INT workshop on « The r-process and the nuclear EOS after LIGO-Virgo's third observing run », May 24, 2022

Confronting neutron star equation of state to present observational data

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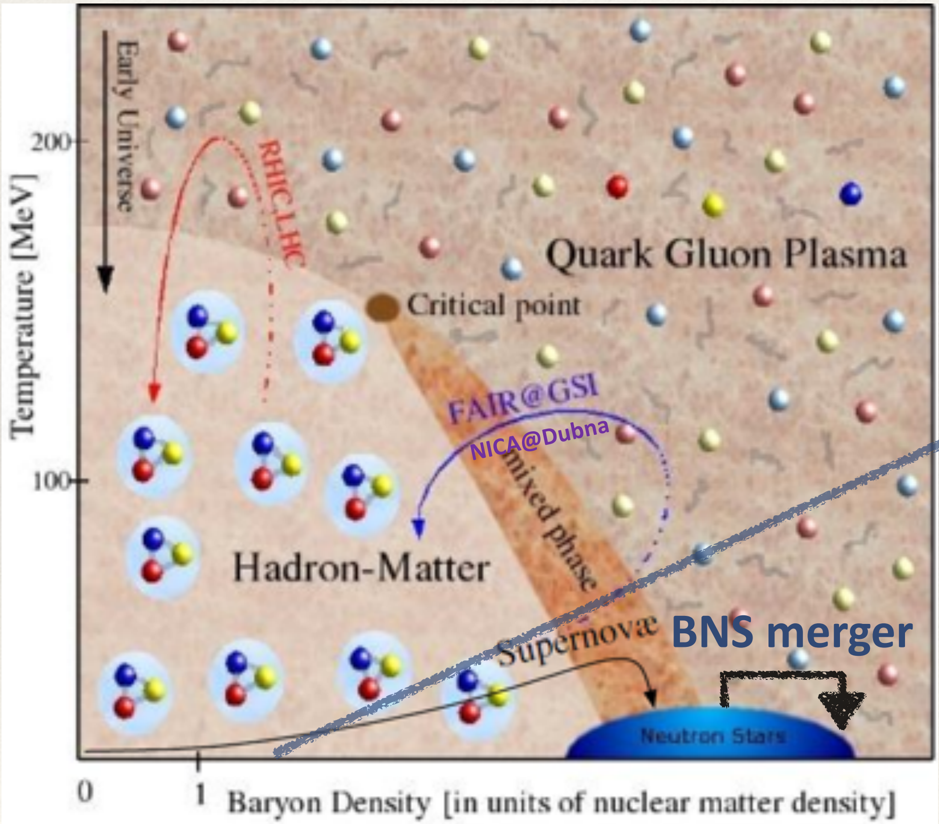
+ collaborators

I: Investigation of dense matter phase transitions
II: Impact of the crust.

Probing extreme matter

Main questions: How changes the **nuclear interaction** with density, isospin asymmetry, temperature?
Which **new particles** appear at supra-saturation densities (phase transition)?
Links between **deconfinement** and **chiral symmetry** restoration?

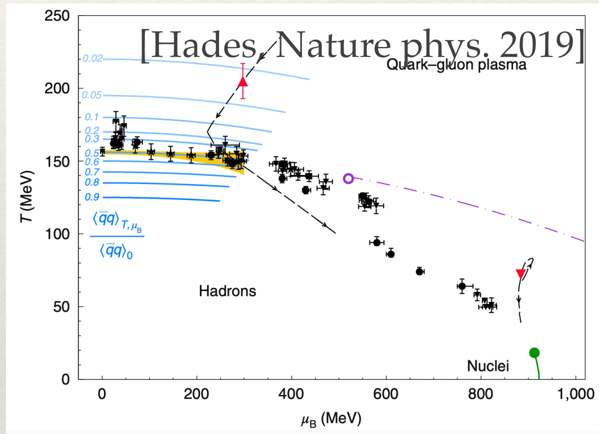


Particle and nuclear accelerators

Astrophysical observations

Neutron stars, supernovae, kilonovae…

Heavy Ion collision



Probe limits of extreme matter

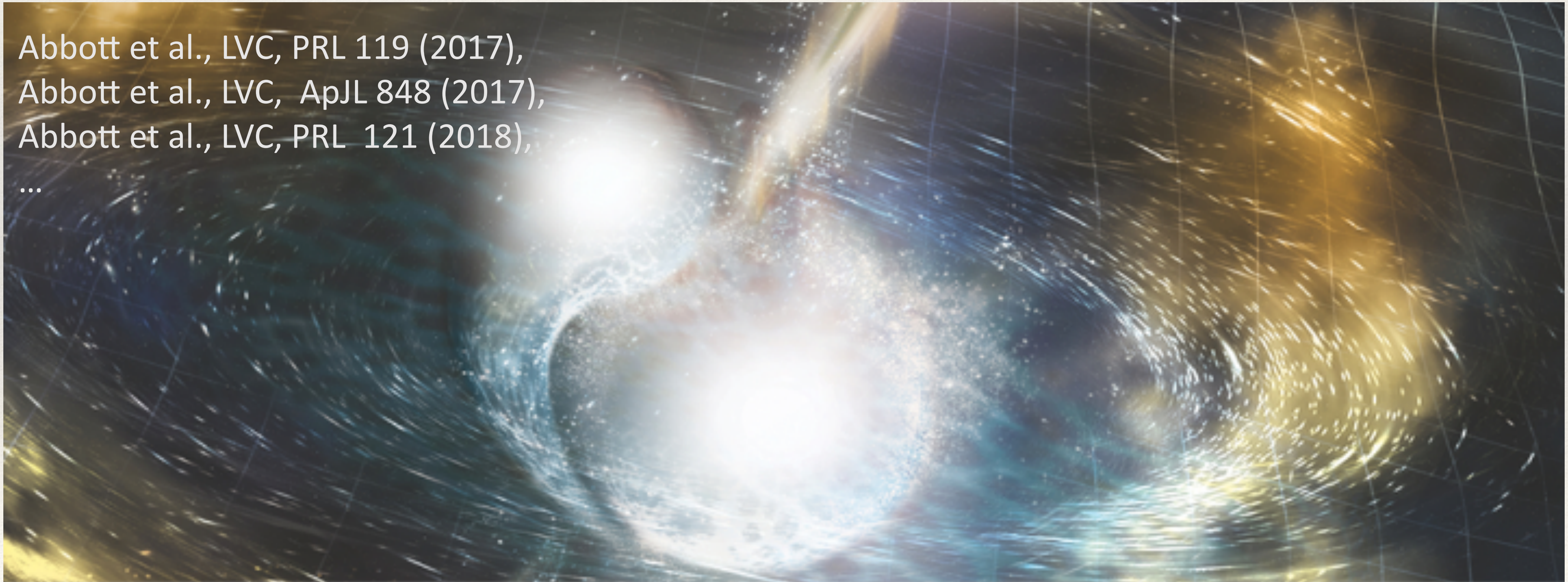
Directly related questions: How **neutrinos** propagate? What are the **transport properties** of extreme matter?
Are BNS the main astrophysical site for the **r-process**?

LIGO-Virgo GW observatory

2015: first detection of GW from BBH (O1).

2017: first detection of GW from BNS (O2). → gravity and cosmology, dark matter and dark energy, **dense matter.**

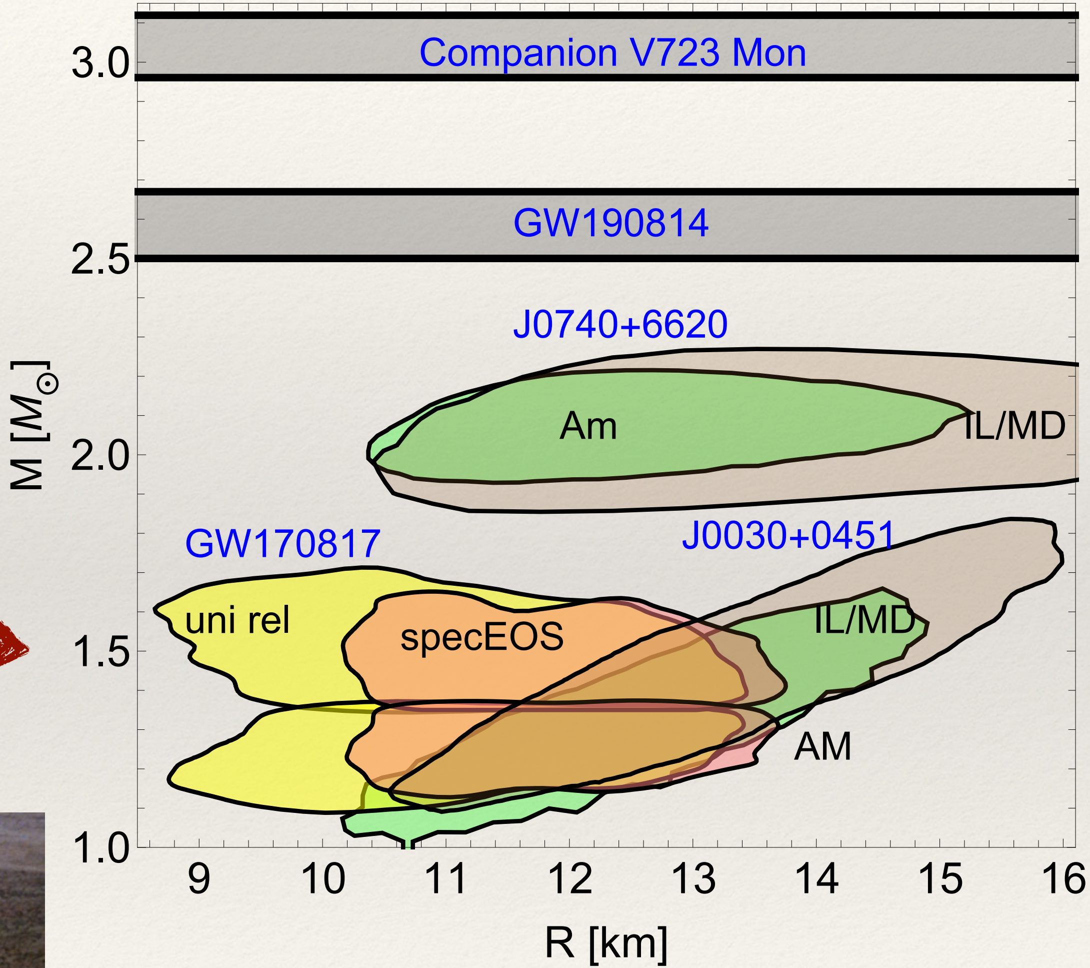
2019: first detection of GW from BHNS (O3).



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

+NICER X-ray observatory

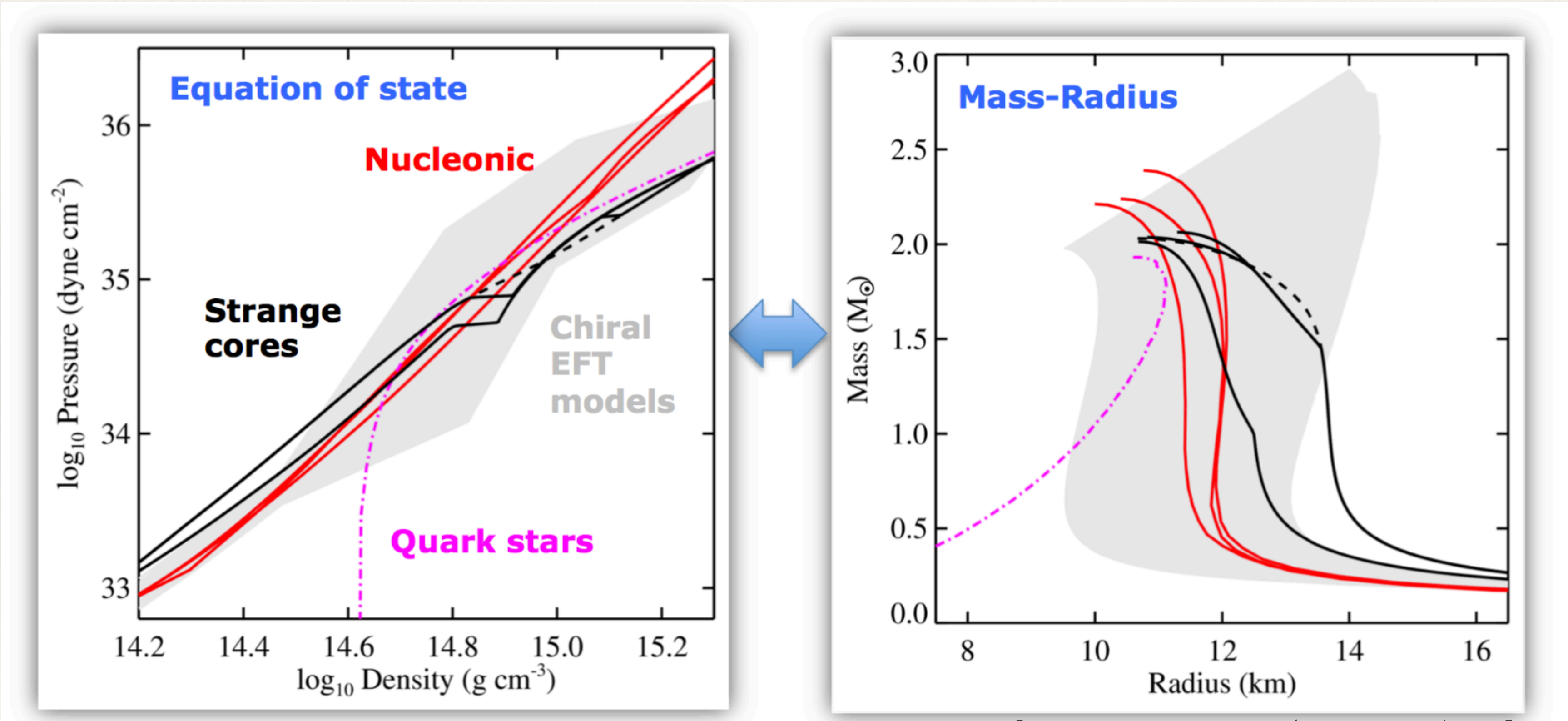
Tan, Dore, Dexheimer+ arXiv:2106.03890[astro-ph.HE]



EoS [nuclear] <=> NS (M,R) [astro]

Tolmann-Oppenheimer-Volkov (TOV) GR equations

P(n) → (M,R)(n_c)



[A. Watts et al., PoD (AASKA 14) 043]

Reverse engineering,
Bayesian statistics

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

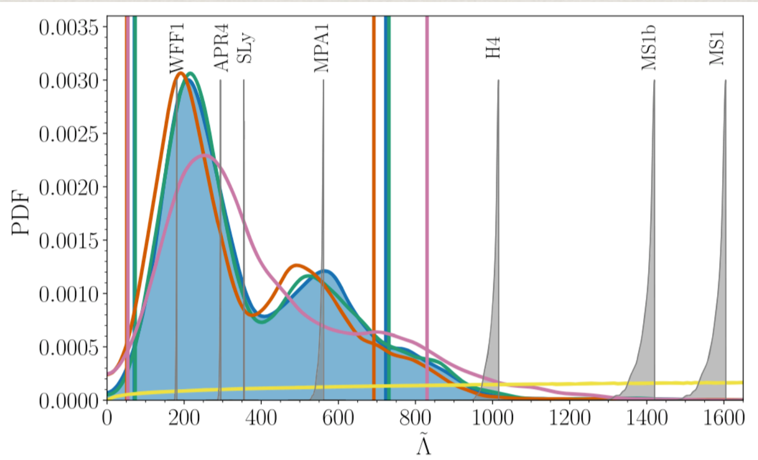
- Tidal field E_{ij} from companion star induces a quadrupole moment Q_{ij} in the NS
- Amount of deformation depends on the stiffness of EOS via the tidal deformability Λ.

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

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

Hinderer+ 2008, Blanchet, Damour

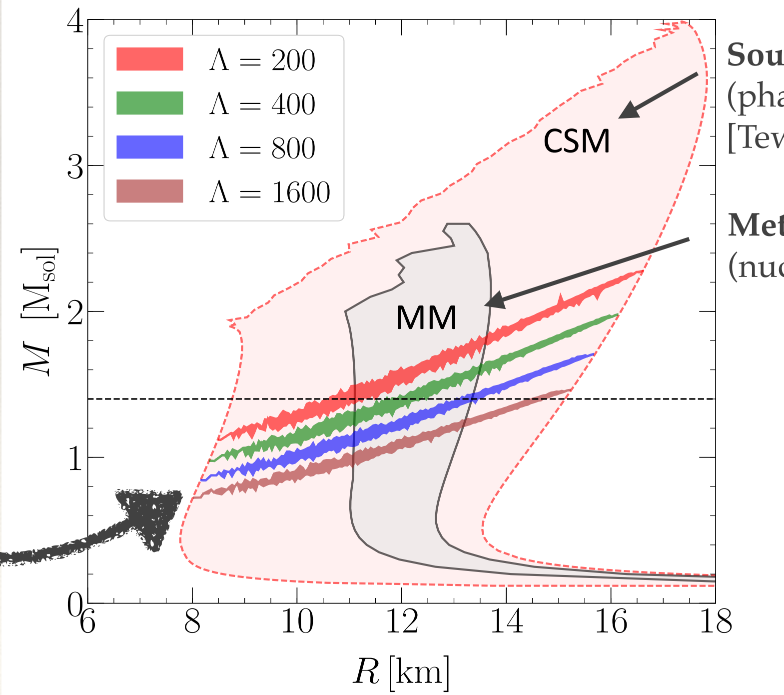
LVC, Phys. Rev. X 9, 011001 (2019)



GW170817
→ 70 ≤ Λ ≤ 720 (90% CL)
→ +E-M 300 ≤ Λ ≤ 800

Universal correlations

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

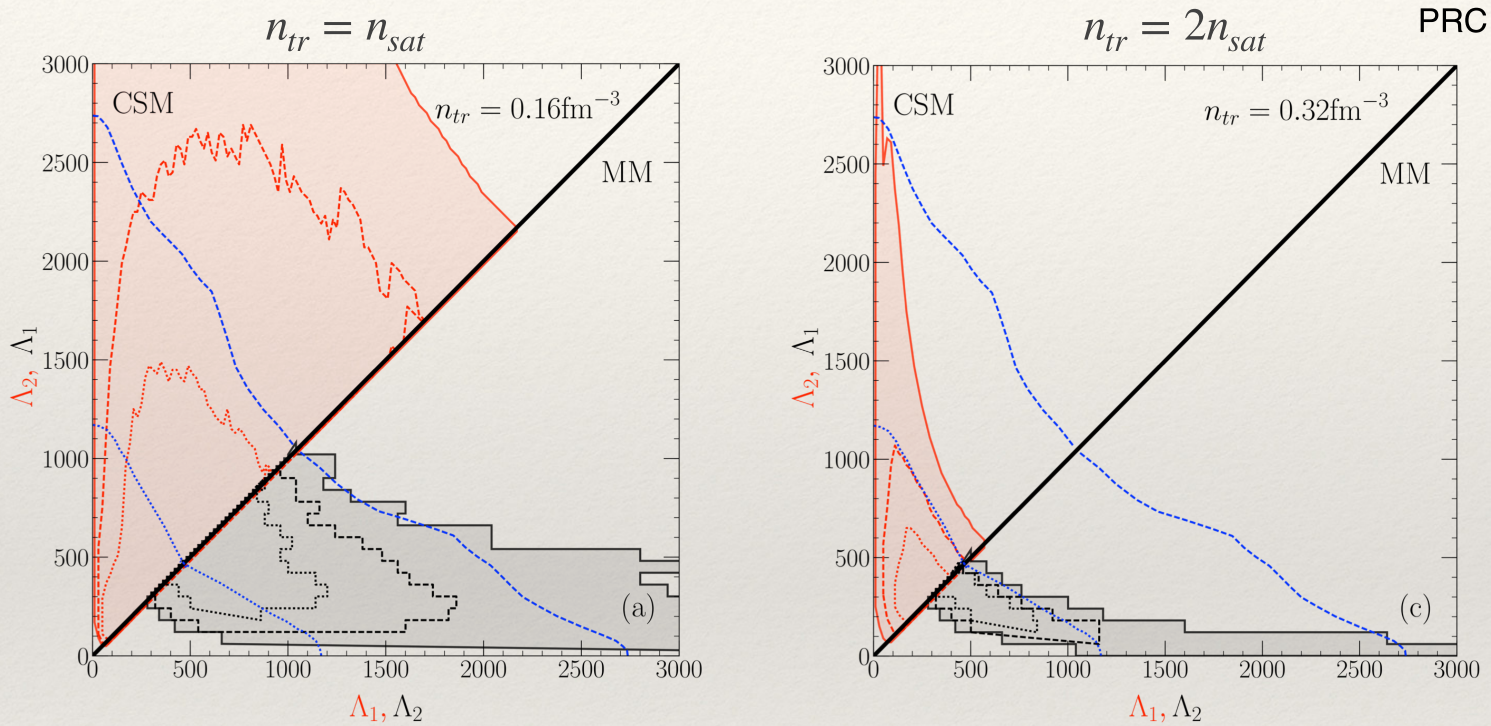


Sound-speed Model (phases transitions) [Tews+ 2018]

Meta-Model (nucleonic)

Confront EoS / GW

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



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

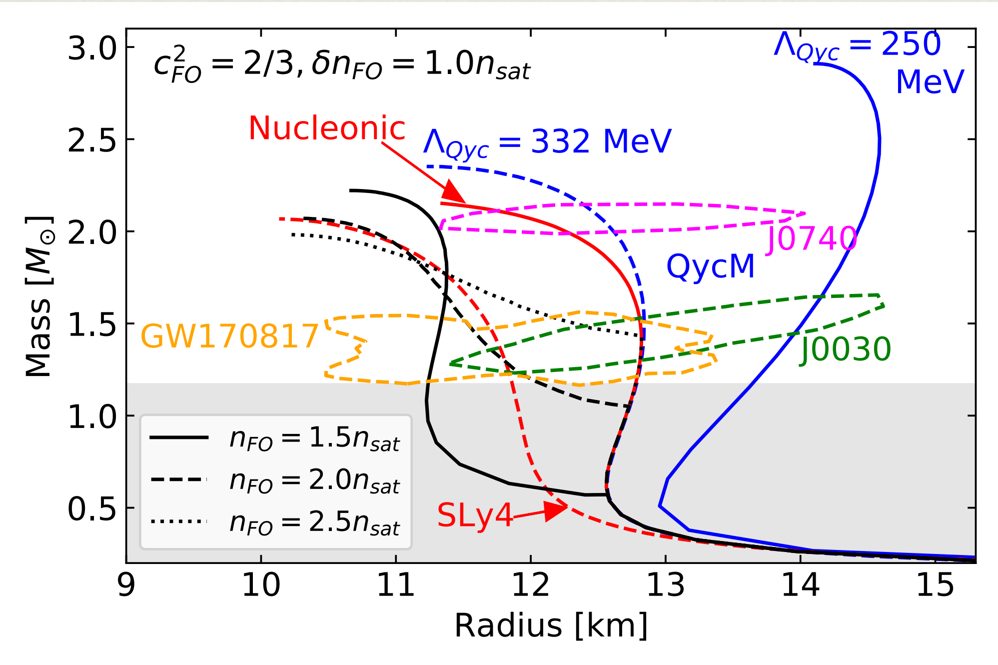
$\Delta\tilde{\Lambda} \approx$ 50-100 → Probe matter composition above $2n_{sat}$

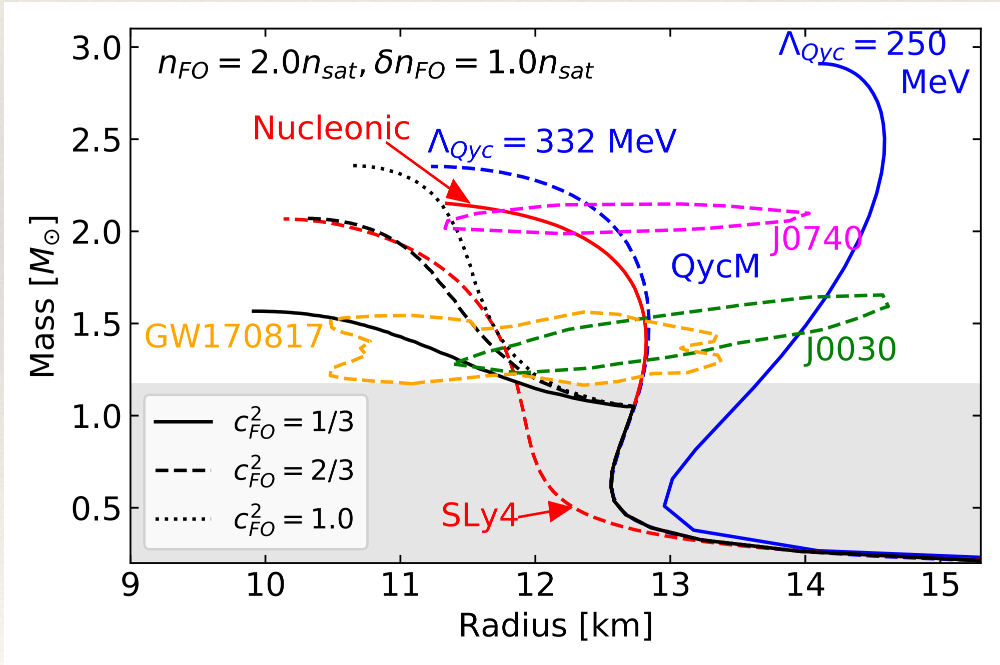
New data from LVC and NICER

Data:
GW170817 and NICER (J0030 + J0740).

EoS modelings:
- SLy4 (often used in GW papers).
- First order phase transition to exotic matter.
- Quarkyonic matter (McLerran & Reddy PRL 2020).

[Somasundaram+, arXiv 2021]





—>First order phase transition softens the EoS

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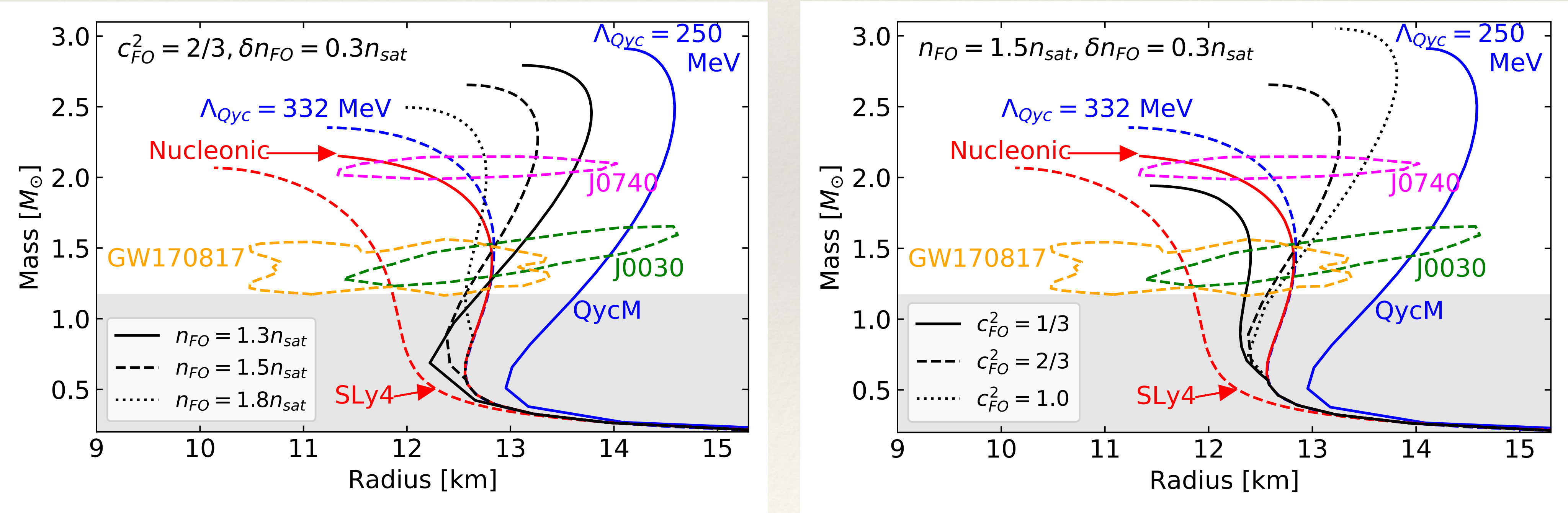
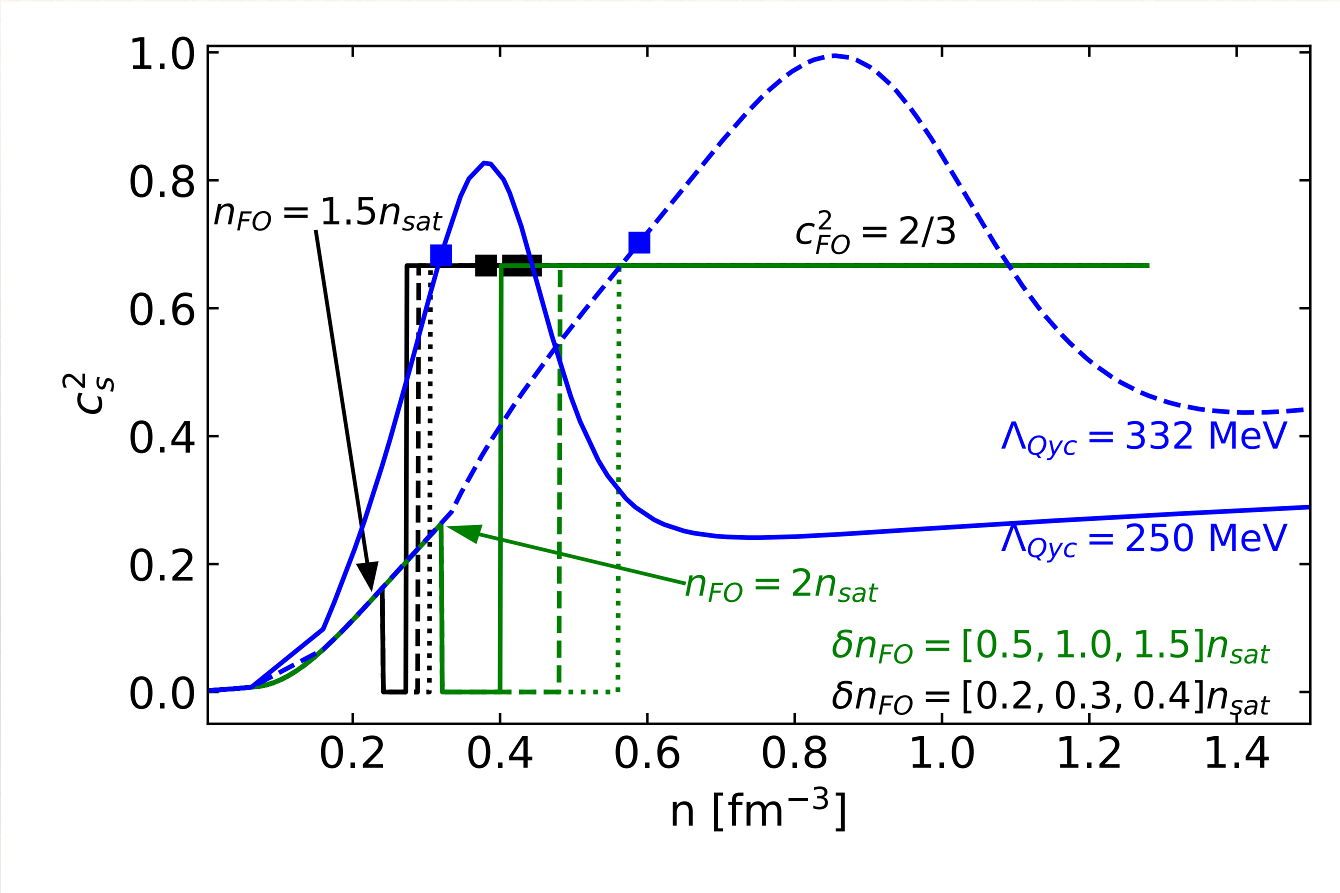


unless it occurs at low density —> masquerade Qyc

Comparison of sound speed: FOPT vs. Qyc

[Somasundaram+, arXiv 2021]

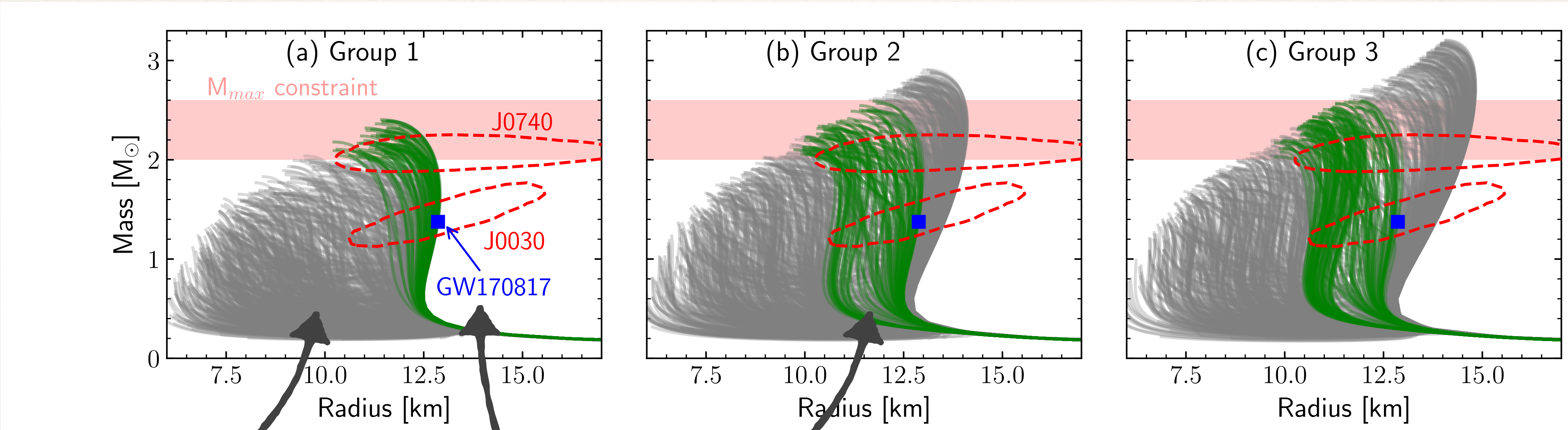


Can we learn more about the sound speed in extreme matter?

Sound speed structure from NS observations

Agnostic approach based on the sound speed approach.

[Somasundaram+, arXiv 2022]



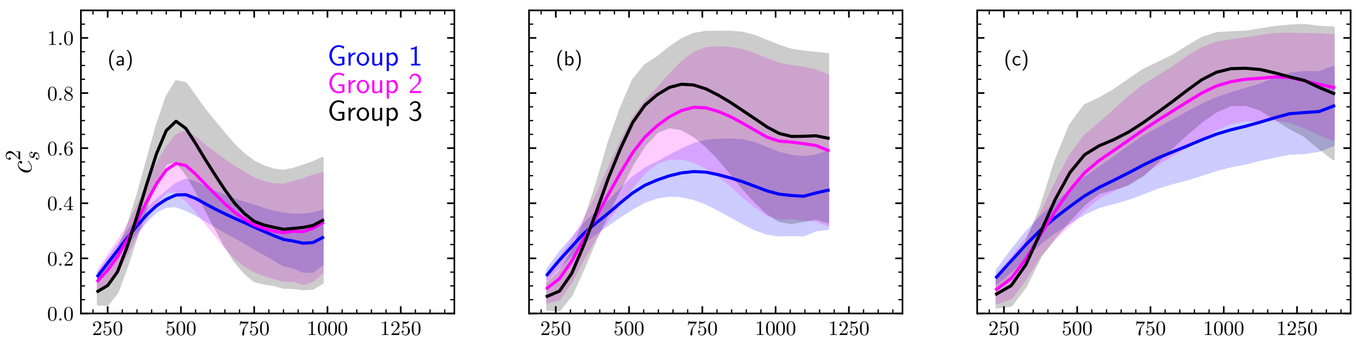
Prior

Posterior

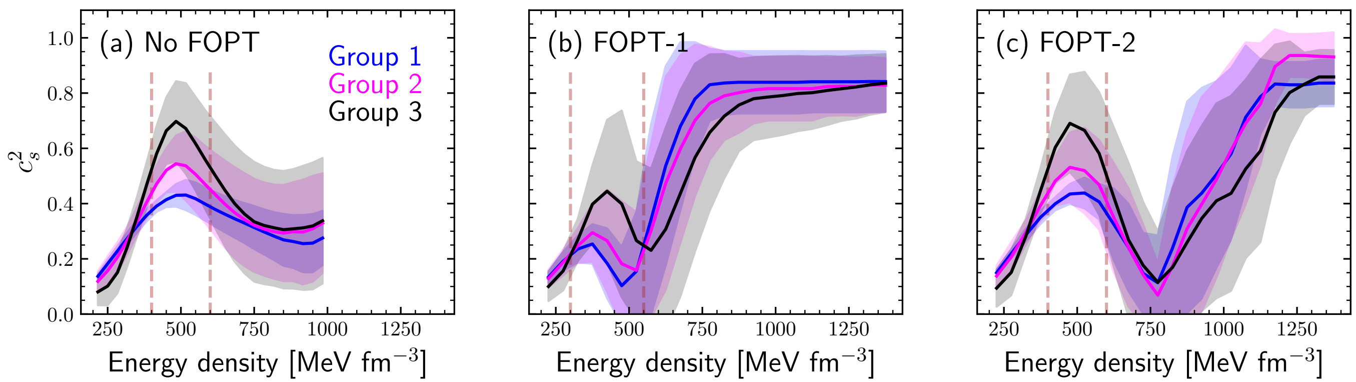
NS observations

Sound speed structure from NS observations

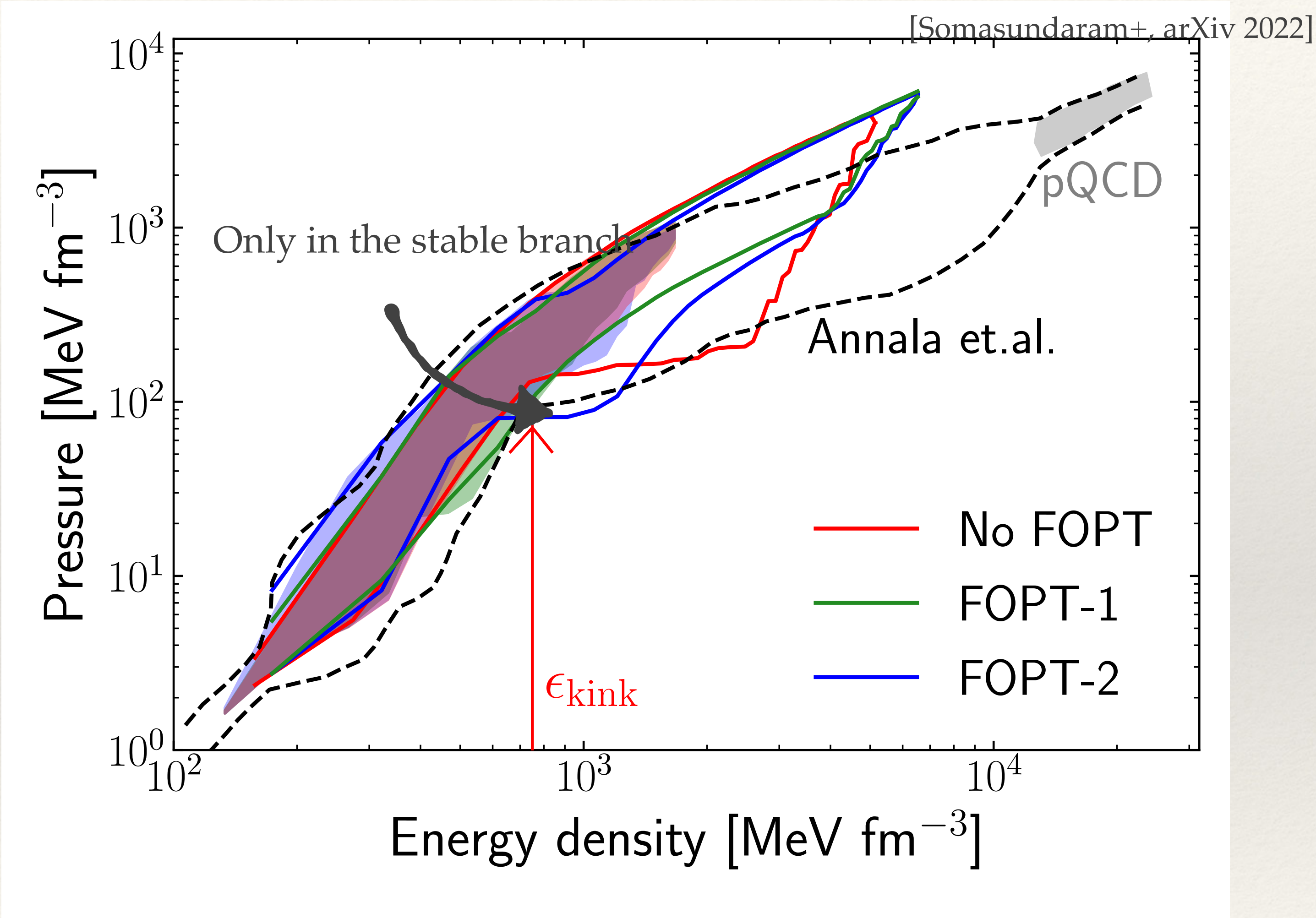
[Somasundaram+, arXiv 2022]



The groups reflect the slope of the sound speed



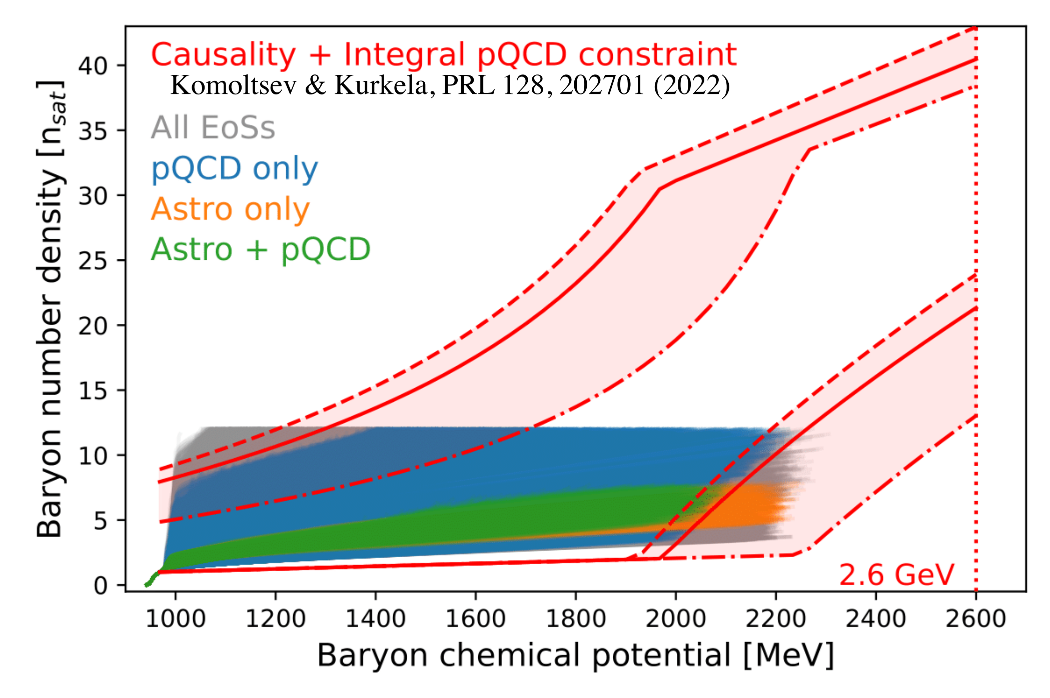
Impact on the EoS



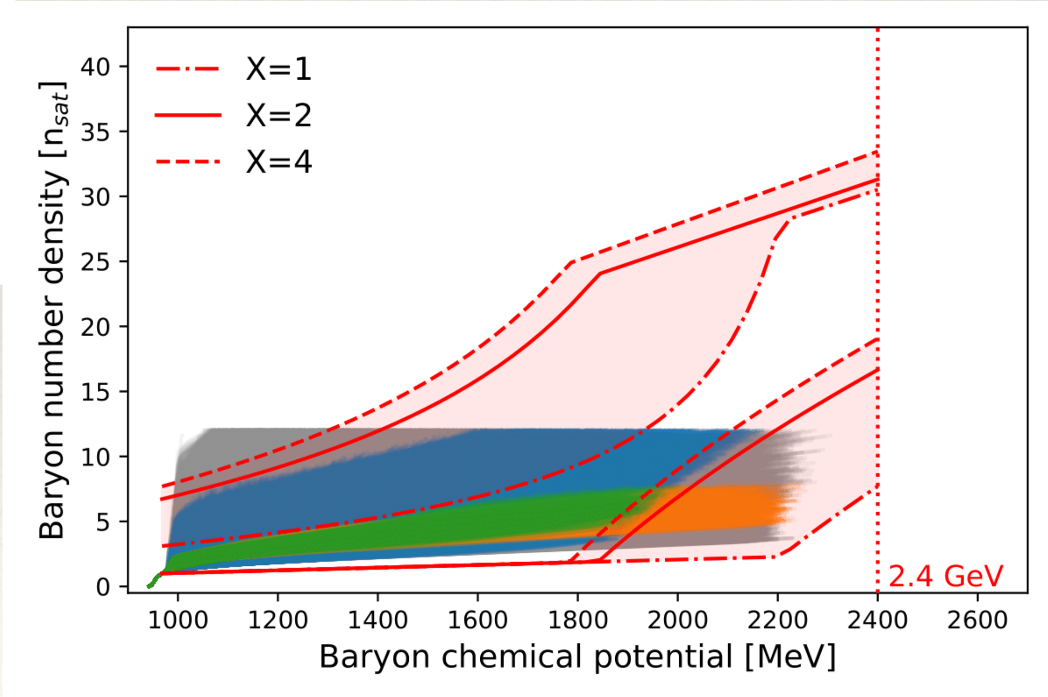
—> astrophysical information to date do not necessarily require a phase transition to quark matter.

Implication of pQCD

[Somasundaram+, arXiv 2022]

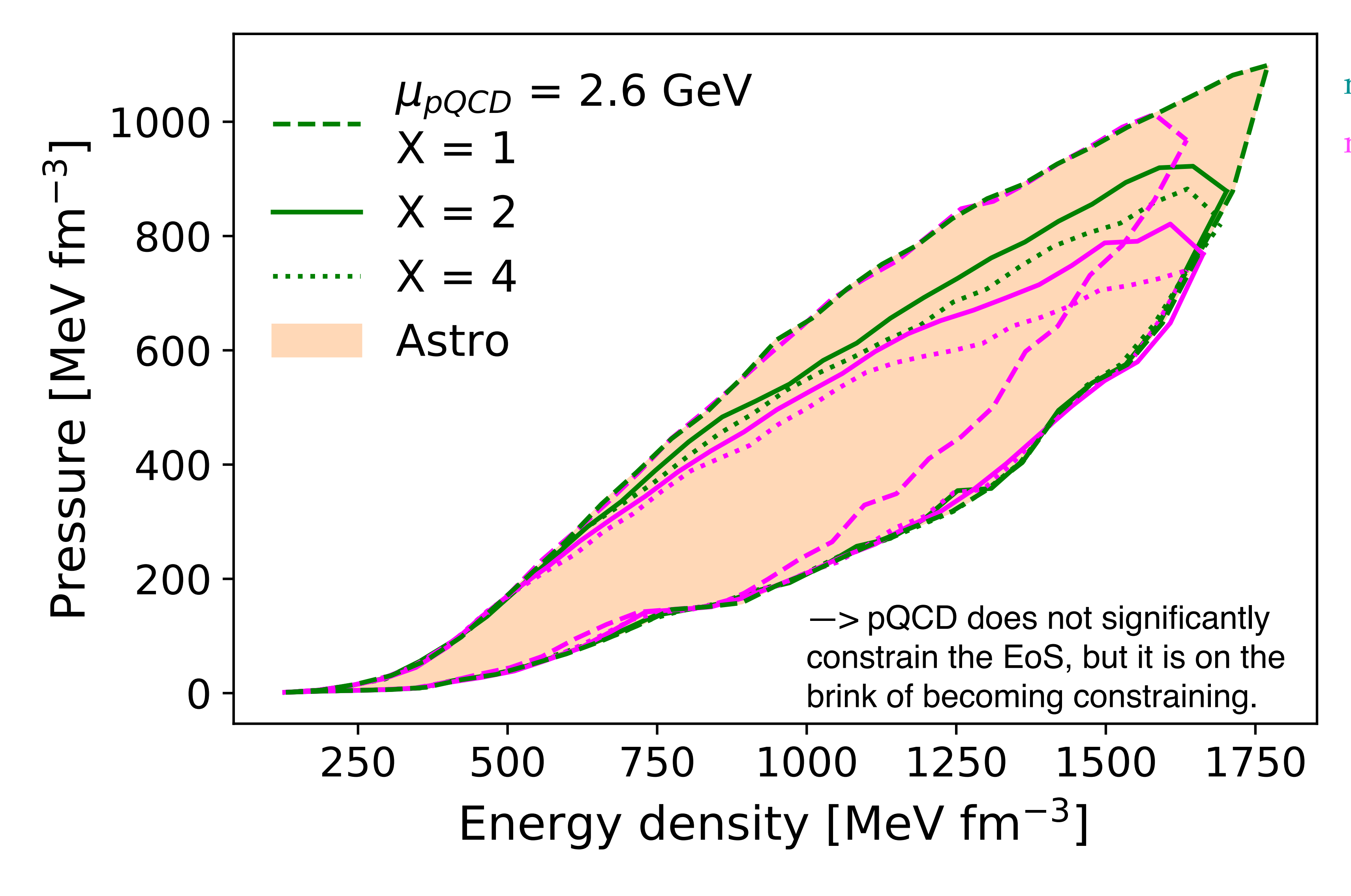


Sensitivity analysis:
Varying mu_pQCD
Varying internal cut-off



Impact on the EoS

[Somasundaram+, arXiv 2022]



mu_pQCD=2.6 MeV

mu_pQCD=2.4 MeV

Conclusions and outlooks

Neutron star observations have recently entered into the age of accurate measurement of neutron star size extension.

ex.: radius, tidal deformability, moment of inertia.

—> it gives hope to constrain more accurately the dense matter EoS.
—> by combining theoretical and observational contraints.
—> + requires good understanding of the uncertainties originating from the crust.

New EOS (15 in total) are available on the CompOSE repository (https://compose.obspm.fr) under the name GMSR(i), with i=H1, …, SLy5, …

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