Are neutron stars actually strange stars ?

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Plan

1. Strange quark matter
2. Theoretical models of strange quark stars
3. Searching for strange quark stars
4. Recent Chandra observations

1

Strange quark matter

The strange quark

Quark properties

flavor	d	u	s	c	b	t
spin	$1/2$					
baryon number	$1/3$					
electric charge	$-\frac{e}{3}$	$\frac{2e}{3}$	$-\frac{e}{3}$	$\frac{2e}{3}$	$-\frac{e}{3}$	$\frac{2e}{3}$
isospin (z-comp.)	$-\frac{1}{2}$	$\frac{1}{2}$	0	0	0	0
mass $[\mathrm{MeV}\,c^{-2}]$	~ 7	~ 3	~ 150	~ 1200	~ 4200	$\sim 175\ \mathrm{GeV}\,c^{-2}$

Recall:
nucleons : **p = uud**, **n = udd**
hyperons : Λ = **usd**, Σ^+ = **uus**,...
mesons : π^+ = **u$\bar{\text{d}}$**, π^- = **$\bar{\text{u}}$d**,...

Strange quark matter hypothesis and strange stars

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**.

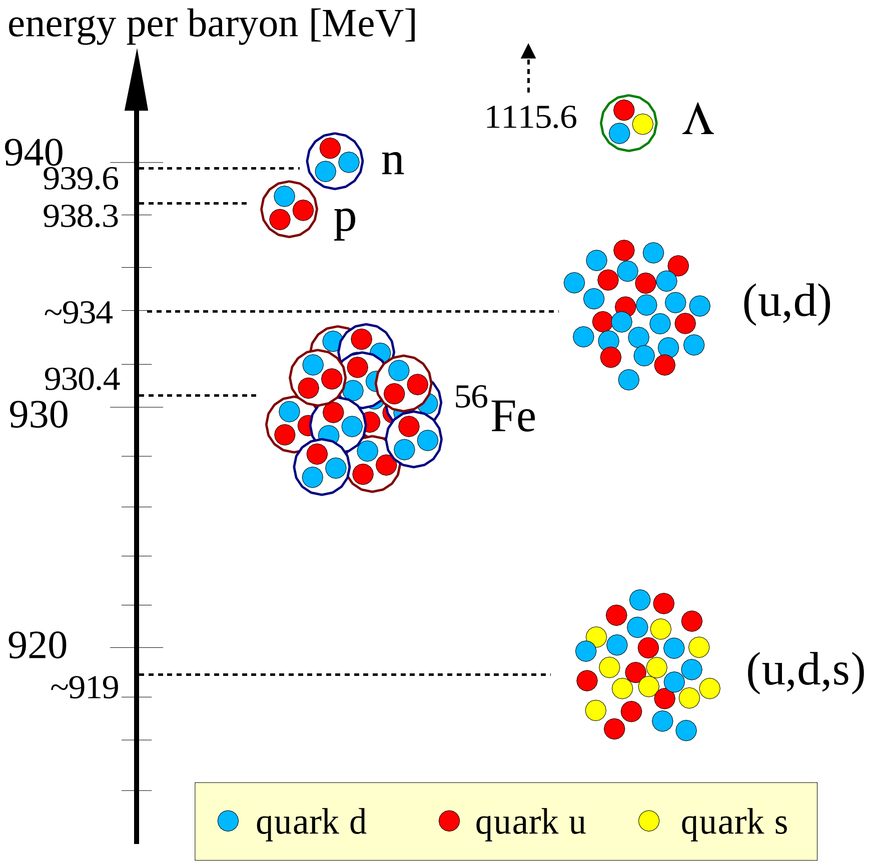
1986: first numerical models of static strange stars by P. Haensel, J.L. Zdunik & R. Schaeffer, as well as C. Alcock, E. Farhi & A.V. Olinto.

1989 : announcement of a half-millisecond pulsar in SN 1987A

1996 : discovery of high frequency QPO in low-mass X-ray binaries

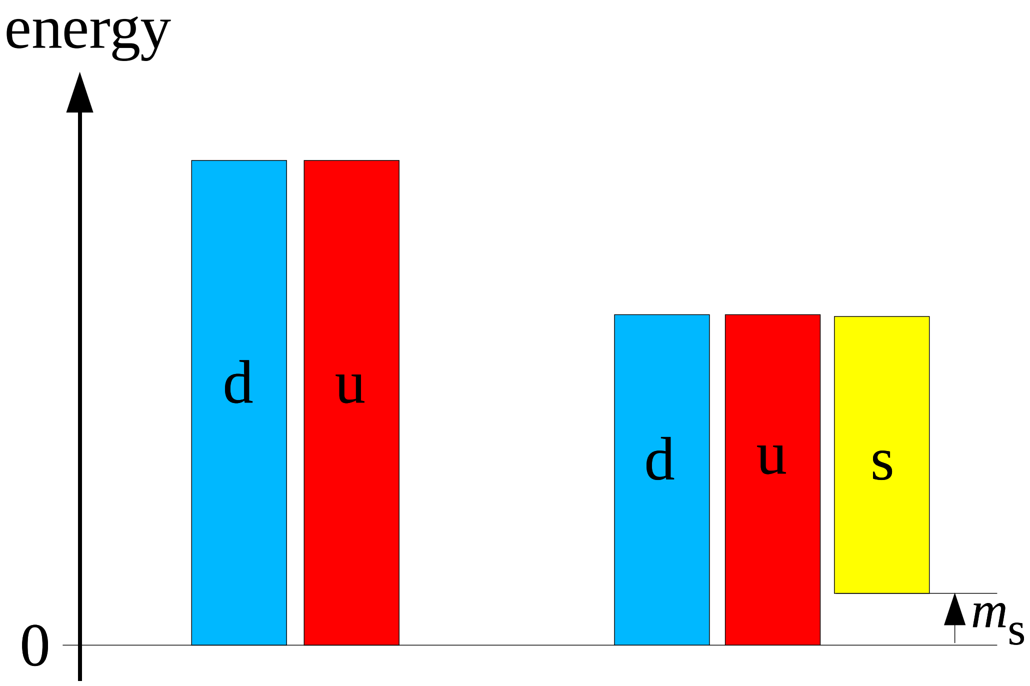
2002 : NASA announcement of “discovery” of two strange quark stars

Ground state of hadronic matter



Why non-zero strangeness ?

Quarks are **fermions:**



Pauli exclusion principle $\Longrightarrow$ 3-flavor quark matter has a lower energy than 2-flavor quark matter.

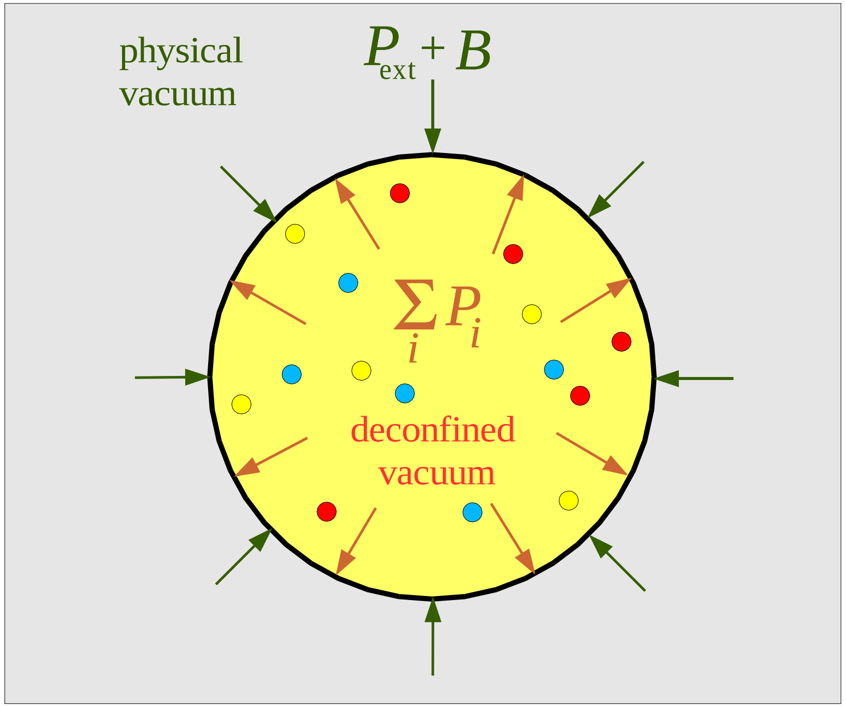
Approximate treatment of QCD

Complexity of QCD $\Longrightarrow$ a direct computation of the quark matter EOS is not doable.

The simplified approach to quark matter EOS:

- describe non-perturbative aspects of QCD (**quark confinement** and **asymptotic freedom**) by a very simplified phenomenological model: **the MIT bag model;**
- describe perturbative effects (**quark interactions** within the bag) by an expansion in $\alpha_\mathrm{s} = g^2/(4\pi)$, where g is the QCD coupling constant .

MIT bag model



Pressure of physical vacuum acting on the bag: B
$\Rightarrow$ balance of total pressure acting on the bag by the total quark pressure:

$$P_{\text{ext}} + B = \sum_{\text{flavor } i} P_i$$

Energy density of deconfined vacuum with respect to physical vacuum: B
$\Rightarrow$ total energy density of the bag:

$$\varepsilon = \sum_{\text{flavor } i} \varepsilon_i + B$$

Bag constant $B \sim 60\ \text{MeV fm}^{-3} =: B_{60}$

.

Simple estimations within the bag model

Approximation: neglect the quark masses, and the quark interactions ($\alpha_{\rm s} = 0$)
$\Rightarrow$ each quark flavor i behaves as a ultra-relativistic Fermi free gas: the pressure at number density n_i is

$$P_i = \frac{1}{4}\left(\frac{6\pi^2}{\gamma_i}\right)^{1/3} \hbar c\, n_i^{4/3} = \frac{1}{3}\varepsilon_i$$

with the degeneracy $\gamma_i = 2(\text{spin}) \times 3(\text{color}) = 6$.

Total pressure: $$P = \frac{\pi^{2/3}}{4}\hbar c \sum_{\text{flavor } i} n_i^{4/3} - B$$

Total energy density: $$\varepsilon = \frac{3\pi^{2/3}}{4}\hbar c \sum_{\text{flavor } i} n_i^{4/3} + B \;=\; 3P + 4B \longleftarrow$$ *NB: asymp. fr.*

Baryon density: $$n_{\rm B} = \frac{1}{3}\sum_{\text{flavor } i} n_i$$

At zero pressure: $\varepsilon = 4B =: \varepsilon_0$ and $\frac{\pi^{2/3}}{4}\hbar c \sum_{\text{flavor } i} n_i^{4/3} = B$

2-flavor quark matter

Hypothesis: only u and d quarks.

Electric neutrality ⇒ $n_{\rm d} = 2n_{\rm u}$.

Then $n_{\rm B} = \frac{1}{3}(n_{\rm d} + n_{\rm u}) = n_{\rm u}$

and, at zero pressure, $\frac{\pi^{2/3}}{4}\hbar c(1 + 2^{4/3})n_{\rm u}^{4/3} = B$

Energy per baryon: $\left.\frac{E}{A}\right|_{\rm (u,d)} = \frac{\varepsilon_0}{n_{\rm B}} = (4\pi^2)^{1/4}(1 + 2^{4/3})^{3/4}(\hbar c)^{3/4}B^{1/4}$

$$\boxed{\left.\frac{E}{A}\right|_{\rm (u,d)} = 943.6\, B_{60}^{1/4}\ \mathrm{MeV}}$$

3-flavor quark matter

Hypothesis: massless u, d and s quarks.

Electric neutrality + weak-reaction equilibrium ⇒ $n_\mathrm{d} = n_\mathrm{u} = n_\mathrm{s}$.

Then $n_\mathrm{B} = \frac{1}{3}(n_\mathrm{d} + n_\mathrm{u} + n_\mathrm{s}) = n_\mathrm{u}$

and, at zero pressure, $\frac{3\pi^{2/3}}{4}\hbar c n_\mathrm{u}^{4/3} = B$

Energy per baryon: $\left.\frac{E}{A}\right|_{(\mathrm{u,d,s})} = \frac{\varepsilon_0}{n_\mathrm{B}} = (4\pi^2)^{1/4} 3^{3/4} (\hbar c)^{3/4} B^{1/4}$

$$\boxed{\left.\frac{E}{A}\right|_{(\mathrm{u,d,s})} = 837.3\, B_{60}^{1/4}\ \mathrm{MeV}}$$

We recover that $\left.\frac{E}{A}\right|_{(\mathrm{u,d,s})} < \left.\frac{E}{A}\right|_{(\mathrm{u,d})}$

Bounds on the bag constant

- **Stability of nucleons against strangelets formation:**

$$\left.\frac{E}{A}\right|_{(\mathrm{u,d})} > \left.\frac{E}{A}\right|_{^{56}\mathrm{Fe}} = 930.4\ \mathrm{MeV} \Longleftrightarrow B > 58.9\ \mathrm{MeV\,fm}^{-3}$$

- **SQM being the ground state of matter:**

$$\left.\frac{E}{A}\right|_{(\mathrm{u,d,s})} < \left.\frac{E}{A}\right|_{^{56}\mathrm{Fe}} = 930.4\ \mathrm{MeV} \Longleftrightarrow B < 91.5\ \mathrm{MeV\,fm}^{-3}$$

But note that surface effects increase E/A for small A ($A \lesssim 30$), making the hyperon Λ ($A = 1$) unstable ($\tau = 3 \times 10^{-10}$ s), and making ordinary matter stable (ouf !).

Conclusion: for massless and non-interacting (except for confinement effects) quarks in the MIT bag model:

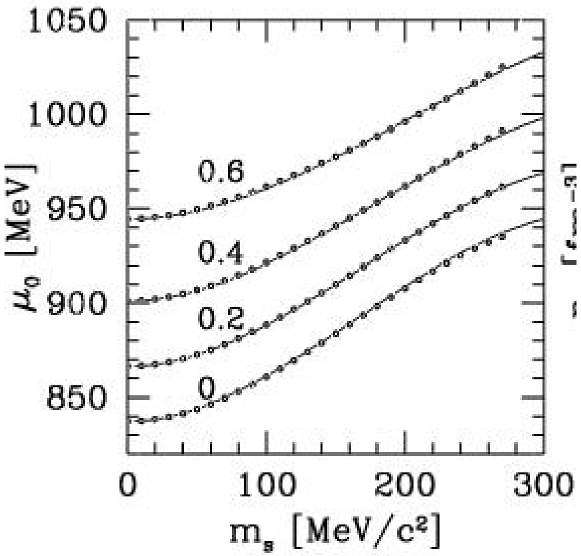
$$\boxed{58.9\ \mathrm{MeV\,fm}^{-3} < B < 91.5\ \mathrm{MeV\,fm}^{-3}}$$

Improved bag model

Take into account

- the finite mass of quark s : $100\ \mathrm{MeV}\,c^{-2} \lesssim m_\mathrm{s} \lesssim 300\ \mathrm{MeV}\,c^{-2}$
- the lowest order gluon interactions, via an expansion in $\alpha_\mathrm{s} = g^2/(4\pi)$, where g is the QCD coupling constant.

$\Longrightarrow$ 3-parameter EOS for SQM matter: $\boxed{(B, m_\mathrm{s}, \alpha_\mathrm{s})}$

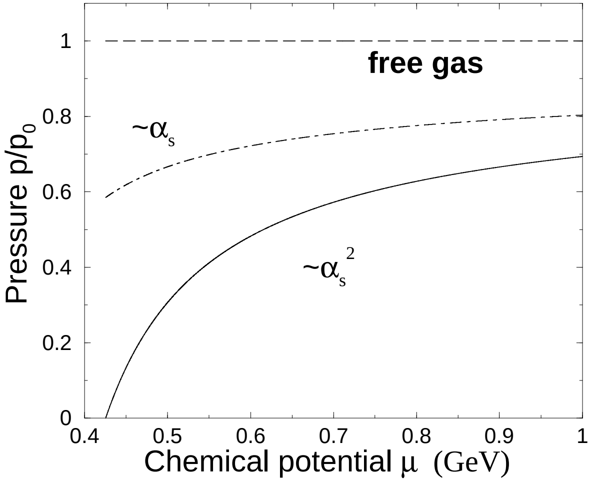


Variation of the energy per baryon E/A with the strange quark mass and the QCD structure constant α_s [from Zdunik, A&A **359**, 311 (2001)]

Alternatives to the bag model for strange quark matter

- **Dey et al. EOS SS1 and SS2** [Dey, Bombaci, Dey, Ray, Samanta, PLB **438**, 123 (1998)]: "dynamical" density-dependent approach to confinement, with asymptotic freedom built in; quark interaction described by
  - ⋆ a colour-Debye-screened inter-quark vector potential originating from gluon exchange
  - ⋆ a density-dependent scalar potential which restores chiral symmetry at high density

- **high density EOS from perturbative QCD** [Fraga, Pisarski, Schaffner-Bielich, PRD **63**, 121702(R) (2001)]: up to the second order in α_s.



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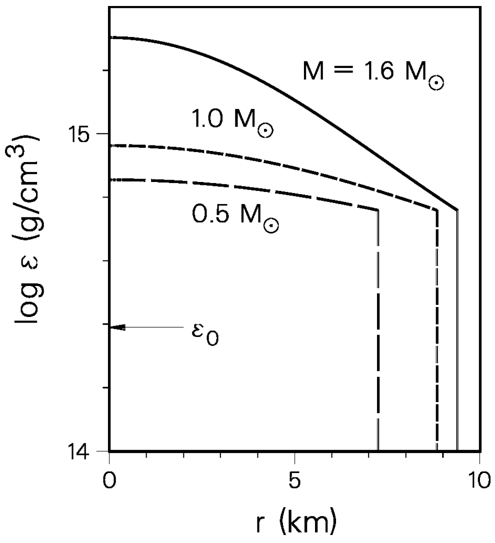
Numerical models of strange quark stars

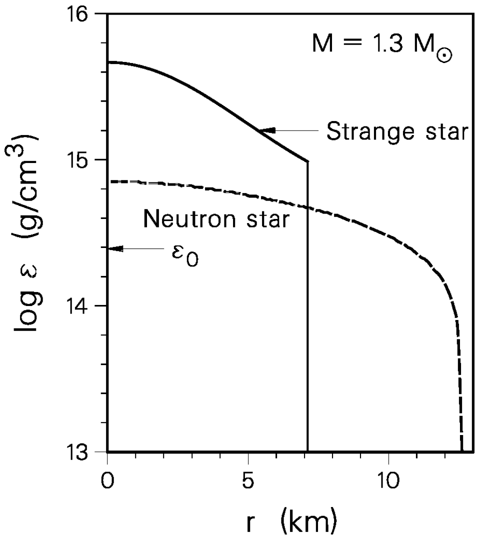
Static strange stars

First numerical models computed by Haensel, Zdunik & Schaeffer [A&A **160**, 121 (1986)] and Alcock, Fahri & Olinto [ApJ **310**, 261 (1986)] by integration of the **Tolman-Oppenheimer-Volkoff equations** with MIT bag-model EOS.

Basic features:

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

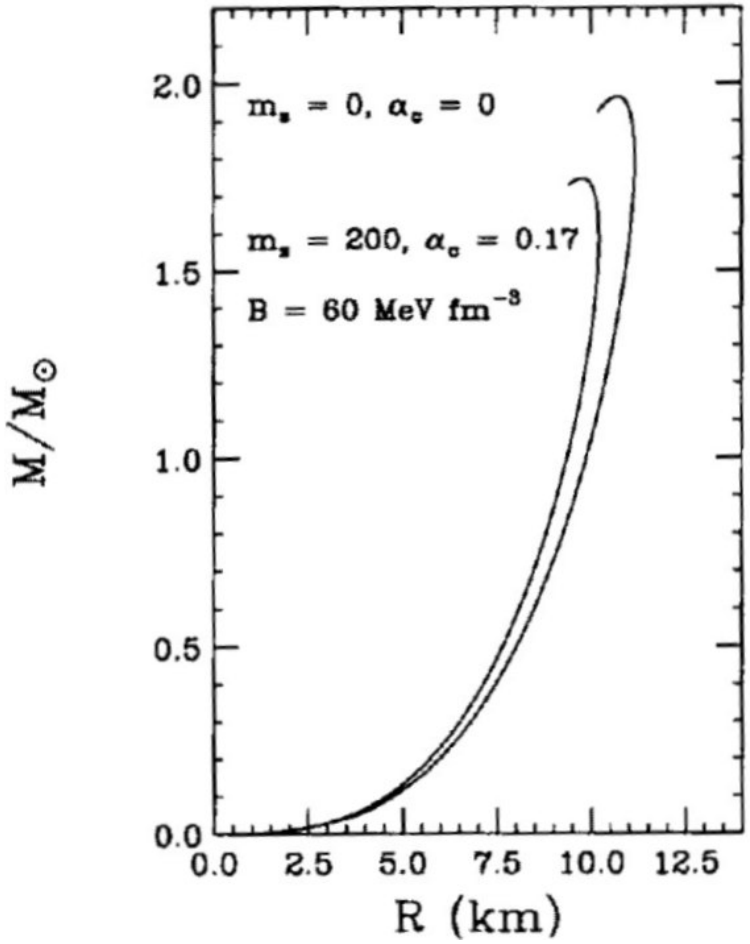




[from Glendenning (1997)]

Mass-radius relation

From strangelets to strange stars



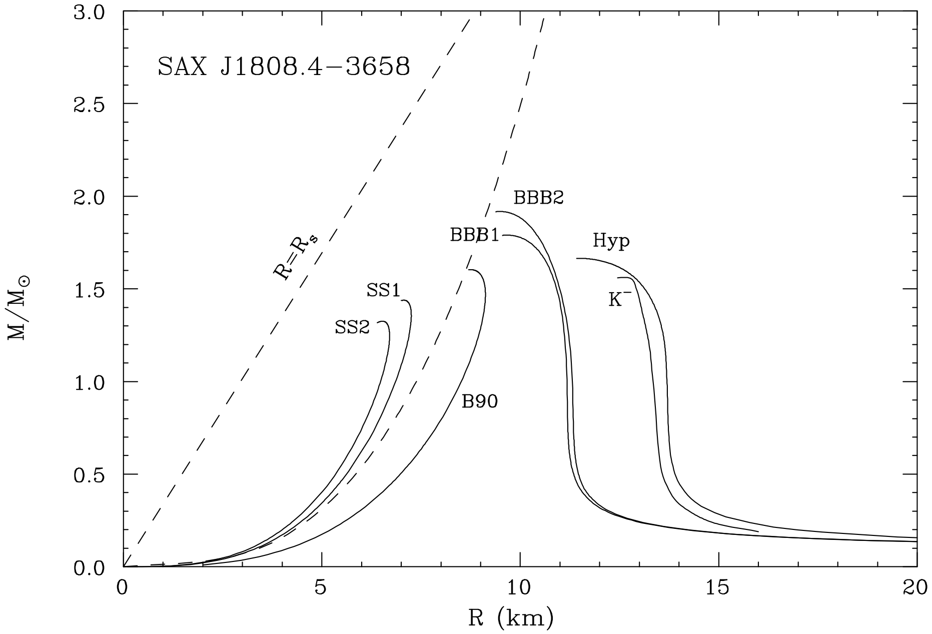
Gravitational mass as a function of the areal radius for nonrotating strange stars in the MIT bag model [from Bombaci (2001)]

Approximate scaling laws (exact for $\alpha_{\rm s} = 0$) [Zdunik, A&A **359**, 311 (2001)] :

$$M \simeq M\left[B_{60} = 1, \alpha_{\rm s}, m_{\rm s} {B_{60}}^{-1/4}\right] \; {B_{60}}^{-1/2}$$

$$R \simeq R\left[B_{60} = 1, \alpha_{\rm s}, m_{\rm s} {B_{60}}^{-1/4}\right] \; {B_{60}}^{-1/2}$$

Comparison with neutron stars



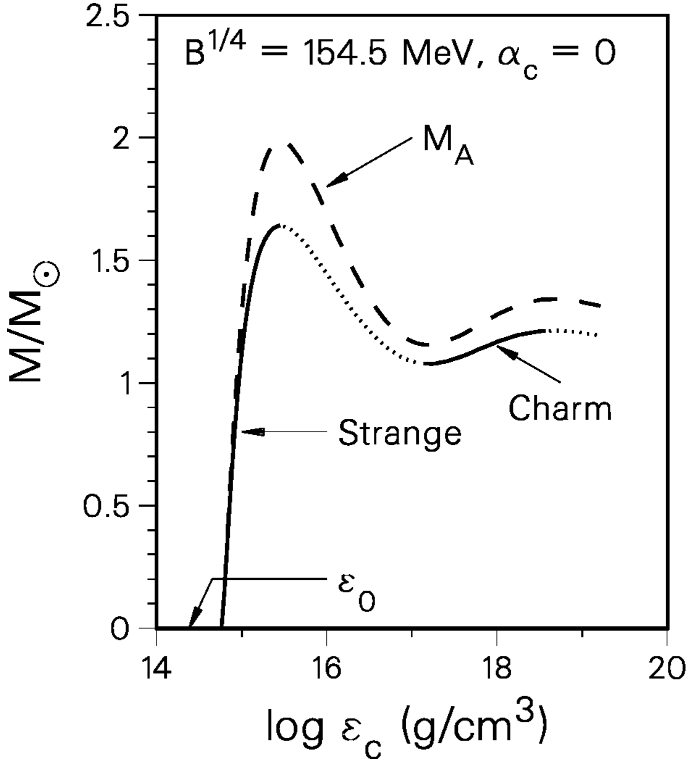
Gravitational mass as a function of the areal radius for nonrotating neutron stars (BBB1, BBB2, Hyp and K^-) and nonrotating strange stars in the MIT bag model (B90) and Dey et al model (SS1 and SS2) [from Bombaci (2002)]

neutron stars = gravitationally bound objects

strange quark stars ∼ self-bound objects

What about charm stars ?

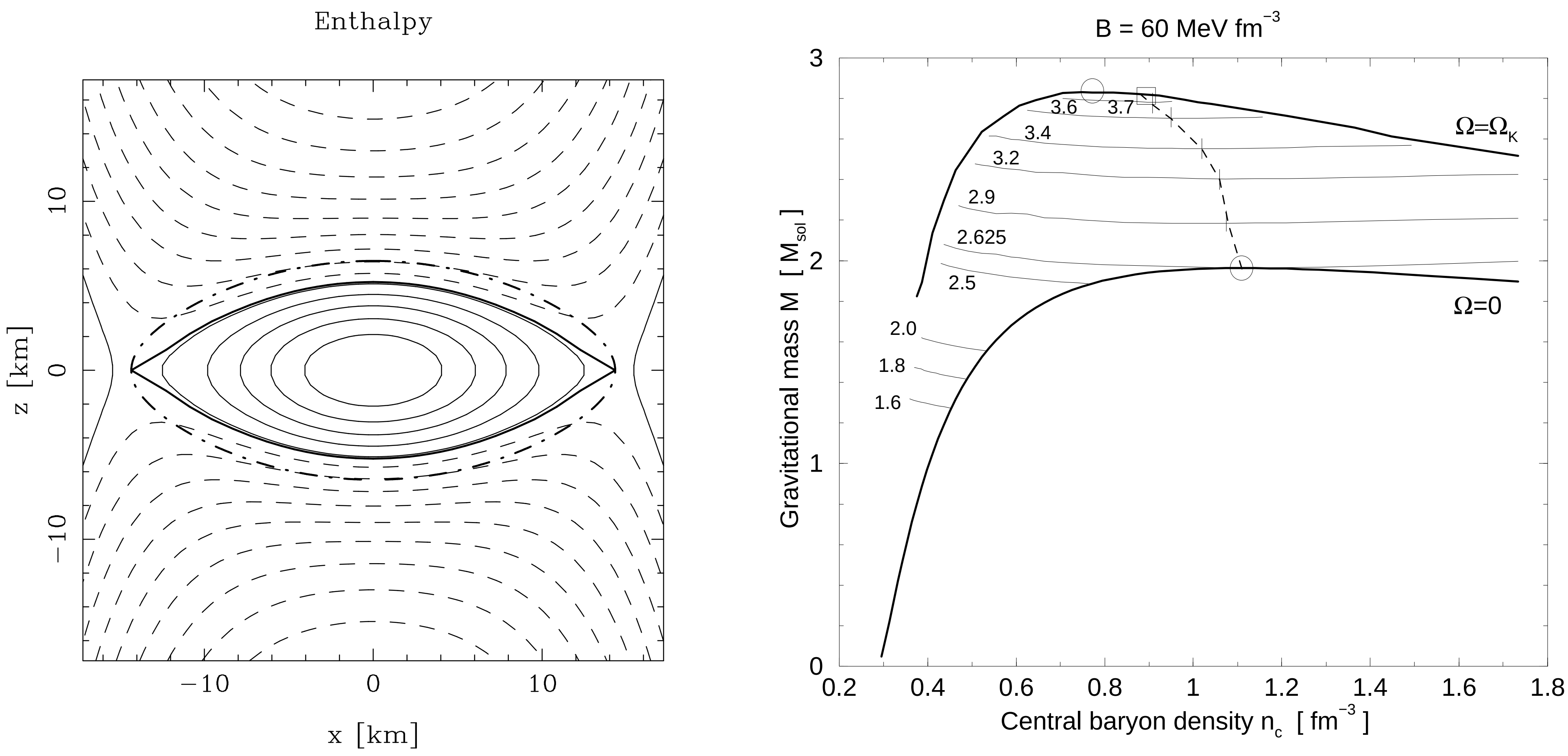
At very high density, charm quarks appear in the medium, in addition to u, d, and s quarks.



[from Glendenning (1997)]

Charm stars are **unstable** with respect to radial perturbations.

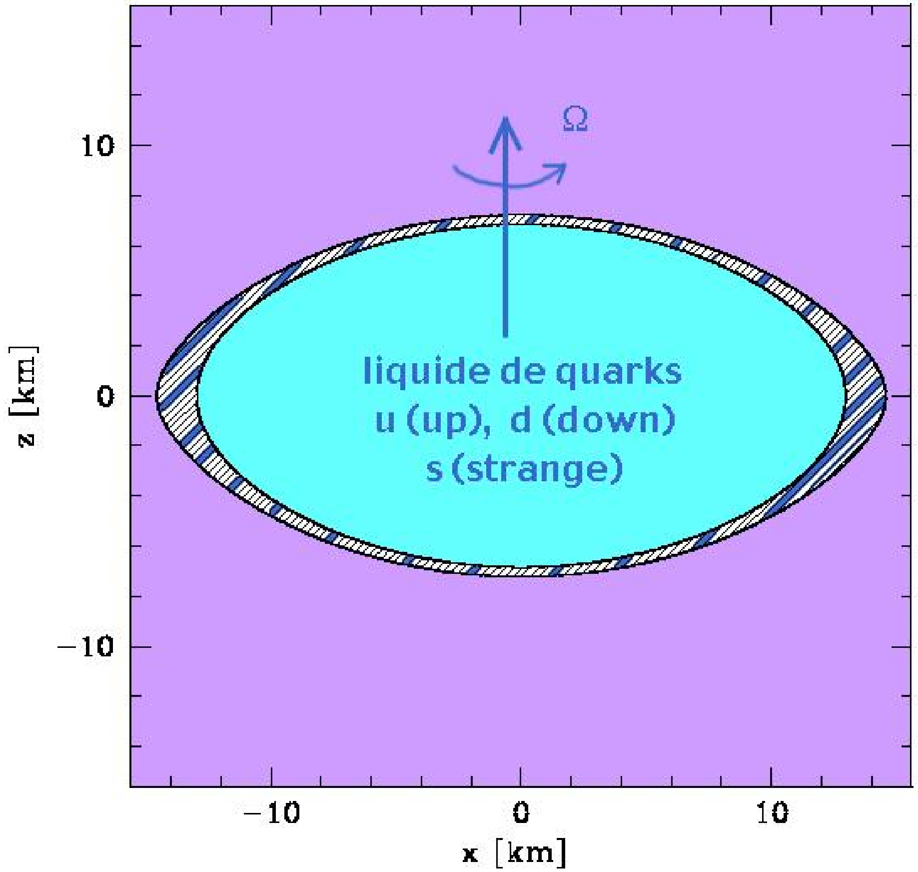
Rotating strange quark stars

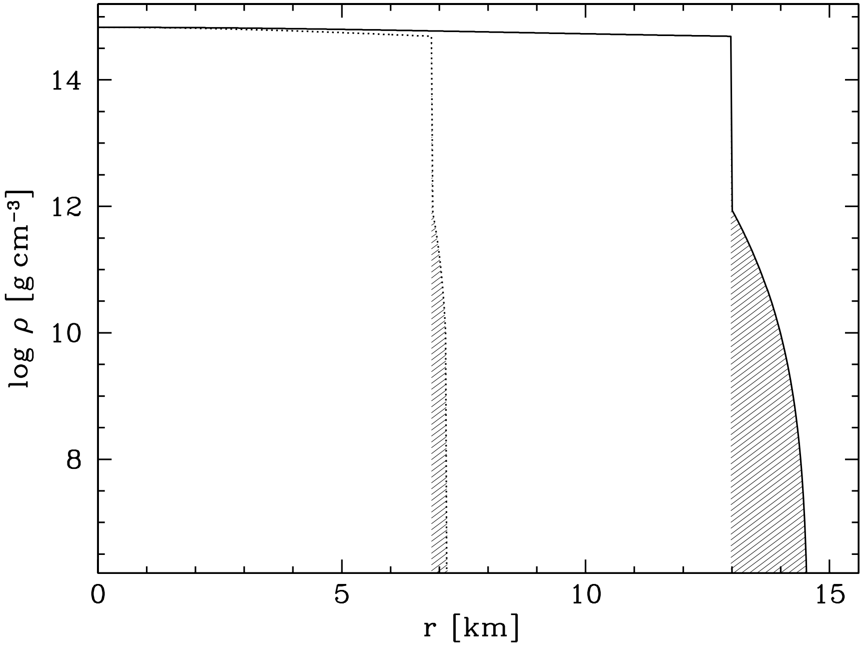


[from Gourgoulhon et al., A&A **349**, 851 (1999)]

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

Solid crust





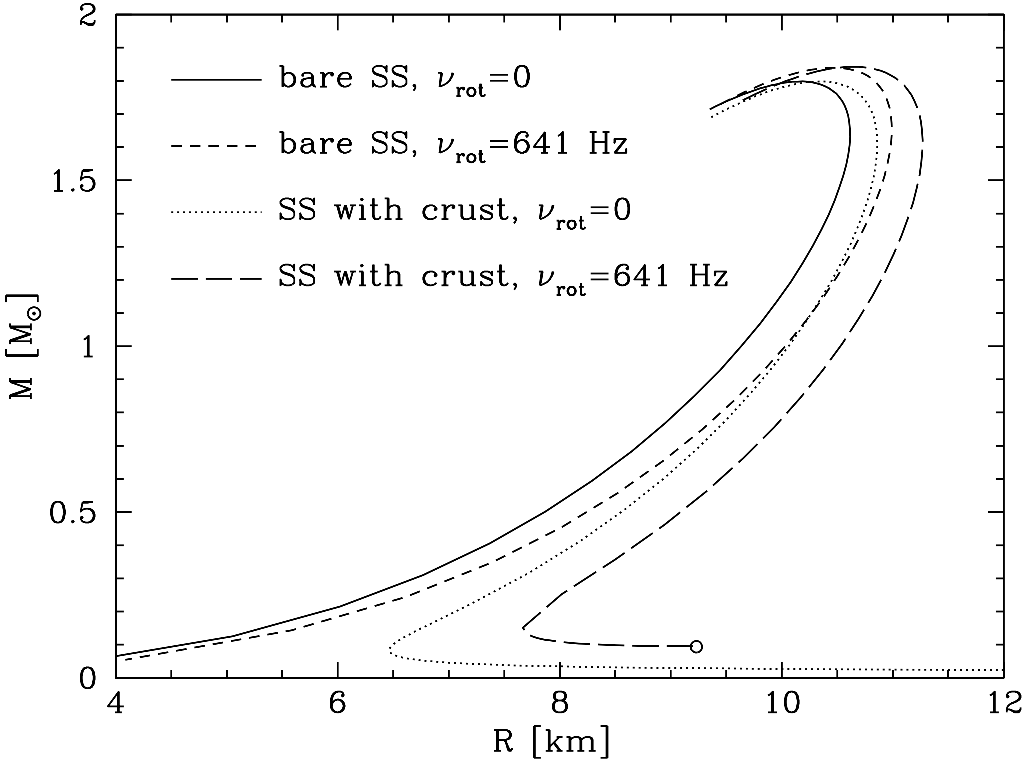
EOS: $B = 56\ \mathrm{MeV\,fm^{-3}}$, $\alpha_\mathrm{s} = 0.2$, $m_\mathrm{s} = 200\ \mathrm{MeV}\,c^{-2}$

star: $M_\mathrm{B} = 1.63\,M_\odot$, $f = 1210\ \mathrm{Hz}$.

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

Stellar radius in presence of crust

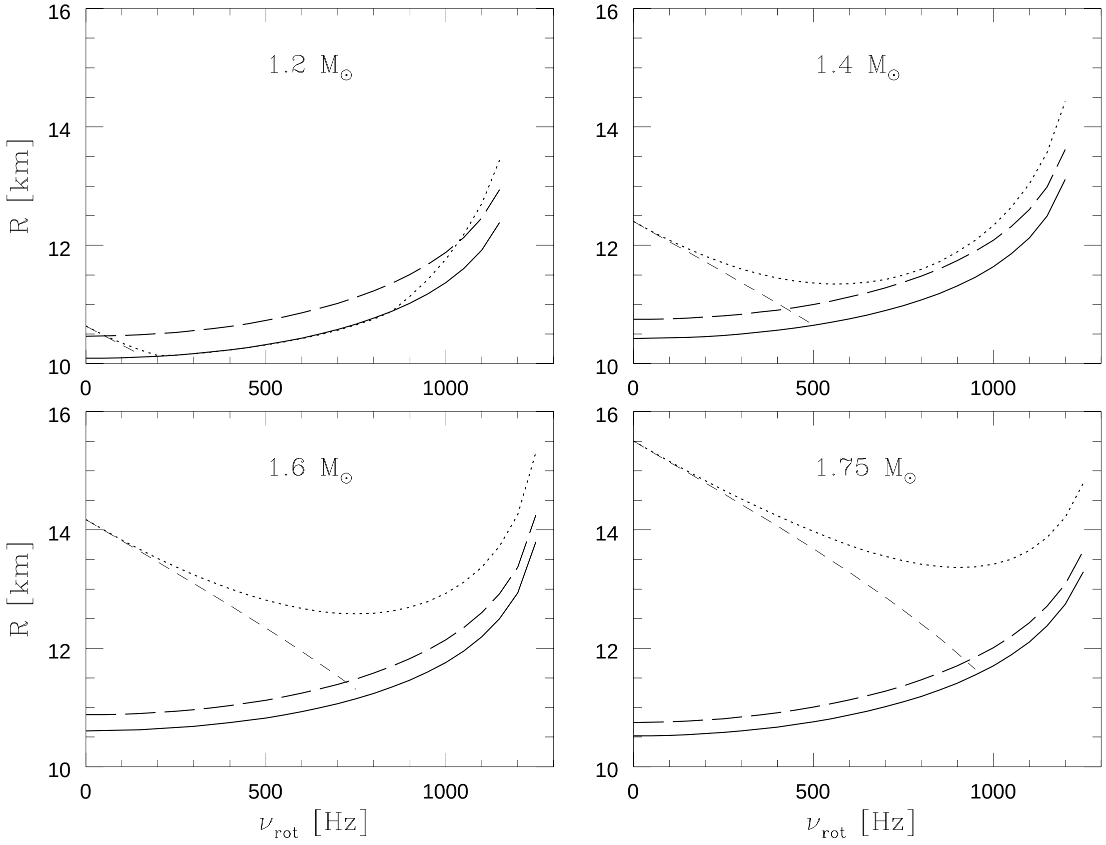
There exists a minimal radius:



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

Innermost stable circular orbit (ISCO)

Relativistic gravitation + rotation-induced oblateness ⇒ ISCO



· · · · · · radius of the ISCO

- - - - ISCO slow rot. approx.

– – – stellar radius with crust

——— radius of bare star

[from Zdunik, Haensel, Gondek-Rosińska, Gourgoulhon, A&A **356**, 612 (2000)]

Small mass strange stars seem to be the only objects in nature to have an ISCO around them given by purely Newtonian gravitational potential [Zdunik & Gourgoulhon, PRD **63**, 087501 (2001)], [Amsterdamski, Bulik, Gondek-Rosińska, Kluźniak, A&A **381**, L21 (2002)]

3

Searching for strange stars

Rapid rotators

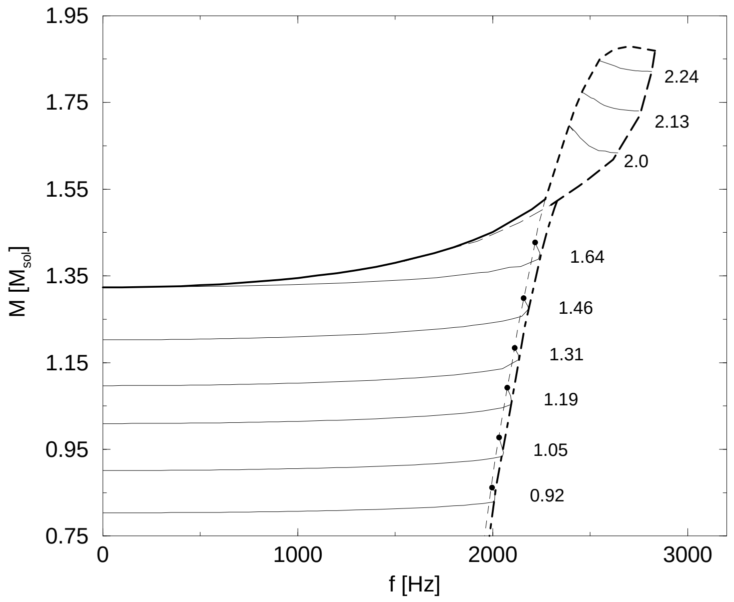
1989: announcement of discovery of a 0.5 ms pulsar in the remnant of supernova 1987A in LMC [Kristian et al., Nature **338**, 234 (1989)]

Rotation rate too rapid for standard neutron star EOS

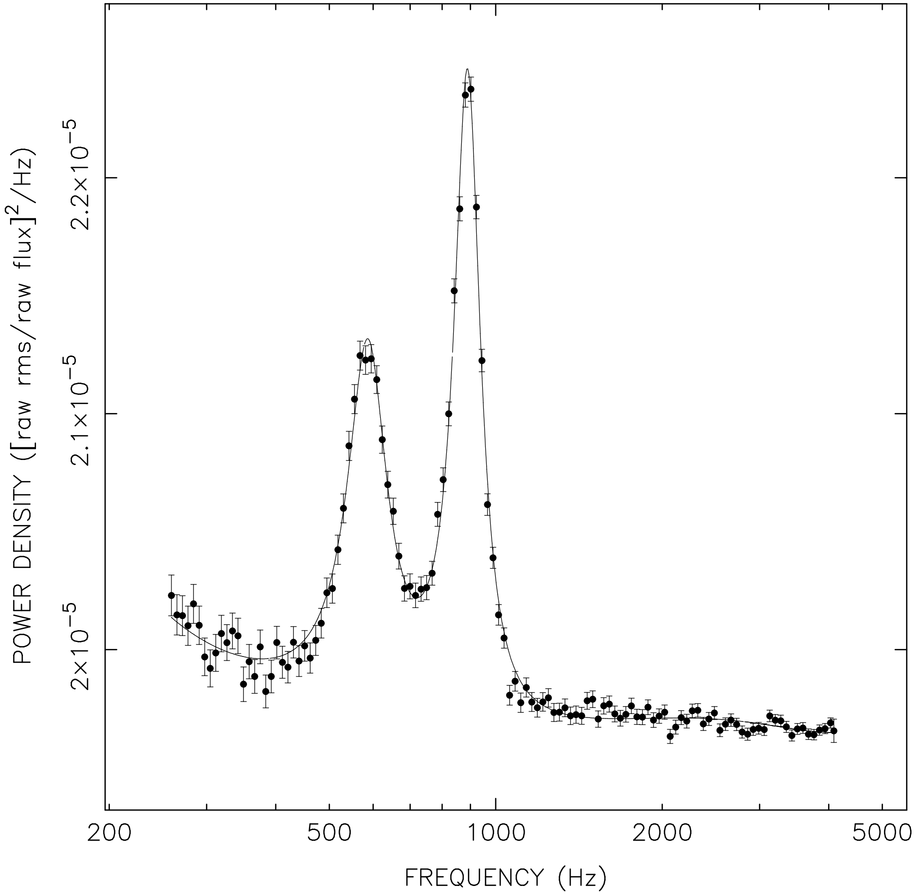
⇒ strange quark star could be a solution [Frieman, Olinto, Nature **341**, 633 (1989)] [Glendenning, PRL **63**, 2629 (1989)]

Mass-frequency plane for rotating strange stars constructed upon the Dey et al. EOS SS2

[from Gondek-Rosińska et al., A&A **363**, 1005 (2000)]



QPO in LMXB

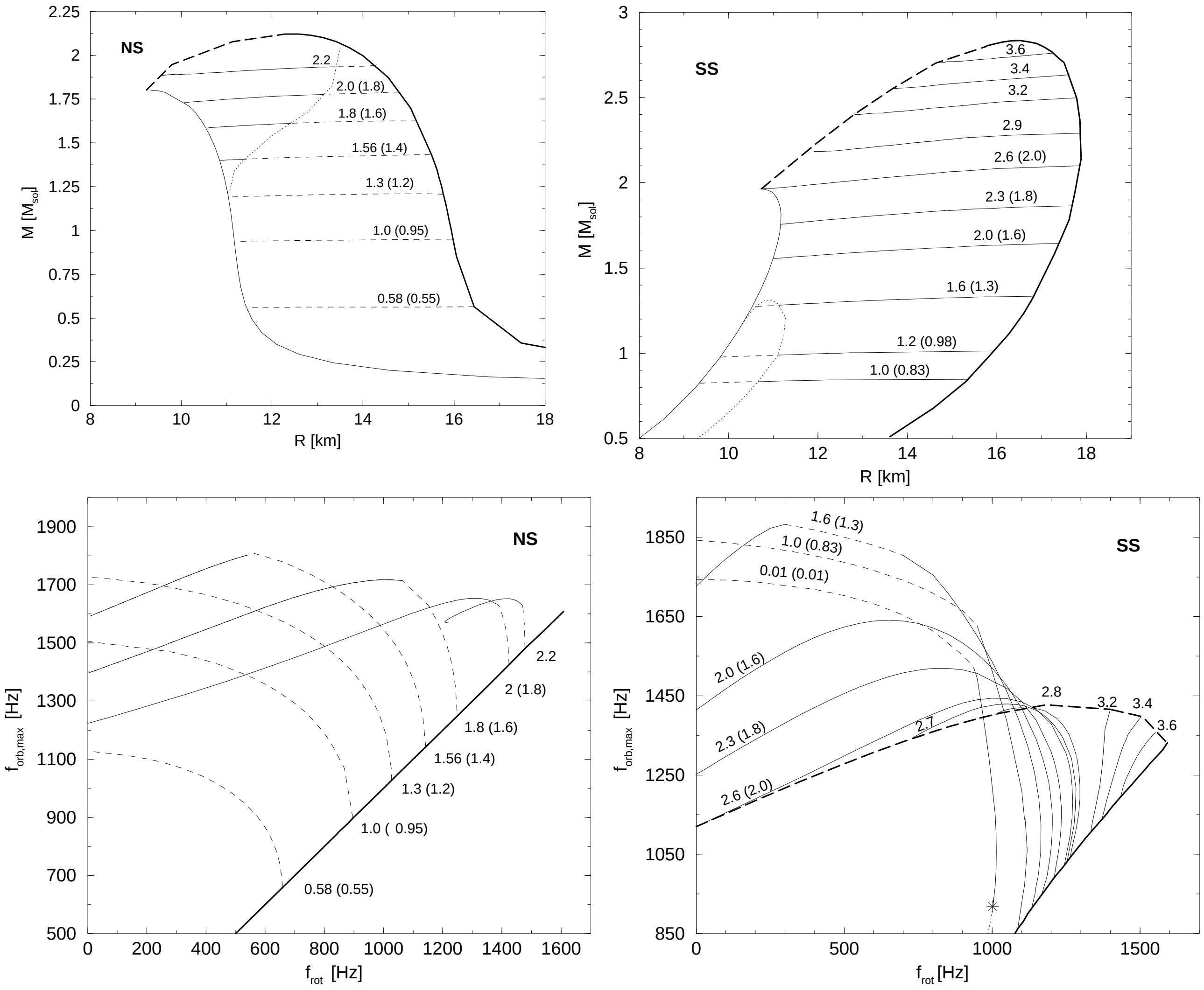


Quasi-periodic oscillations (QPO) observed by RXTE in the X-ray binary Sco X-1.

In the most popular model of QPOs, the high frequency peak gives the **orbital frequency at the inner edge of the accretion disk** ⇒ ISCO

Interpreting the QPO in terms of ISCO

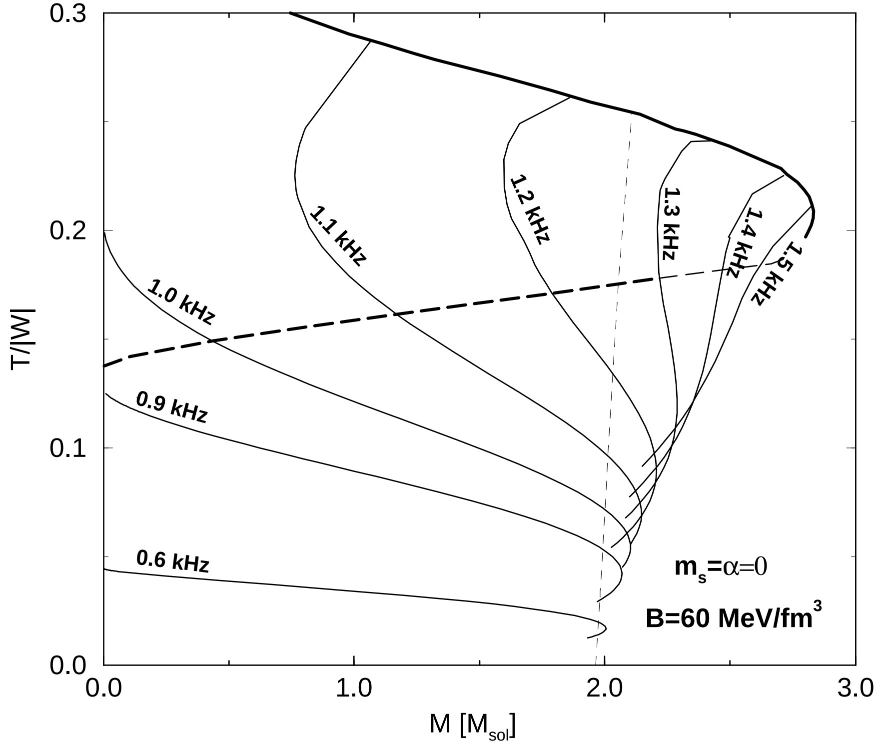
Neutron stars and strange quark stars have very different ISCO behavior:



[from Gondek-Rosińska, Kluźniak, Proc. Moriond 2002]

Gravitational radiation

Strange quark stars can have large T/W ratio $\Rightarrow$ Jacobi-like bar-mode instability (viscosity-driven) $\Rightarrow$ gravitational wave emission at twice the rotation frequency



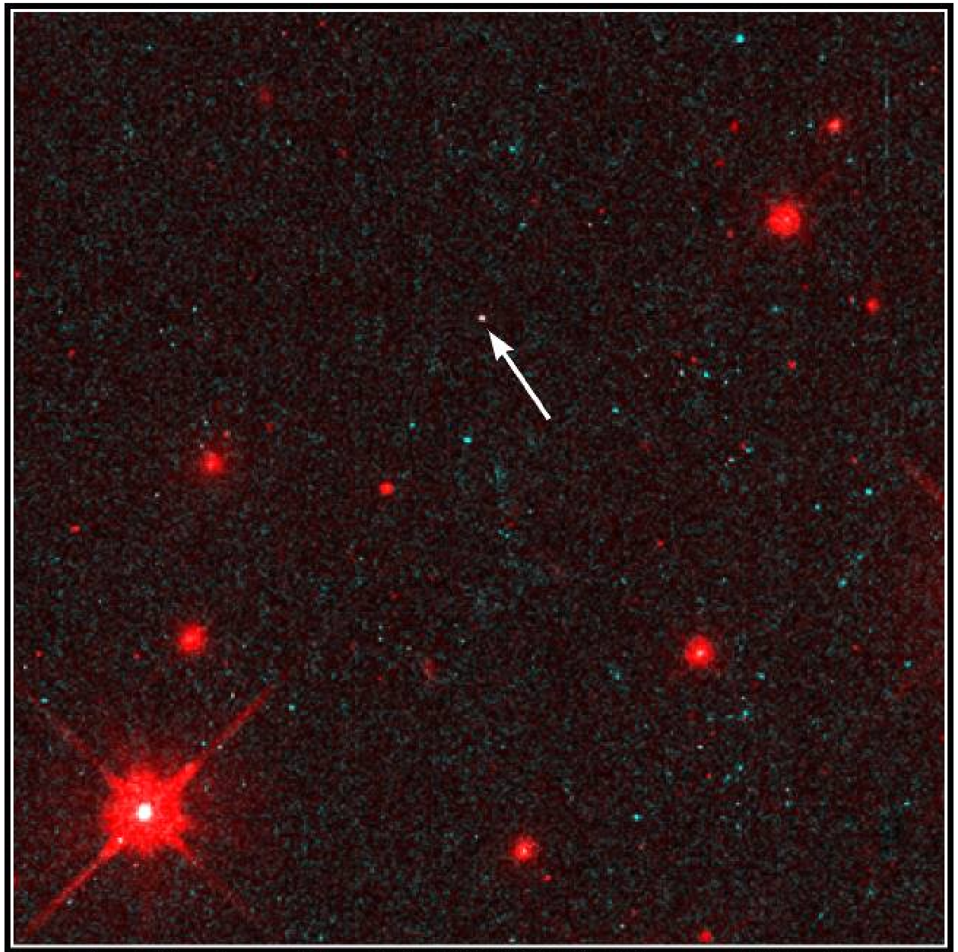
All configurations above the dashed line are unstable

[from Gondek-Rosińska, Gourgoulhon, Haensel, in preparation]

4

Chandra observations

RX J1856.5-3754

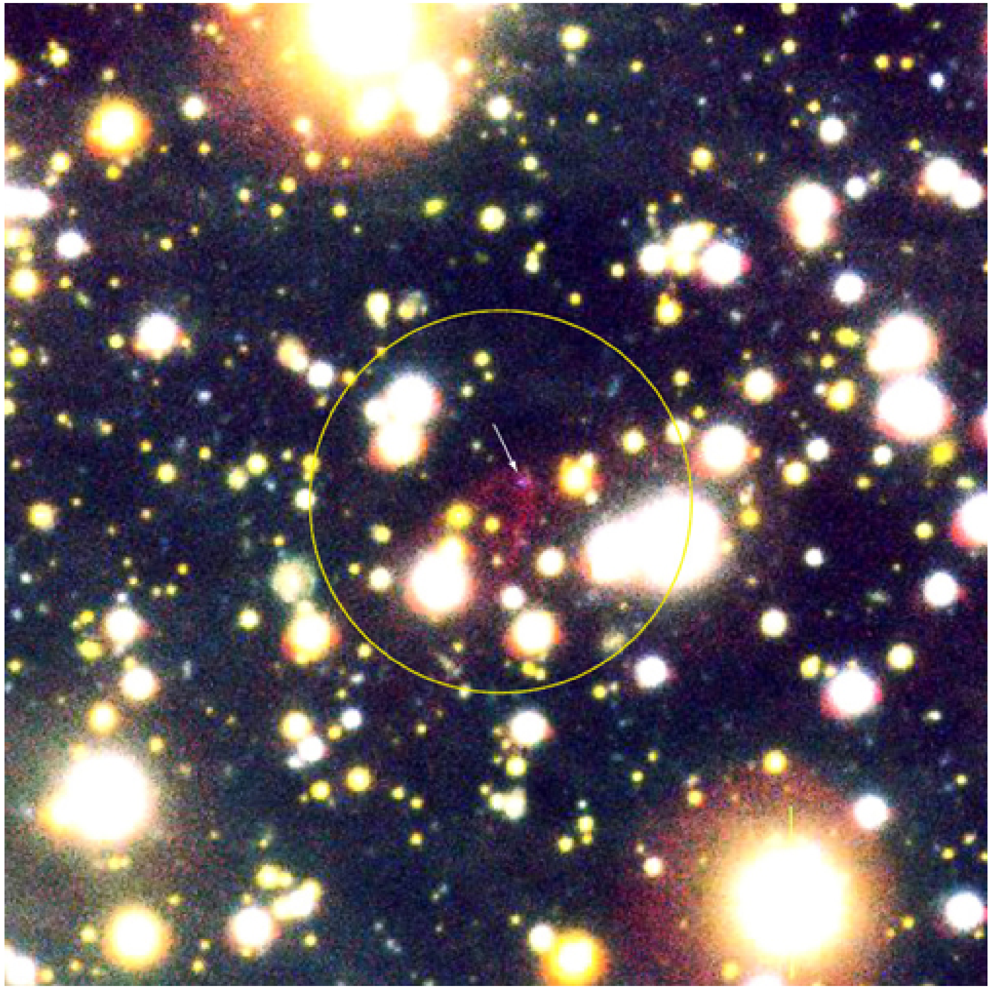


Isolated Neutron Star RX J185635-3754 HST • WFPC2
PRC97-32 • ST ScI OPO • September 25, 1997
F. Walter (State University of New York at Stony Brook) and NASA

- 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 $\Longleftrightarrow T_\infty \simeq 6.6 \times 10^5$ 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

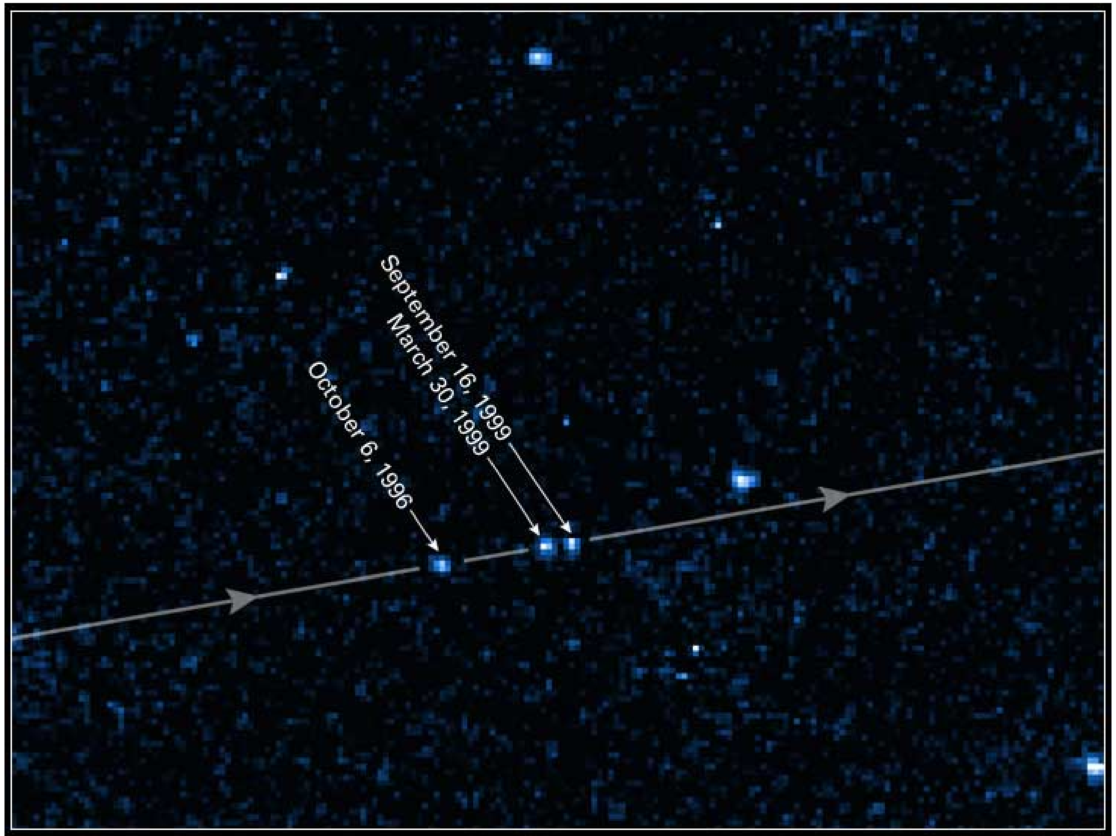
RX J1856.5-3754 observed by VLT



VLT Kueyen + FORS2 (field: $80" \times 80"$)

→ bowshock (heated interstellar gas by accelerated e^{-} and p from the star ?) [ESO 2000]

Distance to RX J1856.5-3754

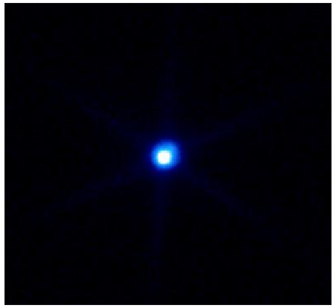


Neutron Star RX J185635-3754 HST • WFPC2

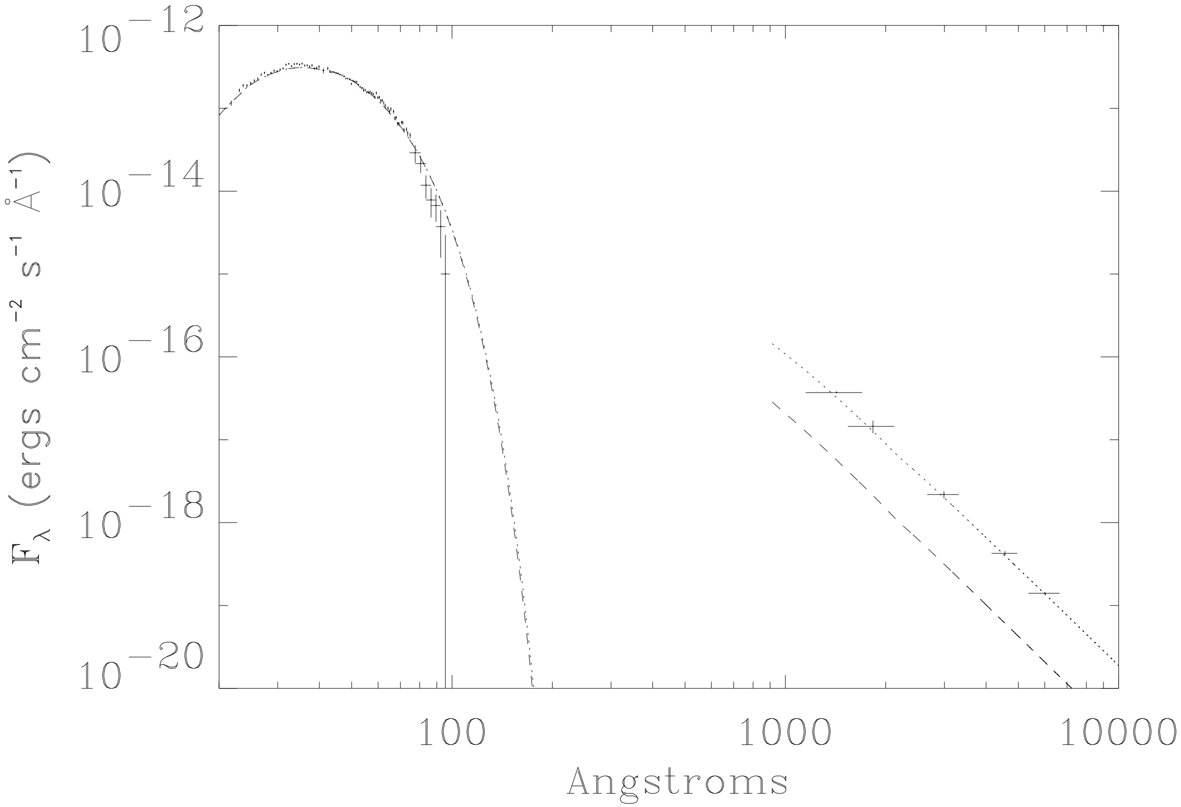
NASA and F. Walter (State University of New York at Stony Brook) • STScI-PRC00-35

- First measure of proper motion and parallax (erroneous) [Walter, ApJ **549**, 433 (2001)]
  $\Rightarrow$ erroneous $d = 61 \pm 9$ pc
- New determinations of parallax:
  $d = 140 \pm 40$ pc [Kaplan, van Kerkwijk, Anderson, astro-ph/0111174]
  $d = 117 \pm 12$ pc [Walter & Lattimer, astro-ph/0204199]

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 $R_\infty(15\text{ eV}) = 5R_\infty(63\text{ eV})$

[from Walter & Lattimer, astro-ph/0204199]

Simple estimation of radius from black body emission

Observed quantities: (at infinite distance from the star)

- electromagnetic flux f_∞
- surface temperature T_∞ (black body fit to the spectrum)
- distance d (parallax)

Estimation of the radius:

Total luminosity for black body emission: $L_\infty = 4\pi R_\infty^2 \sigma T_\infty^4$

Flux on Earth: $f_\infty = \dfrac{L_\infty}{4\pi d^2} = \left(\dfrac{R_\infty}{d}\right)^2 \sigma T_\infty^4$

Hence the radius "measured" at infinity: $\boxed{R_\infty = \dfrac{d}{T_\infty^2}\left(\dfrac{f_\infty}{\sigma}\right)^{1/2}}$

Relation between R_∞ and the true radius of the star R

Areal radius of the star (surface value of the Schwarzschild coordinate r): R

Redshift factor at the surface of the star: $N = \sqrt{-g_{00}} = \left(1 - \frac{2GM}{c^2 R}\right)^{1/2}$

Gravitational dilation of time: $dt_\infty = N^{-1} dt \quad$ (N : *lapse function*)

Energy and wavelength of a particle reaching infinity: $E_\infty = NE$ and $\lambda_\infty = N^{-1}\lambda$

Luminosity at infinity: $L_\infty = \frac{dE_\infty}{dt_\infty} = N^2 \frac{dE}{dt} = N^2 L$

Local black body emissivity: R areal radius $\Rightarrow L = 4\pi R^2 \sigma T^4$

“Observed” temperature: $\lambda_{\max} T = \mathrm{const.} \Rightarrow T_\infty = NT$

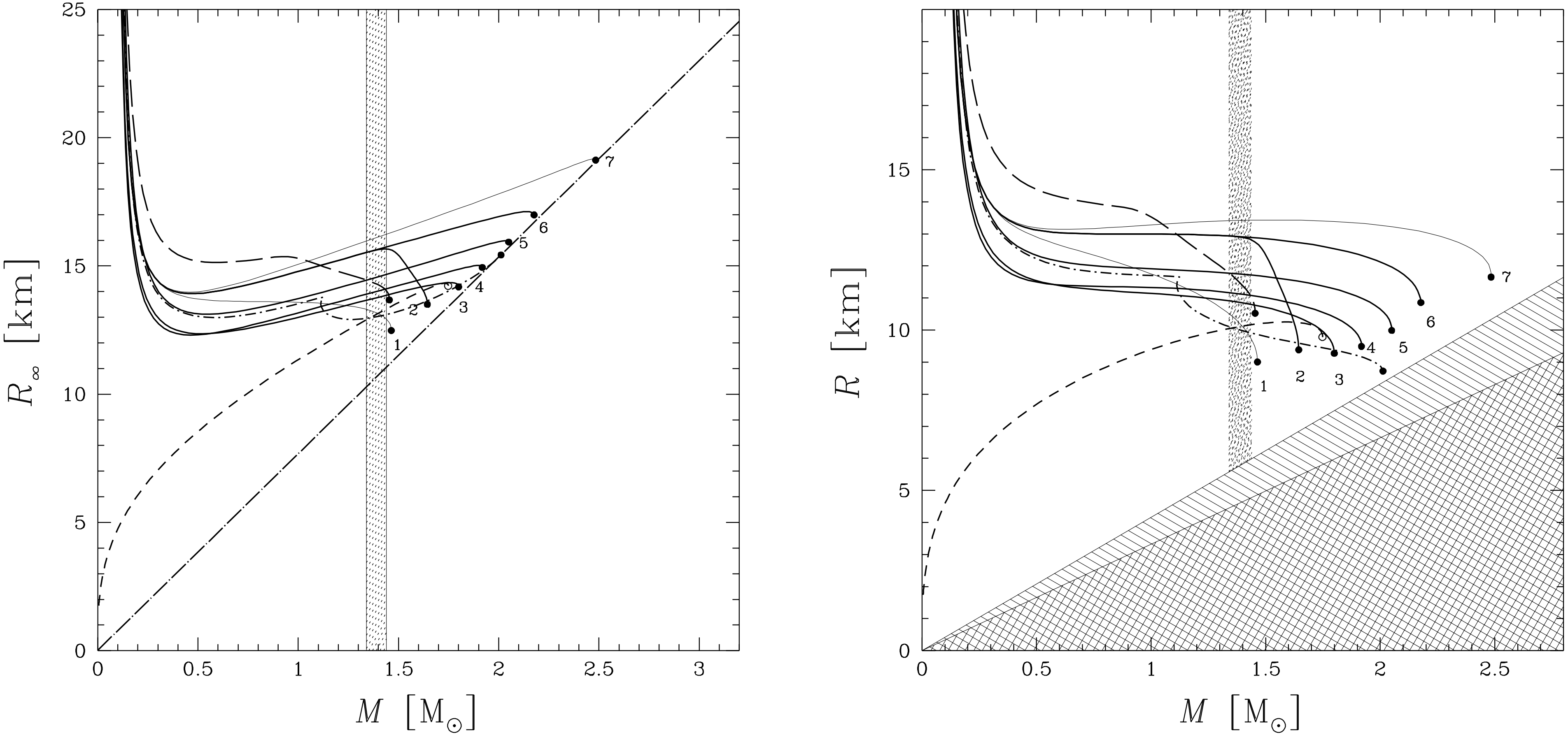
Observed black body: $L_\infty = 4\pi R_\infty^2 \sigma T_\infty^4$

Hence $R_\infty = N^{-1} R$, i.e. $\boxed{R_\infty = \left(1 - \frac{2GM}{c^2 R}\right)^{-1/2} R}$

The very small radius puzzle

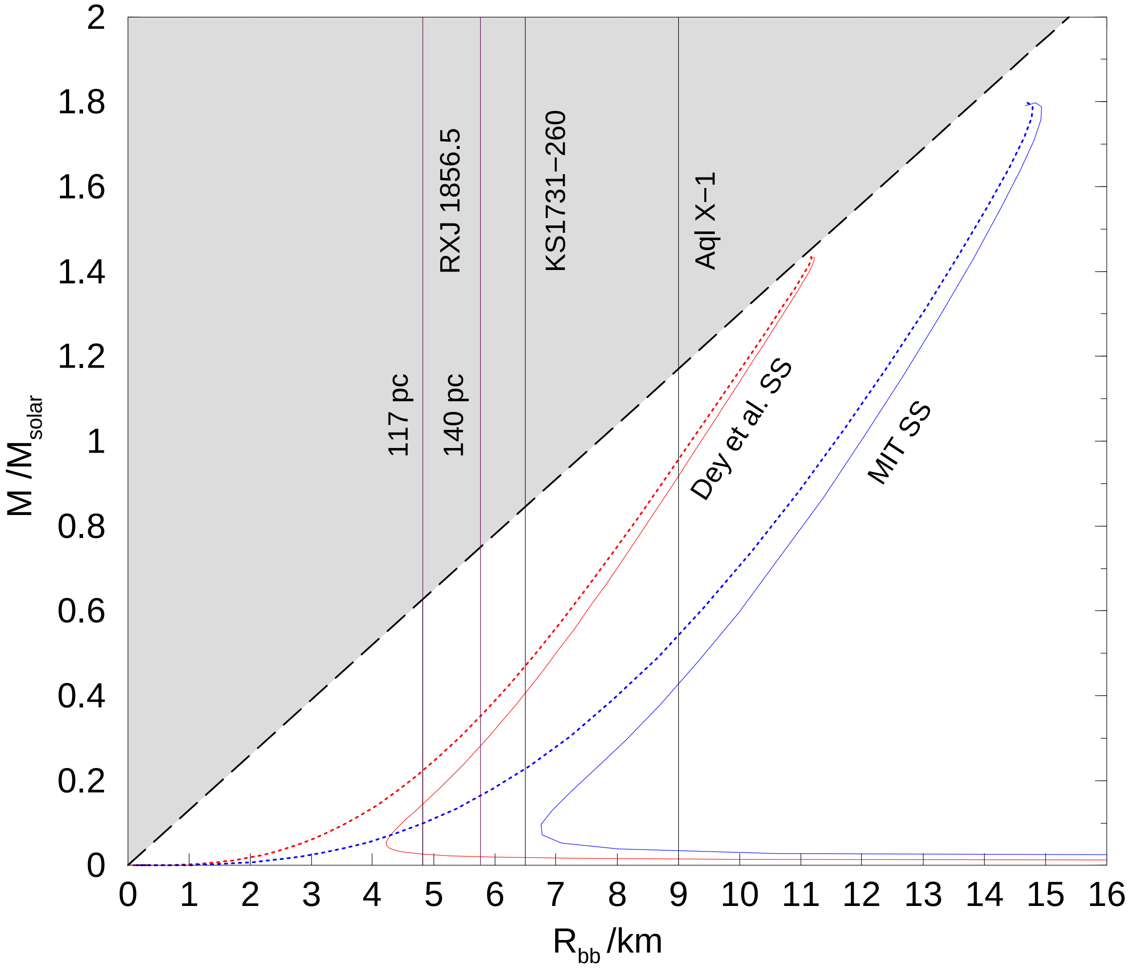
- Erroneous distance of Walter 2001 : $d = 61\ \mathrm{pc} \Rightarrow R_\infty = 3.3\ \mathrm{km}$ (for $f_\infty^{\mathrm{ROSAT}}$ and $kT_\infty = 57\ \mathrm{eV}$).
- New distance of Walter & Lattimer 2002 : $d = 117\ \mathrm{pc} \Rightarrow R_\infty = 4.8\ \mathrm{km}$ (for $f_\infty^{\mathrm{Chandra}}$ and $kT_\infty = 61\ \mathrm{eV}$).
- New distance of Kaplan et al. 2002 : $d = 140\ \mathrm{pc} \Rightarrow R_\infty = 5.8\ \mathrm{km}$ (for $f_\infty^{\mathrm{Chandra}}$ and $kT_\infty = 61\ \mathrm{eV}$).

Minimal radius of neutron stars



Solid lines: neutron star models; *dashed line:* strange quark star with MIT bag model EOS: $B = 41\ \mathrm{MeV\,fm^{-3}}$, $m_{\mathrm{s}} = 150\ \mathrm{MeV}\,c^{-2}$, $\alpha_{\mathrm{s}} = 0.6$ [from Haensel, A&A **380**, 186 (2001)].

Minimal radius of strange quark stars



[from Gondek-Rosińska, Kluźniak & Stergioulas, in preparation (2002)]

A proposed solution

Pons et al. [ApJ **564**, 981 (2002)] : the emission is not a pure black body one.

Two atmospheric models:

1. Uniform temperature + heavy elements (Fe)
2. Two thermal components (optical flux from cooler part)

Model 1 ⇒ $R_\infty \simeq 15\ \mathrm{km}$ for $d = 117\ \mathrm{pc}$, $f_\infty^{\mathrm{ROSAT}}$ and $kT_\infty = 57\ \mathrm{eV}$

Model 2 ⇒ $R_\infty \simeq 21\ \mathrm{km}$ for $d = 117\ \mathrm{pc}$, $f_\infty^{\mathrm{Chandra}}$ and $kT_\infty = 63\ \mathrm{eV}$

[Walter & Lattimer, astro-ph/0204199]

Recent Chandra observations

Drake et al. [ApJ **572**, 996 (2002)] have conducted deep observations of RX J1856.5-3754 in October 2001 (446 ks of data).

Findings:

- X-ray spectrum well represented by a black body spectrum with $kT_\infty = 61.2 \pm 1.0\ \mathrm{eV}$ ($T_\infty = 7.1 \times 10^5\ \mathrm{K}$)
- no heavy element spectral lines ⇒ disfavors atmospheric model 1 of Pons et al. (2002)
- no X-ray pulsation (pulse fraction $< 2.7\%$) ⇒ disfavors atmospheric model 2 of Pons et al. (2002)

Inferred pure black body radius: $R_\infty = 4.12 \pm 0.68\ \mathrm{km}\ \dfrac{d}{100\ \mathrm{pc}}$

Has a strange quark star been discovered ?

Maybe, but one should remain cautious:

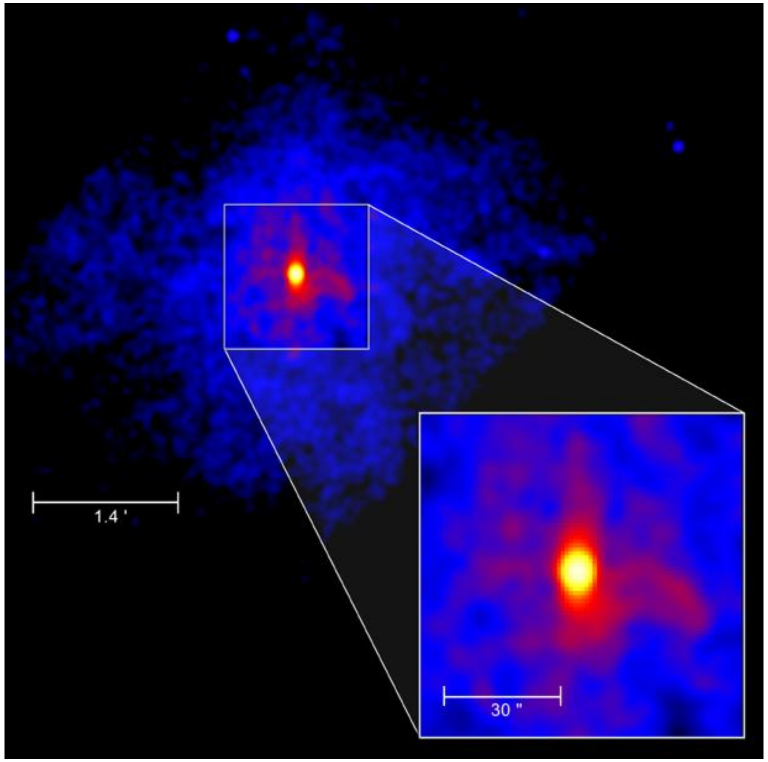
- extrapolation of the $\sim 61\ \mathrm{eV}$ black body spectrum to low frequencies underpredicts the optical flux by a factor 6 [Walter & Lattimer, astro-ph/0204199]
- disagreement between Chandra flux and ROSAT one: $f_{\mathrm{Chandra}} \sim 0.8 f_{\mathrm{ROSAT}}$
- $R_\infty = 5.8\ \mathrm{km}$ $(d = 140\ \mathrm{pc})$ implies a maximum mass of only $\sim 0.7\, M_\odot$ $\Rightarrow$ how to form such light star ?

A possible answer proposed by Nakamura [astro-ph/0205526] :
Gravitational collapse of a very rapidly neutron star with Kerr parameter J/M^2 larger than 1 does not lead to a black hole but to a small mass quark star $+$ a jet. In addition this provides a source for gamma ray bursts !

The second strange star candidate: 3C 58

3C 58: remnant of the supernova SN 1181 (younger than Crab nebula: SN 1054)

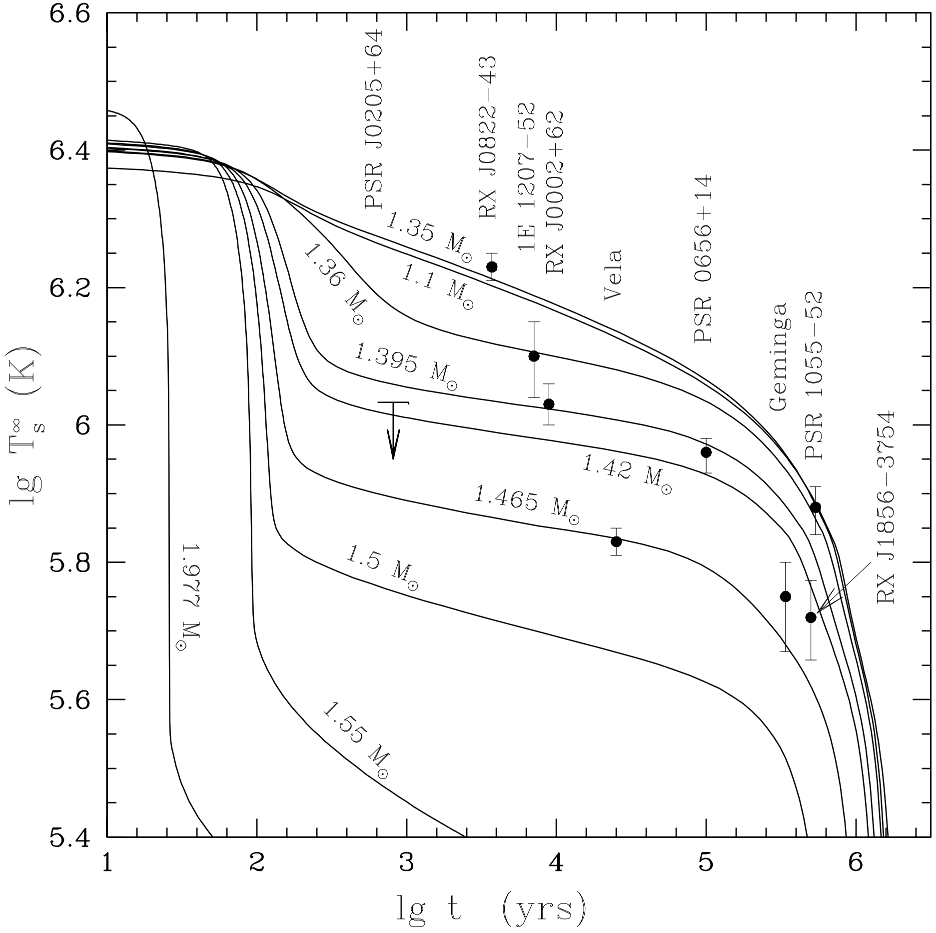
Central object: X-ray and radio pulsar PSR J0205+6449, $P = 65\ \mathrm{ms}$, discovered by Chandra observations [Murray et al., ApJ **568**, 226 (2002)]



Argument for a strange quark star: $T_\infty < 1.1 \times 10^6\ \mathrm{K}$, too cold for a neutron star 820 years old [Slane, Helfand, Murray, ApJ **571**, L45 (2002)]

...but this argument is not conclusive !

Many alternatives are possible within cooling theories of ordinary neutron stars:



[from Yakovlev, Kaminker, Haensel, Gnedin, astro-ph/0204233]

Conclusions and perspectives

- From our (poor) knowledge of strong interaction, it is not inconceivable that **strange quark matter** constitutes the ground state of cold dense matter.

- A class of compact stellar objects, bound by strong interaction (in addition to gravity), would then constitute an alternative to neutron stars: **strange quark stars**.

- Strange quark stars have some features (small radius, large break-up rotation velocity, location of ISCO, etc...) than make them **observationally distinguishable** from neutron stars.

- Discovering a strange quark star would be an extremely valuable contribution of **astrophysics** to **particle physics**.

- From the two claims of discovery based on recent Chandra observations, of **RX J1856.5-3754** can be considered as providing a strange quark star serious candidate. It has to be **confirmed** by further observational studies.

Conclusions and perspectives (cont'd)

- If RX J1856.5-3754 is confirmed as a strange star, there remains to explain the formation of such a **small mass** object.

- Since RX J1856.5-3754 is one of the closest compact stars, it would be then likely that **most, if not all, compact stars are actually strange quark stars**.

- A strong support for the possible existence of strange quark star would be the discovery of **strangelets** in the next generation of ultra-relativistic heavy ion colliders (RHIC at Brookhaven, LHC at CERN).