Equation of State in the era of new nuclear physics and multimessenger constraints

Chiranjib Mondal

University of Barcelona
July 10, 2024

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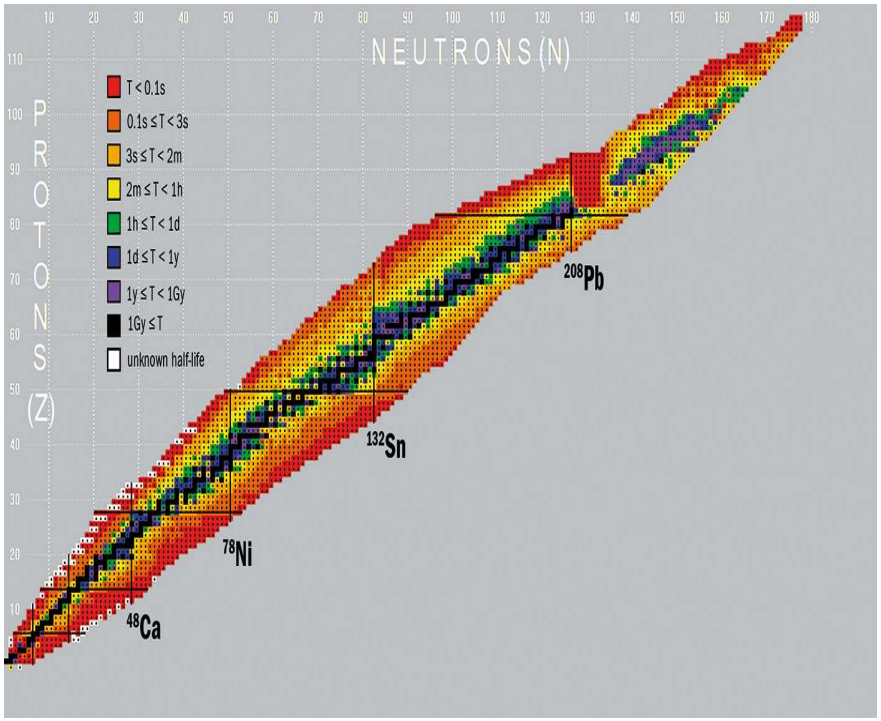
Low energy Nuclear Physics

We have knowledge from Nuclear Physics in the laboratory

Finite nuclear properties



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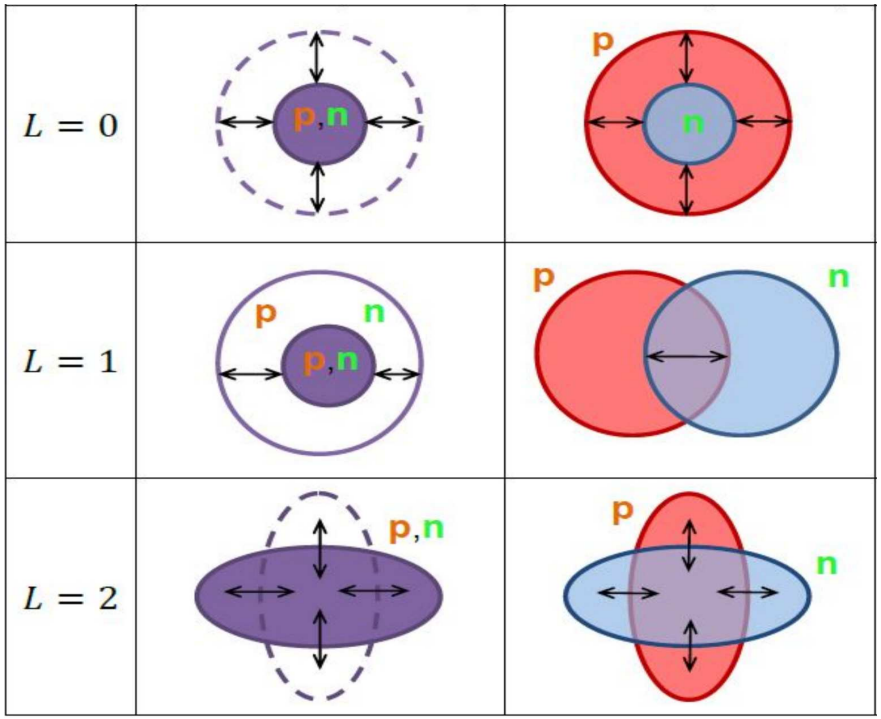

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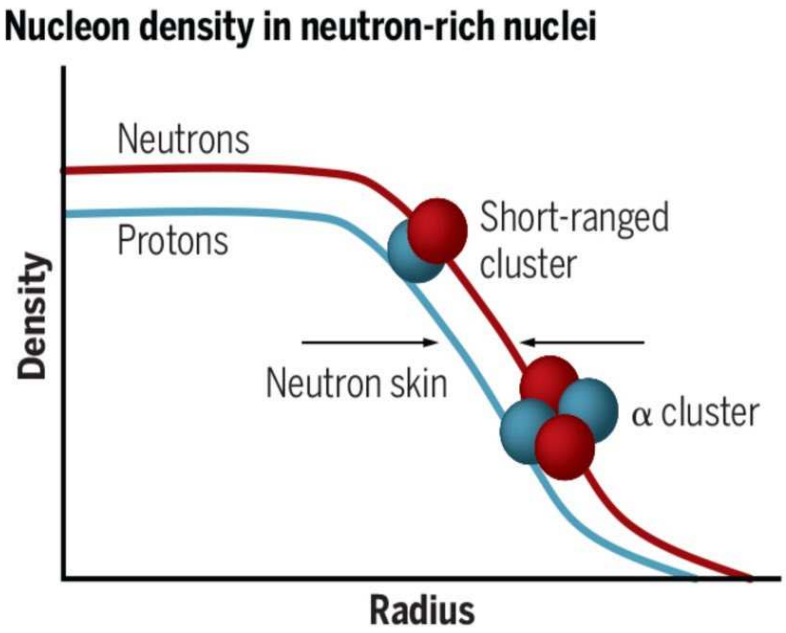

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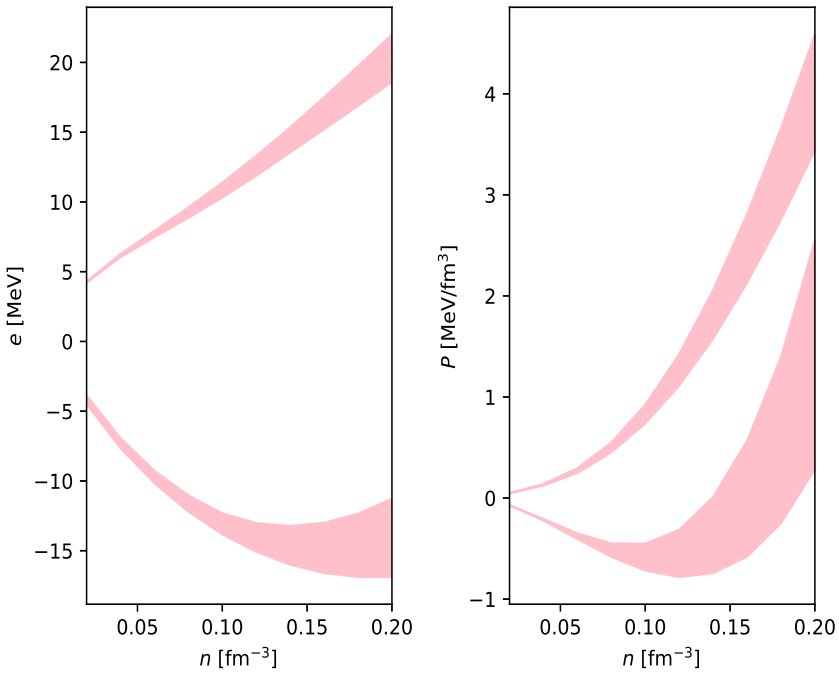

Drischler *et. al.* PRC 93, 05431 (2016)

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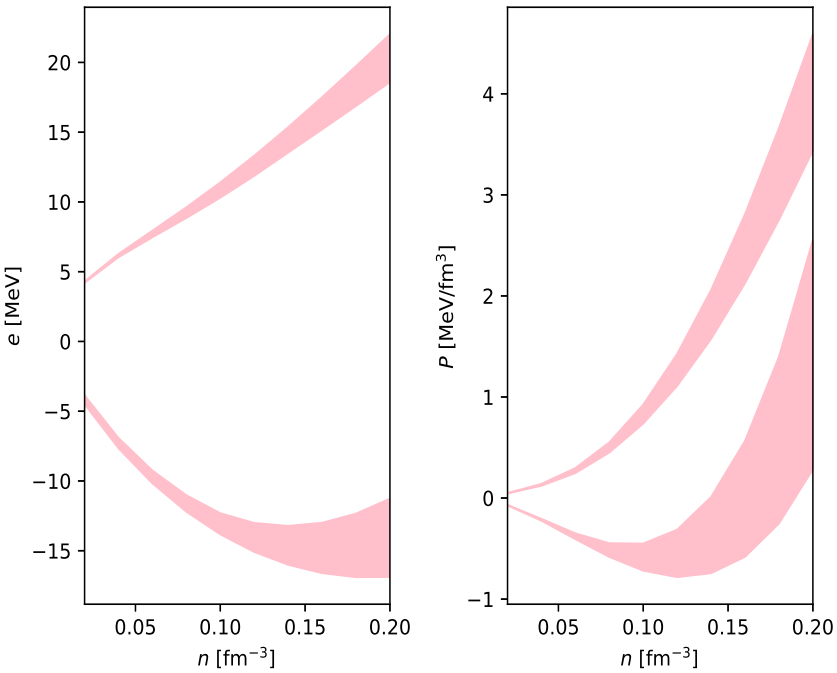

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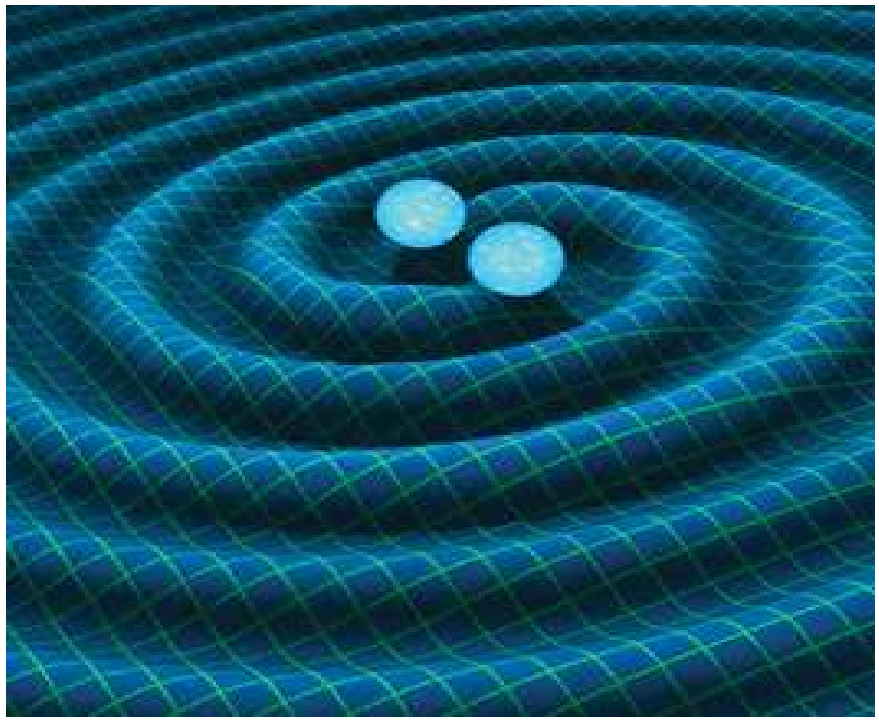

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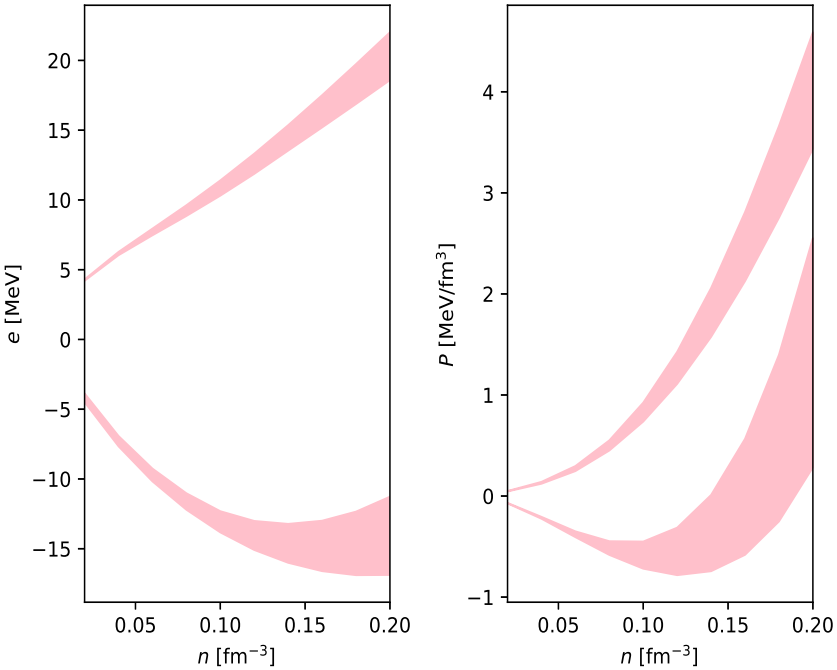

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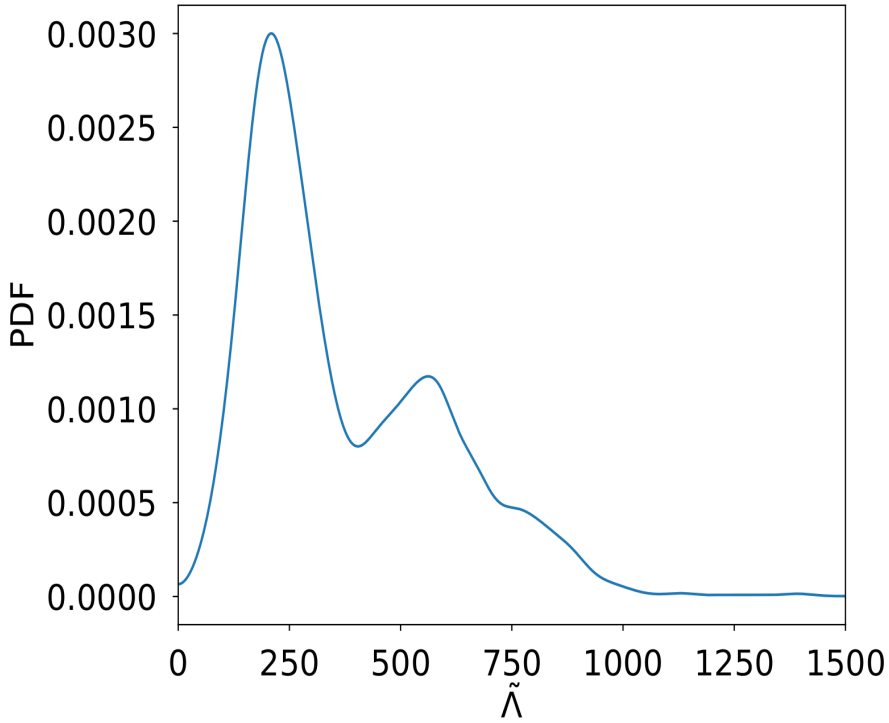

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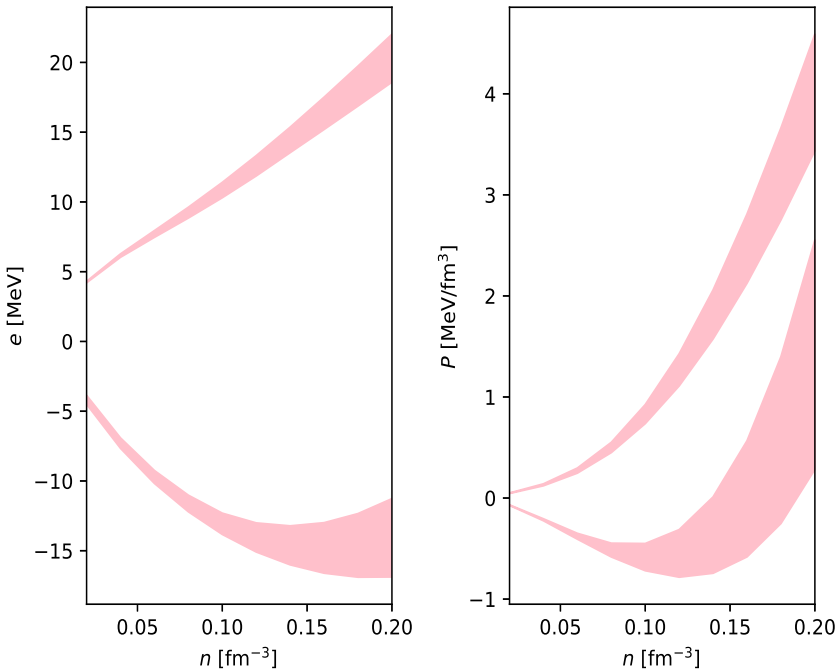

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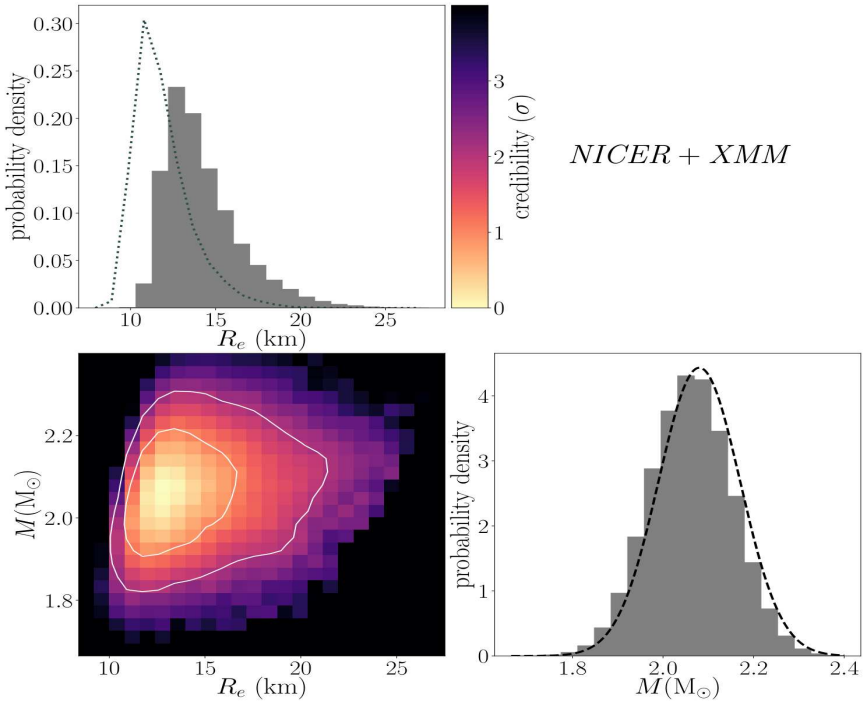

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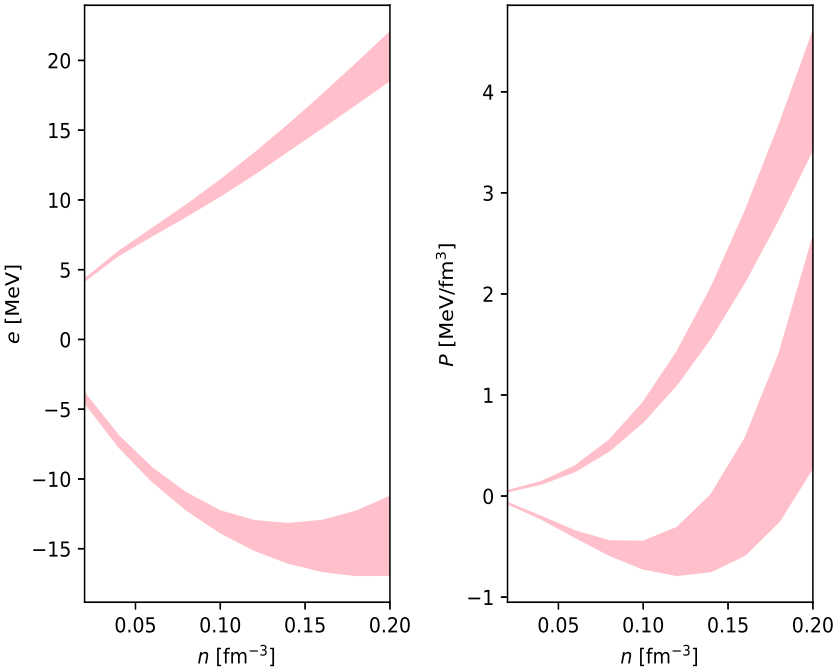

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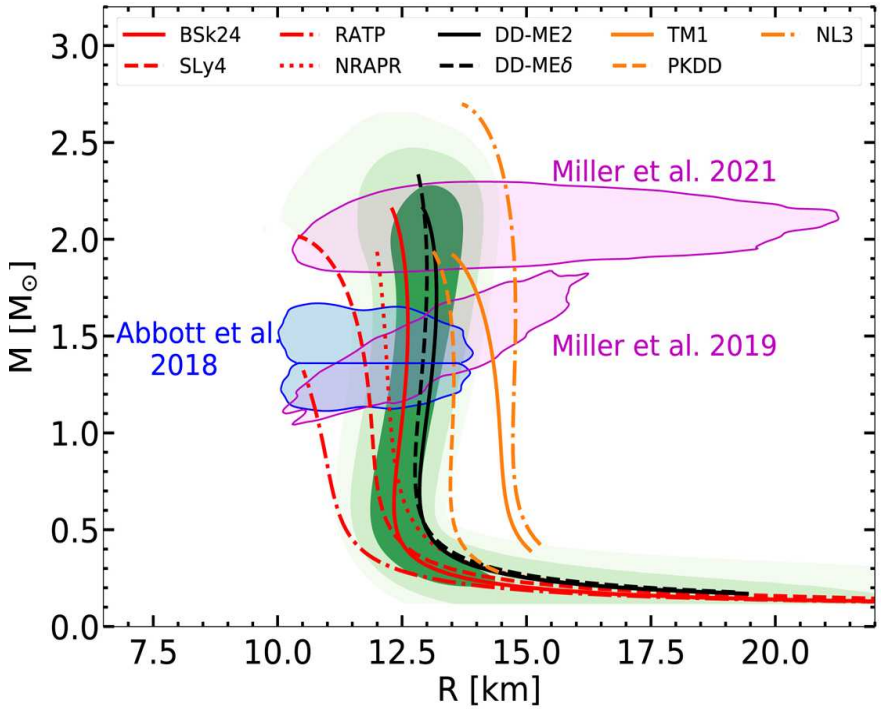

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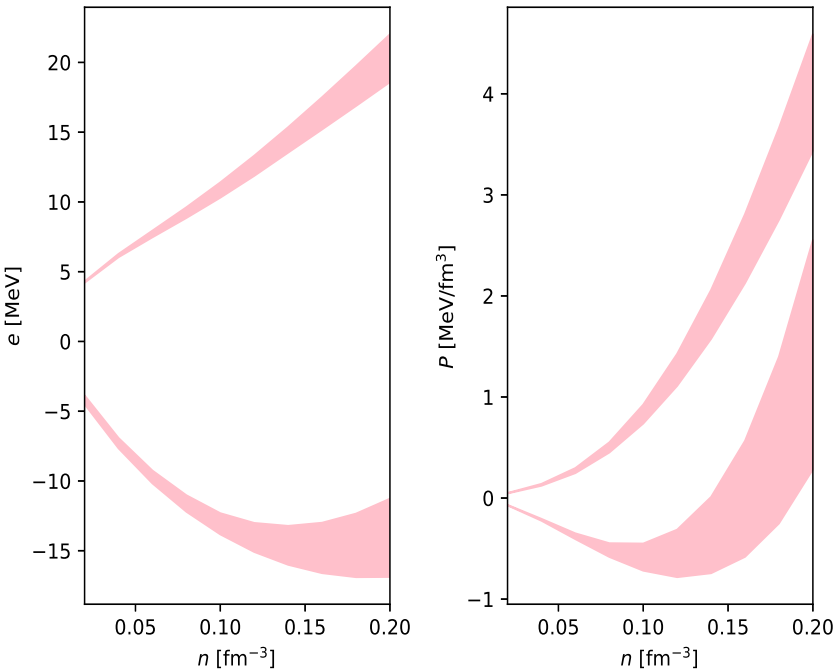

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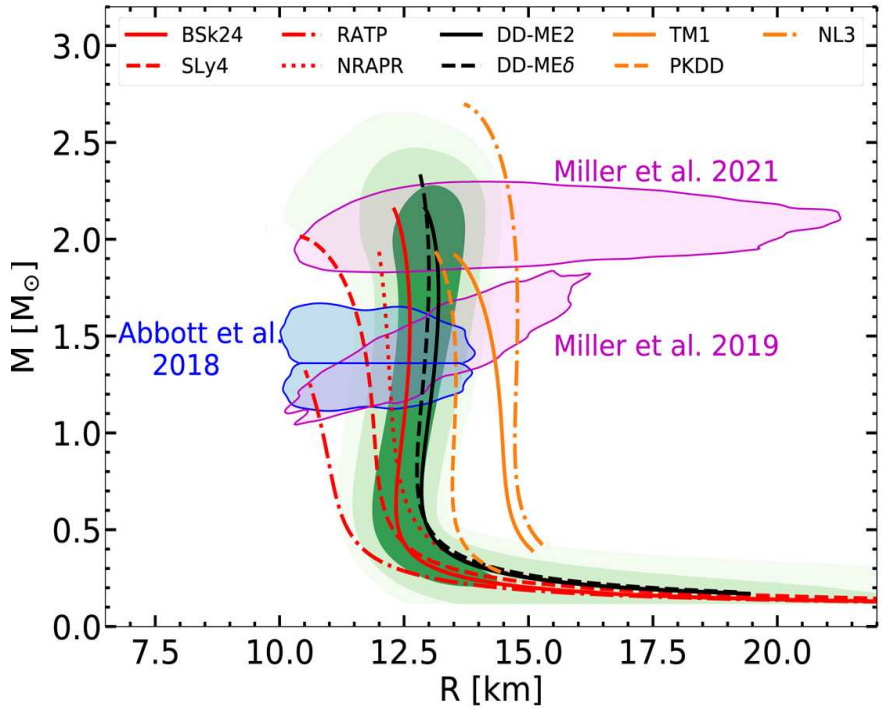

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We can construct equation of state (EoS) with nuclear models. (!!!!)

Nucleonic meta-modelling

Founding aspects [PRC 97, 025805 (2018)]

Features:

- **Flexible functional $e(n_n, n_p)$ able to reproduce existing effective nucleonic models and interpolate between them.**
- **Expansion in powers of the Fermi momentum or of the density.**
- **Expansion around saturation: Parameter space = emp. par. $\overrightarrow{X}$.**
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- **β-equilibrium!!!**
- **The energy per particle can be rewritten as,**

$$
\begin{aligned}
e(n_n, n_p) &\simeq e_{\rm SNM}(n, 0) + e_{\rm sym}(n)\delta^2 \\
e_{meta}(n_n, n_p) &= KE(n_n, n_p) + \sum_{\alpha \geq 0} \frac{1}{\alpha!} \left(v_\alpha^{is} + v_\alpha^{iv} \delta^2 \right) x^\alpha . \\
v_\alpha^{is(iv)} &\equiv f\left(E_{\rm sat}, K_{\rm sat} \cdots J_{\rm sym}, L_{\rm sym} \cdots \right).
\end{aligned}
$$

Neutron skin in PREX-II and CREX era

Constraints from lab and sky

Bayesian studies with metamodel

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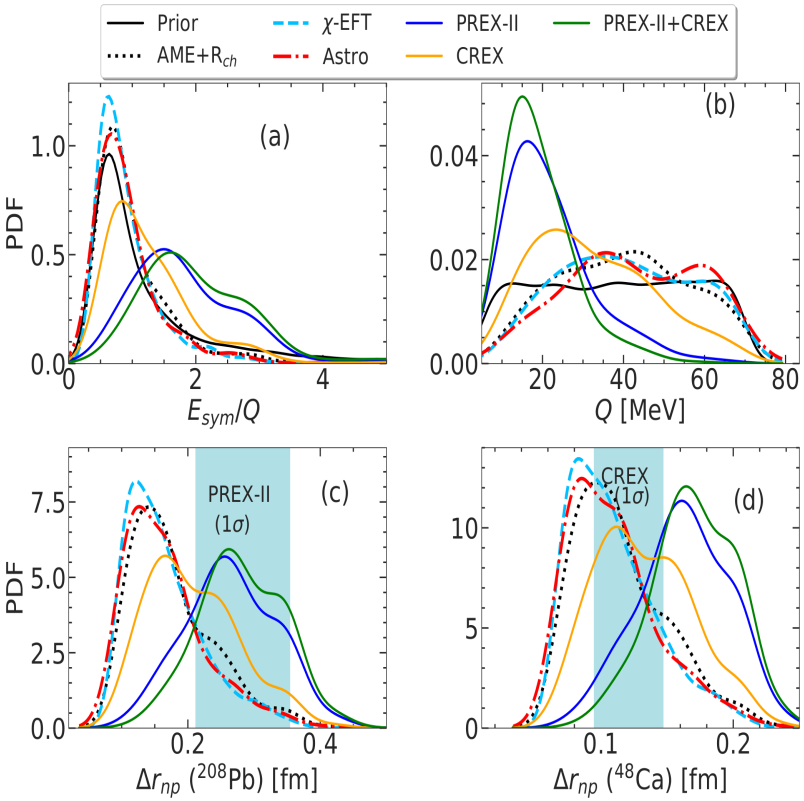
CM and F. Gulminelli PRC 107, 015801 (2023)



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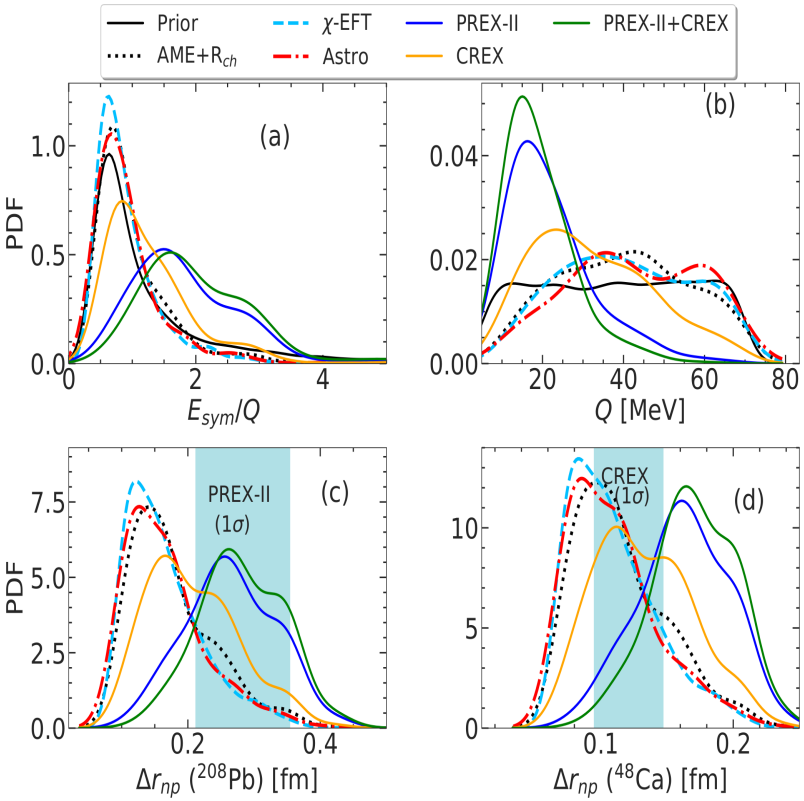

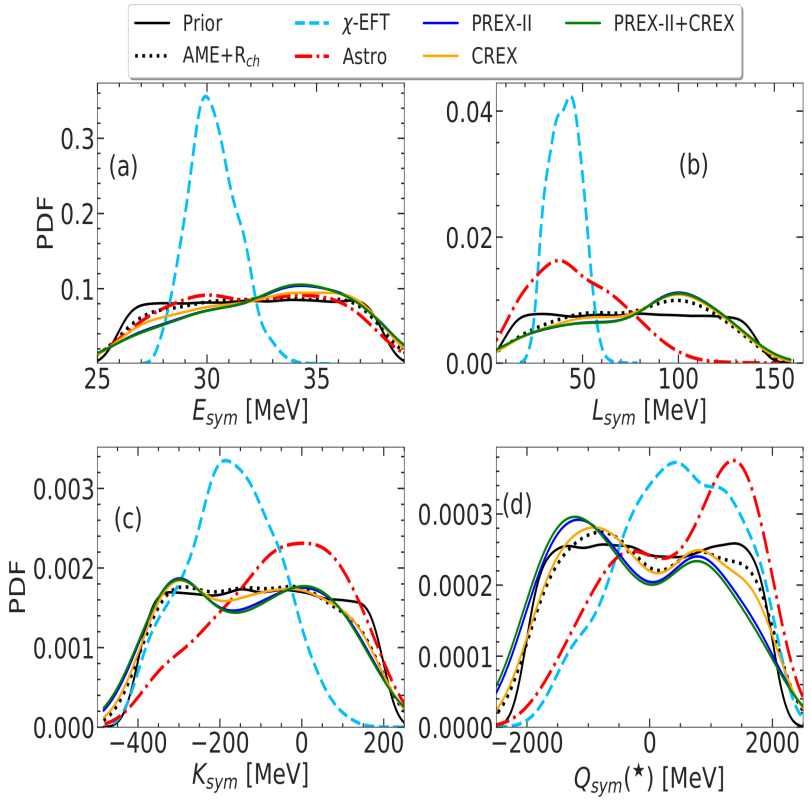

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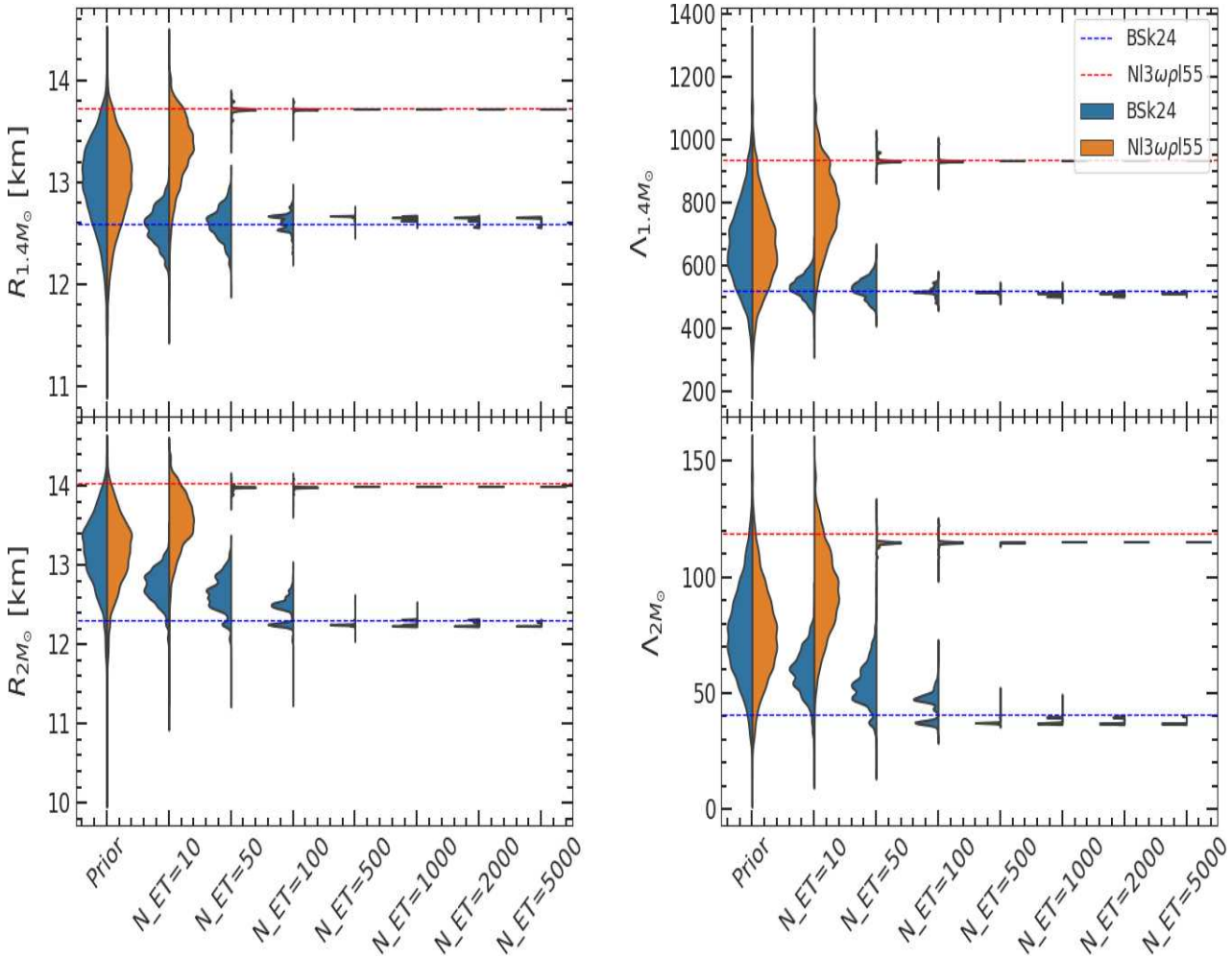

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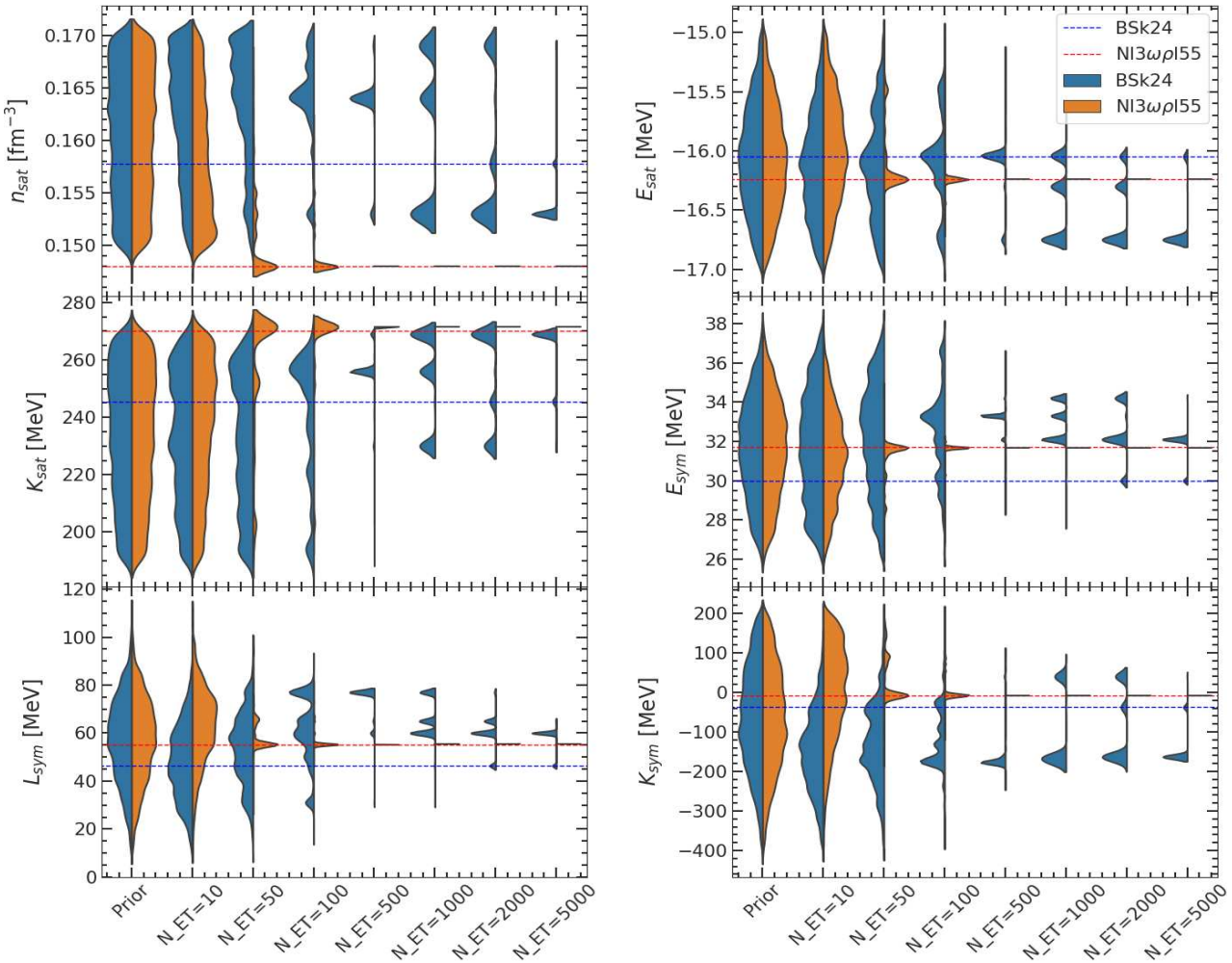

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Merger simulations

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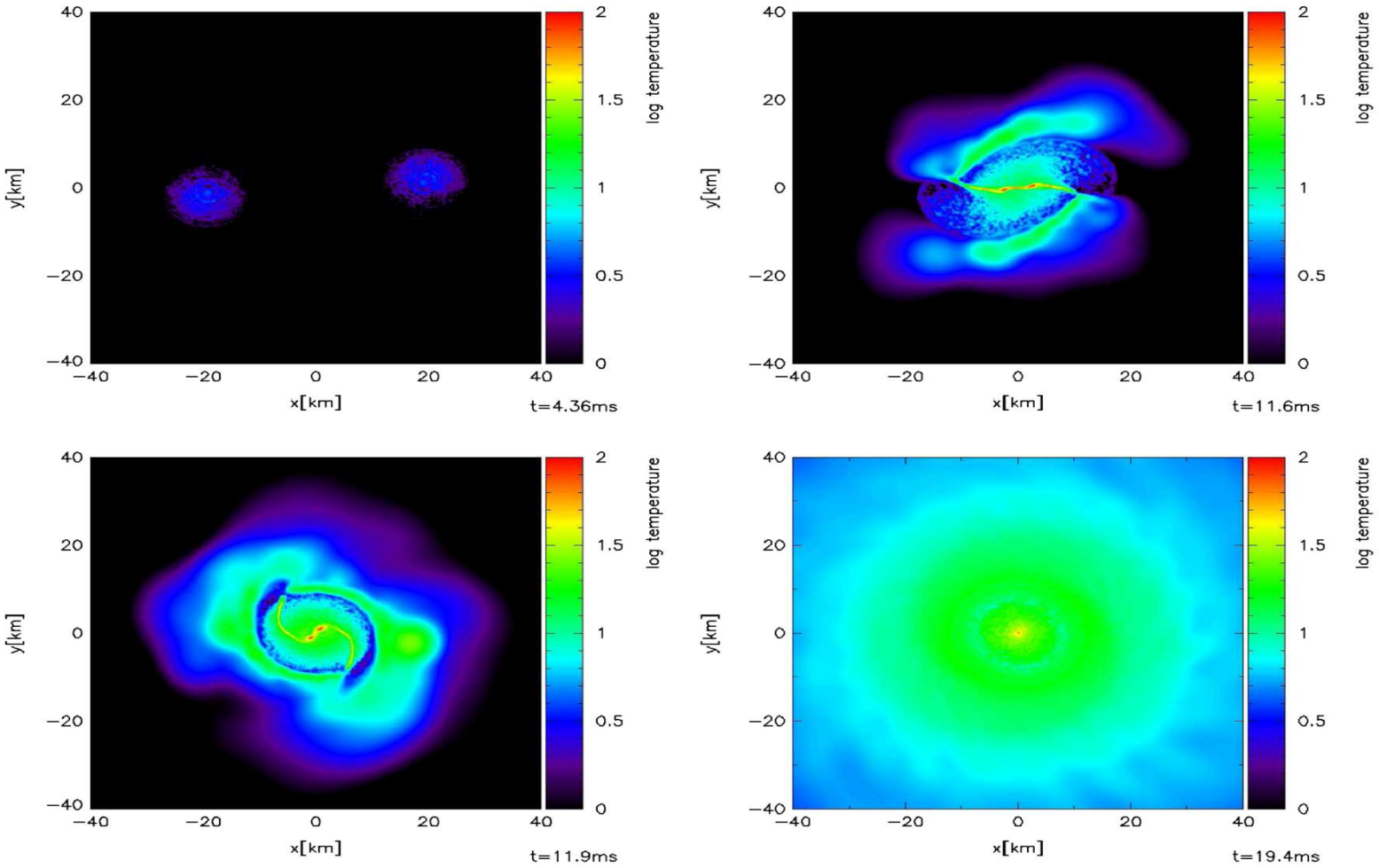

Fig Courtesy:
Bauswein *et. al.* PRD 82, 084043 (2010)

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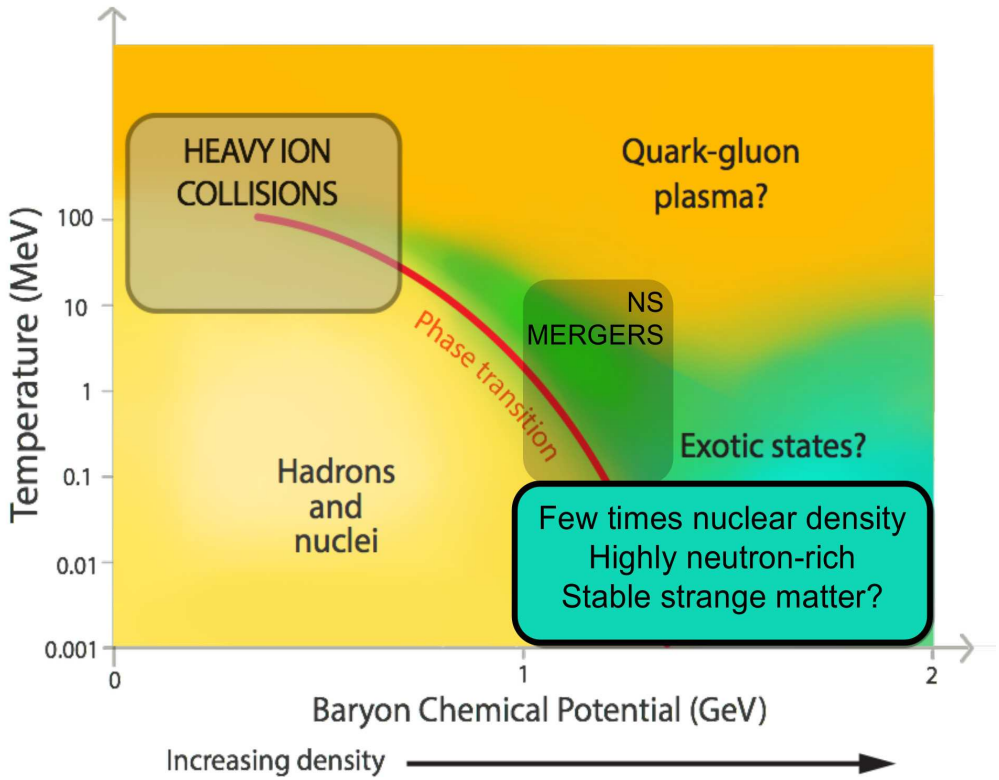
Merger simulations and matter phase diagram



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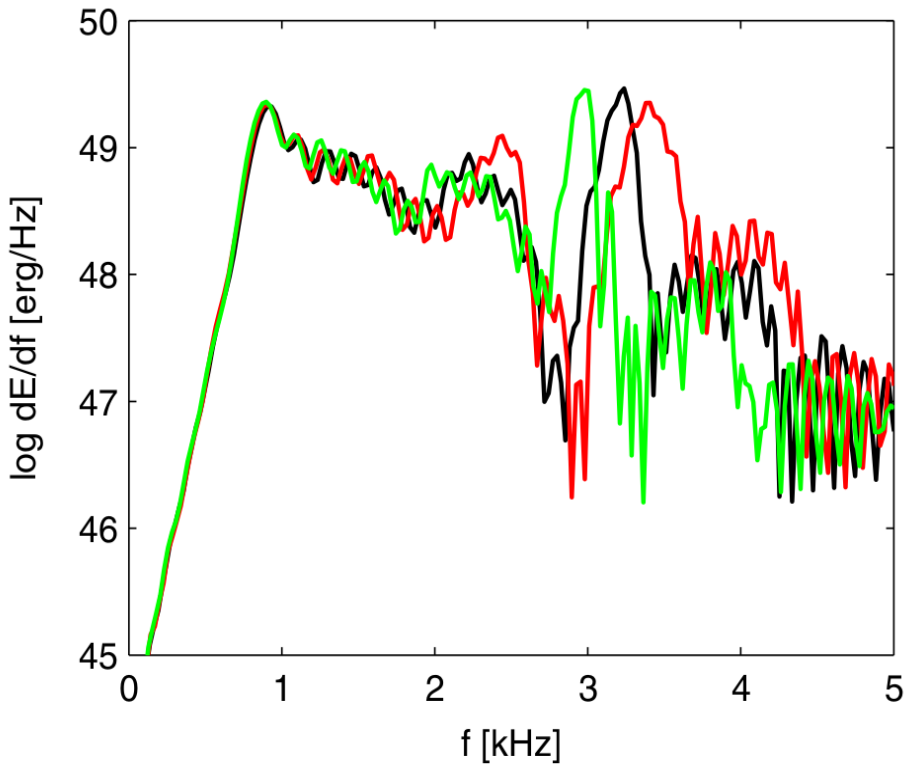

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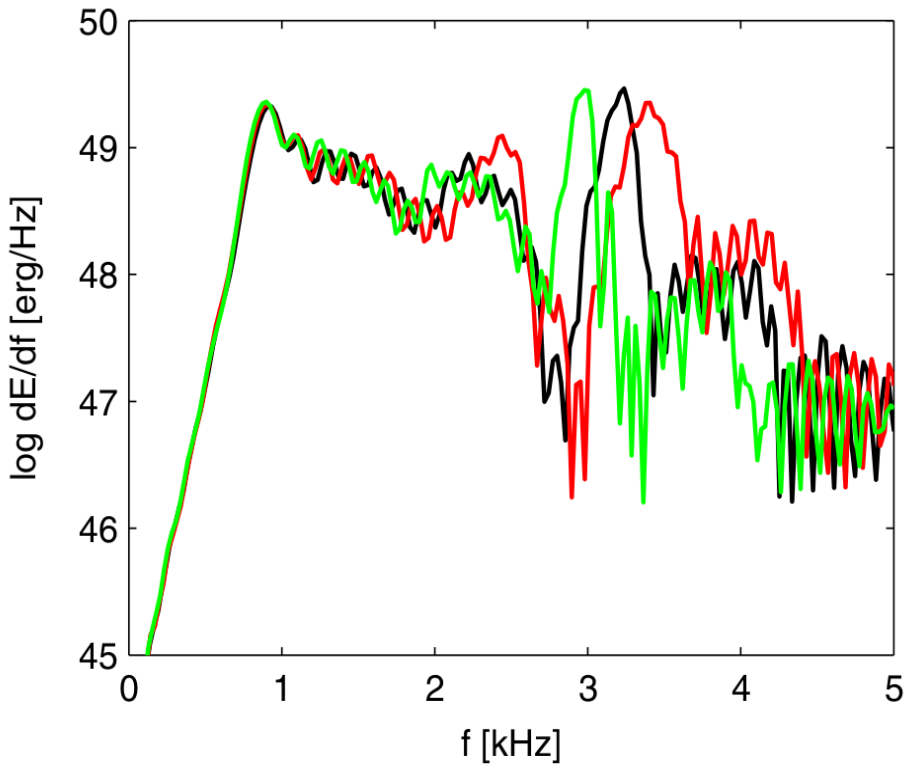

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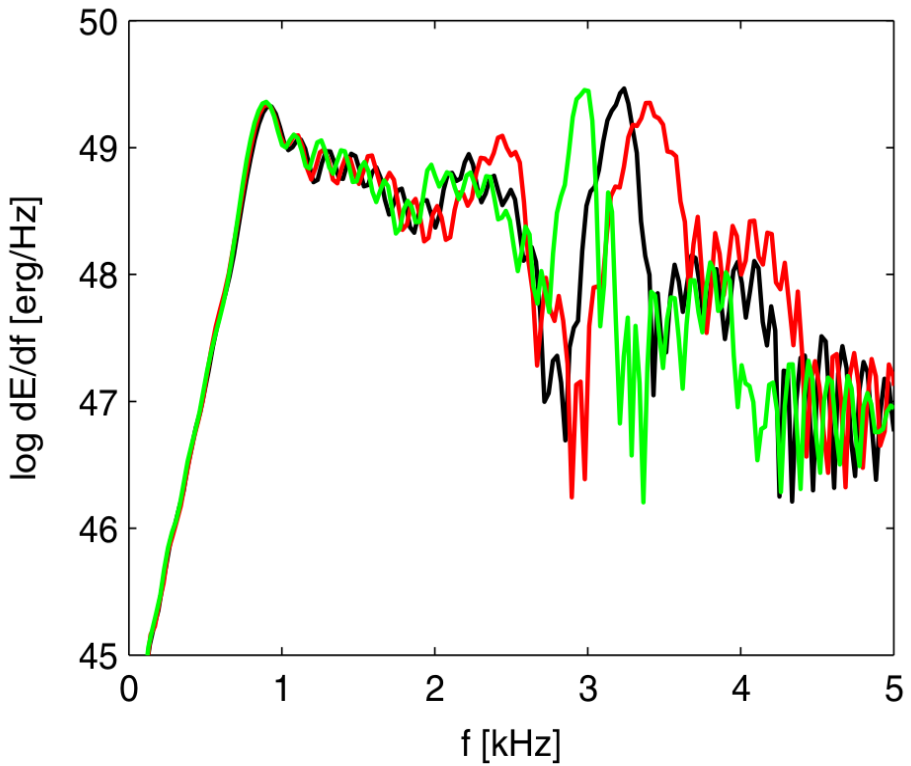

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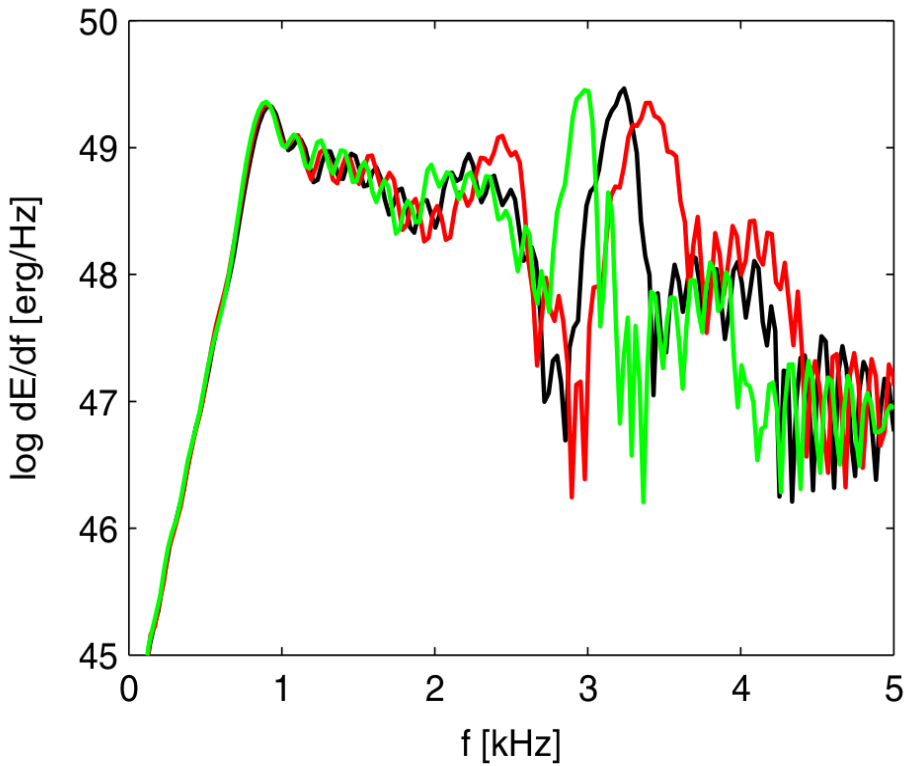

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- See Constantinou *et. al* for effective mass; Raithel *et. al* for extension from zero temp β-equilibrium.

Usage of a common framework

BSkG3 model

- End-to-end NS merger simulations =>
  Hydrodynamics, Nucleosynthesis, radiative transfer

  [See Just *et. al.* ApJL 951, 12 (2023), MNRAS 510, 2804 (2022), MNRAS 510, 2820 (2022)]

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Energy Density Functional

Brussels Skyrme model

- At baryon density n, asymmetry $\delta \left(= \frac{n_n - n_p}{n}\right)$, temperature T,

$$\mathcal{F} \equiv \mathcal{E} - T\mathcal{S},$$

$$\text{where } \mathcal{E} = \sum_q \frac{\hbar^2}{2M_q^*}\tau_q + \frac{1}{8}t_0\left\{3 - (2x_0 + 1)\delta^2\right\}n^2$$

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$$\text{with } \frac{\hbar^2}{2M_q^*} = \frac{\hbar^2}{2M_q} + f(n, \delta)$$

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- The density and kinetic density involves Fermi integrals (q=n,p):

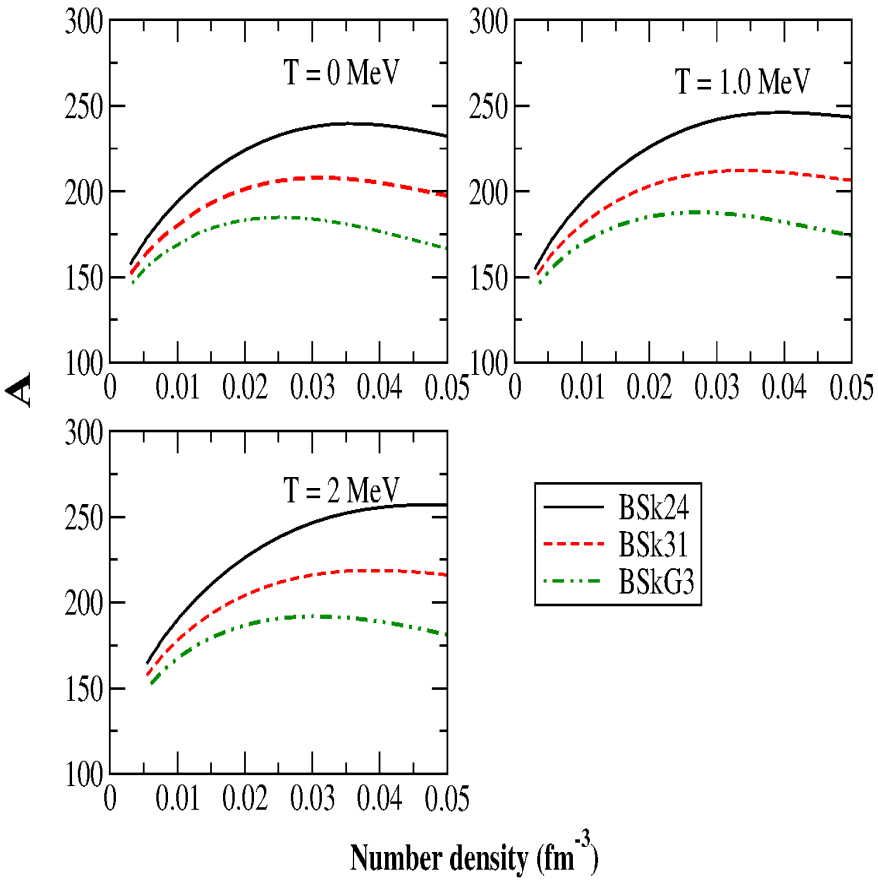
$$\mathrm{n_q} = \frac{1}{2\pi^2}\left(\frac{2\mathrm{M}^*_{\mathrm{q}}}{\hbar^2}\right)^{\frac{3}{2}} \mathrm{T}^{\frac{3}{2}}\mathrm{I}_{\frac{1}{2}}(\nu_{\mathrm{q}}); \quad \tau_{\mathrm{q}} = \frac{1}{2\pi^2}\left(\frac{2\mathrm{M}^*_{\mathrm{q}}}{\hbar^2}\right)^{\frac{5}{2}} \mathrm{T}^{\frac{5}{2}}\mathrm{I}_{\frac{3}{2}}(\nu_{\mathrm{q}})$$

where, $\mathrm{I}_\sigma(\nu_{\mathrm{q}}) = \int_0^\infty \frac{x^\sigma}{1+\exp(x-\nu_{\mathrm{q}})}\,dx$

Crust composition

BSk models (Extended Thomas Fermi)

Particle Number



With G. Grams and N. Shchechilin

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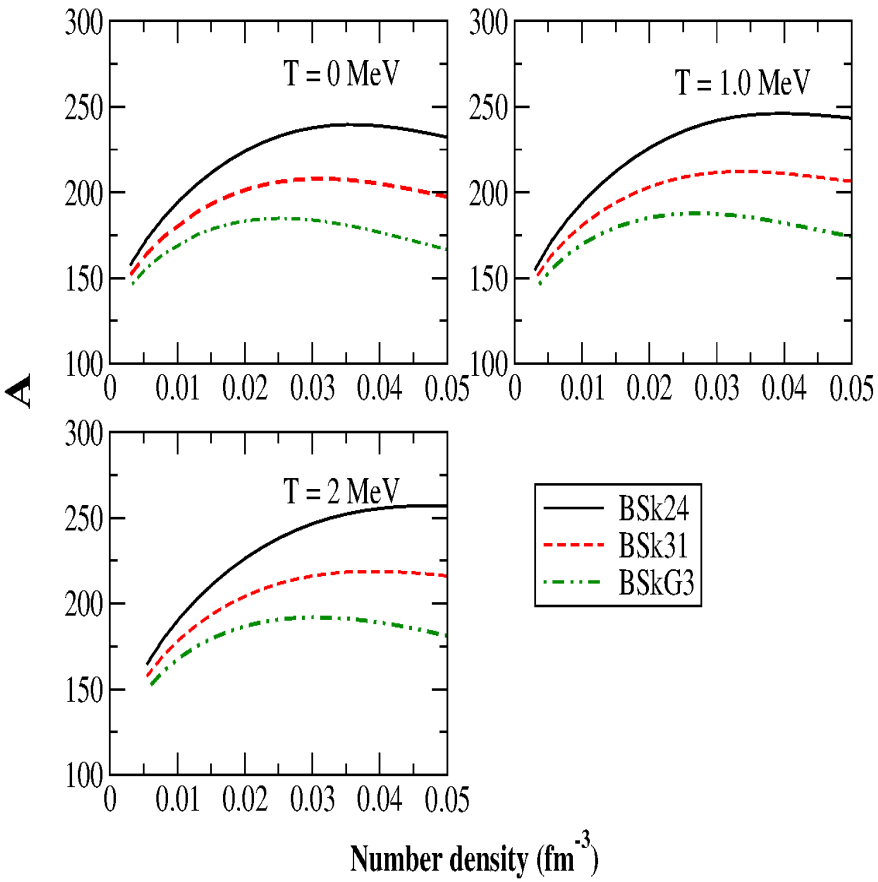
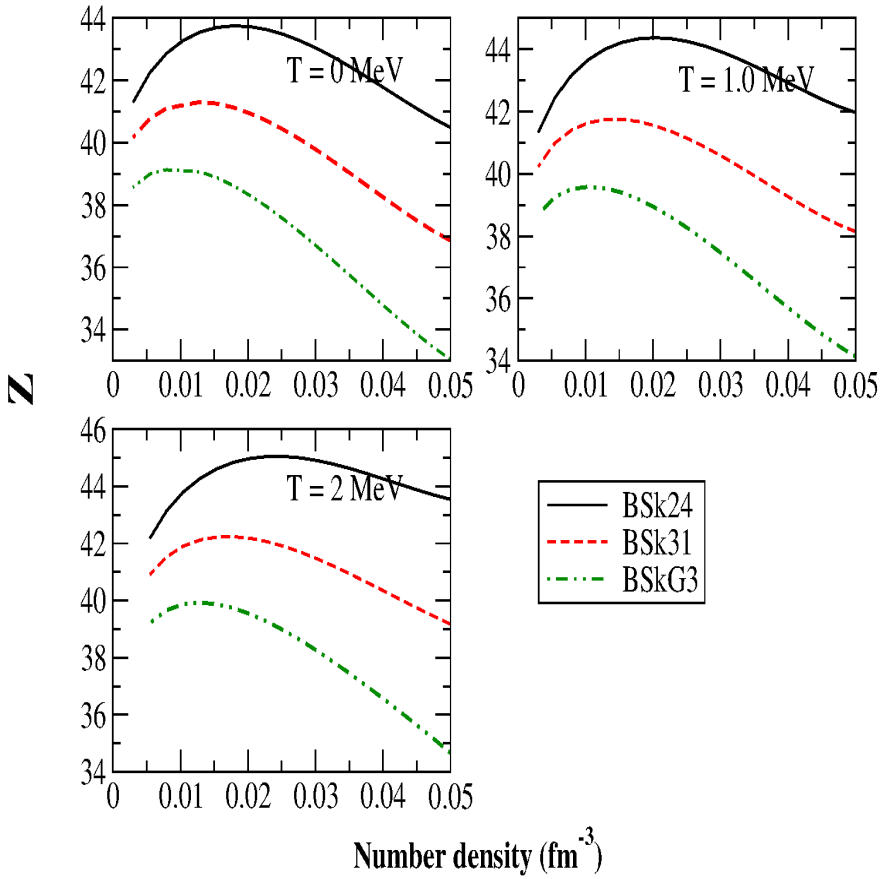


Proton number



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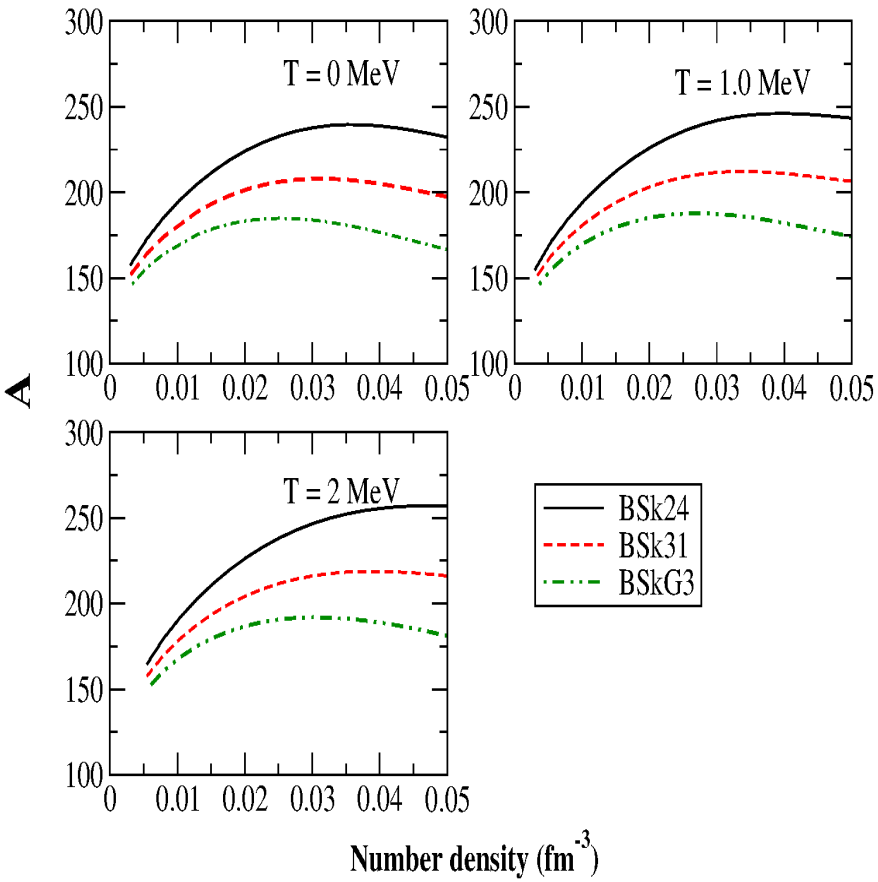

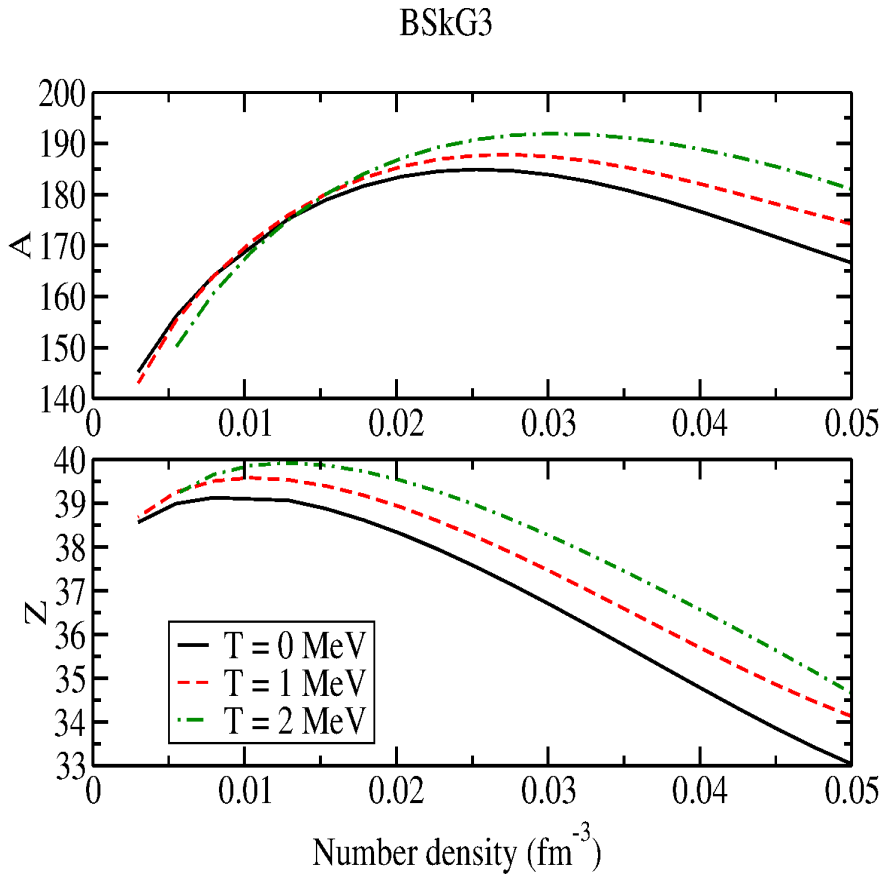

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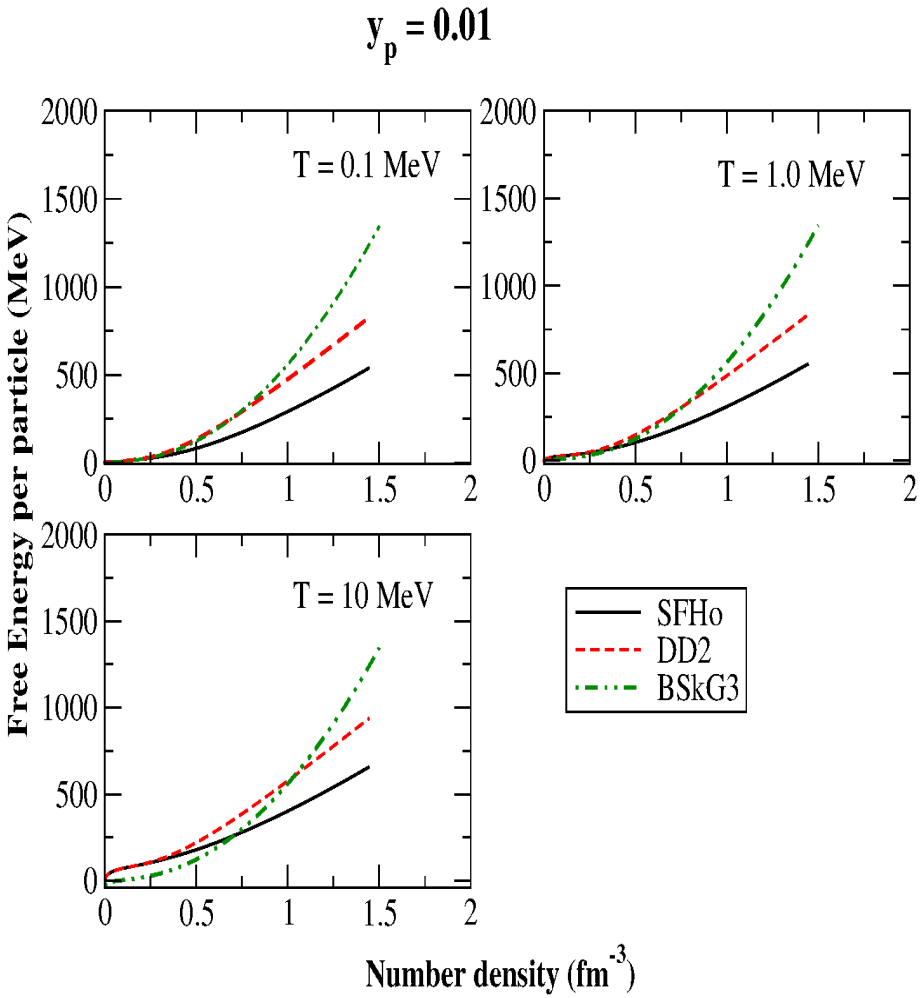
Results for free energy

BSk's and other models

Arbitrary proton fraction



https://compose.obspm.fr

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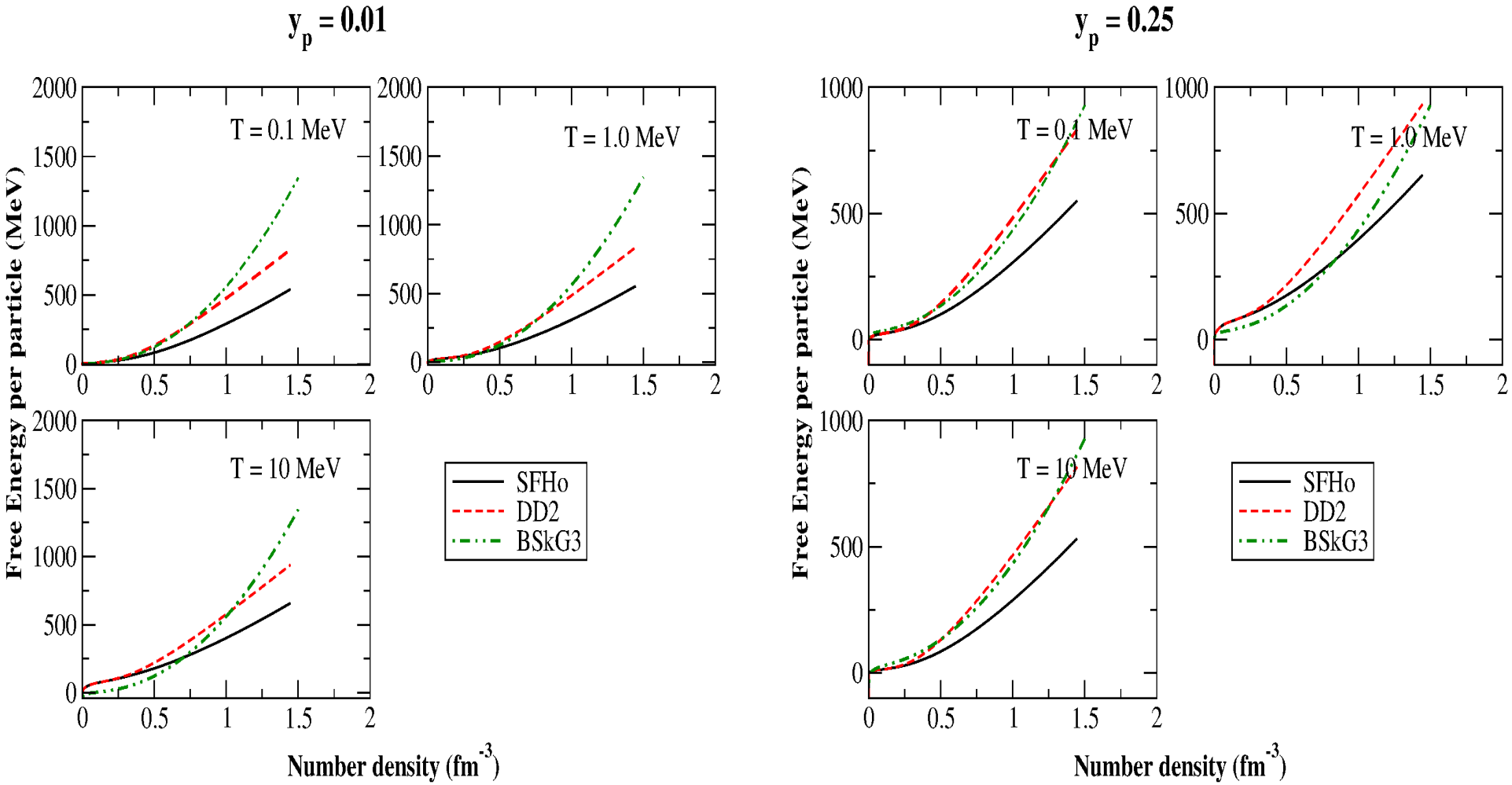

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Collaborators

- IAA Université Libre de Bruxelles Group
- Caen-Strassbourg Virgo Theory Group