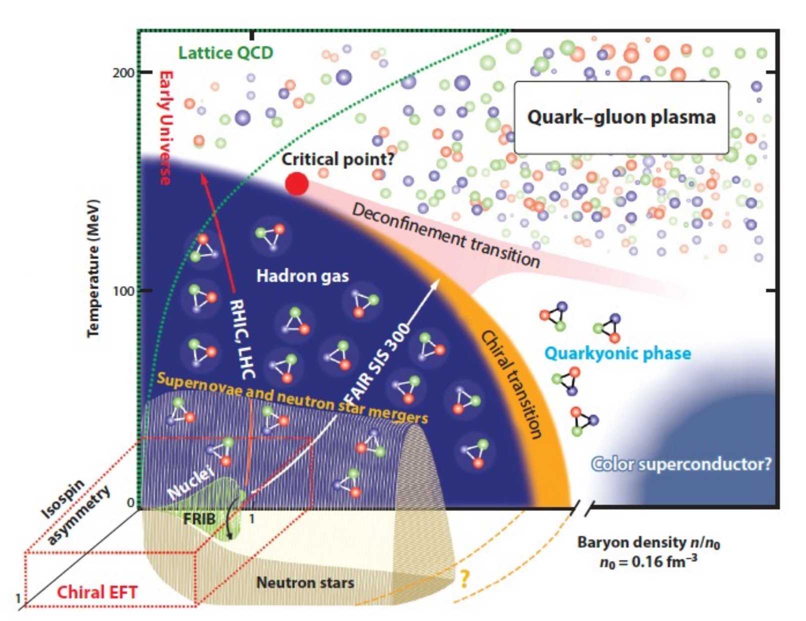
Dense-matter equation of state and neutron stars: Nuclear-physics and multi-messenger constraints

Anthea F. Fantina

EuNPC,
22 – 26 September 2025, Caen (France)

Probing extreme conditions in NSs



Drischler et al., Ann. Rev. Nucl. Part. Sci. 71, 403 (2021)

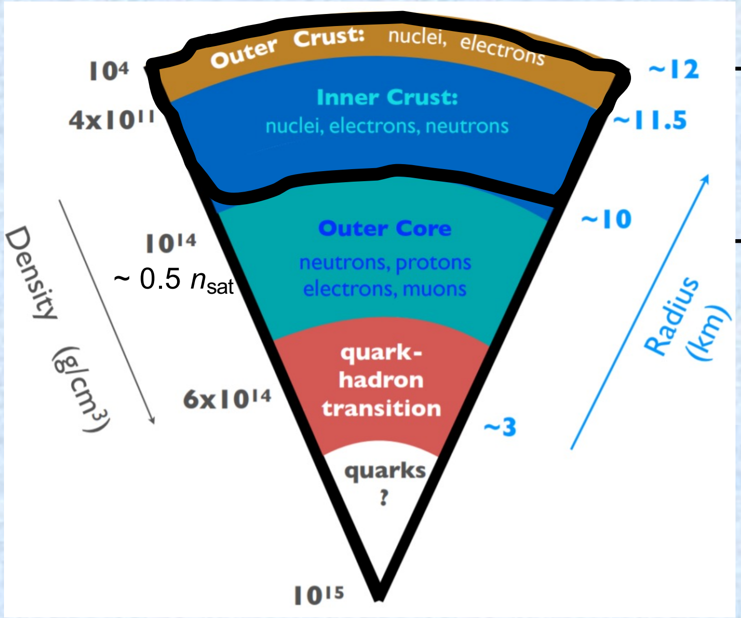


Image Credit: 3G Science White Paper

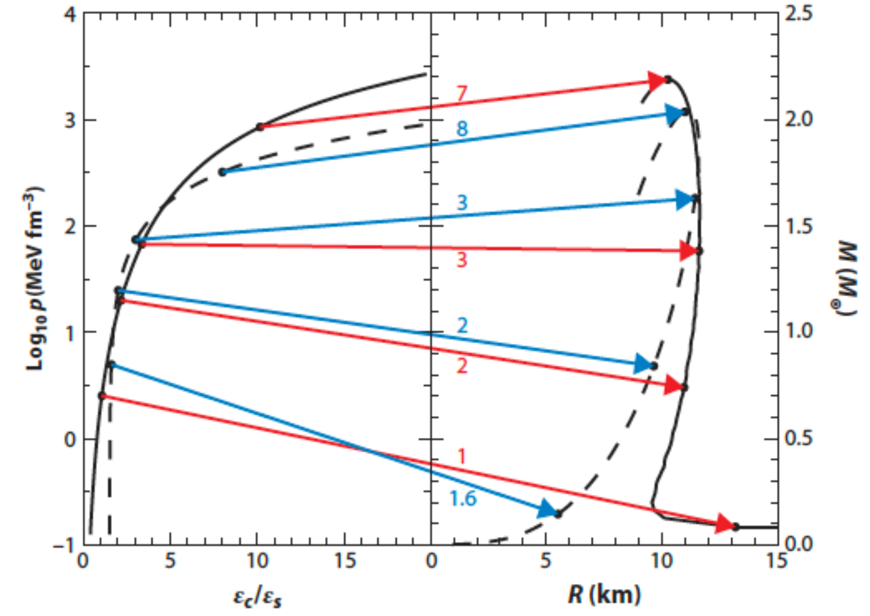
CRUST:
~ 1% of M_{NS}
~ 10% R_{NS}
$\rho < \rho_{sat}$

different states of matter spanned in NSs
→ inhomogeneous (crust), "pasta" phase, homogeneous (core), "exotic" particles (?)
+ superfluidity, (strong) magnetic field, etc.

→ Not all conditions can be probed in terrestrial labs → theoretical models !
→ Consistent description very challenging

N.B.: In this talk: beta-equilibrated T=0 matter, NS static properties
→ OK for cold NS and pre-merger binary NSs

EoS ←→ NS (static) observables (1)



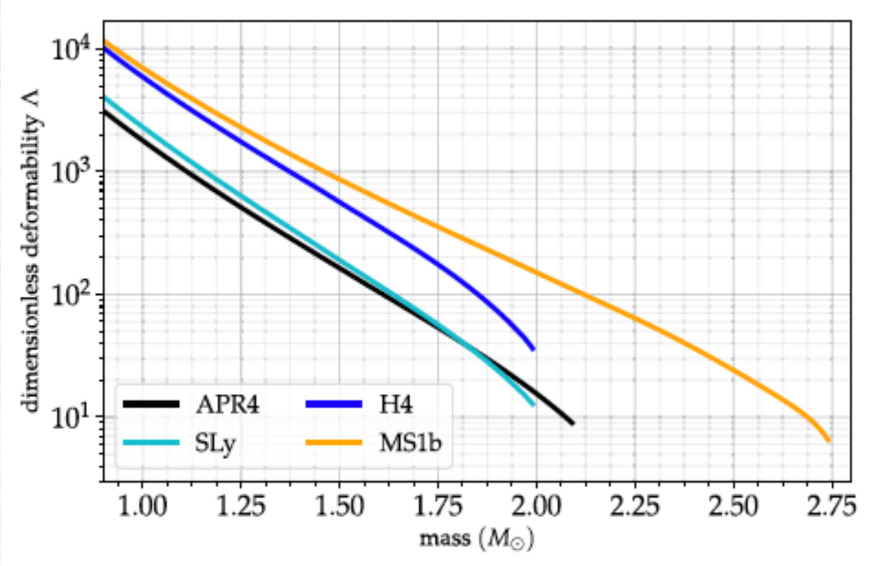
Lattimer, Annu. Rev. Part. Nucl. Sci. 62, 485 (2012)

- **TOV → *M*(*R*)** (Tolmann 1939; Oppenheimer&Volkoff 1939; see also Haensel et al. Springer 2007)

$$\frac{\mathrm{d}P(r)}{\mathrm{d}r} = -\frac{G\rho(r)\mathcal{M}(r)}{r^2}\left[1+\frac{P(r)}{c^2\rho(r)}\right]\left[1+\frac{4\pi P(r)r^3}{c^2\mathcal{M}(r)}\right]\left[1-\frac{2G\mathcal{M}(r)}{c^2 r}\right]^{-1}$$

$$\mathcal{M}(r) = 4\pi\int_0^r \rho(r')r'^2\mathrm{d}r'$$

⇨ $P(\mathcal{E})$ EoS needed!



Dietrich et al., Gen. Rel. Gravit. 53, 27 (2021)

➡ GR → direct correspondence
EoS ←→ NS static properties

?
→ trace back to EoS and composition?

see talk by T. Hinderer

N.B.: GR in slow rotation limit w/o magnetic field !

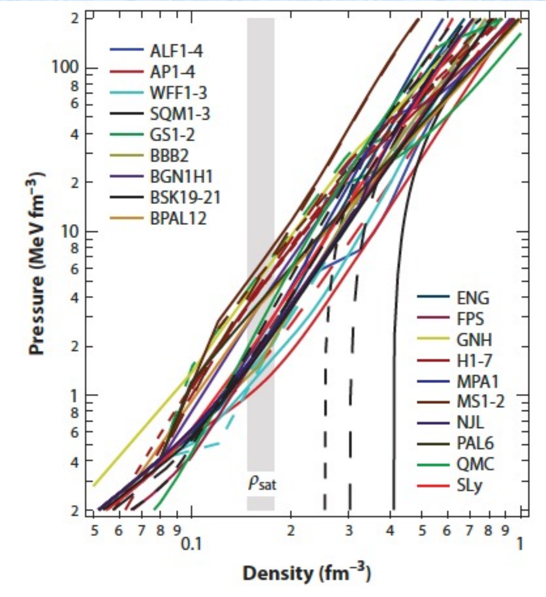
EoS ←→ NS (static) observables (2)

but:

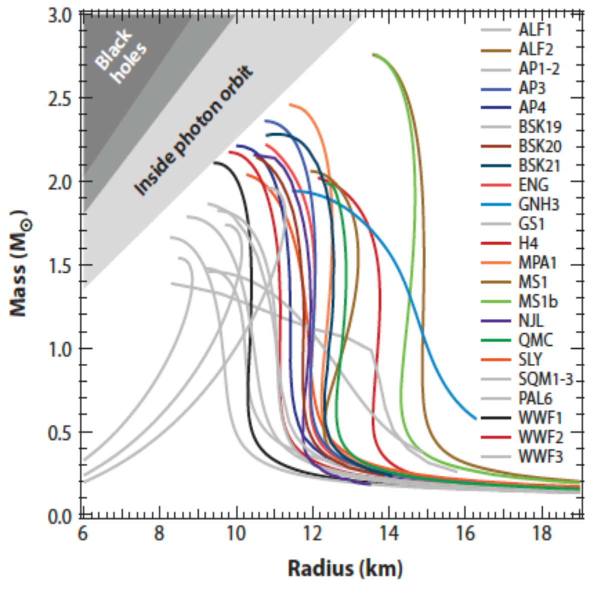
✗ EoS model dependent ! (higher uncertainties at higher ρ)

✗ no ab-initio dense-matter calculations
in all regimes → phenomenological models

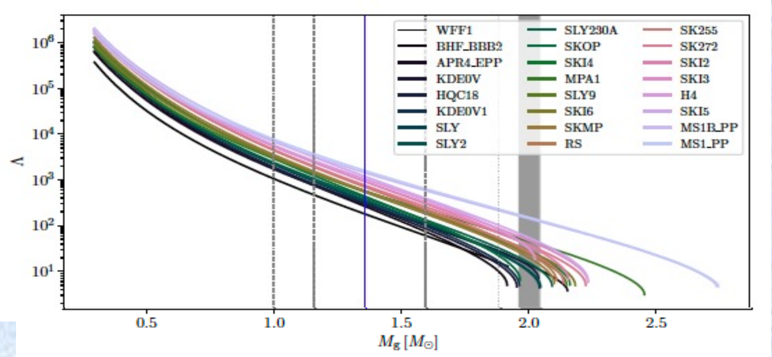
✗ composition ←→ EoS → $M(R)$?



Ozel & Freire, ARAA 54, 401 (2016)



Ozel & Freire, ARAA 54, 401 (2016)

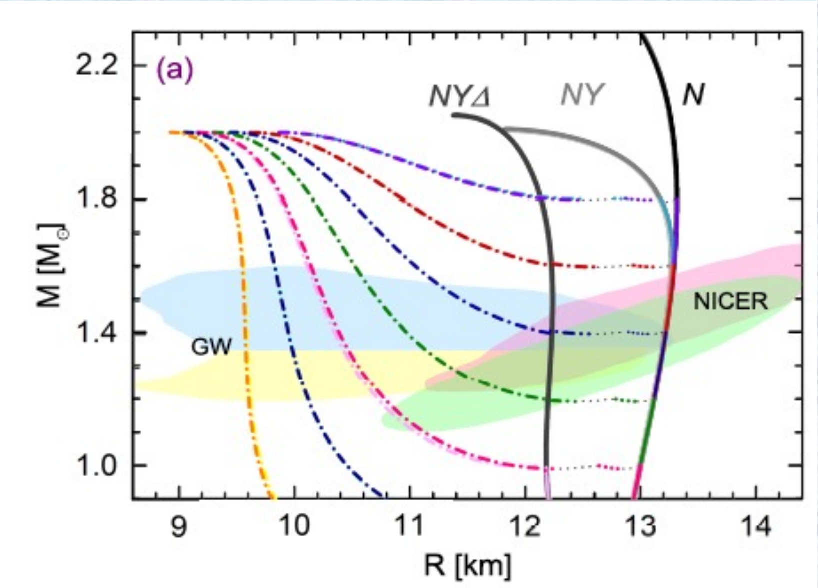


Abbott et al., Class. Quantum Grav, 37, 045006 (2020)

(see e.g. Haensel et al., “Neutron Star Structure”, Springer 2007; Oertel et al., Rev. Mod. Phys. 2017; Burgio & Fantina, ASSL Springer 2018; Blaschke & Chamel, ASSL Springer 2018 for a review)

High-density EoS → additional d.o.f.?

- Role of "exotic" degrees of freedom?
  Hyperons → softer EoS → lower $M_{\max}$ (+ reduction of R and Λ for intermediate-mass) but large uncertainties on Y !
  Quarks → not clear



Li et al., PRD 101, 063022 (2020)

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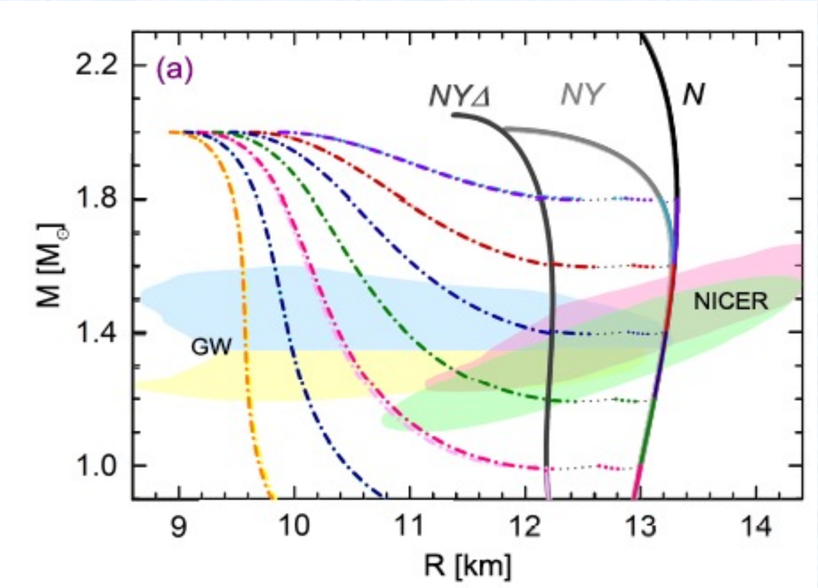
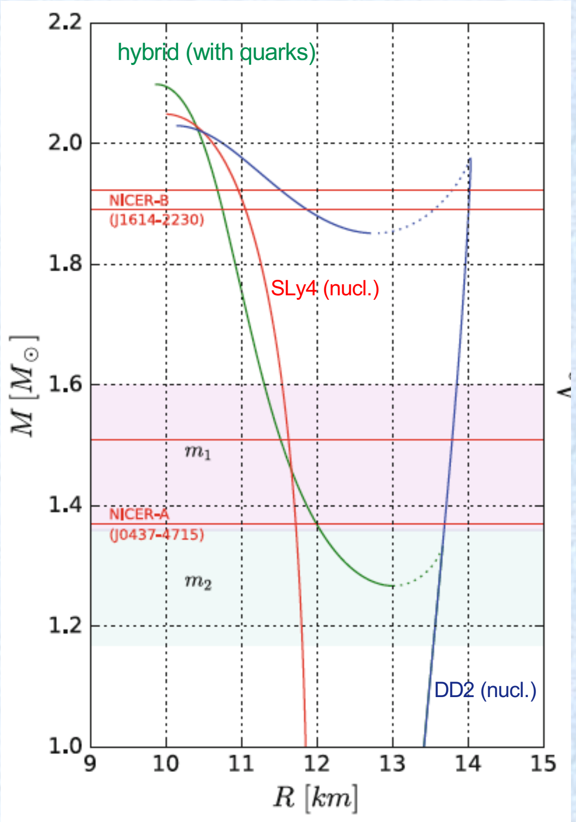
- "Masquerade" effect



Li et al., PRD 101, 063022 (2020)



Blaschke & Chamel, ASSL 457, 337 (2018);

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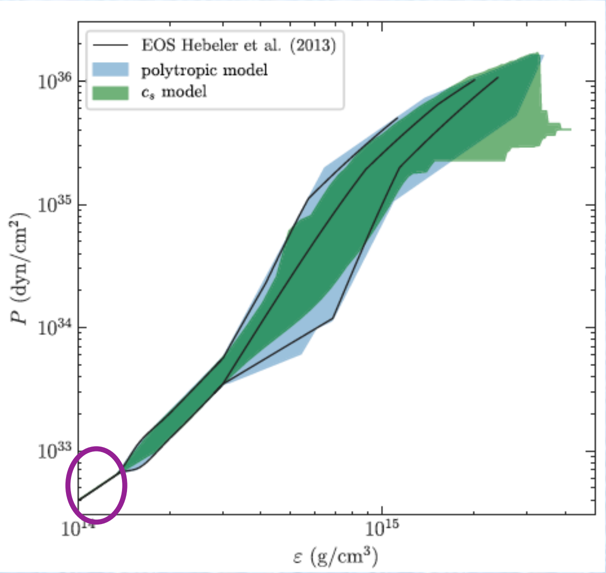
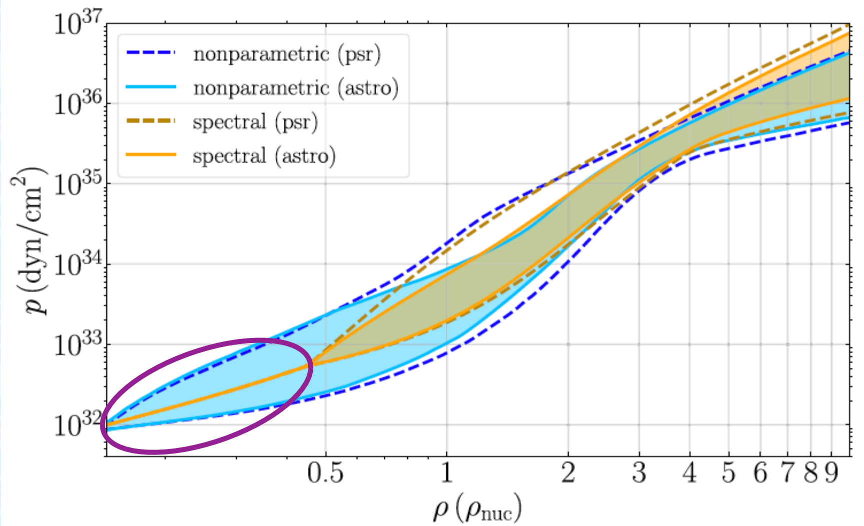
➢ *Agnostic* ("non-nuclear") approaches for NS core (e.g. piecewise polytropes, c_s models, Gaussian process, etc…) (conditioned by astro)



Hebeler, Phys. Rep. 980, 1 (2021)



Legred et al. PRD 105, 043016 (2022)

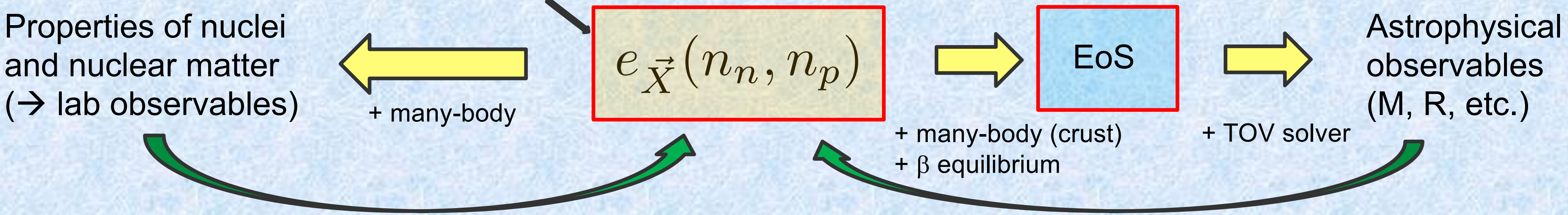
✓ poweful → no underlying hypotheses
✗ no info on composition
✗ often unique (non-consistent) low-density EoS
→ uncertainties underestimated

A semi-agnostic approach: nucleonic meta-model

- **Nucleonic Meta-model (MM)** (Margueron et al., PRC 97, 025805 (2018), Char et al., PRD 108 (2023))
  see also e.g. Lim&Holt 2019, Tsang et al. 2020

→ nucleonic → no additional particles
→ flexible functional, based on Taylor expansion around saturation density.
Model parameters $\{\boldsymbol{X}_i\}$ related to properties of nuclear matter (nuclear empirical param.)

$$\vec{X} = \{E_{\mathrm{sat,sym}}, L_{\mathrm{sym}}, K_{\mathrm{sat,sym}}, \ldots\}$$



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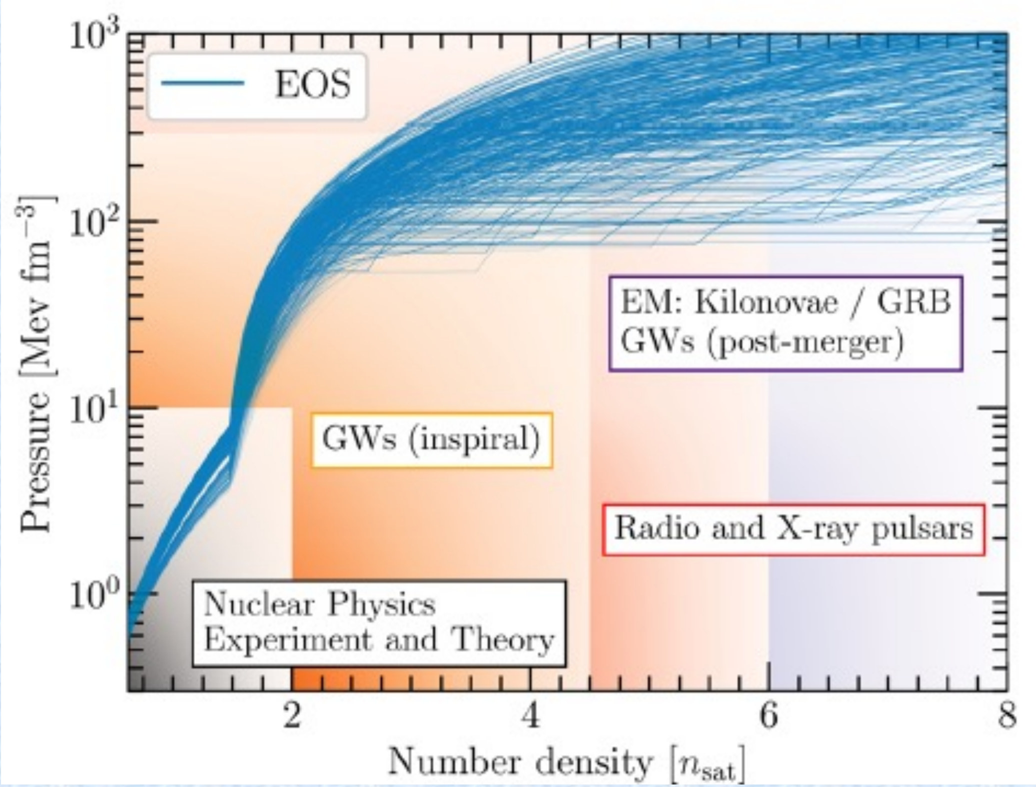
Properties of nuclei and nuclear matter (→ lab observables) ⇐ (+ many-body) ⇐ $e_{\vec{X}}(n_n, n_p)$ ⇒ (+ many-body (crust), + β equilibrium) ⇒ EoS ⇒ (+ TOV solver) ⇒ Astrophysical observables (M, R, etc.)

✓ Different $\{X\}$ → reproduce different effective models (EDF / RMF)
✓ Vary $\{X\}$ → large parameter space → statistical (Bayesian) analysis → possible correlation with nuclear param.
✓ Possible to couple MM approach for crust to agnostic EoS (e.g. polytropes, etc.) at high density

- N.B. : For application to NS crust → many-body method (e.g. CLDM or ETF) → see T. Diverrès talk
  e.g. Carreau et al., EPJA 2019; Dinh Thi et al., A&A 2021; Grams et al., EPJA 2022; Mondal et al., MNRAS 2023; Davis et al., A&A 2024; Montefusco et al., A&A 2025, Grams et al., Universe 2025; Klausner et al. arXiv2505.16929; Burrello et al., PRC 2025

Model exploration: Bayesian inference

$$p_{\text{post}}(\vec{X}|\vec{c}) \propto p(\vec{X}) \prod_i p(c_i|\vec{X})$$



Pang et al., Nat. Comm. 14, 8352 (2023)

$p(\vec{X})$ prior → large parameter space (non-informative / nuc.-phys. informed)

$p(c_{\text{nuc}}|\vec{X})$ Nuclear data (e.g. nuclear masses)
Ab-initio calculations

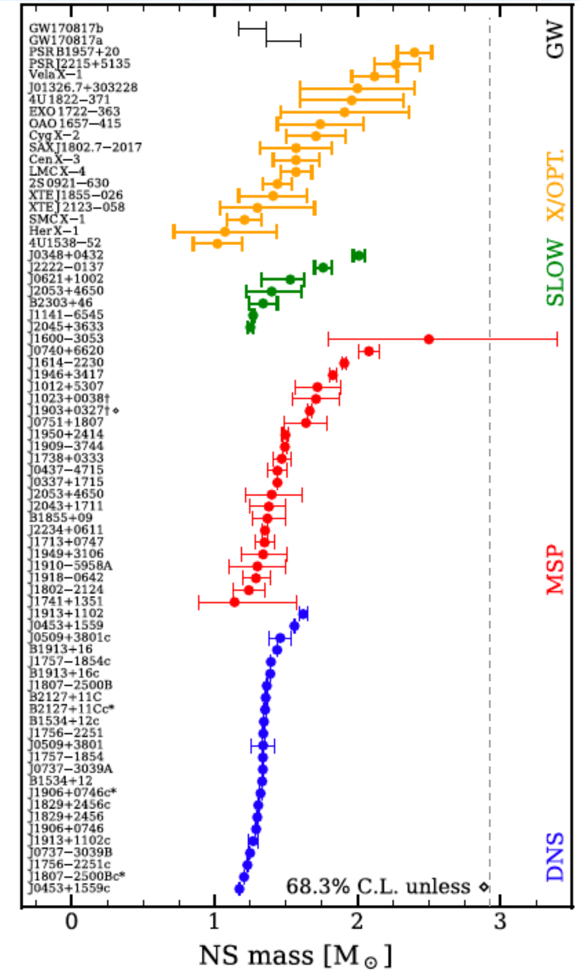
→ Low-density constraints

$p(c_{\text{astro}}|\vec{X})$ Causality + thermo stability
Astro data: M_{max}, GW, NICER

→ High-density constraints

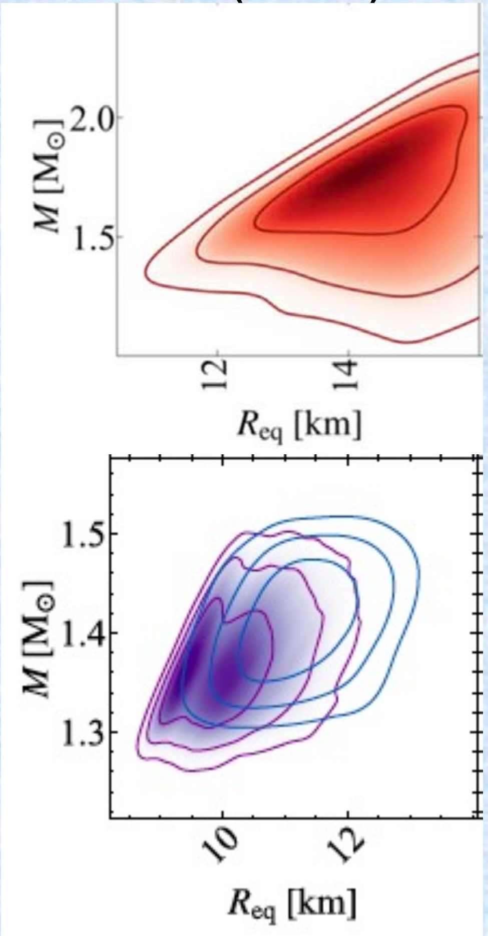
Constraints from astrophysics

MASSES



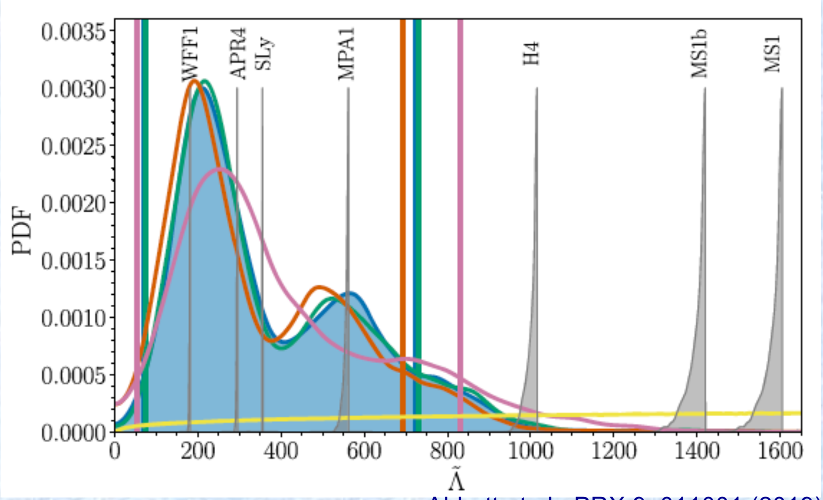
Suleiman et al., PRC 104, 015801 (2021)

RADII (NICER)



Choudhury et al., ApJL 971, L20 (2024);
Vinciguerra et al., ApJ 961, 62 (2024)
see also Miller et al. , Riley et al., ApJL 2019, 2021

TIDAL DEFORMABILITY



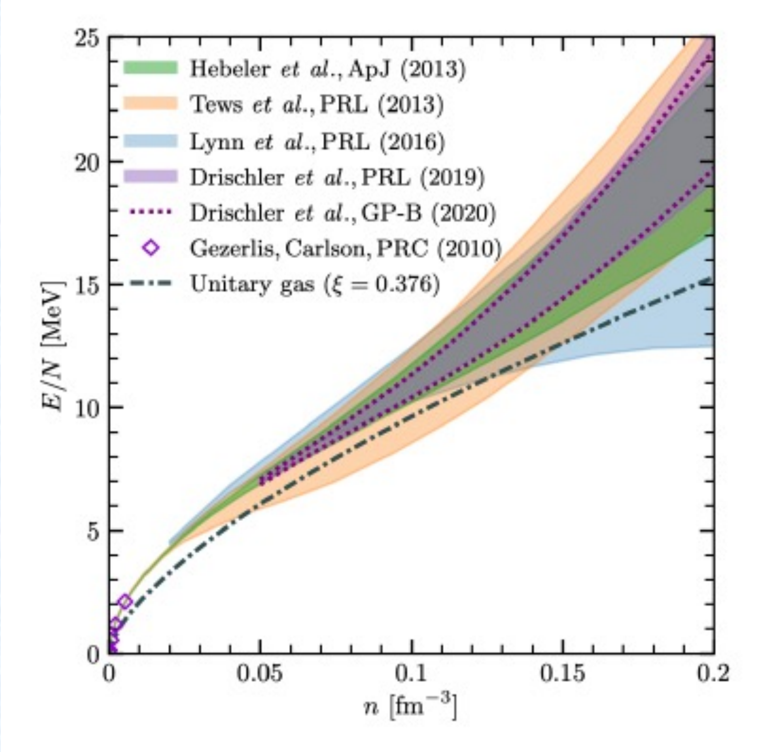
Abbott et al., PRX 9, 011001 (2019)

see talk by T. Hinderer

see also Koehn et al., arXiv:2402.04172 for a compilation

Constraints from nuclear physics: theory

PURE NEUTRON MATTER



Huth et al., Nature 606, 276 (2022)

- different many-body methods
- (relatively) low densities

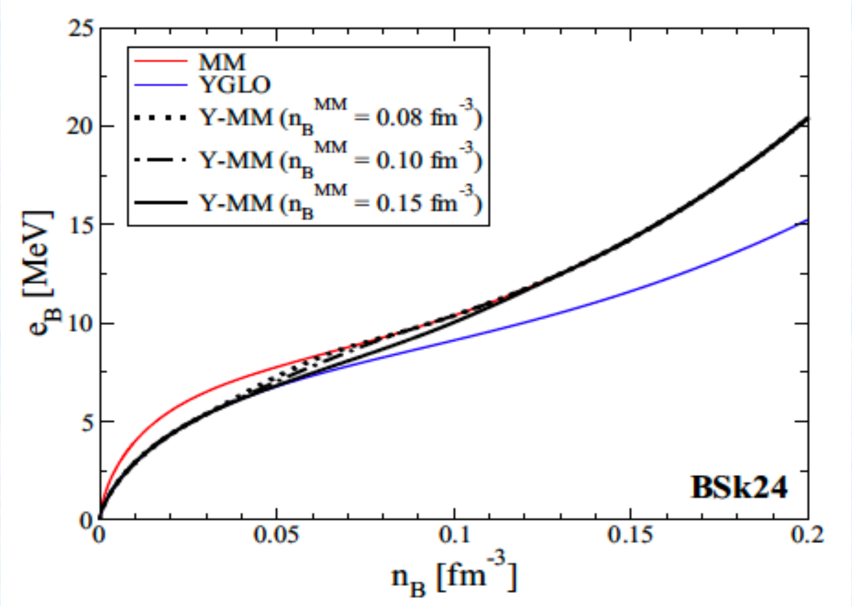
→ "uncertainty band"

N.B.: ab-initio for symmetric matter much less constraining
(but progress for nuclei! see talks by V. Somà, A. Porro, C. Barbieri, …)

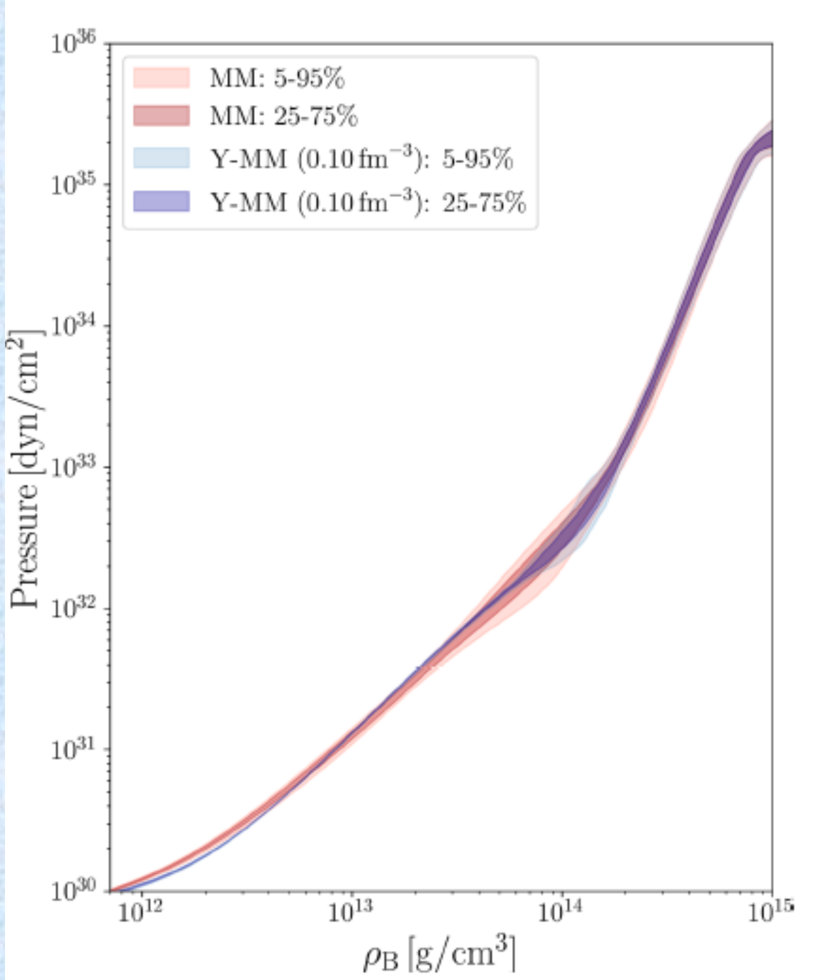
→ Reasonable agreement of ab-initio (PNM) up to ~ saturation density
→ benchmark (for phenomenological models) & constraints

see also Oertel et al., Rev. Mod. Phys. 89, 015007 (2017), Burgio&Fantina, ASSL Springer 2018, Burgio et al., PPNP 120, 103879 (2021)

Impact of low-density EoS



Burrello et al., PRC 112, 035802 (2025)

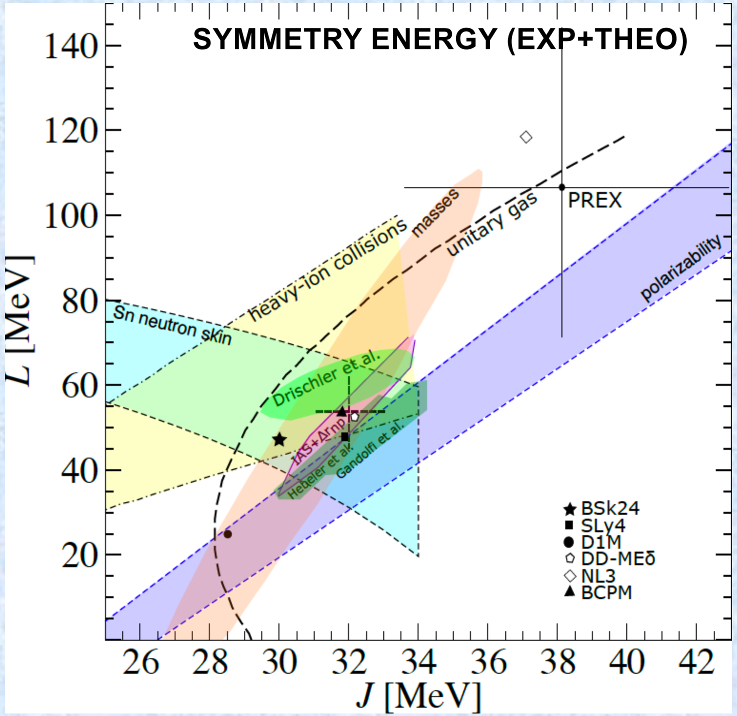


improvement of meta-model at very low density benchmarked on ab-initio calculations

→ importance of low-density EoS
→ reduction of uncertainties especially at sub-saturation

Constraints from nuclear physics: experiments

(1)



Gulminelli&Fantina, Nucl. Phys. News 31, 9 (2021);
Fantina&Gulminelli, J.Phys.Conf.Ser. 2586, 012112 (2023)
see also recent INDRA-FAZIA constraints (Ciampi et al., PLB 2025)

(2)

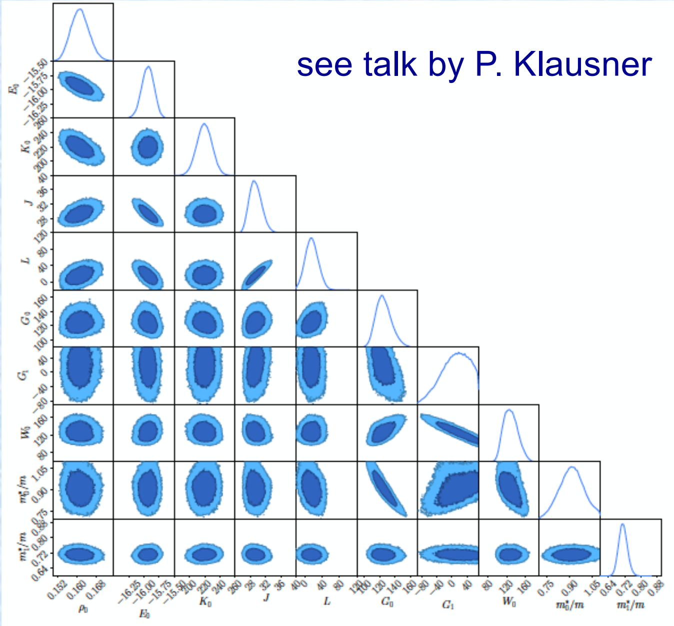
Ground-state properties			
	$B.E.$ [MeV]	$R_{\rm ch}$ [fm]	$\Delta E_{\rm SO}$ [MeV]
^{208}Pb	1636.4 ± 2.0*	5.50 ± 0.05*	2.02 ± 0.50*
^{48}Ca	416.0 ± 2.0*	3.48 ± 0.05*	1.72 ± 0.50*
^{40}Ca	342.1 ± 2.0*	3.48 ± 0.05*	-
^{56}Ni	484.0 ± 2.0*	-	-
^{68}Ni	590.4 ± 2.0*	-	-
^{100}Sn	825.2 ± 2.0*	-	-
^{132}Sn	1102.8 ± 2.0*	4.71 ± 0.05*	-
^{90}Zr	783.9 ± 2.0*	4.27 ± 0.05*	-

Isoscalar resonances		
	$E^{\rm IS}_{\rm GMR}$ [MeV]	$E^{\rm IS}_{\rm GQR}$ [MeV]
^{208}Pb	13.5 ± 0.5*	10.9 ± 0.5*
^{90}Zr	17.7 ± 0.5*	-

Isovector properties			
	$\alpha_{\rm D}$ [fm^3]	$m(1)$ [MeV fm^2]	$A_{\rm PV}$ (ppb)
^{208}Pb	19.60 ± 0.60	961 ± 22	550 ± 18
^{48}Ca	2.07 ± 0.22	-	2668 ± 113

Klausner et al., PRC 111, 014311 (2025)

parameter fit
through emulator



"compilation" of results
("bands") → uniform prior

observables directly included in model fit
→ nuc.-phys. informed prior

→ Constraints at "low" densities → low-order parameters
N.B.: model dependence of constrains

Impact of nucl.-phys. informed prior: crust

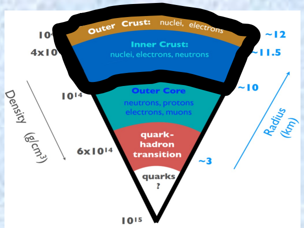
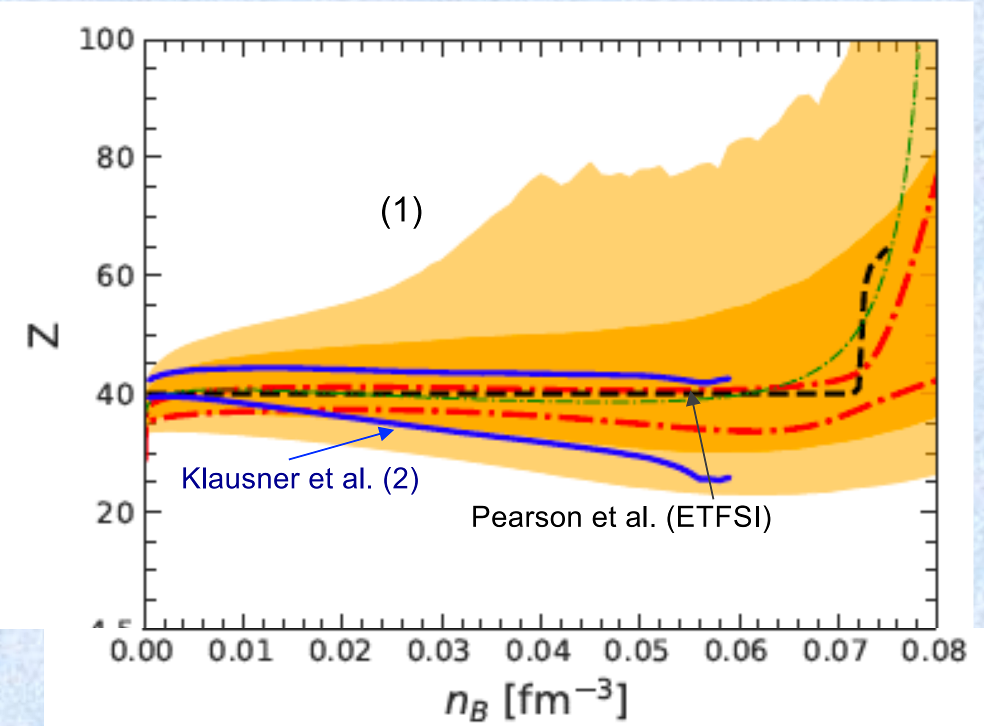


Image Credit: 3G Science White Paper

→ *important e.g. for pulsar glitches, NS cooling / transport properties*

COMPOSITION



Diverrès et al., in prep. (2025)

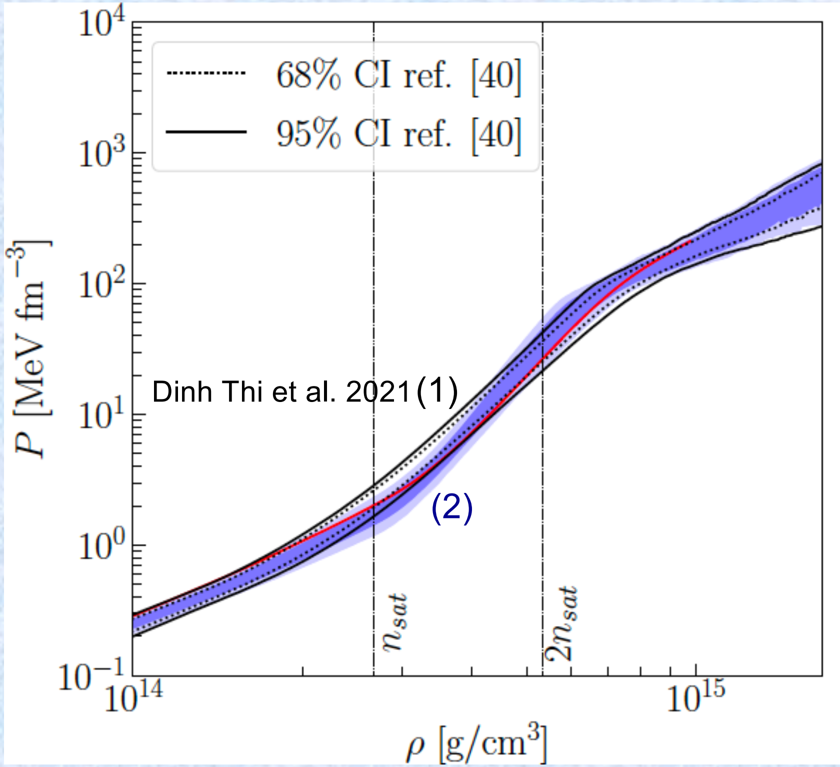
→ impact on trasport / elastic properties

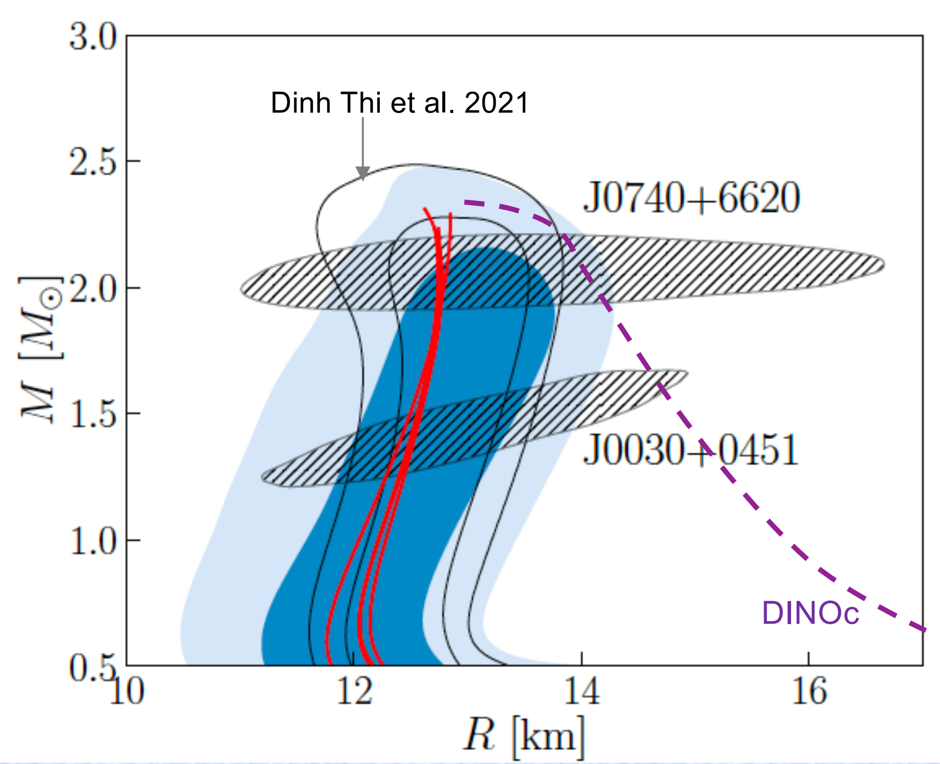
see talk by T. Diverrès

→ inclusion of nuclear phys. exp. observables constrains NS-crust properties

see also Carreau et al., PRC 100, 055803 (2019), Balliet et al., ApJ 918, 79 (2021)

EoS and observables





Klausner et al., arXiv2505.16929 (see also Dinh Thi et al., Universe 2021, Fantina&Gulminelli, J. Phys. 2023)

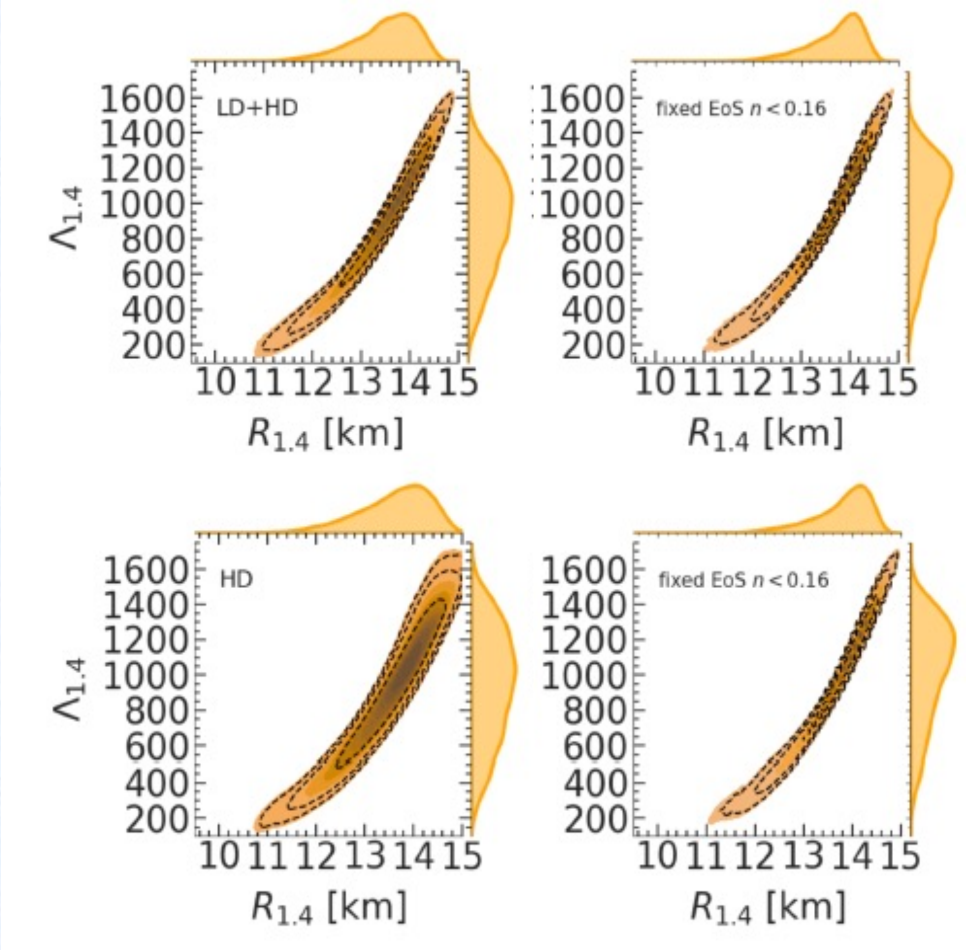
→ inclusion of nuc.-phys. exp. observables effect on EoS and M-R: lower R (softer EoS) and thinner 1σ predictions for low-mass NSs

→ nucleonic hp compatible with observations → observations not yet constraining enough!

similar conclusions in Lim&Holt, EPJA 2019; Malik et al., ApJ 2022

see talk by P. Klausner

Effect of the (non-unified) crust



Davis et al., A&A 687, A44 (2024); Davis et al., EPJA 61, 120 (2025);
Fantina & Gulminelli, PoS QNP2024, 153 (2025)

→ use of unique low-density EoS does not change much averages (~ few %)

→ ok for current GW detectors, but next generation ?

(see also Gamba et al., Class. Quant. Grav. 37, 025008 (2020) → ~ 3%)

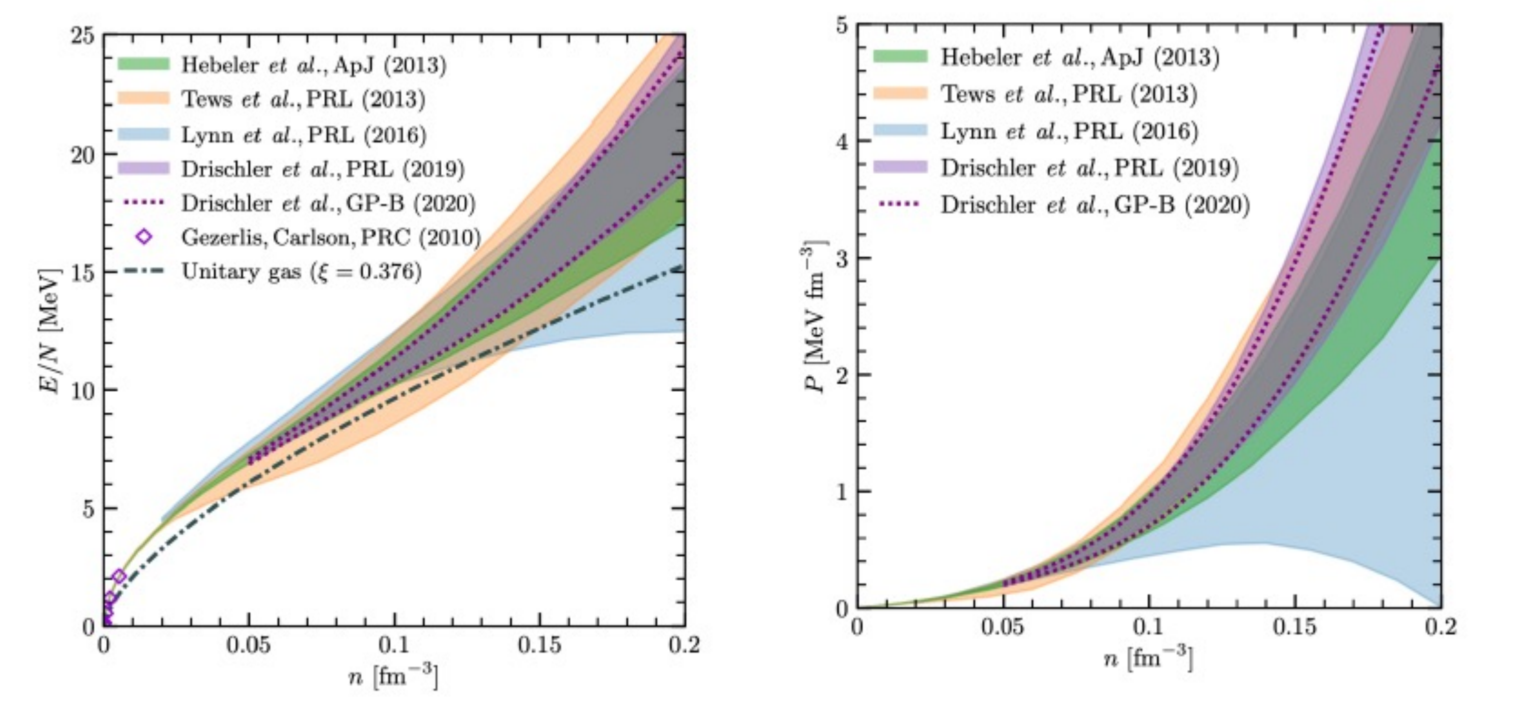
→ use of unique crust underestimates uncertainties

→ **CUTER code** to reconstruct a *thermodynamically consistent and unified* low-density EoS from a given (high-density) β-equilibrium EoS (non necessarily based on a nuclear model) (v1 and v2 publicly available on Zenodo)

CUTER = Crust Unified Tool for Equation-of-state Reconstruction

How to discriminate models? (nuc. phys. theory)

- ***Nuclear physics (theory + experiments)*** → information up to ~ 1.5 – 2 n_{sat}
  - *Ab-initio prediction of derived quantities (not only E/A, but also P, etc.)*
    → propagation of uncertainties
    → constraints on more phenomenological functionals

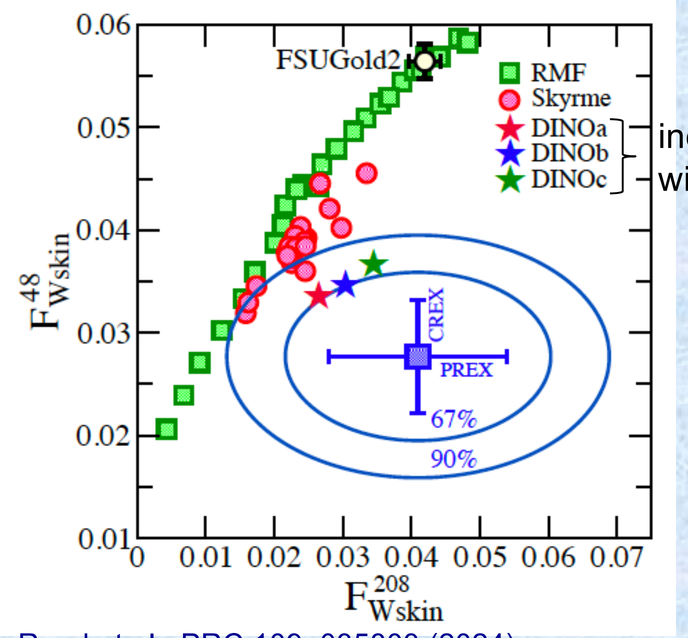


Hebeler, talk @MICRA2023; Huth et al., Nature 606, 276 (2022)

How to discriminate models? (nuc. phys. exp)

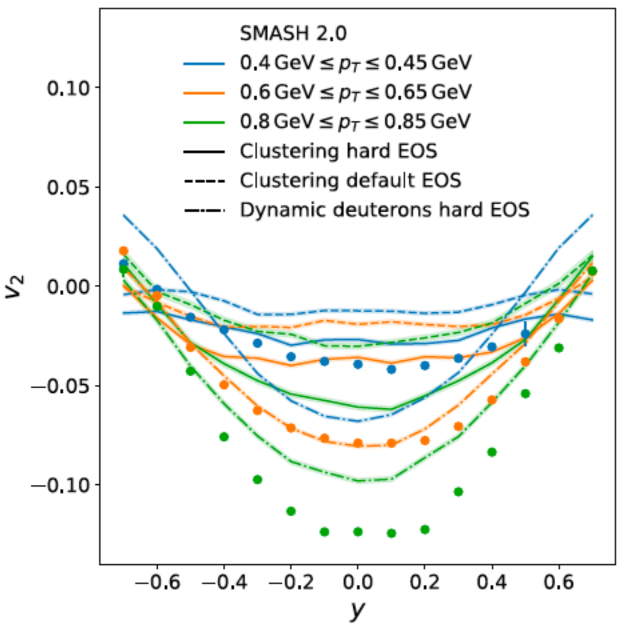
❖ ***Nuclear physics (theory + experiments)*** → information up to ~ 1.5 – 2 n_{sat}

- *"PREX/CREX dilemma" vs reduced error bar in (neutron skin) measurements vs other observables?*
  → constraints on low-order parameters in isospin sector
- *constraints at high density (e.g. HADES, FOPI, Asy-EoS → transport model vs data, systematics?)*
  → constraints on isoscalar / isovector sector (at ~2n_{sat})



incompatible with astro!

Reed et al., PRC 109, 035803 (2024)
see also Kunjipurayil et al., arXiv:2503.07405

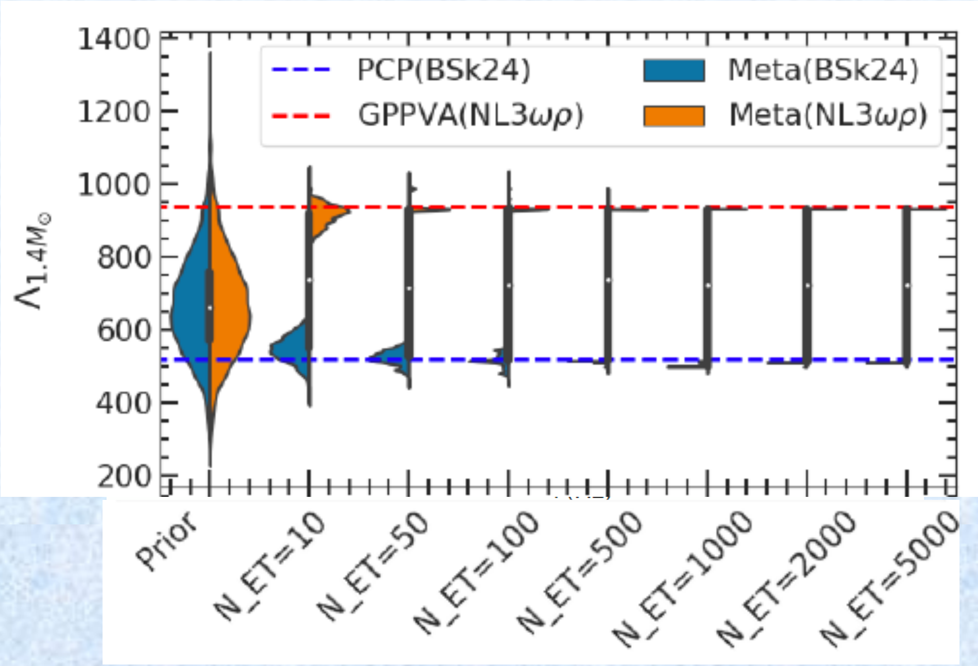


Mohs et al., PRC 105, 034906 (2022)

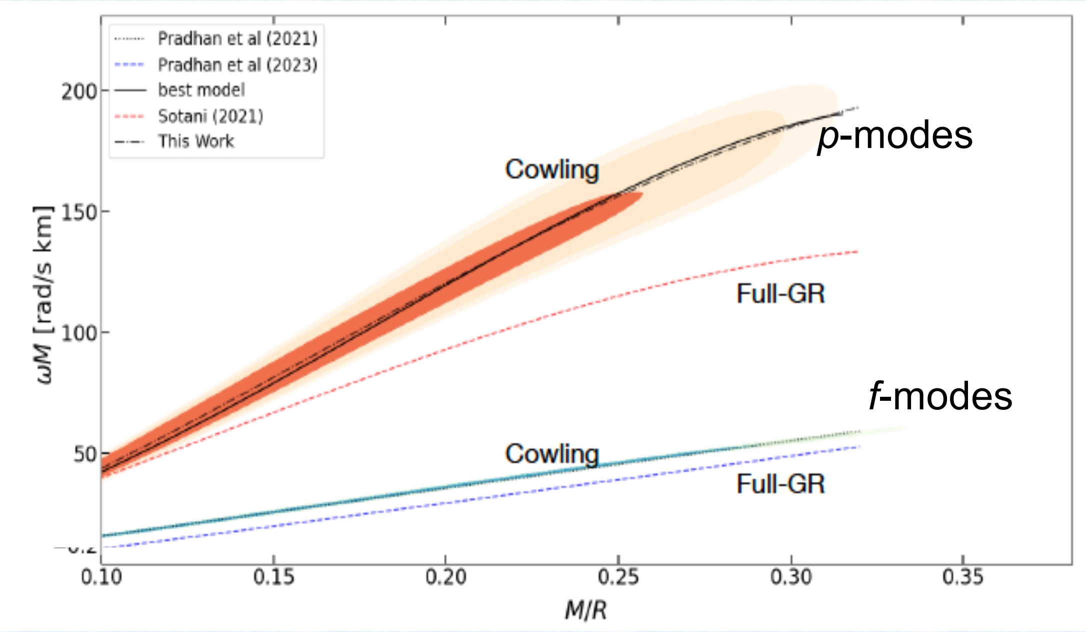
→ Better extrapolation of models

How to discriminate models? (astro)

- more and more precise data (e.g. M, R, Λ, ...) – or even a “smoking gun” observation!
- more sensitive detectors → new generation → post-merger → *phase transition?*
  (ET, CE) → properties from (or discrepancy from) (quasi-)universal relations



Iacovelli et al., PRD 2023 (also Mondal et al., MNRAS 2023; ET collab., arXiv:2503.12263)



Montefusco et al., A&A 694, A150 (2025)

- More reliable prediction / interpretation of astrophysical observations
- Better knowledge of dense matter in compact stars → *Phase transition to deconfined matter (quarks, …) ?*

Conclusions & open questions

- Nuclear physics + astrophysics → constraints on EoS but still hard to discriminate
  → nucleonic hp compatible with observations, no (dis)proof of exotic matter to now

  - ✓ need of (microscopic) reliable theoretical model + experimental data to calibrate models
  - ✓ need of (more precise / numerous) astrophysical observations + post-merger?
    → phase transition, oscillation modes (?)

- `CUTER` tool for consistent crust EoS reconstruction available

- Extrapolation from raw data → **model dependence of the constraints**
- Lab. exper. mostly "low" density (~ saturation density), low *T* probed
  → **extrapolation to astro conditions (high *T* and density, asymmetry, charge neutral) ?**
- Uncertainties in high-density EoS → **blurring of different effects ?**
- Astro simulations vs microphysics inputs → **effects of microphysics inputs in astro modelling** ?
  → consistent implementation
  → systematic studies / bayesian analysis → uncertainties, implementation of consistent probab. distributions
  → static vs dynamical properties


Thank you
NASA - X-ray: CXC, Optical: STSCI, Infrared: JPL