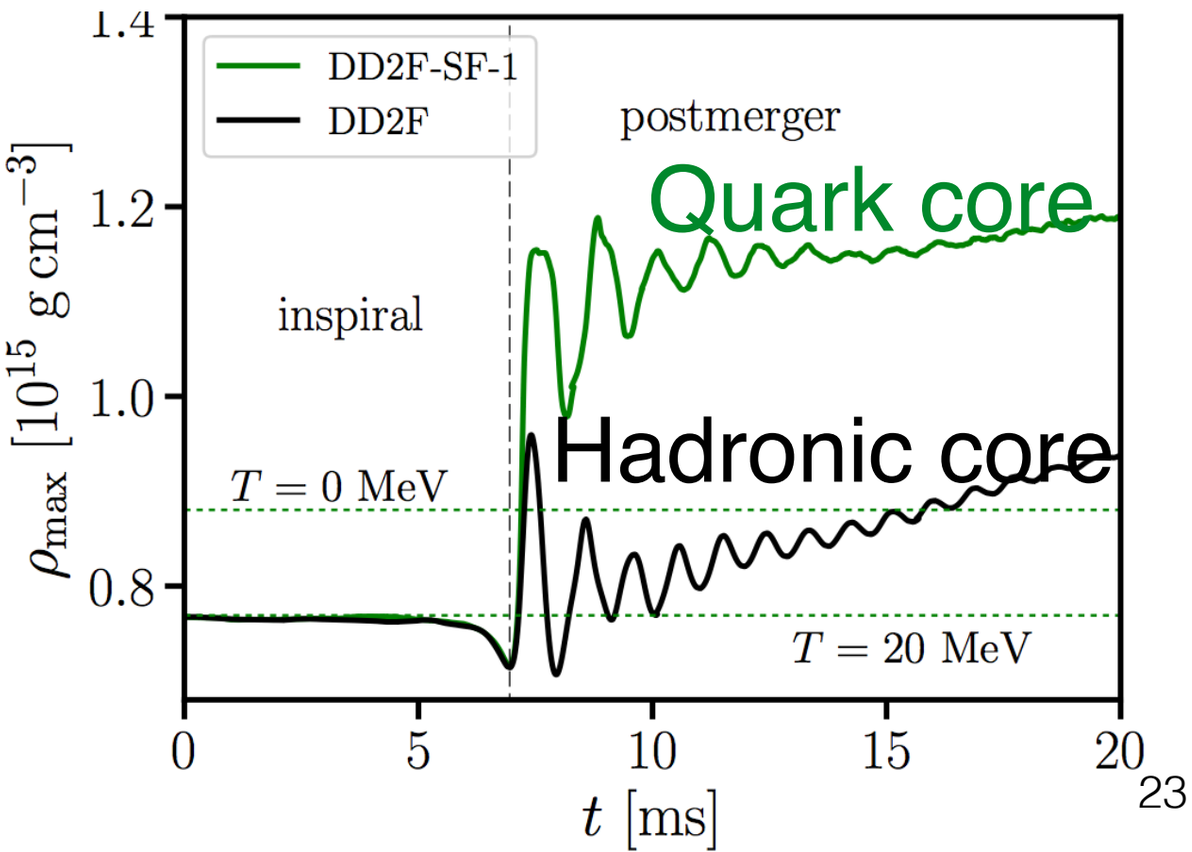
An instrument ~3 times better than aLIGO would have observed the GW170817 post-merger

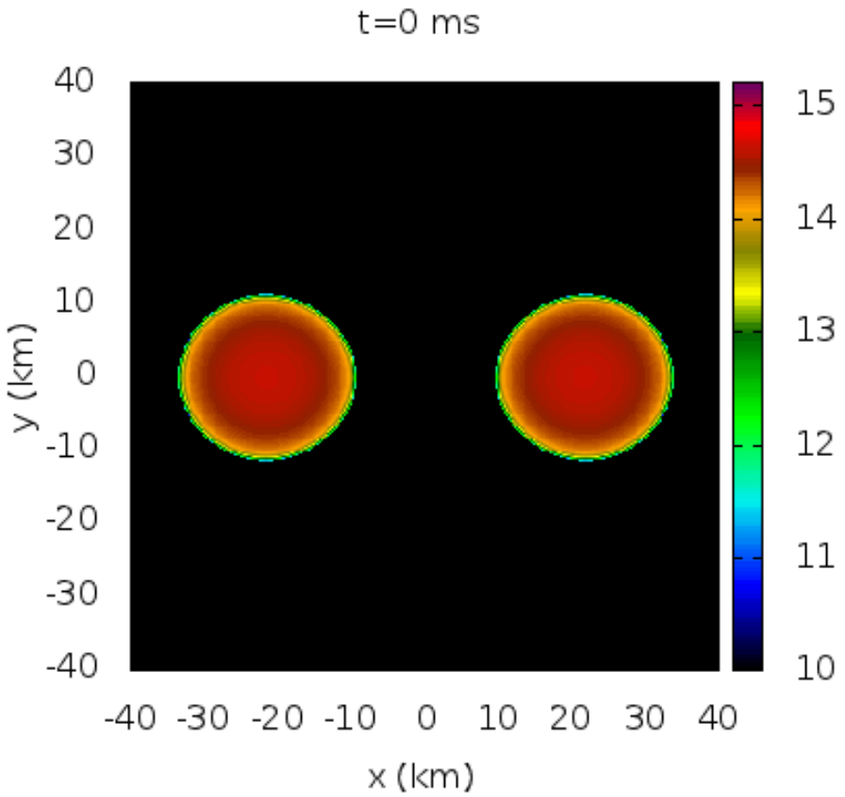
Torres-Rivas+ (including KC) (arxiv:1811.08931)

Within reach of proposed and/or funded instruments

Quark phase transition





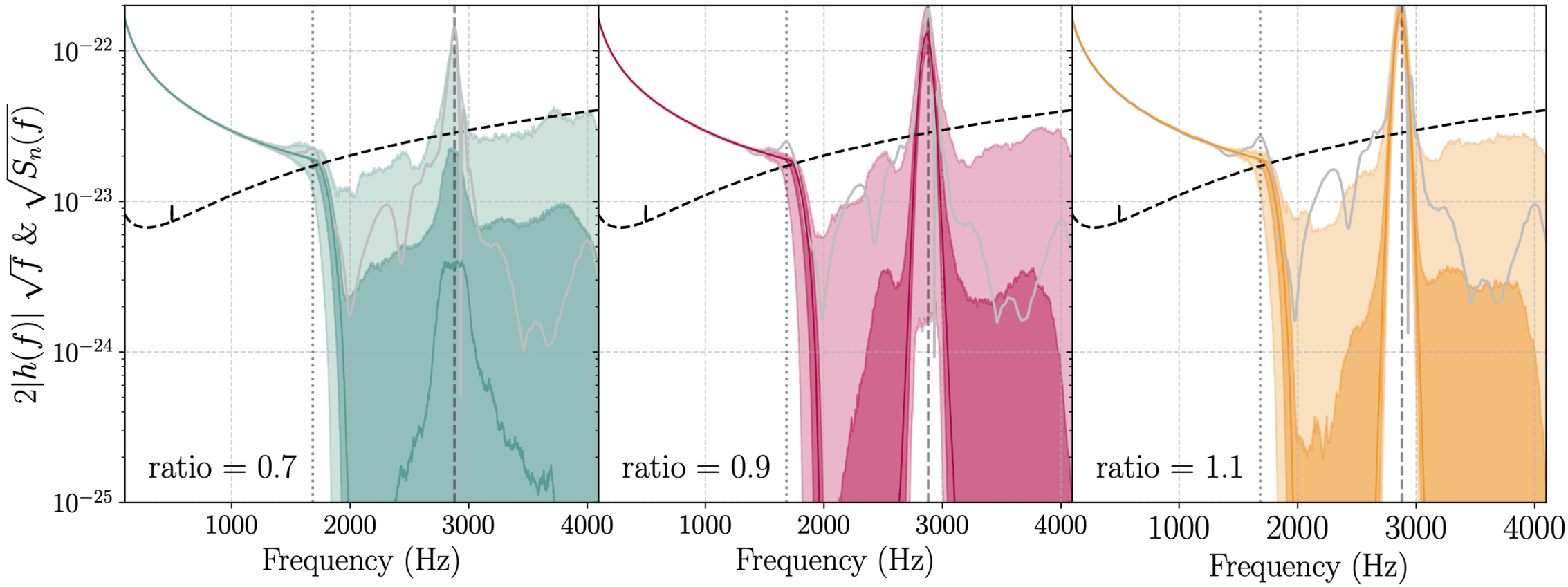


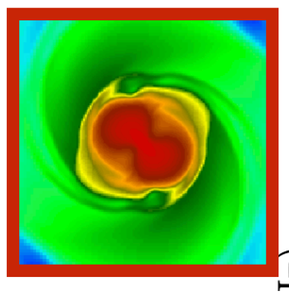
Simulations by Kenta Hotokezaka

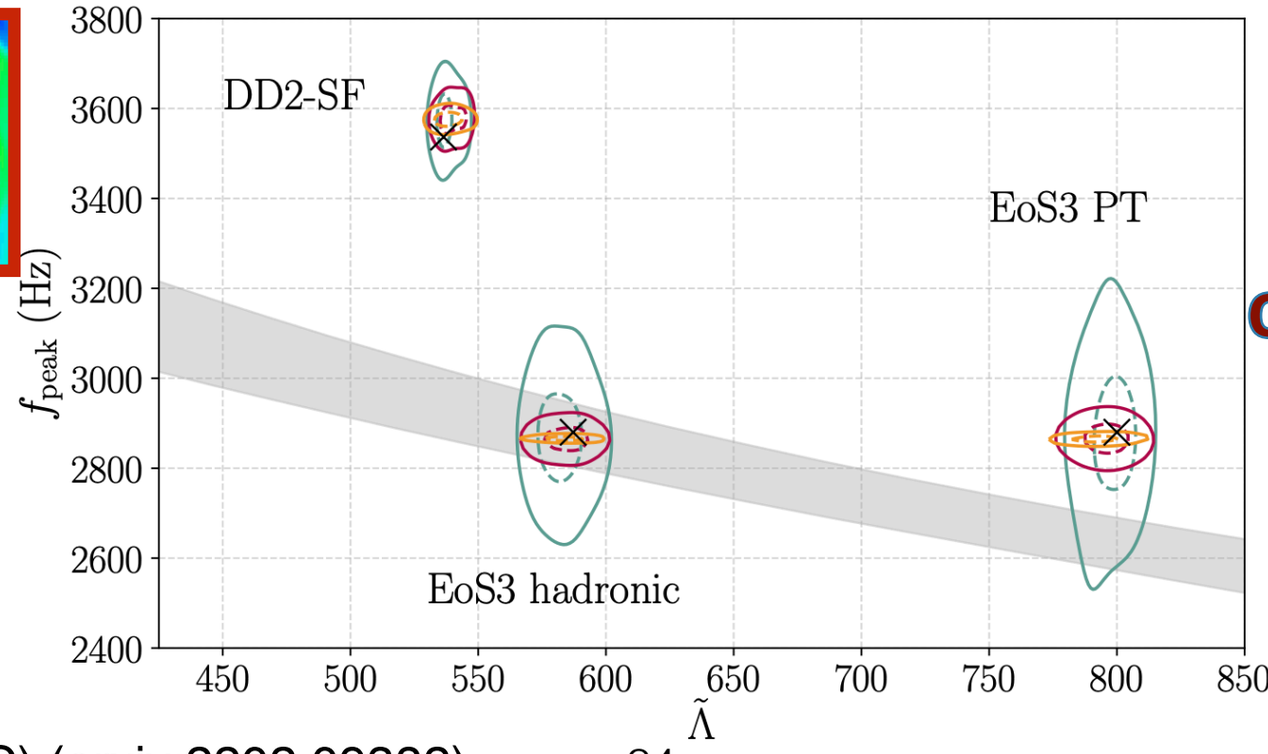
The merger remnant exceeds the threshold density for the phase transition, and ‘develops’ a dense quark core

Bauswein+ (including KC) (arxiv:1809.01116)

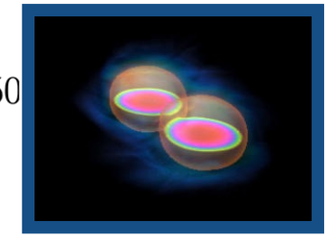
Neutron star cores





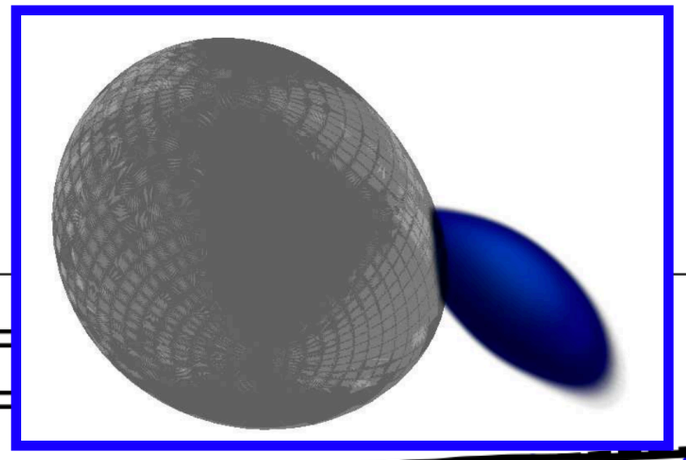


What are neutron star cores made of?

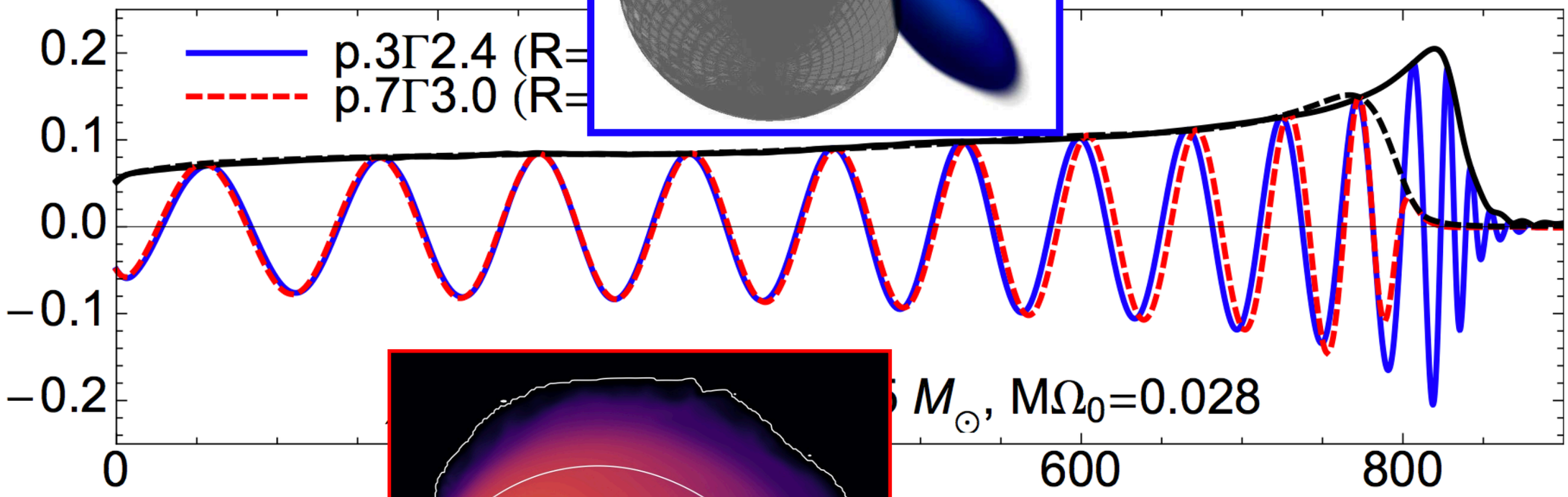


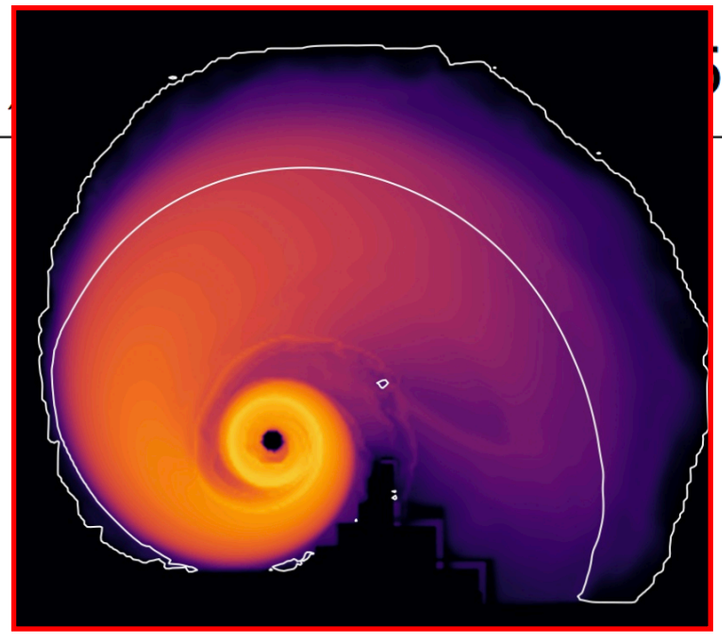
Wijngaarden+ (including KC) (arxiv:2202.09382)

Mixed neutron star-black hole binaries



BBH-like signal



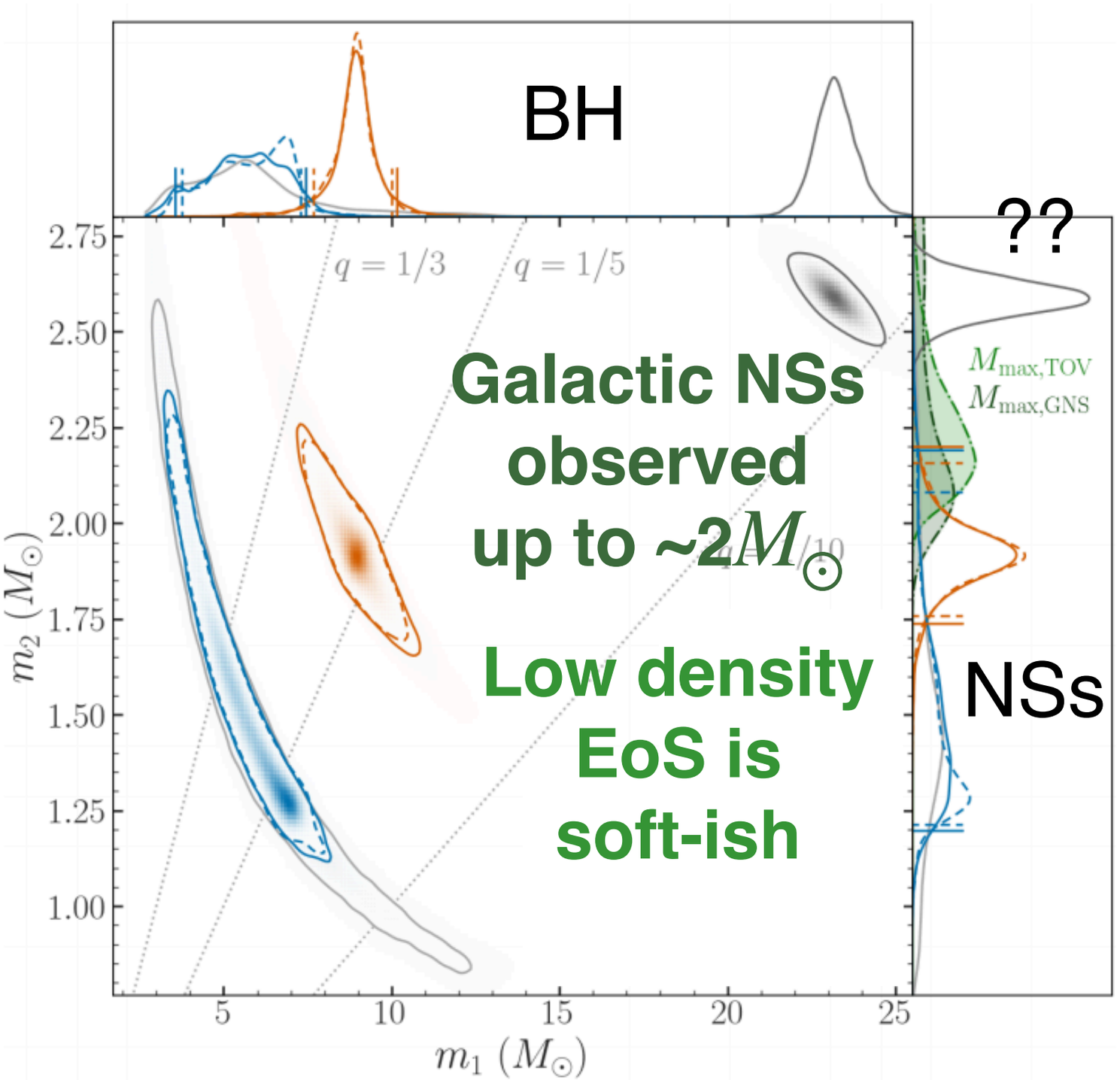


Signal shuts off

Relation between the disruption radius and the "plunge" radius

Lackey+ (arxiv:1303.6298)
Foucart+ (arxiv:1307.7685)
Foucart+ (arxiv:1807.00011)

Observations



No tidal signature in any event, need external input?

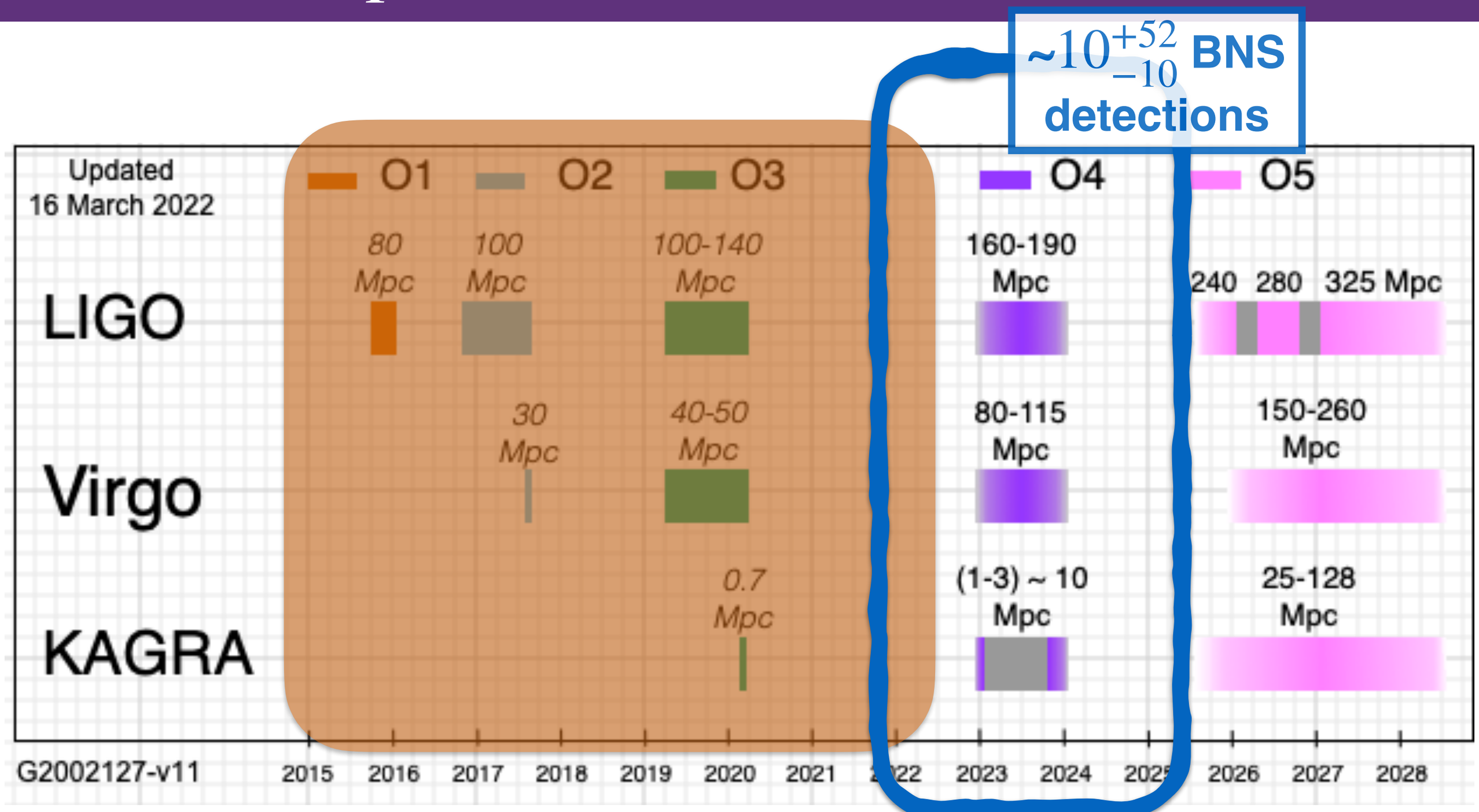
A $2.6M_\odot$ object:

- BH
- Spinning NS
- Phase transitions
- Statistical outlier
- …

LVC (arxiv:2106.15163)
LVC (arxiv:2006.12611)
PE: Veitch+ (arxiv:1409.7215), Ashton+ (1811.02042)
Waveforms: Khan+ (arxiv:1911.06050), Ossokine+ (arxiv:2004.09442), Pratten+ (2004.06503)

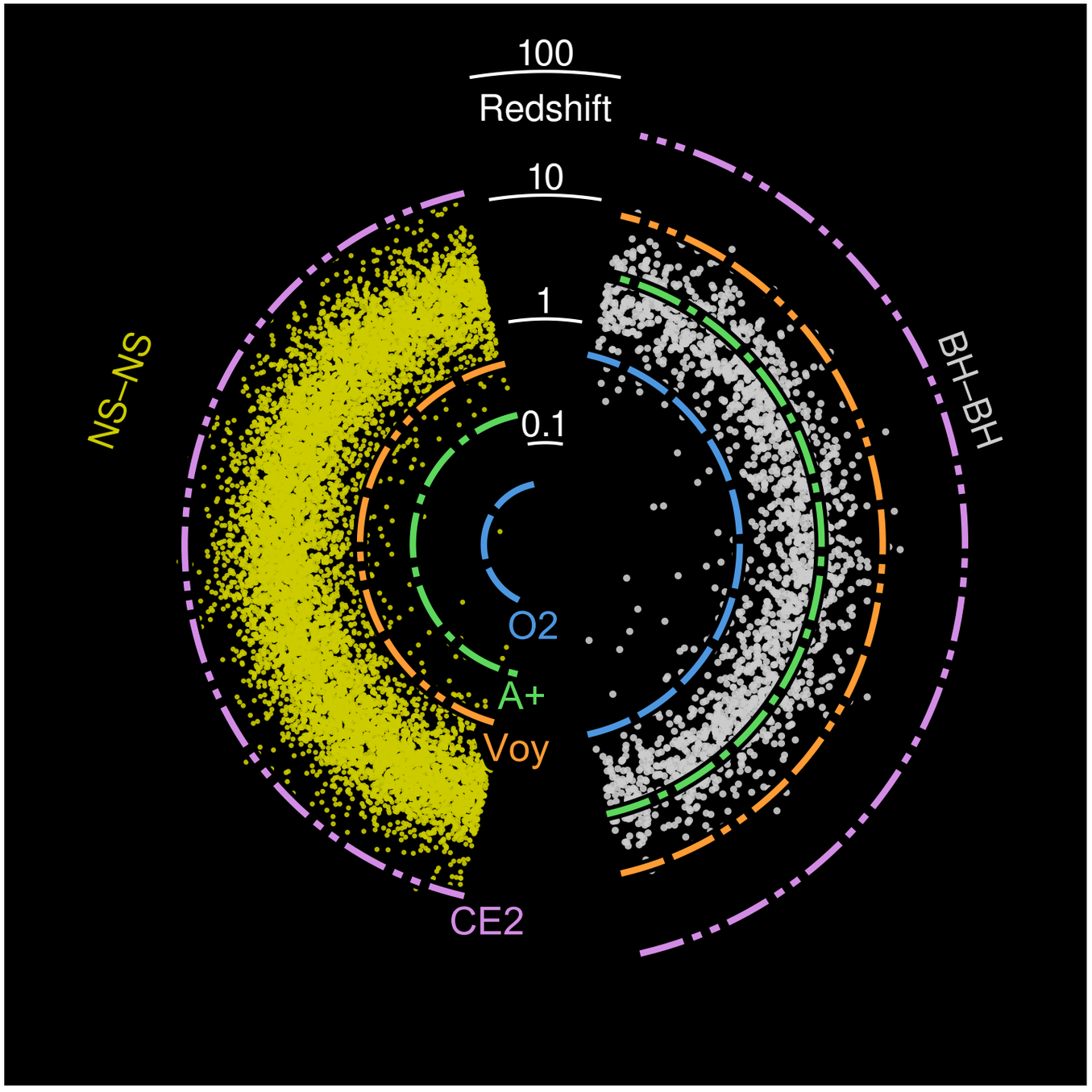
Tan+ (arxiv:2006.16296)
Essick+ (arxiv:2007.01372)
Dexheimer+ (arxiv:2007.08493)
Tews+ (arxiv:2007.06057)
Fattoyev+ (arxiv:2007.03799)

The next steps



Pulsar timing arrays (nHz; $10^9 M_\odot$)

Even further ahead



O2: 10 binary black holes, 1 binary neutron star

O5/A+: 2xLIGO

Voyager: ceiling for current sites

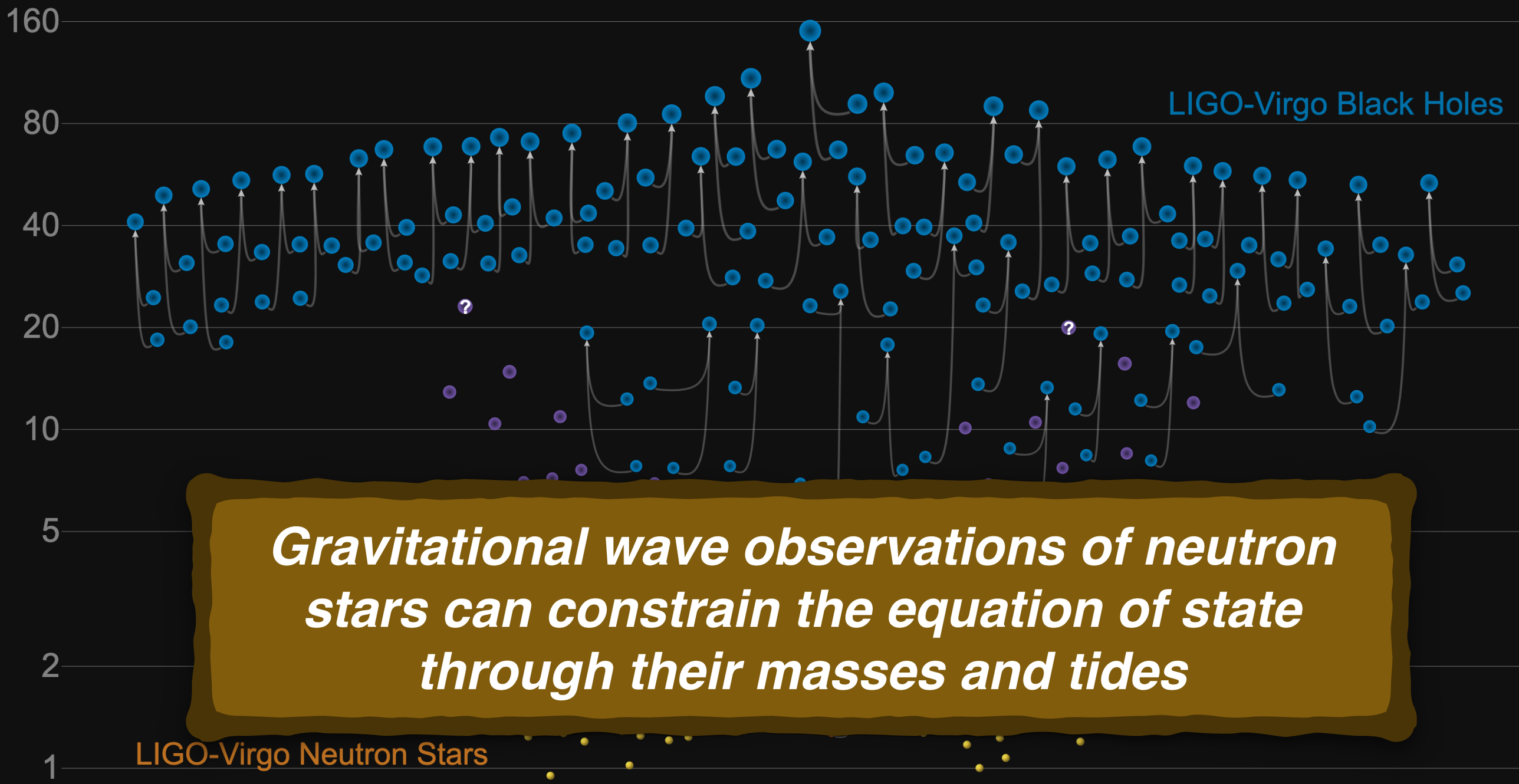
CE2: 3rd gen detectors, science case

LISA (mHz; $10^6 M_\odot$, WD, EMRIs,…)

Hall/Vitale/MIT

Masses in the Stellar Graveyard

in Solar Masses



Gravitational wave observations of neutron stars can constrain the equation of state through their masses and tides

LIGO-Virgo | Frank Elavsky, Aaron Geller | Northwestern