Electromagnetic Signatures of r-process Nucleosynthesis in Neutron Star Binary Mergers,
July 24 - August 18, 2017 (INT-17-2b)

Neutron star equation of state: the known and the unknown

Jérôme Margueron, IPN Lyon & INT Seattle

1- There exist many predictions for the nuclear EOS.
  - How could we quantify their differences?
  - How close there are from nuclear experimental knowledge?

2- Cold neutron stars: How nuclear experimental uncertainties propagate in extrapolation at high densities and isospin asymmetries?

3- Hot proto-neutron stars and ν propagation: What is the melting T of the pasta?

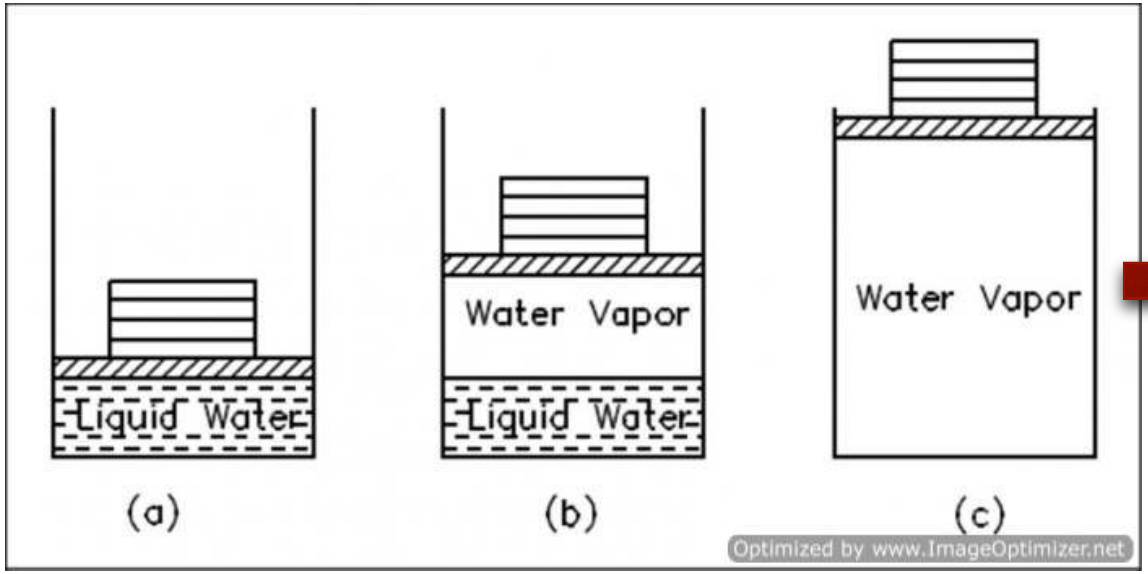
Collaboration with R. Casali (CTA Brazil), F. Gulminelli (LPC Caen), S. Reddy (INT), A. Roggero (INT).

Motivations

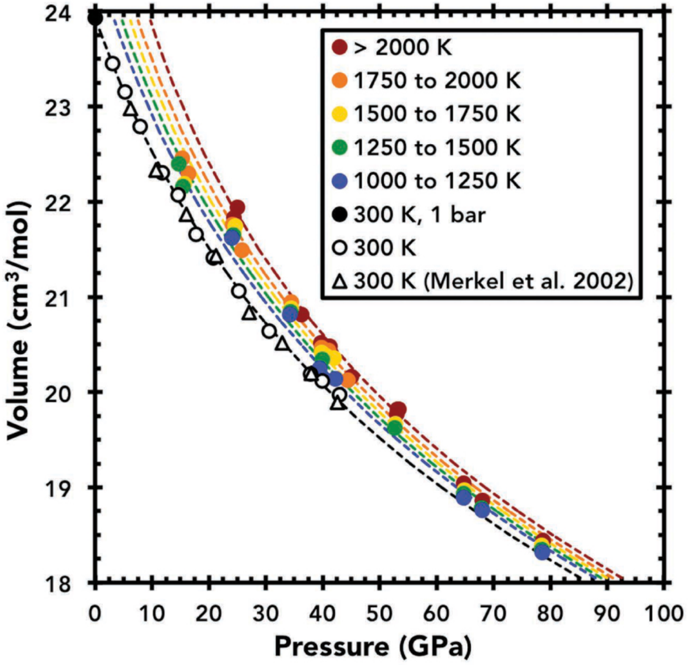
EOS: a nuclear physic challenge !

Equation of state in **condensed matter physics** :

Instrumental apparatus

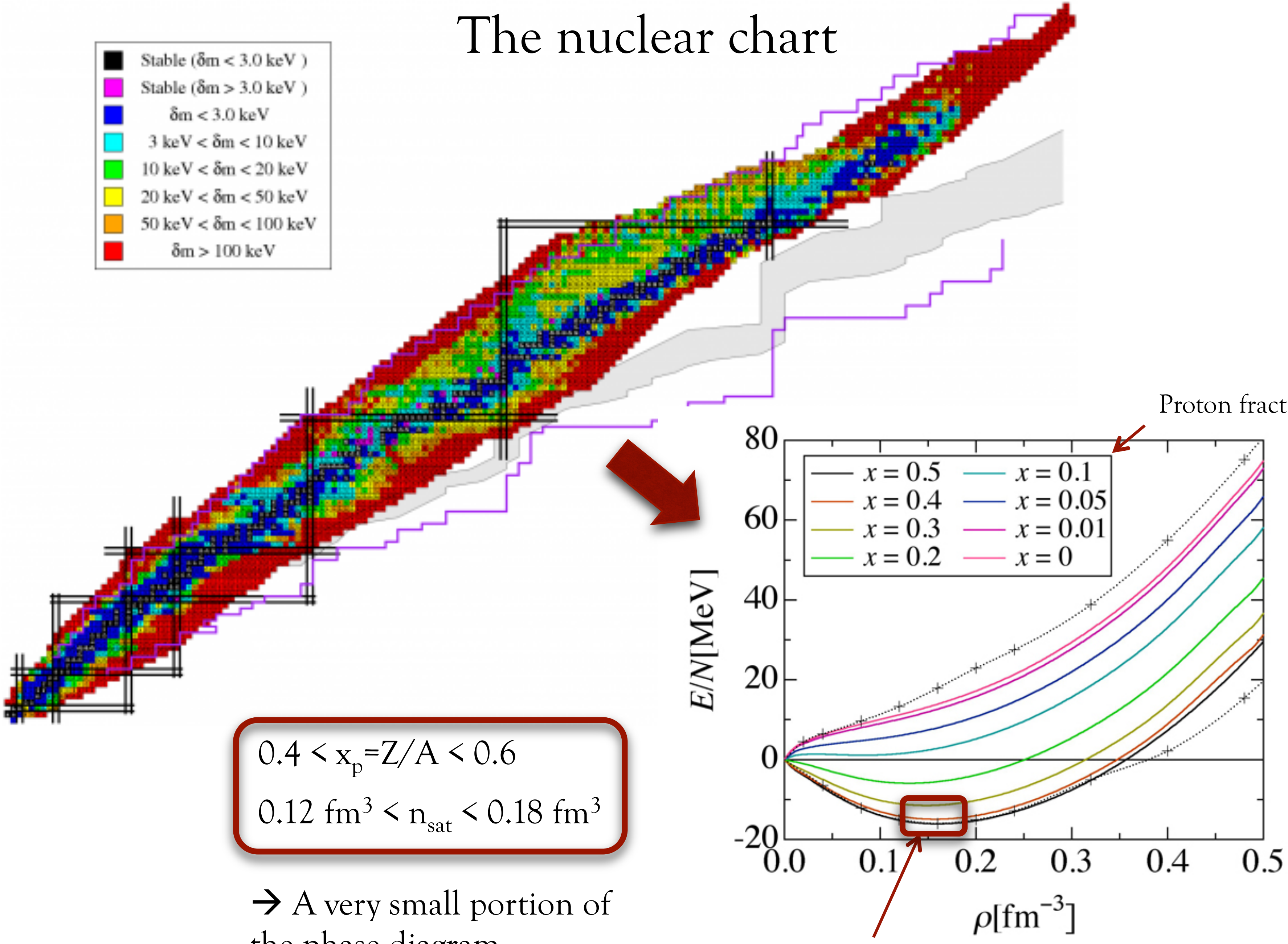


EOS of pyrite to 80 GPa and 2400 K,
Thompson et al.,
American Mineralogist 101 (2016) 1046



In nuclear physics, we only have 1 density (almost) at pressure P=0 !

The nuclear chart



Proton fraction

$0.4 < x_p = Z/A < 0.6$

$0.12\ \mathrm{fm}^3 < n_{sat} < 0.18\ \mathrm{fm}^3$

Saturation density n_{sat}

→ A very small portion of the phase diagram

Could NS observation data provide the nuclear EoS ?

Recent attempts to deduce the nuclear EoS from:

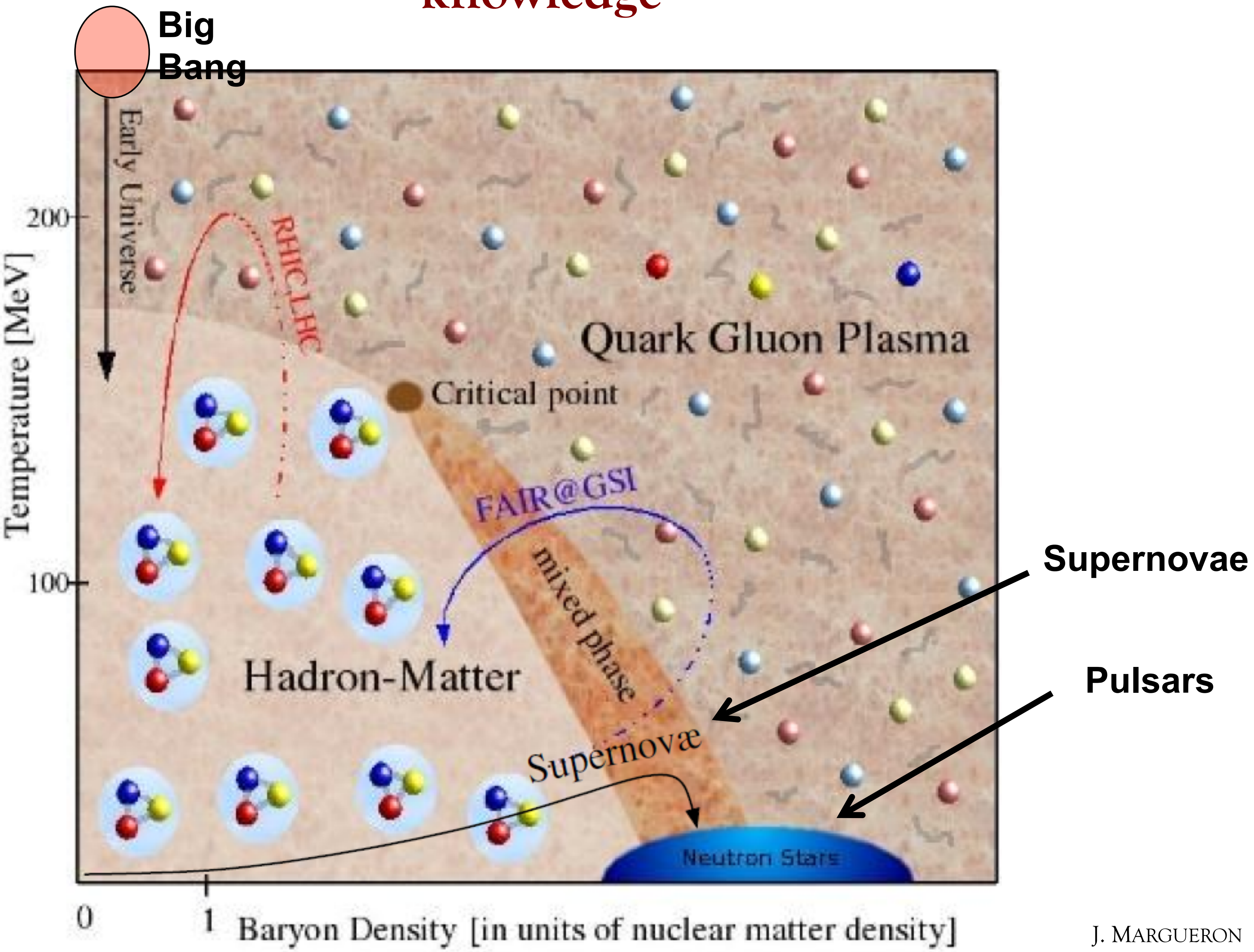
- thermal X-rays emission,
- X-ray pulsations (NICER),
- Photospheric expansion,
- …

Hebeler 2013
Ozel 2010, 2012, 2014
Steiner 2010, 2013
…

… NS merging (expected data from VIRGO/LIGO)

Maybe.. maybe not.. but nuclear physics experimental knowledge could help !

Prediction over the dense phase diagram challenges our knowledge



The empirical parameters:
a way to characterise the nuclear EOS
and
to link them to nuclear experimental data

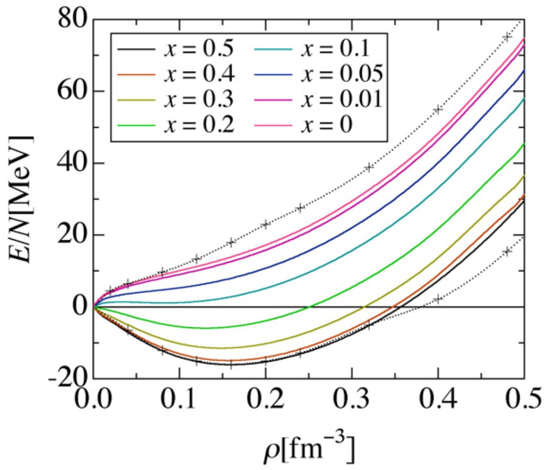
Empirical parameters

The **empirical parameters** code the **bulk** properties of the nuclear EoS.

Taylor expansion of the EoS around ρ_0 (theory):

$$\frac{E}{A} = E_{sat} + E_{sym}\delta^2 + (L_{sym}\delta^2)x + \frac{1}{2}(K_{sat} + K_{sym}\delta^2)x^2 + \dots$$

$$\text{where} \quad x = \frac{n - n_{sat}}{3n_{sat}} \quad \text{and} \quad \delta = \frac{n_n - n_p}{n}$$



Phenomenological mass formula (experiment):

- LD formula: $B(A,Z) = \overbrace{E_{sat} + E_{sym}I^2}^{\text{bulk}} + \overbrace{E_{surf}A^{-1/3}}^{\text{surface}} + \dots$
- Droplet formula: including skin contribution
- Compressible LD formula: $B(A,Z) = \frac{E}{A}(n_A, I) + E_{surf}A^{-1/3}$

$$A = N + Z$$

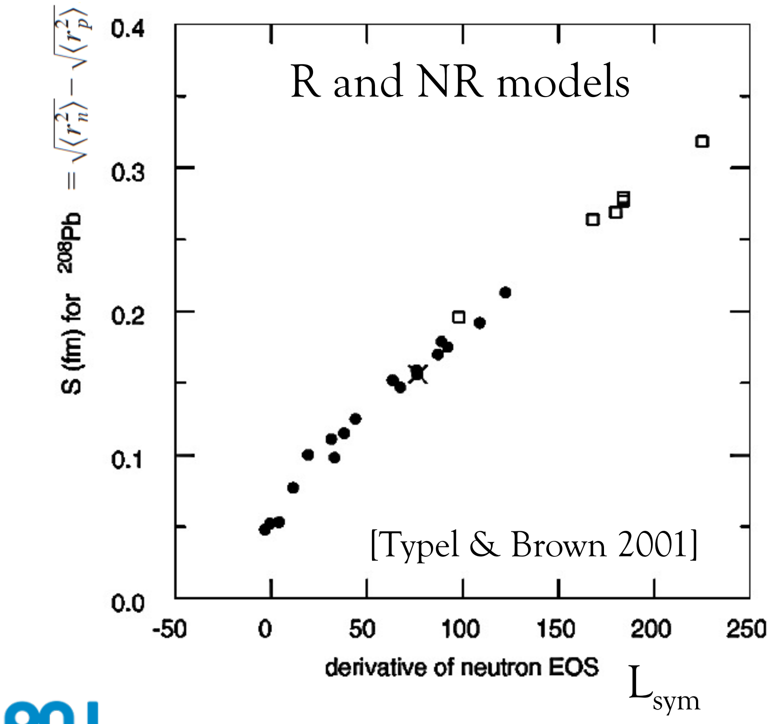
$$I = \frac{N - Z}{A}$$

$$n_A = n_{sat}\left(1 - \frac{3L_{sym}}{K_{sat}}I^2\right)$$

Experimental determination of the empirical parameters

- E_{sat}, E_{sym}: From fit of LDM through the nuclear chart, or from DFT adjustment.
- K_{sat}: from ISGMR [Blaizot, 1980]

  → better correlated to M_c [Khan, J.M. 2012]
- L_{sym}, K_{sym}: more difficult
  - Neutron skin in Pb,
  - ISGMR in neutron rich nuclei (K_{sym}, K_τ) [Garg+2010]



R and NR models

[Typel & Brown 2001]

Measurement of neutron skin:

With strong probes:

- p-N elastic diffusion
- π, α, d scattering
- π photoproduction
- Heavy-ion collisions
- Electric dipole polarizability

With weak probes:

- PREX / C-REX

How well do we know the empirical parameters ?

Definition:

Around n_{sat}: $$\frac{E}{A}(n,\delta) \approx e_{sat}(n) + e_{sym}(n)\delta^2 + e_{sym,4}(n)\delta^4 + \dots$$

with $$e_{sat}(n) = E_{sat} + \frac{1}{2}K_{sat}x^2 + \frac{1}{6}Q_{sat}x^3 + \frac{1}{24}Z_{sat}x^4 + \dots$$

$$e_{sym}(n) = E_{sym} + L_{sym}x + \frac{1}{2}K_{sym}x^2 + \frac{1}{6}Q_{sym}x^3 + \frac{1}{24}Z_{sym}x^4 + \dots$$

Determination:

- → Systematic comparison of model predictions:
  - → Non relativistic interactions: Skyrme, Gogny, …
  - → Relativistic: RMF, RHF
- → For models being adjusted on nuclear properties (binding energy, charge radius, etc…)

Empirical parameters from various effective approaches

Model		ρ_0	E_0	K_0	Q_0	Z_0	E_{sym}	L_{sym}	K_{sym}	Q_{sym}	Z_{sym}
		fm^{-3}	MeV	MeV	MeV	MeV	MeV	MeV	MeV	MeV	MeV
Skyrme	Average	0.1586	-15.91	251.68	-300.20	1178.35	31.22	53.52	-130.15	316.68	-1890.99
	σ	0.0040	0.21	45.42	157.81	848.47	2.03	31.06	132.03	218.23	1191.23
RMF	Average	0.1494	-16.24	267.99	-1.94	5058.30	35.11	90.20	-4.58	271.07	-3671.83
	σ	0.0025	0.06	33.52	392.51	2294.07	2.63	29.56	87.66	357.13	1582.34
RHF	Average	0.1540	-15.97	248.06	389.17	5269.07	33.97	90.03	128.16	523.29	-9955.49
	σ	0.0035	0.08	11.63	350.44	838.41	1.37	11.06	51.11	236.80	4155.74
Average		0.1540	-16.04	255.91	29.01	3835.24	33.43	77.92	-2.19	370.34	-5172.77
σ		0.0051	0.20	34.39	424.59	2401.14	2.64	30.84	142.71	298.54	4362.35

$$e_{sat}(n) = E_{sat} + \frac{1}{2}K_{sat}x^2 + \frac{1}{6}Q_{sat}x^3 + \frac{1}{24}Z_{sat}x^4 + \ldots$$

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Empirical parameters from various effective approaches

1 % accuracy

Model		ρ_0	E_0	K_0	Q_0	Z_0	E_{sym}	L_{sym}	K_{sym}	Q_{sym}	Z_{sym}
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Empirical parameters from various effective approaches

10-20 % accuracy

Model		ρ_0	E_0	K_0	Q_0	Z_0	E_{sym}	L_{sym}	K_{sym}	Q_{sym}	Z_{sym}
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Empirical parameters from various effective approaches

50 % accuracy

Model		ρ_0	E_0	K_0	Q_0	Z_0	E_{sym}	L_{sym}	K_{sym}	Q_{sym}	Z_{sym}
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Empirical parameters from various effective approaches

Very large inaccuracy

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Empirical parameters from various effective approaches

fixed Explore inside small interval Consider large interval

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σ		0.0051	0.20	34.39	424.59	2401.14	2.64	30.84	142.71	298.54	4362.35

- In the following, we neglect any correlation among the empirical parameters.
- Another approach is possible: apply the eEOS directly in nuclei and fix the uncertainties directly from the experimental data ++ bring physical correlations (work in progress).

Phenomenological + ab-initio approaches

Model (N_α)	der. order	E_{sat} MeV 0	E_{sym} MeV 0	n_{sat} fm^{-3} 1	L_{sym} MeV 1	K_{sat} MeV 2	K_{sym} MeV 2	Q_{sat} MeV 3	Q_{sym} MeV 3	Z_{sat} MeV 4	Z_{sym} MeV 4	m^*_{sat}/m -	$\Delta m^*_{sat}/m$ -	κ_v -	K_τ MeV -
					Phenomenological approaches										
Skyrme	Average	-15.88	30.25	0.1595	47.8	234	-130	-357	378	1500	-2219	0.73	0.08	0.46	-344
(16)	σ	0.15	1.70	0.0011	16.8	10	66	22	110	169	617	0.10	0.24	0.27	25
Skyrme	Average	-15.87	30.82	0.1596	49.6	237	-132	-349	370	1448	-2175	0.77	0.127	0.44	-354
(35)	σ	0.18	1.54	0.0039	21.6	27	89	89	188	510	1069	0.14	0.310	0.37	45
RMF	Average	-16.24	35.11	0.1494	90.2	268	-5	-2	271	5058	-3672	0.67	-0.09	0.40	-549
(11)	σ	0.06	2.63	0.0025	29.6	34	88	393	357	2294	1582	0.02	0.03	0.06	153
RHF	Average	-15.97	33.97	0.1540	90.0	248	128	389	523	5269	-9956	0.74	-0.03	0.34	-572
(4)	σ	0.08	1.37	0.0035	11.1	12	51	350	237	838	4156	0.03	0.01	0.07	169
Total	Average	-16.03	33.30	0.1543	76.6	251	-3	13	388	3925	-5268	0.72	0.01	0.39	-492
(50)	σ_{tot}	0.20	2.65	0.0054	29.2	29	132	431	289	2270	4282	0.09	0.20	0.22	166
	Min	-16.35	26.83	0.1450	9.9	201	-394	-748	-86	-903	-16916	0.38	-0.47	0.00	-835
	Max	-15.31	38.71	0.1746	122.7	355	213	950	846	9997	-5	1.11	1.02	2.02	-254
					Ab-initio approaches										
APR	Average	-16.0	33.12	0.16	50.0	270	-199	-665	923	337	-2053	1.0	0.0	0.0	-376
(1)	σ	$-^\dagger$	0.30	$-^\dagger$	1.3	2	13	30	67	94	125	$-^\dagger$	$-^\dagger$	$-^\dagger$	30
χ-EFT	Average	-15.16	32.01	0.171	48.1	214	-172	-139	-164	1306	-2317	-	-	-	-428
Drischler 2016	σ_{tot}	1.24	2.09	0.016	3.6	22	40	104	234	214	379	-	-	-	63
(7)	Min	-16.92	28.53	0.140	43.9	182	-224	-310	-640	901	-2961	-	-	-	-534
	Max	-13.23	34.57	0.190	53.5	242	-108	24	96	1537	-1750	-	-	-	-334

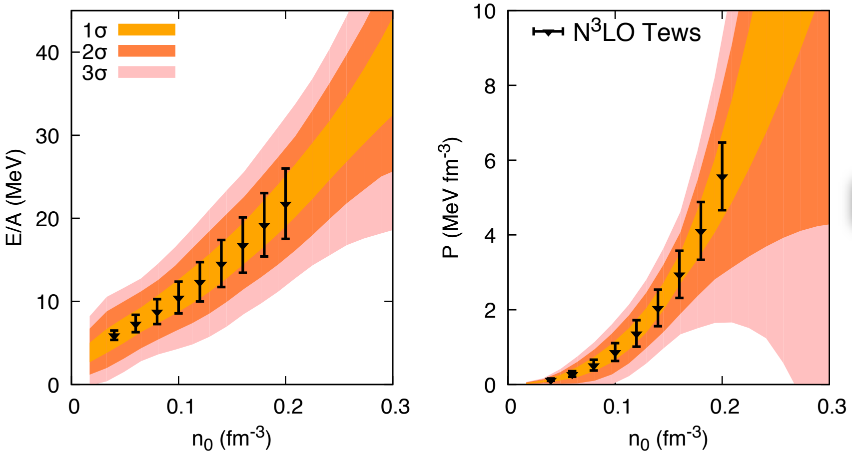
† This parameter is fixed.

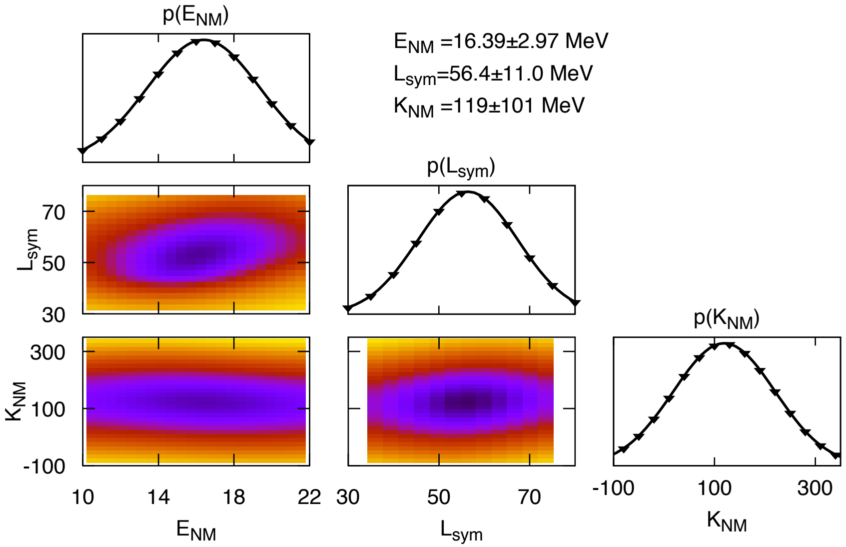
In neutron matter

Model (N_α)		E_{NM} MeV	L_{sym} MeV	K_{NM} MeV	Q_{NM} MeV	Z_{NM} MeV
Phenomenological approaches						
Skryme	Average	14.95	49.6	106	21	-727
(35)	σ	1.72	21.6	116	276	1580
RMF	Average	18.86	90.2	263	269	1386
(11)	σ	2.69	29.6	121	750	3876
RHF	Average	17.99	90.0	376	912	-4686
(4)	σ	1.46	11.1	63	587	4994
Ab-initio approaches						
APR	Average	17.27	50.0	71	258	-1716
(1)	σ	0.30	1.3	15	97	219
GCR 2012	Average	16.76	45.8	77	80	-131
(7)	σ	1.39	9.7	43	29	15
χ-EFT	Average	16.39	56.4	119	-	-
Tews 2013	σ	2.97	11.0	101	-	-
χ-EFT	Average	16.93	48.3	41	-314	-991
Drischler 2016 (7)	σ	0.92	3.5	33	226	349

Bayesian analysis of chiral EFT predictions

I. Tews et al., PRL 110, (2013)





E_{NM} =16.39±2.97 MeV
L_{sym}=56.4±11.0 MeV
K_{NM} =119±101 MeV

Estimation of the error: $\chi^2 = \frac{1}{2M-3}\sum_{i=1}^{M}\left(\frac{e_i - e_{ELFc}(n_0^i)}{\varepsilon_i^e}\right)^2 + \left(\frac{p_i - p_{ELFc}(n_0^i)}{\varepsilon_i^p}\right)^2$

Likelihood probability: $p(E_{NM}, L_{sym}, K_{NM}) = \exp(-\chi^2/2)$

1-parameter probability: $p(A) = \sum_{B,C} p(A,B,C)$

The « model independent » EOS can include constraints from ab-initio calculations.

In Summary

In the following, we consider the following central values and uncertainties (1σ):

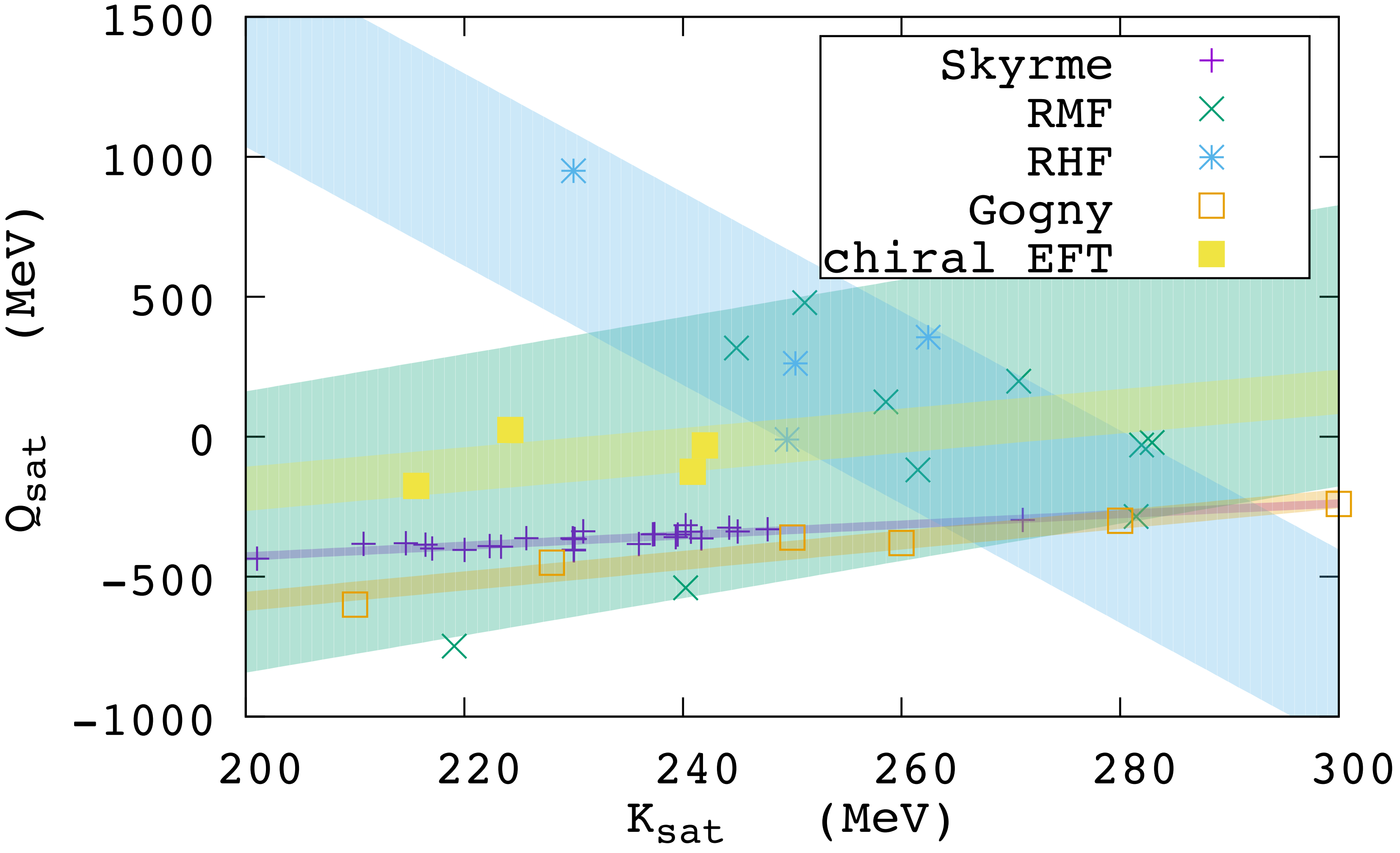
P_α	E_{sat}	E_{sym}	n_{sat}	L_{sym}	K_{sat}	K_{sym}	Q_{sat}	Q_{sym}	Z_{sat}	Z_{sym}	m^*_{sat}/m	$\Delta m^*_{sat}/m$
	MeV	MeV	fm^{-3}	MeV	MeV	MeV	MeV	MeV	MeV	MeV		
$\langle P_\alpha \rangle$	-15.8	32	0.155	60	230	-100	300	0	-500	-500	0.75	0.1
σ_{P_α}	±0.3	±2	±0.005	±15	±20	±100	±400	±400	±1000	±1000	±0.1	±0.1

Large uncertainties

→ What impact for the nuclear EOS?

A “model independent” nuclear EOS

The question of the spurious correlations



→ To few parameters in symmetric matter.

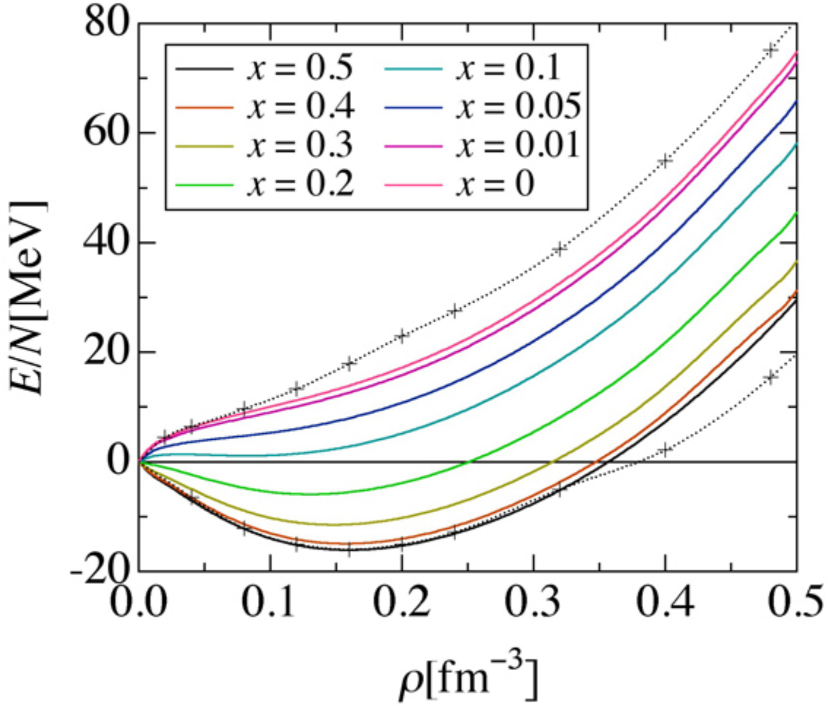
→ General issues: results can be model-dependent.

Needs for a "model independent" nuclear EoS

- For the analysis of NS observation (thermal X-rays, X-ray pulsations, etc…)
  - Extraction of NS radius
- For implementation in hydro-dynamical codes (CCSN, NS mergers, etc…)
- For Heavy Ion Collisions (Hadron physics) and analysis of the results

The nuclear EoS is a function of the density, isospin asymmetry (n/p ratio) and temperature.

Here we do not consider phase transitions to hyperon matter or quark matter.



An “model independent” nuclear EoS

Hypothesis:

1) Matter is non-relativitic (→ E=T+V),
2) Nuclear potential quadratic in δ,
3) The EoS is analytic in x (→ polynomial expansion possible),
4) lim e(ρ,δ) → 0 for ρ → 0.

Kinetic energy:

$$t^{eff}(\rho,\delta) = \frac{1}{2} t_0^{FG} \left(\frac{\rho}{\rho_0}\right)^{2/3} \left[f^{FG}(\delta) + \frac{\rho}{\rho_0} f^{eff}(\delta) \right]$$

Binding energy:

$$e^N(\rho,\delta) = t^{eff}(\rho,\delta) + \sum_{\alpha\geq 0}^{N} \left[v_\alpha^{s,is} + v_\alpha^{s,iv} \delta^2 \right] \frac{x^\alpha}{\alpha!} u_\alpha(\rho)$$

satisfy the limit ρ→0

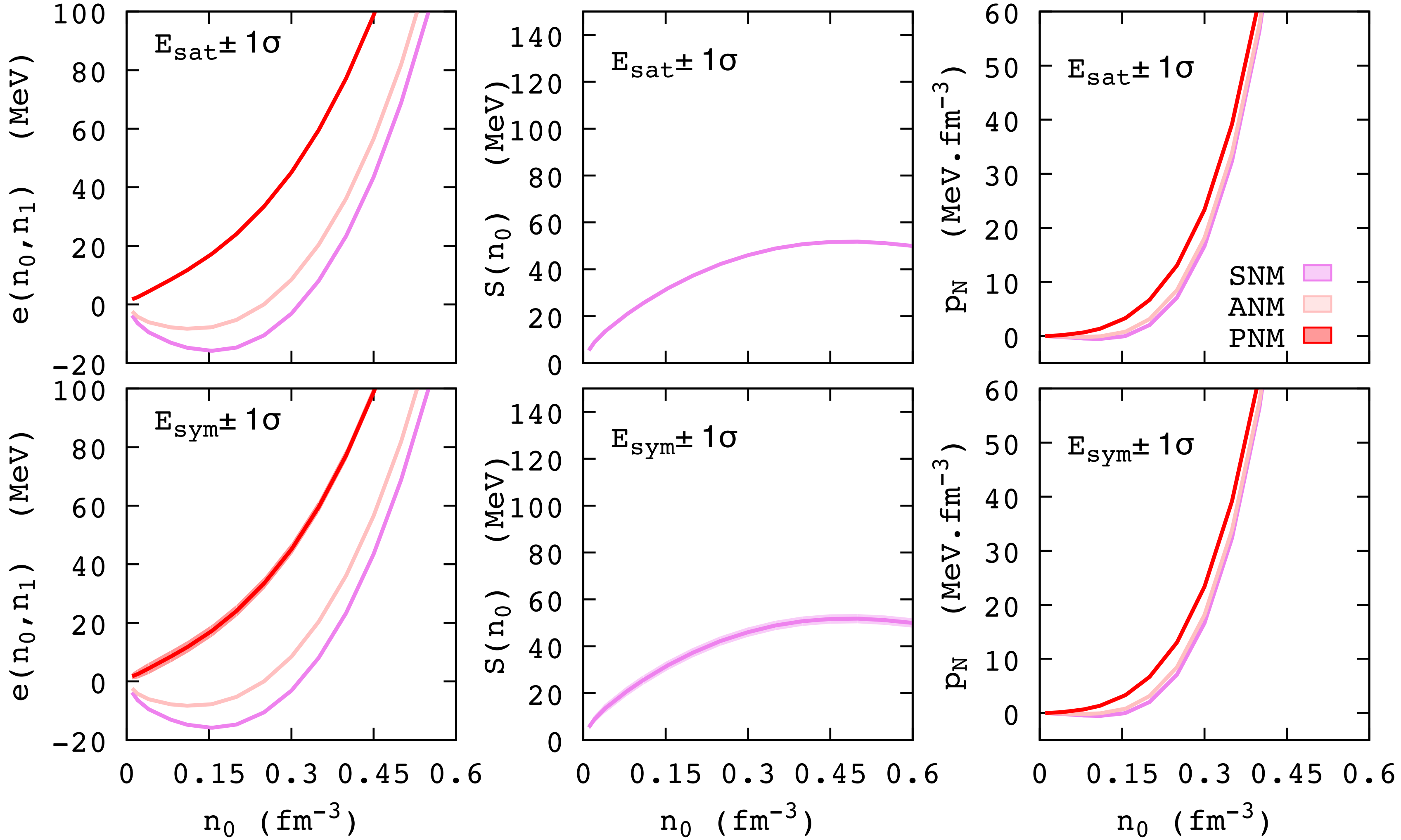
→ One-to-one correspondence between model parameters and empirical quantities:

$$v_{\alpha=0}^{s,is} = E_0 - t_0^{FG}(1+\bar{M})$$
$$v_{\alpha=1}^{s,is} = -t_0^{FG}(2+5\bar{M})$$
$$v_{\alpha=2}^{s,is} = K_0 - 2t_0^{FG}(-1+5\bar{M})$$
$$v_{\alpha=3}^{s,is} = Q_0 - 2t_0^{FG}(4-5\bar{M})$$
$$v_{\alpha=4}^{s,is} = Z_0 - 8t_0^{FG}(-7+5\bar{M})$$

→ Flexible model with no hidden correlations among parameters.

→ Can map most of nucleon EOS (up to 4n_{sat}): “model independent” EOS.

Impact of E_{sat} & E_{sym}



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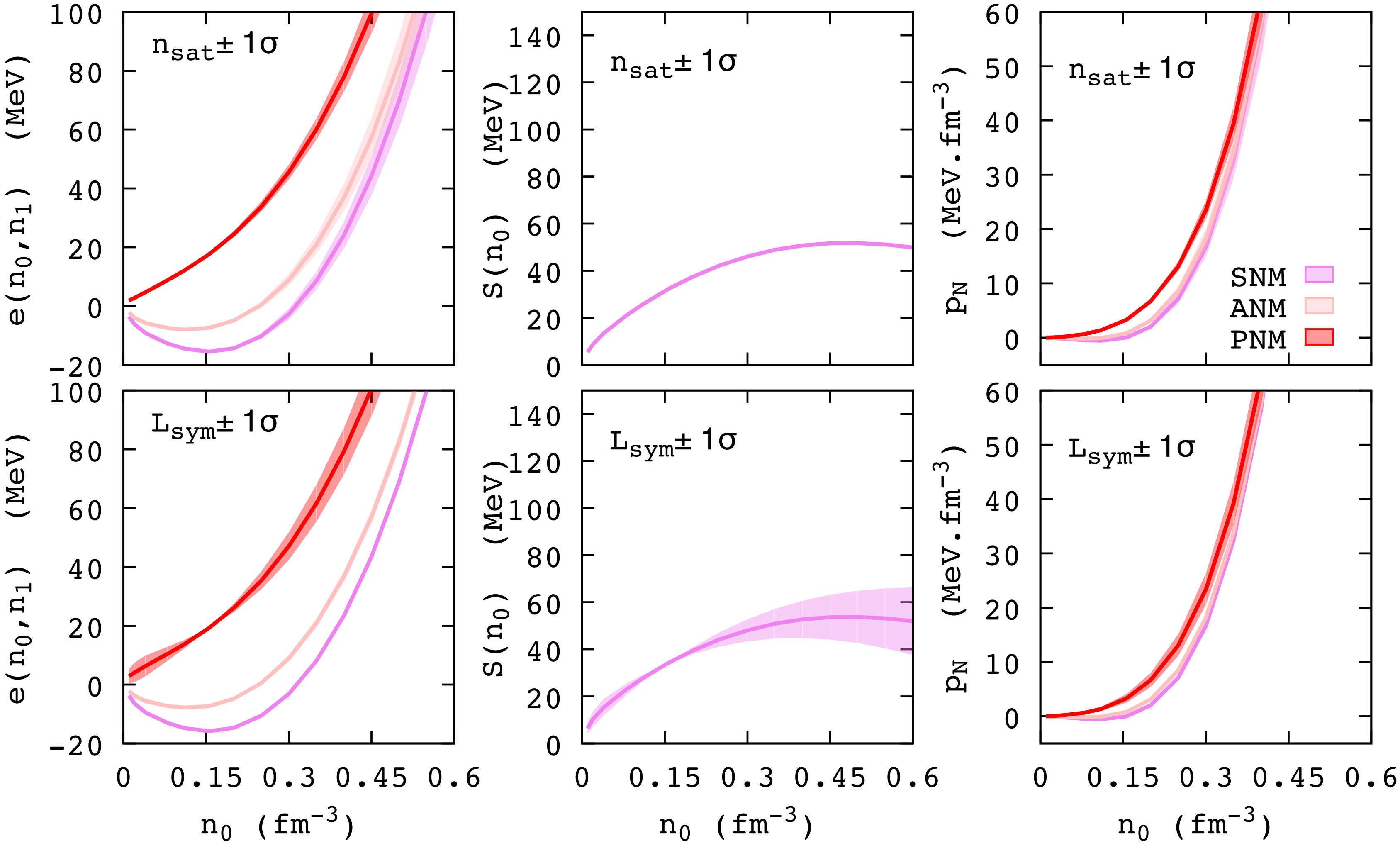
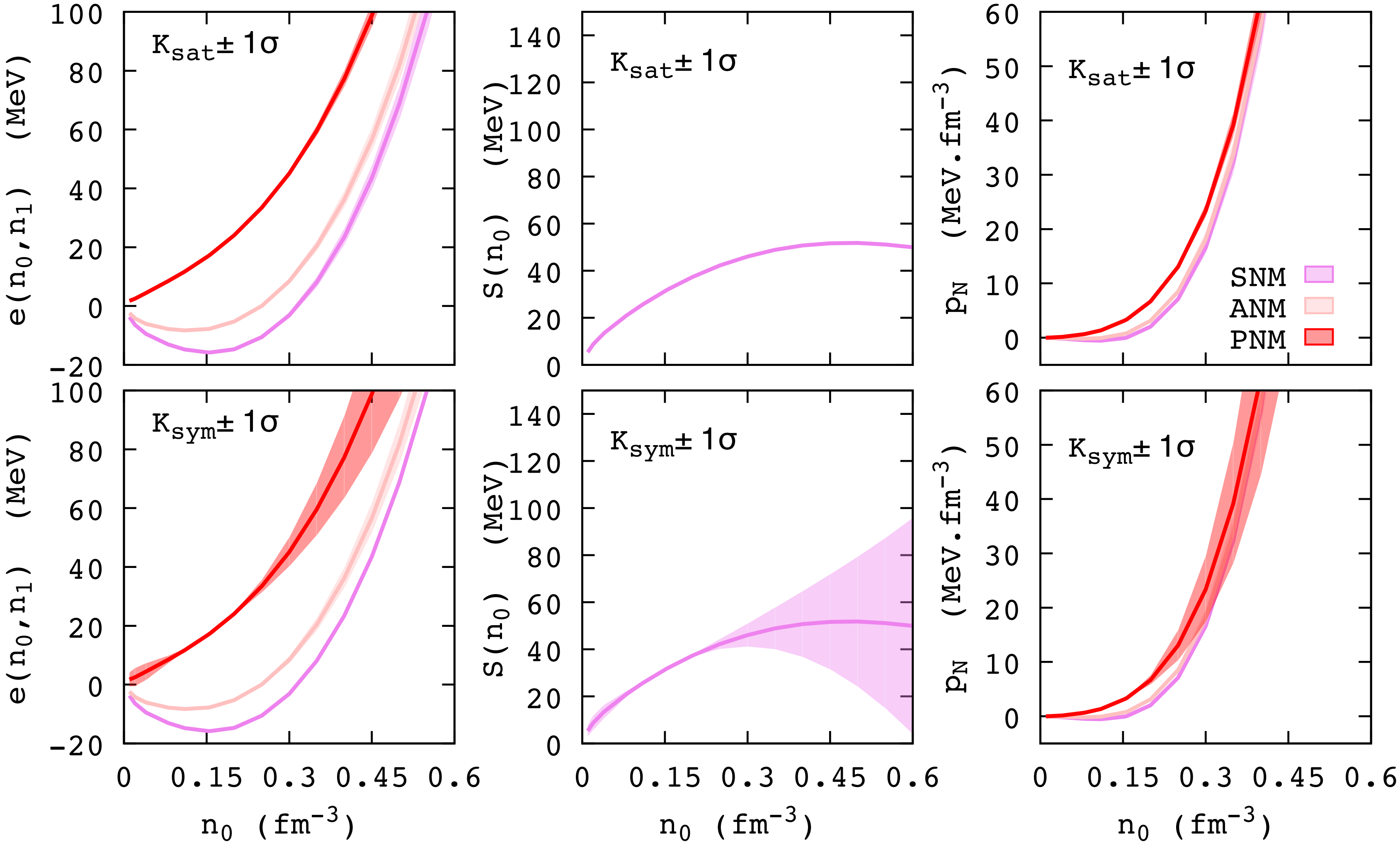
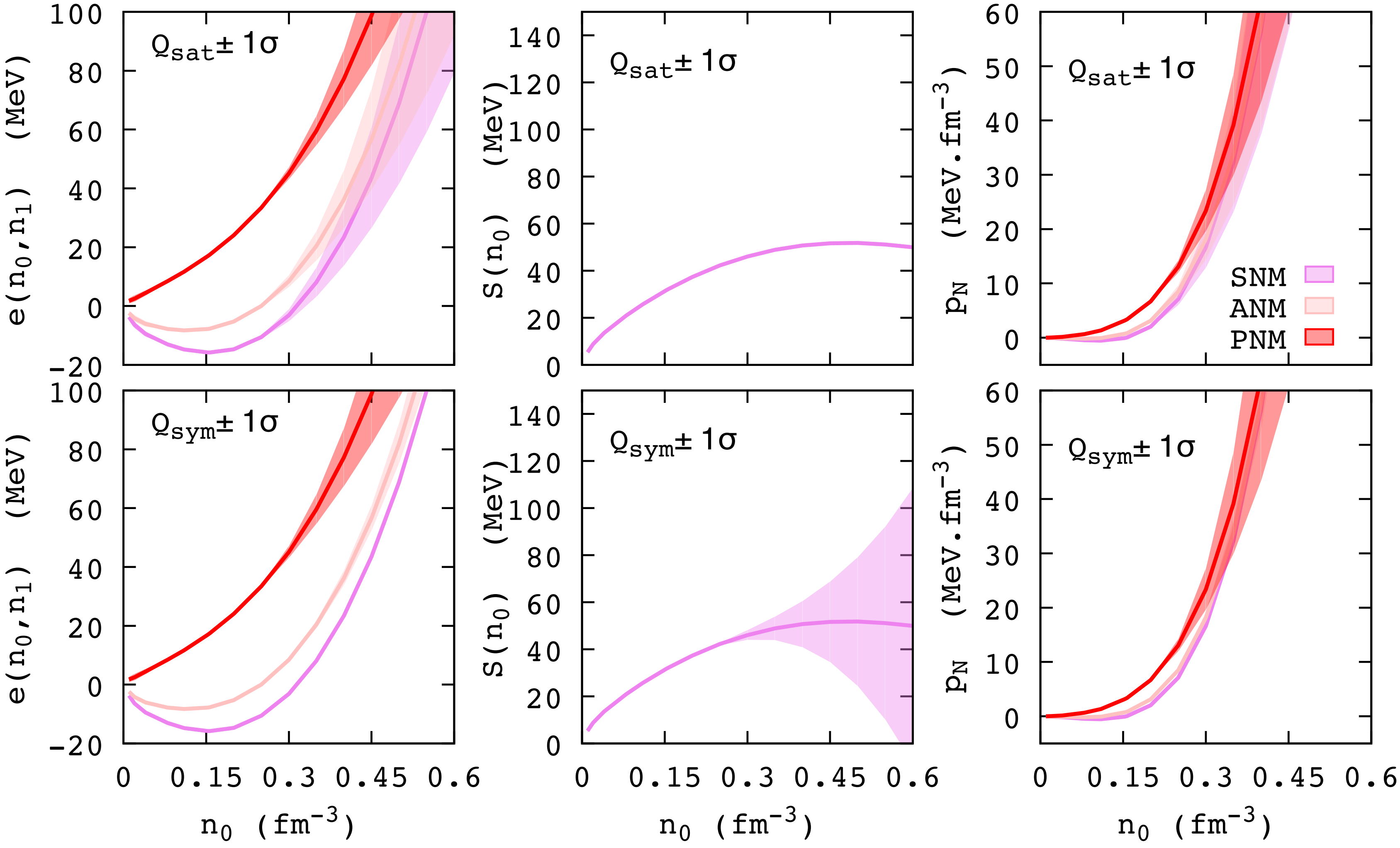
Impact of n_{sat} & L_{sym}



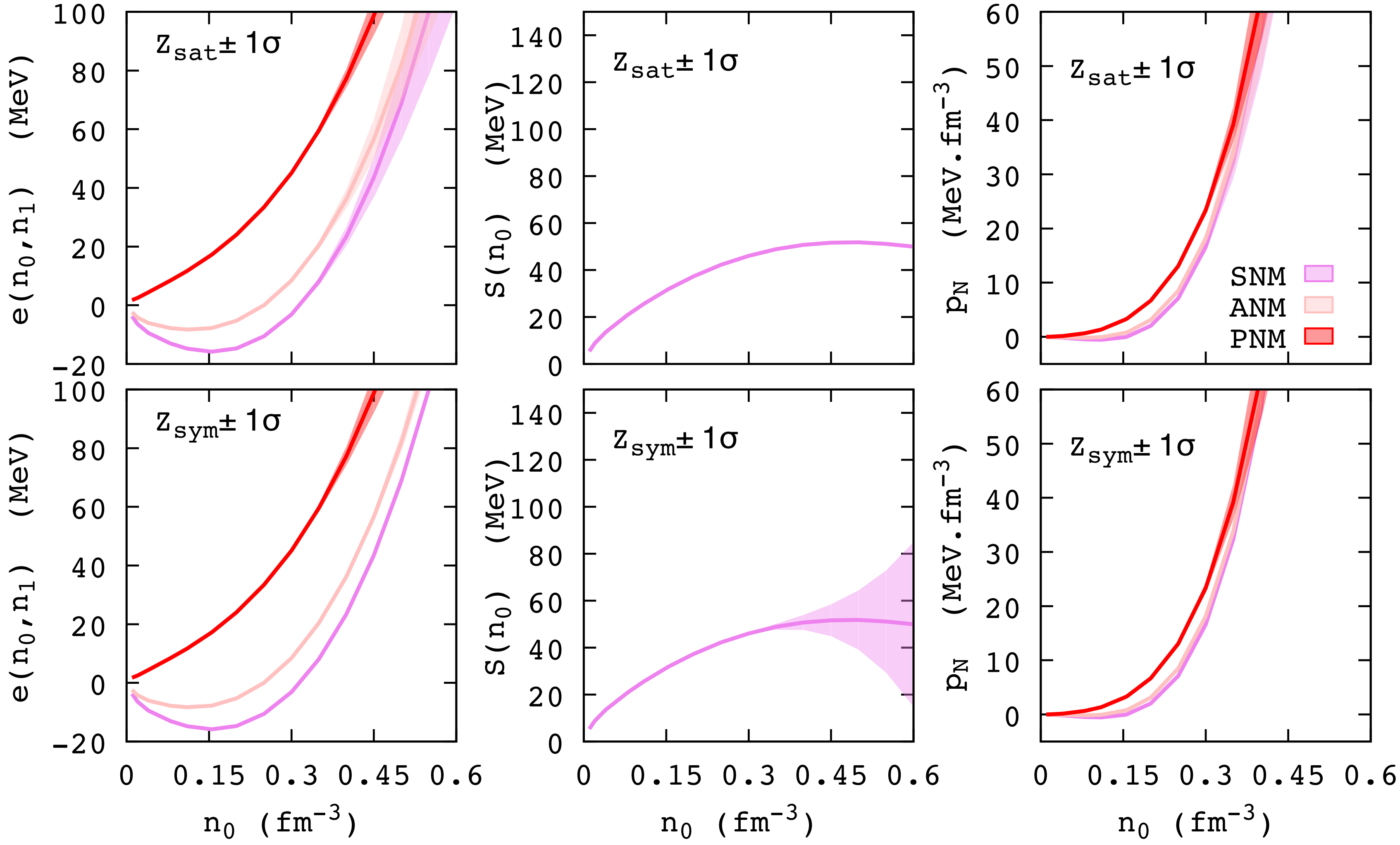
Impact of K_{sat} & K_{sym}



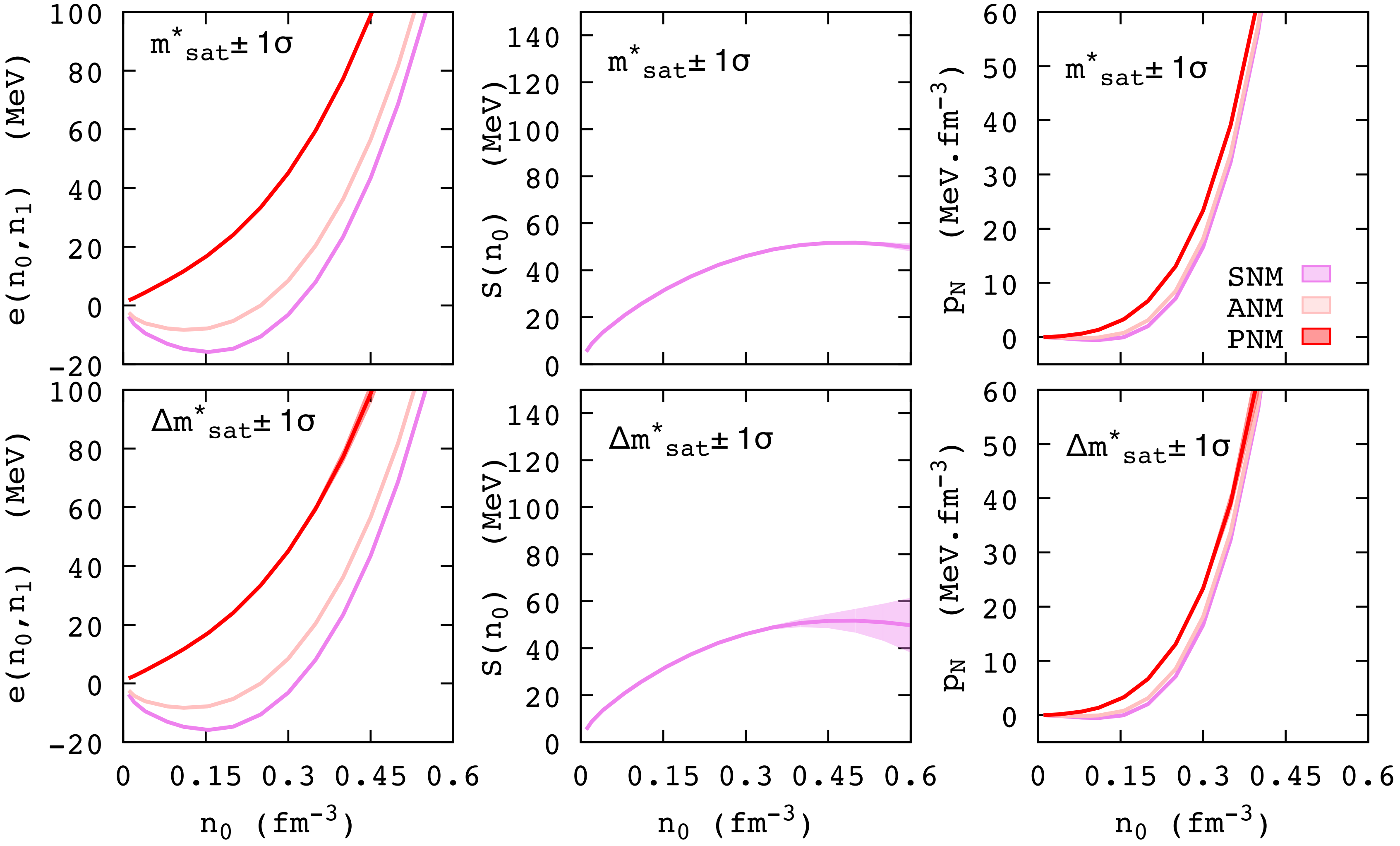
Impact of Q_{sat} & Q_{sym}



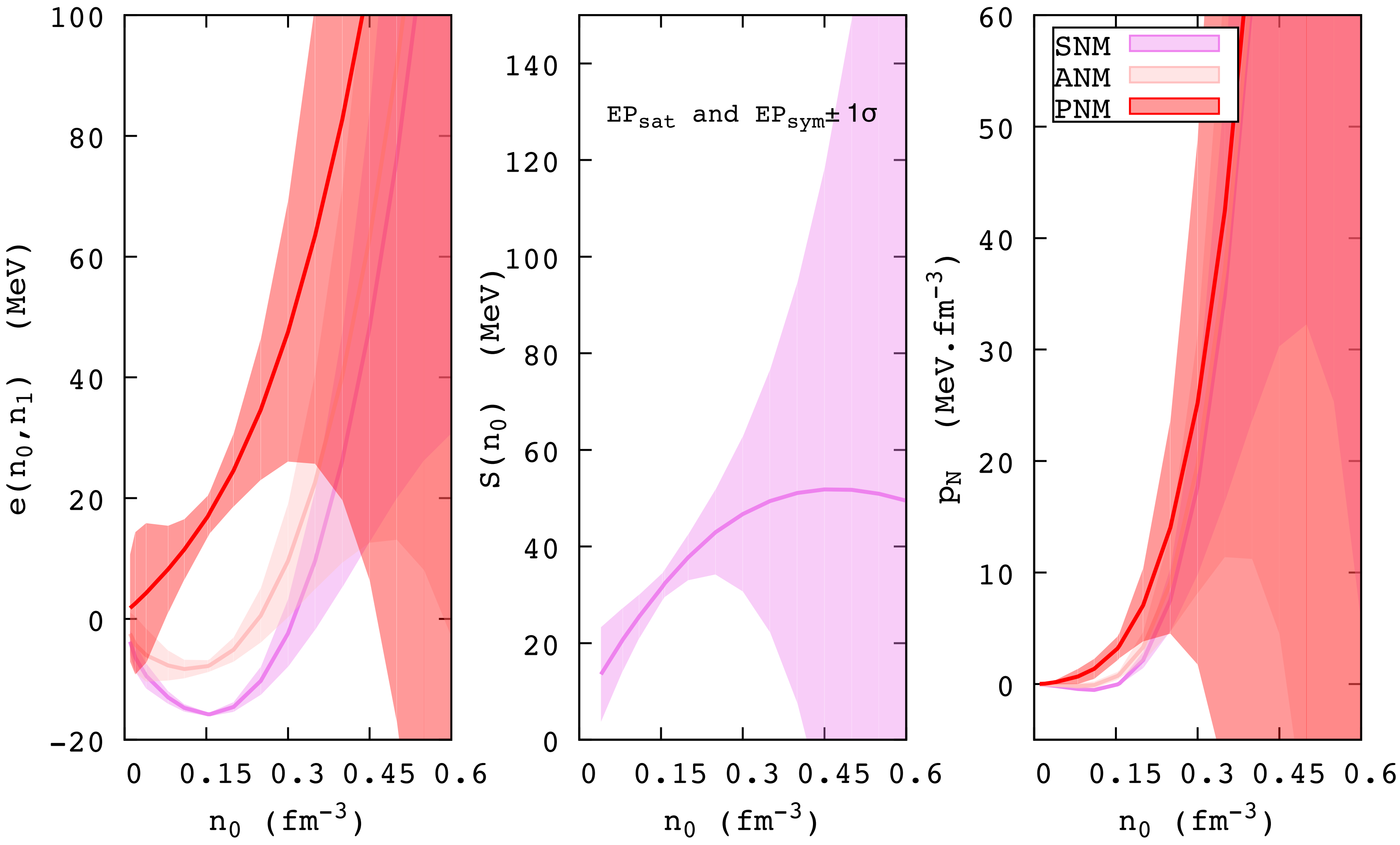
Impact of Z_{sat} & Z_{sym}



Impact of m^*_{sat} & Δm^*_{sat}



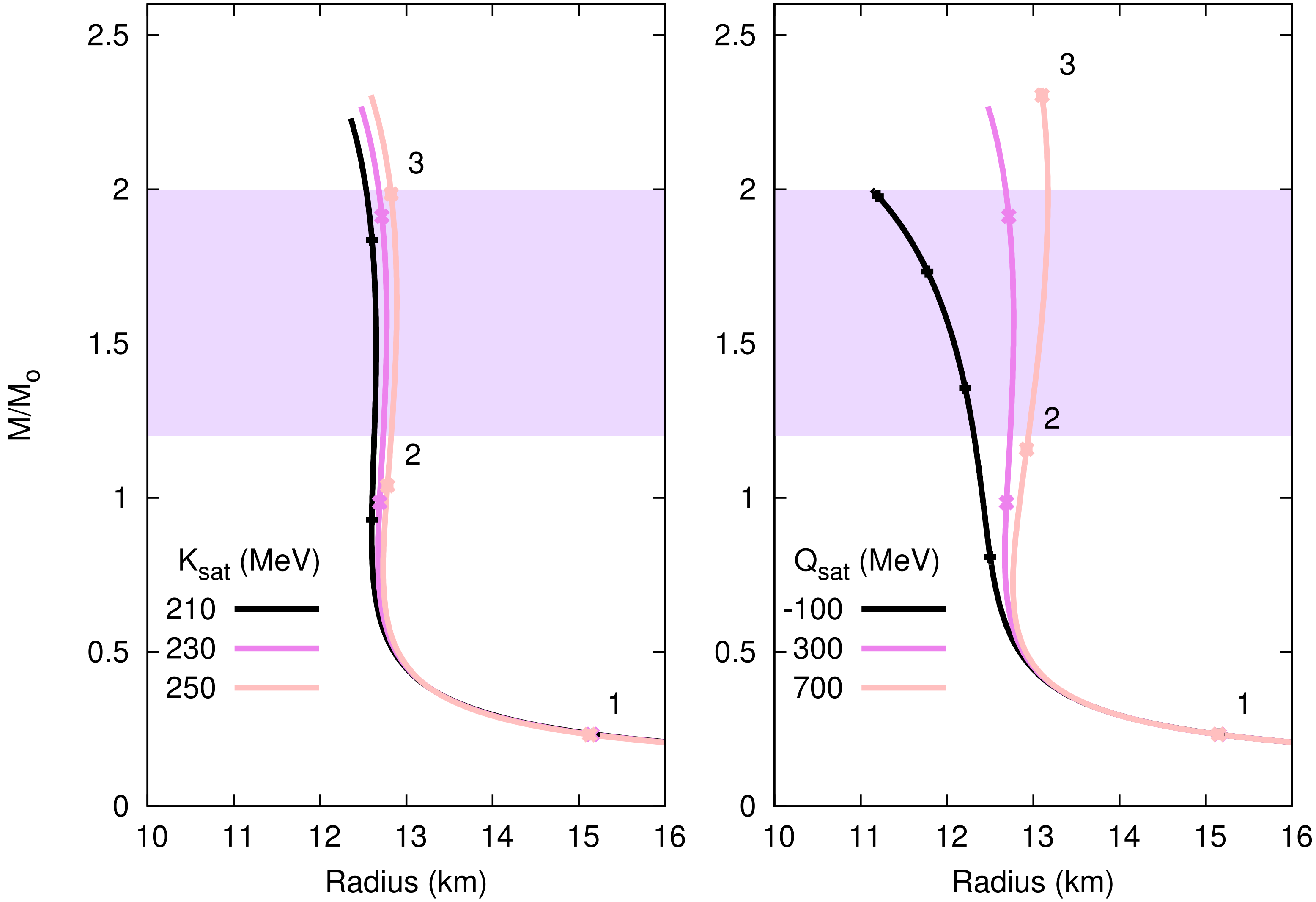
Impact of varying all uncertainties ± 1σ



Many EOS does not satisfy basic requirements (stability, causality, …)
→ We need to remove them

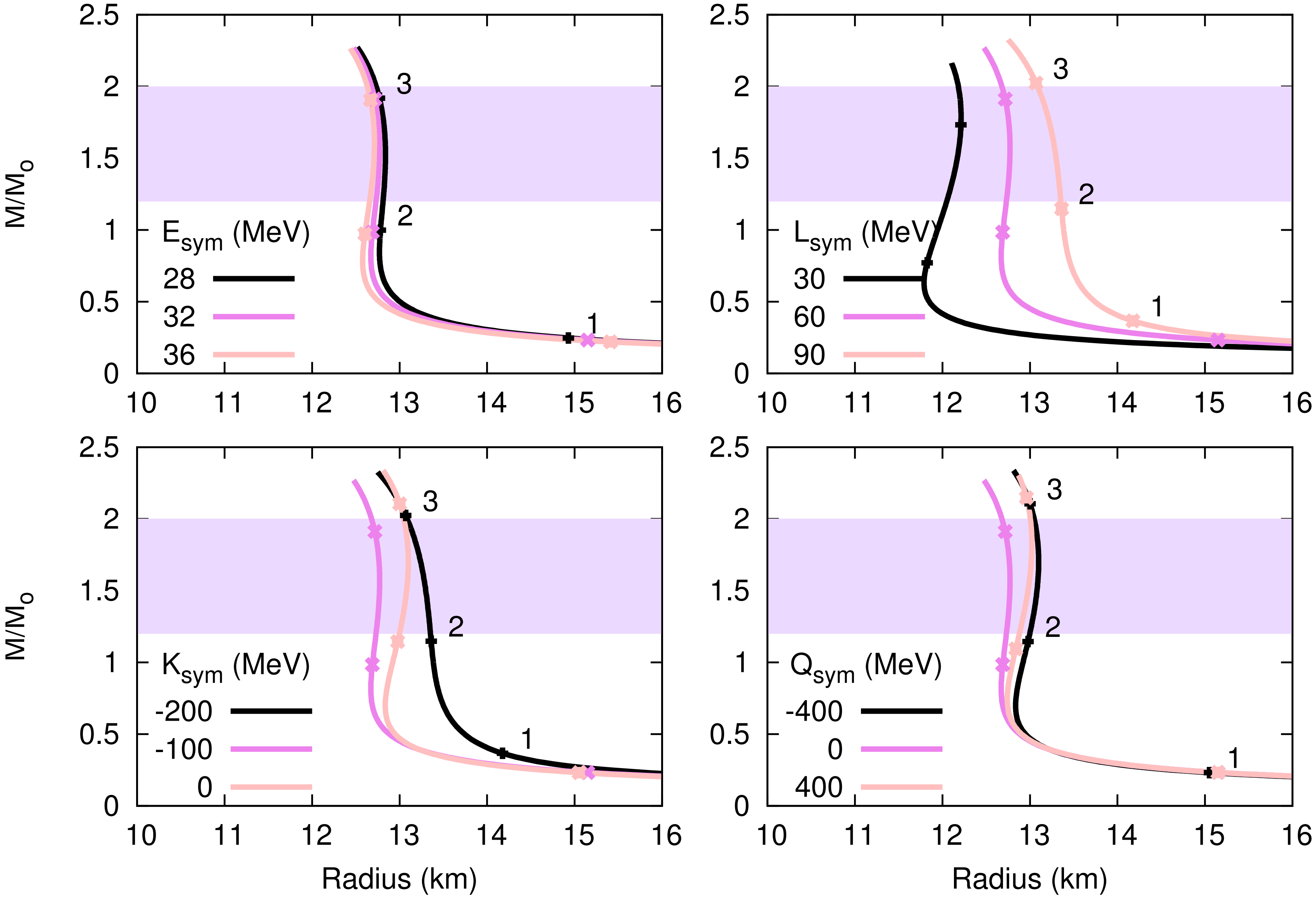
Application to neutron star

Impact of the isoscalar empirical parameters



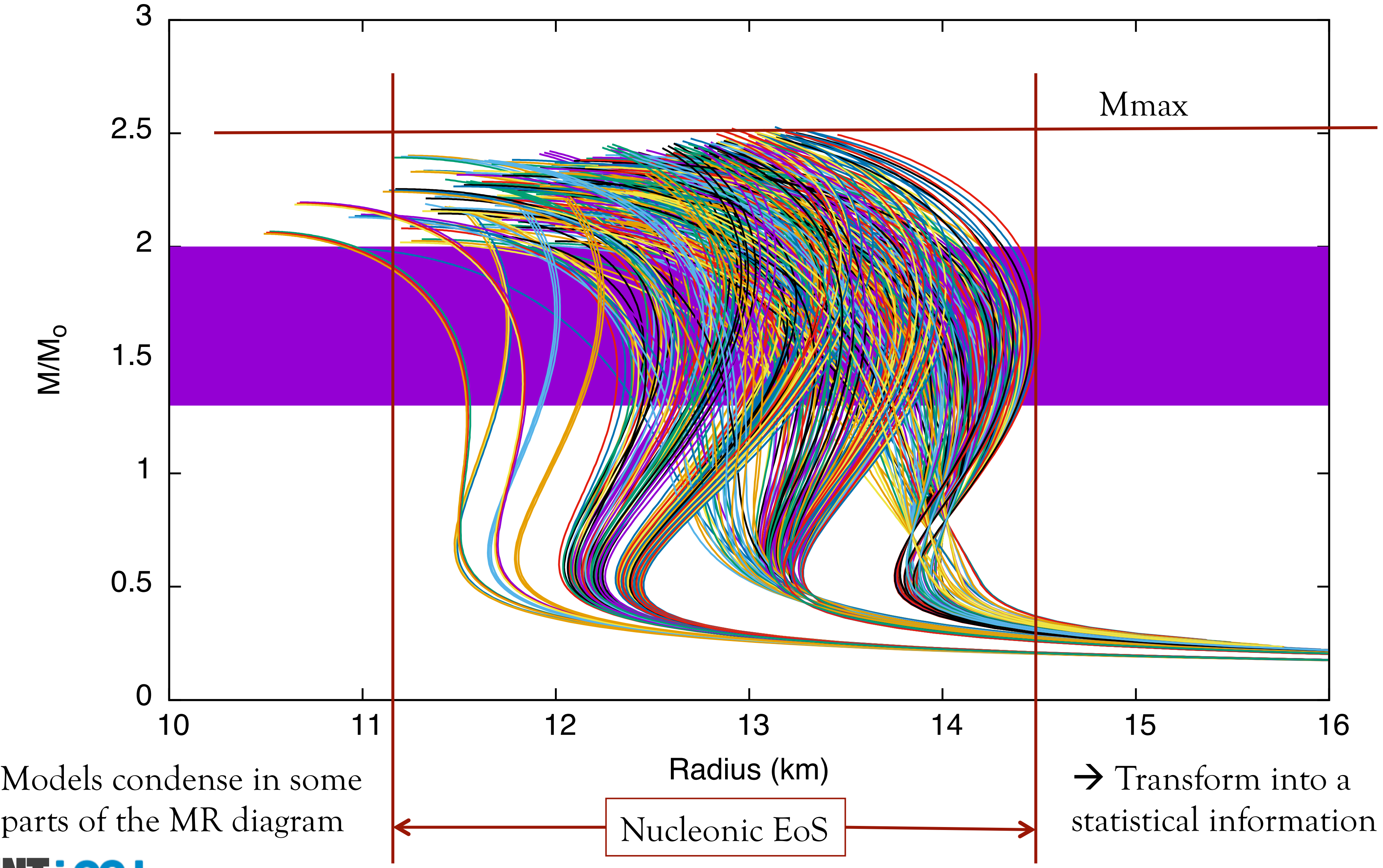
Small impact of these parameters

Impact of the isovector empirical parameters



Largest source of uncertainty: Lsym and Ksym

Impact of the “exp” unknown on the Mass/Radius relation



Models condense in some parts of the MR diagram

→ Transform into a statistical information

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Bayesian analysis

Prior probability distribution: $g_{P_{\alpha,1},P_{\alpha,2}}(P_\alpha) = \frac{1}{\sqrt{2\pi}P_{\alpha,2}} \exp -\frac{1}{2}\left(\frac{P_\alpha - P_{\alpha,1}}{P_{\alpha,2}}\right)^2$;

P_α	E_{sym} MeV	L_{sym} MeV	K_{sat} MeV	K_{sym} MeV	Q_{sat} MeV	Q_{sym} MeV	Z_{sat} MeV	Z_{sym} MeV
$P_{\alpha,1}$	32	60	230	-100	300	0	-500	-500
$P_{\alpha,2}$	2	15	20	100	400	400	1000	1000
Min	26	20	190	-400	-1300	-2000	-4500	-5500
Max	38	90	270	200	1900	2000	3500	4500
step	2	10	20	75	400	400	1000	1000
N	7	8	5	9	9	11	9	11

Likelihood probability: filter imposing general physical constraints

$$p_{lik}(\{P_\alpha\}_i) = \frac{1}{N_{lik}} w_{\text{filter}}(\{P_\alpha\}_i) \prod_{\alpha=1}^{8} g_{P_\alpha^1,P_\alpha^2}(P_\alpha)$$

prior

Physical filters: Stability: $\Delta P > 0$ Causality : $v_s^2 < c^2$

Positiveness of the symmetry energy

M_{max}>2Mo

3 hypothesis for the cooling of NS: some NS may need fast cooling

DURCA-0: No fast (dUrca) cooling for all observed NS

DURCA-1: Fast cooling only for NS with M>1.8Mo

DURCA-2: Fast cooling only for NS with 1.8Mo>M>1.6Mo

DURCA: Impact on the proton fraction $x_p=n_p/n_b$

The direct URCA process

$$n \rightarrow p + e^- + \bar{\nu}_e, \quad p + e^- \rightarrow n + \nu_e$$

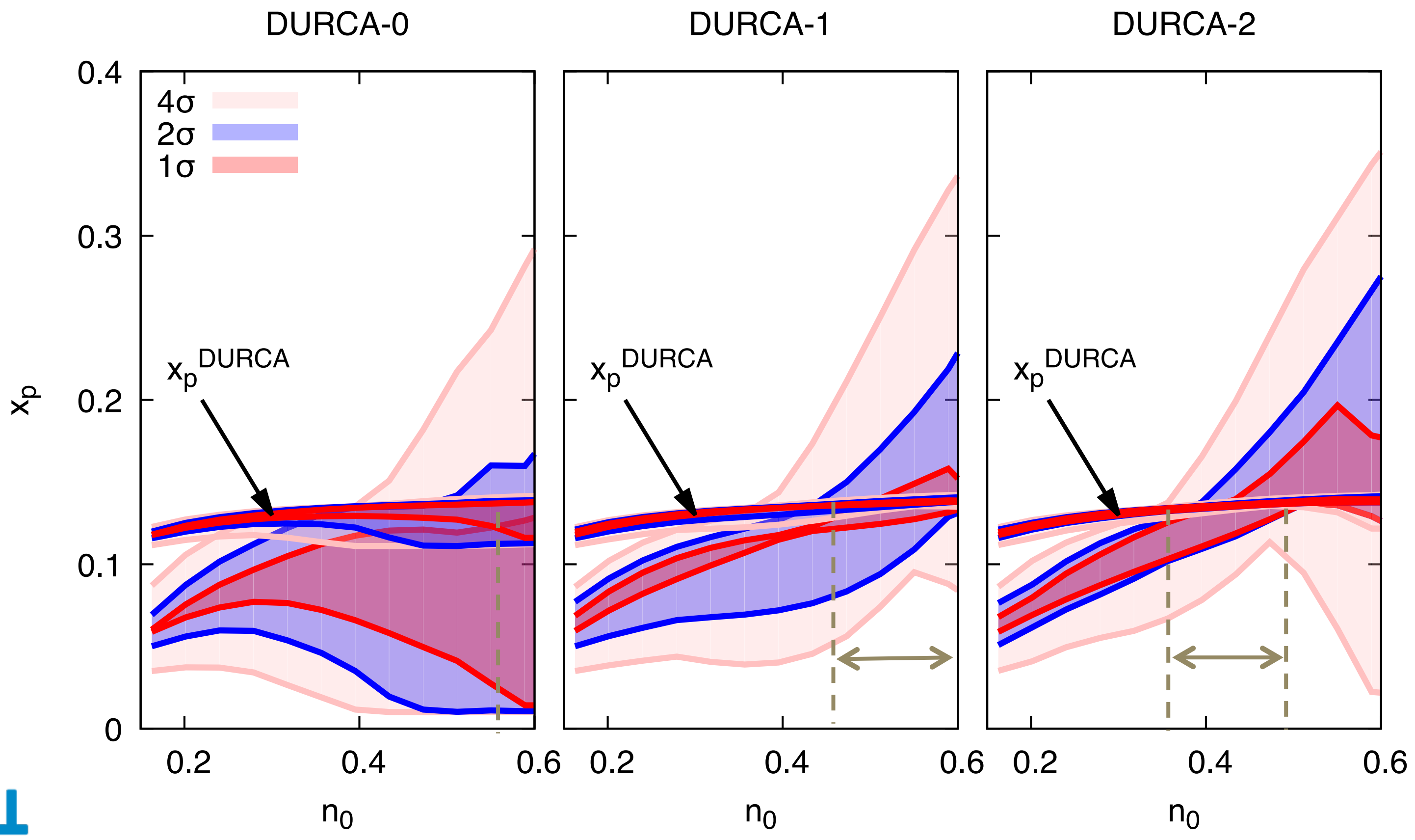
Energy and momentum conservation:

$$p_{Fp} + p_{Fe} > p_{Fn} \quad ➡ \quad x_p > x_{DU} \approx 1/9$$

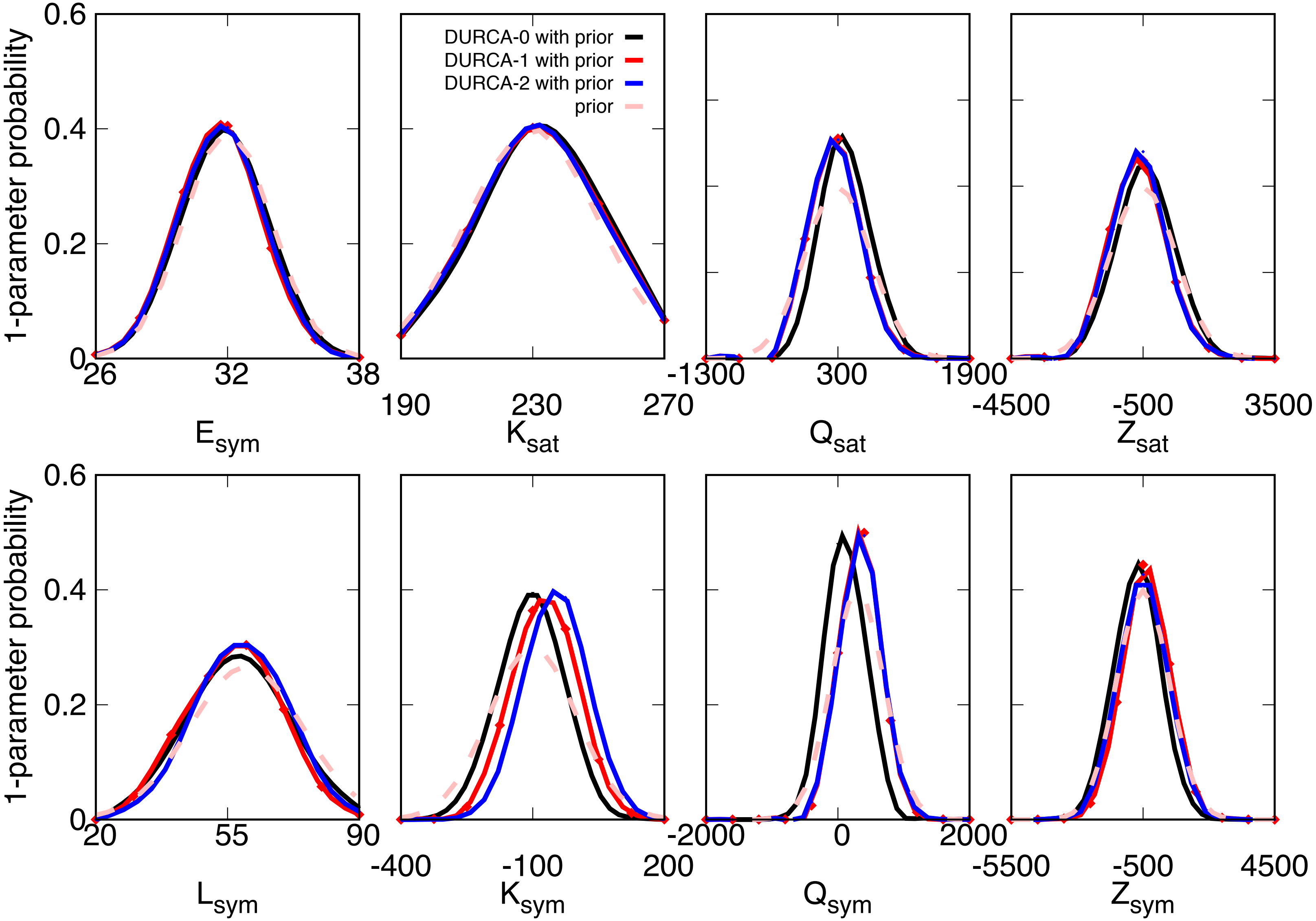
For n, p, e⁻, μ⁻ matter: $x_{DU} = \left[1 + \left(1 + x_{ep}^{1/3}\right)^3\right]^{-1}$

with $x_{ep} = n_e/n_p = n_e/(n_e + n_\mu)$

Gamow-Shoenberg 1941,
Lattimer et al., PRL 1991



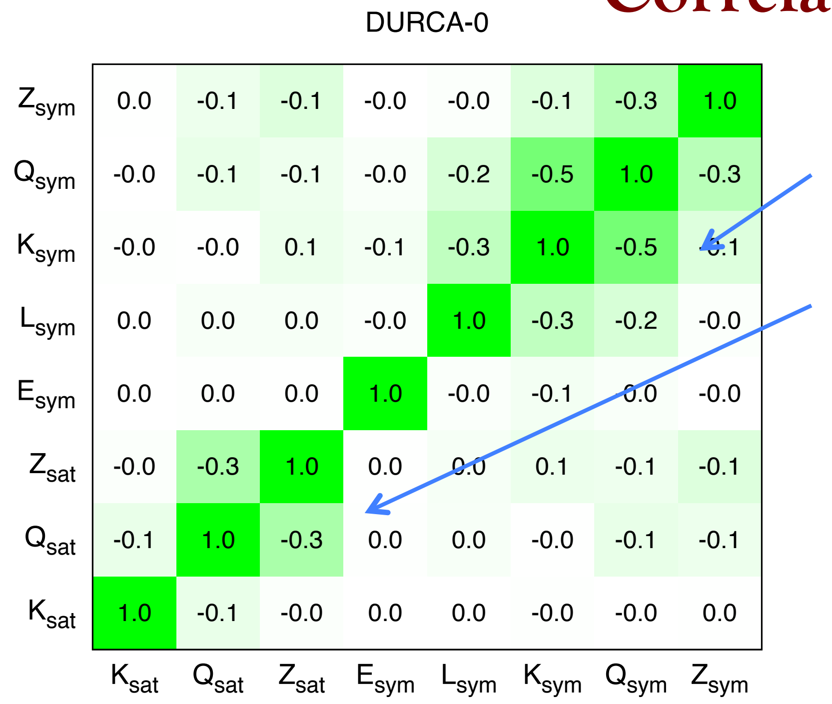
Posterior probabilities



Weak effect of the the filters → flexibility of the EOS

Correlation matrix

$$\mathrm{corr}(P_\alpha,P_\beta)=\frac{\mathrm{cov}(P_\alpha,P_\beta)}{\sigma_\alpha\sigma_\beta}$$



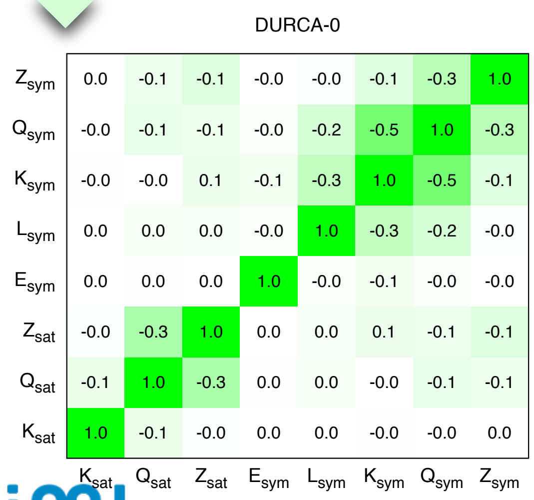
DURCA-0

	K_{sat}	Q_{sat}	Z_{sat}	E_{sym}	L_{sym}	K_{sym}	Q_{sym}	Z_{sym}
Z_{sym}	0.0	-0.1	-0.1	-0.0	-0.0	-0.1	-0.3	1.0
Q_{sym}	-0.0	-0.1	-0.1	-0.0	-0.2	-0.5	1.0	-0.3
K_{sym}	-0.0	-0.0	0.1	-0.1	-0.3	1.0	-0.5	-0.1
L_{sym}	0.0	0.0	0.0	-0.0	1.0	-0.3	-0.2	-0.0
E_{sym}	0.0	0.0	0.0	1.0	-0.0	-0.1	-0.0	-0.0
Z_{sat}	-0.0	-0.3	1.0	0.0	0.0	0.1	-0.1	-0.1
Q_{sat}	-0.1	1.0	-0.3	0.0	0.0	-0.0	-0.1	-0.1
K_{sat}	1.0	-0.1	-0.0	0.0	0.0	-0.0	-0.0	0.0

DURCA hypothesis

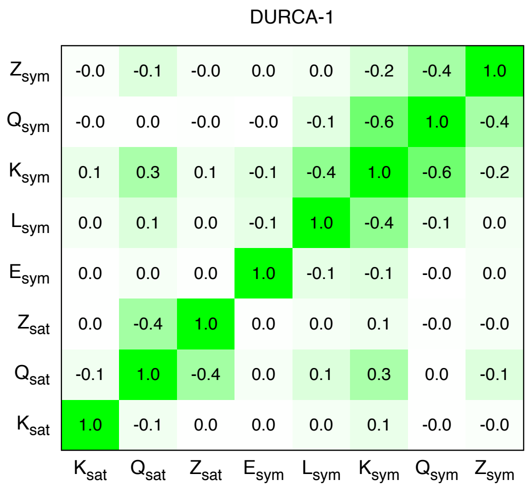
causality

Low order empirical parameters are very weakly impacted.
Correlations remain weak.



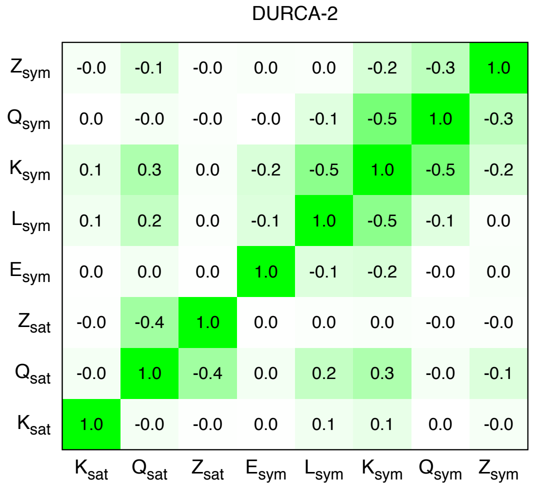
DURCA-0

	K_{sat}	Q_{sat}	Z_{sat}	E_{sym}	L_{sym}	K_{sym}	Q_{sym}	Z_{sym}
Z_{sym}	0.0	-0.1	-0.1	-0.0	-0.0	-0.1	-0.3	1.0
Q_{sym}	-0.0	-0.1	-0.1	-0.0	-0.2	-0.5	1.0	-0.3
K_{sym}	-0.0	-0.0	0.1	-0.1	-0.3	1.0	-0.5	-0.1
L_{sym}	0.0	0.0	0.0	-0.0	1.0	-0.3	-0.2	-0.0
E_{sym}	0.0	0.0	0.0	1.0	-0.0	-0.1	-0.0	-0.0
Z_{sat}	-0.0	-0.3	1.0	0.0	0.0	0.1	-0.1	-0.1
Q_{sat}	-0.1	1.0	-0.3	0.0	0.0	-0.0	-0.1	-0.1
K_{sat}	1.0	-0.1	-0.0	0.0	0.0	-0.0	-0.0	0.0



DURCA-1

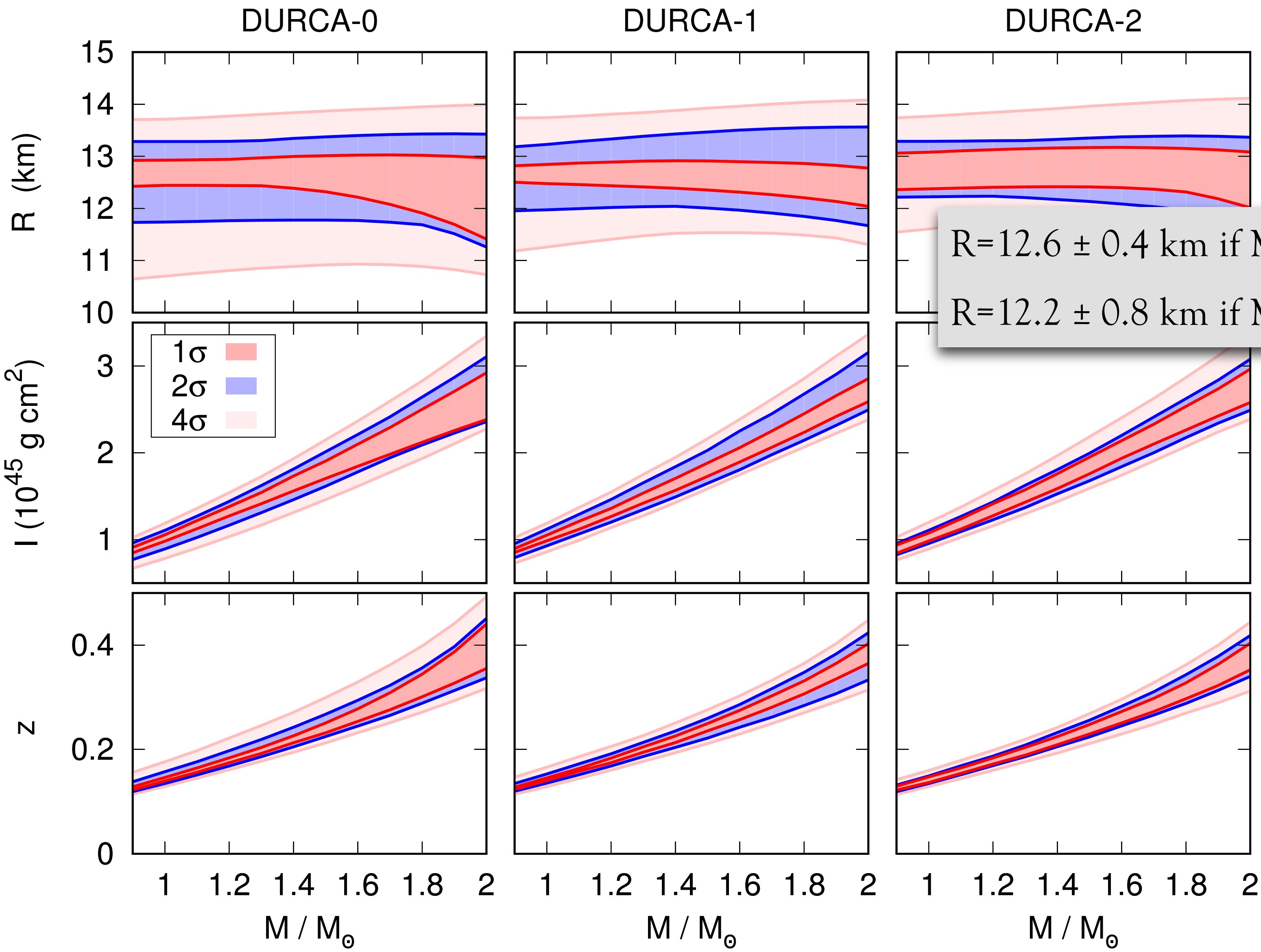
	K_{sat}	Q_{sat}	Z_{sat}	E_{sym}	L_{sym}	K_{sym}	Q_{sym}	Z_{sym}
Z_{sym}	-0.0	-0.1	-0.0	0.0	0.0	-0.2	-0.4	1.0
Q_{sym}	-0.0	0.0	-0.0	-0.0	-0.1	-0.6	1.0	-0.4
K_{sym}	0.1	0.3	0.1	-0.1	-0.4	1.0	-0.6	-0.2
L_{sym}	0.0	0.1	0.0	-0.1	1.0	-0.4	-0.1	0.0
E_{sym}	0.0	0.0	0.0	1.0	-0.1	-0.1	-0.0	0.0
Z_{sat}	0.0	-0.4	1.0	0.0	0.0	0.1	-0.0	-0.0
Q_{sat}	-0.1	1.0	-0.4	0.0	0.1	0.3	0.0	-0.1
K_{sat}	1.0	-0.1	0.0	0.0	0.0	0.1	-0.0	-0.0



DURCA-2

	K_{sat}	Q_{sat}	Z_{sat}	E_{sym}	L_{sym}	K_{sym}	Q_{sym}	Z_{sym}
Z_{sym}	-0.0	-0.1	-0.0	0.0	0.0	-0.2	-0.3	1.0
Q_{sym}	0.0	-0.0	-0.0	-0.0	-0.1	-0.5	1.0	-0.3
K_{sym}	0.1	0.3	0.0	-0.2	-0.5	1.0	-0.5	-0.2
L_{sym}	0.1	0.2	0.0	-0.1	1.0	-0.5	-0.1	0.0
E_{sym}	0.0	0.0	0.0	1.0	-0.1	-0.2	-0.0	0.0
Z_{sat}	-0.0	-0.4	1.0	0.0	0.0	0.0	-0.0	-0.0
Q_{sat}	-0.0	1.0	-0.4	0.0	0.2	0.3	-0.0	-0.1
K_{sat}	1.0	-0.0	-0.0	0.0	0.1	0.1	0.0	-0.0

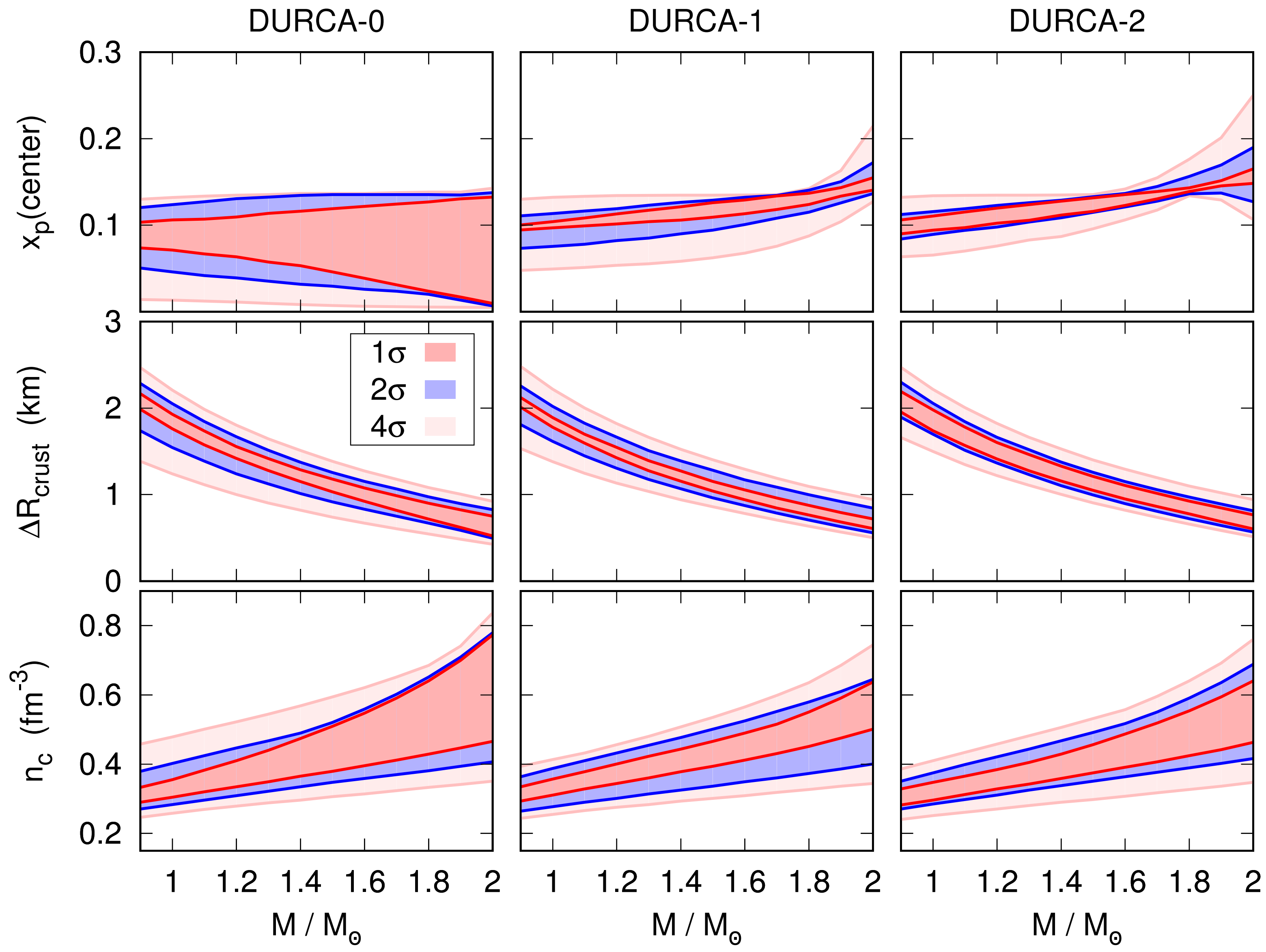
Predictions of general properties (M)



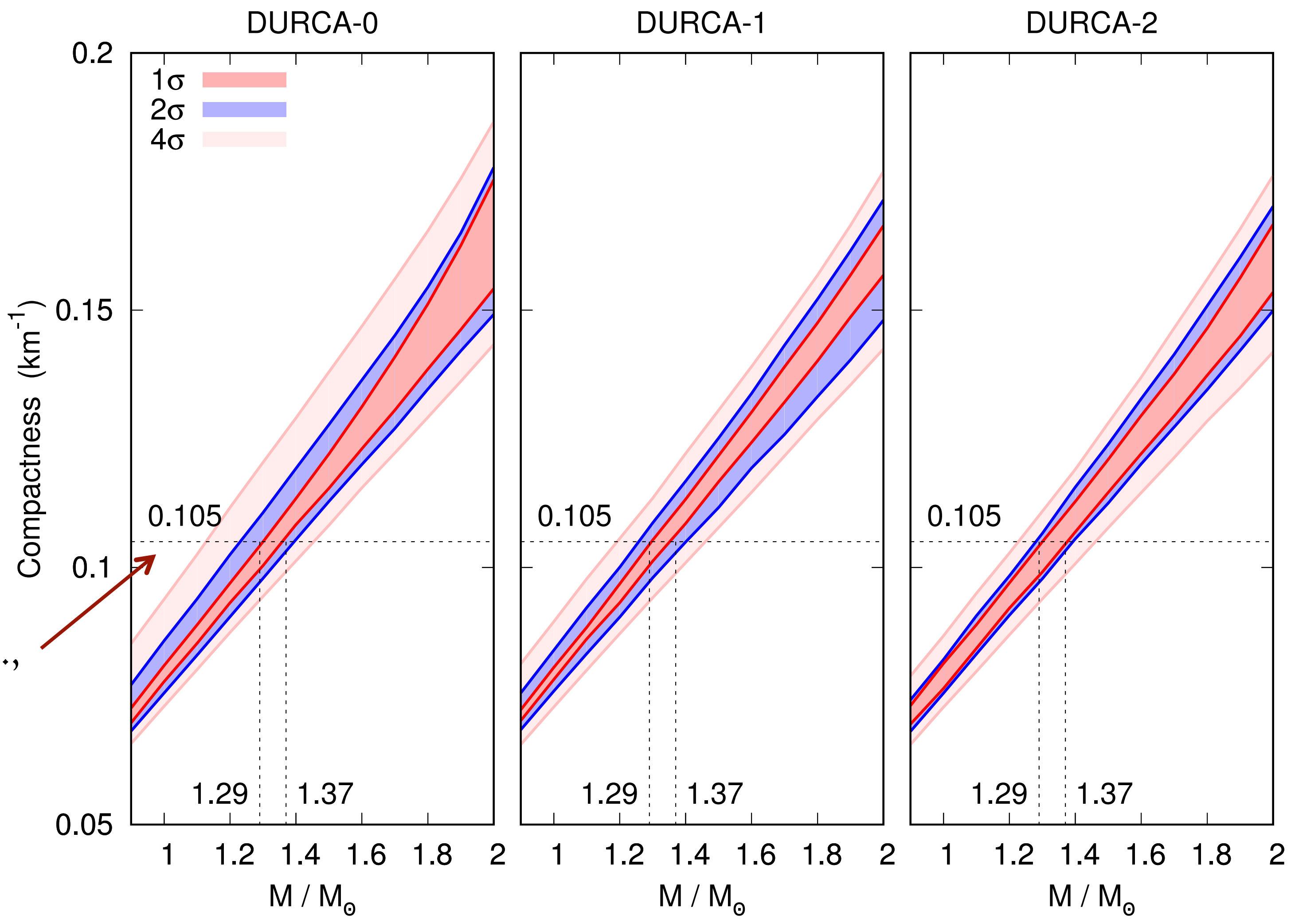
R=12.6 ± 0.4 km if M<1.6Mo

R=12.2 ± 0.8 km if M>1.6Mo

Predictions of general properties (M)

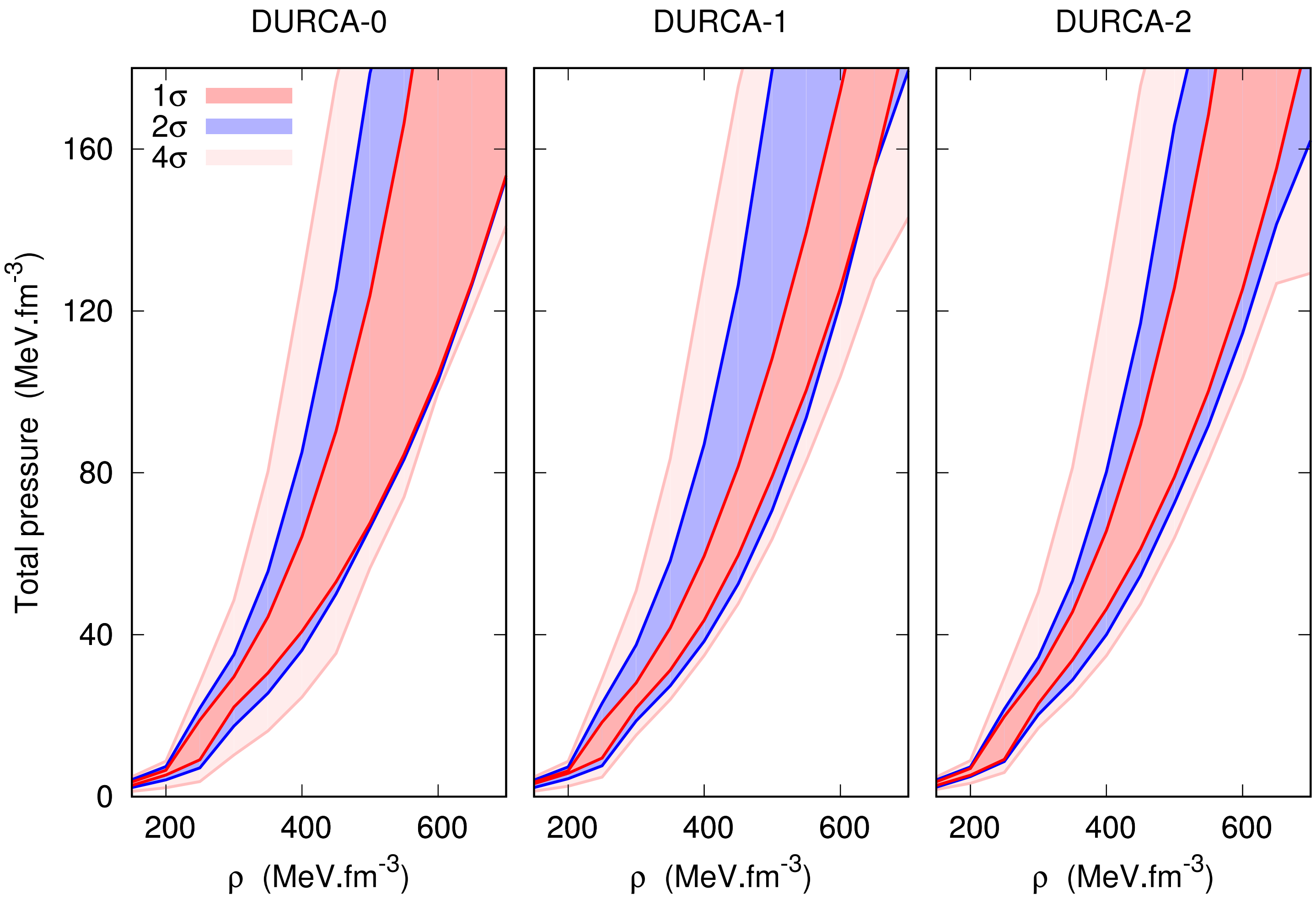


Compactness of RX J0720.4-3125

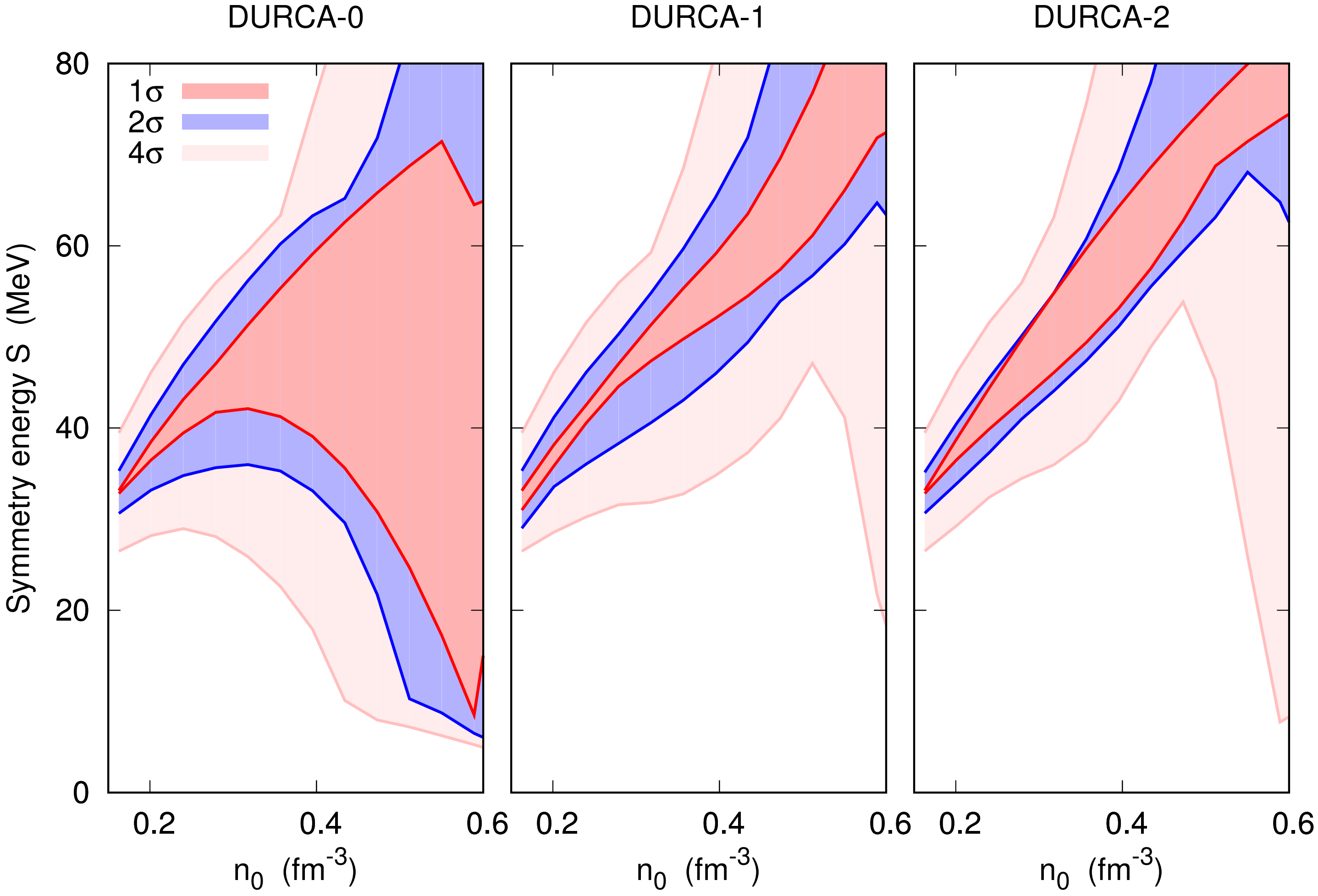


Hambaryan et al.,
A&A 2017

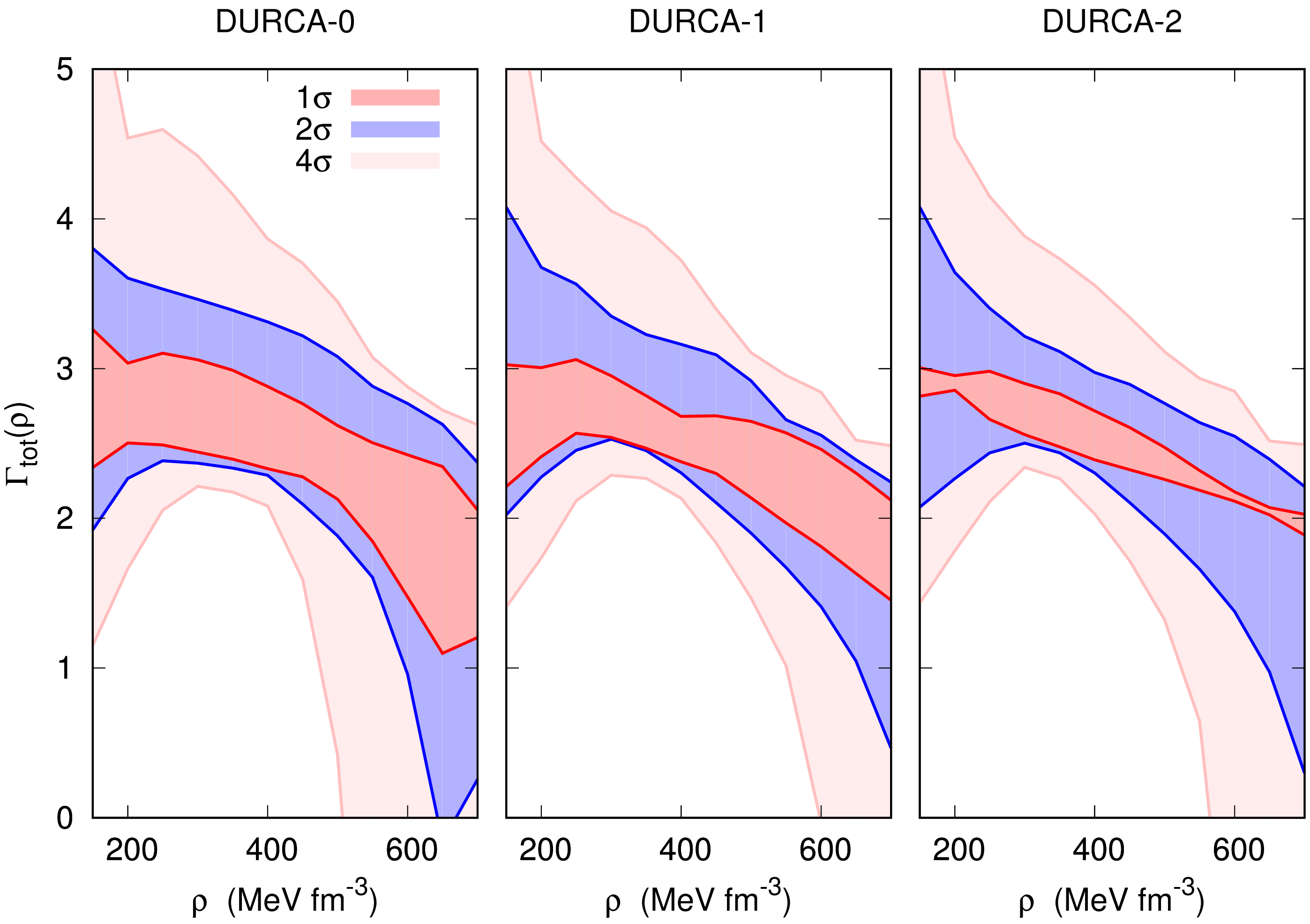
Prediction for the nuclear EOS at β-equilibrium



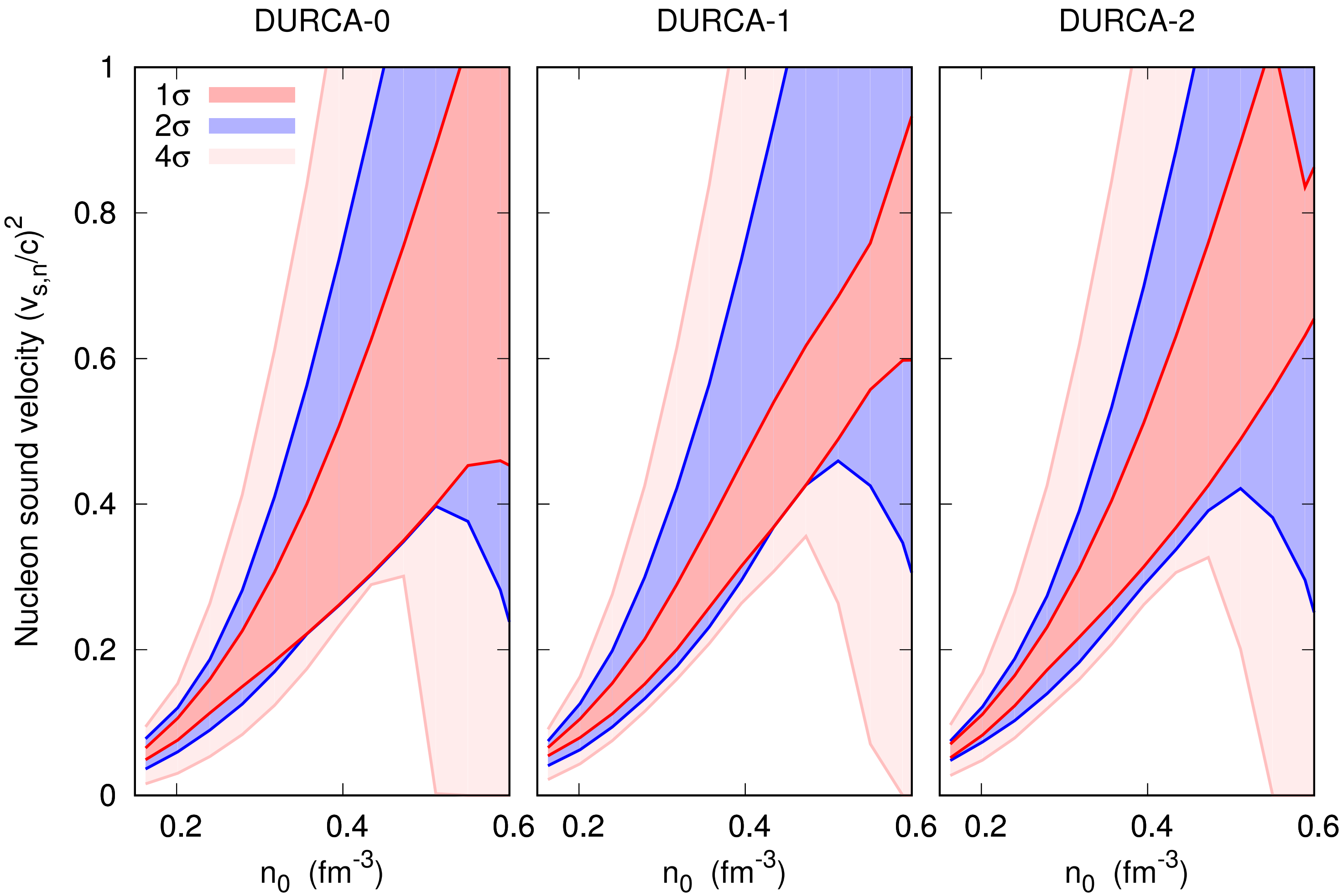
Prediction for the symmetry energy S(n)



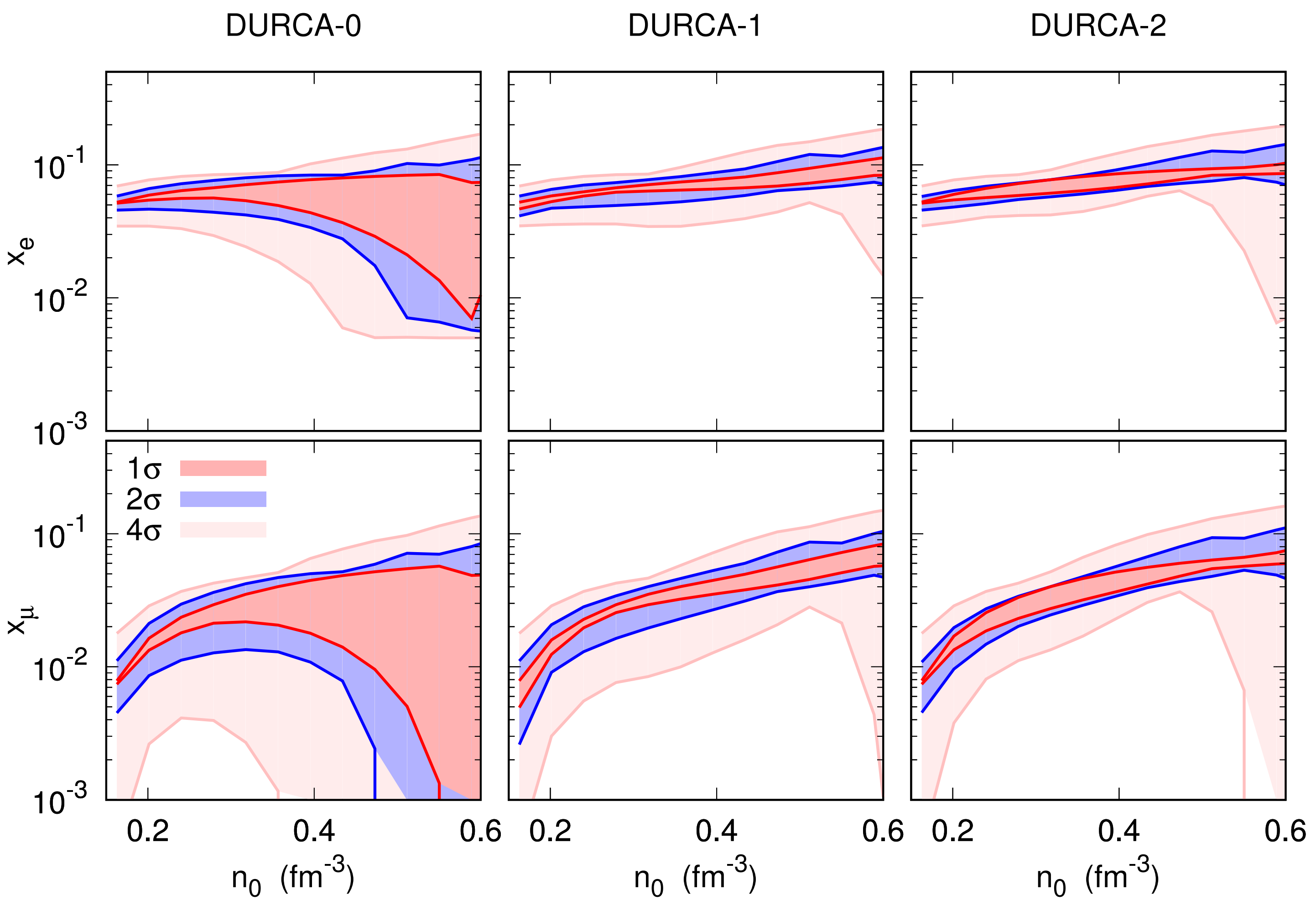
Prediction for the adiabatic index Γ(n)



Prediction for sound velocity $v_s(n)$



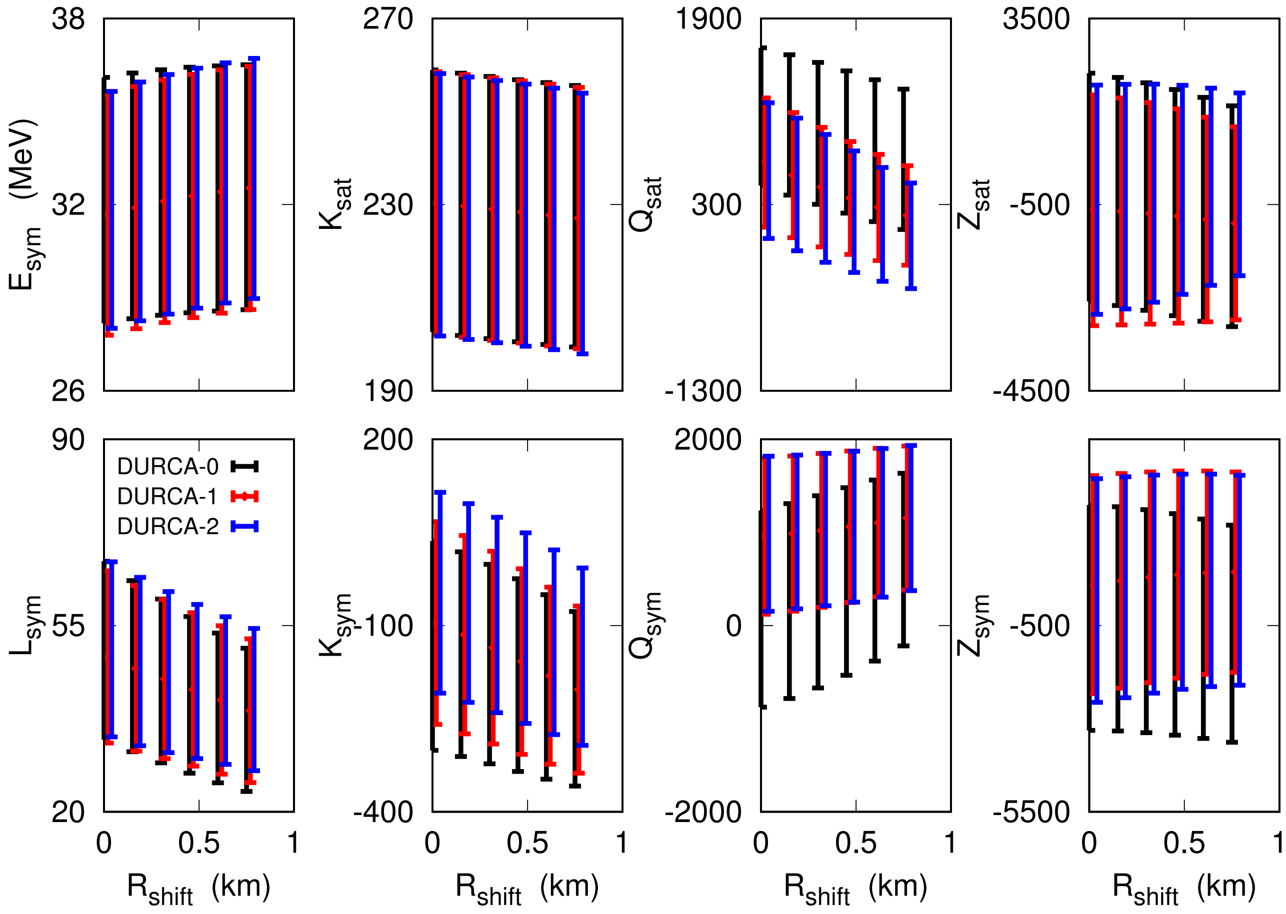
Prediction for particle fractions



If it can be proved that dUrca exist → possible tight constraint for the nuclear EOS

Inversion problem: what is the impact of the empirical parameters of the measure of MR relation?

$R_{best}(M)$ is our most probable MR relation.
Suppose it is shifted as $R_{best}(M)$-R_{shift}



Conclusions

- We propose a flexible form of the EoS which can mimic most of existing nucleonic EoS.
- Information from nuclear physics can be easily encoded, but are not enough and astrophysical information are also needed.
- **Most important parameters are L_{sym} and $K_{sym,}$ as well as $Q_{sat/sym}$**
- We can predict universal features for nuclear EoS (MR diagram):
  R=12-13 km
  P(ρ)
- If it can be proven that dUrca exists → possible tight constraint for the nuclear EOS.
- At β-equilibrium, melting temperature of clusters is expected to be quite low (<5 MeV)
  → The impact of clusters on ν propagation remains quite weak.