Properties of neutron star crust within nuclear physics uncertainties

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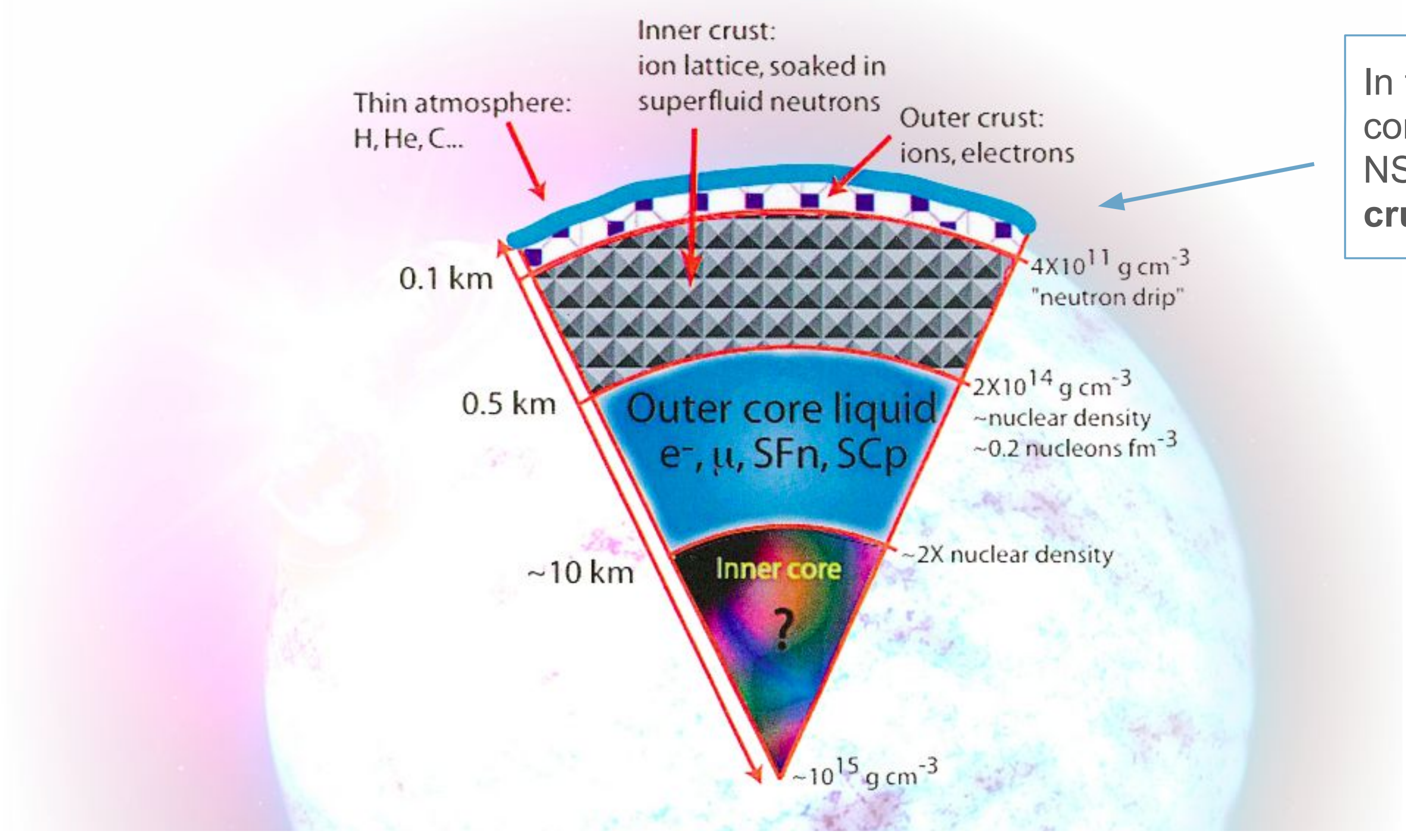
Presentation to Master Project MAC
28/05/2021

Neutron star structure



In this work I concentrate in the NS outer and inner **crust**.

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

Meta-model within CLDM + finite size terms

First: Homogeneous matter

1. Use the flexibility of the meta-model to **fit** a set of Hamiltonians based on NN and 3N **chiral interactions**.
2. Add high density constraint to obtain a 2Msun NS.

Second: Inhomogeneous matter

1. Use a Compressible Liquid Drop model (CLDM).
2. Introduce four ordered finite (FS) size models.
3. Fit CLDM parameters to nuclear masses.

WORK

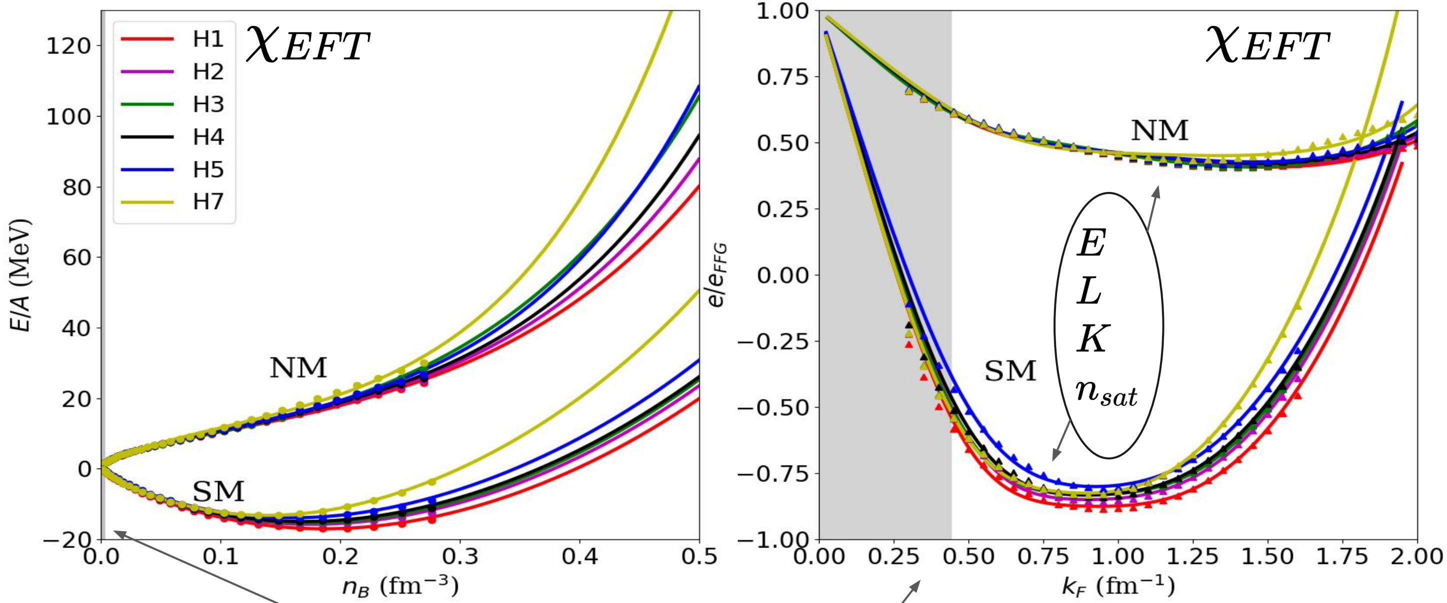
- Analyze the FS models, and the Hamiltonians, on finite nuclei and NS crust properties.

Homogeneous matter

$$E_{sat}(n) = E_{sat} + \frac{1}{2}K_{sat}x^2 + \frac{1}{6}Q_{sat}x^3 + \frac{1}{24}Z_{sat}x^4$$

$$x = \frac{n - n_{sat}}{3n_{sat}}$$

$$E_{sym}(n) = E_{sym} + L_{sym}x + \frac{1}{2}K_{sym}x^2 + \frac{1}{6}Q_{sym}x^3 + \frac{1}{24}Z_{sym}x^4$$

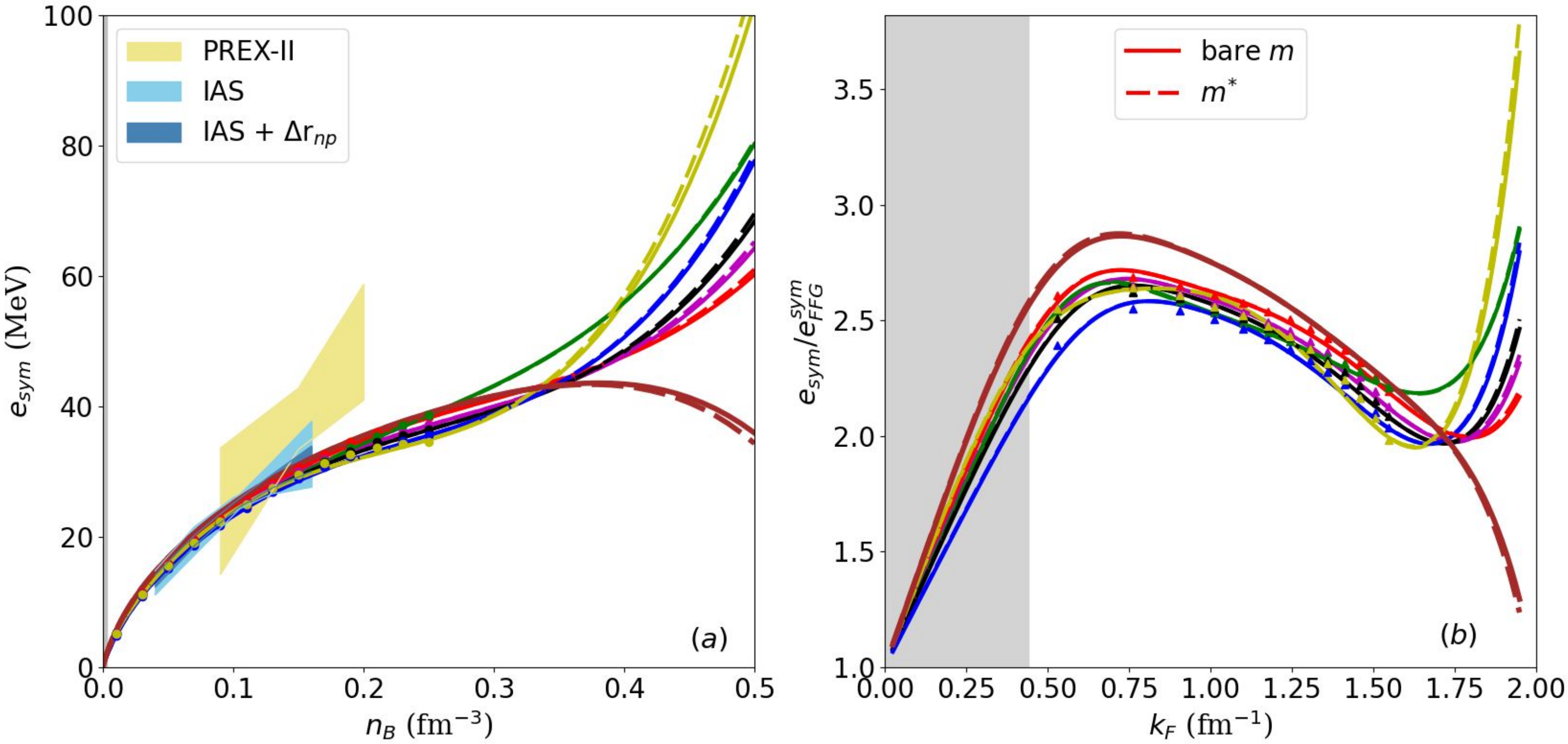


$2M_\odot NS$

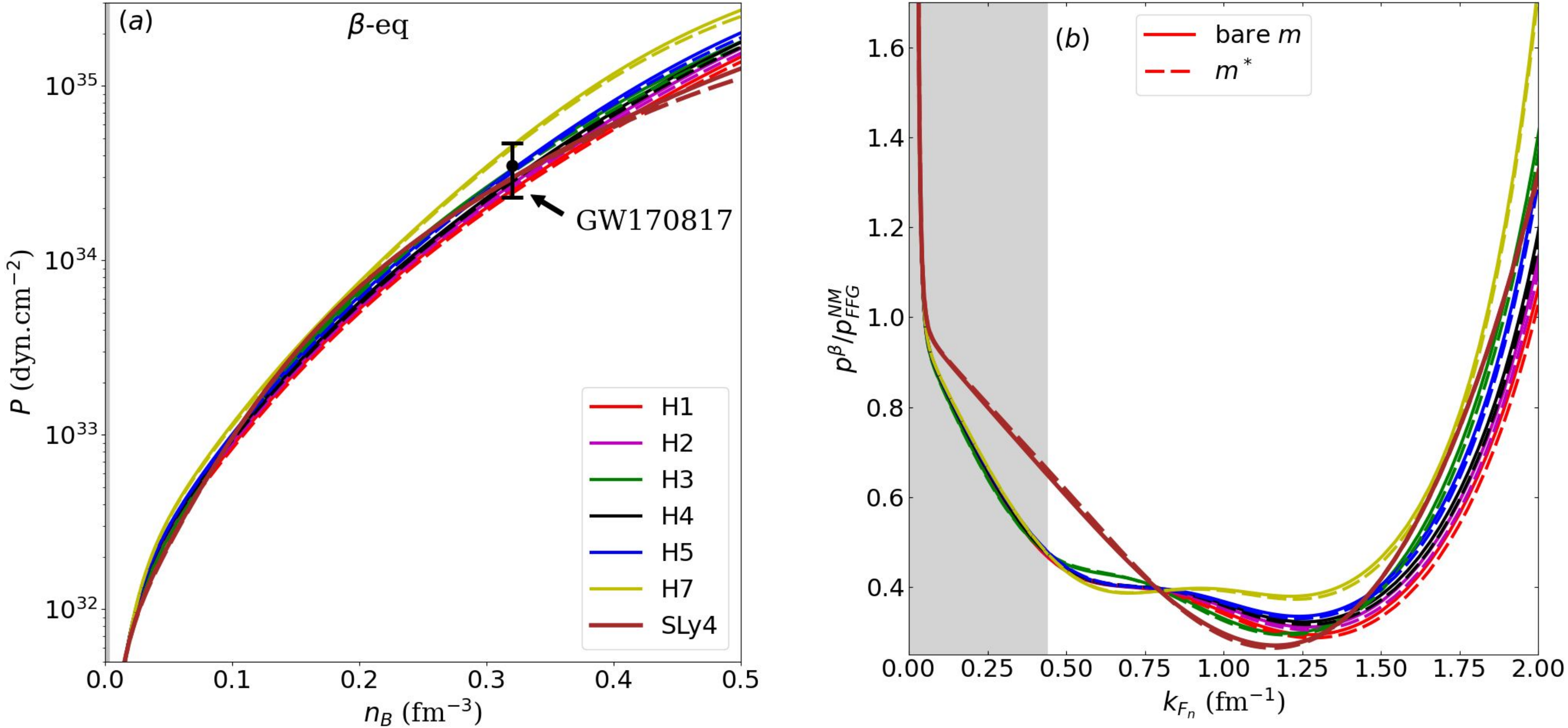
Q
Z

limit of the fit

Homogeneous matter



Homogeneous matter



Finite nuclei in CLDM

$$E_{nuc}(A, I, n_{cl}) = E_{bulk}(A, I, n_{cl}) + E_{FS}(A, I, n_{cl,} n_e = 0)$$

$$E_{FS}(A, I, n_{cl}) = E_{coul}(A, I, n_{cl}) + E_{surf}(A, I, n_{cl}) + E_{curv}(A, I, n_{cl})$$

Model	Variables	FS1	FS2	FS3	FS4
Bulk from MM	$(I,\ n_{cl})$	×	×	×	×
FS Surface	(n_{sat})	×	–	–	–
FS Coulomb (Dir.)	(n_{sat})	×	–	–	–
FS Surface	(n_{cl})	–	×	×	×
FS Coulomb (Dir.)	(n_{cl})	–	×	×	×
FS Curvature	(n_{cl})	–	–	×	×
FS Coulomb (Ex.)	(n_{cl})	–	–	–	×
Number of param.		3	3	5	5

The surface and curvature contributions:

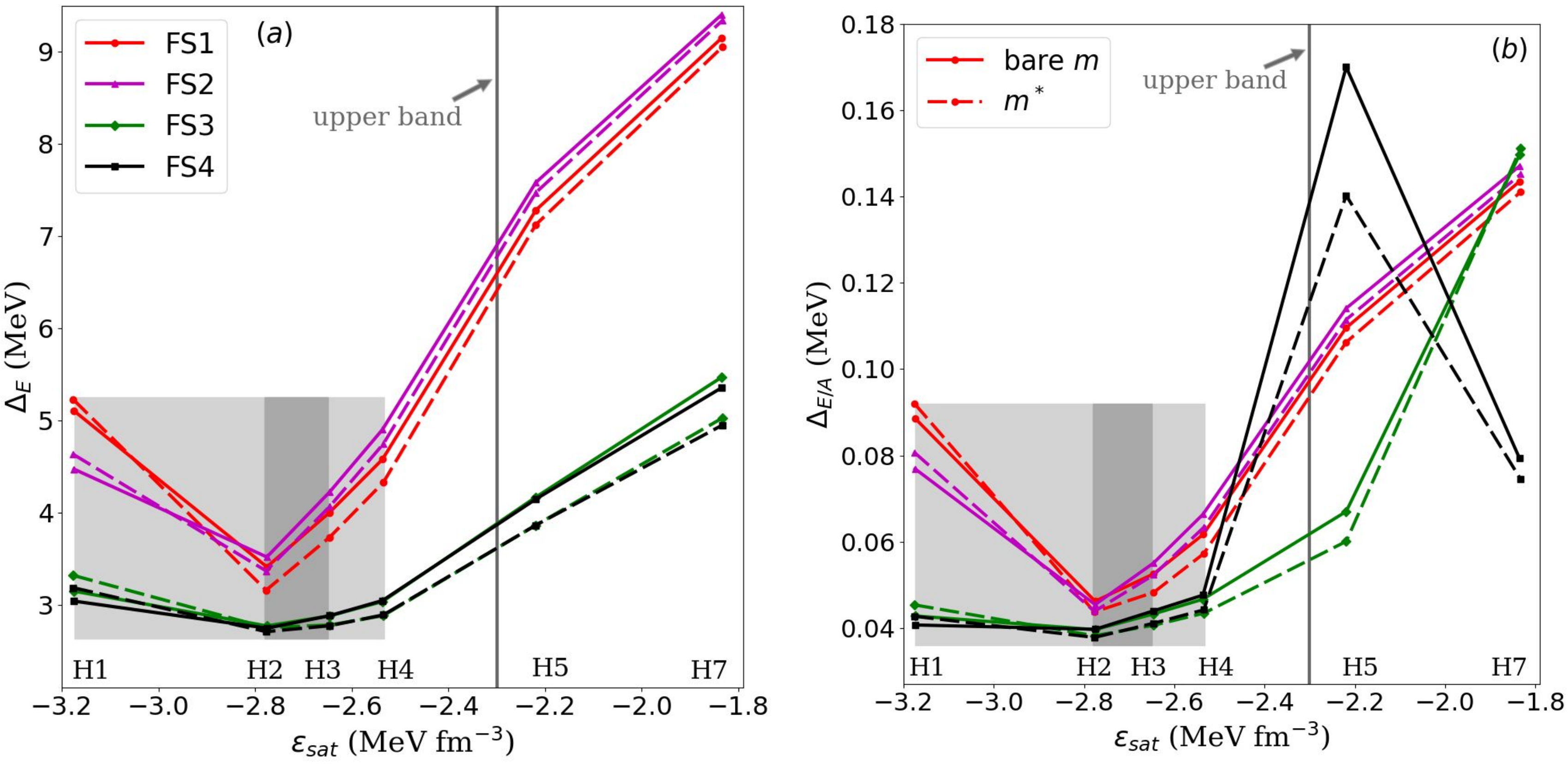
$$E_{surf}(A, I, n_{cl}) = 4\pi R_{cl}^2 \sigma_{surf}(I)$$

$$E_{curv}(A, I, n_{cl}) = 8\pi R_{cl} \sigma_{curv}(I)$$

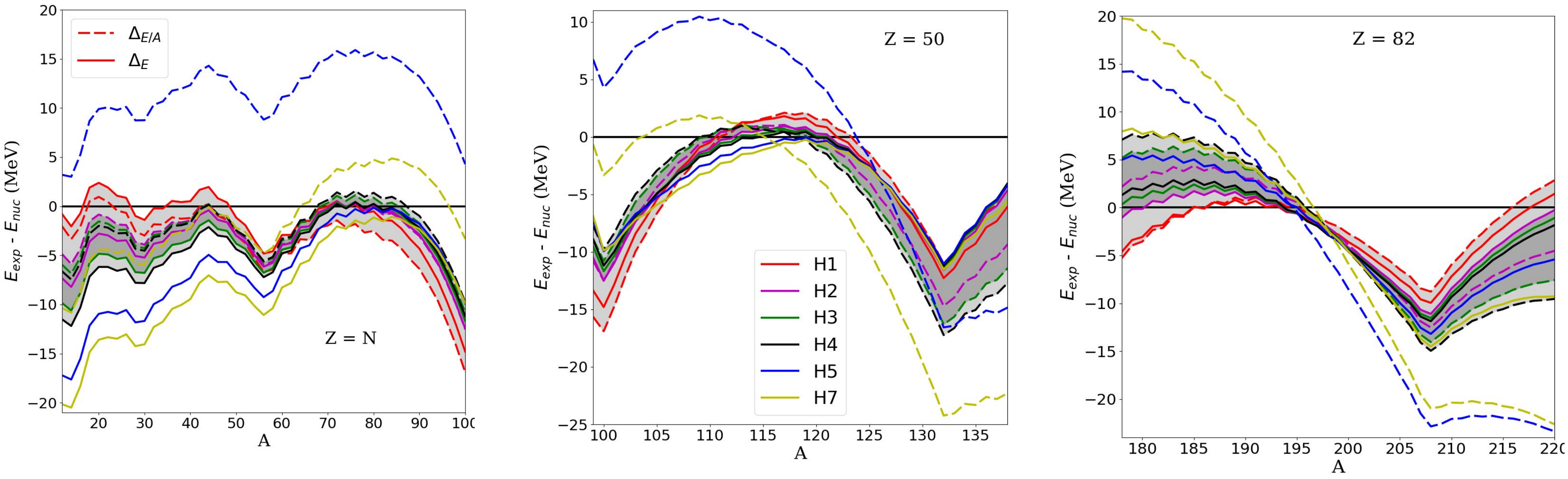
$$\sigma_{surf}(I) = \sigma_{surf,sat} \frac{2^{p_{surf}+1} + b_{surf}}{Y_p^{-p_{surf}} + b_{surf} + (1-Y_p)^{-p_{surf}}}$$

$$\sigma_{curv}(I) = \sigma_{curv,sat} \frac{\sigma_{surf}(I)}{\sigma_{surf,sat}} \alpha \left[\beta_{curv} - \frac{1-I}{2}\right]$$

Cost function for the different models

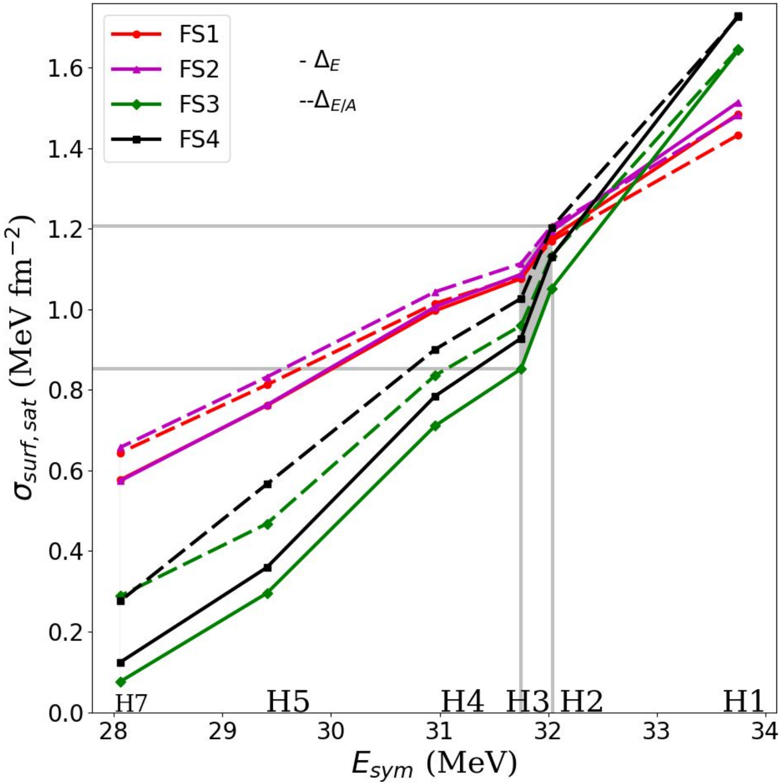


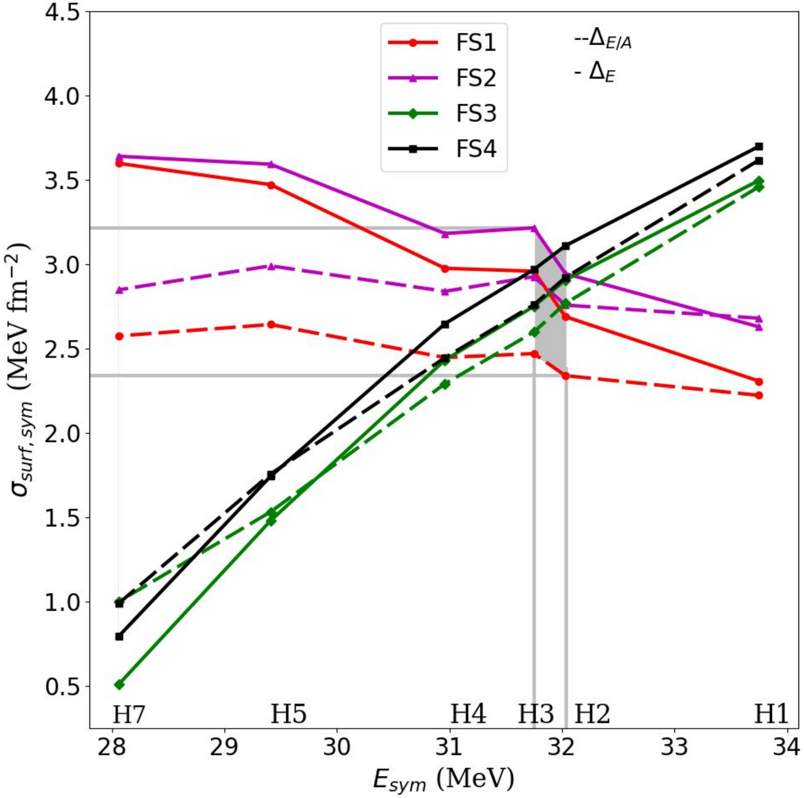
Residuals for the six Hamiltonians



FS4 model

Inhomogeneous matter





Unified EoS for neutron star

- Crust modeled in a CLDM approach.
- Nuclear interaction given by the meta-model fitted to chiral EFT.

System composed by clusters, free neutrons and electrons.

Equilibrium equations:

1.Virial theorem: $$2E_{coul} = E_{surf} + 2E_{curv}\,,$$

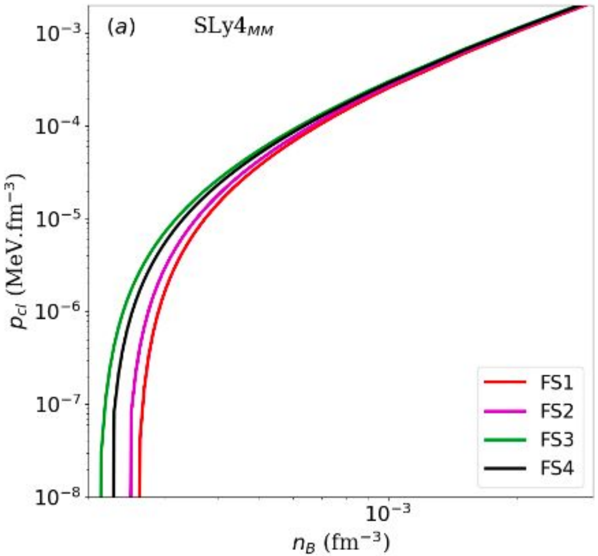
2. Mechanical equilibrium: $$P_{cl} = P_{gas}\,,$$

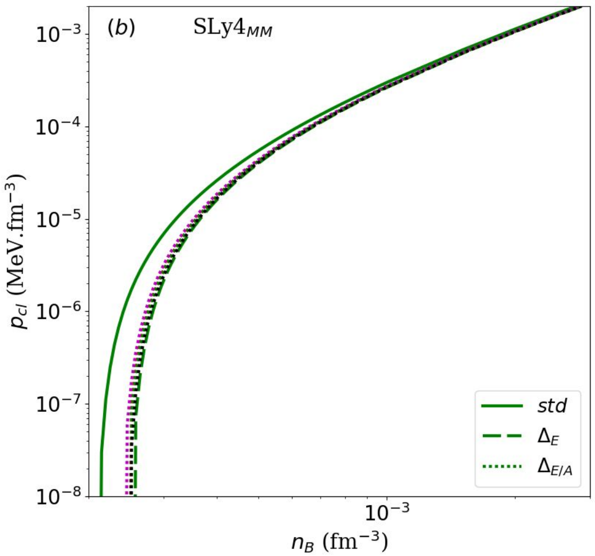
3. Chemical equilibrium: $$\mu^n_{cl} = \mu^n_{gas}\,,$$

4. Beta equilibrium: $$\mu^n_{cl} = \mu^p_{cl} + \mu_e + \Delta mc^2$$

NS crust properties (SLy4): impact of FS and minimization function

Cluster pressure at inner crust

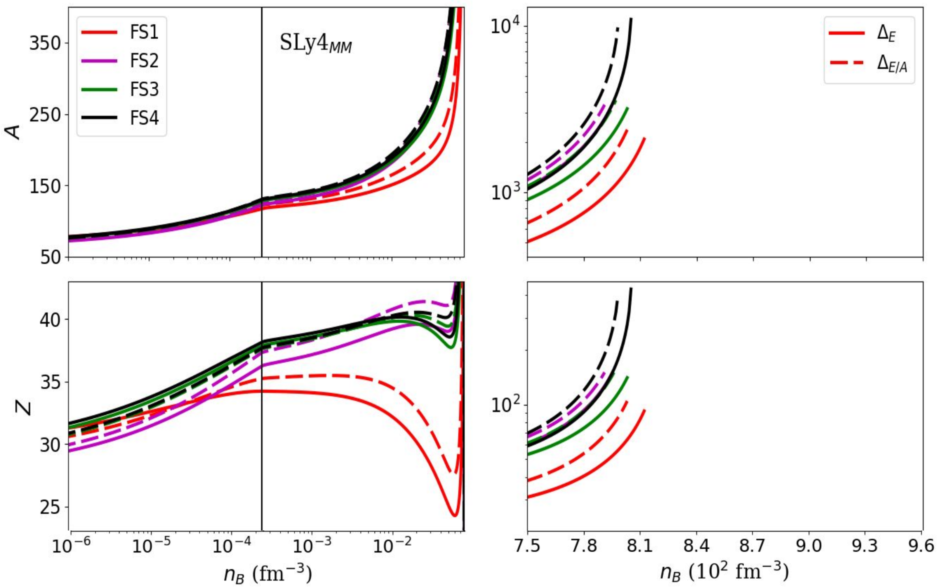


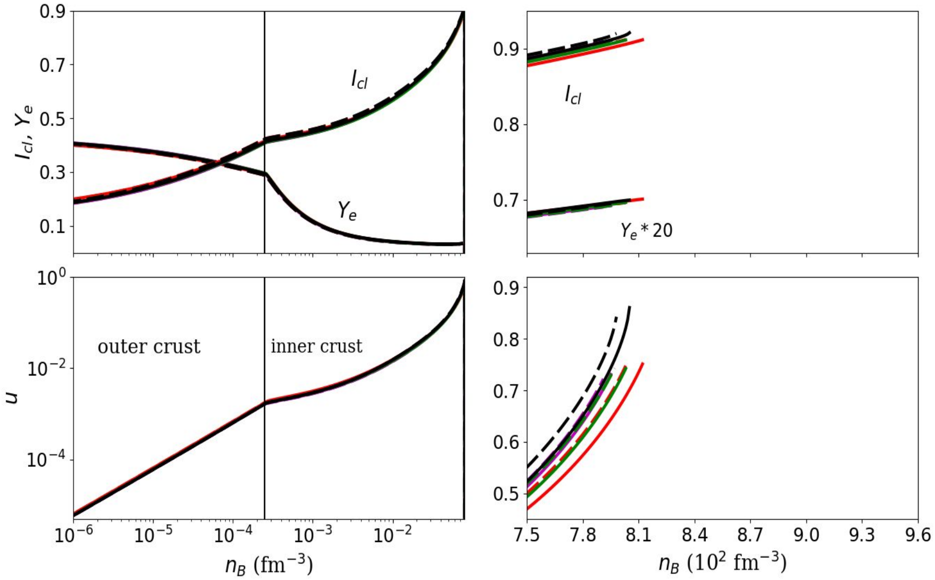


Composition at inner crust. n_B = 0.01 fm^{-3}

FS	$A_{cl,0.01}$	$Z_{cl,0.01}$	$n_{cl,0.01}$ 10^2 fm^{-3}
FS1	141	30	12.4
FS2	170	37	13.0
FS3	209	46	13.1
FS4	209	46	13.1

NS crust properties (SLy4): impact of FS and minimization function



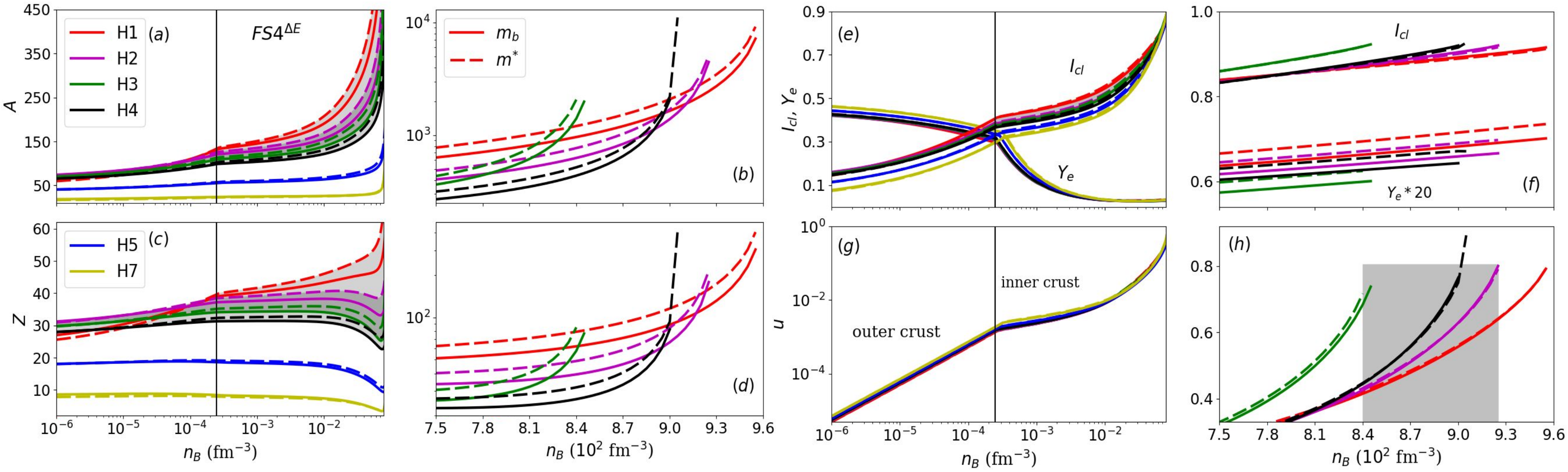


Crust core transition density, n_{cc}, for SLy4 in previous works:

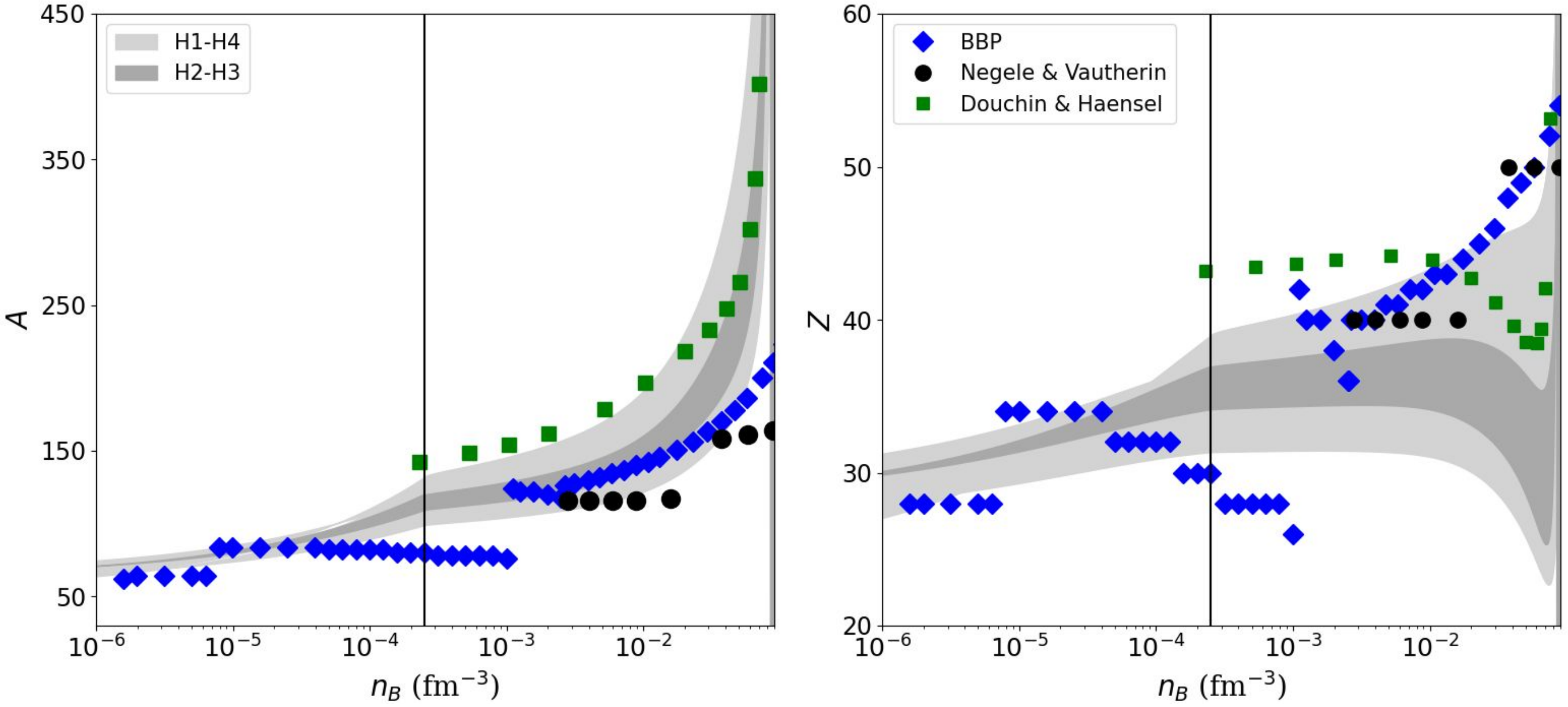
- Douchin & Haensel: 0.076 (fm^{-3})
- Carreau *et al.*: 0.073 - 0.083 (fm^{-3})
- Viñas *et al.*: 0.072 - 0.09 (fm^{-3})

$1.0\ M_\odot$ Model	FS	n_{cc} 10^2 fm^{-3}	$R_{1.0}$ (km)	$CT_{1.0}$ (km)	$ICT_{1.0}$ (km)	$\Lambda_{1.0}$	I_{crust}/I %
SLy4$_{MM}$	FS1	8.00	12.02	1.64	0.81	2189	5.00
SLy4$_{MM}$	FS2	7.80	12.03	1.64	0.80	2183	4.74
SLy4$_{MM}$	FS3	7.75	11.99	1.60	0.80	2182	4.91
SLy4$_{MM}$	FS4	7.95	12.01	1.63	0.81	2198	4.70

NS crust properties: impact of Hamiltonians and effective mass



Crust composition: comparison of chiral Hamiltonians with previous works.

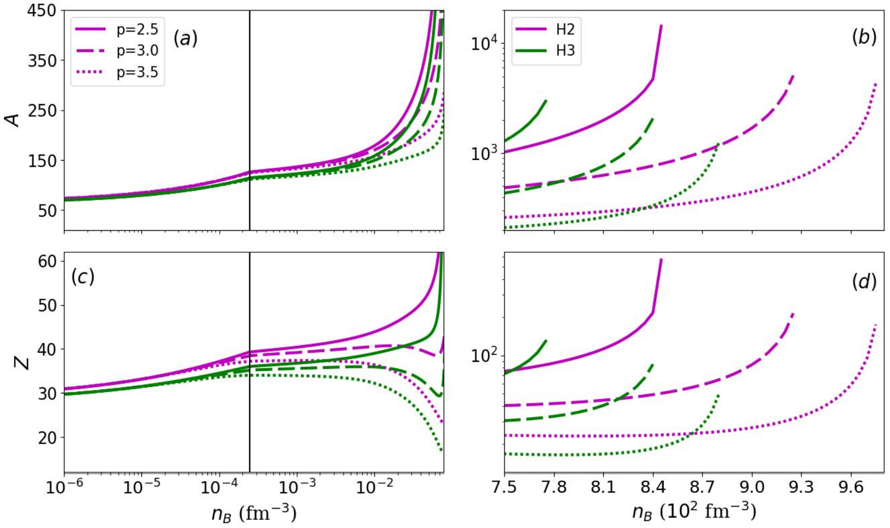


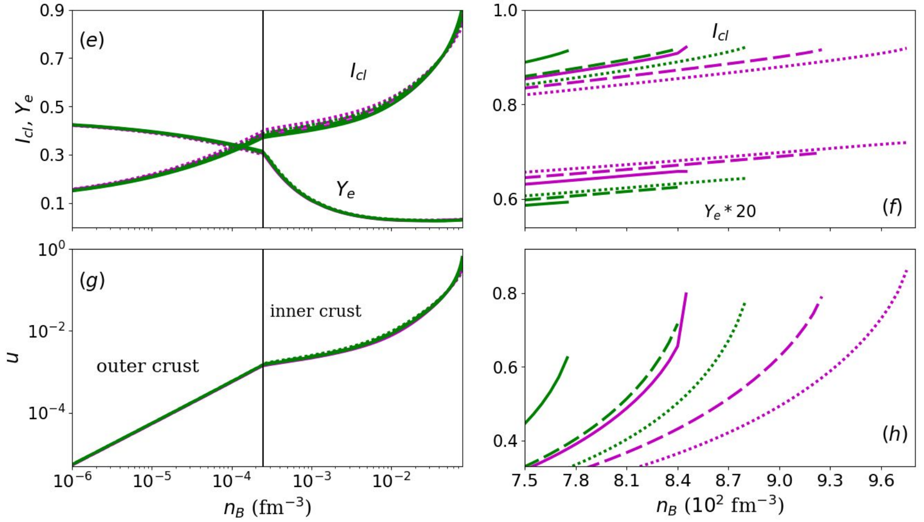
NS crust properties: impact of Hamiltonians, effective mass and minimization function

Model $1.0M_\odot$	n_{cc} 10^2 (fm^{-3})	$R_{1.0}$ (km)	$CT_{1.0}$ (km)	$ICT_{1.0}$ (km)	$\Lambda_{1.0}$	$(\mathrm{I_{crust}/I})_{1.0}$ %	$\mathrm{A_{cl,0.01}}$	$\mathrm{Z_{cl,0.01}}$	$n_{\mathrm{cl},0.01}$ 10^2 fm^{-3}
$\mathrm{H1^{FS4}_{MM_{bare}}}$	9.55 (9.55)	11.53 (11.54)	1.54 (1.55)	0.80 (0.80)	1861 (1862)	5.80 (5.80)	191 (185)	43 (42)	16.0 (16.0)
$\mathrm{H1^{FS4}_{MM_{m^*}}}$	9.55(9.60)	11.44 (11.44)	1.51 (1.51)	0.77 (0.77)	1764 (1764)	5.41 (5.47)	207 (201)	46 (44)	16.3 (16.3)
$\mathrm{H2^{FS4}_{MM_{bare}}}$	9.25 (9.10)	11.72 (11.72)	1.62 (1.61)	0.84 (0.83)	2012 (2002)	5.99 (5.81)	157 (160)	38 (39)	15.3 (15.3)
$\mathrm{H2^{FS4}_{MM_{m^*}}}$	9.25 (9.15)	11.63 (11.63)	1.58 (1.58)	0.82 (0.81)	1955 (1947)	5.80 (5.71)	170 (167)	41 (40)	15.5 (16.5)
$\mathrm{H3^{FS4}_{MM_{bare}}}$	8.45 (8.35)	12.14 (12.13)	1.69 (1.68)	0.85 (0.84)	2392 (2395)	5.75 (5.62)	139 (149)	34 (36)	14.6 (14.6)
$\mathrm{H3^{FS4}_{MM_{m^*}}}$	8.40 (8.30)	12.05 (12.04)	1.65 (1.63)	0.82 (0.81)	2263 (2263)	5.59 (5.46)	146 (155)	36 (37)	14.9 (15.0)
$\mathrm{H4^{FS4}_{MM_{bare}}}$	9.00 (8.85)	11.88 (11.87)	1.68 (1.66)	0.86 (0.85)	2093 (2084)	6.00 (5.82)	122 (135)	31 (34)	14.8(14.8)
$\mathrm{H4^{FS4}_{MM_{m^*}}}$	9.05 (8.90)	11.80 (11.78)	1.65 (1.63)	0.84 (0.84)	2176 (2051)	5.96 (5.83)	131 (144)	33 (35)	15.0 (15.0)

$\Delta_E(\Delta_{E/A})$

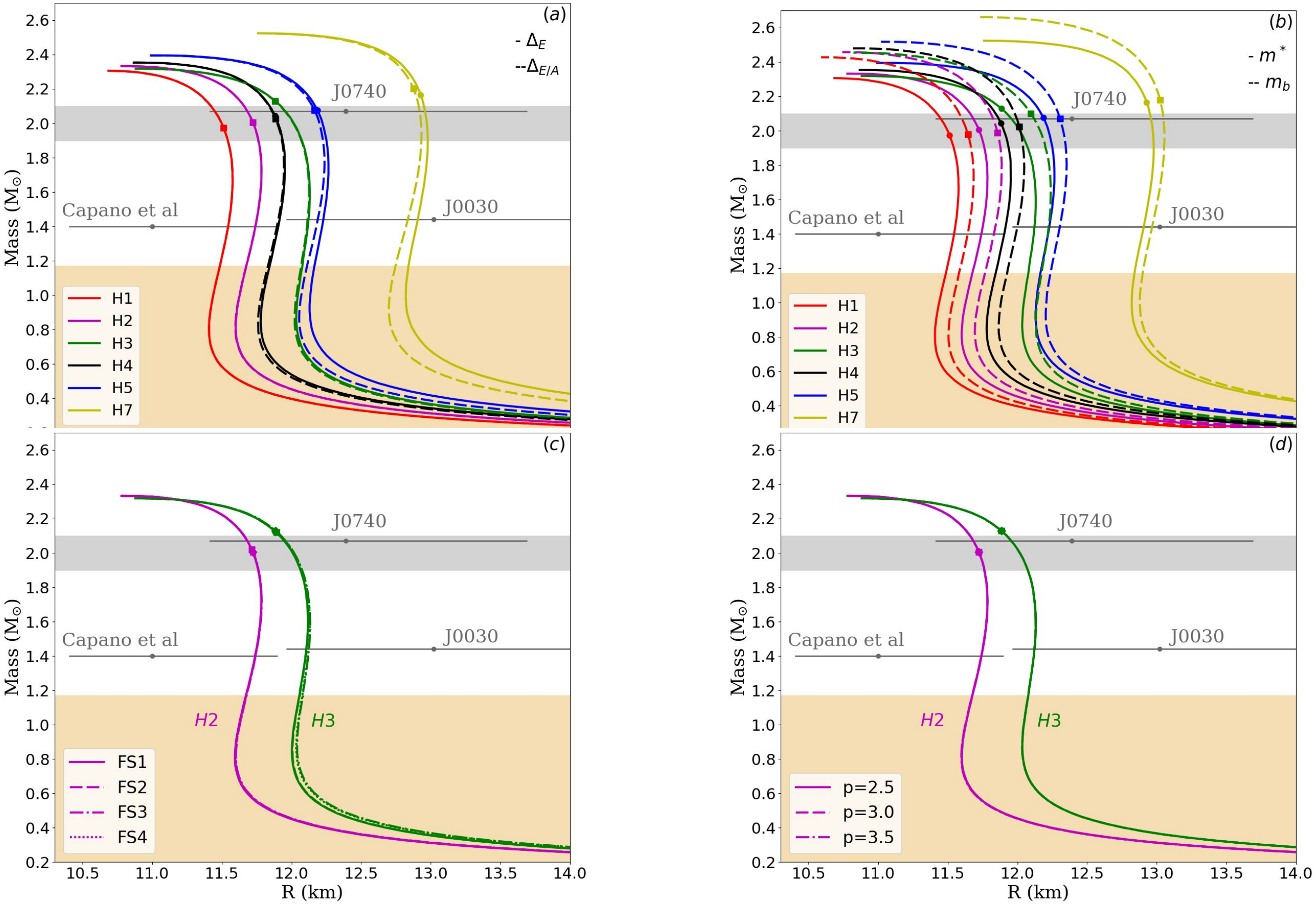
NS crust properties (H2 and H3): impact of surface parameter p_{surf}





p_{surf} $1.0M_\odot$	n_{cc} 10^2 fm^{-3}	$R_{1.0}$ (km)	$CT_{1.0}$ (km)	$ICT_{1.0}$ (km)	$\Lambda_{1.0}$	$(I_{crust}/I)_{1.0}$ %	$A_{cl,0.01}$	$Z_{cl,0.01}$	$n_{cl,0.01}$ 10^2 fm^{-3}
2.5	8.45	11.67	1.58	0.77	2015	4.93	178	43	15.7
3.0	9.25	11.67	1.62	0.82	1955	5.75	170	40	15.5
3.5	9.75	11.67	1.65	0.84	1915	6.30	156	36	15.3

Neutron star mass and radius



SUMMARY

- We adjusted the nucleon meta-model to chiral Hamiltonians.
- We introduced four ordered finite size models in the CLDM.
- Confronted the CLDM to experimental nuclear masses.
- Predicted NS crust properties.

Finite nuclei

- A conservative upper band to the energy density ~ -2.2 MeV.fm^{-3}.
- Select four, out of six, Hamiltonians H1-H4. Where the best two are H2 and H3.
- Identified a model dependence on the correlation between the surface parameters and Esym.

Neutron star crust

- The two Hamiltonians, H5 and H7, excluded in the finite nuclei study, predict A and Z far from the convergence values of the others.
- All models show $R_{1.4}$ ~ 12 km, in the lower band of NICER and upper band of Capano *et al*.
- Compared to previous works we reduce the uncertainties on the crust composition.