The thermal index of neutron-star matter in the virial approximation

G. Rivieccio, A. Nadal-Matosas, A.Rios and M.Ruiz

ApJ accepted
arxiv: 2501.16795

Ayuda CPI-23-478 financiada por CIDEGENT/2021/046
and Prometeo CIPROM/2022/49

2ND WORKSHOP ON MODERN EQUATION OF STATE AND SPECTROSCOPY IN NEUTRON STAR MATTER

ALCALÀ DE HENARES - 28 MAY 2025

GENERALITAT VALENCIANA
Conselleria de Educación, Universidades y Empleo

MINISTERIO DE CIENCIA E INNOVACIÓN

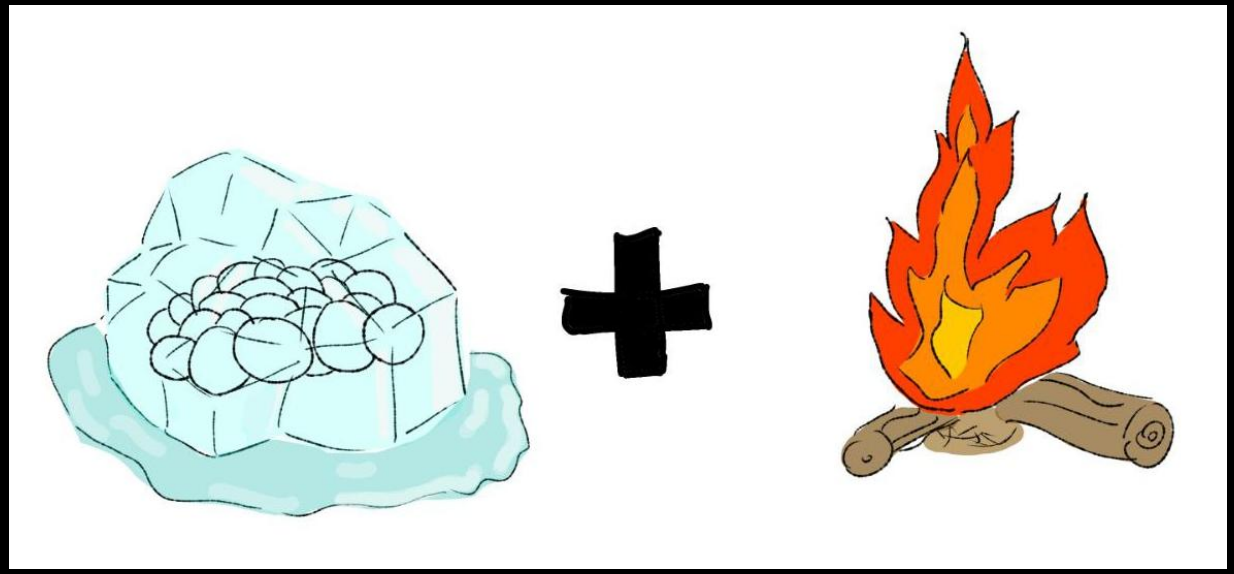
VNIVERSITAT DE VALÈNCIA

THERMAL DECOMPOSITION

$$P_{Th} \coloneqq P(T, n, Y_e) - P(0, n, Y_e)$$

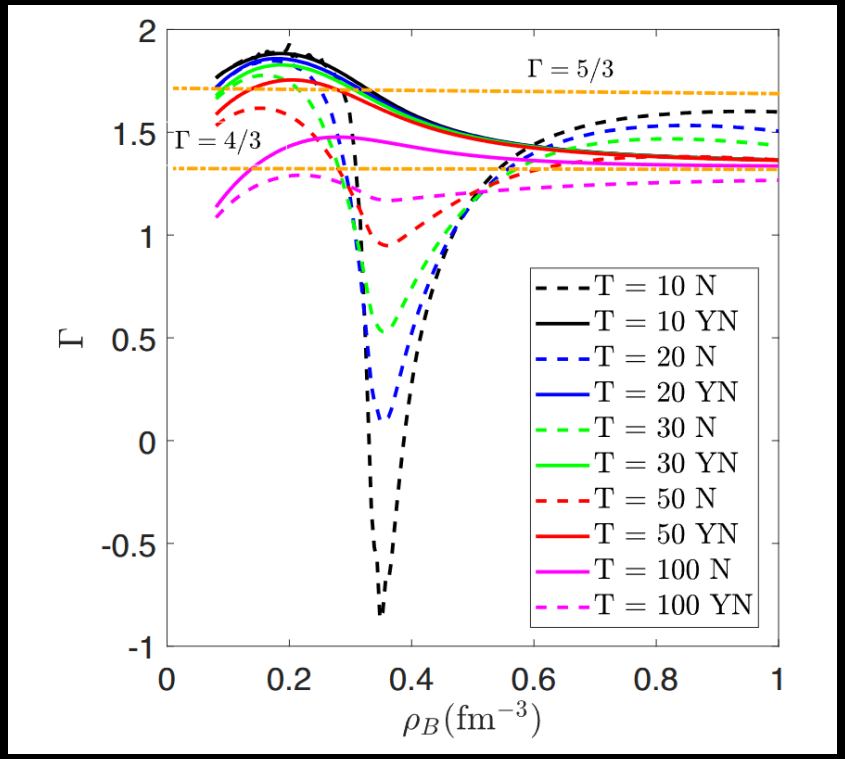
THERMAL INDEX:

$$\Gamma_{Th} \coloneqq 1 + \frac{P_{Th}}{\varepsilon_{Th}}$$

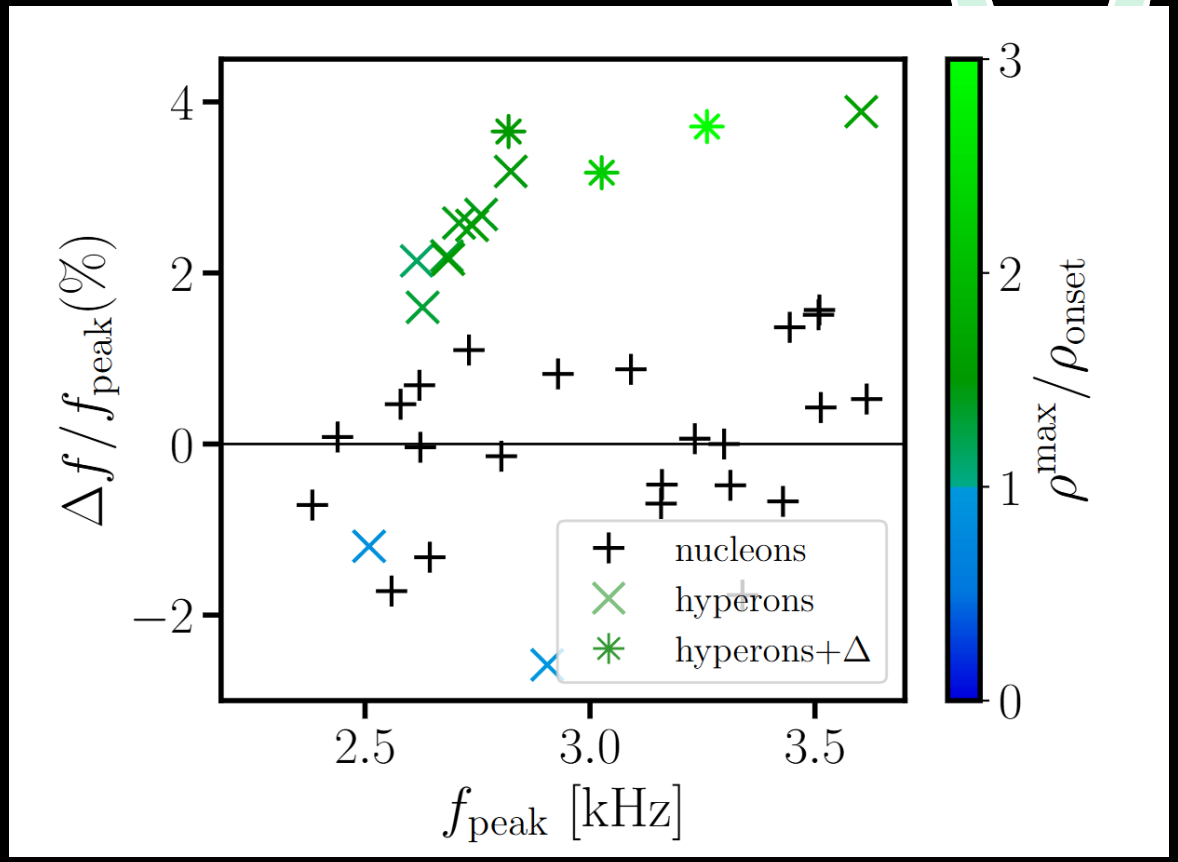


Γ_{Th} in Literaterature

- Raduta et al. 2021, Eur.Phys.J.A 57, 329
- Raithel et al. 2023, Phys. Rev. D 108, 083029
- Kochankovski et al. 2022, MNRAS, 517, 507
- Kochankovski et al. 2025, arxiv: 2501.12905



Kochankovski et al. 2022



Kochankovski et al. 2025

VIRIAL EXPANSION

- HUANG K., STATISTICAL MECHANICS, 2ND EDITION
- HOROWITZ & SCHWENK, PHYS. LETT. B, 638, 153159
- HOROWITZ & SCHWENK, NUC. PHYS. A, 776, 055079

MODEL INDEPENDENT

$$P_{Th} = \sum_{n=1} b_{(n)} z^n \qquad z = e^{\mu/T}$$

$$b_{(1)} = 1$$

NON-INTERACTING GAS

$$b_{(2)}(T) = -2^{-\frac{5}{2}} + \frac{1}{\sqrt{2}\pi T} \int_0^\infty dE \; e^{-\frac{E}{2T}} \delta_{Tot}(E)$$

NAVARRO ET AL. 2013, 10.1103/PHYSREVC.88.024002

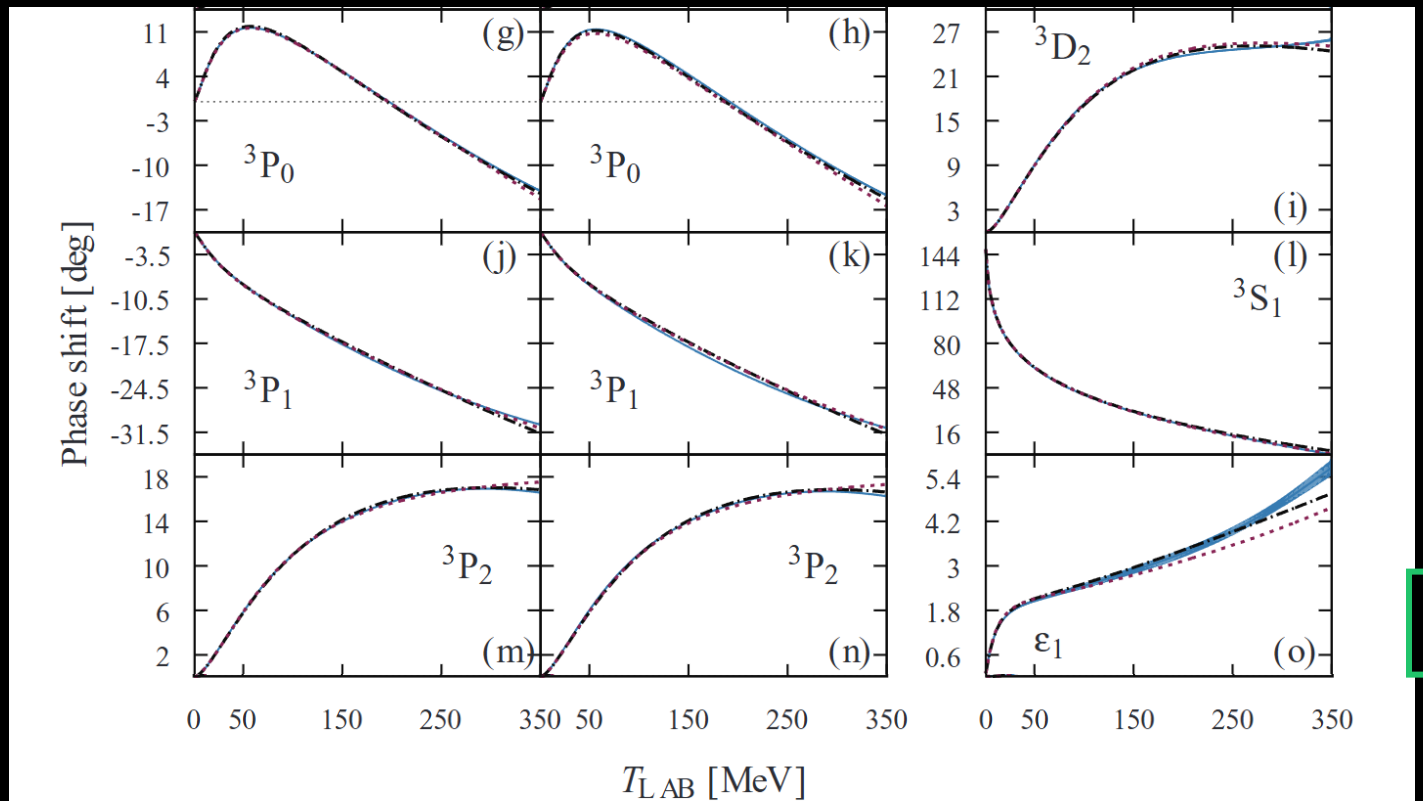
VIRIAL EXPANSION

HUANG K., STATISTICAL MECHANICS, 2ND EDITION

$$b_{(2)}(T) = -2^{-\frac{5}{2}} + \frac{1}{\sqrt{2}\,\pi\,T}\int_0^{\infty} dE\; e^{-\frac{E}{2T}}\,\delta_{Tot}(E)$$

$$\delta_{Tot} = \sum_{S,L,J}(2J+1)\,\delta_{2S+1L_J}(E)$$

MODEL INDEPENDENT

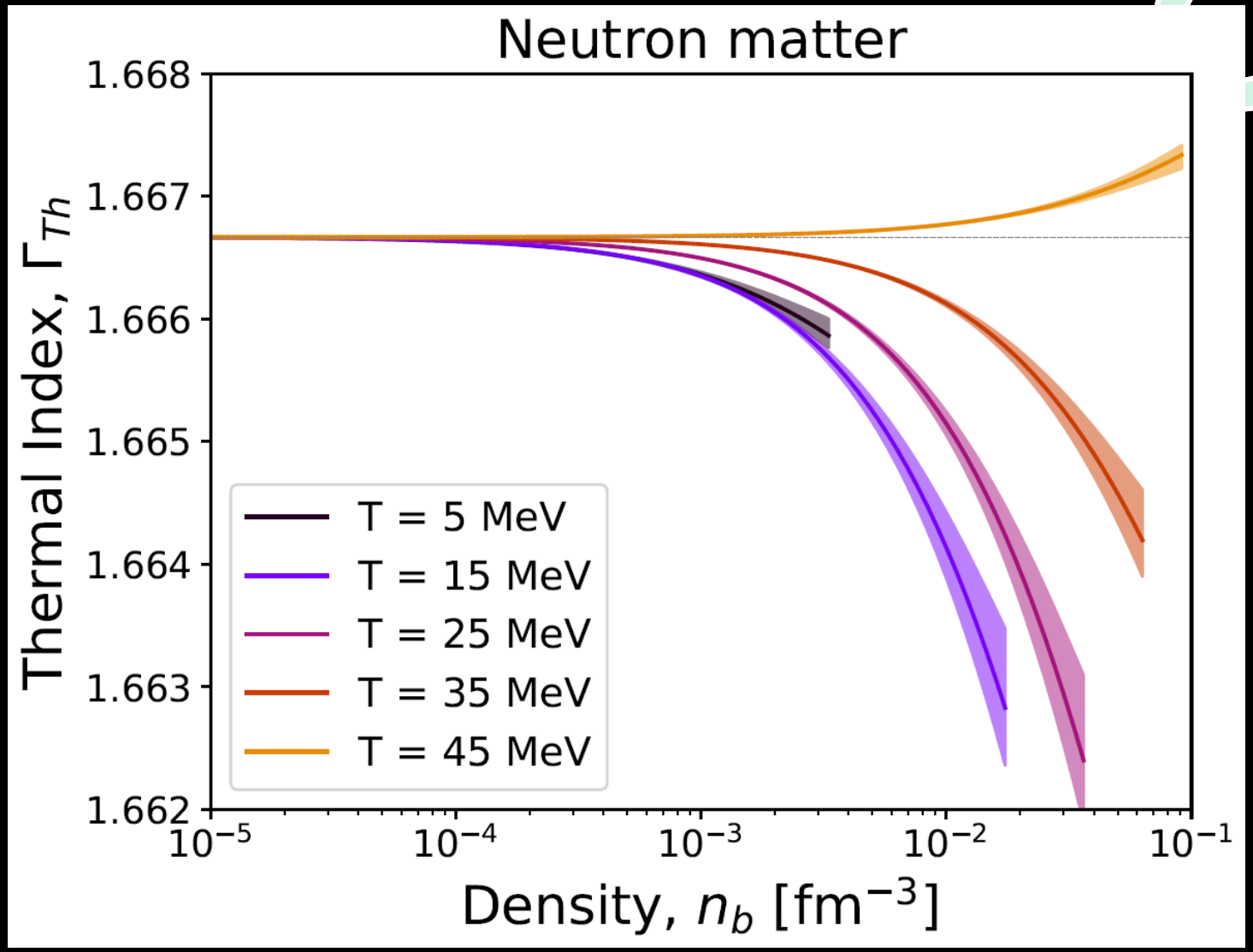


NAVARRO ET AL. 2013, 10.1103/PHYSREVC.88.024002

Pure Neutron Matter

- Little deflection from non-interacting limit (≲0.3%)
- Change of direction

$$T \geq 41 \text{ MeV}$$



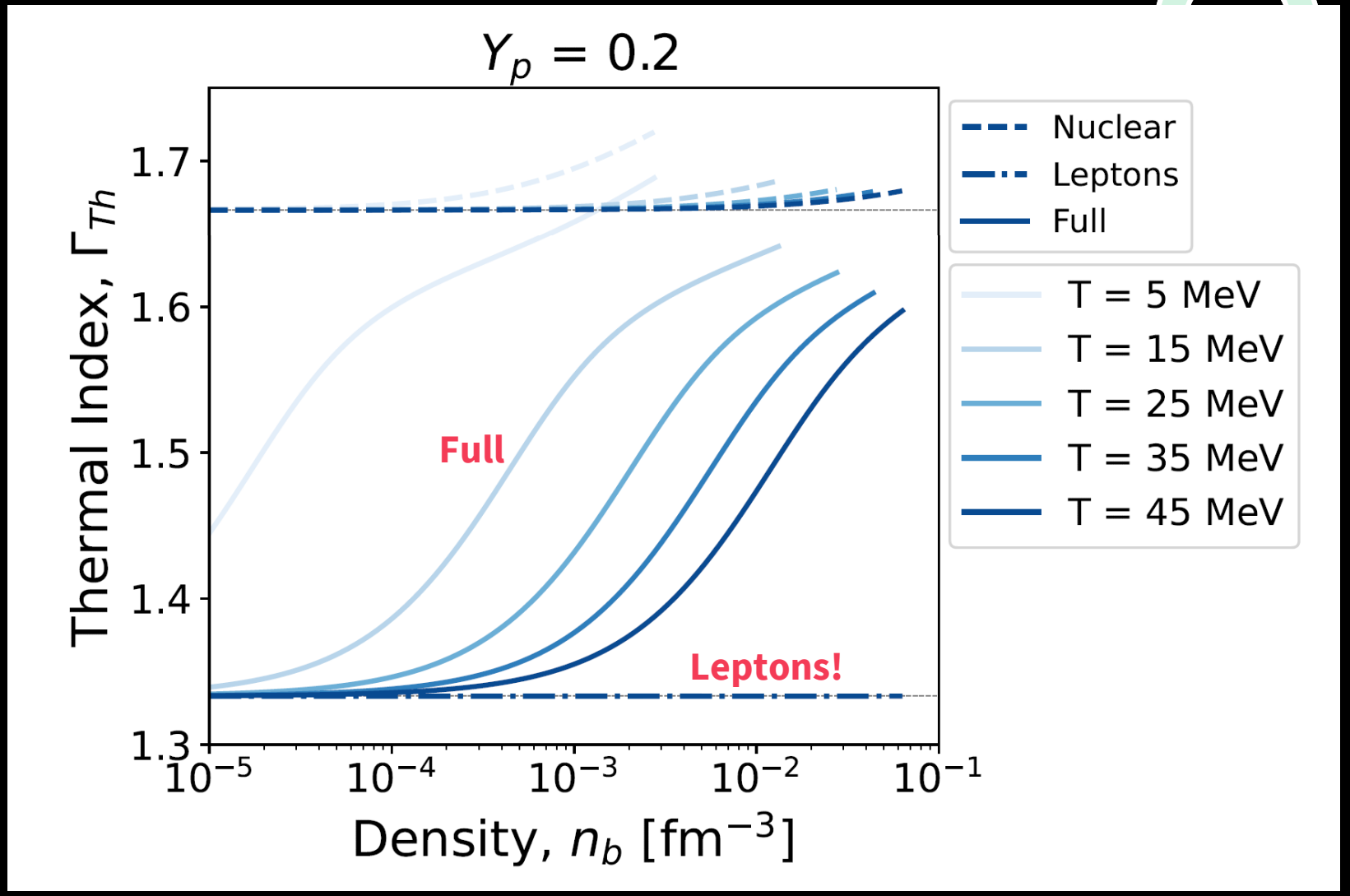
G.R. et al 2025

Asymmetric Matter

- Leptons are always relativistic
- Full Γ_{Th} is similar to sigmoid

$$\Gamma_{Full} = 1 + \frac{P_{Th}^{nuc} + P_{Th}^{lep} + P_{Th}^{\gamma}}{\varepsilon_{Th}^{nuc} + \varepsilon_{Th}^{lep} + \varepsilon_{Th}^{\gamma}}$$

- Interaction increases the effective Γ_{Th} for baryons



G.R. et al 2025

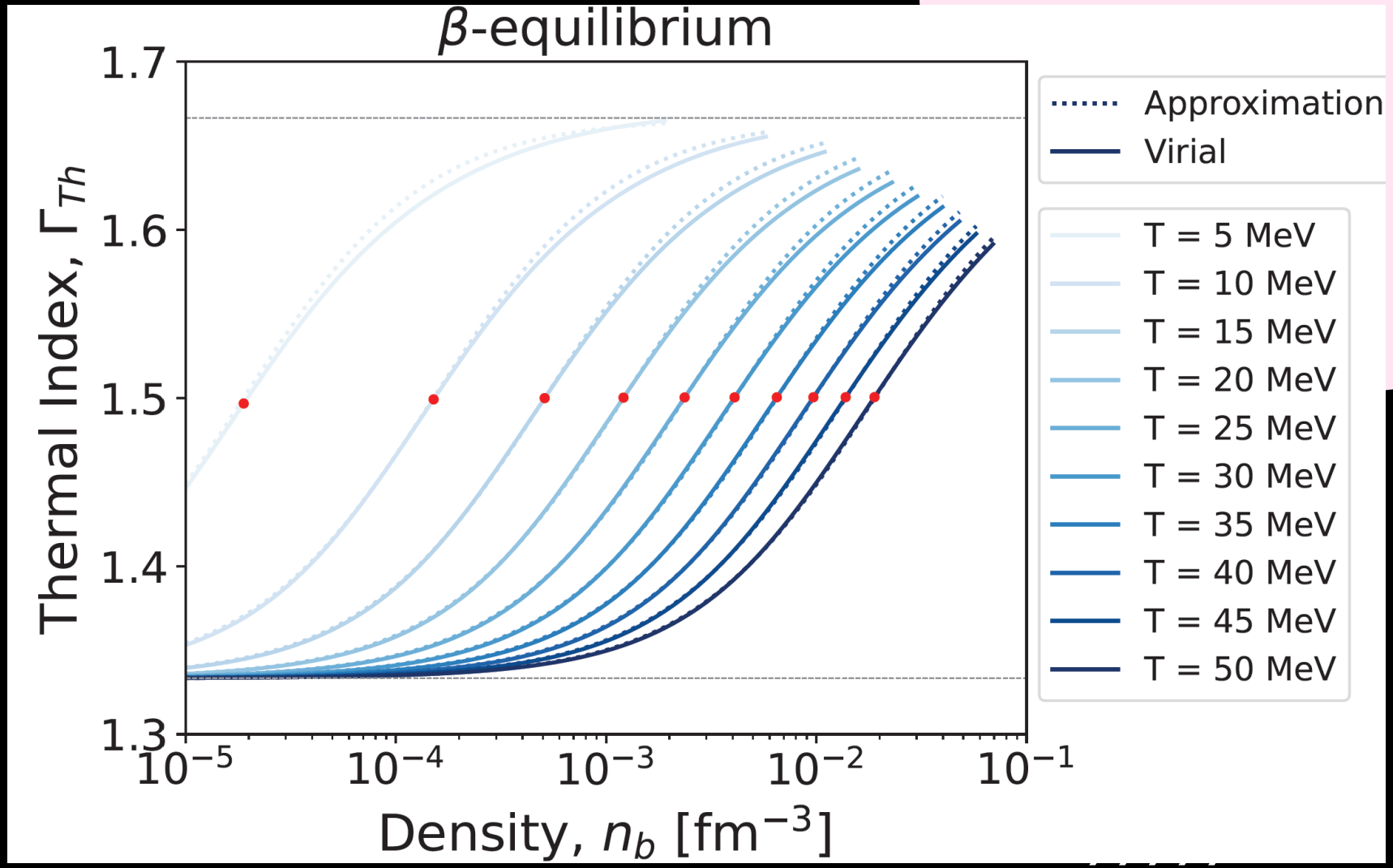
β-equilibrated Matter

- Extremely accurate approximation ($\lesssim$0.5%)

$$\Gamma = \frac{4}{3} + \frac{1}{3}\frac{n_b}{n_b + n_{inf}}$$

$$n_{inf} = 1.5 \times 10^{-4} \left(\frac{T}{10\ MeV}\right)^3$$

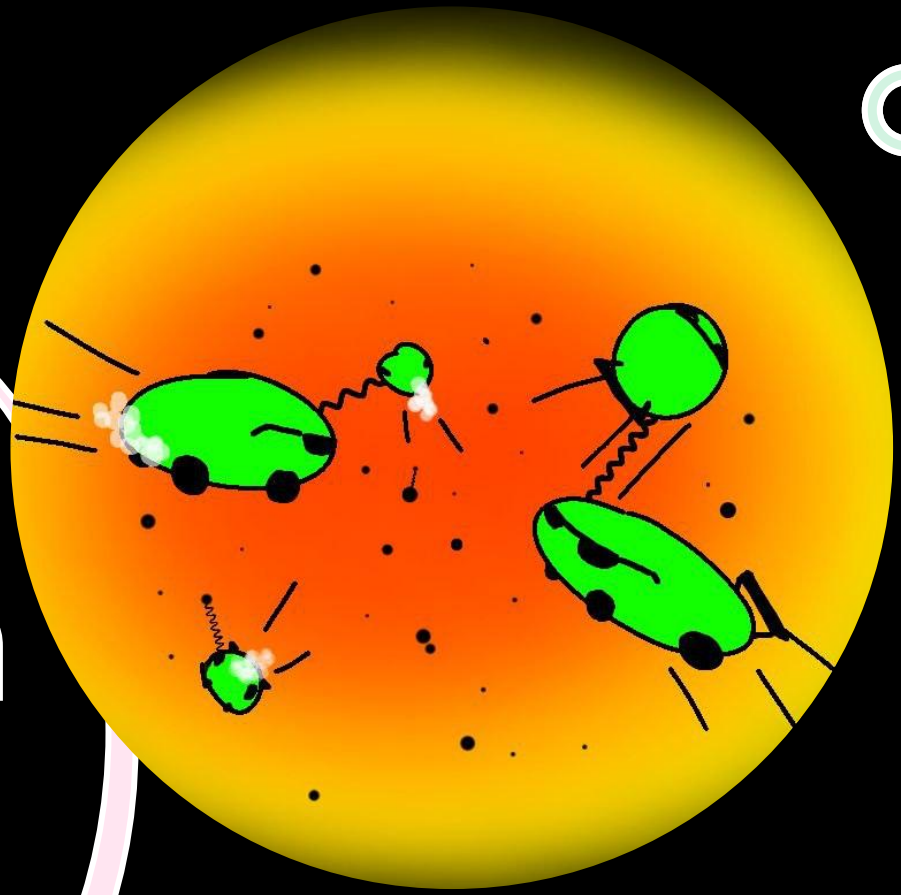
- Suitable for BNS simulation



G.R. et al 2025

Comparison with EoSs

Let’s take a Step back!

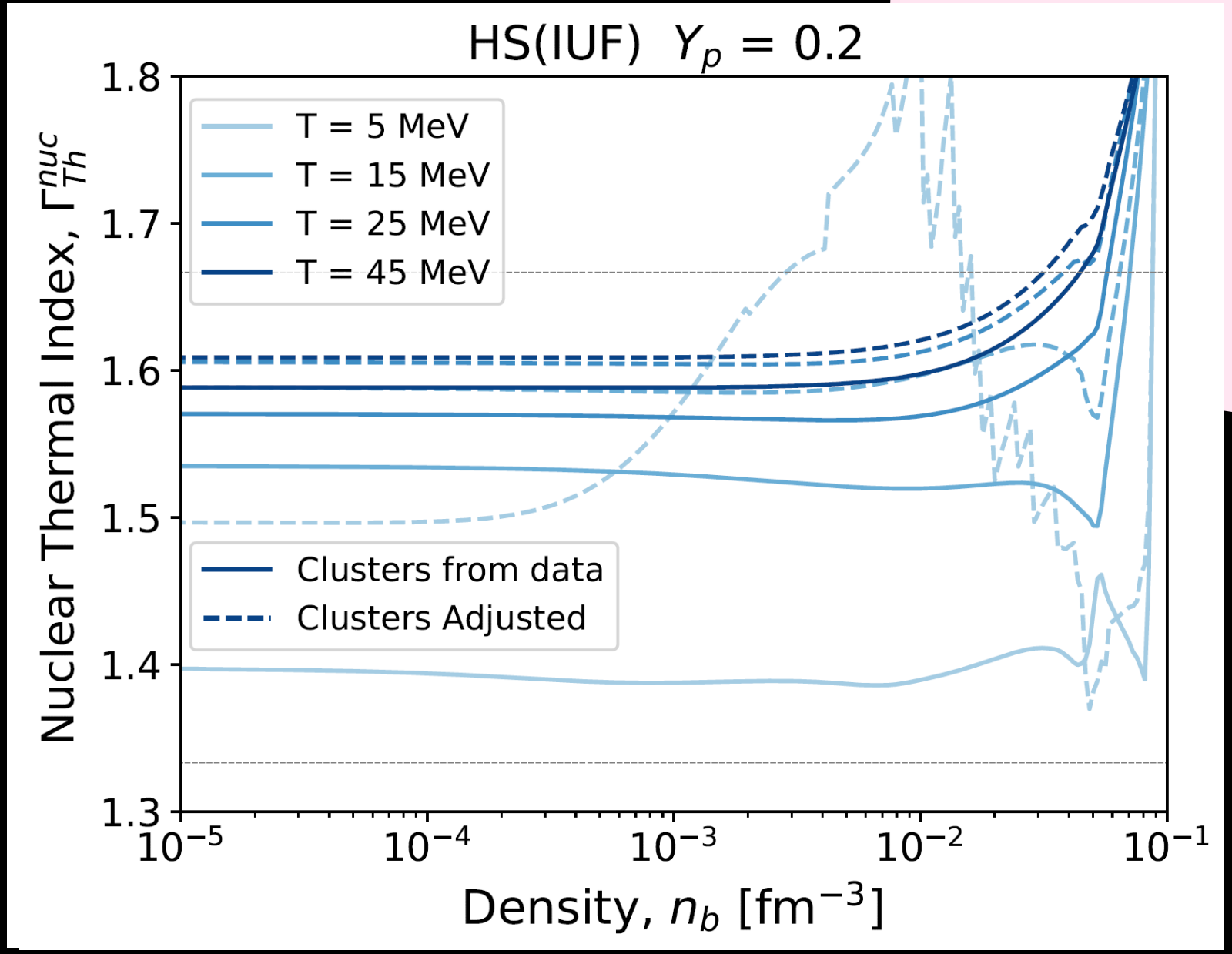


Adjusting for Clusters

G.R. et al 2025

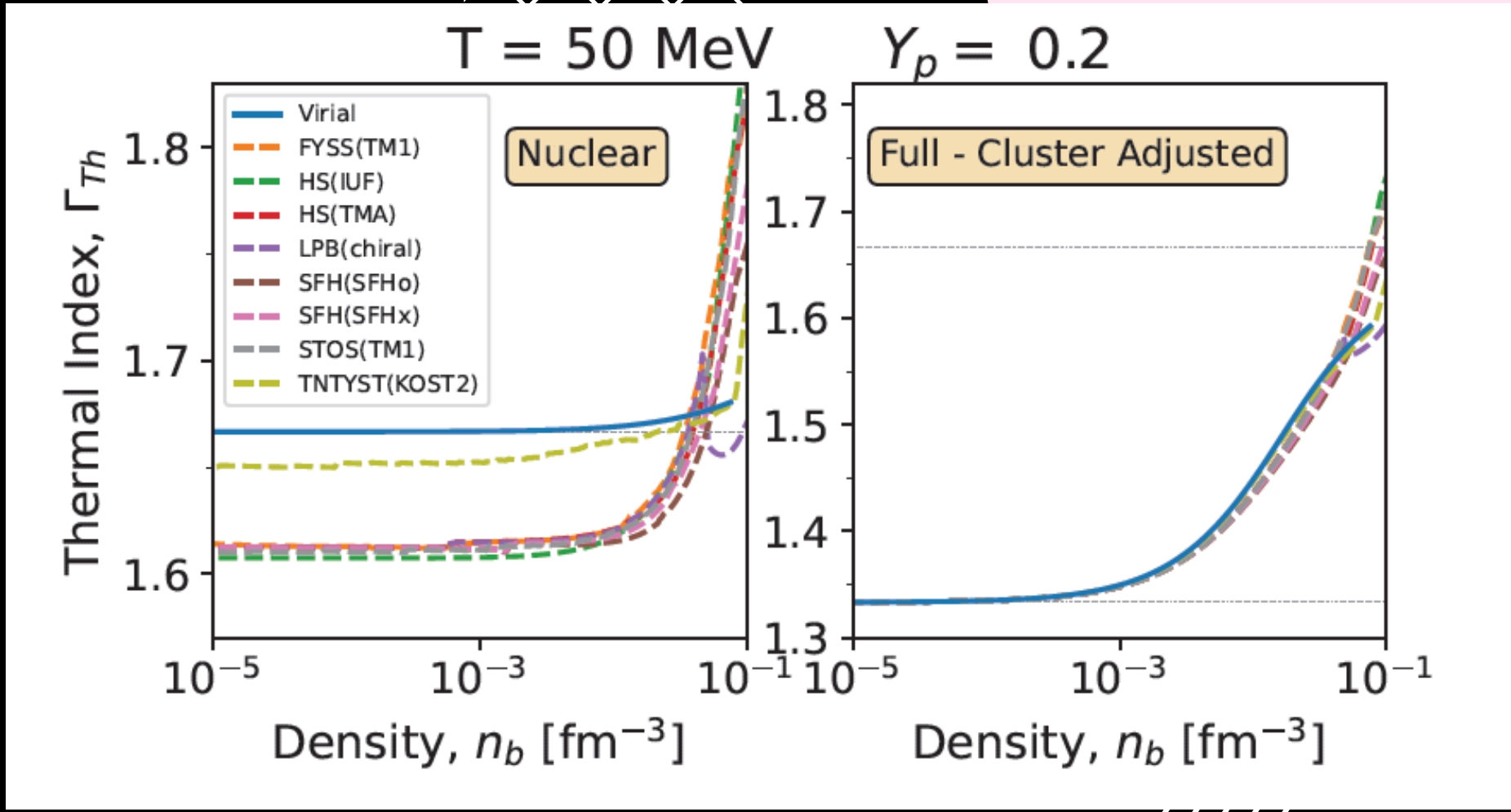
We focus on Baryons

- Low temperature means a relativistic gas?
- Clustering affect thermal properties
- LDM adjusted cluster are closer to non-relativistic limit



Comparison at high T

- Cluster adjusted EoS are consistently close to Virial approx and 5/3
- Almost negligible for the full thermal index

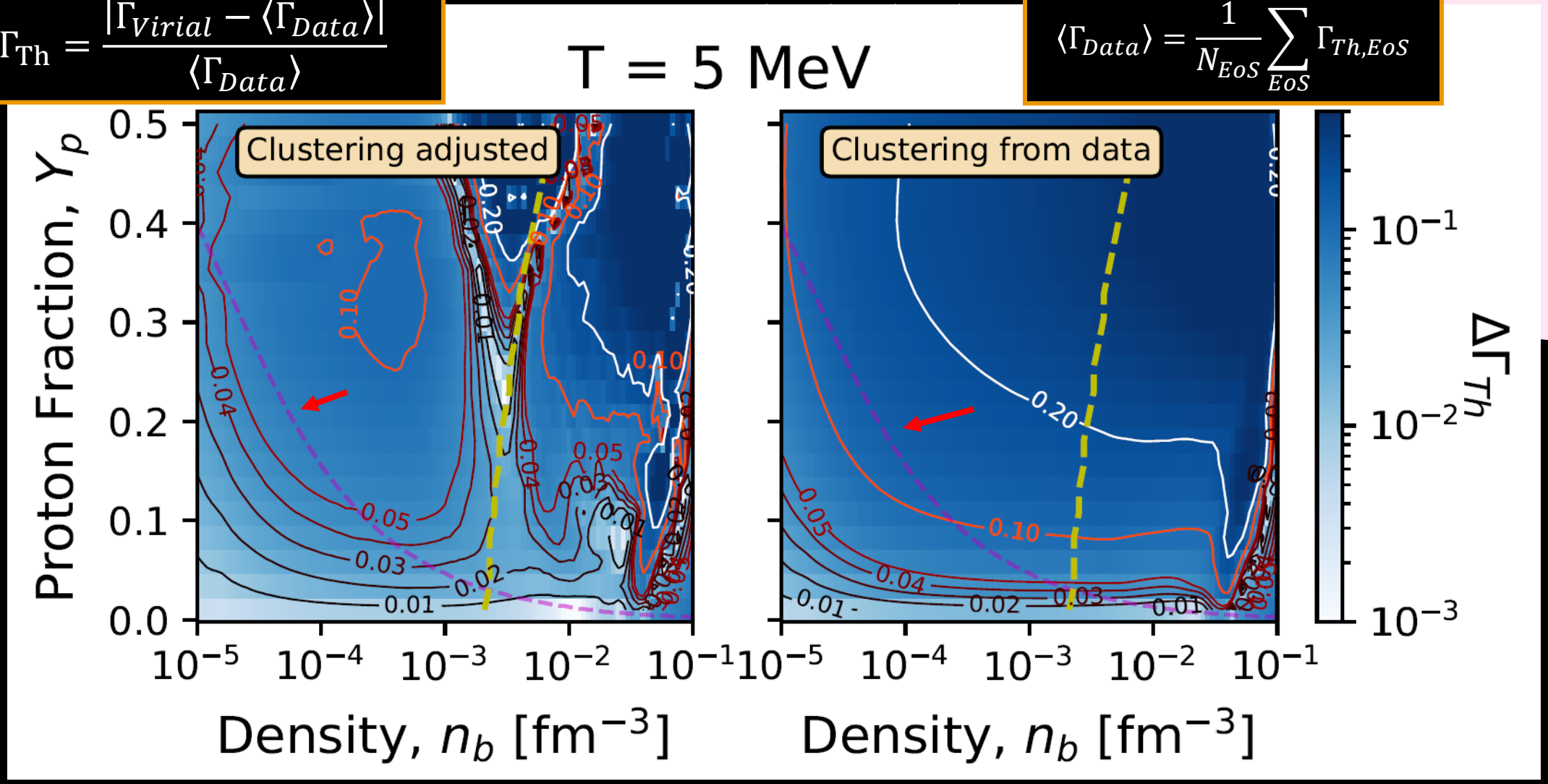


G.R. et al 2025

Comparison at high T respect to average

$$\Delta\Gamma_{\mathrm{Th}} = \frac{|\Gamma_{Virial} - \langle\Gamma_{Data}\rangle|}{\langle\Gamma_{Data}\rangle}$$

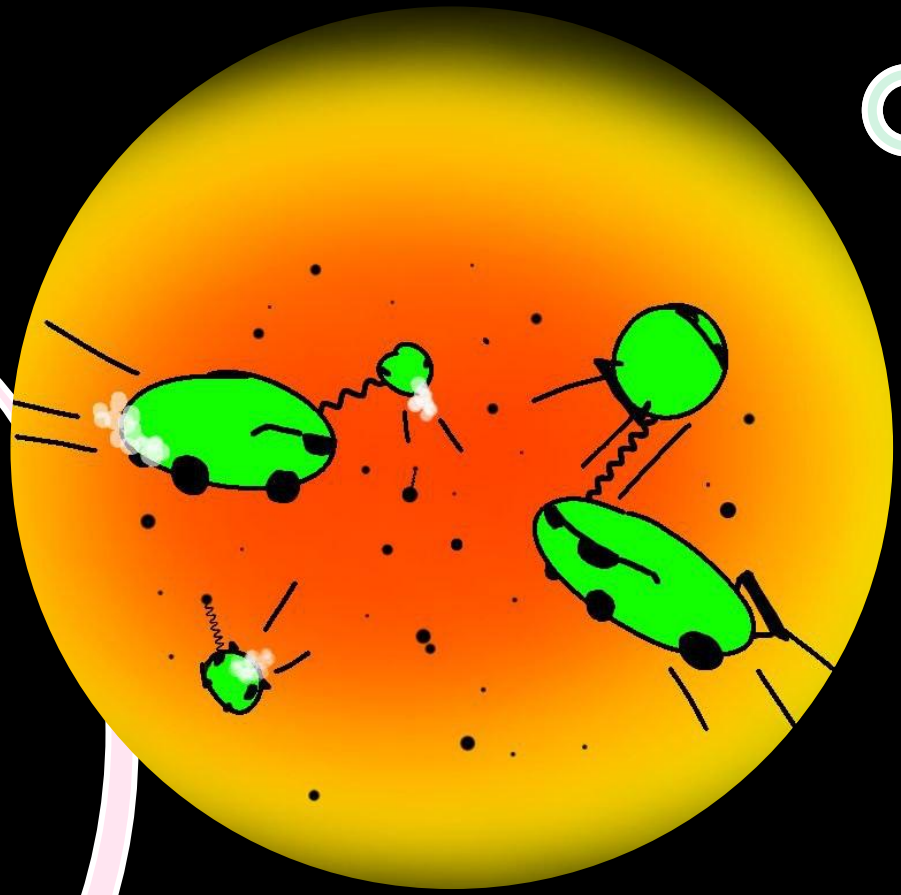
$$\langle\Gamma_{Data}\rangle = \frac{1}{N_{EoS}}\sum_{EoS}\Gamma_{Th,EoS}$$



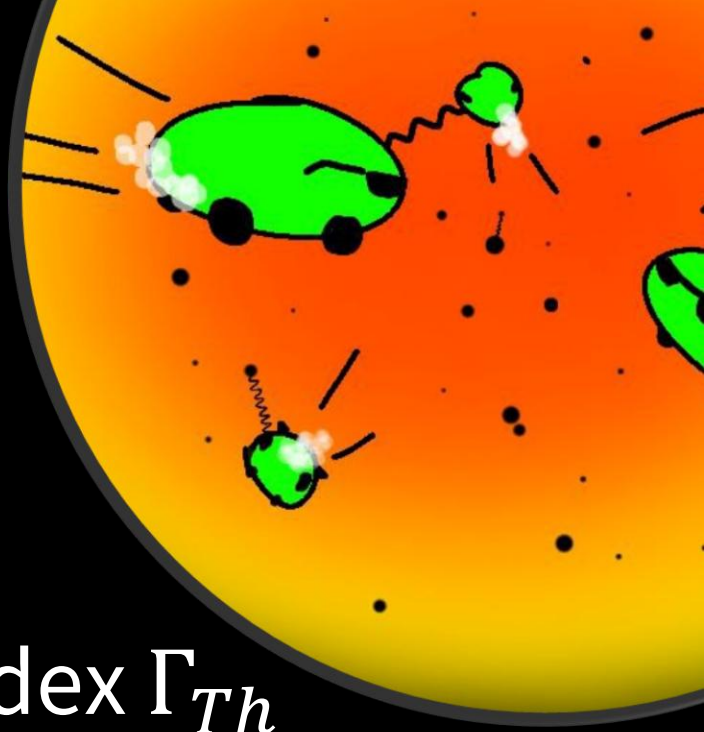
G.R. et al 2025

Conclusion

Almost coffee
break time!!



Conclusion & Future Prospective



- Viable in low density – high T regime
  - Test in BNS simulations
- Interaction are increasing the thermal index Γ_{Th}

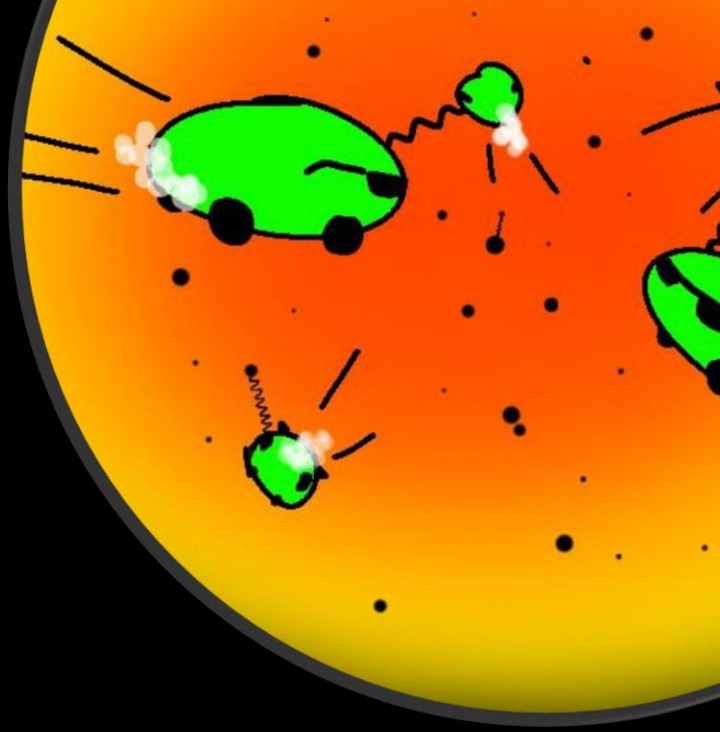
- **Model Independent** approach at most is 5% off the average database EoS in β-equilibrated matter
  - Model high density matter

ApJ accepted
arxiv: 2501.16795

Adriana Nadal Matosas

Milton Ruiz

Arnau Rios



Thanks!

giuseppe.rivieccio@uv.es

Ayuda CPI-23-478 financiada por CIDEGENT/2021/046
and Prometeo CIPROM/2022/49

2ND WORKSHOP ON MODERN EQUATION OF STATE AND SPECTROSCOPY IN NEUTRON STAR MATTER

ALCALÀ DE HENARES - 28 MAY 2025