Gravitational Laboratories for Nuclear Physics

Prospects for Binary Neutron Star Observations
and their Impact on the Equation of State

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Perimeter Institute for Theoretical Physics

Basic Physics of Compact Binary Coalescences (CBCs)

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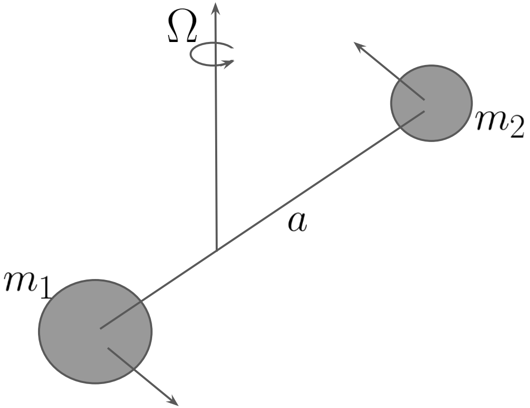
$$E = -\frac{Gm_1m_2}{a}$$

$$\Omega^2 = \frac{G(m_1 + m_2)}{a^3}$$

Keplerian Orbit



Peters+Mathews (1963)

Basic Physics of Compact Binary Coalescences (CBCs)

$$\langle P \rangle = \frac{32G^4}{5c^5}\left(\frac{m_1^2 m_2^2 (m_1+m_2)}{a^5}\right)\xcancel{\left(\frac{1}{(1-e^2)^{7/2}}\left(1+\frac{73}{24}e^2+\frac{37}{96}e^4\right)\right)}$$

General Relativiy
"Larmor formula"

circular orbit : $e = 0$

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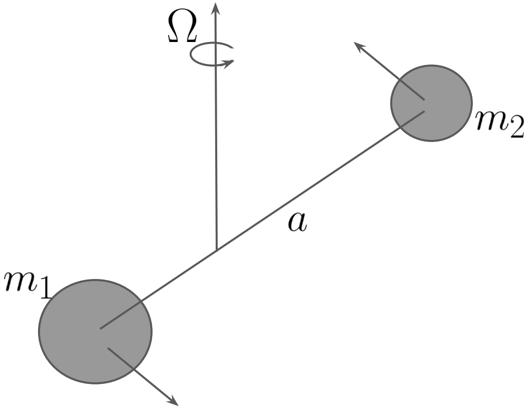

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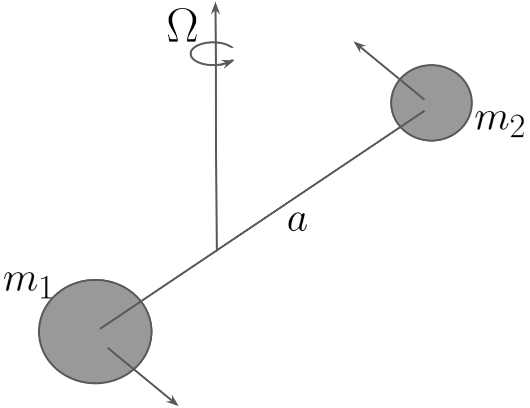

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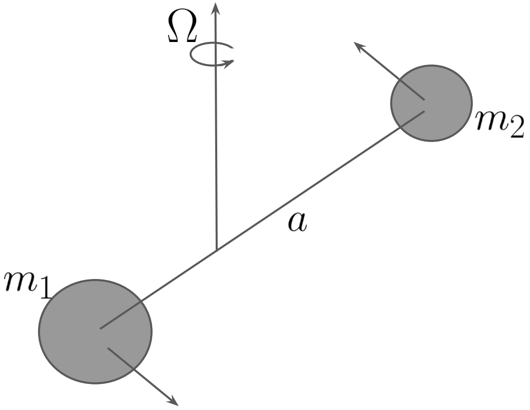

$$\langle P\rangle = -\frac{dE}{dt}$$

Post Newtonian Energy Balance

$$\boxed{f(m_1,m_2,\Omega) = g(m_1,m_2,\Omega)\frac{d\Omega}{dt}}$$

evolution of the orbital frequency is directly imprinted within GWs

$$h \sim e^{i(2\Omega)t}$$

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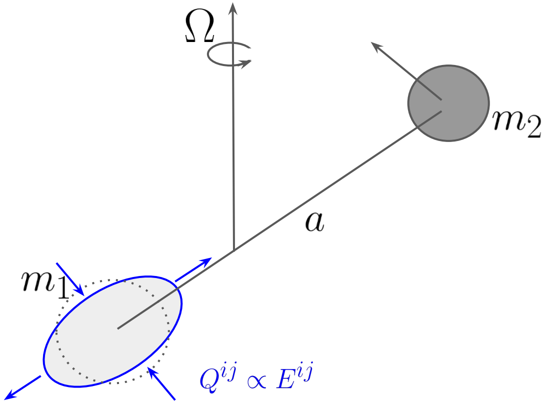
changes **flux** and orbit’s **binding energy**



adiabatic tides
deform stars

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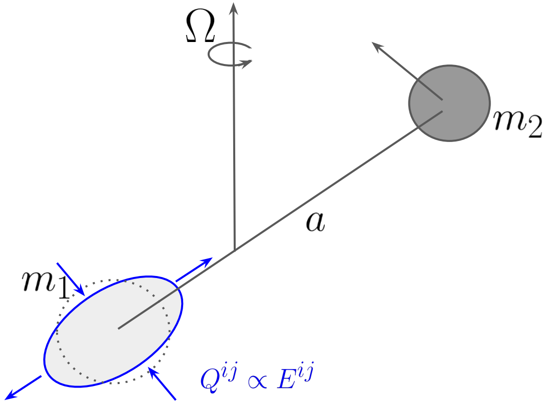
adiabiatic tides $\Lambda(m) \sim k_2 \left(\frac{R(m)}{m}\right)^5$

$$\tilde{\Lambda} = \left(\frac{16}{13}\right)\frac{(m_1 + 12m_2)m_1^4\Lambda(m_1) + (m_2 + 12m_1)m_1^4\Lambda(m_2)}{(m_1 + m_2)^5}$$



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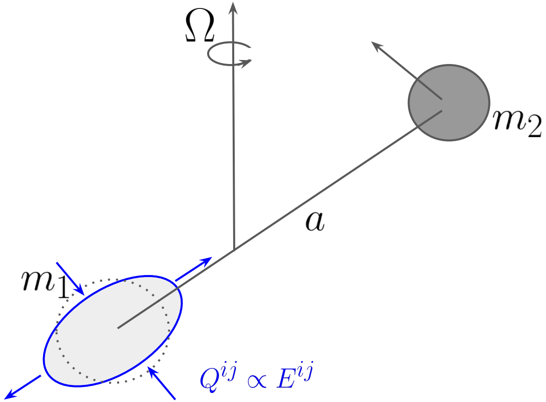

adiabiatic tides

linear tidal resonances
Pratten+ (2021)
nonlinear tidal instabilities
Weinberg (2016)
Abbott+ (2019)

orbital energy transferred to stellar normal modes

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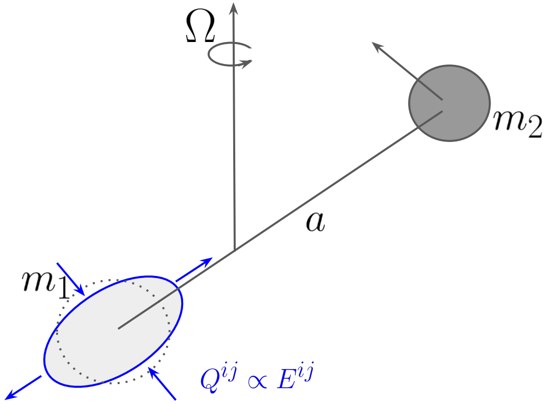

adiabiatic tides

$$\left.\begin{array}{l}\text{linear tidal resonances} \\ \qquad \text{Pratten+ (2021)} \\ \text{nonlinear tidal instabilities} \\ \qquad \text{Weinberg (2016)} \\ \qquad \text{Abbott+ (2019)}\end{array}\right\}$$

orbital energy transferred to stellar normal modes

post-merger signals
- Most+Raithel (2021)
- Weih+ (2020)

Why are we concerned with orbital phase?

$$\phi(t) = \int_{-\infty}^{t} d\tau\, f(\tau)$$

orbital evolution gives time-domain phase

$$\psi(f) = i(2\pi f t - \phi(t)) - \pi/4$$

frequency-domain phase is related to time-domain phase
(saddle point approximation)

$$\ln \mathcal{L} \sim \int df \frac{\mathcal{R}\{\tilde{d}^{*}\tilde{h}\}}{S}$$

$$\sim \int df \boxed{\frac{|\tilde{d}||\tilde{h}|}{S}} \boxed{\cos(\Delta\psi)}$$

varies slowly

oscillates rapidly

likelihood of GW data is an integral over a rapidly oscillating function of the difference of freq-domain phases

significant likelihood only when $\Delta\psi$ is small and/or varies slowly at all frequencies

Current Astrophysical Constraints on the High-Density, Cold Equation of State

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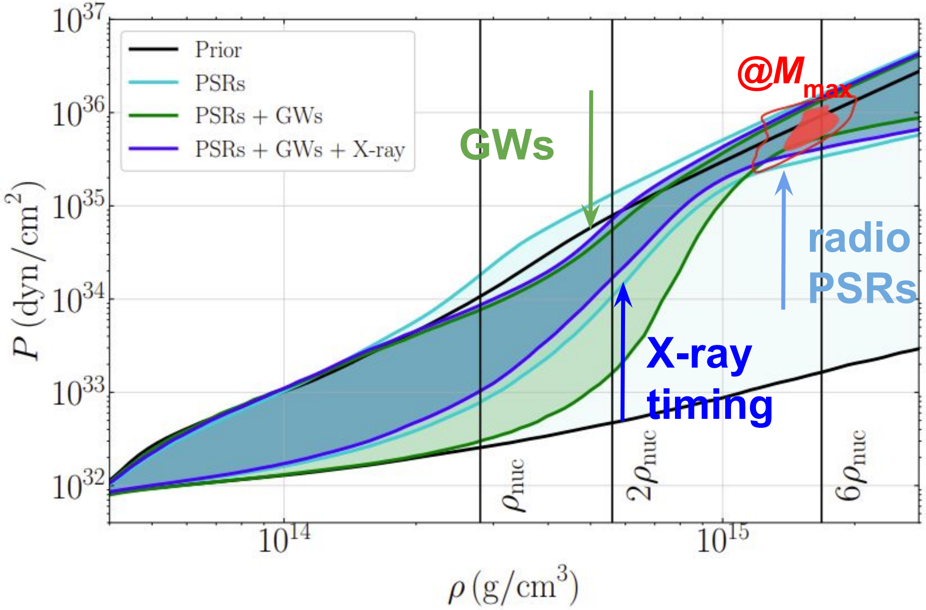

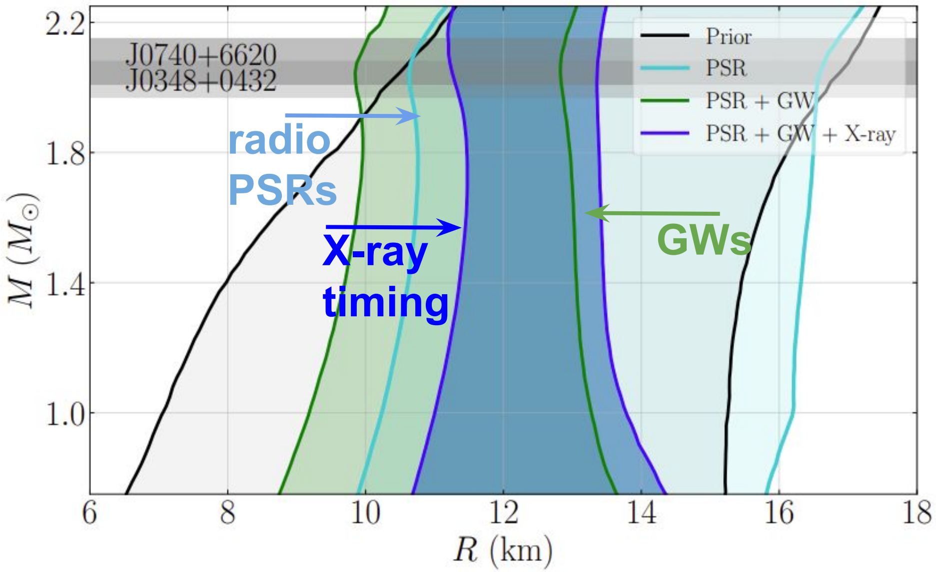

Legred+ (2021)

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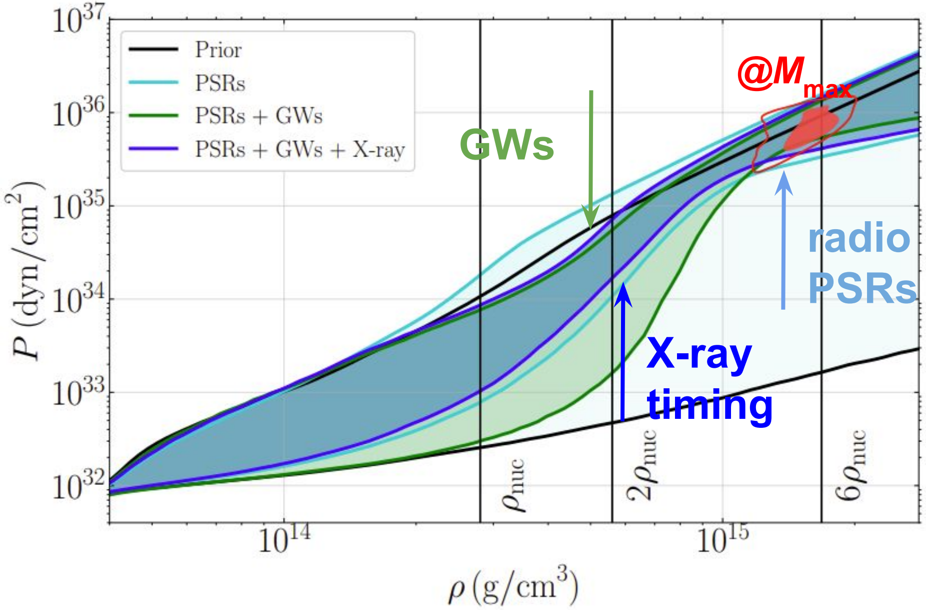

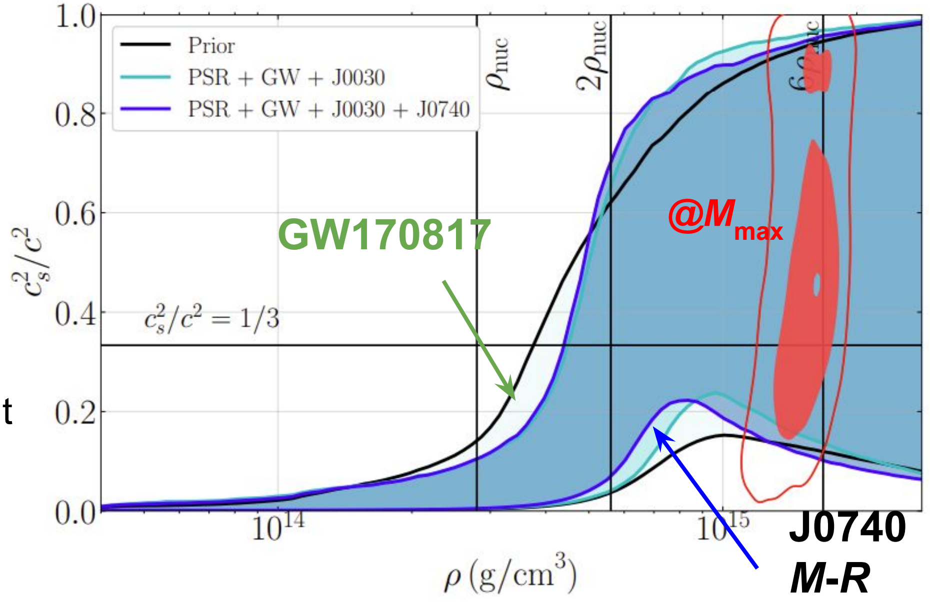

sound speed almost certainly exceeds the conformal limit
(suggests strongly-coupled interactions)

Legred+ (2021)

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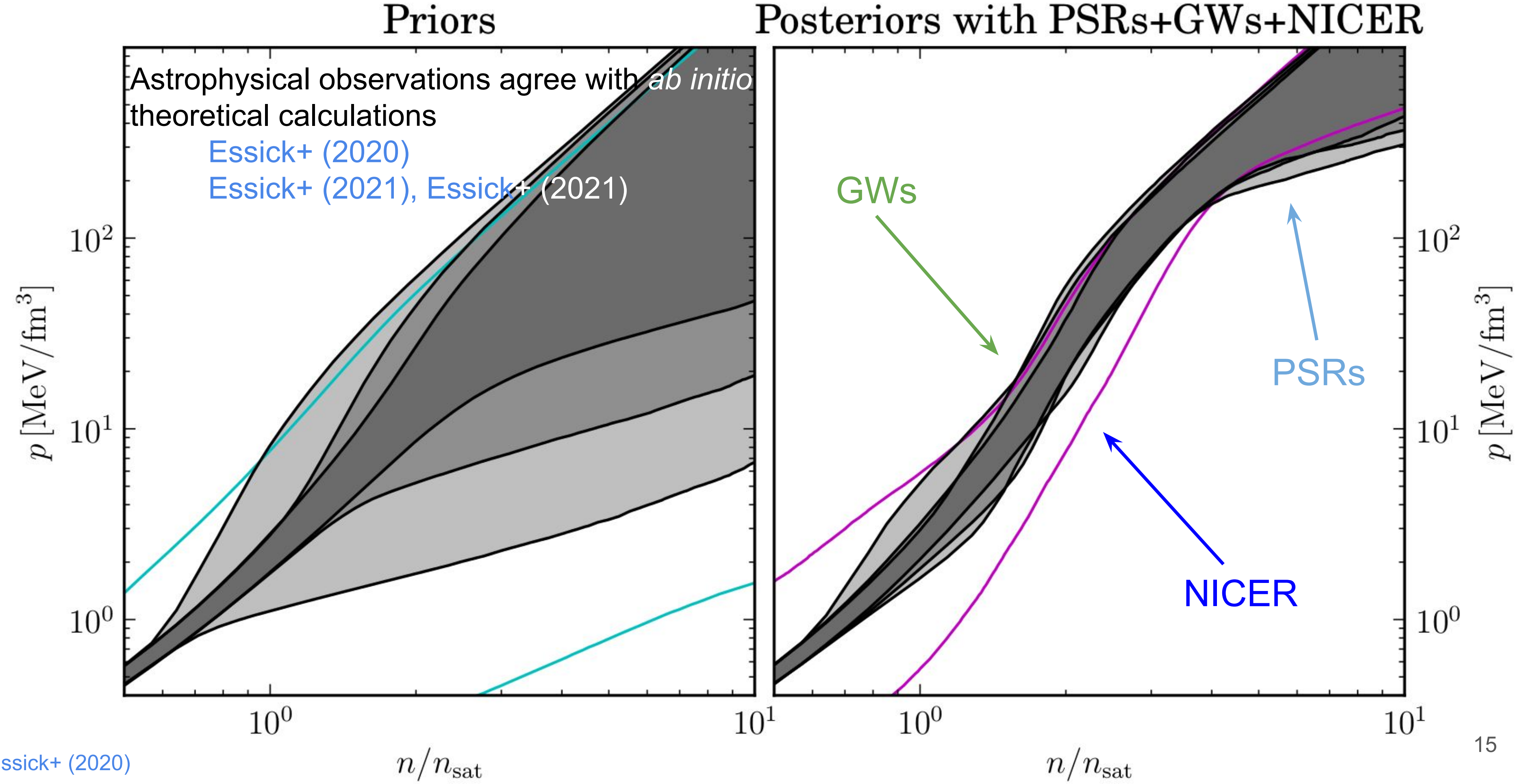


Astrophysical observations agree with *ab initio* theoretical calculations

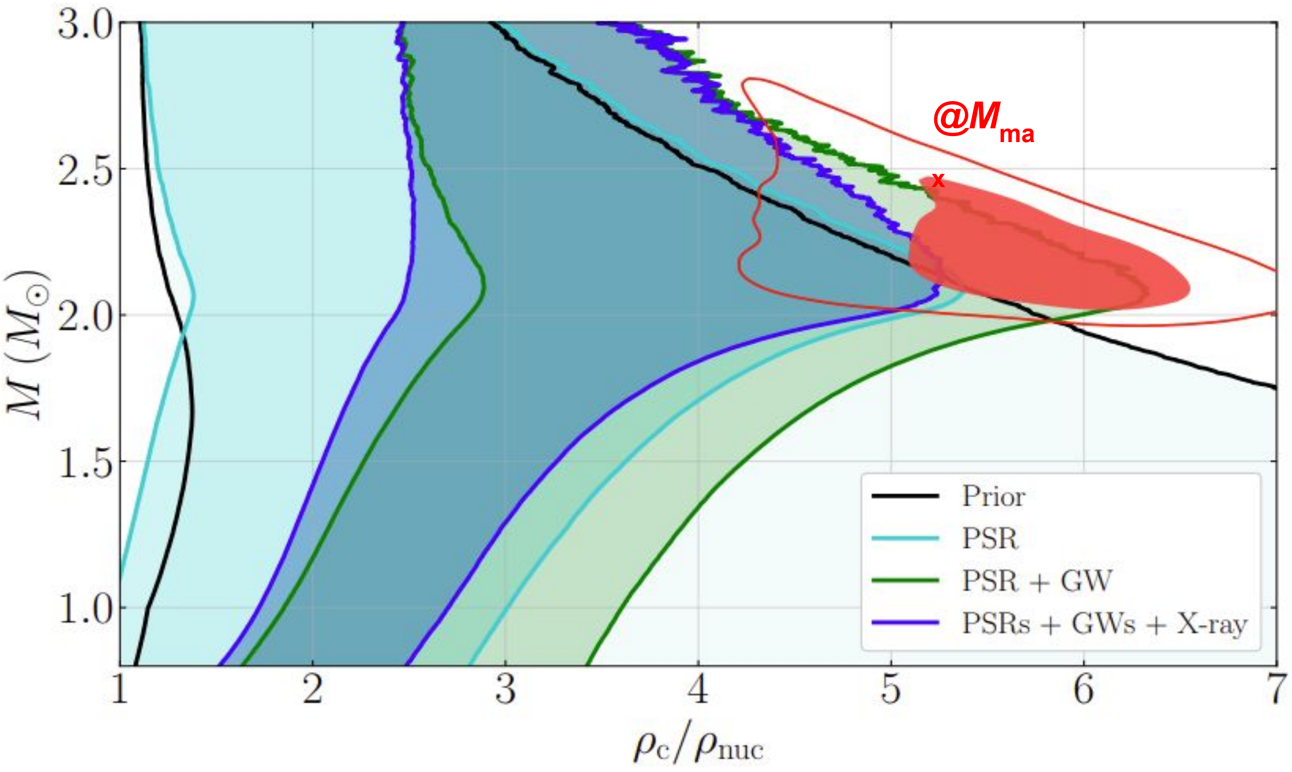
Essick+ (2020)

Essick+ (2021), Essick+ (2021)

Essick+ (2020)

Current Astrophysical Constraints on the High-Density, Cold Equation of State

There is a limit to the densities we can probe within NSs



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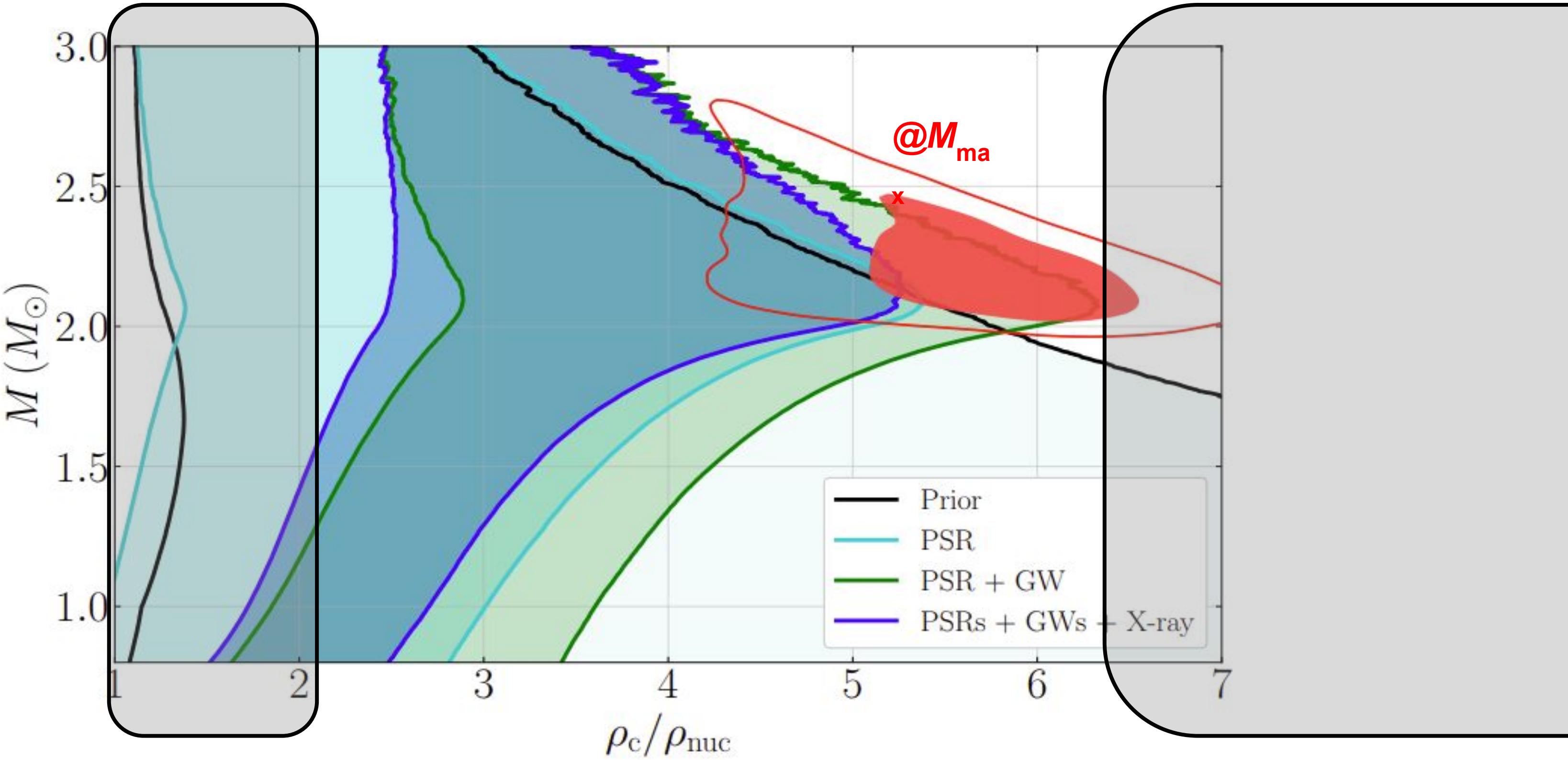

χEFT

Lynn+ (2016)
Drischler+ (2020), Drischler+ (2020)

pQCD

Komoltsev+Kurkela (2022)
Gorda+ (2022)

Legred+ (2021)

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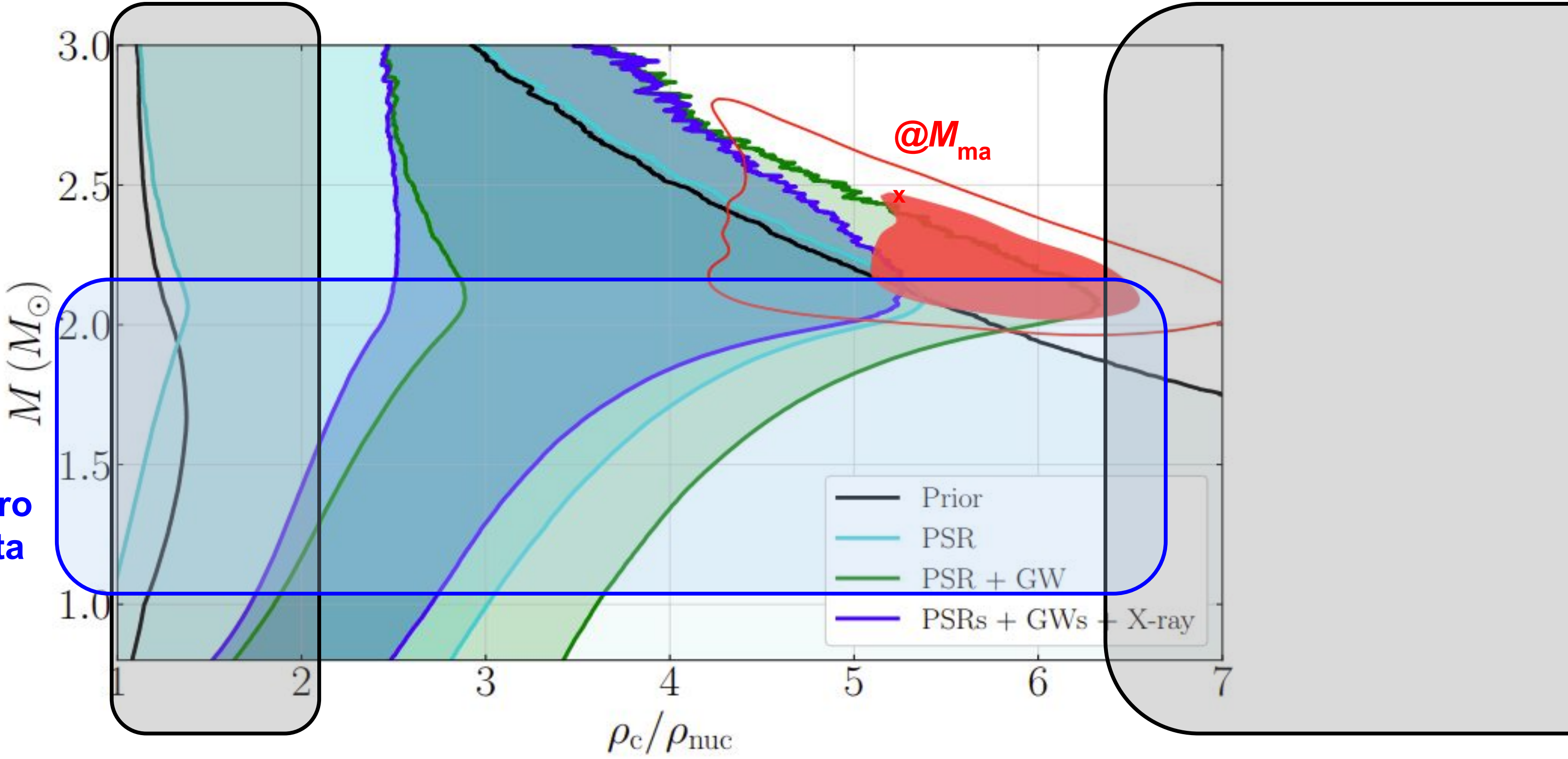

Astro Data

Abbott+ (2021)
Farah+ (2022)
Landry+Read (2021)

Legred+ (2021)

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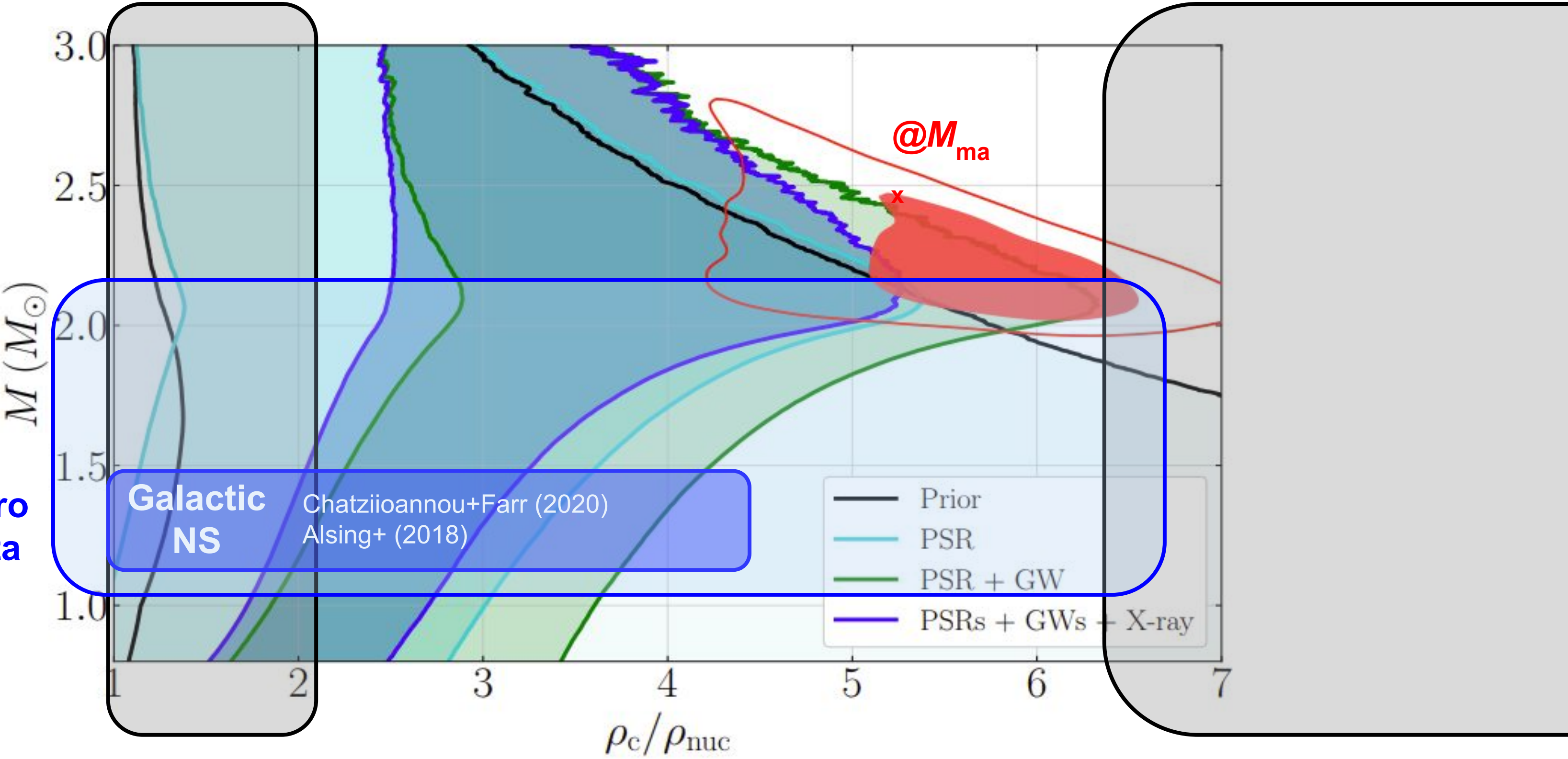

@$M_{\rm ma}$

Galactic NS

Chatziioannou+Farr (2020)
Alsing+ (2018)

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Prospects for Measuring $\Lambda(m)$

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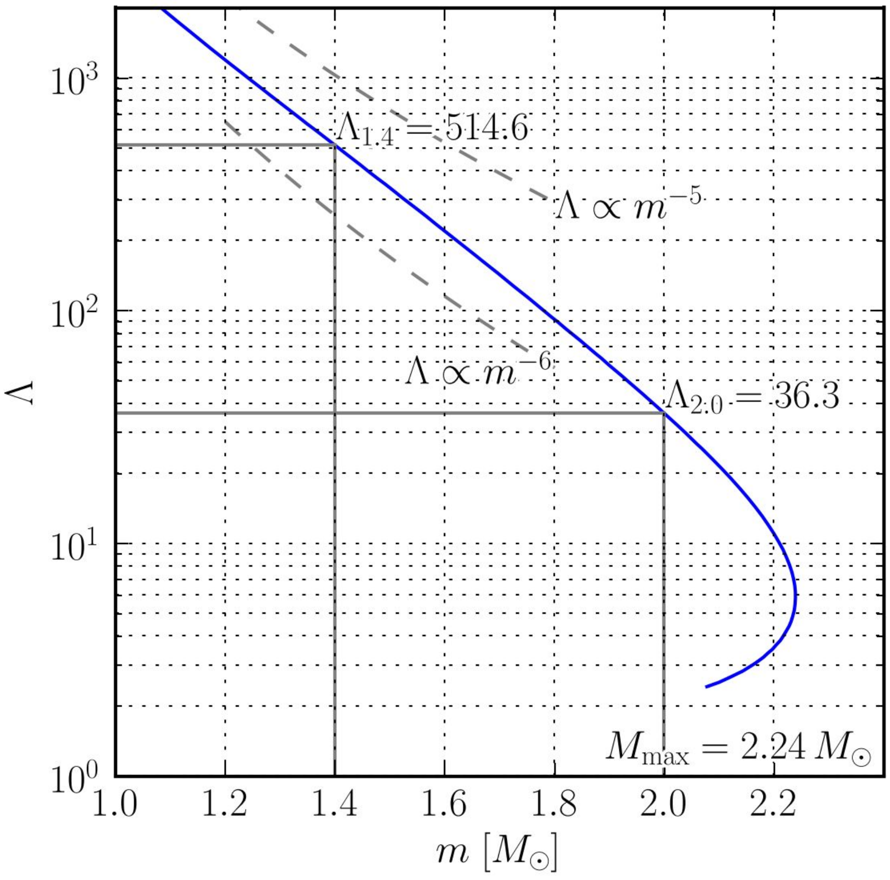
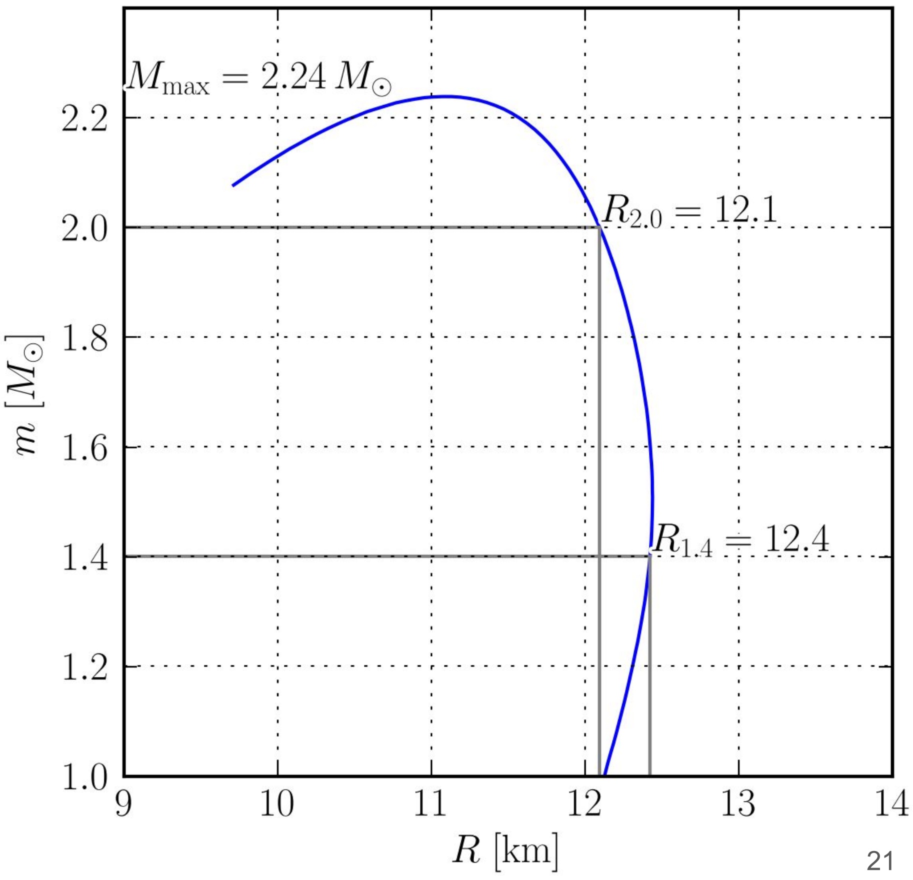
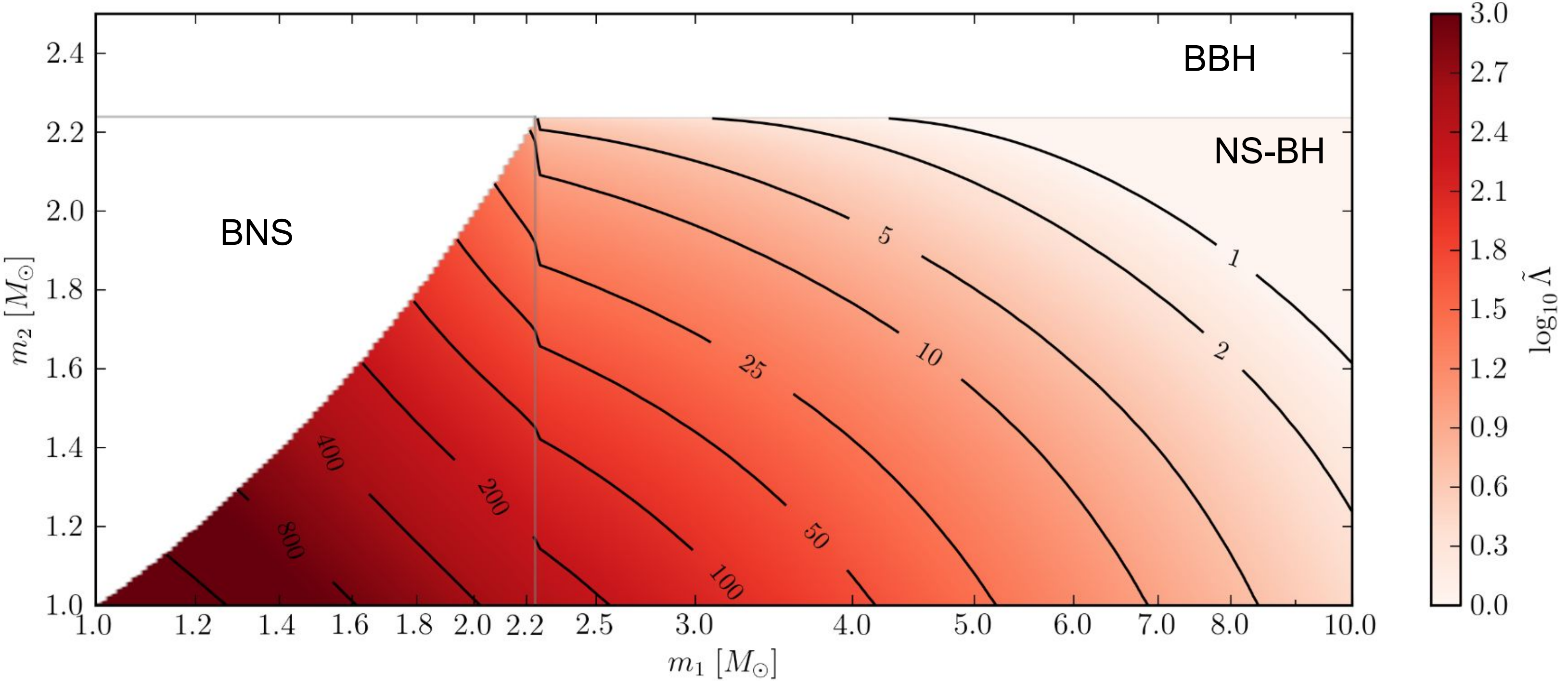




Prospects for Measuring Λ(m)

Leading-order adiabatic tidal term



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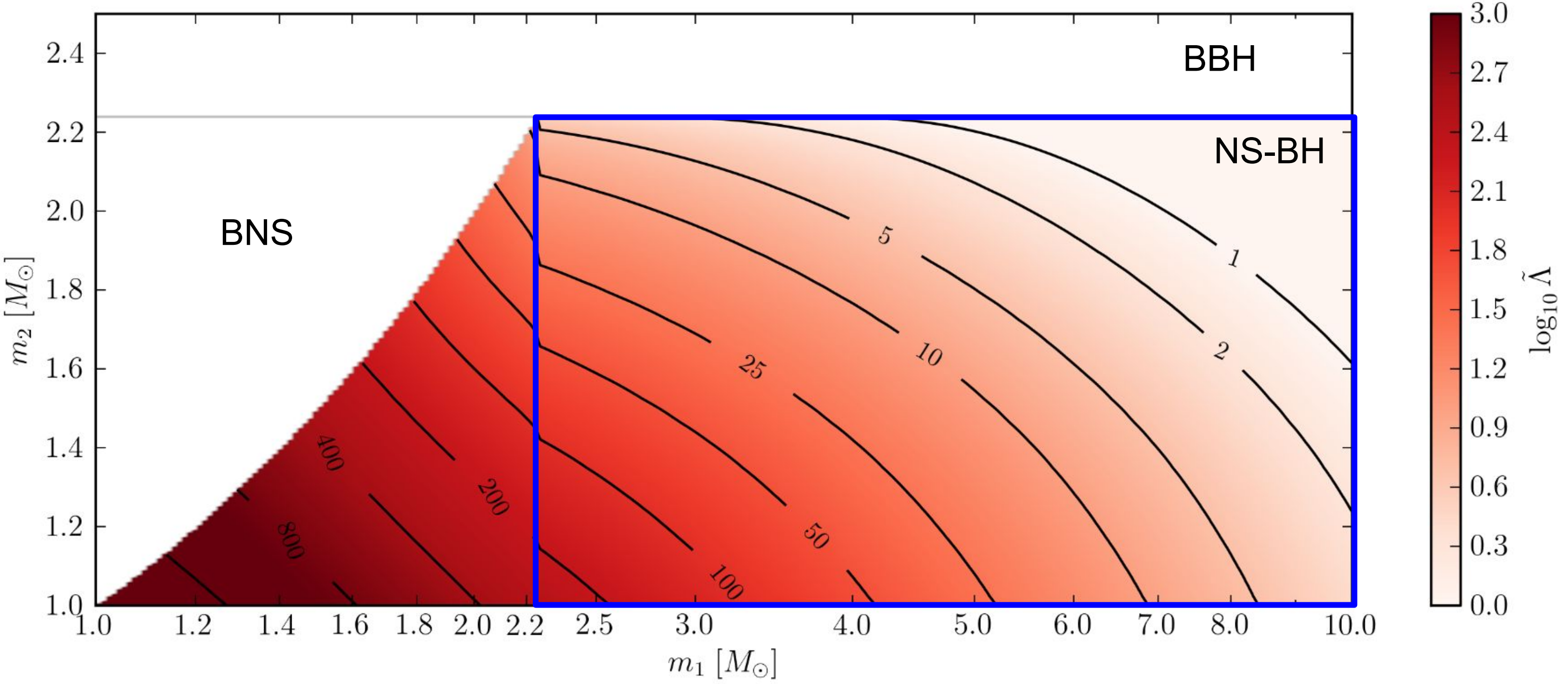
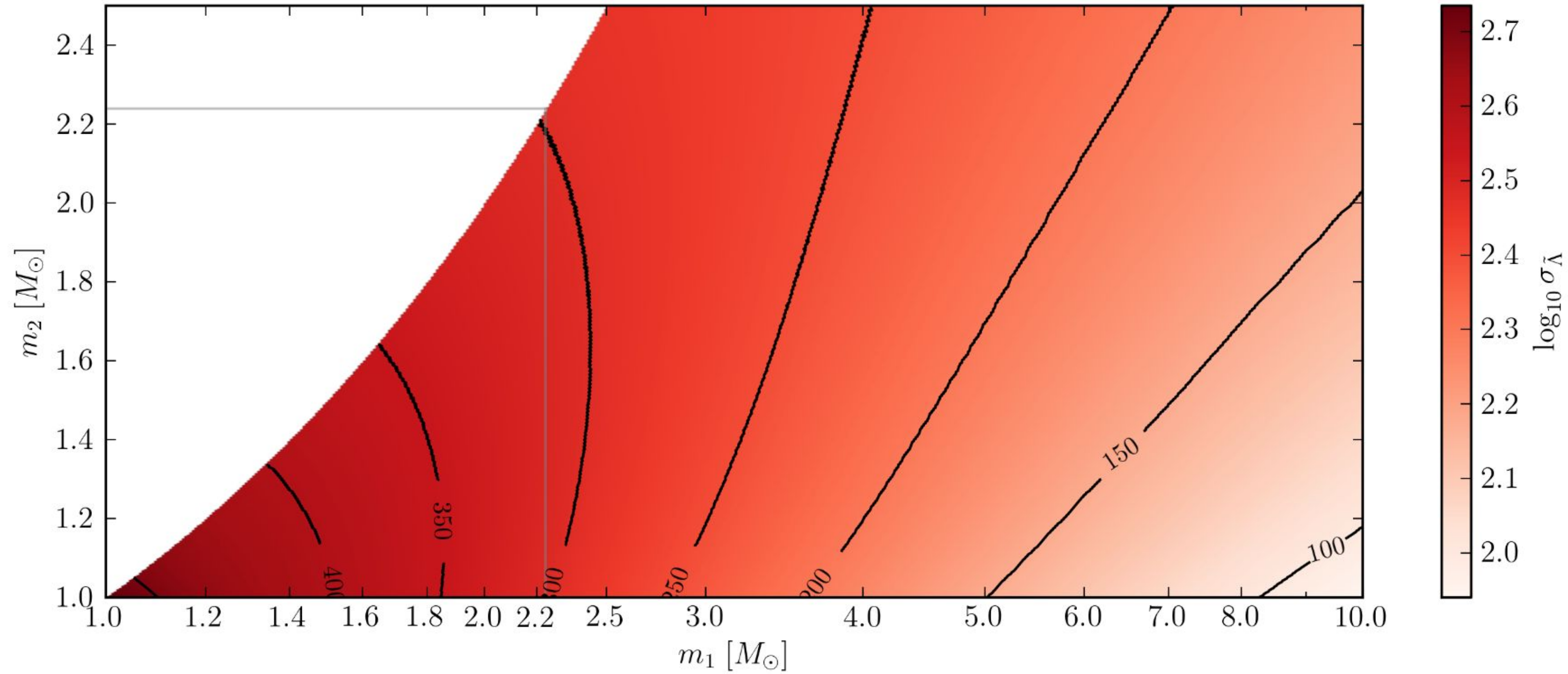
Leading-order adiabatic tidal term

$$\tilde{\Lambda} = \frac{16}{13}\frac{(q+12)\boxed{q^4\Lambda(m_2)}}{(1+q)^5} \qquad q = \frac{m_2}{m_1}$$



Prospects for Measuring Λ(m)

Fisher Matrix : simplistic PN phasing, aLIGO design sensitivity, **SNR=10**, wide priors on spins, mass ratio
→ “best case” scenario (Cramer-Rao bound) that strictly holds only in the high-SNR limit



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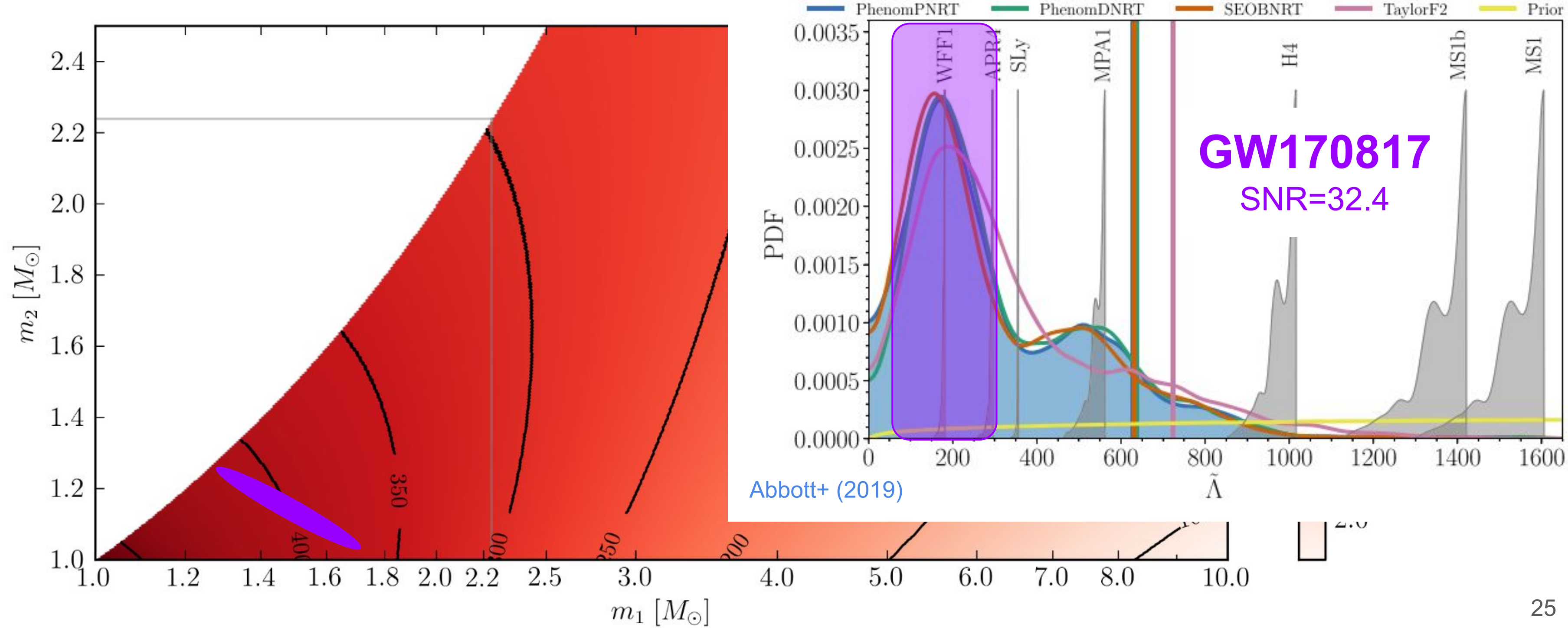


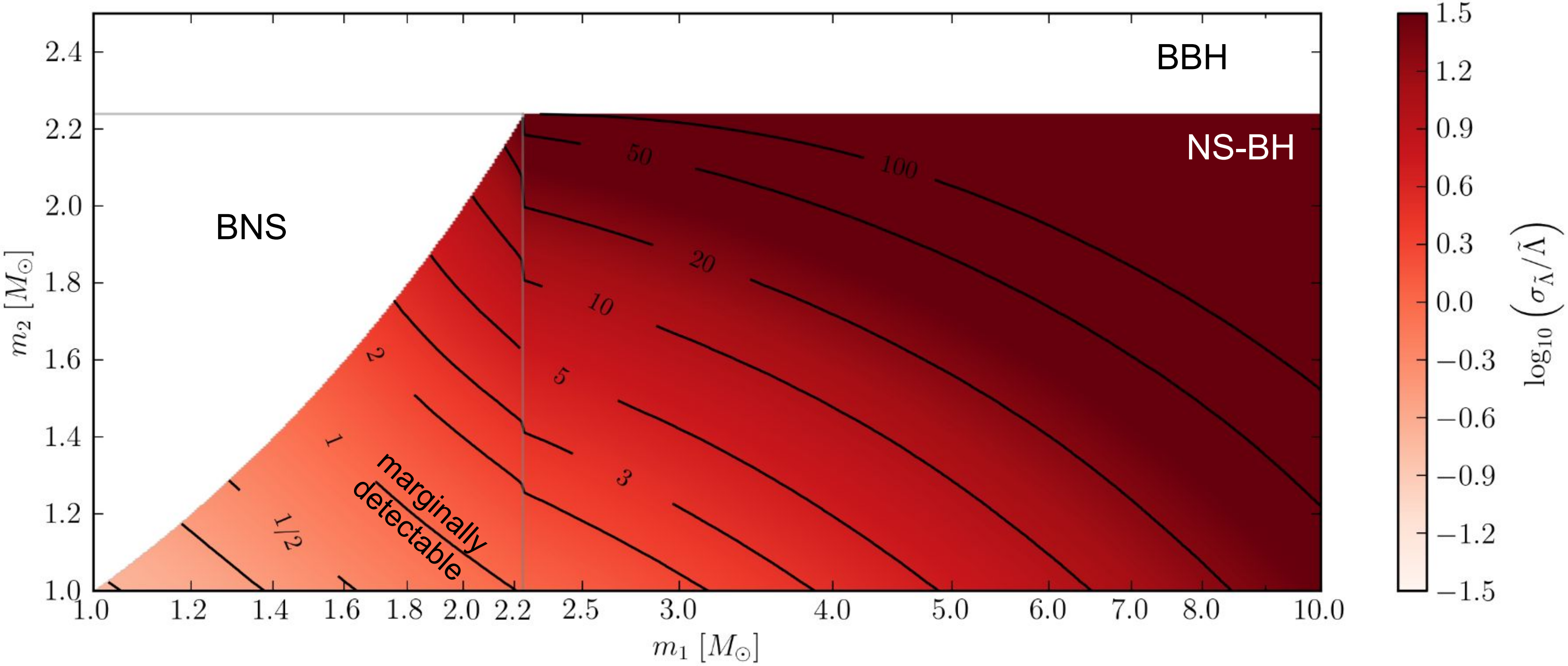
GW170817

SNR=32.4

Abbott+ (2019)

Prospects for Measuring Λ(m)

Uncertainty in leading order tidal term is still broad : **$\Lambda_{1.4}$ ~ 500 +/- 250** at 90% credibility (Legred+ 2021)
Fisher Matrix may **underpredict uncertainty** by a factor of O(few)



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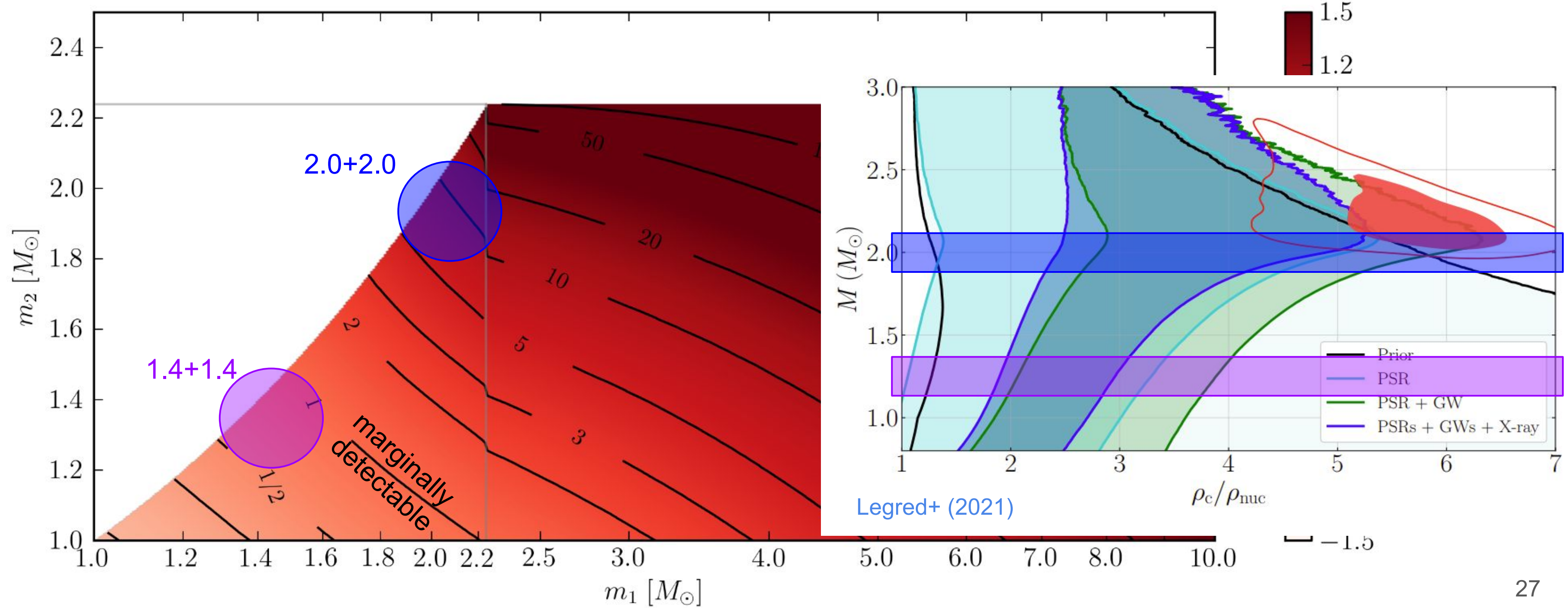
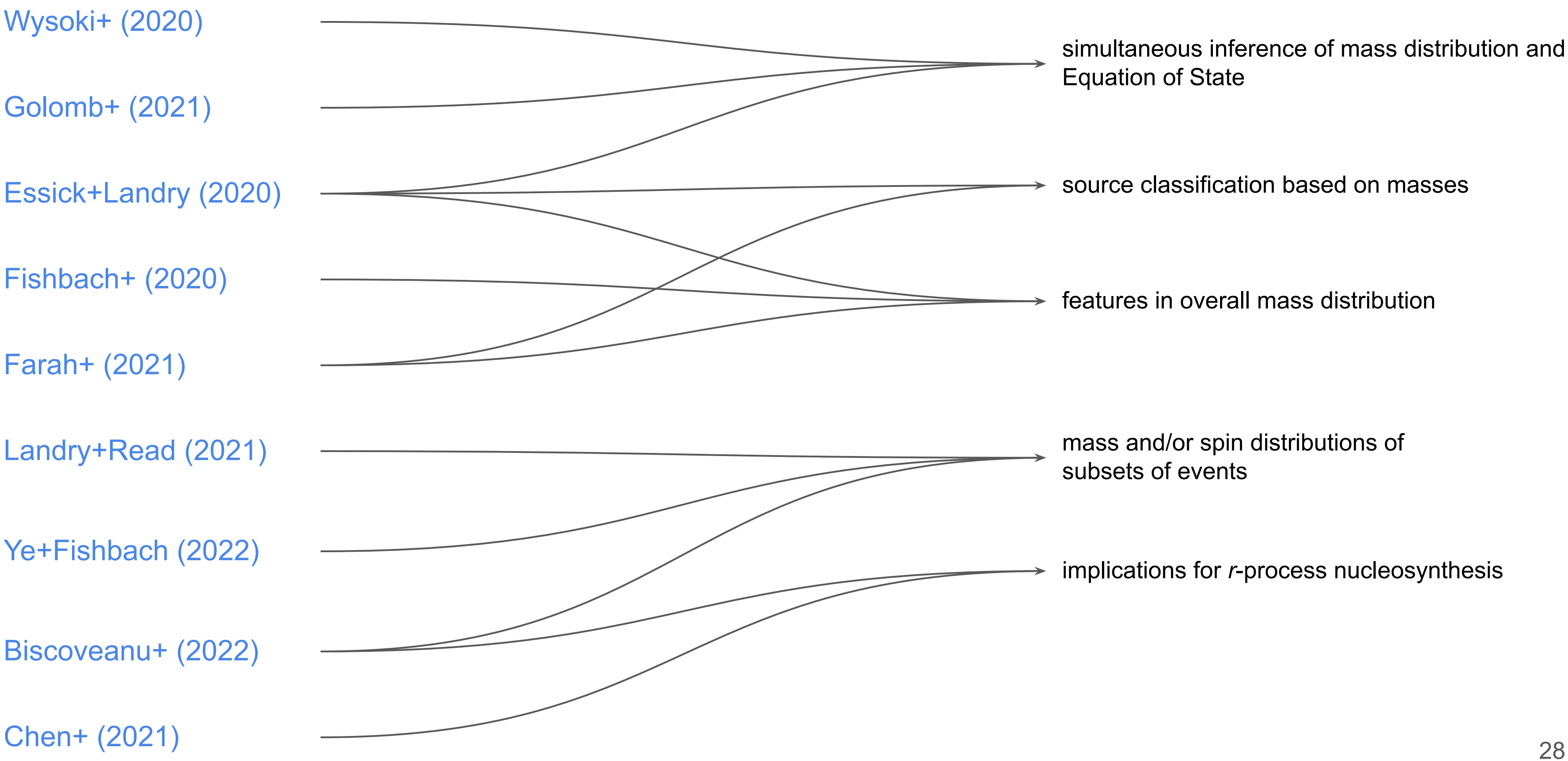
relative precision could be 10x worse for 2.0+2.0 compared to 1.4+1.4
→ need ~100x as many events to compensate



Legred+ (2021)

Prospects for Measuring $\Lambda(m)$

Connections to astrophysical mass distribution



Wysoki+ (2020)

Golomb+ (2021)

Essick+Landry (2020)

Fishbach+ (2020)

Farah+ (2021)

Landry+Read (2021)

Ye+Fishbach (2022)

Biscoveanu+ (2022)

Chen+ (2021)

simultaneous inference of mass distribution and Equation of State

source classification based on masses

features in overall mass distribution

mass and/or spin distributions of subsets of events

implications for *r*-process nucleosynthesis

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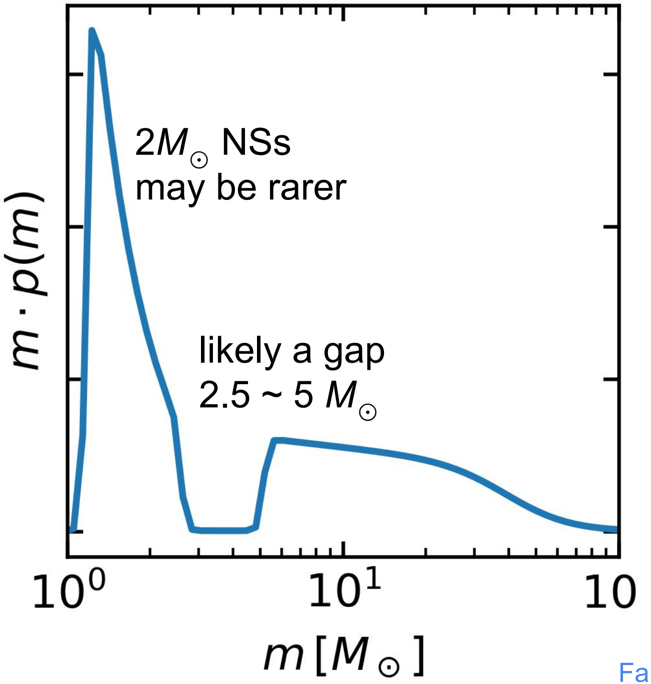
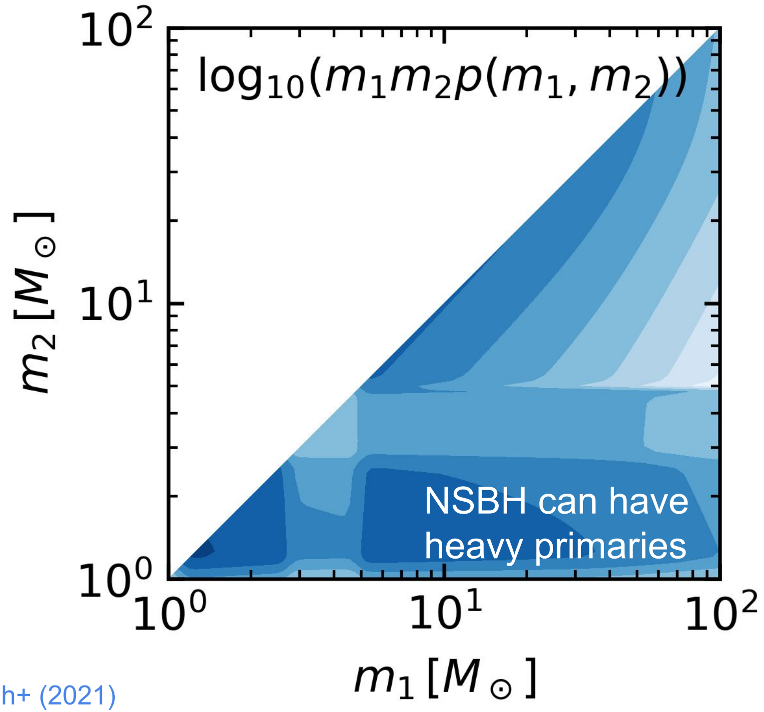




Farah+ (2021)

Prospects for O4

starts March 2023

We will hold a one-hour Zoom meeting on **21 July 2022 at 14:00 UTC** (09:00 Central Time). Please register in advance for the Zoom meeting at

https://bit.ly/3PbWa48

The agenda is being developed at

https://wiki.gw-astronomy.org/OpenLVEM/Telecon20220721

Similar to previous calls, the first ~30 minutes will be devoted to **updates from LIGO-Virgo-KAGRA relating plans for O4** including the run schedule and some planned changes to the public alert infrastructure.

We encourage the OpenLVEM community to use these town hall meetings to share plans and progress with us and each other. In this first call of the O4 series, we have assigned 25 minutes for short presentations from the community. If you would like to make a short presentation at this, or a future call, please submit a request to

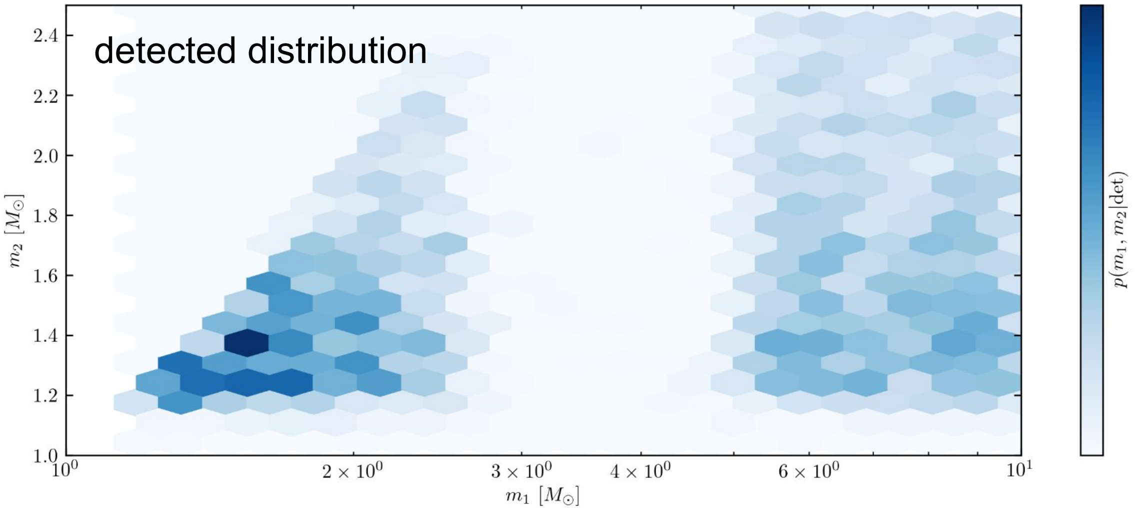
https://forms.gle/tieqoa2xsnm7Sqpr7

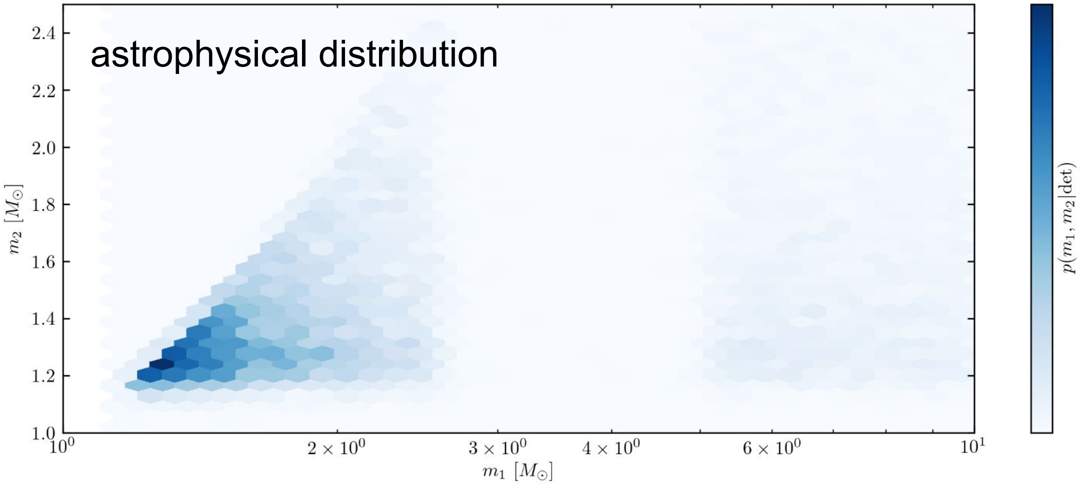
We look forward to your participation; feel free to forward this announcement to others who may be interested.

Patrick Brady, Giovanni Losurdo and Jun'ichi Yokoyama
for the LIGO-Virgo-KAGRA Collaboration (LVK)

Prospects for O4

100% duty cycle at design sensitivity
uniformly distributed in
co-moving-volume+source-frame time





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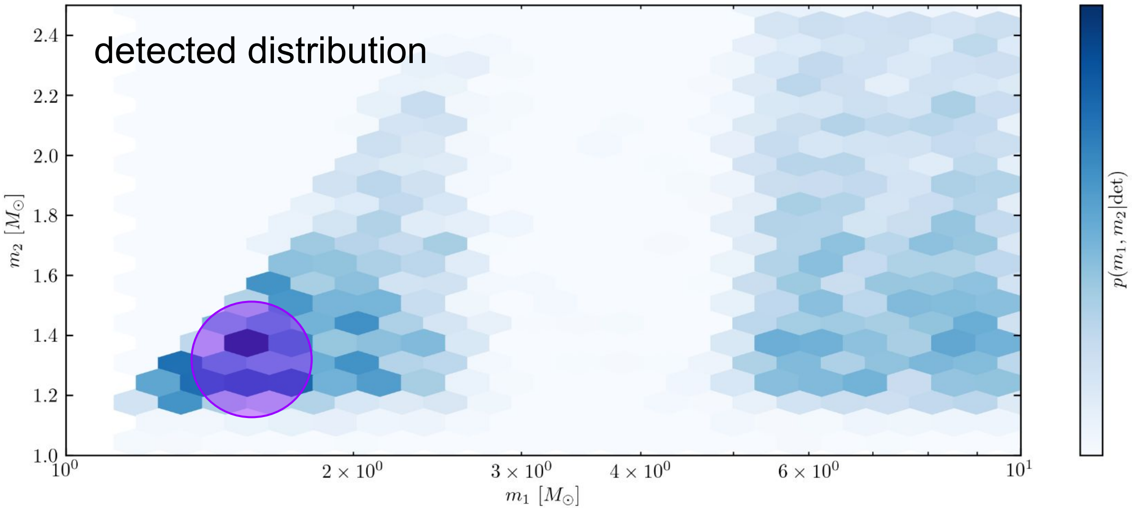
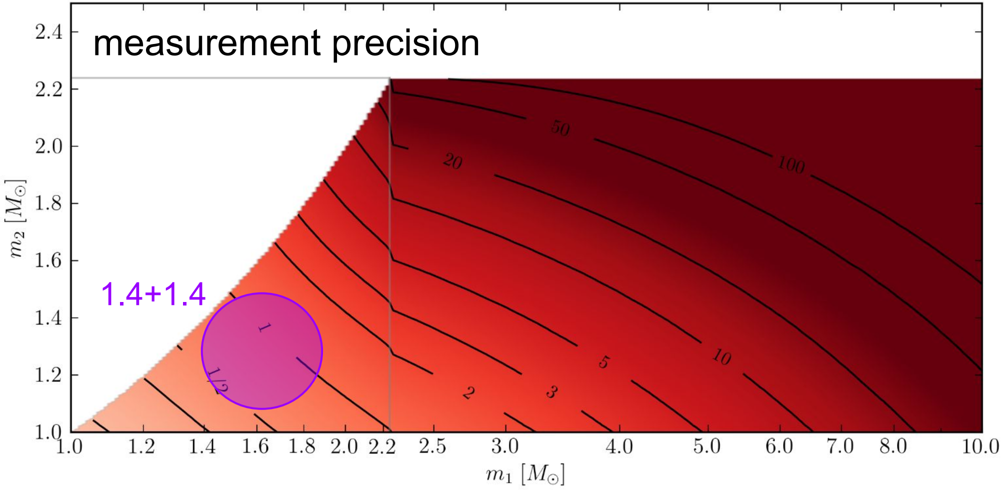
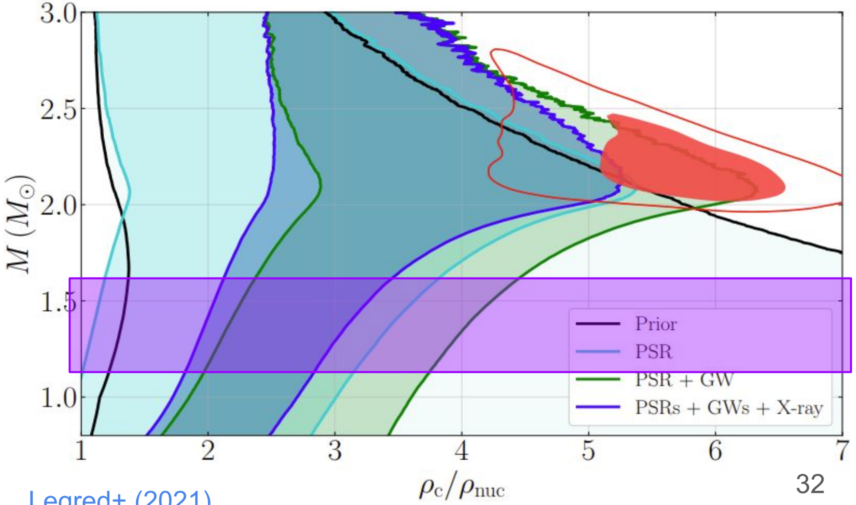
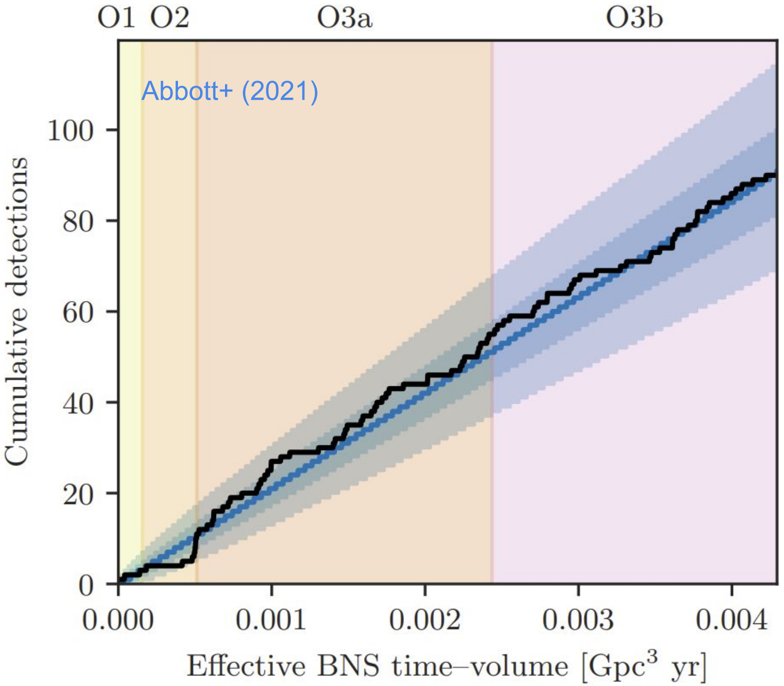


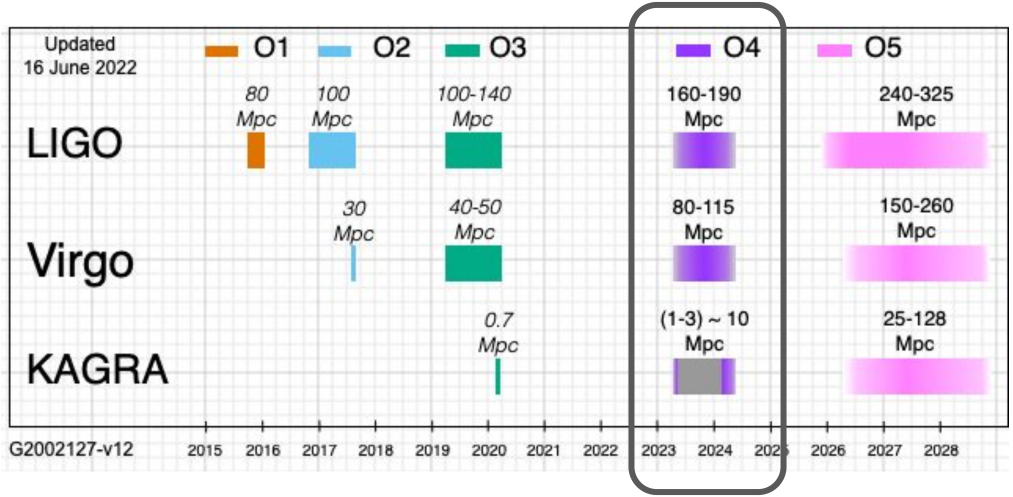




Legred+ (2021)

Prospects for O4





$$\langle VT\rangle_{O4} \sim (0.012 - 0.020)\,\mathrm{Gpc^3 yr}$$

Expect 3 - 5 times more VT from O4
→ 6 - 10 expected BNS detections in O4

Estimate of rates span 10 - 1700 BNS/Gpc^{3}yr (Abbott+ 2021)
→ 0.12 - 32 expected BNS detections in O4

What about 3G Detectors?

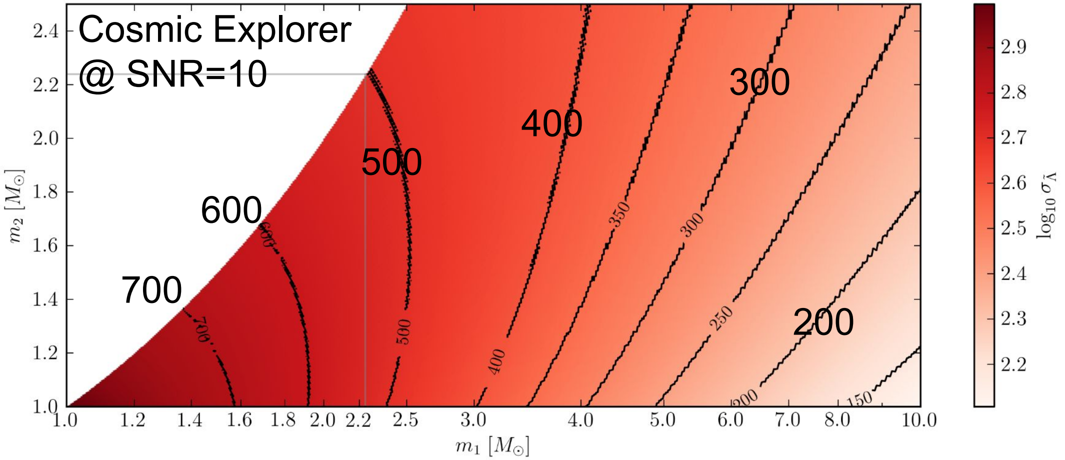
What about 3G Detectors?

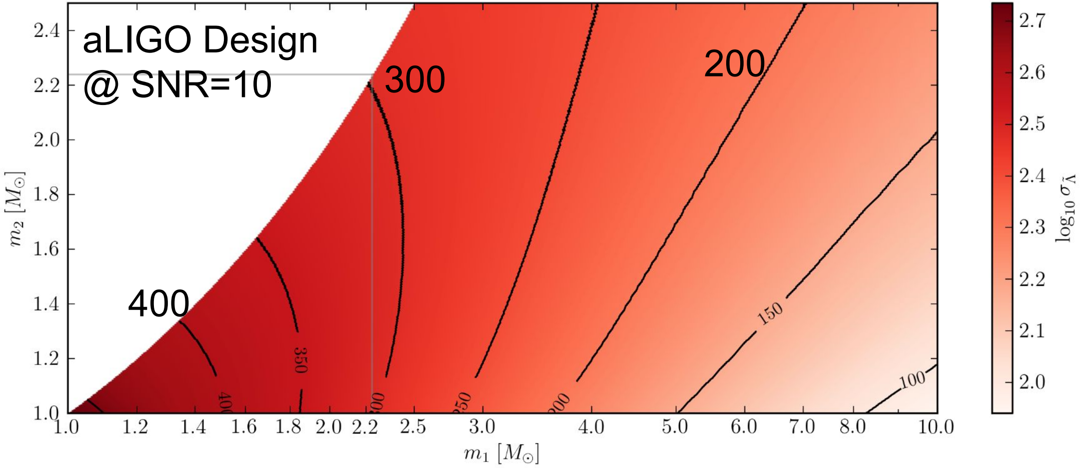
Cosmic Explorer Horizon Study

At a ***fixed SNR***, ***measurement of tides is worse***

low-freq sensitivity increases more than high-freq sensitivity for “nominal” CE (e.g., Essick 2022)

detectors may be tuned to target tidal effects Srivastava+ (2022)



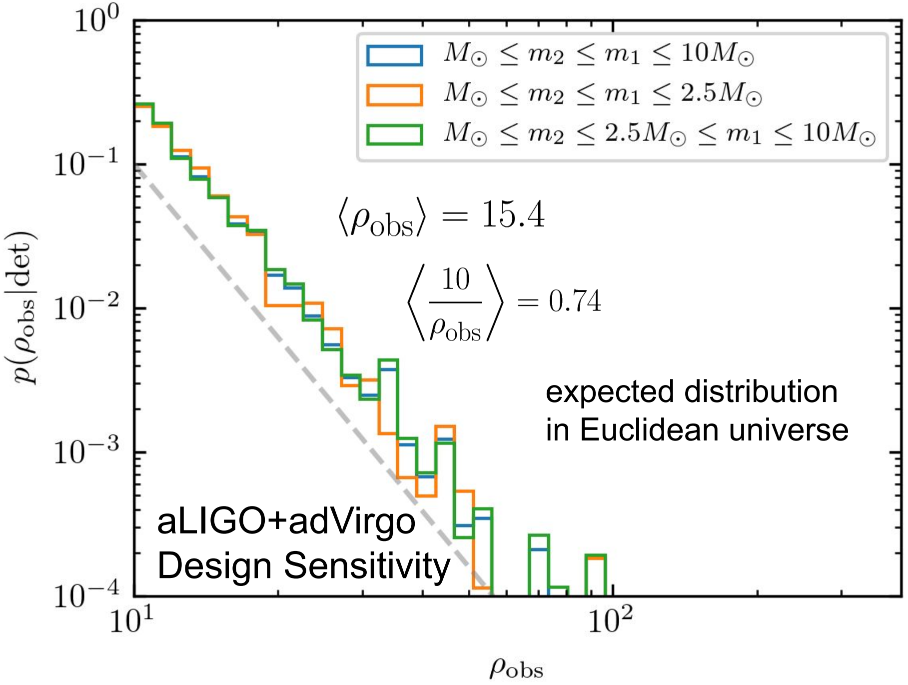


Each individual source will have a higher SNR in 3G than in aLIGO.

→ will the proportion of high-SNR signals be larger in 3G detectors?

What about 3G Detectors?

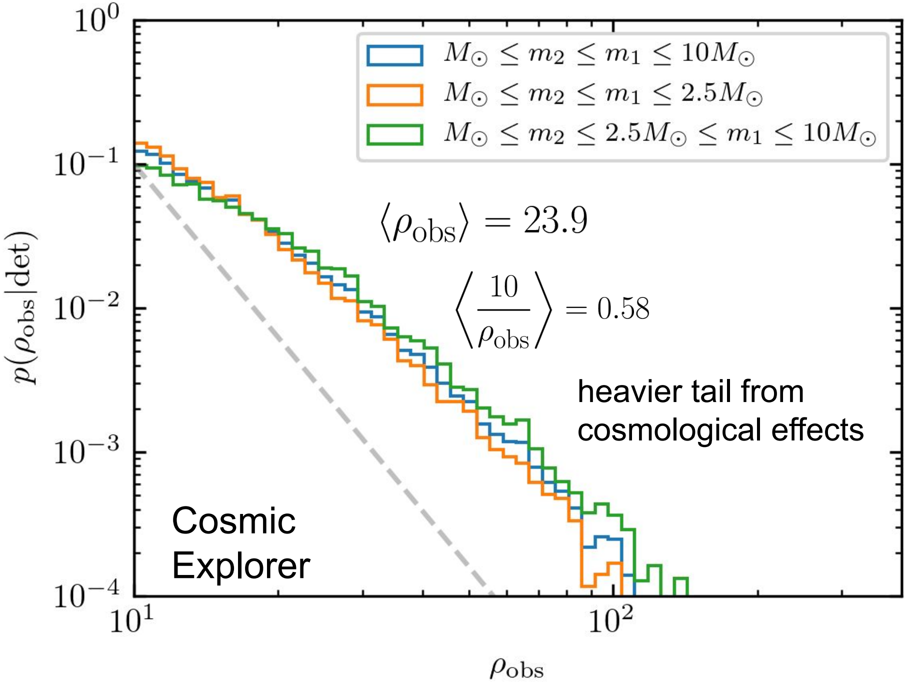
Most low-mass events in 3G will still be near the detection threshold (compare to Vitale 2016)



$\langle \rho_{\rm obs} \rangle = 15.4$

$\left\langle \frac{10}{\rho_{\rm obs}} \right\rangle = 0.74$

expected distribution in Euclidean universe



$\langle \rho_{\rm obs} \rangle = 23.9$

$\left\langle \frac{10}{\rho_{\rm obs}} \right\rangle = 0.58$

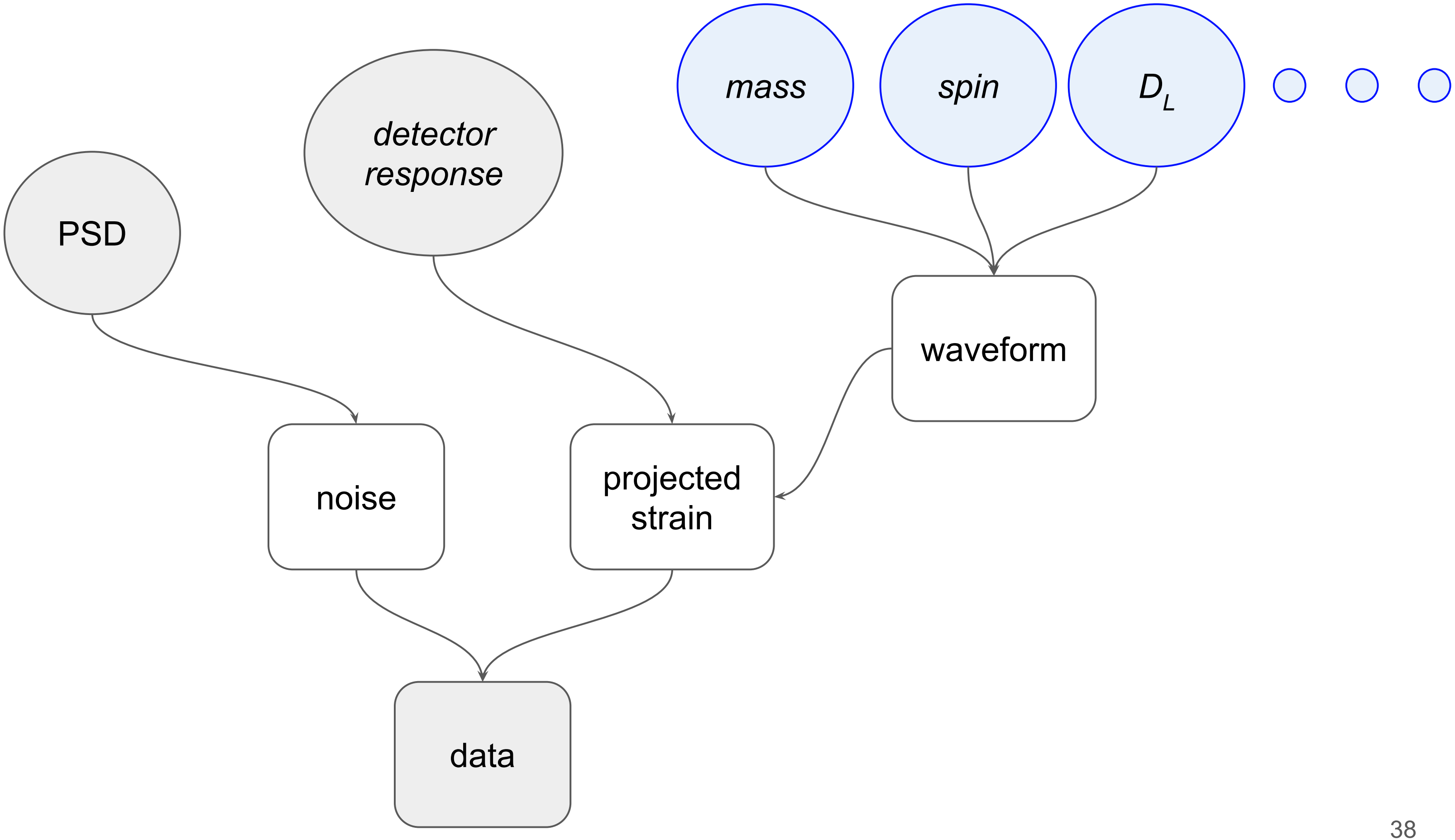
heavier tail from cosmological effects

For the average event, increased SNR with CE will ***not*** overcome
the decreased precision in adiabatic tidal measurements

Pain Points

Pain Points : Gravitational Wave Data Analyses

Chatziioannou (2021)



Pain Points : Gravitational Wave Data Analyses

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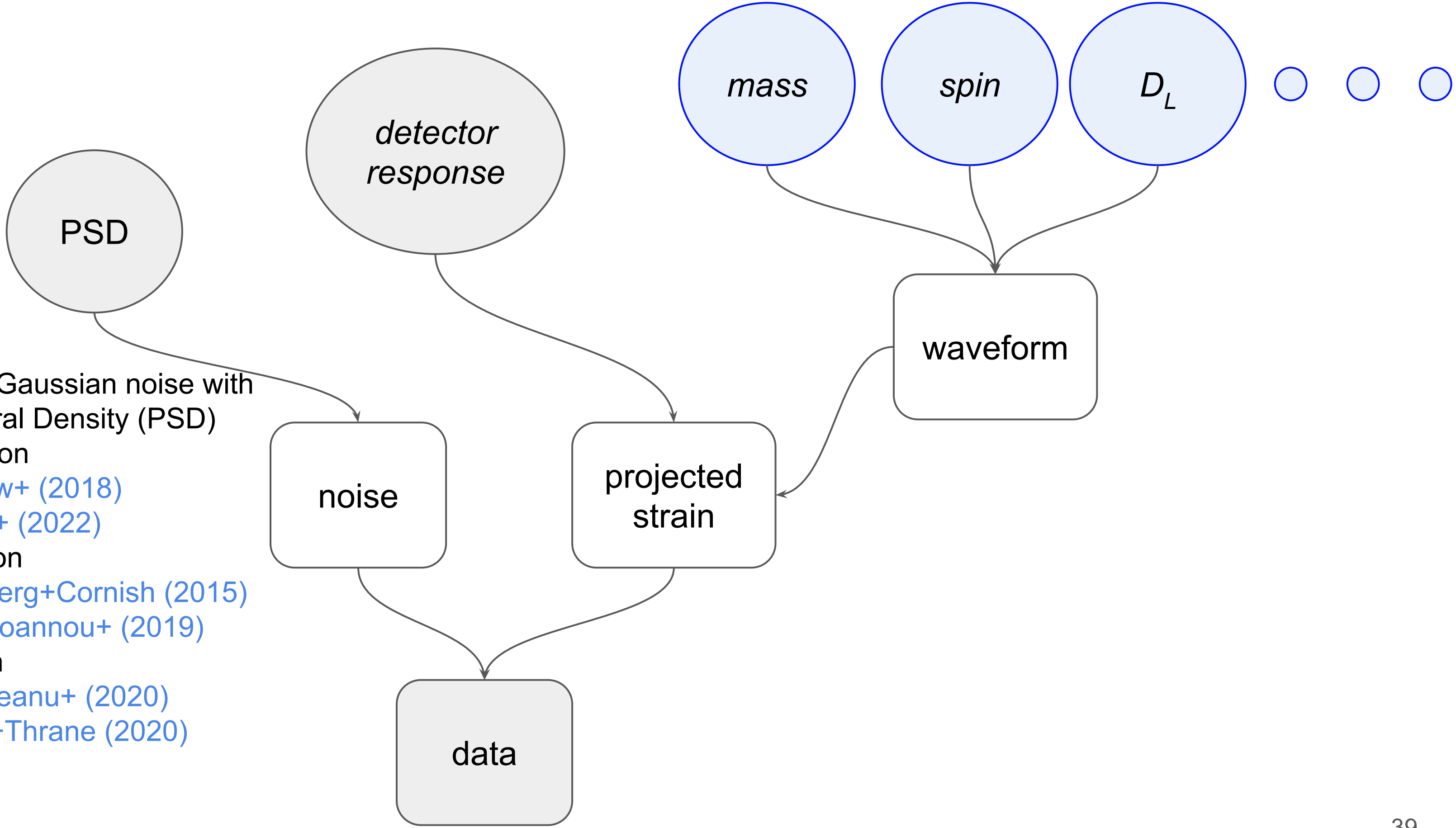

Additive, stationary, Gaussian noise with known Power Spectral Density (PSD)

- Glitch mitigation
  - Pankow+ (2018)
  - Payne+ (2022)
- PSD estimation
  - Littenberg+Cornish (2015)
  - Chatziioannou+ (2019)
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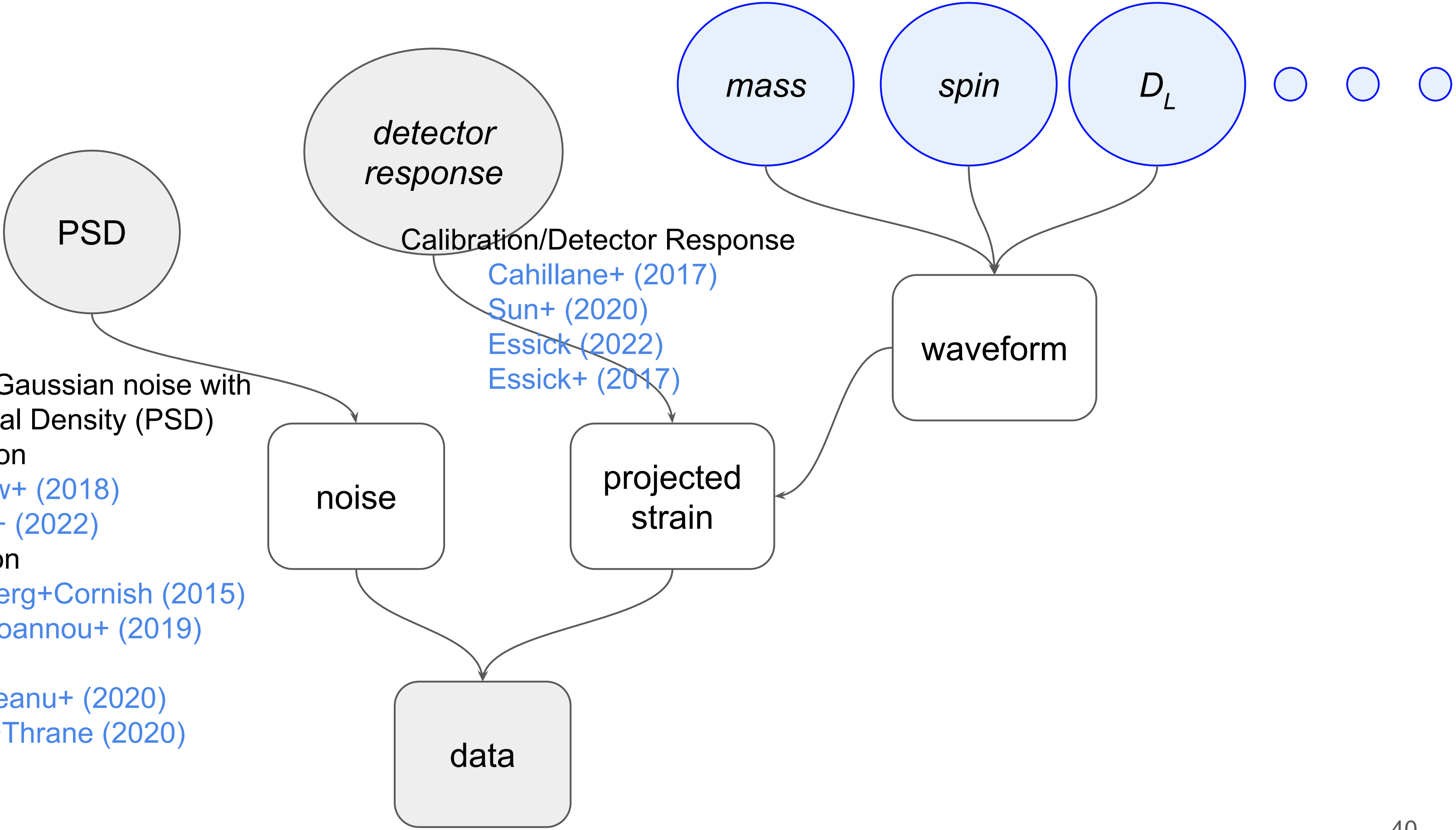

Calibration/Detector Response
- Cahillane+ (2017)
- Sun+ (2020)
- Essick (2022)
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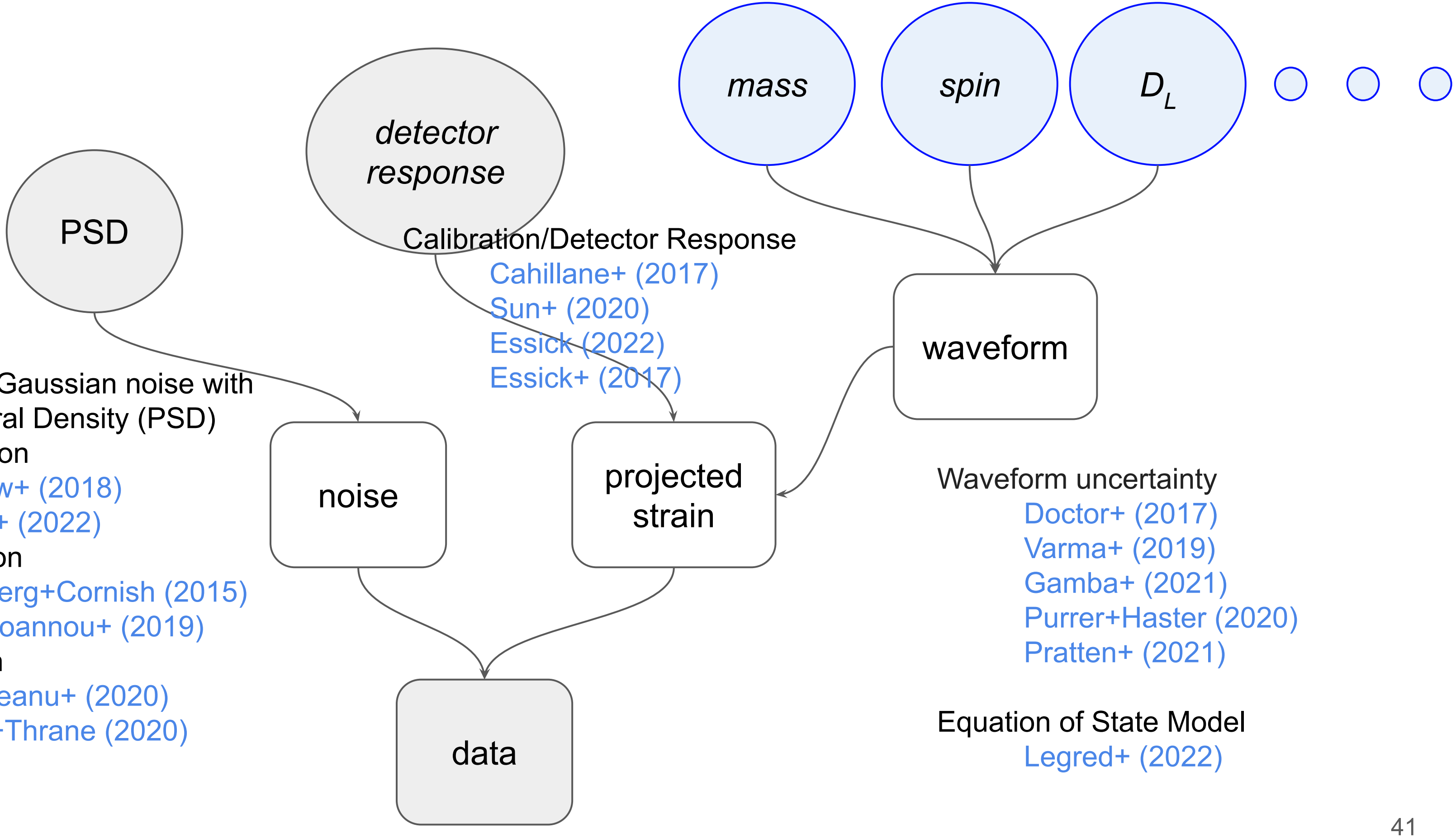

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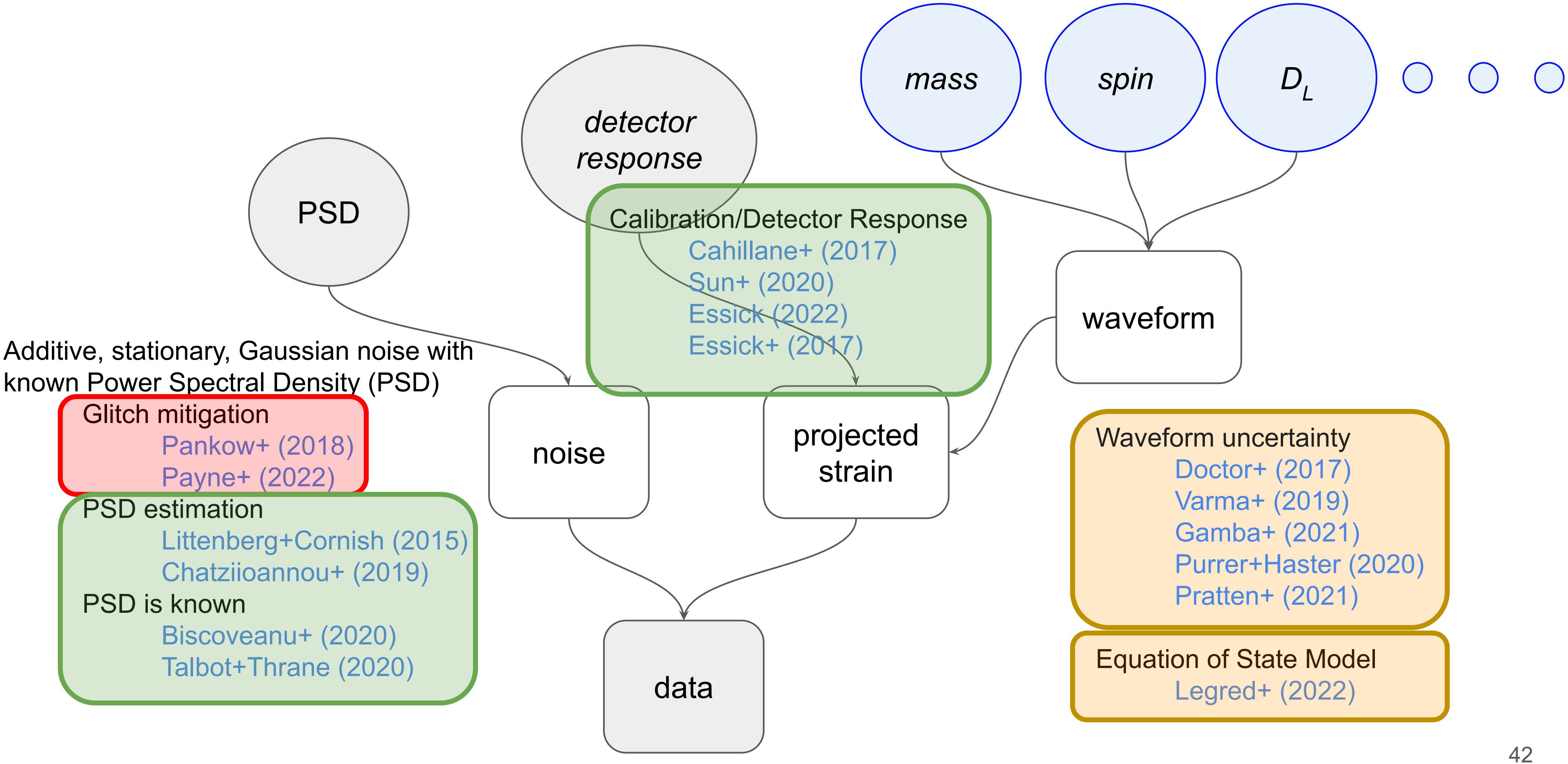
Waveform uncertainty
- Doctor+ (2017)
- Varma+ (2019)
- Gamba+ (2021)
- Purrer+Haster (2020)
- Pratten+ (2021)

Equation of State Model
- Legred+ (2022)

Pain Points : Gravitational Wave Data Analyses

Chatziioannou (2021)



Additive, stationary, Gaussian noise with known Power Spectral Density (PSD)

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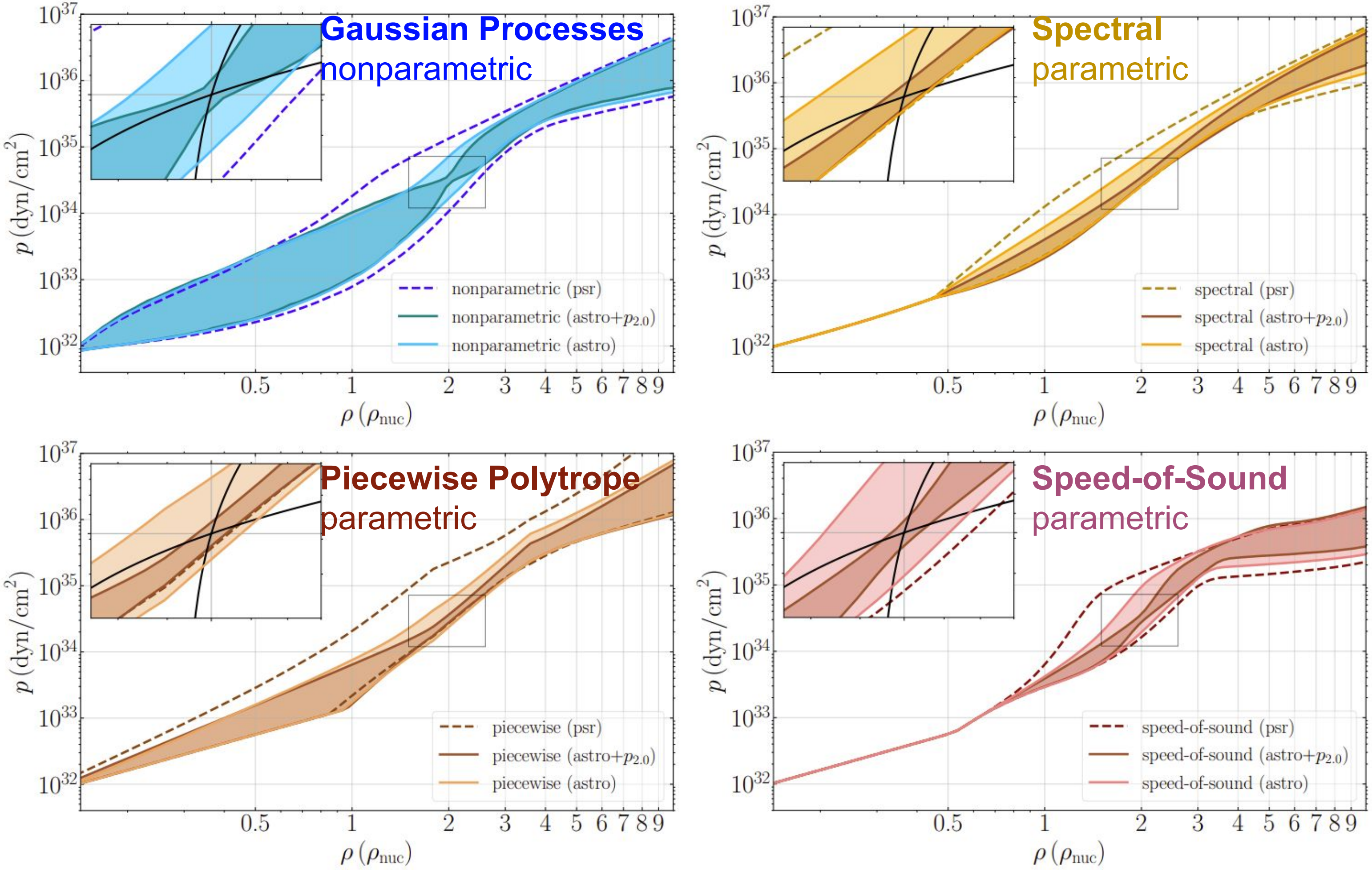
Pain Points : Phenomenological EoS Models and Implicit Assumptions

priors – dashed

astro data – light

astro + $p(2n_{\mathrm{sat}})$ – dark



Gaussian Processes
nonparametric

Spectral
parametric

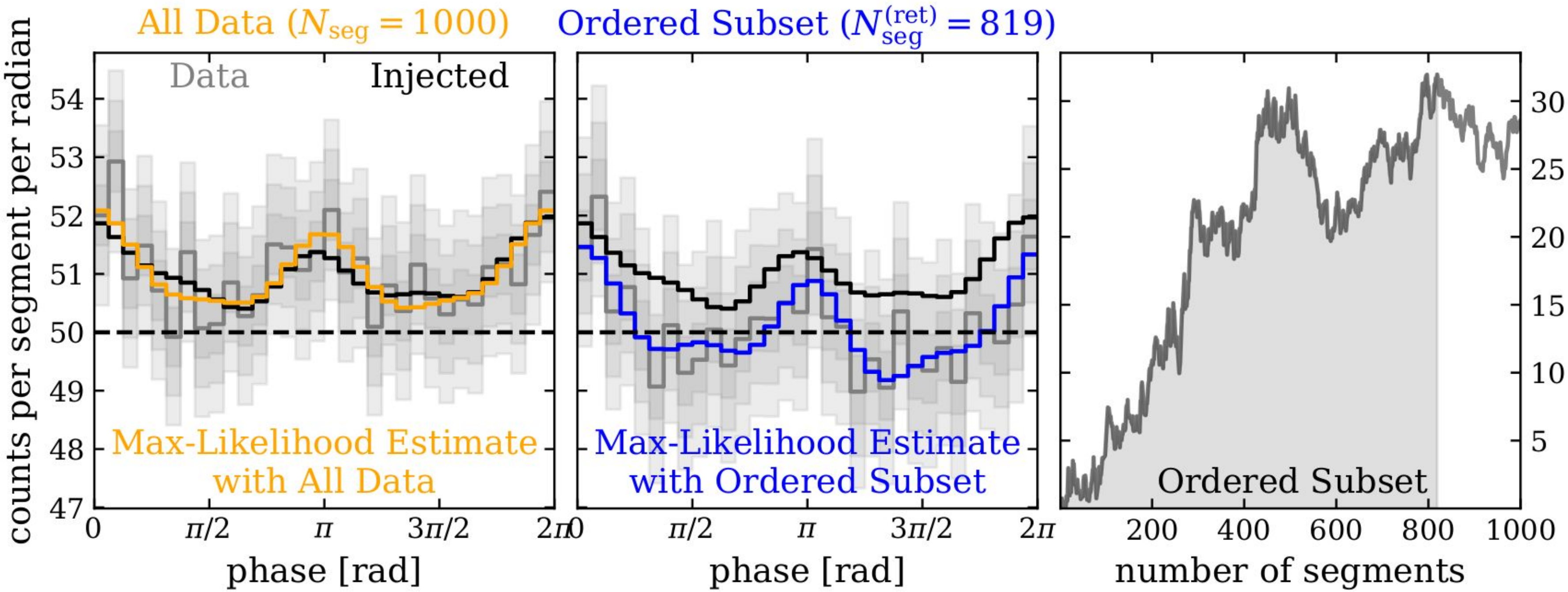
Piecewise Polytrope
parametric

Speed-of-Sound
parametric

Legred+ (2022)

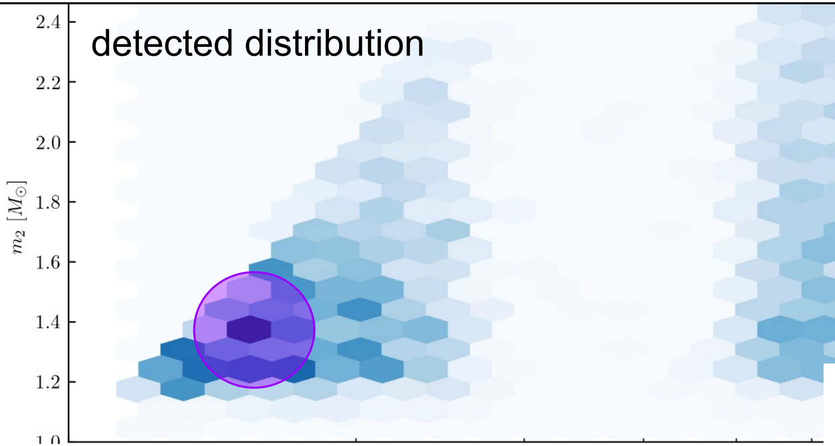
Pain Points : (X-ray) Data Selection

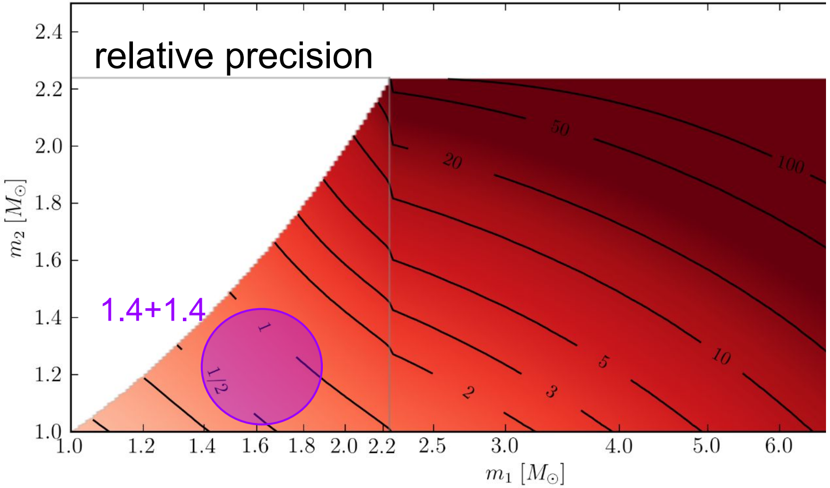
These analyses have a lot of moving parts, and seemingly small choices can have unexpected consequences.
→ NICER*’s data selection procedure* (*for J0740*) *introduces small biases*



Essick (2021)

Summary

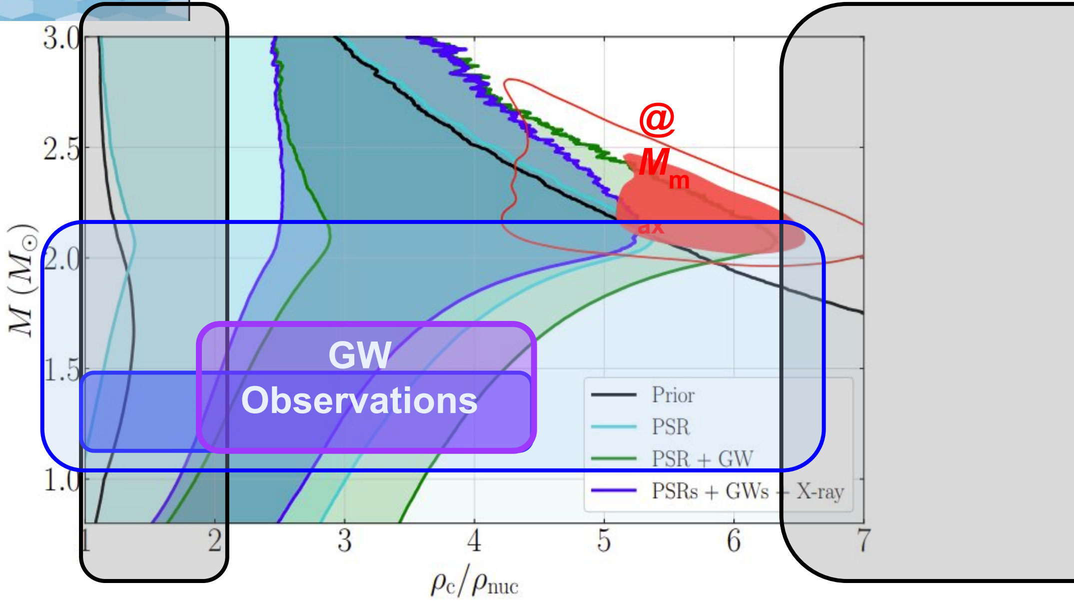

detected distribution


relative precision

1.4+1.4

Expect 3 - 5 times more VT from O4
→ 6 - 10 expected BNS detections in O4

Estimate of rates span 10 - 1700 BNS/Gpc^{3}yr (Abbott+ 2021)
→ 0.12 - 32 expected BNS detections in O4


@ M_{max}

GW Observations

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