Title: Gravitational Laboratories for Nuclear Physics (in light of GWTC-2)

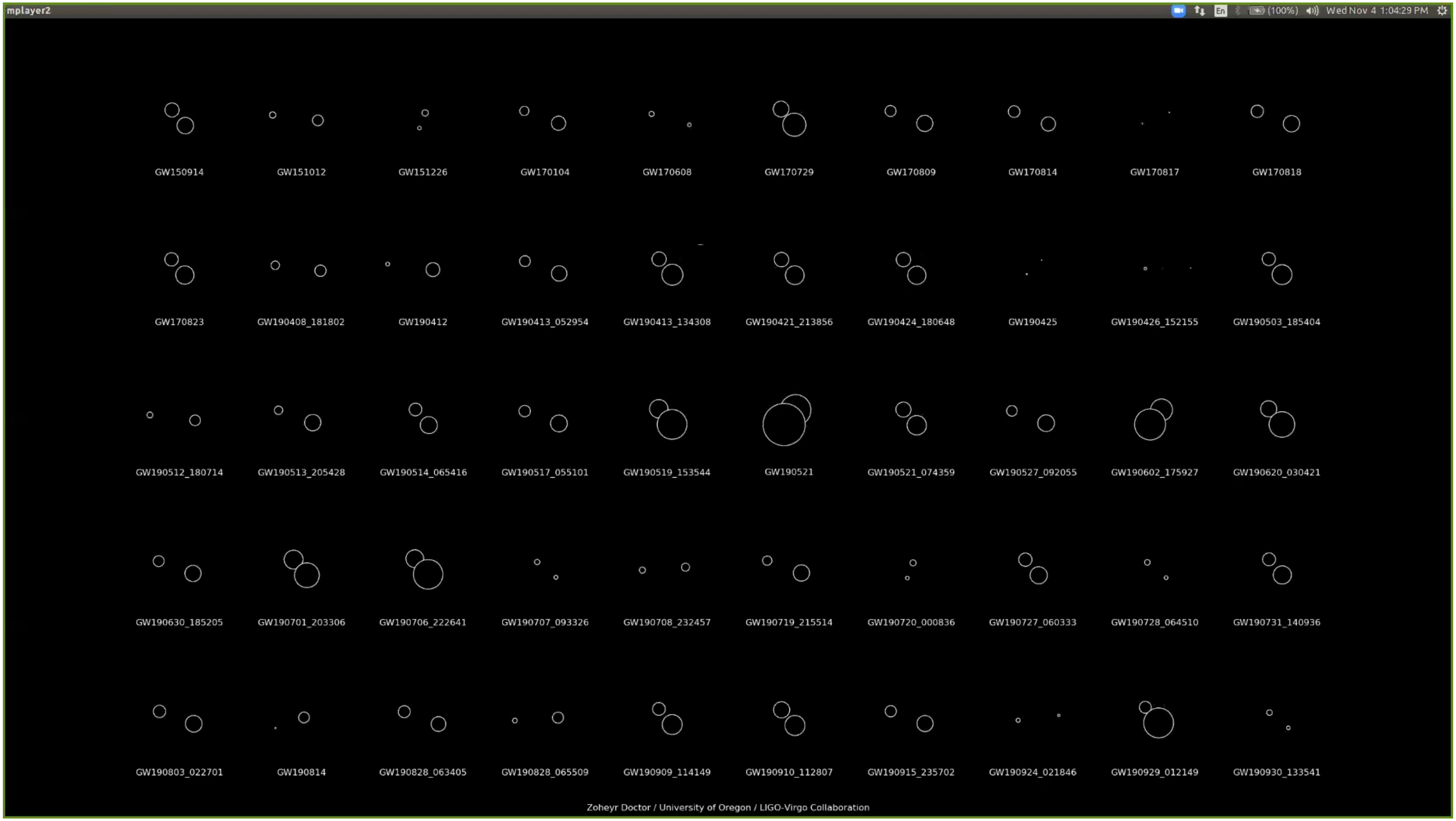
Speakers: Reed Essick

Series: Colloquium

Date: November 04, 2020 - 2:00 PM

URL: http://pirsa.org/20110041

Abstract: Gravitational waves provide a unique way to study the universe. From the initial direct detection of coalescing black holes in 2015, to the ground-breaking multimessenger observations of coalescing neutron stars in 2017, and continuing with the now routine detection of merging stellar remnants, gravitational wave astronomy has quickly matured into a key aspect of modern physics. After briefly discussing what we've begun to learn from the new gravitational-wave transient catalog published by the LIGO, Virgo, and KAGRA collaborations (GWTC-2), I will discuss novel tests of fundamental physics GWs enable. In particular, I will focus on our current understanding of matter effects during the inspiral of compact binaries and matter at supranuclear densities, including possible phase transitions, through tests of neutron star structure. Detailed knowledge of dynamical interactions between coalescing stars, observations of extreme relativistic astrophysical systems, terrestrial experiments, and nuclear theory provide complementary views of fundamental physics. I will show how combining aspects from all these will improve our understanding of dense matter through the example of how we can determine whether newly observed objects are neutron stars or black holes.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Wed Nov 4 1:04:29 PM
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GW151226
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GW170814
GW170817
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GW170823
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GW190527_092055
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GW190620_030421
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GW190720_000836
GW190727_060333
GW190728_064510
GW190731_140936
GW190803_022701
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GW190910_112807
GW190915_235702
GW190924_021846
GW190929_012149
GW190930_133541
Zoheyr Doctor / University of Oregon / LIGO-Virgo Collaboration

Gravitational Laboratories for Nuclear Physics

(in light of GWTC-2)

Reed Essick

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Perimeter Institute

GWTC-2 References

LIGO-Virgo-Kagra webinars start tomorrow! (Nov 5 at 10am ET)
register here:
https://us02web.zoom.us/webinar/register/WN_ATI9_eBQQfuRiGHjPuXAhw

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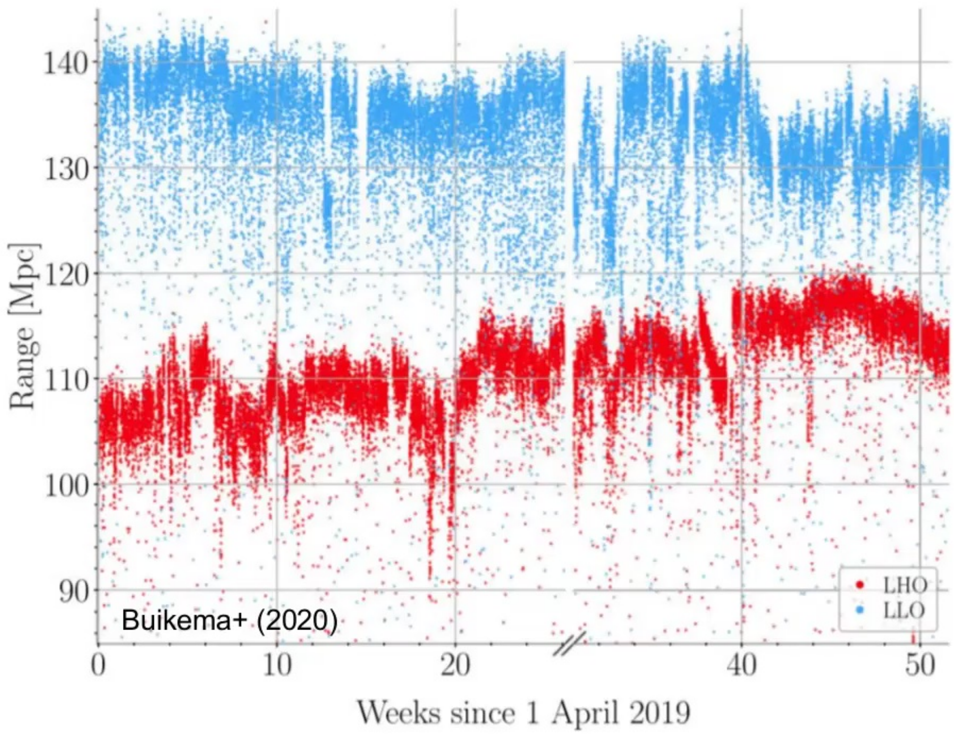
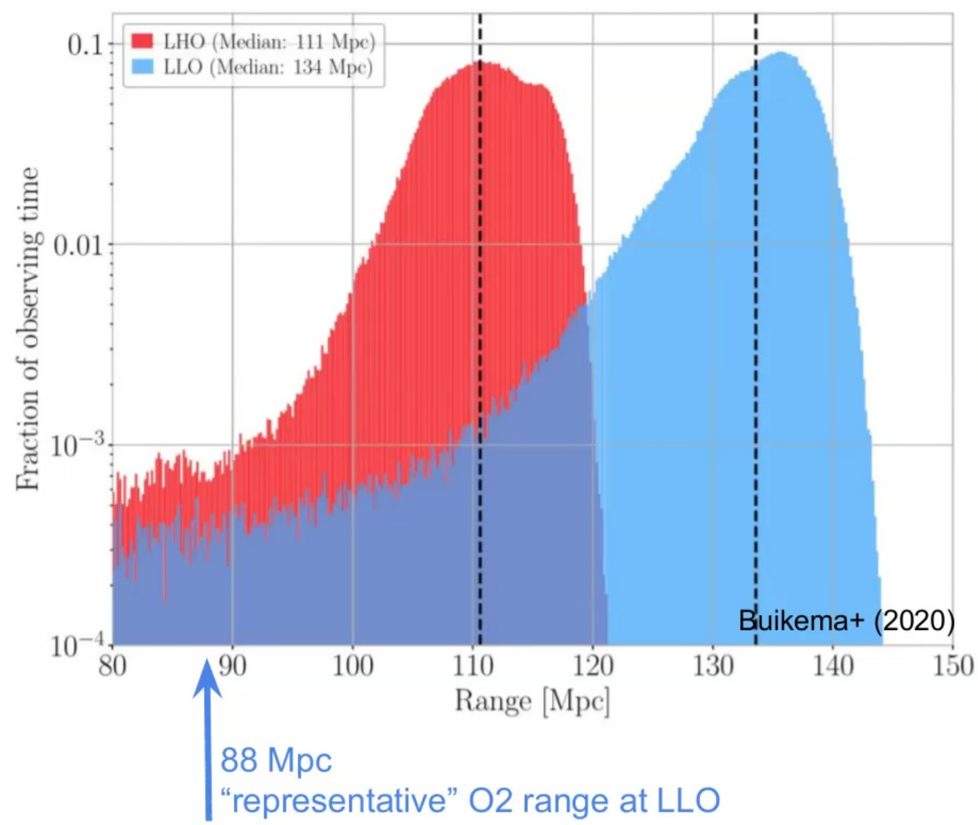
GWTC-2 Data Release (Gravitational Wave Open Science Center): https://www.gw-openscience.org/GWTC-2/

A. Buikema, et al., *Sensitivity and Performance of the Advanced LIGO Detectors in the Third Observing Run*. Phys. Rev. D 102, 062003 (2020).

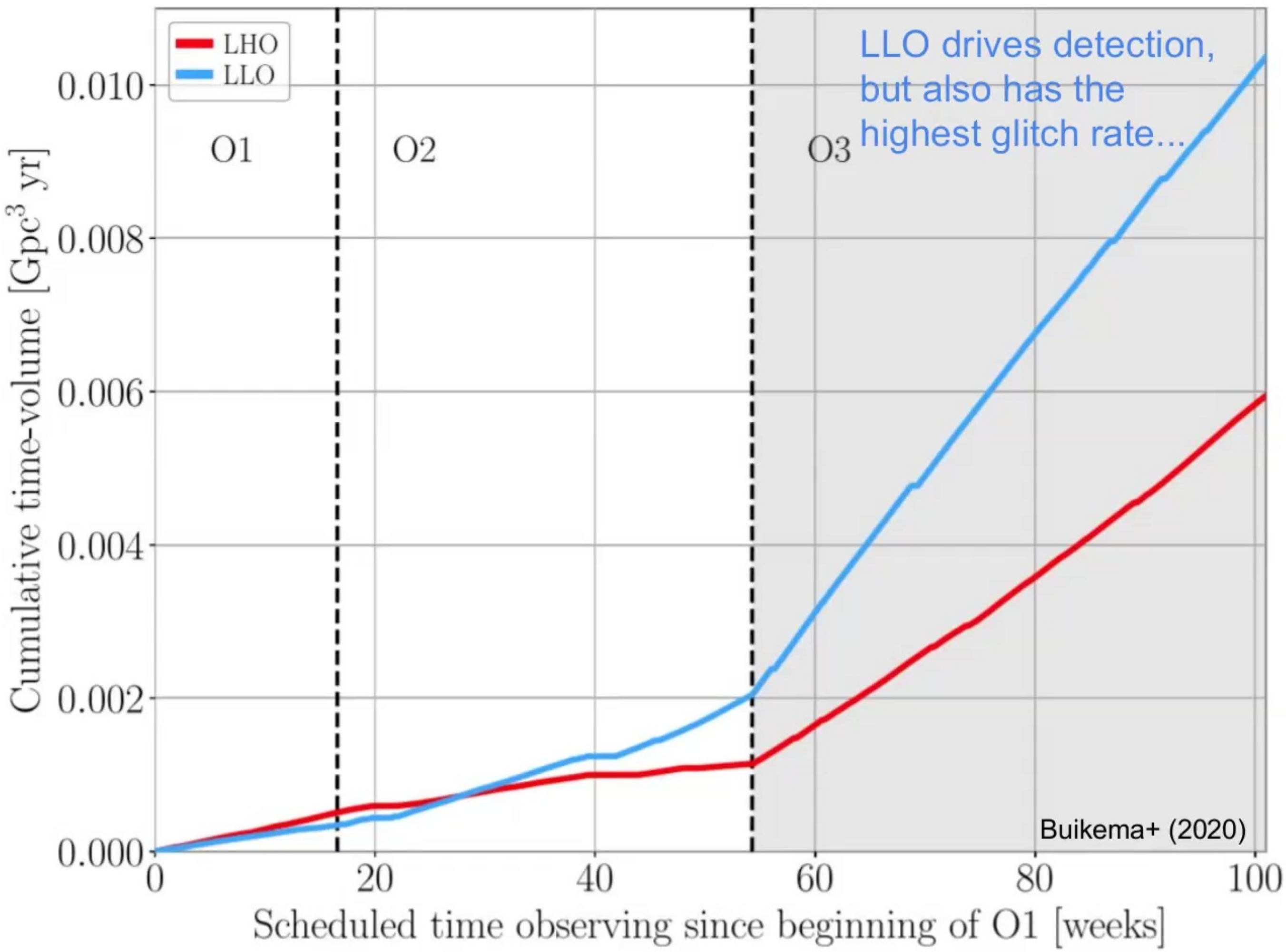
O3 LIGO Interferometers





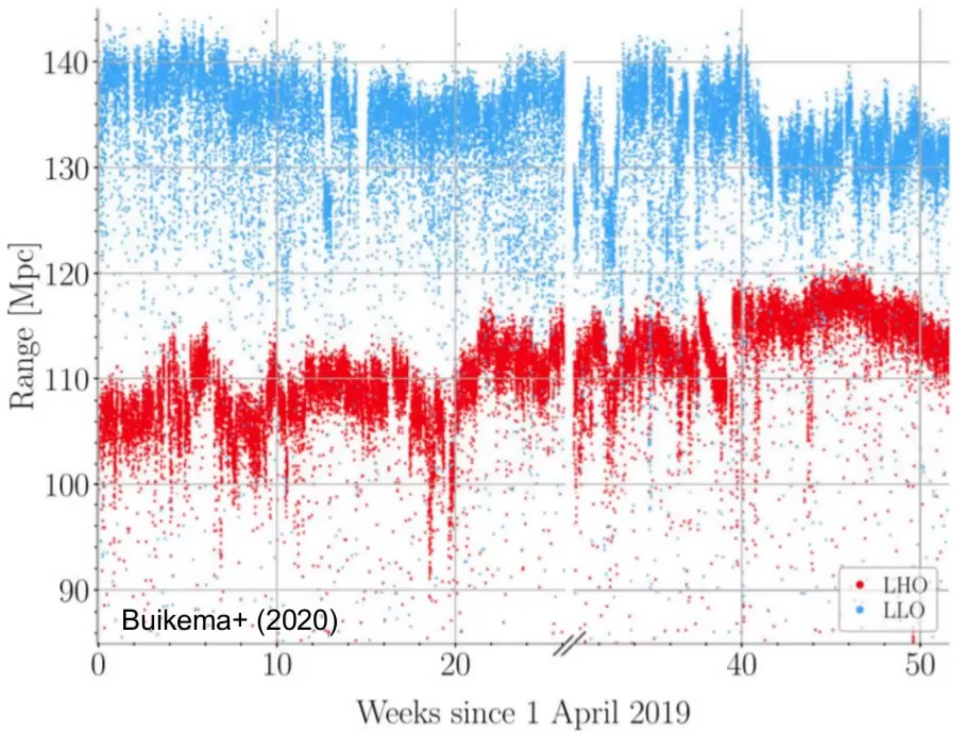
3

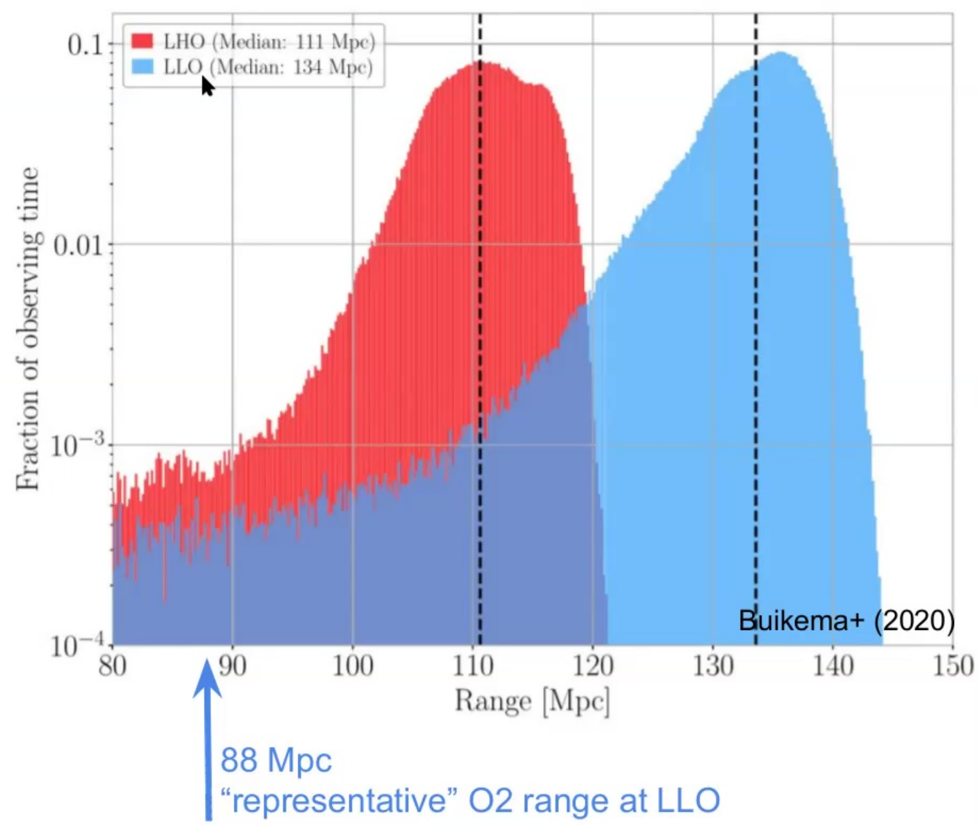
O3 LIGO Interferometers



4

O3 LIGO Interferometers



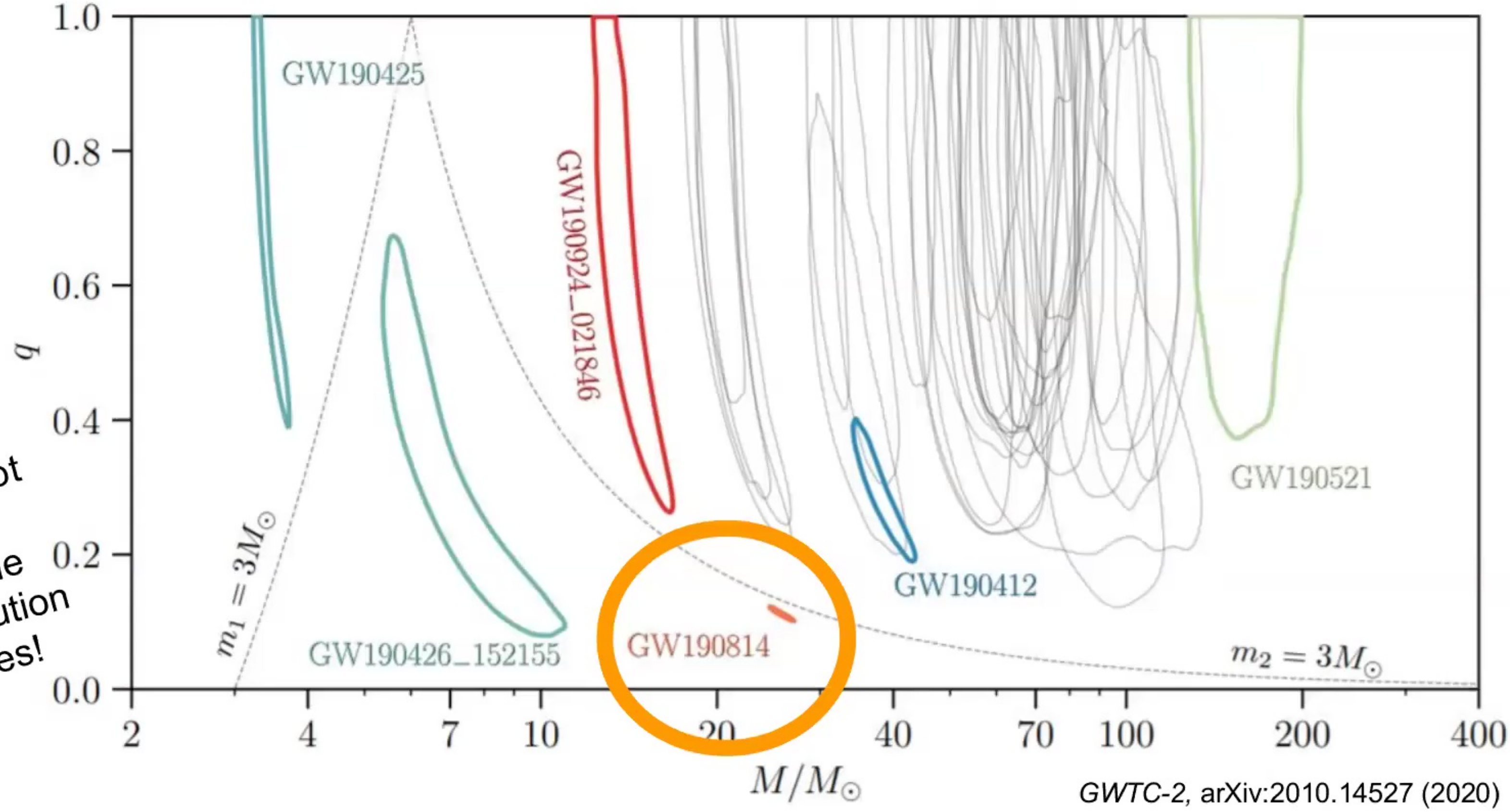


3

GWTC-2 Events

39 new candidates (False Alarm Rate < 2/yr)

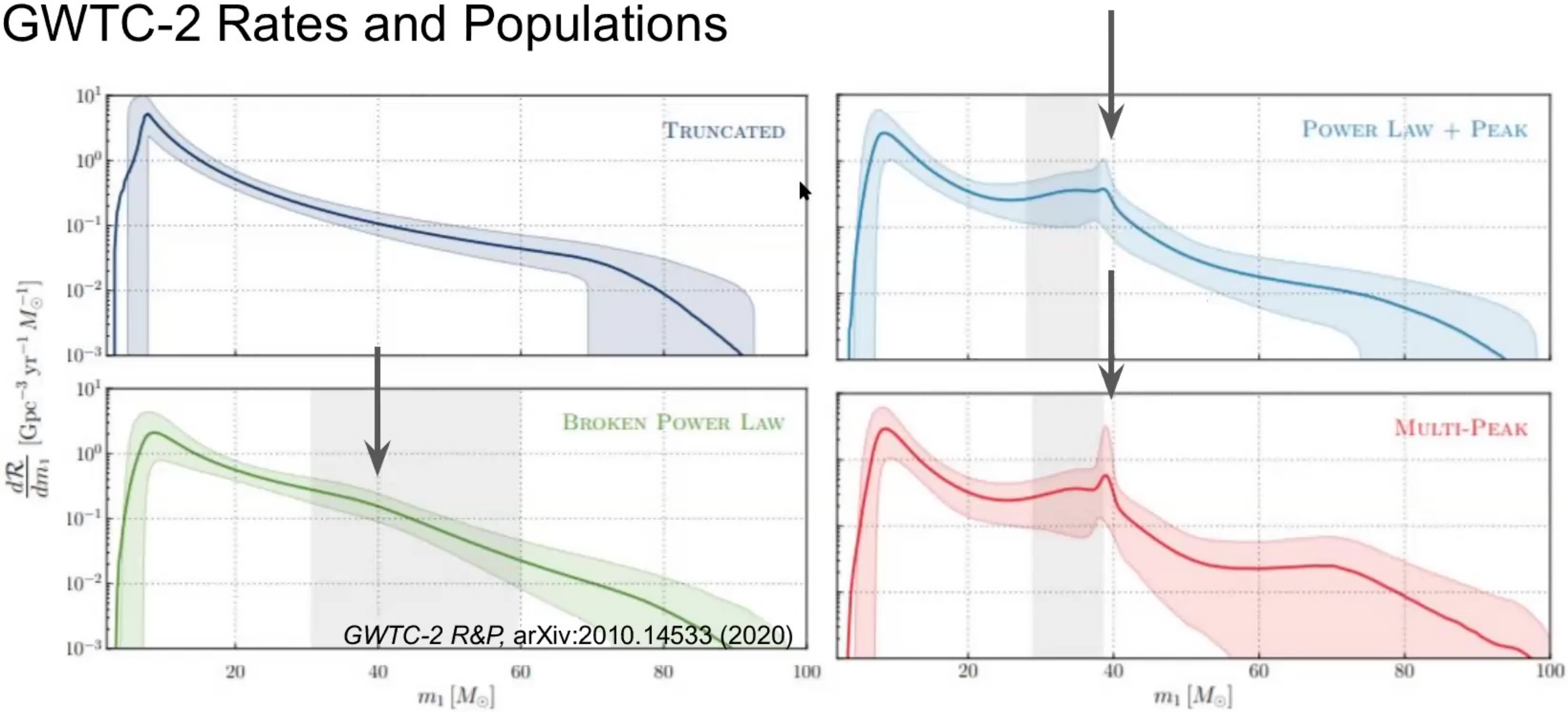
- 26 found in low-latency
- 13 reported for the first time



NOTE
these posteriors do not account for our understanding of the astrophysical distribution of compact binaries!

GWTC-2, arXiv:2010.14527 (2020)

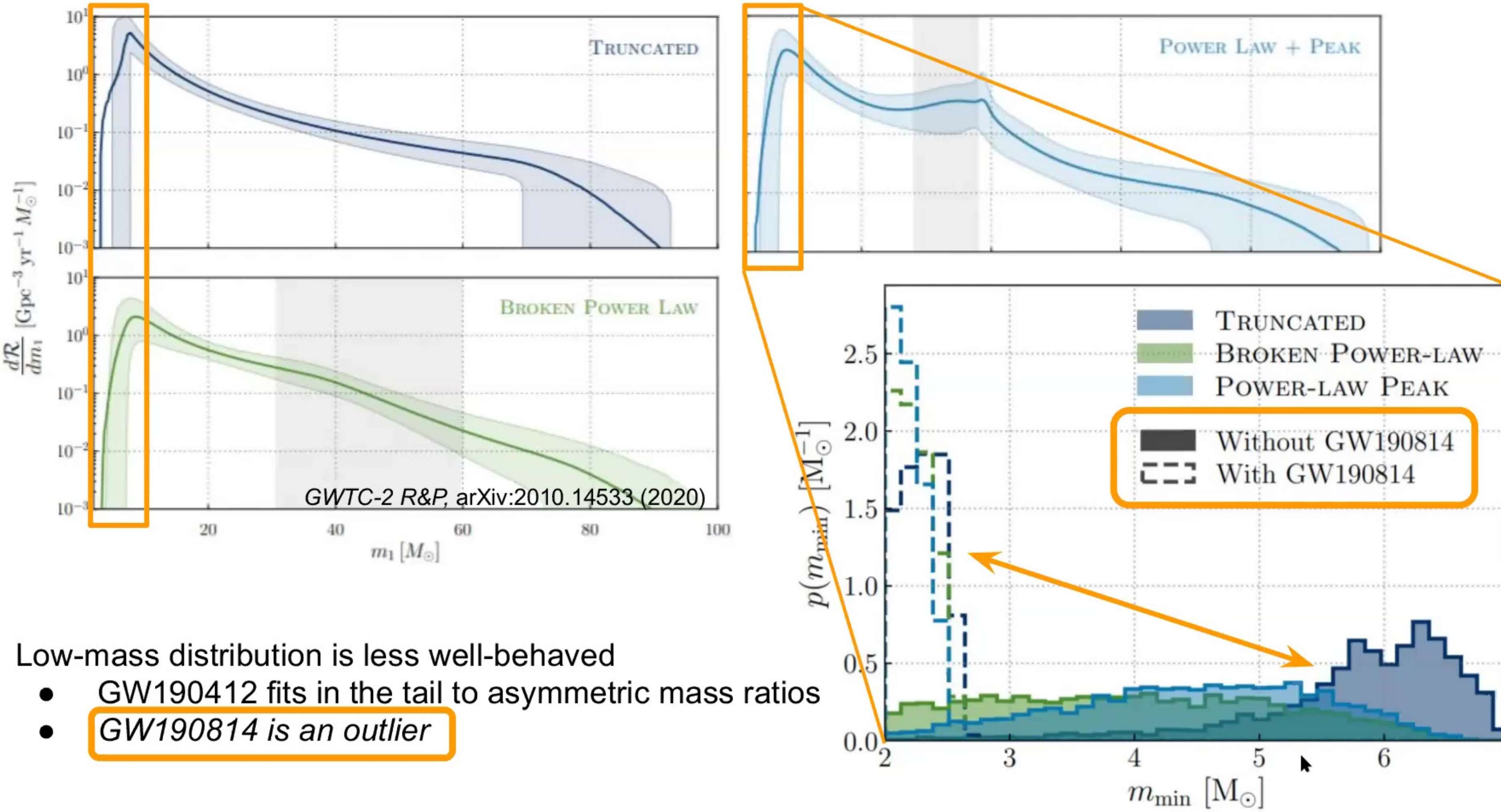
GWTC-2 Rates and Populations



4 models with varying complexity, and we mostly learn about the high-mass end of the distributions.

- ***There is robust evidence for a "Pair Instability Supernova" feature near 40 M_{sun}.***
- High-mass events, like *GW190521*, fit well within these models (*not necessarily an "outlier"*).

GWTC-2 Rates and Populations



Low-mass distribution is less well-behaved

- GW190412 fits in the tail to asymmetric mass ratios
- *GW190814 is an outlier*

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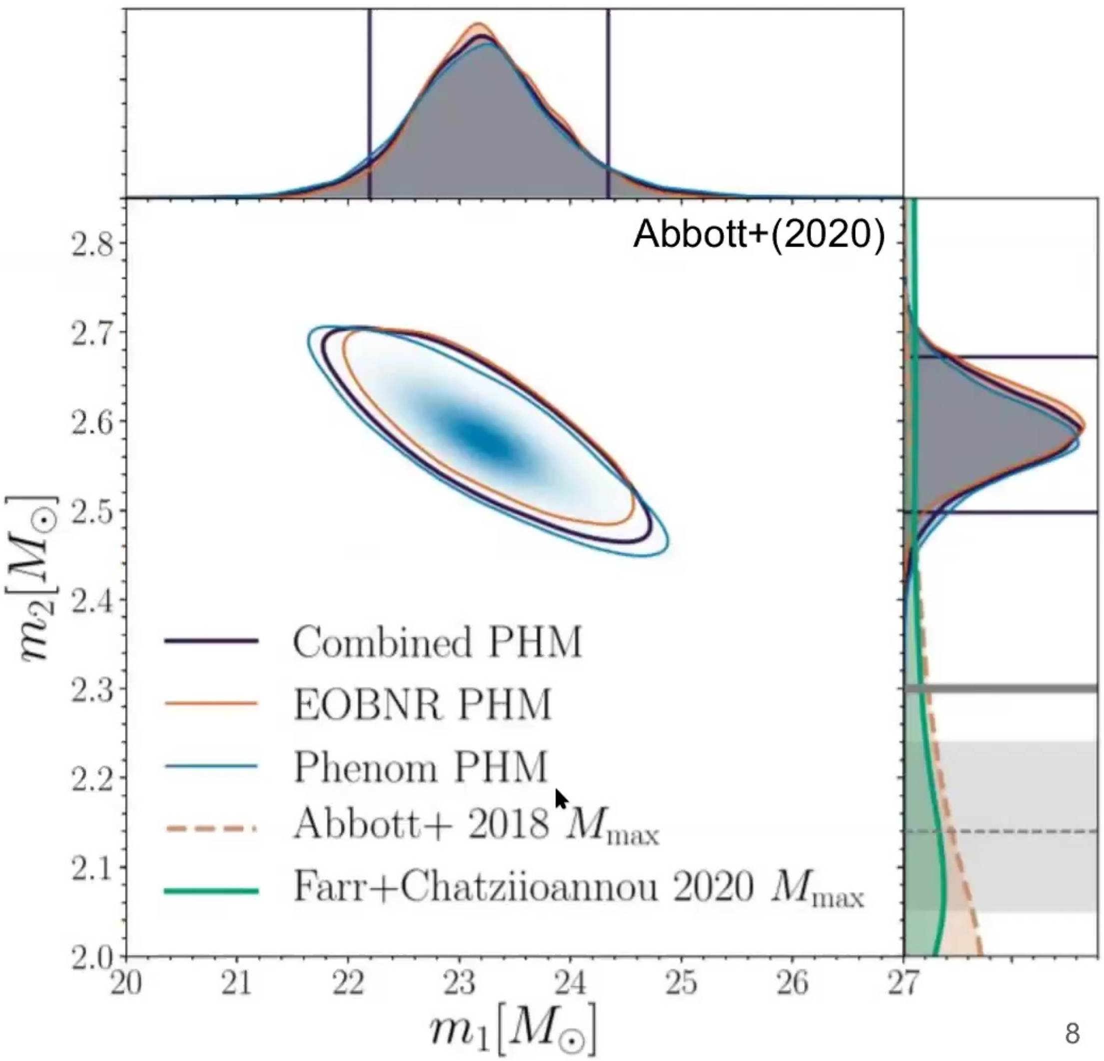
In the context of GW190814

What can we learn about nuclear physics from NS observations?

Can we make progress on understanding the low-mass distribution?

Can we distinguish between neutron stars and black holes?



Nonparametric Equation of State Inference

getting the EoS right

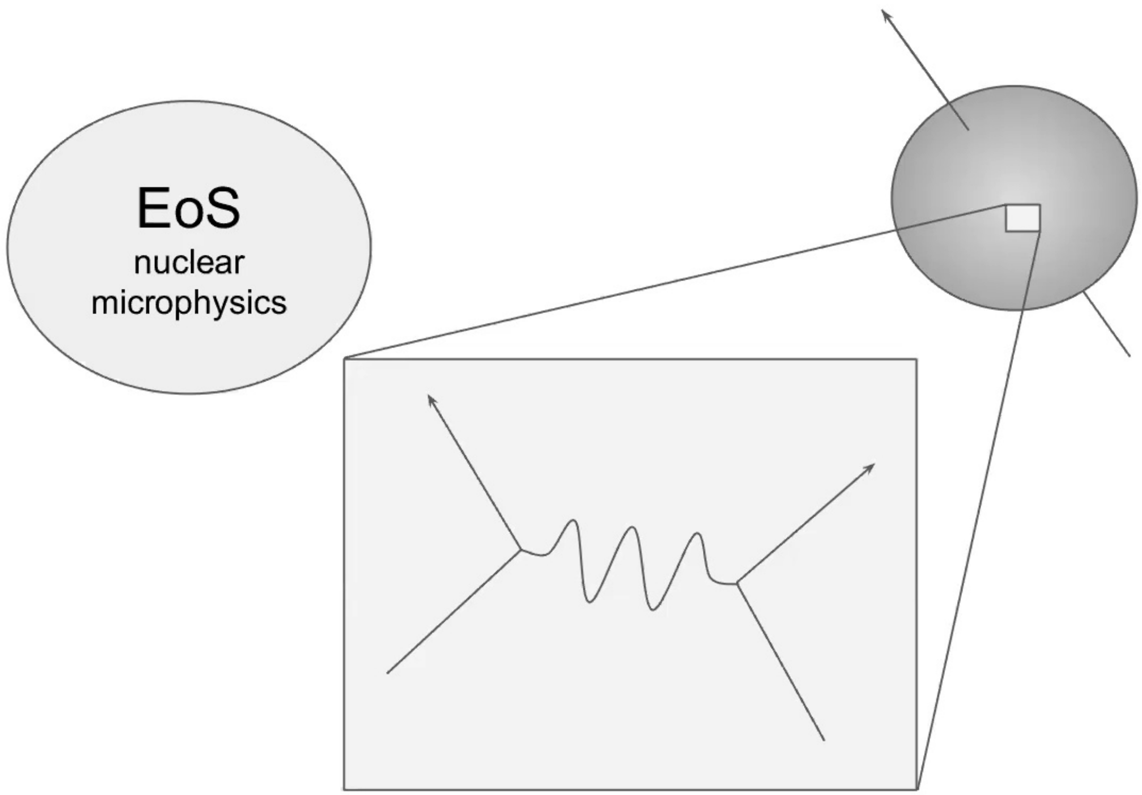
P. Landry and R. Essick, *Nonparametric Inference of the Neutron Star Equation of State from gravitational Wave Observations*, PRD 99, 084049 (2019)

R. Essick, P. Landry, and D. E. Holz, *Nonparametric Inference of Neutron Star Composition, Equation of State, and Maximum Mass with GW170817*, PRD 101, 063007 (2020)

P. Landry, R. Essick, and K. Chatziioannou, *Nonparametric Constraints on Neutron Star Matter with Existing and Upcoming Gravitational Wave and Pulsar Observations*, PRD 101, 123007 (2020)

R. Essick, I. Tews, P. Landry, S. Reddy, D. E. Holz, *Direct Astrophysical tests of Chiral Effective Field Theory at Supranuclear Densities*, arXiv:2004.07744 (2020)

What do we observe?

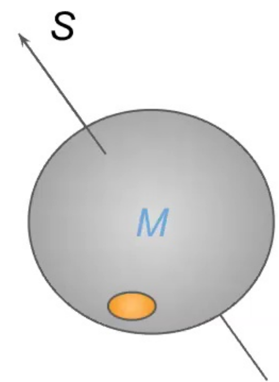


What do we observe?

M_{max}

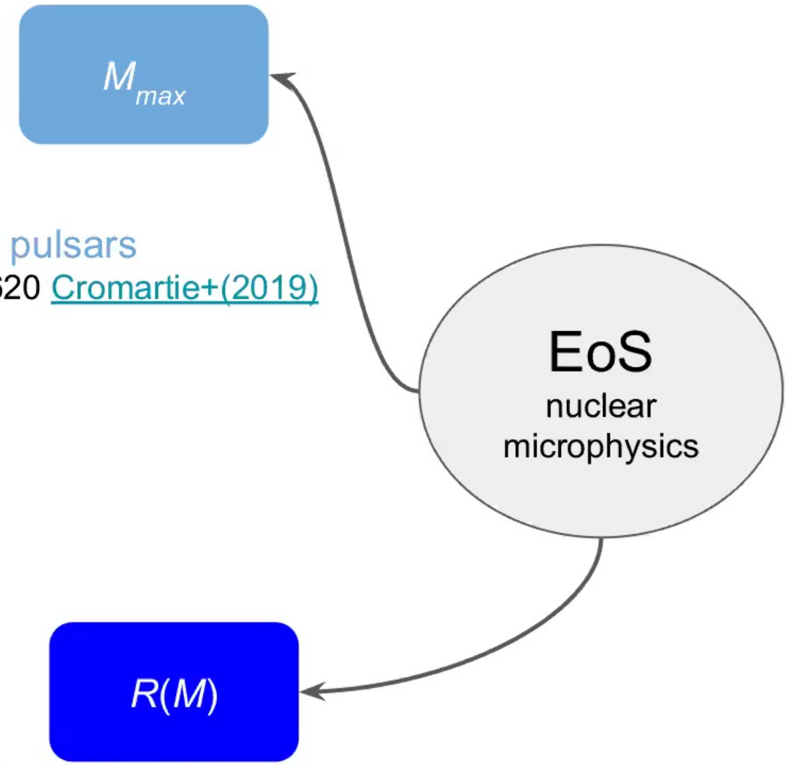
Massive pulsars
J0740+6620 Cromartie+(2019)

EoS
nuclear
microphysics



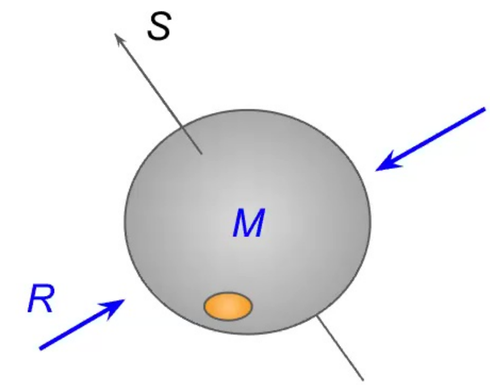
pulsar observations
radial velocity
Shapiro delay

What do we observe?



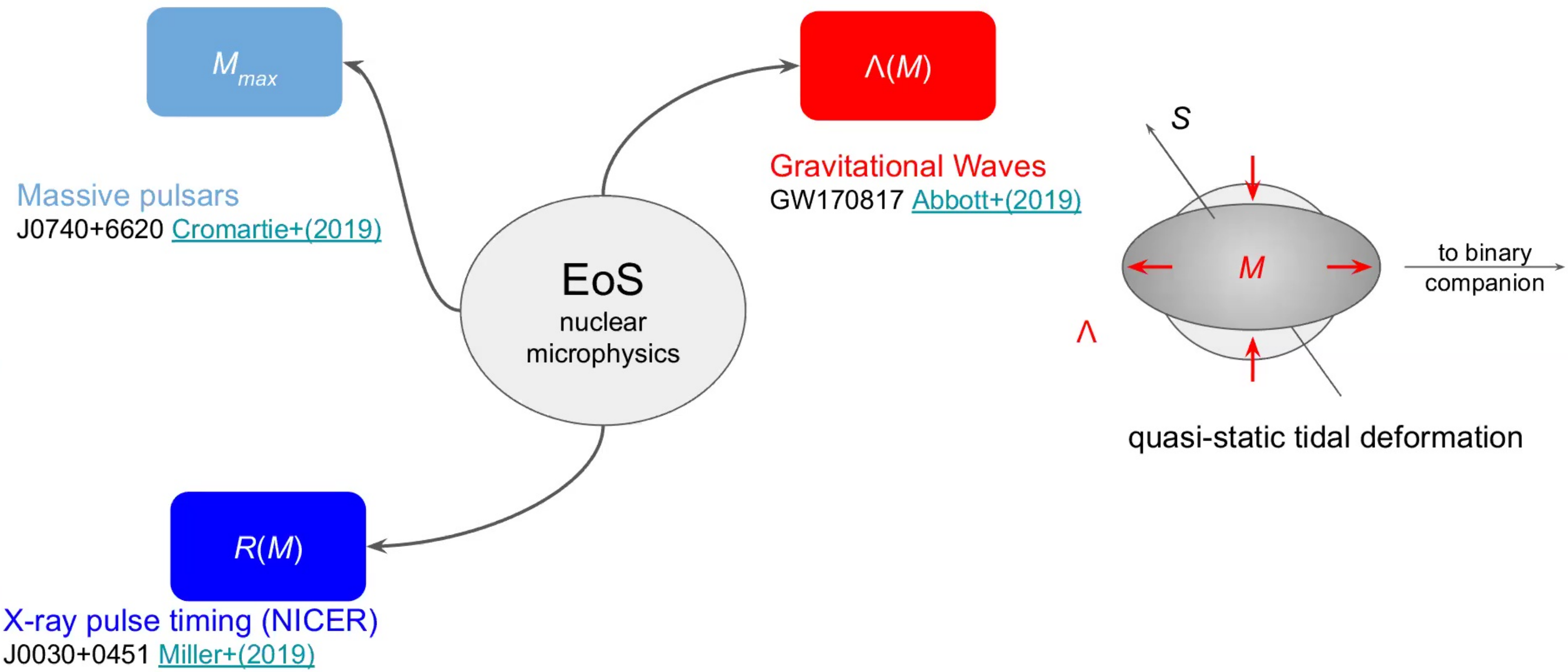
Massive pulsars
J0740+6620 Cromartie+(2019)

X-ray pulse timing (NICER)
J0030+0451 Miller+(2019)

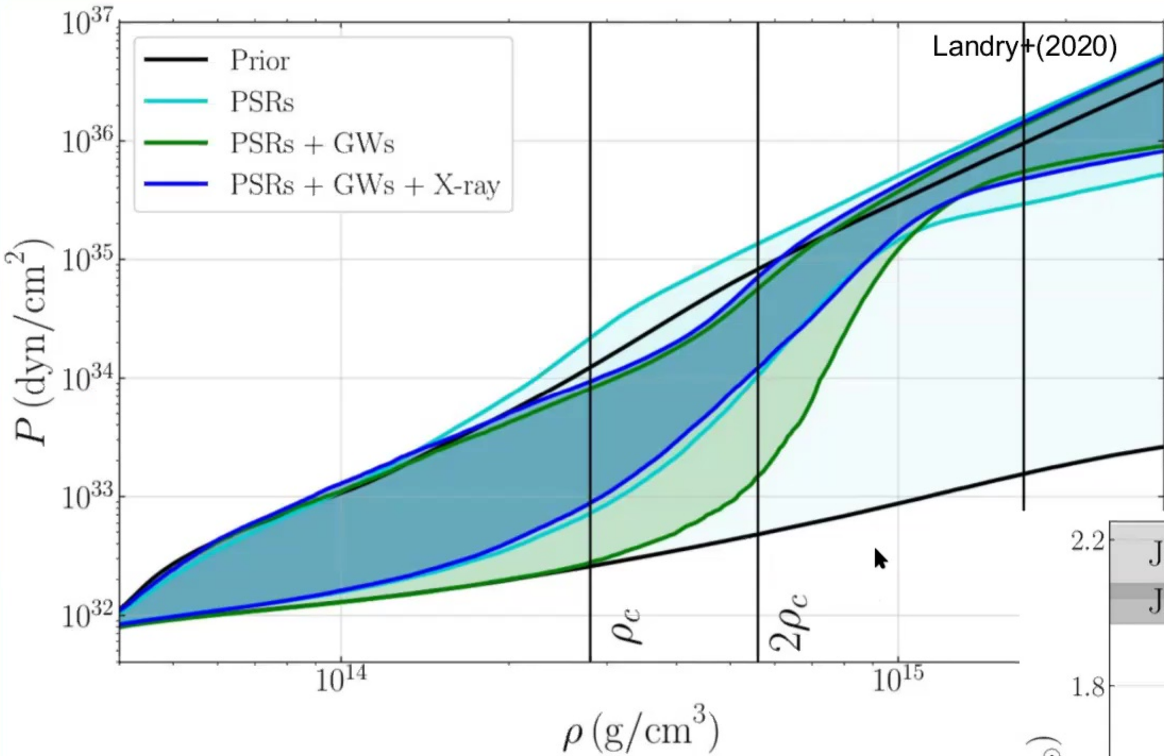


X-ray timing
Pulse profile modeling

What do we observe?

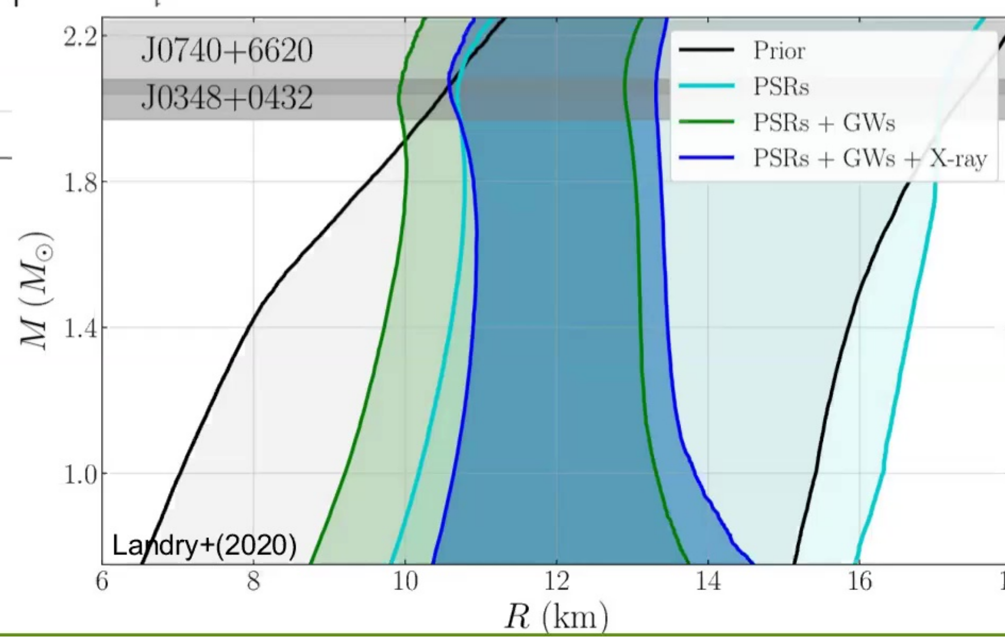


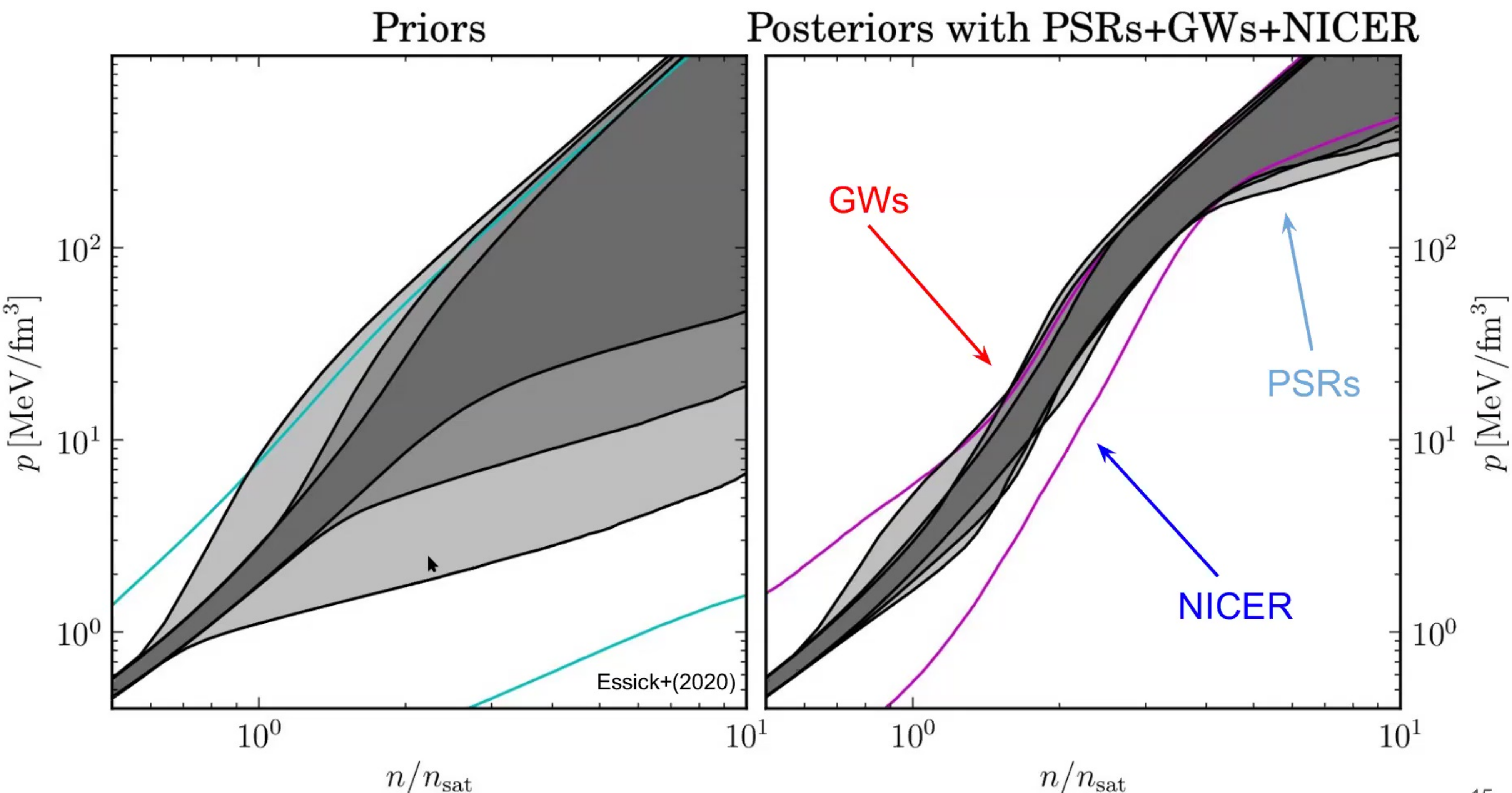
13



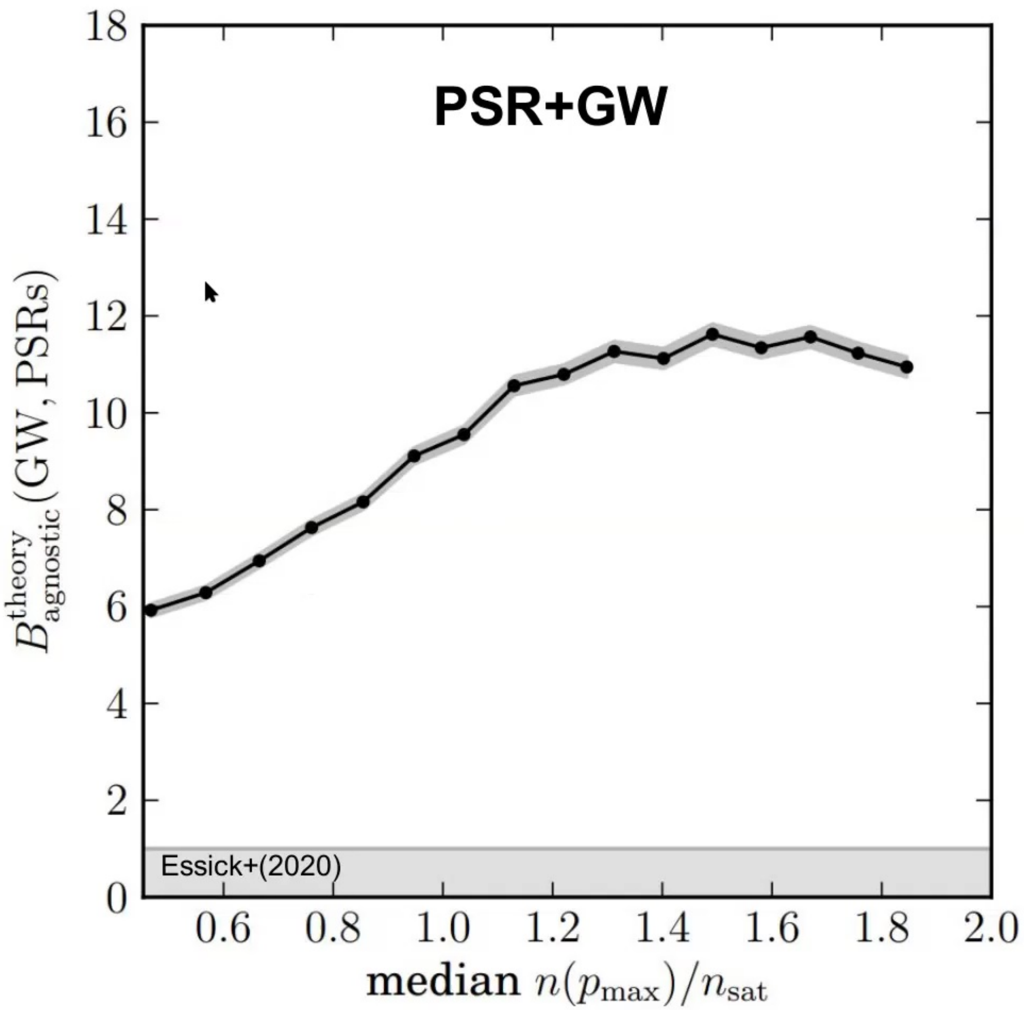
improve our knowledge
of fundamental nuclear physics

improve our understanding
of astrophysical phenomena

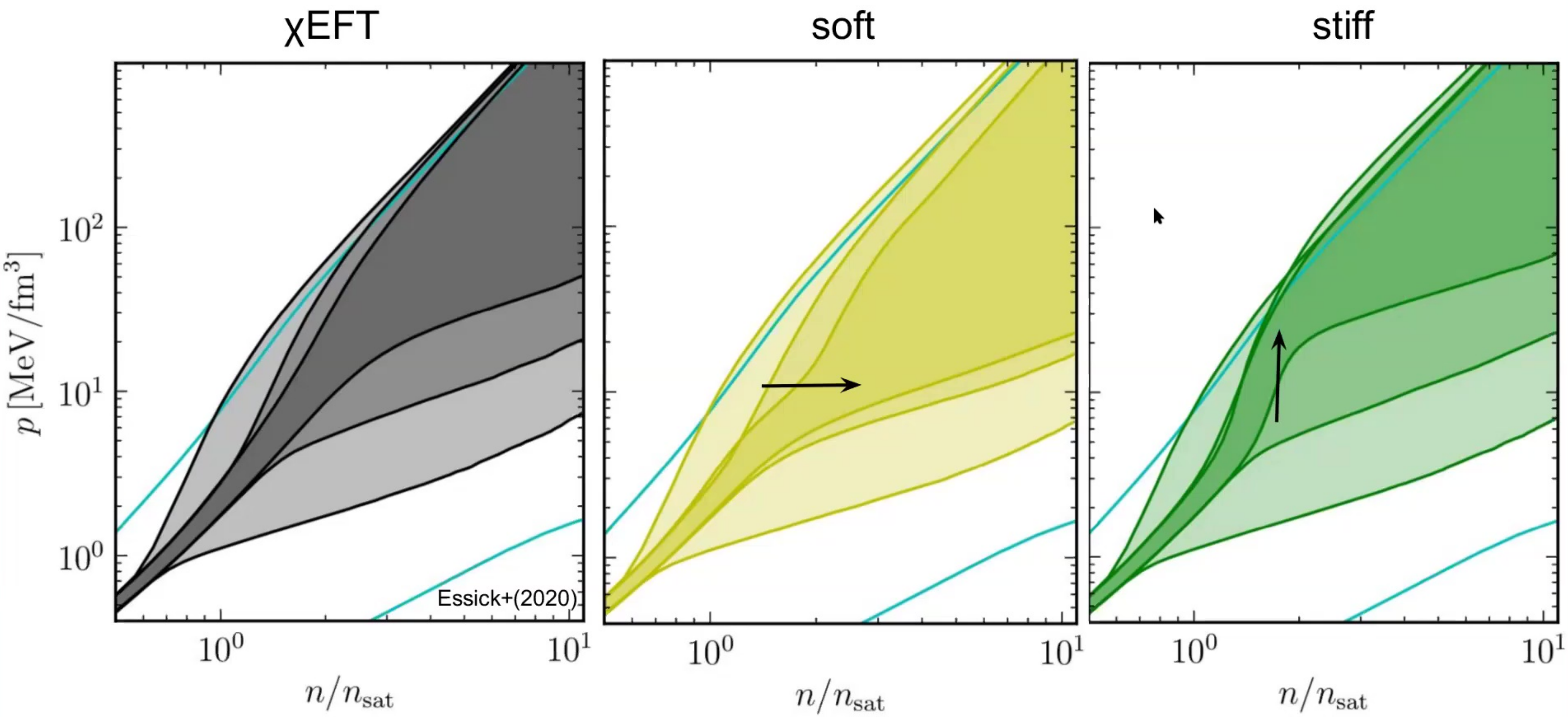




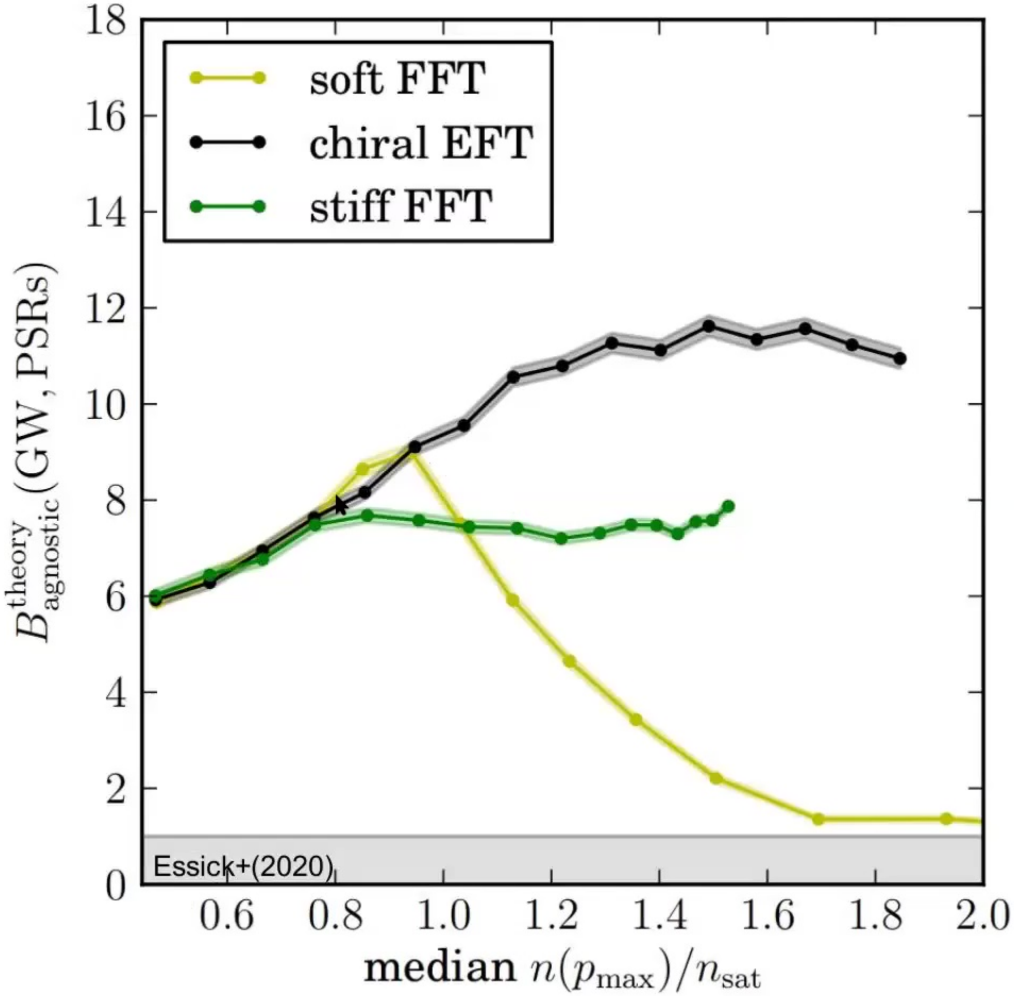
Priors
Posteriors with PSRs+GWs+NICER
$p\,[\mathrm{MeV/fm^3}]$
10^2
10^1
10^0
n/n_{sat}
Essick+(2020)
GWs
PSRs
NICER


PSR+GW
$B^{\mathrm{theory}}_{\mathrm{agnostic}}(\mathrm{GW},\ \mathrm{PSRs})$
median $n(p_{\mathrm{max}})/n_{\mathrm{sat}}$
Essick+(2020)
0
2
4
6
8
10
12
14
16
18
0.6
0.8
1.0
1.2
1.4
1.6
1.8
2.0

16

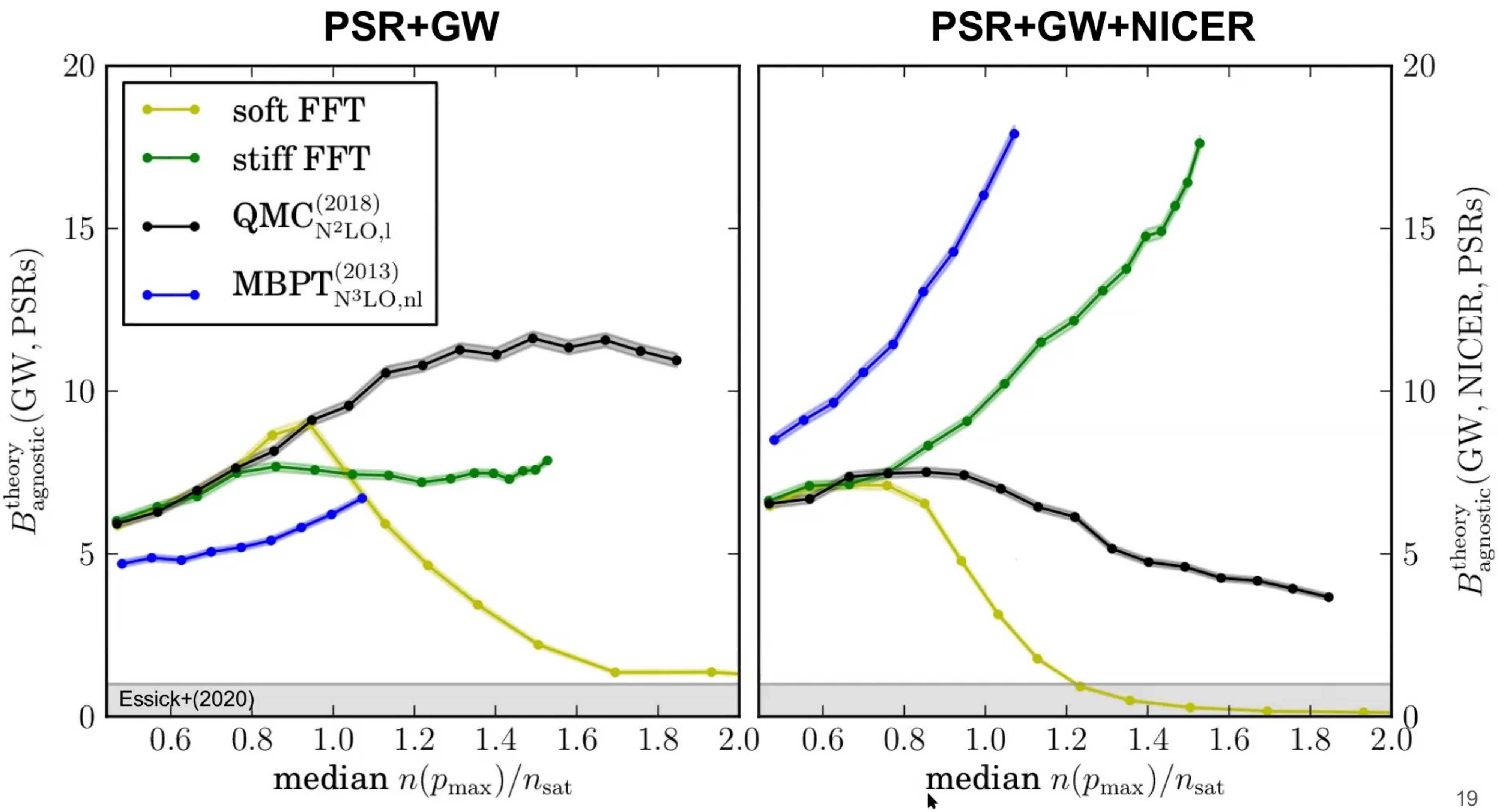

χEFT
soft
stiff
$p\,[\mathrm{MeV/fm^3}]$
10^0
10^1
10^2
n/n_{sat}
Essick+(2020)

PSR+GW



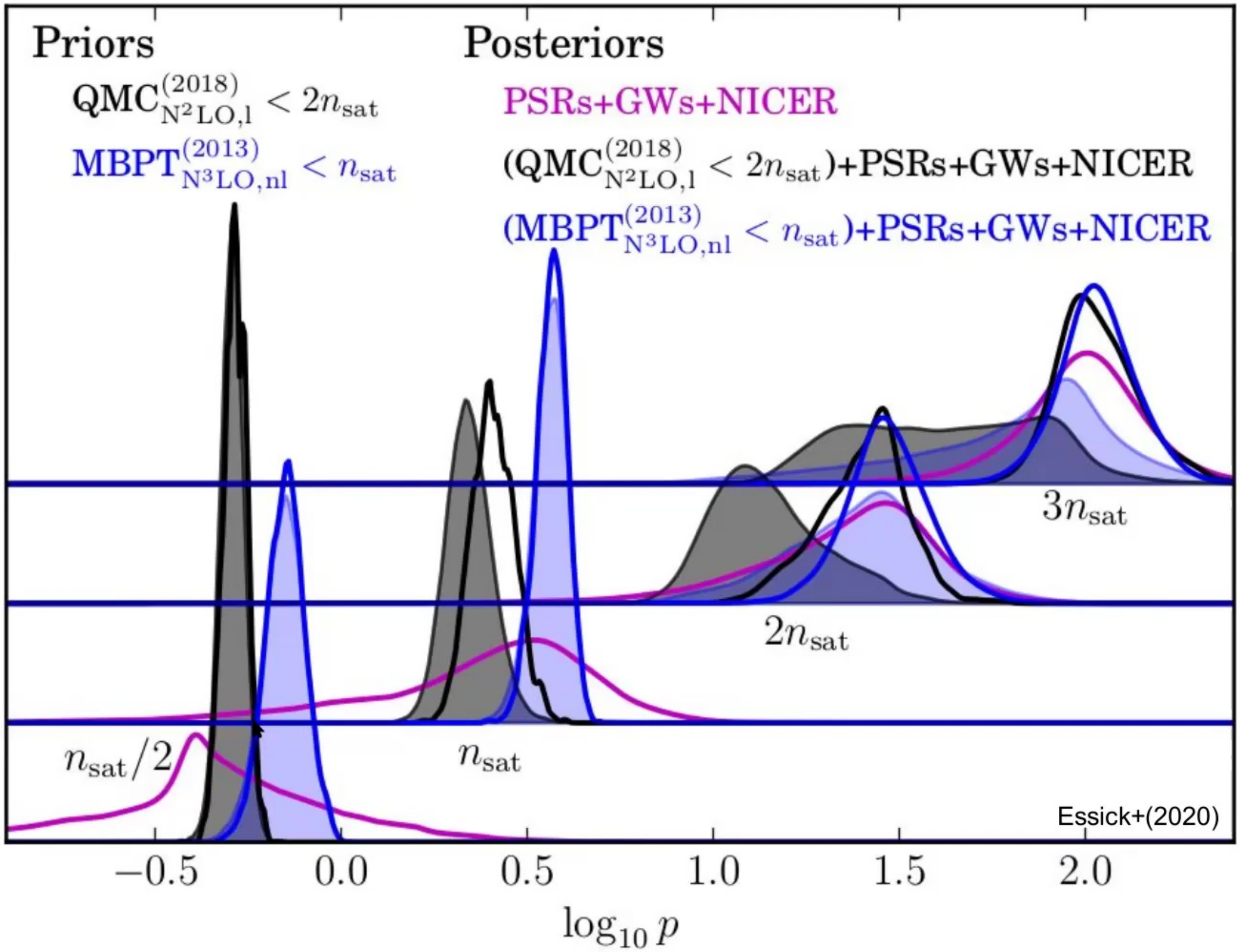
soft FFT
chiral EFT
stiff FFT
$B^{\rm theory}_{\rm agnostic}(\rm GW, PSRs)$
median $n(p_{\rm max})/n_{\rm sat}$
Essick+(2020)
0
2
4
6
8
10
12
14
16
18
0.6
0.8
1.0
1.2
1.4
1.6
1.8
2.0

18



PSR+GW
PSR+GW+NICER
soft FFT
stiff FFT
$\mathrm{QMC}^{(2018)}_{\mathrm{N^2LO,l}}$
$\mathrm{MBPT}^{(2013)}_{\mathrm{N^3LO,nl}}$
$B^{\mathrm{theory}}_{\mathrm{agnostic}}(\mathrm{GW},\mathrm{PSRs})$
$B^{\mathrm{theory}}_{\mathrm{agnostic}}(\mathrm{GW},\mathrm{NICER},\mathrm{PSRs})$
Essick+(2020)
median $n(p_{\mathrm{max}})/n_{\mathrm{sat}}$
median $n(p_{\mathrm{max}})/n_{\mathrm{sat}}$
0
5
10
15
20
0.6
0.8
1.0
1.2
1.4
1.6
1.8
2.0

19



PSR+GW+NICER

20

Looking for signatures of matter from mass distribution of compact objects

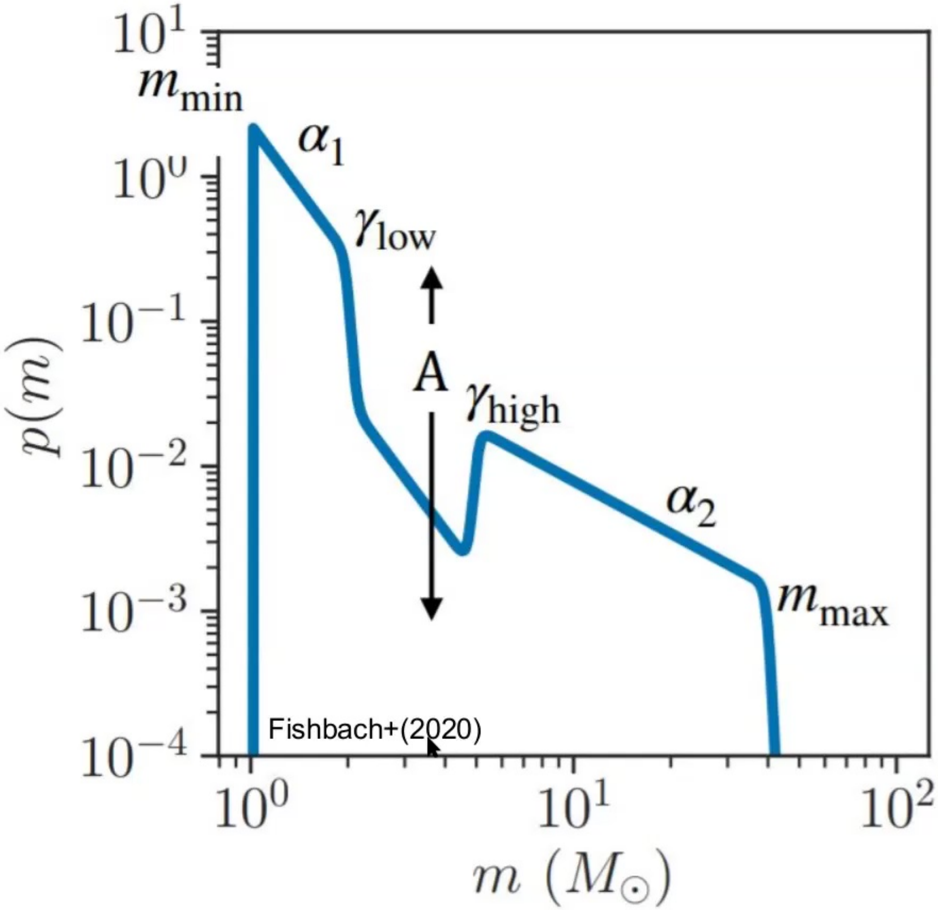
observing the overall mass distribution

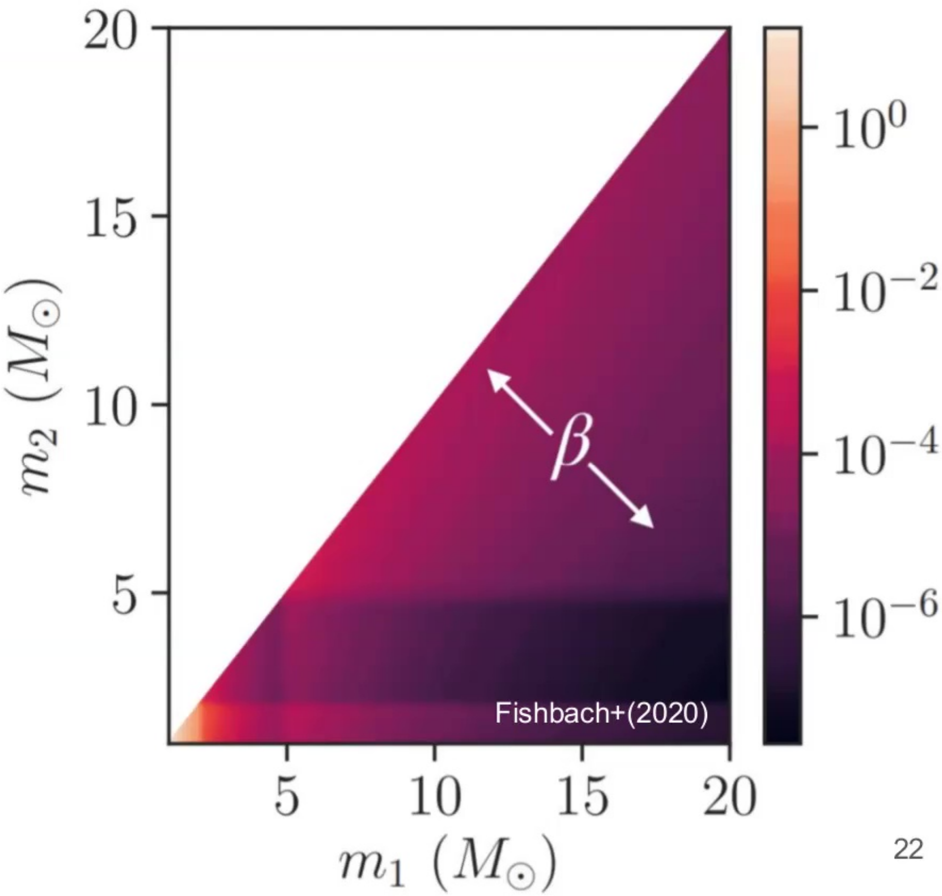
M. Fishbach, R. Essick, and D. E. Holz, *Does Matter Matter? Using the Mass Distribution to Distinguish Neutron Stars and Black Holes*, ApJ Lett. 899, 1 (2020)

→ ***only*** uses results from ***GWTC-1*** (O1 and O2)

Overall mass distribution

$$p(m_1,m_2 \mid \Lambda) \propto p(m = m_1 \mid \lambda)\, p(m = m_2 \mid \lambda) \left(\frac{m_2}{m_1}\right)^{\beta} \Theta(m_2 \leq m_1)$$





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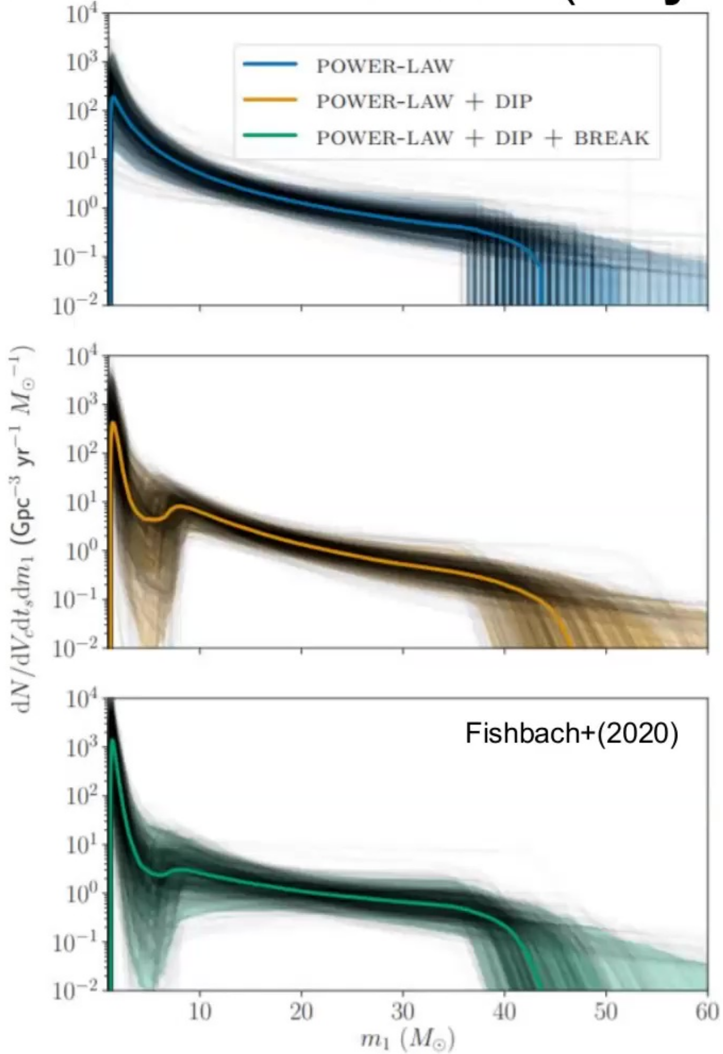
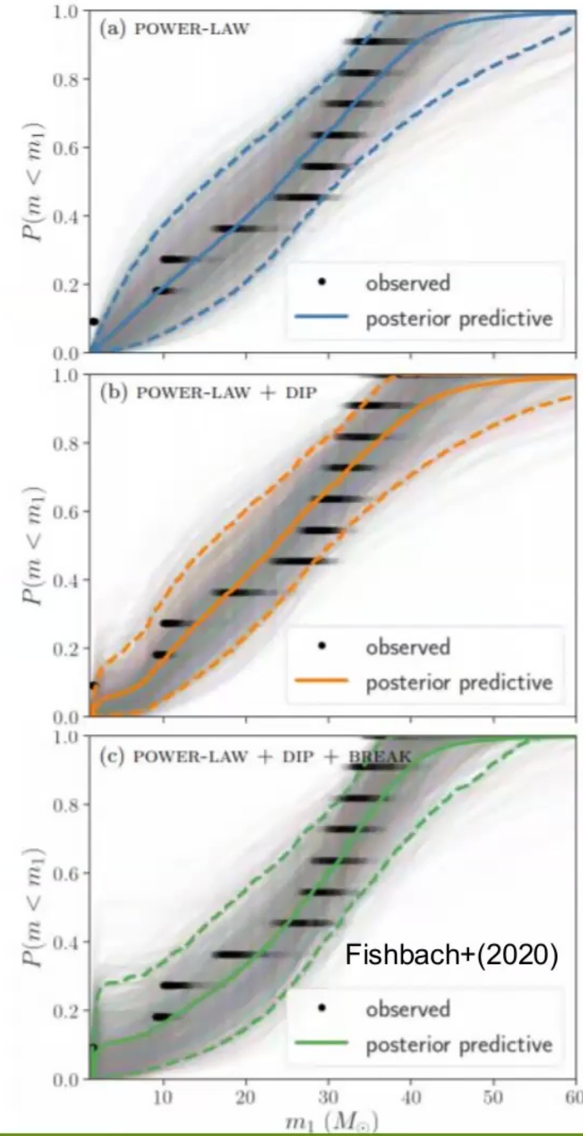
Overall mass distribution (**only GWTC-1**)



less model freedom

more model freedom



Overall mass distribution (**only GWTC-1**)

Rates based on fixed boundaries in mass ranges

BNS : 1 $M_{sun} < m_2 < m_1 < 2.5\ M_{sun}$

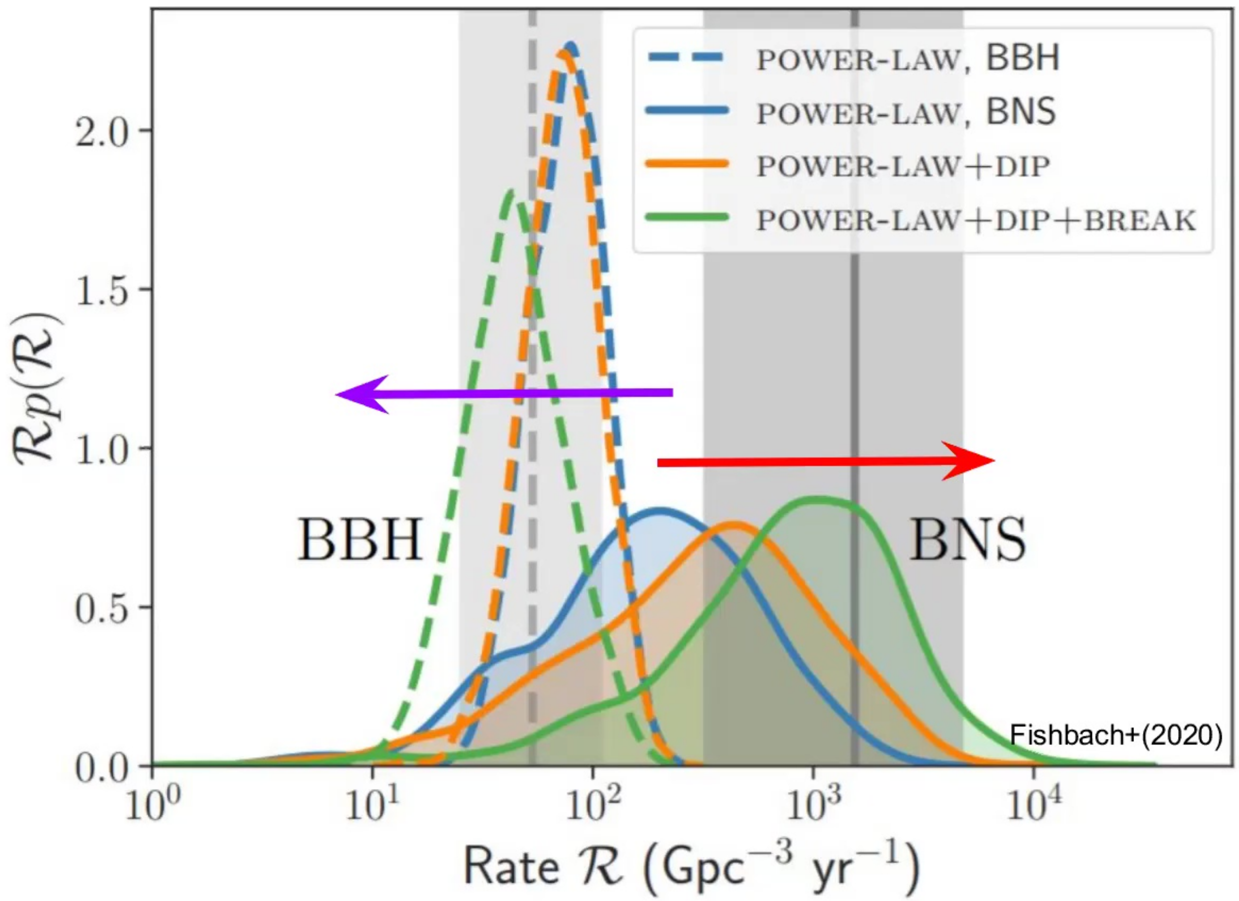
BBH: 5 $M_{sun} < m_2 < m_1 < 100\ M_{sun}$

More model freedom slightly

increases BNS rate

decreases BBH rate

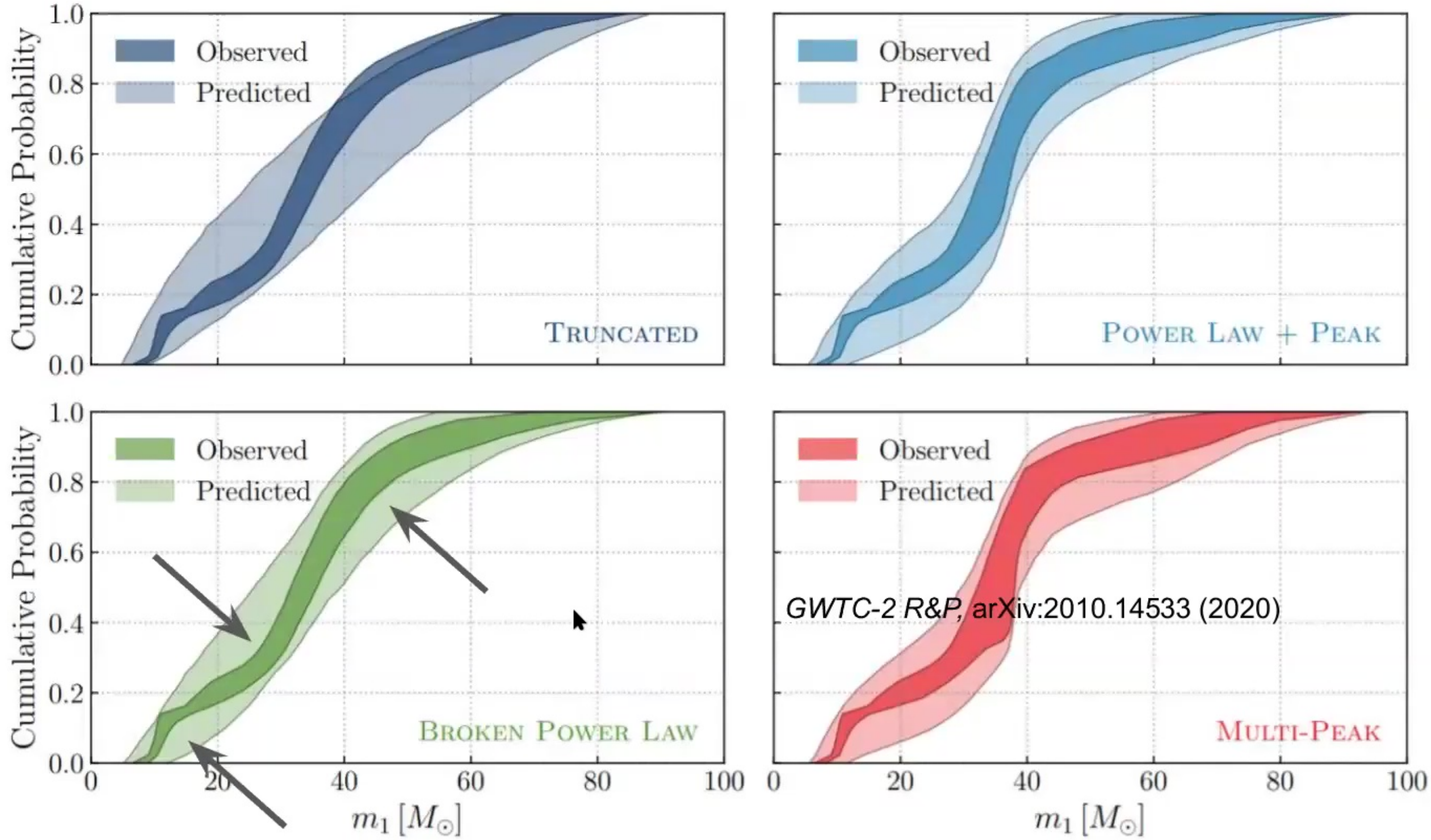
but distributions are consistent



24

Overall mass distribution (GWTC-2)

Observed distributions show more features than predicted distributions, *particularly at low densities*!



GWTC-2 R&P, arXiv:2010.14533 (2020)

25

Connecting it all together

Determining whether an object could be a NS

R. Essick and P. Landry, *Discriminating between Neutron Stars and Black Holes with Imperfect Knowledge of the Maximum Neutron Star Mass*, arXiv:2007.01372 (2020)

R. Abbott et al, *GW190814: Gravitational Waves from the Coalescence of a 23 Solar Mass Black Hole with a 2.6 Solar Mass Compact Object*, ApJ Lett 896, 2 (2020)

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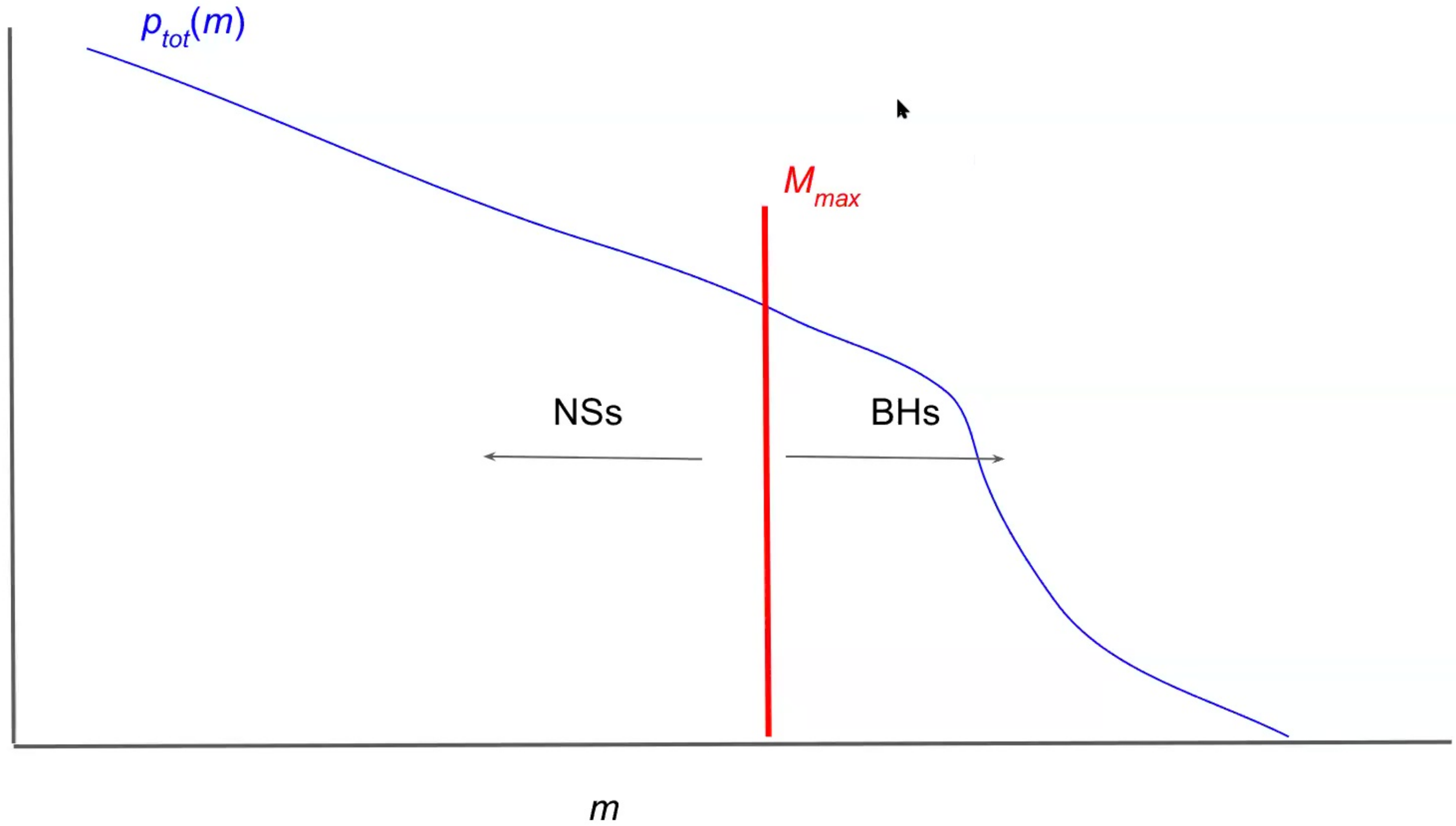
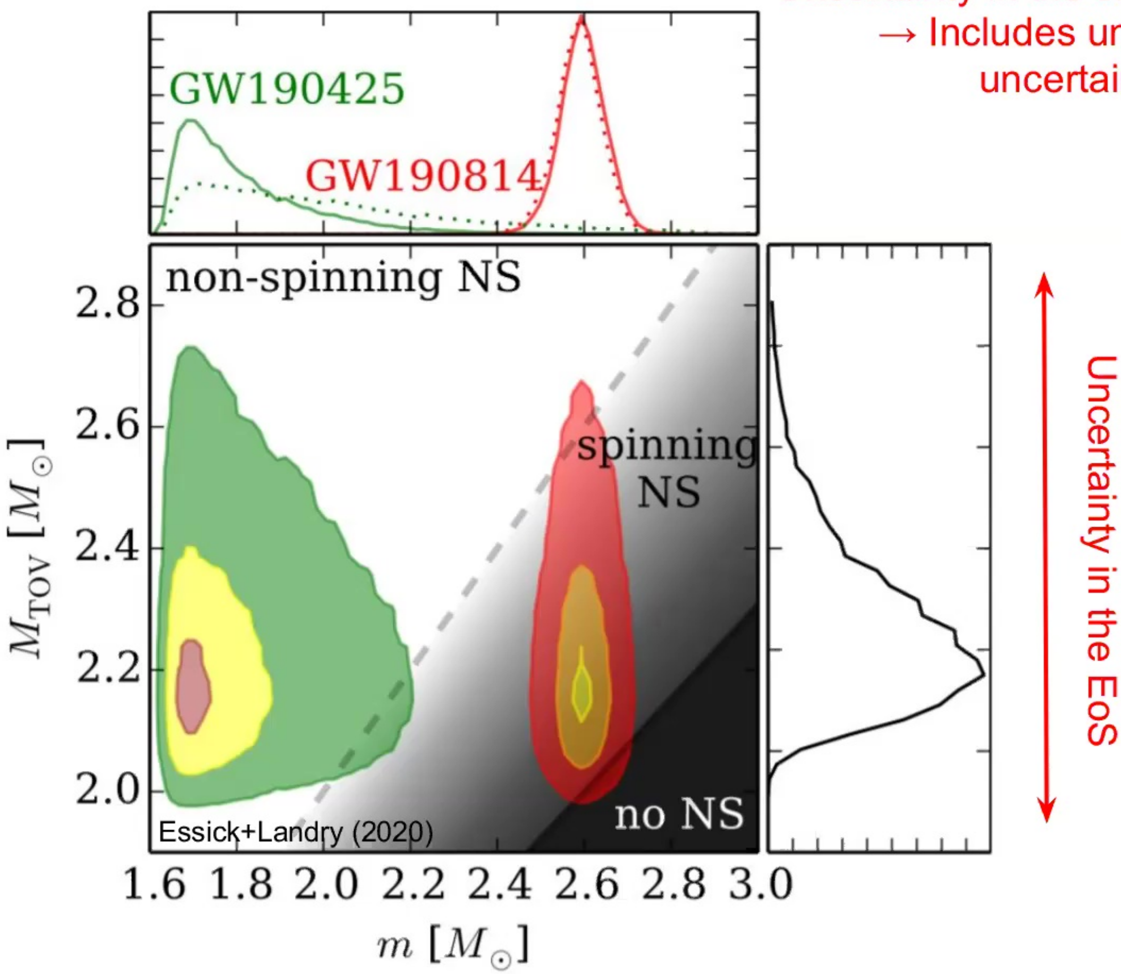
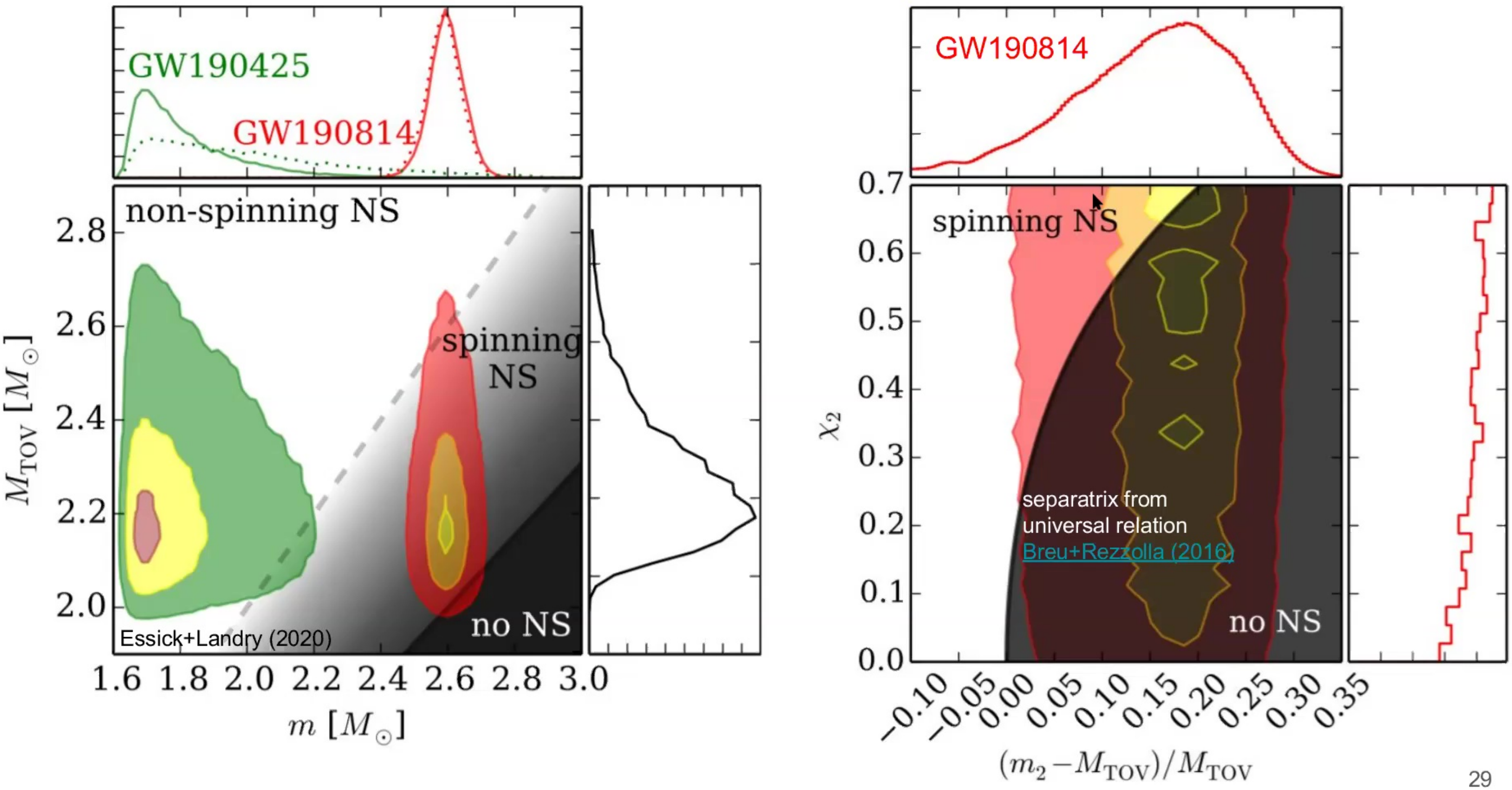




Uncertainty in the single-event parameters
→ Includes uncertainty from *both* the likelihood and the uncertainty in the astrophysical mass distribution


GW190425
GW190814
non-spinning NS
spinning NS
no NS
Essick+Landry (2020)
$M_{\rm TOV}\ [M_\odot]$
$m\ [M_\odot]$
1.6 1.8 2.0 2.2 2.4 2.6 2.8 3.0
2.0 2.2 2.4 2.6 2.8
GW190814
spinning NS
separatrix from
universal relation
Breu+Rezzolla (2016)
no NS
χ_2
$(m_2 - M_{\rm TOV})/M_{\rm TOV}$
0.0 0.1 0.2 0.3 0.4 0.5 0.6 0.7
−0.10 −0.05 0.00 0.05 0.10 0.15 0.20 0.25 0.30 0.35

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