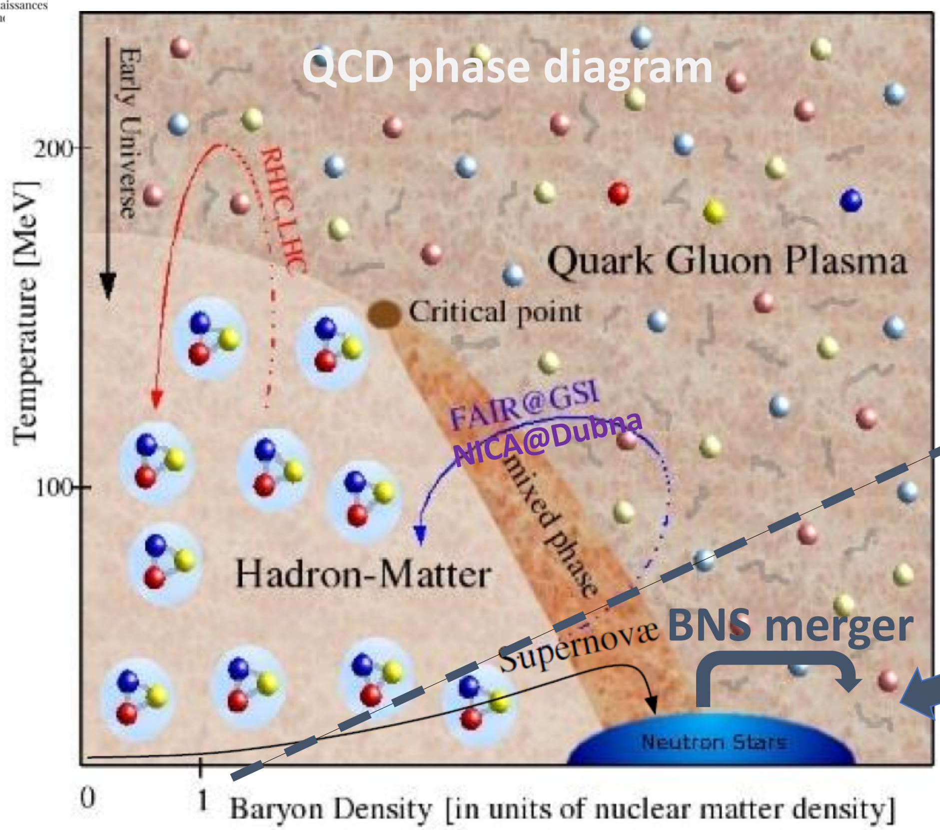
Assemblée générale du GdR Ondes Gravitationnelles, Oct. 11, 2019

Towards a better understanding of dense matter with gravitational waves

J. Margueron, IP2I Lyon



Particle and nuclear accelerators

Astrophysical observations

New limits for extreme matter

Neutron stars, supernovae, kilonovae…

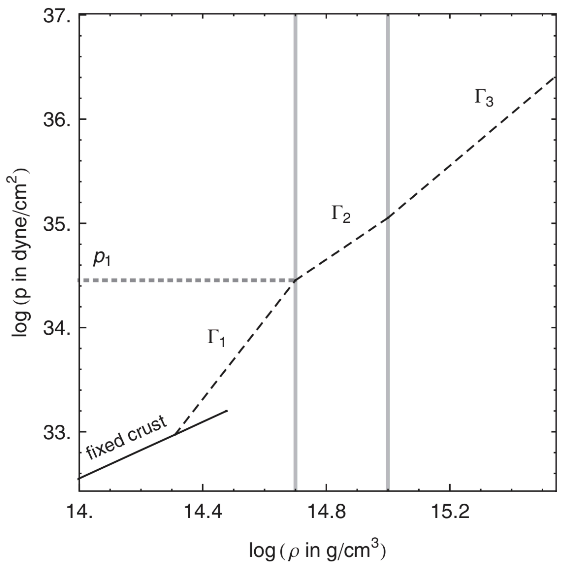
Plan:

- Modeling of dense matter EoS in an “agnostic way”
- Confrontation to GW and nuclear physics data

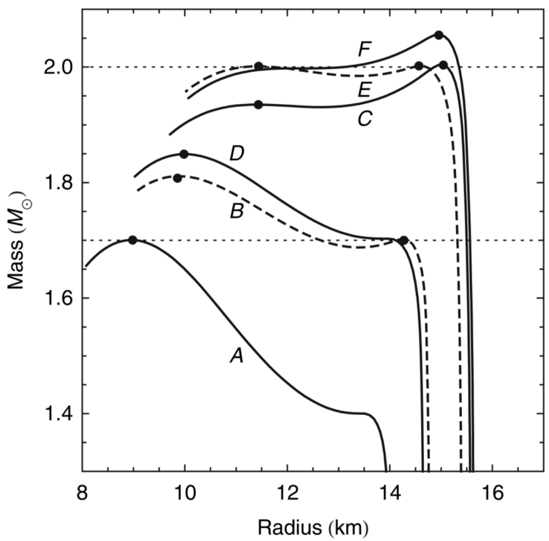
Agnostic modeling for the dense matter EoS

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

Read et al., PRC 2009
Özel 2009, 2010, Steiner 2013, …



TOV solution



Sound speed model (CSM):

Tews, Carlson, Gandolfi, Reddy, PRC 2018

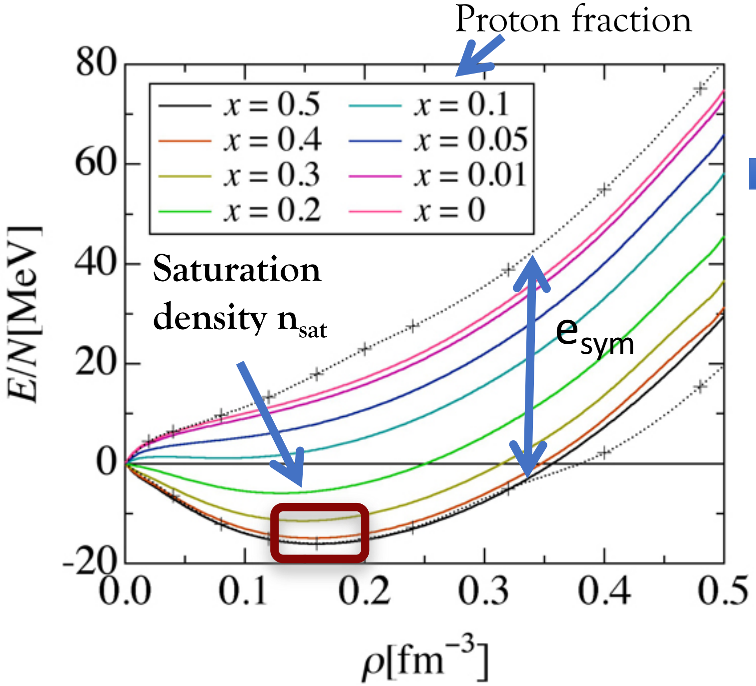
Reconstruct p(n) & ε(n) from $c_s(n)$:

$$c_s^2 = \frac{\partial p(\epsilon)}{\partial \epsilon} \qquad p = n\frac{\partial \epsilon}{\partial n} - \epsilon$$

Advantage:
- continuous sound speed,
- Explicitly includes 1st order phase transition.

Pros: very general, maximize the EoS uncertainties. **Cons**: Ignore matter composition.

Agnostic modelling with matter composition



Nuclear empirical parameters

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

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

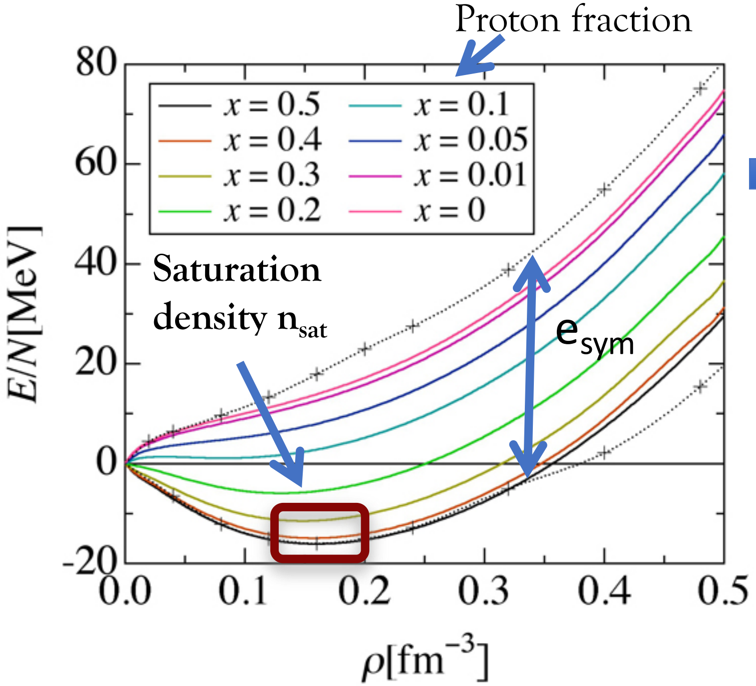
Density parameter: $x = (n - n_{sat})/(3n_{sat})$

Asymmetry parameter: $\delta = (n_n - n_p)/n$

Total energy per particle:

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

Agnostic modelling with matter composition



Nuclear empirical parameters

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

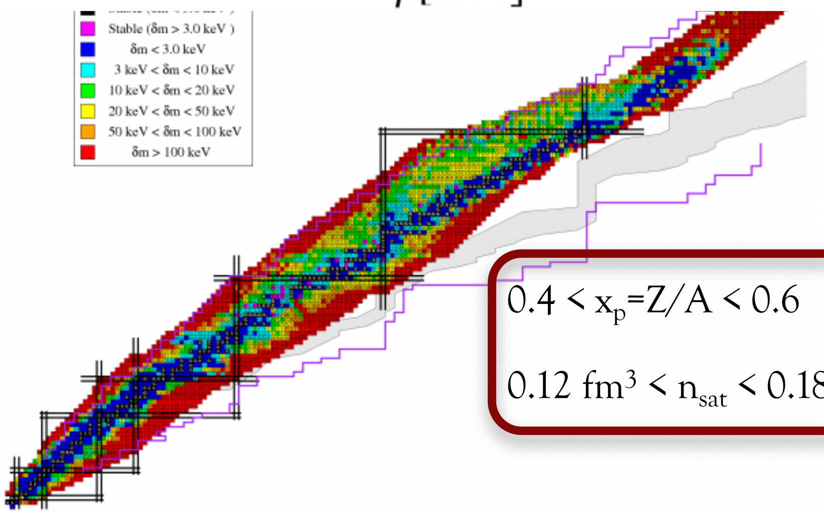
$$e_{sym}(n) = E_{sym} + L_{sym}x + \frac{1}{2}K_{sym}x^2 + \frac{1}{6}Q_{sym}x^3 + \frac{1}{24}Z_{sym}x^4 + \ldots$$

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

Asymmetry parameter: $\delta = (n_n - n_p)/n$

Total energy per particle:

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

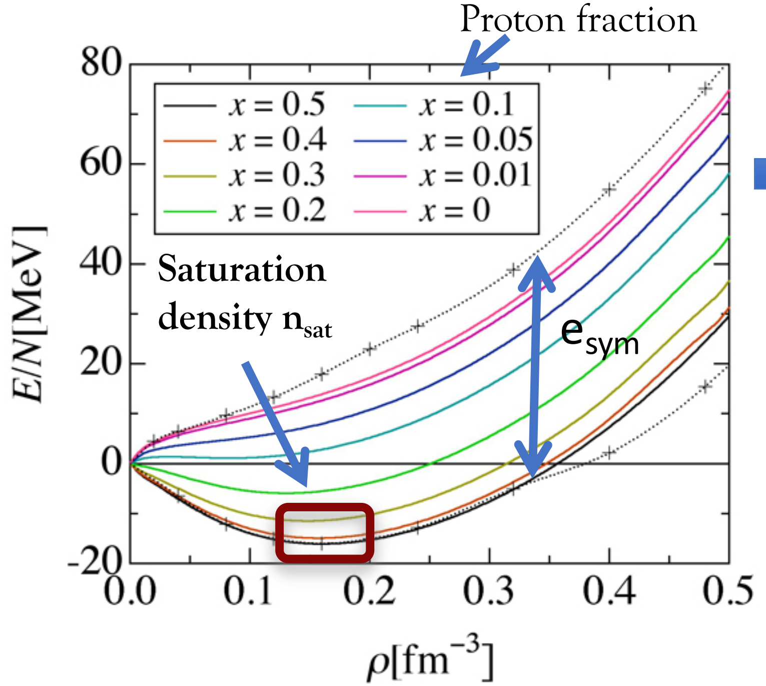


$0.4 < x_p = Z/A < 0.6$

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

→ A very small region of the phase diagram

Agnostic modelling with matter composition



Nuclear empirical parameters

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

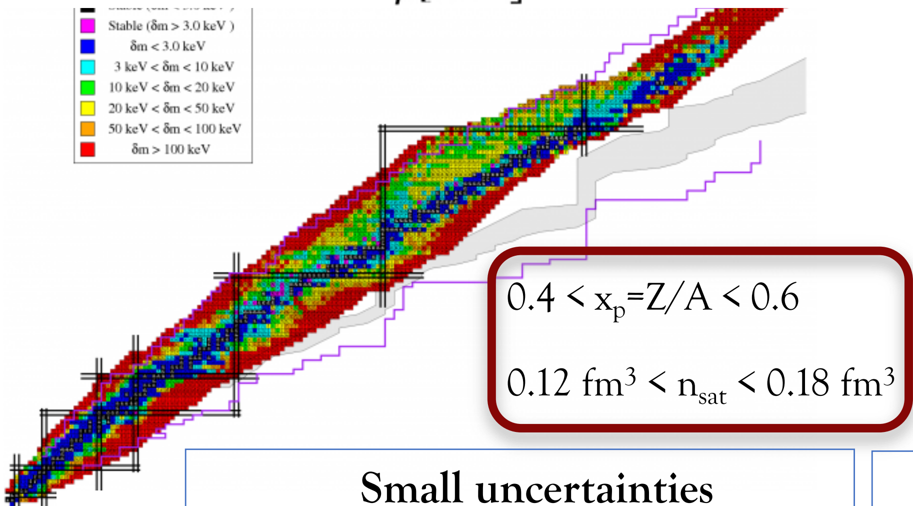
$$e_{sym}(n) = E_{sym} + L_{sym}x + \frac{1}{2}K_{sym}x^2 + \frac{1}{6}Q_{sym}x^3 + \frac{1}{24}Z_{sym}x^4 + \ldots$$

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

Asymmetry parameter: $\delta = (n_n - n_p)/n$

Total energy per particle:

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



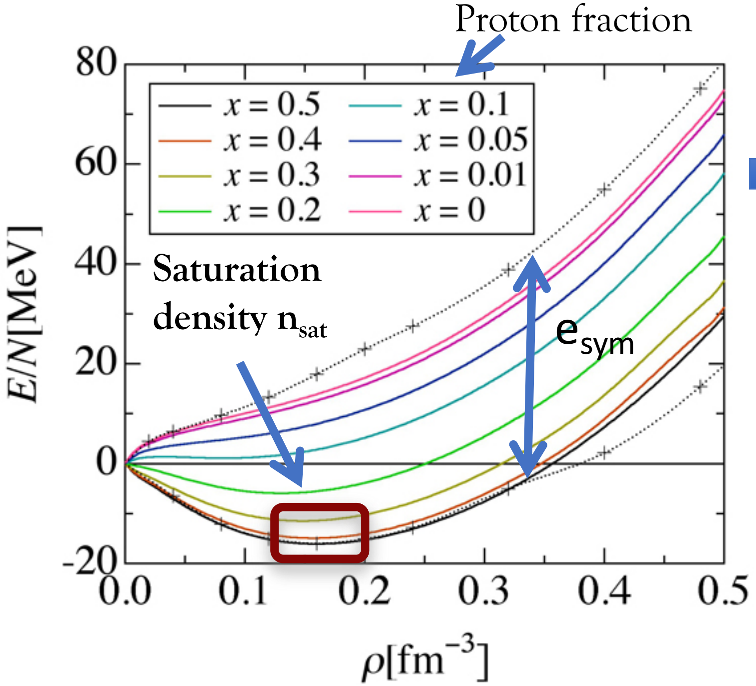
→ A very small region of the phase diagram

	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

JM, Casali, Gulminelli, PRC 2018

small impact on EOS at T=0

Agnostic modelling with matter composition



Nuclear empirical parameters

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

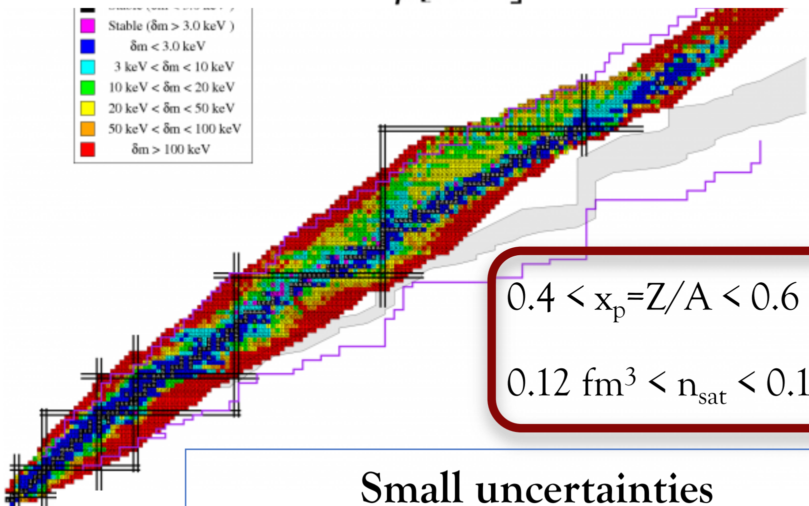
$$e_{sym}(n) = E_{sym} + L_{sym}x + \frac{1}{2}K_{sym}x^2 + \frac{1}{6}Q_{sym}x^3 + \frac{1}{24}Z_{sym}x^4 + \ldots$$

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

Asymmetry parameter: $\delta = (n_n - n_p)/n$

Total energy per particle:

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



$0.4 < x_p = Z/A < 0.6$

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

→ A very small region of the phase diagram
→ Needs to be completed with other data:
  → Heavy ion collision
  → Observation of NS

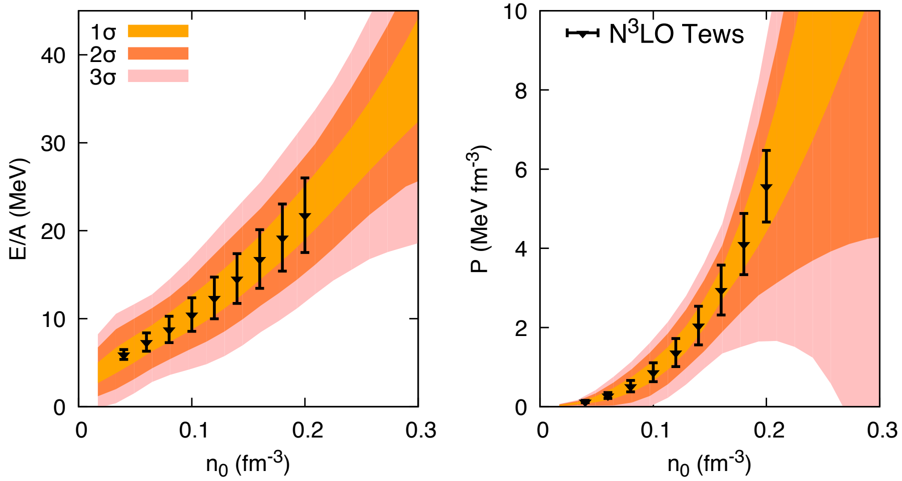
P_α	E_{sat} MeV	E_{sym} MeV	n_{sat} fm^{-3}	L_{sym} MeV	K_{sat} MeV	K_{sym} MeV	Q_{sat} MeV	Q_{sym} MeV	Z_{sat} MeV	Z_{sym} MeV	m^*_{sat}/m	$\Delta m^*_{sat}/m$
	Small uncertainties					Large uncertainties					Large uncertainties	
$\langle P_\alpha \rangle$	-15.8	32	0.155	60	230	-100	300	0	-500	-500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

JM, Casali, Gulminelli, PRC 2018

small impact on EOS at T=0

Constraints from chiral EFT at low density

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



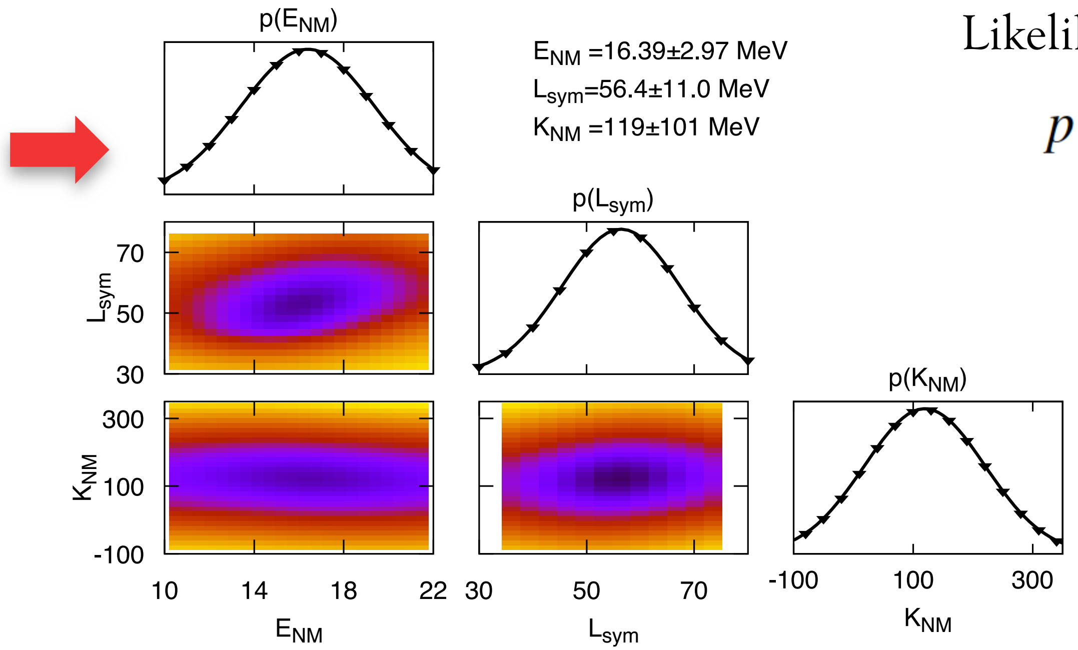
$$\frac{E}{A}(n_b, \delta = 1) = E_{NM} + L_{sym}x + \frac{1}{2}K_{NM}x^2 + \ldots$$

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

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

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:

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

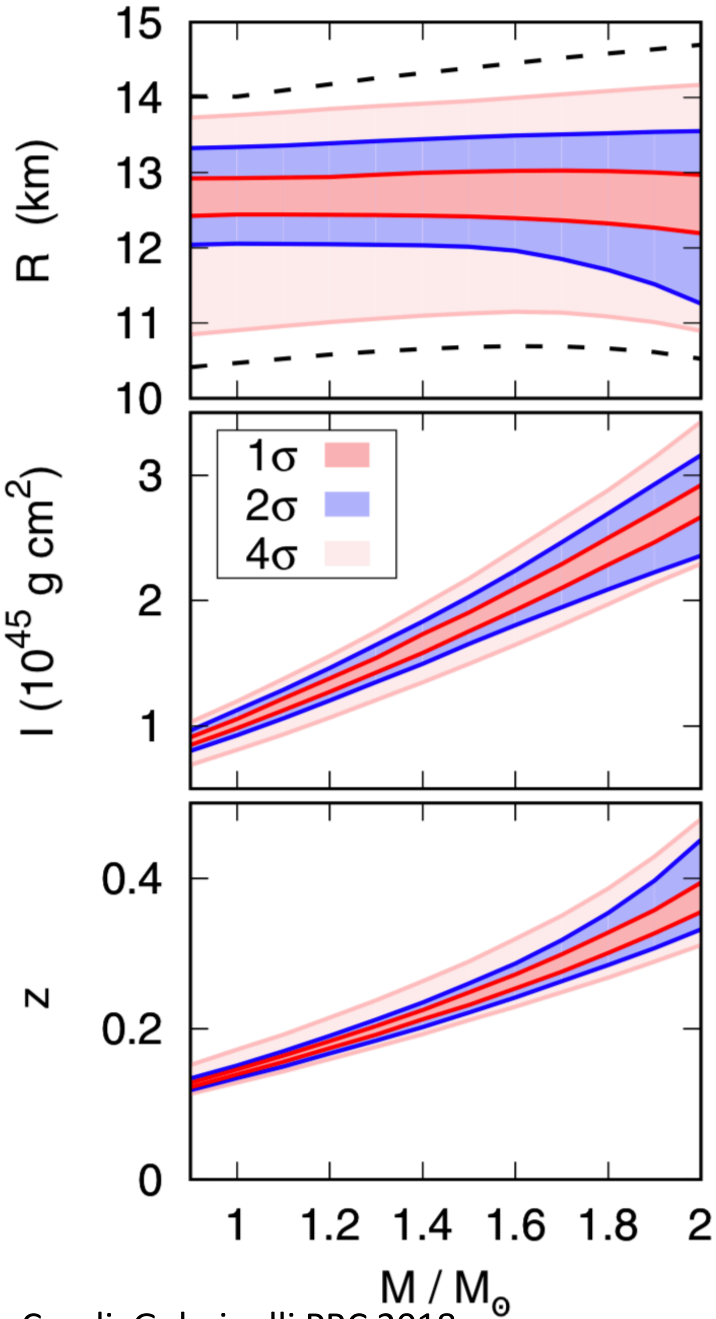
$$L_{sym} \approx 56 \pm 11\text{MeV}$$

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

Chiral EFT predictions represent correctly our current experimental uncertainty.

JM, Casali, Gulminelli PRC 2018

Bayesian predictions for NS radius



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

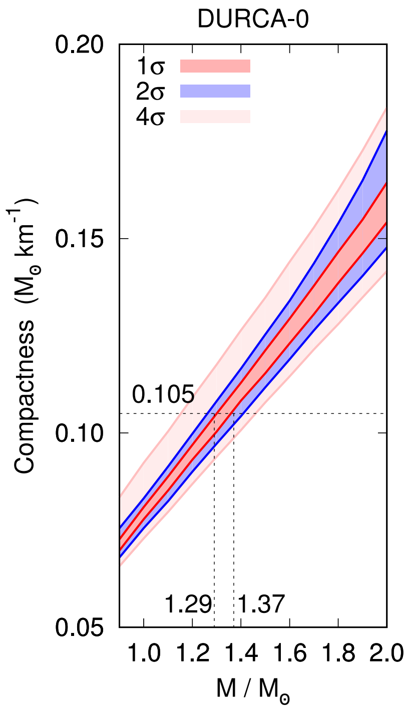
Filtering against causality, stability, M_{max}

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

for nucleonic matter

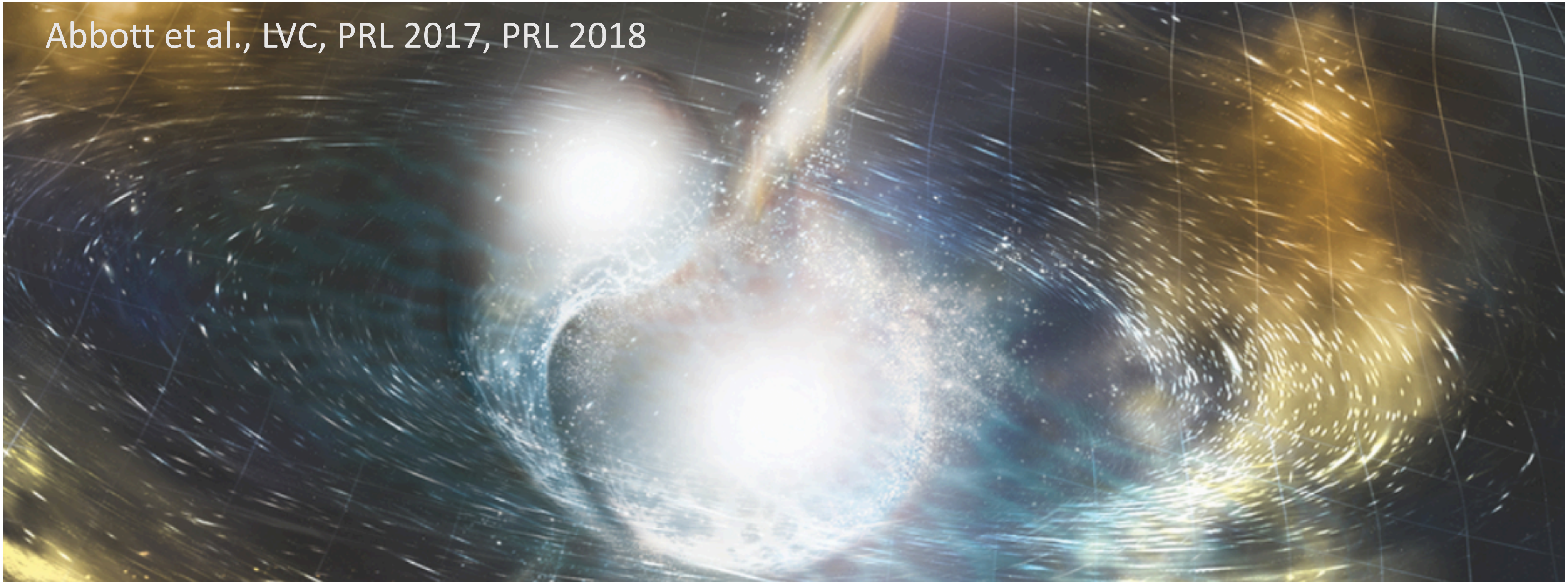
RX J0720.4-3125

Hambaryan et al., A&A 2017



Probing extreme matter with GW

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



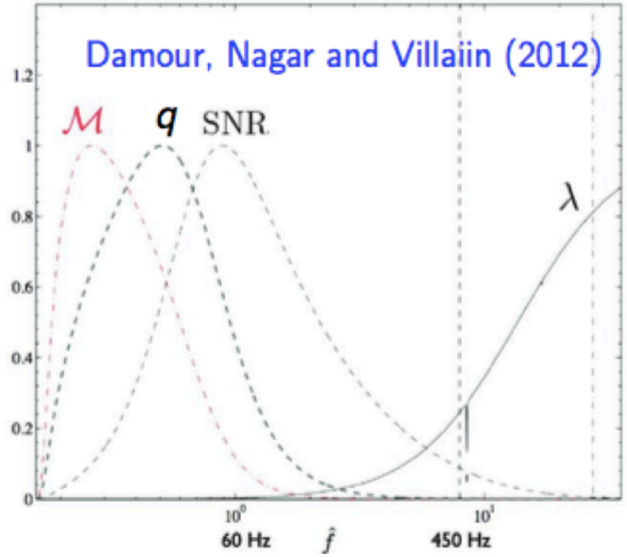
Cataclysmic Collision Artist's illustration of two merging neutron stars. The rippling space-time grid represents gravitational waves that travel out from the collision, while the narrow beams show the bursts of gamma rays that are shot out just seconds after the gravitational waves. Swirling clouds 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

What have we learned from GW170817 ?

$Q_{ij} = -\Lambda(\mathrm{EOS}, m) m^5 \mathcal{E}_{ij}$

Tidal deformability

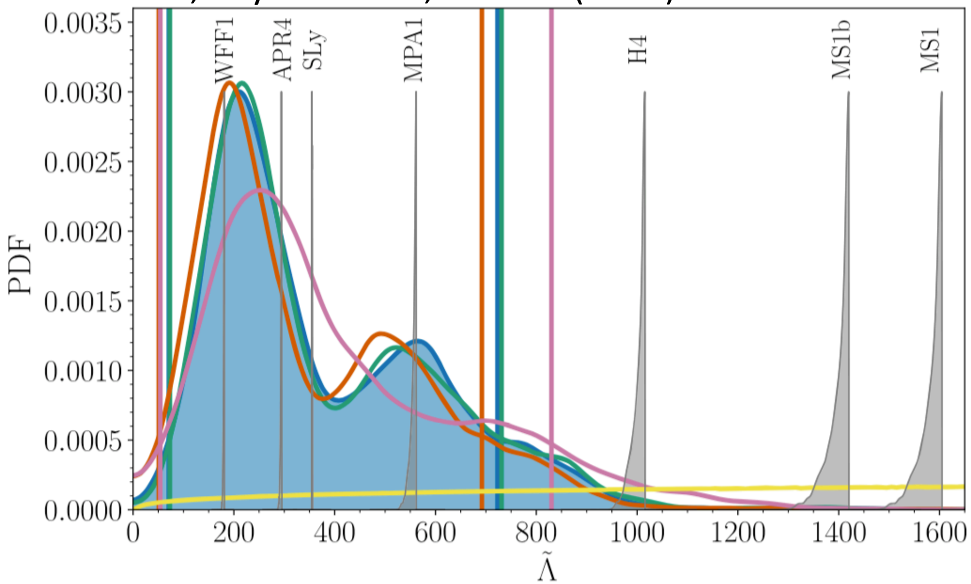
- Tidal field E_{ij} from companion star induces a quadrupole moment Q_{ij} in the NS
- Amount of deformation depends on the stiffness of EOS via the tidal deformability Λ.



Post-Newtonian expansion of the waveform: Tidal effect enters at 5th order.

Hinderer+ 2008, Blanchet, Damour

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



GW170817
→ 70 ≤ Λ ≤ 720 (90% CL)

What have we learned from GW170817 ?

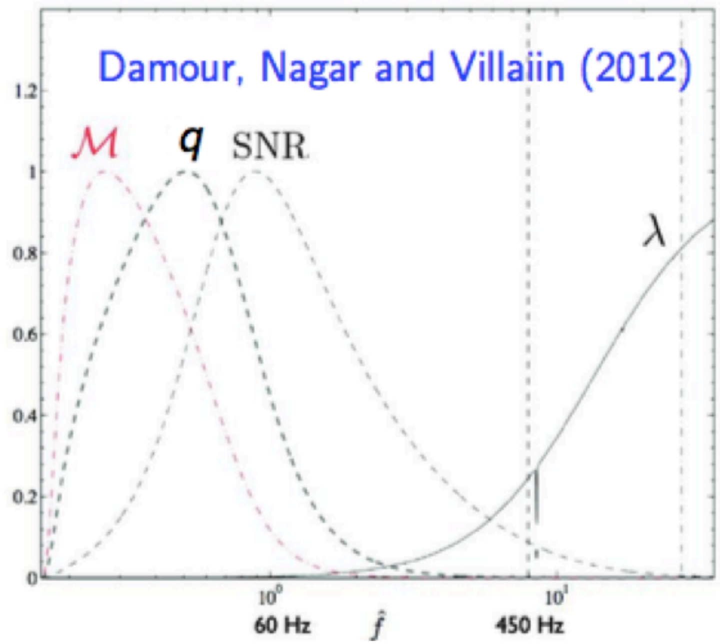
$$Q_{ij} = -\Lambda(\mathrm{EOS}, m) m^5 \mathcal{E}_{ij}$$

Tidal deformability

- Tidal field E_{ij} from companion star induces a quadrupole moment Q_{ij} in the NS
- Amount of deformation depends on the stiffness of EOS via the tidal deformability Λ.

Post-Newtonian expansion of the waveform: Tidal effect enters at 5^{th} order.

Hinderer+ 2008, Blanchet, Damour



By contrasting two dense matter modelings

Minimal model (meta-model):

- Continuous extrapolation of nuclear matter
- Chiral EFT at low density
- Properties of nuclei
- Causality, stability

Maximal model (CSM):

- Extension of polytrope with continuous cs
- Includes 1^{st} order phase transition
- Chiral EFT at low density
- Causality, stability

What have we learned from GW170817 ?

We contrast two dense matter modelings

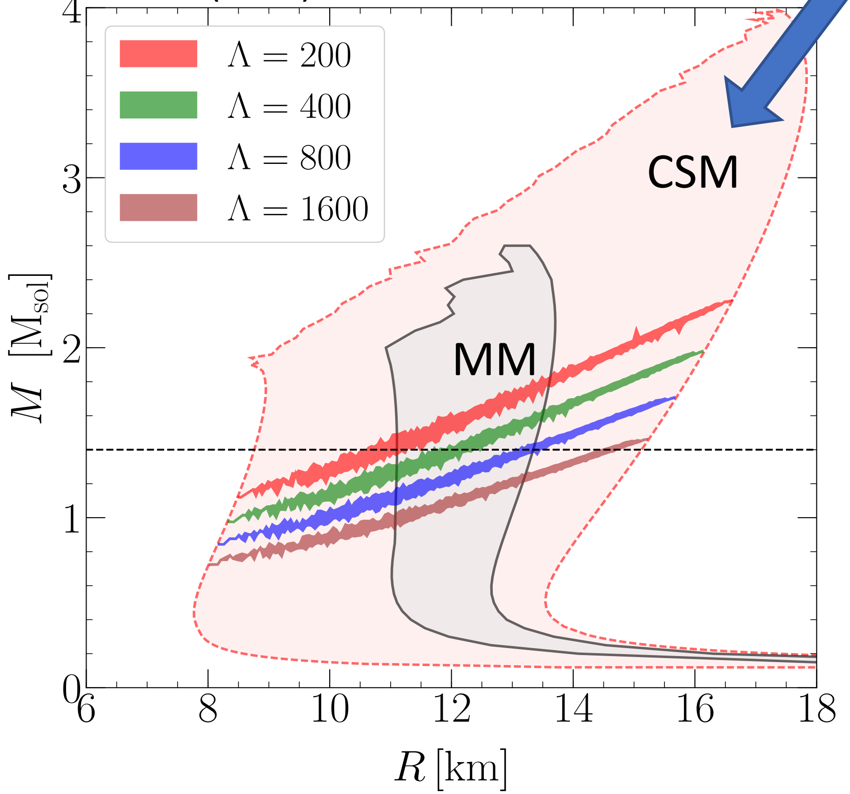
Minimal model (meta-model):

- Continuous extrapolation of nuclear matter
- Chiral EFT at low density
- Properties of nuclei
- Causality, stability

Maximal model (CSM):

- Extension of polytrope with continuous cs
- Includes 1st order phase transition
- Chiral EFT at low density
- Causality, stability

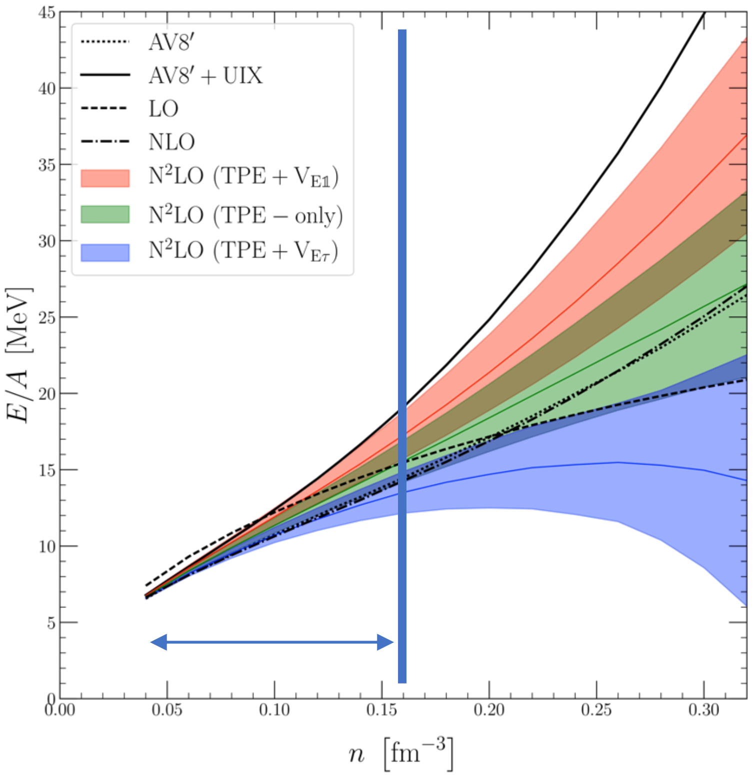
Tews, Margueron, Reddy, EPJA special issue on GW (2019)



Impact of nuclear physics knowledge

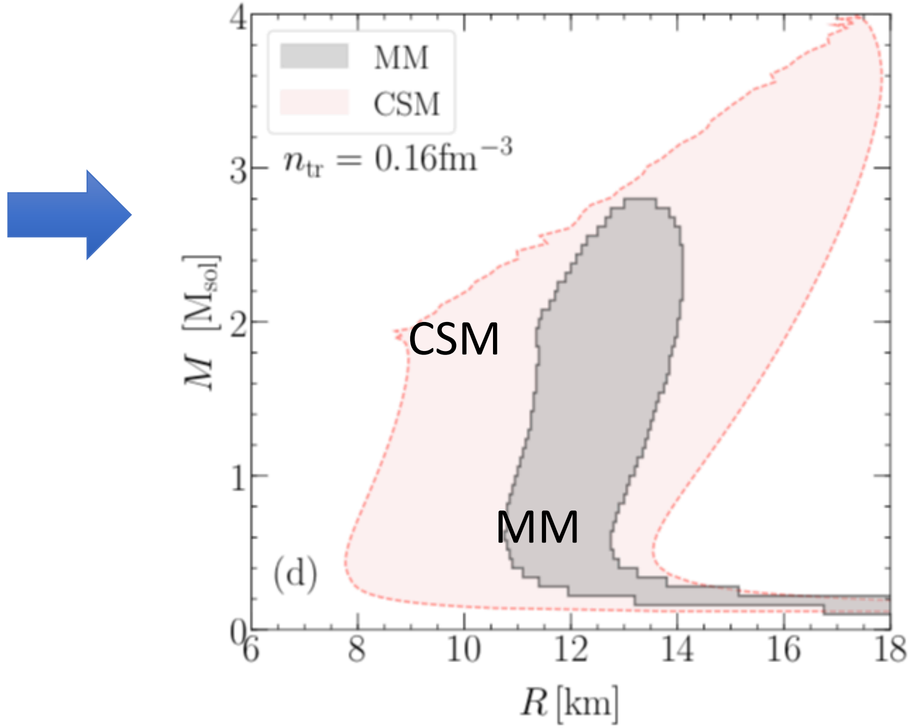
Limited to n_{sat}

QMC calculations with local chiral potentials



Tews, Carlson, Gandolfi, Reddy, PRC 2018

Solution of the non-rotating TOV eqs.

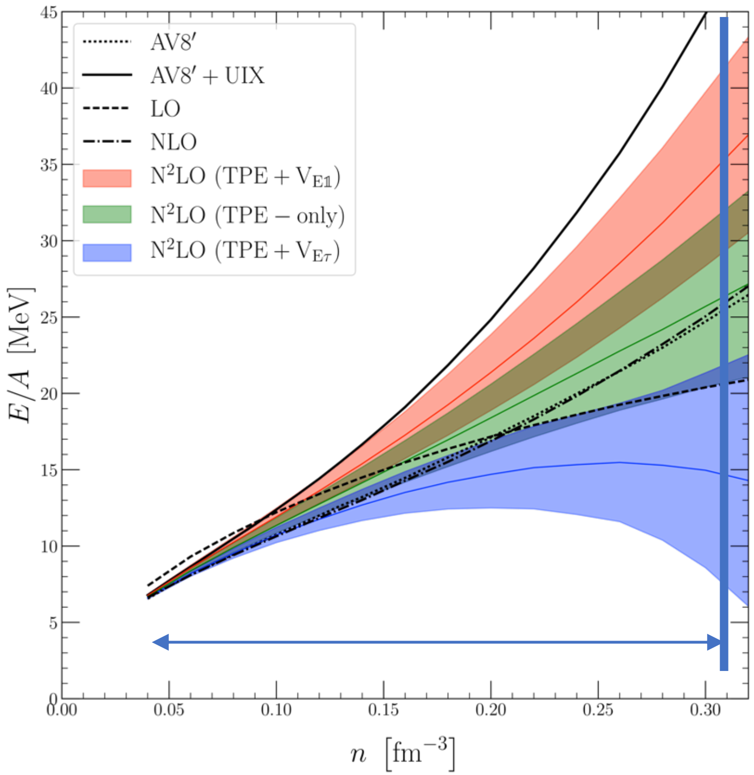


Tews, JM, Reddy, PRC 2018

Impact of nuclear physics knowledge

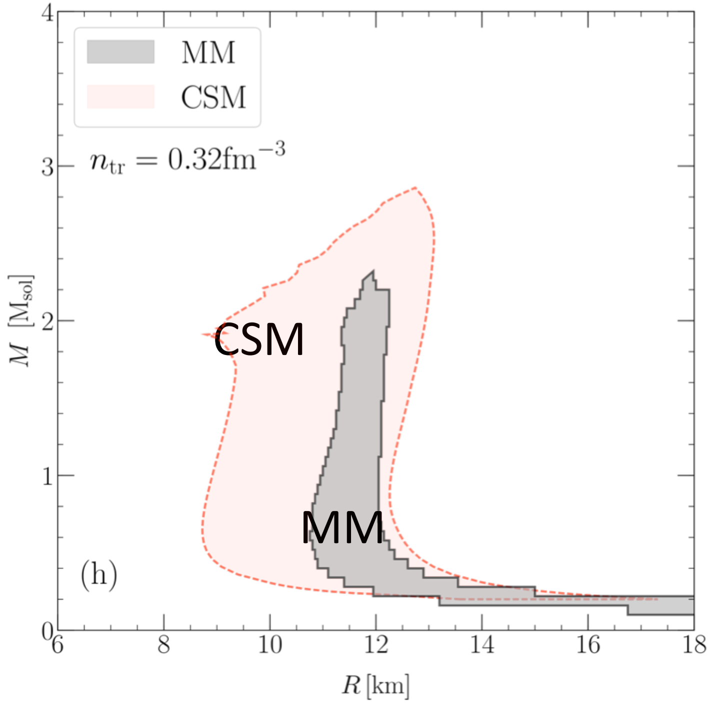
Limited to $2n_{sat}$

QMC calculations with local chiral potentials



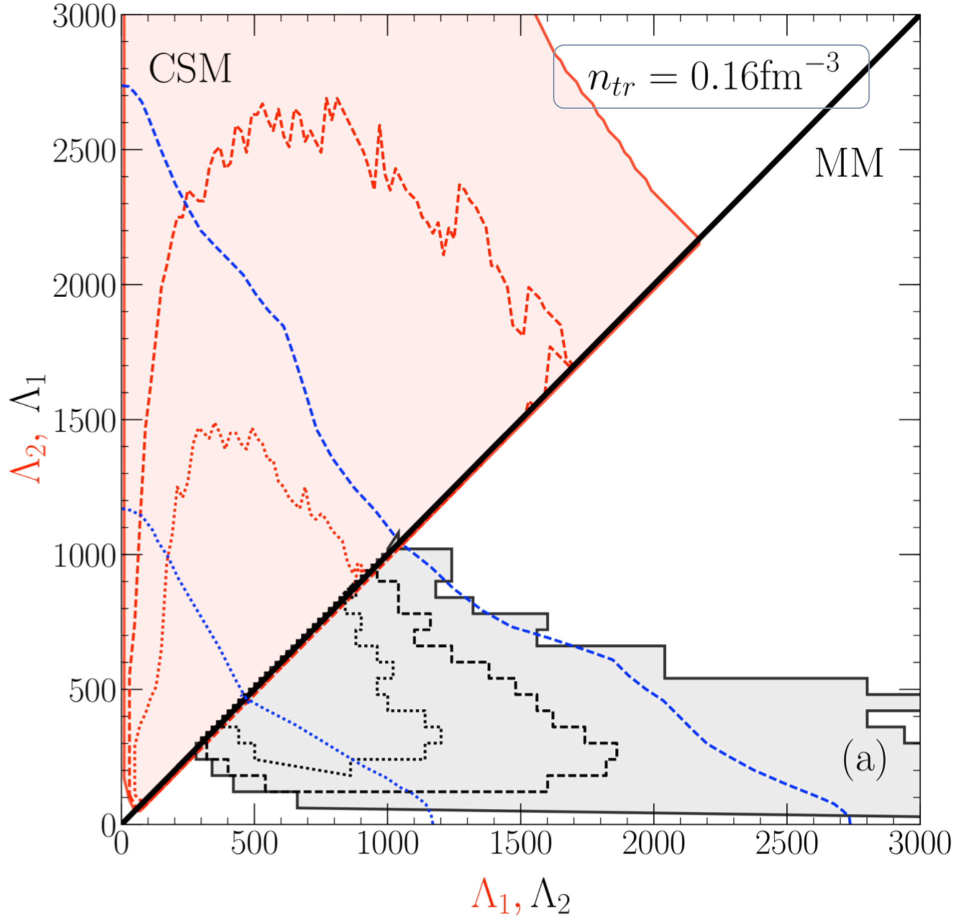
Tews, Carlson, Gandolfi, Reddy, PRC 2018

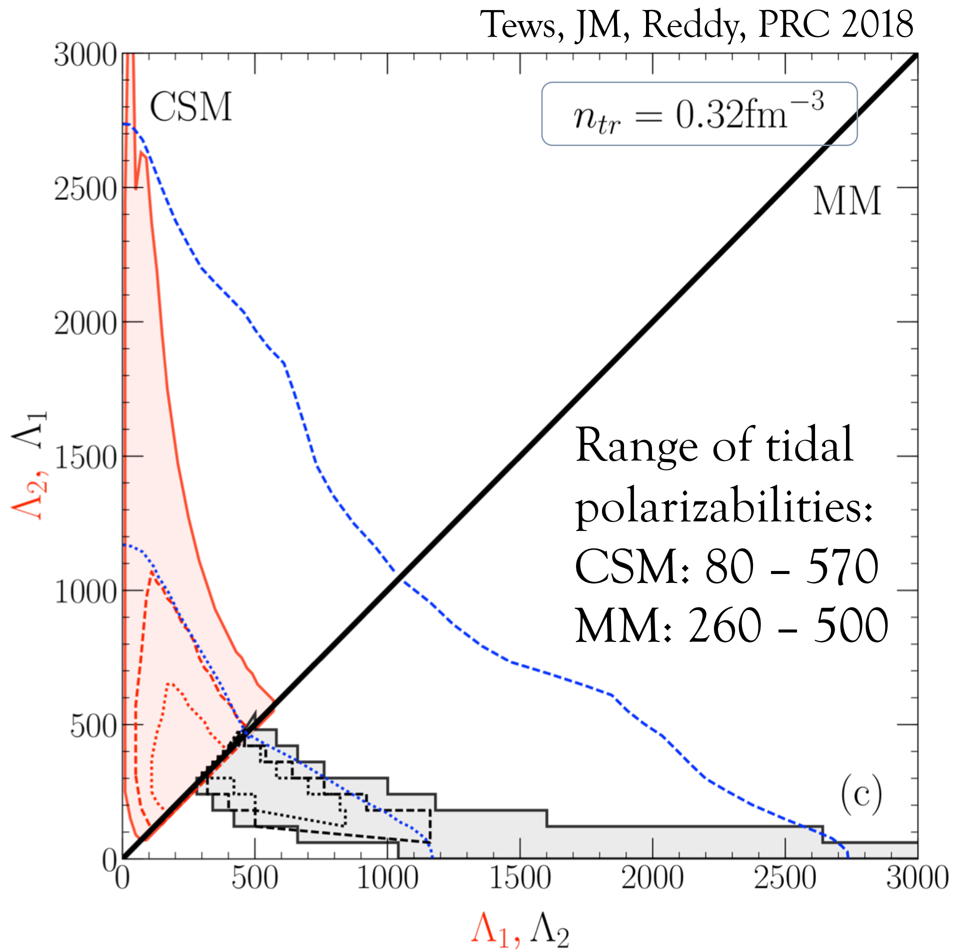
Solution of the non-rotating TOV eqs.



Tews, JM, Reddy, PRC 2018

Predictions for Λ_1-Λ_2





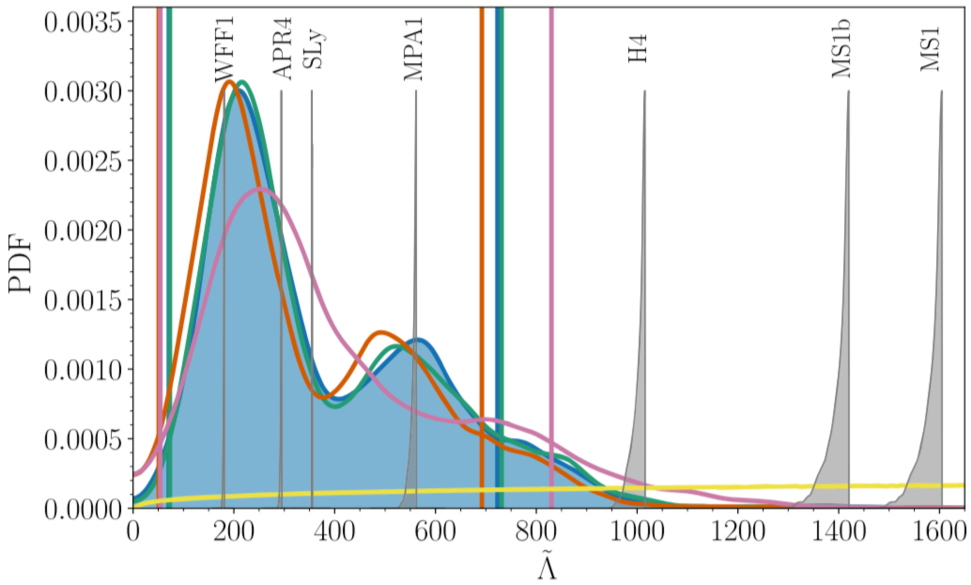
Required GW accuracy to improve our knowledge:

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

Confirm or rule out nuclear physics

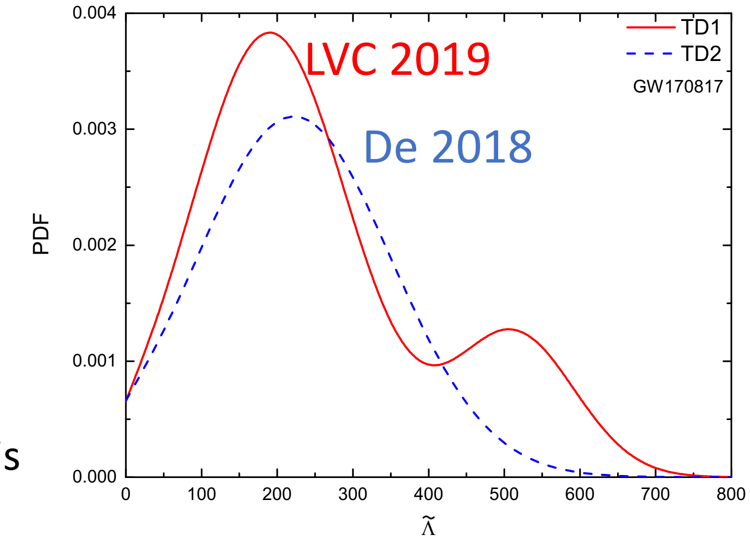
$\Delta\tilde{\Lambda} \approx$ 50-100 → Probe matter composition above $2n_{sat}$

Better exploitation of the structure of the pdf



GW170817
→ 70 ≤ Λ ≤ 720 (90% CL)

H. Güven et al, to be submitted.



Impact of 2 different pdf:

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

S. De et al., Phys. Rev. Lett. 121, 091102 (2018).

→ Bayesian analysis

Impact of 2 prior sets:

#1: small ranges from a global nuclear physics analysis

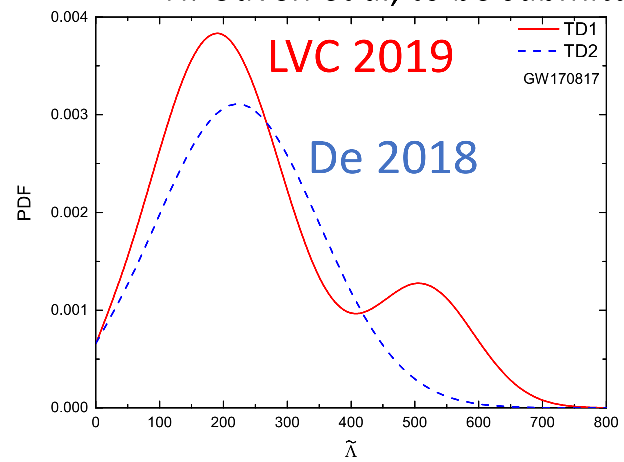
#2: larger ranges

Better exploitation of the structure of the pdf

H. Güven et al, to be submitted.

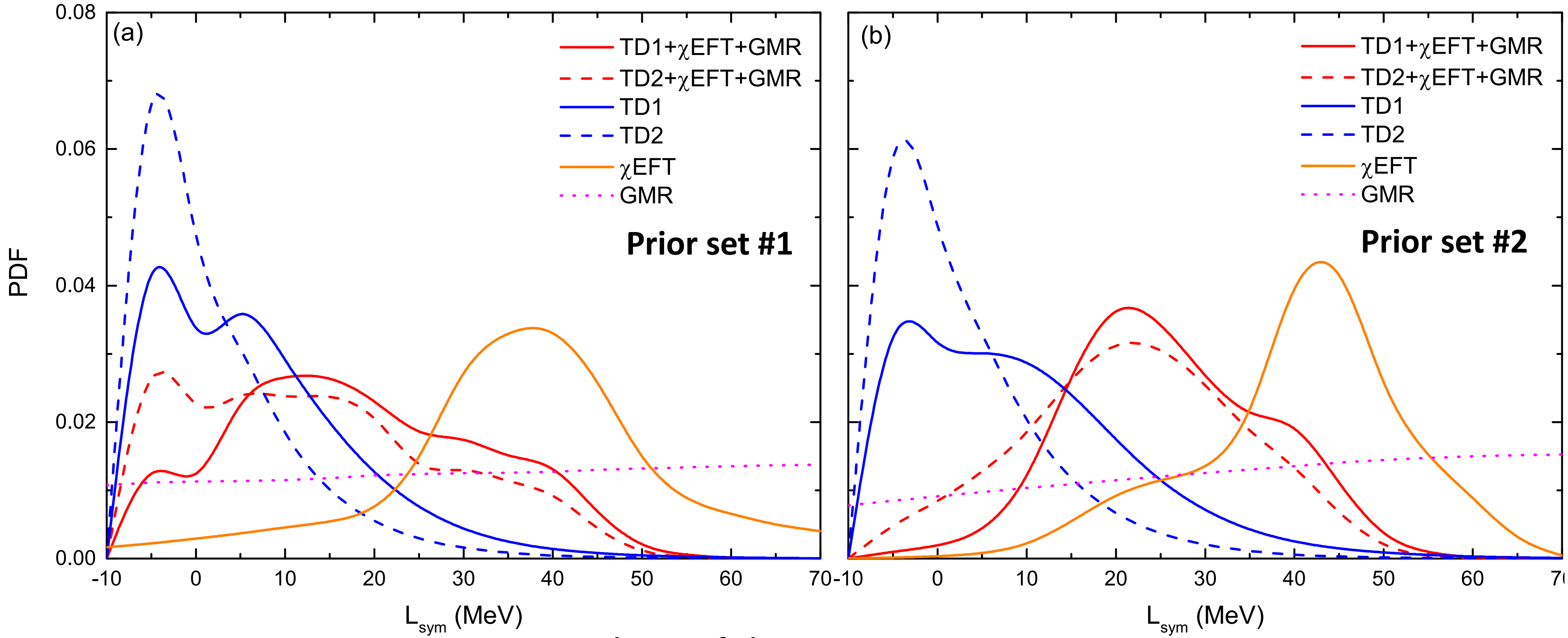
Impact of 2 different pdf:

LVC, Phys. Rev. X 9, 011001 (2019).
S. De et al., Phys. Rev. Lett. 121, 091102 (2018).



Impact of 2 prior sets:

#1: small ranges from a global nuclear physics analysis
#2: larger ranges

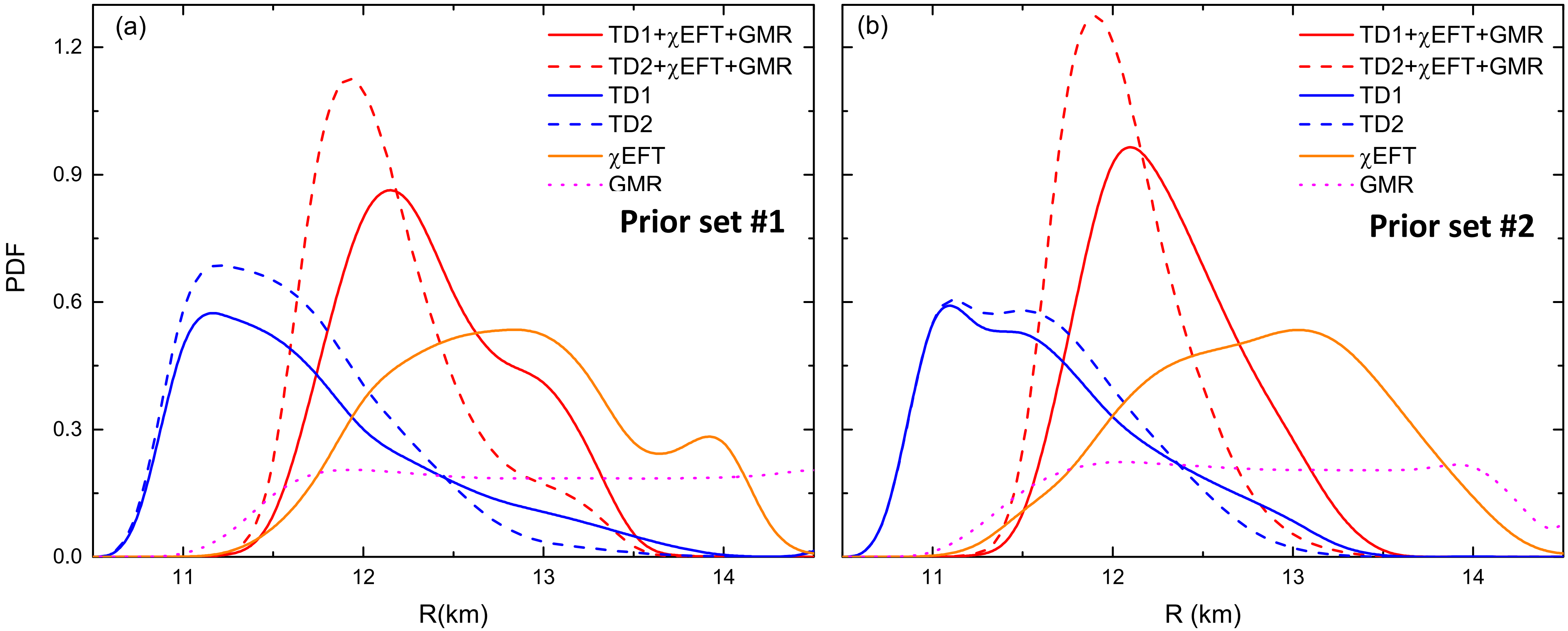


Slope of the symmetry energy

Better exploitation of the structure of the pdf

H. Güven et al, to be submitted.

Impact on the NS radius:



→ There is a tension between low density constraints (χEFT) and higher density constraints (TD).

→ First hint for a phase transition? To be explored...

Conclusions and Outlook

A large amount of new observational data! (GW, NICER, nuclear physics, …).
It allows us to believe the **dense matter properties will soon be accurately known** (at least for E, P, c_s).

Expected $\Delta\Lambda \approx$ 50-100 clearly constrain the dense matter EOS.

However, present Λ-pdf suggests possible hint for phase transition → to be explored…

Plans for the future:

- enrich the meta-model, more degrees of freedom (Δ, Y, QGP, …).
- Extend to finite temperature, include consistent neutrino interaction rates.
- Incorporate meta-model into global simulations
  - post-merger GW,
  - multi-messenger physics.

Einstein Telescope (ET) is the 3rd generation earth interferometer project for 2030 by GWIC dedicated to the study of stellar BH and NS.
More information + letter of intent at: http://www.et-gw.eu