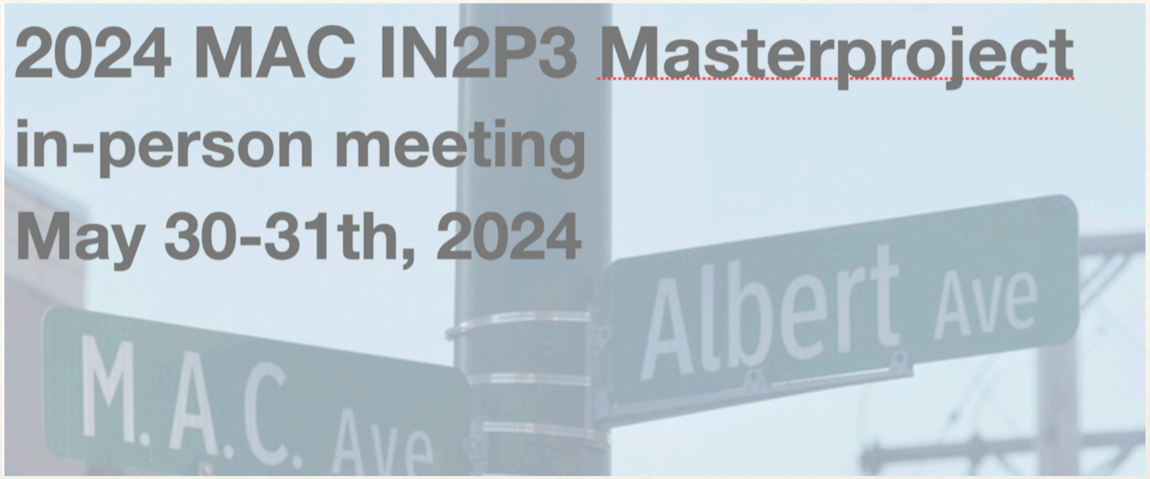


MAC meeting, IJCLab Orsay, May 30-31, 2024

Beyond meta-modeling

Symmetry energy,
phase transition(s).

Jérôme Margueron, IRL NPA, CNRS & MSU, FRIB, East Lansing, USA.

Anatomy of a Neutron Star

Conjectured 1934 (**Bade & Zwickly**) **Known** ~ 3300 **Expected** ~10^8 (in our galaxy)

Discovered 1967 (**Bell & Hewish**)

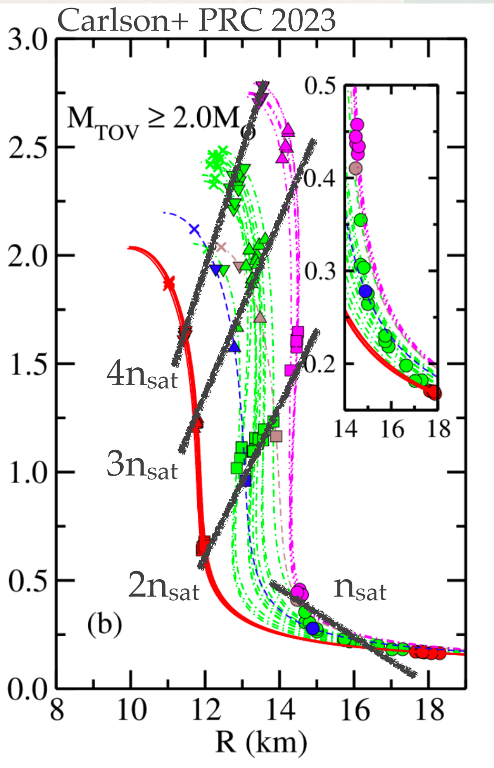
Radius ≈ 10 – 14km

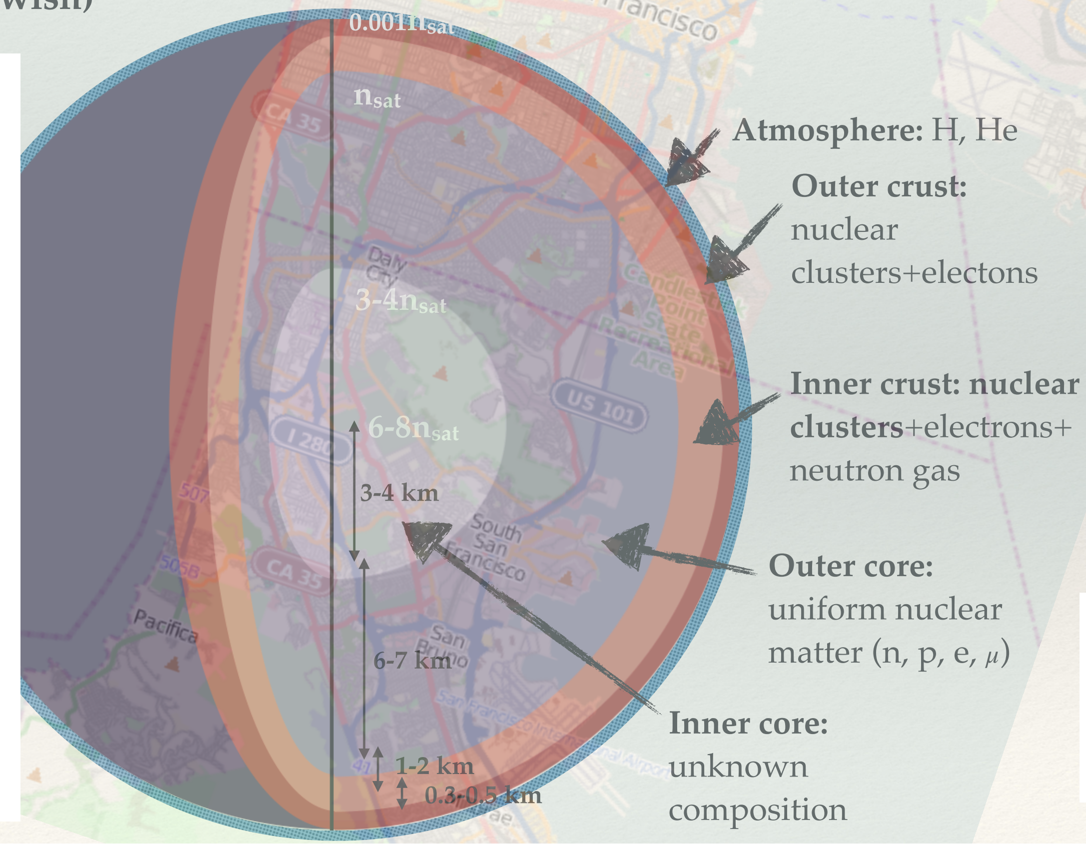
Mass ≈ 1.2 – 2.1$M_\odot$ (observed)

Density ≈ 10^{15} g cm^3

Spin ≥ 716 **Hz**

Magnetic field up to ~10^{16} **G**



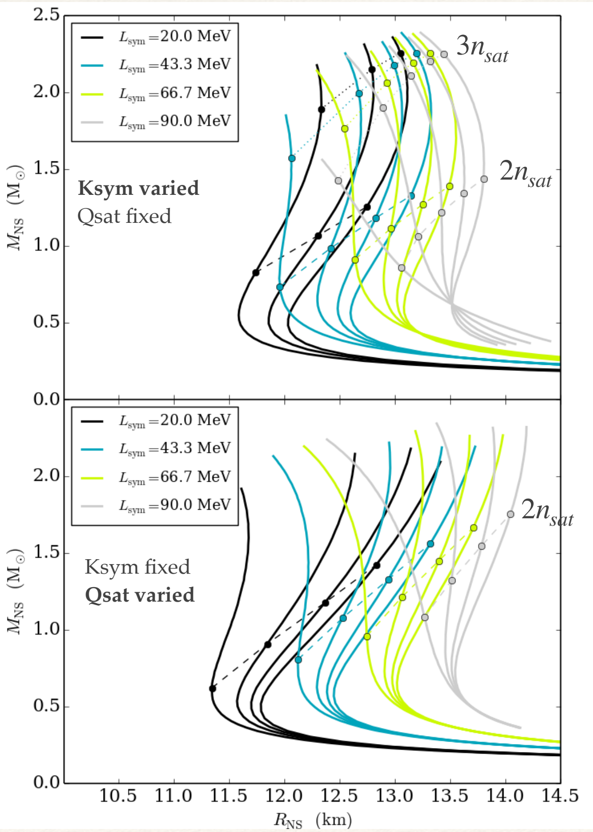


The understanding of NS is mainly due to our knowledge in nuclear physics (+ general relativity).

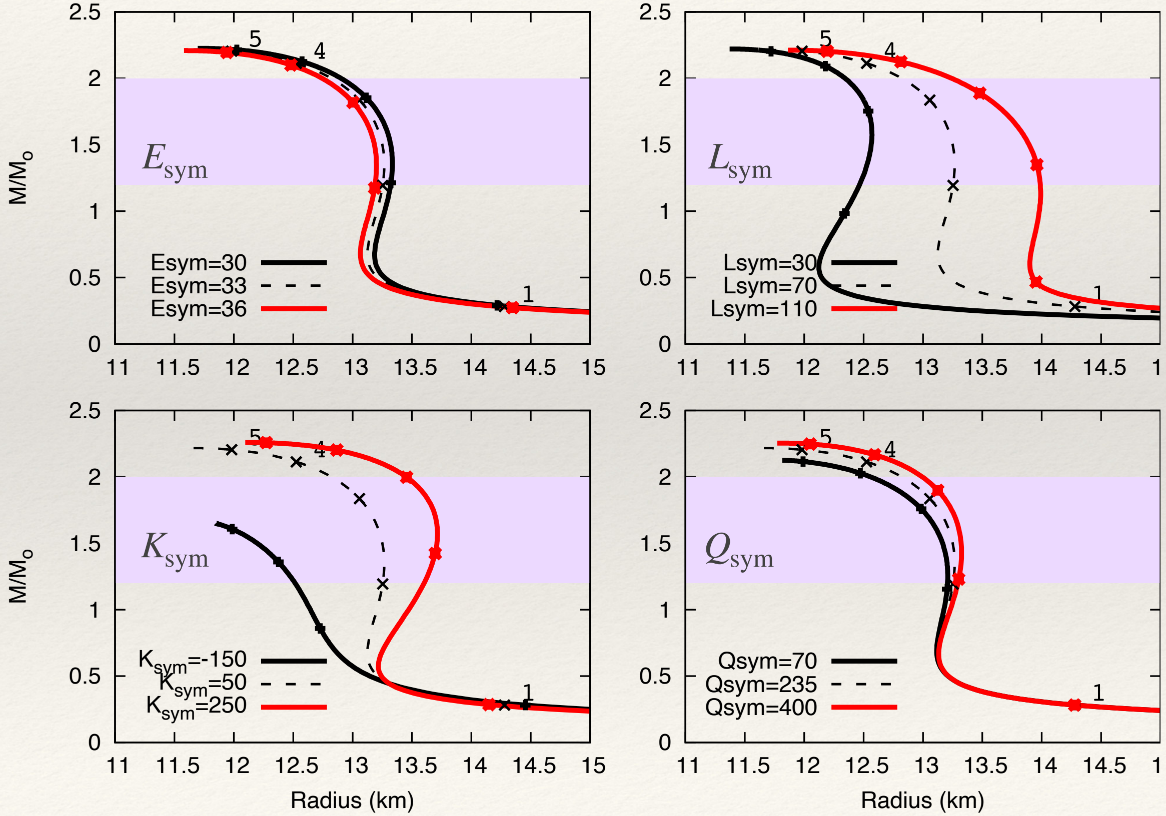
NS **radius** provides information about the **core**, but there is also a contribution from the crust (10%).

meta-modeling of extreme matter EoS

Impact of changing the NEP on the MR relation of neutron stars:



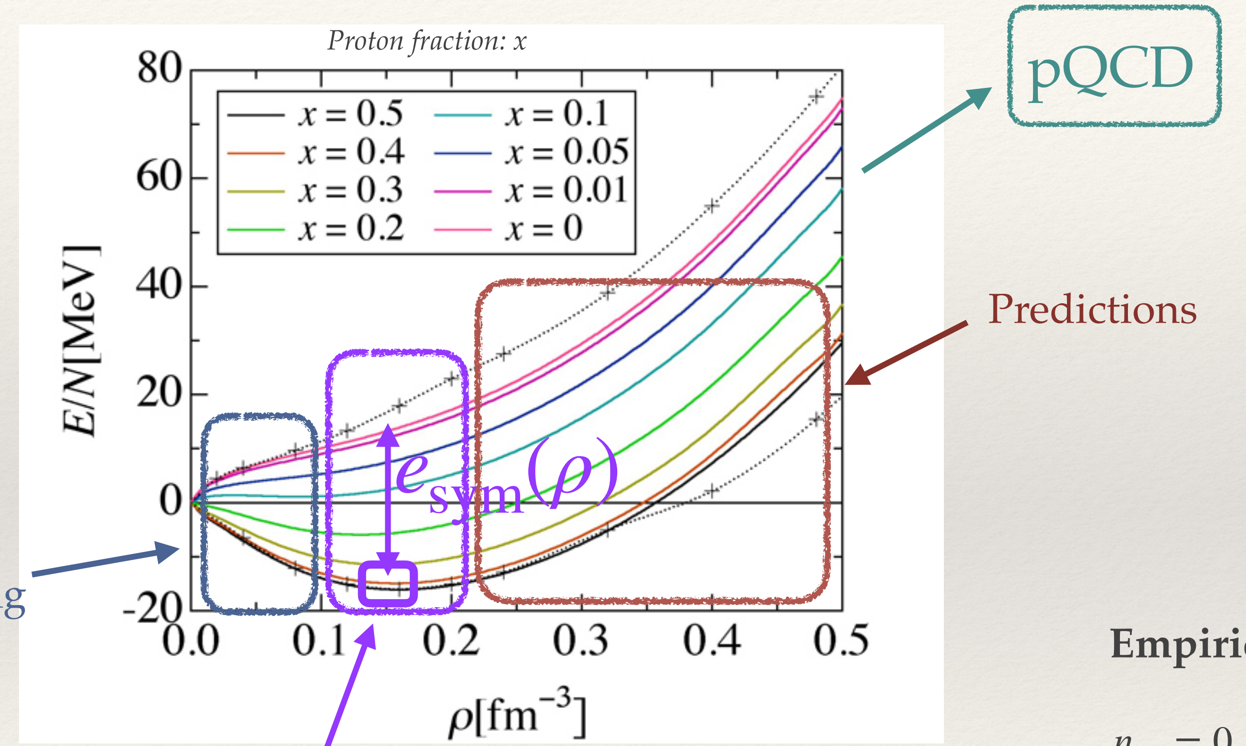
Isovector channel



Questions:

- Justification of the meta-model for massive NS?
- Constraints from HIC data?
- Low density nuclear matter and NS crust?

Known and unknown of the nuclear EOS



Controlled by low density QCD modeling

Saturation density n_{sat} & energy E_{sat}, E_{sym}, … → **Controlled by nuclear experiments.**

Empirical parameters:

$n_{\rm sat} = 0.155 \pm 0.005\ {\rm fm}^{-3}$ $\quad E_{sym} = 32 \pm 2$ MeV

$E_{sat} = -15.8 \pm 0.4$ MeV $\quad L_{sym} = 60 \pm 15$ MeV

$K_{sat} = 240 \pm 20$ MeV

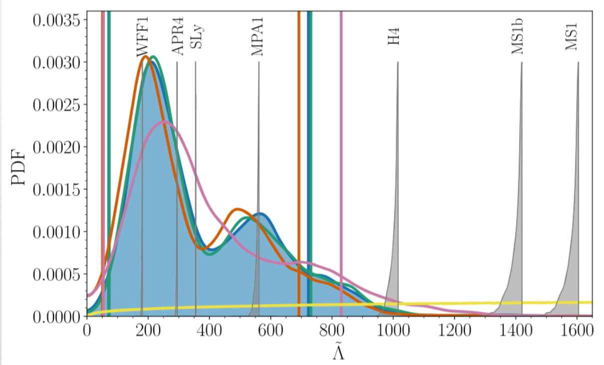
Beyond meta-modeling

- High density for the inner core: phase transitions and pQCD constraints
- Medium density for the core: relativistic approaches and HIC
- Low densities for the crust: correlations and the unitary limit

BNS GW [astro] <=> EoS [nuclear]

Analysis of GW170817 waveform:

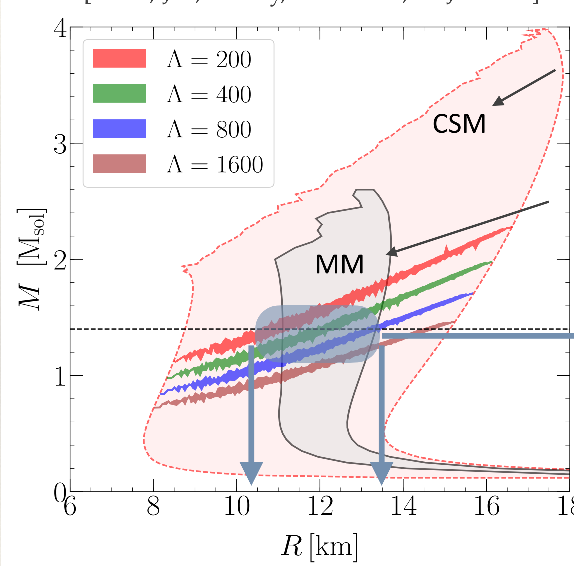
LVC, Phys. Rev. X 9, 011001 (2019)



GW170817:
→ $70 \leq \Lambda \leq 720$ **(90% CL)**

The tidal deformability $\tilde{\Lambda}$ is a measure of the compactness of the star:

[Tews, JM, Reddy, PRC 2018, EPJA 2019]



Sound-speed Model (phases transitions) [Tews+ 2018]

Meta-Model (nucleonic) [JM+ 2018]

The present measure is compatible with the hypothesis of nucleonic matter but also of matter with phase transition.

Relativistic meta-modeling

See talk by Mohamad CHAMSEDDINE.

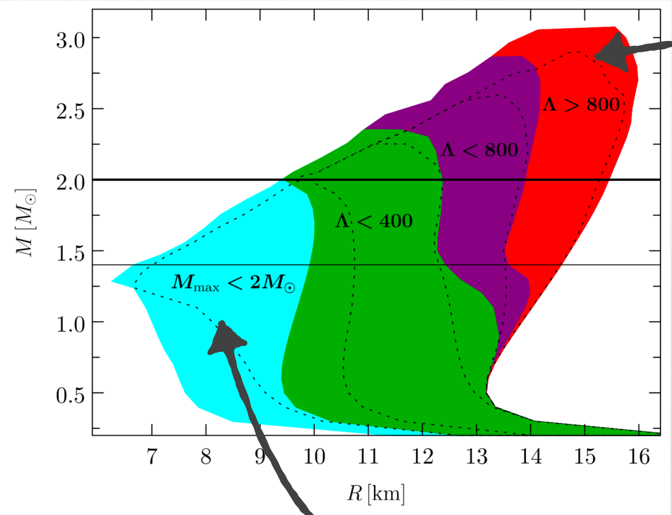
Above saturation density: sound speed becomes comparable to c.

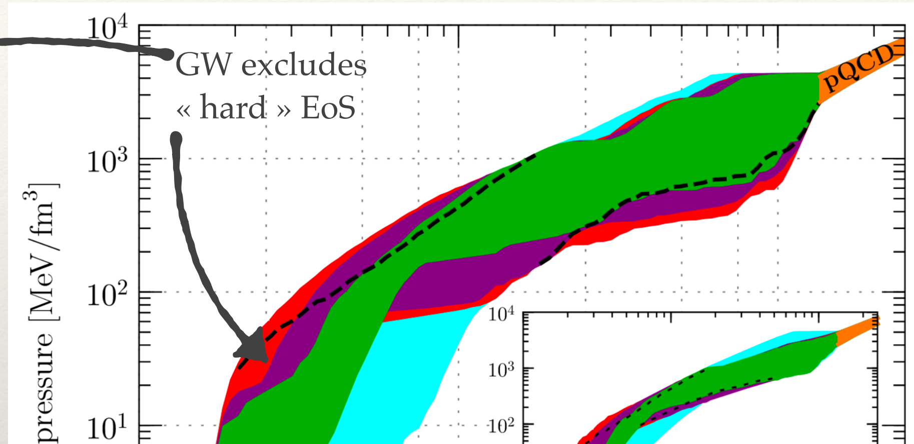
—> need to consider relativistic modeling of dense matter.

Phase transition(s) in the inner core

Consequences for extreme matter EoS

Annala+, PRL 120, 172703 (2018)

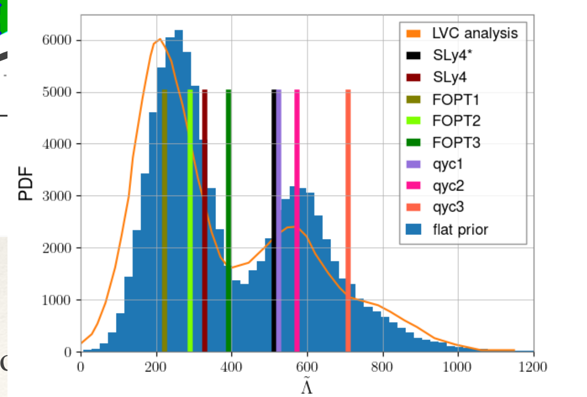




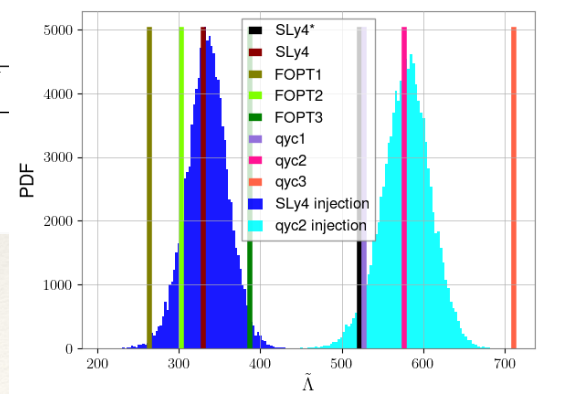
GW excludes « hard » EoS

Excluded by M_{TOV} limit « soft » EoS

Observation in 2017:



As it would be if detected in 2024:



Coupechoux+ PRD 107, 124006 (2023)

Expectations from GW analysis:

Radio and GW astronomy bound the EoS:

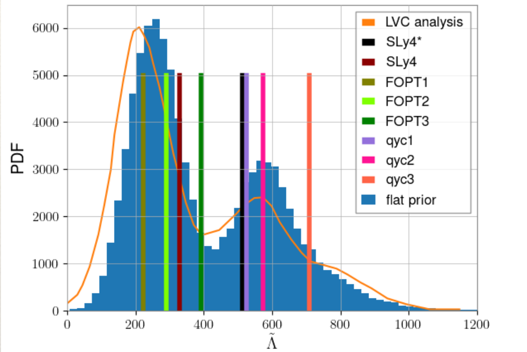
- Simple illustration of a multi-messenger analysis.
- More accurate measurement of $\tilde{\Lambda}$ -> further reduction of Eo

GW detections during O4 (2023-2025)

Coupechoux+ PRD 107, 124006 (2023)

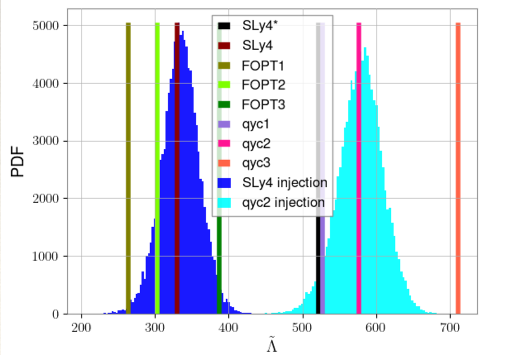
How GW170817 was measured:

GW170817 (w O2 noise):



How it will be measured nowadays:

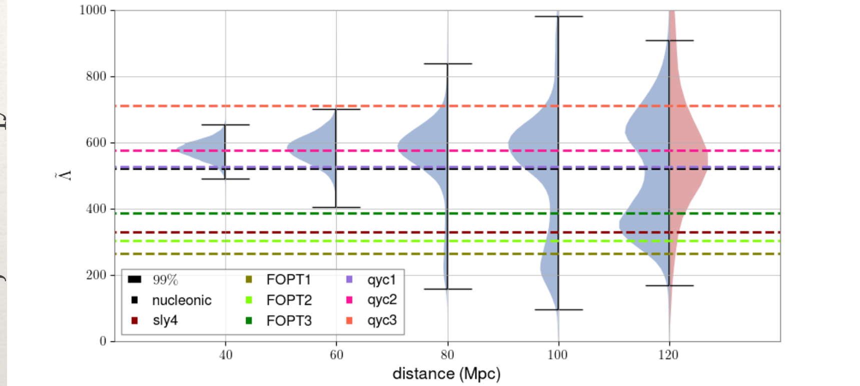
Simulation of GW170817 (w O4 noise):



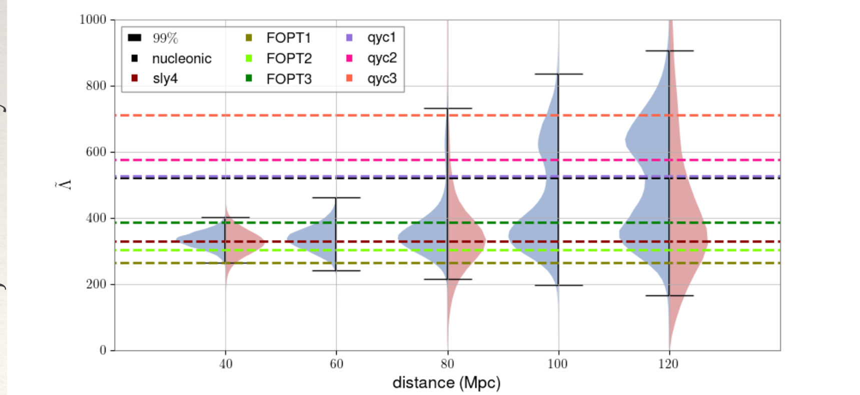
How all events will be measured:

Simulation of GW170817 (w O4 noise) at various distances:

Injection of qyc2



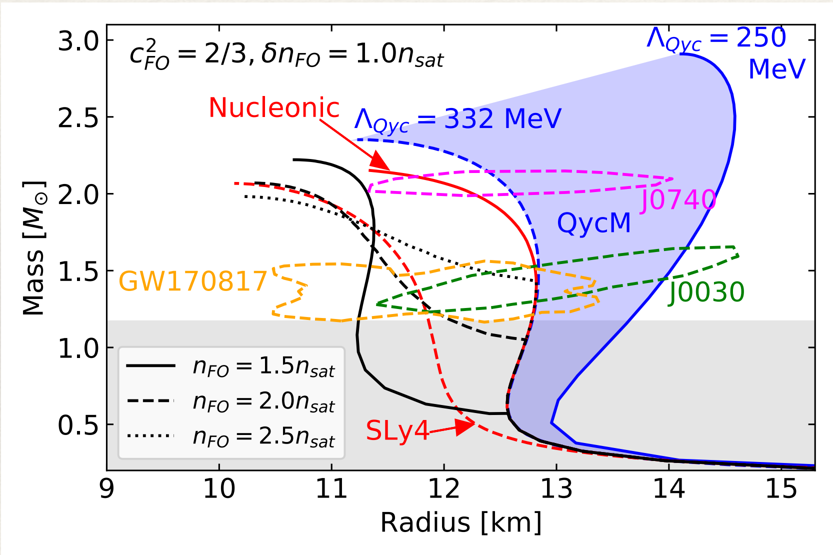
Injection of SLy4



—> an event similar to GW170817 with D<100 Mpc will bring new information.

Astro data and dense matter modeling

Impact of phase transitions in the core of neutron stars



[Somasundaram, JM, EPL 138 (2022)]

Compatibility between GW and NICER results?

Cf talk by Elias.

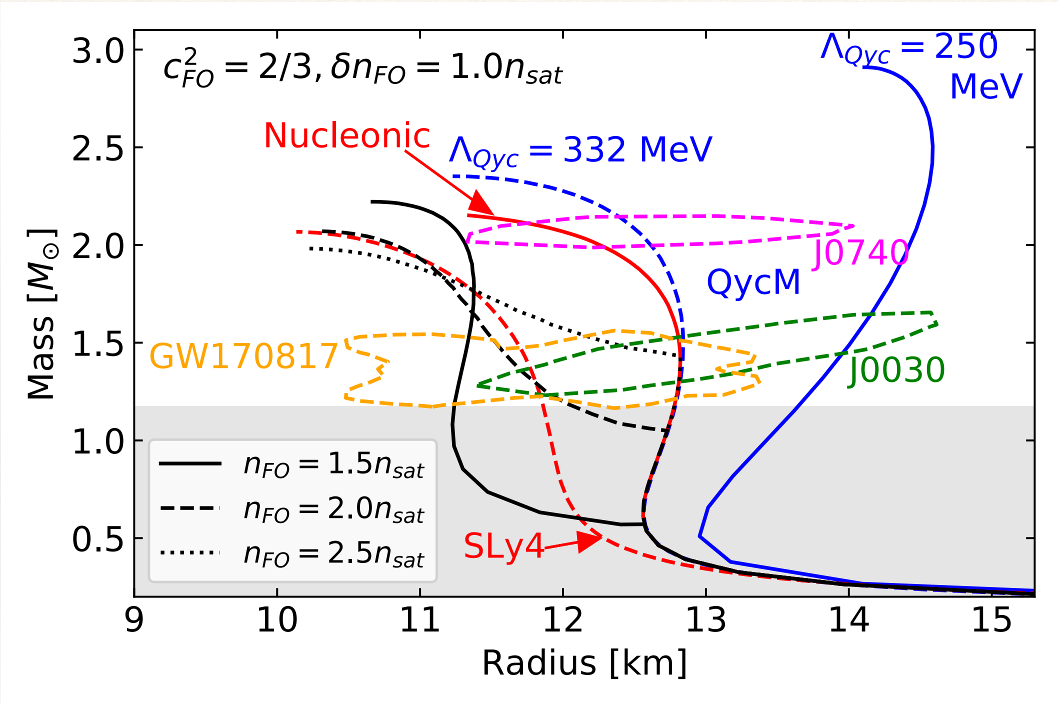
FOPT:

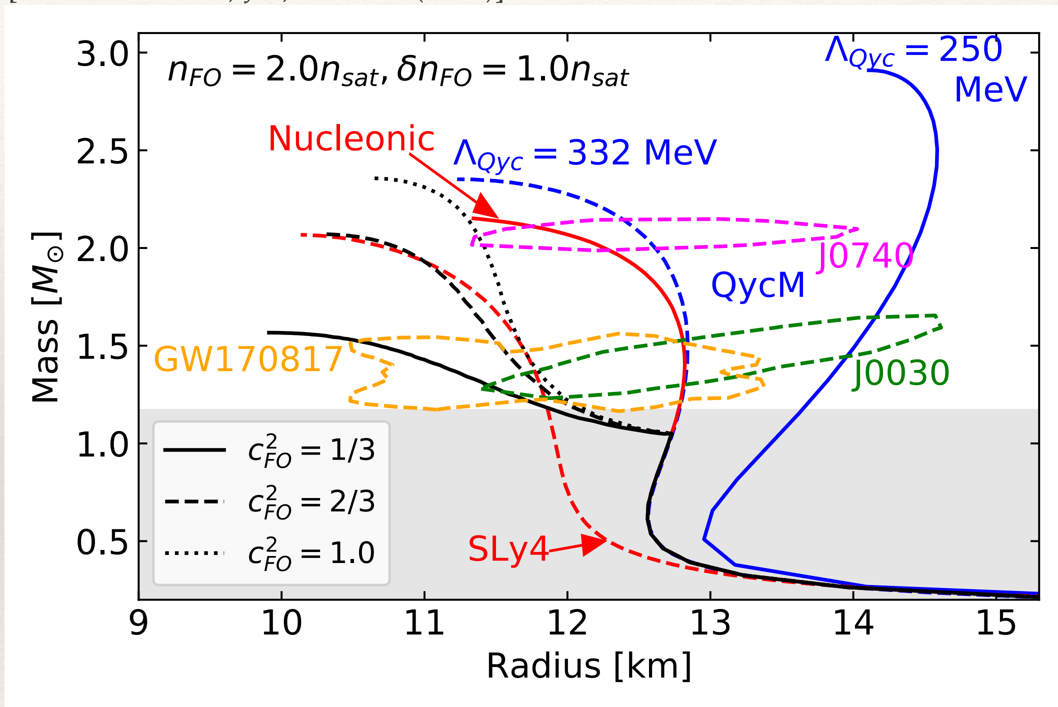
$$\varepsilon(p) = \begin{cases} \varepsilon_{\rm NM}(p) & p < p_{\rm PT} \\ \varepsilon_{\rm NM}(p_{\rm PT}) + \Delta\varepsilon_{\rm PT} + (p - p_{\rm PT})/\alpha & p \geq p_{\rm PT} \end{cases}$$

Qyc: quarkyonic model with smooth cross-over.

Phase transition(s) in NS

[Somasundaram, JM, EPL 138 (2022)]



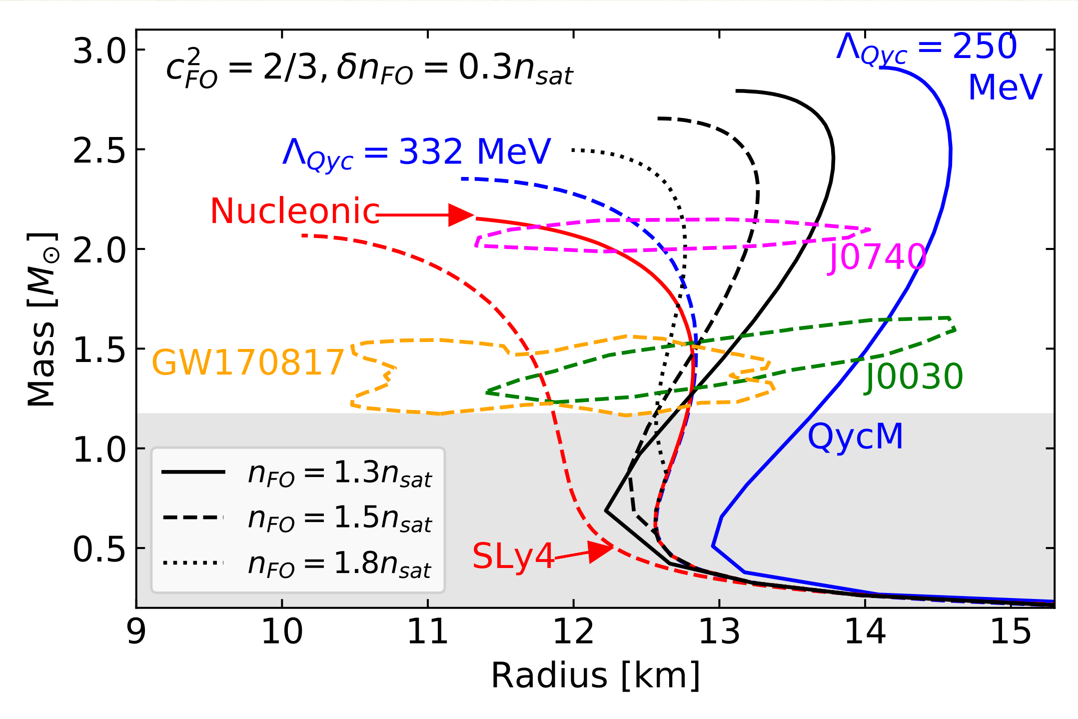


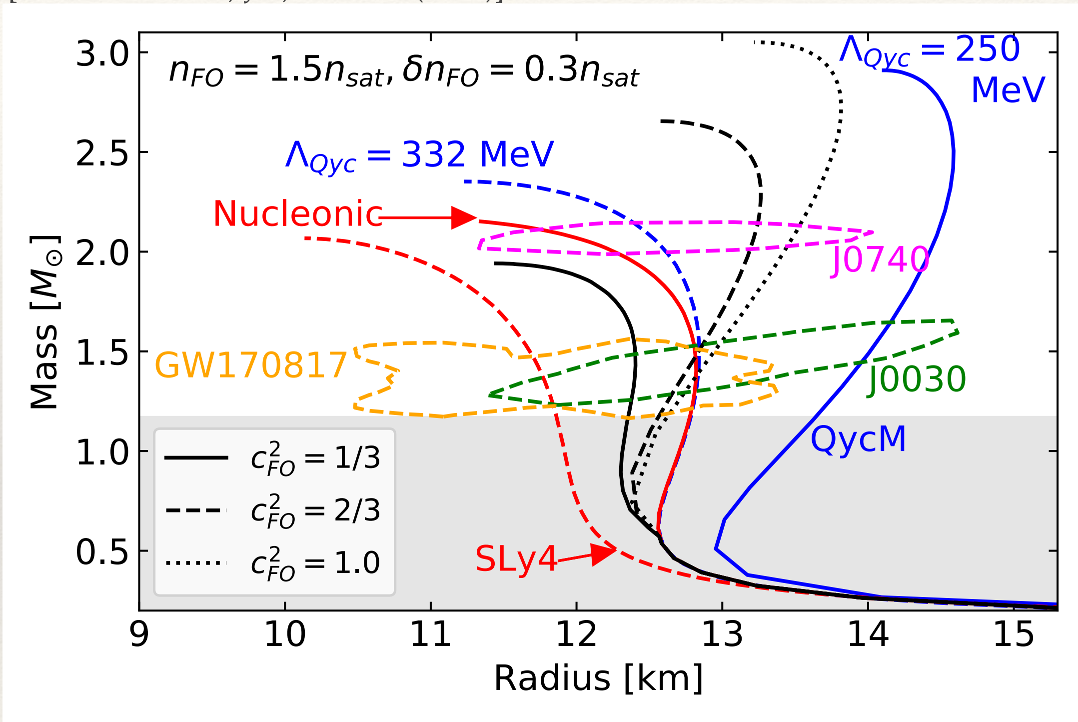
—> First order phase transition softens the EoS while crossover hardens it.

The radius of hybrid stars informs us about the kind of transition from nucleons to quarks.

Phase transition(s) in NS

[Somasundaram, JM, EPL 138 (2022)]



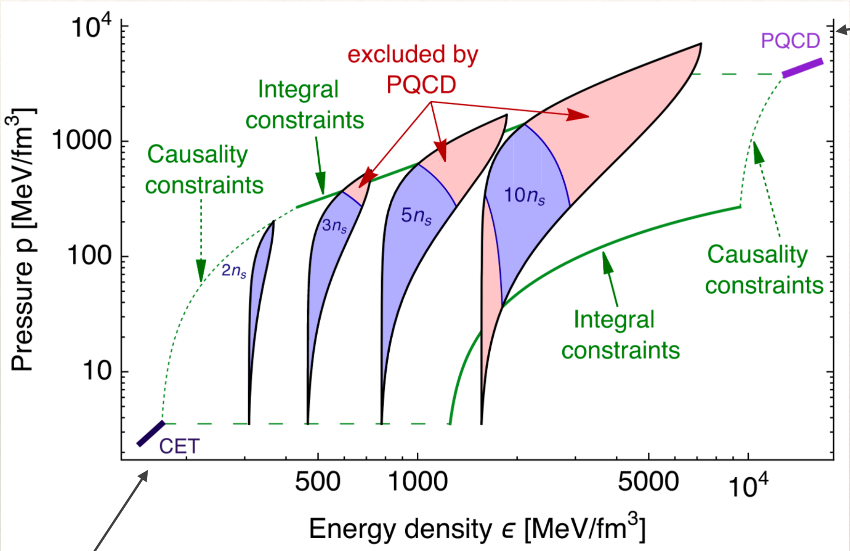


unless the FOPT occurs at low density —> masquerade Qyc and produce bigger stars.

pQCD constraints for the inner core

Connection to pQCD at high density

Komoltsev and Kurkela, PRL 128, 202701 (2022)

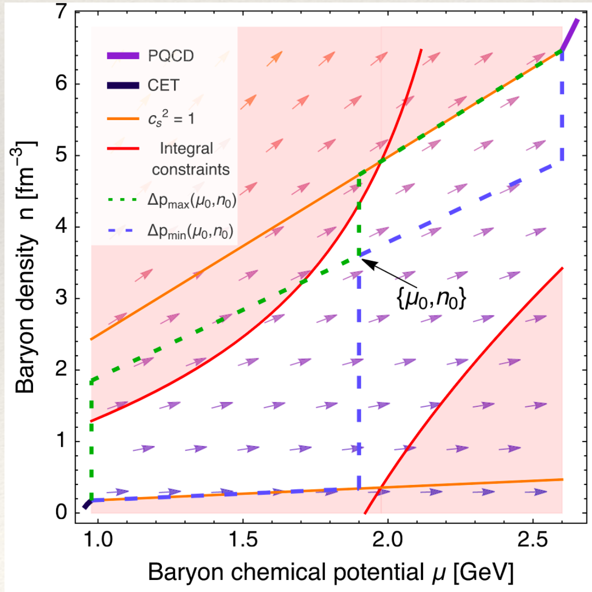


	PQCD		
	$X=1$	$X=2$	$X=4$
μ (GeV)		2.6	
n (1/fm^3)	6.14	6.47	6.87
p (MeV/fm^3)	2334	3823	4284

Loop scale parameter

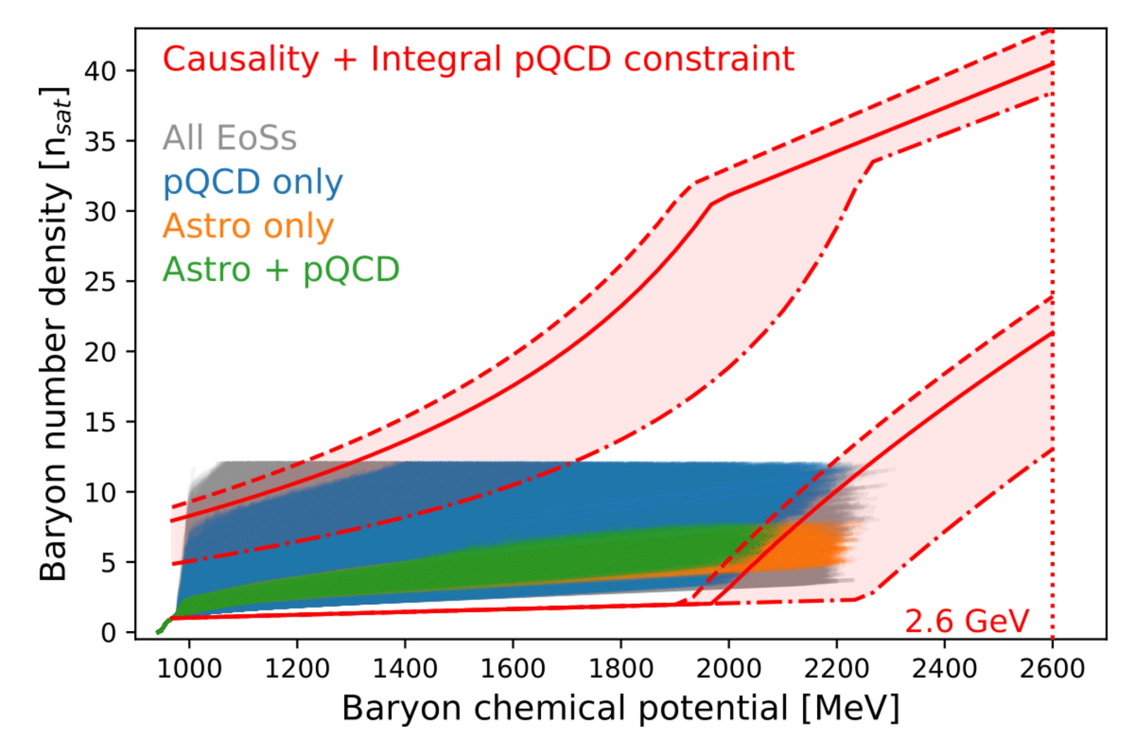
Constraints
from chiral EFT

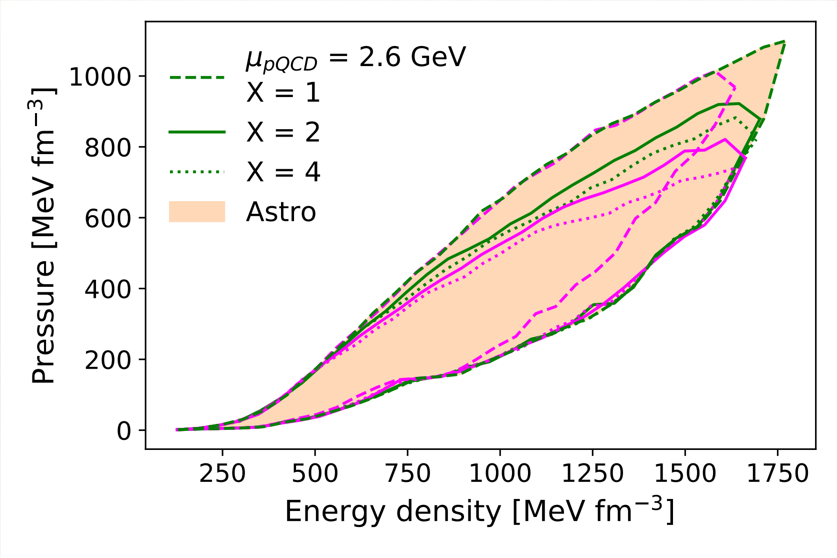
The most general way to connect to pQCD.



Connection to pQCD at high density

Somasundaram, Tews and JM, PRC (2023)

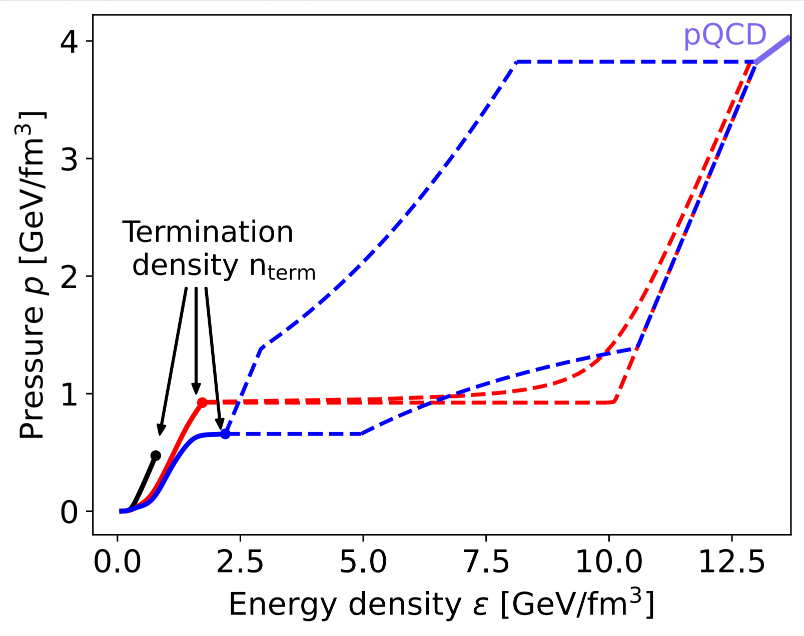


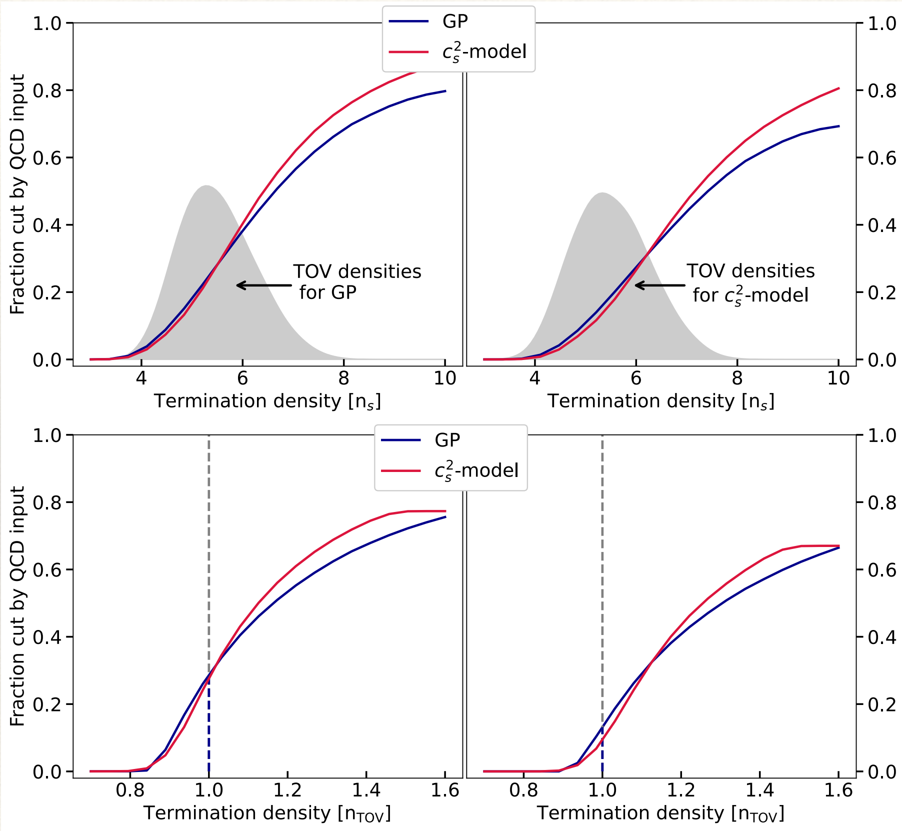


Constraints from astrophysical observations are still better than pQCD.
Note opposite conclusions from Gorda, Komoltsev and Kurkela, ApJ (2023).

Origine of the different conclusions

- different EOS modeling (CSM versus GP)
- Different statistics (hard cut versus bayesian stat.)
- Different termination densities.



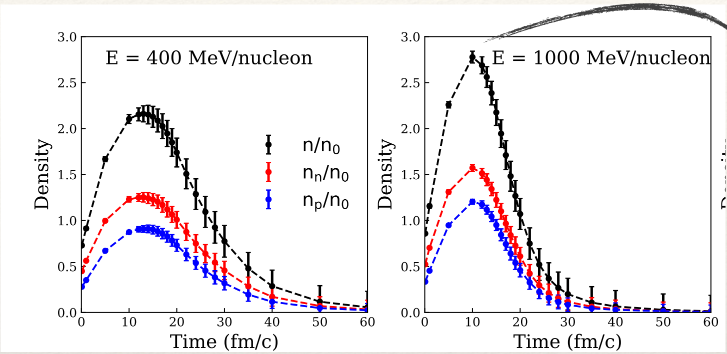


Probing dense matter EOS from HIC

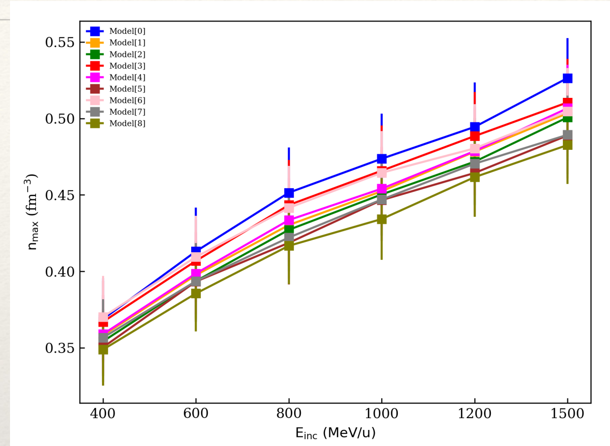
Flow data (FOPI) from HIC

FOPI data for 197Au+197Au @ Einc=400-1500 MeV/u

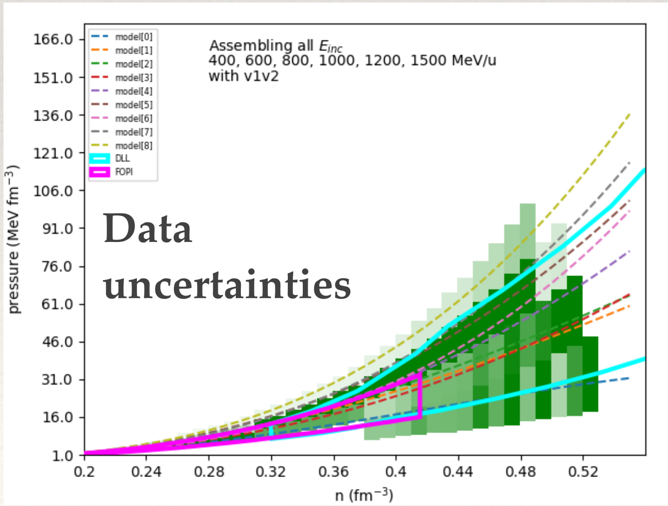
Densities from IQMD simulation:

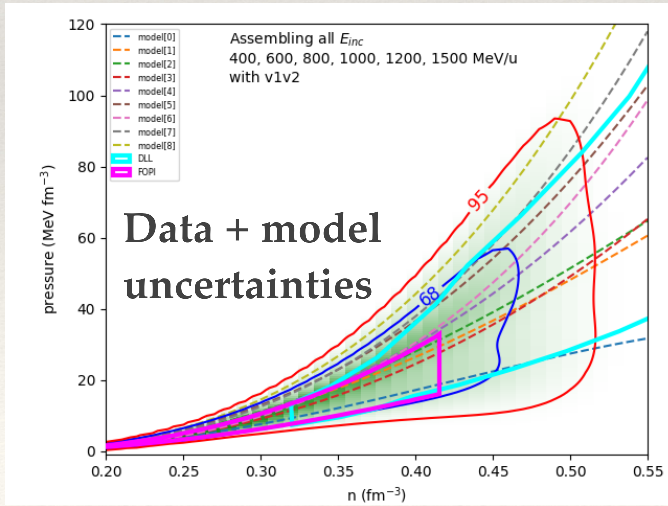


n_{max} (Einc, model)



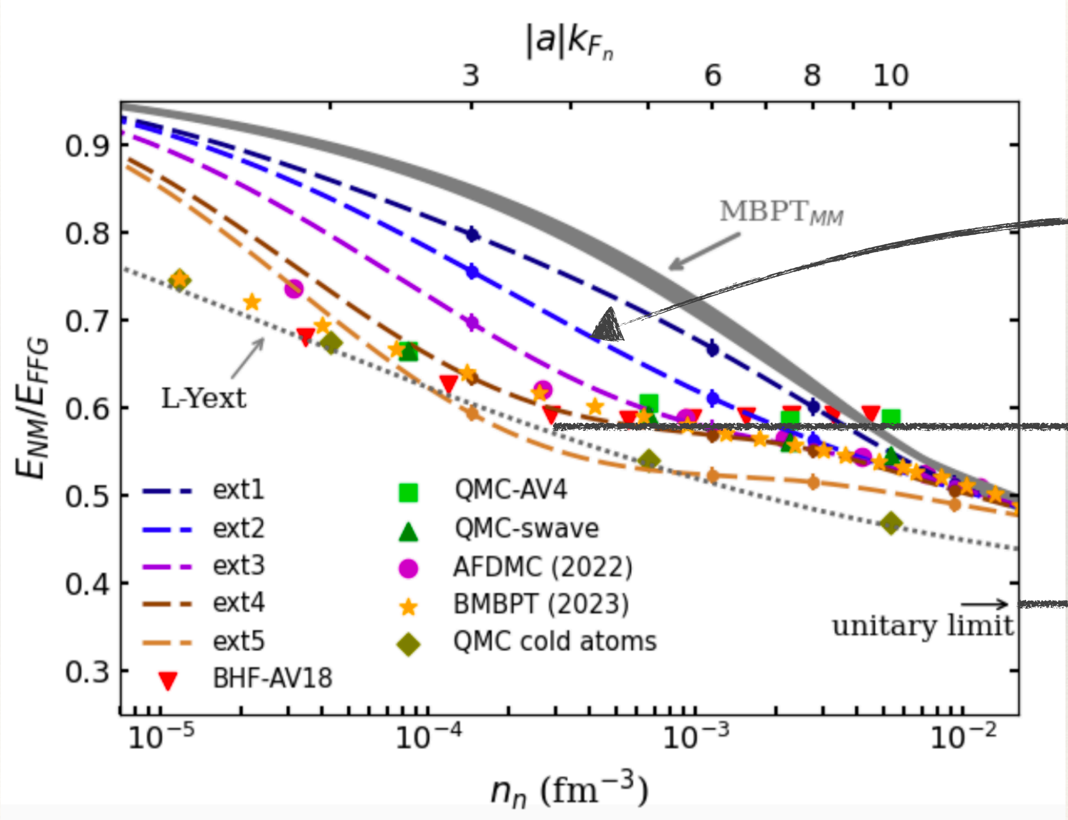
Bayesian analysis combining data and simulations with respective uncertainties:





Low densities and NS crust

Unitary limit and dilute NM



$$E = E_{HF} + E_{corr}$$

Correlations beyond HF

Dilute NM

Reduction of the correlations in NM

Unitary limit

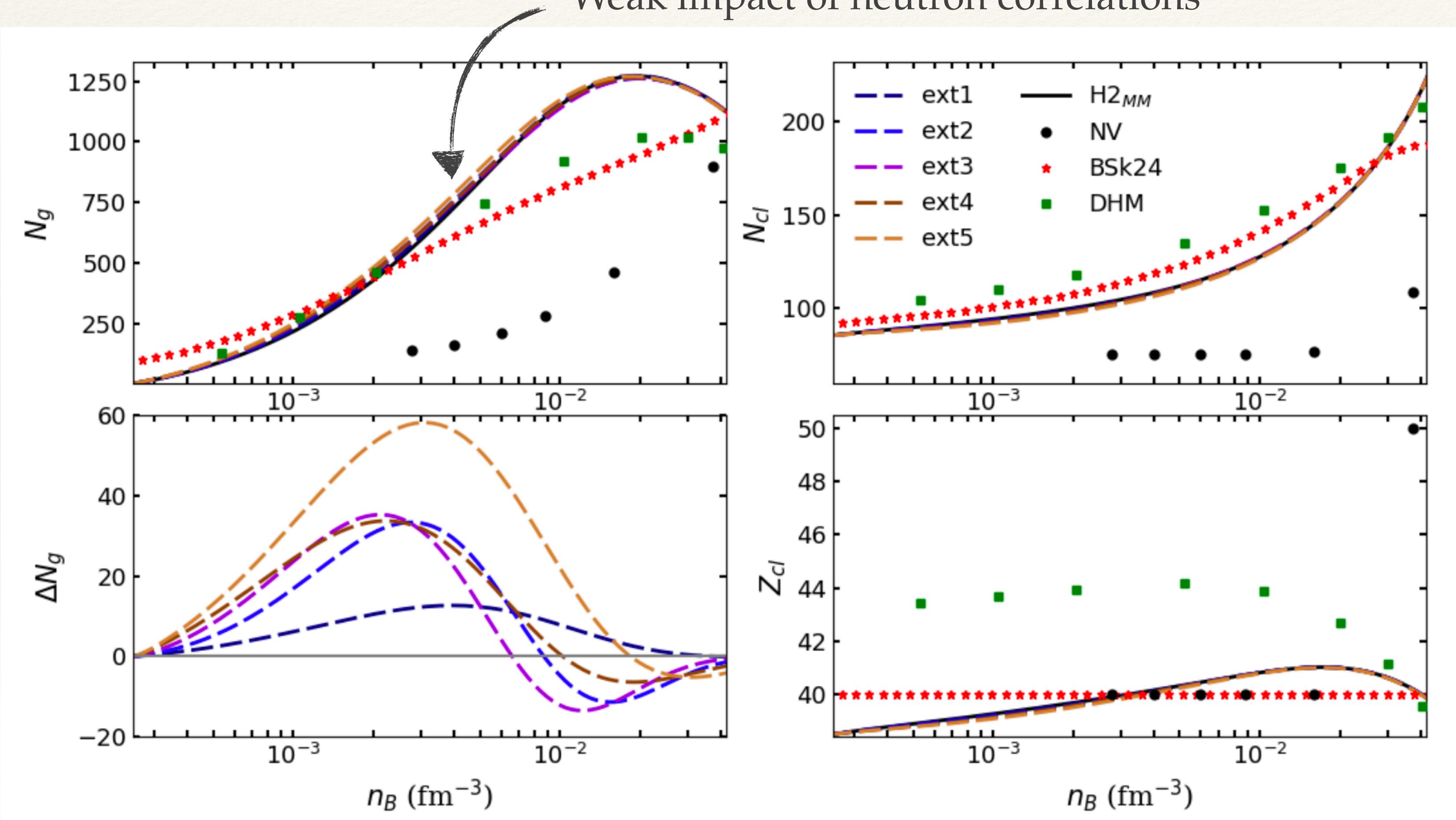
$$r_e \ll k_F^{-1} \ll |a_s| \quad \rightarrow \quad E = \xi_s E_{FFG}$$

Bertsch constant

[Grams+, EPJA 2024]

Impact for the NS crust

Weak impact of neutron correlations



In the inner-crust:

- Neutrons,
- Leptons,
- Nuclear clusters.

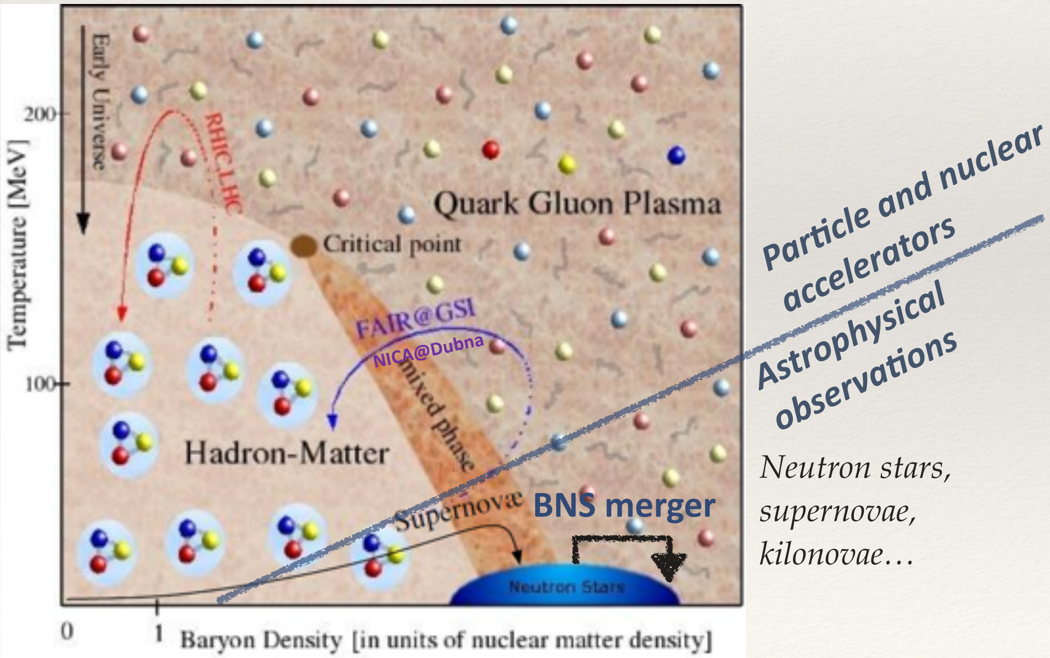
[Grams+, EPJA 2024]

Conclusions beyond the meta-modeling

From nuclear physics: ⟵ **Complementarity** ⟶ **From astrophysics:**

- Better determination of the density dependence of the EoS (Heavy ion collisions, collective motion).
- Better or new measurements of L_{sym}, K_{sym}, Q_{sat}.

- Future detections by Advanced LIGO and Virgo (O4 and O5): expect several BNS at long distance, not always with electromagnetic counterparts.
- NICER: release of new pulsars or updated analyses on existing results.



Neutron stars, supernovae, kilonovae…

It is very possible that the question of the existence of phase transition(s) in the core of neutron stars will get an answer in the next 10 years.

But, it will not necessarily be easy since:

- The properties of neutron star core at the densities above n_{sat} are yet impossible to determine from first principle.
- Data alone may not be accurate enough (despite tremendous progress in nuclear experiments and astrophysical observations).

Future discoveries require :

- reliable model(s) for dense matter,
- new data with improved accuracy,
- and an efficient way to combine data and model together.