

Analyzing GW231109_235456 and its implications for the neutron star equation of state

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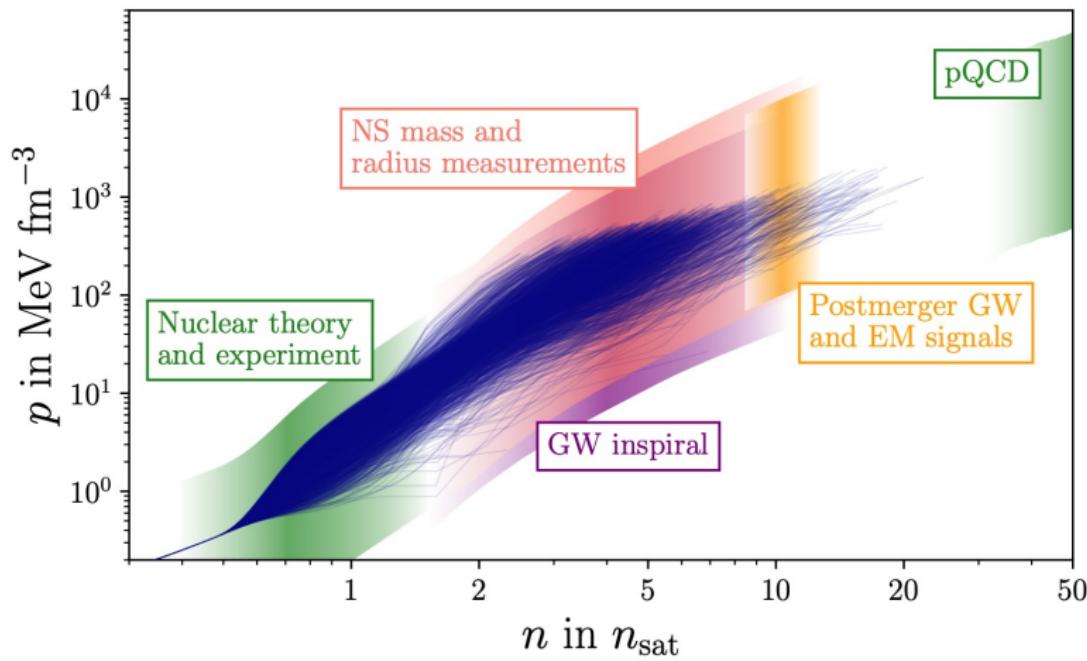
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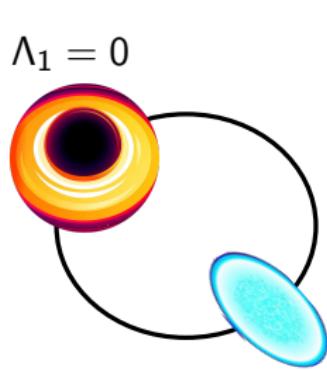
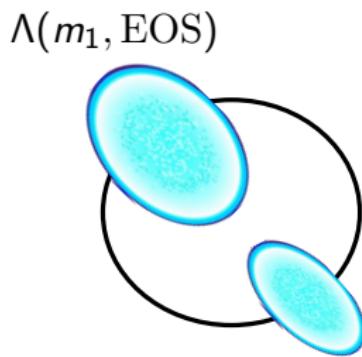
Neutron stars and the equation of state

Neutron stars probe the high-density part of the equation of state (EOS) of dense nuclear matter [1]



Tidal deformability

- Neutron stars are tidally deformed in a binary
- Quantified by tidal deformability Λ , depends on equation of state
- **Challenge:** Λ harder to measure than masses (higher-order effect)


$$\Lambda(m_2, \text{EOS})$$

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Binary neutron star mergers: GW170817 and GW190425

So far, two confident BNS detections:

① **GW170817** [2]

- First multimessenger detection (GW + EM)
- SNR ~ 32 (distance: ~ 40 Mpc)
- Loud signal \rightarrow excellent constraints on EOS

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② GW190425 [3]

- Heavier system: total mass $\sim 3.4 M_{\odot}$
- SNR ~ 12 (distance: ~ 160 Mpc)
- Fainter, more massive \rightarrow poor EOS constraints

GWTC-4.0 and GW231109_235456

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- **No confident BNS detections** in O4a
- However: sub-threshold candidate **GW231109_235456** identified [5]
 - **SNR ~ 9.7** (distance: ~ 165 Mpc)
 - Fainter, but mass closer to GW170817 than GW190425

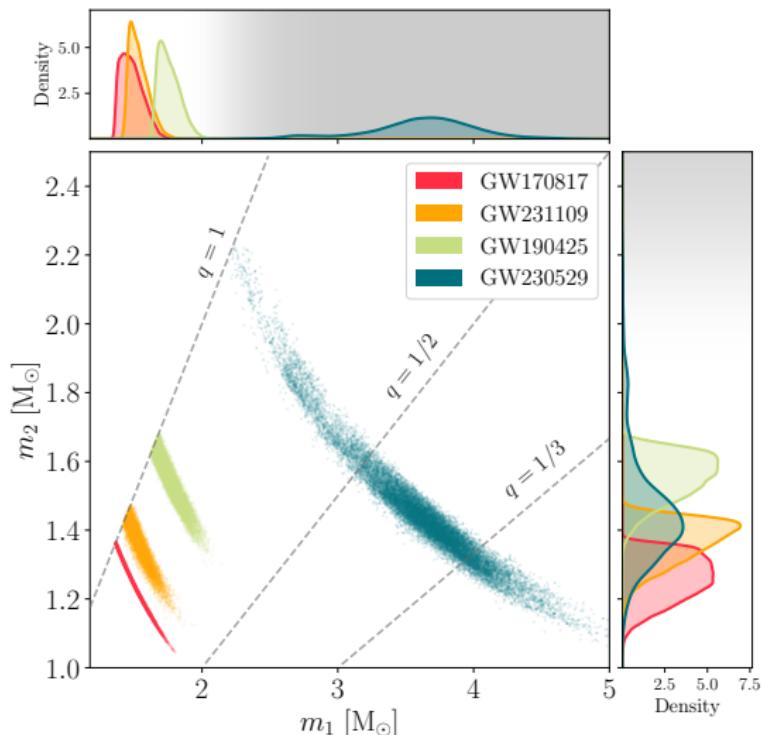
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Can we still learn something about the EOS?

GW231109: component masses

Component masses compared to other low-mass GW events [2, 3, 6]



This work

We analyze GW231109_235456 and investigate:

- ① Can we extract *any* additional information about the EOS?
- ② How will future detectors (Einstein Telescope, Cosmic Explorer) improve constraints for similar events?

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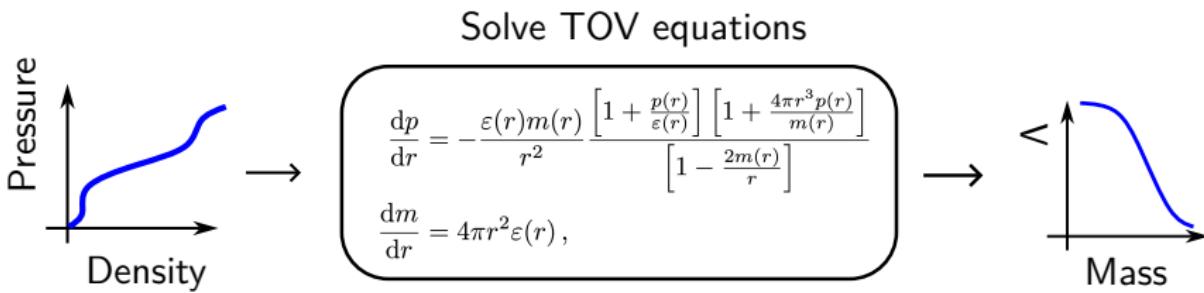
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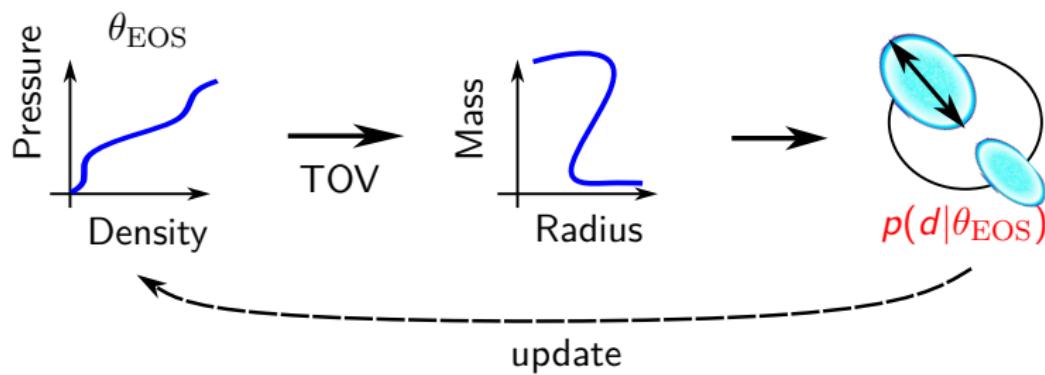
Equation of state inference

- To predict neutron star properties, we solve the TOV equations: ordinary differential equations (ODEs)



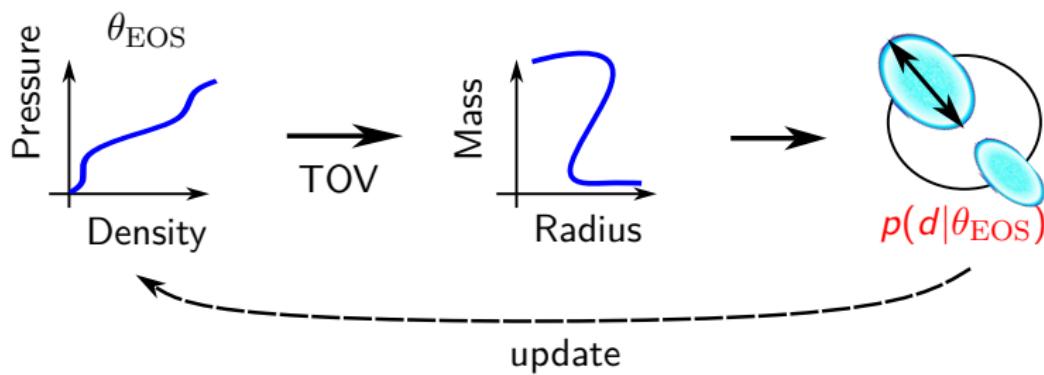
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- Done while sampling parametrization for the EOS: **costly likelihood**



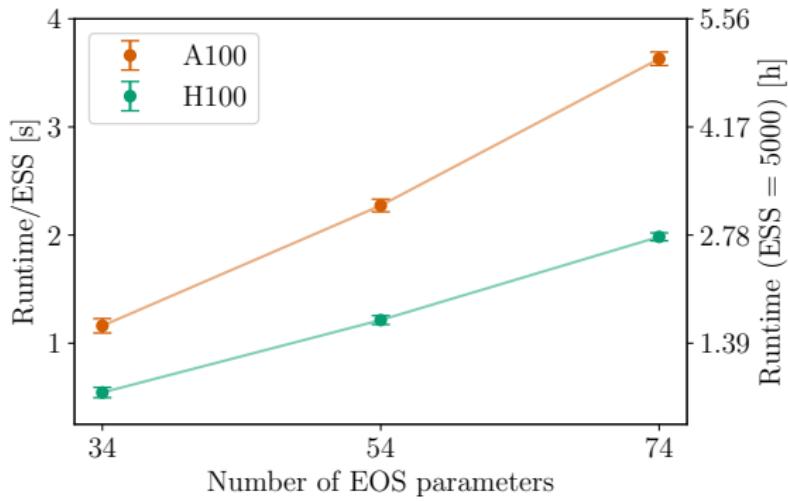
Equation of state inference

- To predict neutron star properties, we solve the TOV equations: ordinary differential equations (ODEs)
- Done while sampling parametrization for the EOS: **costly likelihood**
- Typically $\mathcal{O}(10^6)$ samples for inference
- Would take **days** with CPUs



GPU acceleration: JESTER

- JESTER  [7]: JAX-based TOV solver
 - $1000\times$ faster, without compromises
 - Full inference in ~ 1 hour on GPU (vs days on CPU)
- Enables systematic studies in EOS inference



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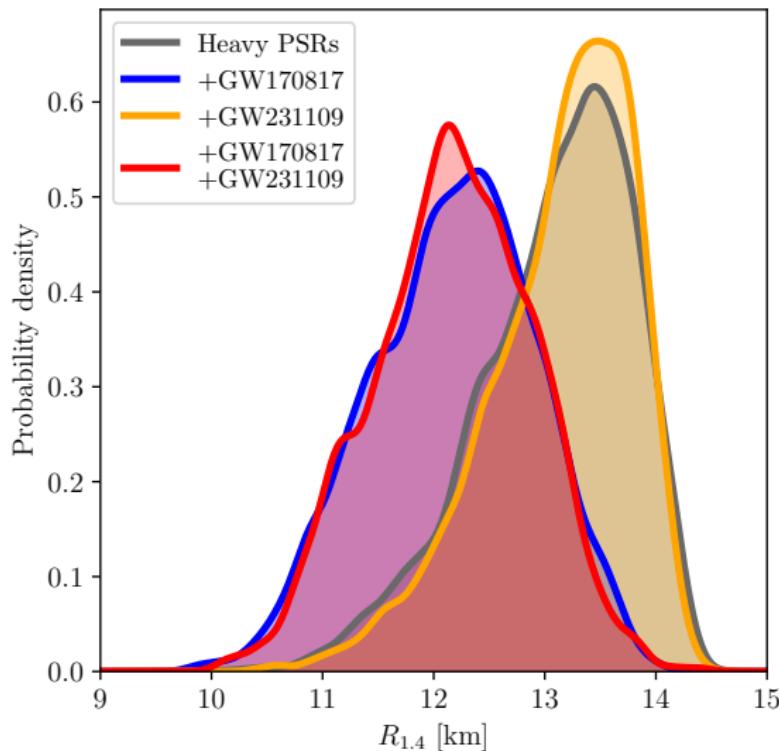
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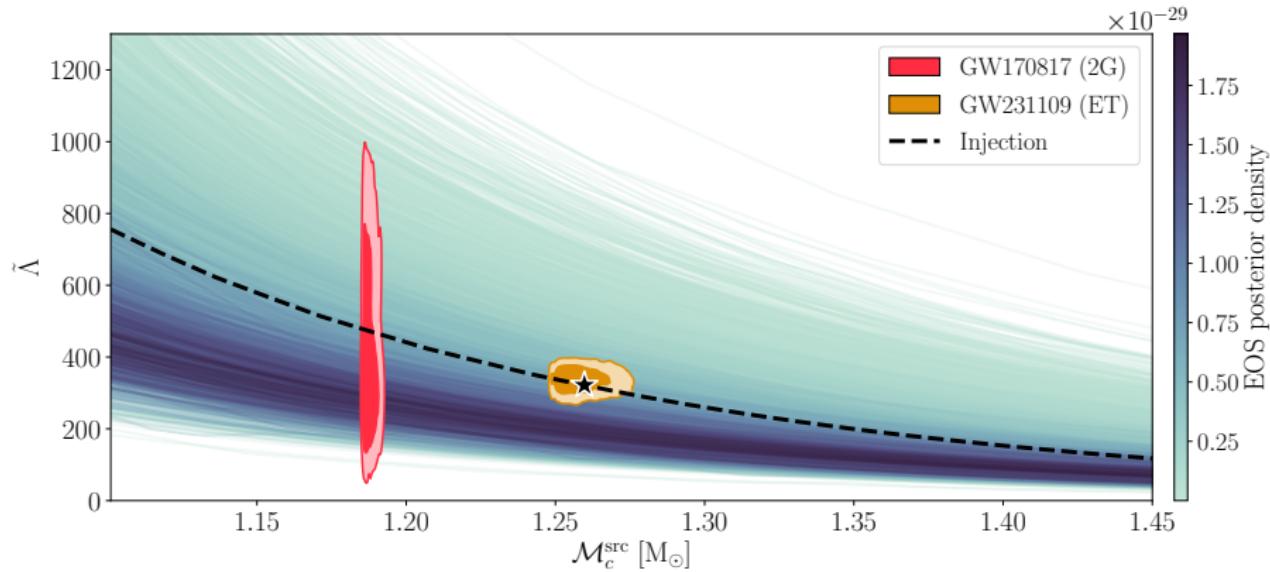
EOS constraints from GW231109

Constraints on radius of $1.4 M_{\odot}$ neutron star ($R_{1.4}$):



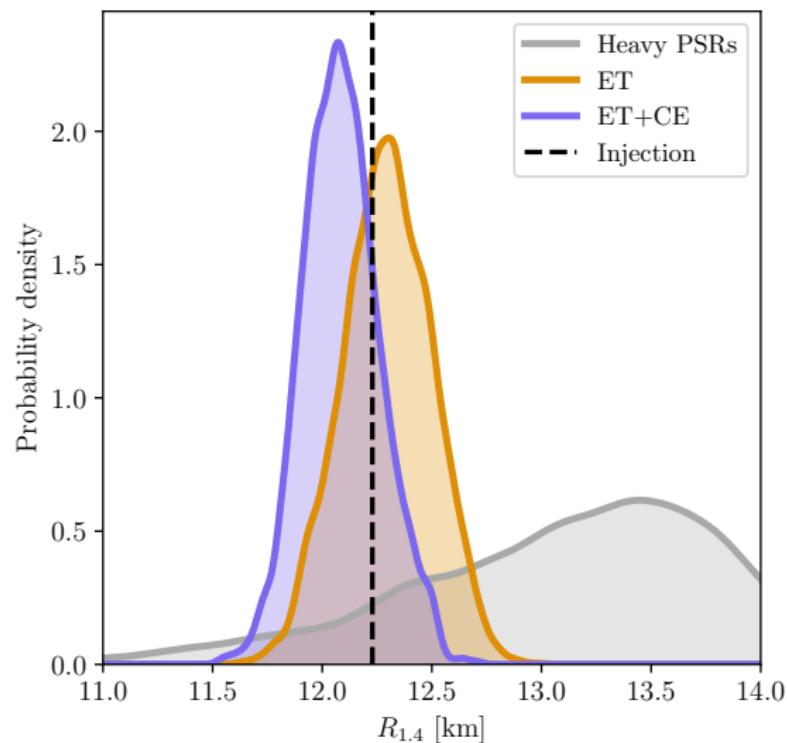
Projection: Einstein Telescope & Cosmic Explorer

- Simulate GW231109-like event with third-generation detectors
- ET: SNR ~ 134 , ET+CE network: SNR ~ 294
- Recovery improved



Projection: radius constraints

Recover radius with accuracy of 300-400 meters (ET+CE vs ET)



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Conclusions

- GW231109_235456: sub-threshold BNS candidate in O4a
- Low SNR (~ 9.7): poor EOS constraints
- Future detectors (ET, CE) will dramatically improve constraints
 - $R_{1.4}$ uncertainty: $\sim 300 - 400$ meters
- GPU-accelerated tools (JESTER):
 - Enable fast systematic studies
 - Can handle Einstein Telescope and Cosmic Explorer signals

Thank you for your attention!

References I

- [1] Hauke Koehn et al. "From existing and new nuclear and astrophysical constraints to stringent limits on the equation of state of neutron-rich dense matter". In: (Feb. 2024). arXiv: [2402.04172 \[astro-ph.HE\]](https://arxiv.org/abs/2402.04172).
- [2] B. P. Abbott et al. "GW170817: Observation of Gravitational Waves from a Binary Neutron Star Inspiral". In: *Phys. Rev. Lett.* 119.16 (2017), p. 161101. DOI: [10.1103/PhysRevLett.119.161101](https://doi.org/10.1103/PhysRevLett.119.161101). arXiv: [1710.05832 \[gr-qc\]](https://arxiv.org/abs/1710.05832).
- [3] B. P. Abbott et al. "GW190425: Observation of a Compact Binary Coalescence with Total Mass $\sim 3.4M_{\odot}$ ". In: *Astrophys. J. Lett.* 892.1 (2020), p. L3. DOI: [10.3847/2041-8213/ab75f5](https://doi.org/10.3847/2041-8213/ab75f5). arXiv: [2001.01761 \[astro-ph.HE\]](https://arxiv.org/abs/2001.01761).
- [4] A. G. Abac et al. "GWTC-4.0: Updating the Gravitational-Wave Transient Catalog with Observations from the First Part of the Fourth LIGO-Virgo-KAGRA Observing Run". In: (Aug. 2025). arXiv: [2508.18082 \[gr-qc\]](https://arxiv.org/abs/2508.18082).
- [5] Wanting Niu et al. "GW231109_235456: A Sub-threshold Binary Neutron Star Merger in the LIGO-Virgo-KAGRA O4a Observing Run?" In: (Sept. 2025). arXiv: [2509.09741 \[astro-ph.HE\]](https://arxiv.org/abs/2509.09741).
- [6] A. G. Abac et al. "Observation of Gravitational Waves from the Coalescence of a 2.5–4.5 M_{\odot} Compact Object and a Neutron Star". In: *Astrophys. J. Lett.* 970.2 (2024), p. L34. DOI: [10.3847/2041-8213/ad5beb](https://doi.org/10.3847/2041-8213/ad5beb). arXiv: [2404.04248 \[astro-ph.HE\]](https://arxiv.org/abs/2404.04248).

References II

- [7] Thibeau Wouters et al. “Leveraging differentiable programming in the inverse problem of neutron stars”. In: (Apr. 2025). arXiv: [2504.15893 \[astro-ph.HE\]](https://arxiv.org/abs/2504.15893).

Posterior distributions for ET/ET+CE injections

