Probing the equation of state of dense matter with neutron stars

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laboratoire commun CEA/DRF CNRS/IN2P3

Outline

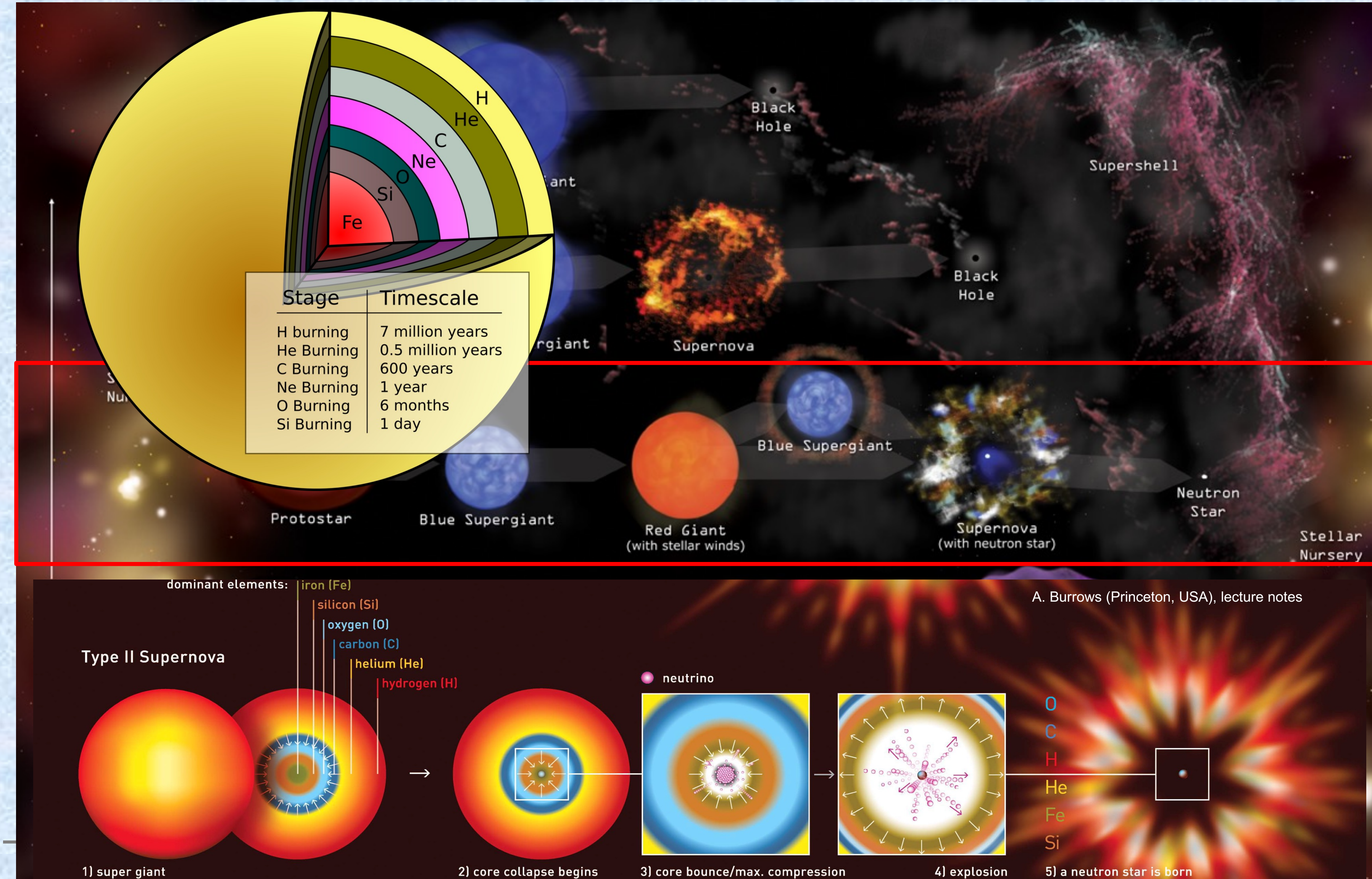
- Introduction
  - Neutron-star (NS) properties

- Equation-of-state (EoS) modelling
  - NS EoS
    - Outer crust
    - Inner crust
    - Homogeneous matter — see also A. Raduta’s talk
  - EoS and neutron-star (NS) properties
    - How to build a global model of NS ?
    - How can we get constraints ?
    - Bayesian analysis — see also M. Beznogov’s talk

- Conclusions and perspectives

N.B.: In this talk, T = 0 and beta-equilibrium matter

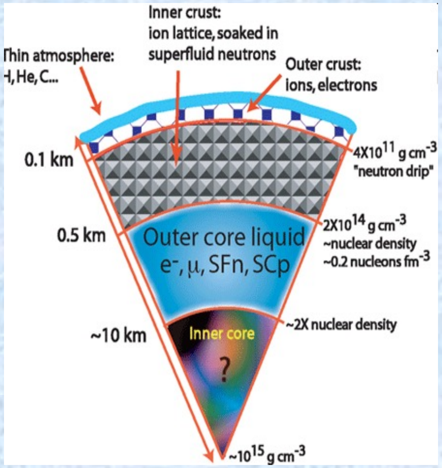
What is a NS ?



Credits: http://chandra.harvard.edu; http://large.stanford.edu

Scenarios for "$T = 0$" NS EoS

Mature neutron stars – cold (NSs)

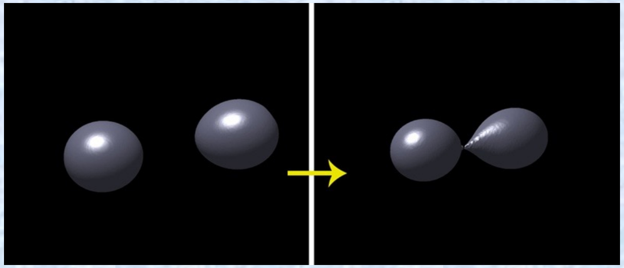


http://www.physics.montana.edu

$$
\begin{aligned}
M &\approx 1 - 2M_\odot \\
R &\approx 10\ \mathrm{km} \\
\bar{\rho} &\approx 10^{14} - 10^{15}\ \mathrm{g\ cm^{-3}} \\
T &< 10^{8}\ \mathrm{K}
\end{aligned}
$$

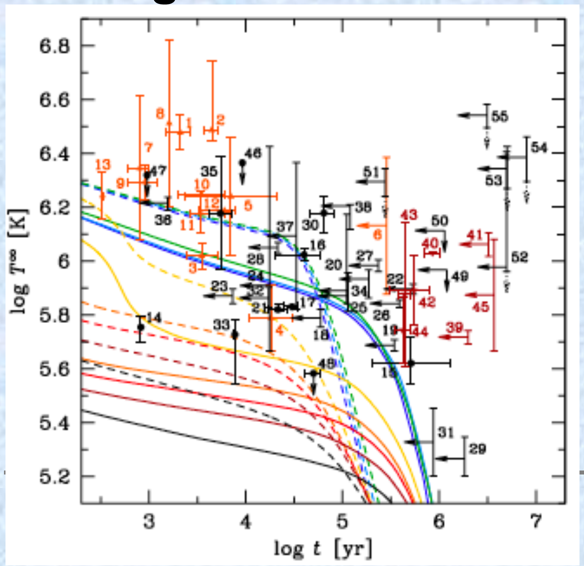
NB: $T = 0 \Leftrightarrow T \ll T_F$

Binary NS mergers ("cold" in inspiral phase)



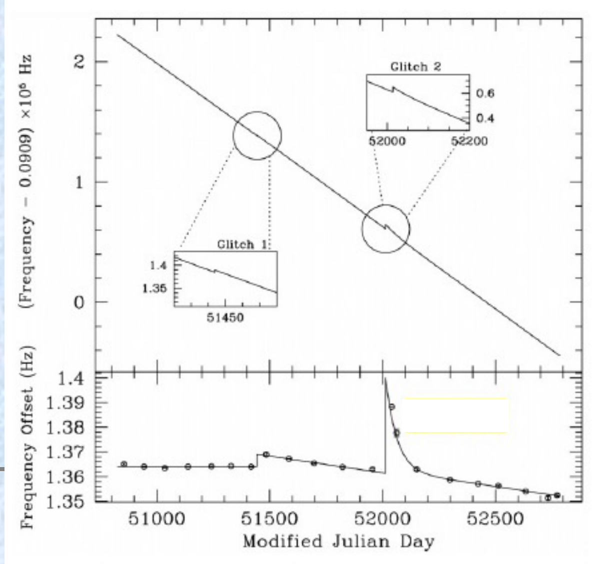
Simulation MPA Garching
(Goriely, Bauswein,Janka, ApJ 738, 2011)

Cooling



Potekhin et al., MNRAS 496, 5052 (2020)

Gliches



from M. Antonelli's talk (2022)

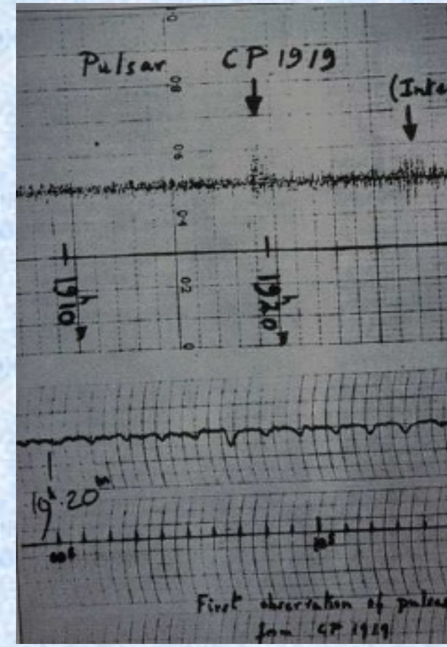
Fortuitous discovery of a pulsar

Jocelyn Bell in 1966

1967: J. Bell, PhD thesis at Cavendish Laboratory, Cambridge on radio sources. With a 3.7m diameter telescope, she discovered a very regular source, with a period of 1.3373012 s.

This source was called LGM ("Little Green Man"); a journalist from Daily Telegraph called this source "*Pulsar*" . It is now known as PSR B1919+21.

In 1974, A. Hewish (Bell's PhD supervisor) received the Nobel prize…



Manchester et al., AJ 129, 1993-2006 (2005)

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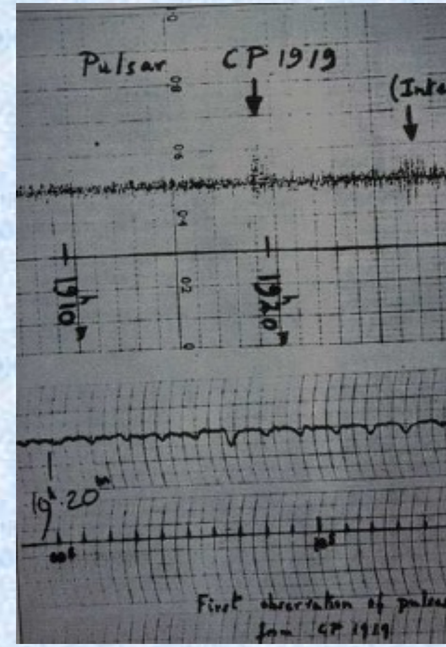
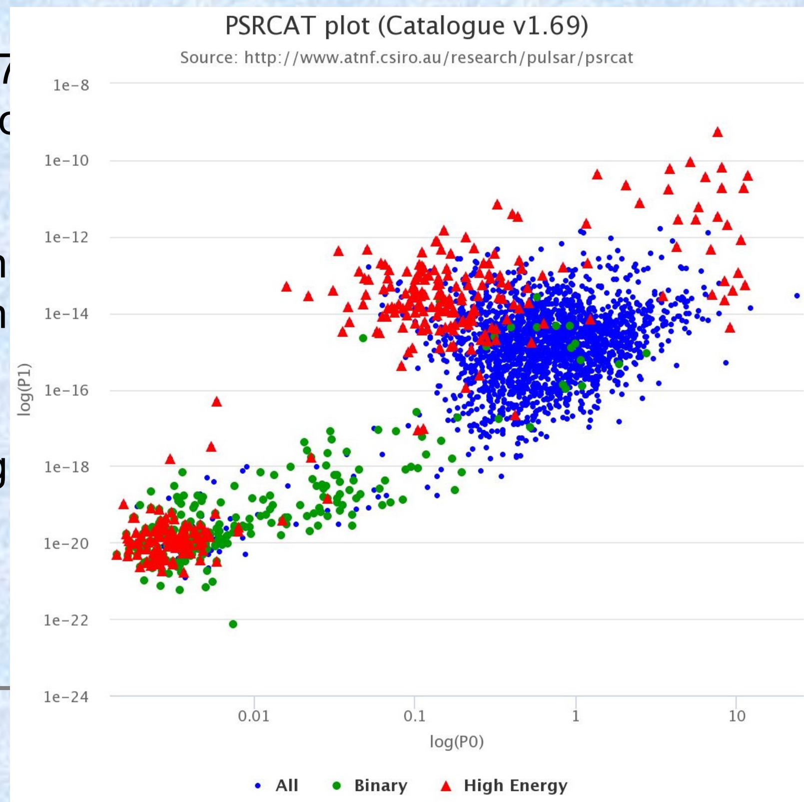
In 197 … eived the No…

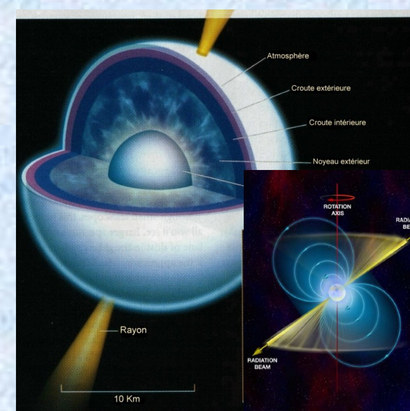


Since 1967, more than 2000 pulsars have been discovered!

Some of them have strong magnetic field

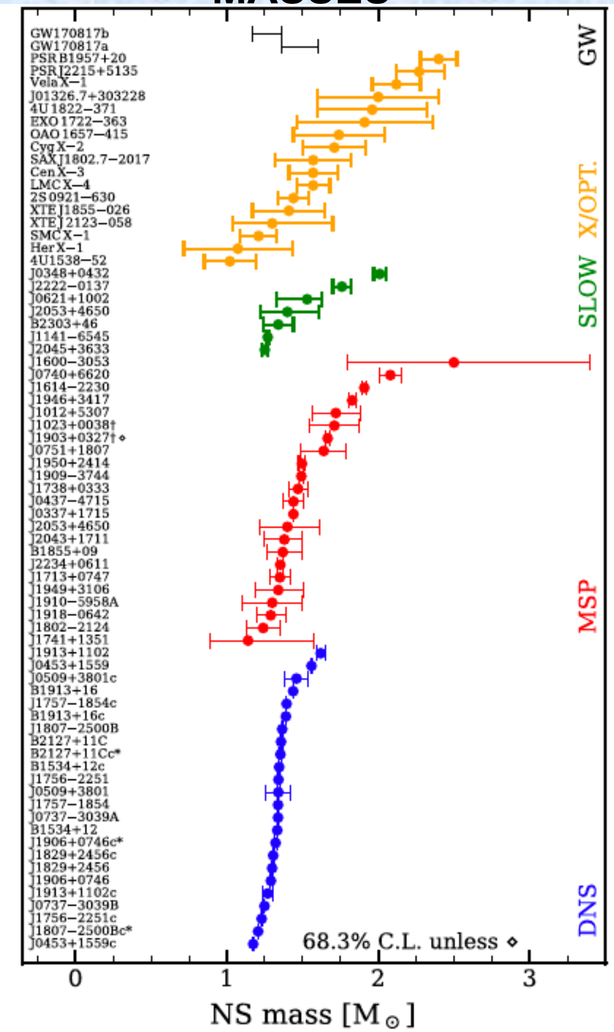


Manchester et al., AJ 129, 1993-2006 (2005)



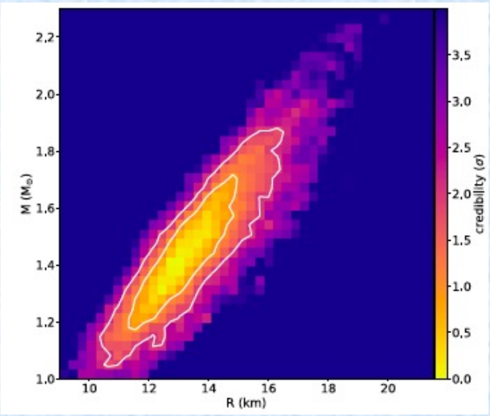
What other properties do we "observe"?

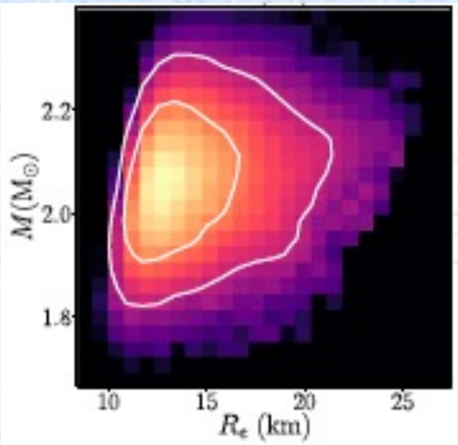
MASSES



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

RADII

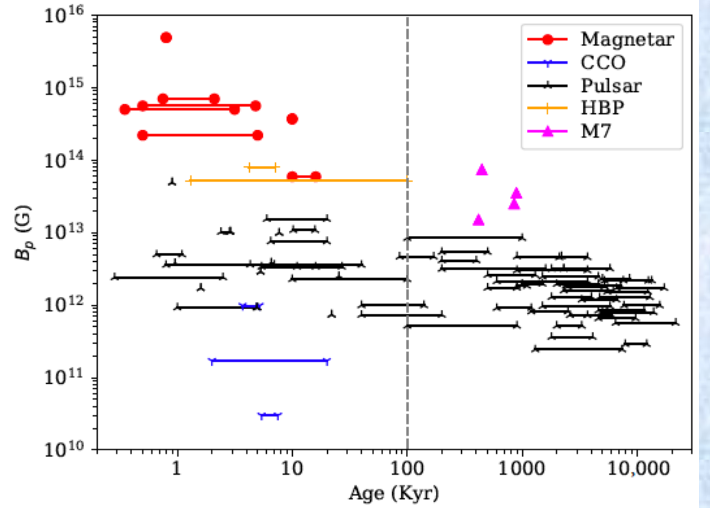




Miller et al., ApJL 2019, 2021;
also Riley et al., ApJL 2019, 2021

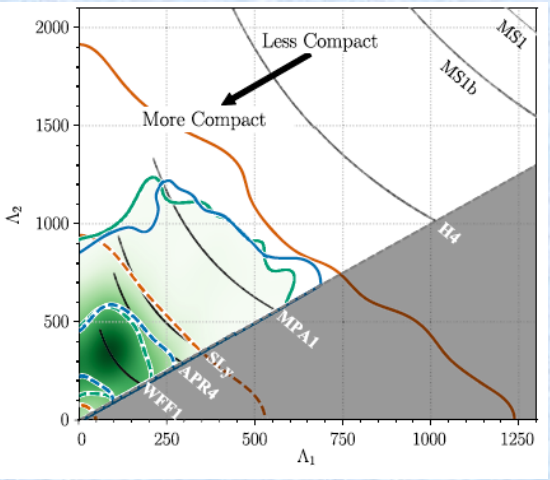
see A. Raduta's talk

MAGNETIC FIELD



Igoshev et al., Universe 7, 00351 (2021)

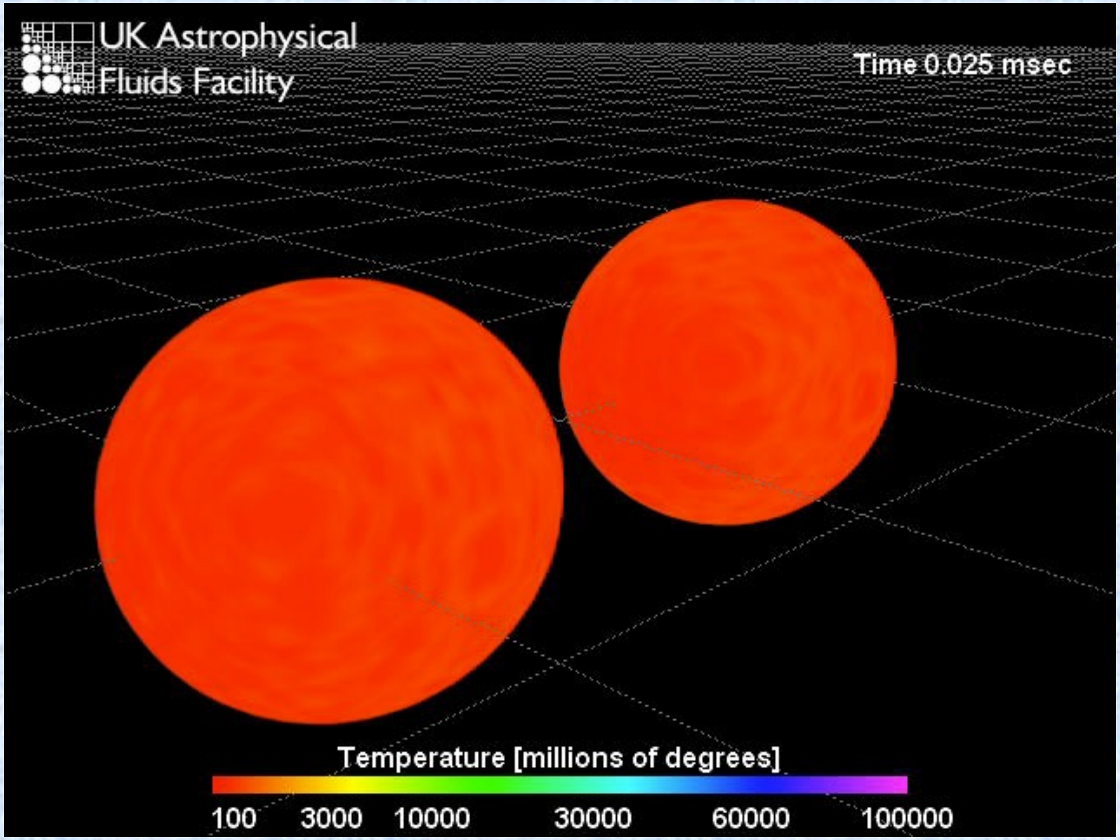
TIDAL DEFORMABILITY



Abbott et al., PRL 121, 161101 (2018)

NB: most are inferred, not "direct" observations, so model dependent !

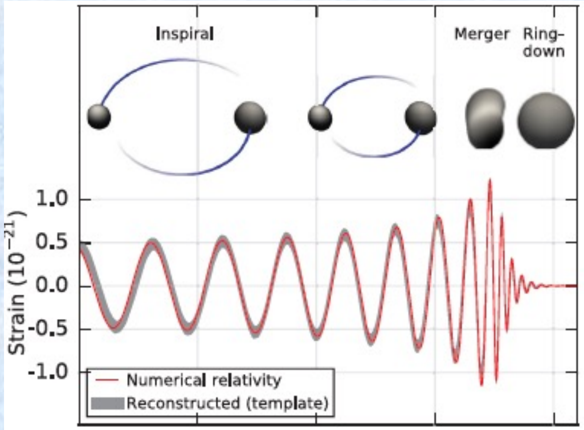
Binary NS merger: simulations



Simulation by S. Rosswog, visualisation R. West
http://www.ukaff.ac.uk/movies/nsmerger/

Gravitational waves (GW): detection

- Predicted by Einstein, observed in 2015 from **black-hole merger**

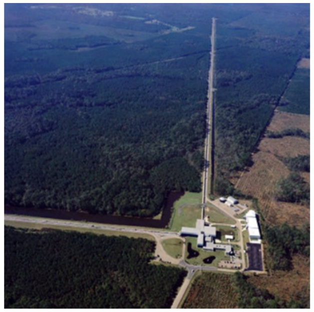


Abbott et al., PRL 116, 061102 (2016)

→ Nobel Prize in physics 2017

2017 Nobel Prize Physics - gravitational waves (Weiss, Barish, Thorne)
Credits: The Royal Swedish Academy of Sciences. Ill. N. Elmehed

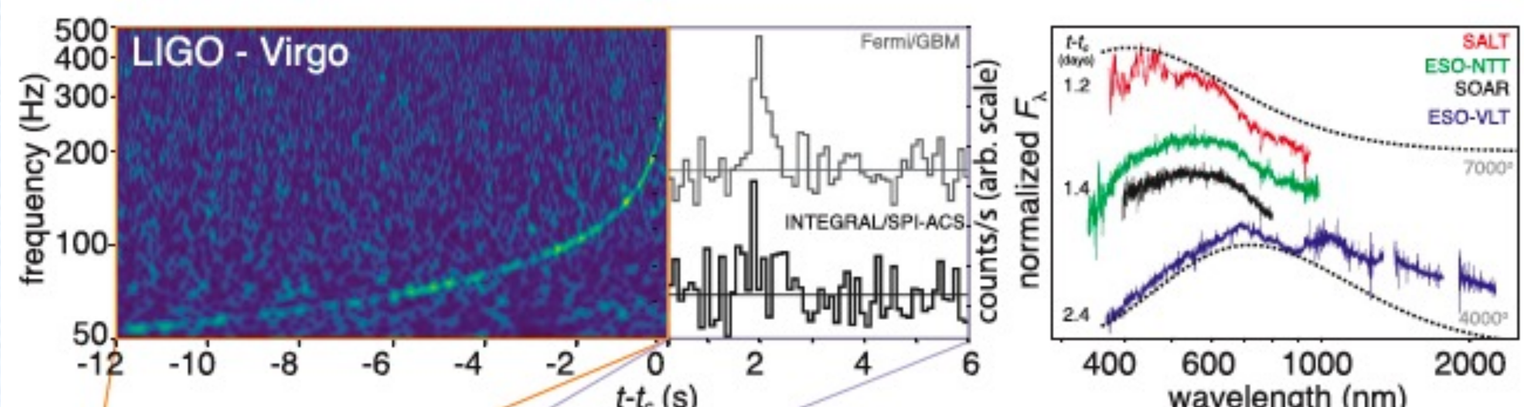
LIGO Hanford Observatory, Washington
(Credits: C. Gray)



LIGO Livingston Observatory, Louisiana
(Credits: J. Giaime)

Virgo detector, Italy
(Credits: Virgo Collaboration)

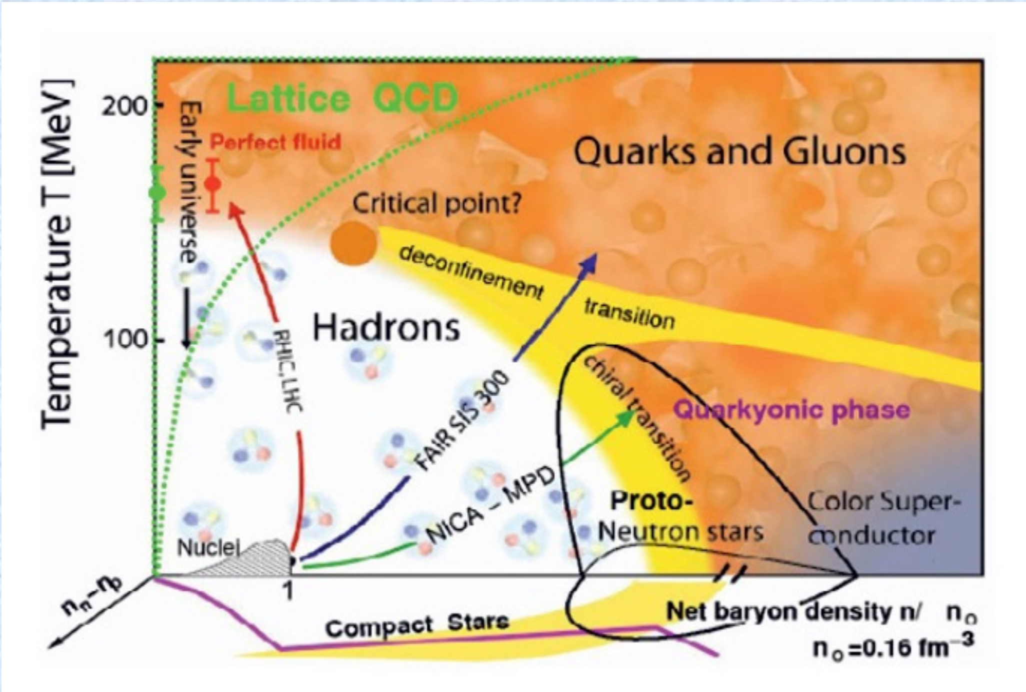
- Detection of GW from **binary NS merger** in 2017 (GW170817)
  → *multi-messenger astronomy*



Abbott et al., ApJL 848, L12 (2017)

→ new window on the Univers

Probing extreme conditions in NSs



Kekelidze et al., EPJ Web of Conf. 70, 00084 (2014)

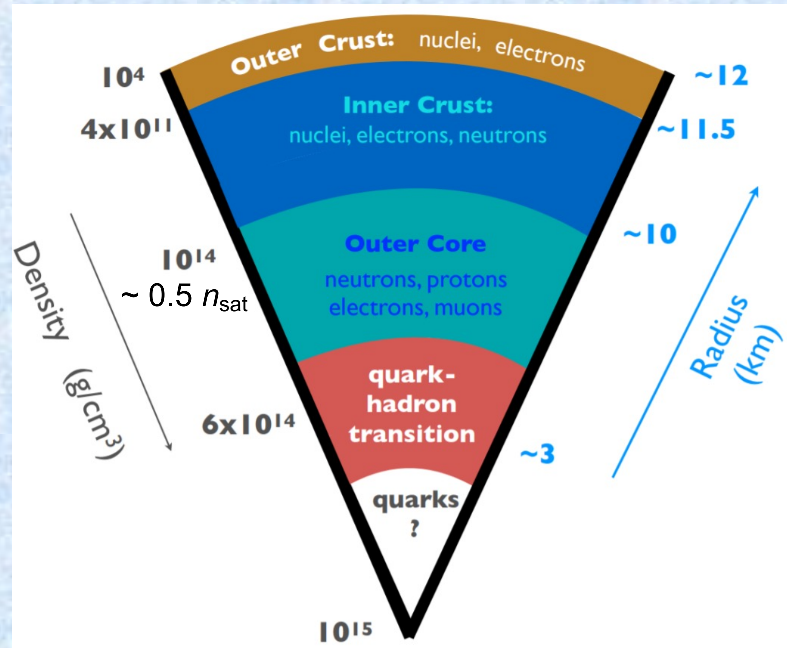
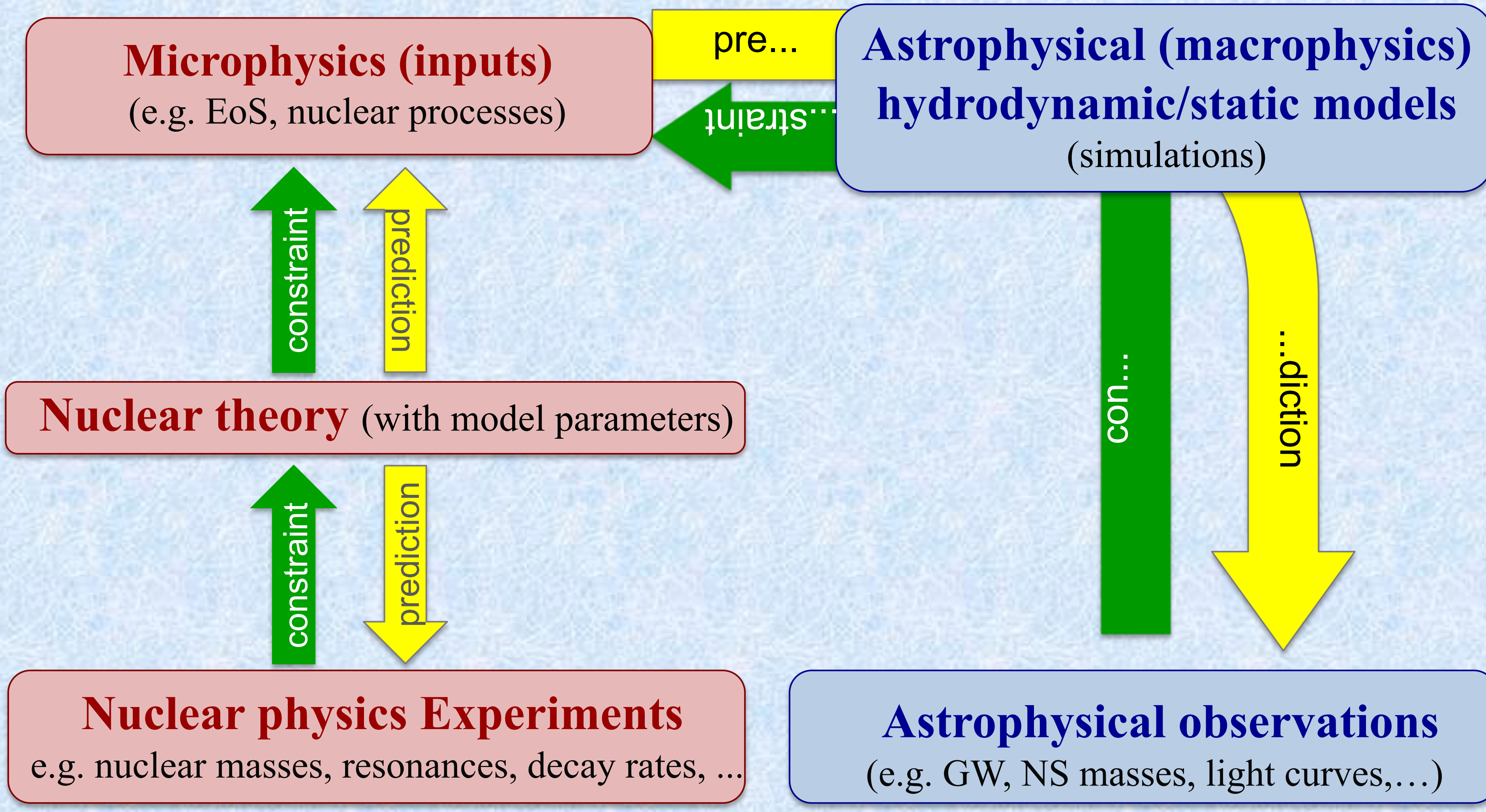


Image Credit: 3G Science White Paper

different states of matter spanned in NSs !
→ inhomogeneous, homogeneous, "exotic" particles (? → see A. Raduta's talk)
+ superfluidity, magnetic field, etc.

→ not all conditions can be probed in terrestrial labs → theoretical models !

Micro to macro through modelling



Micro to macro through modelling

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

pre...

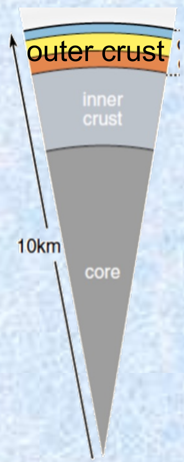
...straint

Astrophysical (macrophysics) hydrodynamic/static models
(simulations)

constraint

prediction

in outer crust !



con...

...diction

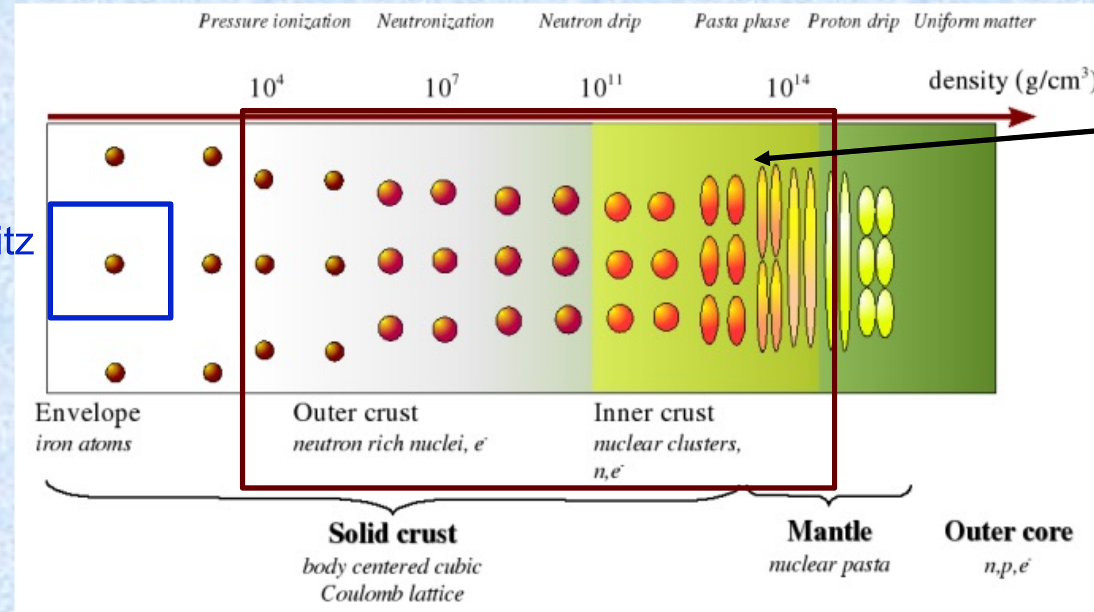
Nuclear physics Experiments
e.g. nuclear masses, resonances, decay rates, ...

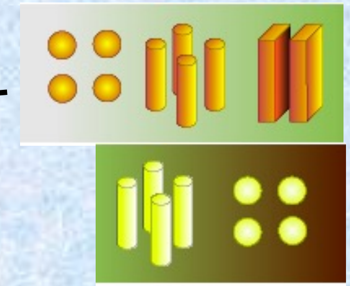
Astrophysical observations
(e.g. GW, NS masses, light curves,…)

NS crust ($T = 0$)

"Cold" (catalysed) NS : T = 0 approx., full (thermodymamic + beta) equilibrium

Wigner-Seitz (WS) cell





clusters

holes

→ possible existence of "pasta" layer at the bottom of the crust

Chamel & Haensel, Liv. Rev. Relativ. 11, 10 (2008); see also Blaschke & Chamel, ASSL 457, 337 (Springer, 2018)

- To obtain the EoS → minimisation $\varepsilon(n_B) = E_{WS}/V_{WS}$ = min

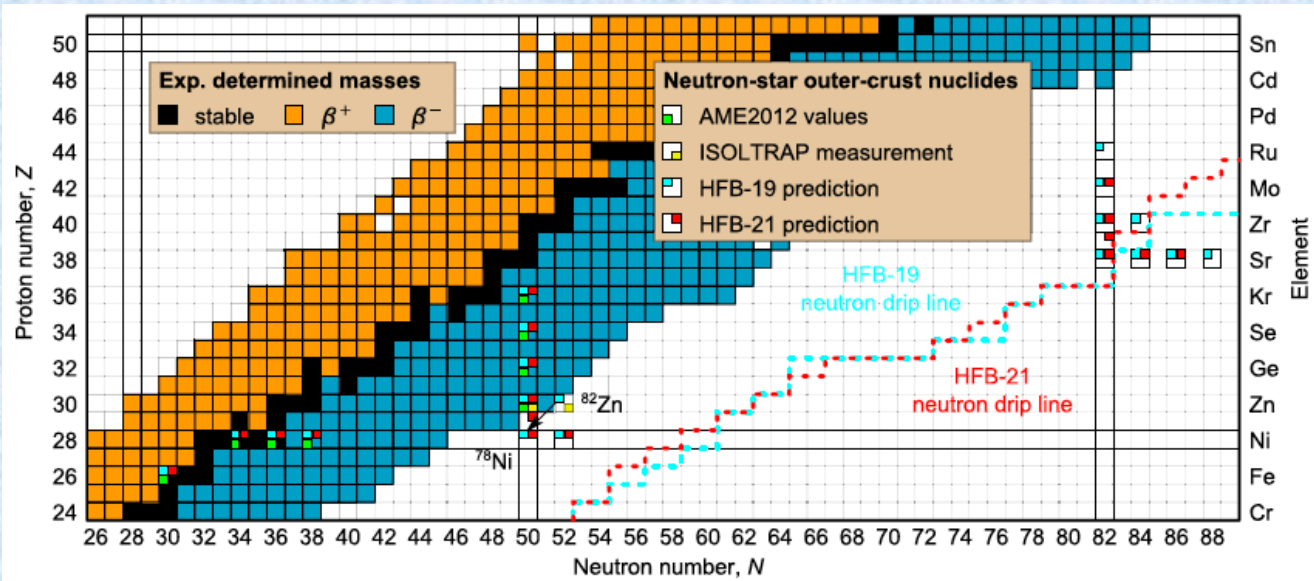
  N.B.: n_B = baryon number density,
  $\rho c^2 = \varepsilon$ mass-energy density !

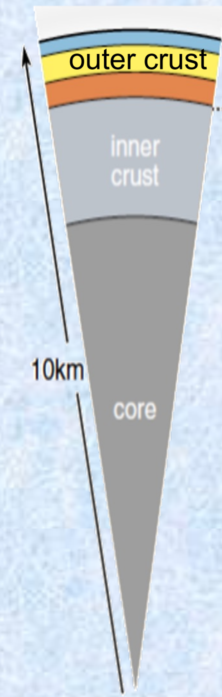
NS outer crust: up to neutron drip

- Nuclei in bcc lattice + electrons: $\epsilon_{\rm WS}(n_B) = \frac{M(A,Z)c^2}{V_{\rm WS}} + \epsilon_e(n_e) + \epsilon_{\rm Coul}$

e-e and e-i int.

Only microscopic inputs are nuclear masses → Experimental or mass models





Wolf *et al.*, PRL 110, 041101 (2013)

- ➢ very neutron-rich nuclei
- ➢ imprint of shell structure

see e.g. Haensel et al. 2007 (Springer), Oertel et al., Rev. Mod. Phys. (2017), Burgio & Fantina, ASSL 457 (2018), Blaschke & Chamel, ASSL 457, 337 (Springer, 2018) for a review and refs. ttherein
for HFB models shown see also Goriely et al. 2010, 2016, Pearson et al., MNRAS 481, 2994 (2018)

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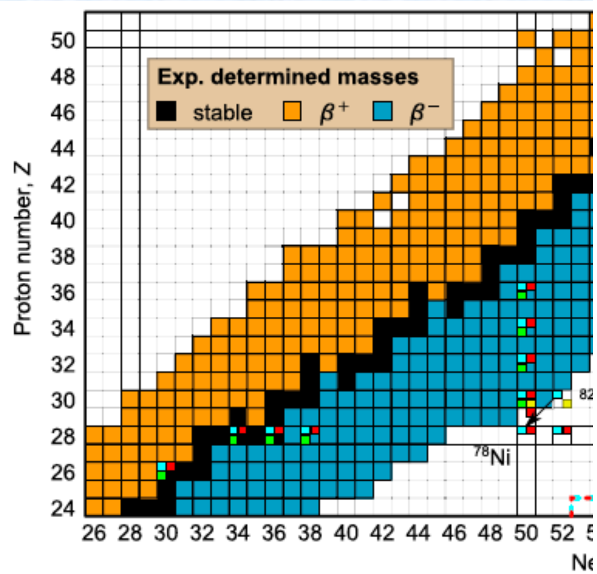

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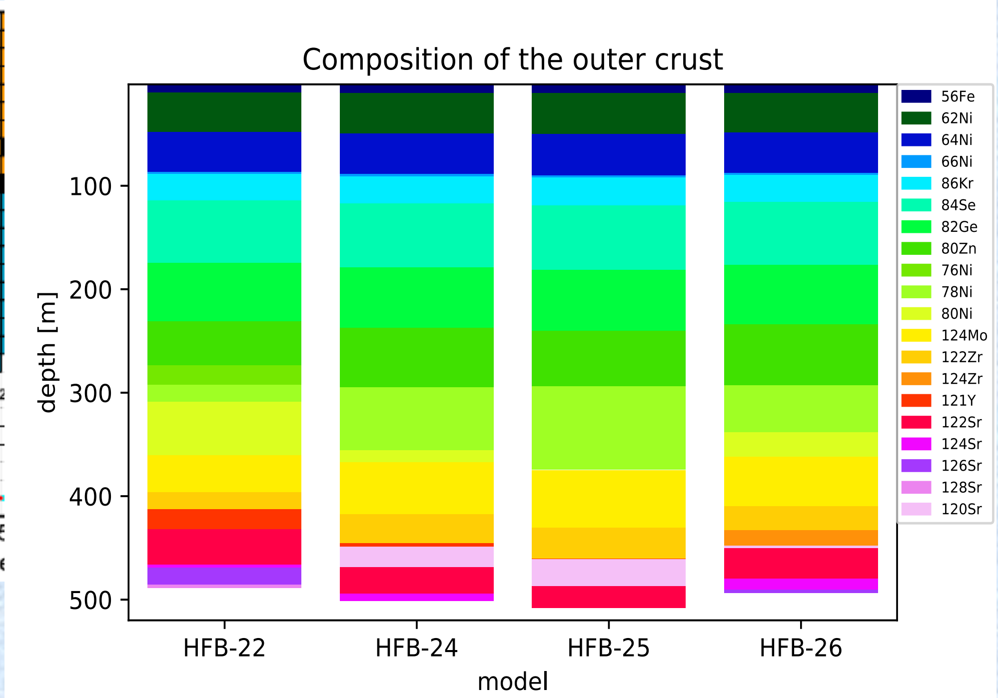

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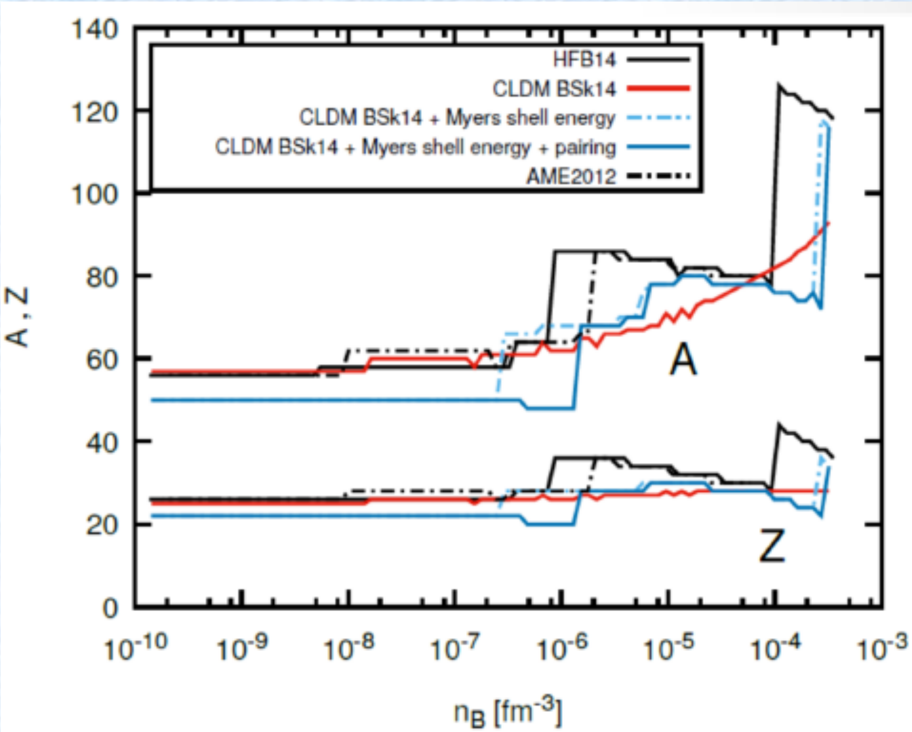
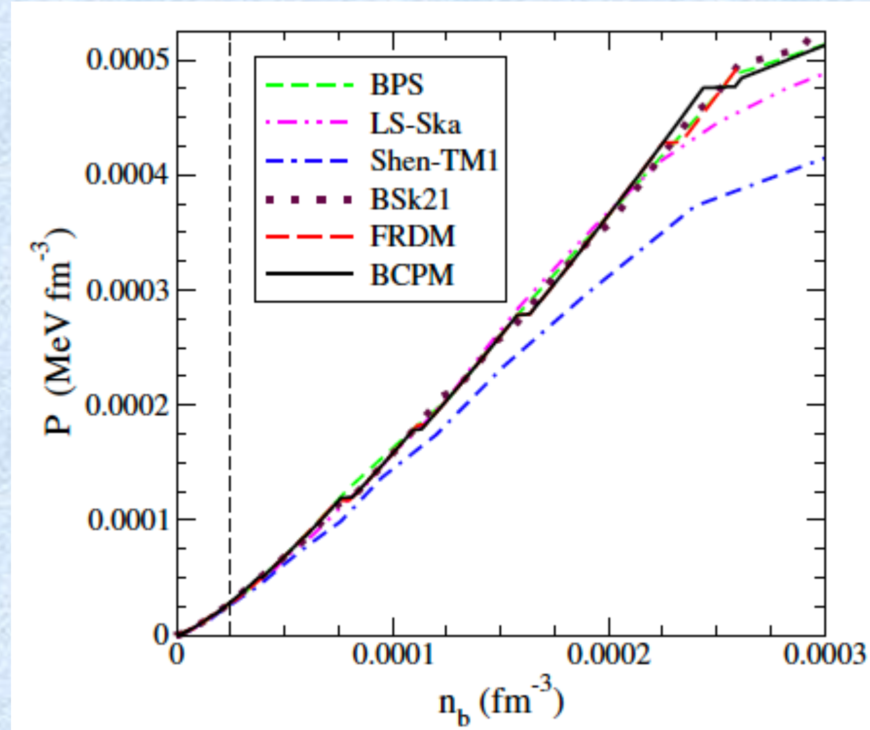
NS outer crust: composition and EoS



F. Gulminelli's talk @GMR workshop (2020)

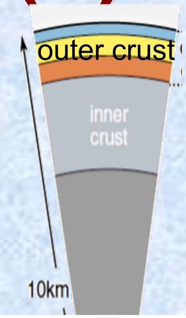


Sharma et al., A&A 584, A103 (2015)

- ➤ dependence on the many-mody method
- ➤ EoS relatively well constrained

see e.g. Haensel et al. 2007 (Springer), Oertel et al., Rev. Mod. Phys. (2017), Burgio & Fantina, ASSL 457 (2018), Blaschke & Chamel, ASSL 457, 337 (Springer, 2018) for a review and refs. therein

NS inner crust: until cc transition (1)



- Nuclei in bcc lattice + electrons + *"free" neutrons* → nuclear modelling

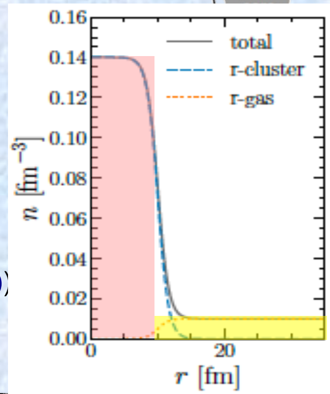
$$\epsilon_{\rm WS}(n_B) = \frac{M(A,Z)c^2}{V_{\rm WS}} + \epsilon_e(n_e) + \epsilon_{\rm Coul} + \epsilon(n_{gn}) + \epsilon_{\rm int}$$

exp./theo masses — Coulomb interaction — nucleus-gas interaction

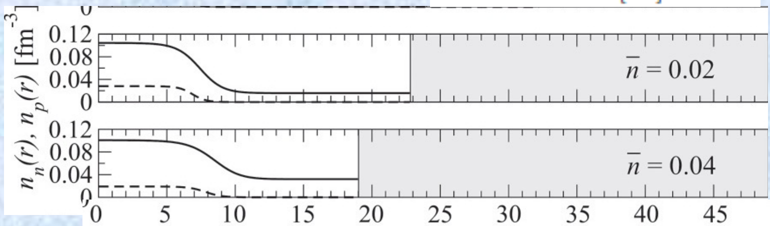
$$\epsilon_{\rm WS}(n_B) = n_n m_n c^2 + n_p m_p c^2 + \epsilon_N + \epsilon_e + \epsilon_{\rm Coul}$$

→ different methods:

1. **Compressible liquid-drop (CLD) model**
   - separation nucleons "inside"/"outside" nuclei (fig. adapted from Carreau, PhD thesis (2020))
   - nuclear energy given by sum of contribution (bulk, surface, Coulomb)

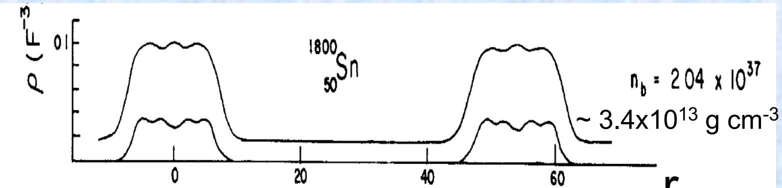


2. **(Extended) Thomas-Fermi ((E)TF)**
   - smooth density profiles
   - nuclear energy functional of density and gradients
   - consistent treatment nucleons "inside"/"outside"



Pearson et al., PRC 85, 065803 (2012)

3. **Hartree-Fock / Hartree-Fock Bogoliubov**
   - quantum calculations → independent particles/qp



Negele & Vauterin, NPA 207, 298 (1973)

 see e.g. Haensel et al. 2007 (Springer), Oertel et al., Rev. Mod. Phys. (2017), Burgio & Fantina, ASSL 457 (2018), Blaschke & Chamel, ASSL 457, 337 (Springer, 2018) for a review and refs. therein

NS inner crust: until cc transition (2)

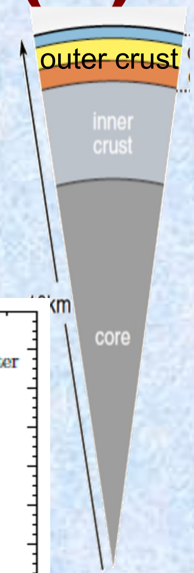
- Nuclei in bcc lattice + electrons + *"free" neutrons* → nuclear modelling

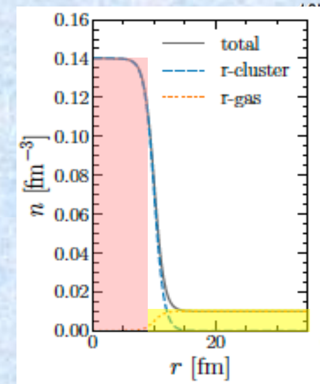
$$\epsilon_{\rm WS}(n_B) = \frac{M(A,Z)c^2}{V_{\rm WS}} + \epsilon_e(n_e) + \epsilon_{\rm Coul} + \epsilon(n_{gn}) + \epsilon_{\rm int}$$

homog. matter

→ model dependences

→ different methods : CLD, (E)TF, self-consistent mean-field





→ variational problem (beta equilibrium)

$$d\left[\epsilon_{\rm WS}(n_B) - \lambda_1\left(\frac{A_{\rm WS}}{V_{\rm WS}} - n_B\right) - \lambda_2\left(\frac{Z_{\rm WS}}{V_{\rm WS}} - n_p\right)\right] = 0$$

λ_1 and λ_2 related to μ_n, μ_p

$Z_{\rm WS} = Z$ if no free p (T=0); $n_p = n_e$

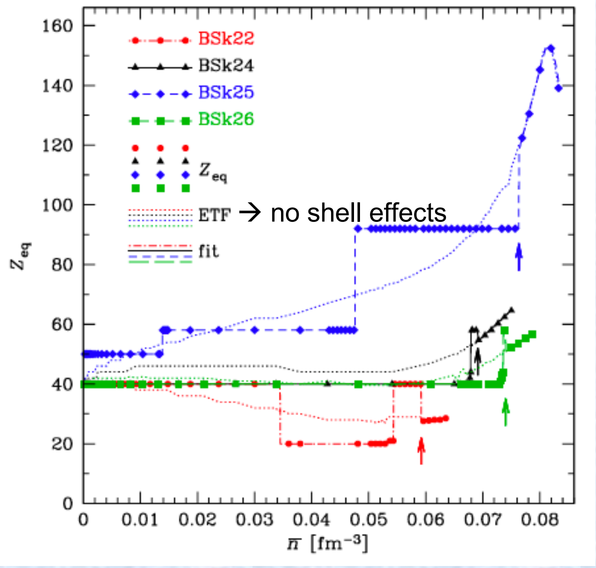
→ at each n_B, solve a system of coupled eqs.

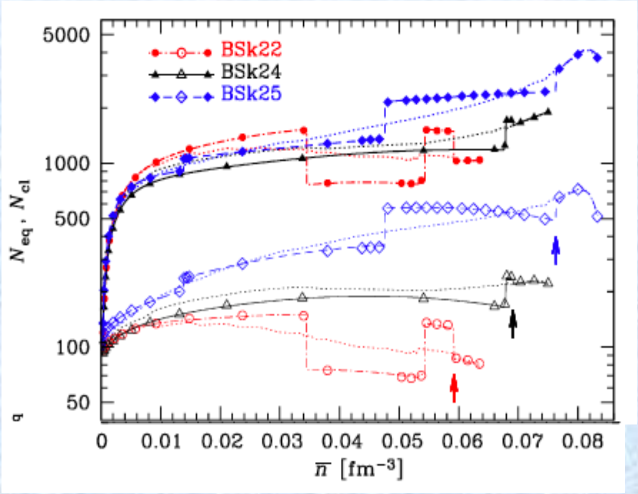
→ obtain variational variables (A,Z,$V_{\rm WS}$,n_{gn}) + shape of WS cell if pasta included

(NB: in HF, minimisation wrt wave functions)

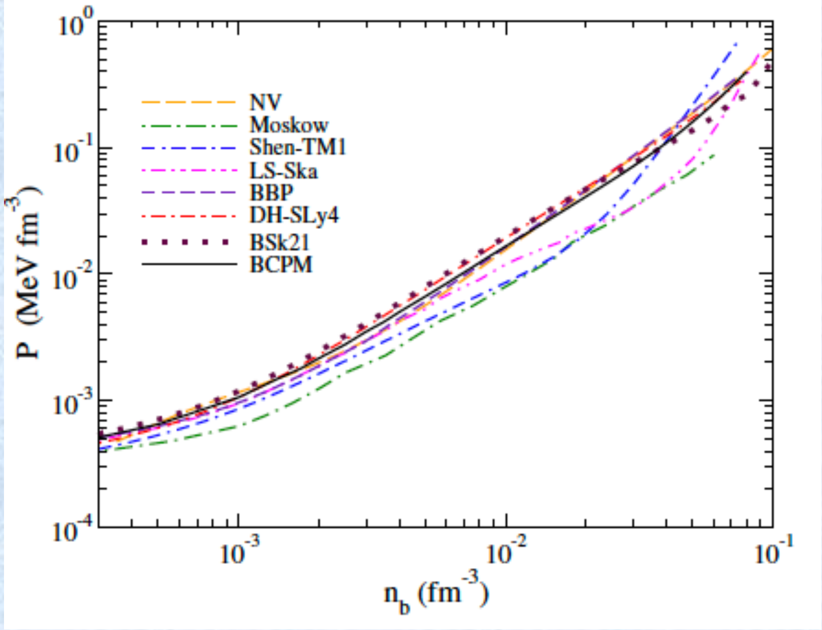
see e.g. Haensel et al. 2007 (Springer), Oertel et al., Rev. Mod. Phys. (2017), Burgio & Fantina, ASSL 457 (2018), Blaschke & Chamel, ASSL 457, 337 (Springer, 2018) for a review and refs. therein

NS inner crust: composition and EoS





Pearson et al., MNRAS 481, 2994 (2018)



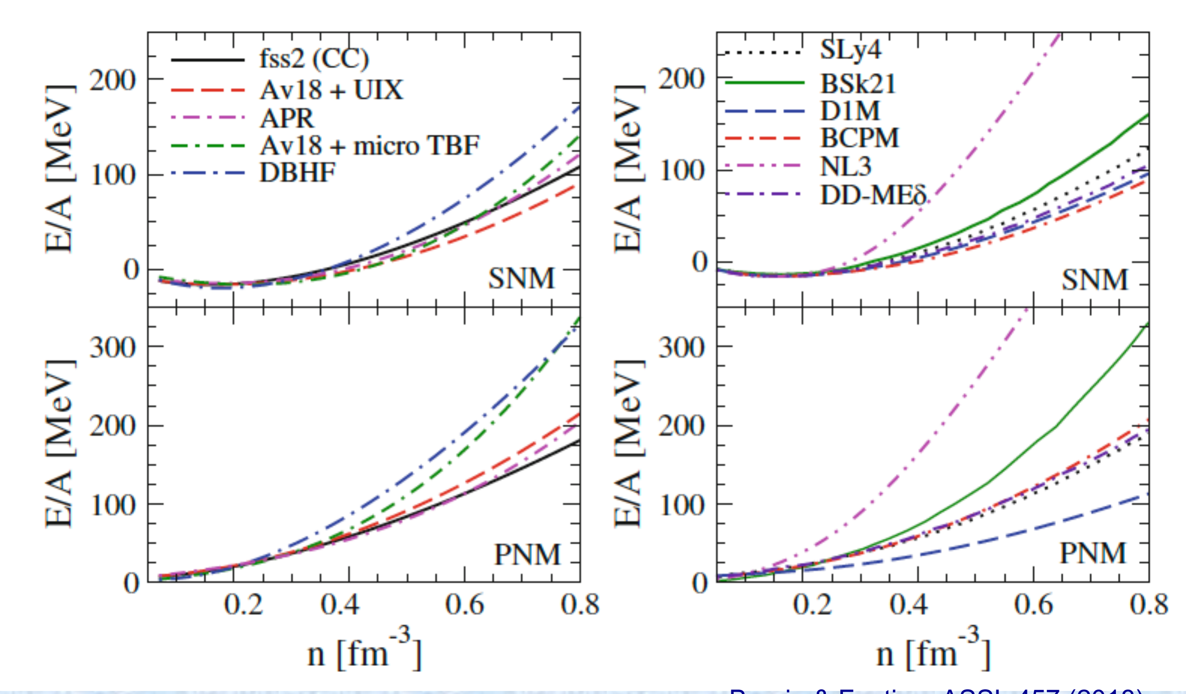
Sharma et al., A&A 584, A103 (2015)

- model-dependence in many-body method
- model-dependence in functional

see e.g. Haensel et al. 2007 (Springer), Oertel et al., Rev. Mod. Phys. (2017), Burgio & Fantina, ASSL 457 (2018), Blaschke & Chamel, ASSL 457, 337 (Springer, 2018) for a review and refs. therein

Homogeneous matter: various approaches

- **Ab-initio ("microscopic") approaches** based on quantum many-body theories from realistic nuclear interactions (variational methods, (D)BHF, chiral EFT, Monte-Carlo, Green's func., …)
  → usually restricted to homogeneous matter (core)
- **Phenomenological approaches** based on effective interactions with parameters adjusted to reproduced nuclear properties (EDF e.g. Skyrme / Gogny, meta-models, …)
  → also applicable for inhomogeneous matter (crust + core)



Burgio & Fantina, ASSL 457 (2018)

for a review see e.g. Haensel et al. 2007 (Springer), Oertel et al., Rev. Mod. Phys. (2017), Burgio & Fantina, ASSL 457 (2018); Burgio et al., Prog. Part. Nucl. Phys. 120, 103879 (2021)

Homogeneous matter: mean-field approx.

- Star is neutral → baryons + leptons (e^- and possibly μ in core); themodynamic limit

$$\epsilon_{\rm tot} = \epsilon_B + \epsilon_l$$

T = 0

- If only nucleons: (see A. Raduta's talk for "exotica")

$$e_{n,p} = \sqrt{(m^\star_{n,p}c^2)^2 + (\hbar c k)^2} + V_{n,p}(n_n, n_p)$$

$$\epsilon_B = \epsilon_n(n_n) + \epsilon_p(n_p) = \epsilon_{{\rm FG},n+p} + \epsilon(n_n, n_p)$$

Energy-density functional
→ to be determined

→ *non-relativistic functionals*: Skyrme (zero-range effective interaction), Gogny (finite-range effective interaction) with parameters constrsined by experiments but ad-hoc density dependence to mimic many-body effects

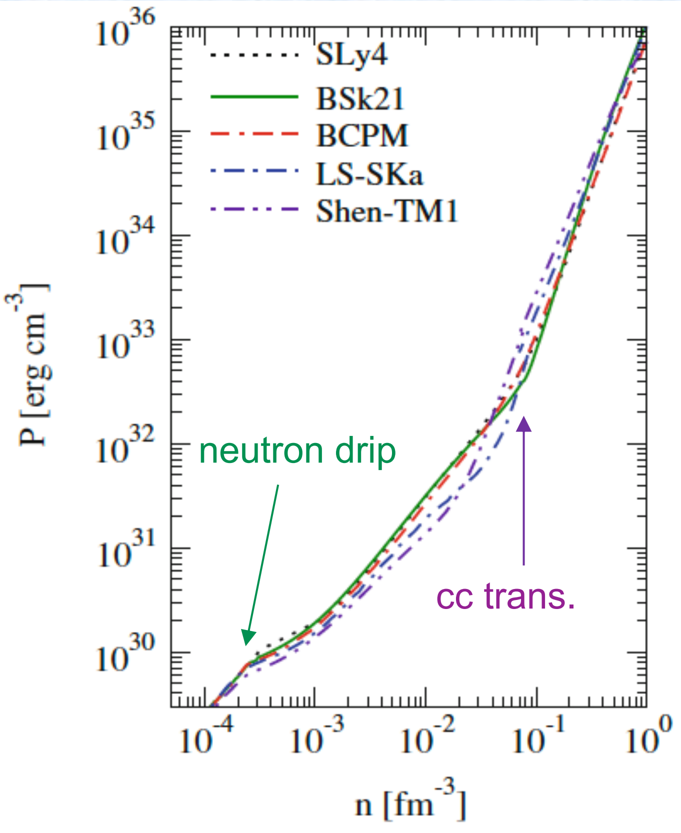
→ *relativistic mean field* (RMF) based on effective Lagrangian, but ad-hoc density dependent or non-linear couplings to mimic many-body effects

➡ a functional form has to be chosen ! Extrapolations ?

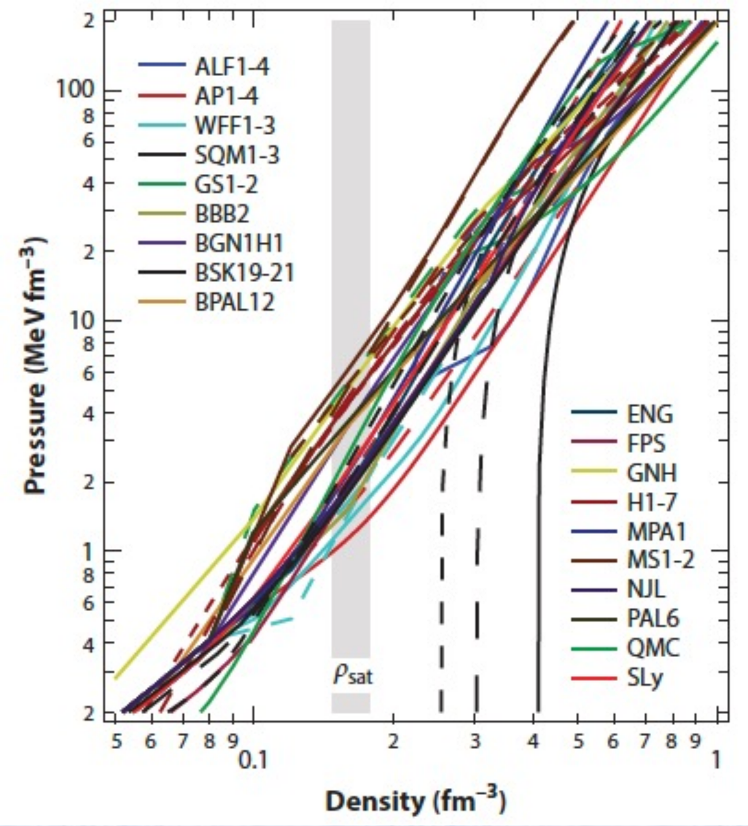
- Plus beyond mean-field: e.g., pairing

for a review see e.g. Ring & Schuck (Springer 2004), Bender et al., Rev. Mod. Phys. 75, 121 (2003), Duguet (Springer 2014), Baldo & Burgio, Rep. Prog. Phys. 75, 026301 (2012), Carlson et al., Rev. Mod. Phys. 87, 1067 (2015), Haensel et al. 2007 (Springer), Oertel et al., Rev. Mod. Phys. (2017), Burgio & Fantina, ASSL 457 (2018); Burgio et al., Prog. Part. Nucl. Phys. 120, 103879 (2021)

NS EoS: crust and core



Burgio & Fantina, ASSL 457 (2018)



Ozel & Freire, ARAA 54, 401 (2016)

- higher uncertainties in the core → uncertainties in the functional

➡ how these uncertainties propagate in NS observables ?

see e.g. Haensel et al. 2007 (Springer), Oertel et al., Rev. Mod. Phys. (2017), Burgio & Fantina, ASSL 457 (2018), Blaschke & Chamel, ASSL 457, 337 (Springer, 2018) for a review and refs. therein

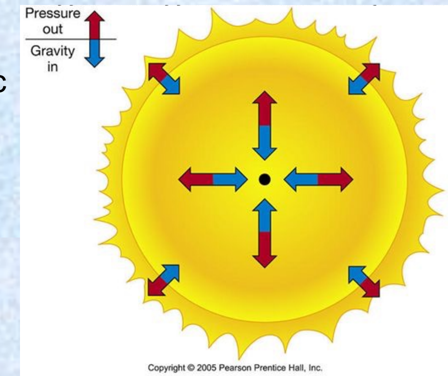
EoS ←→ NS (static) observables (1)

- **TOV → *M*(*R*)** (Tolmann 1939; Oppenheimer&Volkoff 1939; see also Haensel, Potekhin, Yakovlev, Springer 2007)

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

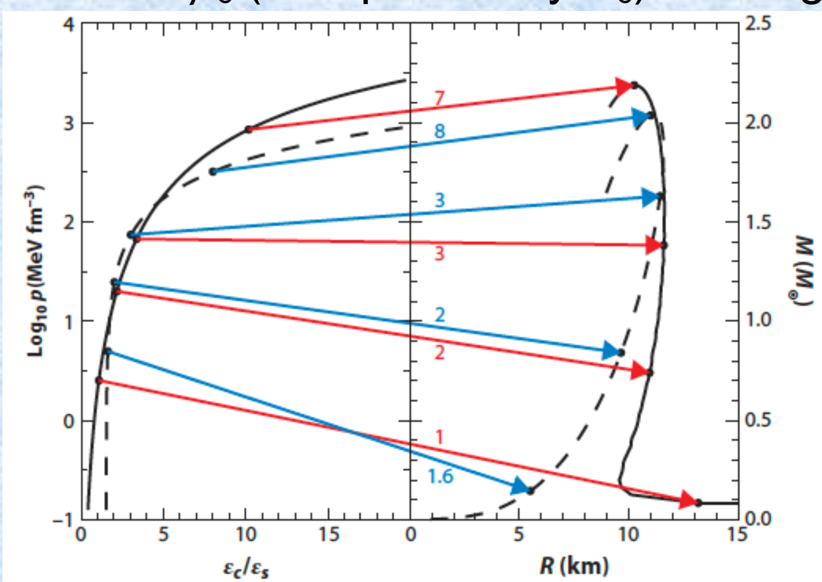
$$\mathcal{M}(r) = 4\pi\int_0^r \rho(r')r'^2\mathrm{d}r'$$

with b.c. $M(r=0) = 0$; $\rho(r=0) = \rho_c$



➡ only EoS $P(\rho)$ is needed !

➡ for each ρ_c (or equivalently P_c) → integration → R, $M(r = R)$

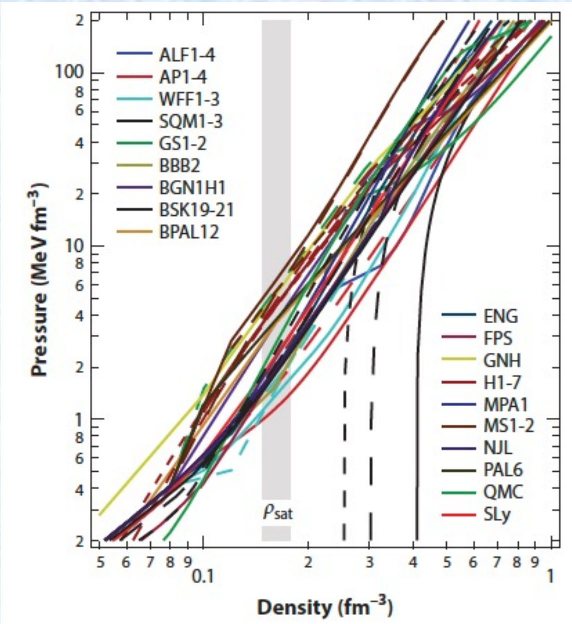


Lattimer, Annu. Rev. Part. Nucl. Sci. 62, 485 (2012)

➡ GR → one-to-one correspondence EoS ←→ NS static properties (non-rotating mature NS)

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

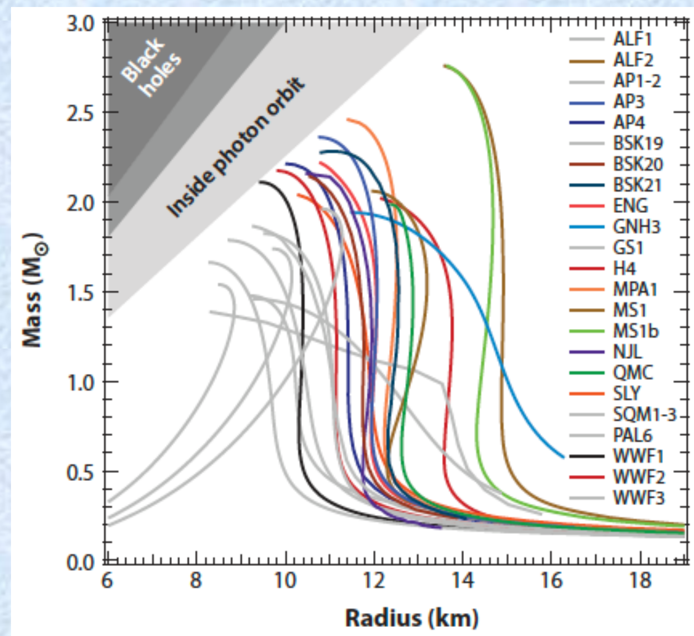
EoS ←→ NS (static) observables (2)



Ozel & Freire, ARAA 54, 401 (2016)

✓ GR → one-to-one correspondence
EoS ←→ NS static properties $M(R)$, $\Lambda(M)$…
(non-rotating mature NS)

✓ Different EoSs ←→ different NS properties
←→ different GW signals
? → trace back to EoS and composition ?



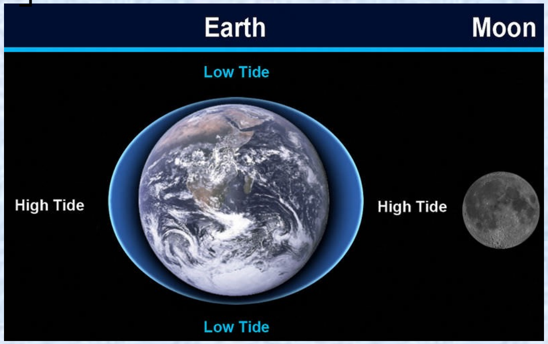
Ozel & Freire, ARAA 54, 401 (2016);
see also Burgio & Fantina, ASSL 457, 255 (2018)

<u>but</u>:
✗ EoS model dependent !
✗ <u>no</u> ab-initio dense-matter calculations in all regimes
→ phenomenological models
✗ composition ←→ EoS → $M(R)$?
✗ role of additional d.o.f. ? → see A. Raduta's talk

EoS ←→ NS (static) observables (3)

- **Influence of second body → eq. for $H(r)$ → $\Lambda(M)$, $\Lambda(R)$** (Thorne & Campolattaro 1967)

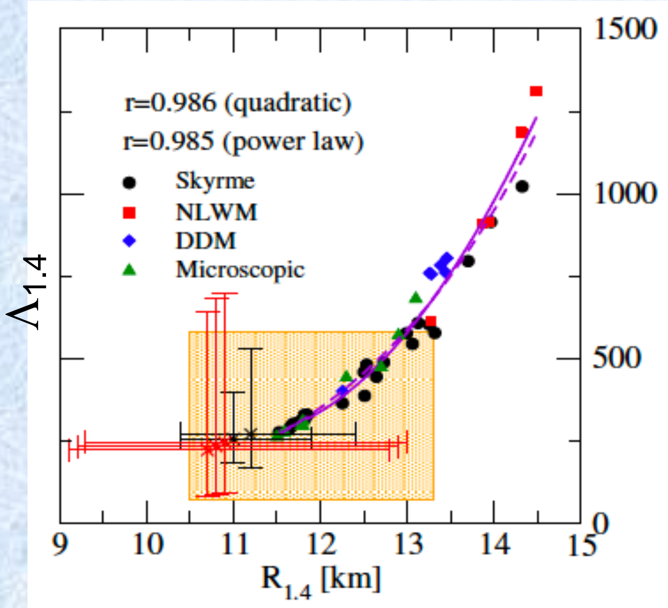
$$H''(r)+H'\left(1-\frac{2G\mathcal{M}(r)}{c^2 r}\right)^{-1}\left[\frac{2}{r}-\frac{2G\mathcal{M}(r)}{c^4}r(\rho(r)-P(r))\right]+H(r)Q(r,P(r),\rho(r))$$



with b.c. $M(r=0) = 0$; $\rho(r=0) = \rho_c$; $H(r=0) = 0$, $H'(r=0) = 0$

➡ only EoS $P(\rho)$ is needed !

➡ for each ρ_c → integration → k_2 → λ tidal response



Burgio & Vidana, Universe 6, 119 (2020)

→ **tidal polarizability** $\Lambda = \lambda(r=R) = \frac{2}{3}k_2\left(\frac{Rc^2}{GM}\right)^5$

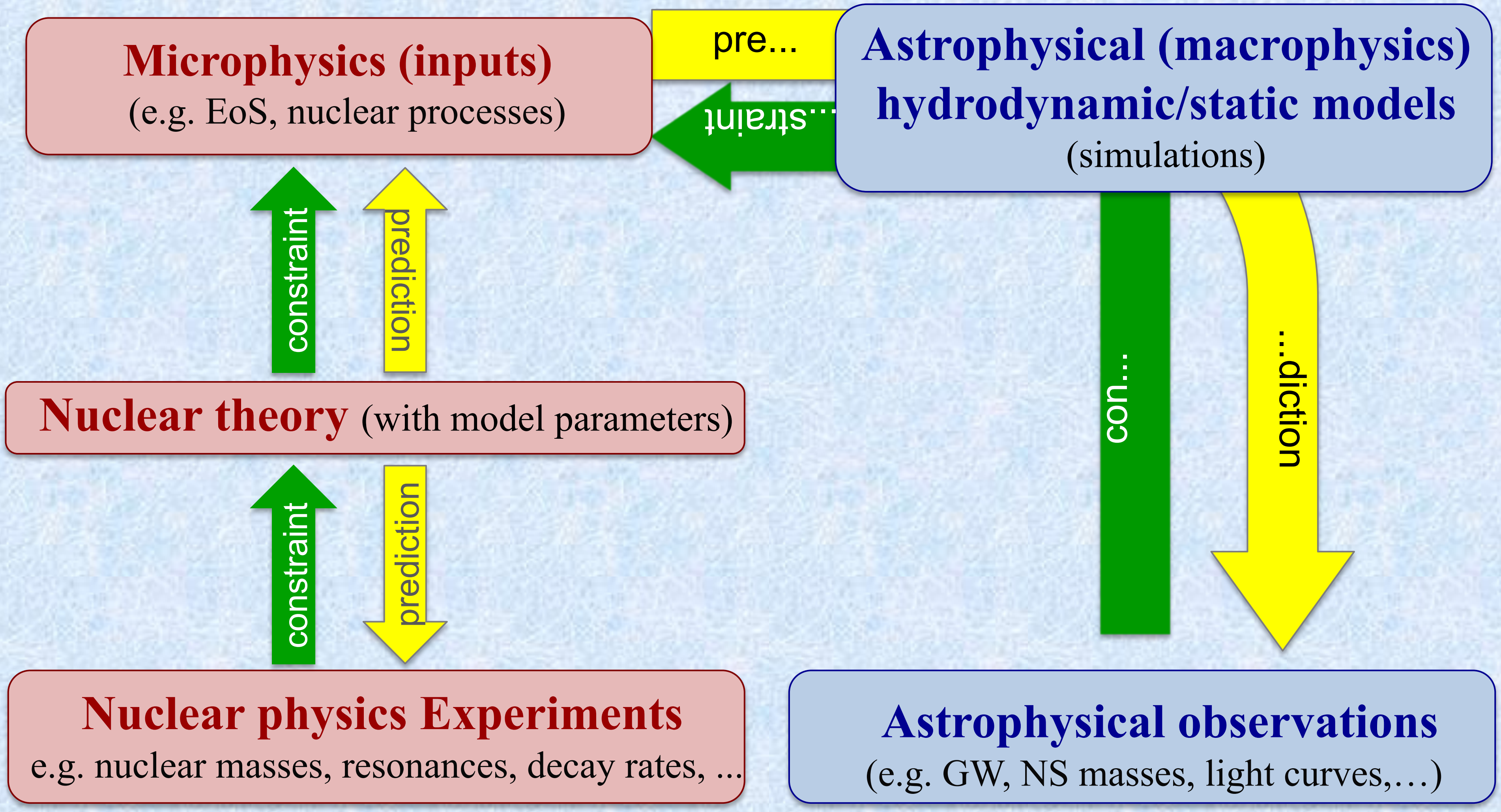
$$\tilde{\Lambda} = \frac{16}{13}\frac{(M_1+12M_2)M_1^4\Lambda_1+(M_2+12M_1)M_2^4\Lambda_2}{(M_1+M_2)^5}$$

→ can be extracted from GW signal

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

see e.g. Haensel et al. 2007 (Springer); Hinderer et al., PRD 81, 123016 (2010); Blanchet, Liv. Rev. Relat. 17, 2 (2014)

Micro to macro through modelling



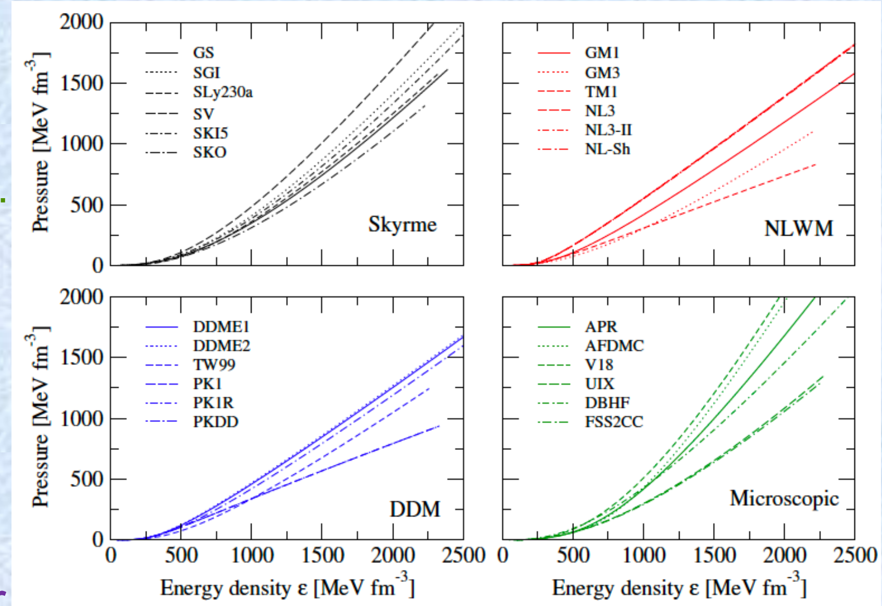
EoS modelling: different approaches

- **Ab-initio (“microscopic”) approaches**
  based on quantum many-body theories from realistic nuclear interactions (variational methods, (D)BHF, chiral EFT, Monte-Carlo, Green’s func., …
  → usually restricted to homogeneous matter (core)

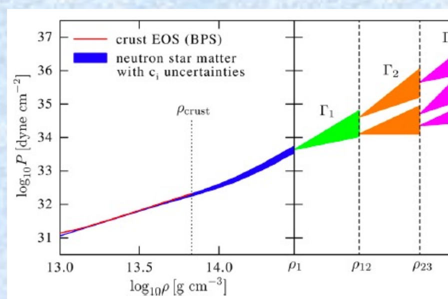
- **Phenomenological approaches**
  based on effective interactions with parameters adjusted to reproduced nuclear properties (EDF e.g. Skyrme/Gogny, meta-models, …)
  → also applicable for inhomogeneous matter (crust + core)

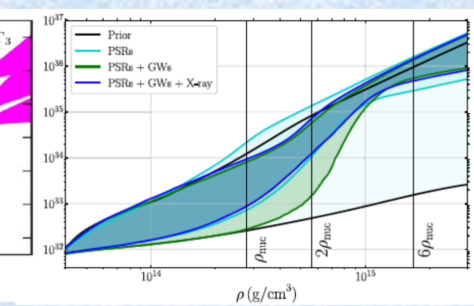
- **Agnostic (non-parametric) approaches**
  - Piecewise polytropes (PP)
  - Speed-of-sound models (CSM)
  - Spectral functions (SF)
  - Gaussian processes (GP)

  → but what about info on composition?



Burgio & Vidana, Universe 6, 119 (2020)





Hebeler et al., ApJ 773, 11 (2013)   Landry et al. PRD 101, 123007 (2020)

for a review see e.g. Haensel et al. 2007 (Springer), Oertel et al., Rev. Mod. Phys. (2017), Burgio & Fantina, ASSL 457 (2018)
Agnostic approaches, e.g. PP: Reed et al. PRD 2009, Hebeler et al. ApJ 2013, Annala et al. PRL 2018, …; CSM: Tews et al. ApJ 2018, Tan et al. PRL 2020; Somasundaram et al., PRC 2023; SF: Lindblom 2010, Lindblom & Indik 2014, …; GP: Landry et al. PRD 2020, Essick et al. PRD 2020; Legred et al. PRD 2021, PRD 2022, …

A choice: meta-model (nucleons)

- **Meta-model** approach for nucleons : flexible functional ("quasi" agnostic)

  → expansion in density and asymmetry around n_{sat} and $\delta = 0$ (with m^*_q included)

$$\epsilon_B(n) \approx n\,(e_B(n,\delta=0) + e_{\rm sym}(n)\delta^2)$$

$$\approx n \sum_{m=0}^{4} \frac{1}{m!} \left(\left.\frac{d^m e_{\rm sat}}{dx^m}\right|_{x=0} + \left.\frac{d^m e_{\rm sym}}{dx^m}\right|_{x=0} \delta^2 \right) x^m$$

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

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

Empirical parameters (bulk) $\boldsymbol{X}_{\rm sat,sym}$ = E_{sat}, K_{sat}, Q_{sat}, E_{sym}, L_{sym}, K_{sym}, …

$$E_{\rm sat} = e_{\rm sat}$$

$$K_{\rm sat} = 9n_{\rm sat}^2 \left.\frac{d^2 e_{\rm sat}}{dx^2}\right|_{n=n_{\rm sat},\delta=0}$$

$$Q_{\rm sat} = 27n_{\rm sat}^3 \left.\frac{d^3 e_{\rm sat}}{dx^3}\right|_{n=n_{\rm sat},\delta=0}$$

…

$$E_{\rm sym} = J = e_{\rm sym}$$

$$L_{\rm sym} = 3n_{\rm sat} \left.\frac{de_{\rm sym}}{dx}\right|_{n=n_{\rm sat},\delta=0}$$

$$K_{\rm sym} = 9n_{\rm sat}^2 \left.\frac{d^2 e_{\rm sym}}{dx^2}\right|_{n=n_{\rm sat},\delta=0}$$

$$Q_{\rm sym} = 27n_{\rm sat}^3 \left.\frac{d^3 e_{\rm sym}}{dx^3}\right|_{n=n_{\rm sat},\delta=0}$$

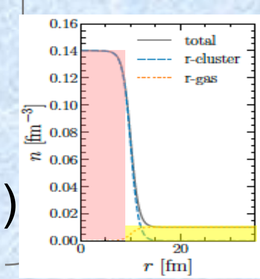
…

~ 15 – 20 parameters

- If one wants to model the crust → + surface and Coulomb term (CLDM)

  → surface parameters

  (plus some additional modifications: *m**, low-density corrections, …)



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), …

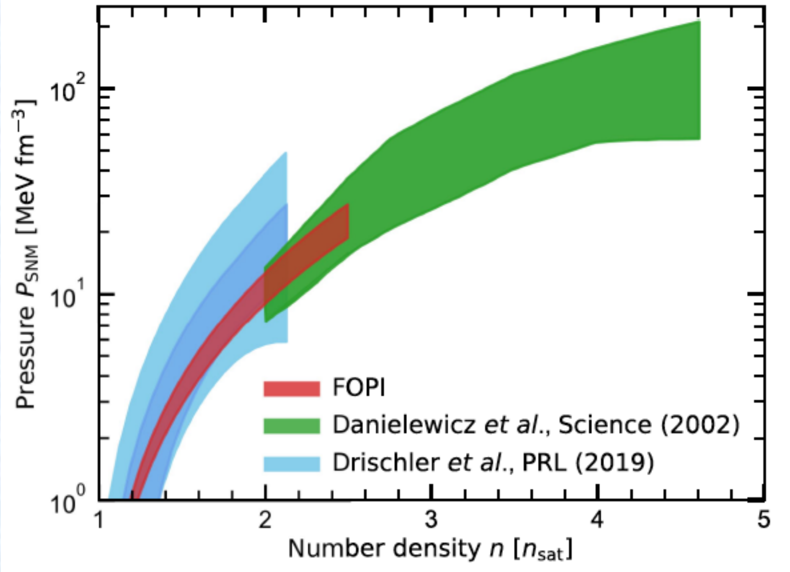
see also M. Jakobs' poster

How can we get constraints?

Nuclear physics exp./ theory

- Measure of **nuclear properties:**
  - masses and radii of nuclei
  - collective modes, polarizability
  - neutron skins, HIC, flows
  etc …
- **ab-initio calculations**

→ **“low” density** (better in nucleonic sector)

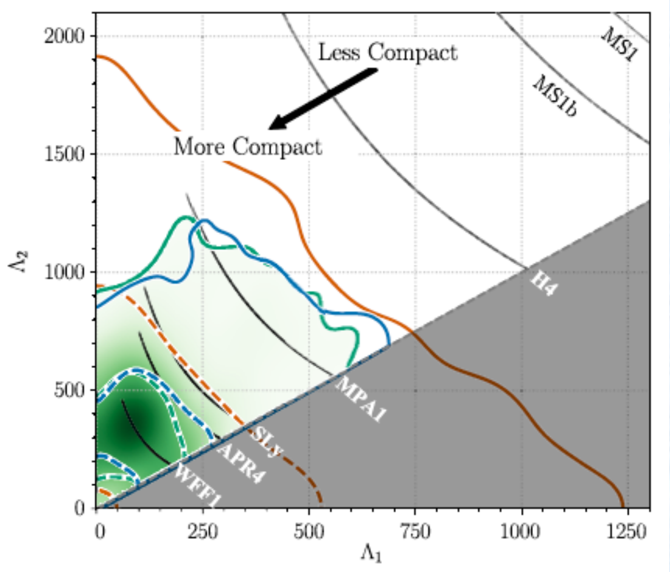


Huth et al., Nature 606, 276 (2022)

Astrophysical observations

- Measure of **NS properties:**
  - NS masses and radii
  - rotational frequency, oscillation modes
  - cooling, moment of inertia
  etc …
- **Gravitational waves**

→ **“high” density**



Abbott et al., PRL 121, 161101 (2018)

see A. Raduta’s talk for astro constraints

How can we get constraints?

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- Measure of **nuclear properties:**
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Astrophysical observations

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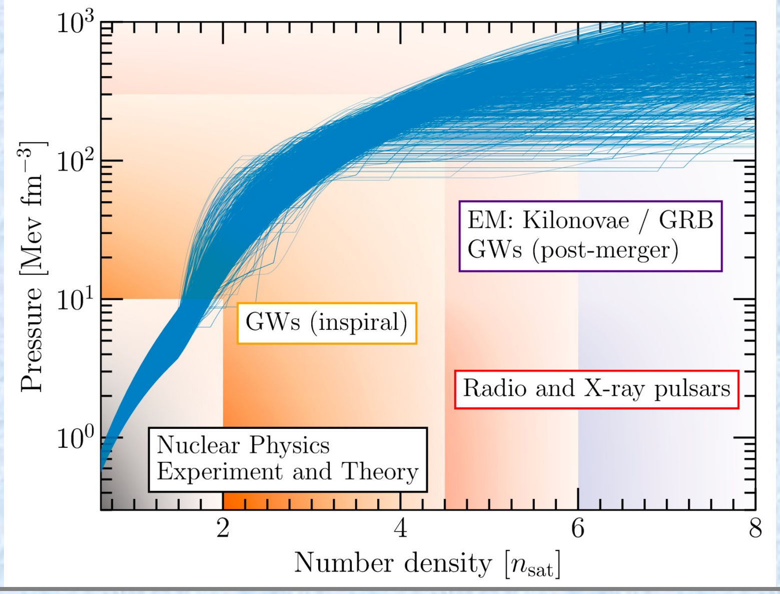
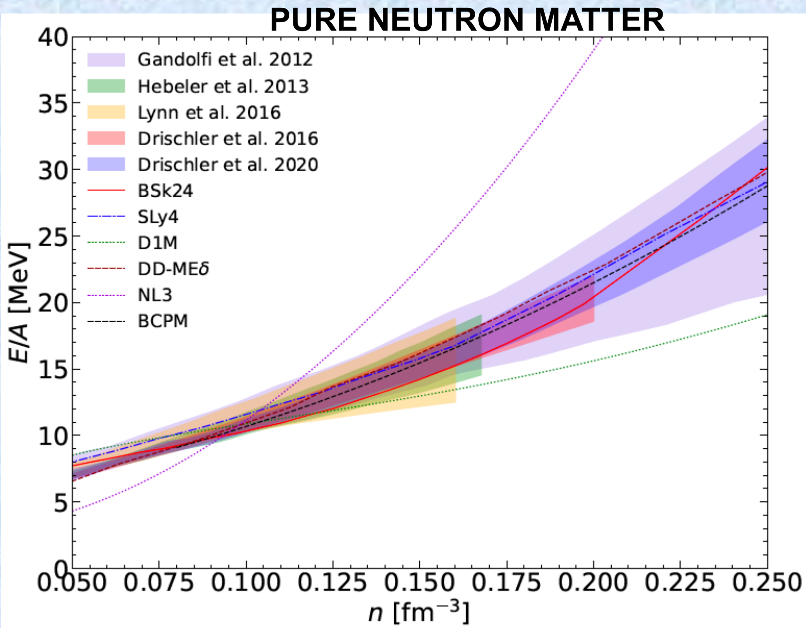


N.B.: rectangles only qualitative,
→ EoS dependence !

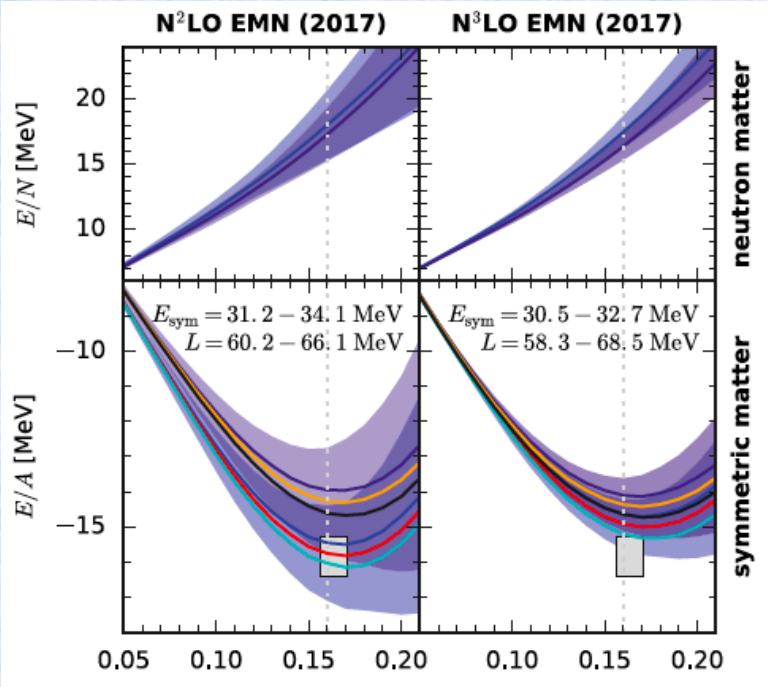
Pang et al., arXiv:2205.08513 (2022)

see A. Raduta’s talk for astro constraints

Constraints from nucl. phys.: theo



Fantina & Gulminelli, J.Phys. Conf. Ser. (submitted 2022);
see also Oertel et al., Rev. Mod. Phys. 89, 015007 (2017)



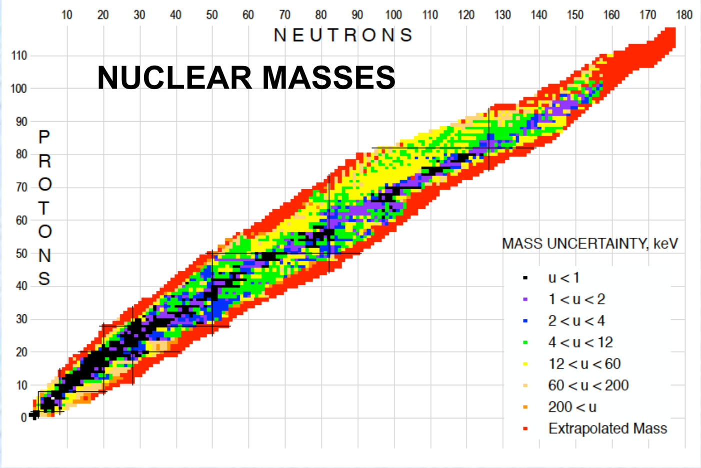
Drischler et al., PPNP 121, 103888 (2021)

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

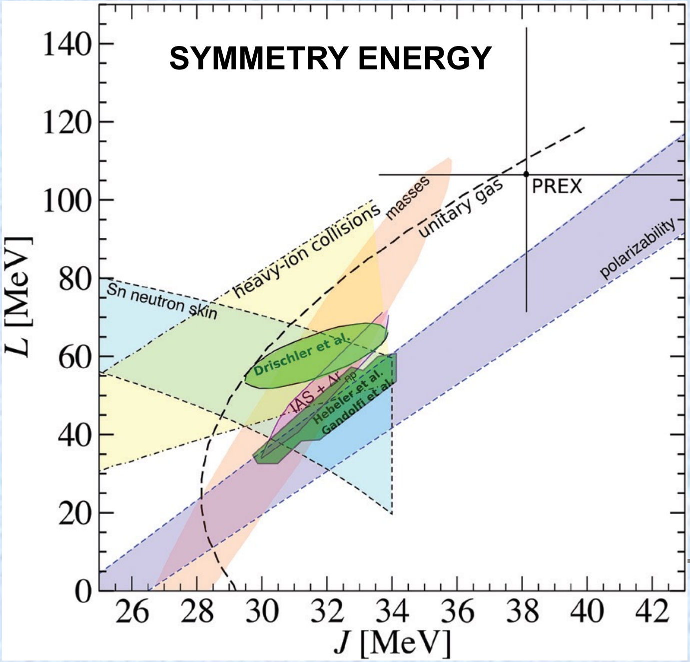
→ Reasonable agreement of ab-initio (PNM) up to ~ saturation density
→ PNM calculations benchmark for phenomenological models

N.B.: for symmetric matter (ab-initio): (i) saturation point difficult to obtain ; (ii) larger uncertainties ; (iii) cluster formation at subsaturation

Constraints from nucl. phys.: exp (1)



Kondev et al., Chin. Phys. C 45, 030001 (2021)

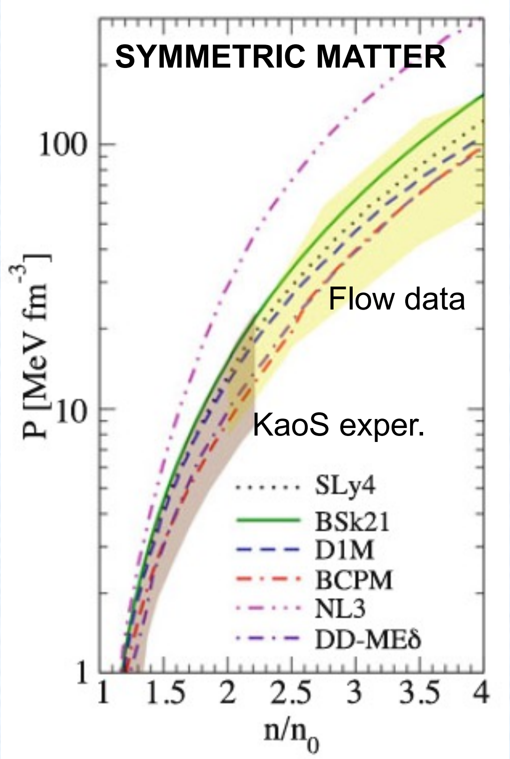


Gulminelli & Fantina, Nucl. Phys. News 31, 9 (2021)

→ Constraints at "low" densities
  → low-order parameters

→ Constraints more on "symmetric" matter

→ Not always "clear" constraints
  → "tension"



Burgio & Fantina, ASSL 457, 255 (2018)
(Flow: Danielewicz et al., Science 2002
KaoS: Lynch et al., PPNP 2009)

N.B.: deduced constraints are often *not* raw data, but combined with models
→ model dependence of constraints !

Constraints from nucl. phys.: exp (2)

Model	Ref.	E_{sat} (MeV)	n_{sat} (fm^{-3})	K_{sat} (MeV)	E_{sym} (MeV)
El. scatt.	Wang-99 [55]		0.1607	235 ±15	
LDM	Myers-66 [56]	−15.677	0.136[a]	295	28.06
LDM	Royer-08 [57]	−15.5704	0.133[a]		23.45
LSD	Pomorski-03 [58]	−15.492	0.142[a]		28.82
DM	Myers-77 [59]	−15.96	0.145[a]	240	36.8
FRDM	Buchinger-01 [60]		0.157 ±0.004		
INM	Satpathy-99 [61]	−16.108	0.1620	288 ±20	
DF-Skyrme	Tondeur-86 [62]		0.158		
DF-Skyrme	Klupfel-09 [63]	−15.91 ±0.06	0.1610 ±0.0013	222 ±8	30.7 ±1.4
DF-BSK2	Goriely-02 [64]	−15.79	0.1575	234	28.0
DF-BSK24, 28,29	Goriely-15 [65]	−16.045 ±0.005	0.1575 ±0.0004	245	30.0
DF-Skyrme	McDonnell-15 [66]	−15.75 ±0.25	0.160 ±0.005	220 ±20	29 ±1
DF-NLRMF	NL3* [67]	−16.3	0.15	258	38.7
DF-NLRMF	PK [68]	−16.27	0.148	283	37.7
DF-DDRMF	DDME1,2 [69,70]	−16.17 ±0.03	0.152 ±0.00	247 ±3	32.7 ±0.4
DF-DDRMF	PK [68]	16.27	0.150	262	36.8
Present Estimation		−15.8 ±0.3	0.155 ±0.005	230 ±20	32 ±2

Model	Ref.	Q_{sat} (MeV)	L_{sym} (MeV)	K_{sym} (MeV)	K_{τ} (MeV)
DF-Skyrme	Berdichevsky-88 [71]	30	0		
DF-Skyrme	Farine-97 [72]	–700 ±500			
DF-Skyrme	Alam-14 [31]	–344 ±46	65 ±14	–23 ±73	–322 ±34
DF-Skyrme	McDonnell-15 [66]		40 ±20		
DF-NLRMF	NL3* [67]	124	123	106	–690
DF-NLRMF	PK [68]	–25	116	55	–630
DF-DDRMF	DDME1,2 [69,70]	400 ±80	53 ±3	–94 ±7	–500 ±7
DF-DDRMF	PK [68]	–119	79.5	–50	–491
Correlation	Centelles-09 [73]		70 ±40		–425 ±175
DF-RPA	Carbone-10 [74]		60 ±30		
Correlation	Danielewicz-14 [75]		53 ±20		
Correlation	Newton-14 [76]		70 ±40		
Correlation	Lattimer-14 [77]		53 ±20		
GMR	Sagawa-07 [78]				–500 ±50
GMR	Patel-14 [79]				–550 ±100
Present Estimation		300 ±400	60 ±15	–100 ±100	–400 ±100

Margueron et al., PRC 97, 025805 (2018)
see also Stone et al., PRC 89, 044316 (2014)

N.B.: parameter estimation from various analysis of experimental data
→ but through different models
→ not straightforward nor unambiguous extraction

Bayesian study

- Explore many models ! → One can vary parameters (independently)

  Empirical parameters (bulk) $\boldsymbol{X}_{\text{sat,sym}} = E_{\text{sat}}, K_{\text{sat}}, Q_{\text{sat}}, E_{\text{sym}}, L_{\text{sym}}, K_{\text{sym}}, \ldots$

$$\text{prob}(\text{hp}|\text{data}) \propto \text{prob}(\text{hp}) \times \text{prob}(\text{data}|\text{hp})$$

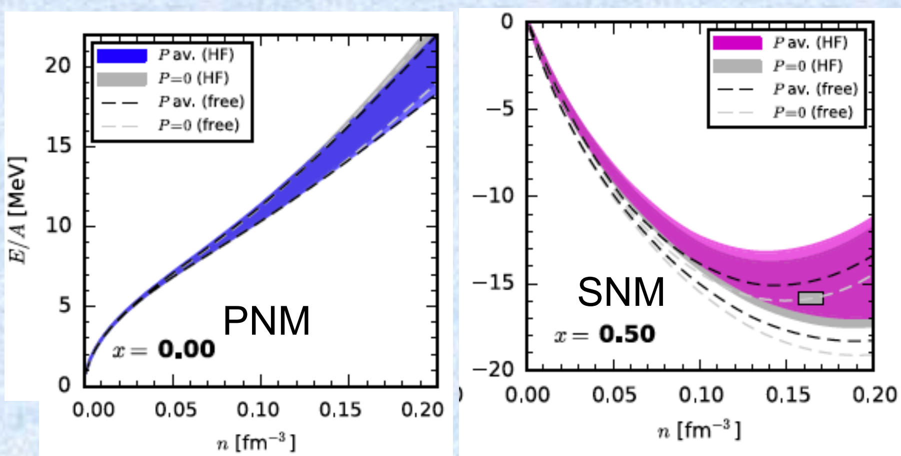
$$p_{\text{post}}(\vec{X}) = \mathcal{N}\, p_{\text{prior}}(\vec{X})\, e^{-\chi^2(\vec{X})/2}\, w_{\text{LD}}(\vec{X})\, w_{\text{HD}}(\vec{X})$$

flat non-informative prior
→ span large parameter space

nuclear masses
(AME2016, AME2020)
→ surf. param.

High-Density filters
→ causality, stability,
$M_{\text{NS,max}}$, $e_{\text{sym}} > 0$
(NICER, tidal from GW)

Low-Density filters
→ ab-initio (EFT)
(e.g. Drischler et al,
PRC 93, 054316 (2016))



Drischler et al, PRC 93, 054316 (2016)

see also M. Beznogov's talk

Crustal properties and correlations

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

n_{CC}

	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	p
LD+HD ($n \geq 0.02$ fm^{-3})	-0.04	-0.07	0.11	-0.05	-0.02	-0.30	-0.57	-0.15	0.45	-0.15	0.05	0.52	-0.15	-0.04	0.51
LD+HD ($n \geq 0.1$ fm^{-3})	-0.06	-0.06	0.33	-0.46	0.17	-0.15	-0.29	-0.10	0.39	-0.16	0.06	0.34	-0.11	-0.08	0.33
Prior	0.14	0.09	0.13	-0.18	0.02	0.08	-0.56	0.11	0.20	-0.05	-0.17	0.07	0.29	0.18	0.18

P_{CC}

	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	p
LD+HD ($n \geq 0.02$ fm^{-3})	-0.05	-0.03	0.08	-0.04	-0.02	-0.08	-0.53	-0.30	0.34	-0.07	0.04	0.47	-0.04	-0.03	0.52
LD+HD ($n \geq 0.1$ fm^{-3})	-0.05	-0.06	0.27	-0.34	0.12	0.02	-0.31	-0.41	0.45	-0.16	0.05	0.19	-0.03	-0.07	0.22
Prior	0.10	0.00	0.08	-0.06	0.02	0.22	-0.06	-0.44	0.42	-0.07	-0.13	-0.07	0.23	0.11	0.10

bulk surface

CRUST-CORE TRANSITION

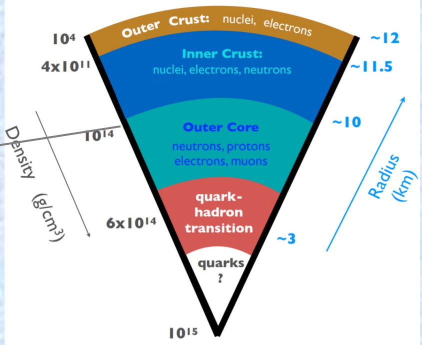


Image Credit: 3G Science White Paper

CRUSTAL MOMENT OF INERTIA

Carreau et al., PRC 100, 055803 (2019)

$I_{crust,1.4} / I_{1.4}$

	n_{sat}	E_{sat}	K_{sat}	Q_{sat}	Z_{sat}	E_{sym}	L_{sym}	K_{sym}	Q_{sym}	Z_{sym}	m^*/m	$\Delta m^*/m$	b	p	σ_0	b_s
LD p=3	0.01	-0.05	0.20	-0.06	-0.06	-0.24	-0.38	0.42	0.77	-0.32	0.00	0.07	-0.04	0.00	0.04	0.19
HD p=3	-0.03	0.24	0.26	-0.22	0.07	0.26	-0.08	-0.33	0.46	-0.10	-0.03	0.04	-0.10	0.00	-0.23	-0.02
LD	0.04	-0.21	0.16	-0.05	-0.04	-0.09	-0.23	0.26	0.52	-0.20	-0.01	0.04	-0.02	0.56	0.46	0.58
HD	-0.02	0.14	0.24	-0.21	0.08	0.25	-0.08	-0.31	0.42	-0.09	-0.02	0.04	-0.09	0.25	-0.09	0.18
Prior	0.02	0.12	0.21	-0.11	0.03	0.25	-0.03	-0.46	0.48	-0.11	-0.04	-0.14	-0.15	0.11	-0.08	0.10

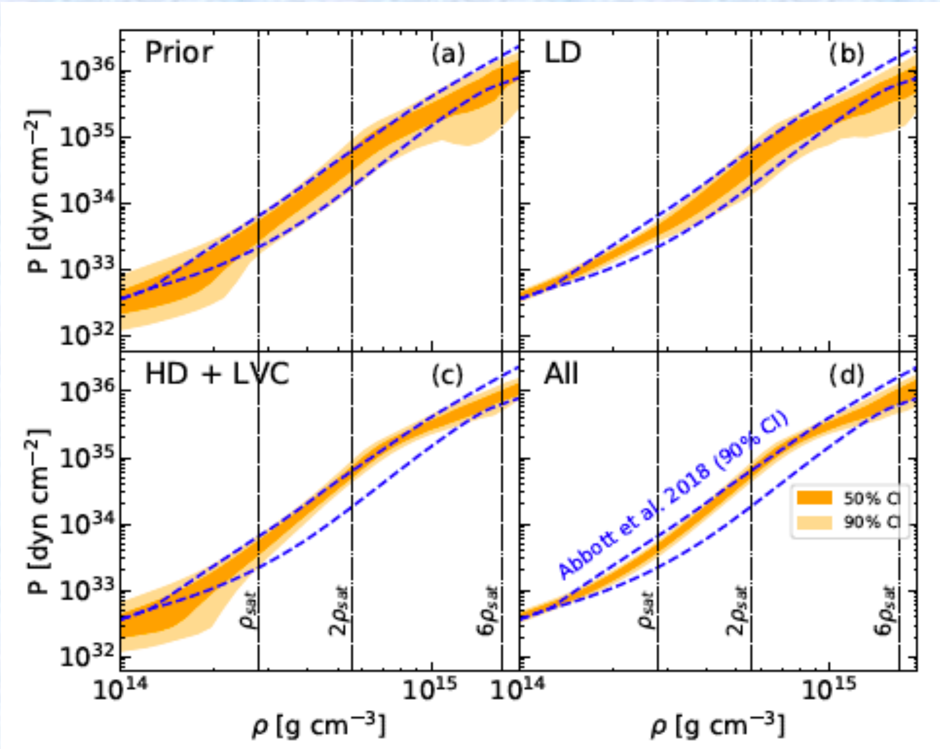
bulk surface

→ importance of parameters (both *bulk* and *surface*) on observables

→ importance of higher-order parameters

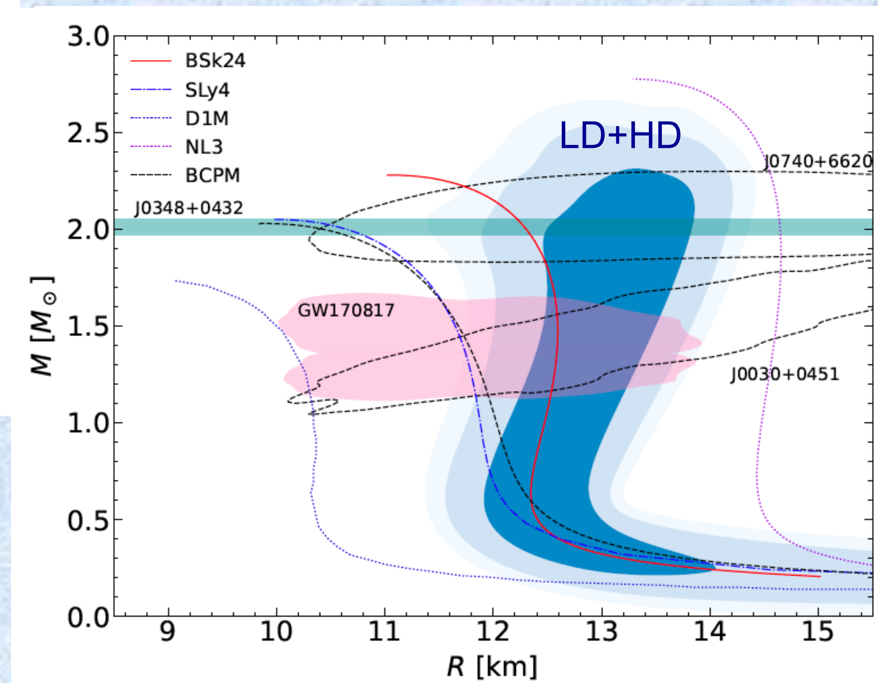
see also Balliet et al., ApJ 918, 79 (2021)

EoS : effect of LD/HD constraints



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

LD (EFT calc.) → low-density (nucl.phys.)
HD → high-density (astro)
(causality, M_{max}, NICER, GW)



Fantina & Gulminelli, submitted,
see also Dinh Thi et al., A&A 654, A114 (2021)

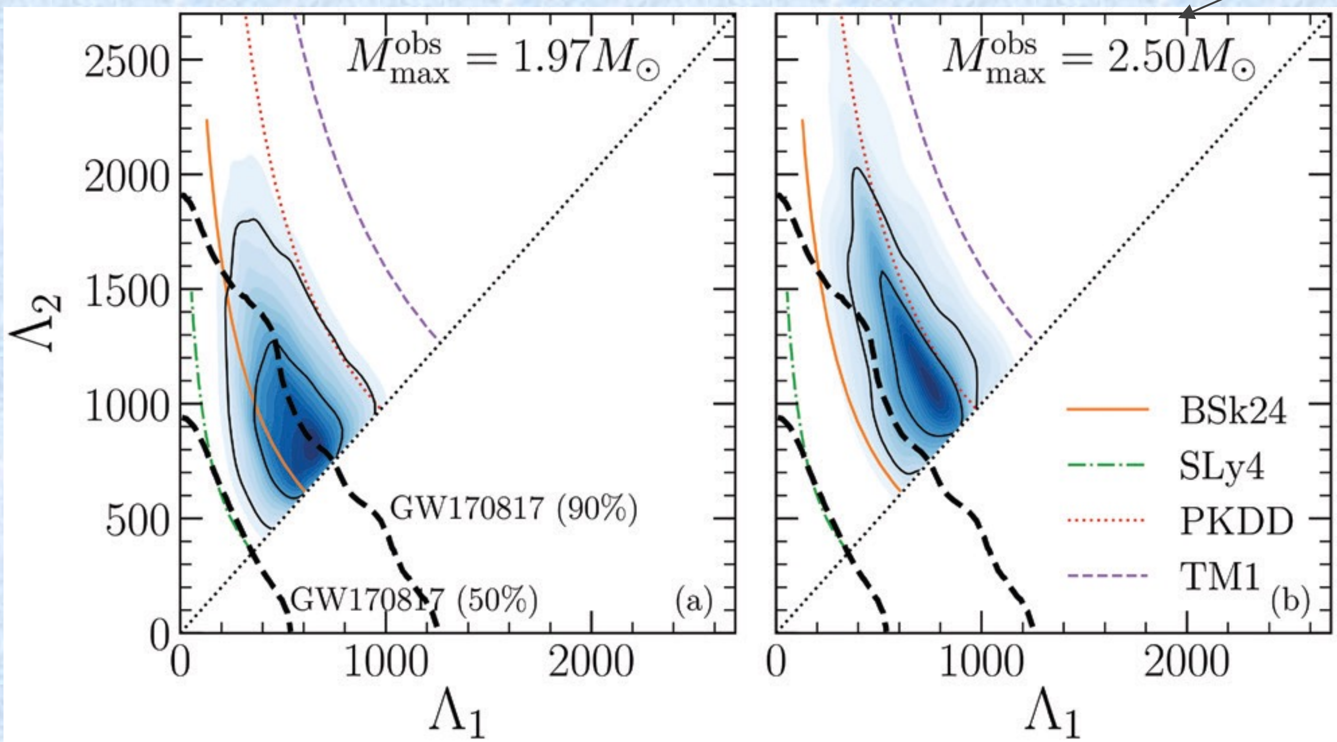
→ filters reduce uncertainties
→ posterior compatible with observations
but: some popular models are not !

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

How to discriminate models ? (1)

- "Smoking gun" observation

GW190426 ?

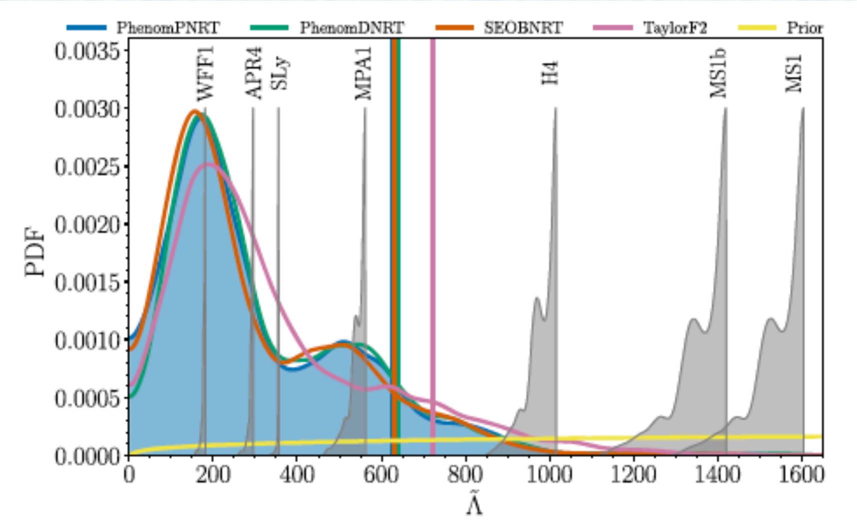


Gulminelli & Fantina, Nucl. Phys. News 31, 2 (2021); T. Carreau, PhD Thesis (2020)

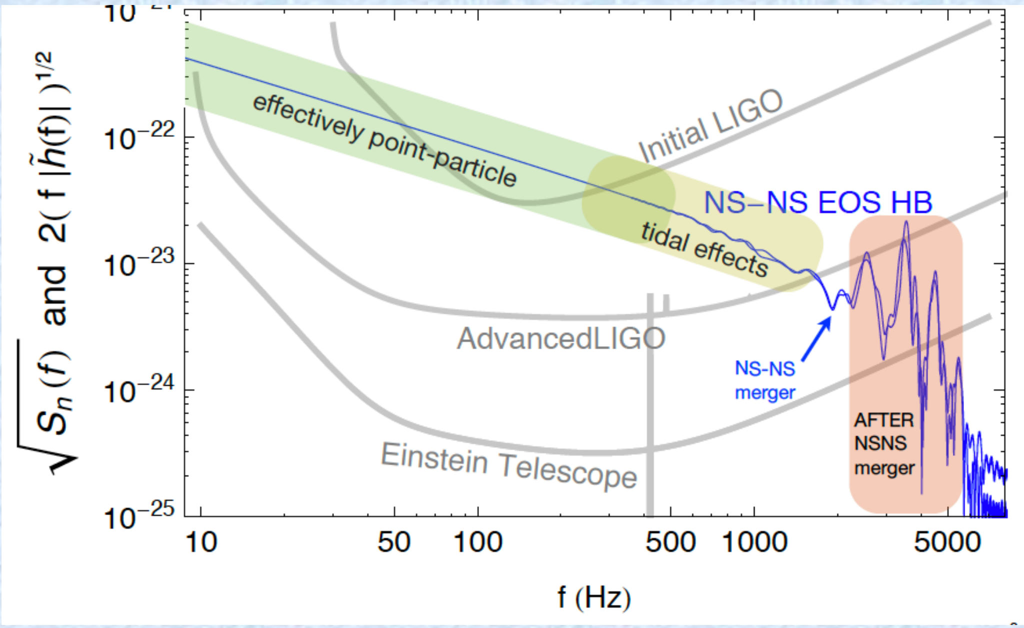
→ posterior (nucleonic matter) compatible with observations
but: if M_{max} ~ 2.5 M_{sun} → challenge for nucleonic hypothesis ! → exotica !
→ meta-model (nucleonic) can be used as null hp

How to discriminate models ? (2)

- More precise determination of observables (e.g. Λ)
- More sensitive detectors → new generation (e.g. ET)



Abbott et al., Phys. Rev. X 9, 011001 (2019)



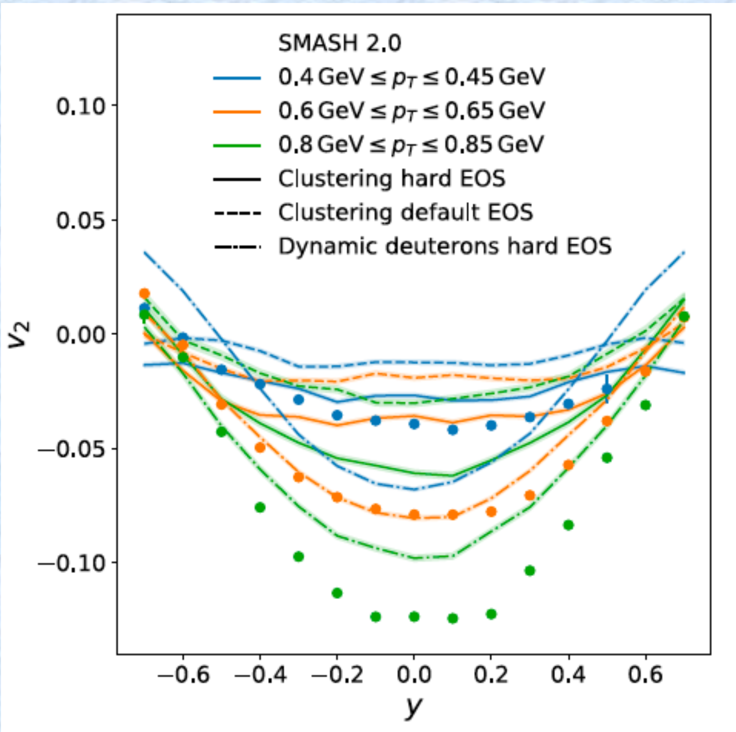
current constraint: $\tilde{\Lambda}$ ~ [0-800]

Read, CGWAS lecture (2015)

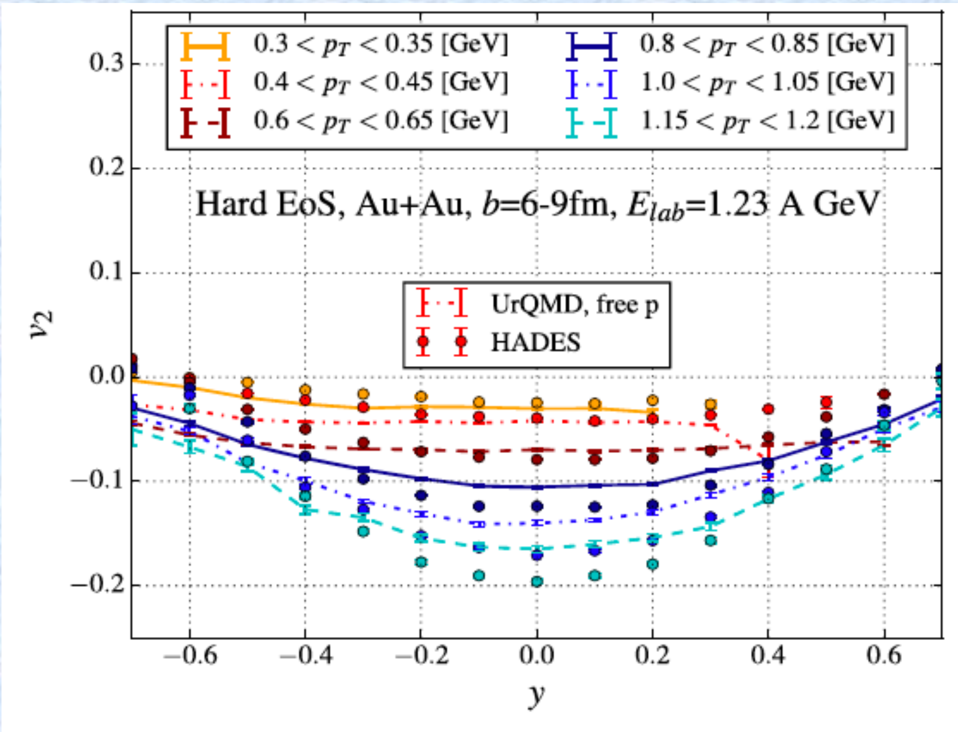
How to discriminate models ? (3)

- More constraints from nuclear physics at high density (~ 2 n_{sat})

  → e.g. HADES collaboration; elliptic flow: transport model vs data



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



Hillman et al., J. Phys. G 47, 055101 (2020)

Conclusions & open questions

❖ Nuclear inputs needed for neutron-star modelling
→ extrapolations of data & theoretical models needed

❖ Nuclear physics + astrophysics → constraints on EoS

❖ Uncertainties in nuclear data → impact astro observables

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

- Extrapolation from raw data → **model dependence of the constraints**

- Lab. exper. mostly "low" density (~ saturation density), low *T* probed; matter in astro sites different from lab → **extrapolation to astro conditions (high *T* and density, asymmetry, charge neutral) ?**

- Astro simulations vs microphysics inputs → **uncertainties in nuclear / astro**, **consistency of inputs** and relative **effects of microphysics inputs in astro modelling** ? → systematic studies / bayesian analysis needed