Central Compact Objects as Anti-magnetars

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Animation from Patnaude & Fesen 2009

Talk Outline

- *Properties of CCOs: a Class of Young NS*
- *The CCO Pulsars Timing: the Anti-magnetars*
- *Individual Anti-magnetars:*

  Pulsars in SNRs Kes 79, 1E 1207.4-5209, Puppis A
- *Implications on the Formation and Evolution of CCOs*
- *Where are the CCO descendants?*
- *New results on Calvera, an new type of NS?*
- *Implications and Future Work*

Distinguishing Properties of CCOs

- *Isolated NSs,*
- *Near center of supernova remnants,*
- *No optical or radio counterparts,*
- *Lacking a pulsar wind nebula,*
- *Steady, thermal X-ray emission, exclusively,*
- *2BB, kT ~ 0.3/0.6 keV; Lx ~ 10^{33} erg/s*
- *(Don't include NS in RCW 103: variable, 6h period)*

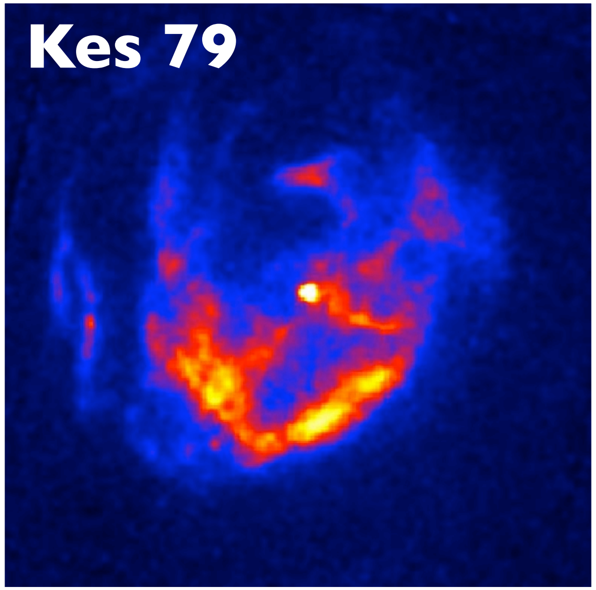
Central Compact Objects in Supernova Remnants

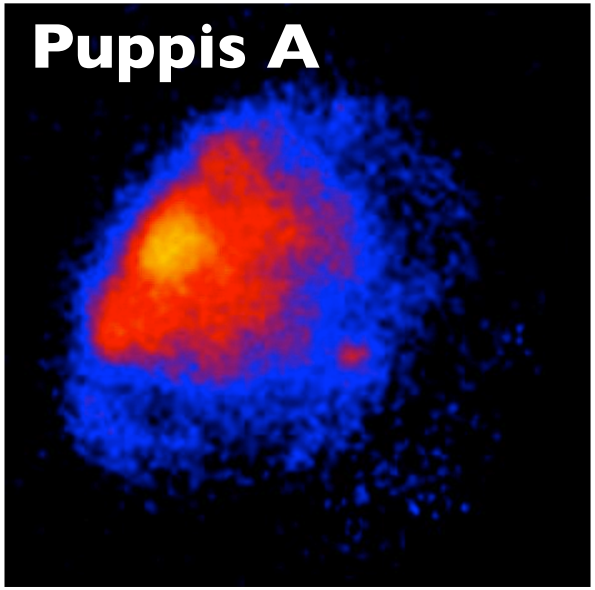
CCO	SNR	Age (kyr)	d (kpc)	P (ms)	f_p [a] (%)	B_s (10^{10} G)	$L_{x,\mathrm{bol}}$ (erg s^{-1})
RX J0822.0−4300	**Puppis A**	**4.5**	**2.2**	**112**	**11**	**2.9**	$\mathbf{5.6 \times 10^{33}}$
1E 1207.4−5209	**PKS 1209−51/52**	**7**	**2.2**	**424**	**9**	**9.8**	$\mathbf{2.5 \times 10^{33}}$
CXOU J185238.6+004020	**Kes 79**	**7**	**7**	**105**	**64**	**3.1**	$\mathbf{5.3 \times 10^{33}}$
CXOU J085201.4−461753	G266.1−1.2	1	1	...	< 7	...	2.5×10^{32}
CXOU J160103.1−513353	G330.2+1.0	$\gtrsim 3$	5	...	< 40	...	1.5×10^{33}
1WGA J1713.4−3949	G347.3−0.5	1.6	1.3	...	< 7	...	$\sim 1 \times 10^{33}$
XMMU J172054.5−372652	G350.1−0.3	0.9	4.5	...	...	...	3.9×10^{33}
CXOU J232327.9+584842	Cas A	0.33	3.4	...	< 12	...	4.7×10^{33}
2XMMi J115836.1−623516	G296.8−0.3	10	9.6	...	...	...	1.1×10^{33}
XMMU J173203.3−344518	G353.6−0.7	~ 27	3.2	...	< 9	...	1.3×10^{34}
CXOU J181852.0−150213	G15.9+0.2	$1-3$	(8.5)	...	...	...	$\sim 1 \times 10^{33}$

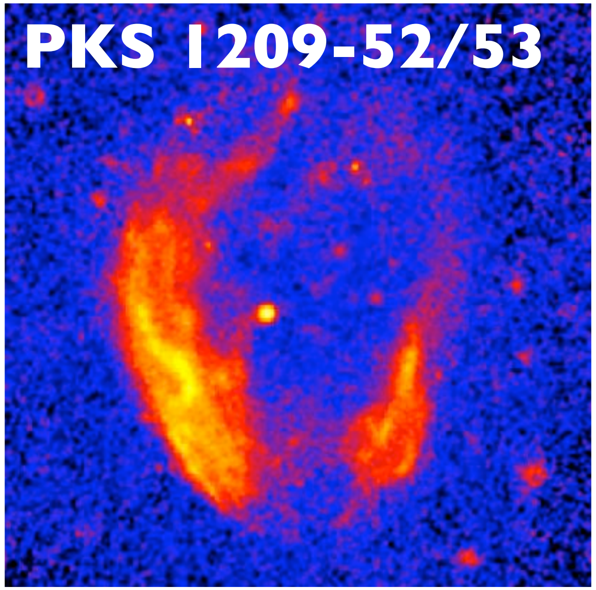
Note — Above the line are eight well-established CCOs. Below the line are three candidates. Upper limits on pulsed fraction are for a search down to $P = 12$ ms or smaller.

Not included: NS in RCW 103, variable, 6h period??

Spin-down of all known anti-magnetars now measured!



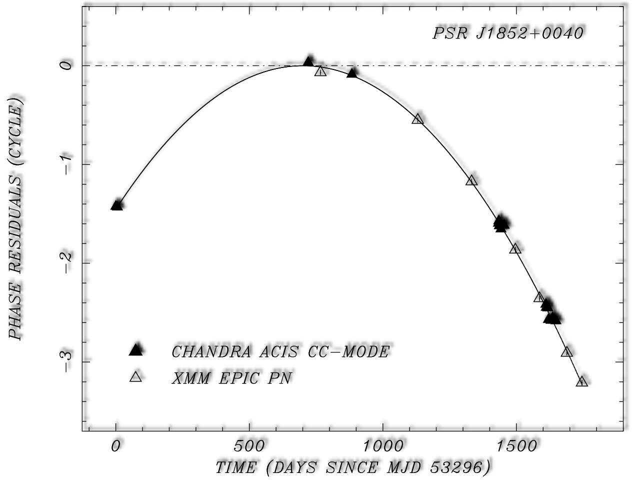


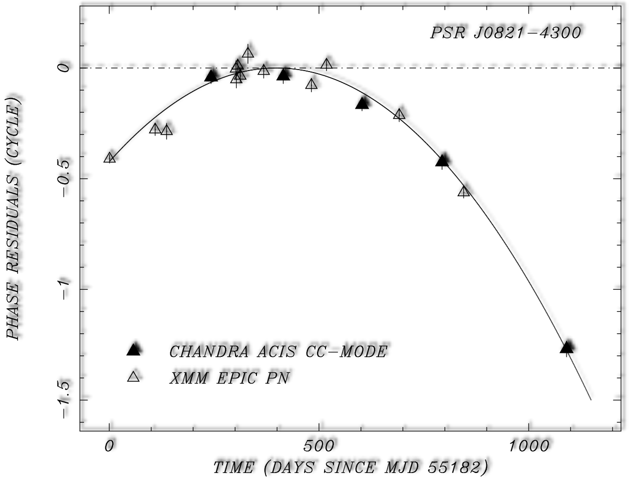


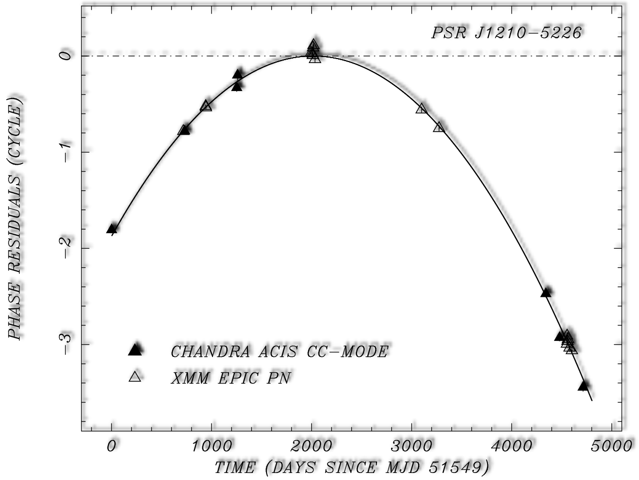
PSR J1852+0040

PSR J0821-4300

PSR J1210-5209

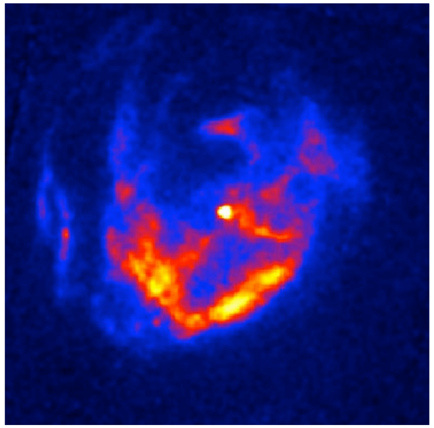
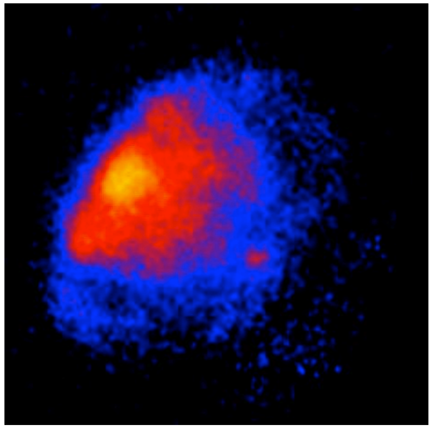
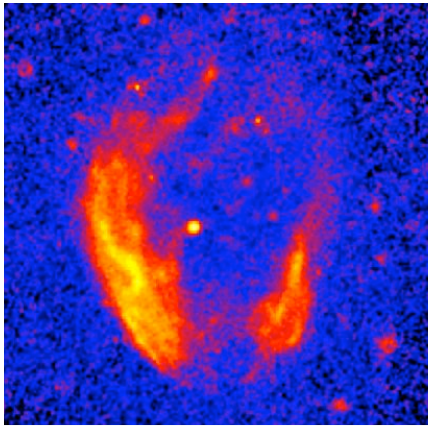






Inferred Properties of Anti-magnetars

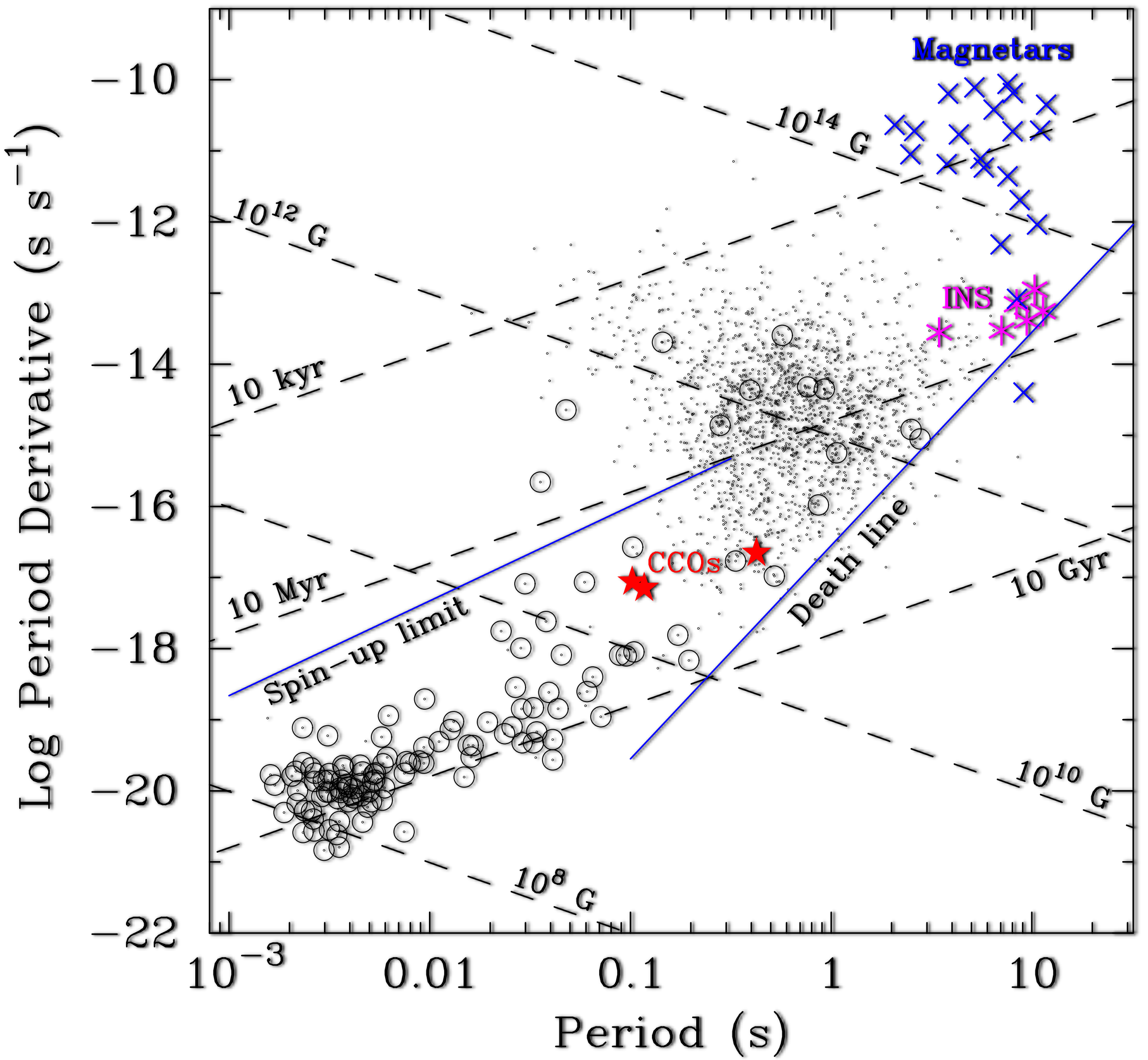
Complete Timing Results on Known *Anti-magnetars*

	PSR J1852+0040 SNR Kes 79	PSR J0821−4300 SNR Puppis A	PSR J1210−5209 SNR PKS 1209−52/52
P (ms)	104.9126	112.7995	424.1307
$\dot{P}(\times 10^{-17})^a$	0.868 ± 0.009	0.704 ± 0.80	2.234 ± 0.009
Pulsed Fraction (%)	64	11	9
$\dot{E} \equiv I\Omega\dot{\Omega}$ (erg s^{-1})	3.0×10^{32}	1.9×10^{32}	1.2×10^{31}
$L(\mathrm{bol})/\dot{E}^b$	18	31	167
$B_p(\times 10^{10}$ G)	3.1	2.9	9.8
$\tau \equiv P/2\dot{P}$ (Myr)	192	254	302
SNR age (kyr)	~ 7	~ 4	~ 7

"The Three ***Magniños***", Olé!

Anti-magnetars on the P-Pdot diagram



Many Mysteries of Anti-magnetars...

- Slow spin-down imply Myr, incompatible with SNR age,
- High X-ray luminosity incompatible with spin-down power,
- Similar spectrum to magnetars, but 10^4 times weaker B-fields,
- Inferred B-field incompatible w/ highly modulated signal of Kes 79.
- Large absorption features in spectrum of 1E 1207.4-5209 ?
- Variable absorption features of Puppis A CCO ?

Rest of the CCOs - similar weak B-field objects?

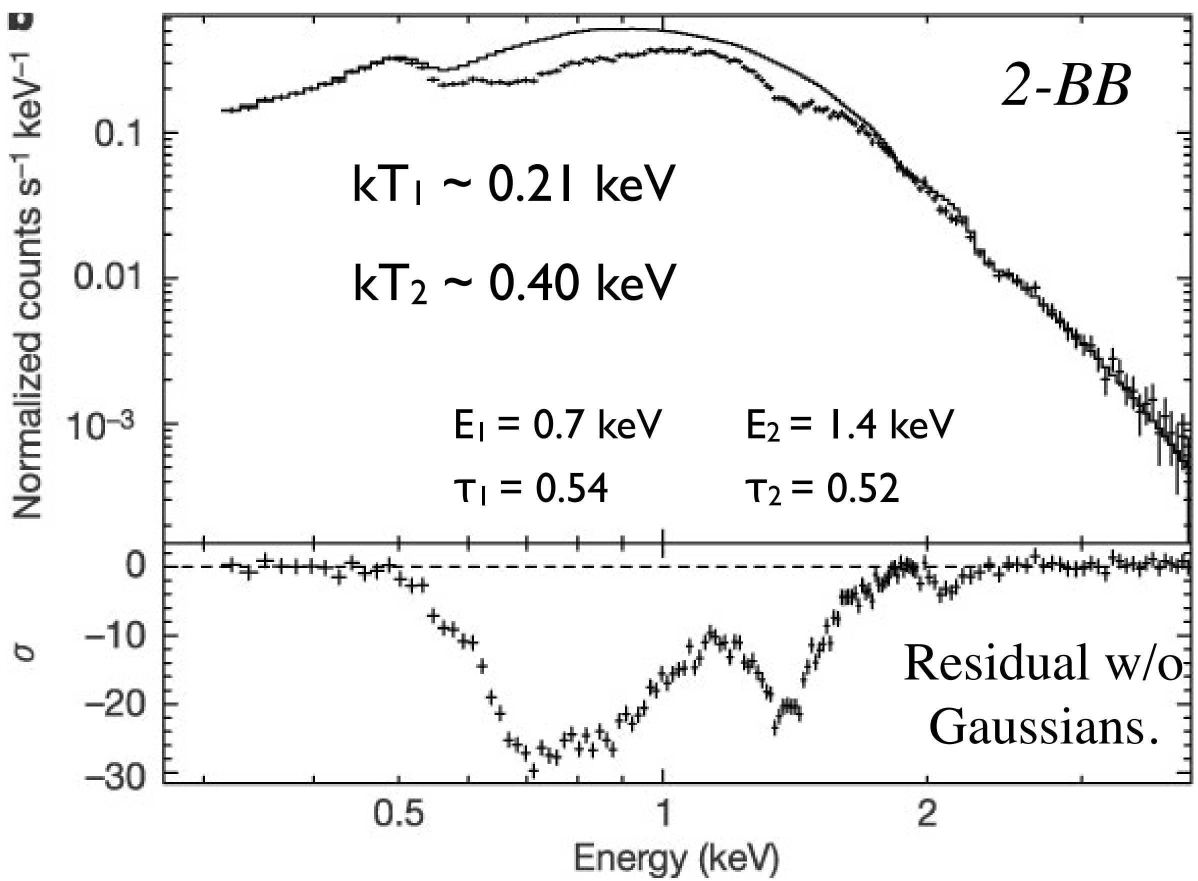
- Consistent properties, in all ways,
- Strong limits on pulsations for some CCOs

More uniform surface temperature? Unfavorable viewing geometry?

E.g, lack of detected pulsations from Cas A implies uniform temp, non-magnetic atmosphere (Ho & Heinke 2009)

Broad Spectral Features in 1E 1207.4-5209

(Sanwal et al. 2002; Bignami et al. 2003)



A deep XMM spectrum fitted with 2BB model.

Strong absorption features at 0.7 keV and 1.4 keV

Much discussion of origin of lines over the years, atmosphere , e^-,e^+ cyclotron lines

$B_{spin\text{-}down}$ is consistent w/ electron cyclotron resonance + harmonics

$B_{cyc} \approx 8 \times 10^{10}$ G vs. $B_{sd} = 9.8 \times 10^{10}$ G

Also explains why its spectrum is unique… Low N_H, B in range!

PSR J1852+0040 in Kes 79: Spectrum

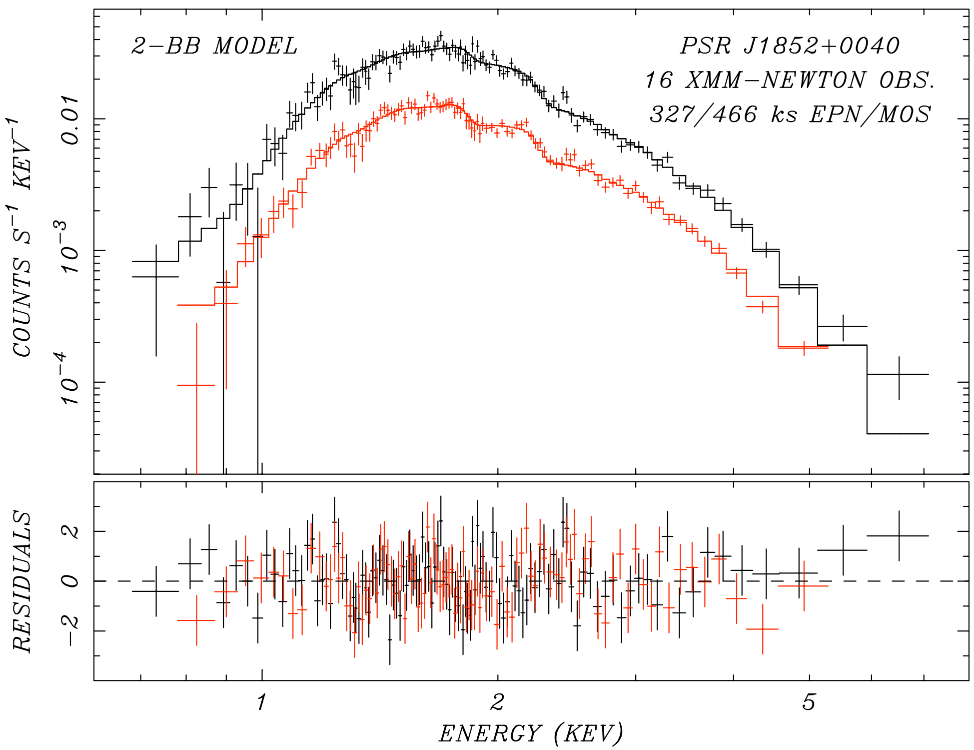


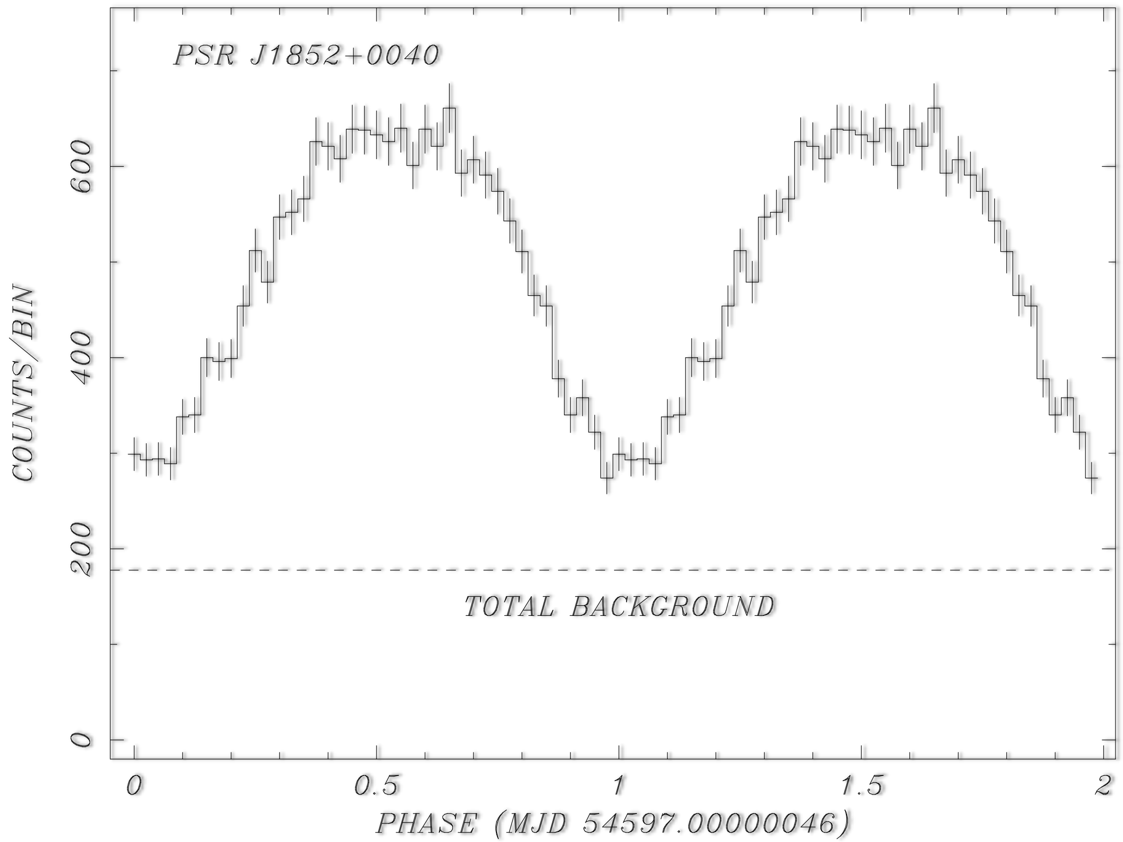
Fig. 3.— Spectrum of the 16 summed *XMM-Newton* observations of PSR J1852+0040, fitted to a double blackbody model. The parameters of the fit are given in Table 3.

Parameter	Two Blackbody
$N_{\rm H}$ (10^{22} cm^{-2})	1.82 ± 0.21
kT_1 (keV)	0.30 ± 0.05
R_1 (km)	$1.9\, d_{7.1}$
kT_2 (keV)	0.52 ± 0.03
R_2 (km)	$0.45\, d_{7.1}$
$F_x(0.5-10$ keV$)^{\rm a}$	2.0×10^{-13}
$L_{\rm bol}{}^{\rm b}$	$5.3 \times 10^{33}\, d_{7.1}^2$
$\chi^2_\nu(\nu)$	1.07(201)

[a] Absorbed Flux erg cm^{-2} s^{-1}.
[b] Luminosity in units of erg s^{-1}.

- Good fit with a 2BB thermal model
- No obvious line features like for PSR J1210-5209
  (but large N_H: E_c = 0.26 keV attenuated)

PSR J1852+0040 Pules Profile



Large modulation, 64% requires large asymmetric temp. distribution

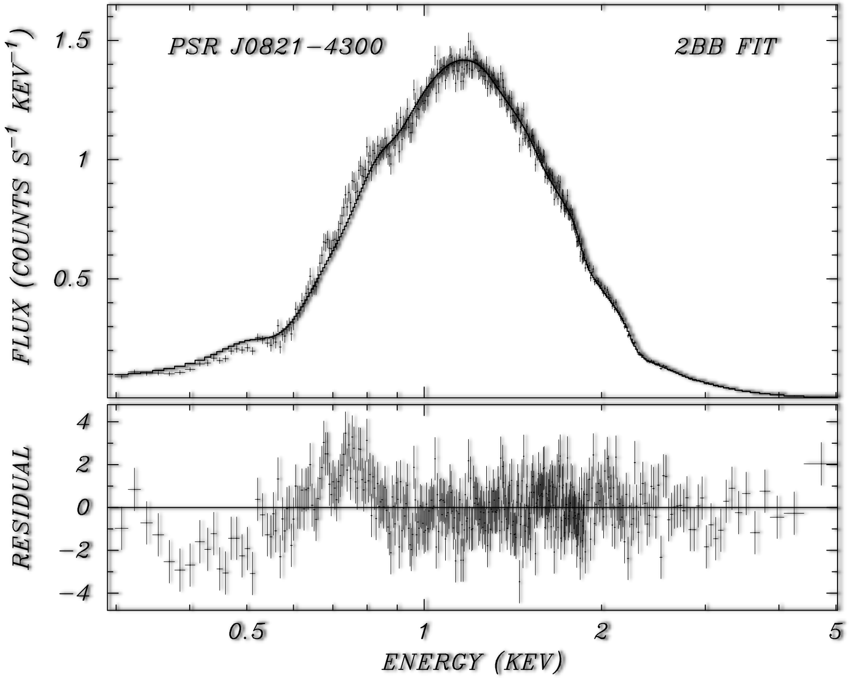
Need large B-field for non-uniform surface temp. or magnetospheric activity

Energy-independent suggests single temperature spot?

Small B-field incompatible with highly modulated signal of Kes 79

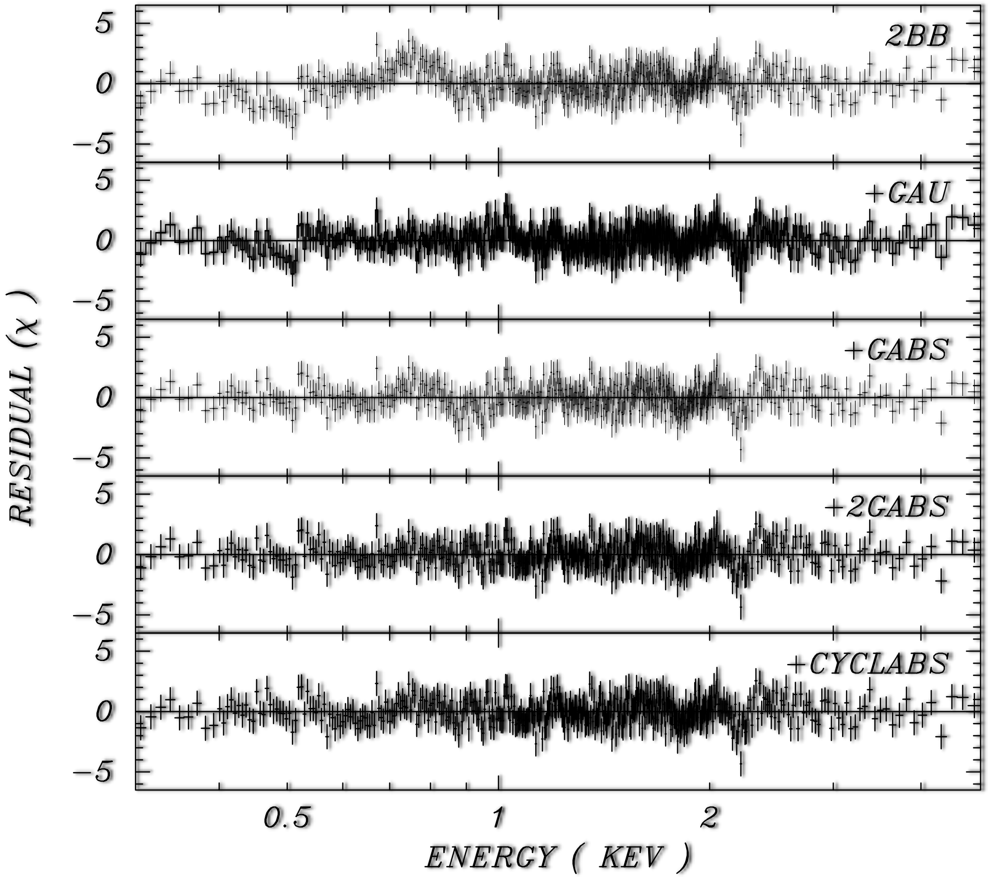
All XMM Data from Timing Observations (307 ks)

Phased Average Spectrum

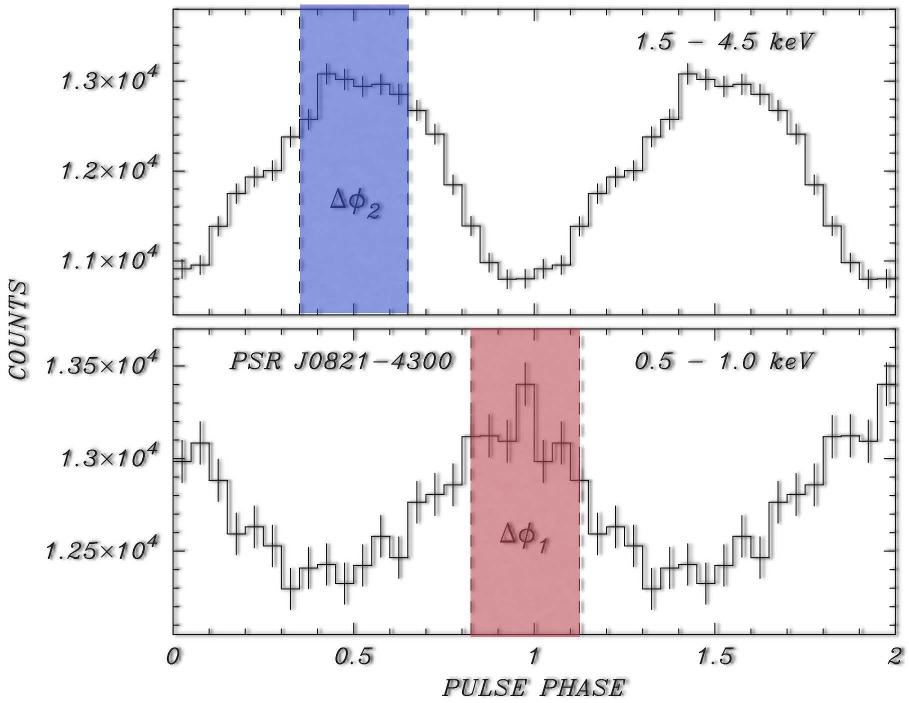


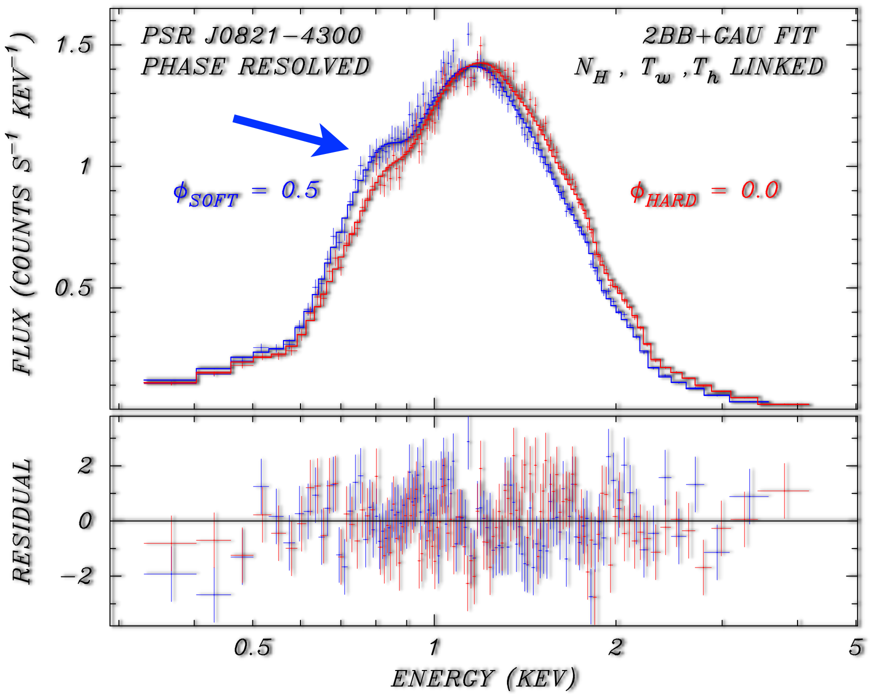
Well fit by either 2 Gaussian absorption model or cyclotron model

Absorption at 0.46 keV now favored over emission line. And more consistent with N_H



Phase Resolved Spectrum of PSR J0821-4300



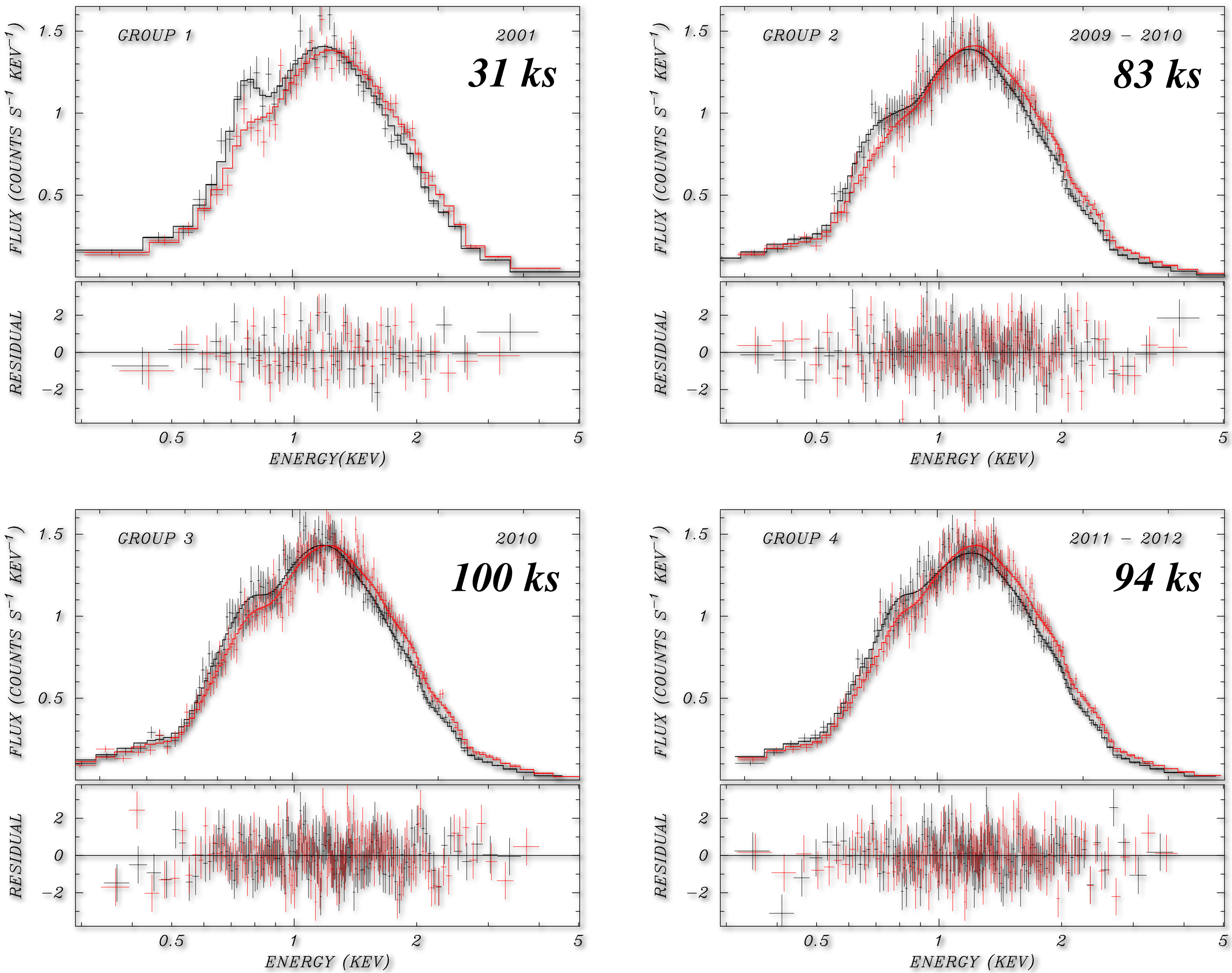


	Warm Spot	Hot Spot
N_H (cm^{-2})	$(2.9 \pm 0.4) \times 10^{21}$	
kT (keV)	0.29 ± 0.01	0.49 ± 0.02
L_{BB} ($\times 10^{33}$ erg s^{-1})[a]	3.0 ± 0.2	1.4 ± 0.3
R_{BB} (km)	1.8 ± 0.8	0.4 ± 0.25
Eo (keV)	0.46 ± 0.01	2×Eo
Width (eV)	106 ± 20	$34 - 62$
τ_o	$0.6 - 1.3$	< 0.035

[a] Blackbody bolometric luminosity at 2.2 kpc

Time dependence of spectral feature

(de Luca et al. 2012)



Groups:

#1 Apr -Nov 2001

#2 Dec 09 - May 10

#3 Apr 11 - Apr 12

#4 Apr 10 -Apr 12

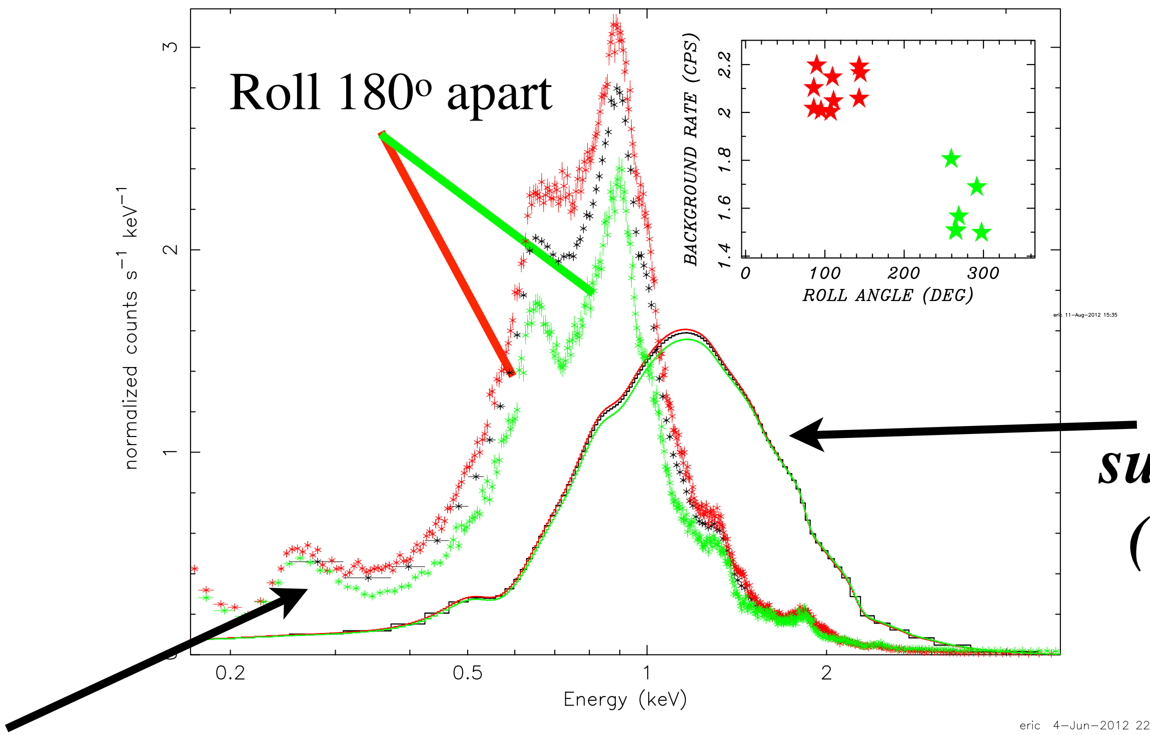
Question:

Is the line variable?

Or,

Is this natural variance and a line width fitting effect?

XMM: Strong Roll Dependence of Puppis A Flux in Source Background Annulus!?!



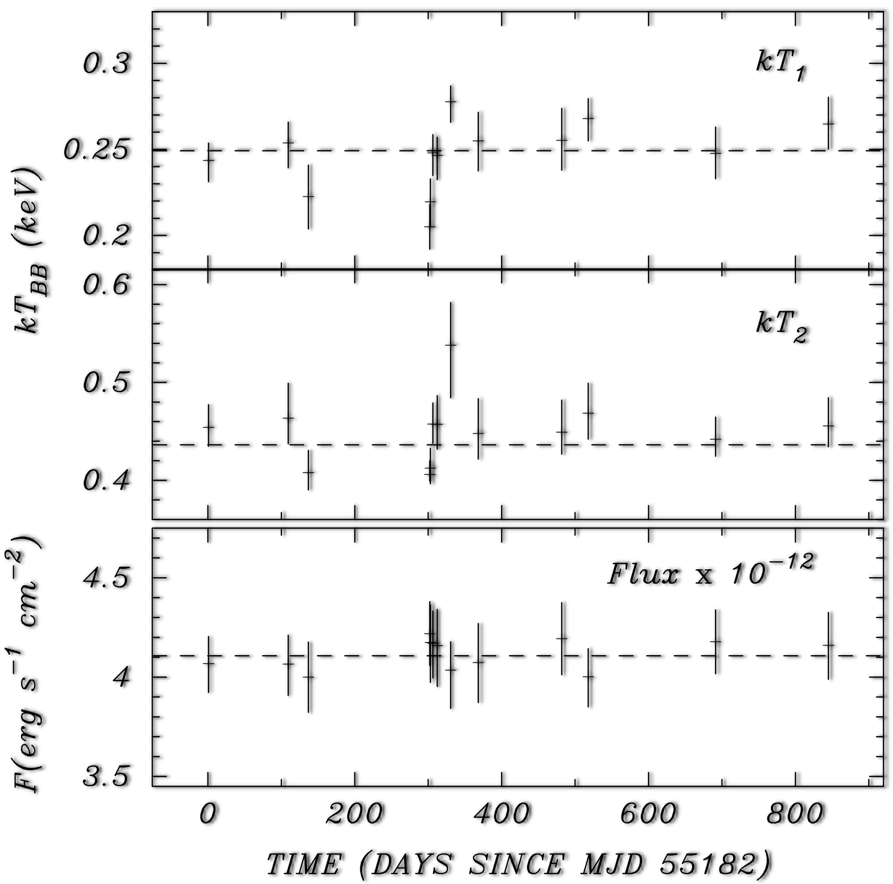
Background subtracted spectra (best fit models)

Background spectra from a 30" < r < 45" annulus around source: nearly all Puppis A SNR emission

Why roll dependent???

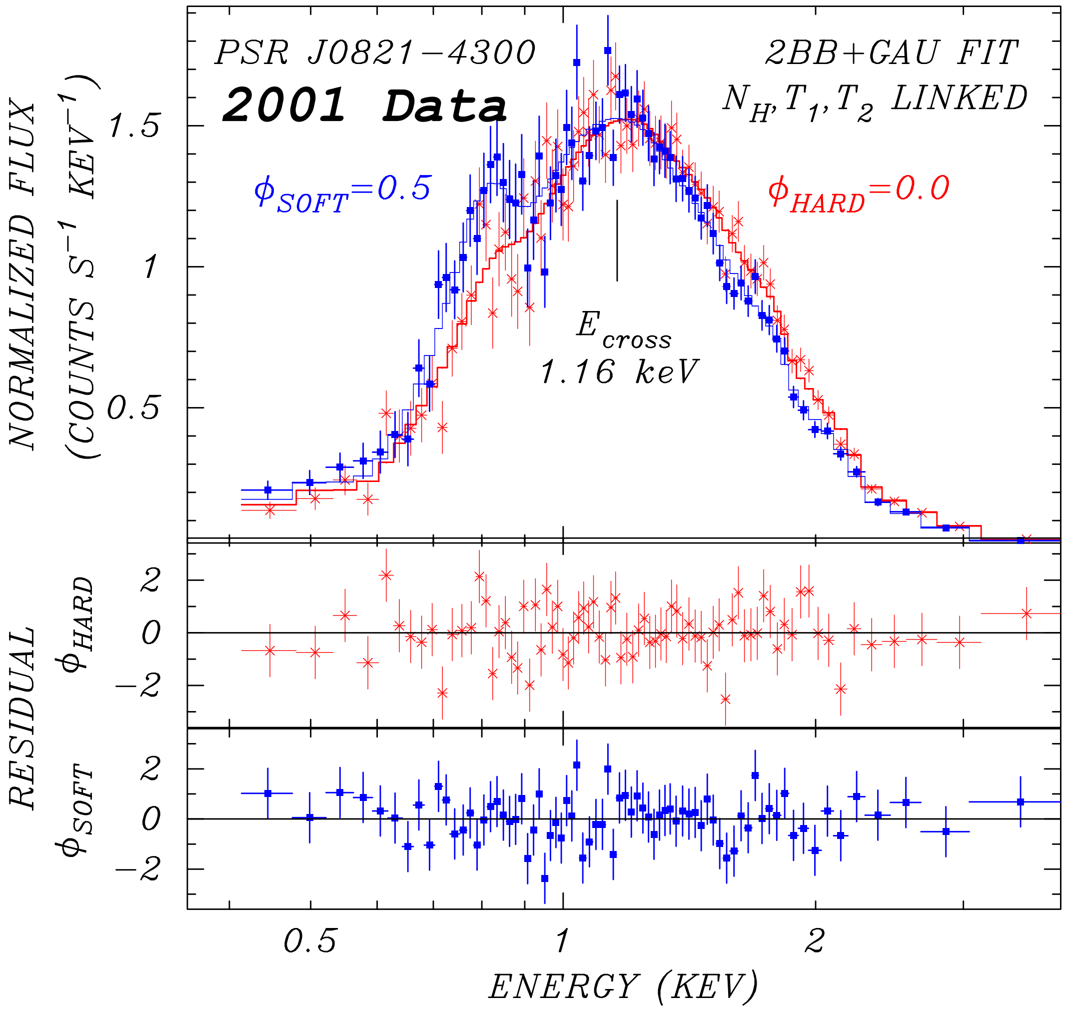
Caution interpreting lines !

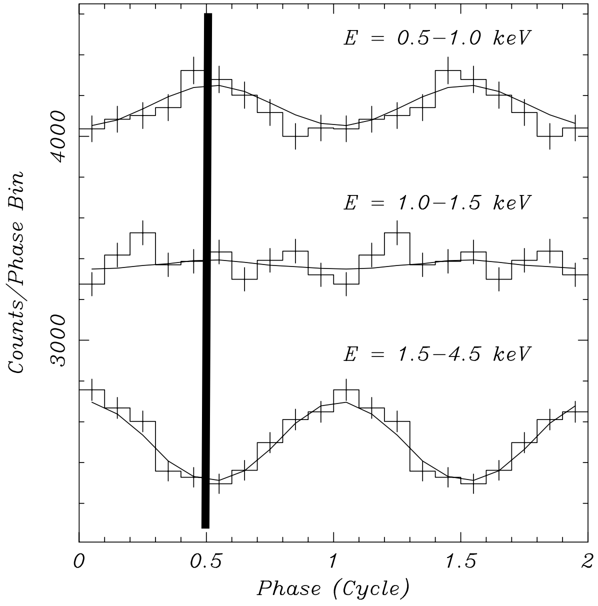
PSR J0821–4300:
Steady Flux and Temperatures

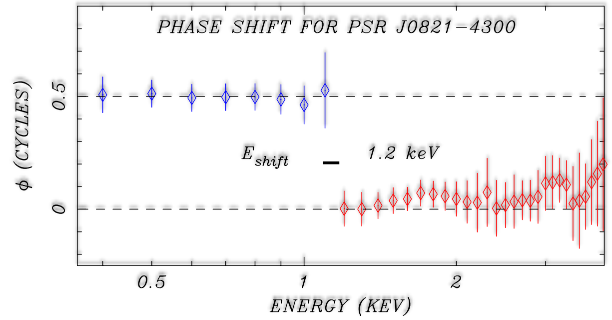


PSR J0821–4300:
The Remarkable Phase-shifting Anti-magnetar

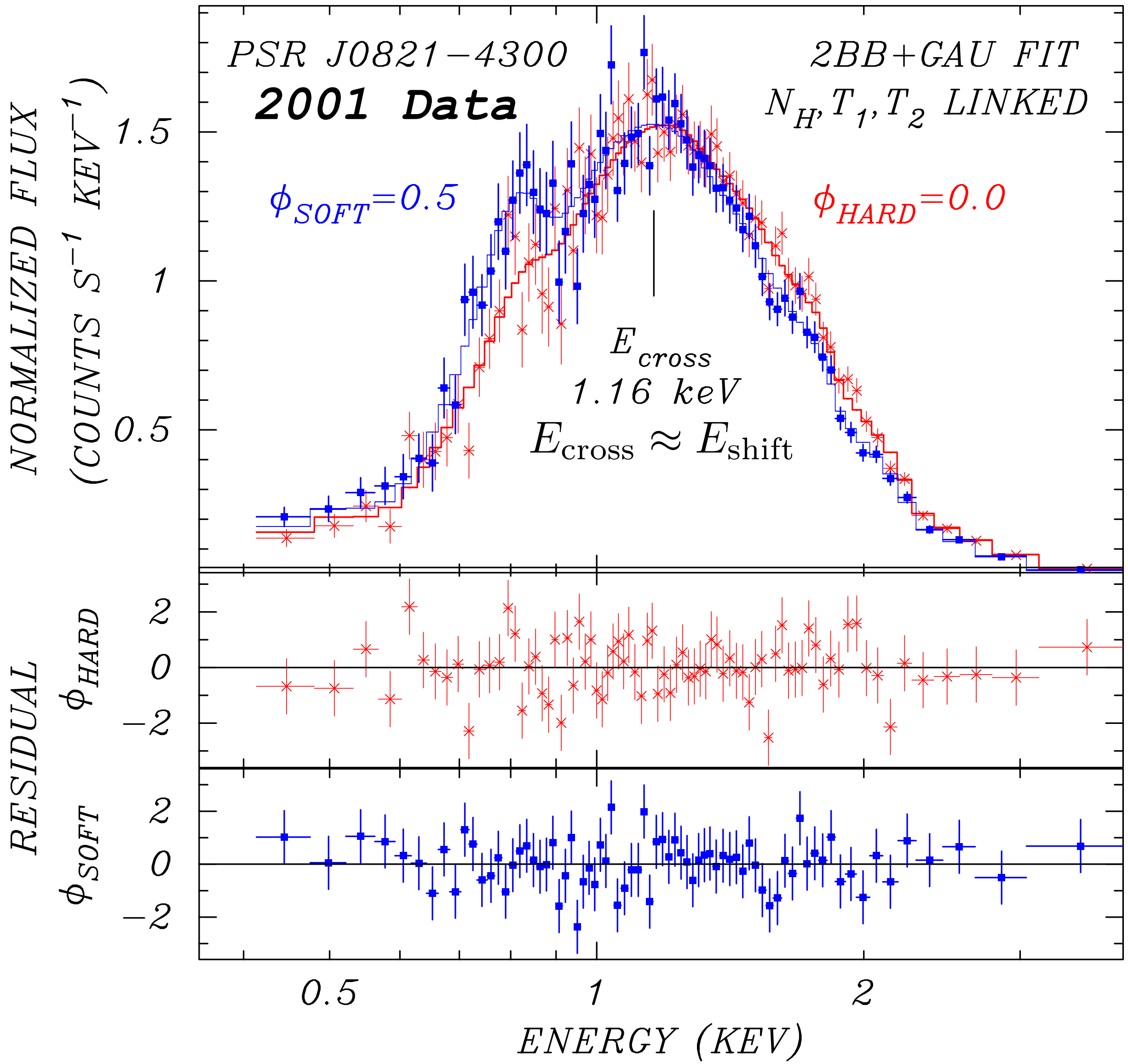
Phase reversal at ~1.2 keV







Phase Resolved Spectrum of PSR J0821-4300



Break up data into two phase bands,

Centered on pulse peak in the soft and hard bands,

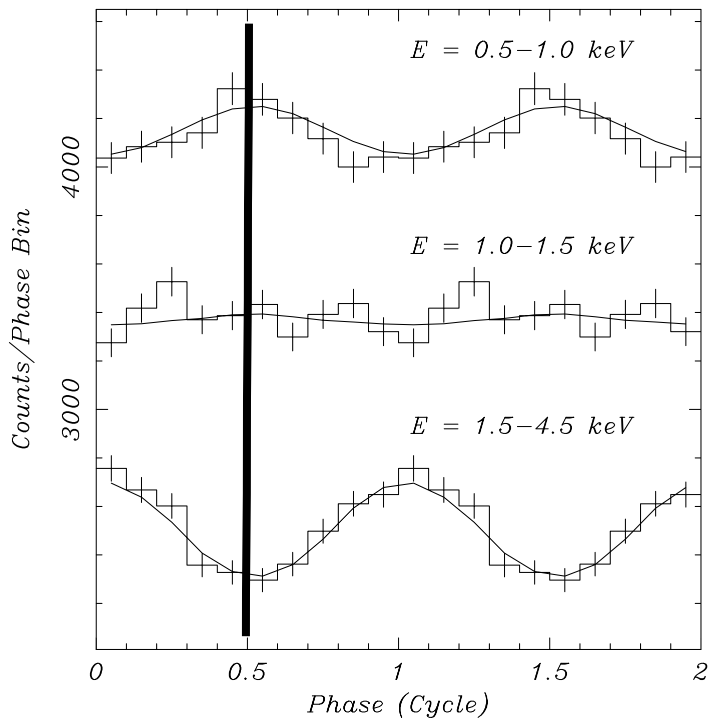
Fit the two spectra simultaneously with same 2BB model...

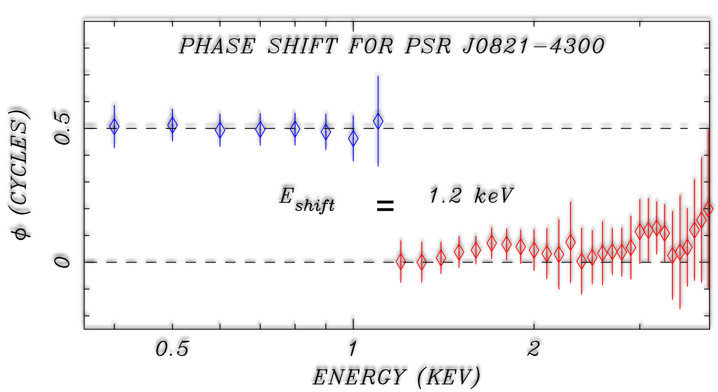
Each spectrum superposition of these two temperatures!!!

Spectral feature associated mainly with Soft Phase spectrum

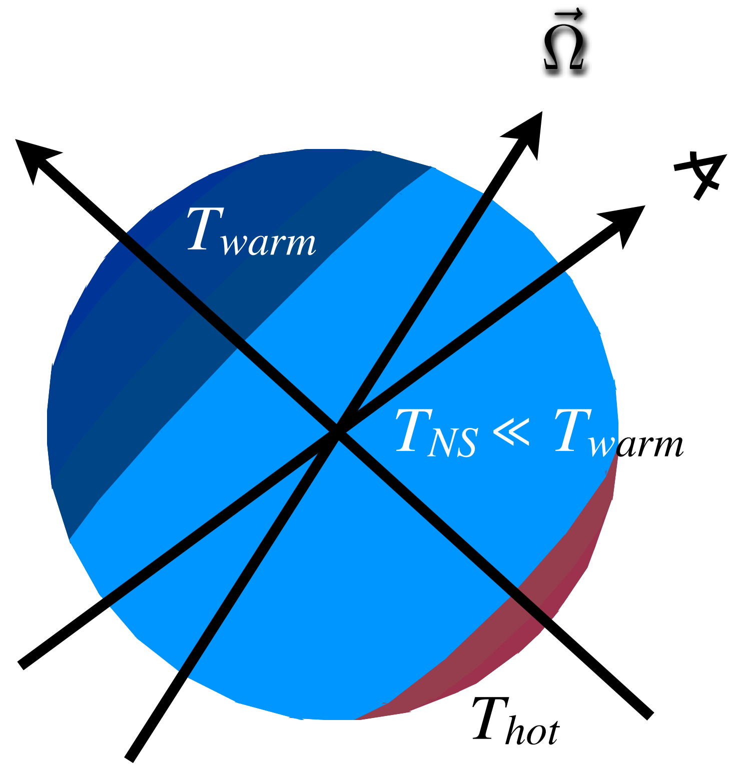
Antipodal Model Derived for 2001 Puppis A Data

(Gotthelf & Halpern 2009)





Two hot spots with distinct T's but similar projected flux…

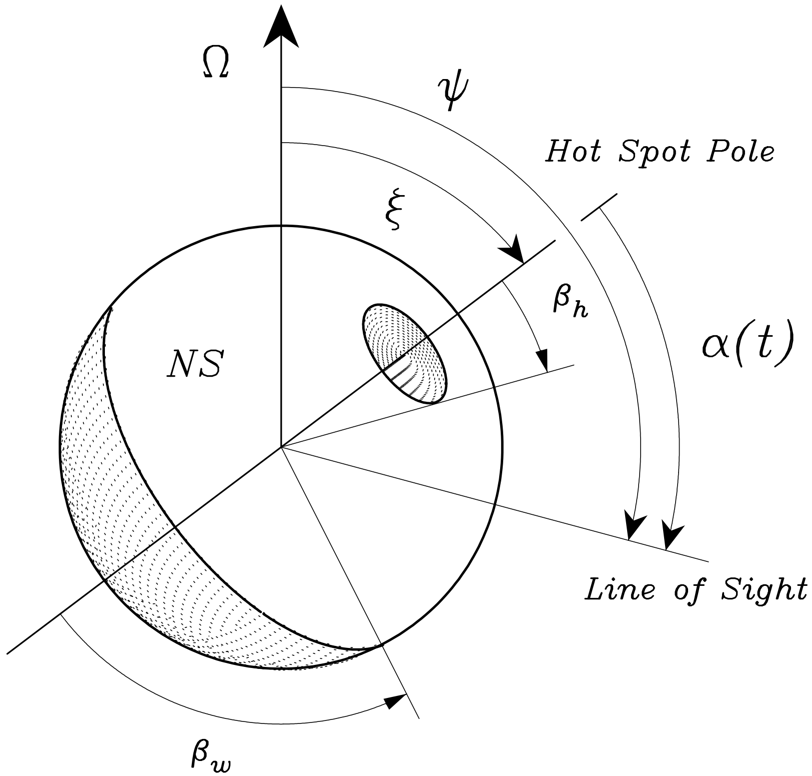


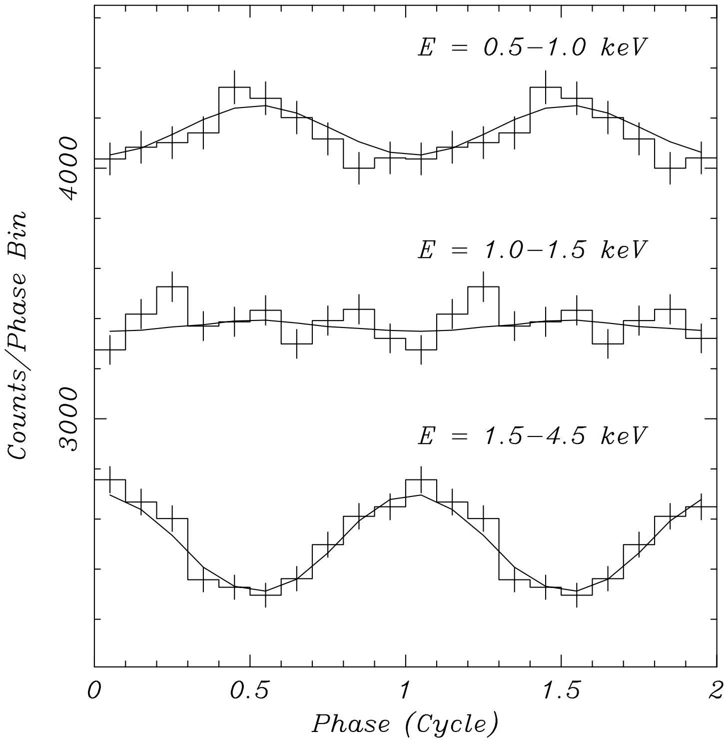
Can explain energy-dependent modulation and phase shift?

Antipodal Model: A Numerical Simulation

(Gotthelf, Perna, & Halpern 2010)

Two antipodal emission spots of size $\boldsymbol{\beta}_{h,w}$ and BB Temp. $\boldsymbol{T}_{h,w}$
XSPEC model spectral fits, assumed N_H, Distance, NS Radius

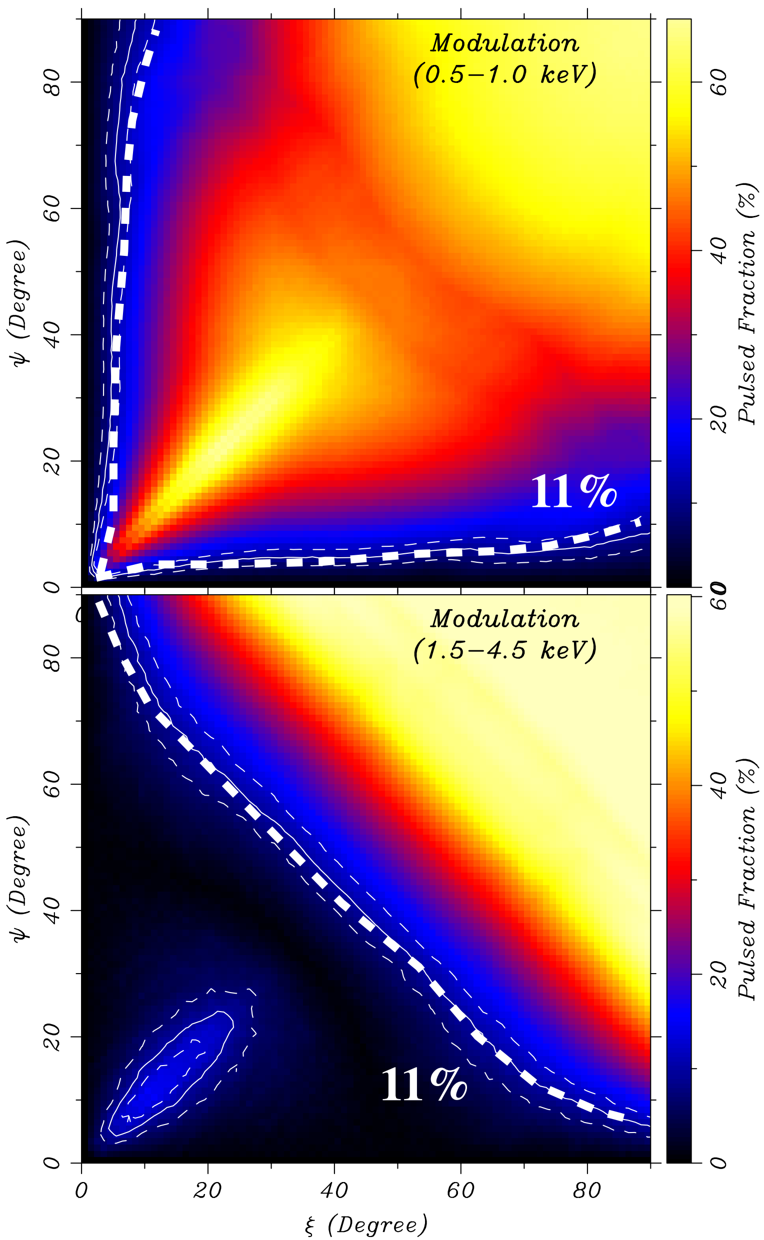




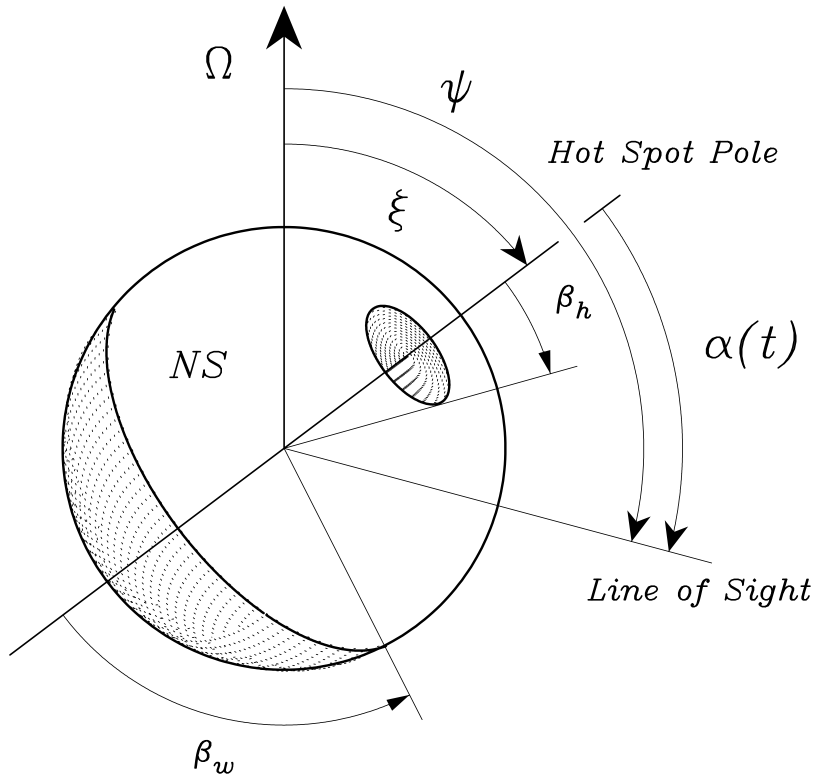
Find (***ξ,ψ***) that can reproduce modulation and phase reversal of energy-dependent pulse profile in three interesting energy bands.

Antipodal Model Predicted Modulation

($N_H = 4.8 \times 10^{21}$ cm^{-2}, D = 2.2 kpc, R = 12 km)

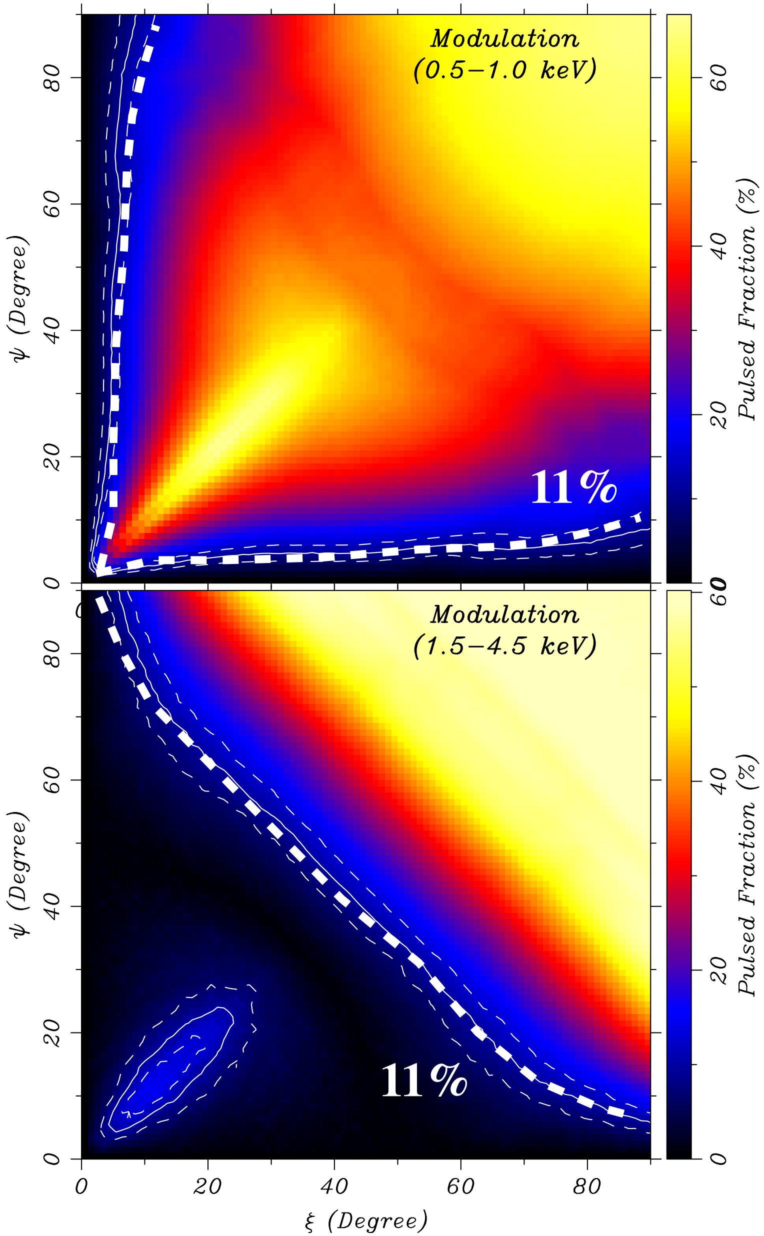


Compute modulation for any give pair of (***ξ***,***ψ***)

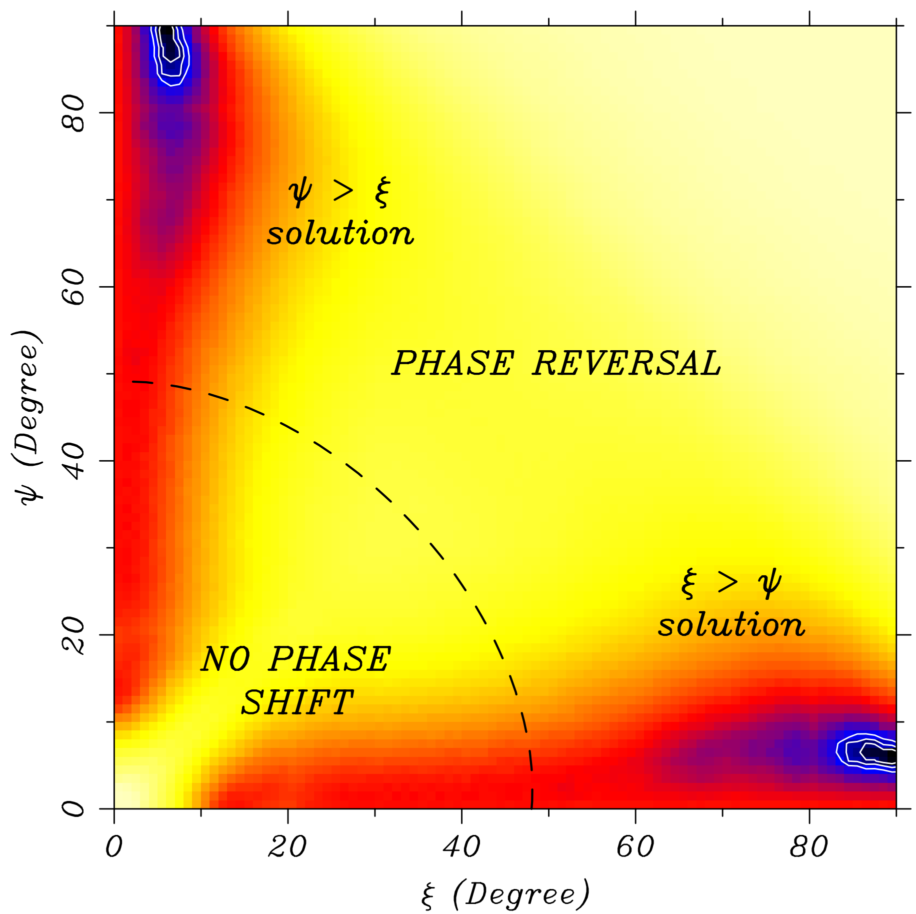


Antipodal Model Predicted Modulation

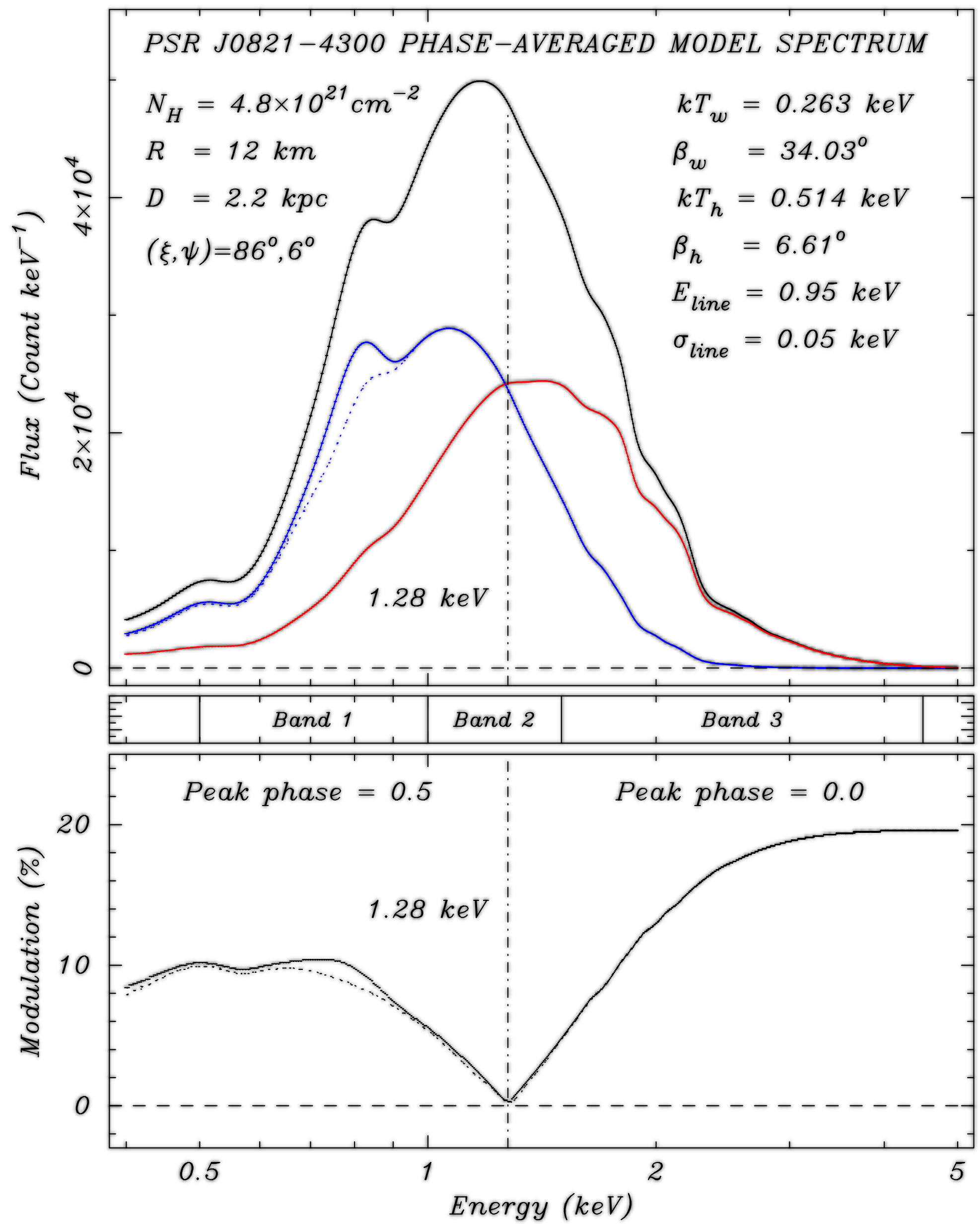
($N_H = 4.8 \times 10^{21}$ cm^{-2}, $D = 2.2$ kpc, $R = 12$ km)



Compared to observations in 3 bands:
Geometry is highly constrained
to (**ξ**,***ψ***) = (86°±2°,6°±1°)



Best-fit Antipodal Model Results



Phase reversal cross-over point is exactly at spectral component cross-over, as observed!

f_p =19.6% at highest energies

f_p of dominant component reduced in proportion to the contribution of other component.

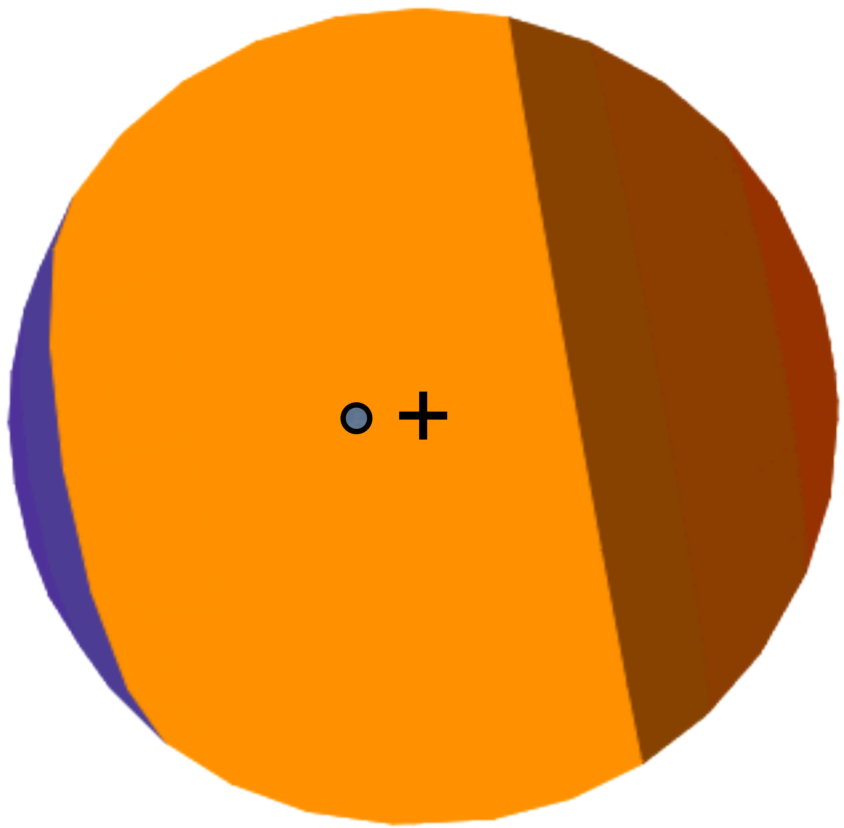
Switch of dominance between hot/warm spot emission component is the cause of phase reversal.

Antipodal Hot Spot Model in Motion

11% modulation (exaggerated here)

$\phi = 0$ ——

T_{warm} max
T_{hot} min



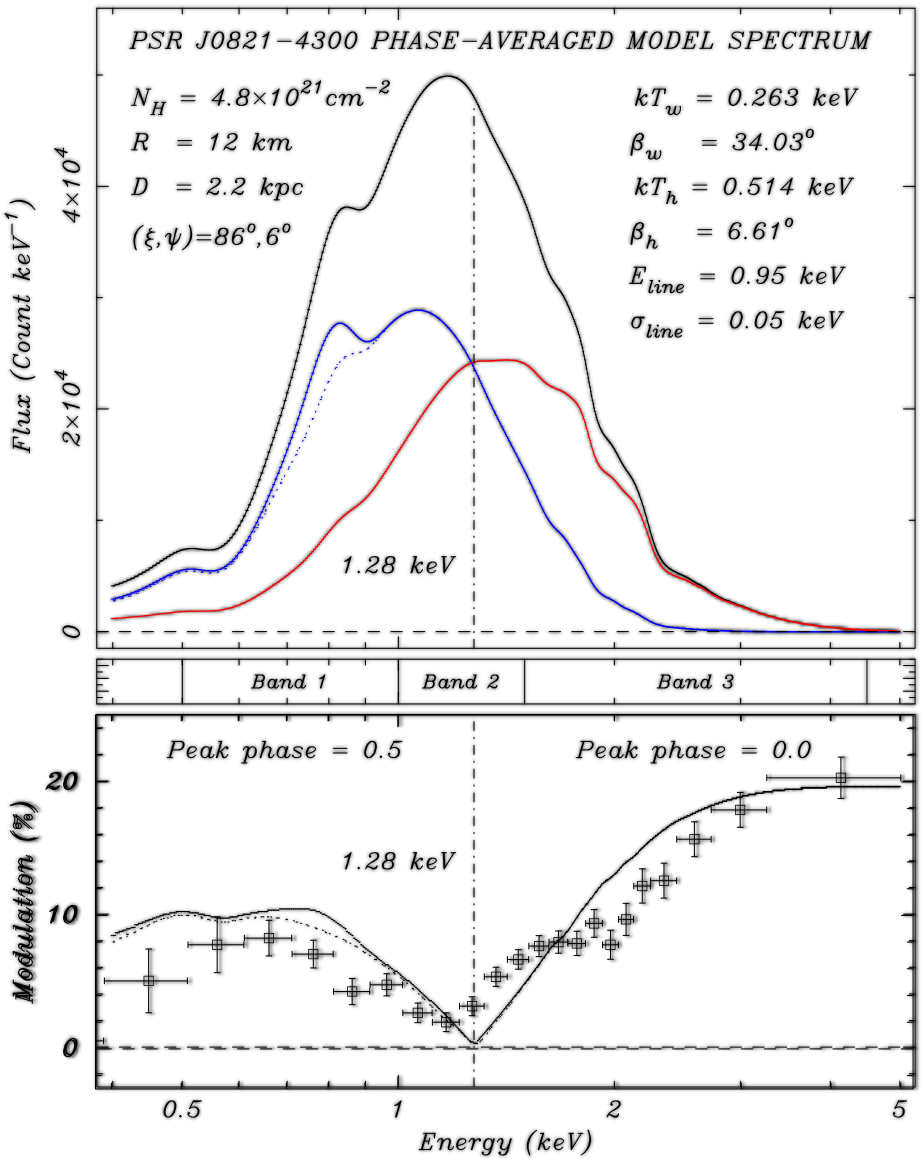
—— $\phi = \pi$

T_{warm} min
T_{hot} max

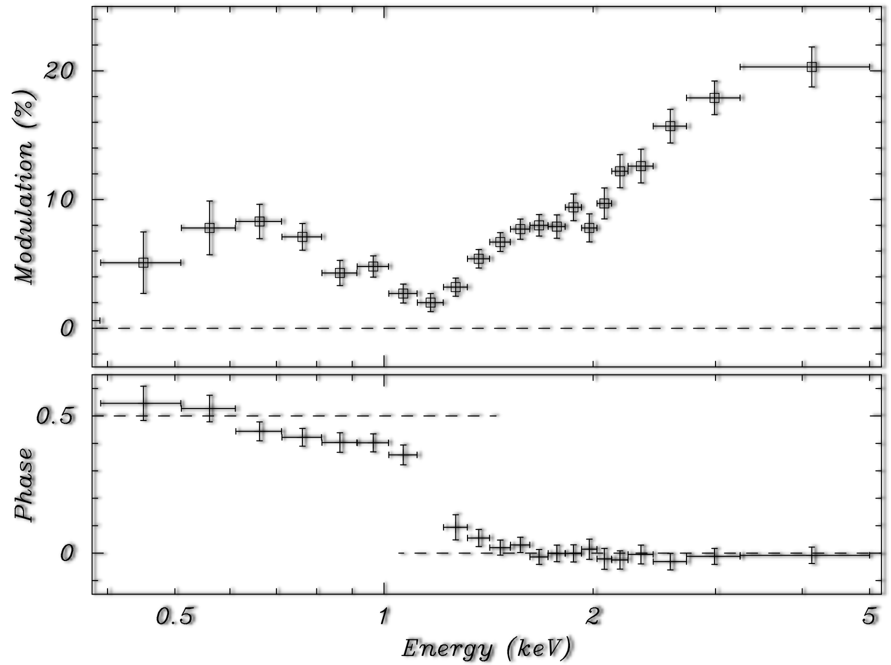
● *Rotation Axis*
+ *Line-of-sight*

Geometry well constrained by numerical model for pulse fractions!

Now can compare with combined XMM data



Sufficient photons to resolve modulations vs. energy instead of just three bands...



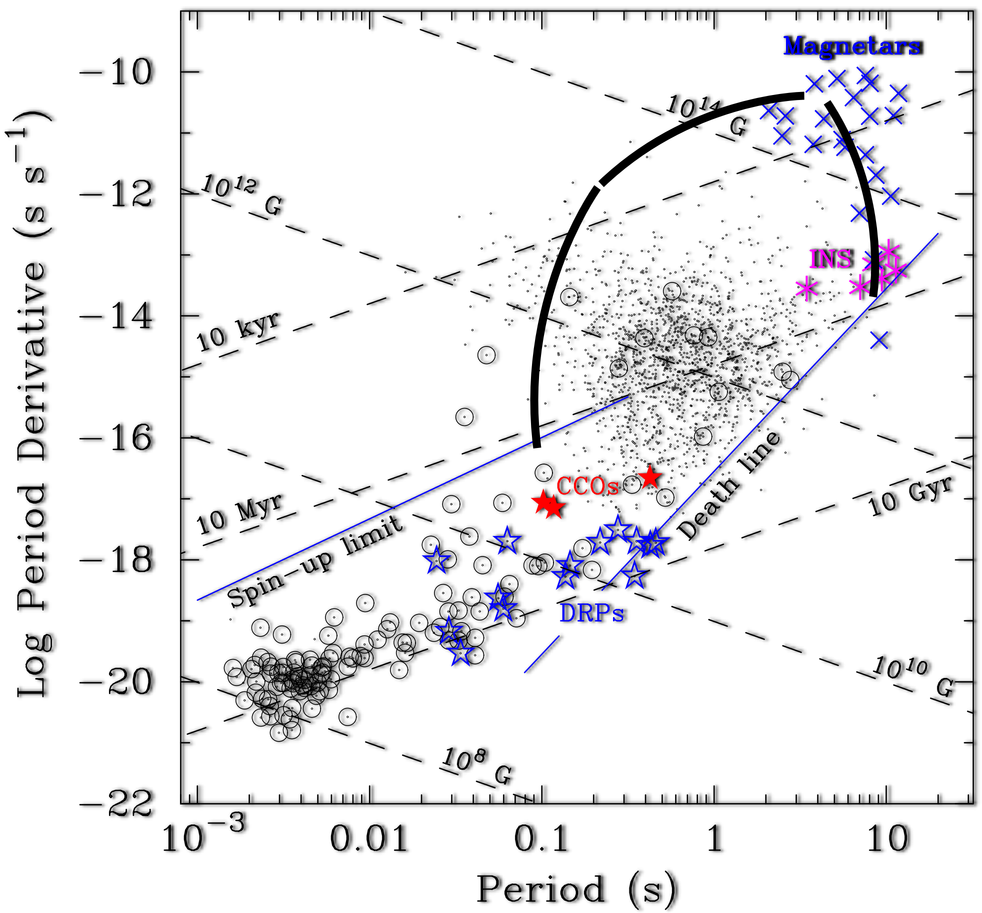
Interesting structure - offset dipole? anisotropic temp distribution?

What is Powering the CCOs?

How to explain $\dot{E} < L_x$ and large modulations with weak B-fields?

- *$\dot{E} < L_x$ => spin-down luminosity can't account for X-rays,*
- *Requires residual NS cooling,*
- *Can anisotropic conduction produce a sufficiently concentrated hot spots?*
- *But need strong B-field or magnetospheric activity to produce large modulation of Kes 79 CCO,*
- *Strong internal toroidal field but weak dipole fields? (talks by Pons, Viganó),*
- *Discrete temperature, small hot spots needed for Puppis A.*

Magnetic Evolution for NSs ?
CCO -> Magnetar -> INS



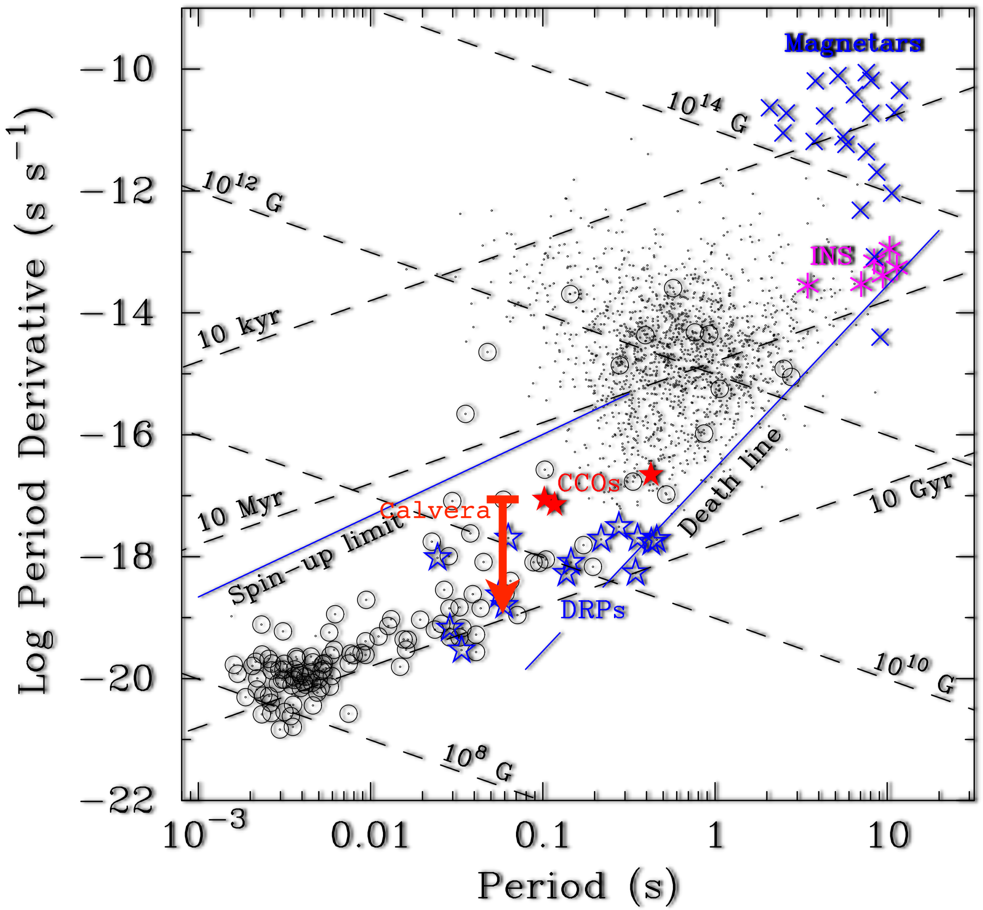
Where are the CCO descendants?

- *As numerous as magnetars, INS, and young RP pulsars,*
- *Should have similar numbers of older examples,*
- *What becomes of a CCO after its SNR disperses (evolution)?*
- *Difficult to notice, low luminosity, without bursts/flares, counterpart,*
- *Anti-magnetars occupy sparse region of (P,Pdot) diagram,*
- *Overlap the Disrupted Recycled Pulsars (DRPs),*

DRPs are old, isolated low B-field radio pulsars similar timing characteristic as CCOs…

Could the population of old DRPs, actually be young, orphan CCOs ?

Disrupted Recycled Pulsars: Orphan CCOs?



13 old, isolated radio pulsars, P > 20 ms and $B_s < 3\times10^{10}$ G (Lorimer 2005; Belczynski 2010)

Partially spun up in binaries, unbounded during 2nd SNe

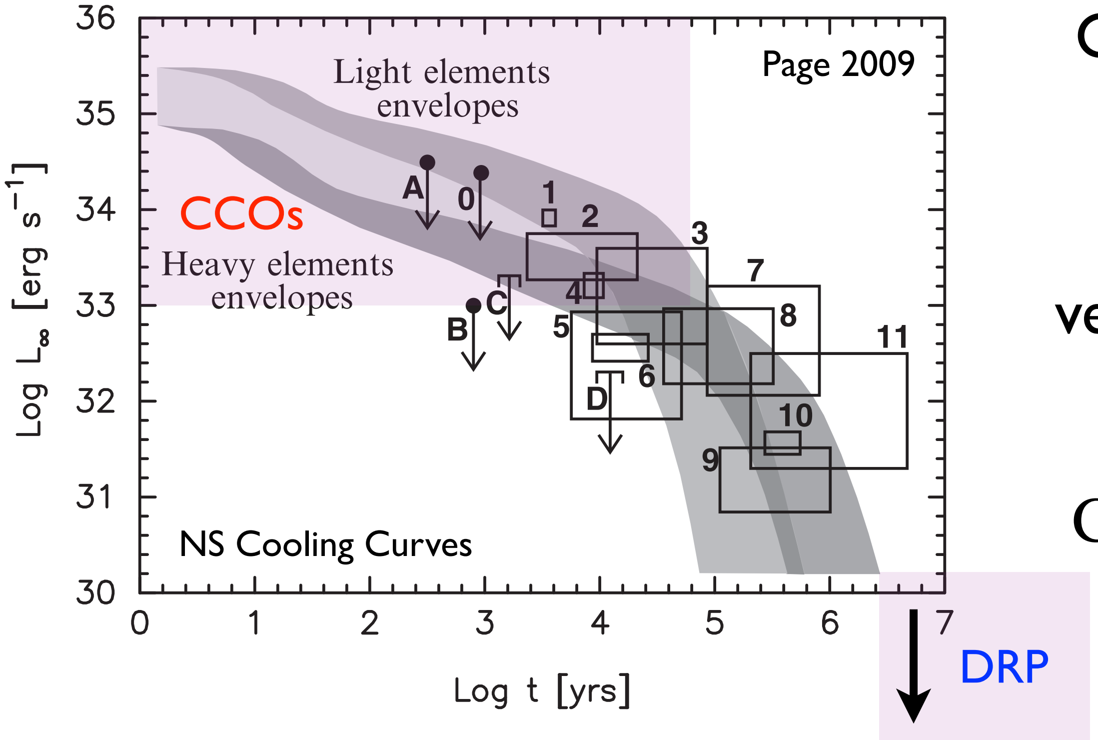
DRPs and anti-magnetars are indistinguishable by timing !!!

Could population of old DRPs, actually be young, orphan CCOs ?

Chandra programs to search for "orphan CCOs"… DRPs and *Calvera*

The Descendants: a Search for Orphan CCOs

(Gotthelf et al. 2013)



Chandra proposal to search all 13 DPRs for X-ray emission

DRPs and CCOs should have very different thermal signatures based on their age

Can distinguish between an old DRP and a young CCO by thermal X-rays...

Do not expect X-rays from the older radio pulsar, $L_x << 10^{29}$ erg/s

Look for X-ray emission from a young, cooling NS, $L_x > 10^{32}$ erg/s

Chandra source detection of 10 cts would be definitive !

3.5 ks Chandra observation sensitive to $\approx 10^5$ yr old CCO

The Descendants: a Search for Orphan CCOs

(Gotthelf et al. 2013)

Results:

No X-ray source found within DRP radio/Chandra error circles

Not a single Chandra photon associated with any DRP!

90% C.L. limits on the BB luminosity for 6 photons

Need to search further into radio population, higher B-fields…

Calvera: An Enigmatic X-ray Pulsar

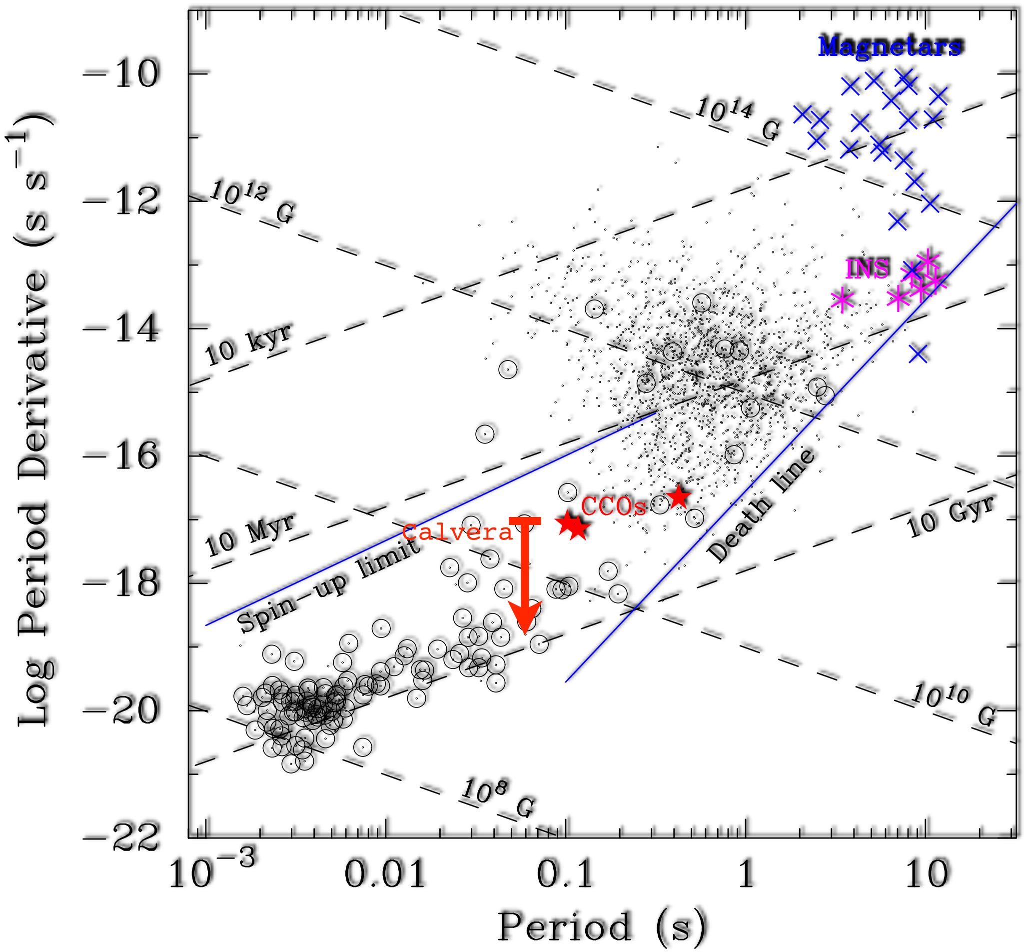
(Rutledge 2008; Zane 2011)

- ROSAT survey object 1RXS J141256.0+792204,
- Enigmatic: does not fall into a known class of NSs
- Cooler than a CCO, hotter than an INS,
- Low N_H, large b=+37° : distance unconstrained,
- Radio quiet (Hessels 2007; Zane 2011),
- 59 ms X-ray pulsar, ~ 20% modulation (Zane 2011),
- Disputed γ-rays signal (Zane 2011, Halpern 2011),
- Escaped from SNR? DRP? Orphan CCO? New Class?

Calvera: New Results !

(Halpern et al. 2013, in Prep.)

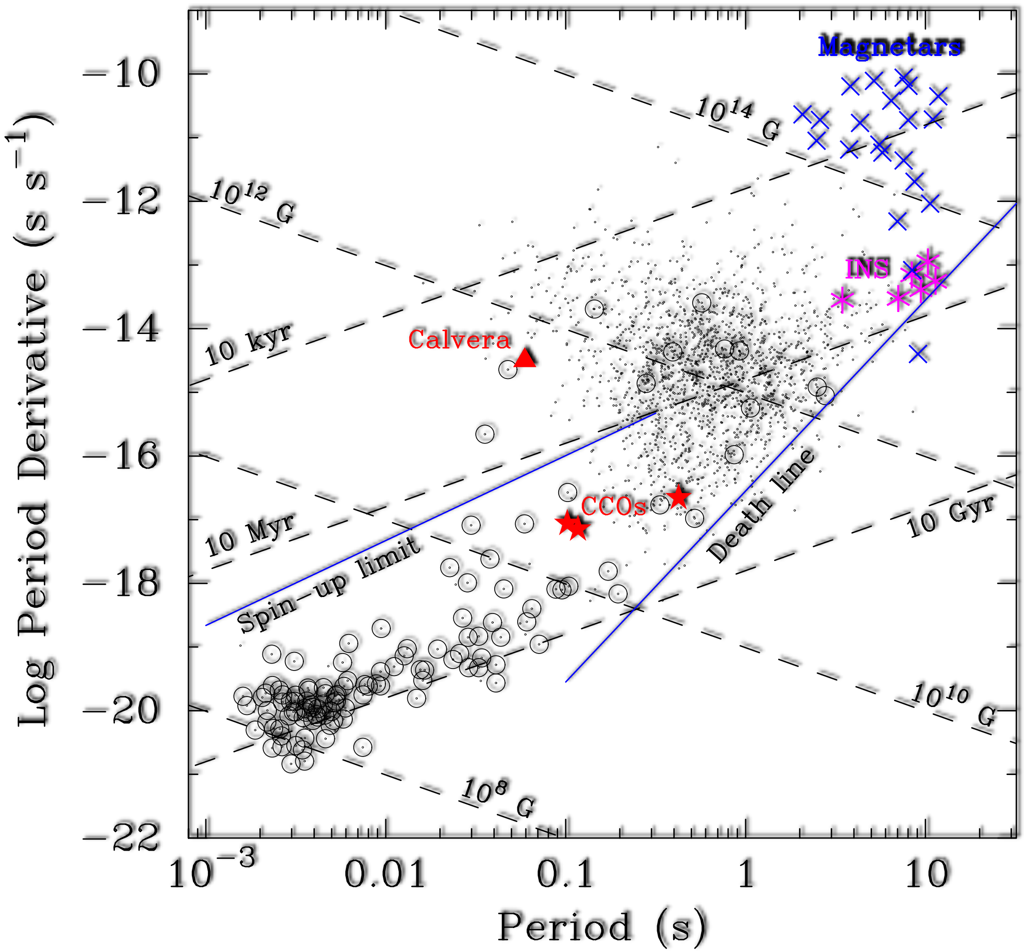
- Feb 2013 Chandra timing obs: 20 ks + 17 ks, 5 days span,
- Determine spin-down rate determined using 2009 XMM data



Calvera: New Results !

(Halpern et al. 2013, in Prep.)

- Calvera is an energetic RP pulsar, $\dot{E} \sim 6 \times 10^{35}$ erg/s,
- Not a DRP - above spin-up limit, $B \sim 5 \times 10^{11}$ G,



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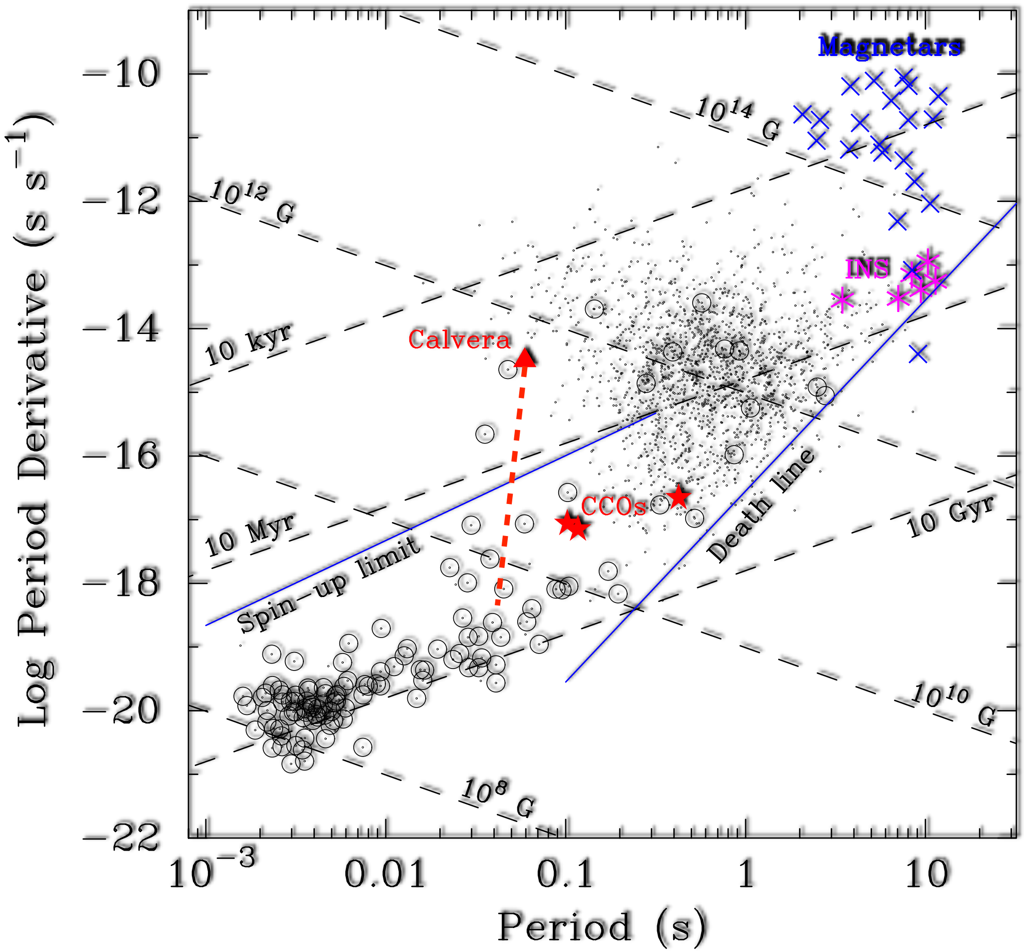

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An orphan CCO with re-emergent B-field?

Future Work

- *Search for new CCOs,*
- *Complete search of current CCOs for pulsations,*
- *Model Puppis A observations with toroidal fields simulations,*
- *Model surface emission and geometry of other anti-magnetars,*
- *Search for descendants, orphan CCOs*

- *Lots to do!!!*