Thermal properties of three *Fermi* pulsars

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Outline

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Thermal radiation from INS. Why important

- from $\sim 10^2$ till $\sim 10^5$ years (middle-aged) NSs cool down via neutrino emission
- neutrino emissivity depends on state and composition of supranuclear matter inside NSs
- also superfluidity
- observations in soft X-rays and UV give us $T_{\rm eff}$
- comparison of $T_{\rm eff}$ with predictions of the cooling theory gives us neutrino emissivity

Nearby middle-aged pulsars, such as Vela and "Three Musketeers" (Geminga, B0656 and B1055), are of particular importance.

Fermi gives us

several promising targets (see Abdo et al. 2013)

PSRs J0357+3205, J1741−2054 and J0633+0632

- their ages are $\sim 10^4$–10^5 years and they are not farther than 1 kpc (Abdo et al. 2013)
- J0357+3205 and J0633+0632. X-ray data were analyzed previously (De Luca et al. 2011, Marelli et al. 2013, Ray et al. 2011)
- J1741−2054 X-ray PWN and Hα bow-shock were detected (Romani et al. 2010)
- Large number of J1741−2054 photons were collected during 300 ks *Chandra* observations, PI Roger Romani, "A Legacy study of the relativistic Shocks of PWN"
- J1741−2054. phase-resolved spectroscopy of the non-thermal component of the X-ray emission based on *XMM* data (Marelli et al. 2014)

We analyzed X-ray data available in *Chandra* and *XMM-Newton* archives. We also observed J0357+3205 in the optical with GTC. For details see papers by Kirichenko et al. 2014 and Karpova et al. 2014

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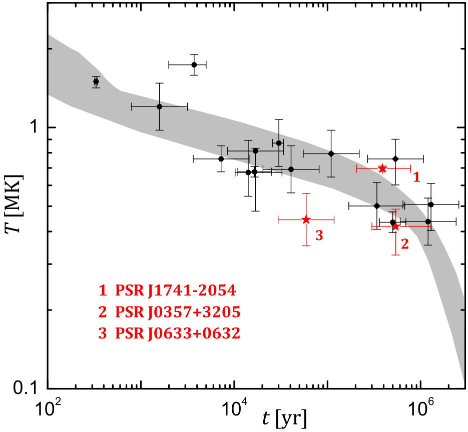
Standard cooling theory predictions

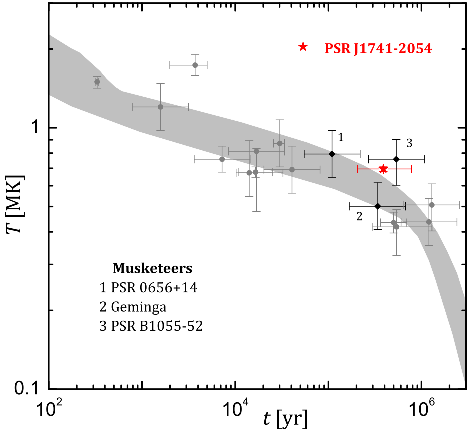
NSs cool down via MURCA, no enhanced neutrino emission, no superfluidity



(see Yakovlev & Pethick 2004 and Yakovlev et al. 2011)

J1741−2054 and “Three Musketeers”

blackbody + power-law, $T_{\rm eff} = 60 \pm 2$ eV, $R = 17 \pm 3\ D_{\rm kpc}$ km



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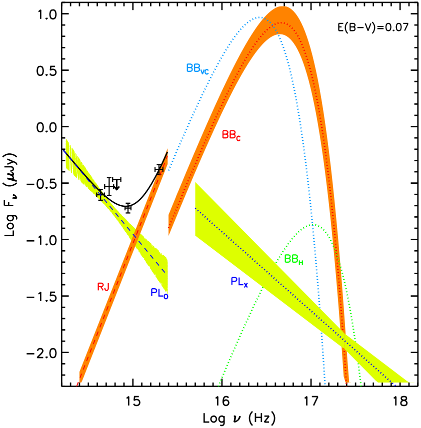
Multiwavelength spectrum of B1055−52

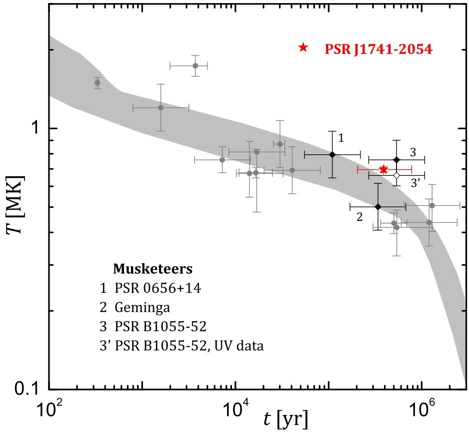
UV observations show that the surface may be cooler.



Mignani, Pavlov & Kargaltsev 2010

Standard cooling scenario

Here "3′" marks temperature of B1055−52 measured from UV



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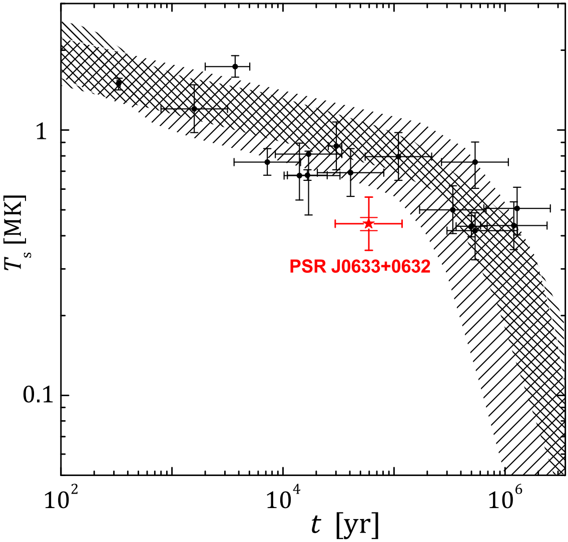
J0633+0632 requires faster cooling processes?

hydrogen atmosphere + power-law, $T_{\mathrm{eff}} \approx 40 \pm 15$ eV



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Summary

- J1741−2054 looks similar to PSR B1055−2054, it is hotter than the standard cooling scenario predicts.
- J0633+0632 is likely the coldest NS on the neutrino cooling stage. Requires faster cooling processes?

What to do next

- Observations of J1741−2054 in UV (Hubble).
- Observations of J0633+0632 with *XMM-Newton*.

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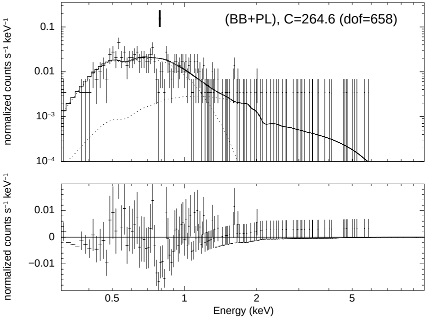
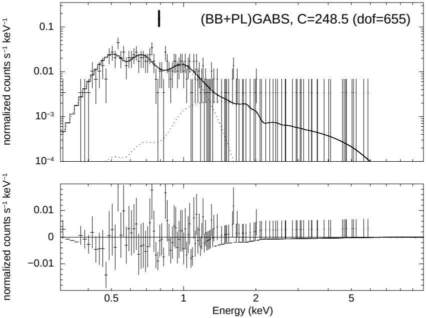
The *Chandra*/ACIS-S spectrum of J0633+0632





Is there a line? Posterior predictive check

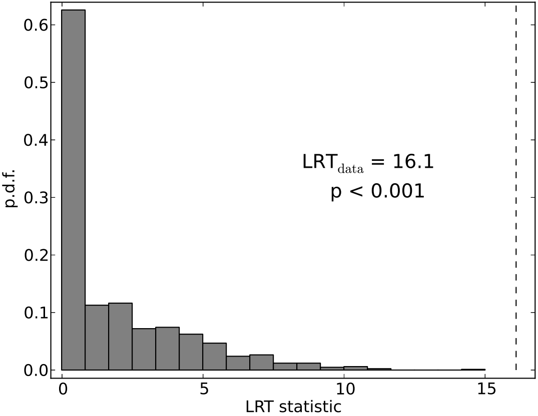


Figure: None of 1000 simulations has LRT greater than the observed one, that is, *p*-value is less than 0.001.

T vs R for NSA+PL

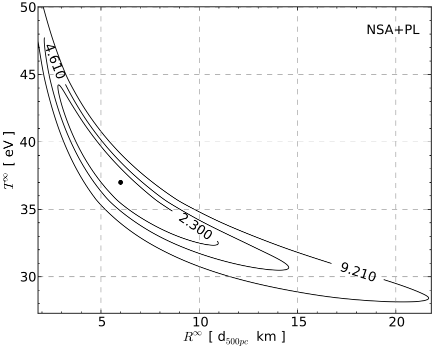
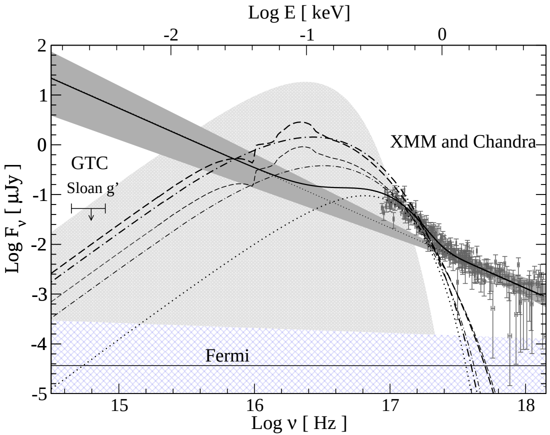


Figure: $\Delta\chi^2 = \chi^2 - \chi^2_{min} = 2.3, 4.61$, and 9.21

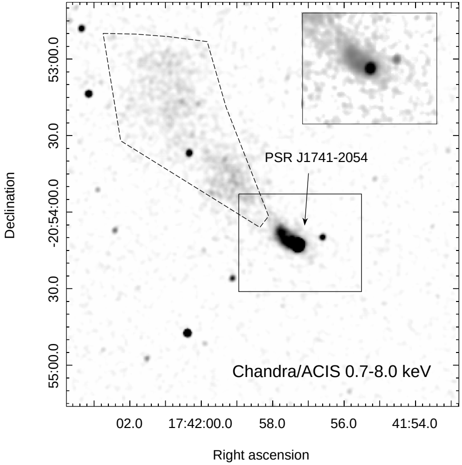
Kirichenko et al. 2014

Multiwavelength spectrum of J0357+3205



Kirichenko et al. 2014

J1741−2054



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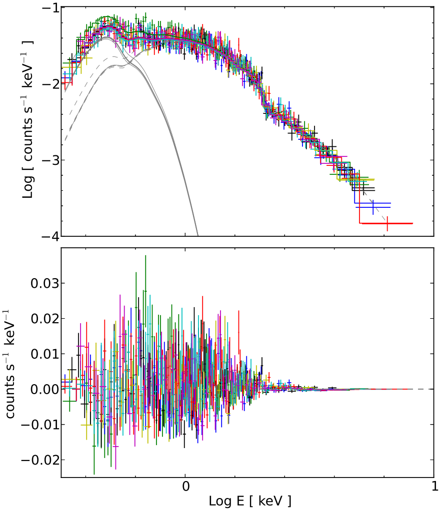
The best-fit BB+PL model



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N_H and T_{eff} vs the distance

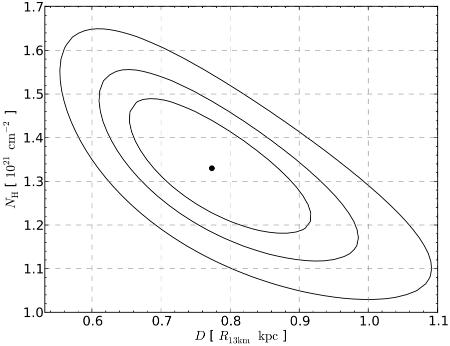

Figure: $\Delta\chi^2 = \chi^2 - \chi^2_{min} = 2.3, 4.61, \text{and } 9.21$

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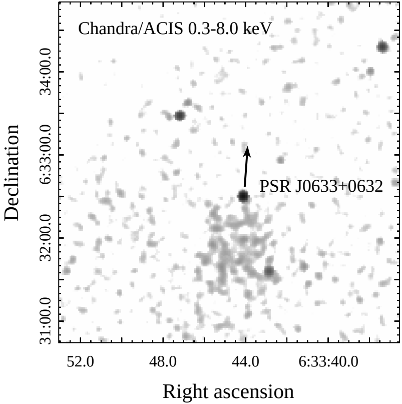
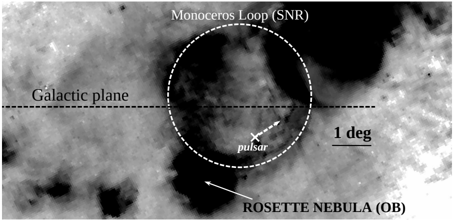
Field of J0633+0632





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What have been done

- J1741 looks like forth Musketeer
- J0633 is probably cool and has an absorption feature

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- *XMM* observations of J0633

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