Internal dissipation and thermal emission from old neutron stars: “rotochemical heating” and constraints on *dG/dt*

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with

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Outline

- Density changes, nonequilibrium reactions, and heating of neutron star cores
- Rotochemical heating:
  - Calculations, comparison to observations
- *dG/dt*?
  - Previous constraints
  - Gravitochemical heating
  - Calculations and observational constraints
- Conclusions

Heating neutron star matter by weak interactions

- Chemical (“beta”) equilibrium sets the relative number densities of particles (n, p, e, ...) at different pressures
- Compressing or expanding a fluid element perturbs the equilibrium
- Non-equilibrium reactions tend to restore the equilibrium
- “Chemical” energy is released as neutrinos and “heat”

Possible forcing mechanisms

- Neutron star oscillations, e.g., r-modes: no conclusive evidence so far
- Accretion: effect overwhelmed by external and crustal heat release
- *dP/dt*: feasible in old, fast neutron stars: **Rotochemical heating** in MSPs
- *dG/dt*: highly speculative, but worth a try! "**Gravitochemical heating**"

"Rotochemical heating"

NS spin-down (decreasing centrifugal support)

$\Rightarrow$ progressive density increase

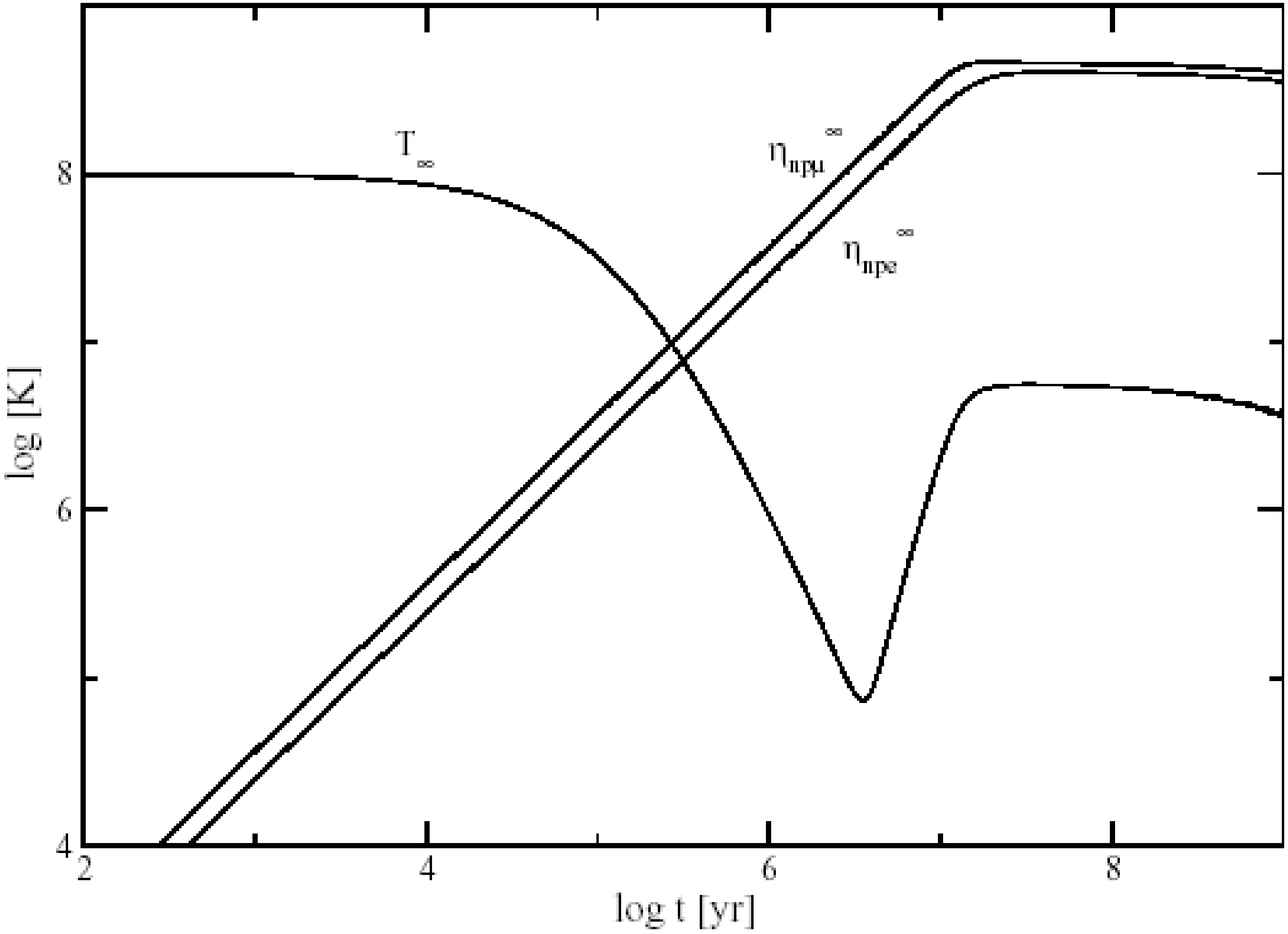
$\Rightarrow$ chemical imbalance $\eta \equiv \mu_n - \mu_p - \mu_{e,\mu} > 0$

$\Rightarrow$ 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
(all ApJ)



Neutron star evolution

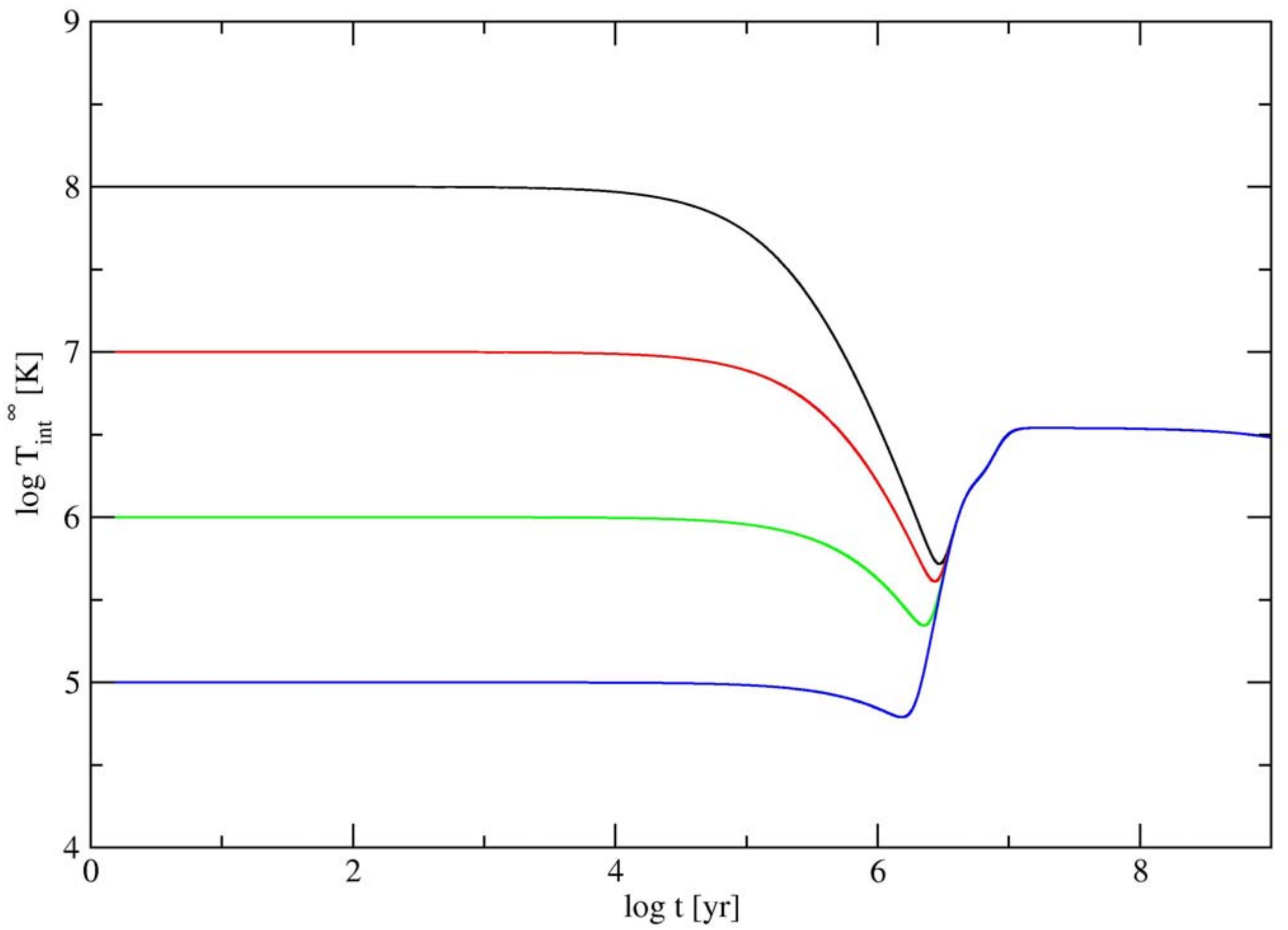
Temperature and chemical imbalances as functions of time (magnetic dipole spin-down with P_0 = 1 ms & B = 10^8G)

Fernández & R. 2005 (ApJ)

MSPs evolve to a <u>stationary state</u> in which as much heat is released by the reactions as radiated away as neutrinos and photons.

A "heater" is even better than a "hot water bottle"!

Insensitivity to initial conditions



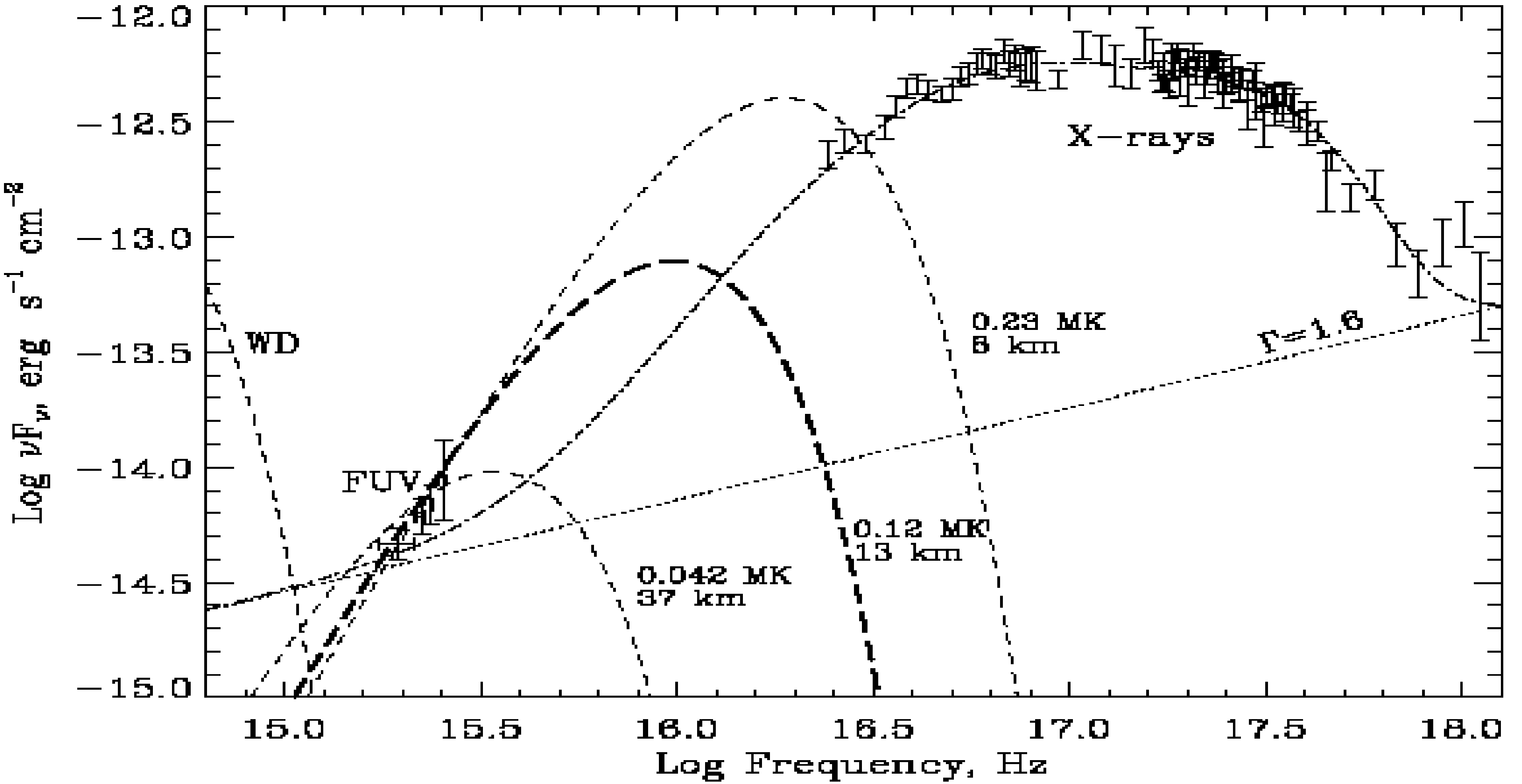
Fernández & R. 2005

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

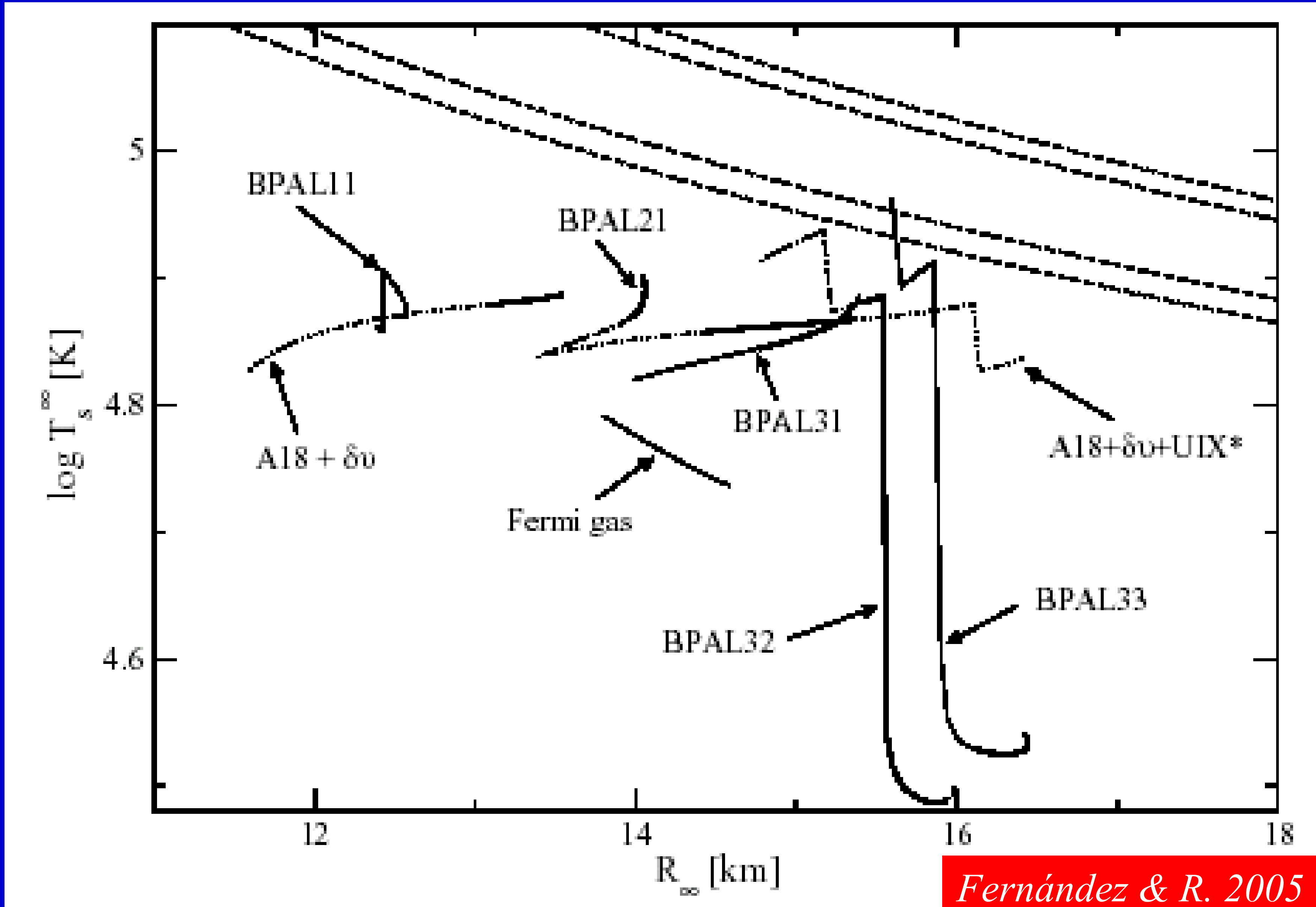
The nearest MSP: PSR J0437-4715

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

Kargaltsev, Pavlov, & Romani 2004



PSR J0437-4715: Predictions vs. observation



Fernández & R. 2005

dG/dt ?

"Beyond Einstein"...

- Dirac: large-number hypothesis
- Extensions to GR: Brans-Dicke et al.
- Present cosmology: excellent fits, great mysteries (dark matter, dark energy)
- "Braneworlds" and curled-up extra dimensions, effective gravitational constant

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

R., Jofré, & Fernández, paper in preparation

Conditions for a good constraint on *dG/dt*

- Pulsar needs to have reached quasi-equilibrium: *large age*

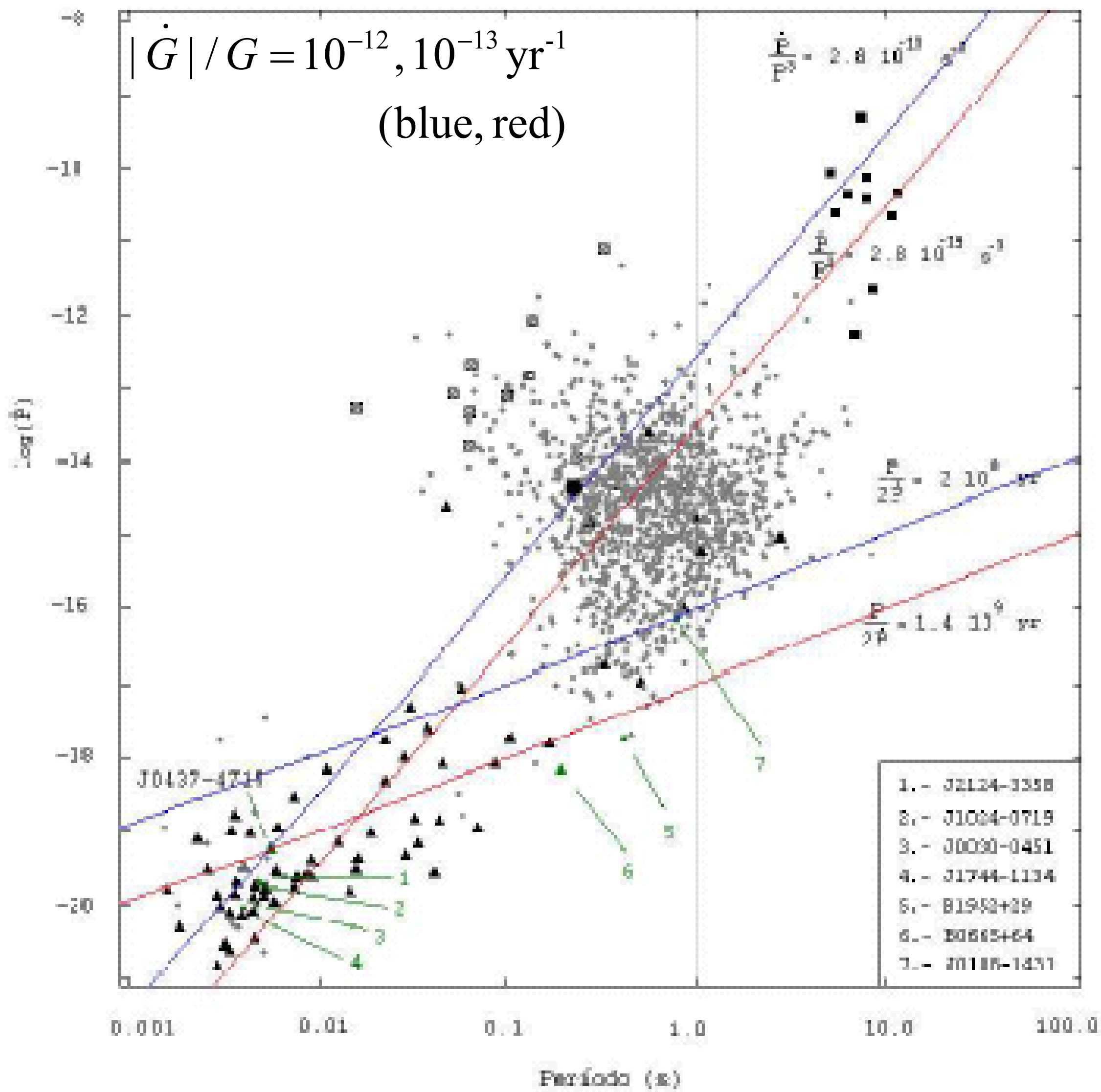
$$t_s = P/(2\dot{P})$$

- Rotochemical effect weaker than gravitochemical: *small*

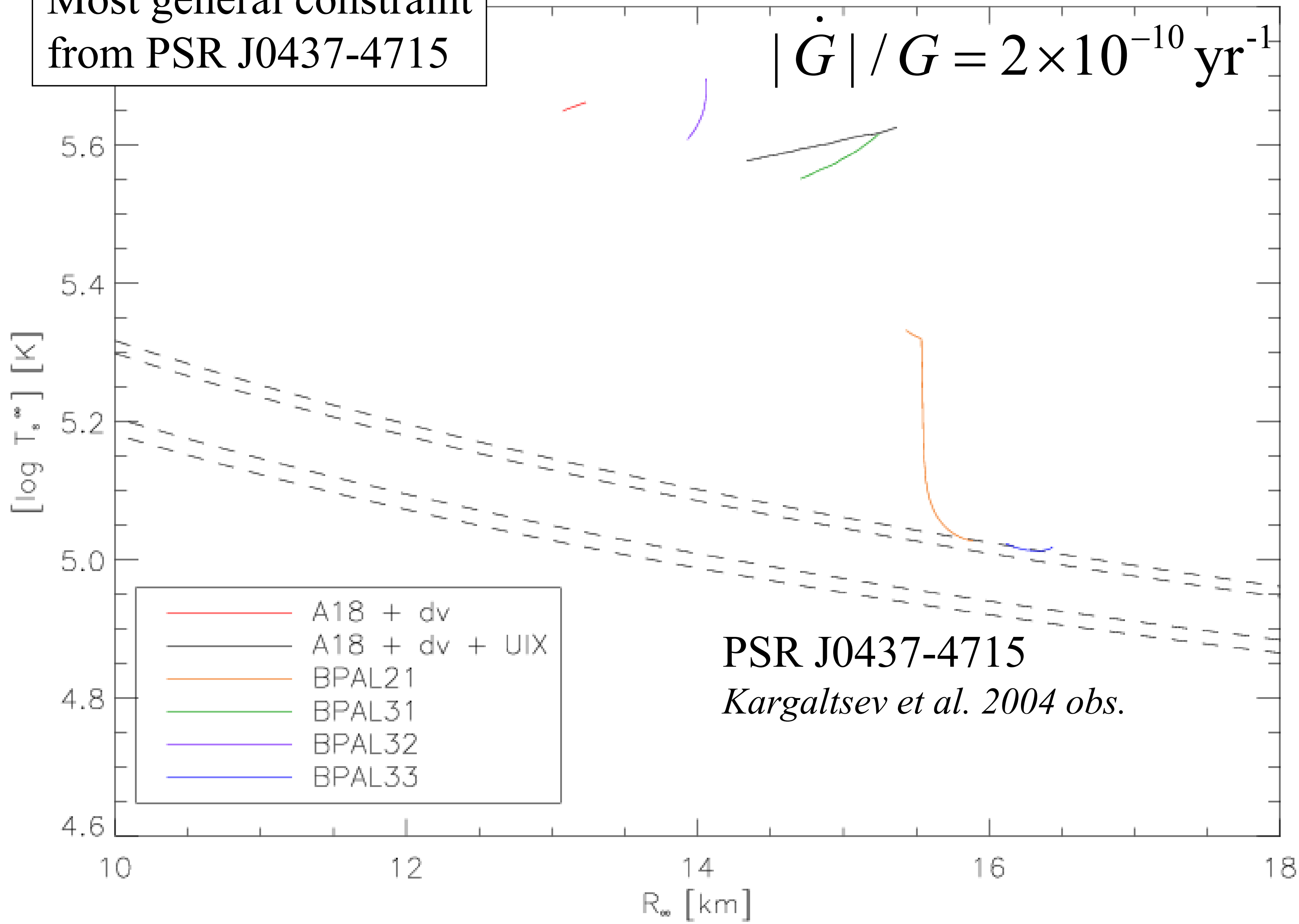
$$\Omega|\dot{\Omega}| \propto \dot{P}/P^3$$

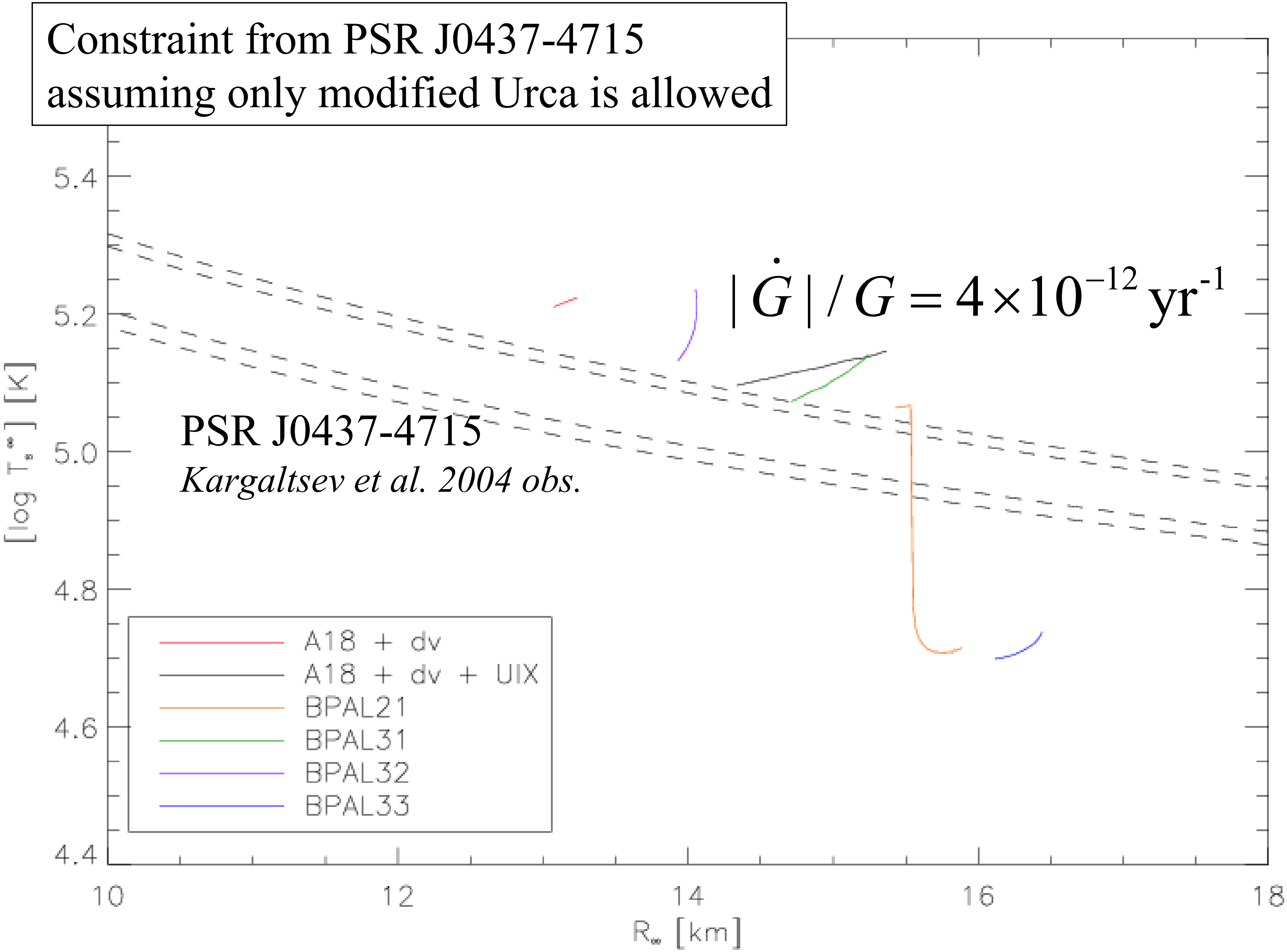
⇒Lower right of pulsar *P-dP/dt* diagram

Also: close enough to measure or constrain thermal emission



Most general constraint
from PSR J0437-4715





Constraint from PSR J0437-4715
assuming only modified Urca is allowed
$|\dot{G}|/G = 4\times10^{-12}\,\mathrm{yr}^{-1}$
PSR J0437-4715
Kargaltsev et al. 2004 obs.
A18 + dv
A18 + dv + UIX
BPAL21
BPAL31
BPAL32
BPAL33
[log T*] [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)

OK!!

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***	***Paula Jofré, undergrad. thesis (to be published)***
Gravitochemical heating of NSs (PSR J0437-4715) ONLY MODIFIED URCA	***4E-12***	***9E+07***	***Paula Jofré, undergrad. thesis (to be published)***
Paleontology: Earth's surface temp. vs. prehistoric fauna	2E-11	4E+09	Eichendorf & Reinhardt (1977)
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Main uncertainties

- Atmospheric model:
  - Deviations from blackbody?
- Neutrino emission mechanism/rate:
  - Slow (mod. Urca) vs. fast (direct Urca, others)
  - Cooper pairing

Not important:

- Heat capacity: steady state
- Heat transport through crust

Conclusions

- *Rotochemical heating* must occur in all neutron stars with decreasing rotation rates
- *Gravitochemical heating* happens if $dG/dt \neq 0$
- Both lead to a stationary state 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 the best existing constraints if fast cooling processes could be ruled out
- Sensitive UV observations of other nearby, old neutron stars of different rotation rates are useful to constrain both mechanisms