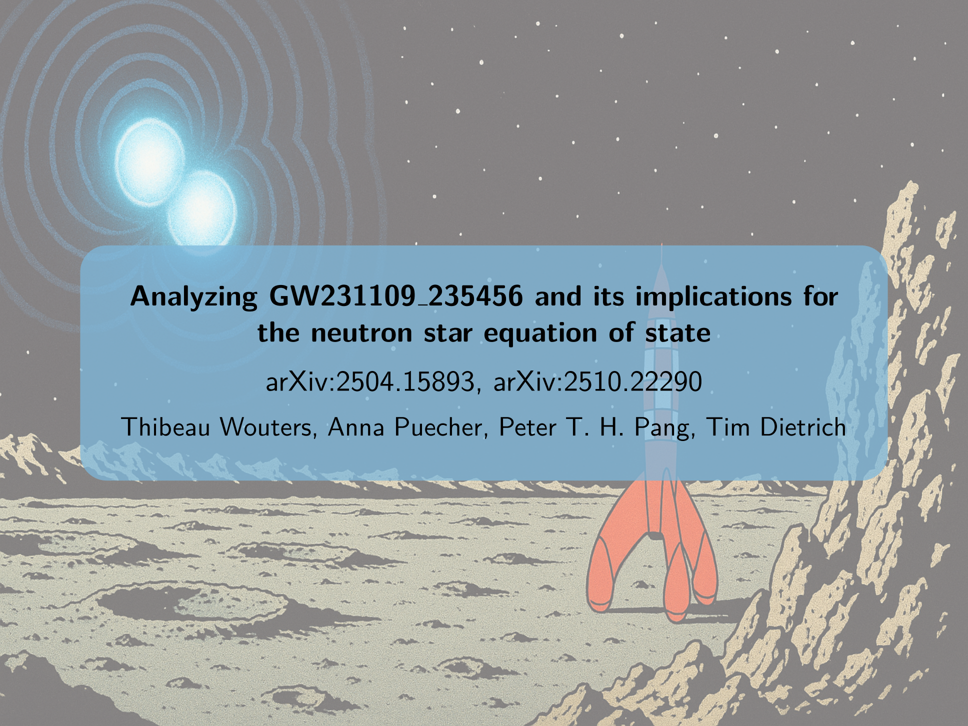

Analyzing GW231109_235456 and its implications for the neutron star equation of state

arXiv:2504.15893, arXiv:2510.22290

Thibeau Wouters, Anna Puecher, Peter T. H. Pang, Tim Dietrich

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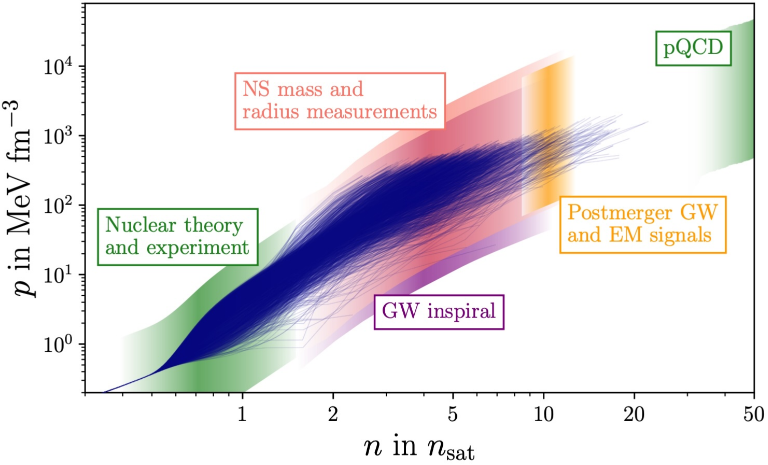
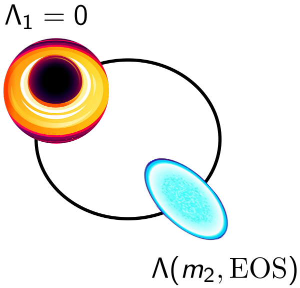
Neutron stars and the equation of state

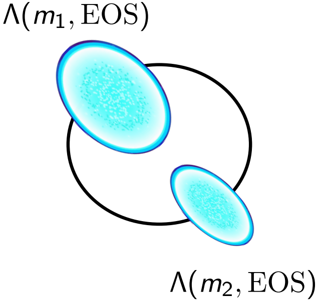
Neutron stars probe the high-density part of the equation of state (EOS) of dense nuclear matter [1]



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)





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

- GWTC-4.0 released recently [4]:
  - Over 200 gravitational wave detections in total

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- However: sub-threshold candidate **GW231109_235456** identified [5]
  - SNR $\sim$ 9.7 (distance: $\sim$ 165 Mpc)
  - Fainter, but mass closer to GW170817 than GW190425

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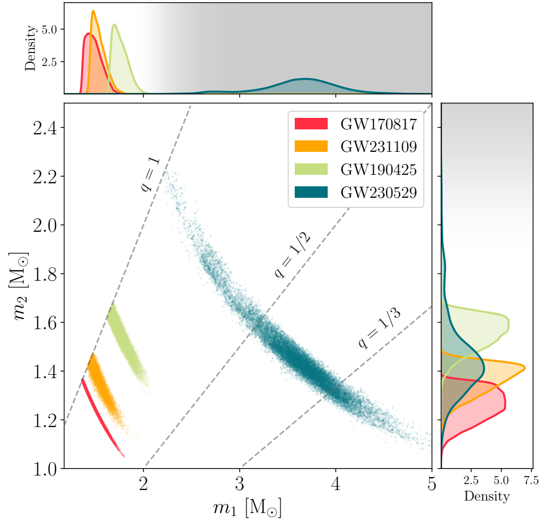
Can we still learn something about the EOS?

GW231109: component masses

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



This work

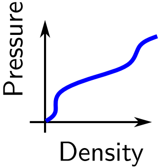
We analyze GW231109_235456 and investigate:

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

Contents

Equation of state inference

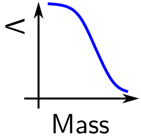
- To predict neutron star properties, we solve the TOV equations: ordinary differential equations (ODEs)



Solve TOV equations

$$\frac{\mathrm{d}p}{\mathrm{d}r} = -\frac{\varepsilon(r)m(r)}{r^2}\frac{\left[1+\frac{p(r)}{\varepsilon(r)}\right]\left[1+\frac{4\pi r^3 p(r)}{m(r)}\right]}{\left[1-\frac{2m(r)}{r}\right]}$$

$$\frac{\mathrm{d}m}{\mathrm{d}r} = 4\pi r^2 \varepsilon(r)\,,$$



Equation of state inference

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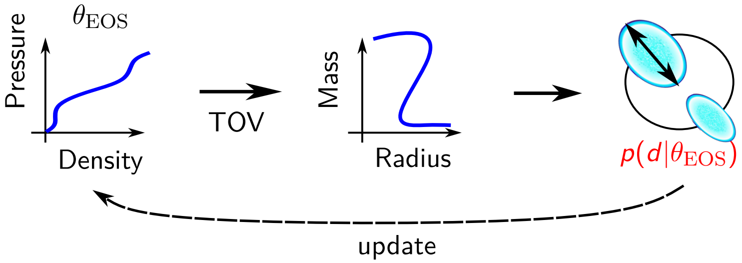
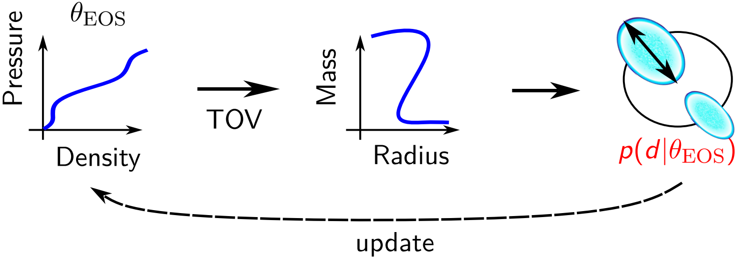
- Done while sampling parametrization for the EOS: costly likelihood



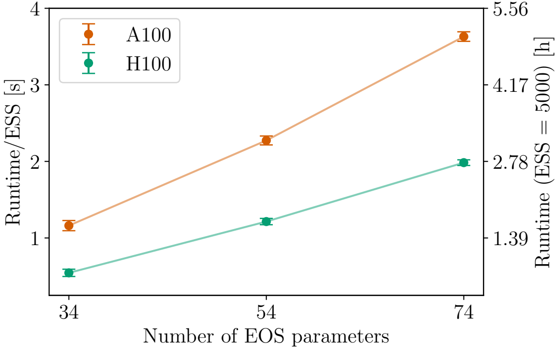
Equation of state inference

- 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 $\sim$1 hour on GPU (vs days on CPU)
- Enables systematic studies in EOS inference



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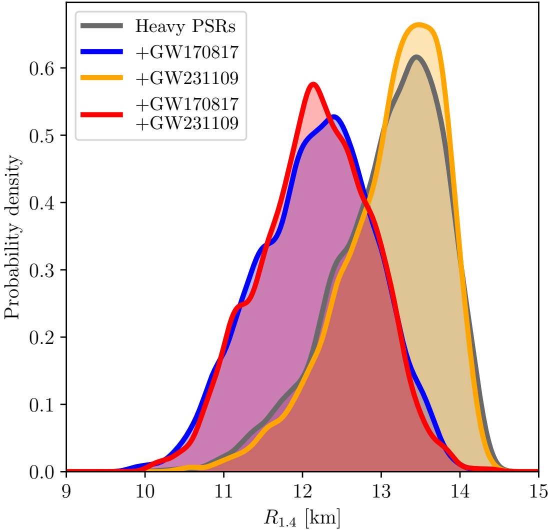
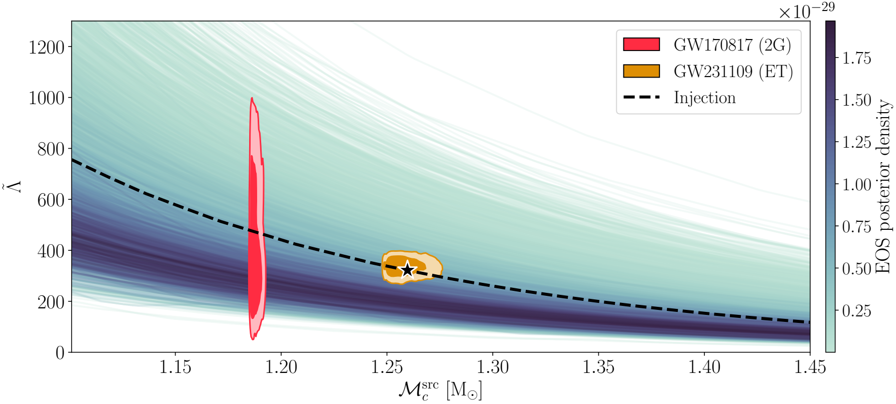
EOS constraints from GW231109

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



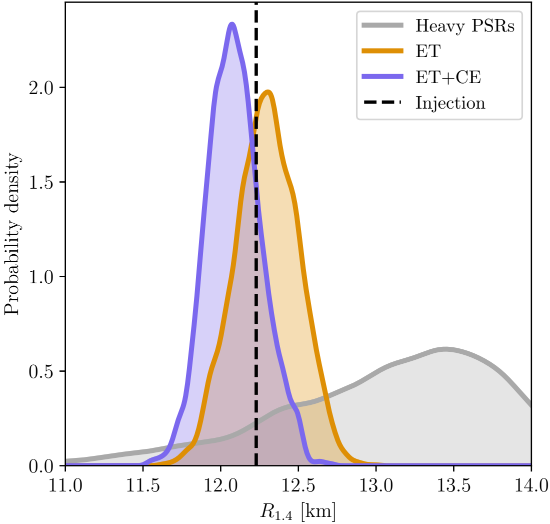
Projection: Einstein Telescope & Cosmic Explorer

- Simulate GW231109-like event with third-generation detectors
- ET: SNR $\sim$ 134, ET+CE network: SNR $\sim$ 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].

[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. arXiv: 1710.05832 [gr-qc].

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[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].

[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. arXiv: 2404.04248 [astro-ph.HE].

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[7] Thibeau Wouters et al. "Leveraging differentiable programming in the inverse problem of neutron stars". In: (Apr. 2025). arXiv: 2504.15893 [astro-ph.HE].

Posterior distributions for ET/ET+CE injections