Young Neutron Stars and the Role of Magnetic Fields in their Evolution

Eric Gotthelf
(Columbia University)

"The X-ray Universe 2011" ☀ *28 June 2011, Berlin Germany*

Talk Outline

- Recent Highlights of Young Isolated Neutron Stars:

  Classic rotation-powered (and flaring?) pulsars...

  Strong (and weak?) magnetic field magnetars...

  *Low-field (and orphaned?) anti-magnetars (**magniños**)…*

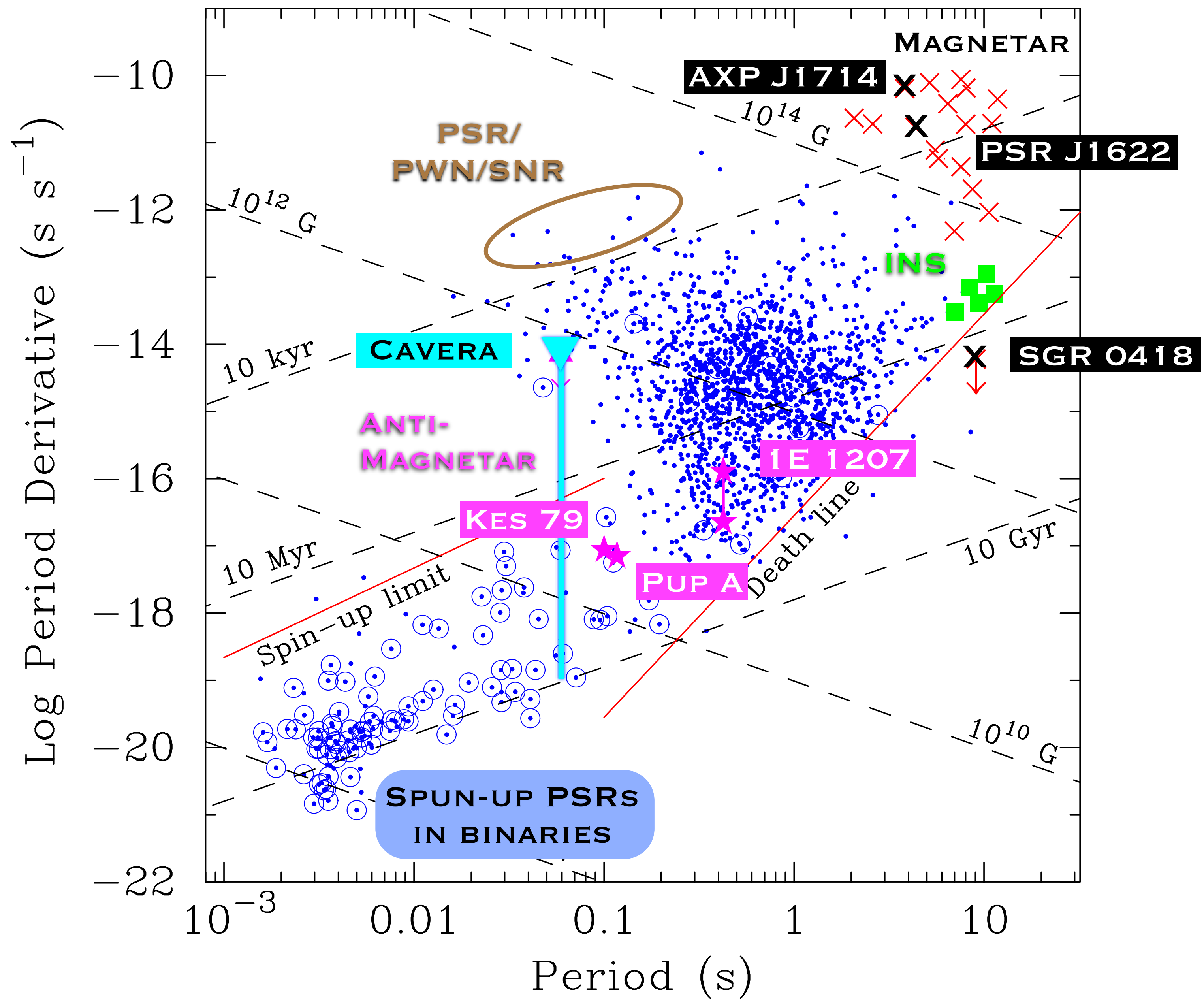
- Latest Results on Anti-magnetar (CCO) pulsars:

  New CCO spin-down measurements and limits…

  An antipodal emission model for the CCO in Puppis A…

  The search for more CCOs as pulsars…

Evolution of Pulsars: P vs $\dot{P}$ Diagram



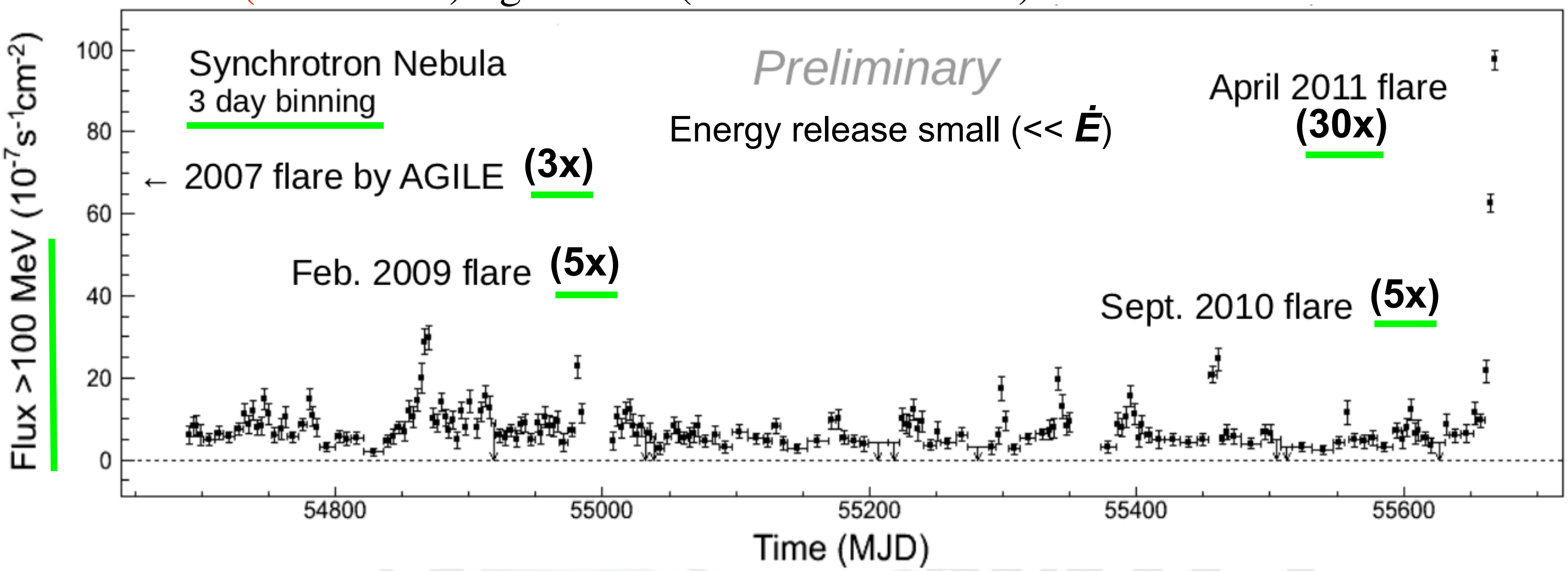
Properties of Young Isolated NSs

	Spin Powered	AXP MAGNETAR	SGR MAGNETAR	CCO AMAG	INS
Examples	~ 40	~ 10	~ 8	~ 10	~10
L_x (erg/s)	≲ 10^{37}	10^{34} - 10^{35}	10^{34} - 10^{35}	10^{33} - 10^{34}	~10^{32}
Emission	Radio (X-γ- ray)	X-ray/IR (Radio)	γ/X-ray/IR	X-ray only	X-ray/IR
Spectrum	Γ ~ 1.5 (X-rays)	kT ~ 0.5 keV kT, Γ ~ 4, E <10 keV Γ ~ 1, E >10 keV	kT ~ 0.2 keV kT, Γ ~ 2, E <10 keV Γ ~ 1, E >10 keV	kT ~ 0.4 keV (2BB)	kT ~ 0.1 keV
Variable?	Steady	Transient/Bursts	Episodic/Bursts	Steady	Steady
PWN?	High $\dot{E}$	No	No	No	No
Periods	16 ms - 8 s	2 - 12 s	2 - 8 s	0.1 - 0.4 s	3 - 11 s
$\dot{P}$	~10^{-14}	~10^{-12}	~10^{-12}	~10^{-17}	~10^{-14}
$\dot{E}$ (erg/s)	≲10^{38}	~10^{33}	~10^{33}	~10^{32}	~10^{30}
B-field	~10^{12} G	~10^{14} G	~10^{14} G	~10^{10} G	>10^{13} G
Age	< 40,000	~ 10^4 yr	~ 10^4 yr	≲ 10^4 yr	~ 10^6 yr

High Energy Flares from the Crab Nebula!

(Tavani et al. 2011; Abdo et al. 2011)

Fermi (>100 MeV) light curve (from Baldini 2011)



- Strong temporal variability from nebula $E > 15$ keV,
- Rapid *Fermi* variability during the 2011 flare implies $< 0.04''$ region,
- Pulsed *RXTE* flux exhibits steady decline consistent with spin-down losses.

Recent Discoveries of Highly Energetic Pulsars

PSR Name	P (ms)	τ (kyr)	B (G)	$\dot{E}$ (erg s^{-1})	SNR	Assoc.	Reference
J2022+3842	24	8.9	1.0×10^{12}	1.2×10^{38}	G76.9+1.0	Radio	Arzoumanian et al. 2011
J1813−1749	45	5.6	2.4×10^{12}	5.6×10^{37}	G12.8−0.0	HESS	Gotthelf & Halpern 2009
J1400−6326	31	13	1.1×10^{12}	5.1×10^{37}	G310.6−1.6	IGR	Renaud el al. 2010
J1747−2809	52	5.3	2.9×10^{12}	4.3×10^{37}	G0.9+0.1	Radio	Camilo et al. 2009
J1849−0001	39	43	7.5×10^{11}	9.8×10^{36}	...	IGR/HESS	Gotthelf et al. 2011

- J2022+3842 - $\dot{E} = 10^{38}$, but faint PWN, like 69 ms PSR J1617-5055,
- J1813-1749 - HESS located, bright X-ray PWN in a radio SNR,
- J1400-6326 - Located in X-ray survey of INTEGRAL sources,
- J1747-2809 - Finally! Very faint radio pulsar in a bright SNR/PWN.
- J1849-0001 - IGR and HESS located, transition from a synchrotron X-ray source to a inverse Compton gamma-ray source?

Key take-aways

- Lot’s more energetic pulsar to be found
- Need multi-wavelength observation to locate
- Exhibit a rich range of spectroscopic properties

New Young GeV Pulsars Discovered with Fermi

(Saz Parkinson et al. 2010) (+3 not show. More?)

1FGL Name	**PSR** Name	P (ms)	τ (kyr)	B (G)	$\dot{E}$ (erg s^{-1})
J1023.0−5746	J1023−5746	111	4.6×10^3	6.6×10^{12}	1.1×10^{37}
J1044.5−5737	J1044−5737	139	4.0×10^4	2.8×10^{12}	8.0×10^{35}
J1413.4−6205	J1413−6205	109	6.3×10^4	1.8×10^{12}	8.3×10^{35}
J1429.9−5911	J1429−5911	115	6.0×10^4	1.9×10^{12}	7.7×10^{35}
J1846.4+0919	J1846+0919	225	3.6×10^5	1.5×10^{12}	3.4×10^{34}
J1954.3+2836	J1954+2836	92	6.9×10^4	1.4×10^{12}	1.0×10^{36}
J1957.6+5033	J1957+5033	374	8.4×10^5	1.7×10^{12}	5.3×10^{33}
J2055.8+2539	J2055+25	319	1.2×10^6	1.2×10^{12}	4.9×10^{33}

In all, 88 Fermi pulsars!

- Total of 27 blind search pulsars in all (16 PSRs of Abdo et al. 2009)
- Only 3 detected as radio pulsars!
- Many associated with unIDed EGRET sources,
- + 34 γ-ray pulsars and 27 MSPs detected using radio ephemerides

Calvera, A Mysterious Pulsar

Rutlege et al. (2007)

- High ***b*** INS whose properties does not allow easy classification,
- Soft thermal spectrum ($kT = 0.2$ keV) similar to MSPs & INSs,
- Inferred distance above the Galactic plane implied extreme velocity

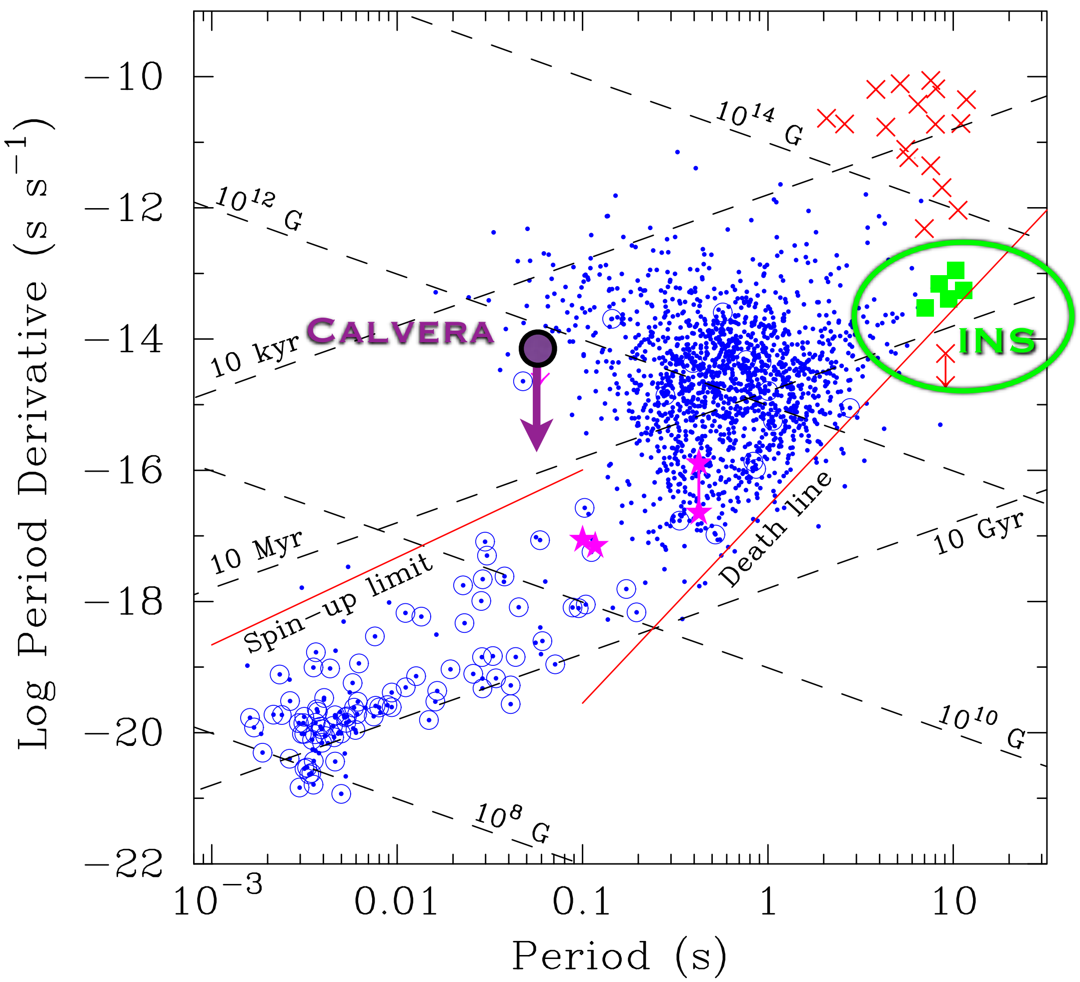
Zane et al. (2011)

- Discovery of 59 ms pulsations !
- Energy-dependent pulse fraction
- No measured spin-down
- Rotation-powered? Orphaned CCO? Mildly Recycled Pulsar?

How does it fit into the big picture?

Calvera, A Mysterious Pulsar

(Rutlege et al. 2007; Zane et al. 2011)



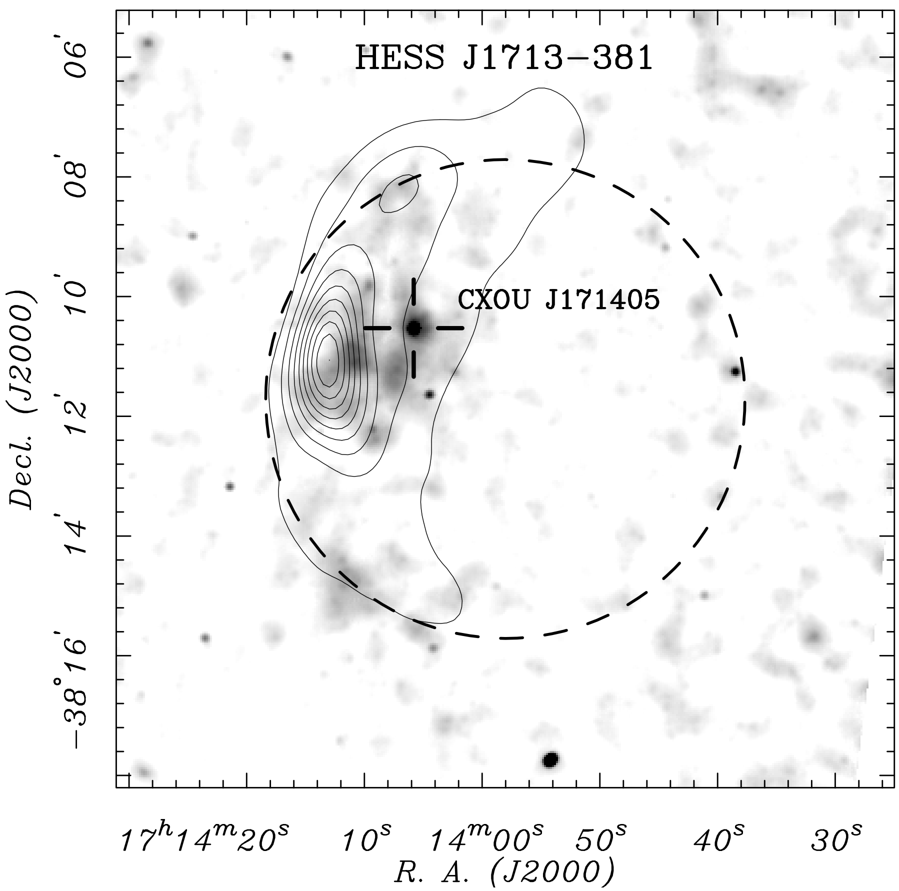
Issue: Is $\dot{E}$ sufficient to power polar cap heating of a RP pulsar?

- If so, partially recycled PSR $B \sim 10^{10}$ G. Why no radio?
- If too low, likely Calvera is an orphan CCO, $B \sim 10^{10}$ G,
- High ***b*** limits distance for a young PSR: if close, expect γ-rays

Period derivative measurement is critical to understanding Calvera!

A magnetar in SNR CTB 37 coincident with HESS J1713-381

(Halpern & Gotthelf 2010, 2011; Sato et al. 2011)



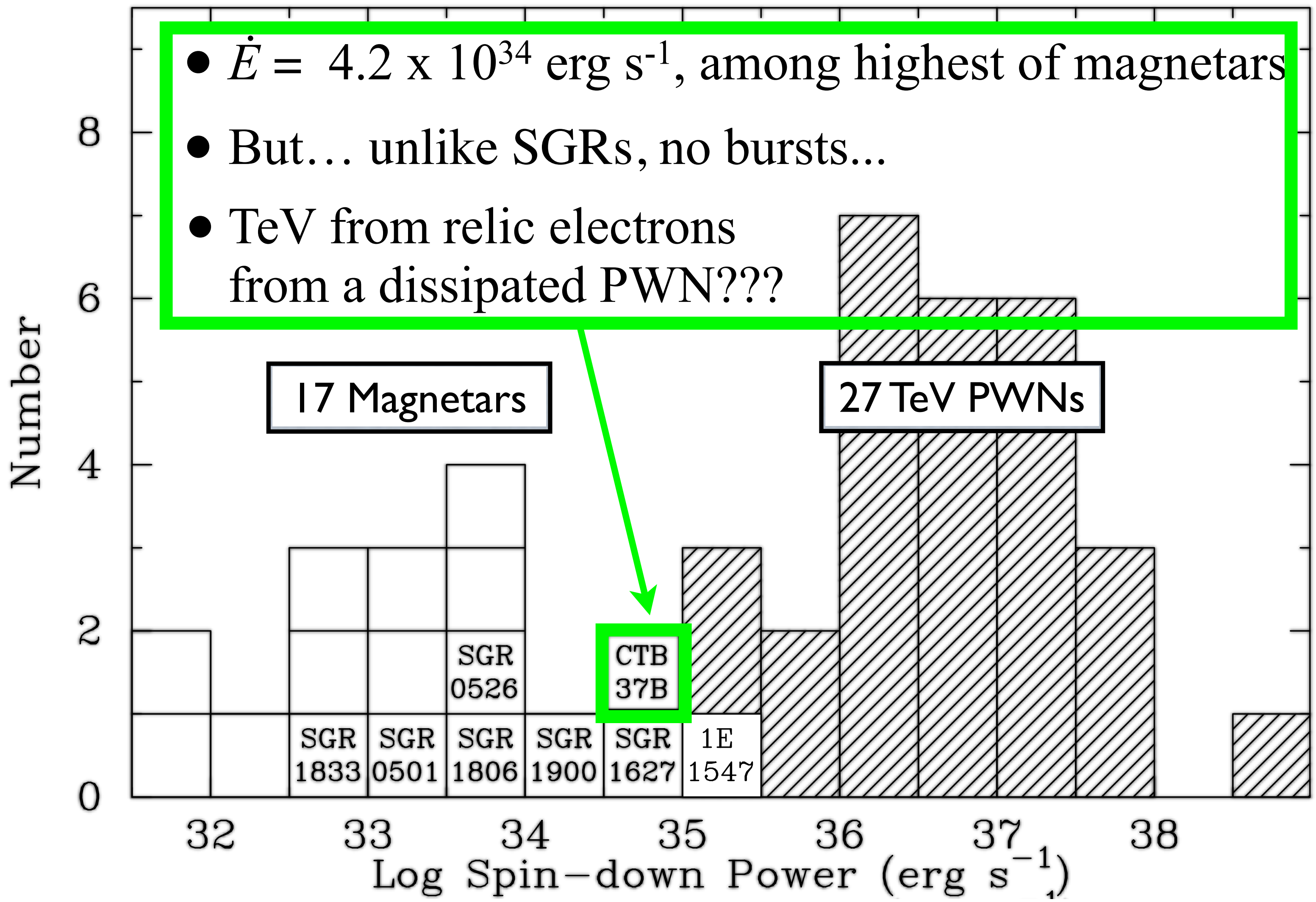
HESS J1713-381 is identified with the young SNR CTB 37

Evidence for a central magnetar:

- 2 comp. magnetar spectrum,
- 3.82 s pulsar PSR J1714-3810 !
- $B_{\mathrm{dipole}} = 5 \times 10^{14}$ G,
- Evidence of variable spin-down.
- $\tau = 1$ kyr, consistent with SNR age.

Unlikely to be historical SN of 393 AD - too far away for long visibility

HESS J1713-38 / SNR CTB 37 Magnetar



PSR J1622-4920: A Radio Discovered Magnetar

(Levin et al 2010)

- Slow, 4.3 s pulsar discovered in high temporal (!) radio survey,
- Rapid spin-down implies $B_{dip} \sim 3 \text{ x}10^{14}$ G, $\dot{E} \sim 8 \text{ x}10^{33}$ erg s^{-1}, $\tau_c > 4$ kyr,
- Extreme variability - 12 years of archival data on nearby pulsars,
- Year-long intervals of non-detections, erratic spin-down,
- Radio behavior similar to the two other radio emitting magnetars, TAXPs
- Steady X-ray emission implies, $L_x/\dot{E} \sim 0.3$, no know X-ray outbursts,
- First example of a magnetar discovered from its radio emission.

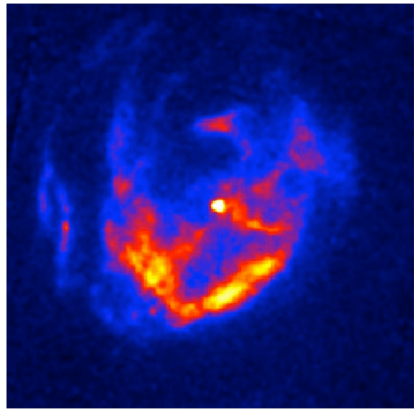
SGR 0418+5729: A Low-field Magnetar?

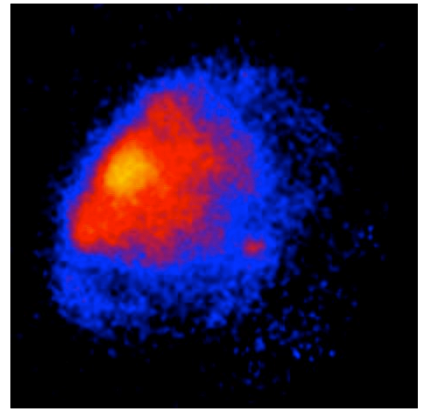
(van der Host et al 2010; Rea et al. 2011)

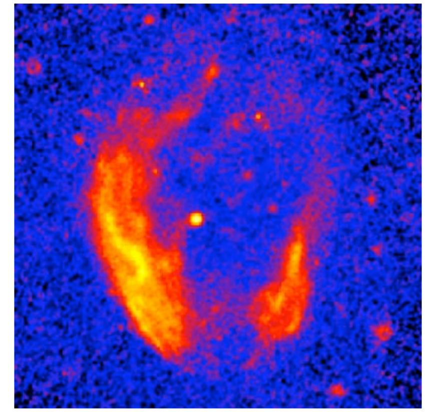
- Discovered via magnetar-like bursts in the Fermi GBM,
- Temporal and spectral properties confirms a magnetar origin,
- $P = 9.1$ s pulsar - but no significant spin-down detected in 500 days!
- Implies $B_{dip} < 7.5 \times 10^{12}$ G ! $\dot{E} < 3 \times 10^{29}$ erg s^{-1} !?! ($\tau_c > 3 \times 10^7$ yr)
- Lower *B*-field than PSR J1622-4950 and even PSR J1846-0258 in Kes 75
- Activity due to stored magnetic energy of internal toroidal field?
- Can account for $L_x = 6 \times 10^{31}$ erg s^{-1} quiescent luminosity?
  ($B^2_{tor} \approx 6 L_x \tau_c / R^3_{NS}$ --> $B_{tor} \approx 5 \times 10^{14}$ G)
- First example of magnetar properties for pulsar with $B_{dip} < B_{QED}$

Program to Measure CCO Pulsar Spin-down

Latest Timing Results on CCO pulsars







	PSR J1852+0040 SNR Kes 79	**PSR J0821−4300** SNR Puppis A	**PSR J1210−5209** SNR PKS 1209−52/52	
			Sol#1	Sol#2
P (ms)	104.9126	112.7995	424.1307	
Pulsed Fraction (%)	64	11	9	
$\dot{P}(\times 10^{-17})^a$	0.868 ± 0.009	0.7 ± 0.1	2.24 ± 0.04	1.27 ± 0.04
$\dot{E} \equiv I\Omega\dot{\Omega}$ (erg s^{-1})	3.0×10^{32}	1.9×10^{32}	1.2×10^{31}	6.6×10^{31}
$L(\mathrm{bol})/\dot{E}^b$	18	31	167	30
$B_p(\times 10^{10}$ G)	3.1	2.8	9.9	24
$\tau \equiv P/2\dot{P}$ (Myr)	192	256	300	53
SNR age (kyr)	~ 7	~ 4	~ 7	

$^a\dot{P}$ measurement for PSR J0821−4300 is likely limited by the Shklovski Effect.

^bL(bol) is the bolometric luminosity at the nominal distance.

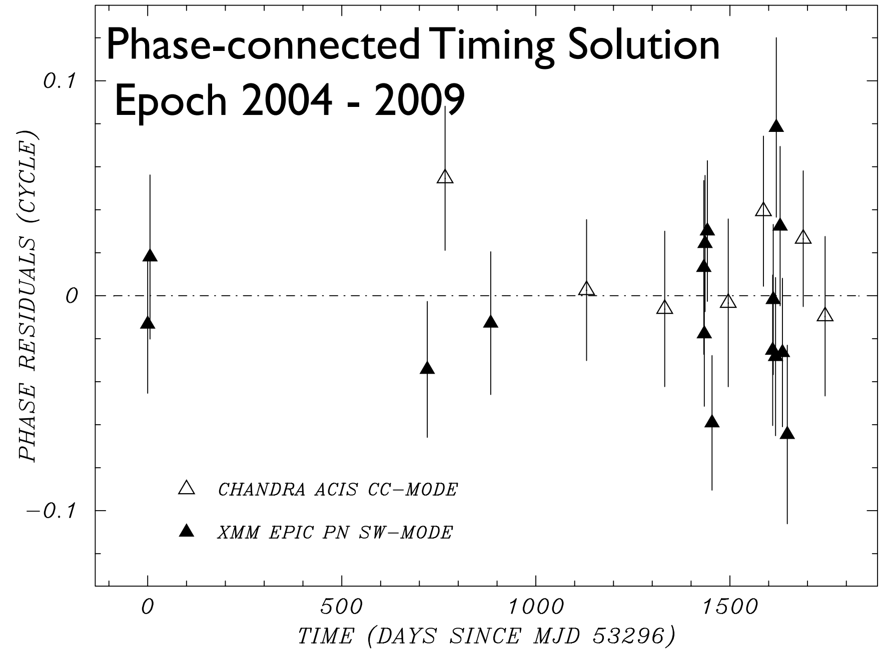
Timing PSR J1852+0040 in Kes 79

(Halpern & Gotthelf 2010)

Table 1. Log of X-ray Timing Observations of PSR J1852+0040

Mission	Instr/Mode	ObsID/Seq#	Date (UT)	Exposure (ks)	Start Epoch (MJD)	Period[a] (ms)	Z_3^2
XMM	EPIC-pn/SW	0204970201	2004 Oct 18	30.6	53296.001	104.912638(39)	121.7
XMM	EPIC-pn/SW	0204970301	2004 Oct 23	30.5	53301.984	104.912612(55)	77.2
XMM	EPIC-pn/SW	0400390201	2006 Oct 08	29.7	54016.245	104.912610(47)	92.4
Chandra	ACIS-S3/CC	6676/500630	2006 Nov 23	32.2	54062.256	104.912592(40)	94.0
XMM	EPIC-pn/SW	0400390301	2007 Mar 20	30.5	54179.878	104.912600(43)	107.5
Chandra	ACIS-S3/CC	9101/500964	2007 Nov 12	33.1	54426.674	104.912615(40)	95.8
Chandra	ACIS-S3/CC	9102/500965	2008 Jun 16	31.2	54628.080	104.912593(40)	115.5
XMM	EPIC-pn/SW	0550670201	2008 Sep 19	21.2	54728.758	104.912563(84)	61.7
XMM	EPIC-pn/SW	0550670301	2008 Sep 21	31.0	54730.066	104.912594(46)	84.2
XMM	EPIC-pn/SW	0550670401	2008 Sep 23	34.8	54732.079	104.912573(42)	80.3
XMM	EPIC-pn/SW	0550670501	2008 Sep 29	33.0	54738.016	104.912596(40)	97.4
XMM	EPIC-pn/SW	0550670601	2008 Oct 10	36.0	54750.006	104.912641(40)	90.0
Chandra	ACIS-S3/CC	9823/501015	2008 Nov 21	30.1	54791.803	104.912645(55)	69.8
Chandra	ACIS-S3/CC	9824/501016	2009 Feb 20	29.6	54882.483	104.912591(53)	80.4
XMM	EPIC-pn/SW	0550671001	2009 Mar 16	27.0	54906.255	104.912610(48)	97.9
XMM	EPIC-pn/SW	0550670901	2009 Mar 17	26.0	54907.609	104.912592(60)	82.9
XMM	EPIC-pn/SW	0550671201	2009 Mar 23	27.3	54913.582	104.912616(46)	104.8
XMM	EPIC-pn/SW	0550671101	2009 Mar 25	19.9	54915.654	104.912544(85)	75.8
XMM	EPIC-pn/SW	0550671301	2009 Apr 04	26.0	54925.539	104.912590(52)	97.9
XMM	EPIC-pn/SW	0550671901	2009 Apr 10	30.5	54931.535	104.912620(48)	82.9
XMM	EPIC-pn/SW	0550671801	2009 Apr 22	28.0	54943.897	104.912621(69)	67.4
Chandra	ACIS-S3/CC	10128/501055	2009 Jun 02	33.2	54984.888	104.912596(37)	117.9
Chandra	ACIS-S3/CC	10129/501056	2009 Jul 29	32.2	55041.231	104.912633(40)	105.6

[a]Barycentric period derived from a Z_3^2 test. The Leahy et al. (1983) uncertainty on the last digits is in parentheses.



PERIOD DERIVATIVE ***MEASURED***! $\dot{P} = 8.7 \times 10^{-18}$!!!

- $\dot{E} = 3.0 \times 10^{32}$ erg/s, ***~10* x *lower*** than its X-ray luminosity,
- $\tau = 192$ Myr, ***~10⁴* x *greater*** than the SNR age,
- B = 3.1×10^{10} G, ***~100* x *too low*** for a typical young PSR.

What is Powering the Pulsed Emission from PSR J1852+0040?

Of the two BB spectral components, the cooler one may be due to residual cooling.

But the 0.7 km radius of the hotter BB component is difficult to explain for a NS with a weak B-field and small E-dot.

- *Can interior cooling with anisotropic conduction produce a sufficiently concentrated hot spot?*
- *Can a locally strong B-field generate a hot spot by magnetic field decay?*
- *Can magnetic field be buried by fall-back of supernova ejecta?*
- *~~Can continuing accretion be the source of energy for the X-ray emission?~~ (Ruled out by small P-dot)*

Implications for CCO Pulsars

1) In the magnetic dipole model, the lower limits on the pulsar spin-down ages exceeded their SNR ages by 3 orders of magnitude…

…this implies that the pulsar was born spinning at its current period.

Their long periods fall within range of radio-pulsar birth periods ($\langle P \rangle \sim 300$ ms, $\sigma_P \sim 150$ ms; Faucher-Giguere & Kaspi 2006).

2) The CCO pulsars lie in a region of the (P, $\dot{P}$) diagram thought to be occupied by old, $\sim 10^8$ year-old radio pulsars…

…many of the apparently older PSRs might be anti-magnetars?

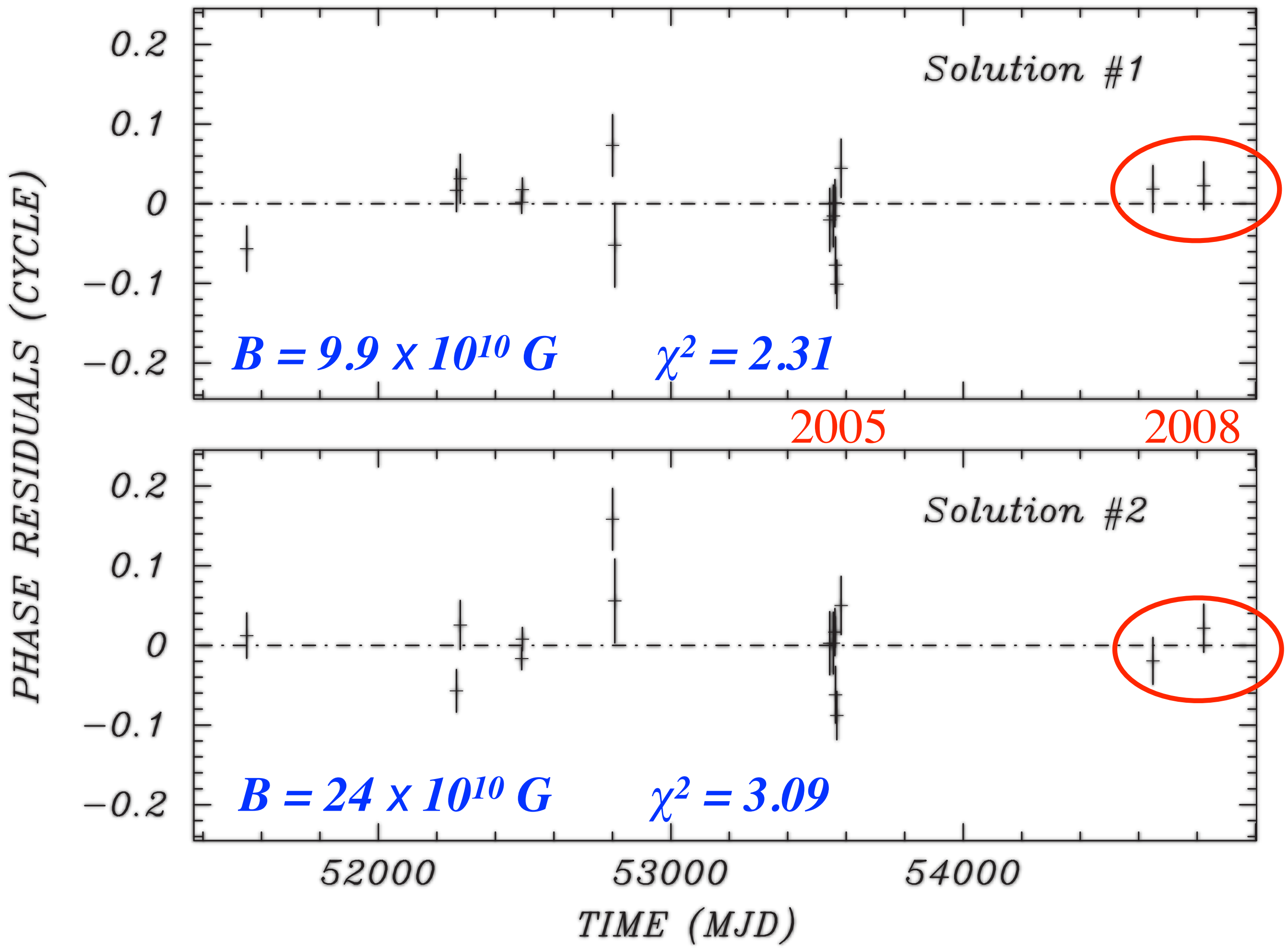
3) X-ray luminosities exceed their spin-down luminosity…

...alternative energy source must account for the observed emission.

A strong challenge to a pure rotation-powered assumption.

Timing PSR J1210-5209: Two Solutions

(Halpern & Gotthelf 2011)

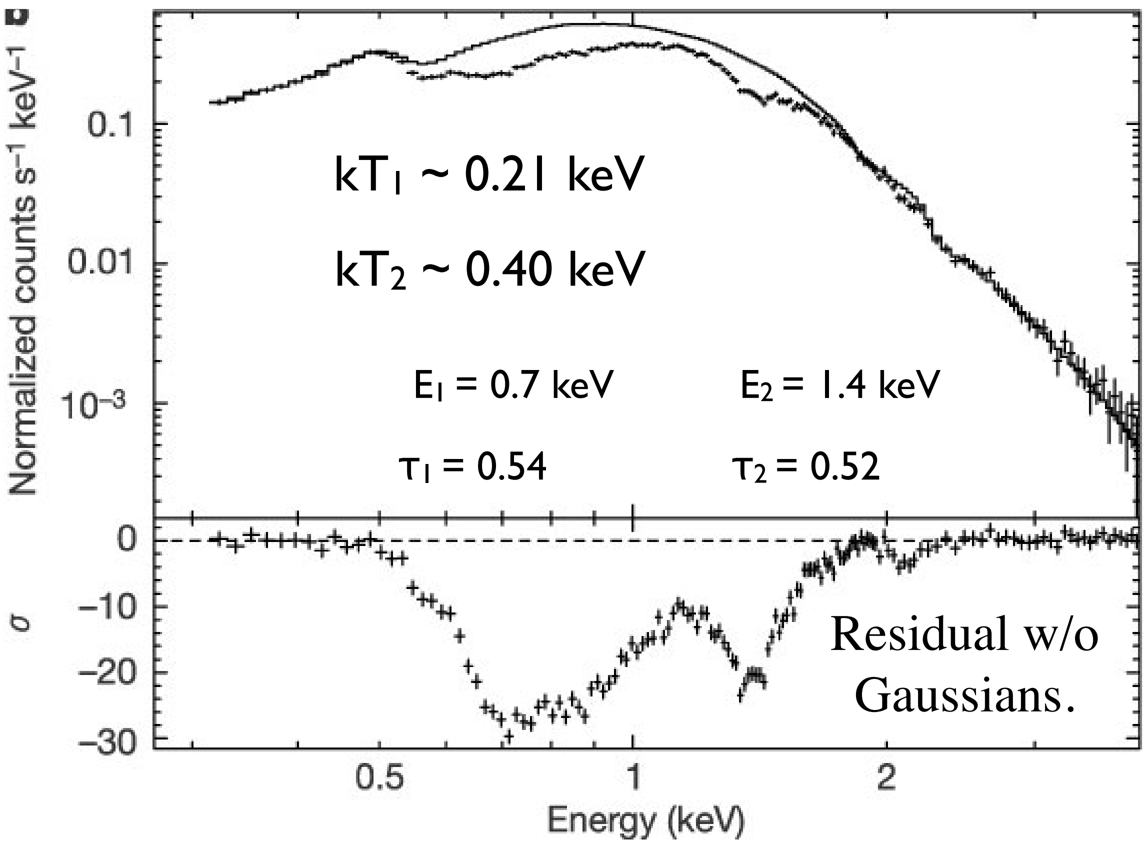


Argh! A phase-connected solution and its alias!

Broad Spectral Features in 1E 1207.4-5209

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

A deep XMM spectrum fitted with a 2-BB model + 2 Gaussian lines.



Cyclotron resonant harmonic feature - consistent with inferred B_{dip}

Explains why its spectrum is unique…

Timing PSR J0821-4300 in Puppis A

Spin-down measurement hits the Shklovski Limit !

The Shklovski Effect: Train-whistle effect

Large transverse velocity component produces apparent increase in P,

Additive $\dot{P}_s$ term $(\dot{P}_m = \dot{P}_s + \dot{P}_i)$ limits measured $\dot{P}_m > \dot{P}_s = (\mathrm{v}_t^2/dc)\, P$

Important for MSP and binary pulsars, until now… small $\dot{P}_i$, large v_i !

Why? Because PSR J0821-4300 is the highest velocity NS and anti-magnetars have small period derivative !

Shklovski Limit for PSR J0821-4300

From proper motion measurements:

Hui & Becker 2006: v_t = 1100 ± 360 km/s -> $\dot{P}_s \simeq 6.8 \times 10^{-18}$

Winkler & Petre 2007: v_t = 1600 ± 240 km/s -> $\dot{P}_s \simeq 1.5 \times 10^{-17}$

Latest (PRELIMINARY!) timing solution:

$$\dot{P}_m = \dot{P}_s + \dot{P}_i = (7 \pm 1) \times 10^{-18} \ !$$

Result still ambiguous, 4 upcoming obs. should reduce uncertainty.

$B_{dip}\ (2\sigma) < 3 \times 10^{10}$ *G including Shklovski Effect*

If it turns out that $\dot{P}_m < \dot{P}_s$, then,
either v_t must be smaller or PSR J0821-4300 must be spinning up !

Compact Central Objects in Supernova Remnants
(CCOs) (SNRs)

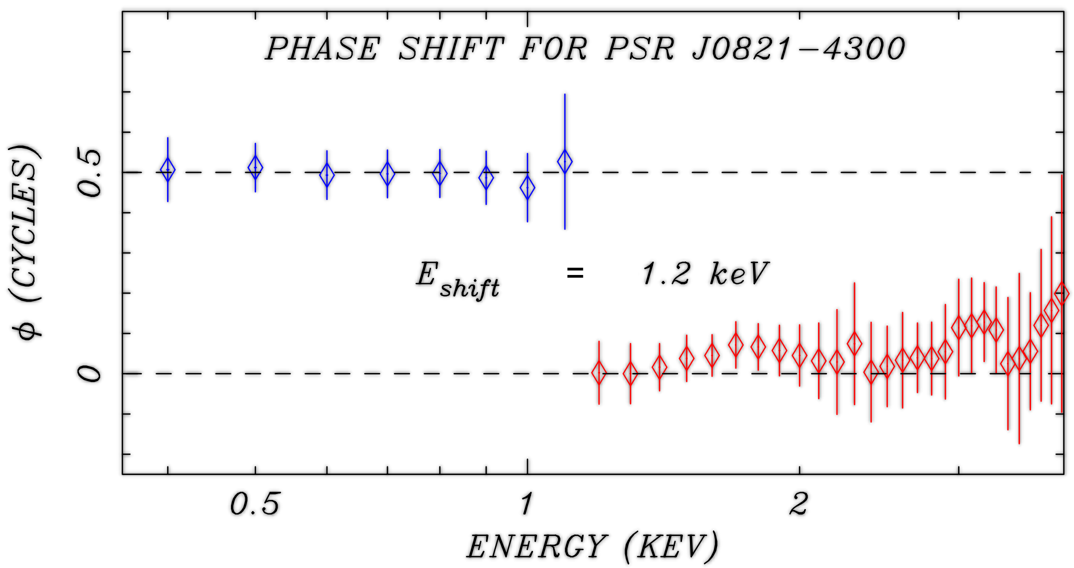
CCO	SNR	Age (kyr)	Dist. (kpc)	P (ms)	f_p^a (%)
CXOU J232327.9+584842	Cas A	0.33	3.4	...	< 12
CXOU J085201.4−461753	Vela Jr.	1	1	...	< 7
1WGA J1713.4−3949	G347.3−0.5	1.6	1.3	...	< 7
CXOU J160103.1−513353	G330.2+1.0	$\gtrsim 3$	5	...	< 40
RX J0822.0−4300	Puppis A	3.7	2.2	112	11
CXOU J185238.6+004020	Kes 79	7	7	105	64
1E 1207.4−5209	PKS 1209−51/52	7	2.2	424	9
XMMU J172054.5−372652	G350.1−0.3	0.9	4.5	...	...
CXOU J181852.0−150213	G15.9+0.2	$1-3$	(8.5)	...	...
XMMU J173203.3−344518	G353.6−0.7	~ 27	3.2	...	...

Notes — Above the line are seven 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.

PSR J0821–4300: the Remarkable Phase-shifting Anti-Magnetar

"Soft Phase" $\phi_{SOFT} = 0.5$

"Hard Phase" $\phi_{HARD} = 0.0$



Signal cancels out in broad-band profile!

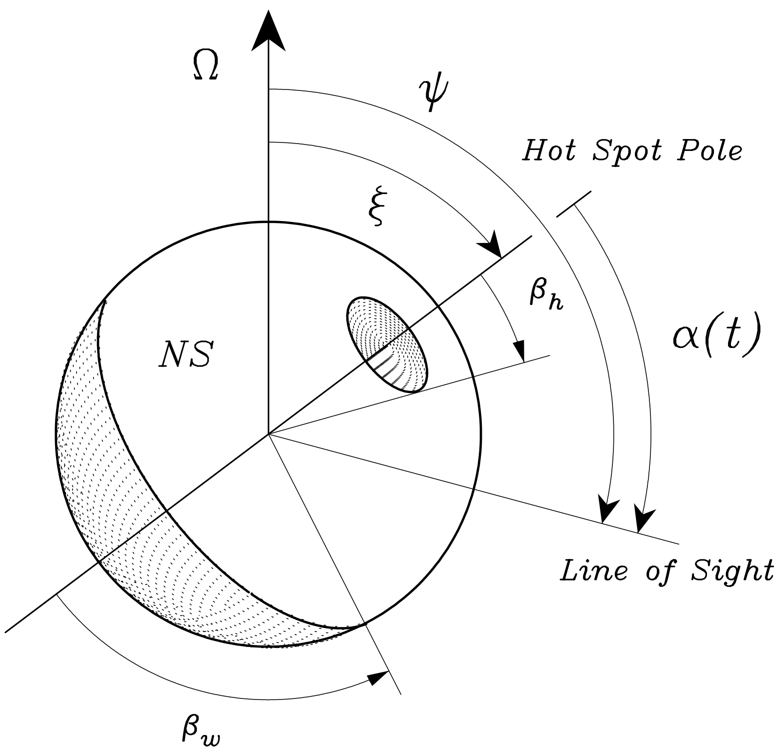
Phase Reversal at ~1.2 keV

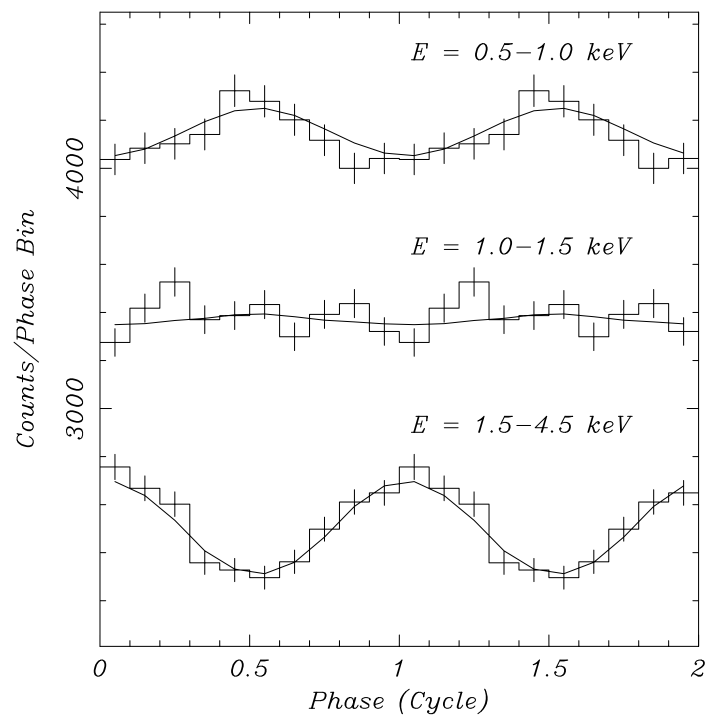
Sharp, 180 degree phase shift at ~1.2 keV

Antipodal Model: A Numerical Simulation

(Gotthelf, Perna, & Halpern 2010)

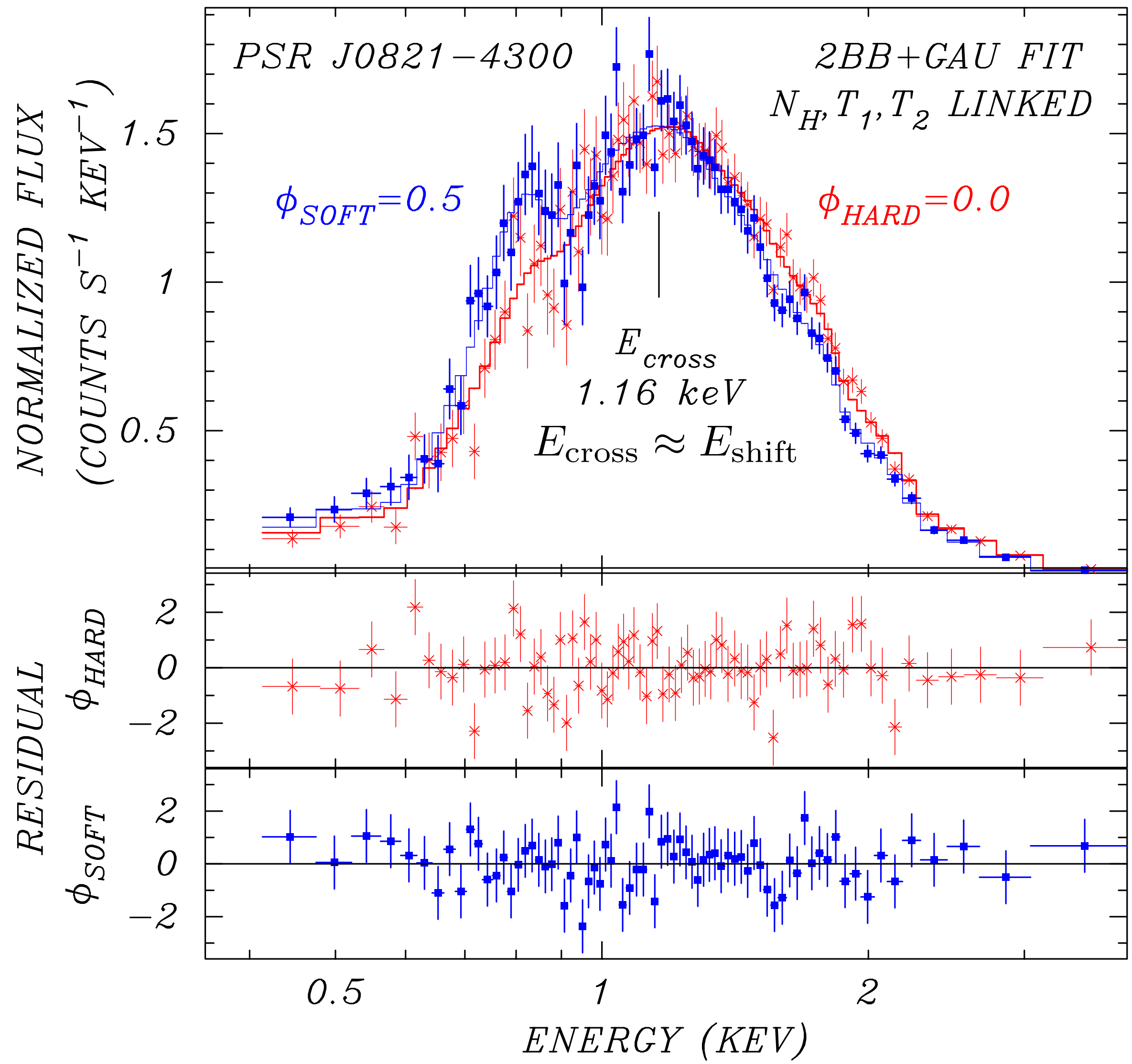
Two antipodal emission spots of size $\boldsymbol{\beta}_{h,w}$ and BB Temp. $\boldsymbol{T}_{h,w}$
XSPEC model spectral fits, assumed N_H, Distance, NS Radius





Find ($\boldsymbol{\xi},\boldsymbol{\psi}$) that can reproduce modulation and phase reversal of energy-dependent pulse profile in three interesting energy bands.

Phase Resolved Spectrum of PSR J0821-4300



Break up data into two phase bands,

Centered on pulse peak in the soft and hard bands,

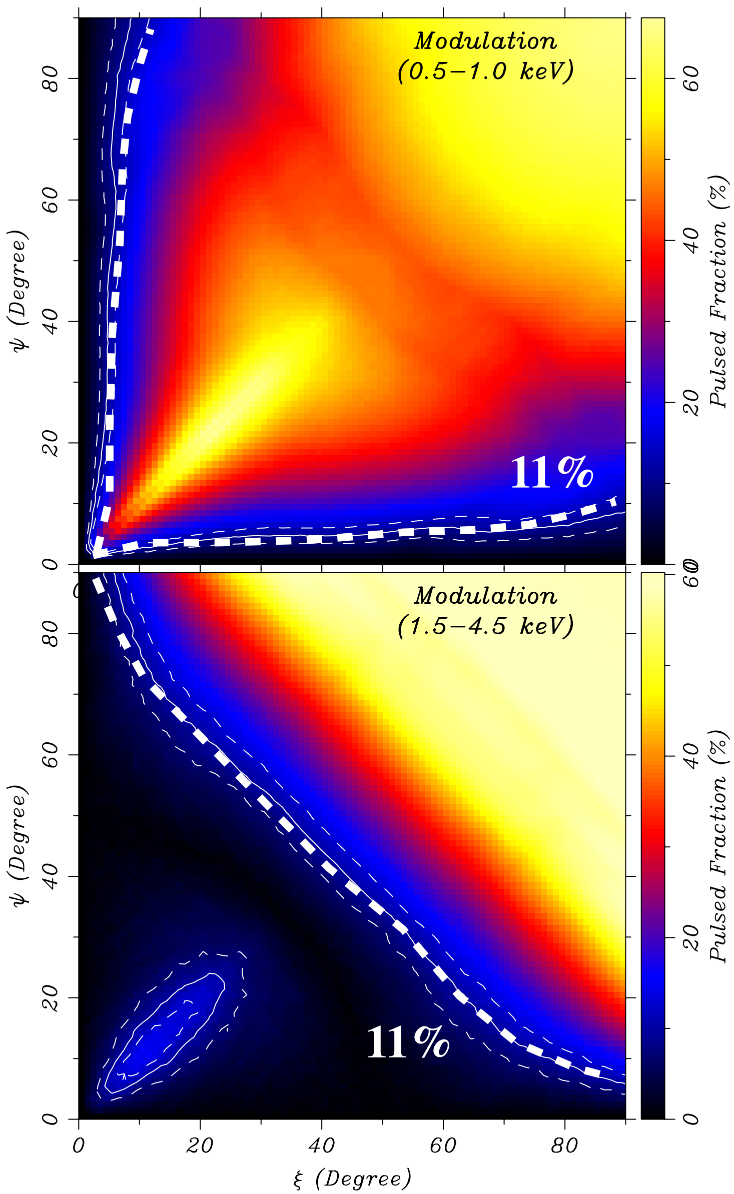
Fit the two spectra simultaneously with same 2BB model...

Each spectrum superposition of the two temperatures!!!

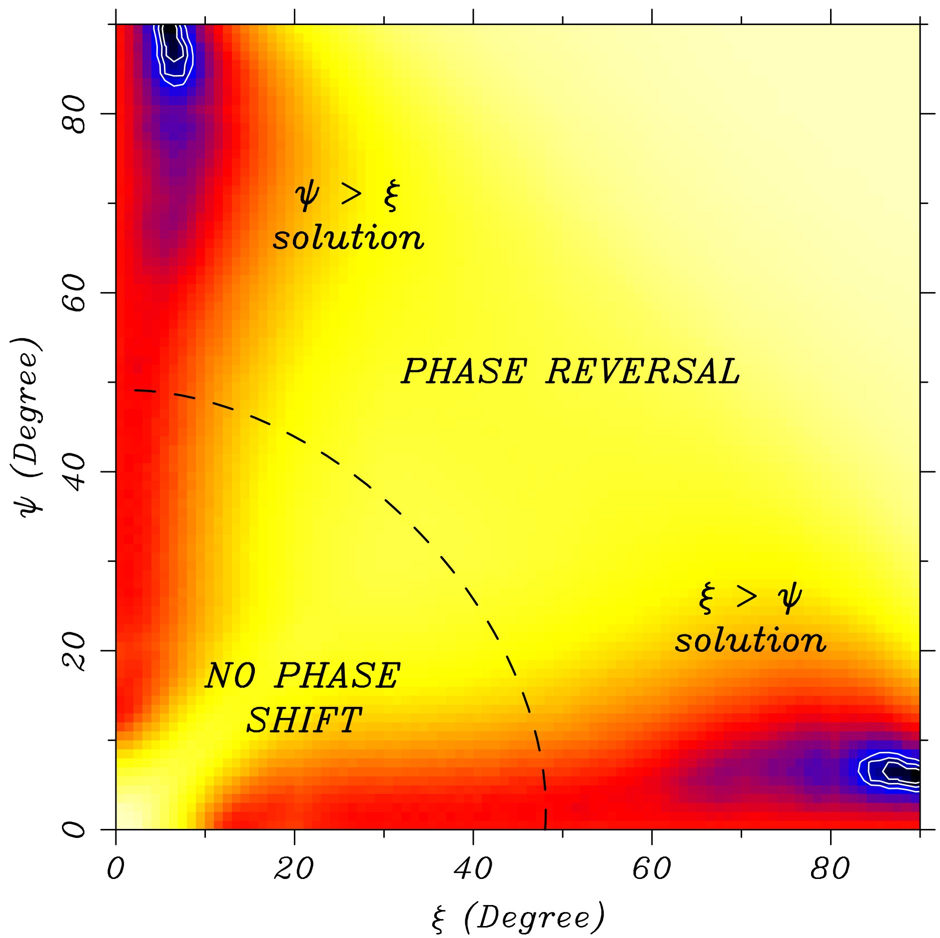
Line Feature associated mainly with Soft Phase spectrum

Antipodal Model Predicted Modulation

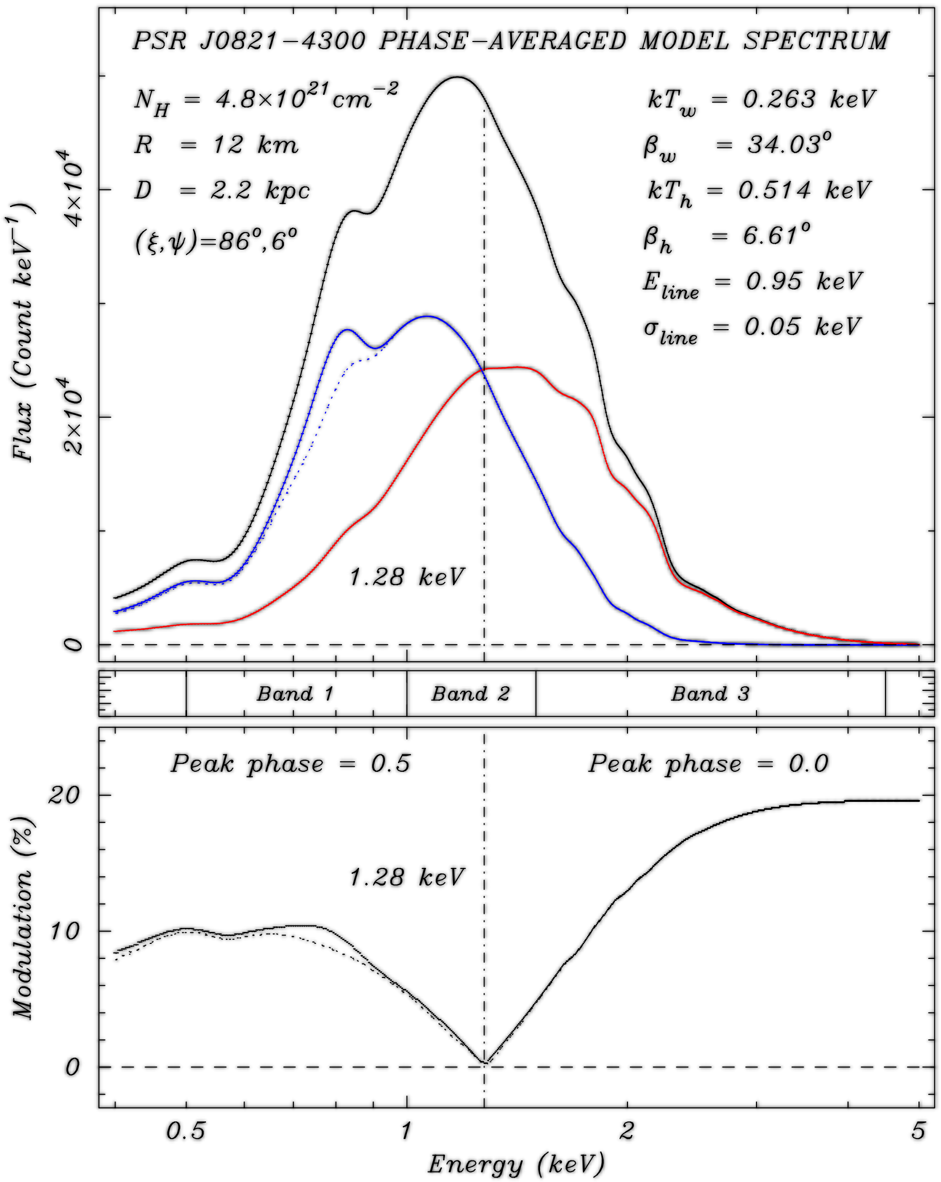
($N_H = 4.8 \times 10^{21}$ cm^{-2}, $D = 2.2$ kpc, $R = 12$ km)



Overlap is highly constrained to $(\xi,\psi) = (86°\pm2°, 6°\pm1°)$



Best-fit Antipodal Model Results



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

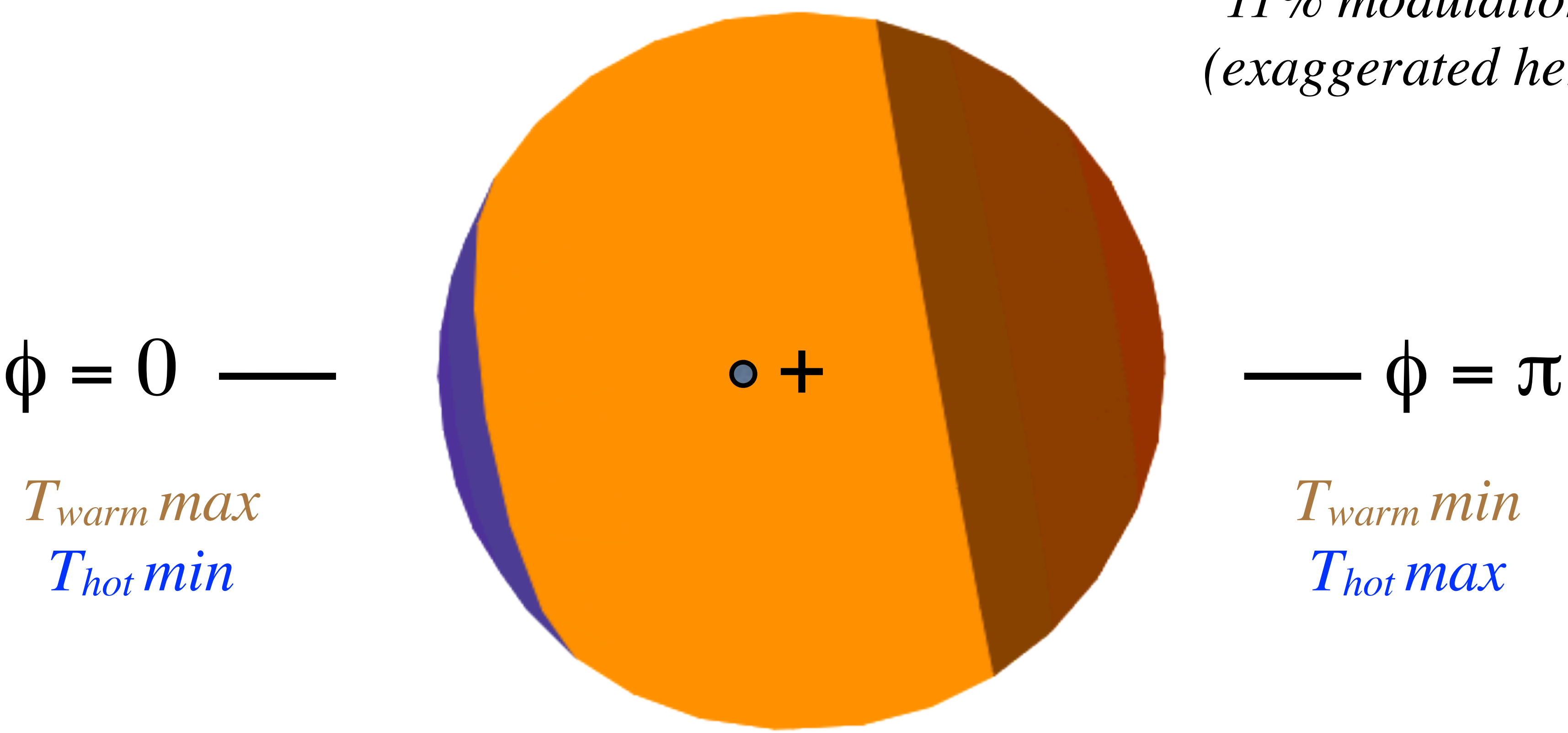
f_p =19.6% at highest energies

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)



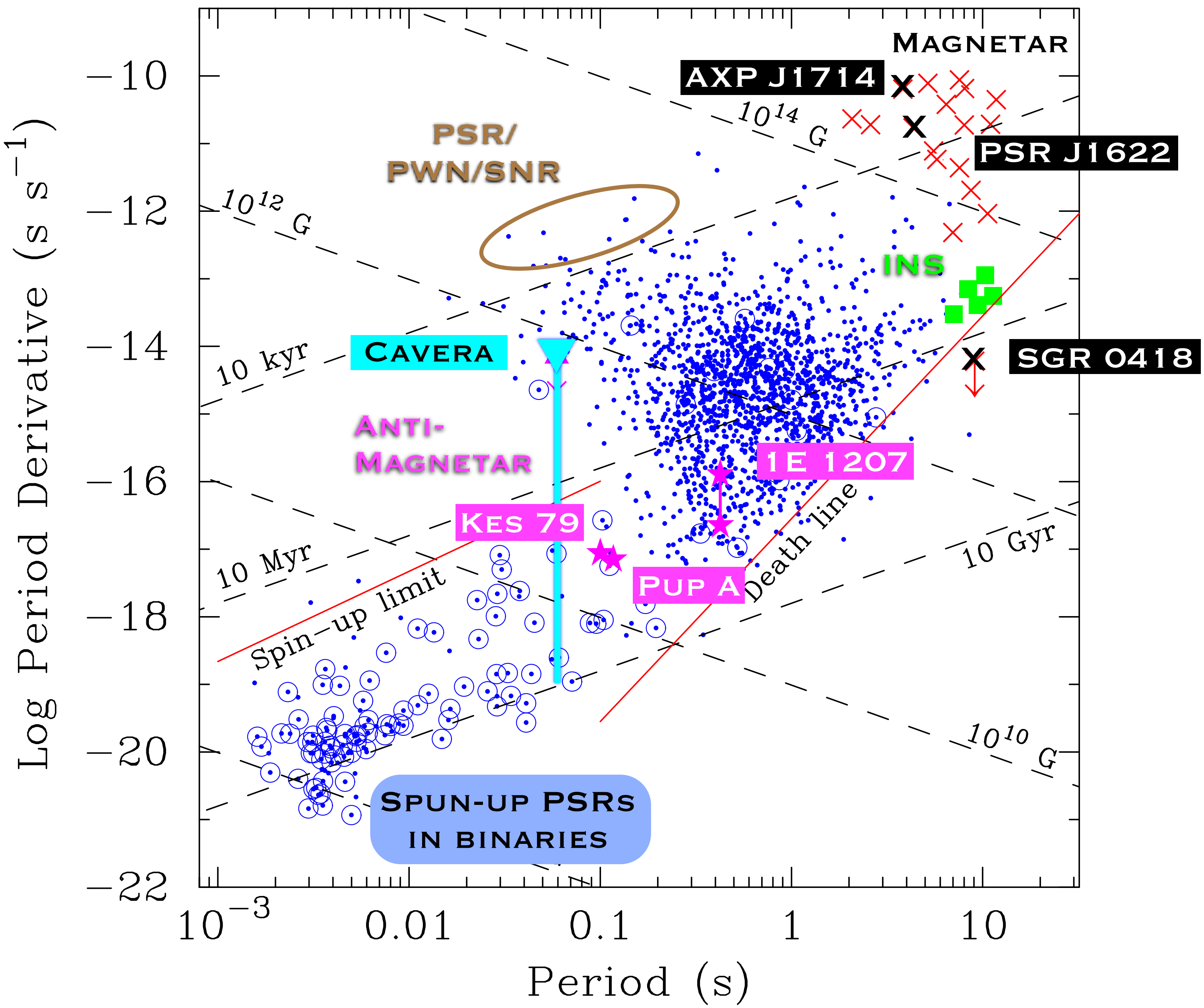
- ● *Rotation Axis*
- + *Line-of-sight*

Geometry well constrained by numerical model for pulse fractions!

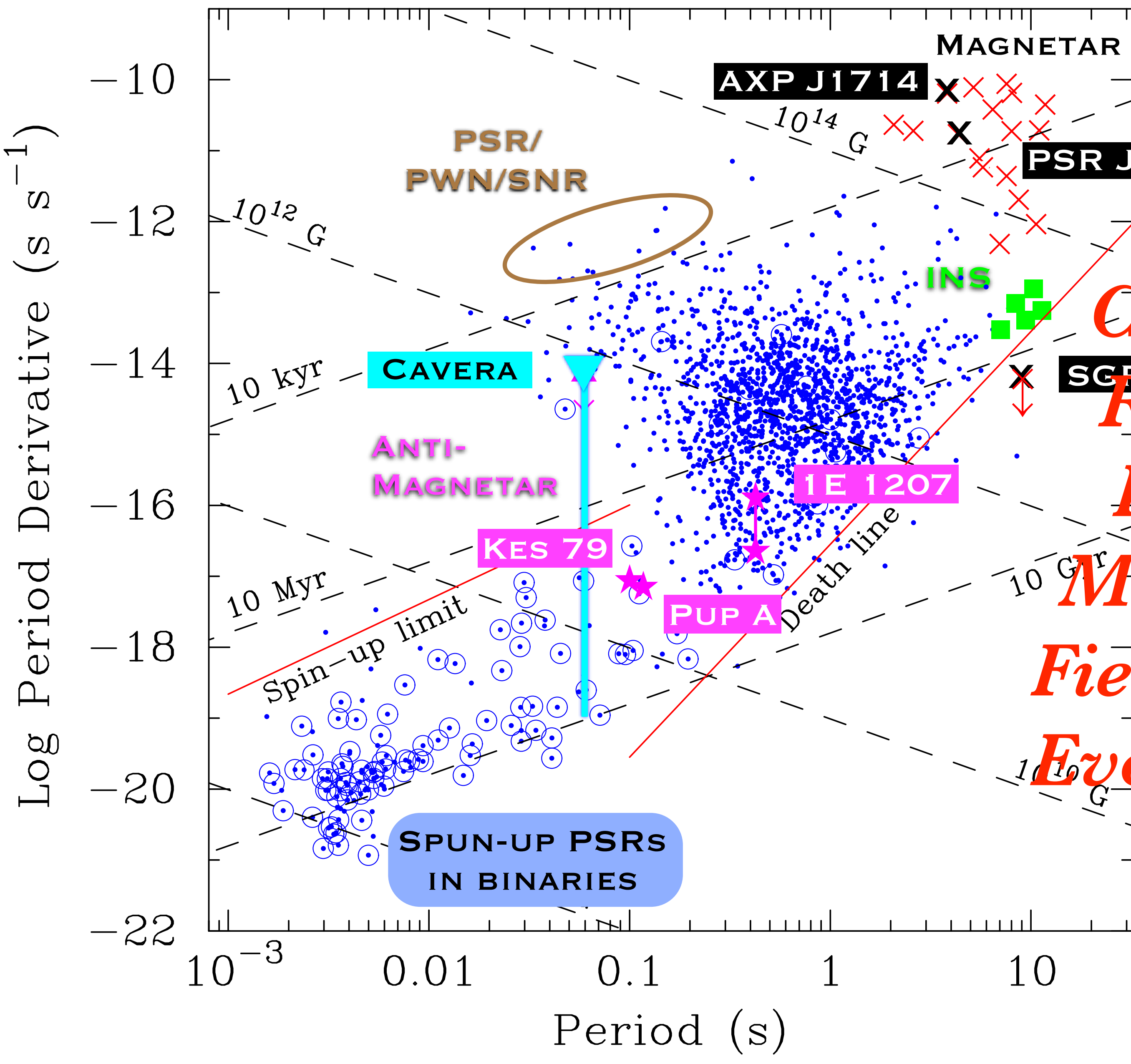
CCO Implications

- ***Weak dipole magnetic field and slow spin constitute the physical basis of the CCO class***
- ***For a NS formed spinning slowly, the birth B-field derived from a turbulent dynamo is weaker (Thompson & Duncan 1993; Bonanno et al. 2006)***
- ***A buried magnetic field may explain the surface hot spots, but a weak external field is required to explain the lack of spin-down***
- ***A CCO born in SN 1987A could explain the lack of observed NS/pulsar, whose $\dot{E}$ is below detection***
- ***Some low B-field, older radio pulsars may turn out to be younger anti-magnetars***

Evolution of Pulsars: P vs $\dot{P}$ Diagram



Young NSs: Pulsars, Magnetars, Magniños



Critical Role of Initial Magnetic Field in NS Evolution!!