Dense matter, strong interactions, and maximum mass of neutron stars

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Neutron stars - history

- **1931** February: *Landau* - "giant nuclei"
- **1932** February: *Chadwick* - discovery of neutron
- **1934** *Baade & Zwicky*: neutron stars formed in supernovae
- **1939** *Oppenheimer & Volkoff*: free neutron gas + hydrostatic equilibrium in General Relativity $\Longrightarrow$ $M_{\rm max} = 0.7\ M_\odot$
- **1968** Pulsars discovered and identified as neutron stars
- ....
- **2003** ca. 2000 radio pulsars, ca. 200 X-ray sources (X-pulsars, X-bursters, ...). 10^9 neutron stars in Galaxy expected.

NS - cosmic laboratories for dense matter & space-time

Physics of matter under extreme astrophysical conditions

density $\sim\ M_\odot/(10\ km)^3\ \sim\ 10^{15}\ g\ cm^{-3}$ (interparticle distance $< 1fm$ $\Longrightarrow$ strong interactions crucial)
temperature up to $10^{11}\ K$, magnetic field $(10^{12} - 10^{15})\ Gs$
space-time strongly curved $R \simeq (2-4)r_{\rm g}$
$r_{\rm g} = 2GM/c^2 = 2.95\ M/M_\odot\ km$

$M_\odot = 1.989 \times 10^{33}\ g$

Structure of Nonrotating Neutron Stars

Tolman, Oppendeimer, Volkoff (1939)

r, θ, ϕ - Schwarzschild coordinates in ref. frame at ∞

$$\mathrm{d}s^2 = c^2\,\mathrm{d}t^2\,\mathrm{e}^{2\Phi} - \mathrm{e}^{2\lambda}\,\mathrm{d}r^2 - r^2\,(\mathrm{d}\theta^2 + \sin^2\theta\,\mathrm{d}\phi^2),$$

in local reference frame $P, \rho = \mathcal{E}/c^2$ ideal fluid

$$\frac{\mathrm{d}P}{\mathrm{d}r} = -\frac{G\rho m}{r^2}\left(1+\frac{P}{\rho c^2}\right)\left(1+\frac{4\pi P r^3}{mc^2}\right)\left(1-\frac{2Gm}{c^2 r}\right)^{-1},$$

$$\frac{\mathrm{d}m}{\mathrm{d}r} = 4\pi r^2\rho,$$

$m = m(r) = E(r' < r)/c^2$

strongly degenerate matter $P = P(\rho)$

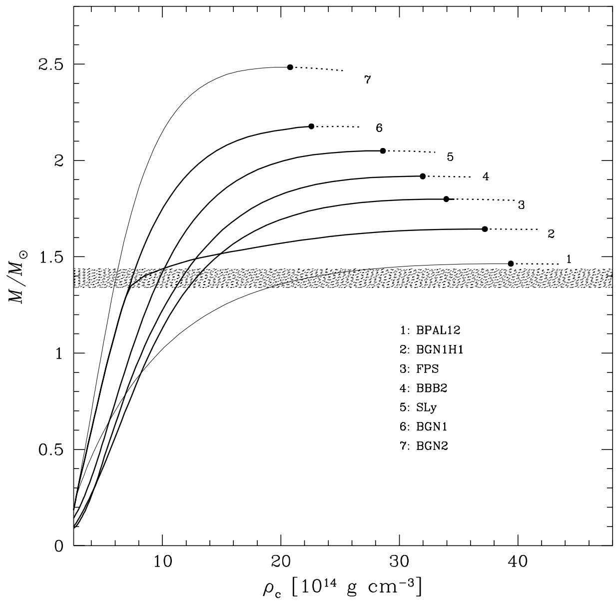
$\mathrm{d}P/\mathrm{d}r < 0$. Integrating TOV from $r = 0 (P = P_\mathrm{c})$ to $r = R(P = 0) \Longrightarrow R$

$M = m(R) = E/c^2$

$\rho = \rho(P) \Longrightarrow \rho(r) \qquad \rho(0) = \rho_\mathrm{c}$

Neutron stars configurations - one parameter family

$M = M(\rho_\mathrm{c})$, $R = R(\rho_\mathrm{c})$, ...



Upper bound $M_{\rm max}$ always exists

Even for incompressible fluid: upper bound

$M^{\rm (inc)}_{\rm max} = M(P_{\rm c} \longrightarrow \infty)$

$$M^{\rm (inc)}_{\rm max} = \frac{4c^3}{3^{5/2}\pi^{1/2}G^{3/2}\rho^{1/2}_{\rm inc}} = 5.09\ {\rm M}_\odot\ \left(\frac{5\times 10^{14}\ {\rm g\ cm}^{-3}}{\rho_{\rm inc}}\right)^{\frac{1}{2}}$$

subluminal EOSs: $v_{\rm s} = \sqrt{{\rm d}P/{\rm d}\rho} \leq c$

$$M_{\rm max} \leq M^{\rm SL}_{\rm max} = 3.0 \left(\frac{5\times 10^{14}\ {\rm g\ cm}^{-3}}{\rho_{\rm s}}\right)^{\frac{1}{2}}\ {\rm M}_\odot\ .$$

limiting SL EOS $P = (\rho - \rho_{\rm s})c^2$

If $M > M_{\rm max}$ compact object cannot be a Neutron Star but is a Black Hole

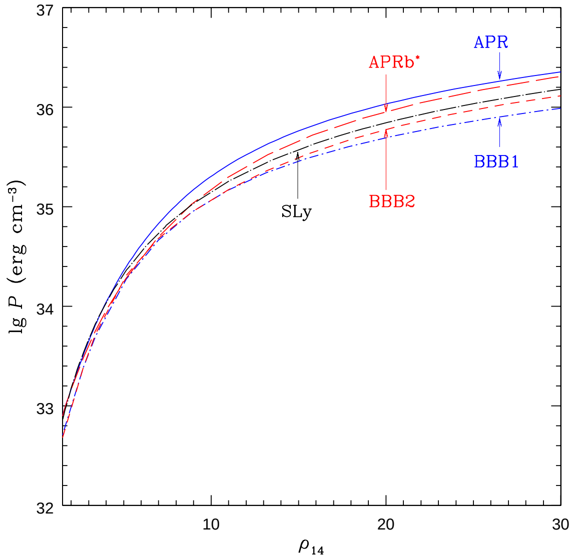
Observations

Hulse-Taylor binary pulsar $M_{\rm PSR} = (1.4408 \pm 0.0006)\ M_\odot$

Good theory: $M_{\rm max} > M^{\rm max}_{\rm obs}$

Dominating effect of strong interactions

$M_{\rm max}(int.)/M_{\rm max}(no\ int.) > 2$



Nucleons and leptons only

$n \;\; p \;\; e \;\; \mu$ (if $\mu_e > m_\mu c^2 = 105\ MeV$)

nucleons non-relativistic, muons mildly relativistic, electrons ultrarelativistic

$\mu_e = 122.1 (n_e/0.05 n_0)^{1/3}\ MeV \quad (n_0 = 0.16\ fm^{-3})$

$\mathcal{E}(n_n, n_p, n_e, n_\mu) = \mathcal{E}_{\rm N}(n_n, n_p) + \mathcal{E}_e(n_e) + \mathcal{E}_\mu(n_\nu)$

fixed $n_{\rm b} = n_n + n_p \qquad \mathcal{E} = min.\ \mu_j = \partial\mathcal{E}/\partial n_j\ (j = n, p, e, \mu)$

beta equilibrium $\quad \mu_n = \mu_p + \mu_e \quad \mu_\mu = \mu_e$

Nucleons constitue a strongly interacting many-body system (asymmetric nuclear matter)

nucleon-nucleon scattering, ^{2}H $\Longrightarrow V_{NN}$

^{3}H, ^{4}He, nuclear matter $\Longrightarrow V_{NNN}$

Different methods of solution of the quantum many-body problem for nucleon component:perturbative, variational, non-relativistic, relativistic, ...

$10^{15}\ g\ cm^{-3} \qquad P = (1.2 - 1.8) \times 10^{35}\ erg\ cm^{-3}$

$M_{\rm max} = (1.9 - 2.2)\ M_\odot$

Historical remark

Cameron 1959 neutron matter with Skyrme interaction $M_{\rm max} = 2.0\ M_\odot$ $\Longrightarrow$ NN interaction can solve the problem of (*Oppenheimer & Volkov 1939*

A.G.W. Cameron recalling his postdoc academic year 1959-1960 at the California Institute of Technology (Caltech) reminds that *"For years Fritz (Zwicky) had been pushing his ideas about neutron stars to anyone would listen and had been universally ignored. I believe that part of the problem was his personality, which implied strongly that people were idiots if they did not believe in neutron stars"* Cameron was one of a few persons who listened.

Nucleons, hyperons & leptons

Cameron 1959 - hyperons could be present as stable particles in neutron-star cores

Salpeter 1960 - first Σ^- then Λ

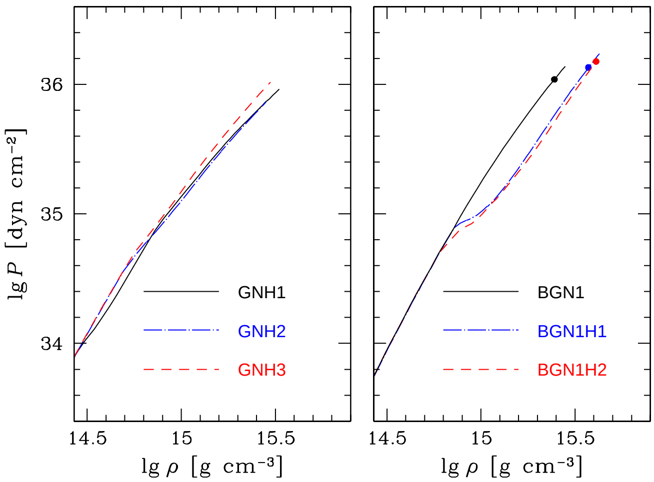
Ambartsumyan & Saakyan - detailed calculation for a mixture of non-interacting Fermi gases of $e, \mu, n, p, \Lambda, \Sigma, \Xi, \ldots$ $M_{\rm max} = 0.6\ M_\odot$

Threshold densities $\rho_{\rm c}^H$

$$\mu_H^0 = \lim_{n_H \longrightarrow 0} \frac{\mathcal{E}(npe\mu; n_H) - \mathcal{E}(npe\mu)}{n_H}$$

$\rho > \rho_{\rm c}^{\Lambda} \quad \mu_n > \mu_\Lambda^0 \quad n + p \longrightarrow p + \Lambda$

$\rho > \rho_{\rm c}^{\Sigma^-} \quad \mu_n + \mu_e > \mu_{\Sigma^-}^0 \quad n + e \longrightarrow \Sigma^- + \nu_e$



Strong interactions in NH matter

in general V_{BB}, V_{BBB}: V_{NH}, V_{HH}, V_{NNH}, $\ldots$

phenomenological

${}^{3}_{\Lambda}\mathrm{H}$, ${}^{3}_{\Lambda}\mathrm{He} \Longrightarrow V_{N\Lambda}$
${}^{6}_{\Lambda\Lambda}\mathrm{He}$, ${}^{10}_{\Lambda\Lambda}\mathrm{Be} \Longrightarrow V_{\Lambda\Lambda}$

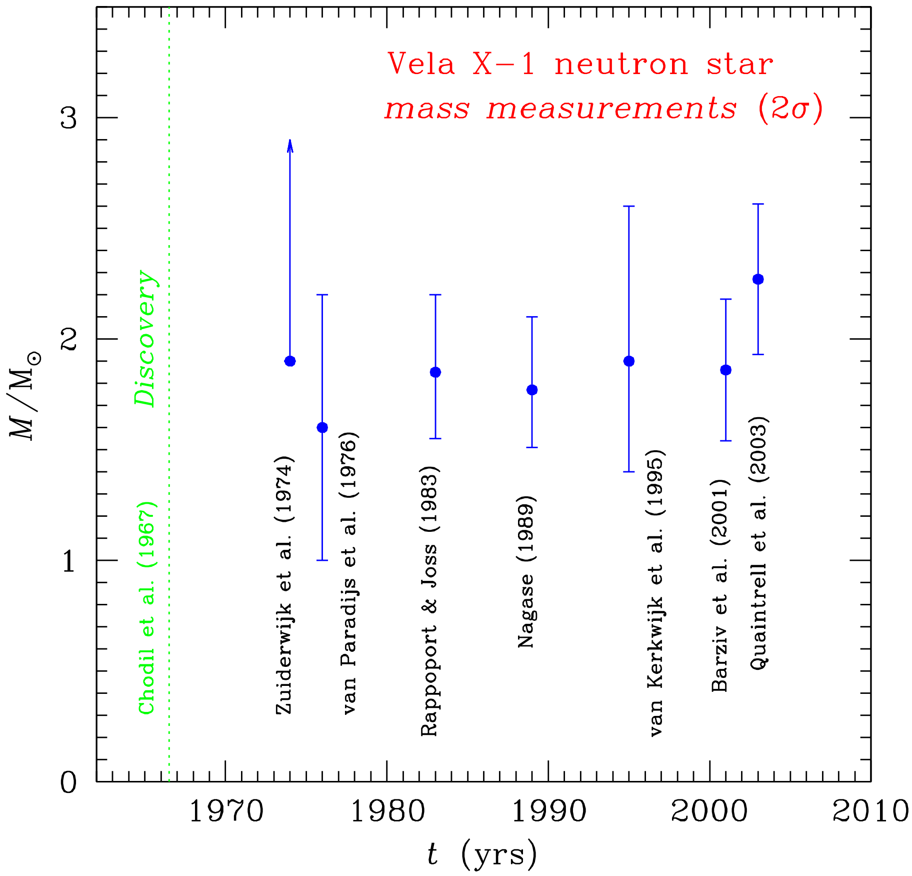
Important effect of $\Sigma - \Lambda$ conversion in baryon medium
Multichannel character & importance of ΛNN force

field-theoretic

one-boson exchange: $\pi, \sigma, \omega, \rho, K, \ldots$
SU(3) symmetry with some breaking to obtain $(B_1 B_2|V|B_3 B_4)$
for the baryon octet $J^{\pi} = \frac{1}{2}^{+}$ (NΣΛΞ)

Hyperon softening of the EOS

rapid nucleon converted into slow more massive hyperons
$M_{\mathrm{max}}(Ne\mu) - M_{\mathrm{max}}(NHe\mu) \simeq (0.3 - 0.5)\ M_{\odot}$

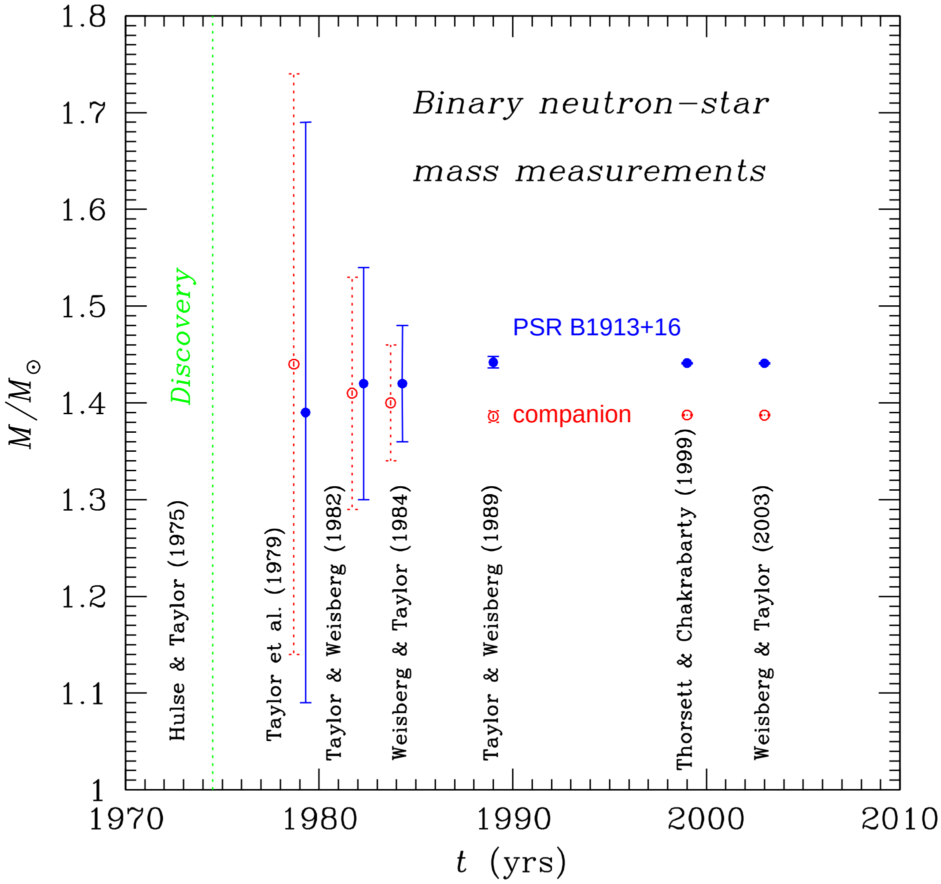


Neutron star masses - X-ray binaries

Newtonian (Keplerian) analysis. Large systematic errors

No clear convergence seen for measured value of M

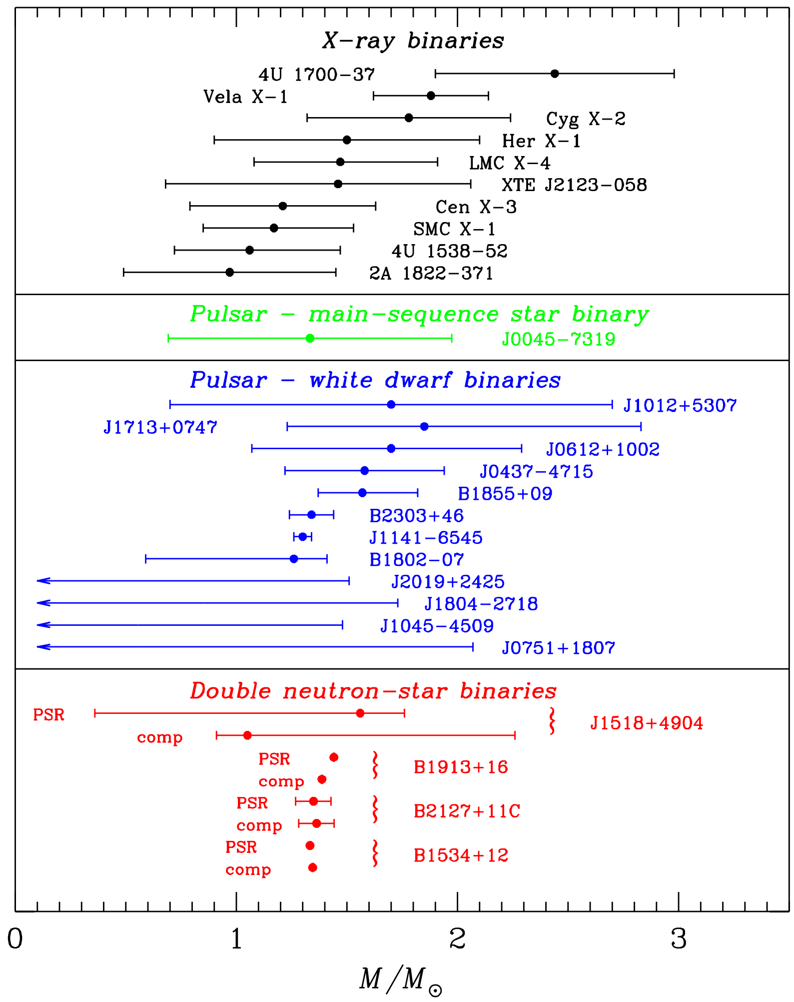
Haensel & Yakovlev 2003



Neutron star masses in radio-pulsar - neutron star binaries

Haensel & Yakovlev 2003

Relativistic analysis. Space-time affected by NS masses. More parameters. Example: Hulse-Taylor binary pulsar. Very high precision can be reached under favorable conditions.



Measured masses - summary 2003

Haensel & Yakovlev 2003

Rotation: $P_{\rm min} = 1.56\ ms\ (641 Hz)$ Increases $M_{\rm max}$ by $\Delta M_{\rm max} \sim 2\%$. Static approximation is OK.

Condition on EOS $\quad M_{\rm max}({\rm EOS}) > M_{\rm obs}^{\rm max}$

What do we get from observations in 2003?

- Very precise neutron star masses in three NS-NS binaries with a radio pulsar. Hulse - Taylor pulsar still the most massive
- It seems that some NS in X-ray binaries have masses significantly higher than $1.44M_{\odot}$ due to accretion of matter from the companion star.
- Three X-ray binaries: Cyg X-2, Vela X-1, 4U 1700-37 contain good candidates for high-mass ($\sim 2M_{\odot}$) neutron stars