$2.0\ M_\odot$ pulsar and equation of state of neutron star cores

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Topics

- $M_{\max}^{(\mathrm{obs})}$ and EOS of dense matter - general
- Largest precisely measured pulsar mass - brief history
- $M_{\max}^{(\mathrm{obs})}$ and importance of strong interactions
- Theory of dense matter in a nutshell
- $M_{\mathrm{NS}} = 2.0\ \mathrm{M}_{\odot}$: the hyperon puzzle & its proposed solutions
- Strange NS cores: hyperons vs. quarks
- Conclusion

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Maximum measured $M_{\rm NS}$ and EOS of dense matter

equation of state (EOS) $\boxed{P = P(\rho)\ , \quad \rho = \mathcal{E}/c^2}$

Oppenheimer & Volkoff (1939)

EOS of free Fermi gas of neutrons

$$\boxed{M_{\rm max}[{\rm FFG}] = 0.7\ {\rm M}_\odot}$$

theory might allow us to calculate **true** $M_{\rm max} = M_{\rm max}[P(\rho)]$ ...

... if we knew **true** EOS

observations give $\{M_{\rm NS}\}$ (ideally: NS mass function ...)

Alas, very strong selection effect in the data ...observational and evolutionary bias - only binary NS are involved...

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Highest **precisely measured** pulsar masses

1975

PSR 1913+16 (**NS+NS**) *Hulse - Taylor binary pulsar*

1989: PSR 1913+16 $1.442 \pm 0.003\ \mathrm{M}_\odot$

2003: PSR 1913+16 $\boxed{1.4408 \pm 0.0003\ \mathrm{M}_\odot}$
Weisberg & Taylor (2003)

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PSR 1903+0327 (**NS+MS**) $\boxed{1.67 \pm 0.02\ \mathrm{M}_\odot}$ (99.7%) *Freire et al. (2011)*

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EOS of "cold dense matter" - baryons + leptons

normal nuclear density $\boxed{\rho_0 \equiv 2.7 \times 10^{14}\ \mathrm{g\ cm}^{-3}}$

$\boxed{\textbf{Fundamental theory of matter : QCD}}$

Terrestrial nuclear physics:

Only three lightest quarks involved, **confined into baryons**: nuclei, nucleons: $\mathbf{u}$, $\mathbf{d}$; hyperons, hypernuclei: additionally s

Many-body theory of nuclear matter $\Longrightarrow$ EOS for $\rho \lesssim \rho_0$

"Effective matter constituents": baryons $\boxed{qqq}$, leptons e, μ

"Effective theory": nuclear forces result from exchange of (virtual) mesons $\boxed{\bar{q}q}$

Basic question: how far this "effective theory" (hadrons+leptons) can be used in dense cold matter?

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Two remarkable features of the QCD: **confinement of quarks** and **asymptotic freedom**

Prediction: for $\rho \gtrsim \rho_{\rm dec}$ cold matter is a plasma of quarks interacting via exchange of gluons. Maybe a small admixture admixture of electrons

Both the value of $\rho_{\rm dec}$ and the EOS for $\rho > \rho_{\rm dec}$ are difficult to calculate: matter is a strongly-interacting quark-gluon plasma

A solid result of QCD: for mean energy of constituents of dense matter (resulting from Fermi statistics) $\gg \Lambda_{\rm QCD} \sim 1000$ MeV

the EOS is $\boxed{P \simeq \frac{1}{3}\rho c^2}$ **Asymptotic Freedom of the QCD**

Asymptopia is reached for $\rho > 10^{18}\ {\rm g\ cm^{-3}}$ - far larger than maximum density reached at centers of massive neutron stars ($5 \times 10^{15}\ {\rm g\ cm^{-3}}$, only $\boxed{\mathbf{u\ d\ s}}$ are relevant for NS)

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3BF: $^{3}\mathrm{H}$ $\boxed{nnp}$, $^{3}\mathrm{He}$ $\boxed{ppn}$, $^{4}\mathrm{He}$ $\boxed{nnpp}$, nuclear matter in atomic nuclei ...

Hyperons & nucleons

NH: hypernuclei, Σ^{-}-atoms

HH: $\Lambda\Lambda$ hypernuclei

+ symmetries of strong interactions

Examples of successful models: **Argonne V18**(nucleons only), **Nijmegen ESC08**(nucleons and hyperons)

Schulze & Rijken (2011)

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NH: hypernuclei, Σ^--atoms

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Examples of successful models: **Argonne V18**(nucleons only), **Nijmegen ESC08**(nucleons and hyperons)

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"hyperon puzzle"

Calculating EOS: Baryons + leptons

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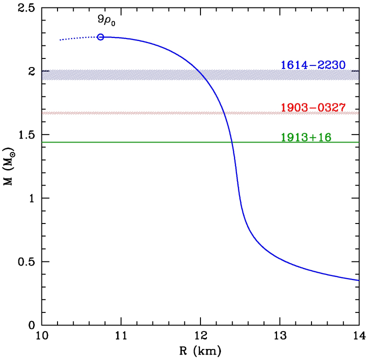

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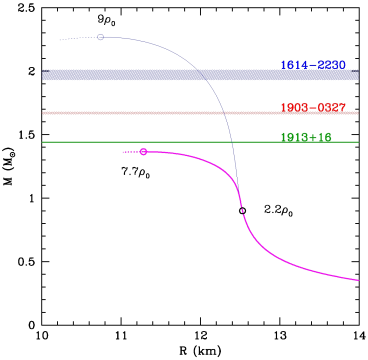

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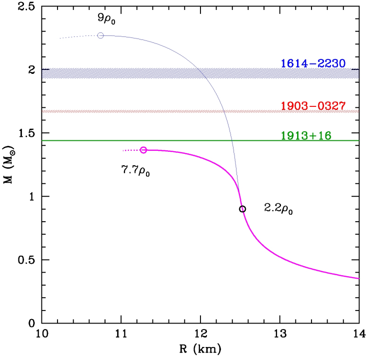

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Solution I: Hyperon-hyperon vector-meson repulsion

General feature

exchange of scalar mesons (spin=0) generates attraction (softening EOS), but exchange of vector mesons (spin=1) generates repulsion (stiffening EOS)

Add a vector meson **coupled to hyperons** yielding a strong repulsive contribution at high density *Dexheimer & Schramm (2008), Bednarek et al. (2011), Weissenborn et al. (2011)*

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

Breaking the SU(6) symmetry can further increase $M_{\rm max}^{\rm (NH)}$ *Weissenborn et al. (2011)*

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General feature - 1

- **significant overall quark repulsion** $\Longrightarrow$ **stiff EOS.Q**

- $\boxed{\mathrm{u\ d\ s}}$

General feature - 2

- **strong attraction** in *a* *channel* $\Longrightarrow$ **strong superconductivity**

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Fitting formulae for the EOS for QM

$\mathcal{E} = \rho c^2 \quad \mu_{\rm b} = (P + \mathcal{E})/n_{\rm b}$

Approximate - but quite precise for a single type of superconductivity. If a sequence of superconductive states - make segmental fits.

EOS of quark matter - EOS.Q

$$\boxed{P^{(\rm Q)}(\mathcal{E}) = a\,(\mathcal{E} - \mathcal{E}_2) + P_1}$$

$v_{\rm sound}/c = \sqrt{a} < 1$

B-Q phase interface

$P_1 = P^{(\rm B)}(\rho_1)\ , \quad \mu_{\rm b}^{(\rm B)} = \mu_{\rm b}^{(\rm Q)}$

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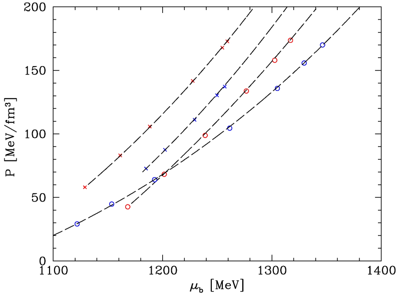

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Replacing H-cores by Q-cores and $M(R)$. Case 1

EOS.B of *Schulze & Rijken (2011)*

$M_{\max}(N) = 2.25\ \mathrm{M}_\odot$, but $M_{\max}(NH) = 1.37\ \mathrm{M}_\odot$

Examples of $M(R)$ with quark cores:

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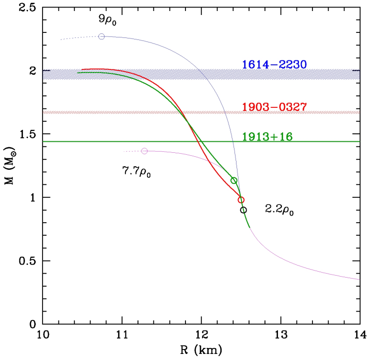

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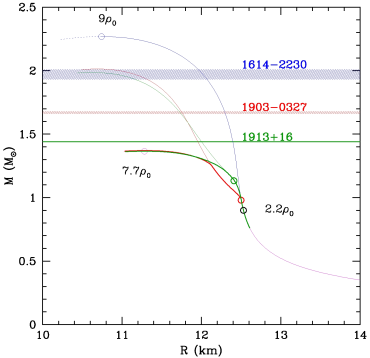

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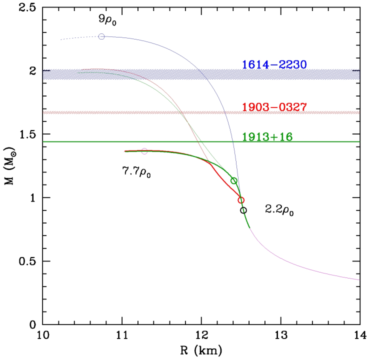

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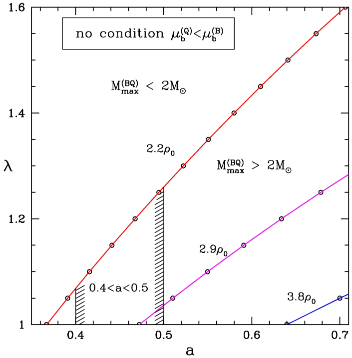
Haensel & Zdunik (2012) $\longrightarrow$



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High-density Q/B stability **is not imposed**

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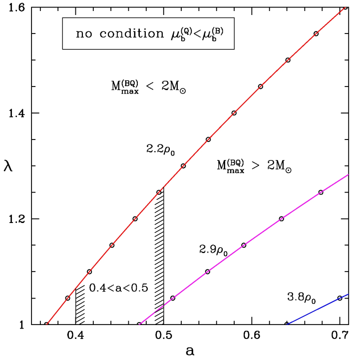

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Conditions on a and λ

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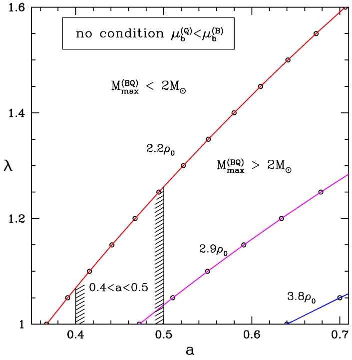

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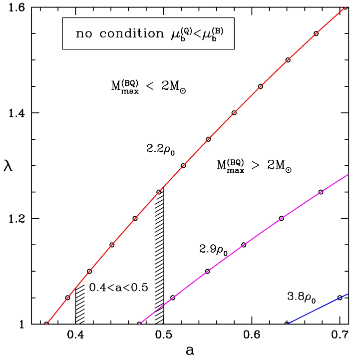

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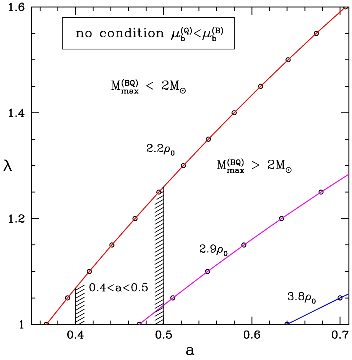

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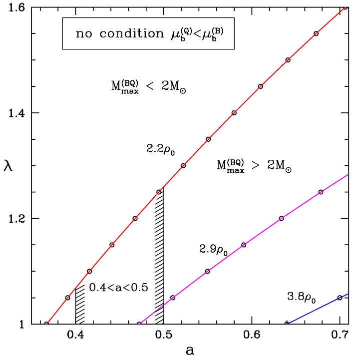

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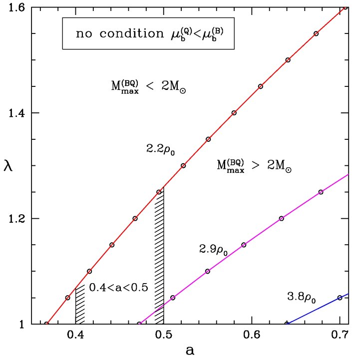

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Replacing H-cores by Q-cores and $M(R)$. Case 2

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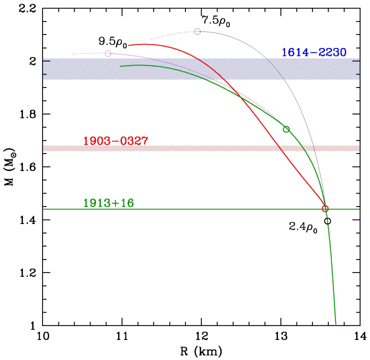

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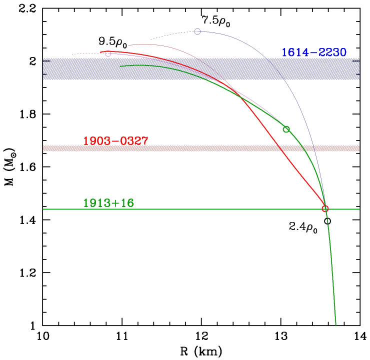

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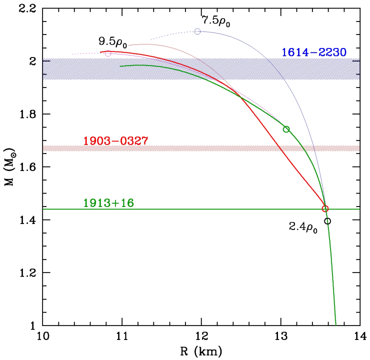

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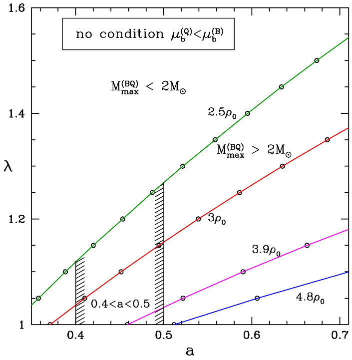

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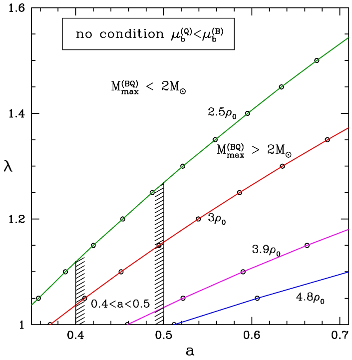

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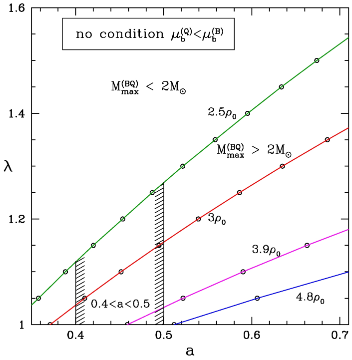

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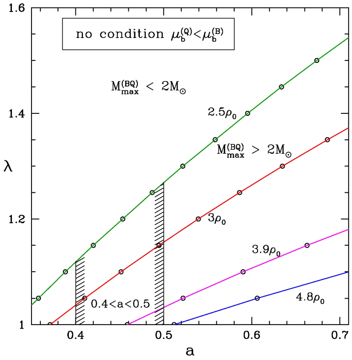

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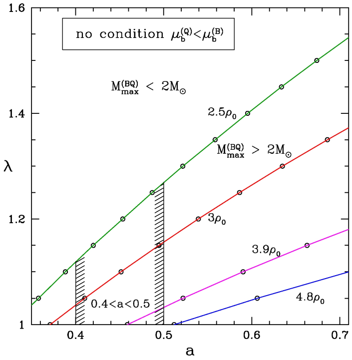

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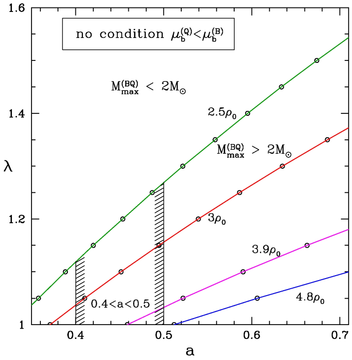

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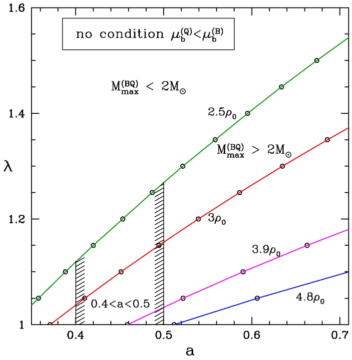

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Conclusion

The existence of $2\mathrm{M}_{\odot}$ pulsar implies several interesting features of cold dense matter:

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- Quark core in neutron stars: strong overall repulsion between quarks and simultaneously strong attraction (pairing) in specific channels to yield strong superconductivity
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