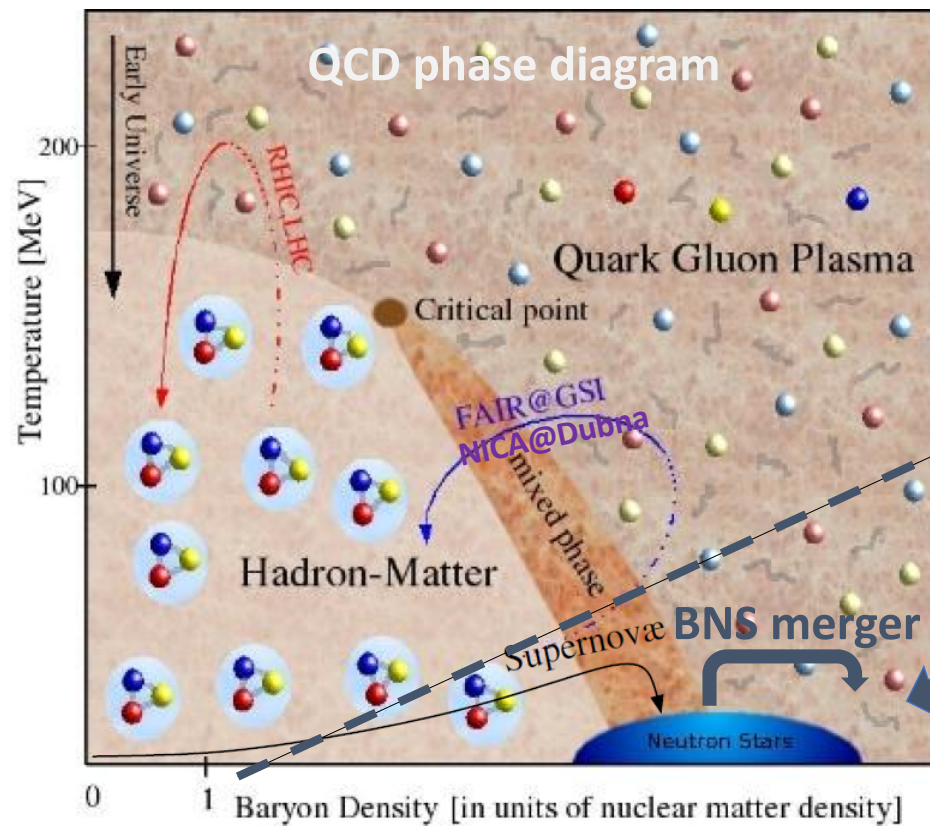


Understanding extreme matter with gravitational waves

J. Margueron, IPN Lyon



Particle and nuclear
accelerators

Astrophysical
observations

New limits for
extreme matter

Neutron stars, supernovae, kilonovae...

What is our current understanding of dense matter properties?

Dense matter properties: composition, energy (E), pressure (P), sound speed (c_s), etc...

Brief history of many-body concepts and developments:

1950: Brueckner-Hrtree-Fock approach (regularization of the hard core).

1960: Bethe ideas pushing towards nuclear interactions with hard cores.

1970: Phenomenological approaches, e.g. Skyrme, Gogny, RMF, RHF, etc...,
and latter Fayans NEDF (1998),

1980: Accurate NN potentials, e.g. Paris, Bonn, Nijmegen, etc...

1990: Ab-initio approaches become feasible with new computers, e.g. self-consistent green's function, no-core shell model, coupled-clusters, etc...

2000: A new paradigm emerges with chiral EFT approaches.

Chiral EFT approach

Ideas:

There is no unique nuclear potential but as many as unitary transformations allow – so an infinite number!

Through unitary transformation, a hard core (non-perturbative) potential can be regularized into a soft-core (perturbative) one, at the cost of making the 3BF larger (in fact it was already contained in the well-known Coester line).

Proposal:

A systematic order-by-order expansion of the nuclear interaction was proposed based on Weinberg ideas. This interaction has a soft-core $\rightarrow$ perturbative but strong 3BF !

Hierarchy of nuclear forces

	Two-nucleon force	Three-nucleon force	Four-nucleon force
Q^0			
Q^2			
Q^3			
Q^4			

Epelbaum, RMP 2009

Machleidt, Phys.Rep. 2011

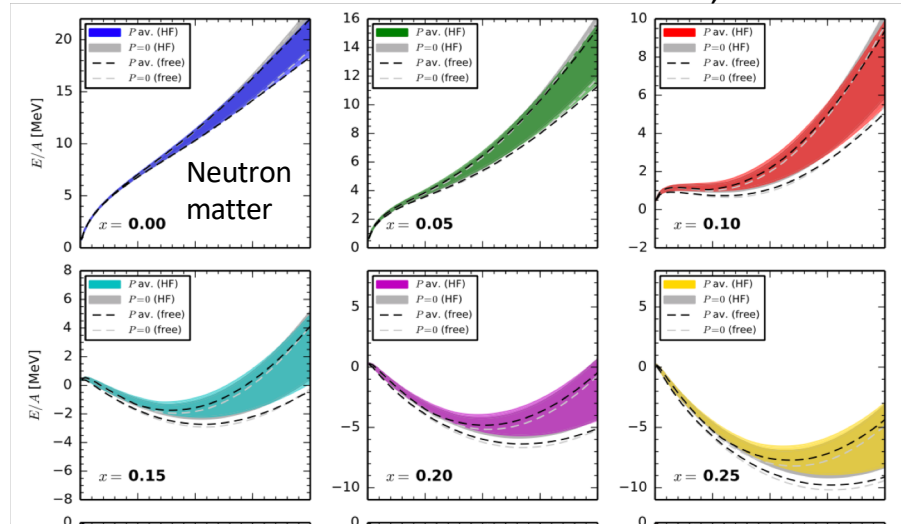
Application to nuclear matter

Small perturbative parameter: q/Λ , $\Lambda \sim 500$ MeV

→ gets larger as the density increases. At saturation density, $q \sim k_F \sim 270$ MeV, → $q \sim 0.5$!

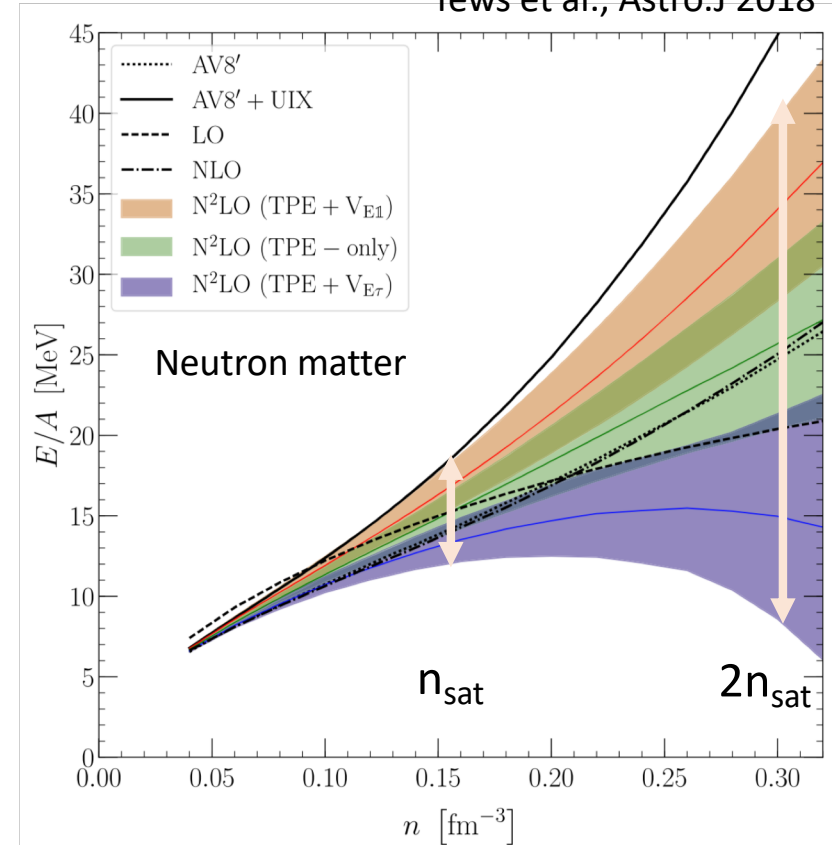
→ Chiral EFT can hardly be extrapolated beyond $1-2 n_{\text{sat}}$.

Drischler et al., PRC 2016



Symmetric
matter

Tews et al., Astro.J 2018

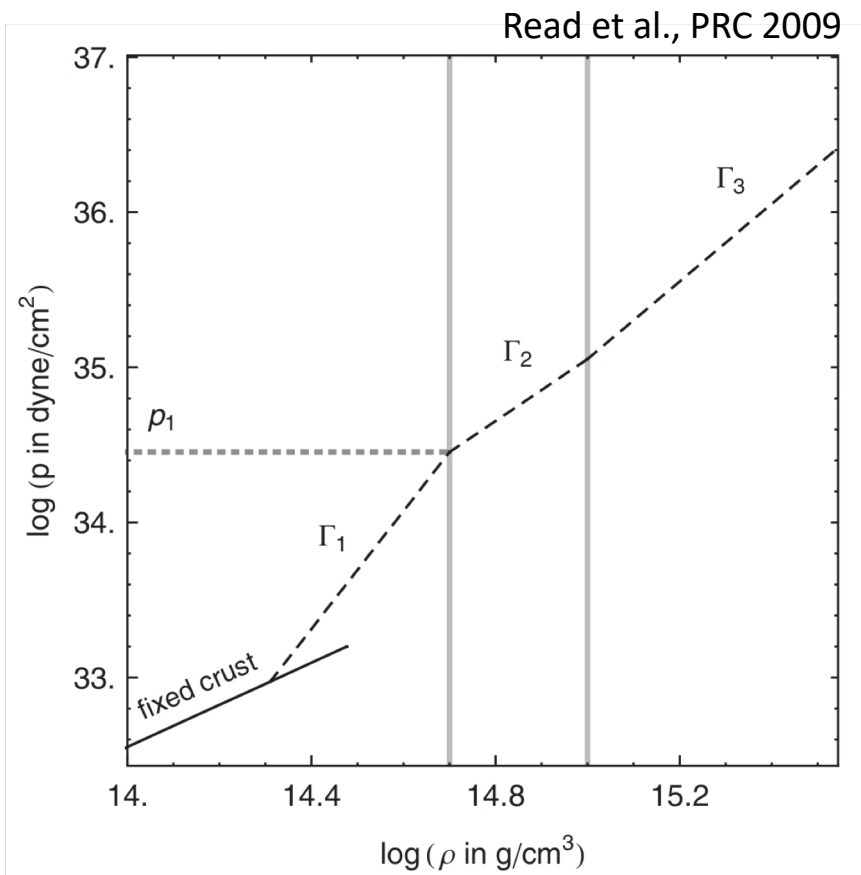


- uncertainties increases from NM to SM (better exp. knowledge).
- uncertainties greatly increases from n_{sat} to $2n_{\text{sat}}$.
- Still, preventing phase transition up to $2n_{\text{sat}}$ is useful information.

Do we need nuclear physicists for the EoS?

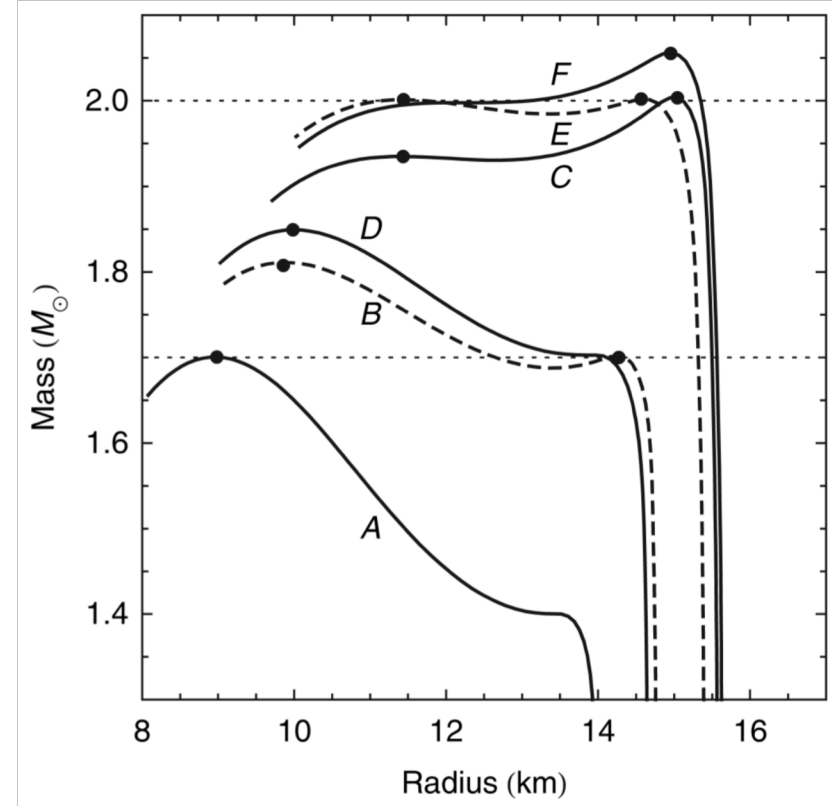
Some observers have set up a parametrization for the EoS which can directly be compared to observations to select a set of compatible EOS (inverse problem, Bayesian inference, MCMC, etc...).

Piecewise polytrope: $p(\rho) = K\rho^\Gamma$

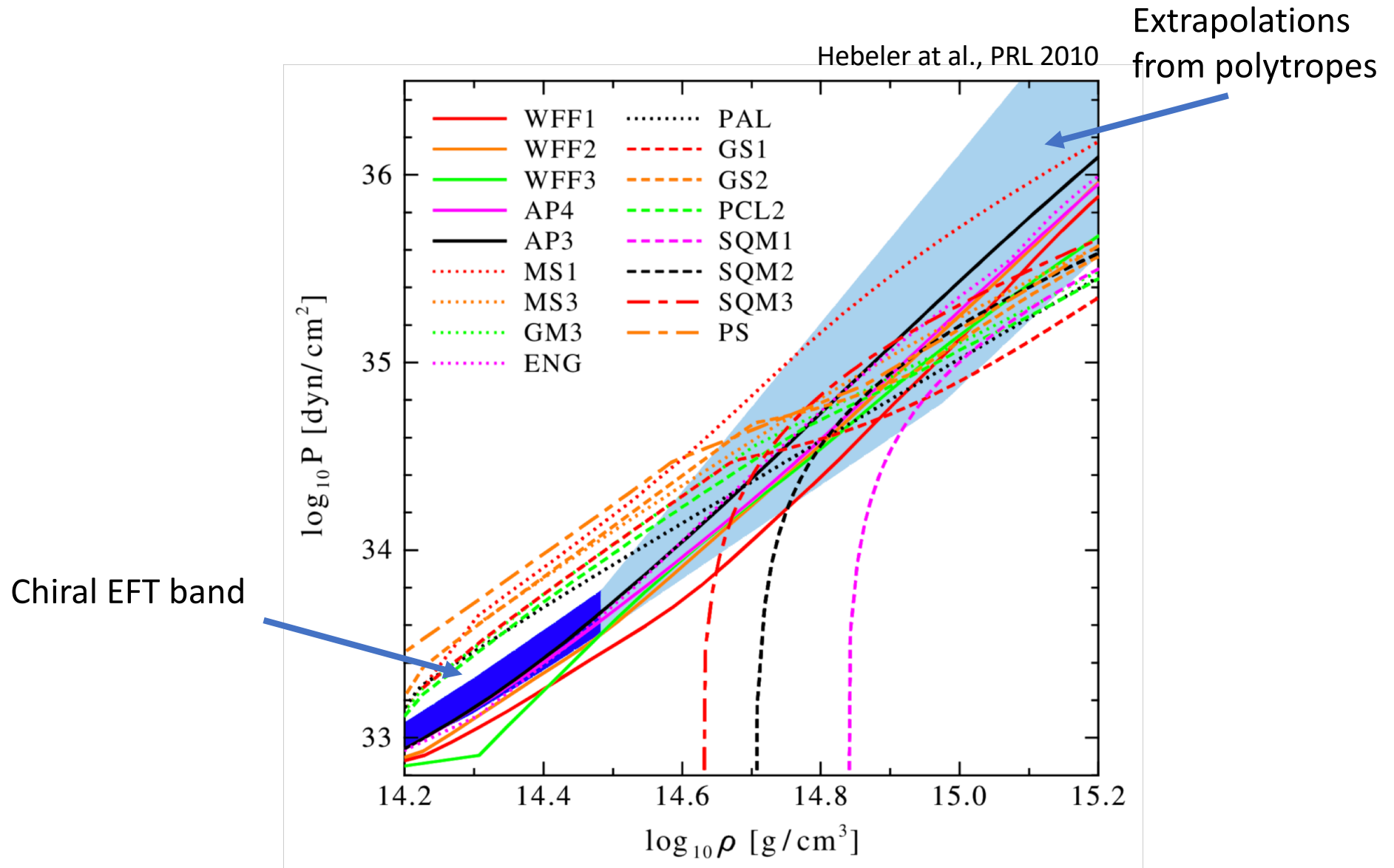


Özel 2009, 2010, Steiner 2013, ...

TOV
solution



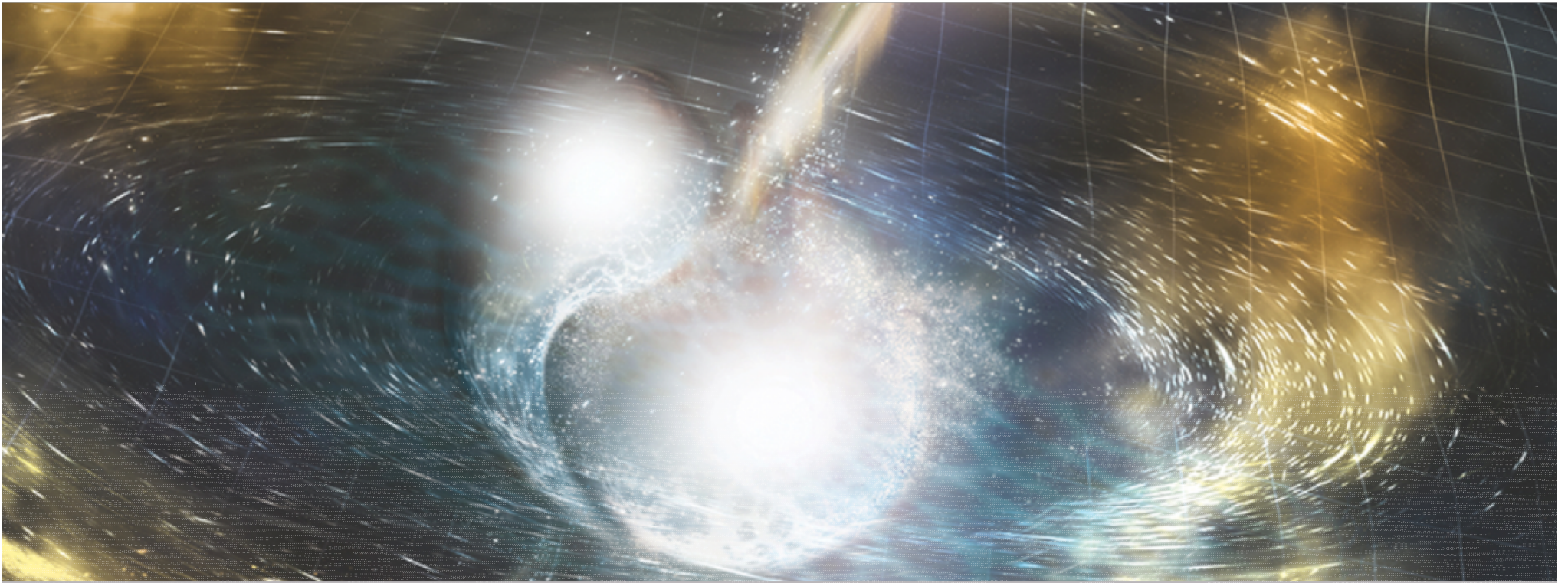
When chiral EFT meets observers



Probing extreme matter with GW

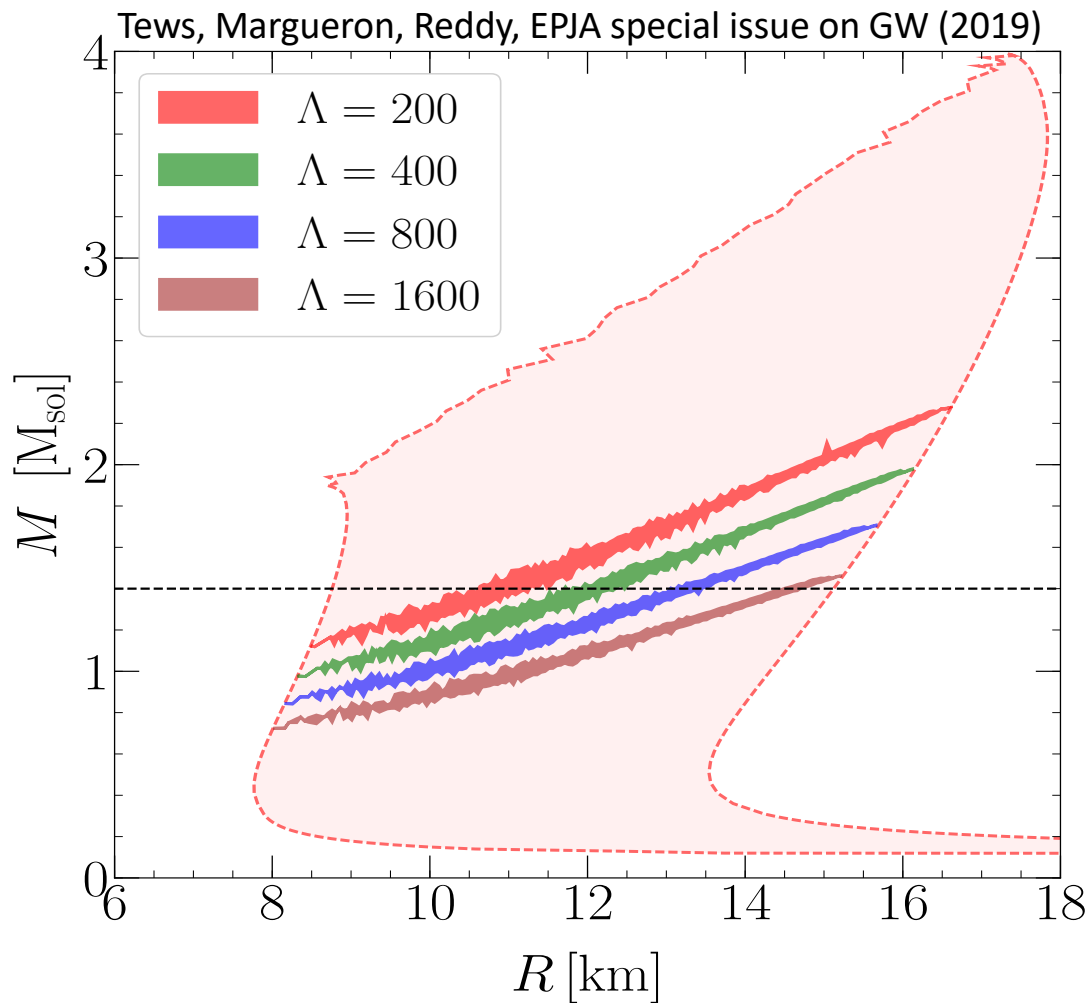
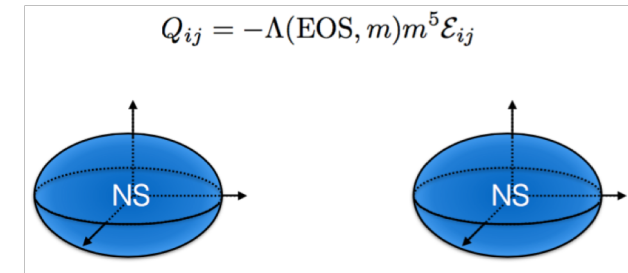
GW170817: First detection of GW from the merger of two neutron stars (BNS)

Abbott et al., LVC, PRL 2017, PRL 2018

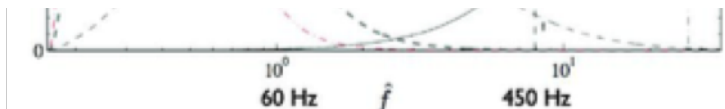
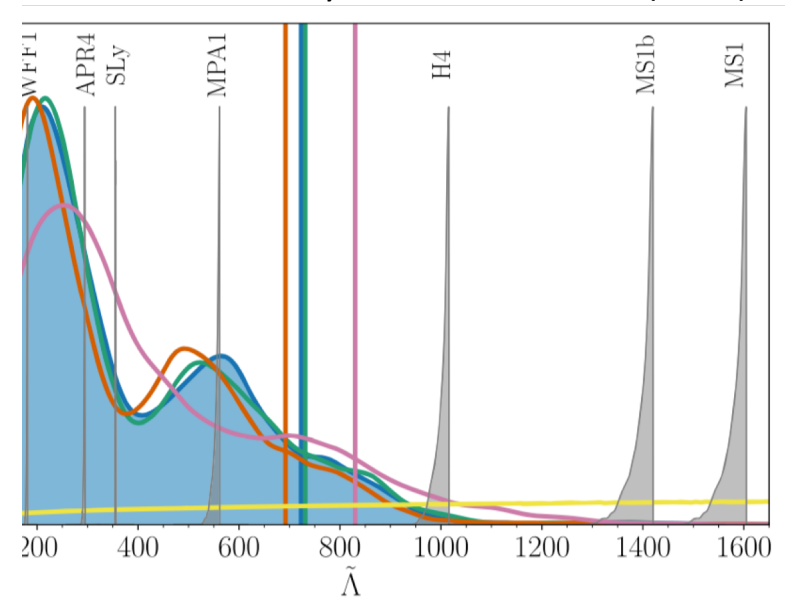


Neutron star matter and inspiral GW signal

Tidal deformability



LVC, Phys. Rev. X 9, 011001 (2019)



GW170817 $\rightarrow 70 \leq \Lambda \leq 720$ (90% CL)

How gravitational waves improves our current knowledge?

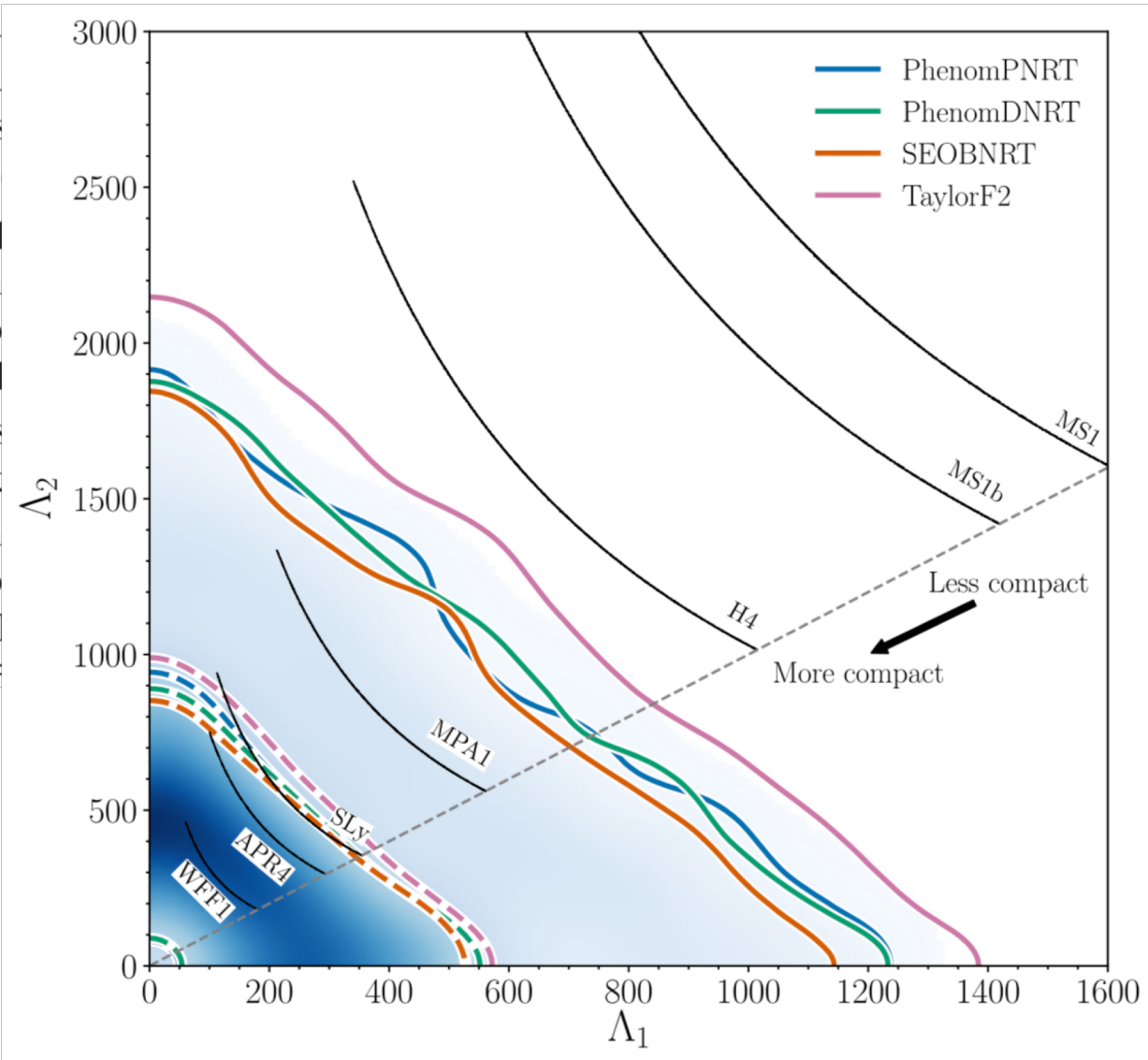
From GW170817

LVC, Phys. Rev. X 9, 011001 (2019)

Low-spin prior ($\chi \leq 0.05$)

High-spin prior ($\chi \leq 0.89$)

Bina
Bina
dis
Dete
Chirp
Prim
Seco
Total
Mass
Effec
Prim
Seco
Tidal



HPD)

$$152^{+21}_{-27} \text{ deg}$$

$$153^{+15}_{-11} \text{ deg}$$

$$1.1976^{+0.0004}_{-0.0002} M_{\odot}$$

$$1.186^{+0.001}_{-0.001} M_{\odot}$$

$$(1.36, 1.89) M_{\odot}$$

$$(1.00, 1.36) M_{\odot}$$

$$2.77^{+0.22}_{-0.05} M_{\odot}$$

$$(0.53, 1.00)$$

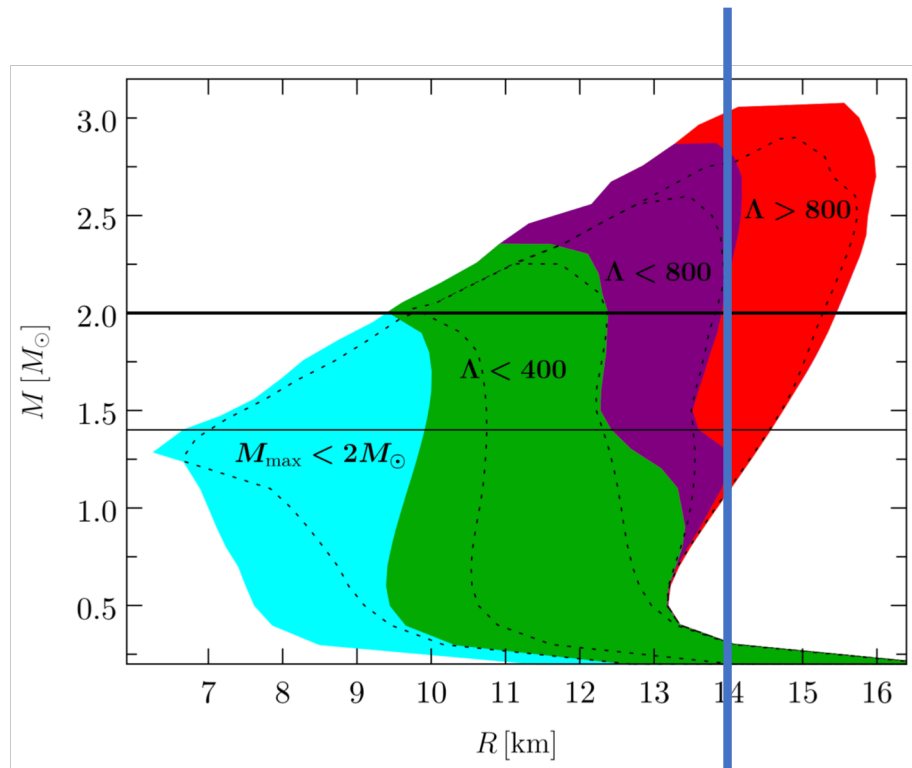
$$0.02^{+0.08}_{-0.02}$$

$$(0.00, 0.50)$$

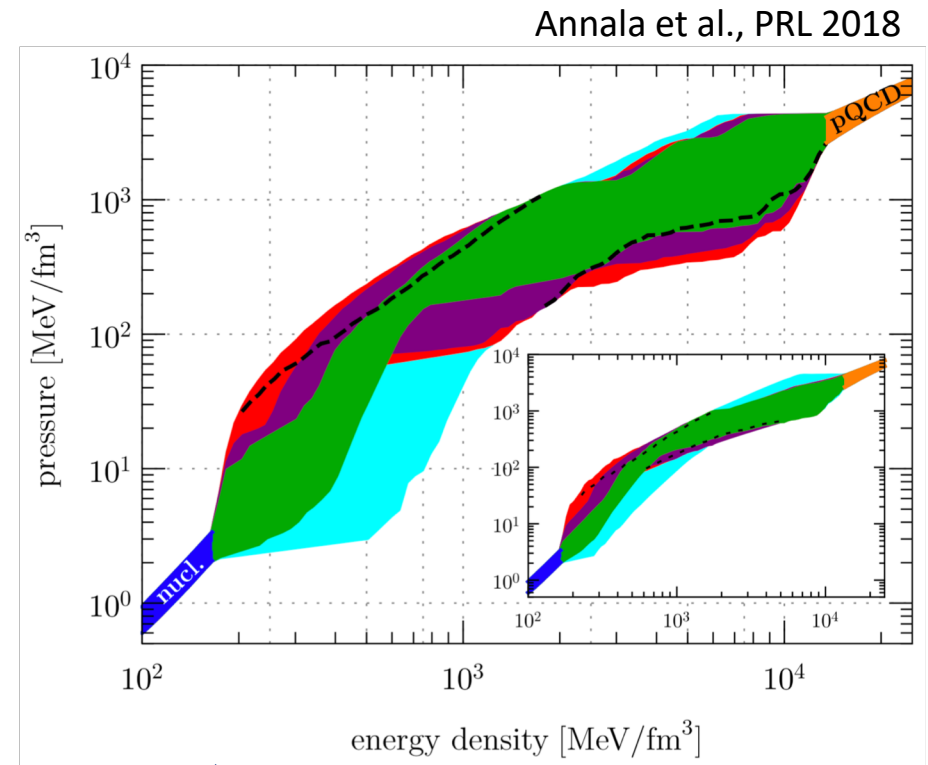
$$(0.00, 0.61)$$

$$(0, 630)$$

Confrontation of polytropic EoS to GW170817



Upper boundary
for R



Annala et al., PRL 2018

Boundaries for the EoS

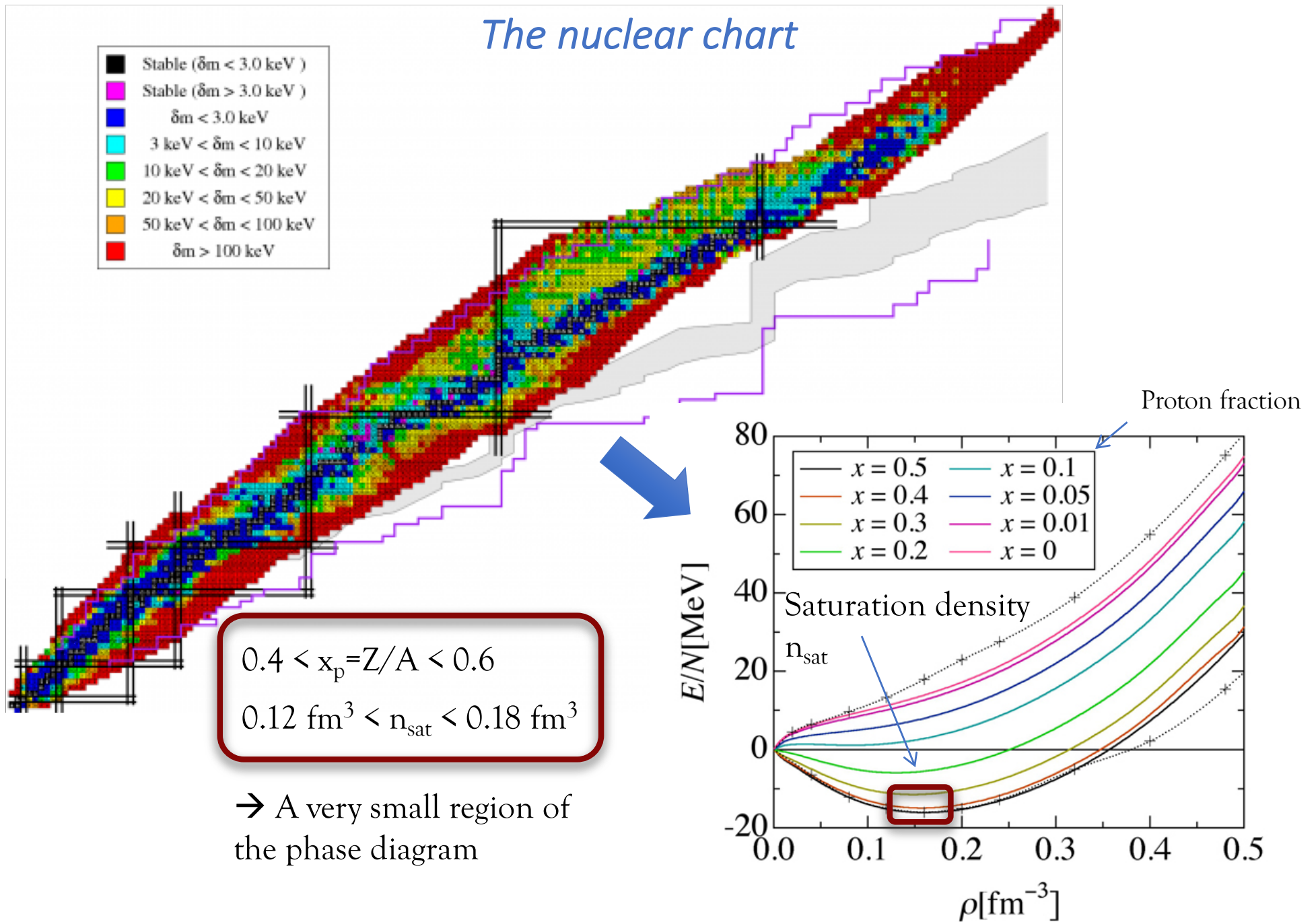
Ok, we have E and P , but what about the composition?

Polytropic EoS is blind to matter composition.

How one can retrieve information about matter composition from observations?

→ We need a model knowing about the composition.

The nuclear chart



Empirical parameters as a characterization of the density and asymmetry dependence of the EOS

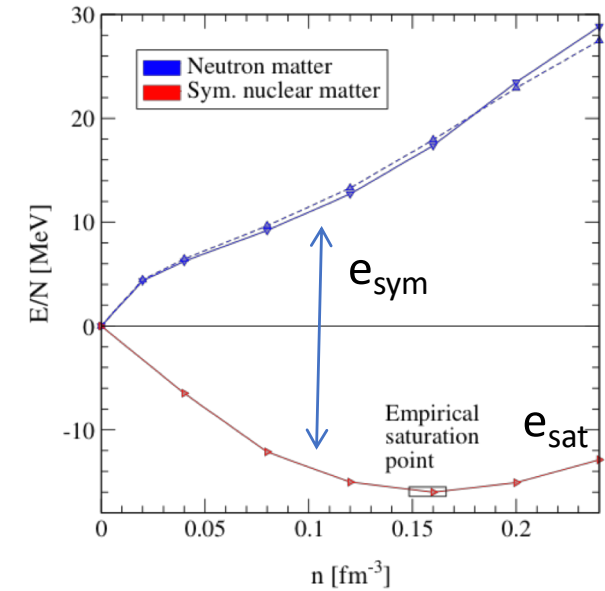
Around saturation, the energy per particle can be Taylor expanded as:

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

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

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

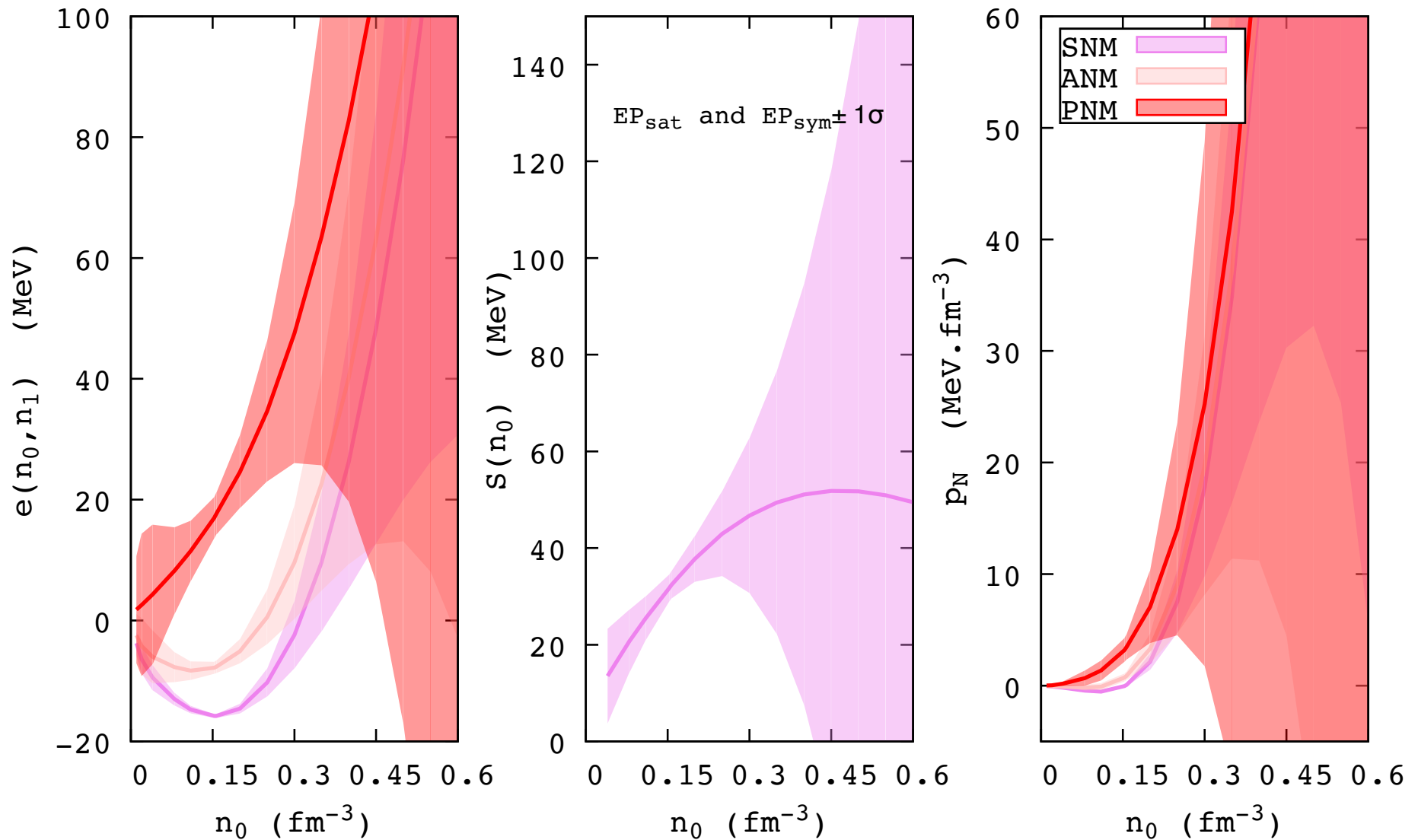
$$e_{sym}(n) = E_{sym} + L_{sym}x + \frac{1}{2}K_{sym}x^2 + \frac{1}{6}Q_{sym}x^3 + \frac{1}{24}Z_{sym}x^4 + \dots$$



	Small uncertainties					Large uncertainties					Large uncertainties	
P_α	E_{sat} MeV	E_{sym} MeV	n_{sat} fm^{-3}	L_{sym} MeV	K_{sat} MeV	K_{sym} MeV	Q_{sat} MeV	Q_{sym} MeV	Z_{sat} MeV	Z_{sym} MeV	m_{sat}^*/m	$\Delta m_{sat}^*/m$
$\langle P_\alpha \rangle$	-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

small impact on EOS

Impact of varying all uncertainties $\pm 1\sigma$

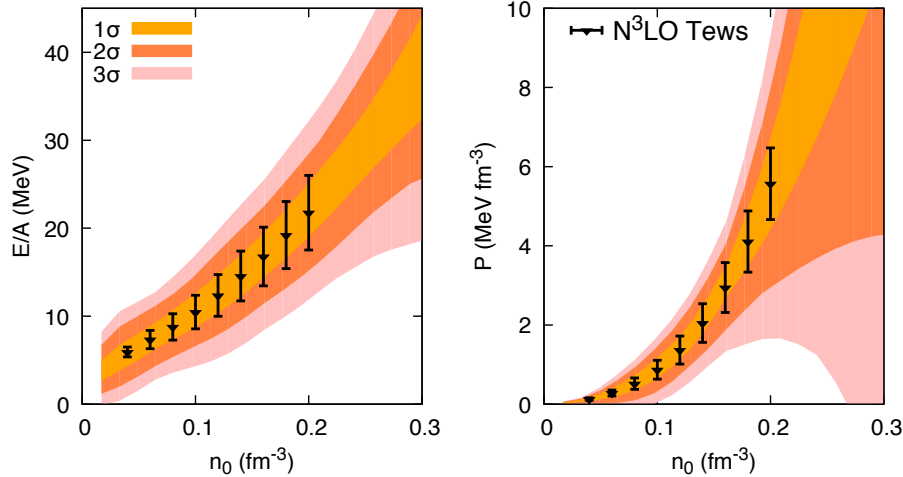


A bit messy... but many meta-EOS does not satisfy basic requirements (stability, causality, ...)

→ We need to filter them

Low density neutron matter predicted by chiral EFT approach

Tews et al., PRL 2013, PRC 2016, PRC 2018



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

$$K_{NM} = K_{sat} + K_{sym}$$

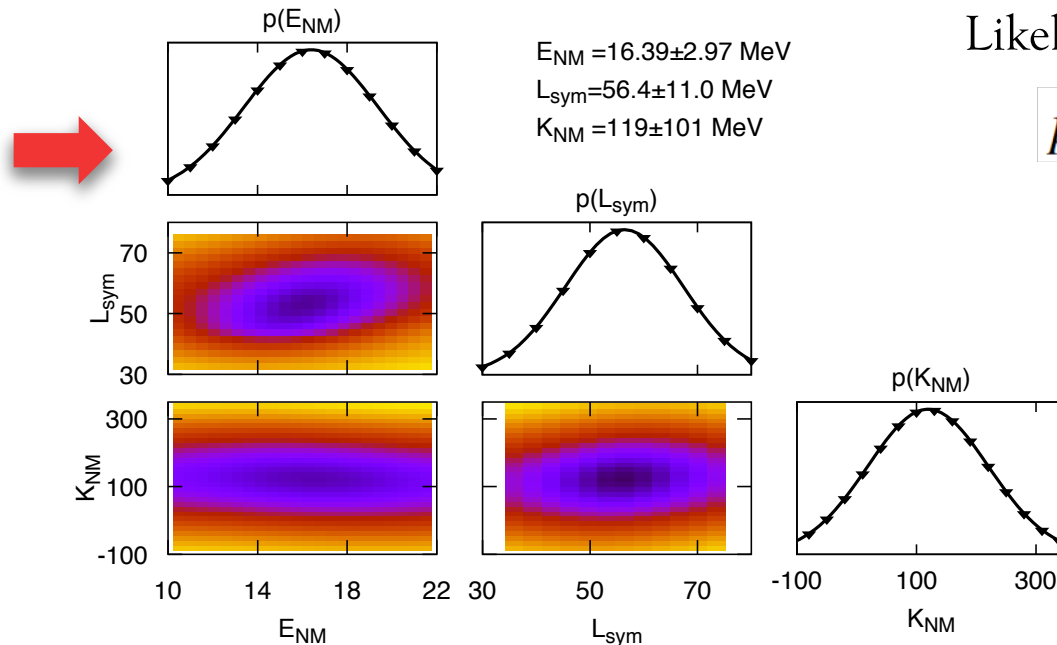
$$P \approx \frac{1}{3}L_{sym}n_{sat} + \dots$$

Estimation of the error function:

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

Likelihood probability:

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



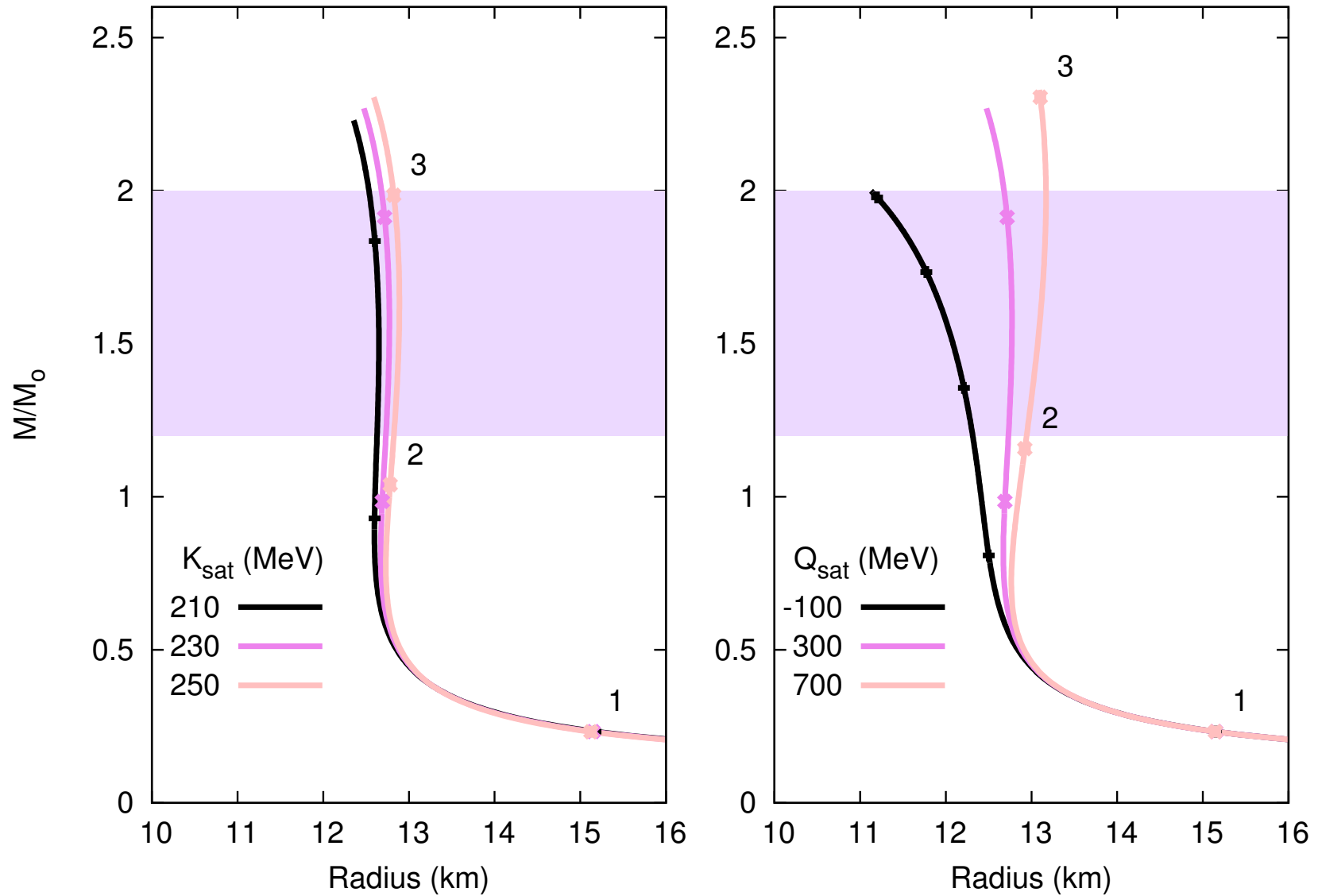
$$L_{sym} \approx 56 \pm 11 \text{ MeV}$$

$$K_{sym} \approx -100 \pm 100 \text{ MeV}$$

Chiral EFT predictions represent correctly our current experimental uncertainty.

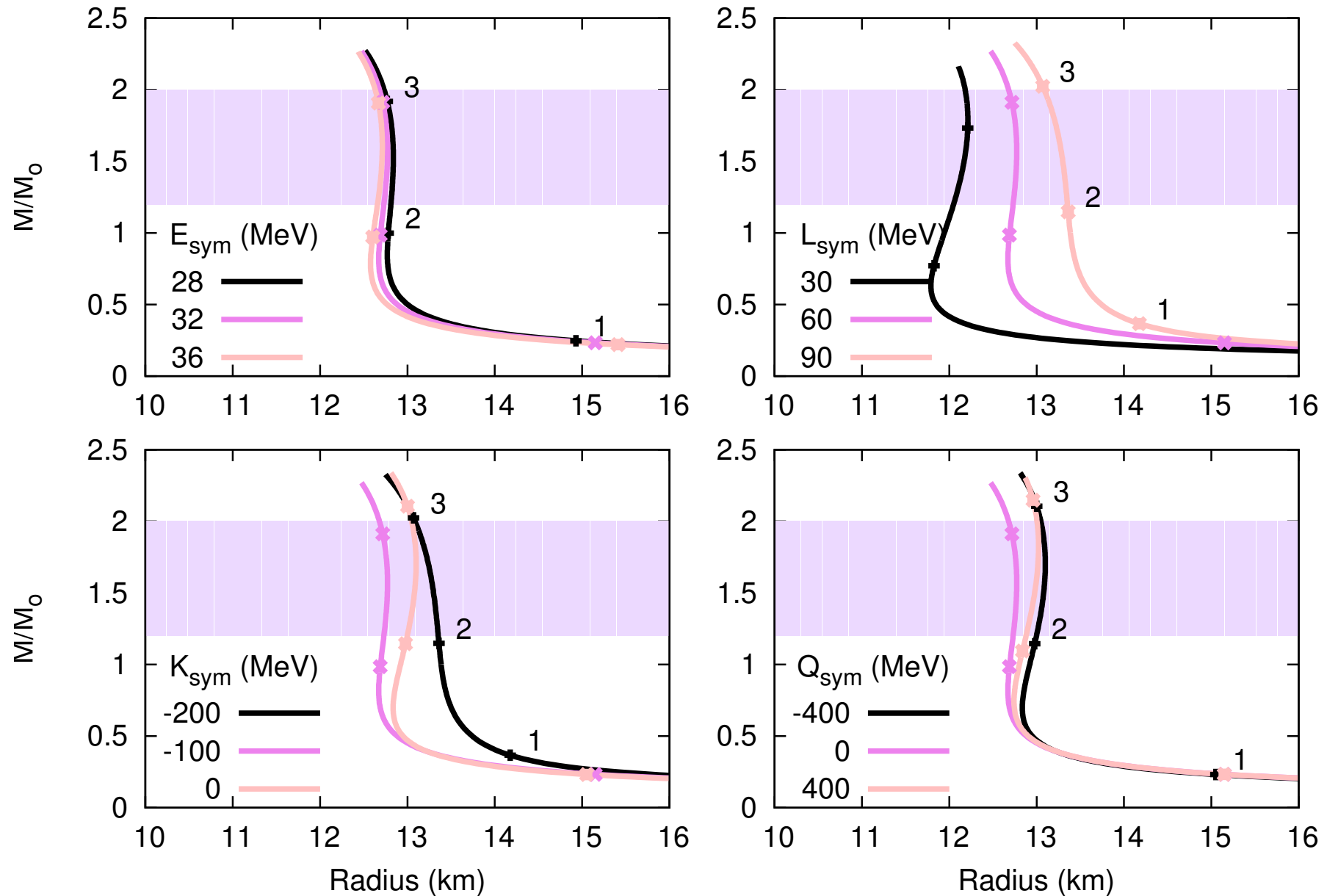
Impact on the MR relation

Impact of the isoscalar parameters

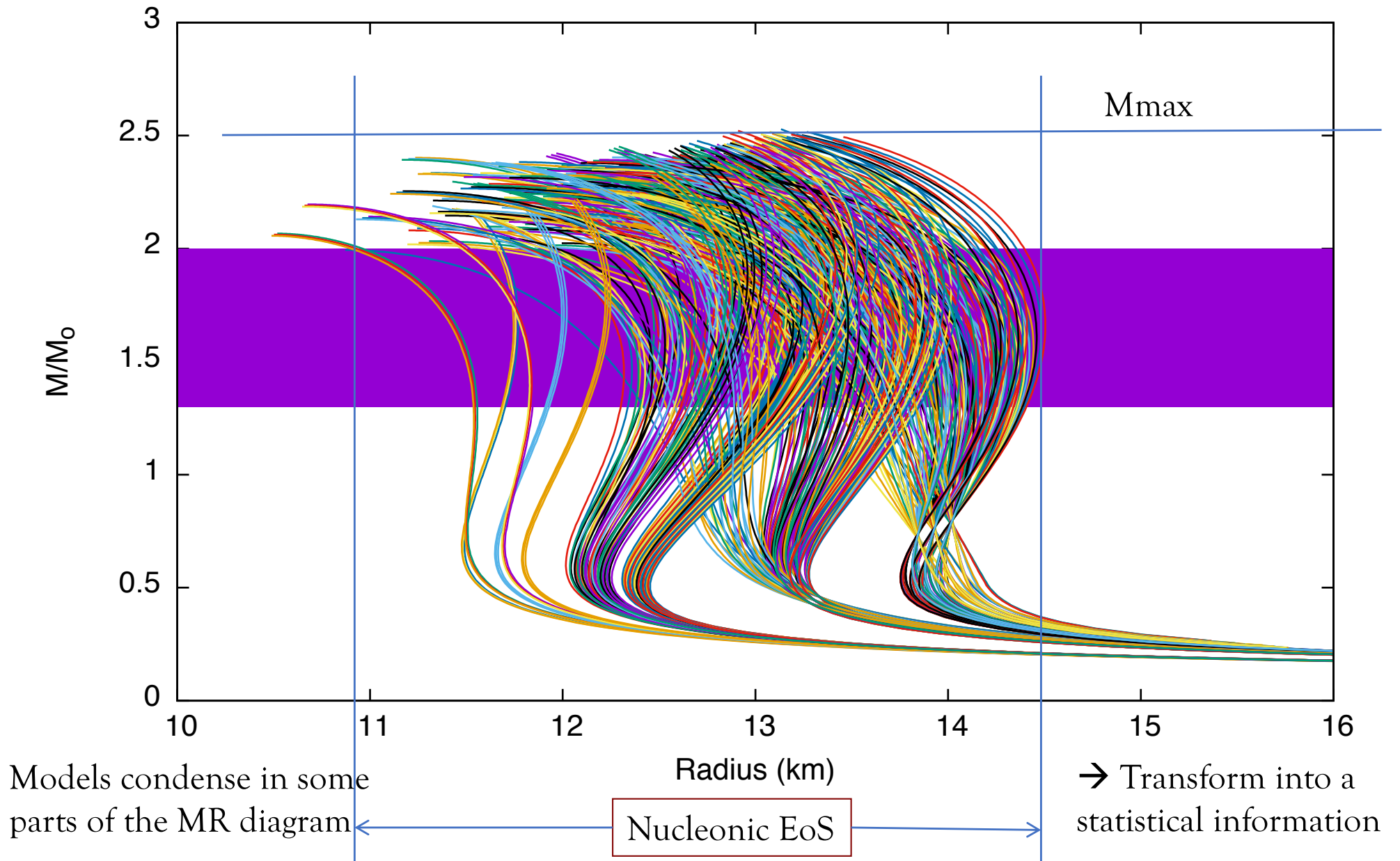


Impact on the MR relation

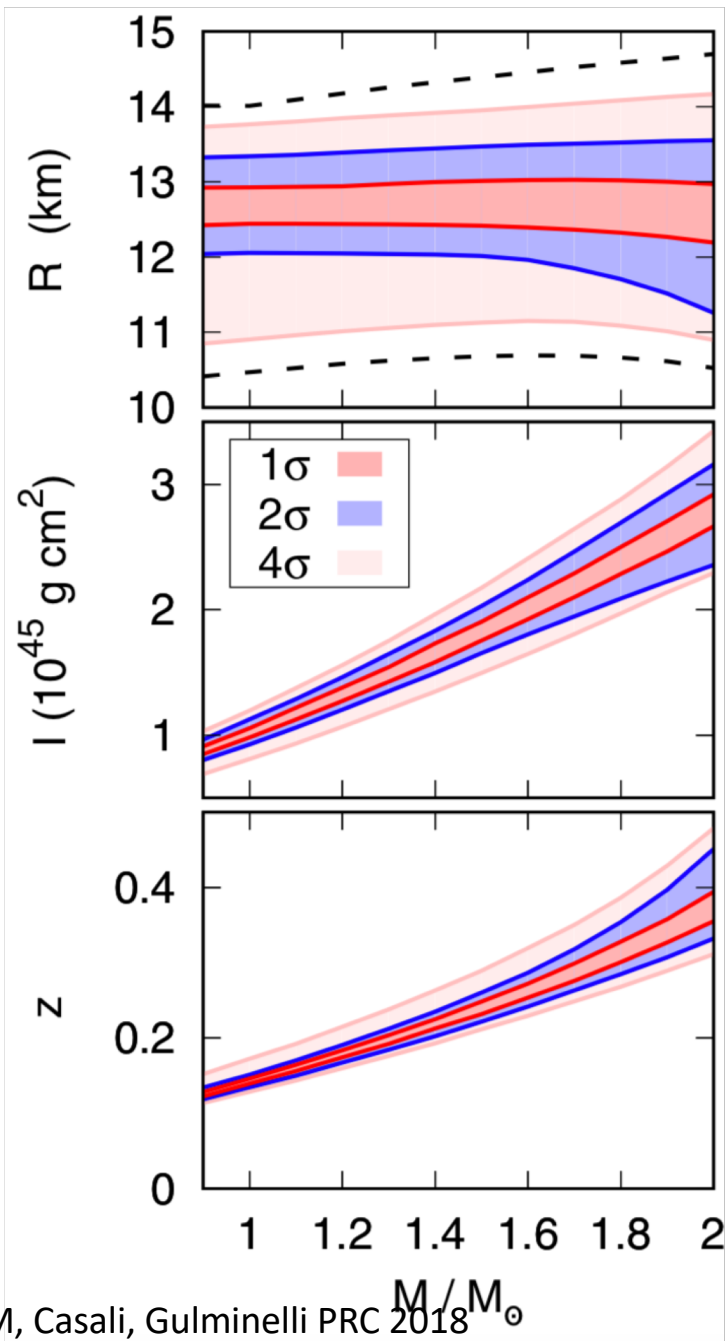
Largest source of uncertainty: L_{sym} and K_{sym}



Impact on the MR relation



Bayesian predictions for NS



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

Gaussian prior on the empirical parameters

Filtering against causality and stability

Notice: no explicit constrain against chiral EFT

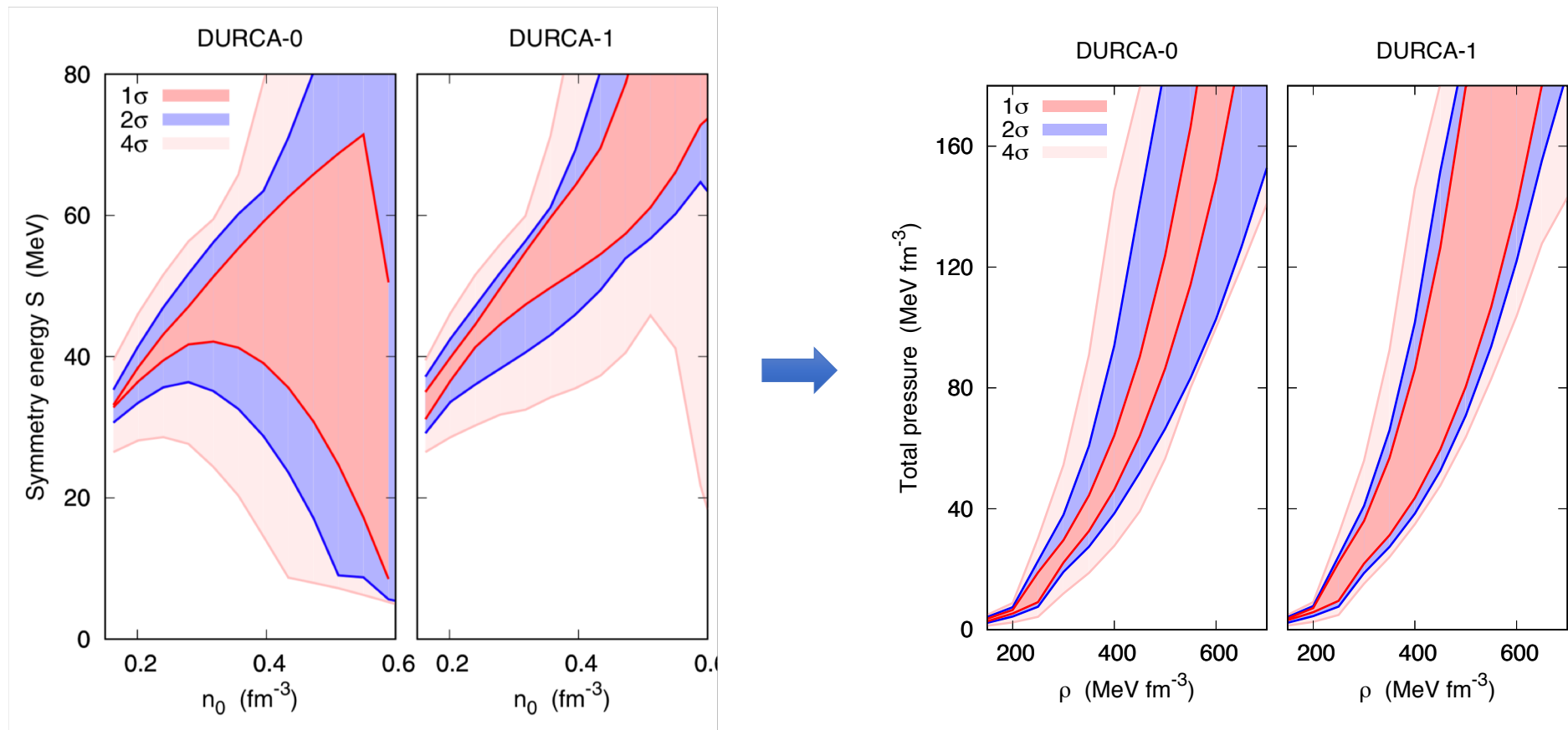
➡ $R_{1.4} = 12.7 \pm 0.4 \text{ km}$
for nucleonic matter

Bayesian predictions for NS

Symmetry energy:

2 classes of models: **DURCA-0**: $x_p < 1/9$ for $M < 2\text{Mo}$ (asy-soft EOS)

DURCA-1: $x_p > 1.9$ for $1.8\text{Mo} < M < 2\text{Mo}$ (asy-stiffer EOS)



Quasi-universality of the nucleonic EOS.

Previously suggested by Blaschke et al., 2016 for DURCA-0 case

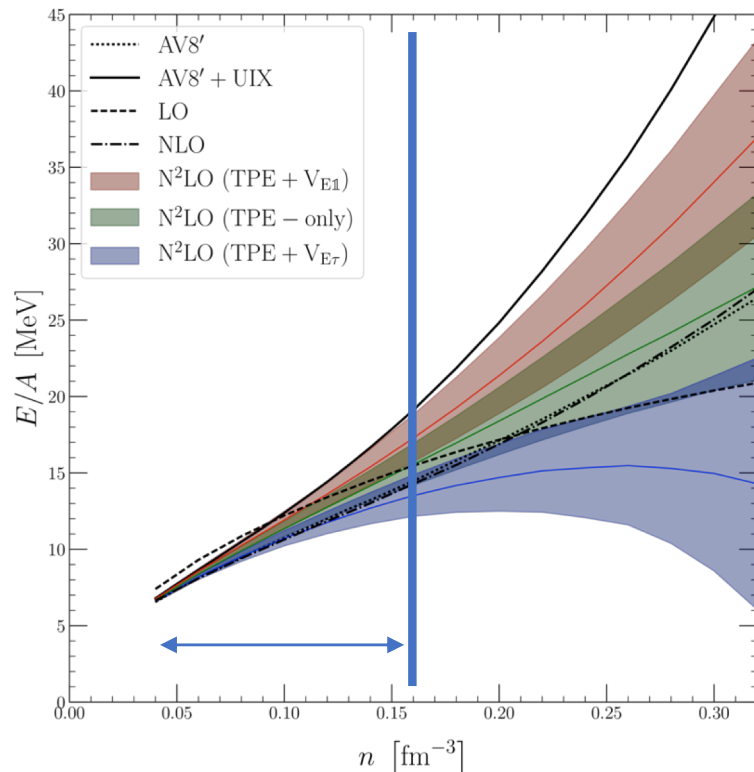
Confronting 2 models: CSM versus MM

We have a meta-model (MM) for the nucleonic EOS.

CSM (sound speed parametrization) is more general and contains explicitly a first-order phase transition.

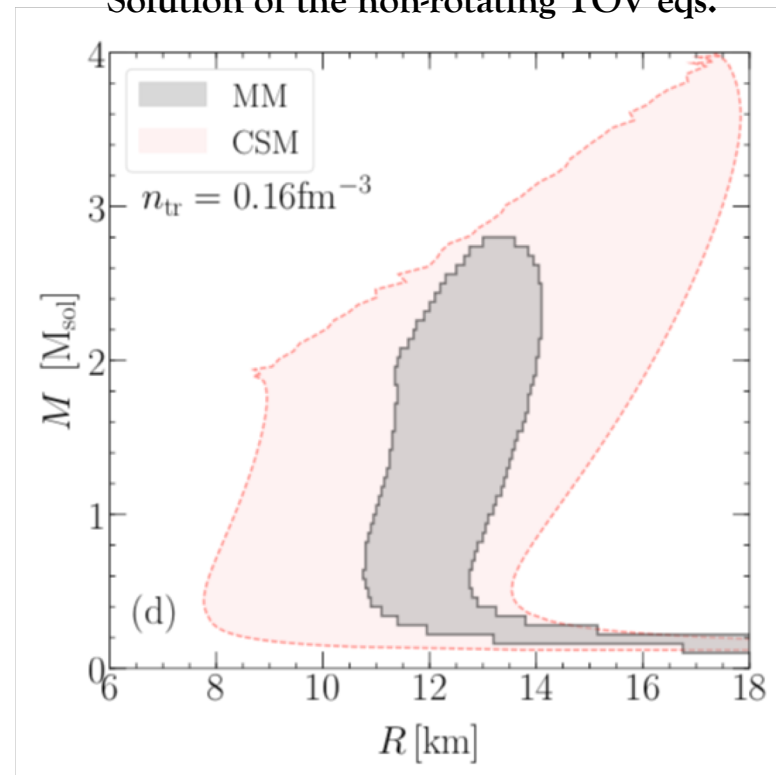
Confronting CSM versus MM provides information about common predictions and expected differences, e.g. masquerade issue.

QMC calculations with local chiral potentials



Tews, Carlson, Gandolfi, Reddy, PRC 2018

Solution of the non-rotating TOV eqs.



Tews, JM, Reddy, PRC 2018

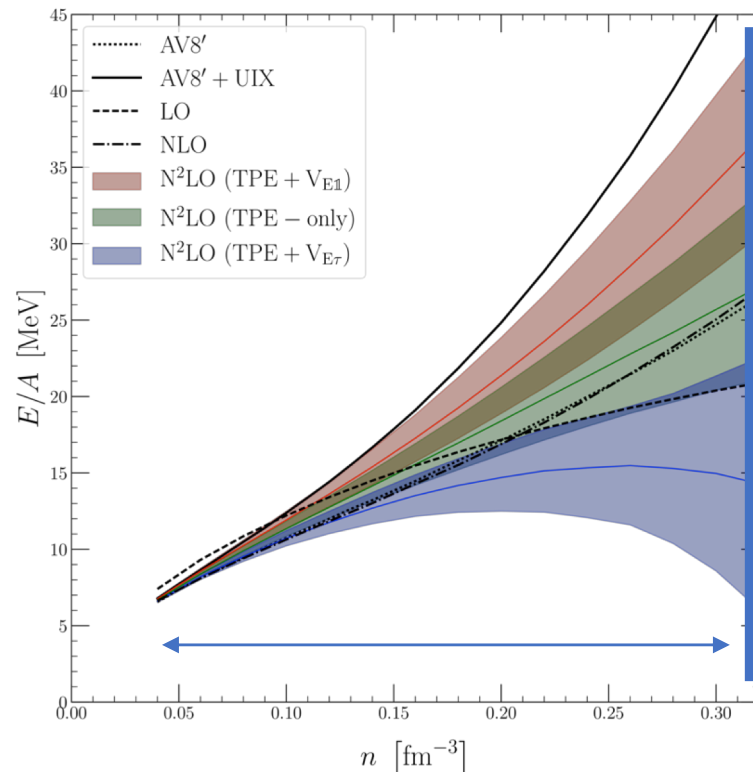
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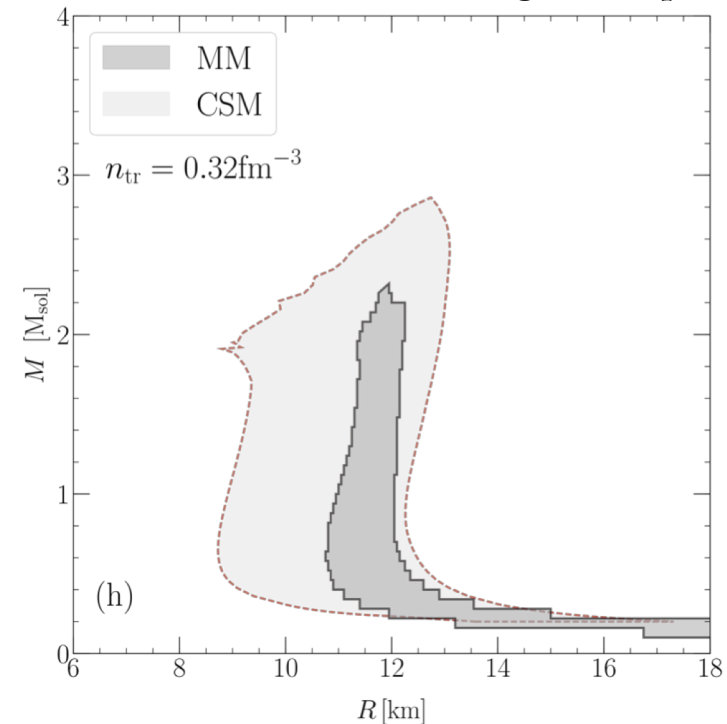
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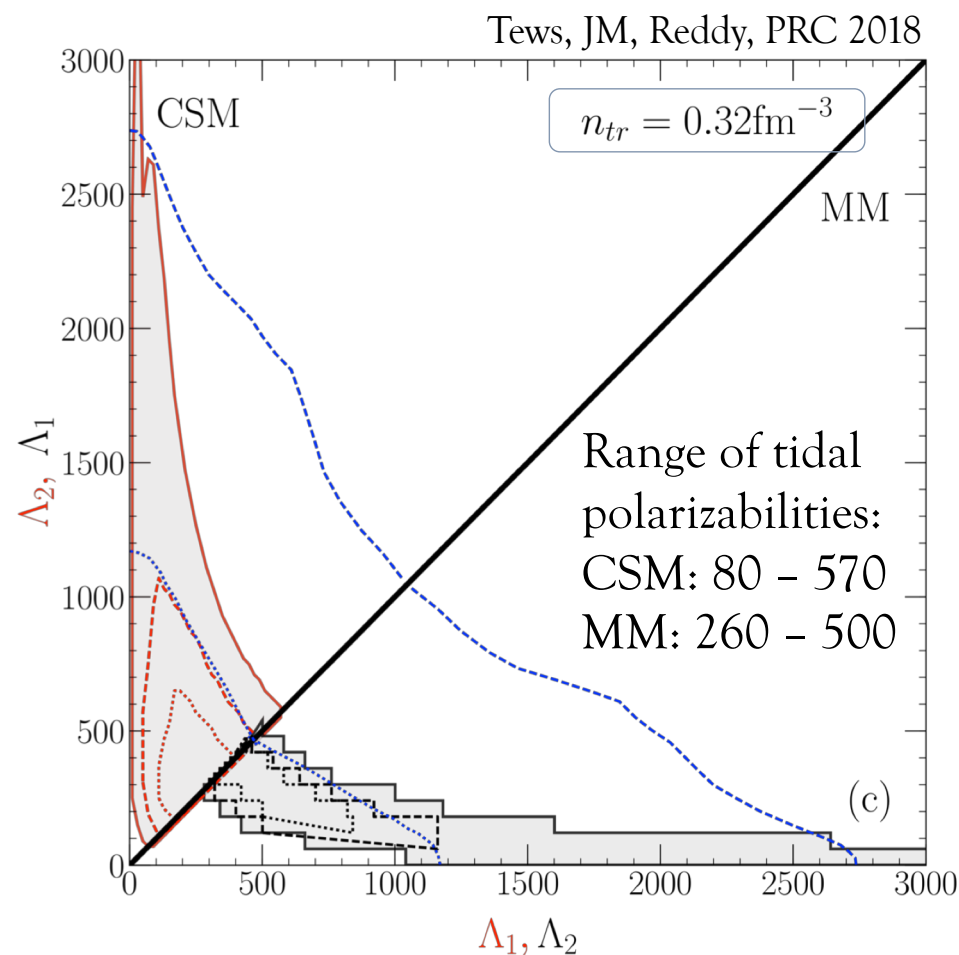
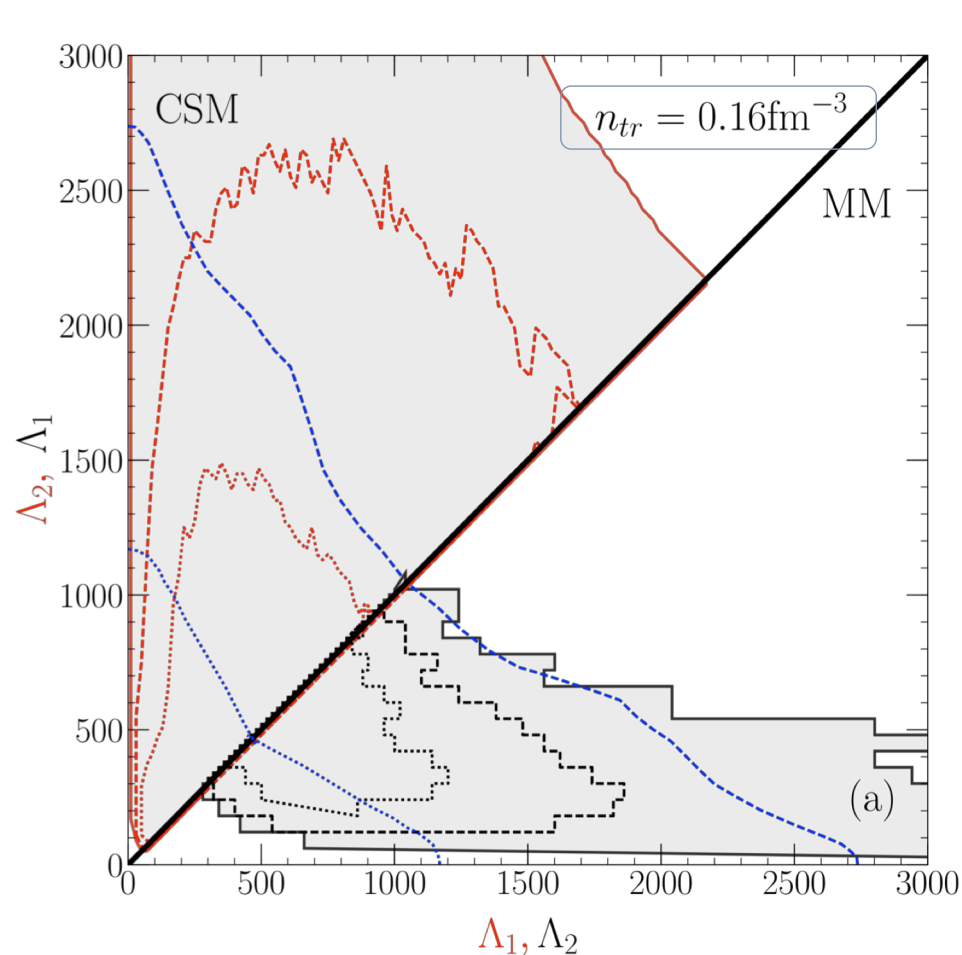
Tews, Carlson, Gandolfi, Reddy, PRC 2018

Solution of the non-rotating TOV eqs.



Tews, JM, Reddy, PRC 2018

Confronting 2 models: CSM versus MM



**Required GW accuracy to
improve our knowledge:**

$$\Delta\Lambda \approx 200-300 \rightarrow$$

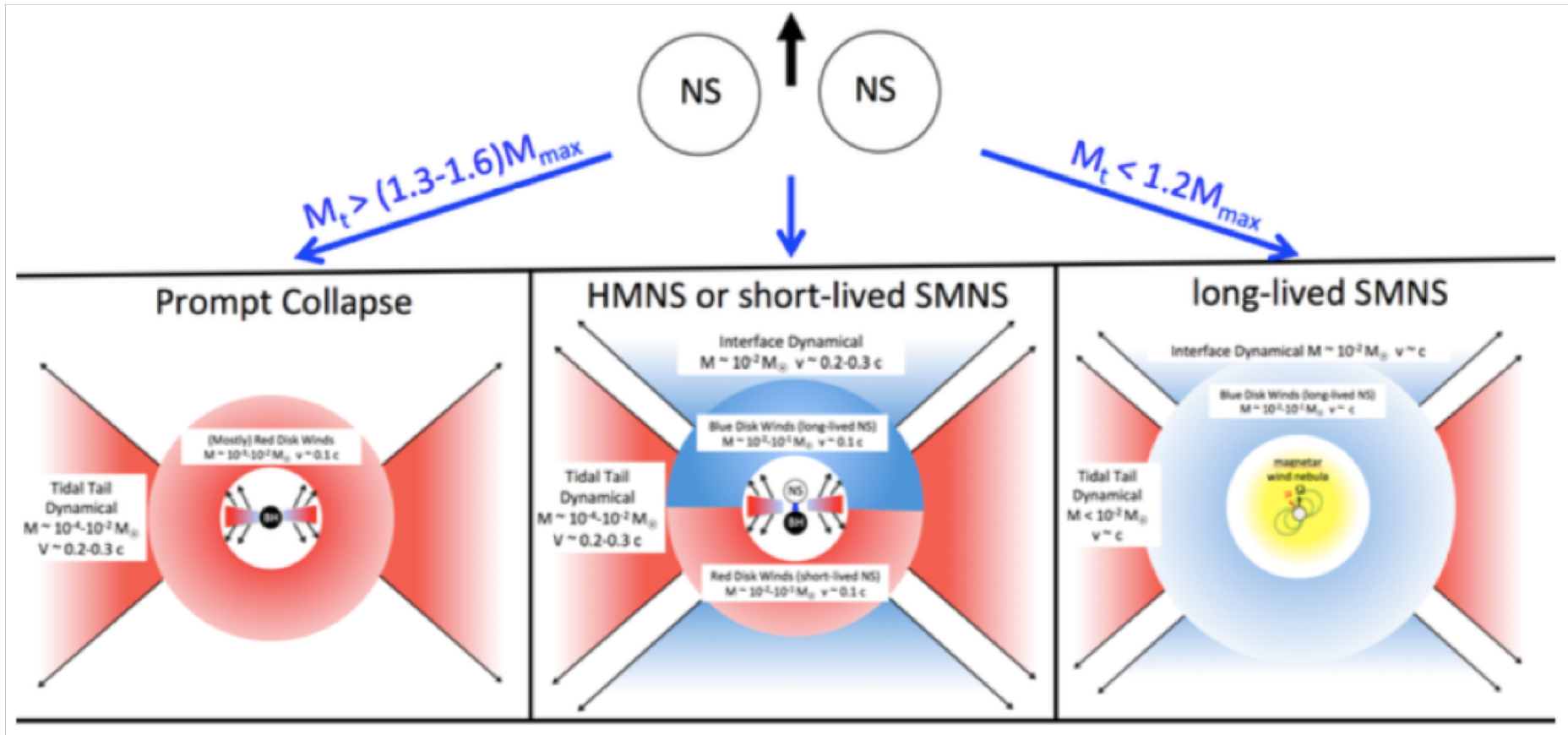
Probe EOS from 1 to $2n_{\text{sat}}$

Confirm or rule out nuclear physics

$$\tilde{\Delta}\Lambda \approx 50-100 \rightarrow$$

Probe matter composition above $2n_{\text{sat}}$

Extreme matter and EM signal



Margalit & Meitzger ApJ 2017

Kilonova (macronova) AT2017gfo $\rightarrow M_{\max} = 2.1-2.3 M_{\odot}$

Rezzolla+ 2018

Extreme matter and EM signal

Nucleosynthesis and Ye of ejecta

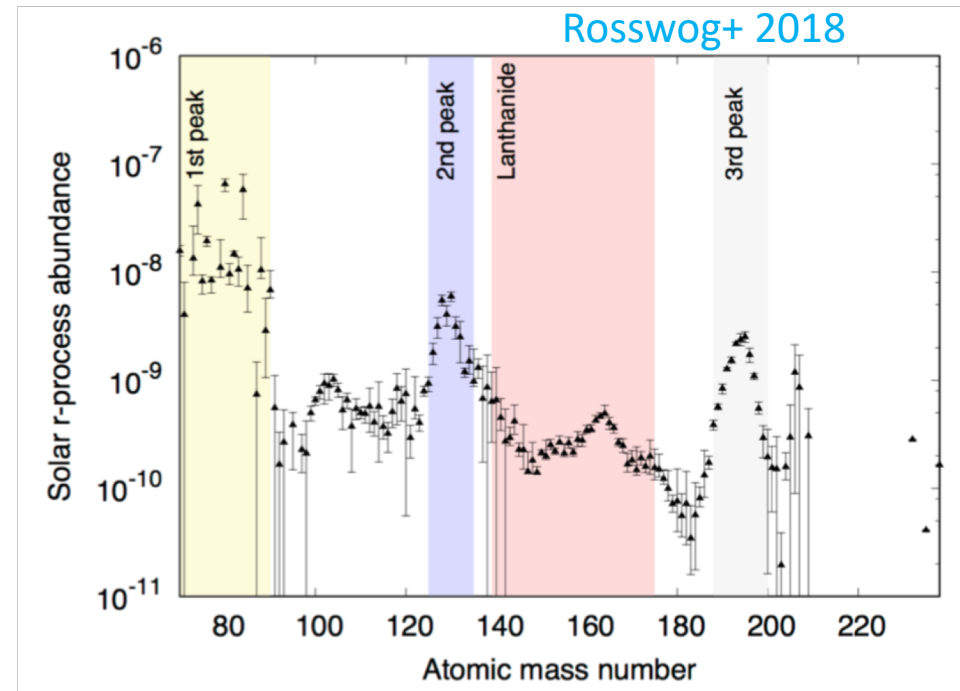
Synthesis of heavy nuclei (above 2nd peak):
What are the conditions for the r-process?

$Y_e < 0.25$:

- Strong r-process $A > 130$
- Insensitive to details of trajectory

$Y_e > 0.25$

- $A < 130$
- Sensitive to details of trajectory

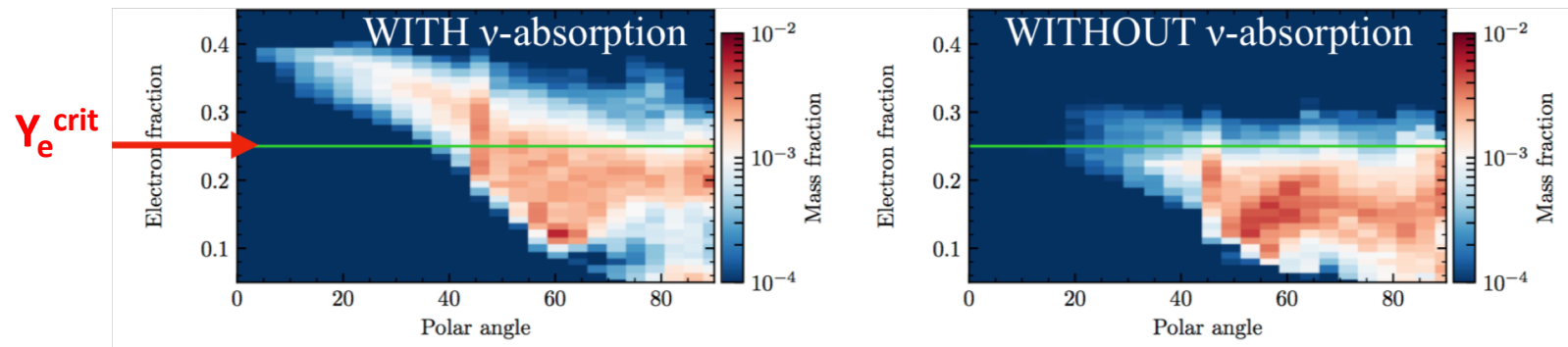


Production of lanthanides (large opacities) → redding of the EM signal

Extreme matter and EM signal

Neutrinos and EM signal

neutrino heating: ejecta from 1.35+1.35Mo



SFHO-EOS Perego+ 2017

Shibata+ 2017

$Y_e > 0.25$
Blue transient



$Y_e < 0.25$
Red transient



→ neutrino-matter interaction
determines the color of the kilonova.

**Accurate treatment of neutrino transport
needed to predict EM-transient.**

Conclusions and Outlook

A large amount of new observational data! (GW, NICER, nuclear physics, ...).

It allow us to believe the **dense matter properties will soon be accurately known**
(at least for E , P , c_s).

Then matter composition will be the next question!

We propose a meta-modelling for nucleonic matter and contrast it with CSM

→ minimal (nucleonic) *versus* maximal (including phase transition) predictions.

Plans for the future:

- enrich the meta-model with more degrees of freedom (Δ , Y , q , ...).
- Extend to finite temperature.
- Incorporate meta-model into global simulations → statistical Bayesian analysis.

Take home message:

Astrophysics and nuclear physics are complementary for the understanding of the QCD phase diagram.