# Neutron stars. Lecture 2

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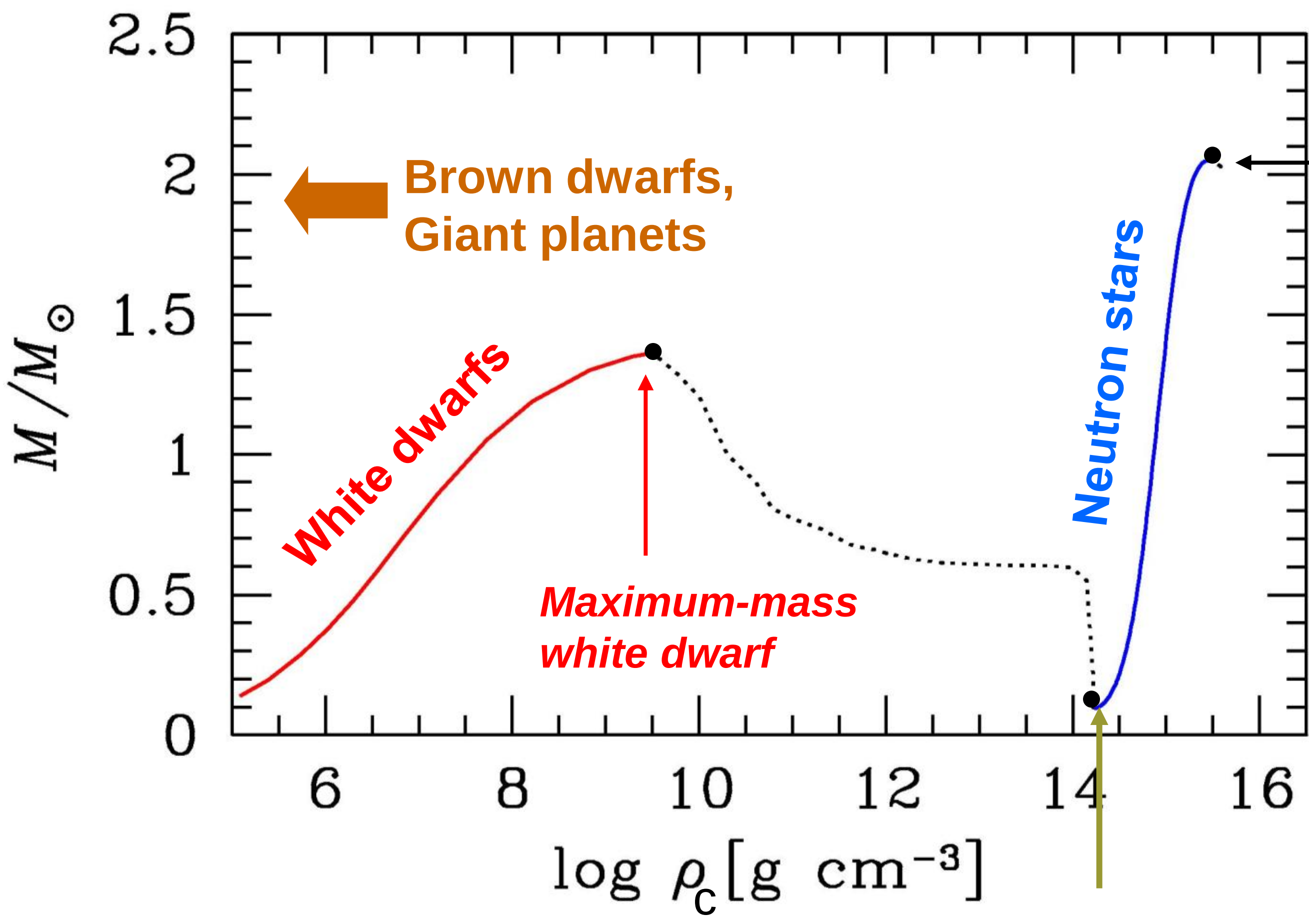
# NS Masses

- Stellar masses are directly measured only in binary systems
- Accurate NS mass determination for PSRs in relativistic systems by measuring PK corrections
- Gravitational redshift may provide M/R in NSs by detecting a *known* spectral line,

$$E_\infty = E(1-2GM/Rc^2)^{1/2}$$

# Neutron stars and white dwarfs




***Maximum -mass neutron star***

$M \sim (1.5-2.5)\, M_{\text{Sun}}$

$R \sim 9-12$ km

***Minimum-mass neutron star***

$M \sim 0.1\, M_{\text{Sun}}$

$R \sim 250$ km

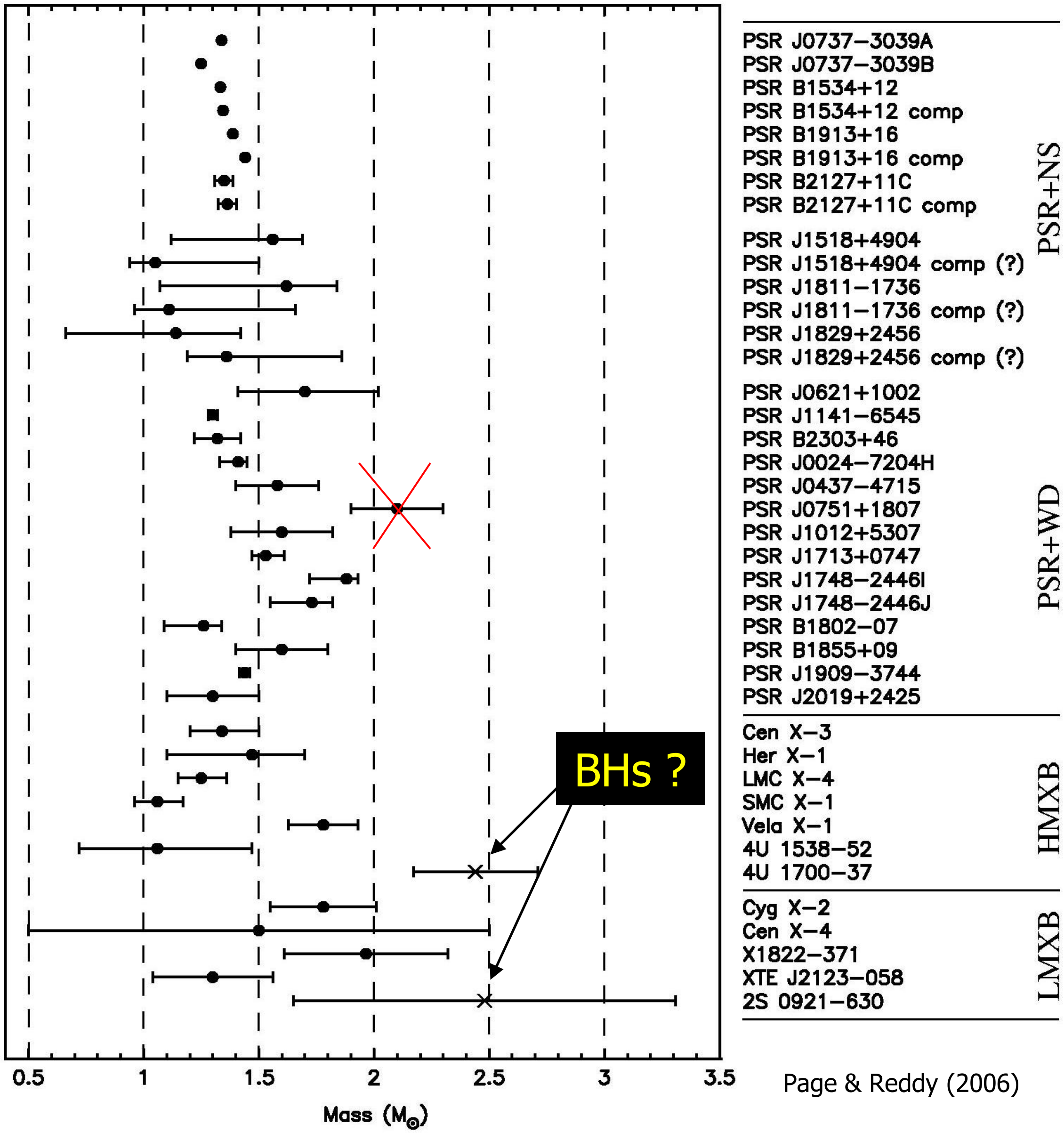
Remember about the difference between baryonic and gravitational masses in the case of neutron stars!

# Minimal mass

In reality, minimal mass is determined by properties of protoNSs.
Being hot, lepton rich they have much higher limit: about 0.7 solar mass.

Stellar evolution does not produce NSs with baryonic mass less than about 1.4 solar mass.

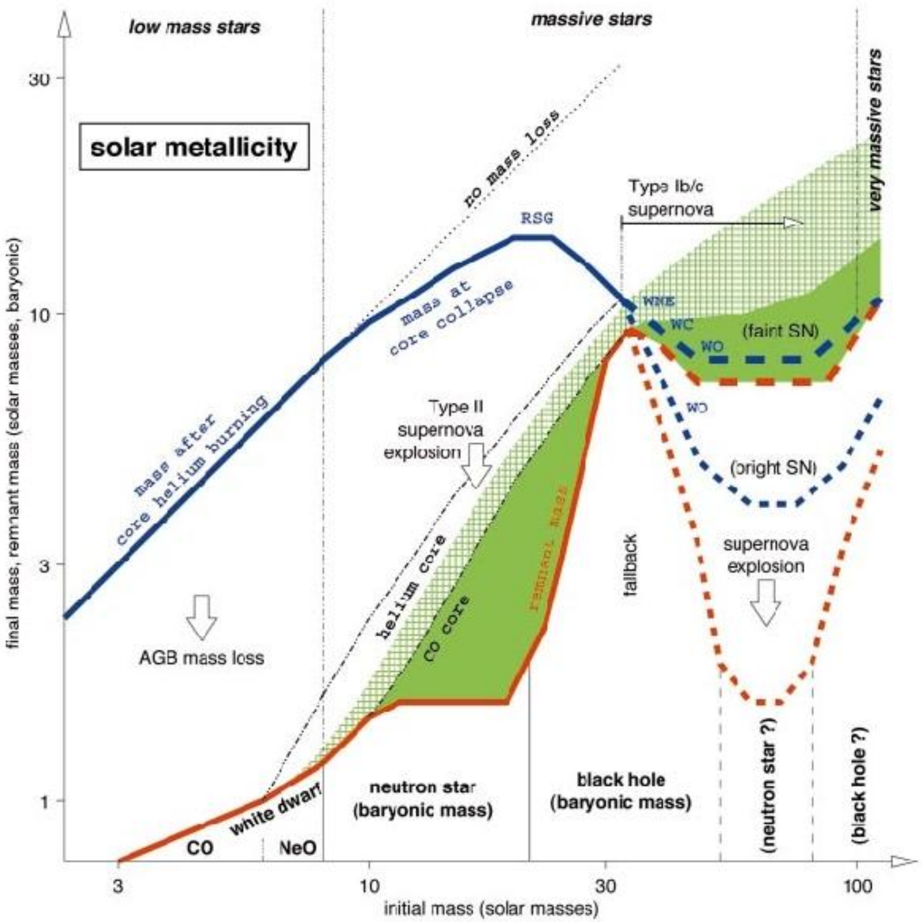
Fragmentation of a core due to rapid rotation potentially can lead to smaller masses, but not as small as the limit for cold NSs.




Page & Reddy (2006)

Here, of course, gravitational masses are measured

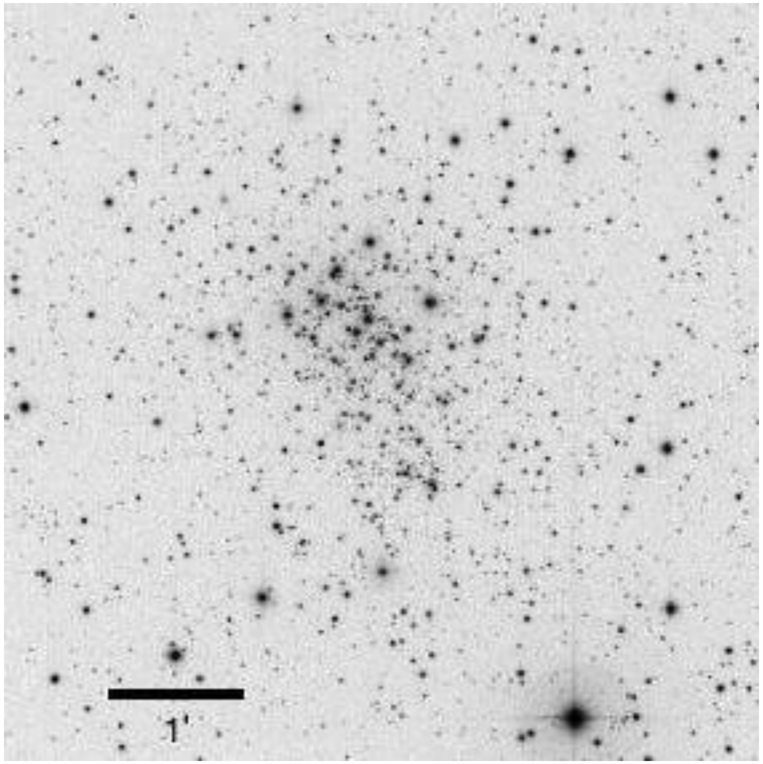
# Compact objects and progenitors. Solar metallicity.




There can be a range of progenitor masses in which NSs are formed, however, for smaller and larger progenitors masses BHs appear.

(Woosley et al. 2002)

# A NS from a massive progenitor




Anomalous X-ray pulsar in the association Westerlund1 most probably has a very massive progenitor, >40 $M_{\odot}$.

(astro-ph/0611589)

# NS+NS binaries

Secondary companion in double NS binaries can give a good estimate of the initial mass if we can neglect effects of evolution in a binary system.

| | Pulsar | Pulsar mass | Companion mass | |
|---|---|---|---|---|
| | B1913+16 | 1.44 | 1.39 | |
| GC → | B2127+11C | 1.35 | 1.36 | |
| | B1534+12 | 1.33 | 1.35 | |
| | J0737-3039 | 1.34 | 1.25 | |
| | J1756-2251 | 1.40 | 1.18 | |
| | J1518+4904 | <1.17 | >1.55 | → 0808.2292 |
| Non-recycled → | J1906+0746 | 1.25 | 1.35 | |
| | J1811-1736 | 1.63 | 1.11 | |
| | J1829+2456 | 1.14 | 1.36 | |

Also there are candidates, for example PSR J1753-2240 arXiv:0811.2027

In NS-NS systems we can neglect all tidal effects etc.

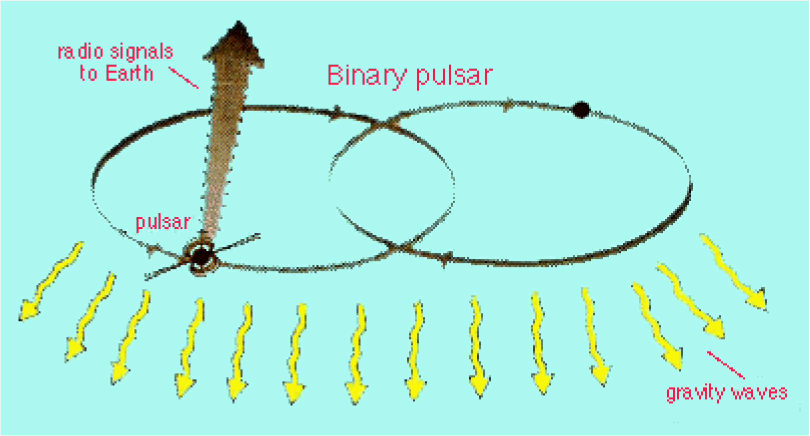
# NS+WD binaries

**Some examples**

1. **PSR J0437-4715. WD companion [0801.2589, 0808.1594 ].**
   **The closest millisecond PSR. $M_{NS}$=1.76+/-0.2 solar.**
   **Hopefully, this value will not be reconsidered.**
2. **The case of PSR J0751+1807.**
   **Initially, it was announced that it has a mass ~2.1 solar [astro-ph/0508050].**
   **However, then in 2007 at a conference the authors announced that the result was incorrect. Actually, the initial value was 2.1+/-0.2 (1 sigma error).**
   **New result: 1.24 +/- 0.14 solar**
   **[Nice et al. 2008, Proc. of the conf. "40 Years of pulsars"]**
3. **PSR B1516+02B in a globular cluster. M~2 solar (M>1.72 (95%)).**
   **A very light companion. Eccentric orbit. [Freire et al. arXiv: 0712.3826]**
   **Joint usage of data on several pulsars can give stronger constraints on the lower limit for NS masses.**

**It is expected that most massive NSs get their additional "kilos" due to accretion from WD companions [astro-ph/0412327 ].**

# Binary pulsars




$$\frac{d\Delta_{E\odot}}{dt} = \sum_i \frac{Gm_i}{c^2 r_i} + \frac{v_\oplus^2}{2c^2} - \text{constant} .$$

$$\Delta_{S\odot} = -\frac{2GM_\odot}{c^3} \log(1 + \cos\theta) ,$$

$$T = t_{\rm obs} - t_0 + \Delta_C - D/f^2 + \Delta_{R\odot}(\alpha, \delta, \mu_\alpha, \mu_\delta, \pi) + \Delta_{E\odot} - \Delta_{S\odot}(\alpha, \delta) - \Delta_R(x, e, P_b, T_0, \omega, \dot{\omega}, \dot{P}_b) - \Delta_E(\gamma) - \Delta_S(r, s)$$

# Relativistic corrections and measurable parameters

$$\dot{\omega}=3\left[\frac{P_b}{2\pi}\right]^{-5/3}(T_\odot M)^{2/3}(1-e^2)^{-1},$$

$$\gamma=e\left[\frac{P_b}{2\pi}\right]^{1/3}T_\odot^{2/3}M^{-4/3}m_2(m_1+2m_2),$$

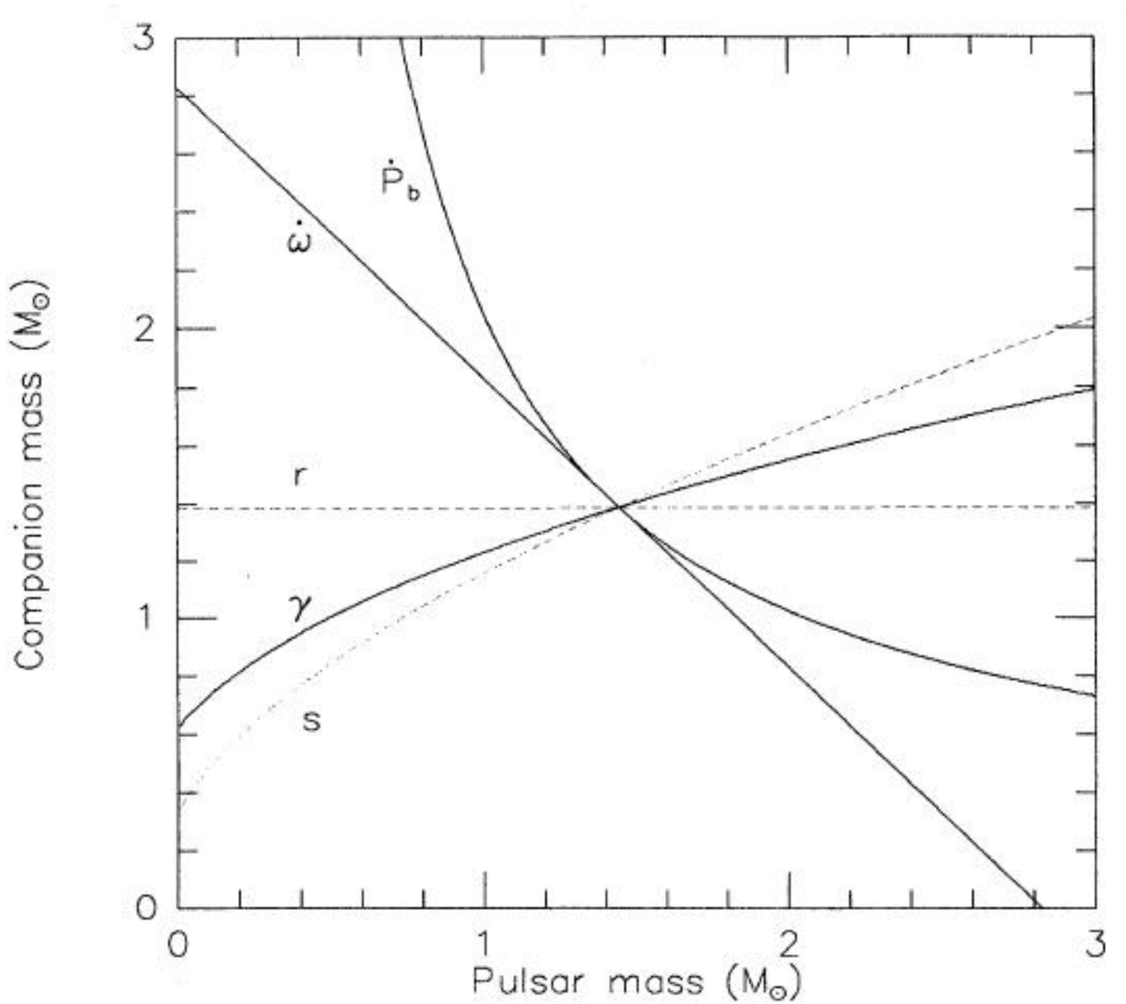
$$\dot{P}_b=-\frac{192\pi}{5}\left[\frac{P_b}{2\pi}\right]^{-5/3}\left[1+\frac{73}{24}e^2+\frac{37}{96}e^4\right]\times(1-e^2)^{-7/2}T_\odot^{5/3}m_1m_2M^{-1/3},$$

$$r=T_\odot m_2,$$

$$s=x\left[\frac{P_b}{2\pi}\right]^{-2/3}T_\odot^{-1/3}M^{2/3}m_2^{-1}.$$

For details see
Taylor, Weisberg 1989
ApJ 345, 434

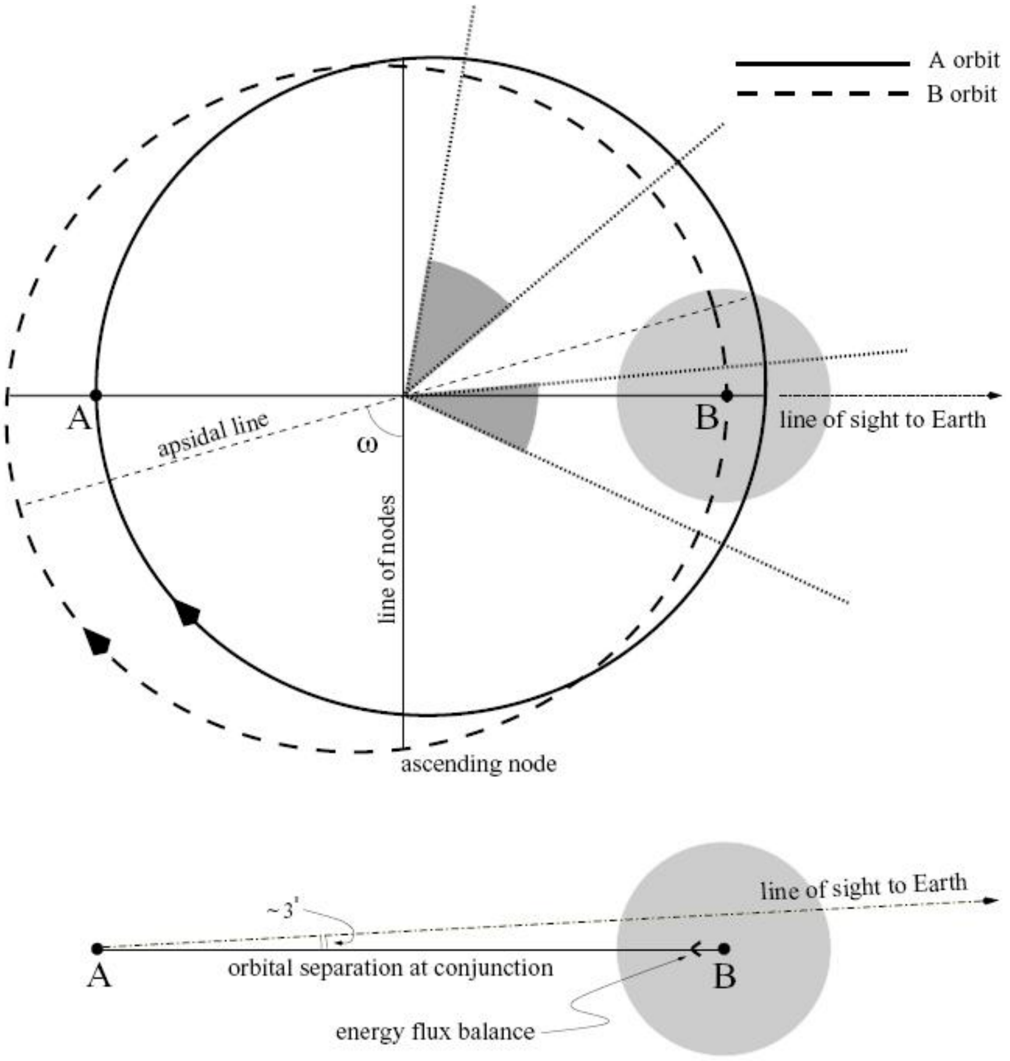
# Mass measurements

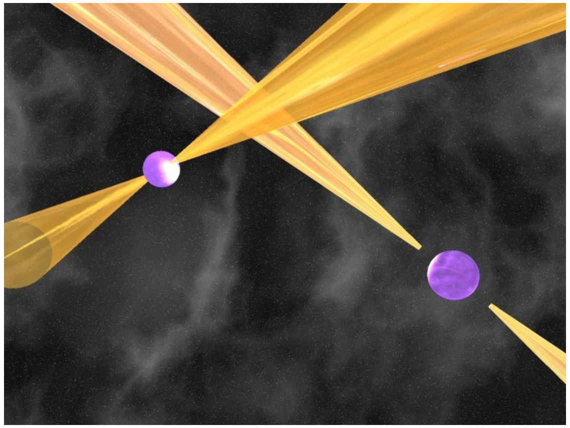



PSR 1913+16

(Taylor)

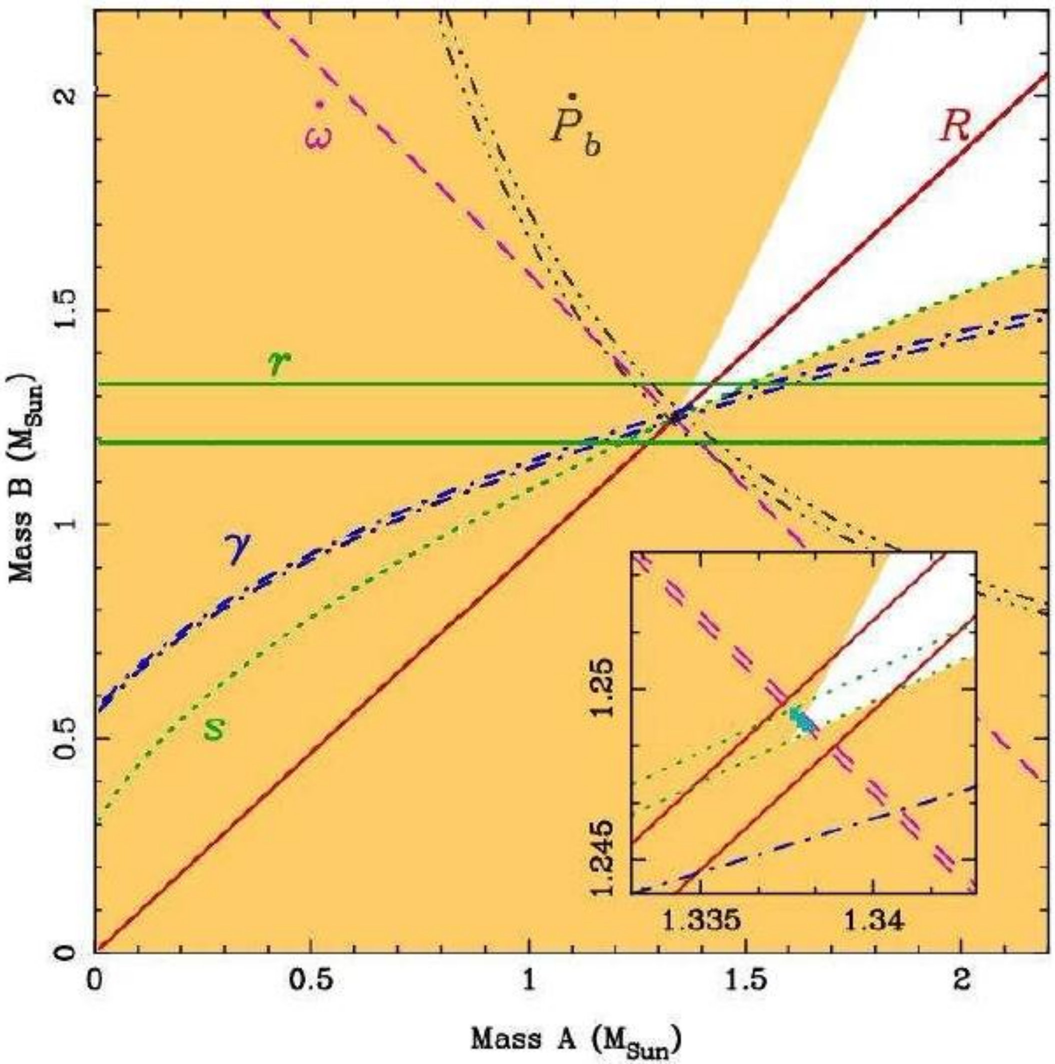
# Double pulsar J0737-3039



(Lyne et al. astro-ph/0401086)

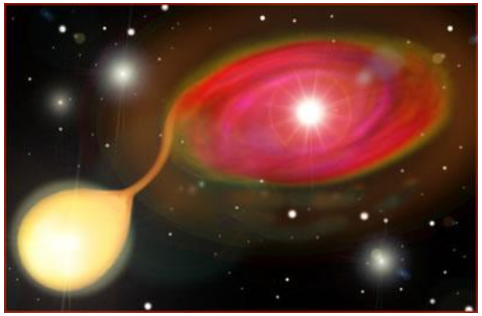
# Masses for PSR J0737-3039




The most precise values.

(Kramer et al. astro-ph/0609417)

# Mass determination in binaries: mass function



$$f_v(m)\frac{m_x^3 \sin i^3}{(m_x+m_v)^2} = 1,038 \cdot 10^{-7} K_v^3 P (1-e^2)^{3/2} ,$$

$m_x$, $m_v$ - masses of a compact object and of a normal star (in solar units),
$K_v$ – observed semi-amplitude of line of sight velocity of the normal star (in km/s),
$P$ – orbital period (in days), $e$ – orbital eccentricity, $i$ – orbital inclination
(the angle between the prbital plane and line of sight).

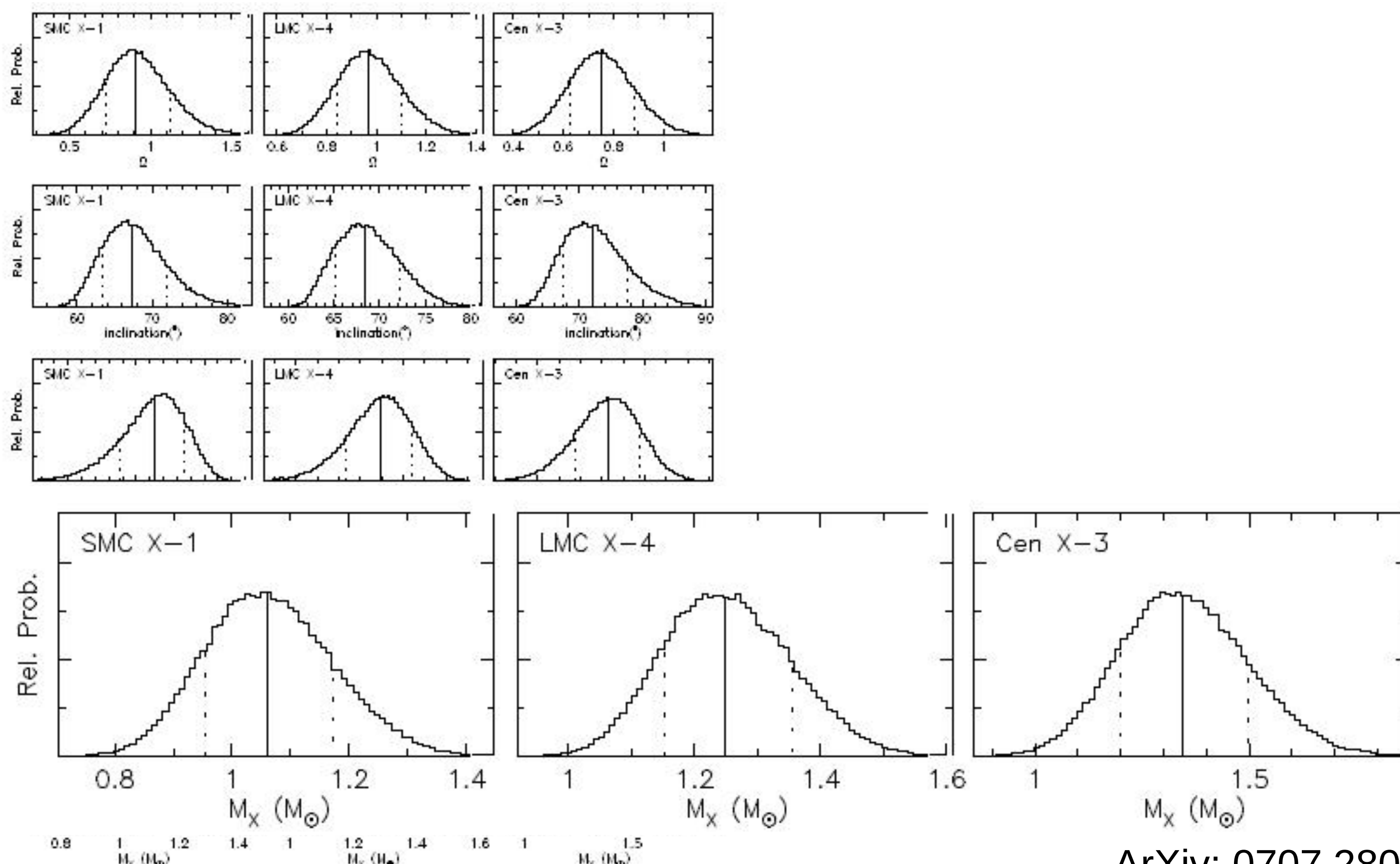
One can see that the mass function is the lower limit for the mass of a compact star.

The mass of a compact object can be calculated as:

$$m_x = f_v(m)\left(1+\frac{m_v}{m_x}\right)^2 \frac{1}{\sin i^3} .$$

So, to derive the mass it is necessary to know (besides the line of sight velocity) independently two more parameters: mass ration $q=m_x/m_v$,
and orbital inclination $i$.

# Some mass estimates

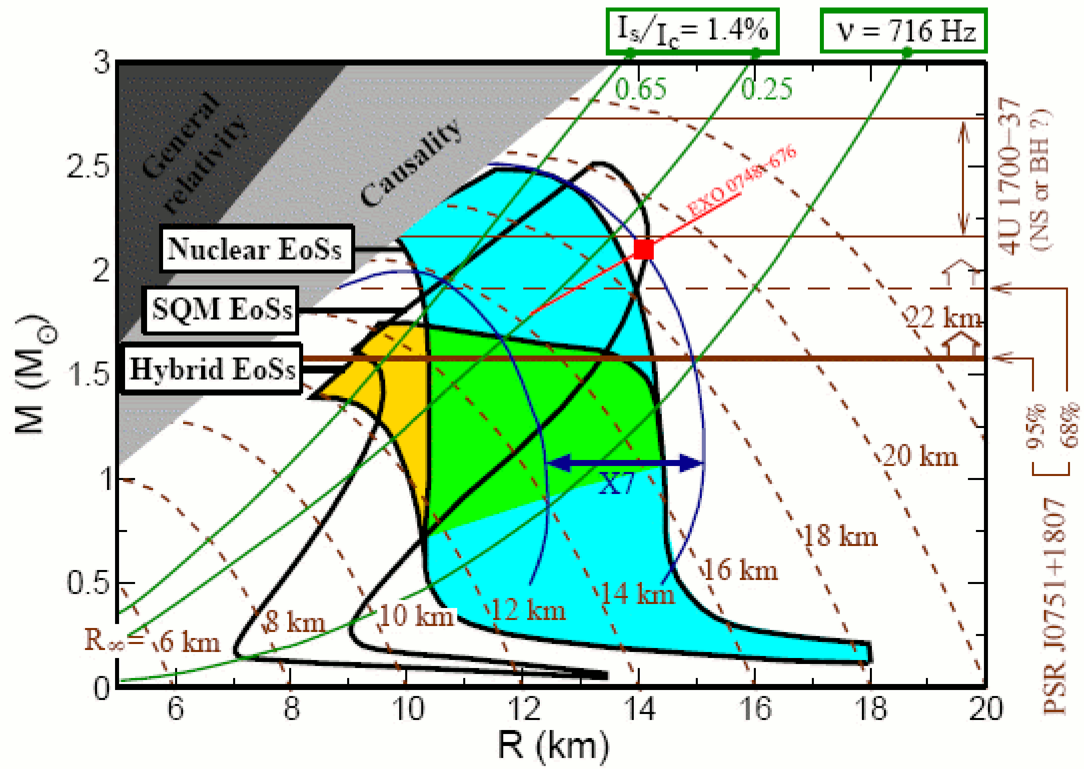



ArXiv: 0707.2802

# Mass-radius diagram and constraints

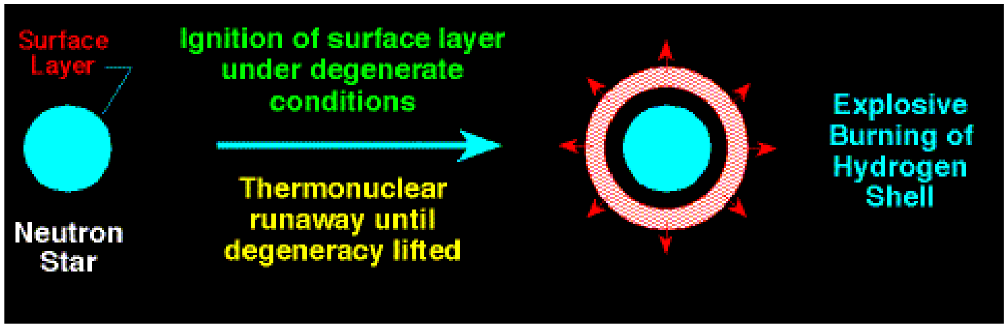
Unfortunately, there are no good data on independent measurements of masses and radii of NSs.

Still, it is possible to put important constraints. Most of recent observations favour stiff EoS.



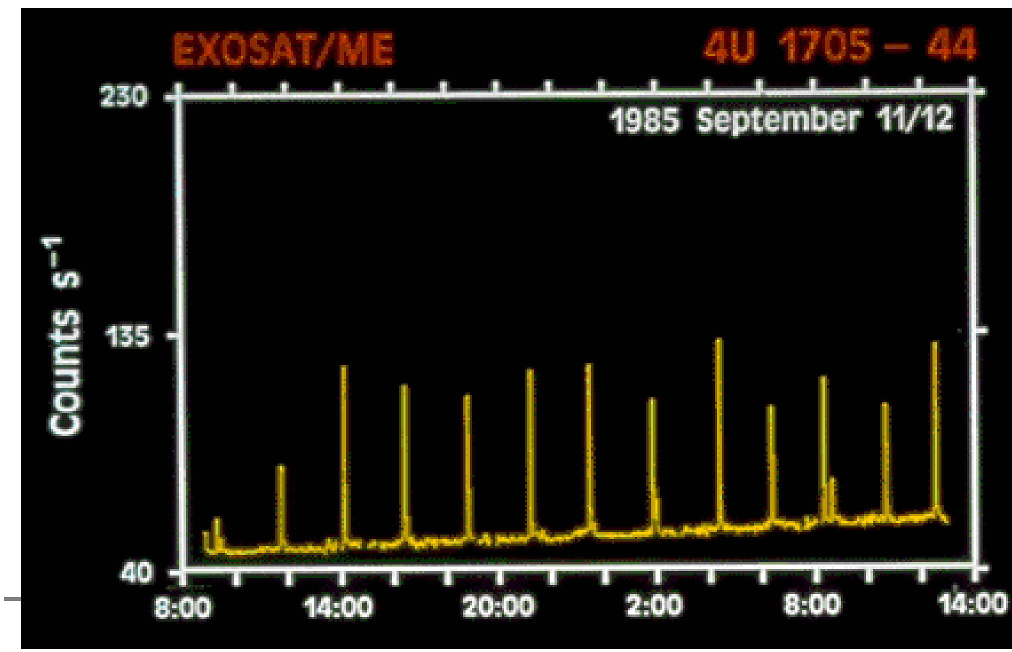

(astro-ph/0608345, 0608360)

# Radius determination in bursters



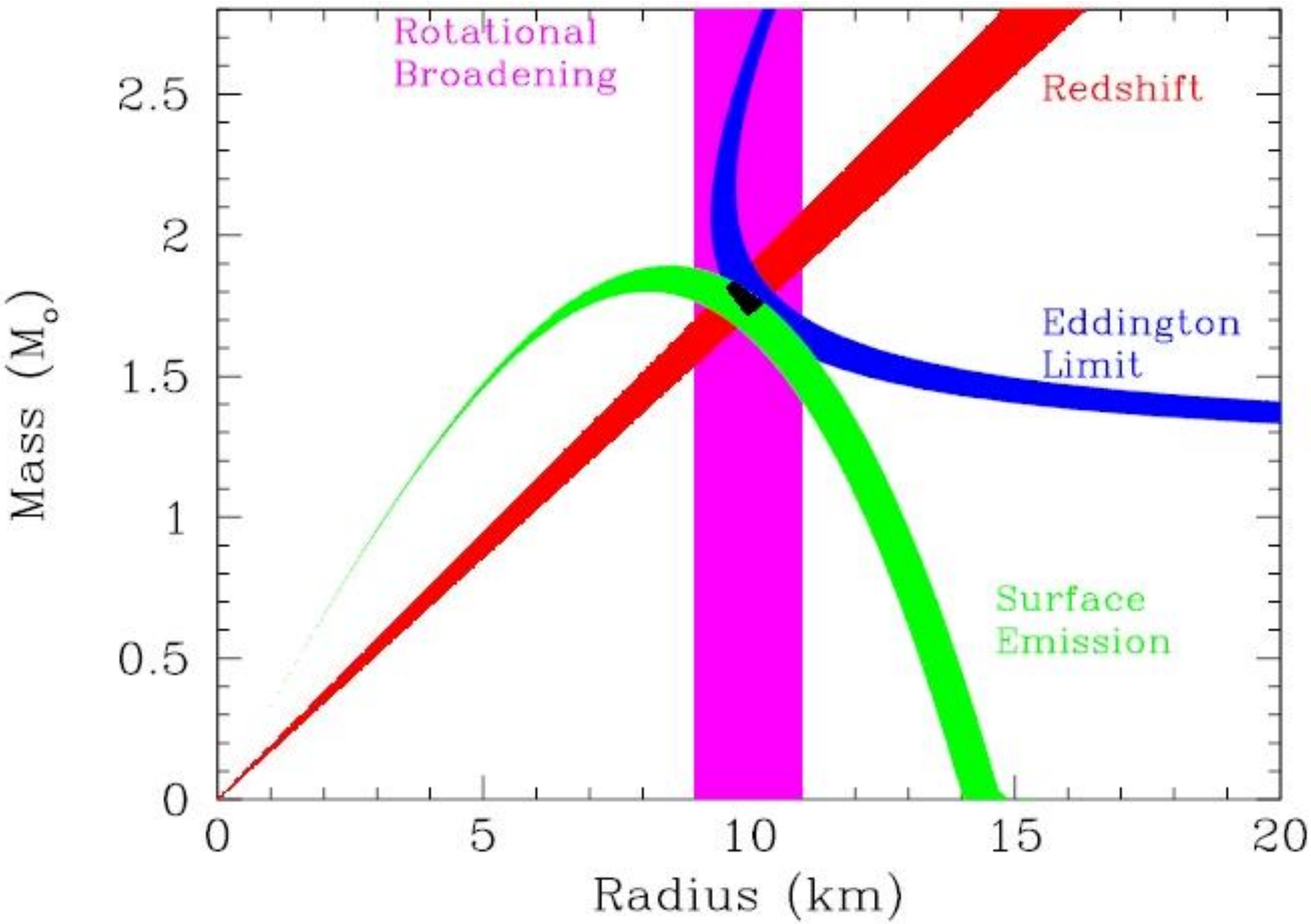

Explosion with a ~ Eddington luminosity.

Modeling of the burst spectrum and its evolution.




See, for example,
Joss, Rappaport 1984,
Haberl, Titarchuk 1995

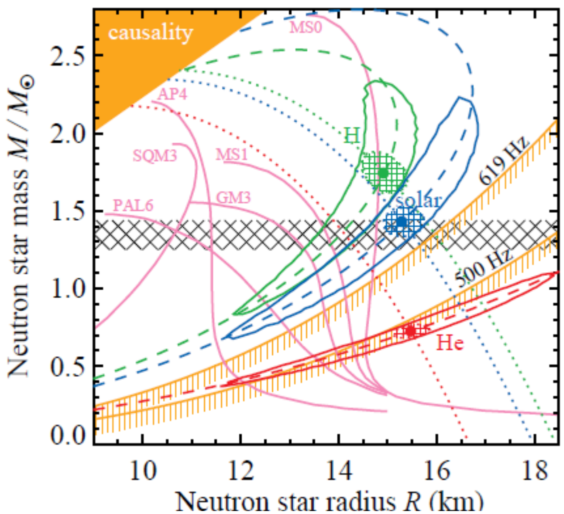
# Combination of different methods




EXO 0748-676

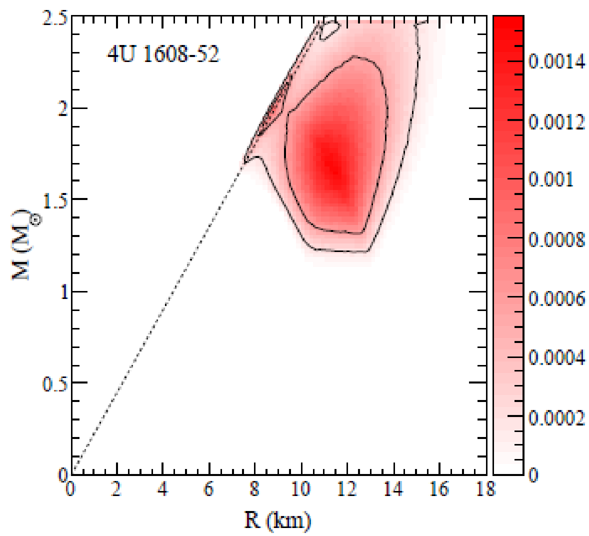
(Ozel astro-ph/0605106)

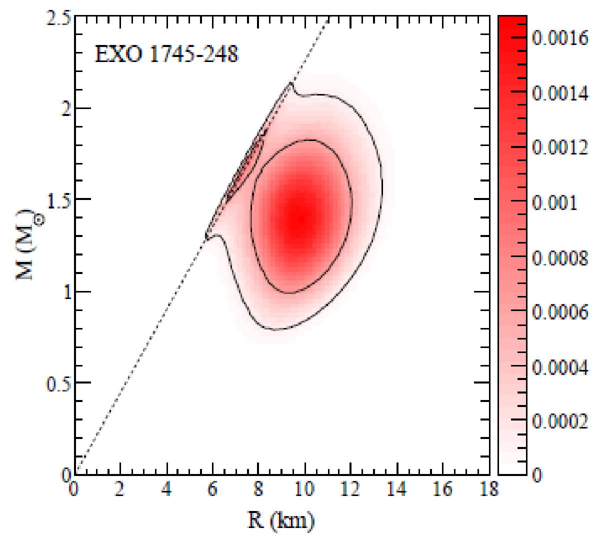
# New results

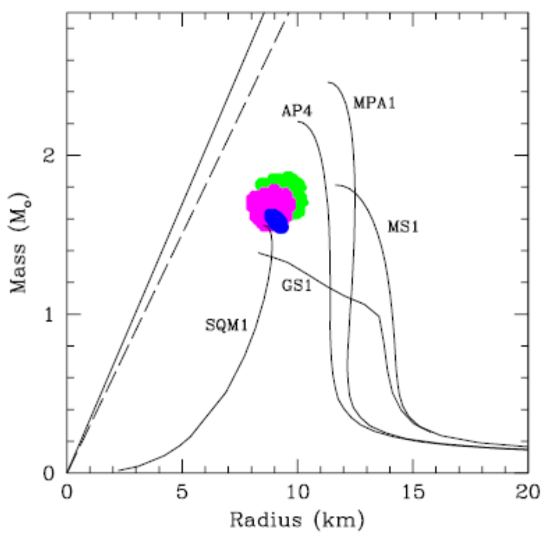



1004.4871

1005.0811



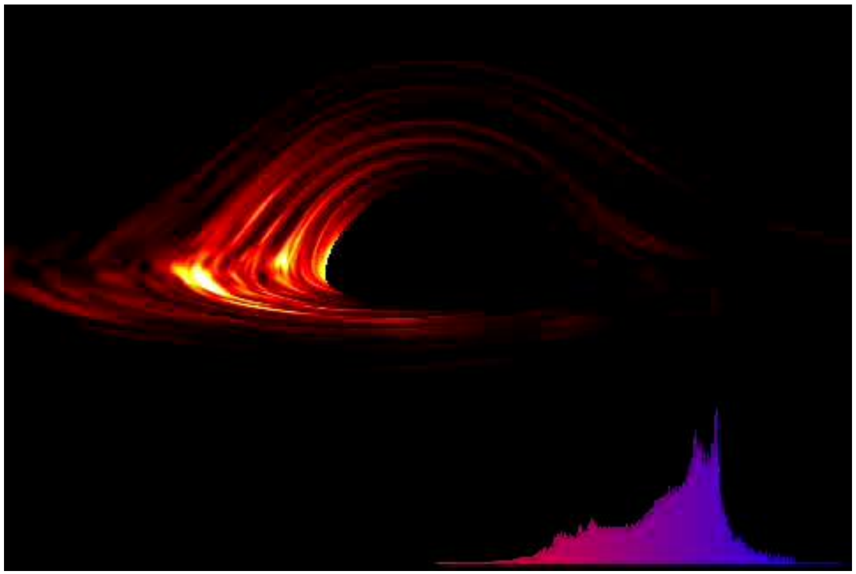



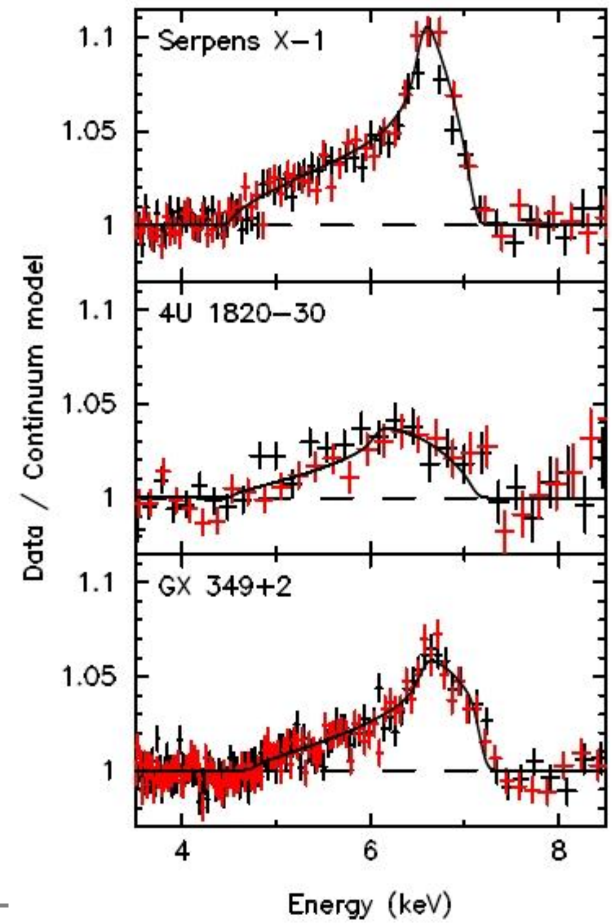

It seems that Ozel et al. underestimate
different uncertainties and make additional assumptions.

1002.3153

# Fe K lines from accretion discs

Measurements of the inner disc radius provide upper limits on the NS radius.





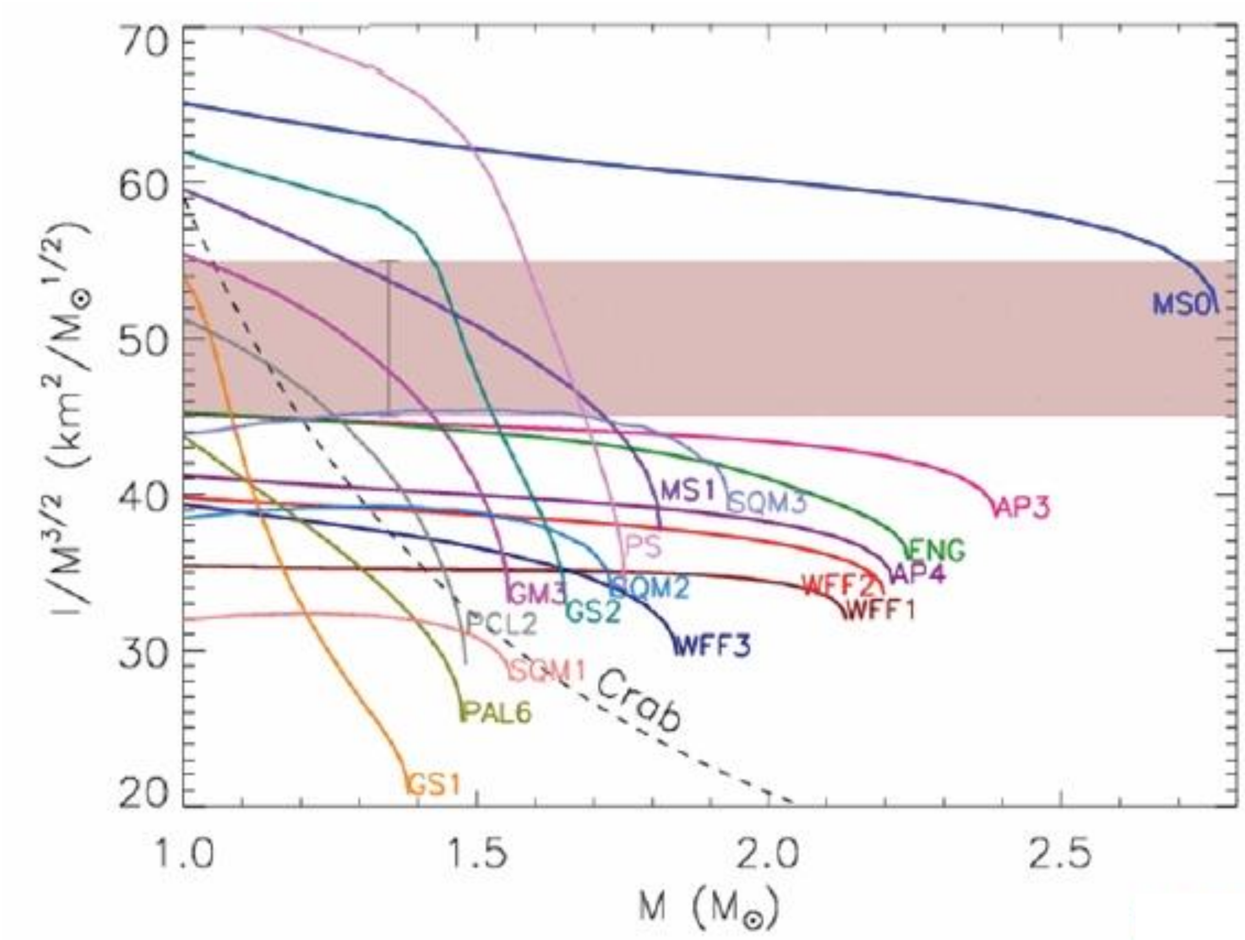

Suzaku observations

Ser X-1 <15.9+/-1
4U 1820-30 <13.8+2.9-1.4
GX 349+2 <16.5+/-0.8
(all estimates for 1.4 solar mass NS)

[Cackett et al. arXiv: 0708.3615]

**See also Papito et al. arXiv: 0812.1149, and a review in Cackett et al. 0908.1098**

# Limits on the moment of inertia



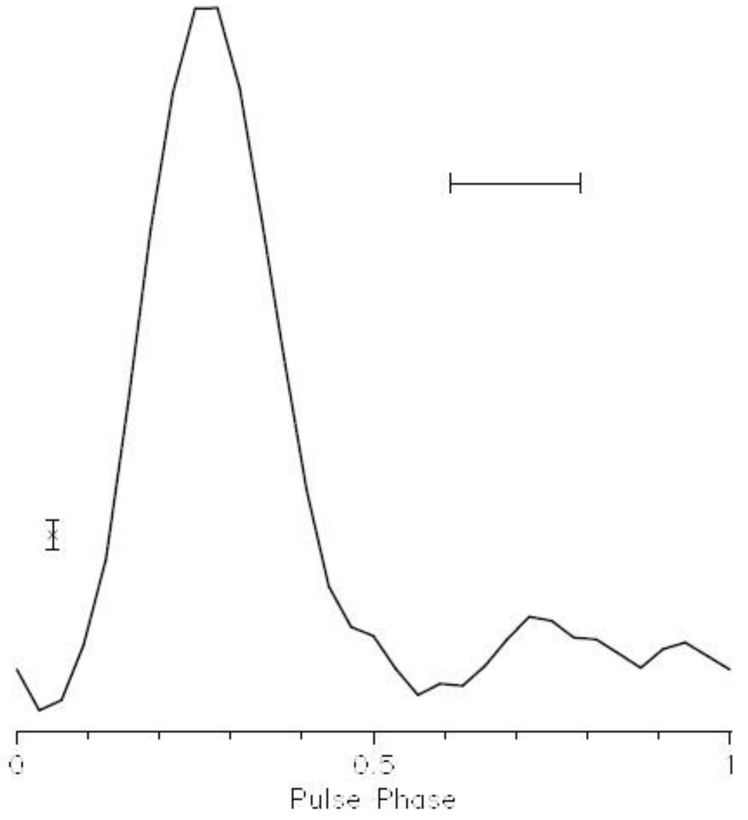

Spin-orbital interaction

PSR J0737-3039
(see Lattimer, Schutz
astro-ph/0411470)

The band refers to a *hypothetical* 10% error.
This limit, hopefully, can be reached in several years of observ.

# Most rapidly rotating PSR

716-Hz eclipsing binary radio pulsar in the globular cluster Terzan 5



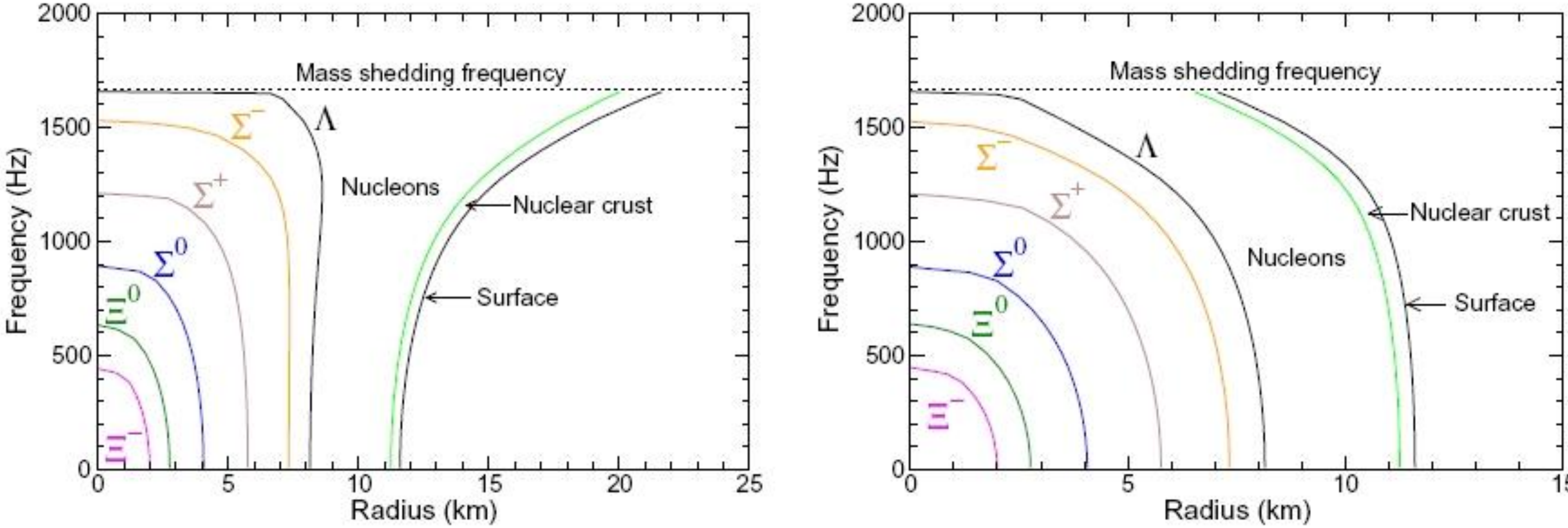

Previous record
(642-Hz pulsar B1937+21)
survived for more than 20 years.

**Interesting calculations for rotating NS have been performed by Krastev et al. arXiv: 0709.3621**

Rotation starts to be important from periods ~3 msec.

(Jason W.T. Hessels et al. astro-ph/0601337)

# Rotation and composition

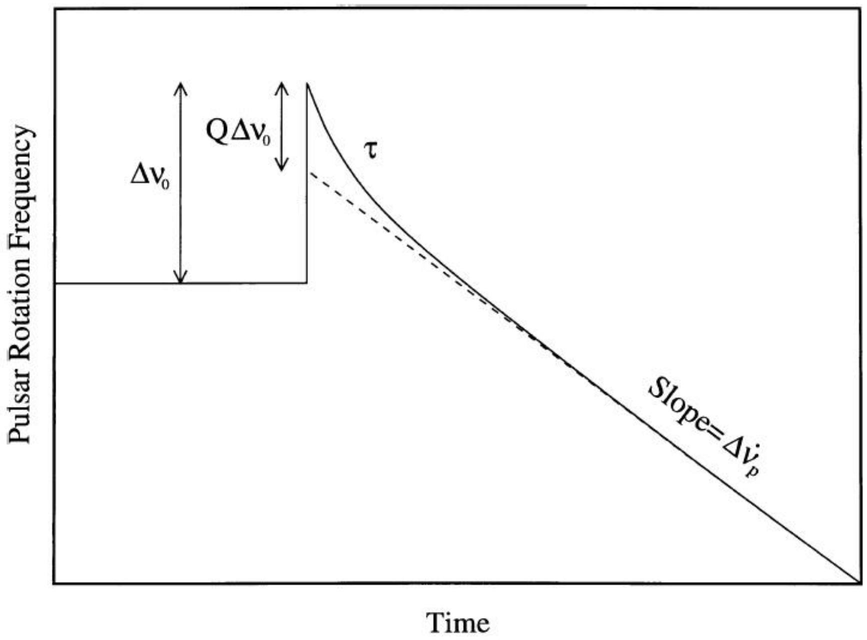



(equatorial) (polar)

Computed for a particular model:
density dependent relativistic Brueckner-Hartree-Fock (DD-RBHF)

(Weber et al. arXiv: 0705.2708)

# What is a glitch?




A sudden increase of rotation rate.

ATNF catalogue gives ~50 normal PSRs with glitches.

The most known: Crab and Vela

$\Delta\Omega/\Omega \sim 10^{-9} - 10^{-6}$

Spin-down rate can change after a glitch. Vela is spinning down faster after a glitch.

**Starquakes or/and vortex lines unpinning - new configuration or transfer of angular momentum**

Glitches are important because they probe internal structure of a NS.

# General features of the glitch mechanism

Glitches appear because some fraction (unobserved directly) rotates faster than the observed part (crust plus charged parts), which is decelerated (i.e., which is spinning-down).

$$\dot{J}_{\rm res} \leq I_{\rm res}|\dot{\Omega}|,$$

The angular momentum is "collected" by the reservoir, related to differentially rotating part of a star (SF neutrons)

$$\frac{I_{\rm res}}{I_c} \geq \frac{\bar{\Omega}}{|\dot{\Omega}|} A \equiv G,$$

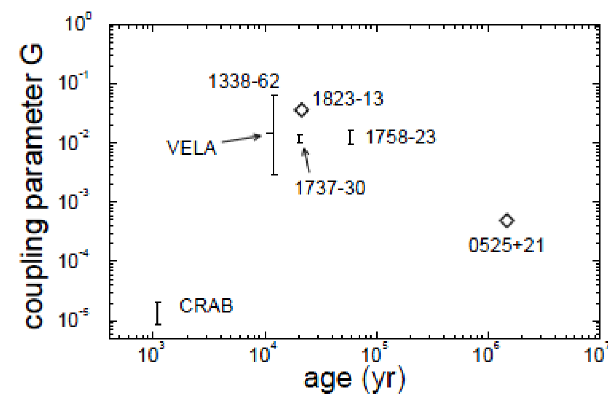
G – the coupling parameter. It can be slightly different in different sources. A – pulsar activity parameter.

Known from observations

$$\frac{I_{\rm res}}{I_c} \geq G_{\rm Vela} = 1.4\%.$$

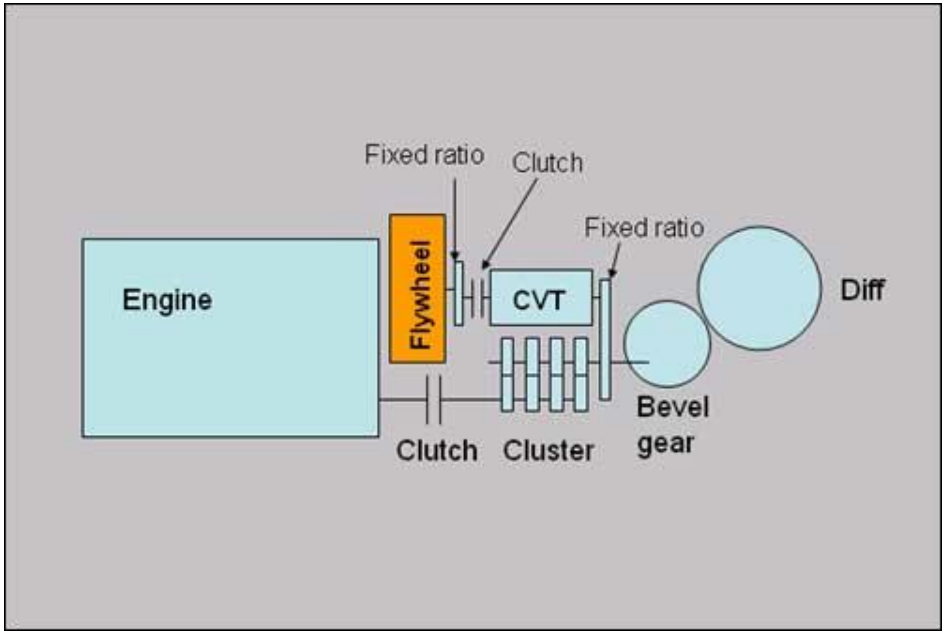
Glitch statistics for Vela provide an estimate for G.

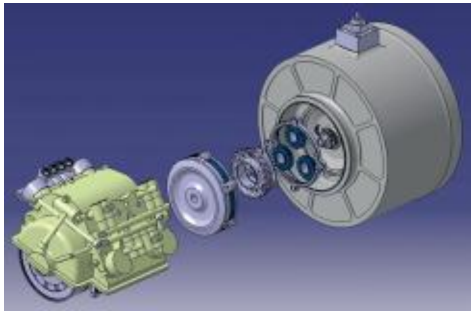
Superfluid is a good candidate to form a "reservoir" because relaxation time after a glitch is very long (~months) which points to very low viscosity.




Link et al. 0001245

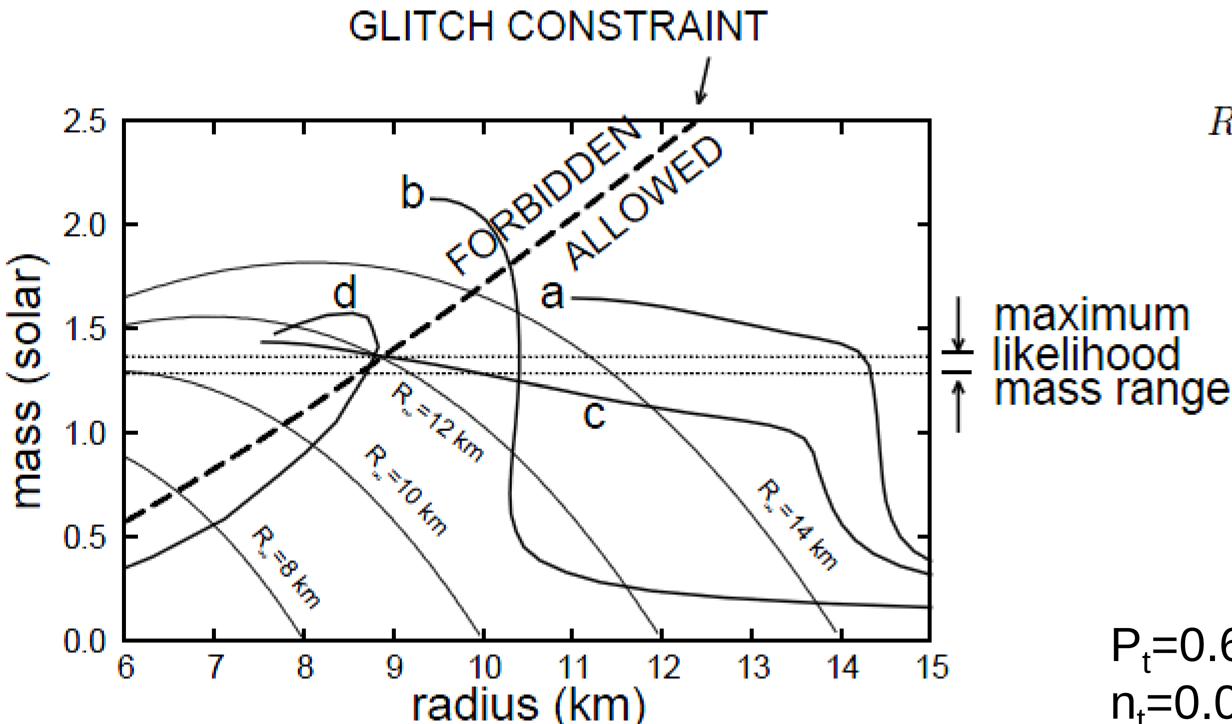
# KERS



Williams-F1 used mechanical KERS.
Energy is stored in a flywheel.


# EoS and glitches




$R = 3.6 + 3.9 M/M_\odot$ .

$P_t$=0.65 MeV fm$^{-3}$
$n_t$=0.075 fm$^{-3}$

grav.redshift

$$\frac{\Delta I}{I} \simeq \frac{28\pi}{3}\frac{P_t R^4}{GM^2}\left[1+\frac{8P_t}{n_t m_n c^2}\frac{4.5+(\Lambda-1)^{-1}}{\Lambda-1}\right]^{-1}$$

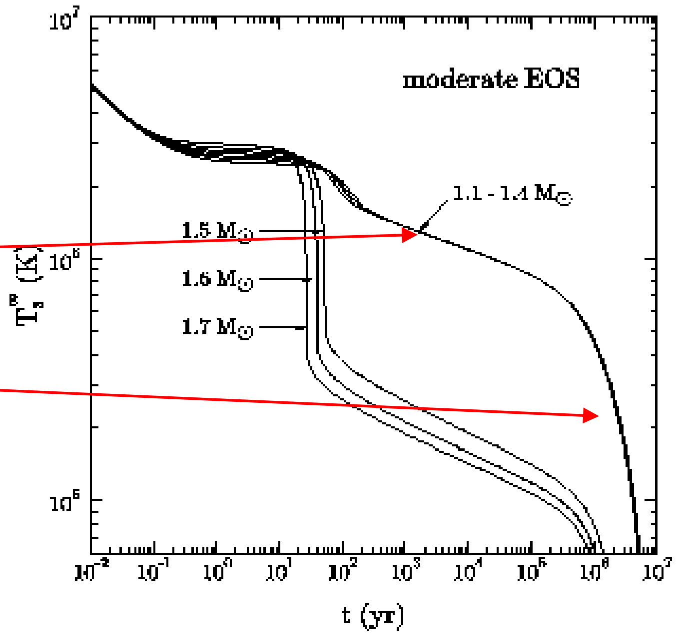
**The fraction of the star's moment of inertia contained in the solid crust (and the neutron liquid that coexists with it)**
**Link et al. (1999)**

$$\Delta I/(I-\Delta I) \geq \Delta I/I_c \geq I_{\rm res}/I_c \geq 0.014.$$

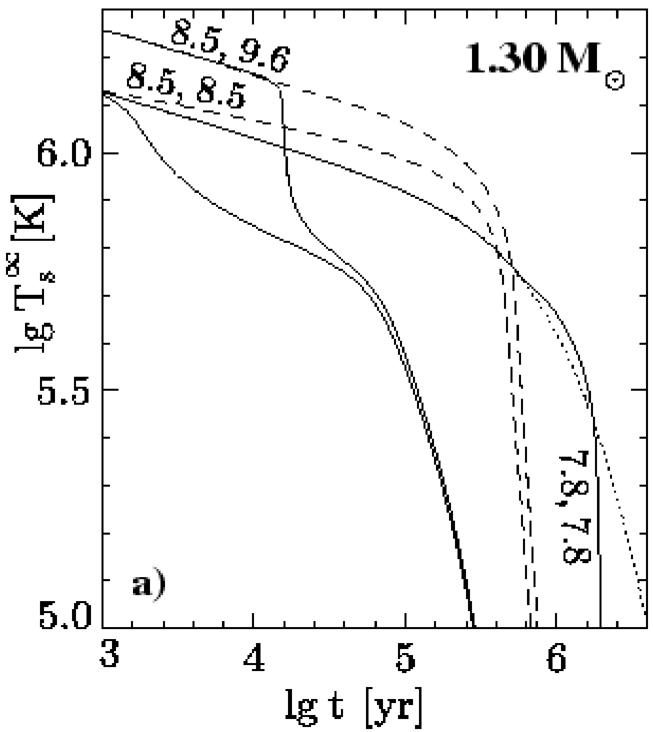
Link et al. 0001245

# Thermal evolution of NSs

Neutrino
cooling stage



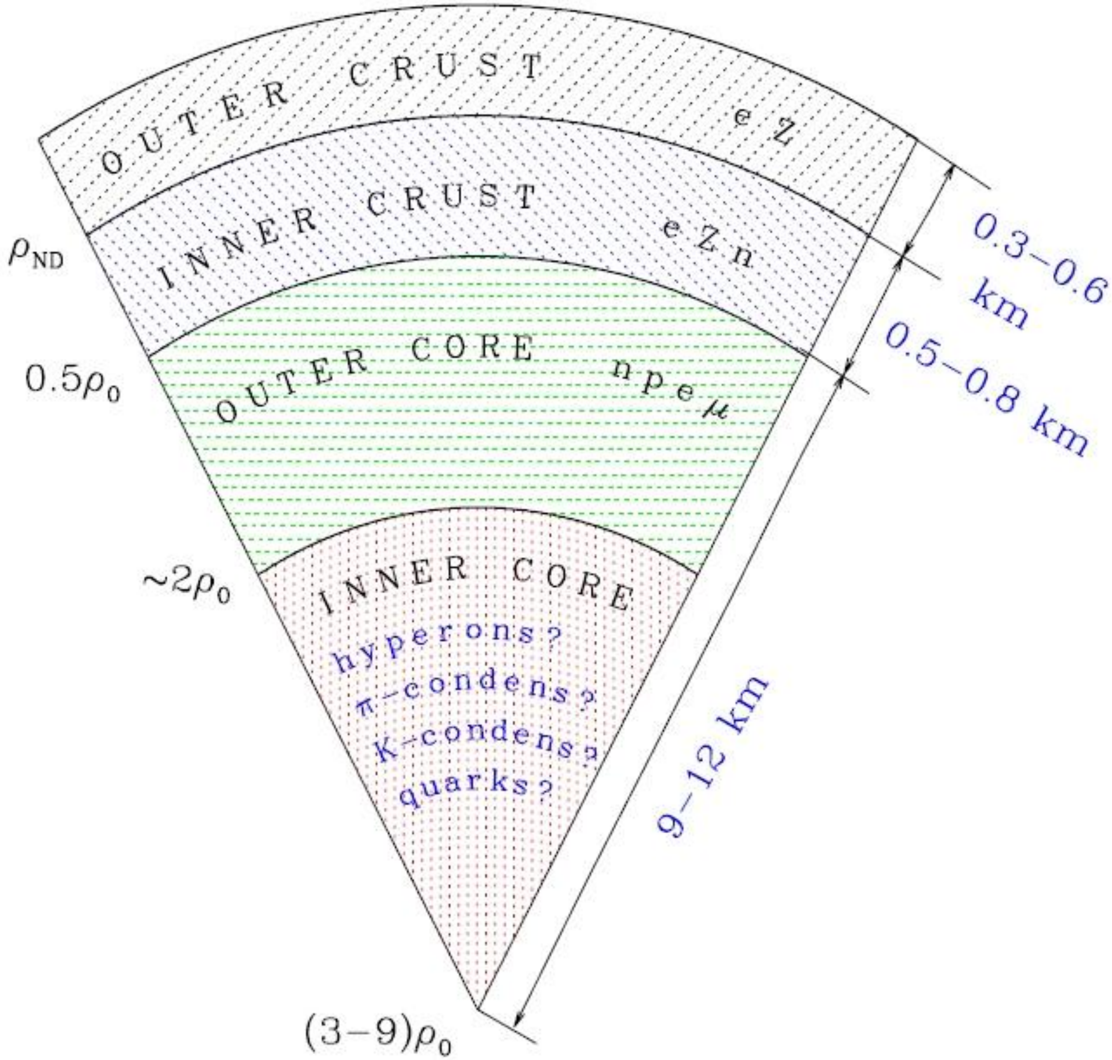

Photon
cooling stage




First papers on the thermal
evolution appeared already
in early 60s, i.e. before
the discovery of radio pulsars.

[Yakovlev et al. (1999) Physics Uspekhi]

# Structure and layers




Plus an atmosphere...

See Ch.6 in the book by Haensel, Potekhin, Yakovlev

$\rho_0 \sim 2.8\ 10^{14}$ g cm$^{-3}$

The total thermal energy of a nonsuperfluid neutron star is estimated as $U_T \sim 10^{48}\ T^2_9$ erg.

The heat capacity of an *npe* neutron star core with strongly superfluid neutrons and protons is determined by the electrons, which are not superfluid, and it is ~20 times lower than for a neutron star with a nonsuperfluid core.

# NS Cooling

- NSs are born very hot, T > $10^{10}$ K
- At early stages neutrino cooling dominates
- The core is isothermal

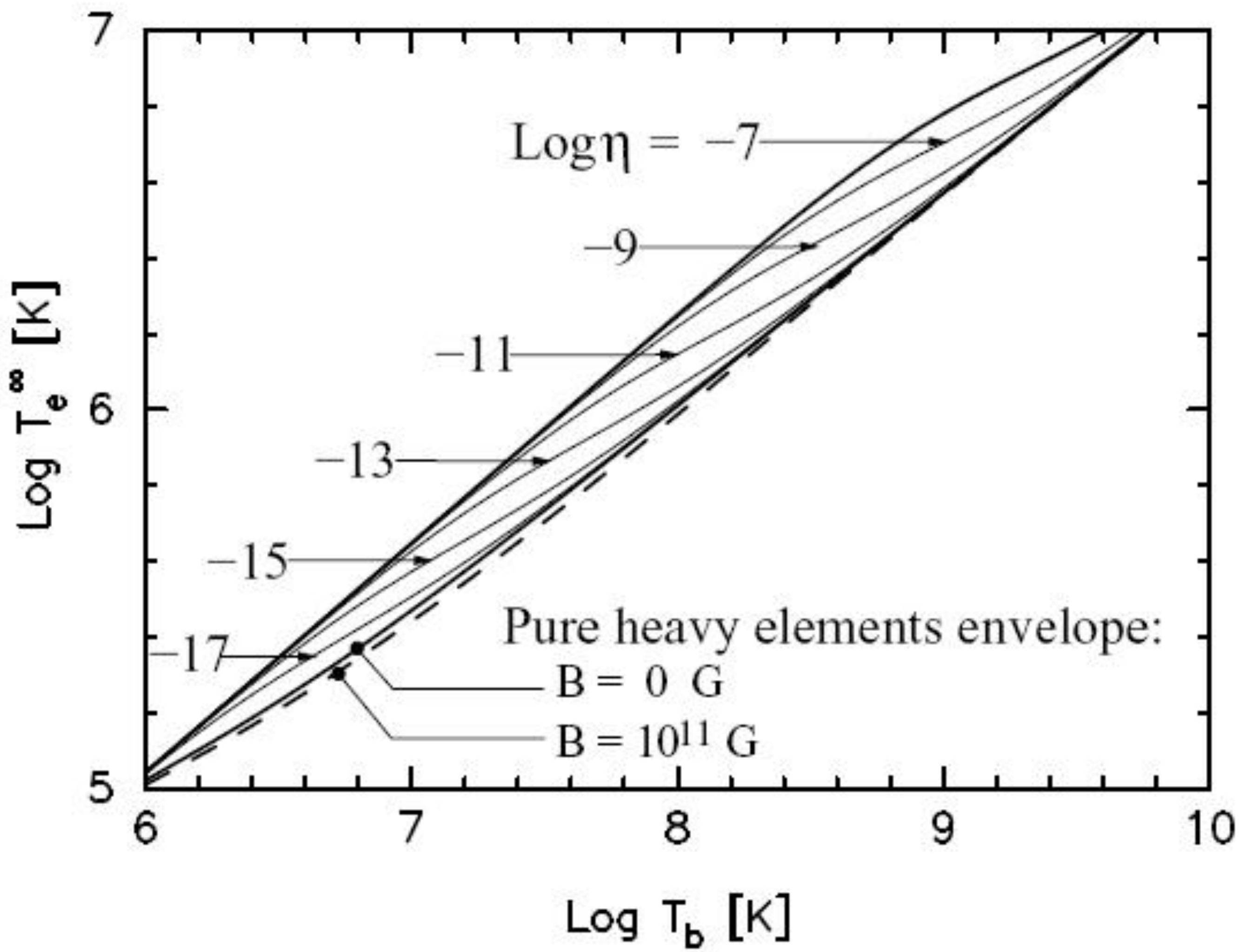
$$\frac{dE_{th}}{dt} = C_V \frac{dT}{dt} = -L_\nu - L_\gamma$$

Photon luminosity ($L_\gamma$)

Neutrino luminosity ($L_\nu$)

$$L_\gamma = 4\pi R^2 \sigma T_s^4, \quad T_s \propto T^{1/2+\alpha} \; (|\alpha| << 1)$$

# Core-crust temperature relation




Heat blanketing envelope.
~100 meters
density ~$10^{10}$ gcm$^{-3}$

Page et al. astro-ph/0508056

# Cooling depends on:

1. Rate of neutrino emission from NS interiors
2. Heat capacity of internal parts of a star
3. Superfluidity
4. Thermal conductivity in the outer layers
5. Possible heating (e.g. field decay)

} Depend on the EoS and composition

(see Yakovlev & Pethick 2004)

Fast Cooling (URCA cycle)

$$n \rightarrow p + e^- + \bar{\nu}_e$$

$$p + e^- \rightarrow n + \nu_e$$

Slow Cooling (modified URCA cycle)

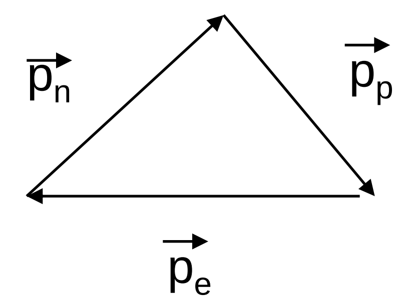
$$n + n \rightarrow n + p + e^- + \bar{\nu}_e$$

$$n + p + e^- \rightarrow n + n + \nu_e$$

$$p + n \rightarrow p + p + e^- + \bar{\nu}_e$$

$$p + p + e^- \rightarrow p + n + \nu_e$$

- Fast cooling possible only if $n_p > n_n/8$
- Nucleon Cooper pairing is important
- Minimal cooling scenario (Page et al 2004):
  - no exotica
  - no fast processes
  - pairing included




$p_n < p_p + p_e$

[See the book Haensel, Potekhin, Yakovlev p. 265 (p.286 in the file) and Shapiro, Teukolsky for details: Ch. 2.3, 2.5, 11.]

# Main neutrino processes

| Model | Process | $Q_f$, erg cm$^{-3}$ s$^{-1}$ |
|---|---|---|
| Nucleon matter | $n \to pe\bar{\nu} \quad pe \to n\nu$ | $10^{26} - 3 \times 10^{27}$ |
| Pion condensate | $\tilde{N} \to \tilde{N}e\bar{\nu} \quad \tilde{N}e \to \tilde{N}\nu$ | $10^{23} - 10^{26}$ |
| Kaon condensate | $\tilde{B} \to \tilde{B}e\bar{\nu} \quad \tilde{B}e \to \tilde{B}\nu$ | $10^{23} - 10^{24}$ |
| Quark matter | $d \to ue\bar{\nu} \quad ue \to d\nu$ | $10^{23} - 10^{24}$ |

| Process | | $Q_s$, erg cm$^{-3}$ s$^{-1}$ |
|---|---|---|
| Modified Urca | $nN \to pNe\bar{\nu} \quad pNe \to nN\nu$ | $10^{20} - 3 \times 10^{21}$ |
| Bremsstrahlung | $NN \to NN\nu\bar{\nu}$ | $10^{19} - 10^{20}$ |

$$Q_{\text{slow}} = Q_s T_9^8, \qquad Q_{\text{fast}} = Q_f T_9^6$$

(Yakovlev & Pethick astro-ph/0402143)

# Equations

Neutrino emissivity → $Q$; heating → $Q_h$

$$\frac{e^{-\lambda-2\Phi}}{4\pi r^2}\frac{\partial}{\partial r}\left(e^{2\Phi}L_r\right) = -Q + Q_h - \frac{c_T}{e^{\Phi}}\frac{\partial T}{\partial t},$$

$$\frac{L_r}{4\pi\kappa r^2} = e^{-\lambda-\Phi}\frac{\partial}{\partial r}\left(Te^{\Phi}\right),$$

$$e^{-\lambda} = \sqrt{1-2Gm(r)/c^2 r},$$

**After thermal relaxation we have in the whole star: $T_i(t)=T(r,t)e^{\Phi(r)}$**

At the surface we have: $\Phi(R) = -\lambda(R)$

$$C(T_i)\frac{dT_i}{dt} = -L_\nu^\infty(T_i) + L_h^\infty - L_\gamma^\infty(T_s),$$

$$L_\nu^\infty(T_i) = \int dV\, Q(T)\, e^{2\Phi}, \text{ and } L_h^\infty = \int dV\, Q_h\, e^{2\Phi}, \quad C(T_i) = \int dV\, c_T(T),$$

$dV = 4\pi r^2 e^{\lambda}\, dr$ is the element of proper volume

$L_\nu^\infty$ is the total neutrino luminosity (for a distant observer)

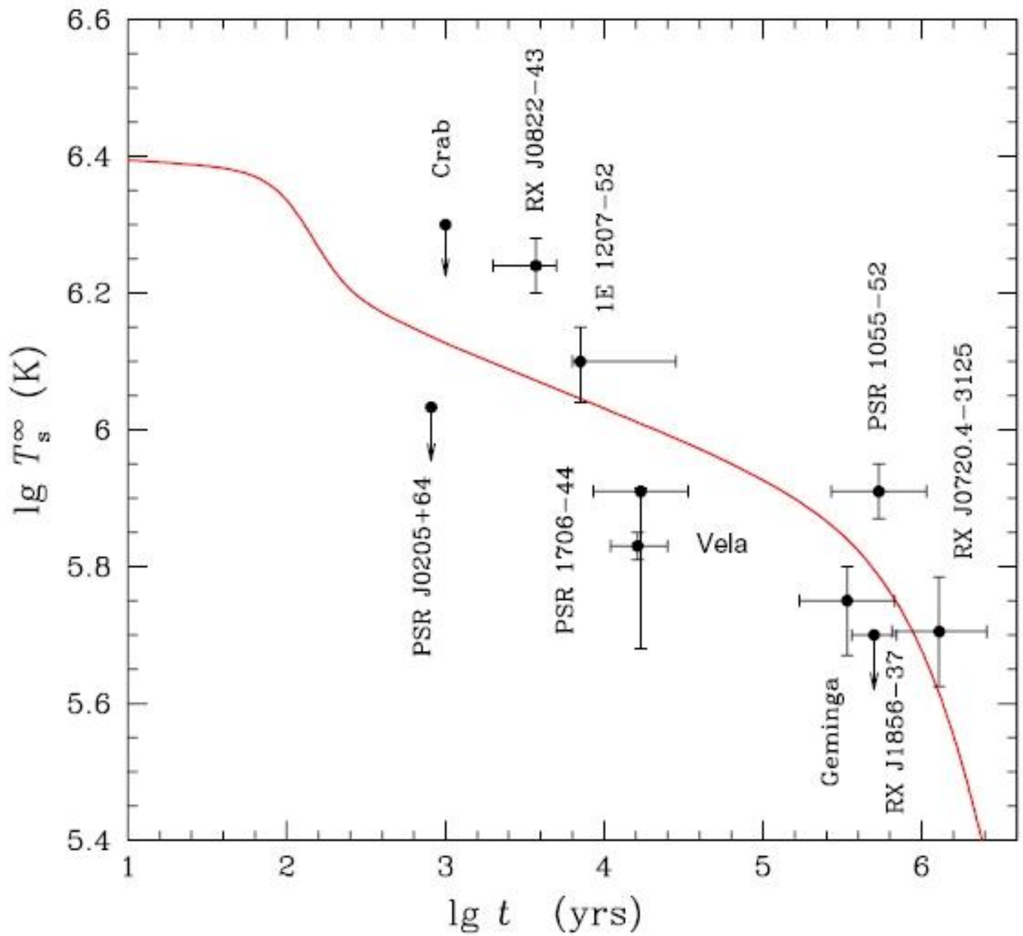
$L_h^\infty$ is the total reheating power.

Total stellar heat capacity → $C(T_i)$

(Yakovlev & Pethick 2004)

# Simple cooling model for low-mass NSs.

No superfluidity, no envelopes and magnetic fields, only hadrons.




Too hot ......
Too cold ....

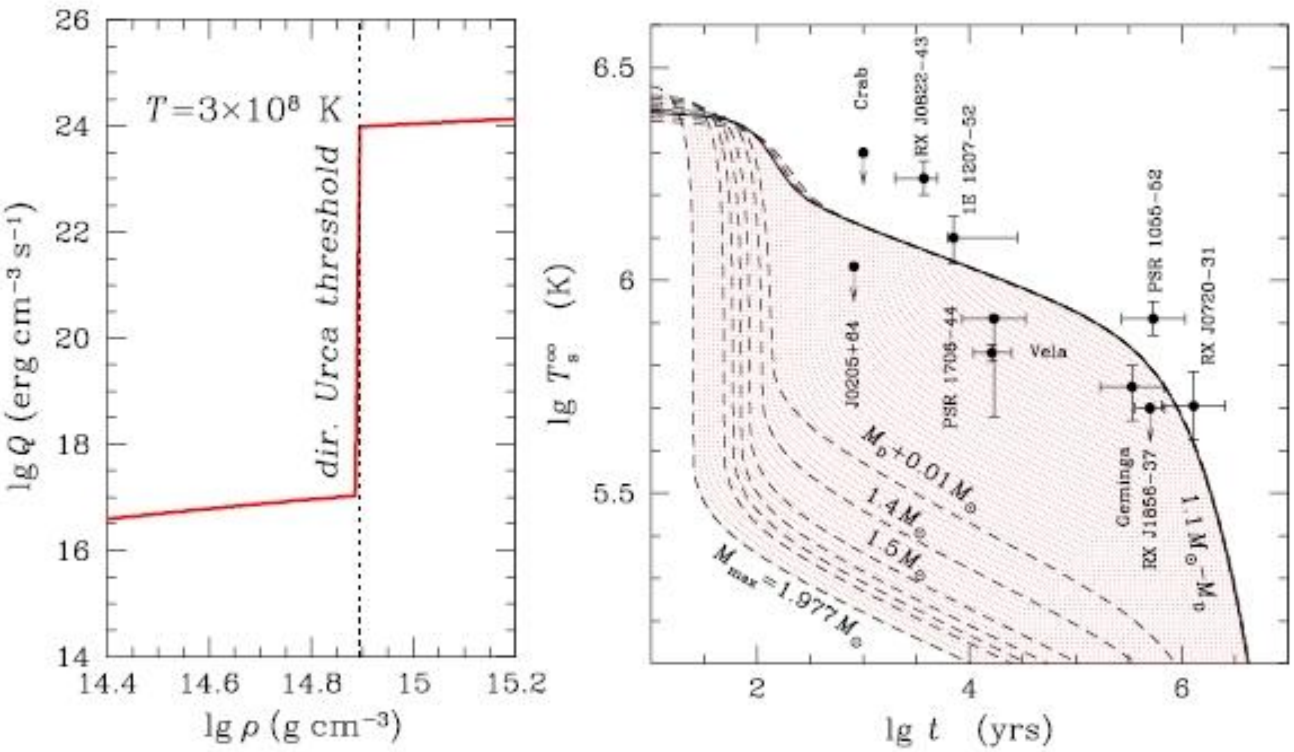
**The most critical moment is the onset of direct URCA cooling.**

$\rho_D$= 7.851 $10^{14}$ g/cm$^3$.

The critical mass depends on the EoS.
For the examples below $M_D$=1.358 $M_{solar}$.

(Yakovlev & Pethick 2004)

# Nonsuperfluid nucleon cores



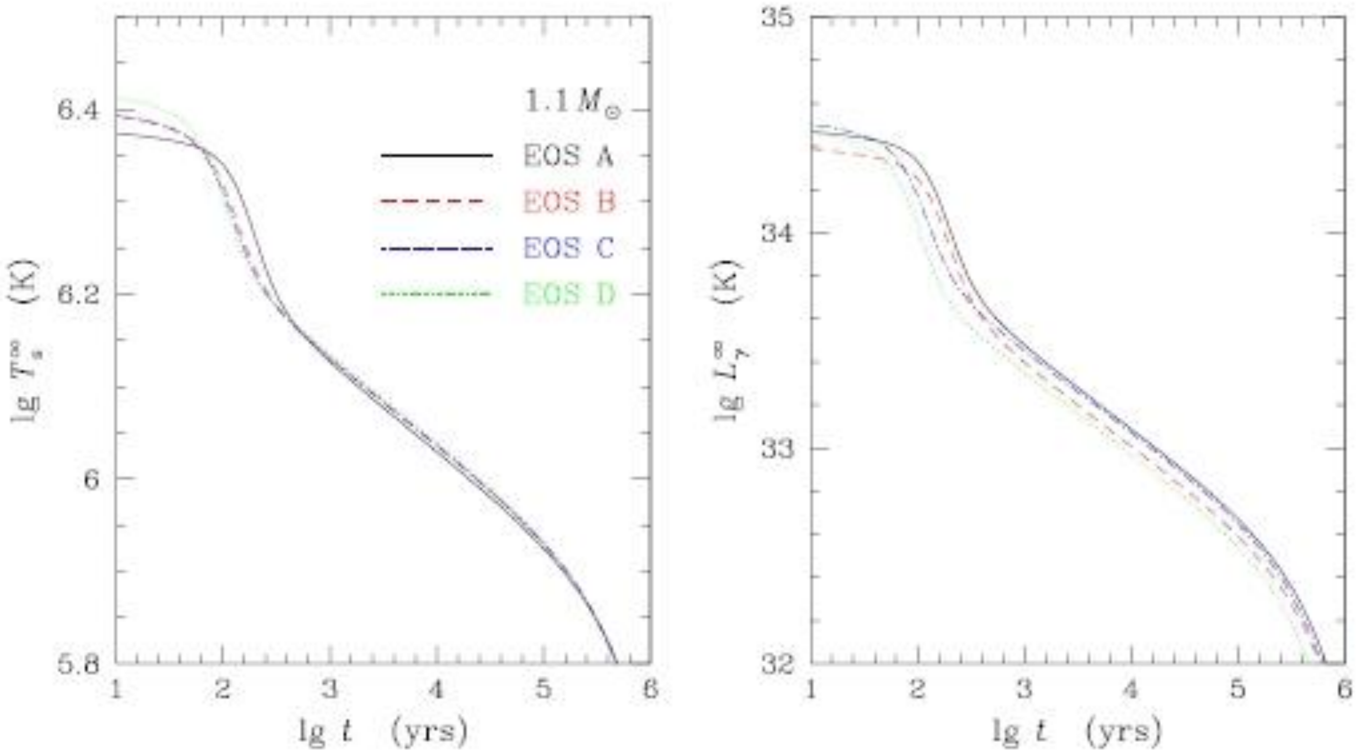

Note "population aspects" of the right plot: too many NSs have to be explained by a very narrow range of mass.

For slow cooling at the neutrino cooling stage $t_{slow} \sim 1\ \mathrm{yr}/T_{i9}^{6}$

For fast cooling $t_{fast} \sim 1\ \mathrm{min}/T_{i9}^{4}$

(Yakovlev & Pethick 2004)

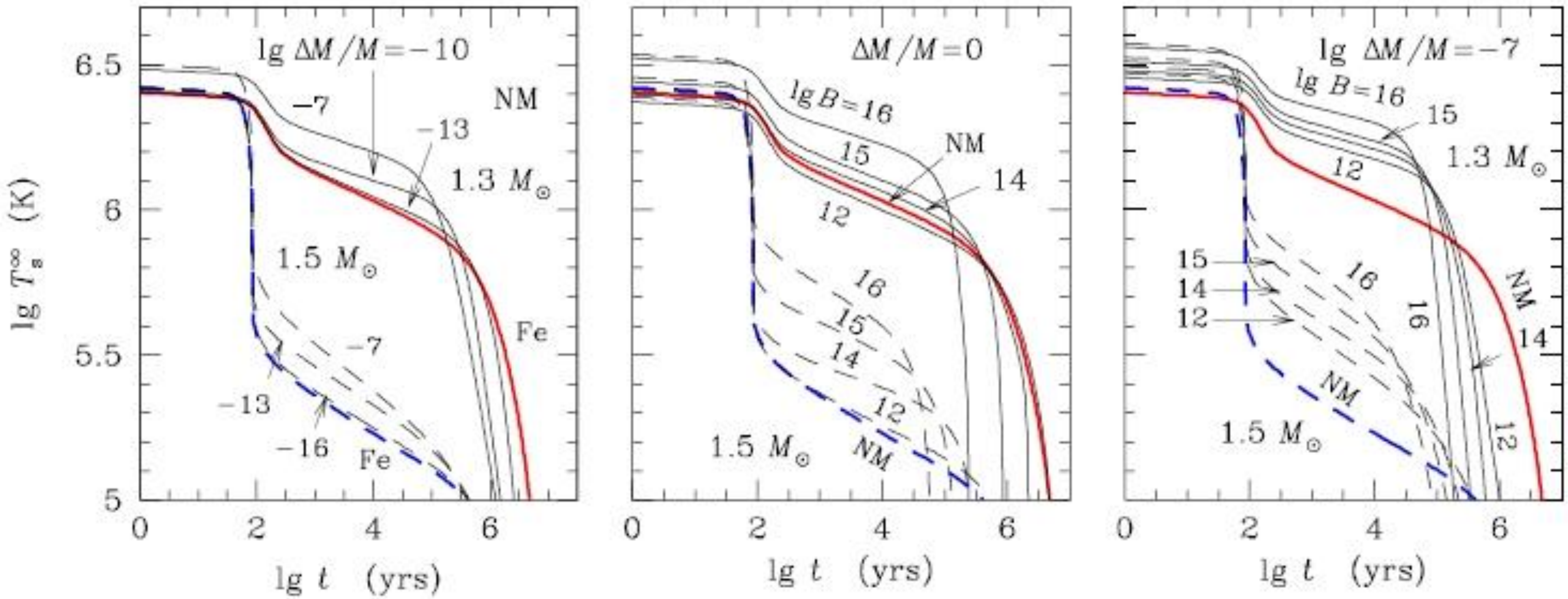
# Slow cooling for different EoS




For slow cooling there is nearly no dependence on the EoS.
The same is true for cooling curves for maximum mass for each EoS.

(Yakovlev & Pethick 2004)

# Envelopes and magnetic field




Non-magnetic stars
Thick lines – no envelope

No accreted envelopes,
different magnetic fields.
Thick lines – non-magnetic

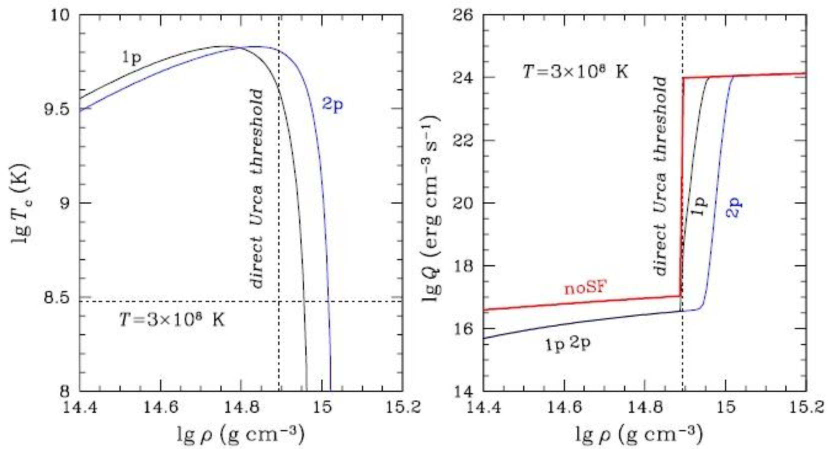
Envelopes + Fields

Envelopes can be related to the fact that we see a subpopulation of hot NS in CCOs with relatively long initial spin periods and low magnetic field, but do not observed representatives of this population around us, i.e. in the Solar vicinity.

Solid line M=1.3 $M_{solar}$, Dashed lines M=1.5 $M_{solar}$

(Yakovlev & Pethick 2004)

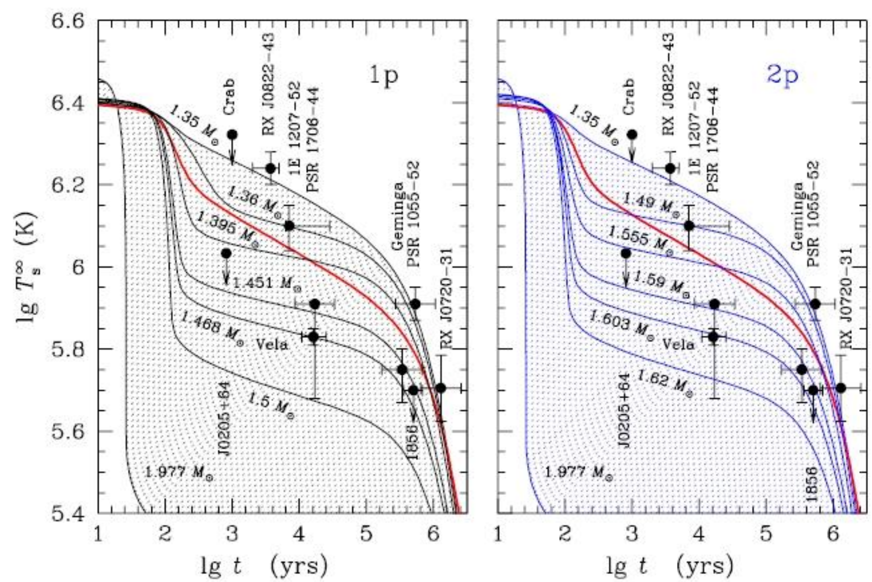
# Simplified model: no neutron superfluidity




Superfluidity is an important ingredient of cooling models.
It is important to consider different types of proton and neutron superfluidity.

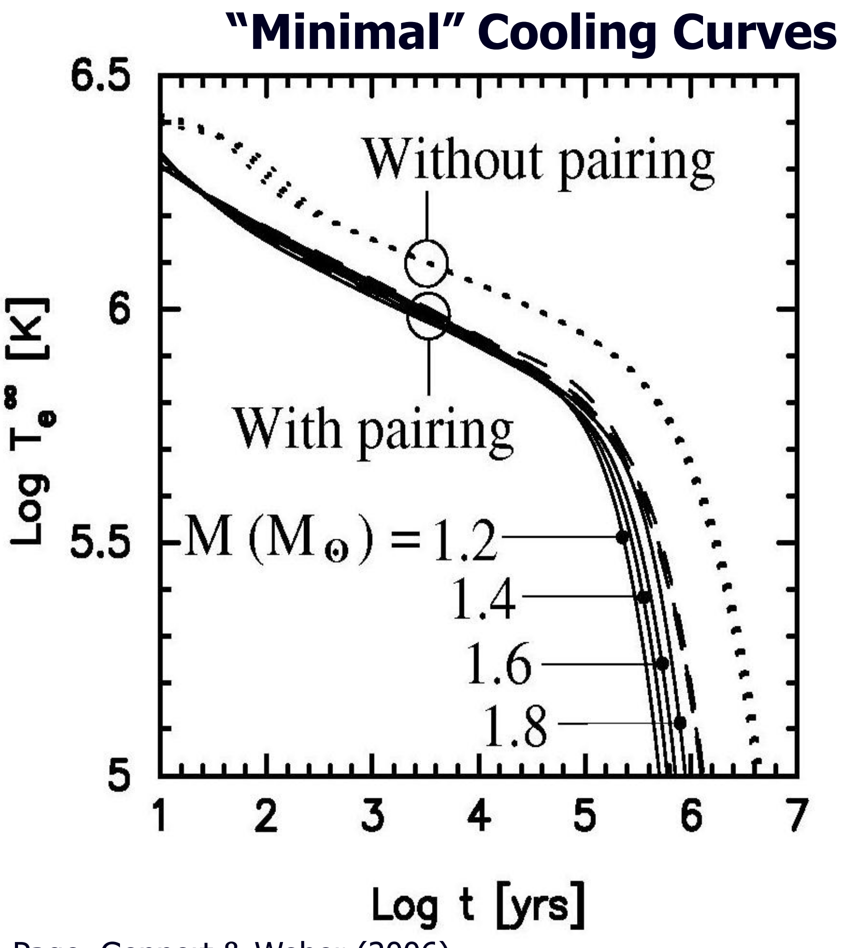
There is no complete microphysical theory which can describe superfluidity in neutron stars.

If proton superfluidity is strong,
but neutron superfluidity
in the core is weak
then it is possible
to explain observations.




(Yakovlev & Pethick 2004)

# Minimal cooling model




Page, Geppert & Weber (2006)

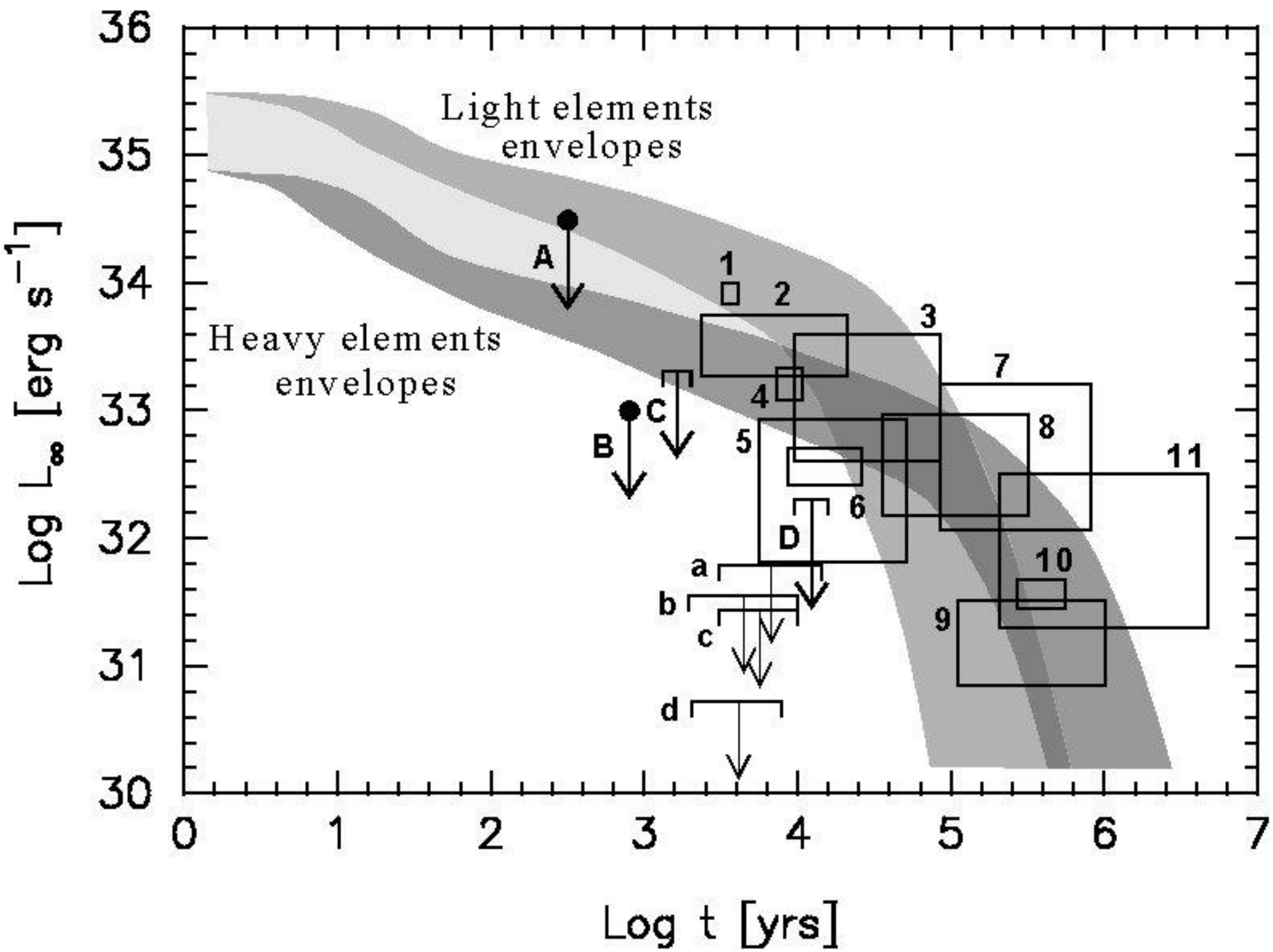
"minimal" means
without additional cooling
due to direct URCA
and without additional heating

---

**Main ingredients of the minimal model**

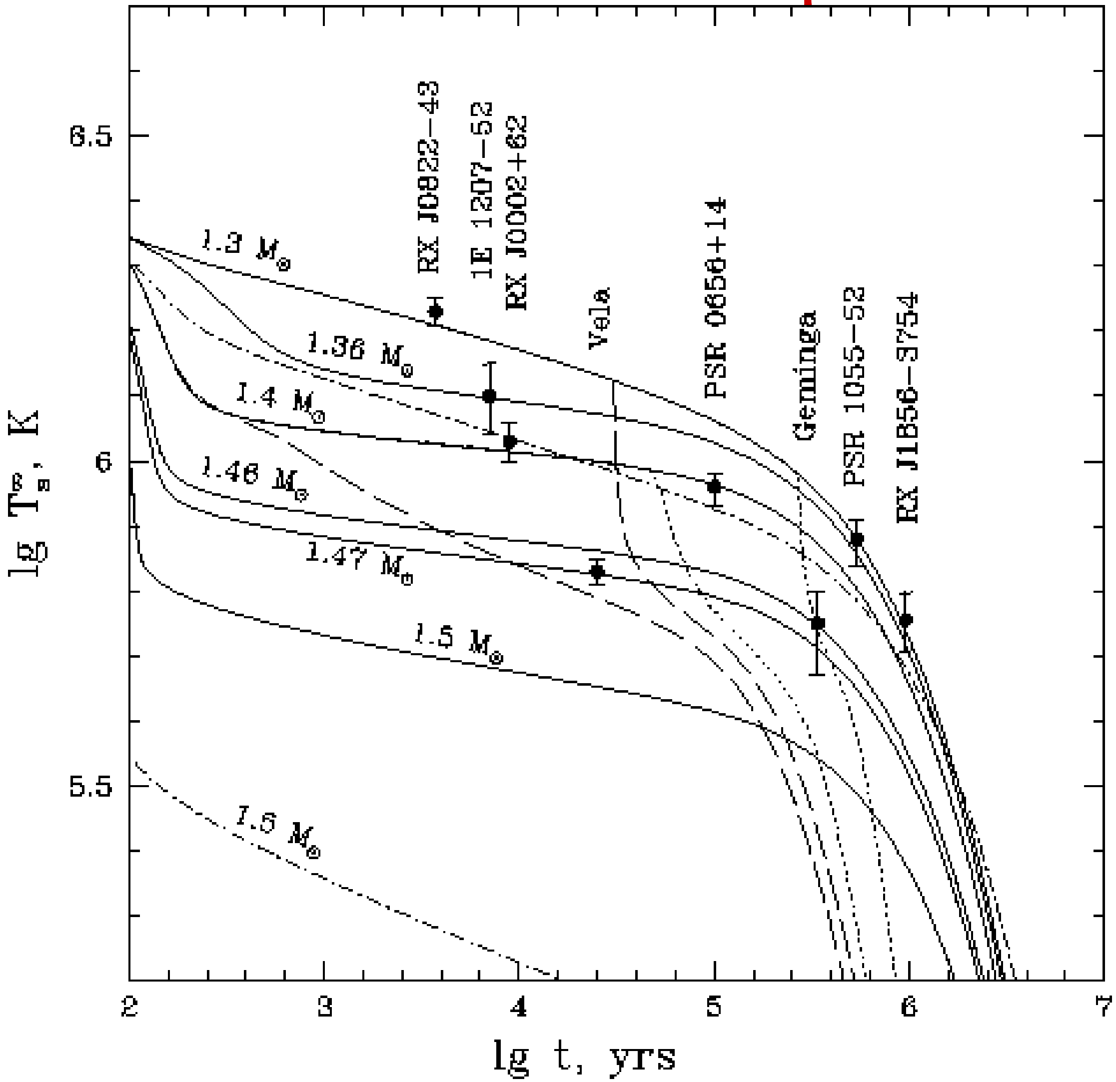
- EoS
- Superfluid properties
- Envelope composition
- NS mass

# Luminosity and age uncertainties




Page, Geppert, Weber
astro-ph/0508056

# Standard test: temperature vs. age




Other tests and ideas:

- Log N – Log S (Popov et al.)
- Brightness constraint (Grigorian)
- Mass constraint (Popov, Grigorian, Blaschke)

Kaminker et al. (2001)

# Data

Neutron Star Properties with Hydrogen Atmospheres

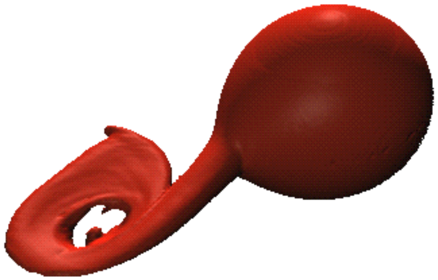
| Star | $\log_{10} t_{sd}$ yr | $\log_{10} t_{kin}$ yr | $\log_{10} T_\infty$ K | $d$ kpc | $\log_{10} L_\infty$ erg/s |
|---|---|---|---|---|---|
| RX J0822-4247 | 3.90 | $3.57^{+0.04}_{-0.04}$ | $6.24^{+0.04}_{-0.04}$ | $1.9-2.5$ | $33.85-34.00$ |
| 1E 1207.4-5209 | $5.53^{+0.44}_{-0.19}$ | $3.85^{+0.48}_{-0.48}$ | $6.21^{+0.07}_{-0.07}$ | $1.3-3.9$ | $33.27-33.74$ |
| RX J0002+6246 | – | $3.96^{+0.08}_{-0.08}$ | $6.03^{+0.03}_{-0.03}$ | $2.5-3.5$ | $33.08-33.33$ |
| PSR 0833-45 (Vela) | 4.05 | $4.26^{+0.17}_{-0.31}$ | $5.83^{+0.02}_{-0.02}$ | $0.22-0.28$ | $32.41-32.70$ |
| PSR 1706-44 | 4.24 | – | $5.8^{+0.13}_{-0.13}$ | $1.4-2.3$ | $31.81-32.93$ |
| PSR 0538+2817 | 4.47 | – | $6.05^{+0.10}_{-0.10}$ | 1.2 | $32.6-33.6$ |

Neutron Star Properties with Blackbody Atmospheres

| Star | $\log_{10} t_{sd}$ yr | $\log_{10} t_{kin}$ yr | $\log_{10} T_\infty$ K | $R_\infty$ km | $d$ kpc | $\log_{10} L_\infty$ erg/s |
|---|---|---|---|---|---|---|
| RX J0822-4247 | 3.90 | $3.57^{+0.04}_{-0.04}$ | $6.65^{+0.04}_{-0.04}$ | $1-1.6$ | $1.9-2.5$ | $33.60-33.90$ |
| 1E 1207.4-5209 | $5.53^{+0.44}_{-0.19}$ | $3.85^{+0.48}_{-0.48}$ | $6.48^{+0.01}_{-0.01}$ | $1.0-3.7$ | $1.3-3.9$ | $32.70-33.88$ |
| RX J0002+6246 | – | $3.96^{+0.08}_{-0.08}$ | $6.15^{+0.11}_{-0.11}$ | $2.1-5.3$ | $2.5-3.5$ | $32.18-32.81$ |
| PSR 0833-45 (Vela) | 4.05 | $4.26^{+0.17}_{-0.31}$ | $6.18^{+0.02}_{-0.02}$ | $1.7-2.5$ | $0.22-0.28$ | $32.04-32.32$ |
| PSR 1706-44 | 4.24 | – | $6.22^{+0.04}_{-0.04}$ | $1.9-5.8$ | $1.8-3.2$ | $32.48-33.08$ |
| PSR 0656+14 | 5.04 | – | $5.71^{+0.03}_{-0.04}$ | $7.0-8.5$ | $0.26-0.32$ | $32.18-32.97$ |
| PSR 0633+1748 (Geminga) | 5.53 | – | $5.75^{+0.04}_{-0.05}$ | $2.7-8.7$ | $0.123-0.216$ | $30.85-31.51$ |
| PSR 1055-52 | 5.43 | – | $5.92^{+0.02}_{-0.02}$ | $6.5-19.5$ | $0.5-1.5$ | $32.07-33.19$ |
| RX J1856.5-3754 | – | $5.70^{+0.05}_{-0.25}$ | $5.6-5.9$ | $>16$ | $0.105-0.129$ | $31.44-31.68$ |
| RX J0720.4-3125 | $6.0\pm0.2$ | – | $5.55-5.95$ | $5.0-15.0$ | $0.1-0.3$ | $31.3-32.5$ |

(Page et al. astro-ph/0403657)

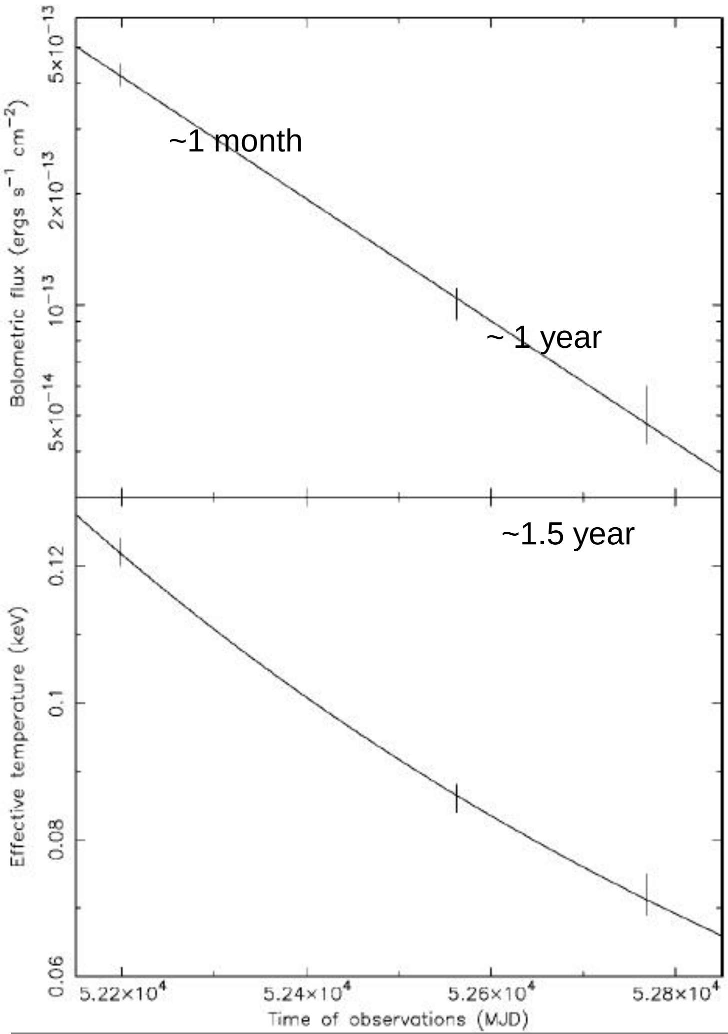
# Cooling of X-ray transients



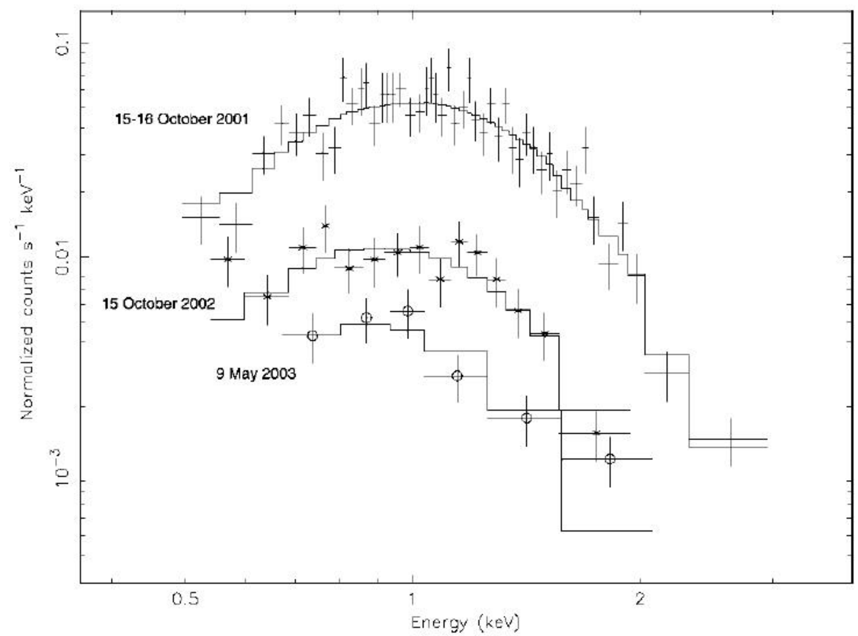
“Many neutron stars in close X-ray binaries are transient accretors (transients);
They exhibit X-ray bursts separated by long periods (months or even years) of quiescence.
It is believed that the quiescence corresponds to a lowlevel, or even halted, accretion onto the neutron star.
During high-state accretion episodes,
the heat is deposited by nonequilibrium processes in the deep layers ($10^{12}$ -$10^{13}$ g cm$^{-3}$) of the crust.
This deep crustal heating can maintain the temperature of the neutron star interior at a sufficiently high level to explain a persistent thermal X-ray radiation in quiescence (Brown *et al.*, 1998).”

(quotation from the book by Haensel, Potekhin, Yakovlev)

# Cooling in soft X-ray transients

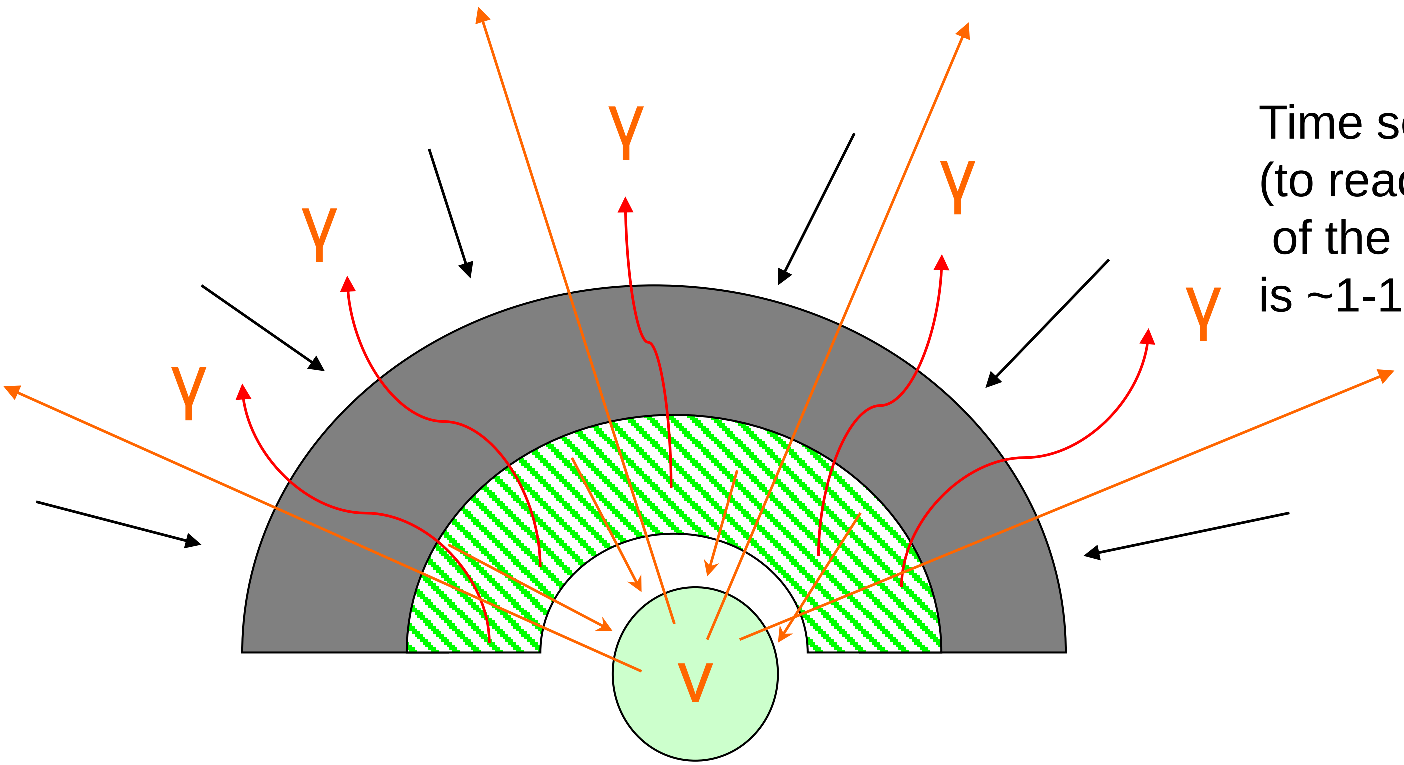



MXB 1659-29
~2.5 years outburst




[Wijnands et al. 2004]

# Deep crustal heating and cooling




Time scale of cooling
(to reach thermal equilibrium
of the crust and the core)
is ~1-100 years.

To reach the
state "before"
takes ~$10^3$-$10^4$ yrs

Accretion leads to deep crustal heating due to non-equilibrium nuclear reactions.
After accretion is off:

- heat is transported inside and emitted by neutrinos
- heat is slowly transported out and emitted by photons

$\rho \sim 10^{12}$-$10^{13}$ g/cm$^3$

See, for example, Haensel, Zdunik arxiv:0708.3996

New calculations appeared very recently 0811.1791 Gupta et al.

# Pycnonuclear reactions

Let us give an example from Haensel, Zdunik (1990)

We start with $^{56}$Fe
Density starts to increase

$^{56}Fe \rightarrow {}^{56}Cr$
$^{56}Fe + e^- \rightarrow {}^{56}Mn + \nu_e$
$^{56}Mn + e^- \rightarrow {}^{56}Cr + \nu_e$

At $^{56}$Ar: neutron drip
$^{56}Ar + e^- \rightarrow {}^{56}Cl + \nu_e$
$^{56}Cl \rightarrow {}^{55}Cl + n$
$^{55}Cl + e^- \rightarrow {}^{55}S + \nu_e$
$^{55}S \rightarrow {}^{54}S + n$
$^{54}S \rightarrow {}^{52}S + 2n$

Then from $^{52}$S we have a chain:
$^{52}S \rightarrow {}^{46}Si + 6n - 2e^- + 2\nu_e$

As Z becomes smaller
the Coulomb barrier decreases.
Separation between
nuclei decreases, vibrations grow.
$^{40}Mg \rightarrow {}^{34}Ne + 6n - 2e^- + 2\nu_e$

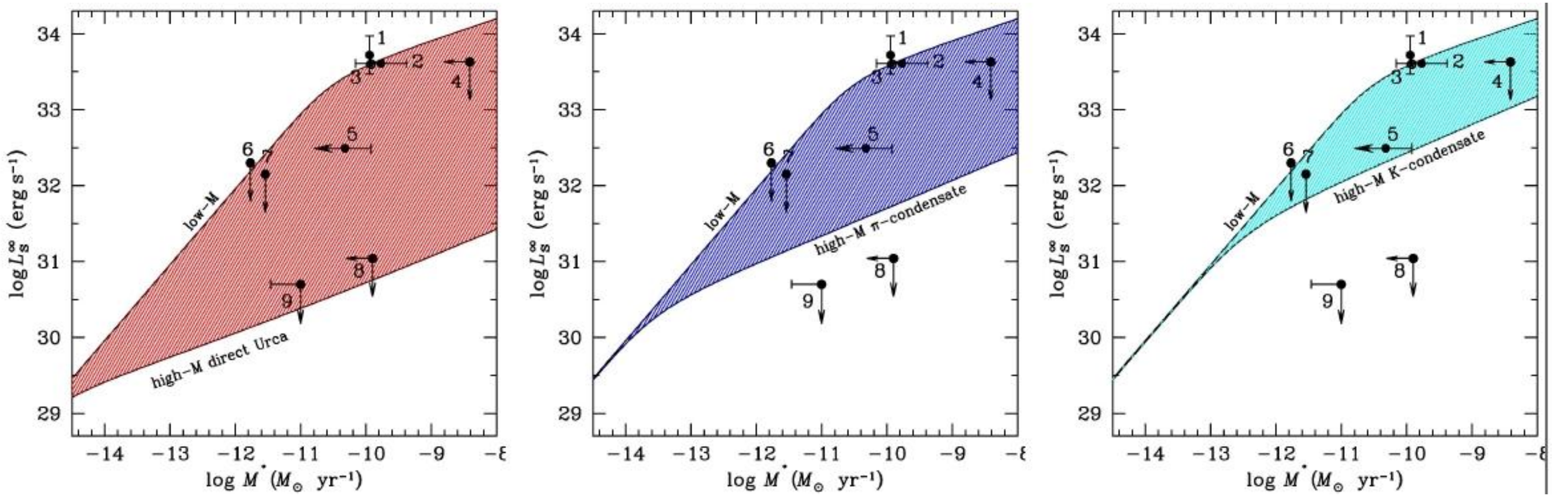
At Z=10 (Ne) pycnonuclear reactions start.

$^{34}Ne + {}^{34}Ne \rightarrow {}^{68}Ca$
$^{36}Ne + {}^{36}Ne \rightarrow {}^{72}Ca$

Then a heavy nuclei can react again:
$^{72}Ca \rightarrow {}^{66}Ar + 6n - 2e^- + 2\nu_e$

$^{48}Mg + {}^{48}Mg \rightarrow {}^{96}Cr$
$^{96}Cr \rightarrow {}^{88}Ti + 8n - 2e^- + 2\nu_e$

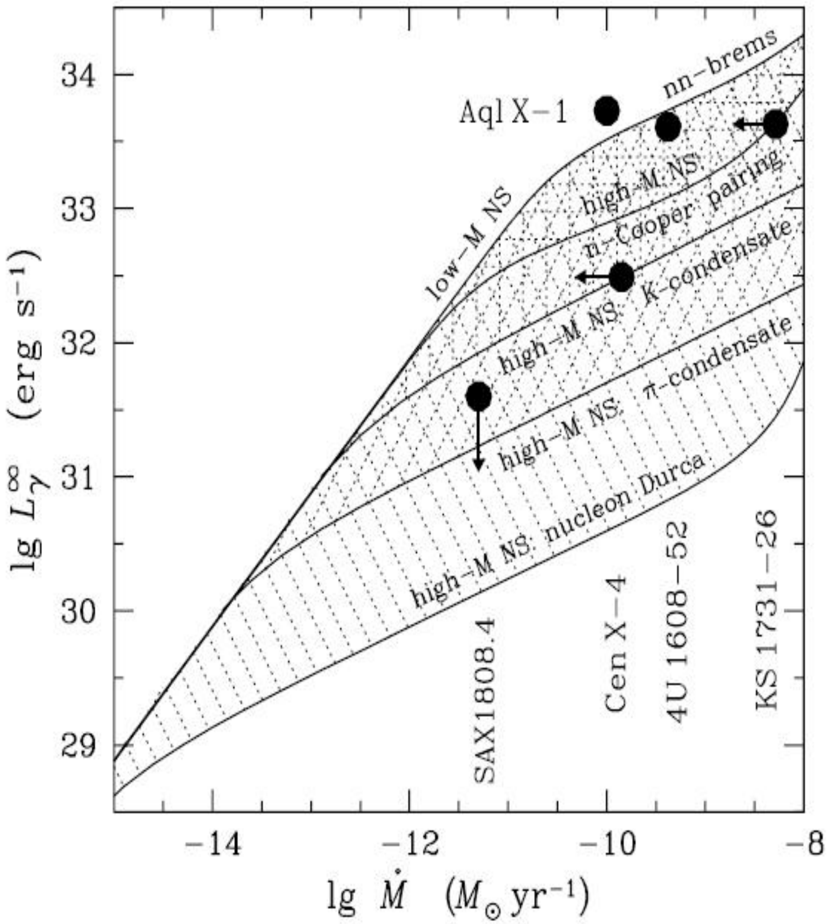
# Testing models with SXT

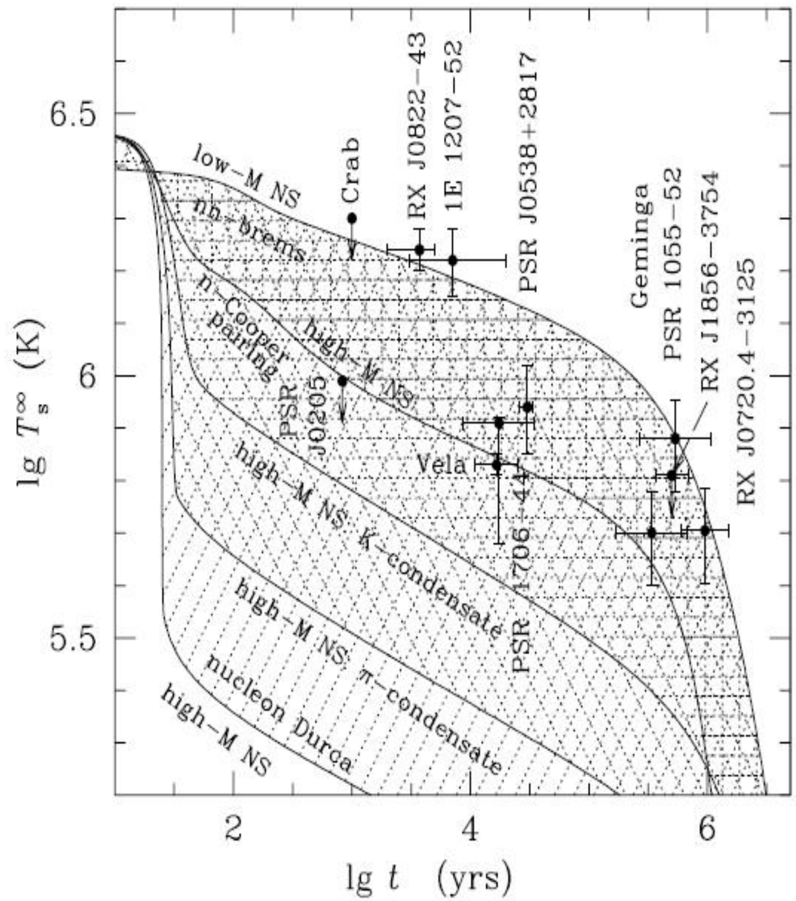



SXTs can be very important in confronting theoretical cooling models with data.

[from a presentation by Haensel, figures by Yakovlev and Levenfish]

# Theory vs. Observations: SXT and isolated cooling NSs




[Yakovlev et al. astro-ph/0501653]