A short walk through the physics of neutron stars

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The final message of this talk

Neutron stars are excellent observatories to test fundamental properties of matter under extreme conditions and offer an interesting interplay between nuclear processes and astrophysical observables

Neutron stars are different things for different people

- For astronomers are very little stars "visible" as radio pulsars or sources of X- and γ-rays.

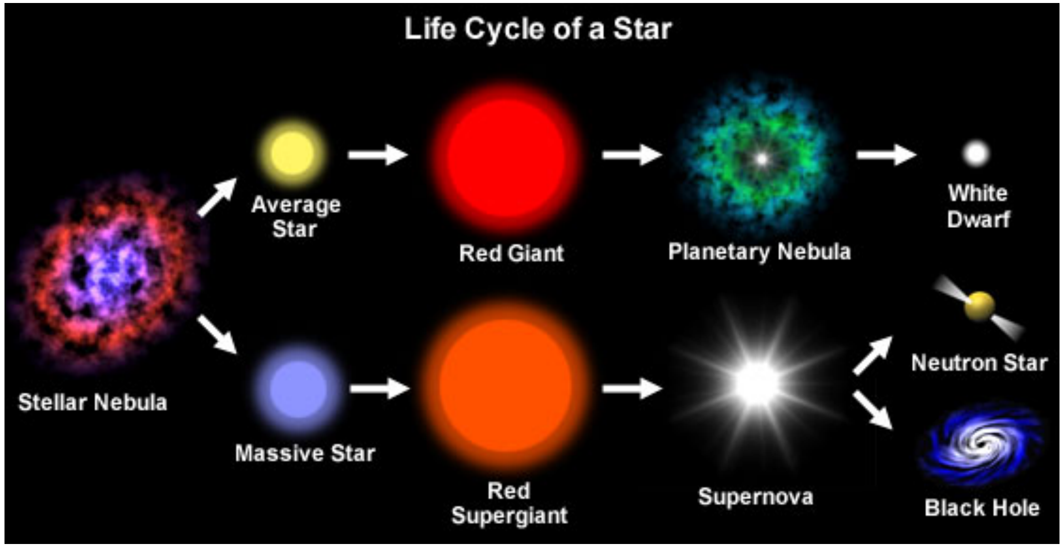
- For particle physicists are neutrino sources (when they born) and probably the only places in the universe where deconfined quark matter may be abundant.

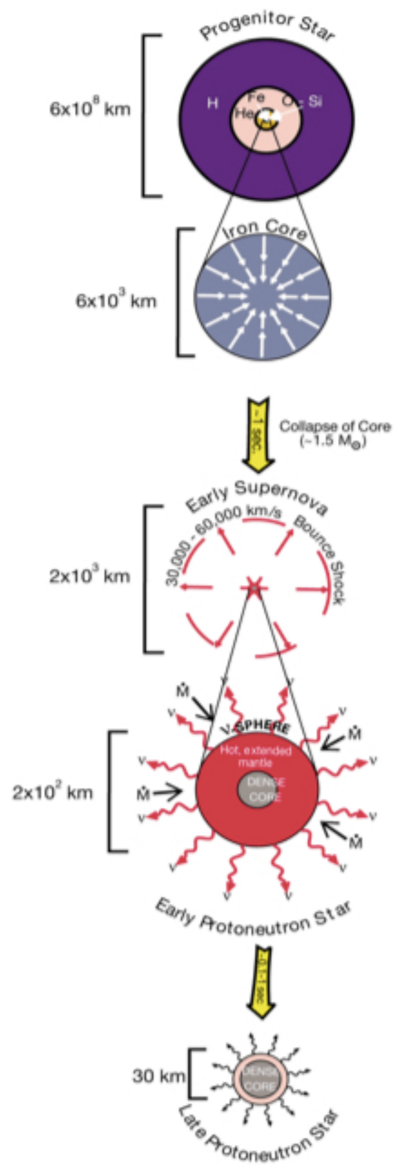
- For nuclear physicists are the biggest nuclei of the universe ($A \sim 10^{56}$-10^{57}, $R \sim 10$ km, $M \sim 1$-$2\ M_{\odot}$).

- For cosmologists are "almost" black holes

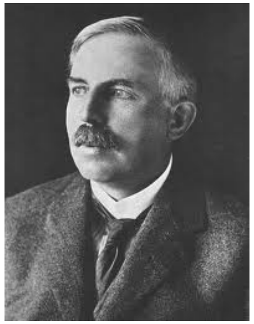
But everybody agrees that …

Neutron stars are a type of stellar compact remnant that can result from the gravitational collapse of a massive star ($8\,M_{\odot} < M < 25\,M_{\odot}$) during a Type II, Ib or Ic supernova event.



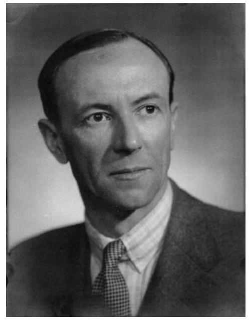


A bit of history & some pictures



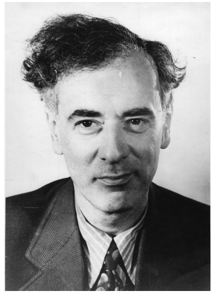
In 1920 Ernest Rutherford predicts the existence of the neutron

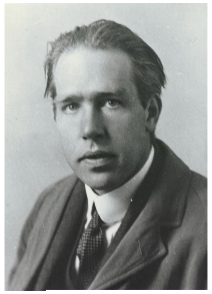
In 1932 James Chadwick discovers the neutron (1935 Nobel Prize) 



In 1934 Walter Baade & Fritz Zwicky predict the existence of neutron stars and their formation in supernova events

Did Landau anticipate their existence in 1931 ?





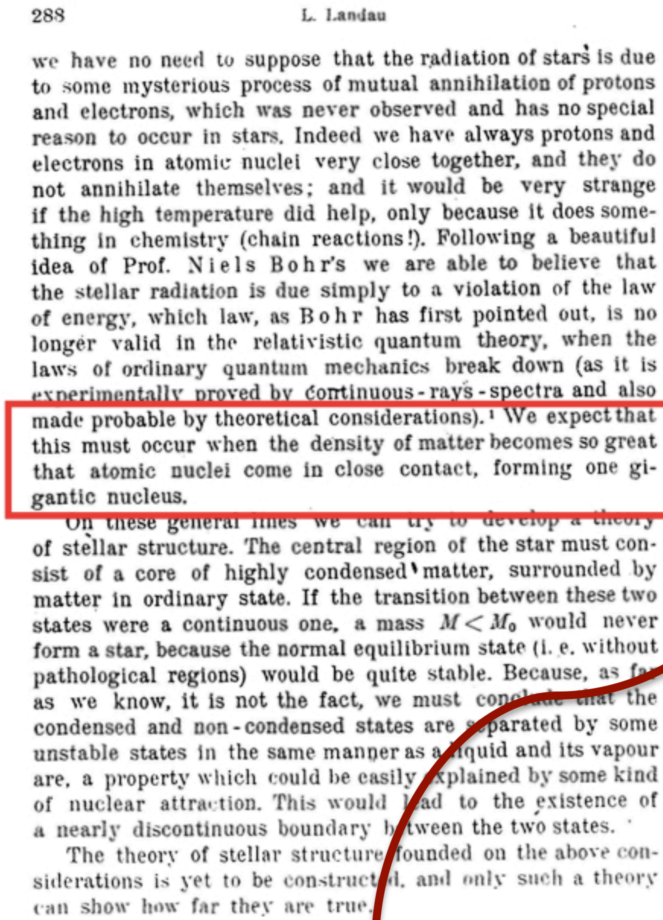
- ✓ February-March 1931 Landau, Bohr & Rosenfeld discuss in Copenhagen a paper by Landau (not published then) about the possible existence of very dense stars

- ✓ In February 1932 Landau publishes the article in a Russian journal that is completely unnoticed.

Source: G. Baym, P. Haensel, C. Petick & D. G. Yakovlev

- ✓ http://www.ift.uni.wroc.pl/ ~karp44/talks/yakovlev.pdf
- ✓ P. Haensel et al., *Neutron Stars 1. Equation of State & Structure (*2007)

Phys. Z. Sowjetunion 1, 285 (1932)



288 L. Landau

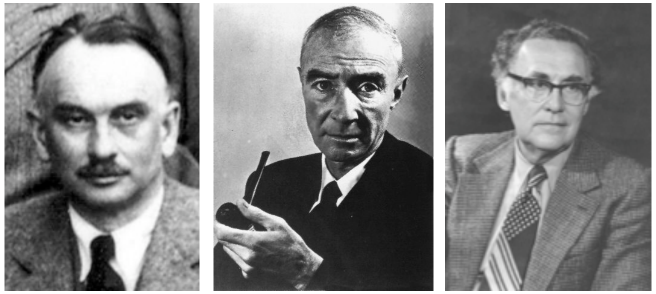
we have no need to suppose that the radiation of stars is due to some mysterious process of mutual annihilation of protons and electrons, which was never observed and has no special reason to occur in stars. Indeed we have always protons and electrons in atomic nuclei very close together, and they do not annihilate themselves; and it would be very strange if the high temperature did help, only because it does something in chemistry (chain reactions!). Following a beautiful idea of Prof. Niels Bohr's we are able to believe that the stellar radiation is due simply to a violation of the law of energy, which law, as Bohr has first pointed out, is no longer valid in the relativistic quantum theory, when the laws of ordinary quantum mechanics break down (as it is experimentally proved by continuous-rays-spectra and also made probable by theoretical considerations).[1] We expect that this must occur when the density of matter becomes so great that atomic nuclei come in close contact, forming one gigantic nucleus.

On these general lines we can try to develop a theory of stellar structure. The central region of the star must consist of a core of highly condensed matter, surrounded by matter in ordinary state. If the transition between these two states were a continuous one, a mass $M < M_0$ would never form a star, because the normal equilibrium state (i. e. without pathological regions) would be quite stable. Because, as far as we know, it is not the fact, we must conclude that the condensed and non-condensed states are separated by some unstable states in the same manner as a liquid and its vapour are, a property which could be easily explained by some kind of nuclear attraction. This would lead to the existence of a nearly discontinuous boundary between the two states.

The theory of stellar structure founded on the above considerations is yet to be constructed, and only such a theory can show how far they are true.

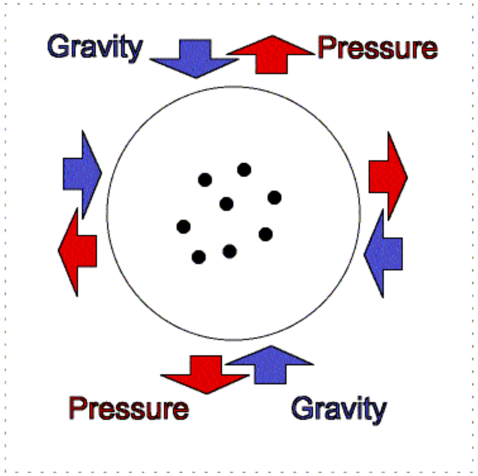
"We expect that this occur when the density of matter becomes so great that atomic nuclei come in contact, forming one gigantic nucleus"

In 1939 Tolman, Oppenheimer & Volkoff obtain the equations that describe the structure of a static star with spherical symmetry in General Relativity (Chandrasekhar & von Neumann obtained them in 1934 but they did not published their work)



Tolman, Phys. Rev. 55, 364 (1939)

Oppenheimer & Volkoff, Phys. Rev. 55, 374 (1939)

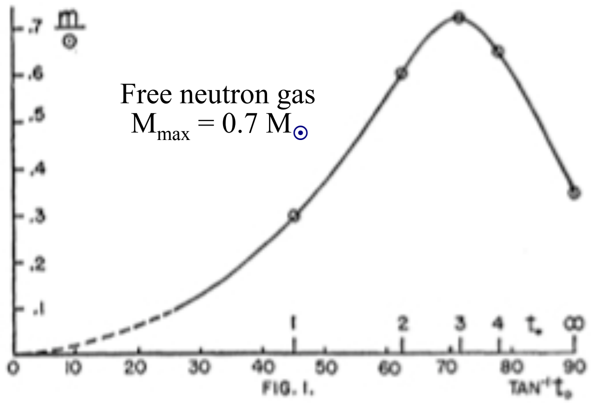


$$\frac{dP}{dr} = -G\frac{m(r)\varepsilon(r)}{r^2}\left(1+\frac{P(r)}{c^2\varepsilon(r)}\right)\left(1+\frac{4\pi r^3 P(r)m(r)}{c^2}\right)\left(1-\frac{2Gm(r)}{c^2 r}\right)^{-1}$$

$$\frac{dm}{dr} = 4\pi r^2\varepsilon(r)$$

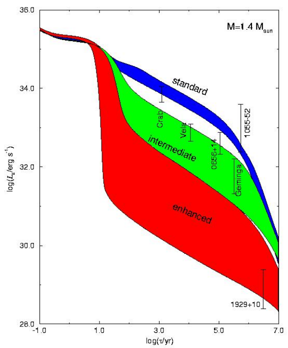
- boundary conditions

$$P(0) = P_o\,, \quad m(0) = 0$$
$$P(R) = 0\,, \quad m(R) = M$$



First “realistic” EoS of dense matter by Wheeler *et al.* in the 50s. In 1959 Cameron studies neutron star models with a Skyrme EoS finding $M_{max} \sim 2M_{\odot}$

In 1959 Migdal suggests superfluidity in neutron stars

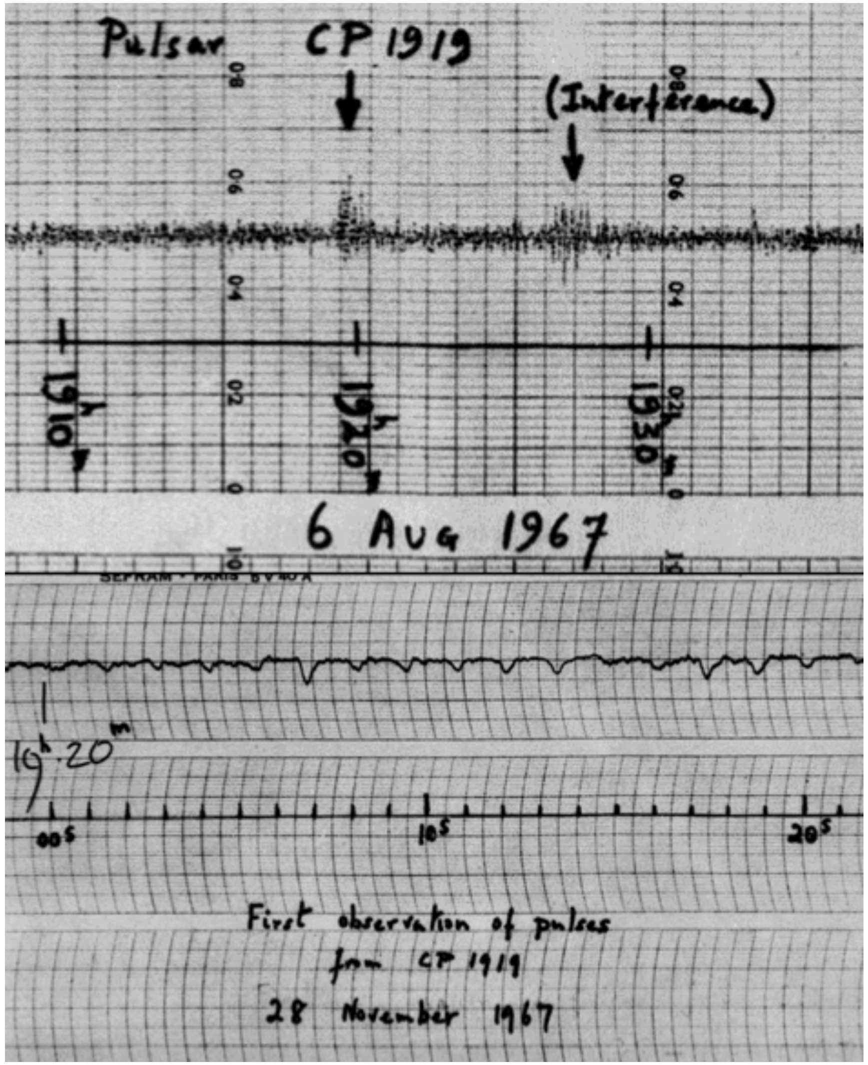


Theoretical efforts in the 60s focused on modeling neutron star cooling motivated by hope of detecting their thermal emission

Riccardo Giacconi starts in the 60s the first observations with X-ray telescopes on board of satellites discovering many X-ray sources (2002 Nobel Prize)

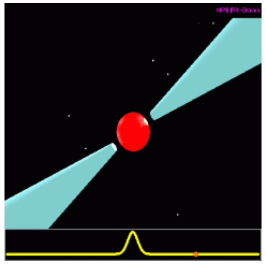
✧ radio pulsar at 81.5 MHz

✧ pulse period P=1.337 s



In 1967 Jocelyn Bell & Anthony Hewish discover the first radio pulsar, soon identified as a rotating neutron star (1974 Nobel Prize for Hewish but not for Jocelyn) 

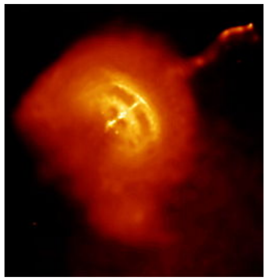
Also in 1967 Pacini shows that a rapidly rotating neutron star with a strong dipole magnetic field could power the Crab nebula



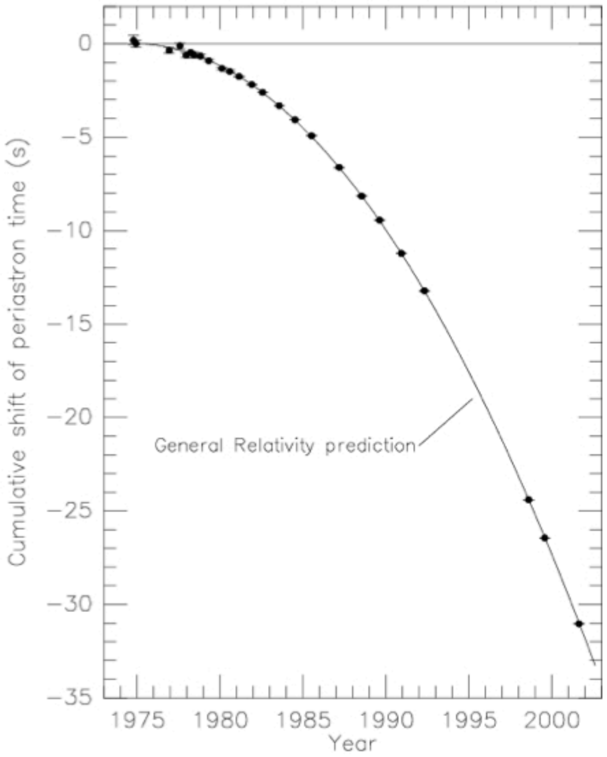
In 1968 Gold proposes that pulsars are strongly magnetized neutron stars radiating at expenses of their rotational energy

http://pulsar.ca.astro.it/pulsar/Figs

$$\dot{E}_{mag} = -\frac{2}{3c^3}\left|\ddot{\vec{\mu}}\right|^2$$



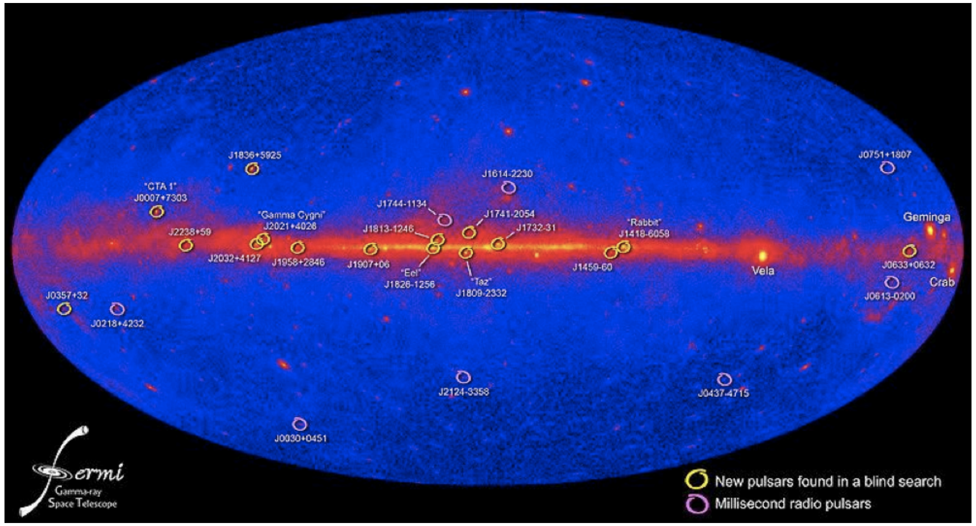
In 1968 the Crab & Velar pulsars are discovered in SNR confirming the prediction of Baade & Zwicky



In 1974 R. A. Hulse & J. H. Taylor discover the first binary pulsar (1993 Nobel Prize)

80's, 90's and 2000's: launch of satellites with X-ray (Einstein, ROSAT, ASCA, Chandra, XMM-Newton) and γ-ray (INTEGRAL, SWIFT, FERMI) telescopes

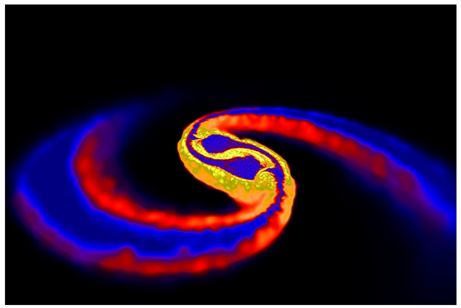
Most NS are observed as pulsars. Nowadays more than 2000 pulsars are known (~ 1900 Radio PSRs (141 in binary systems), ~ 40 X-ray PSRs & ~ 60 γ-ray PSRs)



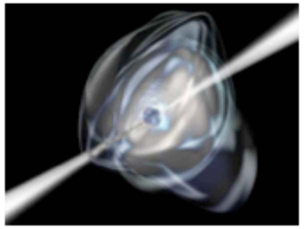
http://www.phys.ncku.edu.tw/~astrolab/mirrors/apod_e/ap090709.html

Observables

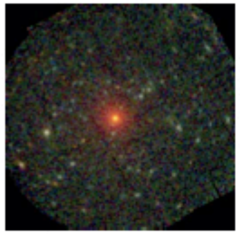
- Period (P, dP/dt)
- Masses
- Luminosity
- Temperature
- Magnetic Field
- Gravitational Waves (NS-NS, BH-NS mergers, NS oscillation modes)



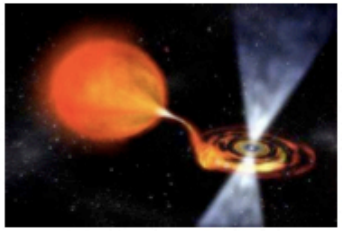
The 1001 Astrophysical Faces of Neutron Stars



Anomalous X-ray Pulsars

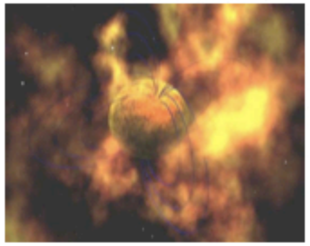


dim isolated neutron stars



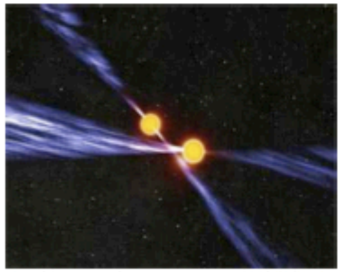
X-ray binaries

bursting pulsars

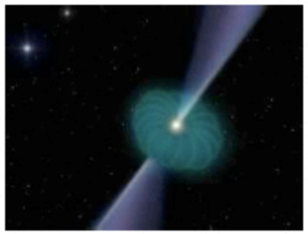


Soft Gamma Repeaters

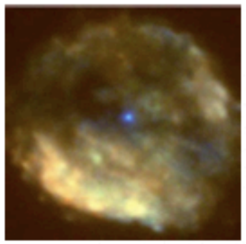
pulsars



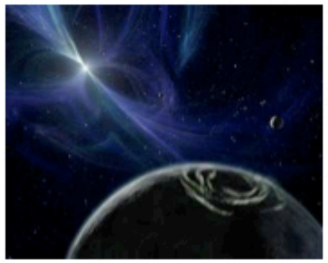
binary pulsars



Rotating Radio Transients



Compact Central Objects



planets around pulsar

Observation of Neutron Stars

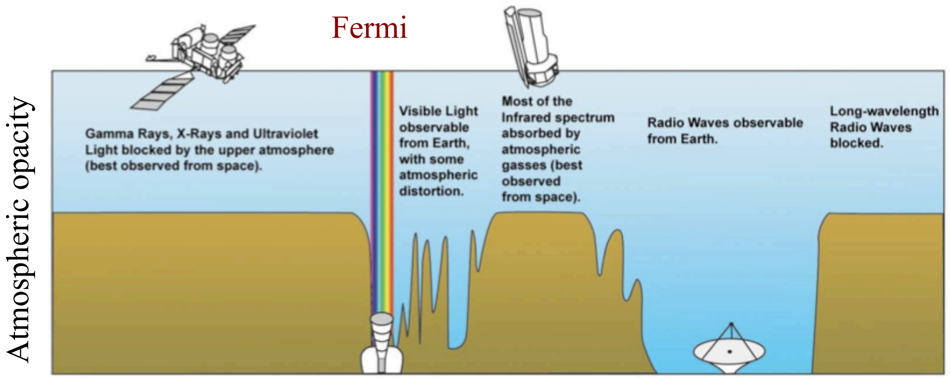
X- and γ-ray telescopes

Chandra

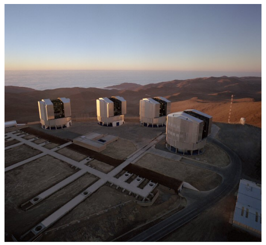
Fermi

Space telescopes

HST (Hubble)



Optical telescopes



VLT (Atacama, Chile)

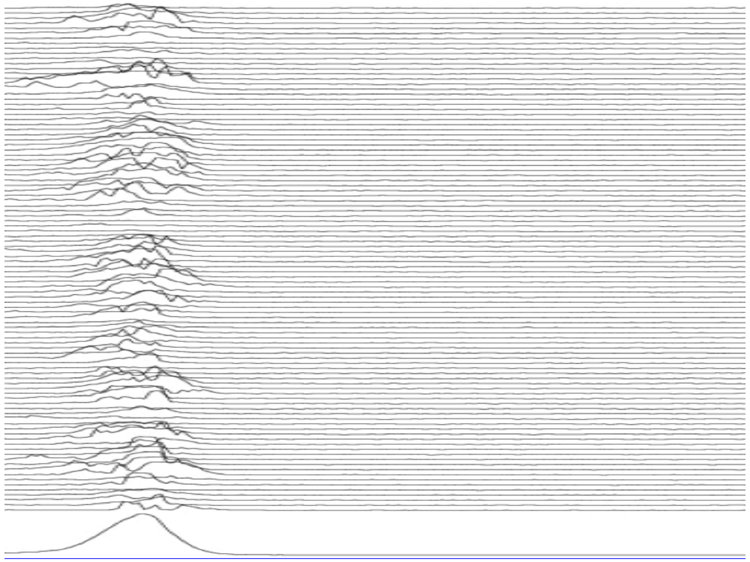
Arecibo (Puerto Rico): d= 305 m

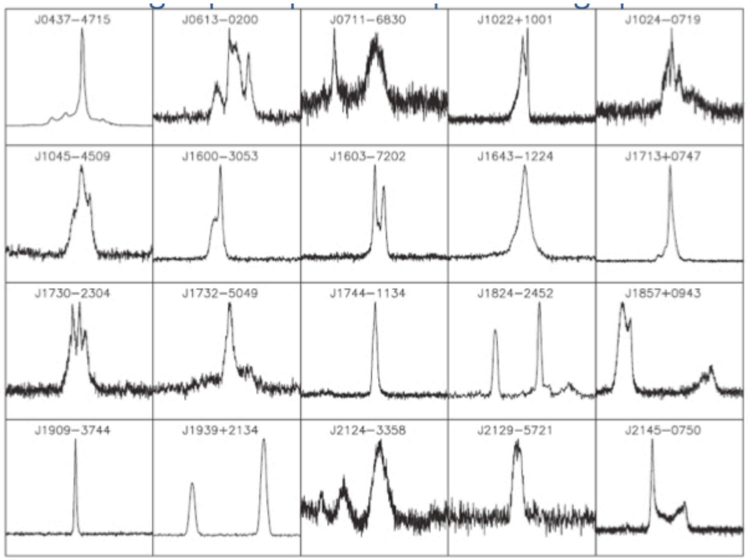
Radio telescopes

Green Banks (USA): d= 100 m

Nançay (France): d ~ 94 m

The Fingerprint of a Pulsar





Individual pulses are very different. But the average over 100 or more pulses is extremely stable and specific of each pulsar

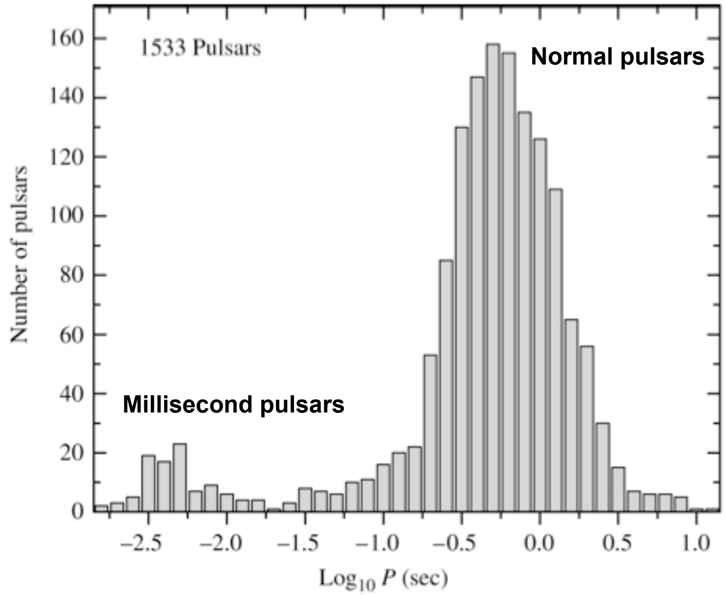
- Top: 100 single pulses from the pulsar PSR B0950+08 (P=0.253 s) showing the pulse-to-pulse variability in shape and intensity
- Bottom: Average profiles of several pulsars

Hobbs et al., Pub Astr. Soc. Aust., 202, 28 (2011)

Pulsar Rotational Period

The distribution of the rotational period of pulsars shows two clear peaks that indicate the existence of two types of pulsars

- normal pulsars with P ~ s
- millisecond pulsars with P ~ ms



Globular cluster Terzan 5

- First millisecond pulsar discovered in 1982 (Arecibo)
- Nowadays more than 200 millisecond pulsars are known
- PSR J1748-2446ad discovered in 2005 is until know the fastest one with P=1.39 ms (716 Hz)

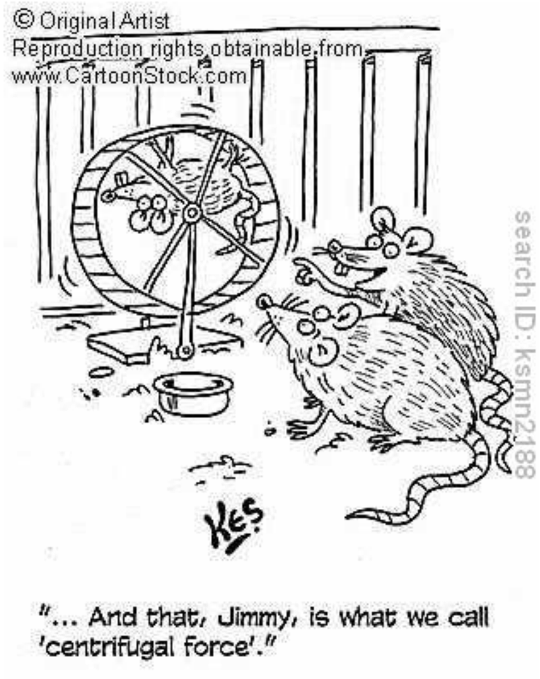
Minimum Rotational Period of a Neutron Star

Pulsar cannot spin arbitrarily fast. The absolute minimum rotational period is obtained when

Centrifugal Force = Gravitational Force

↓

Keplerian Frequency



In Newtonian Gravity

$$P_{\min} = 2\pi\sqrt{\frac{R^3}{GM}} \approx 0.55\left(\frac{M_{sun}}{M}\right)^{1/2}\left(\frac{R}{10km}\right)^{3/2} \quad ms$$

In General Relativity

$$P_{\min} = 0.96\left(\frac{M_{sun}}{M}\right)^{1/2}\left(\frac{R}{10km}\right)^{3/2} \quad ms$$

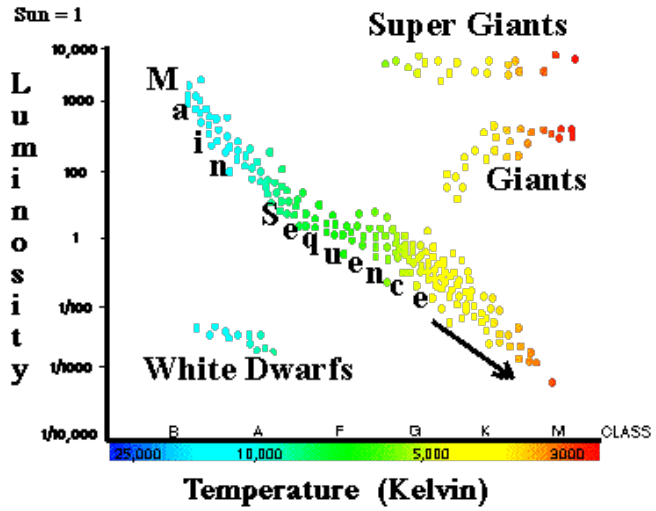
Actual record: PSR J1748-2446ad → P=1.39595482 ms

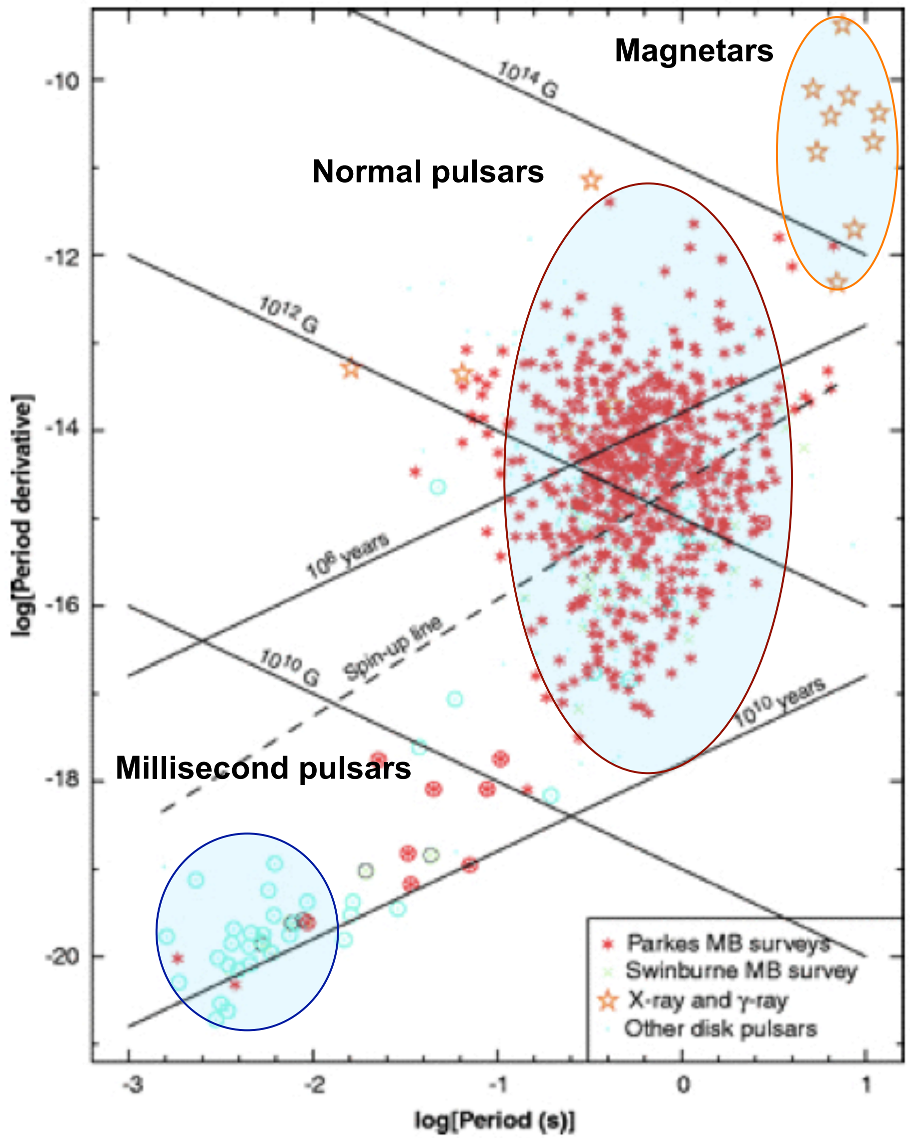
Pulsar distribution in the P-$\dot{P}$ plane

$$\log \dot{P} = \log\left[\frac{(2\pi)^2 R^6}{6c^3 I} B_P^2 \sin^2\alpha\right] - \log P$$

$$\log \dot{P} = \log P - \log(2\tau)$$

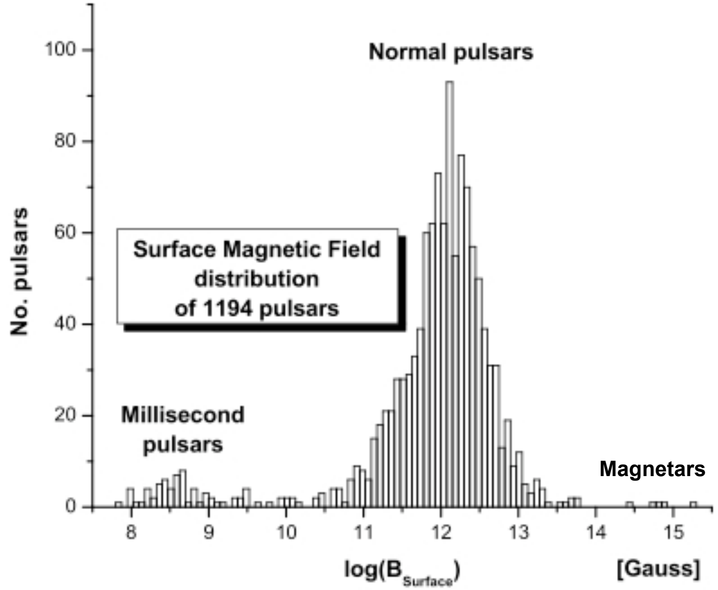
Pulsar equivalent of the Hertzprung-Russell diagram for ordinary stars





Magnetic Field of a Pulsar

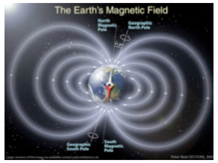
Type of Pulsar	Surface magnetic field
Millisecond	$10^8 - 10^9$ G
Normal	10^{12} G
Magnetar	$10^{14} - 10^{15}$ G



Extremely high compared to …

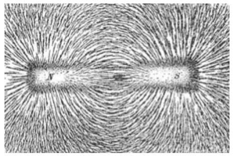
Earth

$0.3 - 0.5G$



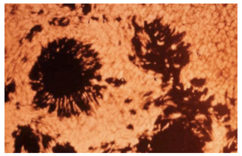
Magnet

$10^3 - 10^4 G$



Sun spots

$10^5 G$

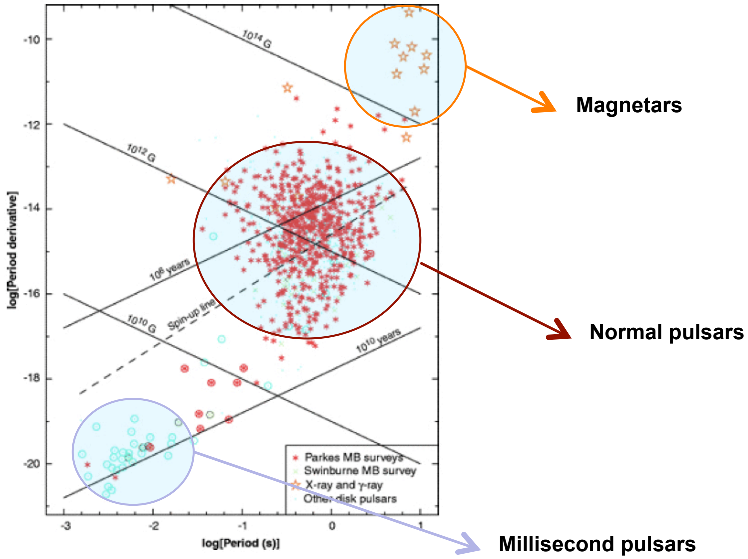


Largest continuous field in lab. (USA)

$4.5x10^5 G$

Largest magnetic pulse in lab. (Russia)

$2.8x10^7 G$



Where the NS magnetic field comes from ?

A satisfactory answer does not exist yet. Several possibilities have been considered:

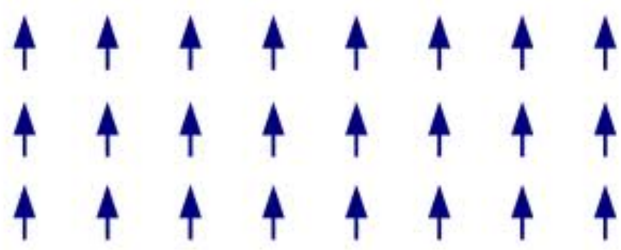
✧ Conservation of the magnetic flux during the gravitational collapse of the iron core

$$\phi_i = \phi_f \Rightarrow B_f = B_i \left(\frac{R_i}{R_f}\right)^2$$

For a progenitor star with $B_i \sim 10^2$ G & $R_i \sim 10^6$ km we have $B_f \sim 10^{12}$ G

✧ Electric currents flowing in the highly conductive NS interior

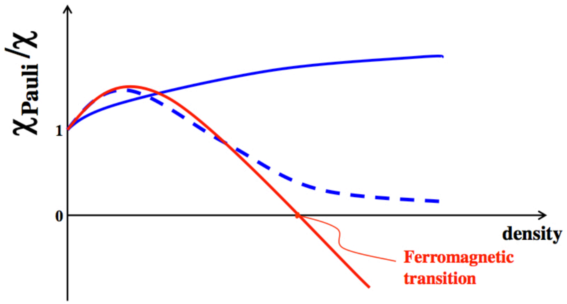
✧ Spontaneous transition to a ferromagnetic state due to the nuclear interaction



Ferromagnetic Transition

Considered by many authors with contradictory results:

Year	Autor/Model	Ferromagnetic Transition ?
1969	Brownell, Callaway, Rice (hard sphere gas)	Yes, k_F>2.3 fm^{-1}
1969	Clark & Chao	No
1970	Ostgard	Yes, k_F>4.1 fm^{-1}
1972	Pandharipande et al., (variational)	No
1975	Backman, Kallaman, Haensel (BHF)	No
1984	Vidaurre (Skyrme)	Yes, k_F>1.7-2.0 fm^{-1}
1991	S. Marcos et al., (DBHF)	No
2001	Fantoni et at. (AFDMC)	No
2002/2005	I.V., et al. (BHF)	No
2005/2006	I.V. et al., (Skyrme,Gogny)	Yes, k_F>2-3.4 fm^{-1}
2007-2011	F. Sammarruca (DBHF)	No



- Calculations based on phenomenological interactions (e.g., Skyrme, Gogny) predict the transition to occur at $(1\text{-}4)\rho_0$

- Calculations based on realistic NN & NNN forces (e.g., Monte Carlo, BHF, DBHF, LOCV) exclude such a transition

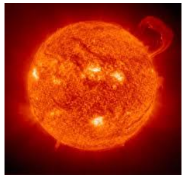
Neutron Star Structure:
General Relativity or Newtonian Gravity ?

Surface gravitational potential tell us how much compact an object is

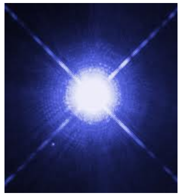
$$\frac{2GM}{c^2 R}$$

➔ Relativistic effects are very important in Neutron Stars and General Relativity must be used to describe their structure

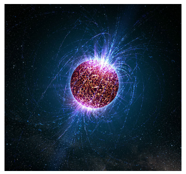
$\sim 10^{-10}$



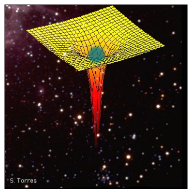
$\sim 10^{-5}$



$\sim 10^{-4} - 10^{-3}$



$\sim 0.2 - 0.4$



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Neutron Stars Structure Equations

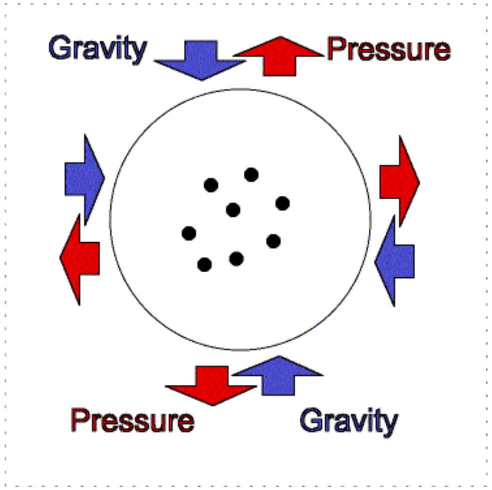
- The structure of a static (i.e., non-rotating) star with spherical symmetry in General Relativity is described by the Tolman-Oppenheimer-Volkoff (TOV) Equations

$$\frac{dP}{dr} = -G\frac{m(r)\varepsilon(r)}{r^2}\left(1+\frac{P(r)}{c^2\varepsilon(r)}\right)\left(1+\frac{4\pi r^3 P(r)m(r)}{c^2}\right)\left(1-\frac{2Gm(r)}{c^2 r}\right)^{-1}$$

$$\frac{dm}{dr} = 4\pi r^2\varepsilon(r)$$

- boundary conditions

$$P(0) = P_o, \quad m(0) = 0$$
$$P(R) = 0, \quad m(R) = M$$

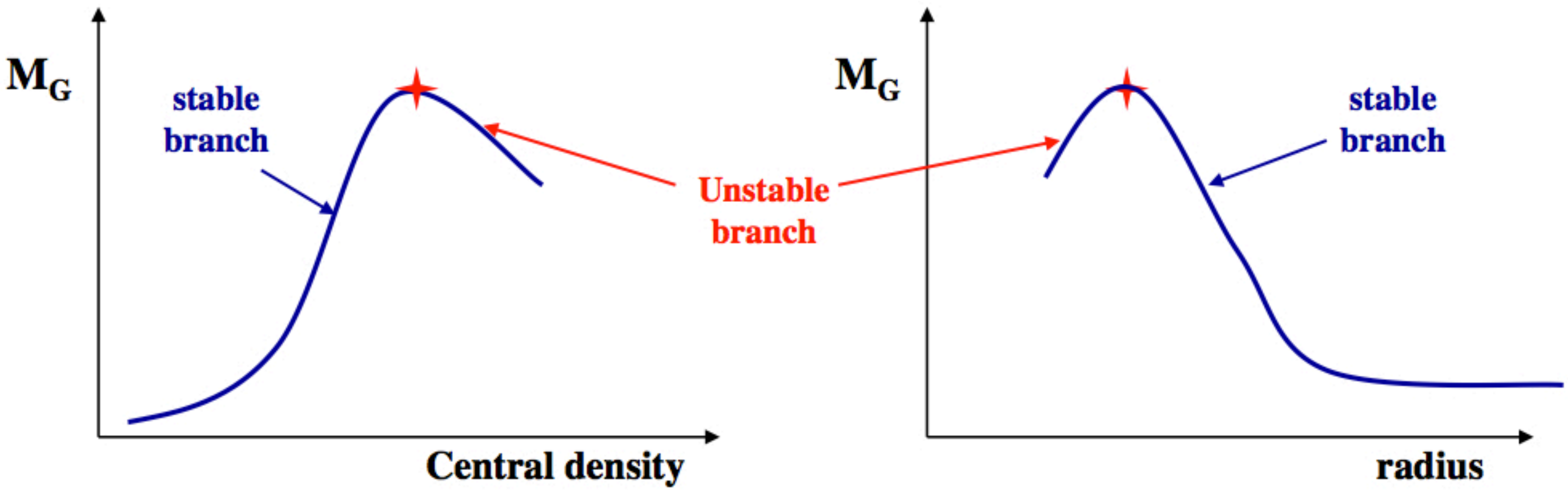


- Rotation breaks spherical symmetry and makes the structure equations "slightly" more complicated

Stability solutions of the TOV equations

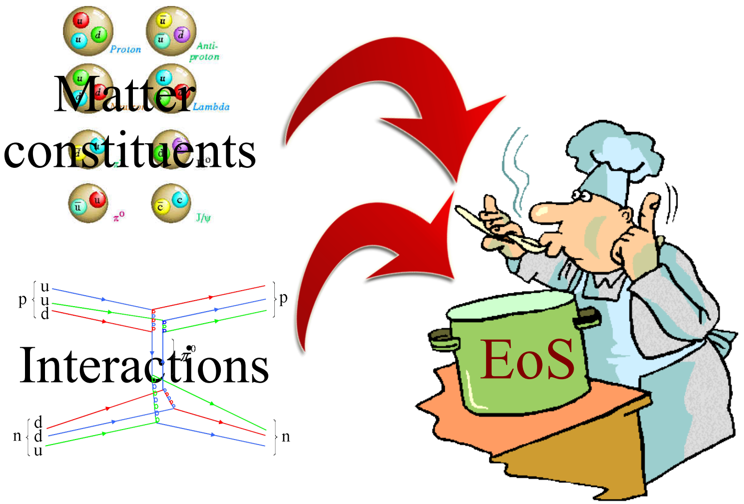
- ✧ The solutions of the TOV eqs. represent static equilibrium configurations
- ✧ Stability is required with respect to small perturbations

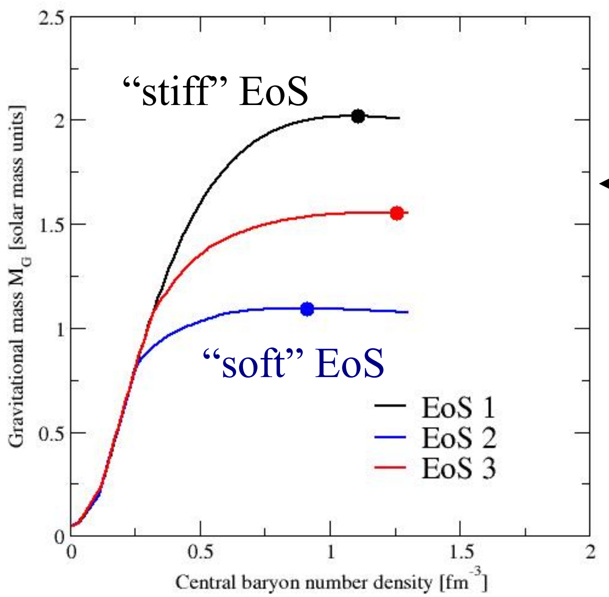
$$\frac{dM_G}{d\rho_c} > 0, \quad or \quad \frac{dM_G}{dr} < 0$$

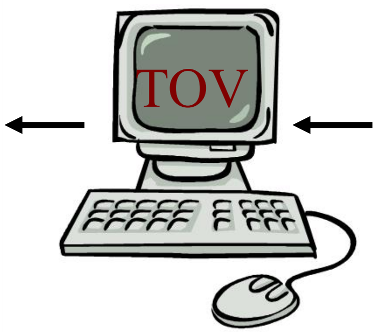


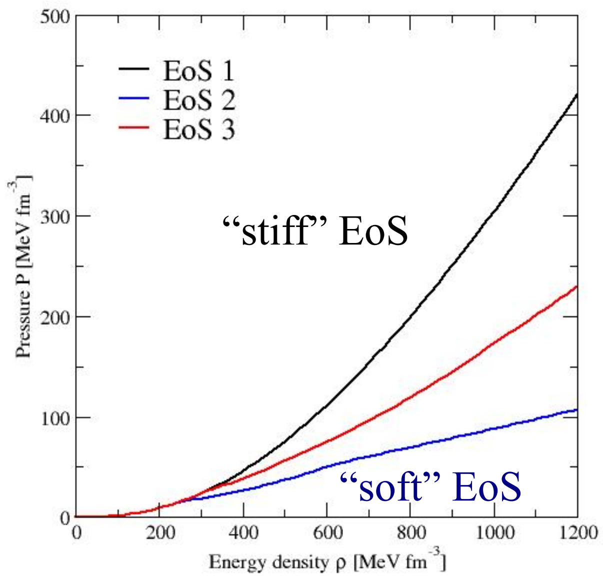
The role of the Equation of State

The only ingredient needed to solve the TOV equations is the (poorly known) EoS (i.e., p(ε)) of dense matter









Upper limit of the Maximum Mass

M_{max} depends mainly on the behaviour of EoS, P(ε), at high densities. Any realistic EoS must satisfy two conditions:

- Causality: $\frac{dP}{d\rho} \leq c^2$
- Stability: $\frac{dP}{d\rho} > 0$

If the EoS is known up to ρ_r, these conditions imply:

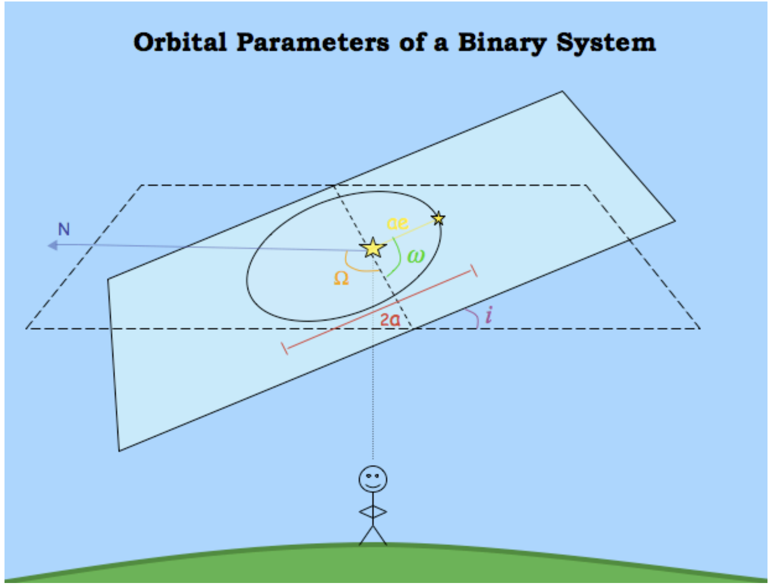
$$M_{\max} \leq 3M_{\odot}\left(\frac{5x10^{14}\, g/cm^3}{\rho_r}\right)^{1/2}$$

If rotation is taken into account M_{max} can increase up to 20%:

$$M_{\max} \leq 3.89M_{\odot}\left(\frac{5x10^{14}\, g/cm^3}{\rho_r}\right)^{1/2}$$

How to Measure Neutron Star Masses

Use Doppler variations in spin period to measure orbital velocity changes along the line-of-sight



- 5 Keplerian parameters can normally be determined:

  P, a sin i, ε, T_0 & ω

- 3 unknowns: M_1, M_2, i

Kepler's 3rd law

$$\frac{G(M_1 + M_2)}{a^3} = \left(\frac{2\pi}{P}\right)^2 \rightarrow$$

$$f(M_1, M_2, i) \equiv \frac{(M_2 \sin i)^3}{(M_1 + M_2)^2} = \frac{Pv^3}{2\pi G}$$

mass function

In few cases small deviations from Keplerian orbit due to GR effects can be detected

Measure of at least 2 post-Keplerian parameters → High precision NS mass determination

$$\dot{\omega} = 3T_{\otimes}^{2/3}\left(\frac{P_b}{2\pi}\right)^{-5/3}\frac{1}{1-\varepsilon}\left(M_p + M_c\right)^{2/3}$$ → Periastron precession

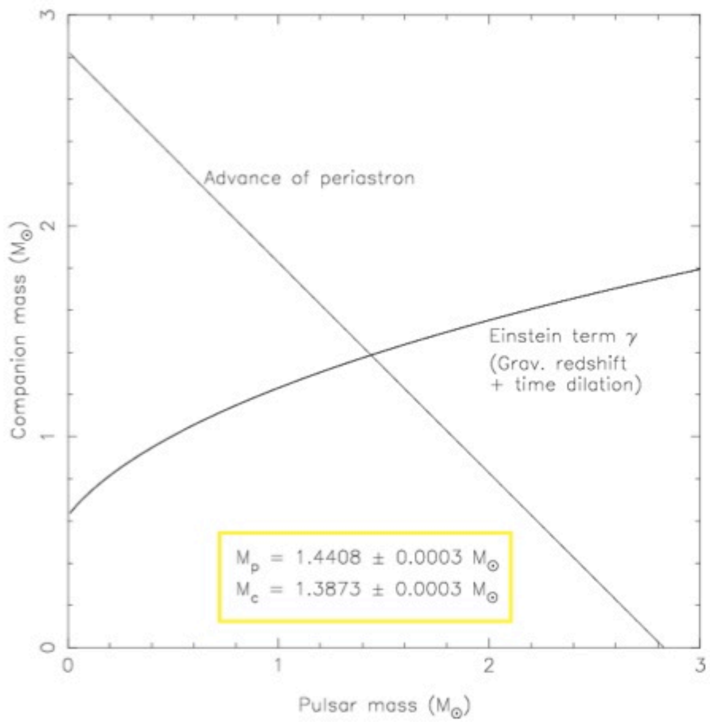
$$\gamma = T_{\otimes}^{2/3}\left(\frac{P_b}{2\pi}\right)^{1/3}\varepsilon\frac{M_c\left(M_p + 2M_c\right)}{\left(M_p + M_c\right)^{4/3}}$$ → Time dilation and grav. redshift

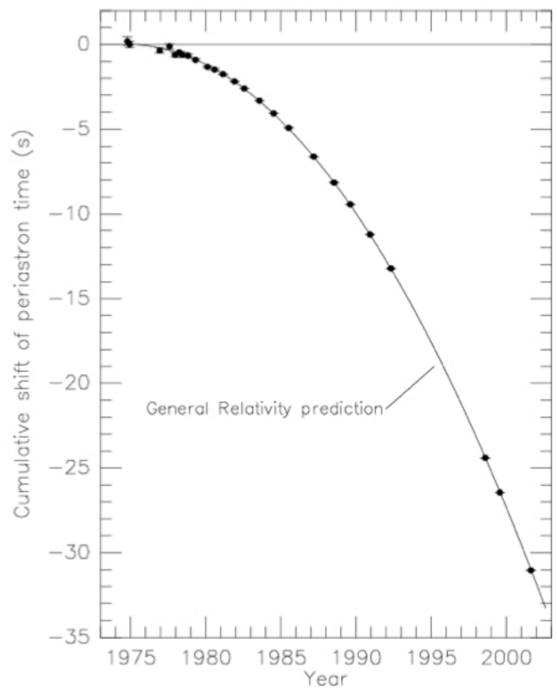
$$r = T_{\otimes}M_c$$ → Shapiro delay "range"

$$s = \sin i = T_{\otimes}^{-1/3}\left(\frac{P_b}{2\pi}\right)^{-2/3}x\frac{\left(M_p + M_c\right)^{2/3}}{M_c}$$ → Shapiro delay "shape"

$$\dot{P}_b = -\frac{192\pi}{5}T_{\otimes}^{5/3}\left(\frac{P_b}{2\pi}\right)^{-5/3}f(\varepsilon)\frac{M_pM_c}{\left(M_p + M_c\right)^{1/3}}$$ → Orbit decay due to GW emission

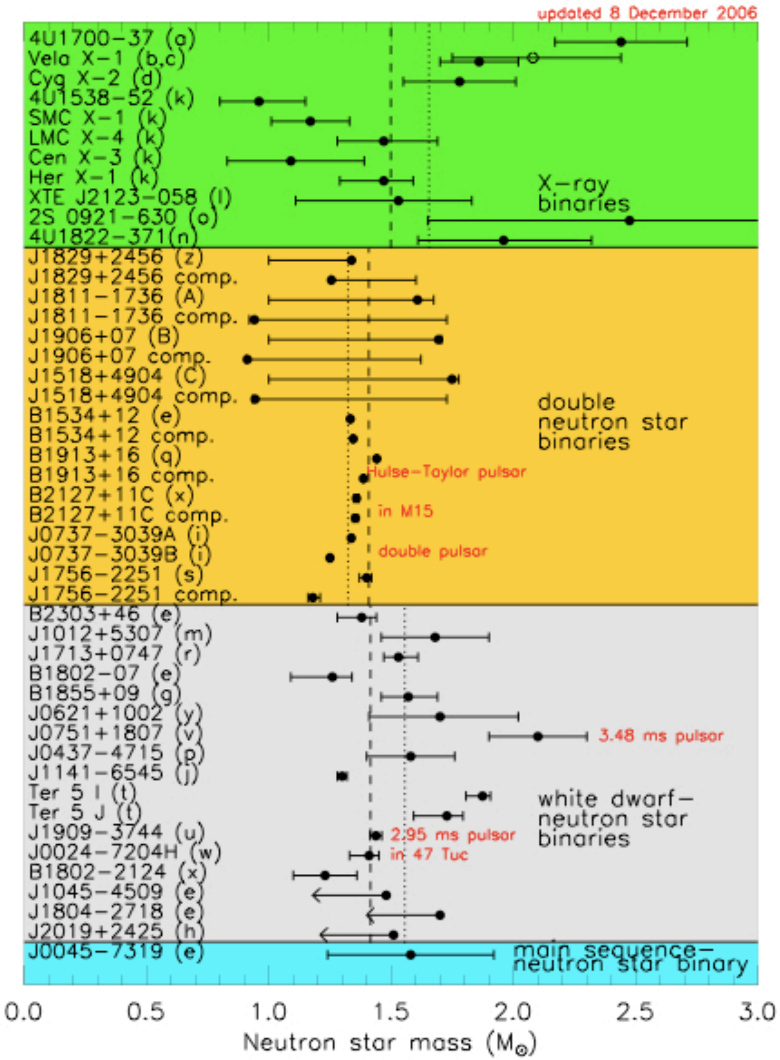
An example: the mass of the Hulse-Taylor pulsar (PSR J1913+16)



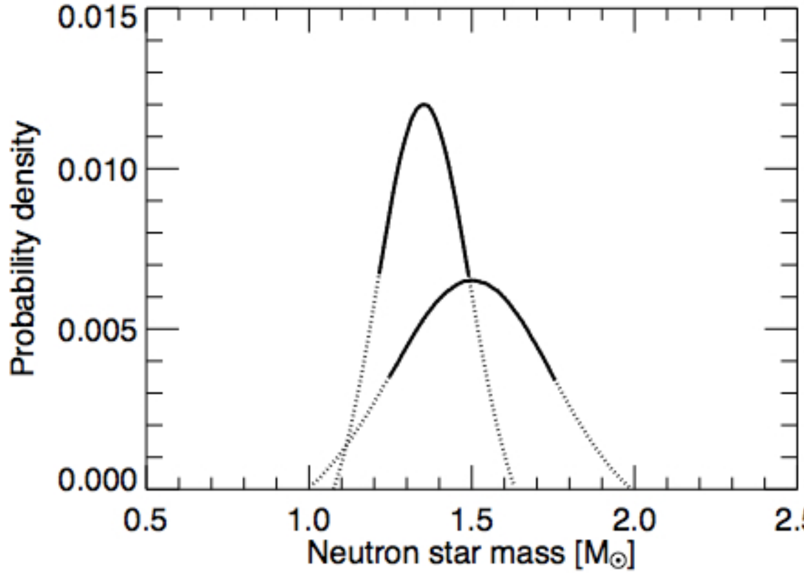


Parameter	Value
Orbital period P_b (d)	0.322997462727(5)
Projected semi-major axis x (s)	2.341774(1)
Eccentricity e	0.6171338(4)
Longitude of periastron ω (deg)	226.57518(4)
Epoch of periastron T_0 (MJD)	46443.99588317(3)
Advance of periastron $\dot{\omega}$ (deg yr^{-1})	4.226607(7)
Gravitational redshift γ (ms)	4.294(1)
Orbital period derivative $(\dot{P}_b)^{obs}$ (10^{-12})	−2.4211(14)

Measured Neutron Star Masses (up to ~ 2006-2008)



(Lattimer & Prakash 2007)



up to ~ 2006-2008 any valid EoS should predict

$$M_{max}\left[EoS\right] > 1.4 - 1.5 M_{\odot}$$

N.B. I will comment on more recent measurements latter when talking about the “hyperon problem”

Limits on the Neutron Star Radius

The radius of a neutron star with mass M cannot be arbitrarily small

General Relativity:
a Neutron Star is not a Black Hole

$$R > \frac{2GM}{c^2}$$

Finite Pressure:
Neutron Star matter cannot be arbitrarily compressed

$$R > \frac{9}{4}\frac{GM}{c^2}$$

Causality:
speed of sound must be smaller than c

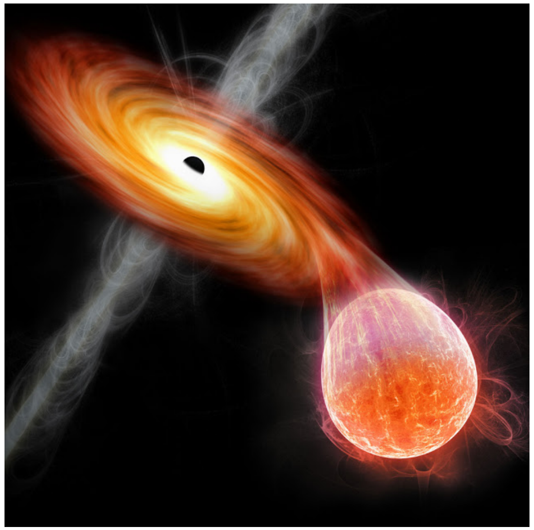
$$R > 2.9\frac{GM}{c^2}$$

How to measure Neutron Star Radii

Radii are very difficult to measure because NS:

- ✧ are very small (~ 10 km)
- ✧ are far from us (e.g., the closest NS, RX J1856.5-3754, is at ~ 400 ly)

A possible way to measure it is to use the thermal emission of low mass X-ray binaries:



NS radius can be obtained from

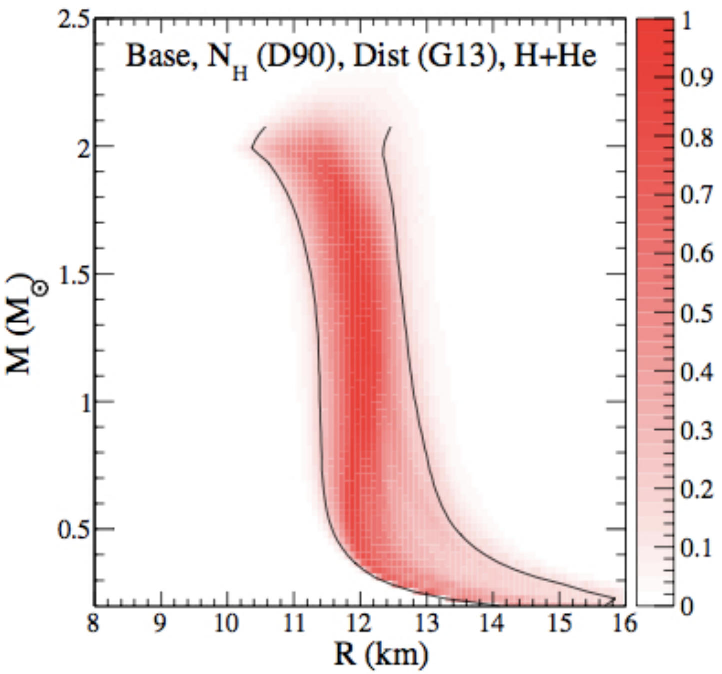
- ✧ Flux measurement +Stefan-Boltzmann's law
- ✧ Temperature (Black body fit+atmosphere model)
- ✧ Distance estimation (difficult)
- ✧ Gravitational redshift z (detection of absorption lines)

$$R_\infty = \sqrt{\frac{FD^2}{\sigma_{SB}T^4}} \rightarrow R_{NS} = \frac{R_\infty}{1+z} = R_\infty\sqrt{1-\frac{2GM}{R_{NS}c^2}}$$

Recent Estimations of Neutron Star Radii

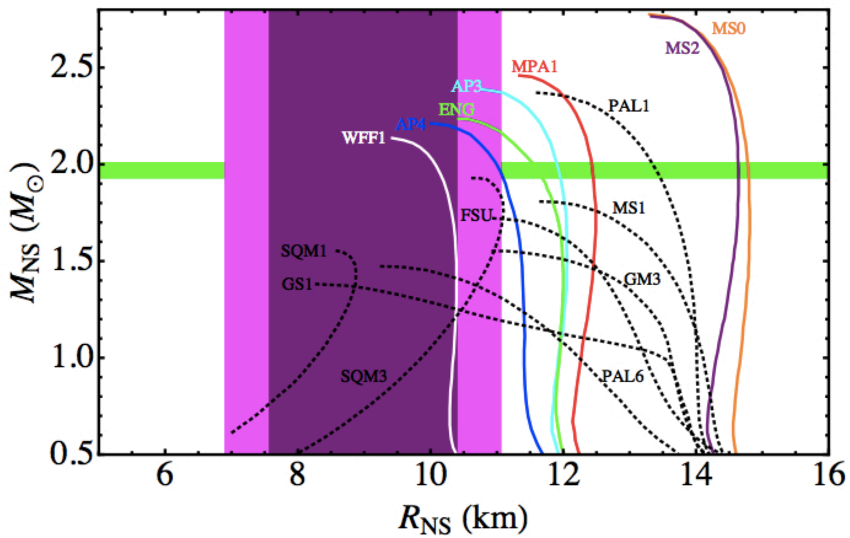
The recent analysis of the thermal spectrum from 5 quiescent LMXB in globular clusters is still controversial

Steiner et al. (2013, 2014)



$$R = 12.0 \pm 1.4 km$$

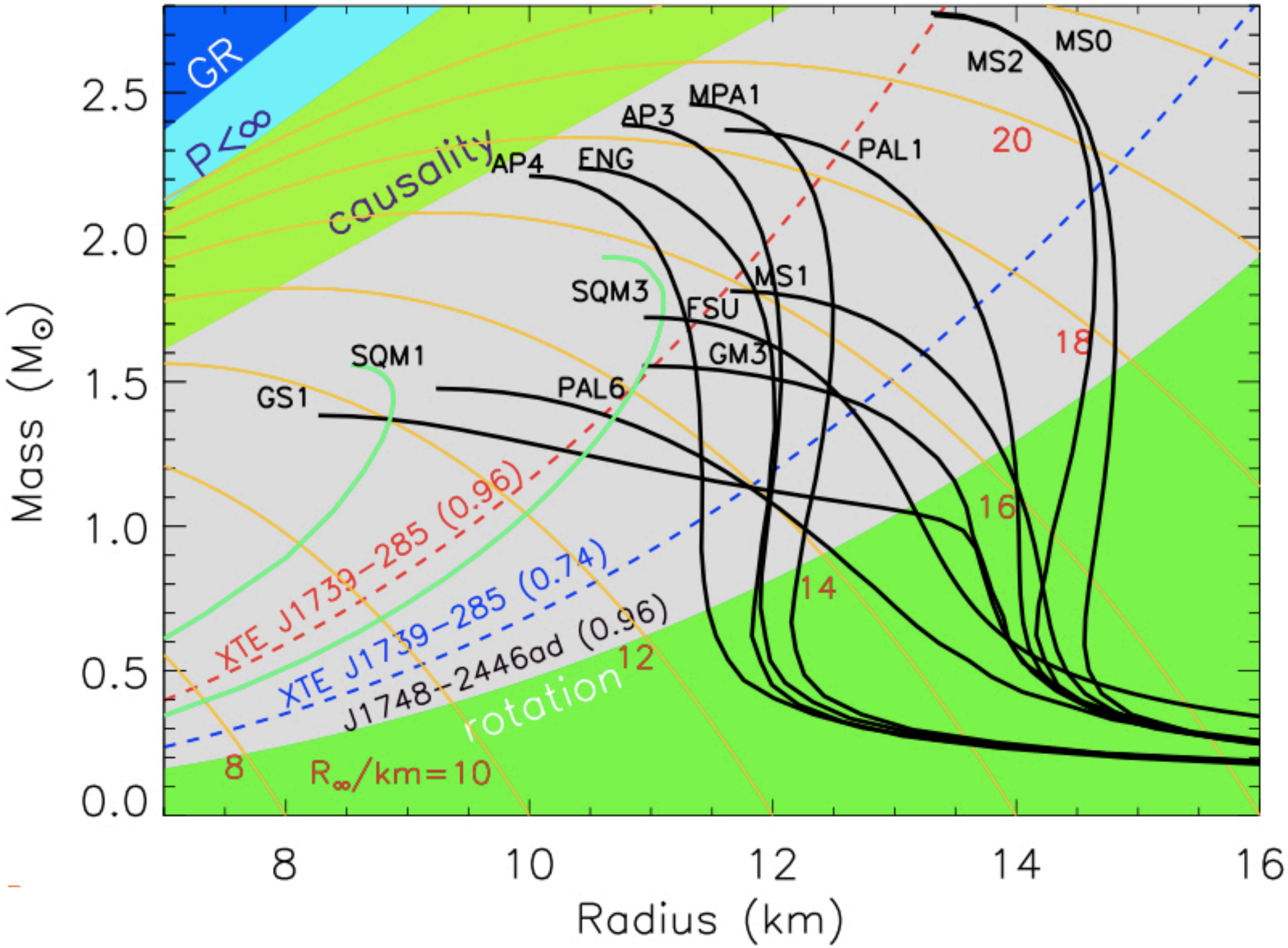
Guillot et al. (2013, 2014)



$$R = 9.1^{+1.3}_{-1.5} km$$ 2013 analysis

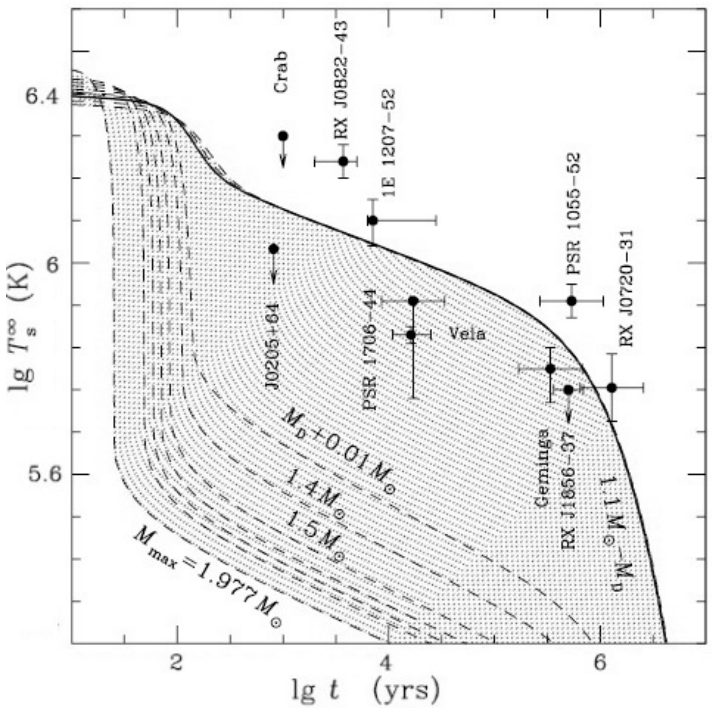
$$R = 9.4 \pm 1.2 km$$ 2014 analysis

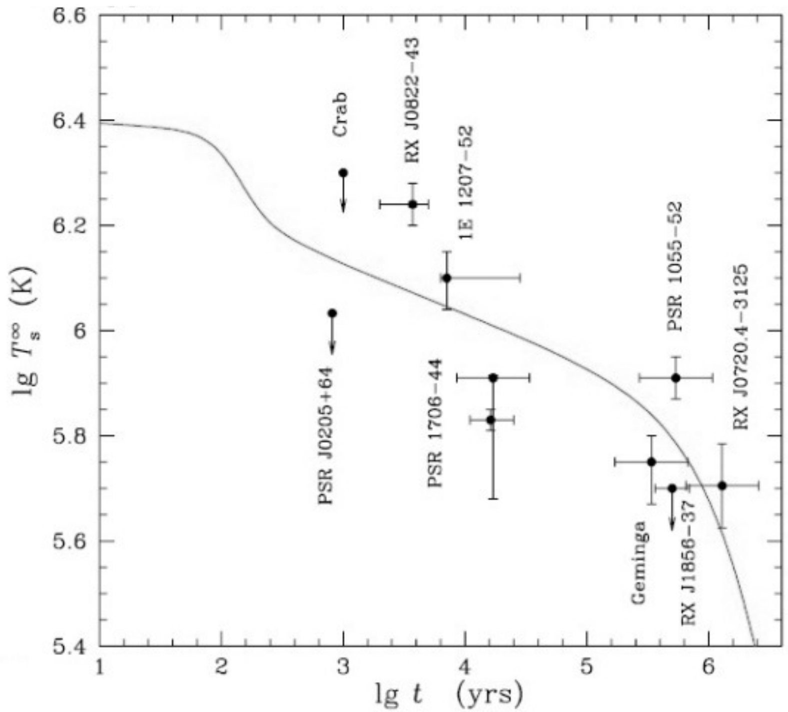
Limits of the Mass & Radius of a Neutron Star



Thermal Evolution of Neutron Stars

Information, complementary to that from mass & radius, can be also obtained from the measurement of the temperature (luminosity) of neutron stars

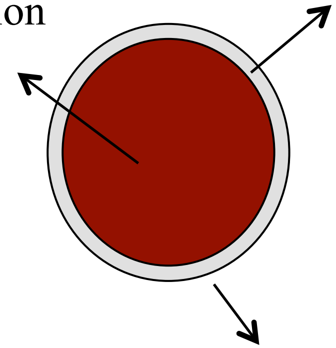




D. G. Yakovlev & C. J. Pethick, A&A 42, 169 (2004)

Neutron Star Cooling in a Nutshell

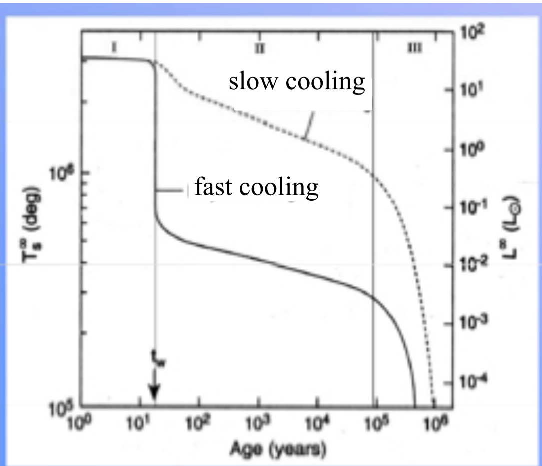
Core cools by neutrino emission



Surface photon emission dominates at $t > 10^6$ yrs

Two cooling regimes

Slow	Fast
Low NS mass	High NS mass



I. Core relaxation epoch
II. Neutrino cooling epoch
III. Photon cooling epoch

$$\frac{dE_{th}}{dt} = C_v \frac{dT}{dt} = -L_\gamma - L_\nu + H$$

- ✓ C_v: specific heat
- ✓ L_γ: photon luminosity
- ✓ L_ν: neutrino luminosity
- ✓ H: "heating"

Neutrino Emission

Name	Process	Emissivity (erg cm^{-3} s^{-1})	
Modified Urca cycle (neutron branch)	$n + n \to n + p + e^- + \bar{\nu}_e$ $n + p + e^- \to n + n + \nu_e$	$\sim 2{\times}10^{21}\, R\, T_9^8$	Slow
Modified Urca cycle (proton branch)	$p + n \to p + p + e^- + \bar{\nu}_e$ $p + p + e^- \to p + n + \nu_e$	$\sim 10^{21}\, R\, T_9^8$	Slow
Bremsstrahlung	$n + n \to n + n + \nu + \bar{\nu}$ $n + p \to n + p + \nu + \bar{\nu}$ $p + p \to p + p + \nu + \bar{\nu}$	$\sim 10^{19}\, R\, T_9^8$	Slow
Cooper pair formations	$n + n \to [nn] + \nu + \bar{\nu}$ $p + p \to [pp] + \nu + \bar{\nu}$	$\sim 5{\times}10^{21}\, R\, T_9^7$ $\sim 5{\times}10^{19}\, R\, T_9^7$	Medium
Direct Urca cycle (nucleons)	$n \to p + e^- + \bar{\nu}_e$ $p + e^- \to n + \nu_e$	$\sim 10^{27}\, R\, T_9^6$	Fast
Direct Urca cycle (Λ hyperons)	$\Lambda \to p + e^- + \bar{\nu}_e$ $p + e^- \to \Lambda + \nu_e$	$\sim 10^{27}\, R\, T_9^6$	Fast
Direct Urca cycle (Σ^- hyperons)	$\Sigma^- \to n + e^- + \bar{\nu}_e$ $n + e^- \to \Sigma^- + \nu_e$	$\sim 10^{27}\, R\, T_9^6$	Fast
π^- condensate	$n + \langle \pi^- \rangle \to n + e^- + \bar{\nu}_e$	$\sim 10^{26}\, R\, T_9^6$	Fast
K^- condensate	$n + \langle K^- \rangle \to n + e^- + \bar{\nu}_e$	$\sim 10^{25}\, R\, T_9^6$	Fast

Anything beyond just neutrons & protons results in an enhancement of the neutrino emission

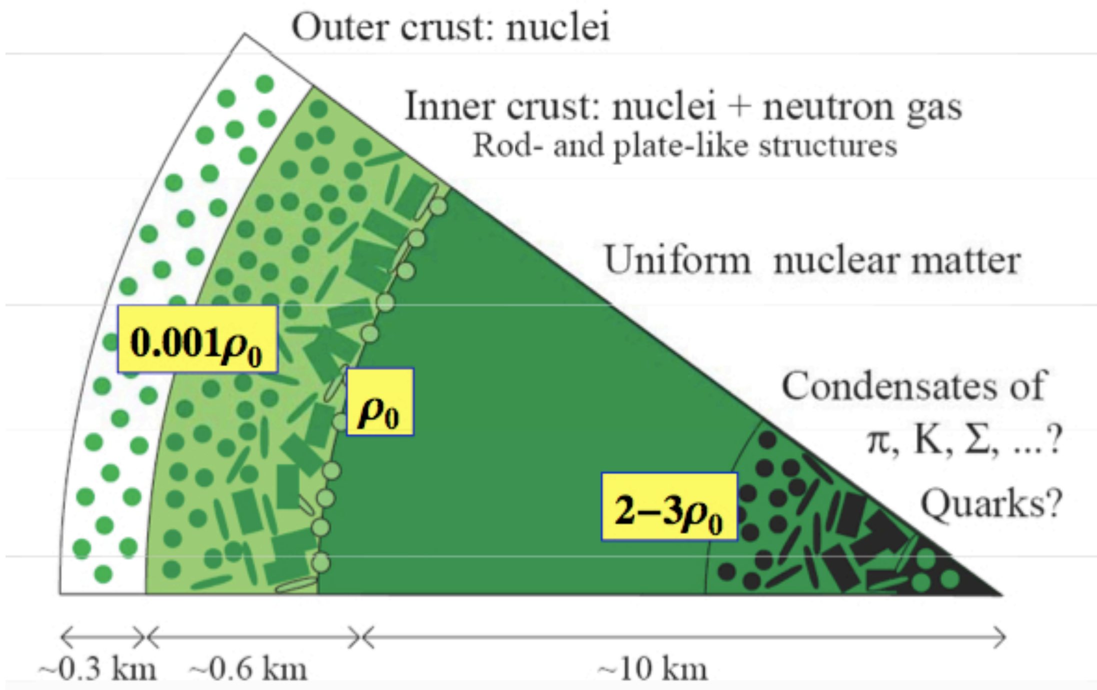
Anatomy of a Neutron Star

Equilibrium composition determined by

- ✓ Charge neutrality

$$\sum_i q_i \rho_i = 0$$

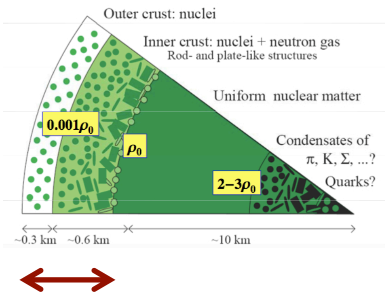
- ✓ Equilibrium with respect to weak interacting processes

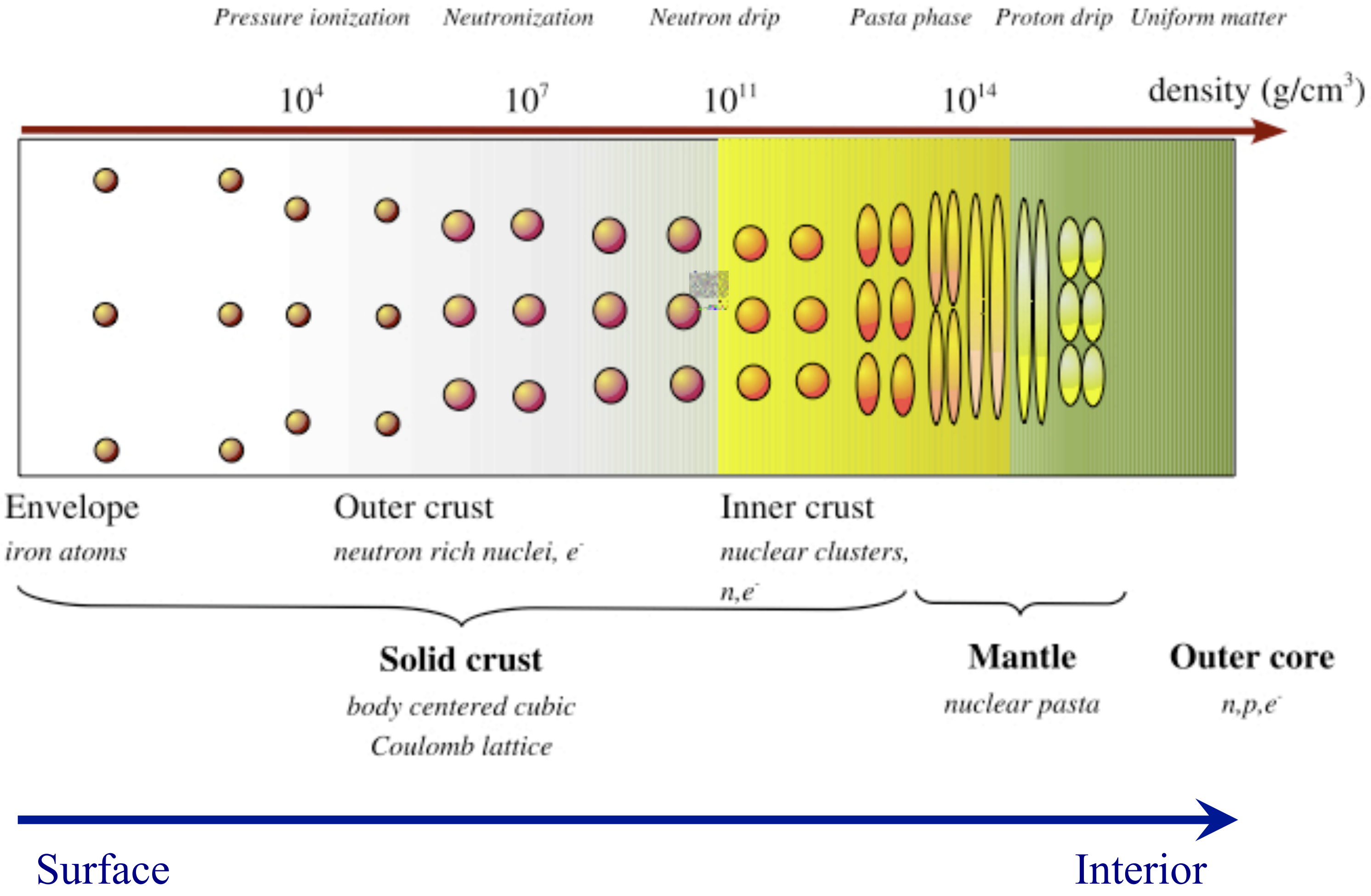


$$b_1 \rightarrow b_2 + l + \bar{\nu}_l$$
$$b_2 + l \rightarrow b_1 + \nu_l$$

$$\longrightarrow \quad \mu_i = b_i \mu_n - q_i \left(\mu_e - \mu_{\nu_e} \right), \quad \mu_i = \frac{\partial \varepsilon}{\partial \rho_i}$$

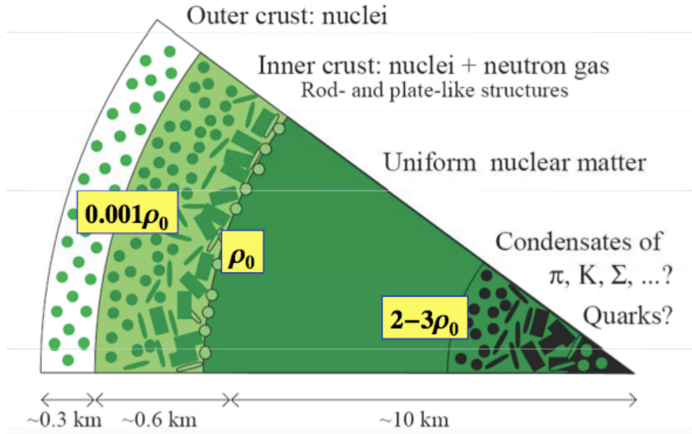
Crust of a Neutron Star

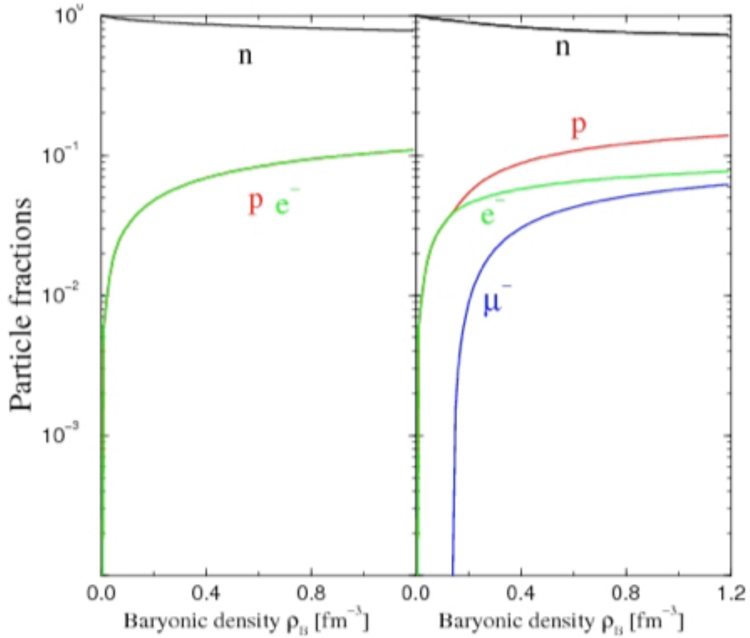




External Core of a Neutron Star

The external core of a neutron star is mainly a fluid of neutron-rich matter in equilibrium with respect to weak interaction processes (β-stable matter)





$$\left.\begin{aligned} n &\rightarrow p + e^- + \bar{\nu}_{e^-} \\ p + e^- &\rightarrow n + \nu_{e^-} \end{aligned}\right\} \longrightarrow \mu_p = \mu_n - \mu_{e^-} + \mu_{\nu_{e^-}}$$

Internal Core of a Neutron Star

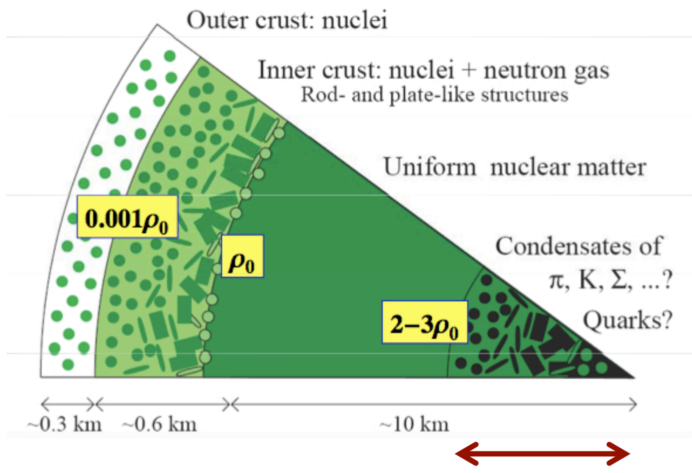
Since:

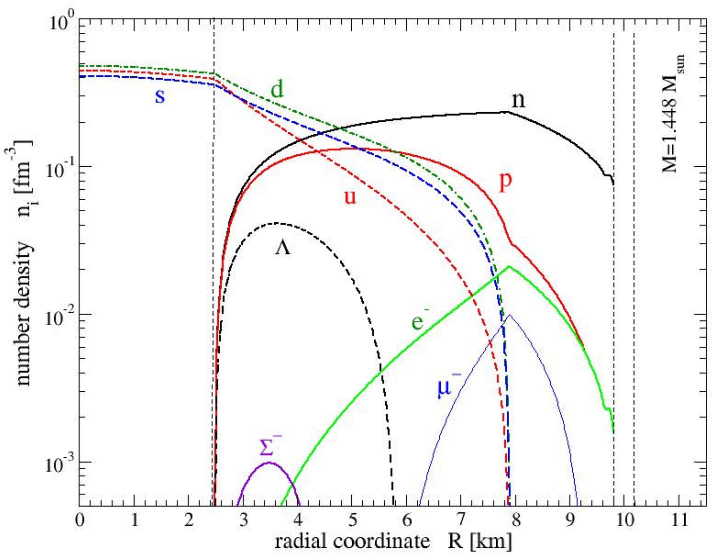
✧ The value of the central density is very high: $\rho_c \sim (4\text{-}8)\rho_0$

($\rho_0 = 0.17\ \mathrm{fm}^{-3} = 2.8 \times 10^{14}\ \mathrm{g/cm}^3$)

✧ Nucleon chemical potential increases rapidly with the density ρ

The presence of exotic degrees of freedom is expected in the Neutron Star interior (π, K^- condensates, hyperons or quarks)





Hyperons in Neutron Stars

Hyperons in NS considered by many authors since the pioneering work of Ambartsumyan & Saakyan (1960)

Phenomenological approaches

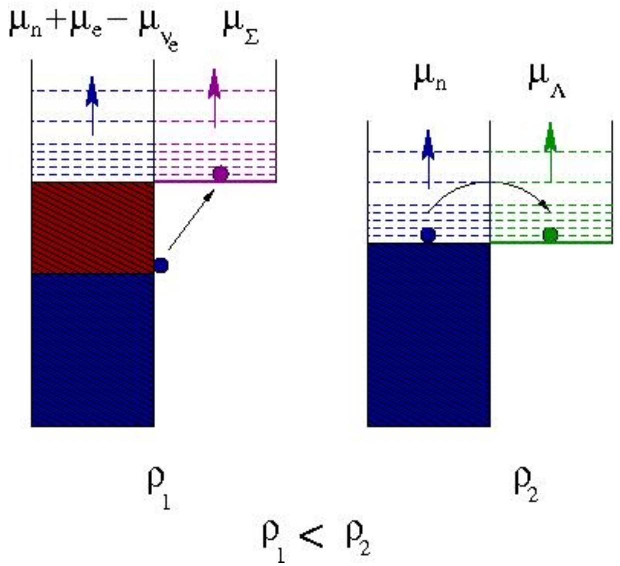
- Relativistic Mean Field Models: Glendenning 1985; Knorren et al. 1995; Shaffner-Bielich & Mishustin 1996, Bonano & Sedrakian 2012, …
- Non-realtivistic potential model: Balberg & Gal 1997
- Quark-meson coupling model: Pal et al. 1999, …
- Chiral Effective Lagrangians: Hanauske et al., 2000
- Density dependent hadron field models: Hofmann, Keil & Lenske 2001

Microscopic approaches

- Brueckner-Hartree-Fock theory: Baldo et al. 2000; I. V. et al. 2000, Schulze et al. 2006, I.V. et al. 2011, Burgio et al. 2011, Schulze & Rijken 2011
- DBHF: Sammarruca (2009), Katayama & Saito (2014)
- $V_{low\ k}$: Djapo, Schaefer & Wambach, 2010
- Quantum Monte Carlo: Lonardoni et al., (2014)

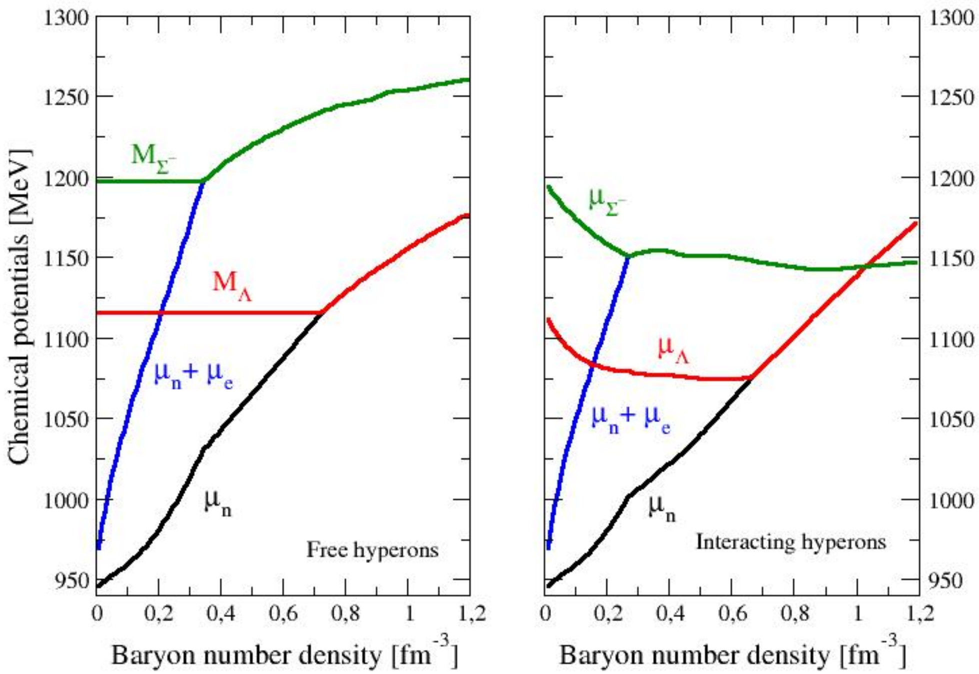
Sorry if I missed somebody

Hyperons are expected to appear in the core of neutron stars at $\rho \sim (2\text{-}3)\rho_0$ when μ_N is large enough to make the conversion of N into Y energetically favorable.



$$\mu_{\Sigma^-} = \mu_n + \mu_{e^-} - \mu_{\nu_{e^-}}$$

$$\mu_\Lambda = \mu_n$$



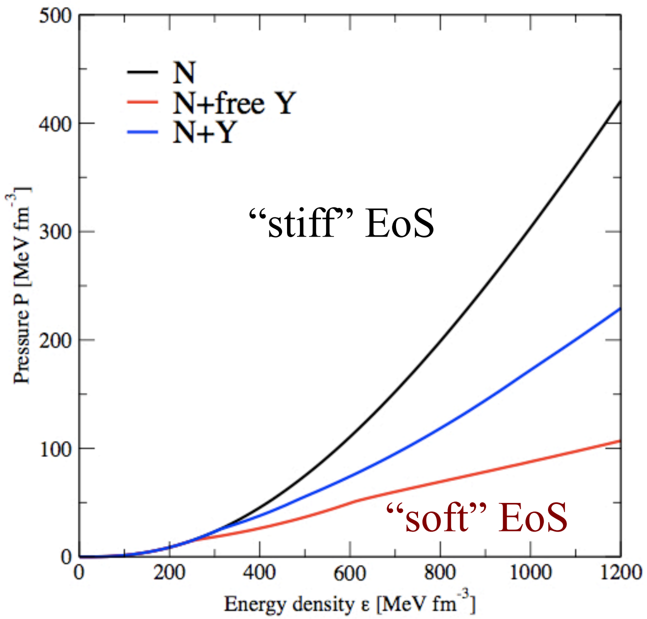
$$n + n \rightarrow n + \Lambda$$

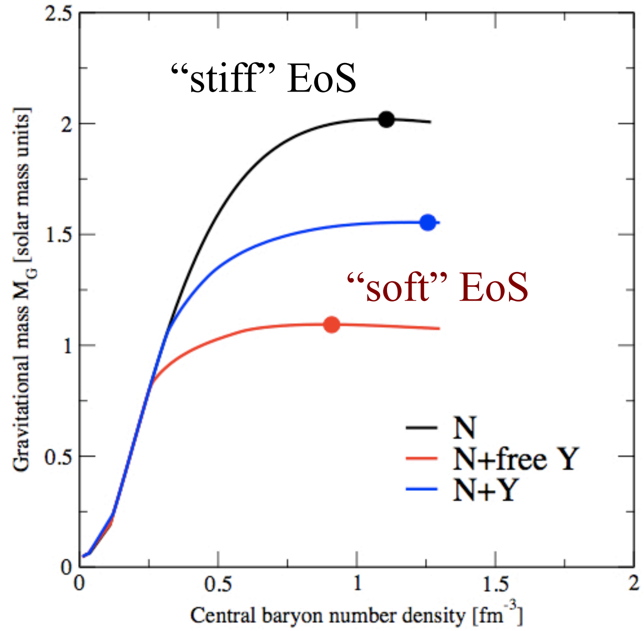
$$p + e^- \rightarrow \Lambda + \nu_{e^-}$$

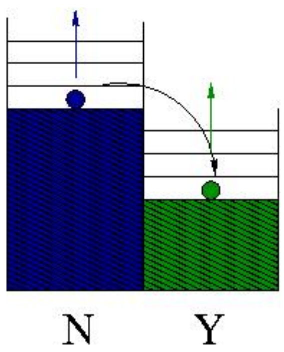
$$n + n \rightarrow p + \Sigma^-$$

$$n + e^- \rightarrow \Sigma^- + \nu_{e^-}$$

Effect of Hyperons in the EoS and Mass of Neutron Stars

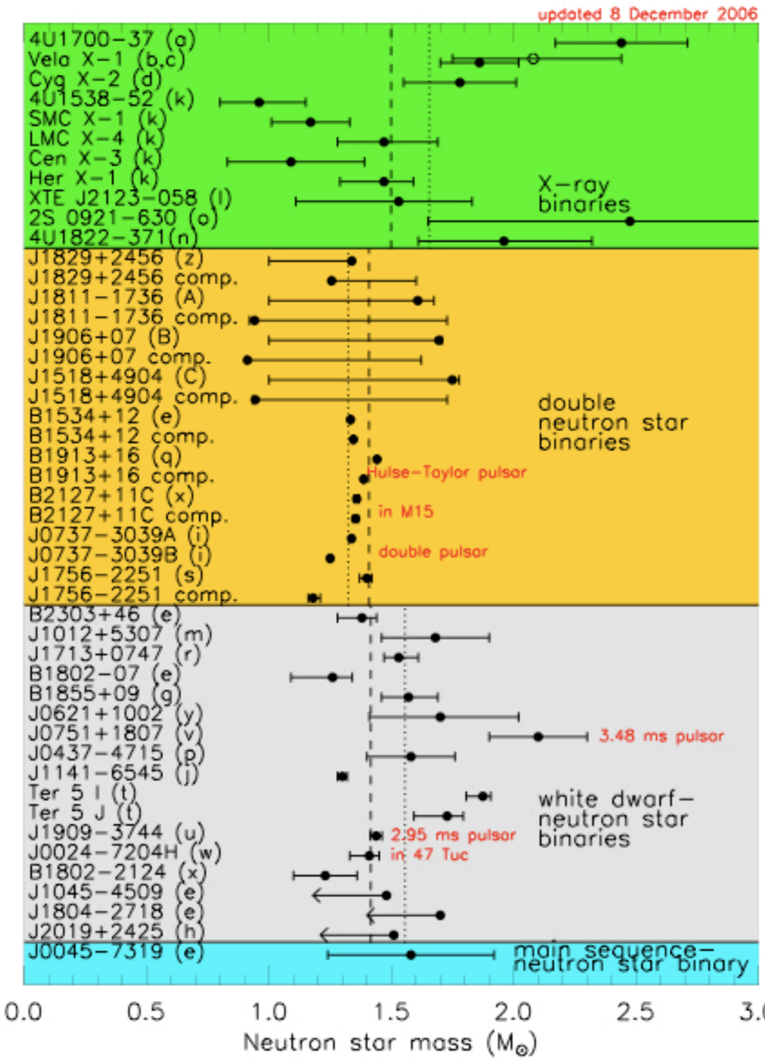






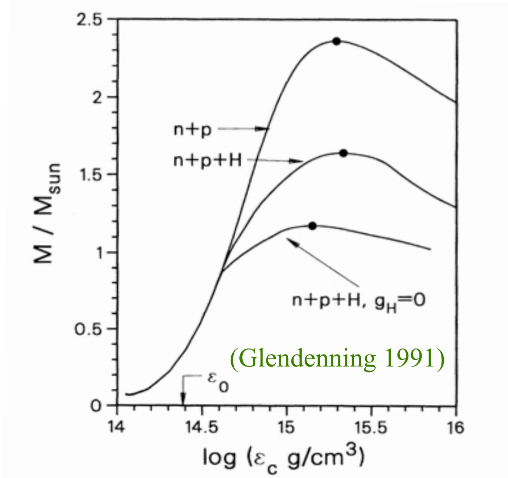
Relieve of Fermi pressure due to the appearance of hyperons ➔ EoS softer ➔ reduction of the mass

Hyperons in NS
(up to ~ 2006-2008)



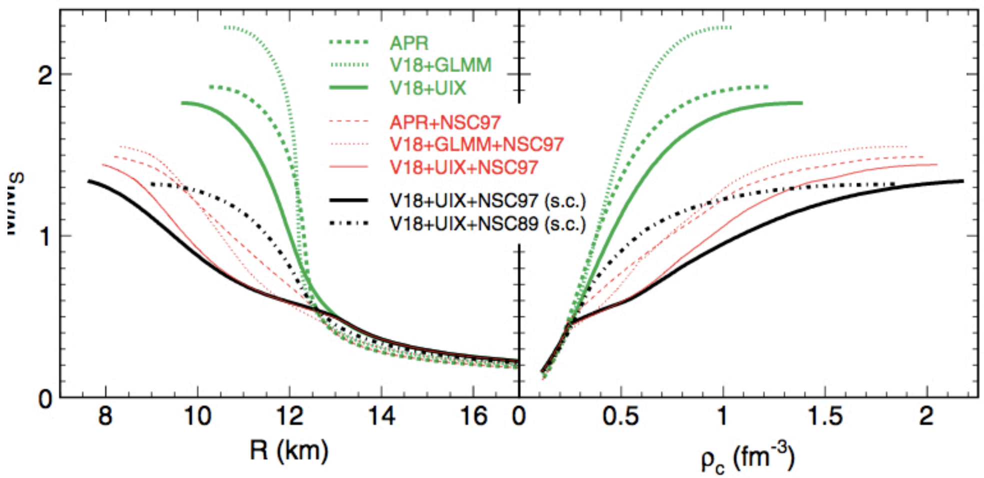
(Lattimer & Prakash 2007)

Phenomenological:
M_{max} compatible with 1.4-1.5 $M_\odot$



(Glendenning 1991)

Microscopic : M_{max} < 1.4-1.5 $M_\odot$



(Schulze, Polls, Ramos & IV 2006)

Recent measurements of high masses ⟶ life of hyperons more difficult

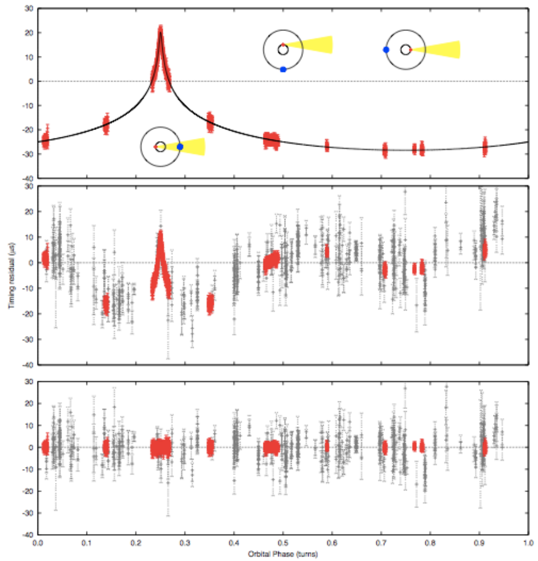
- PSR J164-2230 (Demorest et al. 2010)

✓ binary system ($P = 8.68d, \quad i = 89.17(2)^0$)

✓ low eccentricity (ε=1.3 x 10^{-6})

✓ companion (WD) mass: $\sim 0.5 M_\odot$

✓ pulsar mass: $M = 1.97 \pm 0.04 M_\odot$



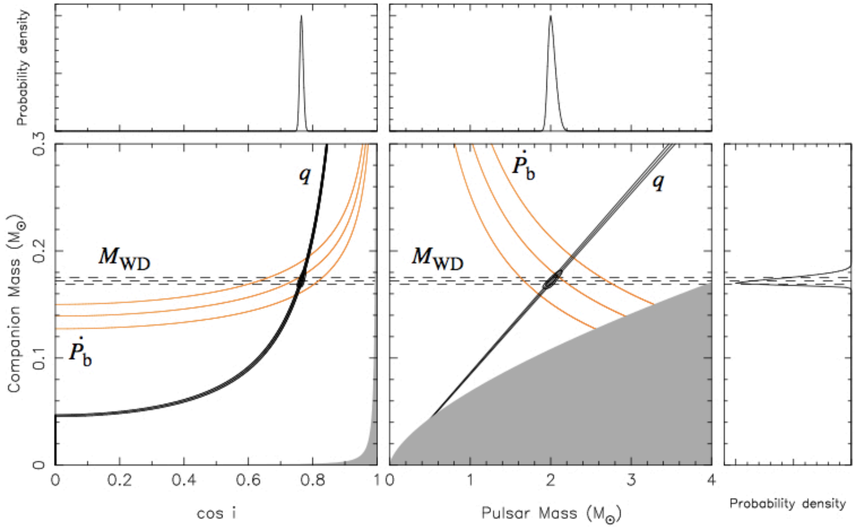
- PSR J0348+0432 (Antoniadis et al. 2013)

✓ binary system ($P = 2.46h, \quad i = 40.2(6)^0$)

✓ very low eccentricity

✓ companion (WD) mass: $0.172 \pm 0.003 M_\odot$

✓ pulsar mass: $M = 2.01 \pm 0.04 M_\odot$



Formation of Binary Systems

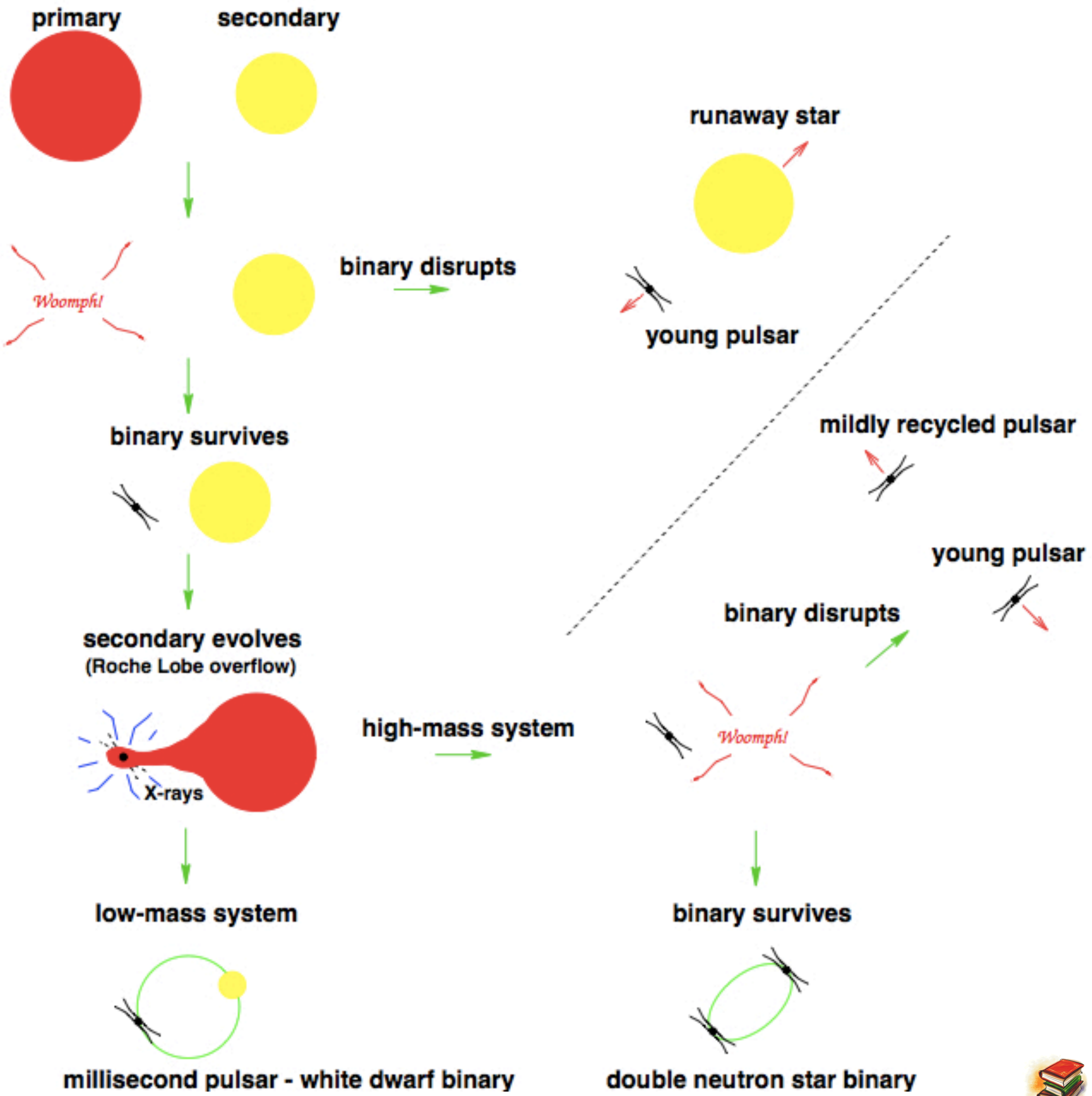
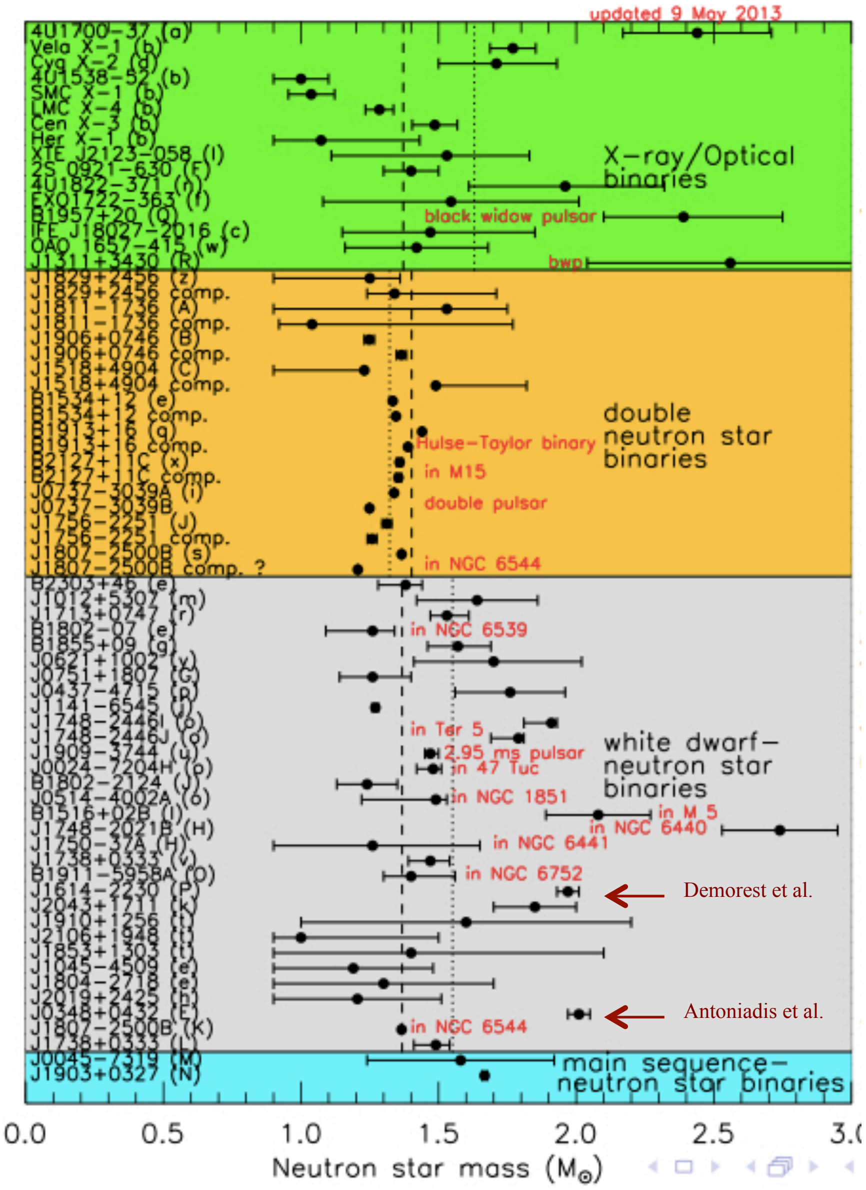


Figure by P.C.C. Freire

Measured Neutron Star Masses (2016)



updated from Lattimer 2013

Observation of ~ 2 $M_\odot$ neutron stars

↓

Dense matter EoS stiff enough is required such that

$$M_{\max}[EoS] > 2M_\odot$$

A natural question arises:

Can hyperons, or strangeness in general, still be present in the interior of neutron stars in view of this constraint ?

The Hyperon Puzzle

"Hyperons → "soft (or too soft) EoS" not compatible (mainly in microscopic approaches) with measured (high) masses. However, the presence of hyperons in the NS interior seems to be unavoidable."

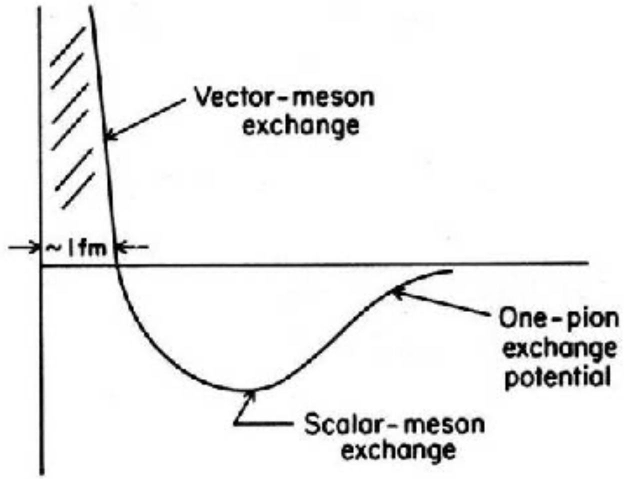
- ✓ can YN & YY interactions still solve it ?
- ✓ or perhaps hyperonic three-body forces ?
- ✓ what about quark matter ?

Solution I: YY vector meson repulsion

(explored in the context of RMF models)

General Feature:

Exchange of scalar mesons generates attraction (softening), but the exchange of vector mesons generates repulsion (stiffening)



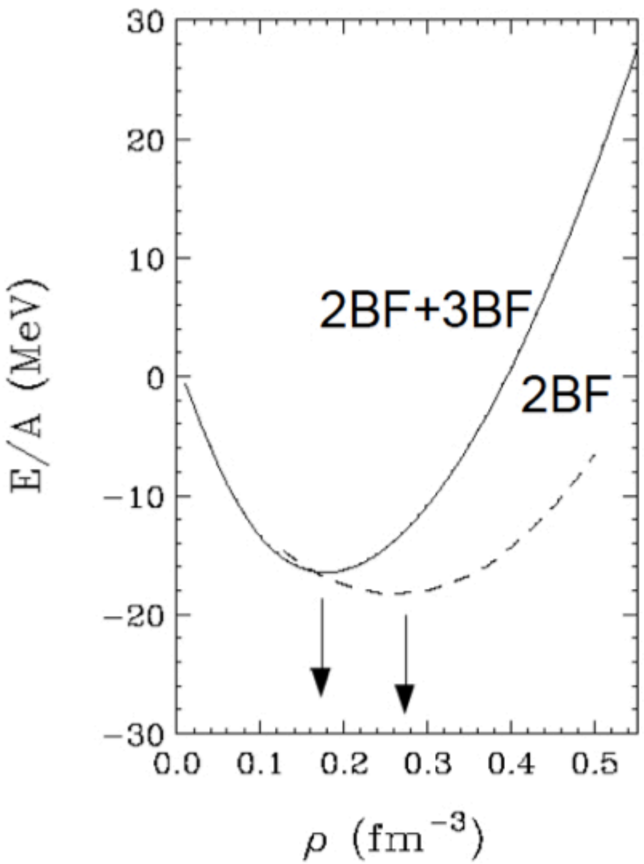
Add vector mesons with hidden strangeness (ϕ) coupled to hyperons yielding a strong repulsive contribution at high densities

Dexhamer & Schramm (2008), Bednarek et al, (2012), Weissenborn et al., (2012)
Oertel et al. (2014), Maslov et al. (2015)

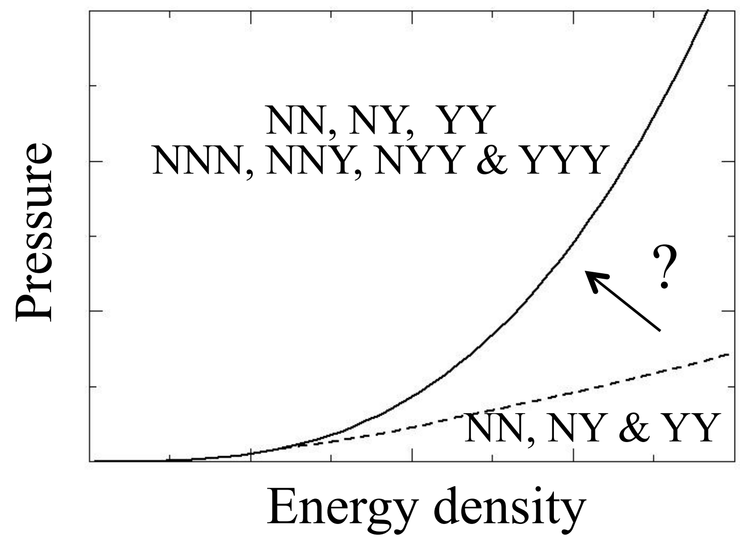
Solution II: can Hyperonic TBF solve this puzzle ?

Natural solution based on: Importance of NNN force in Nuclear Physics
(Considered by several authors: Chalk, Gal, Usmani, Bodmer, Takatsuka, Loiseau, Nogami, Bahaduri, Yamamoto, Lonardoni, IV)

NNN Force



NNY, NYY & YYY Forces



Can hyperonic TBF provide enough repulsion at high densities to reach $2M_\odot$?

Solution III: Quark Matter Core

General Feature:

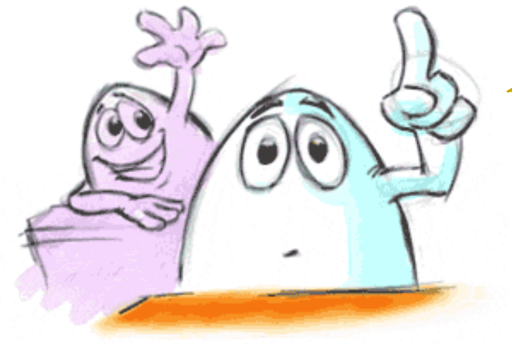
Some authors have suggested an early phase transition to deconfined quark matter as solution to the hyperon puzzle. Massive neutron stars could actually be hybrid stars with a stiff quark matter core.

To yield $M_{\max} > 2M_{\odot}$ Quark Matter should have:

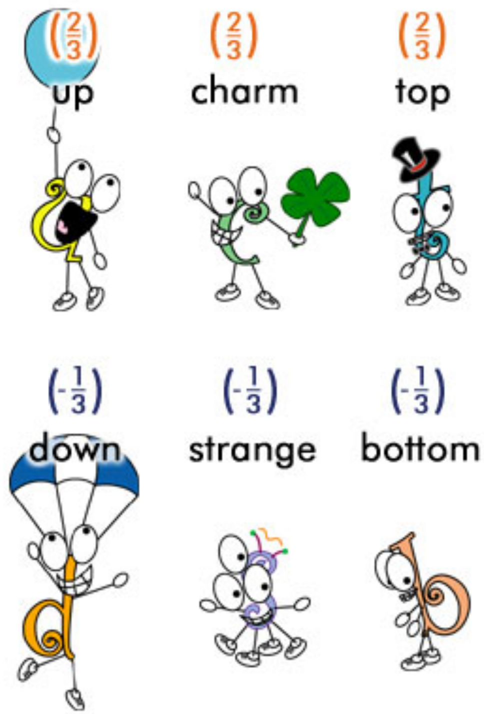
- significant overall quark repulsion $\longrightarrow$ stiff EoS
- strong attraction in a channel $\longrightarrow$ strong color superconductivity

Ozel et al., (2010), Weissenborn et al., (2011), Klaehn et al., (2011), Bonano & Sedrakian (2012), Lastowiecki et al., (2012), Zdunik & Haensel (2012)

What quark flavors are expected in a Neutron Stars ?



Flavor	Mass	Charge [e]
u	~ 5 MeV	2/3
d	~ 10 MeV	-1/3
s	~ 200 MeV	-1/3
c	~ 1.3 GeV	2/3
b	~ 4.3 GeV	-1/3
t	~ 175 GeV	2/3



Suppose: ✓ u, d, s non-interacting
✓ $m_{u=}m_d=m_s=0$ ⟶ i.e., ideal ultra-relativistic Fermi gas (*)

❖ Threshold density for the c quark (similar for b & t)

$$s \rightarrow c + e^- + \bar{\nu}_e \Rightarrow \mu_s = \mu_c + \mu_e + \mu_{\bar{\nu}_e}$$

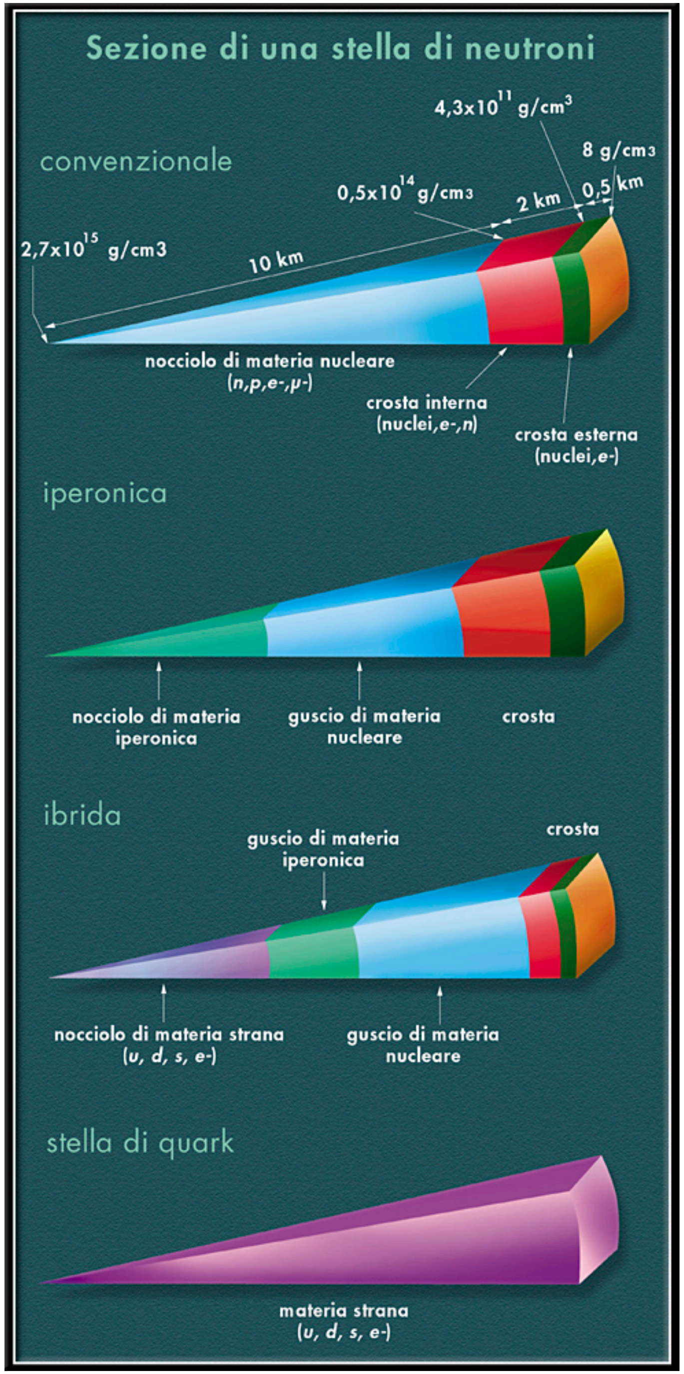
but ✓ u, d, s in β-equilibrium
✓ $Q_{tot=}=0$ ⟶

$$n_B = n_u = n_d = n_s$$
$$n_e = n_{\bar{\nu}_e} = 0$$

then

$$\mu_s = E_{F_s} = \hbar c\left(\pi^2 n_s\right)^{1/3} = \hbar c\left(\pi^2 n_B\right)^{1/3} \geq m_c = 1.3 \quad GeV$$
$$\Rightarrow n_B \geq 29 \quad fm^{-3} \sim 180 n_0$$

Only u,d,s quarks are expected in Neutron Stars



Two families of Compact Stars

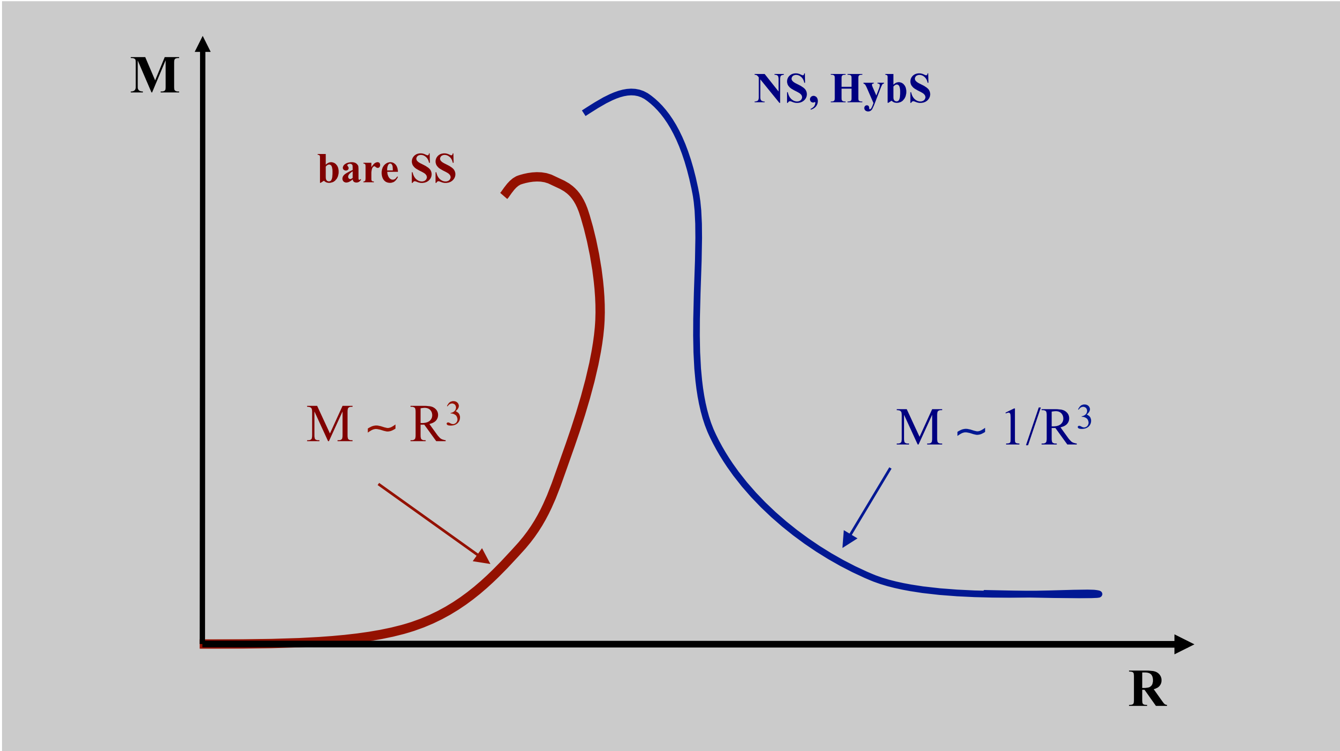
Hadron Stars (HS)

- Nucleonic Stars
- Hyperonic Stars

Quark Stars (QS)

- Hybrid Stars
- Strange Stars

Mass-radius relation



- Strange Stars are self-bound bodies i.e., bound by the strong interactions
- Hadronic or Hybrid Stars are bound by gravity.

The Strange Matter Hypothesis

Bodmer (1971), Terezawa (1979) & Witten (1984)

Three-flavour u,d,s quark matter in equilibrium with respect to the weak interactions, could be the true ground state of strongly interacting mater, rather than ^{56}Fe

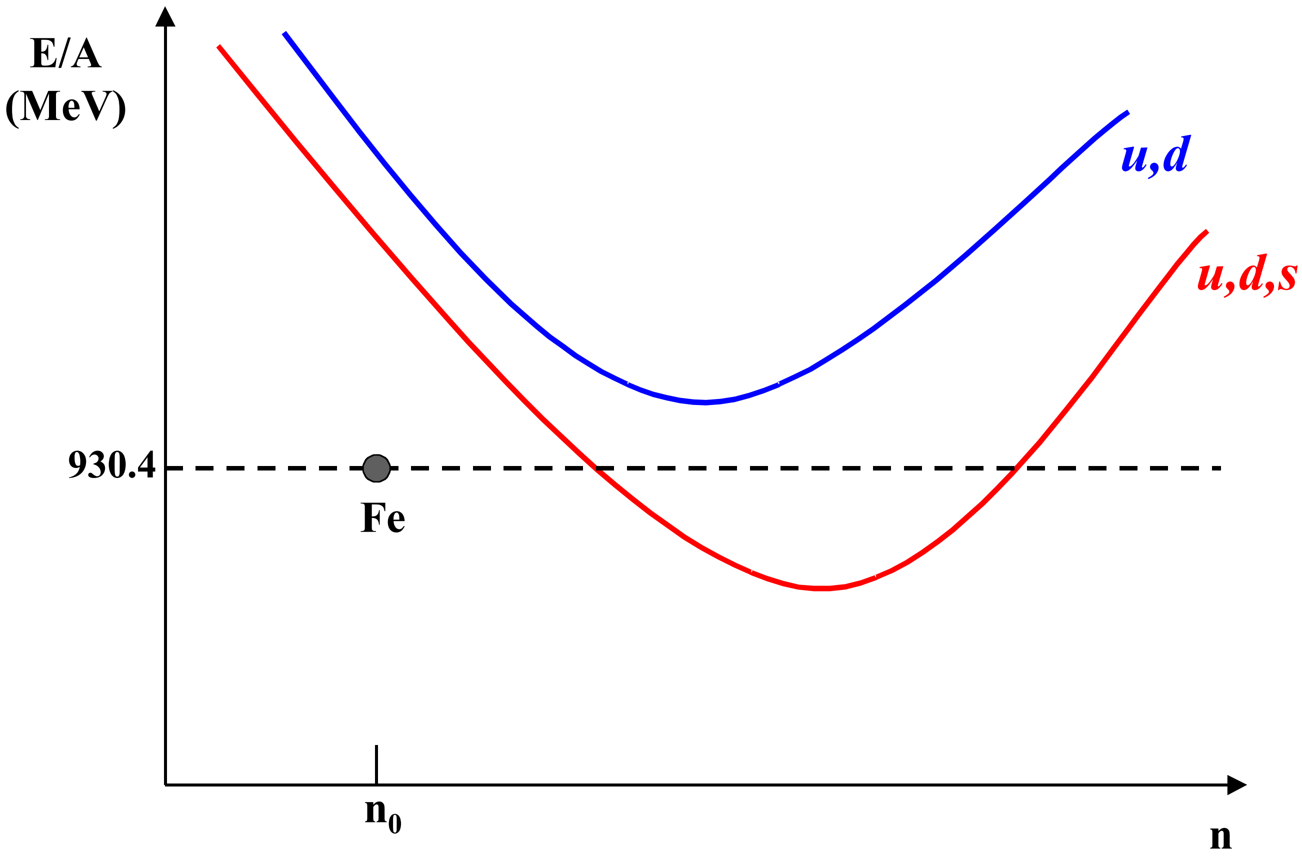
$$E/A|_{SQM} < E(^{56}\mathrm{Fe})/56 \sim 930 \text{ MeV}$$

Stability of nuclei with respect to u,d quark matter

The success of traditional nuclear physics provides a clear indication that quarks in the atomic nuclei are confined within neutrons and protons

$$E/A|_{ud} > E(^{56}\mathrm{Fe})/56 \sim 930 \text{ MeV}$$

Schematically



- If the SQM hypothesis is true, why nuclei do not decay into SQM droplets (strangelets) ?
- One should explain the existence of atomic nuclei in Nature

Stability of Nuclei with respect to SQM

- Direct decay of ^{56}Fe to a SQM droplet

$$^{56}Fe \rightarrow {}^{56}(SQM) \Longrightarrow$$

~ 56 simultaneous strangeness changing weak process

$$u \rightarrow s + e^{+} + \nu_e$$
$$d + u \rightarrow s + u$$

The probability for the direct decay is $P \sim (G_F^2)^{56} \sim 0$ and the mean-life time of ^{56}Fe with respect to the direct decay to a drop of SQM is

$\tau \gg$ age of the Universe

- Step by step decay of ^{56}Fe to a SQM droplet

$$^{56}Fe \rightarrow X^{56}_{\Lambda} \rightarrow Y^{56}_{\Lambda\Lambda} \rightarrow \ldots \rightarrow {}^{56}(SQM)$$

$$^{56}Fe \rightarrow Fe^{56}_{\Lambda}$$

$$^{56}Fe \rightarrow Mn^{56}_{\Lambda}$$

These processes are not energetically possible since

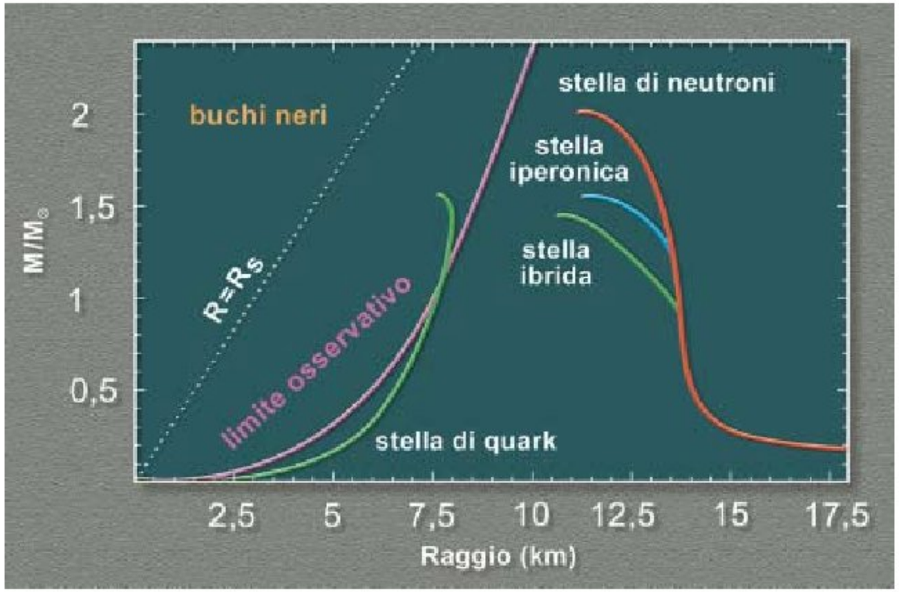
$$Q = M(^{56}Fe) - M(X^{56}_{\Lambda}) < 0$$

Thus, according with the Bodmer-Terezawa-Witten hypothesis, nuclei are metastable states of strong interacting matter with a mean-life time

τ >> age of the Universe

One of the most likely strange star candidate is the X-ray burster SAX J1808.4-3658

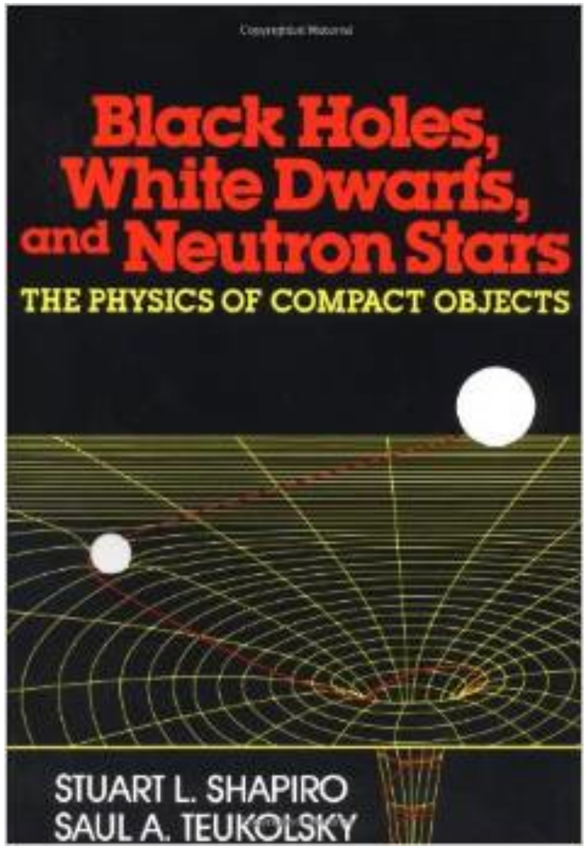
- Discovered in September 1996 by Beppo SAX
- Two bright type-I X-ray burst detected ($\Delta T < 30$ s)
- Millisecond PSR: coerent pulsation with P=2.49 ms
- Member of a LMXB: P_{orb}=2.01 hours

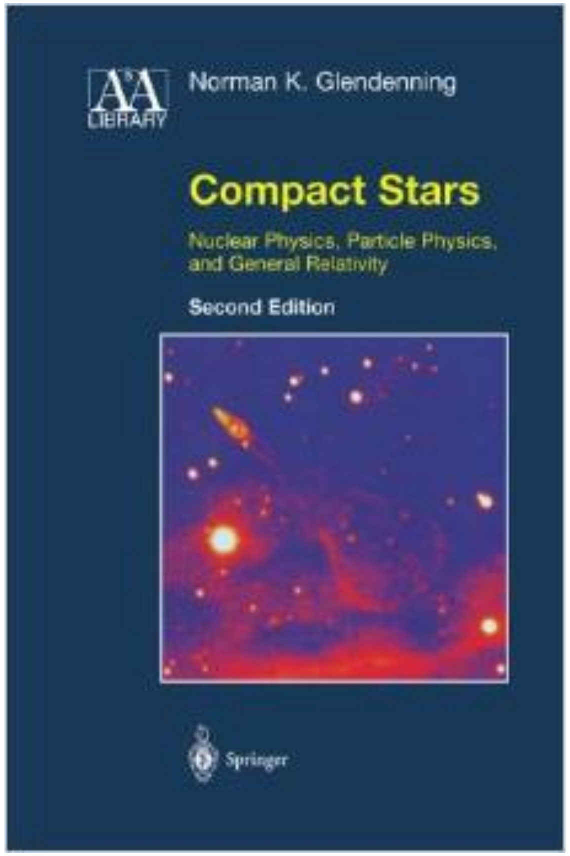


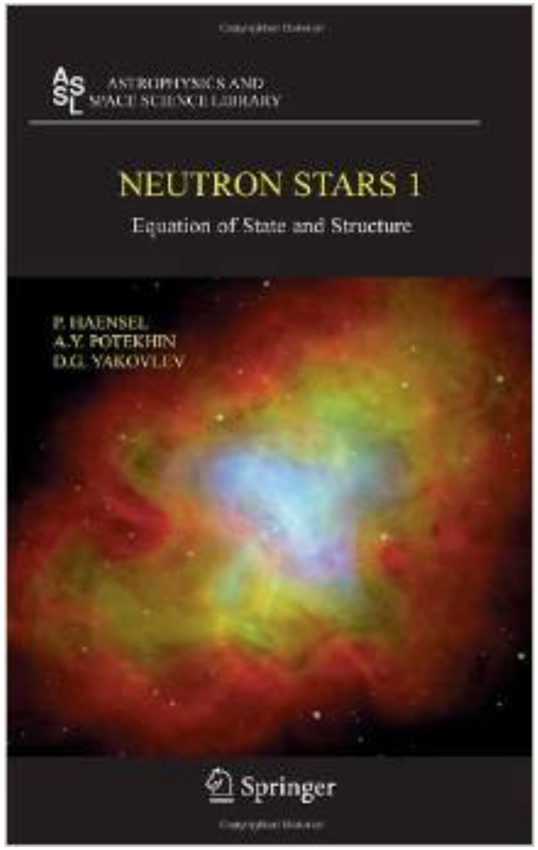
Observatonal limit by Li et al., PRL 83, 3776 (1999)

$$R < \left(\frac{F_{\min}}{F_{\max}}\right)^{2/7} \left(\frac{GM}{4\pi^2}\right)^{1/3} P^{2/3}$$

This short talk is just a brush-stroke on the physics of neutron stars. Three excellent monographs on this topic for interested readers are:







The final message of this talk

Neutron stars are excellent observatories to test fundamental properties of matter under extreme conditions and offer an interesting interplay between nuclear processes and astrophysical observables

- You for your time & attention
- Catalina for her invitation