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EXCELENCIA MARÍA DE MAEZTU

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@HadNucAtUB

Ab initio finite-temperature effects for neutron star simulations

Rivieccio, Nadal-Matosas, Rios & Ruiz, *ApJ* **987**, 67 (2025)
D Guerra, Rios et al arxiv:2512.05118
Kochankovski, Rozalén, Rios & Ramos, *in prep*

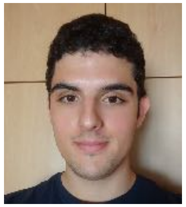
VIRGO GROUP VALENCIA

UNIVERSITAT DE BARCELONA

Guerra

Rivieccio

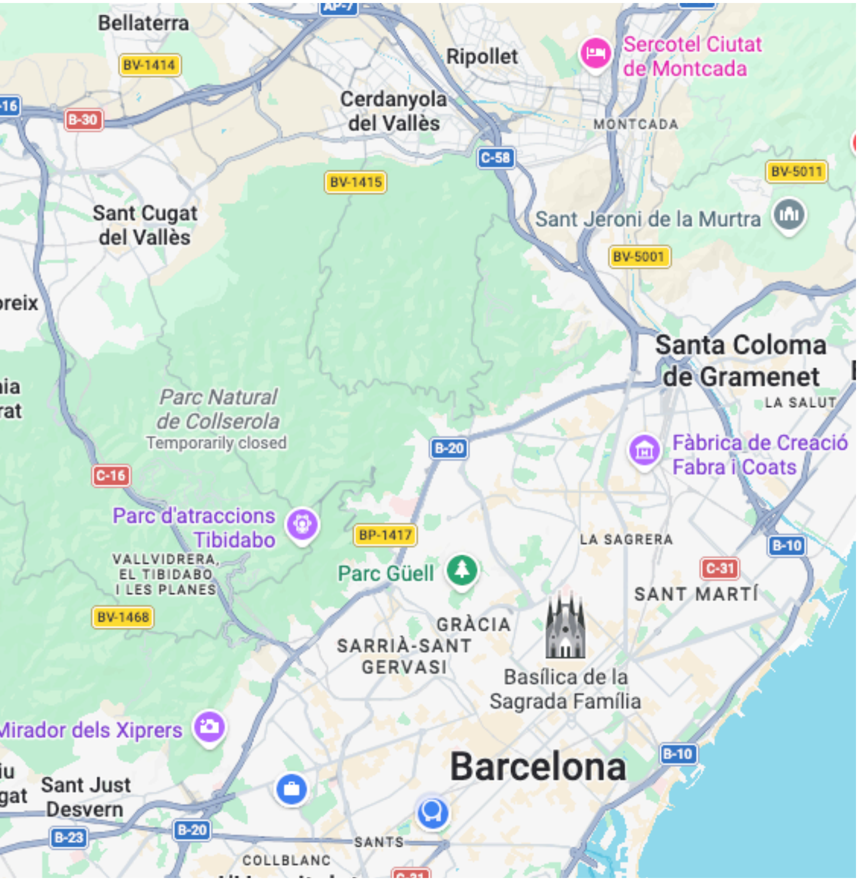
Rozalén



Kochankovski

Arnau Rios Huguet
Associate Professor
Institute of Cosmos Sciences
Universitat de Barcelona
arnau.rios@fqa.ub.edu

CSQCD
19 May 2026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C-58
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BV-5011
Sant Cugat del Vallès
Sant Jeroni de la Murtra
BV-5001
Santa Coloma de Gramenet
LA SALUT
Parc Natural de Collserola
Temporarily closed
B-20
Fàbrica de Creació Fabra i Coats
C-16
Parc d'atraccions Tibidabo
BP-1417
LA SAGRERA
B-10
C-31
VALLVIDRERA, EL TIBIDABO I LES PLANES
Parc Güell
SANT MARTÍ
BV-1468
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SARRIÀ-SANT GERVASI
Basílica de la Sagrada Família
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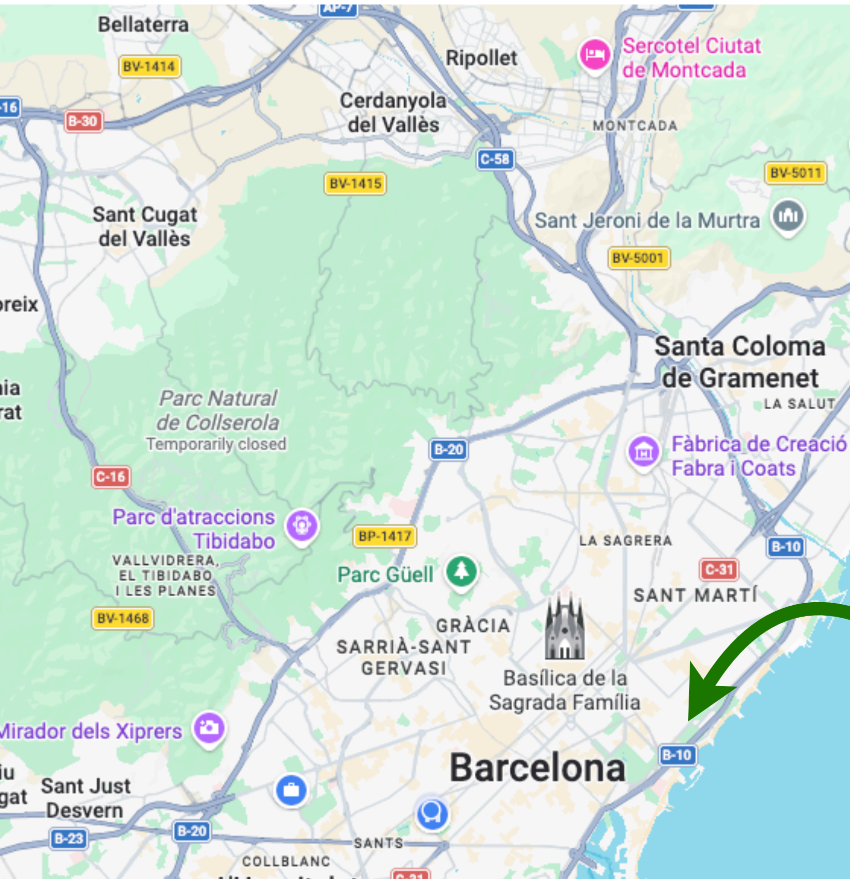
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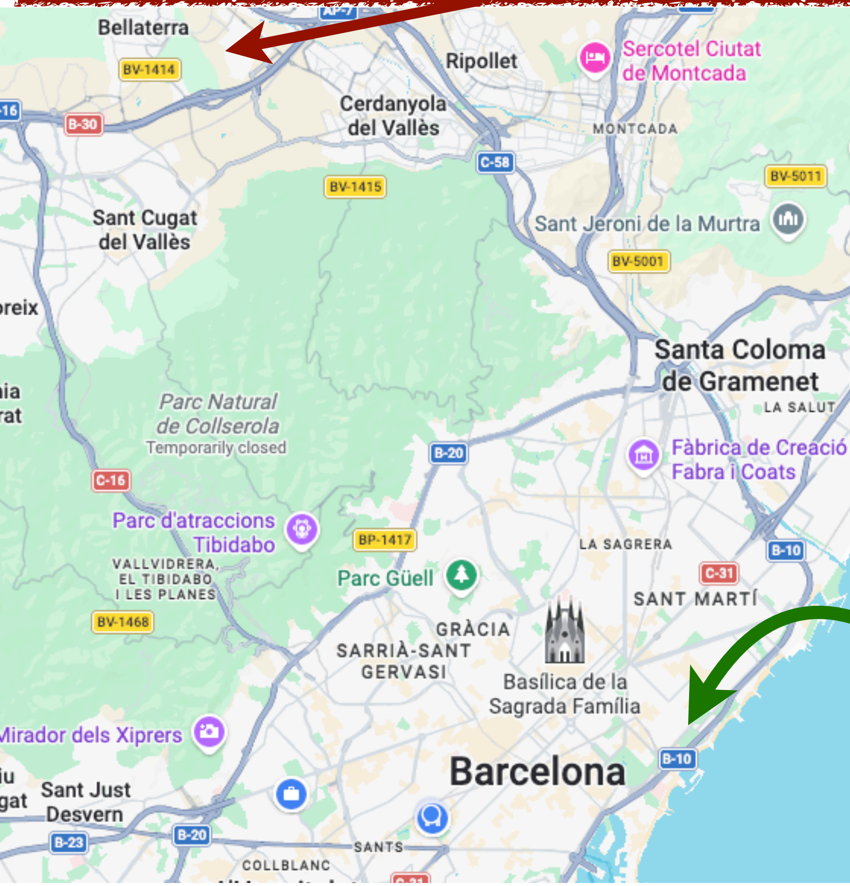

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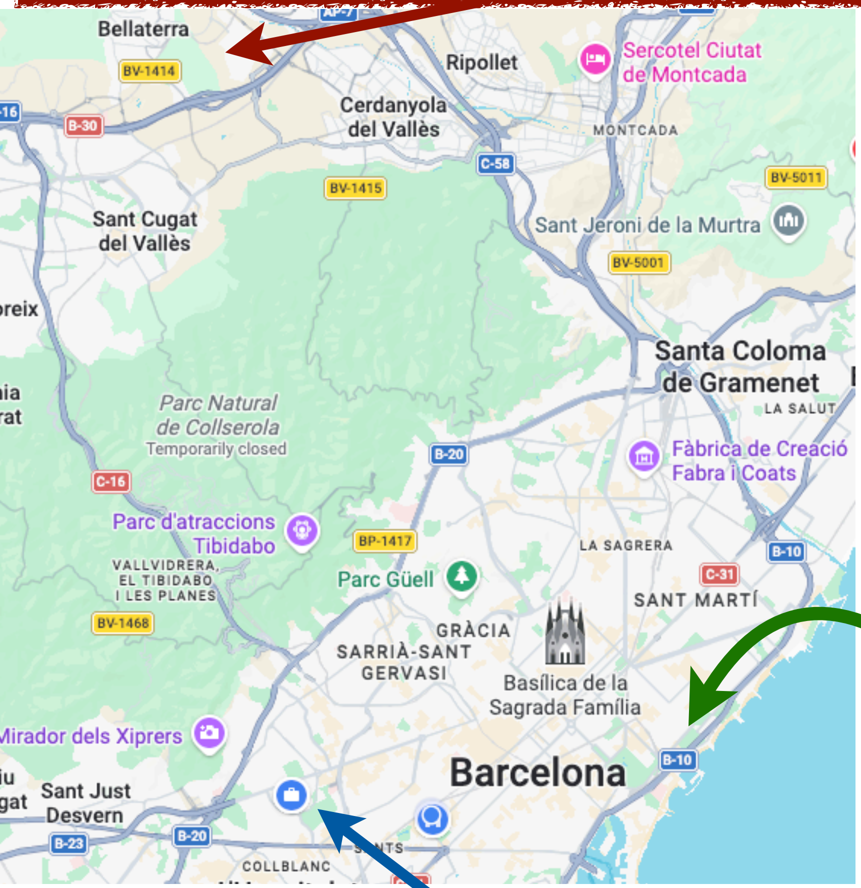

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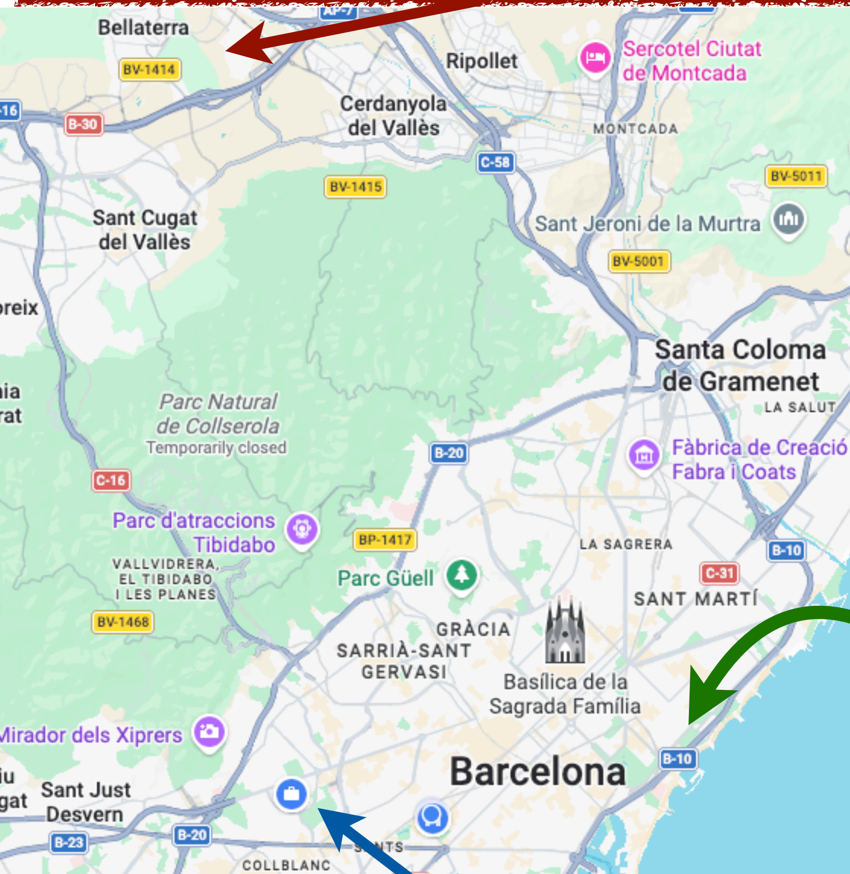

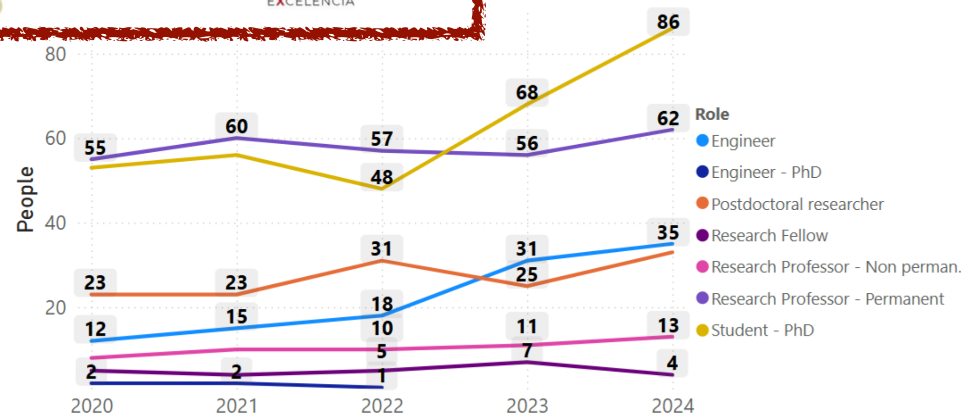

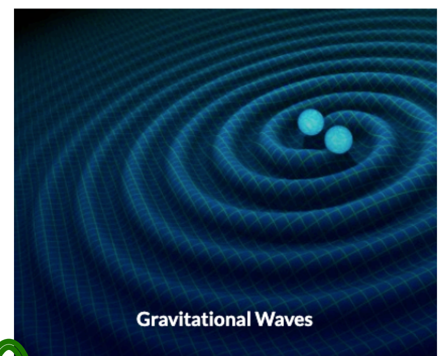

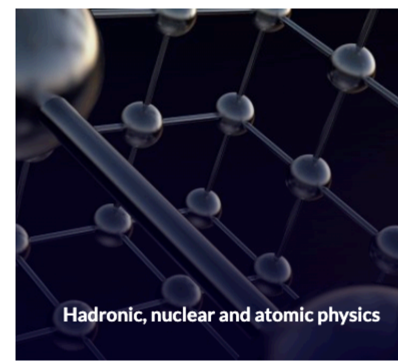

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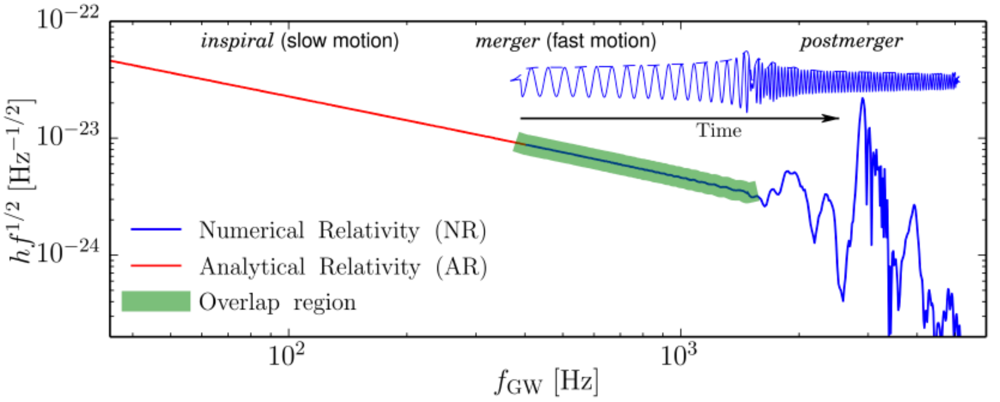
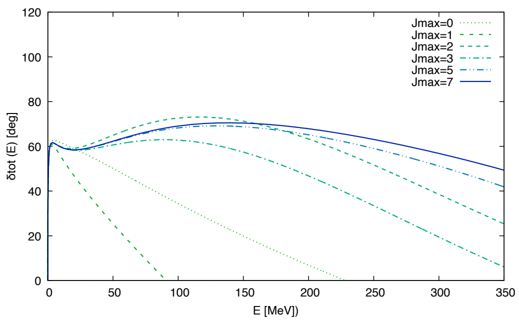
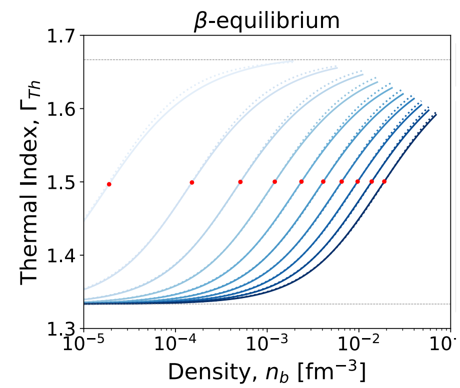
Outline

- **Motivation**

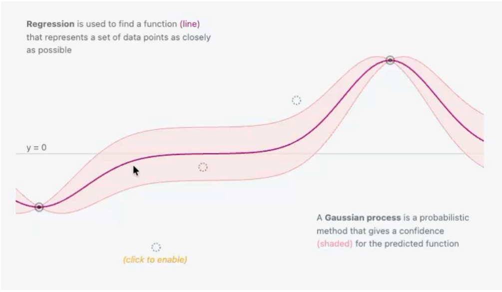


- Virial approximation & thermal effects in BNS





- Gaussian processes



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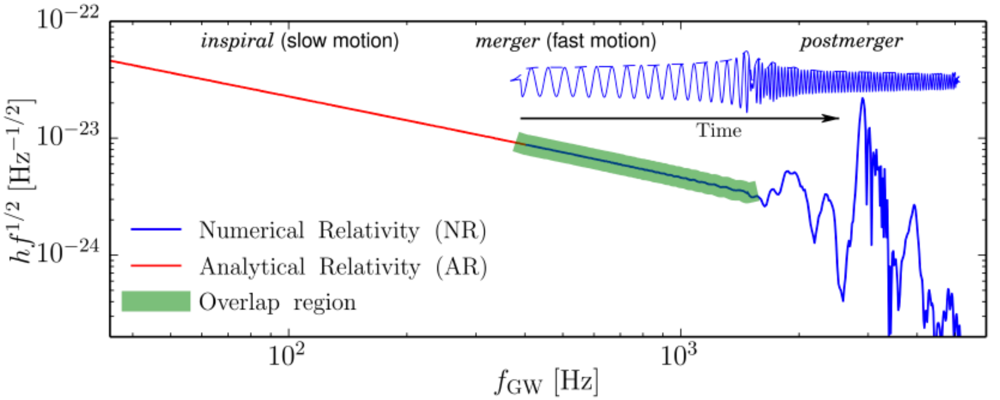

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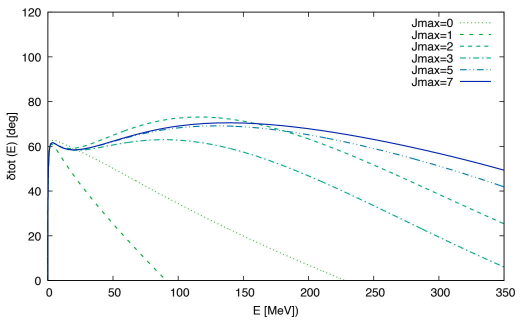

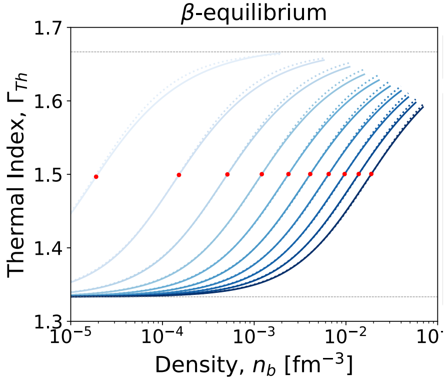

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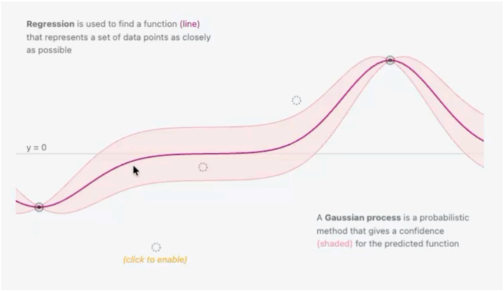
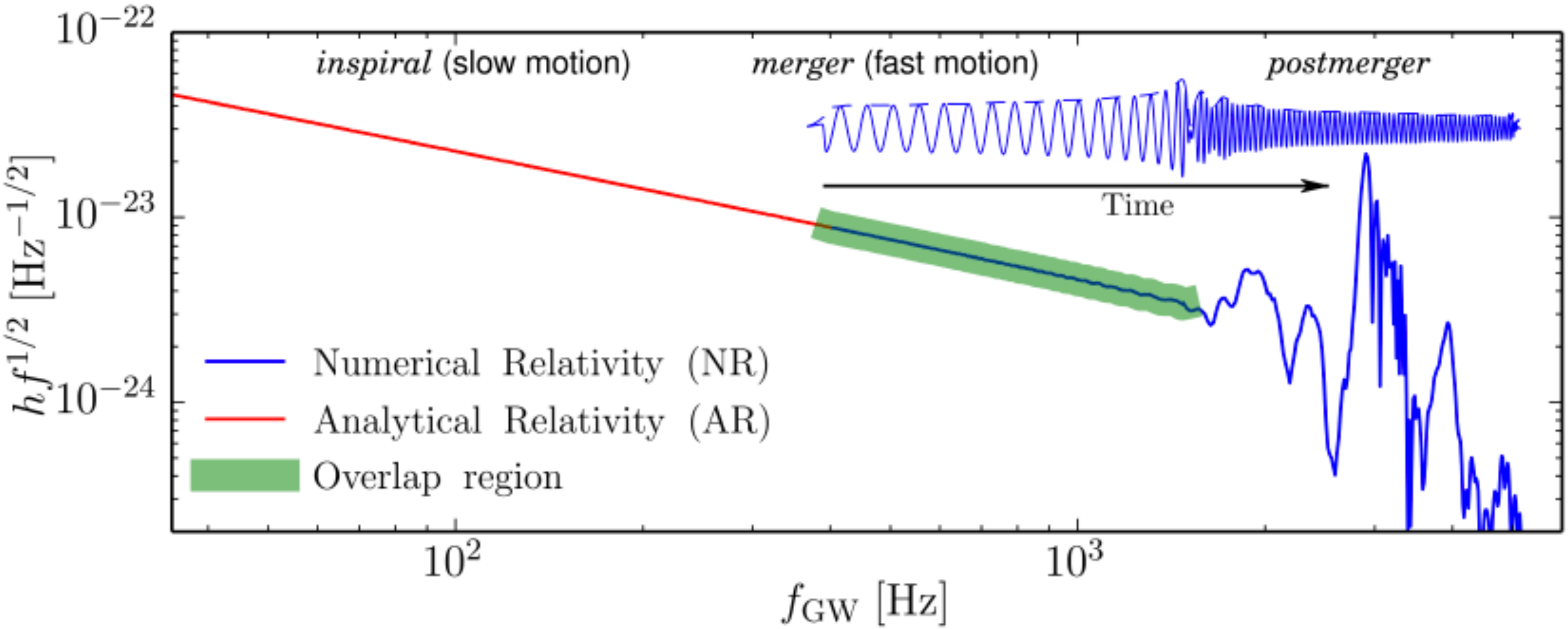


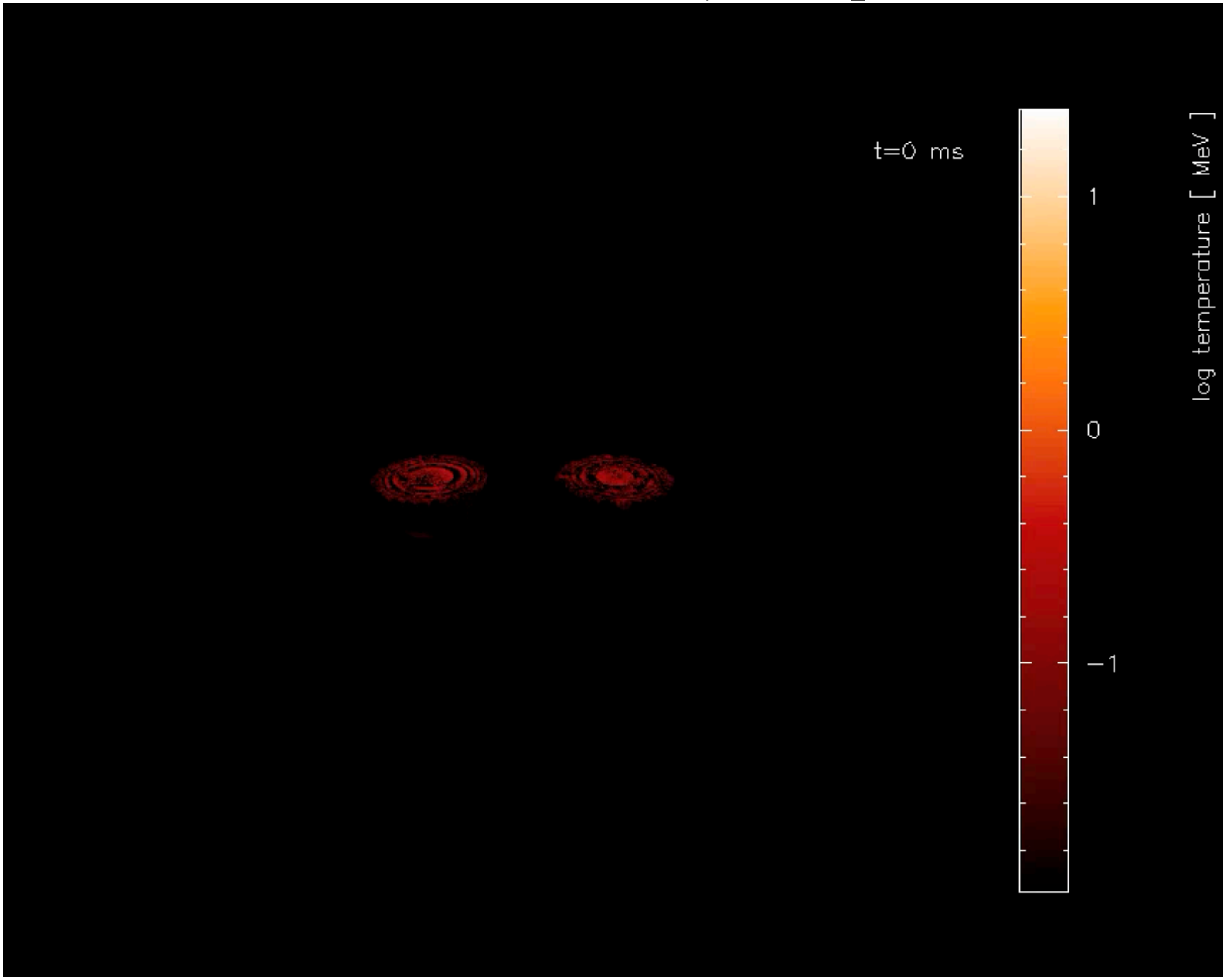
GW modelling



Radice, Bernuzzi & Perego, Annu. Rev. Nucl .Part. Sci. **70** 95 (2020)

- **Inspiral**: analytical relativity (eg 1B approaches)
- **Post-merger**: numerical relativity.
- **Complete waveform models**: matching the two approaches in the region where both are valid

$1.4M_{\odot}+1.3M_{\odot}$ NS binary: **temperature**



Rosswog group, http://compact-merger.astro.su.se/movies.html

Motivation

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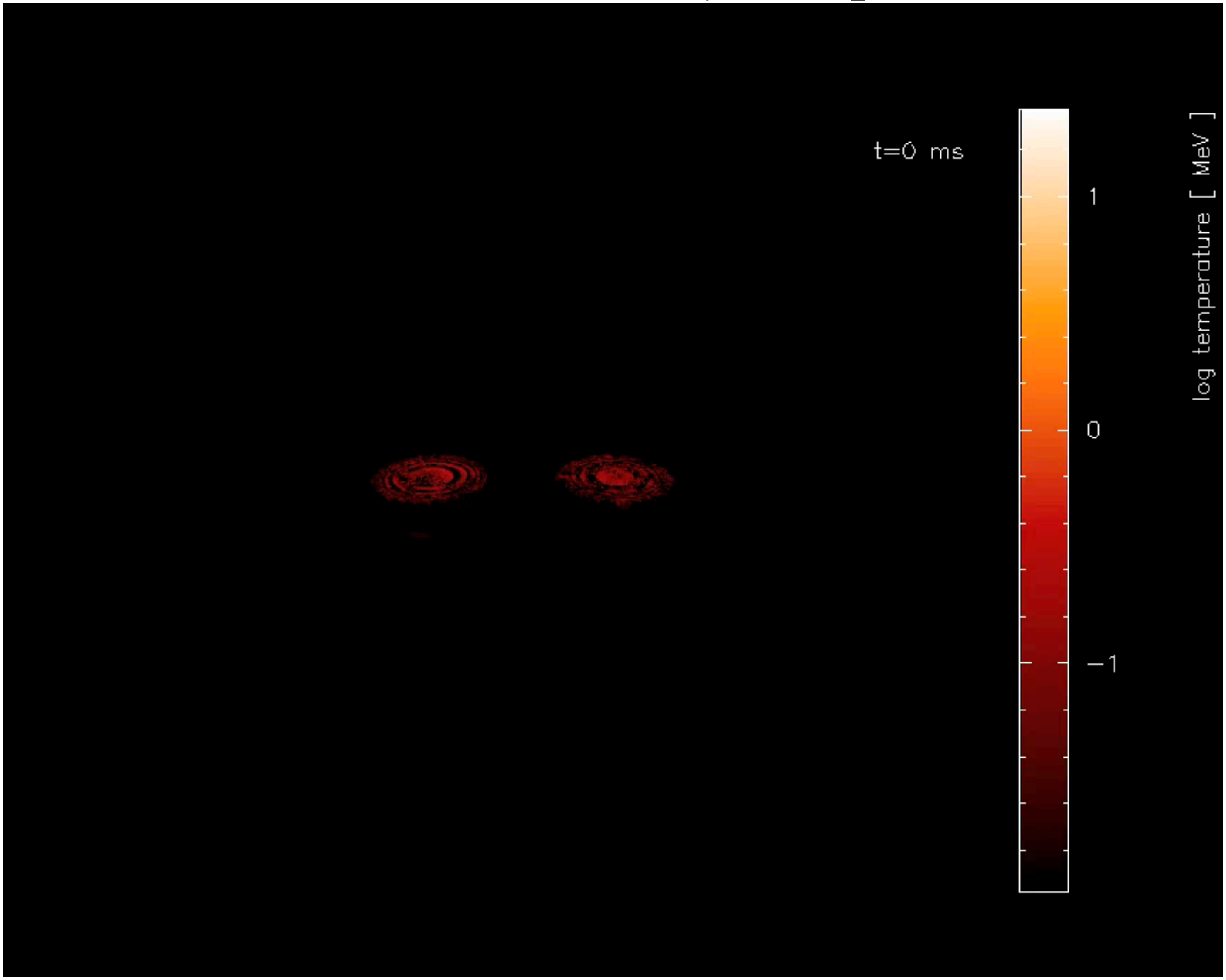

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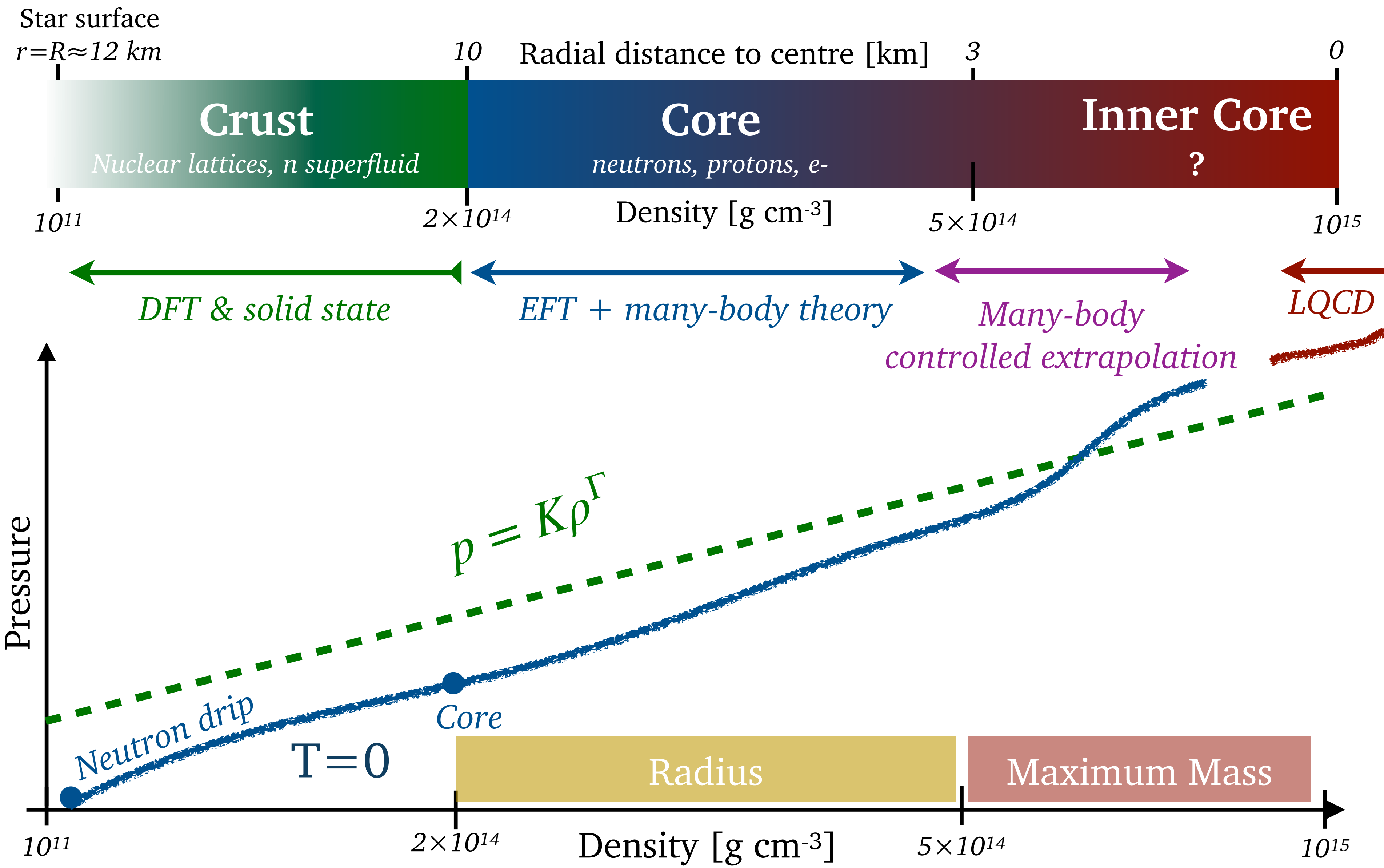
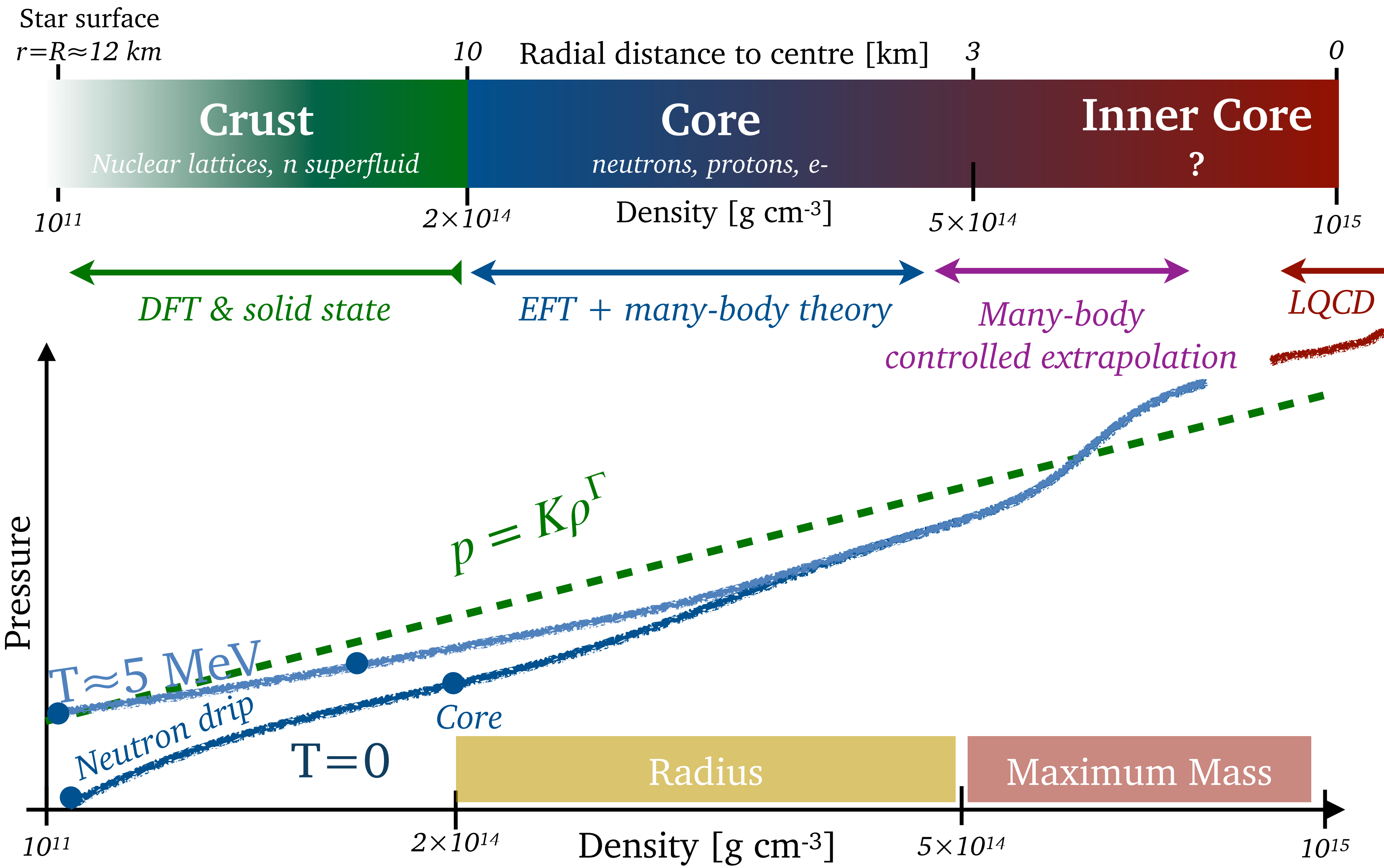
Neutron-star modelling



Neutron-star modelling



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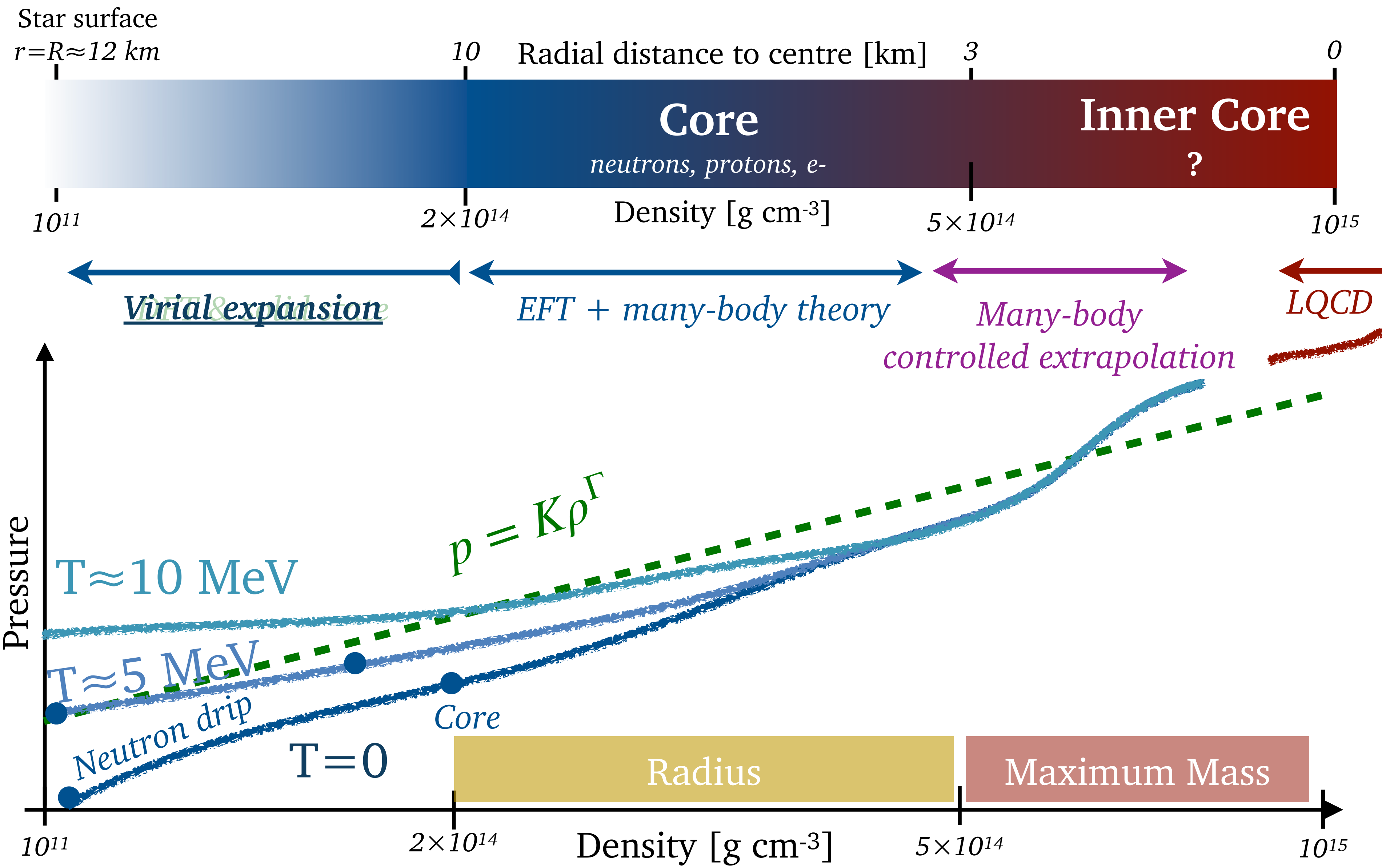
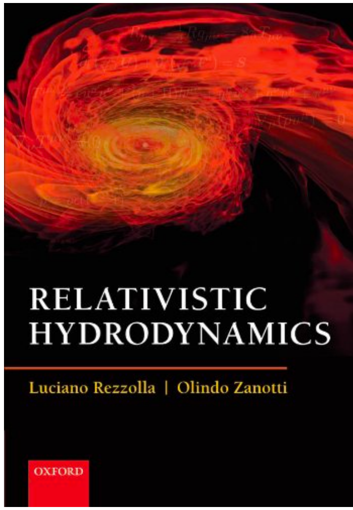


Hot neutron stars

Simulations require **coupled dynamics** of:

- A fluid which is essentially **cold** (eg NSs before merger)
- A fluid **heated by shocks**, with kinetic energy dissipated into internal energy

$$P(\epsilon, T) = P(\epsilon, T=0) + P_{\rm th}(\epsilon_{\rm th})$$



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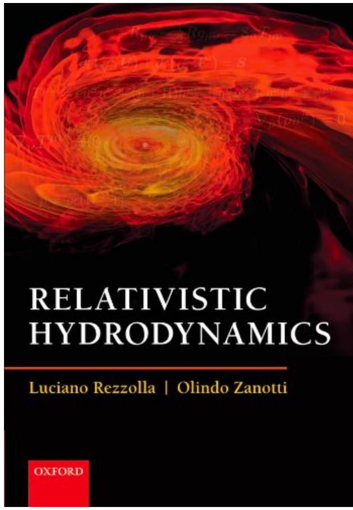

$$P(\epsilon, T) = P(\epsilon, T=0) + P_{\rm th}(\epsilon_{\rm th})$$

Cold part

(Piecewise polytrope)

$$P(\epsilon, T=0) = K\epsilon^{\Gamma_c}$$

No thermal energy

Read et al, *Phys Rev D* **79** 124032 (2009)

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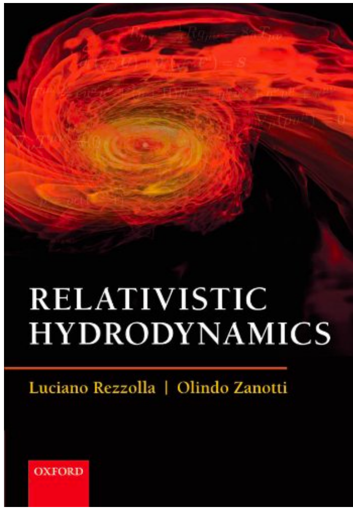

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Read et al, *Phys Rev D* **79** 124032 (2009)

Thermal part

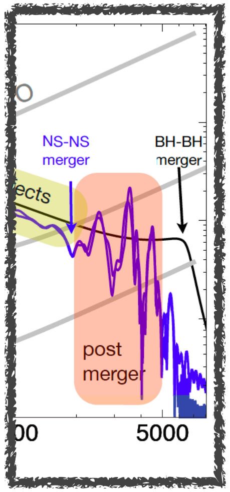
Thermal index

$$P_{\rm th}(\epsilon_{\rm th}) \equiv [\Gamma_{\rm th} - 1]\,\epsilon_{\rm th}$$

$$\Gamma_{\rm th}(\epsilon_{\rm th}) = 1 + \frac{P_{\rm th}(\epsilon_{\rm th})}{\epsilon_{\rm th}}$$

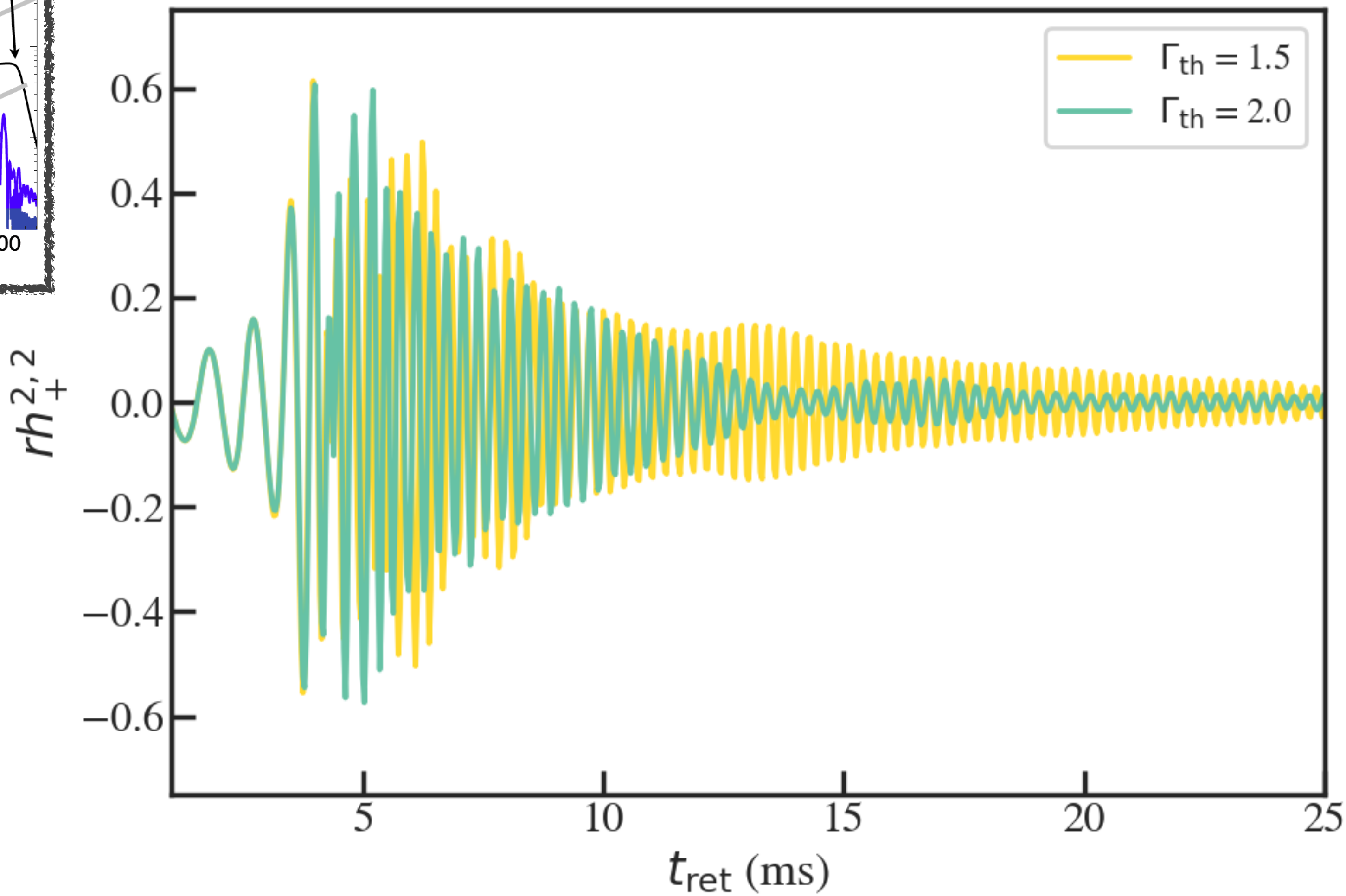
$$\epsilon_{\rm th} = \epsilon(T) - \epsilon_0$$

Post-merger: from Γ_{th} to GWs



$1.4M_\odot + 1.4M_\odot$ GW spectrum

Same cold component, different constant Γ_{th}



Raithel, Paschalidis & Ozel, *Phys Rev D* **104** 063016 (2021)

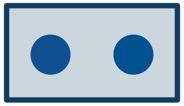
Known situations

Cold part

Thermal part

Non-relativistic

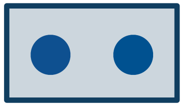
$$\Gamma_c = \frac{5}{3}$$



$$\Gamma_{\rm th} = \frac{5}{3}$$

Relativistic

$$\Gamma_c = \frac{4}{3}$$



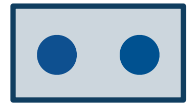
$$\Gamma_{\rm th} = \frac{4}{3}$$

Known situations

Cold part | **Thermal part**

Non-relativistic

$$\Gamma_c = \frac{5}{3}$$



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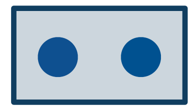
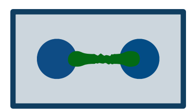


$$\Gamma_{\rm th} = \frac{4}{3}$$

Unitary

$k_F a_S \gg 1$

$$\Gamma_c = \frac{5}{3}$$



$$\Gamma_{\rm th} = \frac{5}{3}$$

Known situations

Cold part / Thermal part

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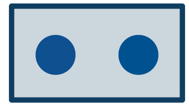

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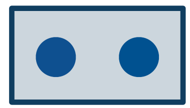
Relativistic

$$\Gamma_c = \frac{4}{3}$$



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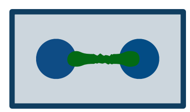
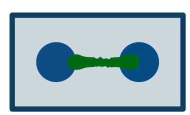


$$\Gamma_{\rm th} = \frac{5}{3}$$

Mean-field/Fermi liquid

$$\Gamma_c = \Gamma_c(\epsilon)$$



$$\Gamma_{\rm th}^{m^*} = \frac{5}{3} - \frac{n}{m^*}\frac{\partial m^*}{\partial \rho}$$

Constantinou, Muccioli, Prakash & Lattimer, *Phys Rev C* **92** 025801 (2015)

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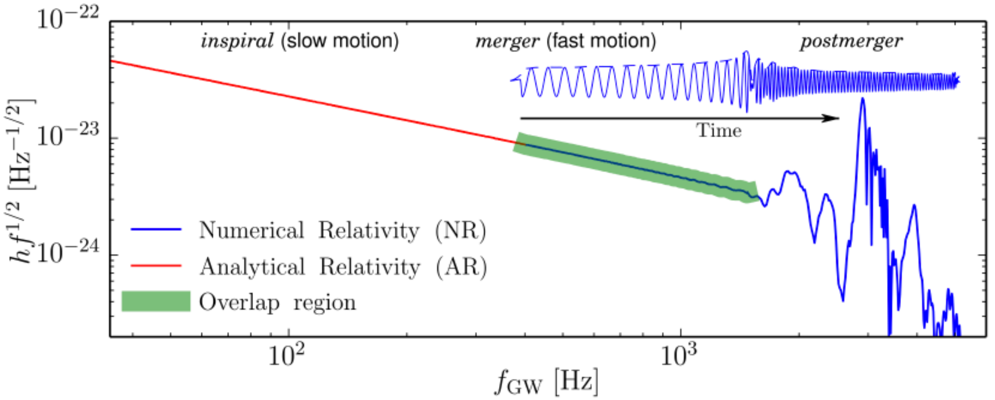

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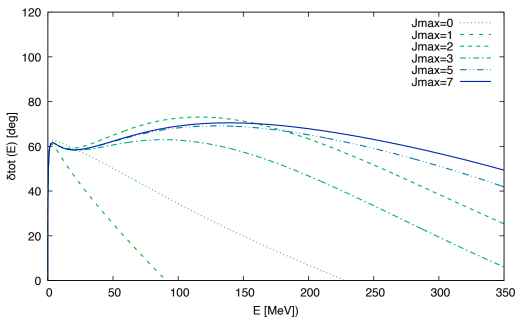
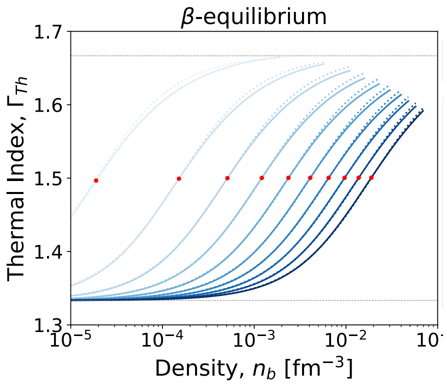
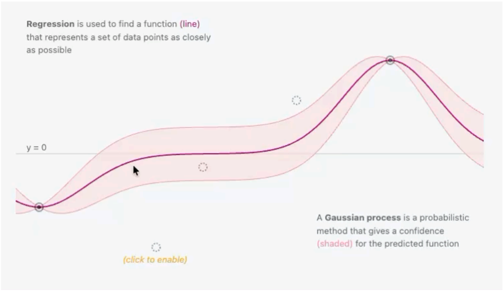




- Gaussian processes



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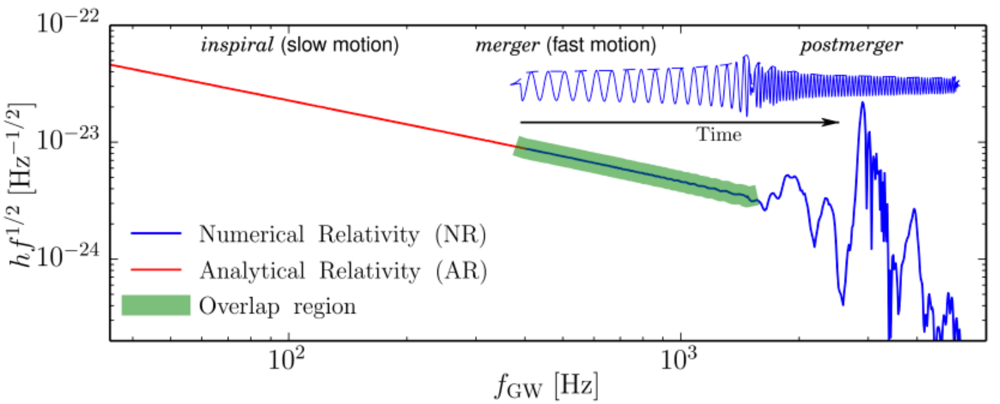

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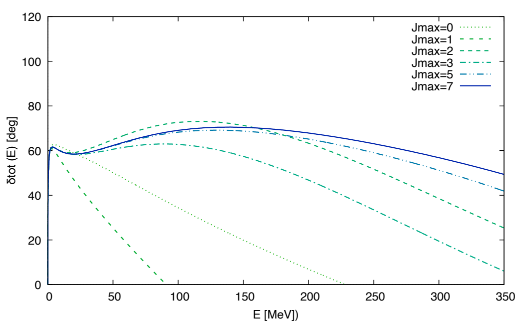

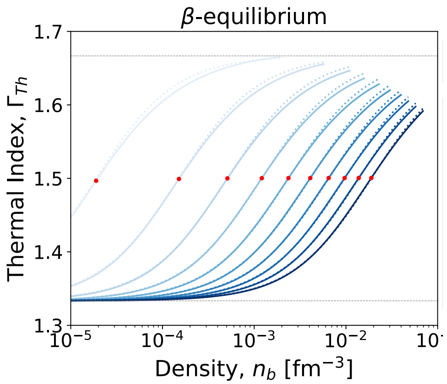

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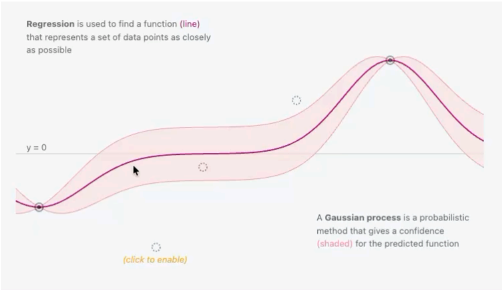


Virial expansion

Expansion

$$P = \frac{2T}{\lambda^3}\left[z + z^2 b_2 + z^3 b_3 + O(z^4)\right]$$

$$n = \frac{2}{\lambda^3}\left[z + 2z^2 b_2 + 3z^3 b_3\right]$$

$$\epsilon = \frac{3}{2}P + \frac{2T^2}{\lambda^3}\left[z^2 b_2' + z^3 b_3'\right]$$

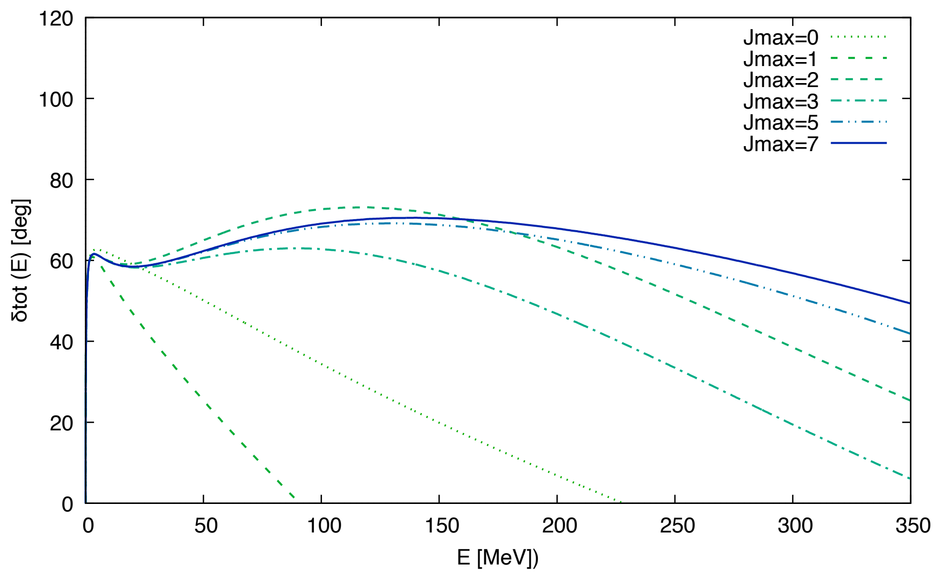
$$z = e^{\mu/T} \quad b_n' = \frac{\partial b_n}{\partial T}$$

Virial coefficients

$$b_2(T) = \frac{1}{\sqrt{2}\pi T}\int_0^\infty dE e^{-E/T}\delta(E) - 2^{-5/2}$$

$$b_3(T) = ?$$

Drut *et al.* Unitary gas



- Systematic expansion
- Improvable order-by-order

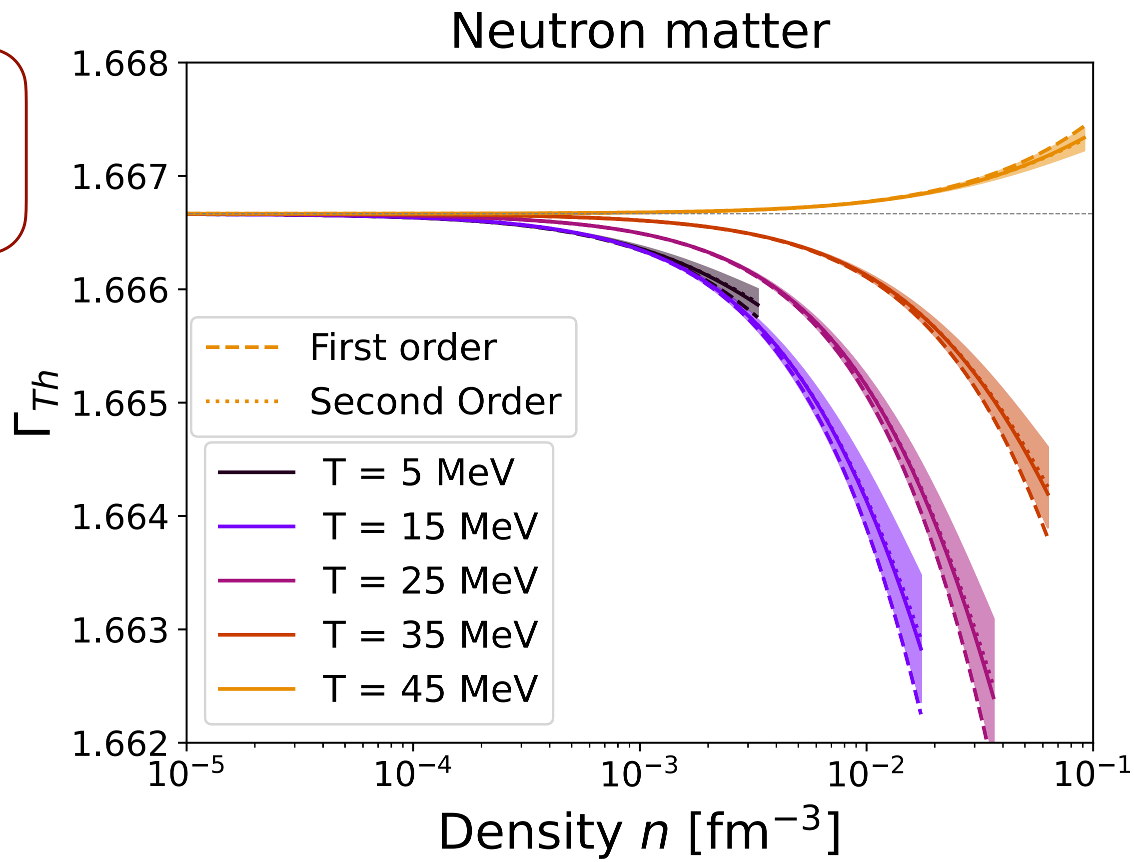
Huang & Kerson, *Statistical Mechanics*
Horowitz & Schwenk, *Phys. Lett. B* **638** 153159 (2006); *Nuc. Phys. A* **776** 055079 (2006)

Thermal index: pure neutron matter

$$\Gamma_{th} = \frac{5}{3} + \Gamma_1 z + \Gamma_2 z^2$$

$$\Gamma_1 = -\frac{4}{9} T b_2' \quad \underline{<0}$$

$$\Gamma_2 = \frac{2}{3} T b_2' + b_2 - \frac{b_3'}{b_2'}$$



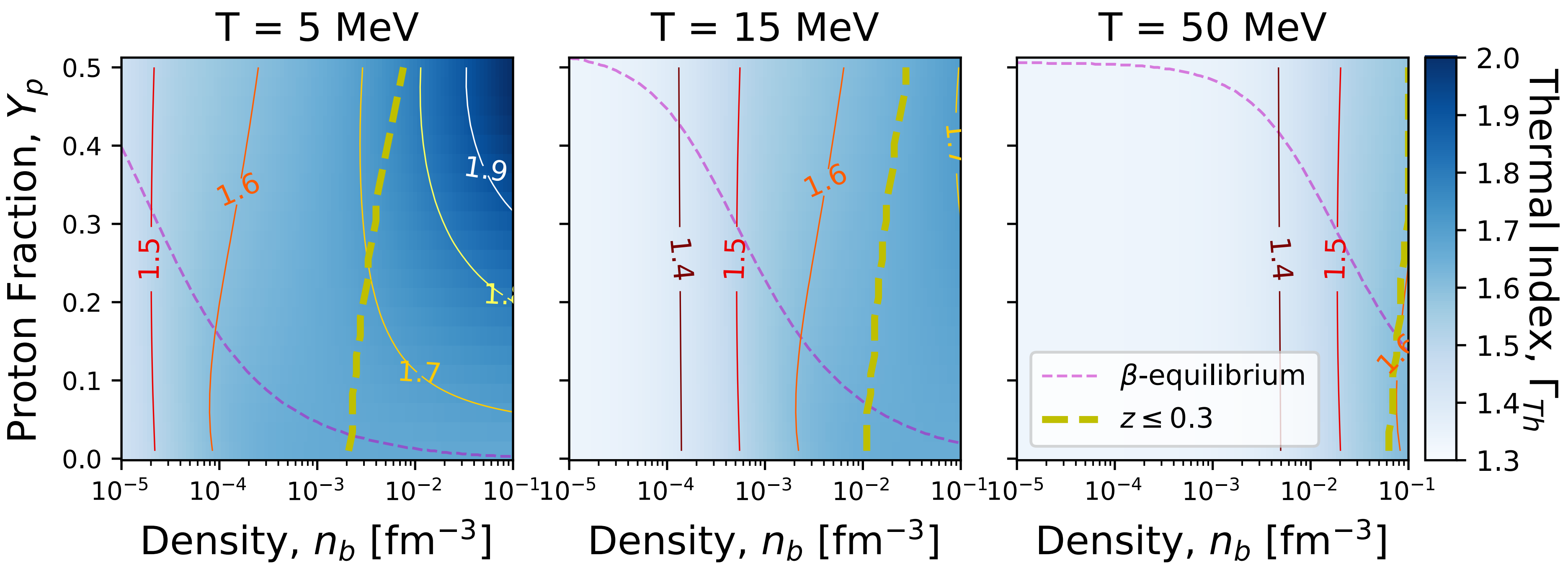
G Rivieccio @ UV

- **Small variation:** 0.3%
- **Small uncertainty:** 0.1%
- **T** dependence mild
- Closeness to **unitary gas**

Nadal TFG@UB

Rivieccio, Nadal-Matosas, Rios & Ruiz, *ApJ* **987**, 67 (2025)

Thermal index: npe matter



Baryon matter

$$P_{\rm th}^{\rm nuc} = \frac{2T}{\lambda^3}\left[z_n + z_p + (z_n^2 + z_p^2)b_n + 2 z_n z_p b_{np}\right]$$

Leptons & photons ultrarelativistic

$$\Gamma_{\rm th} = \frac{4}{3}$$

β equilibrium

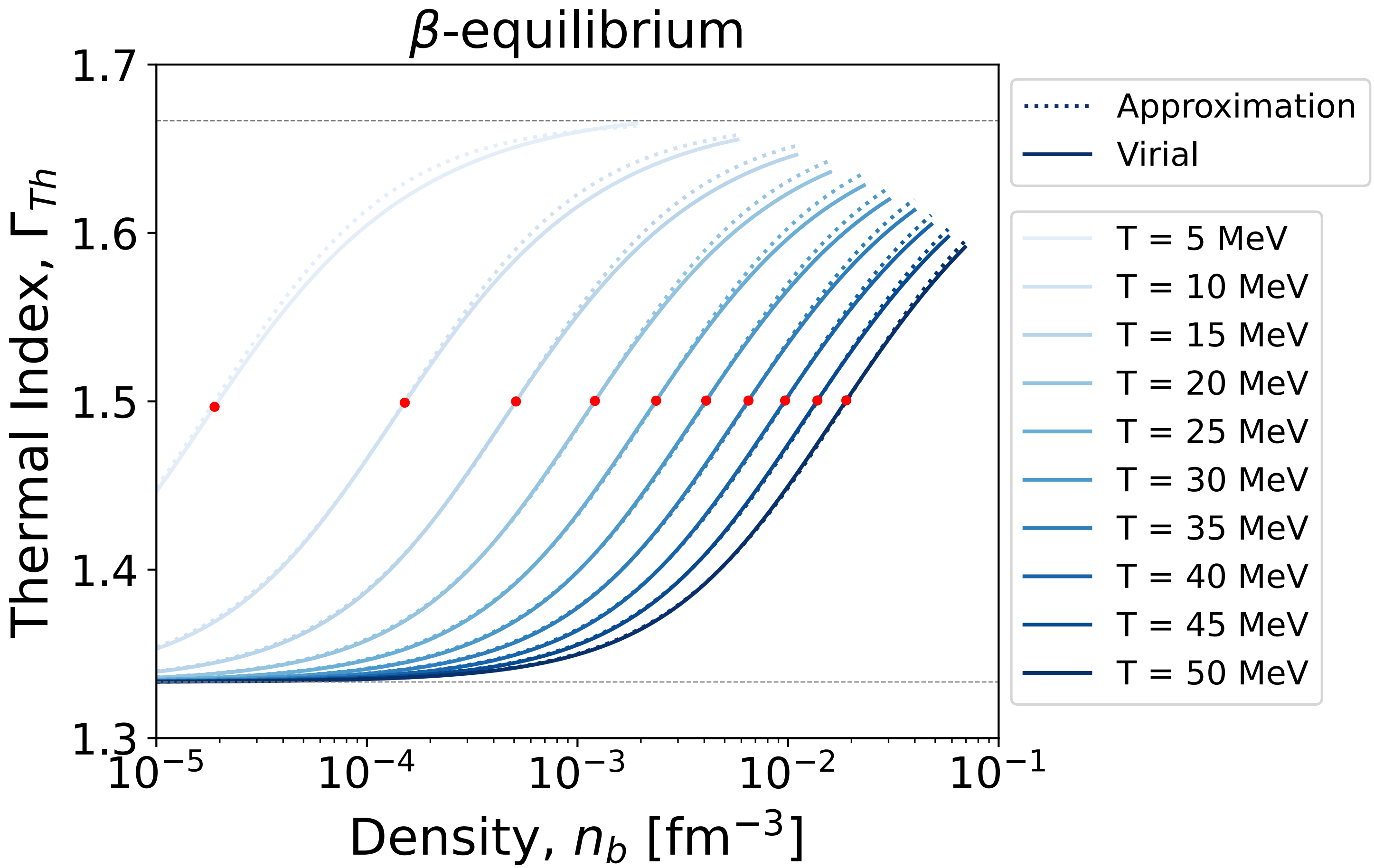
$$\mu_n = \mu_p + \mu_e$$

Thermal index

$$\Gamma_{\rm th} = 1 + \frac{P_{\rm th}^{nuc} + P_{\rm th}^{lep} + P_{\rm th}^{\gamma}}{\epsilon_{\rm th}^{nuc} + \epsilon_{\rm th}^{lep} + \epsilon_{\rm th}^{\gamma}}$$

Rivieccio, Nadal-Matosas, Rios & Ruiz, *ApJ* **987**, 67 (2025)

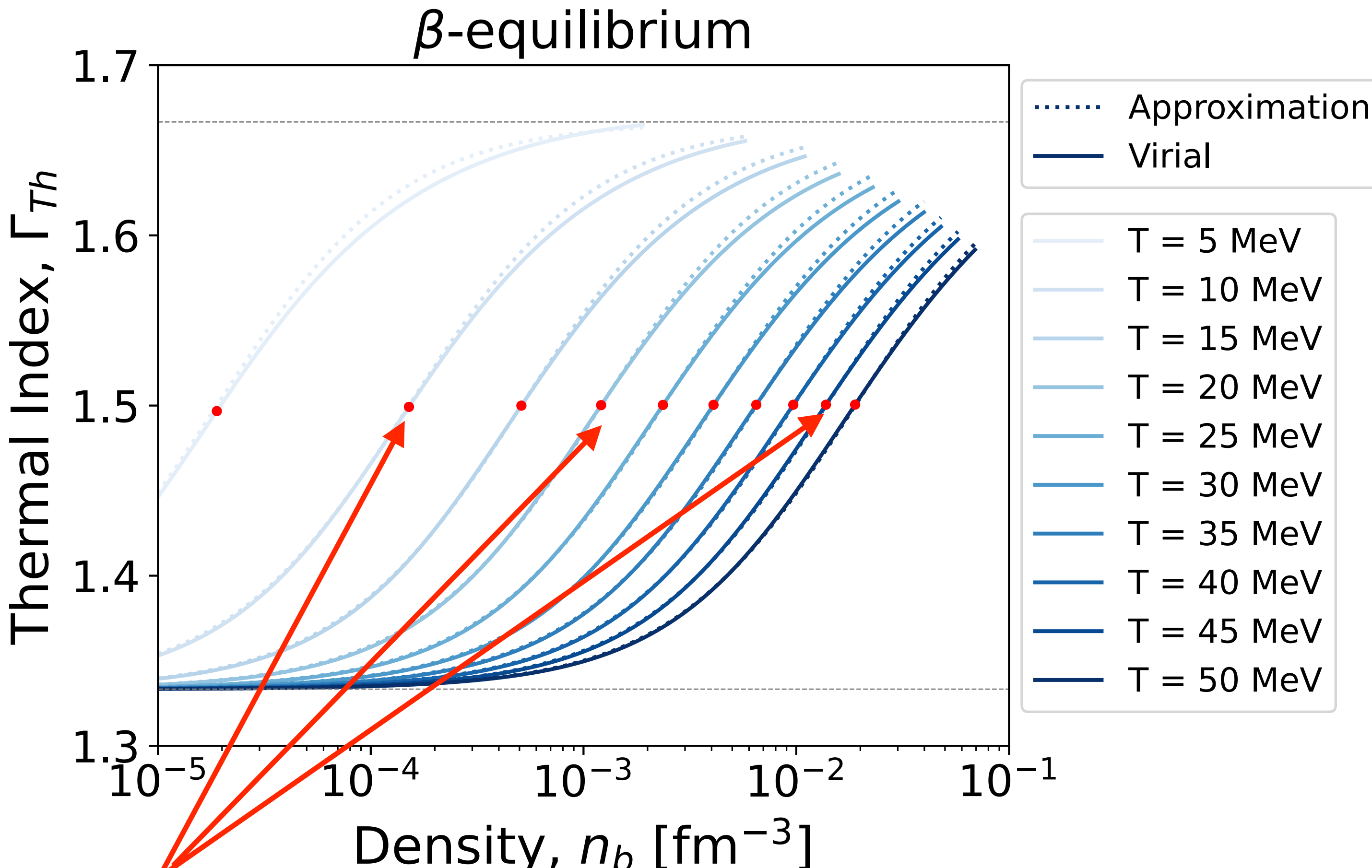
Thermal index: parametrization



$$\Gamma_{\rm th} = \frac{4}{3} + \frac{1}{3}\frac{n_b}{n_b + n_{\rm inf}}$$

Rivieccio, Nadal-Matosas, Rios & Ruiz, *ApJ* **987**, 67 (2025)

Thermal index: parametrization



Regime change

$$P_{\rm th}^{\rm nuc} \approx P_{\rm th}^{\rm lep}$$

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

$$\Gamma_{\rm th} = \frac{4}{3} + \frac{1}{3} \frac{n_b}{n_b + n_{\rm inf}}$$

Rivieccio, Nadal-Matosas, Rios & Ruiz, *ApJ* **987**, 67 (2025)

Thermal effects

On the treatment of thermal effects in the equation of state on neutron star merger remnants

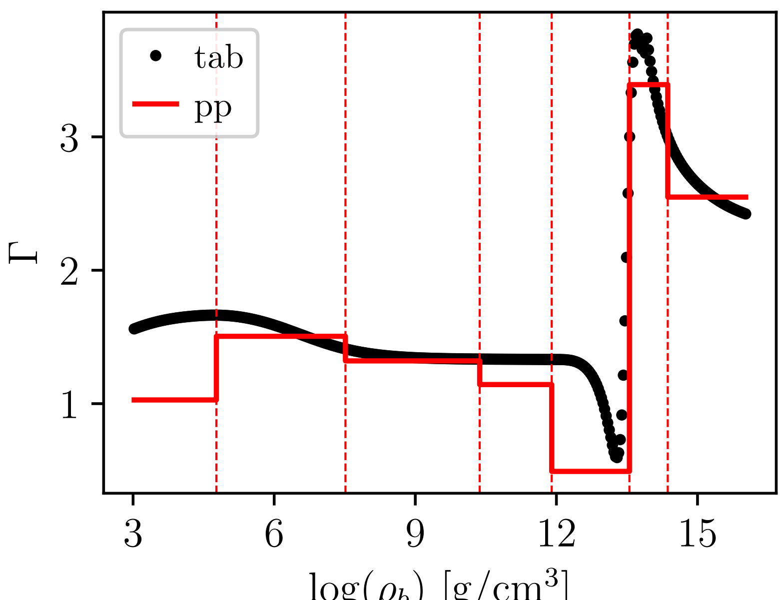
Davide Guerra,[1,*] Milton Ruiz,[1] Michele Pasquali,[2] Pablo Cerdá-Durán,[1,3] Arnau Rios,[4,5] and José A. Font[1,3]

[1]*Departamento de Astronomía y Astrofísica, Universitat de Valéncia, Dr. Moliner 50, 46100, Burjassot (València), Spain*
[2]*Department of Chemistry, Life Sciences and Environmental Sustainability, University of Parma, 43124 Parma, Italy*
[3]*Observatori Astronómic, Universitat de Valéncia, C/ Catedrático José Beltrán 2, 46980, Paterna (Valéncia), Spain*

$$P(\epsilon, T) = P(\epsilon, T=0) + P_{\rm th}(\epsilon_{\rm th})$$

Polytropic / Piecewise

$$P_{th}(\rho, T) = K\rho^{\Gamma_{th}}$$

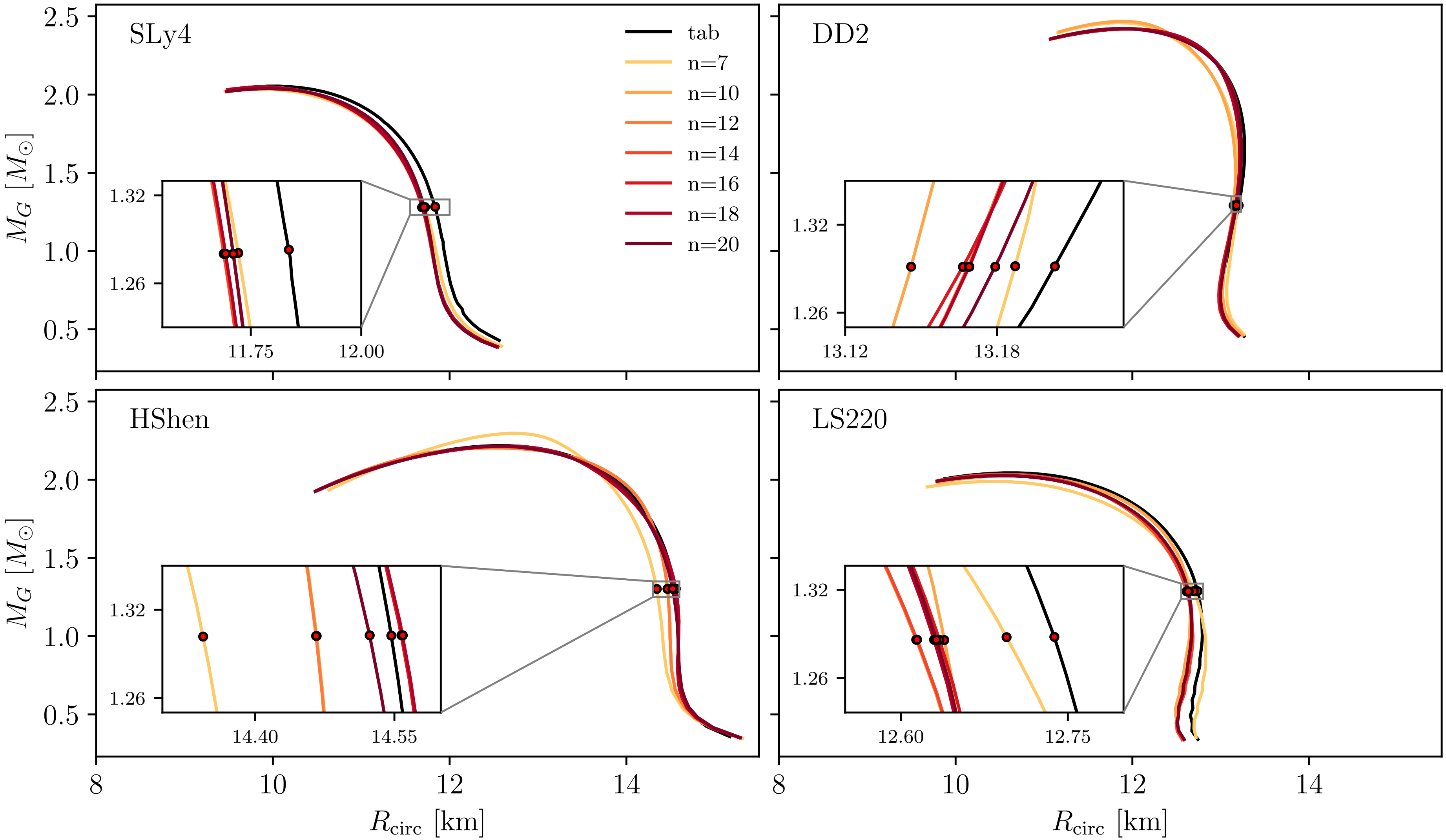


Tabulated

ρ	T	ε	P	Γ_{th}

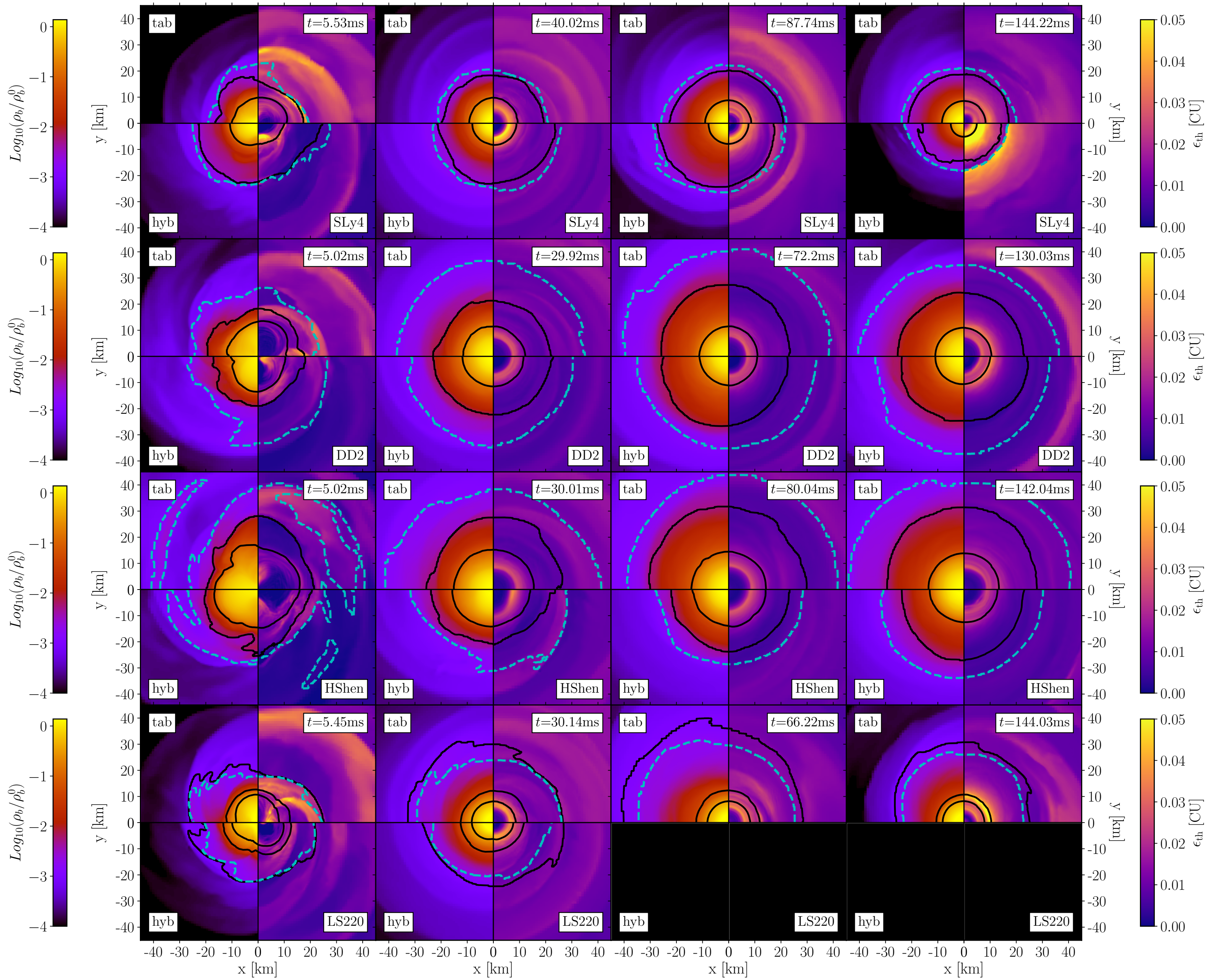
Davide Guerra, *et al.* arxiv:2512.05118

Piecewise T=0 results



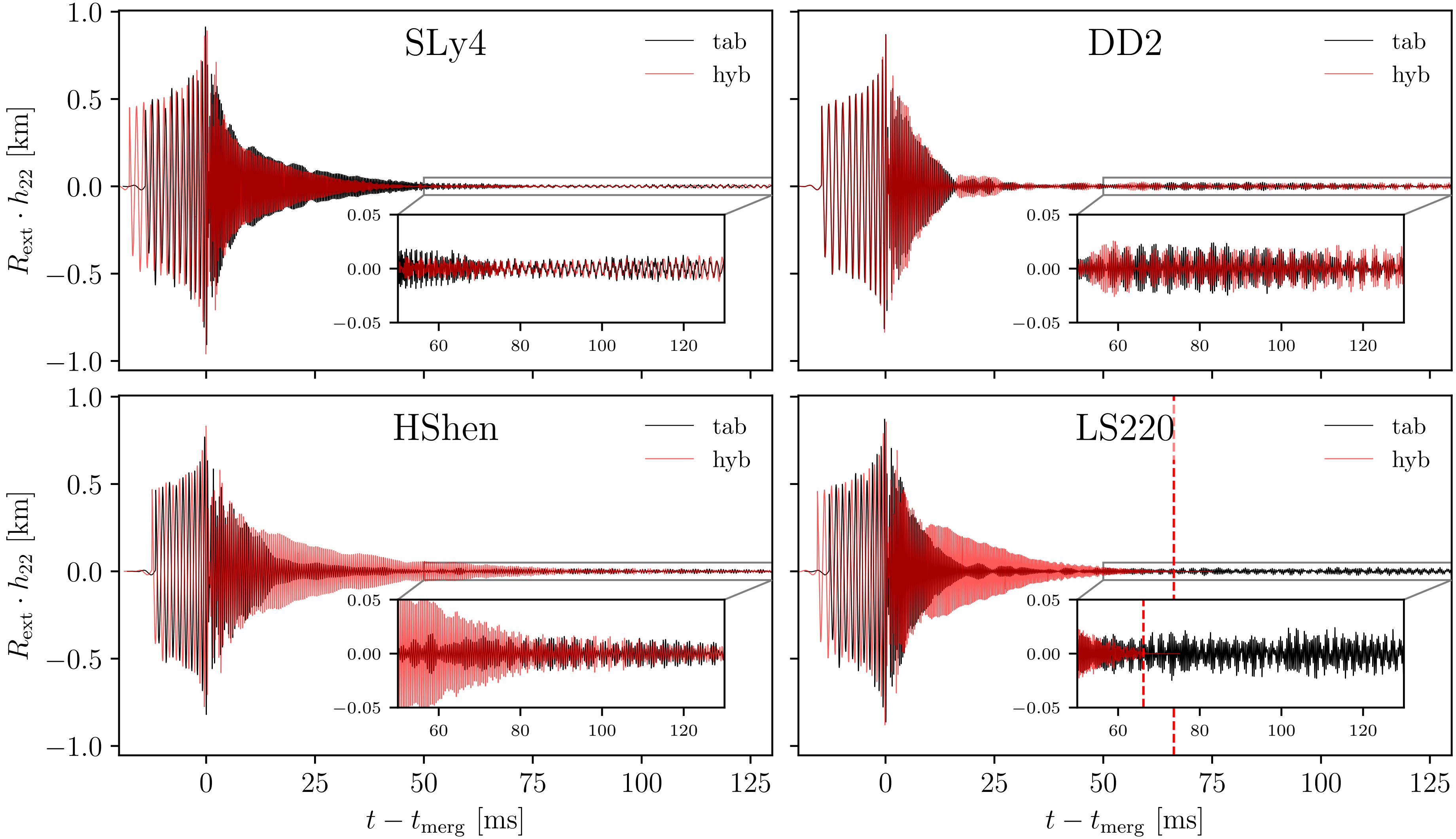
Davide Guerra, *et al.* arxiv:2512.05118

Density and temperature



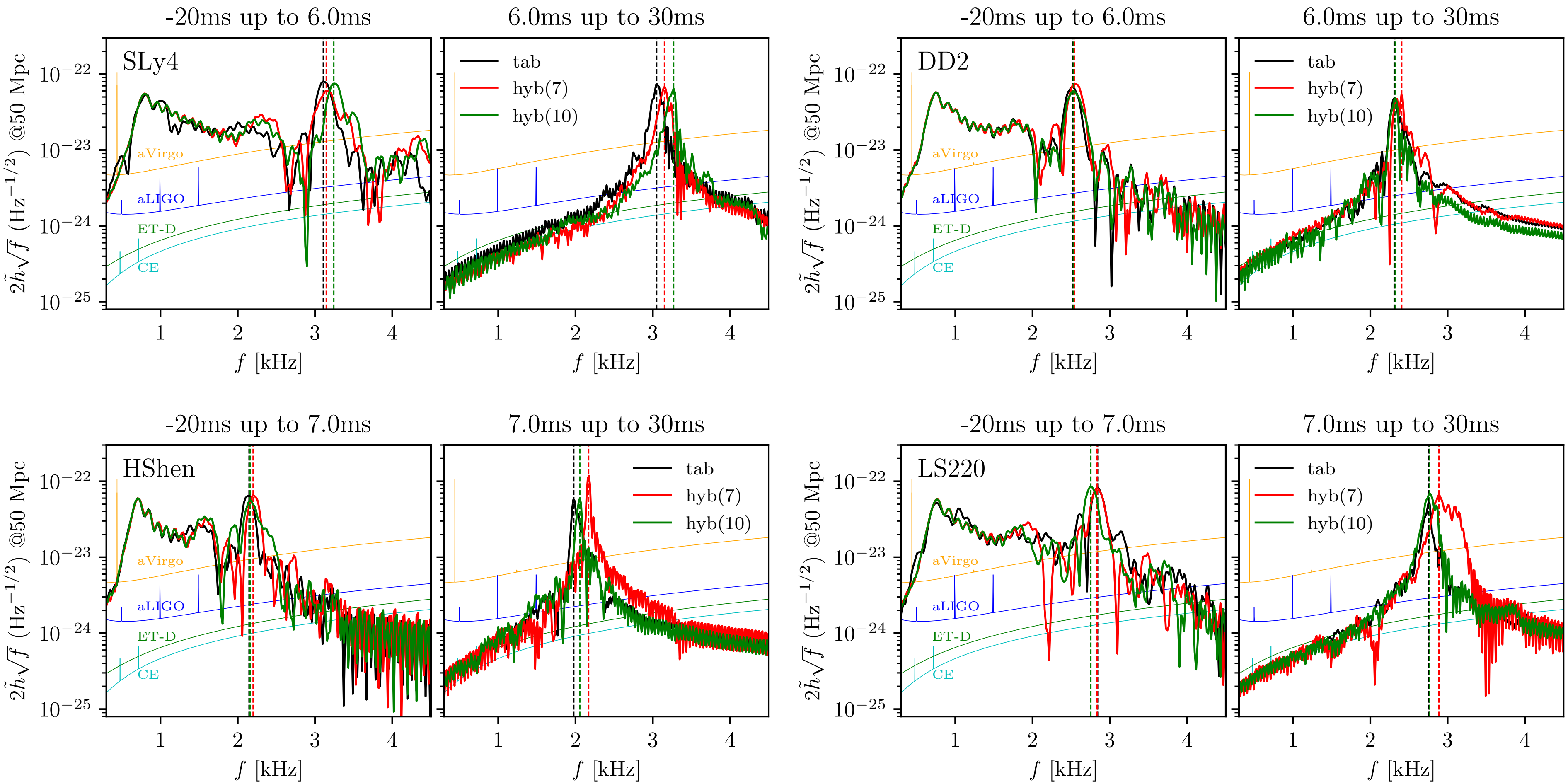
Davide Guerra, et al. arxiv:2512.05118

GW emission: late times



Davide Guerra, *et al.* arxiv:2512.05118

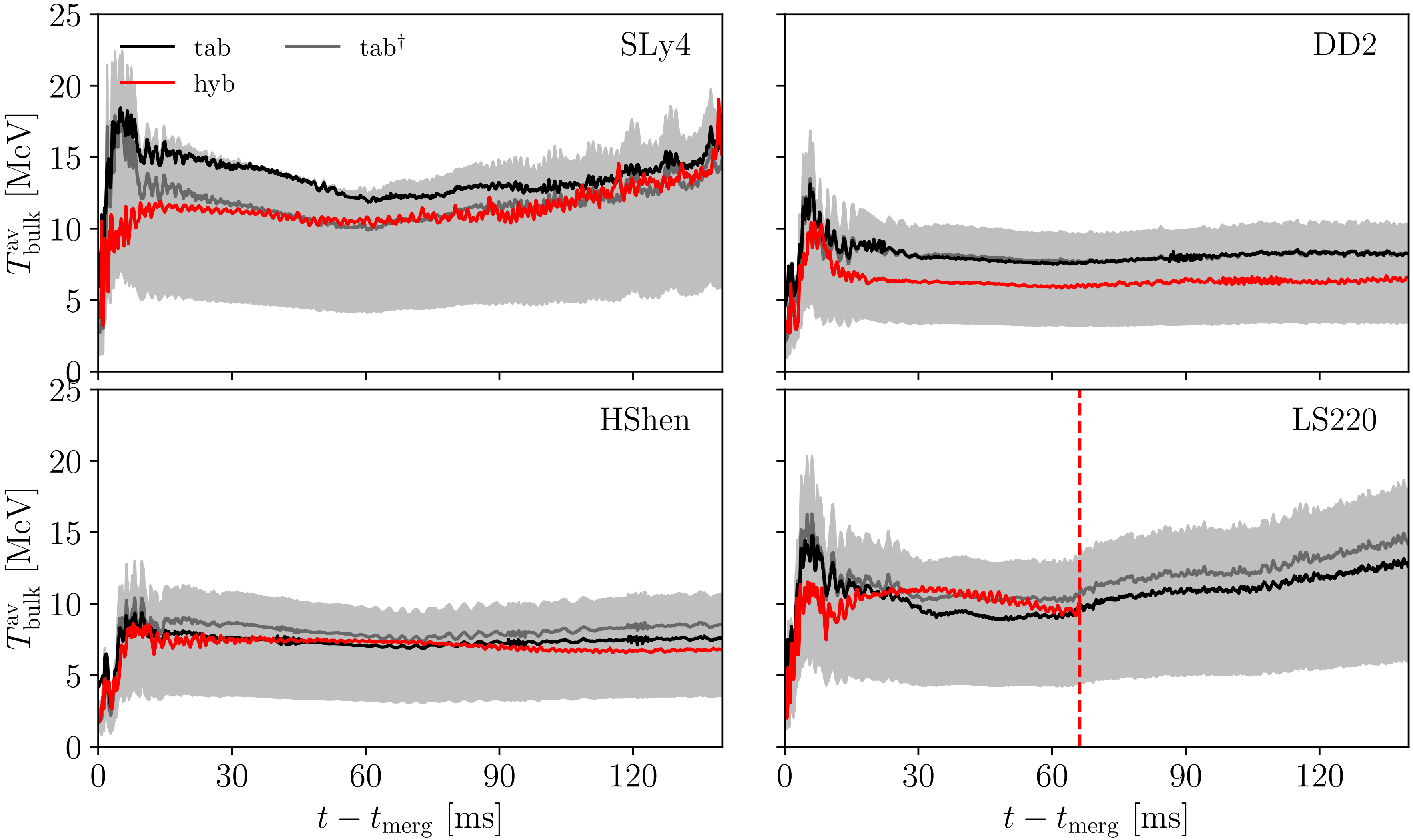
GW spectra



Davide Guerra, *et al.* arxiv:2512.05118

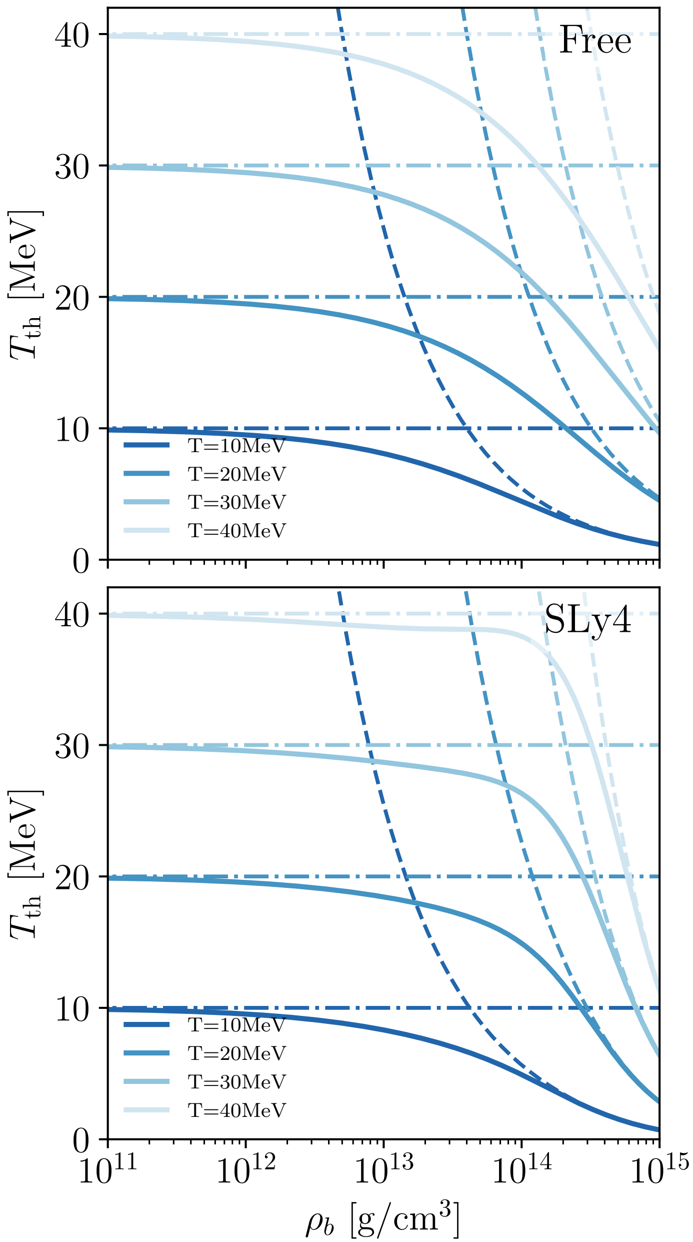
Temperature estimate

$$T_{hyb} = (\Gamma_{th} - 1)\epsilon_{hyb}$$



Davide Guerra, *et al.* arxiv:2512.05118

Estimate error in T



$$e(\rho, T) = e(\rho, T=0) + e_{\rm th}(\rho, T)$$

$$p(\rho, T) = p(\rho, T=0) + (\Gamma_{\rm th} - 1)\, \rho e_{\rm th}(\rho, T)$$

$$T_{\rm th} = (\Gamma_{\rm th} - 1)\, e_{\rm th}(n, T)$$

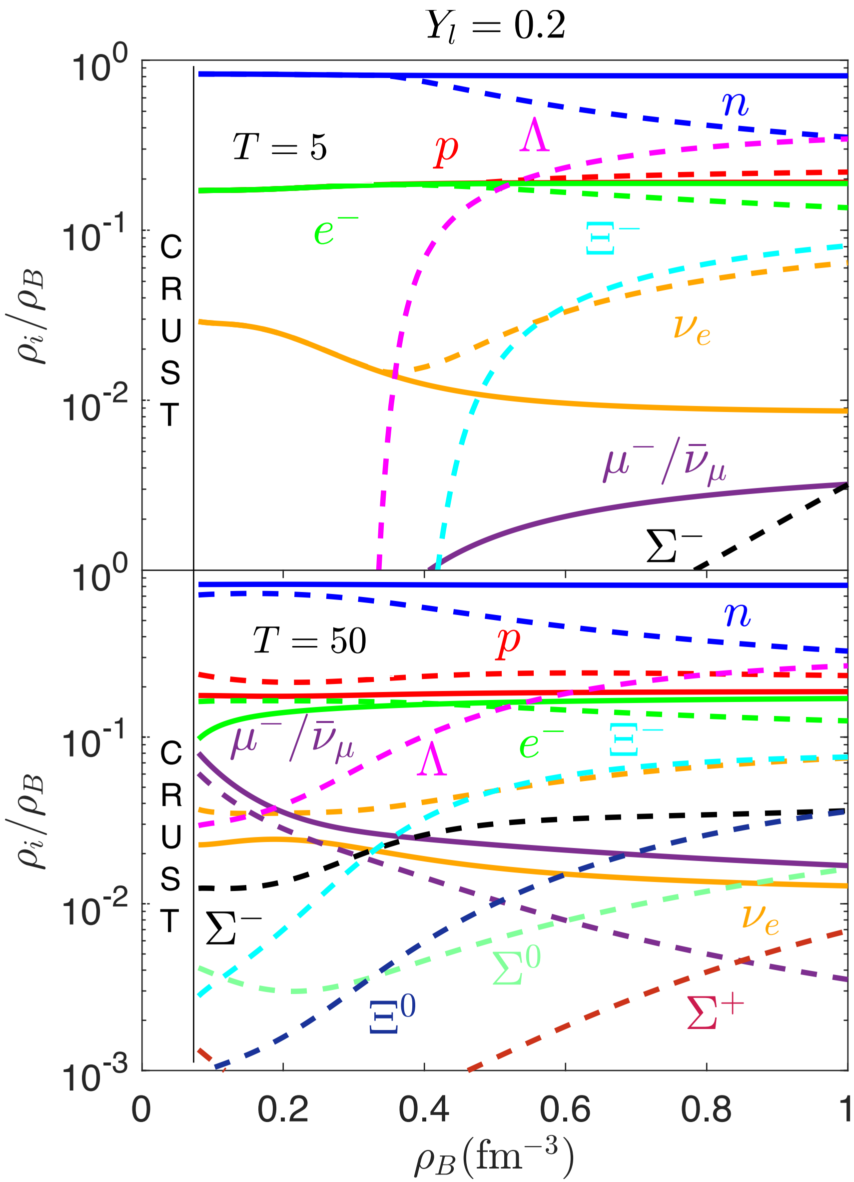
Ideal Gas $\quad T_{\rm th} = \left(\frac{5}{3} - 1\right)\frac{3}{2}T = T$

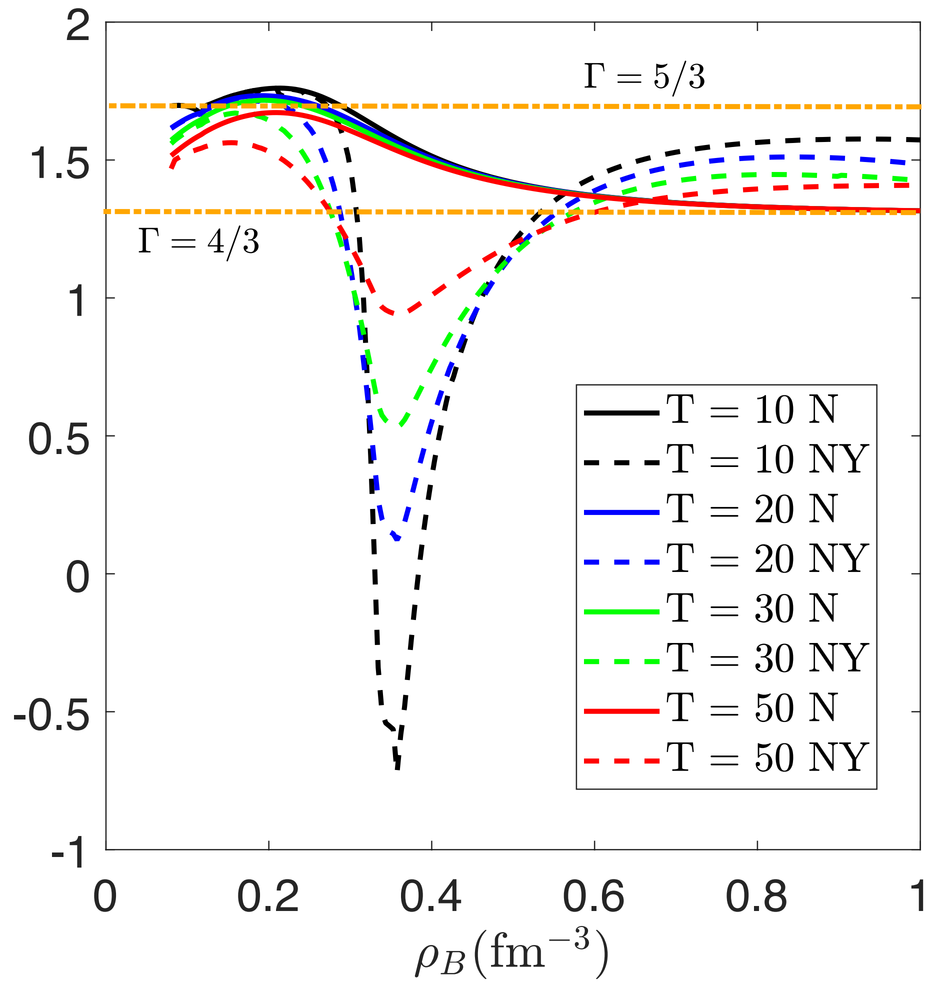
Degenerate Gas

$$T_{\rm th} = \frac{\pi^2}{6}\frac{T^2}{\varepsilon_F^*}\left[1 - \frac{3}{2}\frac{n}{m_n^*}\frac{\partial m_n^*}{\partial n}\right]$$

Davide Guerra, *et al.* arxiv:2512.05118

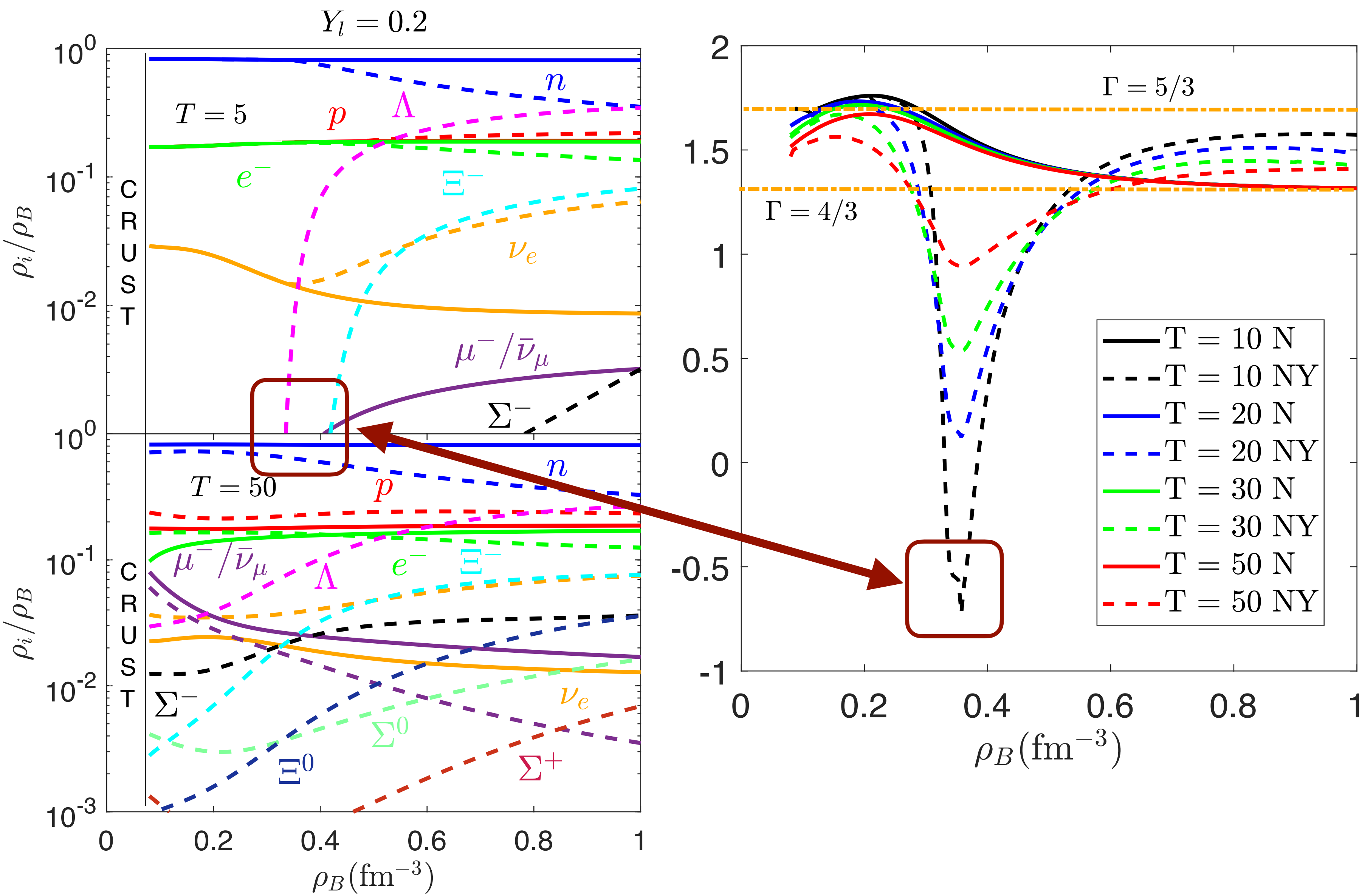
Multicomponent systems: hyperons





Kochankowski, Ramos & Tolos, MNRAS **517** 507 (2022)

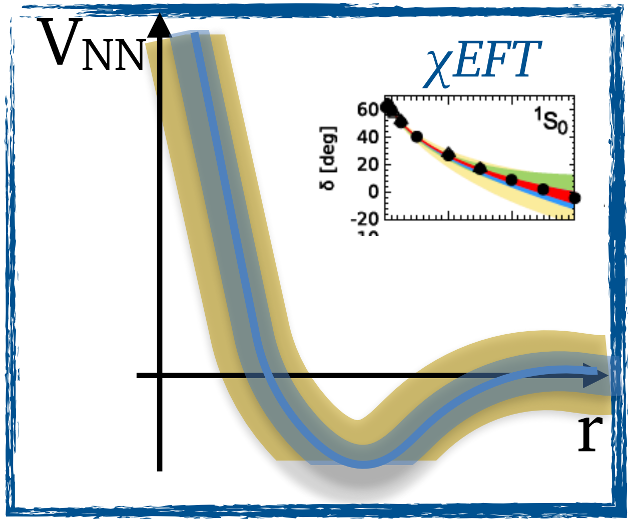
Multicomponent systems: hyperons



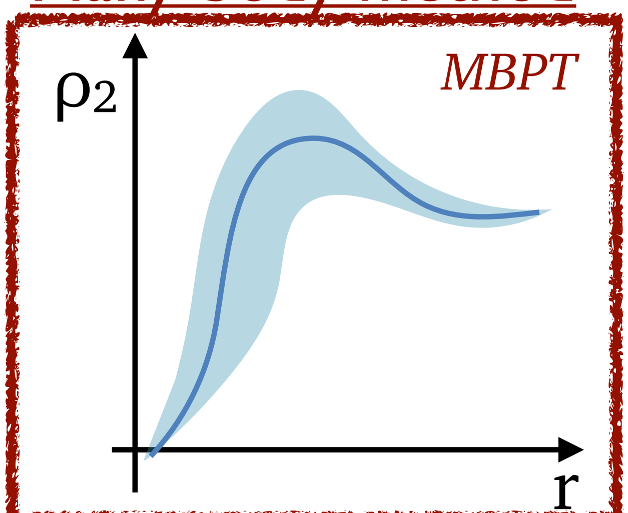
Kochankowski, Ramos & Tolos, MNRAS **517** 507 (2022)

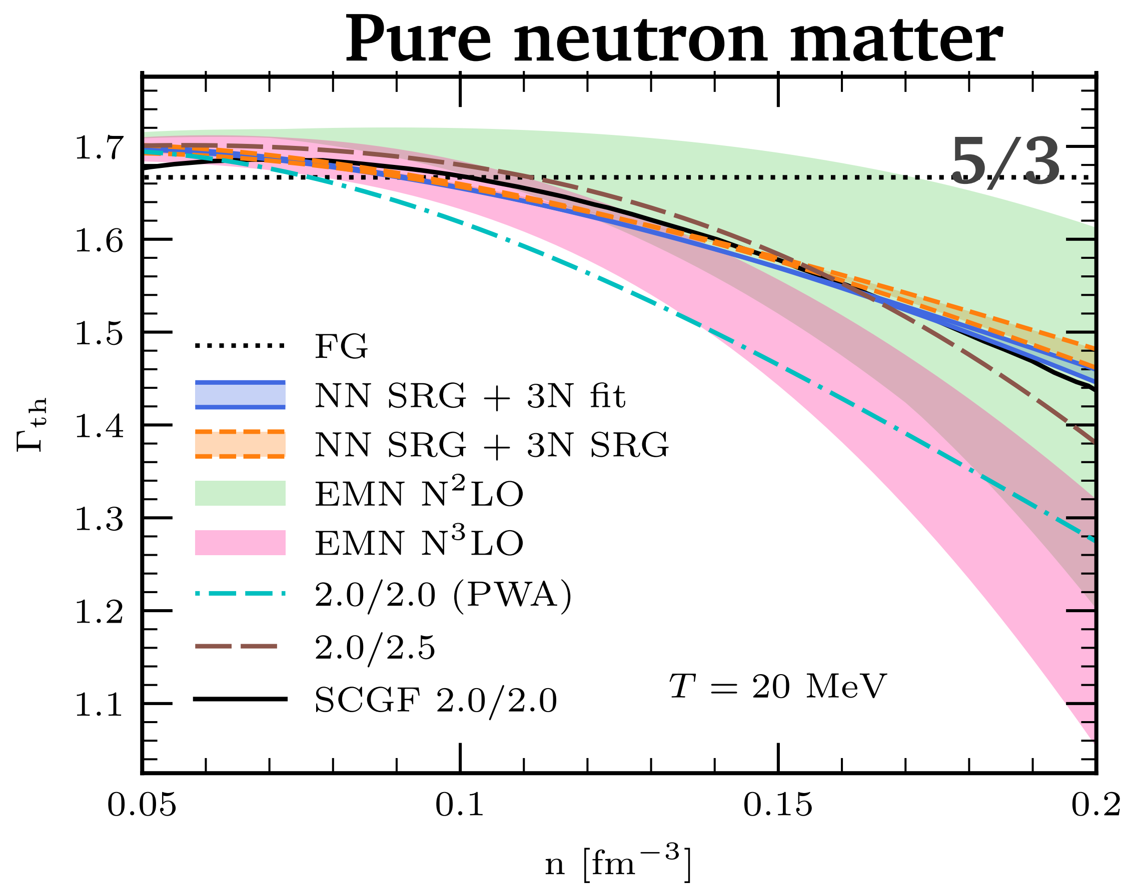
Ab initio thermal index

Hamiltonian



Many-body method

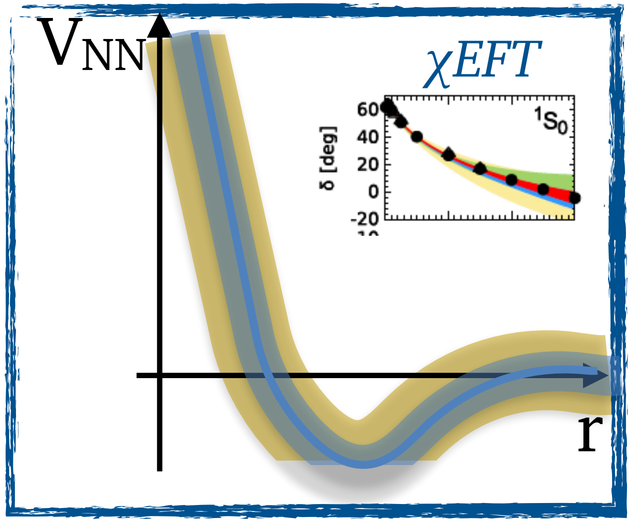




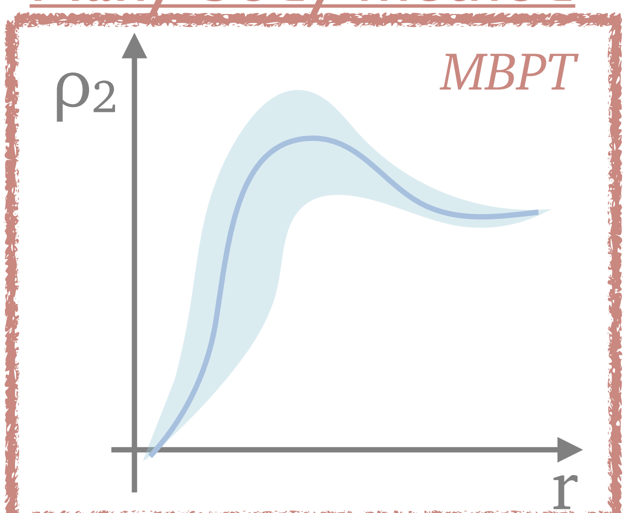
Keller, Wellenhofer, Hebeler & Schwenk *Phys Rev C* **103**, 055806 (2021)

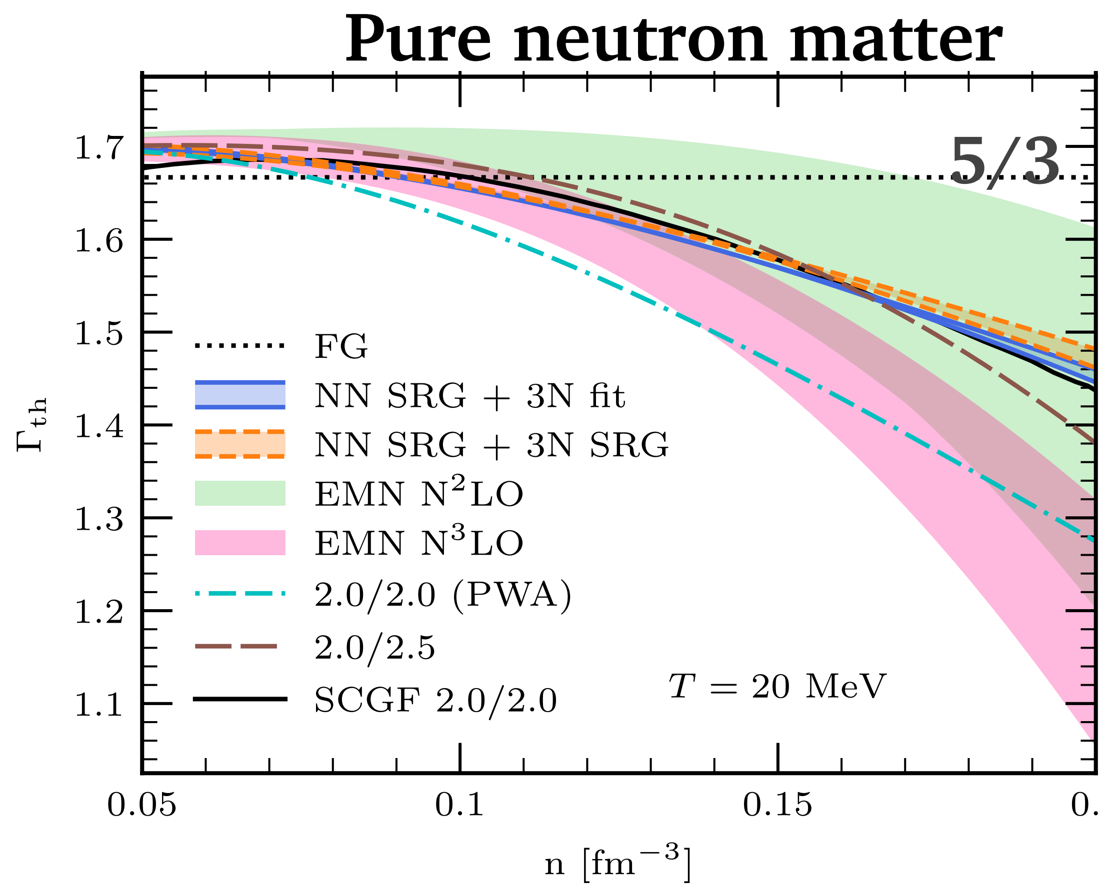
Ab initio thermal index

Hamiltonian



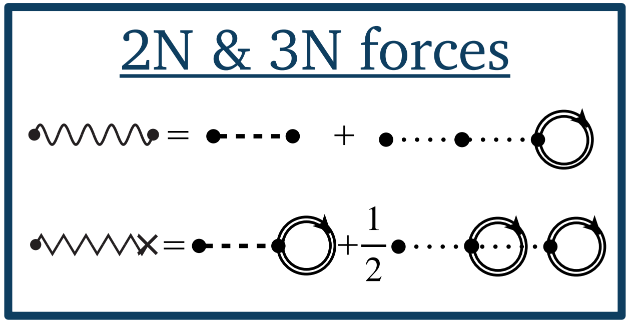
Many-body method

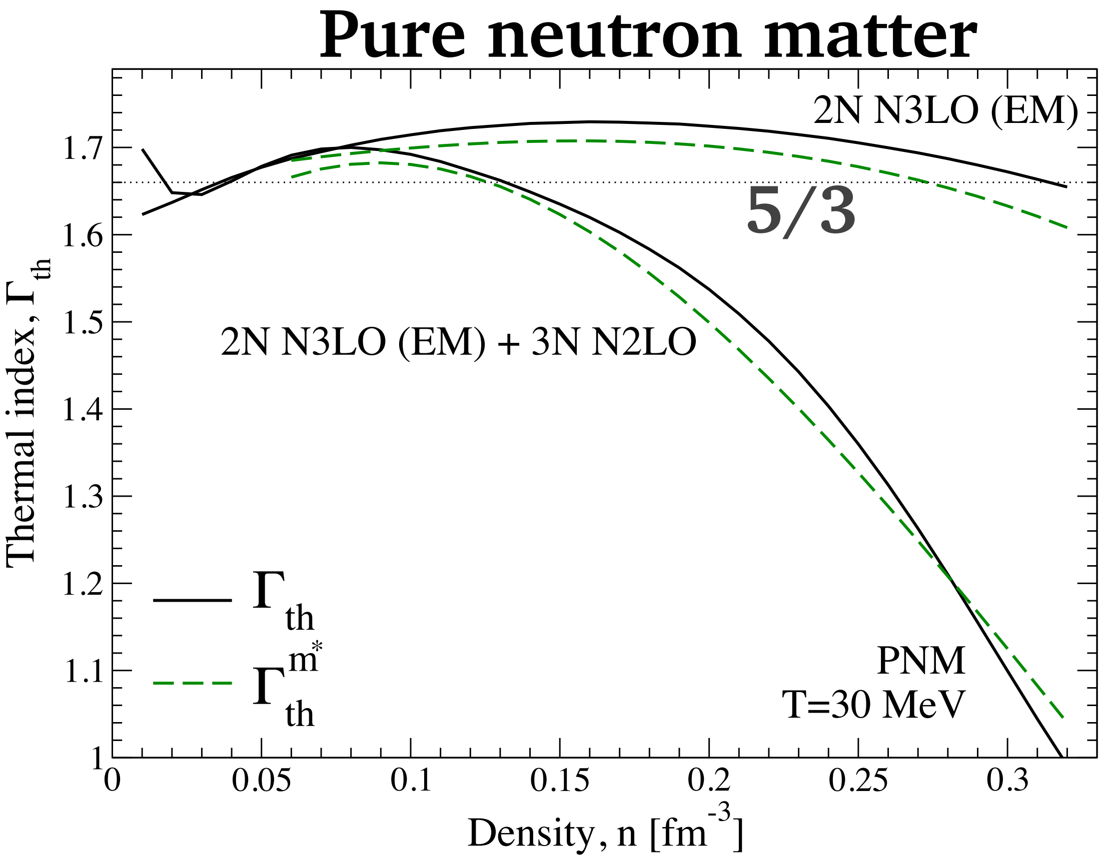




Keller, Wellenhofer, Hebeler & Schwenk *Phys Rev C* **103**, 055806 (2021)

Ab initio thermal index

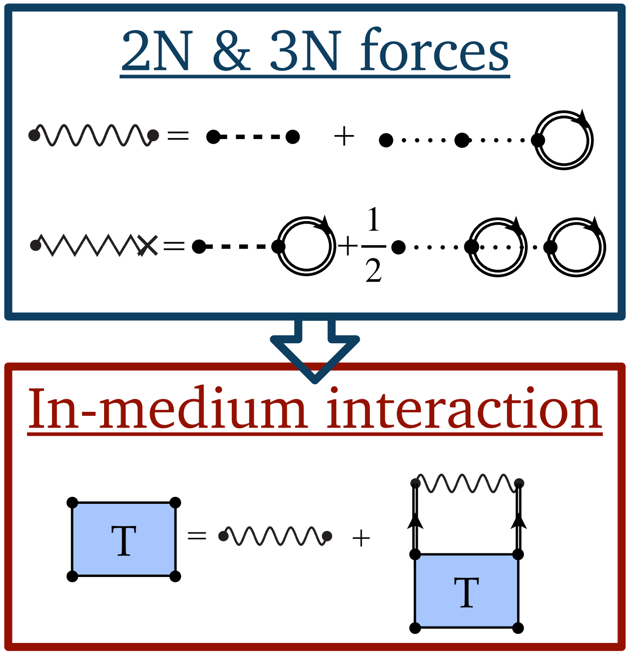


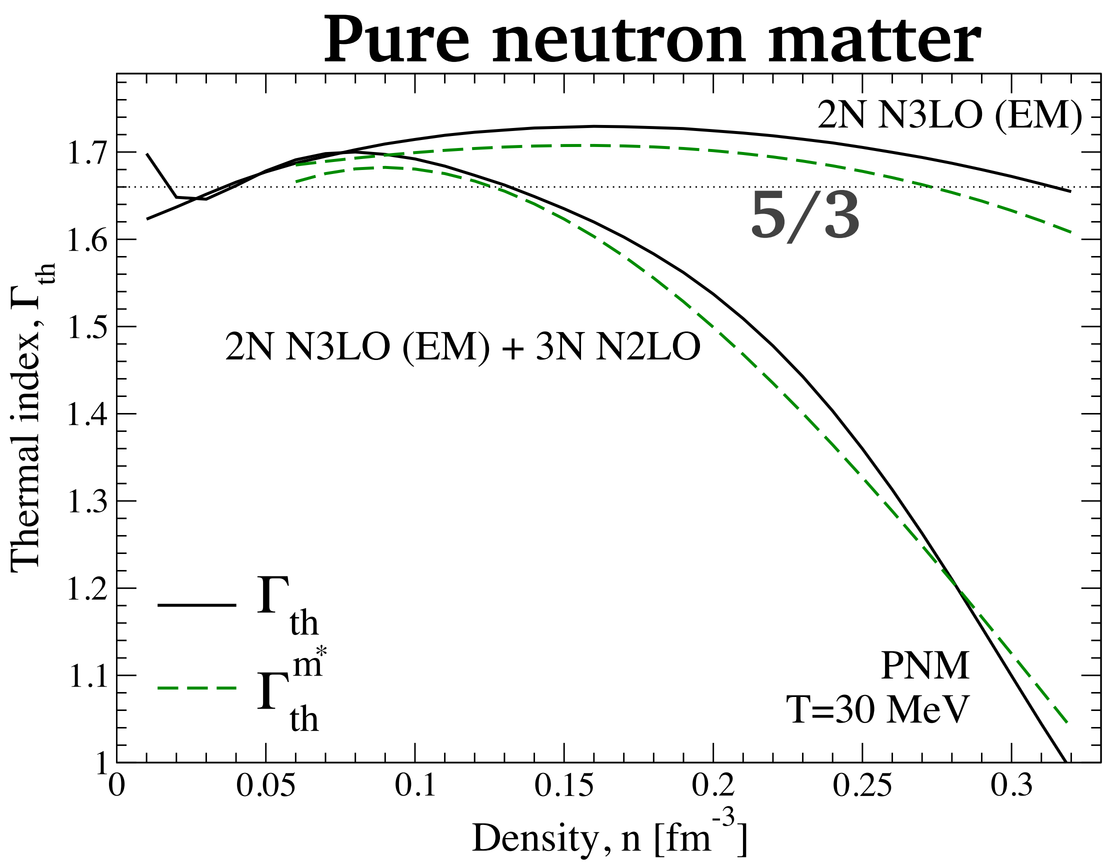


Carbone & Schwenk *Phys Rev C* **100** 025805 (2019)

Carbone, Polls & Rios, Phys Rev C **88** 044302 (2014)
Rios, Front. Phys. 8 387 (2020), arxiv:2006.10610

Ab initio thermal index





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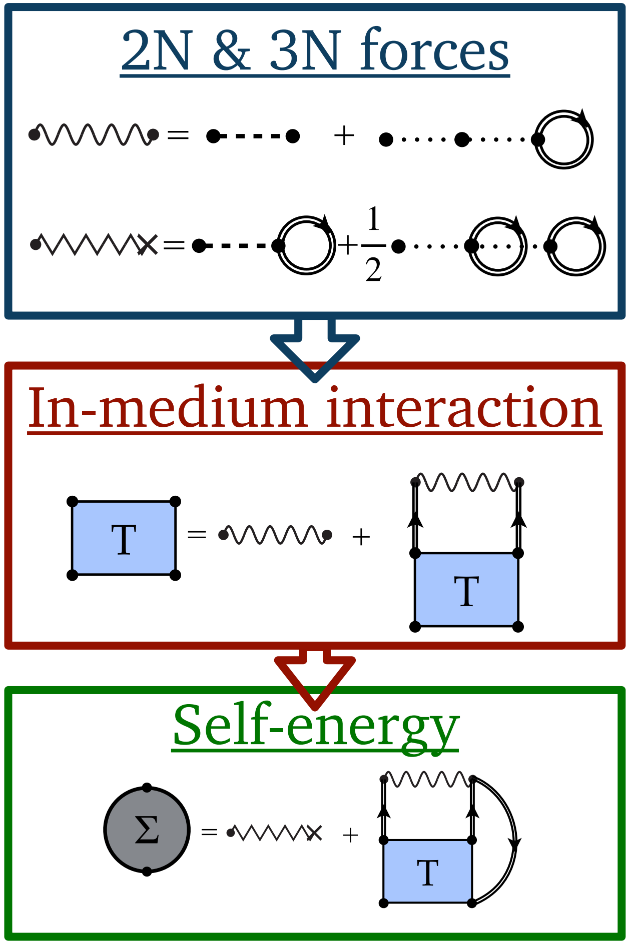

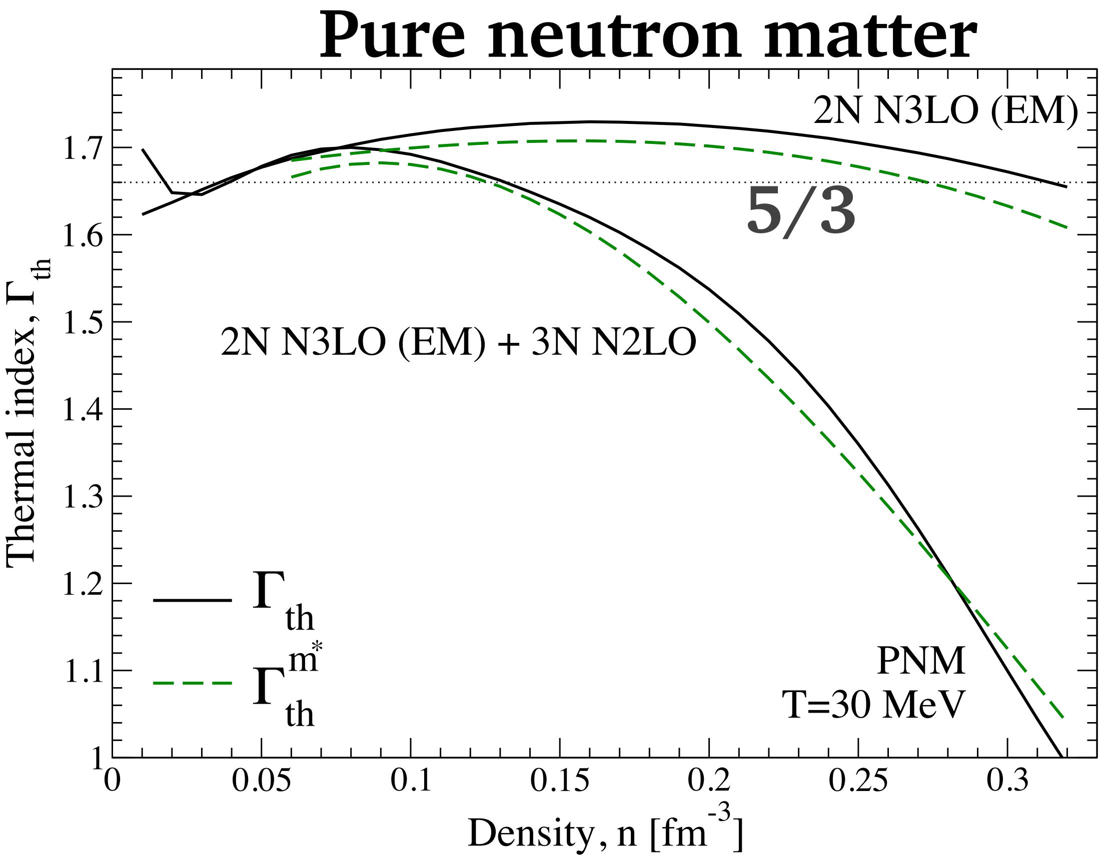

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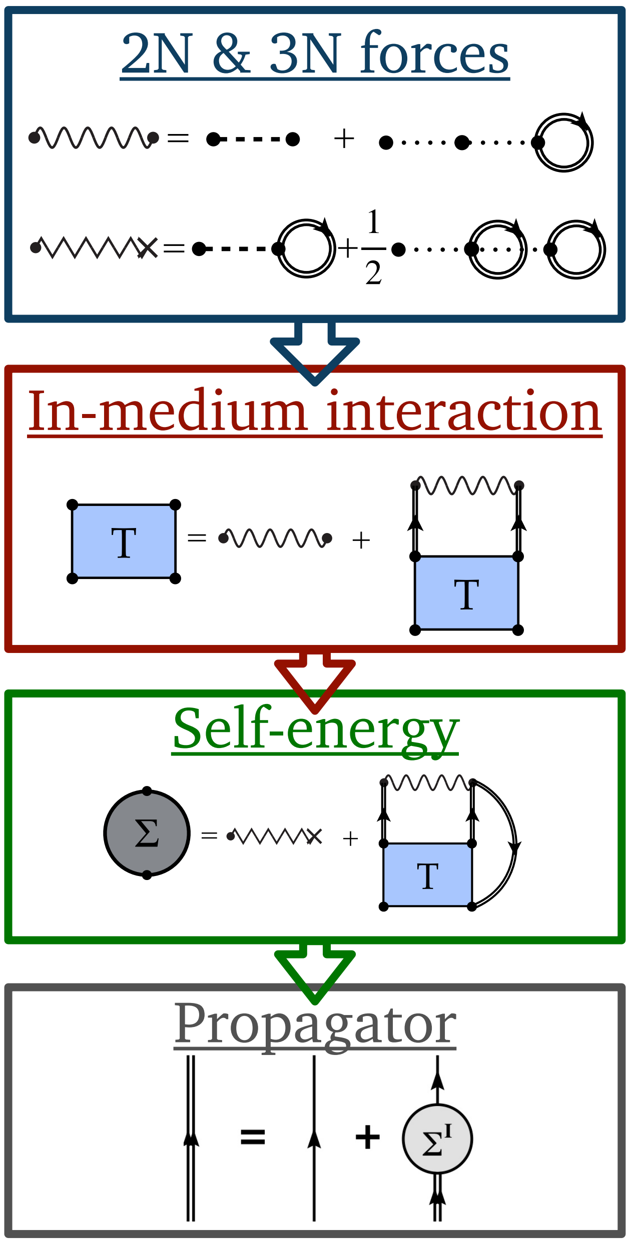

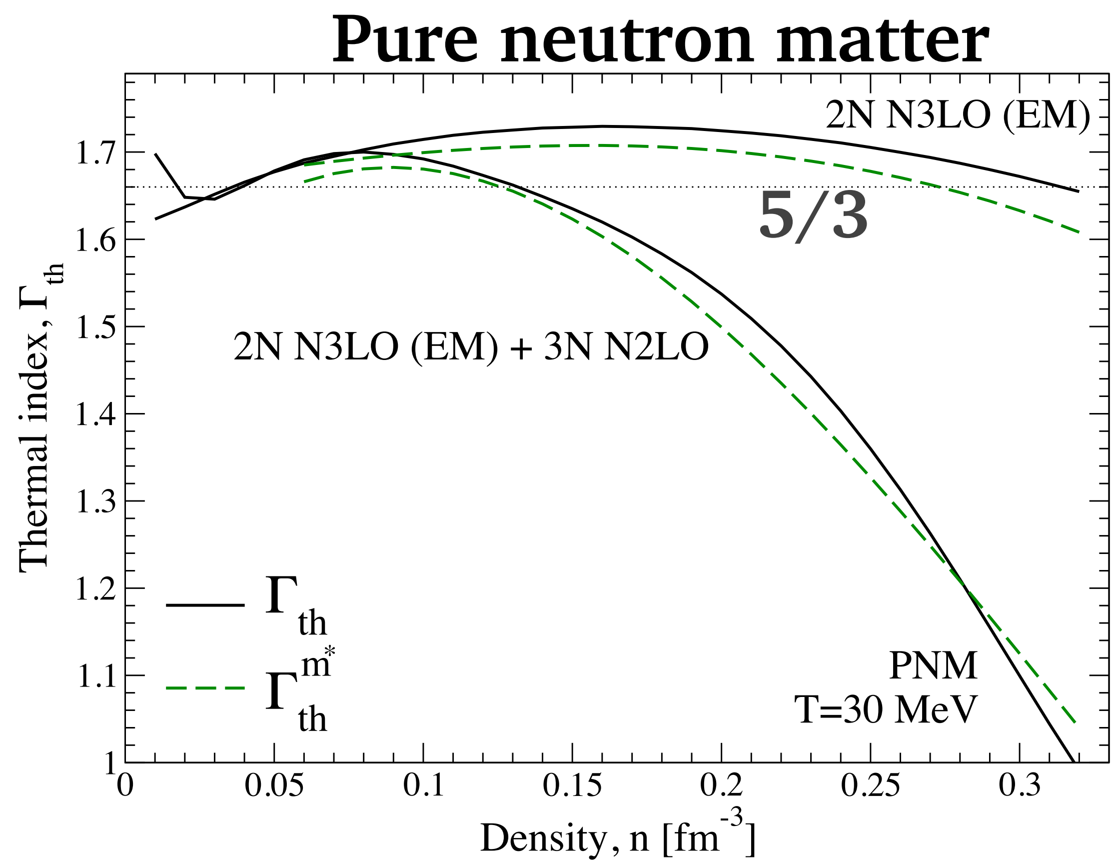

Carbone & Schwenk *Phys Rev C* **100** 025805 (2019)

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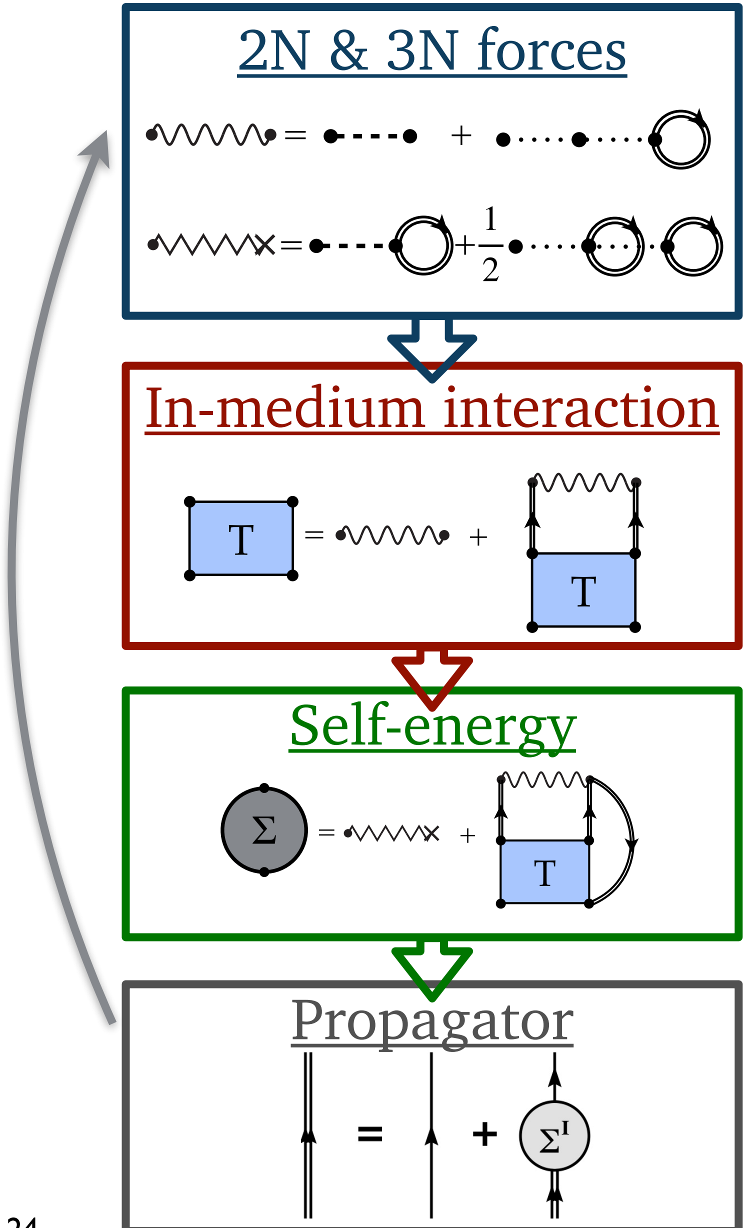

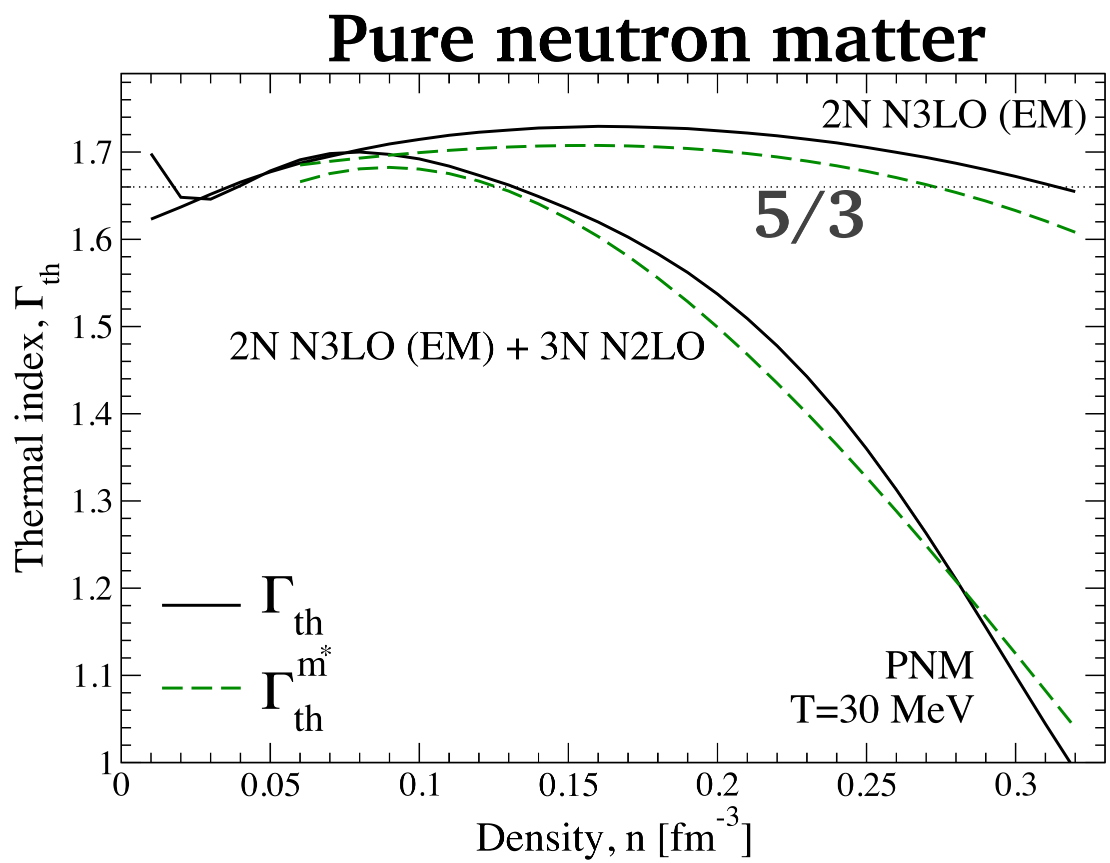

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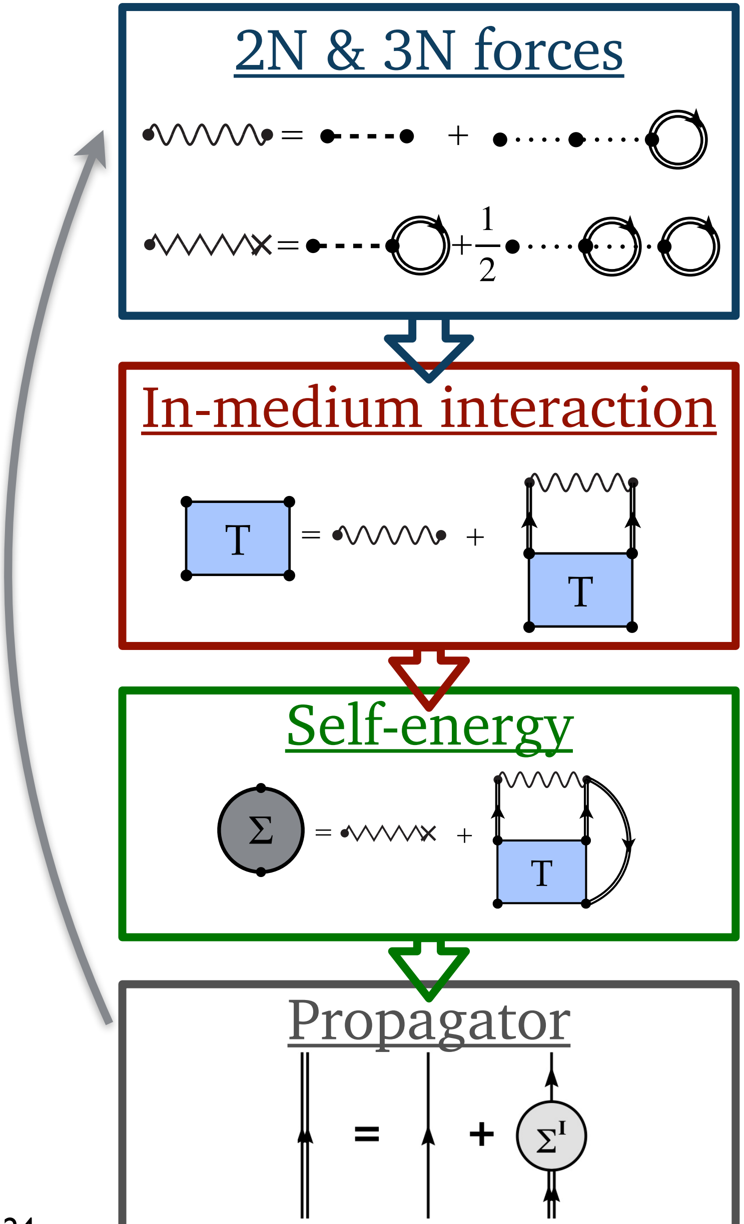
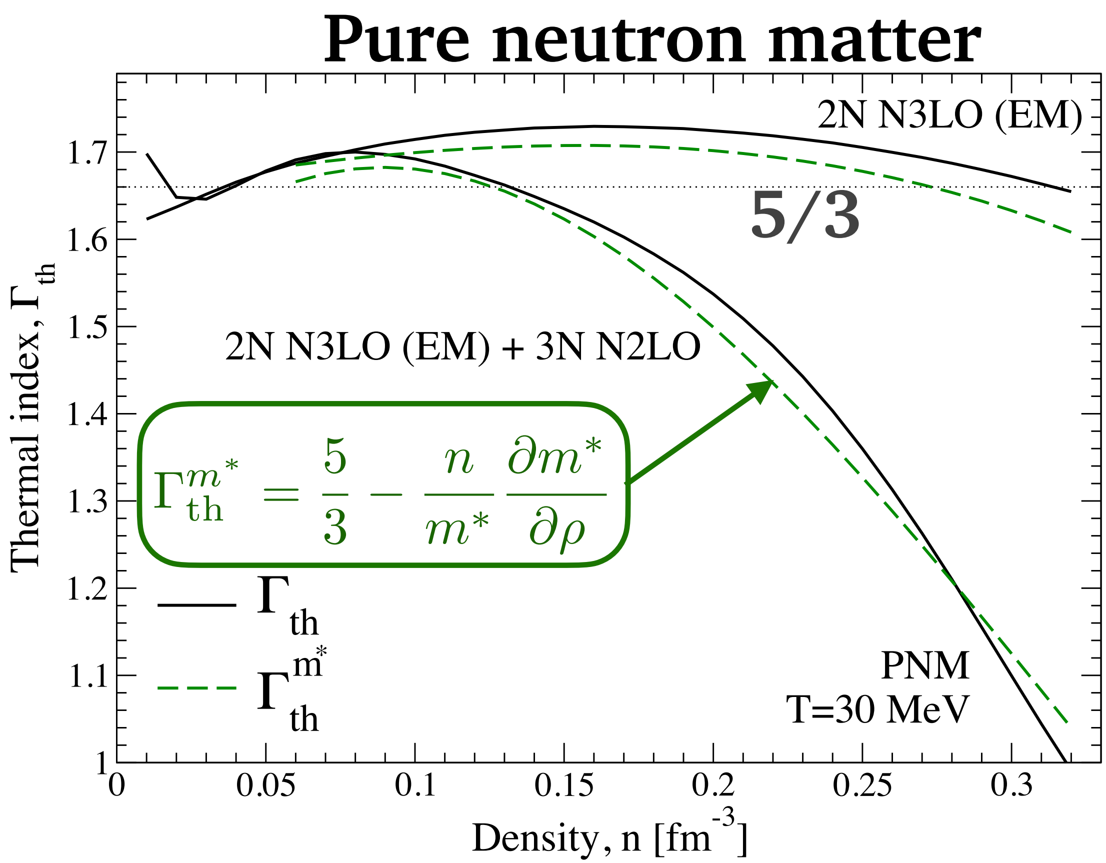
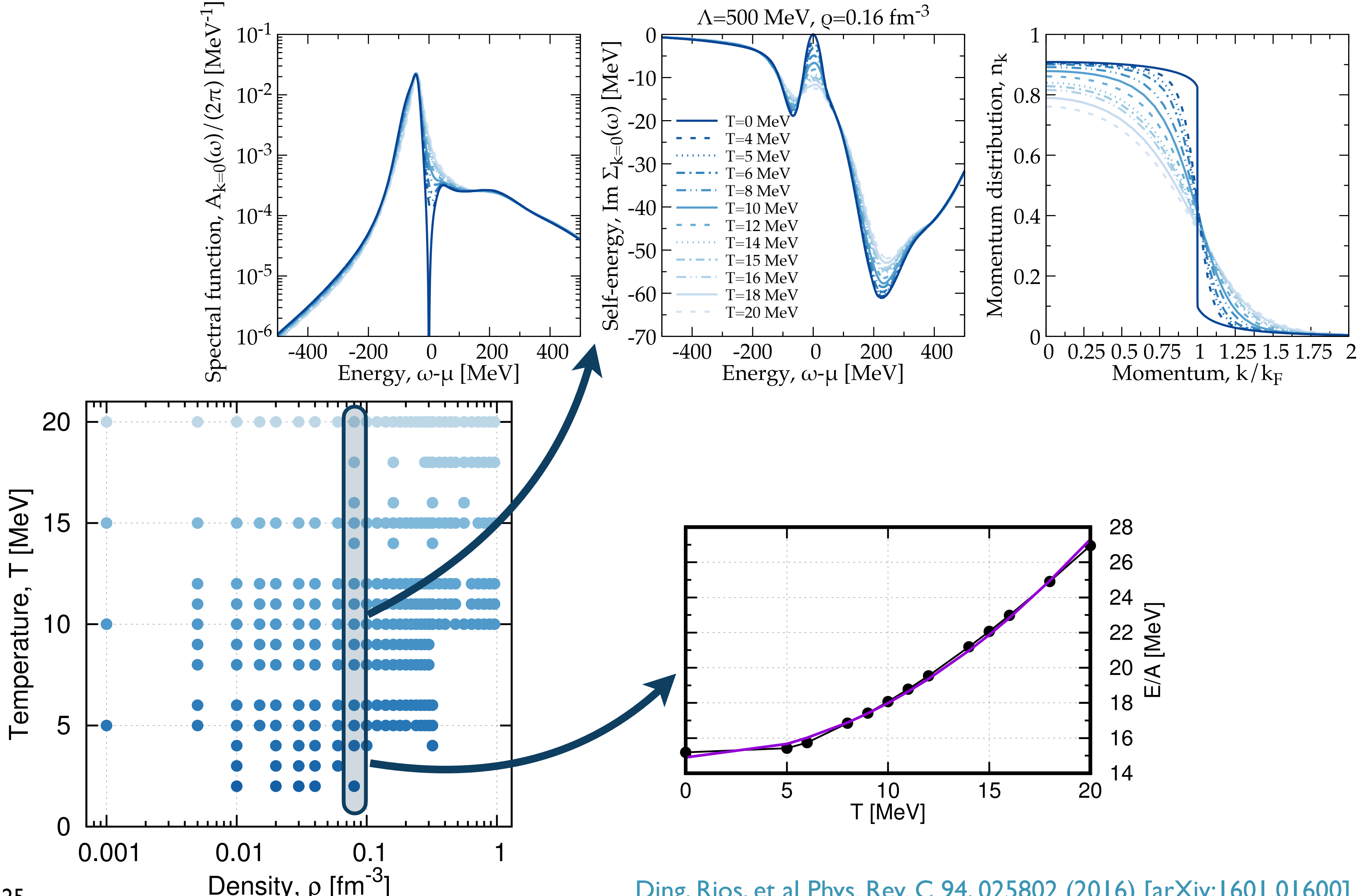




Carbone & Schwenk *Phys Rev C* **100** 025805 (2019)

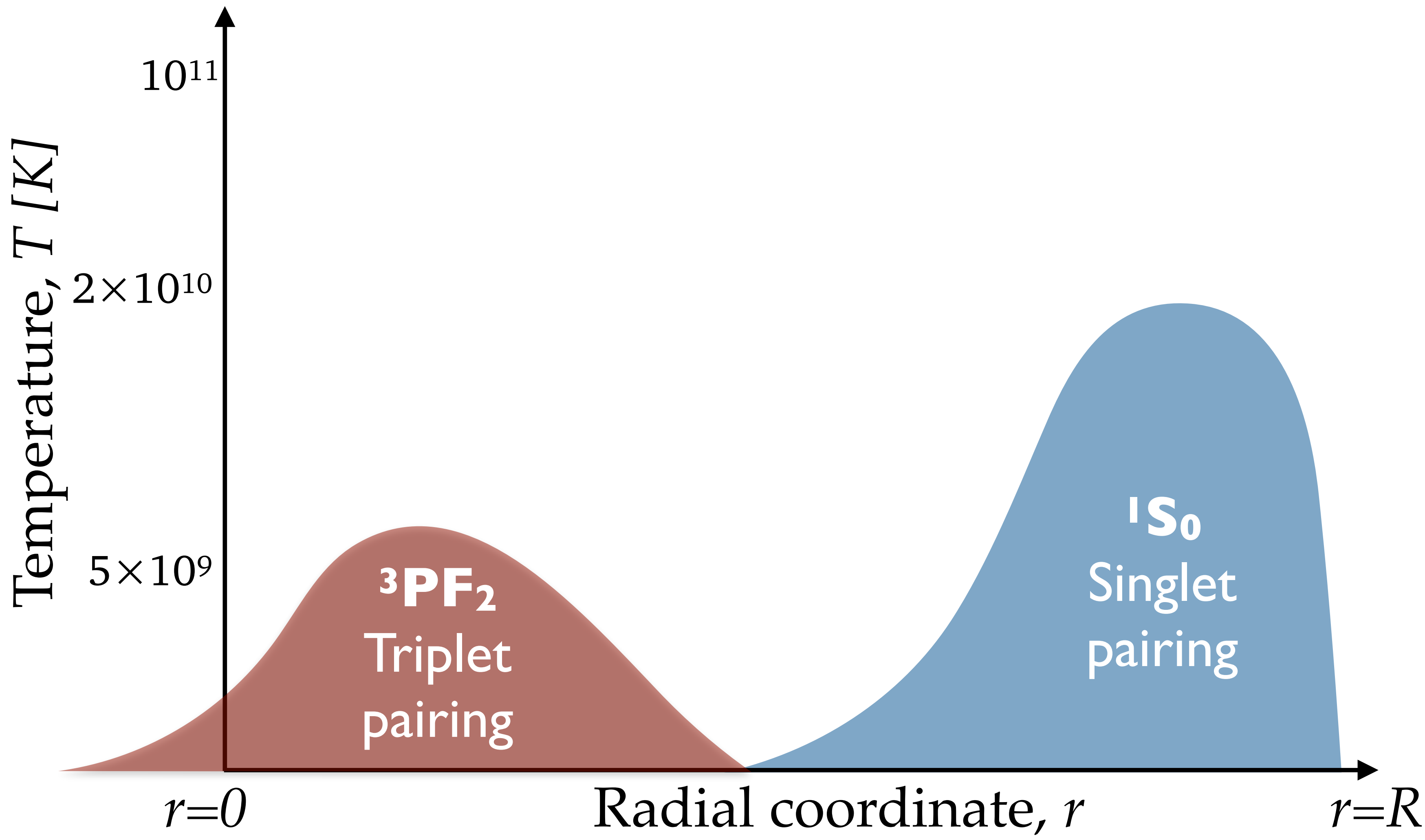
Carbone, Polls & Rios, Phys Rev C **88** 044302 (2014)
Rios, Front. Phys. 8 387 (2020), arxiv:2006.10610

Zero temperature extrapolation

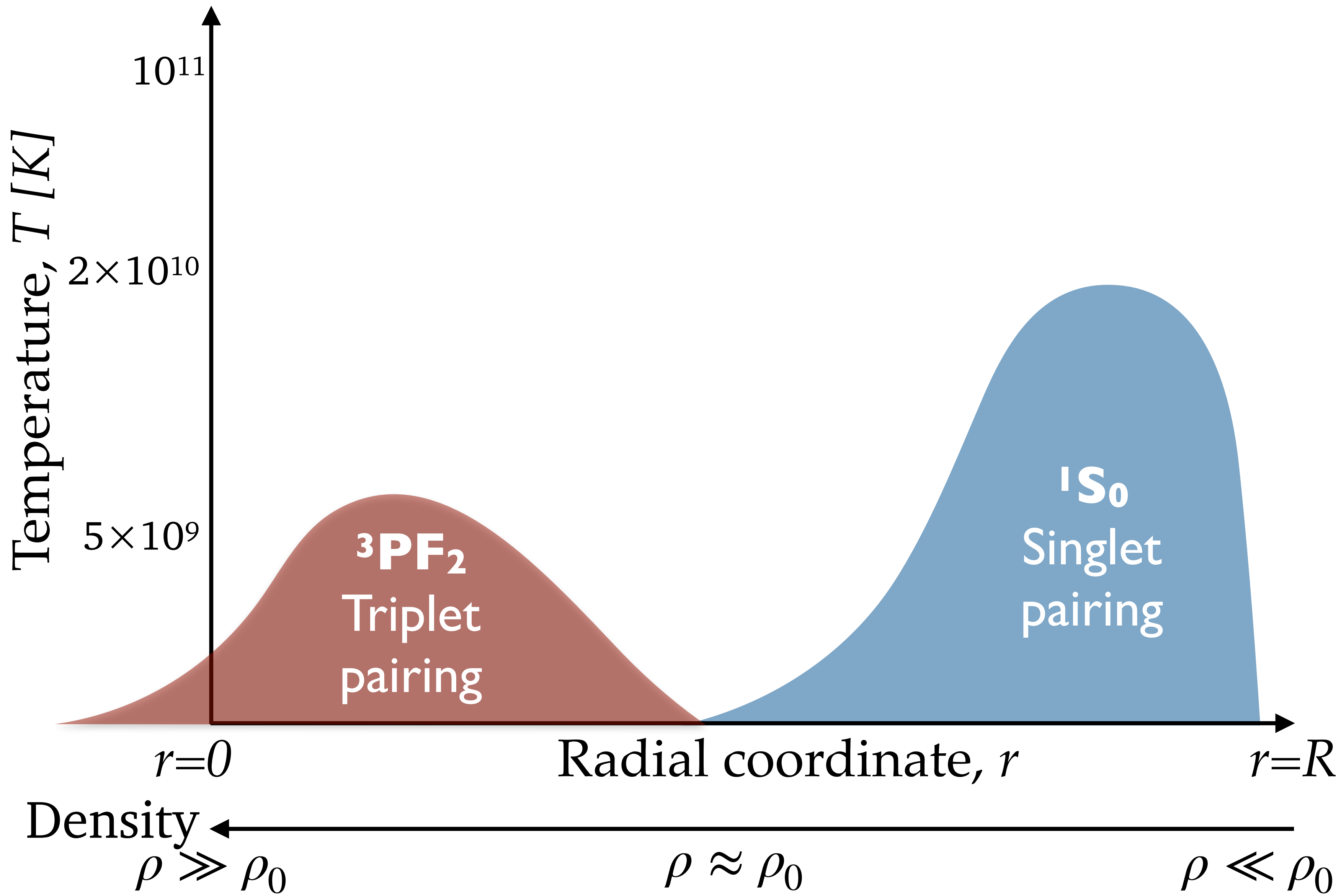


Ding, Rios, et al Phys. Rev. C 94, 025802 (2016) [arXiv:1601.01600]

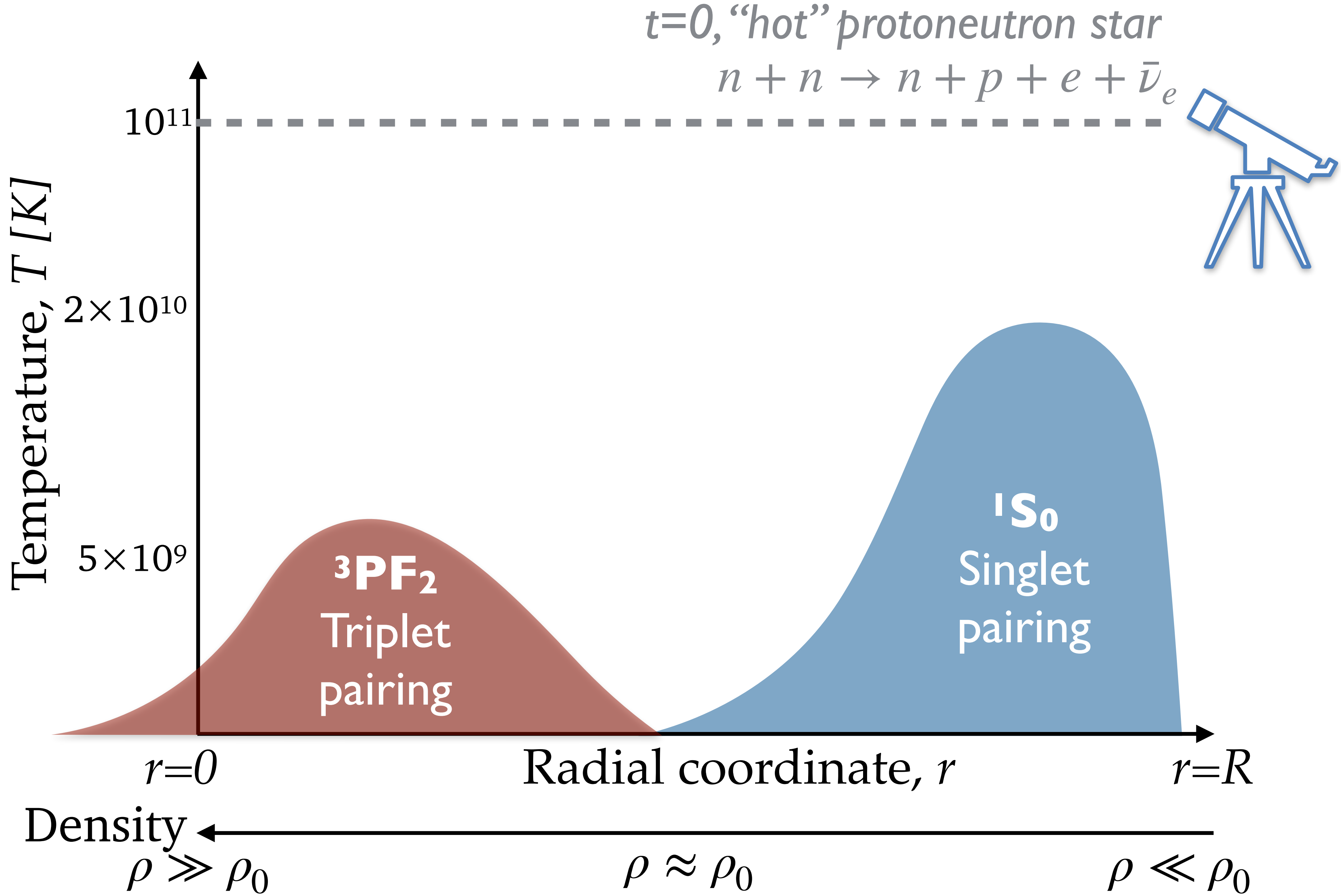
Pairing gaps & cooling



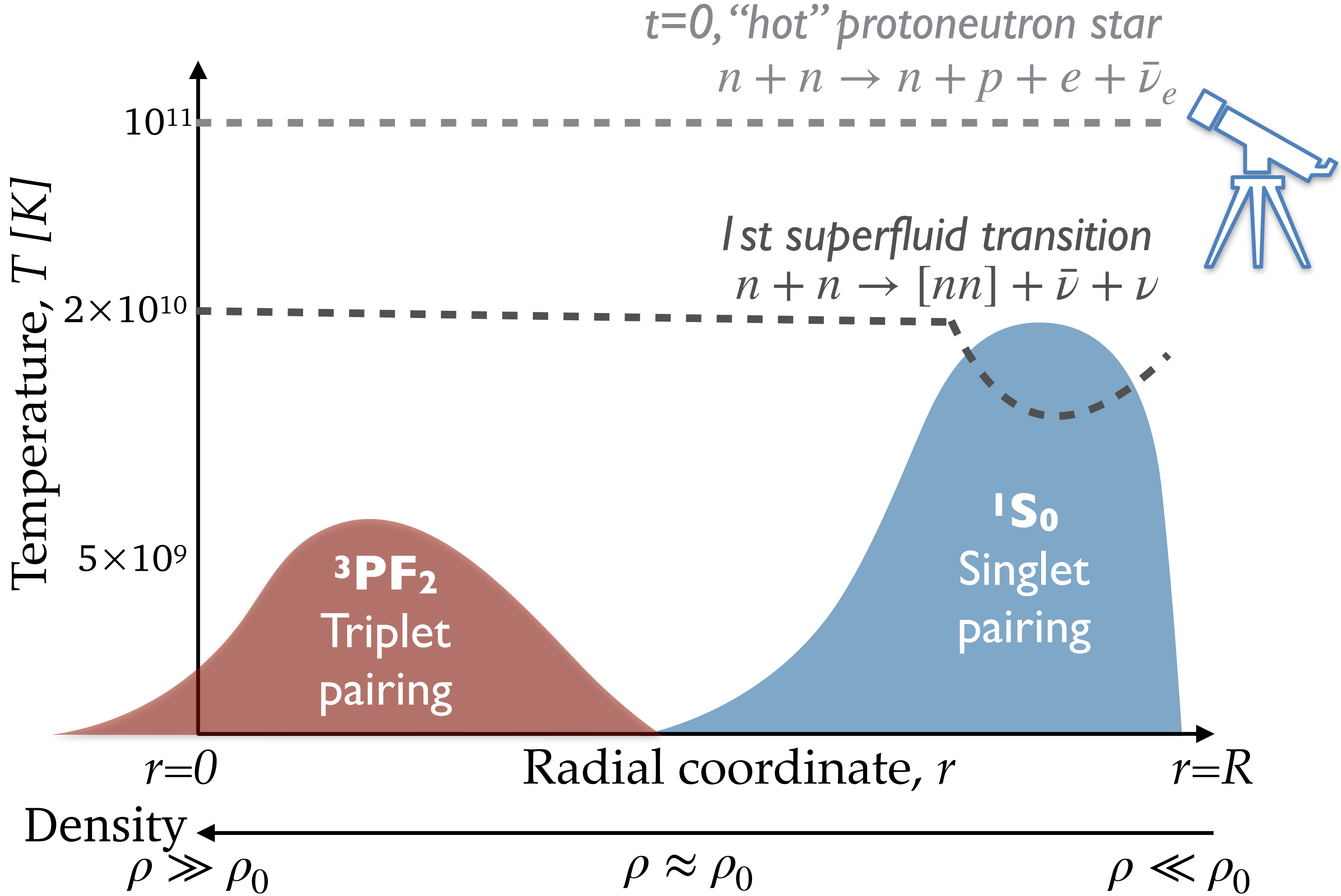
Pairing gaps & cooling



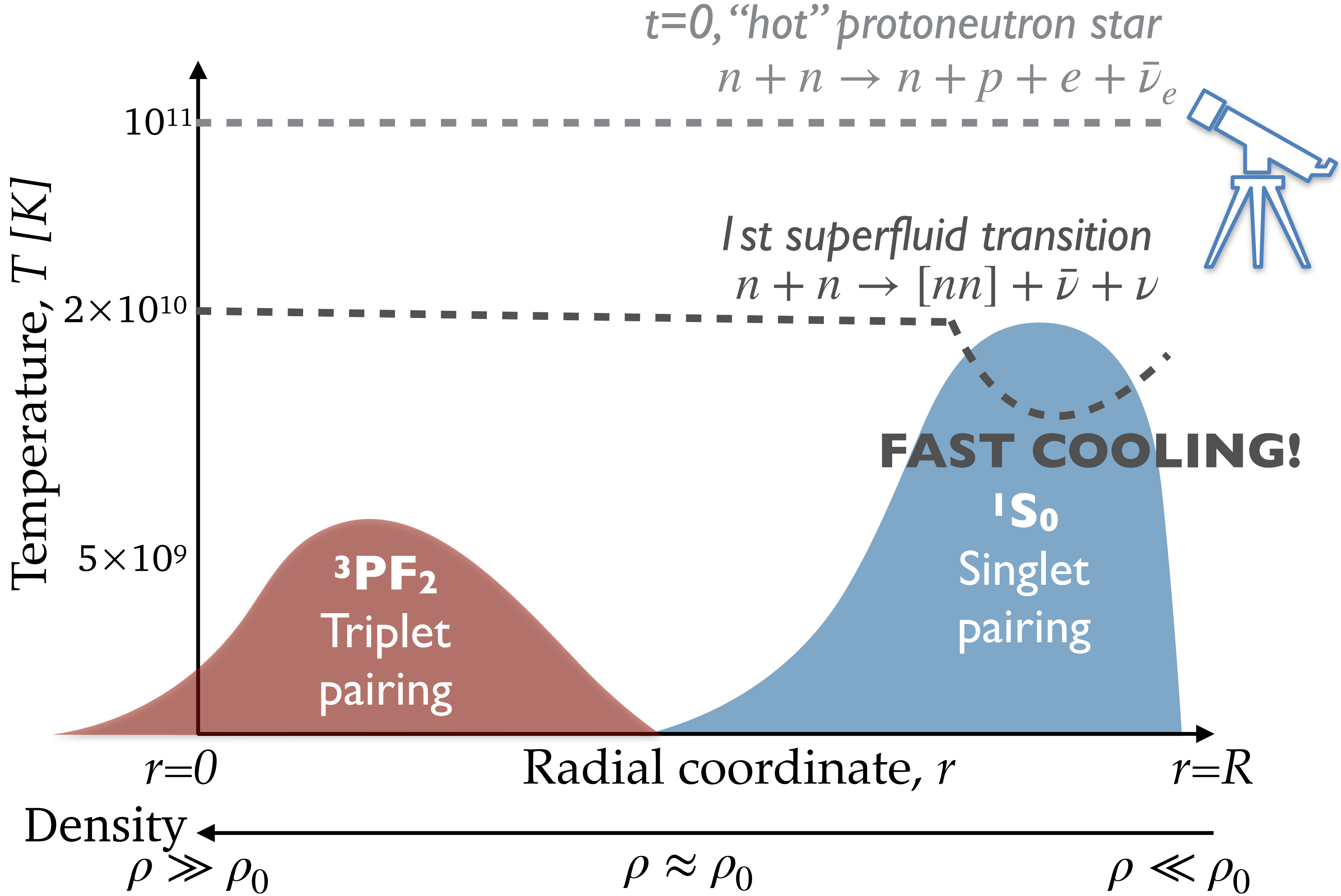
Pairing gaps & cooling



Pairing gaps & cooling



Pairing gaps & cooling



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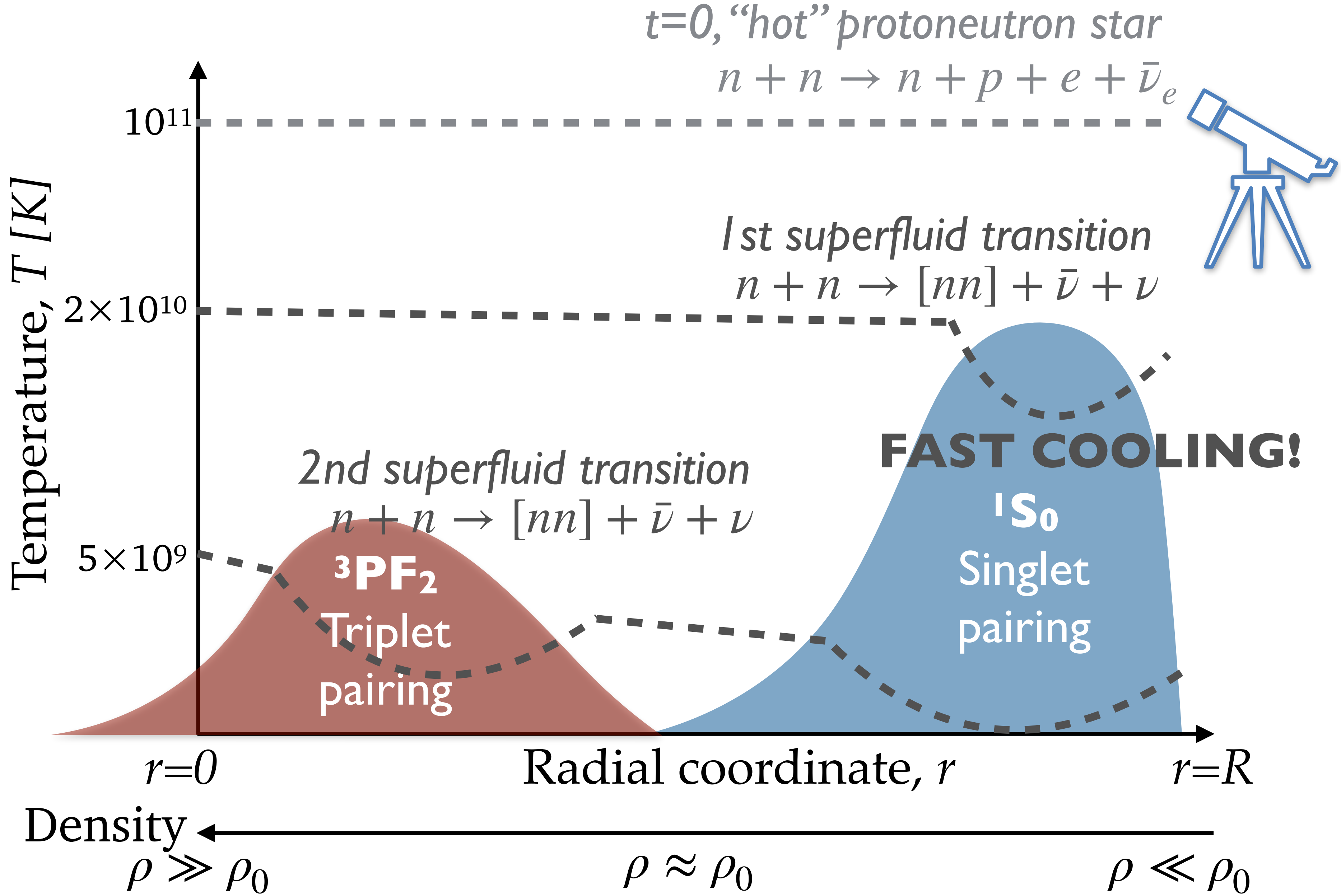
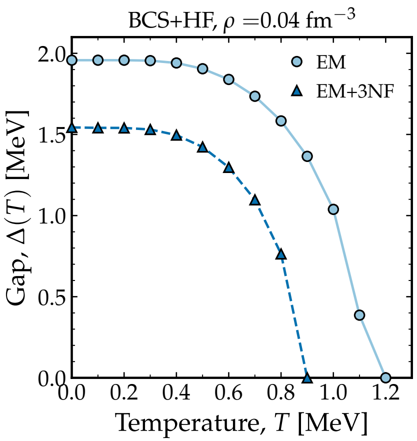
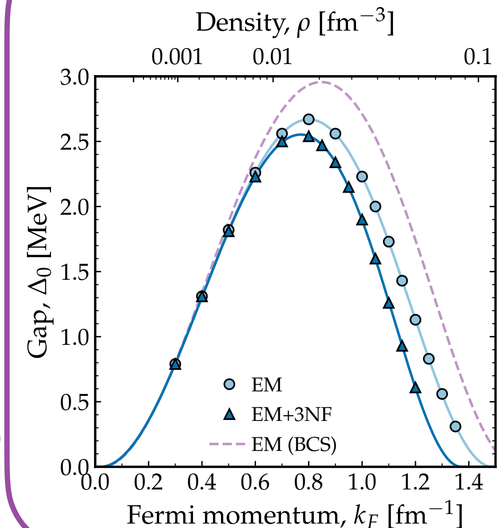


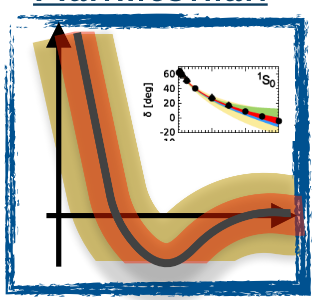
Finite Temperature BCS



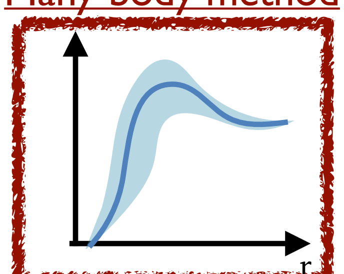
BCS+HF



Hamiltonian

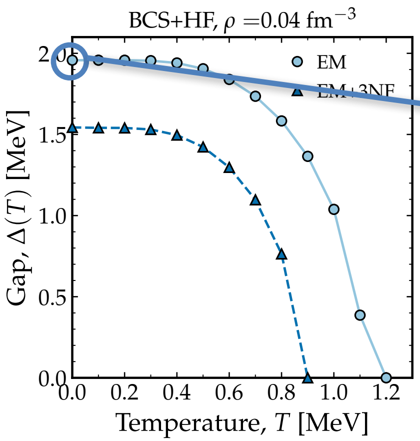


Many-body method

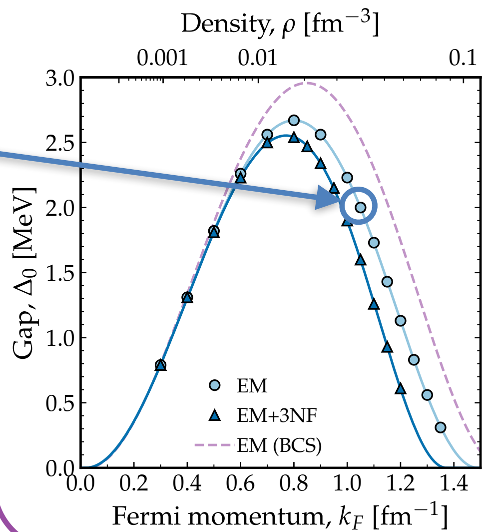


Drissi & Rios, Eur. Phys. J. A 58, 90 (2022) [arXiv:2202.07501]

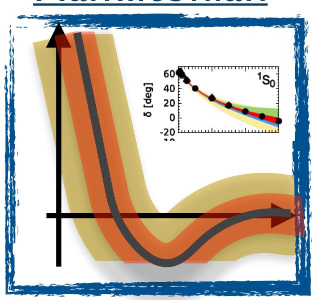
Finite Temperature BCS



BCS+HF



Hamiltonian



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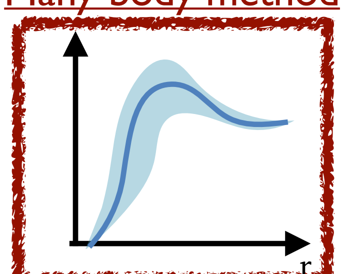
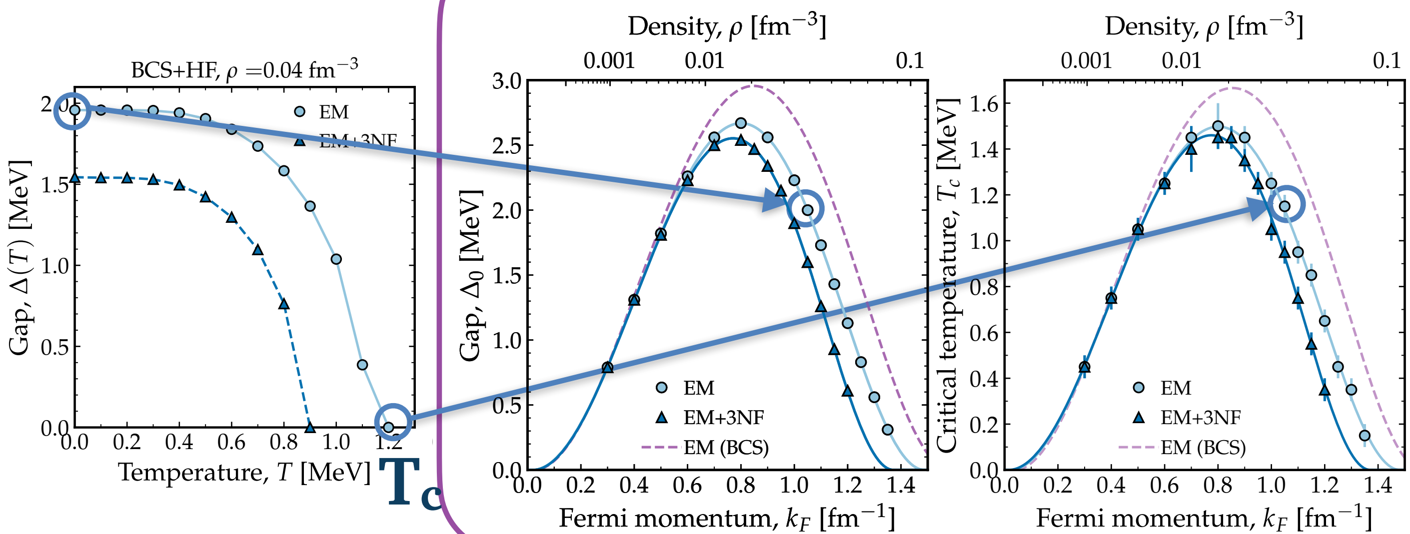


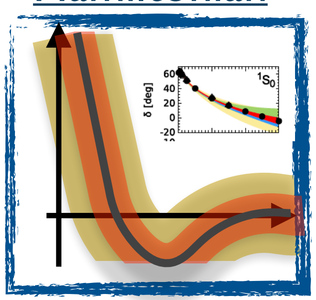
Drissi & Rios, Eur. Phys. J. A 58, 90 (2022) [arXiv:2202.07501]

Finite Temperature BCS

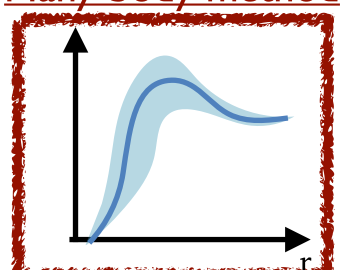
BCS+HF



Hamiltonian



Many-body method



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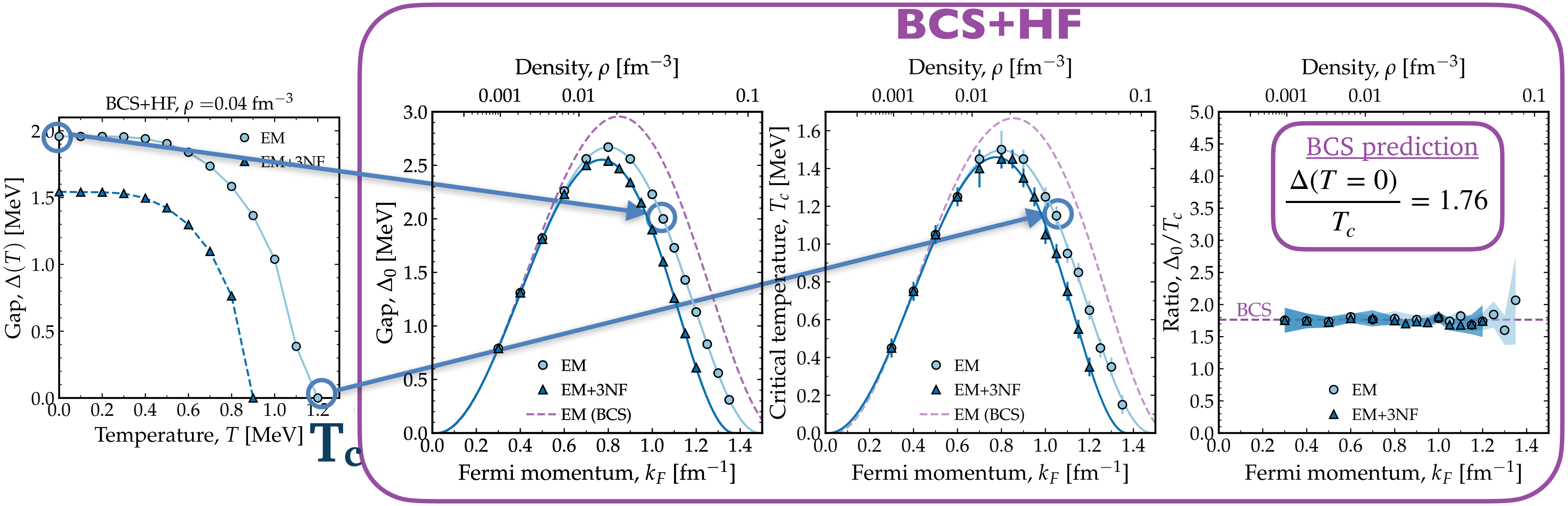
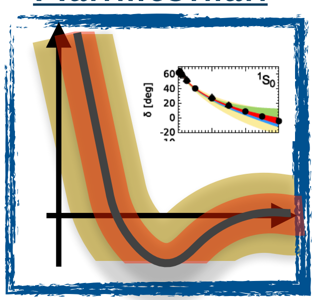
Finite Temperature BCS



Hamiltonian



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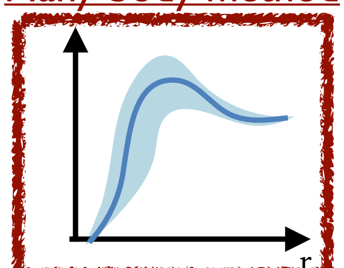
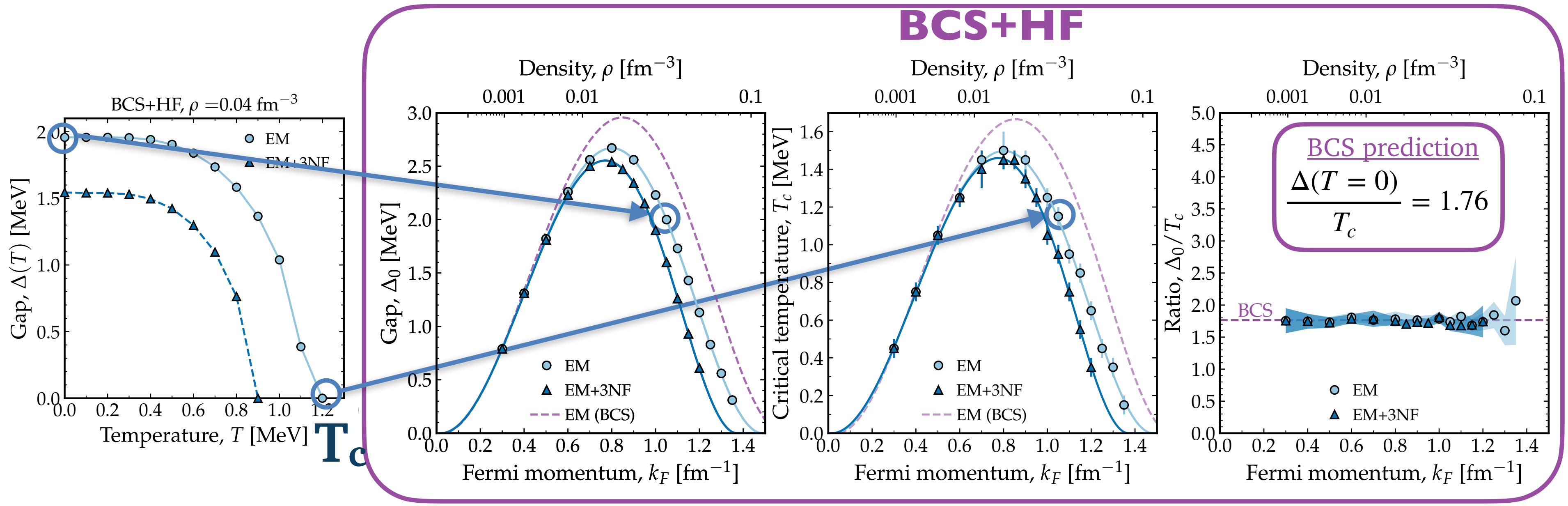
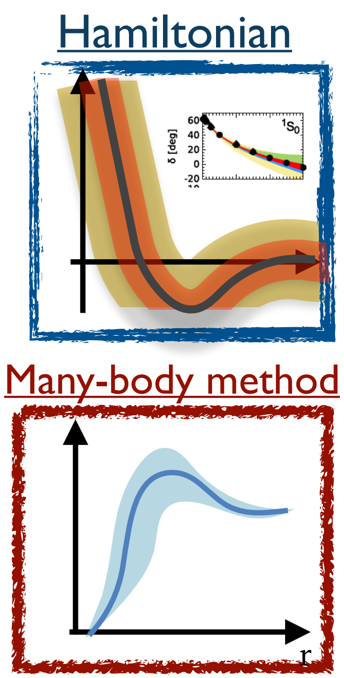


Drissi & Rios, Eur. Phys. J.A 58, 90 (2022) [arXiv:2202.07501]

Finite Temperature BCS



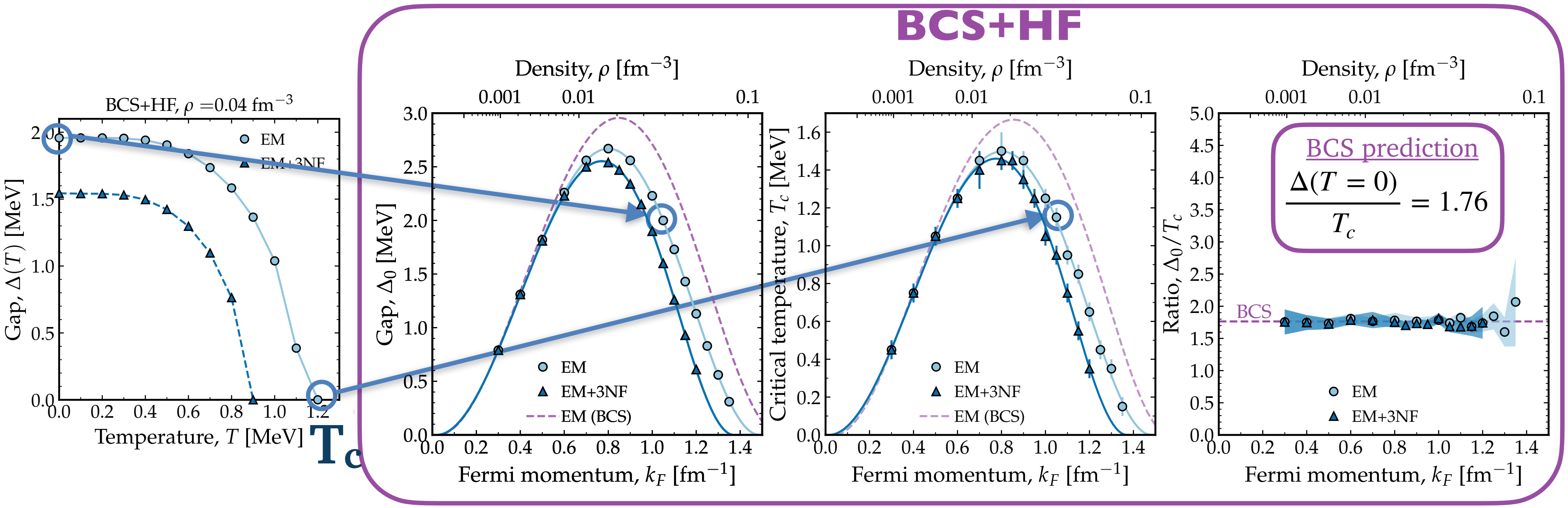


- **BCS** prediction based on **constant V**
- Full chiral **NN** interactions
- Full **HF spectrum**
- 3NFs do not change the ratio!

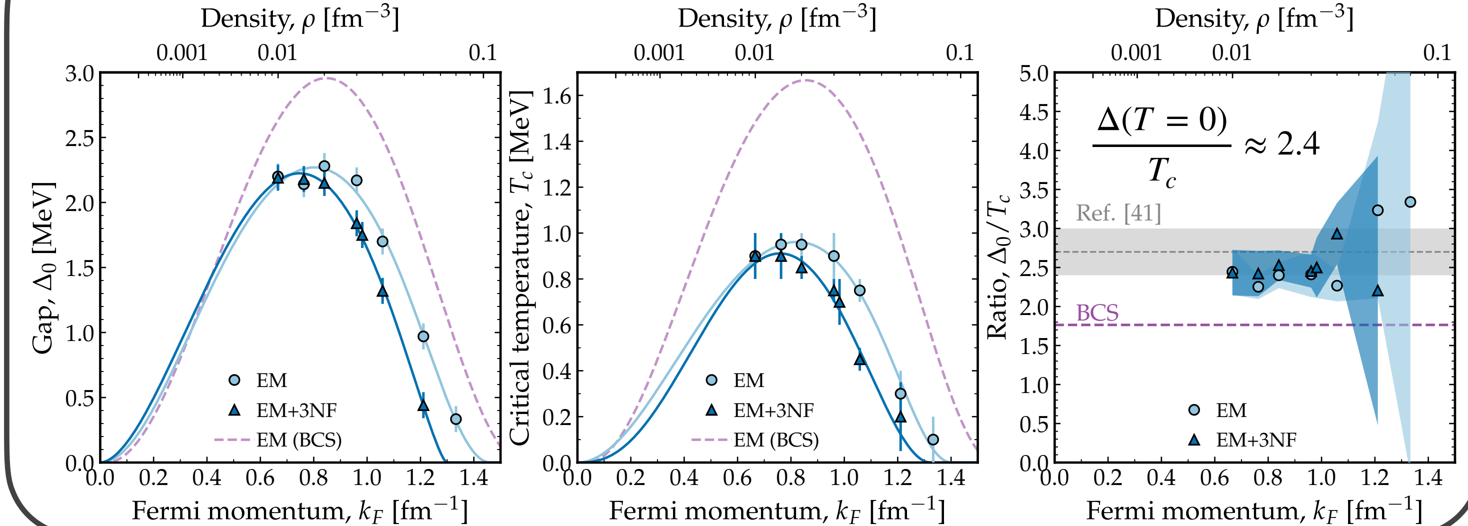
Drissi & Rios, Eur. Phys. J. A 58, 90 (2022) [arXiv:2202.07501]

Finite Temperature beyond-BCS

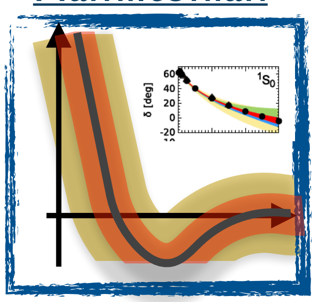
BCS+HF



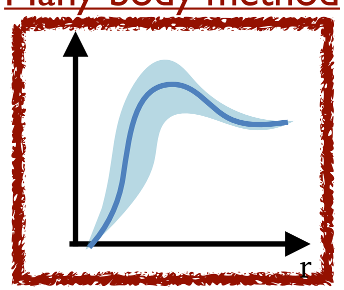
"Beyond"-BCS SCGF approach



Hamiltonian

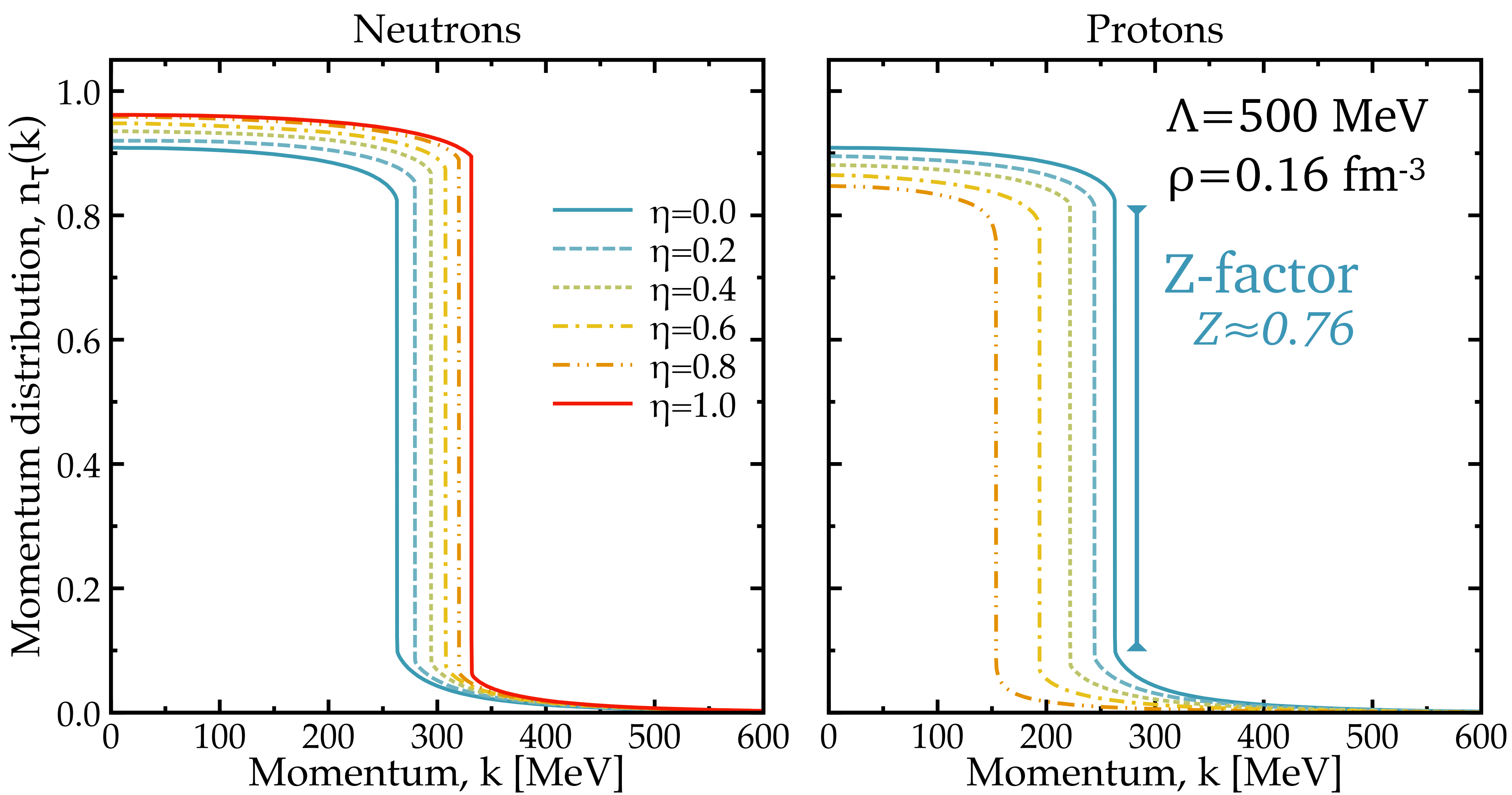


Many-body method



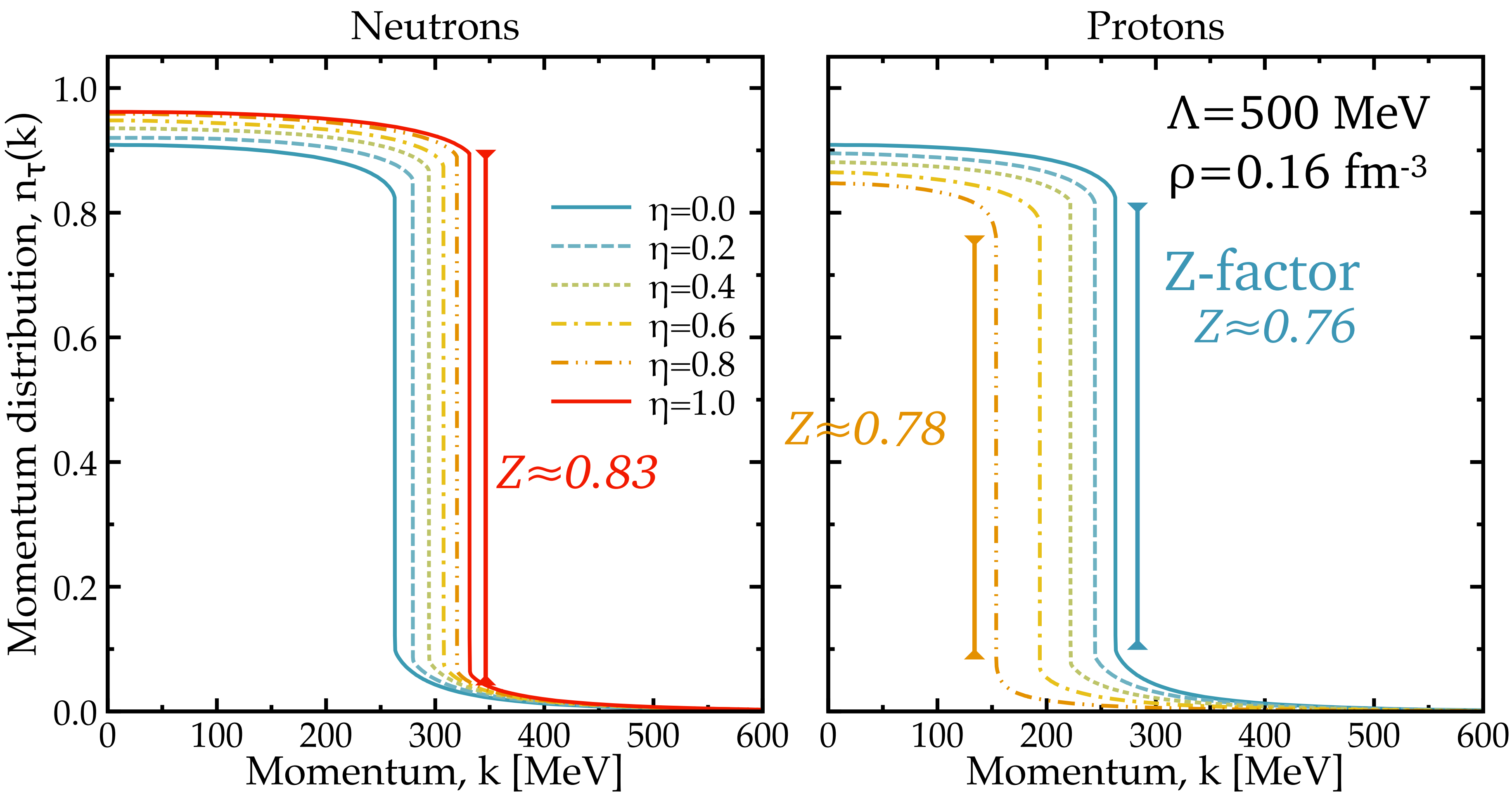
Drissi & Rios, Eur. Phys. J.A 58, 90 (2022) [arXiv:2202.07501]

Momentum distribution



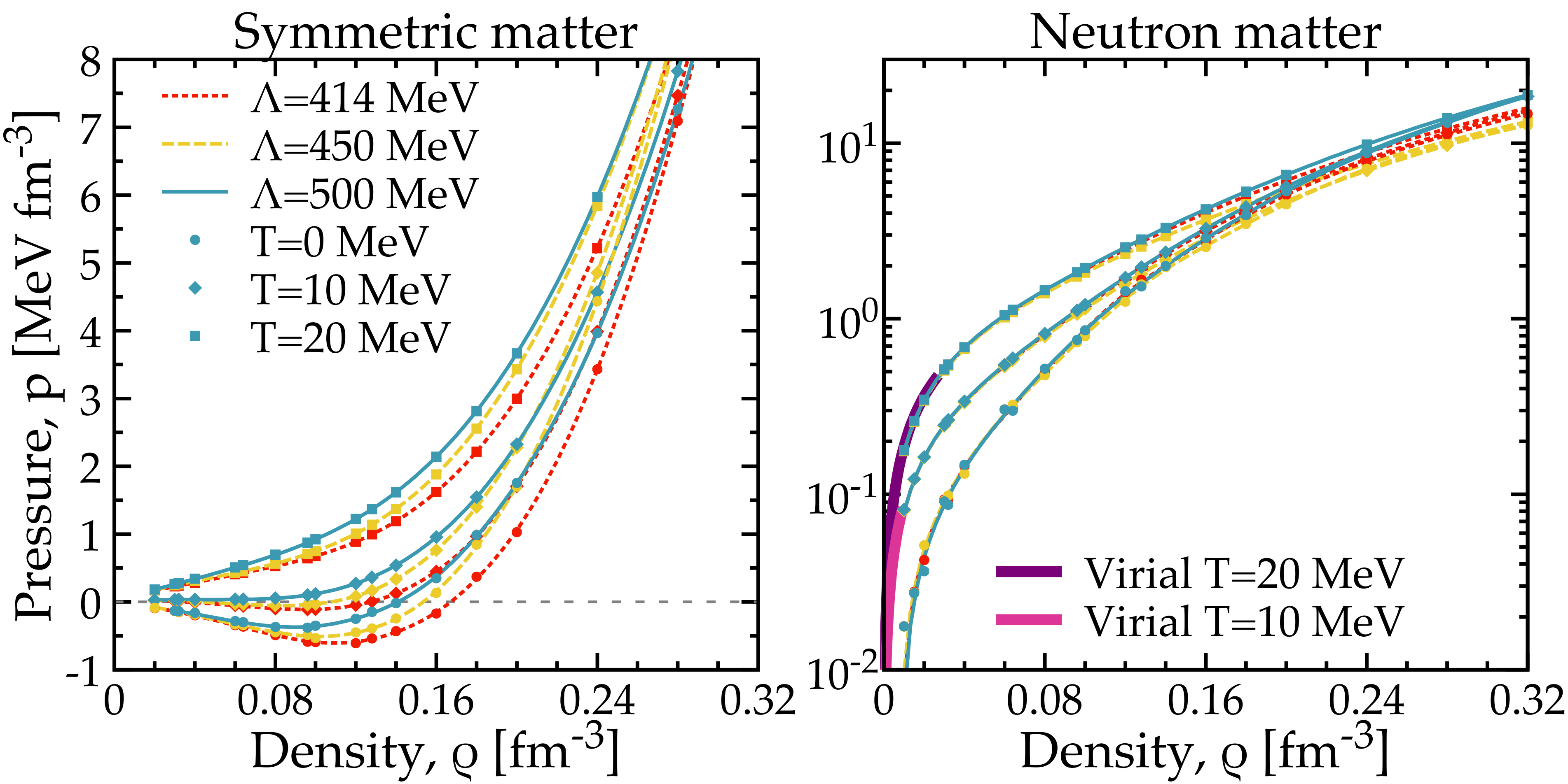
Rios, Frontiers Physics fphy.2020.00387 (2020)
[arXiv:2006.10610]

Momentum distribution



Rios, Frontiers Physics fphy.2020.00387 (2020)
[arXiv:2006.10610]

EoS at finite temperature

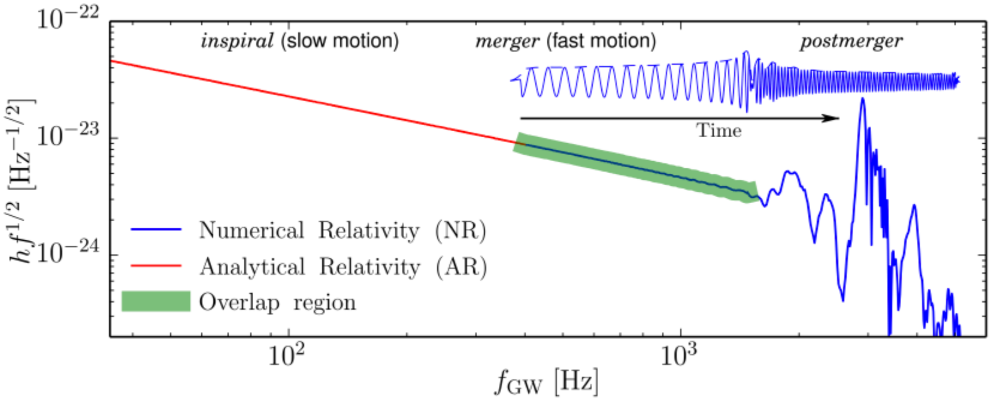


- From a finite set of points to functions?

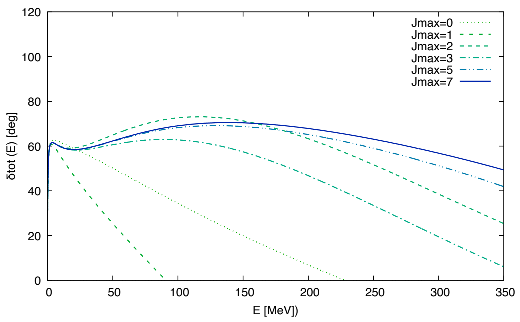
Rios, Frontiers Physics fphy.2020.00387 (2020)
[arXiv:2006.10610]

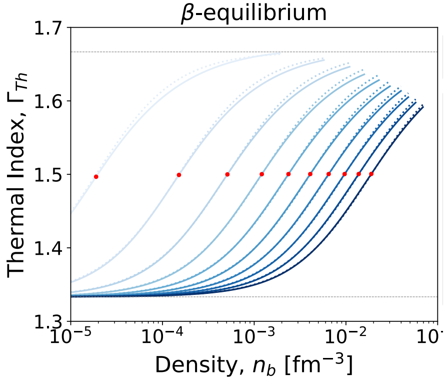
Outline

- Motivation

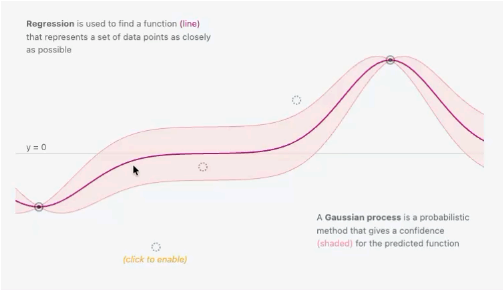


- Virial approximation & thermal effects in BNS



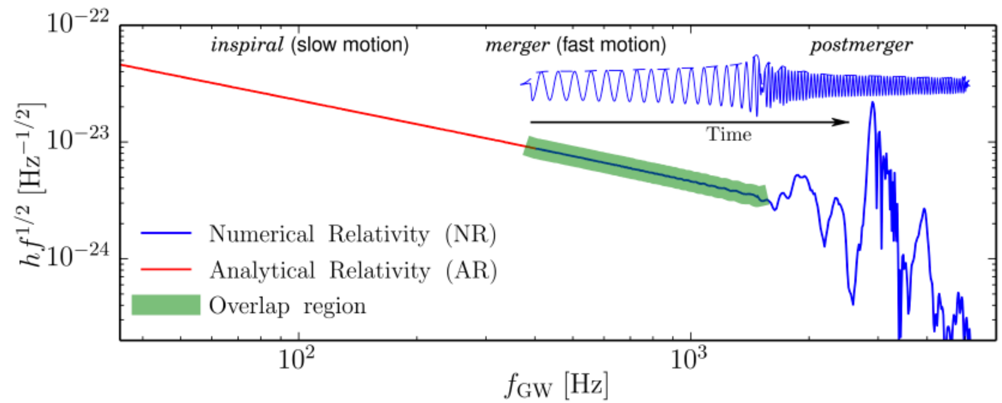


- **Gaussian processes**

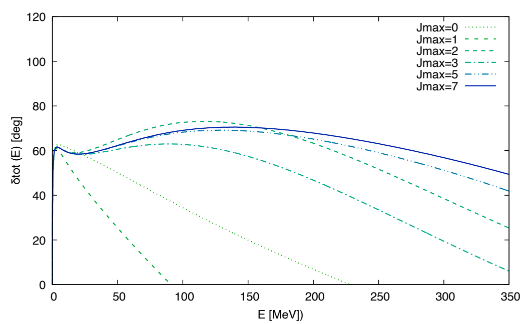


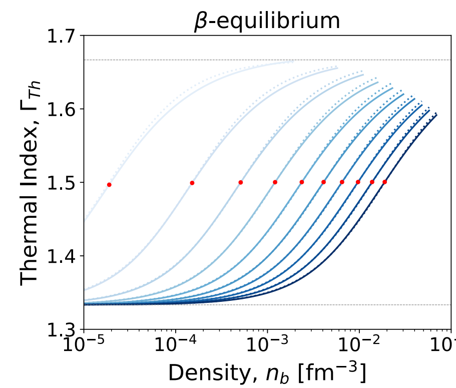
Outline

- Motivation

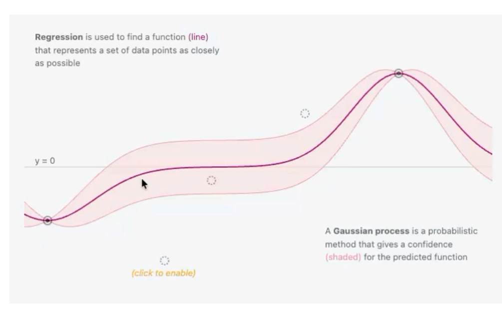


- Virial approximation & thermal effects in BNS





- **Gaussian processes**

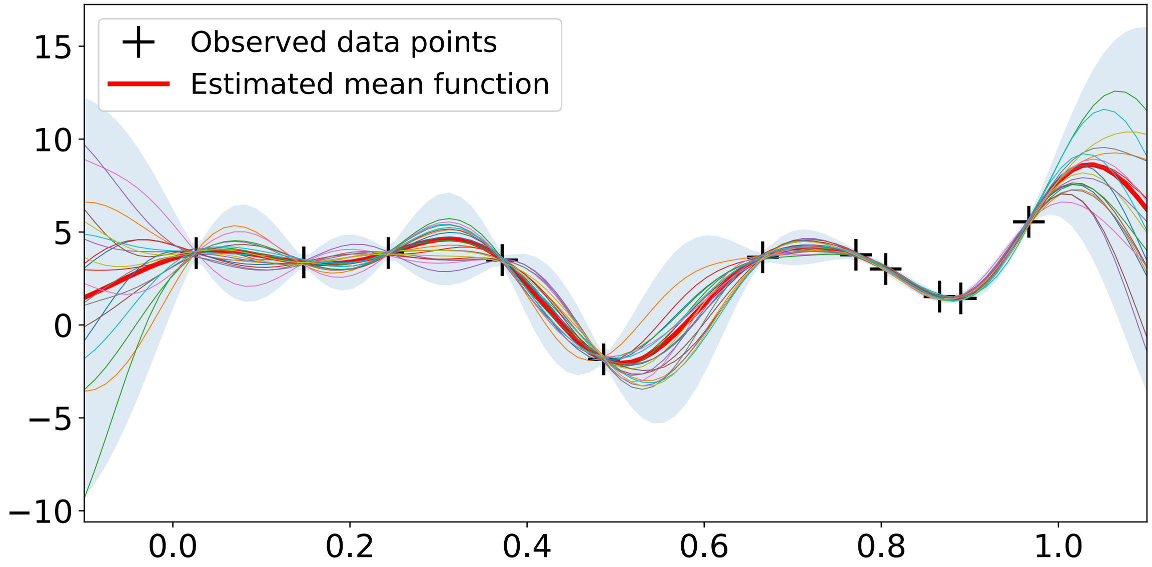


Gaussian processes

If we denote a real-valued function $f(x)$ over an input space X, then saying that f is distributed as a *Gaussian Process* means that for any finite set of inputs $\{x_1, x_2, \ldots, x_n\} \subset X$, the vector of function values

$$\boldsymbol{f} = \left(f(\boldsymbol{x}_1),\ f(\boldsymbol{x}_2),\ \ldots,\ f(\boldsymbol{x}_n)\right)^\top$$

follows a multivariate Gaussian distribution.



$$f(\boldsymbol{x}) \sim \mathcal{GP}\big(m(\boldsymbol{x}),\ k(\boldsymbol{x}, \boldsymbol{x}')\big)$$

mean

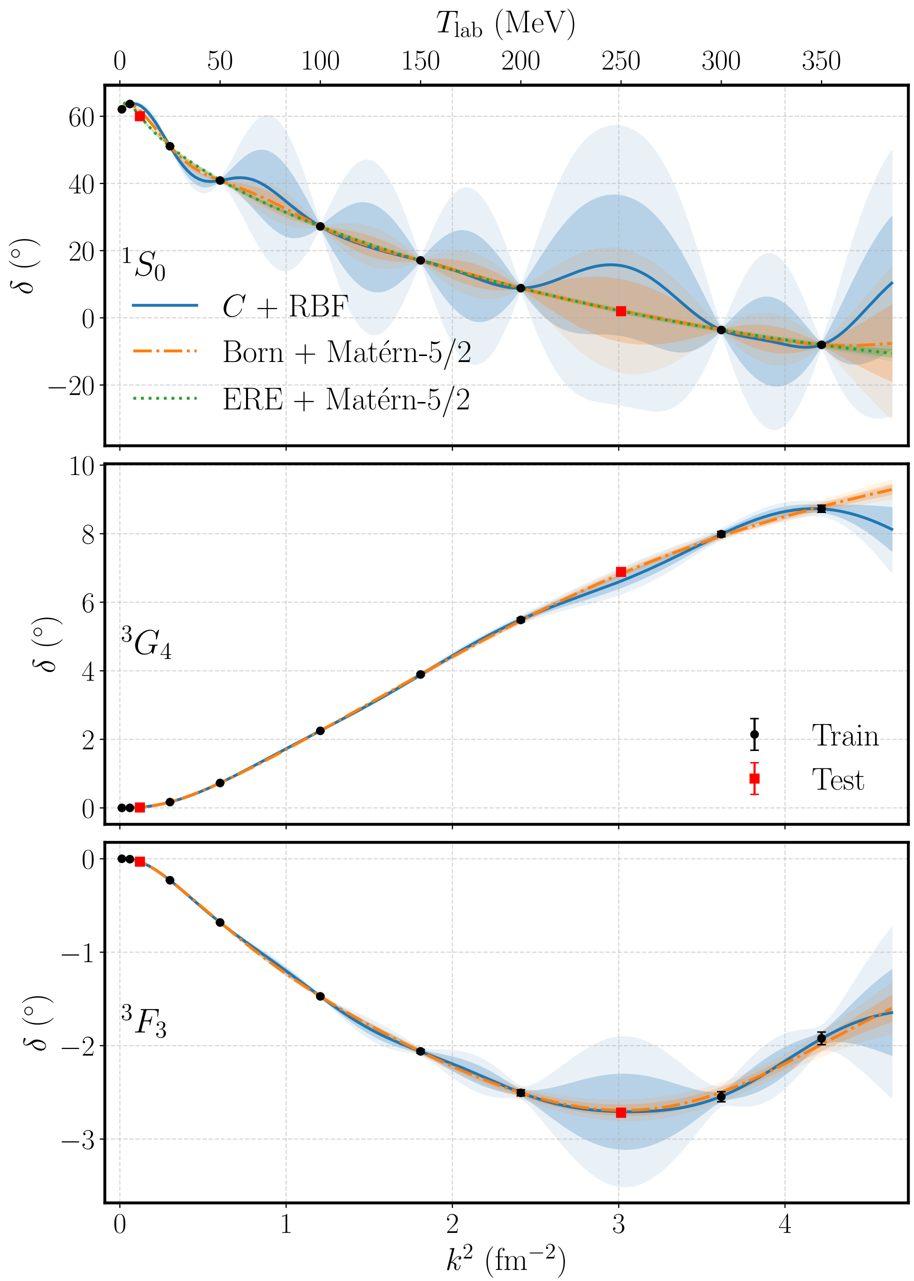
$$m(\boldsymbol{x}) = \mathbb{E}\left[f(\boldsymbol{x})\right]$$

kernel

$$k(\boldsymbol{x}, \boldsymbol{x}') = \mathbb{E}\left[\left(f(\boldsymbol{x}) - m(\boldsymbol{x})\right)\left(f(\boldsymbol{x}') - m(\boldsymbol{x}')\right)\right]$$

Wang, https://arxiv.org/a2009.10862v5

Gaussian processes



GP pros

- Guaranteed to reproduce data
- Bayesian interpolator
- Errors accounted for
- Differentiable model

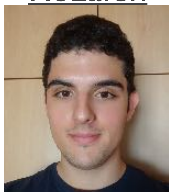
GP cons

- Extrapolation "misguided"

$$f(\boldsymbol{x}) \sim \mathcal{GP}\big(m(\boldsymbol{x}),\, k(\boldsymbol{x},\boldsymbol{x}')\big)$$

$$m(\boldsymbol{x}) = \mathbb{E}\left[f(\boldsymbol{x})\right] \approx C$$

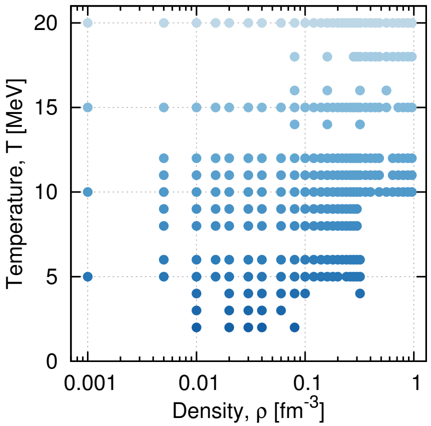
Rozalén



Kochankovski

Kochankovski, Rozalén, Rios & Ramos, *in prep*

Modelling the mean



Mean model for EoS

$$m_{\text{par}}(\rho_B, T, Y_q) = (e_0(\rho_B) + f_{0,\text{th}}(\rho_B, T)) + (e_{\text{sym}}(\rho_B) + f_{\text{sym,th}}(\rho_B, T))\,\delta^2 + m_{\text{el}}(\rho_B, T, Y_q)$$

Cold part

$$\chi = \frac{\rho_B - n_0}{3n_0}$$

$$e_0(\rho_B) = E_{\text{sat}} + \tfrac{1}{2}K_0\,\chi^2 + \tfrac{1}{6}Q_0\,\chi^3$$

$$e_{\text{sym}}(\rho_B) = J + L\,\chi + \tfrac{1}{2}K_{\text{sym}}\,\chi^2$$

Thermal part

$$f_{0,\text{th}}(\rho_B, T) = -\frac{a_0(\rho_B)\,T^2}{1 + b_0(\rho_B)\,T}$$

$$f_{\text{sym,th}}(\rho_B, T) = -\frac{a_{\text{sym}}(\rho_B)\,T^2}{1 + b_S(\rho_B)\,T}$$

$$a_\tau(\rho) = \frac{\pi^2}{2}\,\frac{m^*_\tau(\rho)/m}{\varepsilon_{F,\tau}(\rho)}$$

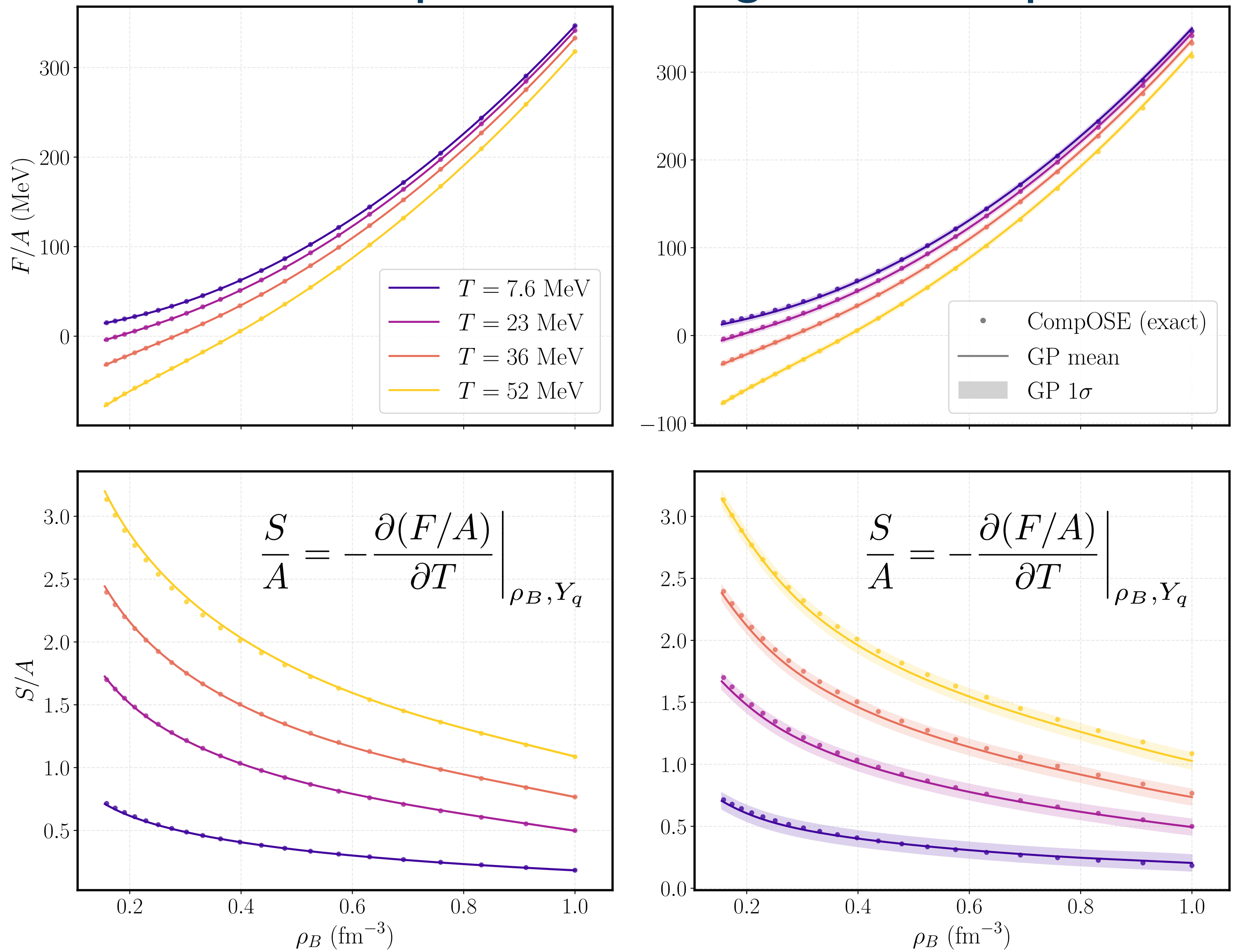
$$\frac{m^*_\tau(\rho)}{m} = \frac{1}{1 + \alpha_\tau \rho/\rho_0}$$

Trainable parameters

$$E_{\text{sat}}, K_0, Q_0, J, L, K_{\text{sym}}, \alpha_0, \alpha_n, \beta_0, \beta_n$$

Nuclear-physics Gaussian processes

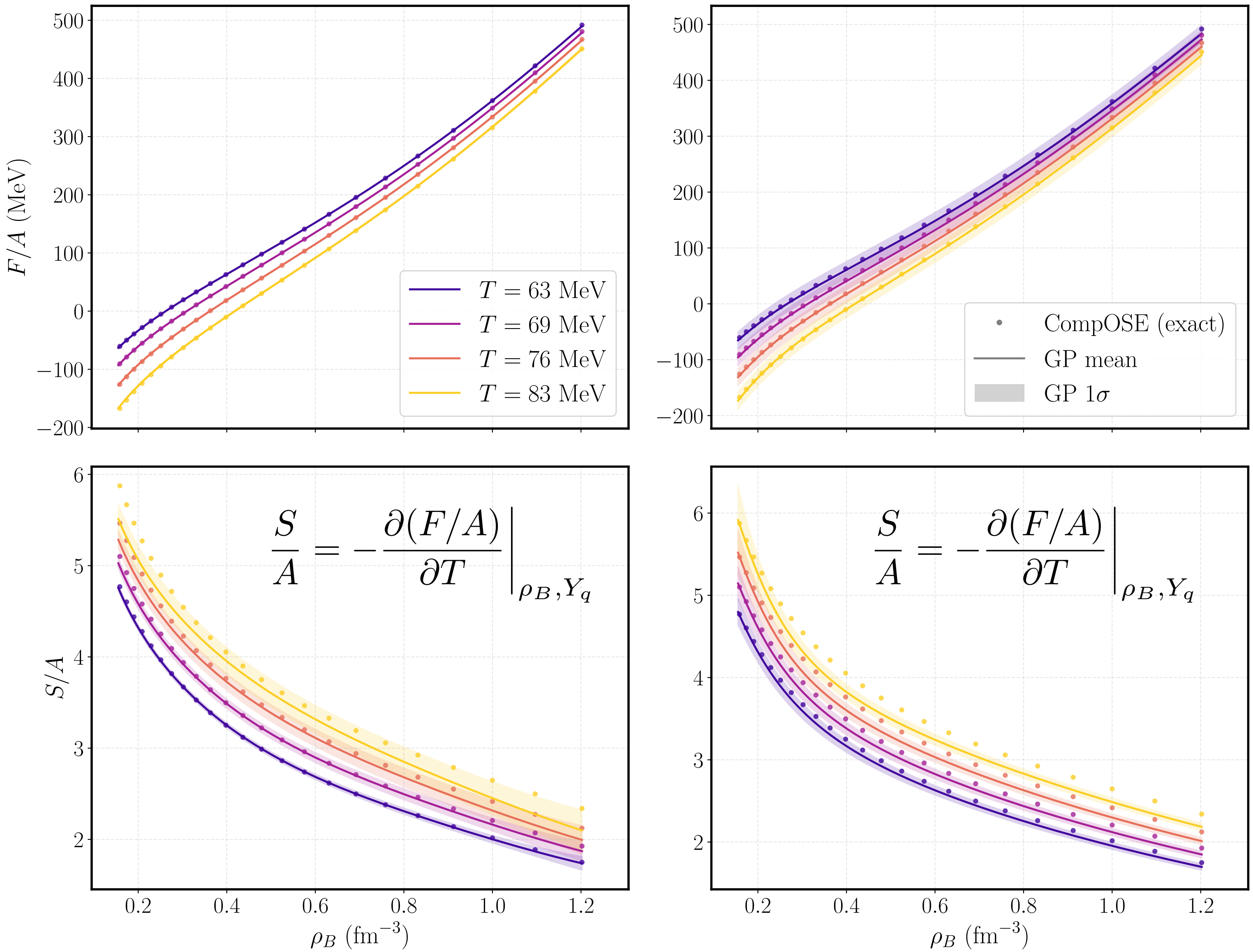
Informed interpolation   Agnostic interpolation



Kochankovski, Rozalén, Rios & Ramos, *in prep*

Nuclear-physics Gaussian processes

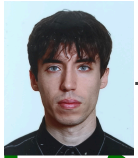
Informed extrapolation | Agnostic extrapolation



Kochankovski, Rozalén, Rios & Ramos, *in prep*

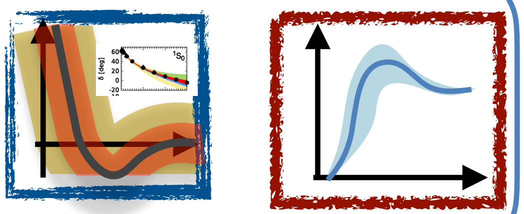
Conclusions

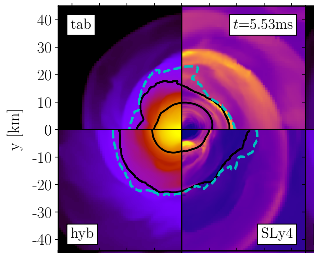
- Ab initio **finite temperature** effects can be simulated & quantified
- **ML** GP techniques can help **interpolate** & **extrapolate** (if physics guided)
- **Challenges**
    - **Uncertainty quantification**
    - **Practical simulability**
    - **Internal NS structure: modes? Phases?**



Márquez

G Rivieccio





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Institut de Ciències del Cosmos
UNIVERSITAT DE BARCELONA

EXCELENCIA MARÍA DE MAEZTU

UNIVERSITAT DE BARCELONA

@HadNucAtUB

Thank you!

arnau.rios@icc.ub.edu

https://sites.google.com/view/arnaurios/

UNIVERSITAT DE BARCELONA

À Ramos

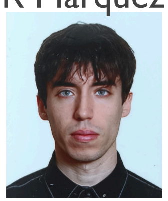
J Rozalén

H Kochankovski

A Nadal

R Bondarescu

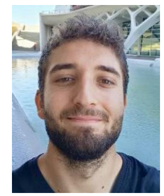
R Márquez



VIRGO GROUP VALENCIA

D Guerra

G Rivieccio



T Font

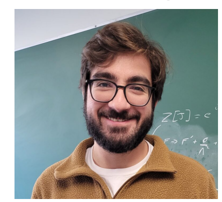
P Cerdá-Duran

M Ruiz

TECHNISCHE UNIVERSITÄT DARMSTADT

M Drissi

G Palkanoglou



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Financiado por la Unión Europea
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