Neutron stars, a lab of particle physics

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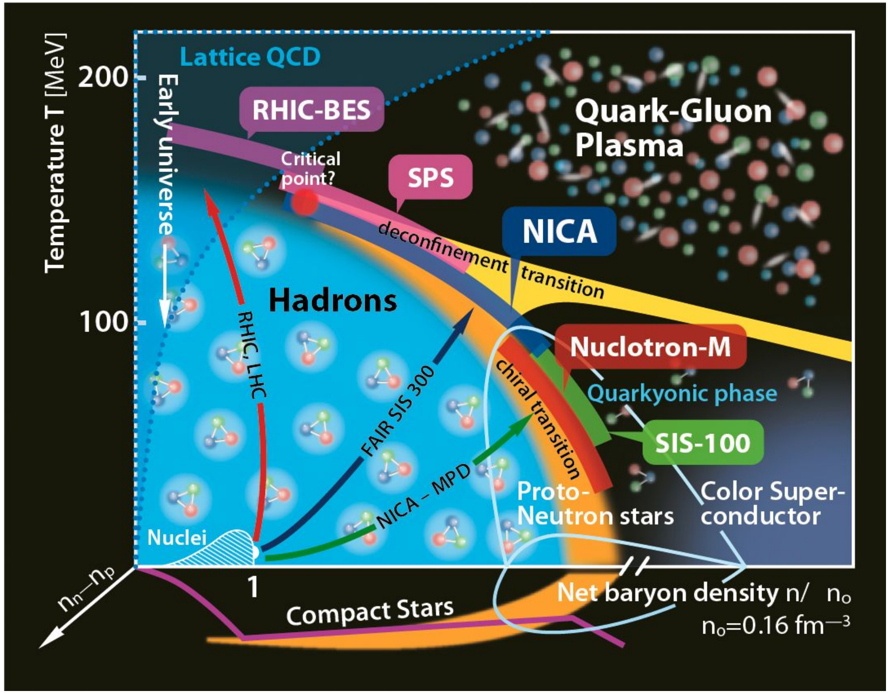
The phases of strongly interacting matter

- The theory (QCD) is solvable at low densities on a lattice (LQCD).
- The matter phases are still unknown for $n > n_0$
- Neutron stars are unique laboratories to understand QCD matter at low temperatures and high densities

$$n_0 > n > 10n_0$$

Nuclear matter around us has

$$n_0 \approx 0.16\,\mathrm{fm}^{-3} = 0.16\,\mathrm{nucleons/fm}^3$$



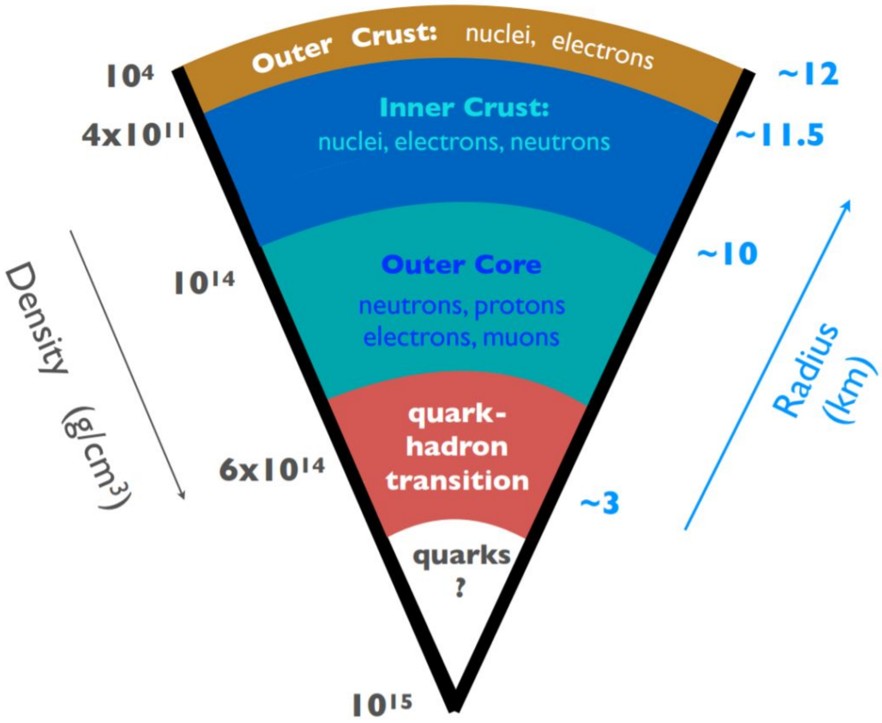
Composition of a neutron star

- The nuclear matter properties (equation of state) remain unknown for

$$\rho \gg \rho_0 \sim 2.51 \times 10^{14} \mathrm{g/cm^3}$$

- The composition in the NS core is still an open question.

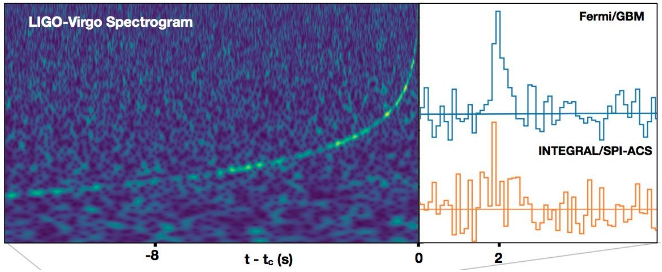
- The likelihood of each possible scenario is determined by facing its predictions with NS observations.



GW170817: a binary neutron star merger

GW170817 and gamma ray burst GRB170817A

LIGO/Virgo Collaboration - PRX9 011001 (2019)



	Low-spin prior ($\chi \leq 0.05$)
Binary inclination θ_{JN}	146^{+25}_{-27} deg
Binary inclination θ_{JN} using EM distance constraint [108]	151^{+15}_{-11} deg
Detector-frame chirp mass $\mathcal{M}^{\rm det}$	$1.1975^{+0.0001}_{-0.0001}$ $M_\odot$
Chirp mass $\mathcal{M}$	$1.186^{+0.001}_{-0.001}$ $M_\odot$
Primary mass m_1	(1.36, 1.60) $M_\odot$
Secondary mass m_2	(1.16, 1.36) $M_\odot$
Total mass m	$2.73^{+0.04}_{-0.01}$ $M_\odot$
Mass ratio q	(0.73, 1.00)
Effective spin $\chi_{\rm eff}$	$0.00^{+0.02}_{-0.01}$
Primary dimensionless spin χ_1	(0.00, 0.04)
Secondary dimensionless spin χ_2	(0.00, 0.04)
Tidal deformability $\tilde{\Lambda}$ with flat prior	300^{+500}_{-190} (symmetric)/ 300^{+420}_{-230} (HPD)

The **tidal deformability** measures how much a NS is deformed by tidal forces generated by the other NS in the binary - **gives information about the NS structure.**

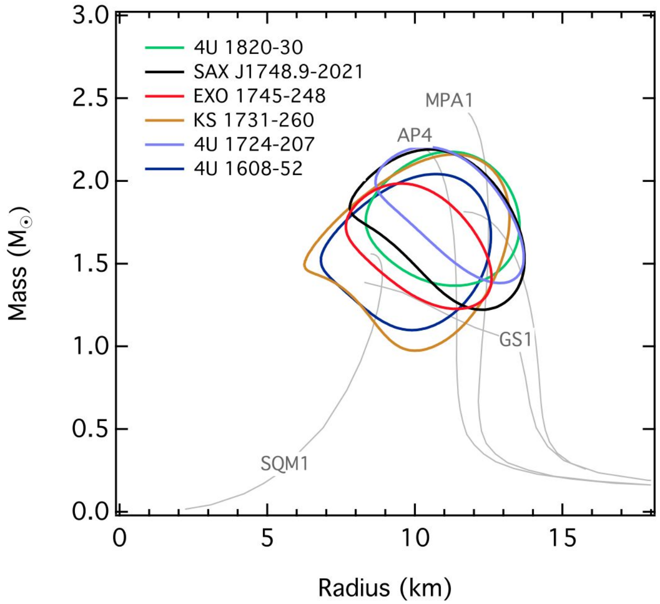
Additional observational constraints

Observed massive NS $\mathbf{M/M_\odot}$

- $\mathbf{2.13} \pm\ 0.04$ (PSR J1810+1714) [Romani et al. (2021)]
- $\mathbf{2.08} \pm\ 0.07$ (PSR J0740+6620) [Fonseca et al. (2021)]
- $\mathbf{2.01} \pm\ 0.04$ (PSR J0348-0432) [Antoniadis et al. (2013)]
- $\mathbf{1.908} \pm 0.016$ (PSR J1614-223) [Demorest et al. (2010)]

Recent radius measurements $\mathbf{R/km}$

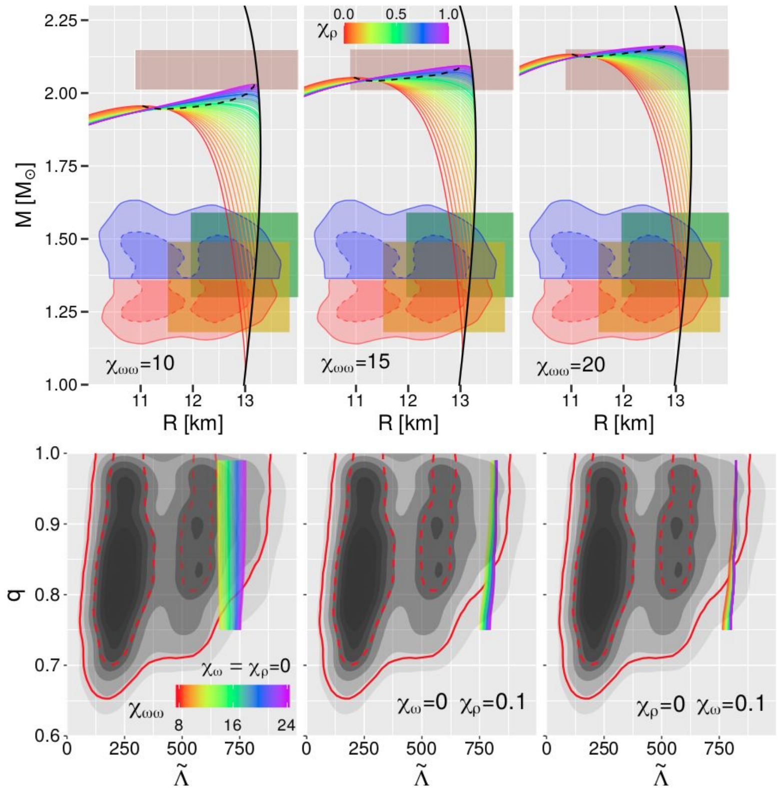
- $\mathbf{12.39}^{+1.30}_{-0.98}$ for $M = 2.072^{+0.067}_{-0.066}\ \mathrm{M}_\odot$ (PSR J0740+6620) [Riley et al. (2021]
- $\mathbf{12.71}^{+1.14}_{-1.19}$ for $M = 1.34^{+0.15}_{-0.16}\ \mathrm{M}_\odot$ (PSR J0030+0451) [Riley et al. (2019)]
- $\mathbf{13.02}^{+1.24}_{-1.06}$ for $M = 1.44^{+0.15}_{-0.14}\ \mathrm{M}_\odot$ (PSR J0030+0451) [Miller et al. (2019)]

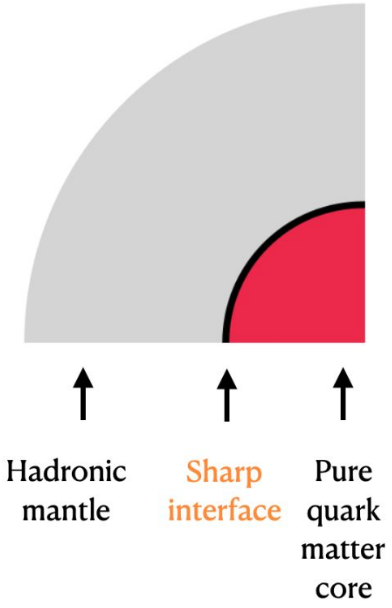


A valid equation of state of nuclear matter must predict all these neutron stars properties.

Possible scenario: Hybrid stars

- First-order transition from hadronic to quark matter





Main conclusion: The existence of hybrid stars is compatible with all present observational constraints when higher order vector interactions are present.

- Smaller mass-radius uncertainties will reduce the uncertainty on the NS composition

Marcio Ferreira, et. al.: Phys. Rev. D 103, 123020 (2021), Phys. Rev. D 101, 123030 (2020), Phys. Rev. D 102, 083030 (2020)