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Projections for Neutron Star EOS Constraints with the LVK Network in A+ Era

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Overview- NS EOS

Current constraints

Abbott et al. 2017, arXiv:1710.05832
2018, arXiv:1805.11581
2019, arXiv:1805.11579

- **GW170817:** First BNS merger with GWs provided key constraints on the NS EOS through Λ measurements
- **Multi-Messenger Astronomy:** Combining data from observations of pulsars, nuclear experiments, and theoretical predictions has refined EOS constraints *Capano et al. 2020, Legred et al. 2021, Huth et al. 2022*

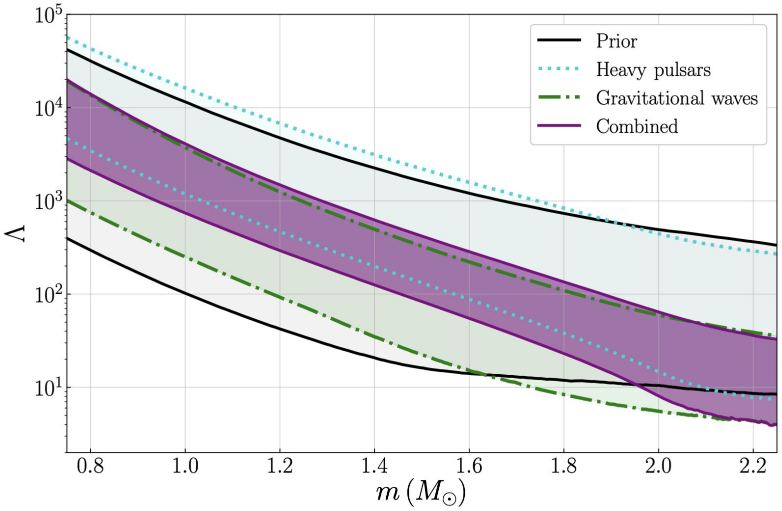
Limitations of Current Observations

- **Low Detection Rate:** Only two BNS mergers (GW170817 and GW190425) *Abbott et al. 2017, arXiv:1710.05832 2020, arXiv:2001.01761*
- **NS-BH Observations:** Existing NS-BH detections provide limited tidal information due to high mass ratios and low spins, which prevent tidal disruption signatures *Abbott et al. 2021, arXiv:2106.15163 Biscoveanu et al. 2023*

Future Observing Prospects

Abbott et al. 2018, arXiv:1304.0670

- **O5 Observing Run:** Upgraded LVK network is expected to increase the detection range for BNS mergers
- **Next-Generation:** Precision constraints on NS matter will likely require future observatories (ET, CE, …) *Maggiore et al. 2020, Evans et al. 2021*



Chatziioannou 2020, arXiv:2006.03168v2

Aim: Constraining NS EOS with LVK Network in A+

Objectives

- **Assess how well we can** constrain NS EOS recovery using simulated BNS mergers detectable by LVK Network
- **Compare different EOS models:** soft (hqc18), intermediate (sly230a), and stiff (mpa1), under realistic observation scenarios

Baym et al.2018 *Chabanat et al. 1997, Danielewicz and Lee 2009, Gulminelli and Raduta 2015* *Müther et al. 1987*

Methodology

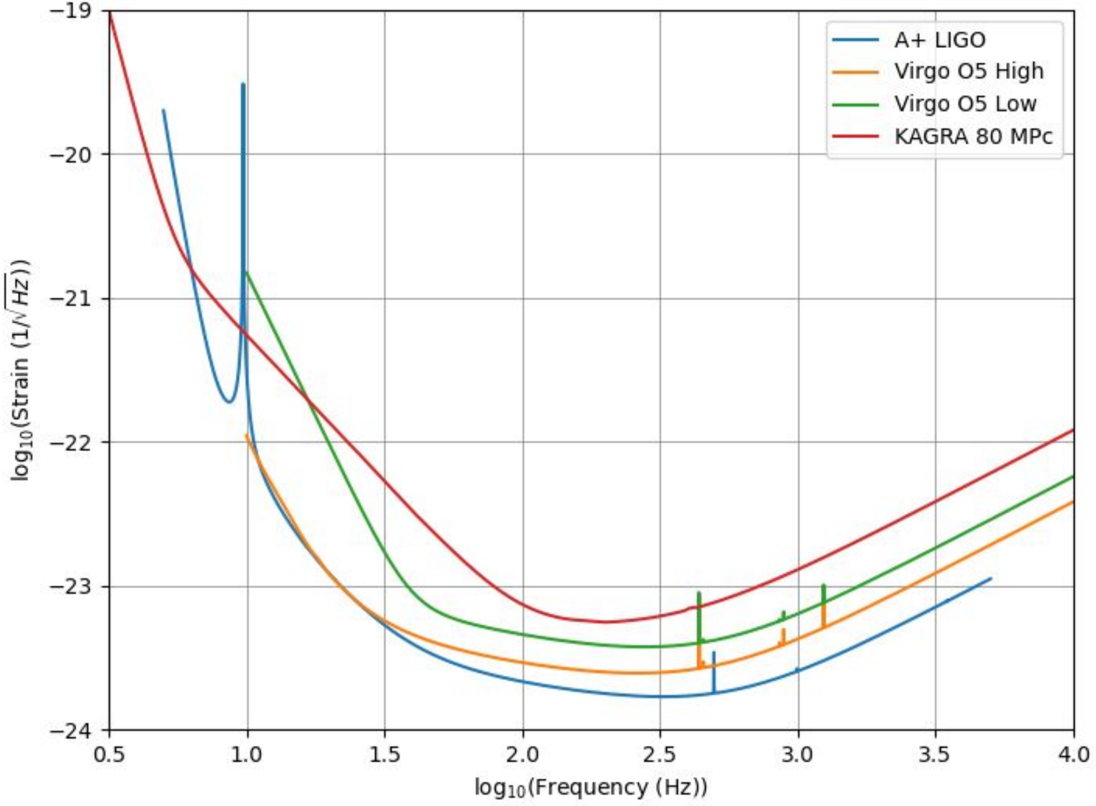
- **Simulate BNS Populations:** Inject large number of BNS events (1,000 events per EOS) into A+ sensitivity
- **Parameter Estimation:** Use ROQs for rapid GW signal analysis in the LVK network *Canizares et al. 2015, Smith et al. 2016*
- **Constrain EOS:** Apply Bayesian inference to extract EOS constraints

EOS Inference Approach

- **Post-process Parameter Estimation:** Use spectral EOS inference with large prior sets
- **Sequential Inference**: Combine EOS information across events, using posteriors from one event as priors for the next

Determine how well the injected EOSs are recovered in all scenarios, based on the number of detected BNS events

Sensitivity curves used



DCC link to sensitivity curves

DCC: T2000012

- APlusDesign.txt
- avirgo_O5high_NEW.txt
- avirgo_O5low_NEW.txt
- kagra_80MPc.txt

Methodology Overview: Simulations of GWs

Injection Setup

Landry and Read 2021, arXiv:2107.04559
Abbott et al. 2023, arXiv:2111.03634

- **BNS Population Model:** Uniform NS mass distribution with random pairing, low spin scenario and sources up to 460 MPc (comoving volume)

Muther et al. 1987, Reinhard and Flocard 1995, Baym et al. 2019

- **Equation of State (EOS) Models:** Tidal deformability (Λ) determined by mass using Λ(m) relation
- **Waveform:** Use IMRPhenomPv2_NRTidalv2 model for 128s and 256s signals

Dietrich et al. 2019

Parameter (Symbol) [Unit]	Injection configuration	Parameter estimation prior
Source-frame primary NS (m_1) [$M_\odot$]	Uniform [1, $m_{\max}{}^*$] with $m_1 \geq m_2$	Determined by $\mathcal{M}_c$ and q
Source-frame secondary NS (m_2) [$M_\odot$]	Uniform [1, $m_{\max}$]	Determined by $\mathcal{M}_c$ and q
Source-frame chirp mass ($\mathcal{M}_c$) [$M_\odot$]	$\frac{(m_1 m_2)^{3/5}}{(m_1+m_2)^{1/5}}$	Uniform [1.6, 2.6] $M_\odot$ for 128 s Uniform [0.98, 1.7] $M_\odot$ for 256 s
Source-frame mass ratio (q)	m_2/m_1	Uniform [0.125, 1]
Dimensionless primary NS spin (a_1)	Uniform [0, 0.05]	Uniform [0, 0.05]
Dimensionless secondary NS spin (a_2)	Uniform [0, 0.05]	Uniform [0, 0.05]
Primary NS tilt (θ_1) [radian]	Uniform Sine $[0, \pi]$	Same as injection
Secondary NS tilt (θ_2) [radian]	Uniform Sine $[0, \pi]$	Same as injection
Relative spin azimuthal angle (ϕ_{jl}) [radian]	Uniform $[0, 2\pi]$	Same as injection
Spin phase angle (ϕ_{12}) [radian]	Uniform $[0, 2\pi]$	Same as injection
Luminosity distance (d_L) [Mpc]	Uniform in square [10, 460] Mpc	Square power law [1, 1000] Mpc
Right ascension (α) [radian]	Uniform [0, 2π]	Uniform [0, 2π]
Declination (δ) [radian]	Uniform Cosine $[-\pi/2, \pi/2]$	Uniform Cosine
Inclination angle (θ_{JN}) [radian]	Uniform Sine [0, π]	Uniform Sine [0, π]
Polarization (Ψ) [radian]	Uniform [0,π]	Uniform [0, π]
Coalescence phase (ϕ) [radian]	Uniform [0, 2π]	Marginalized
Geocenter time (t_c) [second]	Trigger time	Uniform [trigger time - 0.1, trigger time + 0.1]
Tidal deformability of primary NS (Λ_1)	Determined by m_1 and EOS	Uniform [0, 5000]
Tidal deformability of secondary NS (Λ_2)	Determined by m_2 and EOS	Uniform [0, 5000]

Methodology Overview: PE and EOS Inference

Parameter Estimation of GWs from BNS Mergers

Qi and Raymond 2020, Soichiro et al. 2023, Ashton et al. 2019

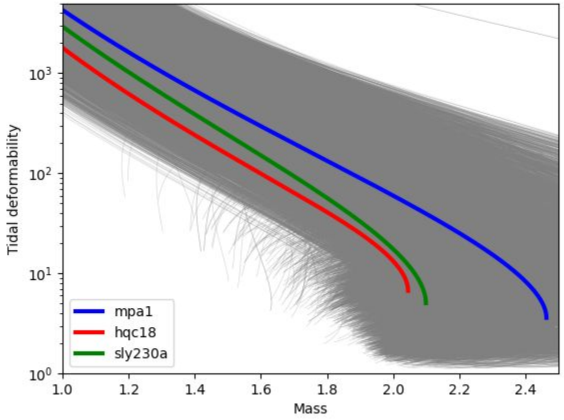
- **Technique:** Apply ROQ-accelerated PE using Bilby (1000 events PE completed in 6 days)
- **Detection Thresholds:** Events detectable with SNR > 11.2 in the LVK network at O5 sensitivity (around 600-700 events for each EOS)
- **Recovered Parameters:** Full parameters, including mass and tidal deformability distributions derived for each event (*priors used for PE detailed in a previous table*)

EOS Inference

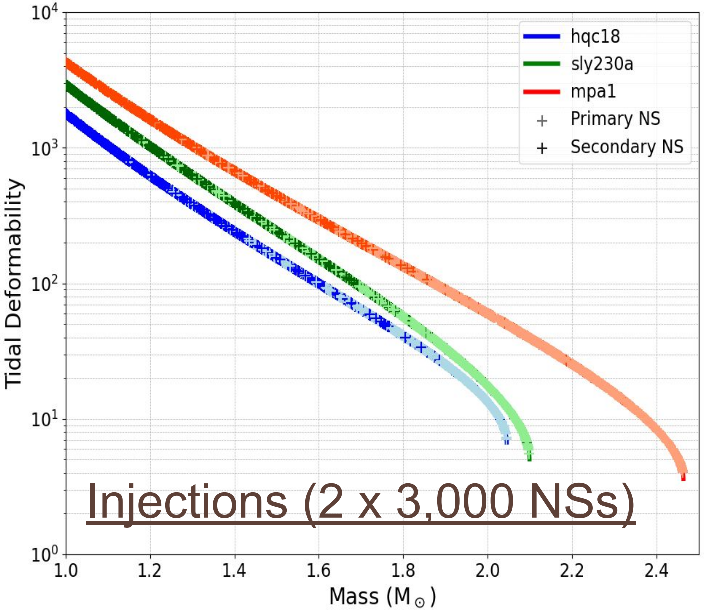
Landry et al. 2020, Legred et al. 2021

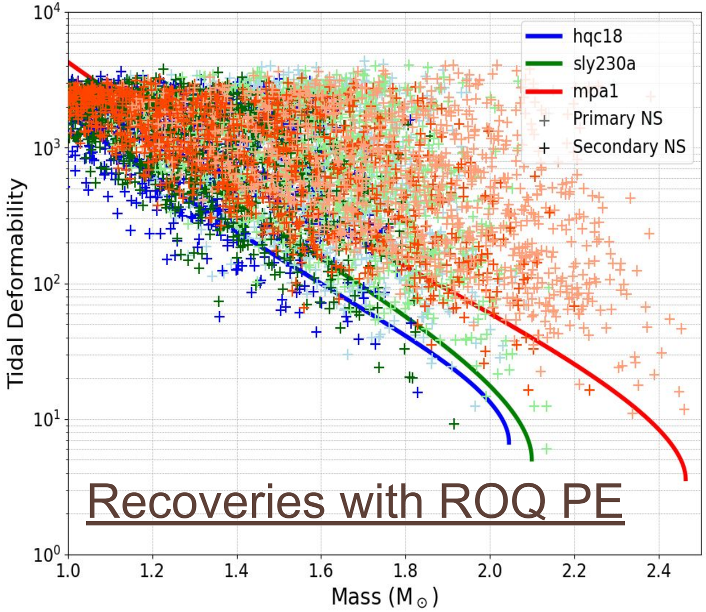
- **Bayesian Framework:** Hierarchical Bayesian inference using lwp software (EOS modeled as a Gaussian process based on 10,000 EOS samples)
- **Likelihood Calculation:** EOS likelihood calculated for each GW event, integrating over mass and tidal parameters / Selection effects considered, but independent of tidal deformability
- **Expected Results:** Constraints on EOS parameters and NS observables (e.g., NS radius, pressure at saturation density)

10k EOSs as prior for EOS constraints



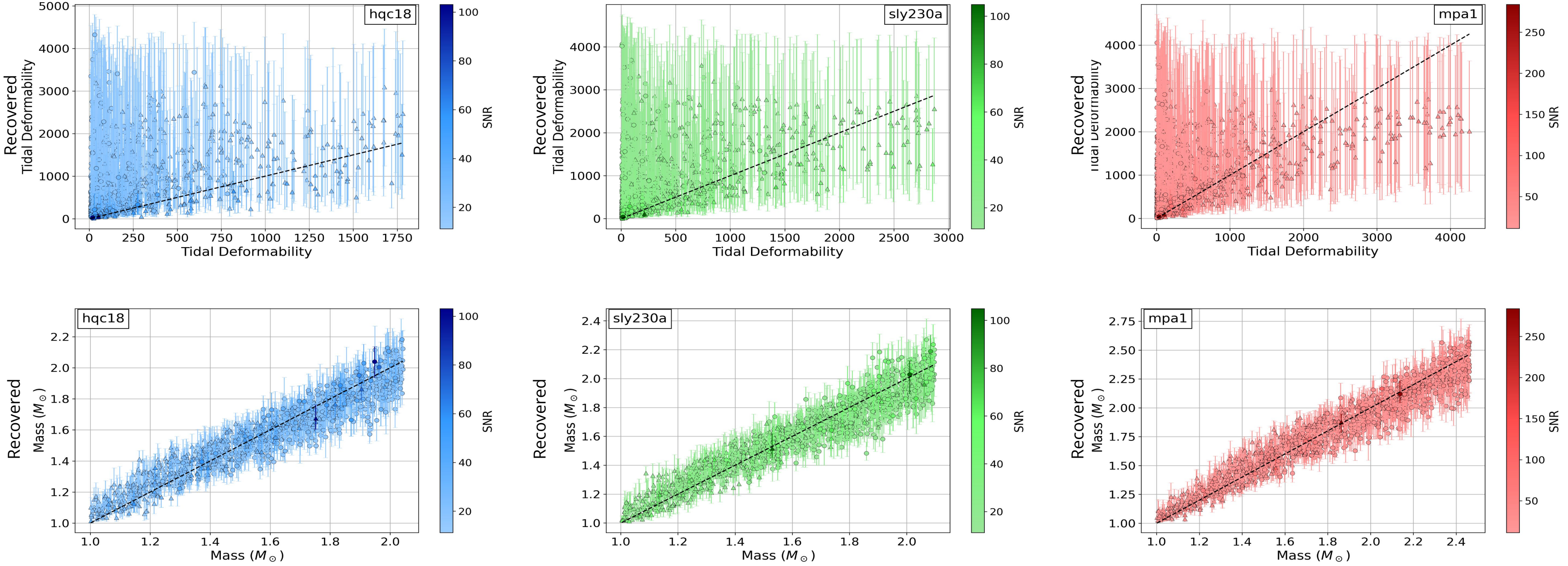
Distribution of Mass and Tidal Deformation





- **Injected vs Recovered values:** good coverage of the mass-Λ parameter space, posteriors cluster tightly
- **After ROQ PE:** Distinguishing EOS models is visually difficult

Medians and Error Bars of Recovered Injections

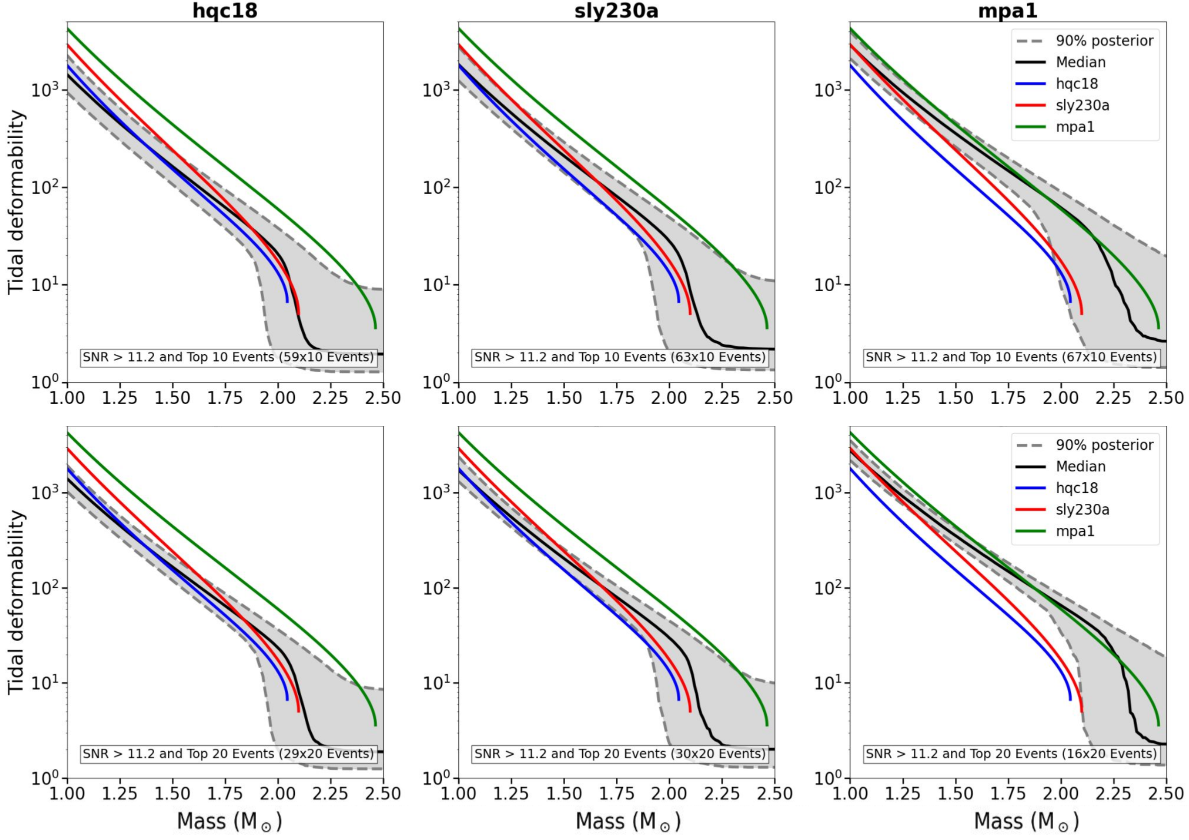


- **Tidal Deformability:** Spread uncertainties, overestimation at low Λ and underestimation at high Λ
- **Mass:** Injected vs. posterior masses align well for all EOS models, with small errors and good accuracy
- **Impact on EOS Recovery:** Biases in the Λ-mass relationship due to systematic errors in Λ estimates

EOS Constraints with Different Numbers of Detections

Combined posteriors for the three EOS for two different size groups (10 and 20 events) + averaging

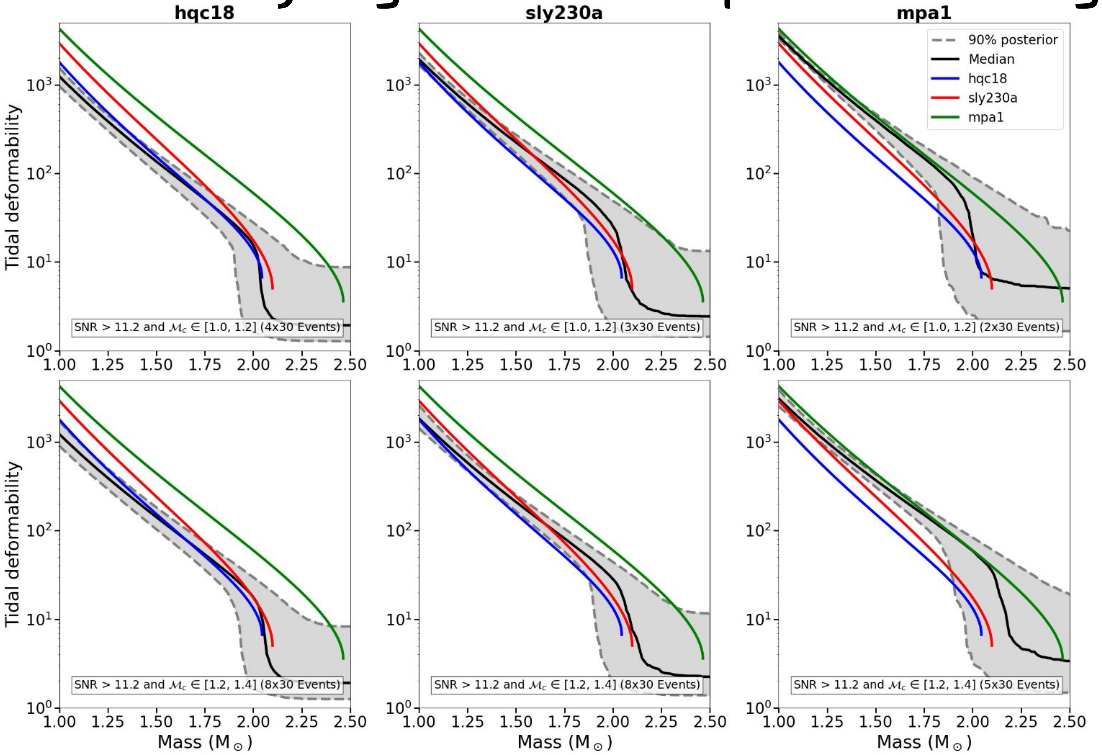
All EOS show biases, even for groups of 10 events. Bias increases with larger group sizes.



N_{eff} > 100

EOS Constraints Varying w.r.t. Chirp Mass Ranges (1/2)

Combined posteriors for the three EOS for different chirp mass ranges considering only the 15 loudest events in groups of 30 + averaging



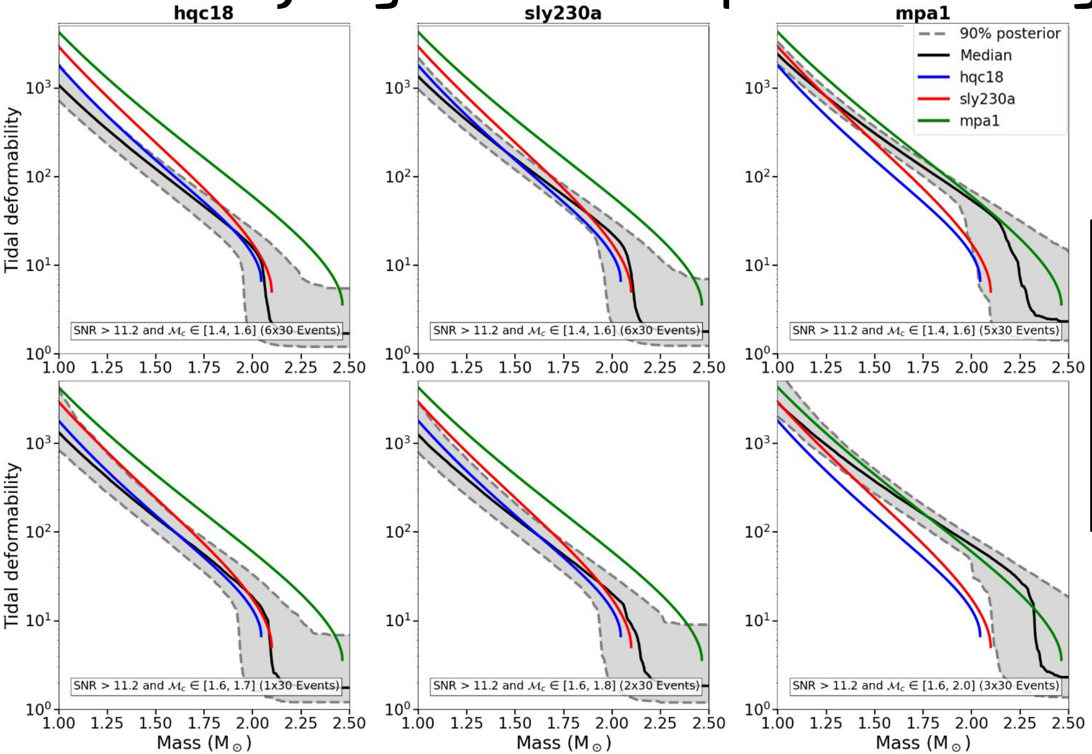
$N_{eff} > 100$

$M_c \in [1.0, 1.2]\ M_{sun}$

$M_c \in [1.2, 1.4]\ M_{sun}$

EOS Constraints Varying w.r.t. Chirp Mass Ranges (2/2)

Combined posteriors for the three EOS for different chirp mass ranges considering only the 15 loudest events in groups of 30 + averaging



$N_{eff} > 100$

$M_c \in [1.4, 1.6]\ M_{sun}$

hqc18 is well recovered. sly230a and mpa1 show biases, especially at lower masses.

$M_c \in [1.6, \text{Max}]\ M_{sun}$

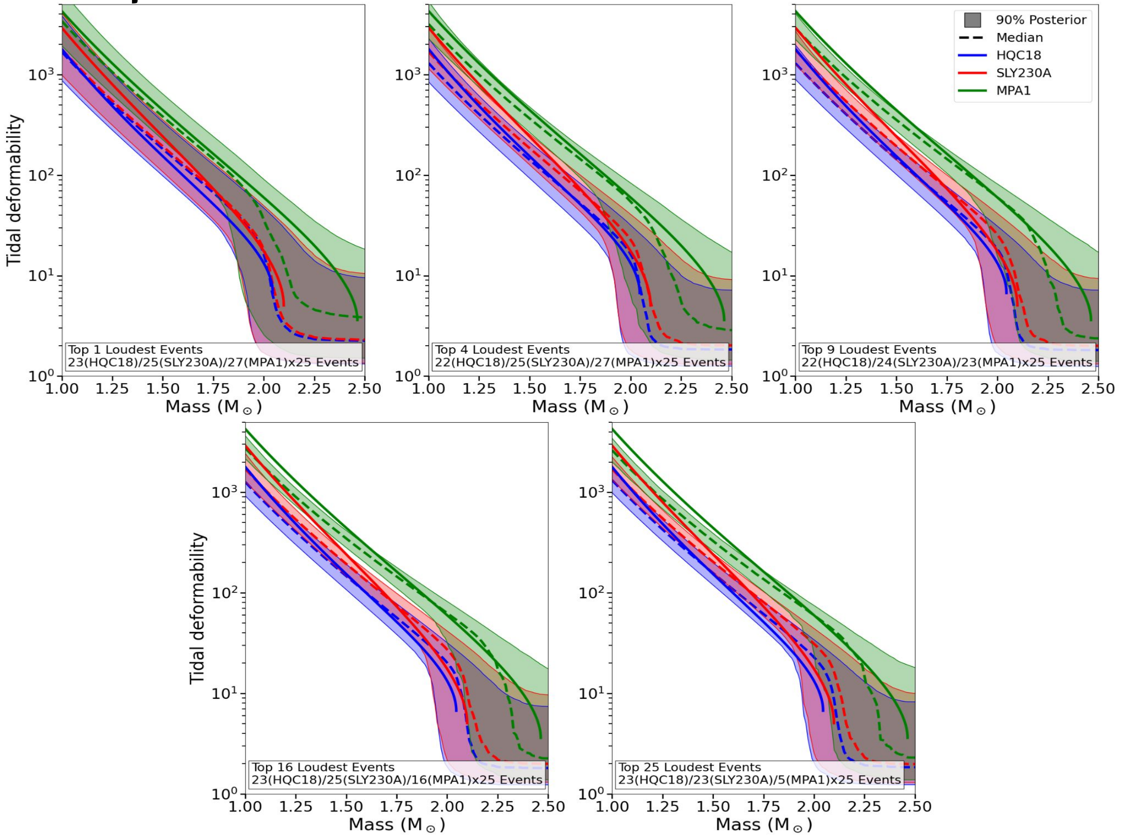
- **Tidal Deformability Bias:** Underestimation at low masses and overestimation at high masses
- **Method Limitations:** Recovery varies by EOS and mass range, better performance at higher M_c

Evolution of EOS Constraints: N Loudest Events (1/3)

Check out the videos showing how the constraints evolve as we include more loudest events for each EOS model

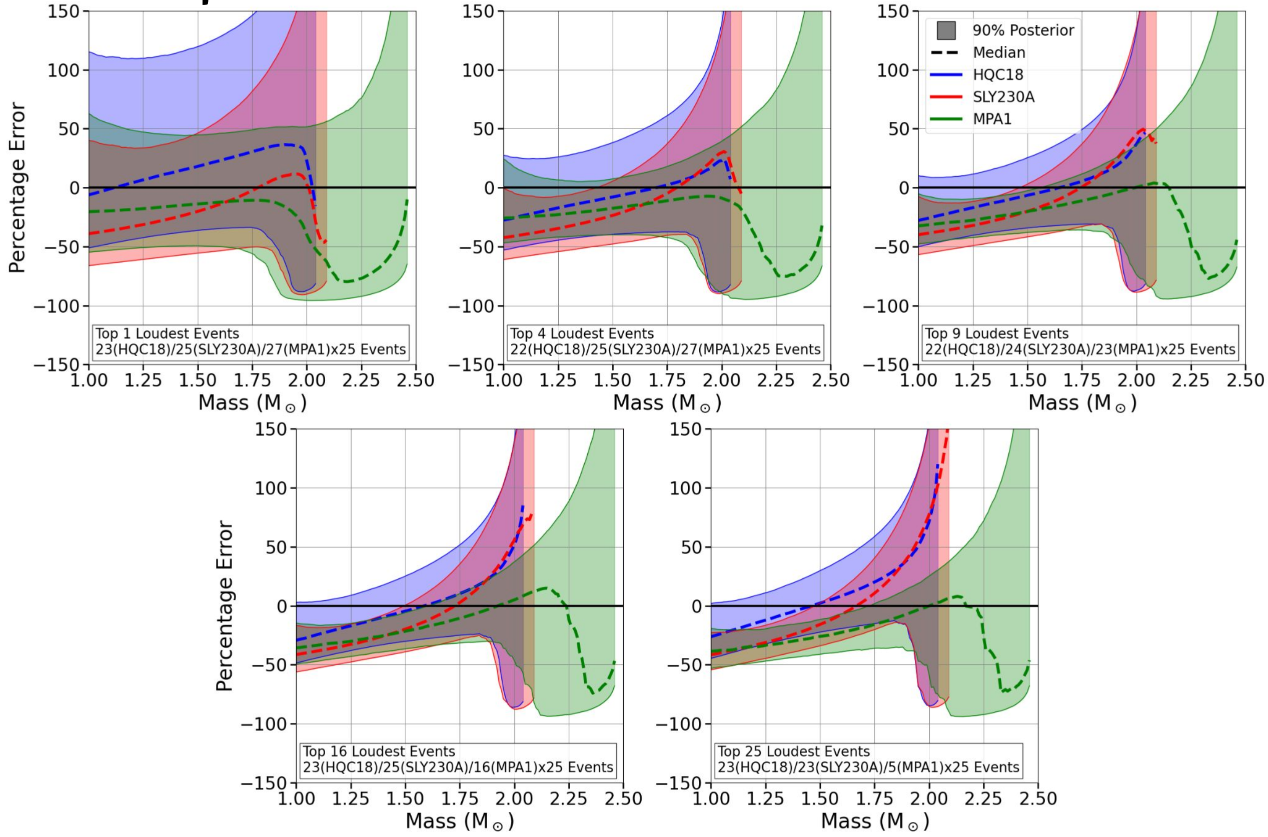
Watch the videos here!

Evolution of EOS Constraints: N Loudest Events (2/3)



$N_{eff} > 100$

Evolution of EOS Constraints: N Loudest Events (3/3)



$N_{eff} > 100$

Conclusions

- **EOS Recovery with O5 LVK Network:** Simulated BNS mergers show promising constraints on NS EOS, especially with more massive systems

- **Biases in Tidal Deformability:** Systematic underestimation at low masses and overestimation at high masses affects accurate EOS recovery (need to take it into account + might me interesting to find out the reasons)