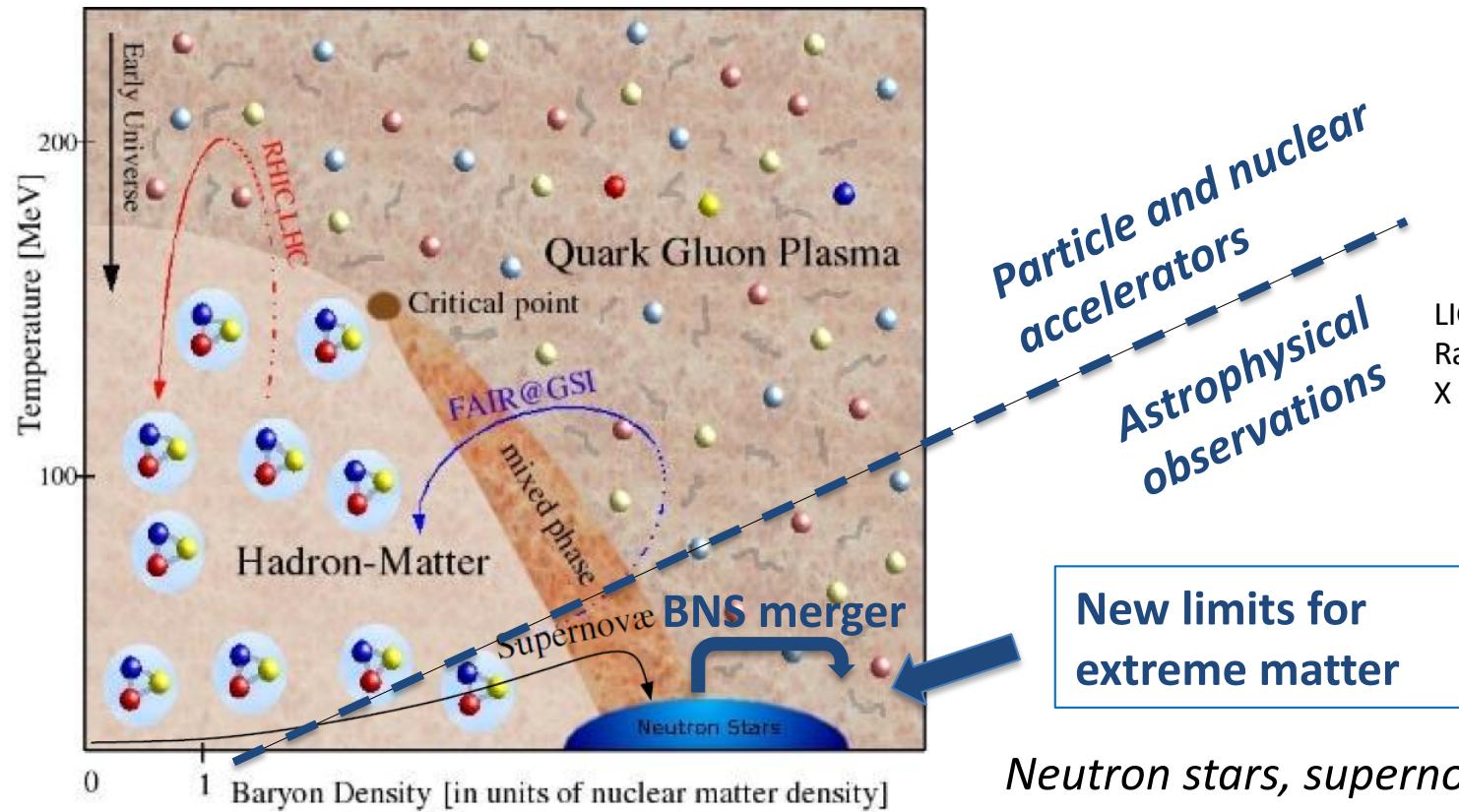


Dense matter equation of state

Jérôme Margueron
IPN Lyon, France

Fundamental physics question:
What is the QCD phase diagram ?



What is a neutron star?

Properties:

- Aftermath of core-collapse supernovae,
- Isolated or in binary,
- Could be a pulsar, from radio to/or γ rays,
- X-ray emission from accretion disk

$M \approx 1 - 2 M_\odot$

$R \approx 10 - 14 \text{ km}$

Average density $\approx 10^{15} \text{ g cm}^{-3}$

$B \approx 10^{12} - 10^{16} \text{ G}$

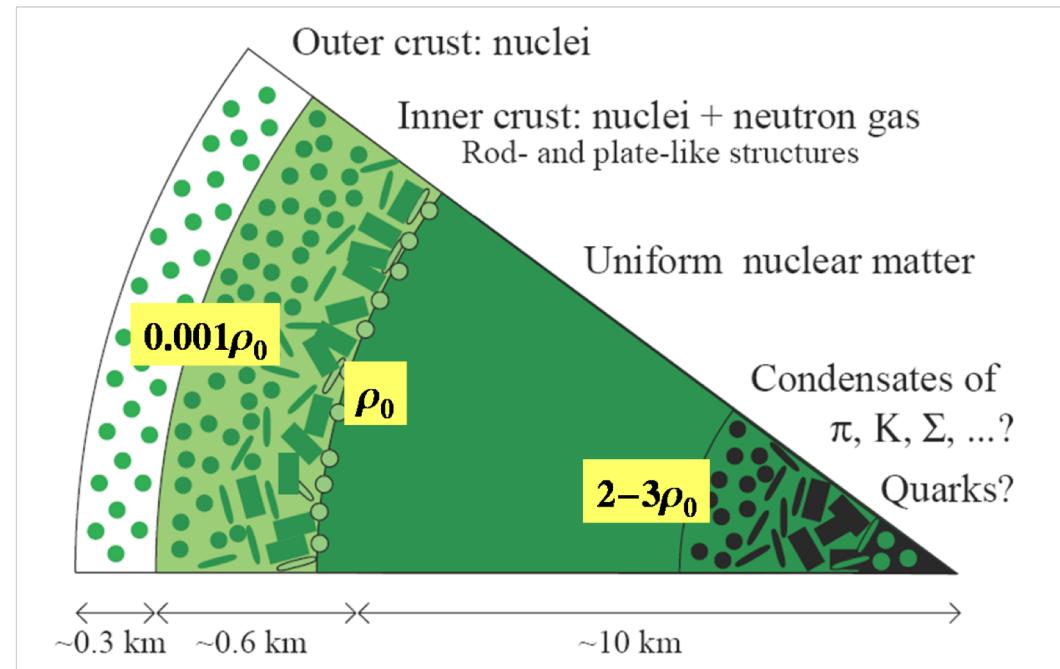
Neutron star composition:

Requires the knowledge of dense matter equation of state.

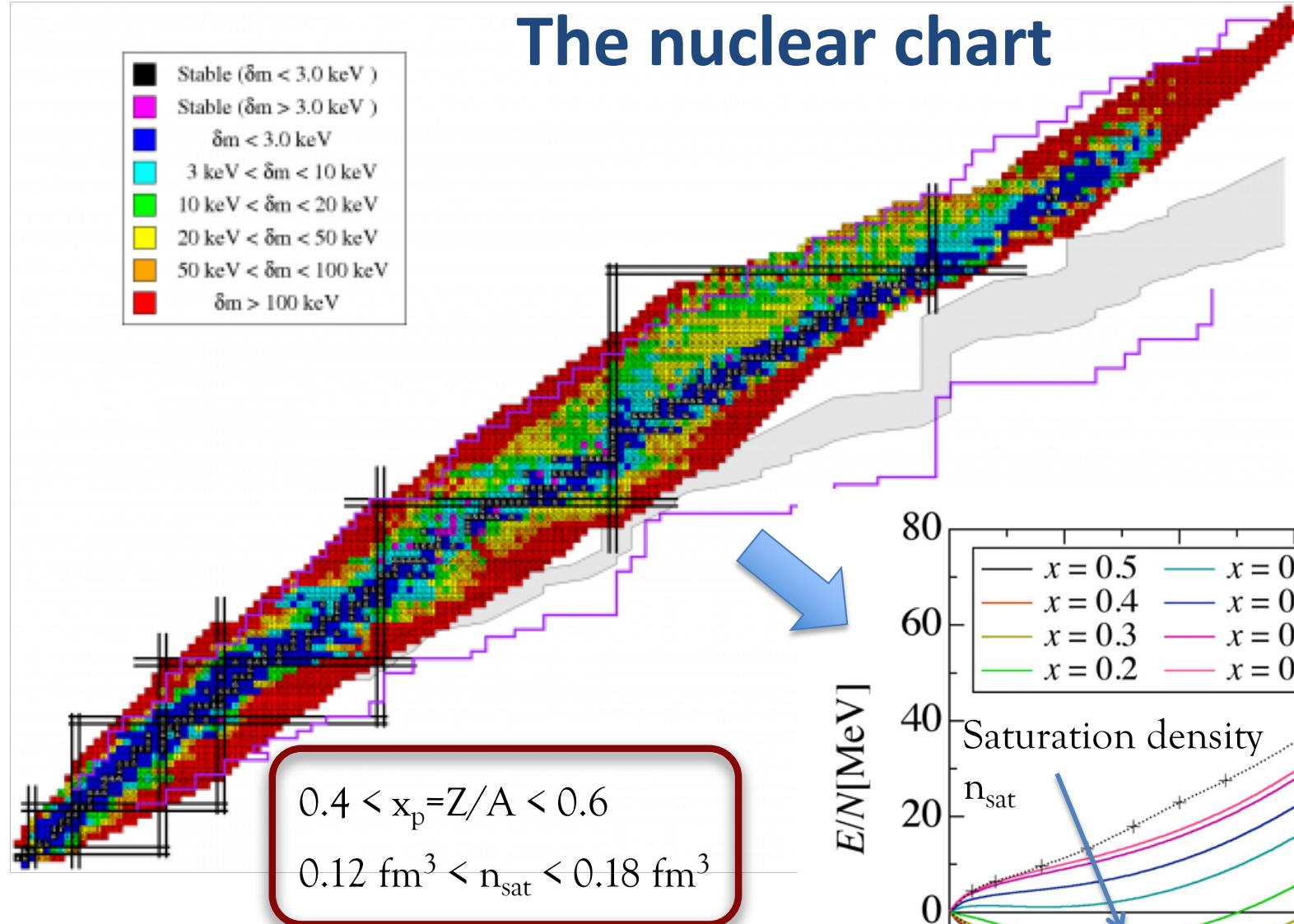
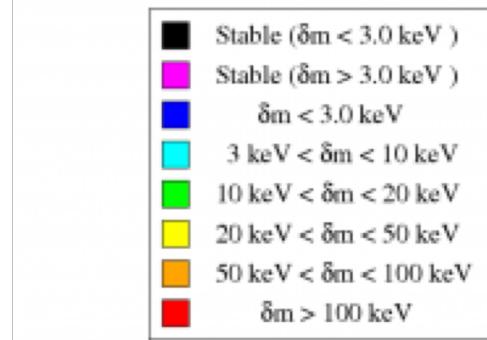
EOS \leftrightarrow Set of (M, R)

Two main questions:

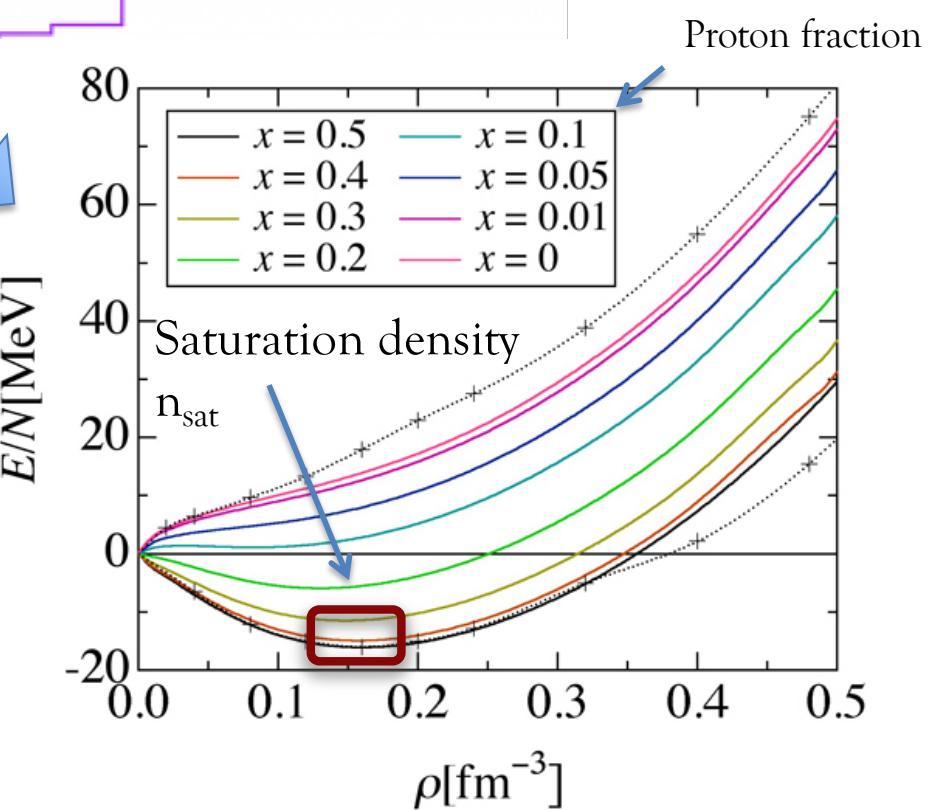
- How accurate is the nuclear physics knowledge?
- Is there a phase transition to hyperon matter or quark matter at high density?



The nuclear chart



→ A very small region of
the phase diagram



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

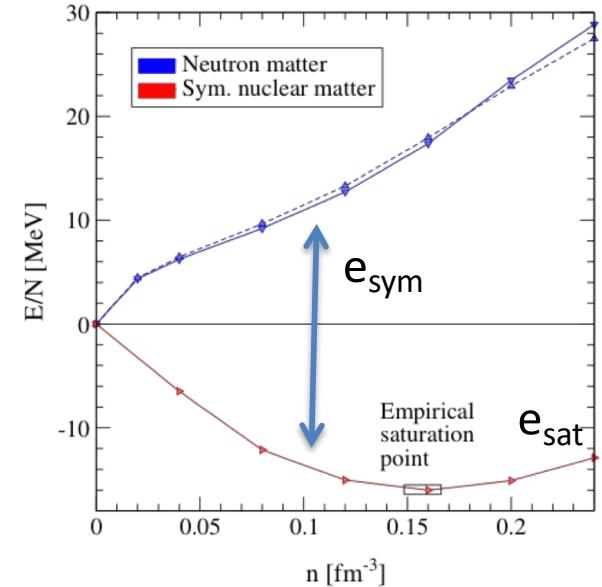
Around saturation, the energy per particle can be Taylor expanded as:

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

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

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

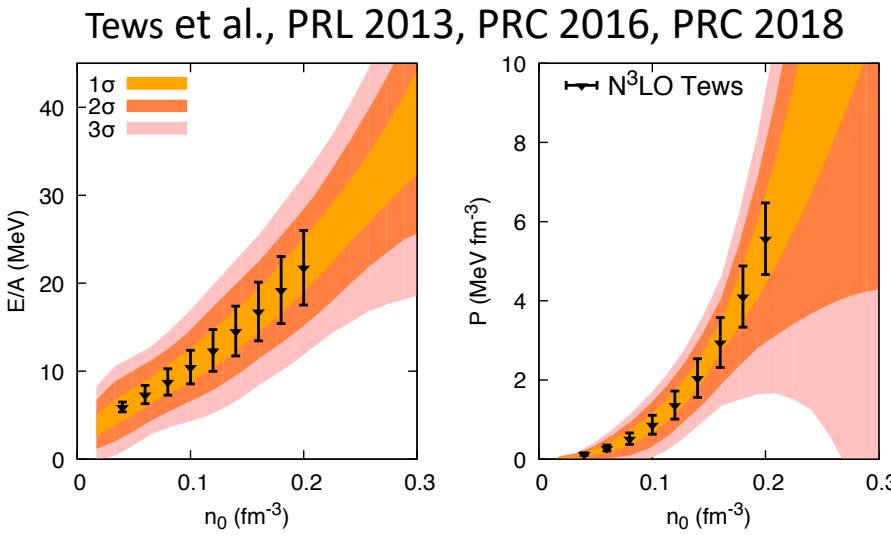
$$e_{sym}(n) = E_{sym} + L_{sym}x + \frac{1}{2}K_{sym}x^2 + \frac{1}{6}Q_{sym}x^3 + \frac{1}{24}Z_{sym}x^4 + \dots$$



	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	-500	0.75	0.1
σ_{P_α}	± 0.3	± 2	± 0.005	± 15	± 20	± 100	± 400	± 400	± 1000	± 1000	± 1000	± 0.1	± 0.1

small impact on EOS

Low density neutron matter predicted by chiral EFT approach



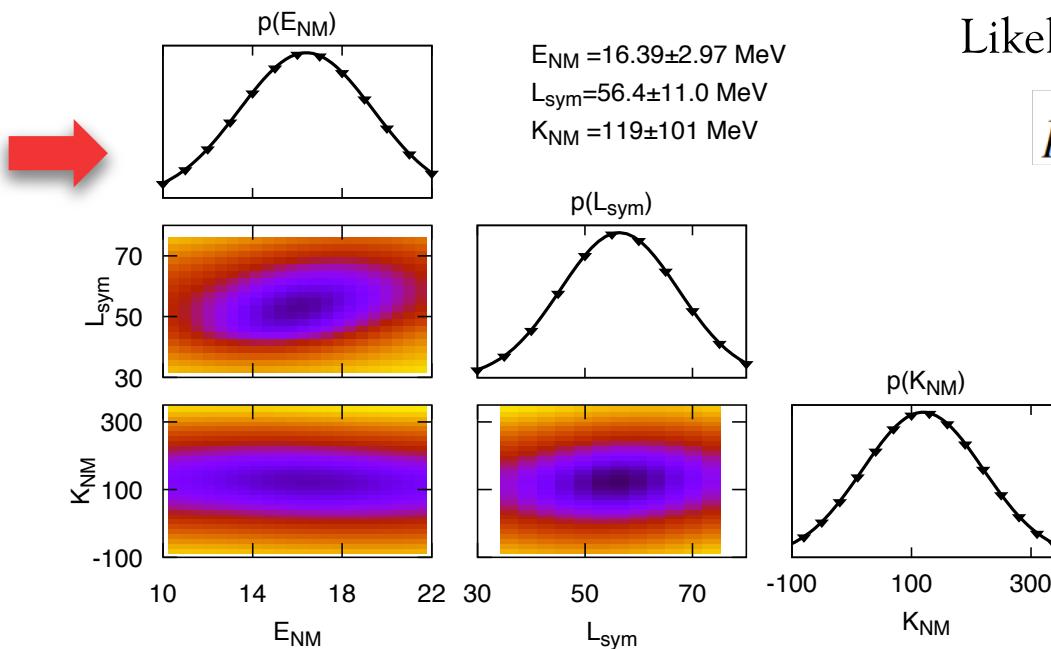
$$\frac{E}{A}(n_b, \delta = 1) = E_{NM} + L_{sym}x + \frac{1}{2}K_{NM}x^2 + \dots$$

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

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

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:

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

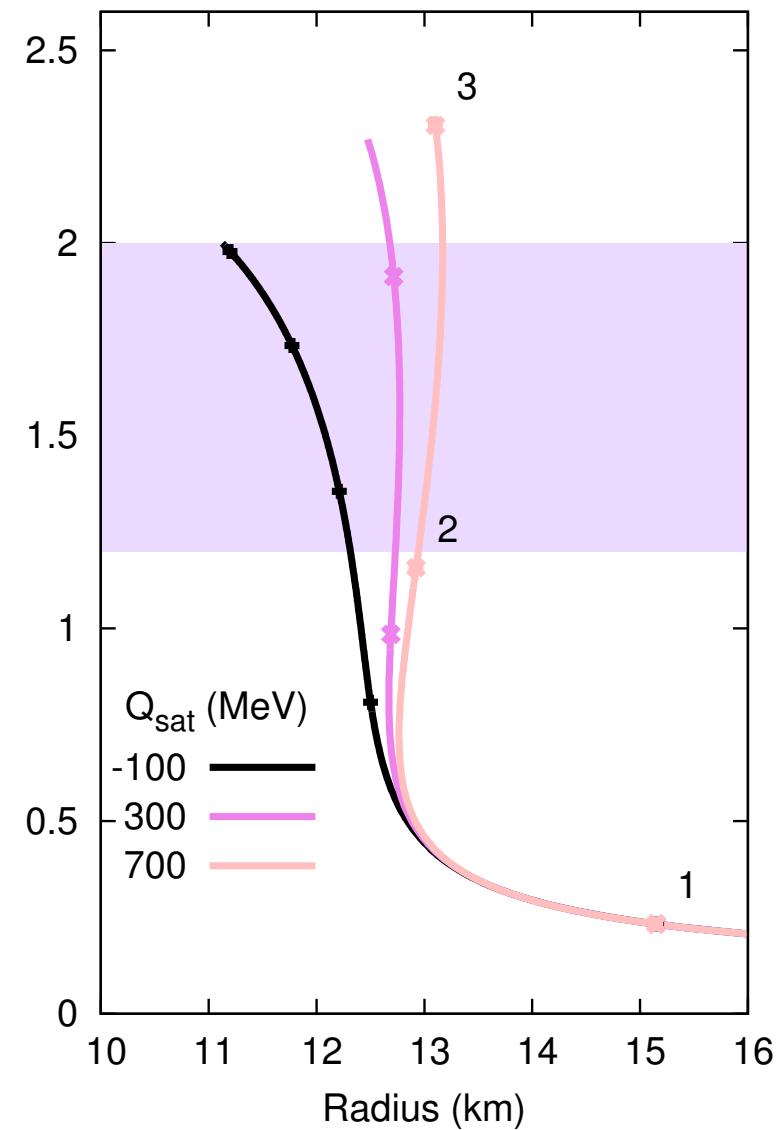
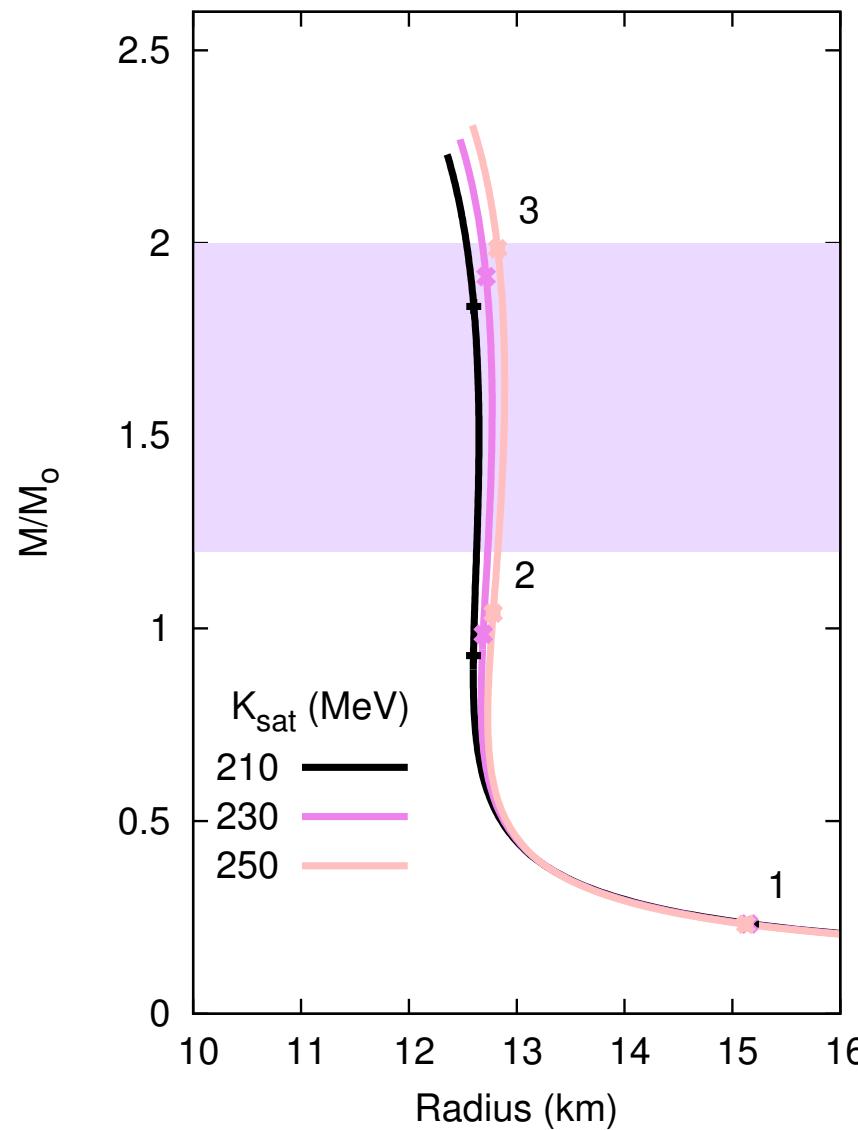
$L_{sym} \approx 56 \pm 11 \text{ MeV}$

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

Chiral EFT predictions represent correctly our current experimental uncertainty.

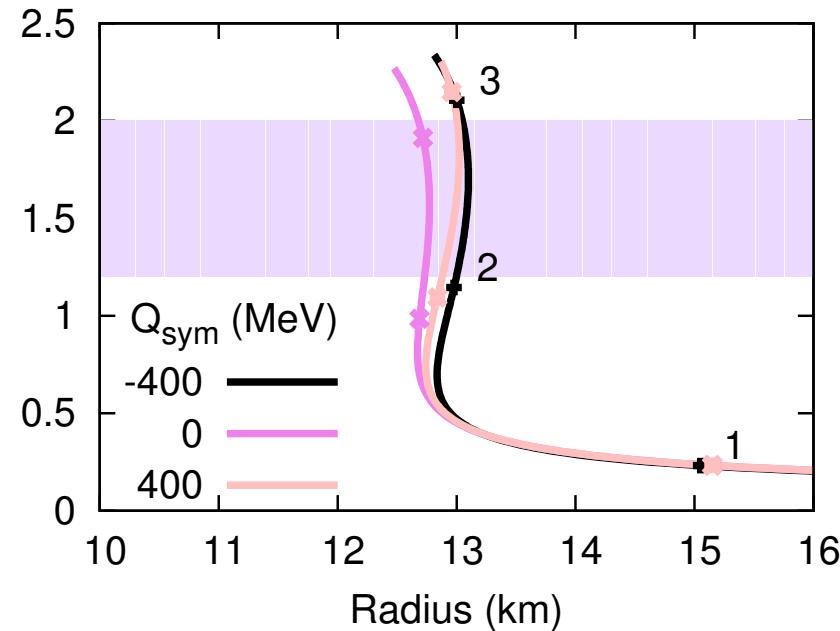
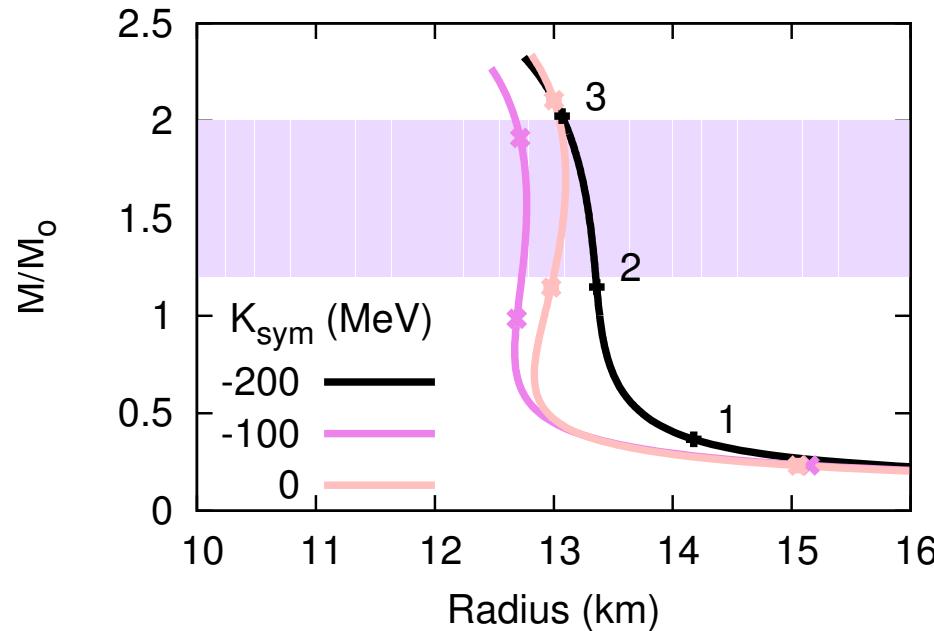
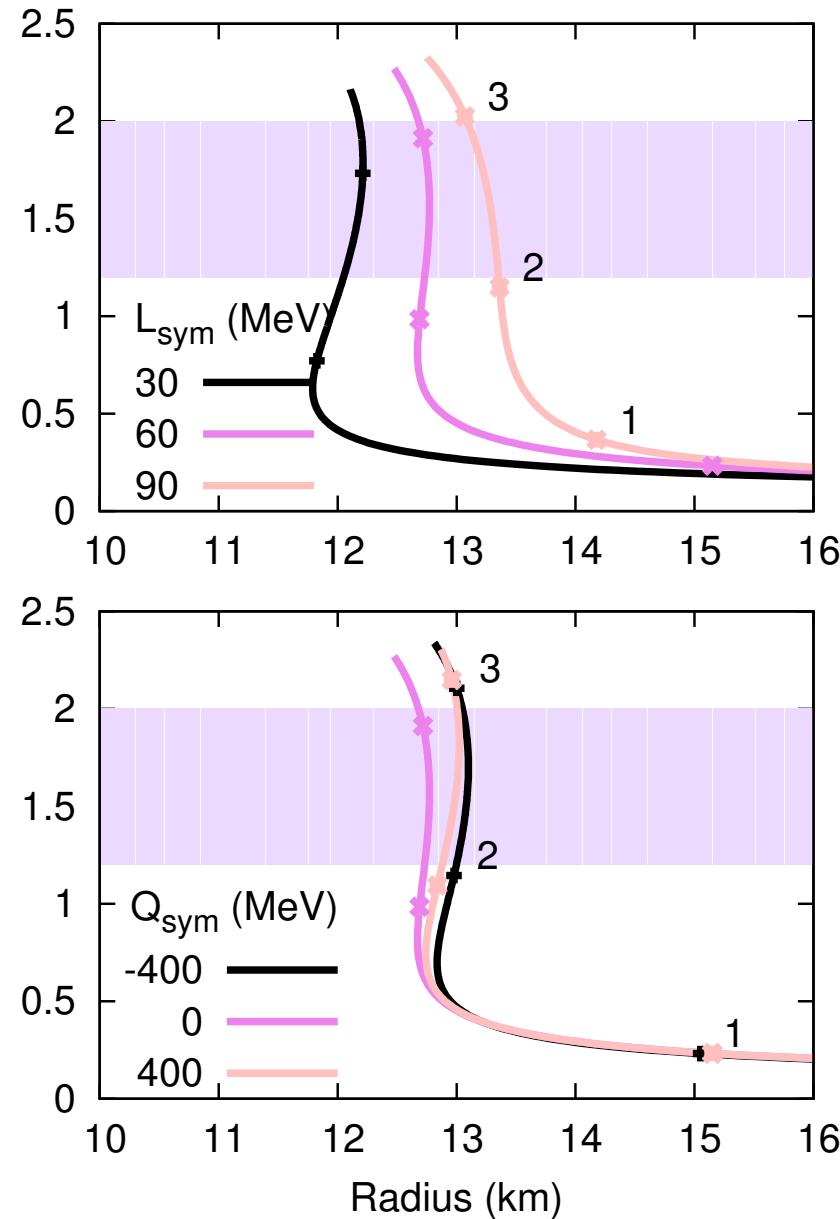
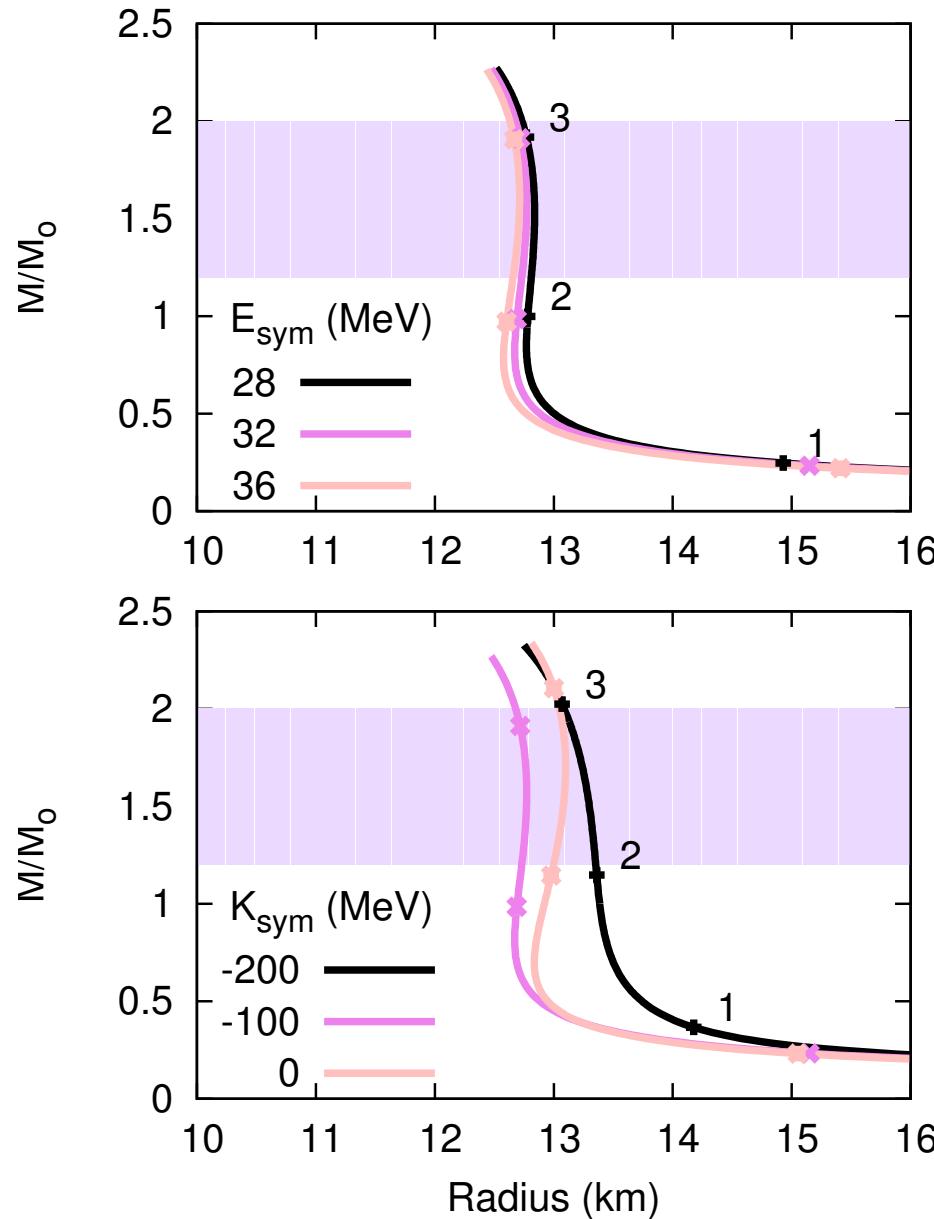
Impact on the MR relation

Impact of the isoscalar parameters

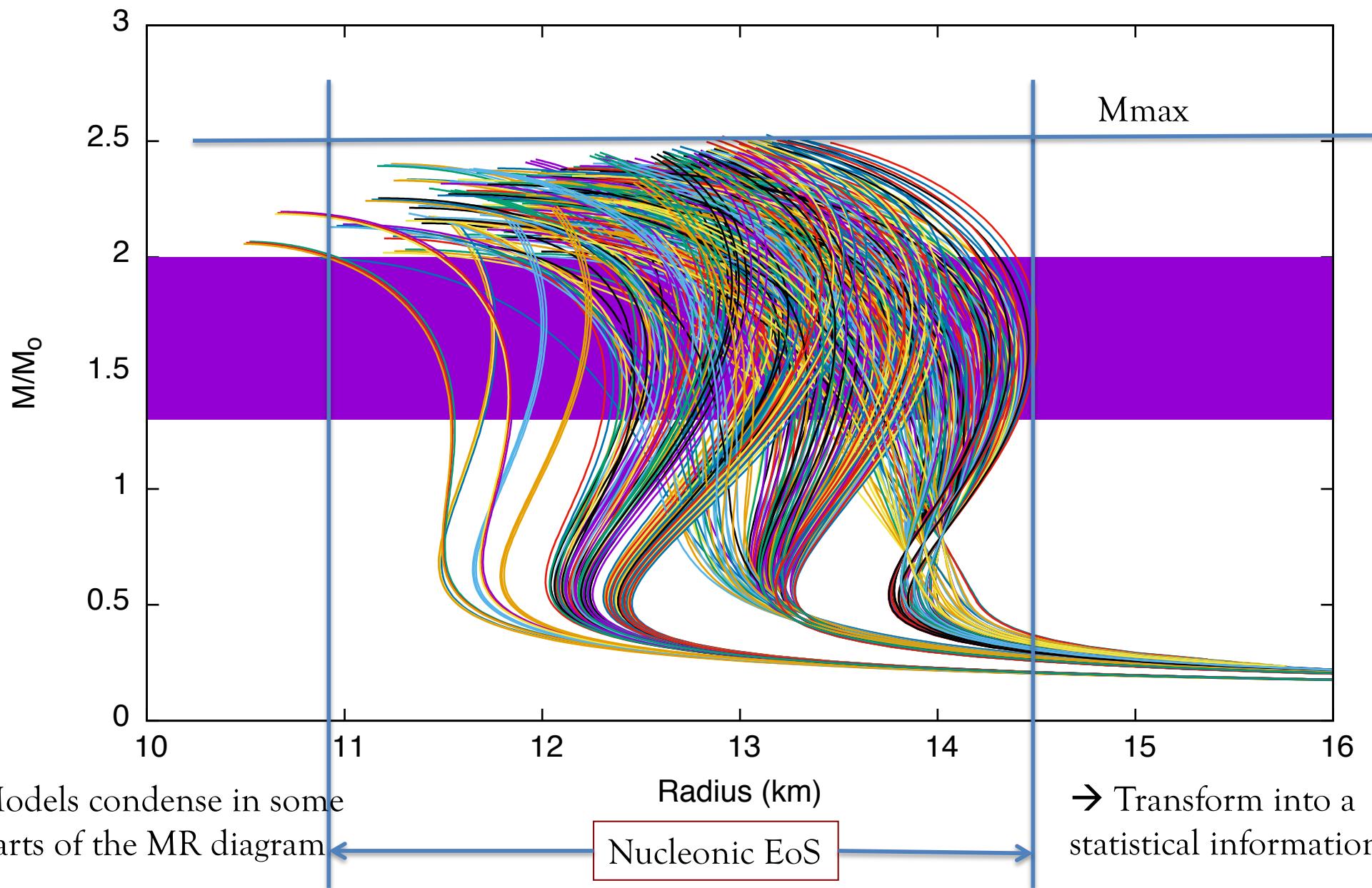


Impact on the MR relation

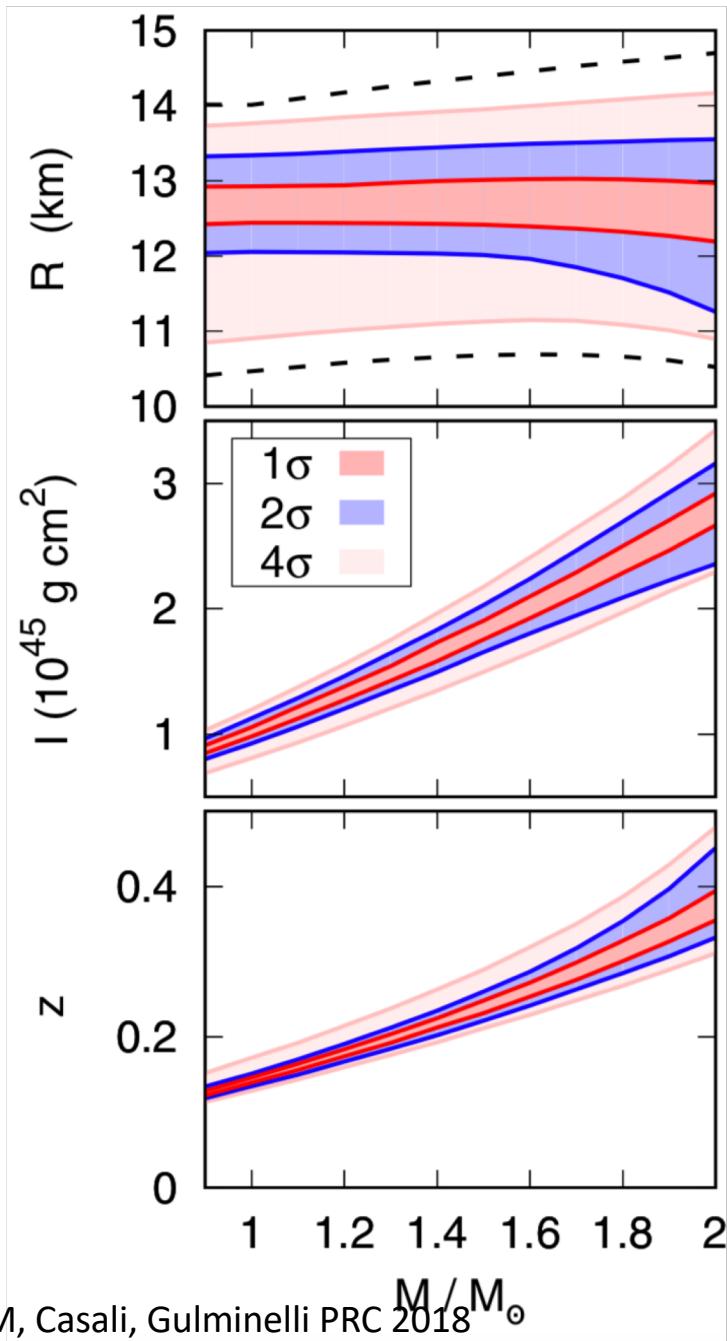
Largest source of uncertainty: Lsym and Ksym



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

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

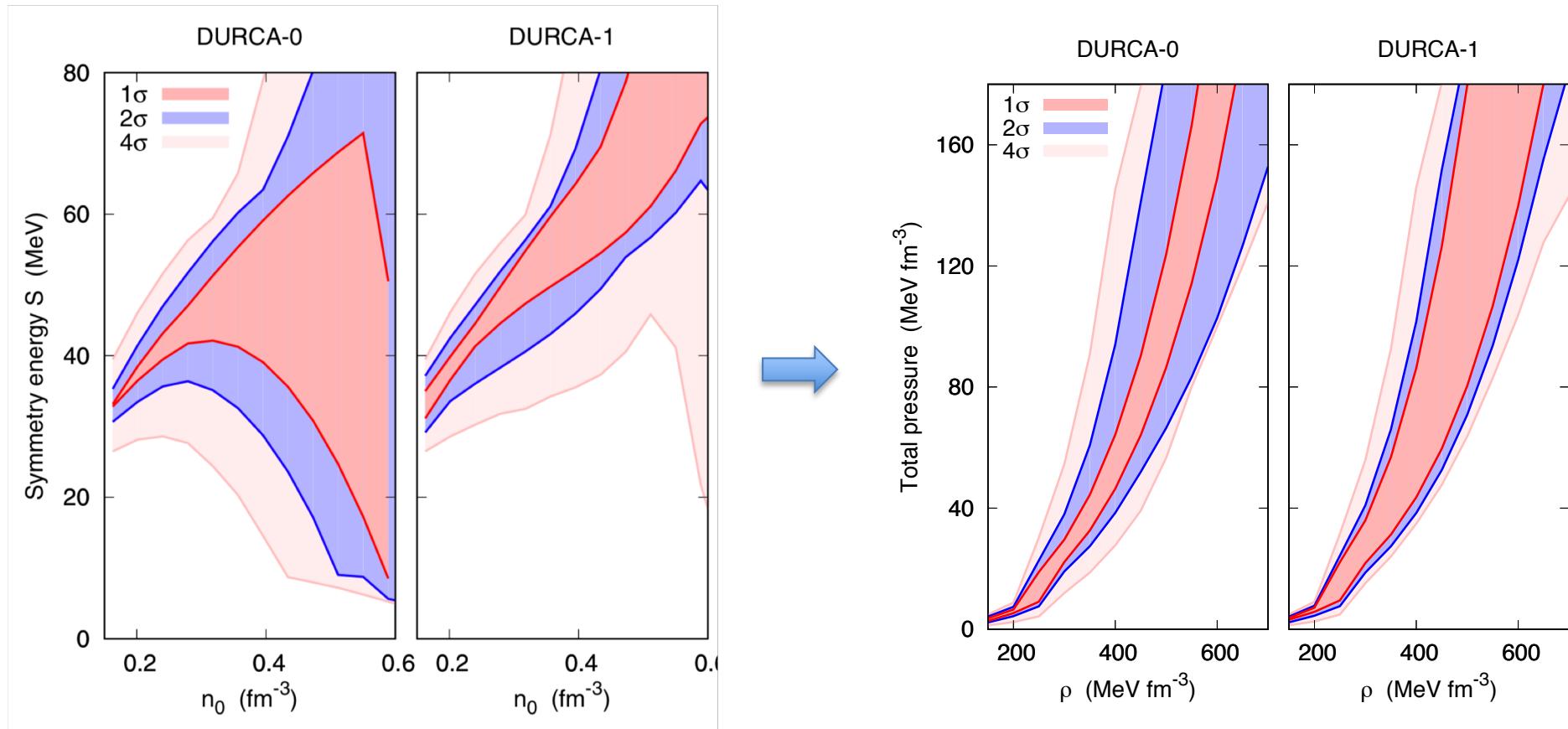
for nucleonic matter

Bayesian predictions for NS

Symmetry energy:

2 classes of models: **DURCA-0**: $xp < 1/9$ for $M < 2M_\odot$ (asy-soft EOS)

DURCA-1: $xp > 1.9$ for $1.8M_\odot < M < 2M_\odot$ (asy-stiffer EOS)



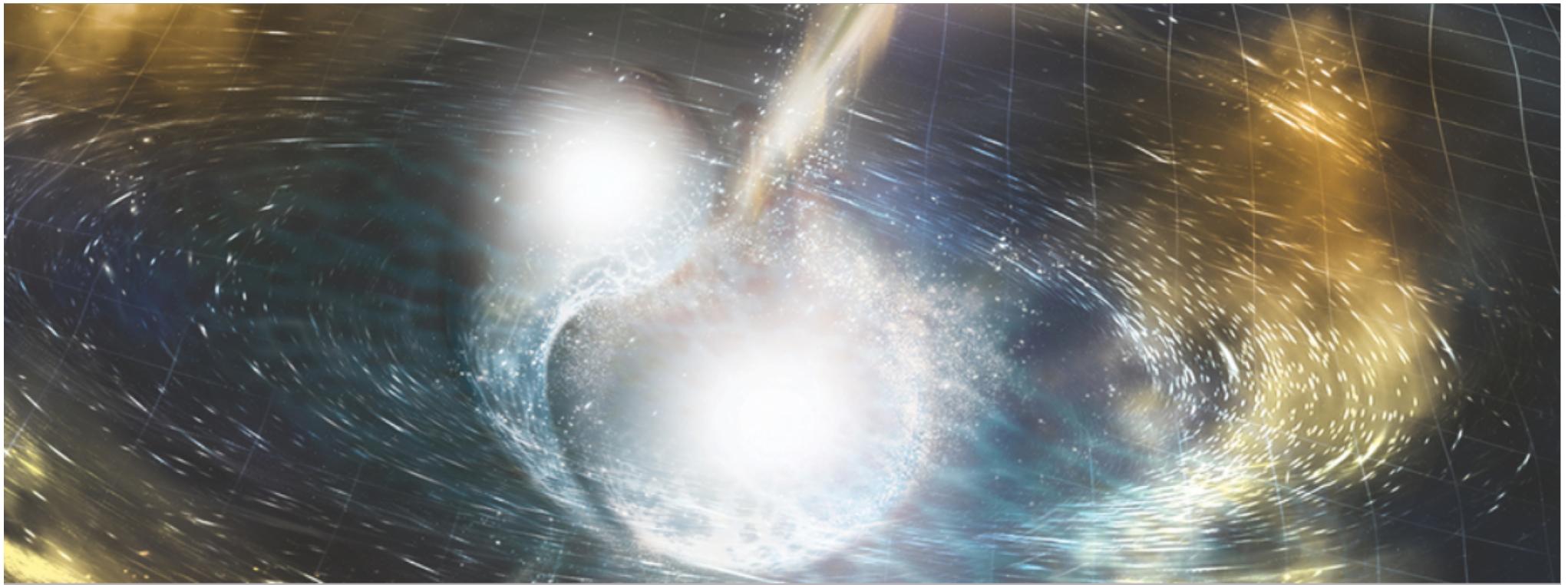
Quasi-universality of the nucleonic EOS.
Previously suggested by Blaschke et al., 2016 for DURCA-0 case

2- Is there a phase transition at high density?

Understanding extreme matter with gravitational waves

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

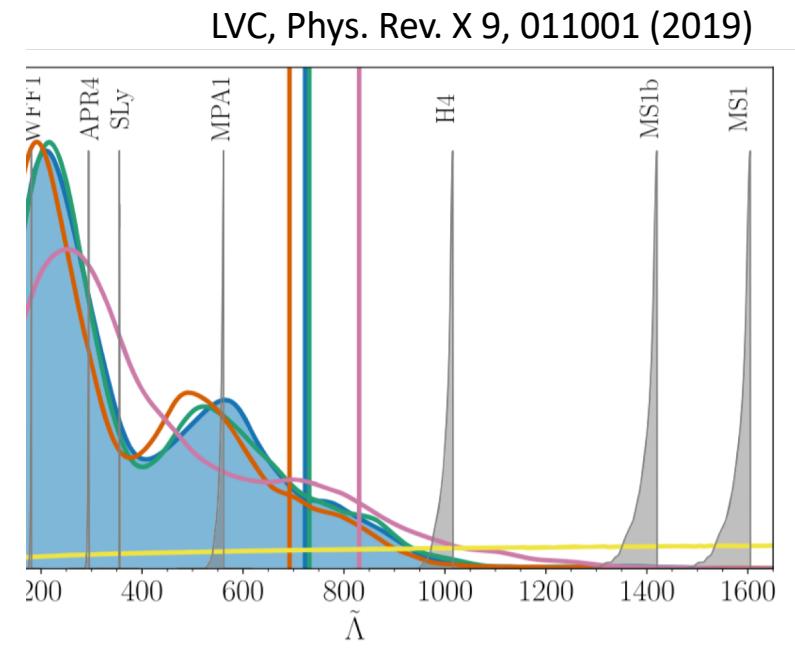
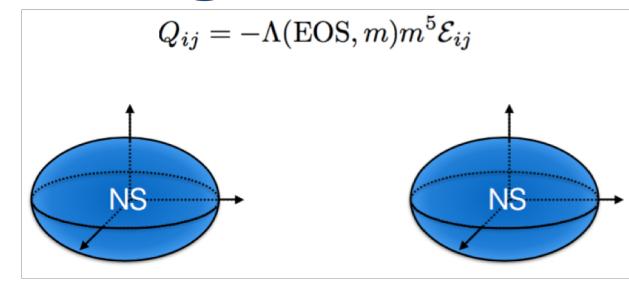
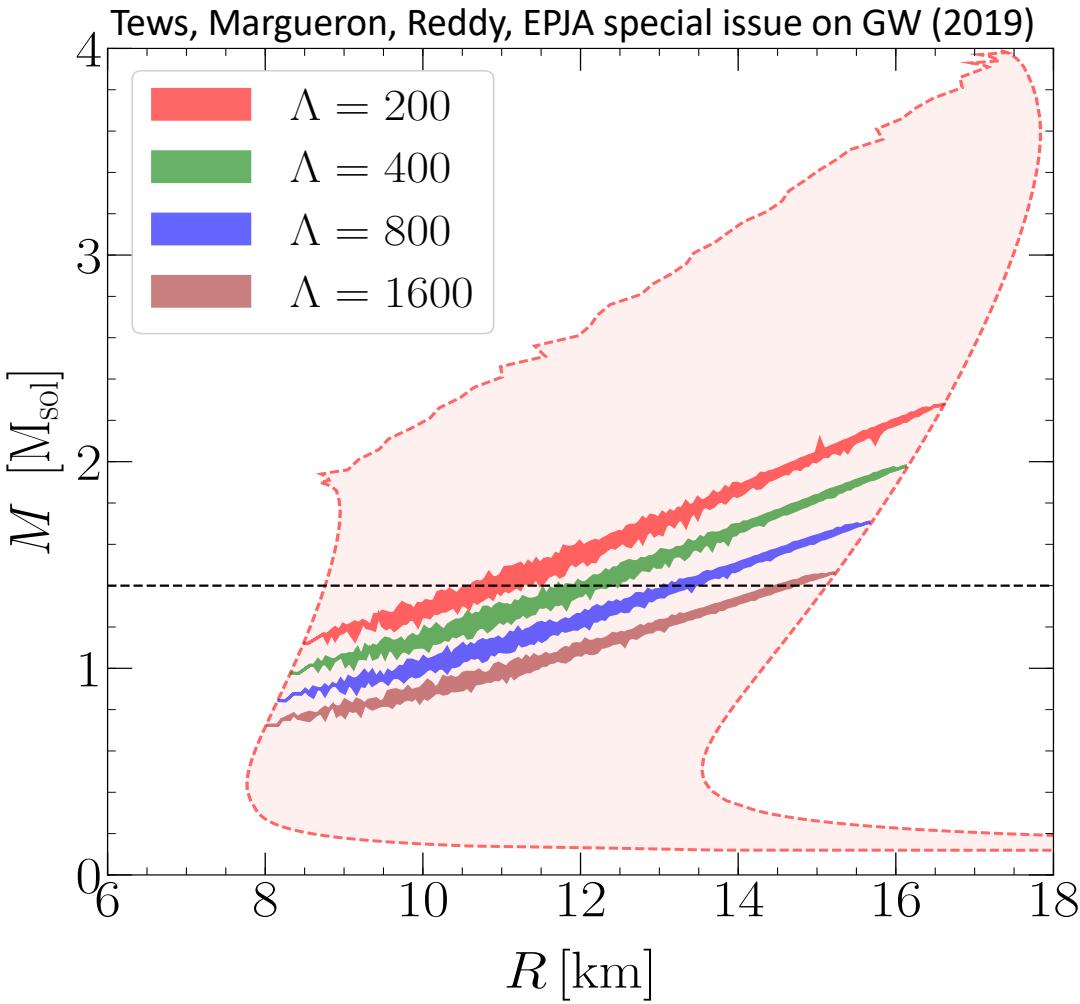
Abbott et al., LVC, PRL 2017, PRL 2018



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

Extreme matter and inspiral signal

Tidal deformability



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

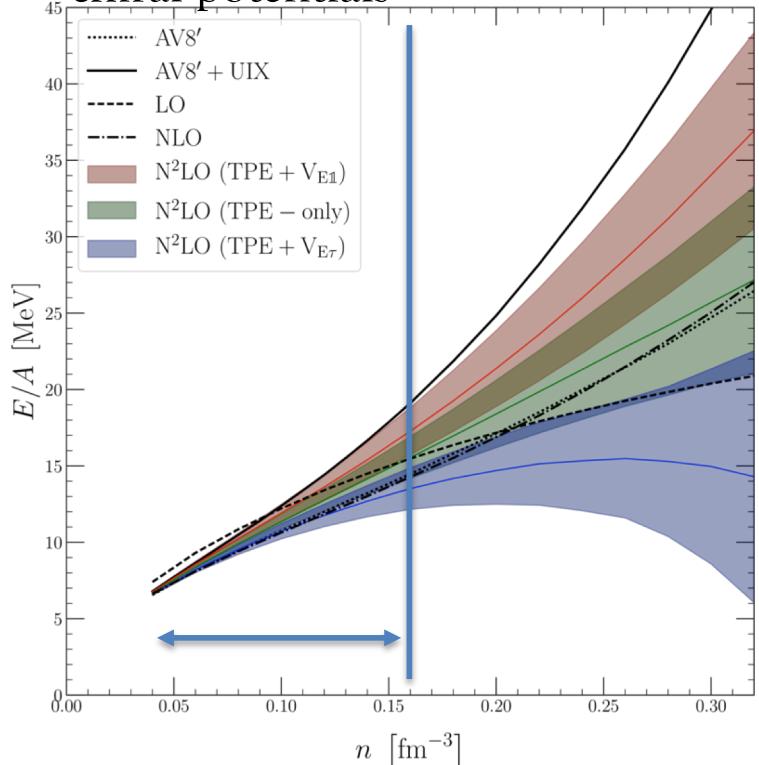
Confronting 2 models: CSM versus MM

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

CSM is more general and contains explicitly a first-order phase transition.

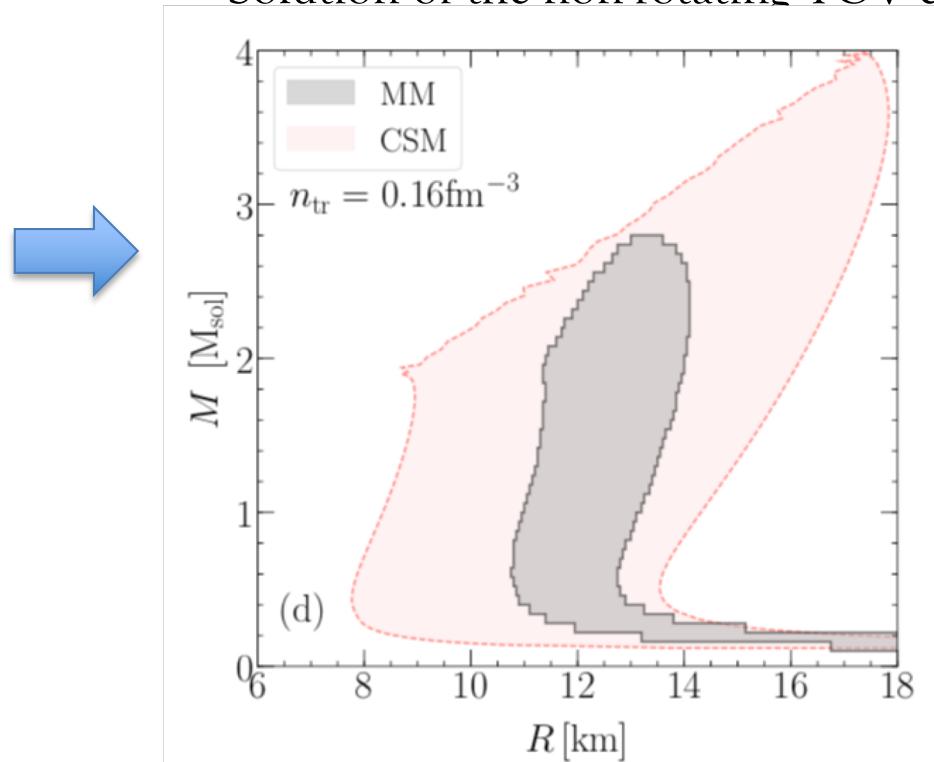
Confronting CSM versus MM provides information about common predictions and expected differences, e.g. masquerade issue.

QMC calculations with local chiral potentials



Tews, Carlson, Gandolfi, Reddy, PRC 2018

Solution of the non-rotating TOV eqs.



Tews, JM, Reddy, PRC 2018

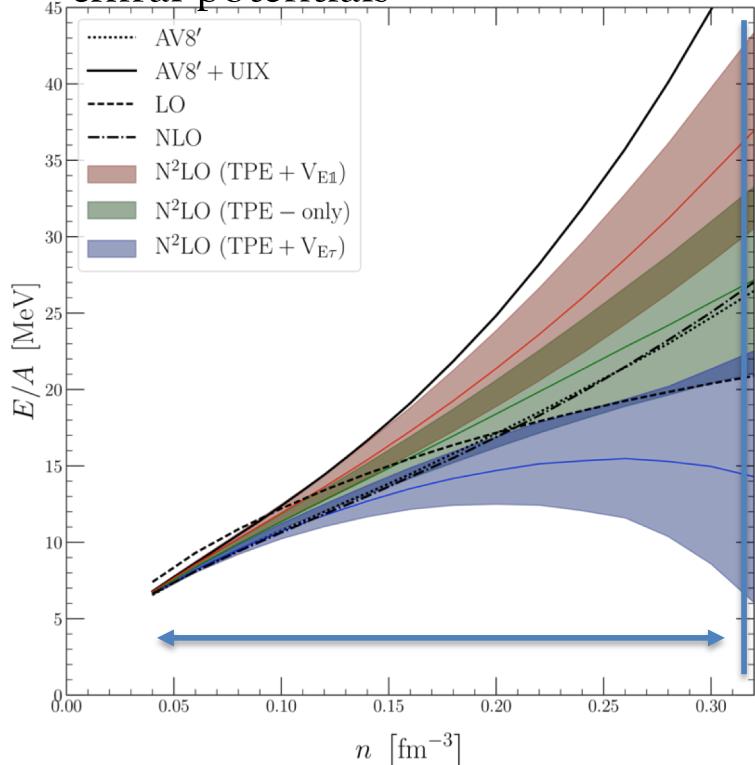
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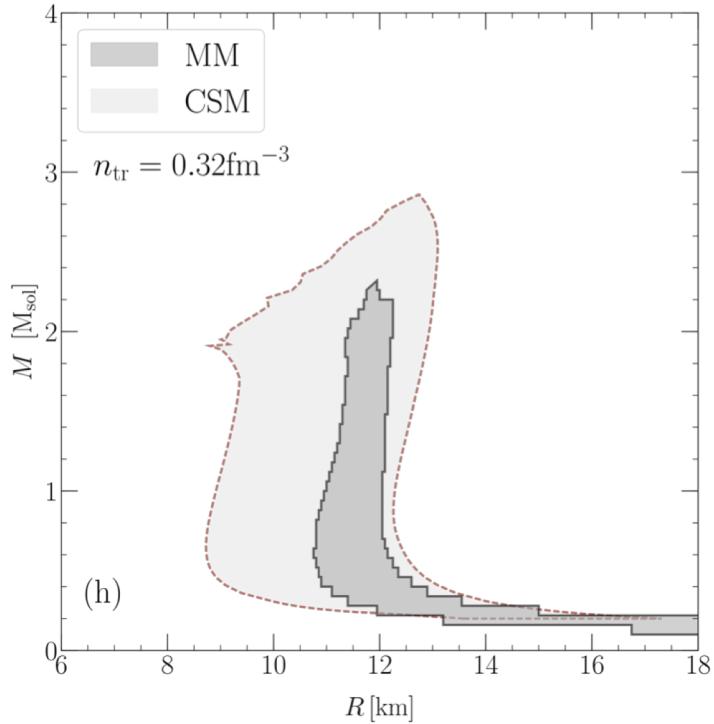
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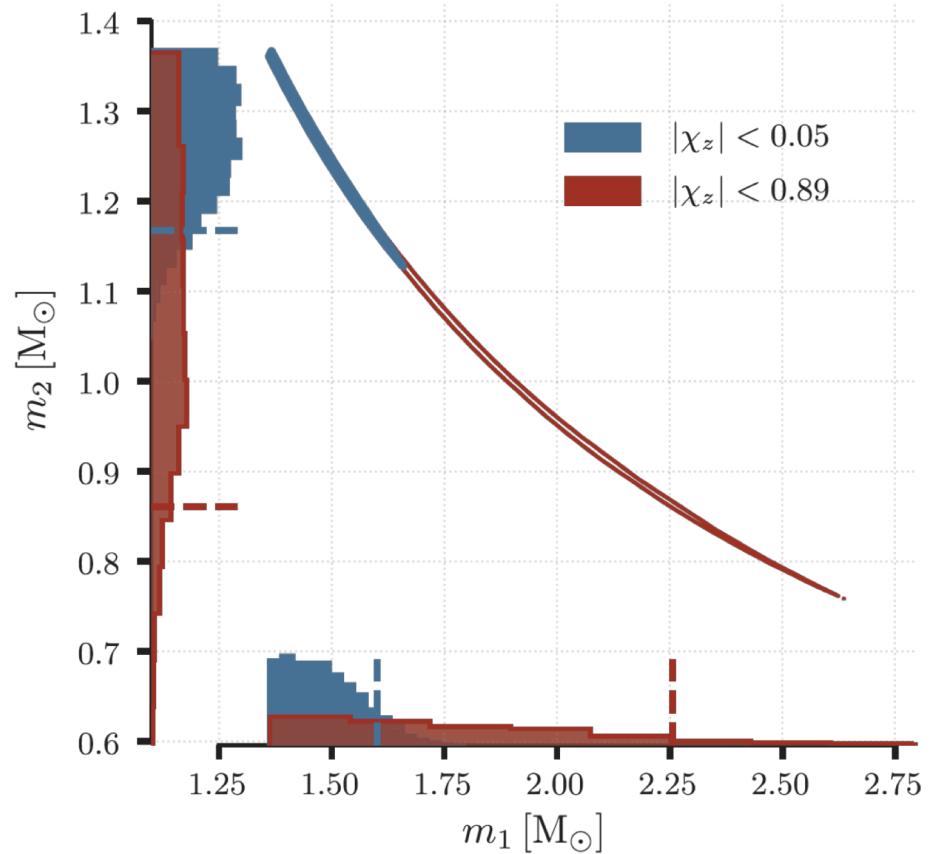
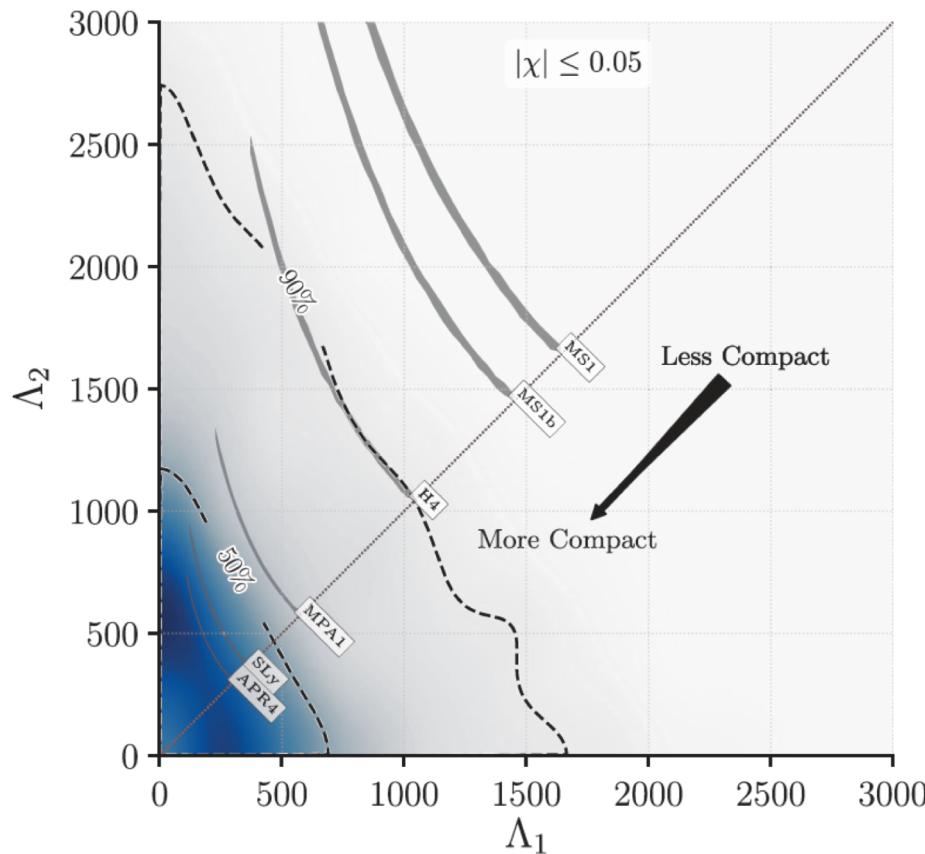
Tews, Carlson, Gandolfi, Reddy, PRC 2018

Solution of the non-rotating TOV eqs.



Tews, JM, Reddy, PRC 2018

GW170817 observation



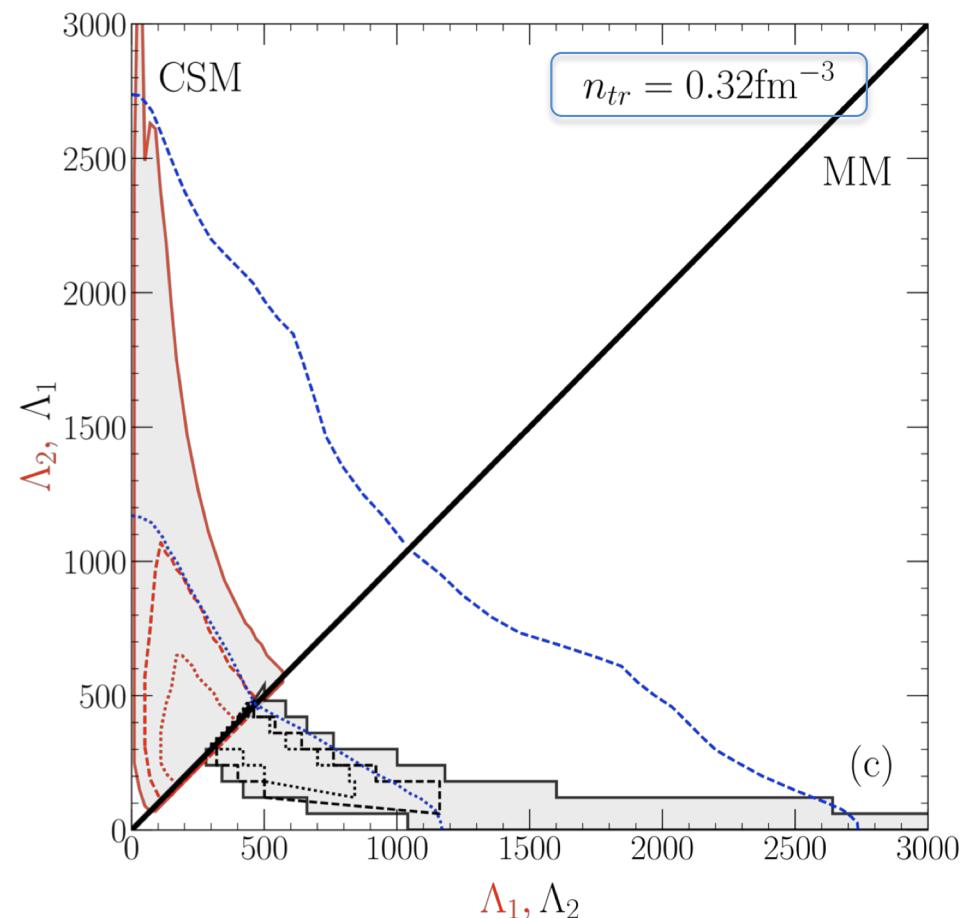
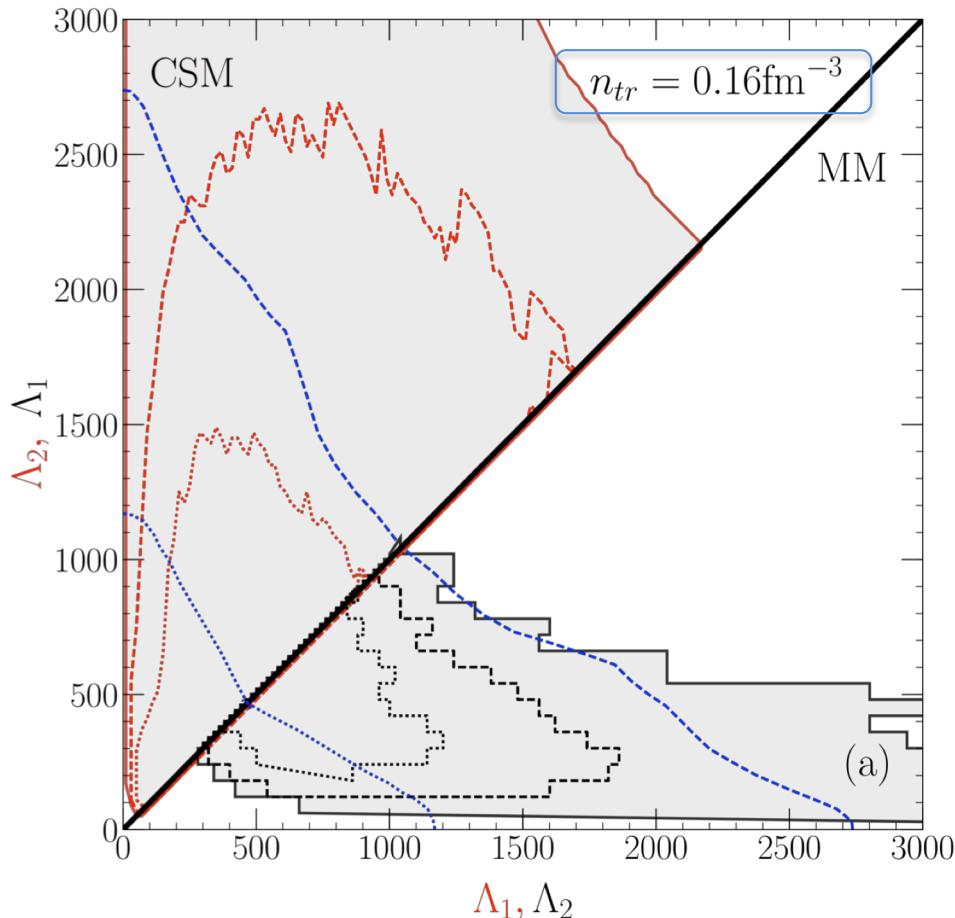
LIGO Virgo collaboration PRL 2017

$\tilde{\Lambda} < 800 \rightarrow$ rule out NS with large radii (> 13.6 km)

Can GW170817 (or future detection) say something about matter composition?

A minimal model is needed \rightarrow boundaries for nucleonic EOS.

Confronting 2 models: CSM versus MM

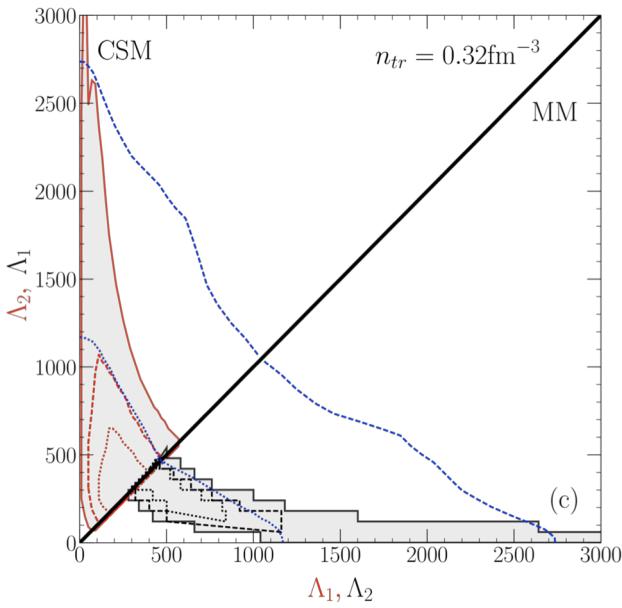


Range of tidal polarizabilities:
CSM: 80 – 570
MM: 260 – 500

Conclusions and outlooks

- The impact of nuclear uncertainties on NS properties can be estimated.
- The most important empirical parameters are L_{sym} and K_{sym} , as well as $Q_{\text{sat/sym}}$
- Quasi-universal behaviour of the nucleon EOS, with or without dUrca: $P(\rho)$.
- For nuclear EoS: $R = 12.7 \pm 0.4$ km.

What is the EOS of super-dense matter?



- Both MM and CSM can reproduce existing observations.
- Nuclear physics is still (slightly) more constraining than GW.
- More constraints are expected soon (NICER, more GWs, ...)

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

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

Confirm or rule out nuclear physics

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

What I haven't presented

- What is the present understanding of kilonovae? Formation of SMNS and HMNS.
- Post-merger GW signal: constrains matter at its extreme.
- Interplay between neutrinos and hydrodynamics.
- R-process nuclei-synthesis: the engine of the EM signal.

The theory group @ IPNL:

Alexandre Arbey: cosmology, black holes, modified gravity.

Hubert Hansen: links with dense phases produced in hadron colliders and in the core of NS.

Jérôme Margueron: dense matter EOS, links with low energy nuclear physics, ν -matter interaction.

Desire common expertise in a short term: hydrodynamical simulations of binary mergers.

- Numerical relativity,
- Nuclear physics: finite-T EOS and ν -matter interaction, nuclei-synthesis, etc...
- Requires HPC.