Neutron star equations of state

PAX-CE Meeting, July 2025

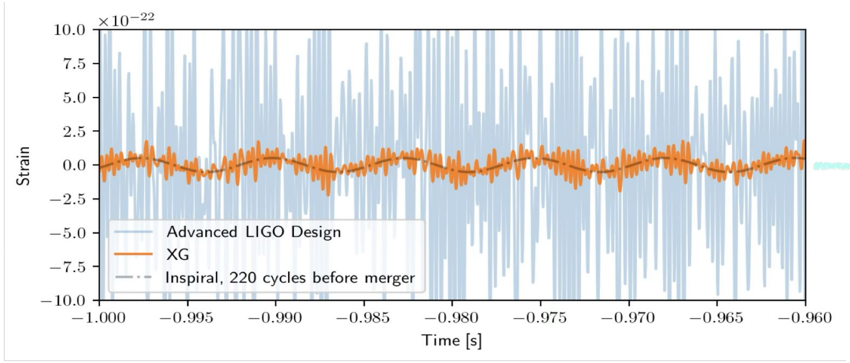
Panel: Jamie Bamber, Jaki Noronha-Hostler, Alexander Haber, Jocelyn Read

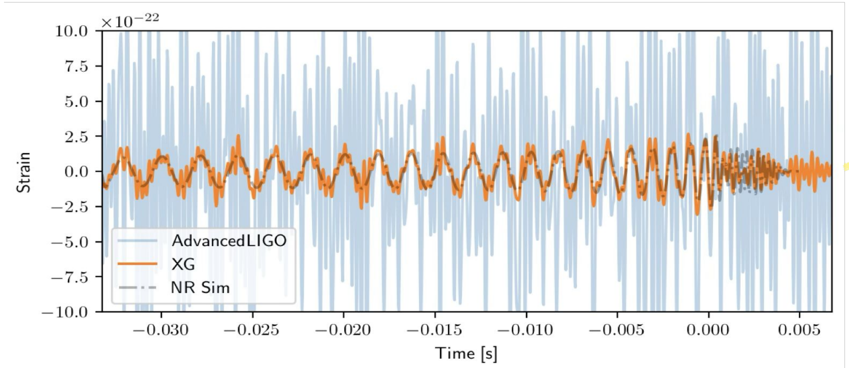
The Panel

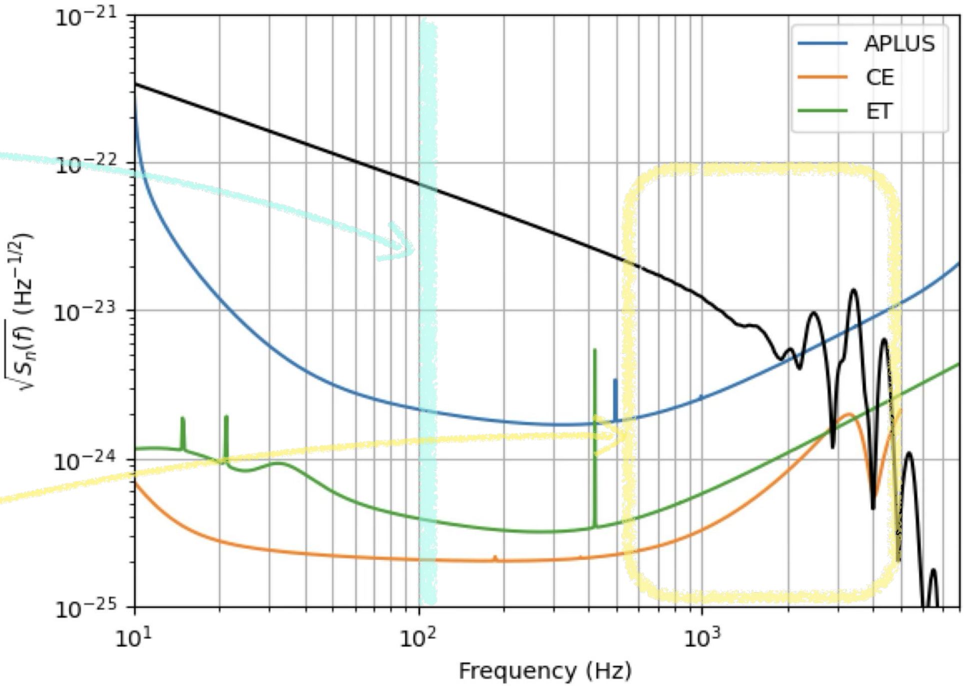
- Jocelyn Read (CSU Fullerton)
- Jacquelyn Noronha-Hostler (UIUC)
- Jamie Bamber (UIUC)
- Alexander Haber (U. of Southampton)




GW170817 as a CE observatory could see it





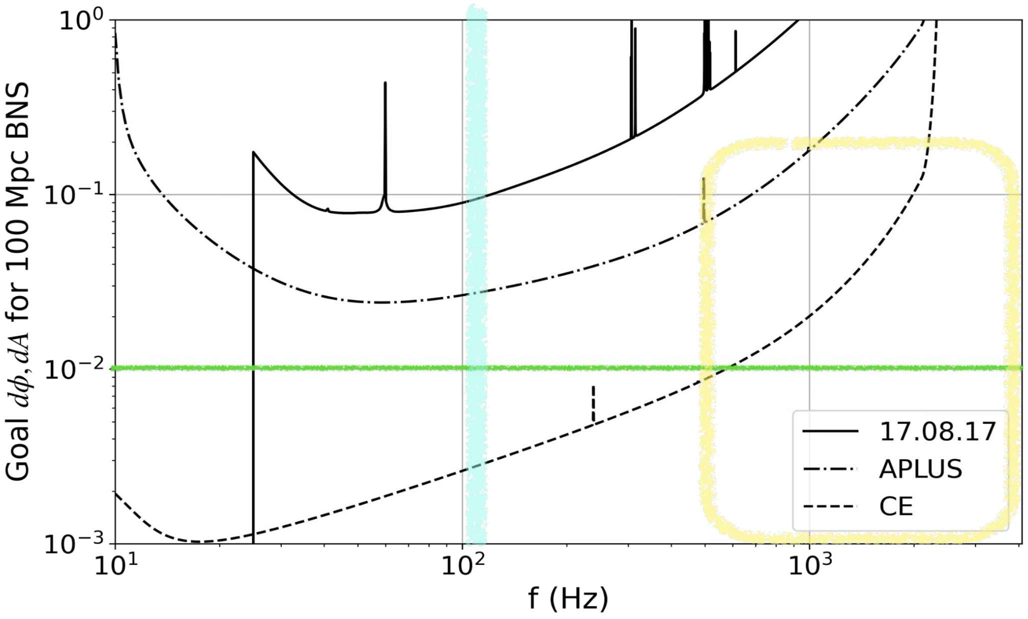


J. Read, A. Nitz (pycbc/lalsimulation + NR from CoRe database)

GW170817 as a CE observatory could see it

- High SNR signals lead to precision measurements from observed waveforms
- How best to:
  - Relax assumed relations
  - Break degeneracies
  - Marginalize over full-physics uncertainties
- Capability for inferring unmodeled corrections to “baseline” PE
  - (source model) GR + waveforms + known EOS effects
  - (calibration) interferometer response to spacetime
- *Interpretation* is the challenge
  - Degeneracies in waveform impact

$$h_{\mathrm{model}}(f) = h_{\mathrm{true}}(f)\big(1+\delta A(f)\big)\exp\big(i\delta\phi(f)\big)$$



Read 2023 Class. Quantum Grav. 40 135002
https://github.com/RyanSR71/waveform_uncertainty

Discussion Questions

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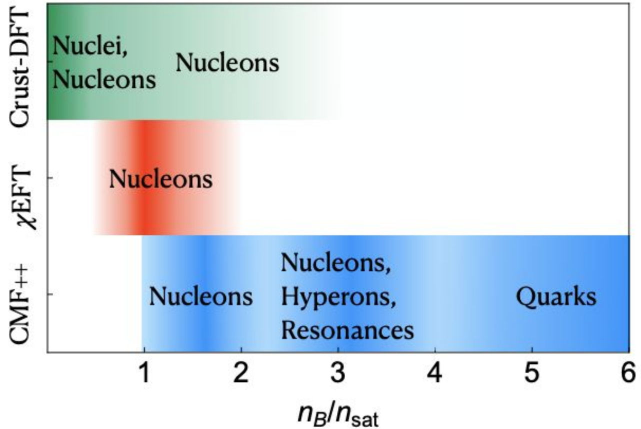
muses collaboration and open-source EOS

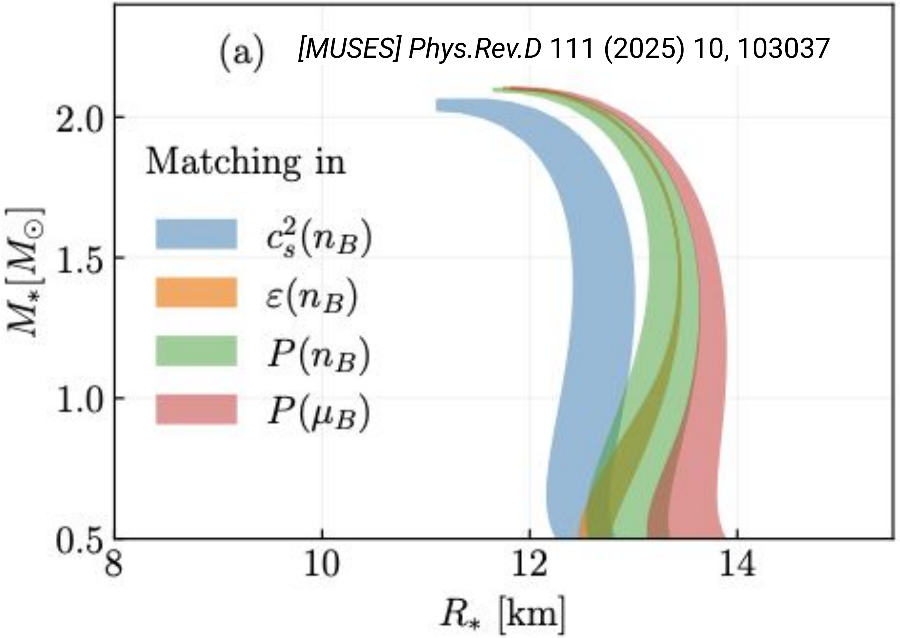
Beta-release for MUSES calculation: includes crust-to-core EOS.

User can freely vary parameters, obtain different M(R) or Λ(R)

Matches different EOS in regime of validity, using different thermodynamic quantities

More EOS (NJL)+ Finite temperature effects coming soon!





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muses collaboration and open-source EOS

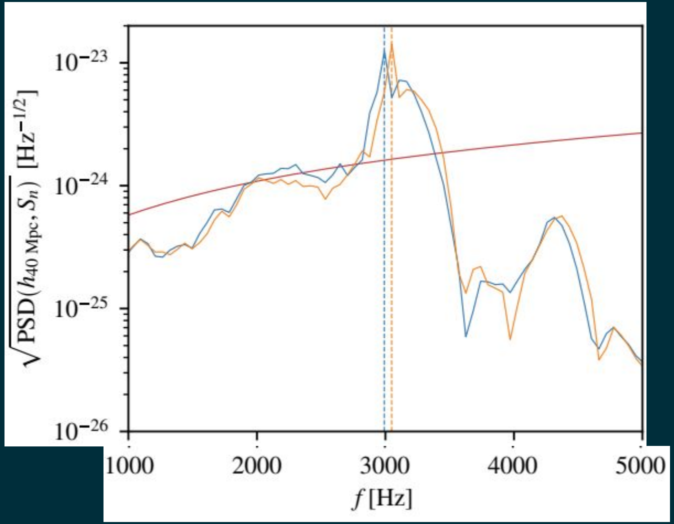
What do other communities want/miss on the EoS front?
Which formats, which features?

Post merger challenges

- Only one observable: f_2 - peak ?
- Quasi-universal relations “muddle” the physics
- Huge **degeneracies** in physics of f_2 - peak

“the 50-100 Hz rule” : thermal effects, out of equilibrium effects, EoS uncertainty, simulation resolution,...

- Smoking gun signals for different phases/particles/physical effects?



Hammond 2205.11377

How to lift post-merger degeneracies?

- higher order peaks: Astroseismology and mode resonances (g-modes, i-modes, p-modes, …)
- TOV mass - resolution problem?
- BH collapse time - viscosity, neutrinos,...
- EM-counterpart
- Kilonovae light curves Ricigliano et al., Mon.Not.Roy.Astron.Soc. 533
- long ringdown Ecker et al., Nature Commun. 16

Which of observables beyond tidal deformability do we have a chance of observing?

What other observables/signals could we use to constrain the EOS?

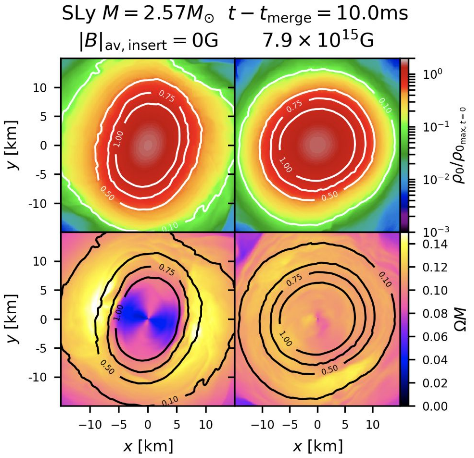
Neutron star EOS: NR simulations

The big issue: computational cost vs realism - what approximations can we get away with? What (micro)physics to prioritize? What outputs/physics do we need for EOS constraints?

- EOS: parametric (e.g. piecewise polytropes [Read+ ‘08], “M* model” [Raithel+ ‘21]) vs tabulated EOS P(ρ, T, Y_e) (artificial surface heating [Gittins+ ‘25]?).
- Need to model v. **small** scales (turbulence, super high res [Kiuchi+ ‘24] vs LES / subgrid methods [Palenzuela ‘22, Most ‘23]?) and **large** time/length scales (jet launching etc.)
- Need to model magnetic fields, neutrinos + other non-EOS physics accurately to avoid **degeneracies**

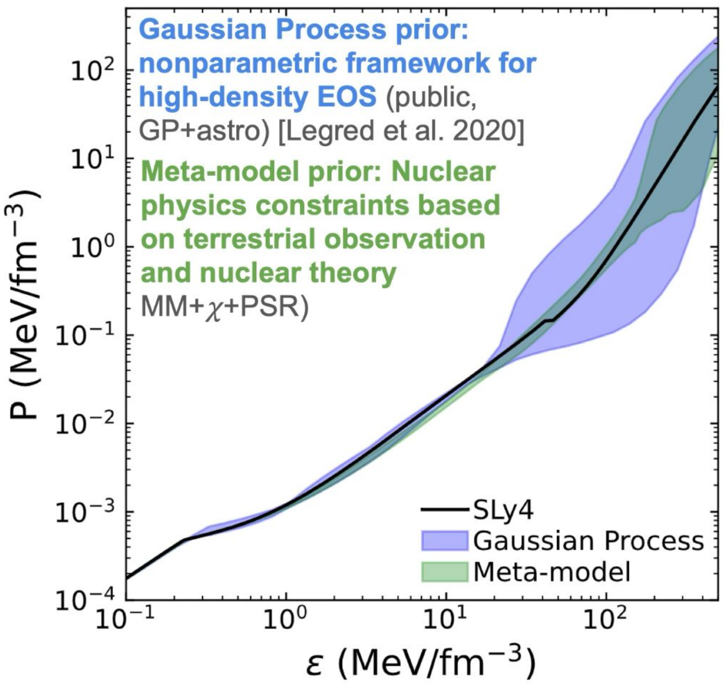
(micro)physics additions:

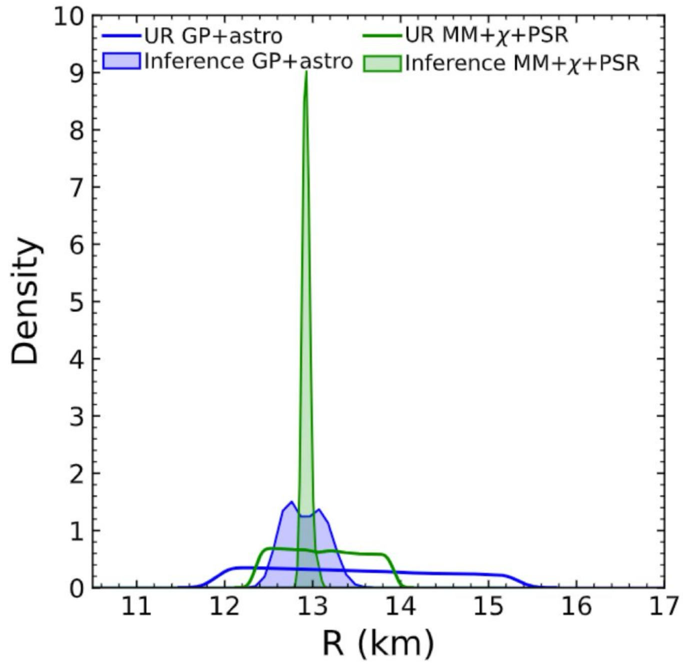
- Phase transitions [e.g. Bauswein+ ‘19, Ujevic ‘23]
- Dissipative and viscous hydro [e.g. Duez+ ‘04, Shibata+ ‘17, Chabanov & Rezzolla ‘25]
- More particles! muons, pions, trapped neutrinos [Gieg ‘24, Pajkos & Most, ‘24, Espino+ ‘24], neutrino flavor transformations [Qiu+ ‘25]
- Dark matter admixture [e.g. Giangrandi+ ‘25]
- strangeness + hyperons?
- (color-) superfluidity and superconductivity?
- **???**



Tsokaros et al. ‘25

Direct EOS inference
(Breaking assumed relations, incorporate nuclear science)





Suleiman & Read Phys. Rev. D 109, 103029 (2024)

How do we integrate GW with other astronomical observations that constrain EOS? (radio pulsars, NICER, kilonovae...)

Challenges at finite temperatures

$$p(T,\vec{\mu}) = p(T=0,\vec{\mu}) + \frac{1}{2}\left(\frac{ds}{dT}\right)_{\vec{\mu},T=0} T^2 + \frac{1}{6}\left(\frac{d^2 s}{dT^2}\right)_{\vec{\mu},T=0} T^3 \ldots$$

Microphysical

Advantages: Can capture wide range of phases, degrees of freedom. Can connect to lab experiments, provides populations. Thermodynamically consistent

Most et al, Phys.Rev.Lett. 122 (2019) 6, 061101

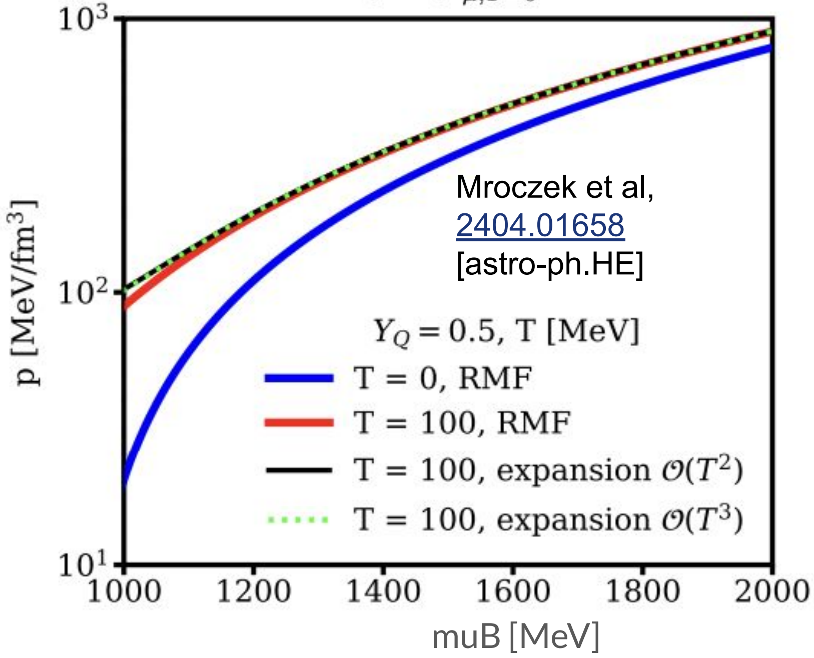
Disadvantages: Codes may be slow, need to match to crust, beholden to certain assumptions. Inversion problem

Finite T expansions

Advantages: Quick, easy, fewer input parameters, easier for inversion problem

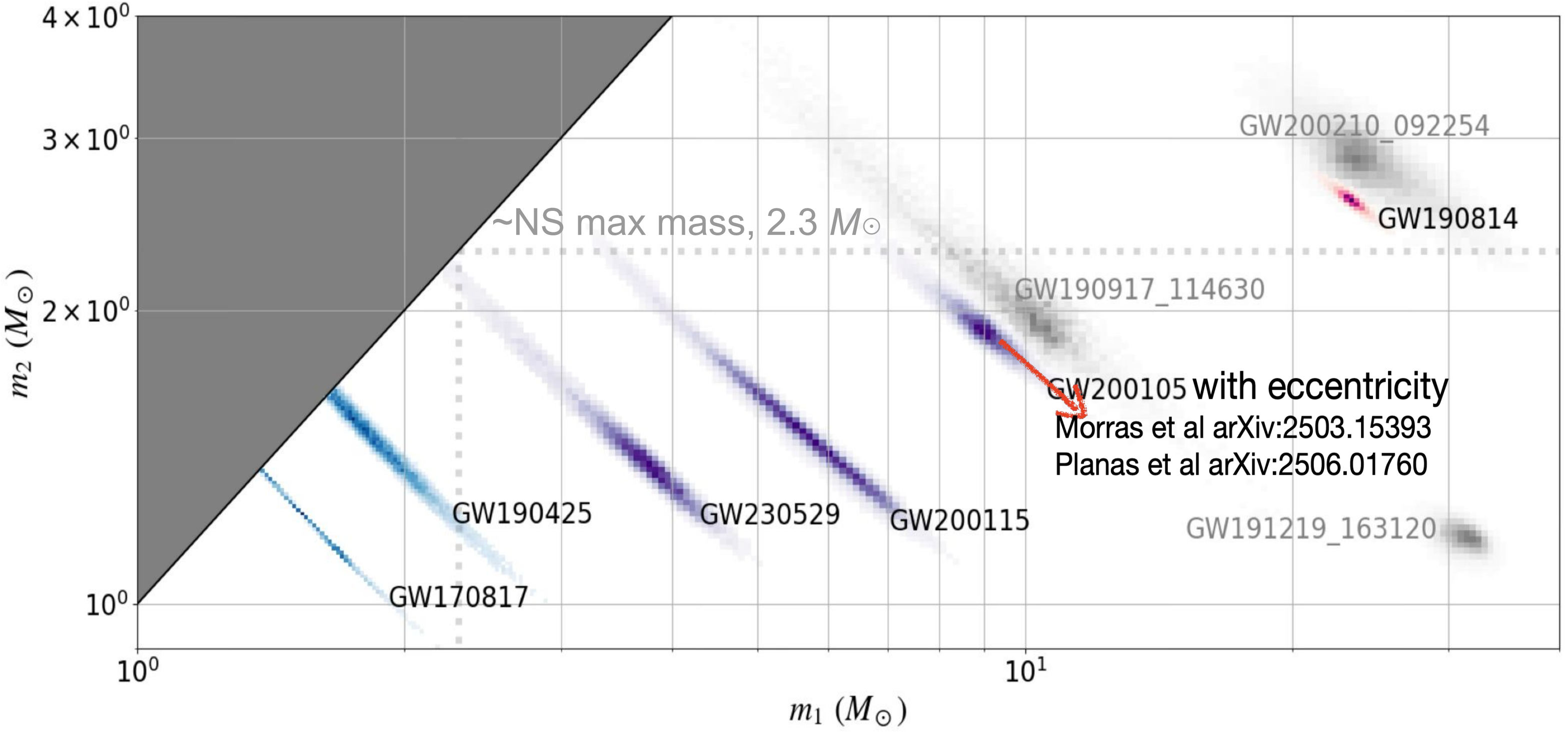
Disadvantages: Speed sacrifices accuracy, normally only for npe matter (no hyperons, no phase transitions, no quarks), might be thermodynamically inconsistent, doesn't connect to lab experiments

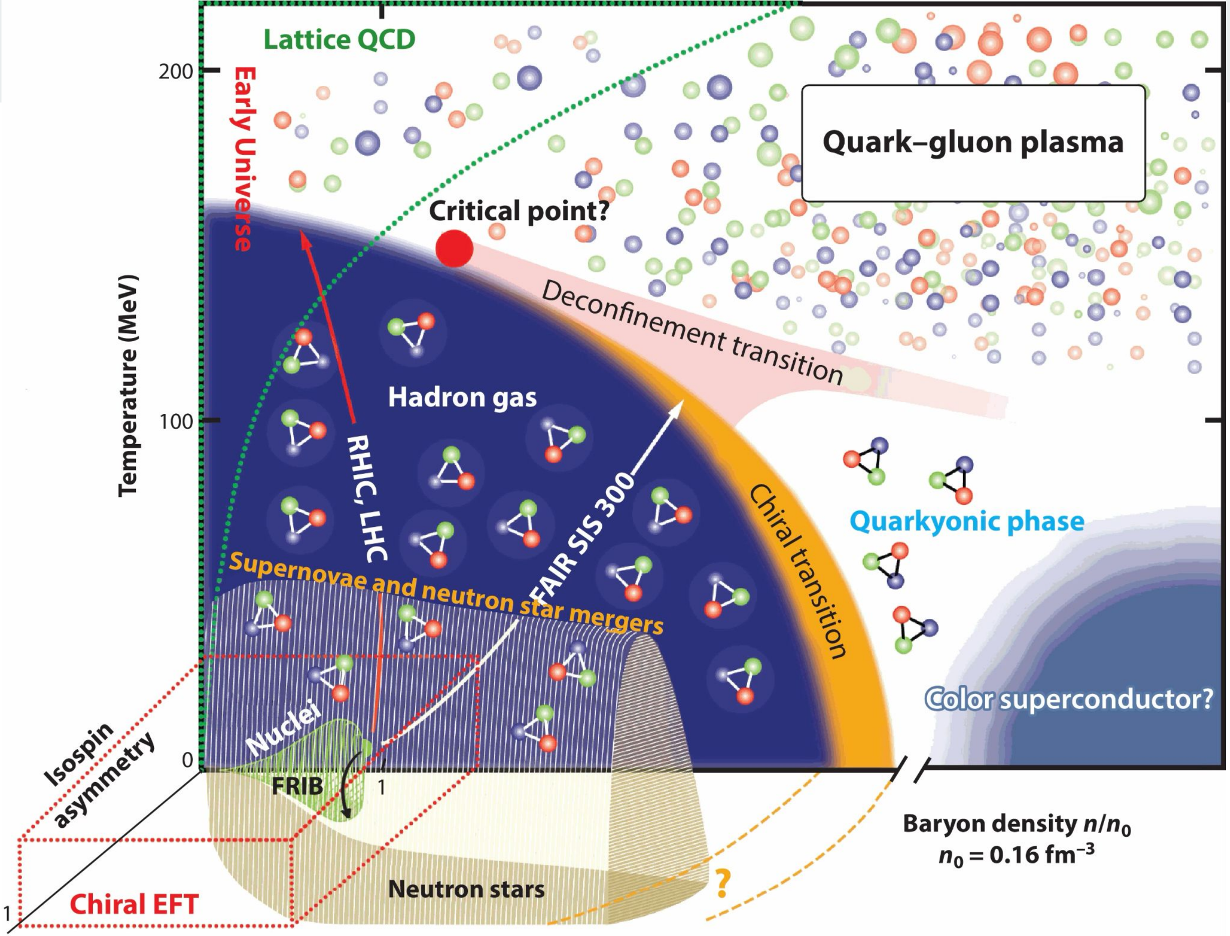
Kochankovski et al, Mon.Not.Roy.Astron.Soc. 528 (2024) 2, 2629-2642; Yang et al, 2504.18764 [nucl-th]



Slides on hand for reference during discussion

Low mass observations on GWOSC to date





Drischler C, et al. 2021
Annu. Rev. Nucl. Part. Sci. 71:403–32

ADDITIONAL QUESTIONS

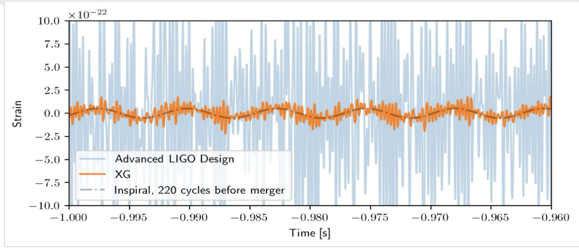
- **Where will simulations limit XG science impact? How do we target simulations to do best science?**
- **Where will XG fit in the broader landscape of nuclear theory and experiment in future decades? [phase diagram, technical challenges to integrate data]?**
- **What do the nuclear physics and observational (GW and non-GW) communities need / want from future GRMHD / numerical relativity codes & simulations?**

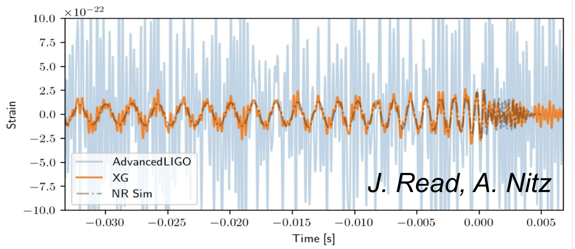
NS EOS Close-out summary slides

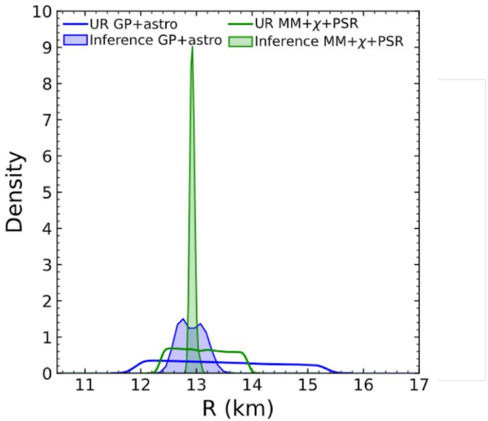
Panel: Jamie Bamber, Jaki Noronha-Hostler, Alexander Haber, Jocelyn Read

NSEOS: Outcome

- Inspiral can constrain the cold EoS well via tidal deformability
- Bayesian Inference that includes nuclear physics input better connects the EoS and radius
- Resonances or dynamics of late stages of the inspiral can teach us about particle composition and phase transitions
- Fascinating and unique physics from the post-merger
- Different fields have different needs for the EoS, collaborations like MUSES providing new framework
- Simulations are progressing and including more and more physics



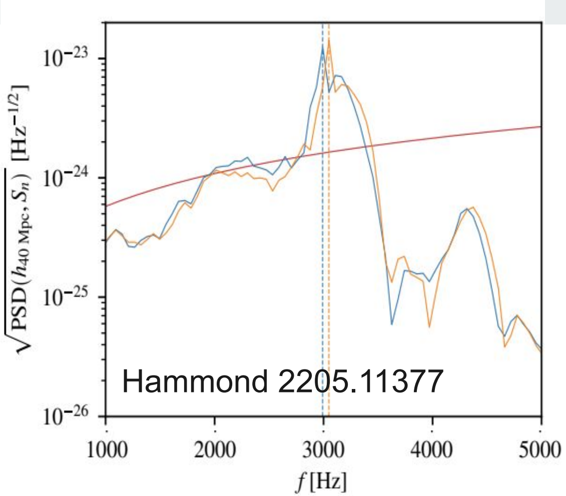


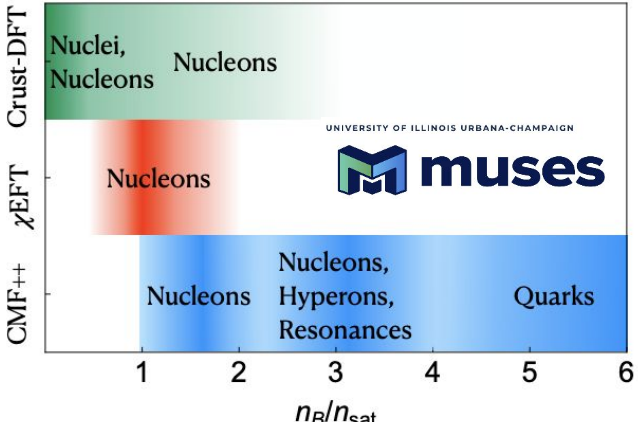


Suleiman & Read Phys. Rev. D 109, 103029 (20

NSEOS: Challenges

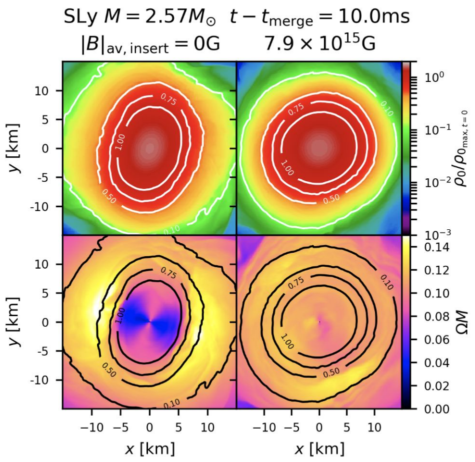
- Current waveforms do not include all the physics needed to constrain the EoS from the inspiral and the (post-)merger
- There is a lot of degeneracy in the physics of the main merger f-peak
- Simulations are not accurate enough at the moment to make good use of additional observables like the kilonova light curves
- Temperatures in simulations have large error bars due to shocks
- Matching of different microphysical EoS models between density regimes introduces additional uncertainty
- **Panel identified thermal effects as the key challenge for simulation-based XG science impact**





NSEOS: Lessons Learned

- Constraining the EoS is a multi-step process that includes phenomenological and microscopical models
- Going beyond inspiral, the easiest to observe quantities (kilonovae light curves e.g.) are the hardest to connect to the EoS
- Quasiuniversal relation breaking may be used to reveal exotic physics in late inspiral, post-merger
- Higher redshift signals could be stacked and help us “see” the postmerger
    - Important analysis challenge that needs all the inference (cosmology, pop models)
- There is hope that the numerical relativity challenges can be overcome by the time that XG detectors come online
    - Precision race between simulation and observation - winner not guaranteed



Tsokaros et al. ‘25