Nuclear Physics Input for Neutron Star Mergers and NP3M

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UTK/ORNL

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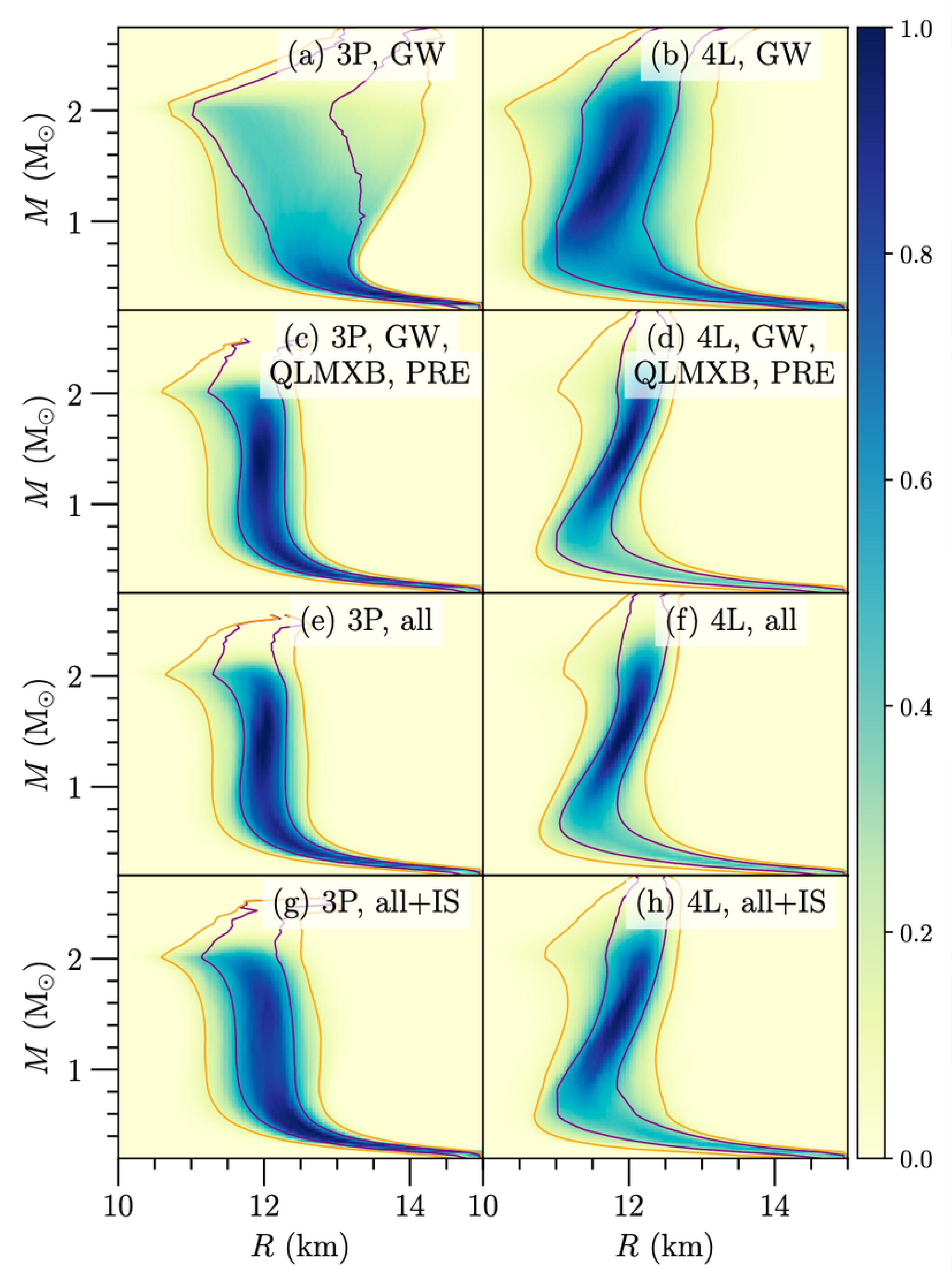
Collaborators: **Mahmudul Hasan Anik**, **Spencer Beloin**, **Xingfu Du**, **Jesse Farr**, Stefano Gandolfi, Sophia Han, Craig Heinke, Jeremy Holt, Jacob Lange, **Zidu Lin**, Jérôme Margueron, Richard O'Shaughnessy, **Satyajit Roy**, Ingo Tews, **Gema Villegas**,

Outline

- Multimessenger inference
- Multimessenger inference with NS cooling
- New DSH EOS tables
- NP3M
- Summary

$P(\varepsilon)$ and the pre-merger signal



- Combining GW and electromagnetic constraints
- Bayes + TOV + MCMC
- Few additional assumptions on the EOS (e.g. differentiability)
- Tested for unknown systematic uncertainties
- Tested variation with maximum mass

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

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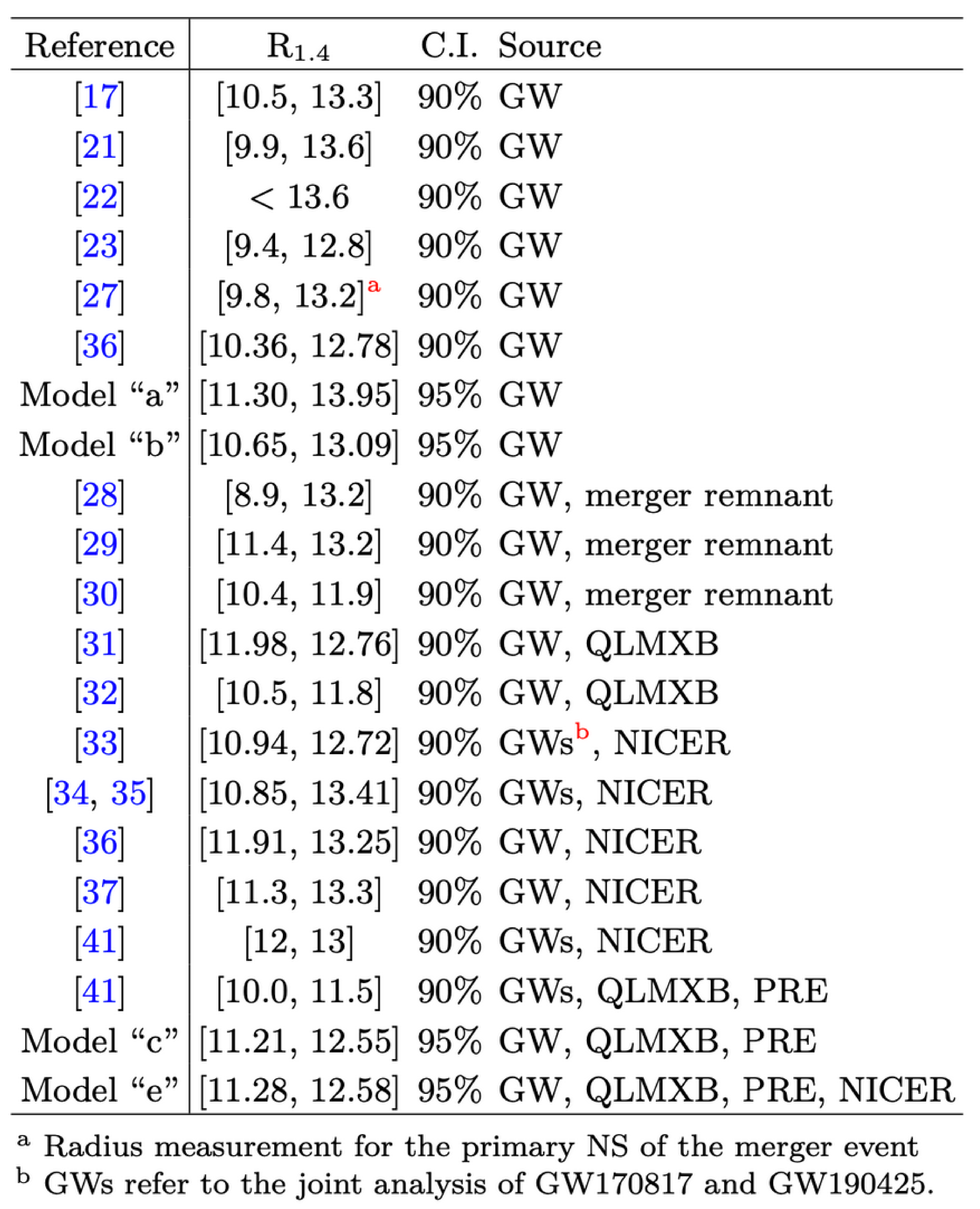

Reference	$R_{1.4}$	C.I.	Source
[17]	[10.5, 13.3]	90%	GW
[21]	[9.9, 13.6]	90%	GW
[22]	< 13.6	90%	GW
[23]	[9.4, 12.8]	90%	GW
[27]	[9.8, 13.2][a]	90%	GW
[36]	[10.36, 12.78]	90%	GW
Model “a”	[11.30, 13.95]	95%	GW
Model “b”	[10.65, 13.09]	95%	GW
[28]	[8.9, 13.2]	90%	GW, merger remnant
[29]	[11.4, 13.2]	90%	GW, merger remnant
[30]	[10.4, 11.9]	90%	GW, merger remnant
[31]	[11.98, 12.76]	90%	GW, QLMXB
[32]	[10.5, 11.8]	90%	GW, QLMXB
[33]	[10.94, 12.72]	90%	GWs[b], NICER
[34, 35]	[10.85, 13.41]	90%	GWs, NICER
[36]	[11.91, 13.25]	90%	GW, NICER
[37]	[11.3, 13.3]	90%	GW, NICER
[41]	[12, 13]	90%	GWs, NICER
[41]	[10.0, 11.5]	90%	GWs, QLMXB, PRE
Model “c”	[11.21, 12.55]	95%	GW, QLMXB, PRE
Model “e”	[11.28, 12.58]	95%	GW, QLMXB, PRE, NICER

[a] Radius measurement for the primary NS of the merger event
[b] GWs refer to the joint analysis of GW170817 and GW190425.

- Combined electromagnetic and GW-based constraints on NS structure
- What should we make of the range of results?
- Some variation from different data sets

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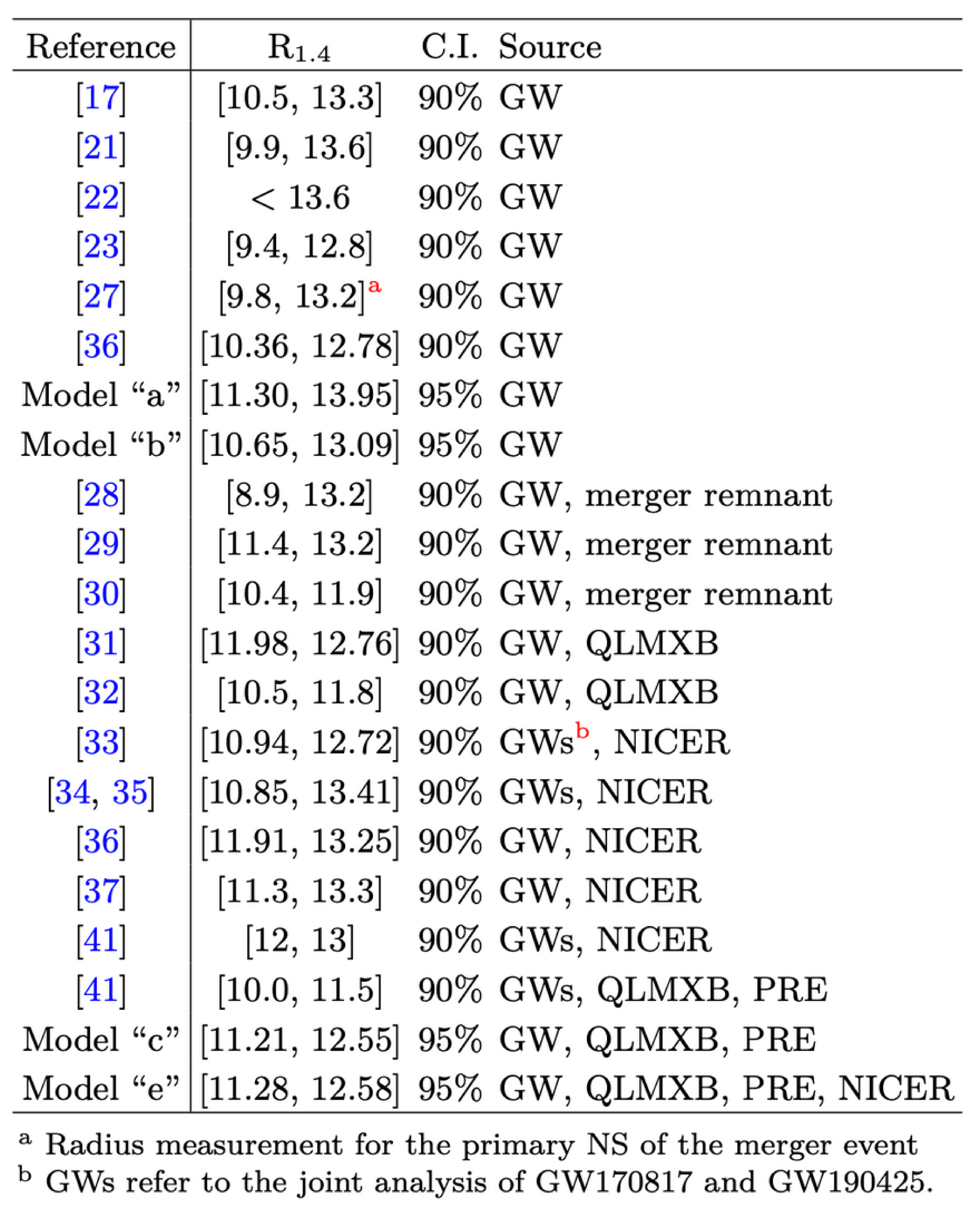

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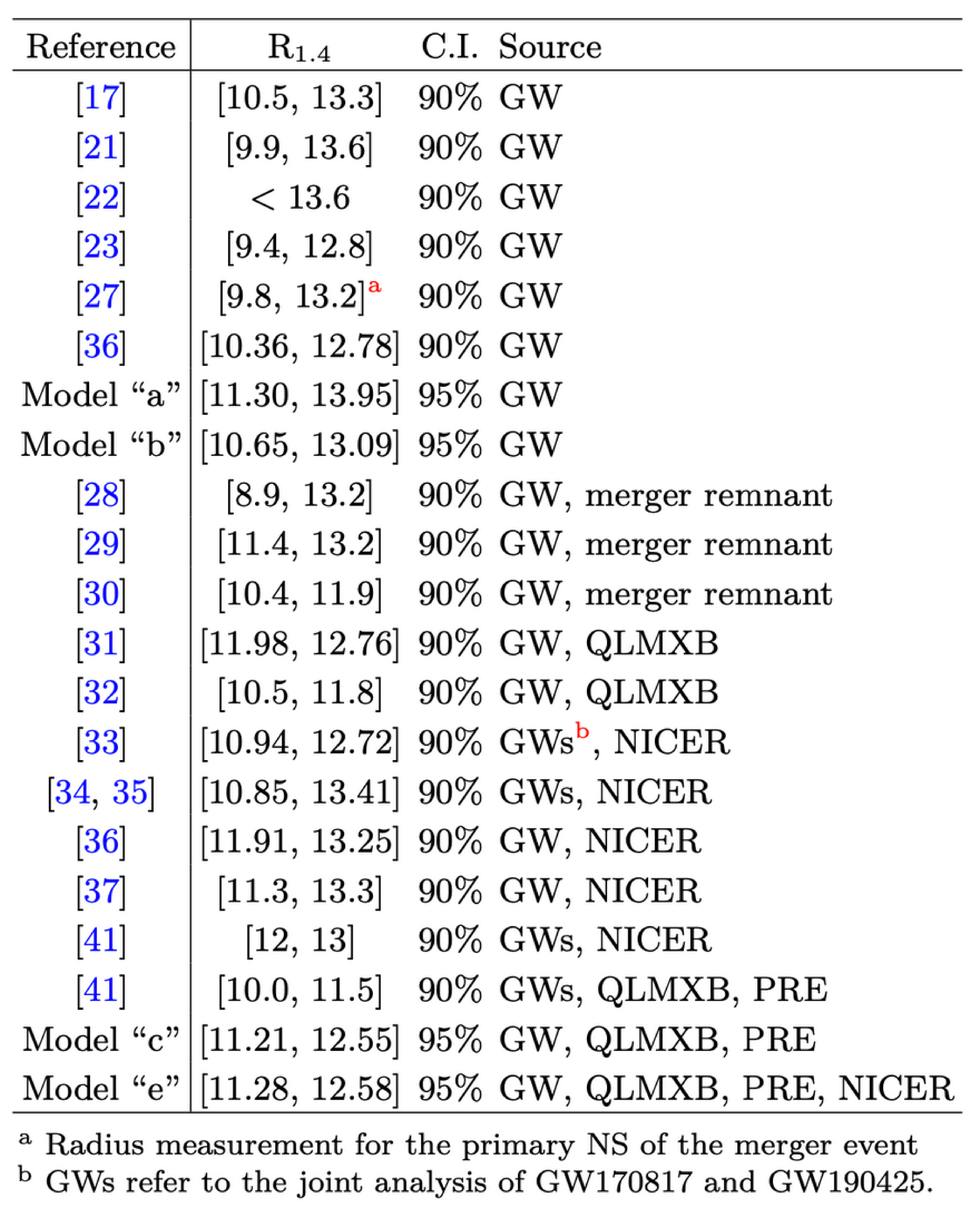

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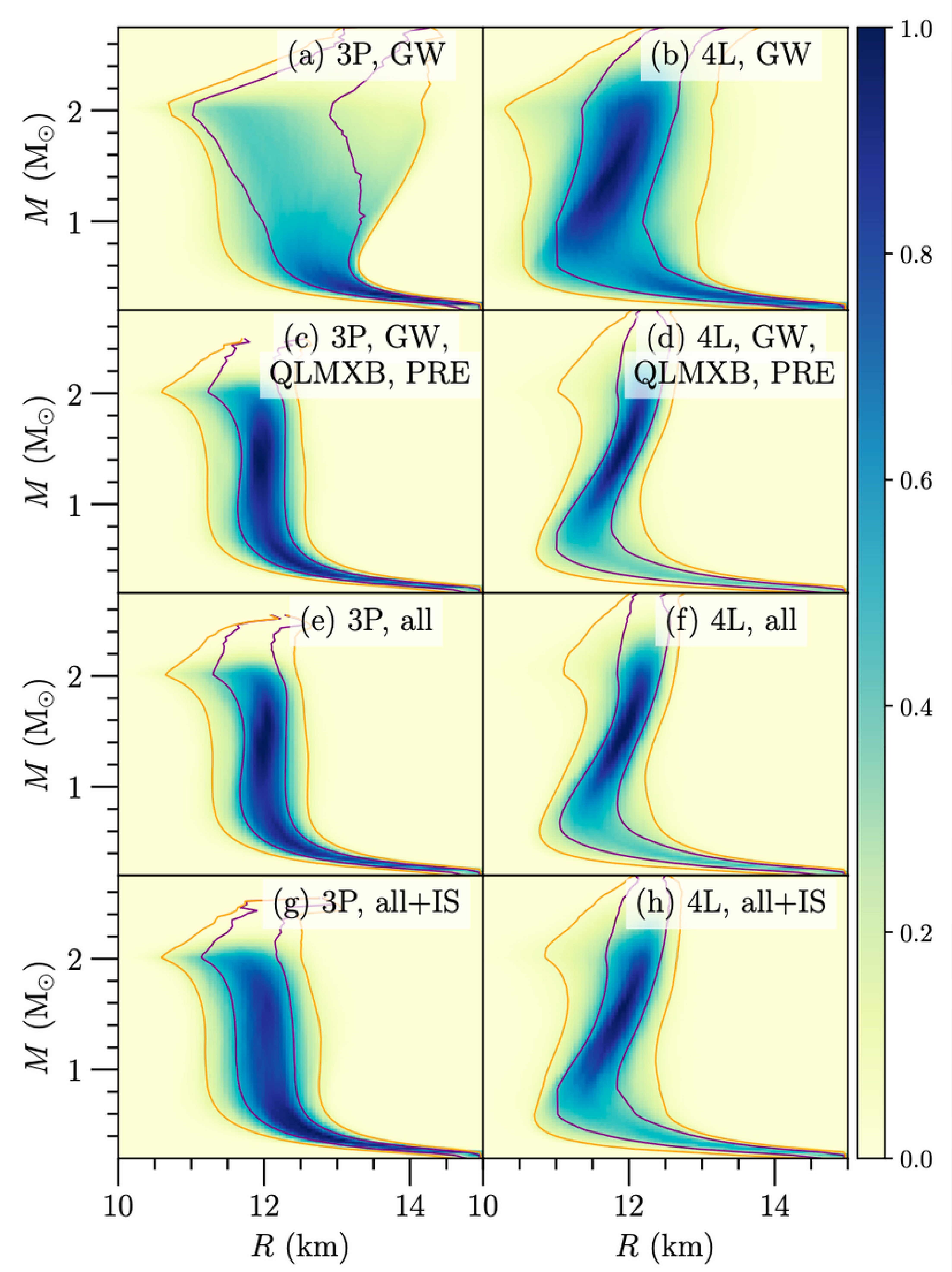
- Combined electromagnetic and GW-based constraints on NS structure
- What should we make of the range of results?
- Some variation from different data sets
- Similar analysis: Bayes + TOV + MCMC
- Fundamentally, these differences result from **different prior distributions**

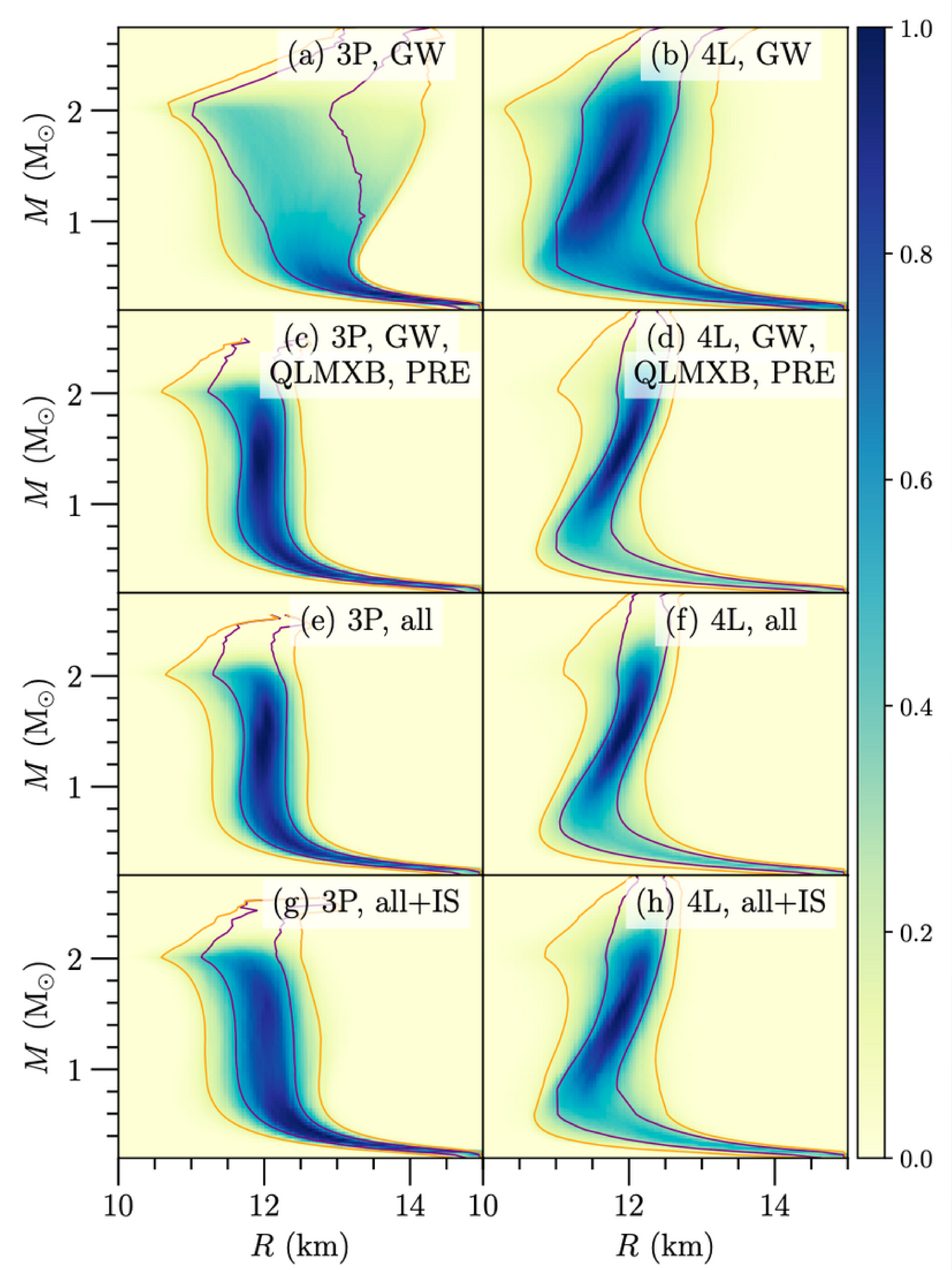
$P(\varepsilon)$ and the pre-merger signal



- Different rows represent different data sets
- Different columns represent different prior choices
- Largest current uncertainty in the EOS is the presence of a phase transition
- One and two-sigma contours vary by 0.5 km or more, depending on the mass
- The posterior radius distribution varies by a factor of a few or more

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

$P(\varepsilon)$ and the pre-merger signal



- What is the solution?
- More data!
- GW observations will eventually determine the $T = 0$ pressure-energy density relation with high accuracy
- Composition, finite temperature, transport properties (neutrinos, superfluidity)

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

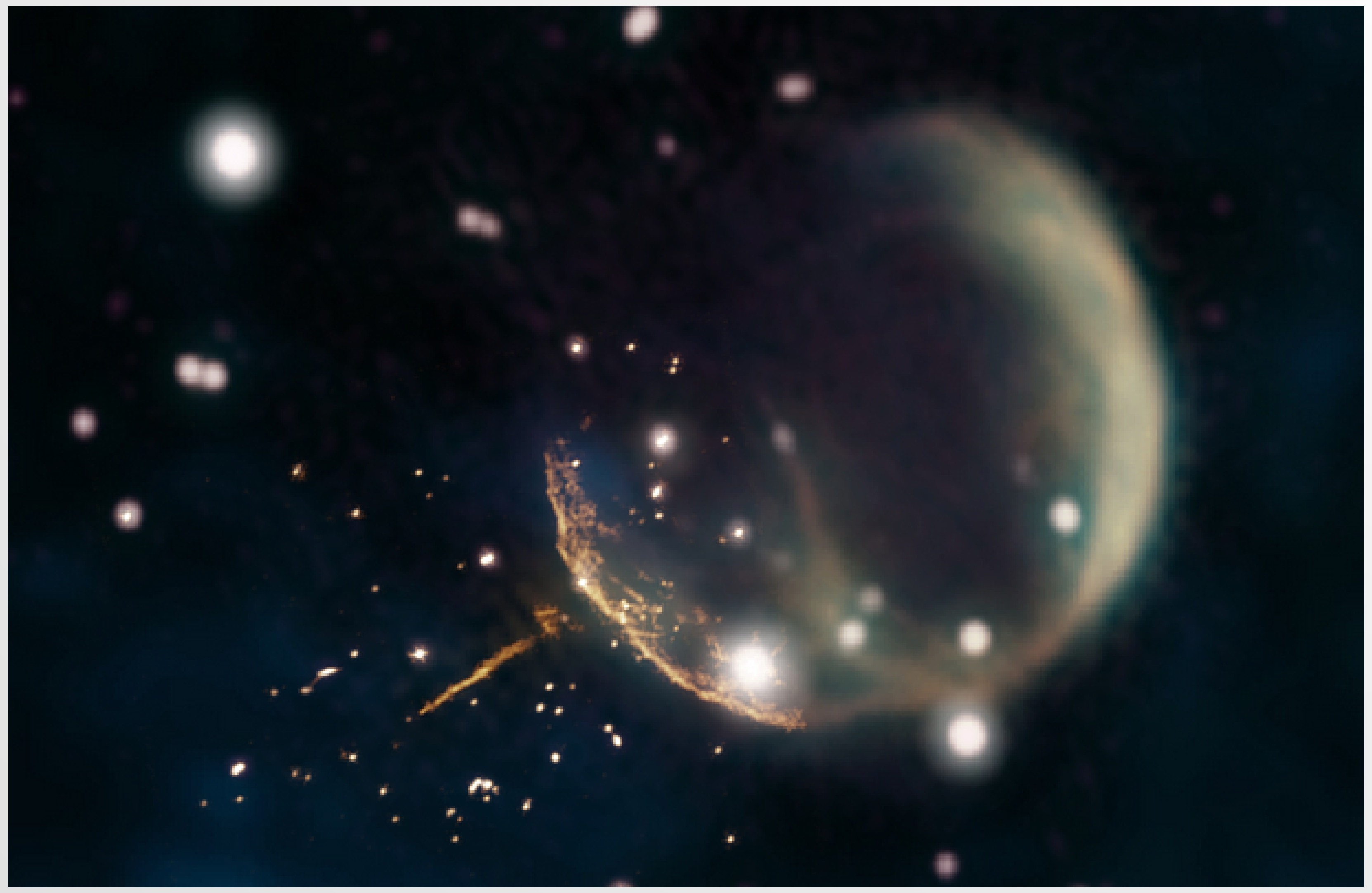
Thermal Emission from Neutron Stars

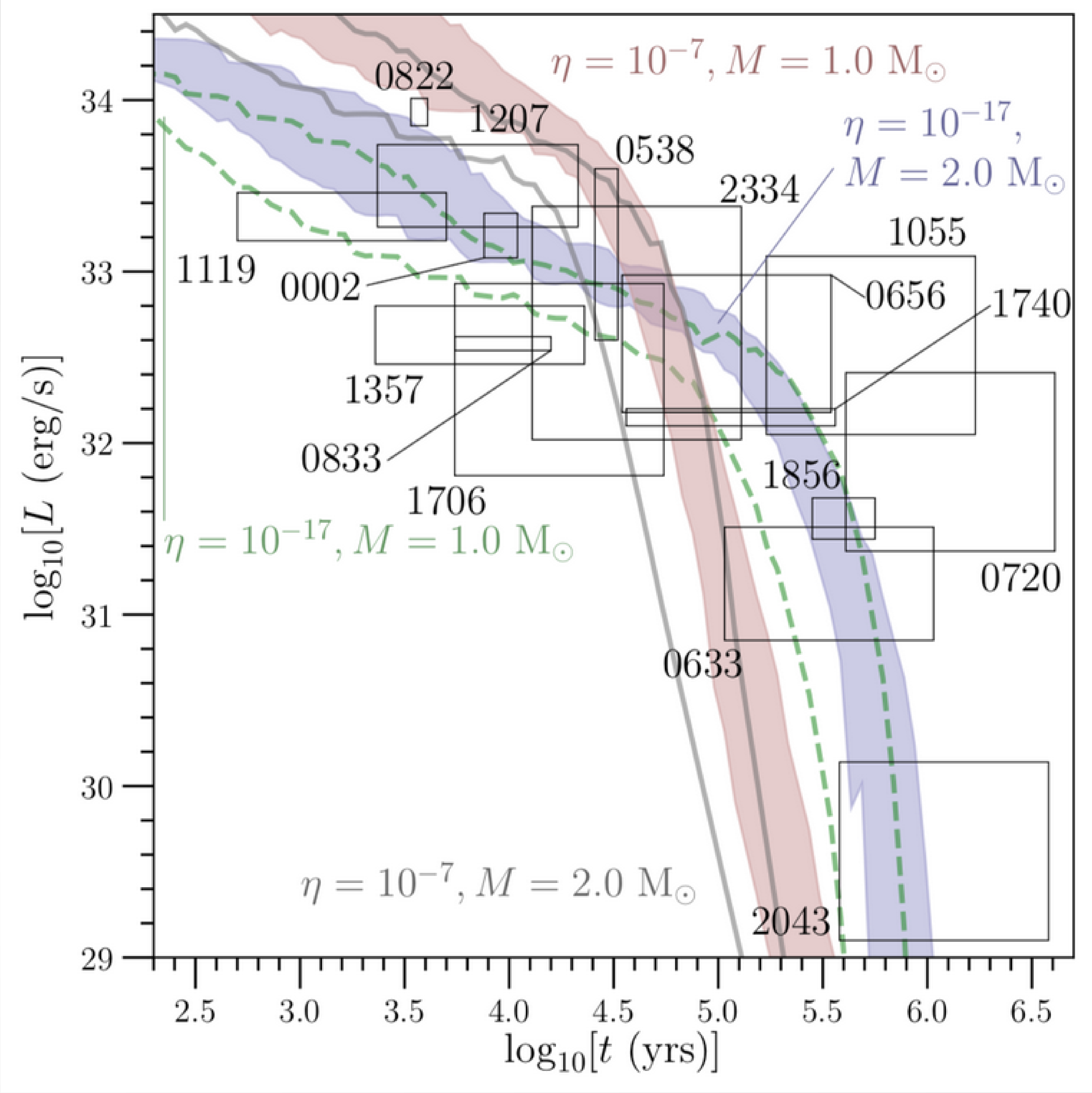
- After ~ 10 years, the neutron star is isothermal ⇒ one temperature = T

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

- Assume only neutrons and protons

- Age taken from, e.g., association with a supernova remnant



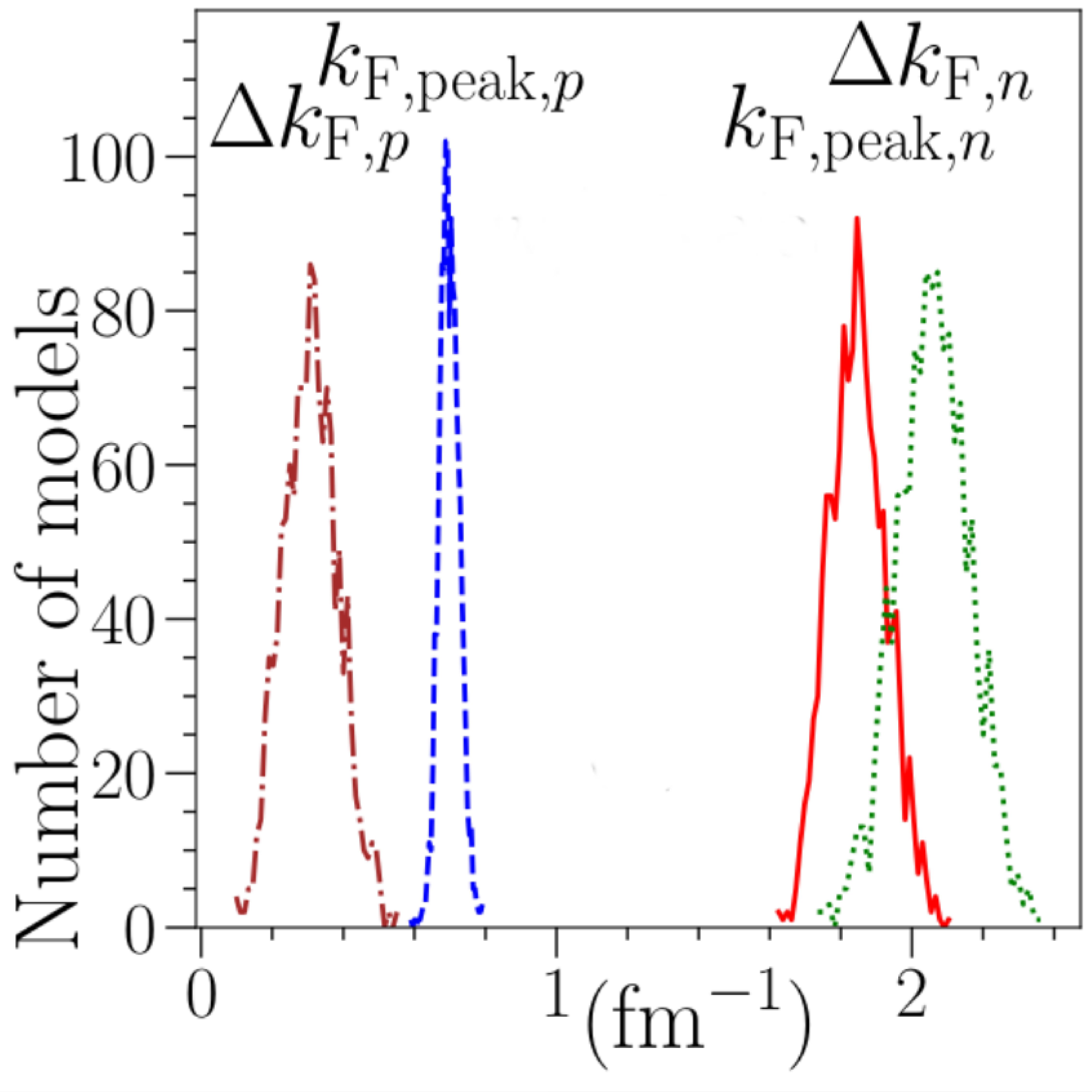


e.g. Beloin et al. (2018, 2019)

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

Early Cooling Results

- Proton fraction large, allowing stars with masses $> 1.4 - 1.7\ \mathrm{M}_\odot$ to cool quickly via beta decay



Beloin et al. (2019)

Early Cooling Results

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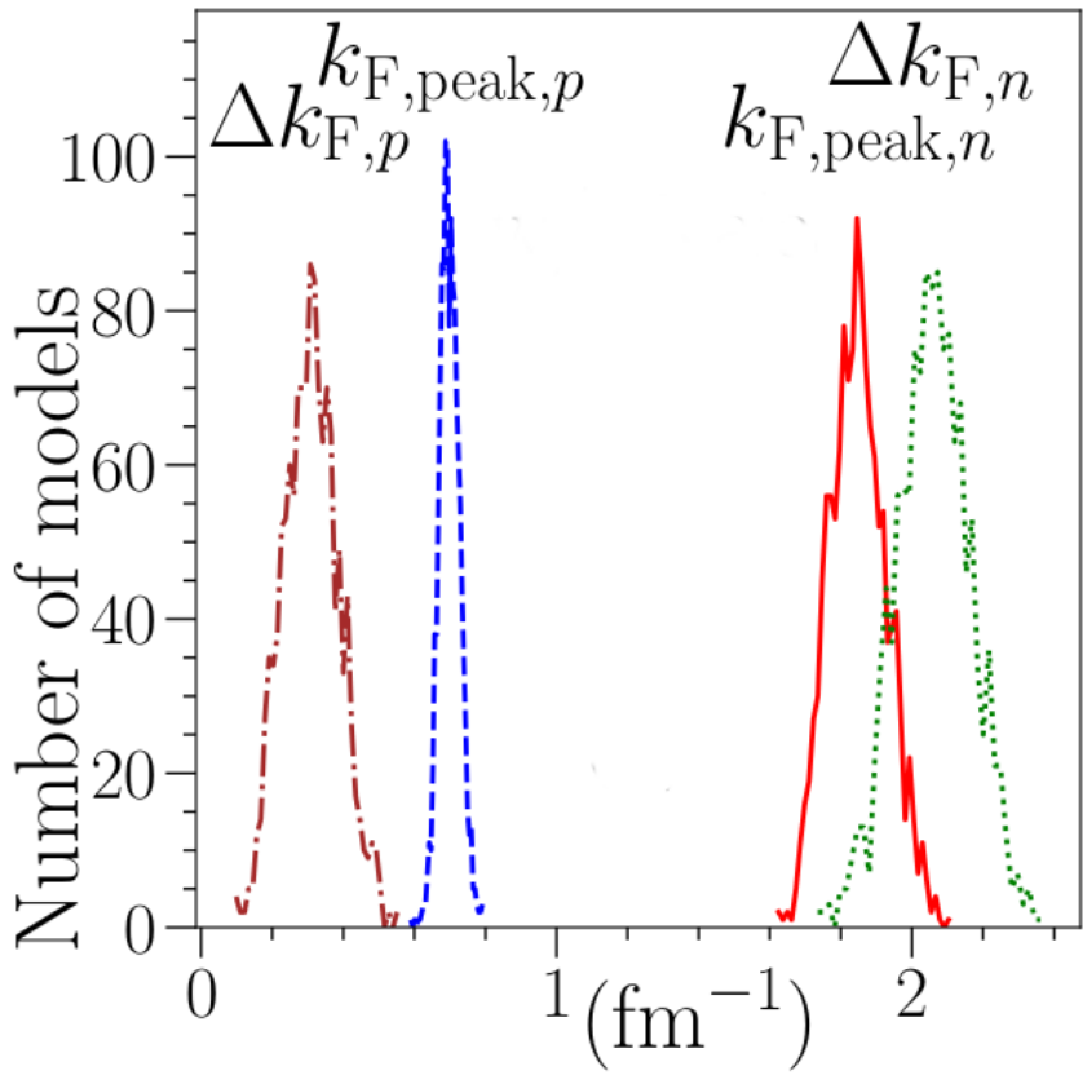
$$T_C \sim T_{C,\max} \exp\left[-\frac{1}{2}\left(\frac{k_F - k_{F,\mathrm{peak}}}{\Delta k_F}\right)^2\right]$$



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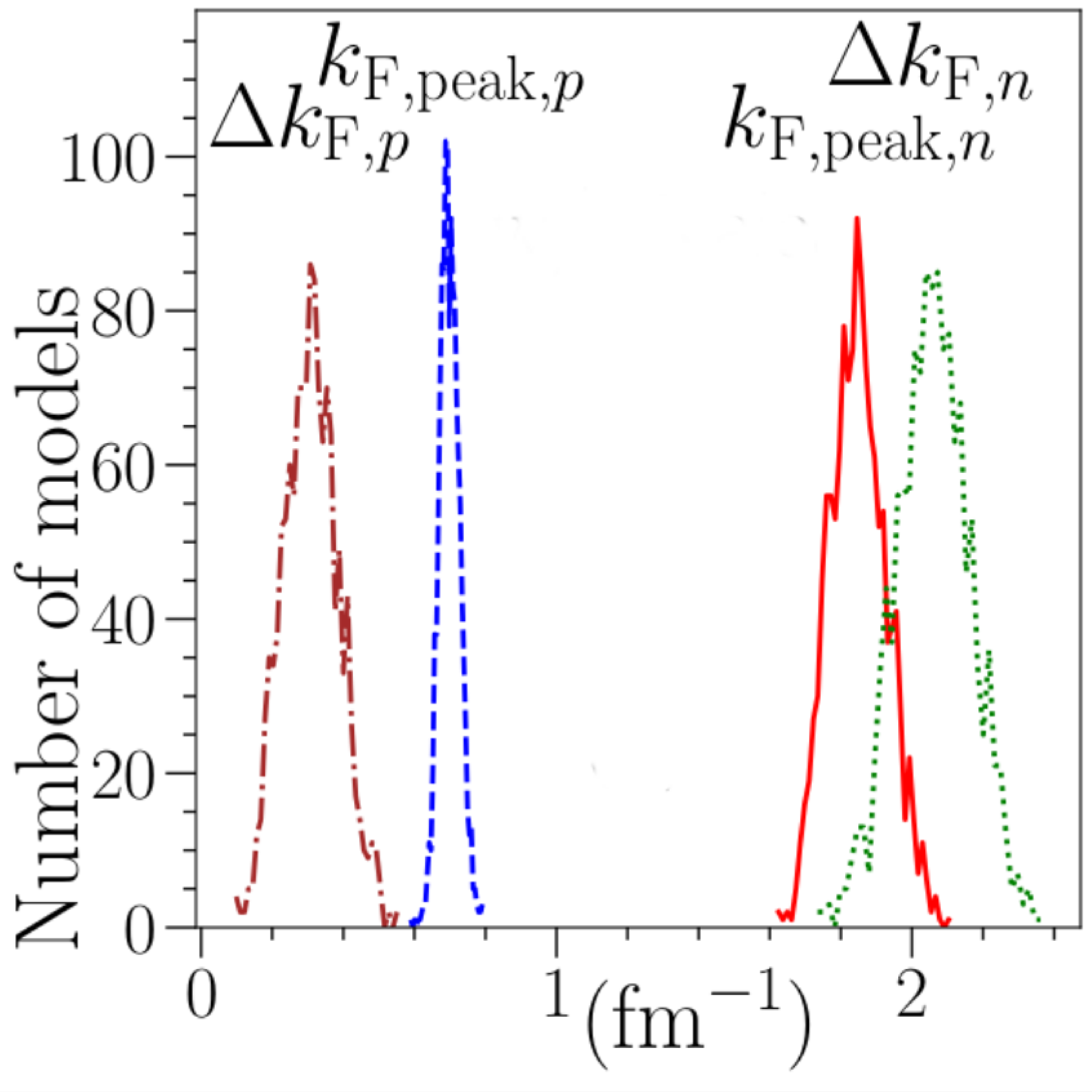
- Thus, beta decay is only allowed for the most massive stars



Beloin et al. (2019)

Post-merger Signal

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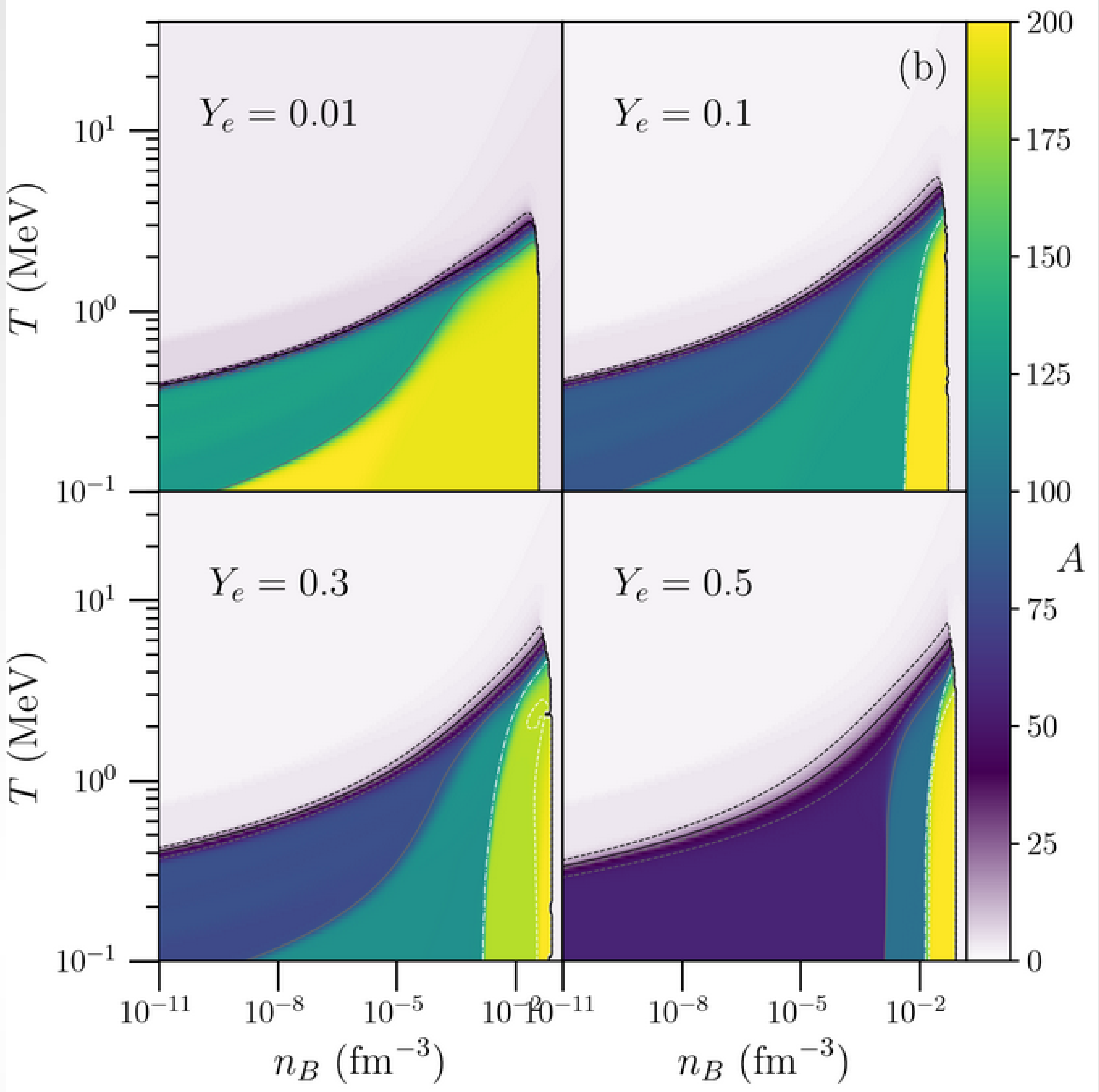
- but we're making progress on both fronts

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

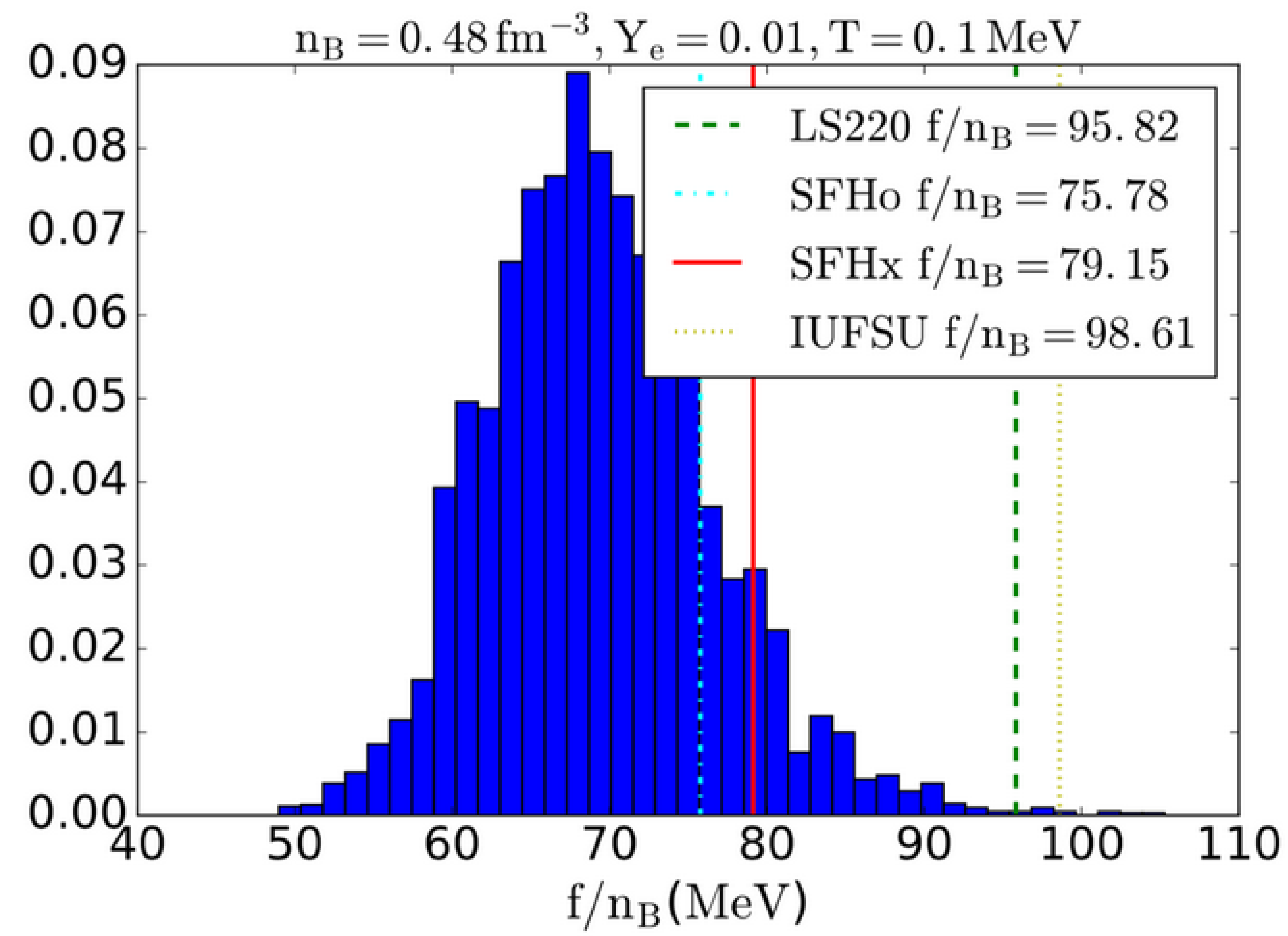
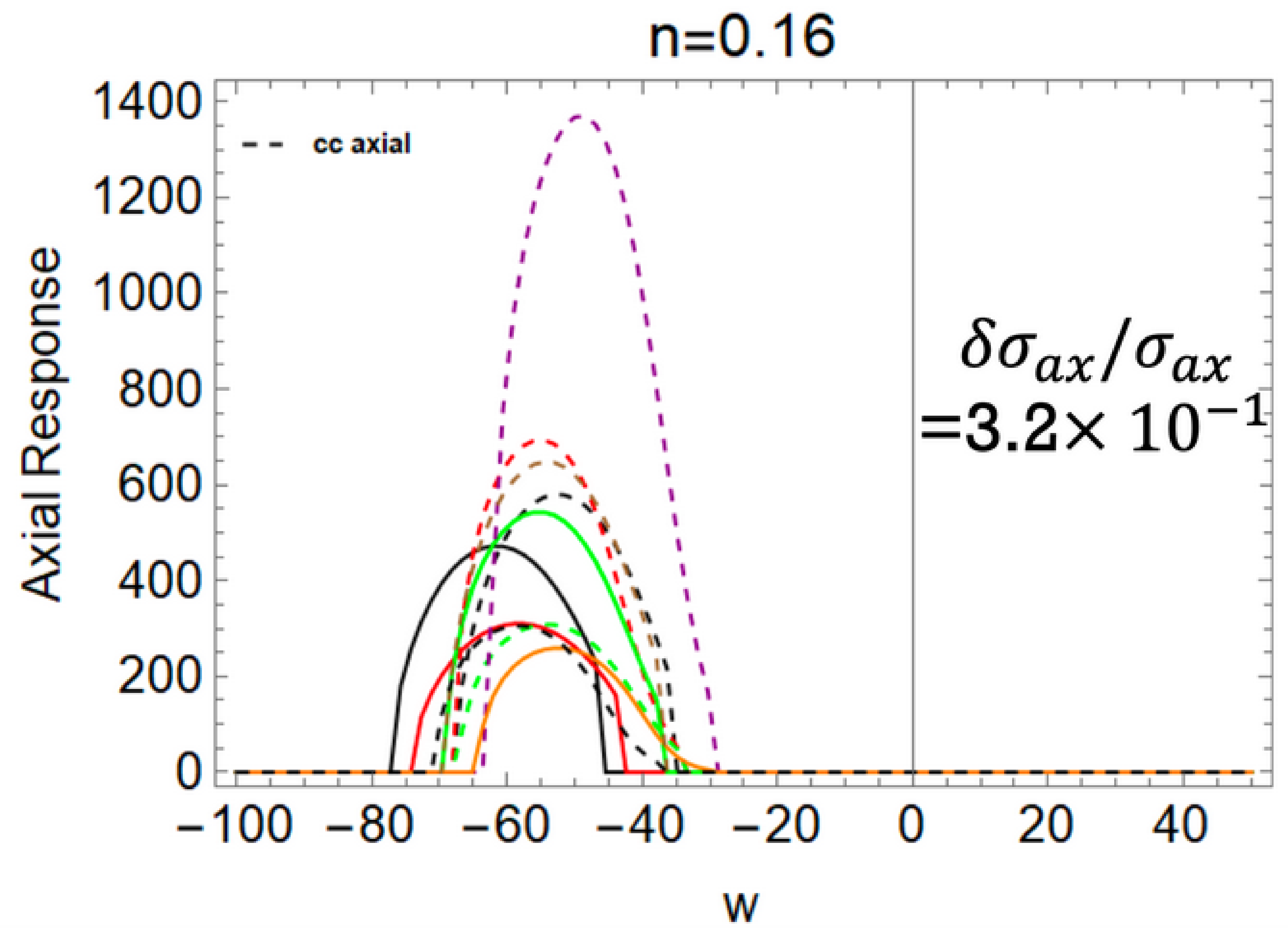


FIG. 6. The probability distribution for the free energy per baryon at $n_B = 0.48\ \mathrm{fm}^{-3}$, $Y_e = 0.10$, and $T = 0.1$ MeV.

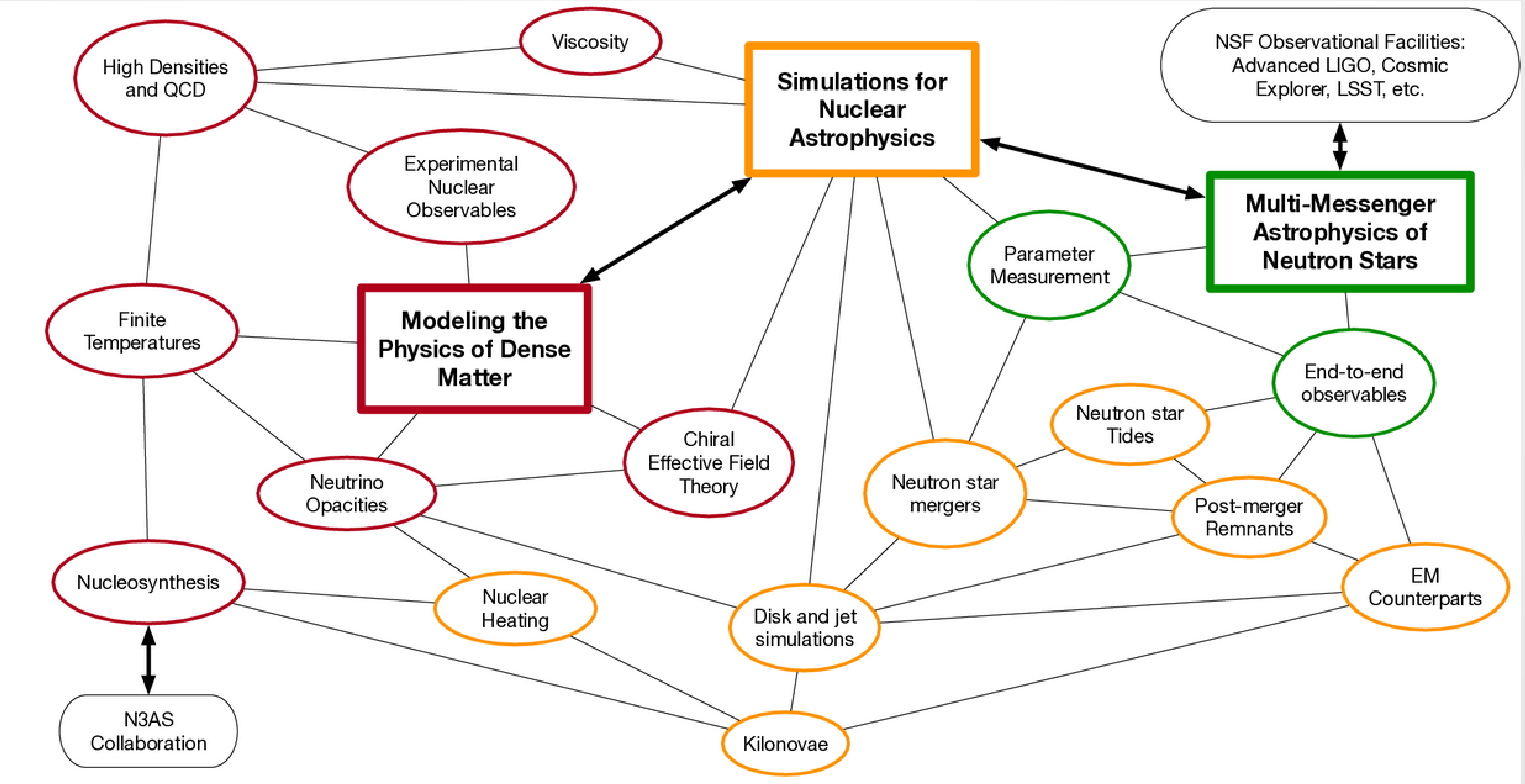


Du et al. (2019, 2022)

and Lin et al. (in prep)

Nuclear Physics of Multi-Messenger Mergers

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



Viscosity

High Densities and QCD

Simulations for Nuclear Astrophysics

NSF Observational Facilities: Advanced LIGO, Cosmic Explorer, LSST, etc.

Experimental Nuclear Observables

Multi-Messenger Astrophysics of Neutron Stars

Parameter Measurement

Finite Temperatures

Modeling the Physics of Dense Matter

End-to-end observables

Neutron star Tides

Chiral Effective Field Theory

Neutrino Opacities

Neutron star mergers

Post-merger Remnants

Nucleosynthesis

Nuclear Heating

Disk and jet simulations

EM Counterparts

N3AS Collaboration

Kilonovae

- Nuclear structure theory, low-energy nuclear theory, high-energy nuclear theory, nuclear experiment, astrophysics theory, astronomical observations, gravitational wave observations
- Fellows: Peter Hammond, Zidu Lin, Konstantin Maslov, Rahul Somasundaram, and Lami Suleiman

Zidu Lin

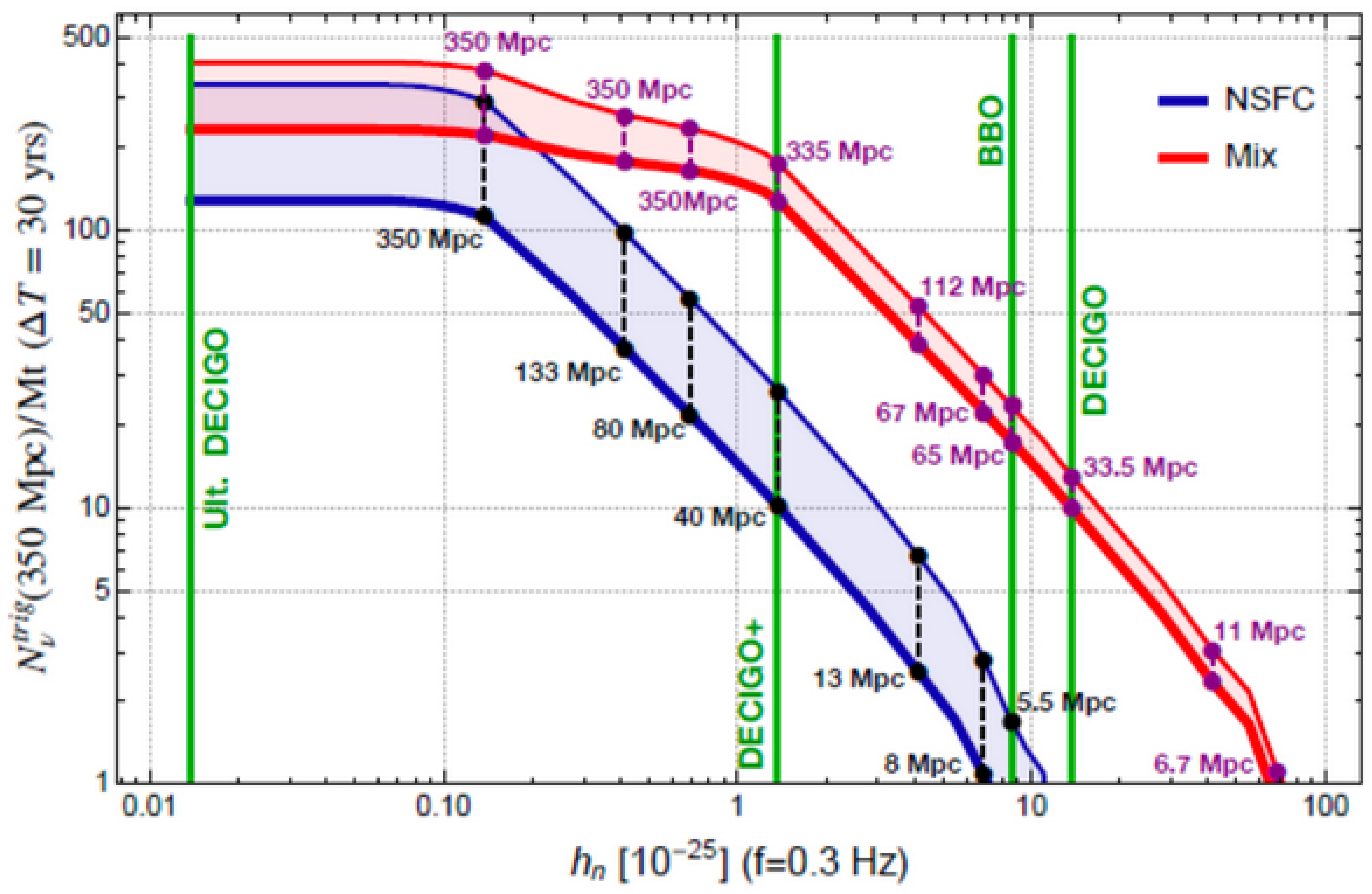
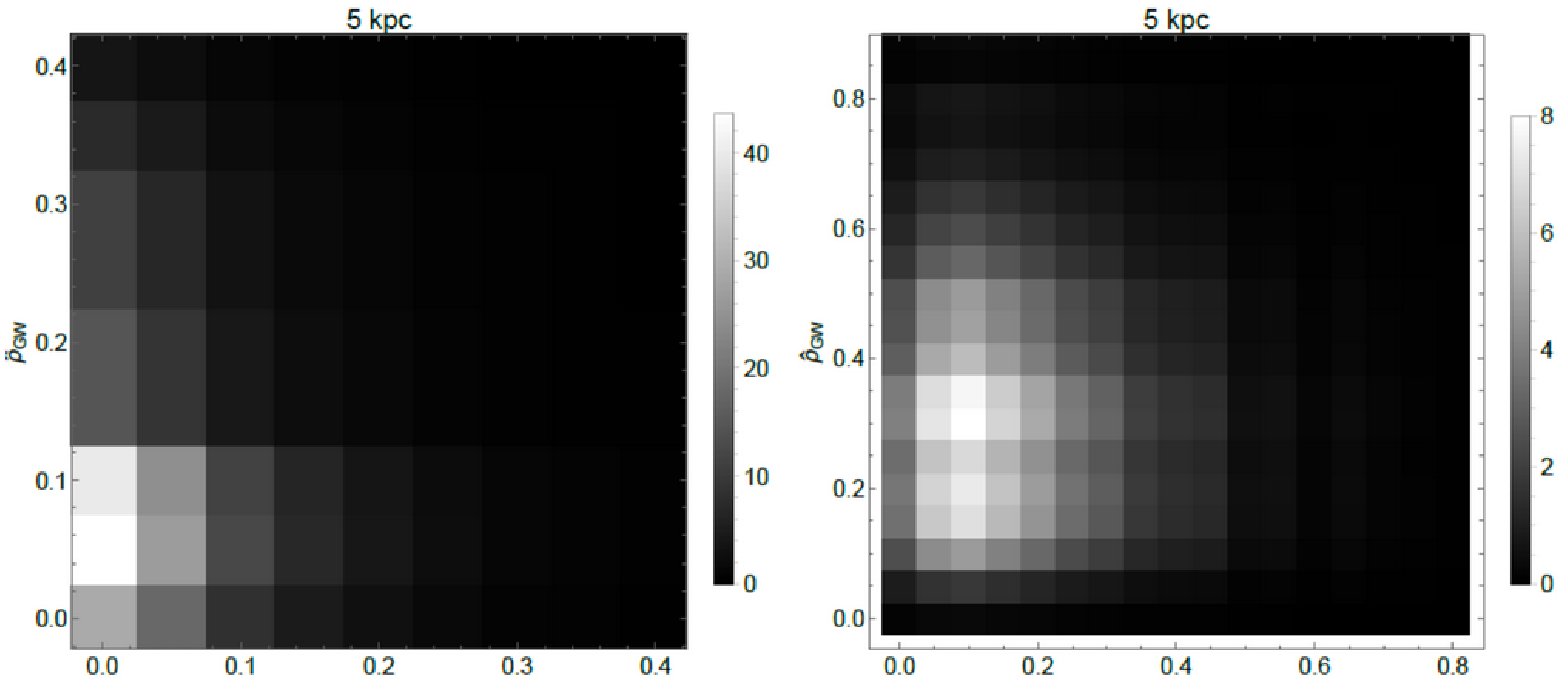


FIG. 1. The number of memory-triggered supernova neutrinos detected at a 1 Mt water Cherenkov detector in 30 years,

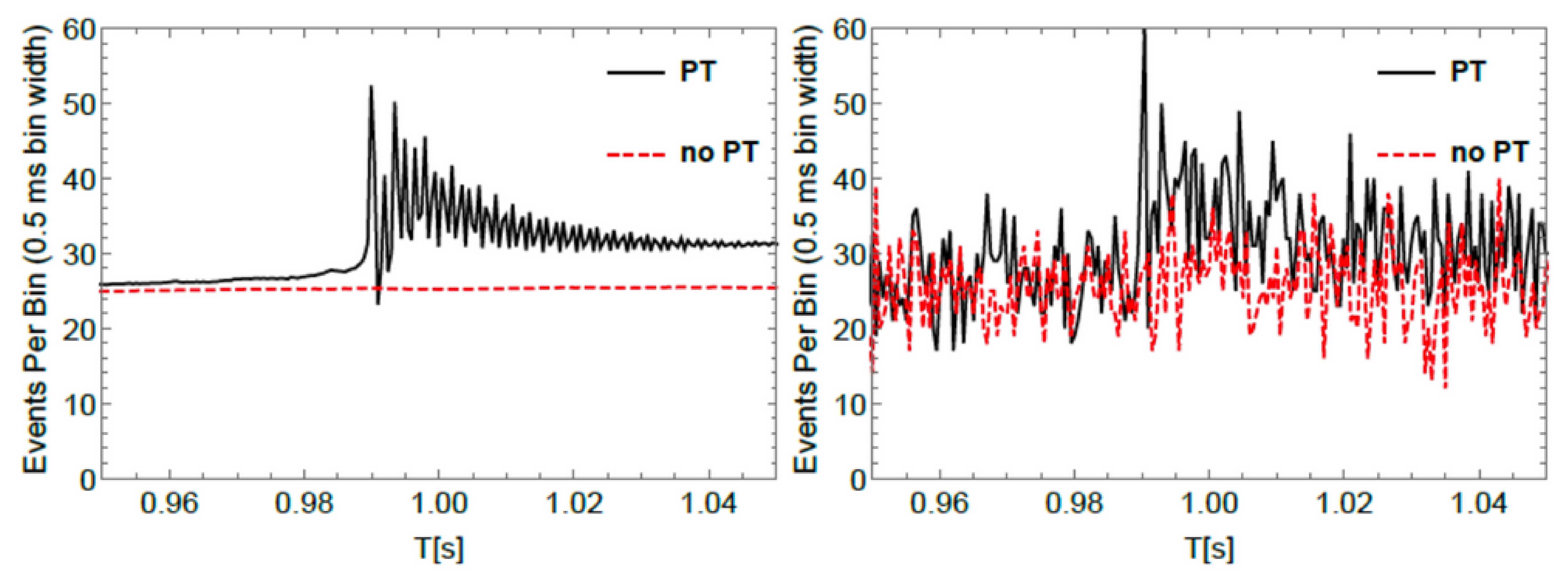
- Observations of the gravitational memory from core collapse supernovae at future Deci-Hz interferometers enable time-triggered searches of supernova neutrinos at Mt-scale detectors

Mukhopadhyay et al. (2021)



- Novel multi-messenger analysis for the standing accretion shock instability (SASI) of a supernova with neutrino and gravitational wave signals

Lin et al. (in prep)

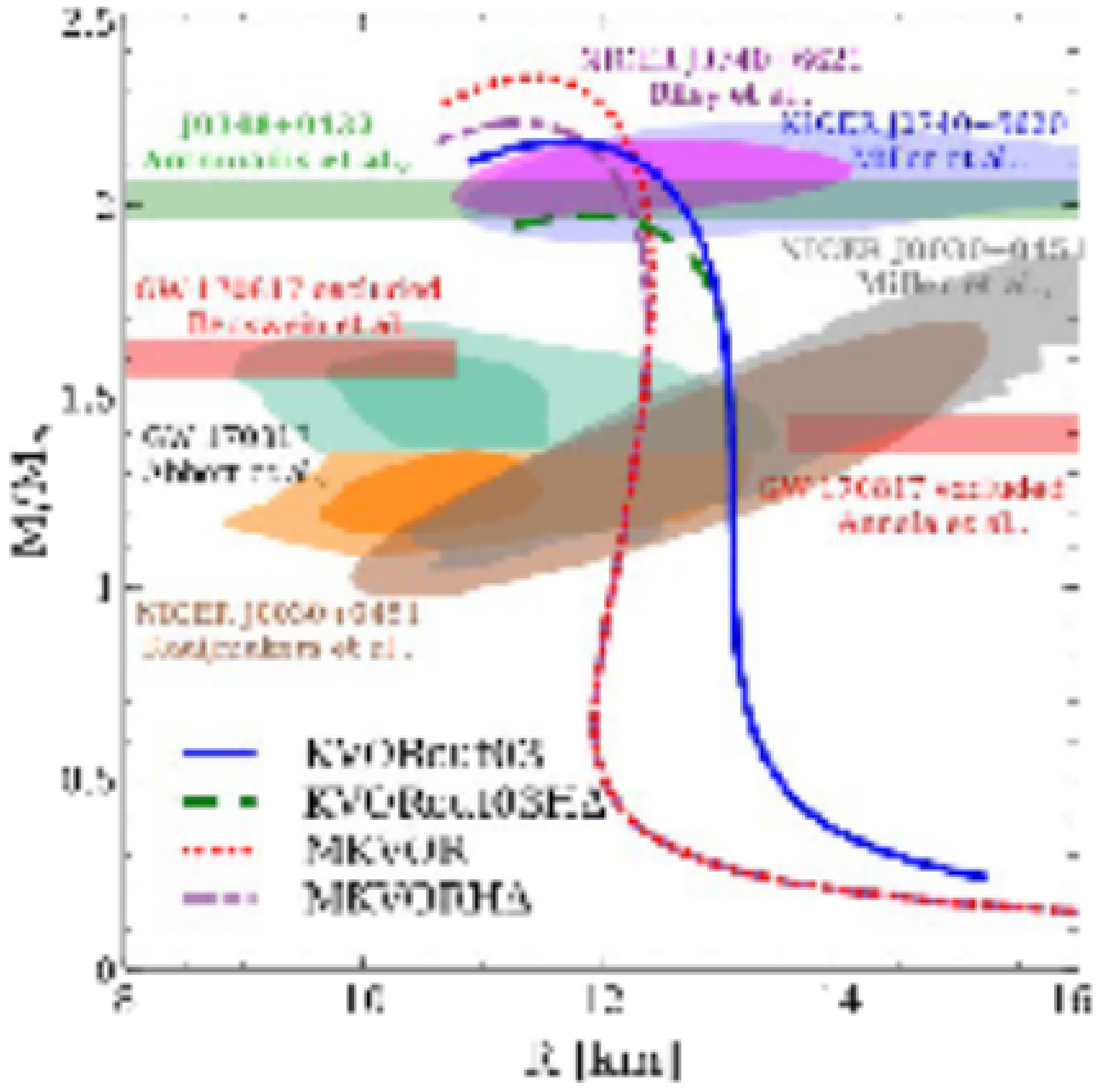


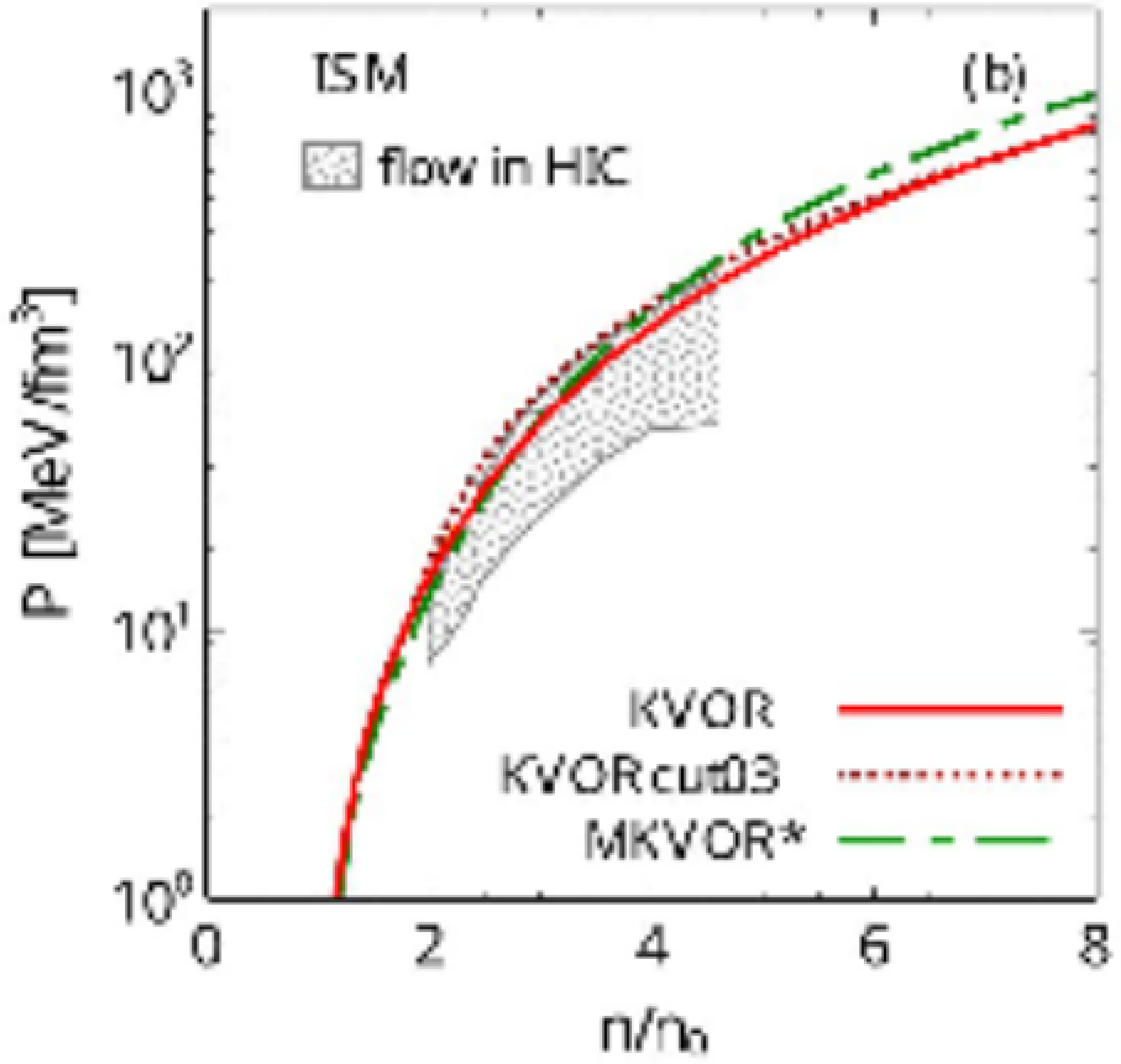
- Systematic method for quantitative test of oscillatory neutrino signals resulting from the hadron-quark phase transition in failing core-collapse supernovae

Lin et al. (2022)

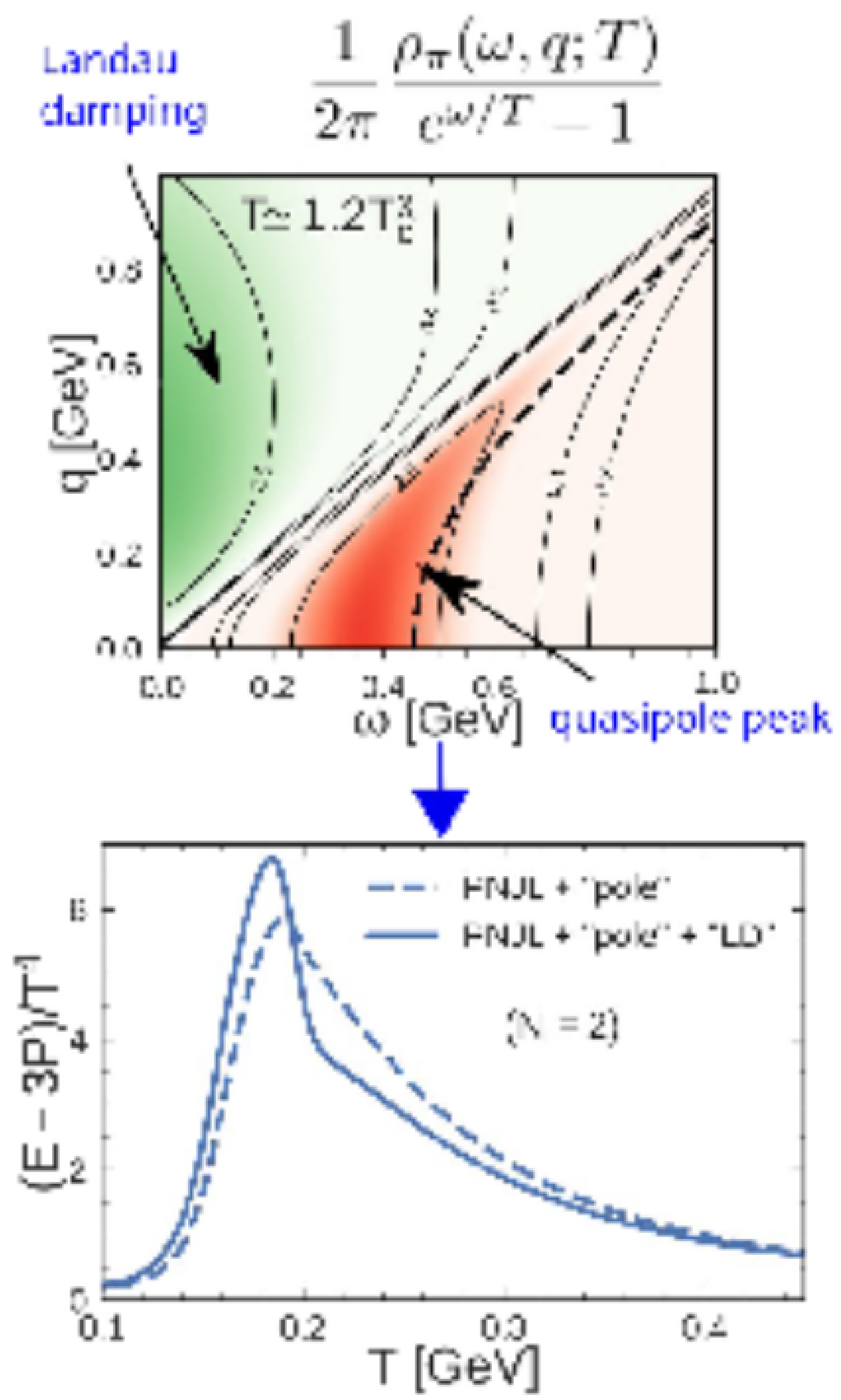
Konstantin Maslov

- Previous work: neutron NS EoS in extended RMF models
- Extension: assume field-dependent couplings and hadron masses
  - Can solve the hyperon and Delta puzzles – large maximum NS mass with these d.o.f. included [Maslov, Kolomeitsev, Voskresensky PLB 748 (2015), NPA 950 (2016), NPA 961 (2017)]
  - Pass many constraints from nuclear physics, including the chiral EFT limits and flow constraint
  - Used to study NS cooling with hyperons [Grigorian, KM, Voskresensky NPA (2018)] and to study quark-hadron pasta phases in NSs [KM, Yasutake et al. PRC 100 (2019)]





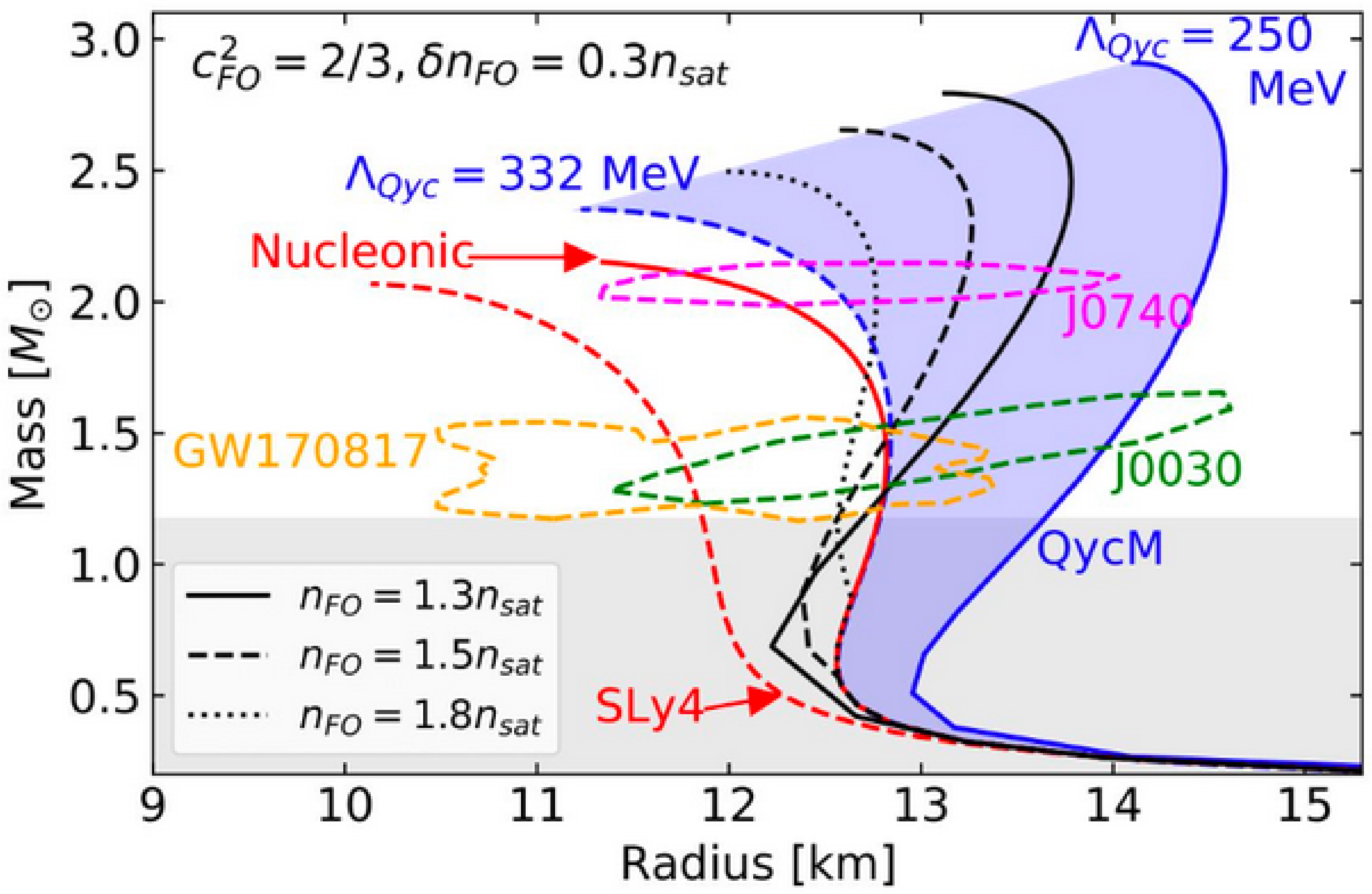
- Recent results: off-shell meson effect on the PNJL EoS
- Excitations in spacelike region of spectral density – Landau damping
- Threated as negligible in many previous works on PNJL model
- Thermal enhancement of soft boson contribution to the pressure – noticeable contribution to EoS
- Quantitatively significant: e.g. shifts the maximum position of the trace anomaly (interaction measure), and the chiral pseudocritical temperature



Collaboration with D. Blaschke (University of Wroclaw), in preparation

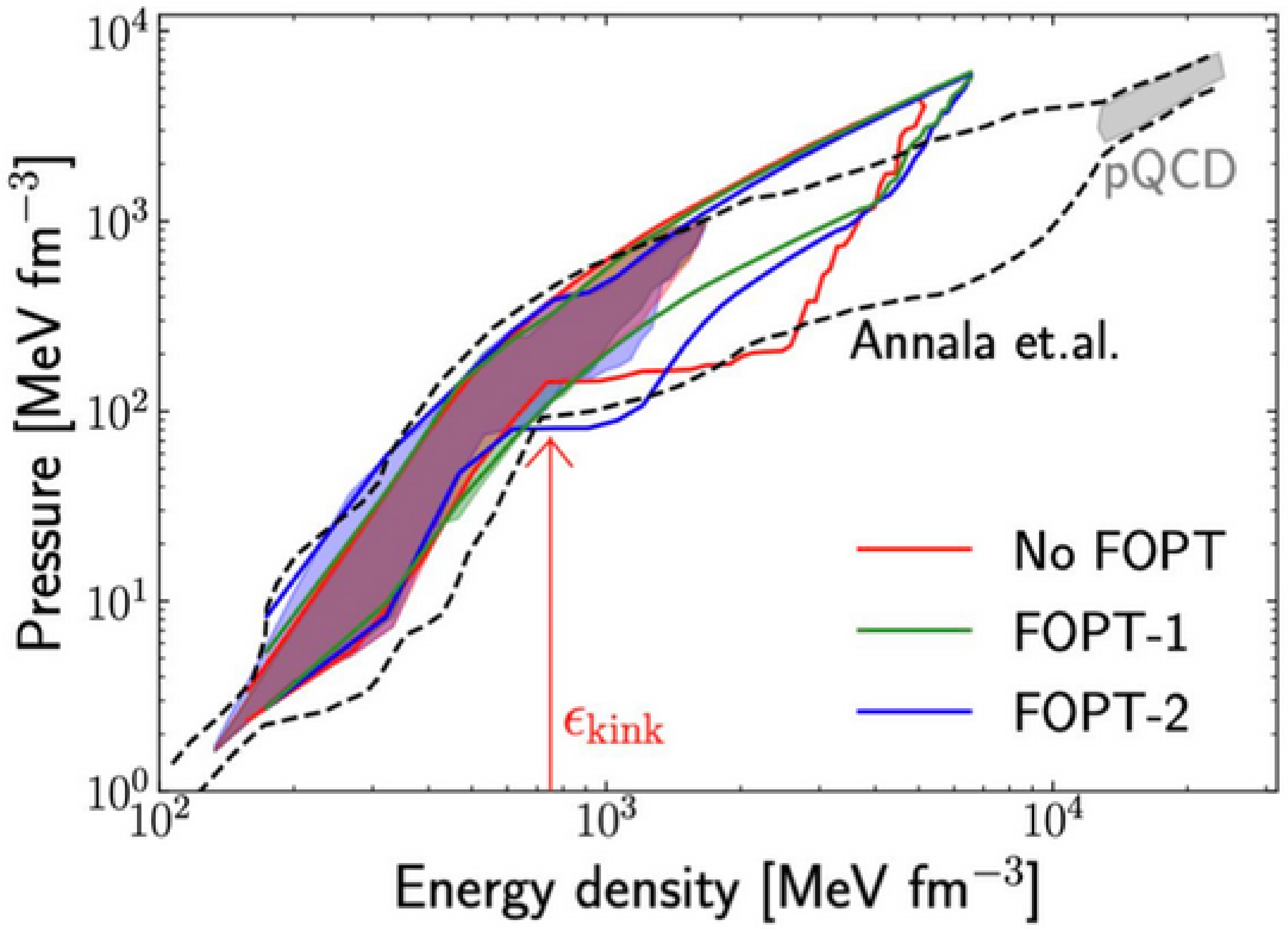
Rahul Somasundaram

Impact of phase transitions for masses and radii



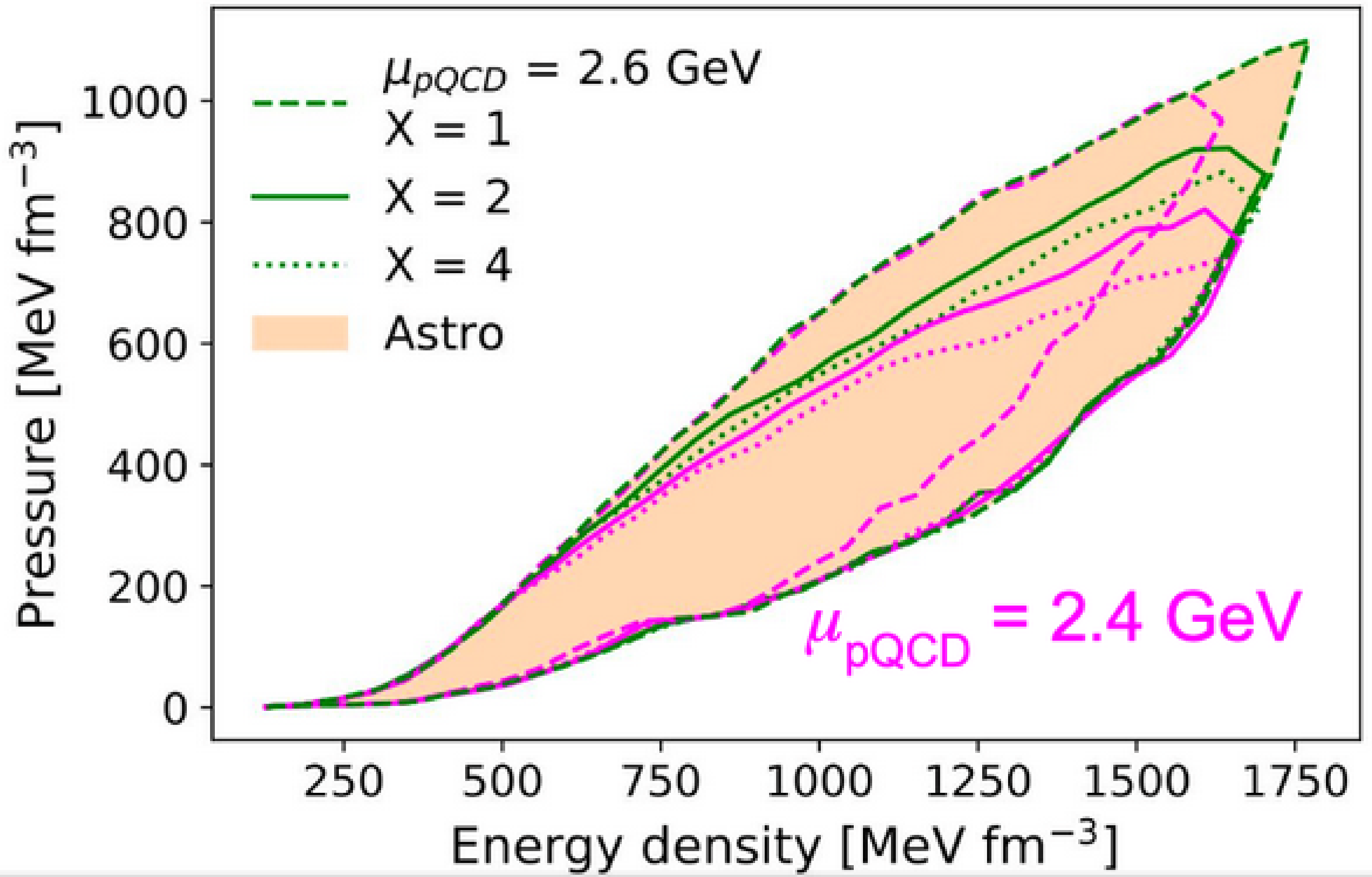
R. Somasundaram and J. Margueron, EPL 138 (2022) 1, 14002

Constraints on the equation of state



R. Somasundaram, I. Tews and J. Margueron, arXiv:2112.08157

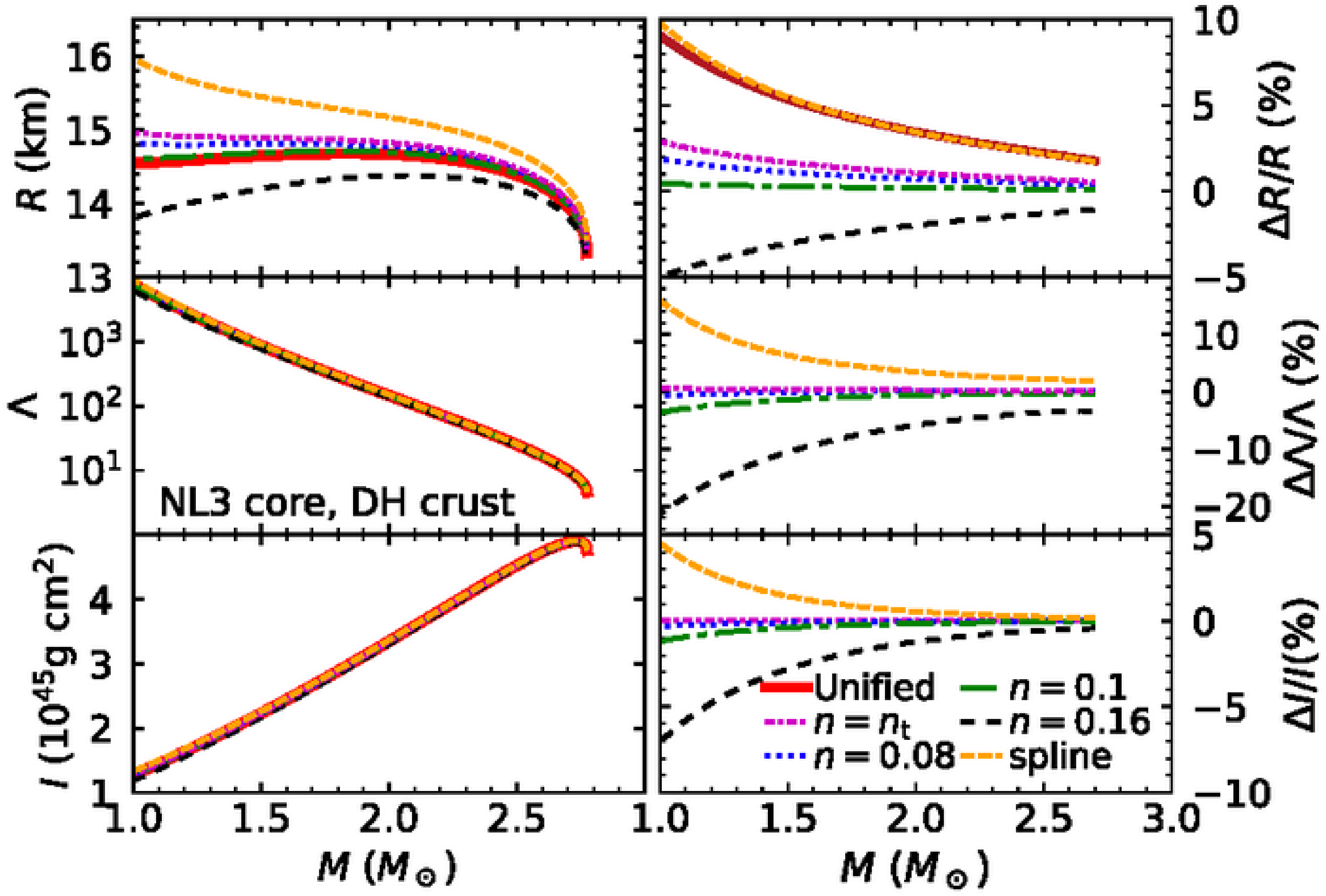
The impact of perturbative QCD calculations



R. Somasundaram, I. Tews and J. Margueron, arXiv:2204.14039

Lami Suleiman

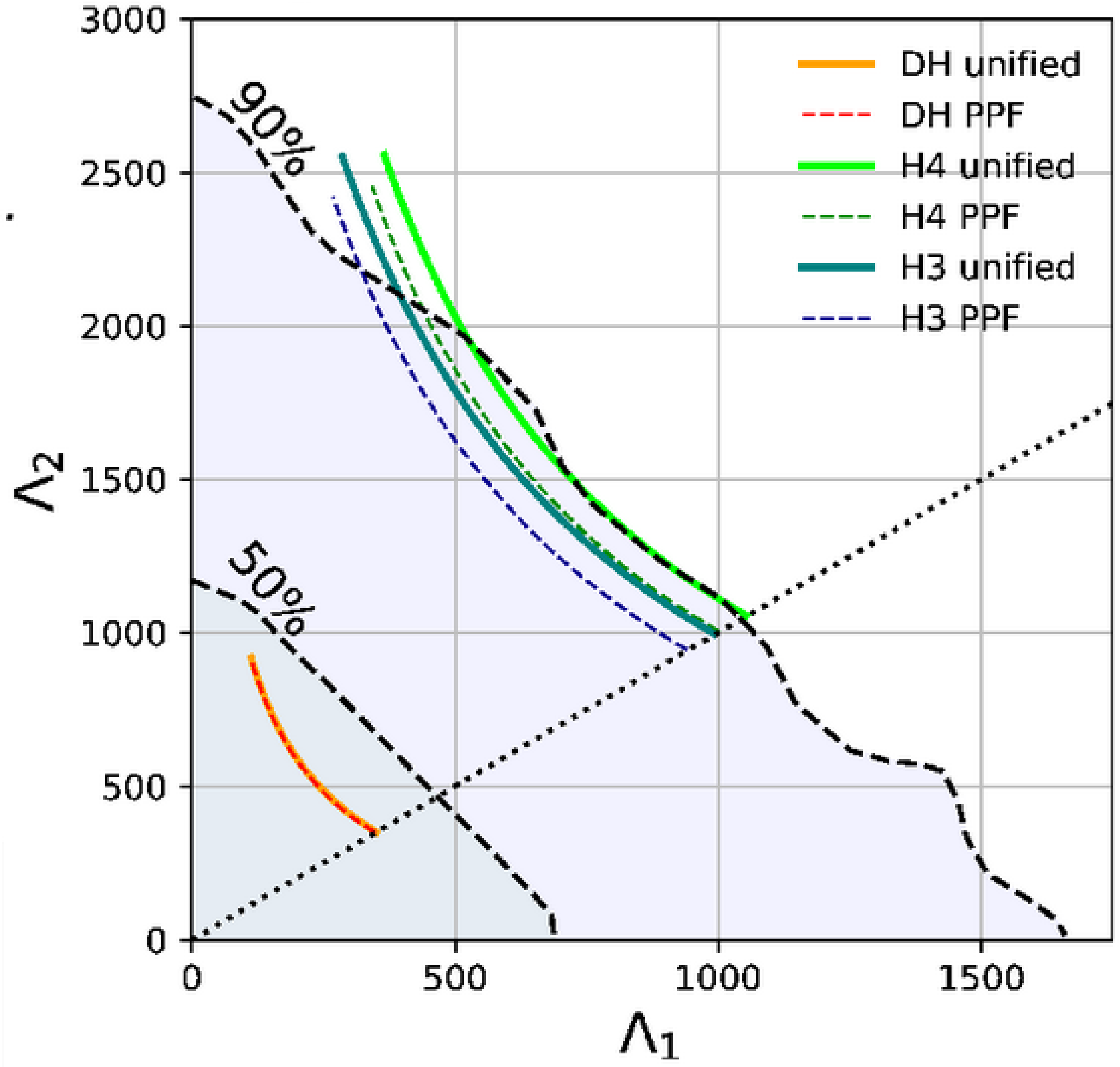
Influence of non-unified equations of state on NS modeling



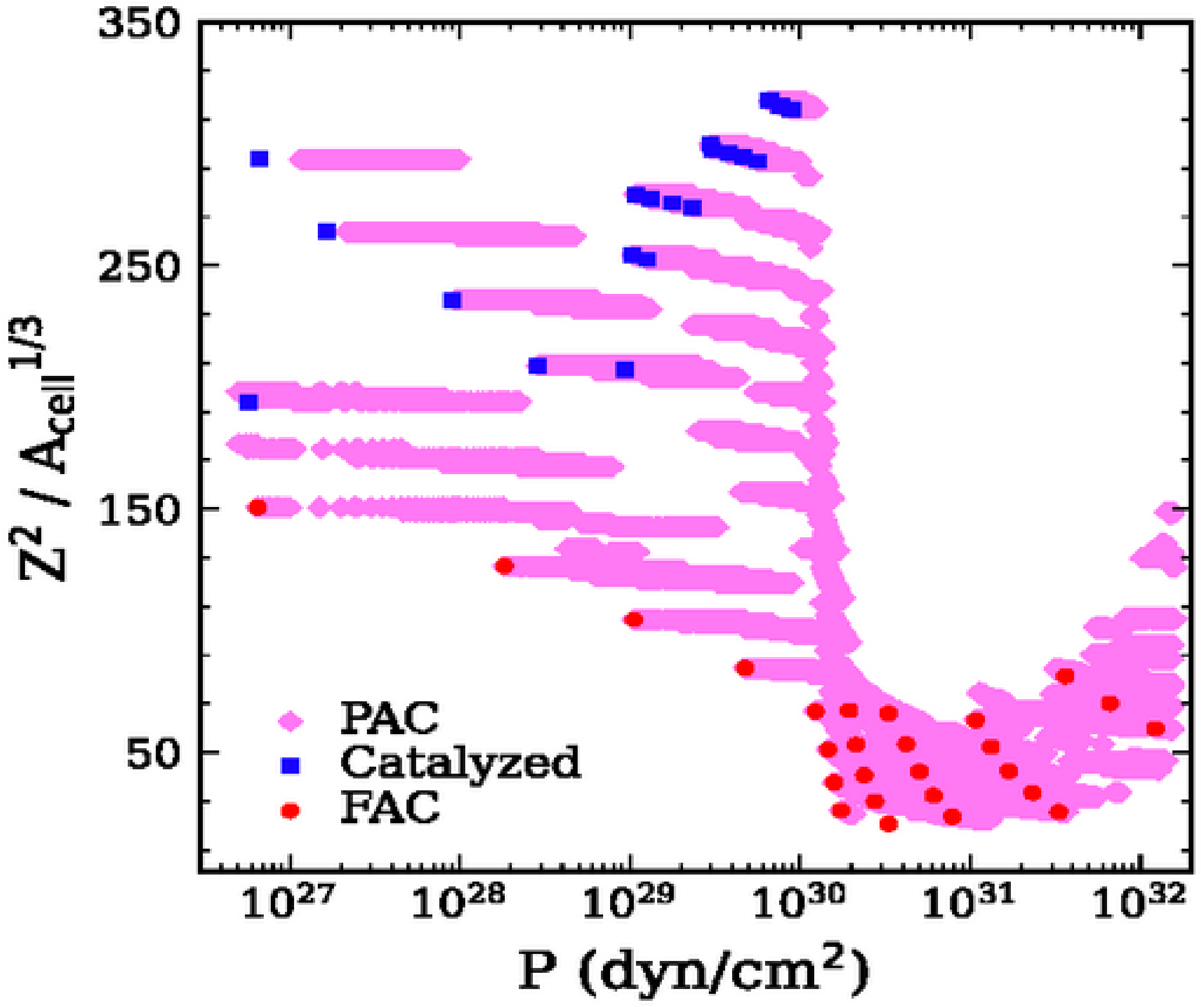
L. Suleiman, M. Fortin, J. L. Zdunik, & P. Haensel
Phys. Rev. C 104, 015801

A revision of piecewise polytropic fits with modern and unified equations of state

L. Suleiman, M. Fortin, J. L. Zdunik, in press.



Heat sources and composition of a partially accreted crust



L. Suleiman, J. L. Zdunik, P. Haensel and M. Fortin, 2022, A&A, 662, A63

Summary

- Leveraging neutron star observations to learn about QCD and the nucleon-nucleon interaction
- Constraints on mass-radius curve and EOS
- Understand the approximate size and the physical origin of the uncertainties in our posteriors
- Nuclear astrophysics needs multi-messenger astronomy
- NS cooling data will provide new constraints on the composition of dense matter
- Generating new nuclear physics input for merger simulations — new tables!
- Propagating uncertainties through EOS and neutrino uncertainties
- NP3M - A new collaboration to address this science at the interface of nuclear physics and neutron star mergers

Very exciting future! FRIB, P/CREX, GWs, NICER, Strobe-X, IXPE, and more!