Compact objects and strange quark stars

Eric Gourgoulhon

Laboratoire Univers et Théories (LUTH)
CNRS / Observatoire de Paris / Université Paris Diderot
F-92190 Meudon, France

eric.gourgoulhon@obspm.fr

http://www.luth.obspm.fr/~luthier/gourgoulhon/

Journées de la division Physique Nucléaire, SFP

Du plasma de quarks et de gluons aux étoiles à neutrons

Nantes, 13-14 May 2008

Plan

1. Compact stars in general relativity
2. Confronting theoretical models and observations: astrophysics as a lab
3. The search for strange stars
4. Gravitational wave observations

Outline

1. Compact stars in general relativity

2. Confronting theoretical models and observations: astrophysics as a lab

3. The search for strange stars

4. Gravitational wave observations

Density and compactness

Spherical object of mass M and radius R

- **density** : $\rho = \frac{M}{\frac{4}{3}\pi R^3}$
- **compactness** : $\Xi := \frac{GM}{c^2 R} \sim \frac{|E_{\rm grav}|}{Mc^2} \sim \frac{|\Phi_{\rm surf}|}{c^2} \sim \frac{V_{\rm esc}^2}{c^2} \sim \frac{R_{\rm S}}{R}$

$E_{\rm grav}$ = gravitational potential energy; $\Phi_{\rm surf}$ = gravitational potential at the surface; $V_{\rm esc}$ = escape velocity from surf.; $R_{\rm S}$ = Schwarzschild radius

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Remark: $\Xi_{\rm Earth} \sim 10^{-10}$ $\Xi_{\rm Sun} \sim 10^{-6}$ $\Xi_{\rm white\ dwarf} \sim 10^{-4}$ $\Xi_{\rm black\ hole} \sim 1$

Einstein equation

$$\boldsymbol{R} - \frac{1}{2} R \boldsymbol{g} = \frac{8\pi G}{c^4} \boldsymbol{T}$$

- $\boldsymbol{g}$ = metric tensor on the 4-dimensional spacetime manifold $\mathscr{M}$
- $\boldsymbol{R}$ = Ricci tensor ; $R = \mathrm{tr}_{\boldsymbol{g}} \boldsymbol{R}$
- $\boldsymbol{T}$ = matter stress-energy tensor
  perfect fluid : $\boldsymbol{T} = (e + p)\boldsymbol{u} \otimes \boldsymbol{u} + p\boldsymbol{g}$ (e = proper energy density, p = pressure, $\boldsymbol{u}$ = fluid 4-velocity)

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Coordinate system (x^α) on $\mathscr{M}$ ⇒Einstein equation results in a system of 10 **coupled non-linear second order partial differential equations** for the 10 coefficients $g_{\alpha\beta}$ of the metric tensor

$$R_{\alpha\beta} = -\frac{1}{2} g^{\mu\nu} \left(\frac{\partial^2 g_{\alpha\beta}}{\partial x^\mu \partial x^\nu} + \frac{\partial^2 g_{\mu\nu}}{\partial x^\alpha \partial x^\beta} - \frac{\partial^2 g_{\nu\beta}}{\partial x^\alpha \partial x^\mu} - \frac{\partial^2 g_{\alpha\nu}}{\partial x^\beta \partial x^\mu} \right) + \mathcal{Q}_{\alpha\beta} \left(g_{\mu\nu}, \frac{\partial g_{\mu\nu}}{\partial x^\rho} \right)$$

$$R = g^{\mu\nu} R_{\mu\nu} \qquad T_{\alpha\beta} = (e+p) u_\alpha u_\beta + p g_{\alpha\beta}$$

Stationary rotating star

- **stationarity:** $\exists$ coordinates (x^α) on $\mathscr{M}$ such that $\dfrac{\partial g_{\alpha\beta}}{\partial x^0} = 0$ and $\boldsymbol{k} := \dfrac{\partial}{\partial x^0}$ asymptotically timelike
- **axisymmetry:** $\exists$ coordinates (x^α) on $\mathscr{M}$ such that $\dfrac{\partial g_{\alpha\beta}}{\partial x^3} = 0$, $\boldsymbol{m} := \dfrac{\partial}{\partial x^3}$ spacelike, vanishes on a 2-surface *(rotation axis)* and has closed orbits

$\boldsymbol{k}$ and $\boldsymbol{m}$ are called **Killing vectors** associated with resp. stationarity and axisymmetry

Stationarity + axisymmetry $\Rightarrow \exists$ coord. $(x^\alpha) = (t, r, \theta, \varphi)$ on $\mathscr{M}$ such that

$$\boxed{g_{\alpha\beta} = g_{\alpha\beta}(r, \theta)}$$

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Another important simplification: **Papapetrou theorem:**

if $\boldsymbol{u} = u^0 \boldsymbol{k} + u^\varphi \boldsymbol{m}$ (circular motion), then $\exists$ coordinates $(x^\alpha) = (t, r, \theta, \varphi)$ on $\mathscr{M}$ such that $g_{tr} = 0$, $g_{t\theta} = 0$, $g_{r\theta} = 0$, $g_{r\varphi} = 0$, $g_{\theta\varphi} = 0$, i.e.

$$g_{\alpha\beta} dx^\alpha dx^\beta = -N^2 dt^2 + A^2 \left(dr^2 + r^2 d\theta^2\right) + B^2 r^2 \sin^2\theta \, (d\varphi + \beta^\varphi dt)^2$$

$$N = N(r, \theta), \quad \beta^\varphi = \beta^\varphi(r, \theta), \quad A = A(r, \theta), \quad B = B(r, \theta)$$

(quasi-isotropic coordinates)

Stationary rotating star in QI coordinates

$$g_{\alpha\beta}dx^\alpha dx^\beta = -N^2c^2dt^2 + A^2\left(dr^2 + r^2d\theta^2\right) + B^2r^2\sin^2\theta\,(d\varphi + \beta^\varphi dt)^2$$

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Important limits:

- Vanishing gravitational field : $N \to 1$, $\beta^\varphi \to 0$, $A \to 1$, $B \to 1$
  $$g_{\alpha\beta}dx^\alpha dx^\beta = -c^2dt^2 + dr^2 + r^2d\theta^2 + r^2\sin^2 d\varphi^2$$
  (Minkowski metric in spherical coordinates)

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  $$g_{\alpha\beta}dx^\alpha dx^\beta = -N^2c^2dt^2 + A^2\left(dr^2 + r^2d\theta^2 + r^2\sin^2\theta d\varphi^2\right)$$
- Weak gravitational field:
  $$g_{\alpha\beta}dx^\alpha dx^\beta = -\left(1 + 2\frac{\Phi}{c^2}\right)c^2dt^2 + \left(1 - 2\frac{\Phi}{c^2}\right)\left(dr^2 + r^2d\theta^2 + r^2\sin^2\theta d\varphi^2\right)$$

  $\Phi \sim$ Newtonian gravitational potential; $|\Phi_{\rm surf}|/c^2 = \Xi$ (compactness)

Einstein equations for a stationary rotating star

In QI coord., the Einstein equations reduce to 4 elliptic equations:

$$\Delta_3 \nu = 4\pi A^2 (E + S^i{}_i) + \frac{B^2 r^2 \sin^2\theta}{2N^2} (\partial\beta^\varphi)^2 - \partial\nu\, \partial(\nu + \ln B)$$

$$\tilde{\Delta}_3 (\beta^\varphi r \sin\theta) = 16\pi \frac{N A^2}{B^2} \frac{J_\varphi}{r\sin\theta} - r\sin\theta\, \partial\beta^\varphi\, \partial(3\ln B - \nu)$$

$$\Delta_2 [(NB - 1)\, r\sin\theta] = 8\pi N A^2 B (S^r{}_r + S^\theta{}_\theta) r \sin\theta$$

$$\Delta_2 \zeta = 8\pi A^2 S^\varphi{}_\varphi + \frac{3B^2 r^2 \sin^2\theta}{4N^2} (\partial\beta^\varphi)^2 - (\partial\nu)^2$$

with the abreviations: $\nu := \ln N$, $\zeta := \ln(AN)$

$$\Delta_2 := \frac{\partial^2}{\partial r^2} + \frac{1}{r}\frac{\partial}{\partial r} + \frac{1}{r^2}\frac{\partial^2}{\partial\theta^2} \qquad \Delta_3 := \frac{\partial^2}{\partial r^2} + \frac{2}{r}\frac{\partial}{\partial r} + \frac{1}{r^2}\frac{\partial^2}{\partial\theta^2} + \frac{1}{r^2\tan\theta}\frac{\partial}{\partial\theta}$$

$$\tilde{\Delta}_3 := \Delta_3 - \frac{1}{r^2\sin^2\theta} \qquad \partial a\, \partial b := \frac{\partial a}{\partial r}\frac{\partial b}{\partial r} + \frac{1}{r^2}\frac{\partial a}{\partial\theta}\frac{\partial b}{\partial\theta}$$

Fluid equations

Energy momentum conservation : $\boxed{\boldsymbol{\nabla} \cdot \boldsymbol{T} = 0}$

Circular motion : $\boldsymbol{u} = \lambda \boldsymbol{\ell}$ with $\boxed{\boldsymbol{\ell} = \boldsymbol{k} + \Omega\, \boldsymbol{m}}$, Ω = angular rotation velocity

Rigid rotation : $\Omega = \mathrm{const} \Rightarrow \boldsymbol{\ell}$ Killing vector $\Rightarrow \exists$ a first integral to $\boldsymbol{\nabla} \cdot \boldsymbol{T} = 0$:

$$\boxed{\boldsymbol{\ell} \cdot (h\boldsymbol{u}) = \mathrm{const}}$$

with $h := \dfrac{e+p}{m_{\mathrm{B}} n c^2}$ (specific enthalpy).

Newtonian limit : $(h-1) + \Phi - \dfrac{1}{2}(\boldsymbol{\Omega} \times \boldsymbol{r})^2 = \mathrm{const}$

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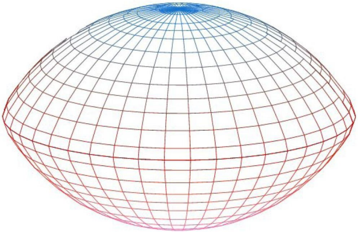
Equation of state (EOS): cold dense matter: $e = e(h), \quad p = p(h), \quad n = n(h)$

closed system of equations

At fixed EOS, a model is fully specified by two parameters, e.g. central density and Ω.

Computational code

Framework: **RotStar** code based on LORENE C++ library
http://www.lorene.obspm.fr/

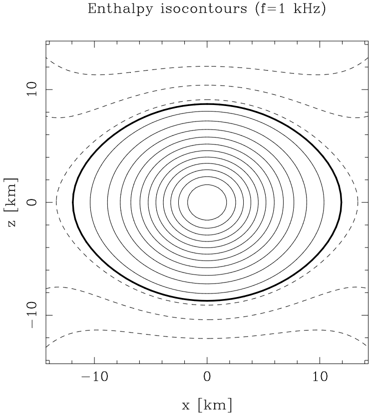


Resolution of Einstein equations for stationary axisymmetric rotating stars

Numerical technique: spectral methods
$\Rightarrow$ high accuracy
Microphysics input: equation of state (EOS)

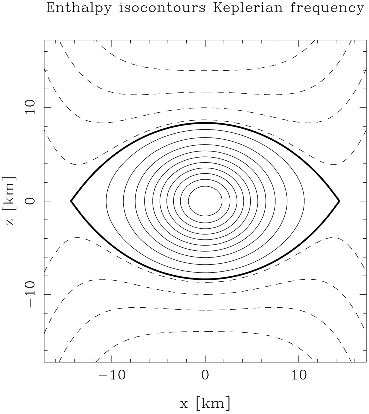
Examples of numerical results

Rapidly rotating model



Maximum rotation rate

(Keplerian limit)



Isocontour of specific enthalpy h :

$h < 1 \iff$ stellar exterior (dashed lines); $h = 1 \iff$ stellar surface (thick solid line)

$h > 1 \iff$ stellar interior (solid line)

Global quantities

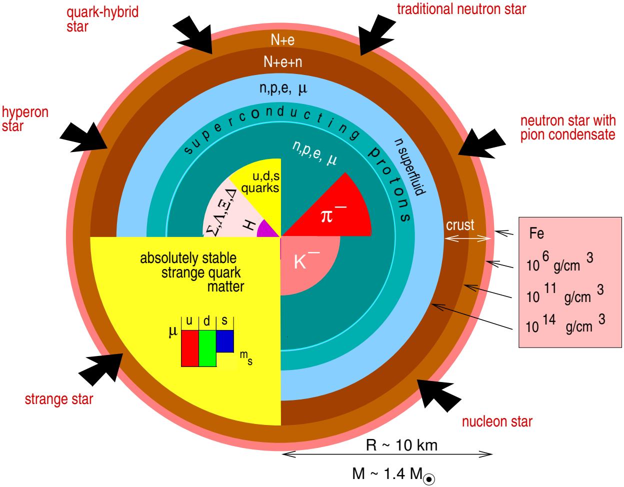
- M : gravitational mass (*)
- M_{B} : baryon mass $= m_{\mathrm{B}} \times$ total baryon number
- J : total angular momentum (about the rotation axis) (*)
- Ω : angular rotation frequency (as seen from infinity)
- R : circumferential radius of the equator
- z_{p}, $z_{\mathrm{eq}}^{\pm}$: redshifts from pole, and equator (forward and backward) (*)
- f_{ISCO} : orbital frequency at the innermost stable circular orbit (*)

(*) = measurable quantities

Outline

Our (poor) knowledge of matter at supernuclear densities

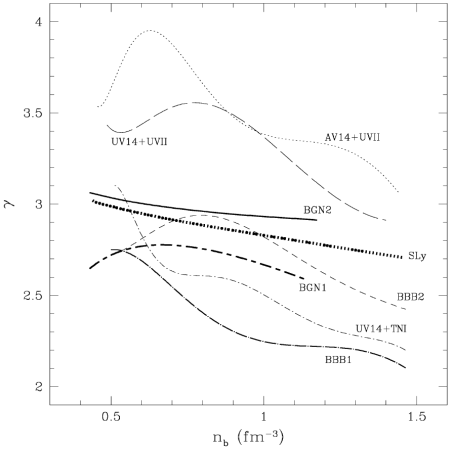
Internal structure of compact stars



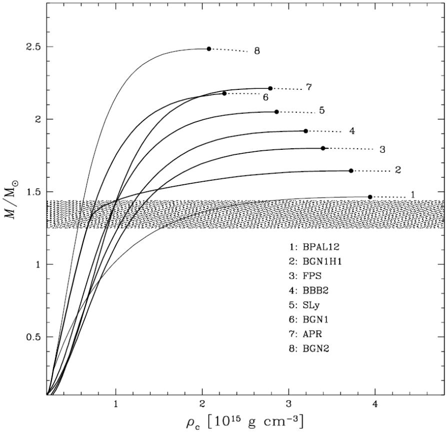
[Weber, J. Phys. G **27**, 465 (2001)]

Large discrepancies in theoretical models...

adiabatic index

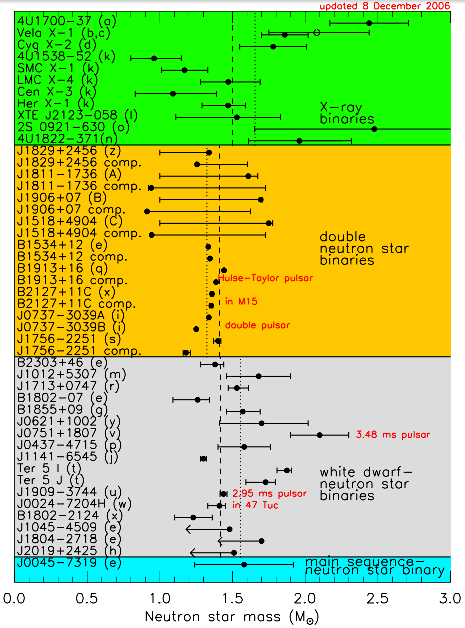


non-rotating neutron star mass



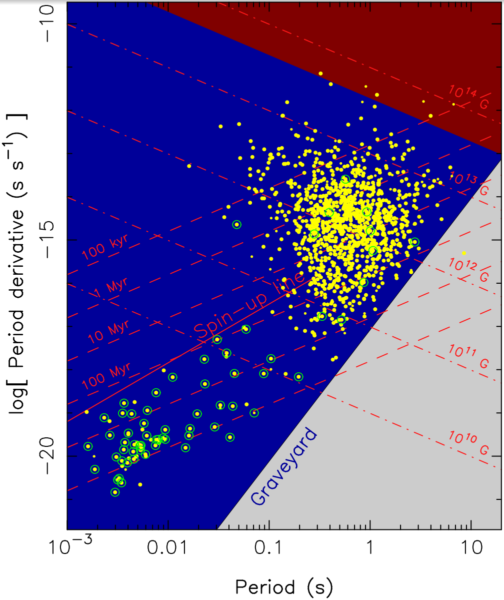
[Haensel, Potekhin & Yakovlev (2007)]

Measured neutron star masses



[Lattimer & Prakash, astro-ph/0612440 (2006)]

Measured rotation velocity



← Period derivative $\dot{P}$ vs period P for radio pulsars

[Lorimer, Liv. Rev. Relat. **8**, 7 (2005)]

Fastest pulsar known to date:
PSR J1748-2446ad

$P = 1.396$ ms $\quad f = 716$ Hz

[Hessels et al., Science **311**, 1901 (2006)]

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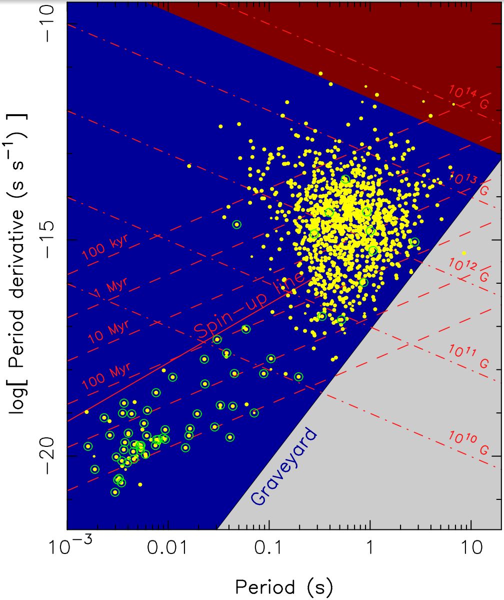

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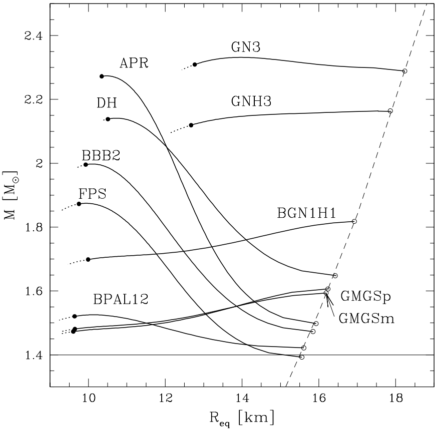
Discovery of an oscillation frequency of $f = 1122$ Hz in a X-ray burst from X-ray transient XTE J1739-285

[Kaaret et al., ApJL **657**, 97 (2007)]

Spin frequency ? This would imply $P = 0.89$ ms !
Not confirmed yet !

Impact of the discovery of very high rotation frequencies

Mass-radius relation at $f = 1122$ Hz



[Bejger, Haensel & Zdunik, A&A **464**, L49 (2007)]

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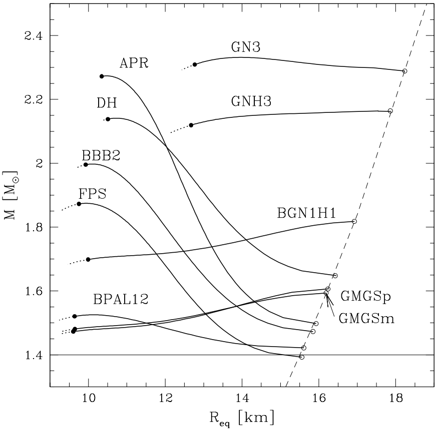
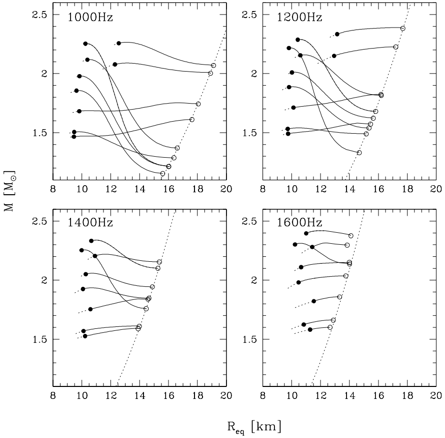


[Bejger, Haensel & Zdunik, A&A **464**, L49 (2007)]

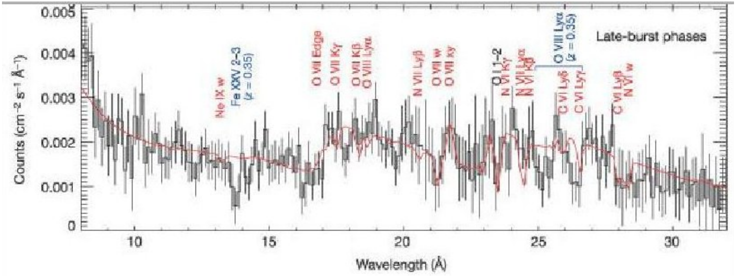
Mass-radius relation at fixed f



[Zdunik, Haensel, Bejger & Gourgoulhon, arXiv:0710.5010]

Measured compactness (M/R)

Observation (XMM-Newton) of iron and oxygen spectral lines from the compact star in the low-mass X-ray binary EXO 07748-676



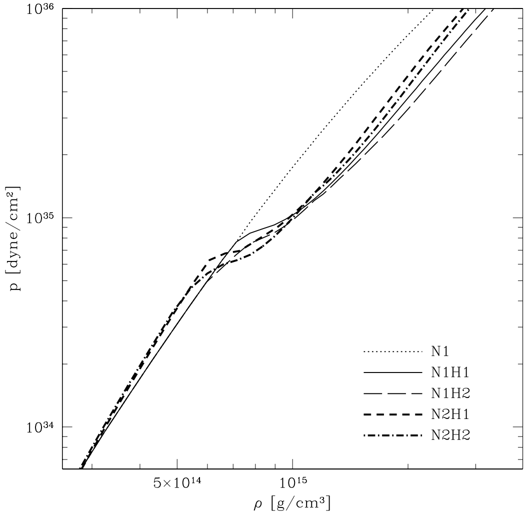
[Cottam, Paerels & Mendez, Nature **420**, 51 (2002)]

$\Rightarrow$ gravitational redshift: $z = \dfrac{\lambda_{\rm obs} - \lambda}{\lambda} = 0.35$ (NB: $z_{\rm Doppler} \sim 10^{-3}$)

$$z = (1 - 2\Xi)^{-1/2} - 1 = 0.35 \Longrightarrow \boxed{\Xi = \frac{GM}{c^2 R} = 0.23}$$

Unfortunately we know neither M nor R for this system...

Search for an indicator of hyperonization of matter (1/2)



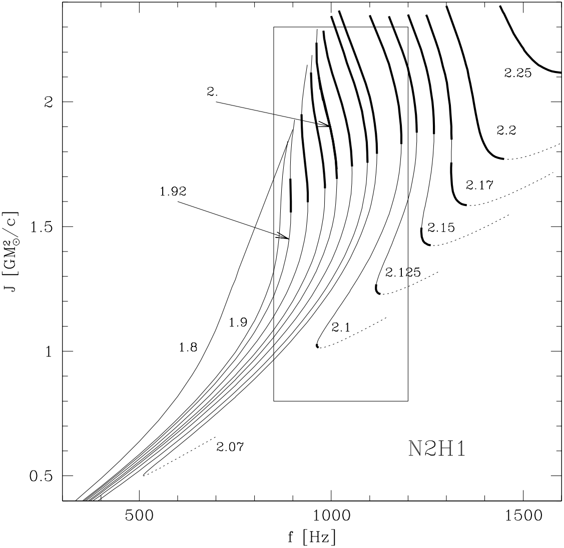
Hyperon = baryon (i.e. hadron + fermion) made of 3 quarks, with at least one strange quark:

- Λ_0 = uds
- Σ^- = dds
- Ξ^0 = uss
- etc...

Should appear at high density ($\rho > 2\rho_{\rm nuc}$)
$\Rightarrow$ EOS softening

N1 = np, N1H1,N2H1 = np$\Lambda\Sigma$,
N1H2,N2H2 = np$\Lambda\Sigma\Xi$
Balberg & Gal (1997)

Search for an indicator of hyperonization of matter (2/2)



Hyperon softening of the EOS $\Rightarrow$ back-bending : spin-**up** by angular momentum **loss**

Detectability: pulsar with $\dot{P} < 0$

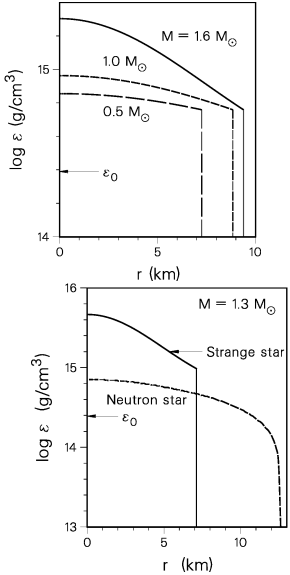
[Zdunik, Haensel, Gourgoulhon & Bejger, A&A **416**, 1013 (2004)]

Outline

A short history of strange stars

- 1970: N. Itoh considered compact stars made of free degenerate Fermi gas of u, d and s quarks of equal mass $m_q = 10$ GeV/c^2 (not self-bound, vanishing density at the surface) $\Rightarrow M_{\rm max} = 10^{-3} M_\odot$.
- 1971: A.R. Bodmer: the ground state of nuclear matter may be a state of **deconfined quarks**.
- 1984: E. Witten reformulated (independently) this idea, and contemplated the possibility that neutron stars are in fact **strange quark stars**.
- 1986: first detailed numerical models of static strange stars by P. Haensel, J.L. Zdunik & R. Schaeffer, as well as C. Alcock, E. Farhi & A.V. Olinto.
- 1989: announcement of a half-millisecond pulsar in SN 1987A
- 1996: discovery of high frequency QPO in low-mass X-ray binaries
- 2002: NASA announcement of “discovery” of two strange stars

Basic properties of strange stars



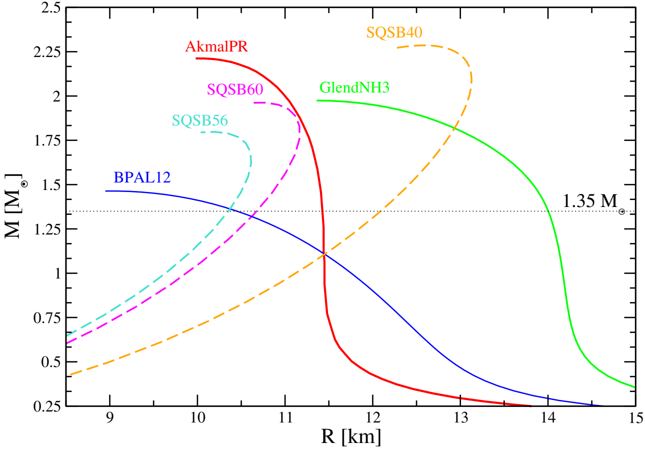
Simplest models: improved **MIT bag model**
$\Rightarrow$3-parameter EOS for SQM matter:
B: bag constant, m_s mass of s quark, α_s: QCD structure constant ($\alpha_s = g^2/(4\pi)$, g: QCD coupling constant)

- finite density at the surface (zero pressure)
- for small mass (weak gravity): almost constant density profile $\varepsilon \sim 4B$
- more compact than neutron stars

$\leftarrow$ figures from [Glendenning (1997)]

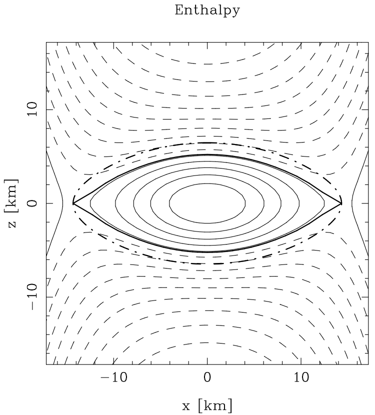
Mass-radius relation

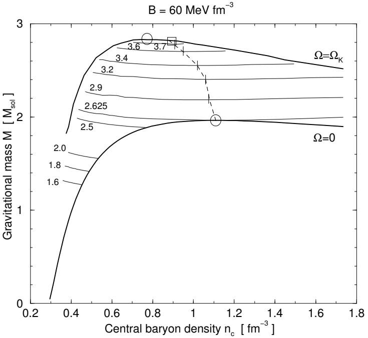
From strangelets to strange stars



[Gondek-Rosińska, Bejger, Bulik, Gourgoulhon, Haensel, Limousin, Taniguchi & Zdunik, ASR **39**, 271 (2007)]

Rapidly rotating strange stars

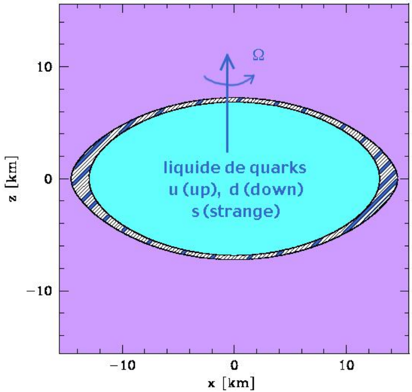


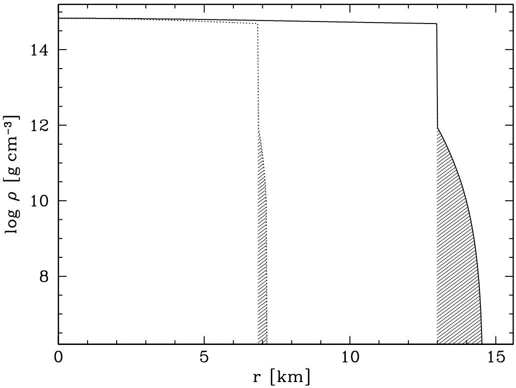


[Gourgoulhon, Haensel, Livine, Paluch, Bonazzola & Marck , A&A **349**, 851 (1999)]

Minimal rotation period (for $m_s = 0$ and $\alpha_s = 0$): $P_{\rm min} = 0.634\, {B_{60}}^{-1/2}$ ms

Models with solid crust

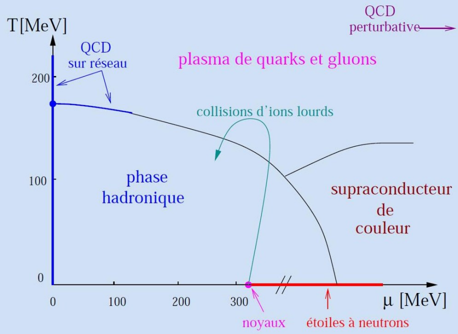


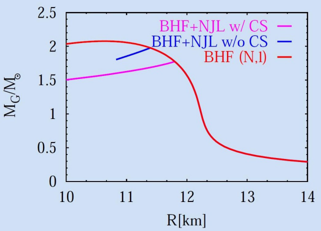


EOS: $B = 56$ MeV fm^{-3}, $\alpha_s = 0.2$, $m_s = 200$ MeV c^{-2}
star: $M_B = 1.63\, M_\odot$, $f = 1210$ Hz.

[Zdunik, Haensel, Gourgoulhon, A&A **372**, 535 (2001)]

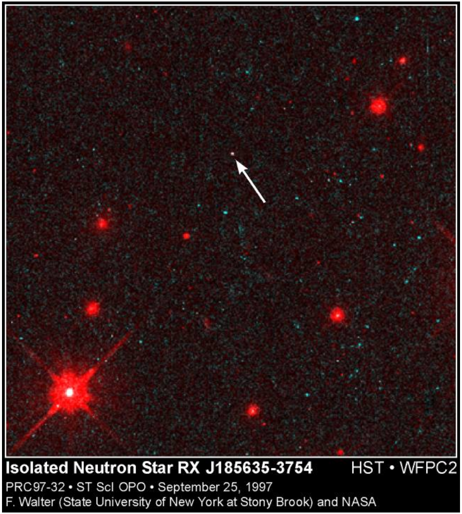
Recent studies of quark matter





- Study of quark matter *(u,d,s)* in color-flavor-locked (CFL) states ⇒ No stable configuration with uniquely CFL matter
  [Buballa, Neumann, Oertel & Shovkoy, PLB **595**, 36 (2004)]
- Goldstone bosons in CFL states
  [Werth, Buballa & Oertel, PPNP **59**, 308 (2007)], [Kleinhaus, Buballa, Nickel & Oertel, PRD **76**, 074024 (2007)]
- Color superconductivity effects on the properties of a strange star: electron atmosphere, transport properties
  [Oertel & Urban, PRD **77**, 074015 (2008)]

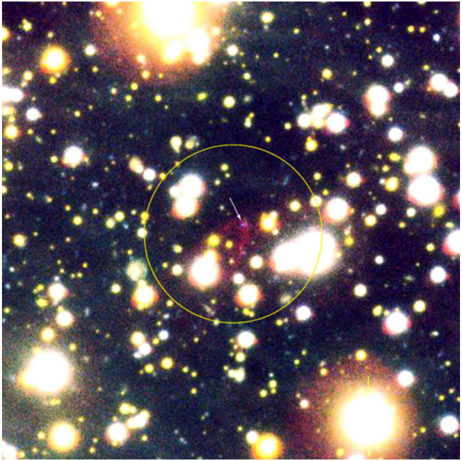
The case of RX J1856.5-3754



- Discovered as an X-ray source with ROSAT in 1996 [Walter et al., Nature **379**, 233 (1996)]
Best fit black body $kT_\infty = 57 \pm 1$ eV
$\iff T_\infty \simeq 6.6 \times 10^5$ K
In front of molecular cloud *R Coronae Australis* $\Rightarrow d \lesssim 130 - 170$ pc

- Optical counterpart discovered in 1997 with HST [Walter & Matthews, Nature **389**, 358 (1997)]
magnitude $V = 25.6$
Optical flux 2 to 3 times larger than the tail of the 57 eV black body

RX J1856.5-3754 observed by VLT

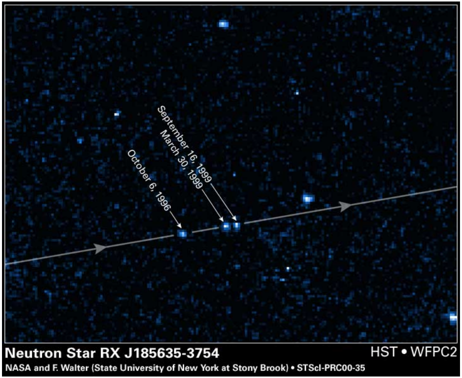


VLT Kueyen + FORS2 (field: 80" × 80")

$\longrightarrow$ bowshock (heated interstellar gas by accelerated e^- and p from the star ?)

[ESO 2000]

Distance to RX J1856.5-3754



- First measure of proper motion and parallax (erroneous) [Walter, ApJ **549**, 433 (2001)]

$\Rightarrow$ erroneous $d = 61 \pm 9$ pc

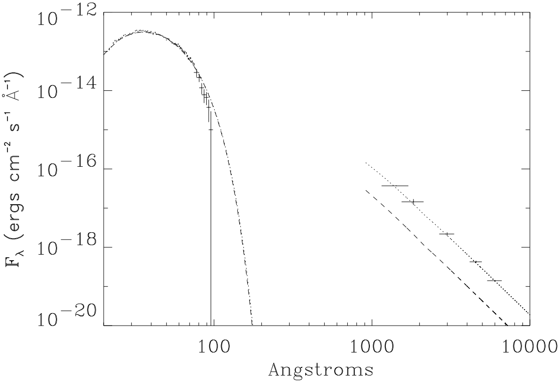
- Correct determinations of parallax:

$d = 140 \pm 40$ pc [Kaplan, van Kerkwijk, Anderson, ApJ **571**, 447 (2002)]

$d = 117 \pm 12$ pc [Walter & Lattimer, ApJ **576**, L145 (2002)]

RX J1856.5-3754 spectrum

Chandra image of RX J1856.5-3754



Spectrum from Chandra, EUVE and HST data:

- - - - : black body best fit to Chandra data $kT_\infty = 63$ eV

[Burwitz et al., A&A **379**, L35 (2001)]

.........: 63 eV black body + 15 eV black body with R_∞(15 eV) $= 5R_\infty$(63 eV)

[Walter & Lattimer, ApJ **576**, L145 (2002)]

Is RX J1856.5-3754 a strange star ?

The small "radius" issue:

Assuming black body emission from the **entire** surface :

$$R_\infty = \frac{d}{T_\infty^2}\left(\frac{f_\infty}{\sigma}\right)^{1/2}$$

$$R_\infty = \left(1 - \frac{2GM}{c^2 R}\right)^{-1/2} R \; > R$$

- Distance of Walter & Lattimer 2002 : $d = 117$ pc $\Rightarrow R_\infty = 4.8$ km
- Distance of Kaplan et al. 2002 : $d = 140$ pc $\Rightarrow R_\infty = 5.8$ km

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Recent discovery of pulsations of period $P = 7.055$ s from XMM-Newton observations (with a pulsed fraction of only 1.2%)

[Tiengo & Mereghetti, ApJ **657**, L101 (2007)]

$\Rightarrow$Hot spot model favored today

Outline

Observing compact stars via gravitational waves

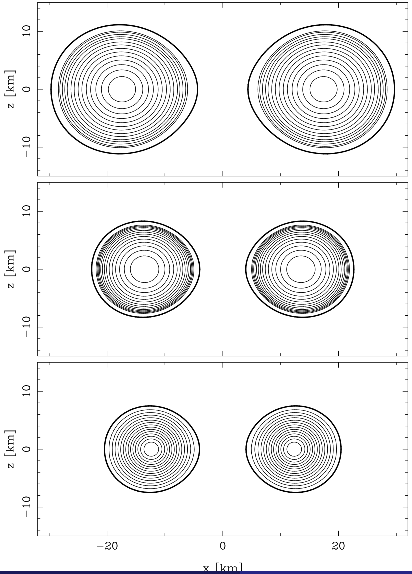
LIGO: USA, Louisiana

LIGO: USA, Washington

VIRGO: France/Italy (Pisa)

Michelson-type lasers VIRGO (3 km) and LIGO (4 km) $\Rightarrow$they are currently acquiring data.

Constraints on EOS from gravitational radiation (1/2)



GW from inspiraling binary neutrons stars

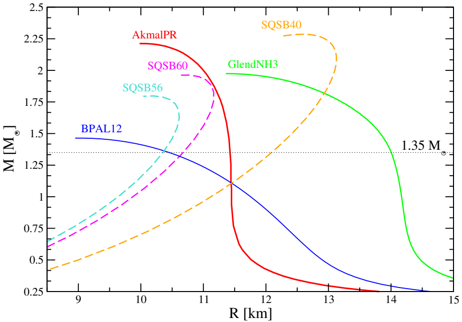
Primary target for VIRGO / LIGO

← Irrotational binary configurations close to mass-shedding limit for GlendNH3, AkmalPR and BPAL12 EOS

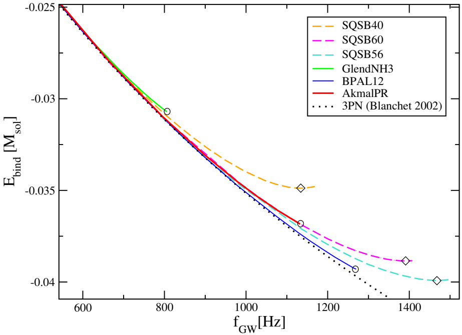
[Bejger, Gondek-Rosińska, Gourgoulhon, Haensel, Taniguchi & Zdunik, A&A **431**, 297 (2005)]

Constraints on EOS from gravitational radiation (2/2)

3 nuclear matter EOS
3 strange matter EOS



Inspiraling sequences



[Bejger, Gondek-Rosińska, Gourgoulhon, Haensel, Taniguchi & Zdunik, A&A **431**, 297 (2005)]

[Limousin, Gondek-Rosińska & Gourgoulhon, PRD **71**, 064012 (2005)]

[Gondek-Rosińska, Bejger, Bulik, Gourgoulhon, Haensel, Limousin, Taniguchi & Zdunik, ASR **39**, 271 (2007)]