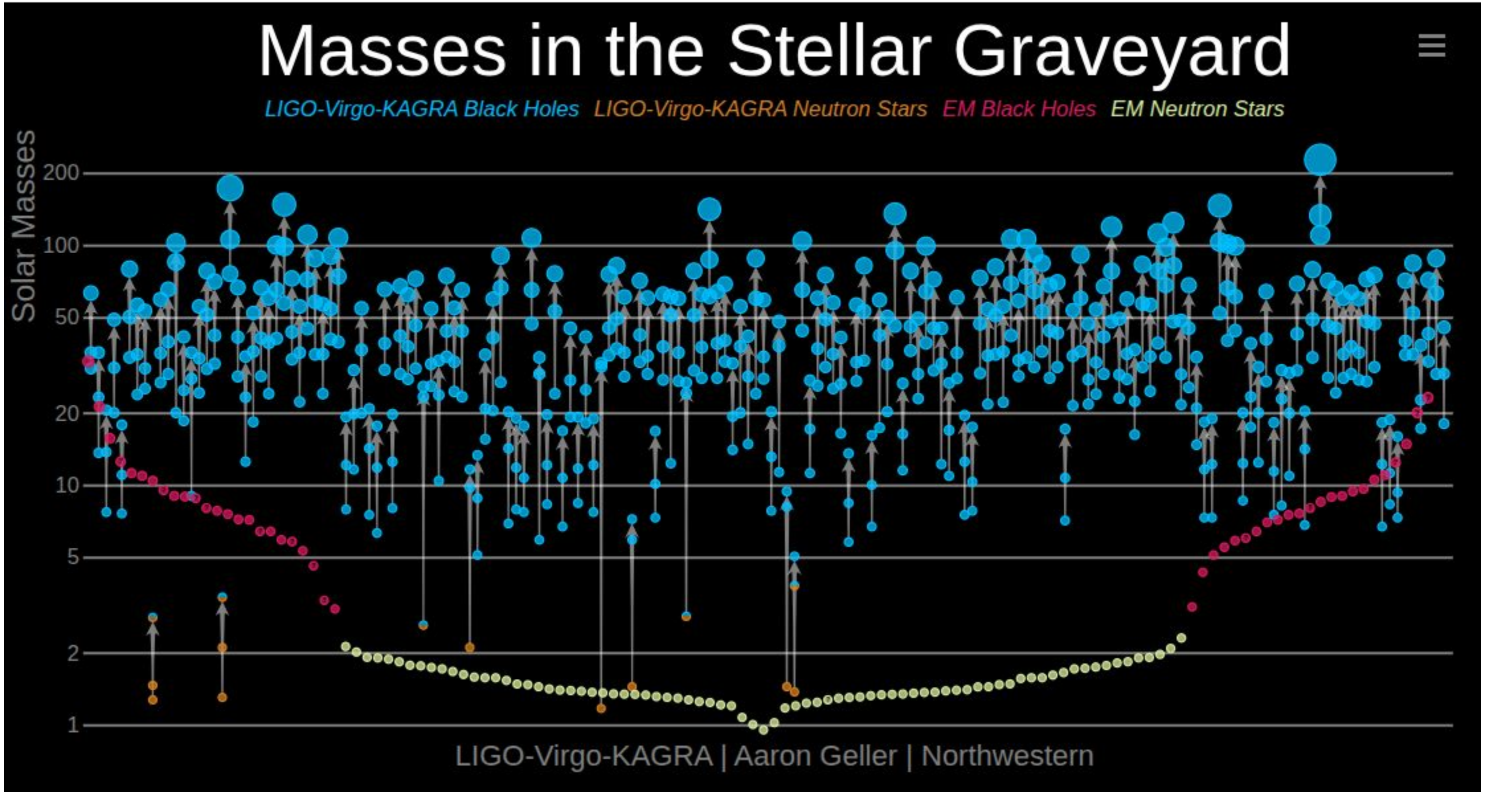
Exploring dense matter physics with Gravitational Waves

TeV Particle Astrophysics, 3rd November 2025, Valencia

Lami Suleiman
Deutsches Elektronen-Synchrotron

Multi-messenger astronomy observations of Neutron Stars (NSs)



Observations from the Gravitational Wave Transient catalogue GWTC-4 catalogue

A lot of Black Holes and just a few **Neutron Stars** (NS).

GWTC-3: Compact Binary Coalescences Observed by LIGO and Virgo During the Second Part of the Third Observing Run

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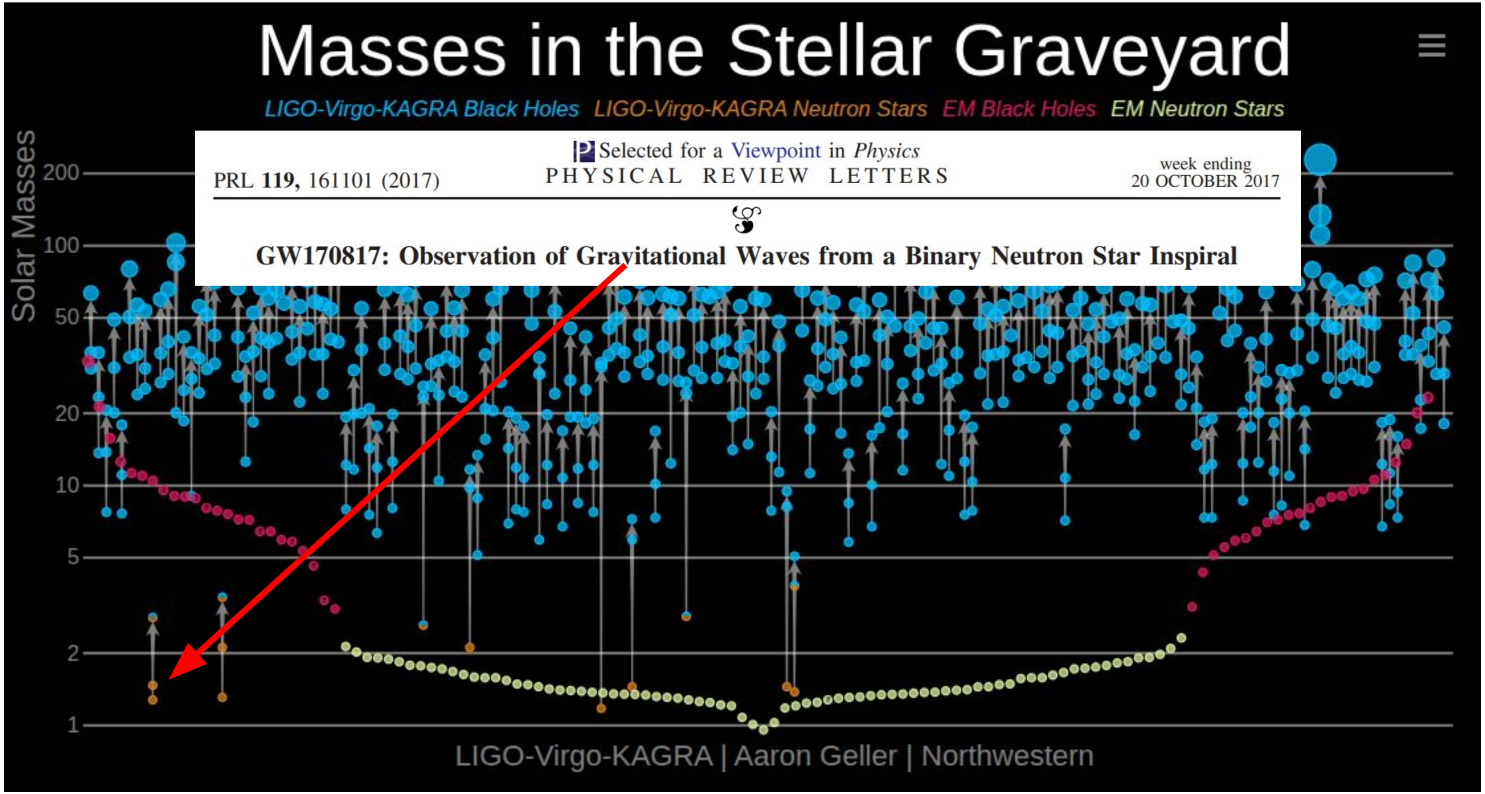

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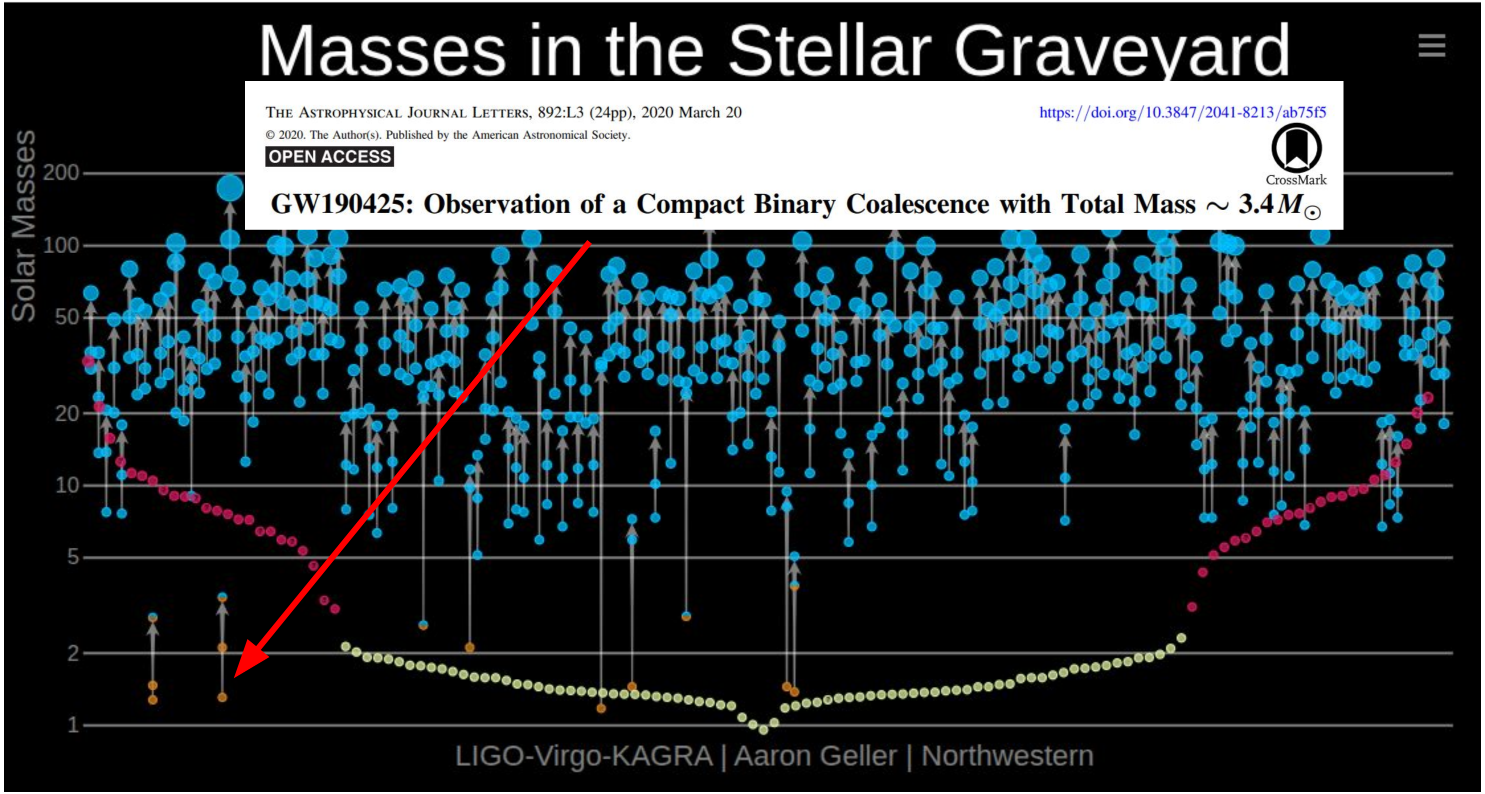

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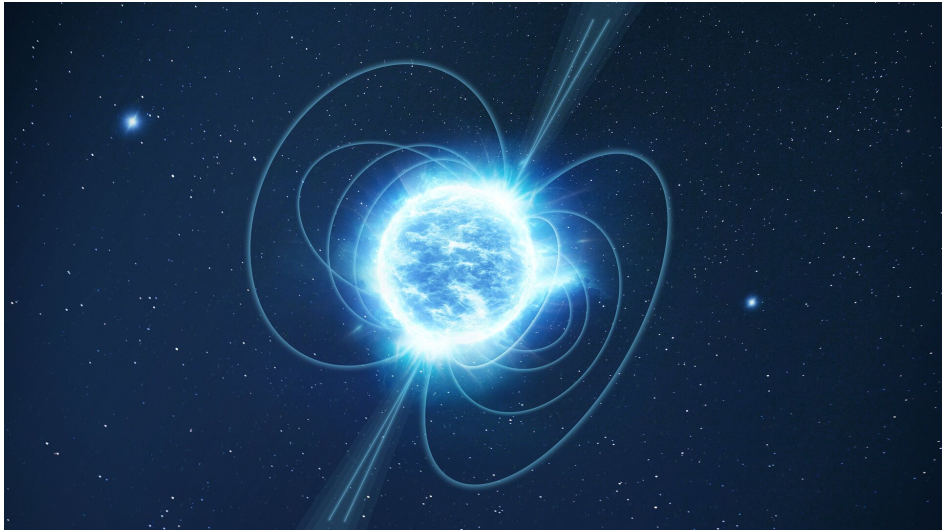
Neutron Stars as probes for Dense Matter Physics

Limited understanding of **strong interaction**

- Non-perturbative nature of strong interaction
- **Experimental data** is limited by thermodynamic conditions

Dense matter properties are poorly know.
Thankfully, we have **Neutron Stars** (NSs)!



Credit ESA website

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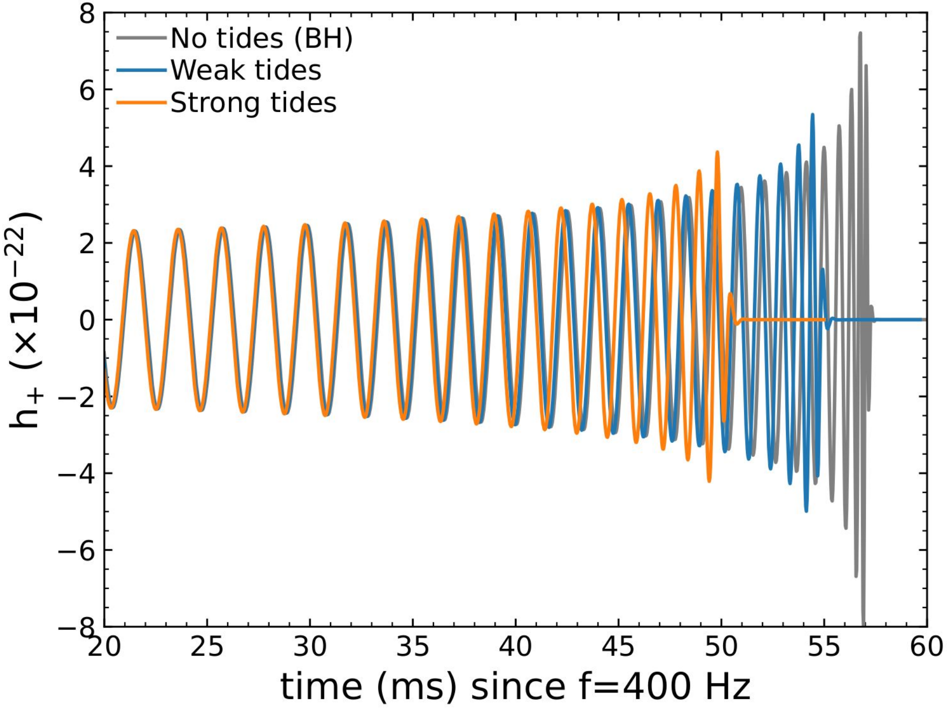
Inspiral and late inspiral information



Simulations with PyCBC: https://doi.org/10.5281/zenodo.10473621

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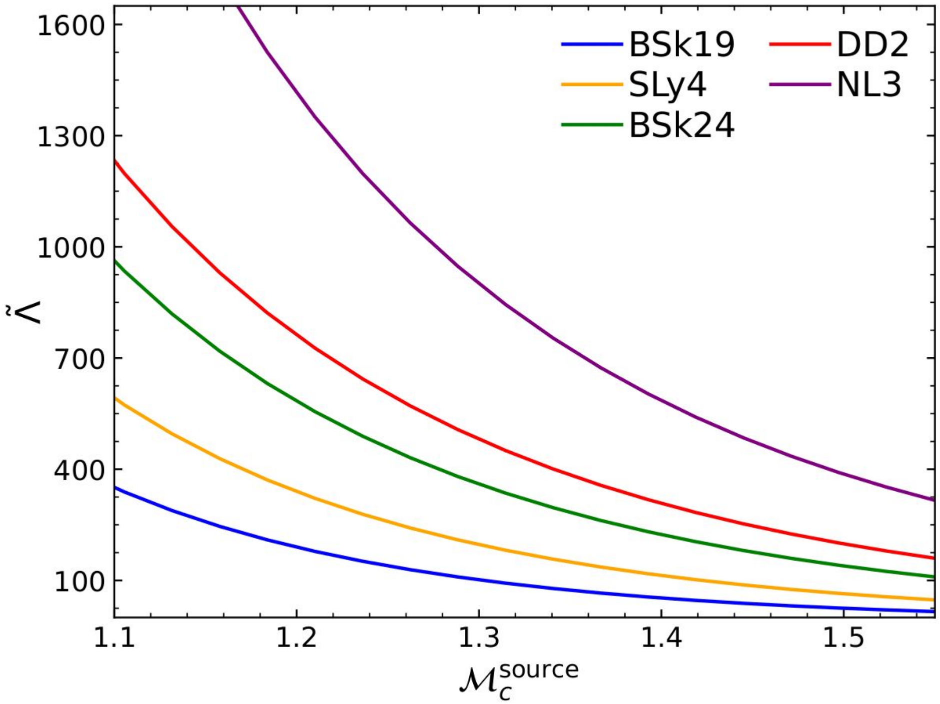

Figure for MANITOU book

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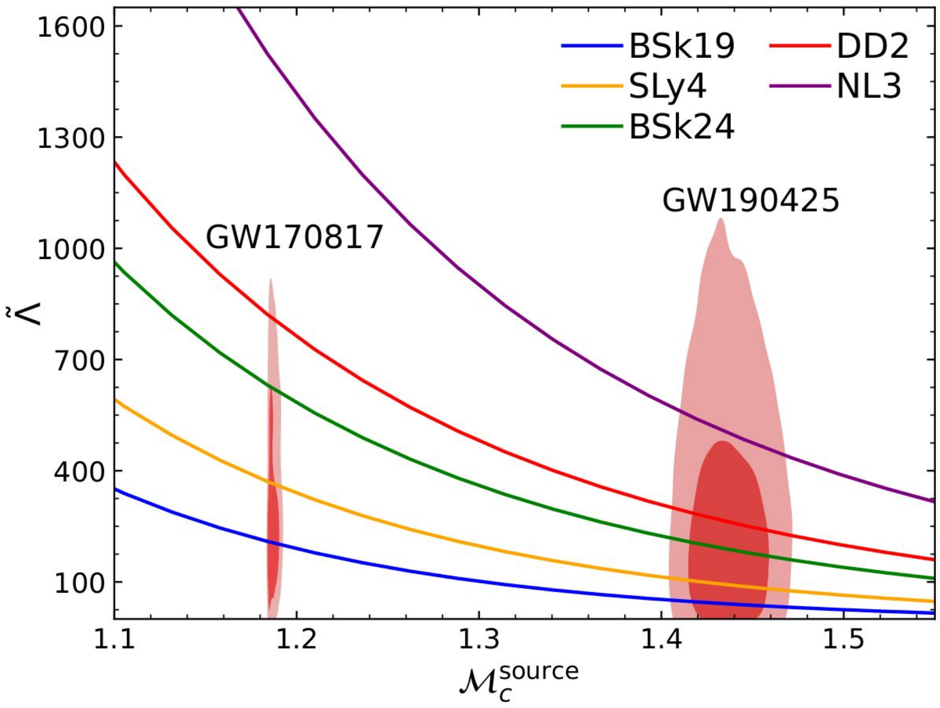
Comparing modeling and observations, we can probe dense matter Physics.



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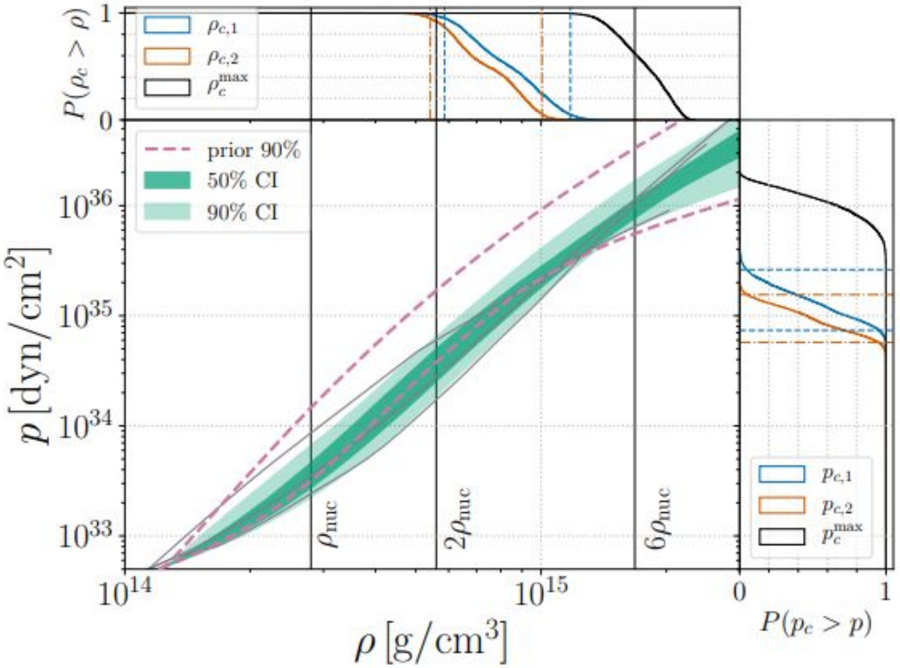
Equation of State inference from GW detections

Instead of testing EoS by EoS, we use **Bayesian approach for inference** that relies on priors of EoSs. Astrophysicists like large and agnostic priors.

➔ **GW170817** EoS inference (2018): spectral representation prior with fixed crust



Abbott et al. 2018 Phys. Rev. Lett. 121, 161101

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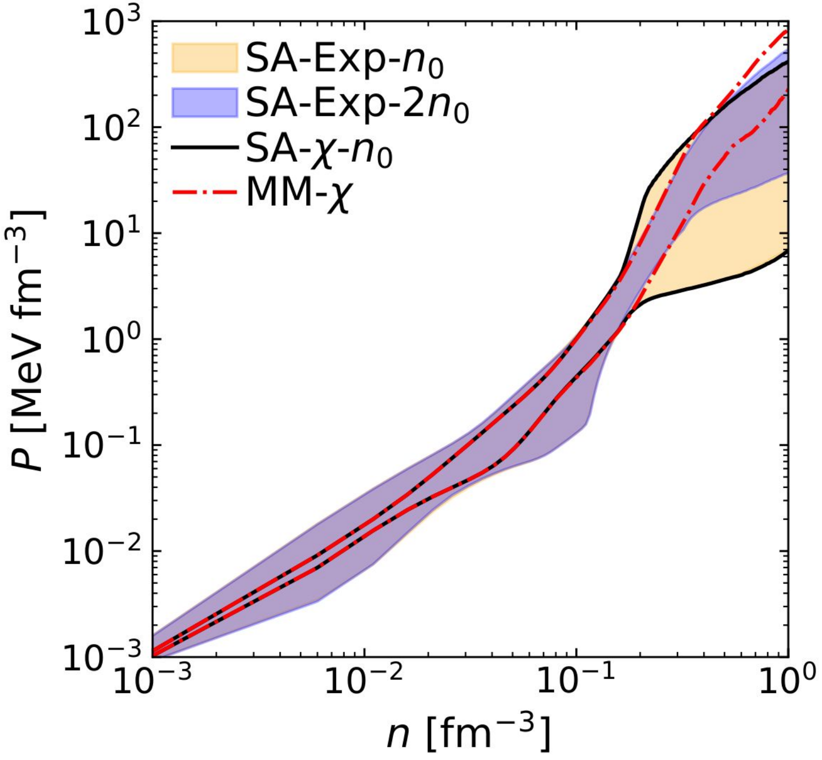
  - ◆ Low density information from theory and experiment
  - ◆ **Semi-agnostic priors**: low density EoS prior **linked to nuclear physics** quantities
  - ◆ **Crust Unified Tool for Eos Reconstruction (CUTER)** Davis et al. 2024 (A&A, 687, A44)



Suleiman et al. 2025 in prep.

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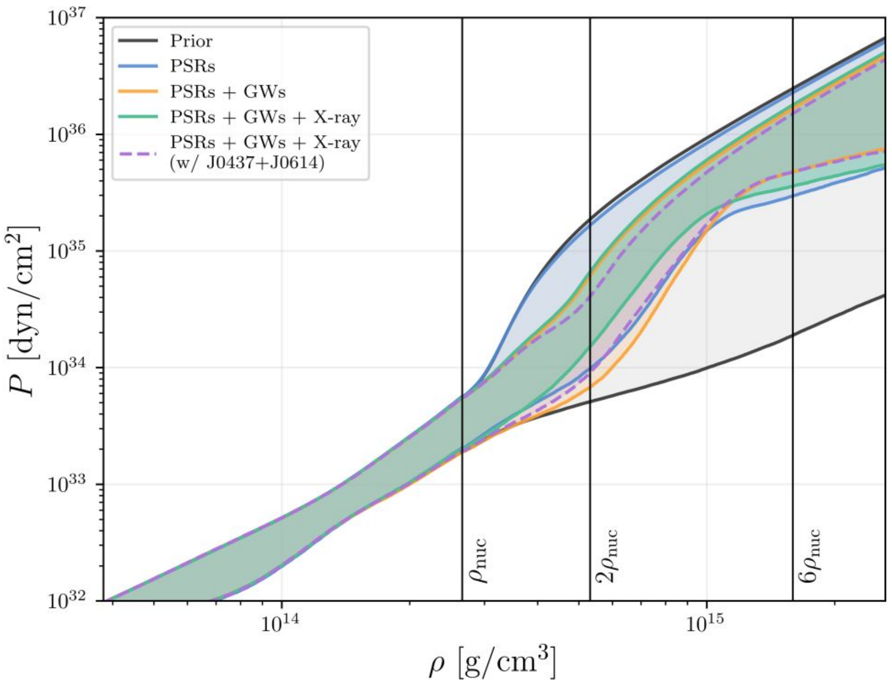
  - ◆ **Crust Unified Tool for Eos Reconstruction (CUTER)** Davis et al. 2024 (A&A, 687, A44)
- ➔ GW data paired with other **astrophysical data**:
  - ◆ Pulsar radio timing
  - ◆ X-ray data



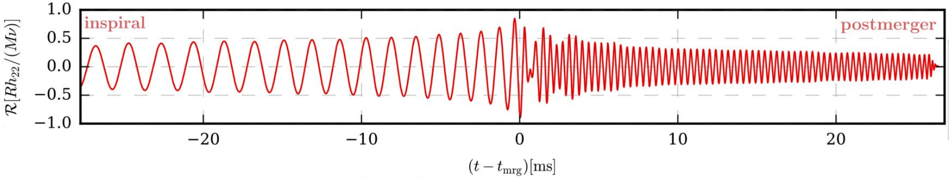
Ng *et al* 2025 *Class. Quantum Grav.* 42 205008

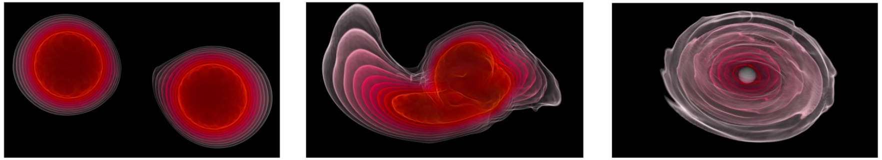
Electromagnetic counterparts of NS involved mergers

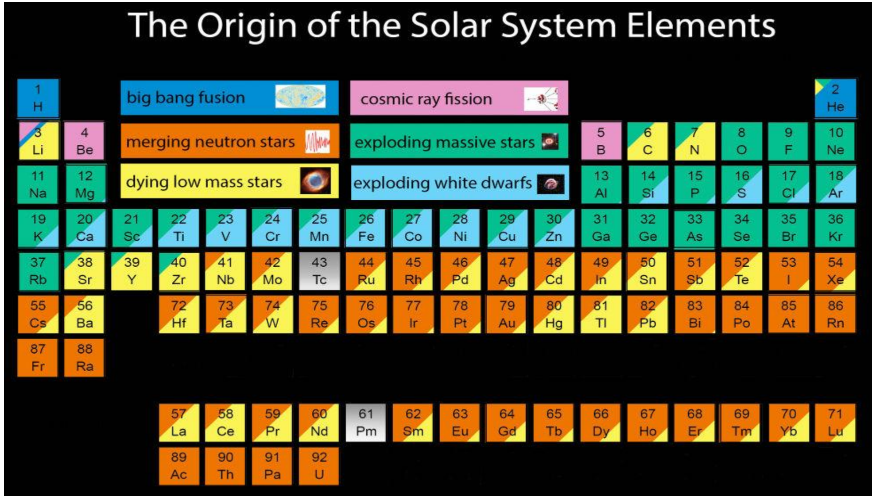
At and after the merger:

- Remnant baryonic matter: hot+dense matter
- Important reactions: **r-processes**
- Source of **heavy element production** in the Universe
- Signature of radioactive decays of heavy nuclei: **Kilonova**

Dietrich,Hinderer & Samajdar, Gen Relativ Gravit 53, 27 (2021)







Credits: J. Johnson ESA/NASA/AASNova

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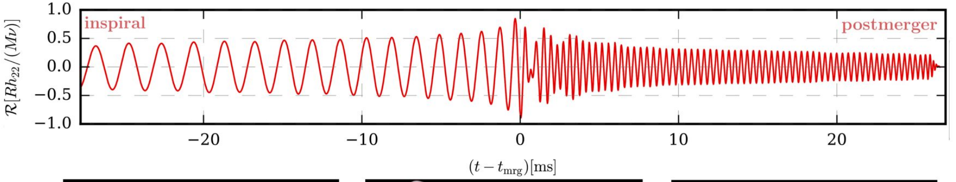
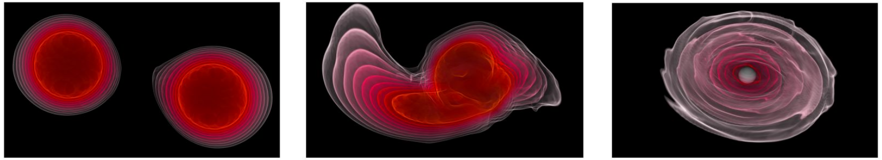
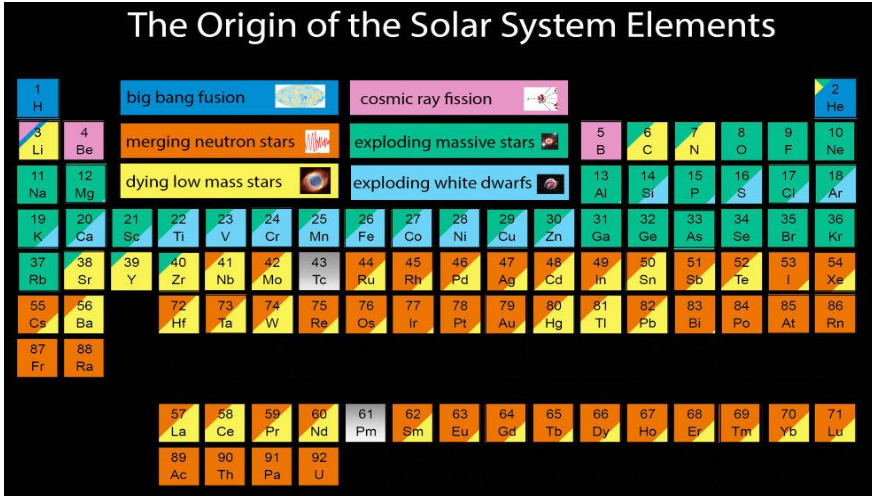
Dense matter physics beyond the inspiral:

- **GW inspiral** information is complemented by **electromagnetic** counterparts of NS involved mergers
- GW170817: detected counterpart in various wavelength of the electro spectrum
- GW230529 from O4: Abac et al 2024 ApJL 970 L34
  - No electromagnetic counterpart detected
  - From object’s masses, estimated electro brightness.
- Future detectors: post merger GW info

Dietrich,Hinderer & Samajdar, Gen Relativ Gravit 53, 27 (2021)







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Conclusion

Exploring dense matter physics with Gravitational Waves

Neutron stars are a laboratory for dense matter physics

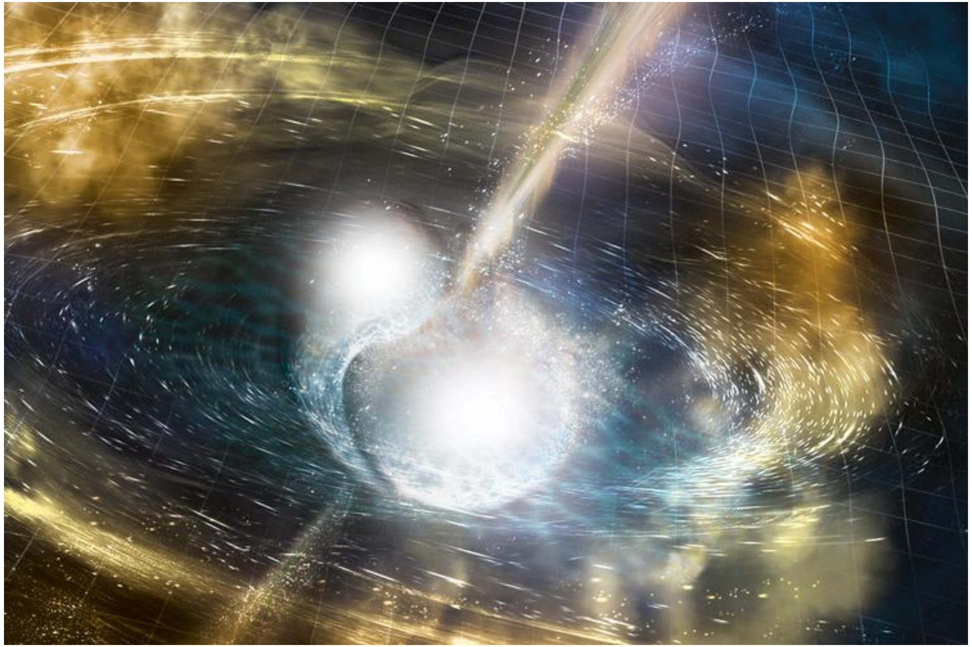
Limited theoretical and experimental information in dense/low-temperature regime

Neutron star involved mergers emit gravitational waves

Tidal deformability extracted from late inspiral constrains the equation of state

Post-merger electromagnetic counterparts inform on heavy element origins

Thank you for your attention.



Aurore Simonnet for sonoma state university