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Probing extreme matter physics with gravitational waves

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LPC Caen: F. Gulminelli.
U. Catolica, Chile: M. Catelan, A. Reisenegger.
USA: S. Reddy (INT Seattle), A. Roggero (INT Seattle), I. Tews (LANL).

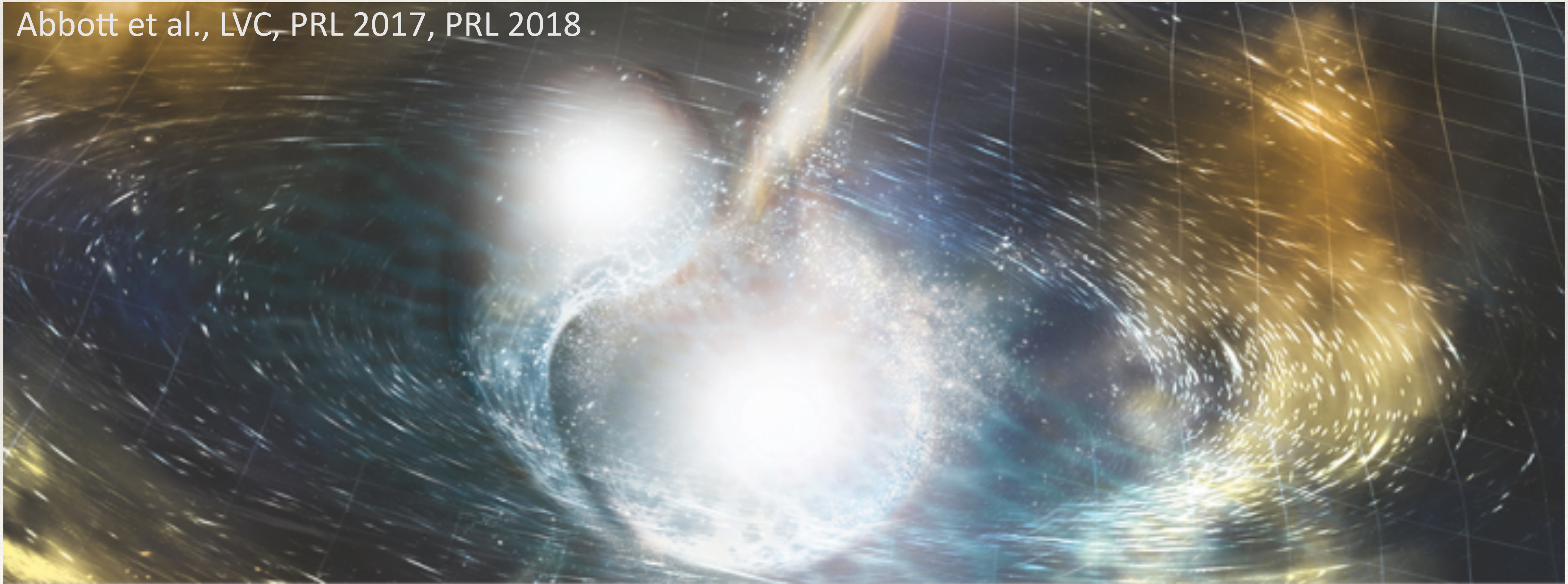
GW: new messengers from violent collisions in the Universe

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

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

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

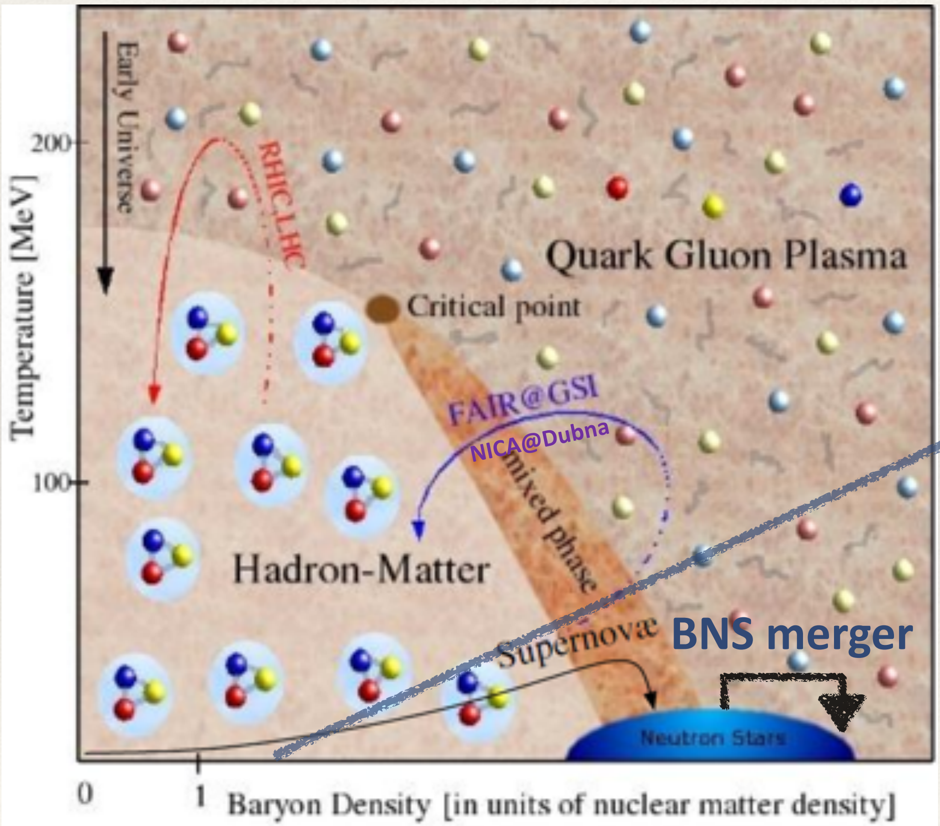
gravity and cosmology,
dark matter and dark energy,
dense matter.



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

Probing extreme matter physics with GW

Main questions: How changes the **nuclear interaction** with density, isospin asymmetry, temperature?
Which **new particles** appear at supra-saturation densities (phase transition)?
Links between **deconfinement** and **chiral symmetry** restoration?

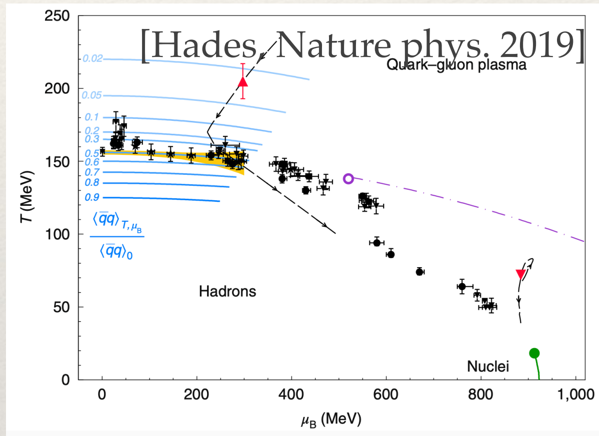


Particle and nuclear accelerators

Astrophysical observations

Neutron stars, supernovae, kilonovae…

Heavy Ion collision

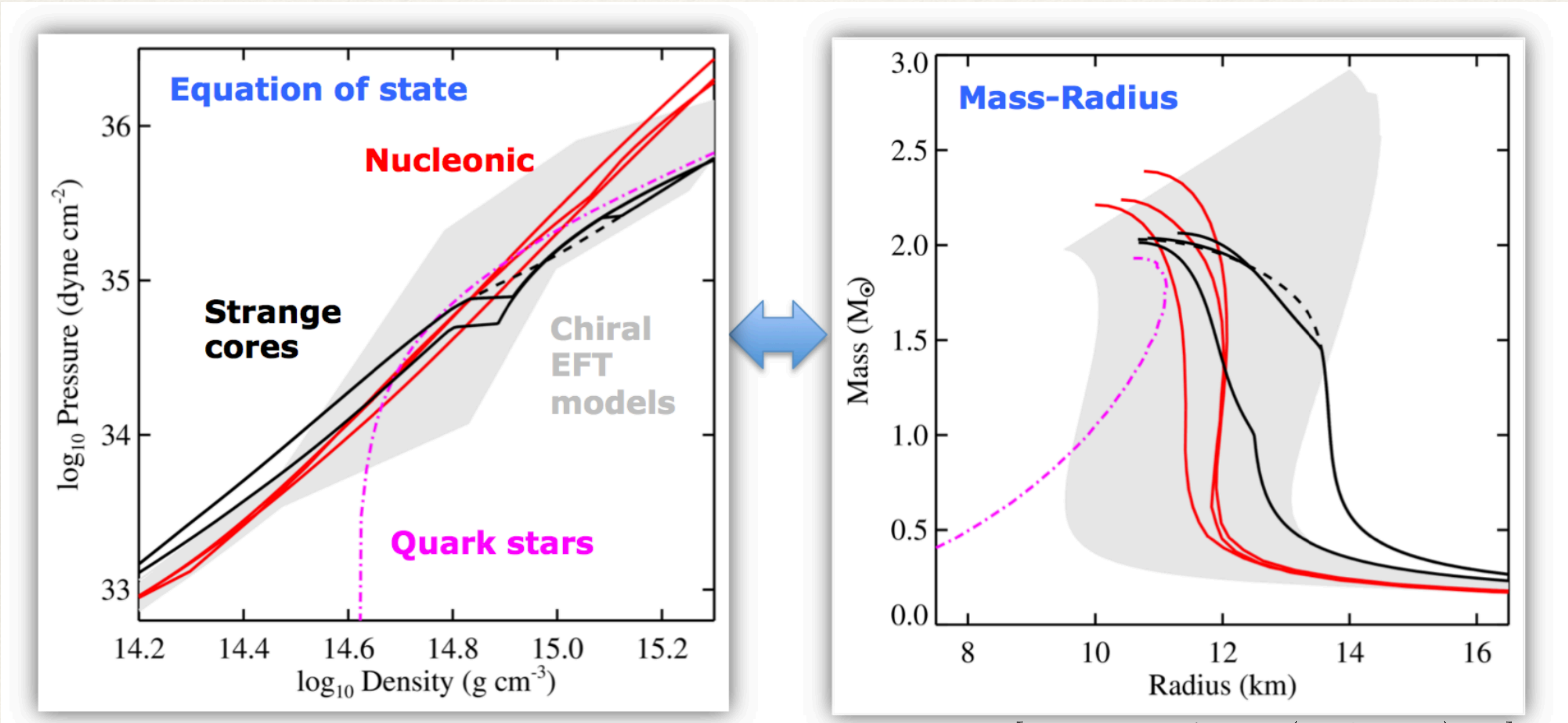


Probe limits of extreme matter

Directly related questions: How **neutrinos** propagate? What are the **transport properties** of extreme matter?
Are BNS the main astrophysical site for the **r-process**?

EoS [nuclear] <=> NS (M,R) [astro]

P(n) → **Tolmann-Oppenheimer-Volkov (TOV) GR equations** → (M,R)(n_c)



[A. Watts et al., PoD (AASKA 14) 043]

Reverse engineering,
Bayesian statistics

EoS [nuclear] <=> BNS GW [astro]

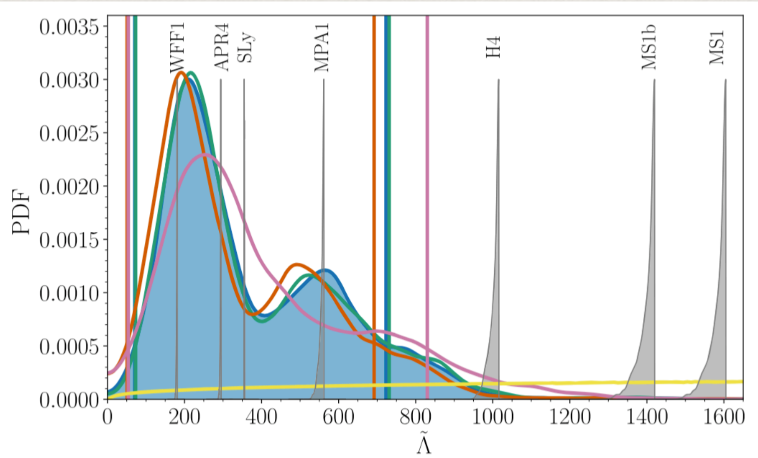
- Tidal field E_{ij} from companion star induces a quadrupole moment Q_{ij} in the NS
- Amount of deformation depends on the stiffness of EOS via the tidal deformability Λ.

$$Q_{ij} = -\Lambda(\mathrm{EOS}, m) m^5 \mathcal{E}_{ij}$$

Post-Newtonian expansion of the waveform: Tidal effect enters at 5th order.

Hinderer+ 2008, Blanchet, Damour

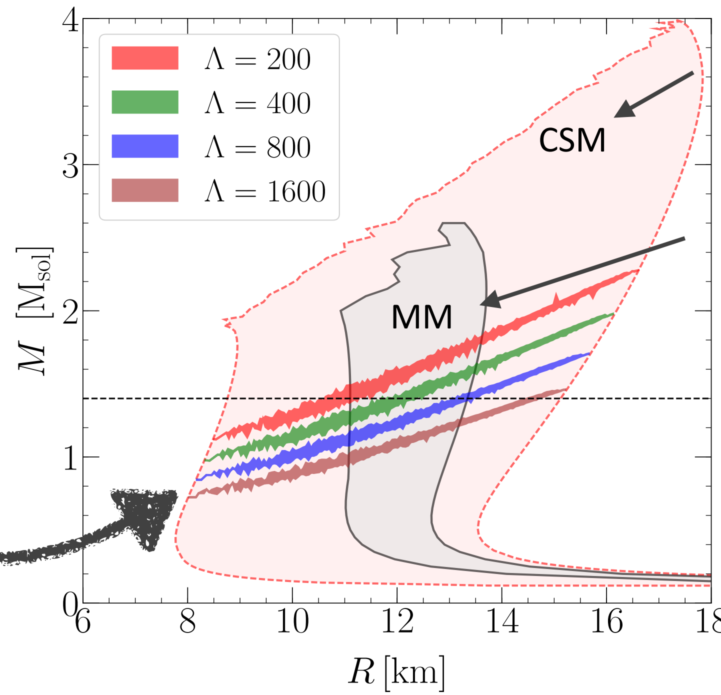
LVC, Phys. Rev. X 9, 011001 (2019)



GW170817
→ 70 ≤ Λ ≤ 720 (90% CL)
→ +E-M 300 ≤ Λ ≤ 800

Universal correlations

[Tews, JM, Reddy, PRC 2018, EPJA 2019]



Sound-speed Model (phases transitions) [Tews+ 2018]

Meta-Model (nucleonic)

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):

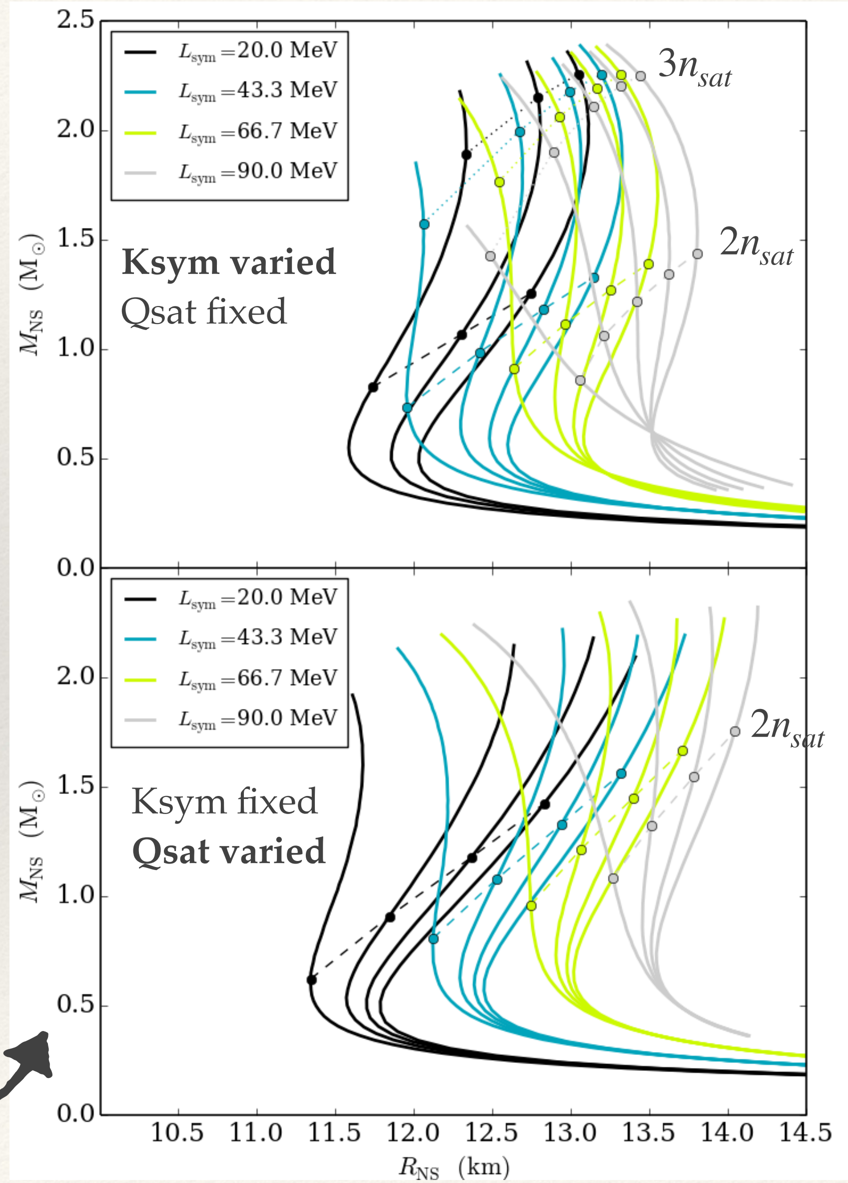
$$e(n, \delta) = t(n, \delta) + v(n, \delta)$$

Kinetic energy (Fermi gas)

Potential energy

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

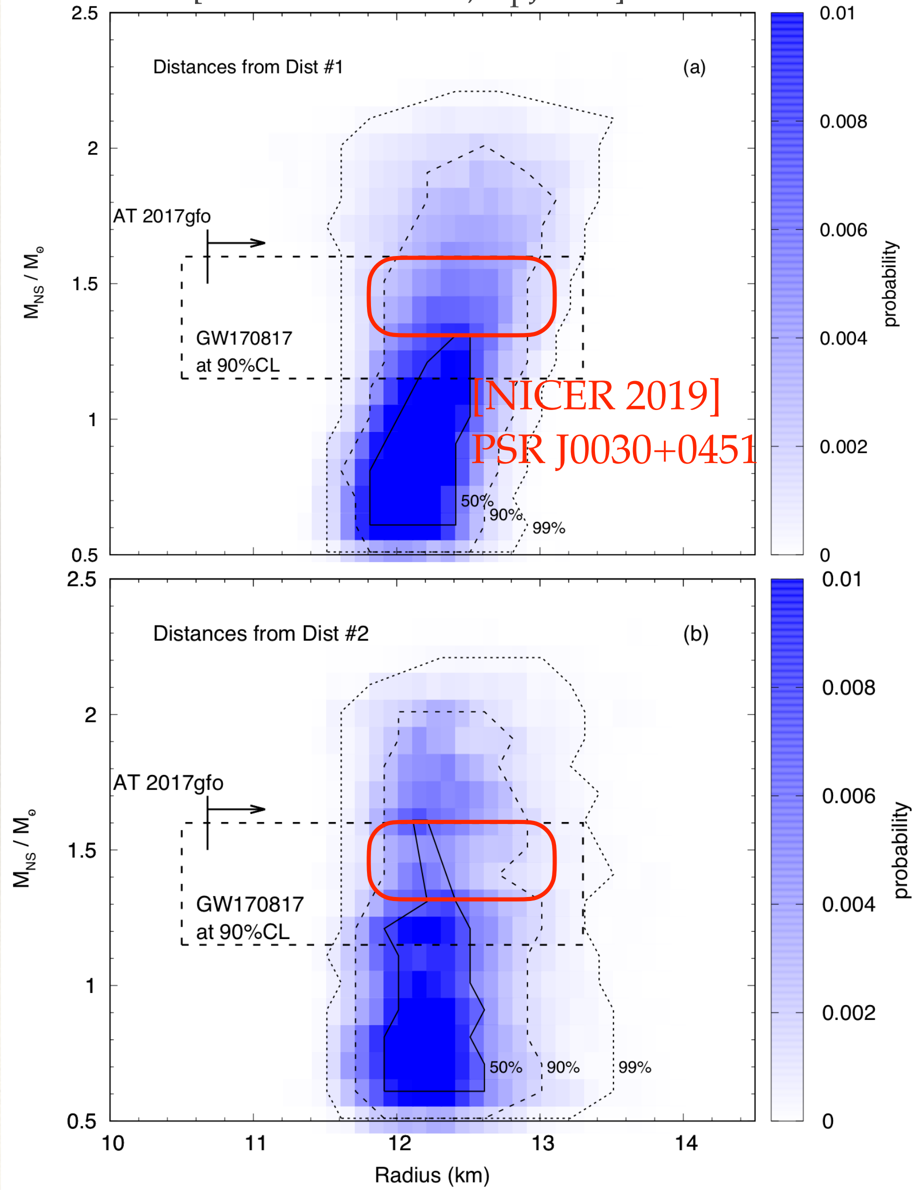
Directly related to NEP



Thermal emission from qLMXB

quiescent Low Mass X-ray binaries

[Baillot d'Étivaux+, ApJ 2019]



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

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

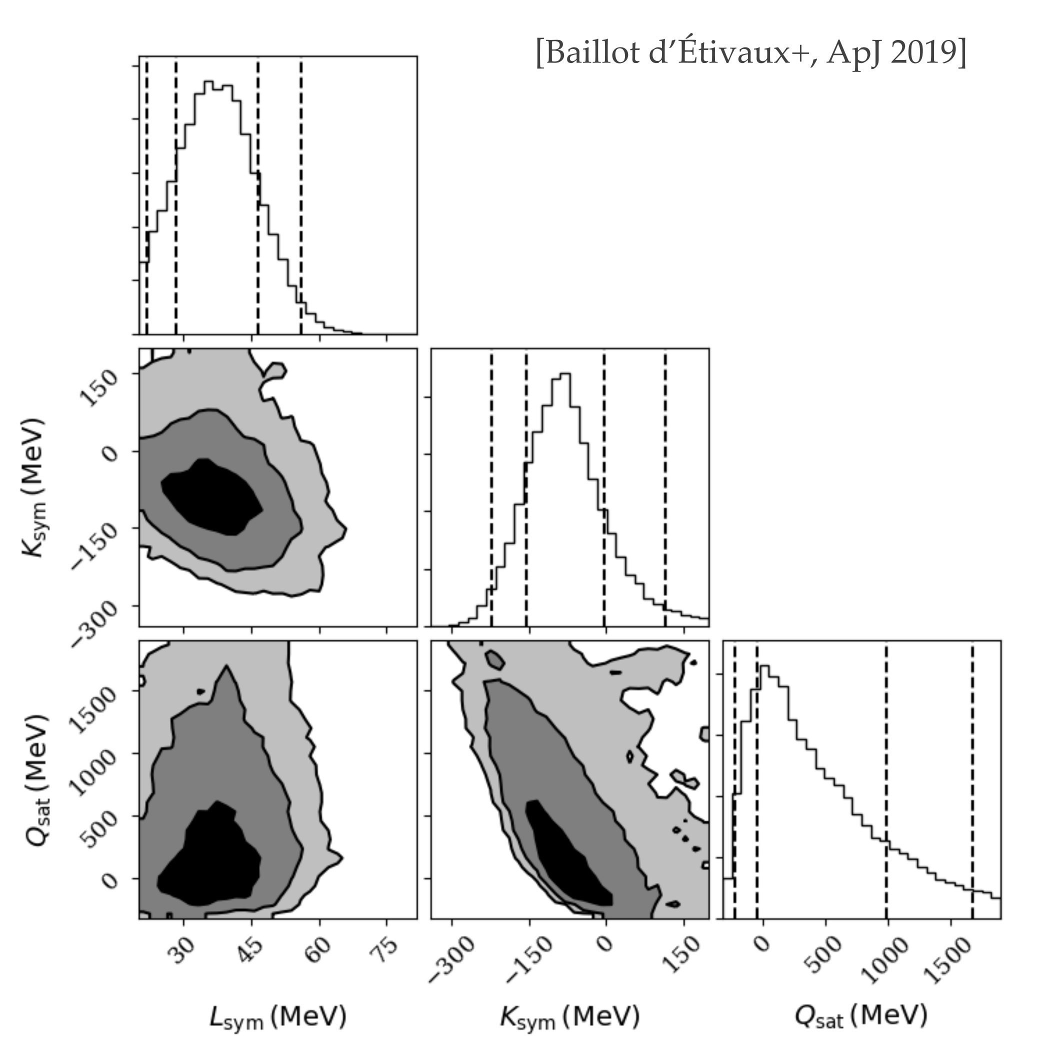
Average radii (12-13km) preferred.

—> The comparison with other approaches (GW170817, AT2017gfo) provides a consistent understanding of the data.

—> But more recent GW170817 analyses prefer **low radii**:

+ $R_{1.4} = 11^{+0.9}_{-0.6}$ km [Capano, Tews+ nature 2020]
+ $R_{1.4} \approx 11$ km [Güven+ PRC 2020]

Confronting qLMXB with nuclear EoS



Bayesian analysis with prior:
Lsym = 50 ± 10 MeV
Ksym [-400:200] MeV
Qsat [-1300:1900] MeV

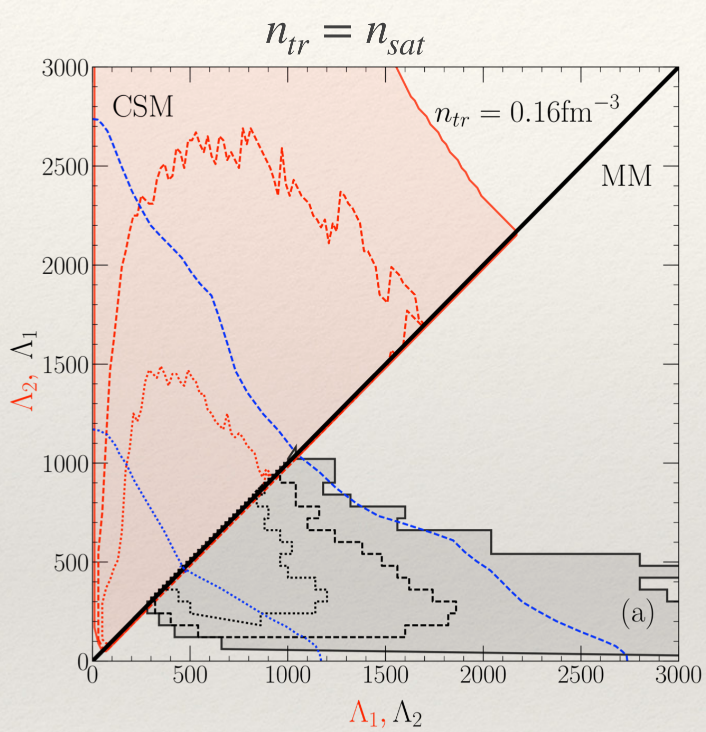
Posteriors:
Lsym = 38 ± 10 MeV
Ksym = −91 ± 80 MeV
Qsat = 350 ± 500 MeV

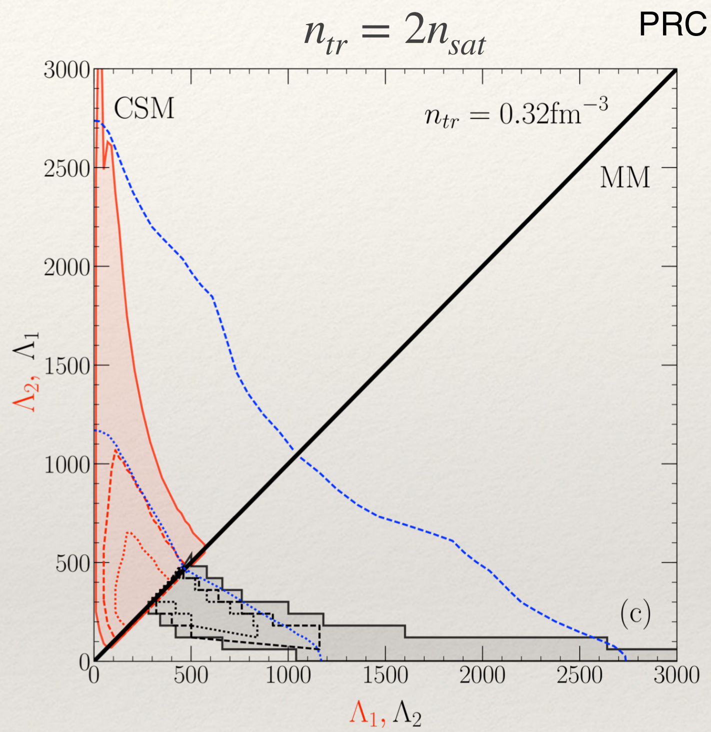
First extraction of Ksym and Qsat from data.

A recent analysis of pygmy GDR concludes:
Ksym = −120 ± 80 MeV [Sagawa 2019]

Confront EoS / GW

[Tews, JM, Reddy, PRC 2018, EPJA 2019]





Required GW accuracy to improve our knowledge:

$\Delta\Lambda \approx$ 200-300 ➡ Probe EOS from 1 to $2n_{sat}$

Confirm or rule out nuclear physics

$\Delta\tilde{\Lambda} \approx$ 50-100 ➡ Probe matter composition above $2n_{sat}$

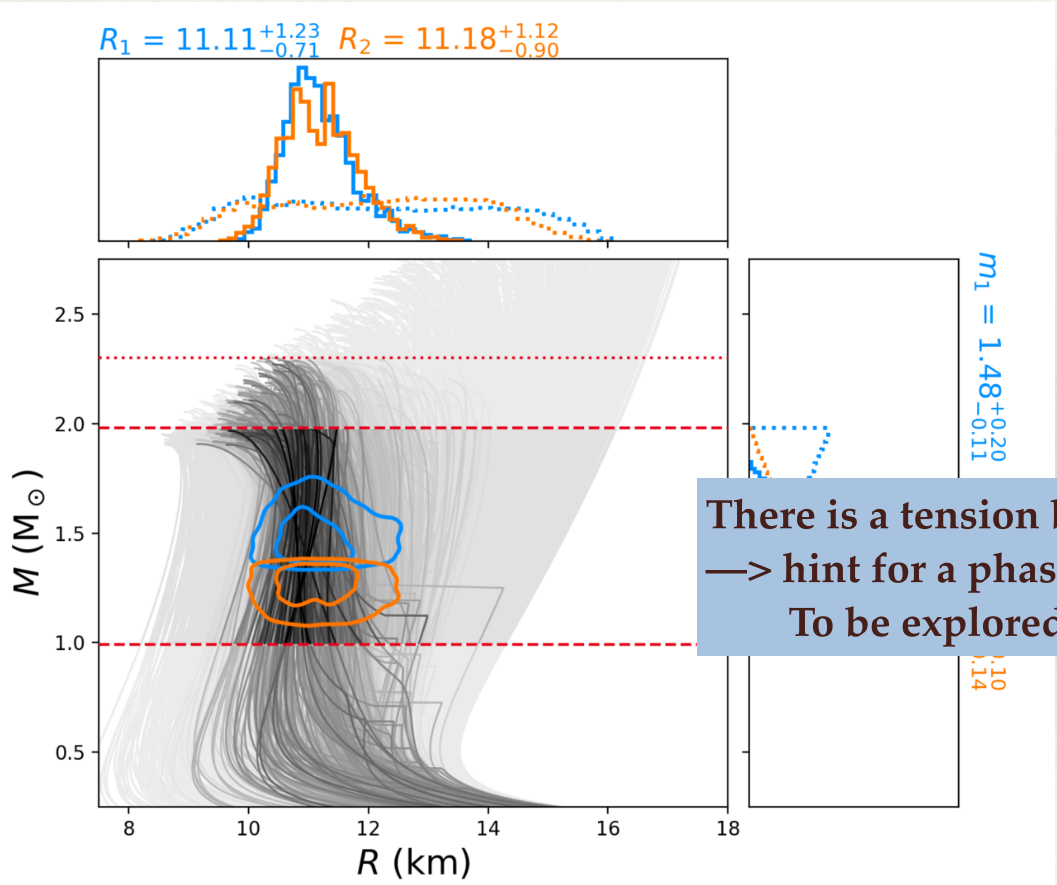
Multi-messenger/physics constraints on NS radii

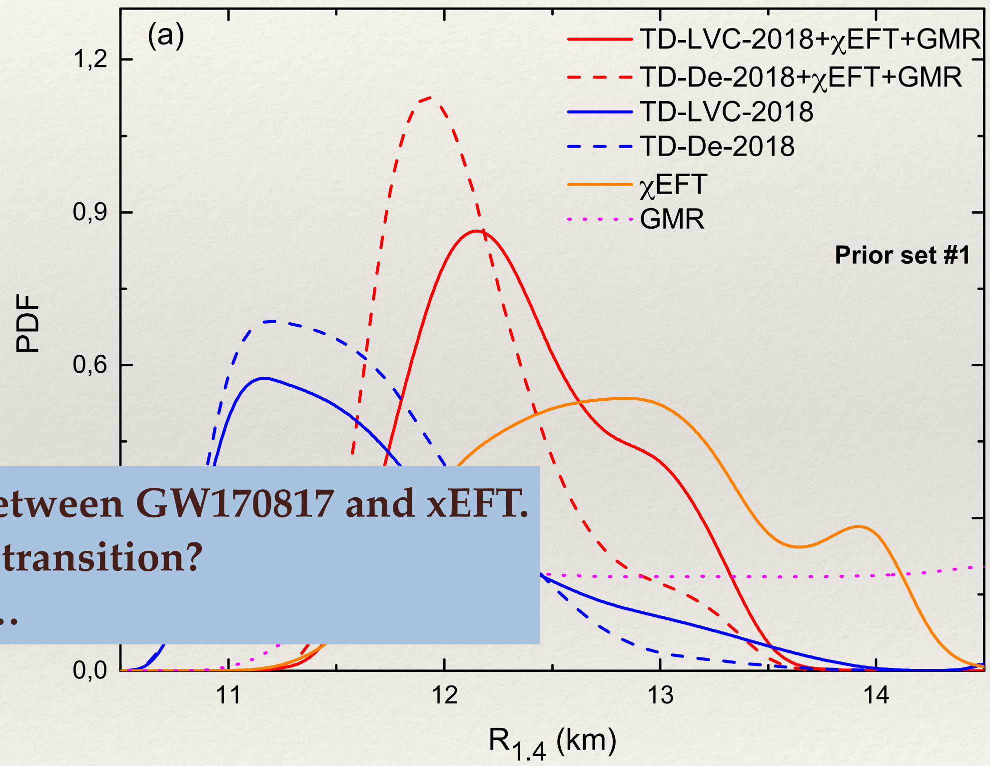
Direct comparison of the GW waveforms to the raw data, with EoS modeling + $M_{total} \leq M_{thresh}(\approx 2.3 M_\odot)$.

[Capano, Tews + Nature 2020]

Bayesian analysis of Λ-pdf confronted to nuclear physics knowledge (xEFT, GMR).

[Güven+ PRC 2020]



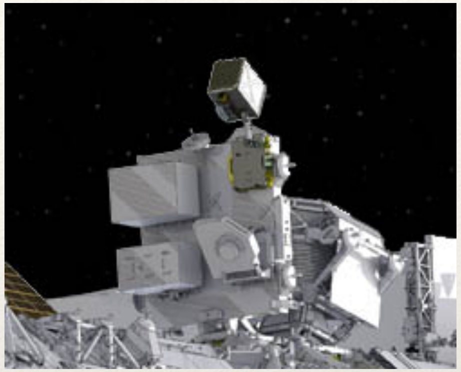


There is a tension between GW170817 and xEFT.
—> hint for a phase transition?
To be explored…

—> **Low NS radii** also seems to be preferred by GW + multi messenger analyses.

NICER X-ray observations of J0030 (2019) and J0740 (2021)

NICER

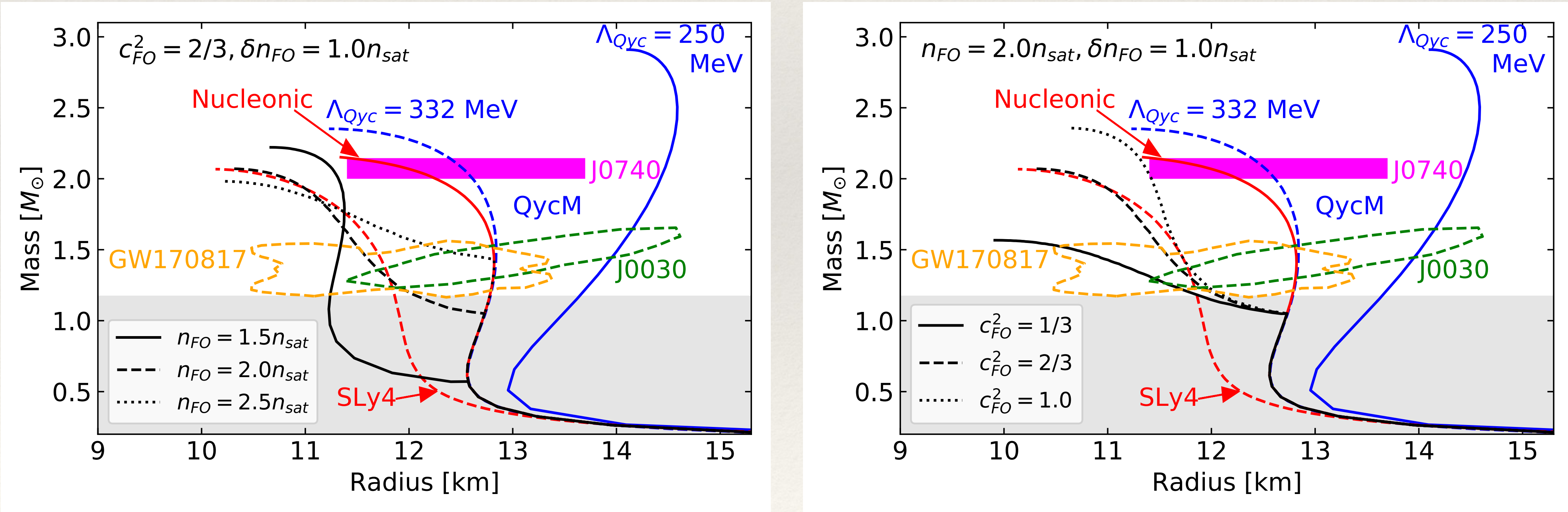


Confront different EoS modelings:

- SLy4 (often used in GW papers).
- First order phase transition to exotic matter.
- Quarkyonic matter (cross-over transition to quark matter).

Against data:
GW170817 and NICER (J0030 + J0740).

[Somasundaram+, arXiv 2021]



—> **NICER pull towards larger radii compared to GW.**

Unified EoS (crust + core)

[Grams+, FBS 2021, arXiv 2021]

2001: Douchin-Haensel EoS is the first unified model
2016: Fortin et al. underlined the importance of unified model for accurate NS radius predictions.

We thus constructed an unified EOS based on the meta-model approach :
- Taking into account chiral EFT predictions for uniform matter.
- Using nuclear experimental masses to rank the nuclear models.

Theoretical modeling:
- compressible liquid-drop approach (CLDM): variational approach where the central density is optimized for each nucleus.

$$E_{\rm nuc} = E_{\rm bulk} + E_{\rm FS}$$

with
$$E_{\rm bulk} = E_{MM}(n = n_{\rm nuc}, \delta = \delta_{\rm nuc})$$
$$E_{\rm FS} = E_{\rm Coul} + E_{\rm surf} + E_{\rm curv} + \dots$$

In the crust: $E_{WS} = E_{\rm nuc} + E_e + E_{ng}$

Electron and neutron gaz contributions

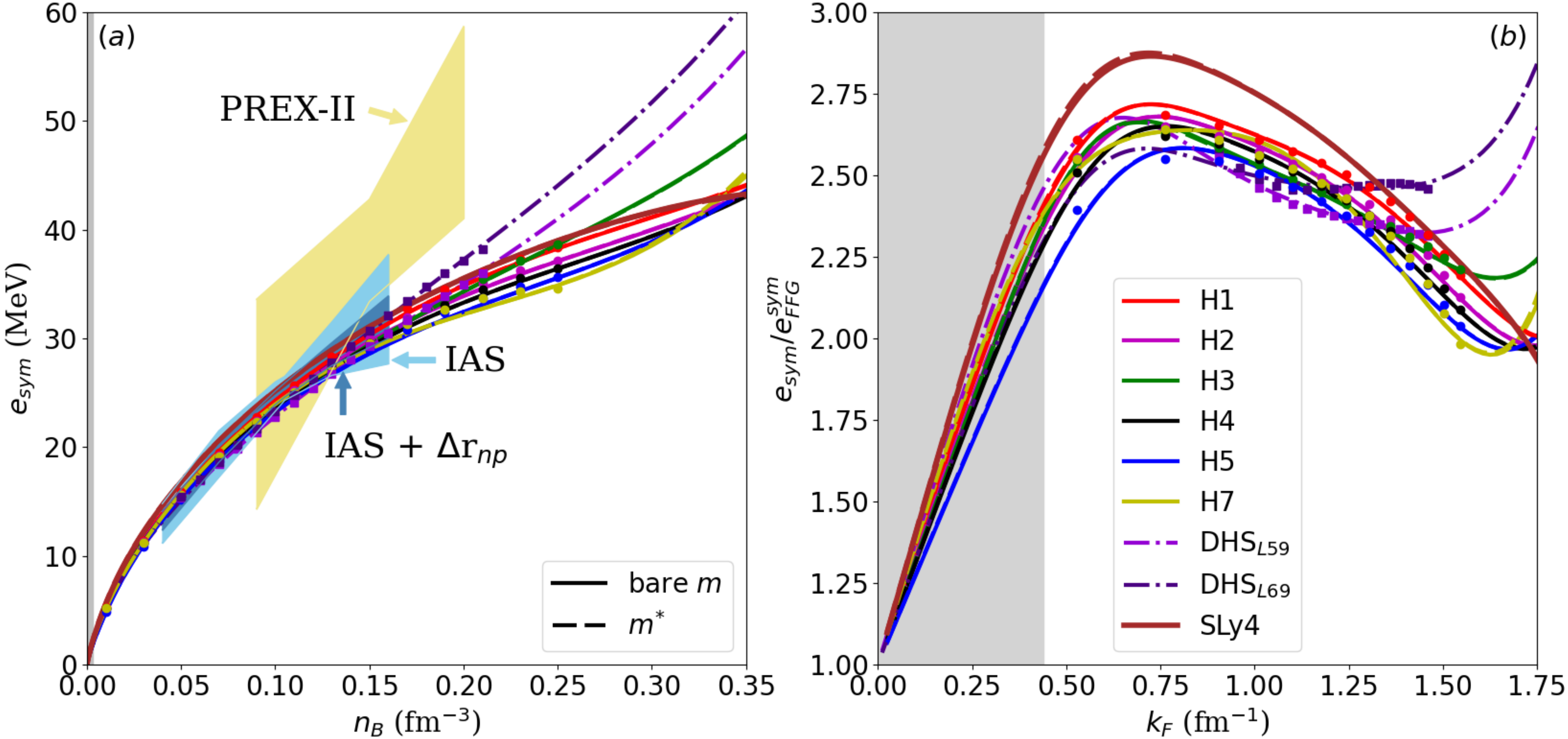
Ordering of the leptodermous contributions:

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

Symmetry energy

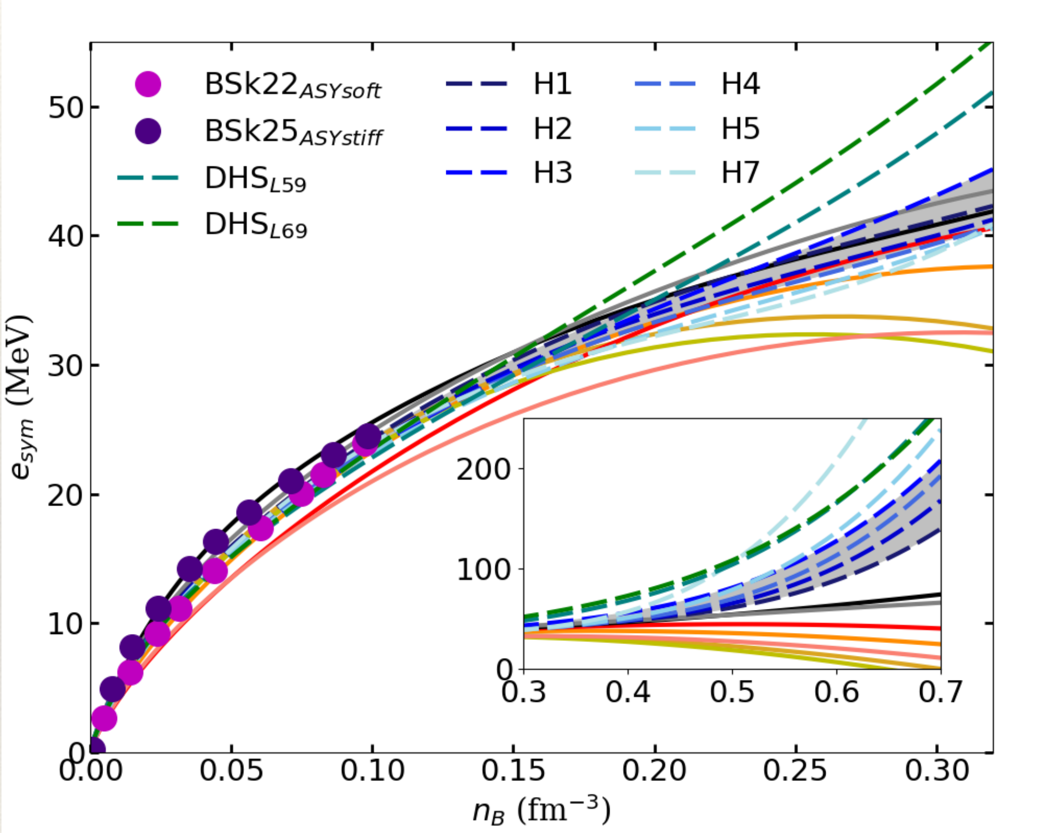
[Grams+, FBS 2021, arXiv 2021]

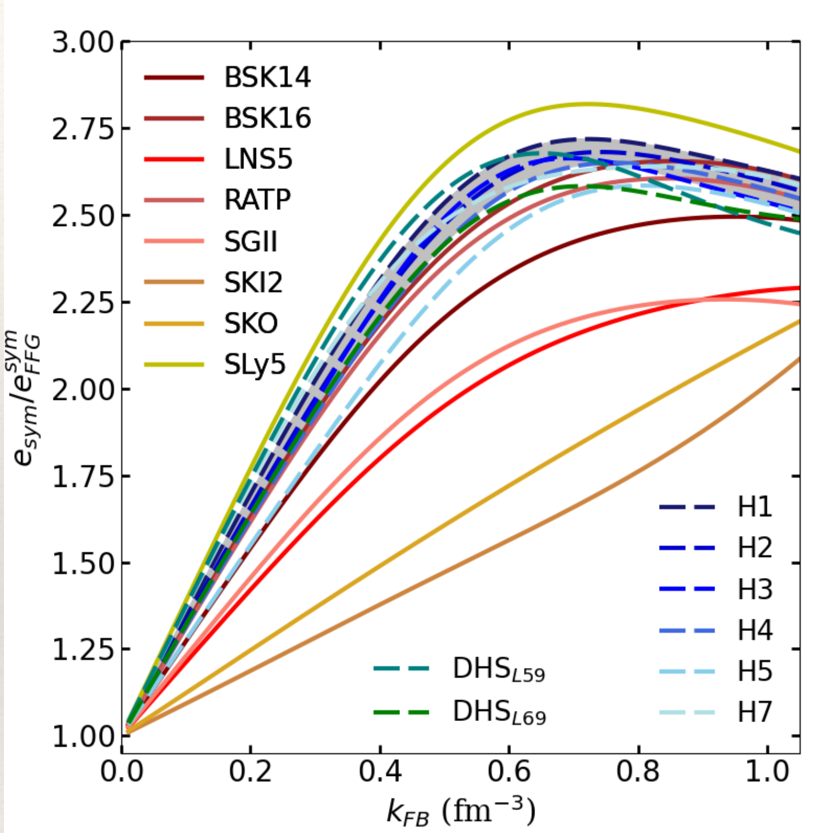
$$E_{\rm sym} = E_{\rm NM} - E_{\rm SM} = E_{\rm sym,2} + \dots \qquad \text{with} \qquad E_{\rm sym,2} = \frac{1}{2}\frac{\partial^2 E}{\partial \delta^2}\Big|_{\delta=0}$$



Symmetry energy: chiral EFT / Skyrme

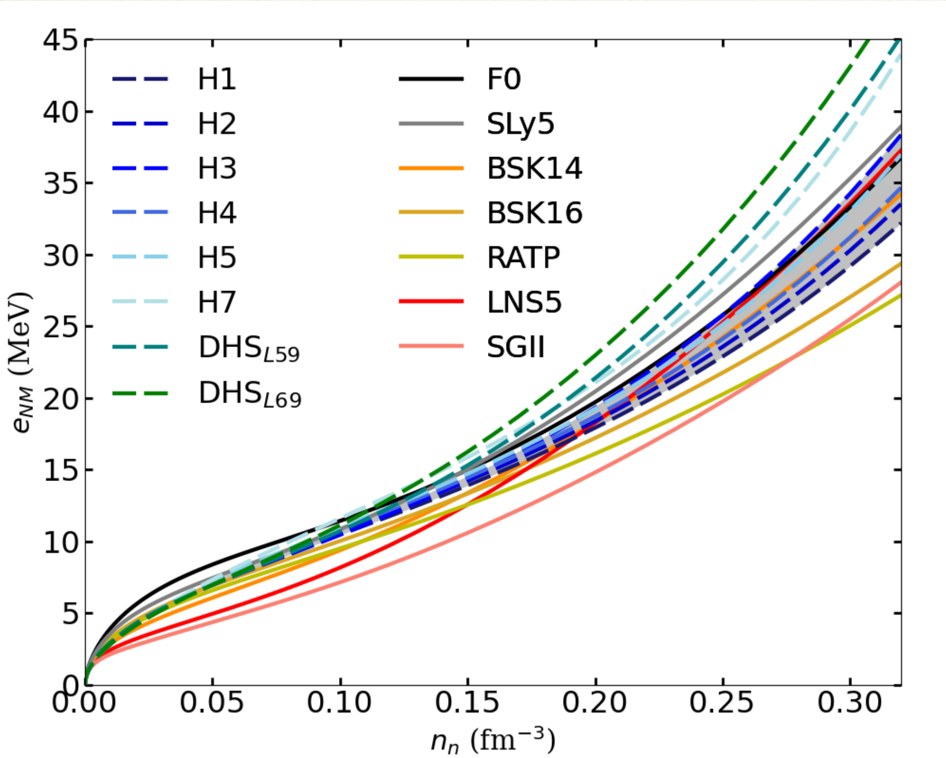
[Grams+, FBS 2021, arXiv 2021]

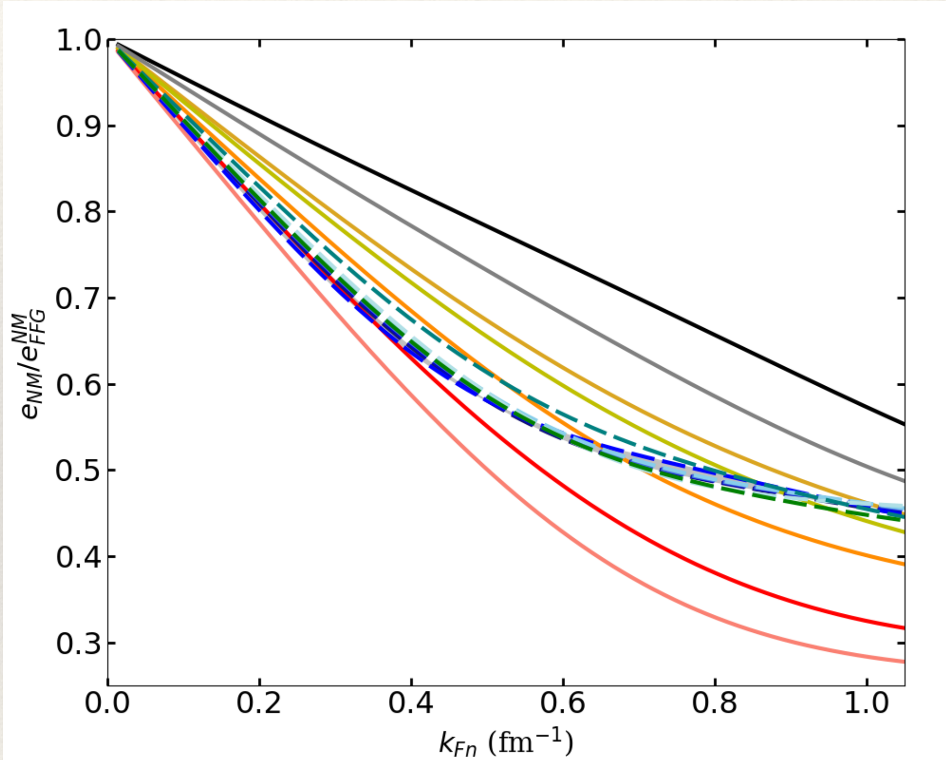




Energy in neutron matter (NM)

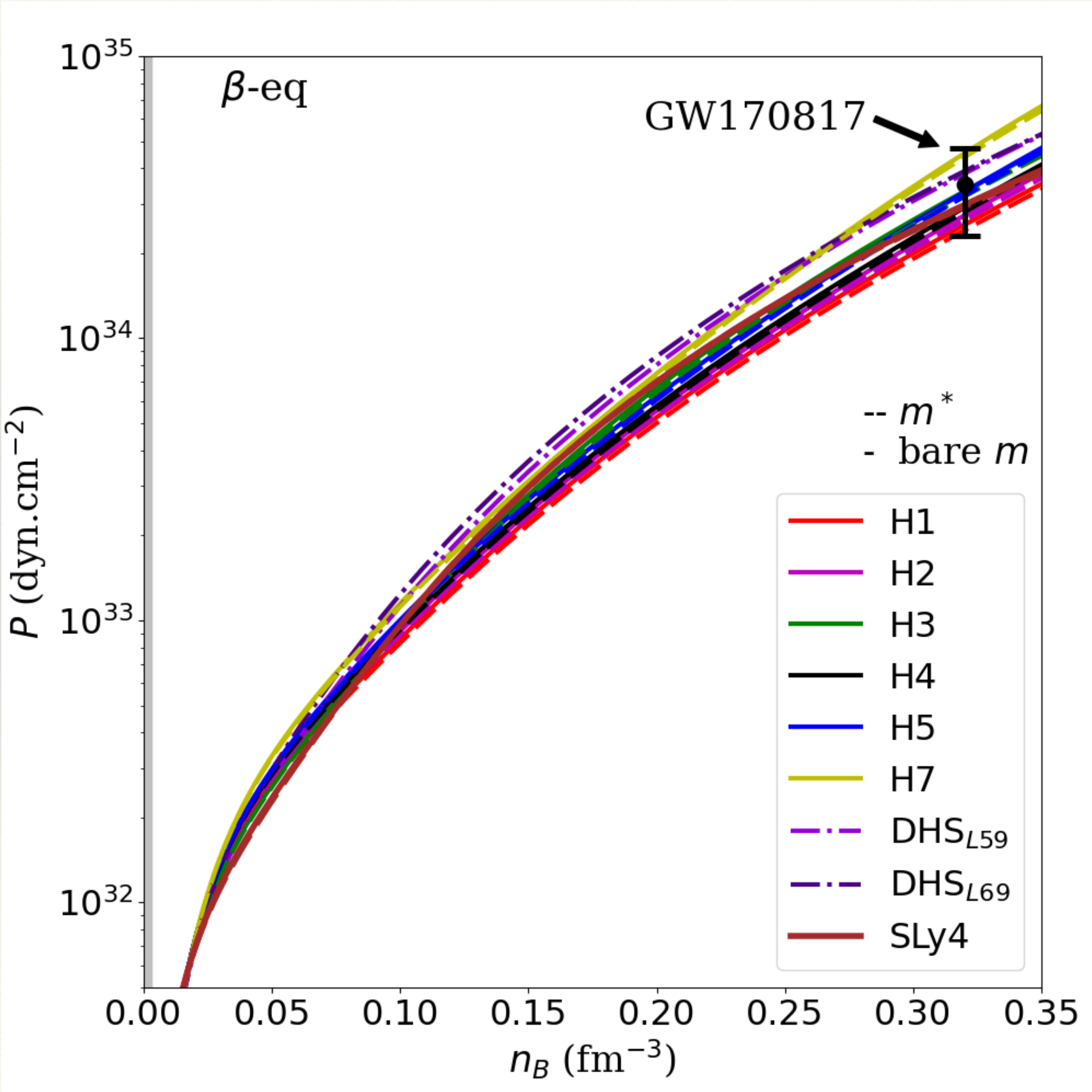
[Grams+, FBS 2021, arXiv 2021]





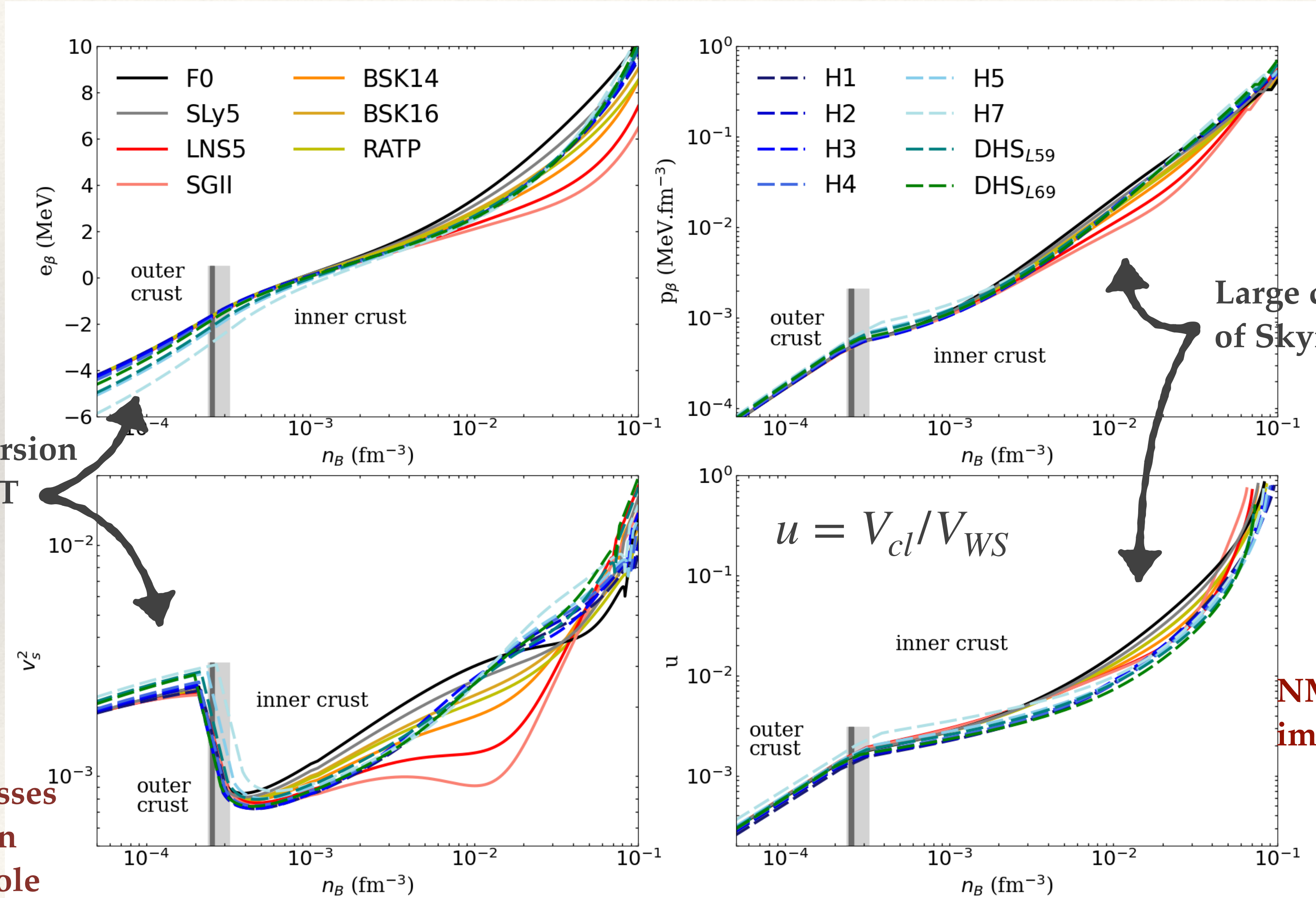
Pressure: constraints from GW170817

[Grams+, FBS 2021, arXiv 2021]



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

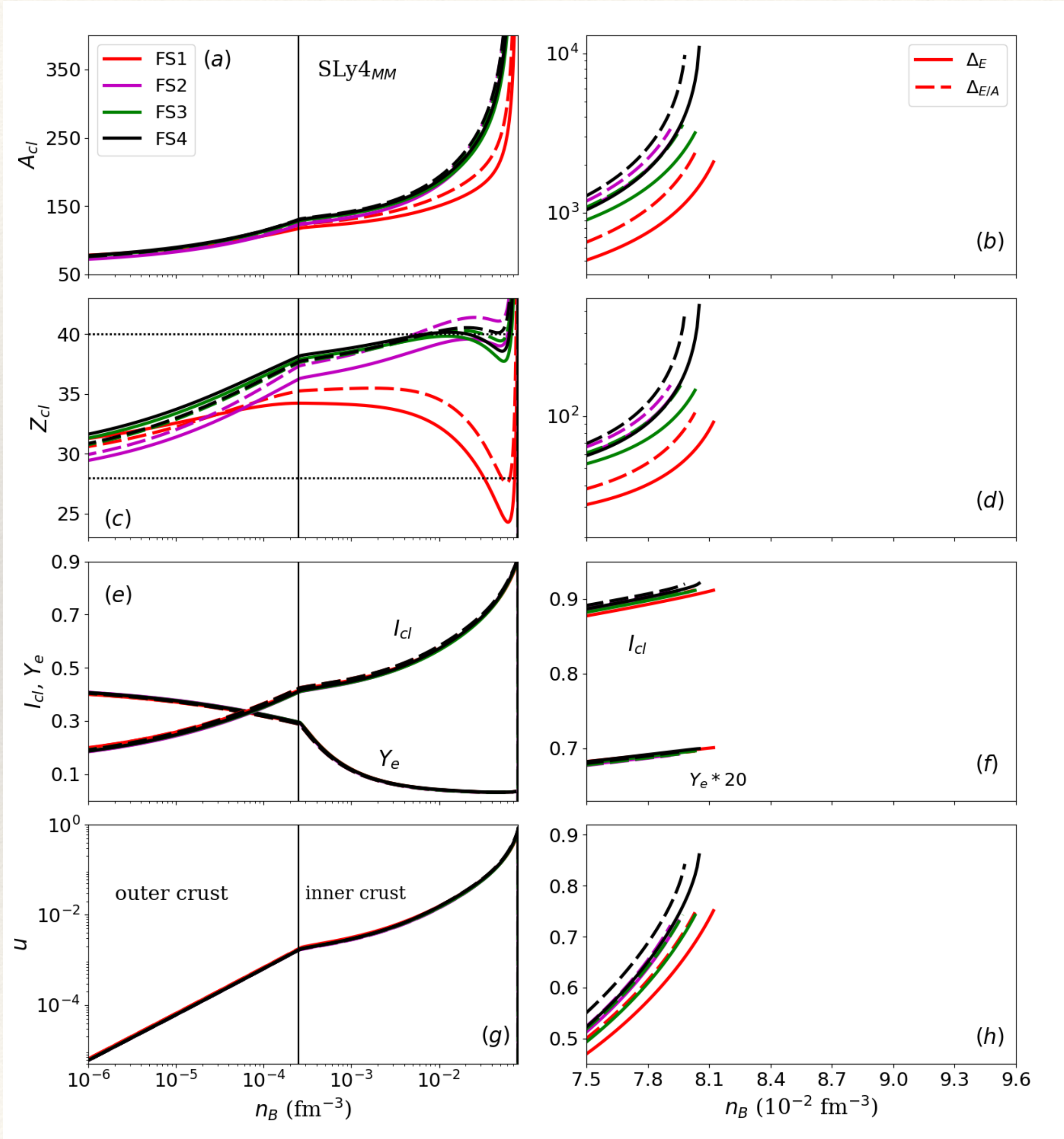
NM plays an important role

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



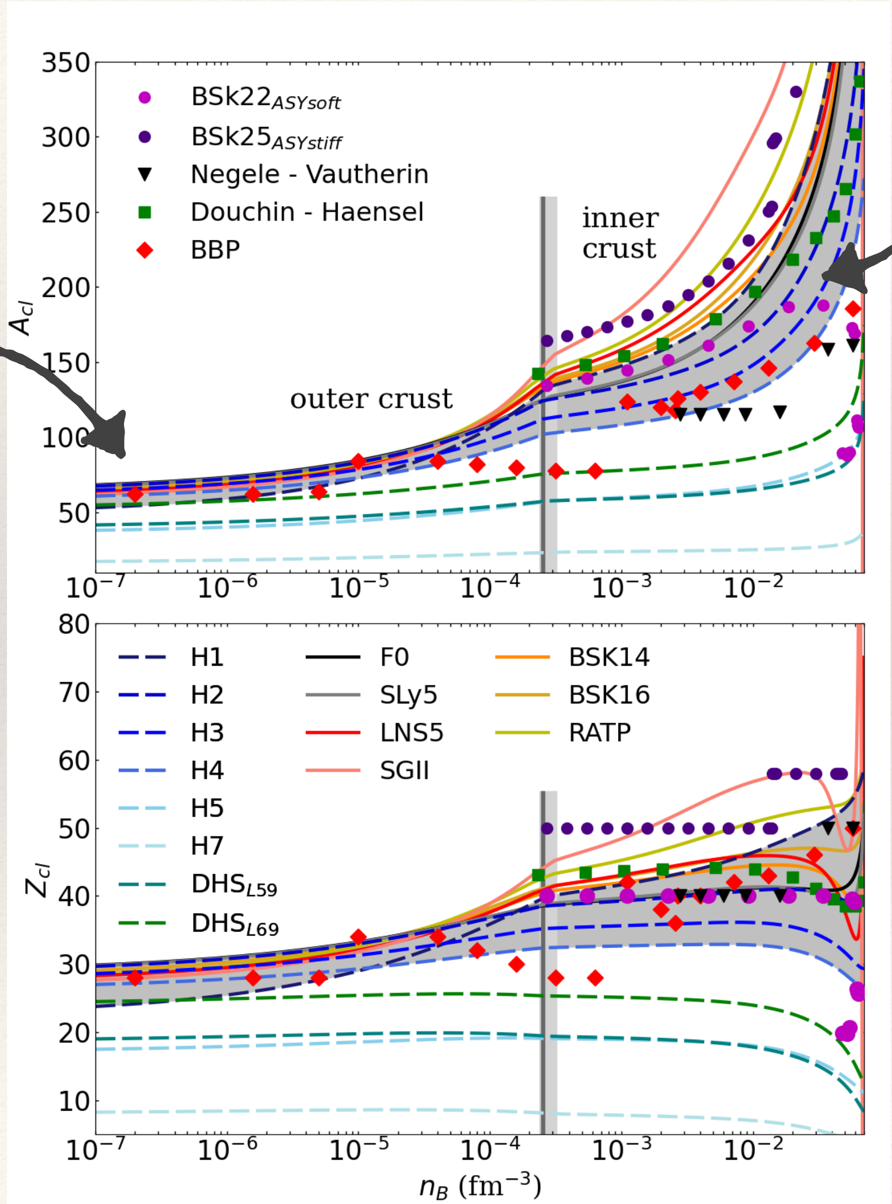
Wigner-Seitz composition (A_{cl}, Z_{cl})

[Grams+, FBS 2021, arXiv 2021]

Comparison to other predictions.

Small dispersion

Nuclear masses play an important role



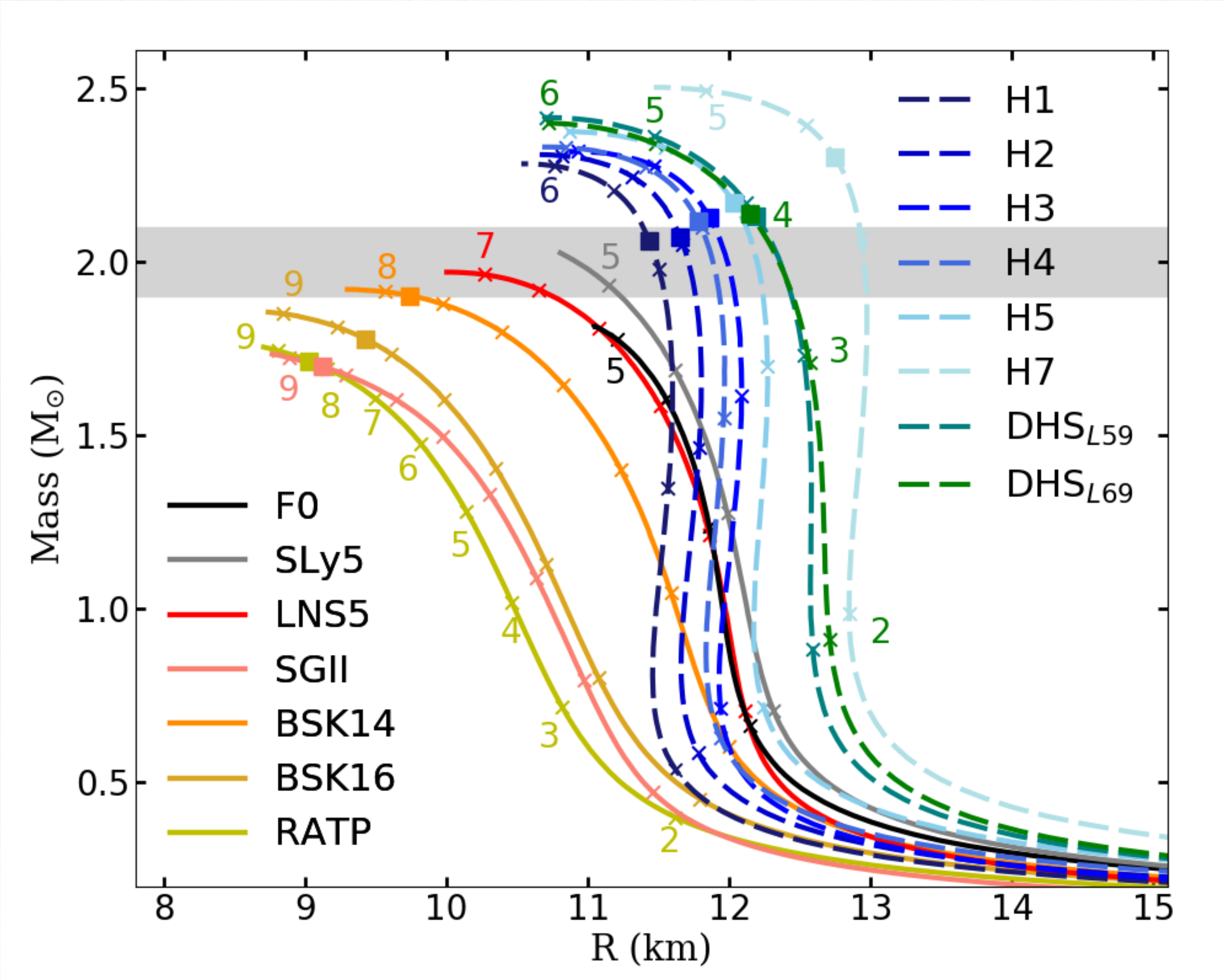
Larger dispersion

Controlled by nuclear masses

NM plays an little role

Mass-radius relations

[Grams+, FBS 2021, arXiv 2021]



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

Conclusions and outlooks

Thanks to GW and x-ray emissions from NS: extreme matter in NS core will be unveiled in a close future:

- LVK interferometers will start again in 2023.
- NICER continue to monitor new NSs.

In the future: Einstein Telescope, Cosmic explorer and Athena.

Simulation in astrophysics is the key to relate modeling of microphysics with observational data.

Links with accelerator physics are complementary:

- probe properties of nuclear matter around saturation (symmetry energy, curvature, …).
- At higher density, HIC probes higher order empirical parameters (Qsat).

Interesting developments in machine Learning technics applied to extreme matter EoS.
(Not adressed in this talk)