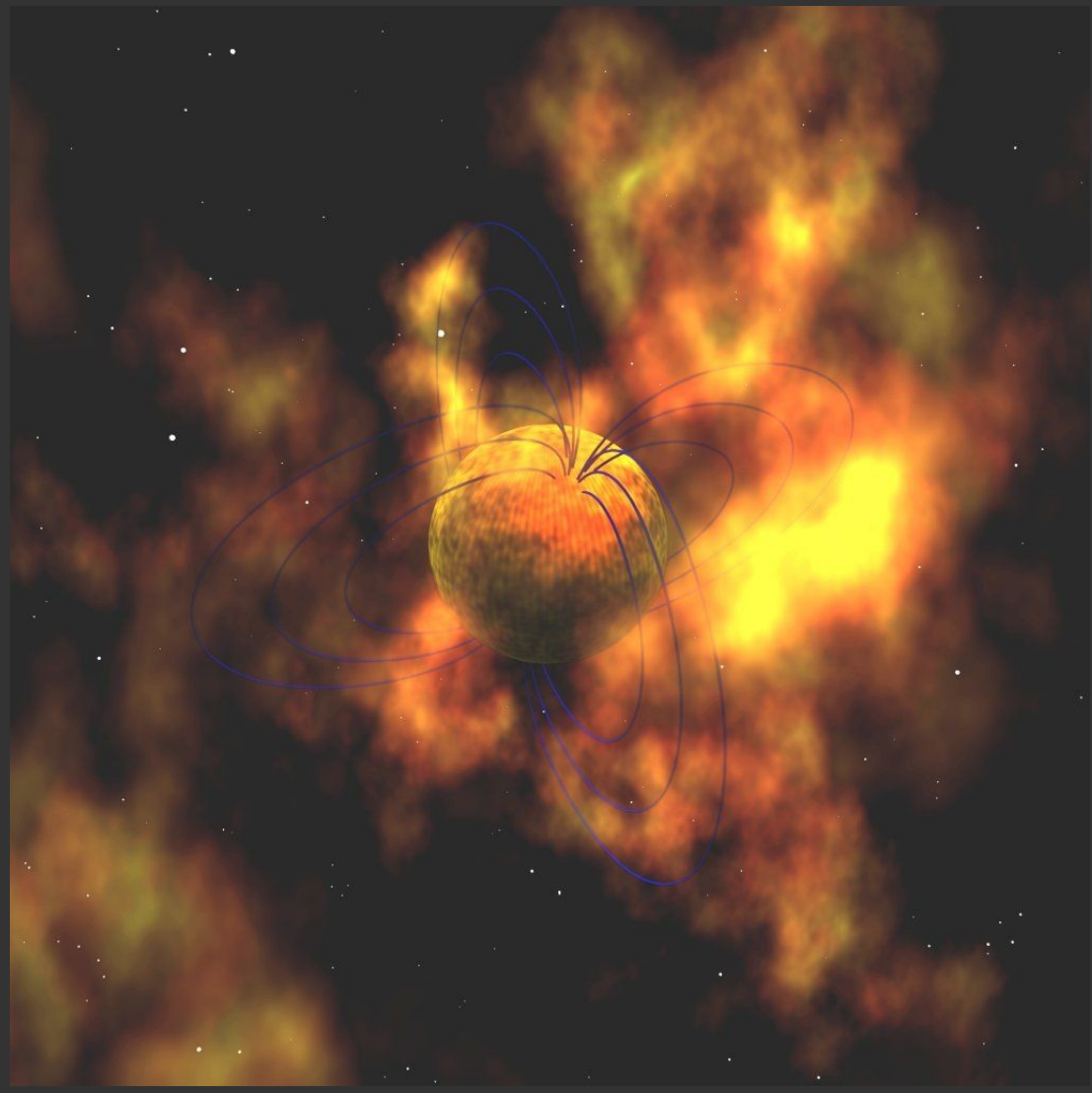
A Decade of Surprises from the Anomalous X-ray Pulsars

Scott Ransom

NRAO

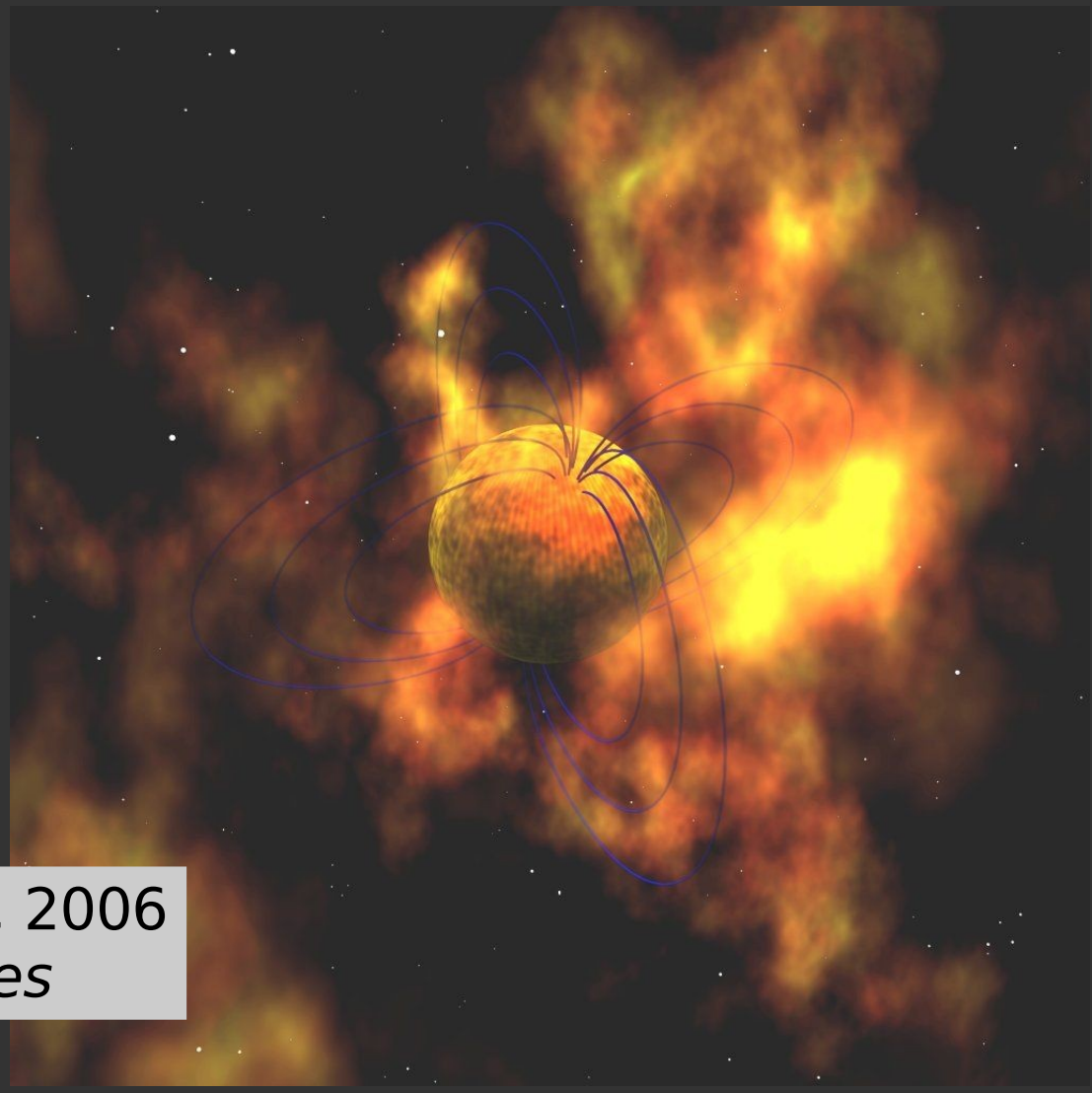


Credit: Robert Mallozzi and NASA

A Decade of Surprises from the Anomalous X-ray Pulsars

Scott Ransom

NRAO

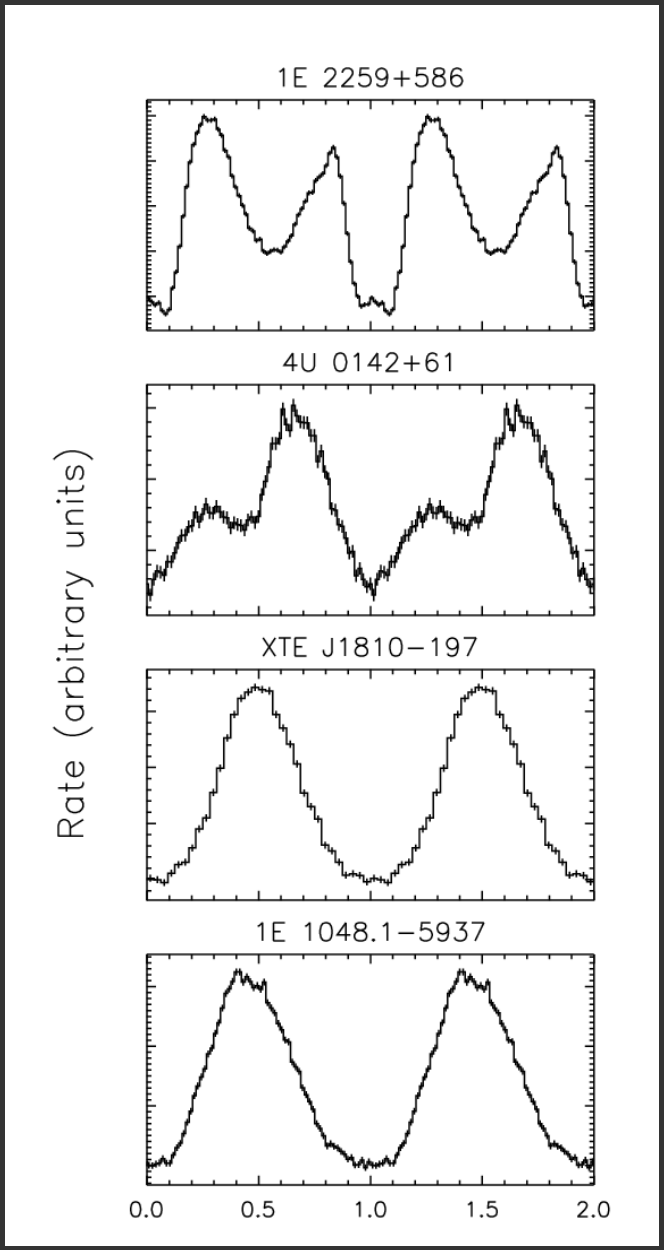


Credit: Robert Mallozzi and NASA

Review: Woods and Thompson, 2006
in *Compact Stellar X-ray Sources*

AXPs 10 years Ago

- 3-4 known (first Fahlman & Gregory 1981 in a SNR)
- 5-9 sec periods, spinning down (Koyama et al 1987)
  - young <10^5 yrs, B ~ 10^{15} Gauss
- L_x~$10^{34\text{-}35}$ erg/s (not spindown!)
- No doppler shifts
- Stable, persistent, soft X-ray flux
- Accretion powered? (fallback disks)? (Corbet et al 1995; van Paradijs 1995; Chatterjee, Hernquist & Narayan 2000) Or Magnetars?



What's a Magnetar?

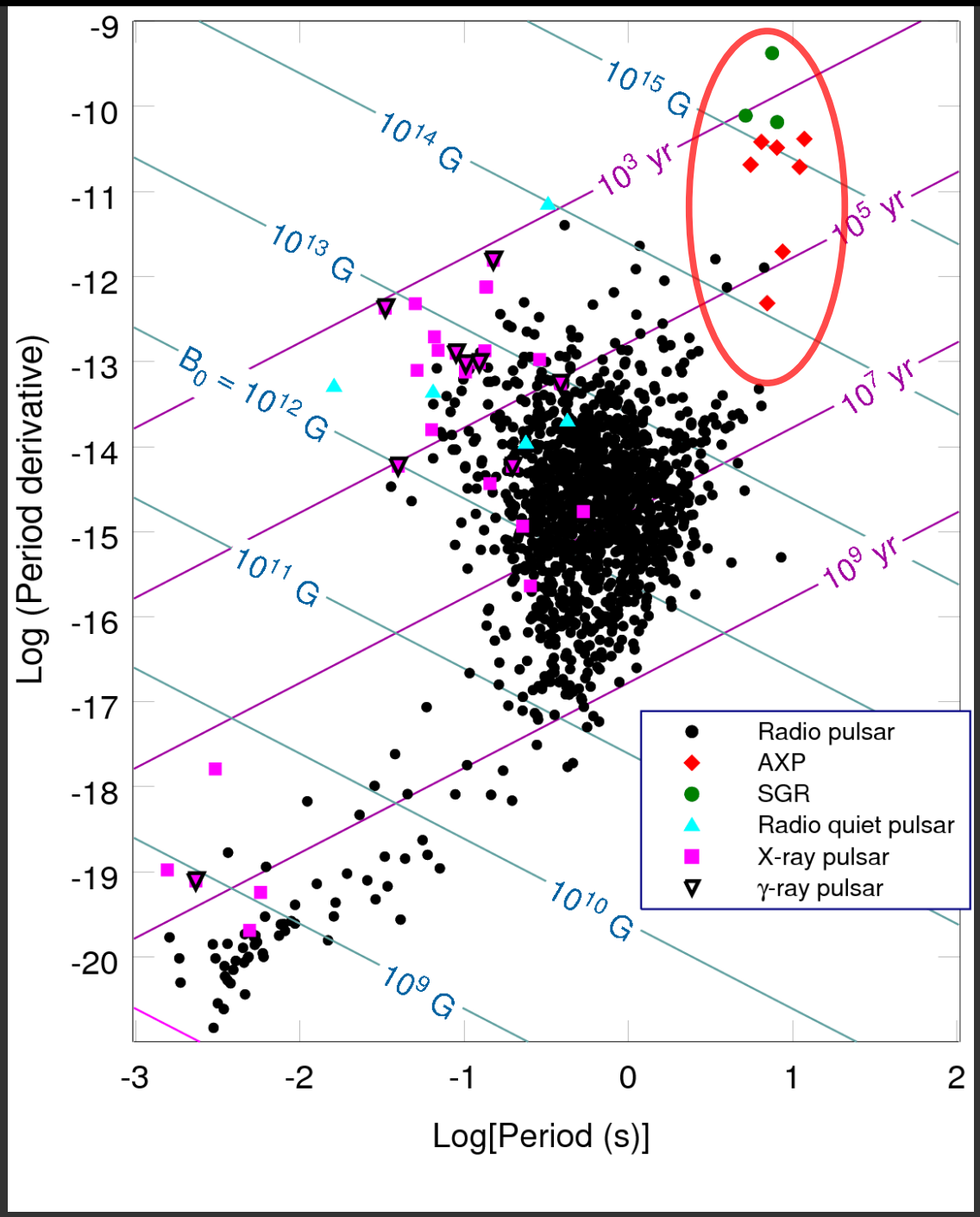
Neutron stars with $B \sim 10^{14\text{-}15}$ Gauss

- Soft Gamma-Ray Repeaters (SGRs)
- Anomalous X-ray Pulsars (AXPs)

Powered by decay of magnetic field

(Thompson & Duncan: '92, '93, '96, ...)

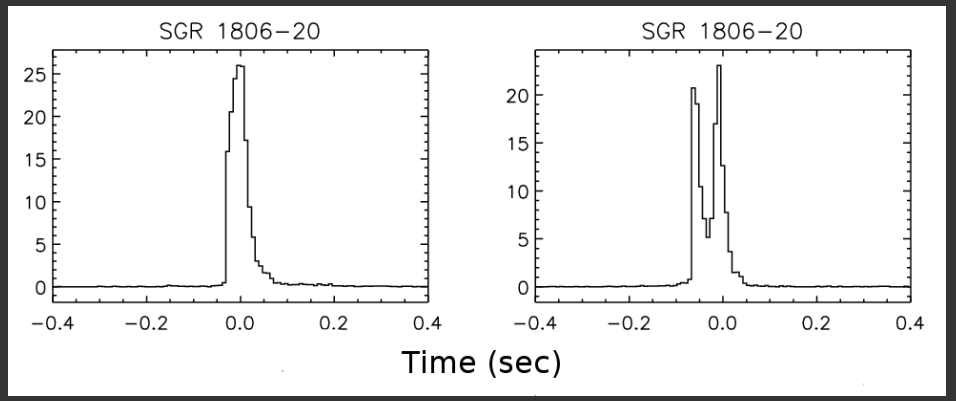
http://www.physics.mcgill.ca/~pulsar/magnetar/main.html

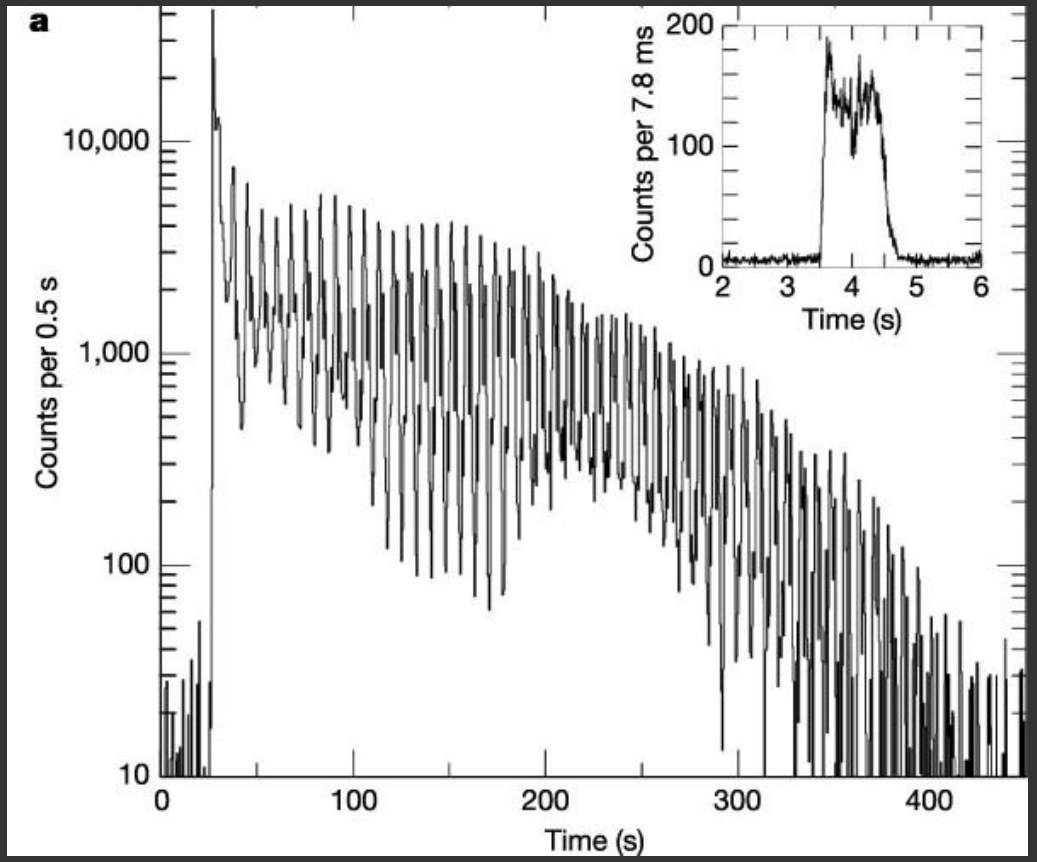


Credit: A. Harding, D. Lai

Soft Gamma-Ray Repeaters

- 4 known (1 in LMC)
- Young (1 in SNR)
- 5-9 sec spins
- Soft BB+PL spectra
- X-ray bursts
- Giant flares
- Often quiescent
- When active, L_x ~ 1-5x10^{35} erg/s



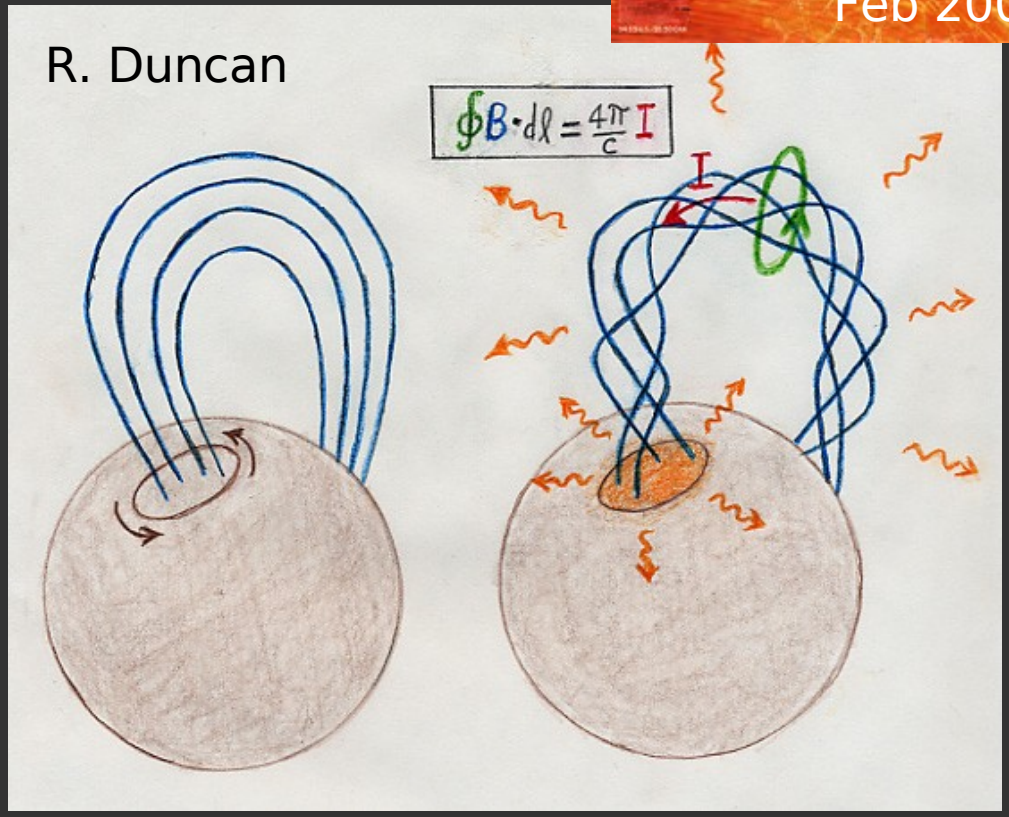


Hurley et al 2005 (RHESSI Data)

How do magnetars work?

- ~10^{15} G magnetic fields created by strong dynamo when hot newborn NS rotates at ms rates
- Wound-up internal field
- External magnetic field causes rapid spin-down
- Field decay heats deep crust and core causing rapid drift of field lines
- Elastic deformation of crust twists and deforms magnetic field
- Reconnection events
- Currents heat surface

R. Duncan & C. Thompson 1992, 1996, 2001 etc.

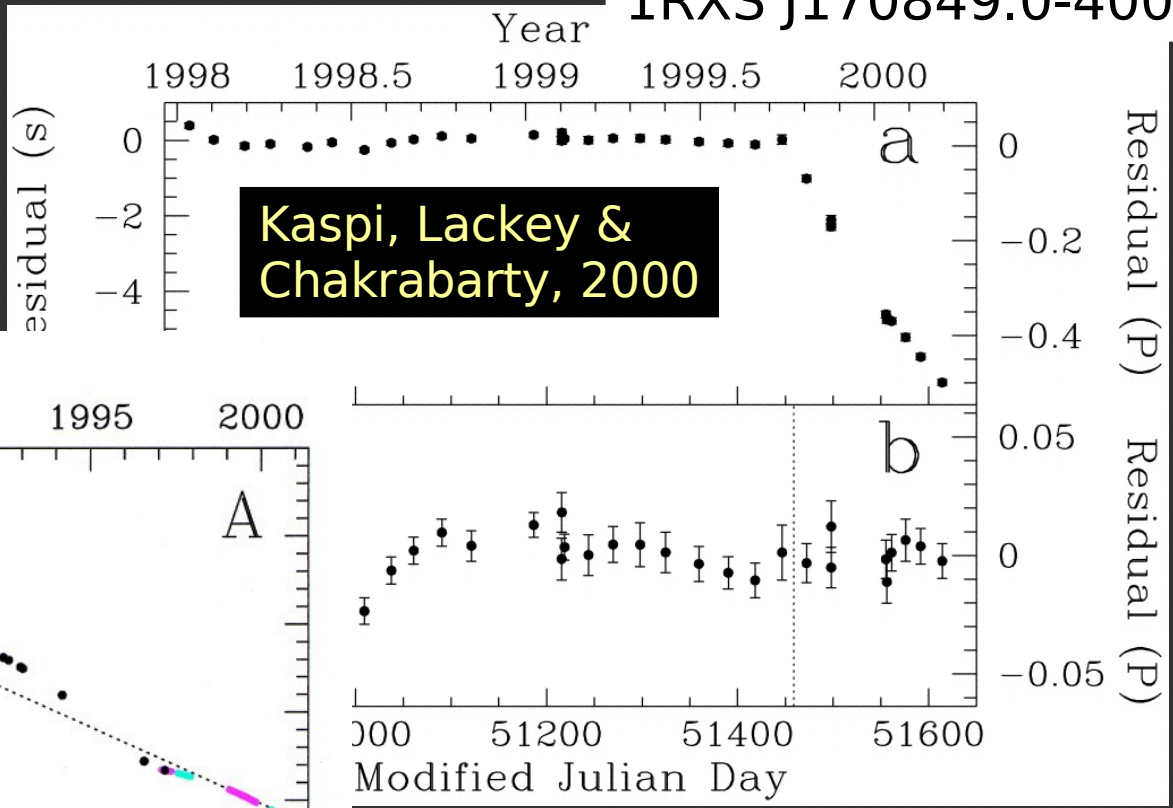


http://solomon.as.utexas.edu/~duncan/magnetar.html

Magnetar Timing with RXTE

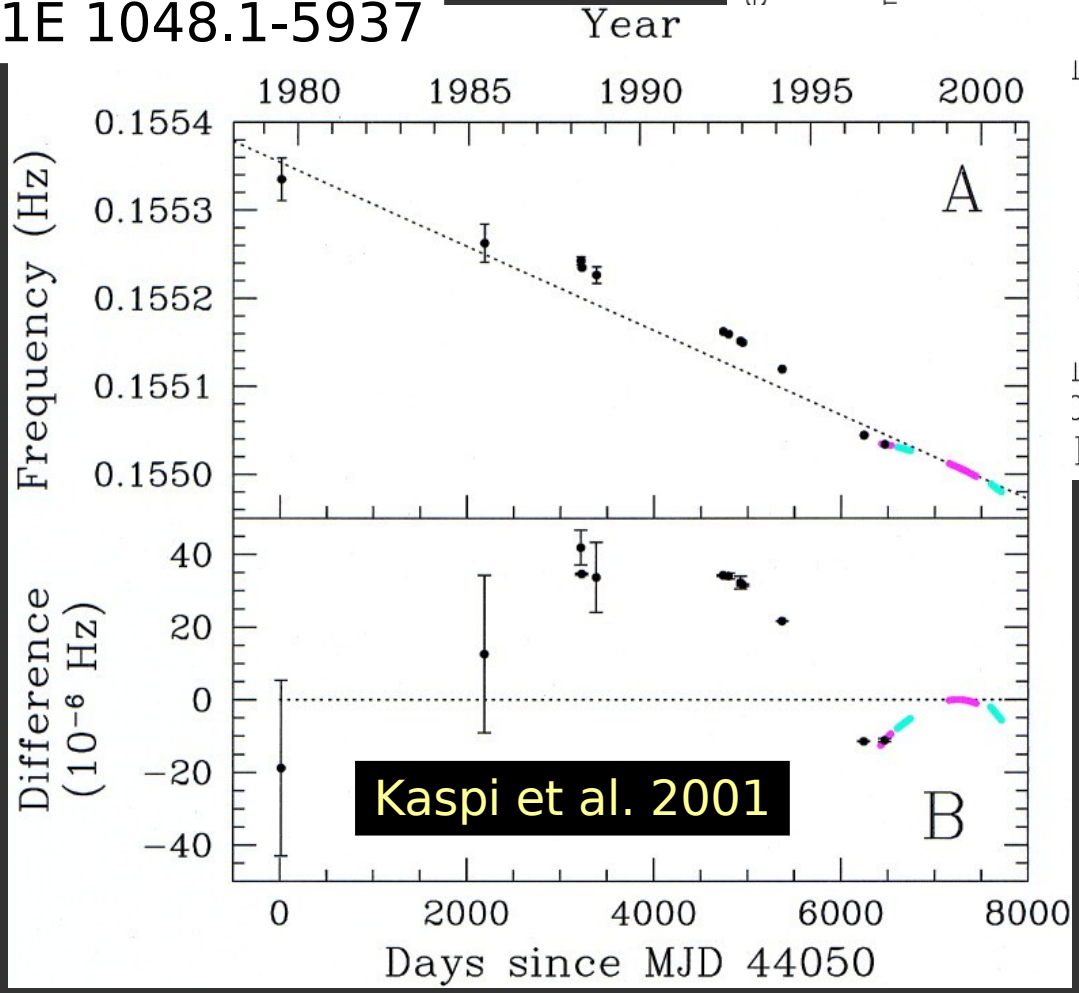
Key: Near-weekly monitoring

1RXS J170849.0-400910



Glitch

1E 1048.1-5937



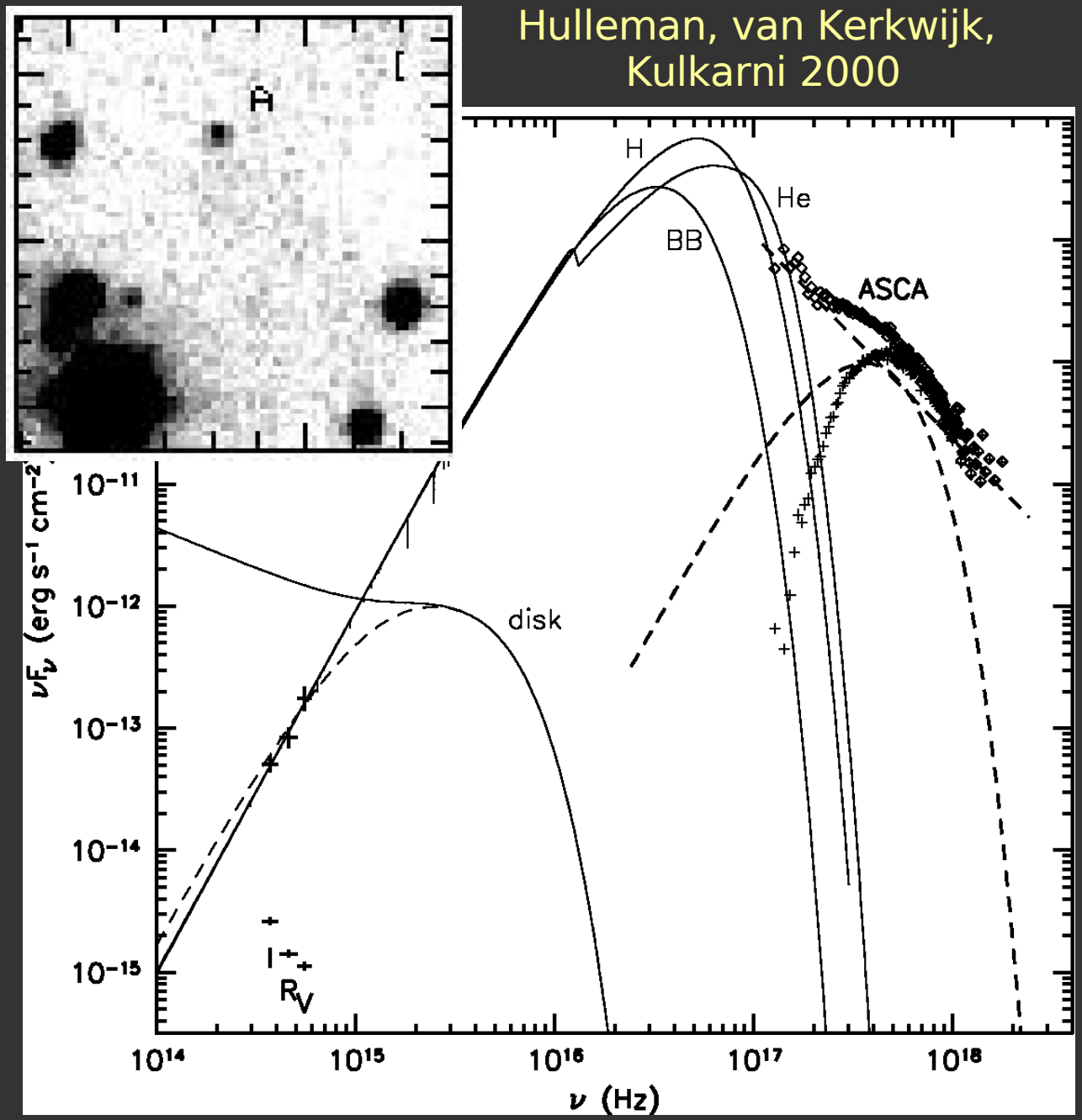
Timing noise

Expected behavior for magnetar model

Optical Detection of 4U 0142+61

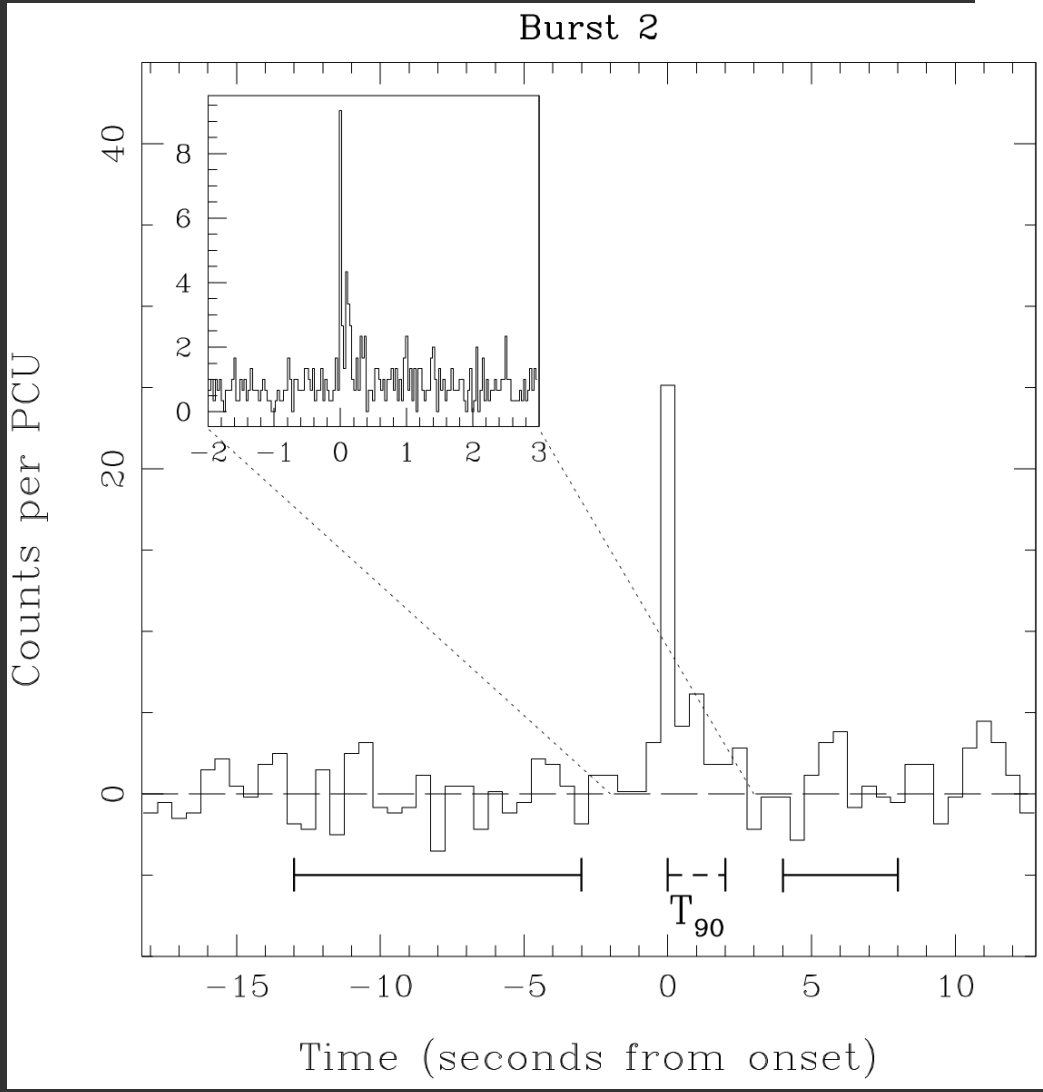
- Faint counterpart with strange colors (since then many more detections)
- Not bright enough for a large disk
- Optical pulsations with large (~27%) pulsed fraction (Kern & Martin 2002)

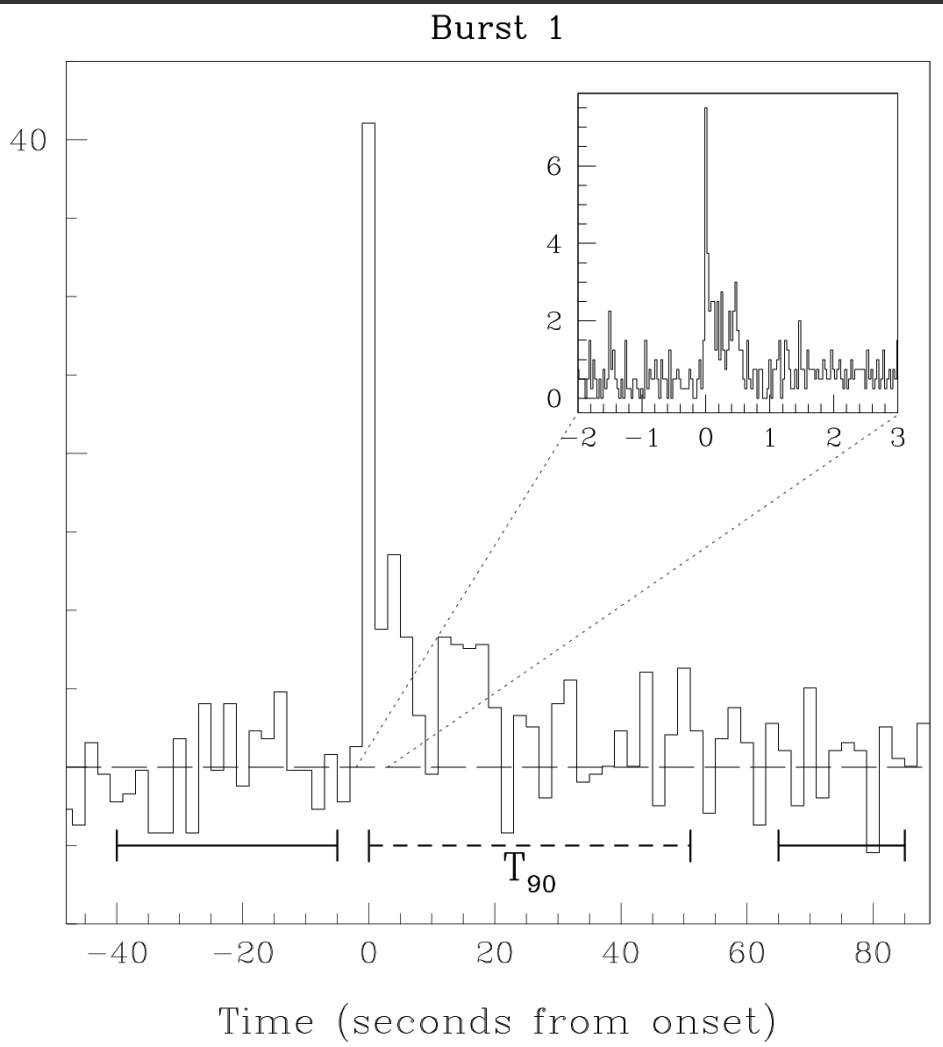
Hulleman, van Kerkwijk, Kulkarni 2000



SGR-like X-ray Bursts

- 2 small bursts from 1E 1048.1-5937

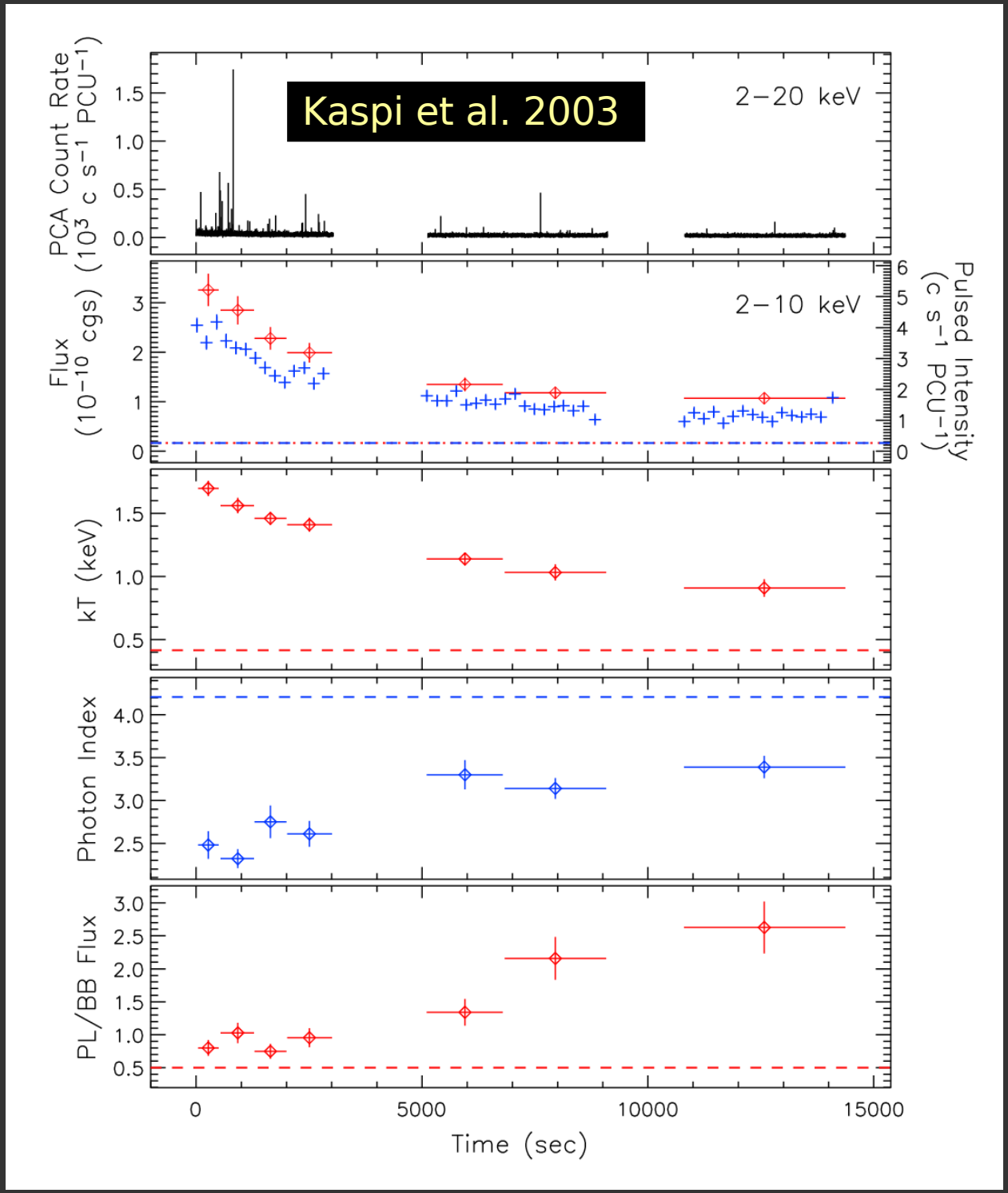




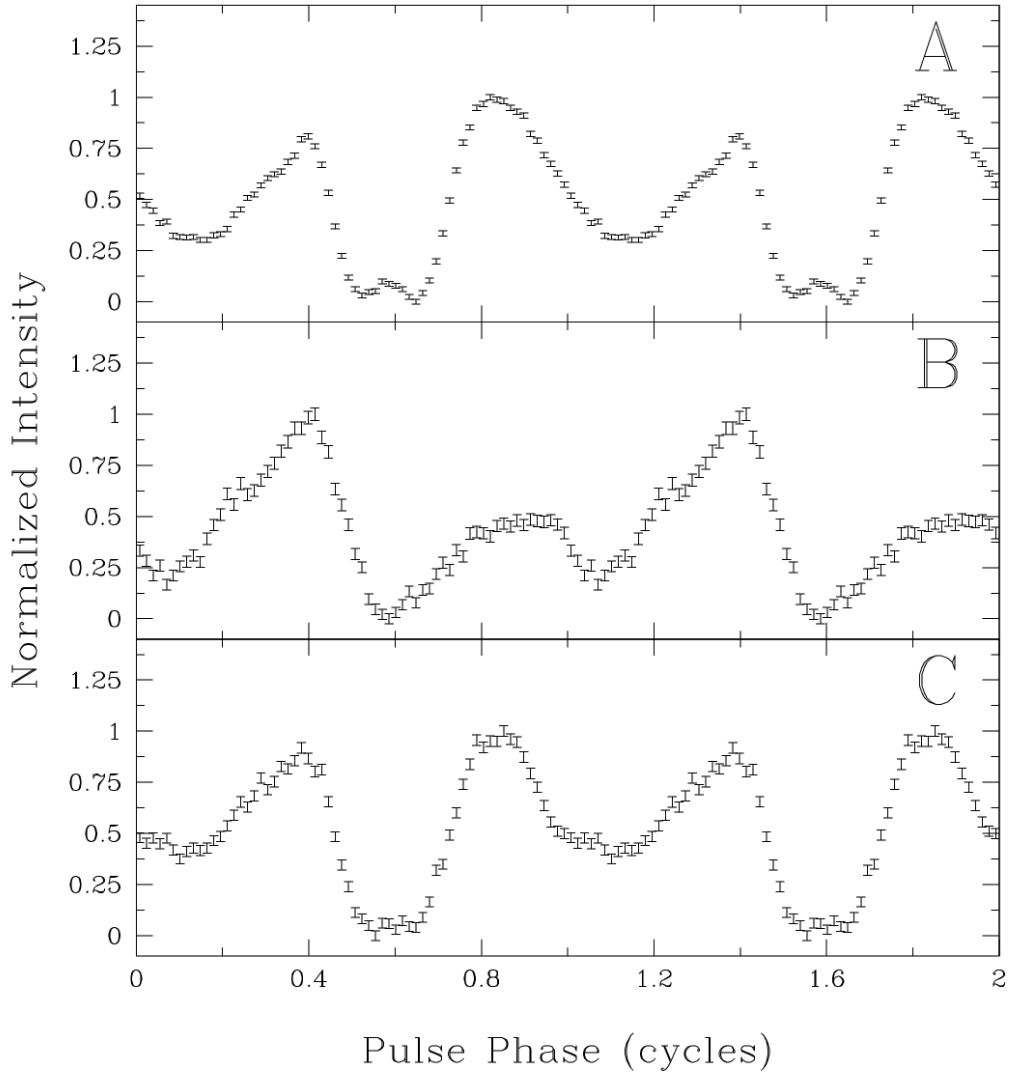
Gavriil, Kaspi, & Woods, 2002

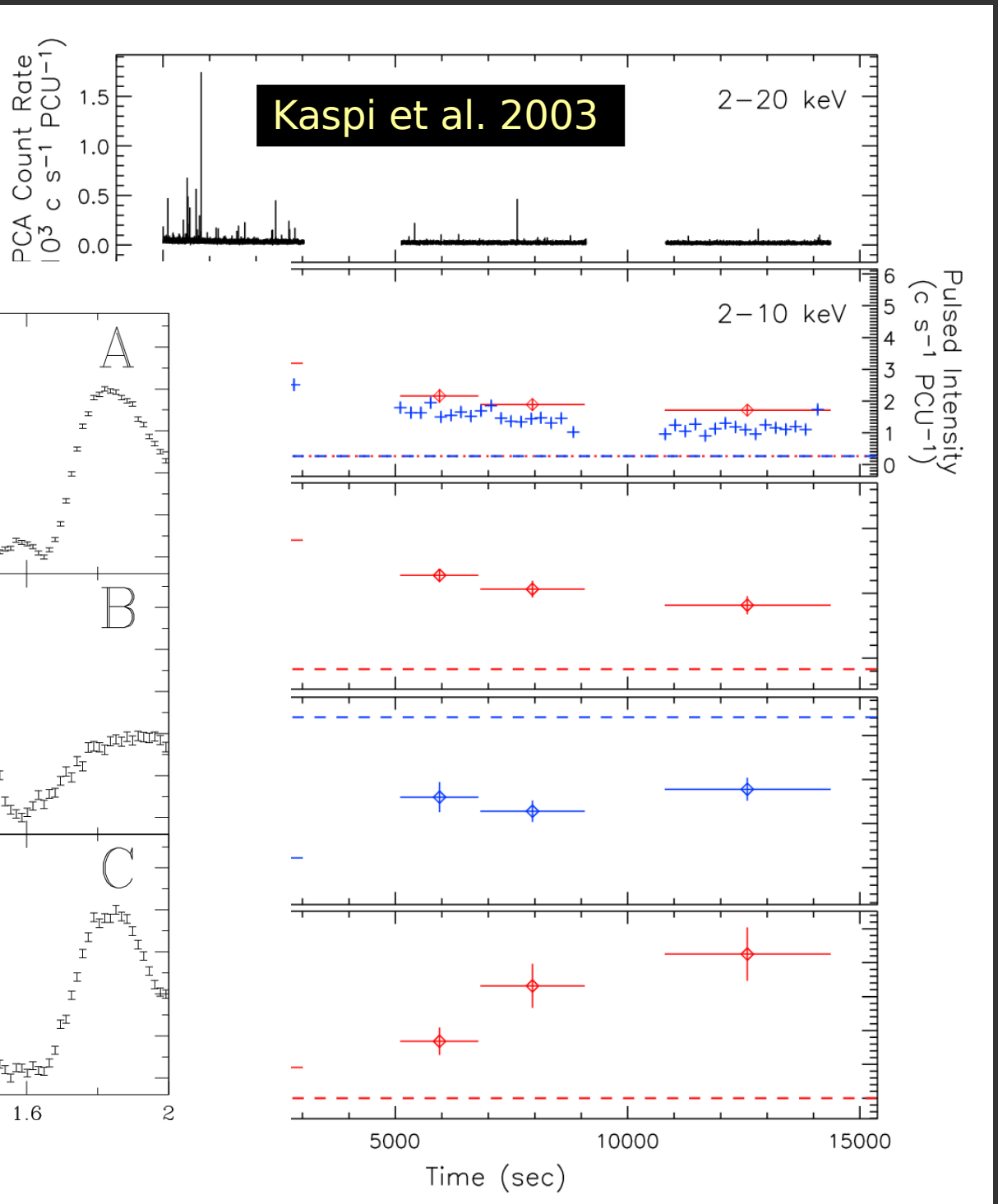
SGR-like Outbursts

- 80+ bursts ~11ks from 1E 2259+586
- Correlated changes in other X-ray properties



SGR-like Outbursts

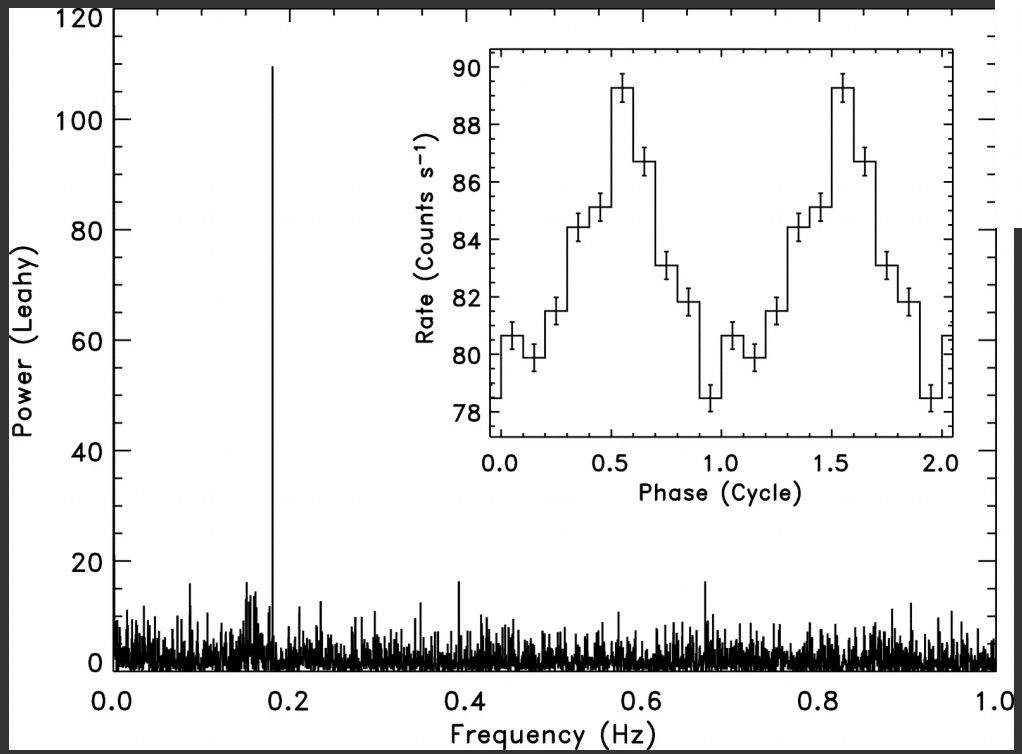


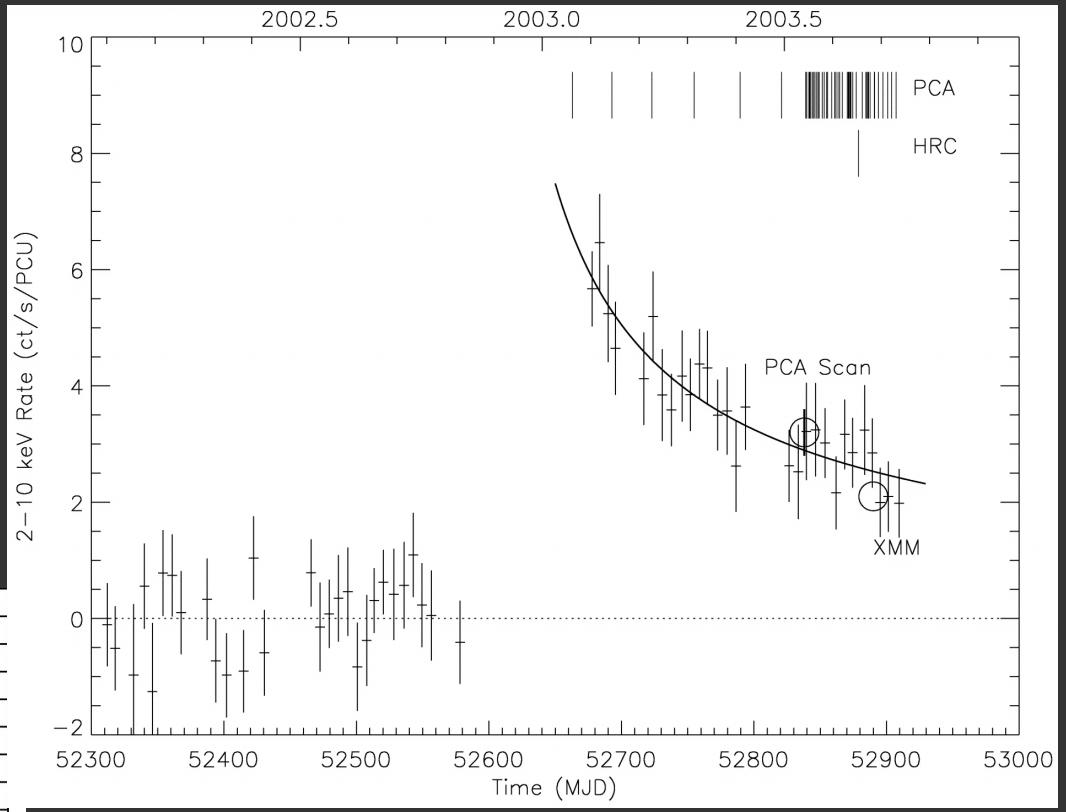


Transient AXP XTE J1810-197

- Oct 2003 X-ray outburst (100x quiescent lumin)
- 5.54 sec pulsations
- Very noisy spin-down

B~3x10^{14}G, Age < 10^{4} yrs

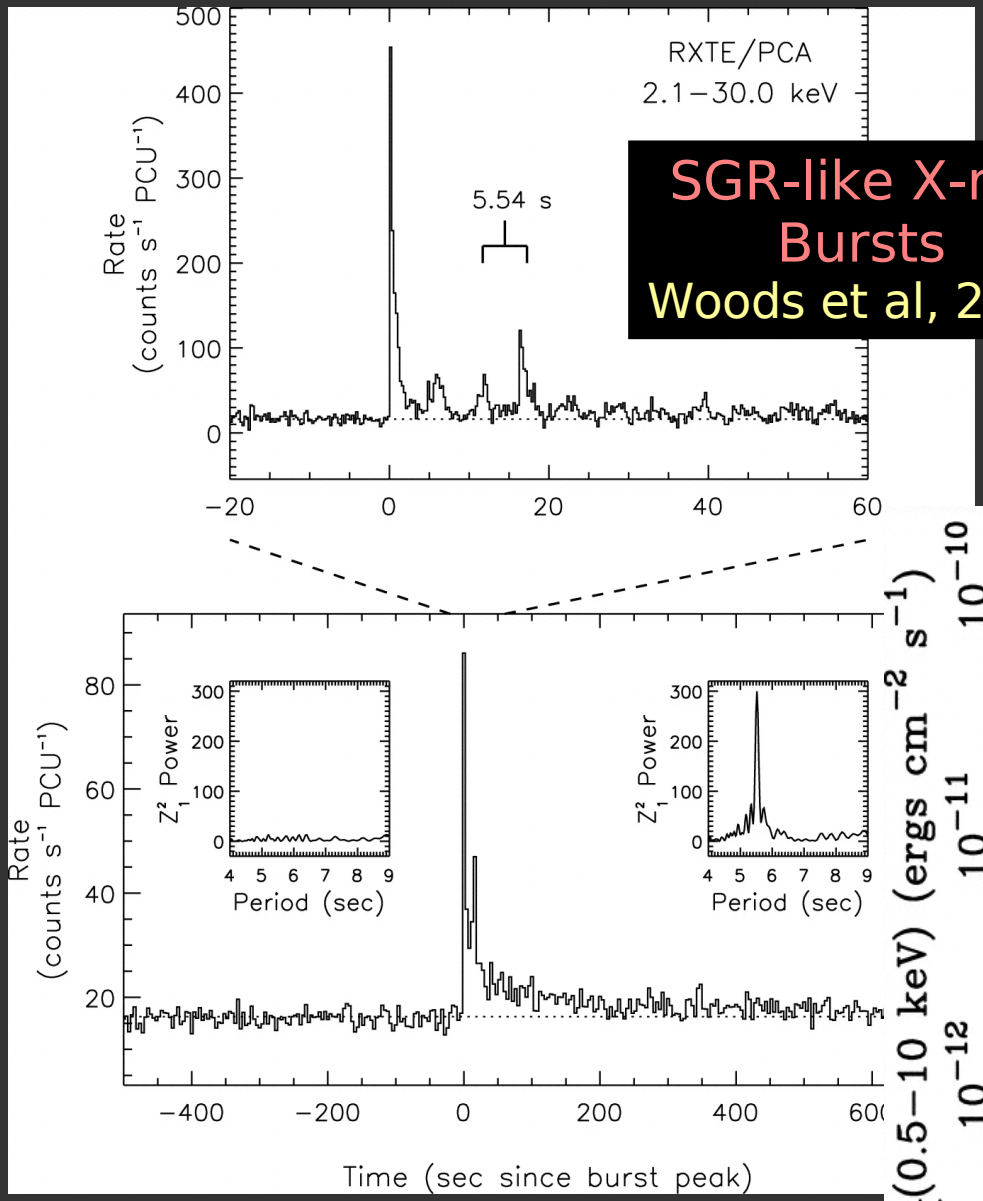




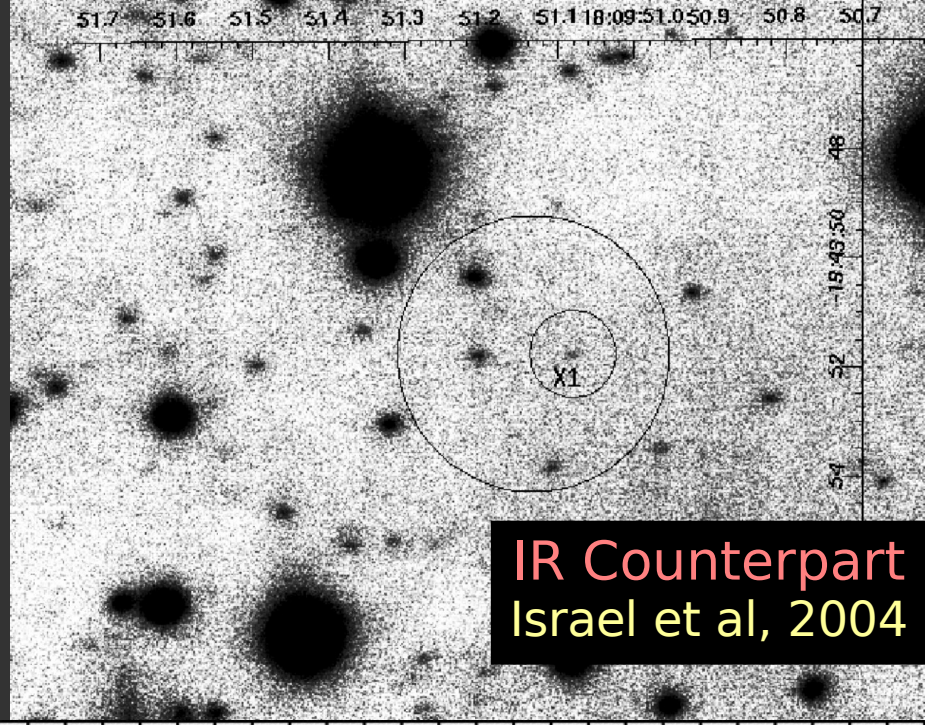
How many more of these are out there?

Ibrahim et al, 2004

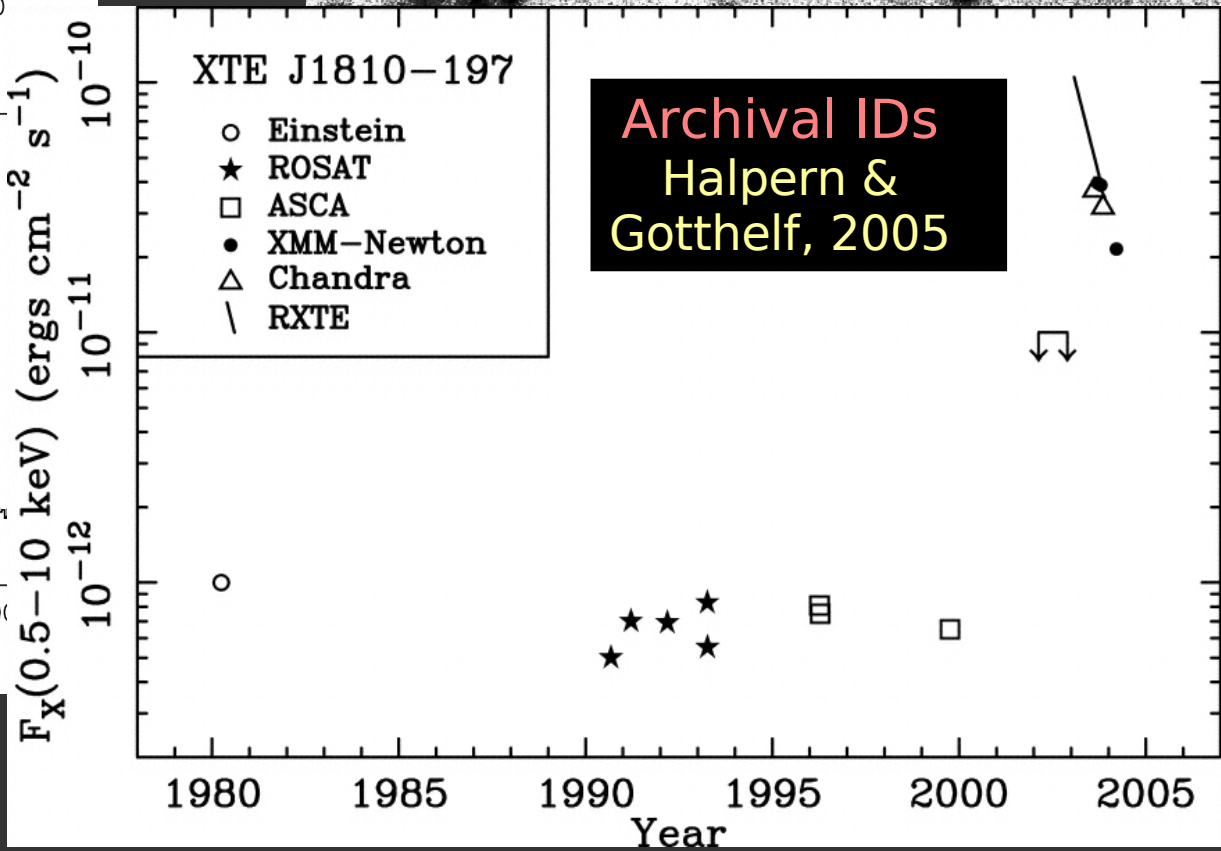
XTE J1810-197



SGR-like X-ray Bursts
Woods et al, 2005



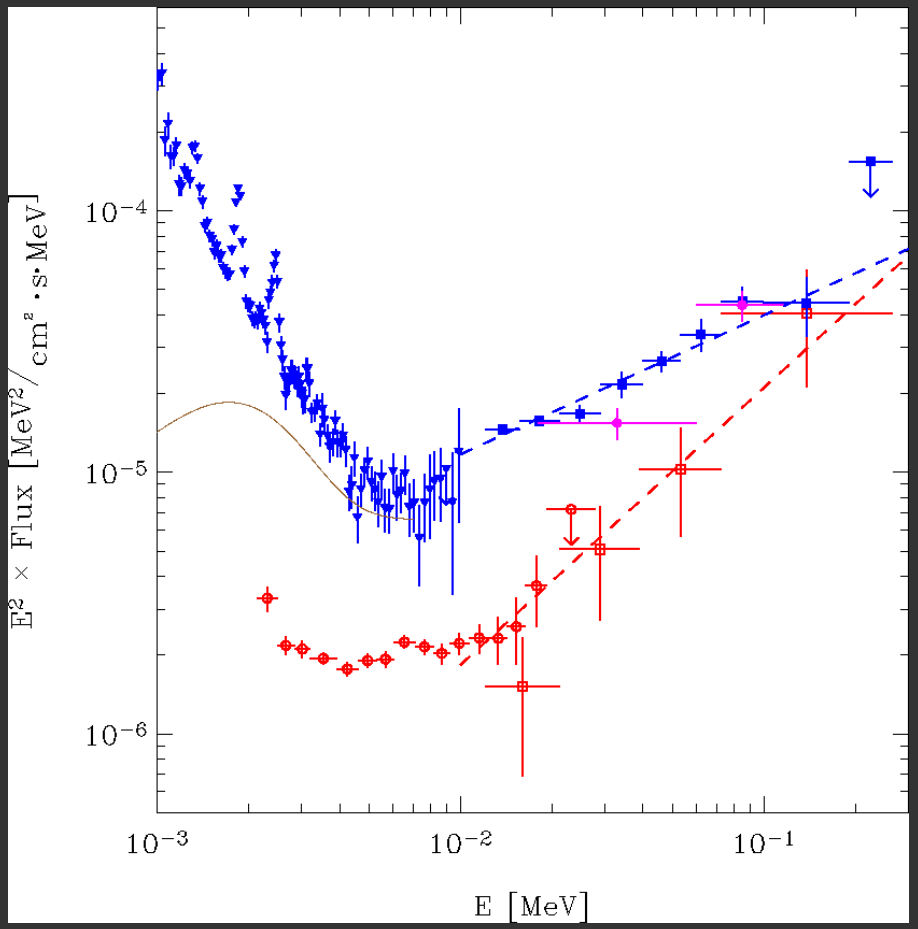
IR Counterpart
Israel et al, 2004

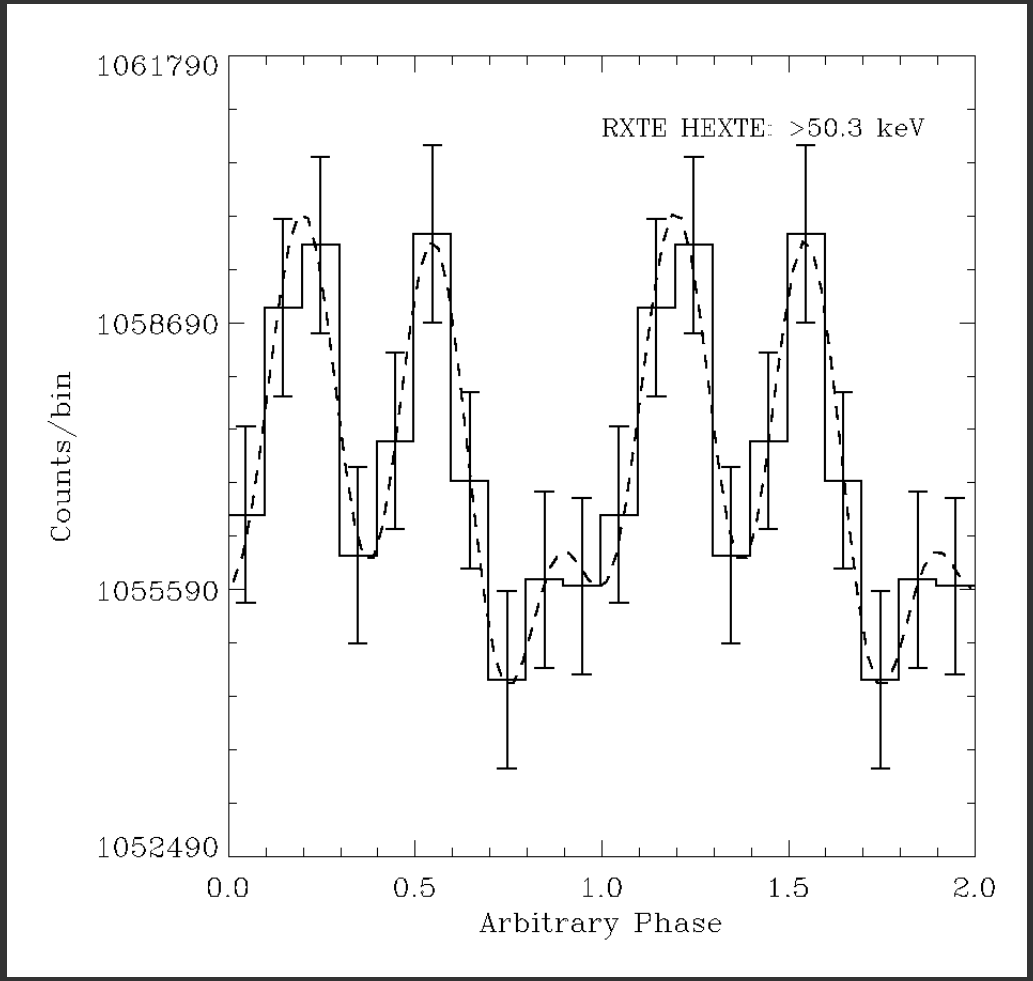


Archival IDs
Halpern & Gotthelf, 2005

Hard Non-thermal X-ray Emission

- Using HEXTE, found 10-150 keV flux for AXP 1E 1841-045 in Kes 73
- Likely magnetospheric





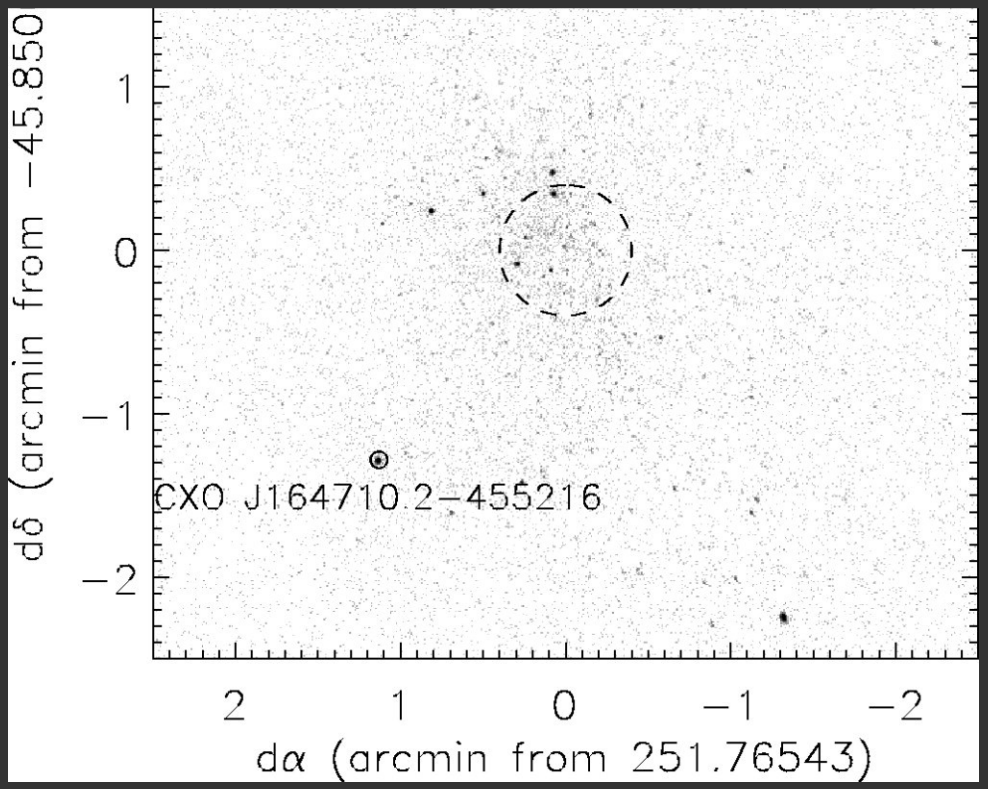
Kuiper, Hermsen & Mendez 2004

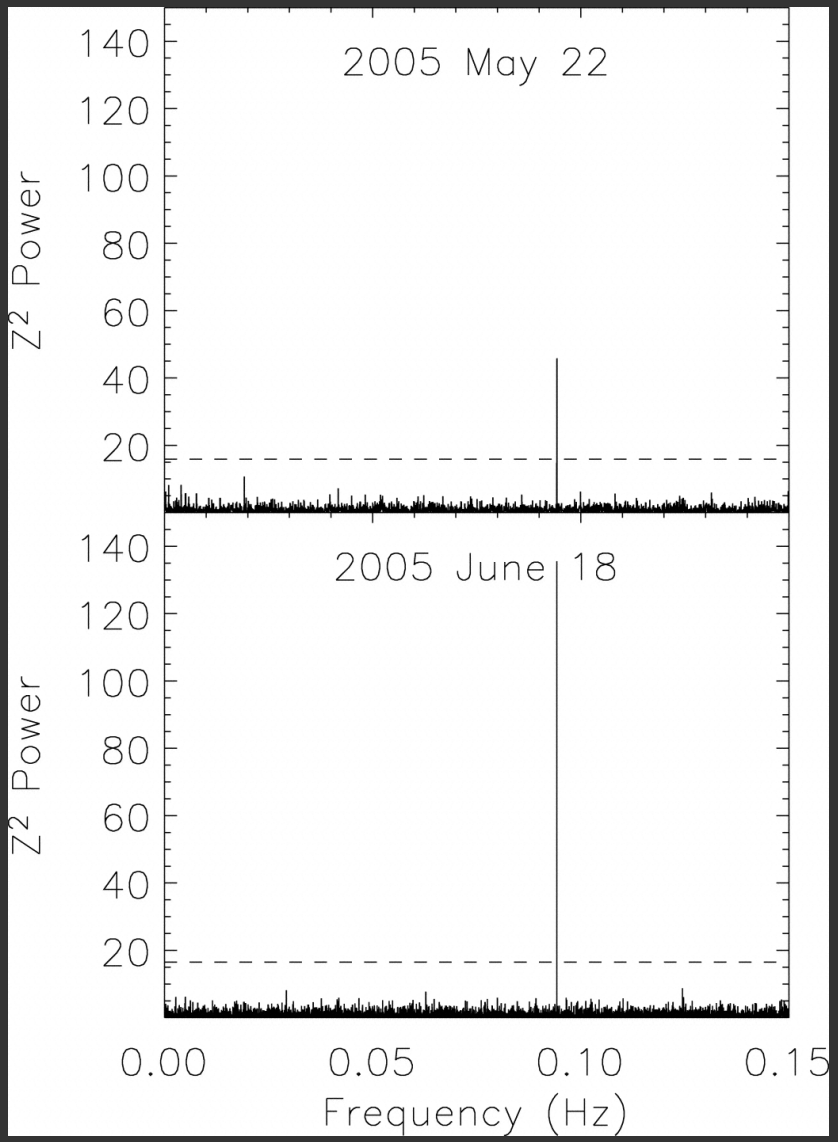
Since then, at least 3 more (Kuiper et al 2006)

AXP in Young Cluster Westerlund 1

- Serendipity with *Chandra*
- 10.6s likely AXP in massive O-star cluster with age 4+/-1 Myr
- AXP progenitor >40 M_{sun}?

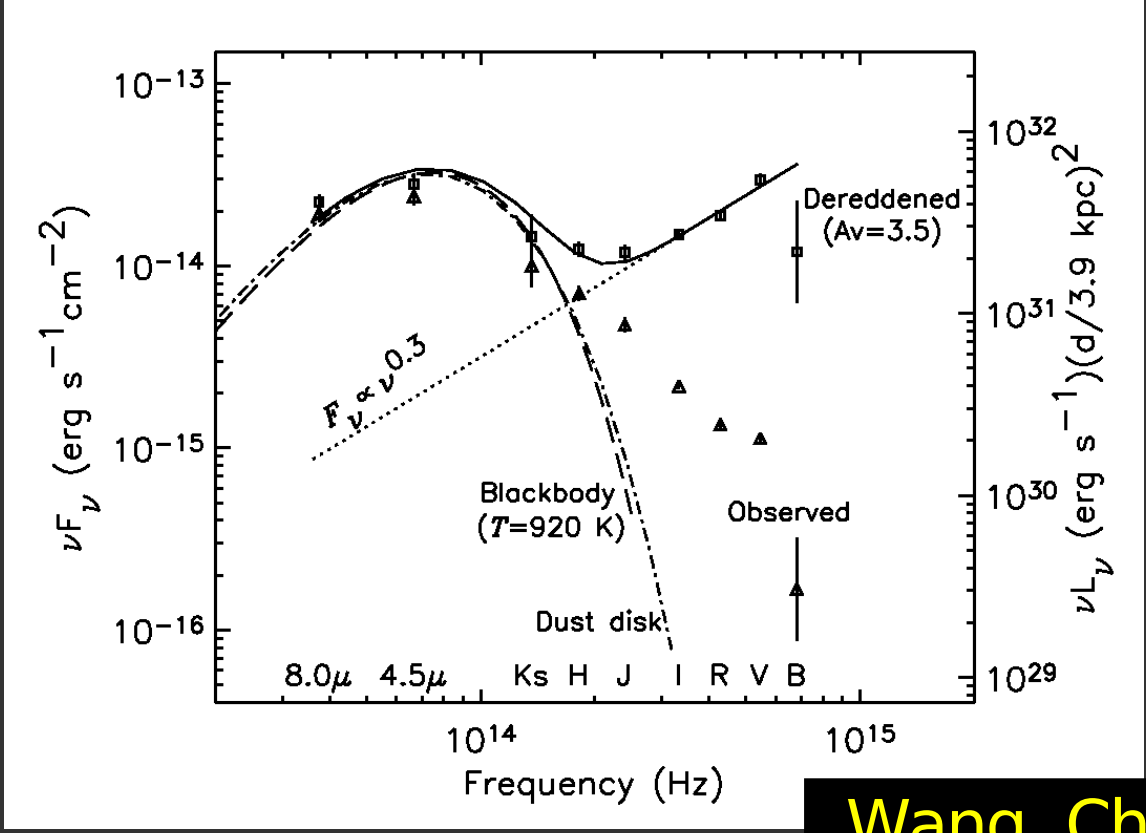
Muno et al. 2006

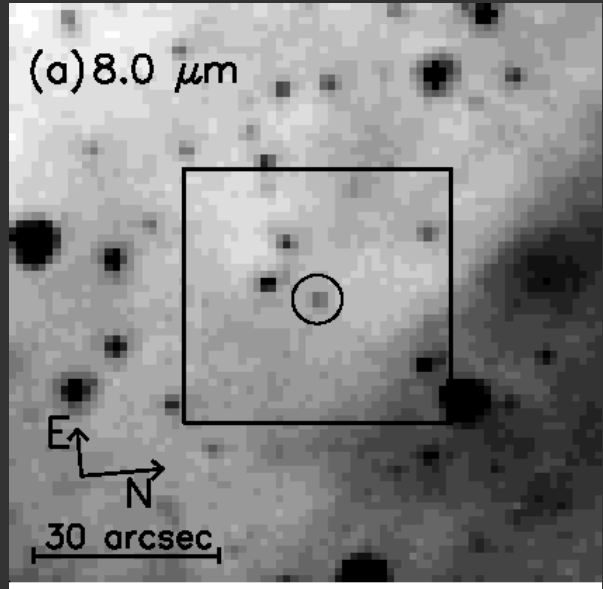


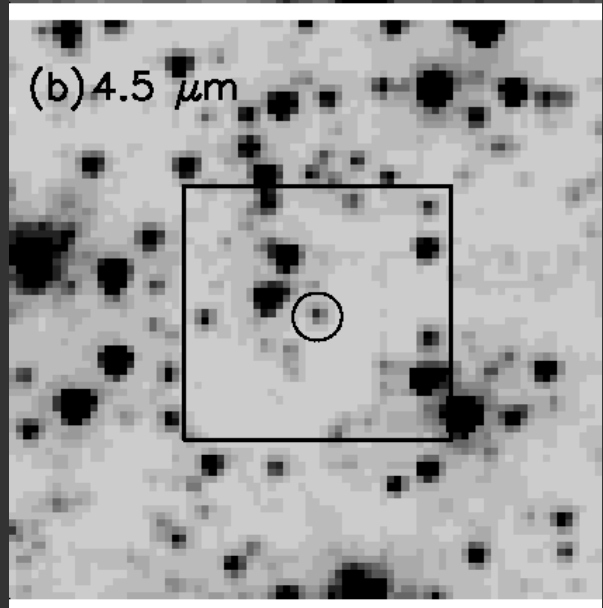


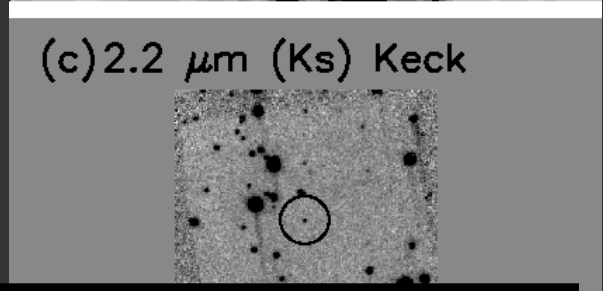
Debris Disk around 4U 0142+61

- *Spitzer* detection of likely fallback disk (~10 M_{earth})
- Does not power AXP
- NS planet formation?





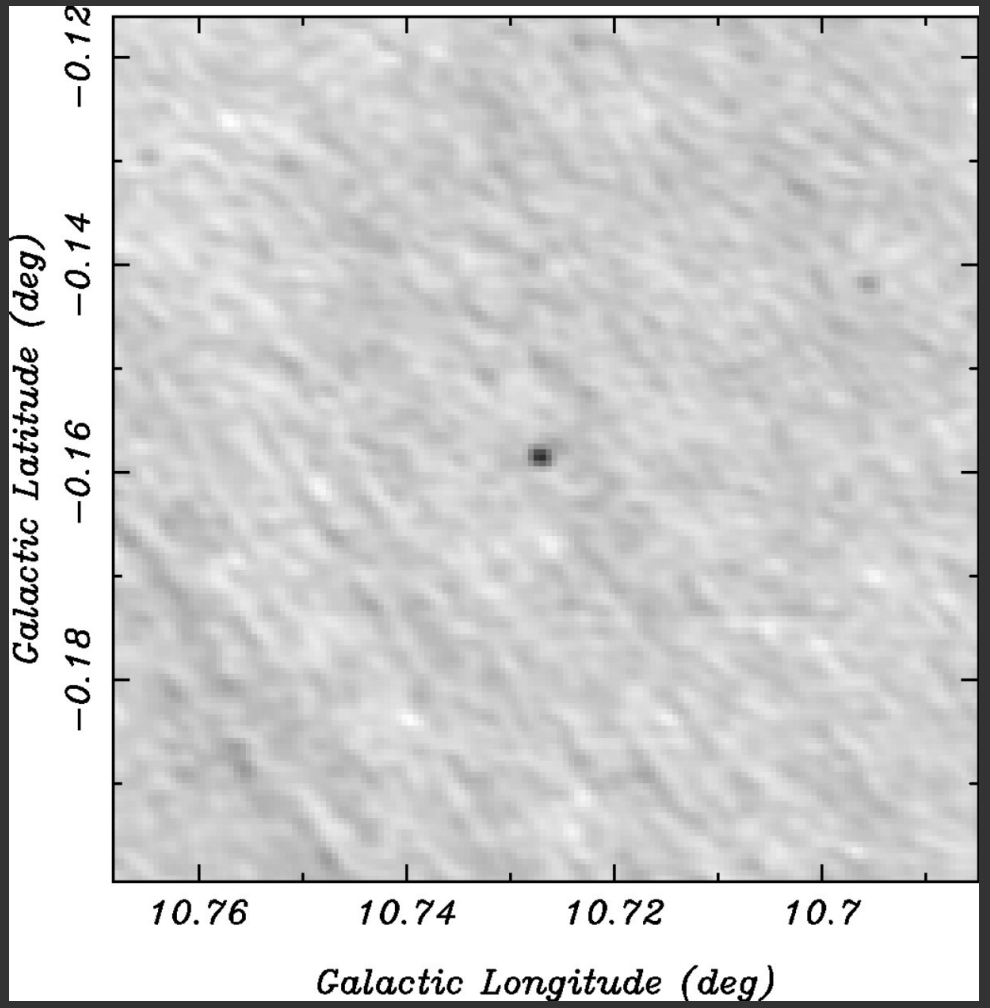




Wang, Chakrabarty & Kaplan 2006

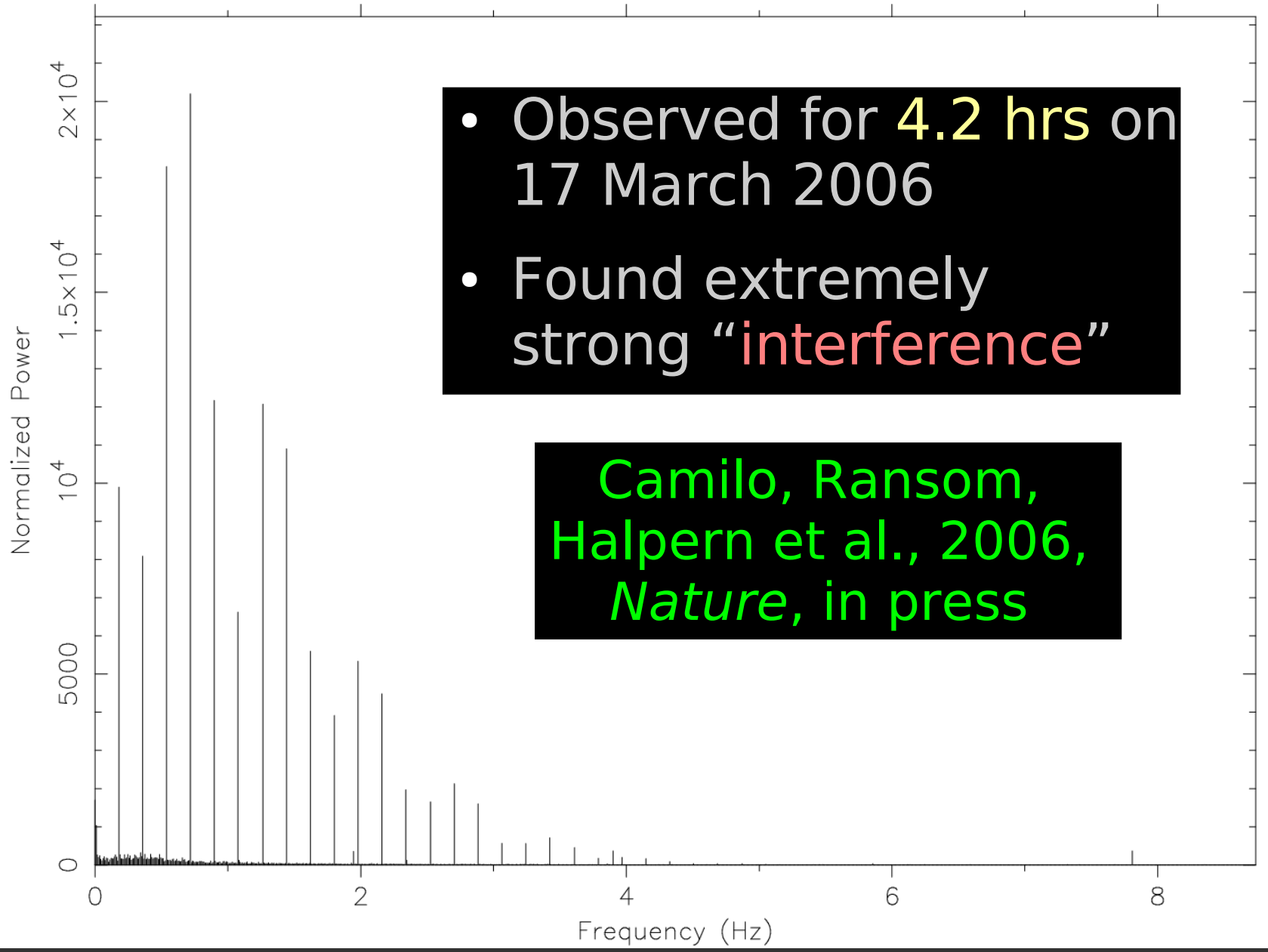
XTE J1810-197 VLA Radio Detection

- Halpern et al., (2004): a 4.5 mJy point source at 1.4 GHz in Jan 2004
- Not detected in Parkes Multibeam PSR Survey ($S_{min} < 0.2$ mJy)
- Attributed to either afterglow or PWN
- No other persistent radio emission has been detected from a magnetar (e.g. Burgay et al. astro-ph/0607614)



Follow-up VLA 1.4 Ghz observations in Feb 2006 found the source at 12.6 mJy

Parkes Observation



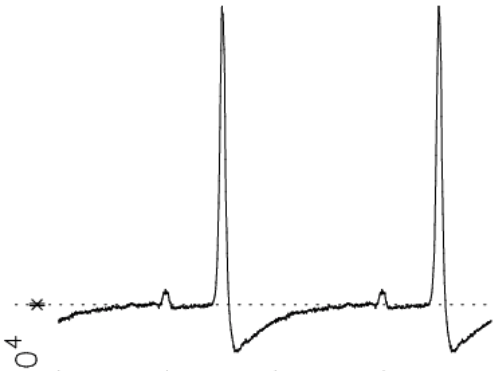
- Observed for 4.2 hrs on 17 March 2006
- Found extremely strong "interference"

Camilo, Ransom, Halpern et al., 2006, *Nature*, in press

2 Pulses of Best Profile

DMT002_2201.pkmb

Search Information



Candidate: 5540.21ms_Cand
Telescope: Parkes Multibeam
$Epoch_{topo}$ = 53811.86494212963
$Epoch_{bary}$ = 53811.86514953652
T_{sample} = 0.00025
Data Folded = 60817408
Data Avg = 50.49
Data StdDev = 4.864
Profile Bins = 512
Profile Avg = 5.996e+06
Profile StdDev = 1676

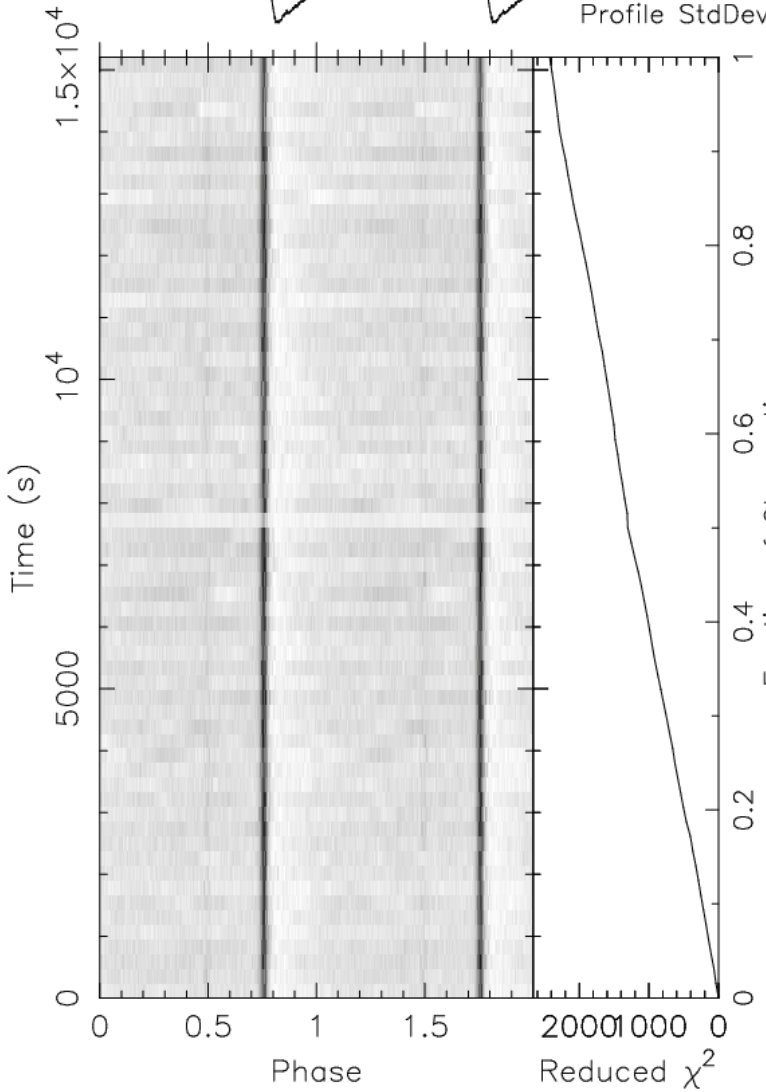
RA_{J2000} = 18:09:51.0980 DEC_{J2000} = −19:43:52.0200

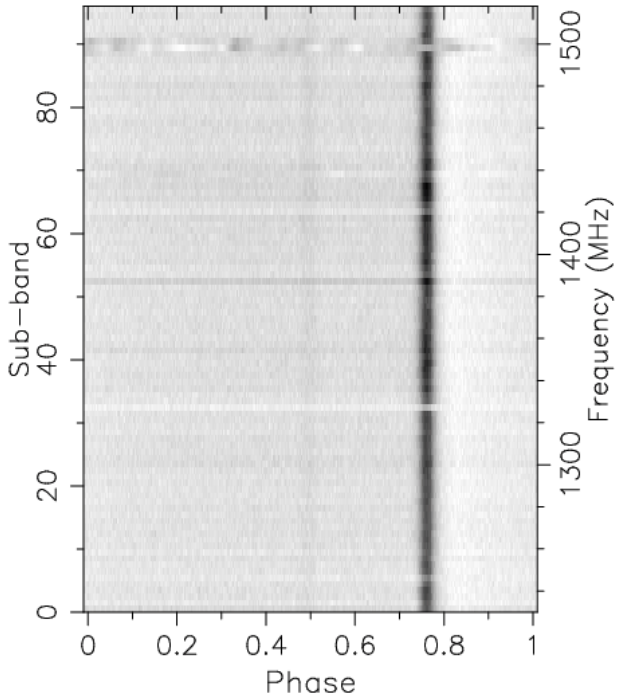
Best Fit Parameters

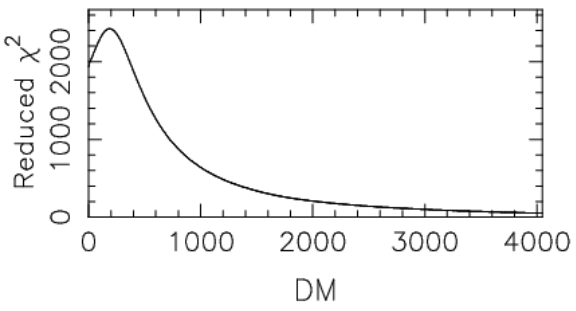
Reduced χ^2 = 2423.224 P(Noise) ~ 0
Dispersion Measure (DM) = 189.782
P_{topo} (ms) = 5539.66196(56) P_{bary} (ms) = 5540.21000(56)
P'_{topo} (s/s) = 5.3(2.9)x10^{-10} P'_{bary} (s/s) = 0.0(2.9)x10^{-10}
P''_{topo} (s/s^2) = 0.0(1.2)x10^{-13} P''_{bary} (s/s^2) = 0.2(1.2)x10^{-13}

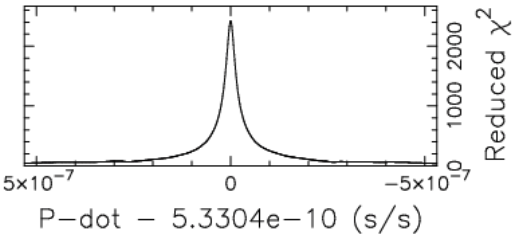
Binary Parameters

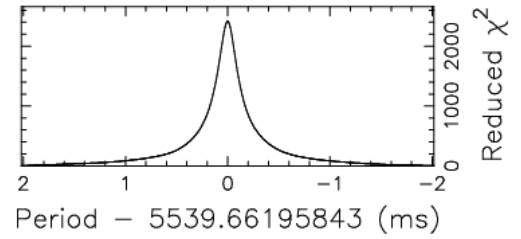
P_{orb} (s) = N/A e = N/A
$a_1 \sin(i)/c$ (s) = N/A ω (rad) = N/A
T_{peri} = N/A

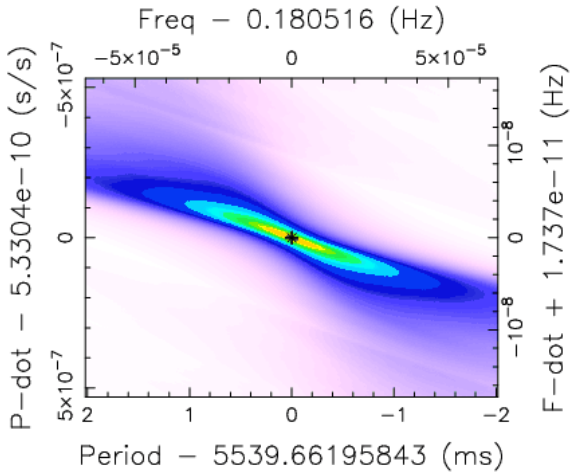






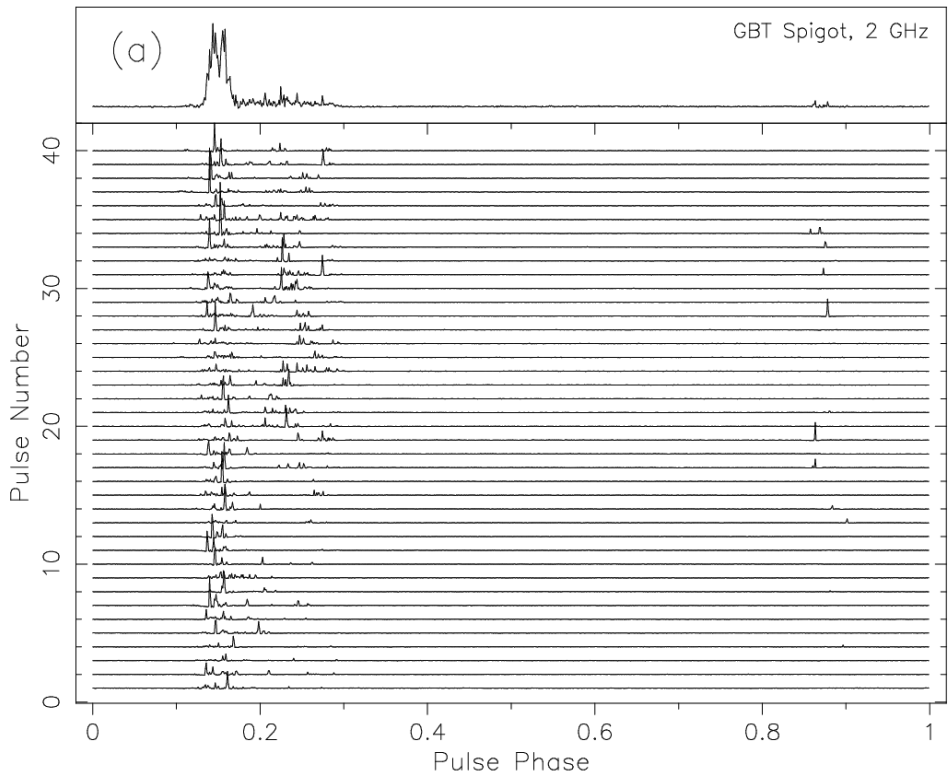


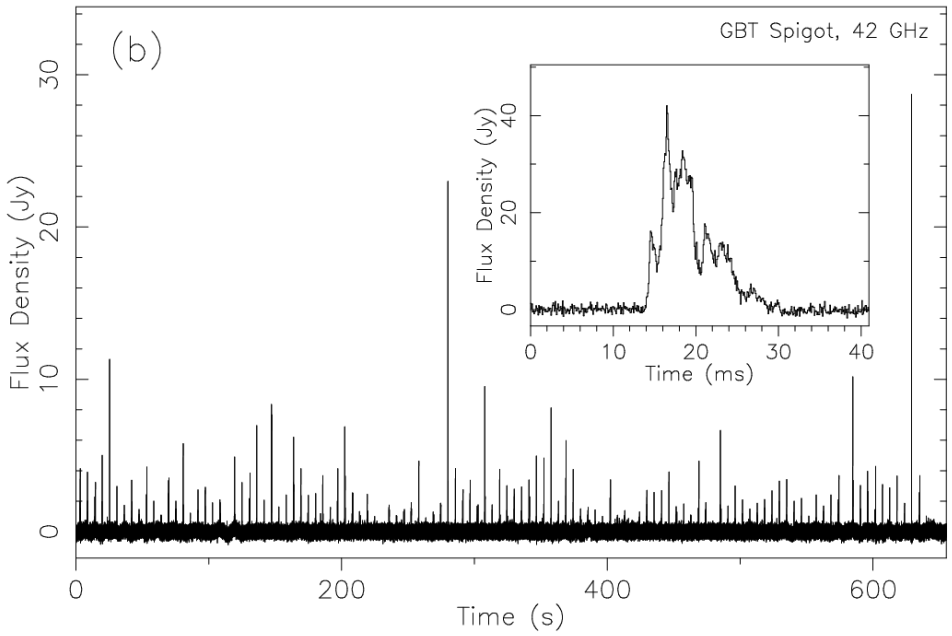




Radio Follow-up

- Immediately requested Parkes and GBT follow-up observations
- Strong 2.9 GHz detection implied flat spectrum
- Single pulses detected in all bands
- 65+% linearly polarized pulses



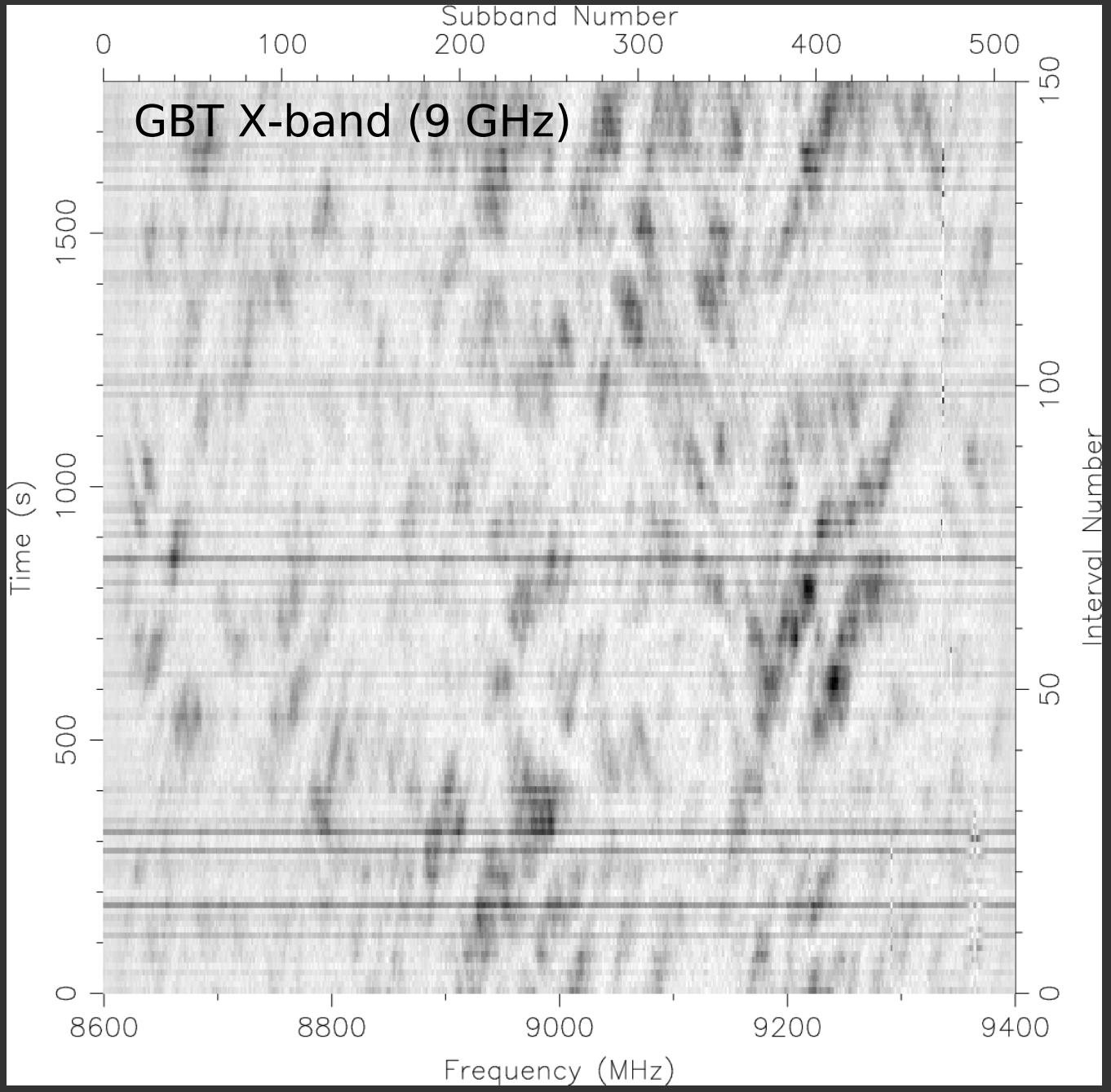


Diffractive Scintillation

Distance ~ 3 kpc
DM = 178 pc/cm^3

NE2001 electron density model predicts tiny scint timescales and bandwidths at “normal” pulsar frequencies

But the pulsar is bright and has a flat spectrum!
$\alpha > -0.5$

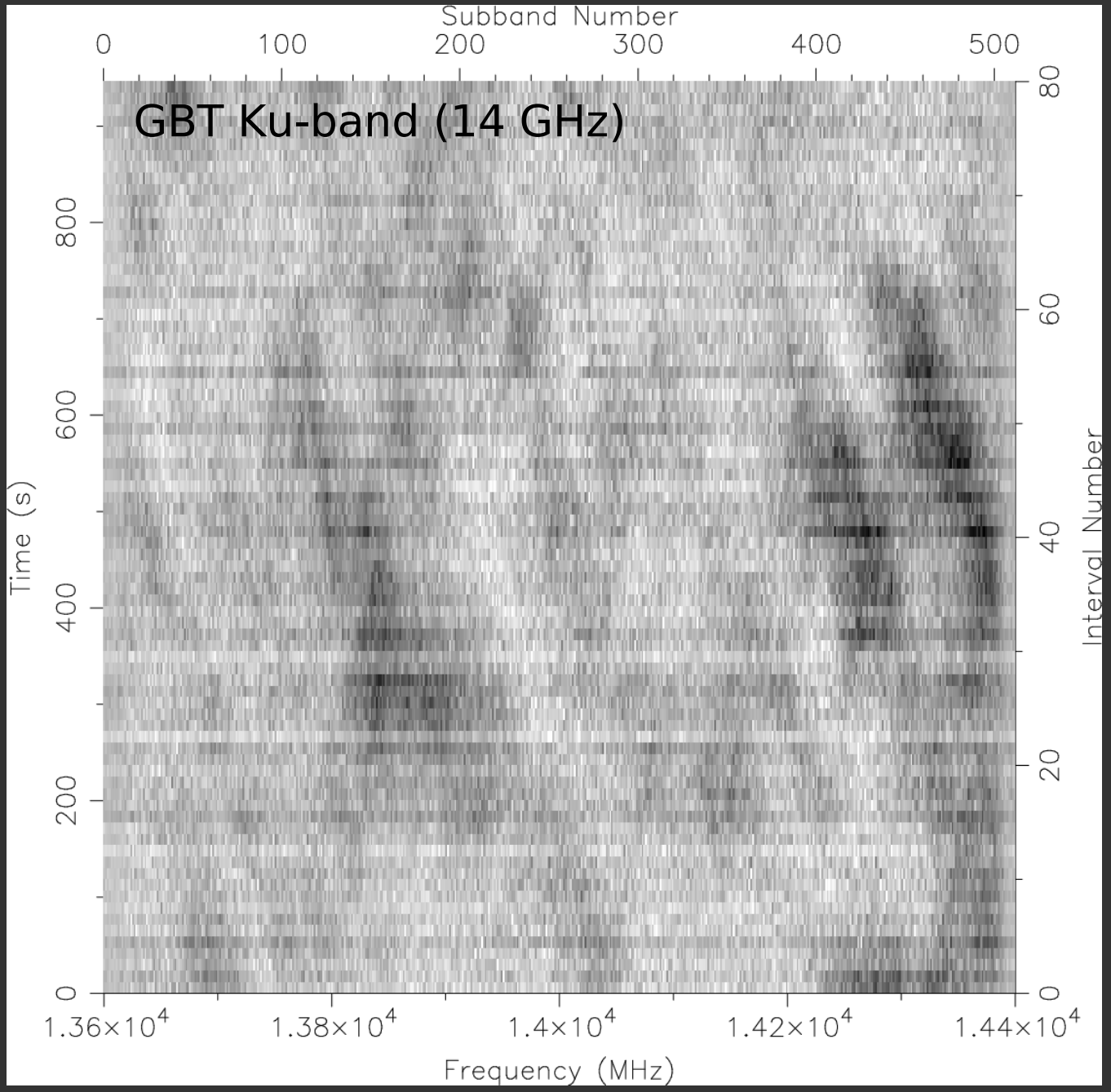


Diffractive Scintillation

Distance ~ 3 kpc
DM = 178 pc/cm^3

NE2001 electron density model predicts tiny scint timescales and bandwidths at “normal” pulsar frequencies

But the pulsar is bright and has a flat spectrum!
$\alpha > -0.5$

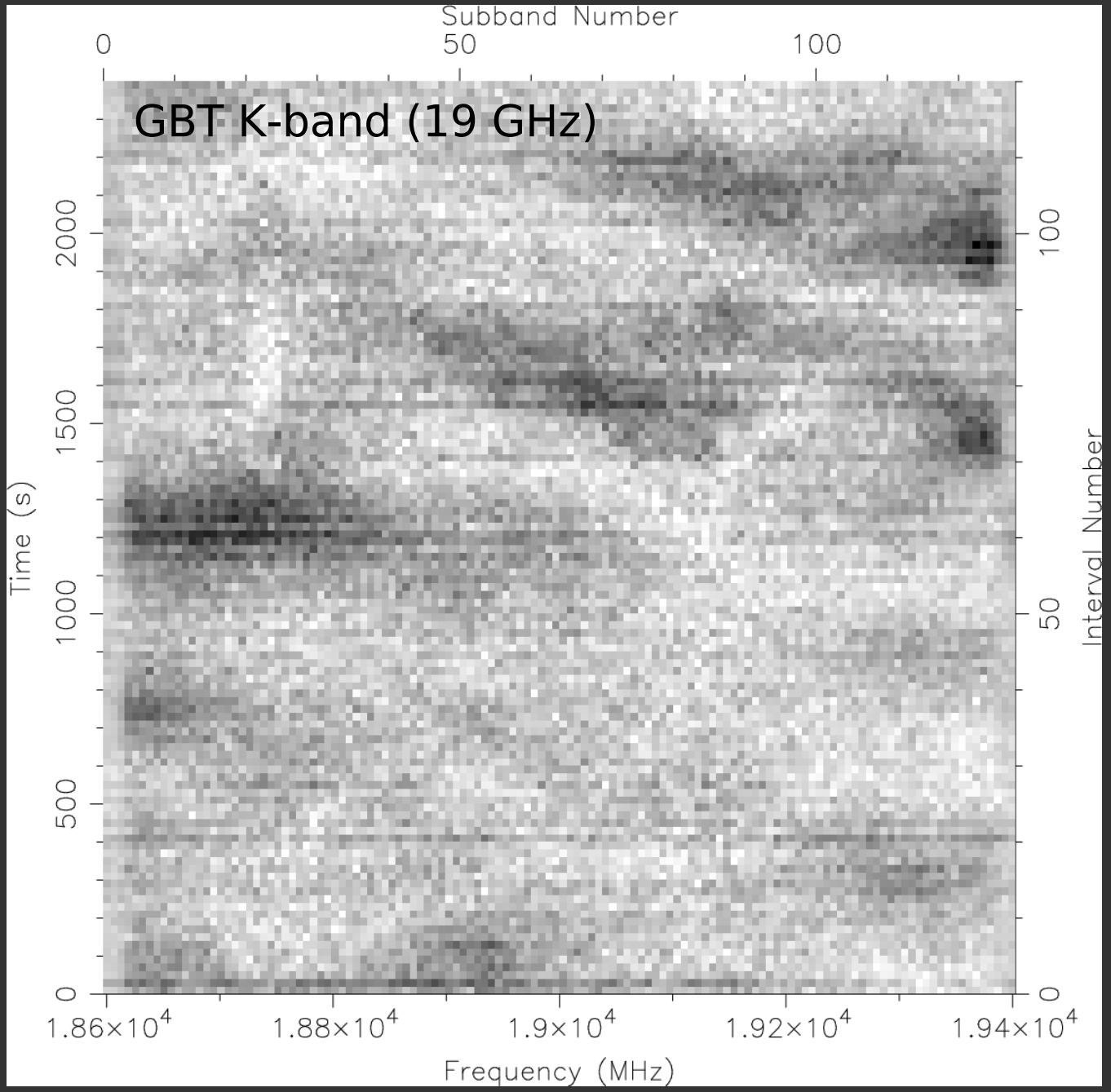


Diffractive Scintillation

Distance ~ 3 kpc
DM = 178 pc/cm^3

NE2001 electron density model predicts tiny scint timescales and bandwidths at “normal” pulsar frequencies

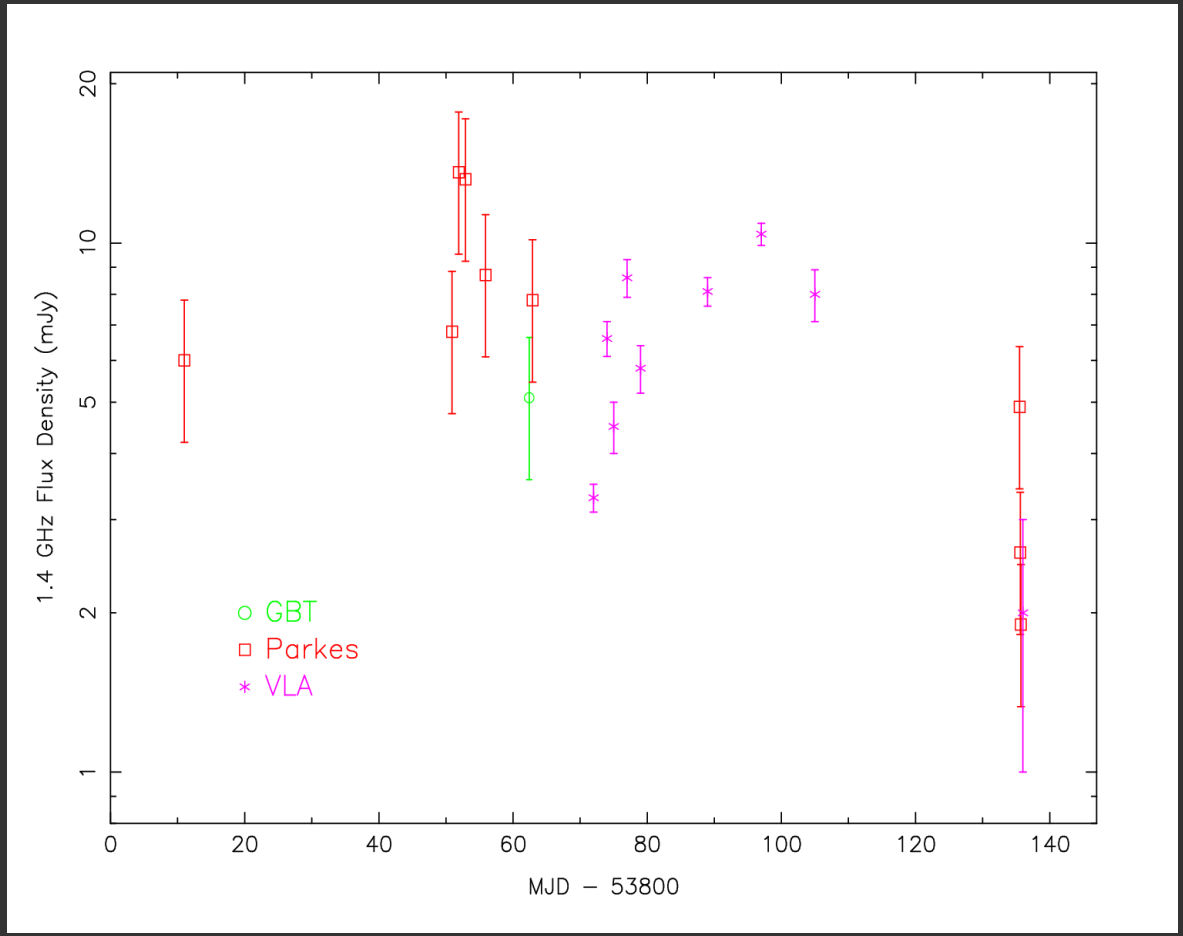
But the pulsar is bright and has a flat spectrum!
$\alpha > -0.5$



Flux Variability

- Variable by factors of ~2 on day to week timescales
- Diffractive scint can explain some >8 GHz
- Magnetar likely causes variability <8 GHz

Changing currents in the magnetosphere?



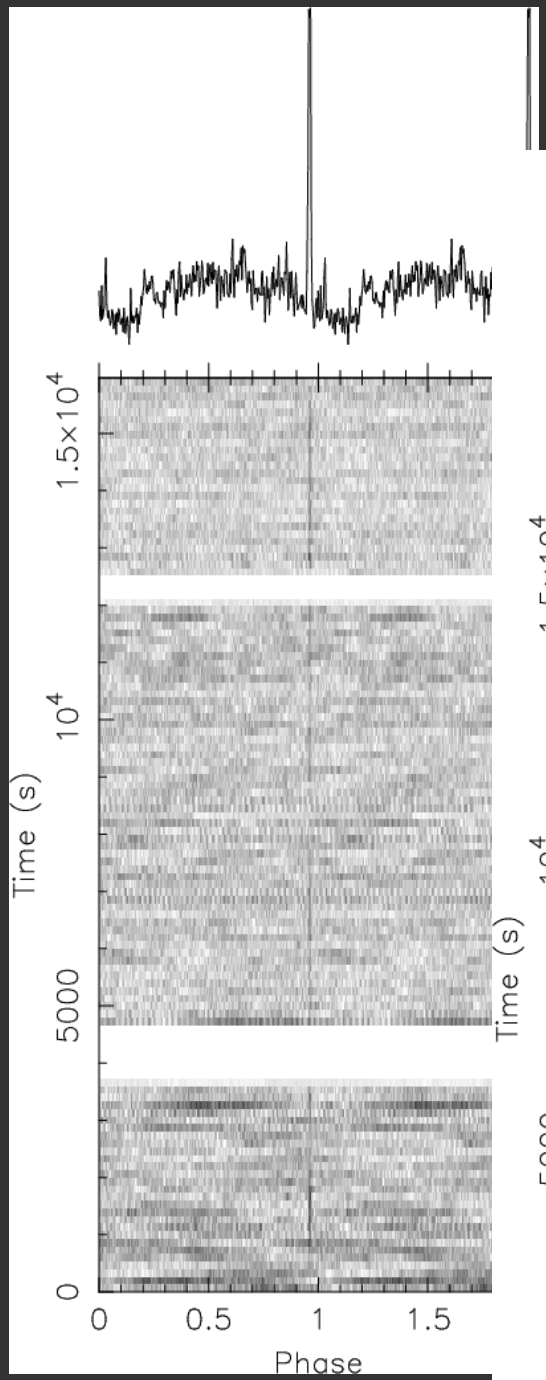
A (3.4)mm PSR

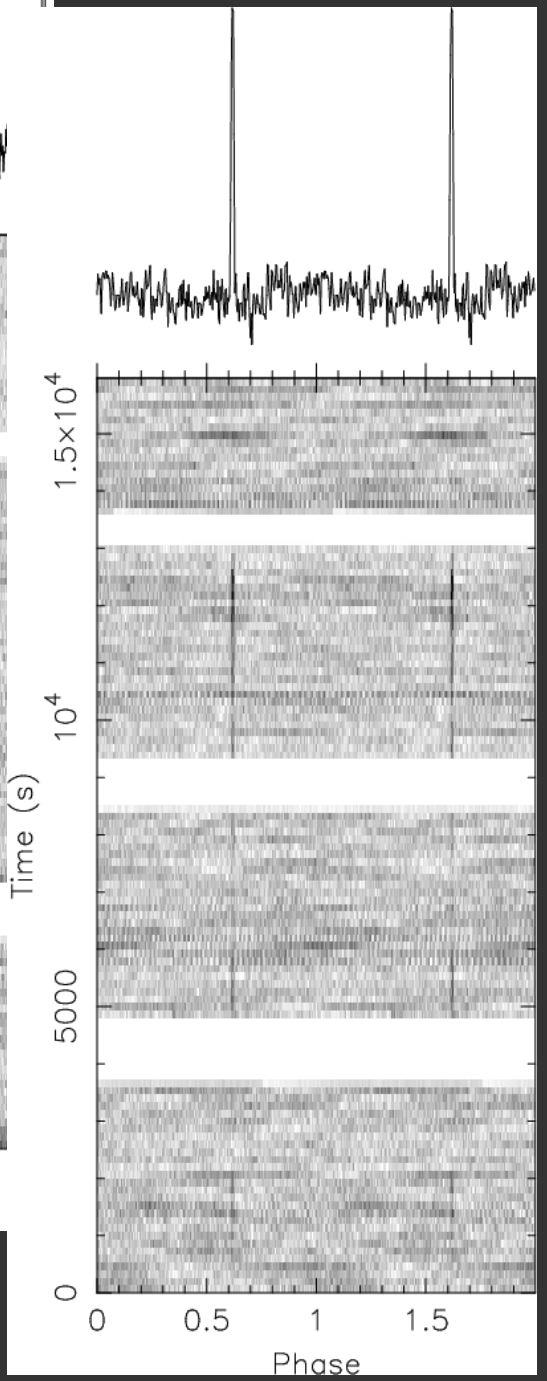
Observed July 2006
at 88 GHz with the
IRAM 30-m telescope

Several single pulses
are visible as well!

Thanks to Aris Karastergiou and Juan Penalver!

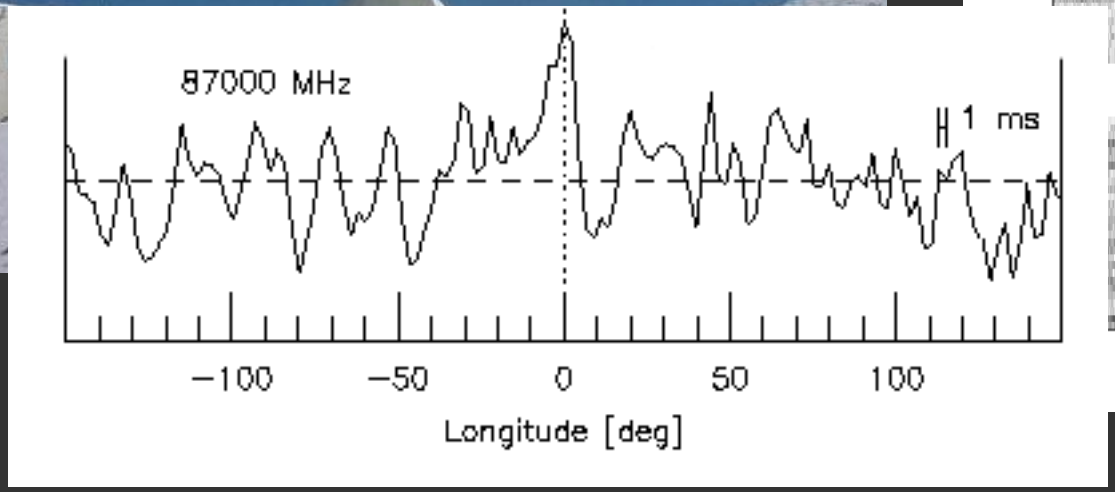
3-5 mJy!





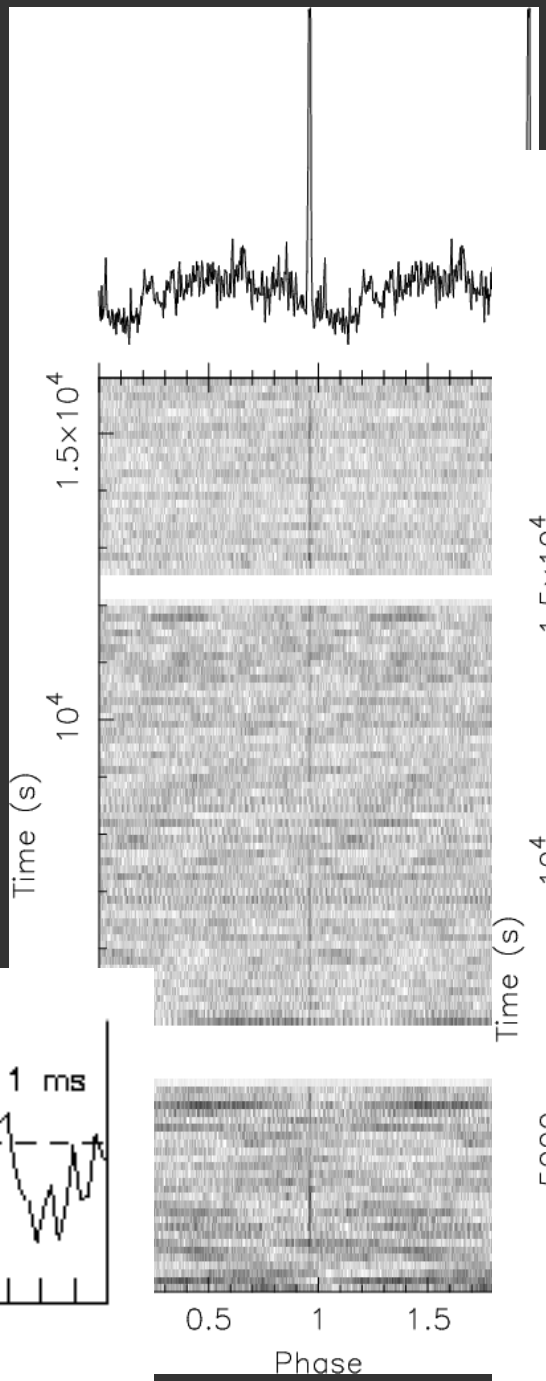
A (3.4)mm PSR

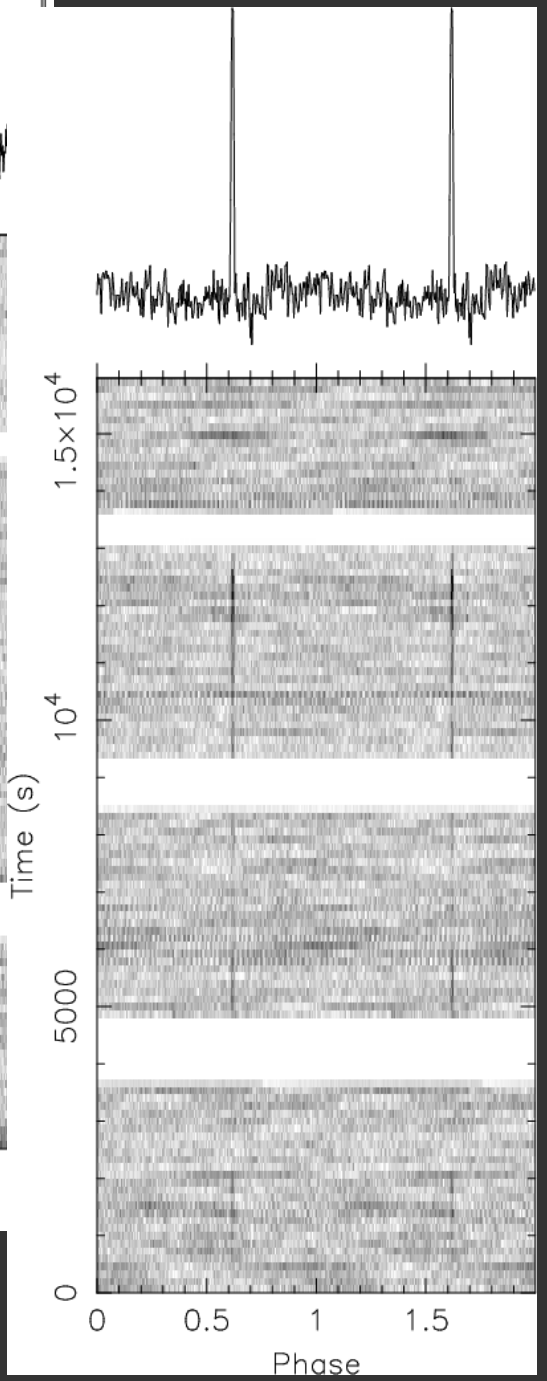
Observed July 2006
at 88 GHz with the
IRAM 30-m telescope



PSR B0355+54 (0.5 mJy) Morris et al., 1997

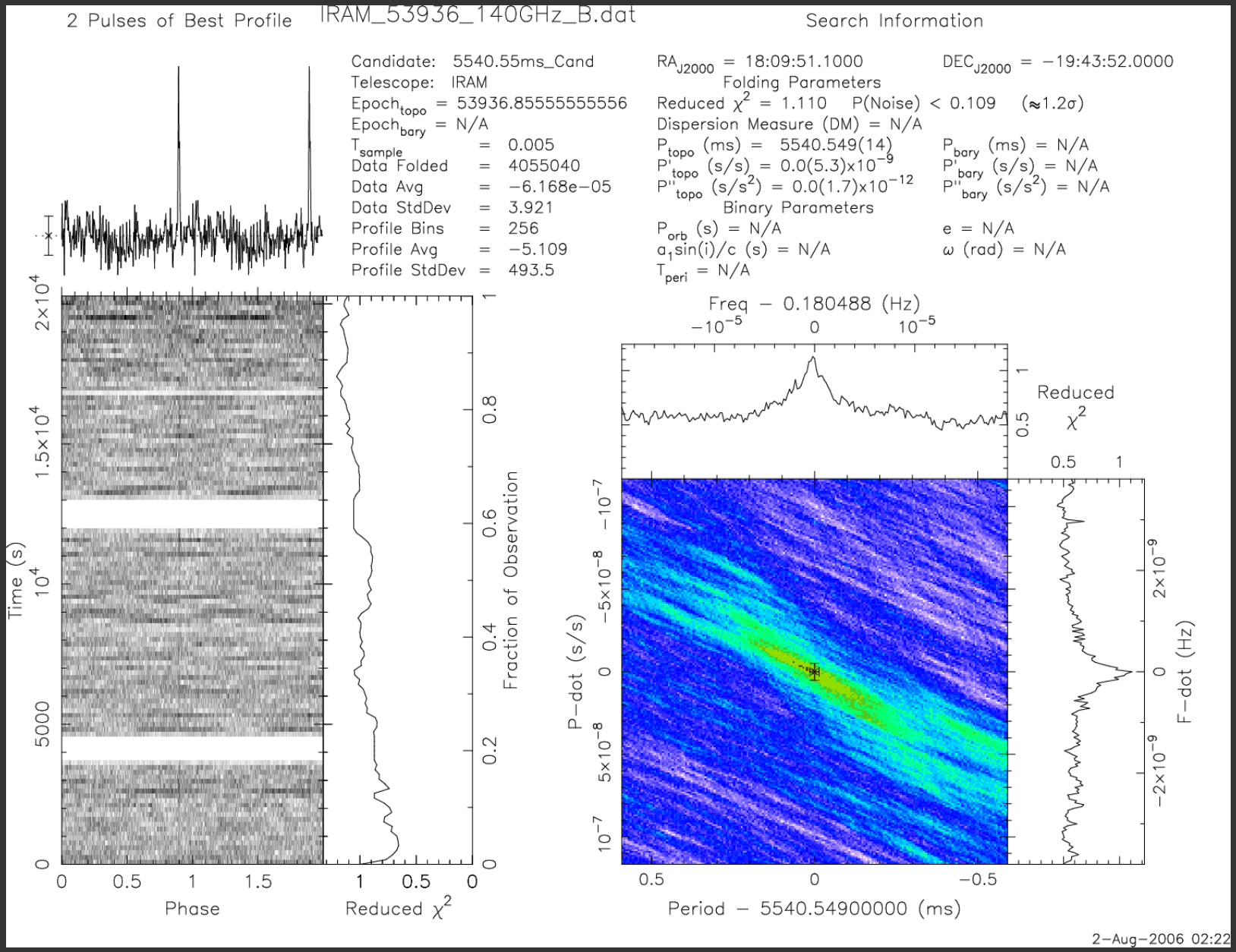
3-5 mJy!





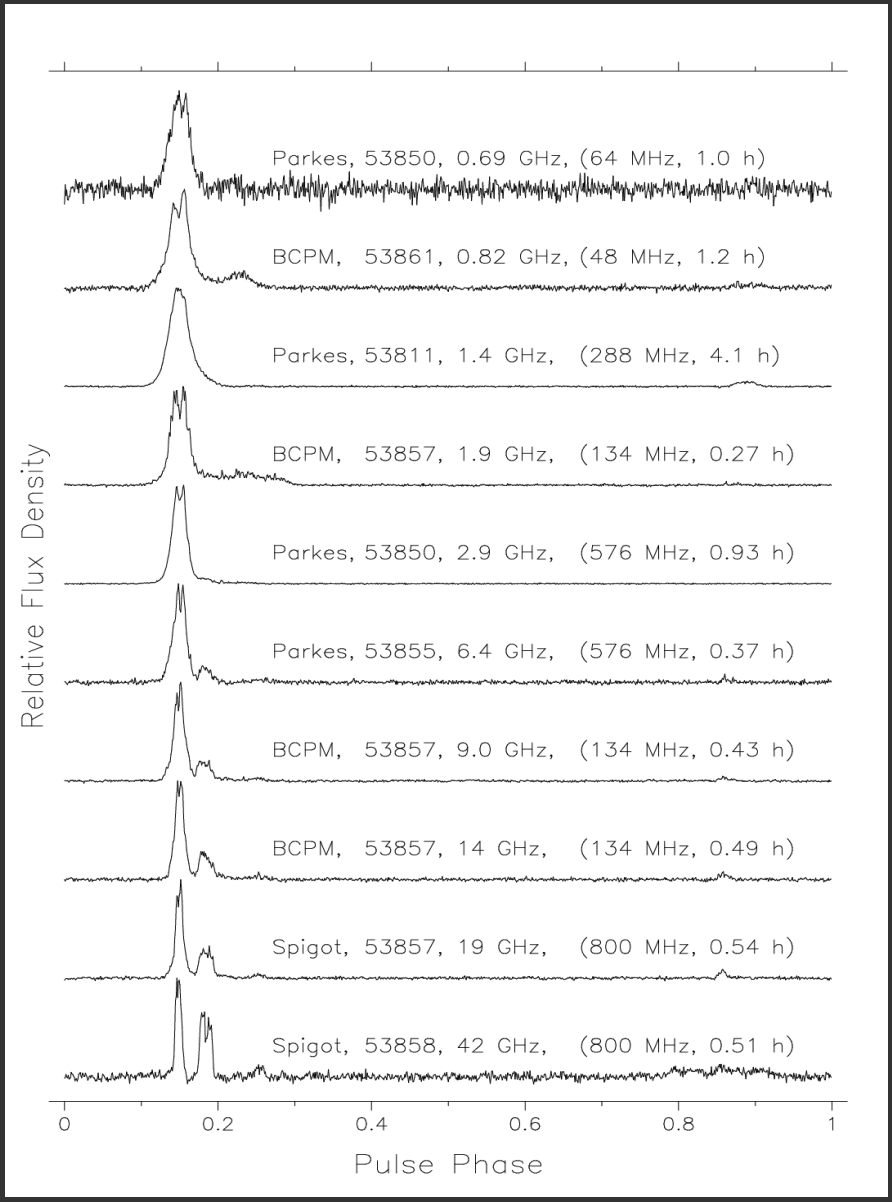
And a 2.1-mm PSR (a new record!)

144 GHz with the IRAM 30-m: ~2 mJy!

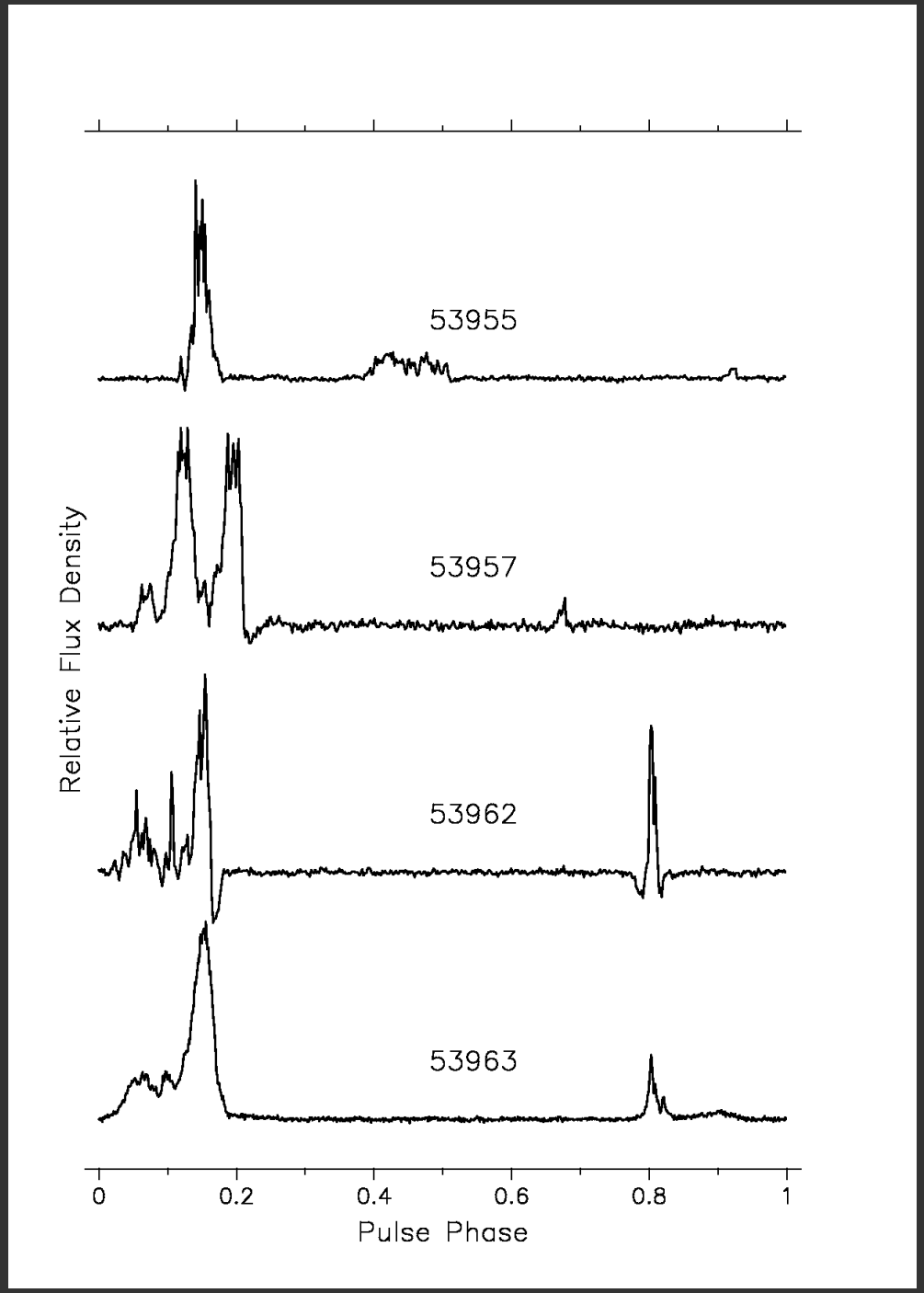


Profile Variations

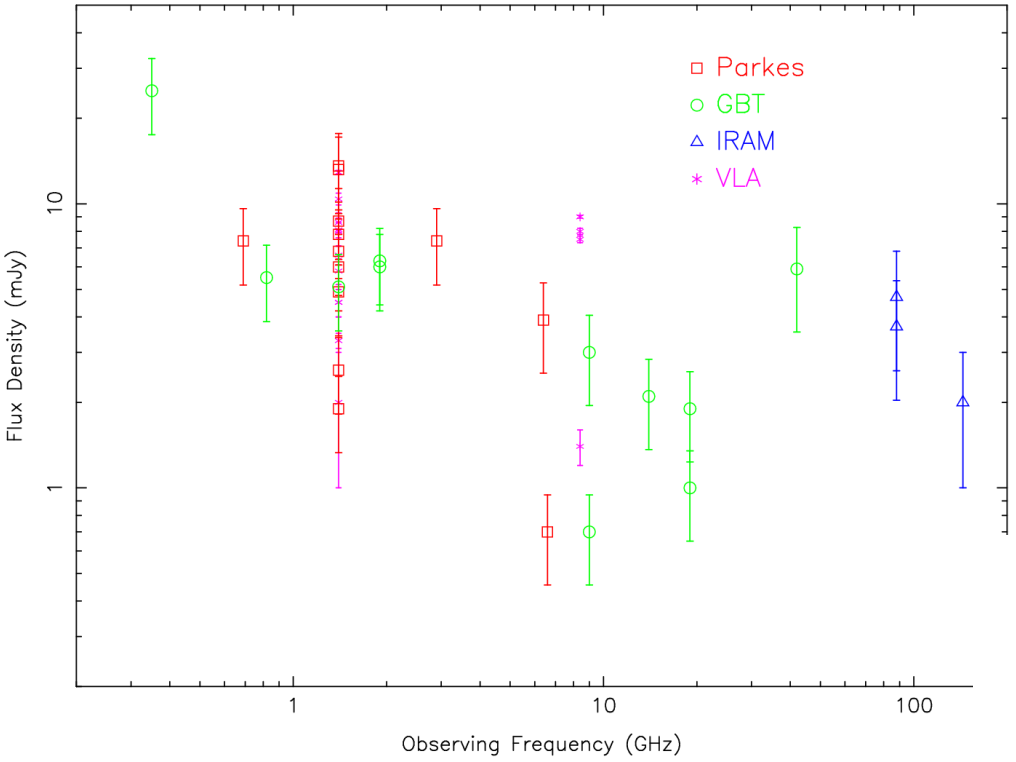
with observing frequency...



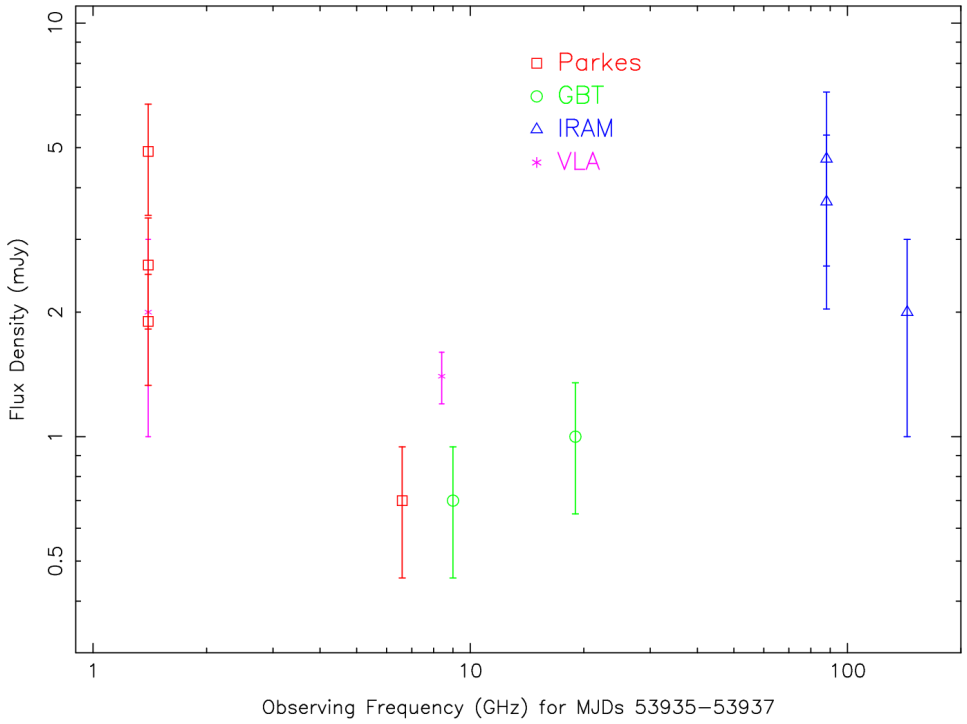
with time (GBT 2GHz)...



Spectrum and Flux Variations



Pulsar has been measured over a range of >400 in observing frequency!



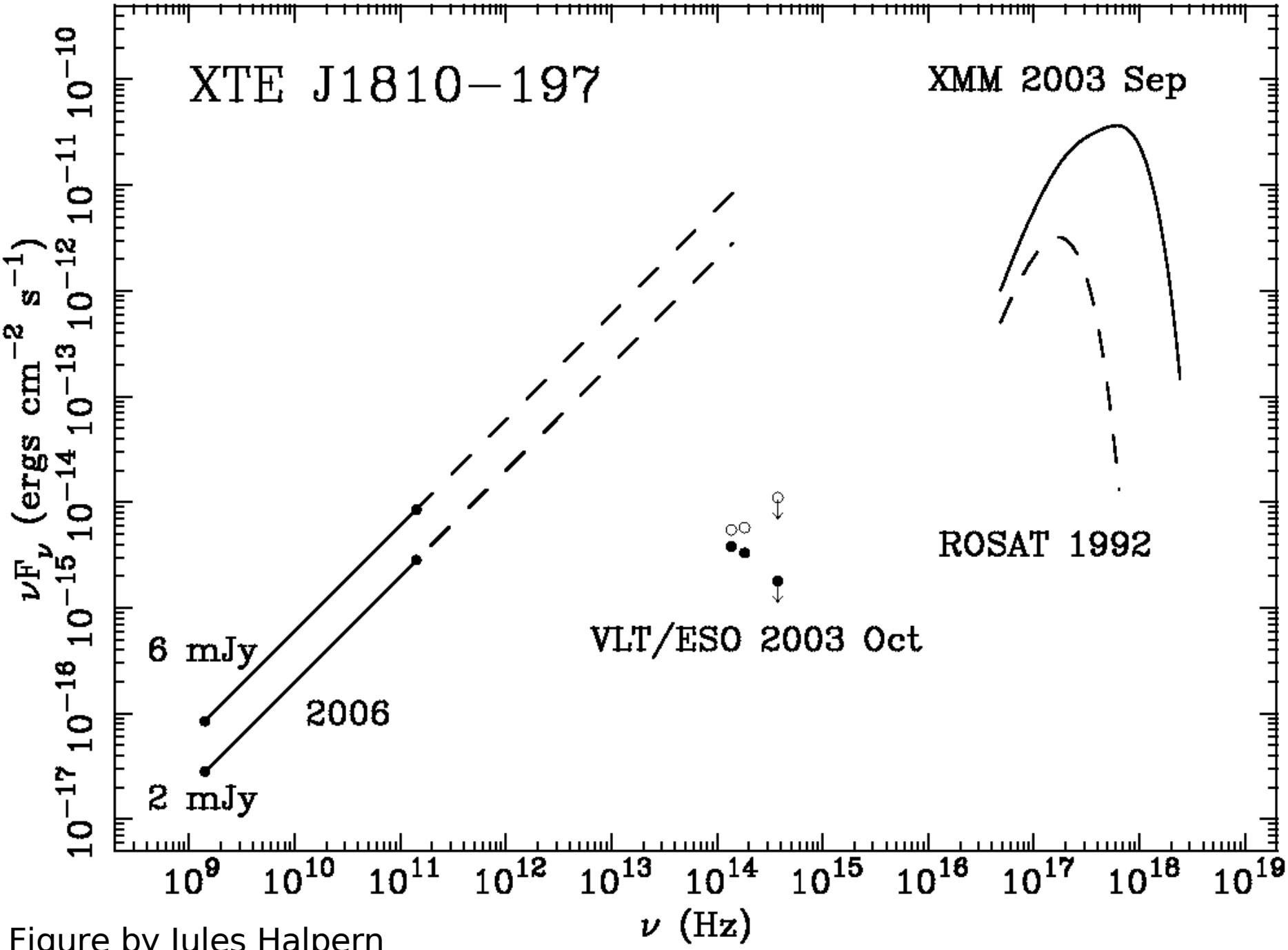
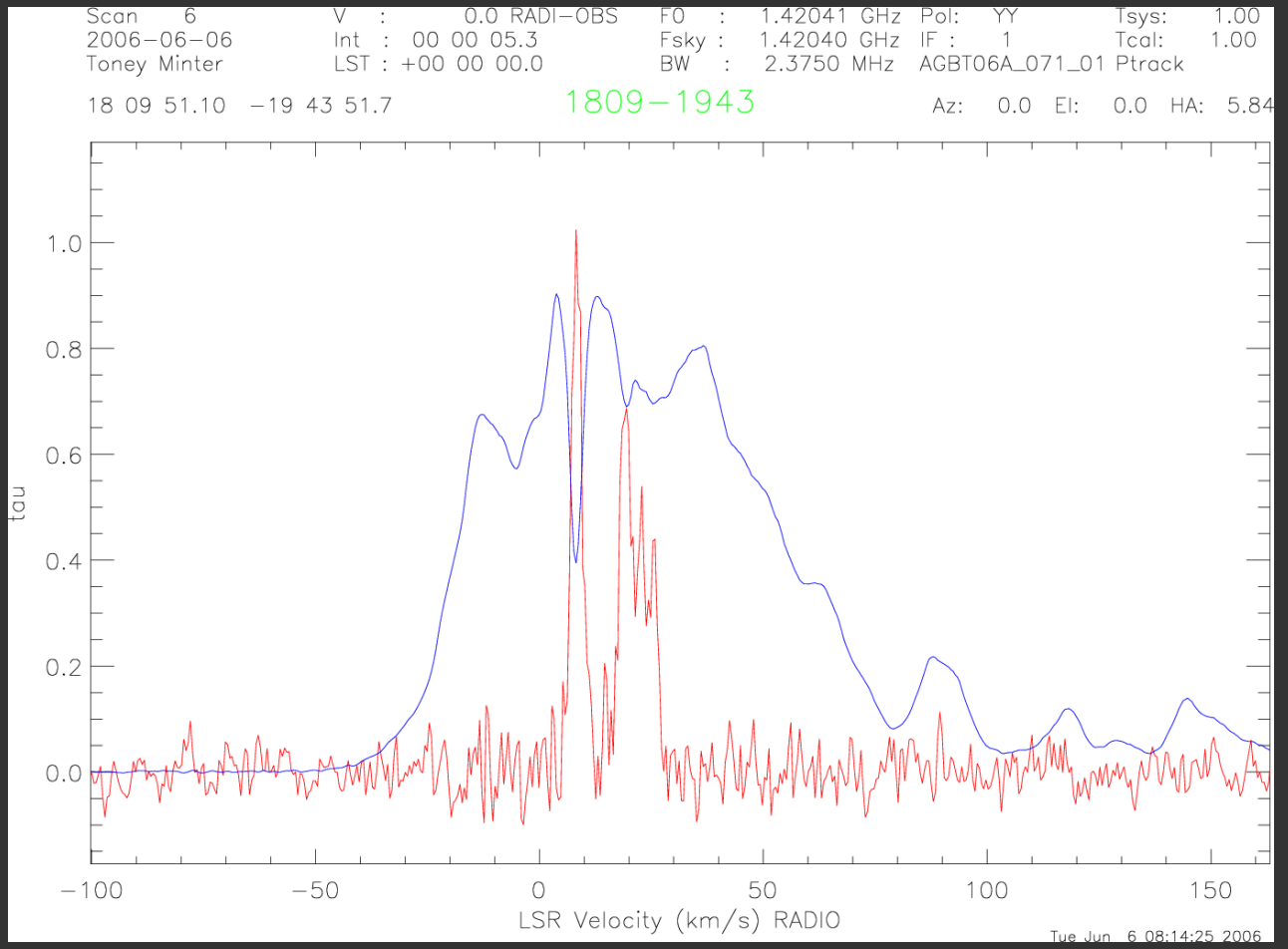


Figure by Jules Halpern

Absorption Measurements

Narrow profile, location in galactic plane (l=10.7º, b=-0.16º), and flat spectrum might allow absorption measurements of molecules (OH, formaldehyde, H_20)

GBT HI observation gives D~3.3 kpc

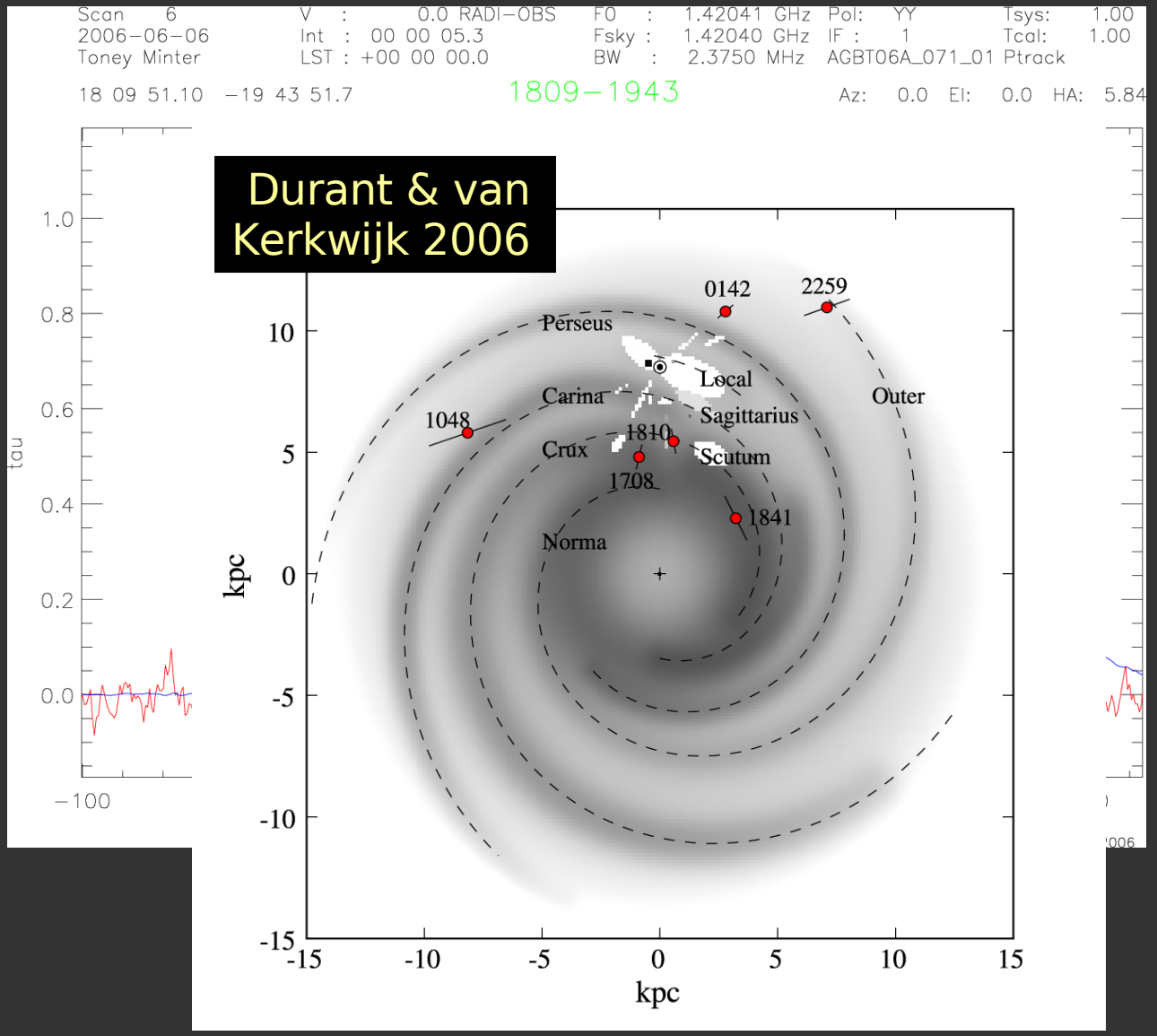


HI opacity spectrum by T. Minter

Absorption Measurements

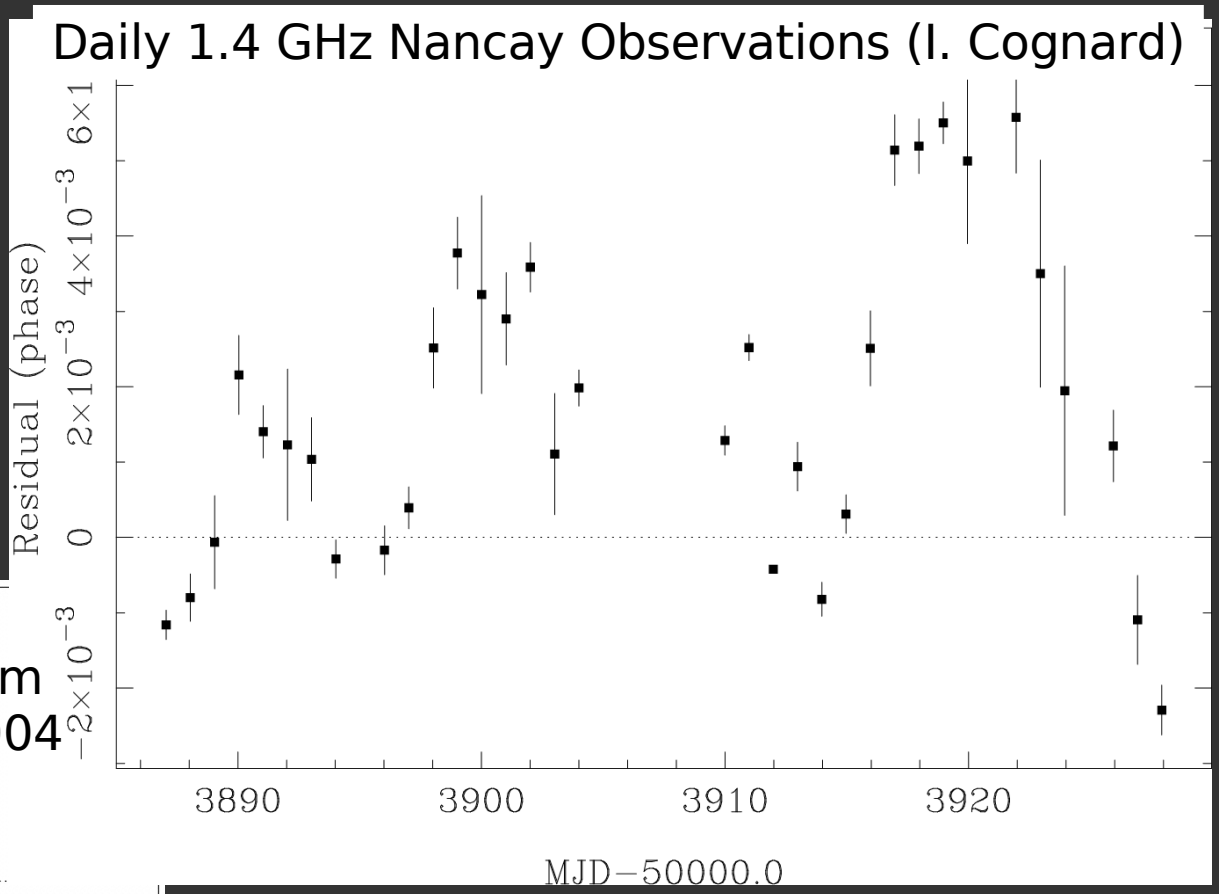
Narrow profile, location in galactic plane (l=10.7º, b=-0.16º), and flat spectrum might allow absorption measurements of molecules (OH, formaldehyde, H_20)

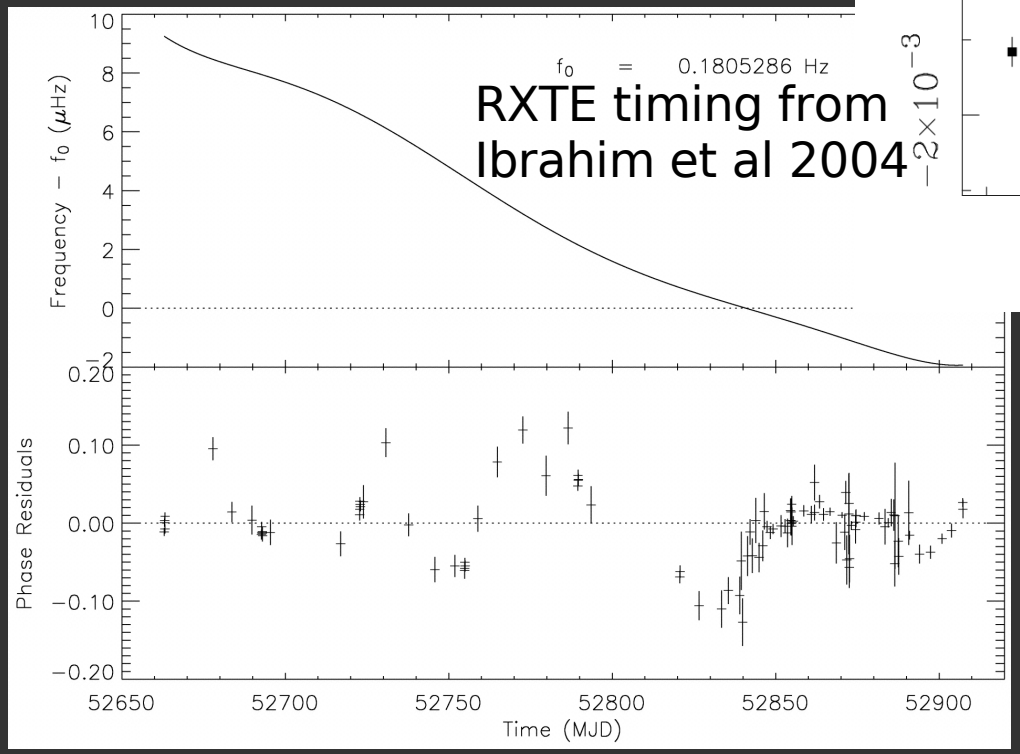
GBT HI observation gives D~3.3 kpc



Timing Noise

Narrow profile and high cadence observations at Parkes, GBT, and Nancay greatly (factor of ~100) improve timing over RXTE





Will the timing noise be correlated with the X-ray or radio luminosity?

Will there be glitches?

So what's the deal?

- *This thing is very strange*
- How is it producing magnetospheric emission?
  - Likely coherent curvature radiation: characteristic frequency $3\gamma^3 c/4\pi r$ is in GHz range when $\gamma \sim 10^3$ and r is of order the light-cylinder radius or smaller
- Whence the pairs and the accelerating regions?
  - Magnetars have twisting B fields due to plastic-like movement of NS crust. This creates large currents and charge densities...
- Is it related to PSR J1718-3718 (P=3.3s, B~7×10^{13}G)? It's not an AXP but the X-ray properties are close to XTE J1810-197 in quiescence (Kaspi & McLaughlin, 2005)
- How long will it last? Are there more? Will other AXPs or SGRs do this? Are we seeing the B-field change? ...

Conclusions

- AXPs are *not* stable, persistent and boring!
- They are very likely magnetars (as described primarily by Thompson & Duncan)
- There is still much to learn:
  - How many are out there?
  - What fraction are “transient”?
  - What are their birthrates (~10% radio psr)?
  - Why are they so different from (and/or so similar to) radio pulsars?
  - What is the evolutionary sequence?

Big thanks go to Woods and Thompson for their excellent review!