Title: Matter in Extreme Conditions

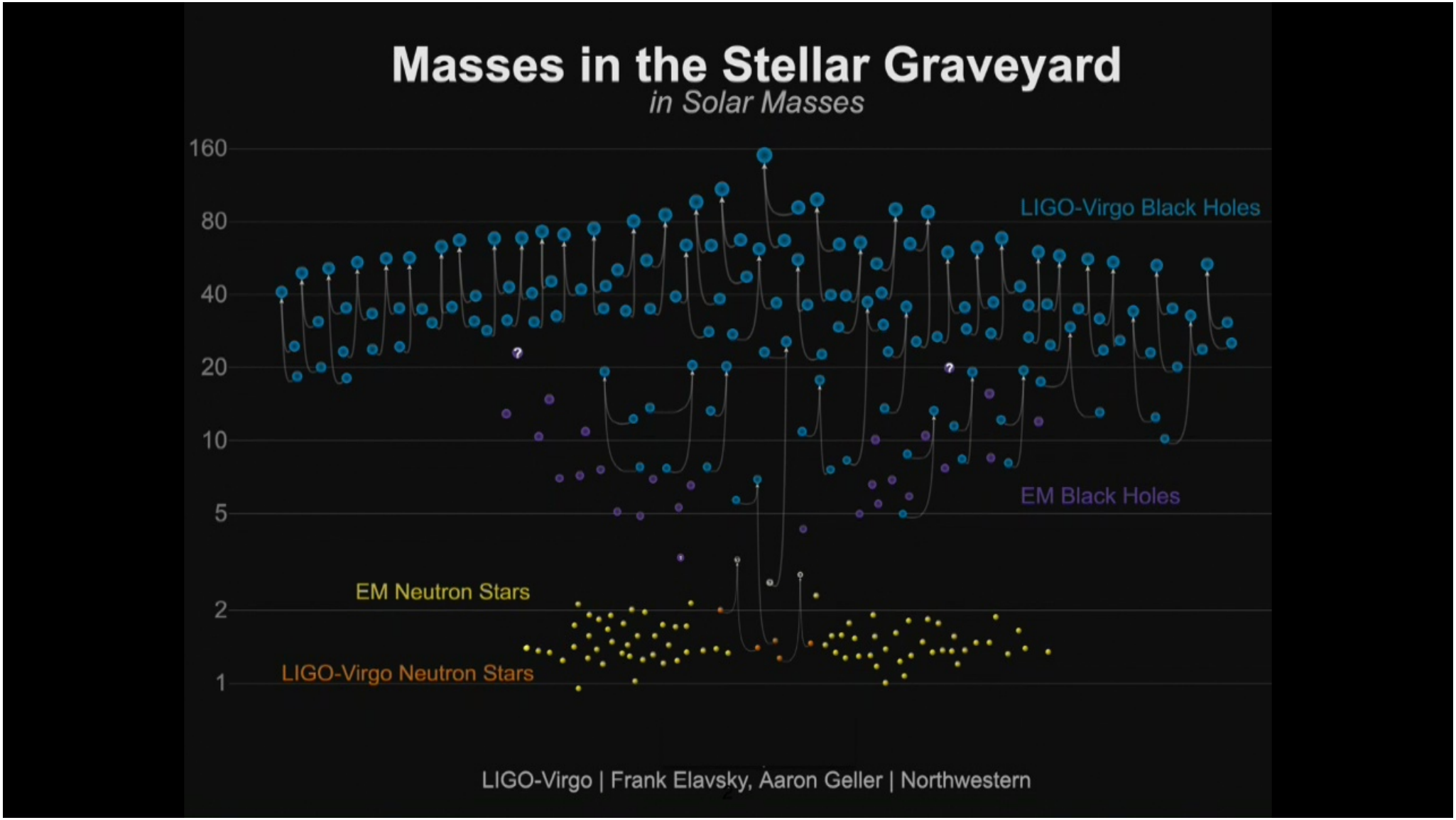
Speakers: Katerina Chatziioannou

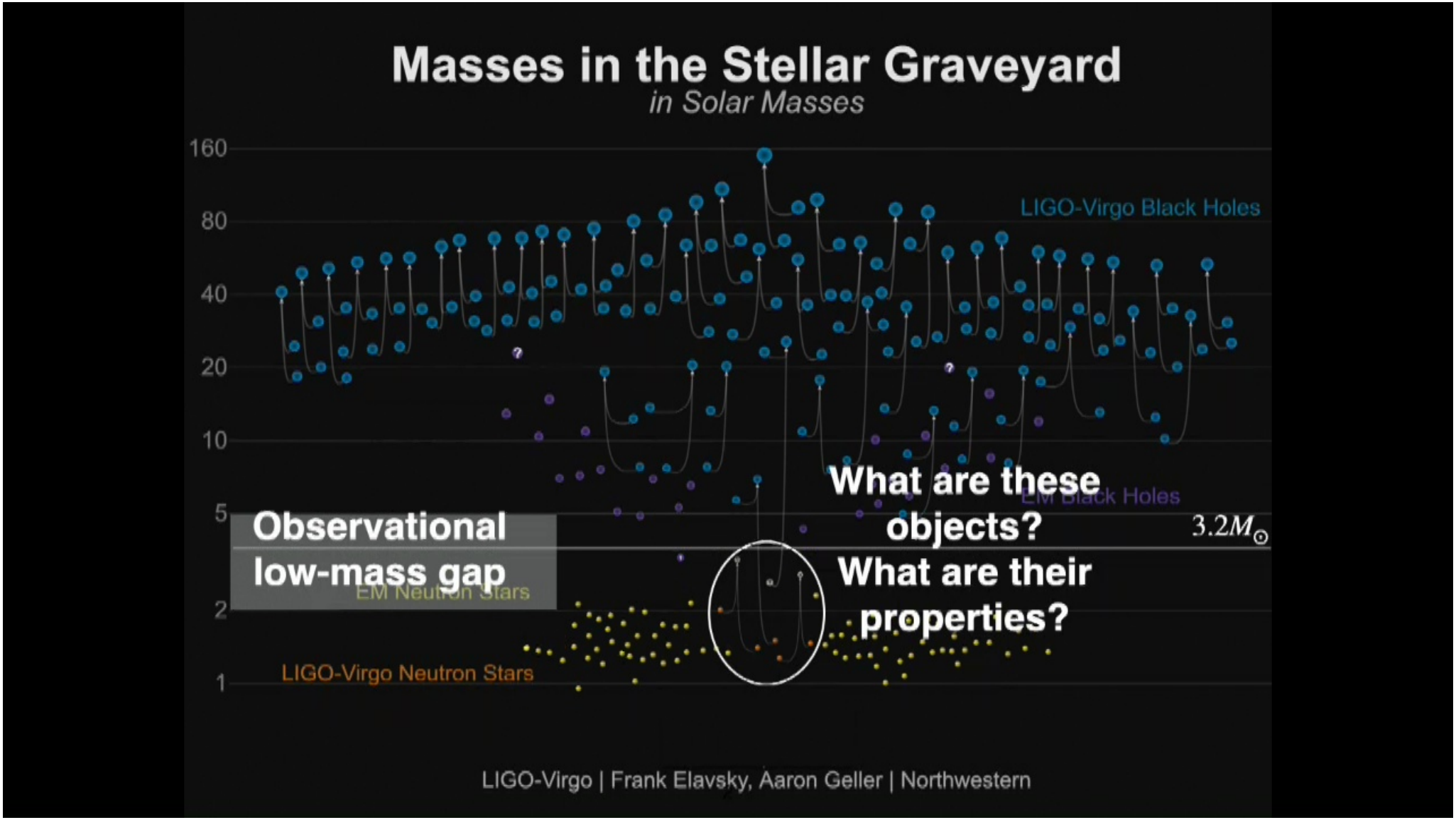
Collection: Gravitational Waves Beyond the Boxes II

Date: April 04, 2022 - 1:15 PM

URL: https://pirsa.org/22040021


Matter in Extreme Conditions
Katerina Chatziioannou
Caltech
Gravitational Waves Beyond the Boxes II, Perimeter Institute
April 4, 2022
1
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
EM Neutron Stars
LIGO-Virgo Neutron Stars
LIGO-Virgo | Frank Elavsky, Aaron Geller | Northwestern


Masses in the Stellar Graveyard
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LIGO-Virgo Black Holes
EM Black Holes
$3.2M_\odot$
Observational low-mass gap
EM Neutron Stars
LIGO-Virgo Neutron Stars
What are these objects?
What are their properties?
LIGO-Virgo | Frank Elavsky, Aaron Geller | Northwestern

What differentiates NSs and BHs

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

Component 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 commonly 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 differentiates NSs and BHs

- Component masses
- Finite-size effects
  Black holes do not exhibit finite-size effects
- Electromagnetic counterpart
- Merger remnant

What differentiates NSs and BHs

- **Component masses**

- **Finite-size effects**

  Black holes do not exhibit finite-size effects

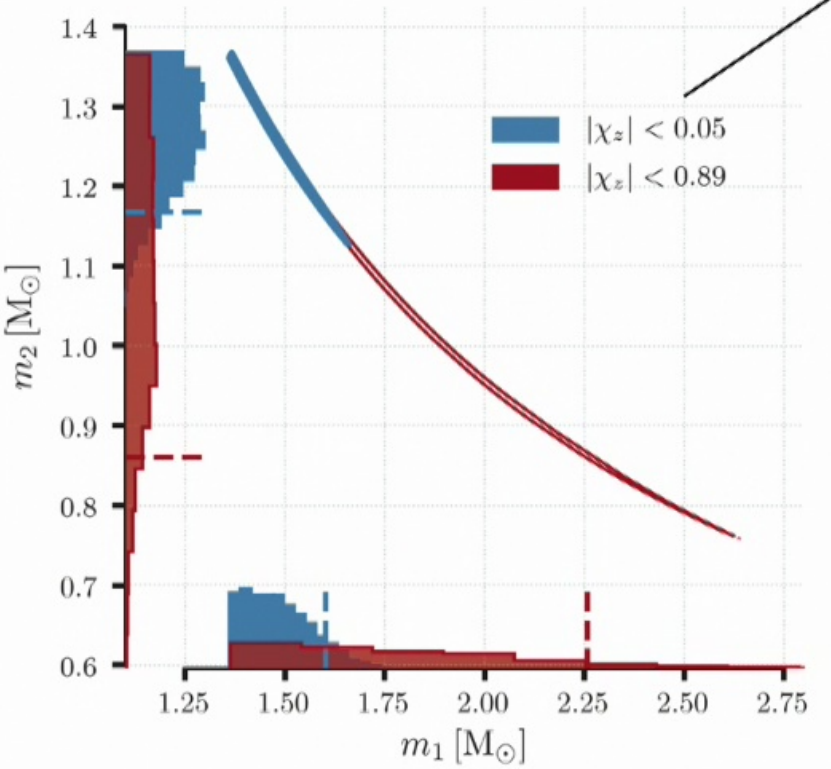
- **Electromagnetic counterpart**

  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



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

The GW170817 masses are consistent with galactic binaries

LVC (arxiv:1710.05832)

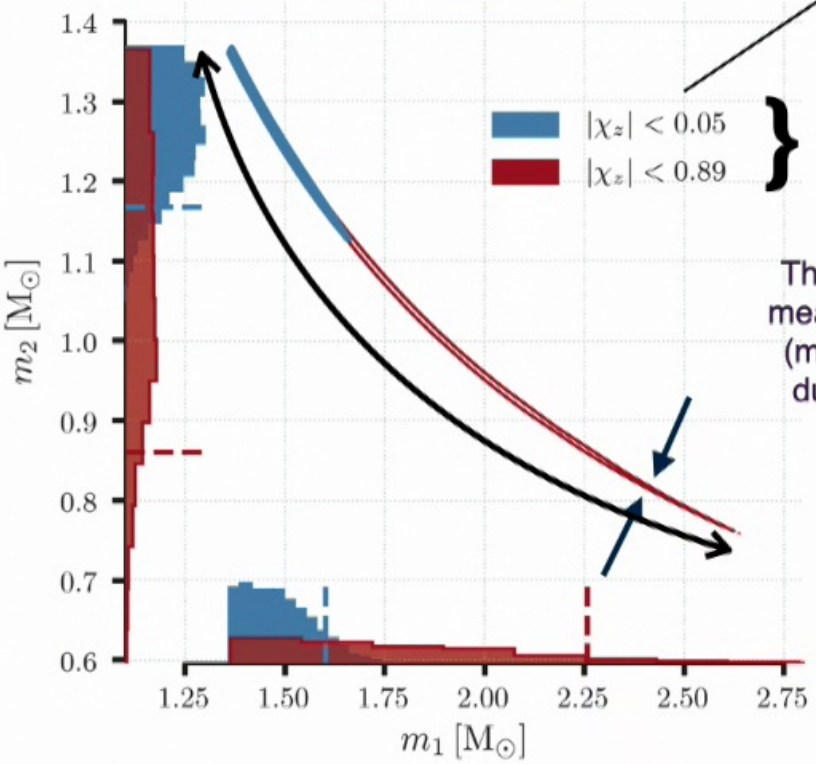
PE: Veitch+ (arxiv:1409.7215)

GW170817 masses

The mass ratio is measured less well

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

The mass ratio is correlated with the spin



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

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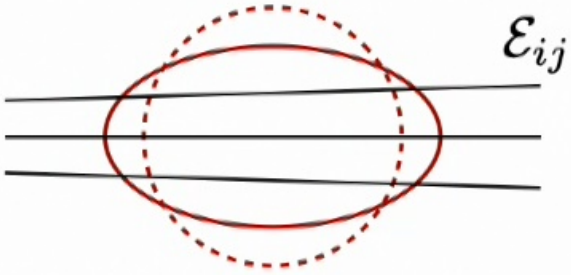
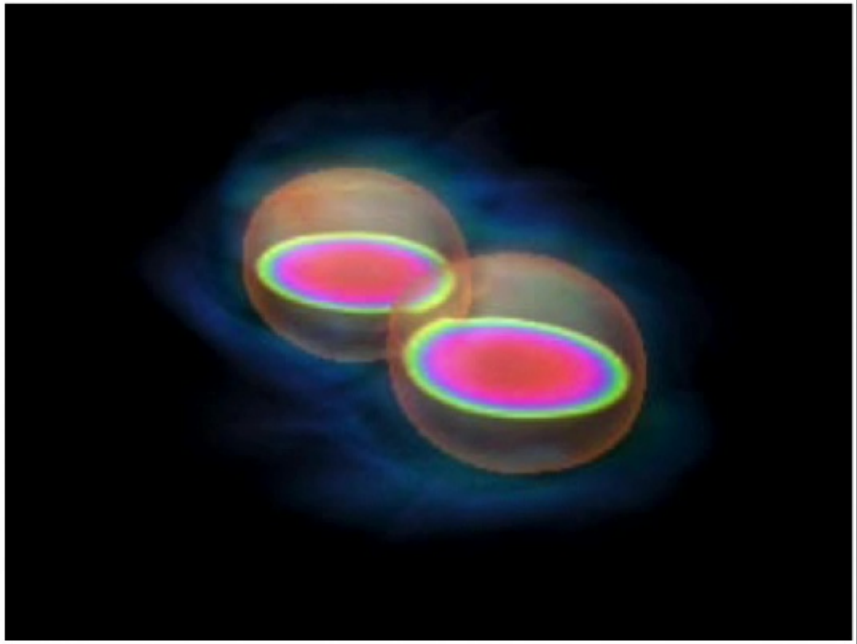
Tidal interactions

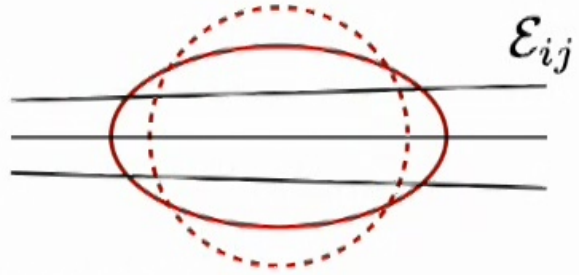


Credit: Aaron Zimmerman



Calder

Tidal interactions



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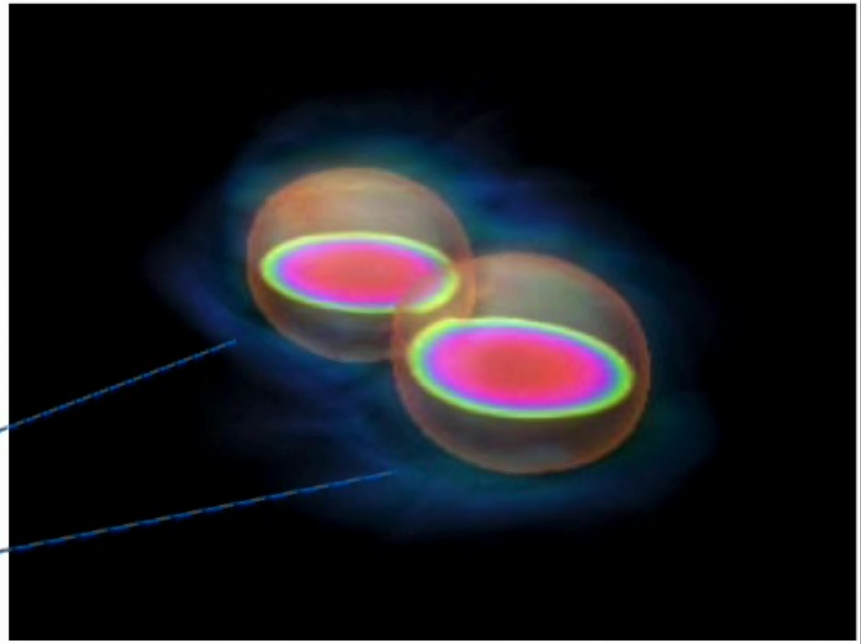

Calder

Tidal deformability

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

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

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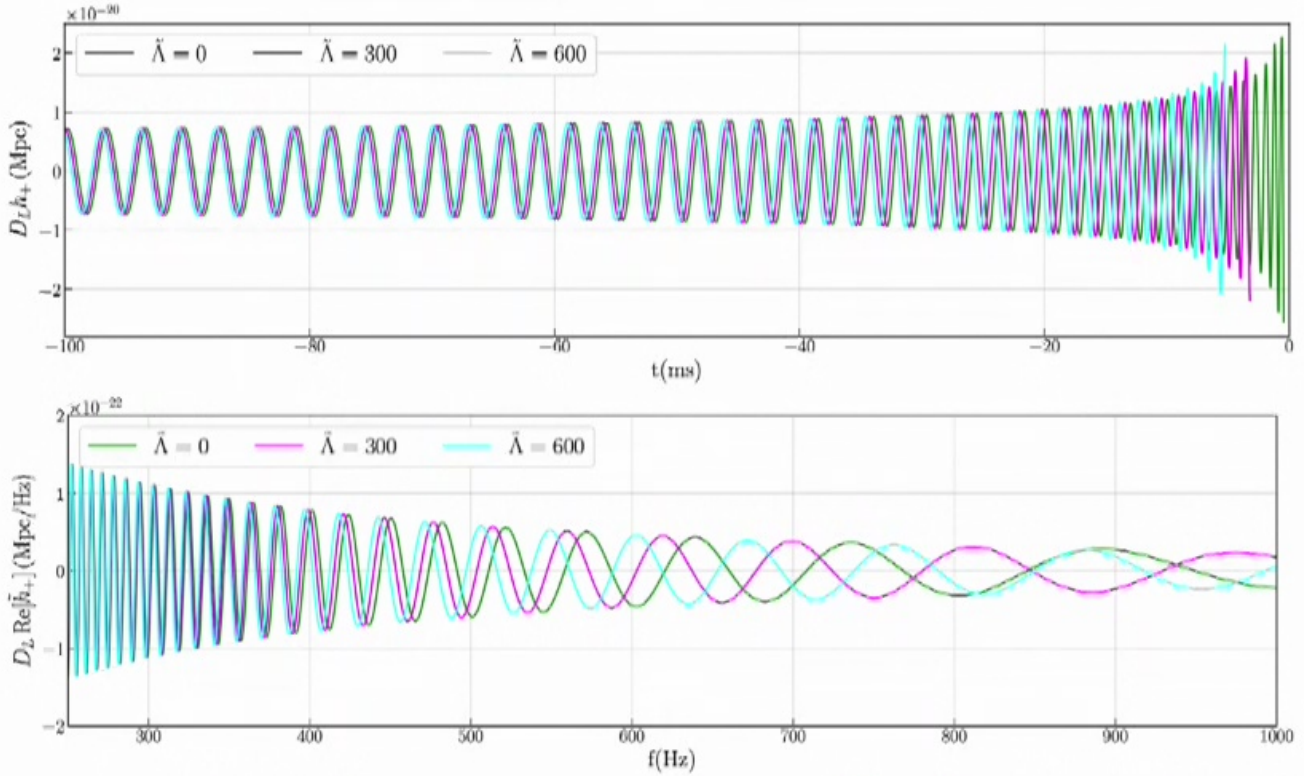
Waveform

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)

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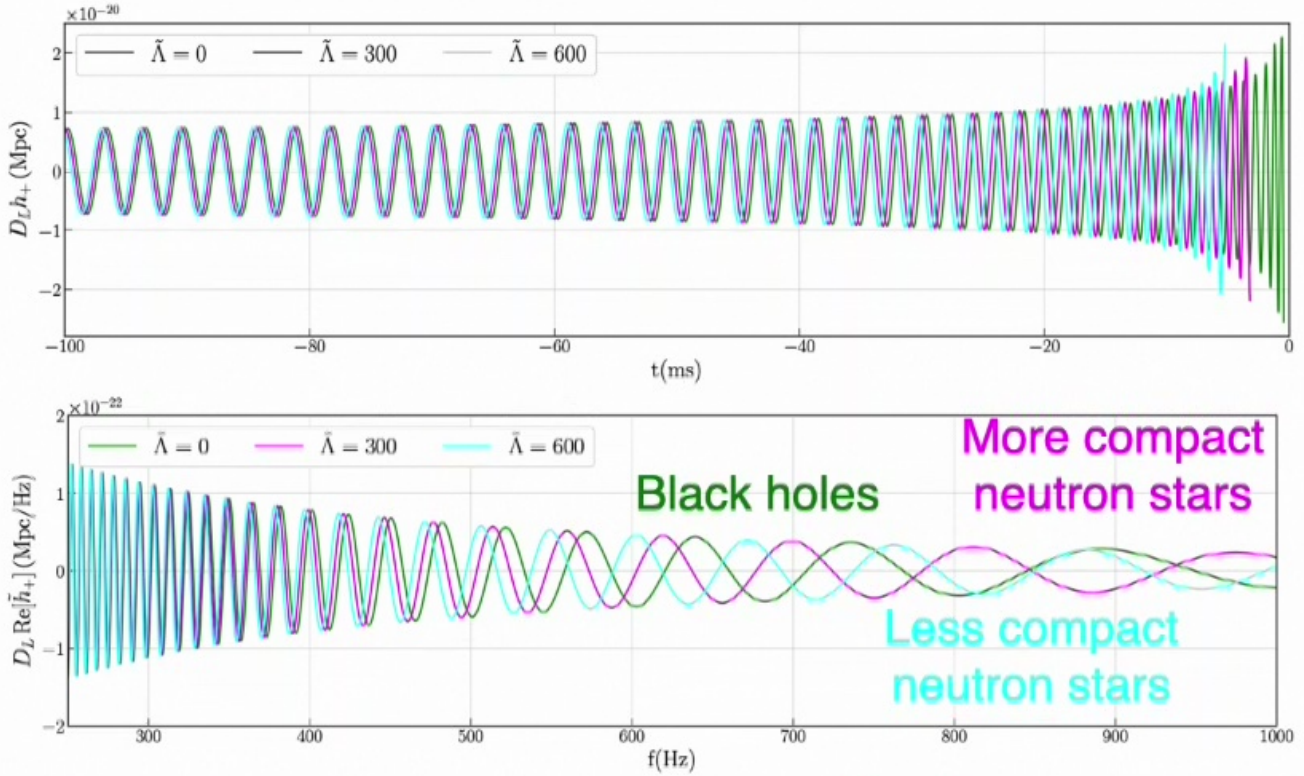

Chatziioannou (arxiv:2006.03168)

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GW170817 tides

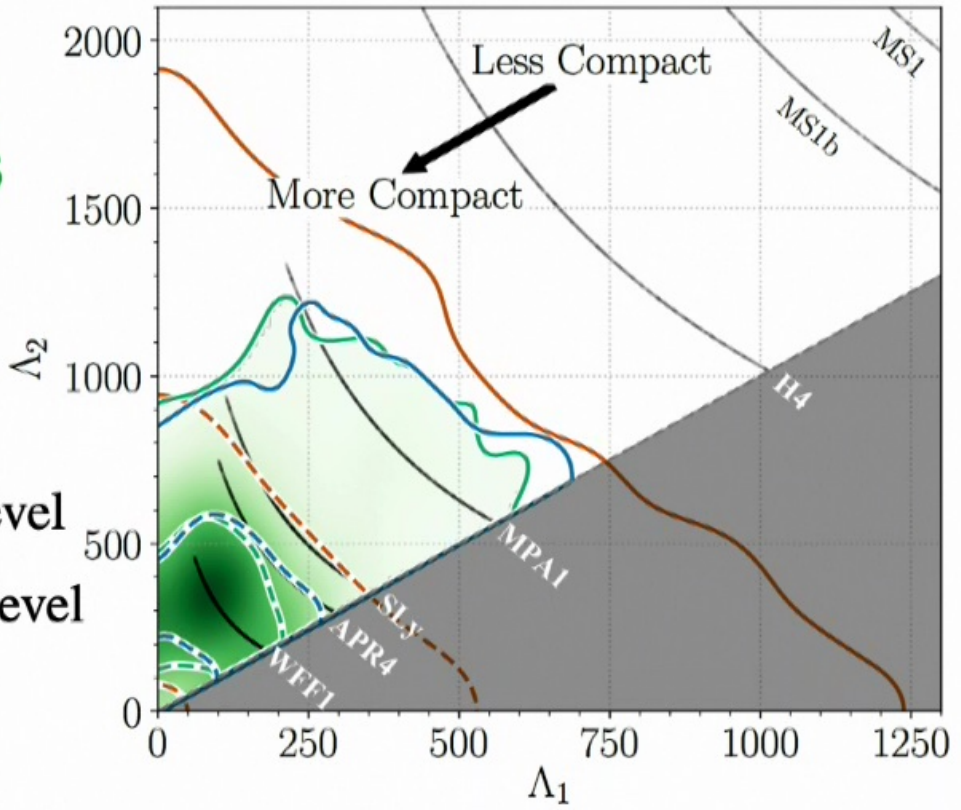
Independent EoSs

Same hadronic EoS

Spectral EoS parametrization

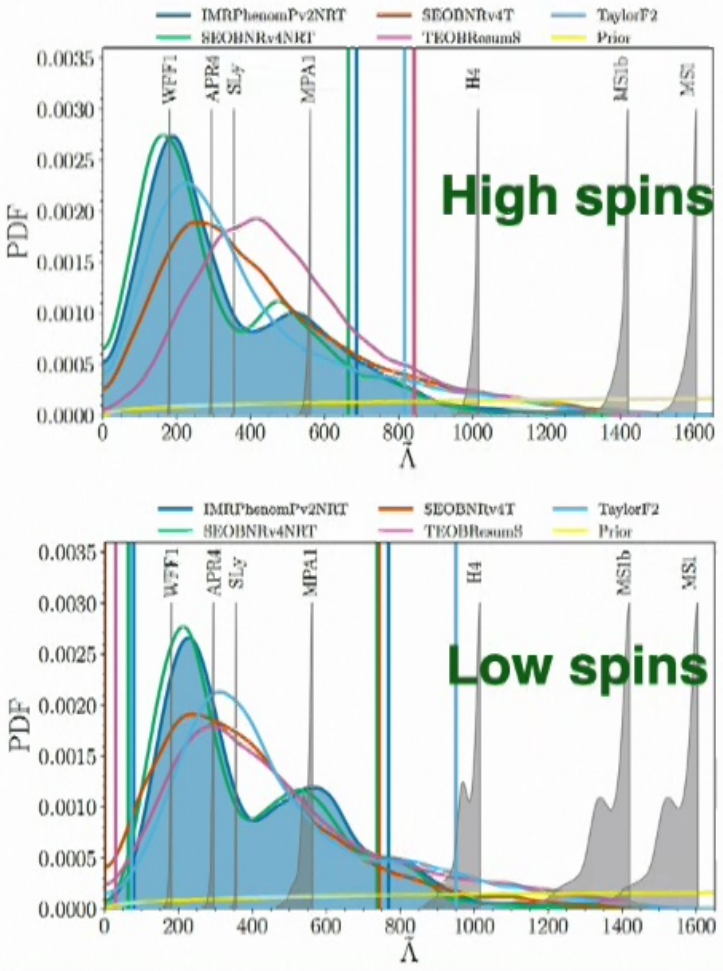
$\tilde{\Lambda} \lesssim 700$ at the 90 % level

$R \lesssim 13$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)

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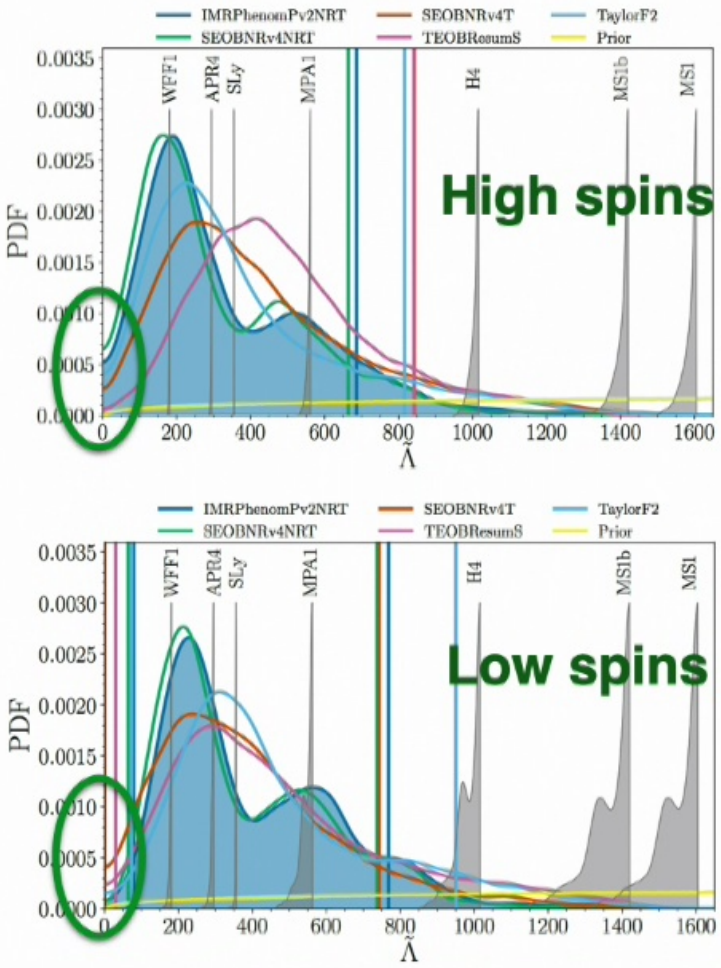

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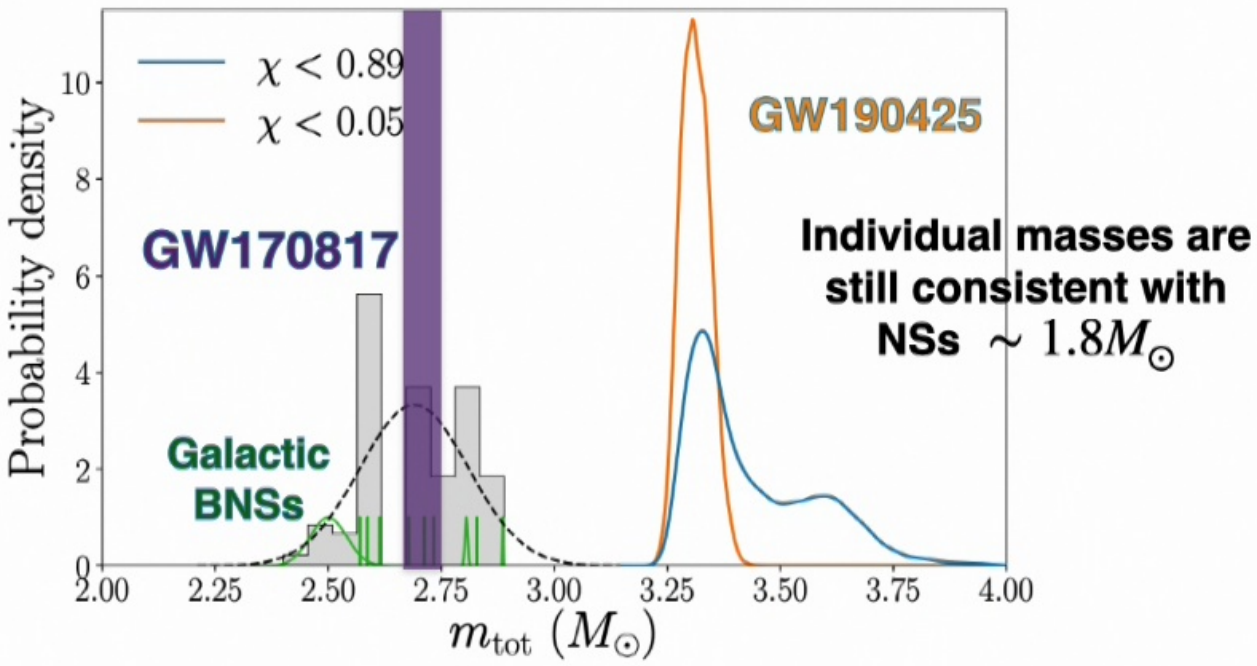
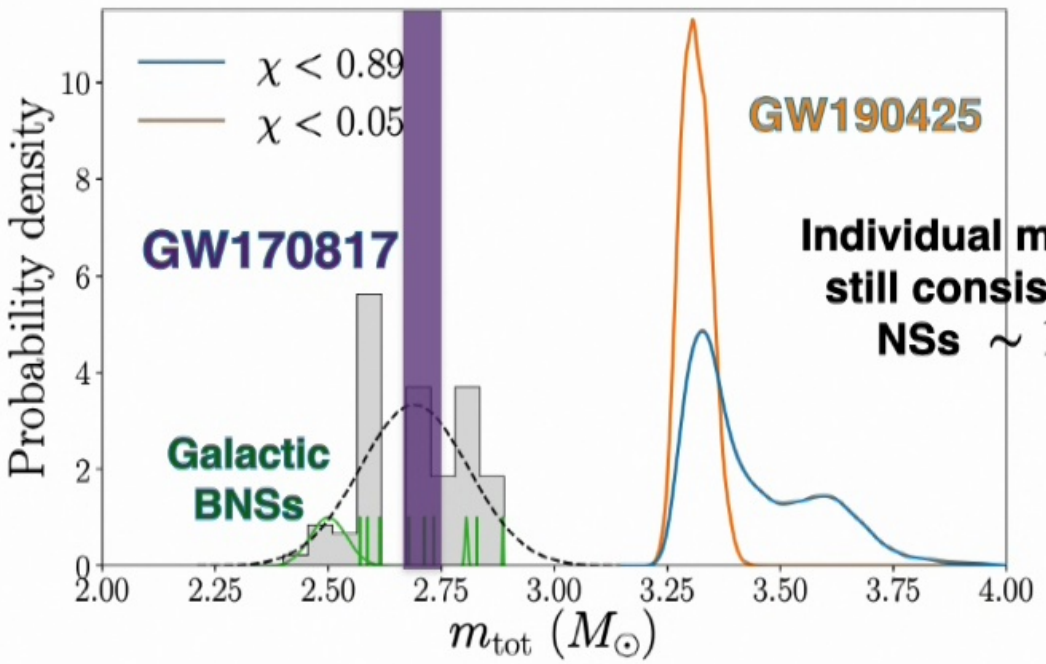
GW190425 masses



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

GW190425 masses



Individual masses are still consistent with NSs $\sim 1.8M_\odot$

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

LVC (arxiv:2001.01761)
PE: Veitch+ (arxiv:1409.7215)
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GW190425 finite-size effects

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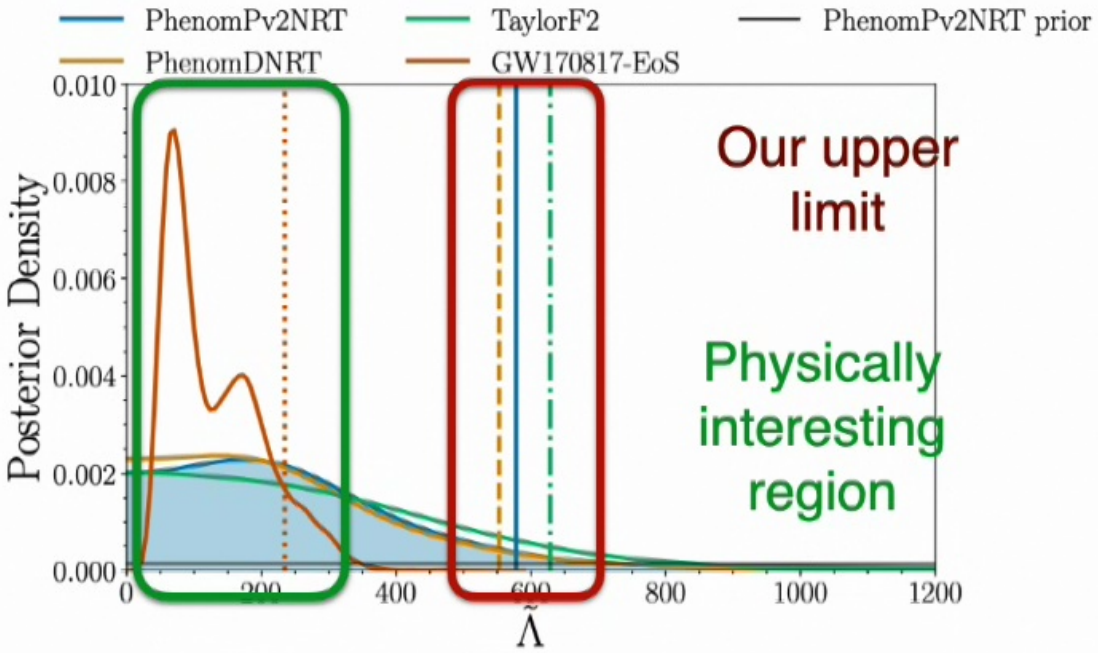
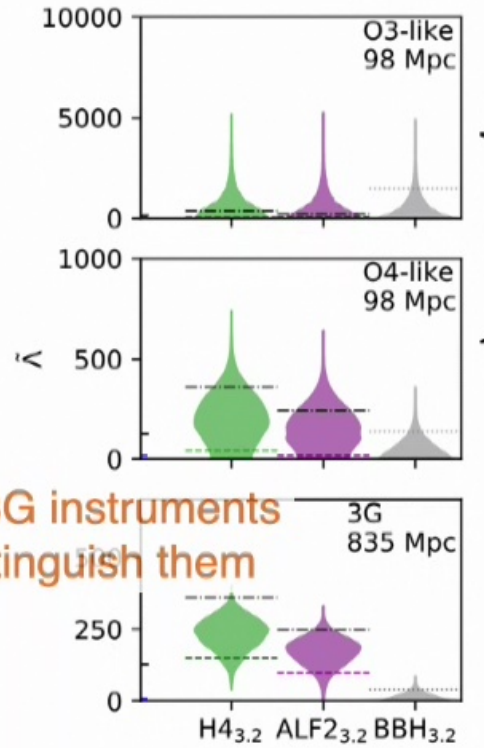


LVC (arxiv:2001.01761)
PE: Veitch+ (arxiv:1409.7215)
Waveform: Dietrich+ (arxiv:1804.02235)

High mass events

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



NSs and BHs are indistinguishable

Need 3G instruments to distinguish them

A non zero tidal parameter proves the presence of one NS, not two.

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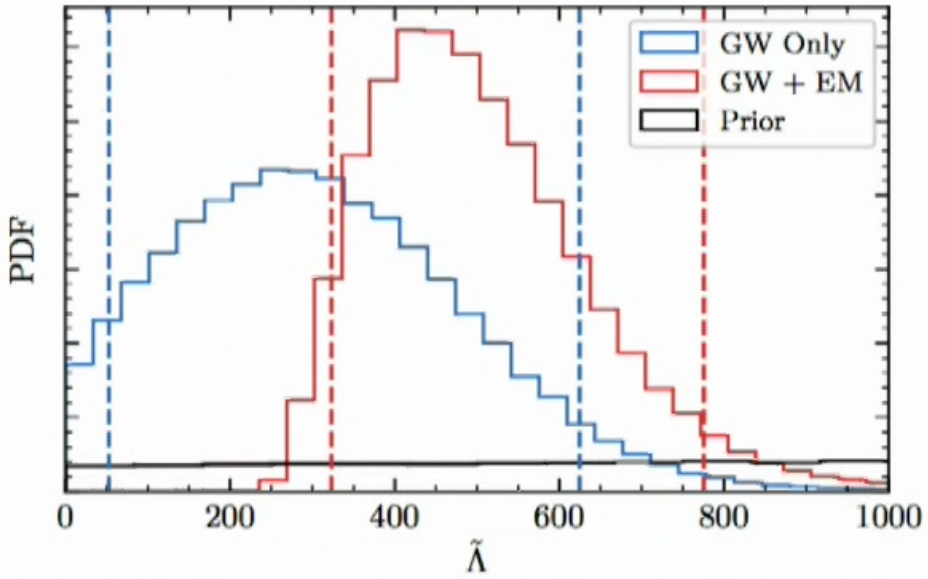
Chen+ (arxiv:2001.11470)

Kilonova

Relations between the disk/ejecta mass (no direct collapse) and the tidal parameters, based on numerical simulations. Systematics?



Radice+ (arxiv:1810.12917)
Coughlin+ (arxiv:1812.04803)

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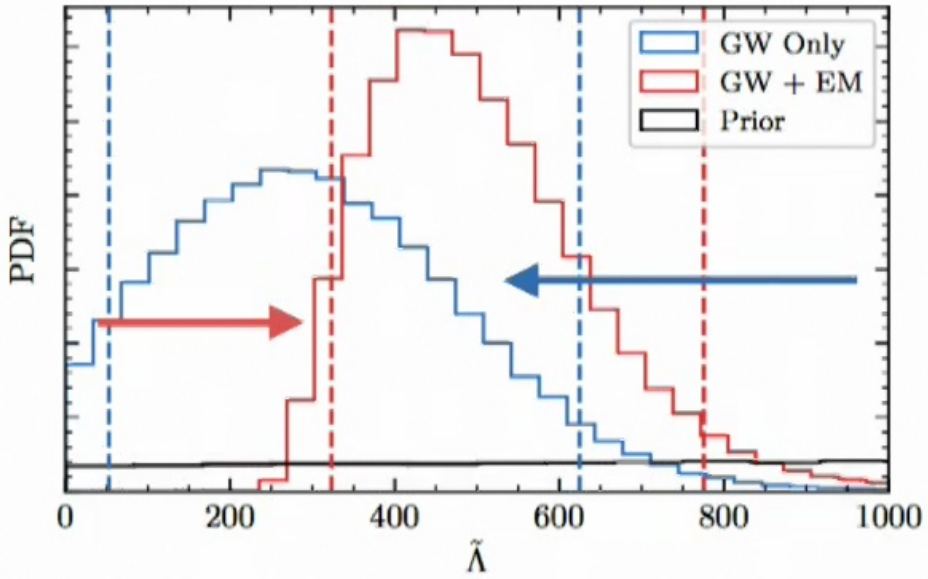

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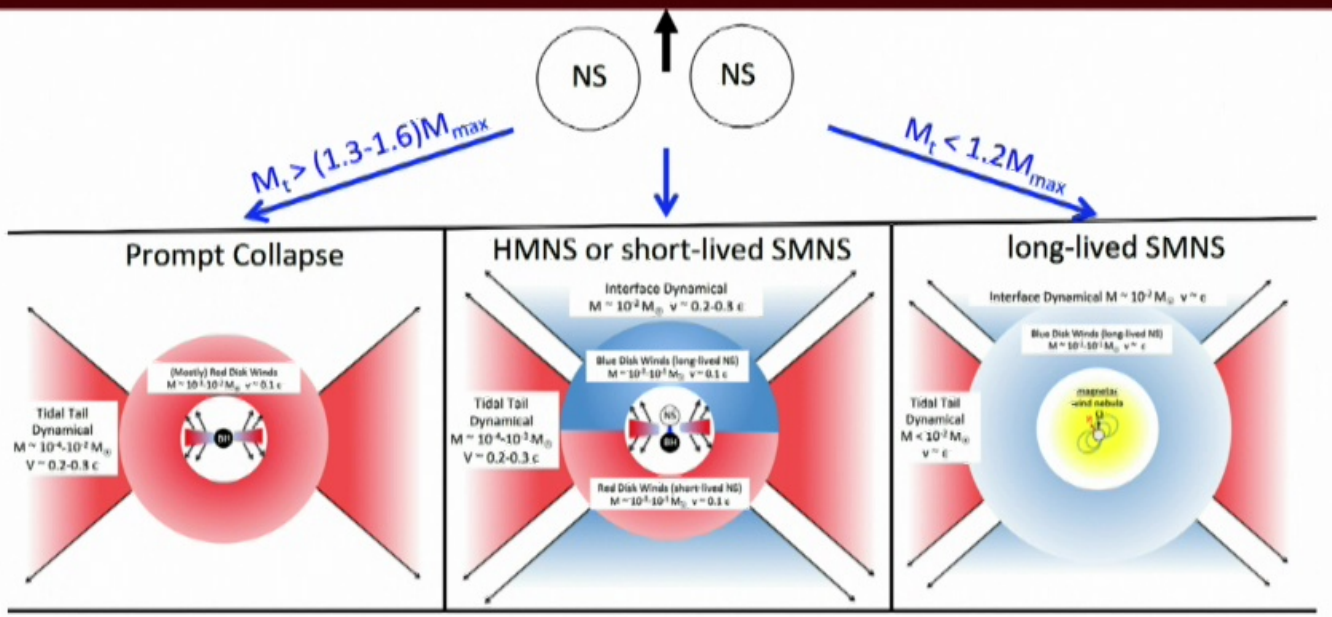
Remnant star



Margalit, Metzger (arxiv:1710.05938)

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

The remnant fate informs the nature of the binary components

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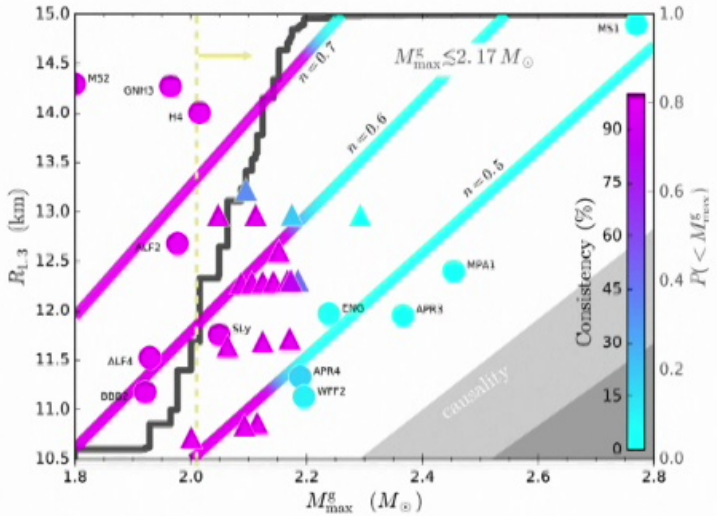
Remnant fate

Information about the fate of the remnant might be extracted from modeling the EM emission



Margalit and Metzger (arxiv:1710.05938)

Total mass (GW) + requirement for a hyper massive neutron star (EM)

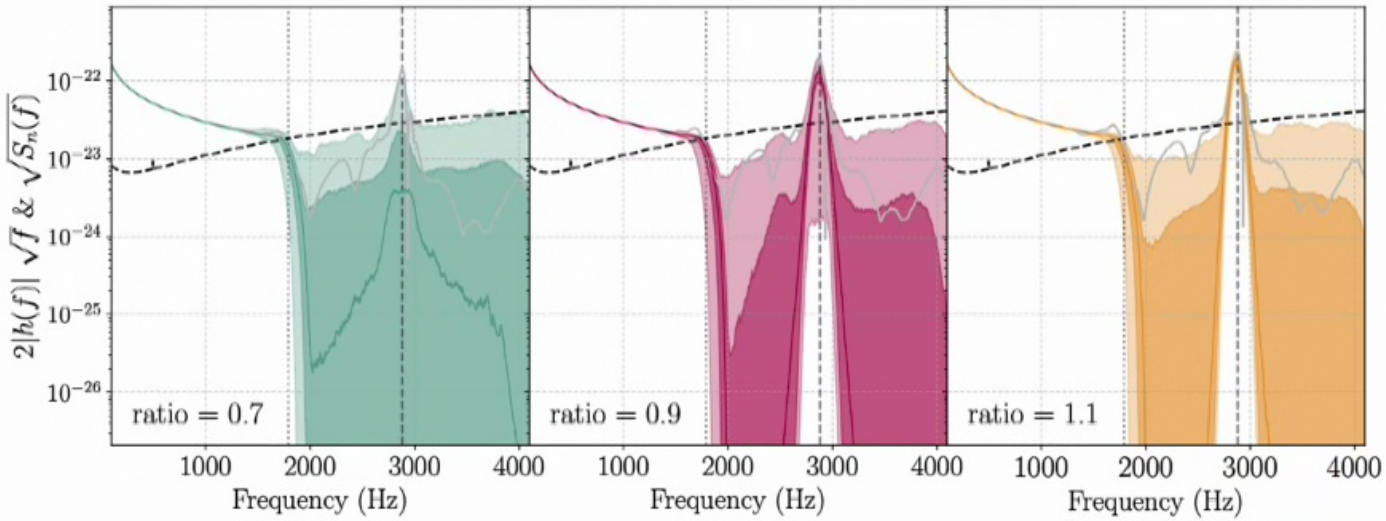
$$M_{max} \lesssim 2.3 M_\odot$$

Post-merger signal

Ignoring the post-merger signal will not affect inspiral constraints

Dudi+ (arxiv:1808.09749)

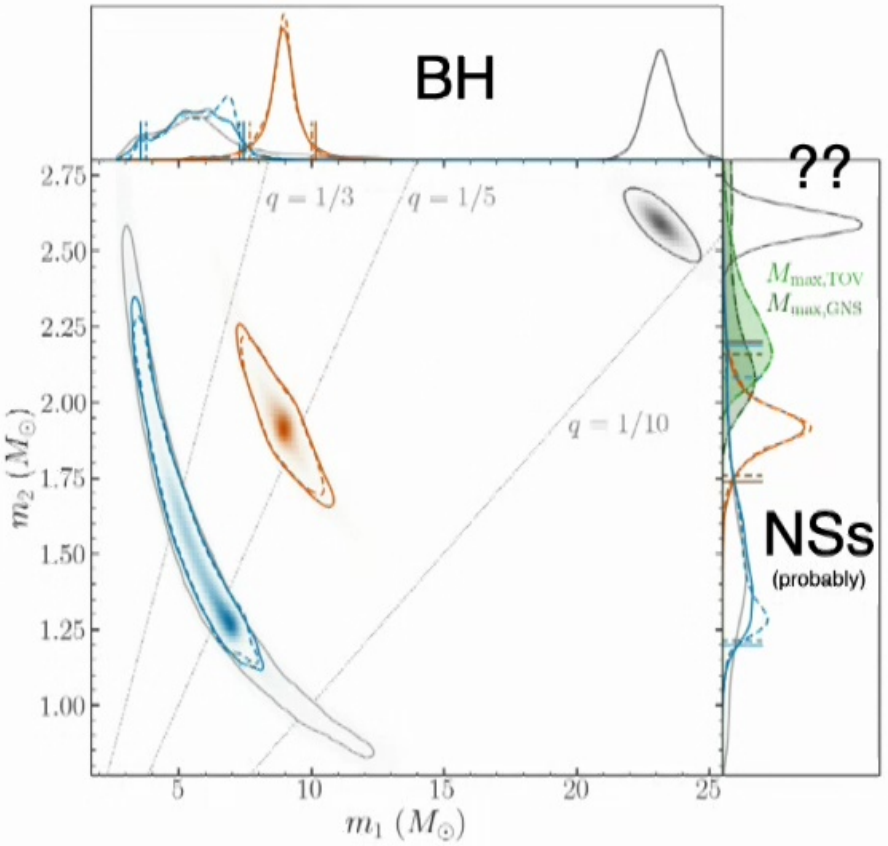
We can extract the main features of the post-merger signal…



…but interpretation is a different story

Wijngaarden+ (including KC) (arxiv:2202.09382)

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)

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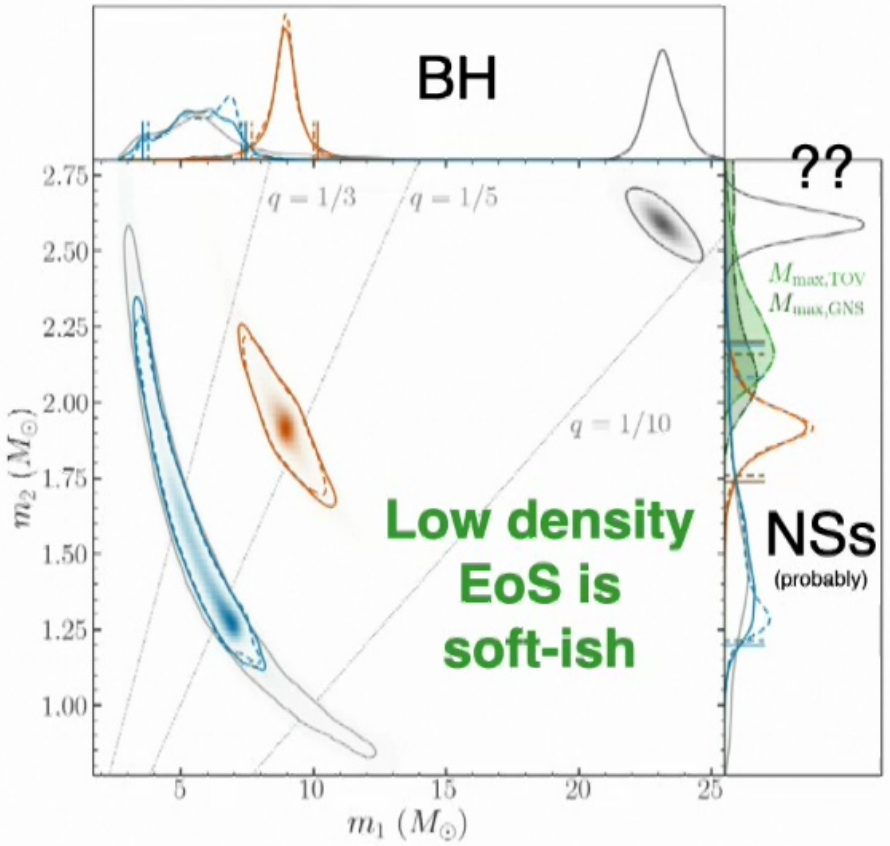

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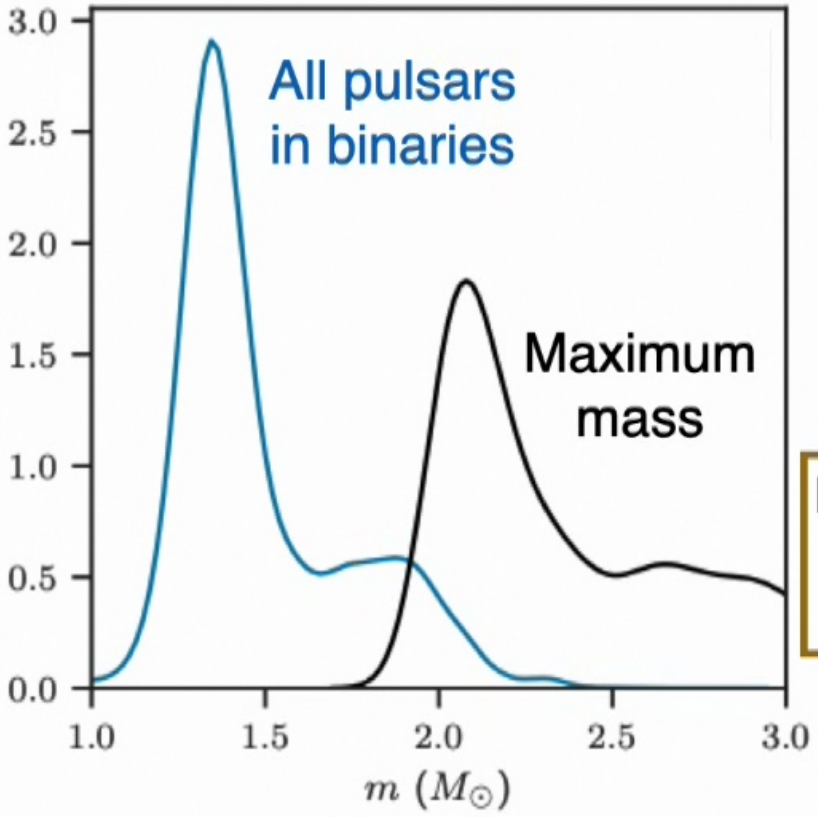
Input from galactic pulsars

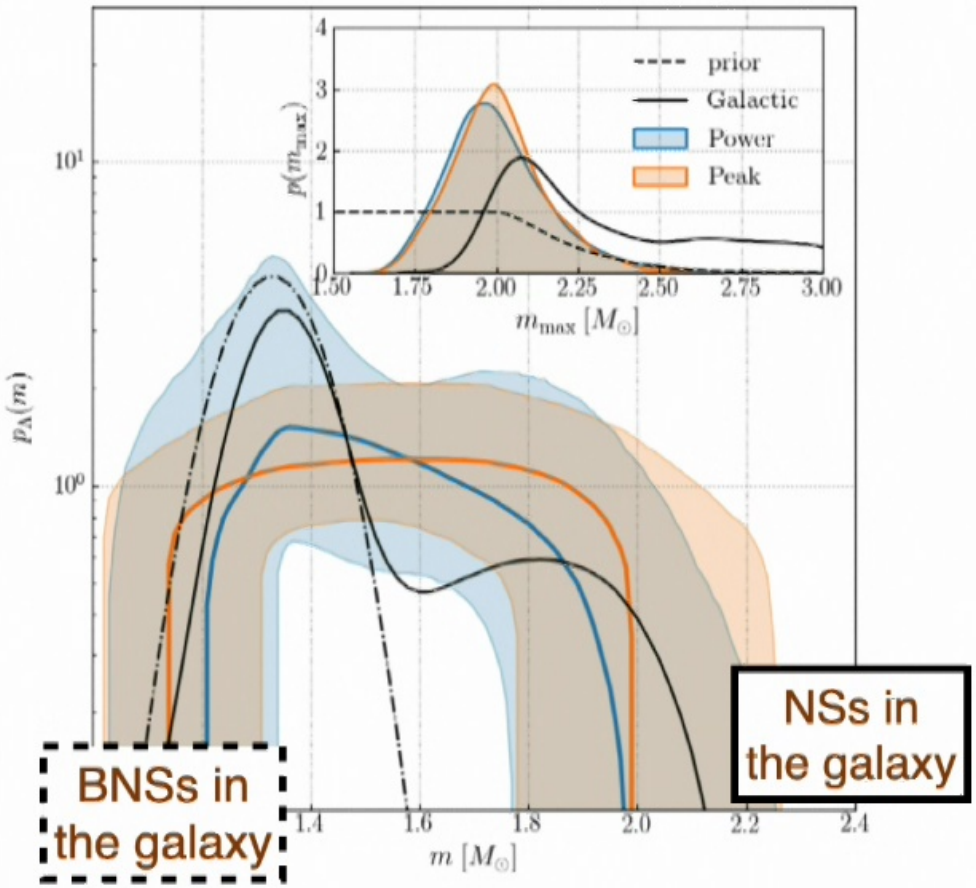


Bimodal distribution and possibility of a cutoff

Do galactic pulsars have the same properties as LIGO sources?

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

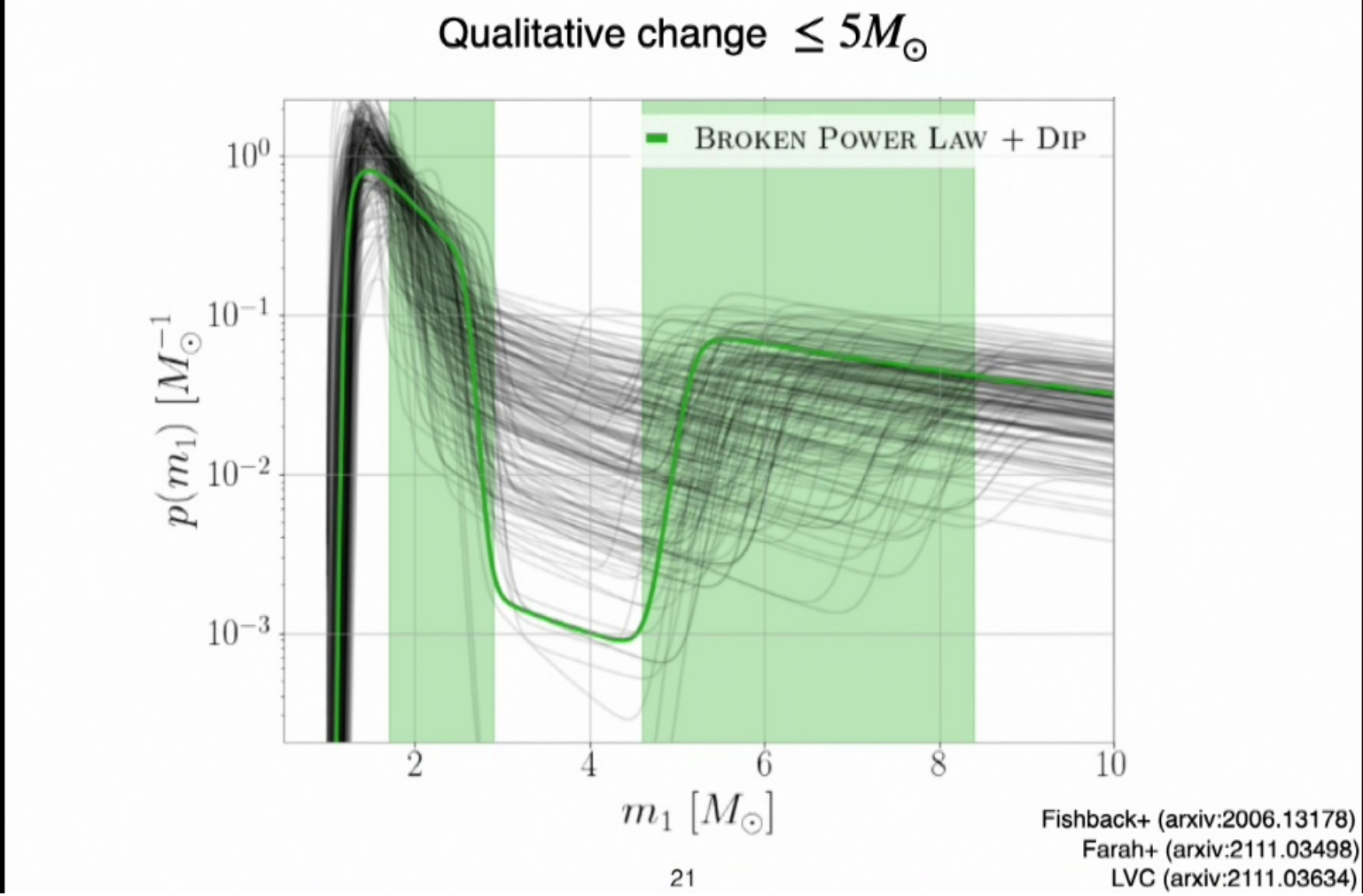
The low-mass objects



NSs observed with GWs/EM have different mass distributions

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

The whole mass distribution



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

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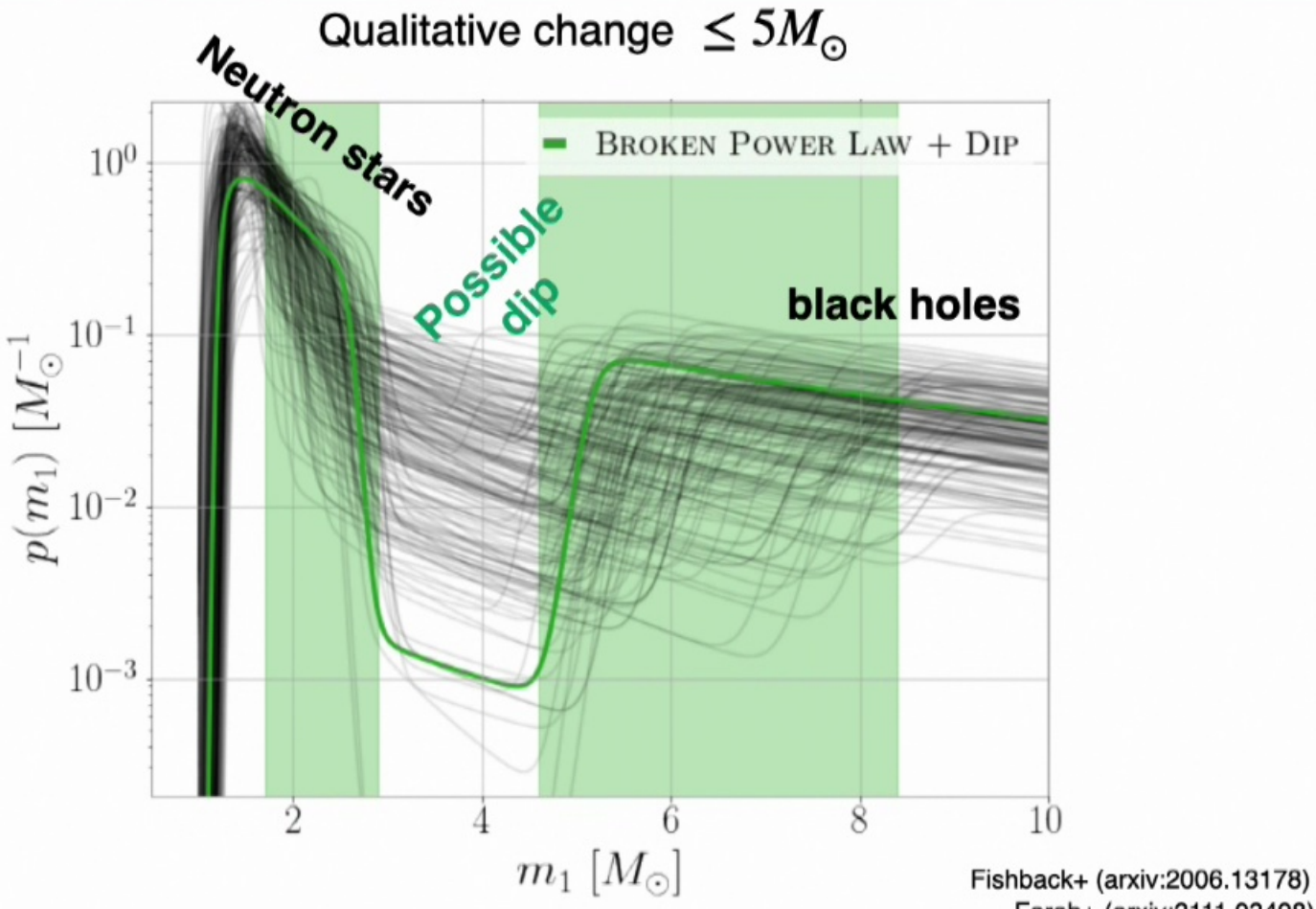

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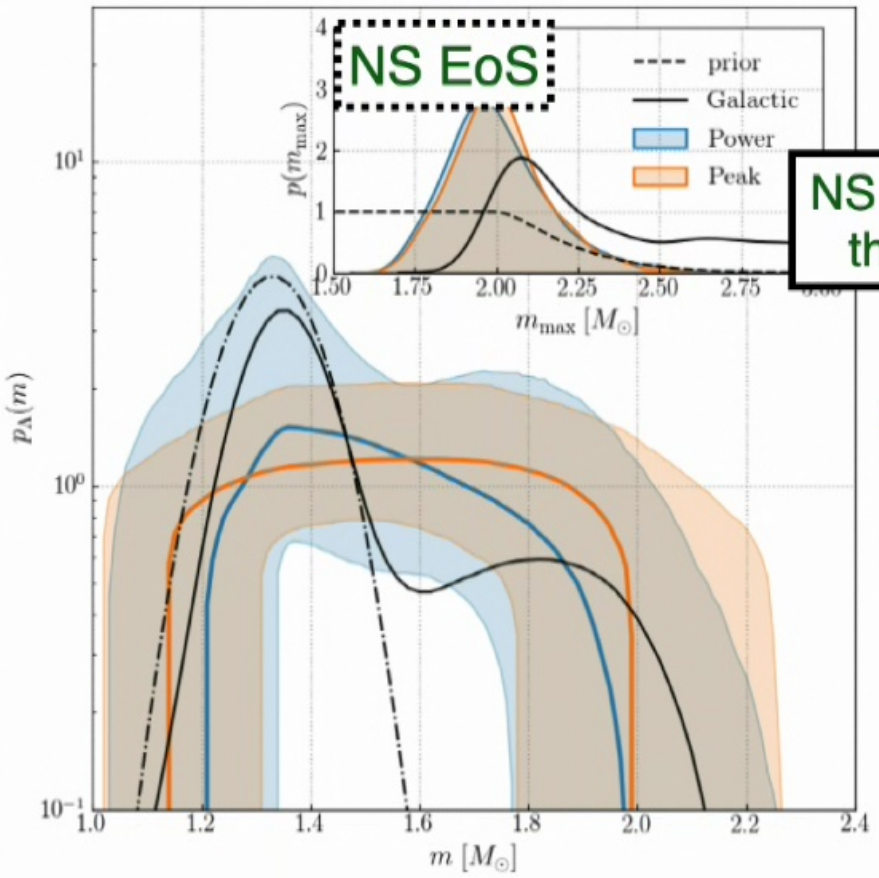


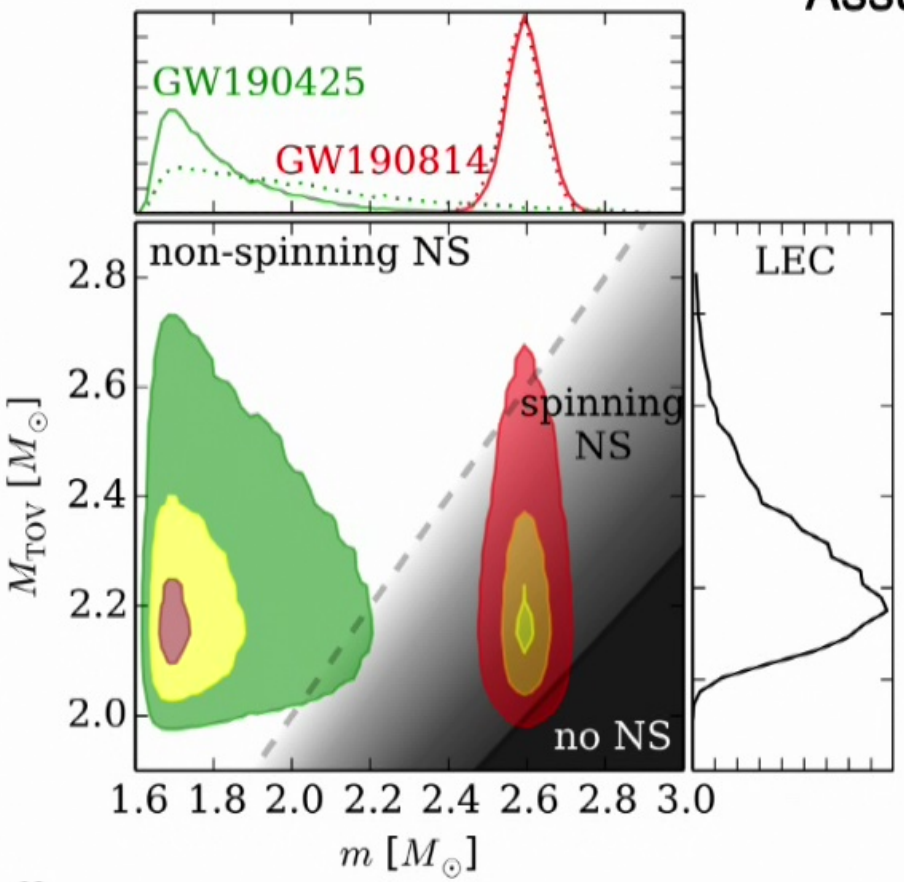
NS masses in the galaxy

Inference from masses and EoS is consistent so far

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

Compare to the maximum neutron star mass

Assume no NS-BH overlap



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Essick and Landry (arxiv:2007.01372)

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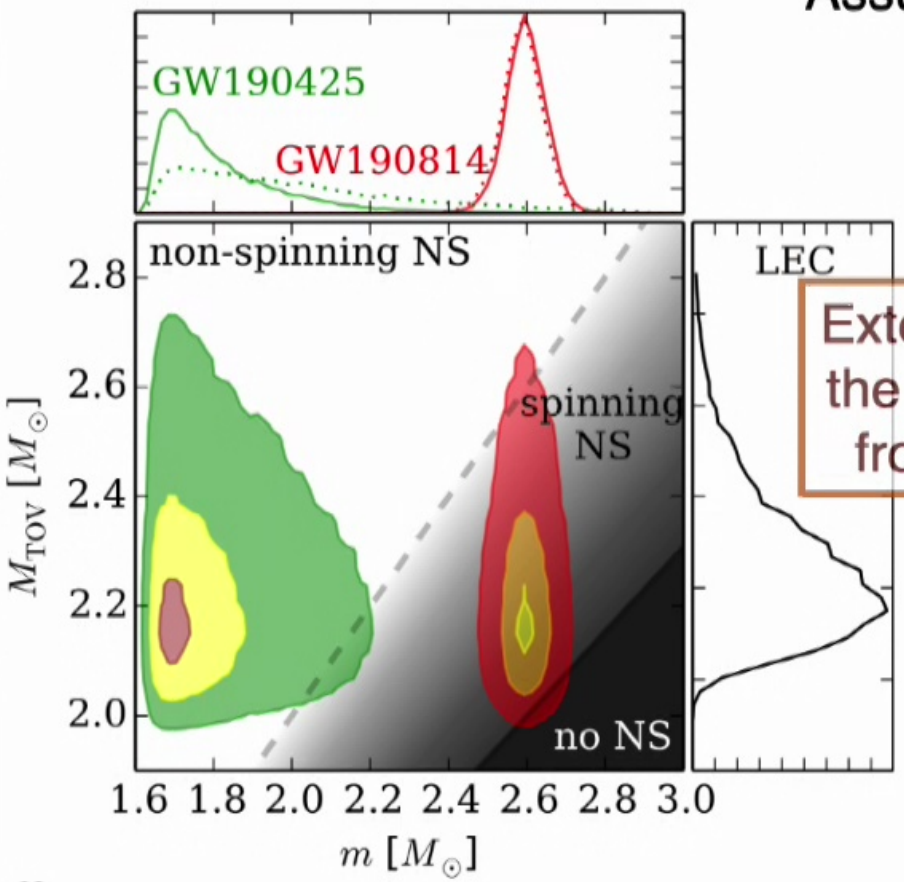

External input about the maximum mass from EoS studies

Essick and Landry (arxiv:2007.01372)

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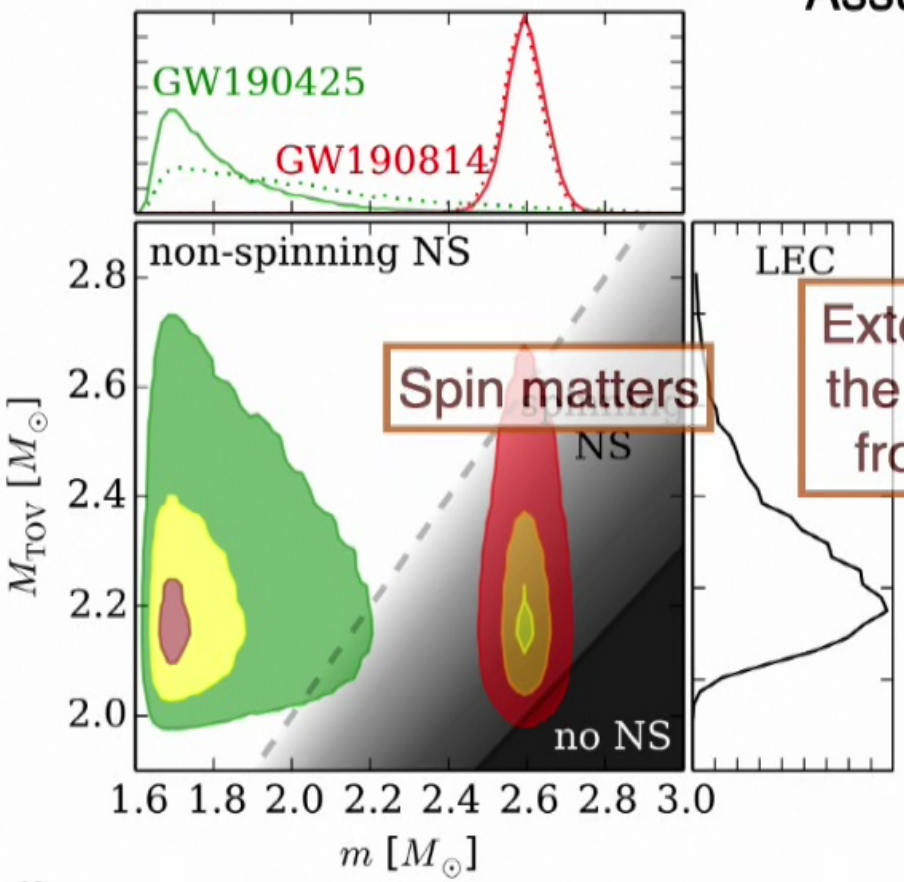


Assume no NS-BH overlap

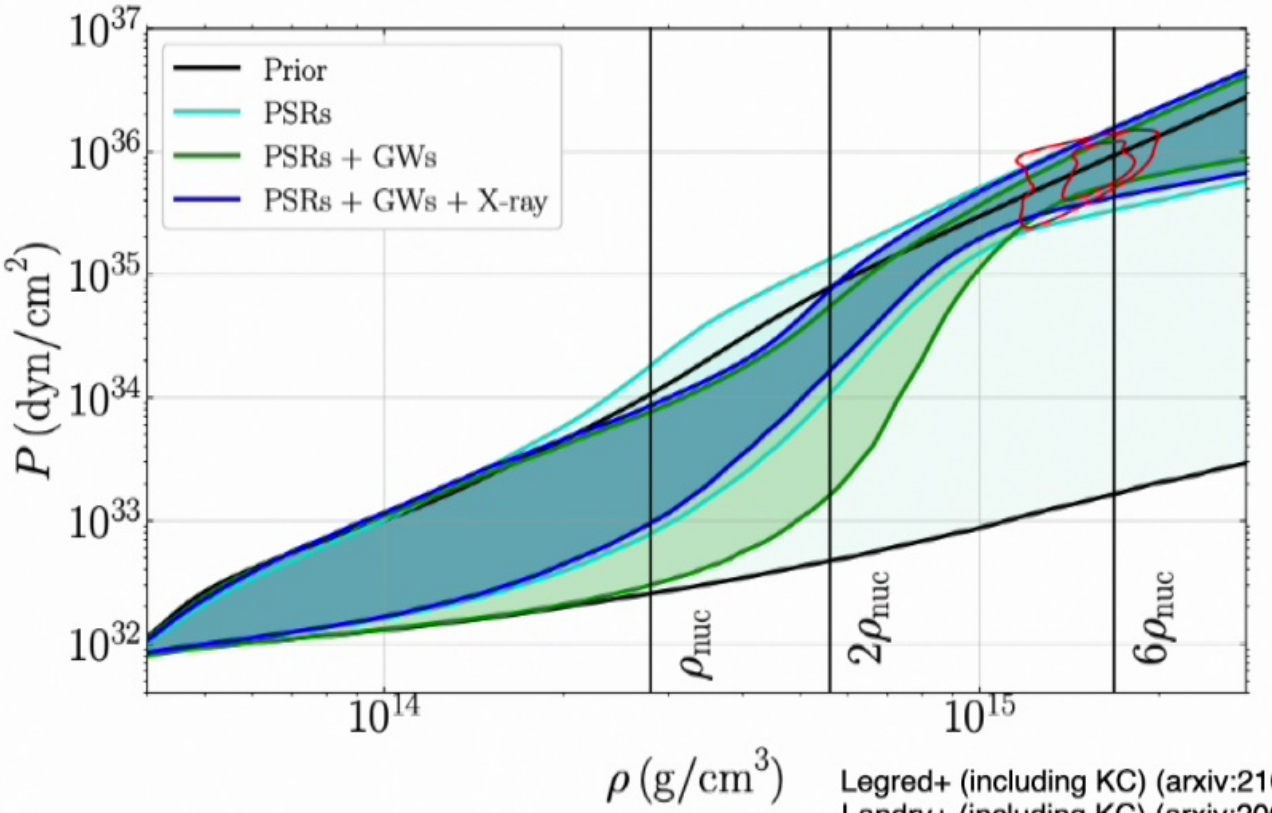
Spin matters

External input about the maximum mass from EoS studies

Essick and Landry (arxiv:2007.01372)

The EoS model

Different measurements probe different density regimes



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

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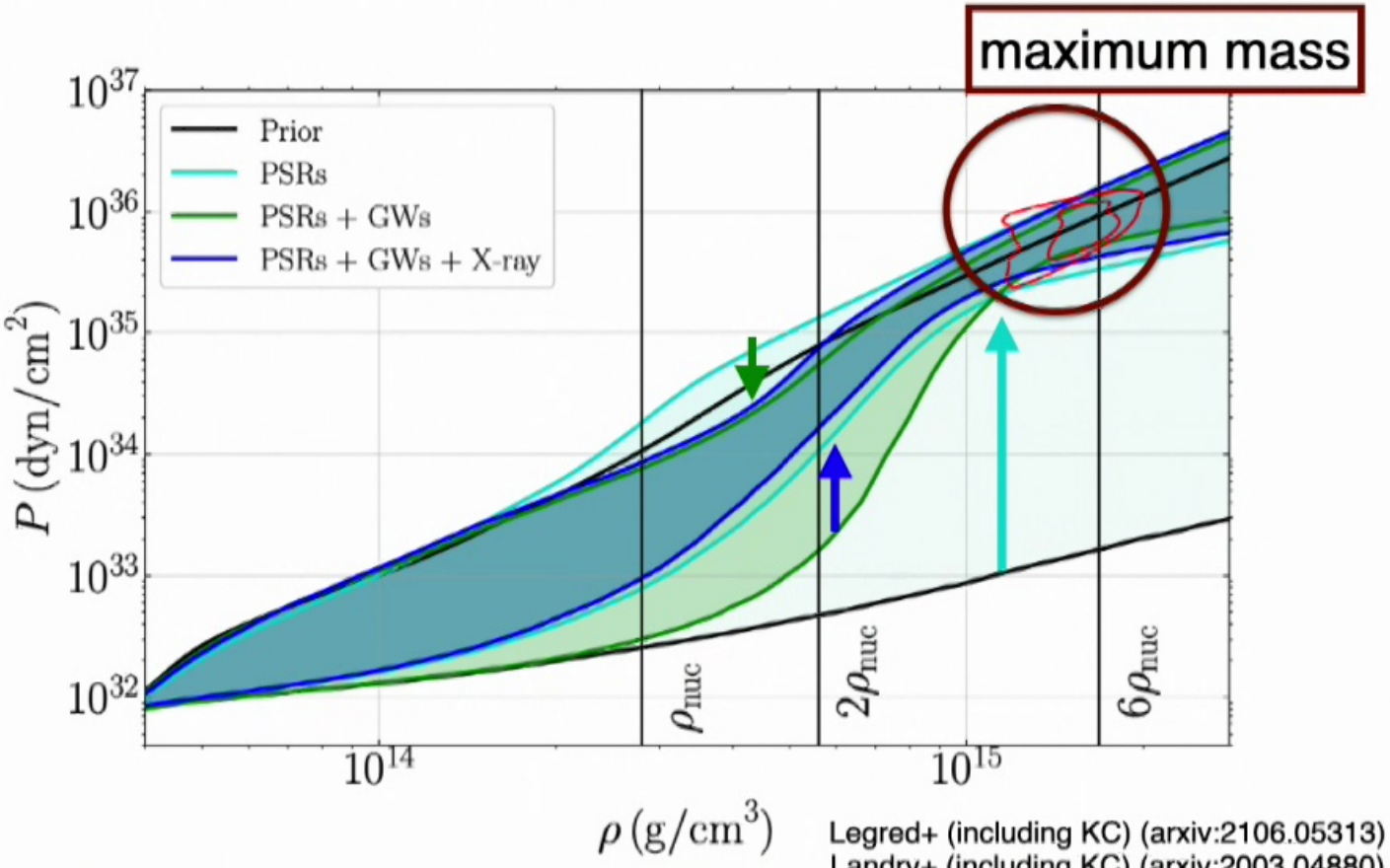

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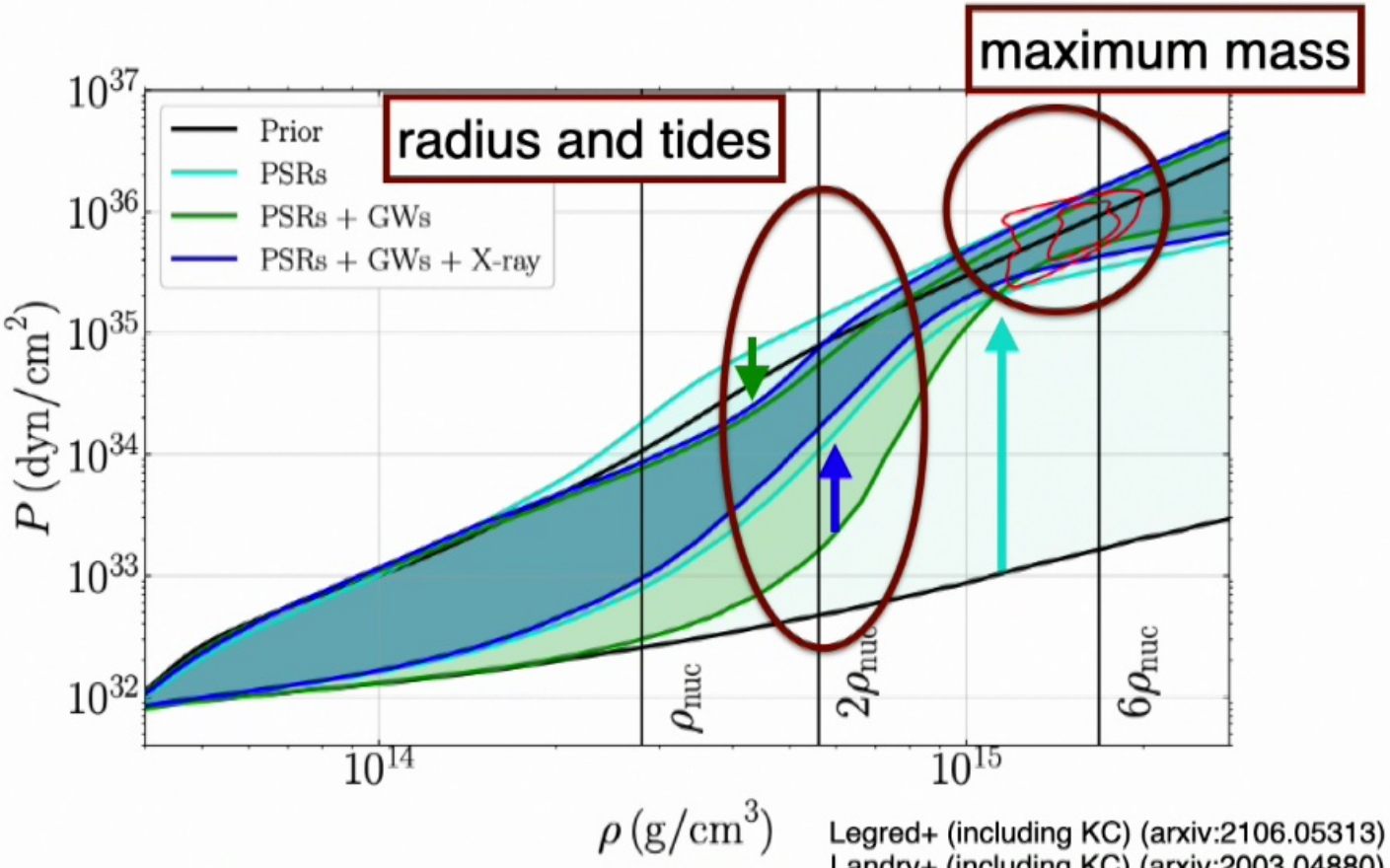

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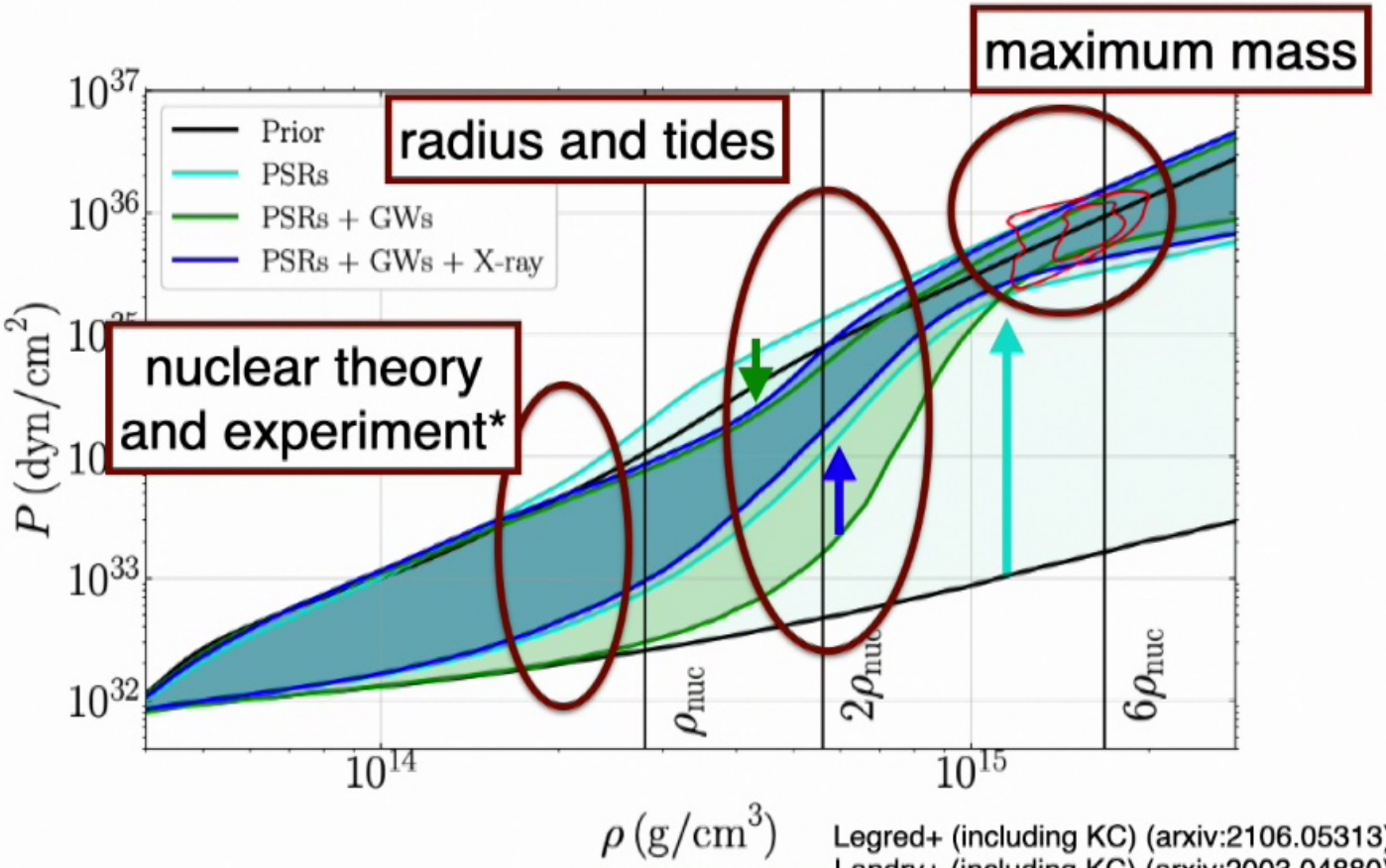

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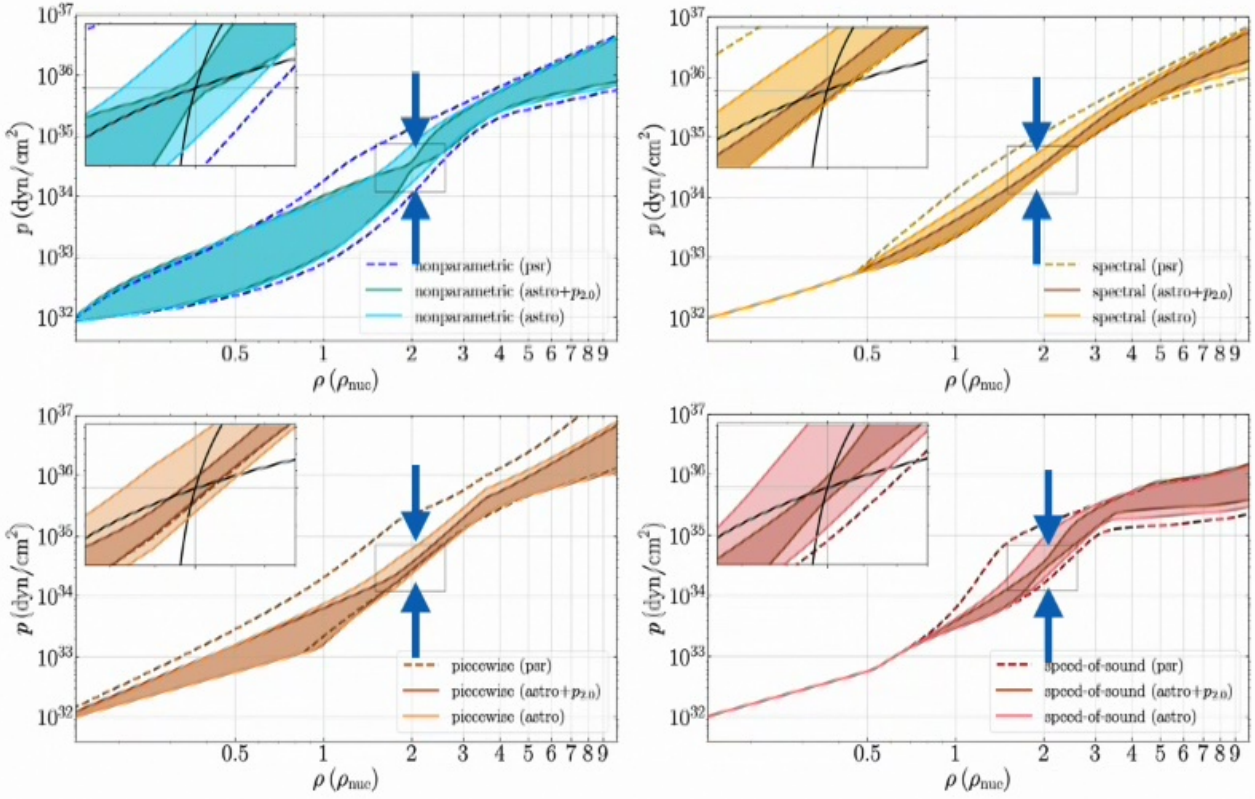
Intra-density correlations

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



Legred+ (including KC) (arxiv:2201.06791)

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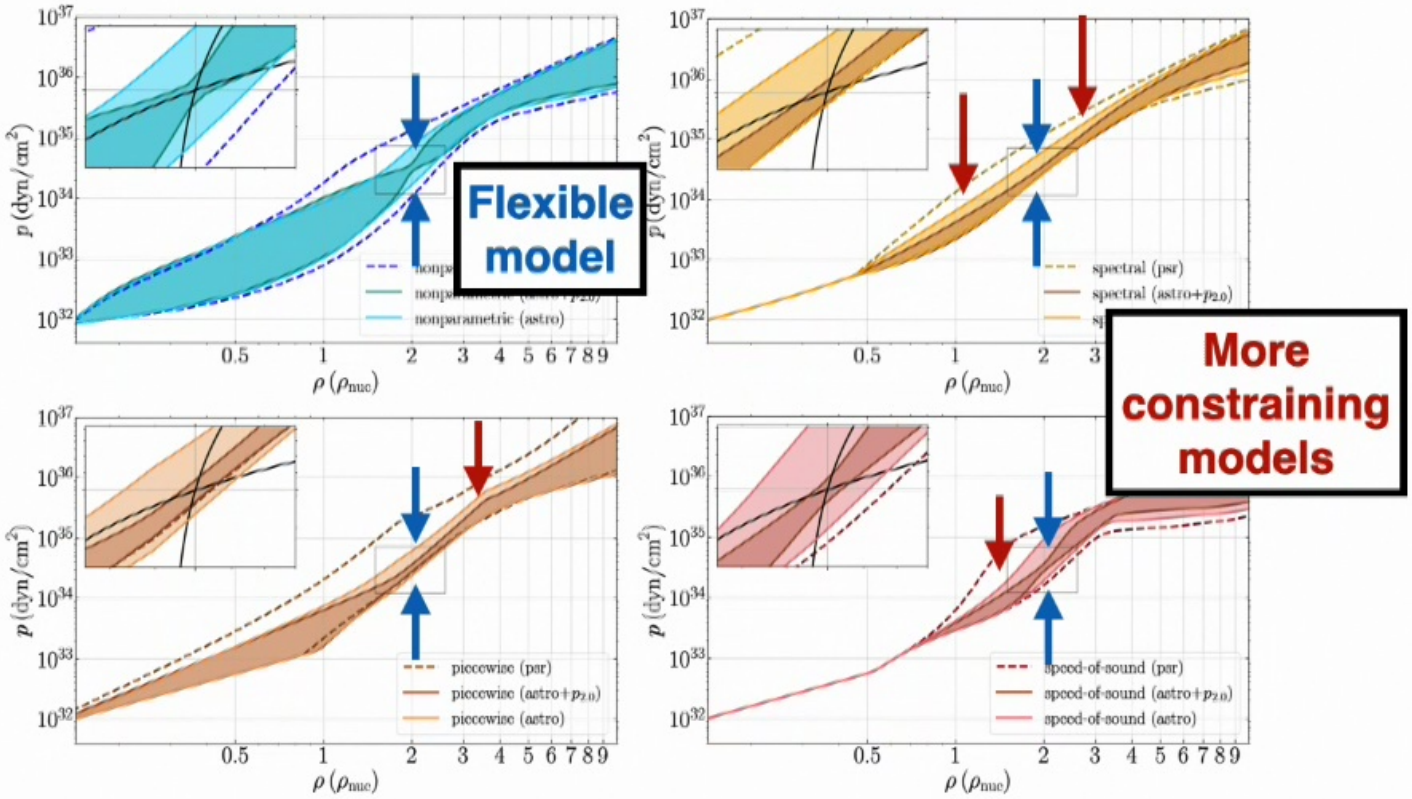
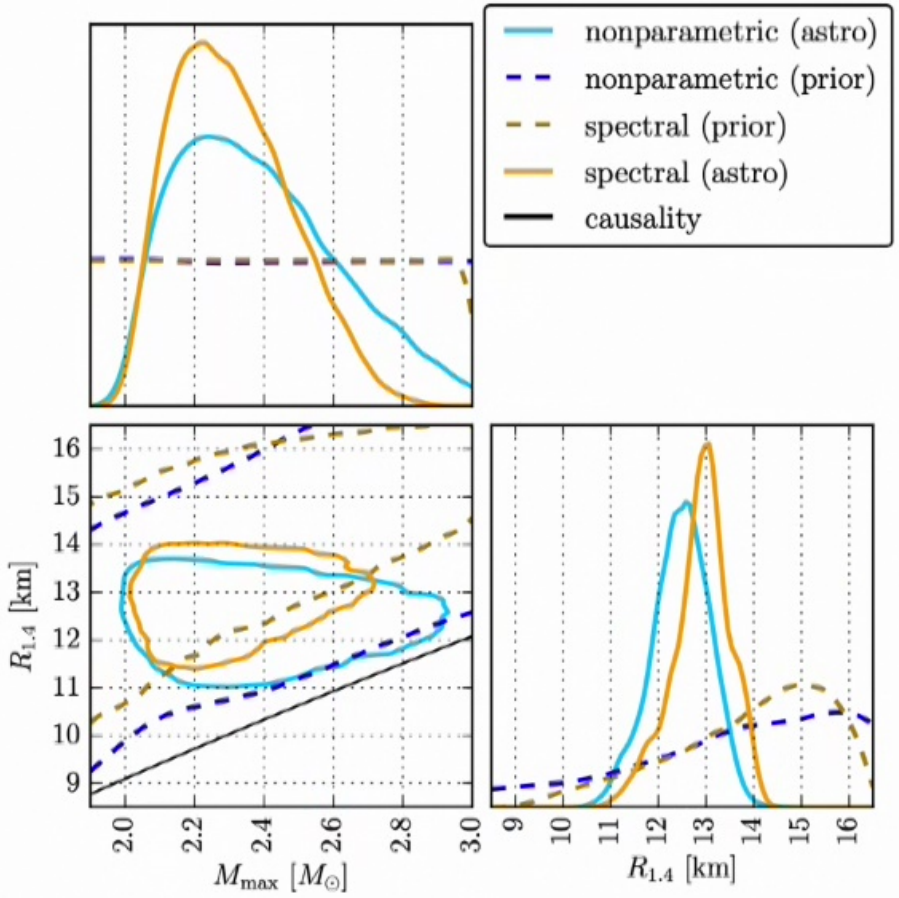
Phenomenological models might introduce unphysical (or at least unjustified) correlations



Legred+ (including KC) (arxiv:2201.06791)

The maximum mass from the EoS



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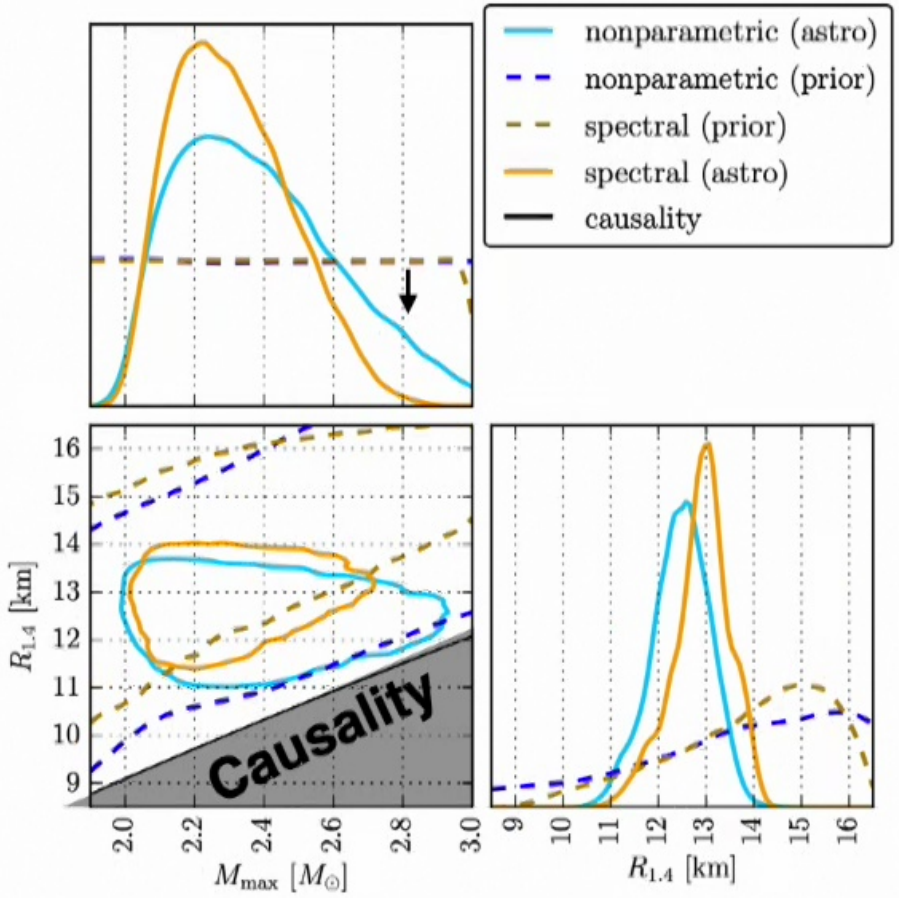

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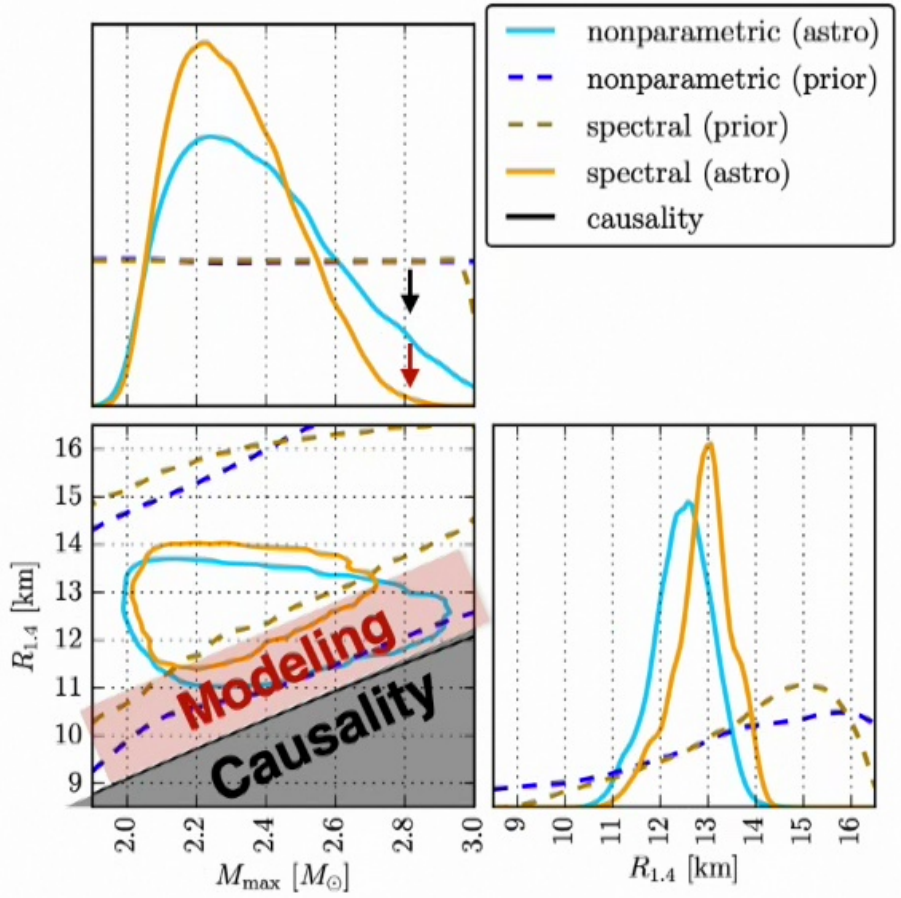
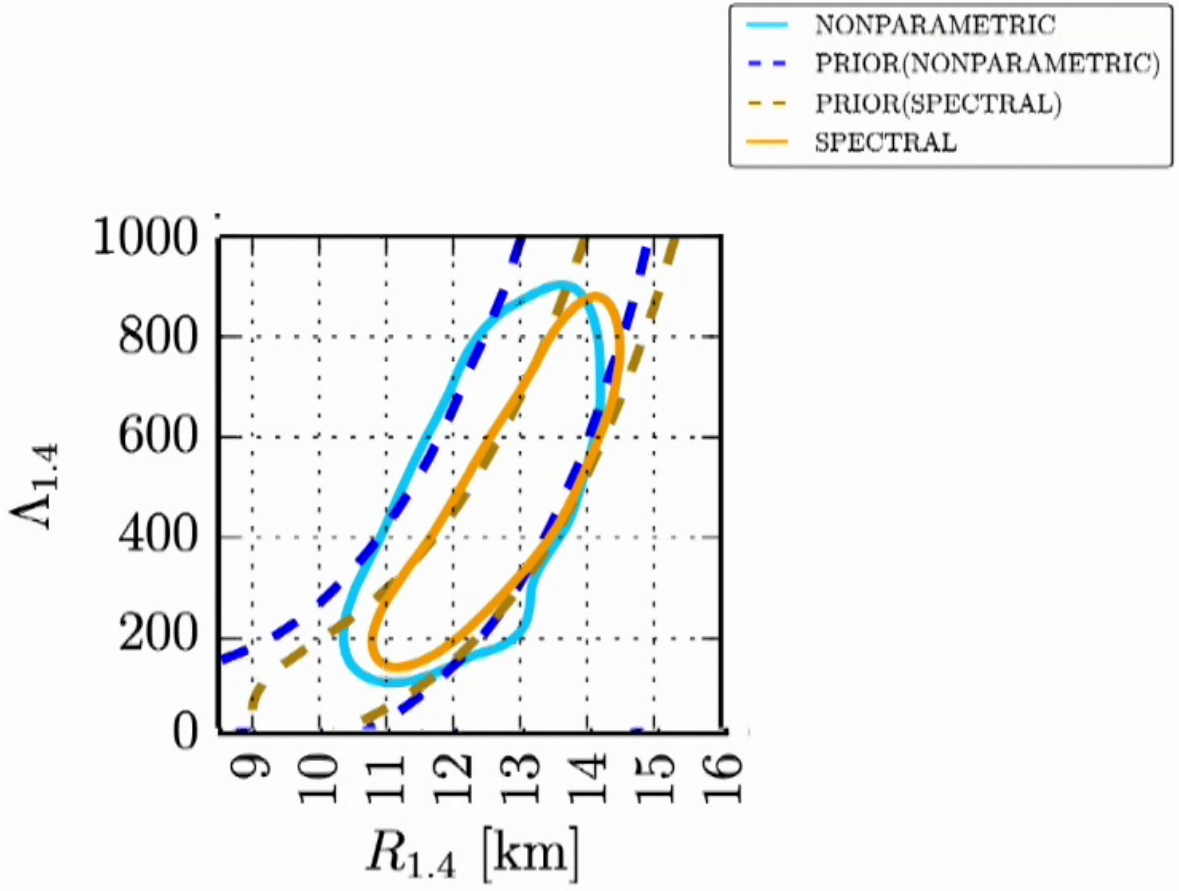


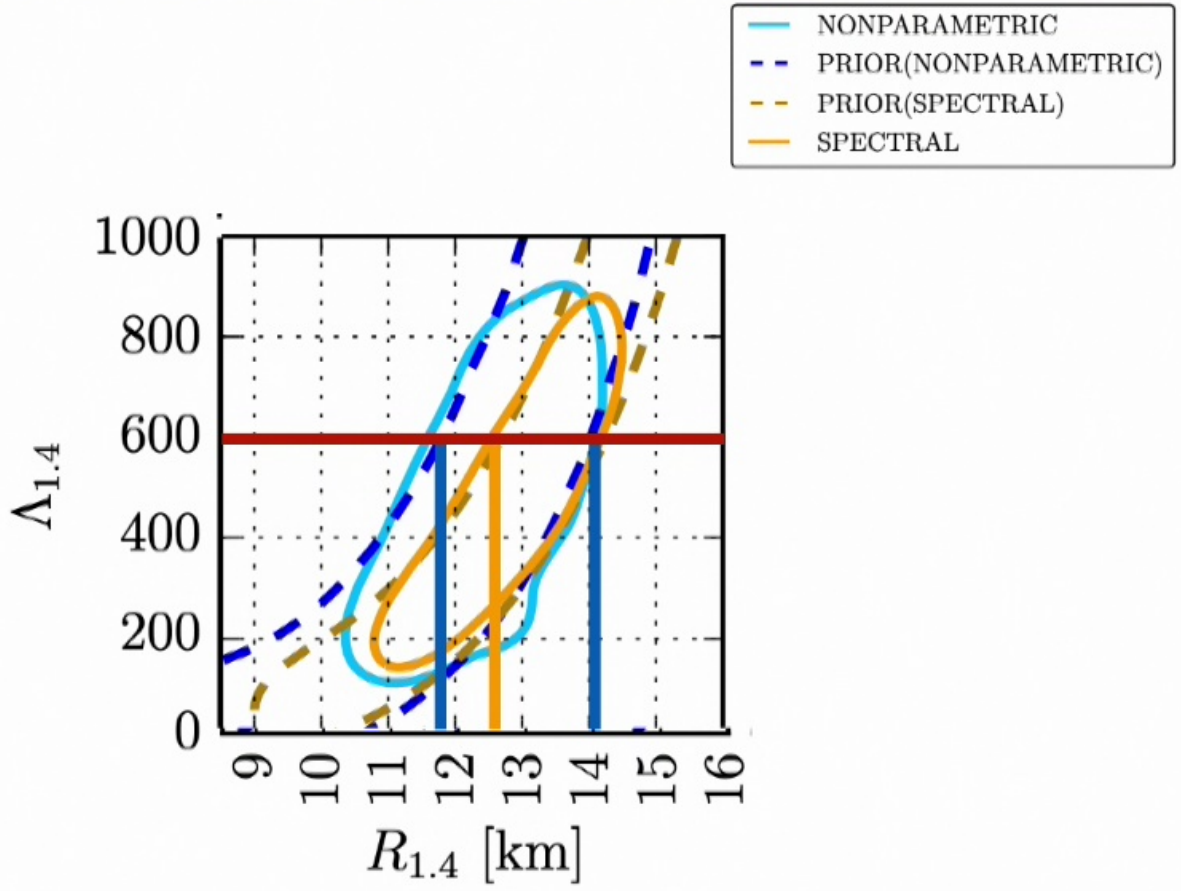
Legred+ (including KC) (arxiv:2201.06791)

The radius from GWs



Legred

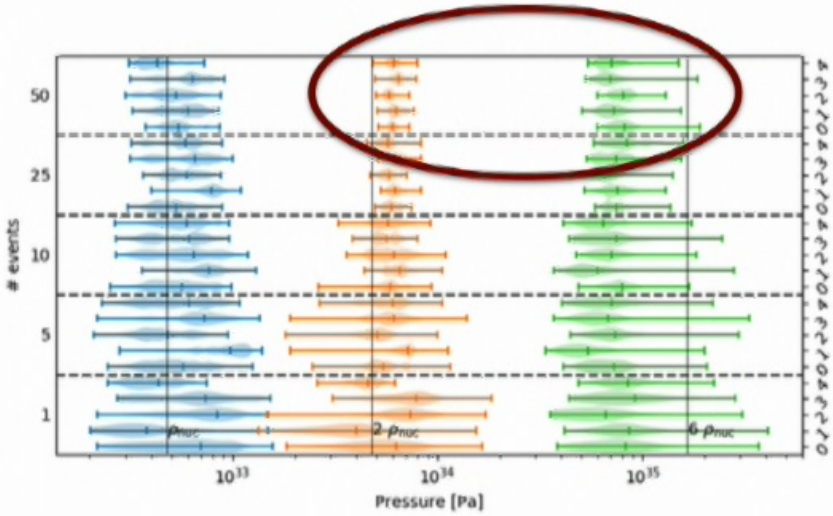
The radius from GWs



Legred

Effect of the mass distribution

Assuming the wrong mass distribution will bias results, need to marginalize over it



Wysocki+ (arxiv:2001.01747)

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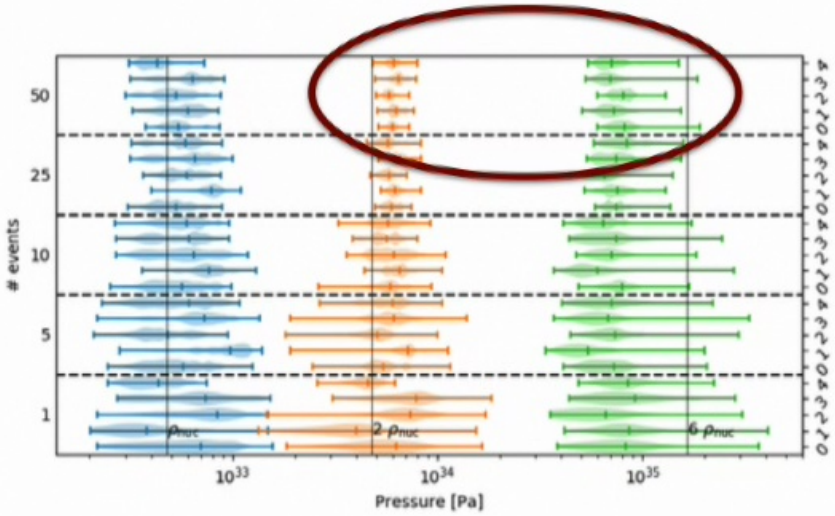
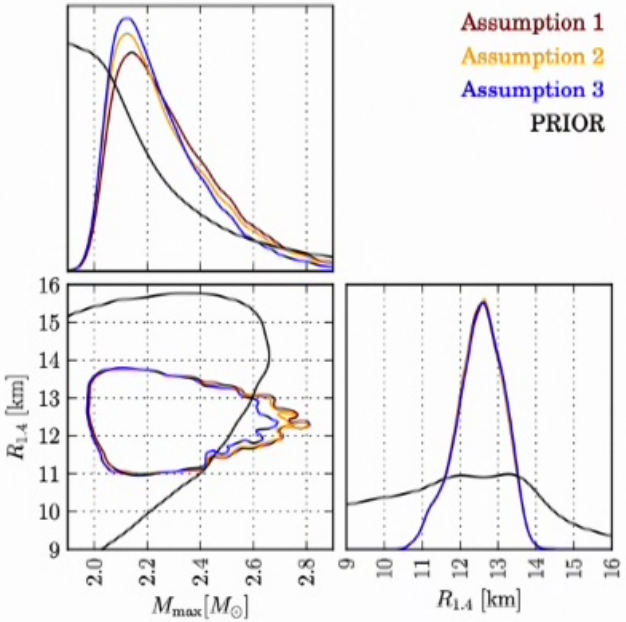


Wysocki+ (arxiv:2001.01747)

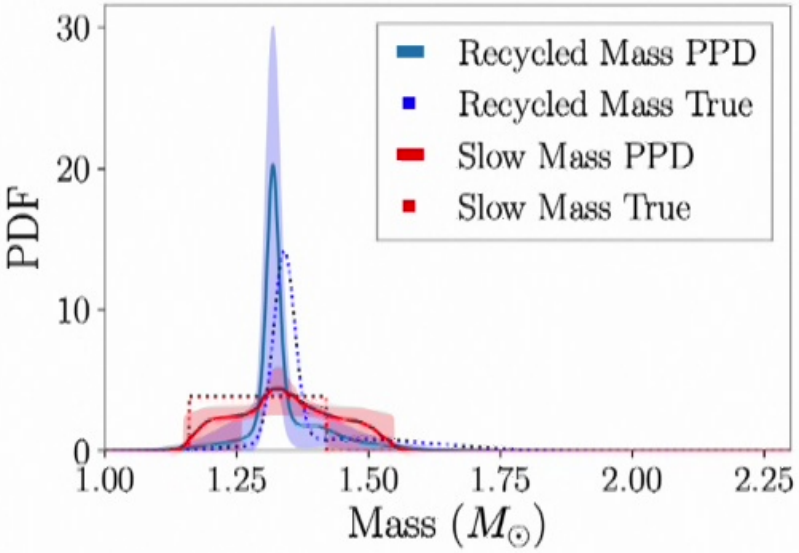
Is the mass distribution limited by the EoS or astrophysics? Currently the effect is small



Legred+ (including KC) (arxiv:2106.05313)

Goes both ways

Ignoring finite-size effects will bias the mass distribution



Golomb+ (arxiv:2106.15745)

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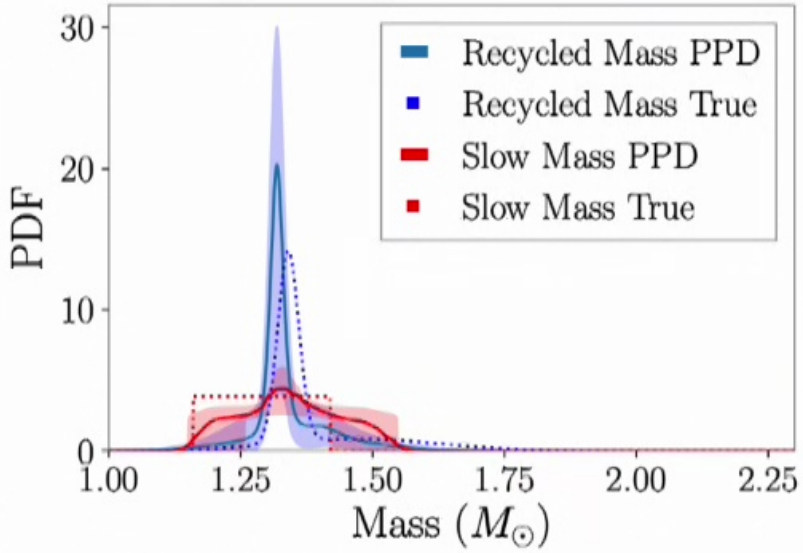
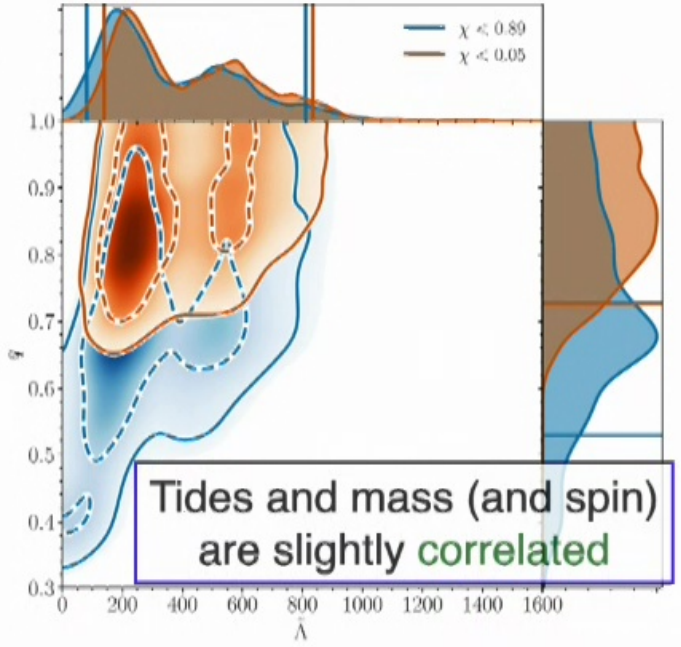


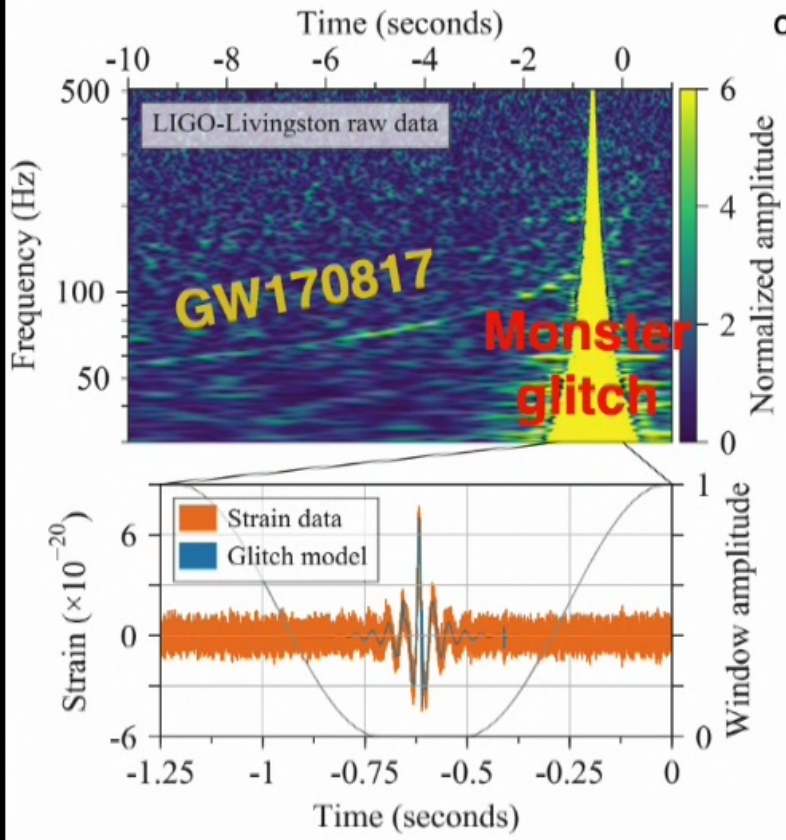
Golomb+ (arxiv:2106.15745)



LVC (arxiv:1805.11580)

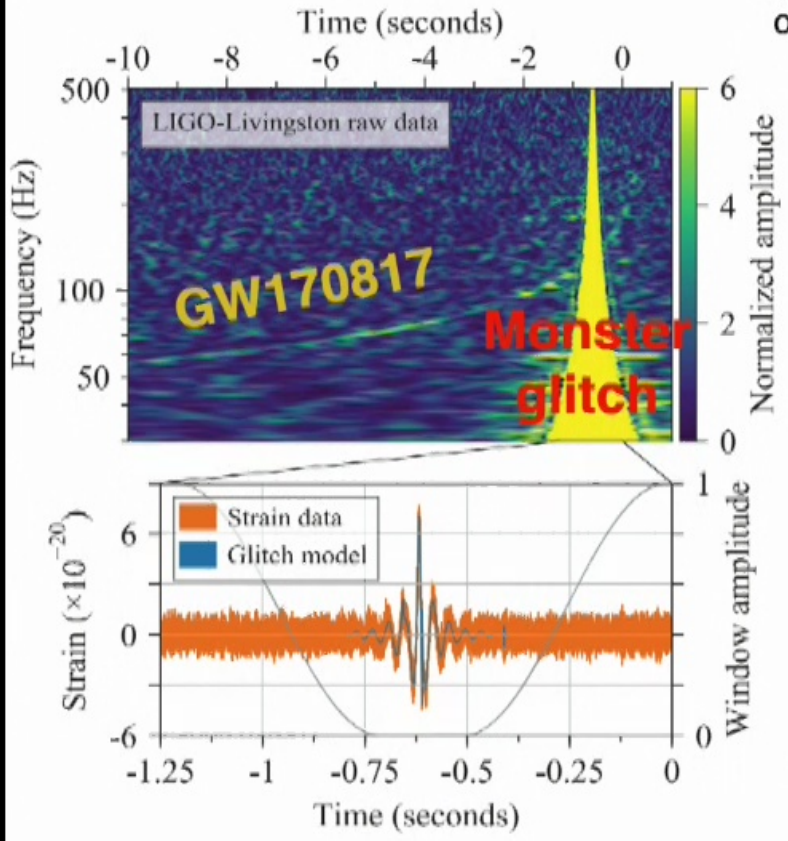
The data

Glitches happened ~1/minute in O3, so they will overlap with BNSs (~2 minute typical duration)



LVC (arxiv:1710.05832)

The data



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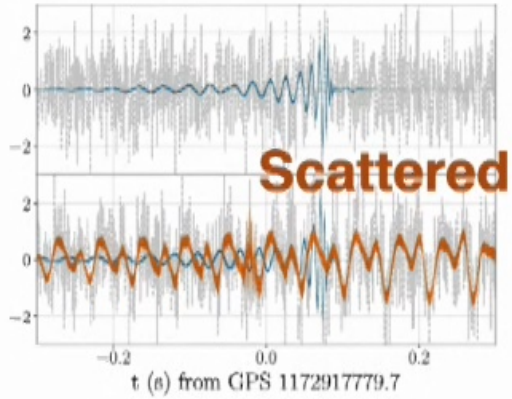
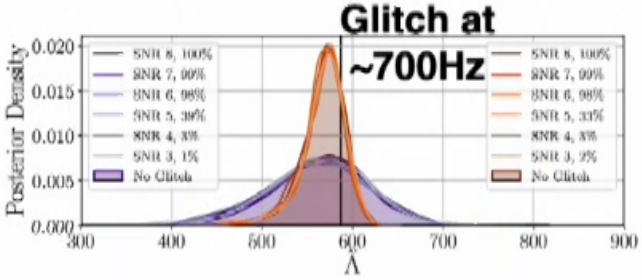


Chatziioannou+ (arxiv:2101.01200)
Hourihane+ (including KC) (in preparation)

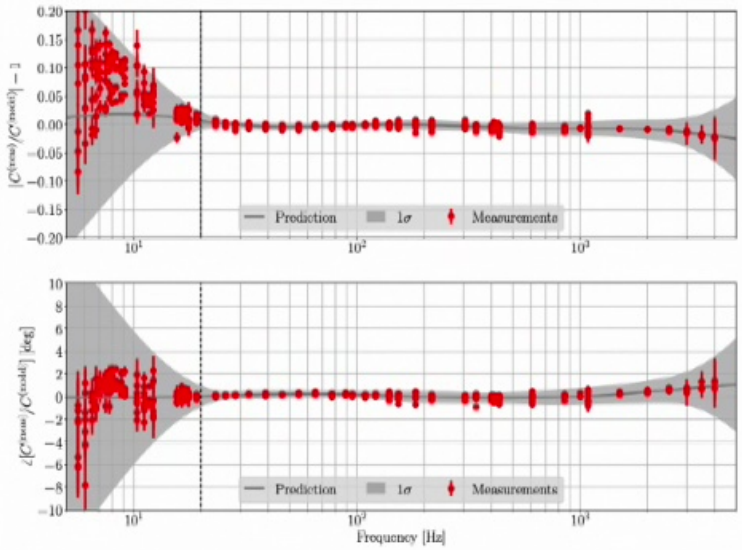


LVC (arxiv:1710.05832)

32

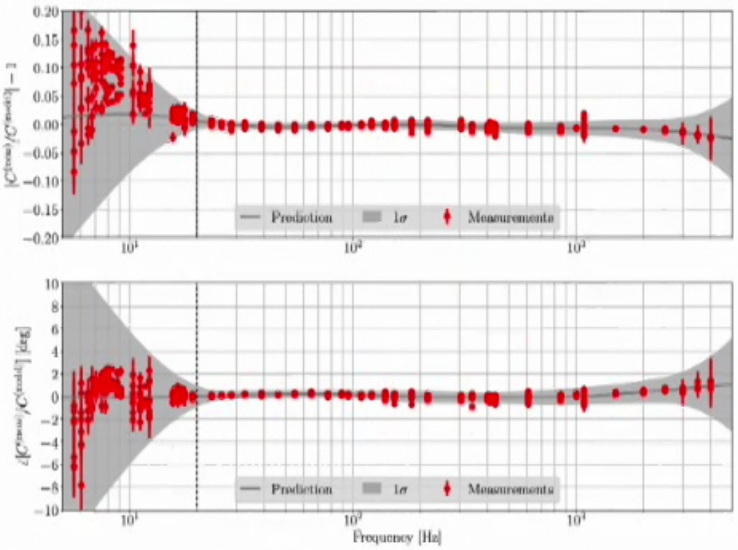
Chatziioannou (arxiv:2108.12368)

Data calibration



Sun+ (arxiv:2005.02531)

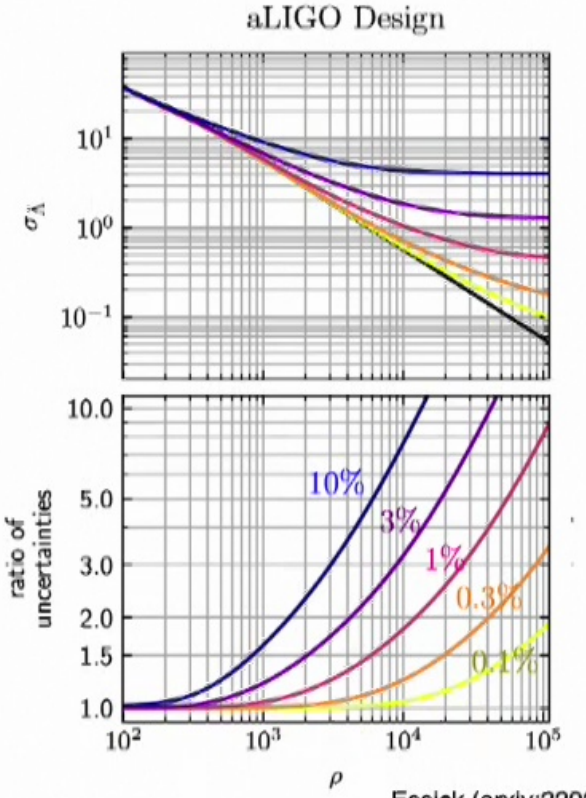
Data calibration



Sun+ (arxiv:2005.02531)

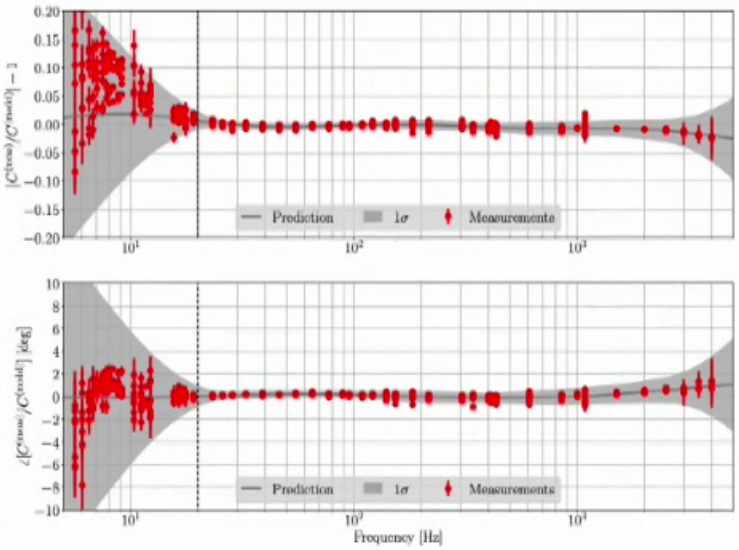
Current calibration uncertainty limits to ~200m radius precision

Chatziioannou (arxiv:2108.12368)



Essick (arxiv:2202.00823)

Data calibration



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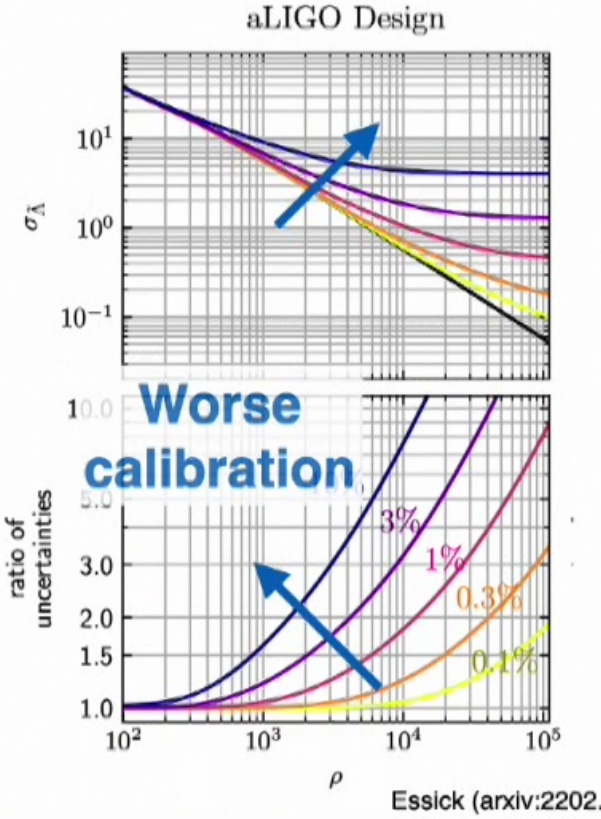
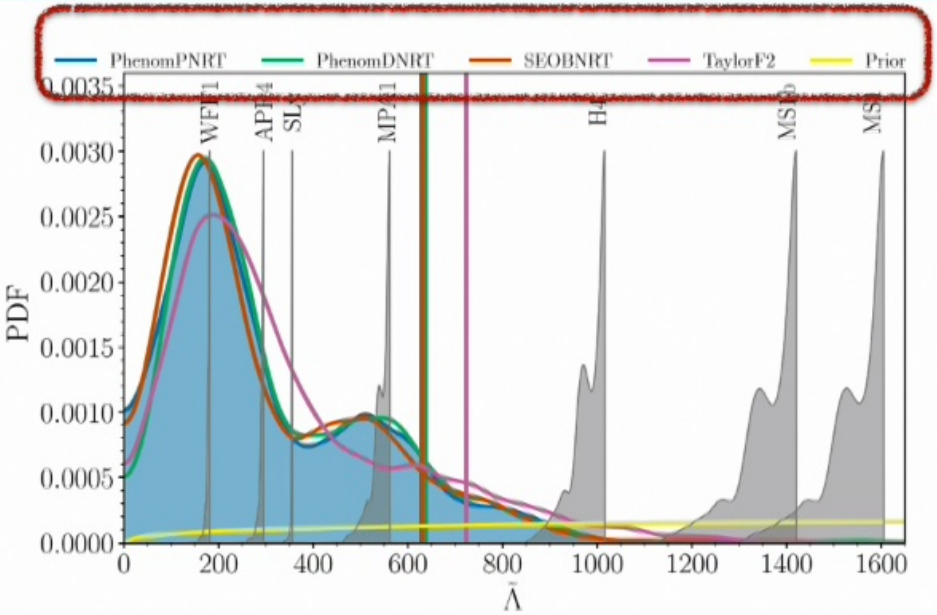


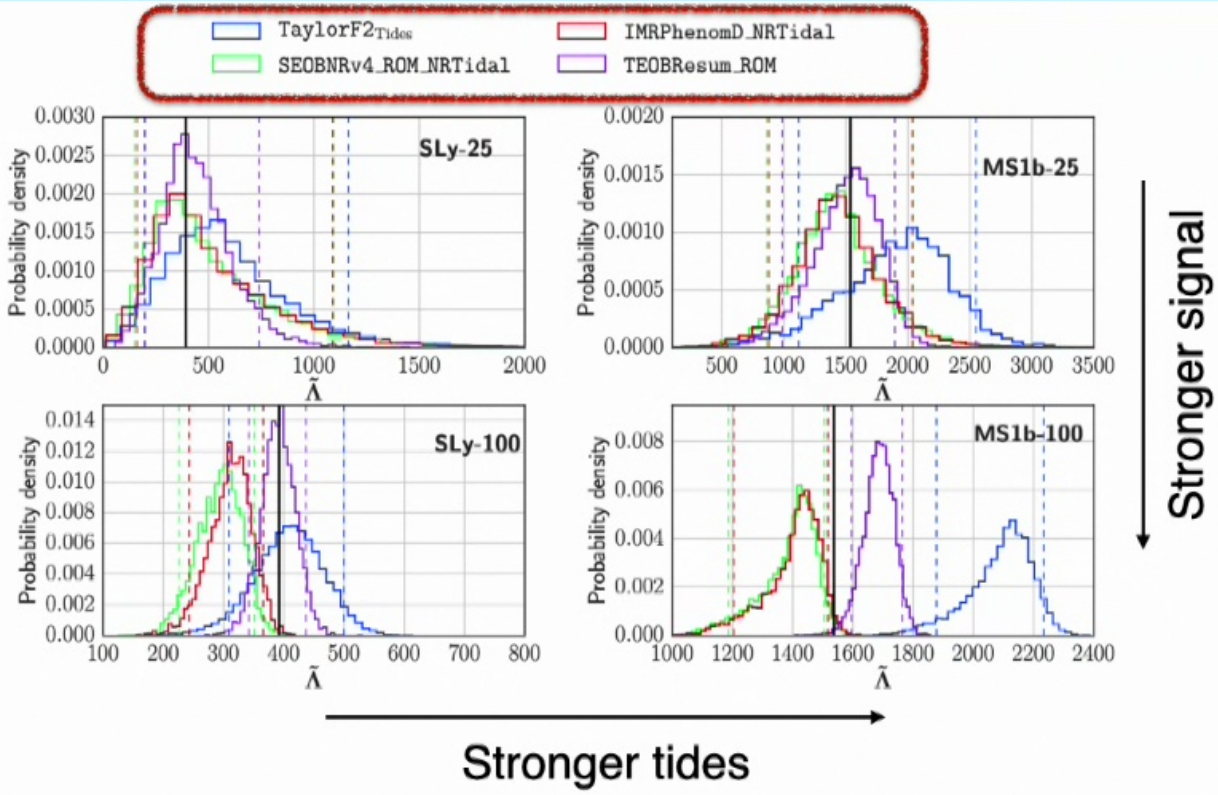
Essick (arxiv:2202.00823)

Waveform modeling



LVC (arxiv:1805.11580)

Where we are headed



GW170817 at design sensitivity would be affected by waveform systematic errors

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