R-M relation for neutron stars with hyperon cores

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Quark matter in compact stars

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Topics

- EOS - general
- Largest precisely measured pulsar mass and importance of strong interactions
- Semi-empirical constraints on EOS
- $M_{\rm NS} = 2.0\ {\rm M}_{\odot}$: the hyperon puzzle and ways out
- Hyperon cores and $M(n_{\rm c})$
- Hyperon cores and $R(M)$
- Tentative conclusion

EOS and NS structure - general

Effect of rotation, magnetic field, elastic stresses - neglected

$n_0 = 0.16 \text{ fm}^{-3}$, $\rho_0 = 2.7 \times 10^{14} \text{ g cm}^{-3}$

Hydrostatic equilibrium configuration is **spherically symmetric**

Except for a thin outer layer matter in NS is **degenerate**

Equation of state (EOS) is of "one parameter type"

$$\boxed{P = P(n_{\rm b}) \; , \mathcal{E} = \mathcal{E}(n_{\rm b})} \qquad \rho = \mathcal{E}/c^2, \; P = P(\rho)$$

Speed of sound $\boxed{v_{\rm s} = (\mathrm{d}P/\mathrm{d}\rho)^{1/2}}$

For a given EOS: NS models form a "one-parameter family". Suitable parameter: central baryon density $\boxed{n_{\rm c}}$

Equilibrium configurations calculated in General Theory of Relativity (GTR) for an assumed EOS: $M(n_{\rm c}), \; R(n_{\rm c}) \Longrightarrow M(R), \ldots$

Crucial consequence of the GTR - $\boxed{M < M_{\rm max}[P(\rho)]}$

Importance of nuclear (strong) interactions

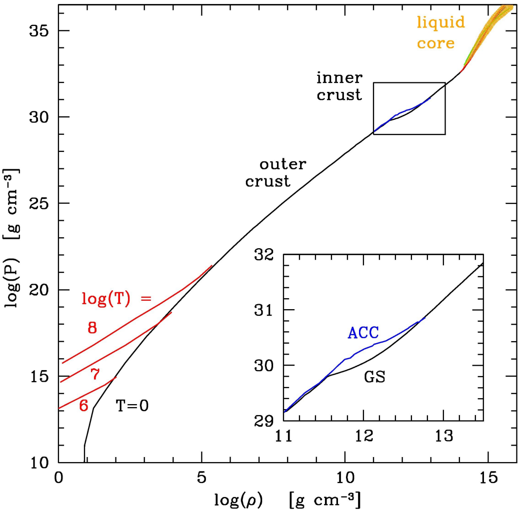
An EOS must satisfy: $\boxed{M_{\rm max}[{\rm EOS}] > 2.0\ {\rm M}_\odot}$

Oppenheimer, Volkoff (1939) $M_{\rm max}[{\rm FFG}] = 0.7\ {\rm M}_\odot$

Today: dominating effect of strong interactions for NS is an (observational) fact!

$$\boxed{M_{\rm max}^{\rm (obs)}/M_{\rm max}[{\rm FFG}] > 2.8}$$

Overview of EOS for NS



Based on

Haensel & Potekhin (2004)

Haensel & Zdunik (2013)

EOS for nucleon and hyperon NS cores

$n_0 = 0.16\ \mathrm{fm}^{-3}$

$$\boxed{P(n_\mathrm{b}) \quad n_0 < n_\mathrm{b} < 8n_0}$$

Nucleons - EOS.N

2BF: a few thousand of data on nucleon-nucleon scattering, $^2\mathrm{H}$ $\boxed{np}$

3BF: $^3\mathrm{H}$ $\boxed{nnp}$, $^3\mathrm{He}$ $\boxed{ppn}$, $^4\mathrm{He}$ $\boxed{nnpp}$, **nuclear matter - 6 semi-empirical parameters at saturation**

Numerous many-body calculations of EOS.N starting from 2BF+3BF (BBG, Variational HNC, Quantum MC, Chiral EFT,...) yield $M_\mathrm{max}[\mathrm{EOS.N}] > 2\ \mathrm{M}_\odot$

Nucleons and hyperons - EOS.H

NH: hypernuclei, Σ^--atoms **HH**: $\Lambda\Lambda$ hypernuclei - **4 semi-empirical parameters**

$+$ symmetries of strong interactions

Hyperon puzzle and a way out

A few existing BBG calculations yield $M_{\rm max}[\rm EOS.H] \lesssim 1.5 M_\odot \Longrightarrow$
HYPERON PUZZLE

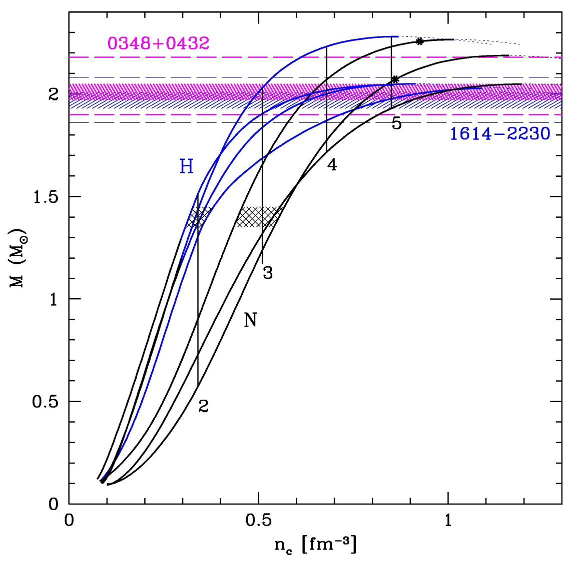
It exists a way out - but only for Relativistic Mean Field Models

High-density hyperon repulsion

Adding vector-meson ϕ $\boxed{s\bar{s}}$ **coupled to hyperons only** *Dexheimer & Schramm (2008), Bednarek et al. (2011), Weissenborn et al. (2011)a,...*

Result: thresholds for hyperons unchanged, but smaller populations of hyperons and $M_{\rm max}^{\rm (NH)} > 2.0\ {\rm M}_\odot$ **TUNING**

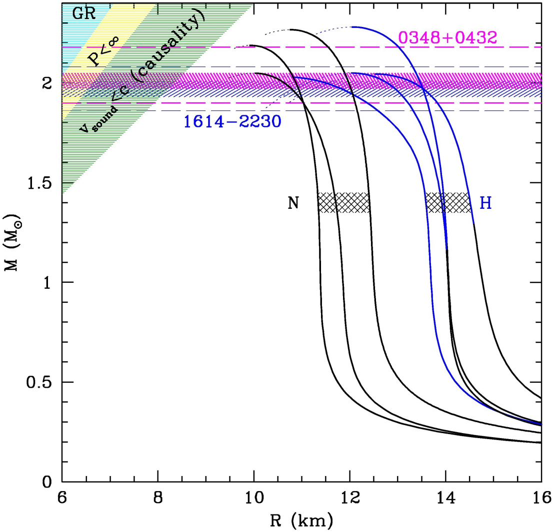
Breaking the SU(6) symmetry can further increase $M_{\rm max}^{\rm (NH)}$ *Weissenborn et al. (2011)b, Colucci & Sedrakian (2013)* **TUNING**



Only EOS.N, EOS.H with $M_{\rm max} > 2.0\ {\rm M}_\odot$

EOS.H has to be very stiff **before H-threshold** in order to yield $M_{\rm max} > 2.0\ {\rm M}_\odot$ after H-softening followed by a high-density stiffening

Neutron stars - $M(R)$



R for $1.0\ \mathrm{M}_\odot - 1.6\ \mathrm{M}_\odot$

EOS.N **11 - 12.5 km**

EOS.H **13.5 - 15 km**

"Radius gap" between N and H bunches for $1.0\ \mathrm{M}_\odot - 1.6\ \mathrm{M}_\odot$

For $M \approx 2\ \mathrm{M}_\odot$ the R-gap between H and N disappears

Close to $M_{\max}$ the range of R is narrower
10 - 12 km

Conclusions (tentative)

Hyperon cores & NS radii

- High stiffness of the nucleon segment needed to allow for $2\ \mathrm{M}_\odot$ (in spite of hyperon softening) implies $R = 14 - 15$ km for $M =$ 1.0 - 1.6 $\mathrm{M}_\odot$ for NS with hyperon cores
- If observations yield $R < 12$ km at 95% confidence level then hyperon cores in NS are ruled out
- If observations yield $R > 13.5$ km at 95% confidence level then actual EOS.N at $2n_0$ is much stiffer then the "standard one" and hyperon cores are allowed

If pulsars with mass larger than $2\ \mathrm{M}_\odot$ are discovered (e.g., $2.2\ \mathrm{M}_\odot$,or $2.4\ \mathrm{M}_\odot$, ...) then then 1 km "R-gap" between N and H bunches persist even at $1.8\ \mathrm{M}_\odot$

LOFT expected reach 5% precision of simultaneously measuring M and R