Constraints on Neutron Star Cooling using Chandra Observations of PSR B1509-58, PSR B1951+32, and RX J0007.0+7303

Tracey DeLaney
Bryan Gaensler
Pat Slane
Steve Murray

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Motivation

- Interior structure of neutron stars is poorly understood
- Cooling of neutron stars depends on the neutrino production rate which depends on the interior structure
- Surface temperatures of neutron stars of known age can be used to determine the cooling rate

Procedure

- Pulsars of known age and distance
- X-ray pulsations
- Timing observations with Chandra HRC
- Determine the off-pulse count rate
- Convert to blackbody temperature

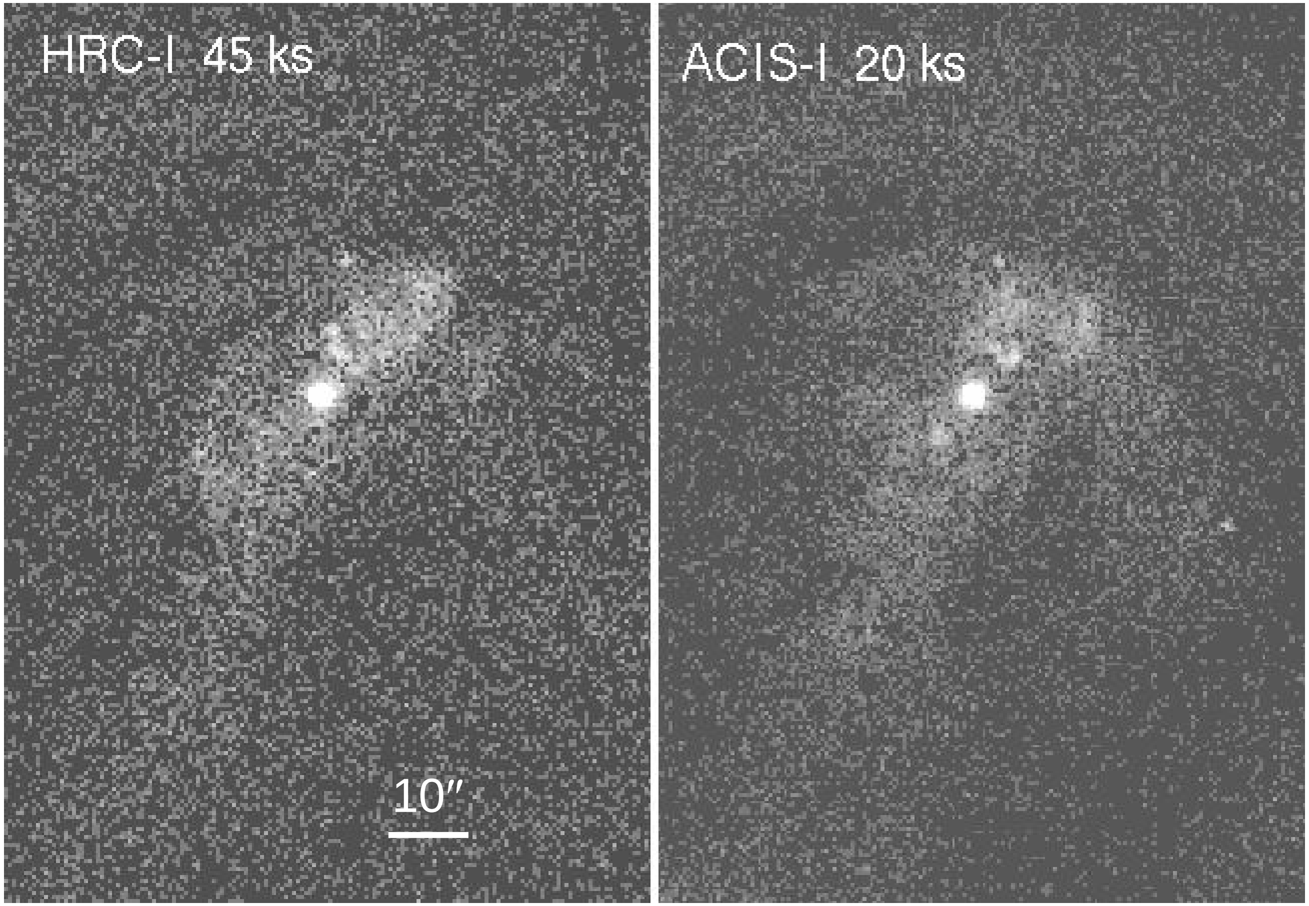
➢ Direct measurement of the surface temperature!

But, not so simple – interesting “problems”

A Sample of Three

1. B1509-58
   - 150 ms
   - SNR G320.4-1.2 (MSH 15-52)
2. B1951+32
   - 39 ms
   - SNR CTB 80
3. RX J0007.0+7303
   - no radio pulsations, discovery of X-ray pulsations
   - SNR CTA 1

B1509-58



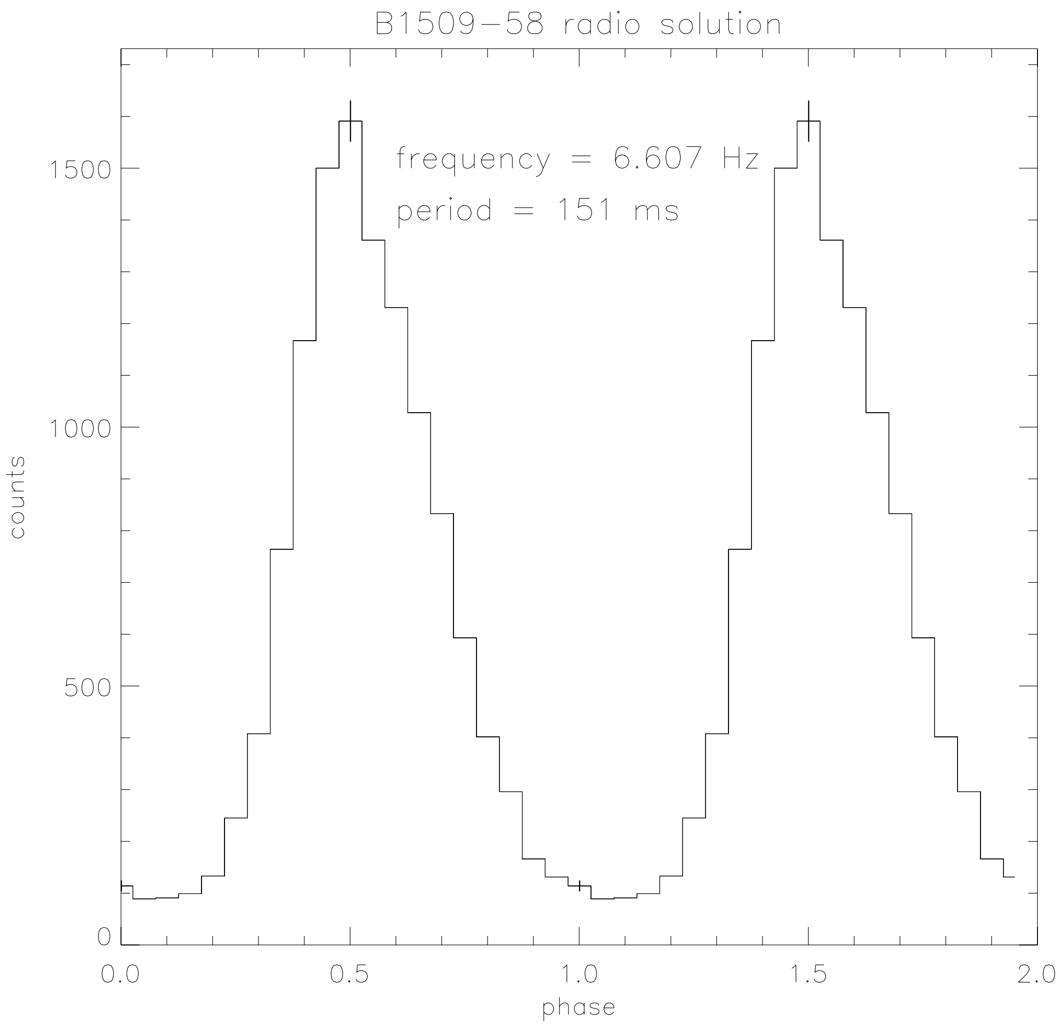
2005 2003

age=1600 yrs
period=150 ms
distance=5.2 kpc

embedded in a PWN
Crab-like

Temperature based on ROSAT observations and spectral modeling
1.8×10^{6} K
(W. Becker 1995, PhD thesis)

B1509-58



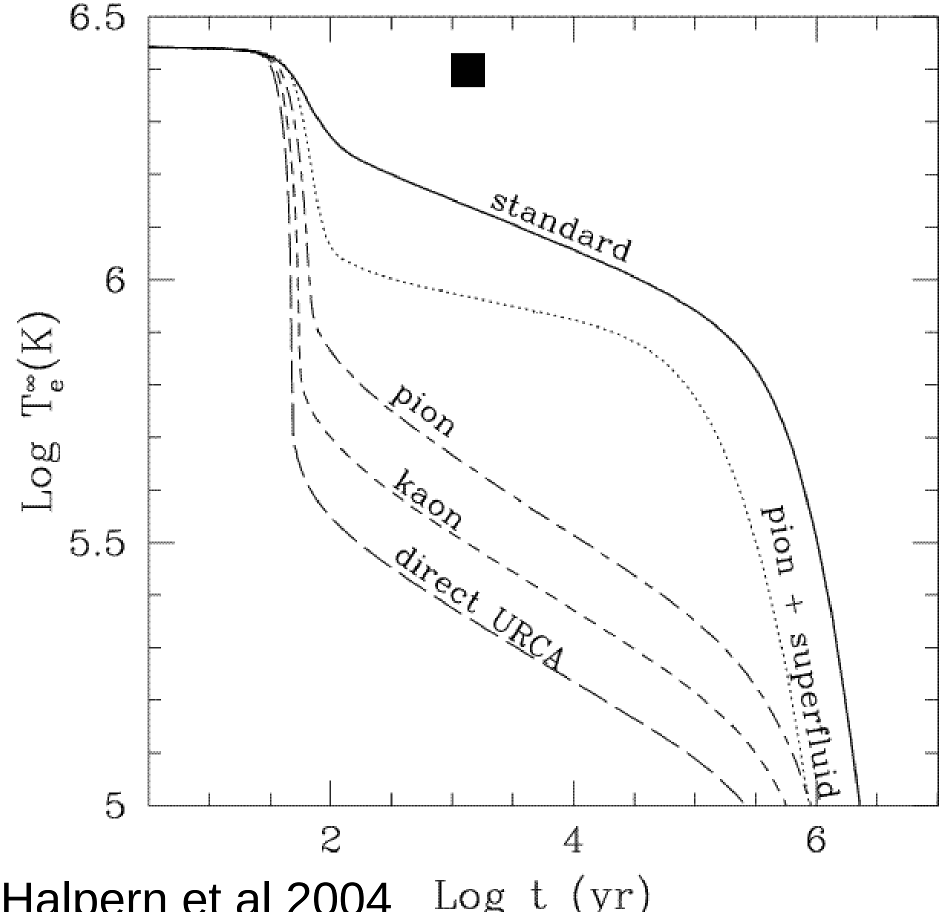
Radio timing solution –
M. Livingstone

Significant off-pulse emission
20% off-pulse time
382 counts
12 background counts

Temperature using nominal values of count rate, distance, N_H, and NS radius = **2×10⁶ K** (kT=0.18)

Upper limit = **2.6×10^6 K** (kT=0.22)
highest count rate
largest distance
highest N_H
smallest radius (8 km)

B1509-58



Halpern et al 2004

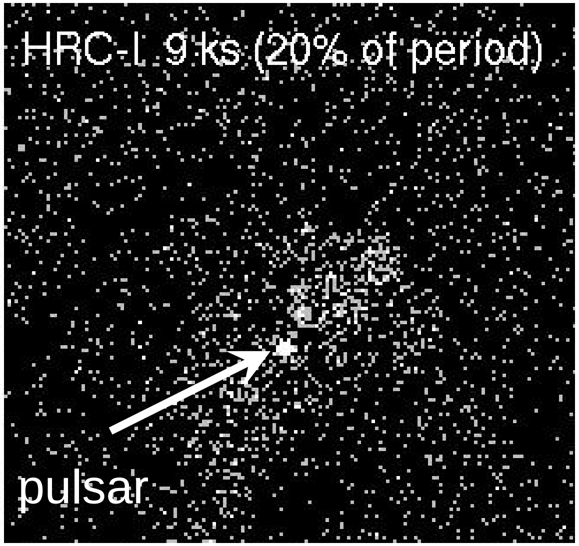
1.4 M_{sun}

Ouch! Very high temperature (just like Crab)

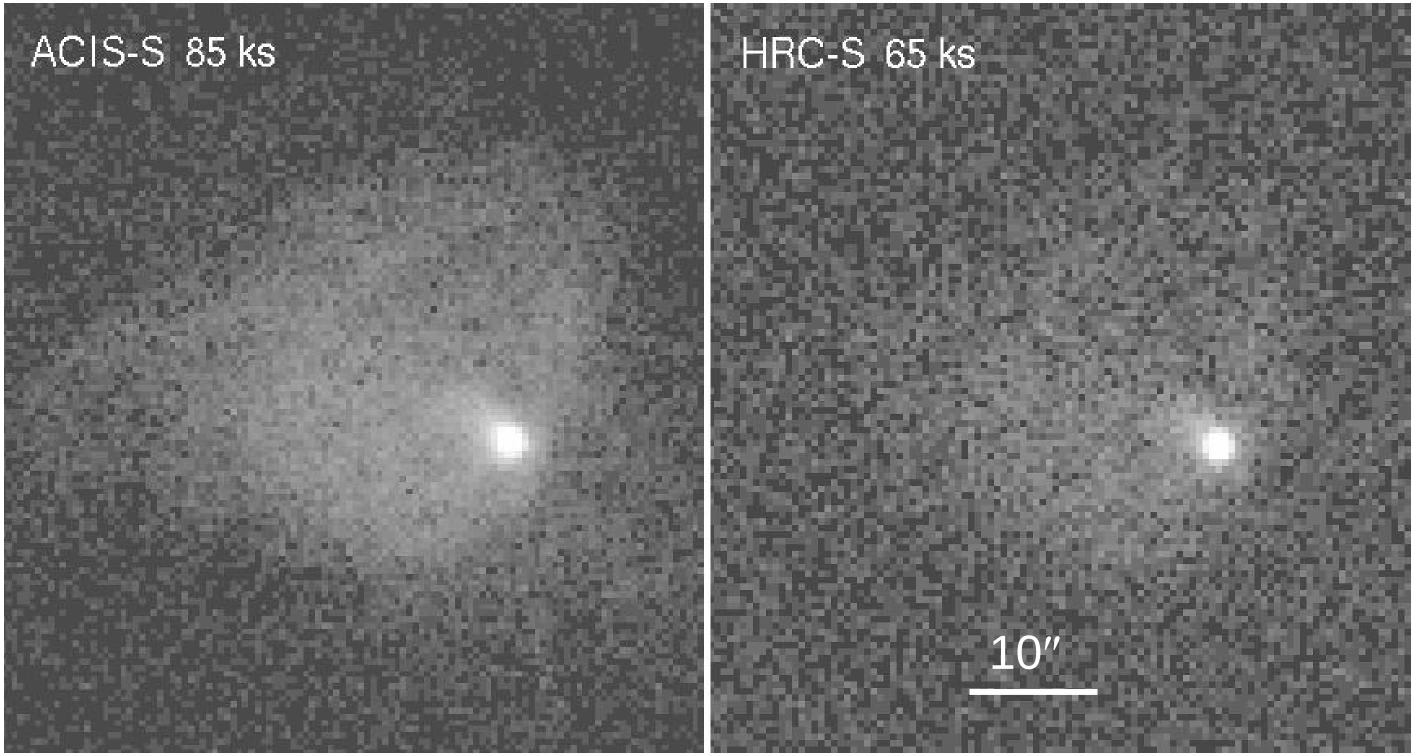
Too high to be useful

Probably contamination from non-thermal emission

Next step is spectral modeling with XMM



B1951+32



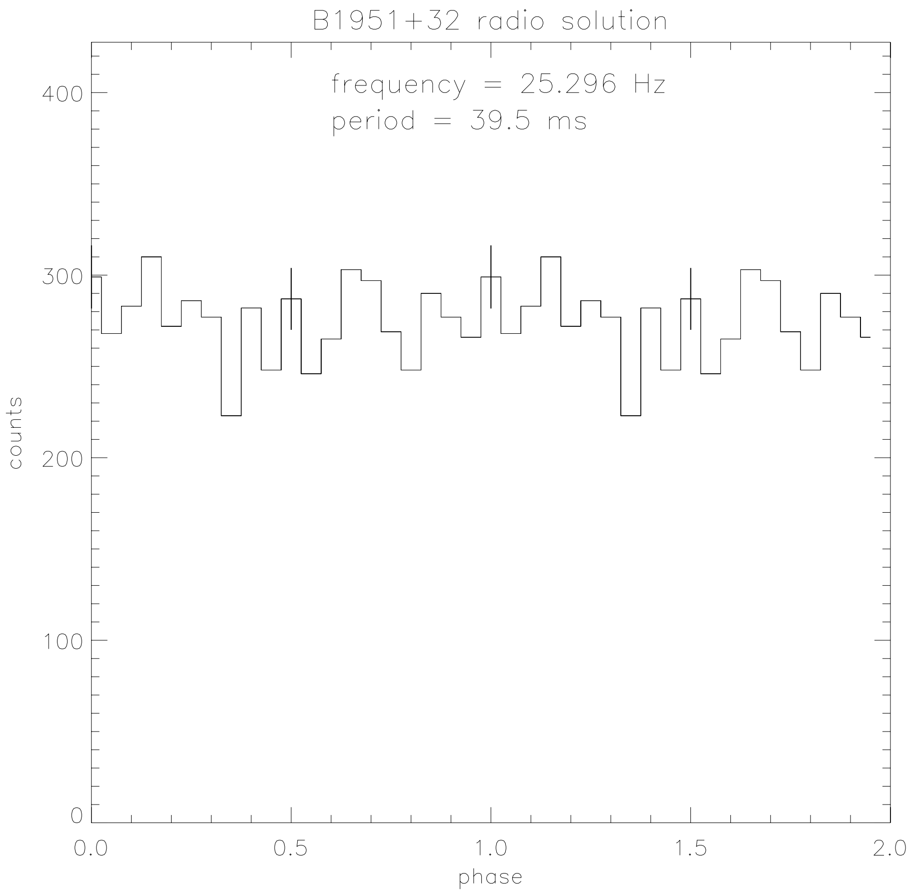
2001 2003

Age=64 kyr (dynamic), 107 kyr (characteristic)
Period=39.5 ms
Distance=2 kpc

Embedded in PWN

Temperature upper limit based on ACIS spectrum=7.8×10^5 K (Li et al 2005)

B1951+32



Radio timing solution from co-eval observations of M. Kramer

Ouch! No Pulse!

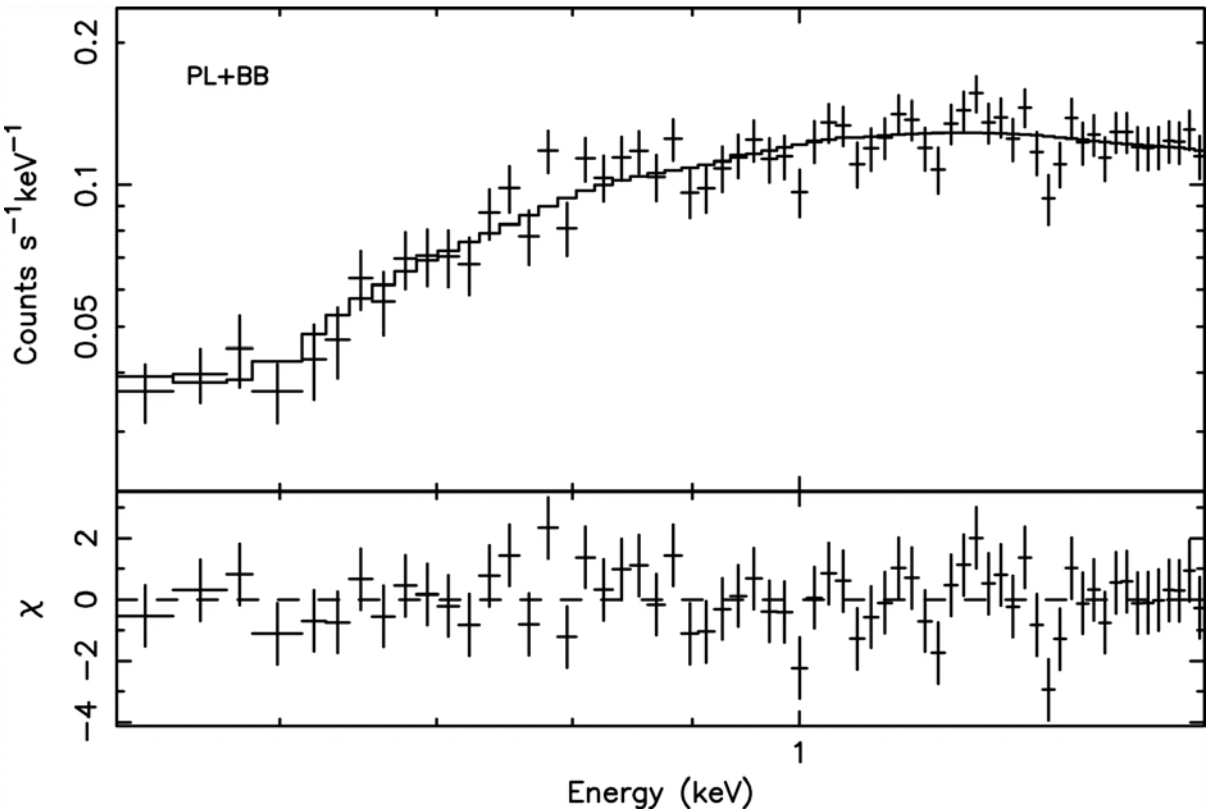
Z^2 test did not find period

S. Ransom did not find period

We even considered that HRC was broken

Expect X-ray Pulsations!

B1951+32

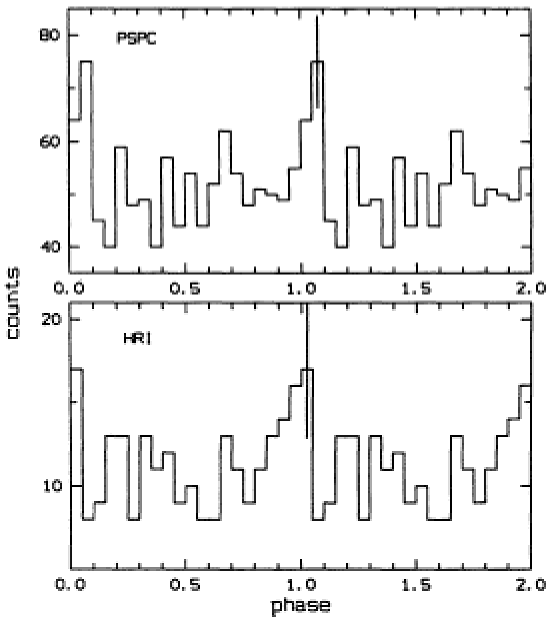


Li et al 2005 ACIS spectrum is well fit by power law with a blackbody at less than 10% level (99.99% confidence)

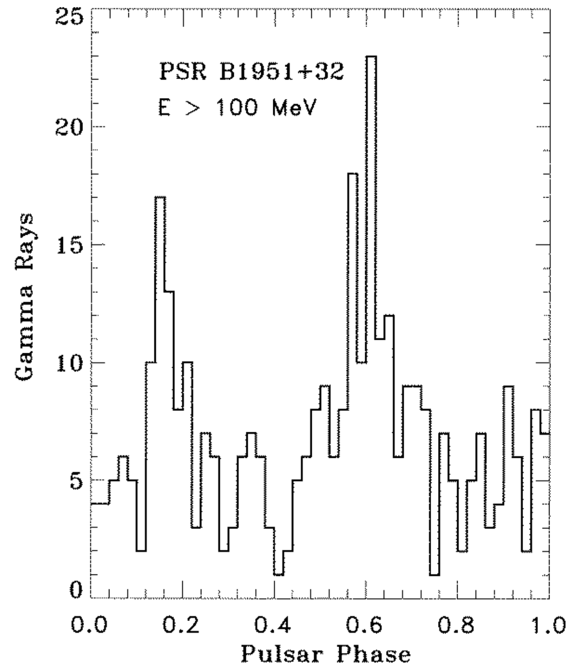
Size of bbody emission region consistent with hotspots

If they force the fit to 12 km, then their 3σ upper limit temperature =7.8×10^5 K

B1951+32



Safi-Harb et al 1995
ROSAT

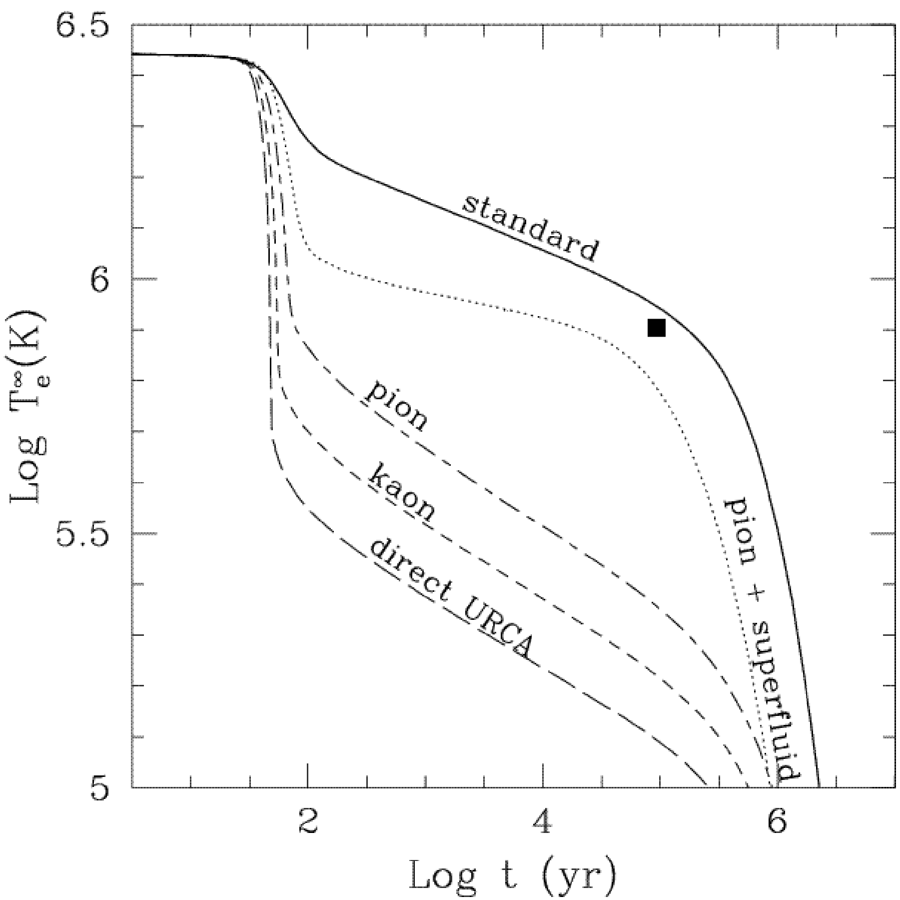


Ramanamurthy et al 2005
EGRET

Pulsations observed with ROSAT and EGRET with periods matching the radio solution

A real puzzle that we don't know the answer to

B1951+32



Let's push the upper limit of Li et al as far as we can go

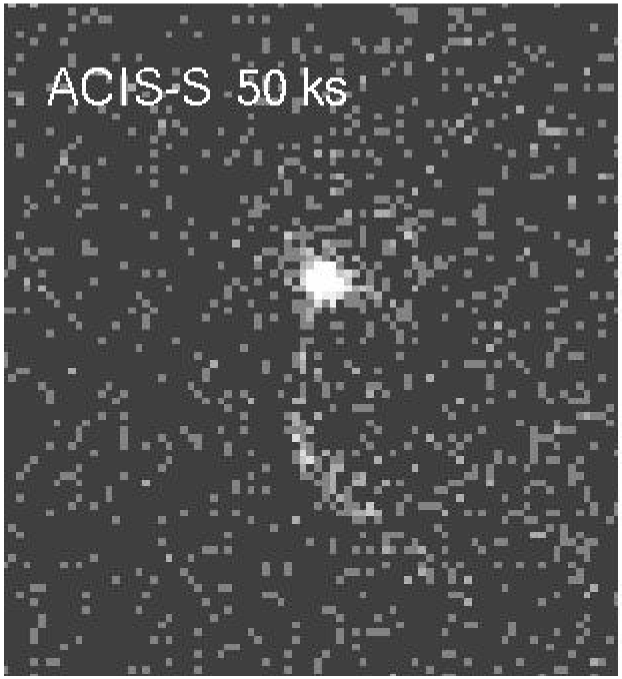
ACIS spectral fit
Power law + blackbody, radius=12 km

Raise kT until the null hypothesis probability gets very small

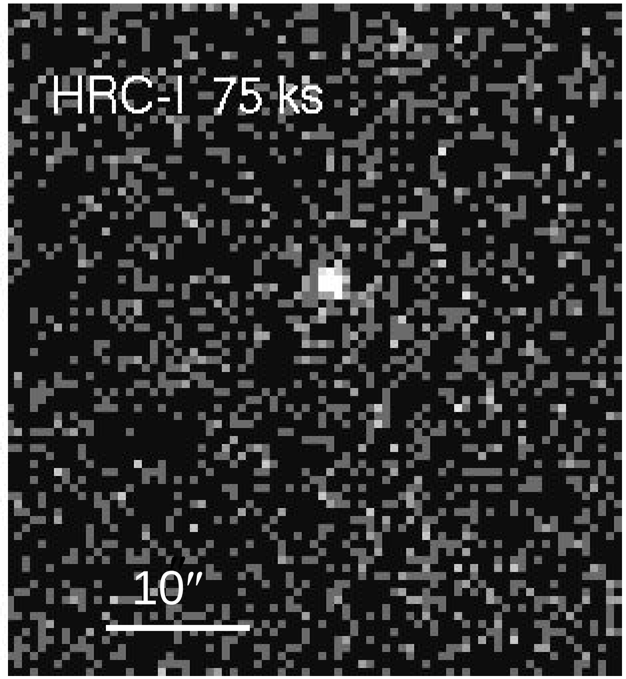
Temperatures > **8.7×10^5 K** (kT=0.075) are excluded at 99.99999%

Next step – ACIS continuous clocking observations – search for pulses at different energies

CTA 1



2003



2004

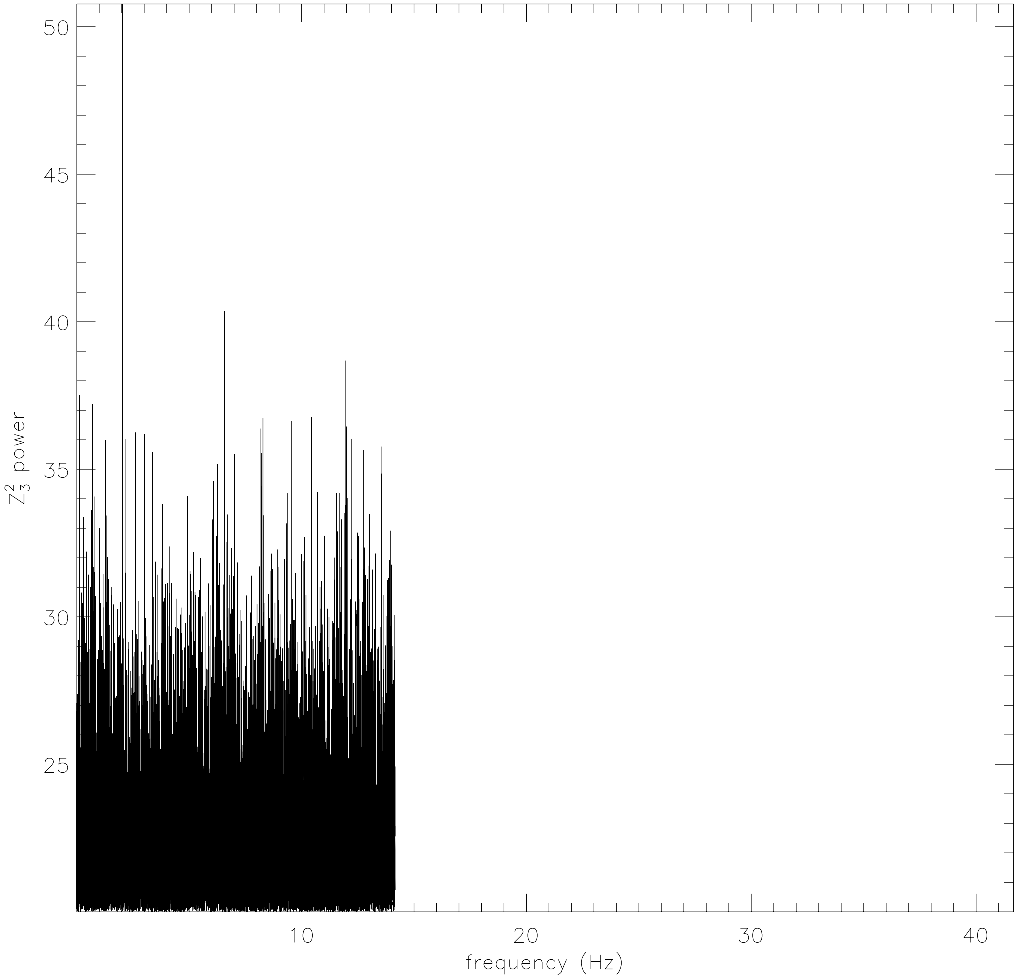
Age=13 kyr
Period=none previously found
Distance=1.4 kpc

Embedded in PWN

Temperature upper limit from ACIS spectral fits = 6.6×10^5 K (Halpern et al 2004)

HRC data taken for proper motion experiment – not originally for this project

CTA 1

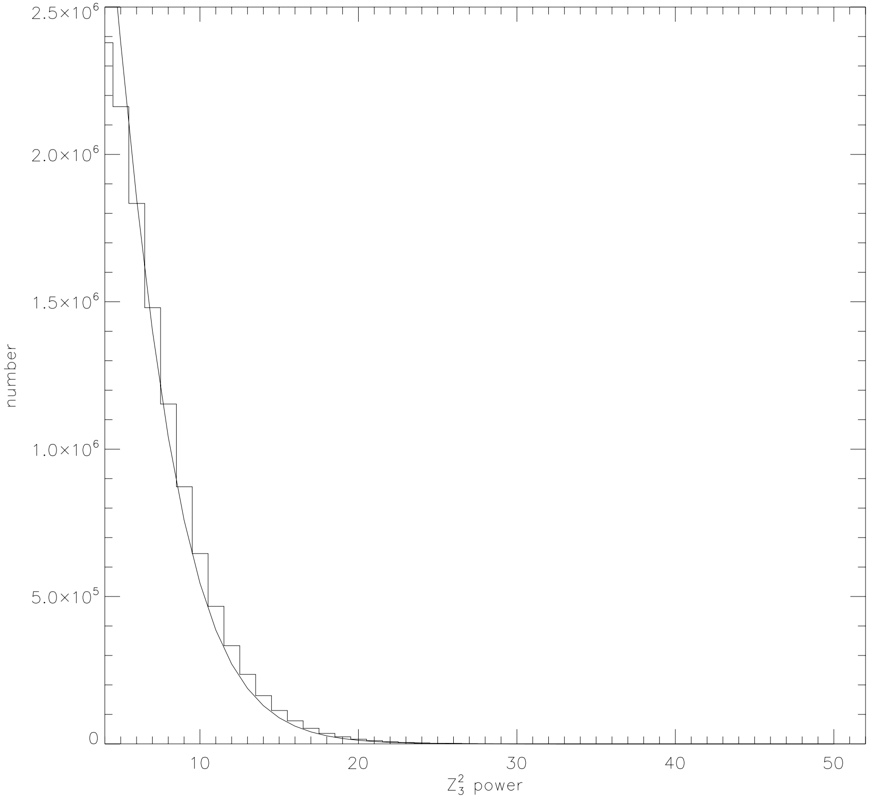


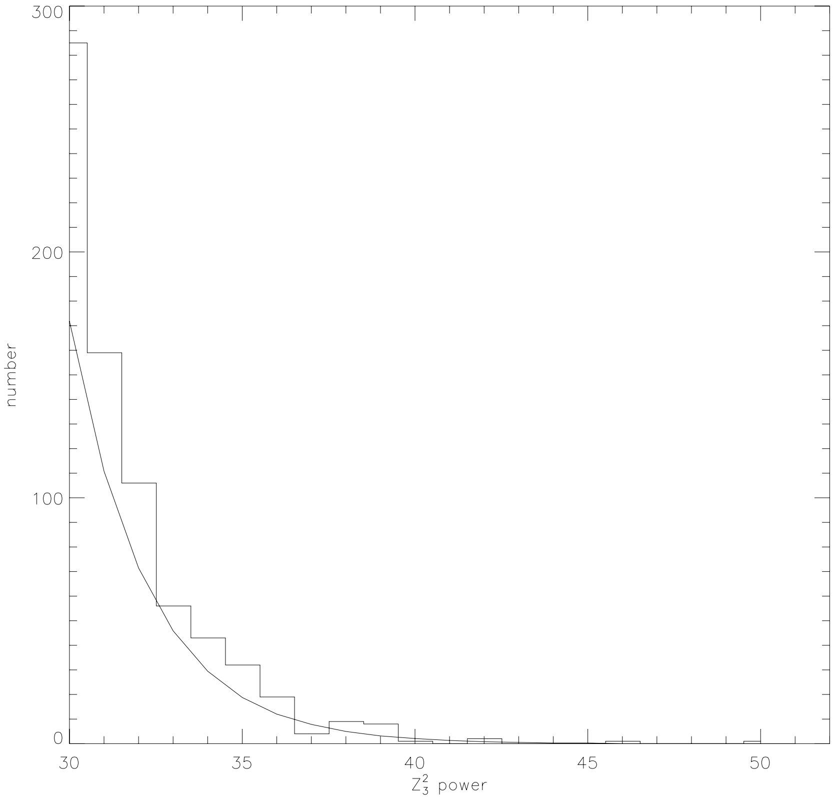
Search for pulsations: Z^2 test

Signal found at 2.035 Hz with the 3rd harmonic with a power of 50.8

This is a 2.5σ result

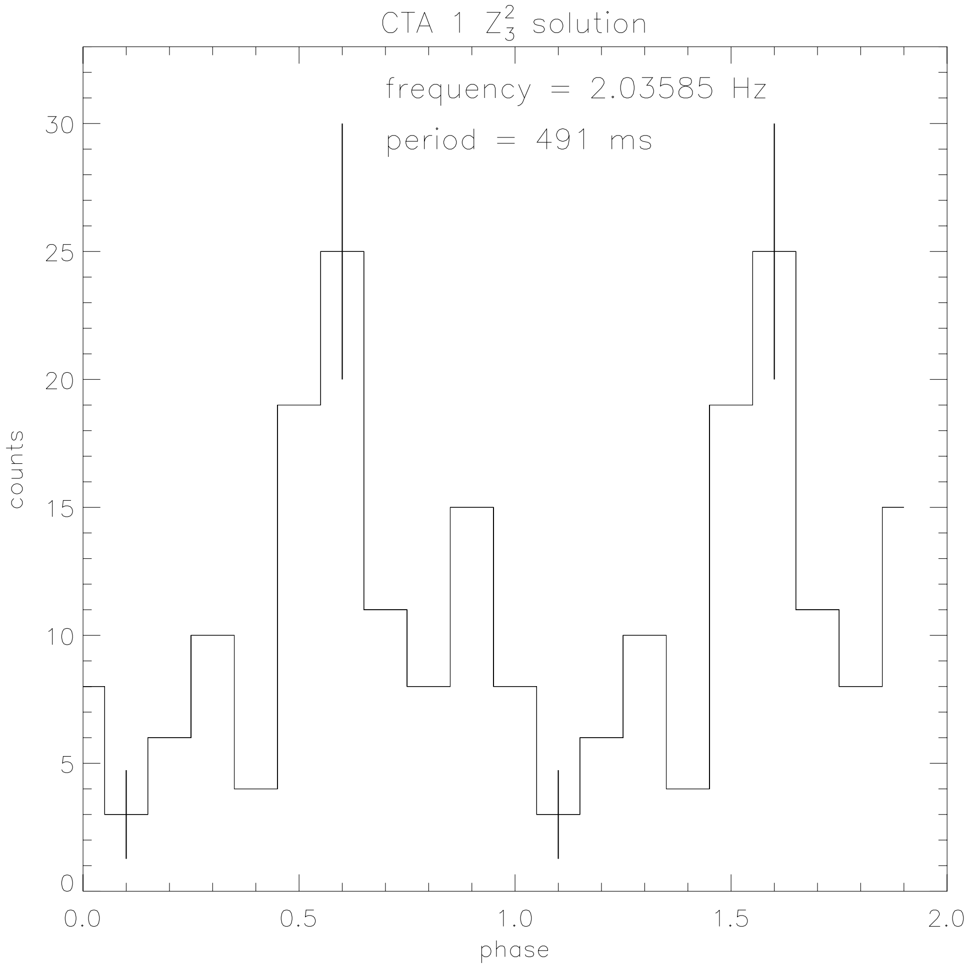
CTA 1





Power spectrum follows a χ^2 distribution

CTA 1



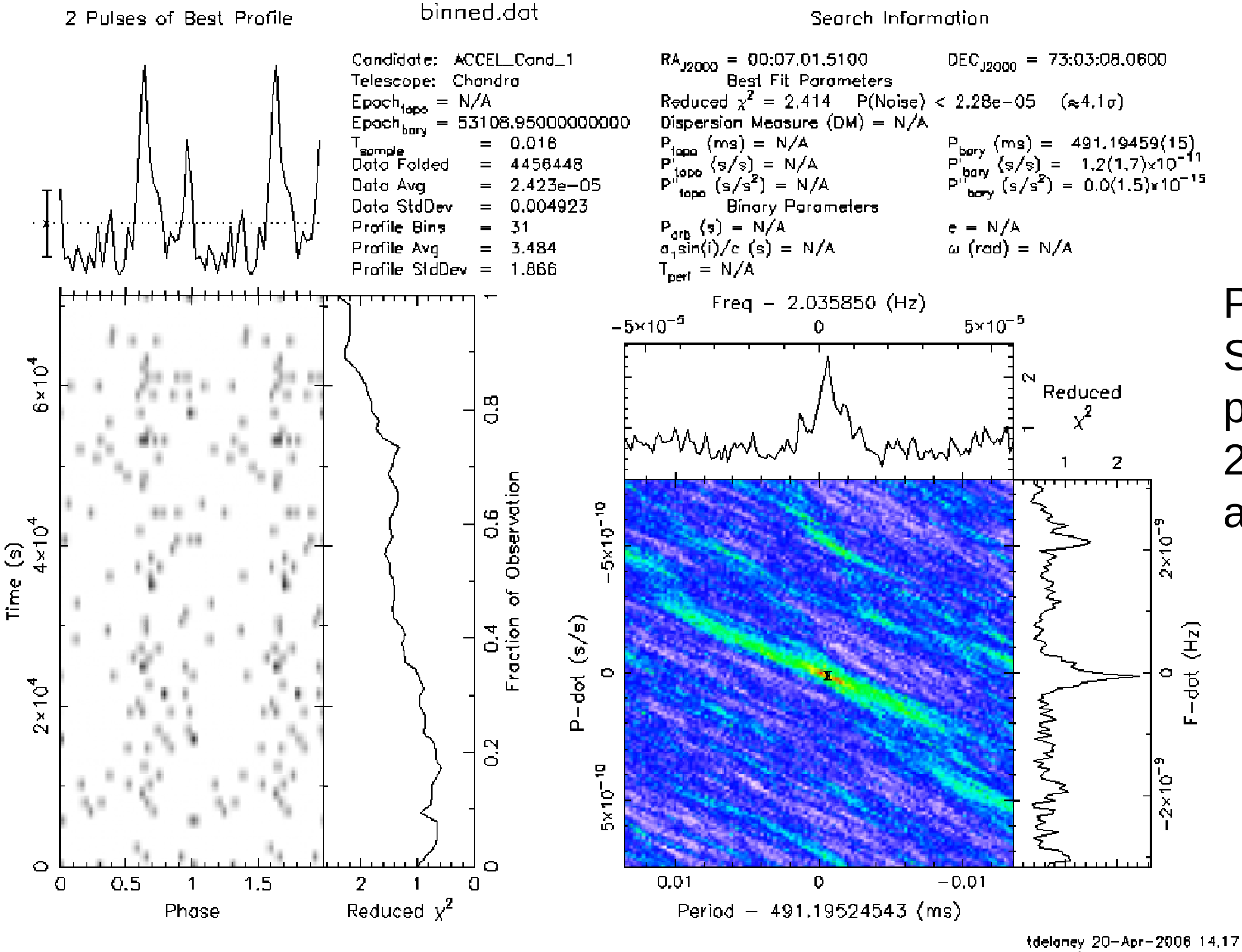
My first pulsar discovery!

(technically, Bryan, Pat, and Steve found it first)

Period=491.195 ms
Frequency=2.03585 Hz

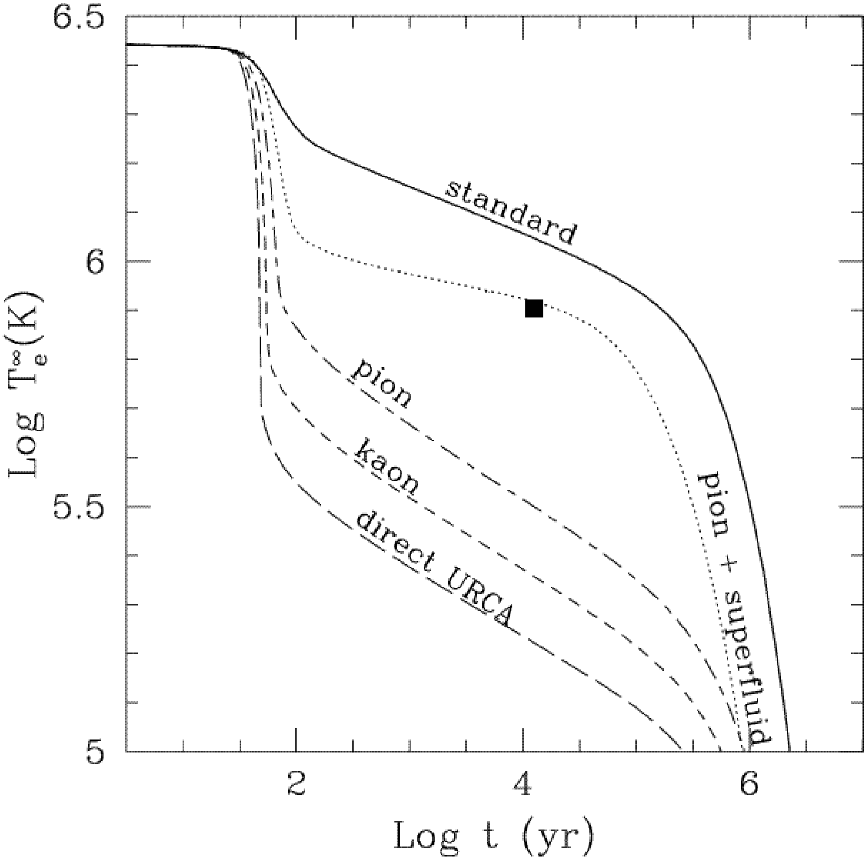
Off-pulse about 50% of time

CTA 1



PRESTO tools from S. Ransom also find pulsations at 2.03585 Hz at 4.1σ level

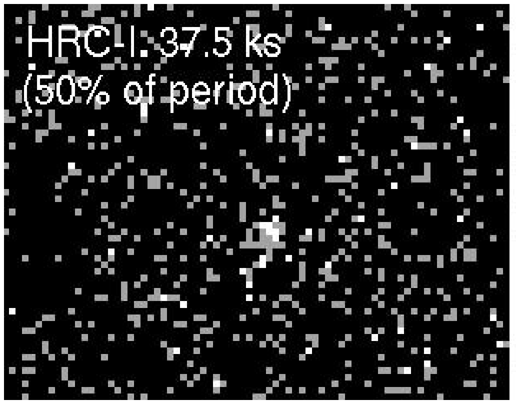
CTA 1



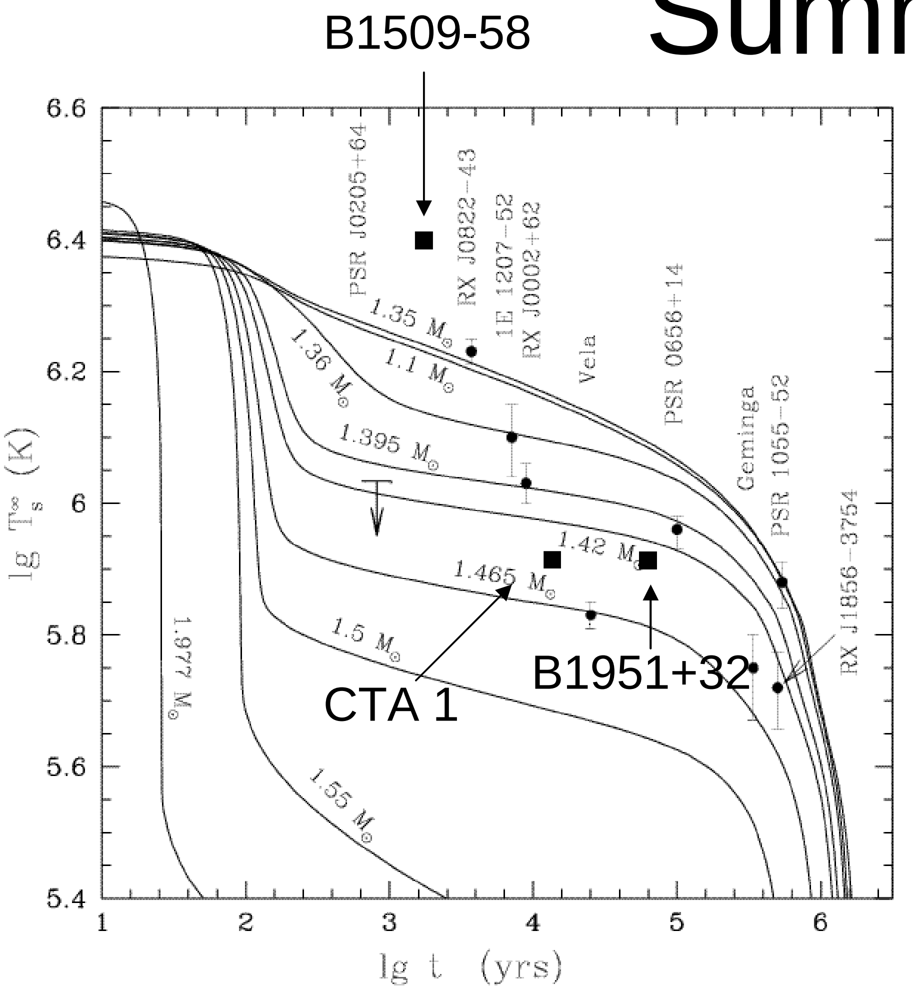
Using 32 off-pulse counts (6 background counts), the HRC count rate gives a blackbody temperature of **6.7×10⁵ K**

The upper limit using
largest distance
smallest radius (8 km)
highest N_H
and highest count rate
T=8.2×10⁵ K (kT=0.07)

Next step: confirm X-ray pulsations



Summary



Raised the upper temperature limits of all 3 sources

For B1509-58, strong off-pulse emission – probably from non-thermal origin

For B1951+32, no pulsations with HRC – a real puzzle considering the spectrum is dominated by a power law

For CTA 1, X-ray pulsations found!

Next step: consult theorists

Halpern et al 2004
Strong proton+weak neutron superfluidity