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Finite temperature effects in binary 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*

Arnau Rios Huguet

Associate Professor

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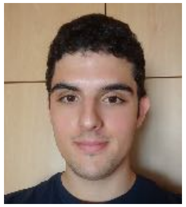
Guerra

Rivieccio

Rozalén



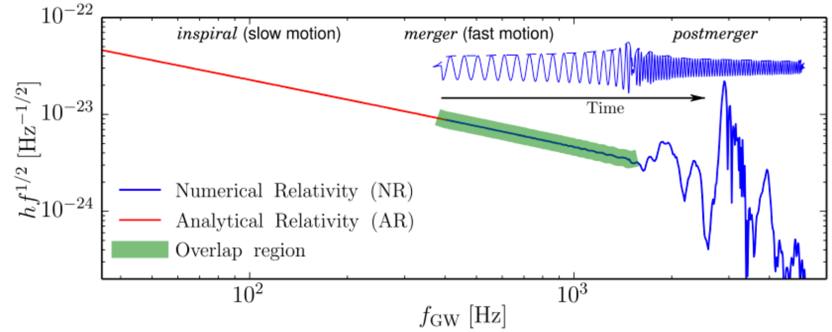
Kochankovski

INT Finite T

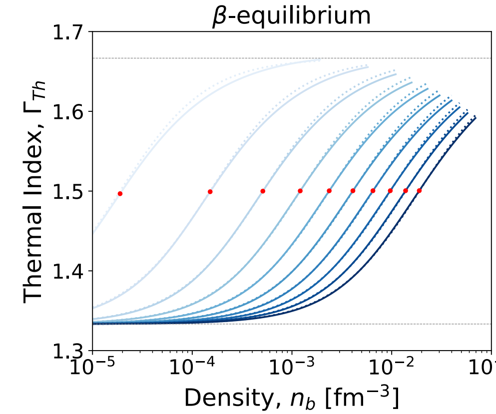
15 June 2026

Outline

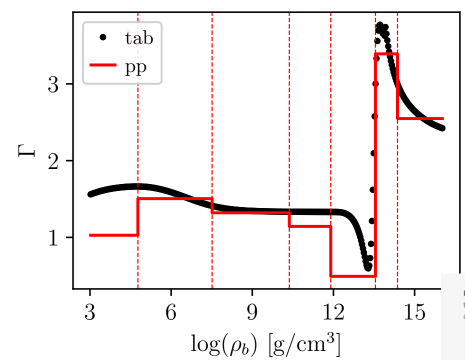
- **Motivation**



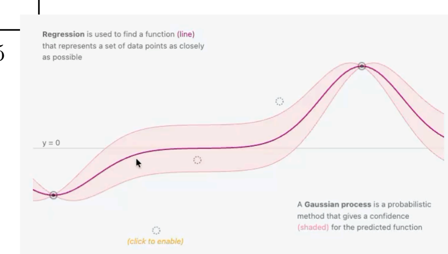
- Virial approximation



- Thermal effects in BNS



- Gaussian processes for finite T



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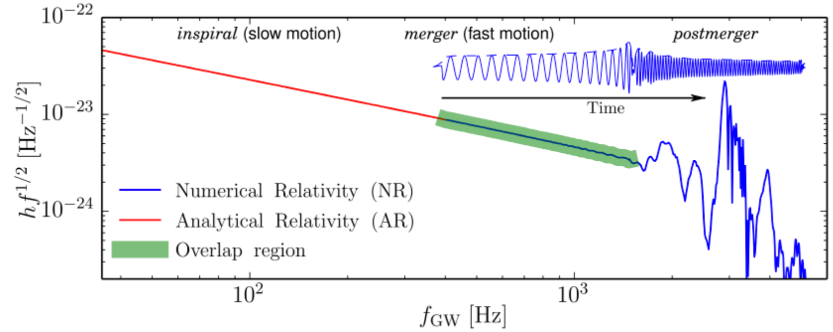

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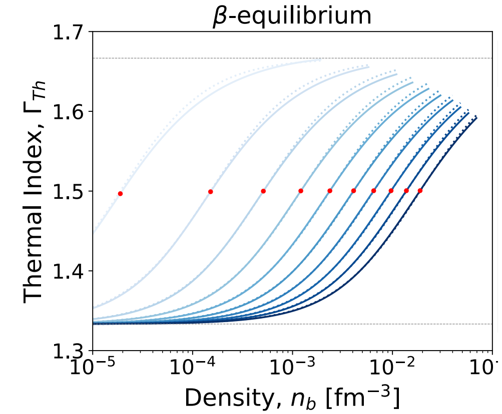

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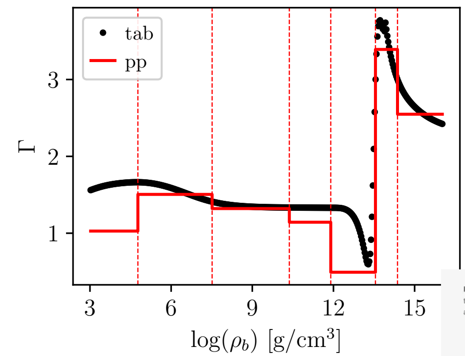


- Gaussian processes for finite T

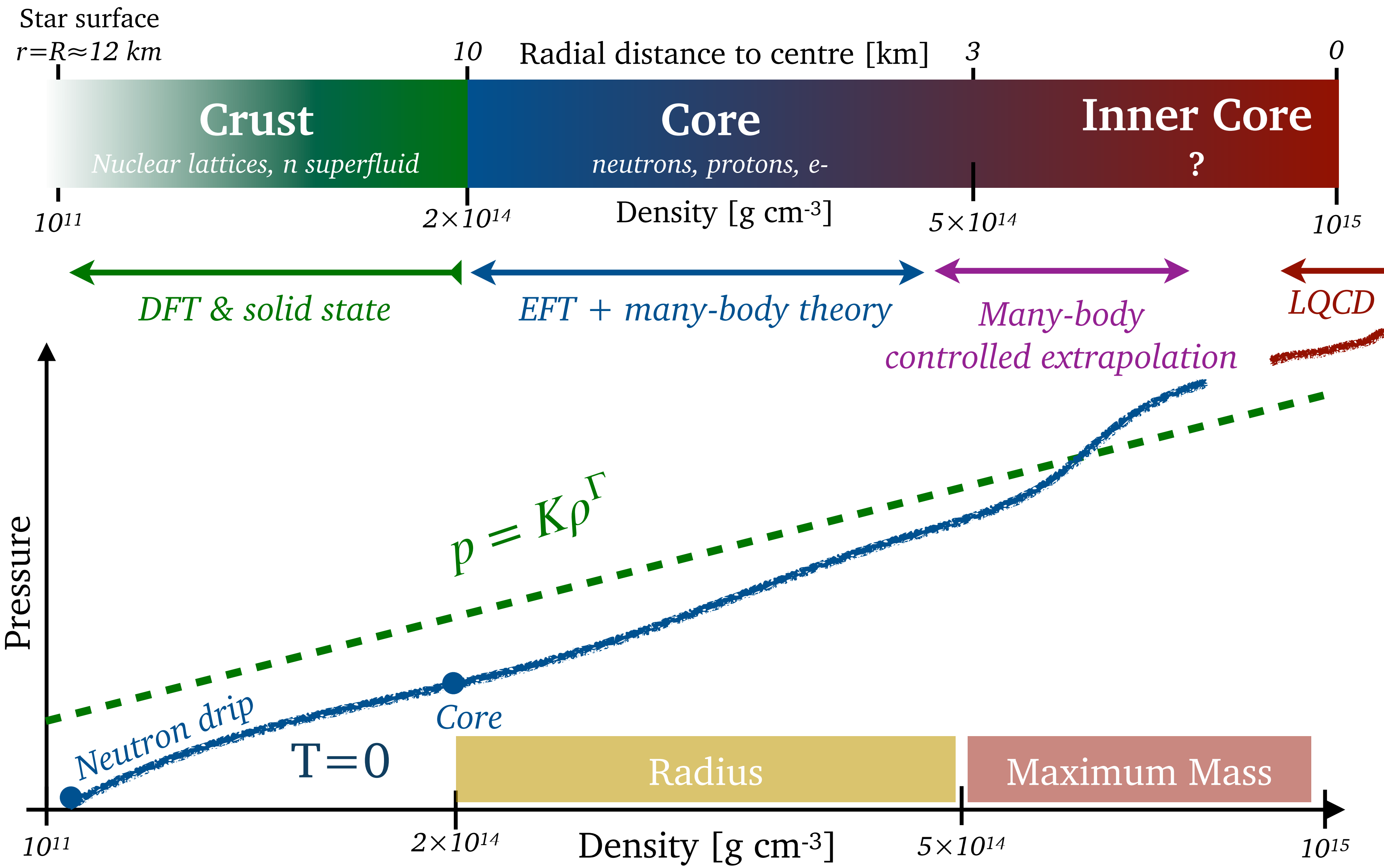
20 years ago!

Thermodynamical Properties of Nuclear Matter from a Self-Consistent Green's Function Approach

Memòria presentada per
Arnau Rios Huguet
per optar al títol de
Doctor en Ciències Físiques.
Barcelona, 23 febrer de 2007.

Programa de doctorat
Física Avançada
Bienni 2002-2004,
del Departament d'Estructura
i Constituents de la Matèria,
Universitat de Barcelona.

Neutron-star modelling



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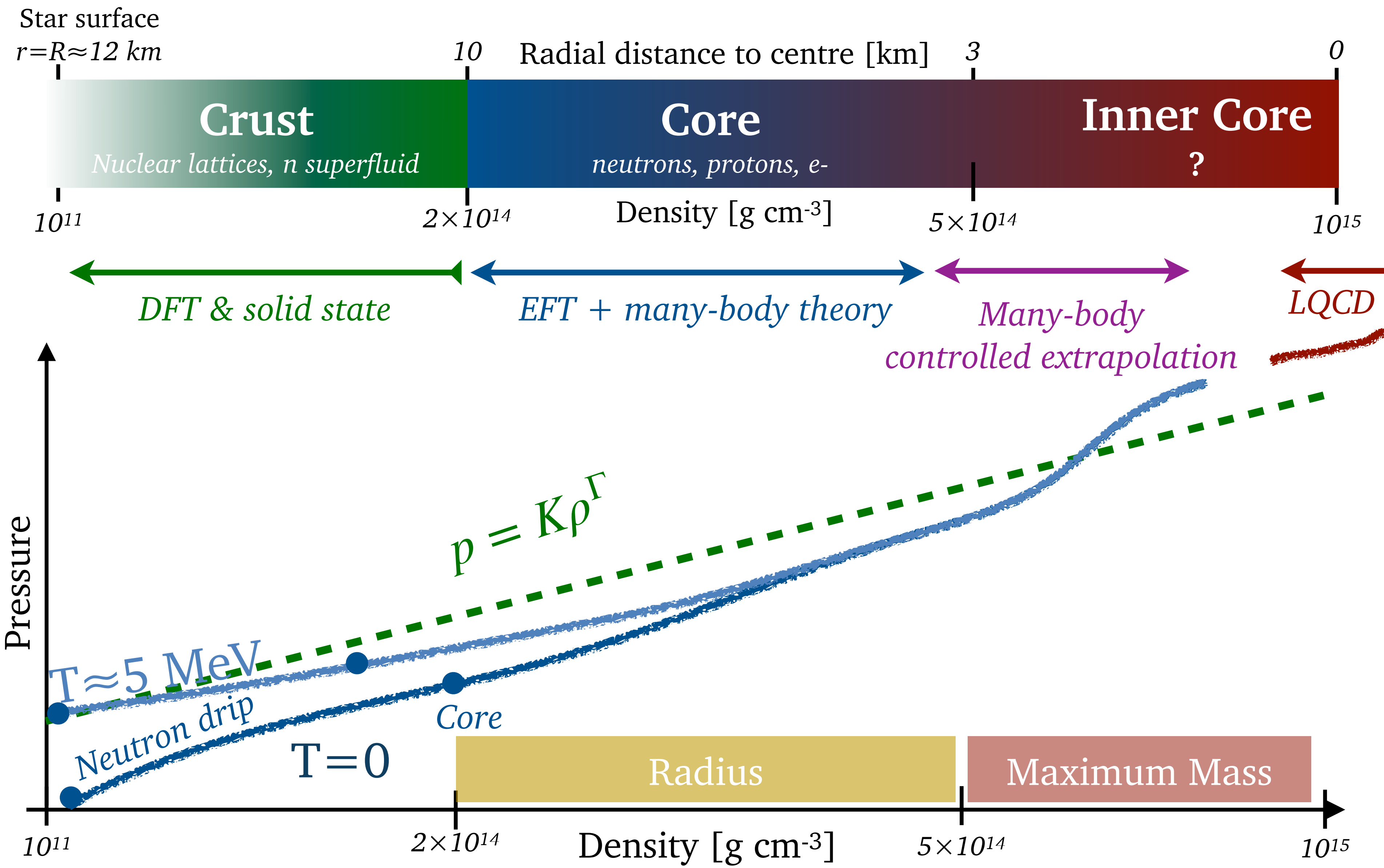

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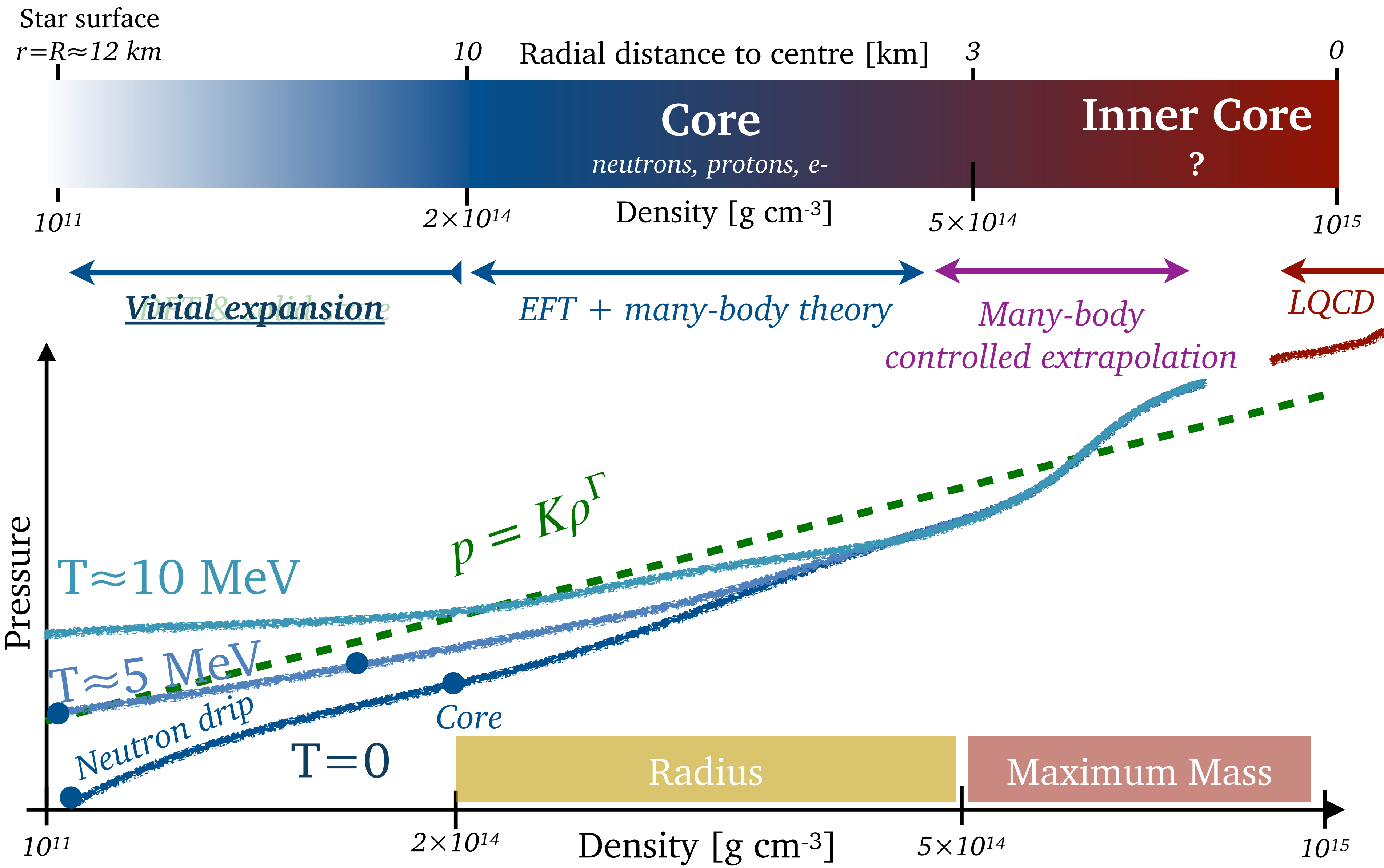
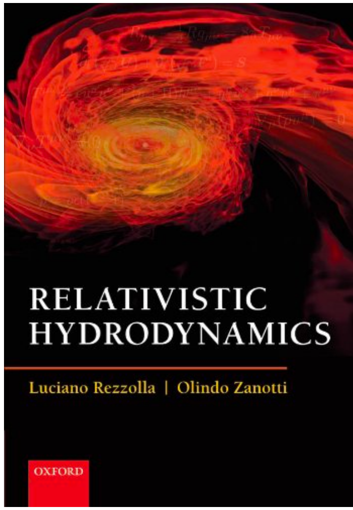


Hot neutron stars

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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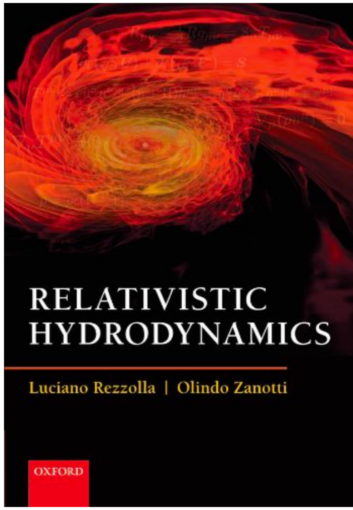

$$P(\epsilon, T) = P(\epsilon, T=0) + P_{\rm th}(\epsilon_{\rm th})$$

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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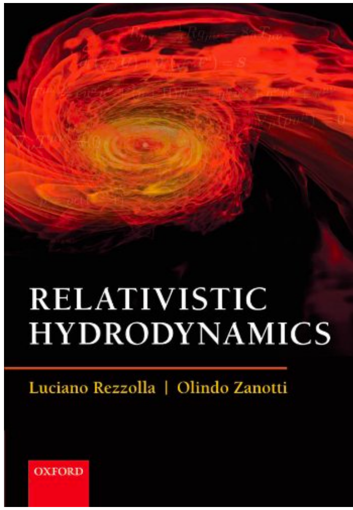

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Thermal part

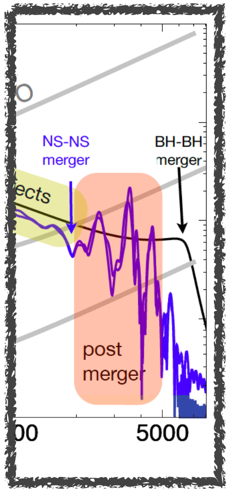
Thermal index

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

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

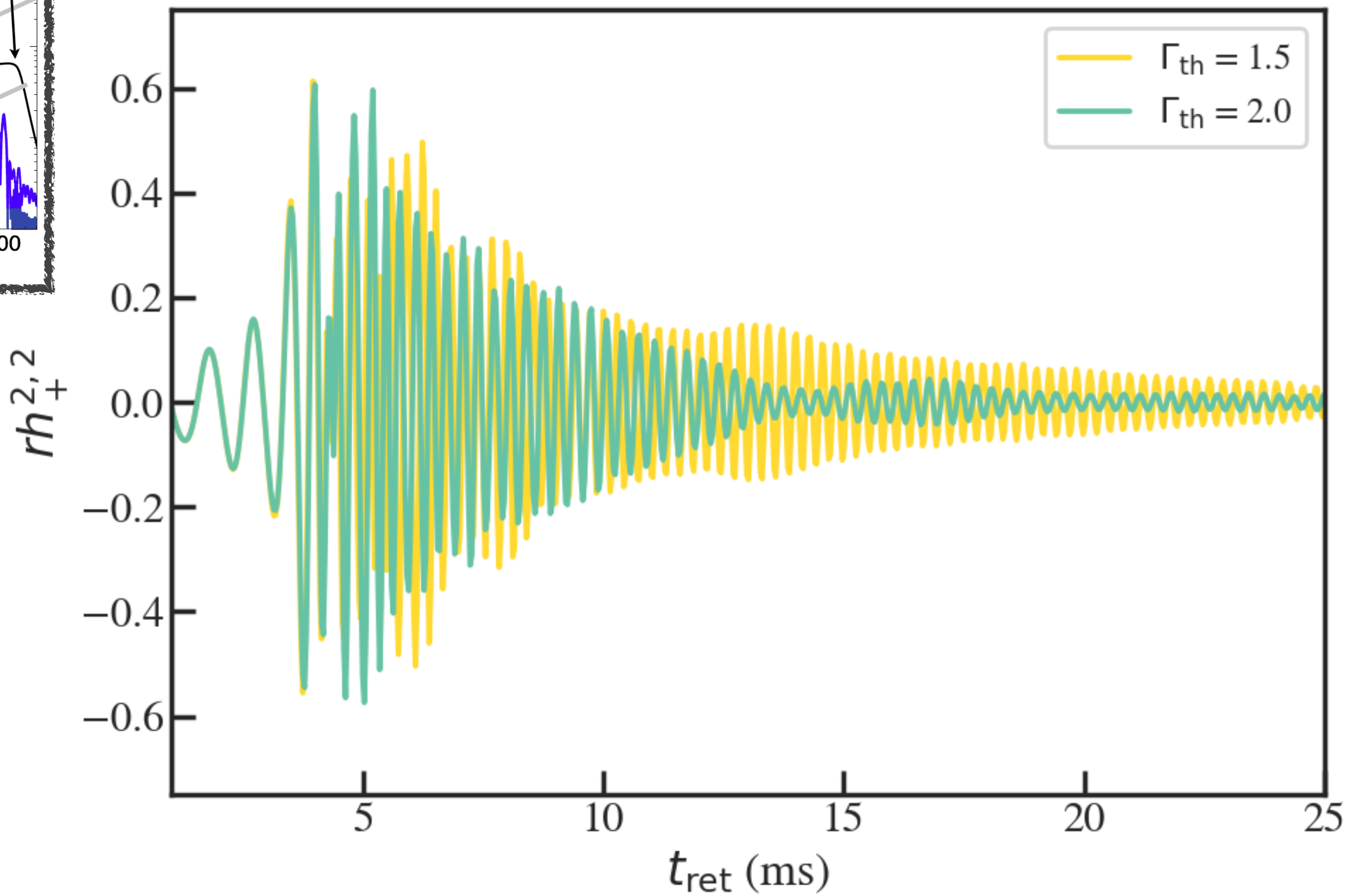
$$\epsilon_{\mathrm{th}} = \epsilon(T) - \epsilon_0$$

Post-merger: from Γ_{th} to GWs



<u>1.4M$_\odot$+1.4M$_\odot$ GW spectrum</u>

<u>Same cold component, different constant Γth</u>



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

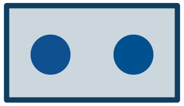
Known situations

Cold part

Thermal part

Non-relativistic

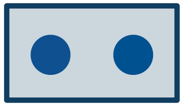
$$\Gamma_c = \frac{5}{3}$$



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

Relativistic

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



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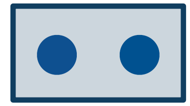

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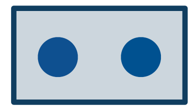

$$\Gamma_{\rm th} = \frac{4}{3}$$

Unitary

$k_F a_S \gg 1$

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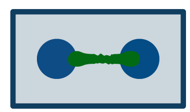

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Known situations

Cold part | **Thermal part**

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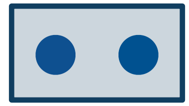

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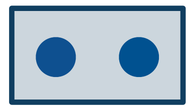

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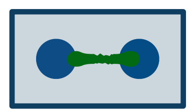
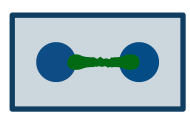


$$\Gamma_{\rm th} = \frac{5}{3}$$

Mean-field/Fermi liquid

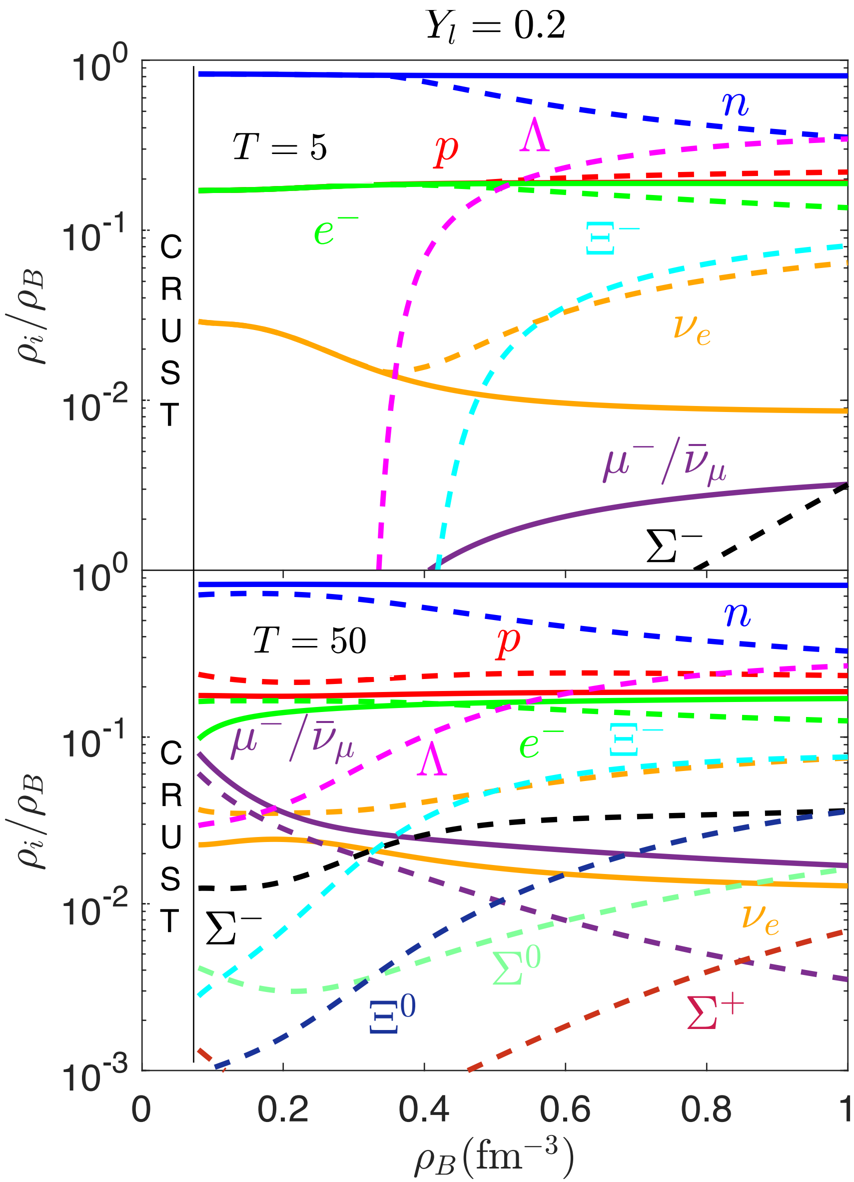
$$\Gamma_c = \Gamma_c(\epsilon)$$

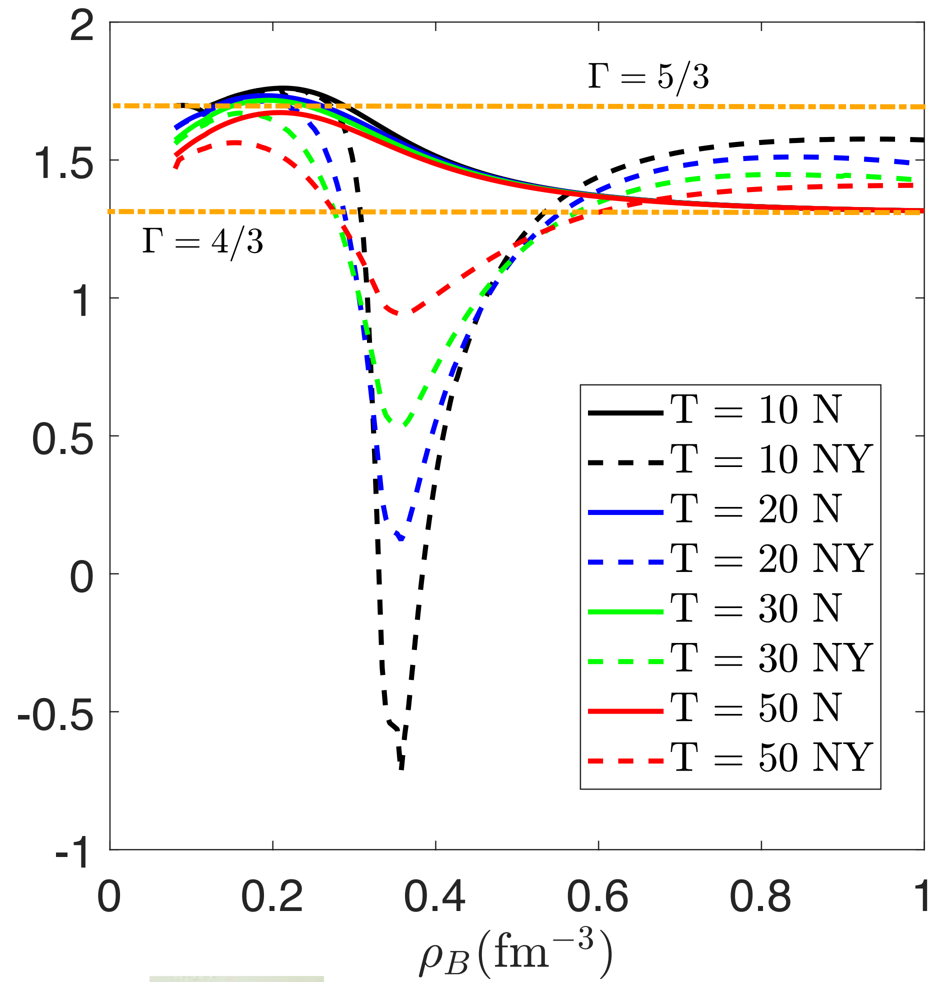


$$\Gamma_{\rm th}^{m^*} = \frac{5}{3} - \frac{n}{m^*}\frac{\partial m^*}{\partial \rho}$$

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

Multicomponent systems: hyperons





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

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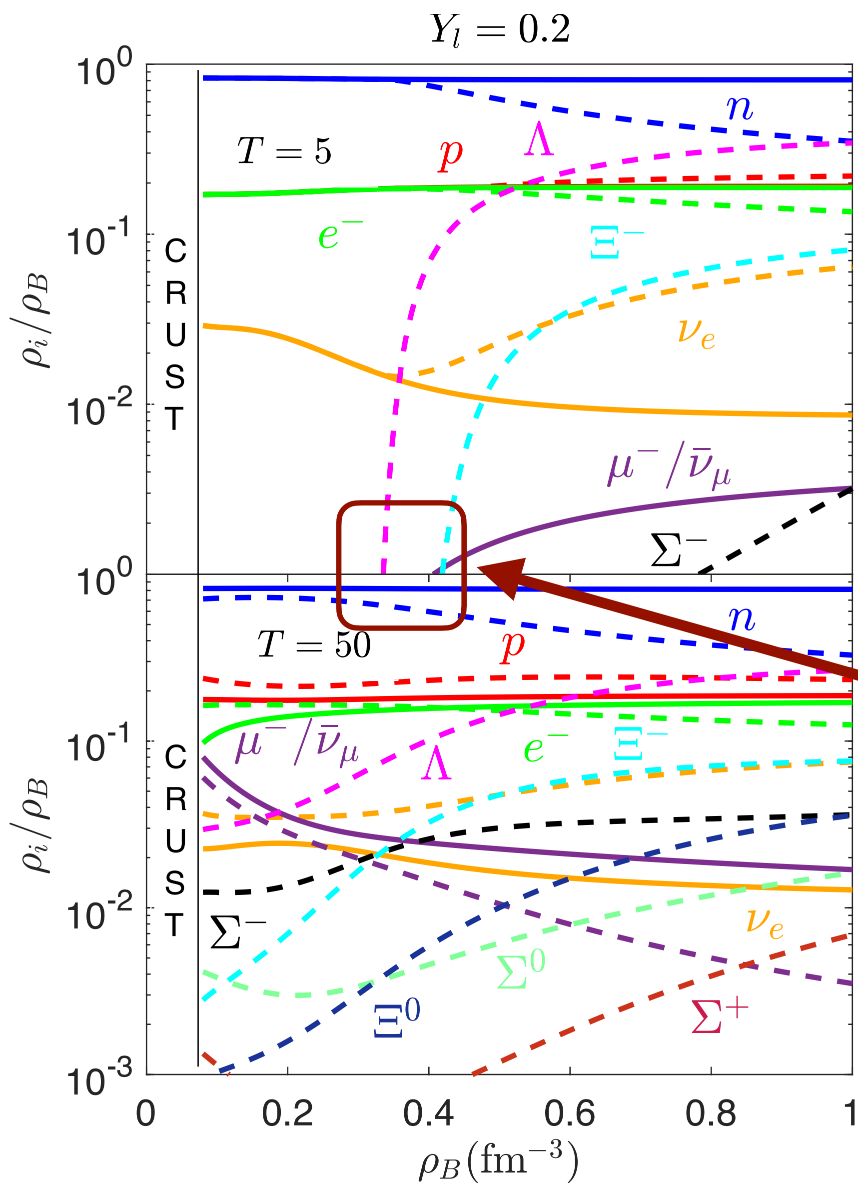

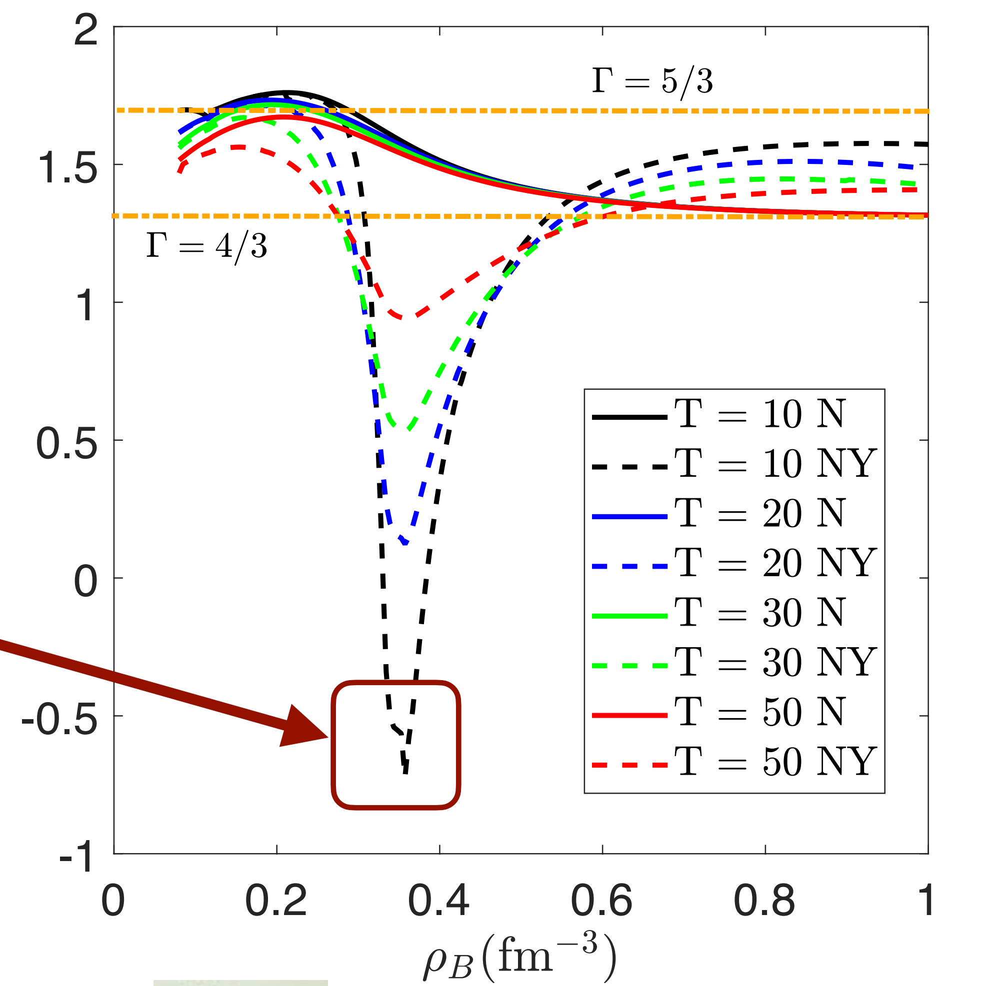

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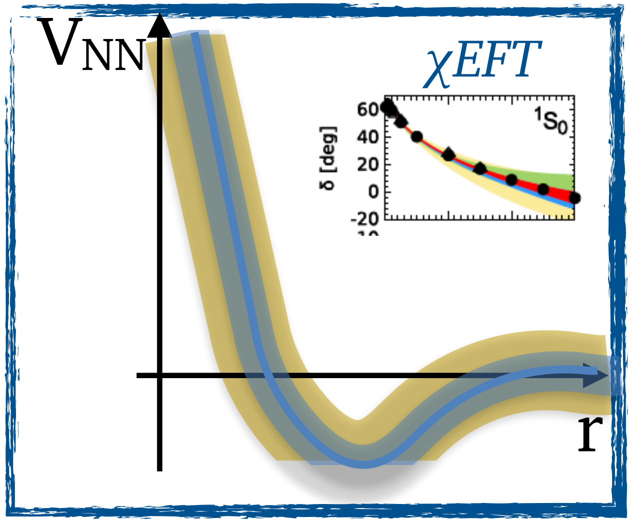
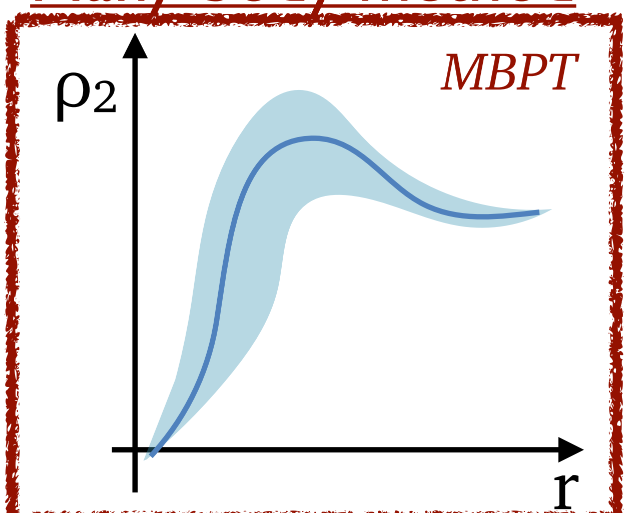
Kochankovski, Ramos & Tolos, MNRAS **517** 507 (2022)

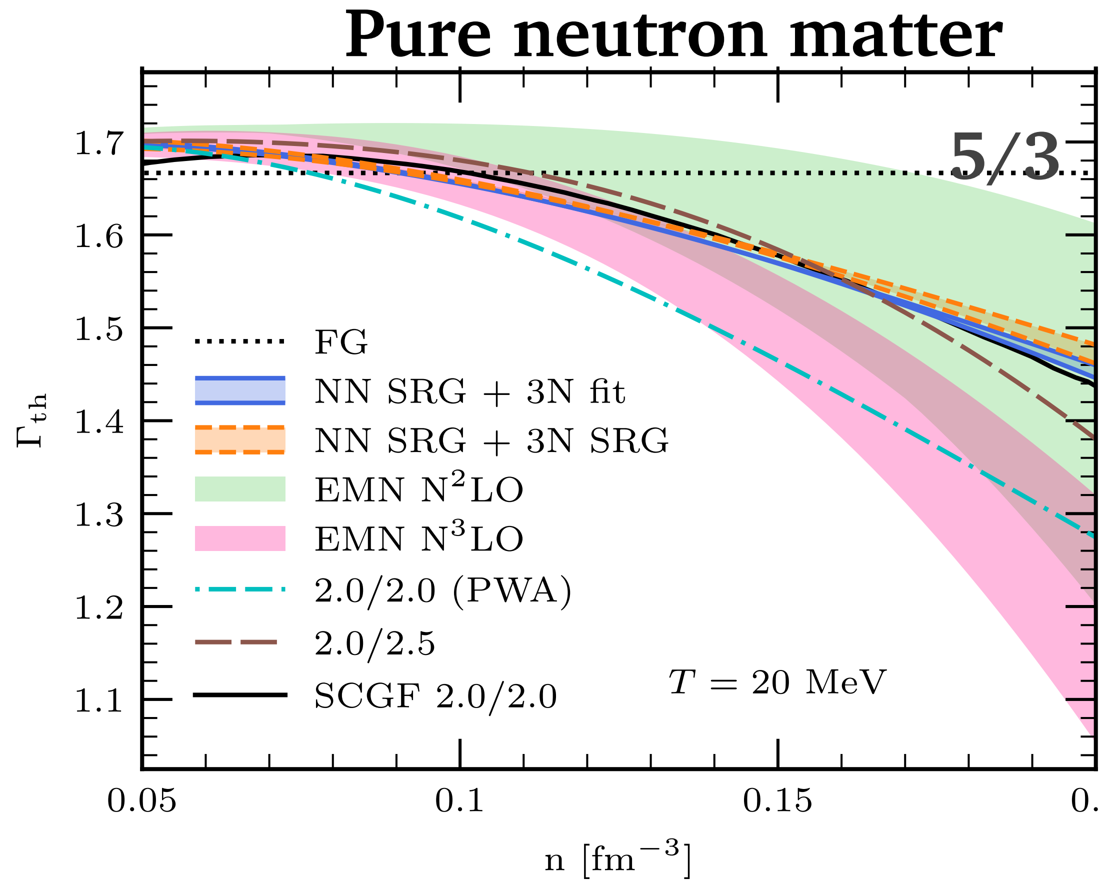
Ab initio thermal index

Hamiltonian



Many-body method





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

Ab initio thermal index

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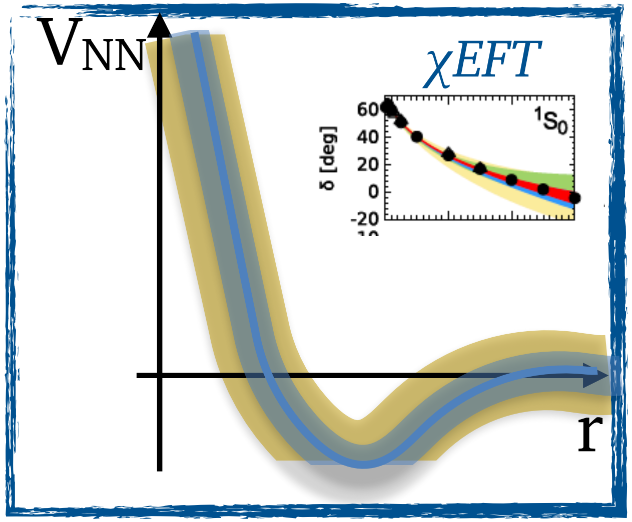

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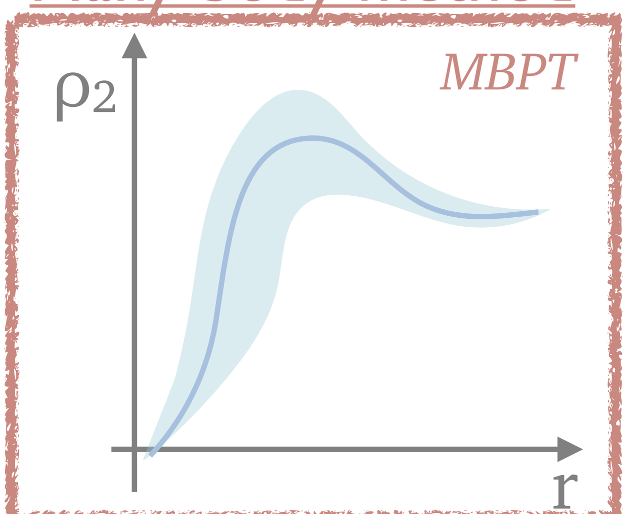

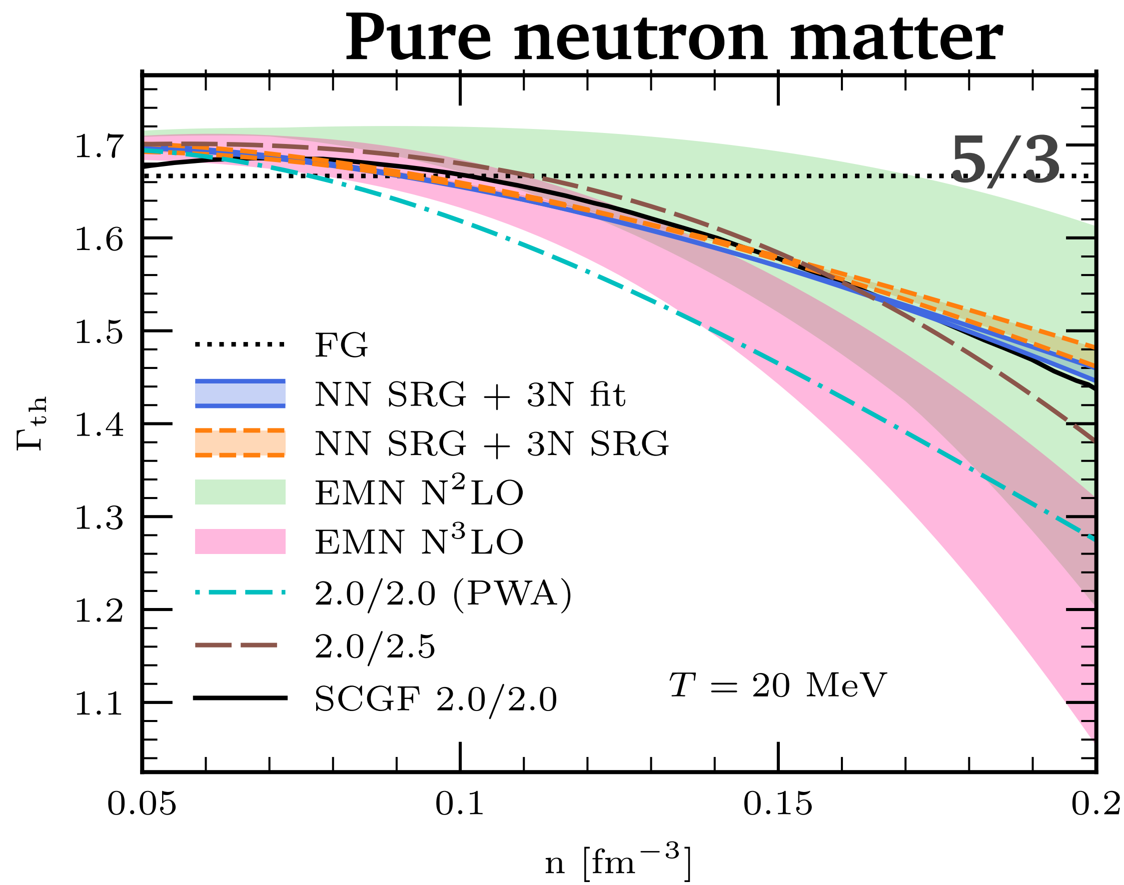

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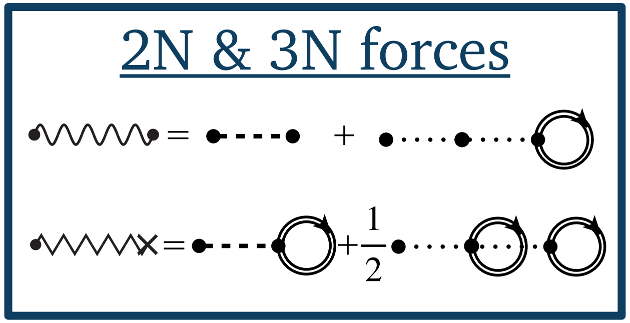
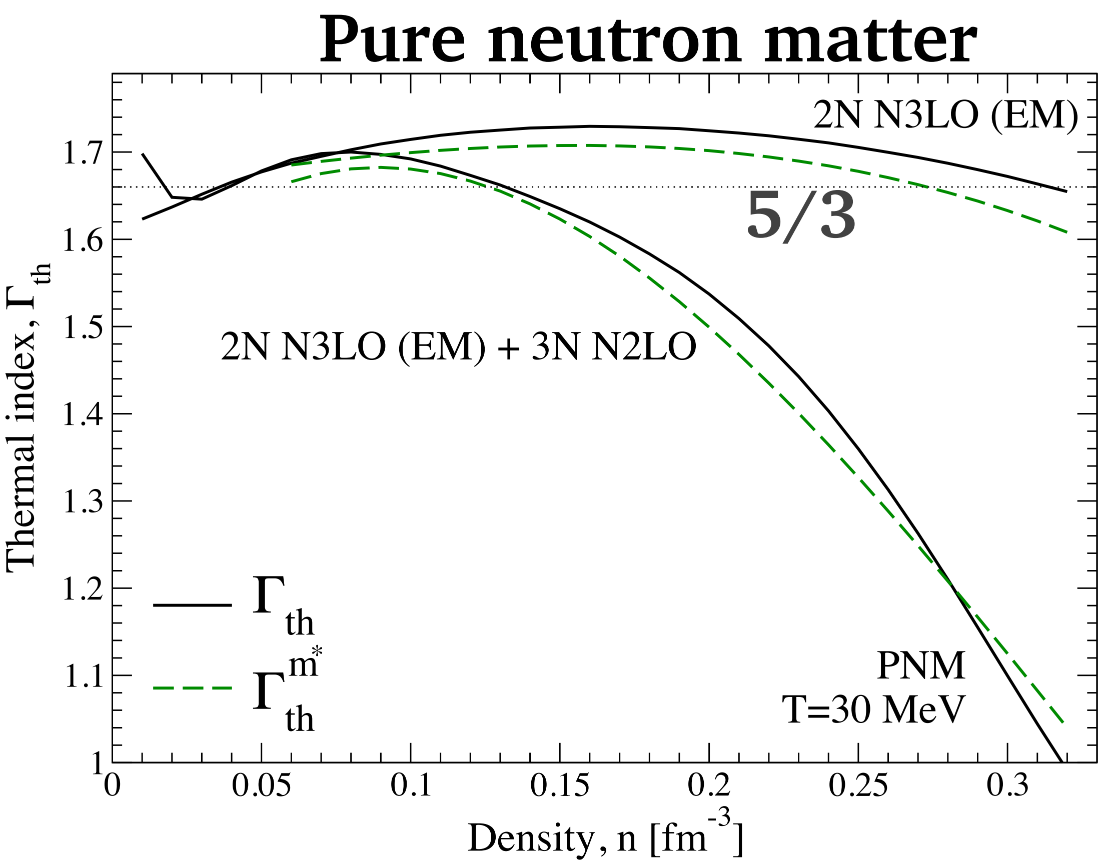


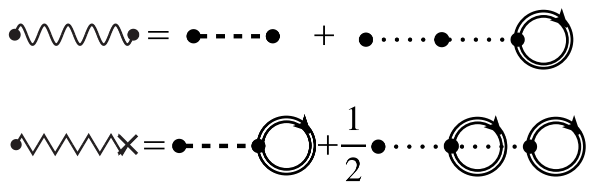


Carbone & Schwenk *Phys Rev C* **100** 025805 (2019)

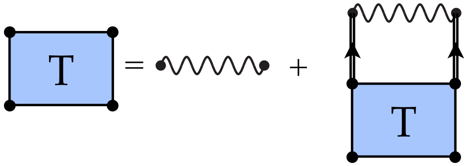
Carbone, Polls & Rios, Phys Rev C **88** 044302 (2014)
Rios, Front. Phys. 8 387 (2020), arxiv:2006.10610

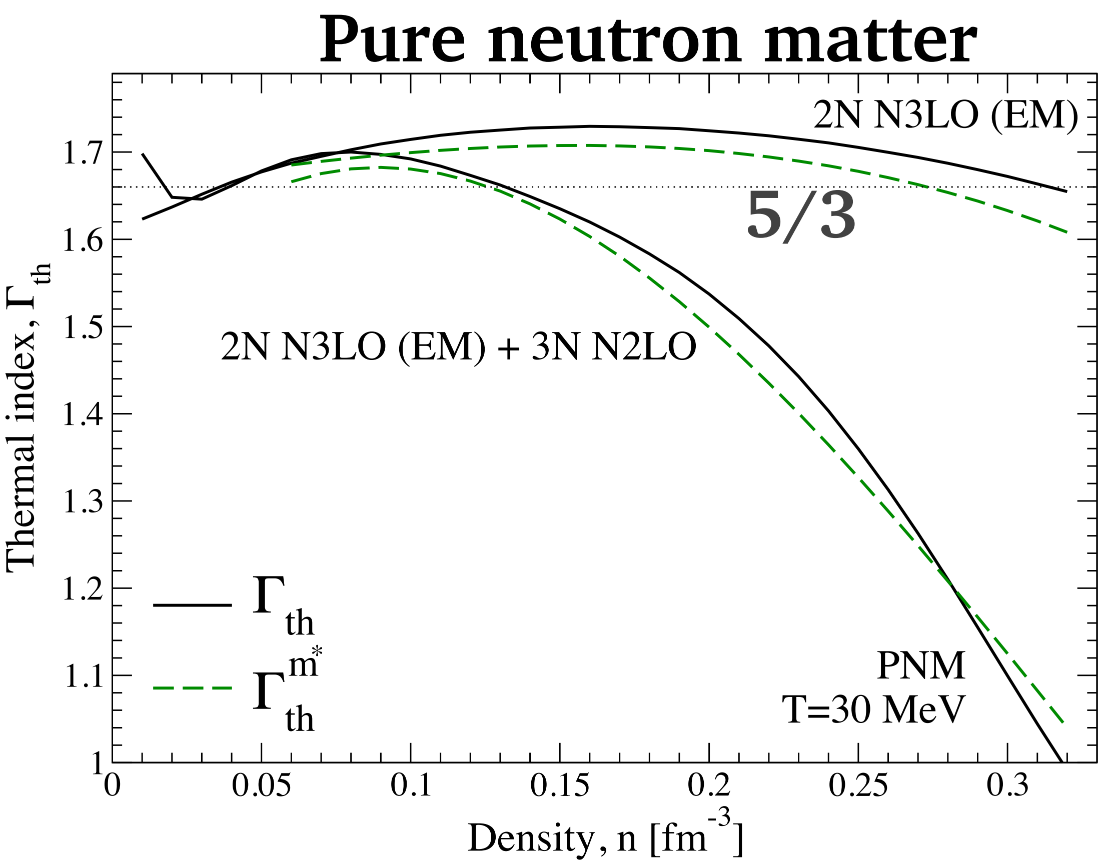
Ab initio thermal index

2N & 3N forces



In-medium interaction





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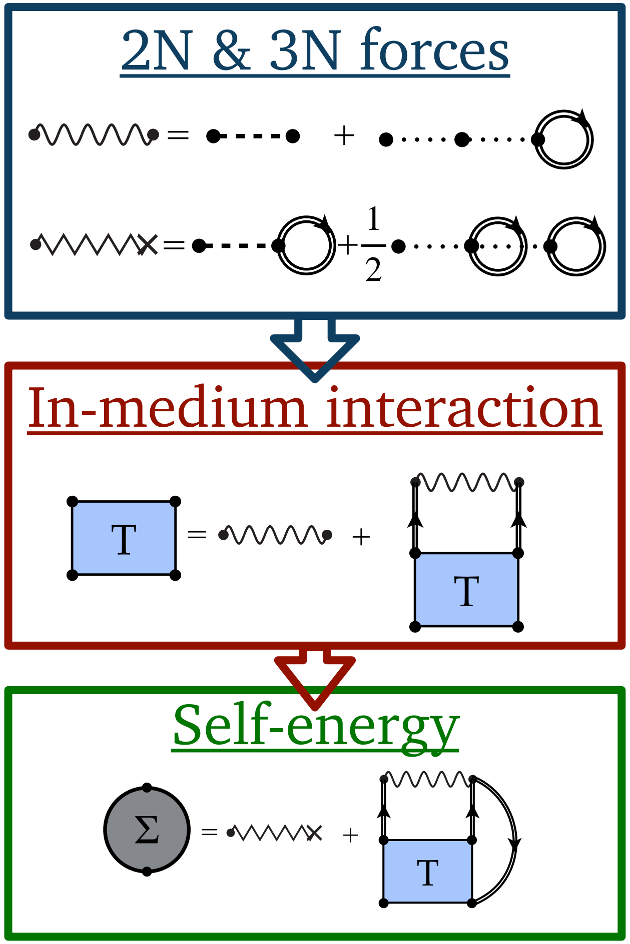

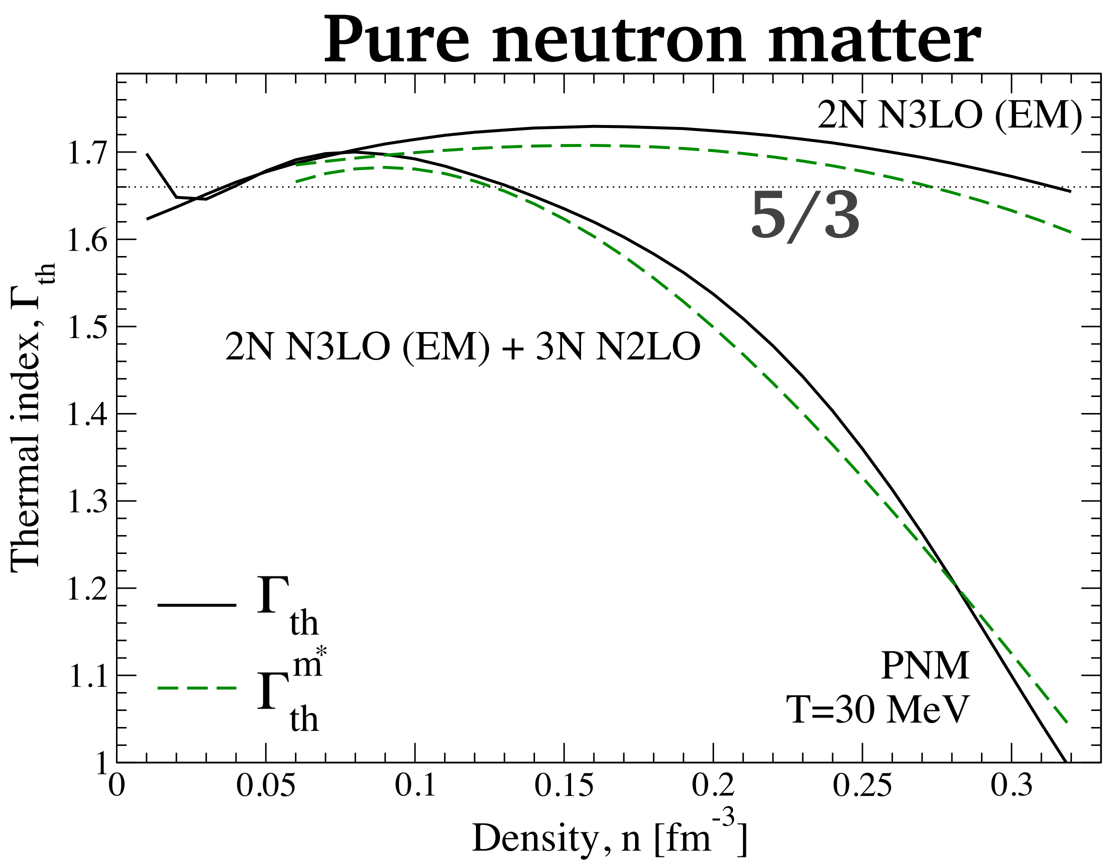

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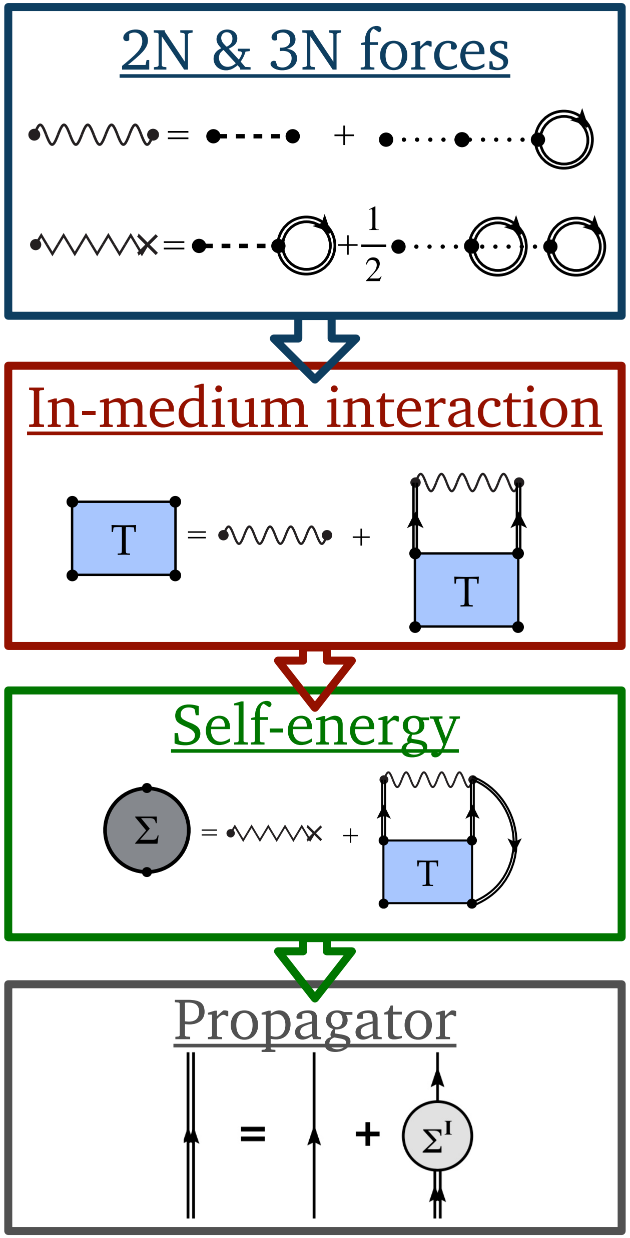

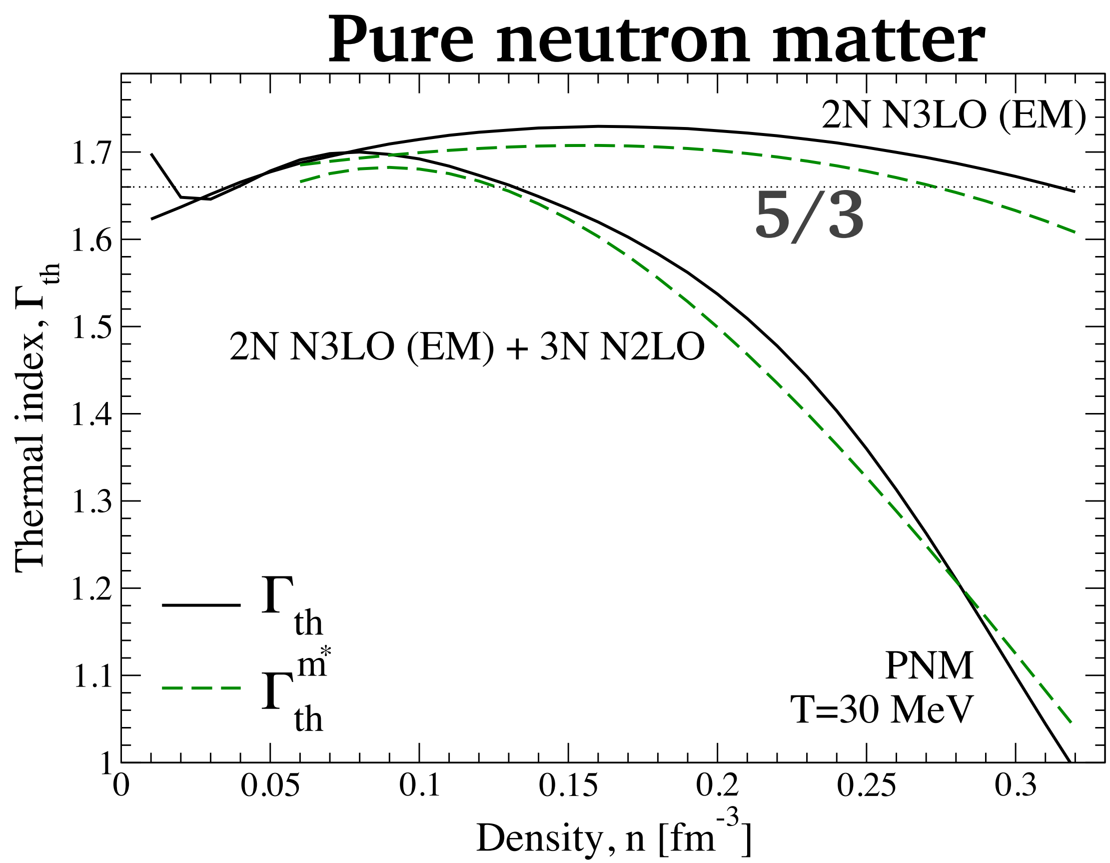

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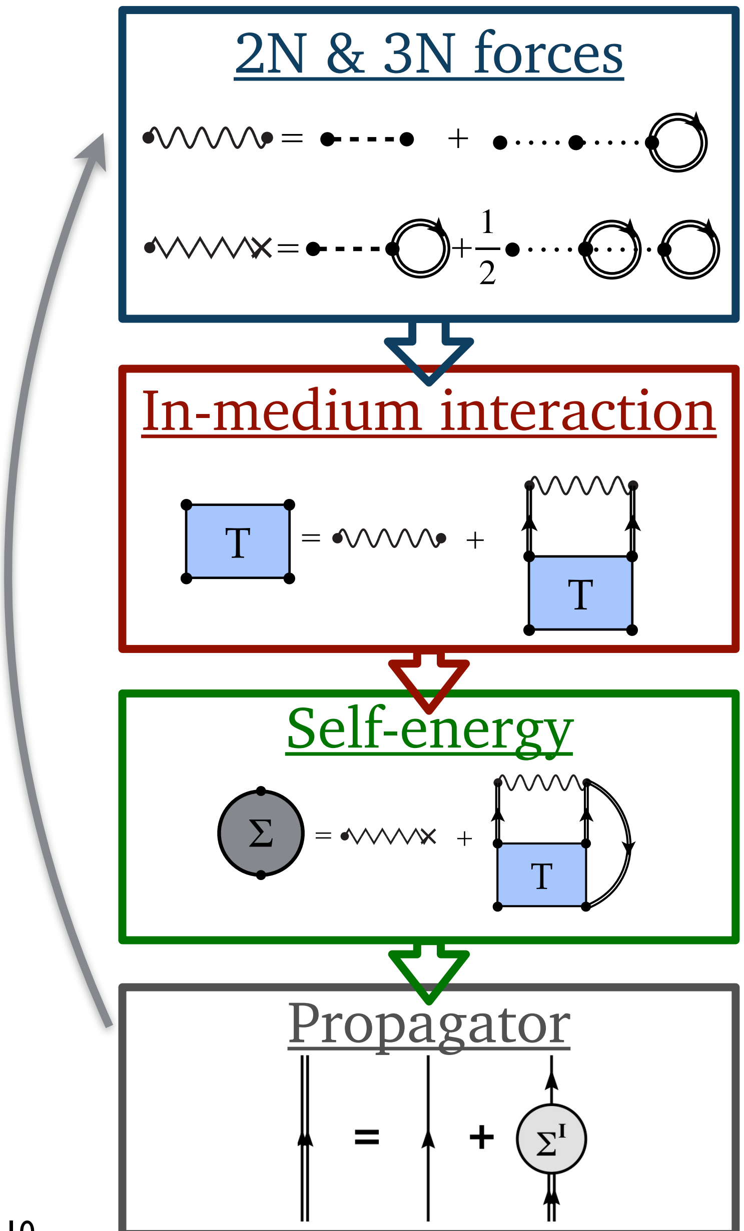

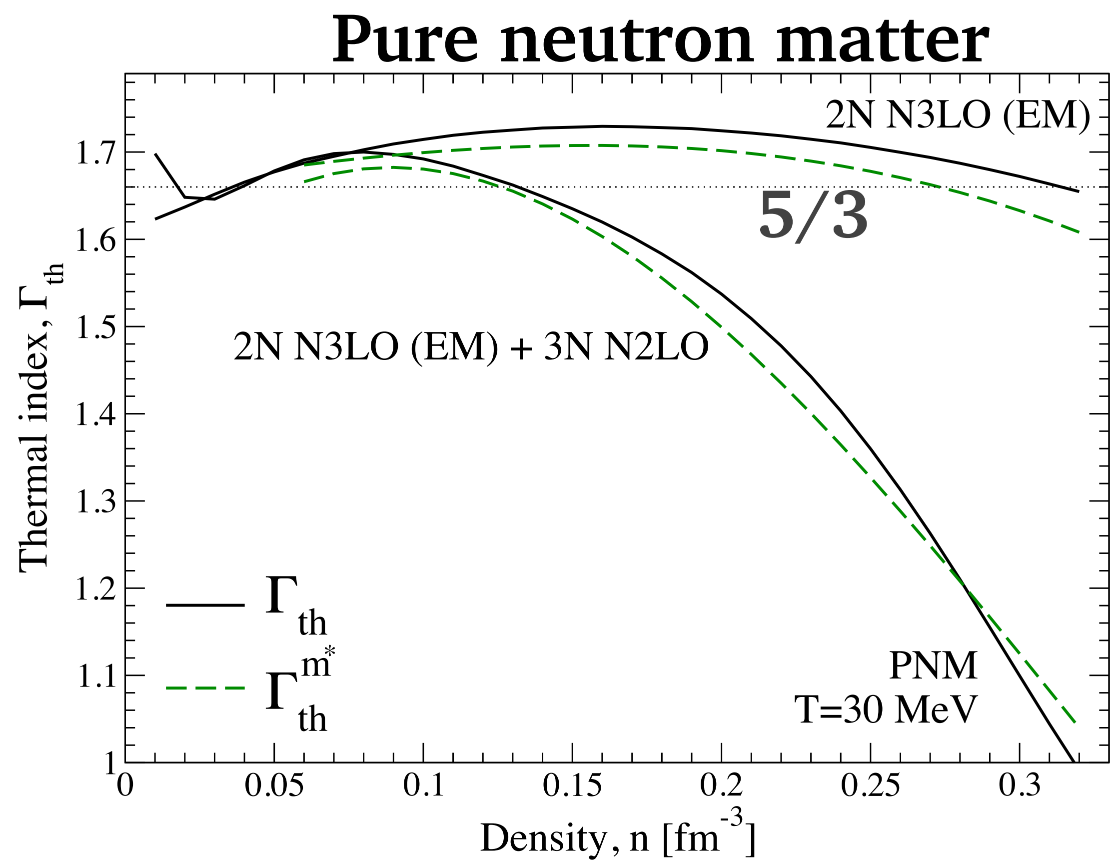

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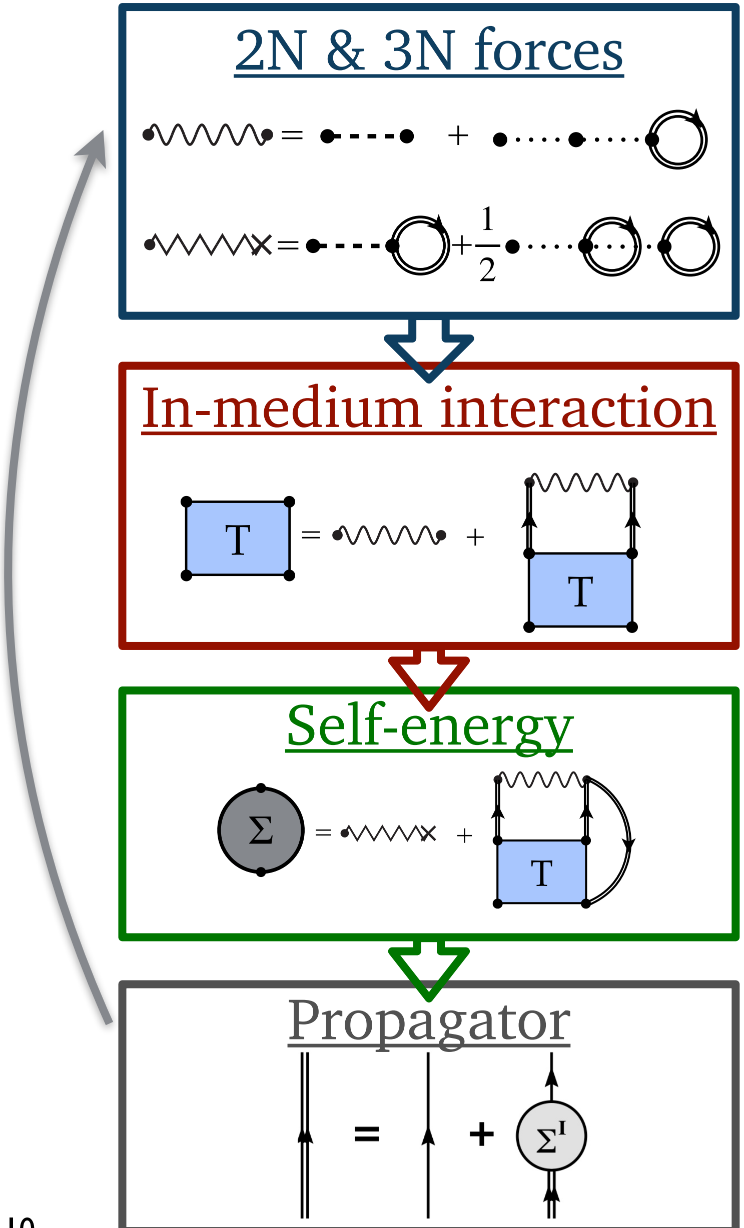
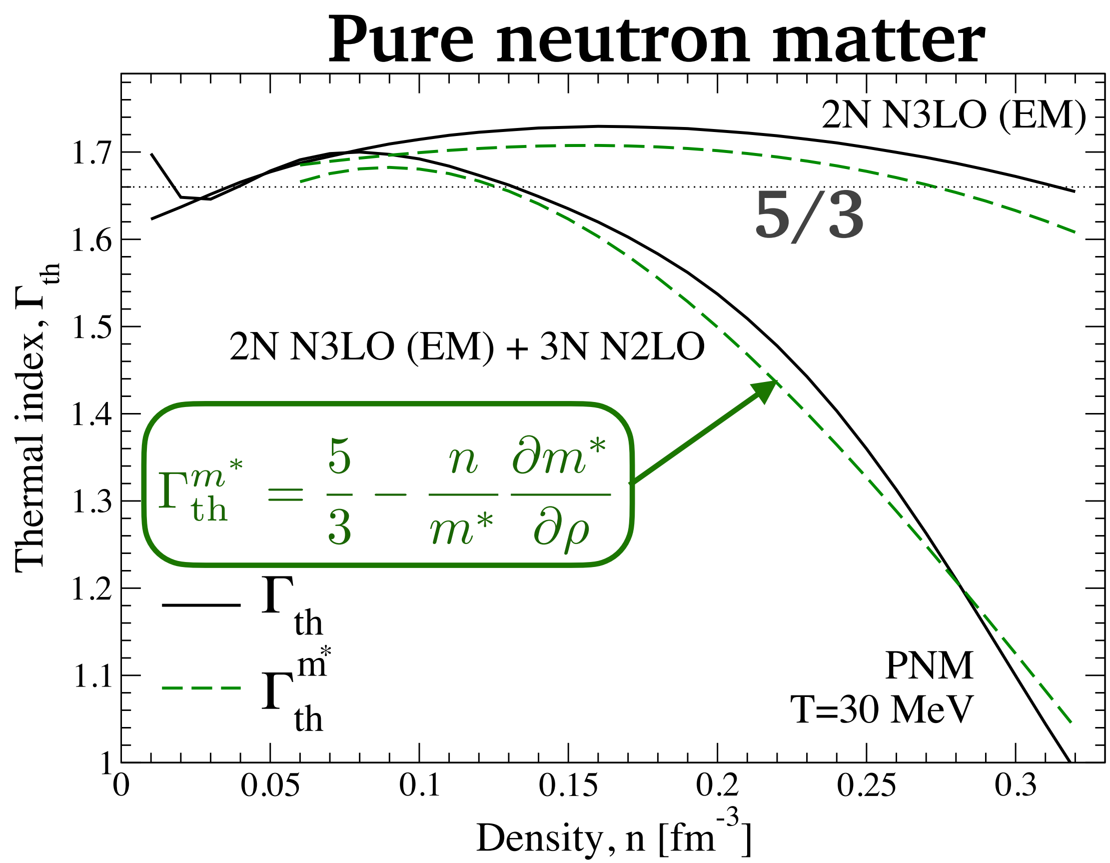




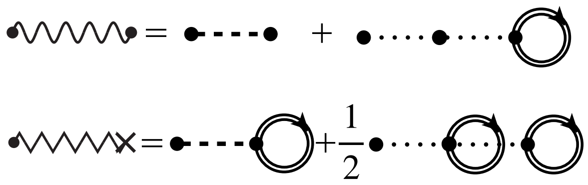
Carbone & Schwenk *Phys Rev C* **100** 025805 (2019)

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

Self-Consistent Green's Functions

(ρ, T) →

2N & 3N forces



Carbone, Rios & Polls PRC **88** 044302 (2013);
PRC **90**, 054322 (2014);
Carbone PhD Thesis

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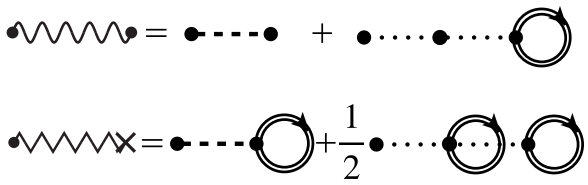
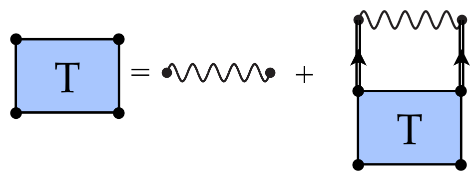


In-medium interaction



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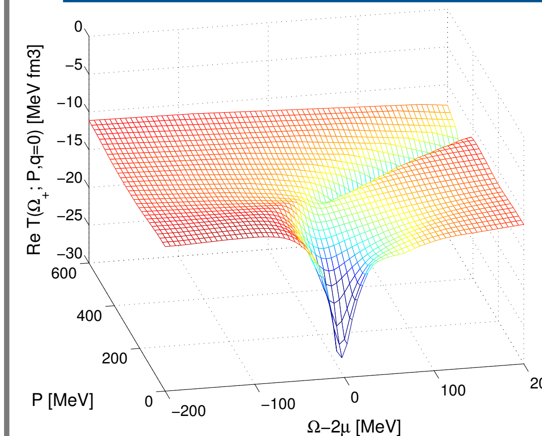
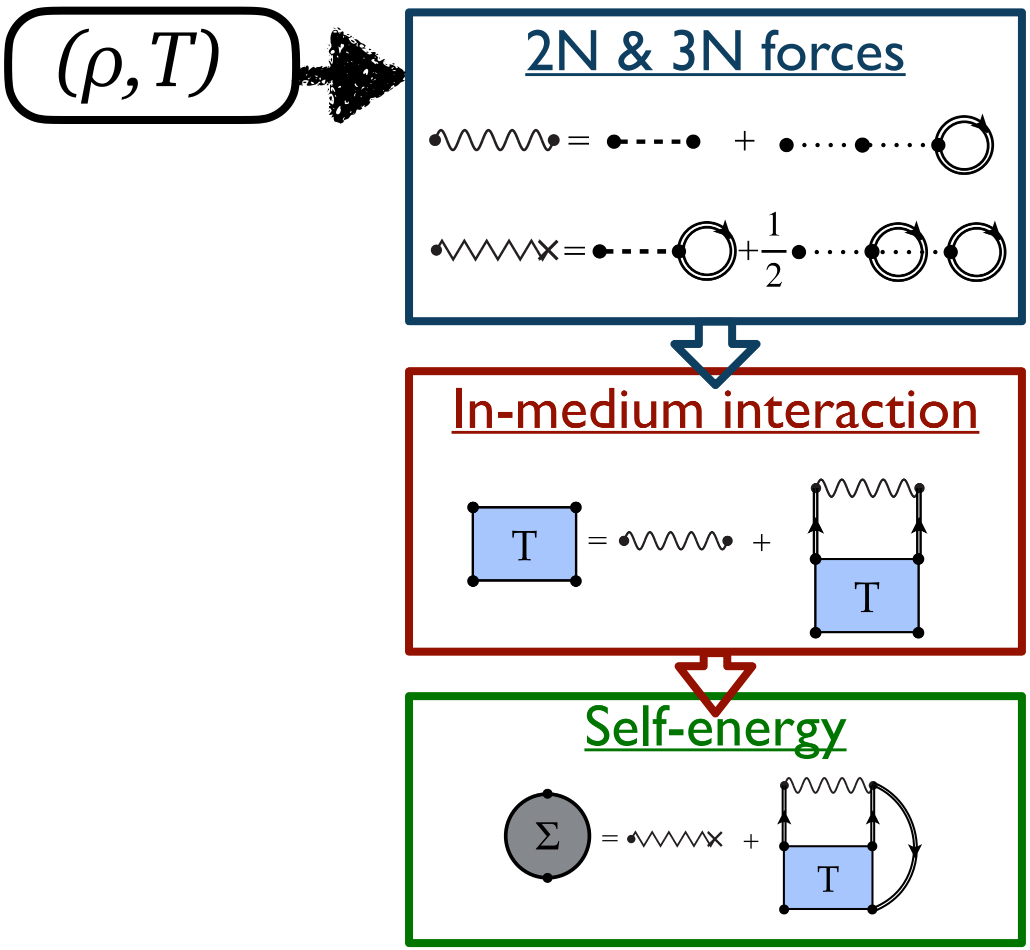
T-matrix at T=5 MeV



Ramos, Polls & Dickhoff, NPA **503** 1 (1989)
Alm *et al.*, PRC **53** 2181 (1996)
Dewulf *et al.*, PRL **90** 152501 (2003)
Frick & Muther, PRC **68** 034310 (2003)
Rios, PhD Thesis, U. Barcelona (2007)
Soma & Bozek, PRC **78** 054003 (2008)
Rios & Soma PRL **108** 012501 (2012)

Self-Consistent Green's Functions



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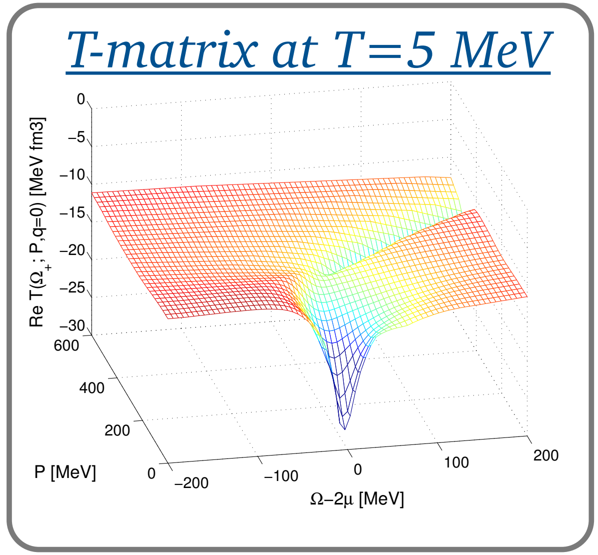

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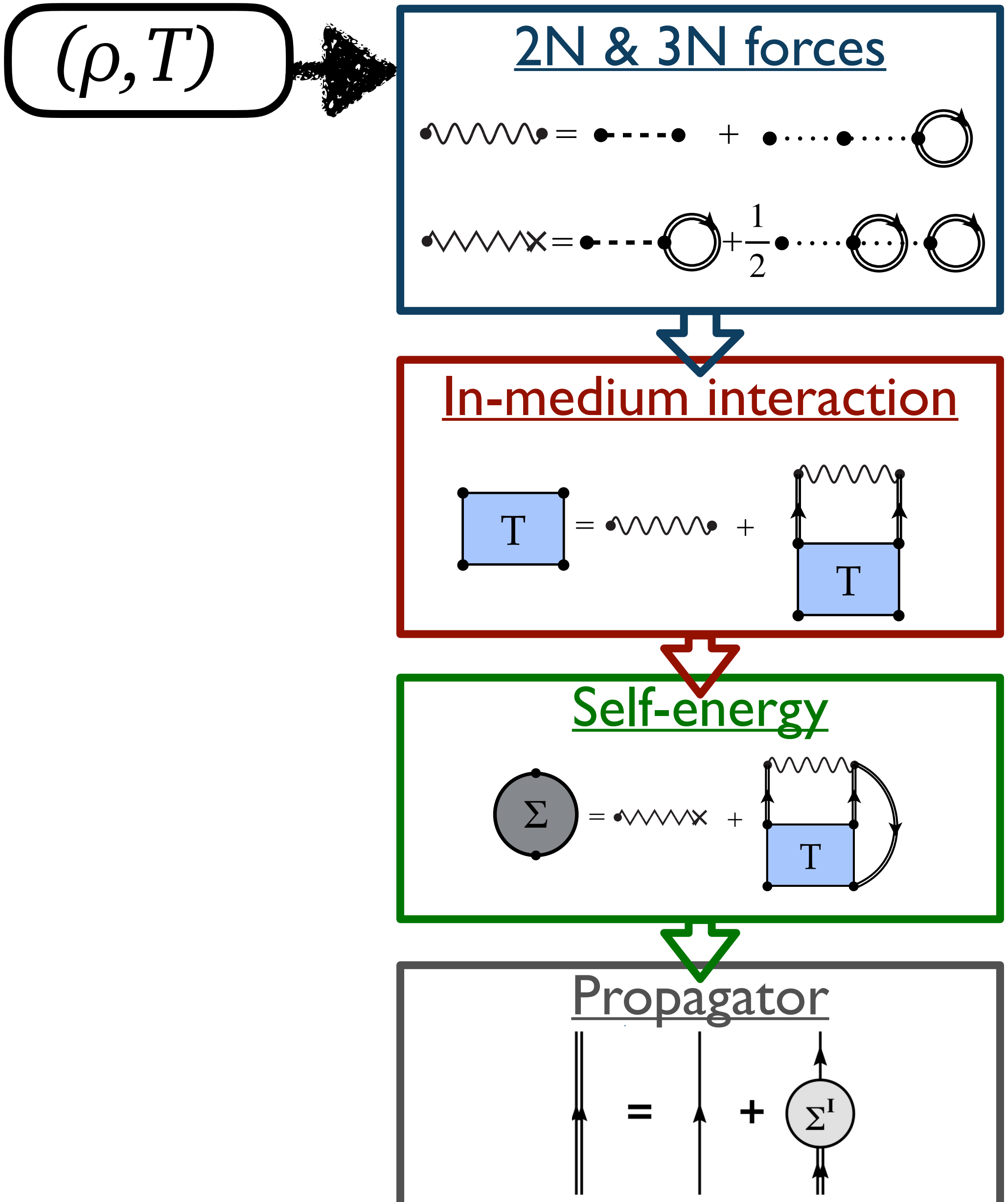
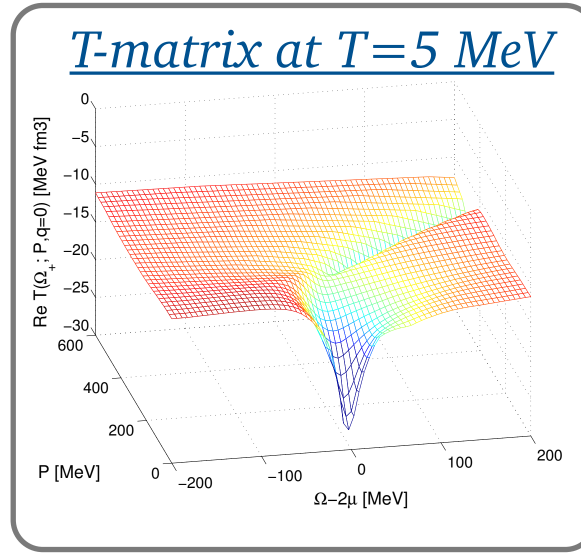
Rios & Soma PRL **108** 012501 (2012)

Self-Consistent Green's Functions

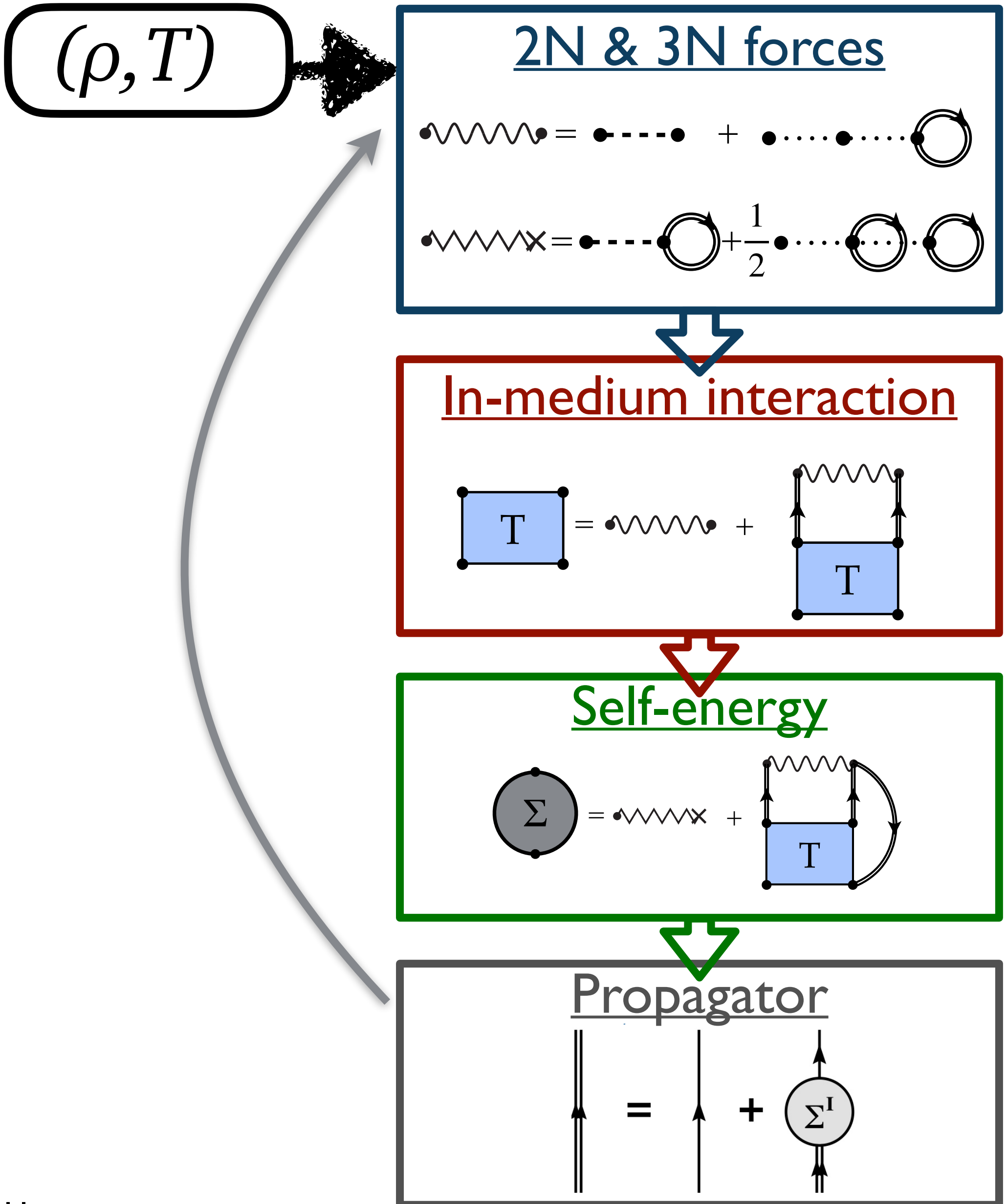


Carbone, Rios & Polls PRC **88** 044302 (2013);
PRC **90**, 054322 (2014);
Carbone PhD Thesis

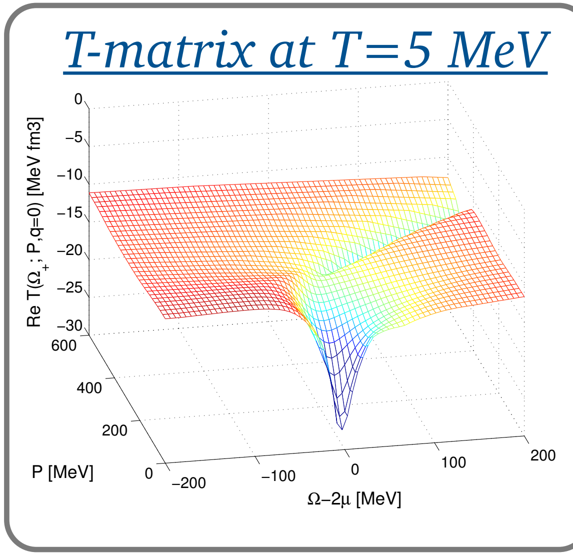


Ramos, Polls & Dickhoff, NPA **503** 1 (1989)
Alm *et al.*, PRC **53** 2181 (1996)
Dewulf *et al.*, PRL **90** 152501 (2003)
Frick & Muther, PRC **68** 034310 (2003)
Rios, PhD Thesis, U. Barcelona (2007)
Soma & Bozek, PRC **78** 054003 (2008)
Rios & Soma PRL **108** 012501 (2012)

Self-Consistent Green's Functions



Carbone, Rios & Polls PRC **88** 044302 (2013);
PRC **90**, 054322 (2014);
Carbone PhD Thesis



Ramos, Polls & Dickhoff, NPA **503** 1 (1989)
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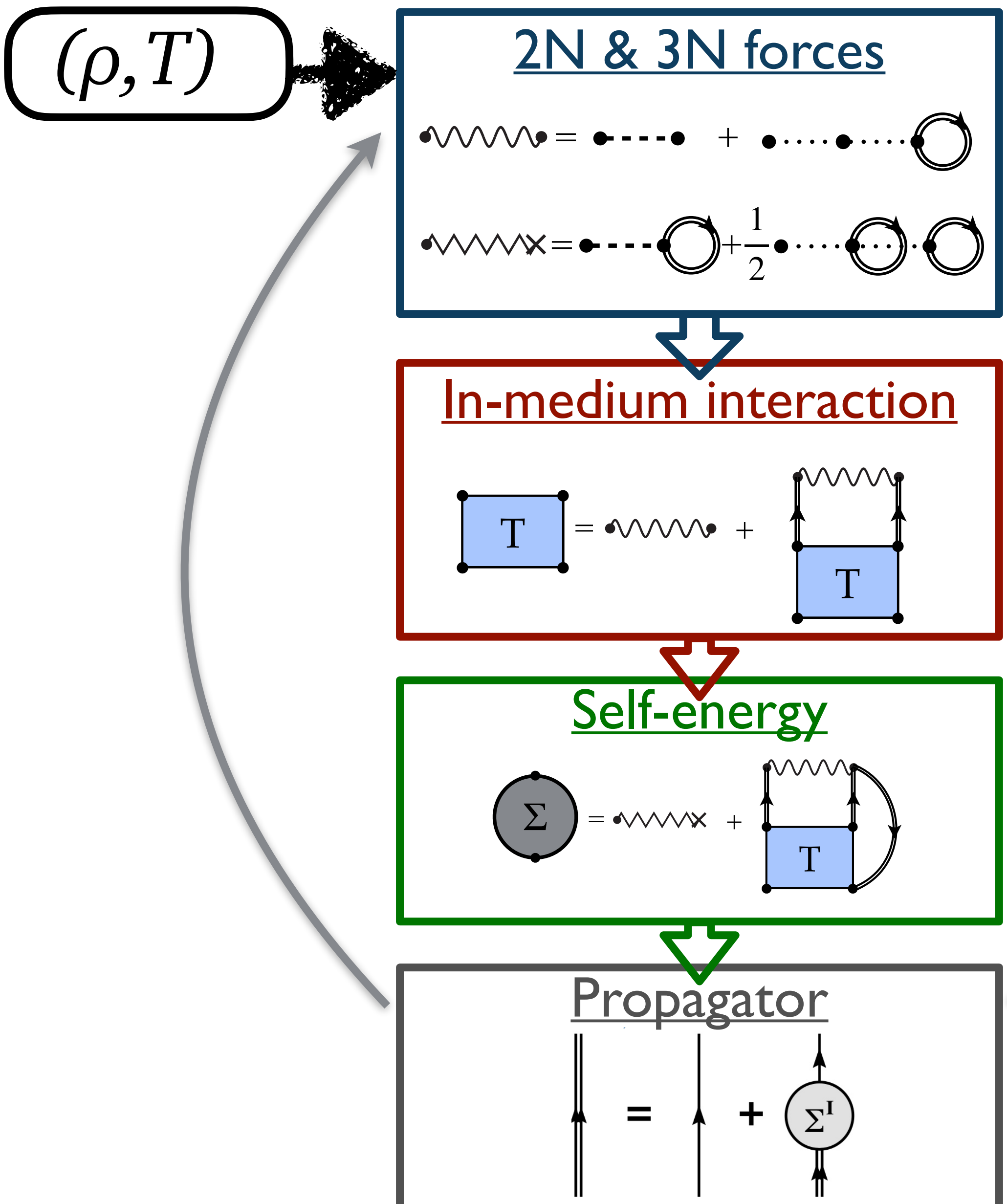
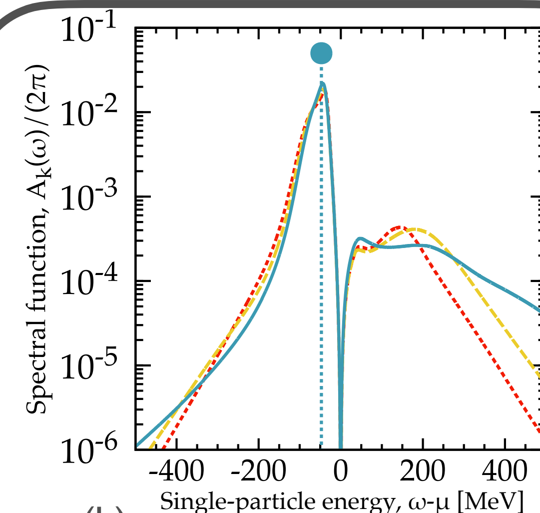
Self-Consistent Green's Functions



Carbone, Rios & Polls PRC **88** 044302 (2013);
PRC **90**, 054322 (2014);
Carbone PhD Thesis



n(k)
Thermodynamics & EoS
Transport

Ramos, Polls & Dickhoff, NPA **503** 1 (1989)
Alm *et al.*, PRC **53** 2181 (1996)
Dewulf *et al.*, PRL **90** 152501 (2003)
Frick & Muther, PRC **68** 034310 (2003)
Rios, PhD Thesis, U. Barcelona (2007)
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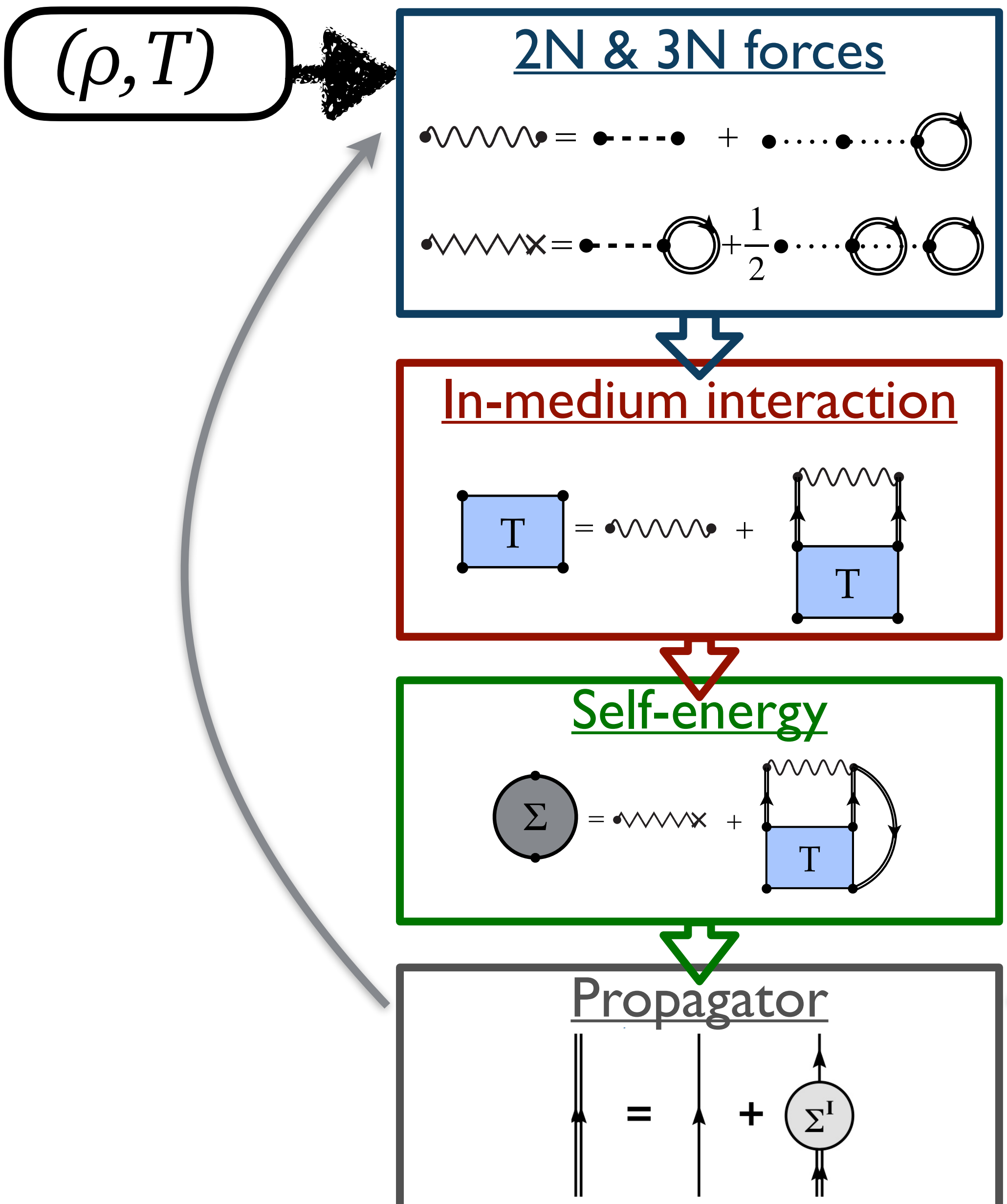
Rios & Soma PRL **108** 012501 (2012)

Self-Consistent Green's Functions



Carbone, Rios & Polls PRC **88** 044302 (2013);
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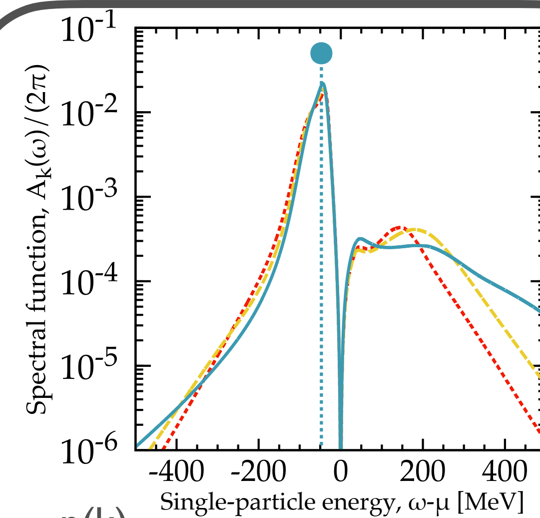
Carbone PhD Thesis

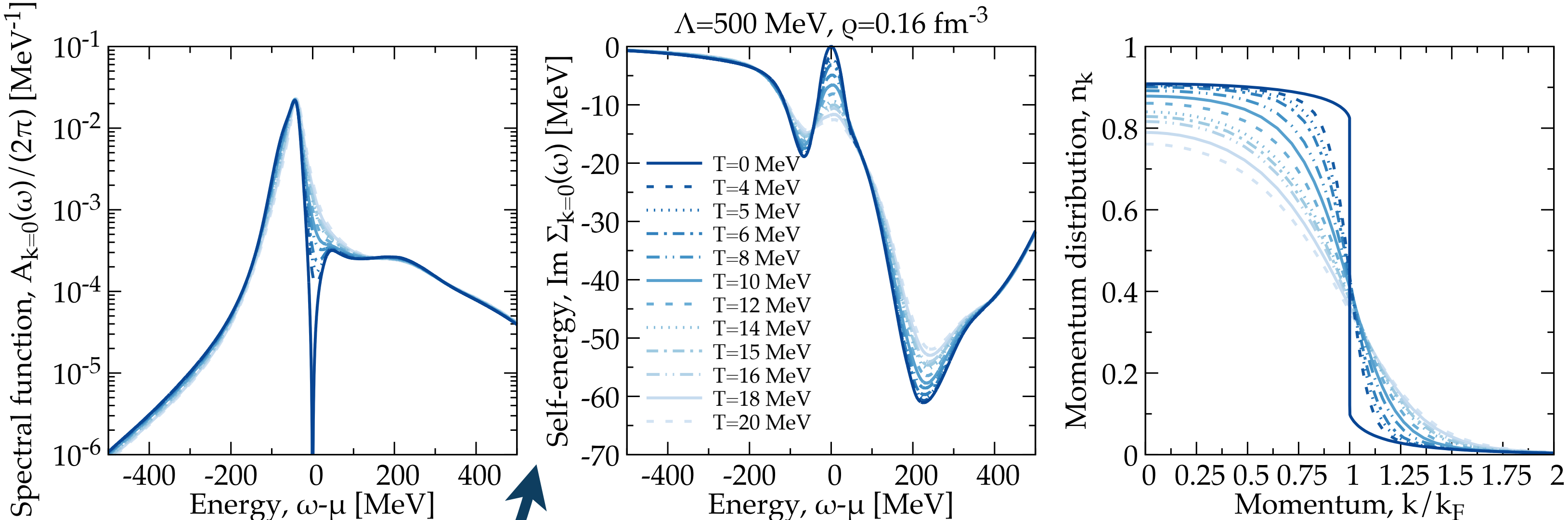


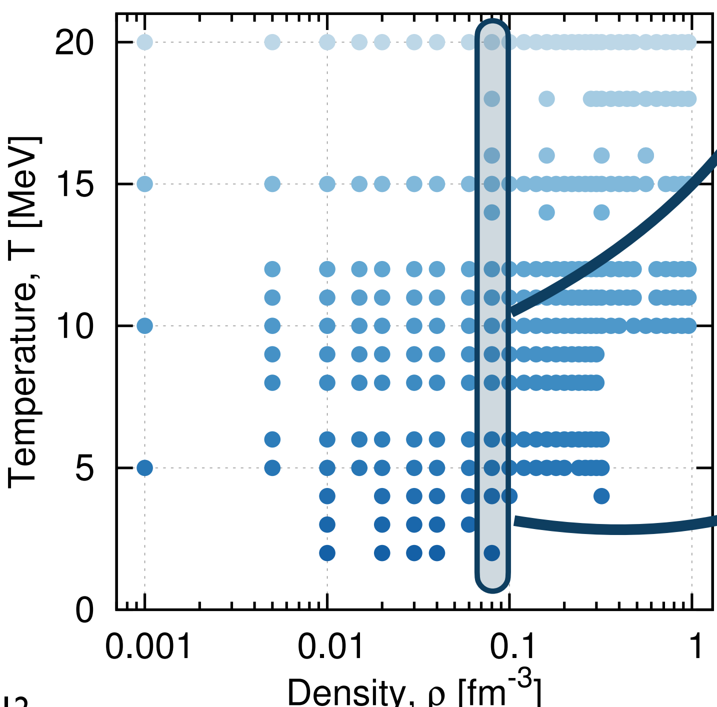
n(k)
Thermodynamics & EoS
Transport

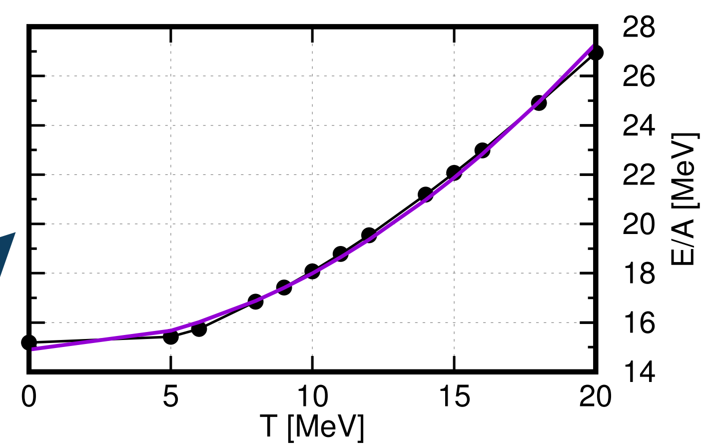
- Off-shell ✔
- Matsubara formalism ✔
- Φ-derivable ✔

Ramos, Polls & Dickhoff, NPA **503** 1 (1989)
Alm *et al.*, PRC **53** 2181 (1996)
Dewulf *et al.*, PRL **90** 152501 (2003)
Frick & Muther, PRC **68** 034310 (2003)
Rios, PhD Thesis, U. Barcelona (2007)
Soma & Bozek, PRC **78** 054003 (2008)
Rios & Soma PRL **108** 012501 (2012)

Zero temperature extrapolation

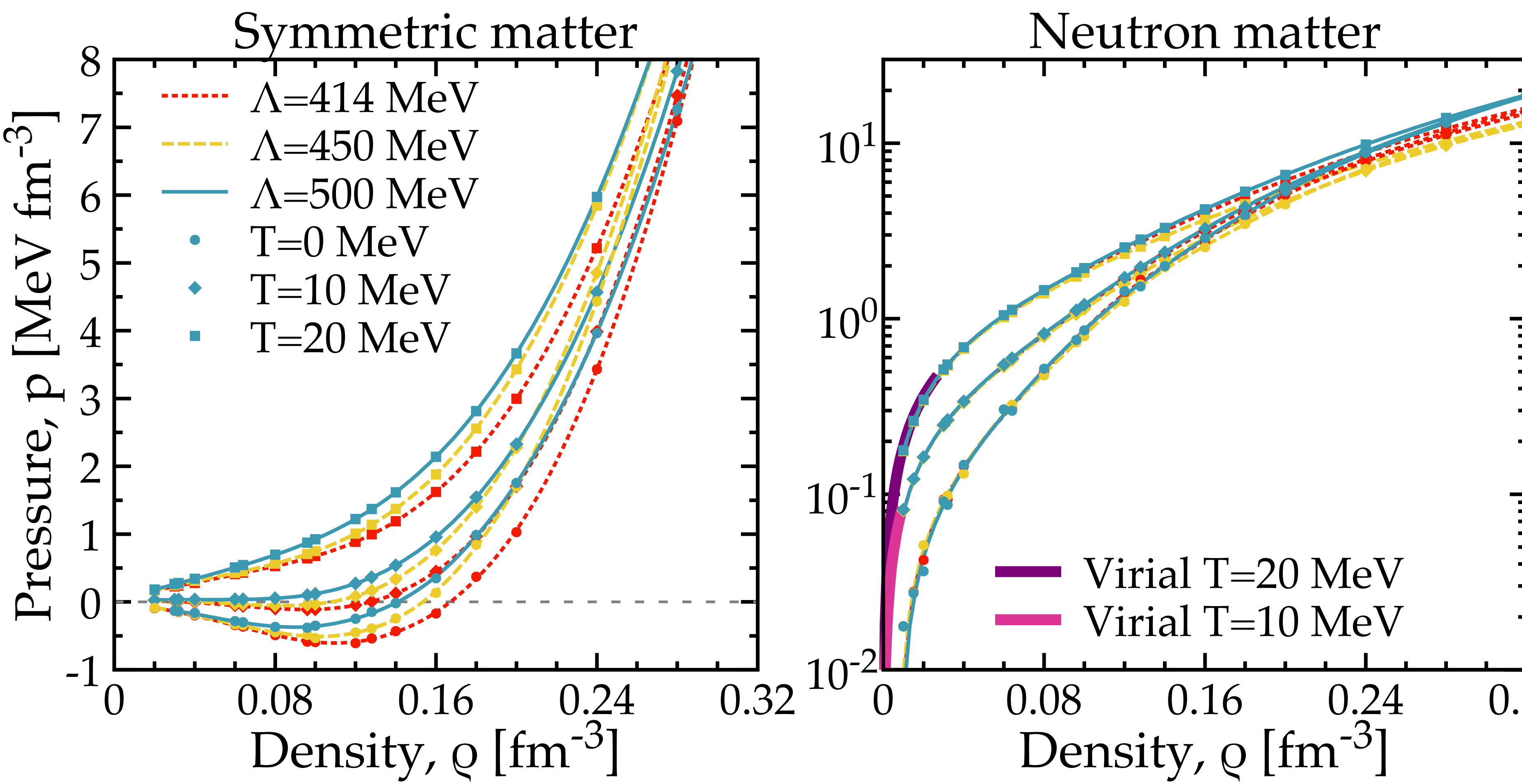






Ding, Rios, et al Phys. Rev. C 94, 025802 (2016) [arXiv:1601.01600]

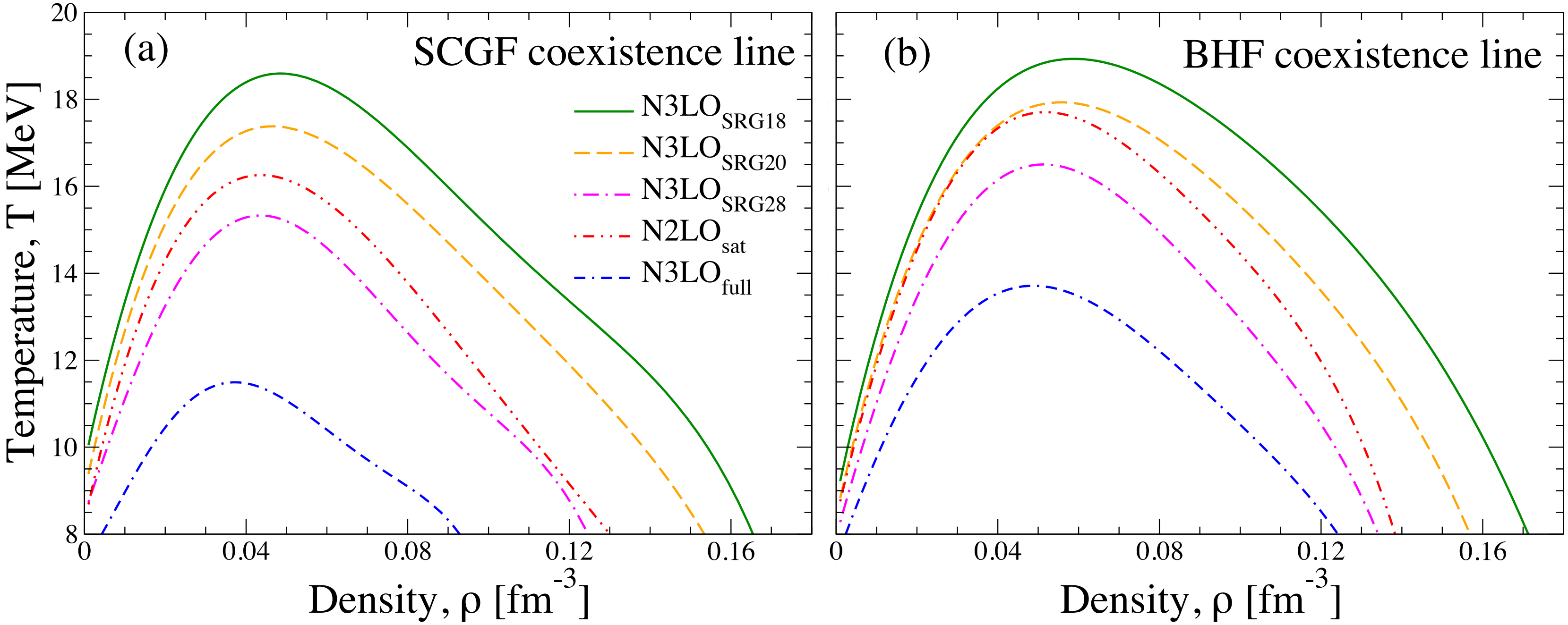
EoS at finite temperature

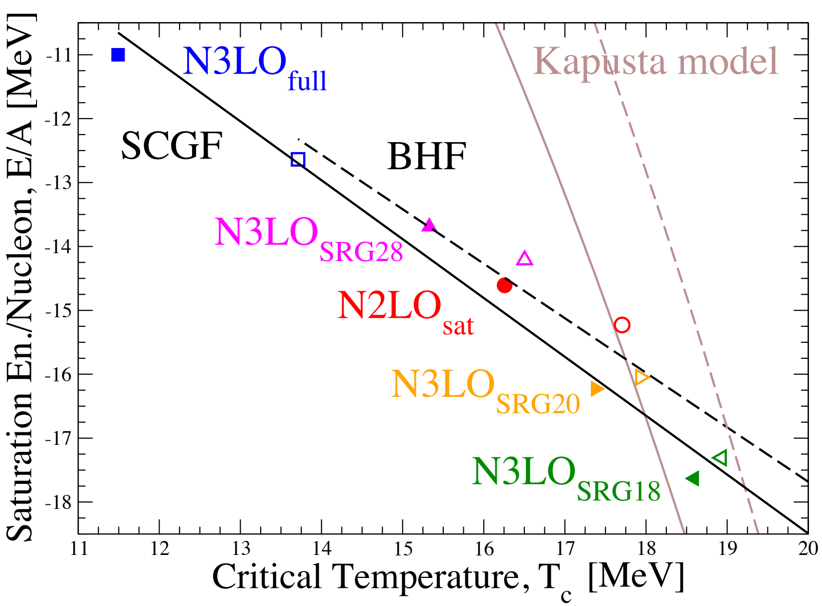


- From a finite set of points to functions?

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

Liquid-gas phase transition



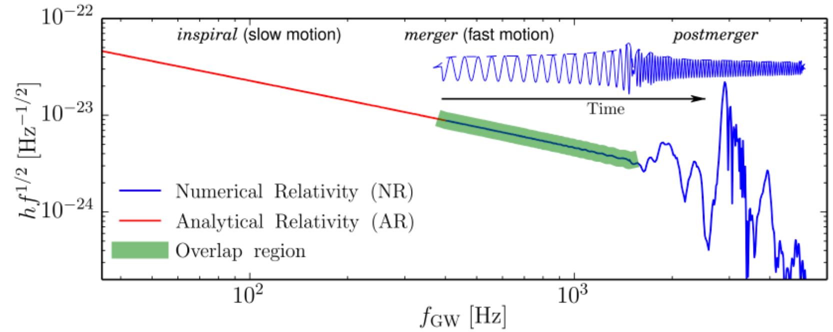


SCGF	ρ_c (fm^{-3})	T_c (MeV)	ρ_0 (fm^{-3})	$\frac{E_0}{A}$ (MeV)	$\frac{m_0^*}{m}$
N3LO$_{SRG18}$	0.048	18.6	0.19	−17.6	0.83
N3LO$_{SRG20}$	0.047	17.4	0.19	−16.2	0.84
N3LO$_{SRG28}$	0.043	15.3	0.16	−13.7	0.88
N2LO$_{sat}$	0.043	16.3	0.15	−14.6	0.90
N3LO$_{full}$	0.038	11.5	0.14	−11.0	0.84
BHF	ρ_c (fm^{-3})	T_c (MeV)	ρ_0 (fm^{-3})	$\frac{E_0}{A}$ (MeV)	$\frac{m_0^*}{m}$
N3LO$_{SRG18}$	0.058	18.9	0.19	−17.3	0.70
N3LO$_{SRG20}$	0.056	17.9	0.18	−16.0	0.73
N3LO$_{SRG28}$	0.051	16.5	0.16	−14.2	0.79
N2LO$_{sat}$	0.051	17.7	0.16	−15.2	0.82
N3LO$_{full}$	0.048	13.7	0.16	−12.6	0.76

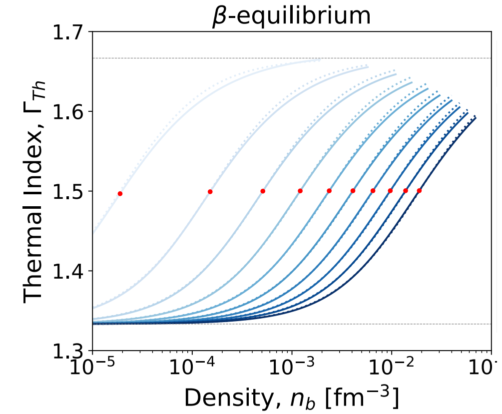
Carbone, Polls & Rios, Phys Rev C **98** 025804 (2018)

Outline

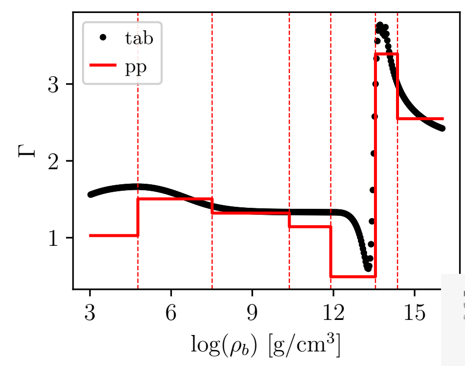
- Motivation



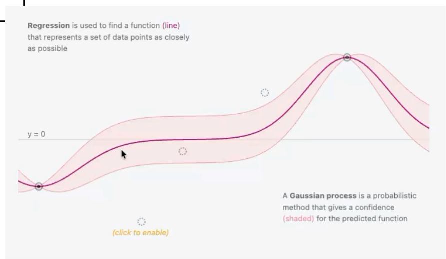
- **Virial approximation**



- Thermal effects in BNS

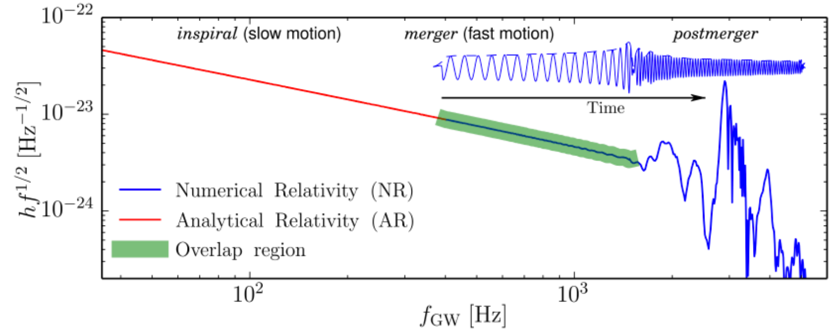


- Gaussian processes for finite T

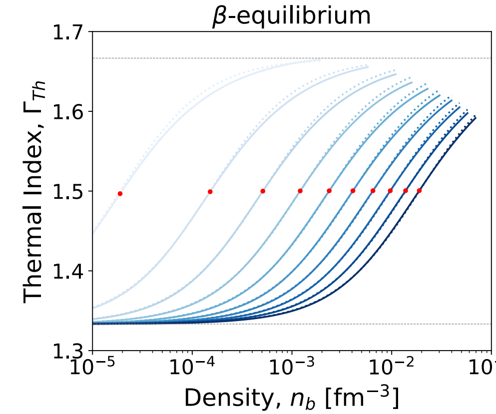


Outline

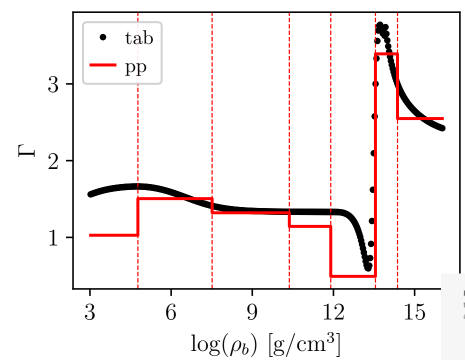
- Motivation



- **Virial approximation**



- Thermal effects in BNS



- Gaussian processes for finite T

Virial expansion

Expansion

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

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

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

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

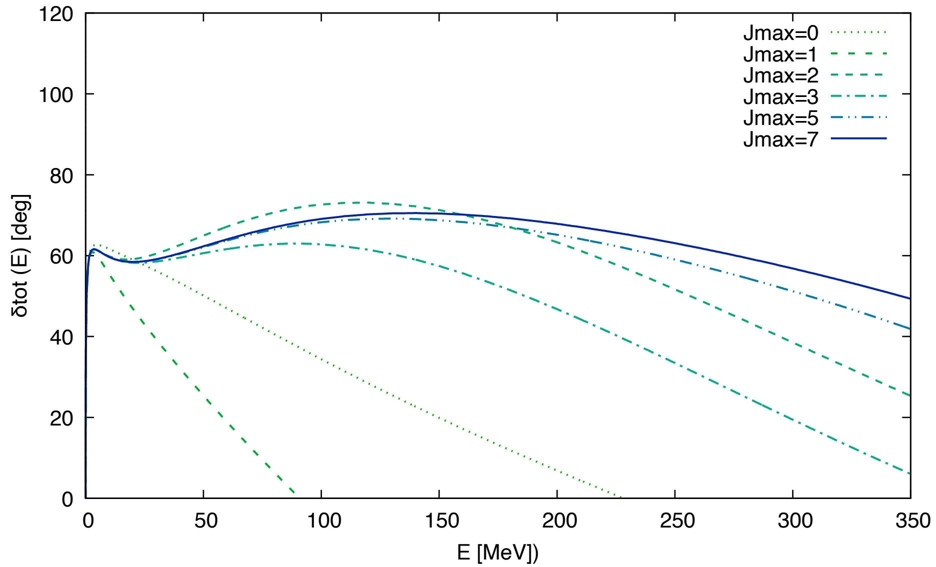
- Systematic expansion
- Improvable order-by-order

Virial coefficients

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

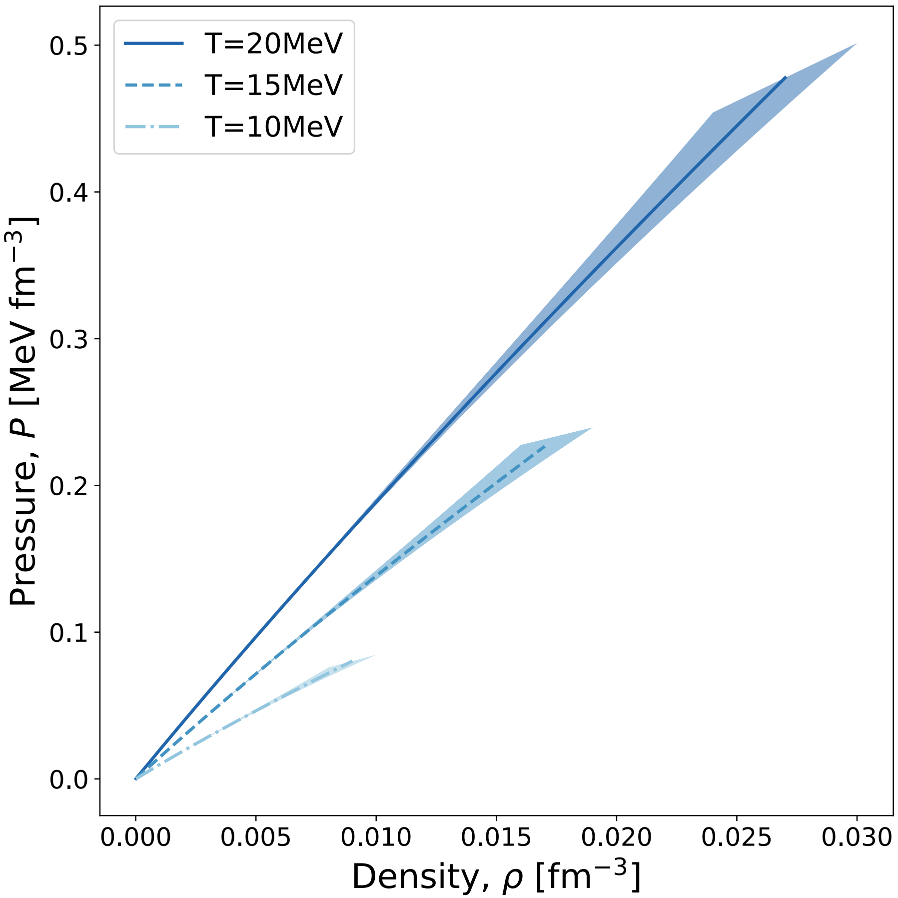
$$b_3(T) = ?$$

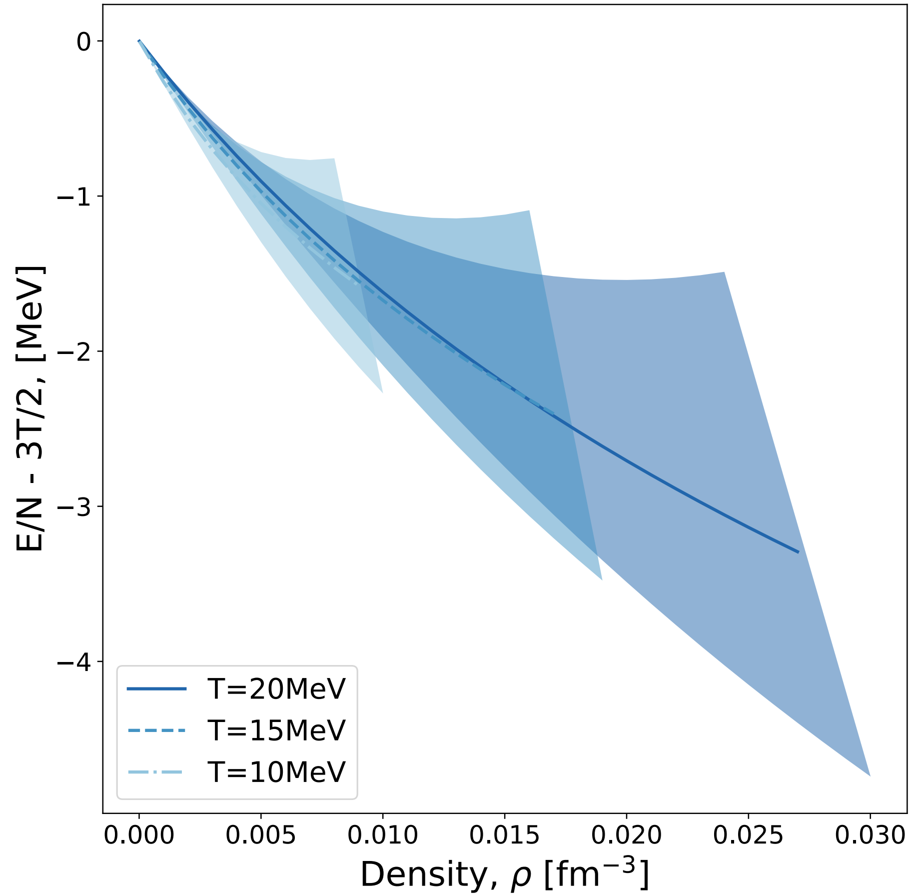
Drut *et al.* Unitary gas



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

Virial expansion: pure neutron matter





Horowitz & Schwenk, *Phys. Lett. B* **638** 153159 (2006); *Nuc. Phys. A* **776** 055079 (2006)
Rivieccio, Nadal-Matosas, Rios & Ruiz, ApJ 987, 67 (2025)

- Use $\pm b_3 = 3^{-5/2} - 0.5 b_2$ for uncertainty
- Truncate at $z = 0.3$
- Granada phase-shifts for calculations

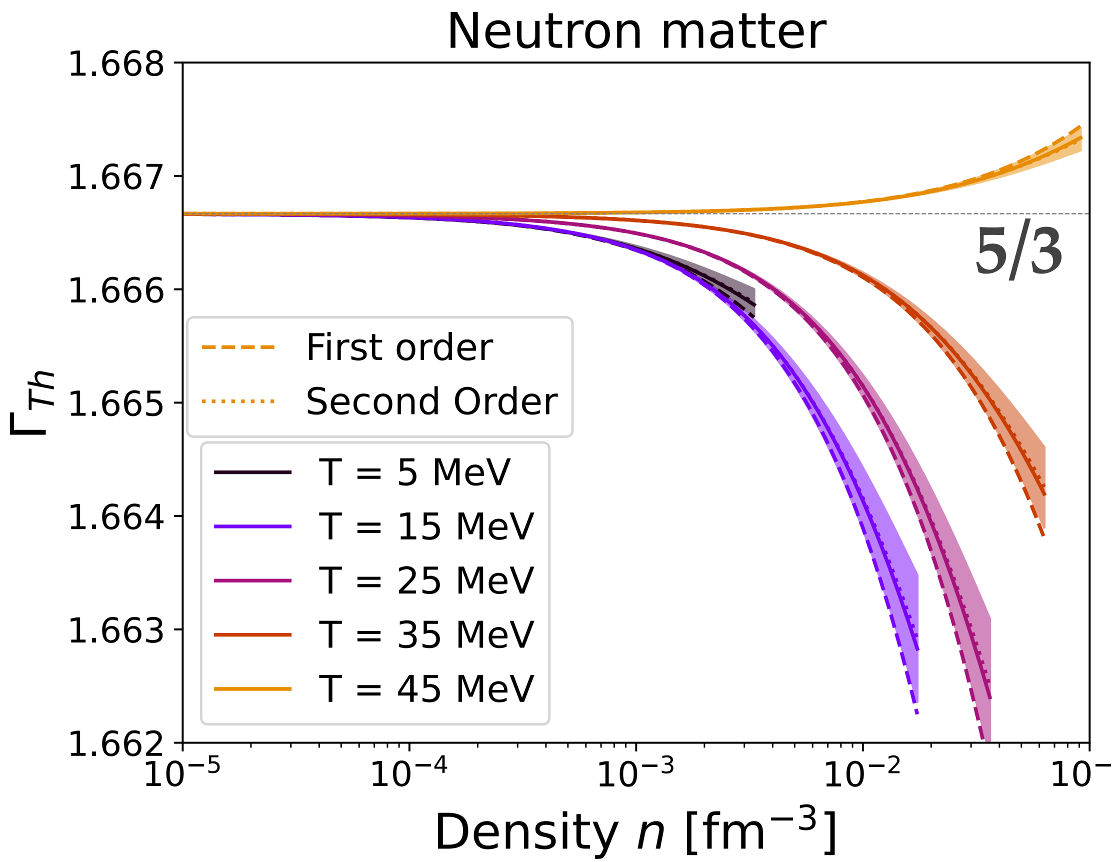
Thermal index: pure neutron matter

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

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

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

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



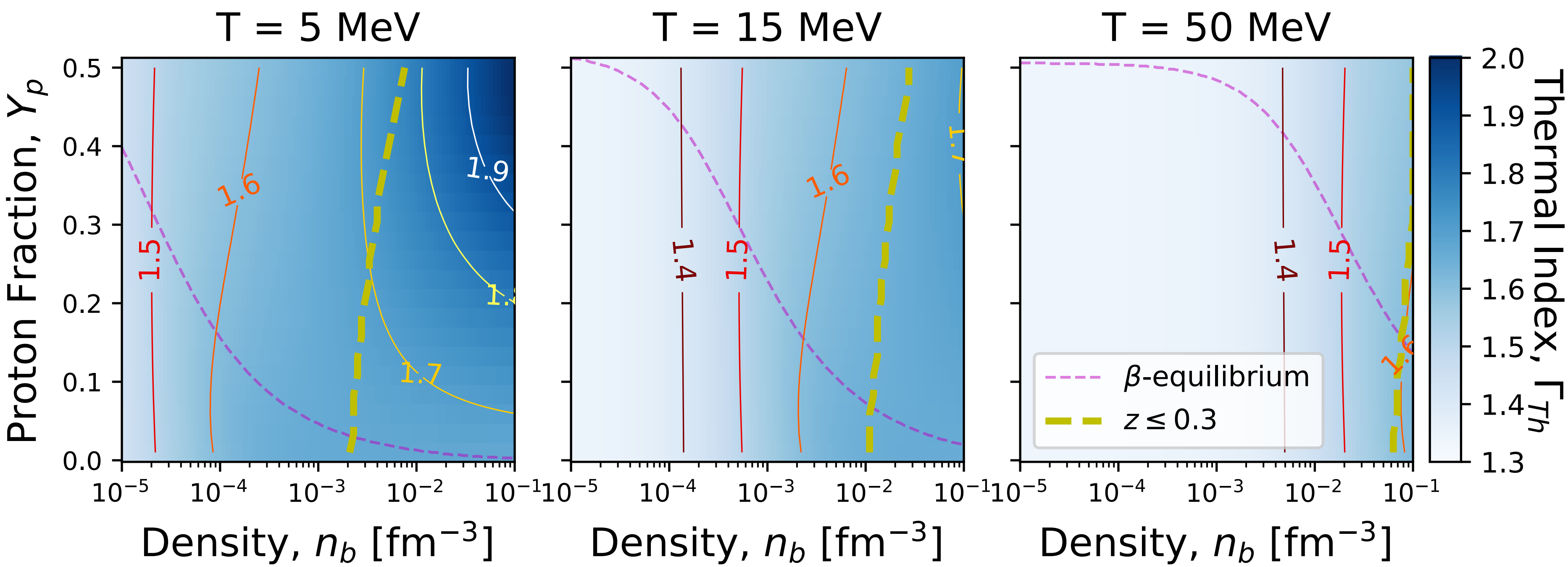
G Rivieccio @ UV

- **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

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

β equilibrium

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

Leptons & photons ultrarelativistic

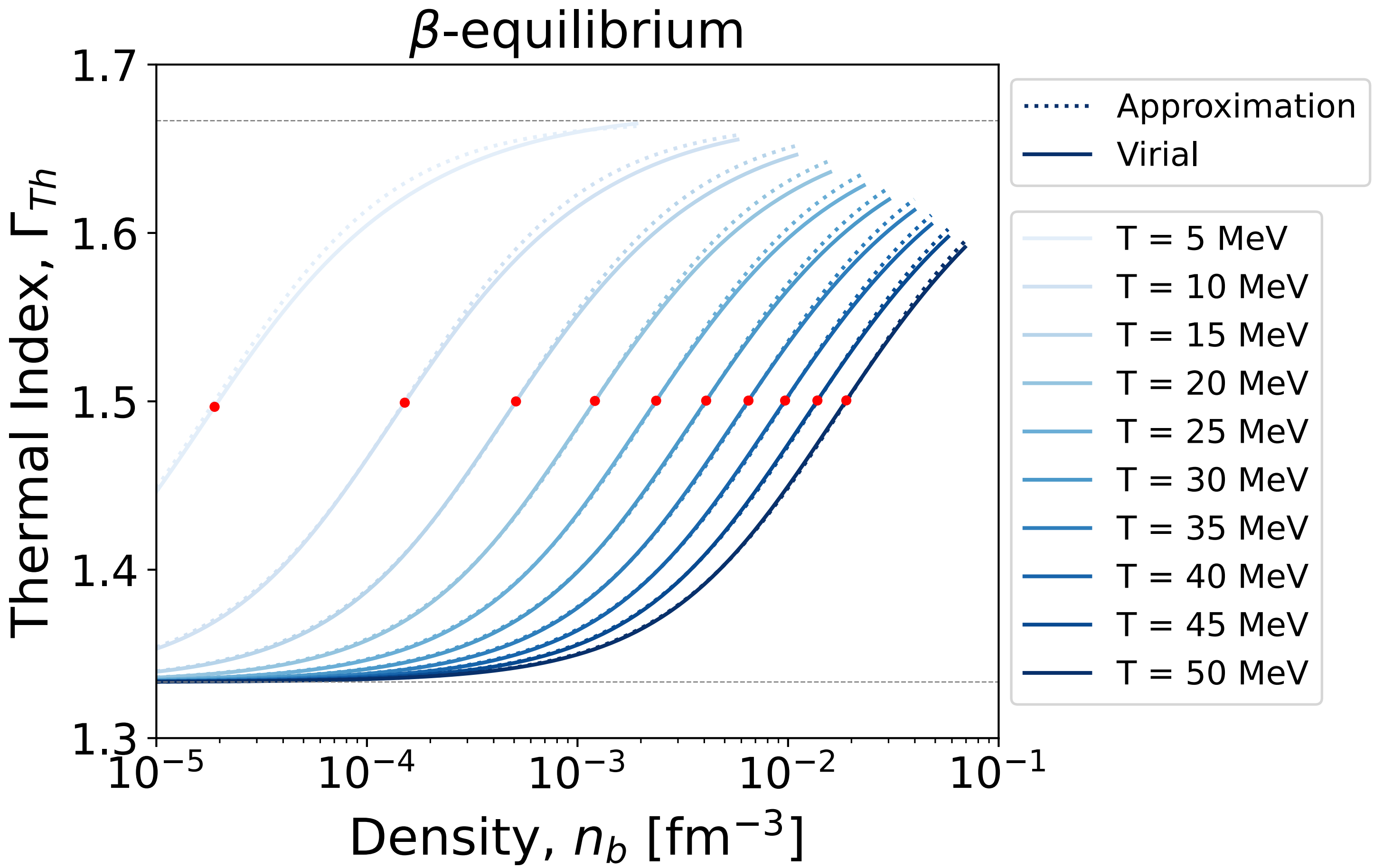
$$\Gamma_{\rm th} = \frac{4}{3}$$

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)

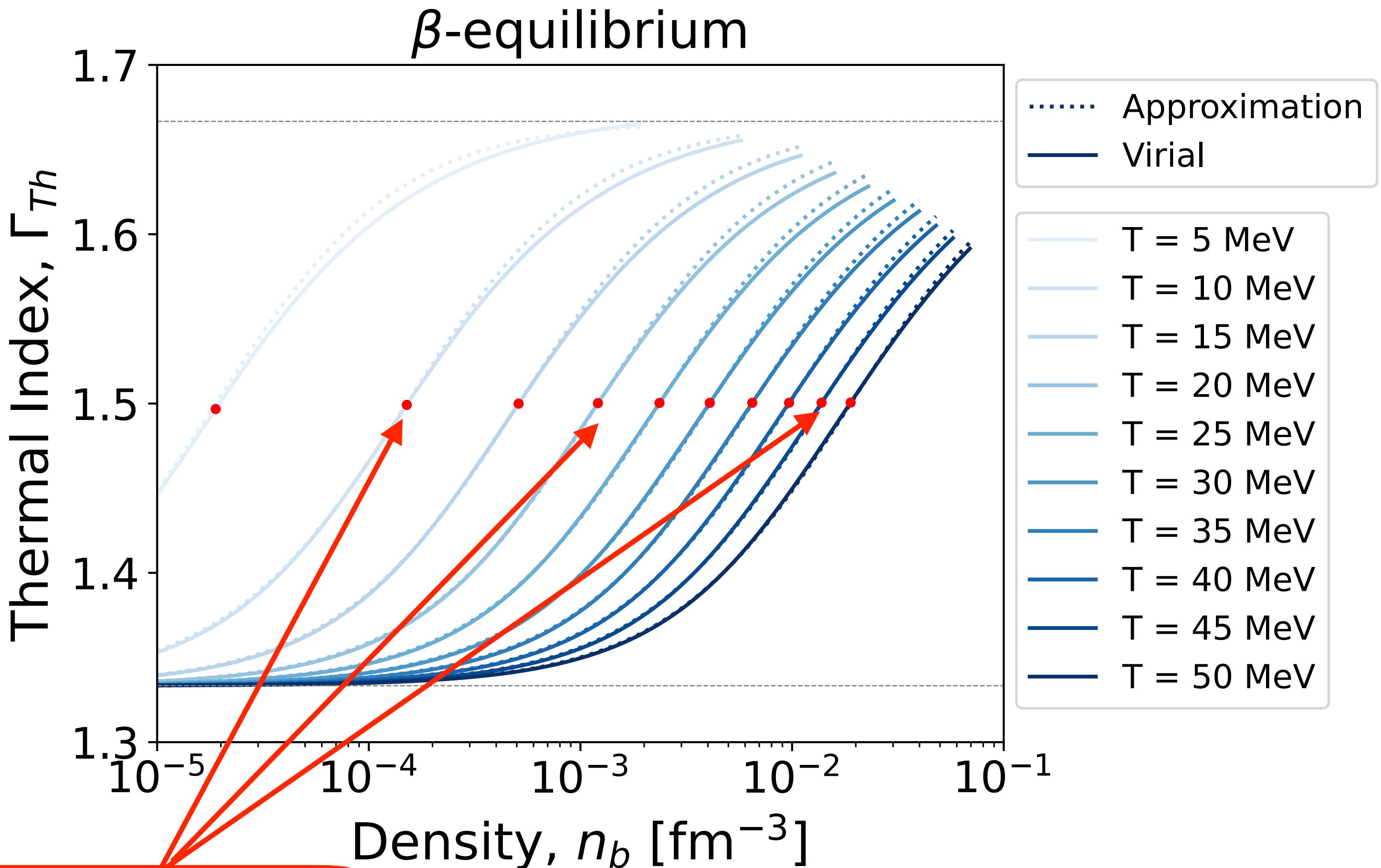
Thermal index: parametrization



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

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

Thermal index: parametrization



Regime change

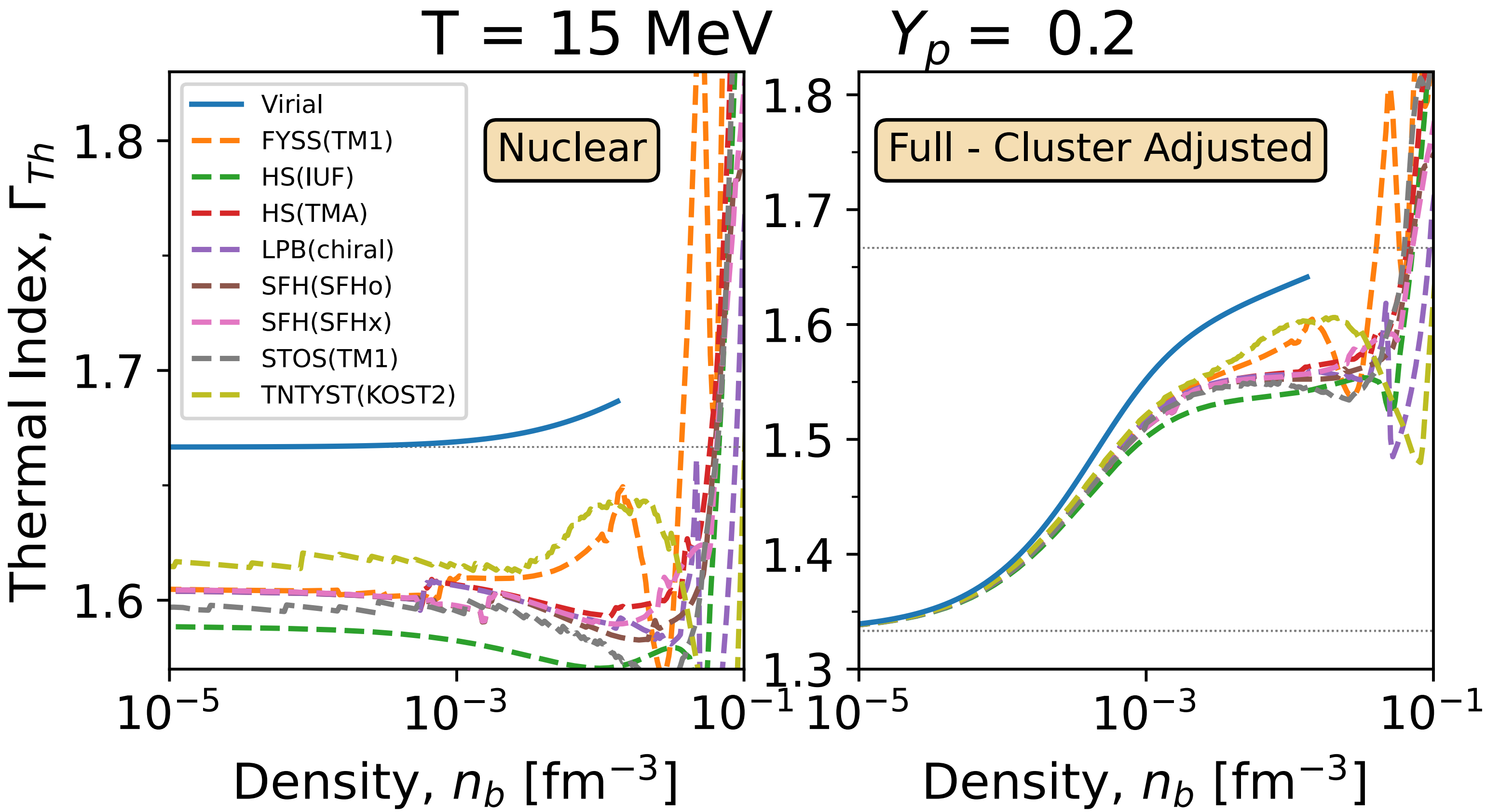
$$P_{\rm th}^{\rm nuc} \approx P_{\rm th}^{\rm lep}$$

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

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

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

Full tabulated comparison



Tabulated

ρ	T	ε	P	Γ_{th}

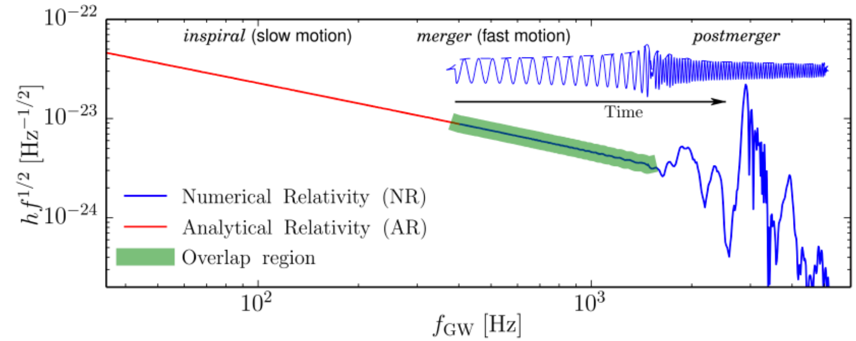
- **Clusters** are nuclear-only contributions
- Irrelevant at T>15 MeV

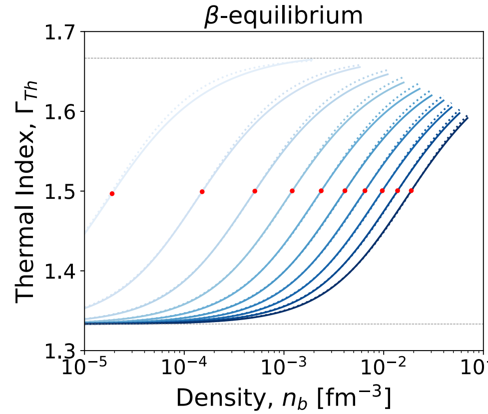
https://github.com/Gpeppee/Virial-EOS.git

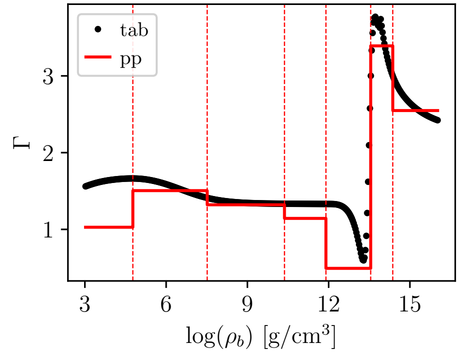
Rivieccio, Nadal-Matosas, Rios & Ruiz, *ApJ* **987**, 67 (2025)

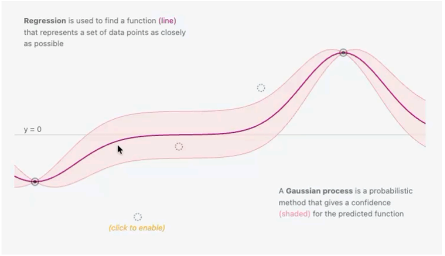
Outline

- Motivation
- Virial approximation
- <u>Thermal effects in BNS</u>
- Gaussian processes for finite T



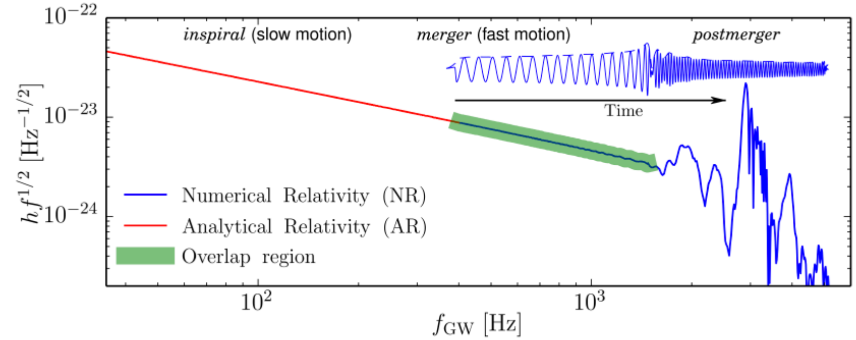




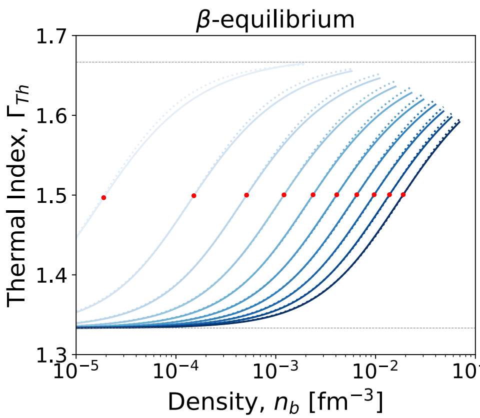


Outline

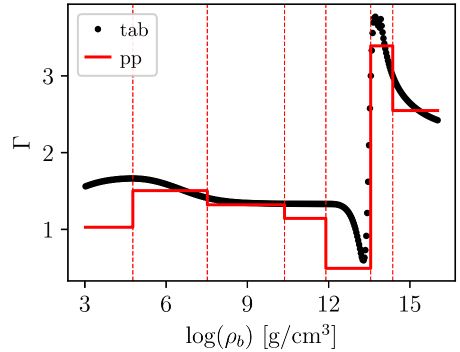
- Motivation



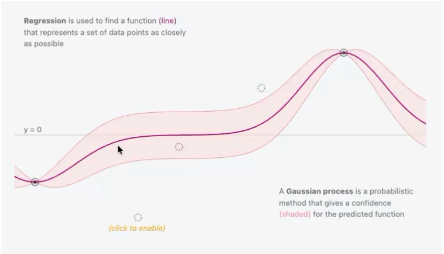
- Virial approximation



- <u>Thermal effects in BNS</u>



- Gaussian processes for finite T



Thermal effects

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

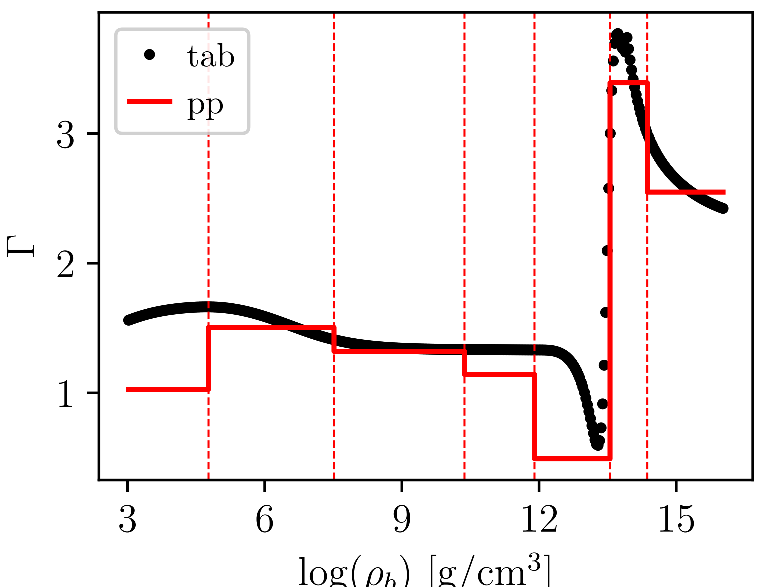
Davide Guerra,[1,*] Milton Ruiz,[1] Michele Pasquali,[2] Pablo Cerdá-Durán,[1,3] Arnau Rios,[4,5] and José A. Font[1,3]

[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

$$Q_{th}(\rho, T) = K_{th}\rho^{\Gamma_{th}}$$

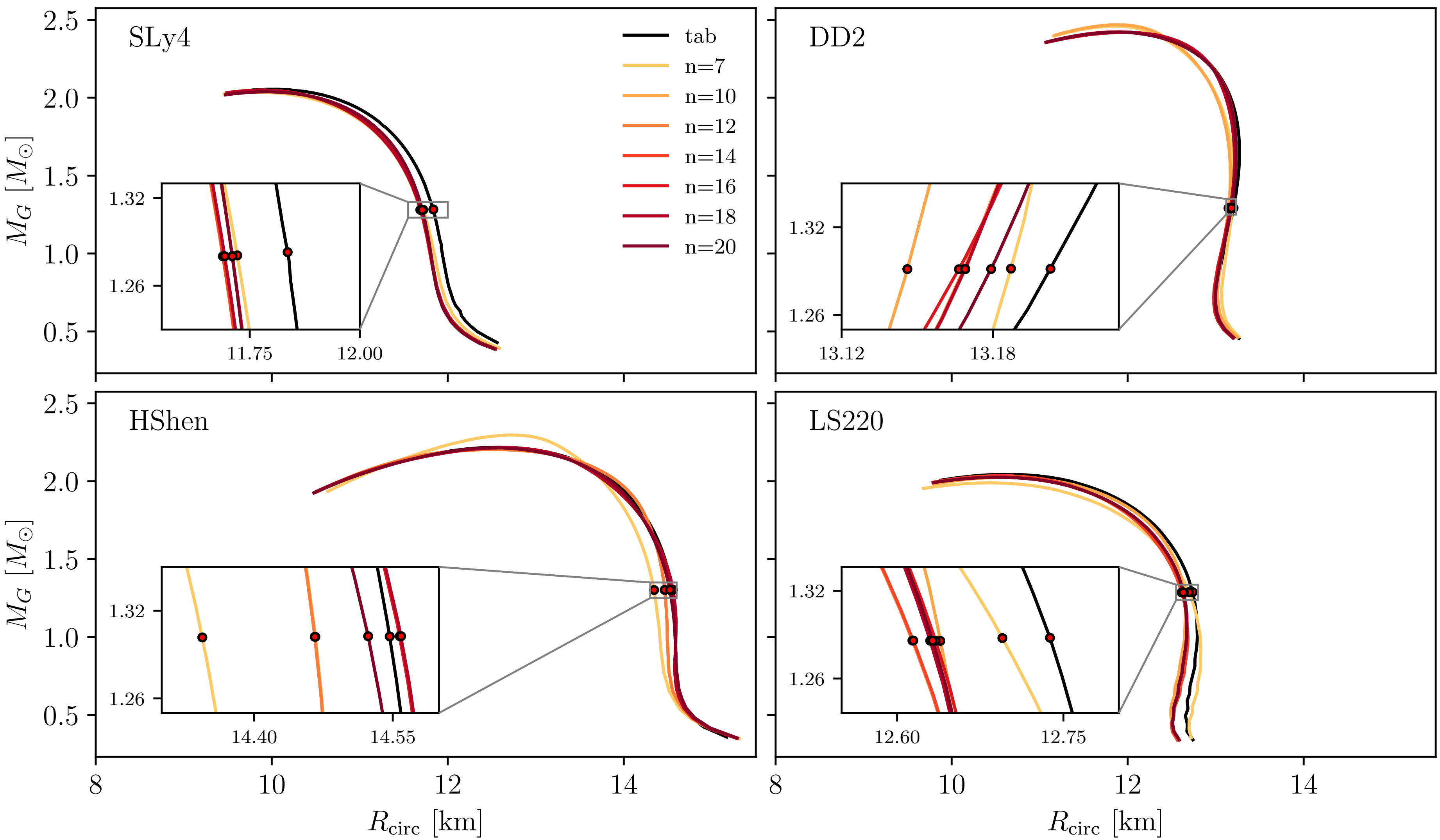


Tabulated

ρ	T	ε	P	Γ_{th}

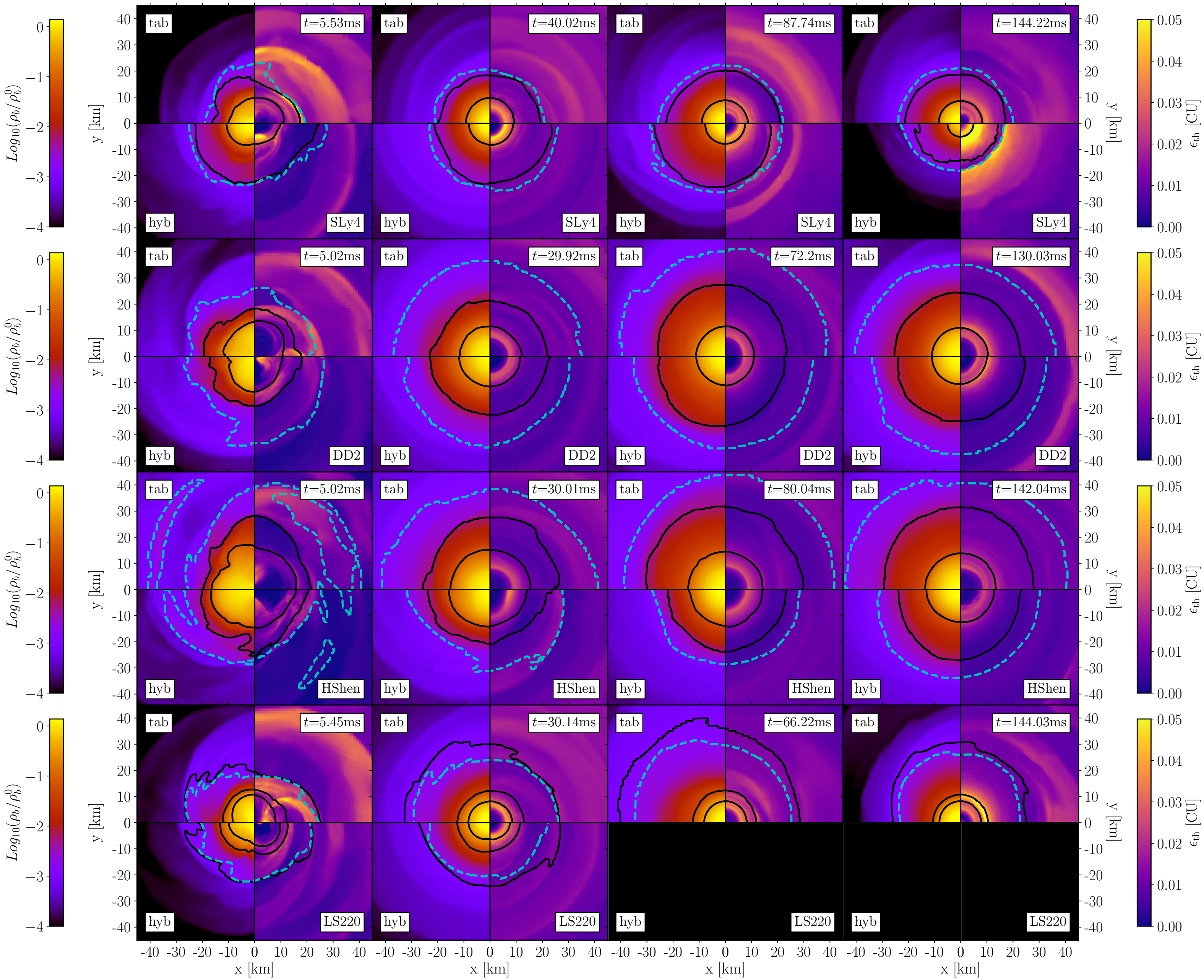
Davide Guerra, *et al.* arxiv:2512.05118

Piecewise T=0 results



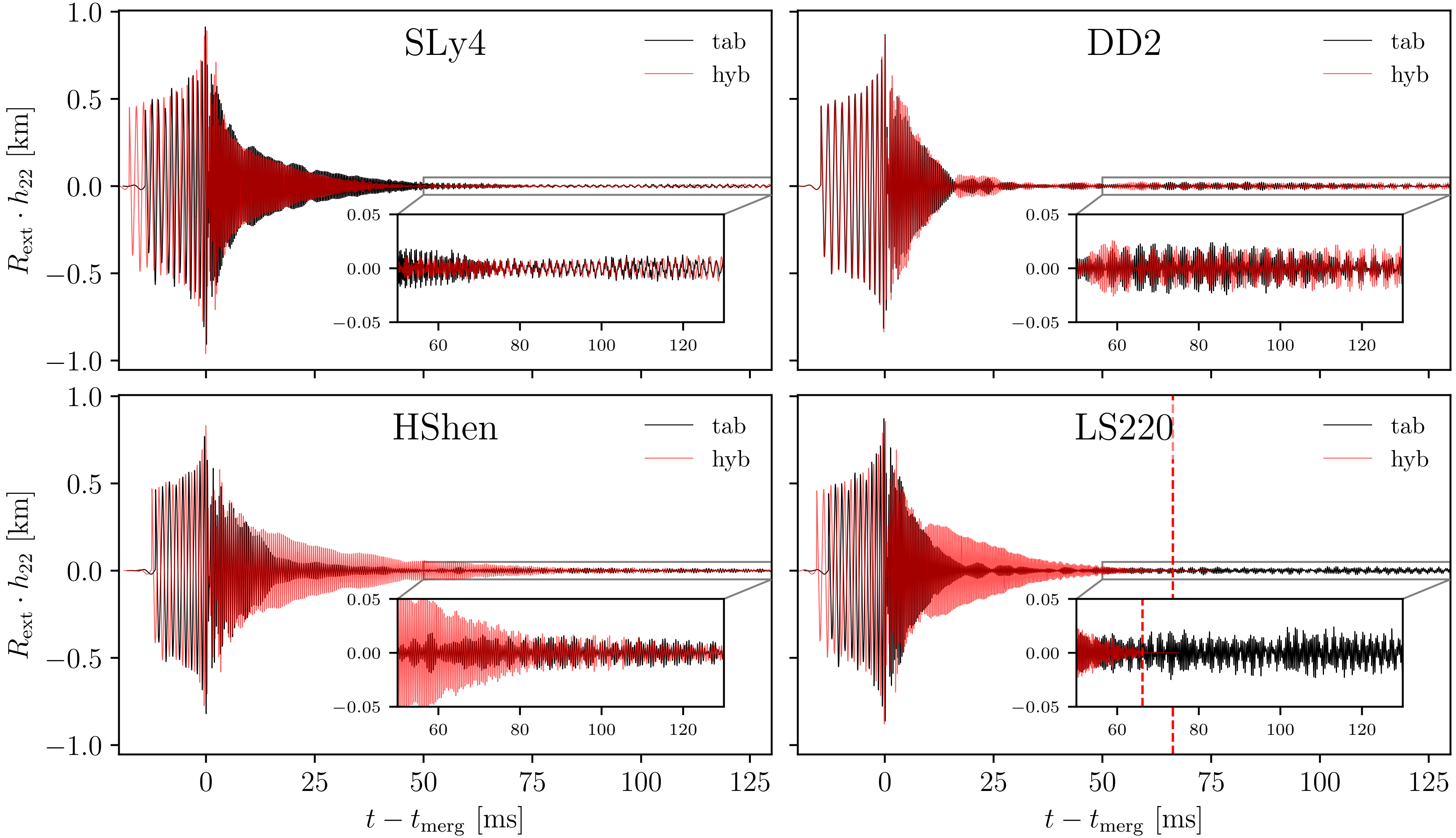
Davide Guerra, *et al.* arxiv:2512.05118

Density and temperature



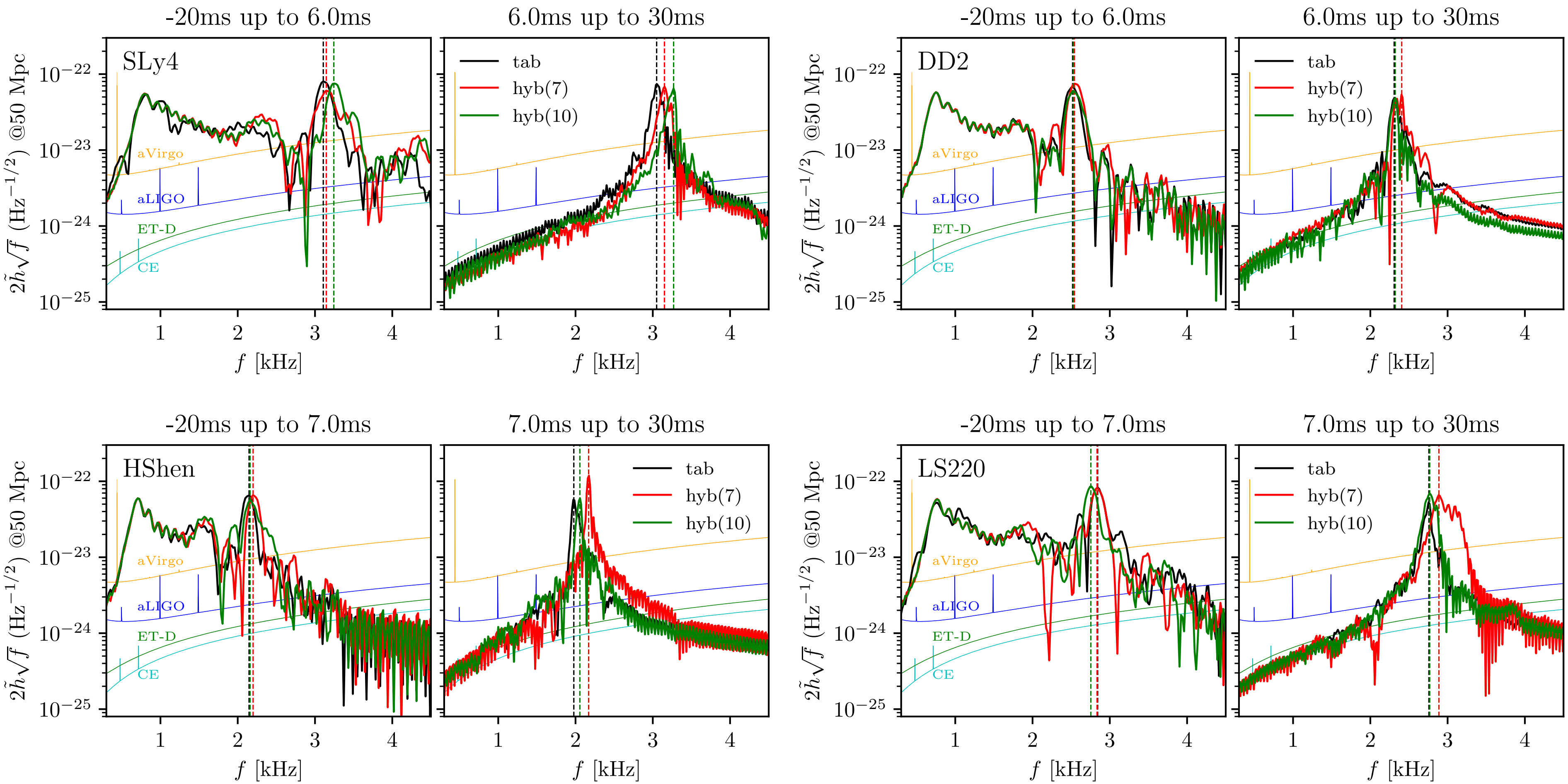
Davide Guerra, et *al.* arxiv:2512.05118

GW emission: late times



Davide Guerra, *et al.* arxiv:2512.05118

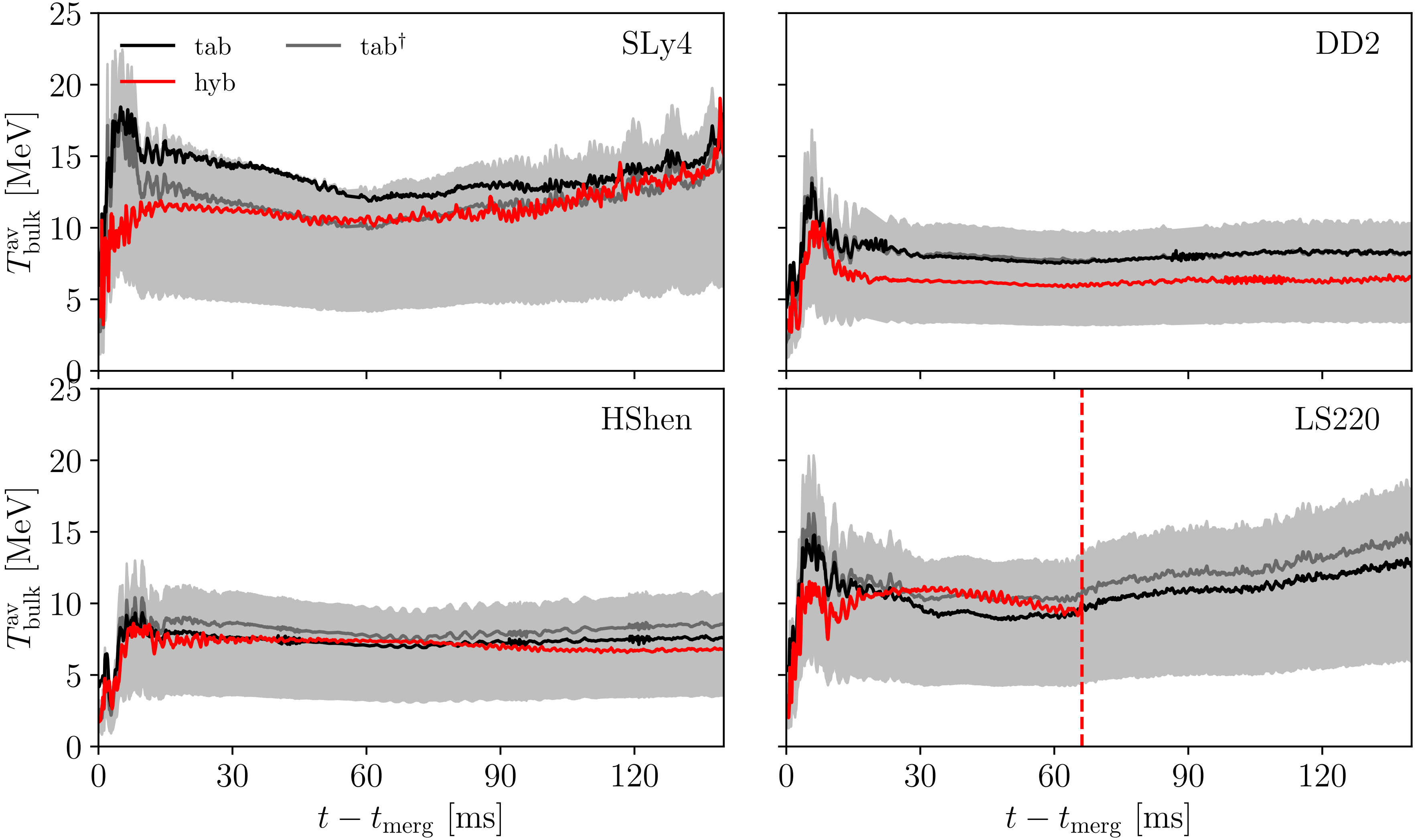
GW spectra



Davide Guerra, *et al.* arxiv:2512.05118

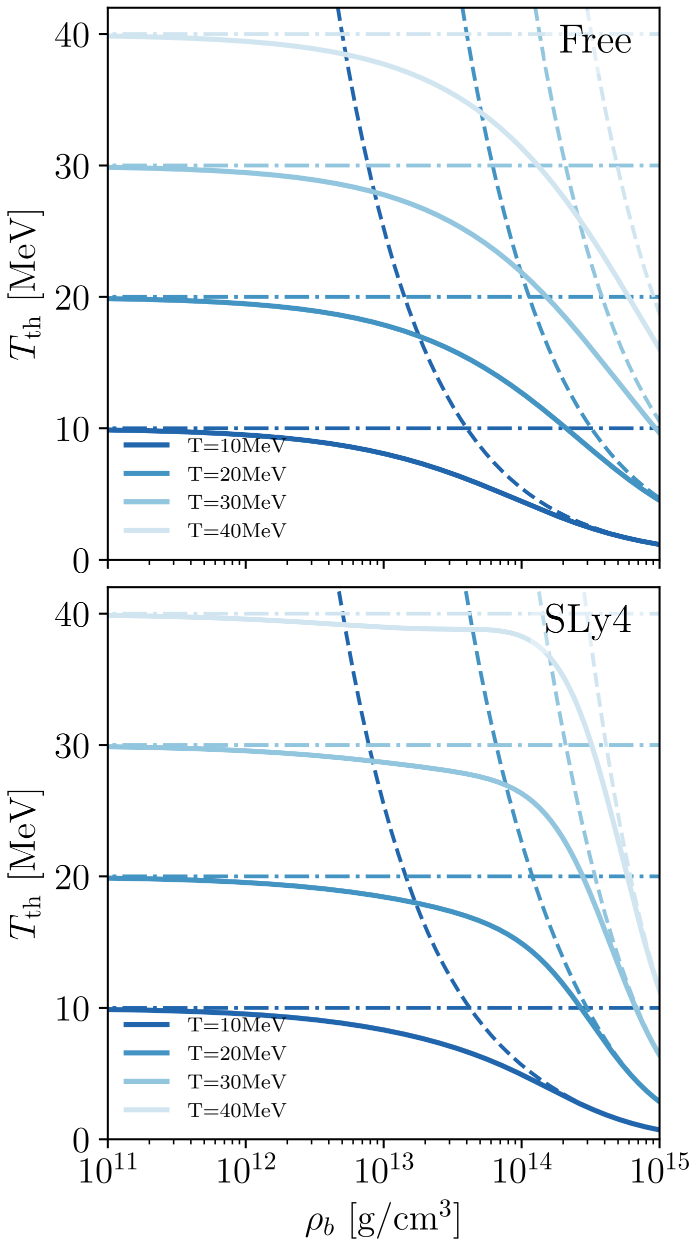
Temperature estimate

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



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

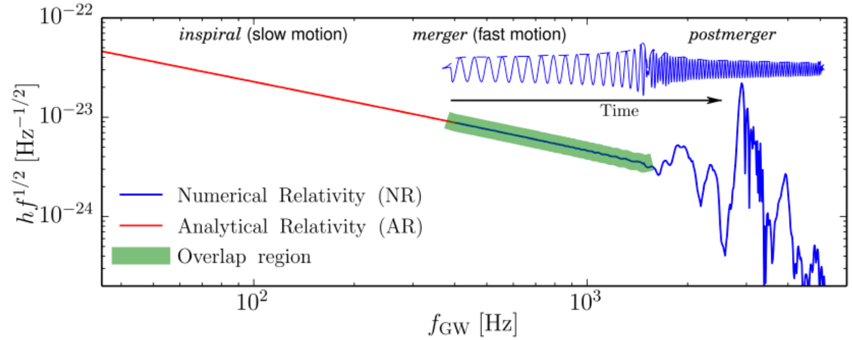
Degenerate Gas

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

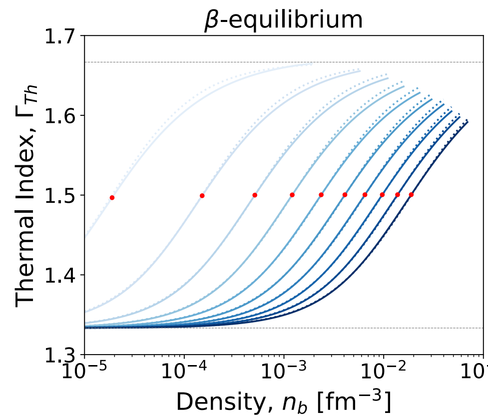
Davide Guerra, *et al.* arxiv:2512.05118

Outline

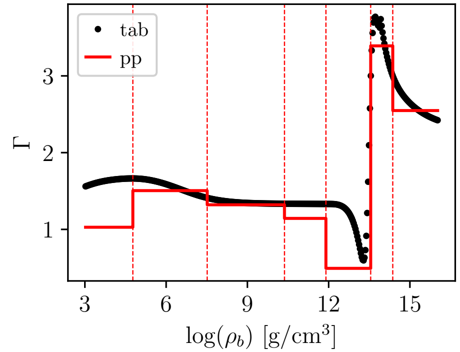
- Motivation



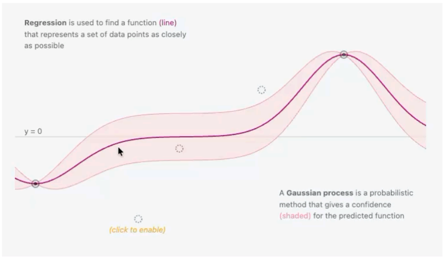
- Virial approximation



- Thermal effects in BNS

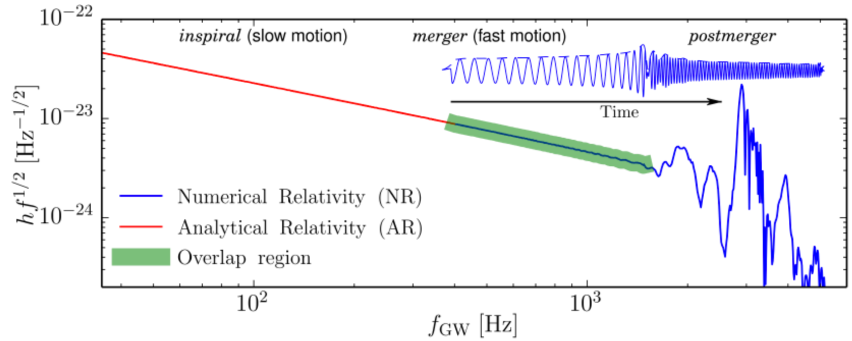


- **Gaussian processes for finite T**

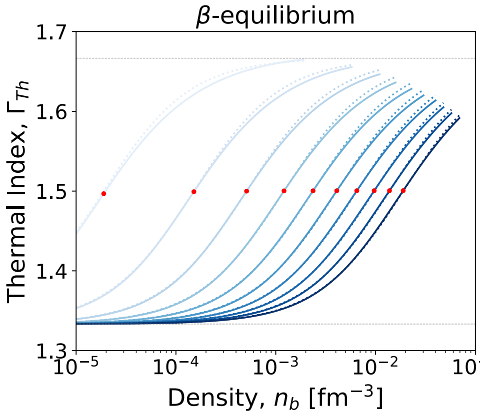


Outline

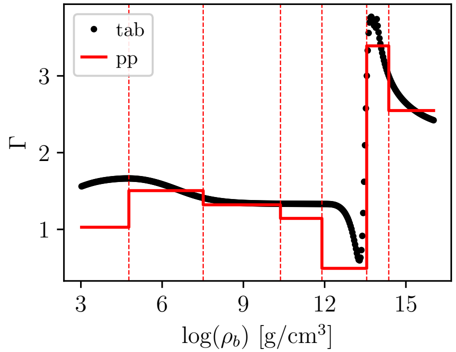
- Motivation



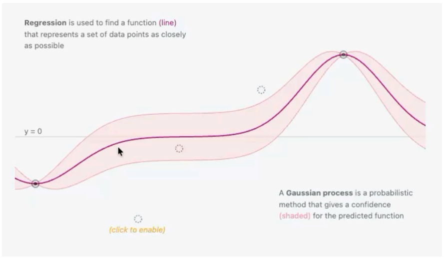
- Virial approximation



- Thermal effects in BNS



- **Gaussian processes for finite T**

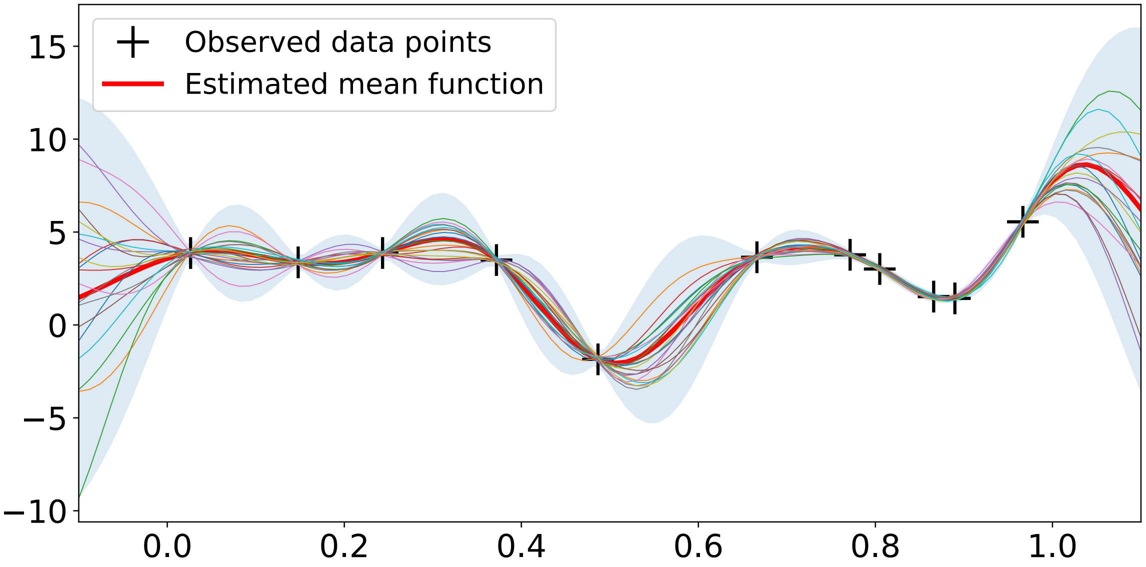


Gaussian processes

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

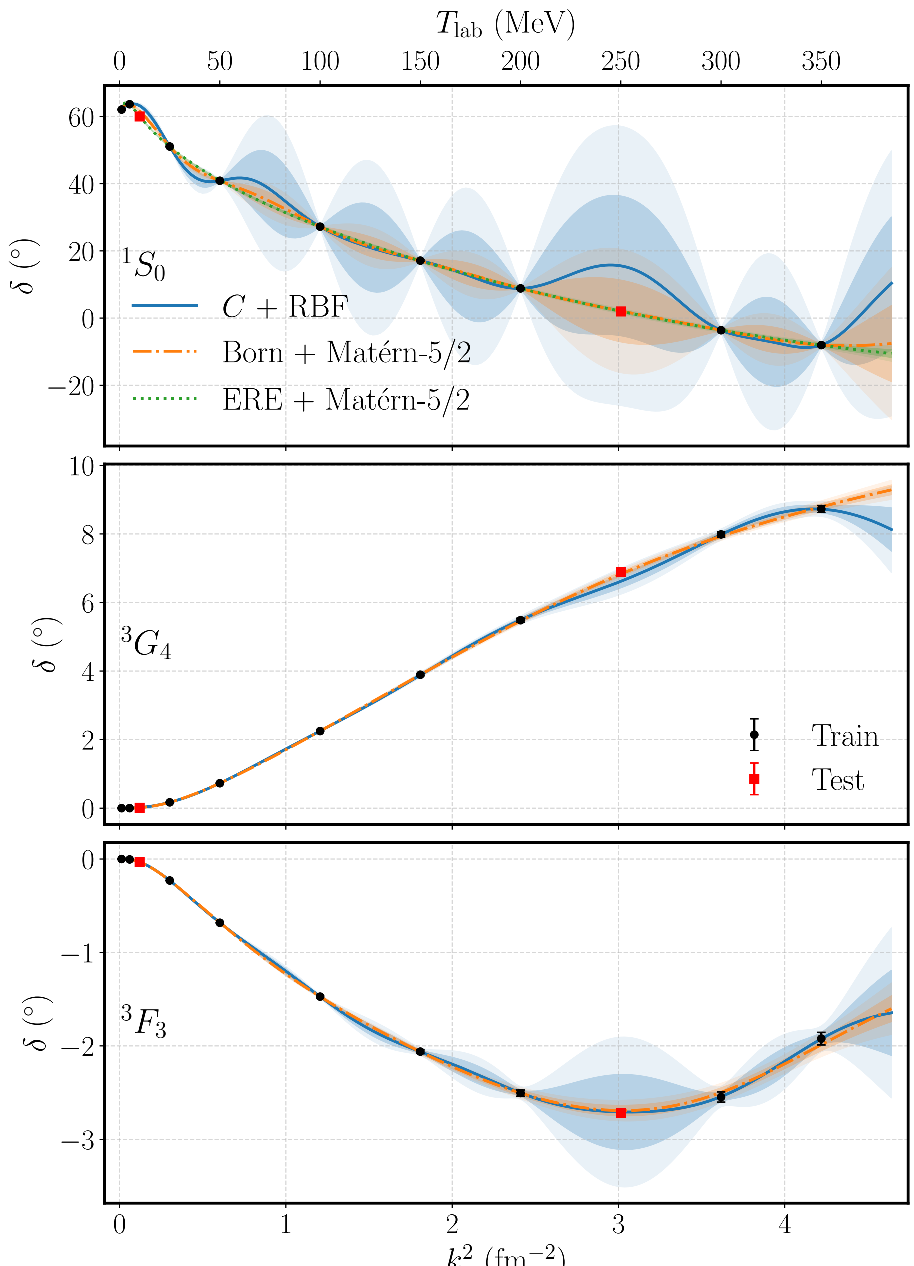
$$m(\boldsymbol{x}) = \mathbb{E}\left[f(\boldsymbol{x})\right]$$

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

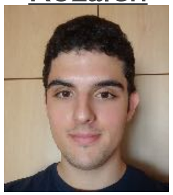
GP cons

- Extrapolation "misguided"

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

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

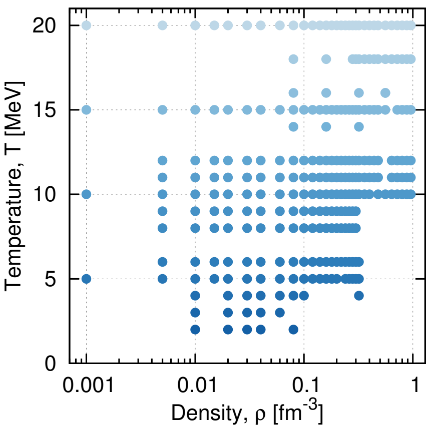
Rozalén



Kochankovski

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

Modelling the mean



Mean model for EoS

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

Cold part

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

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

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

Thermal part

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

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

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

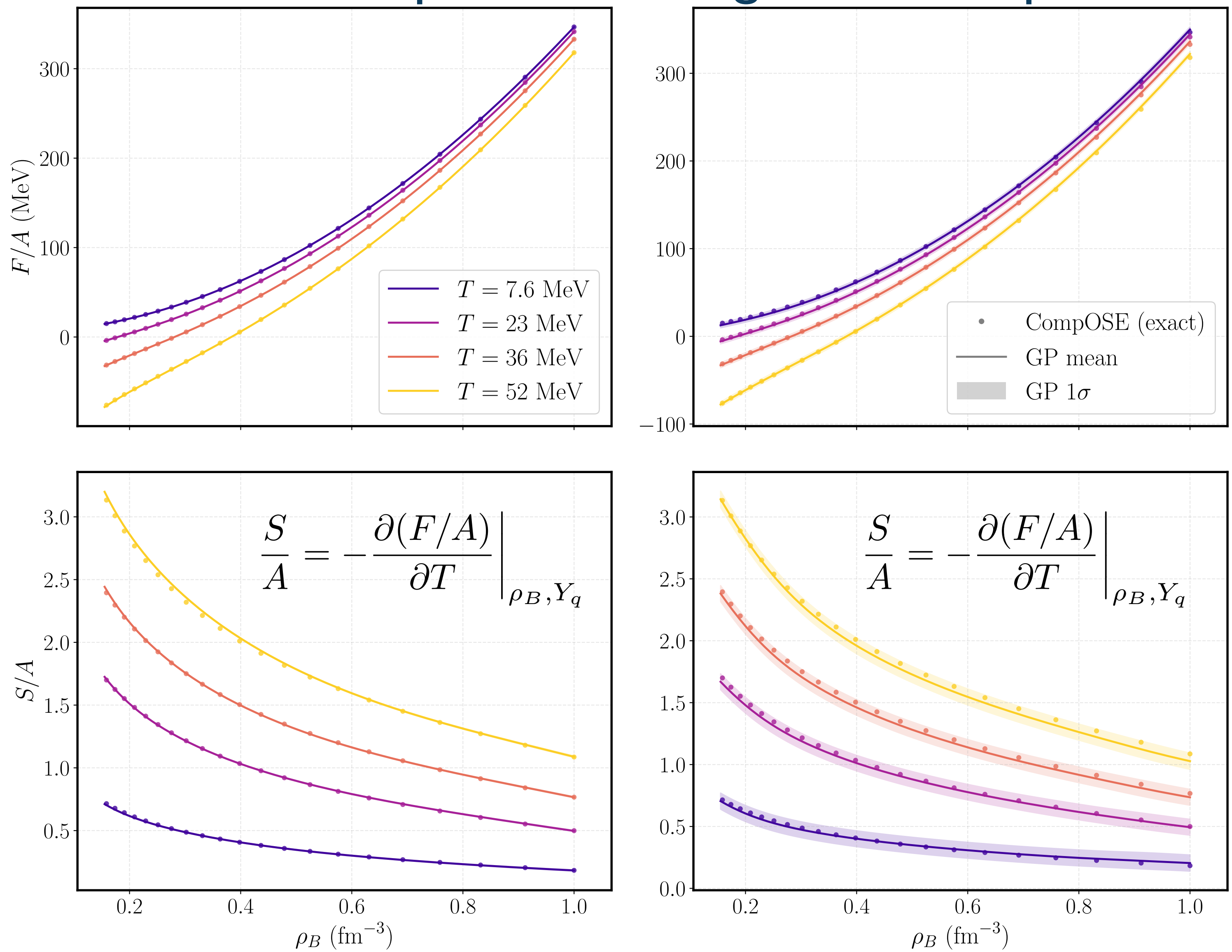
$$\frac{m^*_\tau(\rho)}{m} = \frac{1}{1 + \alpha_\tau\rho/\rho_0}$$

Trainable parameters

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

Nuclear-physics Gaussian processes

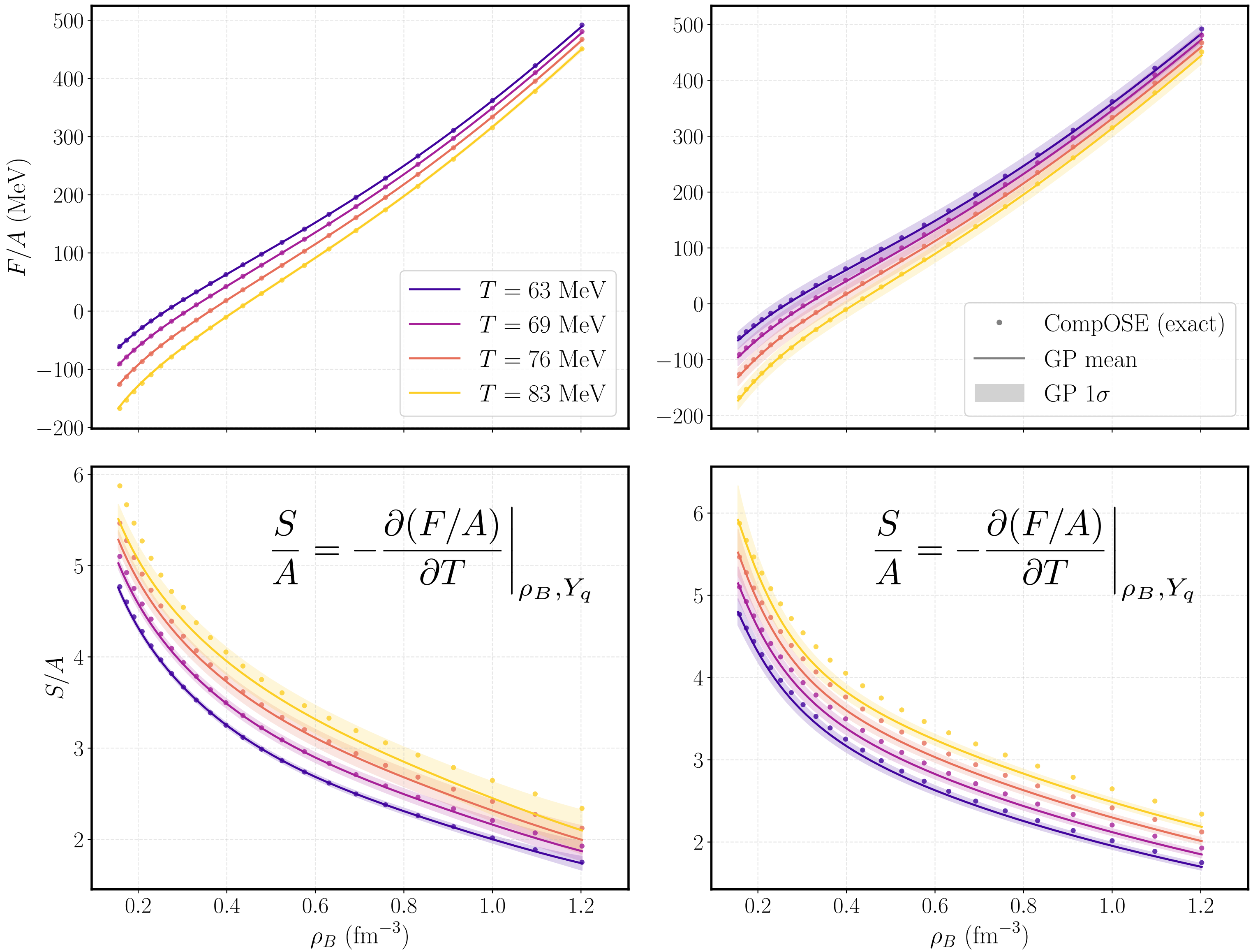
Informed interpolation | Agnostic interpolation



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

Nuclear-physics Gaussian processes

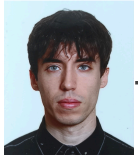
Informed extrapolation | Agnostic extrapolation



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

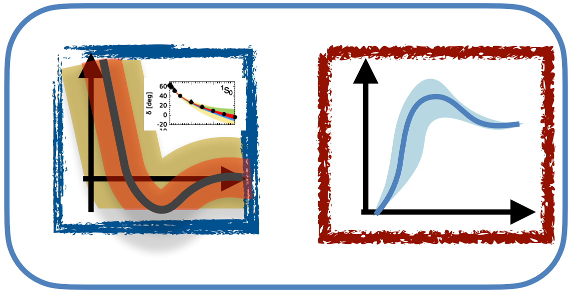
Conclusions

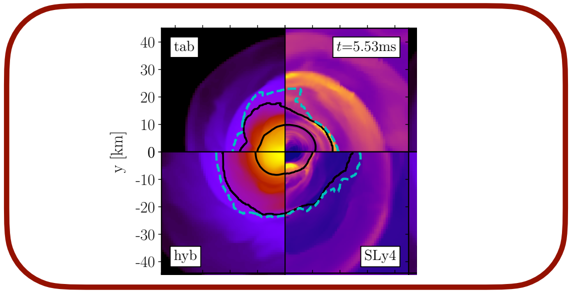
- Ab initio **finite temperature** effects can be simulated & quantified
- **ML** GP techniques can help **interpolate** & **extrapolate** (if physics guided)
- **Challenges**
  - **Uncertainty quantification**
  - **Practical simulability**
  - **Internal NS structure: modes? Phases?**



Márquez

G Riviecchio





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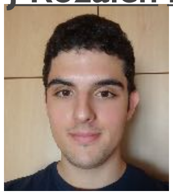
À Ramos

J Rozalén

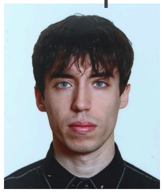


H Kochankovski

A Nadal

R Bondarescu

R Márquez



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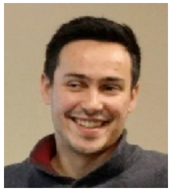
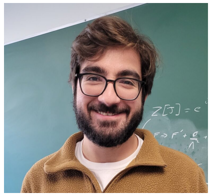


G Palkanoglou



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