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Properties of neutron star crust

Jérôme Margueron
iP2i Lyon
+ collaborators *

Quantifying and correlating uncertainties with improved nuclear physics.

IP2I Lyon: G. Chanfray, J.-F. Coupechoux, H. Hansen, **R. Somasundaram***.
ULB Bruxelles: G. Grams*.
IJCLab Orsay: E. Khan.
IRAP Toulouse: S. Guillot, N. Webb.
Italy: R. Ciolfi (INAF Padova), B. Giacomazzo (Univ. Milano-Bicocca).
Yildiz TU Istanbul: K. Bozkurt, Hasim Güven.
USA: S. Reddy* (INT Seattle), A. Roggero (INT Seattle), I. Tews (LANL).
ITA Brazil: B. Carlson, M. Dutra, O. Lourenço.

Neutron star observations

Neutron star observations have recently entered into the age of accurate measurement of neutron star size extension.

ex.: radius, tidal deformability, moment of inertia.

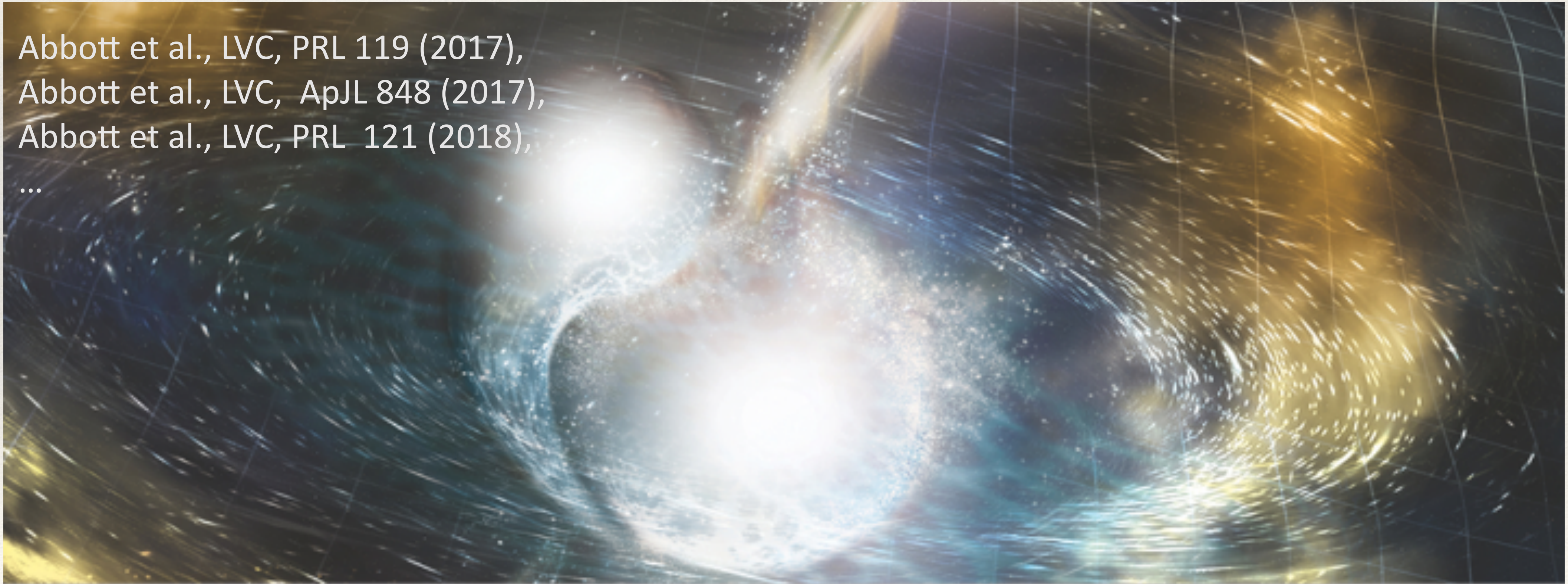
LIGO-Virgo GW observatory

2015: first detection of GW from BBH (O1).

2017: first detection of GW from BNS (O2).

2019: first detection of GW from BHNS (O3).

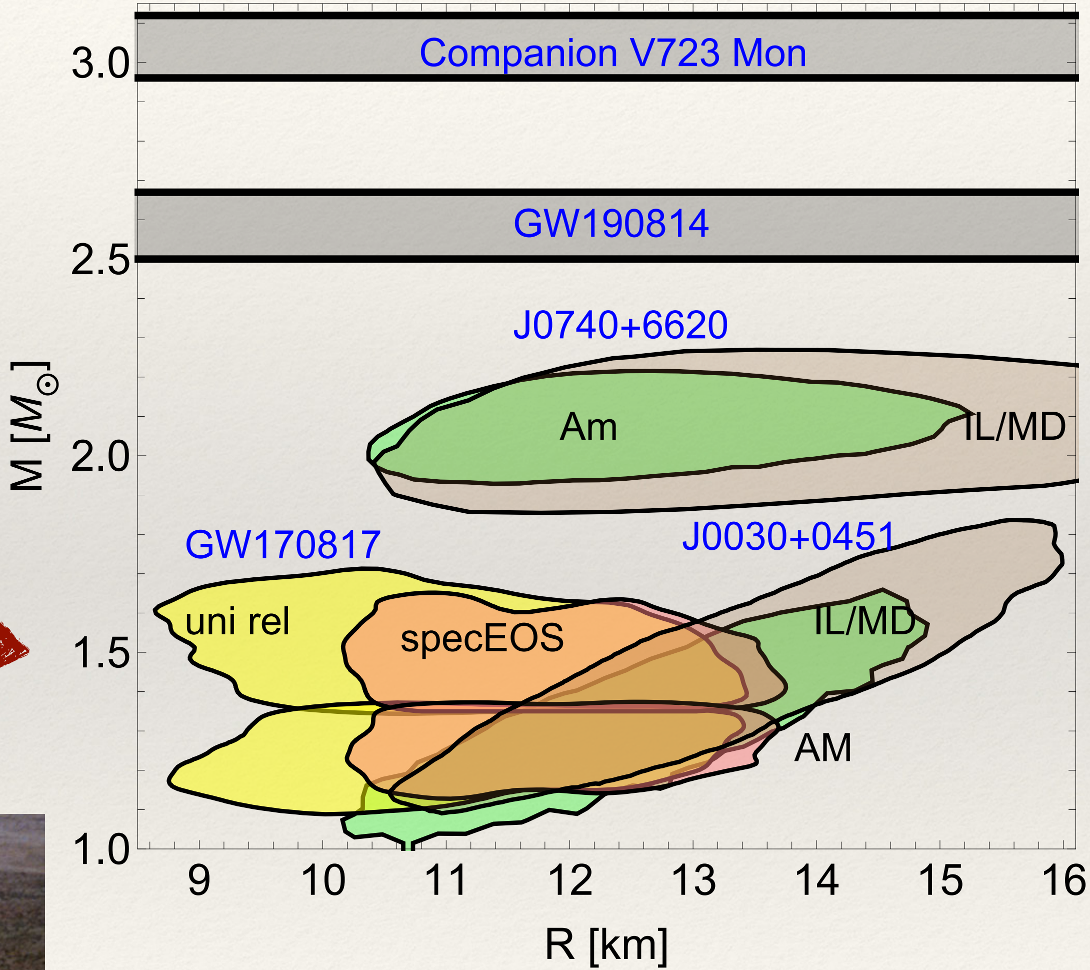
→ gravity and cosmology,
dark matter and dark energy,
dense matter.



Cataclysmic Collision Artist's illustration of two merging neutron stars. The rippling space-time grid represents gravitational waves that travel out from the collision, while the narrow beams show the bursts of gamma rays that are shot out just seconds after the gravitational waves. Swirling clouds of material ejected from the merging stars are also depicted. The clouds glow with visible and other wavelengths of light. Image credit: NSF/LIGO/Sonoma State University/A. Simonnet

+NICER X-ray observatory

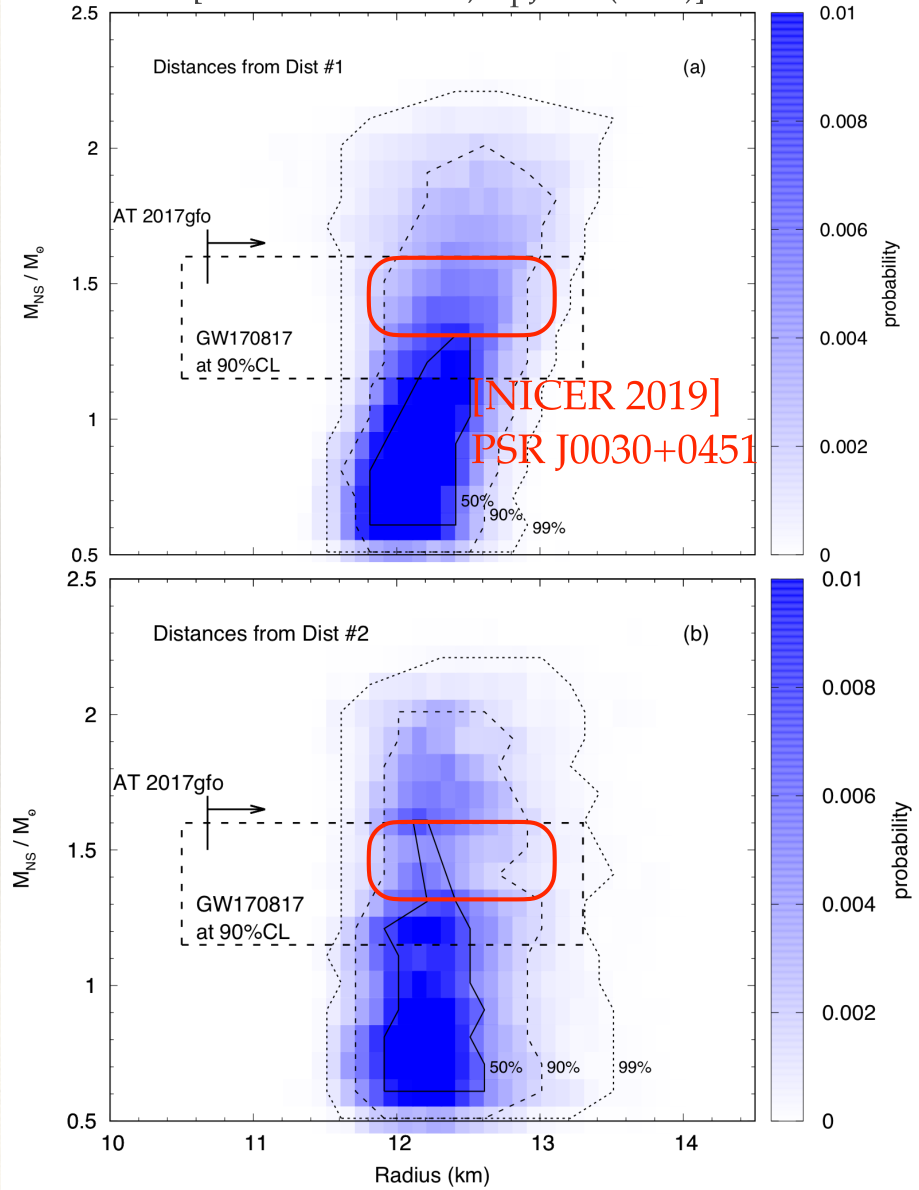
Tan, Dore, Dexheimer+ arXiv:2106.03890[astro-ph.HE]



+Thermal emission from qLMXB

quiescent Low Mass X-ray binaries

[Baillot d’Étivaux+, ApJ 887 (2019)]



Black body like emission: $F \# T^4(R_{inf}/D)^2$

Rutledge+ ApJ 577 (2002)
Guillot+ ApJ 732 (2011), ApJ 738 (2011), ApJ 772 (2013), ApJL 796 (2014)
Özel RPP 76 (2013)
Steiner+, ApJL 765 (2013), MNRAS 476 (2018)
Heinke+ MNRAS (2014)
Lattimer+ ApJ 784 (2014)
Bogdanov+ ApJ 831 (2016)

Baillot d’Étivaux+, ApJ 887 (2019):

—> Bayesian analysis considering 7 sources in globular clusters, where the EoS is directly injected into the data analysis (first time).

Average radius (12-13km) preferred.

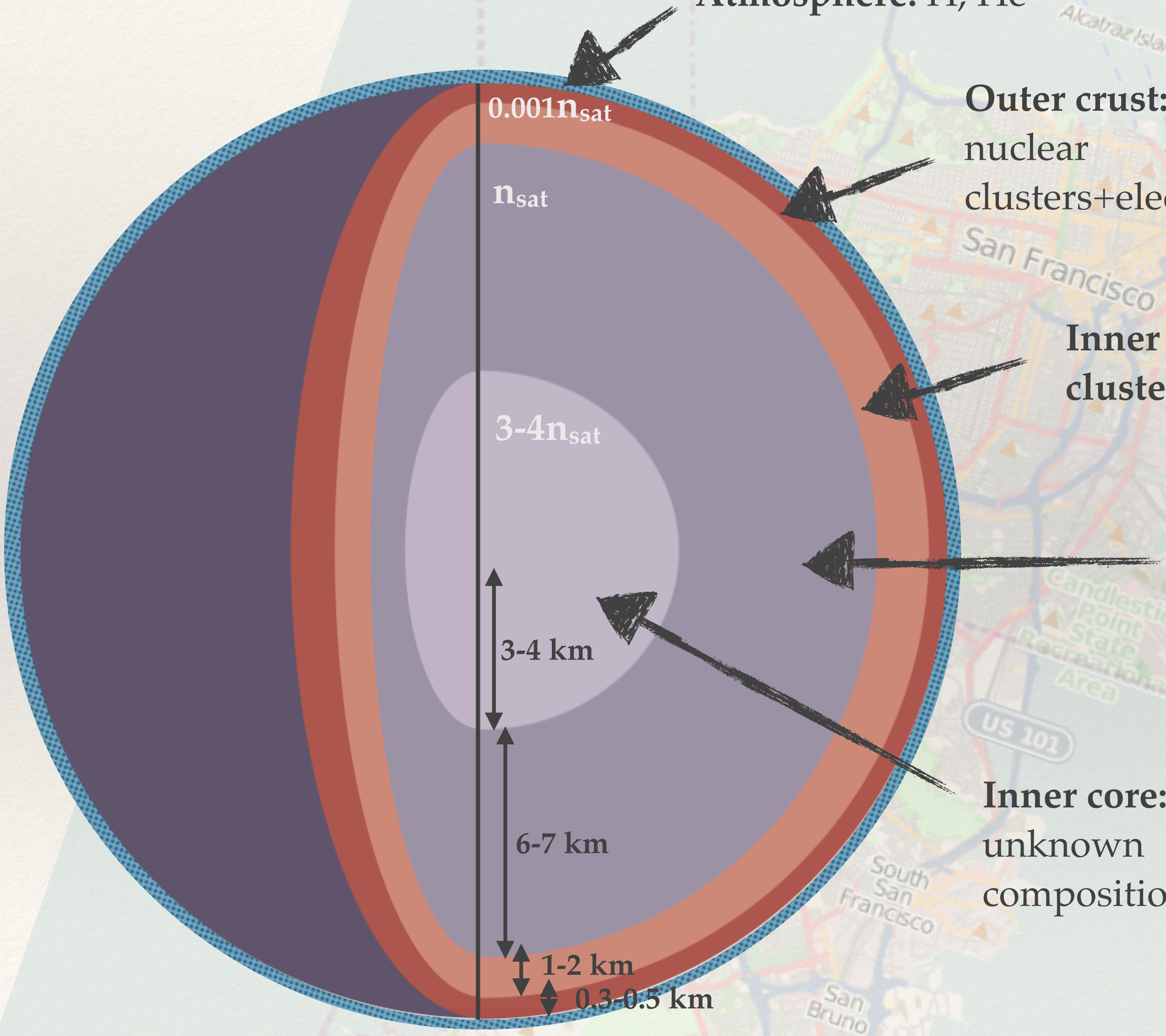
—> These results are consistent with GW and NICER data.

Towards a better understanding of NSs:

Atmosphere: H, He

Mass $\approx 1.2 - 2.2 M_\odot$

Radius $\approx 10 - 14$ km



Outer crust: nuclear clusters+electons

Inner crust: nuclear clusters+electrons+neutron gas

Outer core: uniform nuclear matter (n, p, e, μ)

Inner core: unknown composition

NS **radii** provide information about the **core**, provided the uncertainties from the crust are under control.
—> a **proper estimate** of the **uncertainties in the crust** is necessary.

Neutron star crust modeling

Baym-Bethe-Pethick BBP EOS (1971) employed the **compressible liquid-drop model** for the description of NS crust with FS surface term only.

Negele-Vautherin (1973) first microscopic HF calculation in the crust.

The Douchin-Haensel EoS (in 2001) is the first **unified model** based on an Skyrme interaction (SLy5) calibrated on the e**xperimental nuclear chart** + variational prediction for **neutron matter**.

M. Fortin et al. PRC 96 (2016) underlined the importance of unified model for **accurate NS radius** predictions.
see also Suleiman+ PRC 104 (2021).

Steiner (in 2008) studied the effect of the **symmetry energy**, the **compressibility** and the l**ow-density NM** affect the composition of the crust.

Tews (2017) introduced constraints from xEFT in NM to calculate EOS, shear properties and spectrum of crustal shear modes. Uncertainties originating mostly from **NM EOS** and neutron entrainment.

Pearson+ (2018) microscopic **HFB** calculation based on BSK forces.

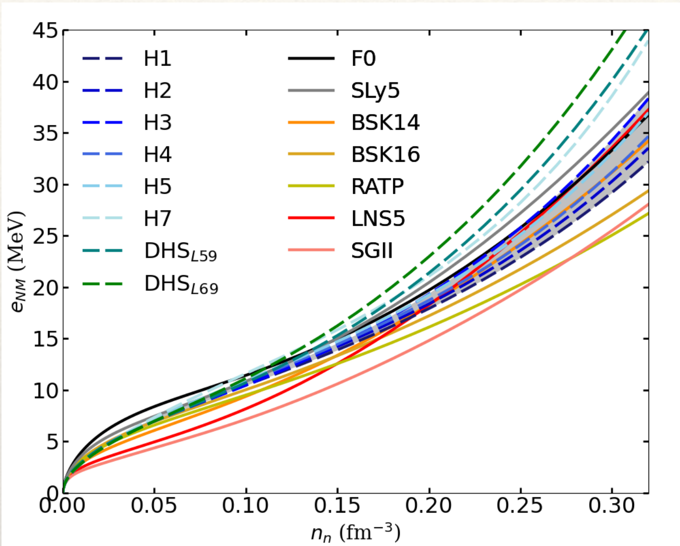
In the following, we analyse the **crust properties** predicted by 2 classes of EOS:
1- CLDM based on **xEFT** predictions in SM and NM,
2- CLDM based on **Skyrme force** calibrated over the nuclear chart (SM close to n_{sat}).

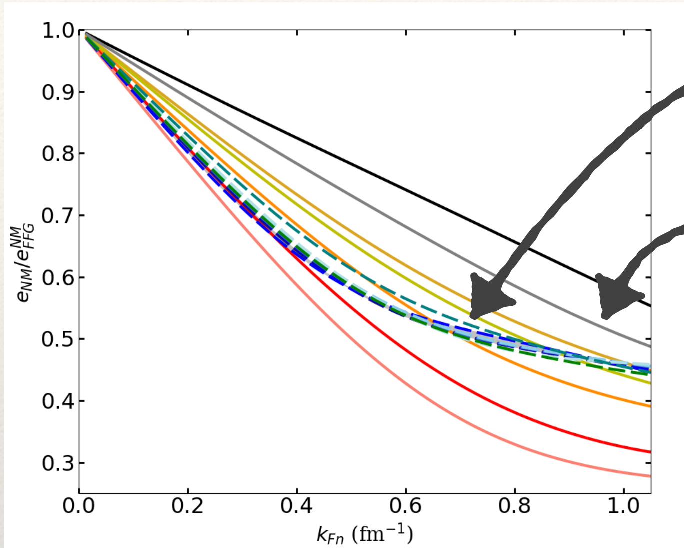
Energy in matter: xEFT / Skyrme

15 EOSs in total

[Grams+, FBS 2021, arXiv 2021]

Neutron matter (NM)





xEFT (dashed lines)

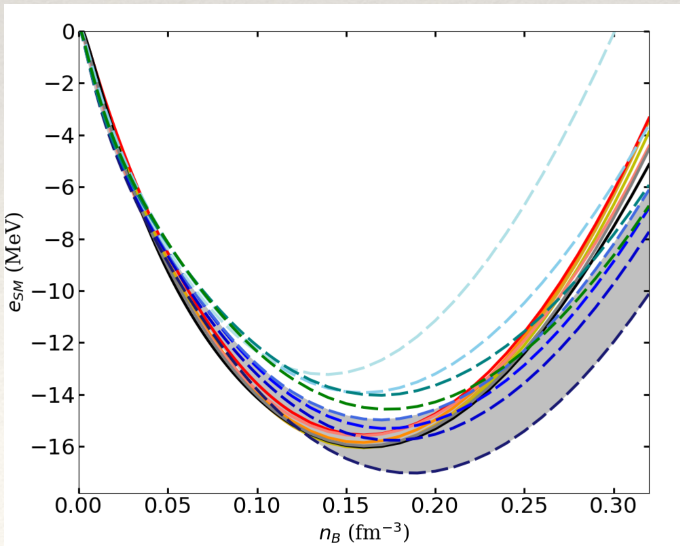
Drischler+ PRC 93 (2016)

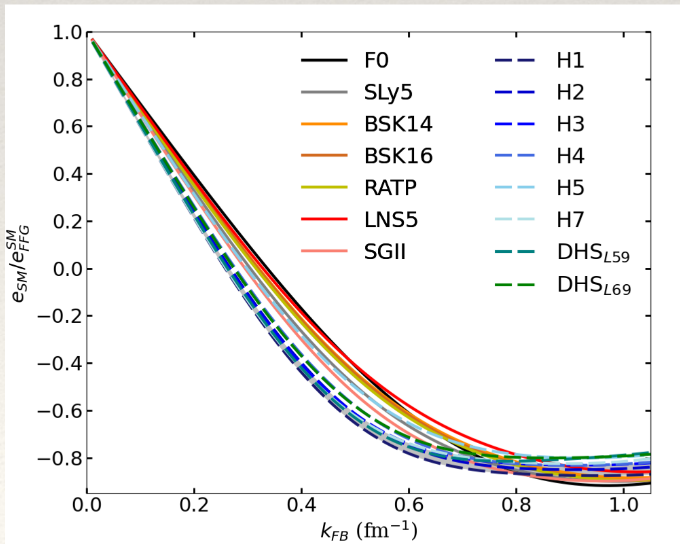
Drischler+ ARNP 71 (2021)

Skyrme (solid lines)

Large dispersion of the Skyrme EOSs in NM.

Symmetric matter (SM)





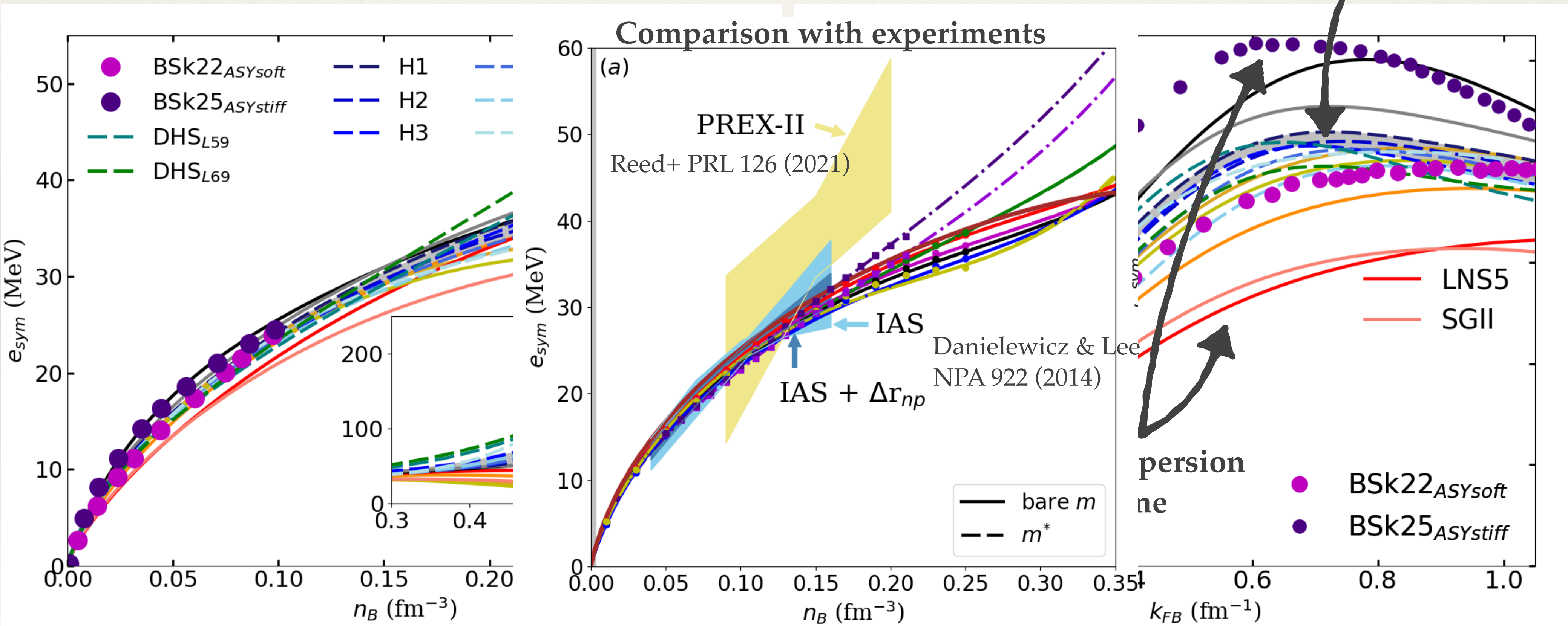
Large dispersion of the xEFT EOSs in SM.

Symmetry energy: xEFT / Skyrme

[Grams+, FBS 2021, arXiv 2021]

$$E_{\text{sym}} = E_{\text{NM}} - E_{\text{SM}} = E_{\text{sym},2} + \ldots \quad \text{with} \quad E_{\text{sym},2} = \frac{1}{2}\frac{\partial^2 E}{\partial \delta^2}\Big|_{\delta=0}$$

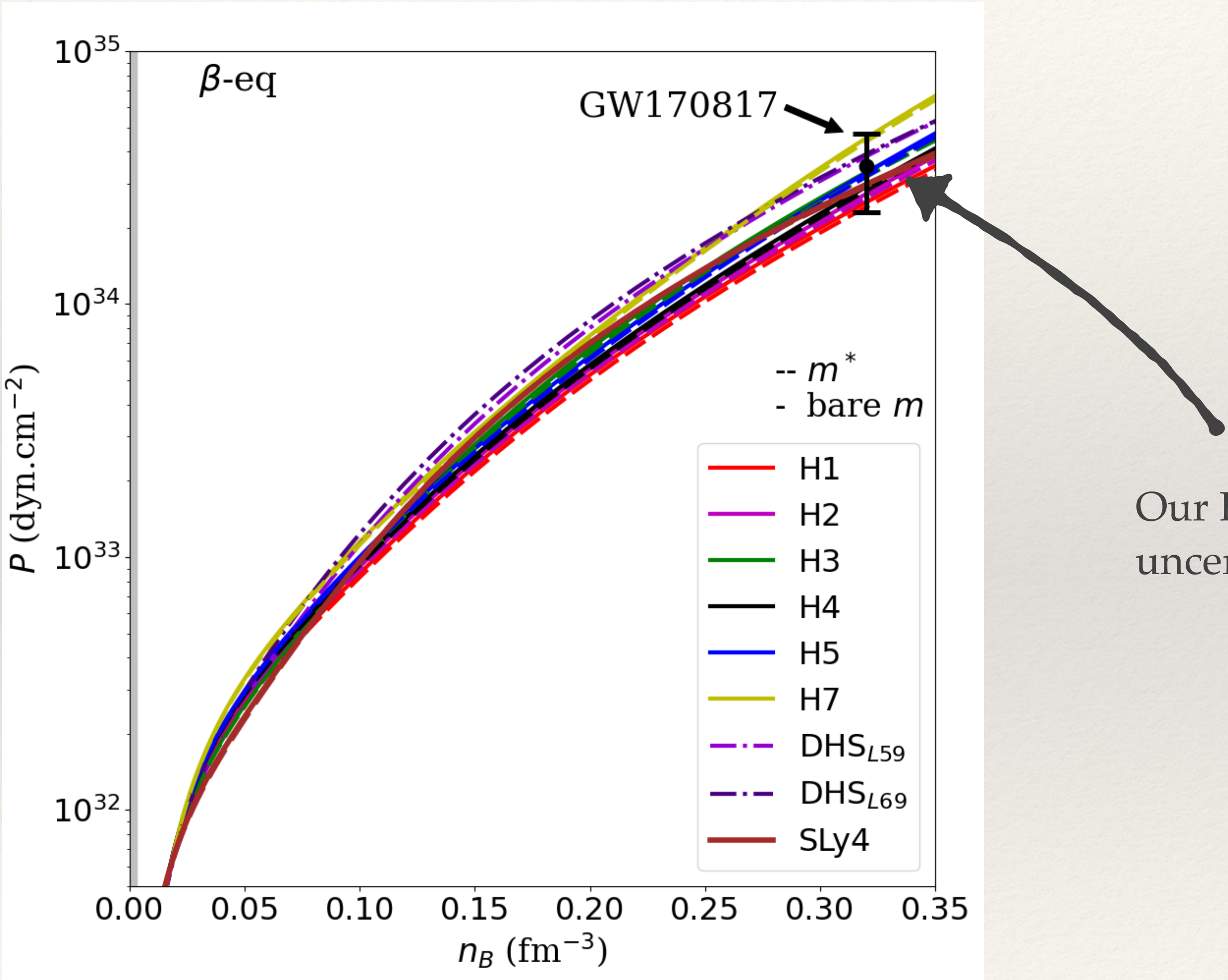
Small dispersion for xEFT



For Skyrme: the large dispersion originates from the NM uncertainty.
For xEFT: small dispersion despite the SM uncertainties.

Pressure: constraints from GW170817

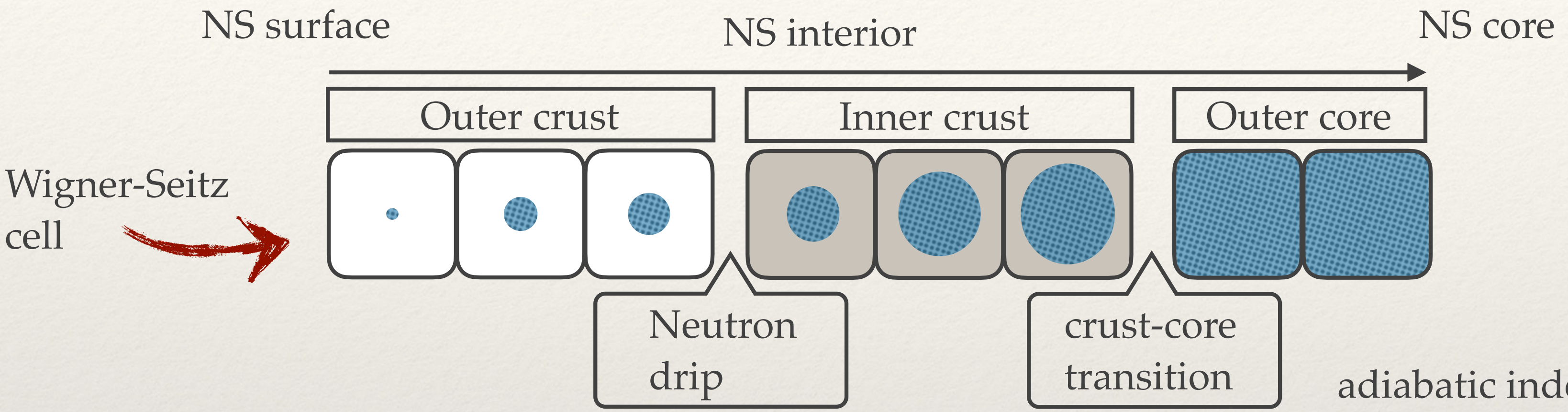
[Grams+, FBS 2021, arXiv 2021]



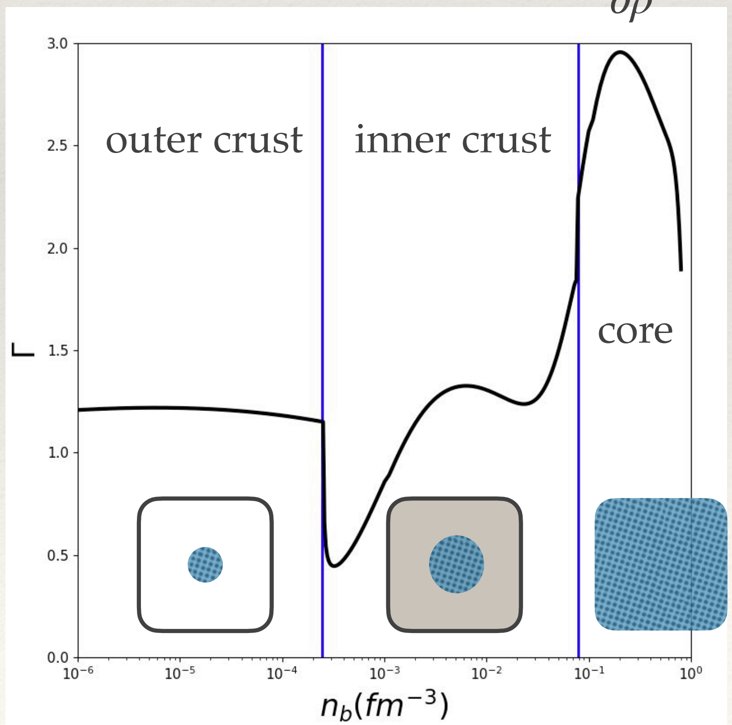
Our EOSs explore entirely the uncertainty fixed by GW170817.

Modeling inhomogeneous matter

[Grams+, FBS 2021, arXiv 2021]



adiabatic index $\Gamma = \frac{\partial P}{\partial \rho}$



Matter composition:

nuclear clusters + electrons

nuclear clusters + electrons + neutron gas

Variables: $(A_{cl}, Z_{cl}, n_{cl}, n_e)$ $(A_{cl}, Z_{cl}, n_{cl}, n_e, n_g)$

Volume fraction occupied by nuclei:

$$u = \frac{V_{cl}}{V_{WS}}$$

$$u = \frac{n_B}{n_{cl}} \propto n_B$$

since $n_{cl} \approx n_{sat}$

$$u = \frac{n_B - n_g}{n_{cl} - n_g} \approx \frac{n_B - n_g}{n_{cl}}$$

since $n_g \ll n_{cl}$

Unified EoS (crust + core)

[Grams+, FBS 2021, arXiv 2021]

Theoretical modeling:

- compressible liquid-drop approach (CLDM): variational approach optimizing the nuclear density.
- comparison between xEFT hamiltonians and Skyrme force.

Isolated nuclei: $E_{\rm nuc} = E_{\rm bulk} + E_{\rm FS}$

with

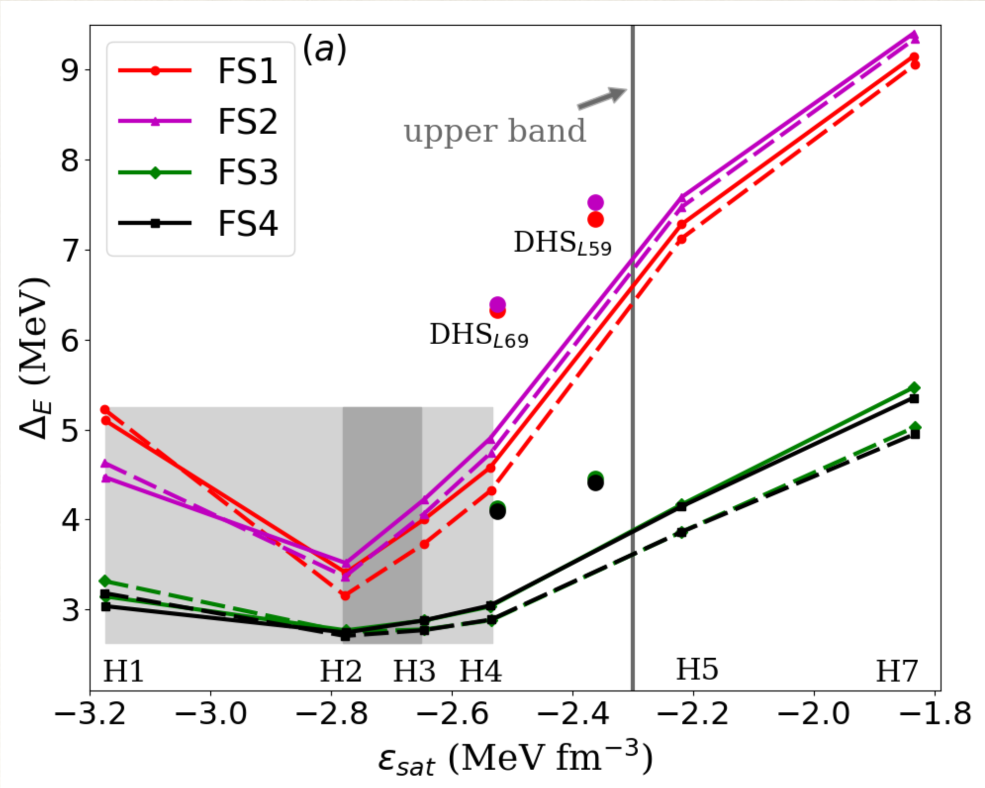
$$E_{\rm bulk} = E_{MM}(n = n_{\rm nuc}, \delta = \delta_{\rm nuc})$$

$$E_{\rm FS} = E_{\rm Coul} + E_{\rm surf} + E_{\rm curv} + \dots$$

Ordering of the leptodermous expansion (FS1-FS4):

Model	Variables	FS1	FS2	FS3	FS4
Bulk from MM	$(I_{\rm cl}, n_{cl})$	×	×	×	×
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

Nuclear experimental masses allows us to rank xEFT Hamiltonians:



Unified EoS (crust + core)

[Grams+, FBS 2021, arXiv 2021]

Theoretical modeling:

- compressible liquid-drop approach (CLDM): variational approach optimizing the nuclear density.
- comparison between xEFT hamiltonians and Skyrme force.

In NS crust:

Nuclear cluster, electron and neutron gas contributions

Total energy: $E_{WS} = E_{\rm nuc} + E_e + E_g$

The equilibrium state is obtained from the following equations:

Virial theorem: $2E_{coul} = E_{surf} + 2E_{curv}$

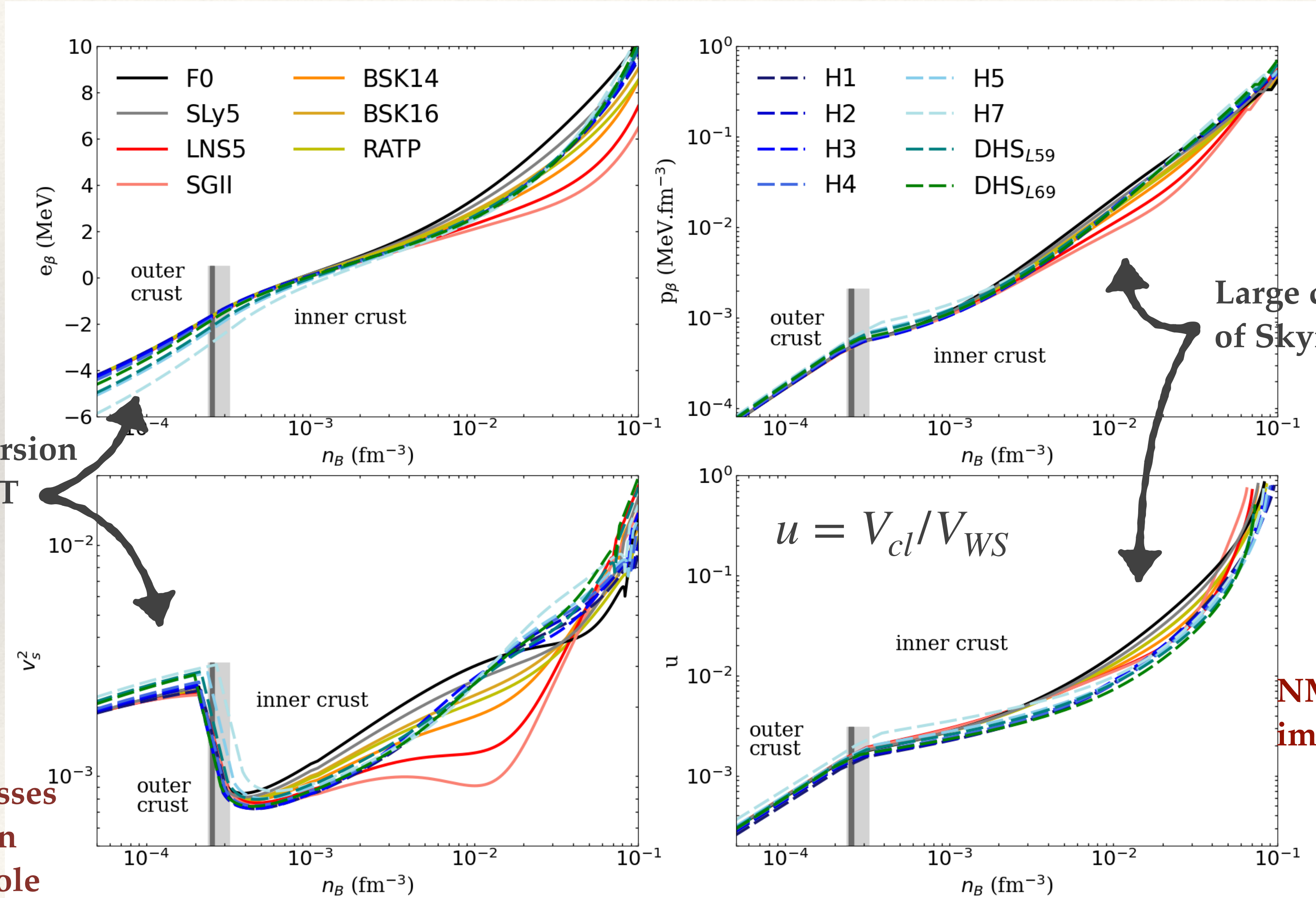
Mechanical equilibrium: $P_{cl} = P_g$

Chemical equilibrium: $\mu_{cl}^n = \mu_g^n$

Beta equilibrium: $\mu_{cl}^n = \mu_{cl}^p + \mu_e + \Delta mc^2$

Impact of NM on crust observables

[Grams+, FBS 2021, arXiv 2021]



Large dispersion of chiral EFT predictions

Large dispersion of Skyrme models

Nuclear masses (SM) play an important role

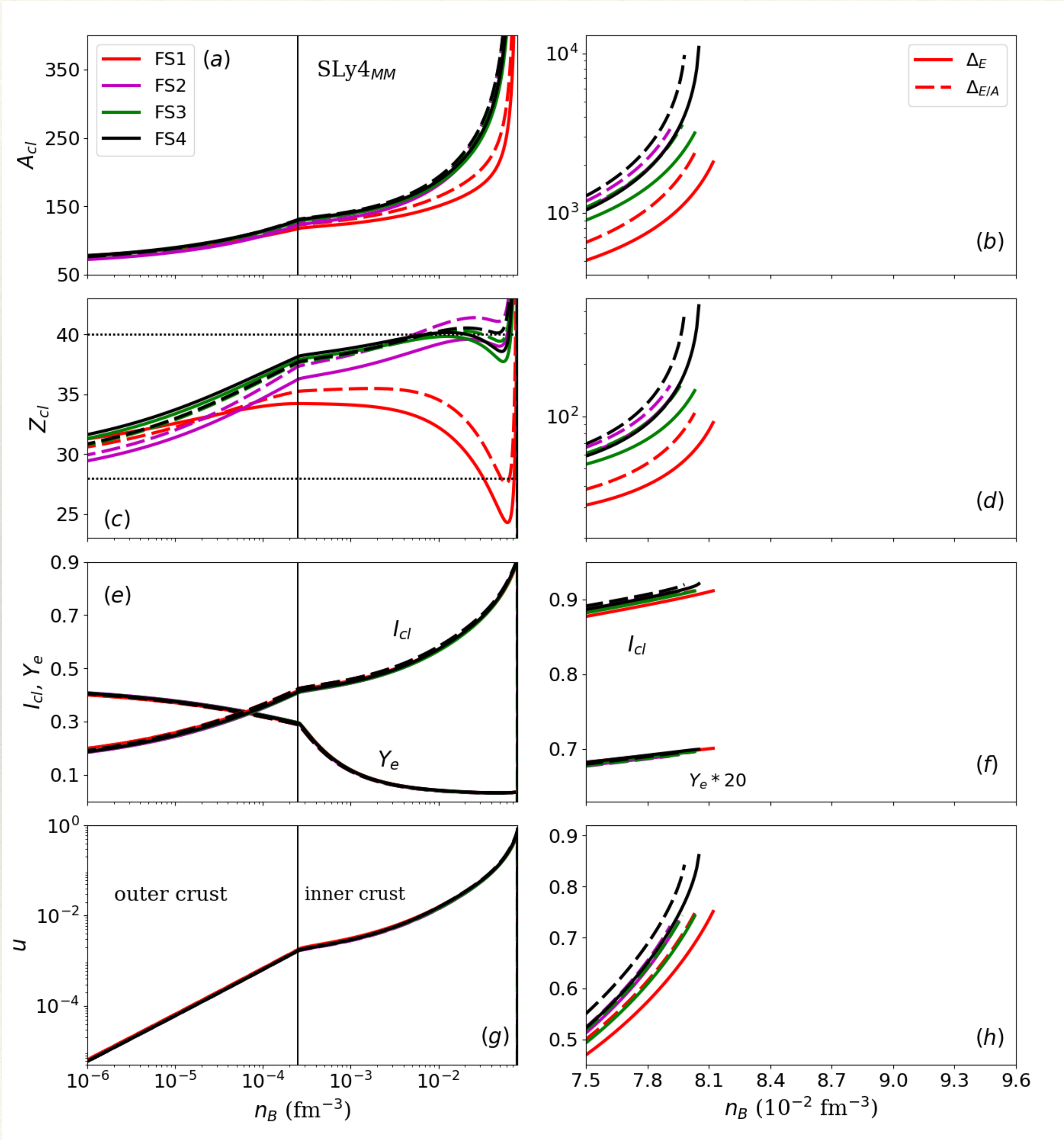
NM plays an important role

Convergence of the leptodermous expansion

[Grams+, FBS 2021, arXiv 2021]

From FS1 to FS4: convergence of the predictions.

Model	Variables	FS1	FS2	FS3	FS4
Bulk from MM	$(I_{\rm cl}, n_{cl})$	×	×	×	×
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



NS crust composition (A_{cl}, Z_{cl})

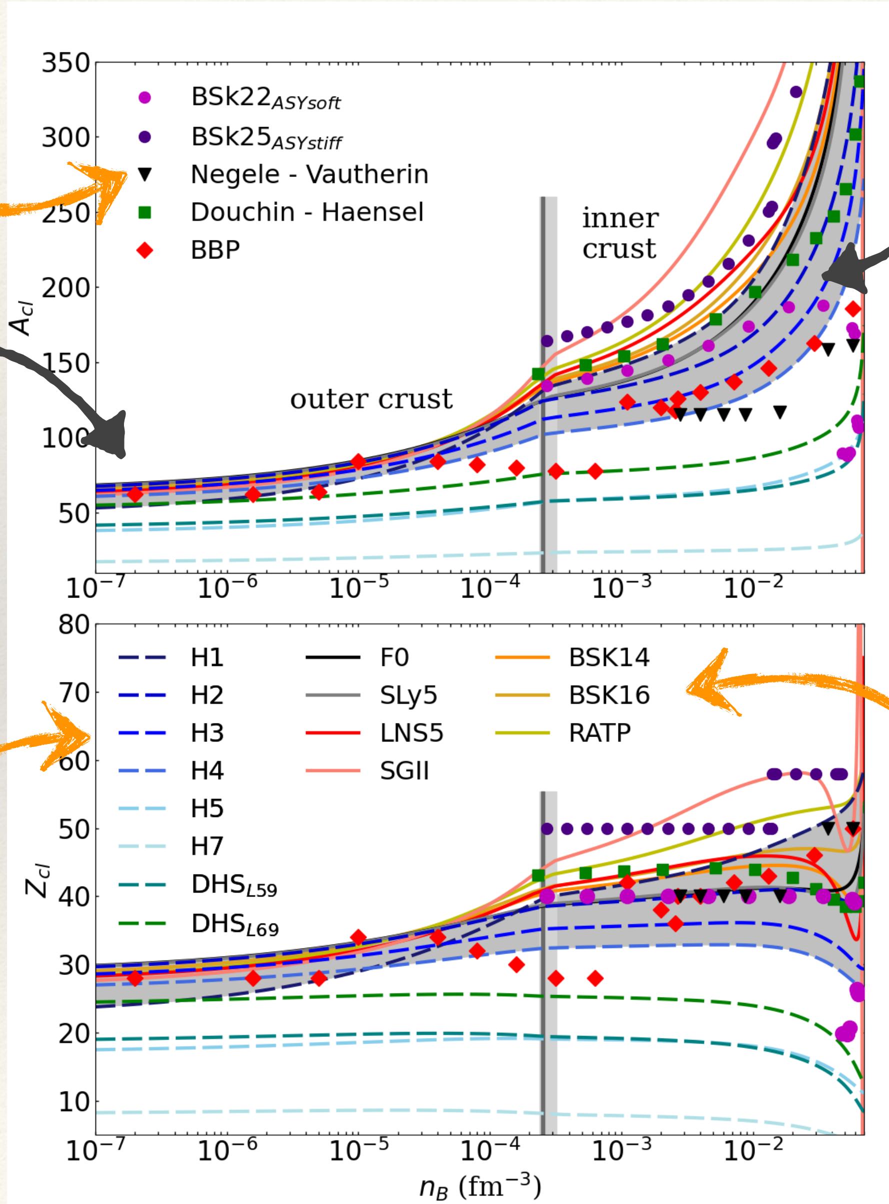
[Grams+, FBS 2021, arXiv 2021]

Comparison to other predictions.

Small dispersion

Nuclear masses play an important role

xEFT



Larger dispersion

Best models to reproduce nuclear masses (H1-H4)

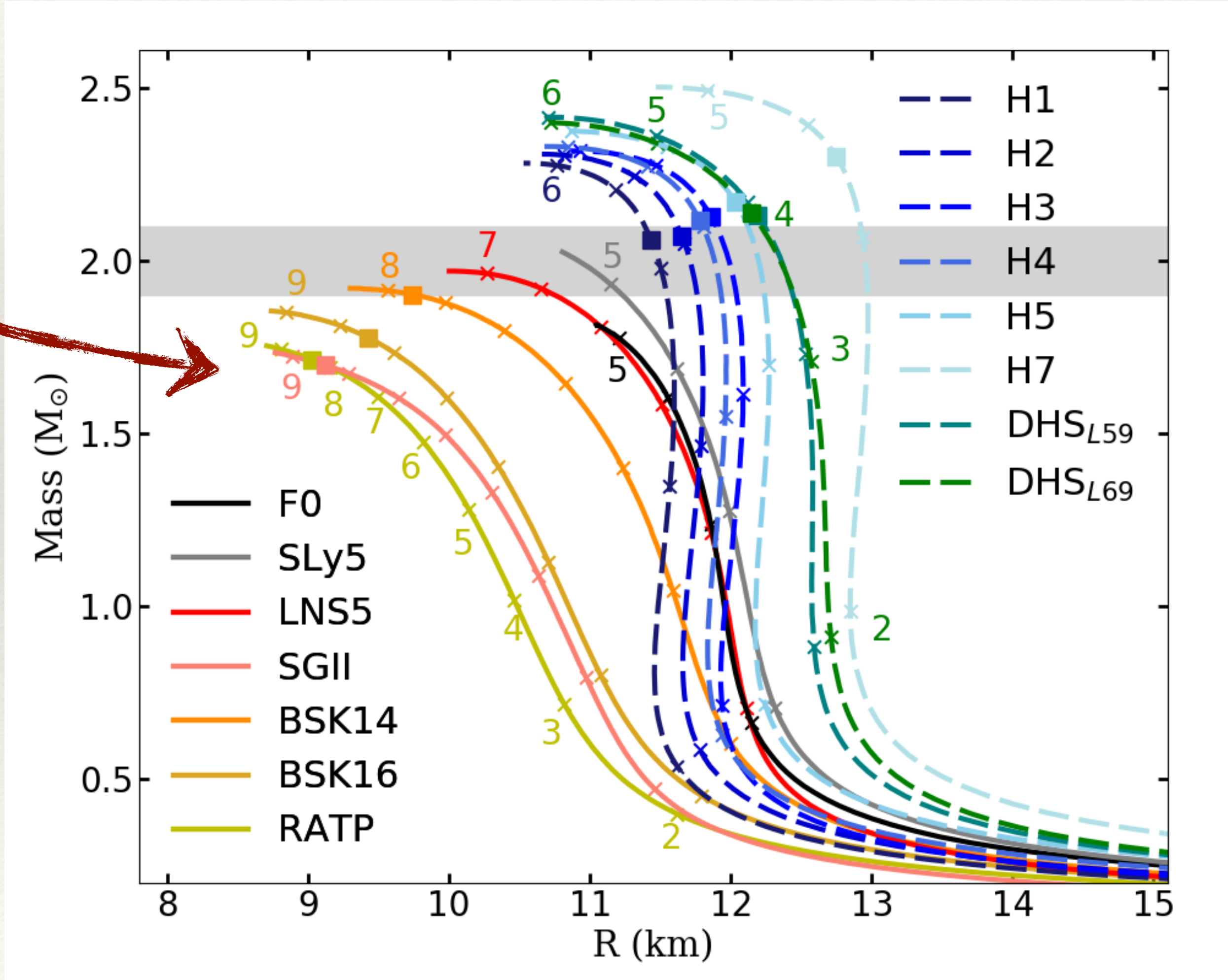
Skyrme

NS global properties

[Grams+, FBS 2021, arXiv 2021]

mass-radius relation

central density of the NS in units of nuclear saturation density.



At a fixed mass, the lower the radius, the larger the central density.

Conclusions and outlooks

We have shown that the leptodermous expansion provides a good series expansion ordering for the different terms contributing to the crust properties.

By confronting xEFT hamiltonians against Skyrme forces, we better understand the **role of SM and NM** in constraining the properties of in-homogeneous matter:

- cluster mass (A), charge (Z), and asymmetry (I) are mostly determined by SM properties close to saturation density. They are thus mainly constrained by experimental nuclear masses.

- The energy per particle, the pressure, the sound speed, the electron fraction are mostly influenced by low-density predictions in NM, where xEFT and Skyrme forces substantially differ.

The new EOS (15 in total) are available on the CompOSE repository (https://compose.obspm.fr) under the name GMSR(i), with i=H1, …, SLy5, …

Simulations in astrophysics is the key to relate modeling of microphysics with observational data.
—> We develop finite temperature EoS to be implemented in simulations.

A semi-agnostic approach for the nuclear EoS

[Baillot d'Étivaux+, ApJ 2019]

The **nuclear empirical parameters** (NEP) capture the properties of the EoS around n_{sat}:

Less known NEP — Unknown NEP

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

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

with $\delta = (n_n - n_p)/(n_n + n_p)$ and $x = (n - n_{sat})/(3n_{sat})$

Various nuclear modeling (Skyrme, Gogny, RMF, …)
[see talk of S. Typel]

Semi-agnostic approach (Meta-model):

$$e(n, \delta) = t(n, \delta) + v(n, \delta)$$

Kinetic energy (Fermi gas)

Potential energy

$$v(n,\delta) = \sum_{\alpha=0}^{N} \left(v_\alpha^{\rm is} + \delta^2 v_\alpha^{\rm iv}\right) \frac{x^\alpha}{\alpha!} u(x),$$

Directly related to NEP