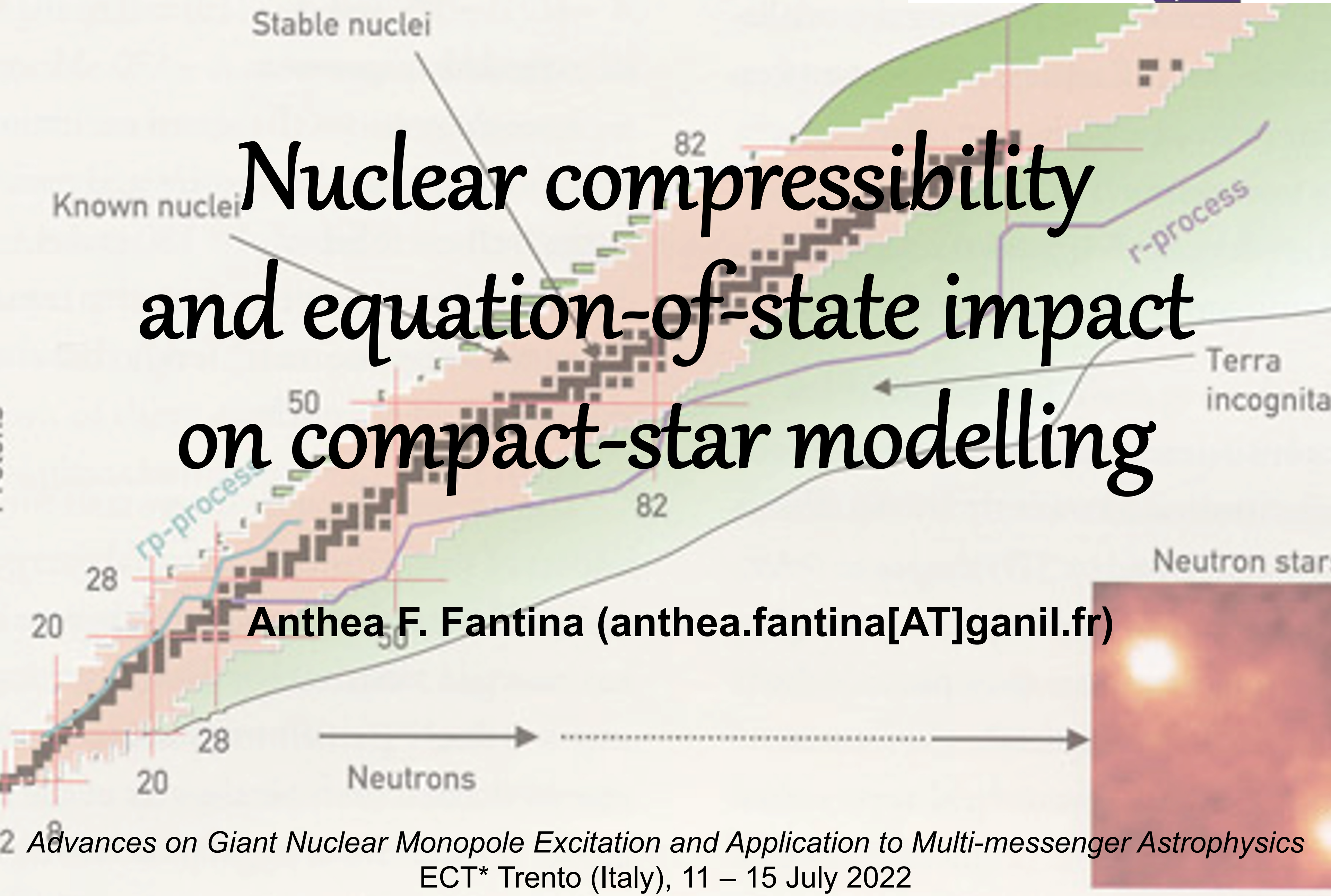


Nuclear compressibility and equation-of-state impact on compact-star modelling

Anthea F. Fantina (anthea.fantina[AT]ganil.fr)

Advances on Giant Nuclear Monopole Excitation and Application to Multi-messenger Astrophysics
ECT* Trento (Italy), 11 – 15 July 2022

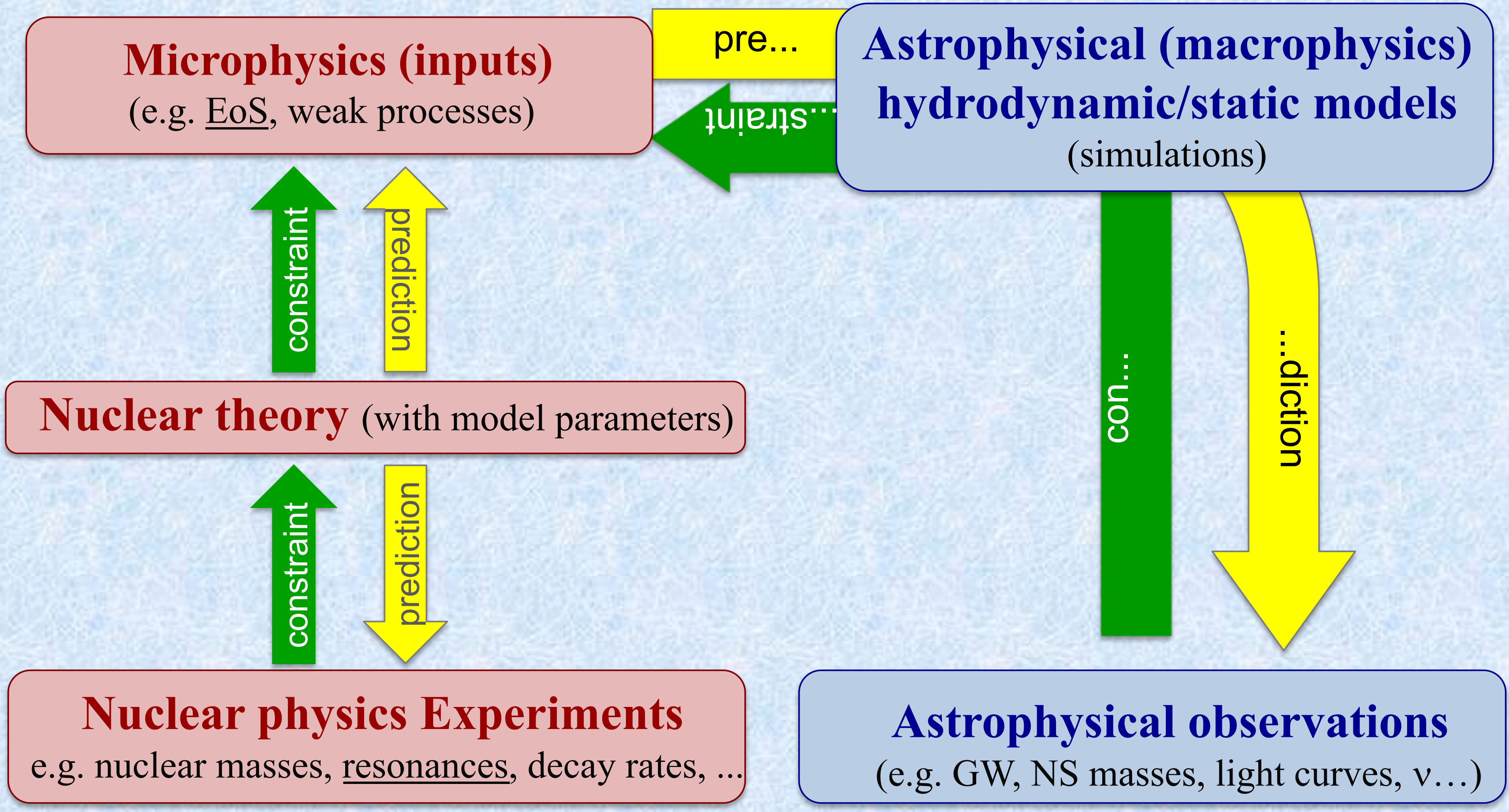
Outline

- Introduction
  - Equation of state (EoS) and empirical parameters
  - Constraints from theory and experiments

- Role of the EoS
  → role of the nuclear compressibility ($K \rightarrow K_{sat}$ or K_{inf}, K_{sym})
  - in core-collapse supernovae (CCSN)
  - in neutron stars (NS)
  - in BNS mergers → see talks by A. Bauswein and A. Steiner

- Conclusions & open questions

Micro to macro: jumping across scales



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

Astrophysical (macrophysics) hydrodynamic/static models
(simulations)

Nuclear theory (with model parameters)

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

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

EoS and empirical parameters

- **Nuclear energy around saturation**

→ expansion in density and asymmetry around n_{sat} and $\delta = 0$

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

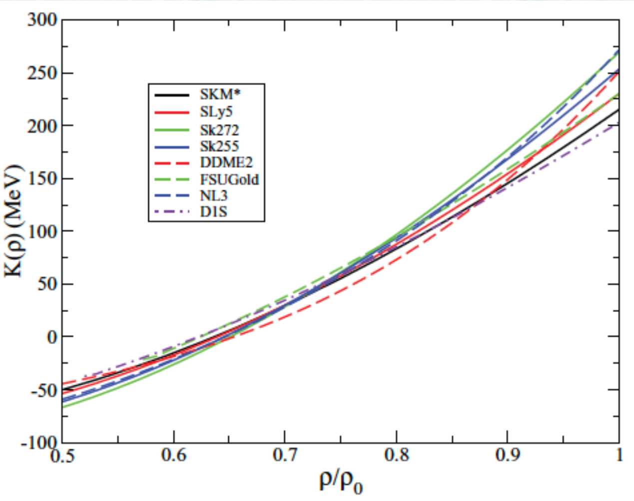
$$x = (n - n_{\rm sat})/3n_{\rm sat}$$
$$\delta = (n_n - n_p)/n$$

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

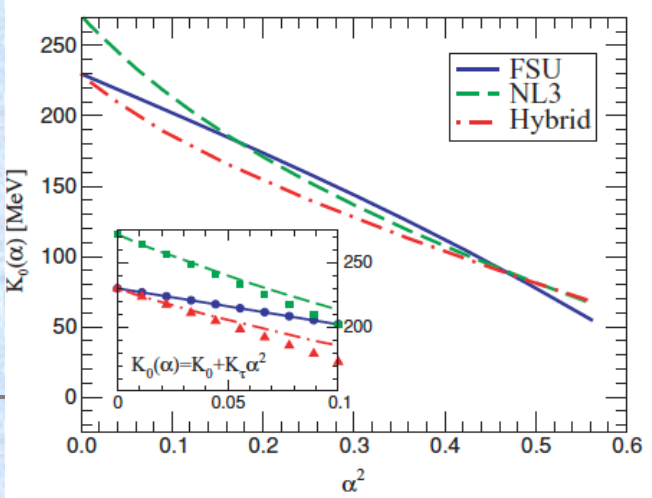
but: K_{sat}, K_{sym} : info on compression at n_0 and symmetric matter

→ other parameters contribute if $n \neq n_0$ and $\delta \neq 0$!

$$K(n) = \frac{18}{n} P(n) + 9n^2 \frac{\partial^2 E(n)/A}{\partial n^2} \qquad K_0(\delta) = K_{\rm sat} + \left(K_{\rm sym} - 6L - \frac{Q_{\rm sat}}{K_{\rm sat}} L \right) \delta^2 + \mathcal{O}(\delta^4)$$



Khan & Margueron, PRC 88, 034319 (2013)



Piekarewicz & Centelles, PRC 79, 054311 (2009)

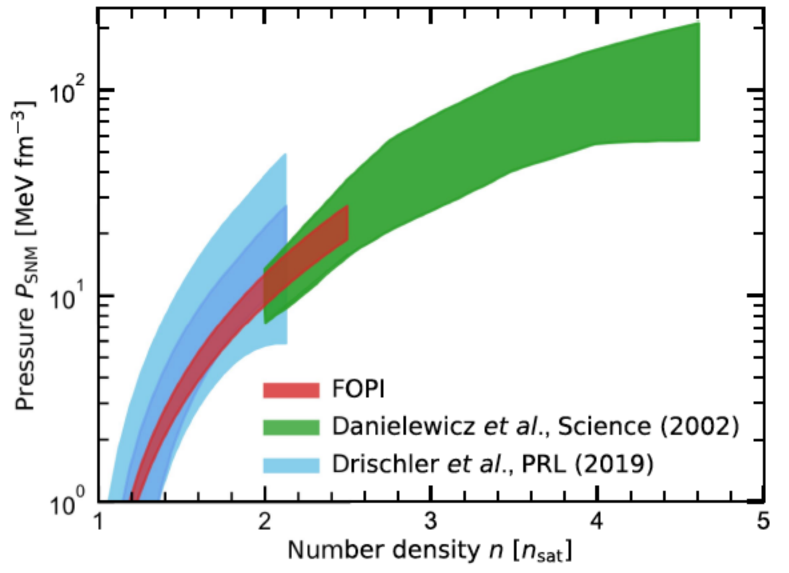
How can we get constraints?

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)



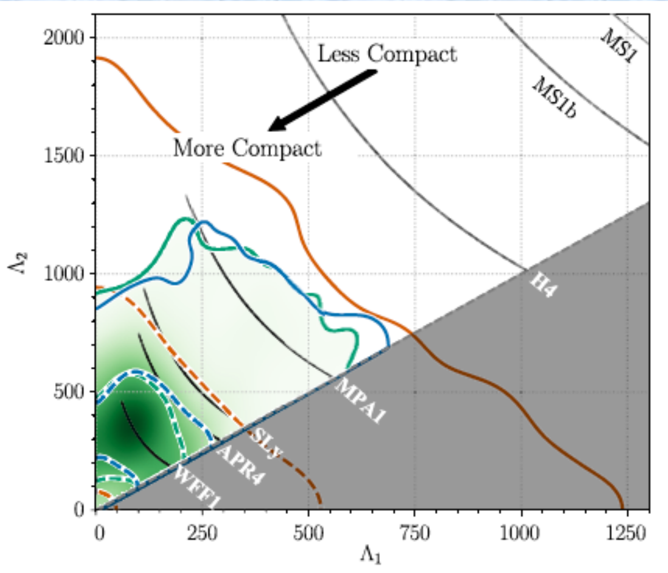
Huth et al., Nature 606, 276 (2022)

Astrophysical observations

- Measure of **NS properties:**
  - NS masses and radii (NICER)
  - rotational frequency, oscillation modes
  - cooling, moment of inertia

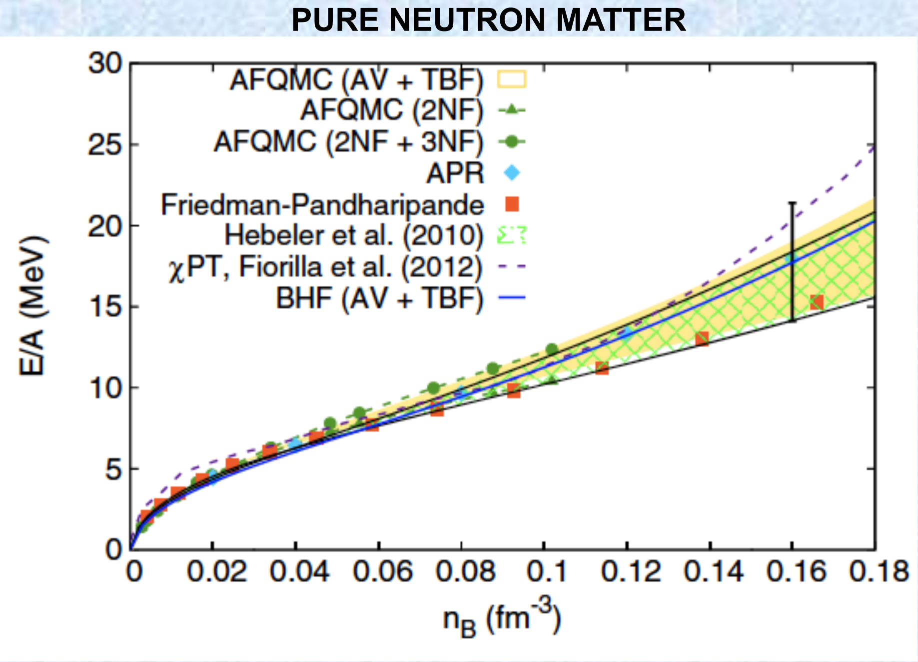
  etc …
- **Gravitational waves**

→ **“high” density**

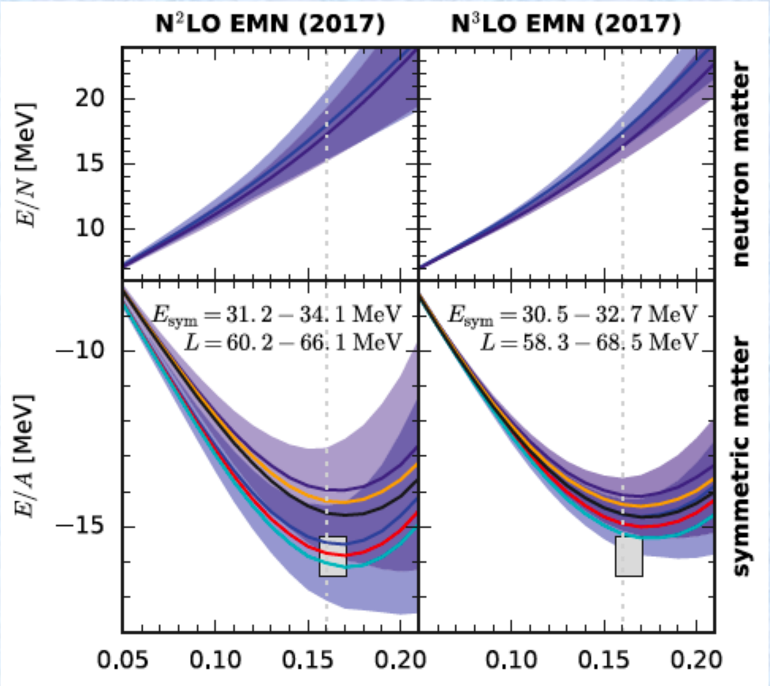


Abbott et al., PRL 121, 161101 (2018)

Constraints from nucl. phys.: theo



Oertel et al., Rev. Mod. Phys. 89, 015007 (2017)

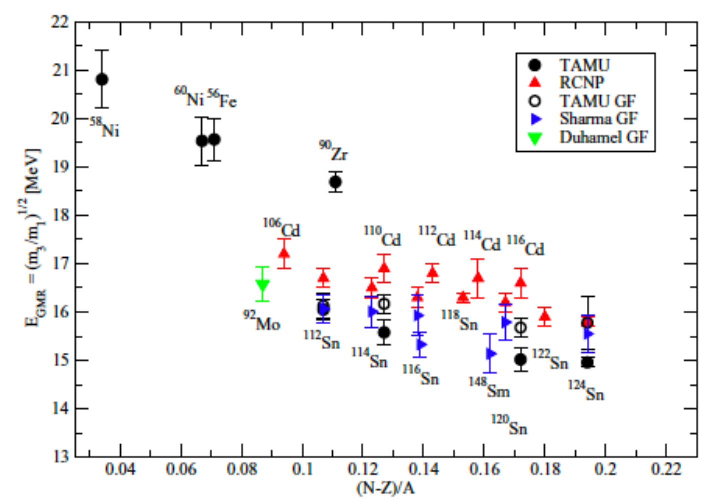


Drischler et al., PPNP 121, 103888 (2021)

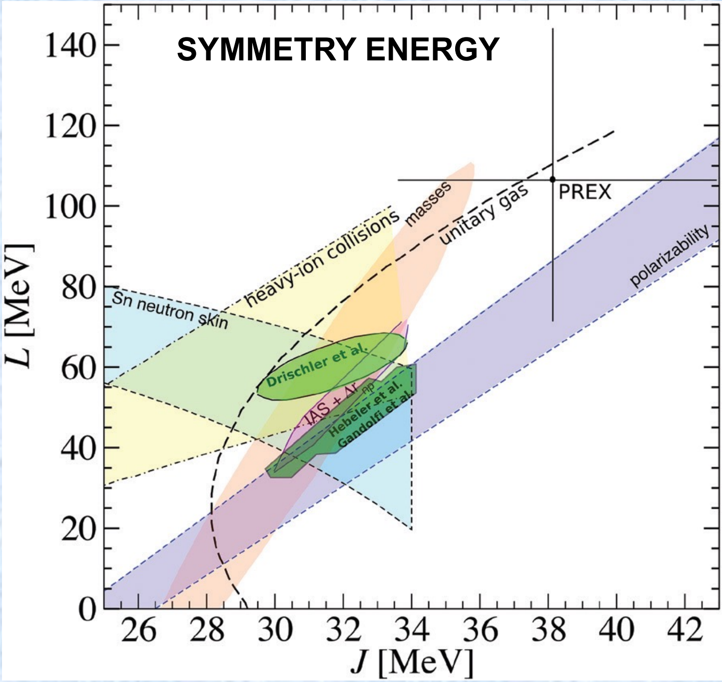
→ Reasonable agreement of ab-initio (PNM) up to ~ saturation density
→ PNM calculations benchmark for phenomenological models

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

Constraints from nucl. phys.: exp (1)



Stone et al., PRC 89, 0044316 (2014)

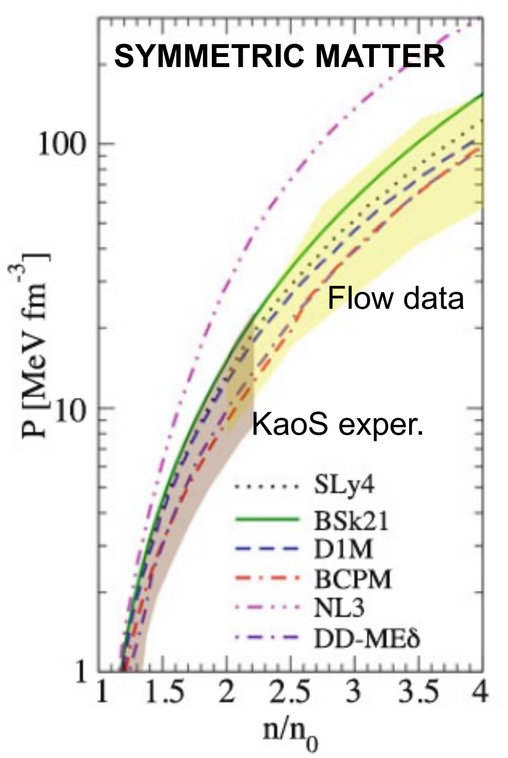


Gulminelli & Fantina, Nucl. Phys. News 31, 9 (2021)

→ Constraints at “low” densities
→ low-order parameters

→ Constraints more on “symmetric” matter

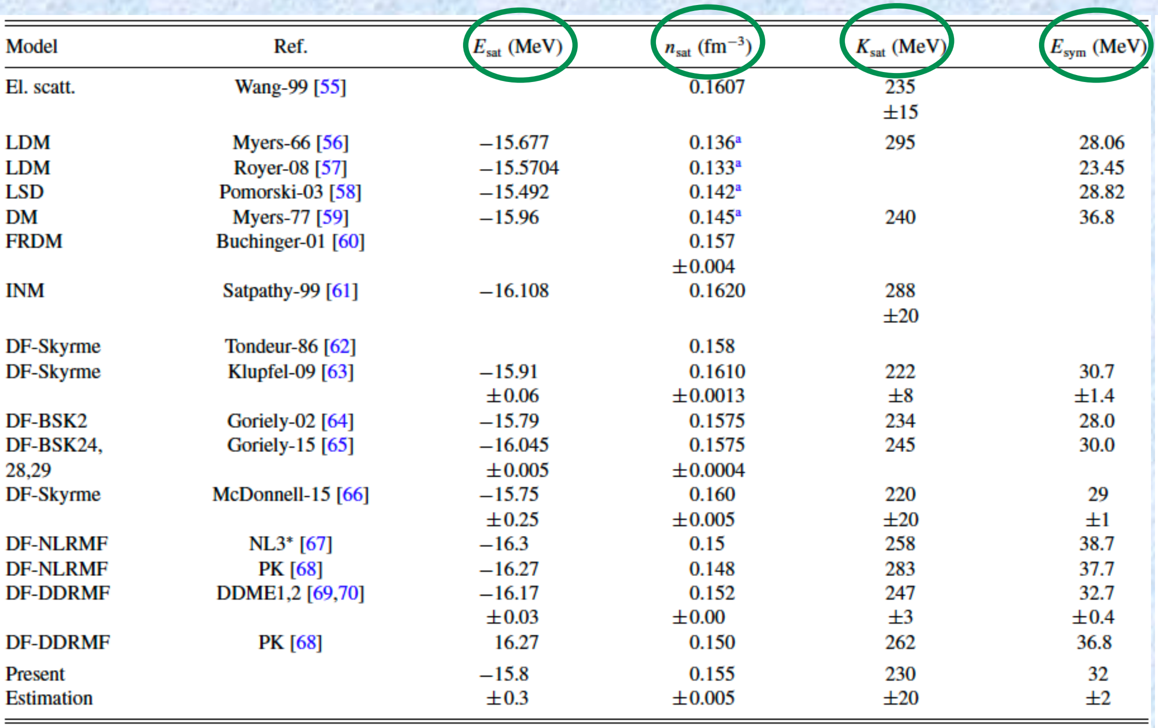
→ Not always “clear” constraints
→ “tension”



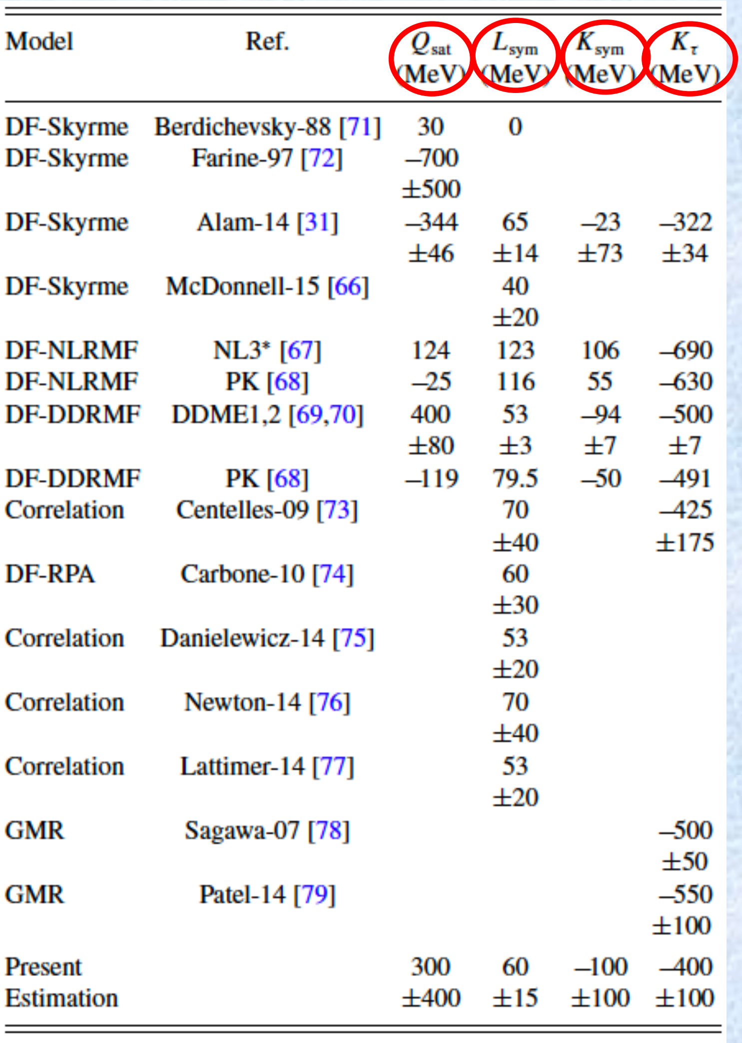
Burgio & Fantina, ASSL 457, 255 (2018)
(Flow: Danielewicz et al., Science 2002
KaoS: Lynch et al., PPNP 2009)

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

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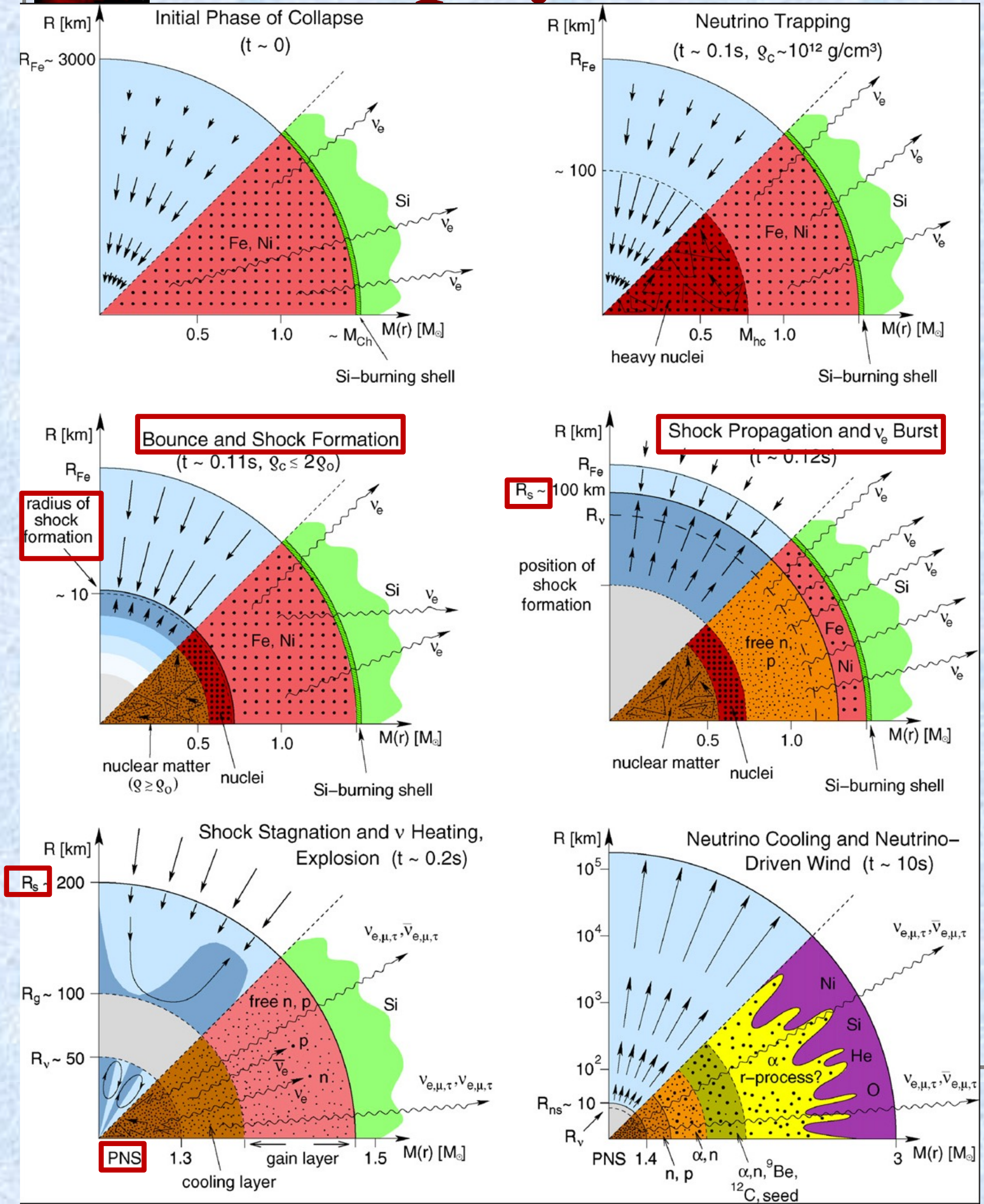
  - in neutron stars (NS)
  - in BNS mergers → see talks by A. Bauswein and A. Steiner

- ❖ Conclusions & open questions

Astrophysical context : CCSN



1. **Infall epoch**
   → core collapse

2. **Bounce and shock propagation**
   → bounce formation
   → shock radius

3. **Explosion**
   → time of explosion

Janka et al., Phys. Rep. 442, 38 (2007)

EoS in CCSN simulations

Most used EoSs (historically) in CCSN :

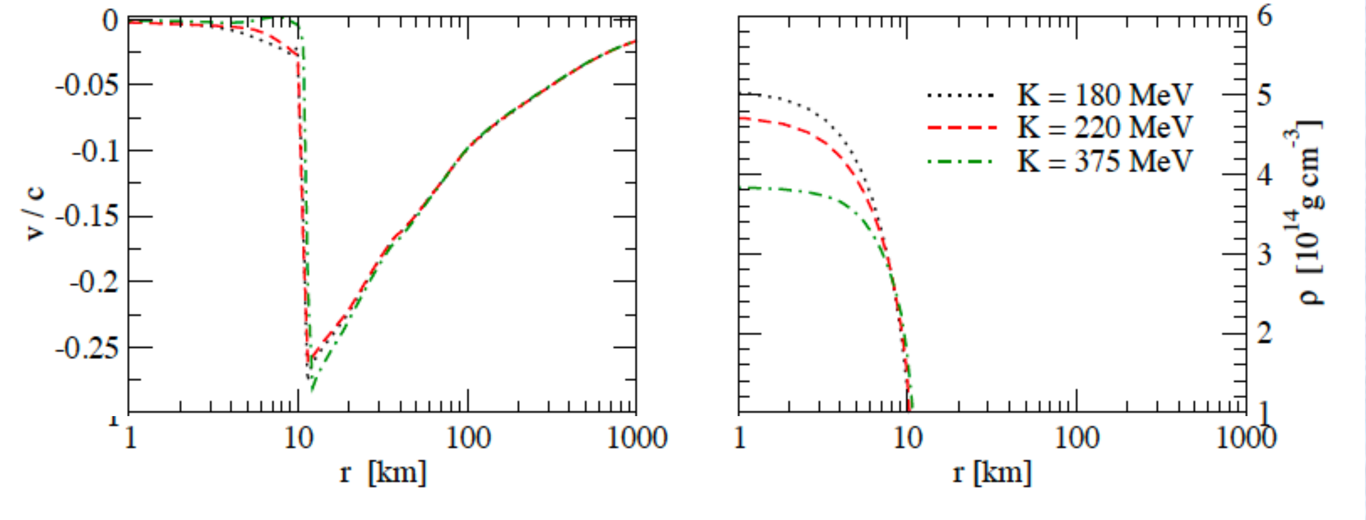
- **Hillebrandt & Wolff 1984** : NSE + SNA at higher density
  Skyrme (Ska) interaction for nucleons. **K_{sat} = 263 MeV**
- **Lattimer & Swesty (LS) 1991** : SNA, nuclei + α + free n,p + leptons
  CLDM and NR simplified Skyrme-like functional for nucleons, α Boltzmann gas
  K_{sat} = 180, 220, 375 MeV
- **Shen et al. 1998** : SNA, nuclei + α + free n,p + leptons
  TF approach, RMF (TM1) for nucleons, α Boltzmann gas. **K_{sat} = 281 MeV**
- **SHFo, SHFx 2013**: NSE, nuclei + α + free n,p + leptons
  RMF for nucleons. **K_{sat} = 245, 239 MeV** (but also symmetry energy parameters differ…)

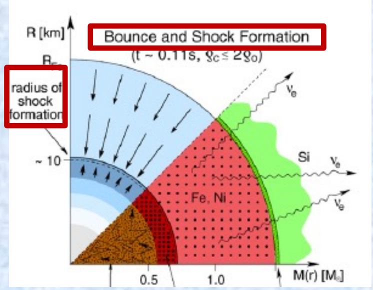
BUT :

❖ when comparing "(in)compressibility" → comparing different models !
❖ Mazurek's law → complex interplay and feedback with hydro/transport

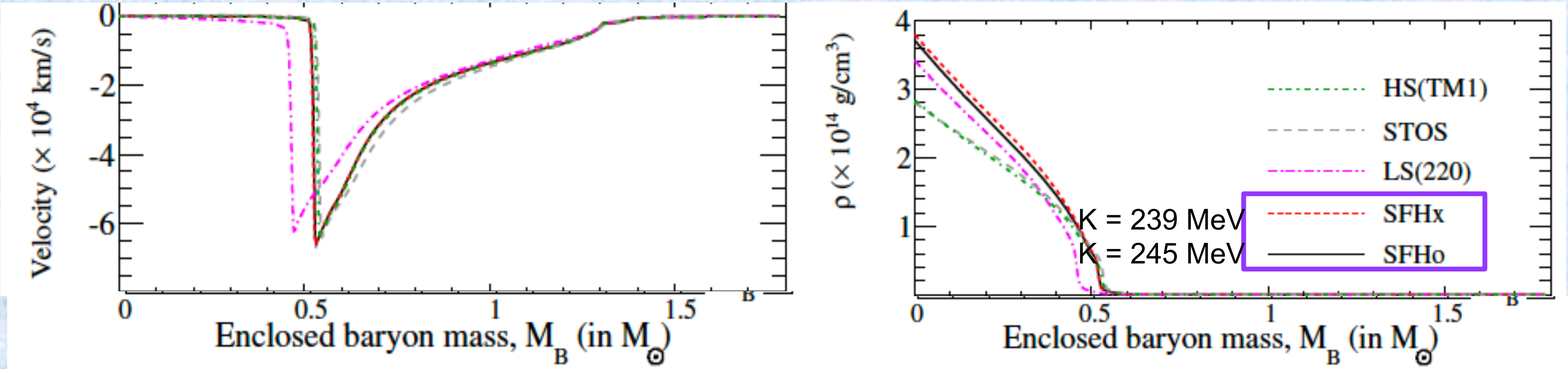
Hillebrandt & Wolff, in "Nucleosynthesis: challenges and new developments" (1985); Lattimer&Swesty, Nucl. Phys. A 535, 331 (1991); Shen et al., Nucl. Phys. A 637, 435 (1998); Steiner et al., ApJ 774, 17 (2013)
for a review: Oertel et al., Rev. Mod. Phys. 89, 015007 (2017), Burgio & Fantina, ASSL 457, 255 (Springer, 2018)

CCSN simulations: *K* and bounce





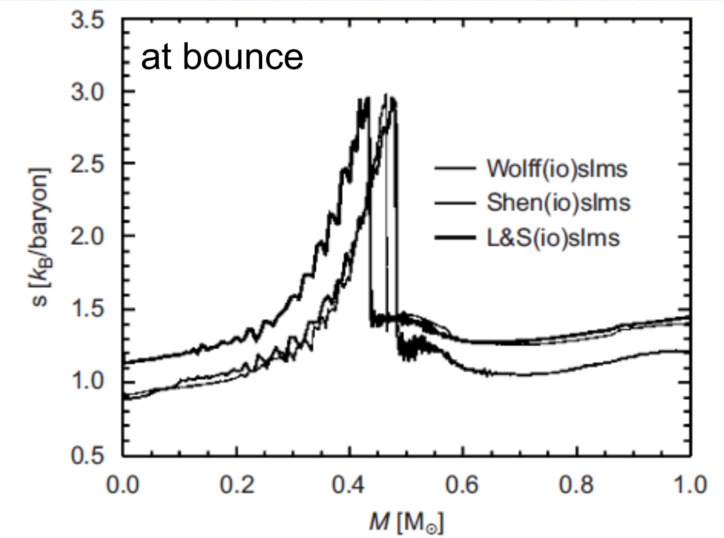
A. F. Fantina, PhD thesis (2010) - 1D GR, Lattimer&Swesty EoS, neutrino leakage-type scheme, 15 M_{sun} progenitor
(see also Suwa et al., ApJ 764, 99 (2013) 1D simulations, Newtonian, LS and Shen EoS, 15 M_{sun} progenitor, ν: diffusion approx. scheme)



Steiner et al., ApJ 774, 17 (2013) - 1D simulation GR, Boltzmann ν transport, 11.2 M_{sun} and 40 M_{sun} progenitors

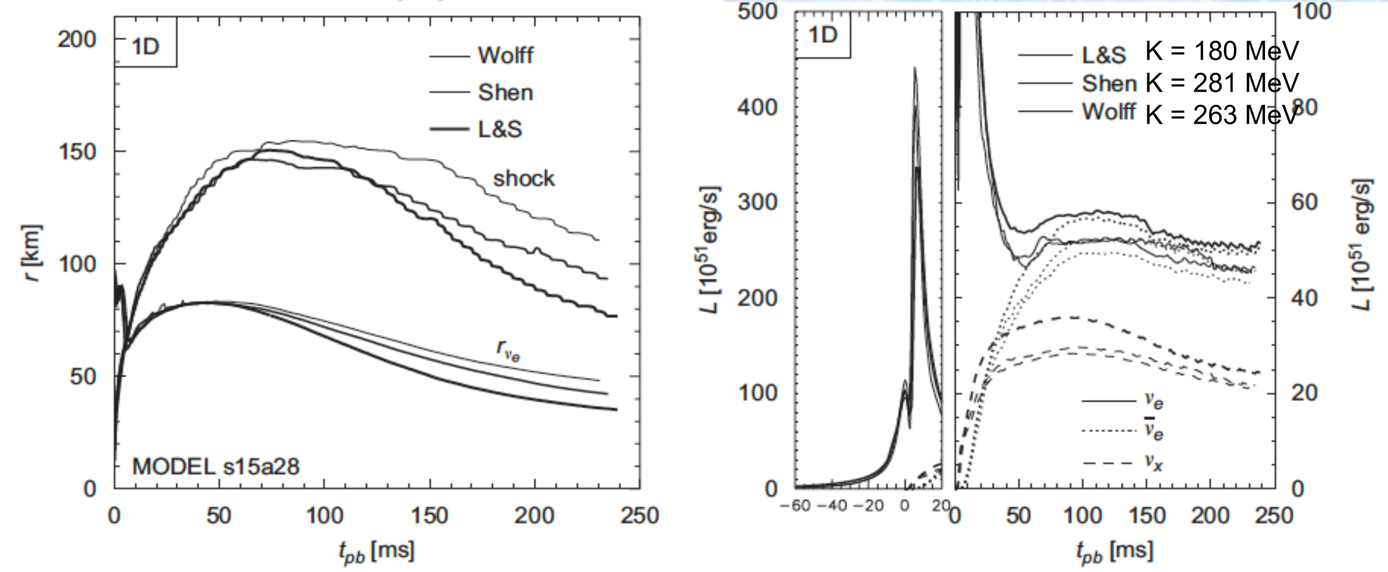
➡ not great impact on dynamics at bounce, impact on matter properties

CCSN simulations: (post-)bounce

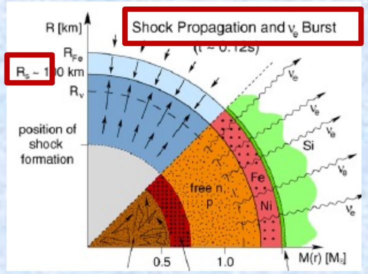


K = 263 MeV
K = 281 MeV
K = 180 MeV

“softer” EoS → smaller inner core
→ more compact PNS
→ higher ν luminosity

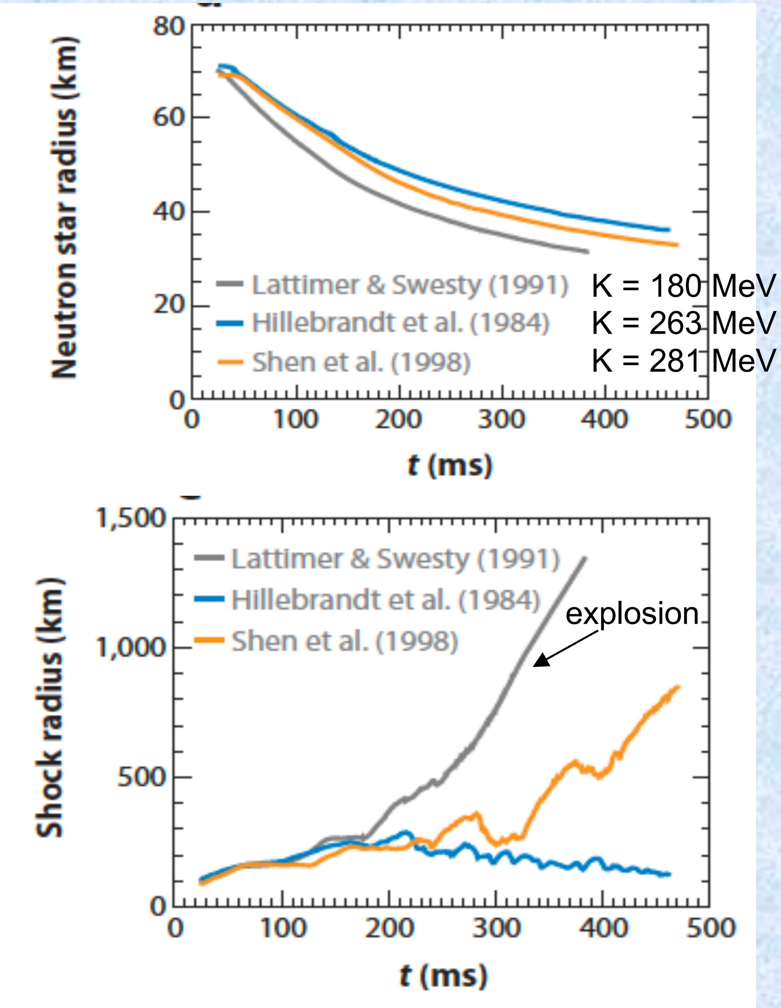


K = 180 MeV
K = 281 MeV
K = 263 MeV



Janka et al., Phys. Rep. 442, 38 (2007) - 1D simulation, 15 M_{sun} progenitor, “ray-by-ray” ν treatment

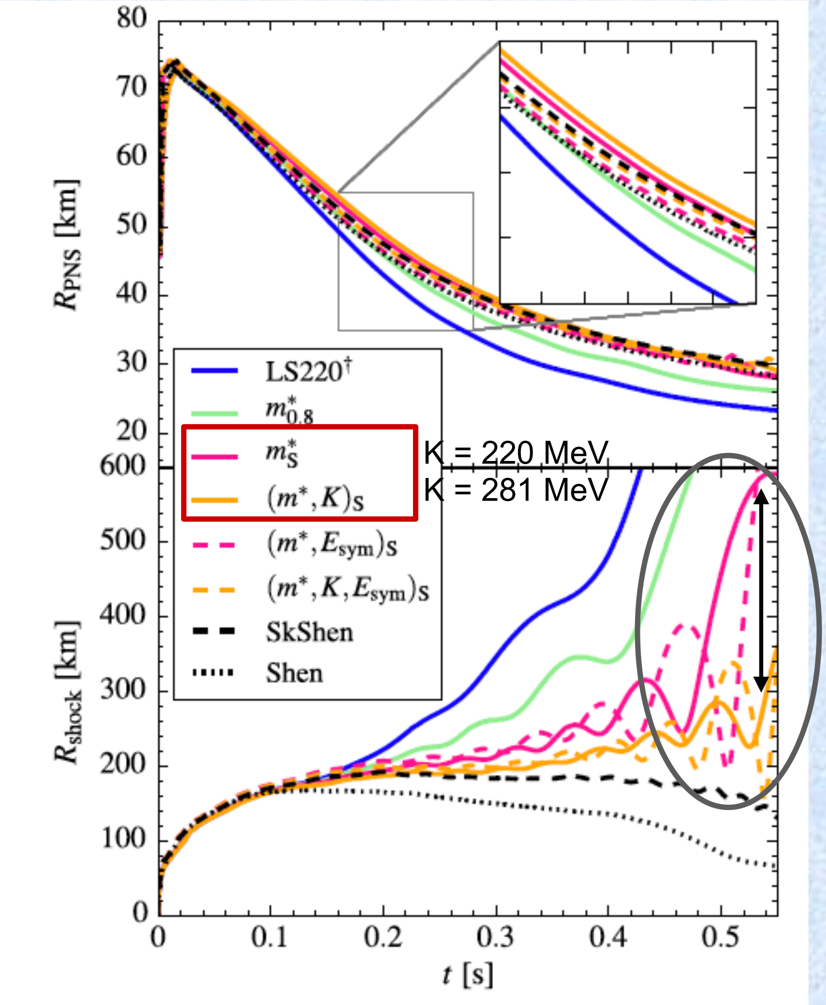
CCSN simulations: shock radius, PNS



K = 180 MeV
K = 263 MeV
K = 281 MeV

explosion

Janka et al., Annu. Rev. Nucl. Part. Sci. 62, 407 (2012)
2D simulations, Newtonian, 11.2 M_{sun} progenitor

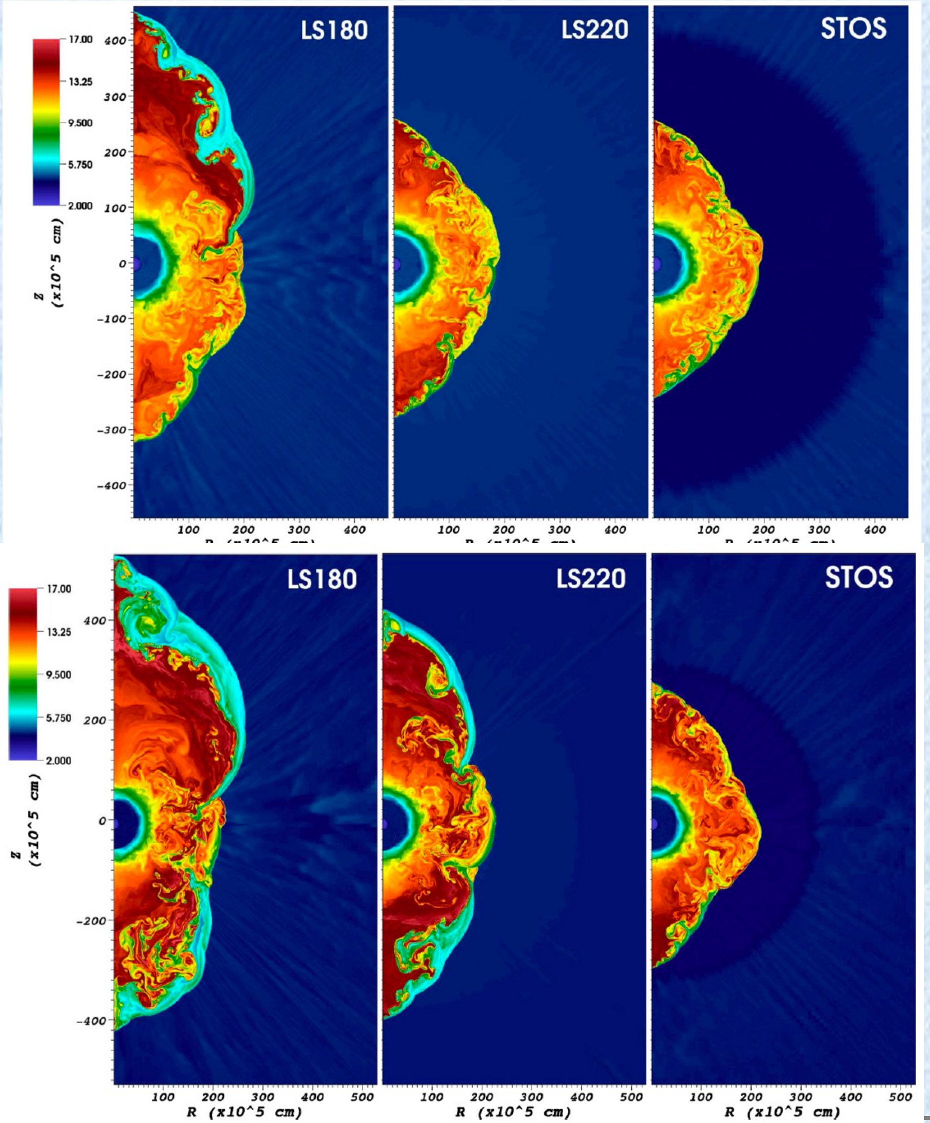


K = 220 MeV
K = 281 MeV

Yasin et al., PRL 124, 097701 (2020)
1D simulations, multi-species neutrino physics,15 M_{sun} progenitor

➡ "softer" EoS → more compact PNS
→ larger shock radii (→ explosion?)

CCSN simulations: instabilities



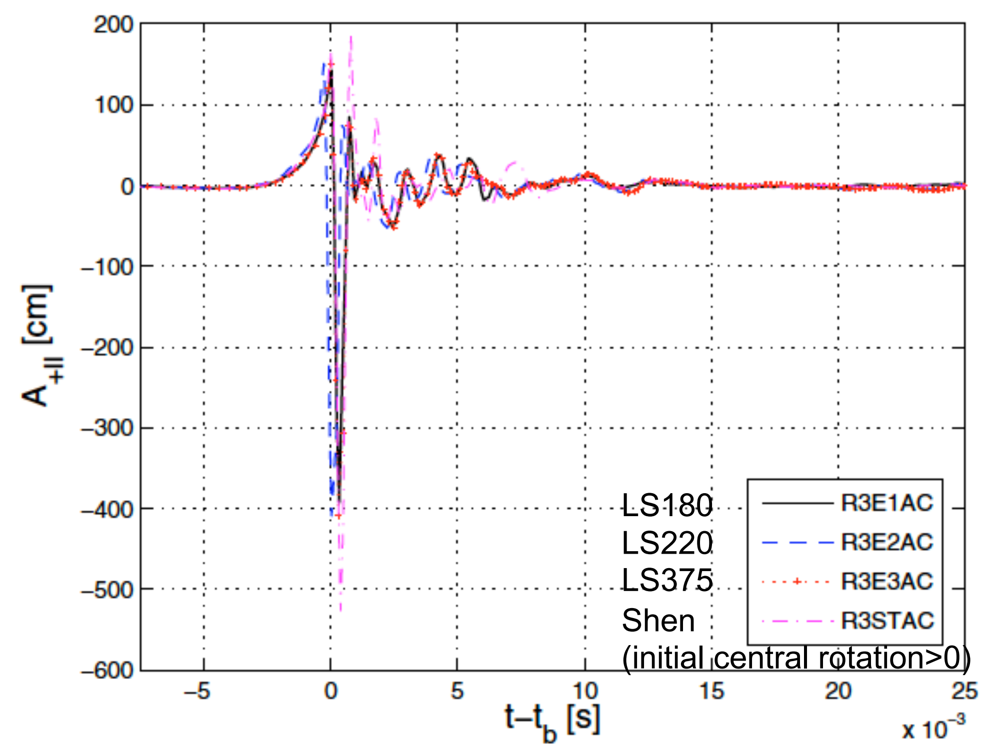
Entropy per baryon (colours)

300 ms after bounce
→ larger instabilities for lower K_{sat}

600 ms after bounce
→ shock expansion for LS,
stationary for Shen et al. EoS

Couch, ApJ 765, 29 (2013). 2D simulations, simplified neutrino physics (fixed L_ν), 15 M_{sun} progenitor

CCSN simulations: GW signal (1)



LS180
LS220
LS375
Shen
(initial central rotation>0)

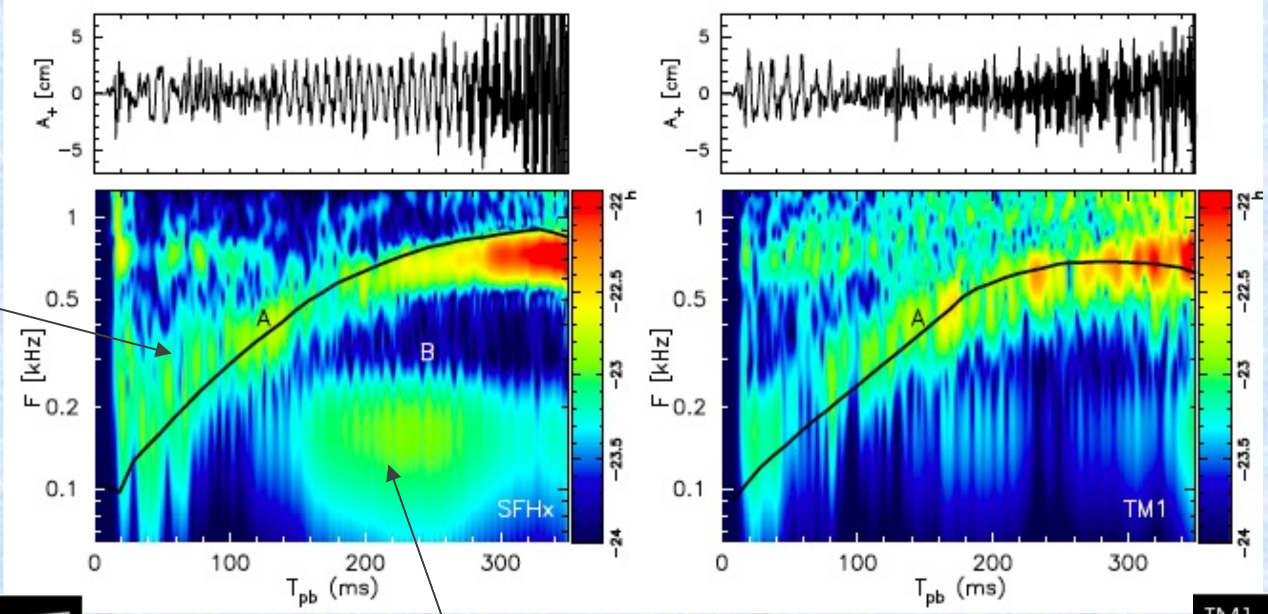
Scheidegger et al., A&A 514, A51 (2010)
3D GR simulations with B field, Boltzmann transport, 15 M_{sun} progenitor

→ impact on GW signal (amplitude in equatorial plane):
hard to discriminate

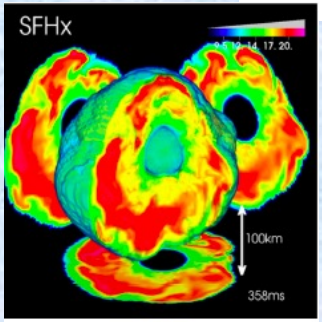
CCSN simulations: GW signal (2)

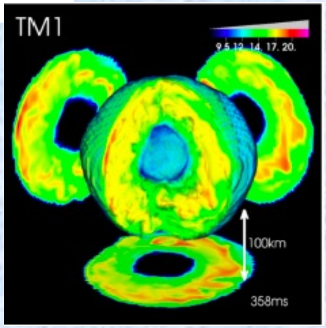
SFHx (“**softer**” EoS) TM1 (“**stiffer**” EoS)

PNS
(g-mode)
oscillations



associated to SASI





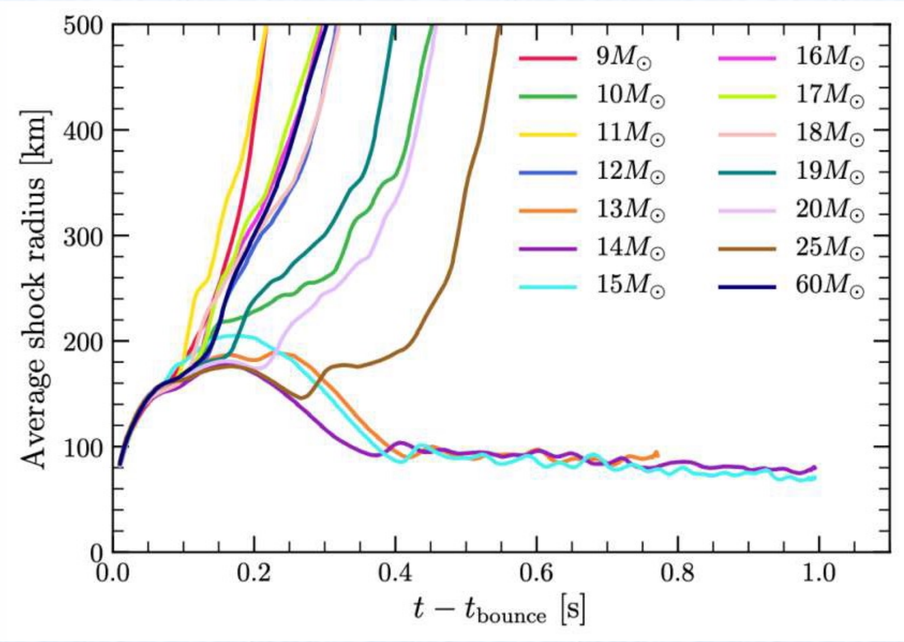
→ SASI activity higher for “softer” EoS

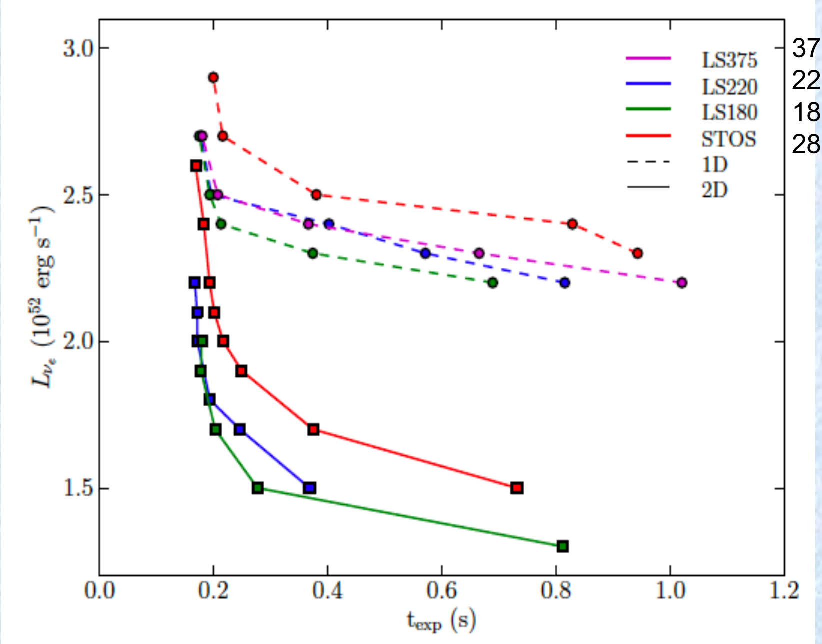
but: different EoSs !

Kuroda et al., ApJL 829, L14 (2016) - 3D GR simulations, 15 M_{sun} progenitor

CCSN simulations: many inputs count!

Other inputs matter ! e.g. progenitor, dimensionality, …





375 MeV
220 MeV
180 MeV
281 MeV

Burrows et al., MNRAS 491, 2715 (2019), 3D, SFHo EoS

Couch, ApJ 765, 29 (2013). 1D and 2D simulations, simplified neutrino physics (fixed L_ν), 15 $M_{\rm sun}$ progenitor (see also Pan et al., ApJ 857, 13 (2018))

→ Progenitor mass dependence: non-monotonic behaviour, dependence on progenitor structure

→ if same EoS, higher $K_{\rm sat}$ → later explosion for given L_ν

but : 1D vs 2D dependence !

Conclusions and open questions (CCSN)

- Roughly speaking, ”*softer*” EoS :
  - → more compact and faster contracting PNS
  - → higher ν luminosities
  - → larger shock radii → more favourable to explosion

<u>but</u> :

✗ Difficult to correlate single nuclear parameters in CC dynamics !

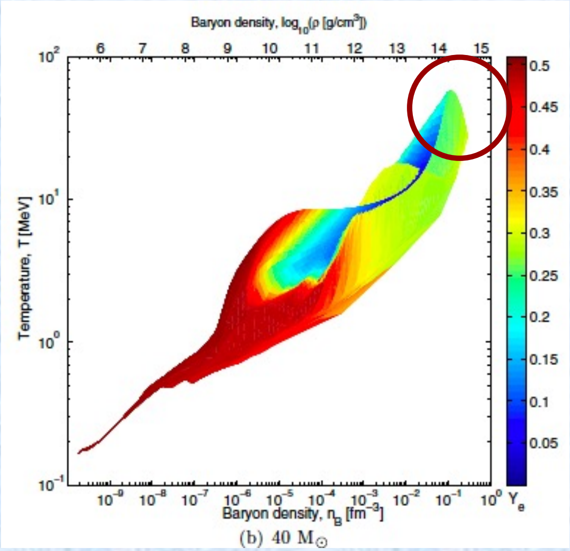
→ EoS models differ from several aspects (nuclear theory, parameters, …)

✗ *Hydro (macro)* vs *micro* effects (also for BNS!)

→ Consistent treatment of phase transitions challenging

→ Extension of many-body methods and extrapolation (e.g. parameters usually fitted at T=0)

→ Need of complex multi-D simulations → other effects: hydro instabilities (SASI, …), progenitors, ν treatment, …



(b) 40 $M_\odot$

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

➡ ✓ <u>no</u> strong conclusive statements can be drawn

✓ K_{sat} not the (only) key parameter

➡ ✓ need of systematic studies / simulations

Astrophysical context : NS

Mature (cold) NS → cold catalysed matter (full equilibrium → ground state)

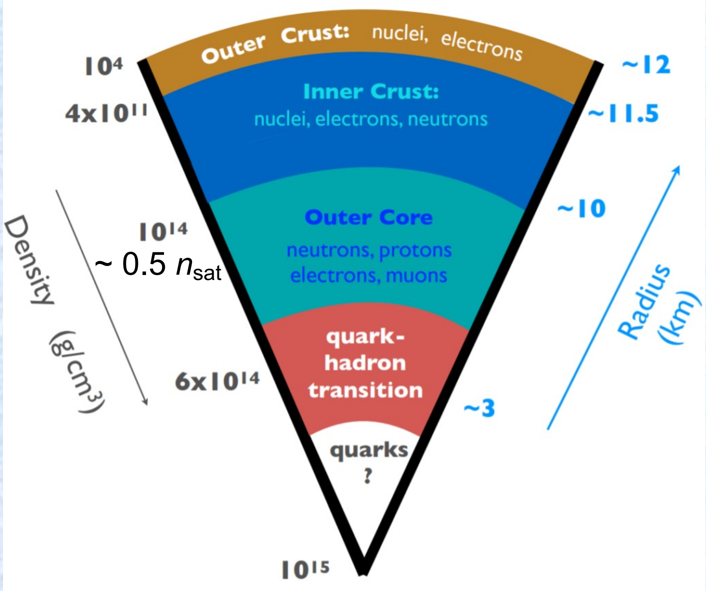
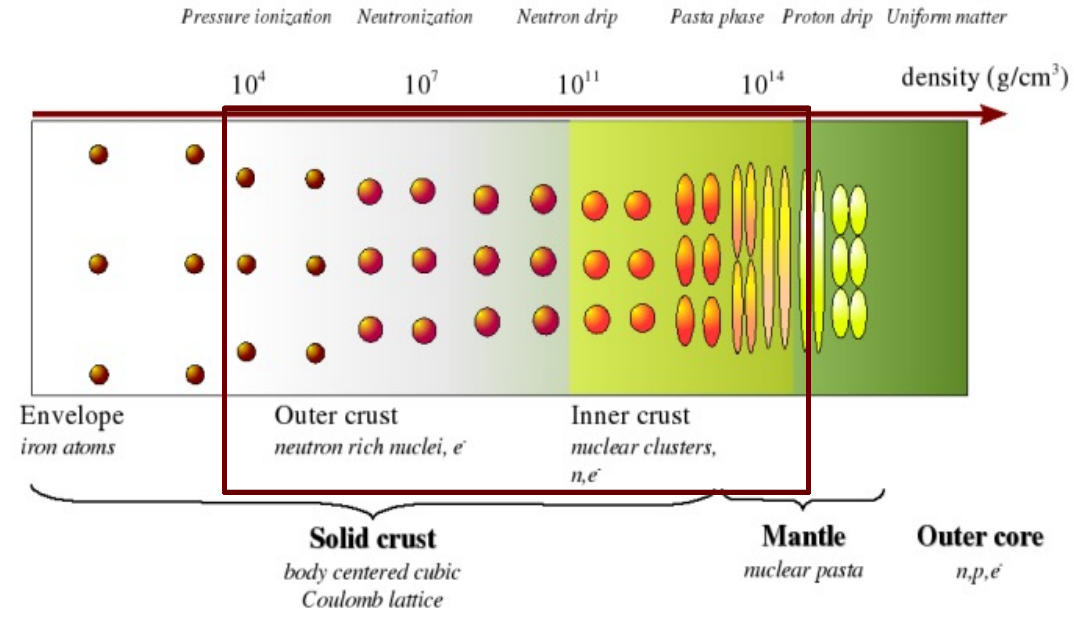


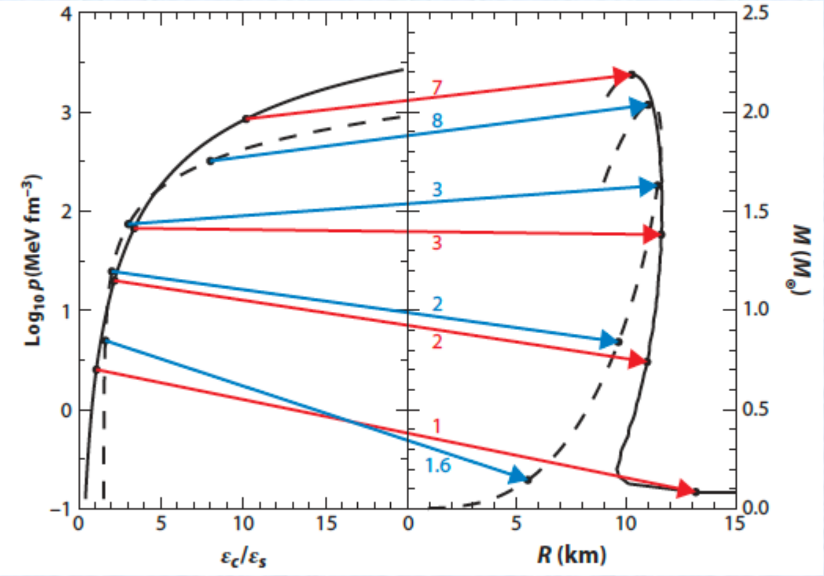
Image Credit: 3G Science White Paper



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

If “mature” (cold) NSs → *T* = 0 and β equilibrium → “easier” (ground-state energy)
but: still challenging because of different states of matter and range of density

EoS and NS properties



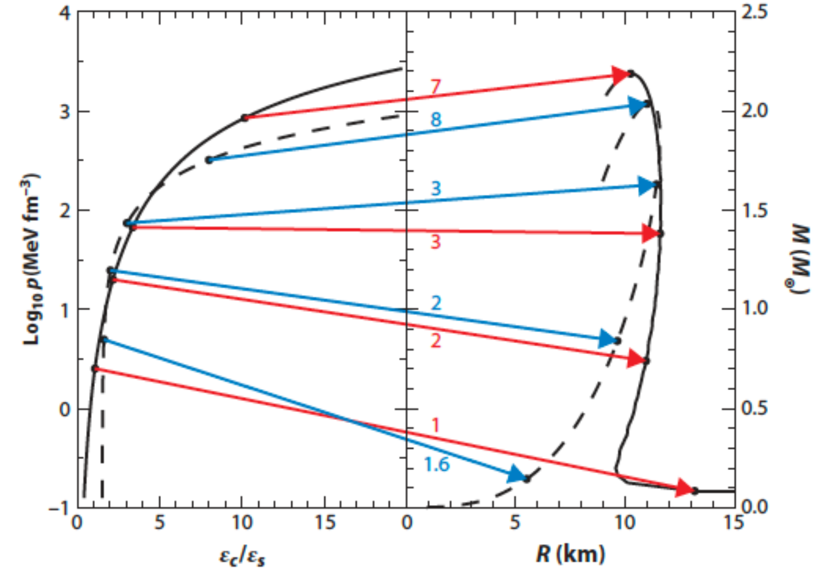
Lattimer, Annu. Rev. Part. Nucl. Sci. 62, 485 (2012)

- ✓ GR → one-to-one correspondence
  EoS ←→ NS static properties $M(R)$, $\Lambda(M)$…
  (non-rotating mature NS)
- ✓ Different EoSs ←→ different NS properties
  ←→ different observational signals (GW,…)
  ?
  → trace back to EoS and composition ?

---

for a review see e.g. Oertel et al., Rev. Mod. Phys. 89, 015007 (2017), Burgio & Fantina, ASSL 457, 255 (2018), Blaschke & Chamel, ASSL 457, 337 (2018)

EoS and NS properties



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

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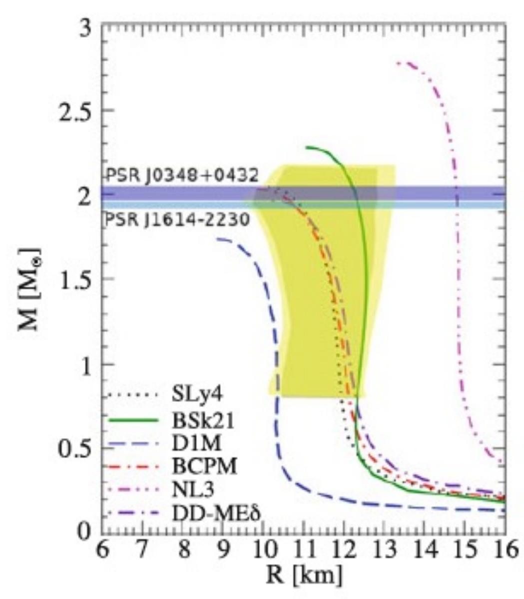
  EoS ←→ NS static properties $M(R)$, $\Lambda(M)$…
  (non-rotating mature NS)
- ✓ Different EoSs ←→ different NS properties
  ←→ different observational signals (GW,…)
  ?
  → trace back to EoS and composition ?

<u>but</u>:

- ✗ EoS model dependent !
- ✗ <u>no</u> ab-initio dense-matter calculations in all regimes
  → phenomenological models
  (*many-body approach* + *functional*)
- ✗ composition ←→ EoS → $M(R)$?
  (e.g. masquerade effect!)



Burgio & Fantina, ASSL 457, 255 (2018)

for a review see e.g. Oertel et al., Rev. Mod. Phys. 89, 015007 (2017), Burgio & Fantina, ASSL 457, 255 (2018), Blaschke & Chamel, ASSL 457, 337 (2018)

EoS: meta-model (nucleons only)

- **Meta-model** approach for <u>nucleons</u> : flexible functional (“quasi” agnostic)

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

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

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

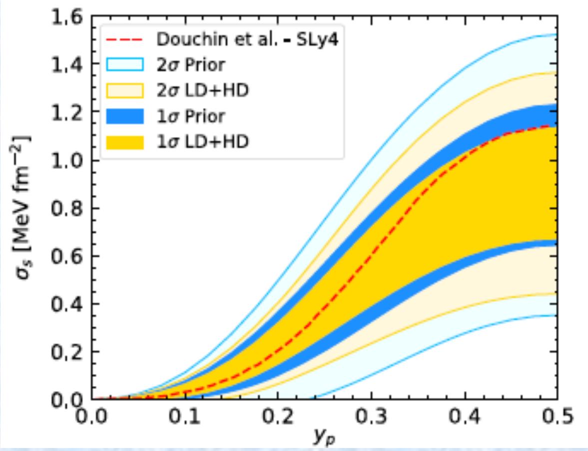
$$\delta = (n_n - n_p)/n$$

Empirical parameters (<u>bulk</u>) $\boldsymbol{X}_{\mathrm{sat,sym}}$ = E_{sat}, K_{sat}, Q_{sat}, E_{sym}, L_{sym}, K_{sym}, …

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

  → <u>surface</u> parameters (σ_0, $\sigma_{0,c}$, β, b_s, p)

~ 15 – 20 parameters



Dinh Thi et al., EPJA 57, 296 (2021) – surface tension

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), …

NS: model dependence of observables

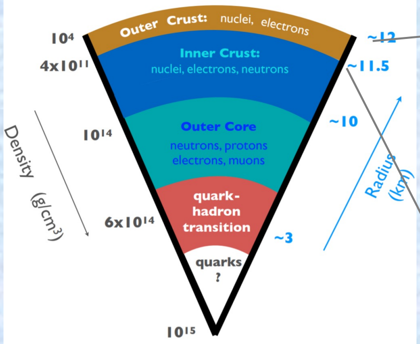
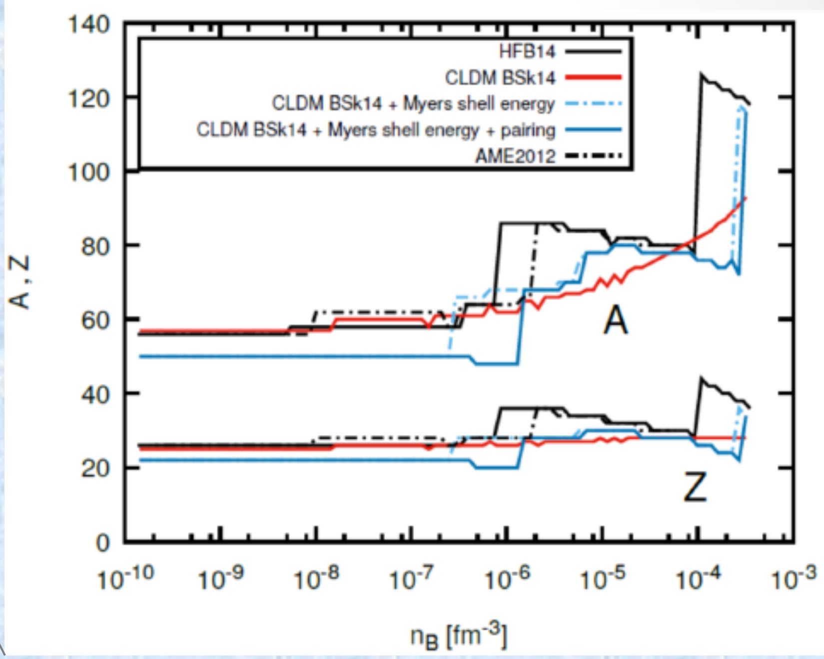


Image Credit: 3G Science White Paper



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

- composition → dependence on many-body method

NS: model dependence of observables

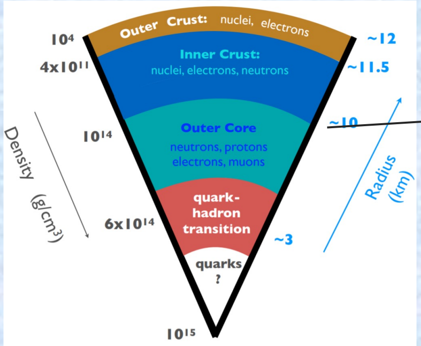
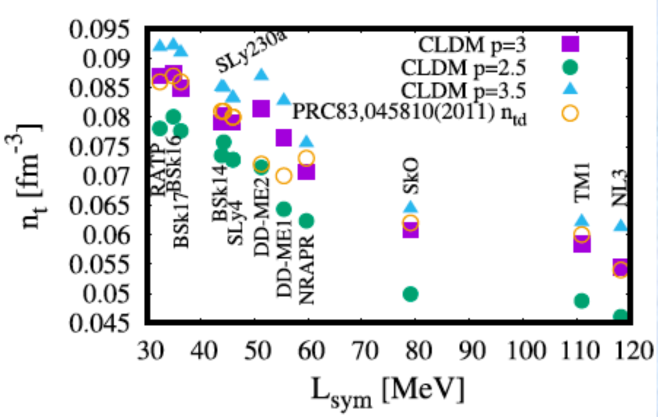
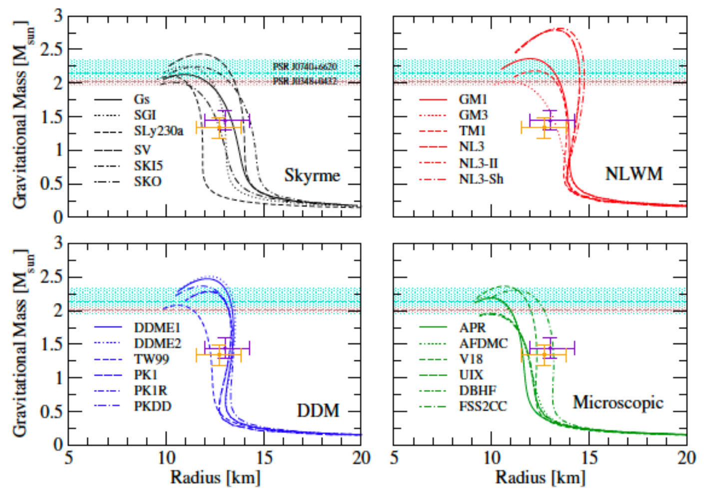


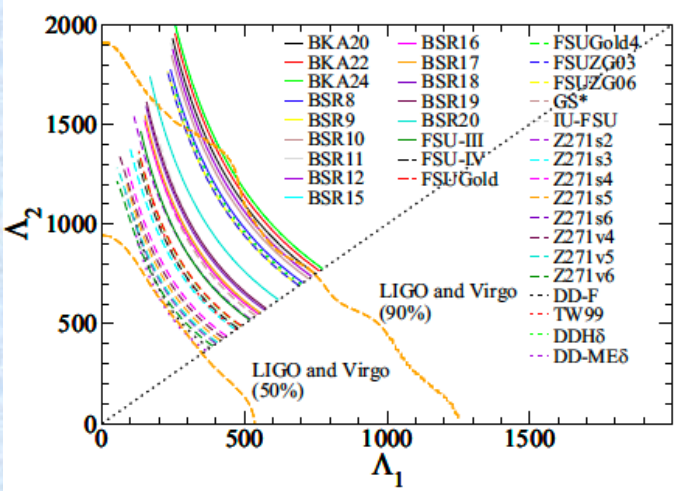
Image Credit: 3G Science White Paper



Carreau et al., PRC 100, 045803 (2019)



Burgio & Vidana, Universe 6, 119 (2020)



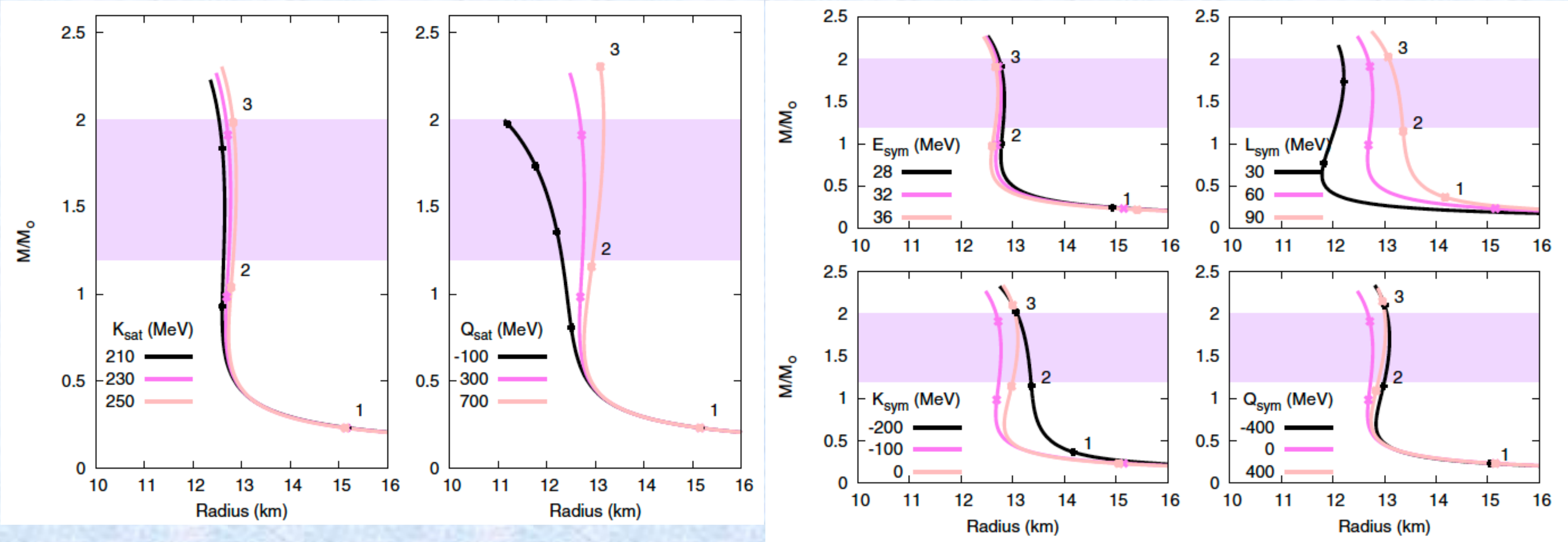
Lourenço et al., PRC 99, 045202 (2019)

- composition → dependence on many-body method
- global observables → dependence on the functional

<u>but</u>: comparison of very different models (≠ parameters, ≠ many-body method) !

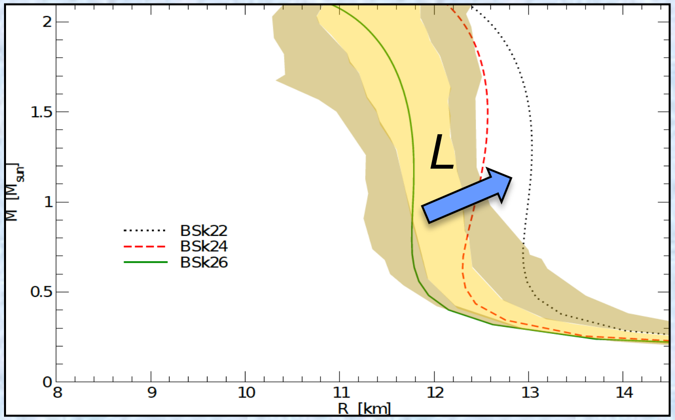
→ *which parameter(s) matter?*

NS: impact of IS/IV parameters



Margueron et al., PRC 97, 025806 (2018) – meta-model

→ impact of isovector parameters
→ impact of high-order parameters



Pearson et al., Eur. Phys. J. A 50, 43 (2014)
(Skyrme-type models)

EoS: meta-model + Bayesian

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

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

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

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

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

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

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

  → surface parameters (σ_0, $\sigma_{0,c}$, β, b_s, p)

~ 15 – 20 parameters

- Apply filters in Bayesian analysis

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

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

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

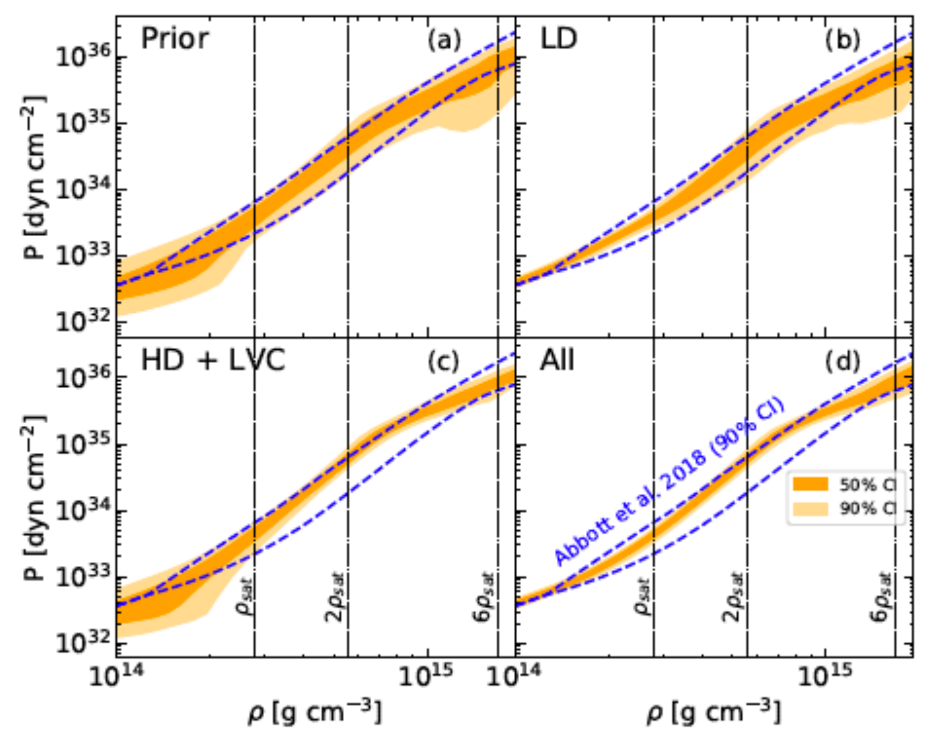
nuclear masses
(AME2016)
→ surf. param. (σ_0, $\sigma_{0,c}$, β, b_s, p)

flat non-informative prior
→ span large parameter space

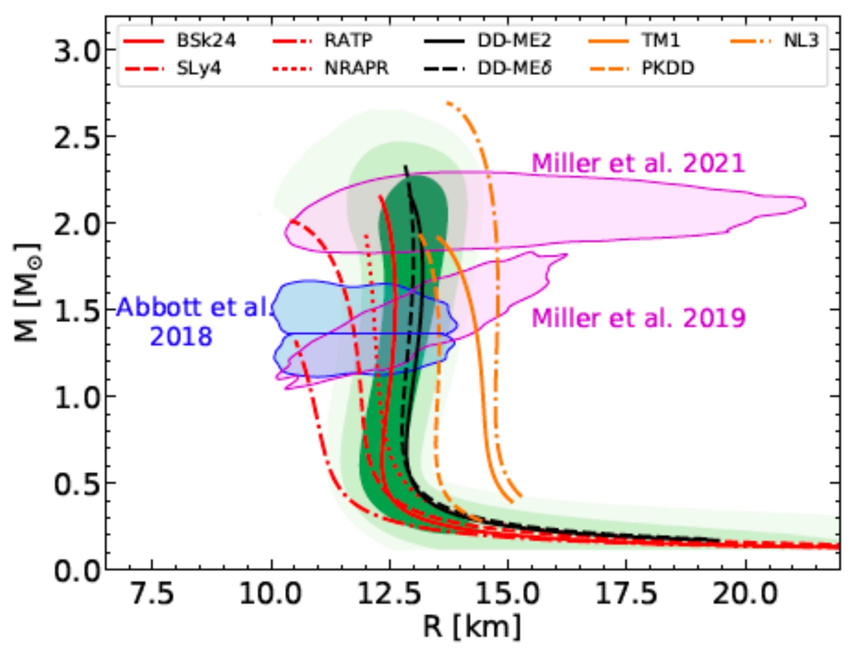
---

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), …

EoS : effect of LD/HD constraints



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

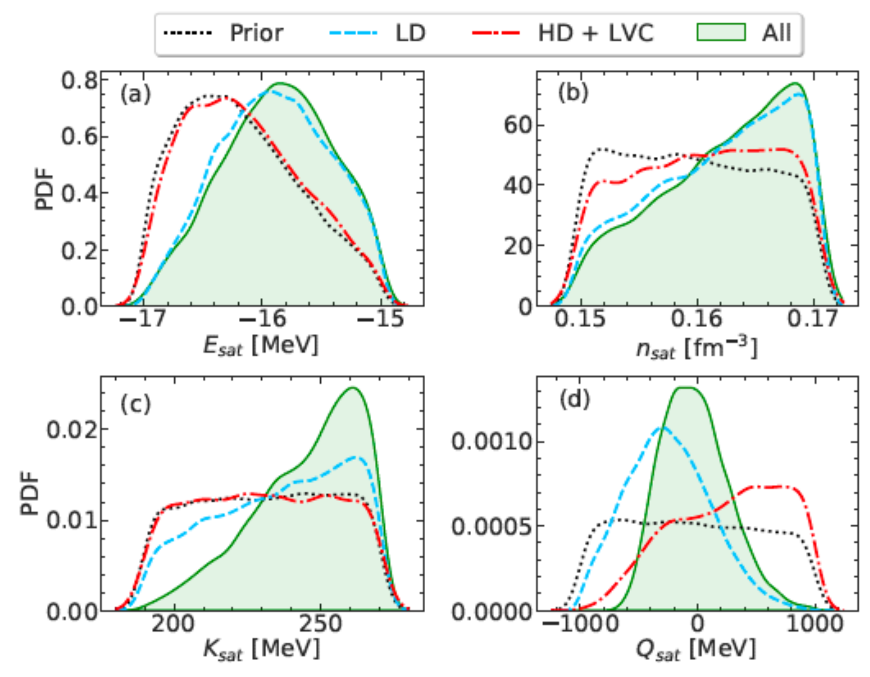


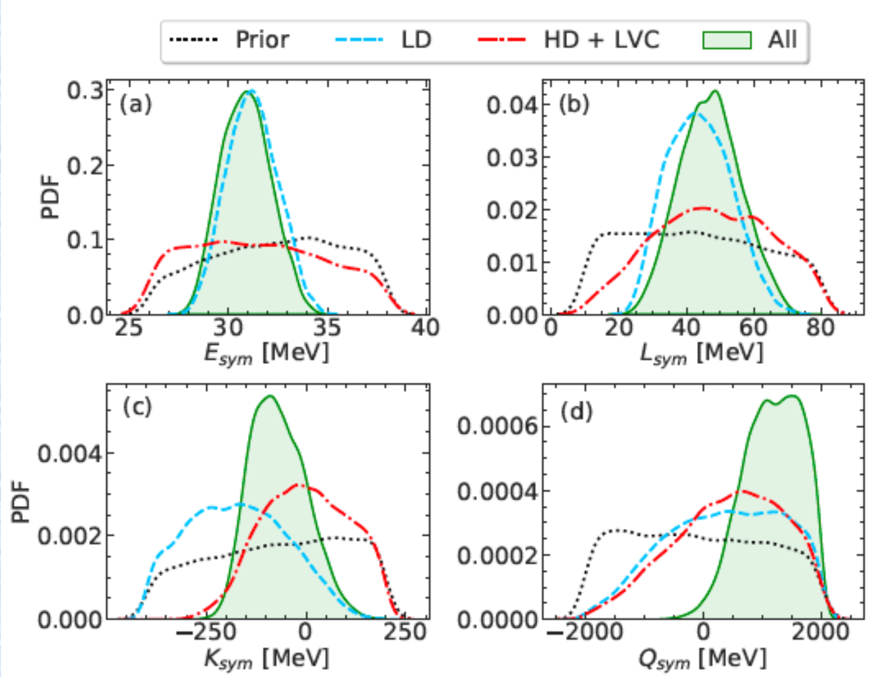
Dinh Thi et al., A&A 654, A114 (2021)

→ posterior compatible with observations
<u>but</u>: some popular models are not !

→ nucleonic hp compatible with observations

NS: empirical parameters





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

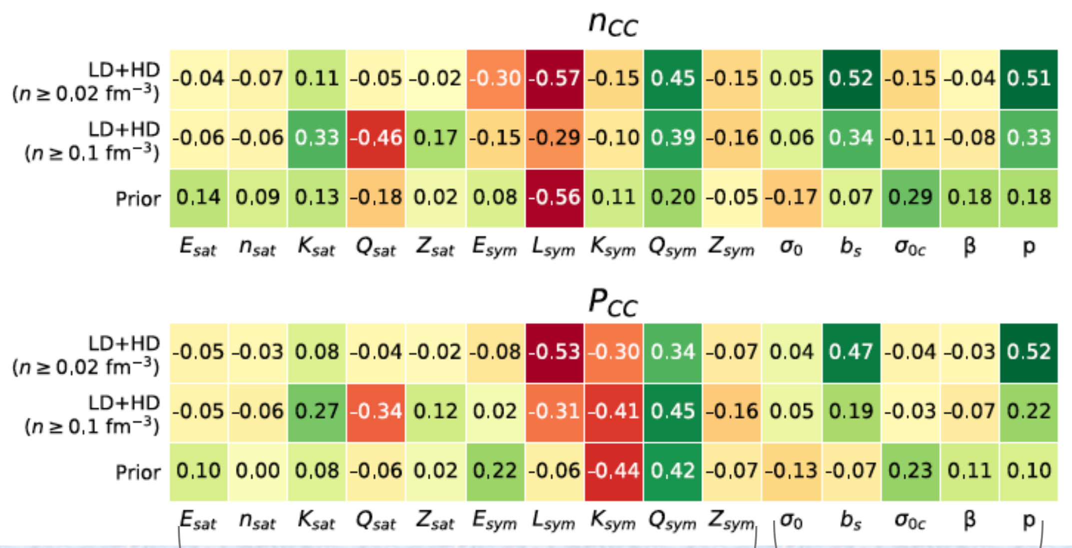
→ HD constraints have almost no impact on low-order parameters,
but impact on high-order parameters (poorly constrained by experiments)

→ LD constraints impact isovector and high-order parameters (also effective at low density)

see also B.A. Li's talk

NS: correlations and empirical param.

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

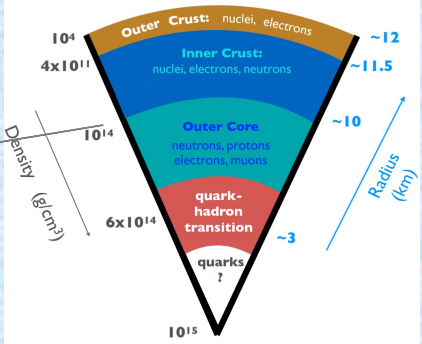
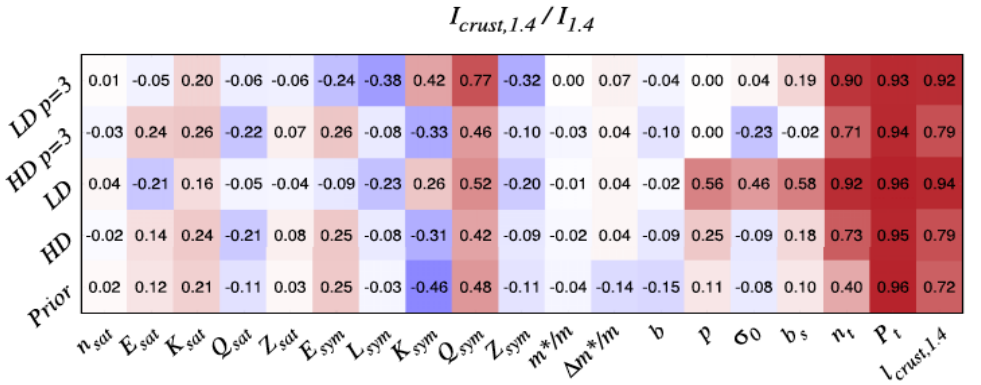


Image Credit: 3G Science White Paper

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	n_t	P_t	$I_{crust,1.4}$
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	0.90	0.93	0.92
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	0.71	0.94	0.79
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	0.92	0.96	0.94
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	0.73	0.95	0.79
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	0.40	0.96	0.72

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)

NS: beyond empirical parameters

LOW-DENSITY EOS

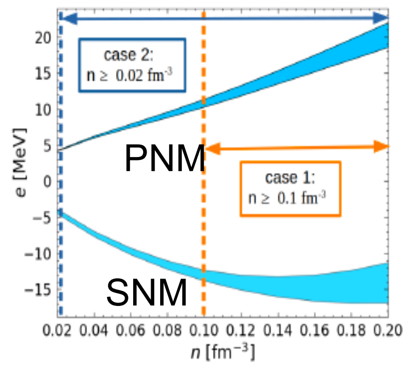
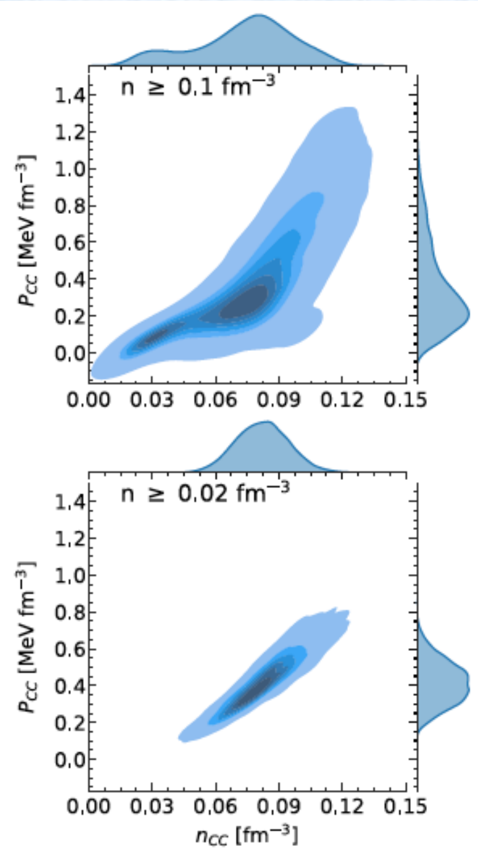
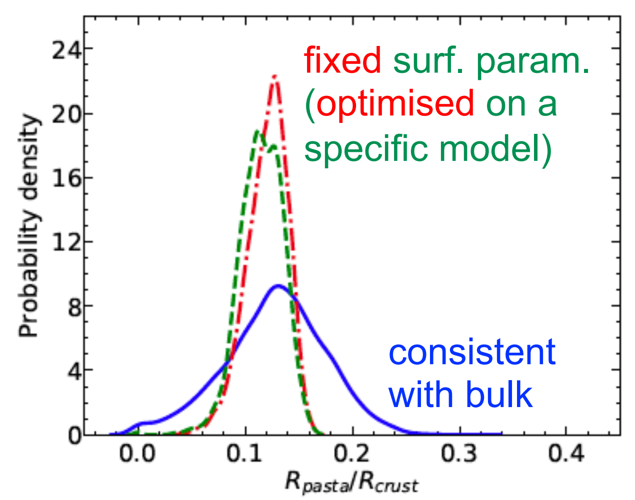


Fig. courtesy of H. Dinh Thi



SURFACE TERMS



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

→ importance of low-density EoS
→ importance of consistent calculation of the surface terms

Conclusions and open questions (NS)

- ❖ Dependence of predictions on the functional (in a complex way)
- ❖ High-order parameters also important for NS modelling
- ❖ Static properties: if GR → possible “extraction” of EoS (with uncertainties)

but :

- ✗ Even if $T = 0$ approx for mature NSs, description of phase transition challenging
- ✗ Other ingredients play a role
  - → low-density EoS
  - → surface terms (in neutron-rich nuclei)

➡ ✓ K_{sat} not the (only) key parameter

➡ ✓ need of (low-density) constraints from ab-initio theory
✓ need of experiments on neutron-rich nuclei to determine/extract different parameters (e.g. skins → L_{sym}; GMR in asymmetric matter → $K_{\tau,sym,\ldots}$)

Thank you