Uncertainty Quantification and the Equation of State of Hot and Dense Matter

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May 23, 2021

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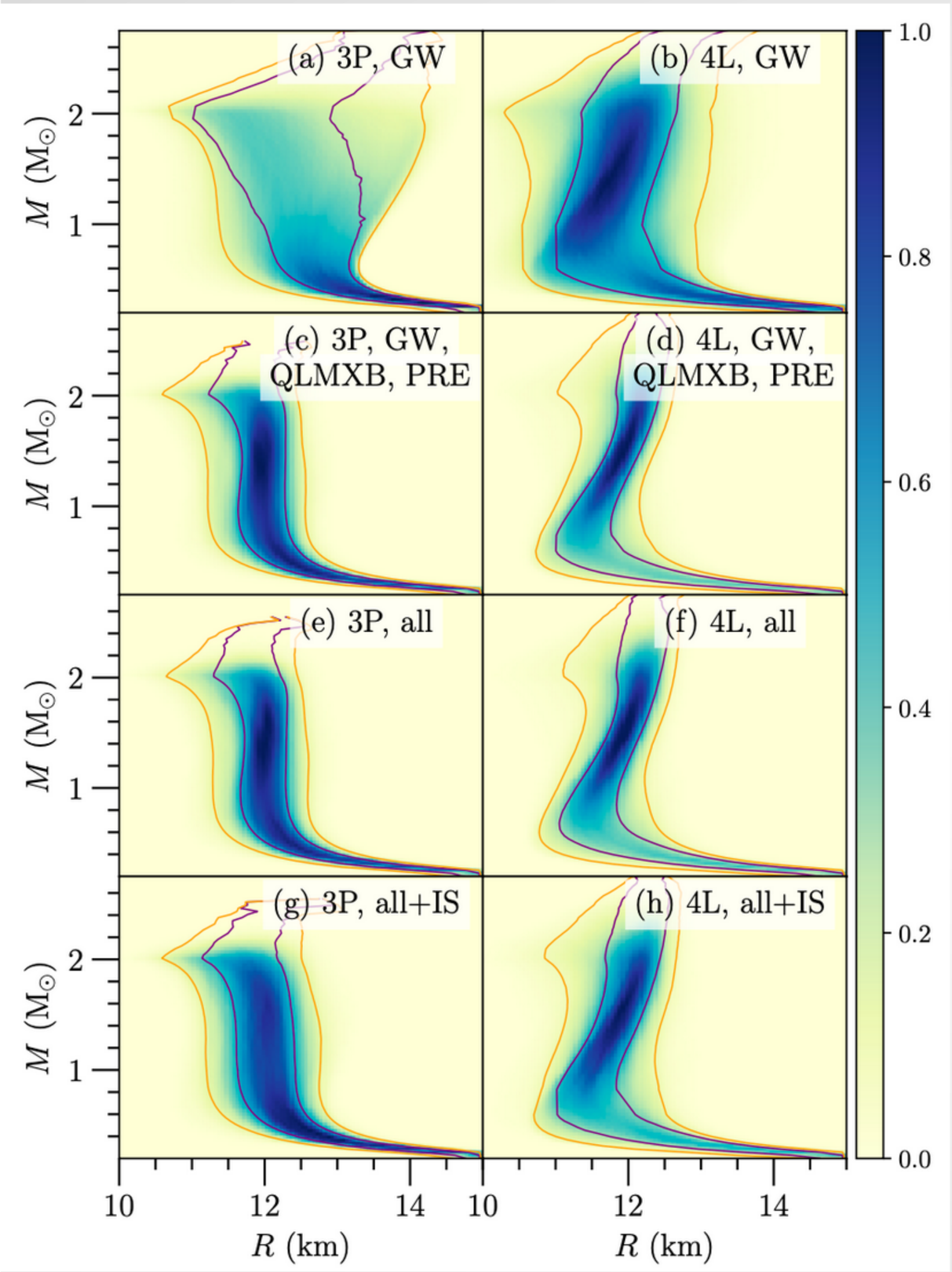
Outline

- Multimessenger inference
- New DSH EOS tables
- Open-source code
- Multimessenger inference with NS cooling
- Generative models
- NP3M
- Questions
- Summary

EOS post-GW 170817

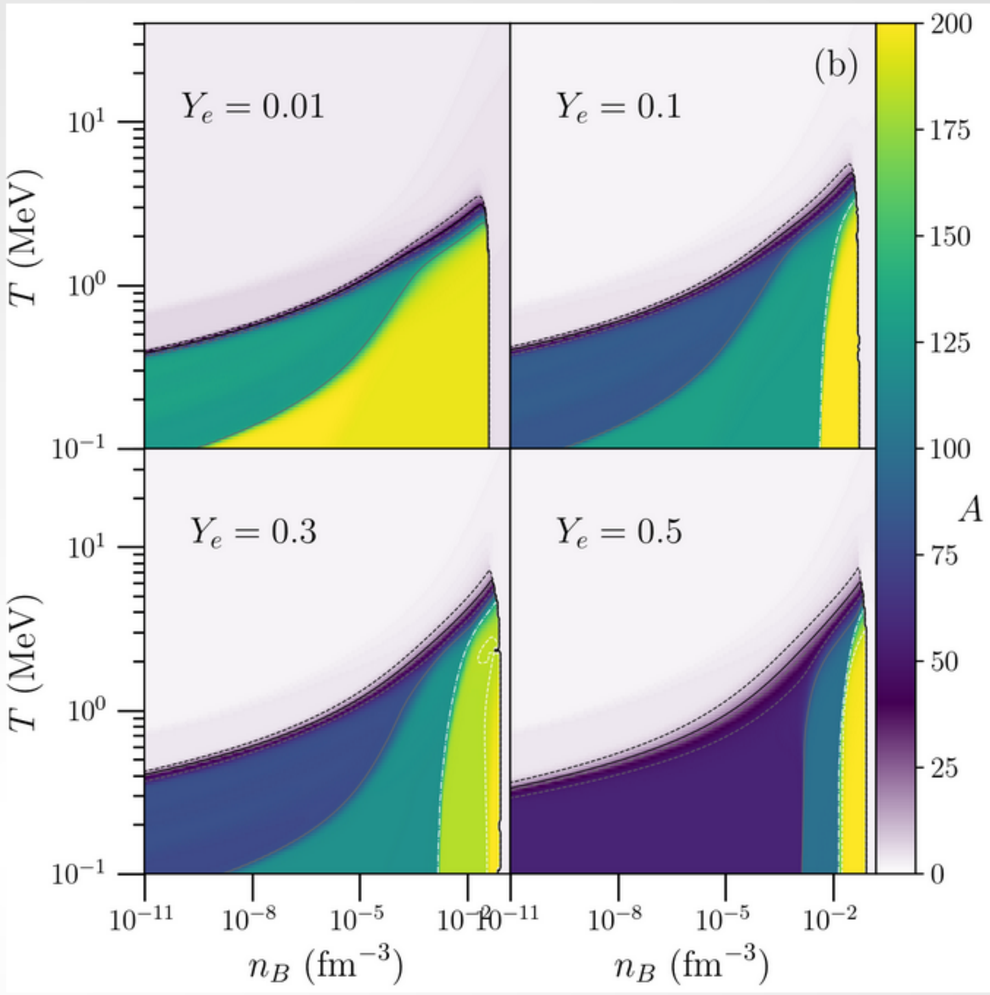


- Now LIGO + 11 EM observations, including NICER
- Still **prior-dominated** in some regions of the M-R curve and across the EOS
- No way to avoid choosing a prior distribution
- We cannot precisely compute the posterior probability distributions, even with a fixed input data set
- Largest current uncertainty in the EOS is the extent to which a decrease in the speed of sound (i.e. from a phase transition) is present

Al-Mamun et al., PRL, (2021)

Quilting an EOS for supernovae and mergers

- Three-dimensional space, $(n_B, Y_e \approx n_p/n_B, T)$
- Canonically, most EOS tables use extrapolation, our method avoids this
- Isospin-symmetric matter near saturation **Laboratory nuclei; NUCLEI collaboration**
- Neutron-rich matter near saturation **Nuclear theory, e.g. Gandolfi et al. (2012)**
- Nearly non-degenerate matter **Nucleon scattering phase shifts, Horowitz et al. (2006)**

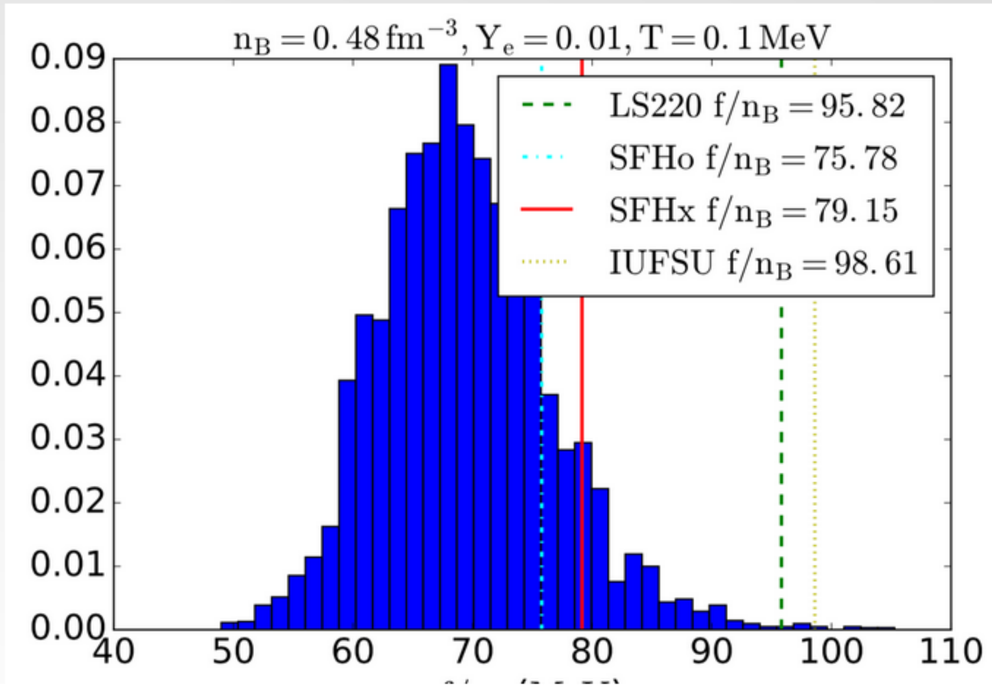


Du et al. (2019, 2022)

- Dense neutron-rich matter **Neutron star observations**
- Hot matter near saturation **Nuclear theory, e.g. Holt et al. (2017)**

EOS as a Probability Distribution

- Probability distribution for EOSs
- Probability density peaks at lower values because of influence of NS radius observations
- Nine sample EOS tables available now!
- Current work on propagating neutrino opacities so that they are consistent with the underlying EOS
- Currently working on core-collapse simulations with these new EOSs



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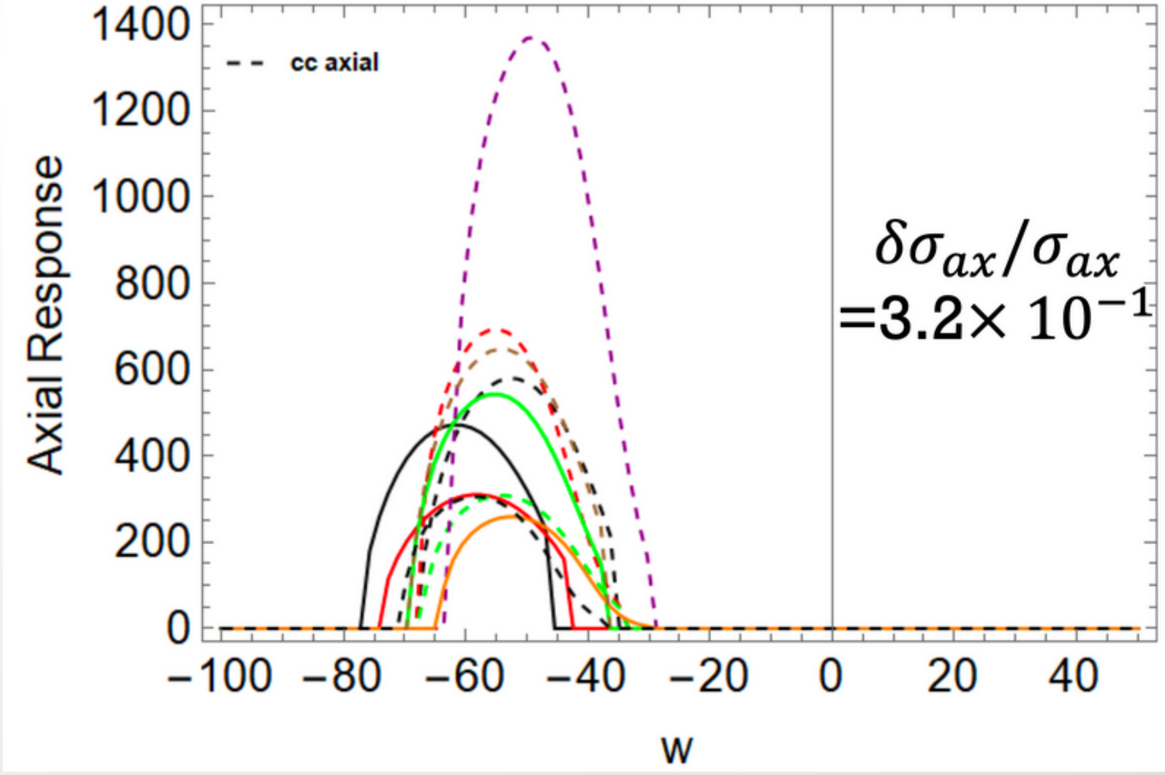


Du et al. (2019, 2022) and Lin et al. (in prep)

Open source code

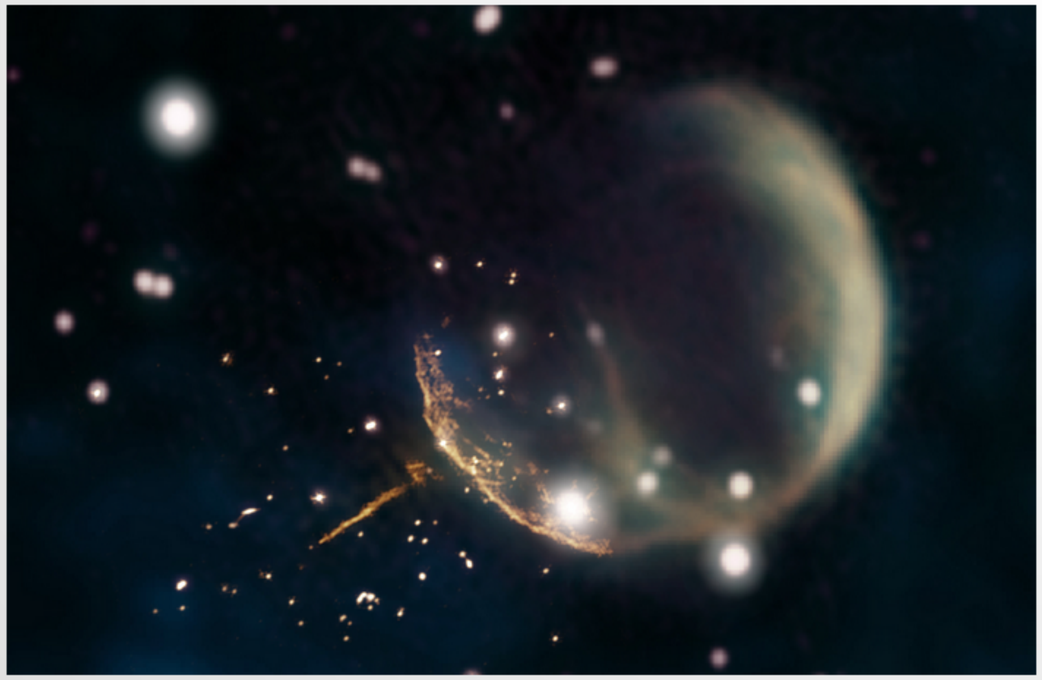
- I strongly believe that our community continually does itself a disservice by not making our code open source (there is a growing list of open-source progress ... particularly on the astronomy side)
- O2scl/O2sclpy, a python interface
  - Skyrme interaction, TOV, tidal deformability
  - SFHo example, compute, plot and analyze the SFHo EOS
  - DSH example, plot a new DSH EOS table
  - Coming soon: openMP/MPI parallel MCMC with an adaptive emulator
- UTK EOS
  - Table format
  - Other helpful documentation, e.g. on chemical potentials

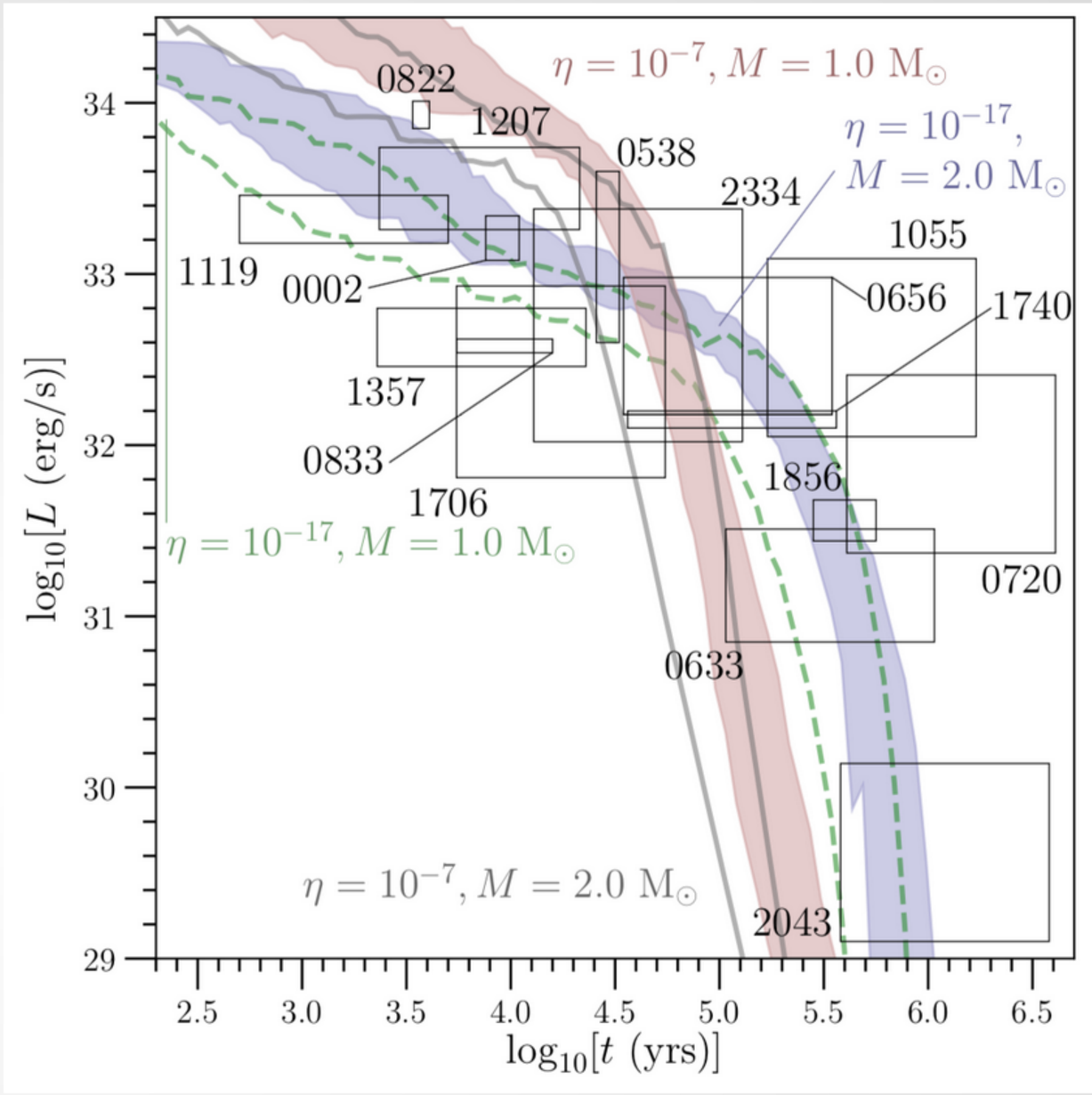
Thermal Emission from Neutron Stars

- After ~ 10 years, the neutron star is isothermal ⇒ one temperature = T

$$C_V \frac{dT}{dt} = L_\nu + L_\gamma$$

- Assume only neutrons and protons
- Age taken from, e.g., association with a supernova remnant





Beloin et al. (2018, 2019)

- Connected to composition of dense matter, neutron superfluidity, and proton superconductivity

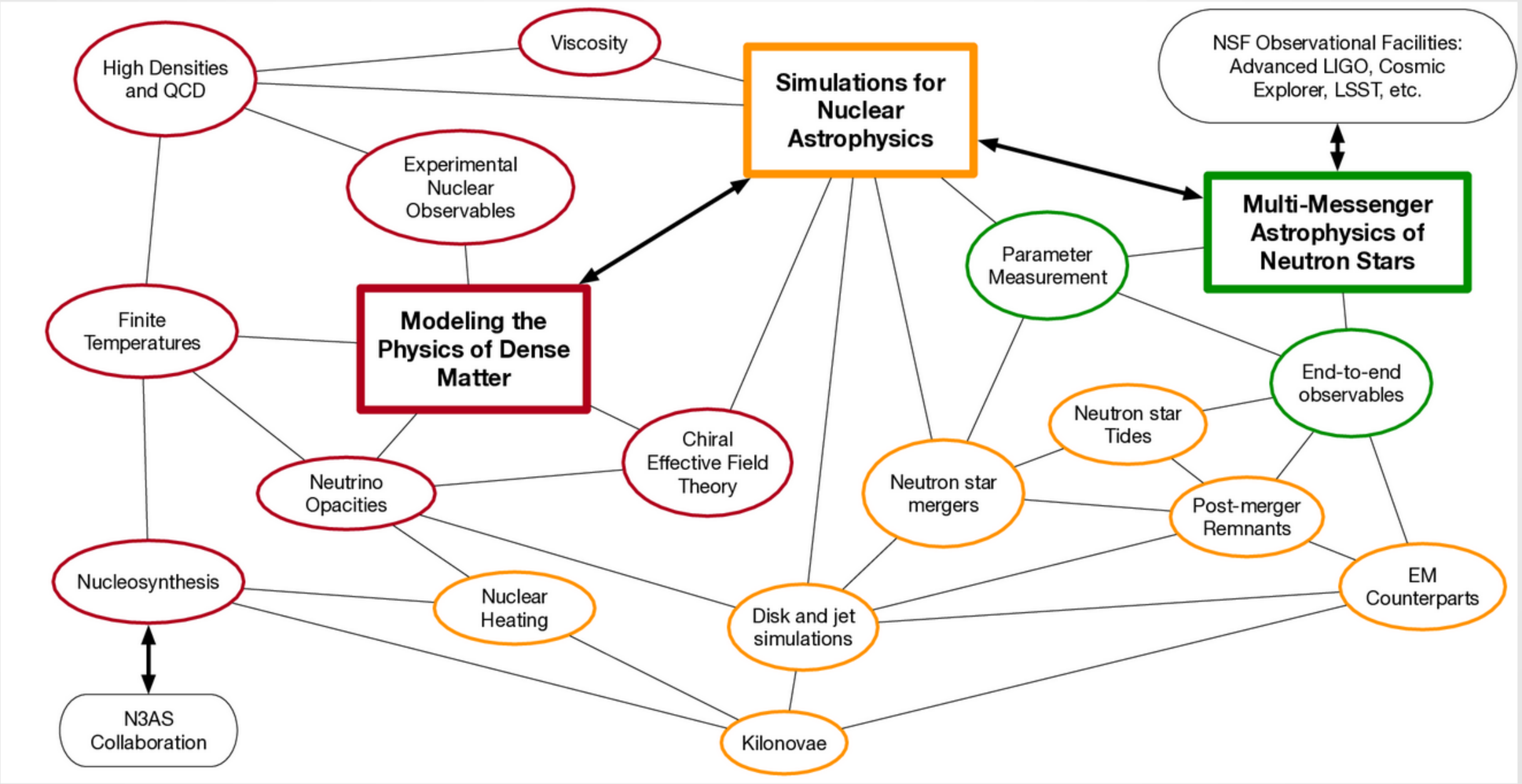
Slides Omitted

- I omitted a couple slides describing unpublished work. Please ask me about them as I am happy to discuss them further.

Nuclear Physics of Multi-Messenger Mergers

- Understanding neutron star mergers will require a coordinated effort between many communities

NP3M



- Nuclear structure theory, low-energy nuclear theory, high-energy nuclear theory, nuclear experiment, astrophysics theory, astronomical observations, gravitational wave observations

Questions

- How large are density fluctuations in mergers? Do we need strange crusts?
- What are all of the neutron star mass functions?
- Do we need muons out of beta equilibrium?
- Is pion condensation relevant for mergers even though it might not be relevant for cold NSs?
- How can we estimate the systematic uncertainties associated with inferring the properties of dense matter from the post-merger signal?
- How do we share our generative likelihoods for multimessenger inference?
- What open-source codes do we need to make progress?

Summary

- Leveraging neutron star observations to learn about QCD and the nucleon-nucleon interaction
- New multi-messenger inference and new EOS tables
- NS cooling data will provide the strongest constraint on the radius, modulo systematics
- Generative models are important to properly address prior distributions

Very exciting future! FRIB, PREX, GWs, NICER, Strobe-X, IXPE, and more!