Modeling of Phase transitions in Neutron Stars

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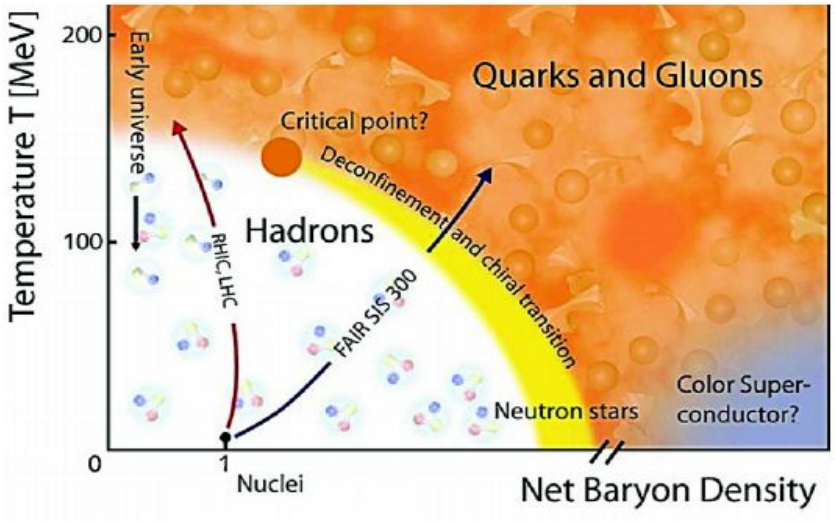
Outline

- Introduction to phase transitions in the inner cores of NSs
- Agnostic modeling of the signatures of phase transitions and confrontation with data.
- The impact of perturbative QCD in the inference of the EoS.



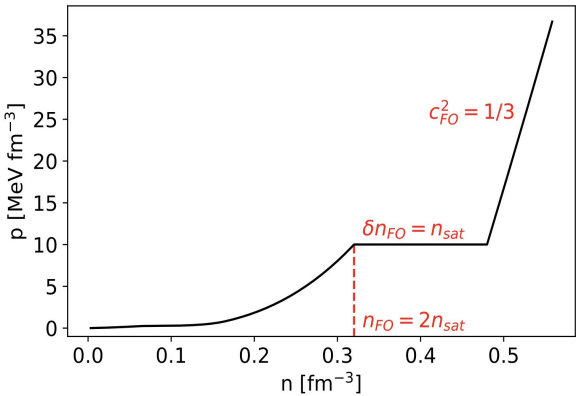
From http://nsmn1.uh.edu/cratti/

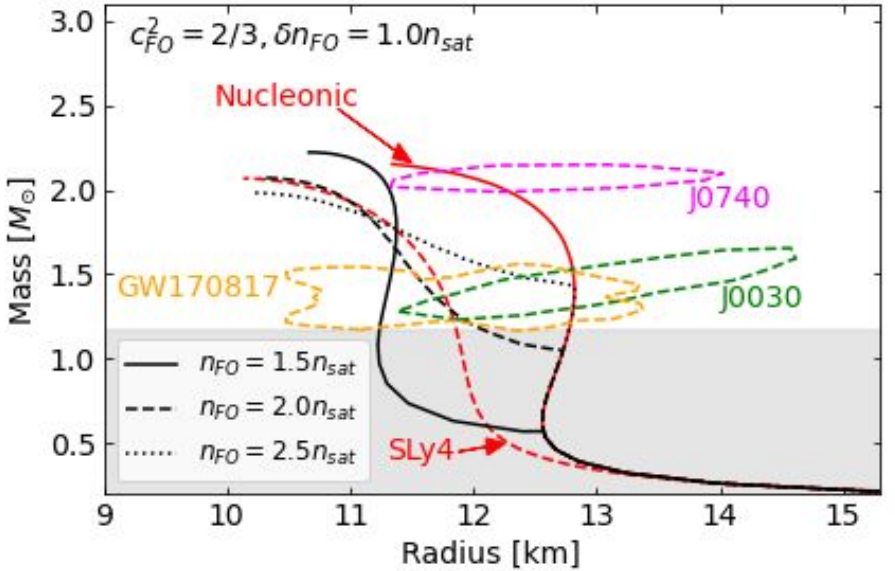
Possible Phase transitions in Dense matter

- Studies of Phase Transitions (PTs) to deconfined quark matter in NSs have a very long history.
- Often, First-Order Phase Transitions (FOPTs) are considered.

In FOPTs, the energy density undergoes a discontinuity. This can produce kinks in NS Mass-Radius curves.

FOPTs also lead to a reduction of pressure. This usually leads to smaller radii.





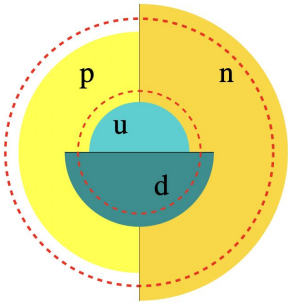
R. Somasundaram and J. Margueron, EPL 138 (2022) 1, 14002

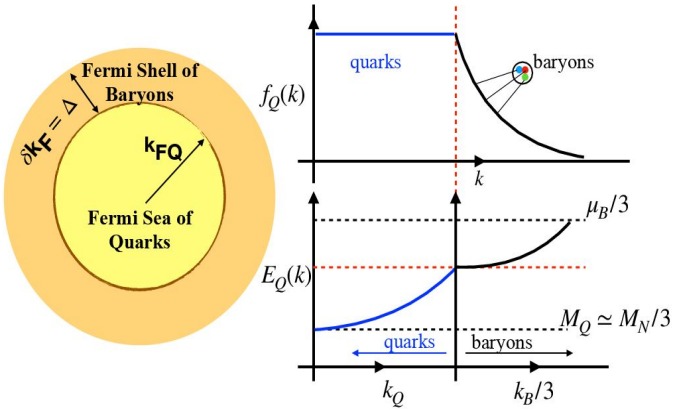
Alford et. al.,Phys. Rev. D,88(2013) 083013998.
Chamel et.al., A&A, 553(2013) A22 and Zdunik et. al., A&A,551(2013) A61.

The Quarkyonic model

It is possible that, instead of first-order phase transitions, the transition is analytic (a crossover).

- At large Fermi energies, the degrees of freedom deep inside the fermi sea can be treated as quarks.
- The strong confining interactions inside the Fermi sea are Pauli-blocked.
- Nucleons emerge through correlations between quarks at the Fermi surface, and occupy a shell.

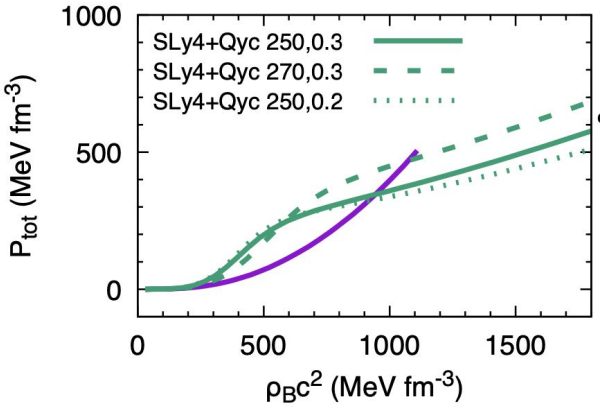




$$n_B = n_n + \frac{k_{Fd}^3 + k_{Fu}^3}{3\pi^2}$$

$$k_{FQ} = \frac{k_{FB} - \Delta}{N_c}\Theta(k_{FB} - \Delta)$$

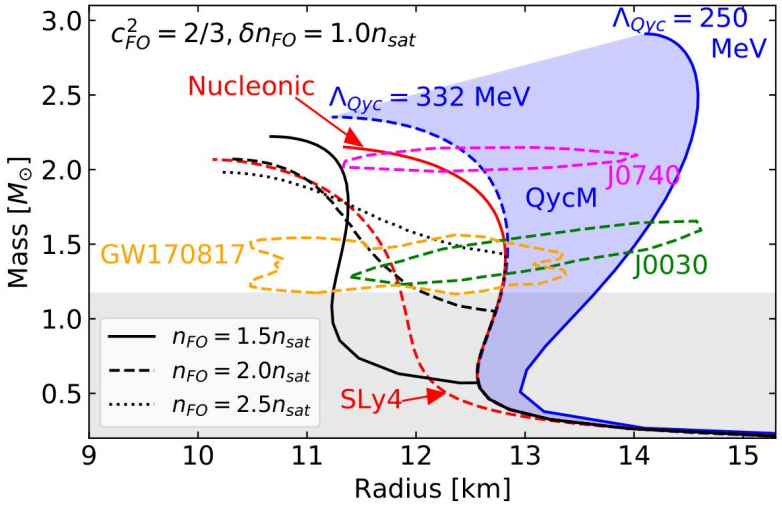
$$c_s^2 = \frac{n}{\mu\ dn/d\mu}$$

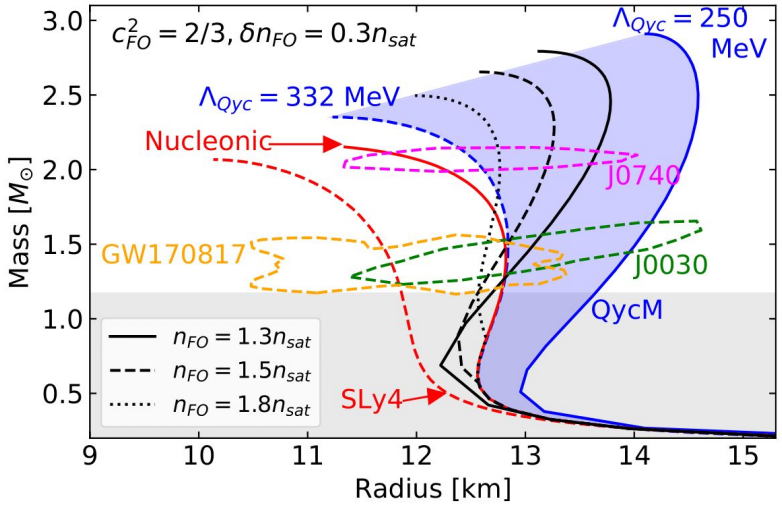


Margueron et. al., PRC 104 (2021) 5, 055803

McLerran, et. al., Phys.Rev.Lett. 122 (2019) 12, 122701

The M-R landscape revisited





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We see that Qyc produces larger radii.

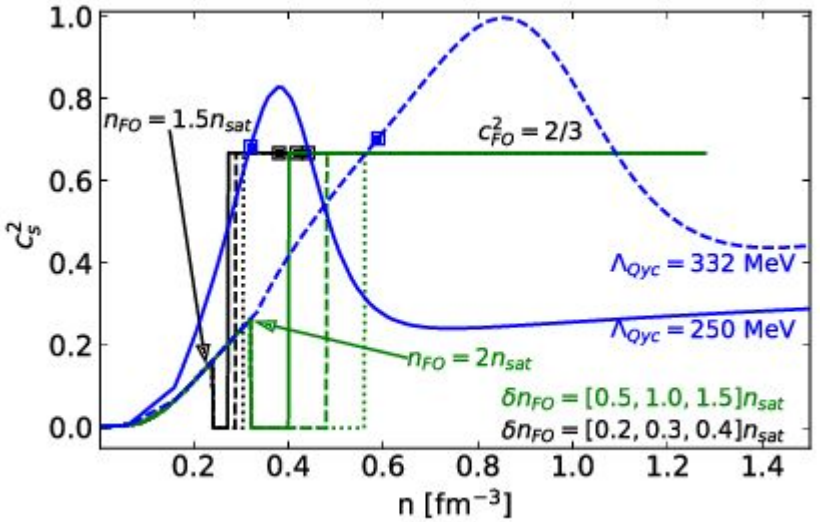
But FOPTs can mascarade this behaviour.

Do NSs observations provide evidence for Phase Transitions?

NS observations can constrain the EoS, but is there an ‘Order Parameter’ we can look at to detect phase transitions?

$$c_s^2 \equiv \frac{\partial p}{\partial \epsilon}$$

- A change in the degrees of freedom can induce non-trivial structures in the sound-speed.
- In FOPTs, the sound-speed discontinuously drops to 0.
- In the Quarkyonic model, the sound-speed (typically) exhibits a bump.



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Do such structures exist?

We chose to vary the sound-speed in an arbitrarily random manner to see which EoSs satisfy observations .

Based on the slope of the sound speed, we classified the EoSs into three groups:

Group 1: $c'_{max} < 3c'_{sat}$

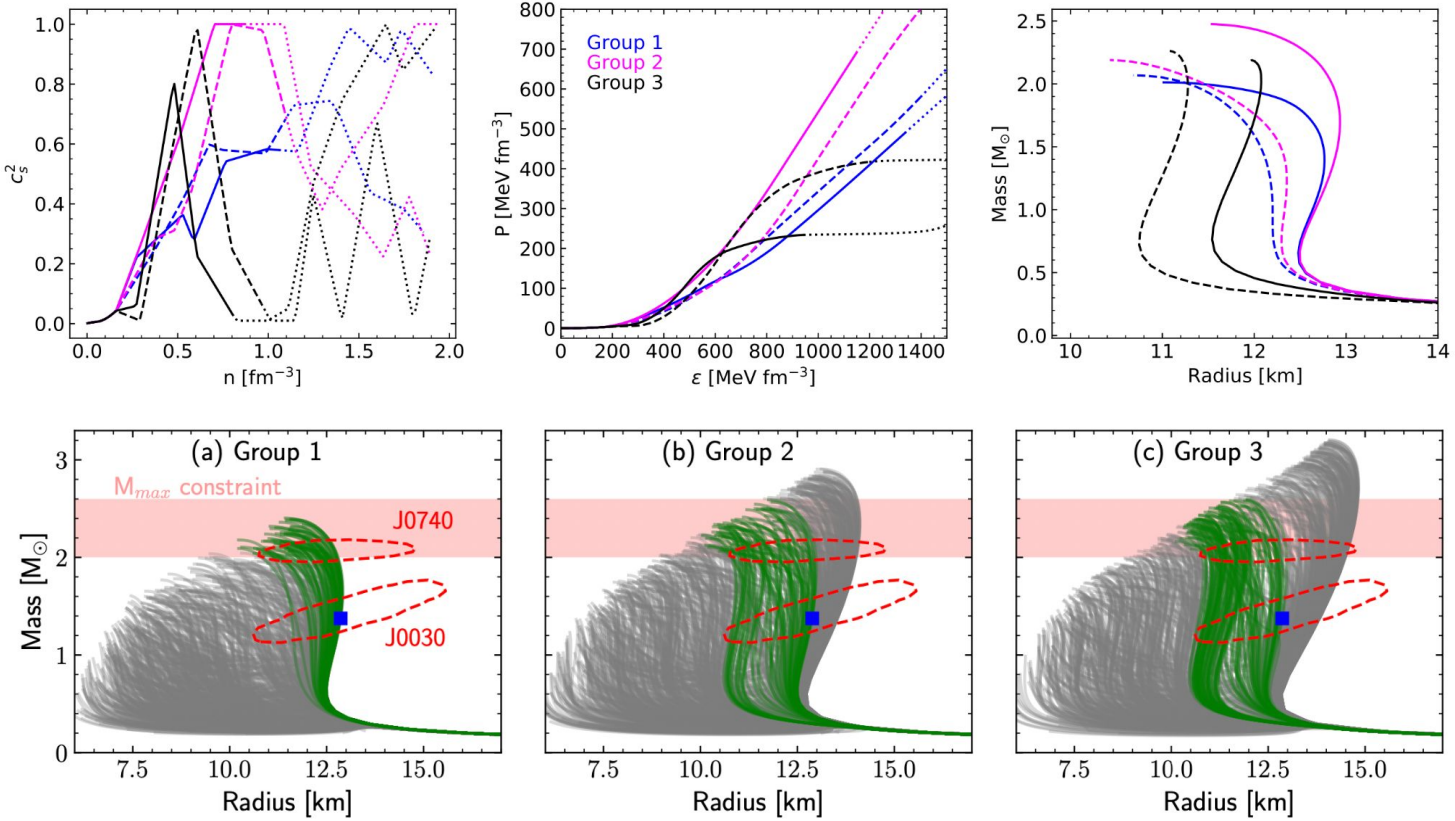
Group 2: $3c'_{sat} < c'_{max} < 6c'_{sat}$

Group 3: $6c'_{sat} < c'_{max} < 9c'_{sat}$

The sound-speed can be used to construct the M(R) curves.

We created tens of thousands of EoSs.

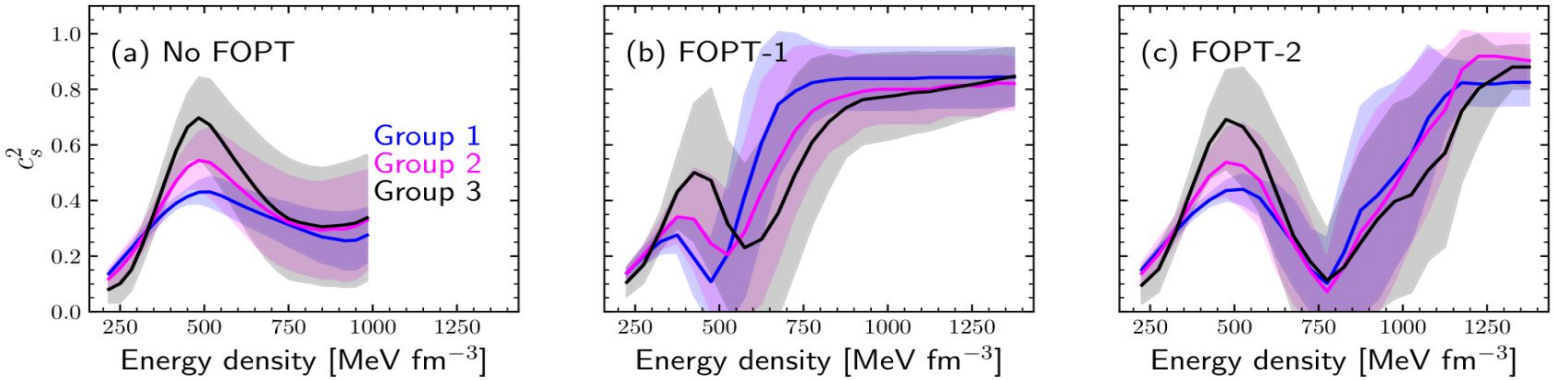
We implement NICER, GW170817, and radio observation of heavy pulsars.



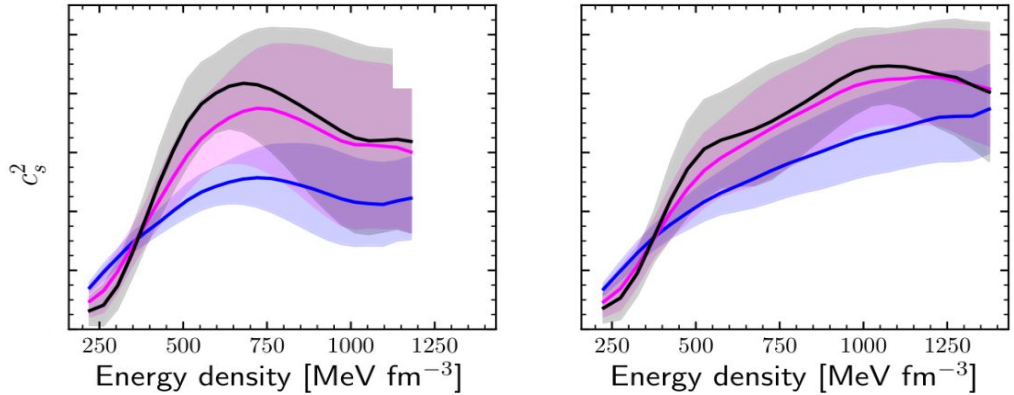
R. Somasundaram, I. Tews and J. Margueron, arXiv:2112.08157

This is what we observed for the EoSs that survived NS observations. We find cases which resemble PTs.

ε_t = [400,600] MeV fm^{-3} ε_t = [600,800] MeV fm^{-3}



But there are others which do not.

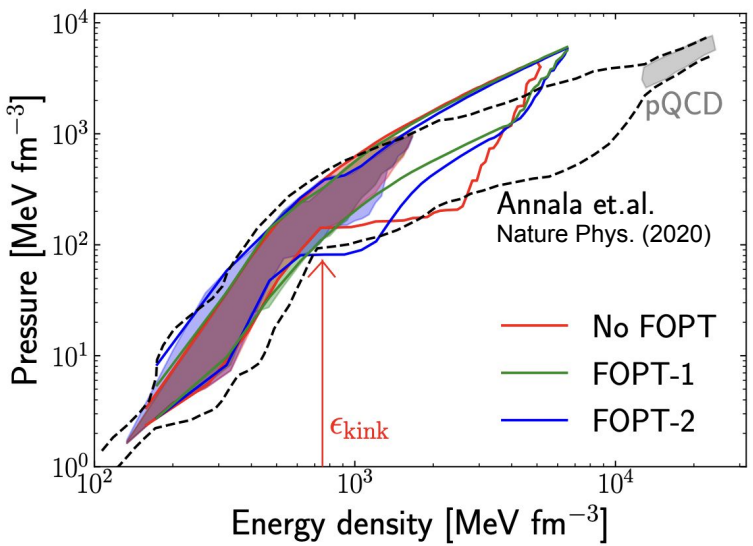


In conclusion, present astrophysical data are consistent with the nucleonic hypothesis as well as the existence of phase transitions.

However, with more data expected in the near future, this could change soon.

R. Somasundaram, I. Tews and J. Margueron, arXiv:2112.08157

Results for the Equation of State



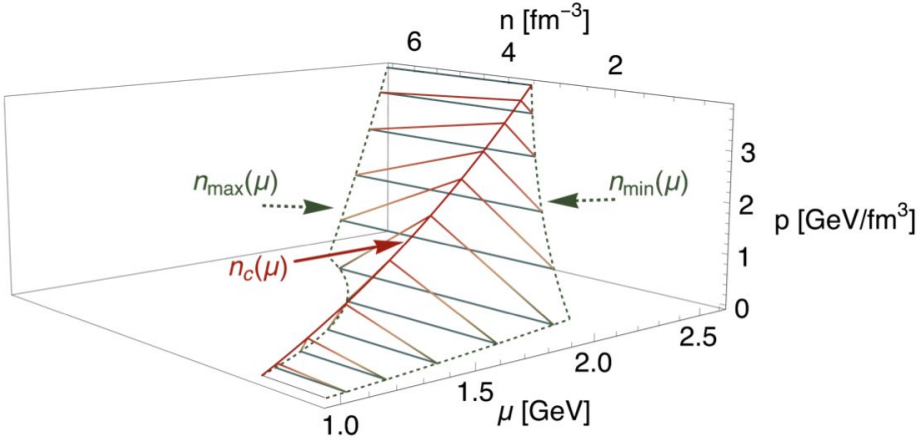
R. Somasundaram, I. Tews and J. Margueron, arXiv:2112.08157

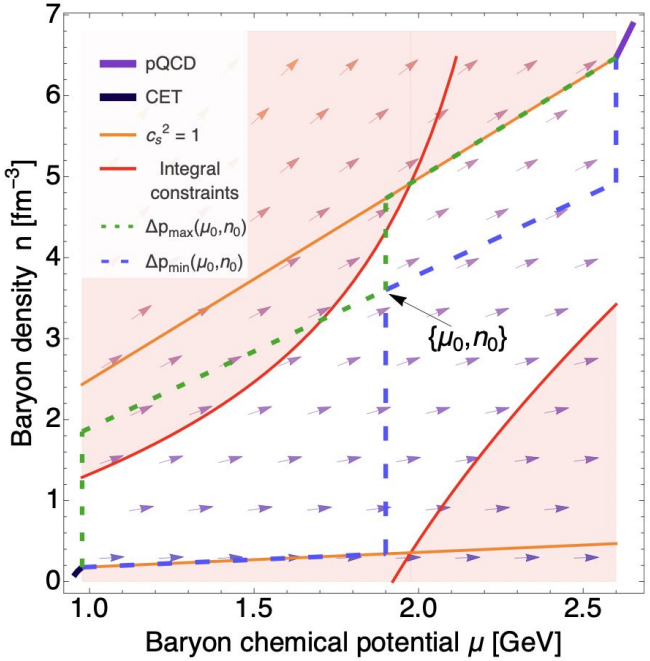
- Our results for the EoS of stable NSs, are consistent with Annala et al.
- However, Annala et al. claim that their analysis provides evidence for the existence of quark matter in NSs.
- This discrepancy might be due to their inclusion of ab-initio perturbative QCD calculations at large densities.
- Note that this generally requires extrapolation of the EoS upto ~40 n_{sat}.

Implications of perturbative QCD calculations

Recently, Kurkela et al. have developed a fully model-agnostic and analytic method to implement pQCD calculations for the inference of the NS EoS.

This is done by requiring consistency of pressure, density and chemical potential.





O. Komoltsev and A. Kurkela, Phys.Rev.Lett. 128 (2022) 20, 202701

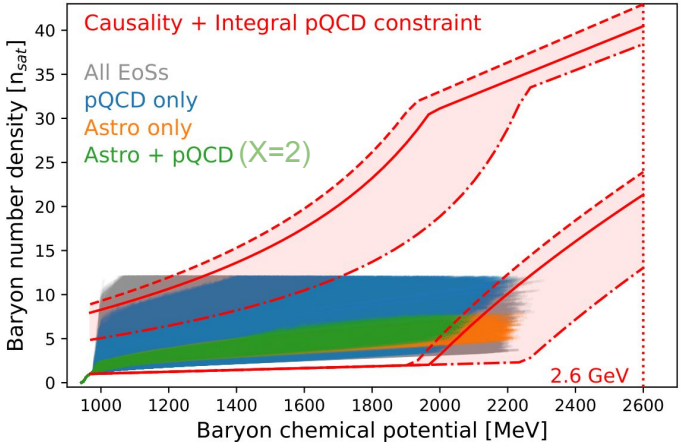
Implications of perturbative QCD calculations

We find an interesting interplay between NS observational data and pQCD: the former ‘requires’ stiff EoSs which are rejected by the latter.

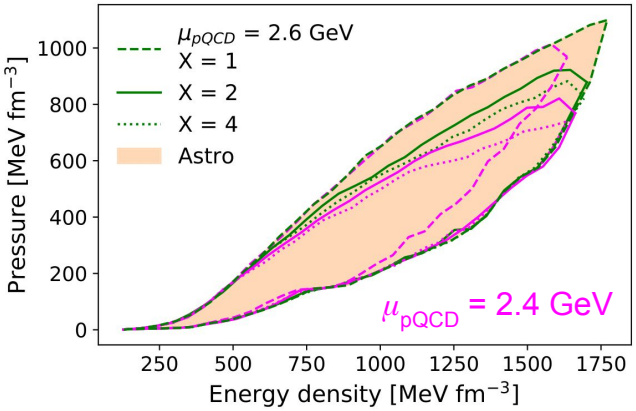
Uncertainties in the pQCD EoS can be estimated by varying the RG scale X.

We found pQCD to be constraining if X>1.3

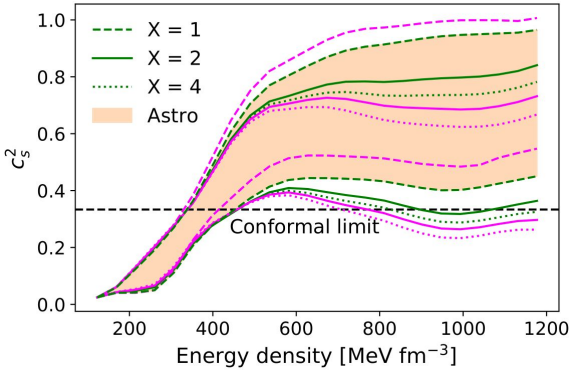
Clearly, pQCD has the potential to determine the existence of quark matter in NSs.



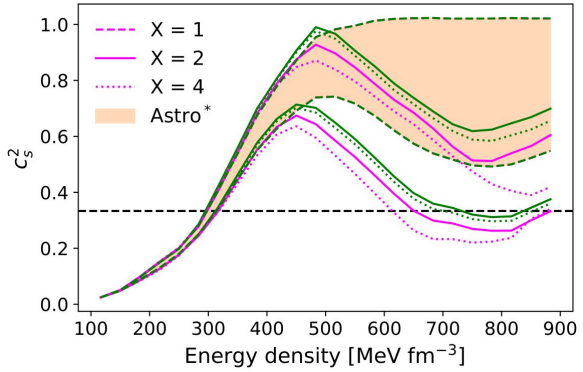
$$\Lambda = X\mu_B/3$$



Present astrophysical data (Astro)



Astro + R_2 > 13 km



Conclusion

- We explored two kinds of phase transitions: a first-order phase transition and a crossover to quarkyonic matter. We showed that one can realistically masquerade the other in the M-R plane.

- Using an agnostic approach to the speed of sound, we concluded that present astrophysical data do not determine the existence of phase transition in NSs.

- We finally showed that pQCD calculations have the potential to be very powerful in the inference of the NS EoS.