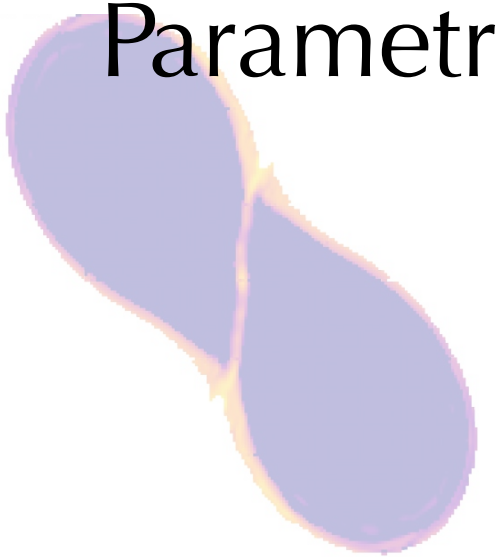
Parametric Finite-Temperature Equation of State in Neutron Star Merger Simulations



Carolyn Raithel
Institute for Advanced Study
Princeton Center for Theoretical Science
Princeton Gravity Initiative

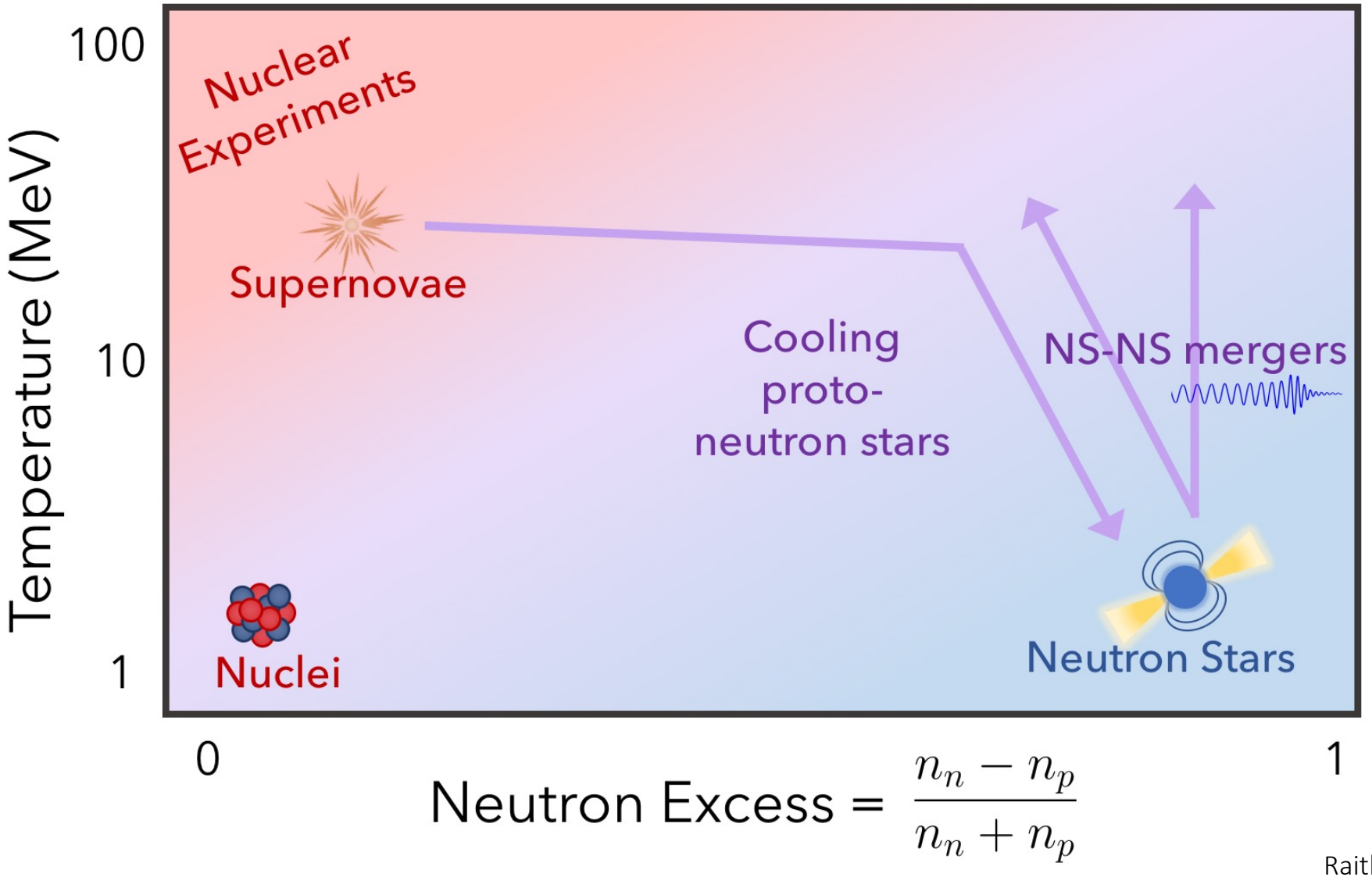
PRINCETON CENTER FOR THEORETICAL SCIENCE

TCAN Collaboration Meeting
July 13, 2021

Princeton gravity Initiative

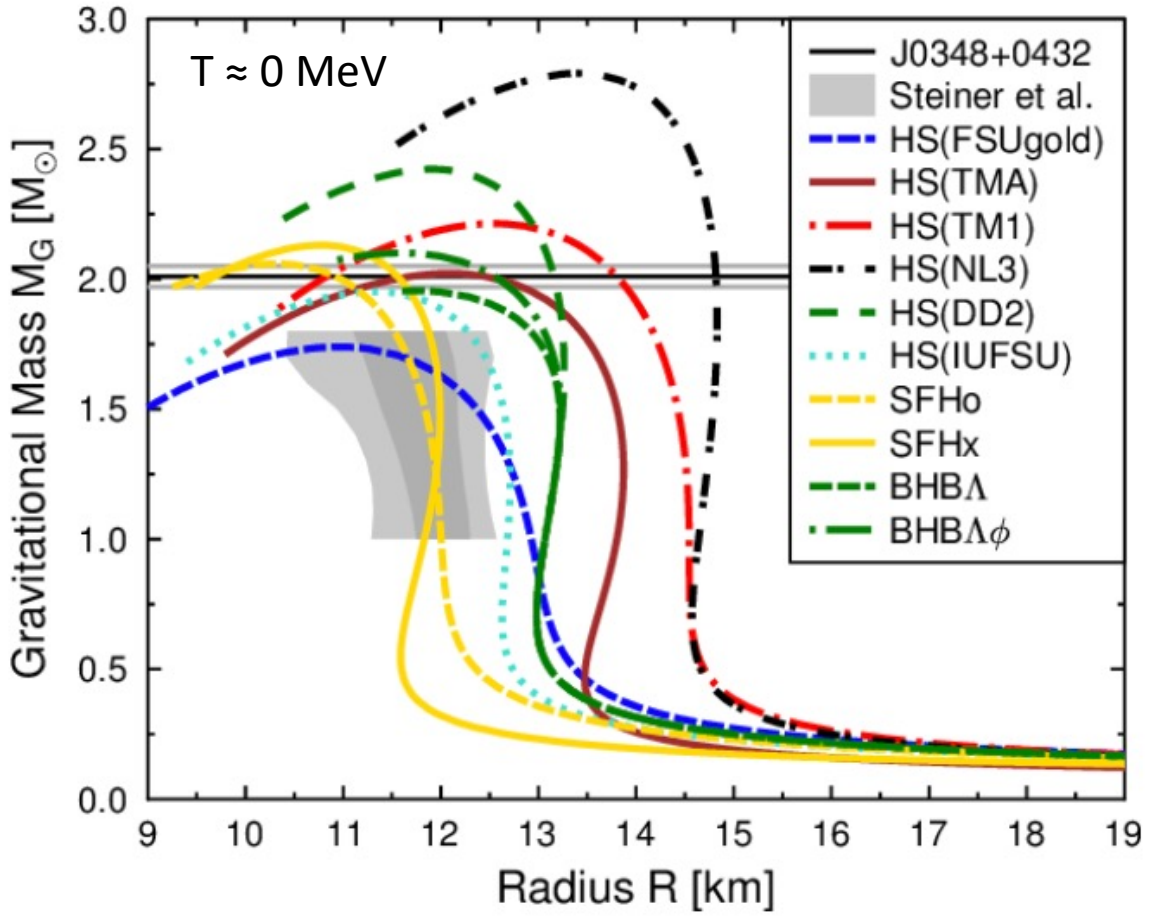
IAS INSTITUTE FOR ADVANCED STUDY

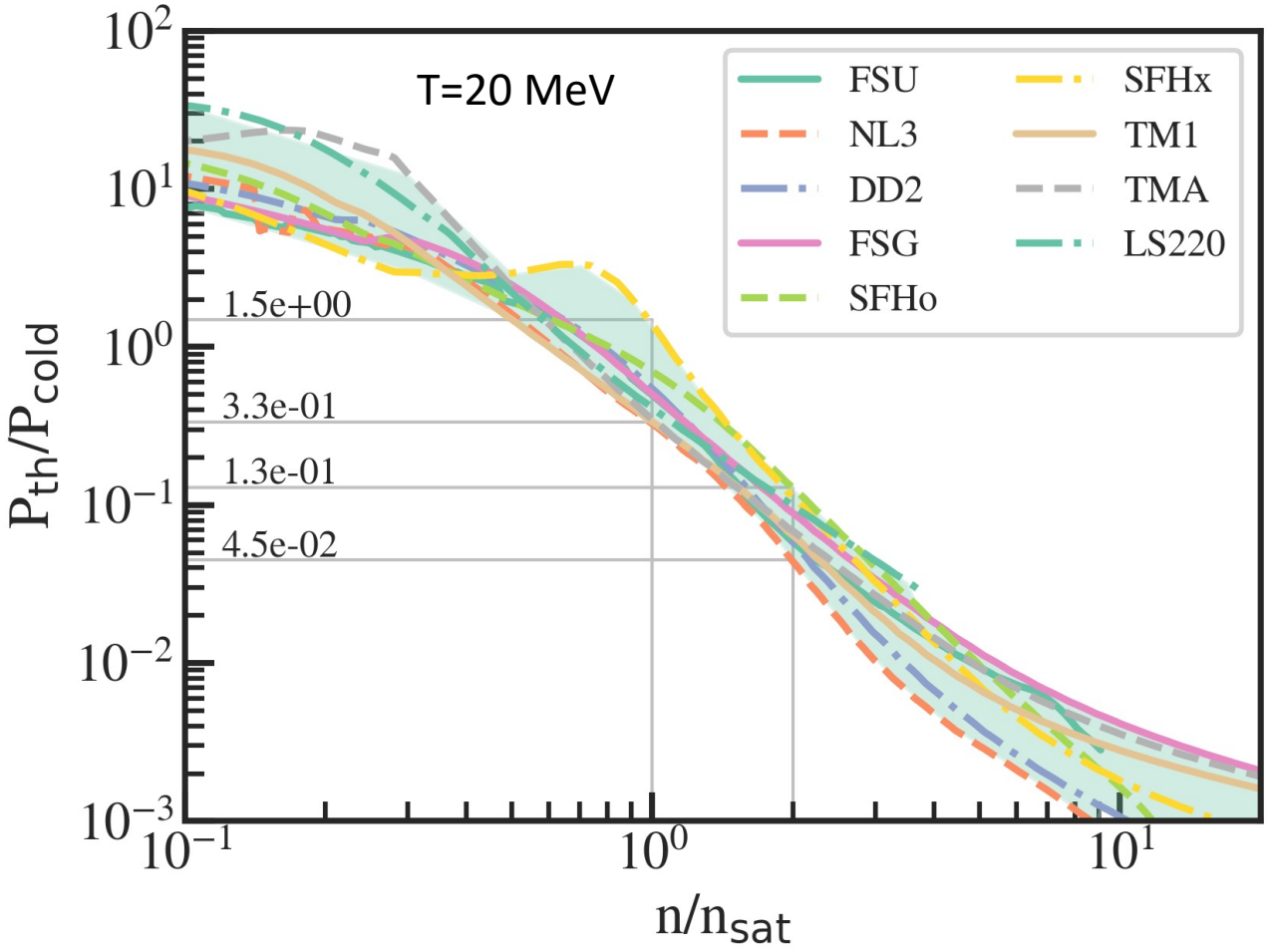
Neutron star mergers probe wide range of **equation of state** parameter space



Raithel, Özel, & Psaltis (2019)

Limitations and uncertainties of existing finite-temperature EOS tables



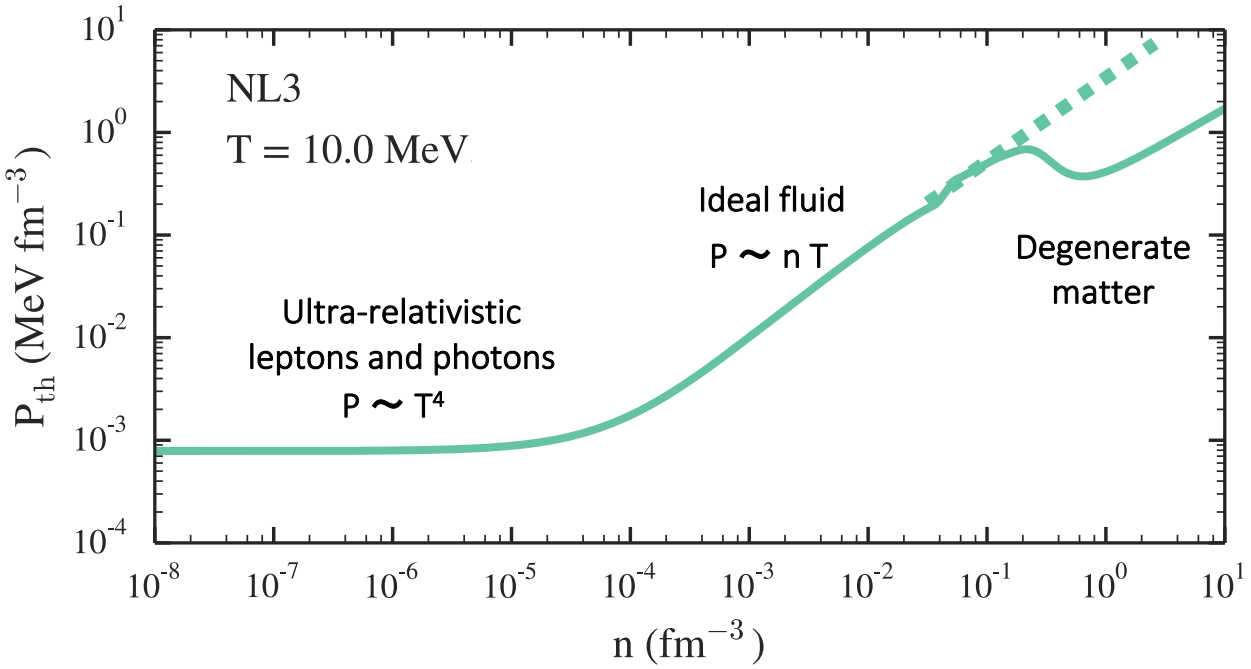


Left: website of Matthias Hempel
Right: Raithel, Paschalidis, Özel (arXiv:2104.07226)

New framework for calculating the EOS at arbitrary temperatures and proton fractions

$$P(n, T, Y_p) \approx P_{\text{cold, }\beta\text{-eq.}}(n) + P_{\text{th}}(n, T) + P_{\text{non-}\beta\text{ eq.}}(n, Y_p) + \ldots$$

Schematic model for the thermal pressure:



Goal: include relevant physics across all density regimes, including leading order effects of degeneracy

C.f.: hybrid approach, $P_{\text{th}} = nE_{\text{th}}(\Gamma_{\text{th}} - 1)$*, which neglects the effects of degeneracy by fixing to a constant* Γ_{th}

Raithel, Özel, & Psaltis (2019)

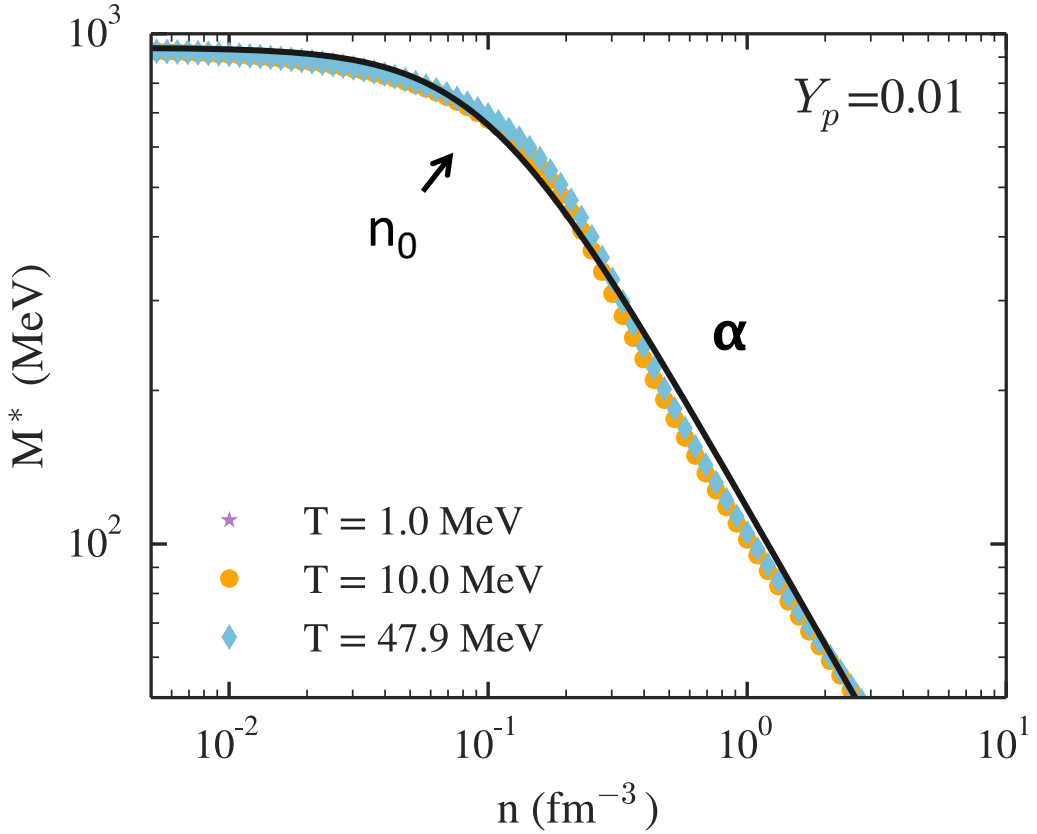
M*-approximation of the degenerate thermal pressure

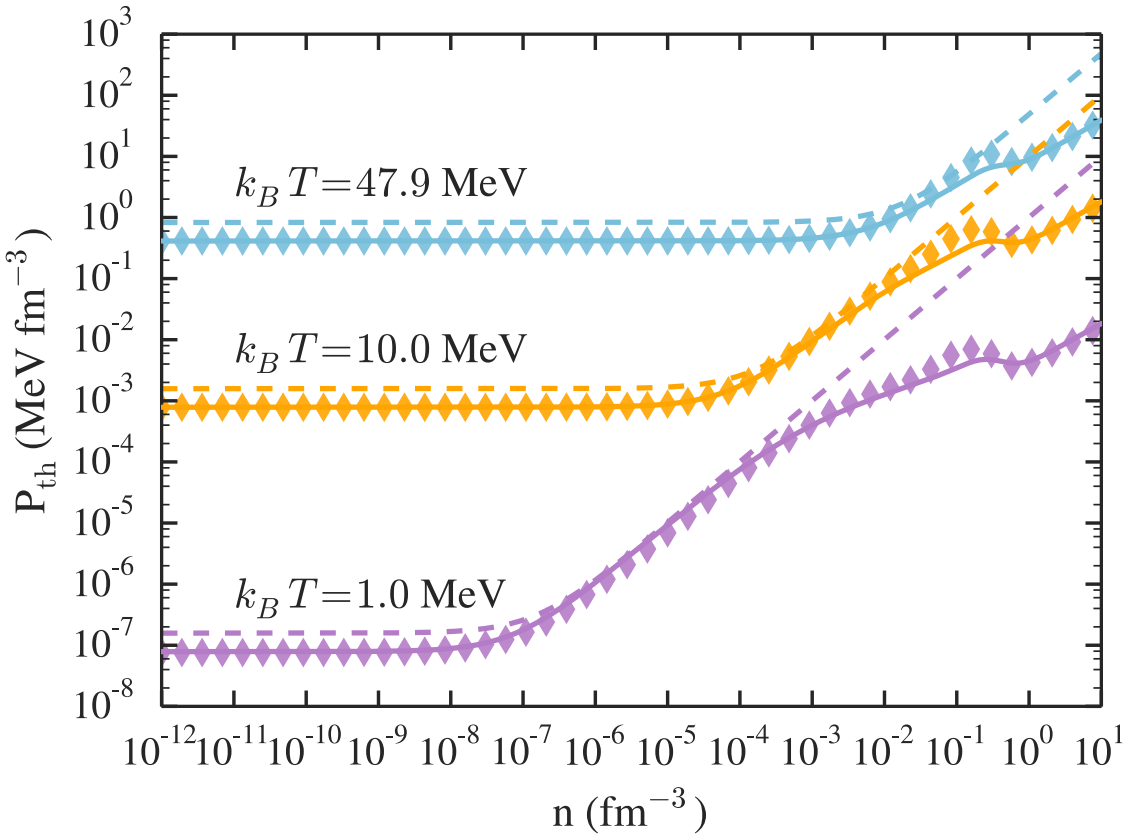
$$M^*(n) = \left[(mc^2)^{-2} + \left(\frac{mc^2 n^{-\alpha}}{n_0^{-\alpha}} \right)^{-2} \right]^{-1/2}$$

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

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

degenerate thermal pressure at leading order, from Fermi Liquid Theory

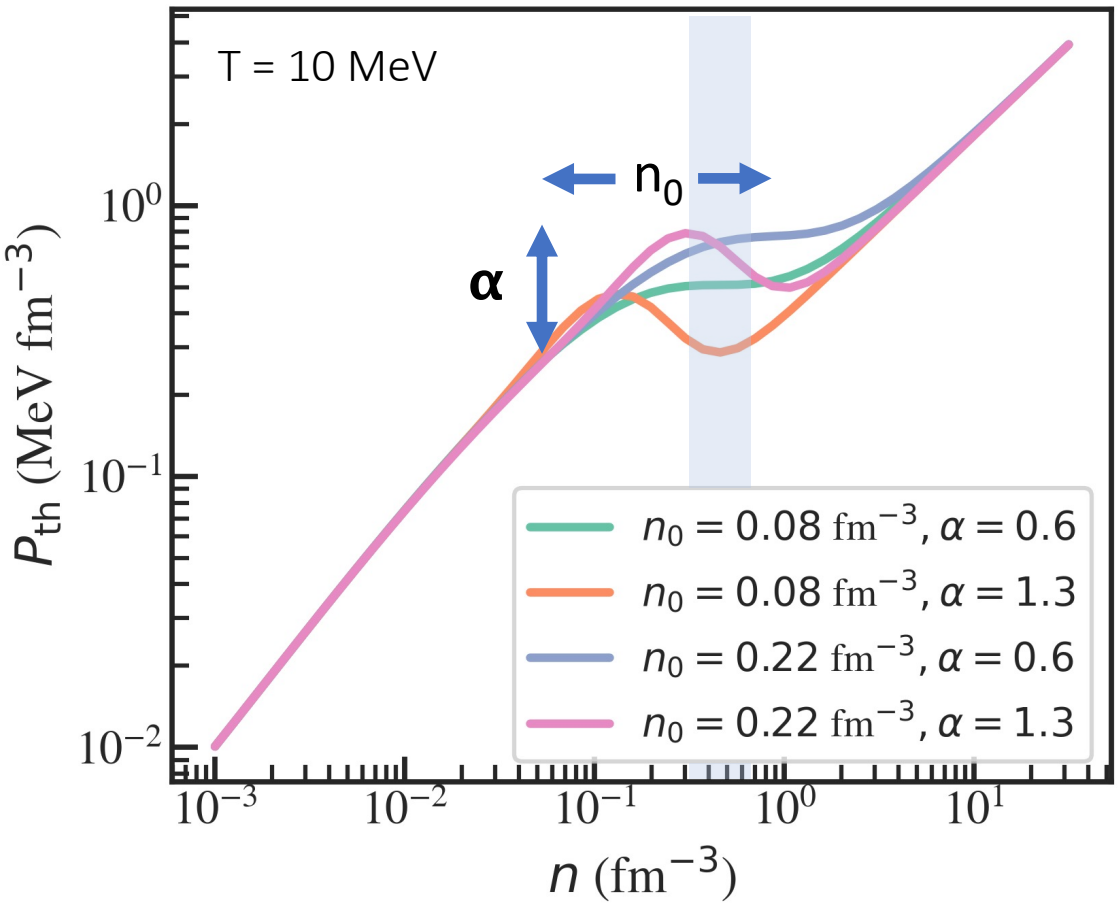




Raithel, Özel, & Psaltis (2019)

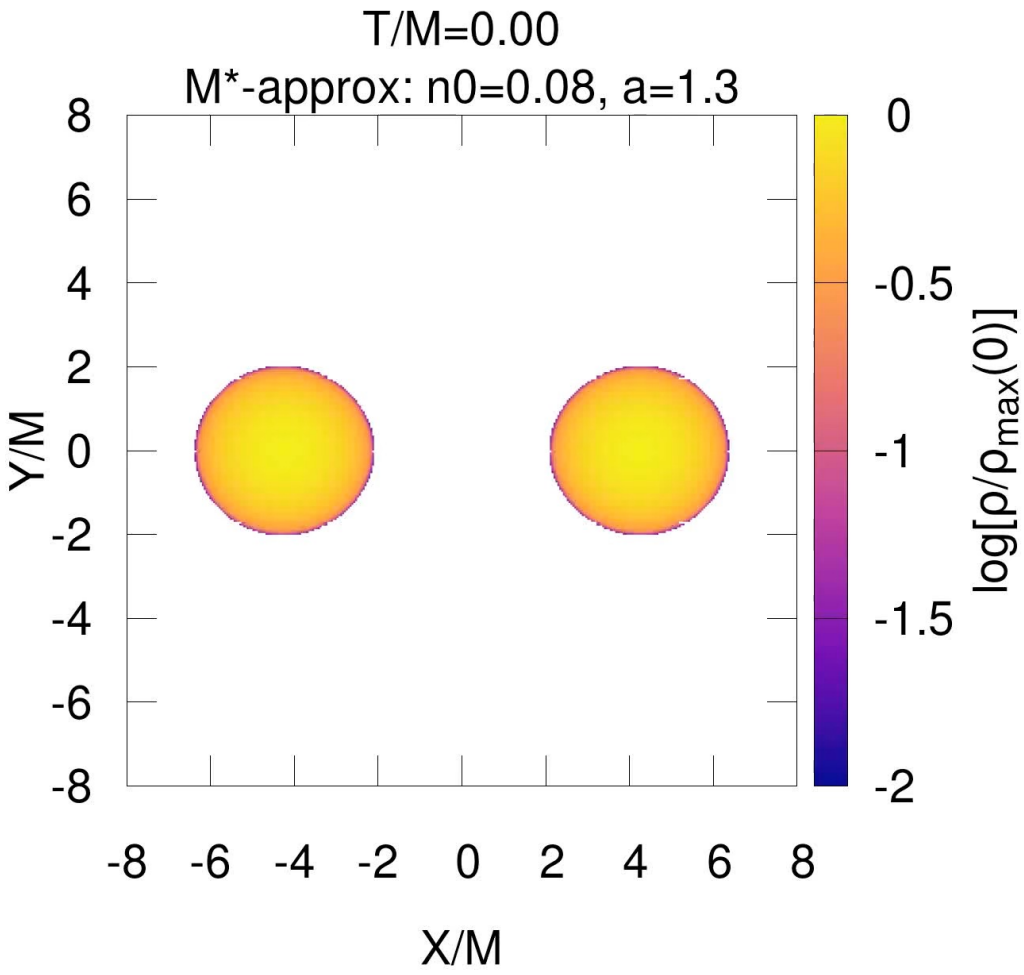
Exploring the parameters of the M*-framework with NS-NS merger simulations

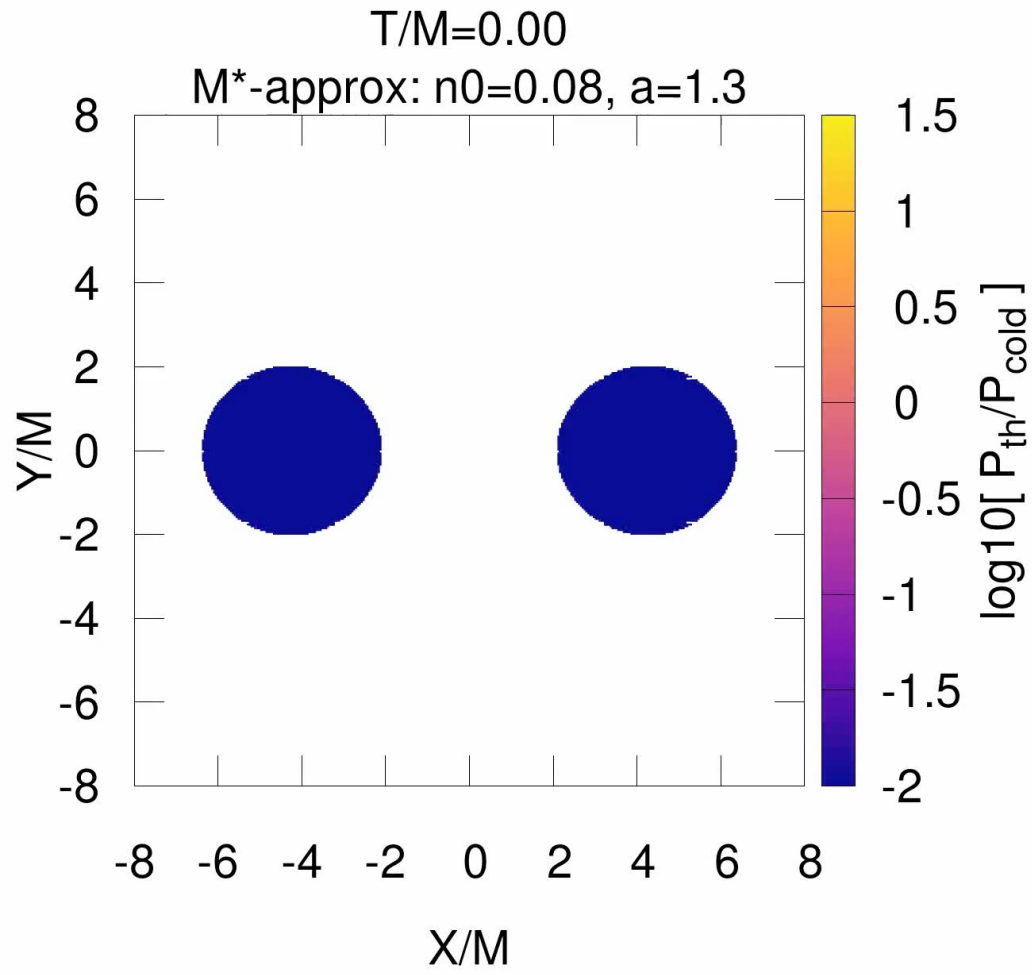
- $1.4\ M_\odot + 1.4\ M_\odot$ neutron star merger simulations
- Cold EOS: ENG
  ($R_{1.4}$ = 12 km, 2.24 M_{max})
- 4 simulations each with a different set of M*-parameters, to bracket range of uncertainty
- Simulations evolved with Illinois dynamical spacetime + GRMHD code (see e.g., Duez+2005, Etienne+ 2015)



Raithel, Paschalidis, Özel (arXiv:2104.07226)

Simulation of 1.4 $M_\odot$ + 1.4 $M_\odot$ binary neutron star merger with M*-approximation

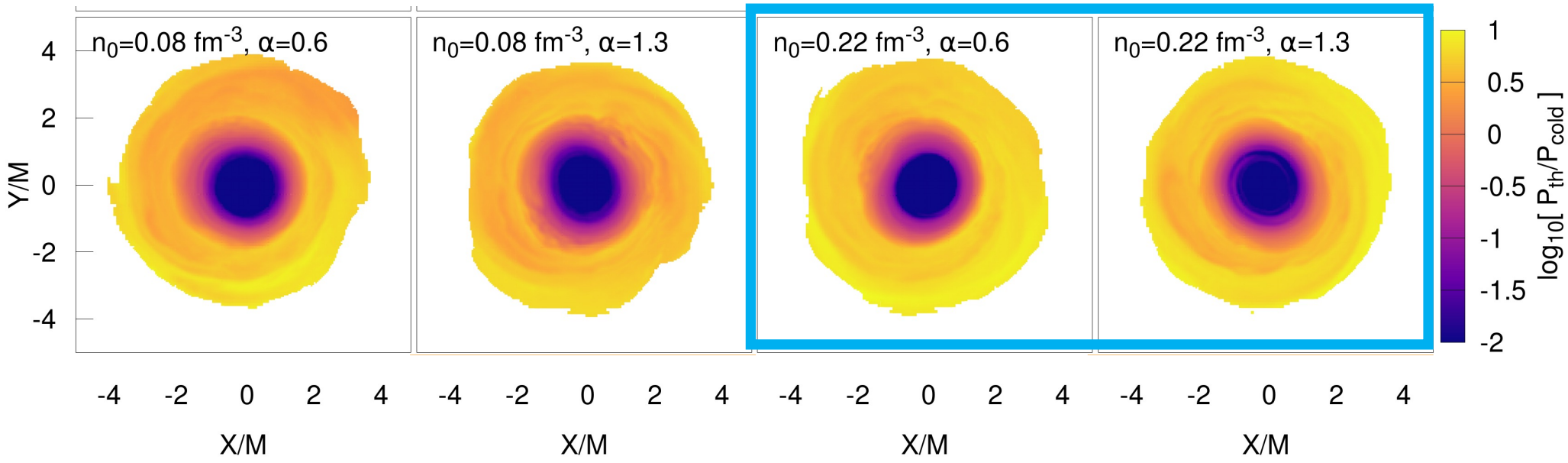




*Matter with $\rho < 10^{-2}\ \rho_{sat}$ masked in white

Raithel, Paschalidis, Özel (arXiv:2104.07226)

Thermal profiles with different M*-parameters

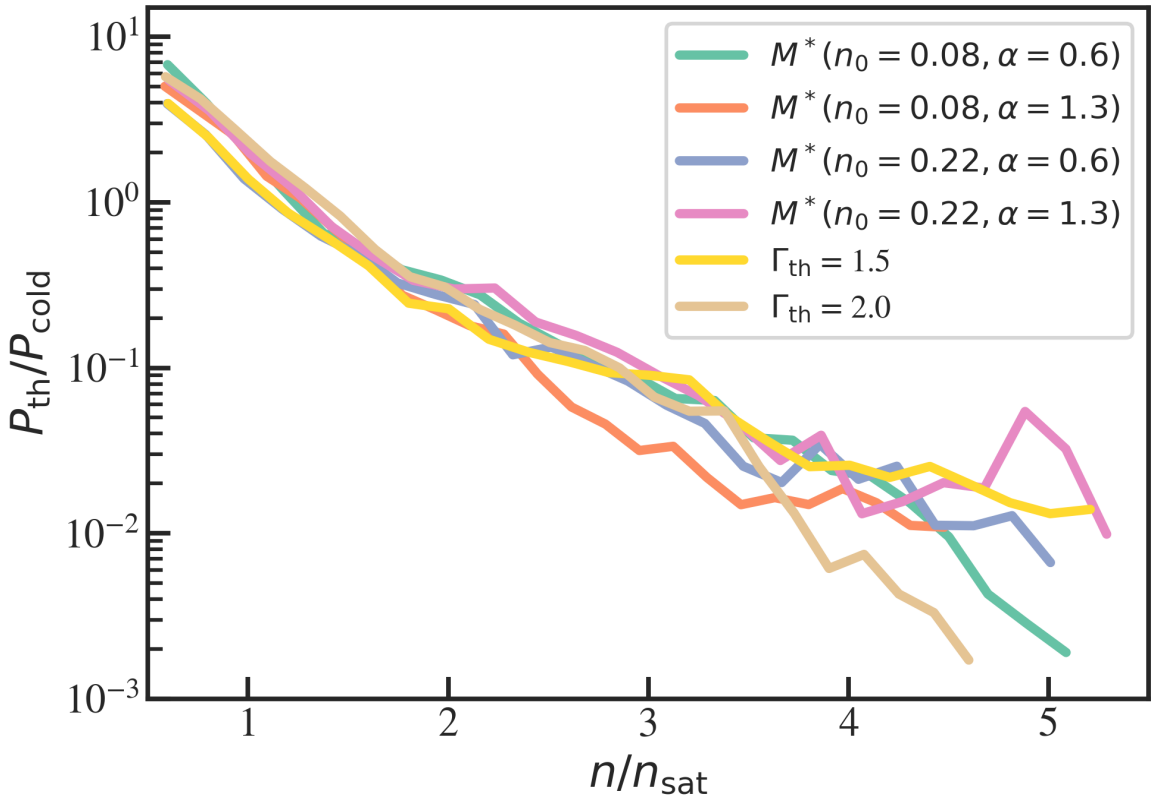


n_0 influences thermal profile in outer layers

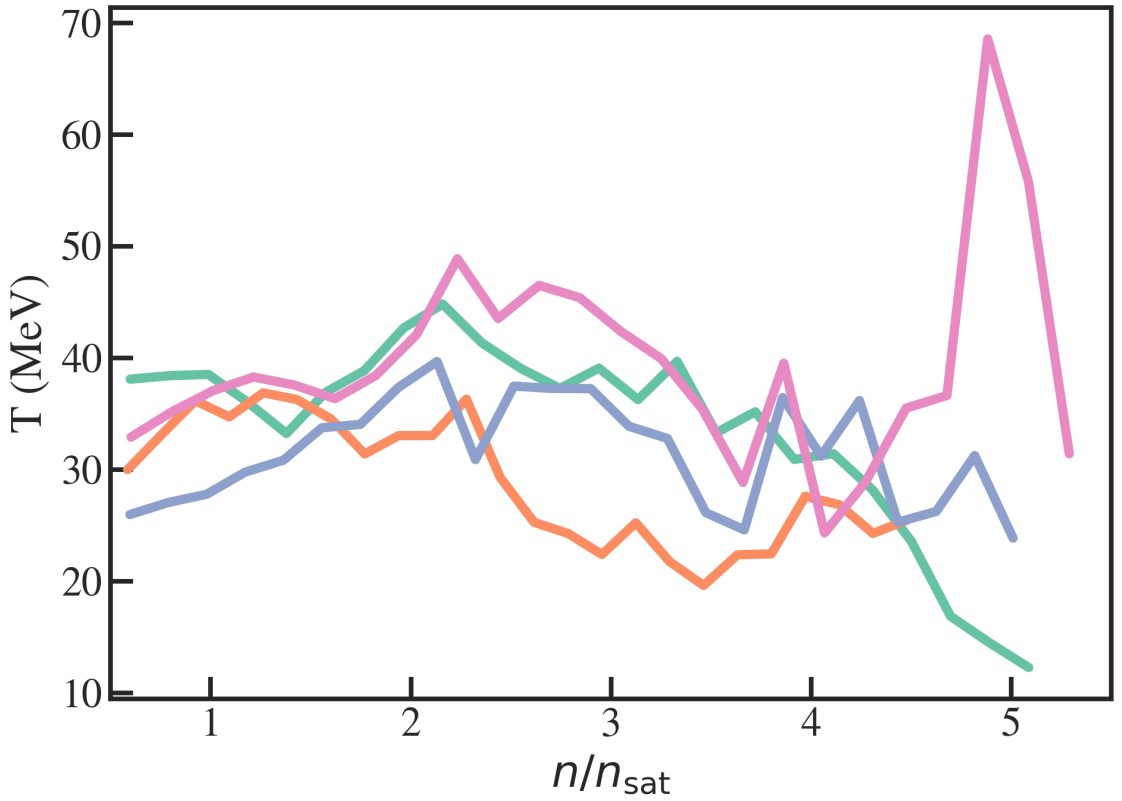
α influences inner core temperature ($x/M \lesssim 1$)

Raithel, Paschalidis, Özel (arXiv:2104.07226)

Thermal profile shortly after merger



P_{th} influences oscillations of remnant, redistribution of matter

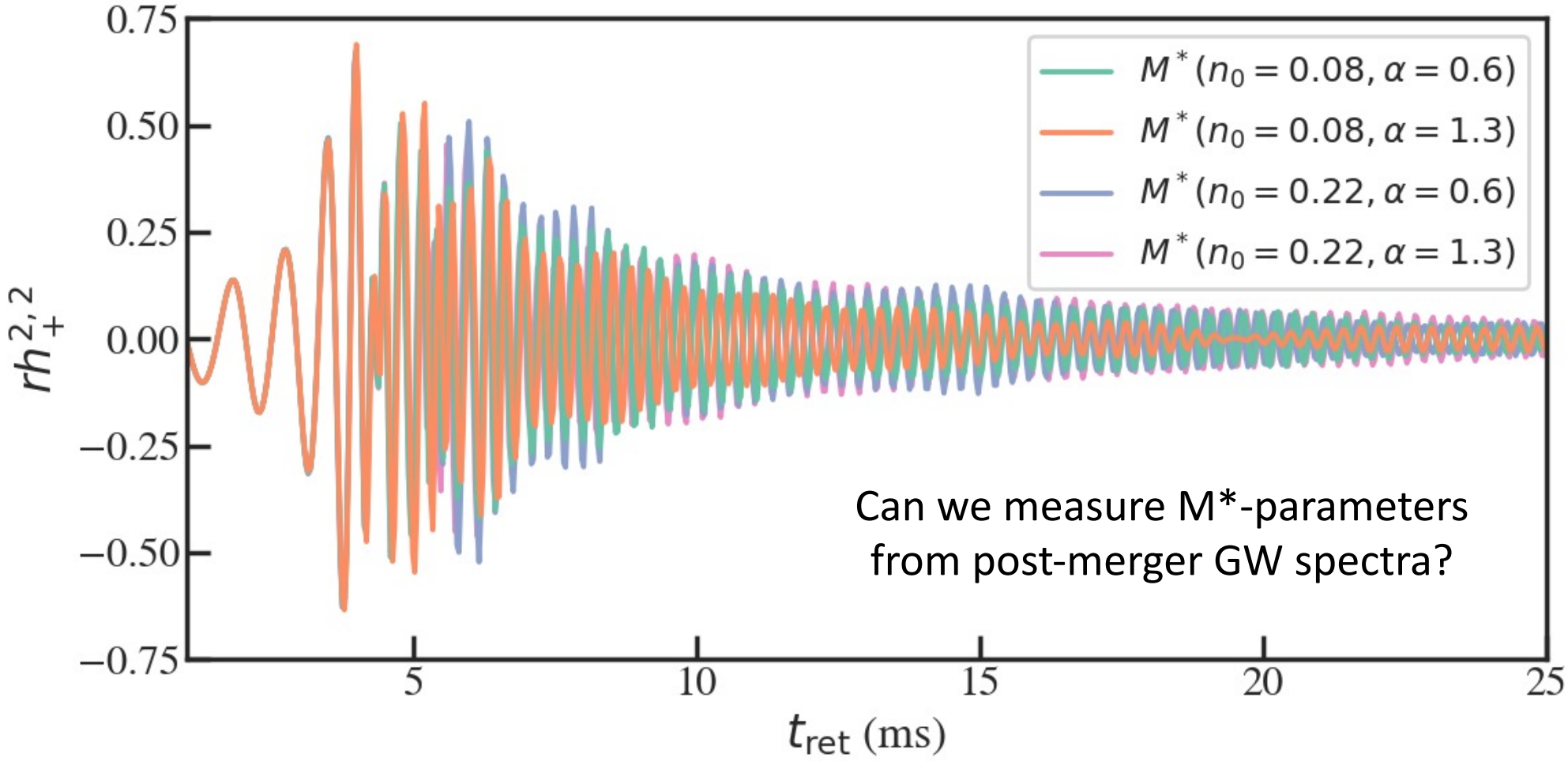


T affects neutrino emissivities, eventual cooling and neutrino irradiation of disk

Raithel, Paschalidis, Özel (arXiv:2104.07226)

Inspirals are identical

Differences in post-merger signal

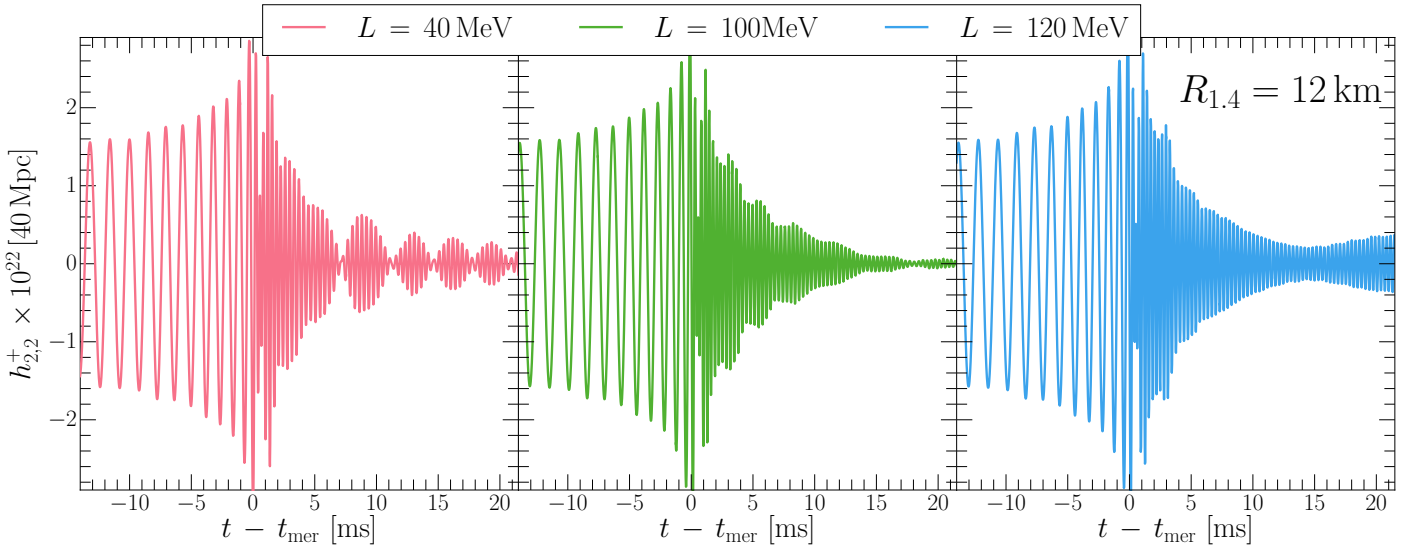


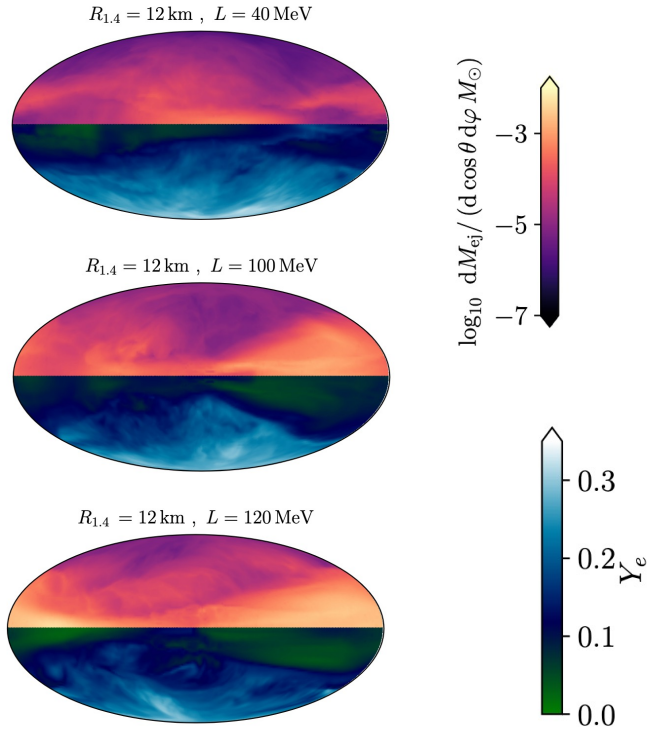
Can we measure M*-parameters from post-merger GW spectra?

Raithel, Paschalidis, Özel (arXiv:2104.07226)

M*-framework can also be used to study new parts of the **cold** EOS parameter space

E.g., new paper on arXiv tomorrow exploring imprints of the **nuclear symmetry energy** in post-merger phase!
(Most & Raithel, in prep)





Summary & future directions

- Post-merger observables probe the finite-temperature EOS
    - M*-framework allows for a robust treatment of thermal physics in merger simulations, added to *any* cold EOS
    - Initial parameter study with one cold EOS shows M*-parameters can affect remnant thermal structure and post-merger GWs (Raithel, Paschalidis, Özel; arXiv:2104.07226)
    - **Next up**: expanding parameter study to include more cold EOSs; more detailed study of post-merger GW spectra
- M*-framework can also be used to parameterically study cold EOS parameter space, with realistic, *identical* finite-T effects
    - See new paper on arXiv tomorrow! (Most & Raithel, in prep)