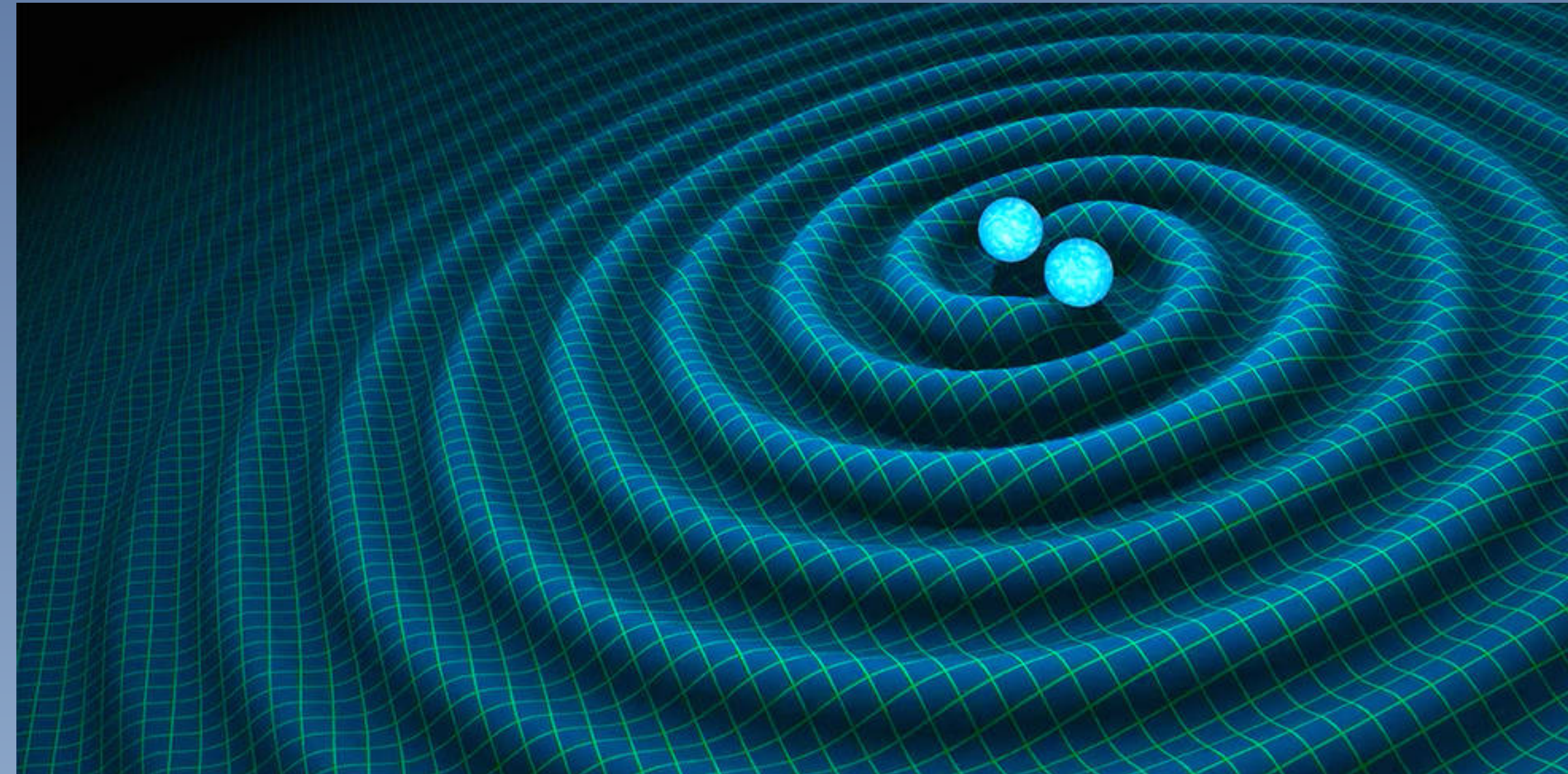


Probing the Finite-Temperature Neutron Star Equation of State with Post-Merger Gravitational Waves



Bhaskar Biswas | Hamburg observatory

CSQCD conference, Barcelona

May 19, 2026



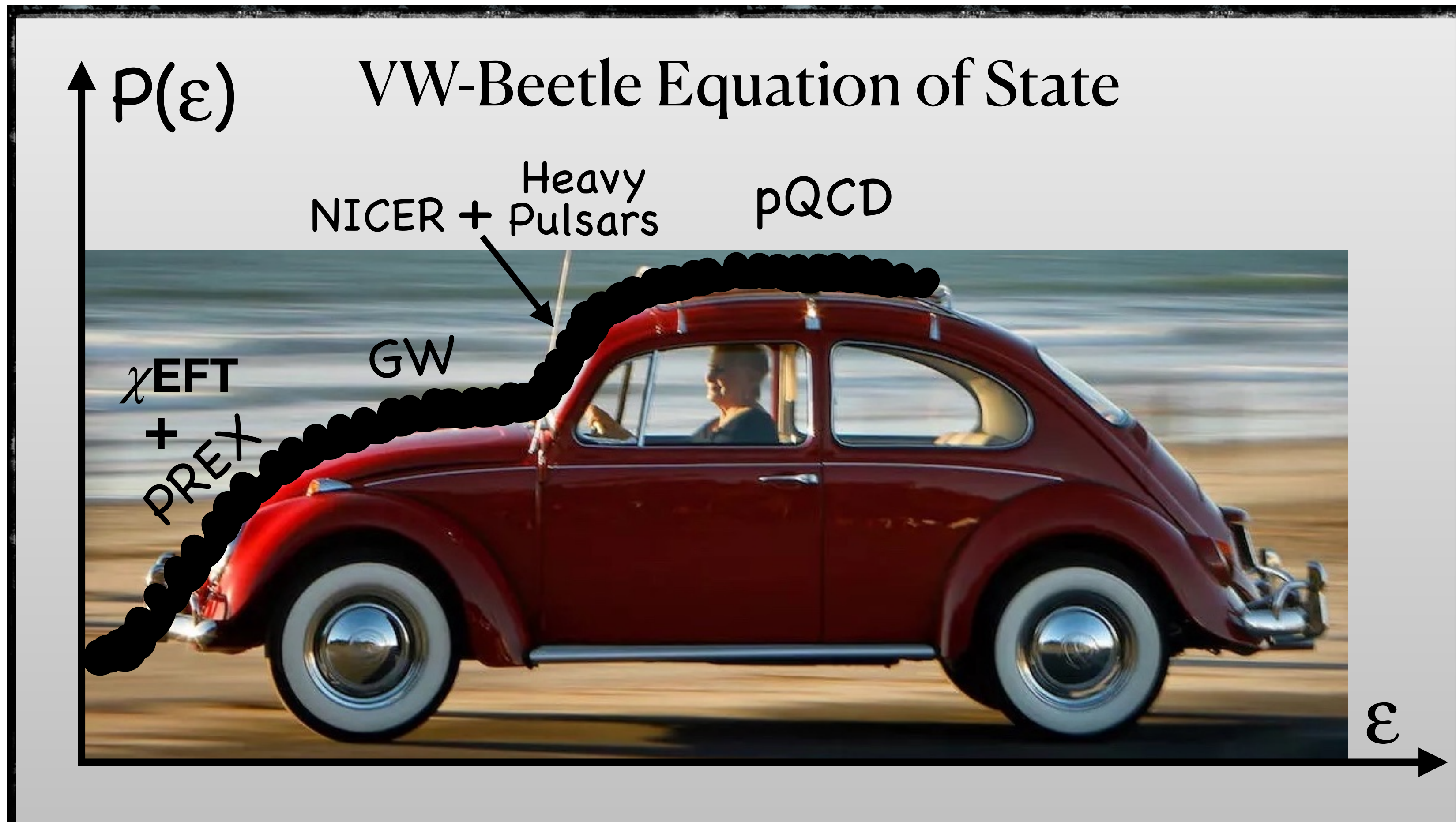
Universität Hamburg

DER FORSCHUNG | DER LEHRE | DER BILDUNG



Alexander von
HUMBOLDT
STIFTUNG

Input from variety of sources



Nuclear Physics

- χ_{EFT}
- pQCD
- PREX/CREX ...

Astrophysics

- Heavy mass pulsar
- X-ray observations by NICER
- Gravitational waves detected by LIGO/Virgo from binary neutron star merger

Piekarewicz, 2024

EOS Parameterization: From Crust to Core

Low Density ($\rho < 2\rho_0$)

EOS anchored to nuclear saturation physics

- Outer crust: SLy EOS (below $0.5\rho_0$)
- Nuclear meta-model (Bombaci et al. 1991):

$$e_{\text{sym}}(\rho) = e_{\text{sym}}(\rho_0) + L\chi + \frac{K_{\text{sym}}}{2}\chi^2 + \dots$$

$$\chi = (\rho - \rho_0)/3\rho_0$$

Free nuclear parameters:

L — slope of symmetry energy

K_{sym} — curvature of symmetry energy

High Density ($\rho > 2\rho_0$)

Two complementary approaches bracket our ignorance

A. Parametric — Piecewise Polytrope (Read et al. 2009)

$$P(n) = K_i n^{\Gamma_i}, \quad n \in [n_i, n_{i+1}]$$

Physically interpretable · computationally efficient

B. Non-parametric — Gaussian Process (Landry & Essick 2018)

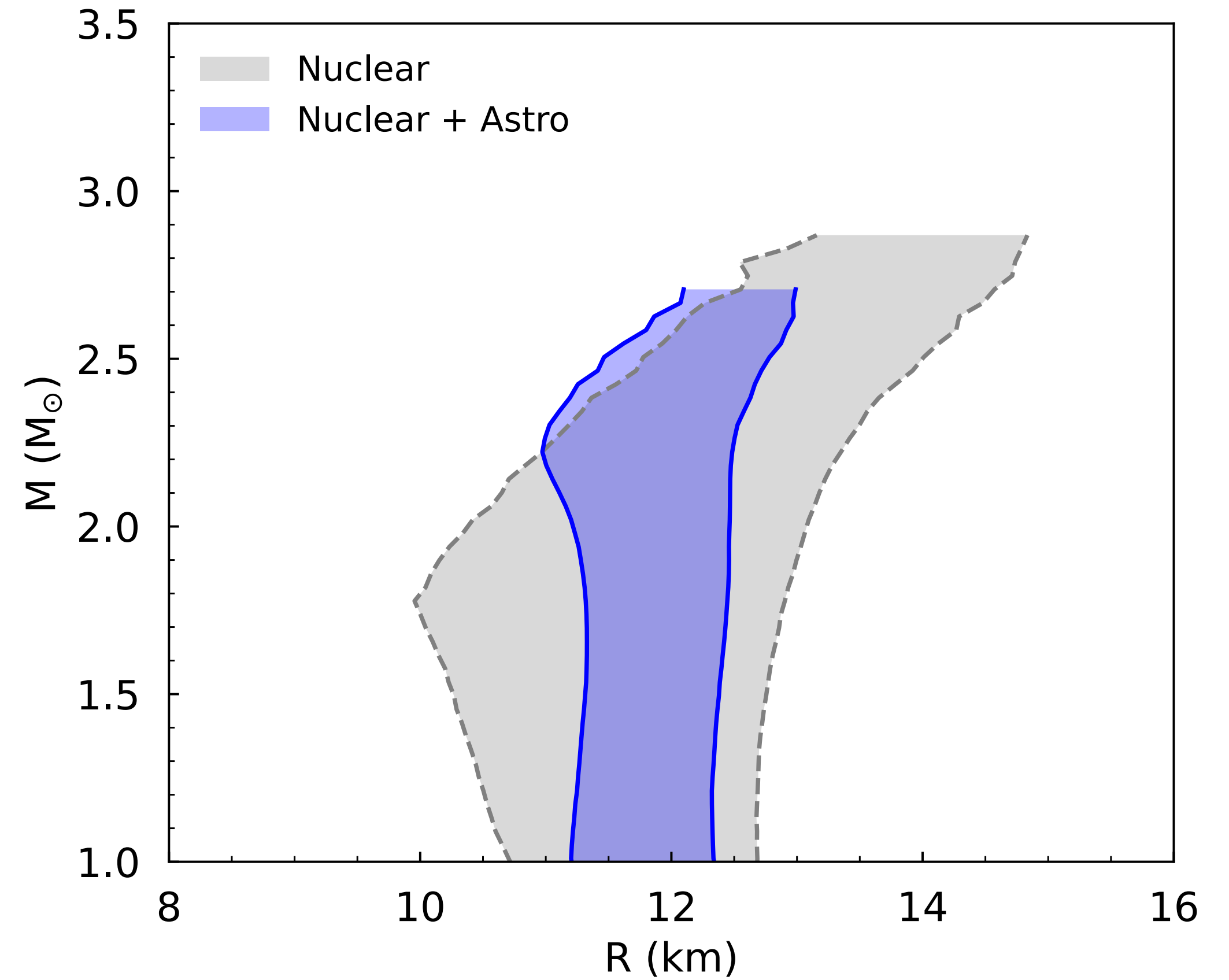
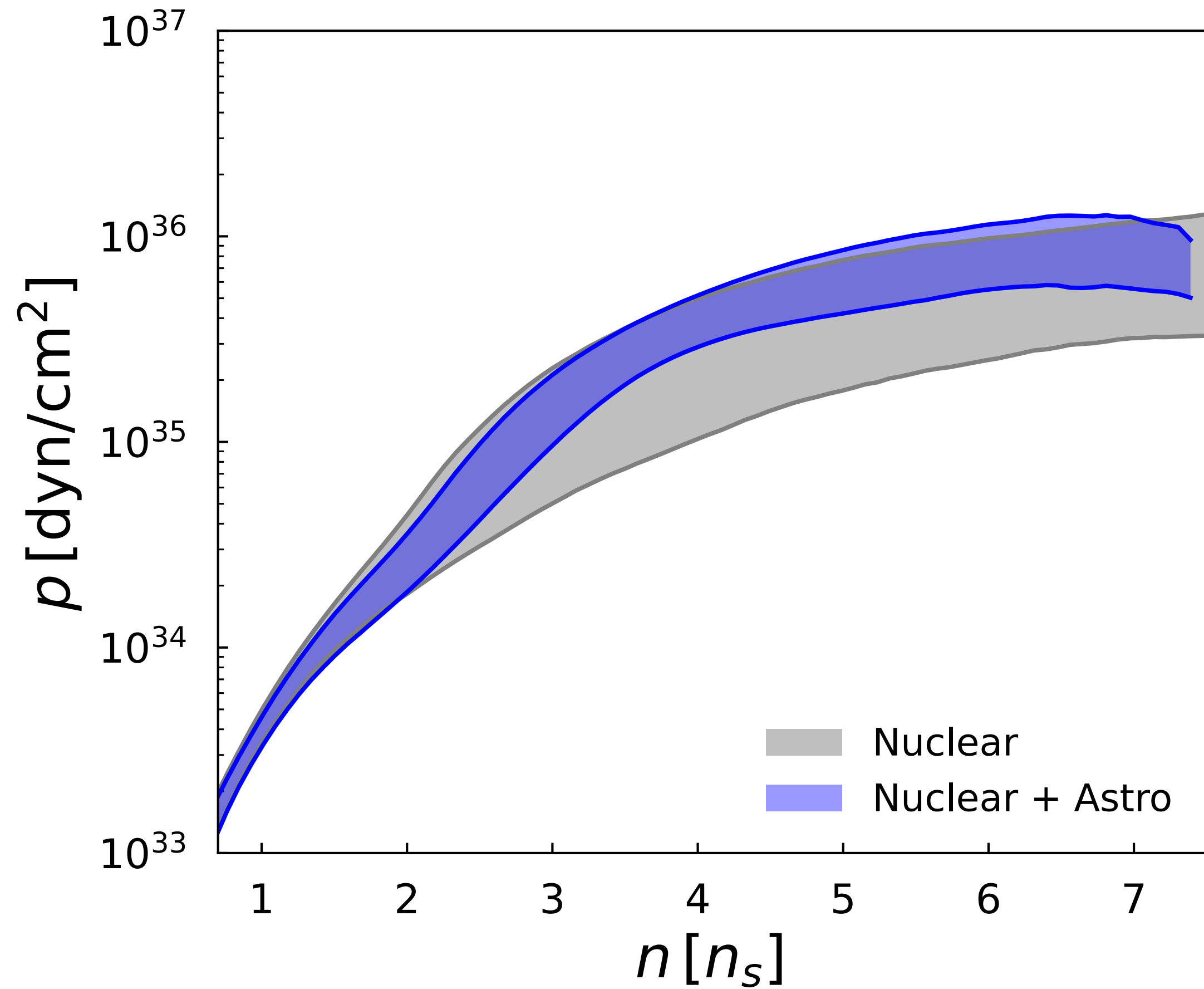
$$\phi(n) \sim \mathcal{N}\left(-\ln\left(\frac{1}{\bar{c}_s^2} - 1\right), K(n, n')\right)$$

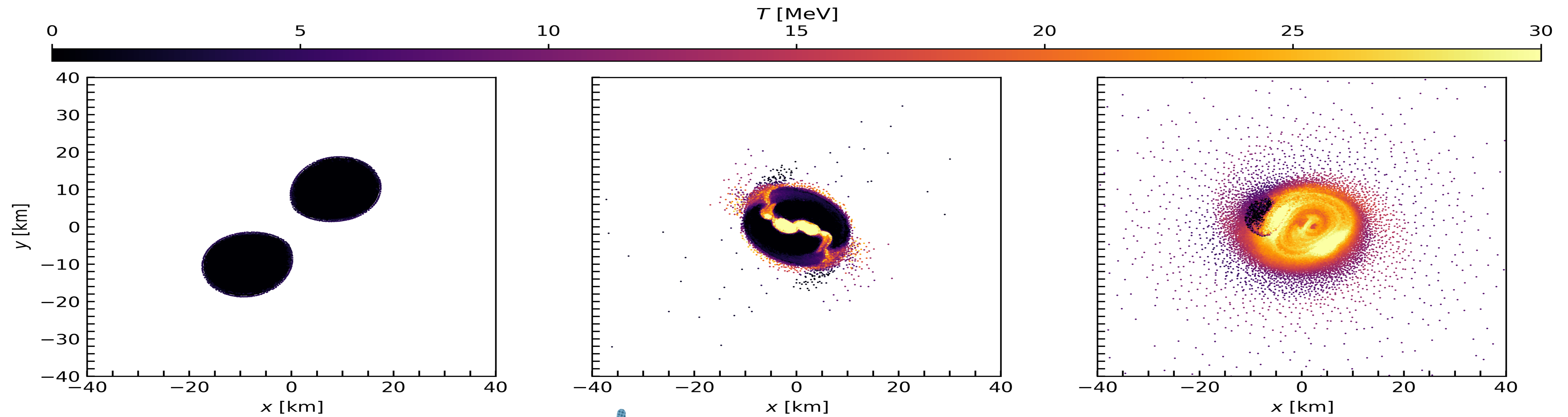
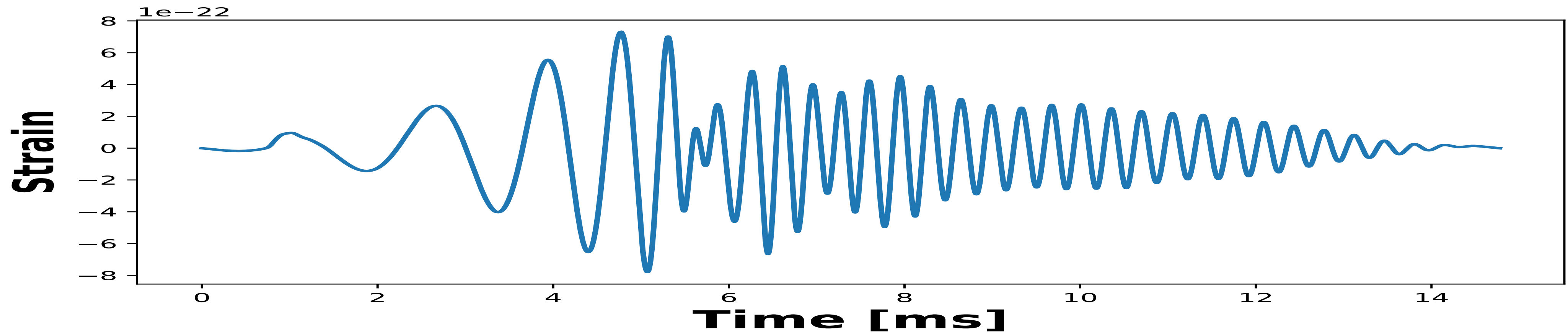
$$\phi(n) = -\ln\left(\frac{1}{c_s^2(n)} - 1\right)$$

Model-agnostic · captures phase transitions

Nuclear meta-model at low density + flexible extrapolation at high density

Uncertainty in cold EOS





Cold Inspiral

$$T \sim 10^6 \text{ K}$$

$$T \sim 10^{-5} \text{ MeV}$$

Hot Merger

$$T \sim 10^{12} \text{ K}$$

$$T \sim 10 - 70 \text{ MeV}$$

Currently we have inspiral data,
but hopefully future detectors
will probe mergers

Post-merger Gravitational waves probe EOS at finite temperatures

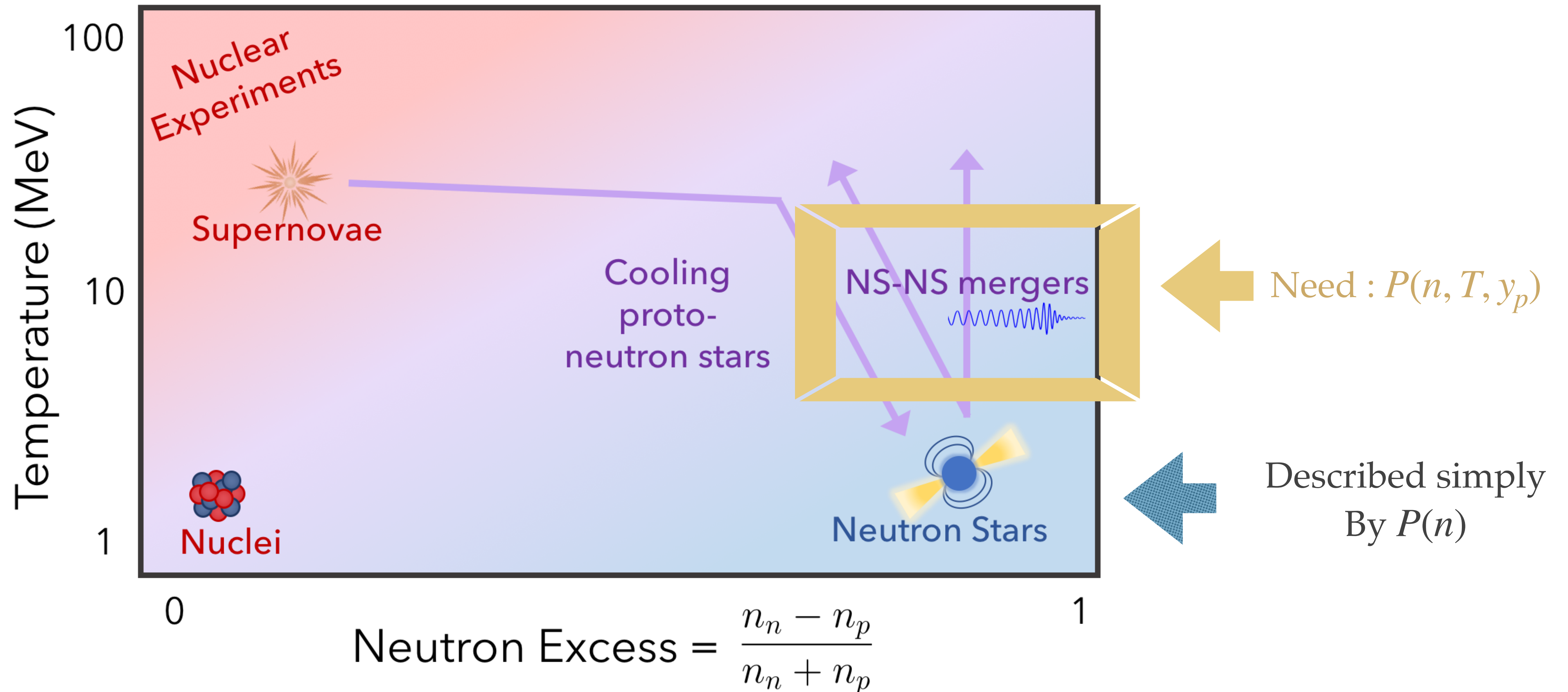
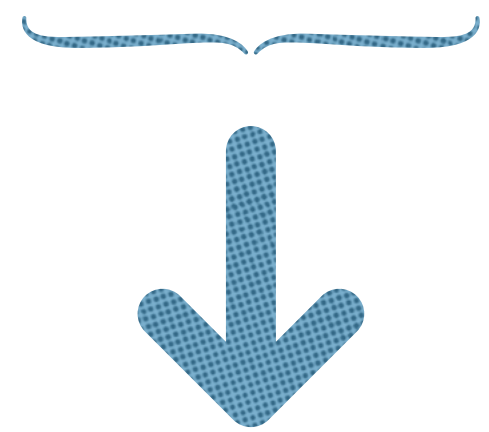


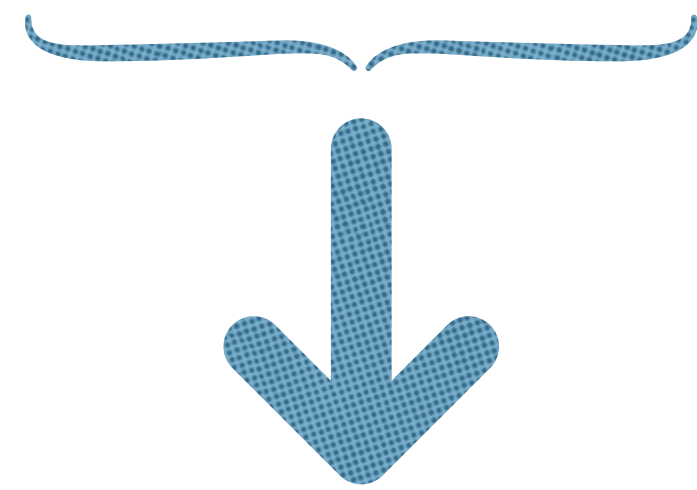
Fig. Credit: Raithel, Ozel, and Psaltis (2019)

There are also uncertainties in the finite-temperature part of the EOS

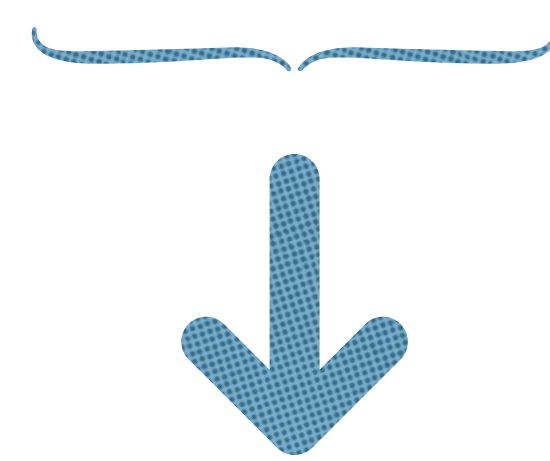
$$P(n, T, y_p) \approx P_{\text{cold}}(n, T = 0) + P_{\text{th}}(n, T) + \dots$$



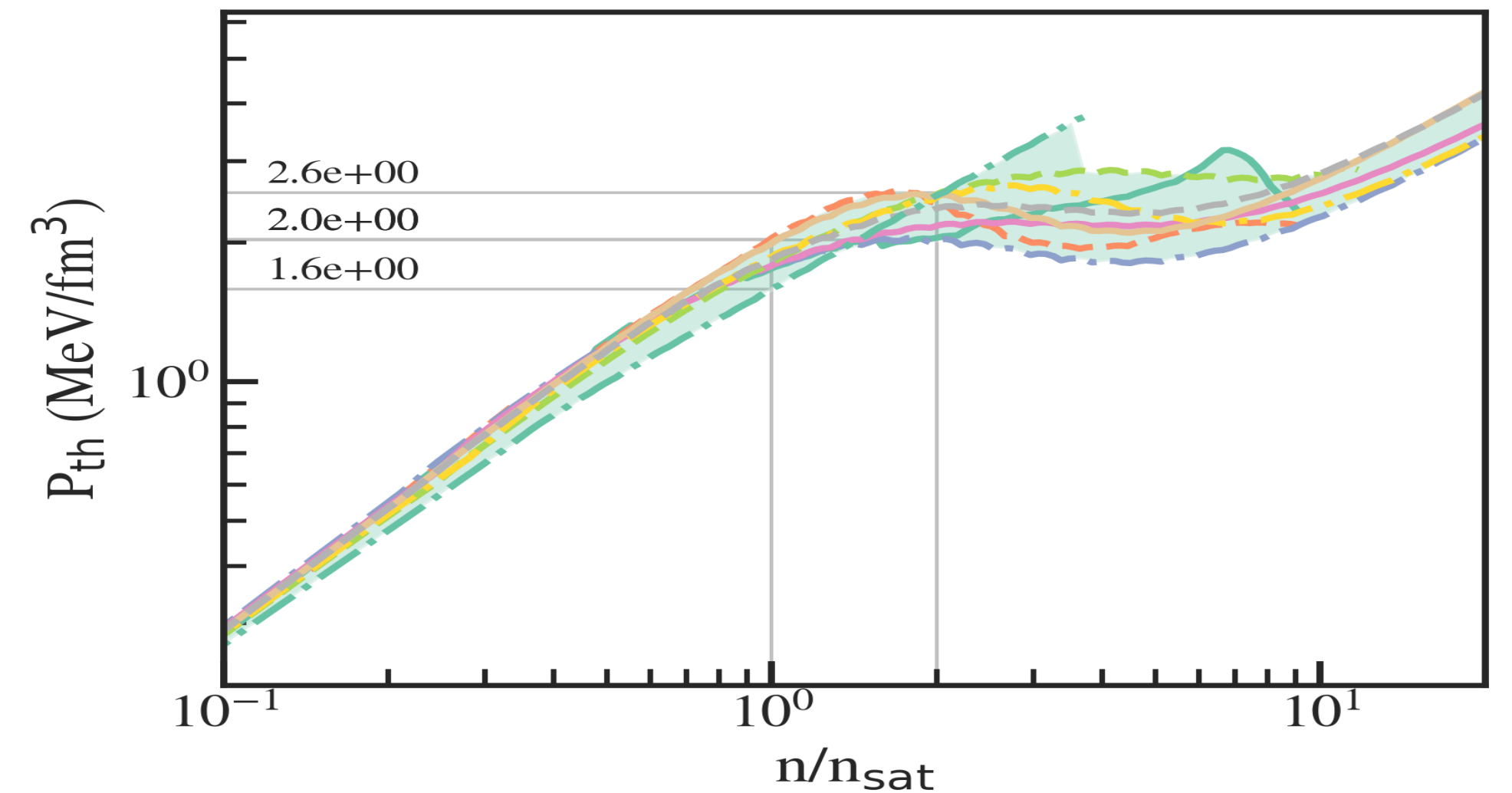
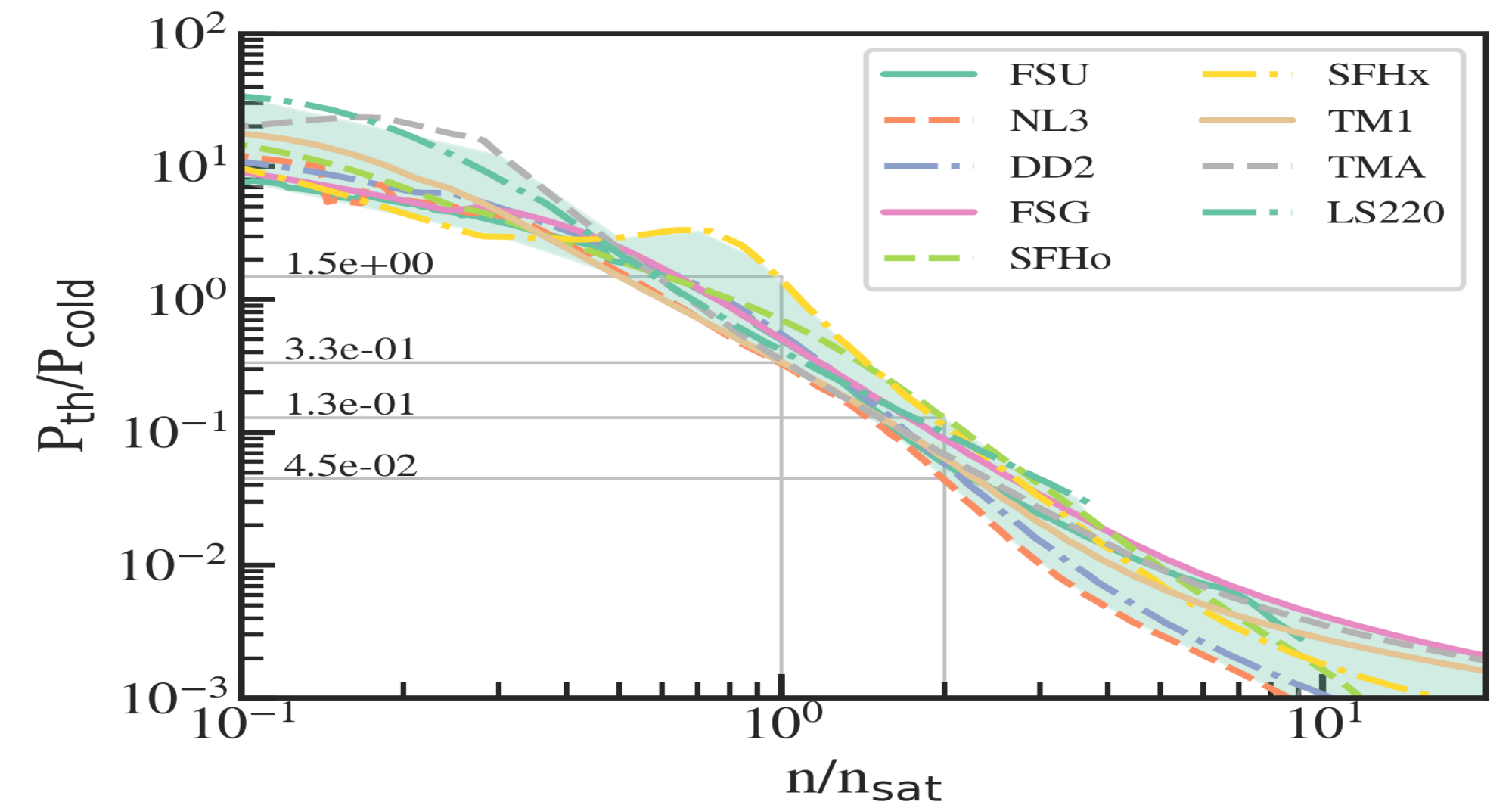
Total Pressure



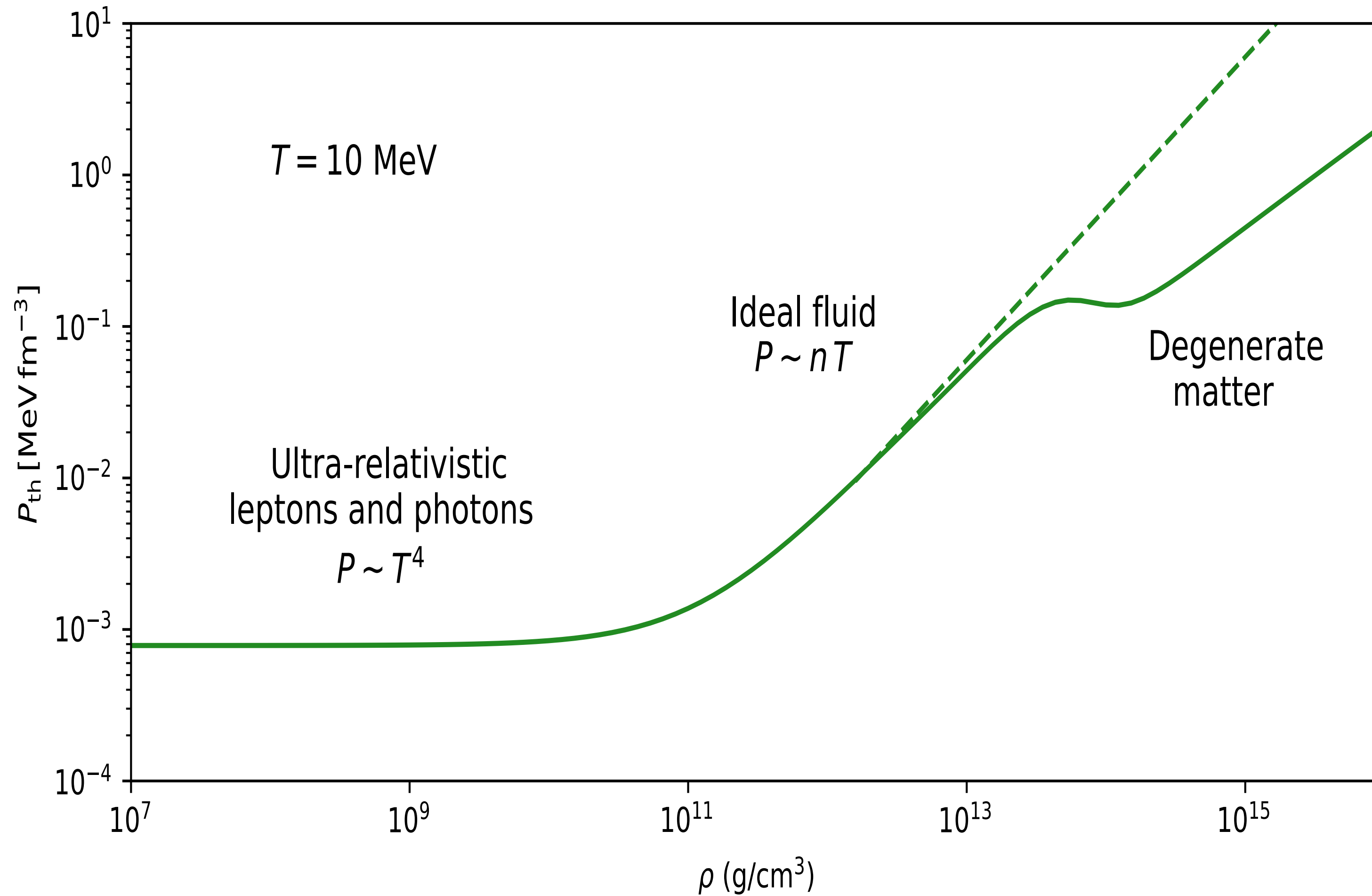
Cold part of the EOS
(e.g. as constrained by tidal deformability or radius)



Finite-temperature part of the EOS



Schematic model for the thermal Pressure



c.f.: hybrid approach, $P_{\text{th}} = nE_{\text{th}}(\Gamma_{\text{th}} - 1)$,
Which neglects the effect of degeneracy
By fixing to a constant Γ_{th}

Goal :
Create a parametric model
that includes
the relevant physics
across all density ranges

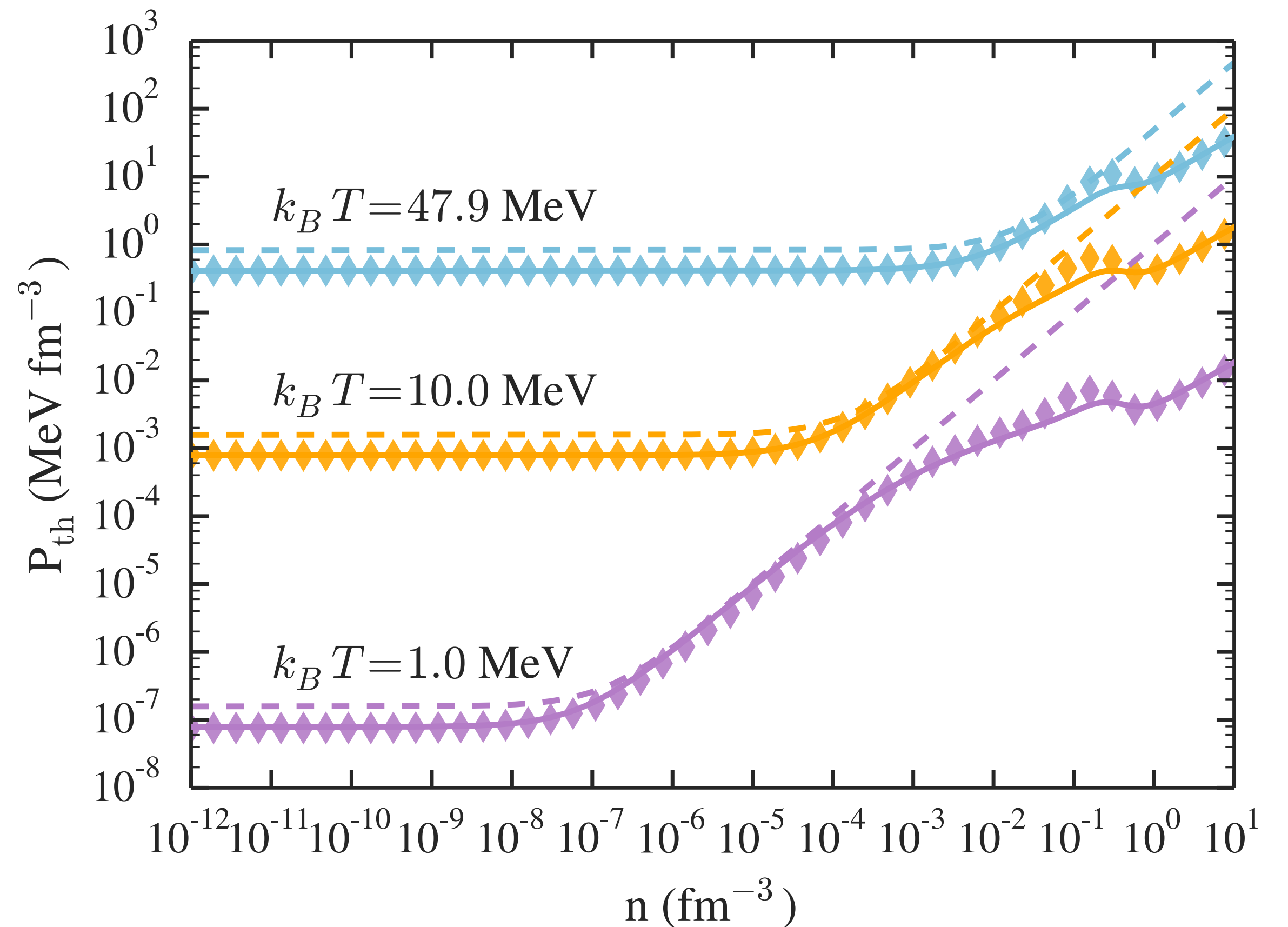
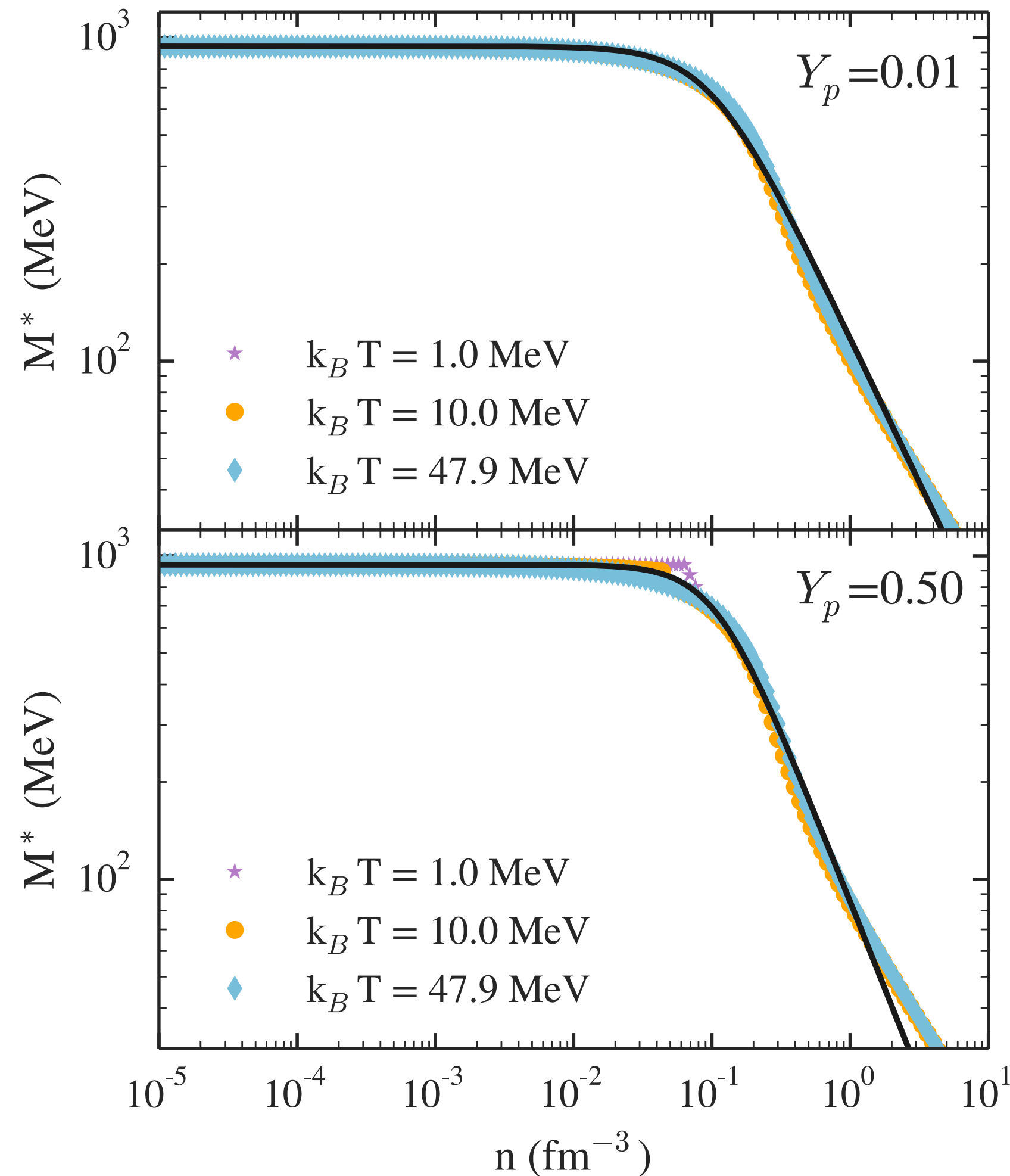
M^* -approximation of degenerate thermal pressure

$$M^*(n) = \left\{ (mc^2)^{-2} + \left[mc^2 \left(\frac{n}{n_0} \right)^{-\alpha} \right]^{-2} \right\}^{-1/2}$$

$$P_{\text{th}} \approx - \frac{\partial a}{\partial n} n^2 T^2$$

$$a(n, M^*) = \frac{\pi^2}{2} \frac{\sqrt{P_F(n)^2 + M^*(n)^2}}{P_F(n)^2}$$

} Degenerate thermal Pressure from Fermi liquid theory



SPHINCS_BSSN: Numerical relativity with particles

(Developed by Stephan Rosswog & Peter Diener)

Current Capability

- ❖ **First Full GR Lagrangian hydrodynamic code**
- ❖ **Spacetime evolution** : Similar to Eulerian codes
Baumgarte-Shapiro-Shibata-Nakamura (BSSN) formalism
- ❖ **Matter evolution** : freely moving **SPH particles**
- ❖ **Cold EOS**: Piecewise polytrope
- ❖ Implemented **Thermal EOS** based on Raithel et al.

SPHINCS

Smoothed Particle Hydrodynamics In Curved Spacetime



Credit : Stephan Rosswog

Major Advantages

- ❖ Neutron star **surface** no problem
- ❖ **Vaccum is vaccum**
- ❖ **Ejecta** evolution

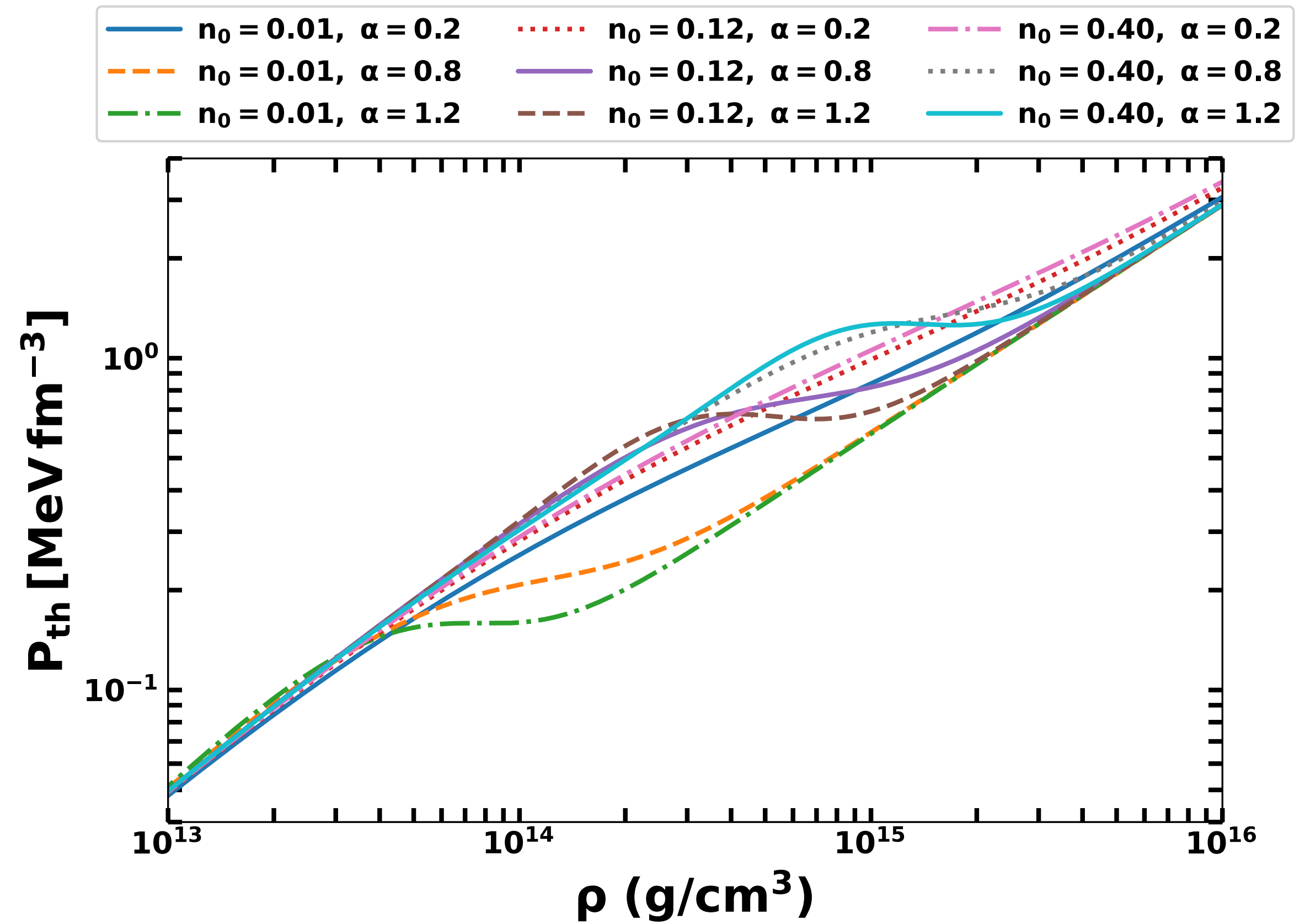
Exploring uncertainties in finite-temperature EOS in neutron star mergers

9 Merger Simulation

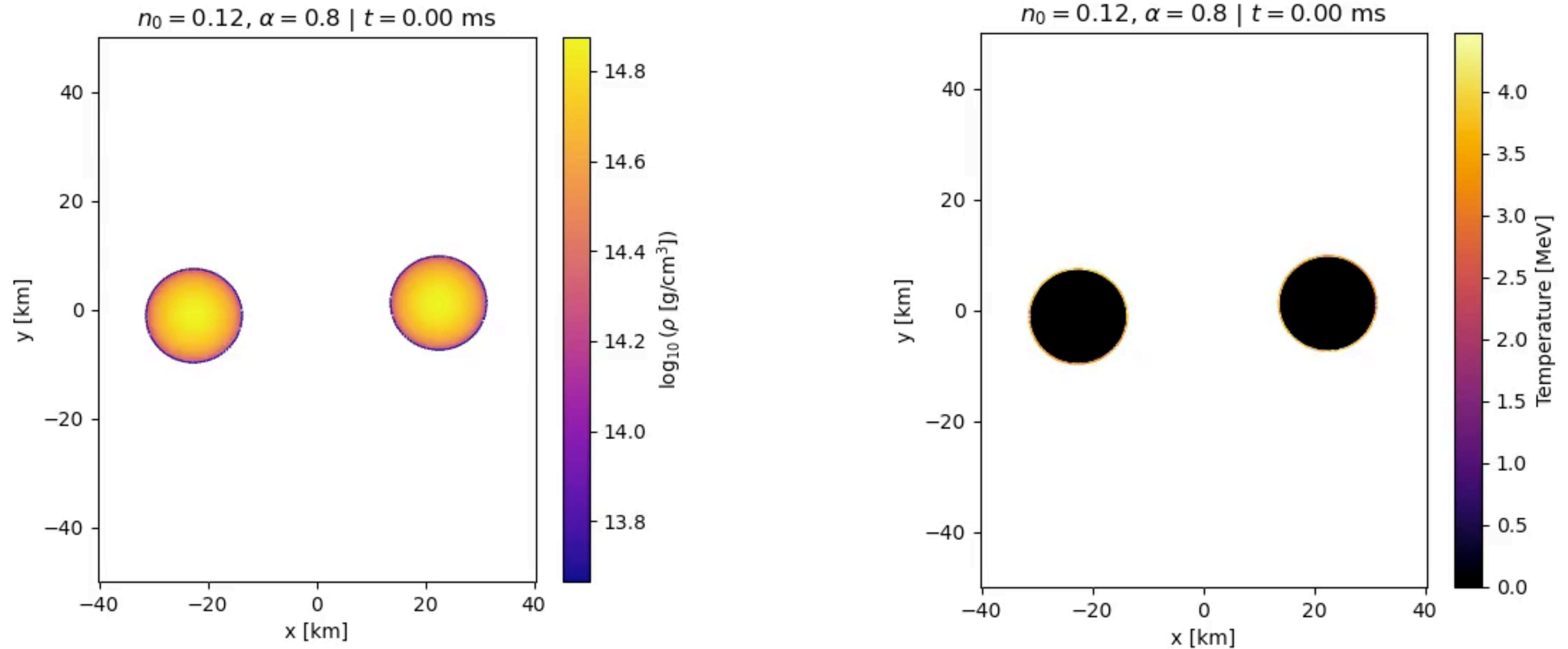
With **SPHINCS_BSSN** code, SPH-based full-GR
(See e.g., Rooswog + Diener 2020)

1 cold EOS (ENG) \times $\left\{ \begin{array}{l} n_0 = 0.01, 0.12, 0.40 \\ \alpha = 0.2, 0.8, 1.2 \end{array} \right.$

That brackets the **range of uncertainty** in the
Finite temperature part of the EOS



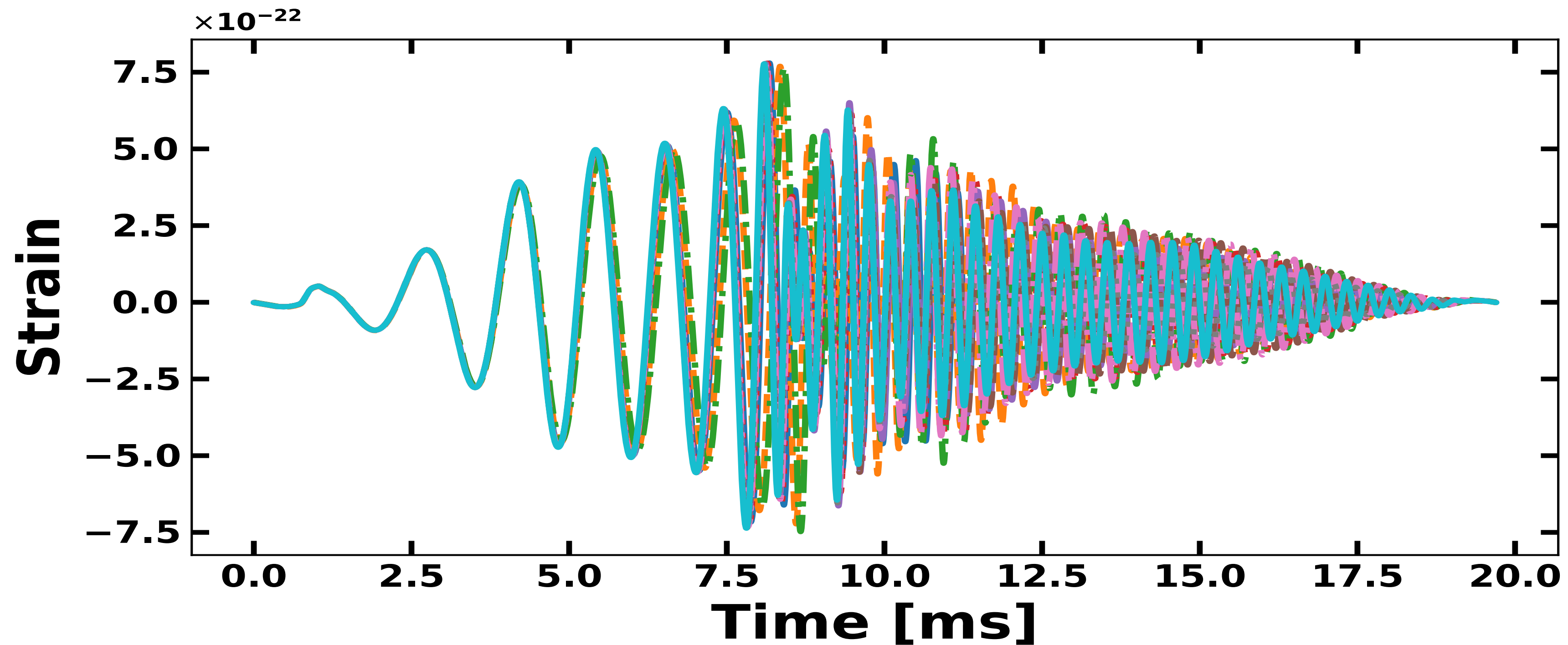
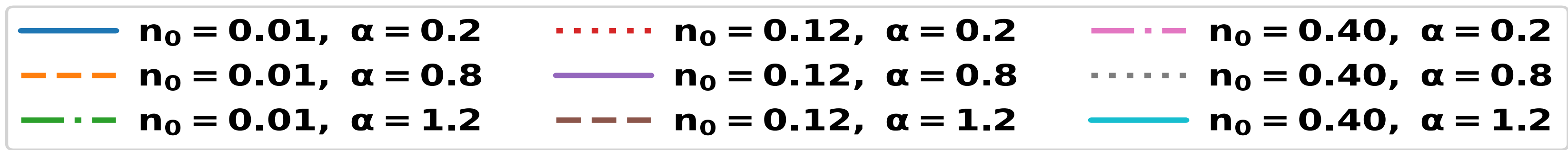
Simulation of $1.3 M_{\odot} - 1.3 M_{\odot}$ binary neutron star mergers with M^* -approximation



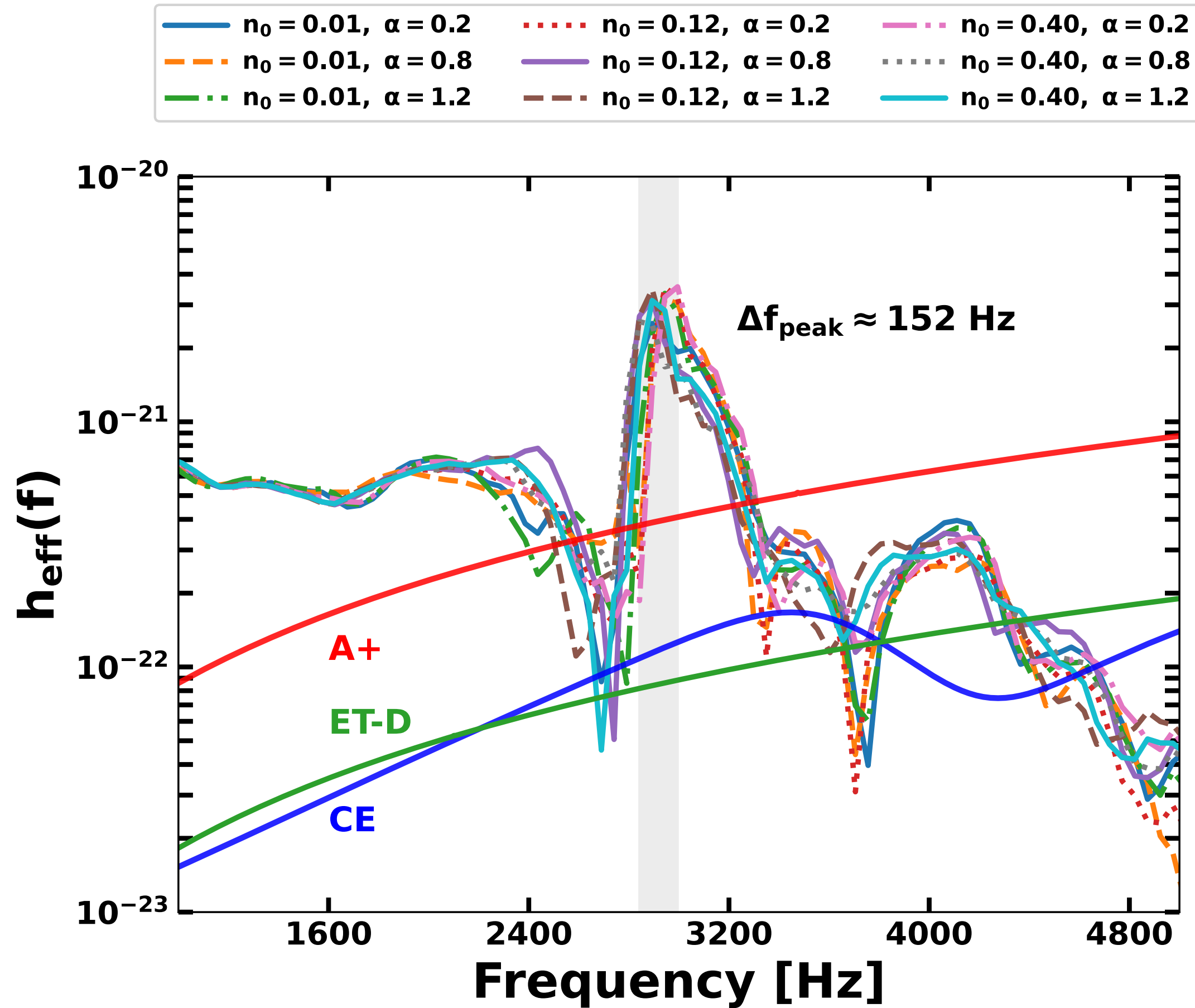
Subtle effect in postmerger signal

Inspirals are
almost identical

Differences in postmerger signals

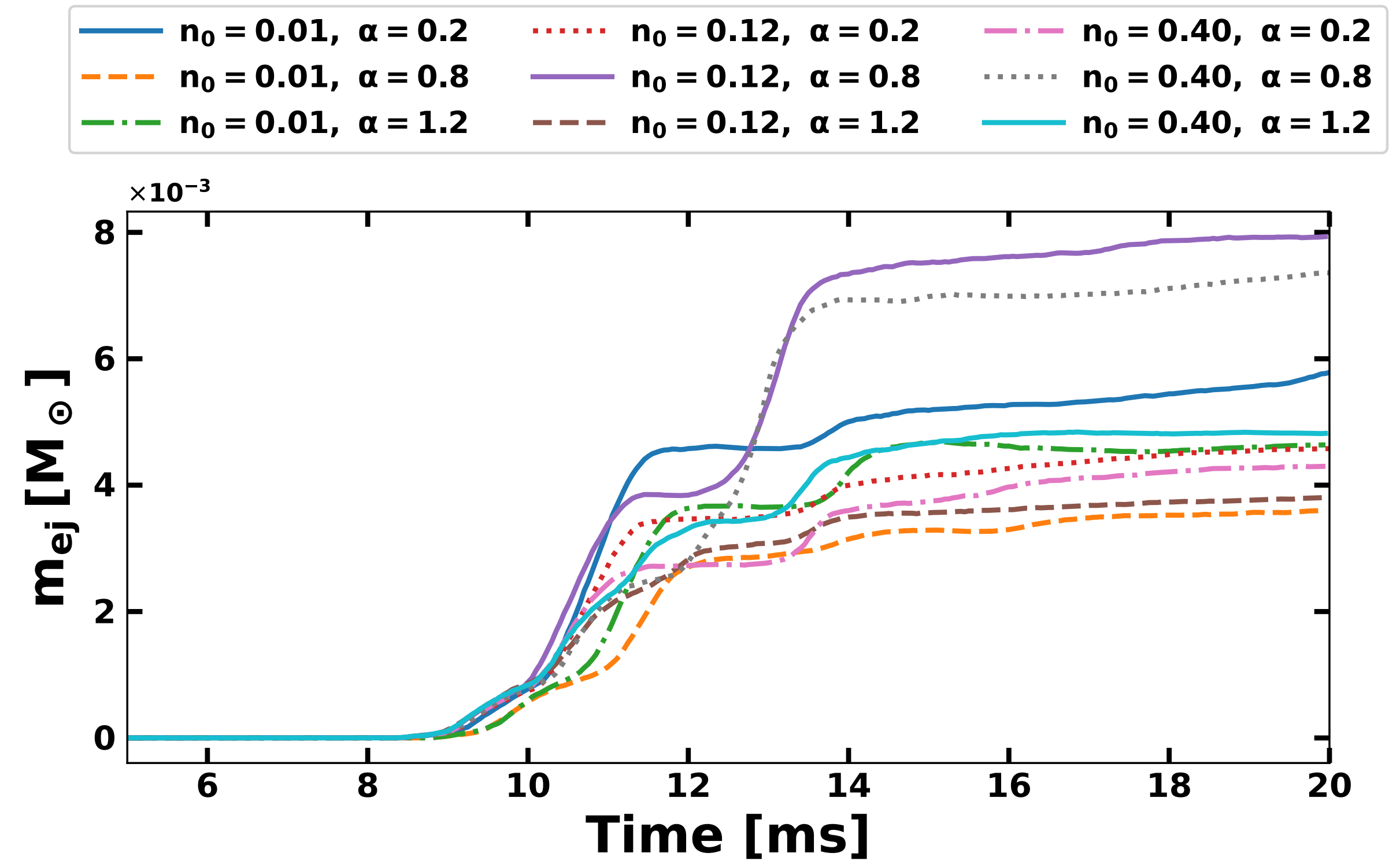


Late time observables



Potentially **detectable** with 3G detectors
 e.g. Cosmic Explorer (CE)

May impact **electromagnetic counterparts**
 associated with the mergers



Biswas, S. Rosswog, P. Diener, & L. Schnabel,
 arXiv:2601.01402, submitted in PRD

Summary & Future direction

- ❖ **Postmerger observables** probe the **Finite-temperature EOS**
 - **M^* -framework** allow for a robust treatment of thermal physics in merger simulation, added to any cold EOS
 - Initial parameter study with one cold EOS shows M^* -parameters can affect remnant thermal structure and postmerger GWs
- ❖ **Next study :**
 - expanding parameter space for **more cold EOS**; more detailed study of postmerger ejecta
 - Implementation of **neutrino transport** : to keep track of y_e **evolution**
 - **Nucleosynthesis** Post-processing: Predict **r-process** yields



“Thanks for your attention !”