Heating old neutron stars

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Heating neutron star matter by weak interactions

- Chemical ("beta") equilibrium sets relative number densities of particles (*n, p, e,* ...) at different pressures $n \leftrightarrow p + (e, \mu) \quad \Rightarrow \quad \mu_n = \mu_p + \mu_e$
- Compressing or expanding a fluid element perturbs equilibrium e.g., $\mu_n > \mu_p + \mu_e$
- Non-equilibrium reactions tend to restore equilibrium $n \rightarrow p + e + \overline{\nu}_e$
- "Chemical" energy released as neutrinos & "heat"

Possible forcing mechanisms

- Neutron star oscillations (bulk viscosity): SGR flare oscillations, r-modes – Not promising
- Accretion: effect overwhelmed by external & crustal heat release – No.
- *$d\Omega/dt$*: **"Rotochemical heating"** – **Yes**
- *dG/dt*: **"Gravitochemical heating"** - !!!???

“Rotochemical heating”

NS spin-down (decreasing centrifugal support)

$\Rightarrow$ progressive density increase

$\Rightarrow$ chemical imbalance $\eta \equiv \mu_n - \mu_p - \mu_{e,\mu} > 0$

$\Rightarrow$ non-equilibrium reactions $n \rightarrow p + (e, \mu) + \bar{\nu}_{e,\mu}$

$\Rightarrow$ internal heating

$\Rightarrow$ possibly detectable thermal emission

Reisenegger 1995, 1997; Fernández & Reisenegger 2005; Reisenegger et al. 2006, submitted (all ApJ)

Fast vs. slow processes

"Direct Urca"

$$n \rightarrow p + e + \overline{\nu}$$

<u>Fast</u>

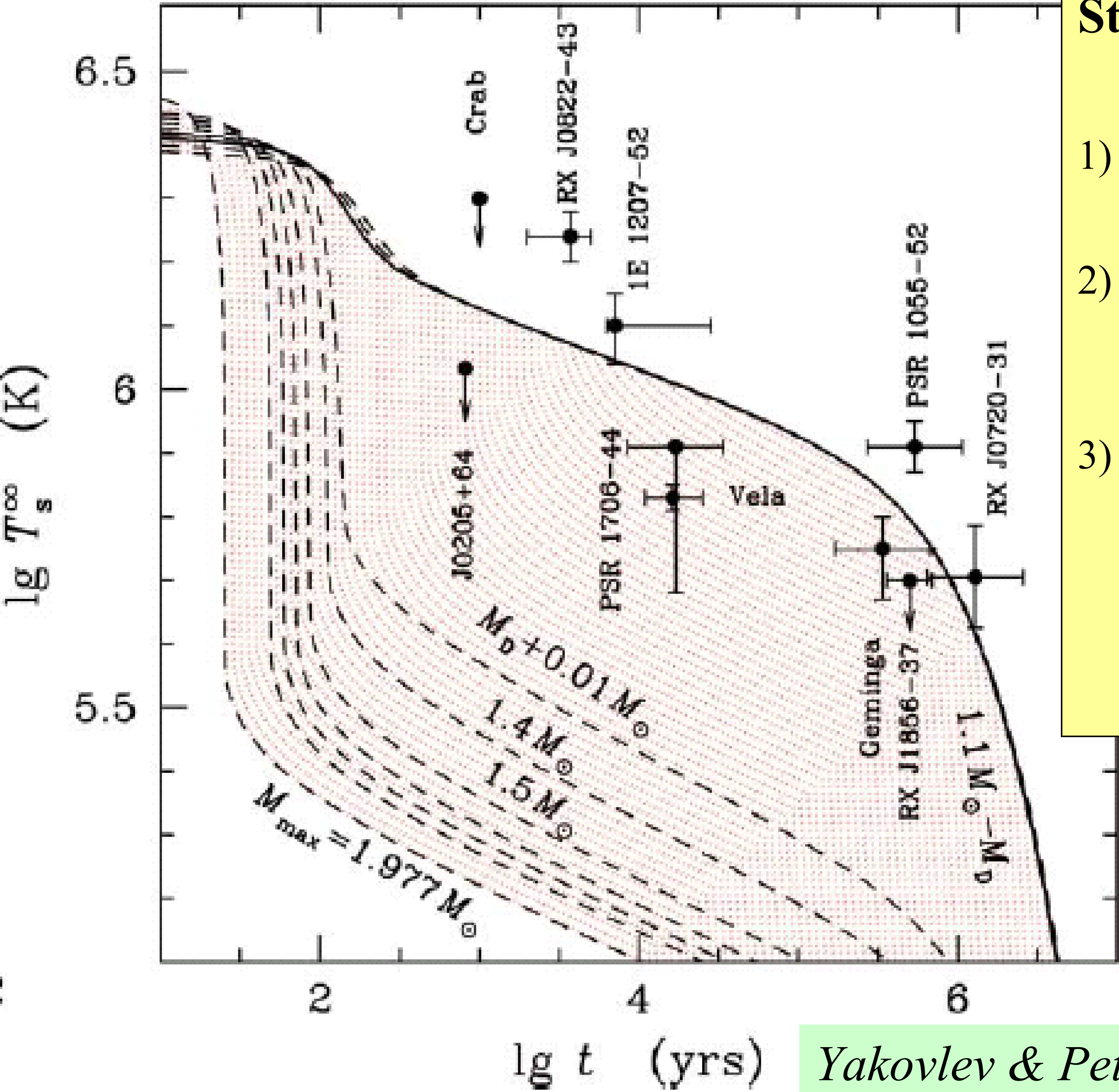
But not allowed if proton density too low.

"Modified Urca"

$$n + n \rightarrow n + p + e + \overline{\nu}$$

Dominant process if direct Urca not allowed, but:

<u>Much slower</u>



Standard neutron star cooling:

1) No thermal emission after 10 Myr.

2) Finite diffusion time matters only during first few 100 yr.

3) Cooling of young neutron stars in rough agreement with slow cooling models (see D. Page's talk)

Yakovlev & Pethick 2004

Thermo-chemical evolution

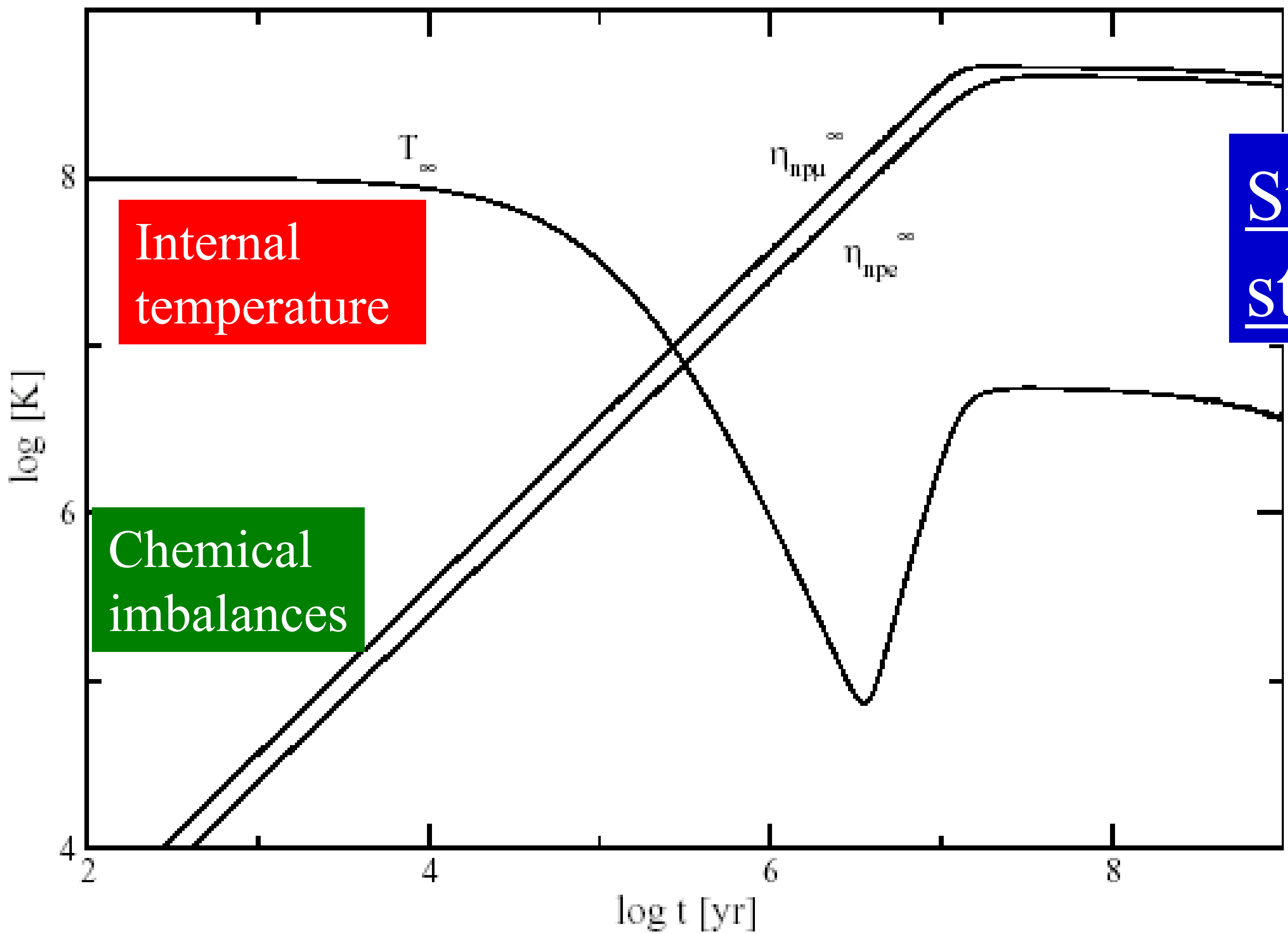
Variables:

- Chemical imbalances $\eta_{e,\mu} \equiv \mu_n - \mu_p - \mu_{e,\mu}$
- Internal temperature ***T***

Both are uniform in diffusive equilibrium.

$$\frac{d\eta}{dt} = \begin{pmatrix} increase\ through \\ compression \end{pmatrix} - \begin{pmatrix} decrease\ through \\ n \leftrightarrow p + e \end{pmatrix}$$

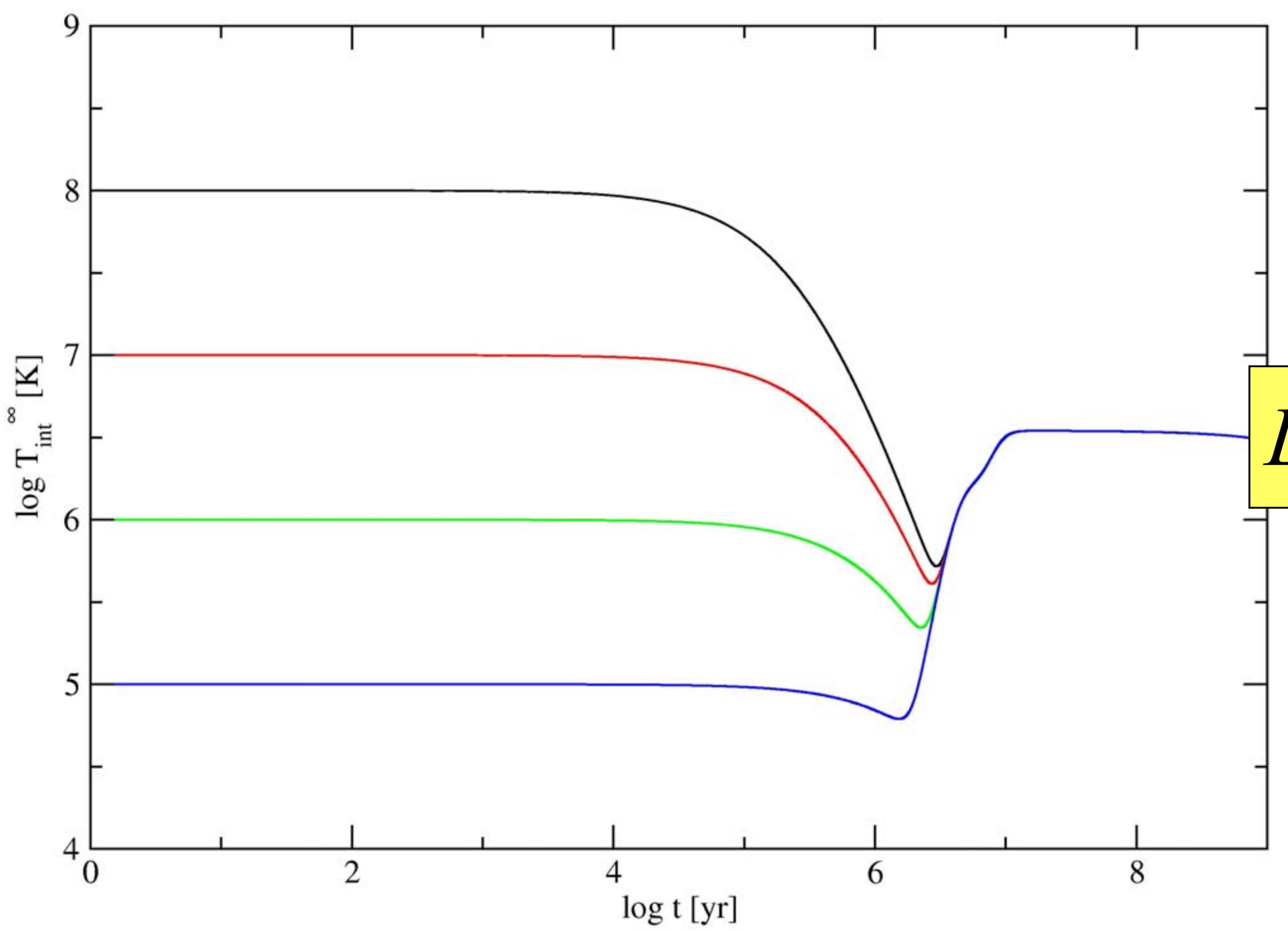
$$\frac{dT}{dt} = \begin{pmatrix} increase\ through \\ n \leftrightarrow p + e \end{pmatrix} - \begin{pmatrix} decrease\ through \\ radiation : \gamma, \nu \end{pmatrix}$$



MSP evolution

Magnetic dipole spin-down (n=3) with $P_0 = 1$ ms; $B = 10^8$G; modified Urca

Insensitivity to initial temperature



$$L_{\mathrm{thermal}} \propto (\Omega\dot{\Omega})^{8/7}$$

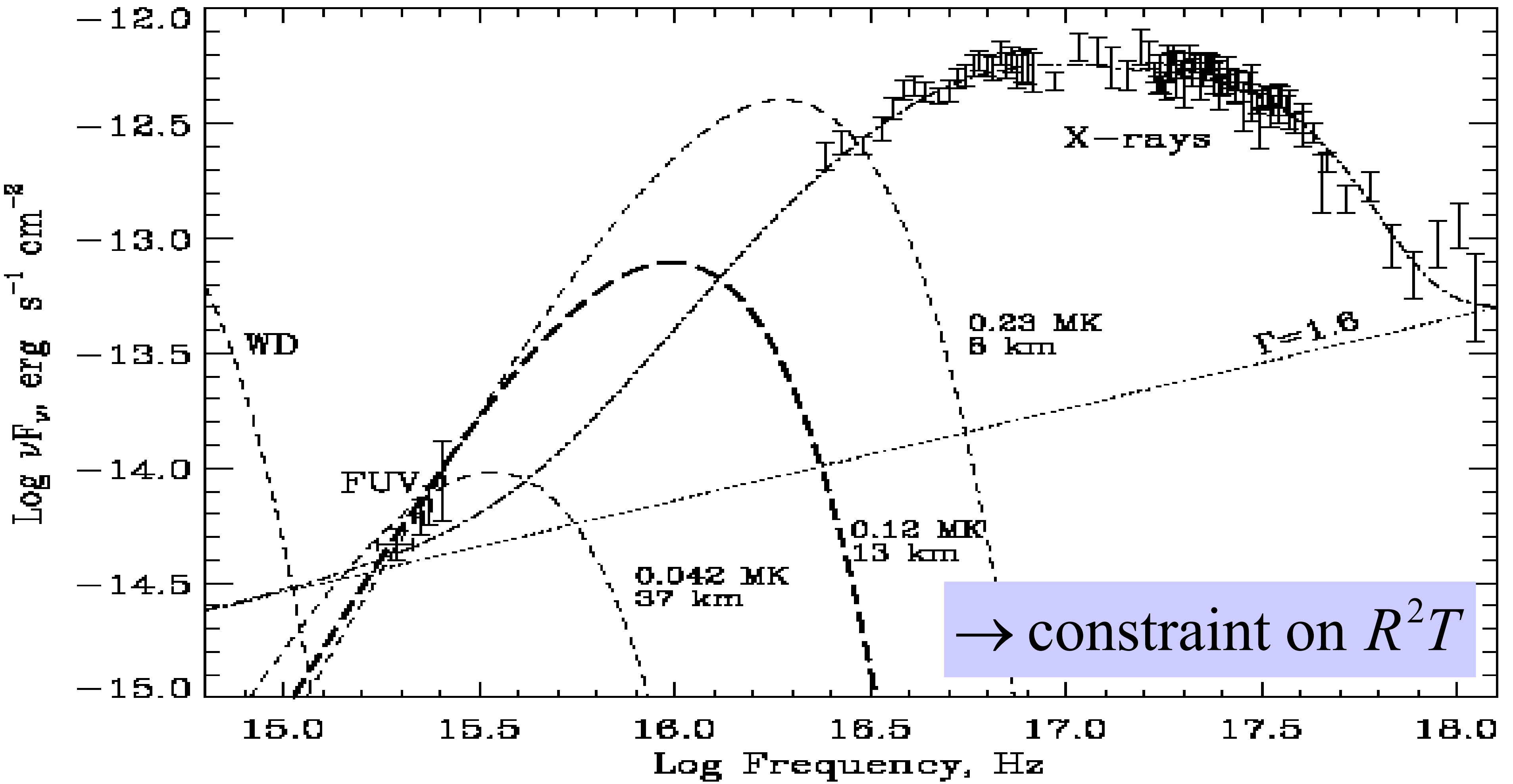
Fernández & R. 2005

For a given NS model, MSP temperatures can be predicted uniquely from the measured spin-down rate.

The nearest MSP: PSR J0437-4715

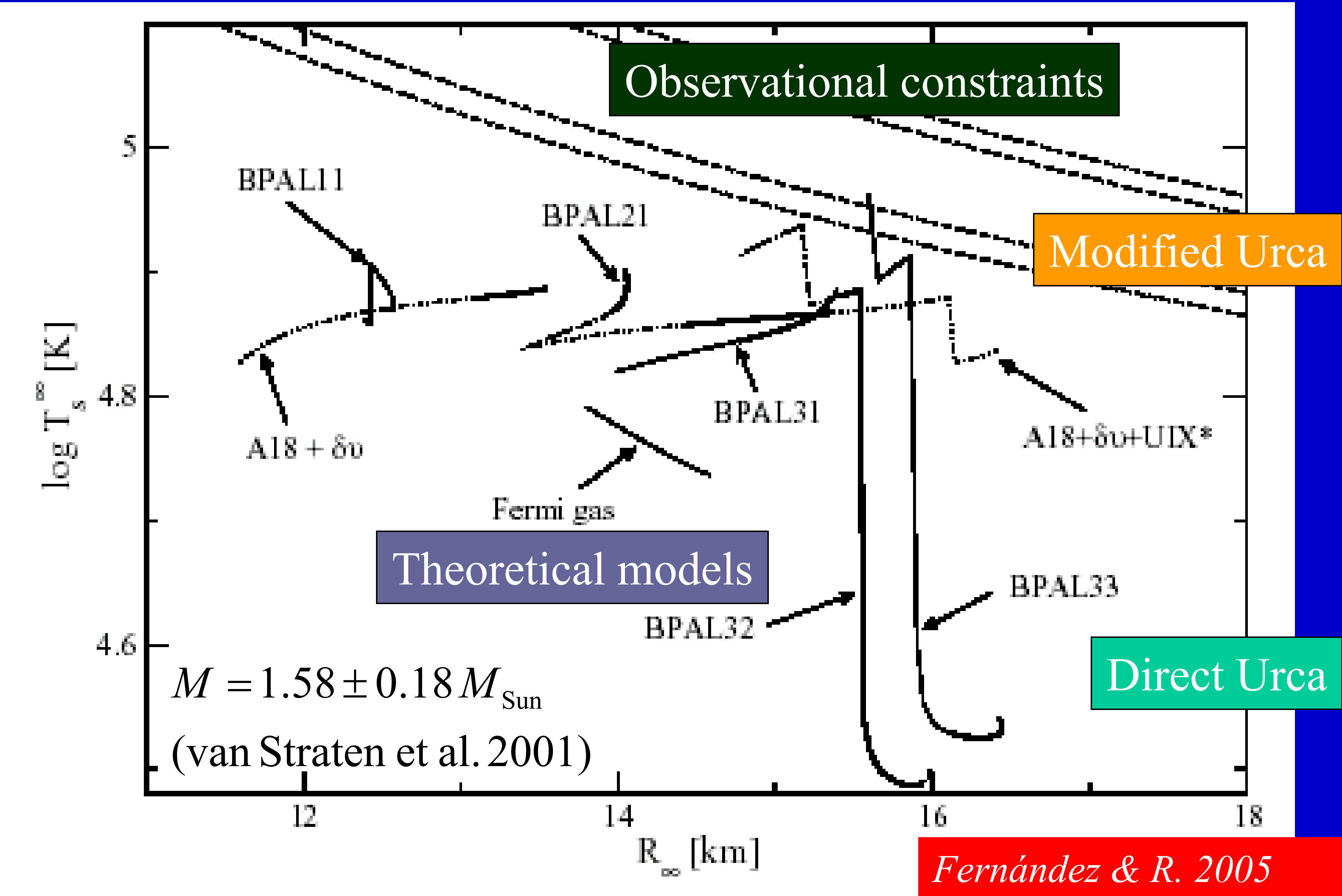
HST-STIS far-UV observation (1150-1700 Å)

Kargaltsev, Pavlov, & Romani 2004



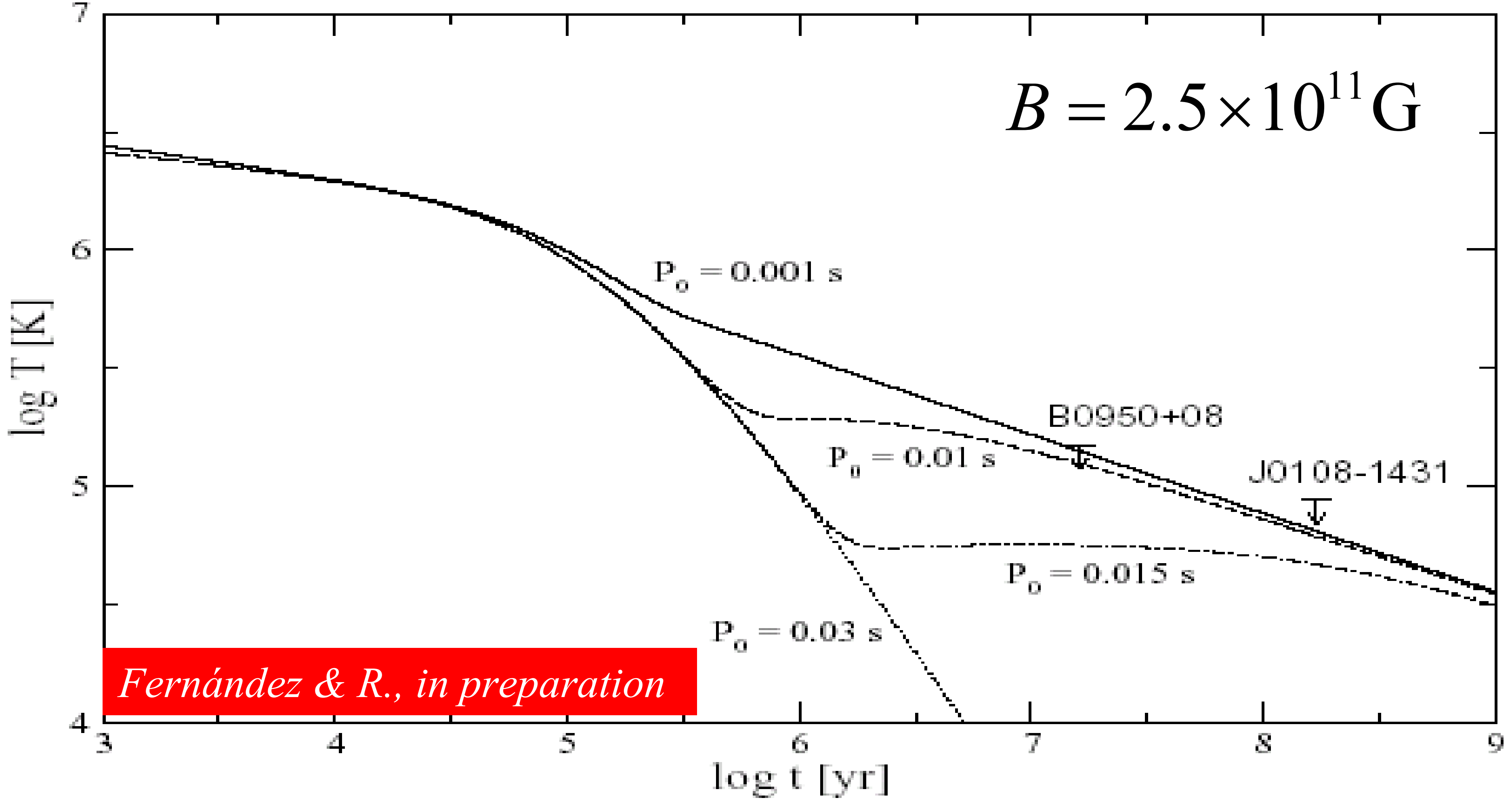
→ constraint on R^2T

PSR J0437-4715: Predictions vs. observation



Fernández & R. 2005

Old, classical pulsars: sensitivity to initial rotation rate



dG/dt ?

- Dirac (1937): constants of nature may depend on cosmological time.
- Extensions to GR (Brans & Dicke 1961) supported by string theory
- Present cosmology: excellent fits, dark mysteries, speculations: “Brane worlds”, curled-up extra dimensions, effective gravitational constant
- Observational claims for variations of
  - $\alpha_{EM} \equiv e^2 / \hbar c$ (Webb et al. 2001; disputed)
  - m_p / m_e (Reinhold et al. 2006)

→ <u>See how NSs constrain *d/dt* of</u> $\alpha_G \equiv G m_n^2 / \hbar c$

Previous constraints on *dG/dt*

Method	G'/G [yr^(-1)]	Timespan[yr]	Reference
Solar System planet and satellite orbits	1E-12	24	Williams et al (1996)
Binary pulsar orbit	5E-12	10	Kaspi et al (1994)
Rotation of isolated PSRs (var. moment of inertia)	6E-11	10	Goldman (1990)
White dwarf oscillations	3E-10	20	Benvenuto et al. (2004)
Paleontology: Earth's surface temp. vs. prehistoric fauna	2E-11	4E+09	Eichendorf & Reinhardt (1977)
Binary pulsar masses (Chandrasekhar mass at time of formation)	2E-12	2E+09	Thorsett (1996)
Helioseismology (Solar evolution models)	2E-12	5E+09	Guenther et al. (1998)
Globular clusters (isochrones vs. age of the Universe)	7E-12	1E+10	Degl'Innocenti et al. (1996)
CMB temperature fluctuations (WMAP vs. specific models)	1E-13	1E+10	Nagata et al. (2004)
Big Bang Nucleosynthesis (abundances of D, He, Li)	2E-13	1E+10	Copi et al. (2004)

***Gravito*chemical heating**

dG/dt (increasing/decreasing gravity)

$\Rightarrow$ density increase/decrease

$\Rightarrow$ chemical imbalance $\eta \equiv \mu_n - \mu_p - \mu_{e,\mu} \neq 0$

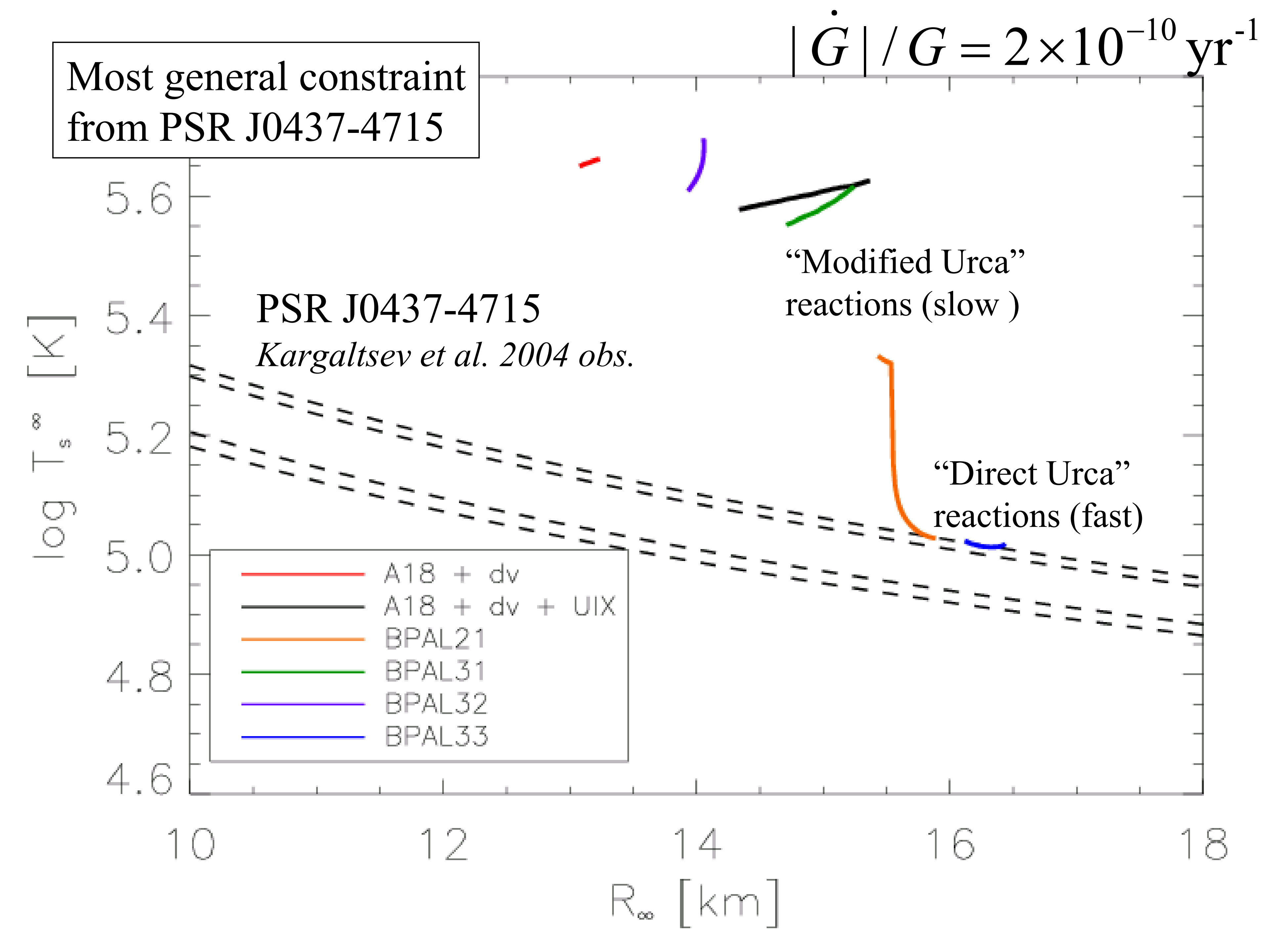
$\Rightarrow$ non-equilibrium reactions $n \leftrightarrow p + (e, \mu)$

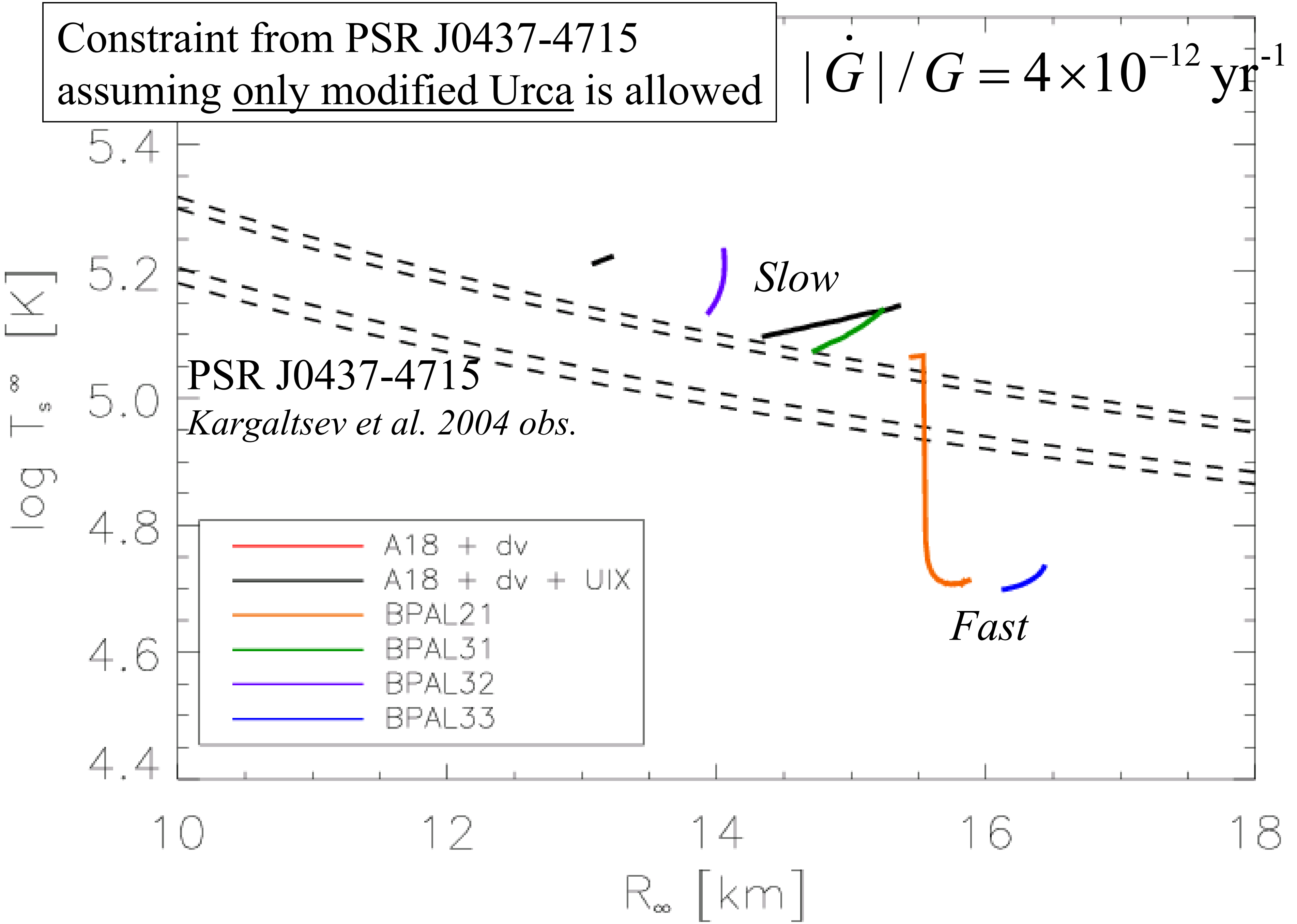
$\Rightarrow$ internal heating

$\Rightarrow$ possibly detectable thermal emission

Paula Jofré, undergraduate thesis

Jofré, Reisenegger, & Fernández, paper in preparation


$|\dot{G}|/G = 2\times10^{-10}\,\mathrm{yr}^{-1}$
Most general constraint from PSR J0437-4715
PSR J0437-4715
Kargaltsev et al. 2004 obs.
"Modified Urca" reactions (slow)
"Direct Urca" reactions (fast)
A18 + dv
A18 + dv + UIX
BPAL21
BPAL31
BPAL32
BPAL33
log T_s^∞ [K]
R_∞ [km]
5.6
5.4
5.2
5.0
4.8
4.6
10
12
14
16
18



Constraint from PSR J0437-4715
assuming only modified Urca is allowed
$|\dot{G}|/G = 4\times10^{-12}\,\mathrm{yr}^{-1}$
Slow
Fast
PSR J0437-4715
Kargaltsev et al. 2004 obs.
A18 + dv
A18 + dv + UIX
BPAL21
BPAL31
BPAL32
BPAL33
log T_s^∞ [K]
R_∞ [km]
5.4
5.2
5.0
4.8
4.6
4.4
10
12
14
16
18

Constraint from PSR J0437-4715:

$$\left|\dot{G}\right| / G < 4 \cdot 10^{-12}\,\mathrm{yr}^{-1}$$

...<u>if</u> only modified Urca processes are allowed, <u>and</u> the star has reached its stationary state.

Required time: $t_{eq} \approx 90\,\mathrm{Myr}$

Compare to age estimates:

$$t_{\text{spin-down}} = 4.9\,\mathrm{Gyr}$$

$$t_{\text{WD cooling}} \approx 2.5 - 5.3\,\mathrm{Gyr}$$

(Hansen & Phinney 1998)

Now:

Method	G'/G [yr^(-1)]	Time [yr]	Reference
Solar System planet and satellite orbits	1E-12	24	Williams et al (1996)
Binary pulsar orbit	5E-12	10	Kaspi et al (1994)
Rotation of isolated PSRs (var. moment of inertia)	6E-11	10	Goldman (1990)
White dwarf oscillations	3E-10	20	Benvenuto et al. (2004)
Gravitochemical heating of NSs (PSR J0437-4715) MOST GENERAL	**2E-10**	**1E+05**	**Jofré et al. (to be published)**
Gravitochemical heating of NSs (PSR J0437-4715) ONLY MODIFIED URCA	**4E-12**	**9E+07**	**Jofré et al. (to be published)**
Paleontology: Earth's surface temp. vs. prehistoric fauna	2E-11	4E+09	Eichendorf & Reinhardt (1977)
Binary pulsar masses (Chandrasekhar mass at time of formation)	2E-12	2E+09	Thorsett (1996)
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Main uncertainties

- Atmospheric model:
  - Deviations from blackbody
    - H atmosphere underpredicts Rayleigh-Jeans tail
- Neutrino emission mechanism/rate:
  - Slow (mod. Urca) vs. fast (direct Urca, others)
  - Cooper pairing (superfluidity): R. 1997; Villain & Haensel 2005; Flores & R., in prep.

Not important (because stationary state):

- Heat capacity: steady state
- Heat transport through crust

Conclusions

- *Rotochemical heating* <u>must</u> occur in all neutron stars with decreasing rotation rates
- *Gravitochemical heating* happens if $dG/dt \neq 0$
- Both lead to a <u>stationary state</u> of nearly constant temperature that can be probed with old enough pulsars (e.g., MSPs)
- Observed UV emission of PSR J0437-4715 may be due to rotochemical heating
- The same emission can be used to constrain $|dG/dt|$:
  - competitive with best existing constraints <u>**if**</u> fast cooling processes could be ruled out
- Sensitive UV observations of other nearby, <u>old</u> neutron stars of different rotation rates are useful to constrain both mechanisms
- Superfluid effects being calculated