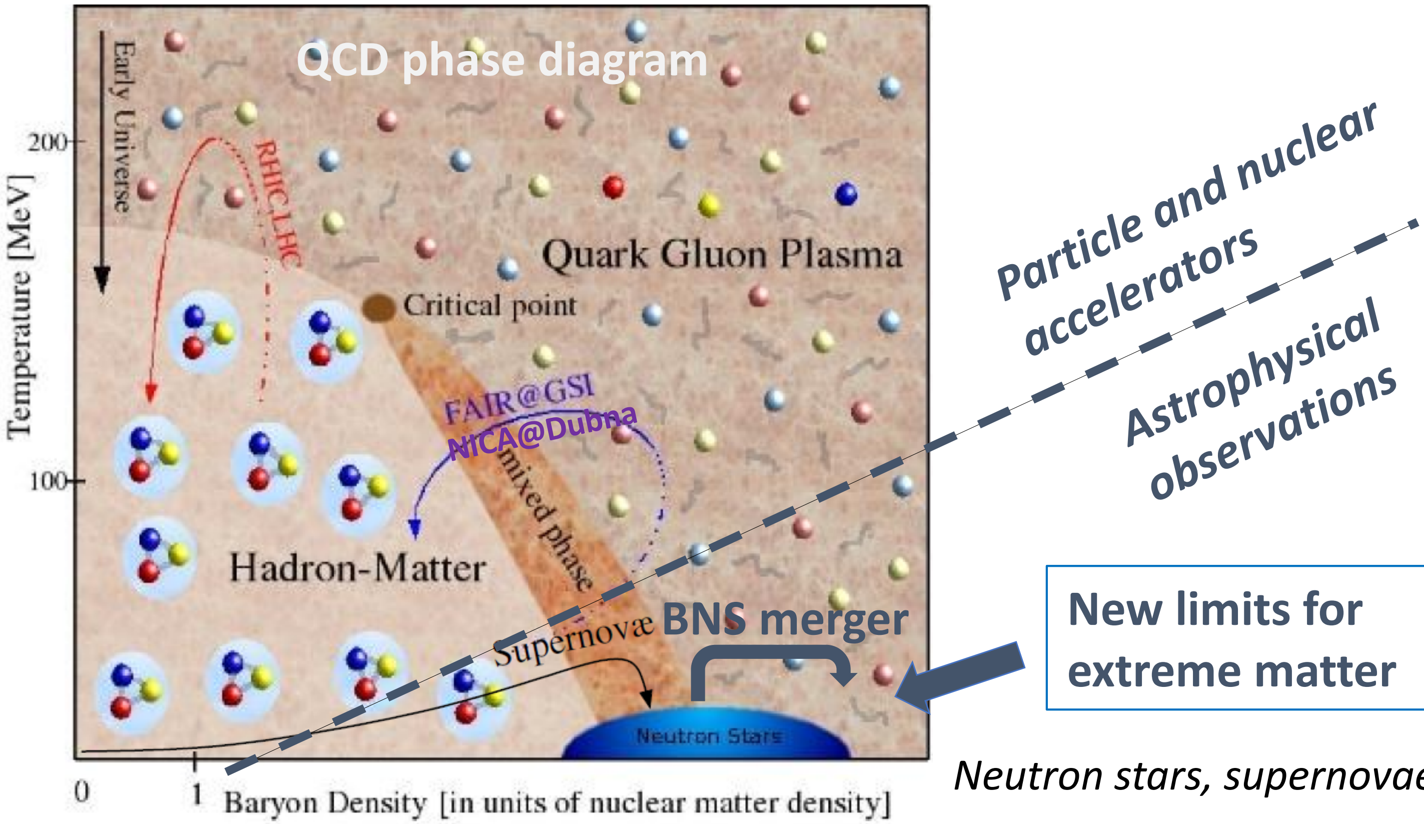
MODE Meeting, Hôtel Dupanloup, Orléans, April 8-10, 2019

Towards a better understanding of dense matter with gravitational waves

J. Margueron, IPN Lyon



New limits for extreme matter

Neutron stars, supernovae, kilonovae…

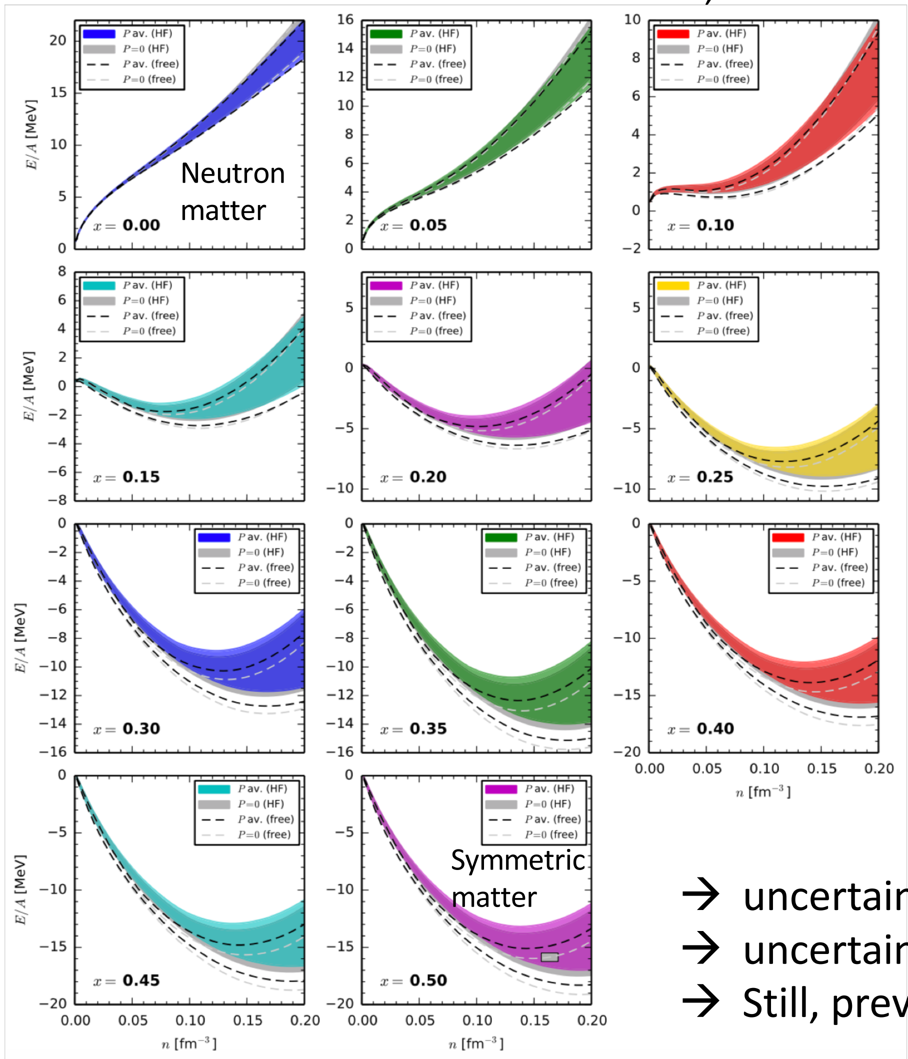
From low density neutron matter (chiral EFT) to high density

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

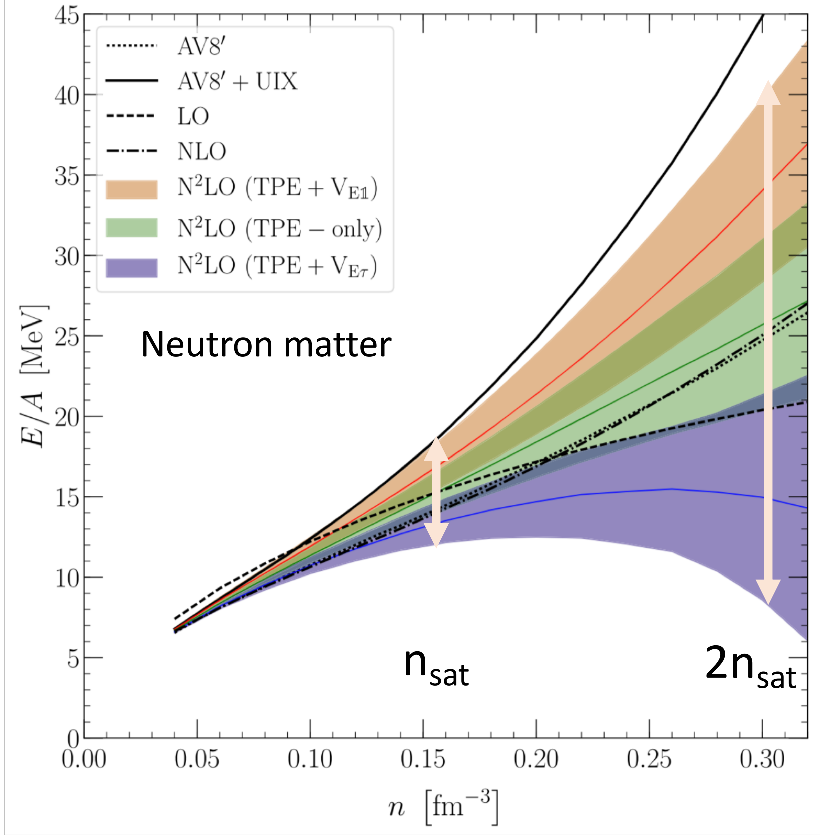
→ gets larger as the density increases. At saturation density, $q \sim k_F \sim 270$ MeV, → $q \sim 0.5$!

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

Drischler et al., PRC 2016



Tews et al., Astro.J 2018



→ uncertainties increases from NM to SM (better exp. knowledge).

→ uncertainties greatly increases from n_{sat} to $2n_{sat}$.

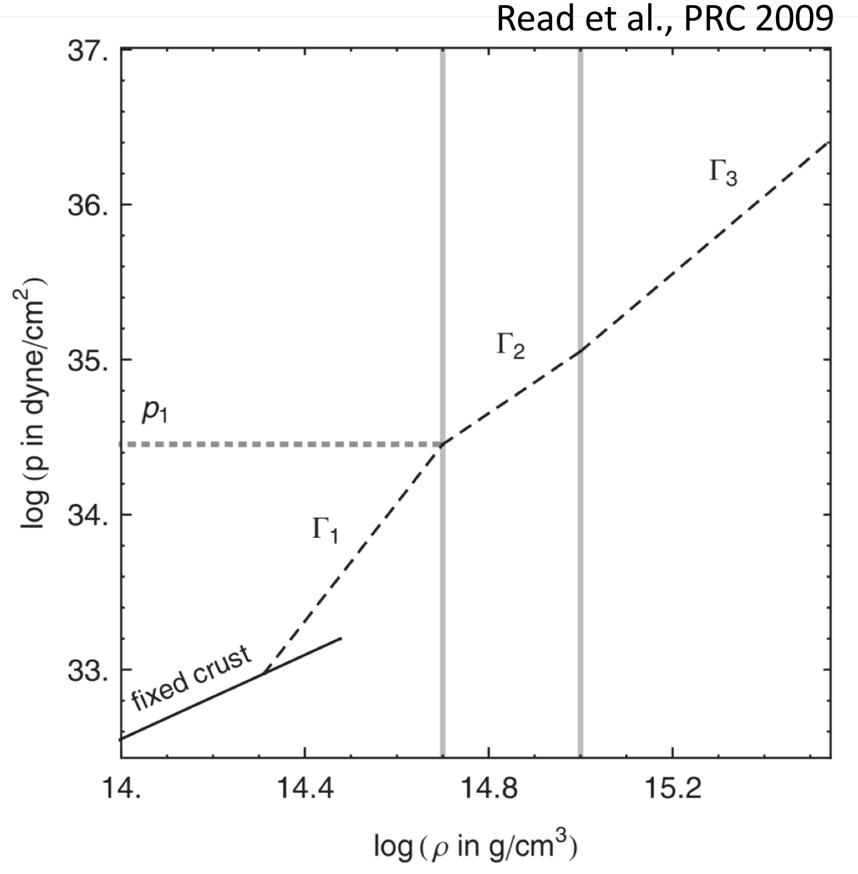
→ Still, preventing phase transition up to $2n_{sat}$ is useful information.

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, Bayesians inference, MCMC, etc…).

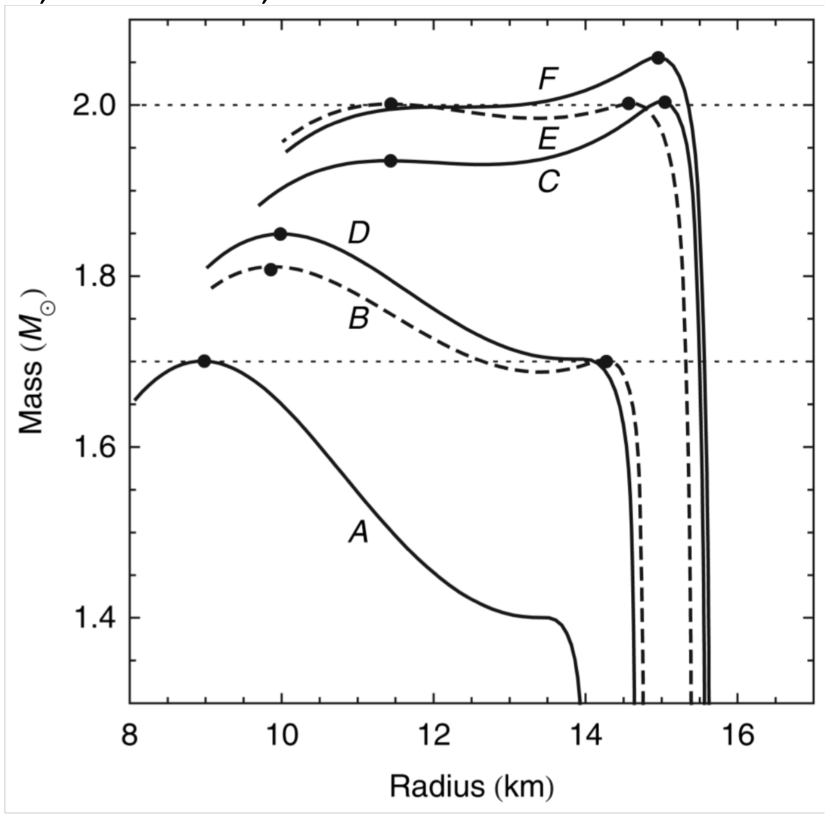
Piecewise polytrope: $p(\rho) = K\rho^{\Gamma}$

Read et al., PRC 2009



TOV solution

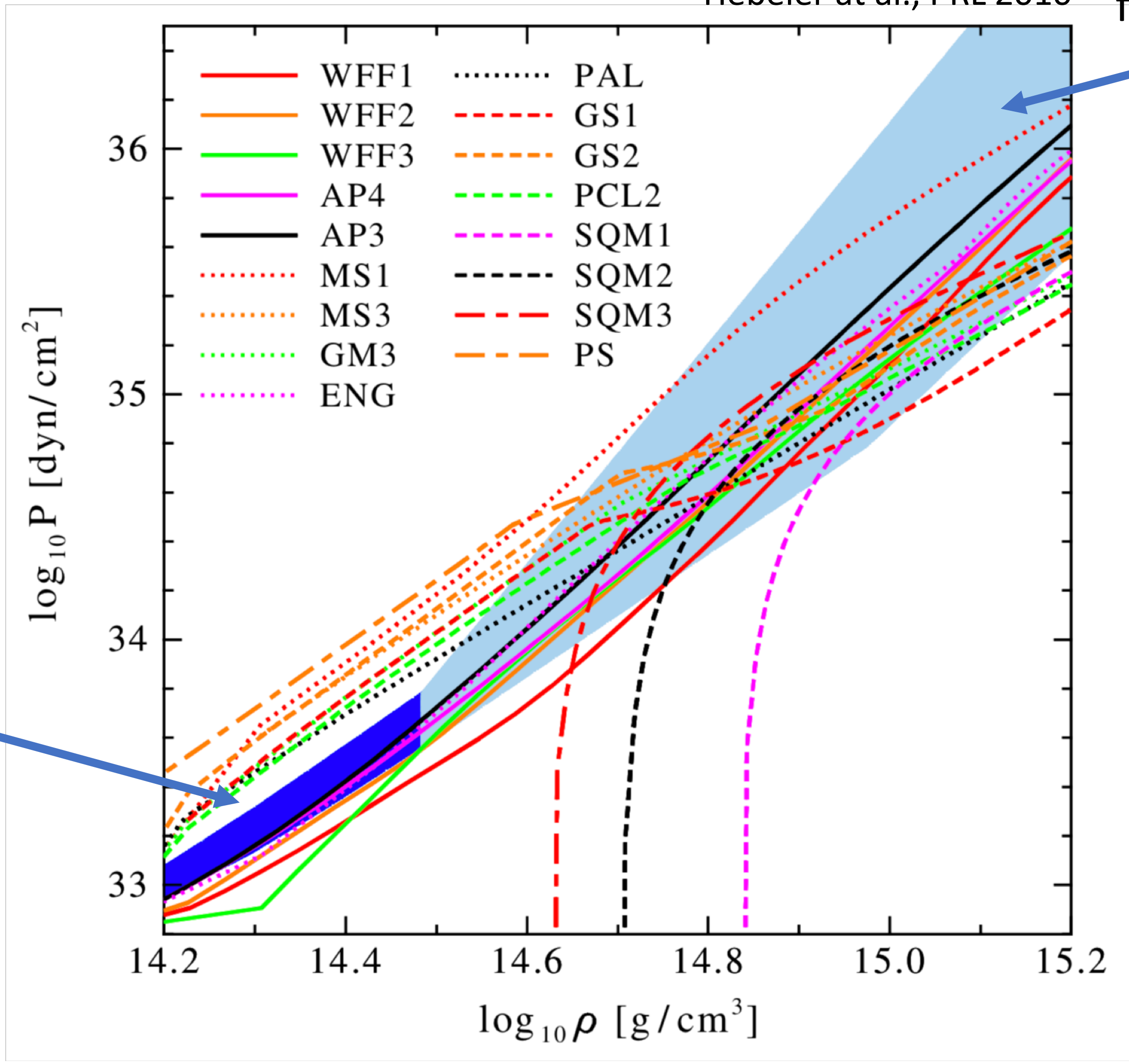
Özel 2009, 2010, Steiner 2013, …



When chiral EFT meets observers

Hebeler at al., PRL 2010

Extrapolations
from polytropes

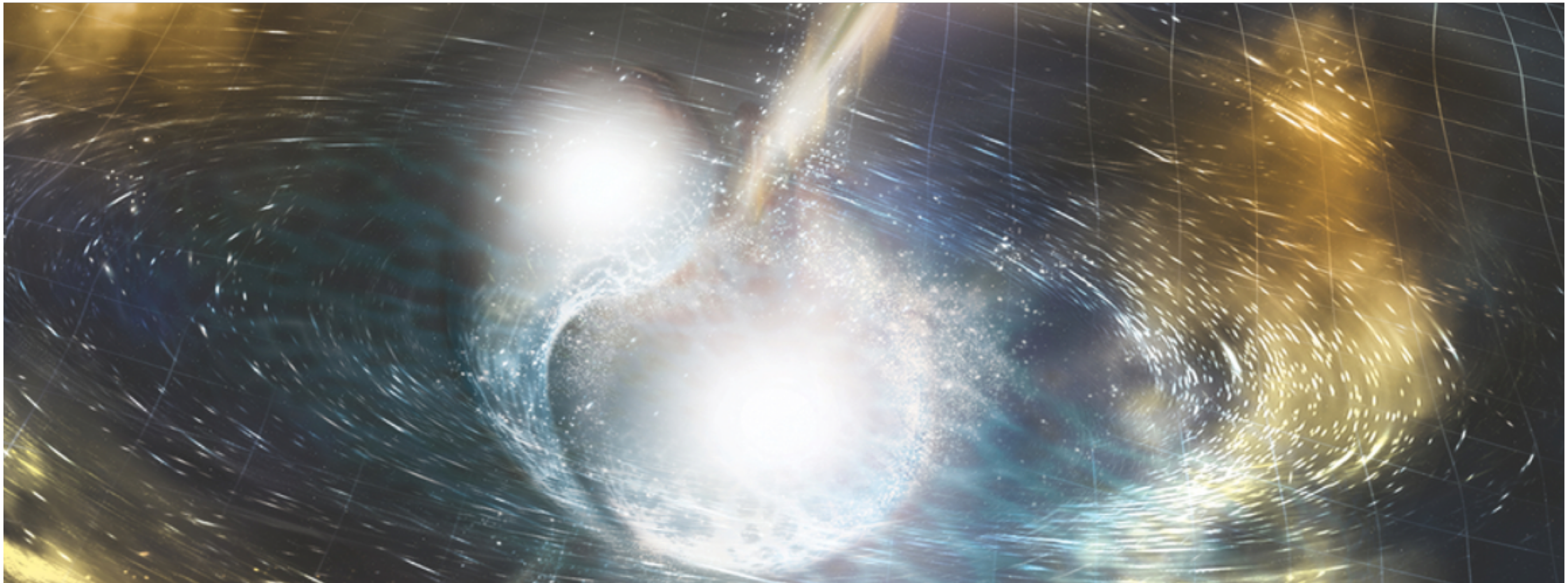


Chiral EFT band

Probing extreme matter with GW

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

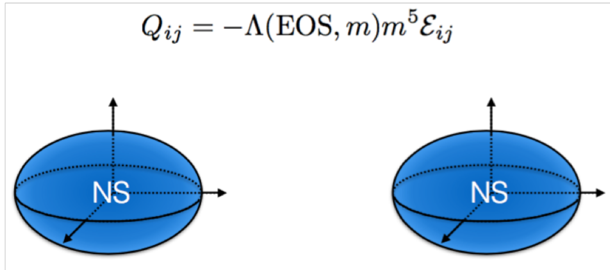
Abbott et al., LVC, PRL 2017, PRL 2018



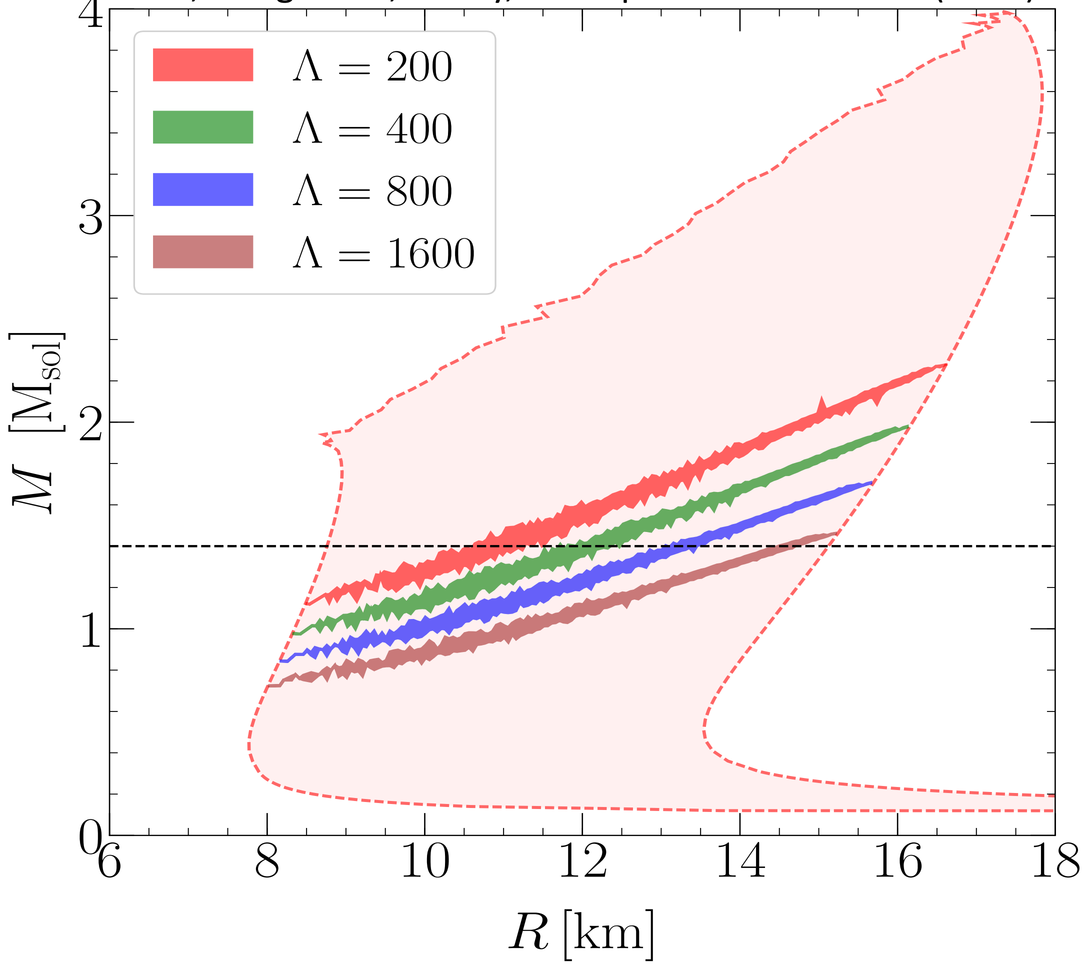
Cataclysmic Collision Artist's illustration of two merging neutron stars. The rippling space-time grid represents gravitational waves that travel out from the collision, while the narrow beams show the bursts of gamma rays that are shot out just seconds after the gravitational waves. Swirling clouds of material ejected from the merging stars are also depicted. The clouds glow with visible and other wavelengths of light. Image credit: NSF/LIGO/Sonoma State University/A. Simonnet

Neutron star matter and inspiral GW signal

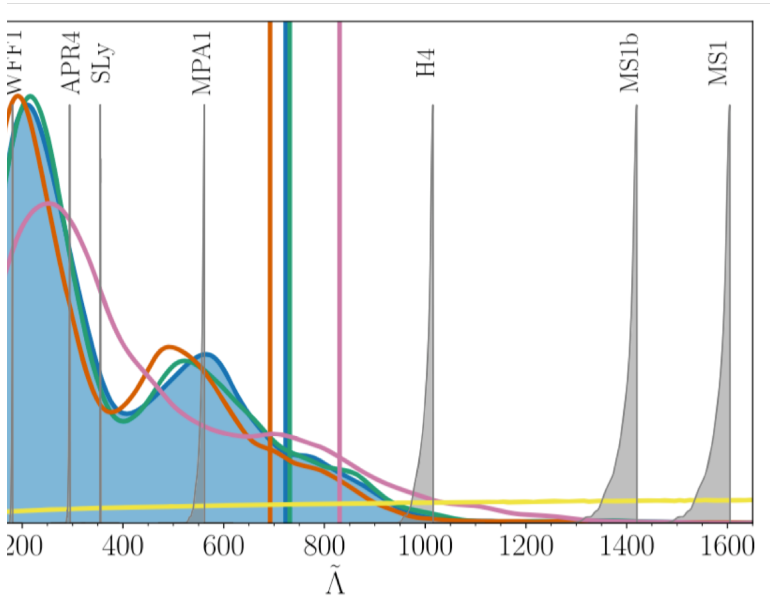
Tidal deformability



Tews, Margueron, Reddy, EPJA special issue on GW (2019)



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

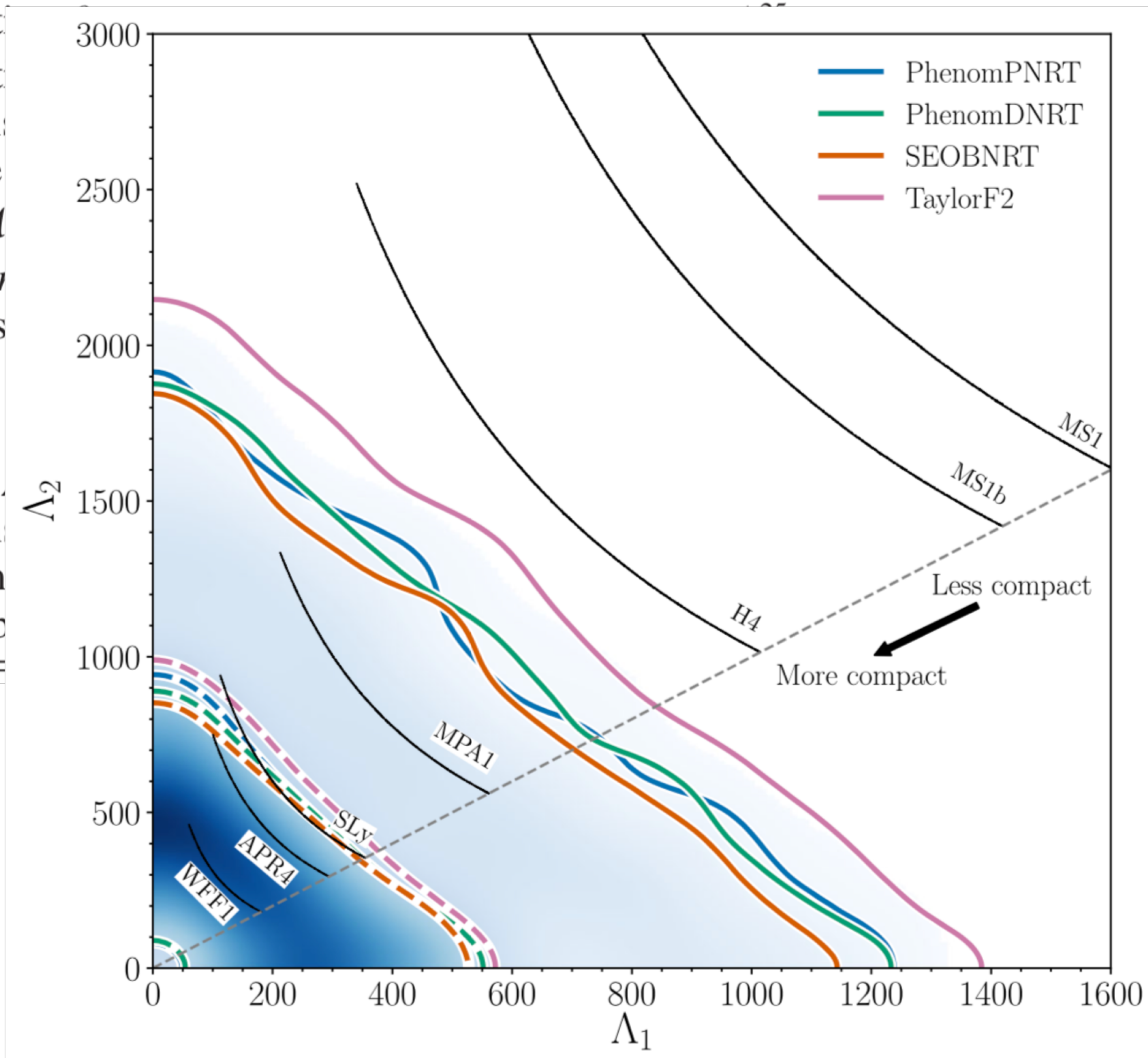


GW170817 → 70 ≤ Λ ≤ 720 (90% CL)

How gravitational waves improves our current knowledge?

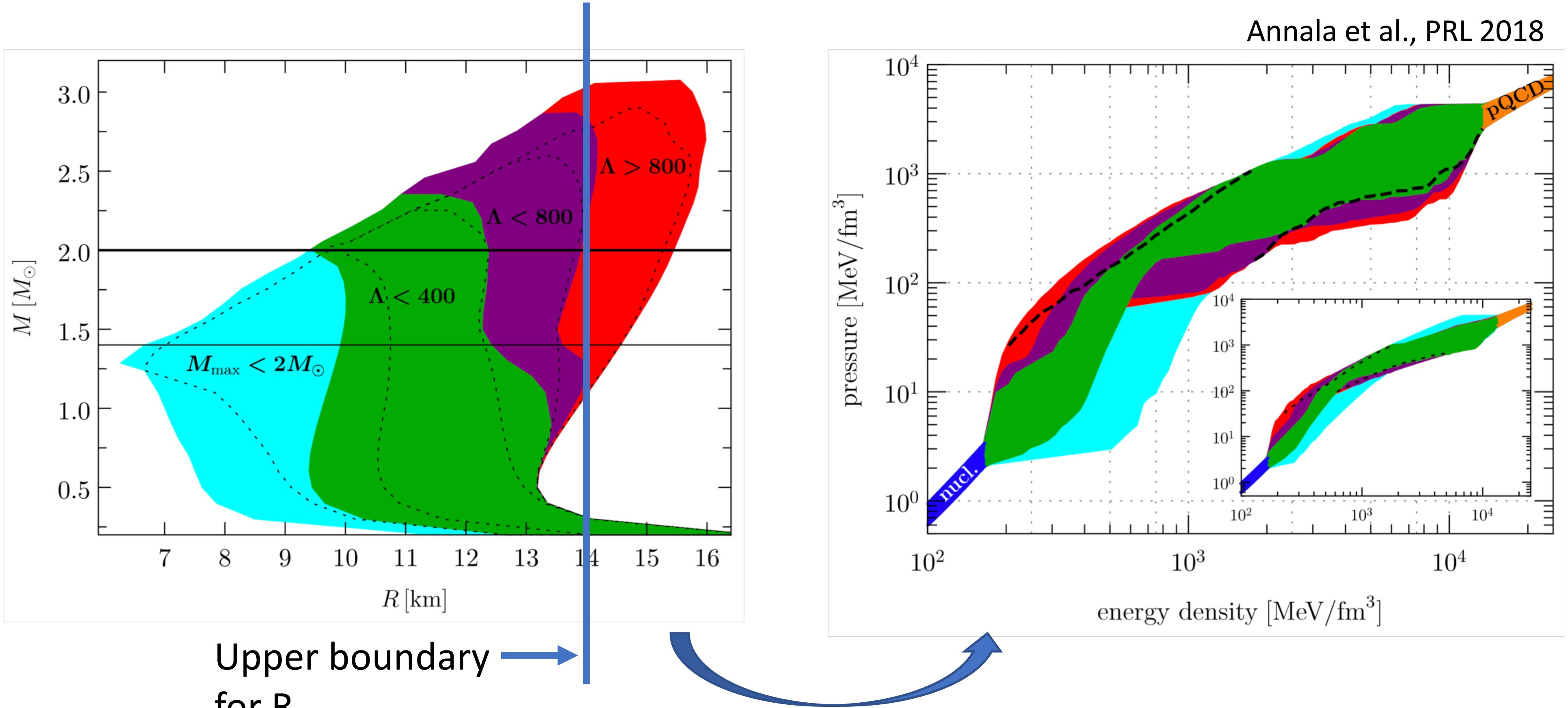
From GW170817 LVC, Phys. Rev. X 9, 011001 (2019)

	Low-spin prior ($\chi \leq 0.05$)	High-spin prior ($\chi \leq 0.89$)
Binary inclinat		152^{+21}_{-27} deg
Binary inclinat distance con		153^{+15}_{-11} deg
Detector-frame		$1.1976^{+0.0004}_{-0.0002}$ $M_\odot$
Chirp mass $\mathcal{M}$		$1.186^{+0.001}_{-0.001}$ $M_\odot$
Primary mass		$(1.36, 1.89)$ $M_\odot$
Secondary mas		$(1.00, 1.36)$ $M_\odot$
Total mass m		$2.77^{+0.22}_{-0.05}$ $M_\odot$
Mass ratio q		$(0.53, 1.00)$
Effective spin		$0.02^{+0.08}_{-0.02}$
Primary dimen		$(0.00, 0.50)$
Secondary dim		$(0.00, 0.61)$
Tidal deformab		$(0, 630)$



Confrontation of polytropic EoS to GW170817

Annala et al., PRL 2018



Upper boundary for R

Boundaries for the EoS

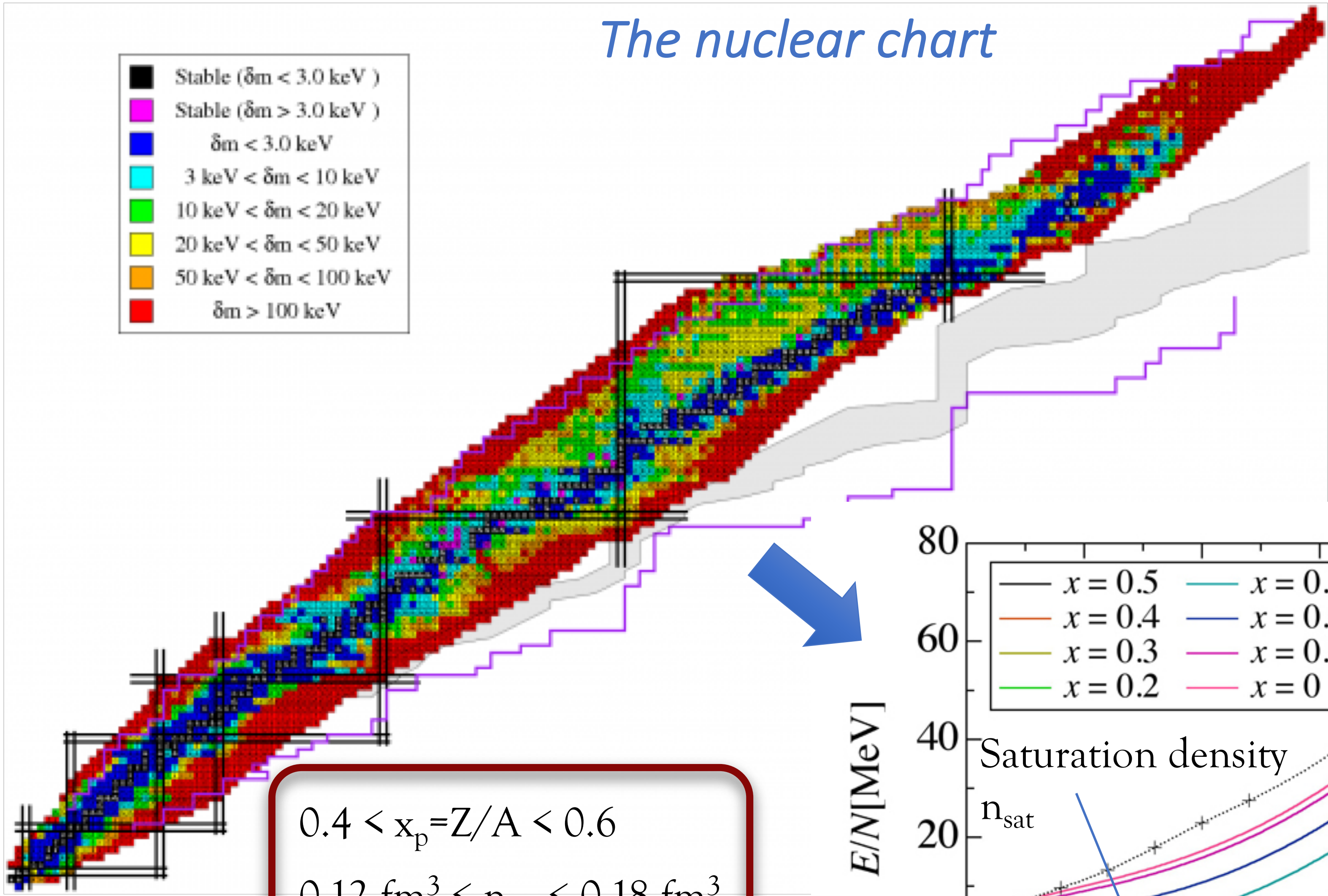
Ok, we have E and P, but what about the composition?

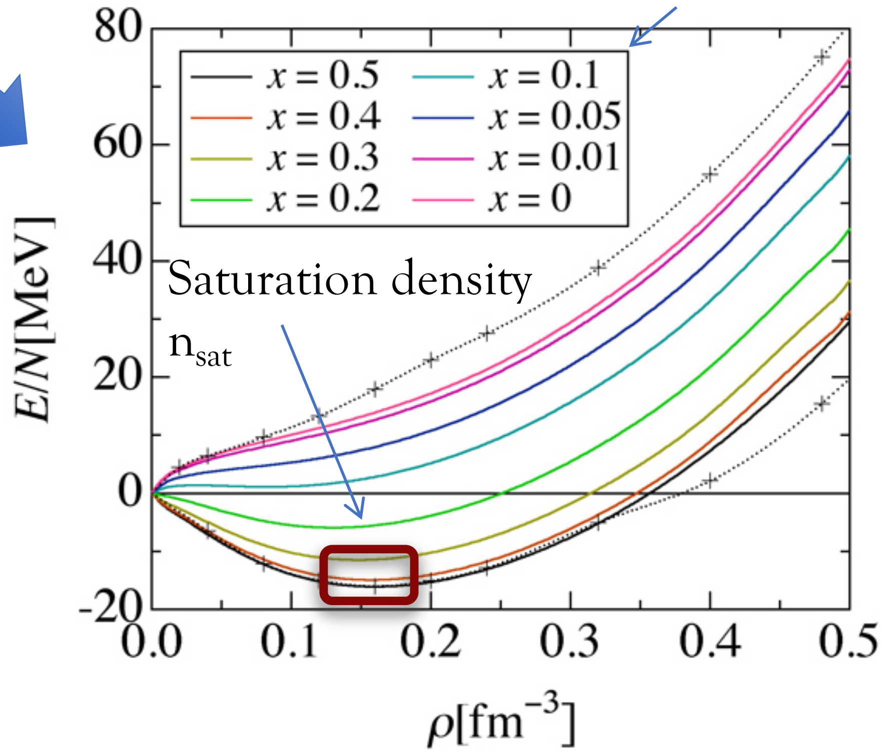
Polytropic EoS is blind to matter composition.

How one can retrieve information about matter composition from observations?

→ We need a model knowing about the composition.

The nuclear chart





$0.4 < x_p = Z/A < 0.6$

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

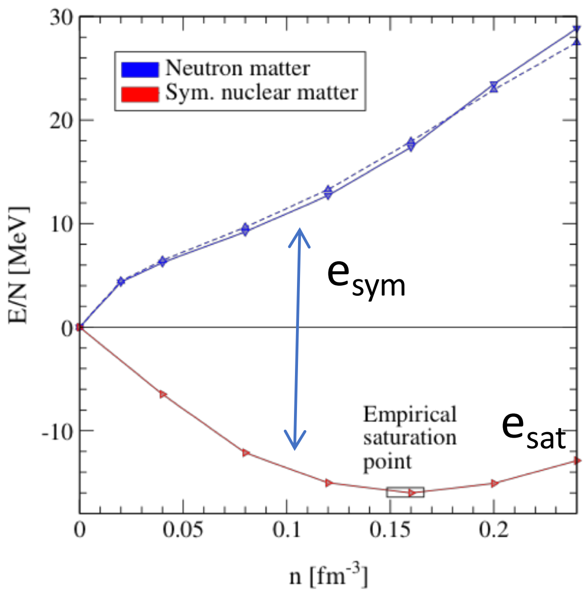
→ A very small region of the phase diagram

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



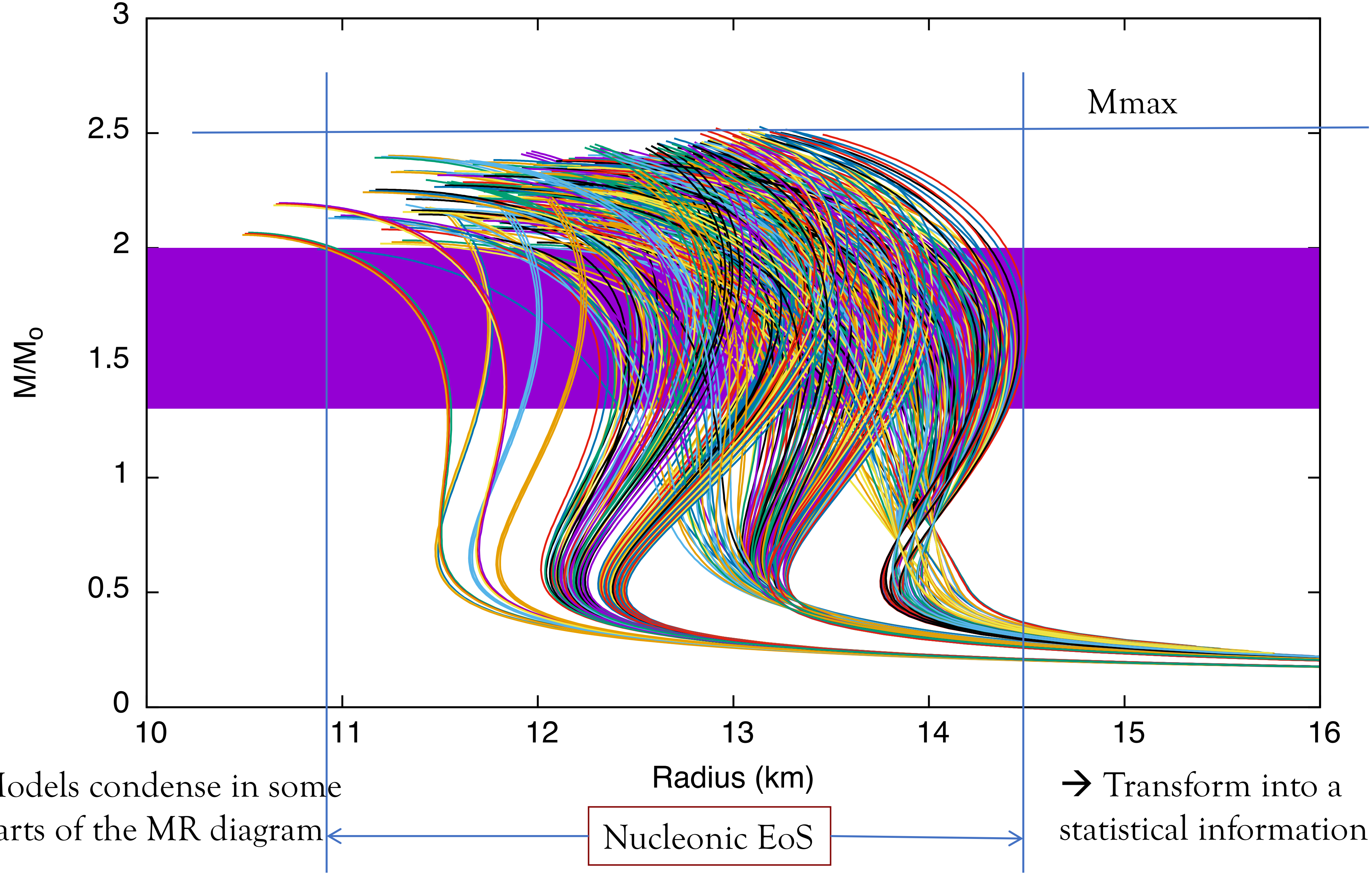
$$e_{sat}(n) = E_{sat} + \frac{1}{2}K_{sat}x^2 + \frac{1}{6}Q_{sat}x^3 + \frac{1}{24}Z_{sat}x^4 + \dots$$

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

	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

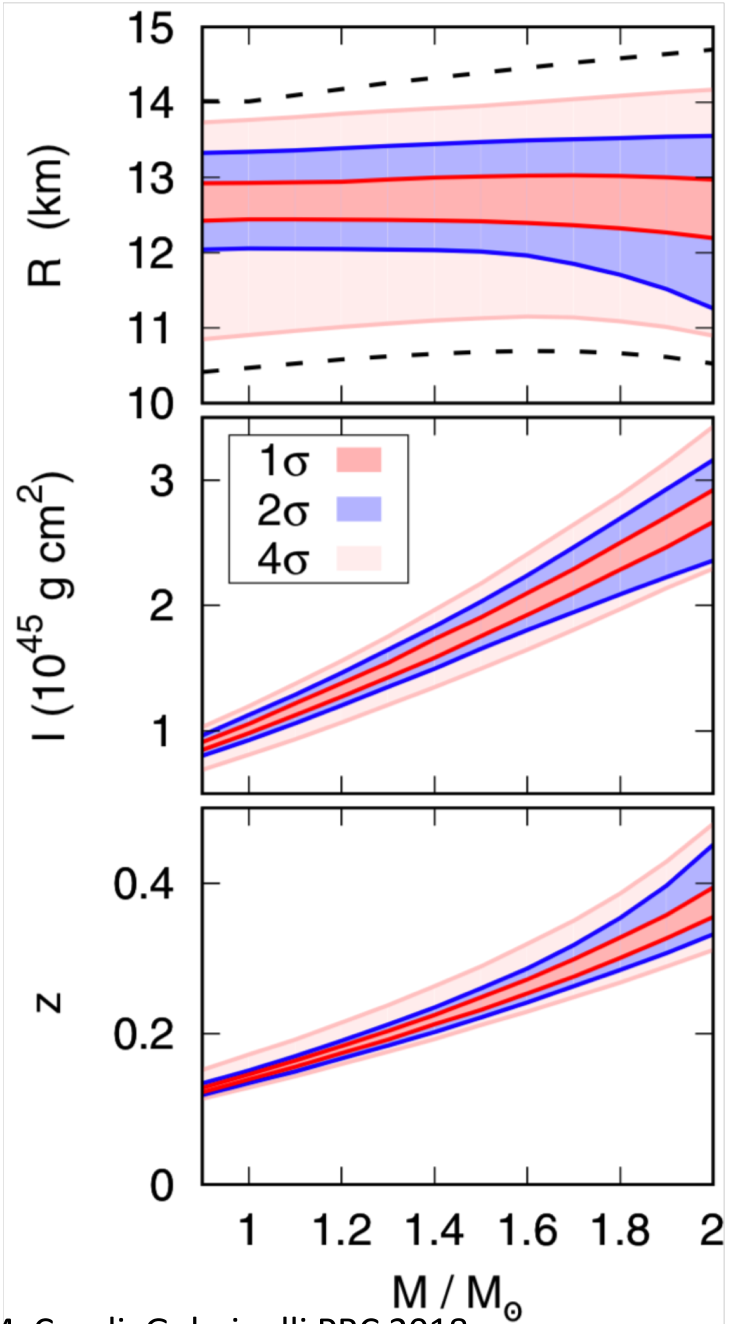
Impact on the MR relation



Models condense in some parts of the MR diagram

→ Transform into a statistical information

Bayesian predictions for NS



JM, Casali, Gulminelli PRC 2018

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

Gaussian prior on the empirical parameters

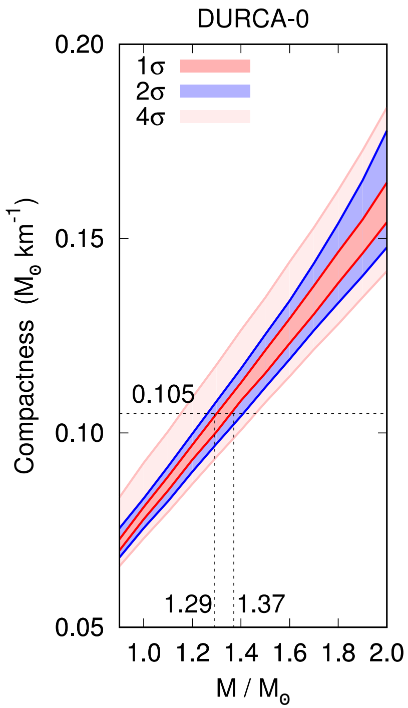
Filtering against causality and stability

$$R_{1.4} = 12.7 \pm 0.4 \text{ km}$$

for nucleonic matter

RX J0720.4-3125

Hambaryan et al., A&A 2017

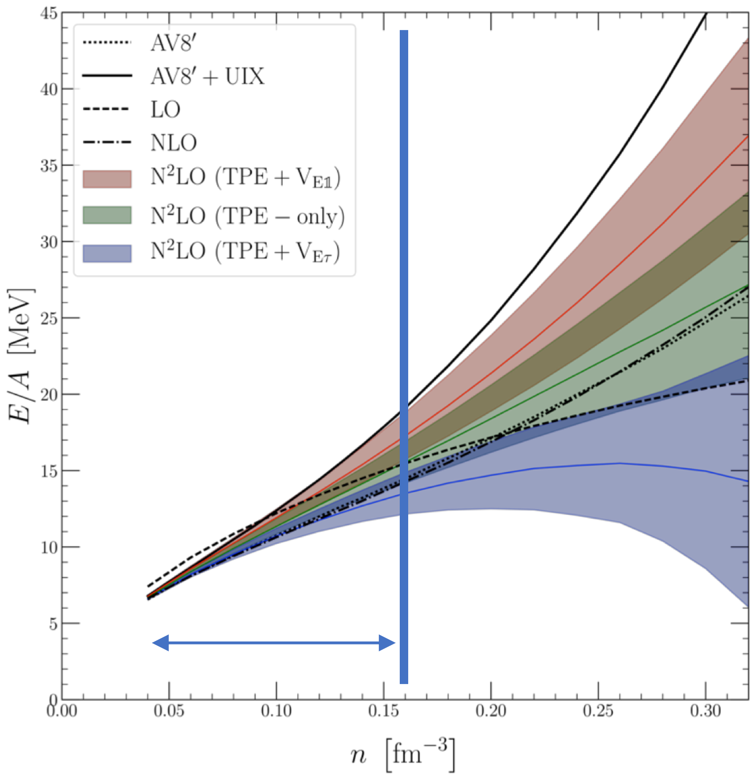


Confronting 2 models: CSM versus MM

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.

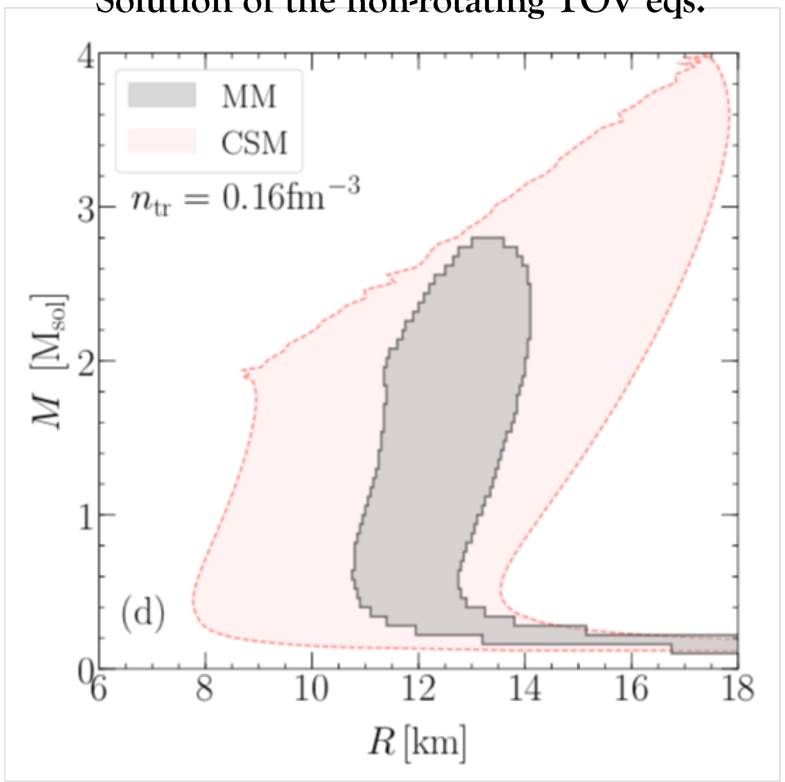
Confronting CSM versus MM provides information about common predictions and expected differences, e.g. masquerade issue.

QMC calculations with local chiral potentials



Tews, Carlson, Gandolfi, Reddy, PRC 2018

Solution of the non-rotating TOV eqs.



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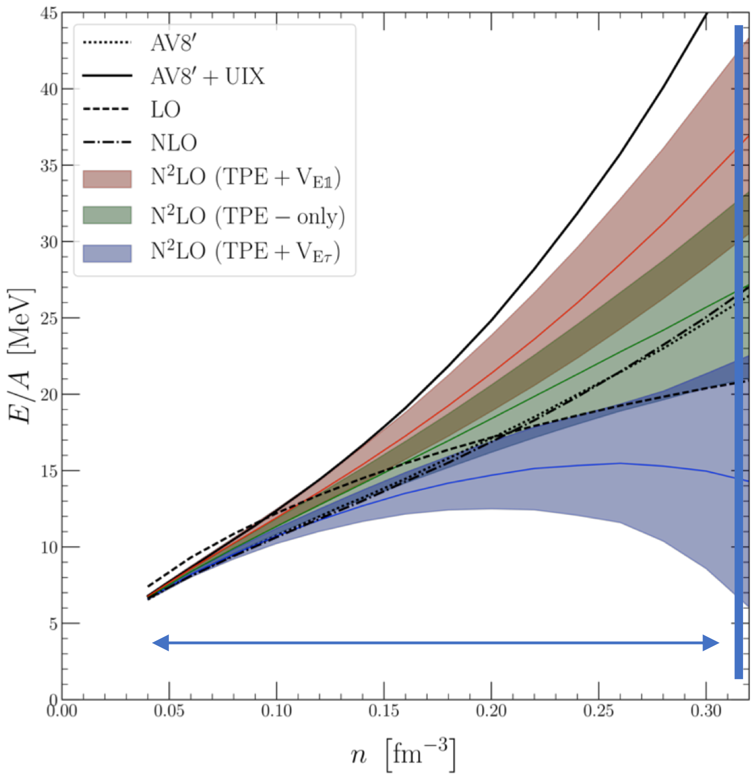

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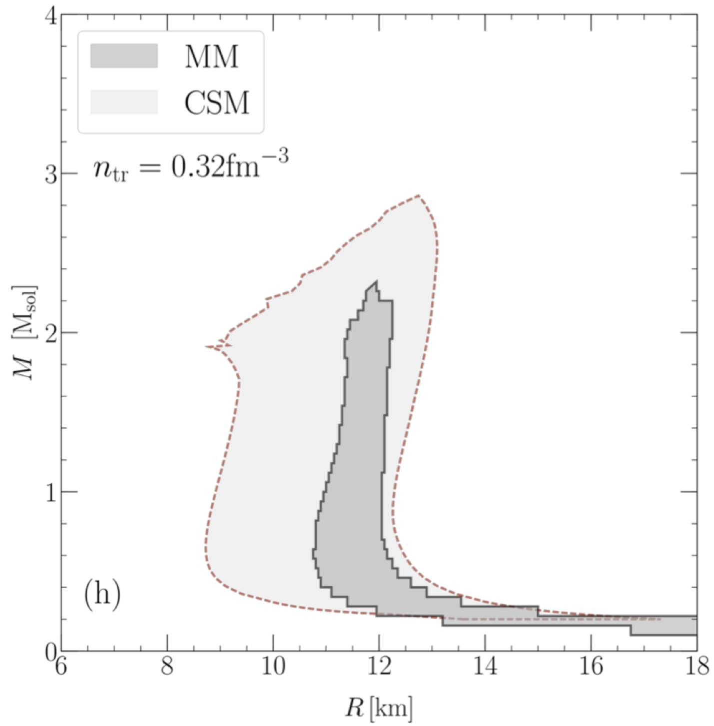

Tews, JM, Reddy, PRC 2018

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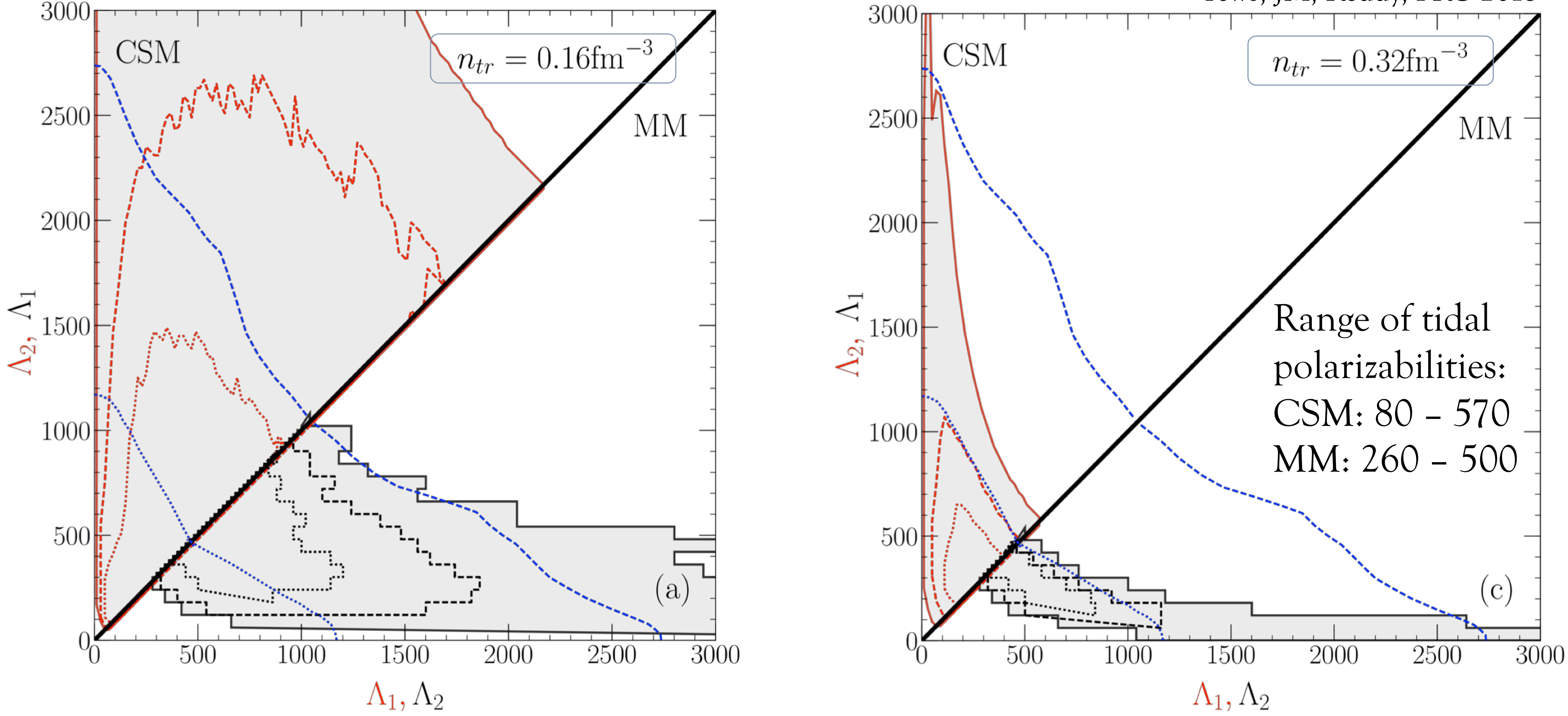

Required GW accuracy to improve our knowledge:

$\Delta\Lambda \approx$ 200-300 ➡ Probe EOS from 1 to $2n_{sat}$

Confirm or rule out nuclear physics

$\Delta\tilde{\Lambda} \approx$ 50-100 ➡ Probe matter composition above $2n_{sat}$

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.

Multi-messenger observation: The kilonovae EM signal is rich in information, that I haven't discussed here.
LVC have started O3 on April 1st for 1 y → Maybe 10 BNS will be observed?

Take home message:
Astrophysics and nuclear physics are complementary for the understanding of the phase diagram of dense matter.

Plans for the future:

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

Addressing fundamental questions at the forefront

From the GWIC 3G science-case meeting (oct. 2018, Postdam)
Sanjay Reddy, Neutron Star WG

1. Does matter in NS and NS mergers contain **novel QCD phases** not realized inside nuclei and heavy-ion collisions?
2. Can NS observations guide and validate **theories of nuclei and nuclear matter**?
3. Is there a diversity in the NS population and what are its implications (families)?
4. How do **nuclear** and **neutrino reactions** shape NS mergers dynamics and **nucleosynthesis**?
5. How do the properties of **nuclei far from stabil**ity impact on the electromagnetic emission from NS merger ejecta?
6. Can NSs sustain long-lived large quadrupolar deformations?
7. Do large scale (magneto)hydrodynamic instabilities influence spinning and merging NSs?
8. Can we combine GW and EM signatures to validate multi-physics simulations of BNS and BHNS mergers to predict ejecta, nucleosynthesis, and the gamma-ray burst mechanisms?
9. Can we model and observe post-merger oscillations to reliably constrain dense matter and merger dynamics.
10. Does **dark matter** and **physics beyond the standard model** play a role in NSs and NS mergers?