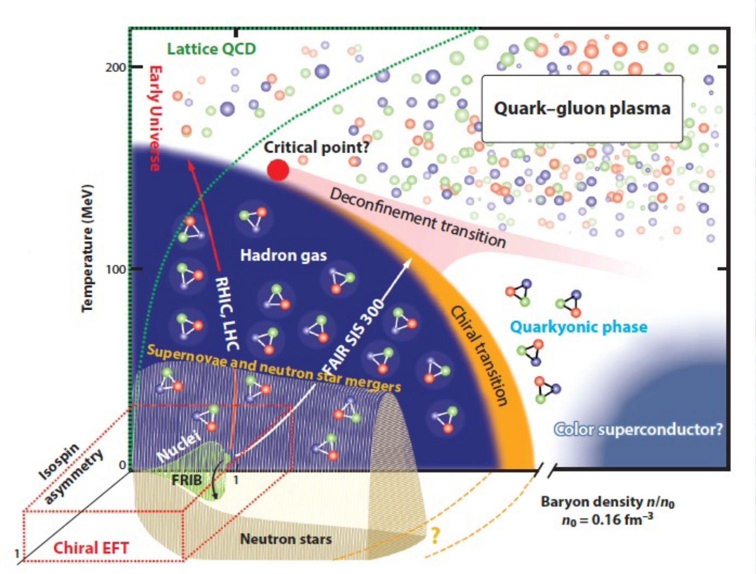
Constraints on the equation of state of dense matter

Anthea F. Fantina

Journées Théorie de la communauté Hautes Energies
04 – 07 Nov. 2024, Paris (France)

Probing extreme conditions in NSs



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

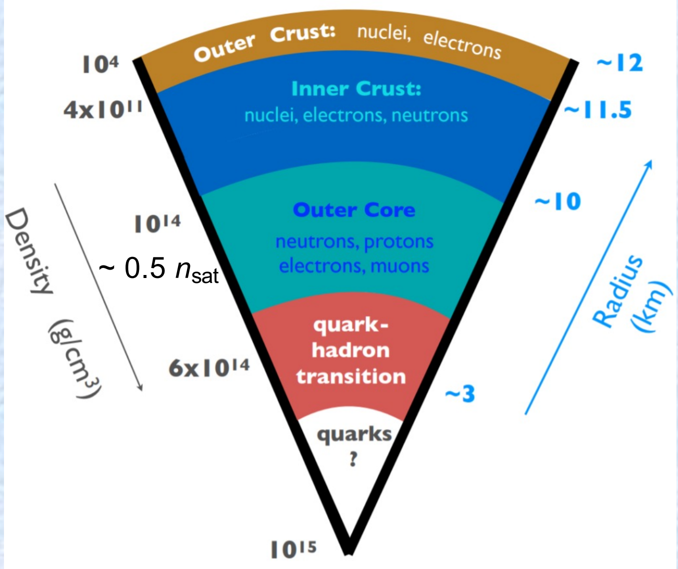


Image Credit: 3G Science White Paper

"cold catalysed matter"
i.e. full equilibrium
(beta equilibrium),
$T = 0$ ($T < \sim 10^8$K)
→ EoS $P(n_B)$

N.B.: In this talk, cold catalysed matter & NS static properties
→ OK for cold NS and pre-merger binary NSs (inspiral phase)

Even then, different states of matter spanned in NSs → inhomogeneous (crust), "pasta" phase, homogeneous (core), "exotic" particles (?) + superfluidity, (strong) $\vec{B}$, etc.

(see e.g. Haensel et al., "Neutron Star Structure", Springer 2007; Oertel et al., Rev. Mod. Phys. 2017; Burgio & Fantina, ASSL Springer 2018)

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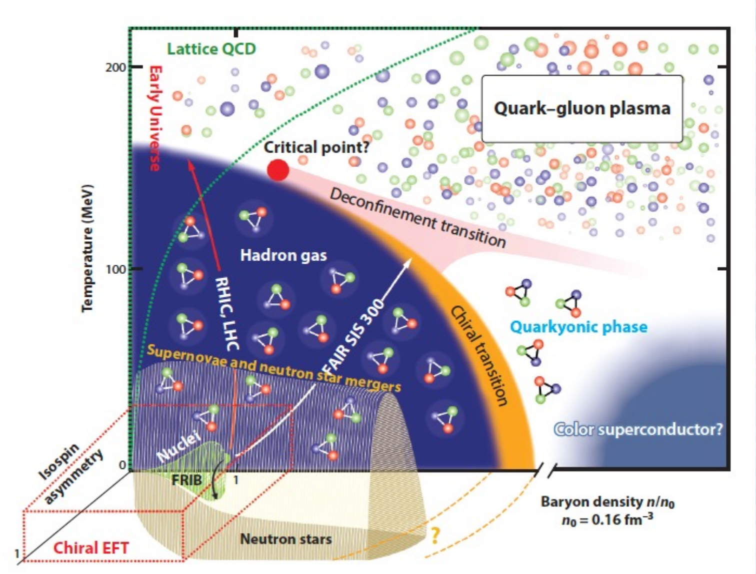

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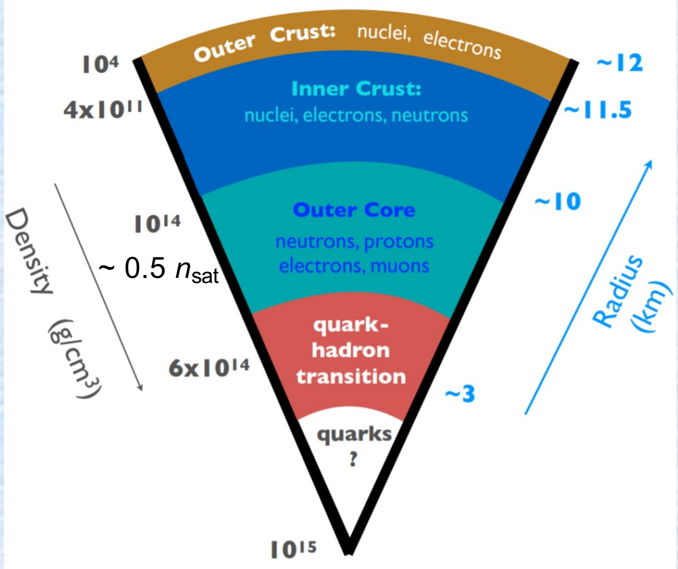

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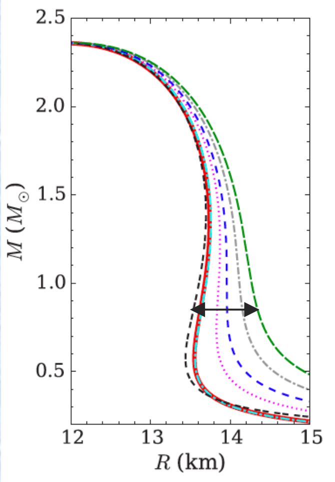
→ Not all conditions can be probed in terrestrial labs → theoretical models !
→ Consistent description very challenging

(see e.g. Haensel et al., "Neutron Star Structure", Springer 2007; Oertel et al., Rev. Mod. Phys. 2017; Burgio & Fantina, ASSL Springer 2018)

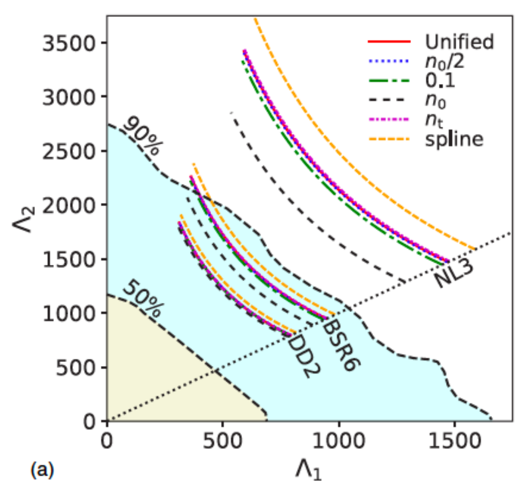
Why a consistent and unified treatment ?

Unified treatment of inhomogeneous & homogeneous matter
→ same nuclear model employed in different regions of star

- Challenging because of wide range of thermodynamic conditions
- Challenging because different states of matter
- But: essential to avoid spurious non-physical effects in numerical modelling



Fortin et al., PRC 94, 035804 (2016)

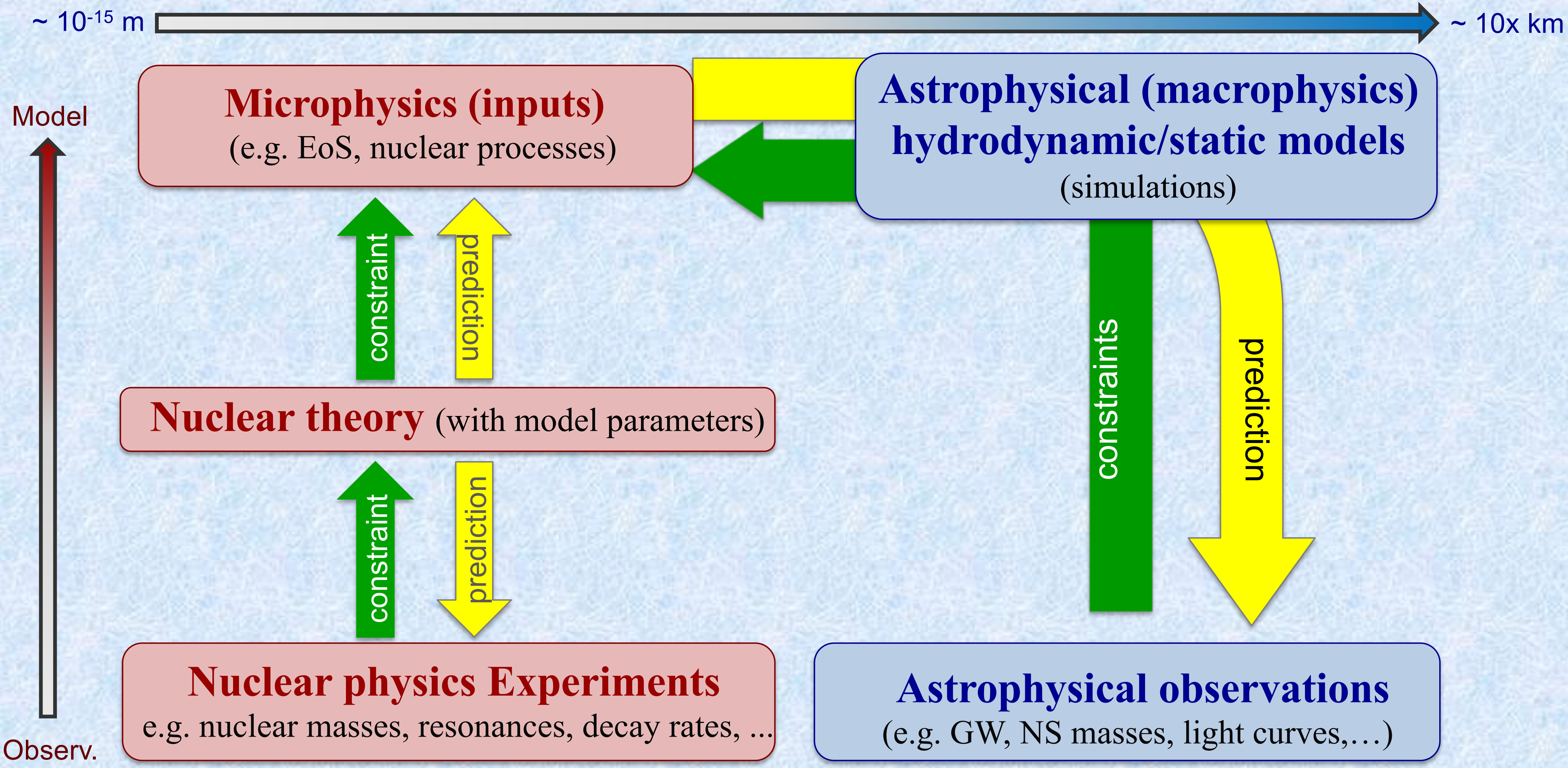


Suleiman et al., PRC 104, 015801 (2021)

see also Ferreira&Providençia 2020

Thermodynamically consistent and unified EoSs for astro modelling & inference analyses
(but not many available, e.g. Douchin&Haensel 2001; Fantina et al. 2013; Raduta&Gulminelli 2015; Viñas et al. 2021; Pearson et al. 2018; Grams et al. 2022; Xia et al. 2022; Scurto et al. 2024; see CompOSE database)

Micro to macro through modelling



~ 10^{-15} m

~ 10x km

Model

Observ.

Microphysics (inputs)
(e.g. EoS, nuclear processes)

Astrophysical (macrophysics) hydrodynamic/static models
(simulations)

constraint

prediction

Nuclear theory (with model parameters)

constraints

prediction

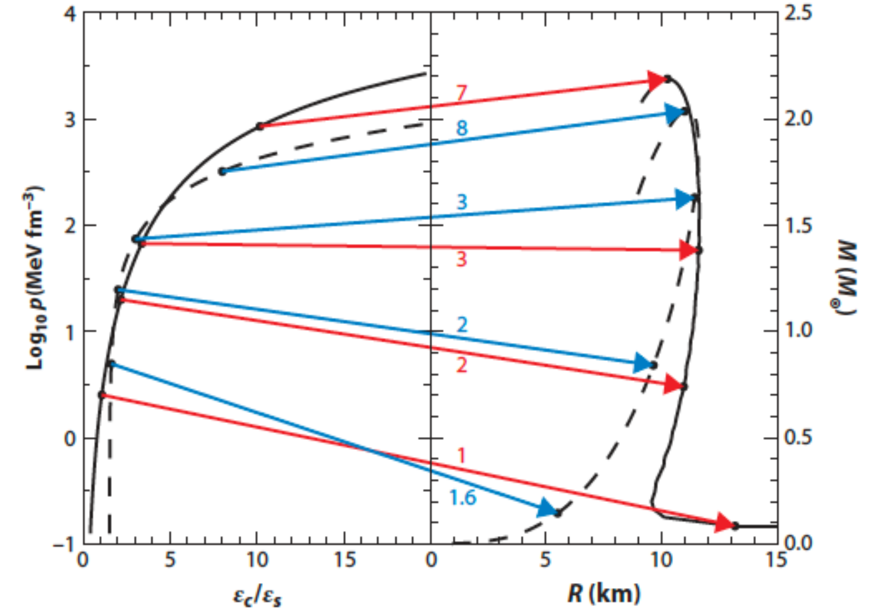
constraint

prediction

Nuclear physics Experiments
e.g. nuclear masses, resonances, decay rates, ...

Astrophysical observations
(e.g. GW, NS masses, light curves,…)

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)

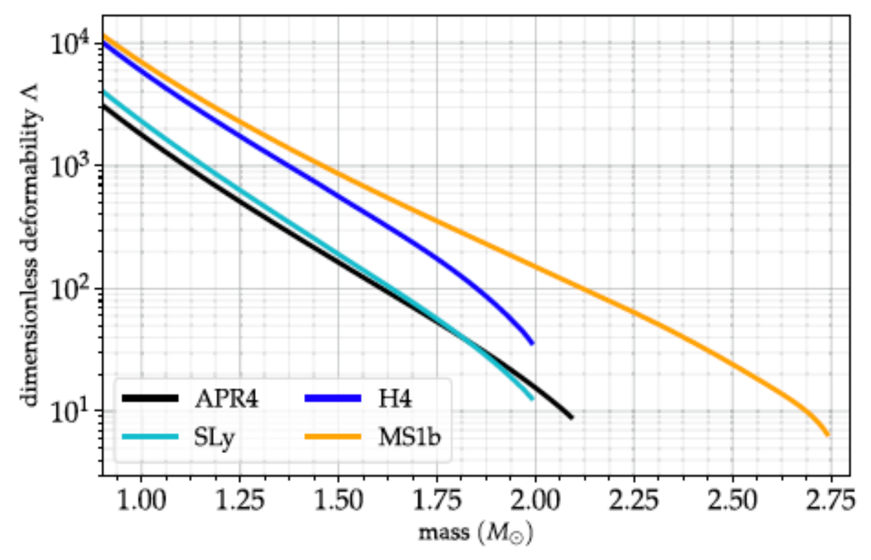
$$\frac{\mathrm{d}P(r)}{\mathrm{d}r} = -\frac{G\rho(r)\mathcal{M}(r)}{r^2}\left[1+\frac{P(r)}{c^2\rho(r)}\right]\left[1+\frac{4\pi P(r)r^3}{c^2\mathcal{M}(r)}\right]\left[1-\frac{2G\mathcal{M}(r)}{c^2 r}\right]^{-1}$$

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

- **+ eq. for *y*(*r*) → Λ(*M*), Λ(*R*)** $r\frac{dy}{dr} + y(r)^2 + F(r)y(r) + Q(r) = 0$

→ Love number k_2

→ $\Lambda = \frac{2}{3}k_2\left[\frac{Rc^2}{GM}\right]^5$



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

GR → direct correspondence
EoS ←→ NS static properties (e.g., *M*, *R*, Λ)

?
→ trace back to EoS and composition?

N.B.: GR in slow rotation limit w/o magnetic field !
see e.g. LORENE library (Gourgoulhon et al.) or RNS code (Stergioulas 2003) for rotating configurations

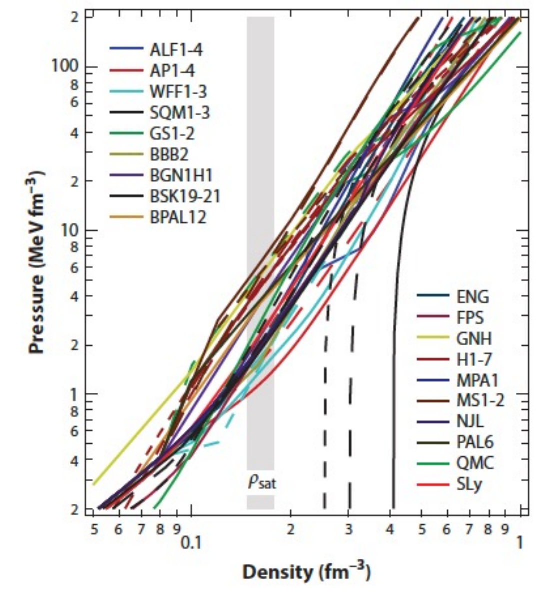
EoS ←→ NS (static) observables (2)

but:

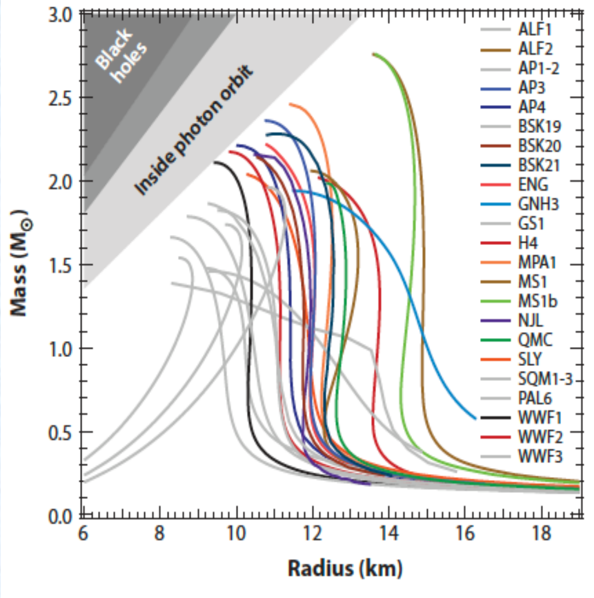
✗ EoS model dependent !

✗ no ab-initio dense-matter calculations ("microscopic" e.g. chiral EFT, Monte Carlo, Green's funct., (D)BHF, …)
in all regimes (usually applied for infinite matter e.g. the core)
→ phenomenological models (e.g. energy density functionals like Skyrme/Gogny, …)

✗ composition ←→ EoS → $M(R)$?



Ozel & Freire, ARAA 54, 401 (2016)



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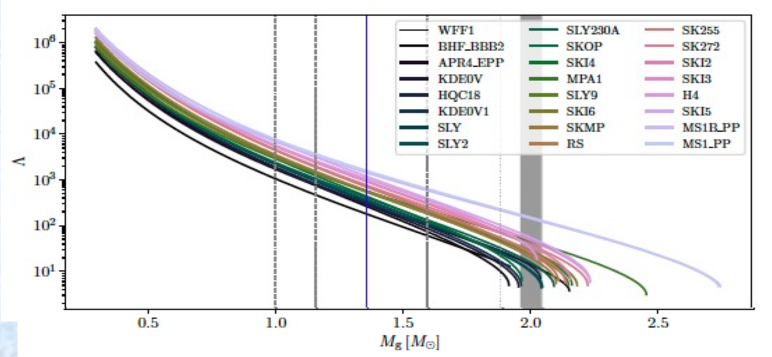
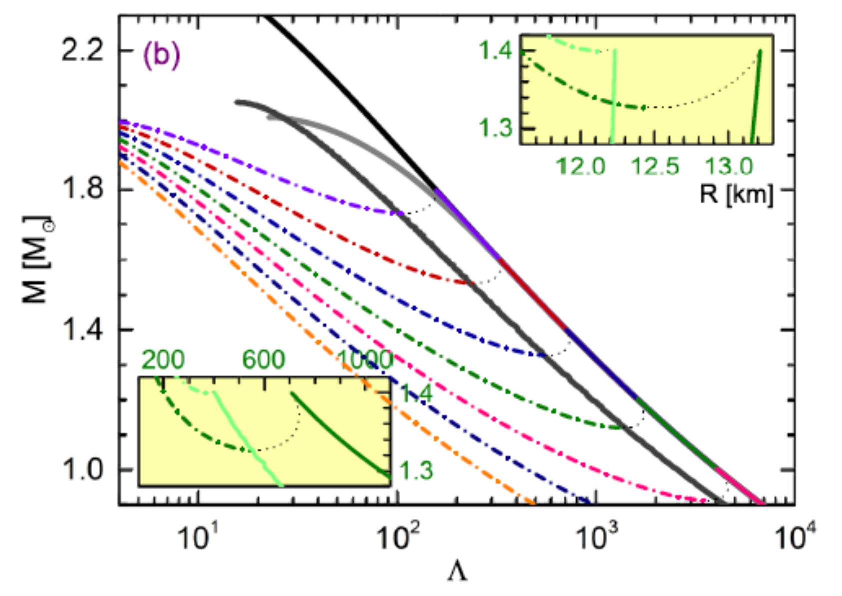


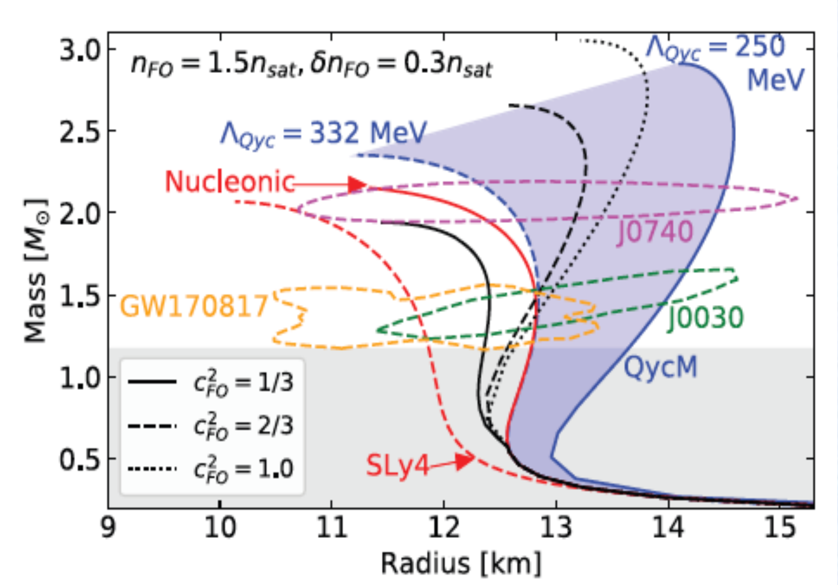
Abbott et al., Class. Quantum Grav, 37, 045006 (2020)

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 hyperons !
  Quarks → not clear



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

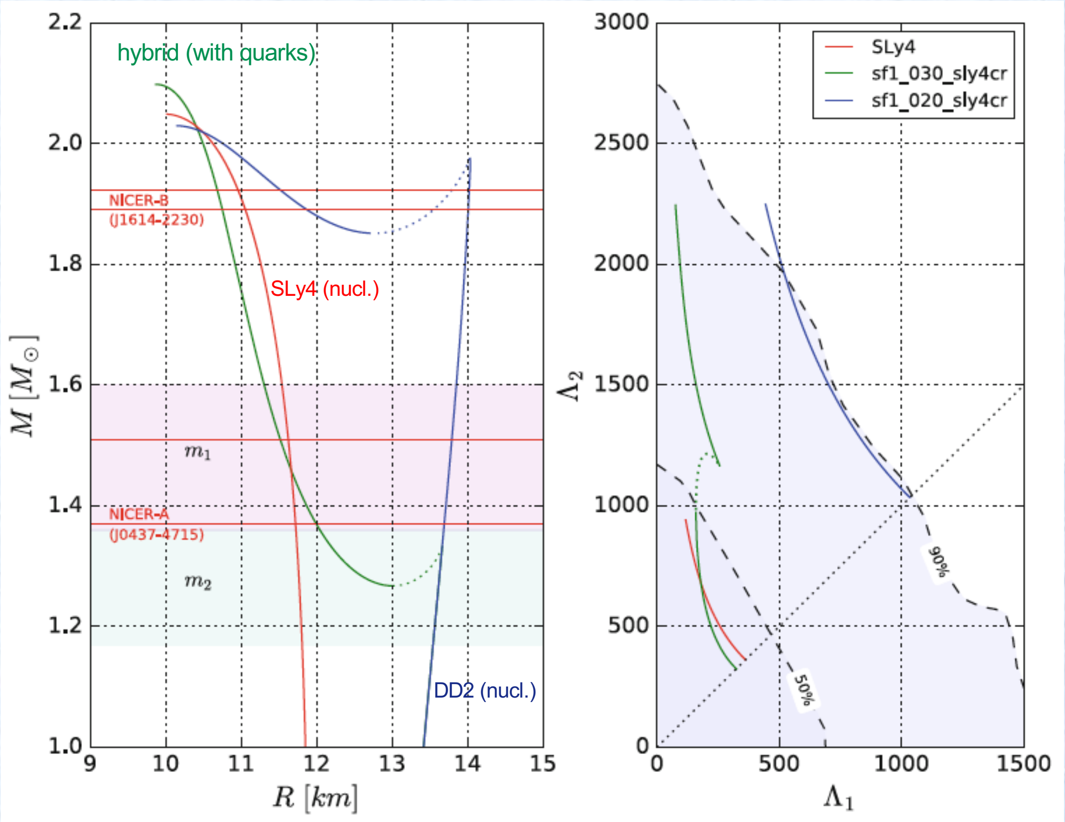


Somasundaram & Margueron, EPL 138, 14002 (2022)

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

- "Masquerade" effect



Blaschke & Chamel, ASSL 457, 337 (2018)

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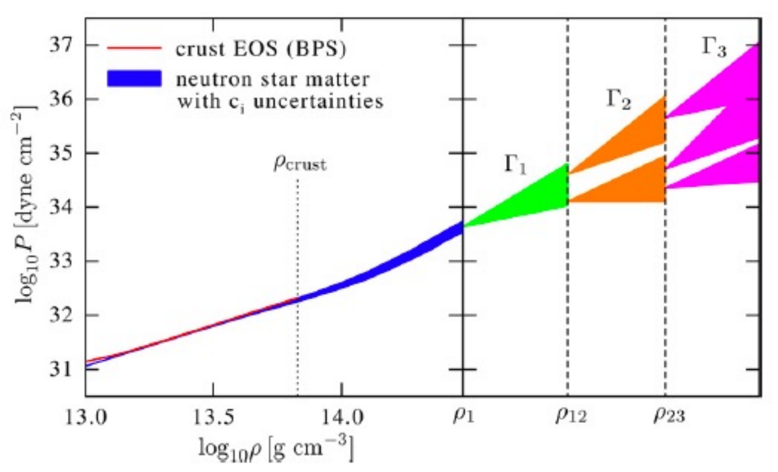
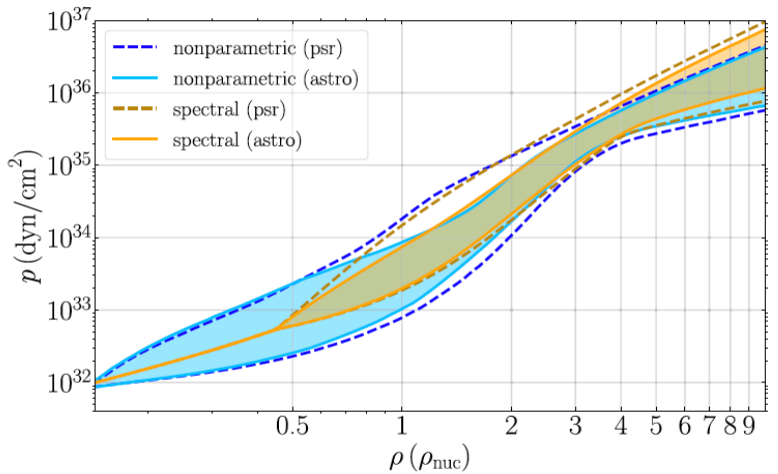
- "Masquerade" effect

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



Hebeler et al., ApJ 773, 11 (2013)



Legred et al. PRD 105, 043016 (2022)

✓ poweful → no underlying hypotheses

✗ what about nuclear physics → composition ?

✗ often unique (non-consistent) low-density EoS → uncertainties underestimated

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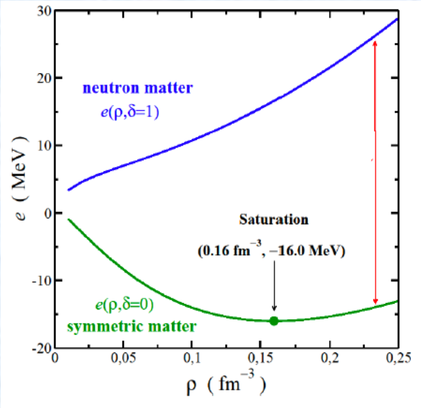
see also e.g. piecewise polytropes: Reed et al. PRD 2009, Annala et al. PRL 2018, Raithel & Most, PRL 2023 …; sound-speed models: Tews et al. ApJ 2018, Tan et al. PRL 2020; Somasundaram et al., PRC 2023; spectral functions: Lindblom 2010, Lindblom & Indik 2014, …; Gaussian process: Landry et al. PRD 2020, Essick et al. PRD 2020; Legred et al. PRD 2021, PRD 2022, …

EoS ←→ nuclear matter parameters

$$x = (n - n_{\rm sat})/3n_{\rm sat}$$

$$\delta = (n_n - n_p)/n$$



Centelles, talk@Primosten (2011)

- Expansion in density and asymmetry around $n_{\rm sat}$ and $\delta = 0$

$$e_{\rm is} = E_{\rm sat} + \frac{1}{2}K_{\rm sat}x^2 + \frac{1}{6}Q_{\rm sat}x^3 + \ldots \quad \rightarrow e_{\rm sat}(n,\delta=0)$$

$$e_{\rm iv} = E_{\rm sym} + L_{\rm sym}x + \frac{1}{2}K_{\rm sym}x^2 + \frac{1}{6}Q_{\rm sym}x^3 + \ldots \quad \rightarrow e_{\rm sym}(n)=e(n,\delta=1) - e(n,\delta=0)$$

→ Nuclear empirical parameters (NEP, bulk) → $\boldsymbol{X}_{\rm sat,sym} = E_{\rm sat}, K_{\rm sat}, Q_{\rm sat}, \ldots, E_{\rm sym}, L_{\rm sym}, K_{\rm sym}, Q_{\rm sym}, \ldots$

see e.g. Bulgac et al., PRC 97, 044313 (2018), Margueron et al., PRC 97, 025805 (2018), Carreau et al, EPJA 55, 188 (2019), Tews et al., EPJ A 55, 97 (2019), Dinh Thi et al., A&A 654, A114 (2021), Dinh Thi et al., EPJA 57, 296 (2021); Essick et al., PRC 104, 065804 (2021), …

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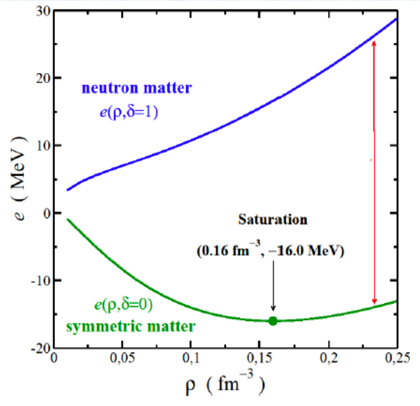

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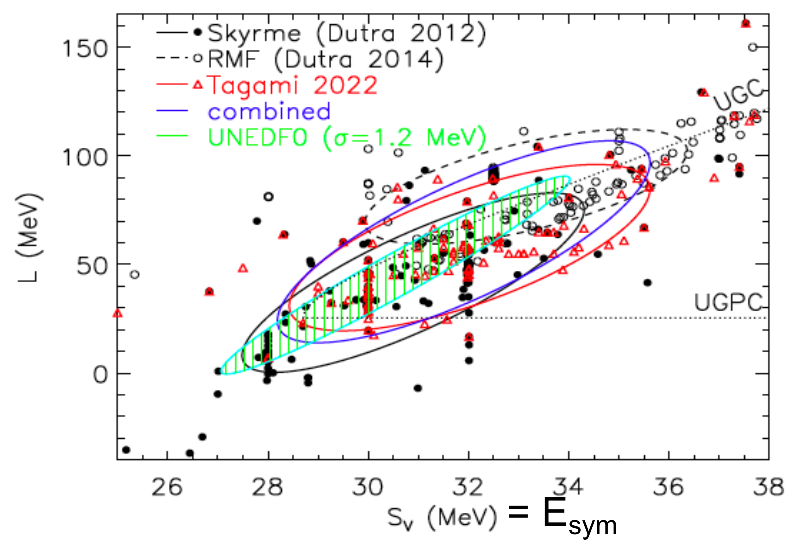
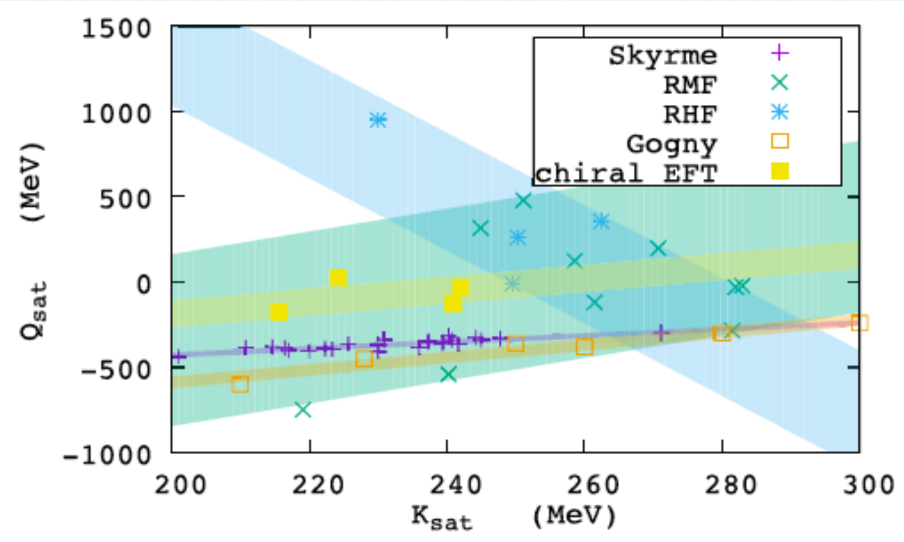


Lattimer, Particles 6, 30 (2023)



Margueron et al., PRC 97, 025805 (2018)

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A semi-agnostic approach: meta-model

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

  → EDF-based but flexible. Based on a Taylor expansion in density and asymmetry.

$$e_{\rm nuc}(n_B,\delta) = t^{\star}_{\rm FG}(n_B,\delta) + e_{\rm is}(n_B) + e_{\rm iv}(n_B)\delta^2$$

kinetic term with *m**

N > 2 → beyond parabolic approx. → important for crust

$$e_{\rm is,iv}(n_B) = \sum_{k=0}^{N} \frac{v_k^{\rm is,iv}}{k!} x^k u_k(x)$$

functions of nuclear empirical parameters

zero-density limit

- For application of MM to NS crust → Compressible Liquid Drop Model

  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

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✓ Possible to reconstruct low-density EoS from any EoS at high density (→ **CUTER**)

✓ Possible to couple MM approach for crust to agnostic EoS (e.g. polytropes, etc.) at high density

✓ Vary NEP → parameter exploration (without a priori correlations) → statistical (Bayesian) analysis

$$p_{\rm post}(\vec{X}) = \mathcal{N}\, p_{\rm prior}(\vec{X})\, e^{-\chi^2(\vec{X})/2}\, w_{\rm LD}(\vec{X}) w_{\rm HD}(\vec{X})$$

flat non-informative prior
→ large parameter space

nuclear masses
(AME)

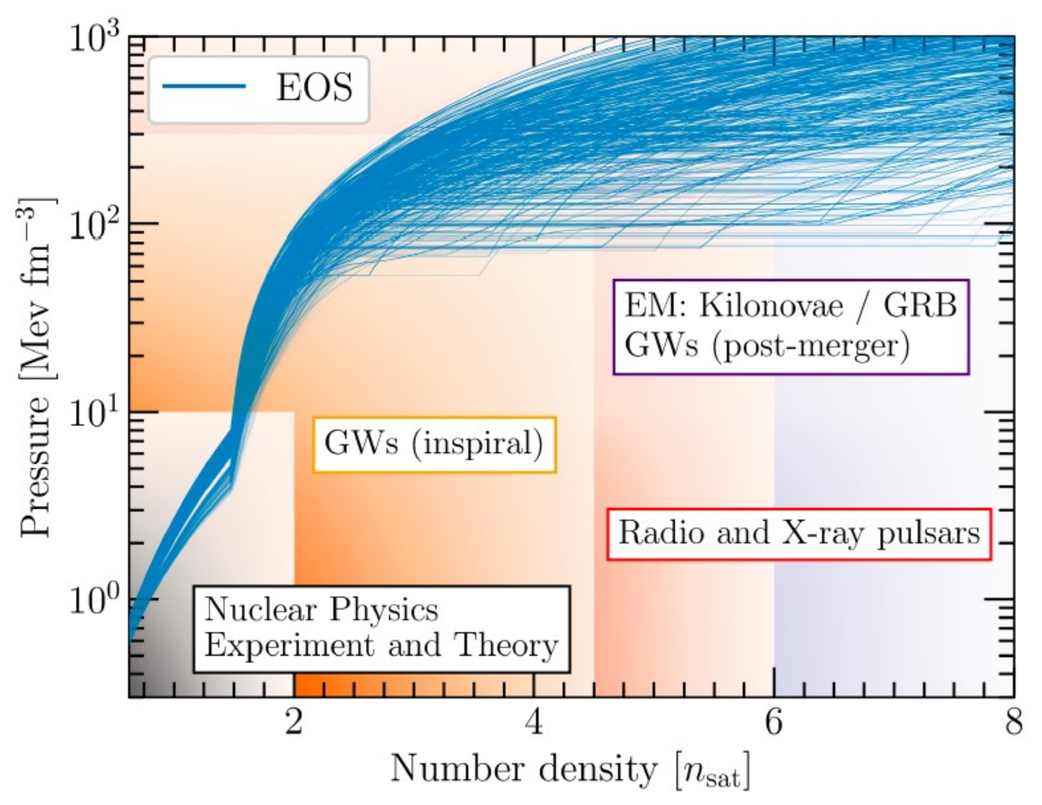
Low-Density filters
→ ab-initio (EFT)

High-Density filters
→ causality, stability, $M_{\rm NS,max}$ (+ NICER, GW)

How to get constraints ?

Nuclear physics exp./ theory

"low" density
(better in nucleonic sector)



Pang et al., Nat. Comm. 14, 8352 (2023); arXiv:2205.08513

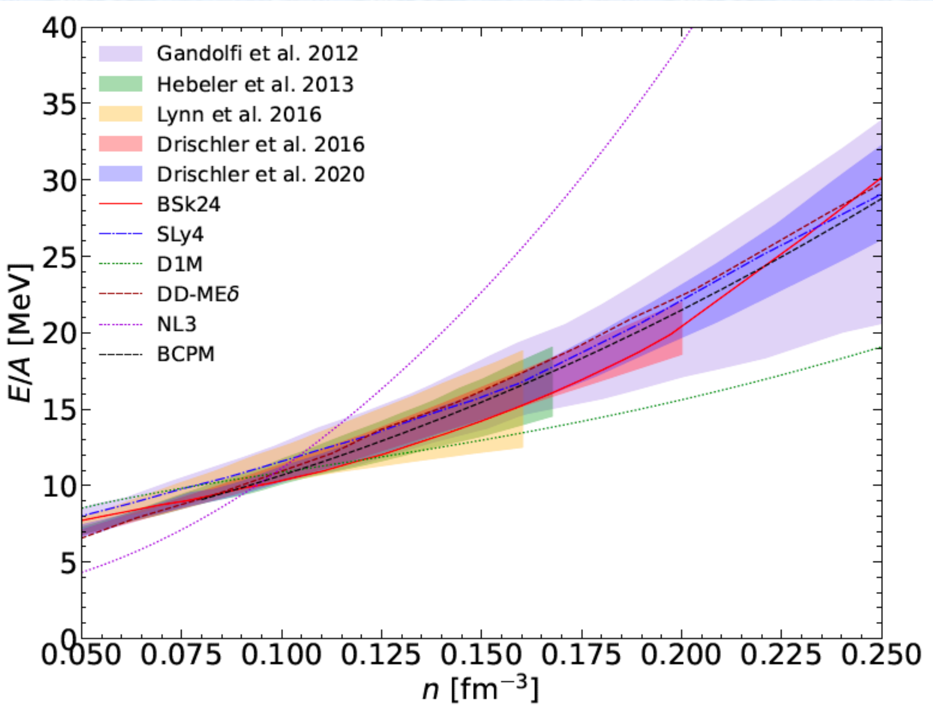
Astrophysical observations

"high" density

N.B.: rectangles only qualitative → also EoS dependence !

Constraints from nuclear physics: theory

PURE NEUTRON MATTER



Fantina & Gulminelli, J.Phys. Conf. Ser. 2586, 012112 (2023)

- different calculations (MC, many-body perturbation theory, interaction from chiral-EFT, …)
- (relatively) low densities

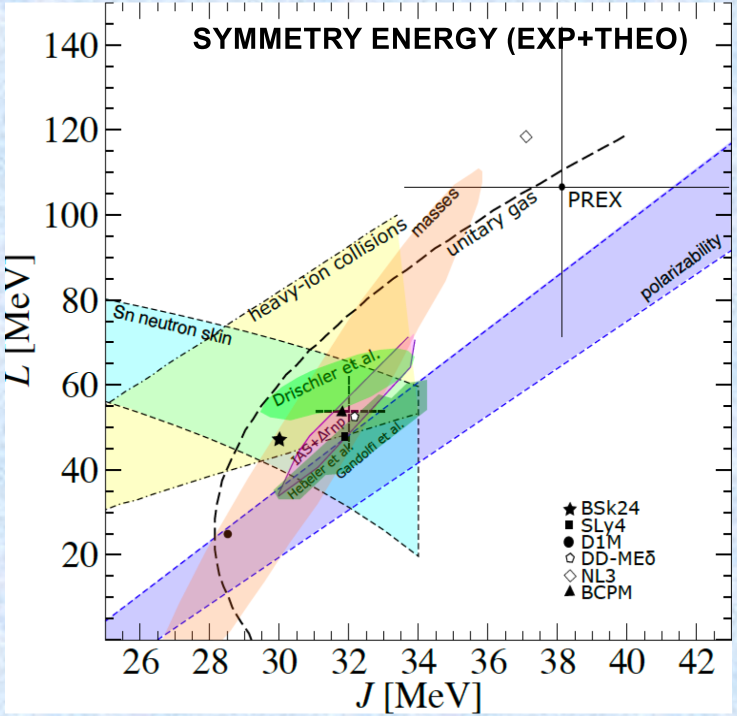
N.B.: ab-initio for symmetric matter much less constraining

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

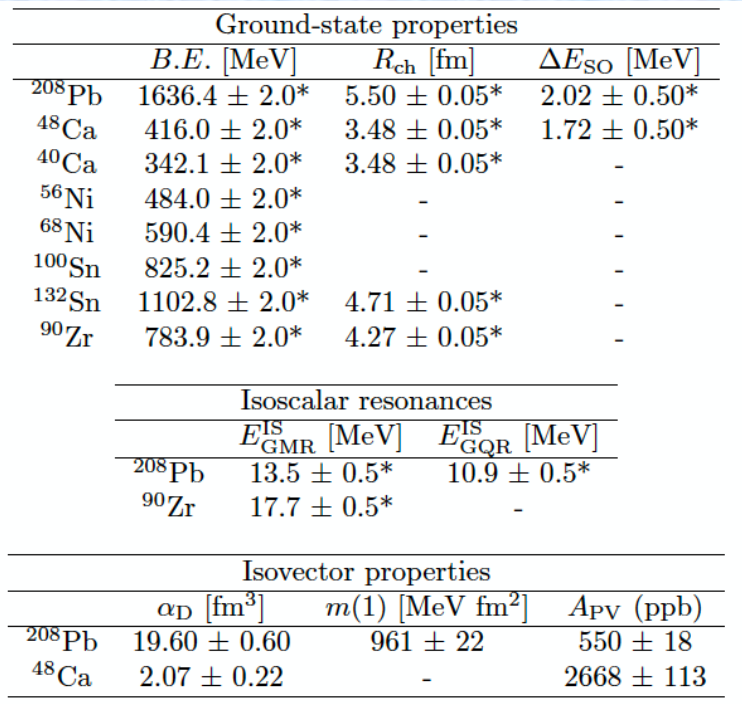
→ **Not all popular models agree with ab-initio constraints!**

see also Oertel et al., Rev. Mod. Phys. 89, 015007 (2017), Burgio&Fantina, ASSL Springer 2018, Burgio et al., PPNP 120, 103879 (2021); Huth et al., Nature 606, 276 (2022)

Constraints from nuclear physics: experiments



Gulminelli&Fantina, Nucl. Phys. News 31, 9 (2021);
Fantina&Gulminelli, J.Phys.Conf.Ser. 2586, 012112 (2023)



Ground-state properties

	$B.E.$ [MeV]	R_{ch} [fm]	ΔE_{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

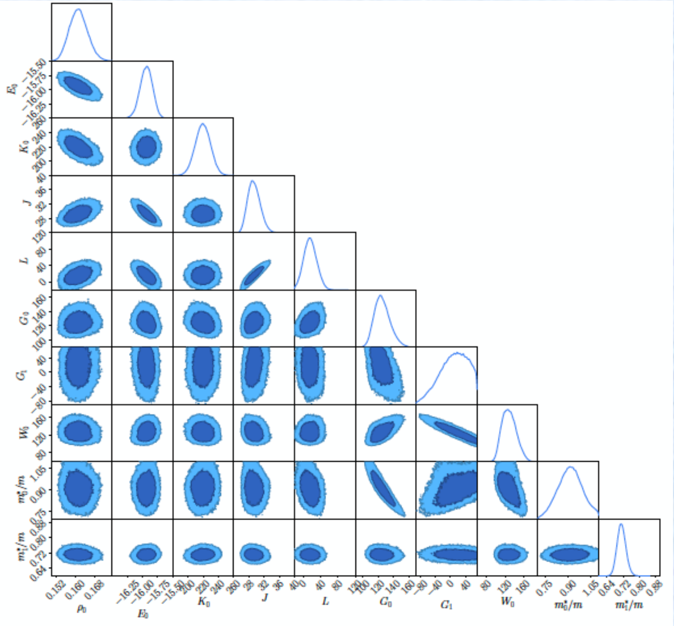
	$E^{\mathrm{IS}}_{\mathrm{GMR}}$ [MeV]	$E^{\mathrm{IS}}_{\mathrm{GQR}}$ [MeV]
^{208}Pb	13.5 ± 0.5*	10.9 ± 0.5*
^{90}Zr	17.7 ± 0.5*	-

Isovector properties

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

Klausner et al., arXiv:2410.18598

parameter fit
through emulator



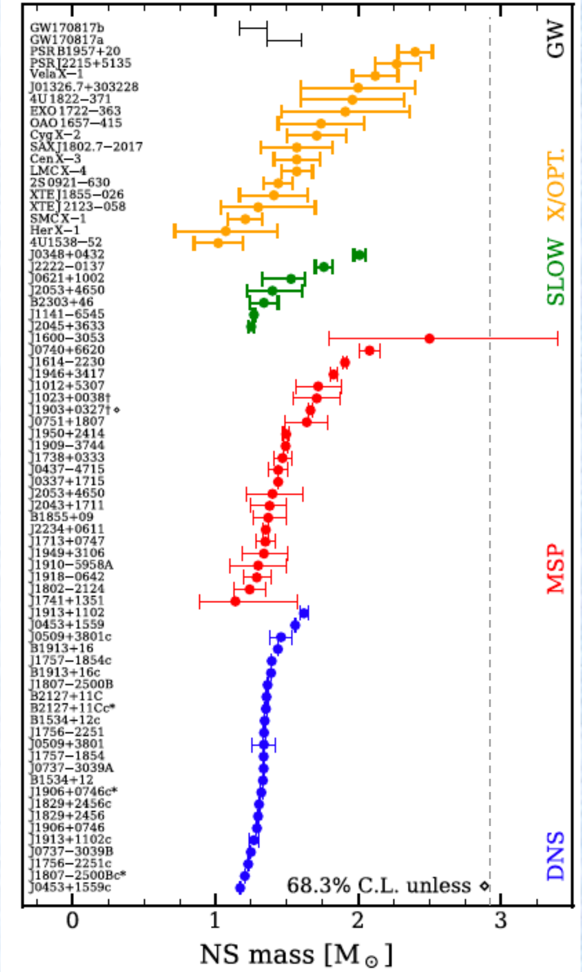
→ Constraints at “low” densities → low-order parameters, and on more on “symmetric” matter

<u>N.B.</u>: deduced constraints from exp. are often *not* raw data, but combined with models
→ model dependence of constraints !

see also Margueron et al., PRC 97, 025805 (2018) for a compilation

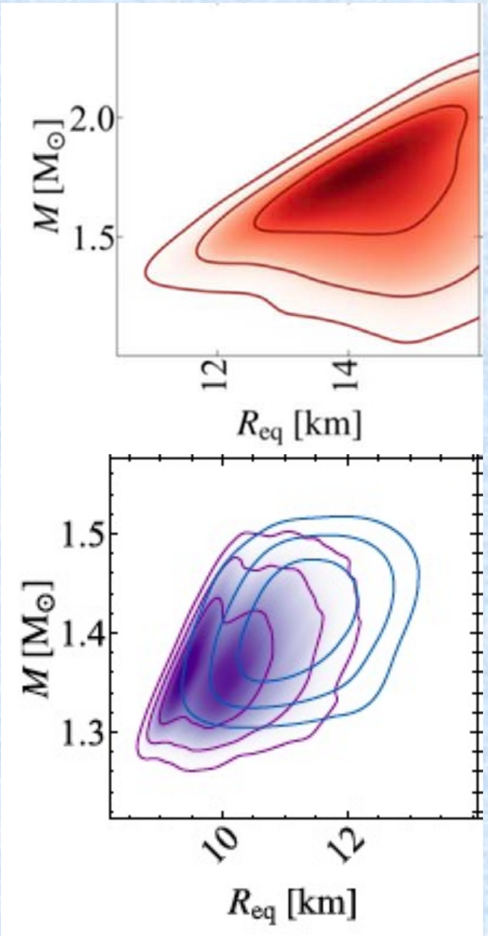
Constraints from astrophysics

MASSES



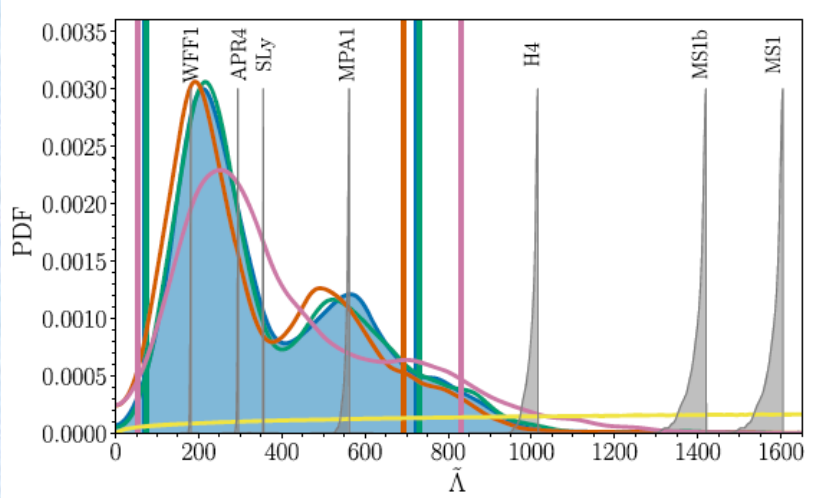
Suleiman et al., PRC 104, 015801 (2021)

RADII

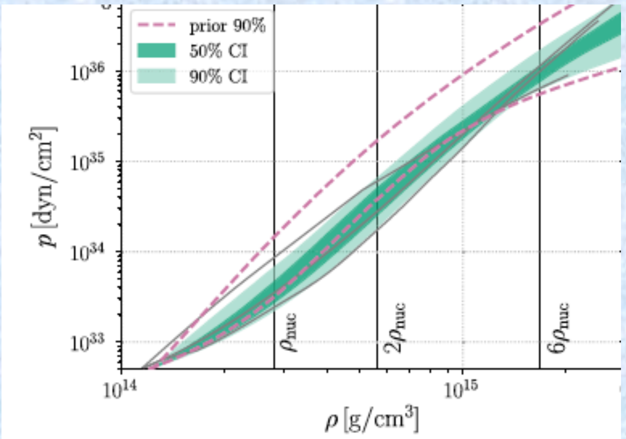


Choudhury et al., ApJL 971, L20 (2024);
Vinciguerra et al., ApJ 961, 62 (2024)
see also Miller et al. , Riley et al., ApJL 2019, 2021

TIDAL DEFORMABILITY



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

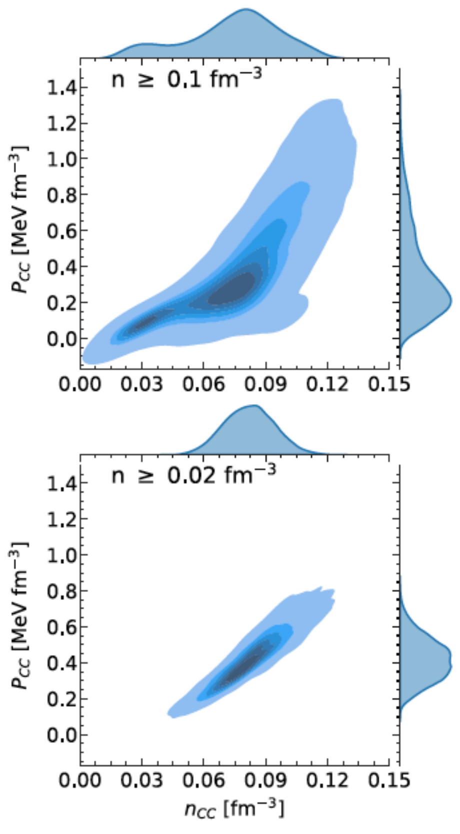


Abbot et al., PRL 121, 161101 (2017)

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

→ Constraints at “high” densities → higher order parameters

Crustal properties: cc transition



Dinh Thi et al., A&A 654, A114 (2021);
EPJA 57, 296 (2021) – non rel. MM

→ *important e.g. for NS cooling, rotational evolution of pulsars, pulsar glitches, …*

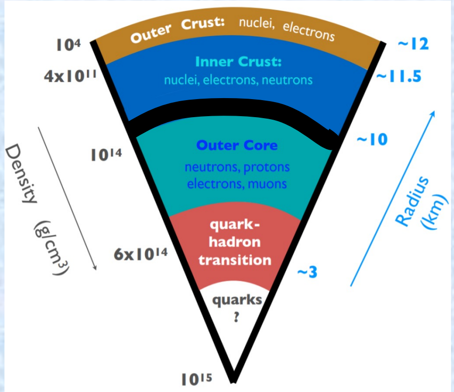


Image Credit: 3G Science White Paper

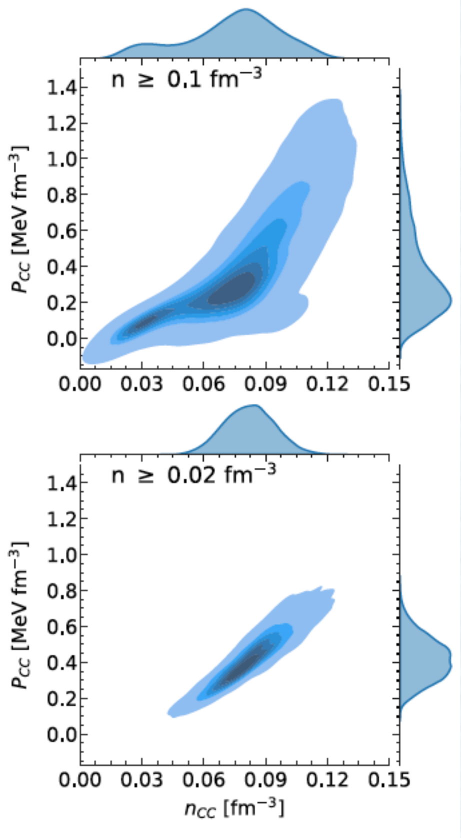
→ importance of low-density EoS

CLDM for crust

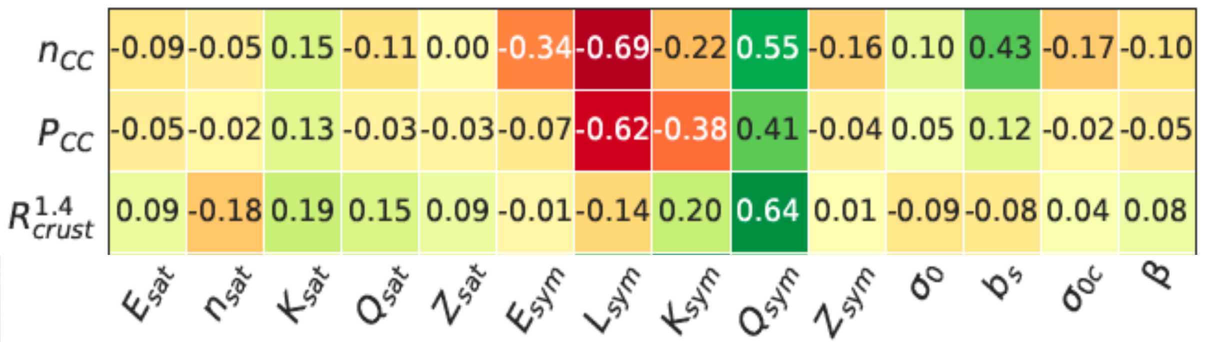
see also e.g. Carreau et al., PRC 100, 055803 (2019), Balliet et al., ApJ 918, 79 (2021); Scurto et al., PRD 109, 103105 (2024)

Crustal properties: cc transition

→ *important e.g. for NS cooling, rotational evolution of pulsars, pulsar glitches, …*



Dinh Thi et al., A&A 654, A114 (2021);
EPJA 57, 296 (2021) – non rel. MM



	E_{sat}	n_{sat}	K_{sat}	Q_{sat}	Z_{sat}	E_{sym}	L_{sym}	K_{sym}	Q_{sym}	Z_{sym}	σ_0	b_s	σ_{0c}	β
n_{CC}	-0.09	-0.05	0.15	-0.11	0.00	-0.34	-0.69	-0.22	0.55	-0.16	0.10	0.43	-0.17	-0.10
P_{CC}	-0.05	-0.02	0.13	-0.03	-0.03	-0.07	-0.62	-0.38	0.41	-0.04	0.05	0.12	-0.02	-0.05
$R^{1.4}_{crust}$	0.09	-0.18	0.19	0.15	0.09	-0.01	-0.14	0.20	0.64	0.01	-0.09	-0.08	0.04	0.08

Dinh Thi et al., Universe 7, 373 (2021)

bulk

surface

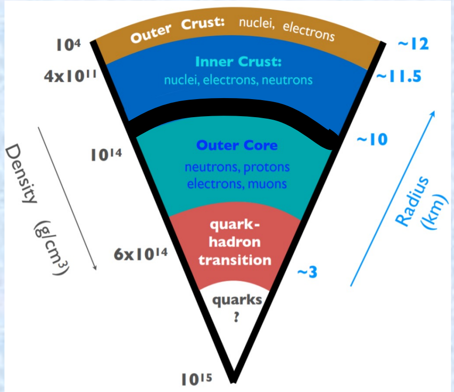


Image Credit: 3G Science White Paper

→ importance of low-density EoS

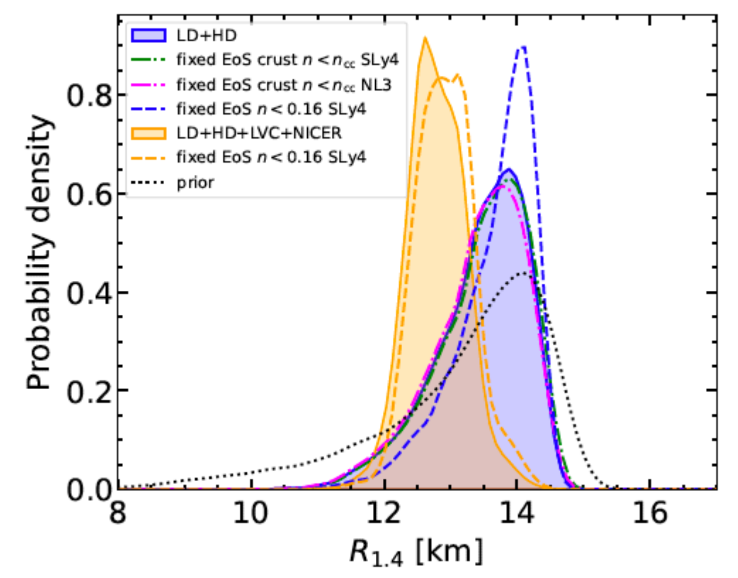
→ importance of parameters (*bulk* + *surface*)
→ importance of higher order (*N* > 2) parameters

CLDM for crust

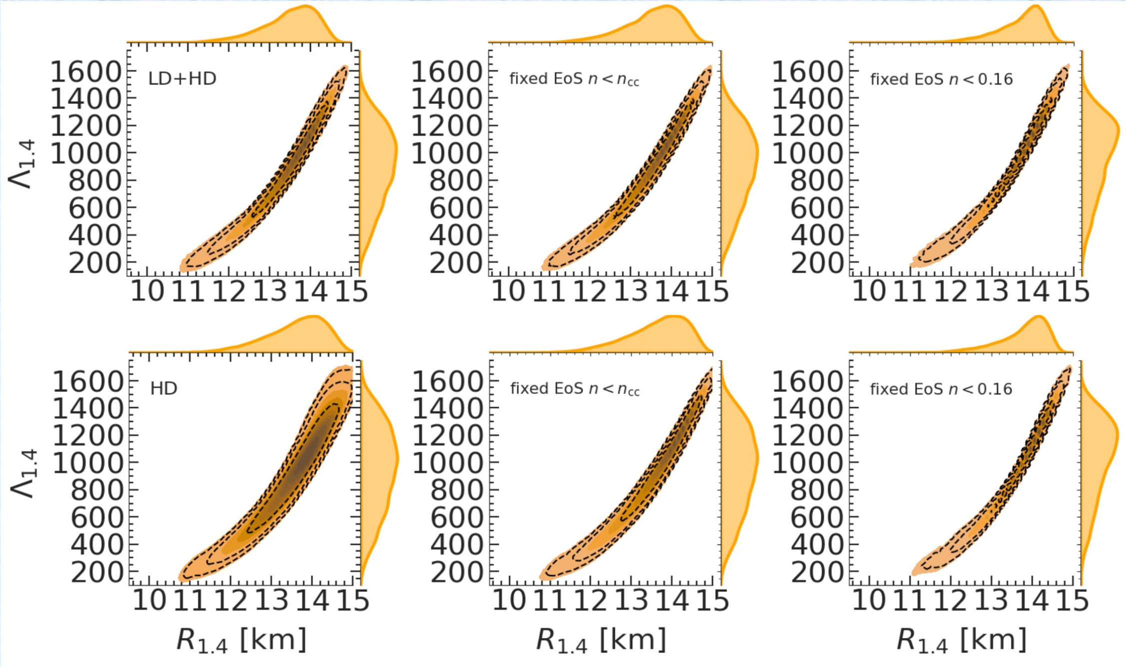
see also e.g. Carreau et al., PRC 100, 055803 (2019), Balliet et al., ApJ 918, 79 (2021); Scurto et al., PRD 109, 103105 (2024)

Effect of the (non-unified) crust (1)

RADIUS & TIDAL DEFORMABILITY



Davis, Dinh Thi, Fantina, Gulminelli, Oertel, Suleiman, A&A 687, A44 (2024)

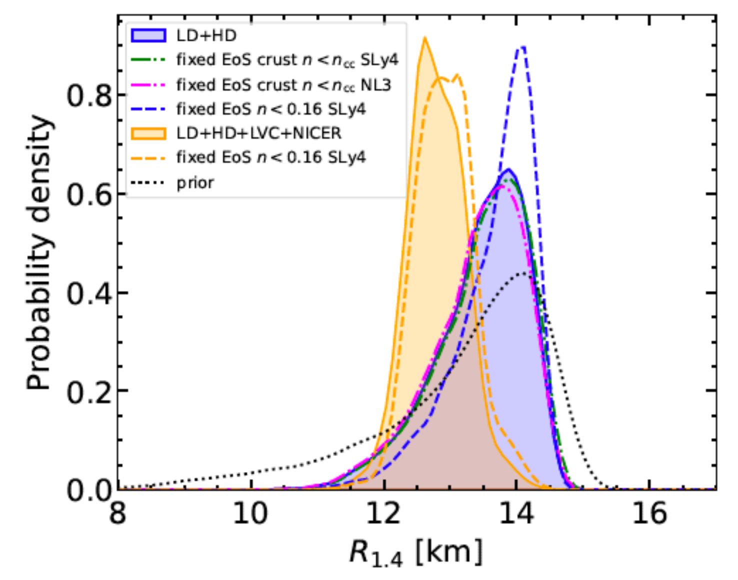


Fantina & Gulminelli, PoS (in prep.)

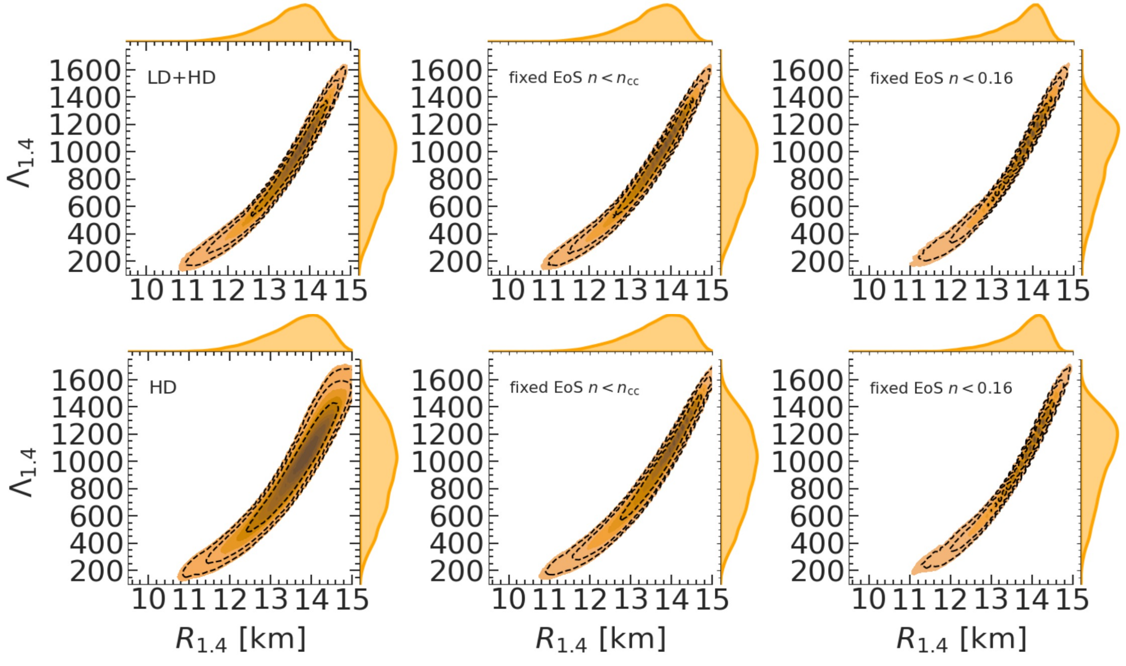
- ➢ use of unique low-density EoS does not change much averages (~ few %)
  (see also Gamba et al., Class. Quant. Grav. 37, 025008 (2020) → ~ 3%)
  → ok if "reasonable" crust applied until cc transition,
  → ok for current GW detectors, but next generation ?
- ➢ filters from GW (& NICER) shift distribution (softer EoS) → effect of unique crust reduced

Effect of the (non-unified) crust (2)

RADIUS & TIDAL DEFORMABILITY



Davis, Dinh Thi, Fantina, Gulminelli, Oertel, Suleiman, A&A 687, A44 (2024)



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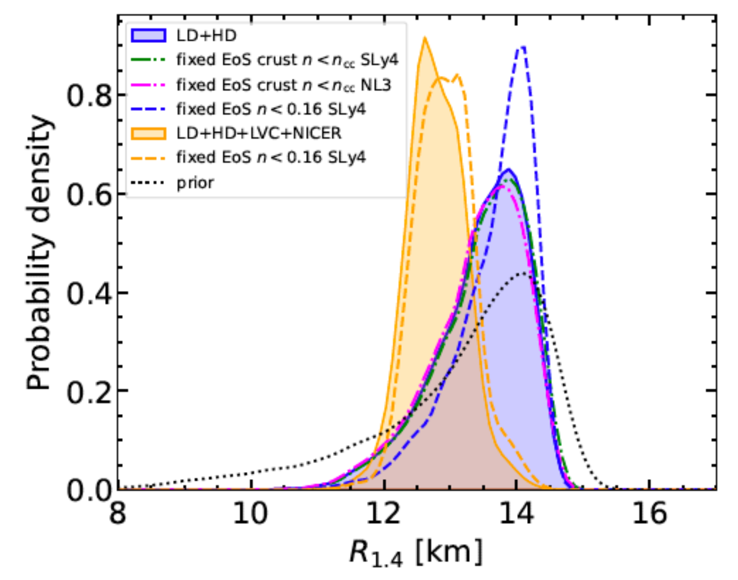
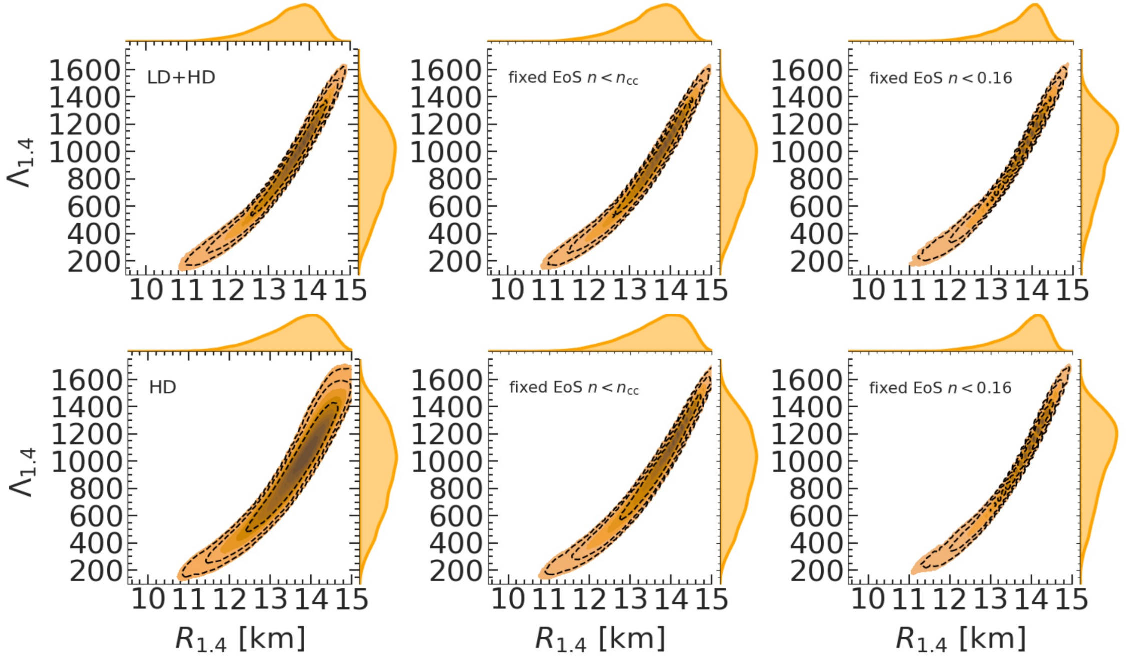
  → ok for current GW detectors, but next generation ?
- ➢ filters from GW (& NICER) shift distribution (softer EoS) → effect of unique crust reduced
- ➢ underestimation of uncertainties in non-consistent approach, especially if no LD filters

Effect of the (non-unified) crust (3)

RADIUS & TIDAL DEFORMABILITY



Davis, Dinh Thi, Fantina, Gulminelli, Oertel, Suleiman, A&A 687, A44 (2024)

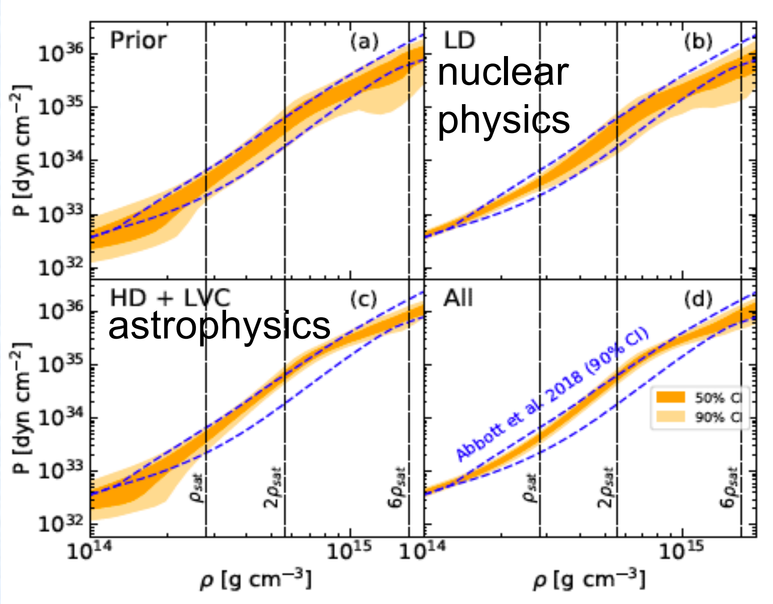


Fantina & Gulminelli, PoS (in prep.)

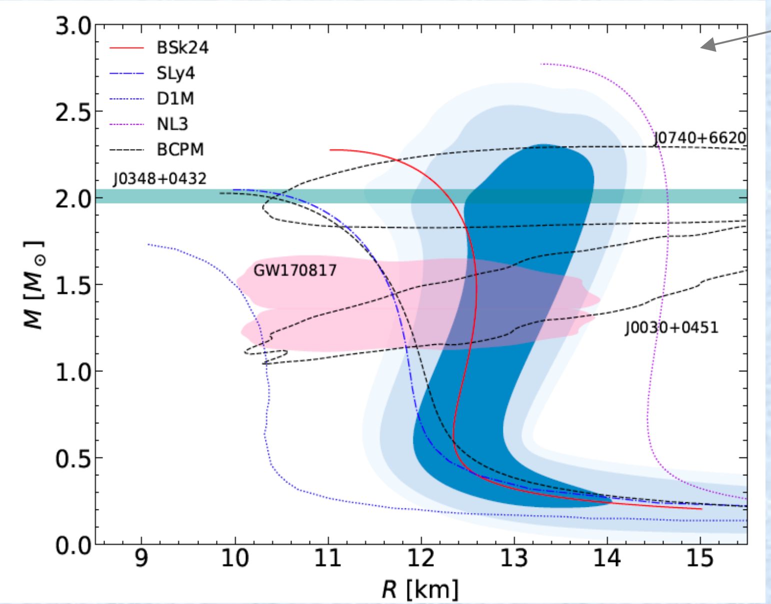
→ **`CUTER` code** to reconstruct a *thermodynamically consistent and unified* low-density EoS from a given (high-density) β-equilibrium EoS (non necessarily based on a nuclear model) (available for LVK collaboration, v1 publicly available on Zenodo)

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

EoSs (informed by nucl. phys.) and NS observables

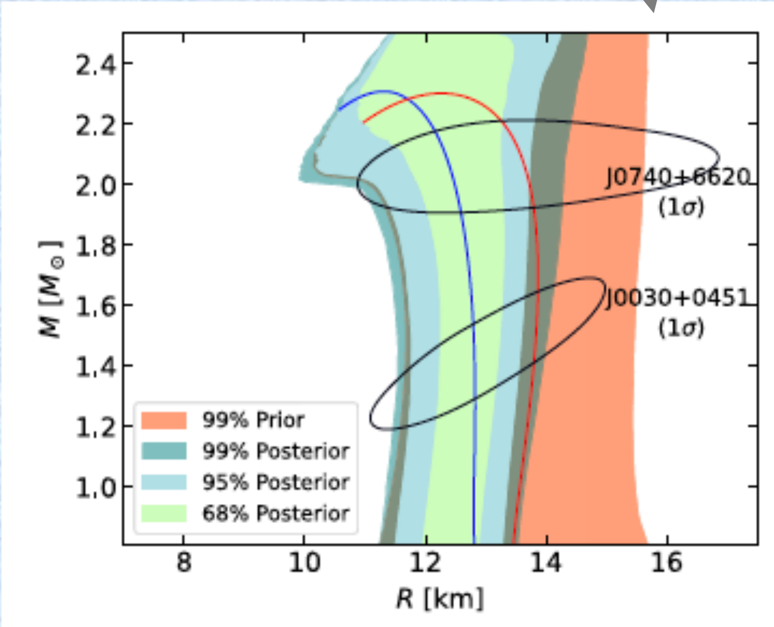


Dinh Thi et al., Universe 7, 373 (2021);
Dinh Thi et al., A&A 654, A114 (2021)



Gulminelli & Fantina, NPN 31, 9 (2021);
Fantina & Gulminelli, J.Phys. Conf.Ser. 2596, 012112 (2023)

Non-relativistic and relativistic MM give compatible predictions !



Char et al., PRD 108, 103045 (2023)

→ posterior compatible with observations, but: some models are not !

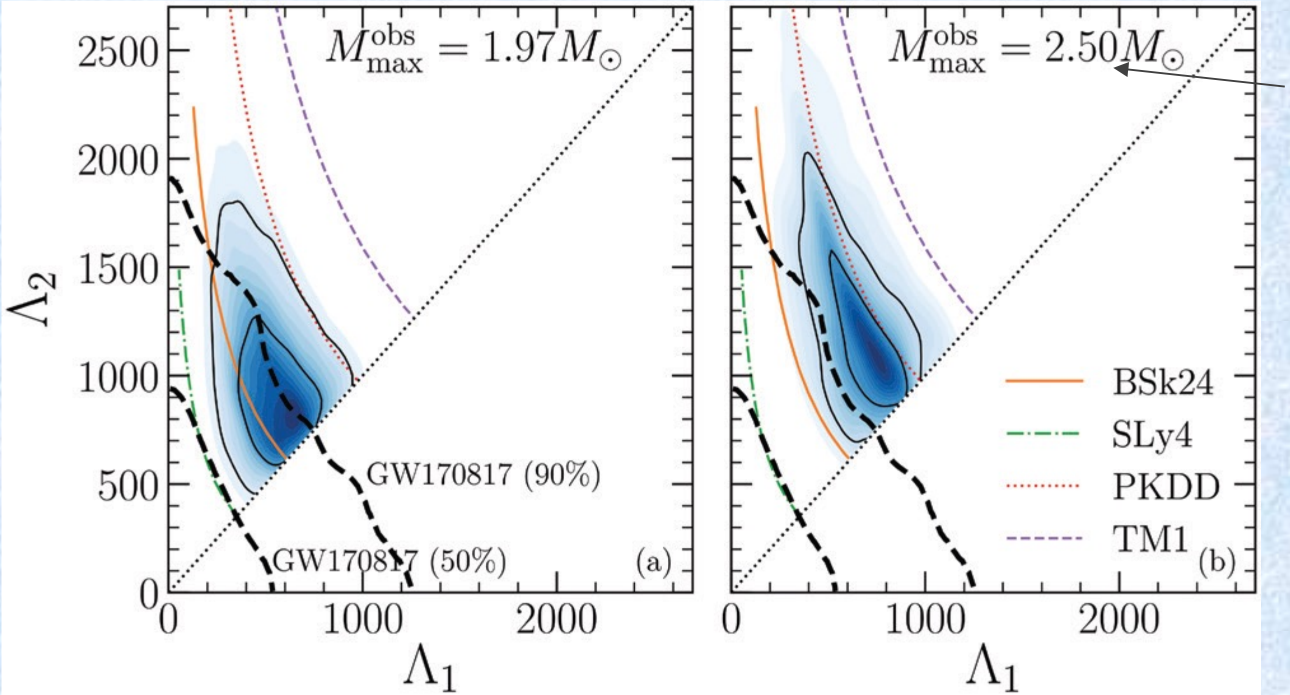
→ nucleonic hp compatible with observations → observations not yet constraining enough!

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

N.B.: Several works within Bayesian analysis trying to constrain NEP / EoS
see also Beznogov & Raduta, PRC (2023); Ghosh et al., EPJA (2022); Char et al., PRD (2023); Imam et al., PRD (2024); Zhu et al., ApJ (2023); Huang et al., arXiv:2303.17518, ….

How to discriminate models? (astro1)

- more and more precise data (e.g. *M*, *R*, Λ, ...) – or even a “smoking gun” observation!



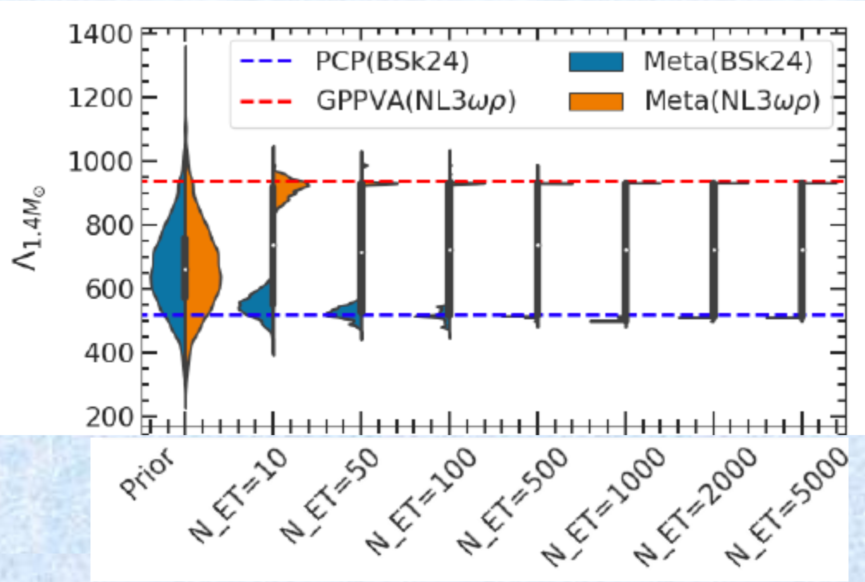
GW190426 ?

Gulminelli & Fantina, Nucl. Phys. News 31, 2 (2021); T. Carreau, PhD Thesis (2020)

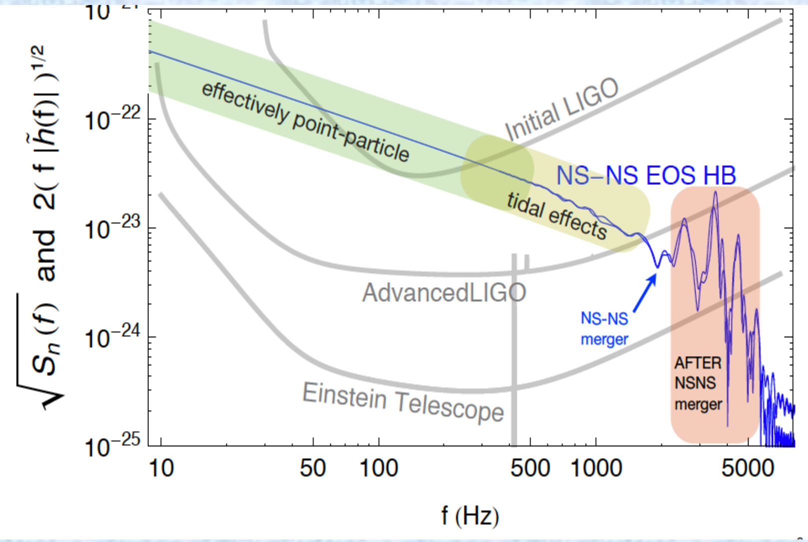
→ posterior with nucleonic matter compatible with observations
but: if $M_{\rm max}$ ~ 2.5 $M_{\rm sun}$ → challenge for nucleonic hypothesis ! → “exotica” ?
→ Nucleonic hp can be used as null hp!

How to discriminate models? (astro2)

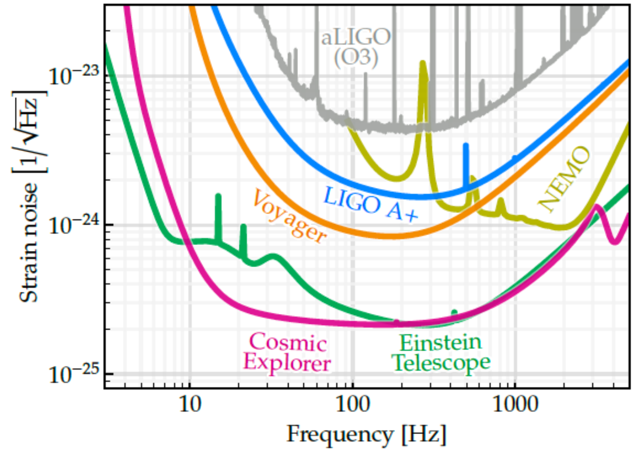
- more and more precise data (e.g. *M*, *R*, Λ, …) – or even a “smoking gun” observation!
- more sensitive detectors → new generation (ET, CE) → post-merger



Iacovelli et al., PRD 2023



Read, CGWAS lecture (2015)

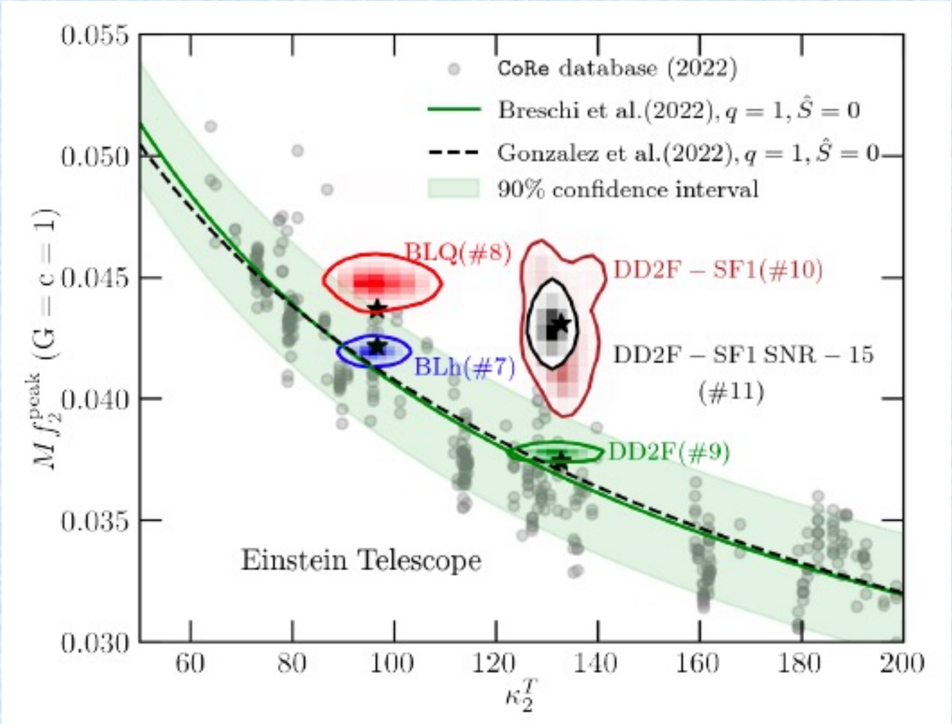


Hall, Galaxies 10, 90 (2022)

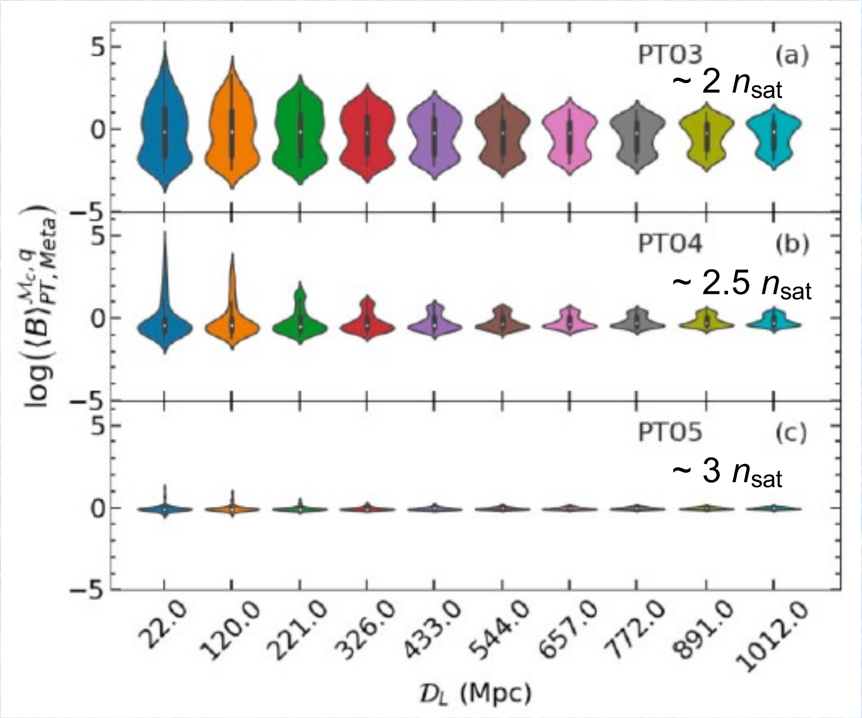
- More reliable prediction / interpretation of astrophysical observations
- Better knowledge of dense matter in compact stars → *Phase transition to deconfined matter (quarks, …) ?*

Additional d.o.f. – *Phase Transition to deconfined matter?*

- observed discrepancy from (quasi-)universal relations
- identification if close detection and early PT



Prakash et al., PRD 109, 103008 (2024)



Mondal et al., MNRAS 524, 3464 (2023)

- if phase transition not strong or “late” → hard to disentangle from other uncertainties
- post-merger signal observations needed → ET / CE!

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see also e.g. Essick et al., PRD 108, 043013 (2023); Blacker&Bausswein, arXiv:2406.14669; Raithel&Most, PRD 108, 023010 (2023); Fujimoto et al., PRL 130, 091404 (2023)

Finite *T* in BNS mergers / CCSN

✓ Finite *T* , high density met in **CCSN and BNS mergers (post-merger)**
→ additional degrees of freedom ? Effect on dynamics ?

Temperature	0 MeV $\leq T < 150$ MeV
Baryon number density	10^{-11} fm$^{-3} < n_B < 10$ fm^{-3}
Electron fraction	$0 < Y_e < 0.6$

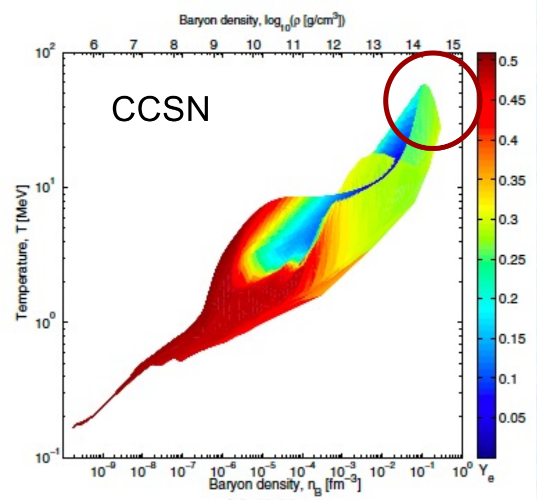
✗ Consistent treatment of phase transitions challenging

✗ Extension of many-body methods and extrapolation of predictions not trivial (e.g. parameters of nuclear phenomenological models usually fitted at *T*=0)

✗ Hydro effects (SASI, convection, etc…), *B* field, …

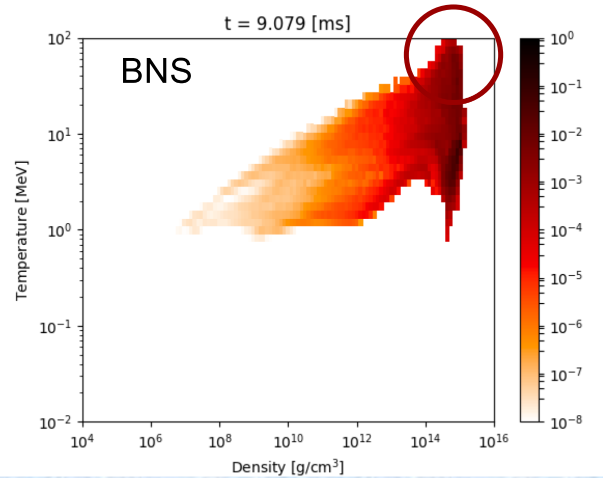
→ see e.g. talks by T. Foglizzo, M. Bugli, A. Reboul-Salze

- ➢ Need of a *unified* “general purpose” EoS (and composition) in very wide thermodynamic conditions
- ➢ Implementation in numerical simulations



(b) 40 $M_\odot$

Fischer et al., ApJSS 194, 39 (2011)



Perego et al., EPJA 55, 124 (2019)

for a review e.g. Oertel et al., Rev. Mod. Phys. 89, 015007 (2017); Burgio & Fantina, ASSL 457, 255 (2018)

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 → future observations?

⇨ ✓ need of (microscopic) reliable theoretical model when no data & experimental data to calibrate models
✓ need of (more precise / numerous) astrophysical observations

- ❖ `CUTER` tool for consistent crust EoS reconstruction available

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- ➢ Extrapolation from raw data → model dependence of the constraints
- ➢ Nuclear physics gives constraints up to ~ 1.5n_{sat} → predicted observable quite robust (with uncertainties)
  → possibility to explore new physics ?
- ➢ Uncertainties in high-density EoS → blurring of different effects ?
- ➢ Astro simulations vs microphysics inputs → uncertainties, consistency of inputs, relative effects of microphysics inputs in astro modelling ?
  - ❖ systematic studies / bayesian analysis → implementation of consistent probability distributions in astro prediction/inference
  - ❖ static properties → if GR, possible "extraction" of EoS (with uncertainties), composition?
    dynamical properties → need of (multi-D) hydro simulations
    → computationally challenging, dependence on different inputs

Thank you

NASA - X-ray: CXC, Optical: STSCI, Infrared: JP