(Low mass) Compact objects and gravitational wave astrophysics

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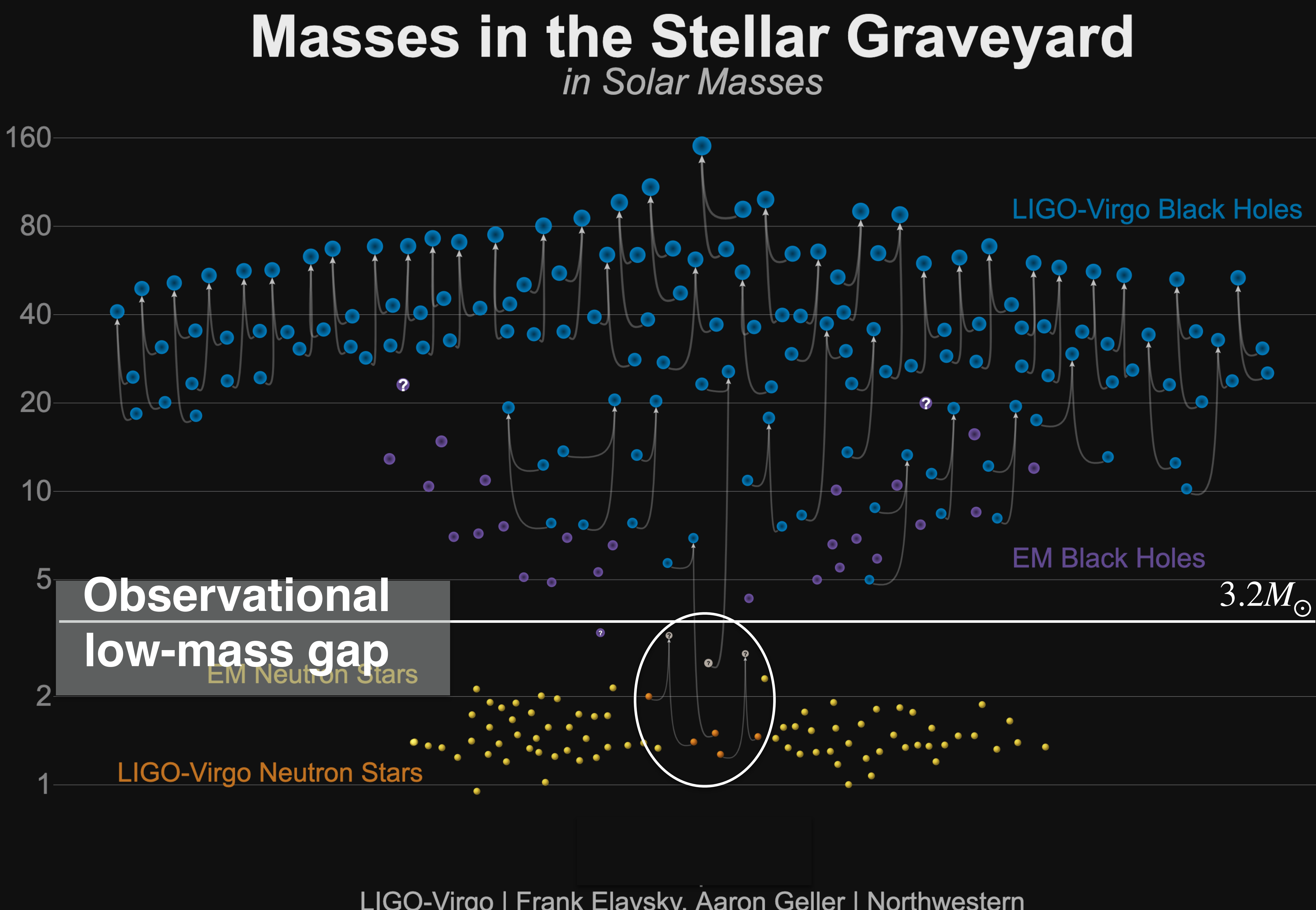
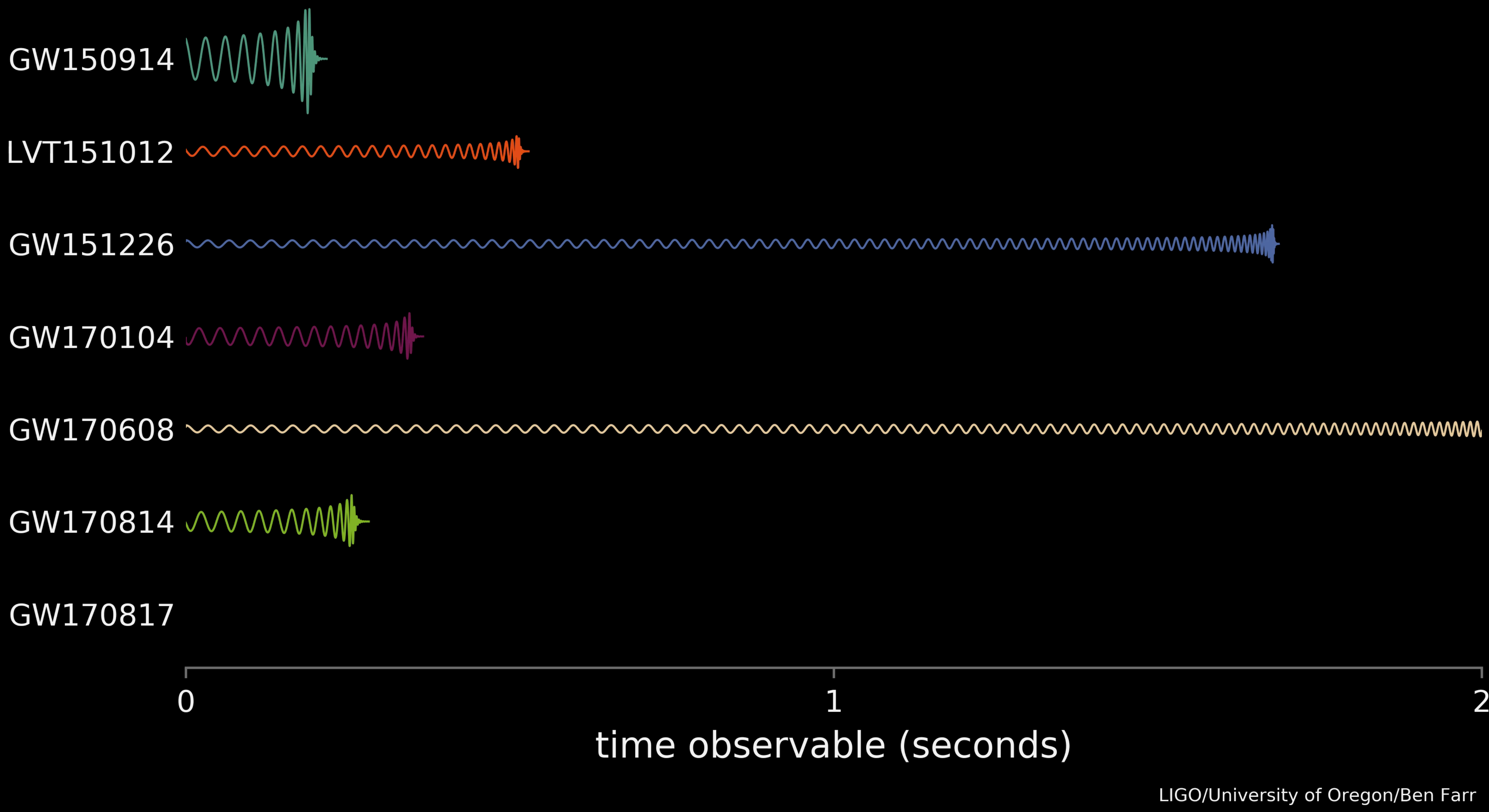
Caltech

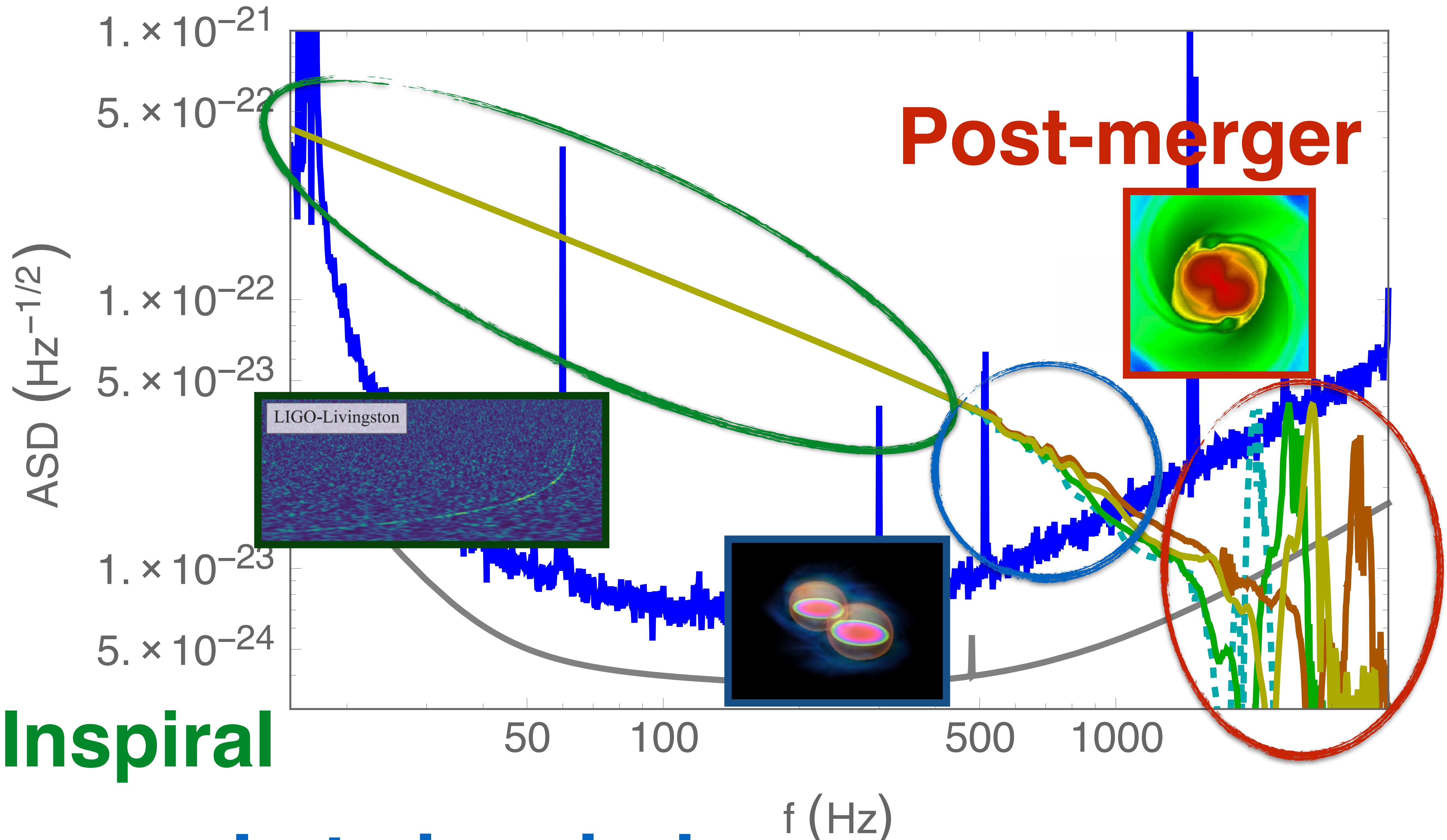
Current Themes in High Energy Physics, Gravity and Cosmology
Niels Bohr Institute
August 21, 2023

Image: Aurore Simonnet


Masses in the Stellar Graveyard
in Solar Masses
160
80
40
20
10
5
2
1
LIGO-Virgo Black Holes
EM Black Holes
Observational
low-mass gap
EM Neutron Stars
LIGO-Virgo Neutron Stars
$3.2M_\odot$
LIGO-Virgo | Frank Elavsky, Aaron Geller | Northwestern


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

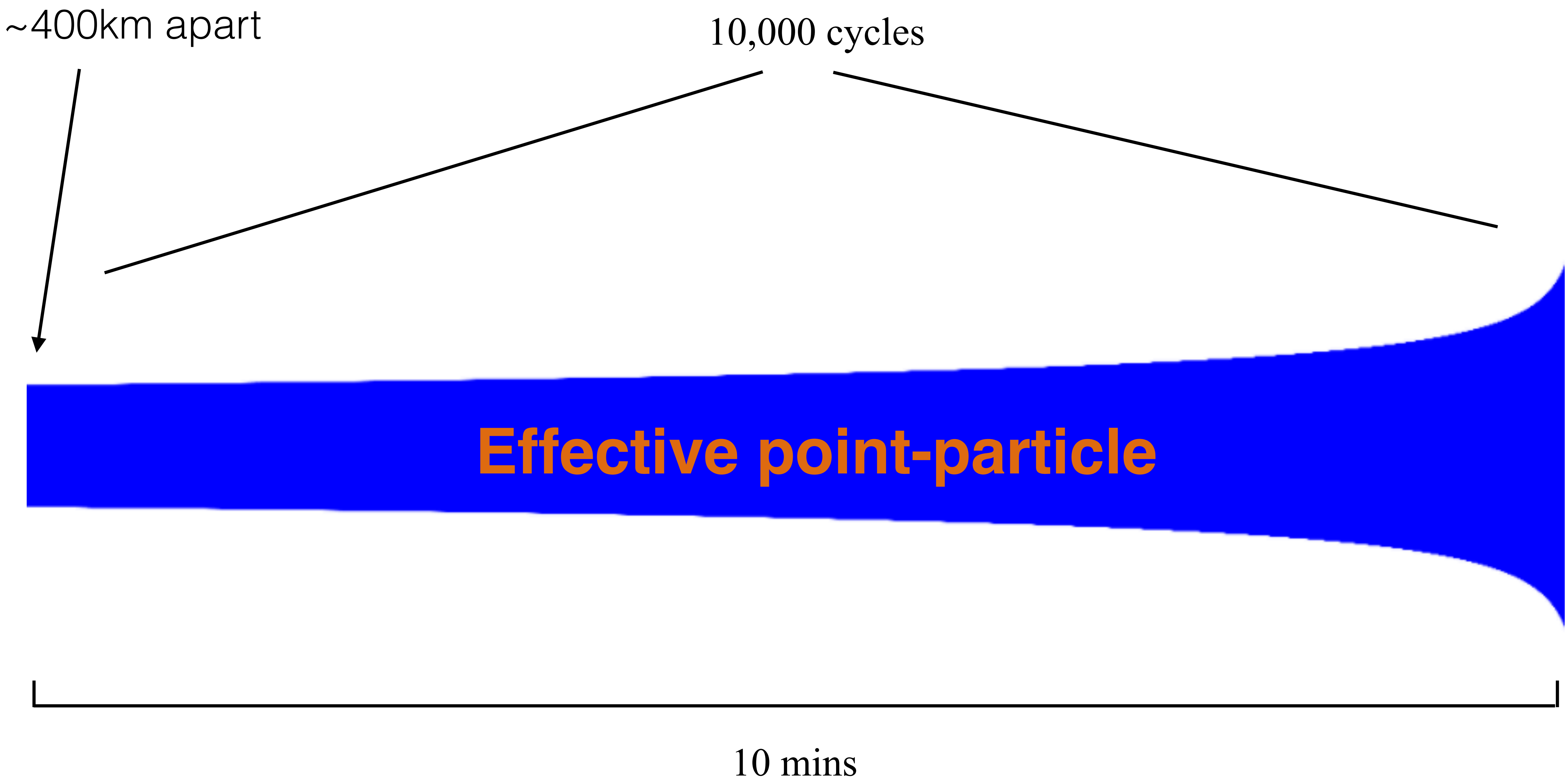
Neutron star binaries



Late inspiral

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

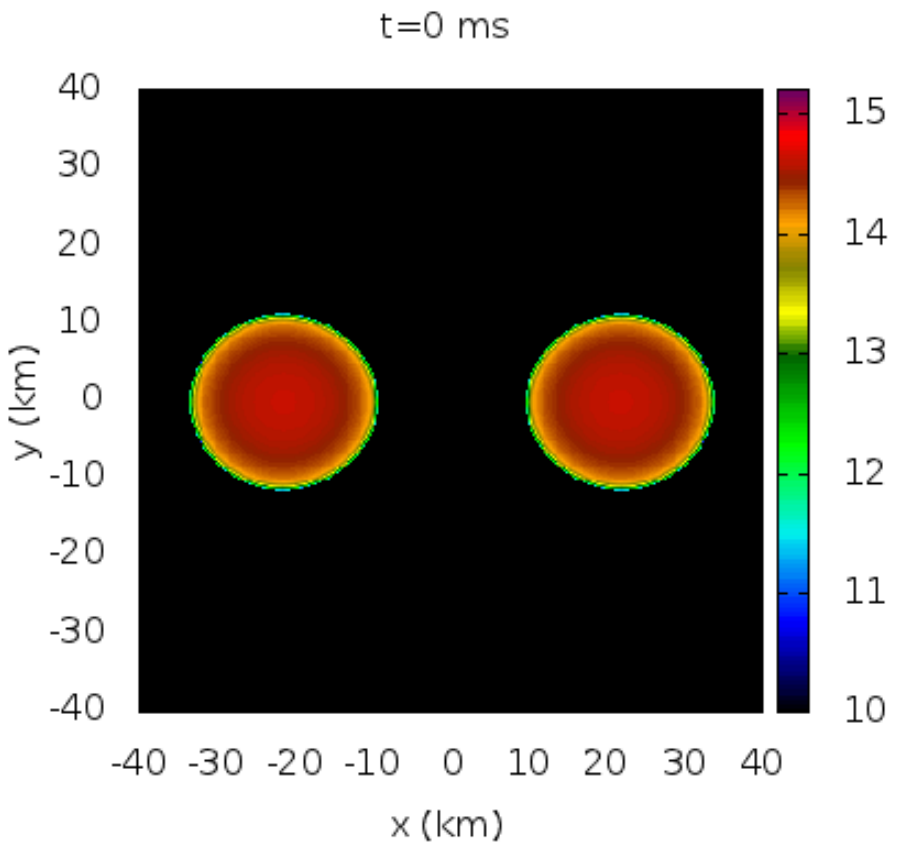
Inspiral

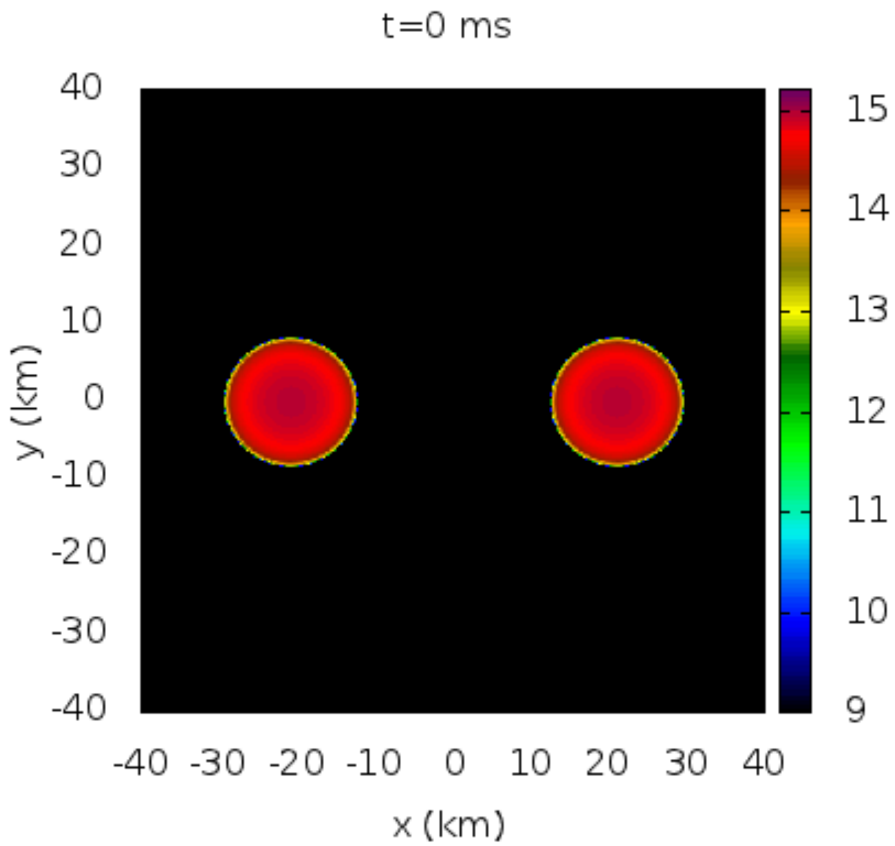


Late inspiral

Larger neutron stars lose energy faster, accelerating the inspiral

Smaller neutron stars take longer to merge



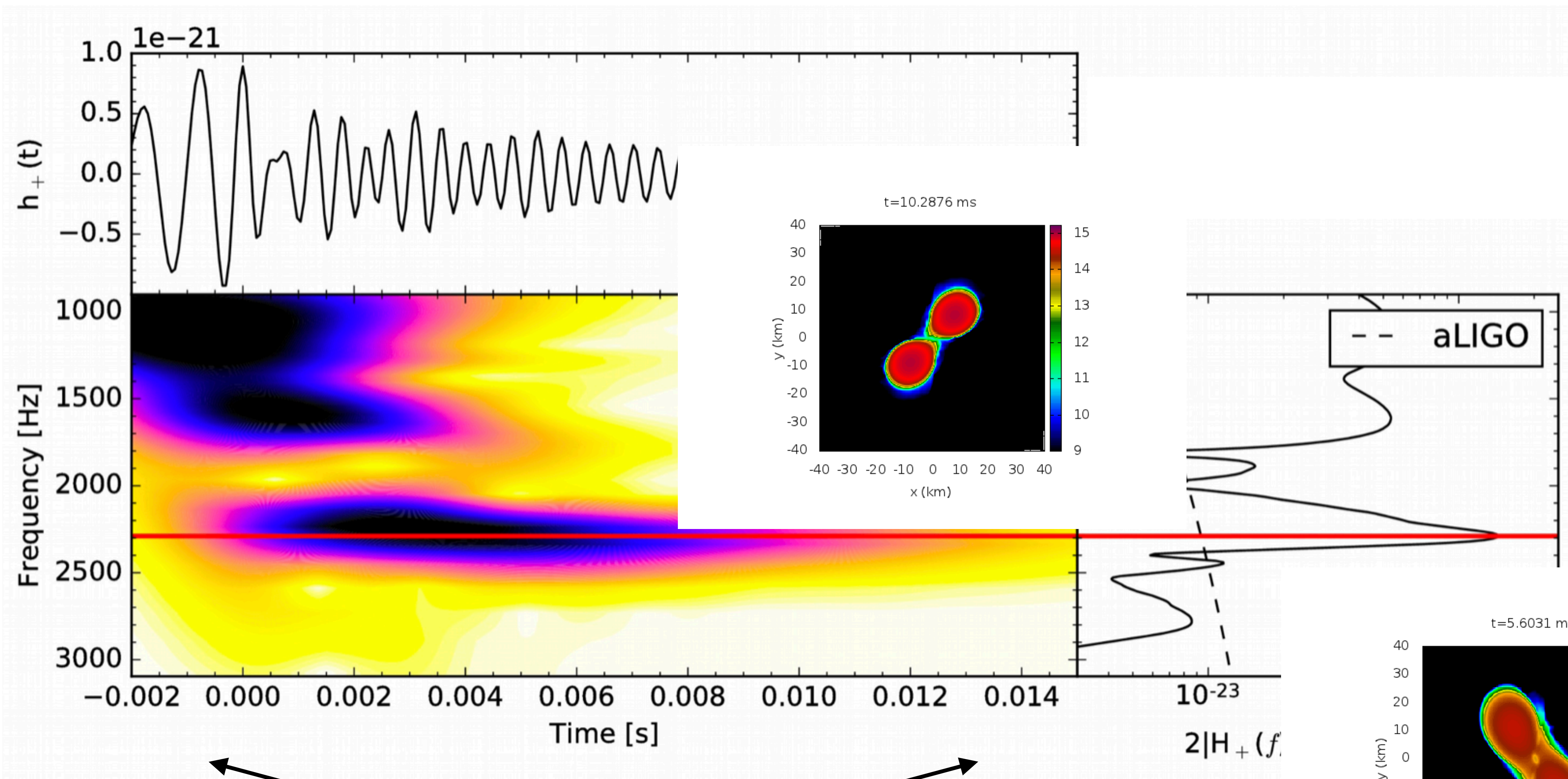


Simulations by Kenta Hotokezaka

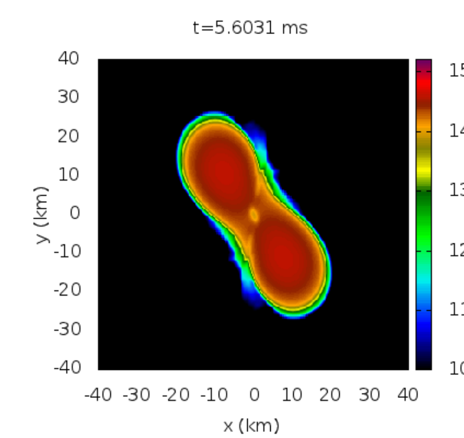
Post-merger

complicated morphology

high frequency



characteristic

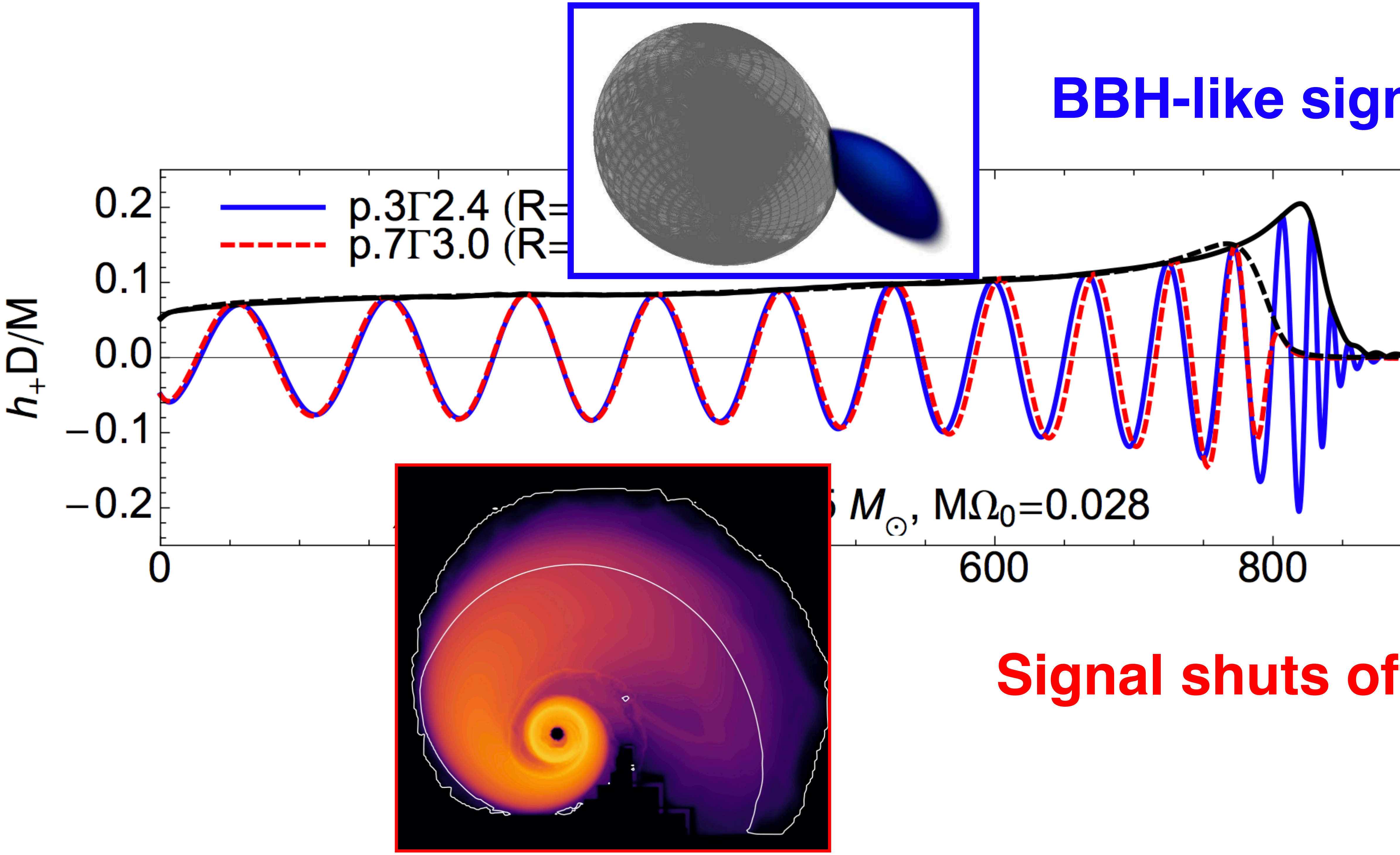


short duration

Clark+ (arxiv:1509.08522)

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)

What differentiates neutron stars and black holes

- Component masses
- Finite-size effects
- Electromagnetic counterpart
- Merger remnant

Masses

What we know

- Neutron stars can be as massive as $\sim 2M_\odot$
- Anything more massive than $\sim 3.2M_\odot$ is a black hole
- Galactic neutron stars in binaries have masses $\sim 1.35M_\odot$

What we sometimes assume

- There's a clean separation between neutron stars and black holes
- Astrophysical black holes cannot have masses below $\sim 2M_\odot$
- Neutron stars cannot have masses below $\sim 1M_\odot$

What we don't know

- Is the maximum observable neutron star mass determined by astrophysics or nuclear physics?

What differentiates neutron stars and black holes

- Component masses

- Finite-size effects

  Black holes do not exhibit finite-size effects

- Electromagnetic counterpart

  EM emission requires matter, so at least one neutron star

  The binary parameters need to satisfy certain criteria

- Merger remnant

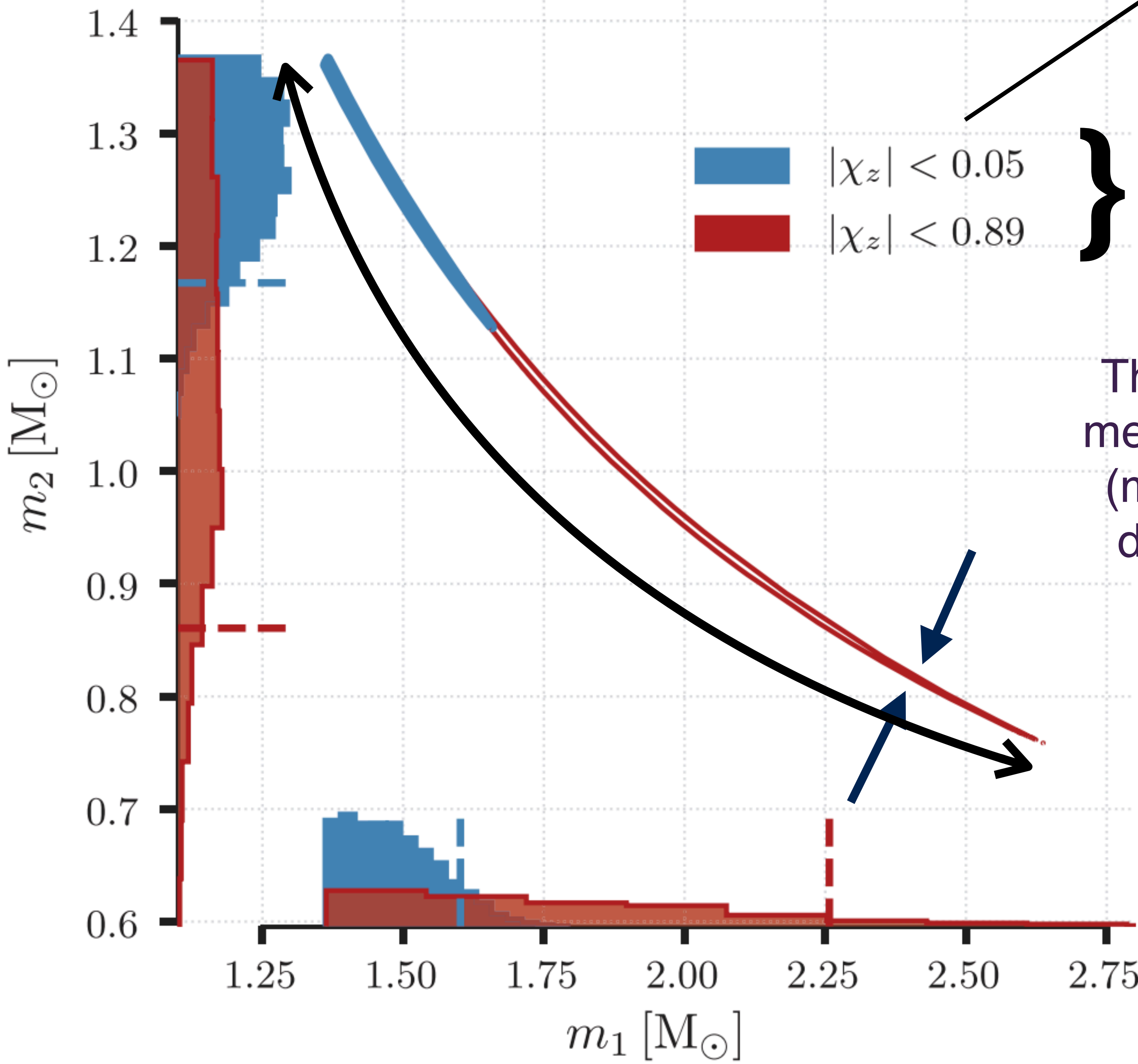
  A neutron star remnant can only come from a neutron star binary

  Relation between remnant and EM counterpart

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

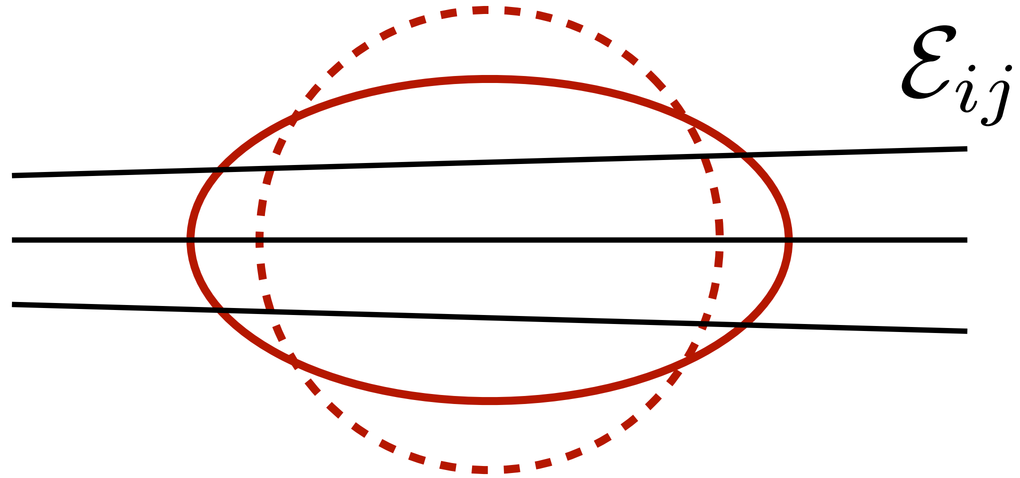
The chirp mass is
measured very well
(main uncertainty
due to distance)

The GW170817 masses
are consistent with
galactic binaries

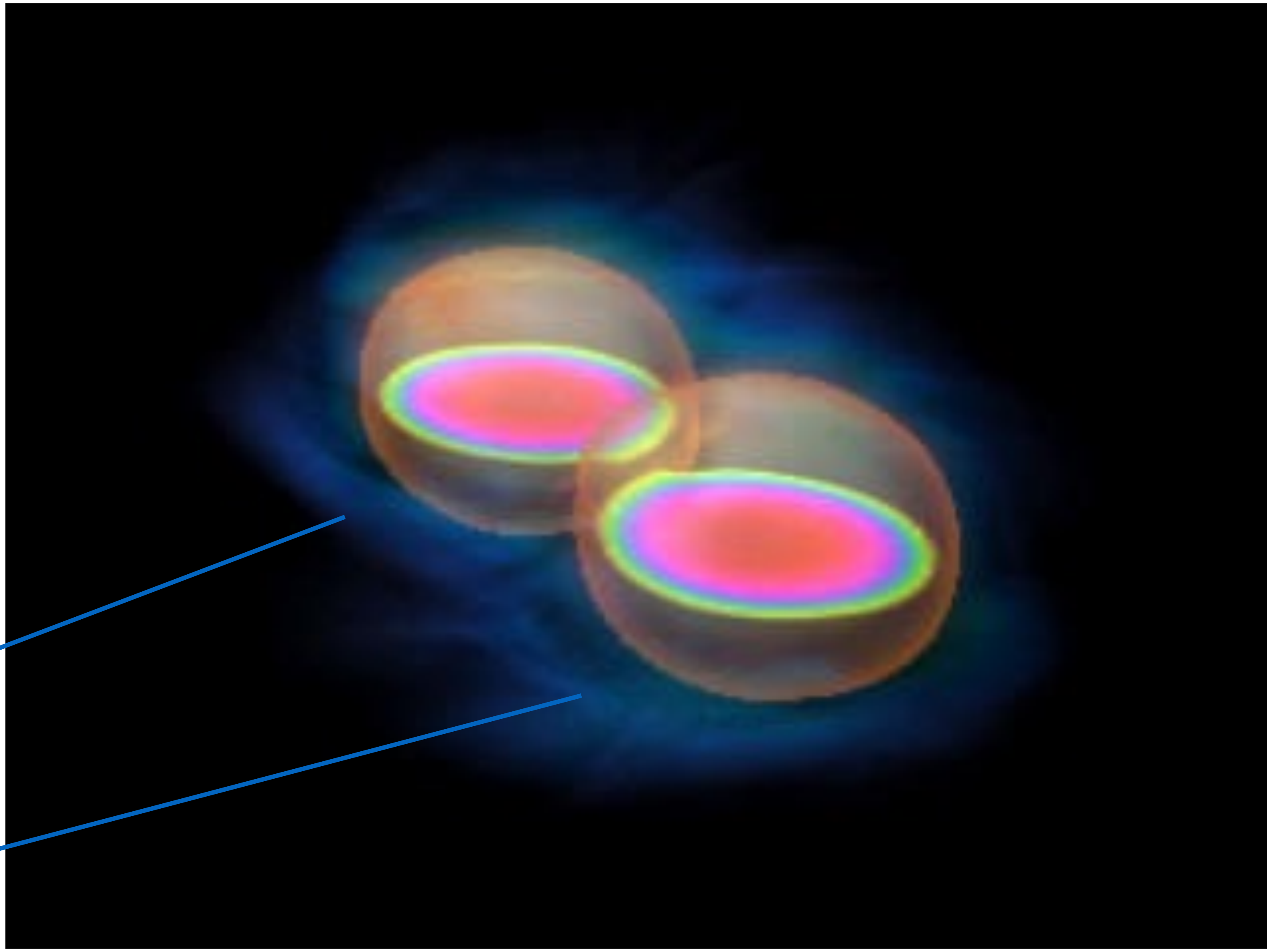
LVC (arxiv:1710.05832)

PE: Veitch+ (arxiv:1409.7215)

Tidal interactions



Credit: Aaron Zimmerman



Calder

Tidal deformability

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

The quadrupole deformation
removes binding energy and sources energy emission
Both affect the GW phase (observable)

GW170817 tides

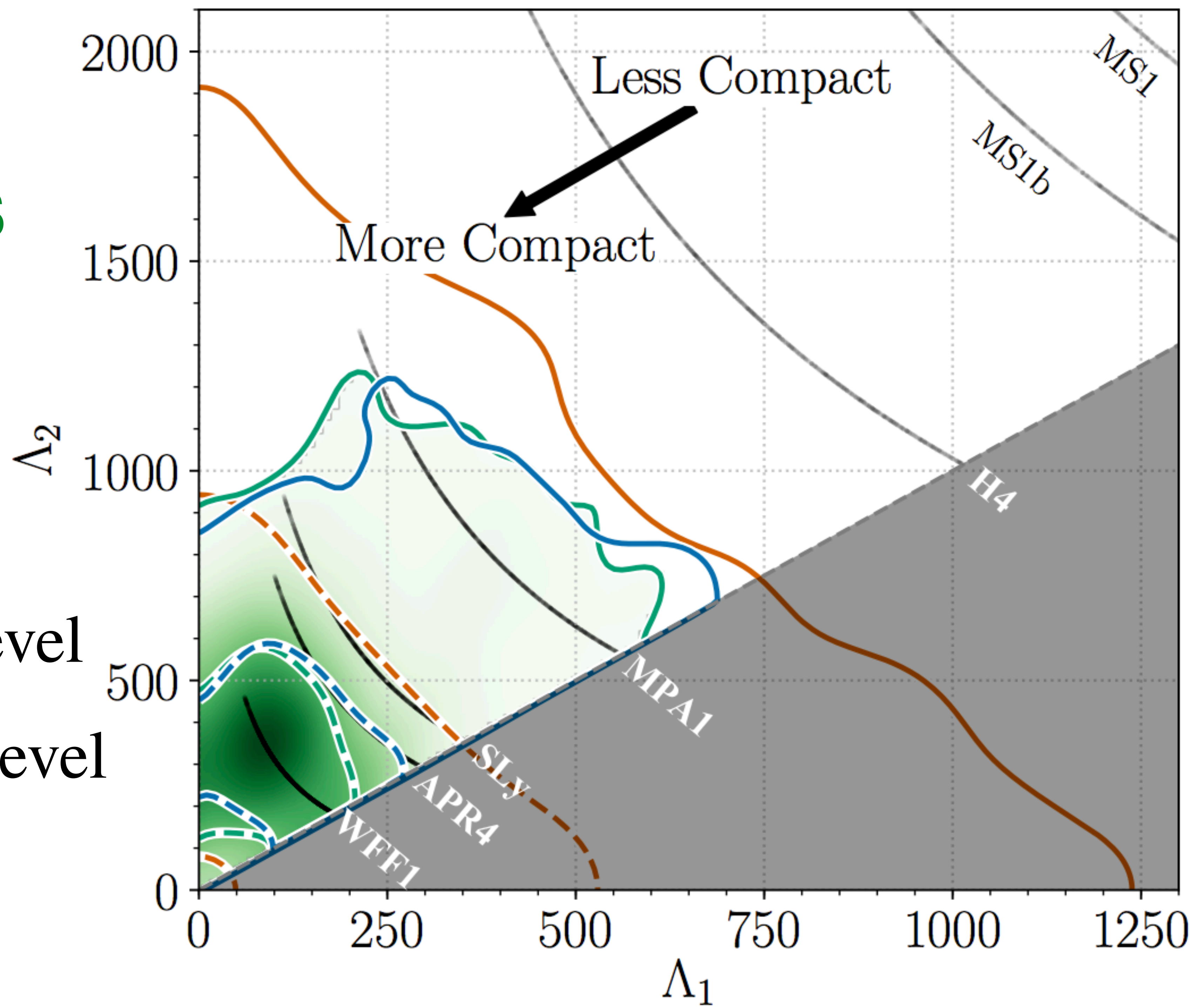
Independent EoSs

Same hadronic EoS

Spectral EoS parametrization

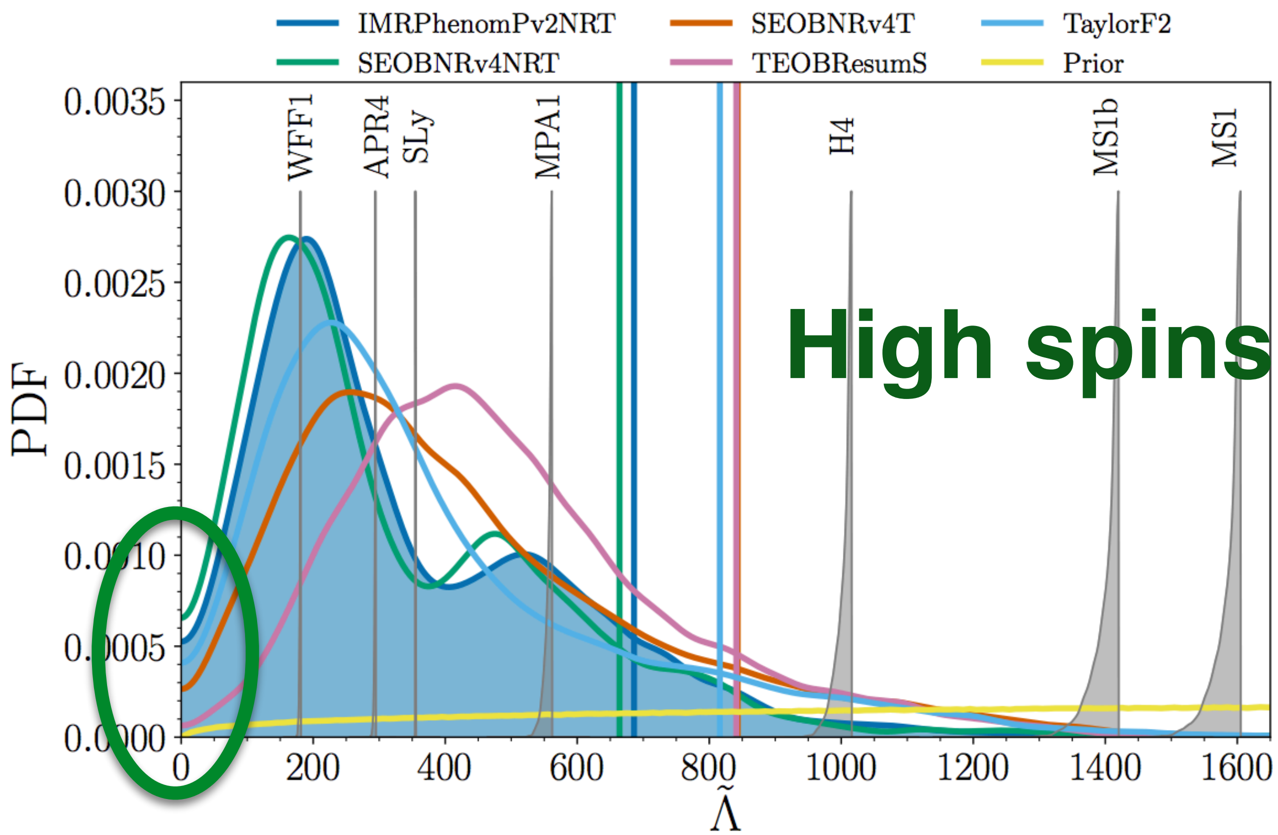
$\tilde{\Lambda} \lesssim 700$ at the 90 % level

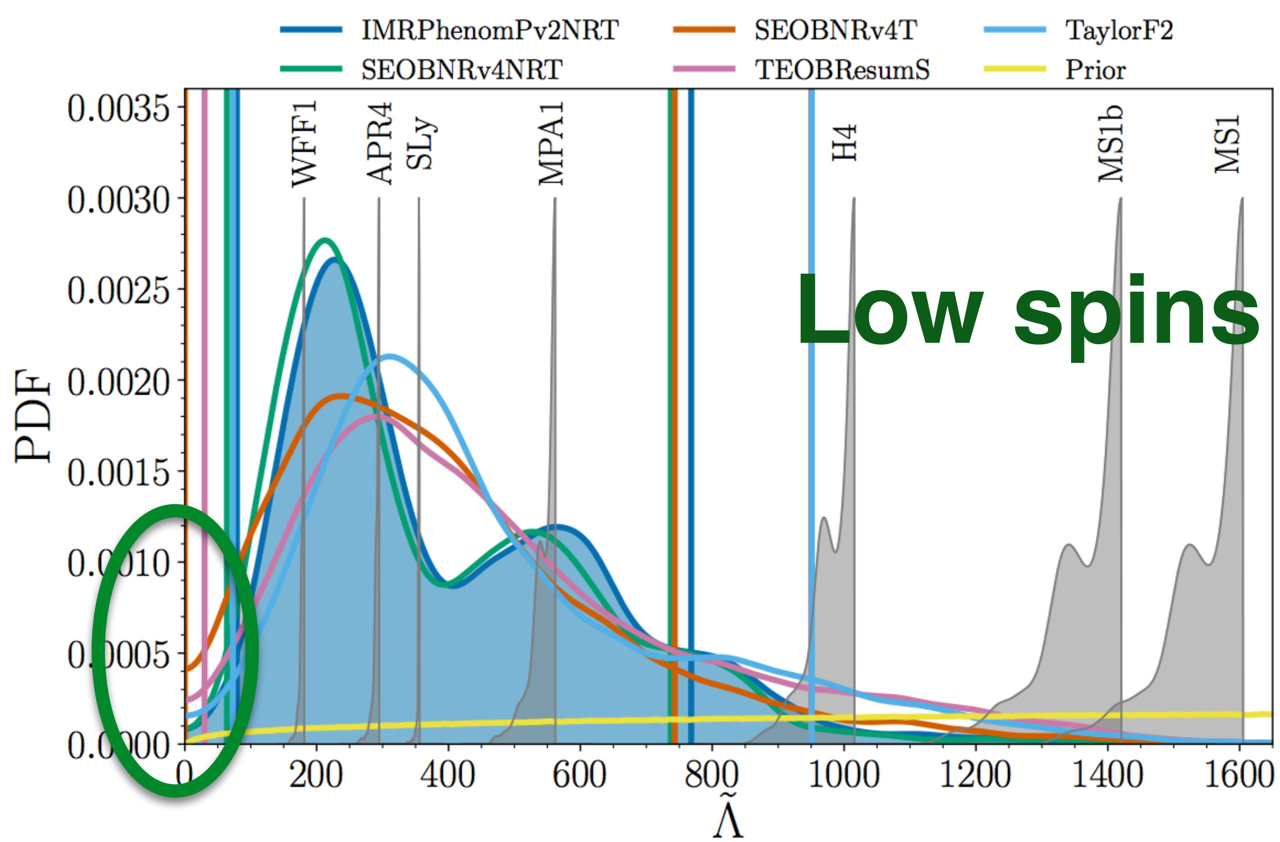
$R \lesssim 13\text{km}$ at the 90 % level



LVC (arxiv:1805.11581)
PE: Veitch+ (arxiv:1409.7215)
Waveform: Dietrich+ (arxiv:1804.02235)
Universal relations: Yagi and Yunes (arxiv:1512.02639), Chatziioannou+ (arxiv:1804.03221)
EoS Parametrization: Lackey and Wade (arxiv:1410.8866), Carney+ (arxiv:1805.11217)

GW170817 finite-size effects





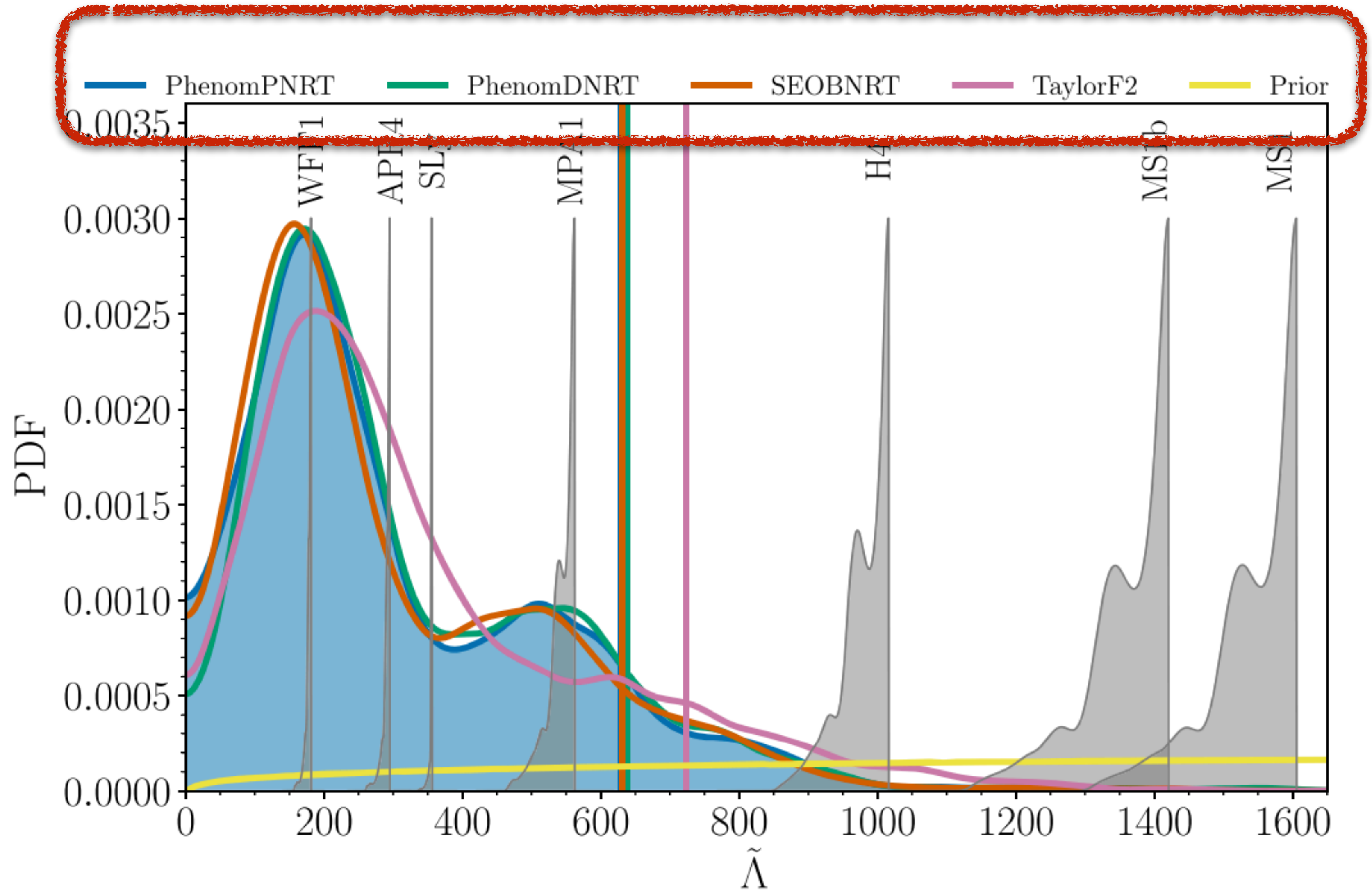
"Detection" of tidal effects
(in 1 binary component)
only if we assume low spins.
GW170817 could be a pair of
highly spinning black holes.

LVC (arxiv:1811.12907)

PE: Veitch+ (arxiv:1409.7215)

Waveforms:
Dietrich+ (arxiv:1804.02235),
Nagar+ (arxiv:1806.01772),
Hinderer+ (arxiv:1602.00599)

Waveform modeling

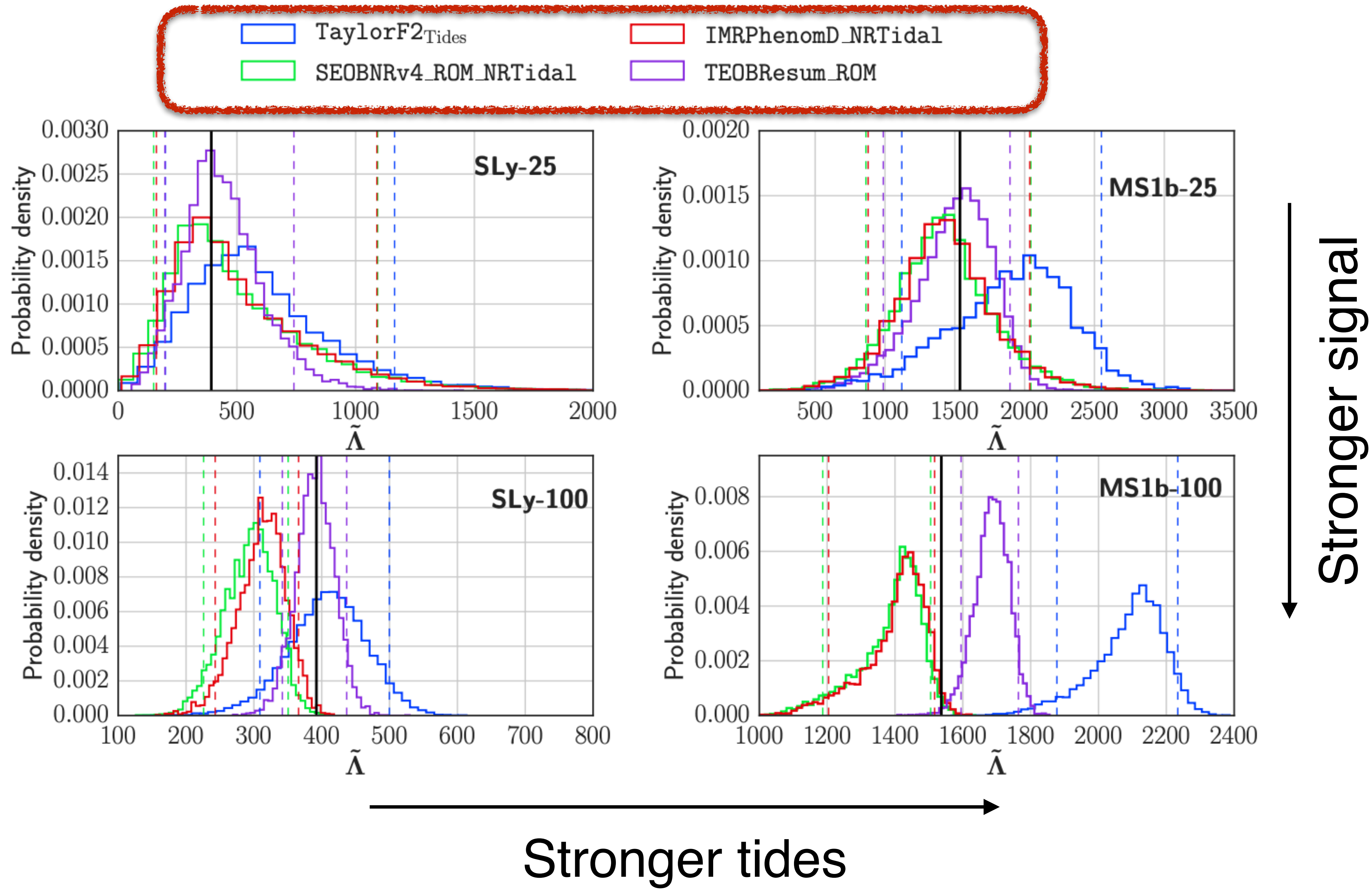


LVC (arxiv:1805.11580)

Models are constructed by adding tidal effects on a black hole binary baseline

Problems can arise both in the point particle (mass)
and the tidal sector (tides)

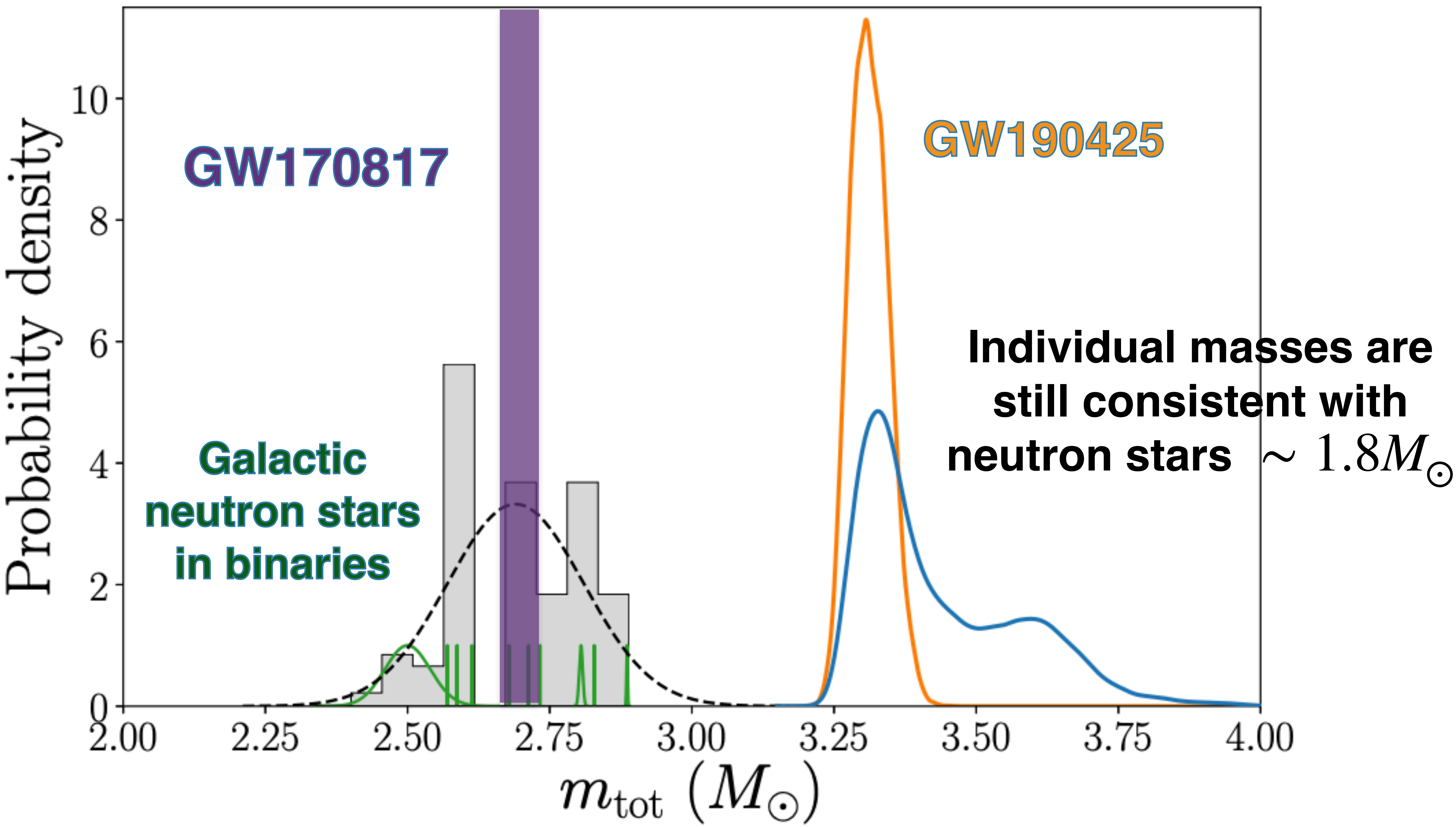
Where we are headed



GW170817 at design sensitivity would be affected by waveform systematic errors

Dudi+ (arxiv:1808.09749)
Samajdar+ (arxiv:1905.03118)

GW190425 masses



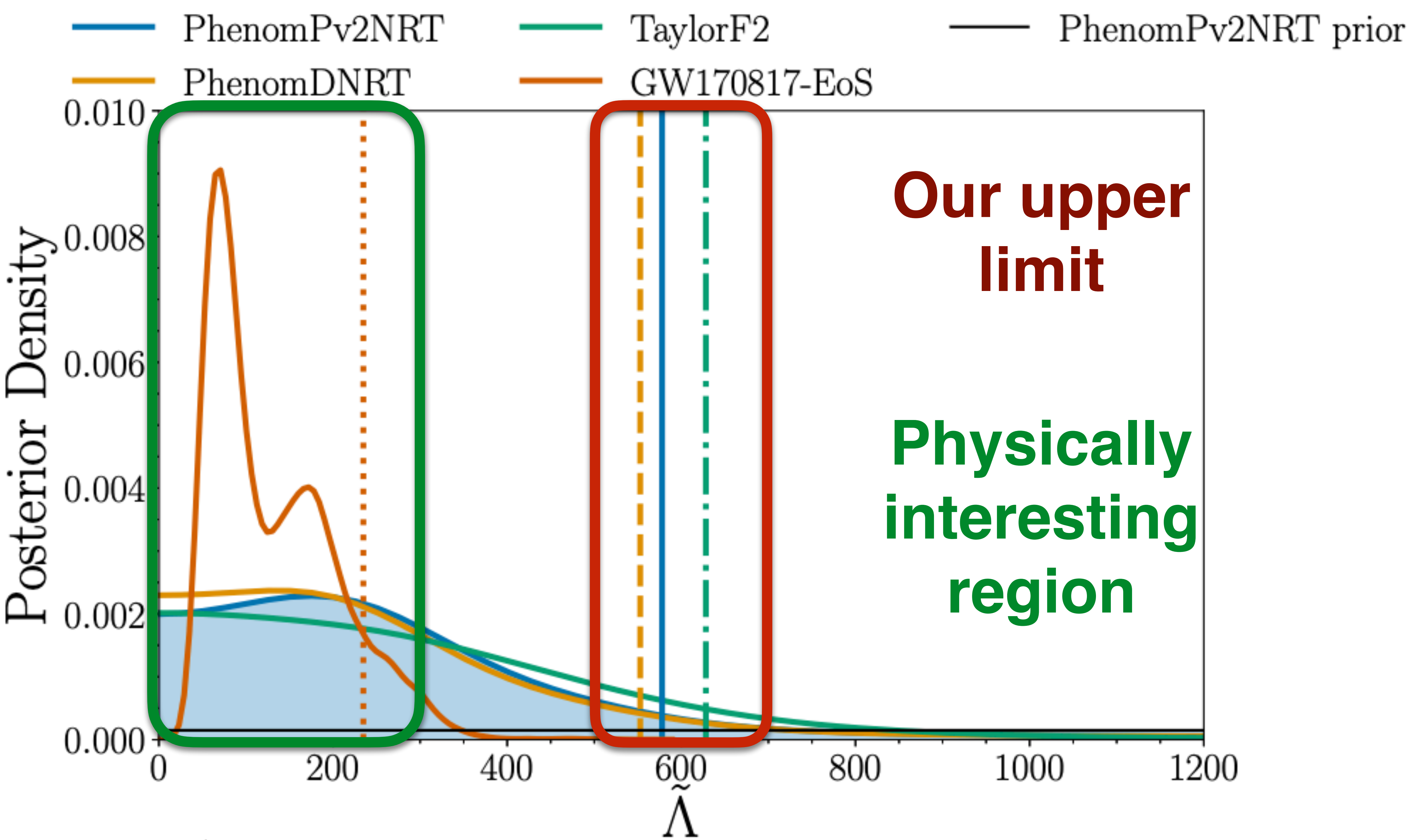
LVC (arxiv:2001.01761)

PE: Veitch+ (arxiv:1409.7215)

Waveform: Dietrich+ (arxiv:1804.02235)

GW190425 finite-size effects

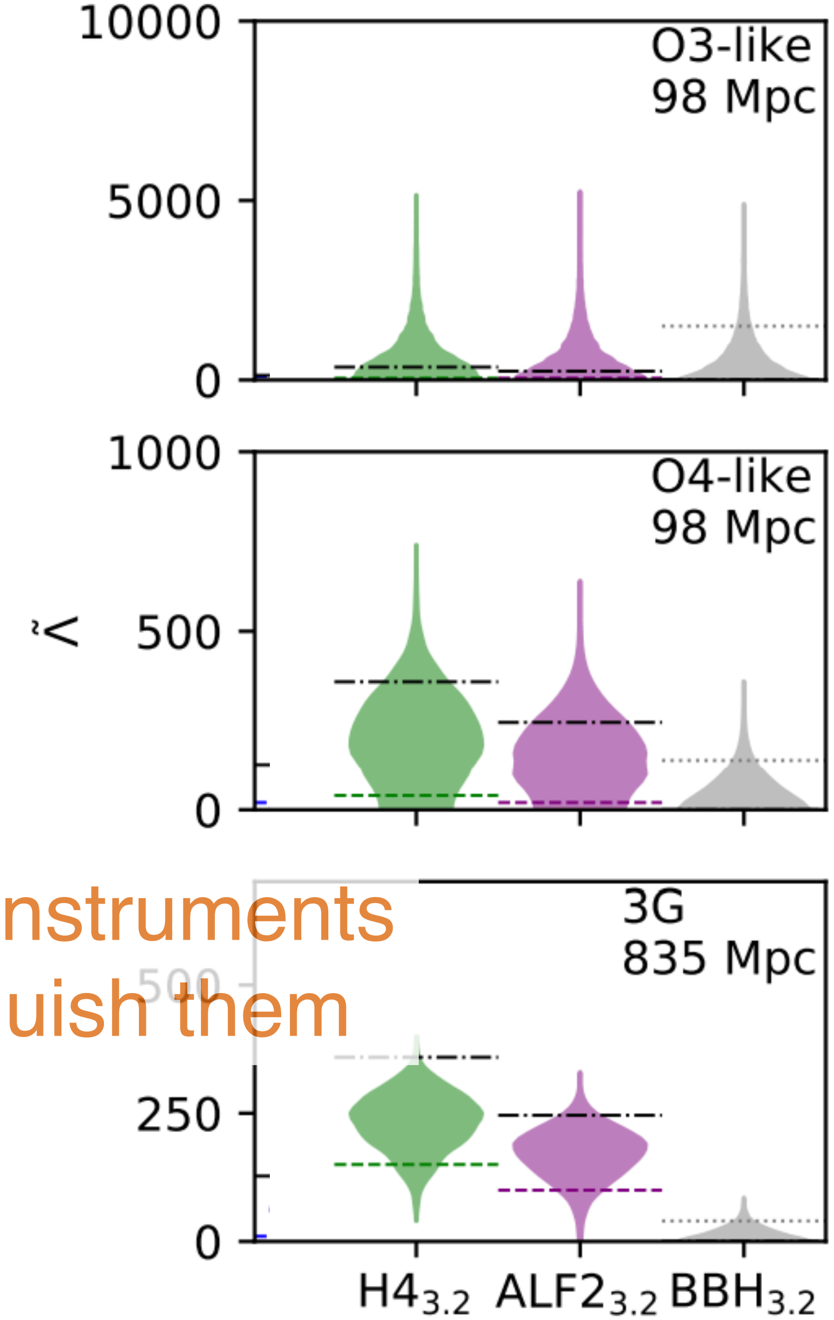
Pro: massive bodies form binaries and merge
Con: tidal interactions are intrinsically weaker



LVC (arxiv:2001.01761)
PE: Veitch+ (arxiv:1409.7215)
Waveform: Dietrich+ (arxiv:1804.02235)

High mass events

Total mass of $3.2M_\odot$ (slightly smaller that GW190425)

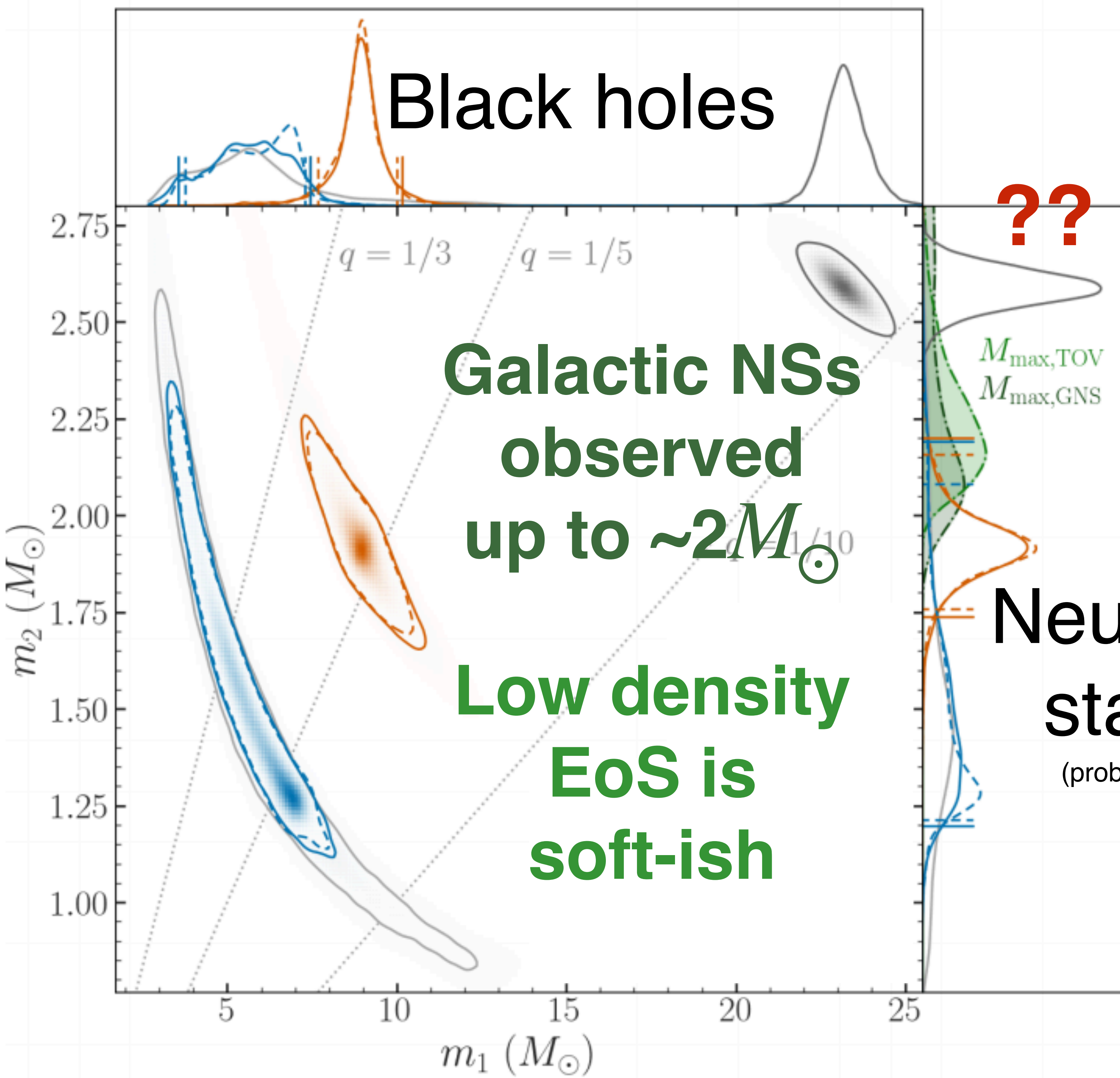


Neutron stars and black holes are indistinguishable

Need 3G instruments to distinguish them

Chen+ (arxiv:2001.11470)

Low-mass observations



Neutron stars

(probably)

No tidal signature in any event, need external input?

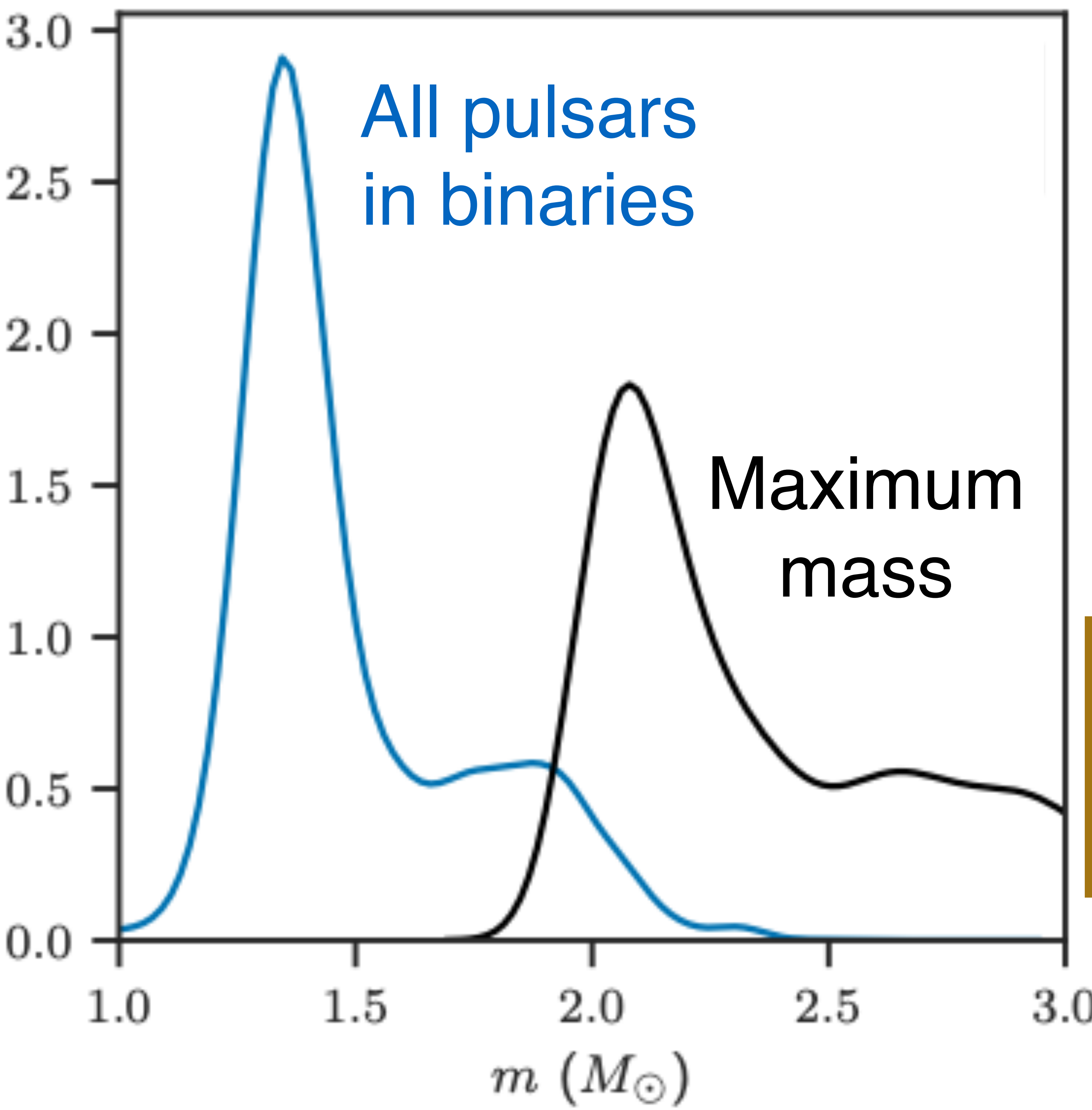
A $2.6M_\odot$ object:

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

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

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)

Input from galactic pulsars

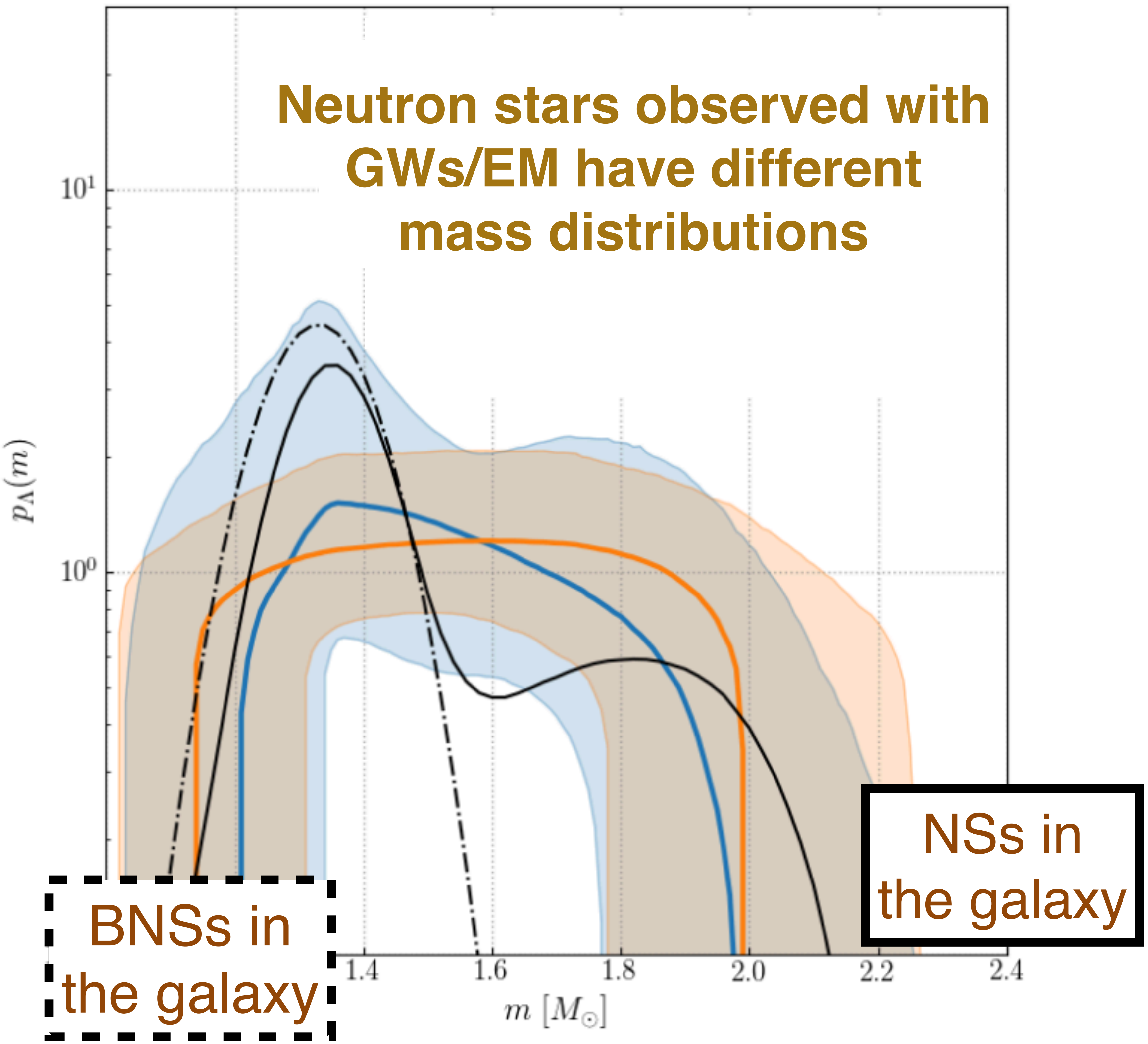


Bimodal distribution and possibility of a cutoff

Do galactic pulsars have the same properties as LIGO sources?

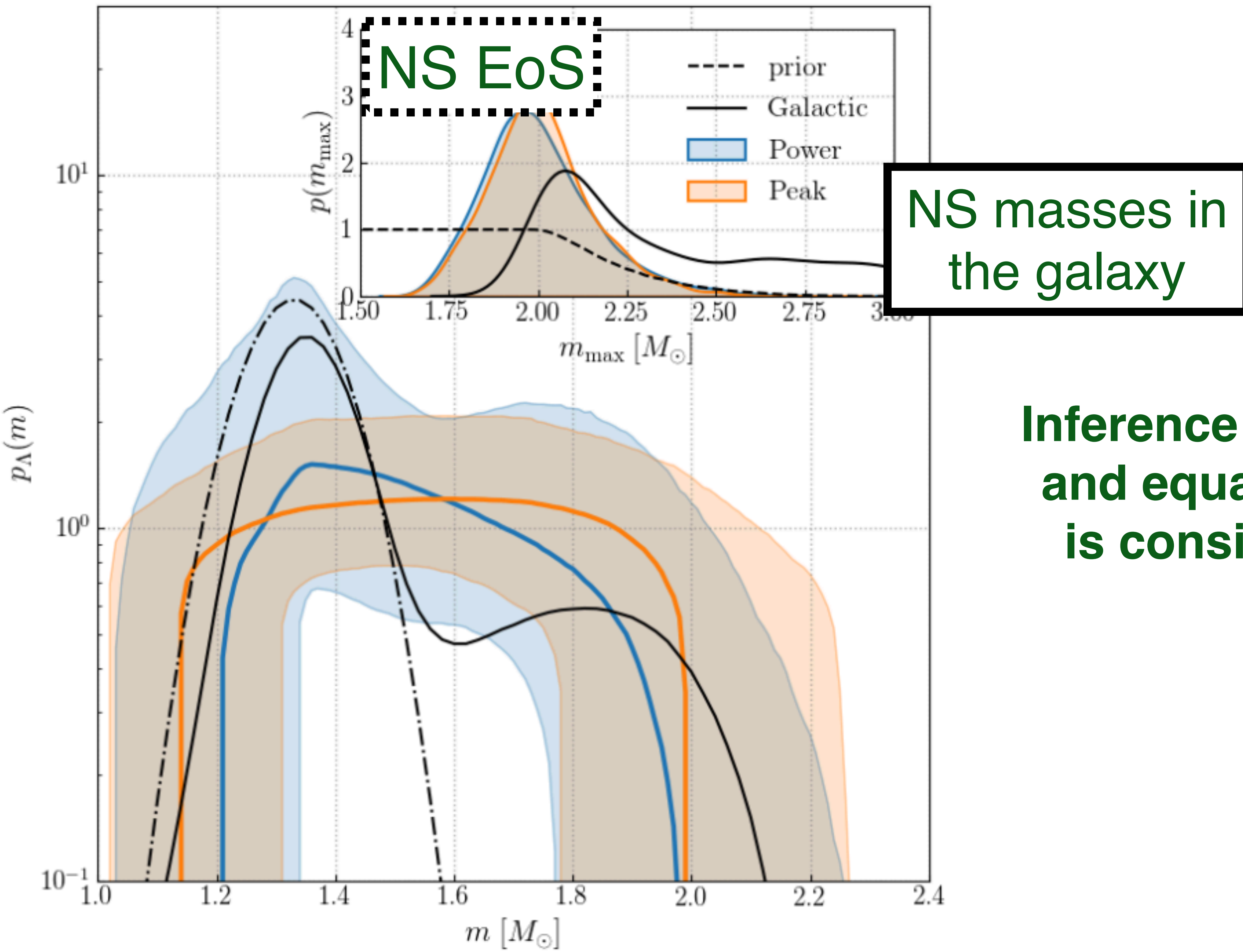
Alsing+ (arxiv:1709.07889)
Antoniadis+ (arxiv:1605.01665)
Farr and Chatziioannou (arxiv:2005.00032)

Neutron star masses



Landry+ (arxiv:2107.04559)
LVC (arxiv:2111.03634)

Input from the Equation of State

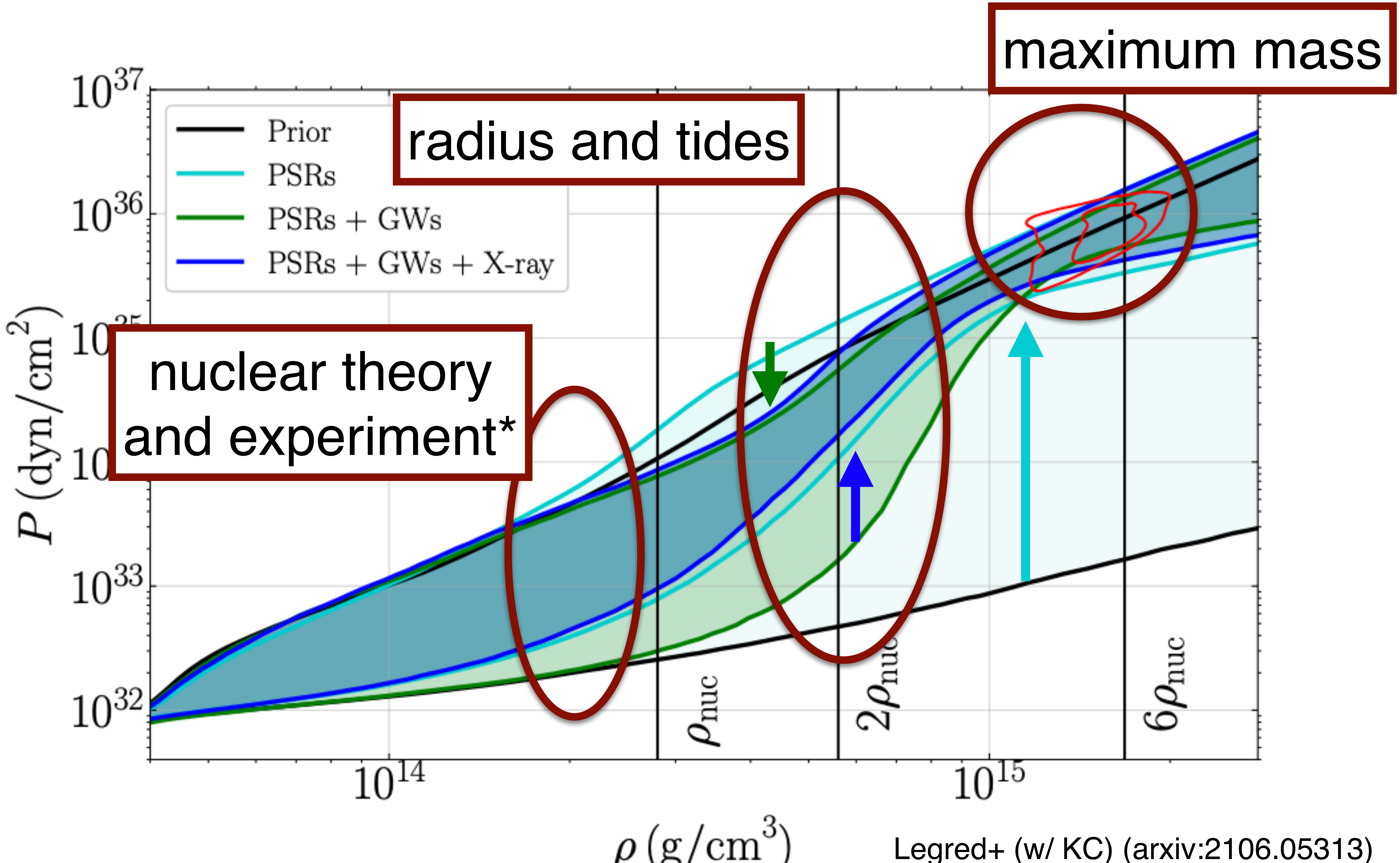


Inference from masses and equation of state is consistent so far

Landry+ (arxiv:2107.04559)
LVC (arxiv:2111.03634)

The Equation of state model

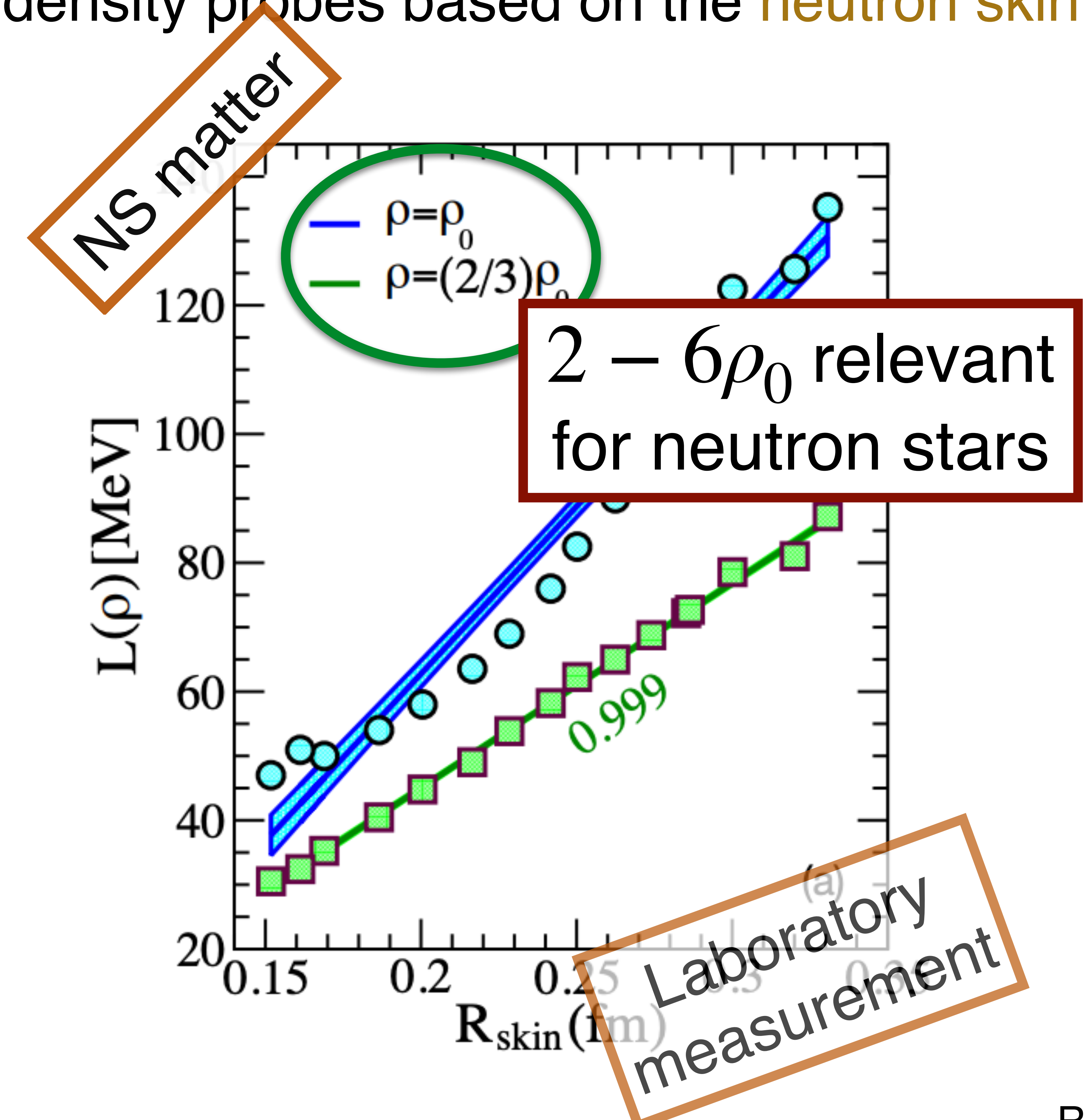
Different measurements probe different density regimes



Legred+ (w/ KC) (arxiv:2106.05313)
Landry+ (w/ KC) (arxiv:2003.04880)

Nuclear experiment

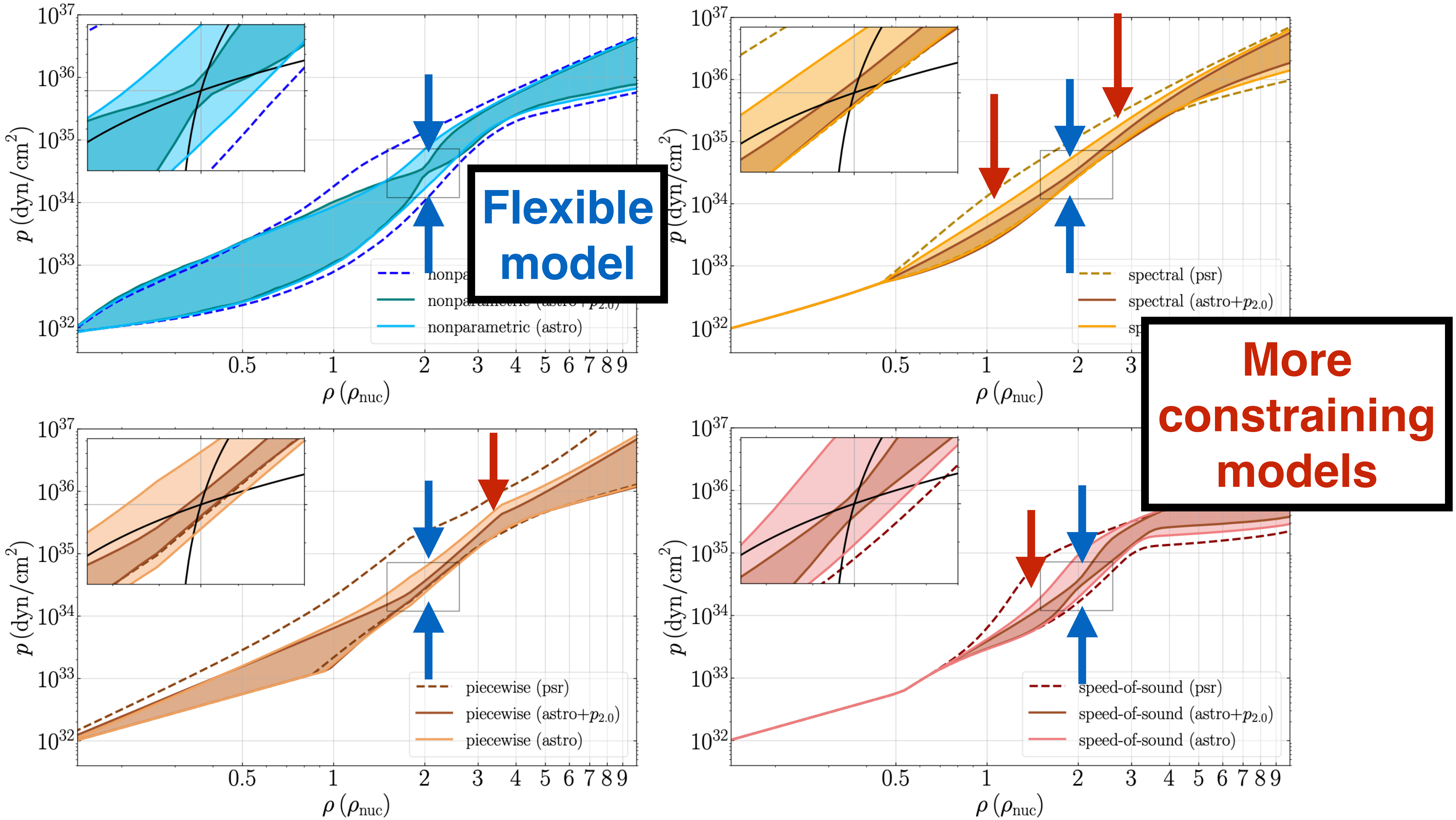
Terrestrial low density probes based on the neutron skin thickness of Pb



Reed+ (arxiv:2101.03193)

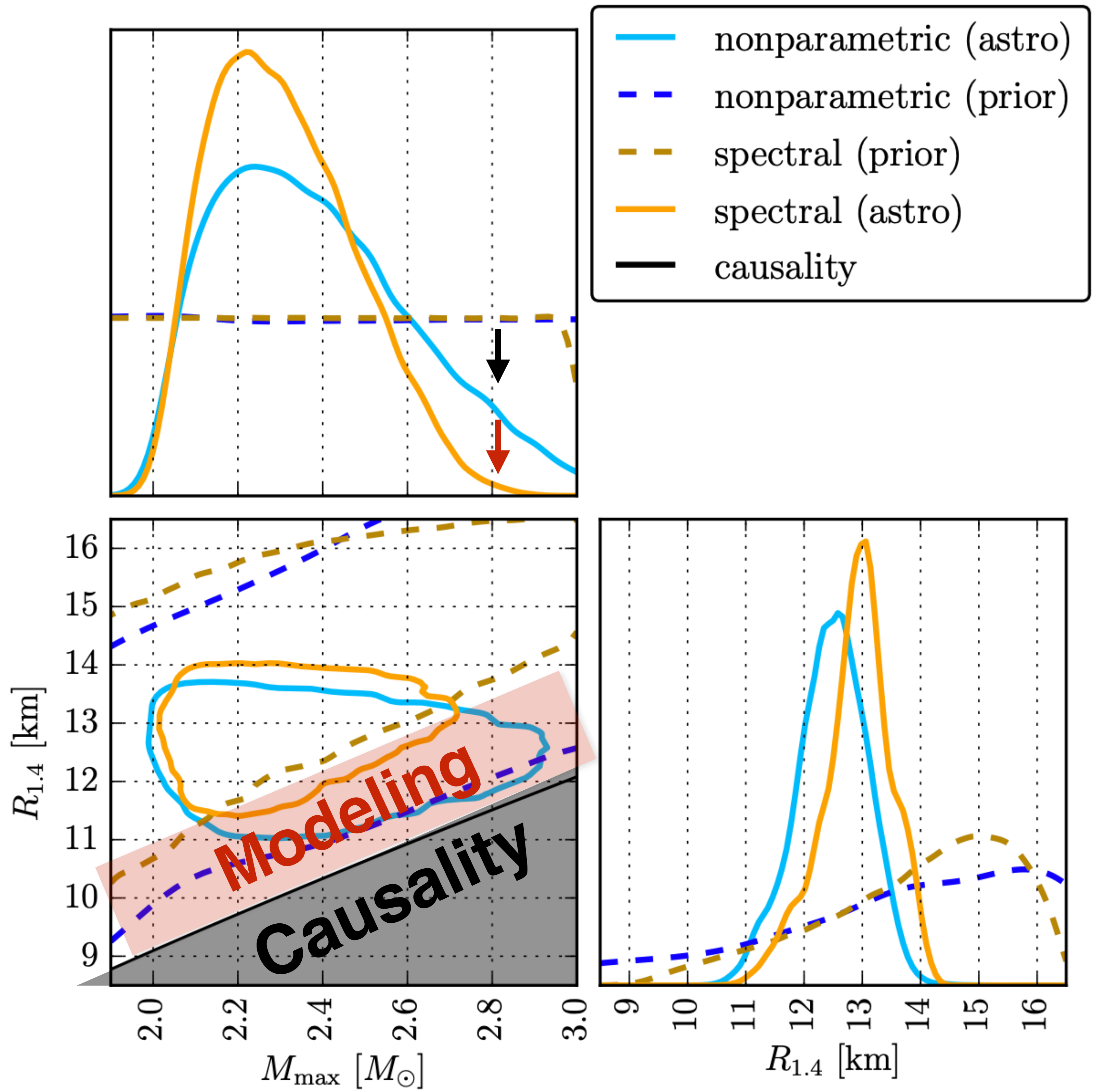
Intra-density correlations

Phenomenological models might introduce unphysical (or at least unjustified) correlations



Legred+ (w/ KC) (arxiv:2201.06791)

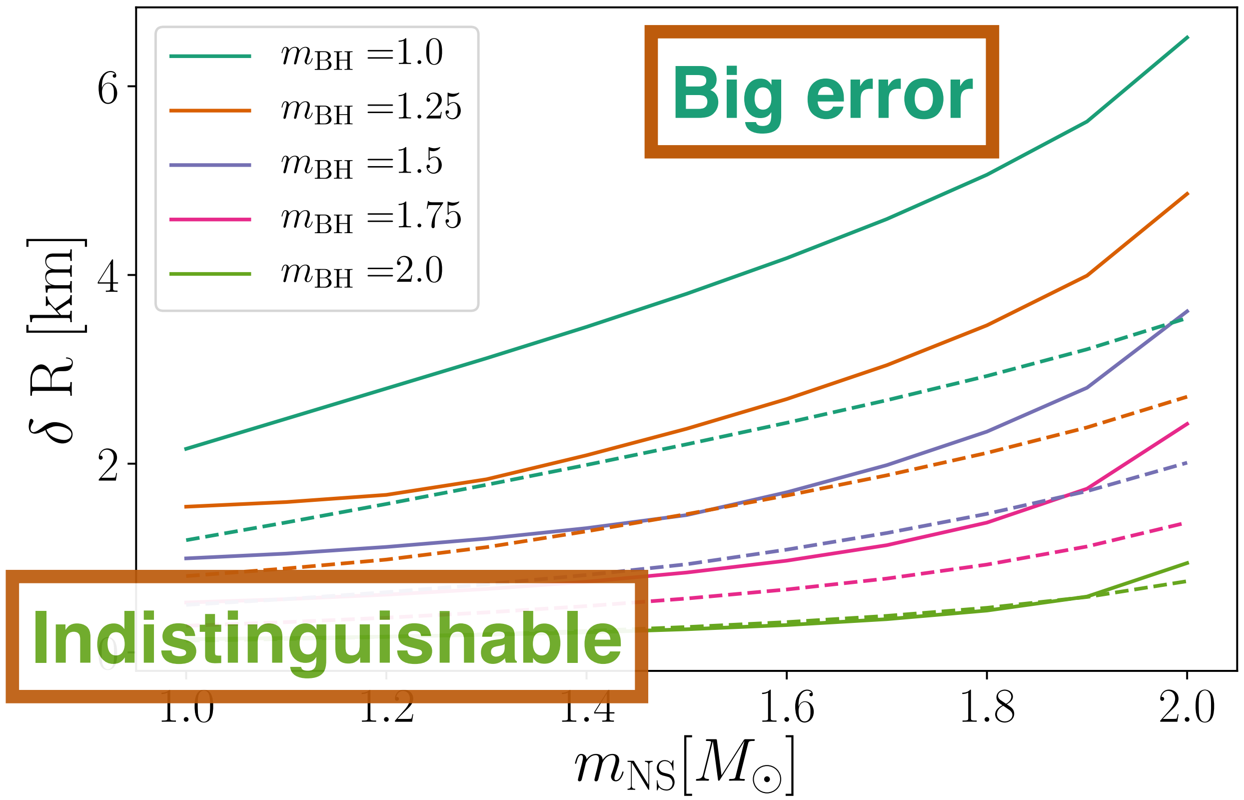
The maximum mass from the Equation of state



Legred+ (w/ KC) (arxiv:2201.06791)

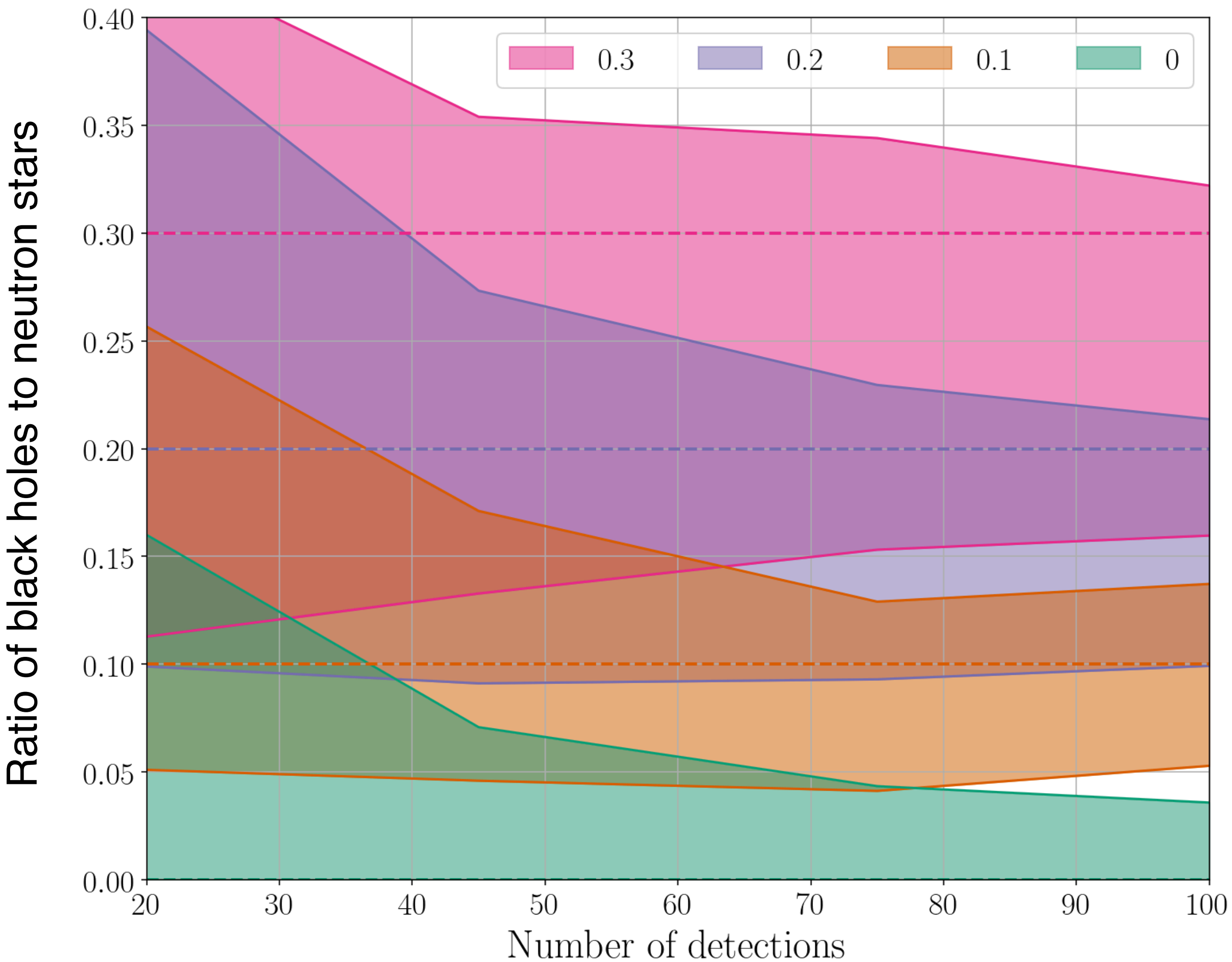
What if black holes and neutron stars overlap?

Back to finite-size effects



Chen and Chatziioannou (arxiv:1903.11197)
Yang+ (arxiv:1710.05891)

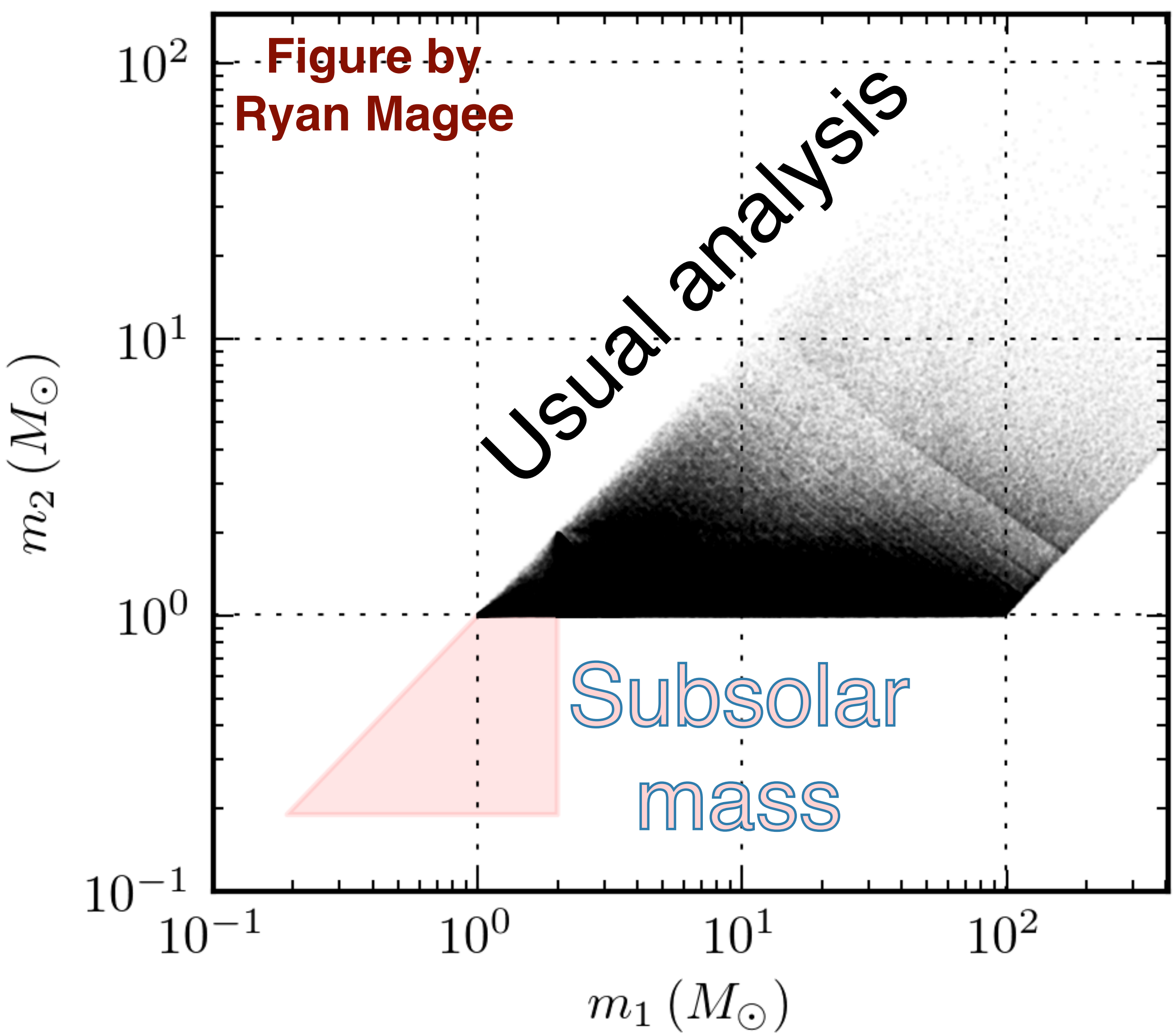
Constrain or detect black holes based on the absence of tides

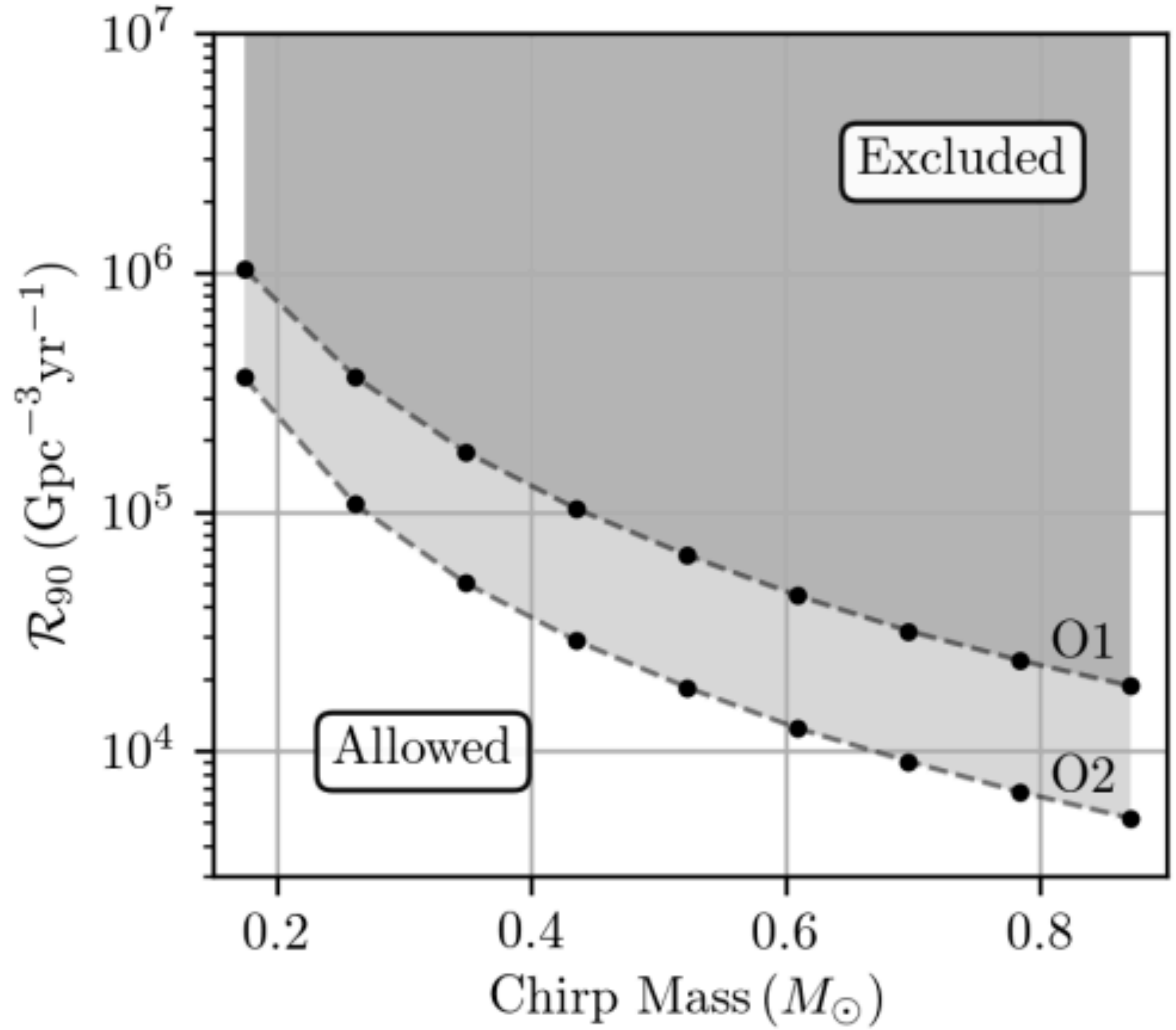


Chen and Chatziioannou (arxiv:1903.11197)

Subsolar-mass black holes

Check for the existence of very light black holes



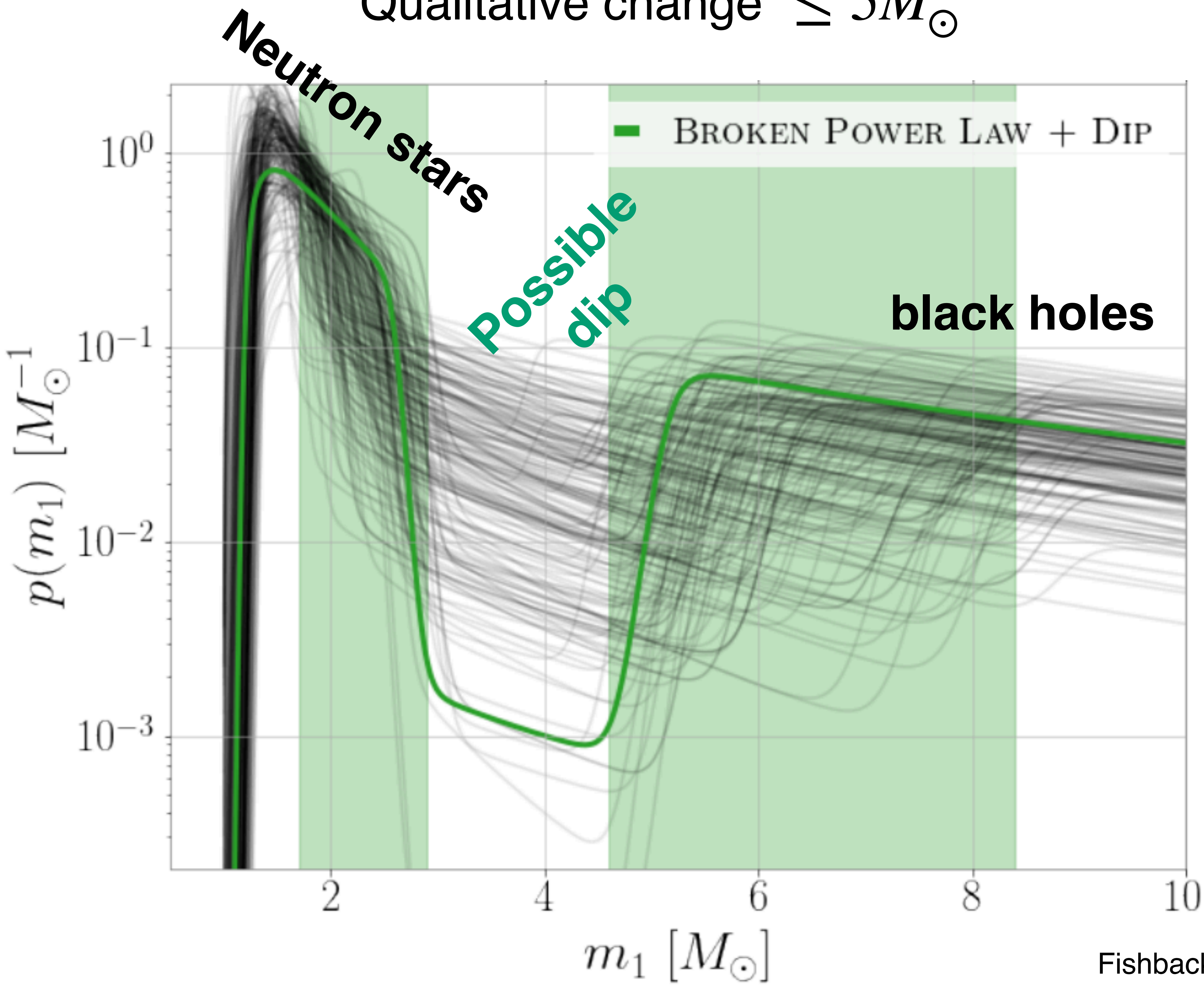


LVC (arxiv:1904.08976)

Method: Magee+ (arxiv:1808.04772)

The whole mass distribution

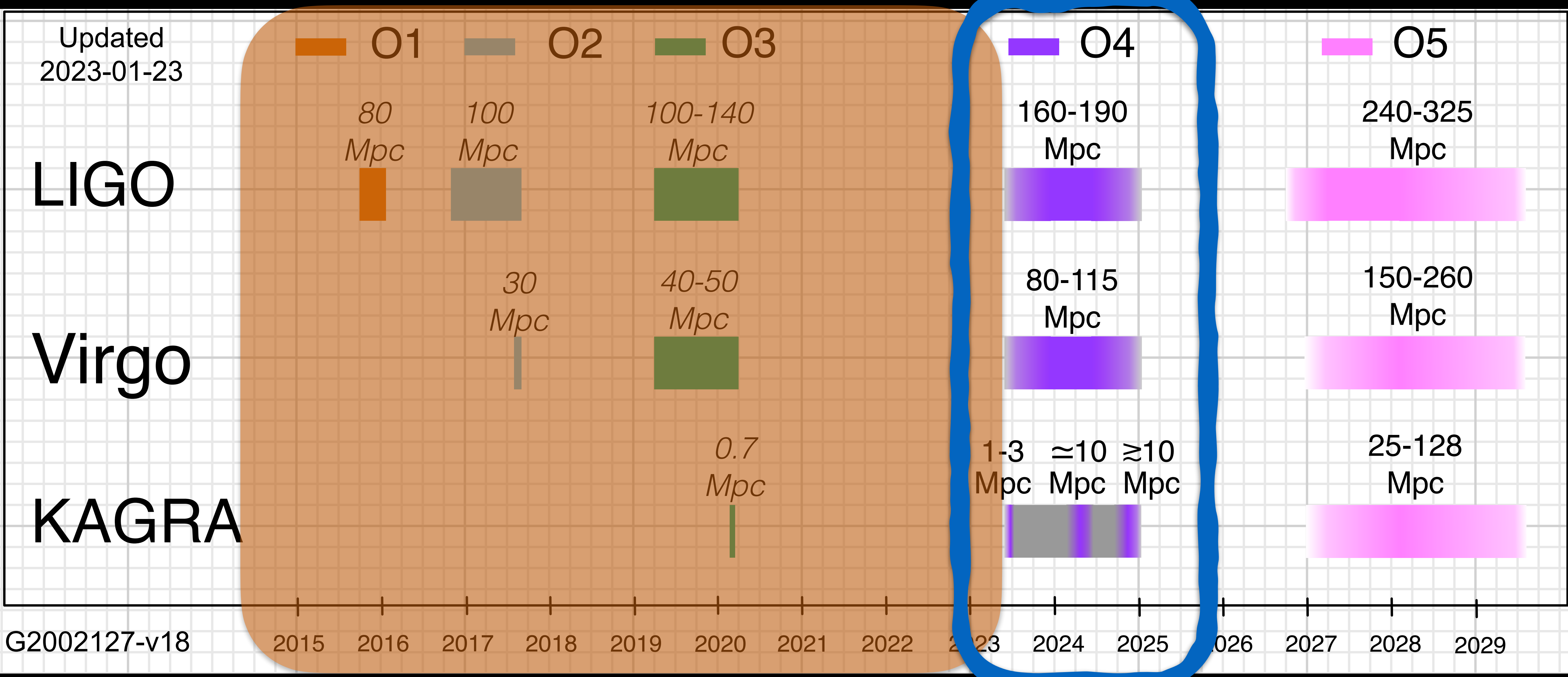
Qualitative change $\leq 5M_\odot$



Fishback+ (arxiv:2006.13178)
Farah+ (arxiv:2111.03498)
LVC (arxiv:2111.03634)

The next steps

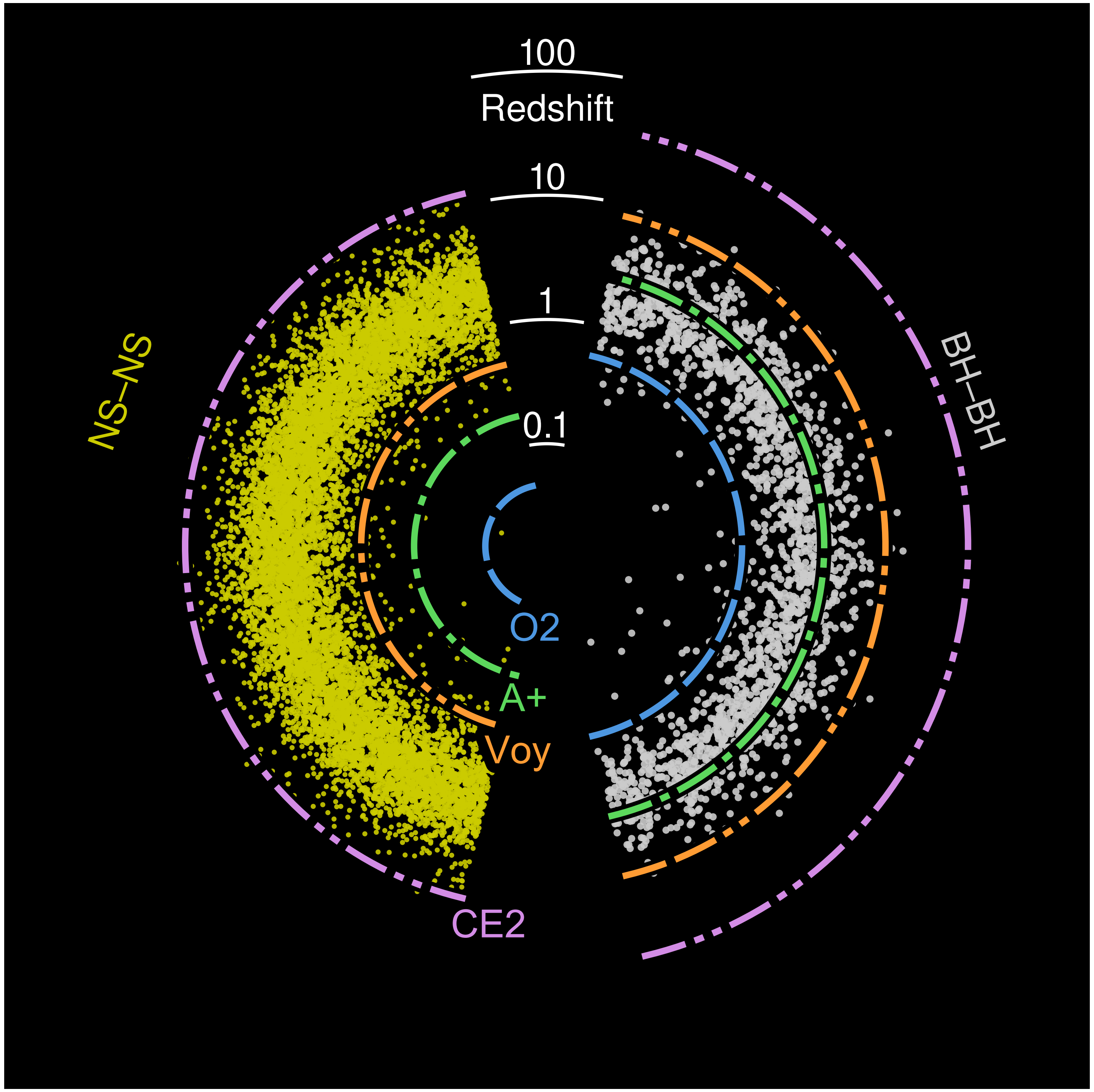
Expect $\mathcal{O}(10)$ BNS detections



2 NSBH candidates

LVC (G2002127 Tech Doc)

Even further ahead



O2: 10 binary black holes, 1 binary neutron star

O5/A+: 2xLIGO

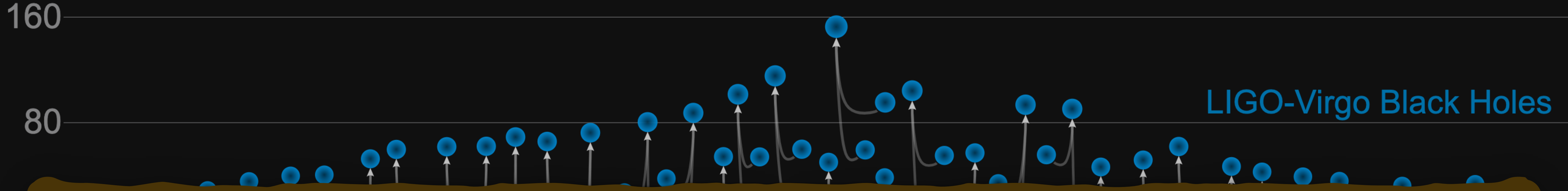
Voyager: ceiling for current sites

CE2: 3rd gen detectors, science case

Hall/Vitale/MIT

Masses in the Stellar Graveyard

in Solar Masses



Gravitational wave observations can probe the properties of low mass compact objects

- ***Current sensitivity: mostly upper limits on tides/radius, better constraints for light neutron stars, difficult to distinguish black holes and neutron stars above*** $\sim 1.6\, M_{\odot}$***, need external input***

- ***3rd-generation detectors:*** $\mathcal{O}(10)$ ***improvements, thousands of detections, massive neutron stars, postmerger signal***

LIGO-Virgo | Frank Elavsky, Aaron Geller | Northwestern