Nuclear physics inputs for neutron stars and nucleosynthesis simulations

Guilherme Grams

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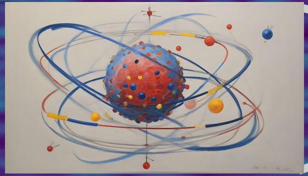
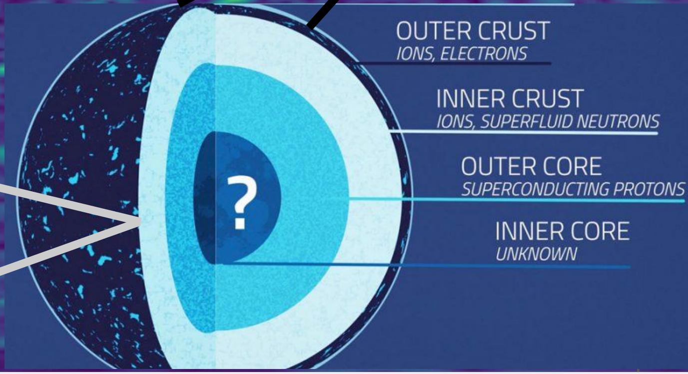
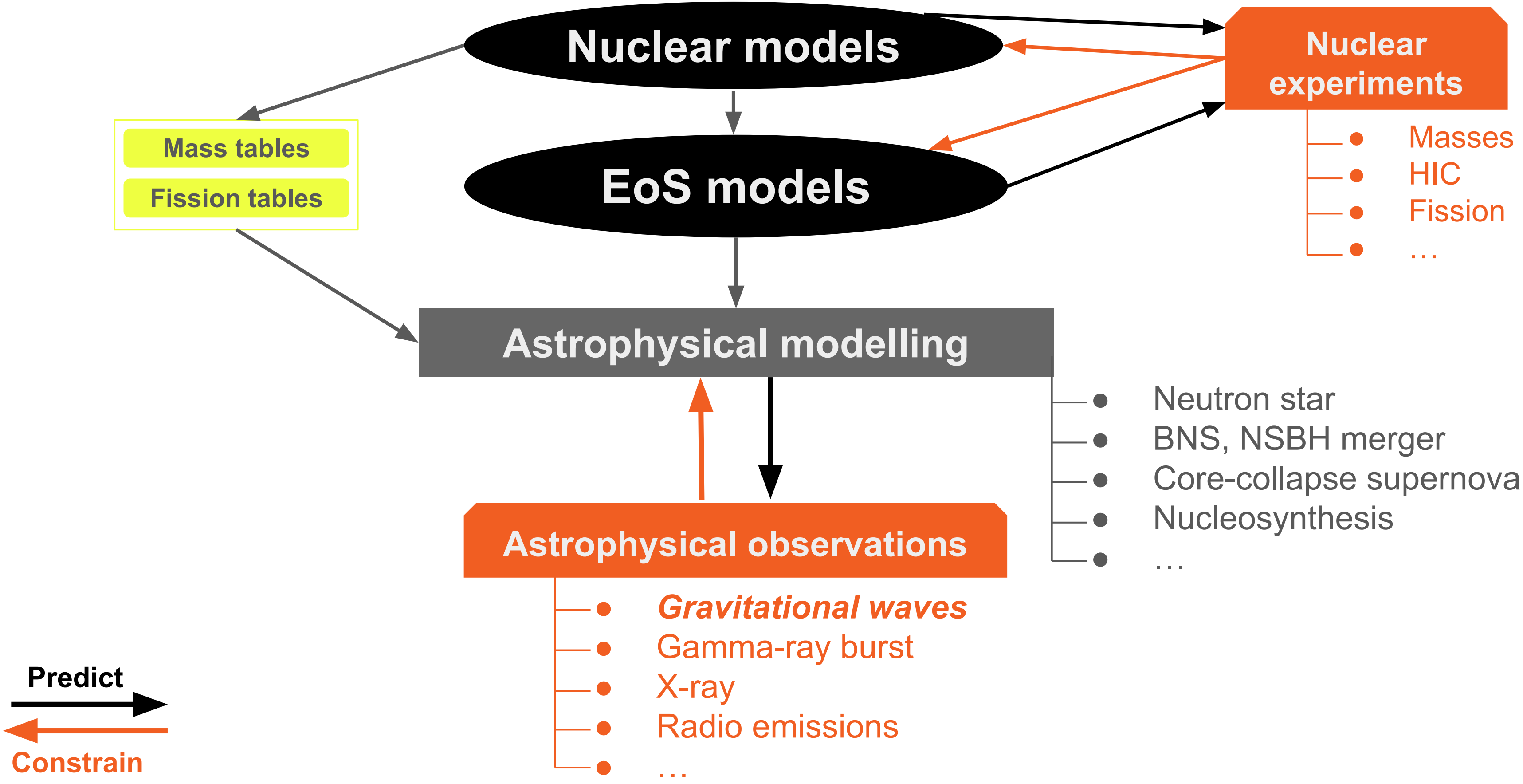


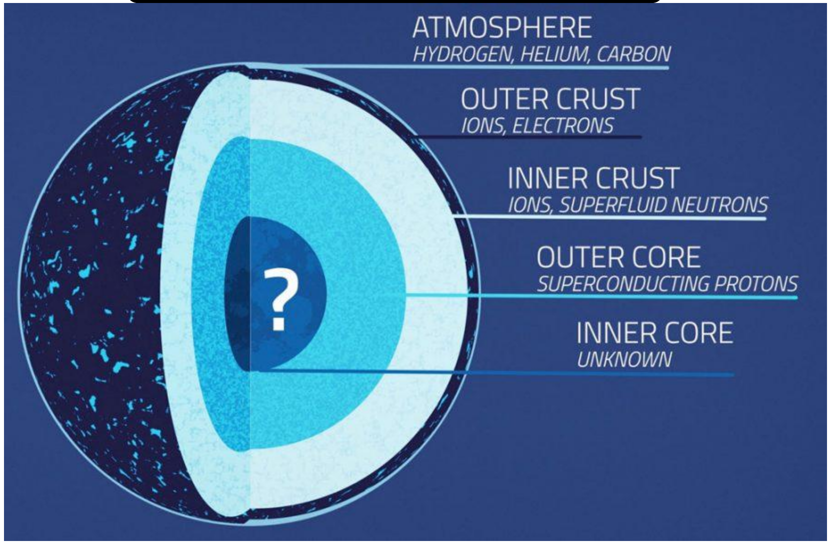


Nuclear physics role in the multimessenger era



Motivation

Neutron star physics



Nuclear physics inputs:

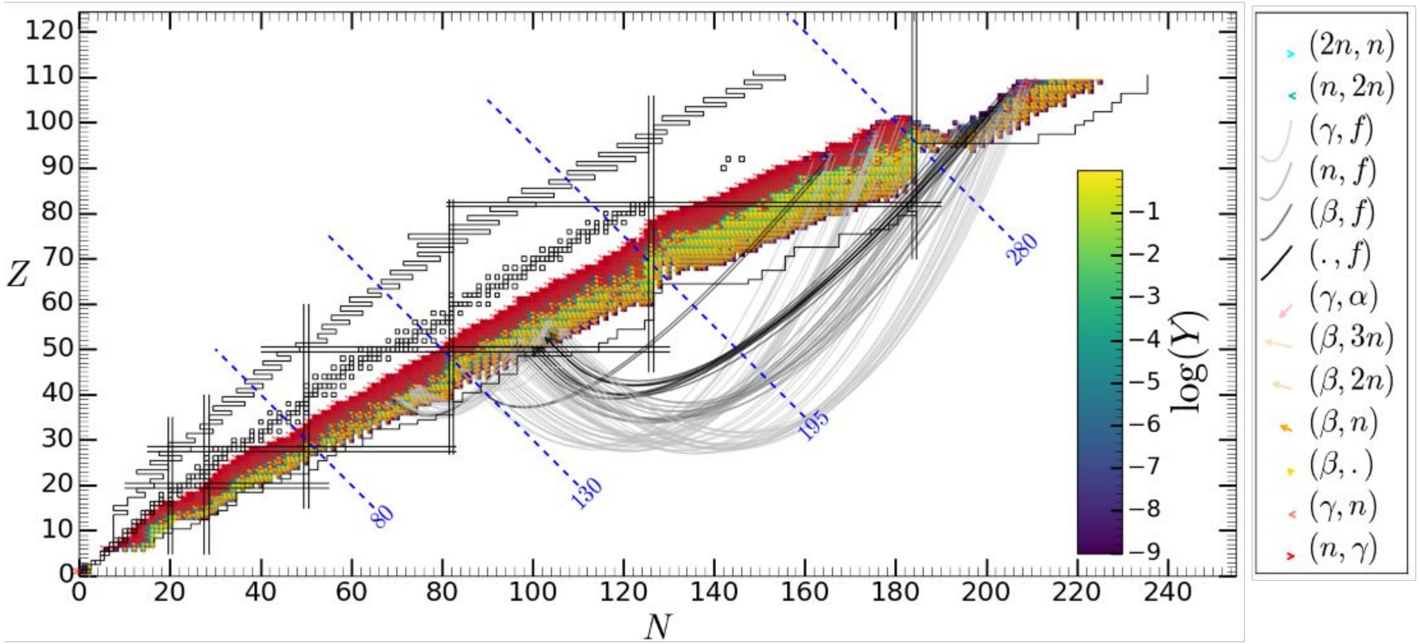
- **masses** -> crust;

- superfluidity -> inner crust and core.
- **infinite nuclear matter ->** crust and core.
- **interaction ->** crust and core.

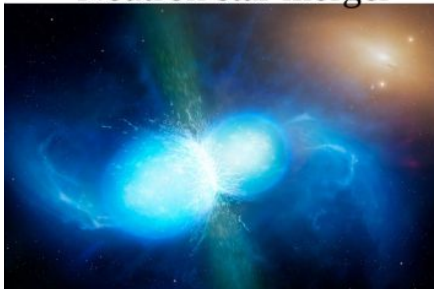
- phase transition(s) (quarks, hyperons, mesons,…) - > inner core.

Motivation

Nucleosynthesis



Neutron star merger



Supernova explosion

Description of **nuclear masses** and **fission** path in regions *unknown experimentally*.

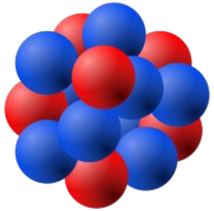
Energy Density Functional (EDF) theory

Energy

Coupling constants

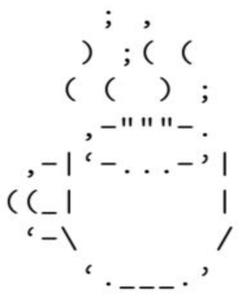
Local densities

$$E = C_1(\rho)\rho^2 + C_2(\rho)\rho\tau + C_3(\rho)\nabla\rho\nabla\rho + \ldots$$



- Effective description of nuclei based on one-body densities.
- **Good compromise between ab-initio and macroscopic calculations.**

Brussels-Skyrme-on-a-grid (BSkG)



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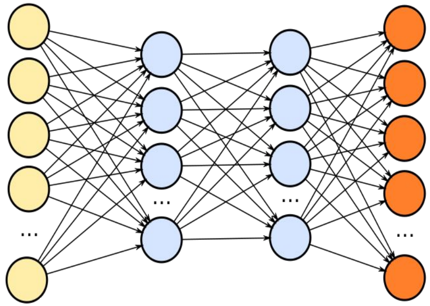
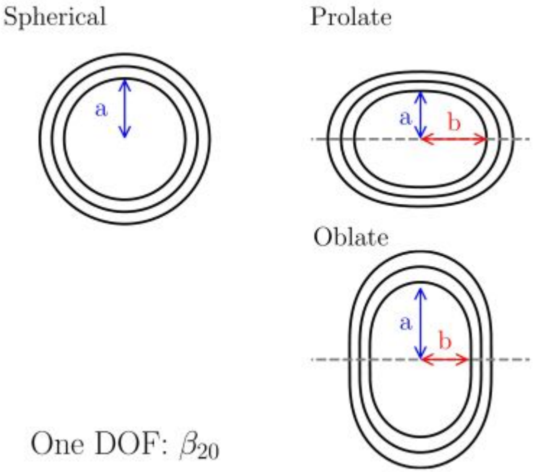


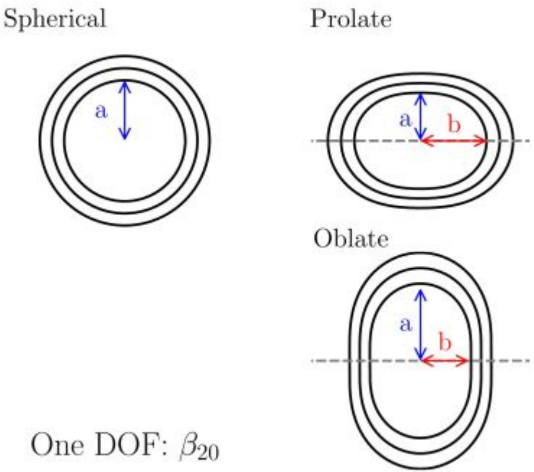
- Hartree-Fock-Bogoliubov (HFB) with a Skyrme force;
- *machine learning* to accelerate the fit.

Nuclear shapes



HFB solver : MOCCa

Nuclear shapes

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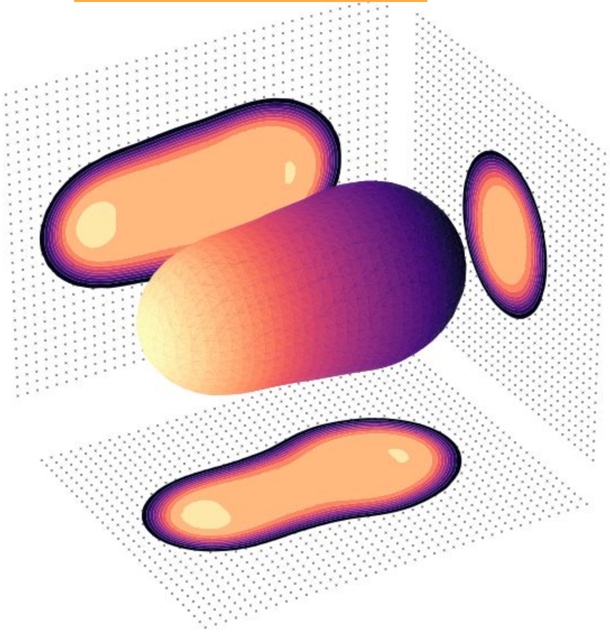
Triaxial + octupole



β_{20}, β_{22} and β_{30}

HFB solver at **3D coordinate-space.**
W. Ryssens PhD Thesis, ULB (2016).

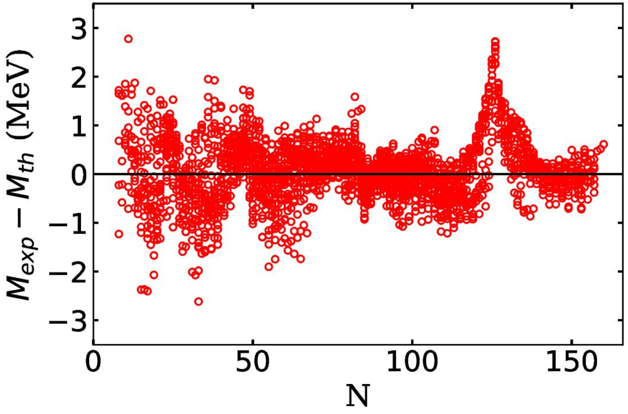
The BSkG3 mass model

Reproduction of known nuclear masses.

σ (M) = 0.631 MeV

σ (R_C) = 0.0237 fm

All 2457 nuclei in the AME2020.



GG, W. Ryssens, G. Scamps, S. Goriely and N. Chamel, EPJA **59**, 270 (2023).

The BSkG3 mass model

Reproduction of known nuclear masses.

σ (M) = 0.631 MeV

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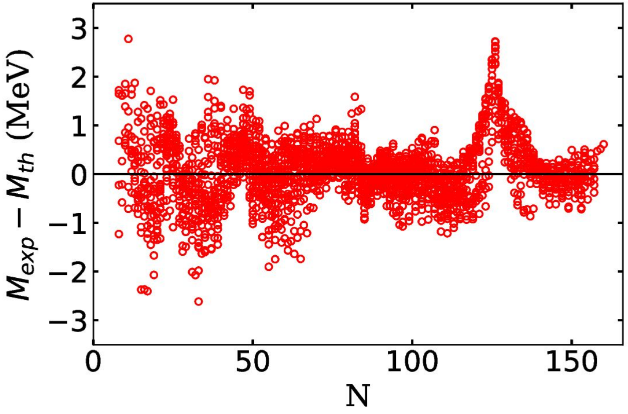
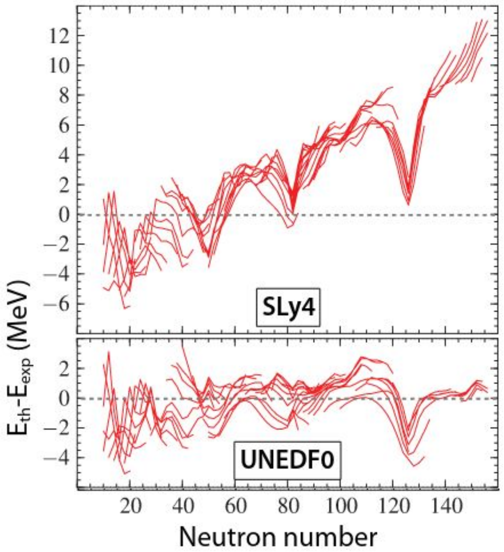
All 2457 nuclei in the AME2020.

Comparison:	
BSkG2 σ (M) = 0.678 MeV **BSkG1** σ (M) = 0.741 MeV	**SLy4** σ (M) = 4.80 MeV **UNEDF0** σ (M) = 1.45 MeV

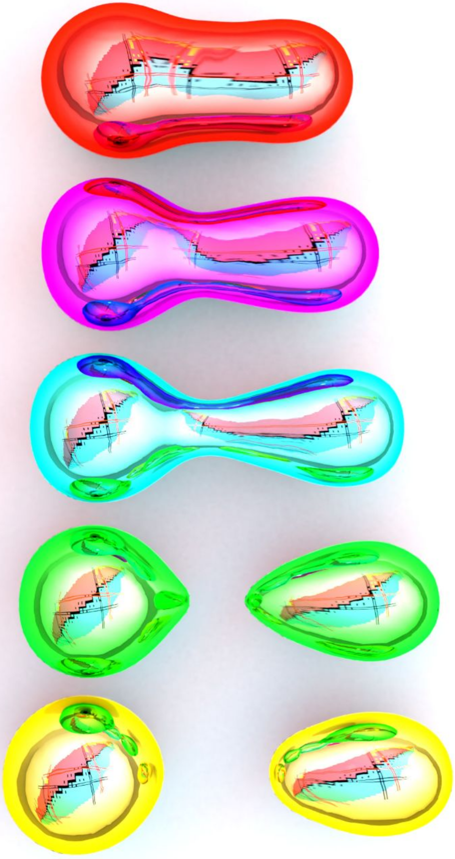




M. Kortelainen, et al., PRC 82, 024313 (2010)

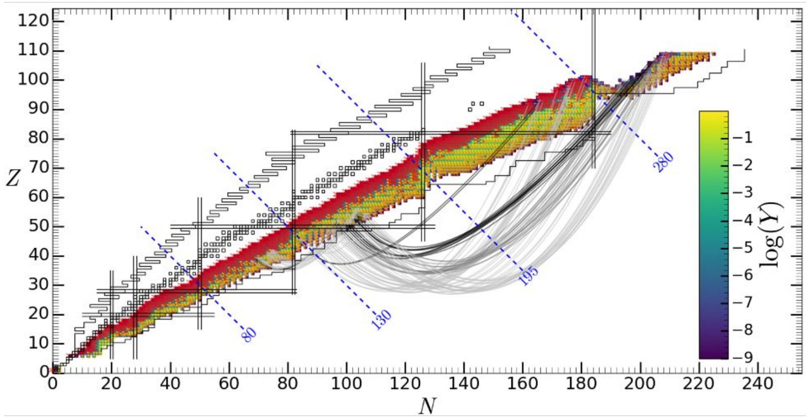
GG, W. Ryssens, G. Scamps, S. Goriely and N. Chamel, EPJA **59**, 270 (2023).

BSkG3 fission



Impact r-process nucleosynthesis:

- "**fission recycling**";
- the **r-process abundances** in the 110 ≤ A ≤ 170 region;
- the production of cosmic chronometers such as Th and U;
- the **heating rate of kilonovae**.



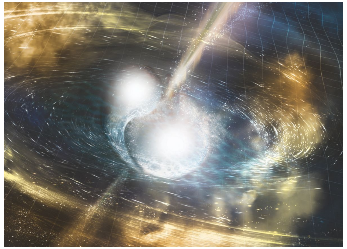


Fig from G. Scamps.

BSkG3 fission

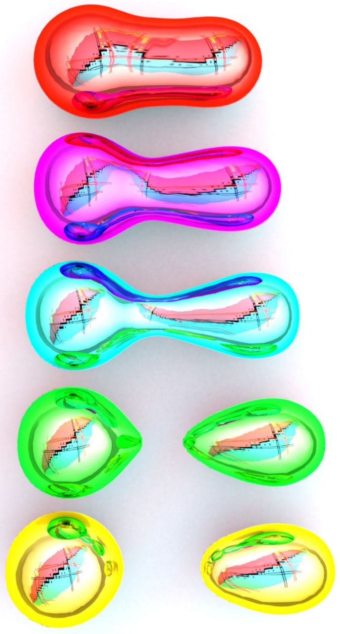
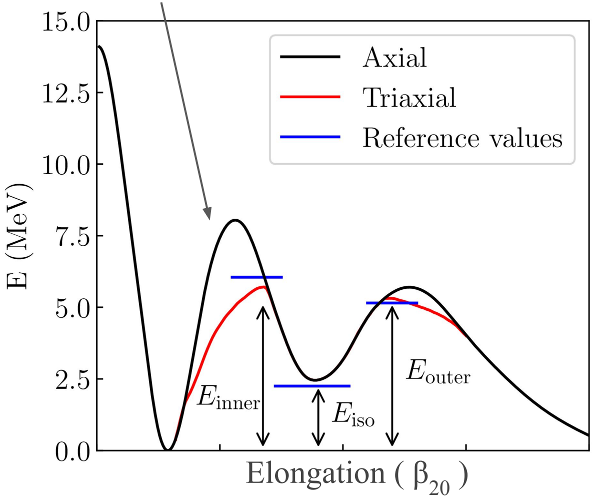


Fig from G. Scamps.

BSkG3:

σ (E_I) = 0.33 MeV
ε (E_I) = +0.06 MeV

Primary (E_I) ***fission barrier*** heights of actinide nuclei.



Comparison:

BSkG2
σ (E_I) = 0.44 MeV

HFB-14
σ (E_I) = 0.60 MeV

FRLDM
σ (E_I) = 0.81 MeV

BCPM
σ (E_I) = 1.42 MeV

SLy6
σ (E_I) = 3.89 MeV

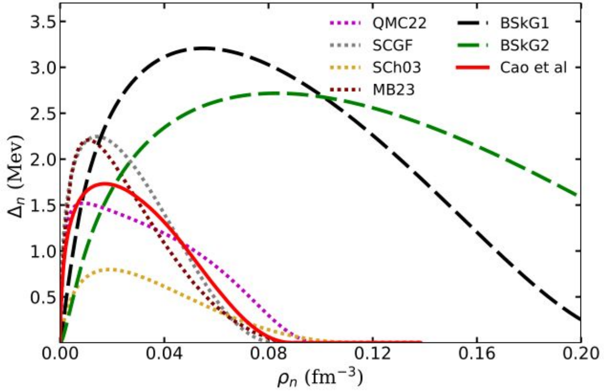
NL3
σ (E_I) = 2.18 MeV

DD-ME2
σ (E_I) = 3.35 MeV

GG, W. Ryssens, G. Scamps, S. Goriely and N. Chamel, EPJA **59**, 270 (2023).

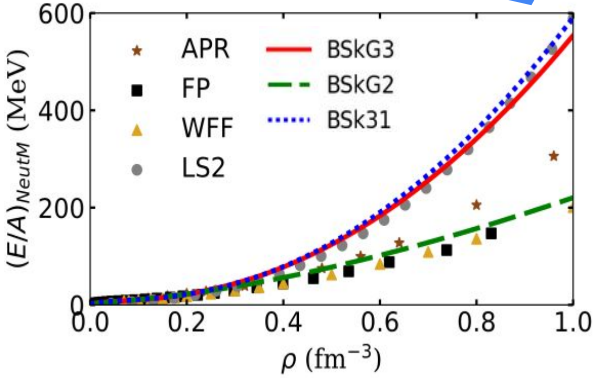
BSkG3 nuclear matter properties

NS inner crust



new **pairing** prescription

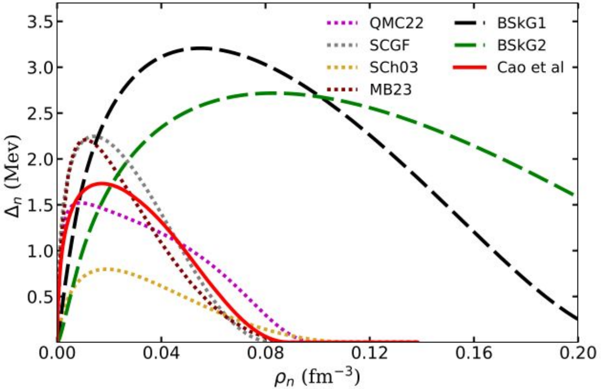
heavy neutron stars



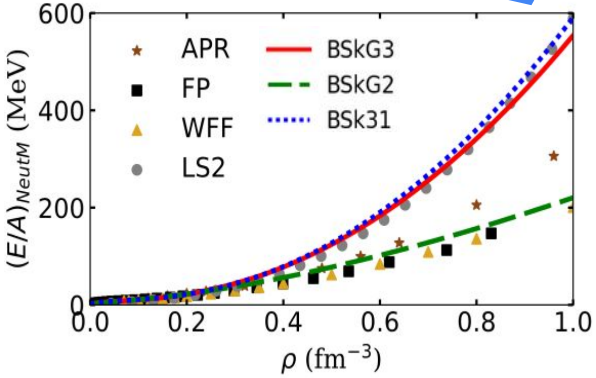
BSkG3 nuclear matter properties

NS inner crust

new **pairing** prescription



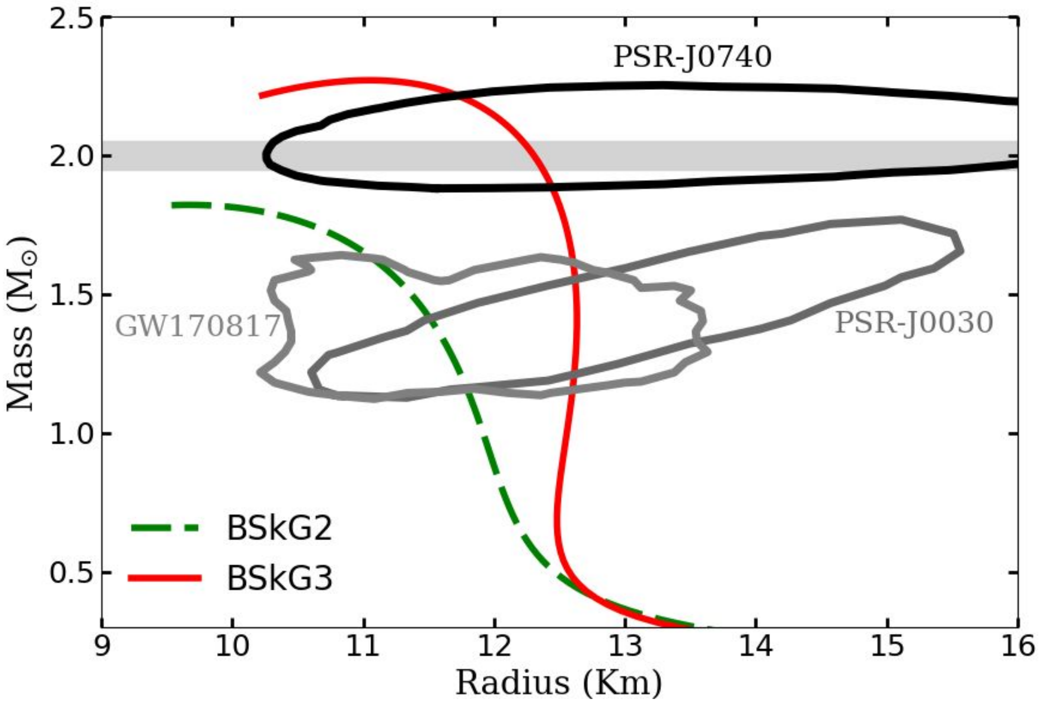
heavy neutron stars



Impacts NS seismology, glitches, cooling, and continuous GW emission.

Essential to describe heavy pulsars

BSkG3 neutron star

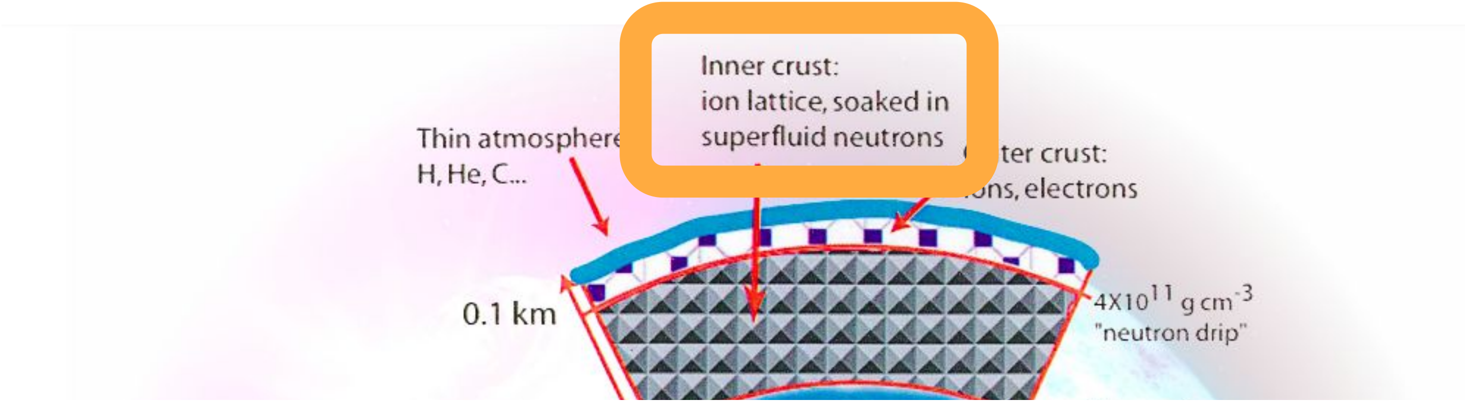


$R_{1.4}$ = 12.6 km

M_{max} = 2.3 Msun
R_{Mmax} = 11.1 km

GG, W. Ryssens, G. Scamps, S. Goriely and N. Chamel, EPJA **59**, 270 (2023).

Nuclear physics in neutron stars crust

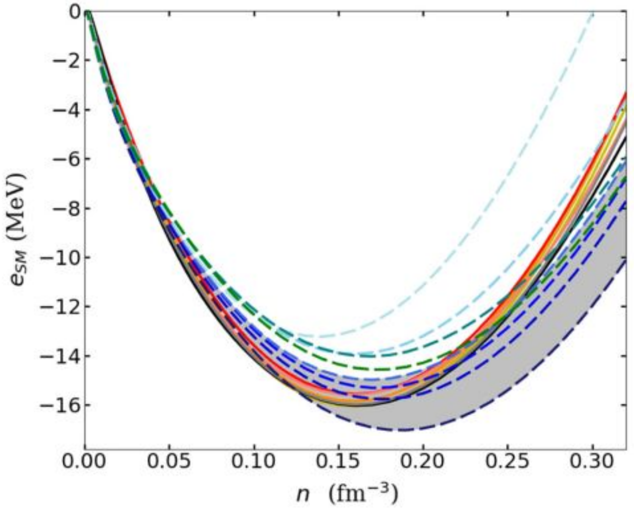


- Uncertainties from model predictions in the crust.
- Meta-model[1] + compressible liquid drop model.

1: J. Margueron et. al., PRC 97 025805 (2018).

Nuclear physics in neutron stars crust

Symmetric nuclear matter



clusters in the crust

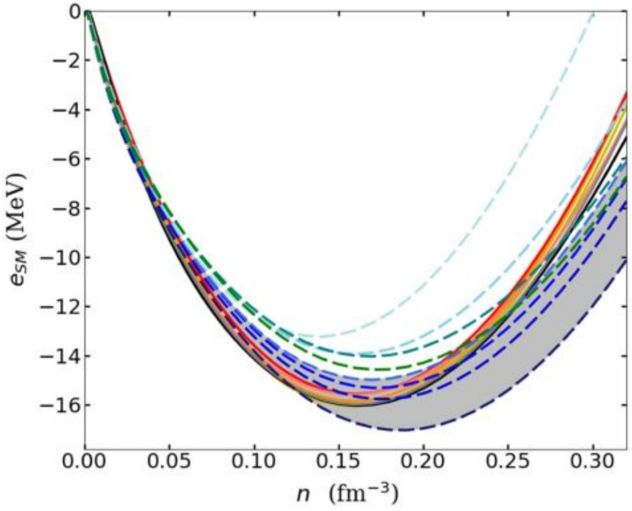
Skyrme

Chiral EFT

GG, J. Margueron, R. Somasundaram, and S. Reddy, EPJA **58**, 56 (2022).

Nuclear physics in neutron stars crust

Symmetric nuclear matter

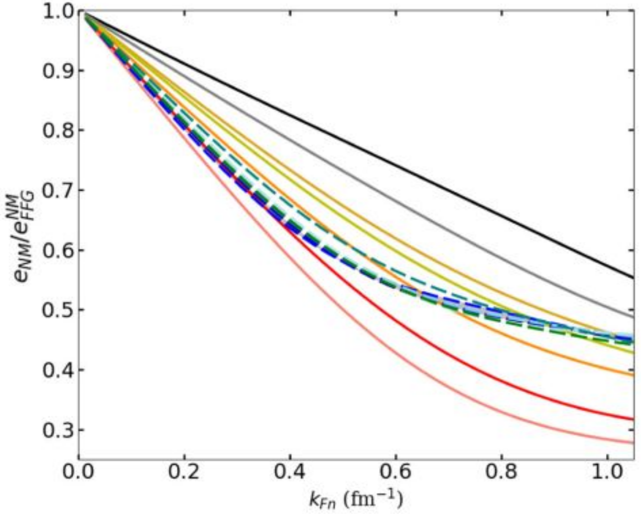


clusters in the crust

Skyrme

Chiral EFT

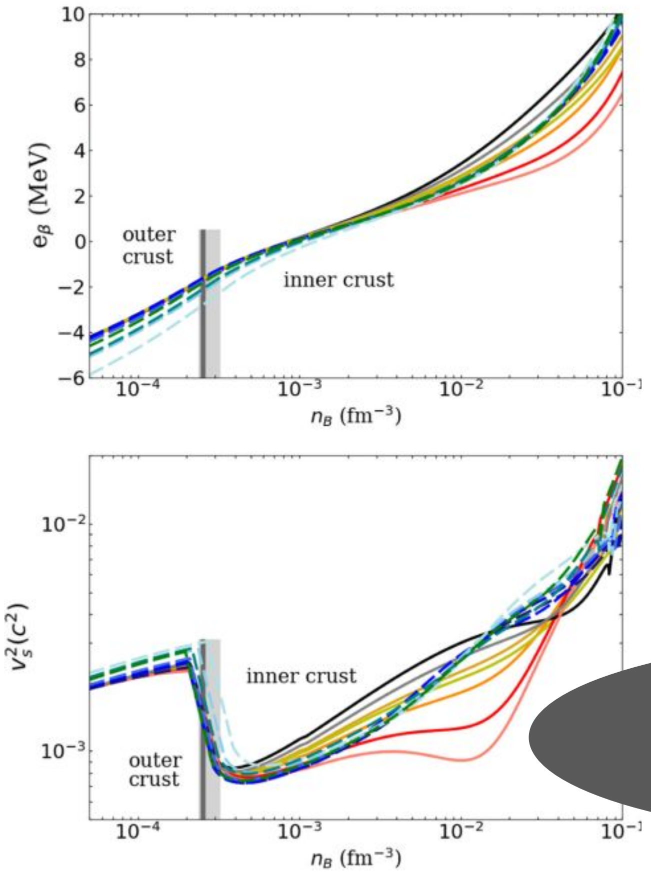
Pure neutron matter

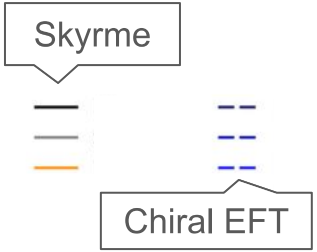


(super)fluid in the inner-crust

GG, J. Margueron, R. Somasundaram, and S. Reddy, EPJA **58**, 56 (2022).

Role of neutron and symmetric matter at the crust?

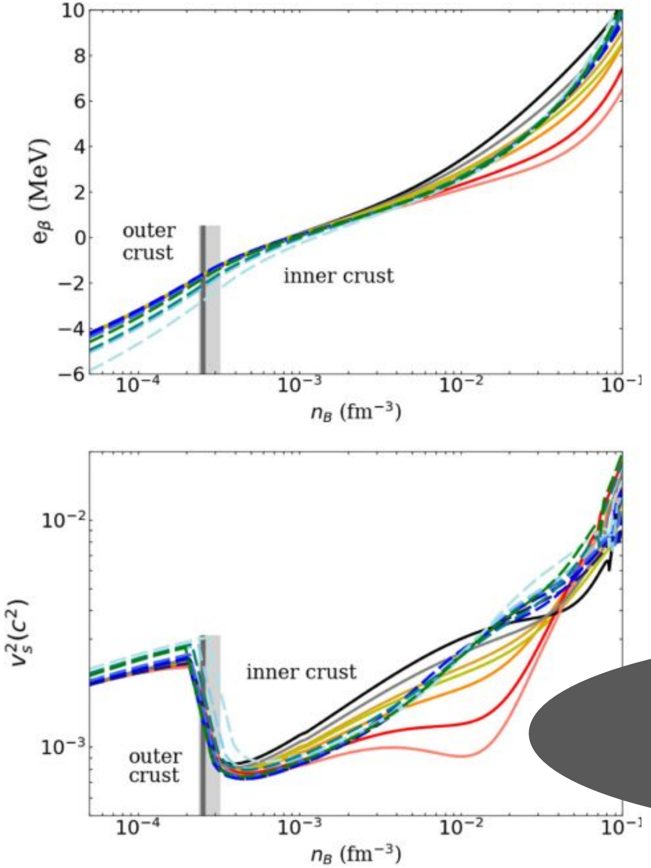


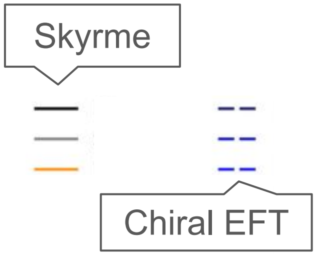


Neutron matter controls energy, and its derivatives

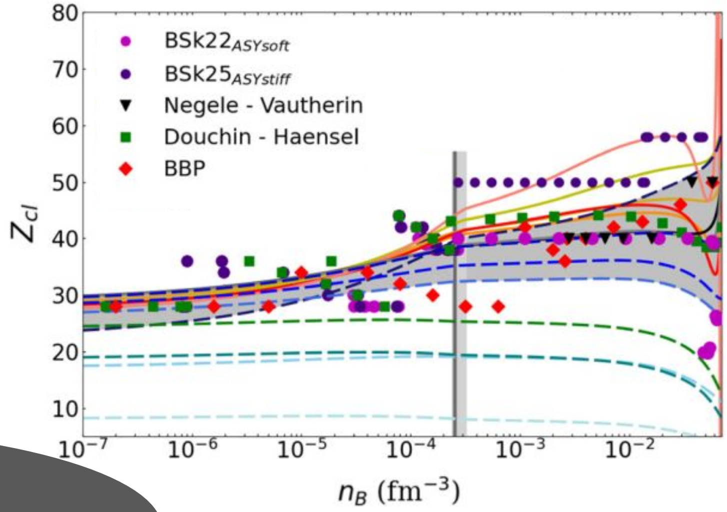
GG, J. Margueron, R. Somasundaram, and S. Reddy, EPJA **58**, 56 (2022).

Role of neutron and symmetric matter at the crust?





Symmetric matter controls composition (Z, A)



Neutron matter controls energy, and its derivatives

GG, J. Margueron, R. Somasundaram, and S. Reddy, EPJA **58**, 56 (2022).

Outlook

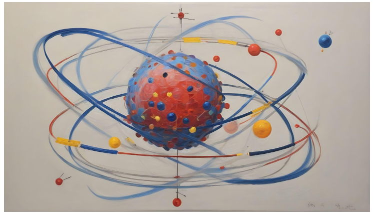
BSkG nuclear structure models

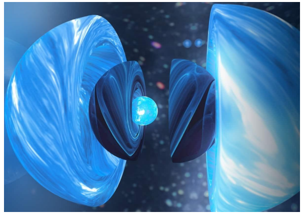
- Competitive for nuclear masses and radii.
- *Unmatched* for fission barriers.

- Link with experimental data.
- Break symmetries: triaxial, octupole shapes.
- **Inputs for neutron stars and nucleosynthesis.**

Uncertainties on NS crust

- Energy, pressure, sound speed, Ye, are controlled by *neutron matter* properties.
- Composition (Z, A) is controlled by symmetric matter and *experimental masses*.

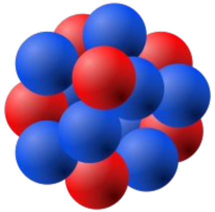


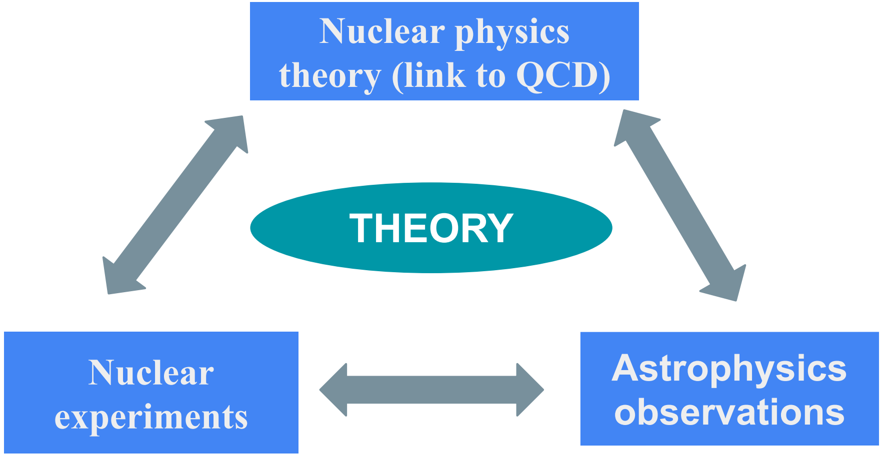


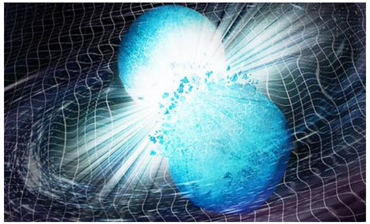
Outlook

- EoS of (hot) dense matter:
  - macroscopic models-Bayesian,
  - Machine learning,
  - Deformed HFB.

- **Impact on multi-messenger observations.**



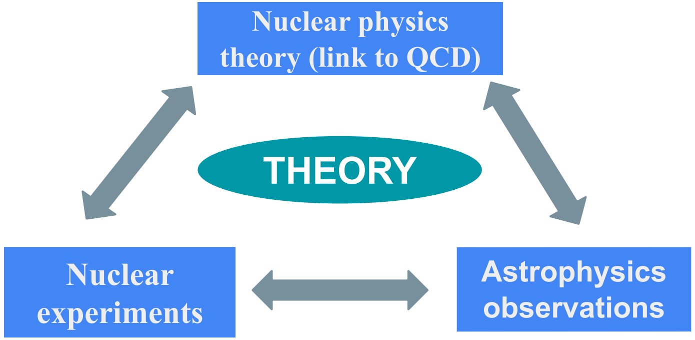




Acknowledgements

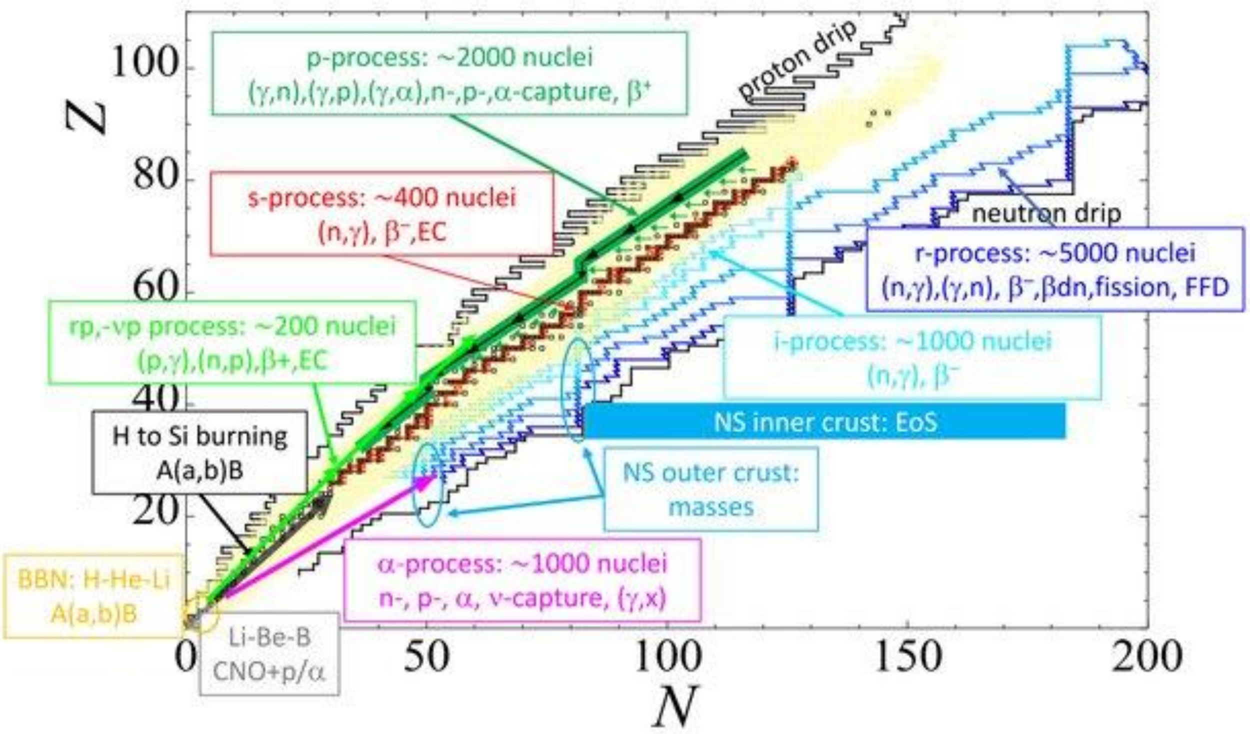
- Collaborators: Wouter Ryssens, Guillaume Scamps, Stephane Goriely, Nicolas Chamel, and Jérôme Margueron.
- Computational resources provided by the *Consortium des Équipements de Calcul Intensif* (CECI).
- Funding agencies FNRS and FWO.
- EVEREST and MANASLU EOS projects.

- **Thank you for the attention!**



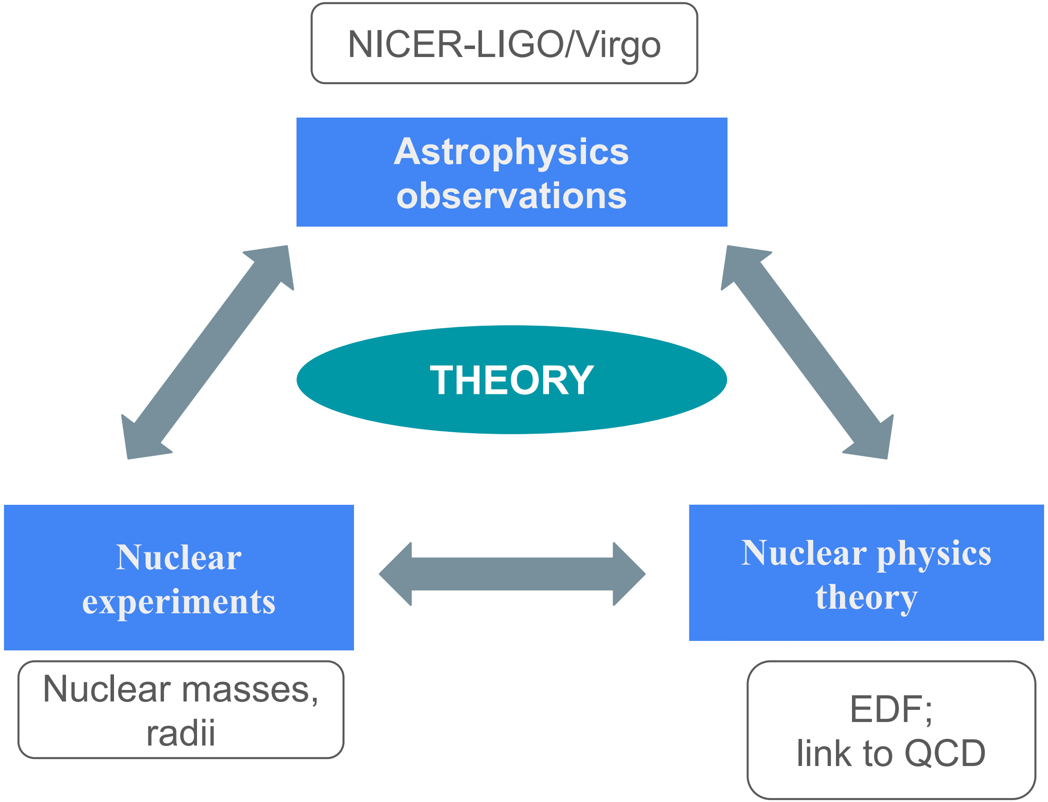
extra slides

Motivation



p-process: ~2000 nuclei
(γ,n),(γ,p),(γ,α),n-,p-,α-capture, β+
proton drip
s-process: ~400 nuclei
(n,γ), β−,EC
neutron drip
r-process: ~5000 nuclei
(n,γ),(γ,n), β−,βdn,fission, FFD
rp,-νp process: ~200 nuclei
(p,γ),(n,p),β+,EC
i-process: ~1000 nuclei
(n,γ), β−
NS inner crust: EoS
H to Si burning
A(a,b)B
NS outer crust:
masses
BBN: H-He-Li
A(a,b)B
α-process: ~1000 nuclei
n-, p-, α, ν-capture, (γ,x)
Li-Be-B
CNO+p/α
Z
N
100
80
60
40
20
0
50
100
150
200

Summary


NICER-LIGO/Virgo
Astrophysics observations
THEORY
Nuclear experiments
Nuclear physics theory
Nuclear masses, radii
EDF; link to QCD

Nuclear physics in neutron stars crust

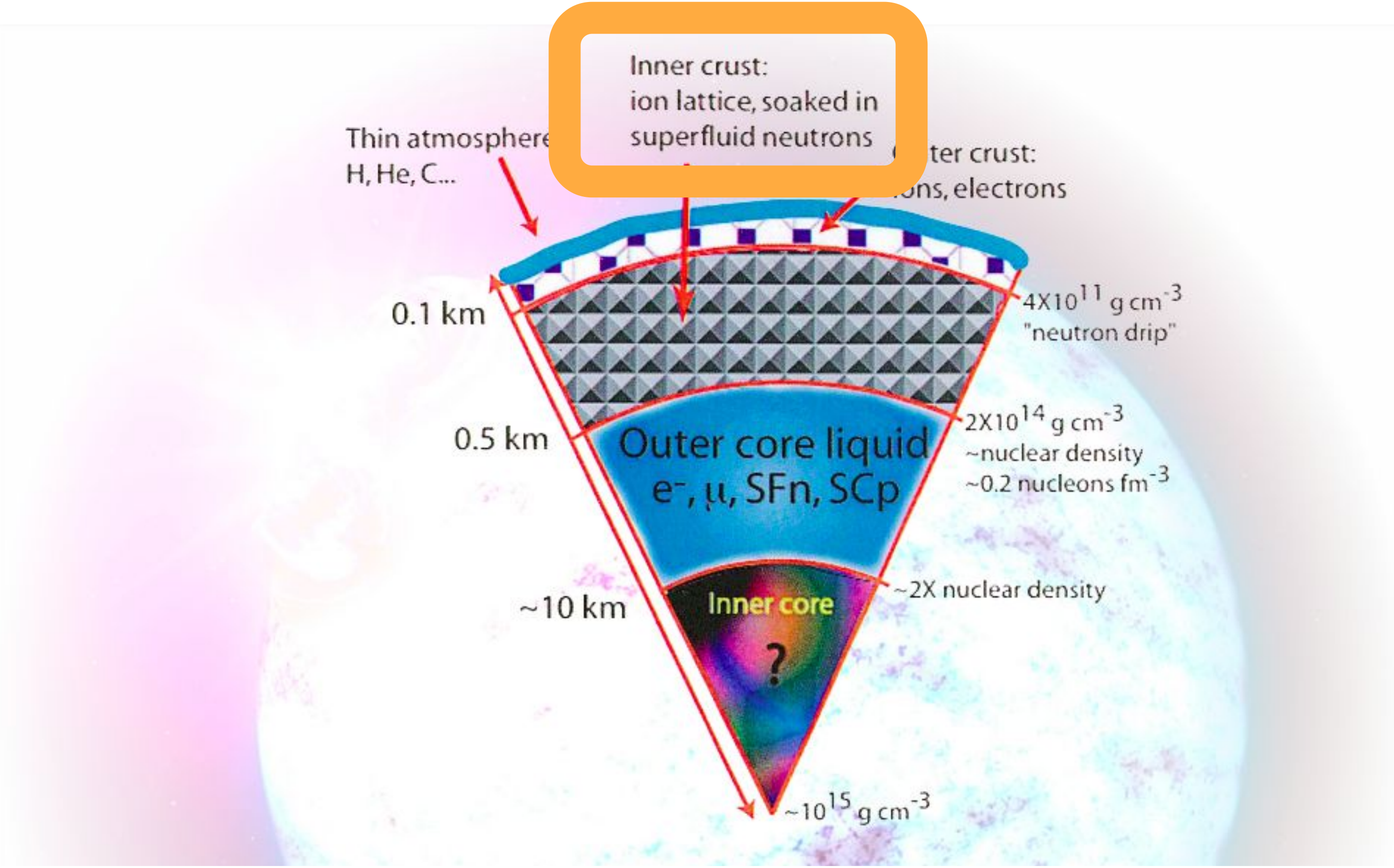
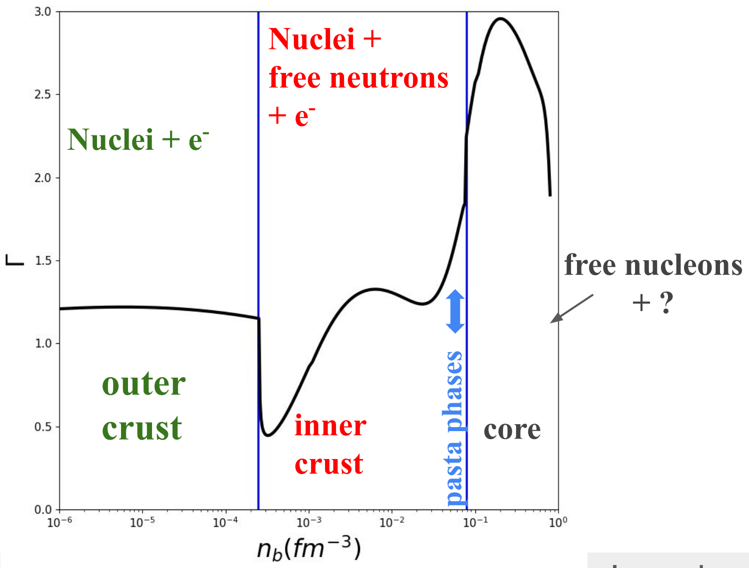


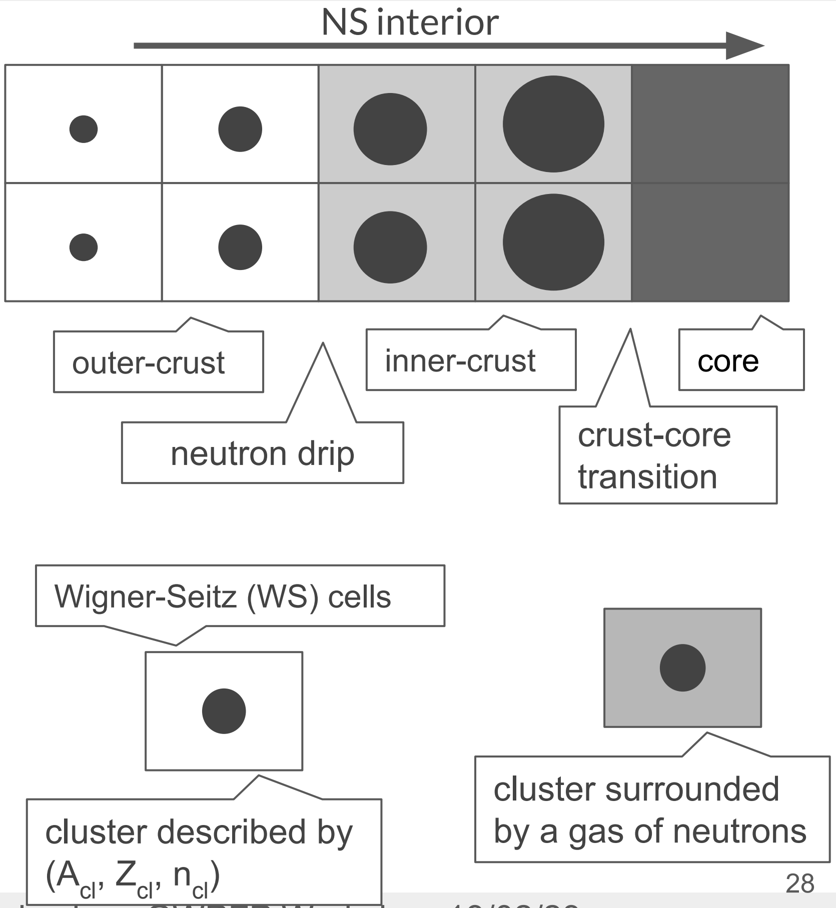
Fig. from Arzoumanian et. al. (2009) arXiv:0902.3264

Finite size effects / nuclei description

Unified EoS = same nuclear interaction to describe:

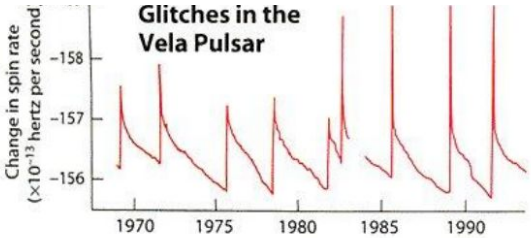
1. Bulk contribution in the cluster (A_{cl}, Z_{cl});
2. Neutron gas;
3. Homogeneous matter (core).



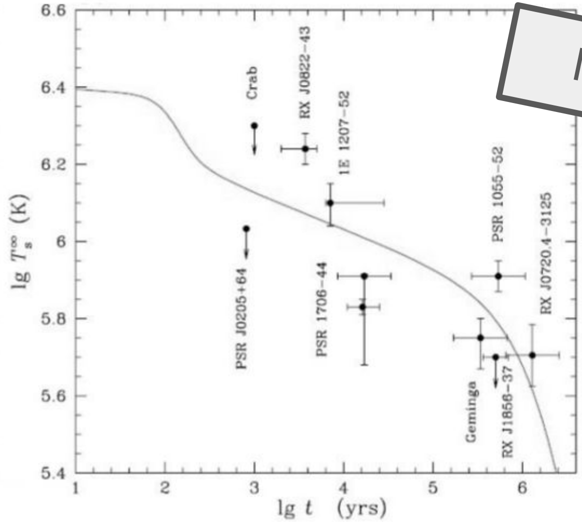


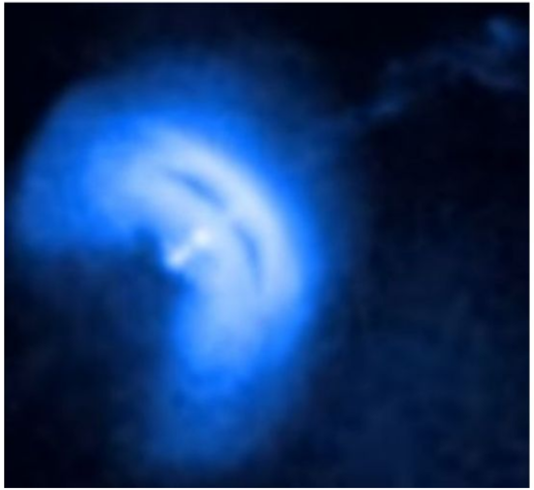
Pairing on NS inner crust

Essential to describe **superfluids** in NSs.

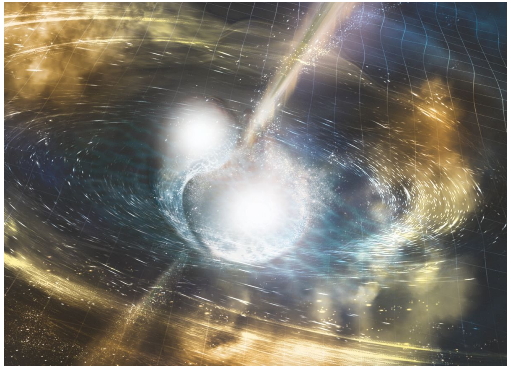


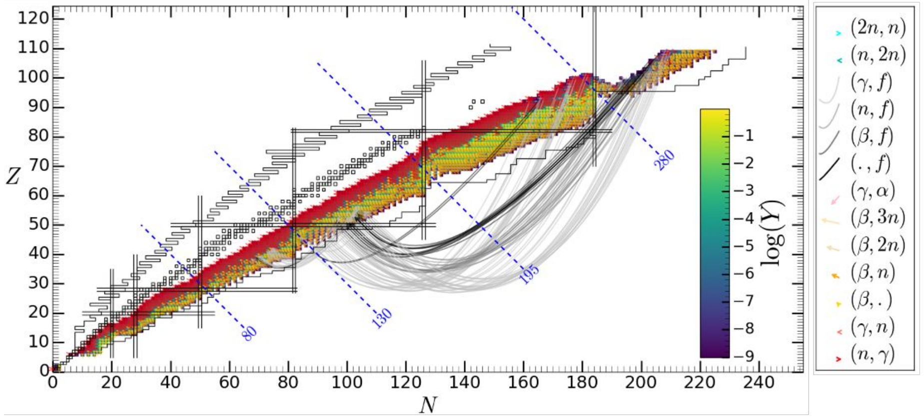
NS cooling





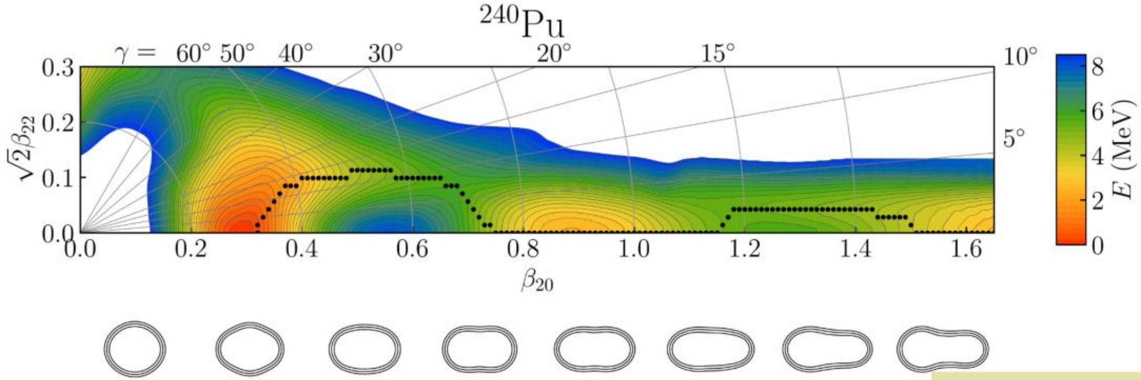
BSkG3 fission barriers



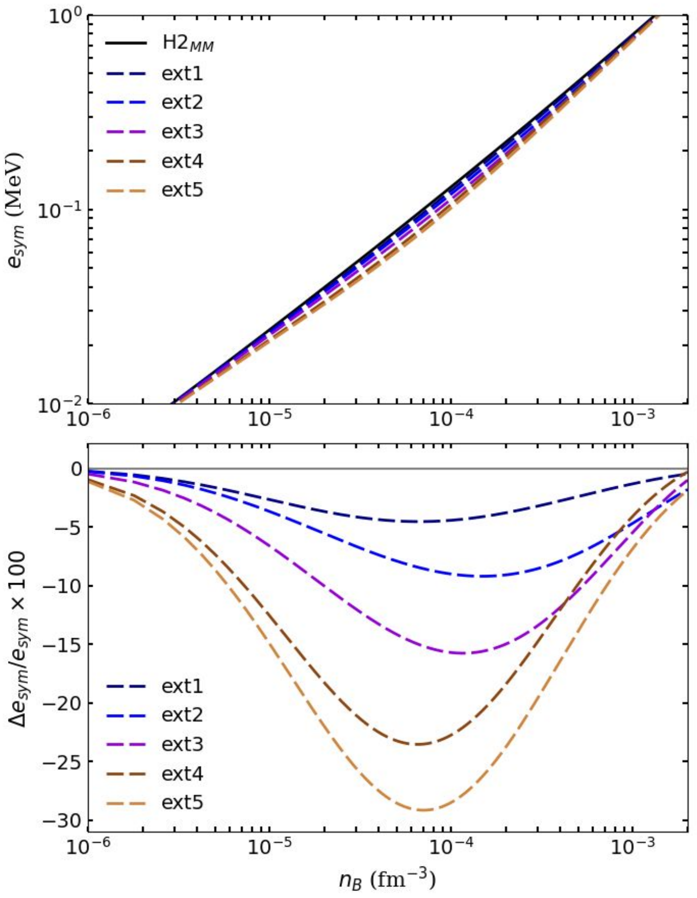


Fission properties impact several aspects of the r-process such as:

- the details of "**fission recycling**";
- the **r-process abundances** in the 110 ≤ A ≤ 170 region;
- the production of cosmic chronometers such as Th and U;
- the **heating rate of kilonovae**.

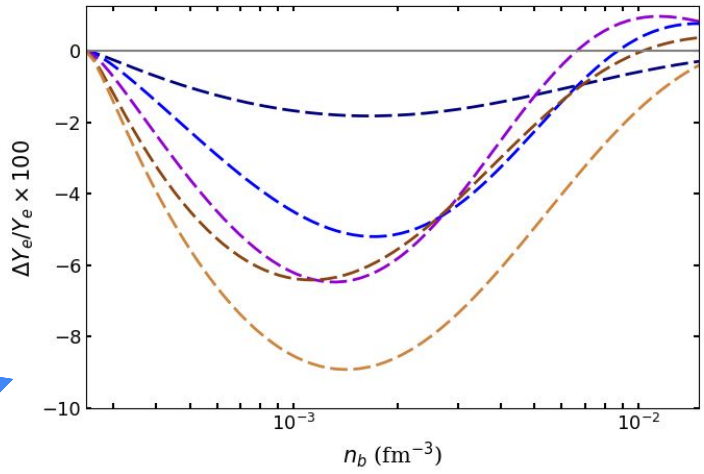


Dilute neutron matter in the NS inner crust



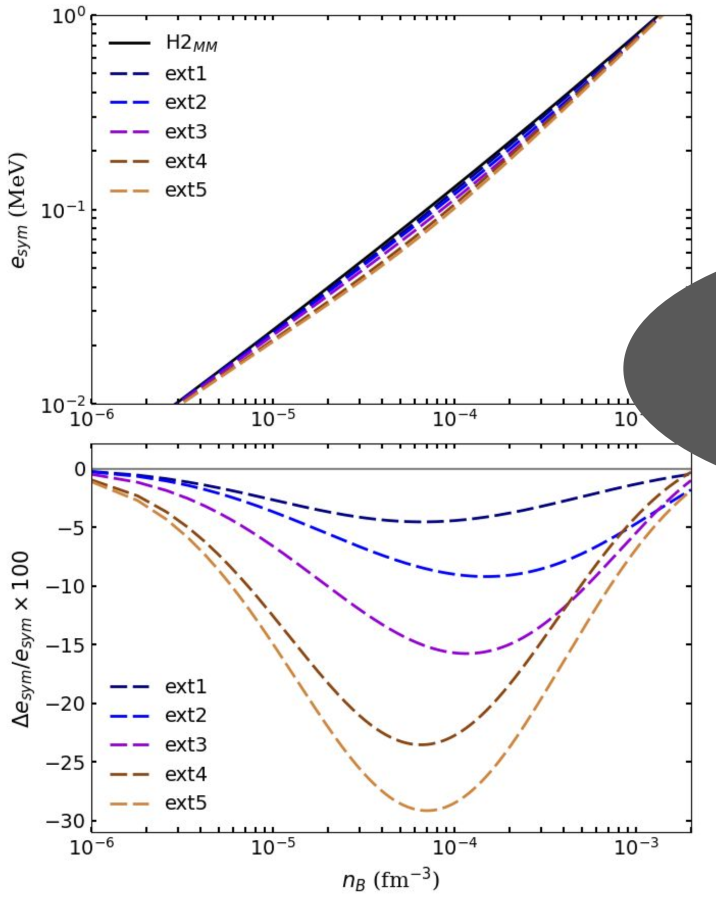
Neutron matter energy impacts the *symmetry energy*:
esym = eNeutM - eSM

Symmetry energy controls particle fractions



GG and J. Margueron, arXiv:2401.13590 (2024).

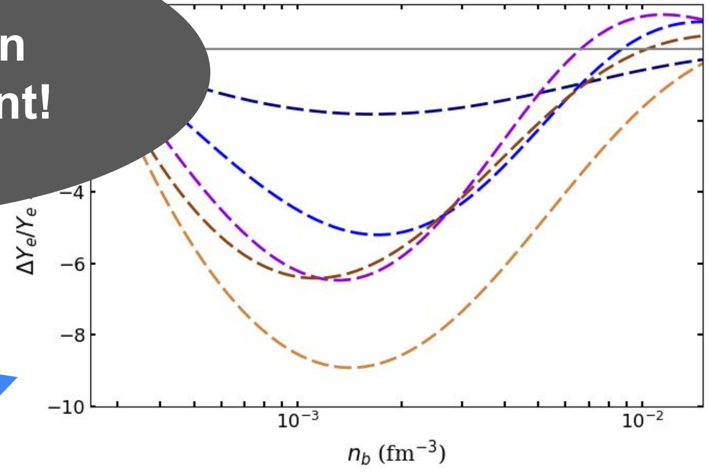
Dilute neutron matter in the NS inner crust



Neutron matter energy impacts the *symmetry energy*: esym = eNeutM - eSM

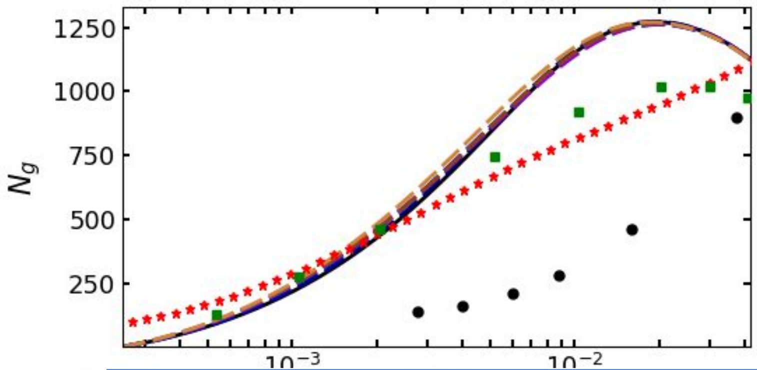
Effect on neutron matter is important!

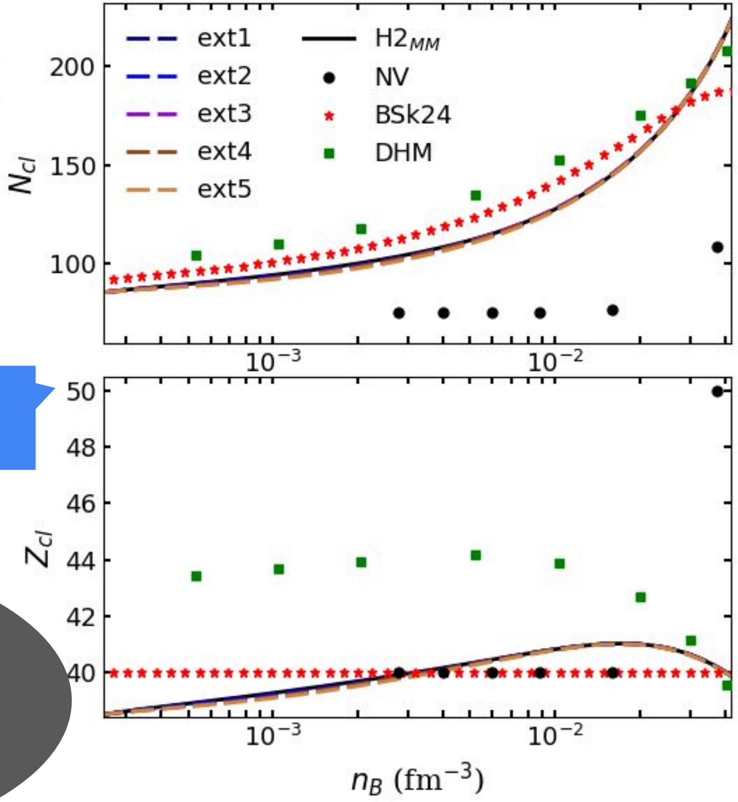
Symmetry energy controls particle fractions



GG and J. Margueron, arXiv:2401.13590 (2024).

Dilute neutron matter in the NS inner crust





Composition (A, Z) controlled by the mean-field.

Impurities in the NS crust reduce the impact expected from neutron matter

GG and J. Margueron, arXiv:2401.13590 (2024).