“GRAND UNIFICATION” in Neutron Stars: A Decade of Chandra Discovery

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Census of Non-Accretion Neutron Stars

Isolated Neutron Stars

(formerly Dim Isolated Neutron Stars – DINs)

CCOs

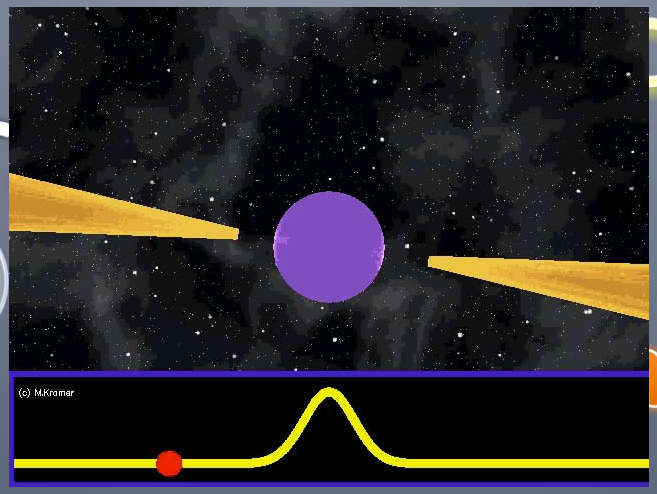
(Central Compact Objects)

RRATs

(Rotating Radio Transients)

RADIO PULSARS

(aka Rotation-Powered Pulsars)



COND PULSARS

Magnetar

(AXPs and SGRs)

agnetars”

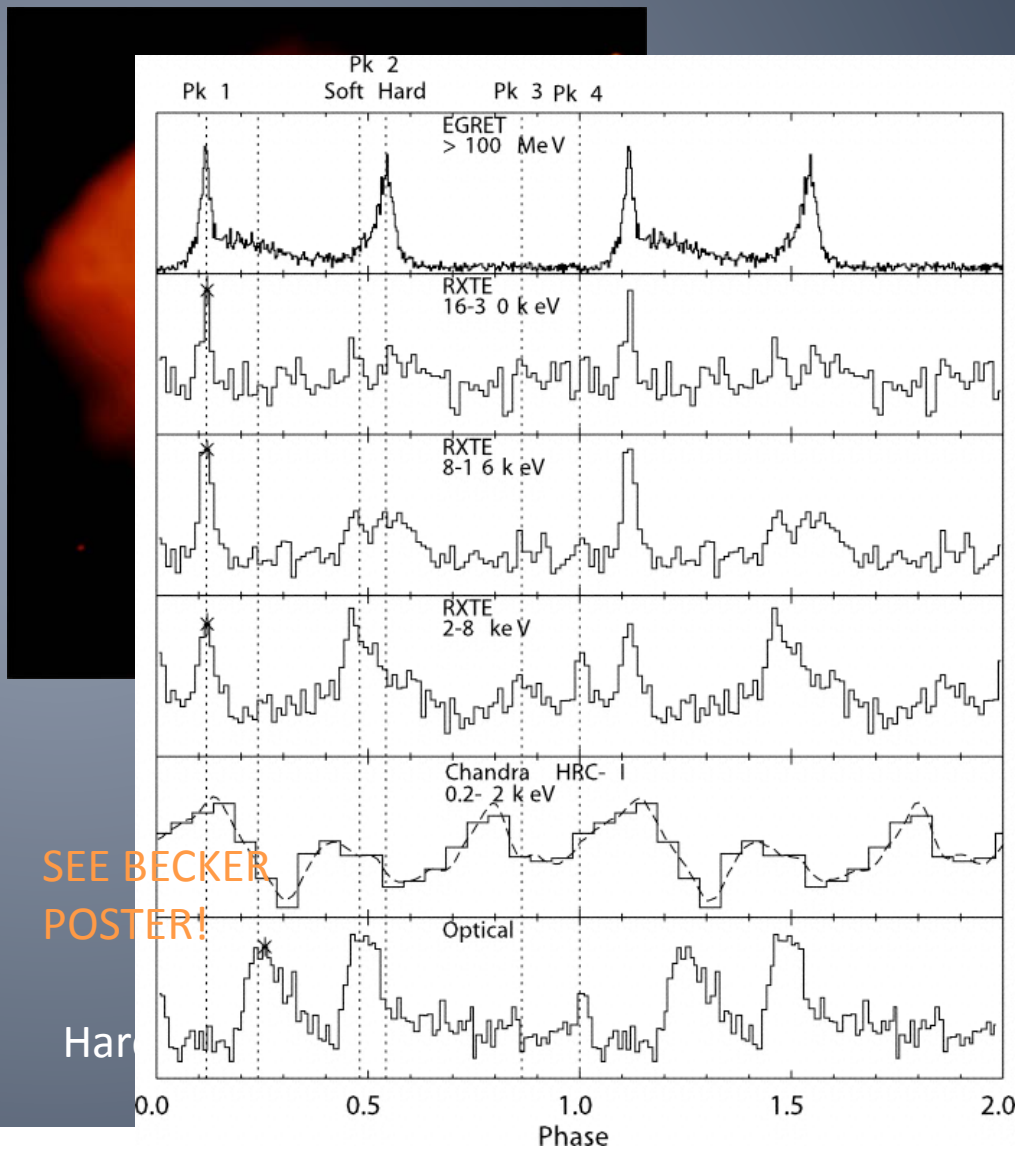
Radio Pulsars
(aka Rotation-Powered Pulsars)

- Born hot in supernova explosions; cool slowly, producing thermal X-rays
- Non-thermal (and some thermal) emission powered by rotation, via magnetic braking
- Infer B from P, Pdot

$$B \cong 3.2 \times 10^{19} (P \dot{P})^{1/2} G$$

- Relativistic particle winds that produce spectacular nebulae, all rotation-powered

$$\dot{E} = \frac{4\pi^2 I \dot{P}}{P^3}$$



SEE BECKER POSTER!

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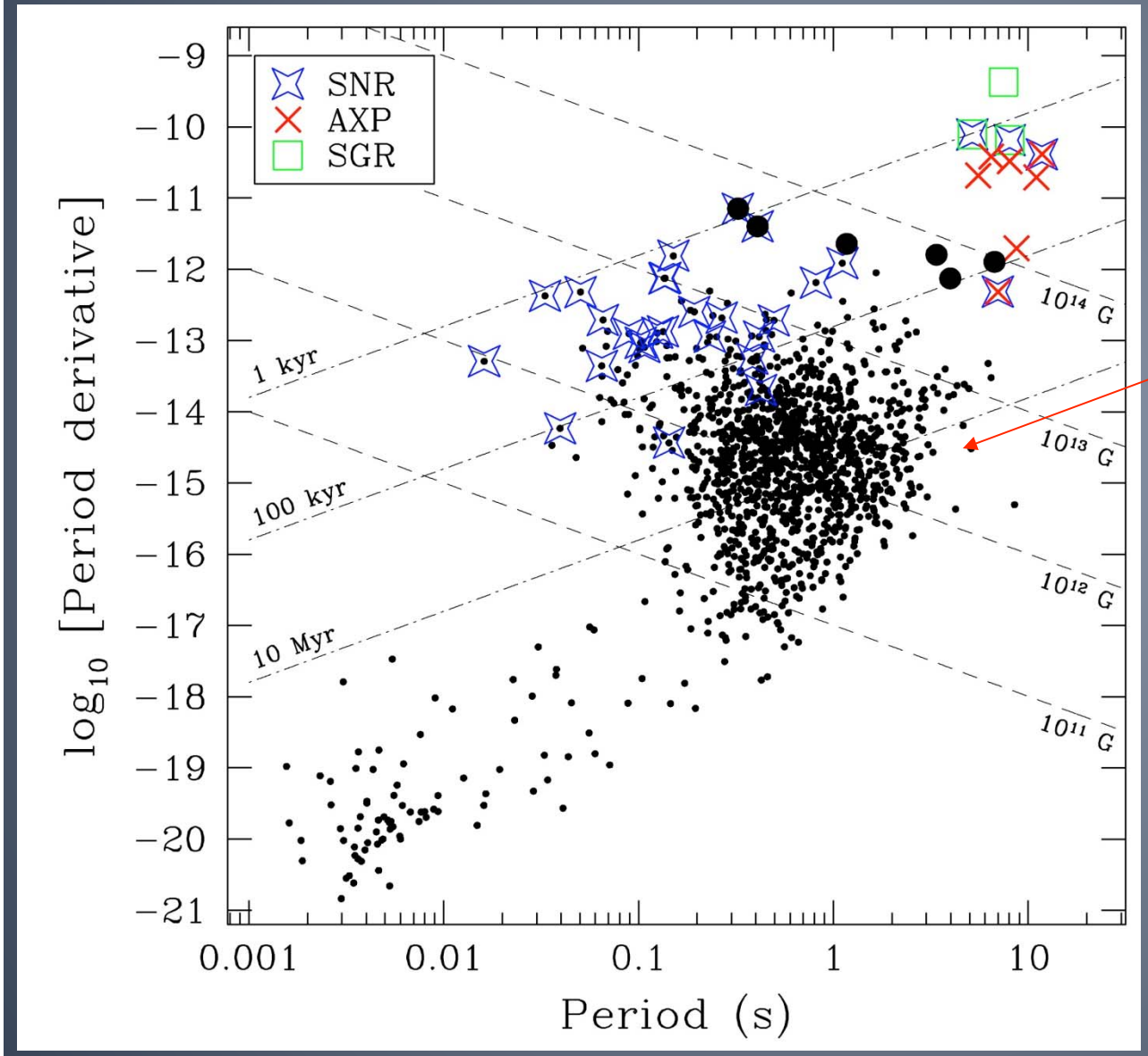
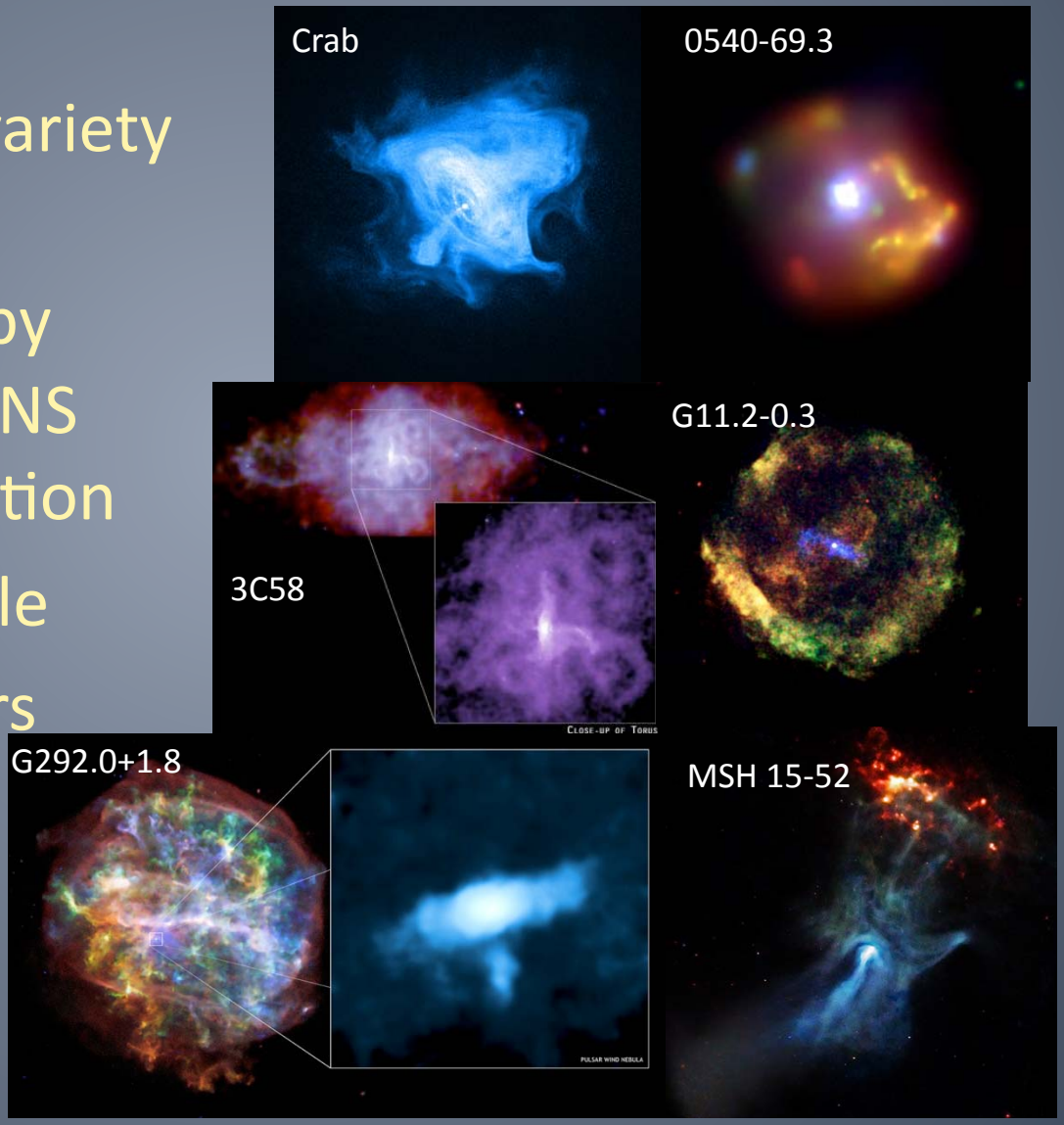
P-Pdot Diagram



Radio Pulsars

Chandra Pulsar Wind Nebulae (PWNe)

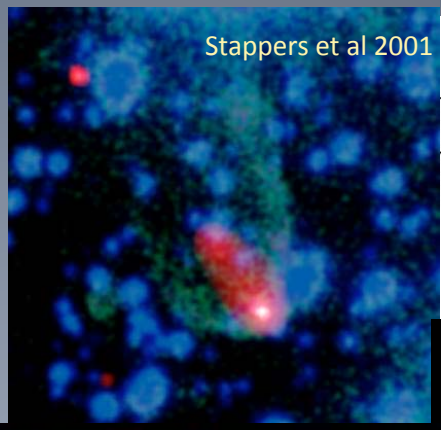
- Wide, surprising variety of morphologies
- Likely influenced by environment and NS geometry and motion
- Temporally variable
- Millisecond pulsars have PWNe too

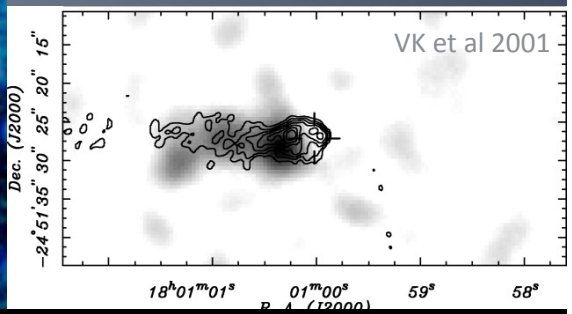


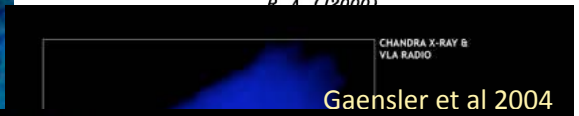
SEE GELFAND TALK!

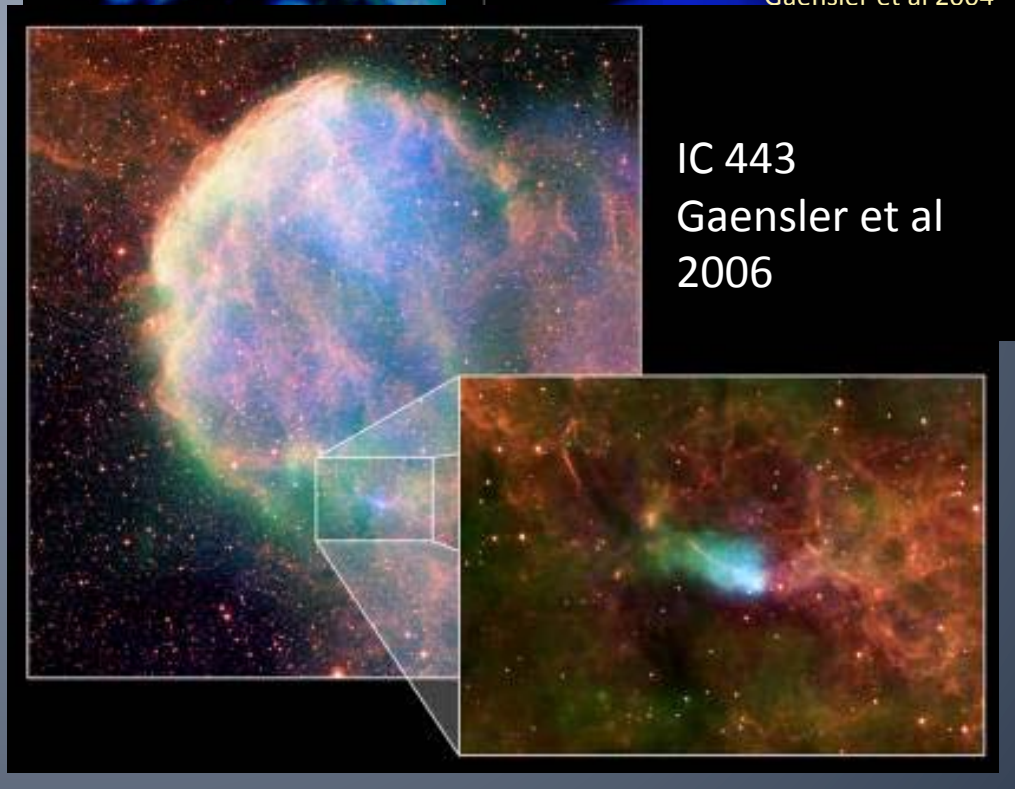
Chandra Ram-Pressure-Confined PWNe

- Ram pressure due to NS motion through ISM dominates
- Bow shock morphology
- Constrain combination of velocity, ambient density, wind filling factor, efficiency factor
- Infer direction of motion
- Test supernova remnant associations





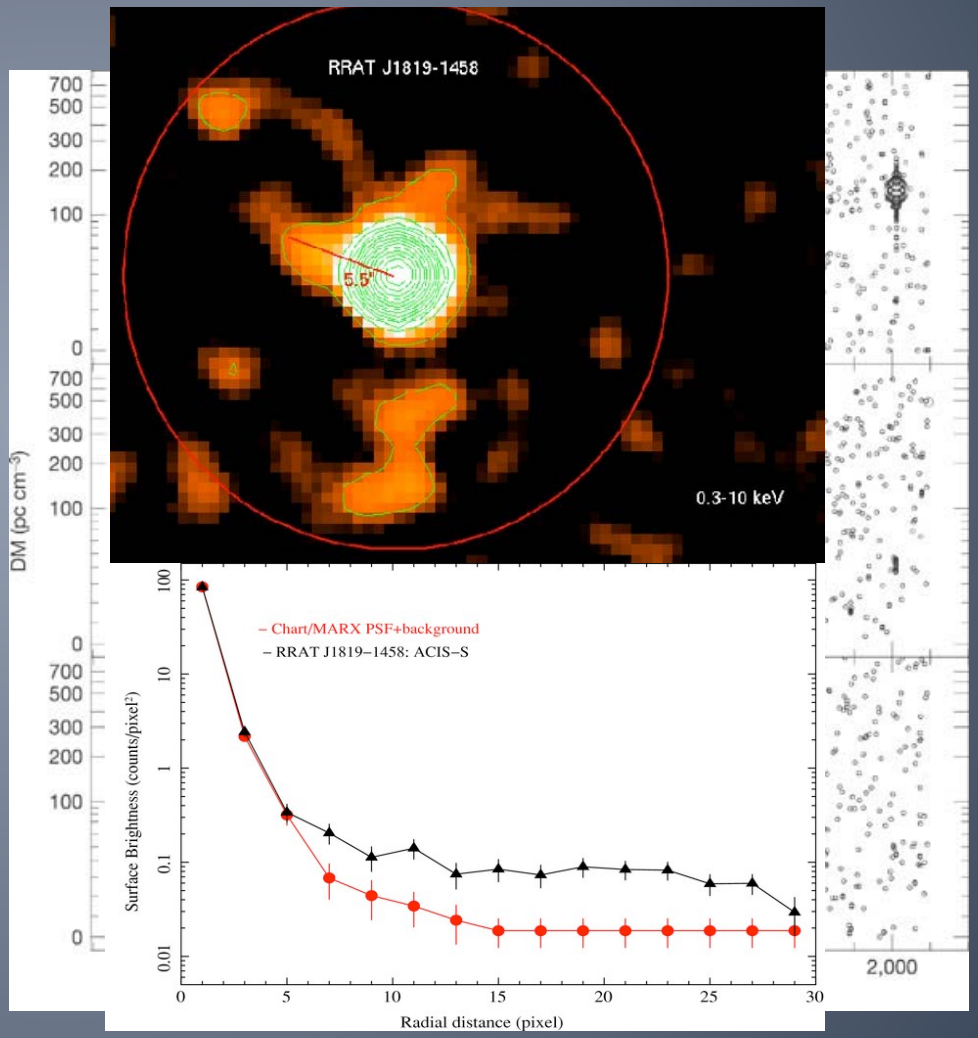




IC 443
Gaensler et al 2006

RRATs
(Rotating Radio Transients)

- Sporadic radio pulse emitters (McLaughlin et al. 2006)
- ~12 known
- On average, P, B higher than general pulsar population (McLaughlin et al. 2009)
- But some nearby radio pulsars would be RRATs if farther (Weltevrede et al. 2006)
- X-ray properties thus far not remarkable, but only one detected (Rea et al. 2009; Reynolds et al. 2006)
- Unusual glitch in RRAT J1819-1458? (Lyne et al. 2009)
- Suggests large missing population...

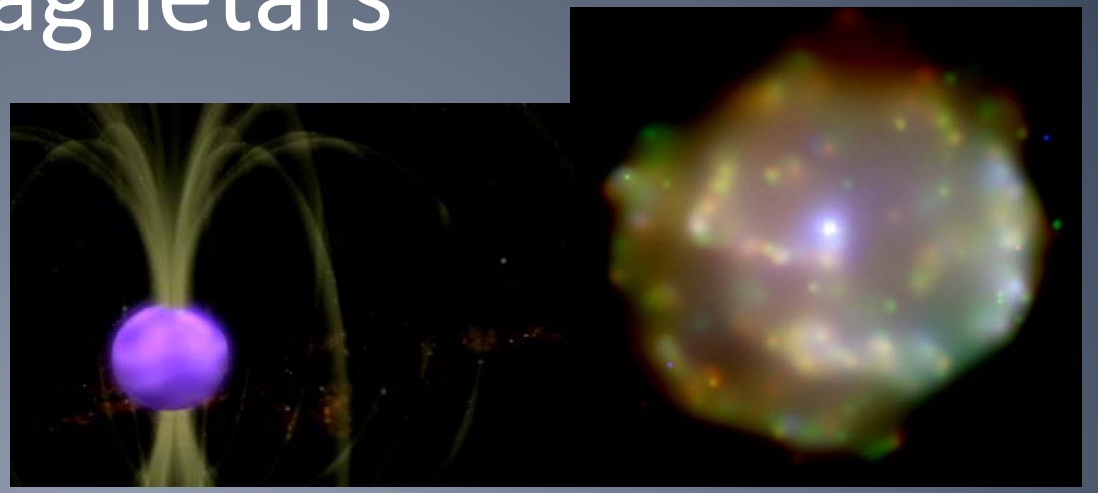


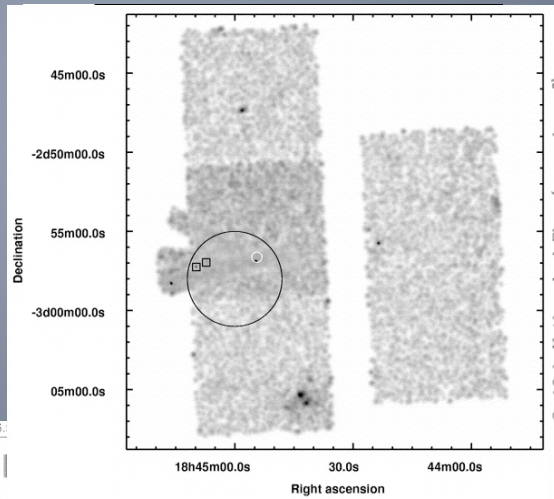
Rea et al. 2009

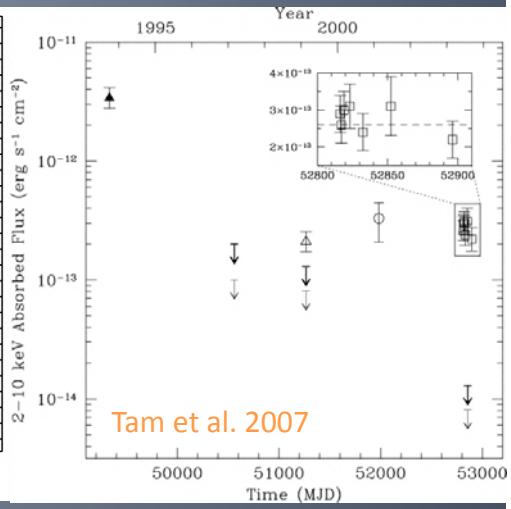
Magnetars

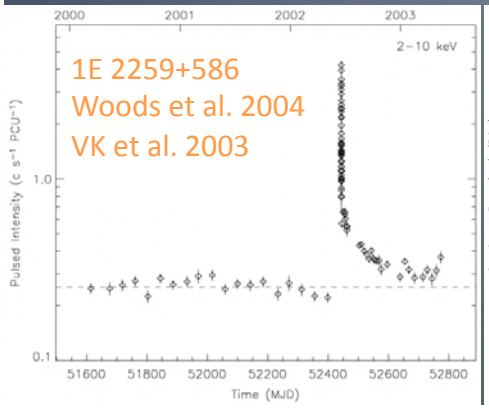
- "Bad Boys": young, volatile
- X-ray pulsations, X-ray/g-ray bursts, outbursts on variety of time scales
- Lx >> spin-down luminosity
- Many arguments for power via enormous B field, as inferred from spin-down
- Anomalous X-ray Pulsars (lower B, softer, burst rarely), Soft Gamma Repeaters (higher B, harder, burst often, larger bursts)
- Relaxation constrains physics of magnetosphere and/or physics + composition of crust
- Accompanied by rotational anomalies, glitches

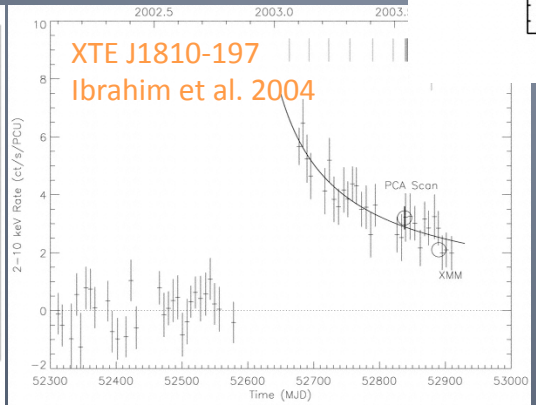
AXP 1E 1841-045 in Kes 73





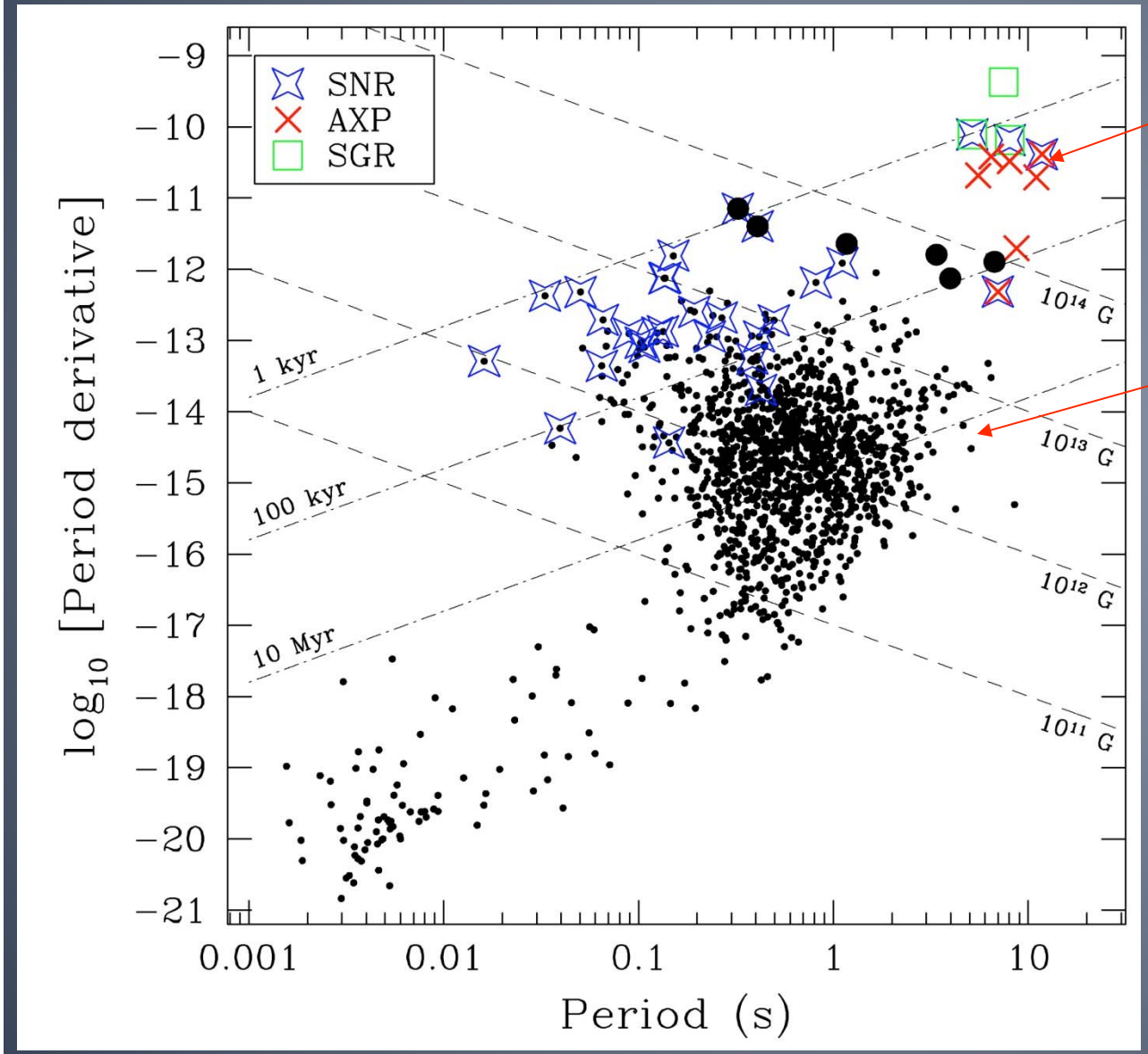






Suggests a large population of unseen magnetars...

P-Pdot Diagram



SGRs, AXPs

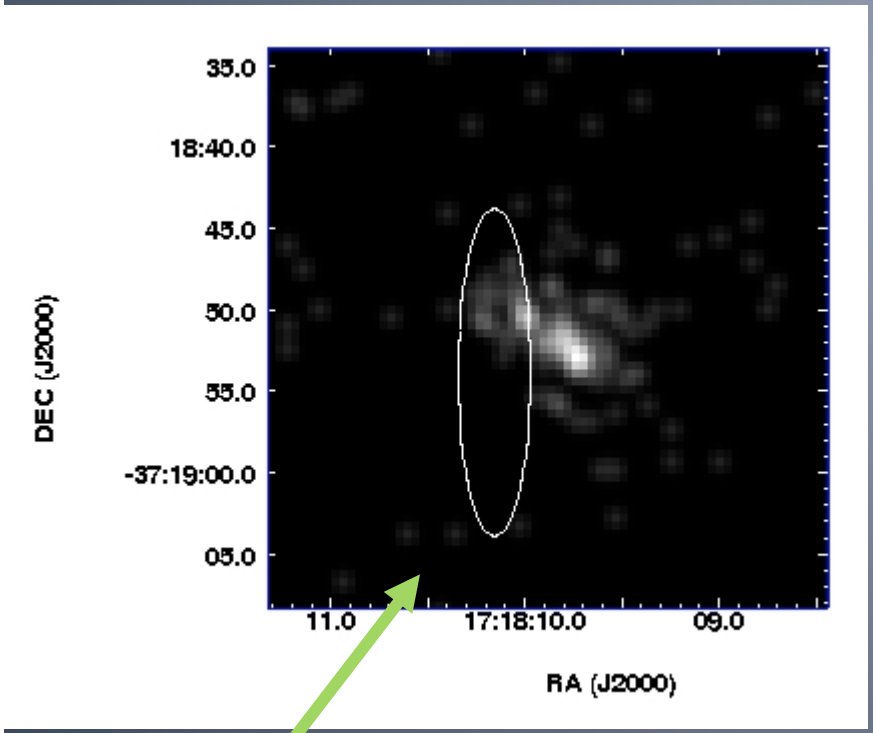
Radio Pulsars

High-B Radio Pulsars

Name	P (s)	Pdot	B (G)	D (kpc)
J1119-6127	0.4	4.1e-12	4.1e13	8.4
J1718-3718	3.4	1.6e-12	7.4e13	4.9
J1734-3333	1.2	2.3e-12	5.2e13	7.4
J1814-1744	4.0	7.4e-13	5.5e13	9.8
J1819-1458 (RRAT)	4.3	5.7e-13	5.0e13	3.6
J1846-0258	0.3	7.1e-12	4.8e13	6
J1847-0130	6.7	1.3e-12	9.3e13	8.4

PSR J1718-3718

- P=3.4 s, B=7.4e13G, D=4.9 kpc
- 50 ks archival Chandra/ACIS obs
- Pulsar 7’ off axis



- formal positional offset: 0.2σ in DEC, 1.6σ in RA
- probability of chance < 1%
- NEW: upcoming 130 ks Chandra observation

radio timing error box

VK & McLaughlin 2005

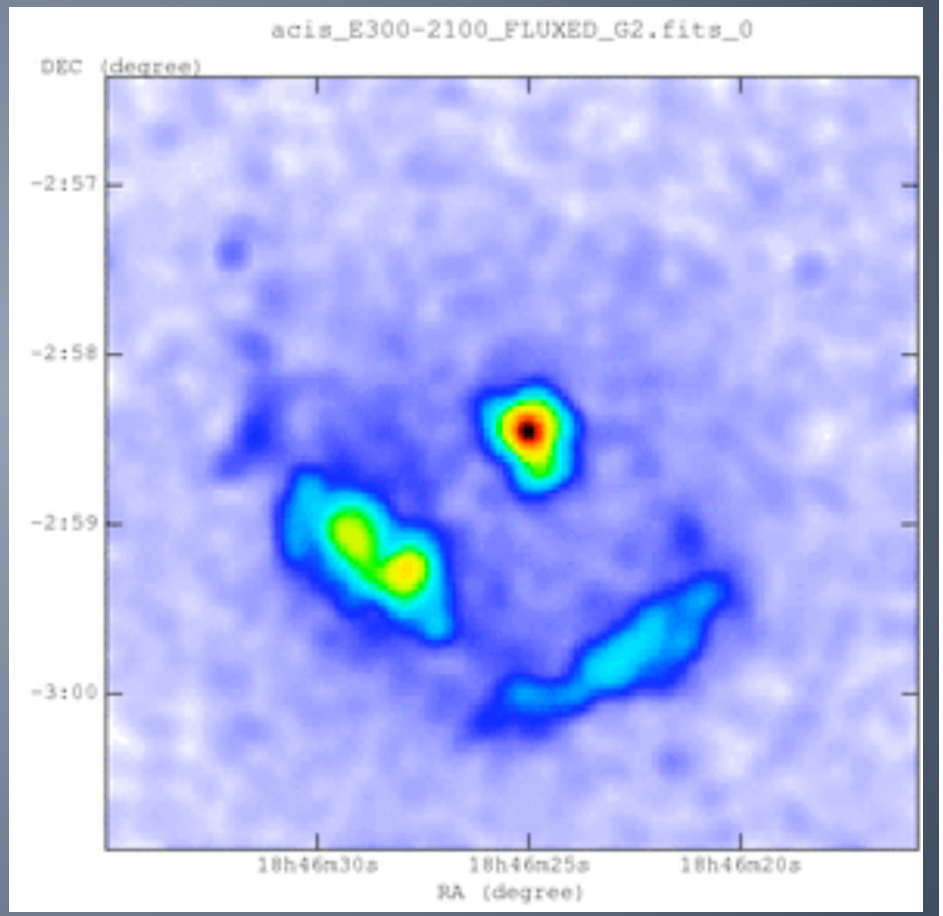
PSR J1718-3718

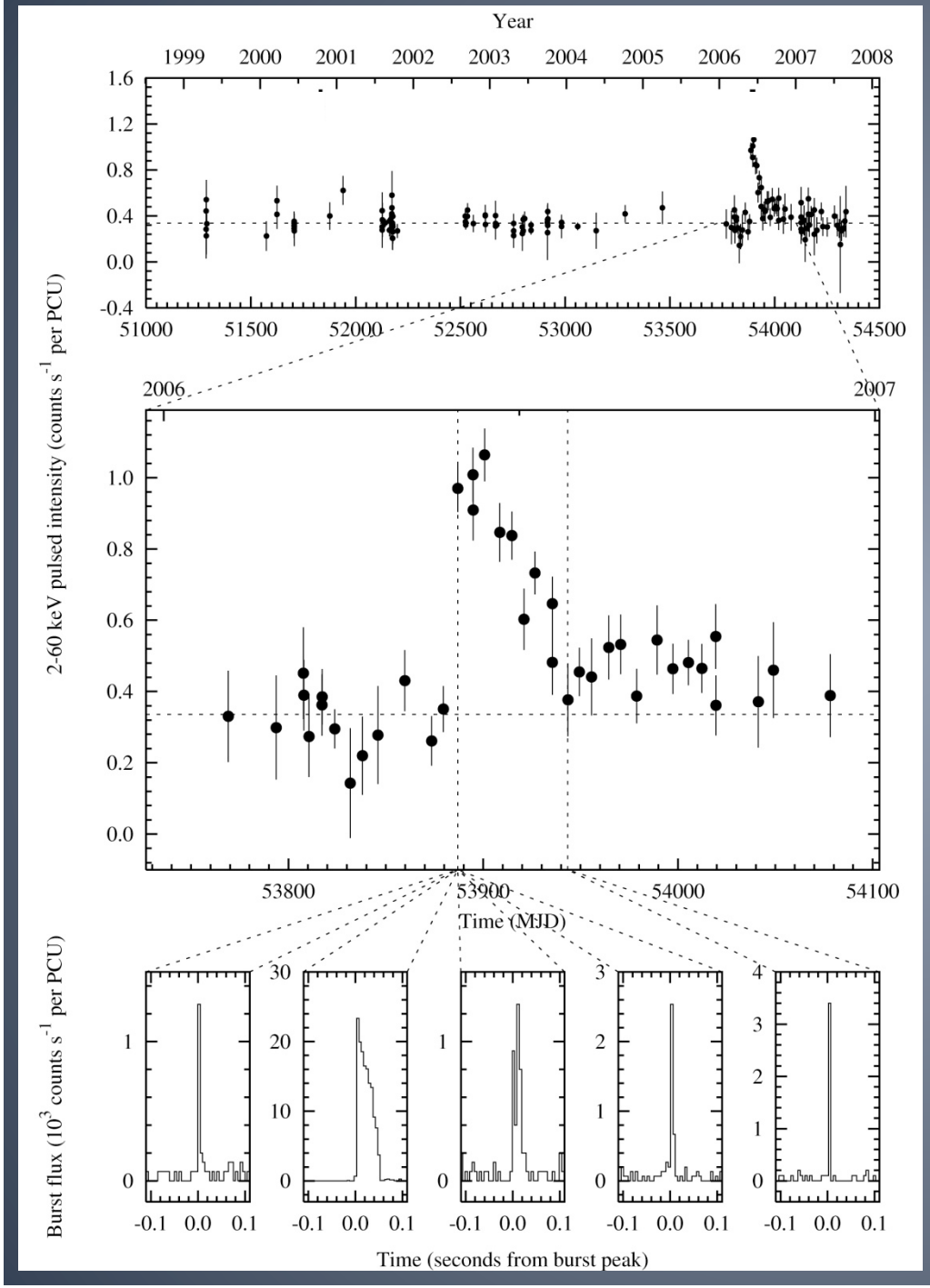
- Spectrum, flux:
  - Consistent with initial cooling
  - Lx > 3 orders of magnitude fainter than for any known persistent AXP
  - …**but** consistent with transient AXP in quiescence…

"This raises the interesting possibility that PSR J1718-3718, and other high-B radio pulsars, may one day emit transient magnetar-like emission, and conversely that the transient AXPs might be more likely to exhibit radio pulsations." (VK & McLaughlin 05)

PSR J1846-0258

- 0.3 s pulsar in SNR Kes 75
- B = 5e13 G
- Youngest known: 884 yr
- *Bona fide* **rotation-powered**:
  - Lx << Edot
  - Power-law X-ray spectrum
  - Pulsar wind nebula
  - Normal timing properties, including n=2.65 (Livingstone et al. 2006)
- Among faintest 1% of known radio pulsars (Archibald et al. 2008)

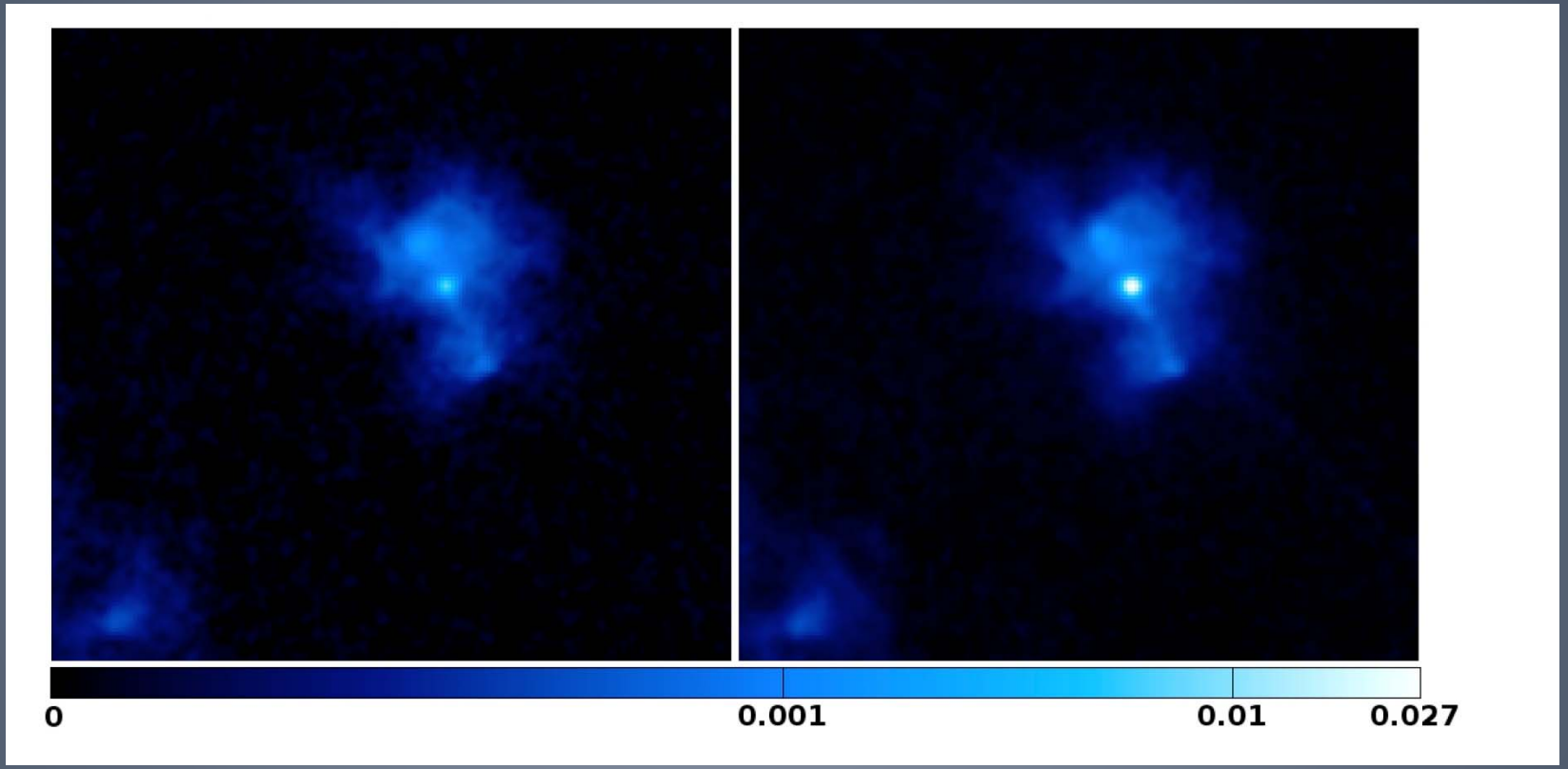




Magnetar-like Behavior in a Rotation-Powered Pulsar in RXTE Observations

Gavriil et al., Science, 2008

Chandra Observations of Kes 75



2000

2006

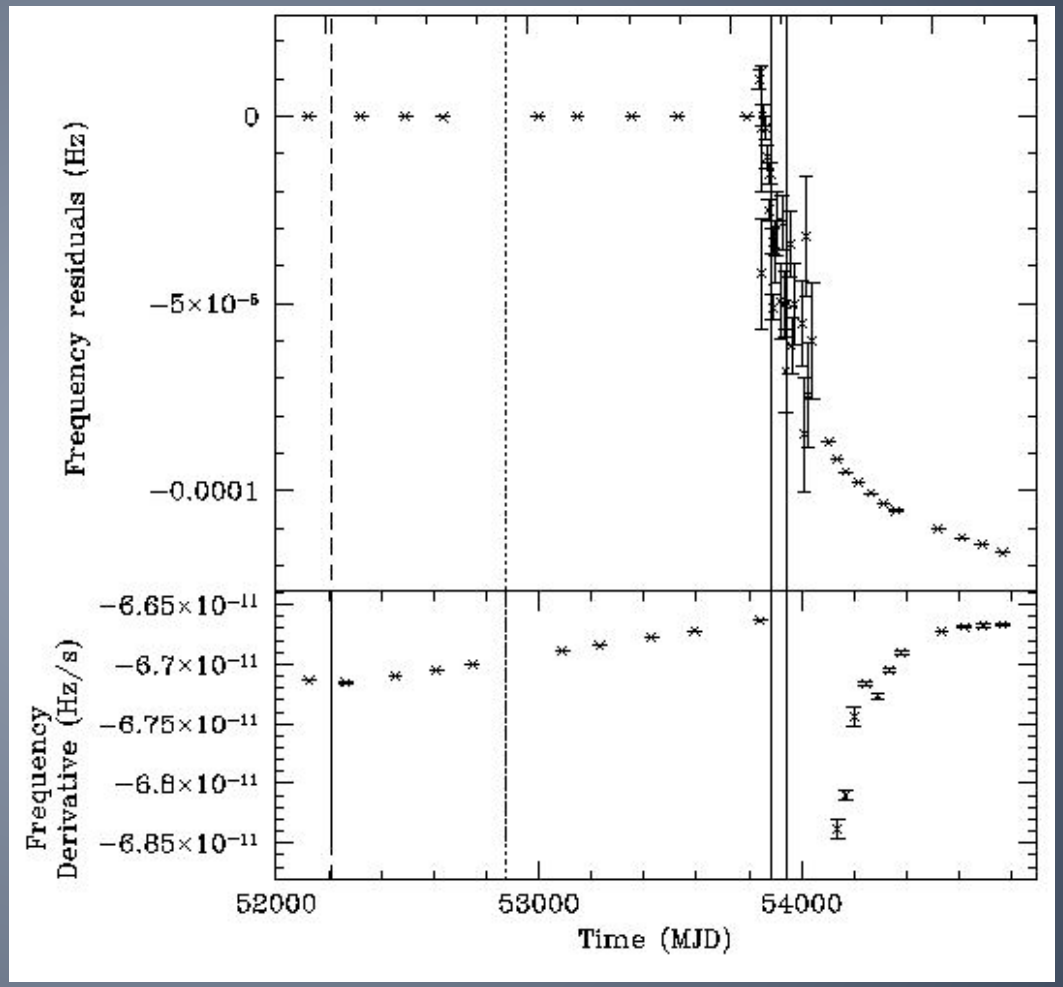
Gavriil et al., 2008; Kumar & Safi-Harb 2008; Ng et al. 2008

New CXO Obs to study PWN changes soon.

Timing Anomaly in PSR J1846-0258

- Pulsar had spin-up glitch (df/f~4e-6) followed by strong spin-down
- Net effect: large spin-down df/f = 5e-5
- Similar to that in SGR (Thompson et al. 2000); also AXP 0142+61 (Gavriil et al., submitted); RRAT 1819-1458 (Lyne et al. 2009)
- Interesting glitch behavior in magnetars!

Chandra ToO Program: Look at High-B radio pulsars at glitch epochs



Livingstone et al. (submitted)
Kuiper & Hermsen 2009

Unification I

RADIO PULSARS
(aka Rotation-Powered Pulsars)

MILLISECOND PULSARS

RRATs
(Rotating Radio Transients)

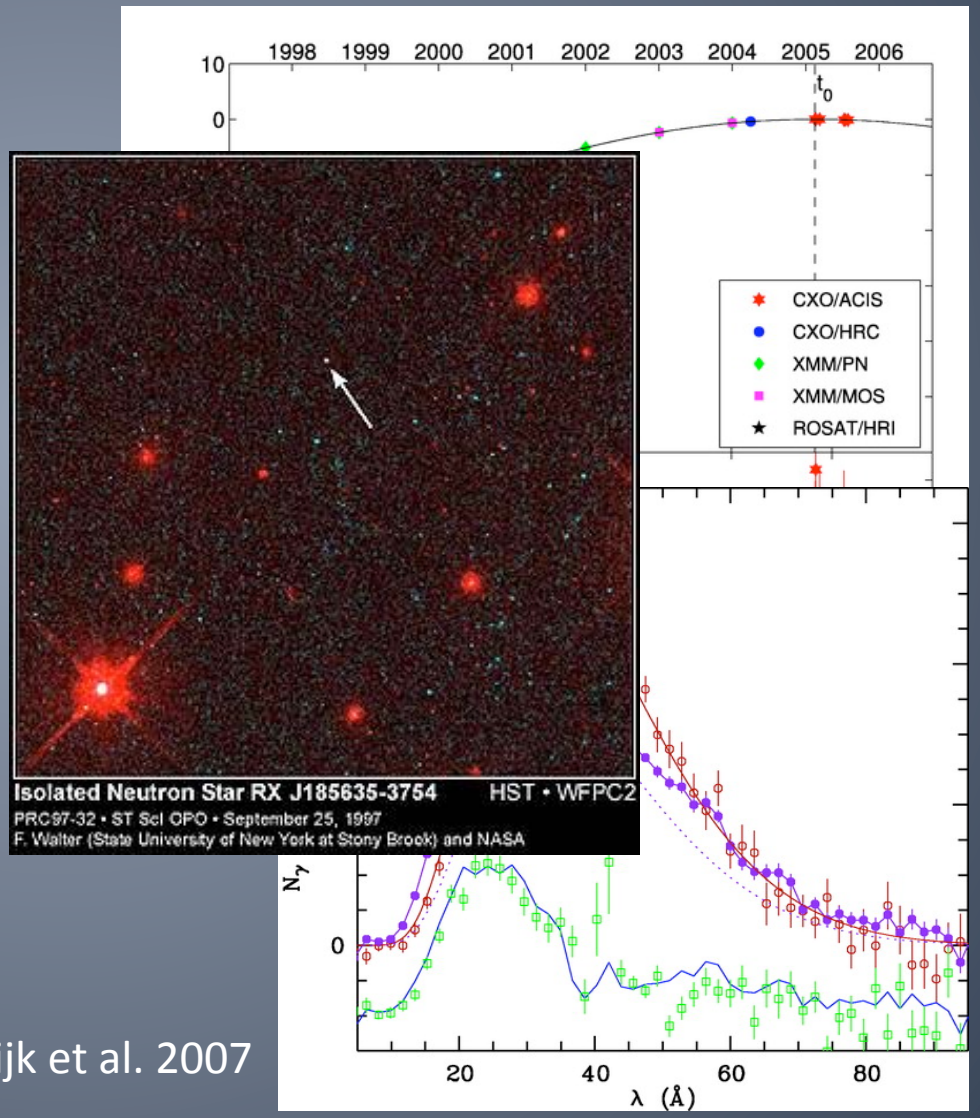
Transition Objects
(e.g. PSR J1846-0258)

Magnetars
(AXPs and SGRs)

Isolated Neutron Stars

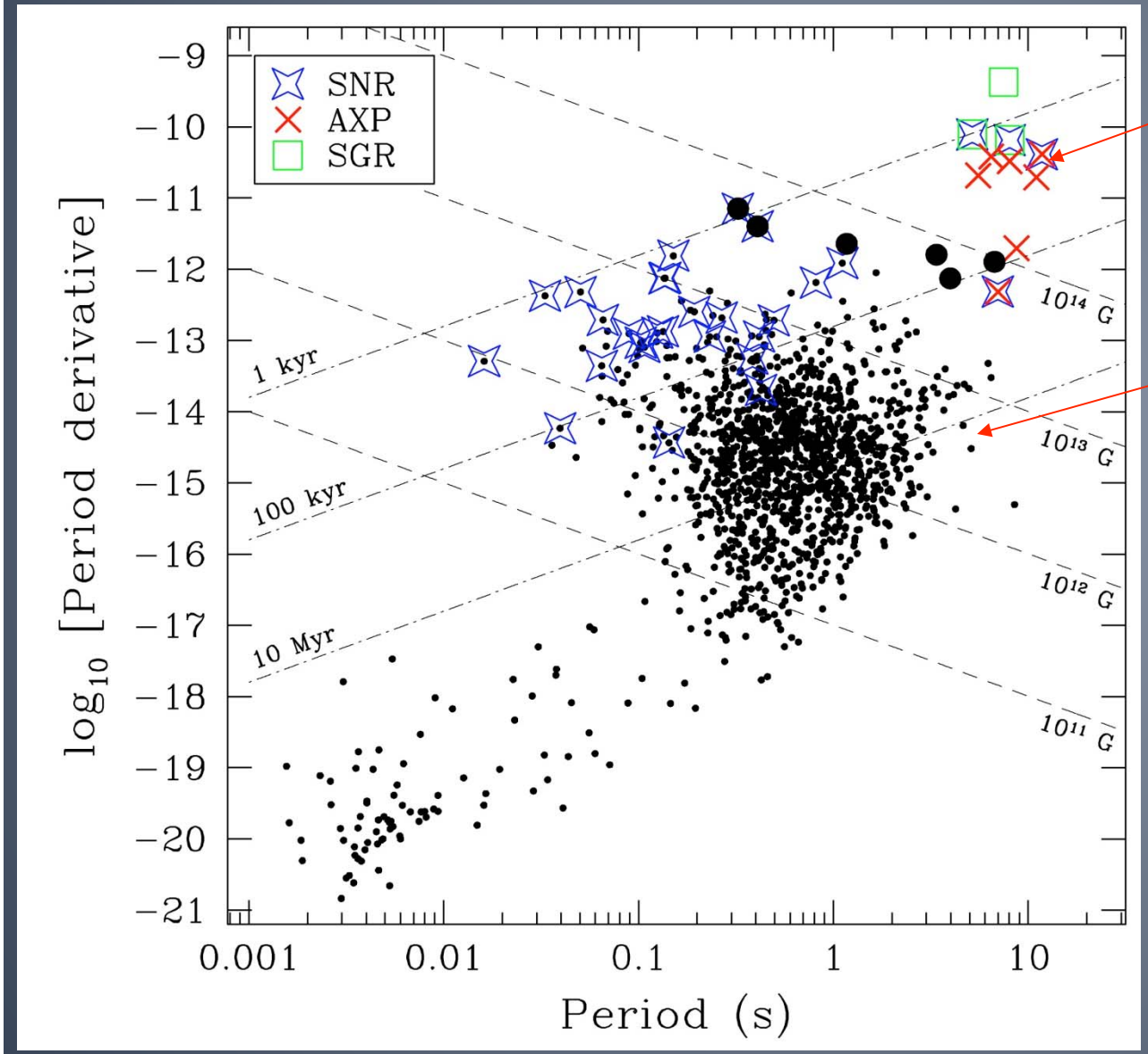
(beware confusing jargon)

- Formerly DINs (or XDINs) until realized not “dim”
- 7+1 known
- Nearby (most < 1kpc)
- P, Pdot measured for ~4: inferred Bs in range 1-3 e 13 G
- No radio emission (e.g. Kondratiev et al. 2009)
- Puzzling features, variation in X-ray spectra
- Most recent discovery Rutledge, Fox & Shevchuk (2008)
  SEE FOX TALK!



Van Kerkwijk et al. 2007

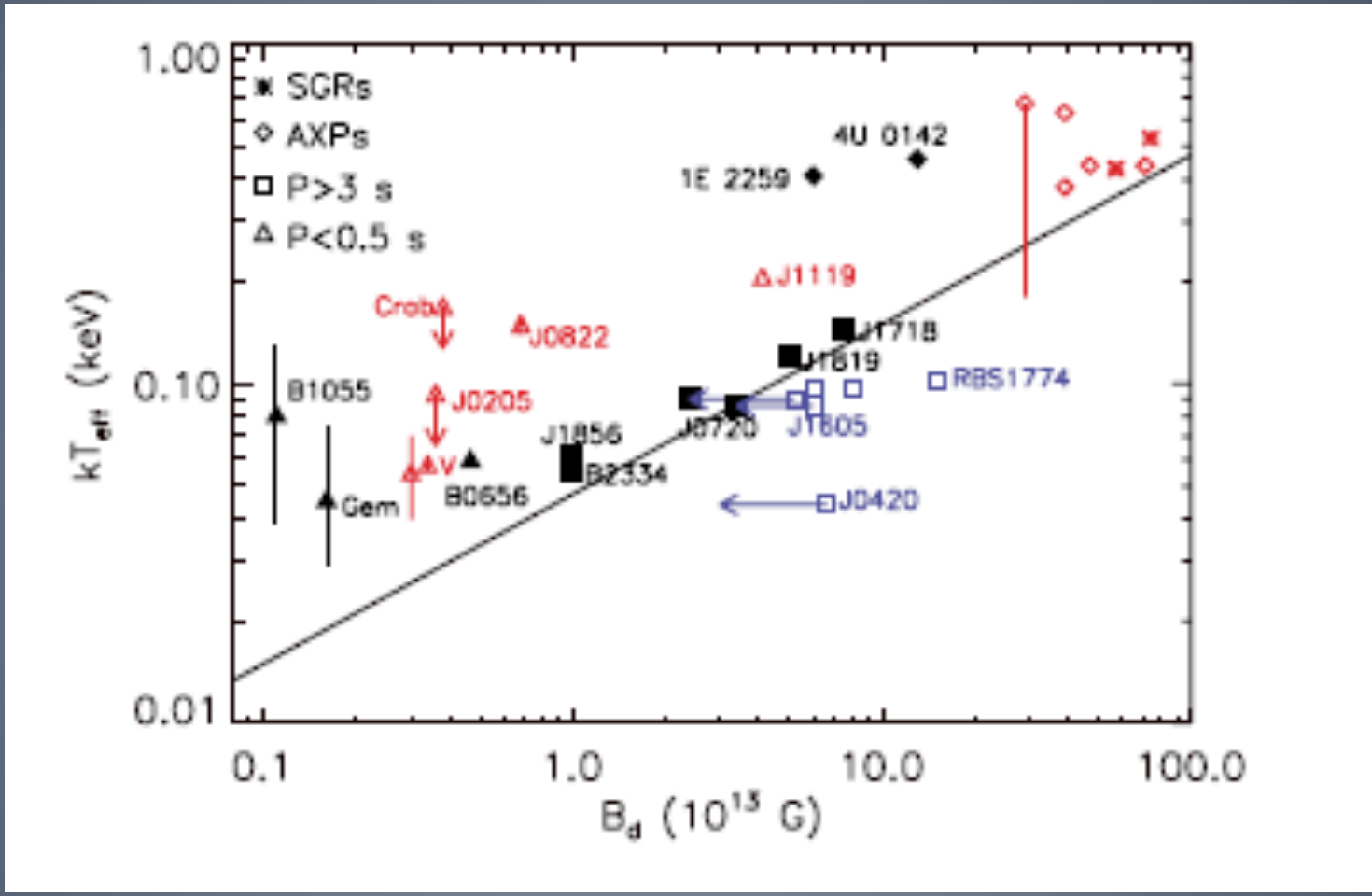
P-Pdot Diagram



SGRs, AXPs

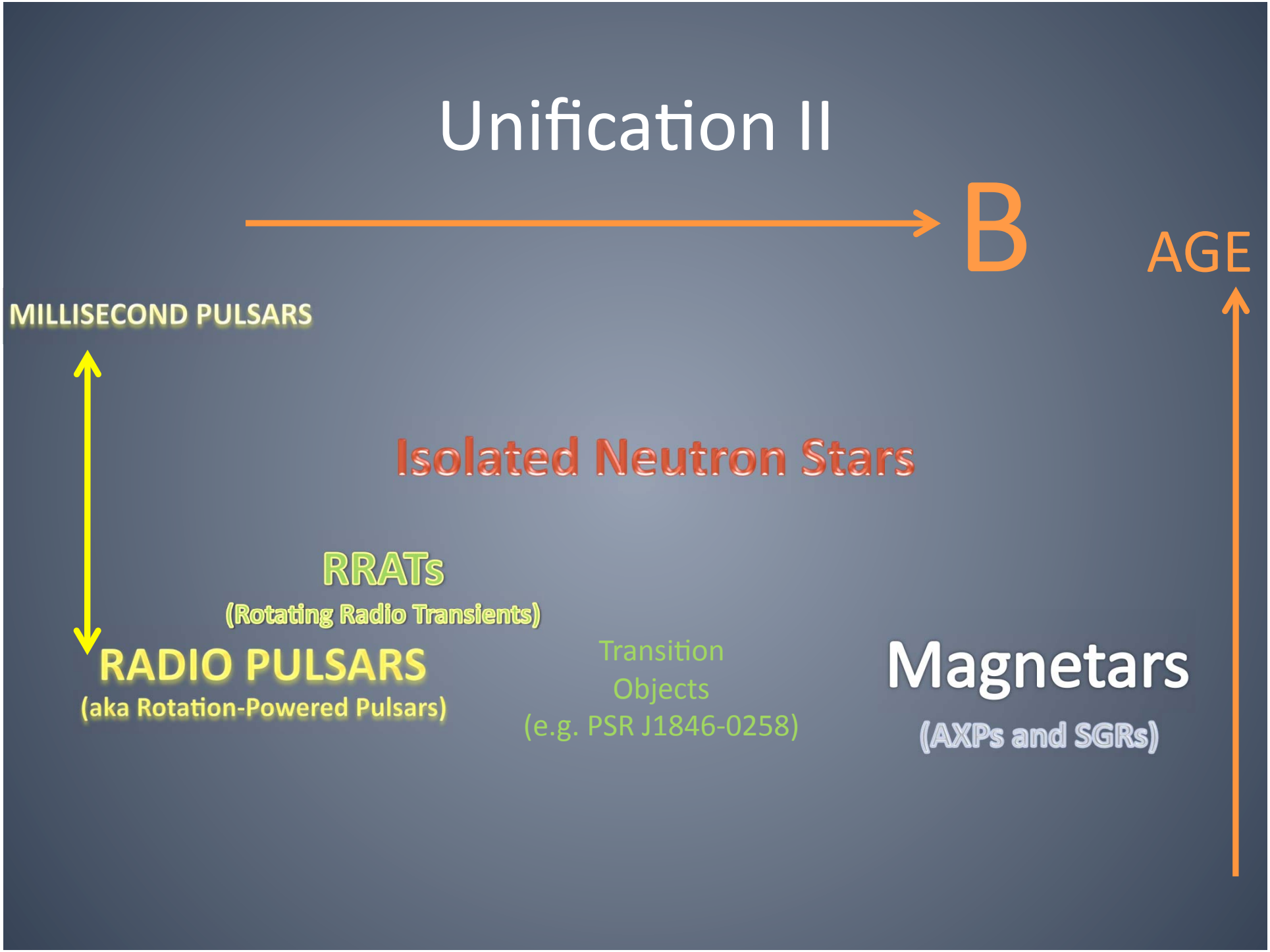
Radio Pulsars

Unification?



Solid line prediction based on simple model of B-decay heating crust and subsequent cooling: B decay delays cooling; highest B NSs stay hotter longer:``magneto-thermal evolution."

Pons et al. 2007, Aguilera et al. 2008, Pons et al. 2009


Unification II
B
AGE
MILLISECOND PULSARS
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(Rotating Radio Transients)
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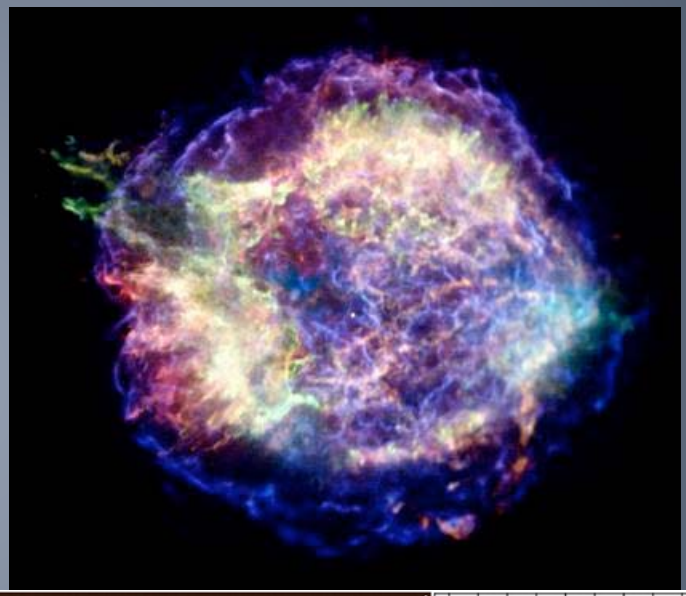
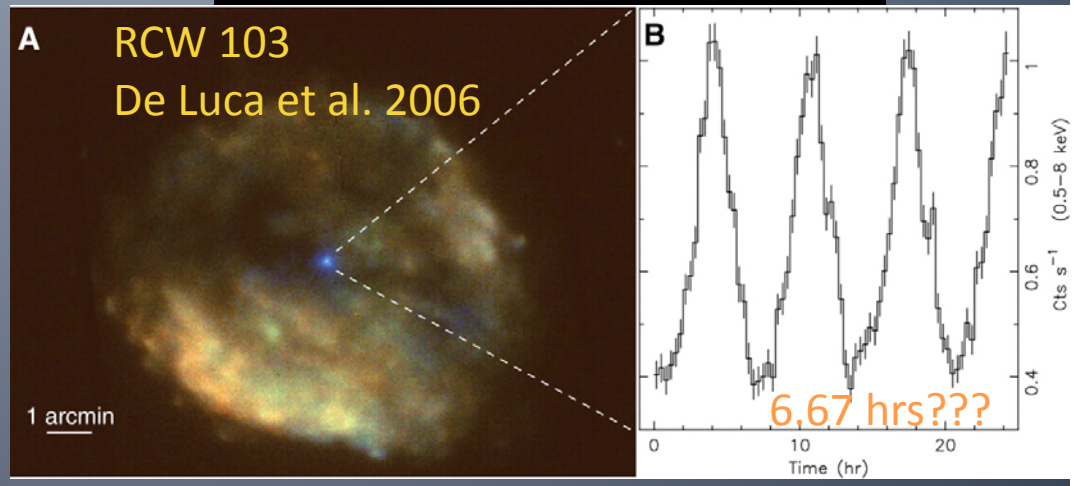
Transition
Objects
(e.g. PSR J1846-0258)
Magnetars
(AXPs and SGRs)

CCOs
(Central Compact Objects)

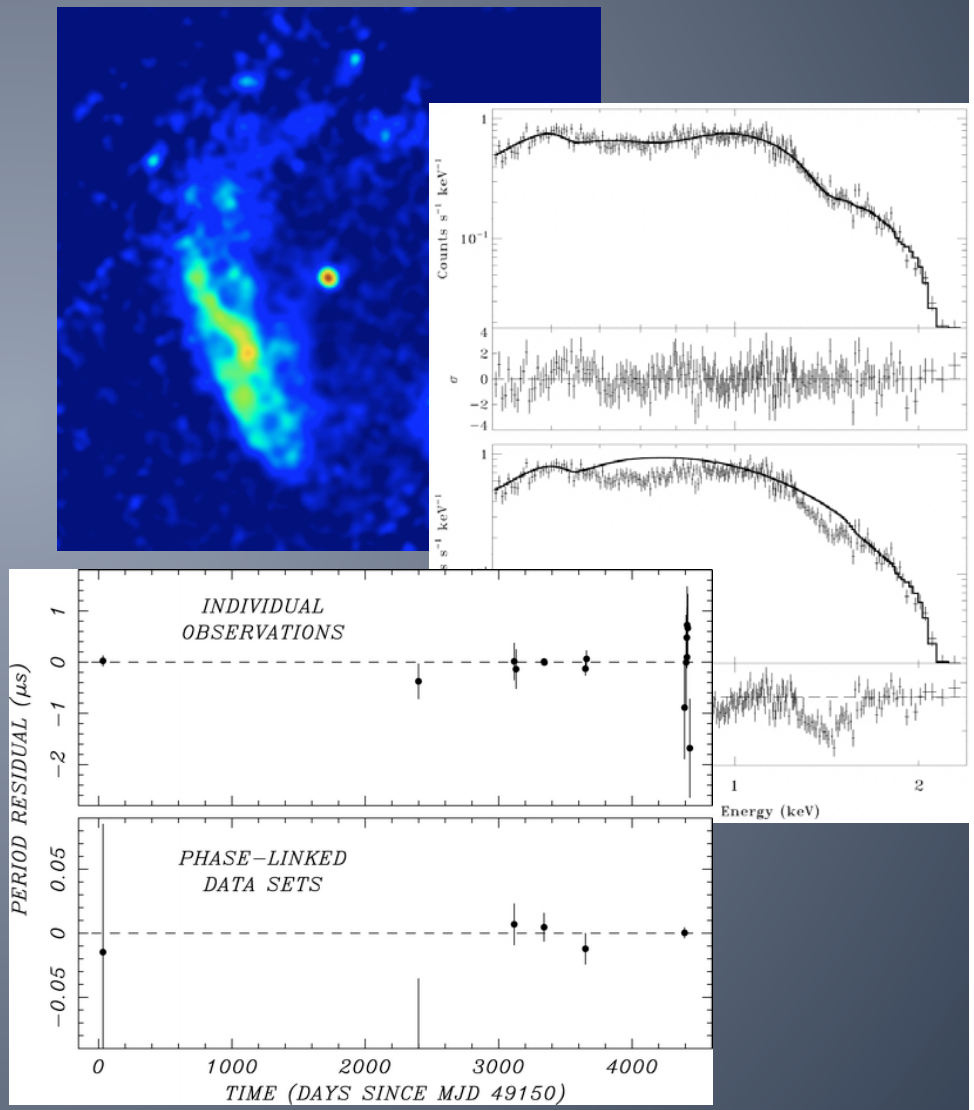
- Miscellaneous bag: unusual compact sources in SNRs
- Cas A: poster-child CCO
  SEE HEINKE TALK!
- RCW 103???
- "CCO" strangeness likely unrelated to central SNR location ...selection effect
- Again confusing name





CCO → "Anti-Magnetar"

- 1E 1207.4-5209 in SNR PKS 1209-52
- Spectral features (Sanwal et al. 2002, Bignami et al. 2003)
- B<3 e 11 G, age>27 Myr (Gotthelf & Halpern 2007)
- Similar low B for CCO in Puppis A (B<10e12 G) Gotthelf &Halpern 2009



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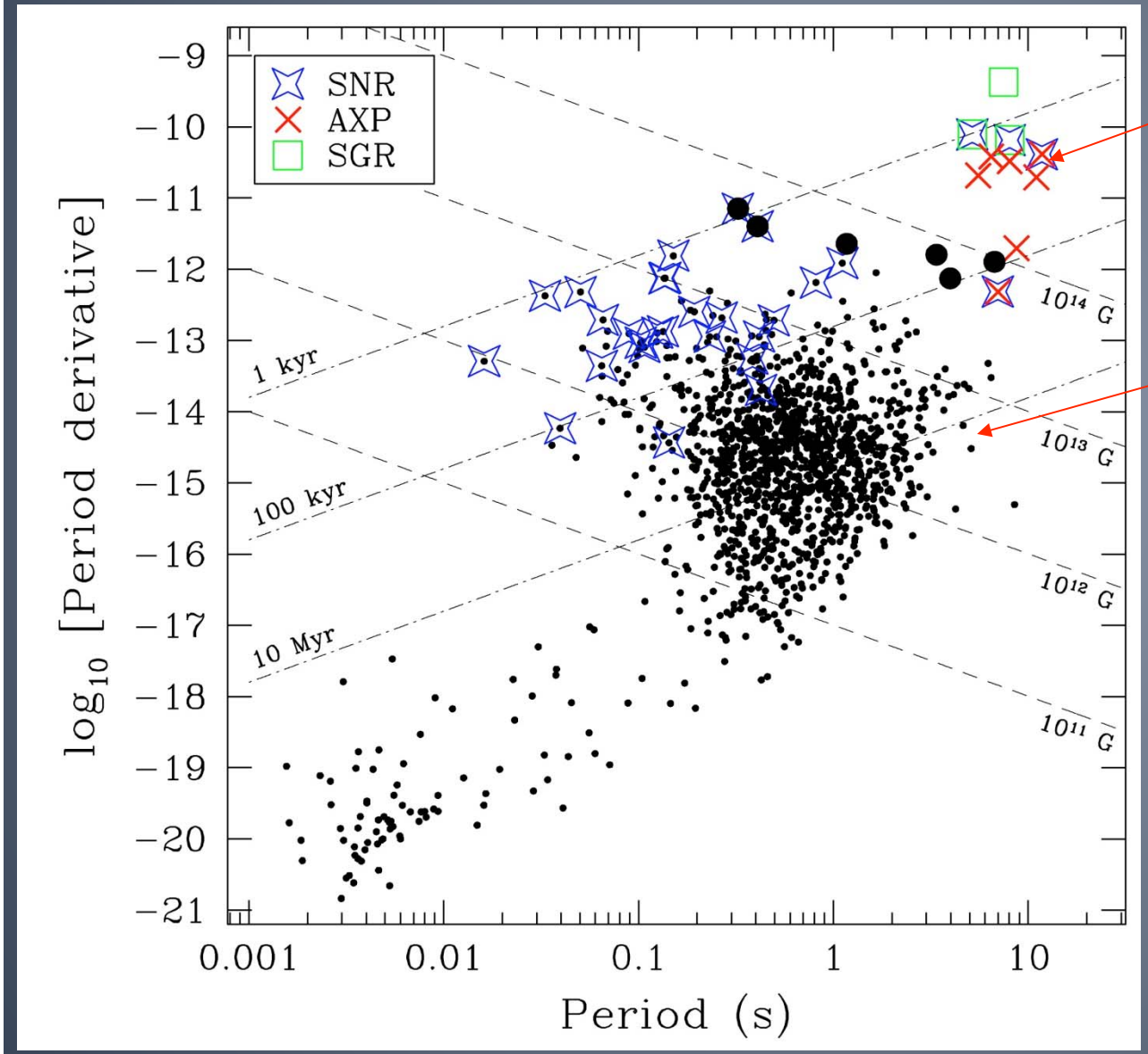

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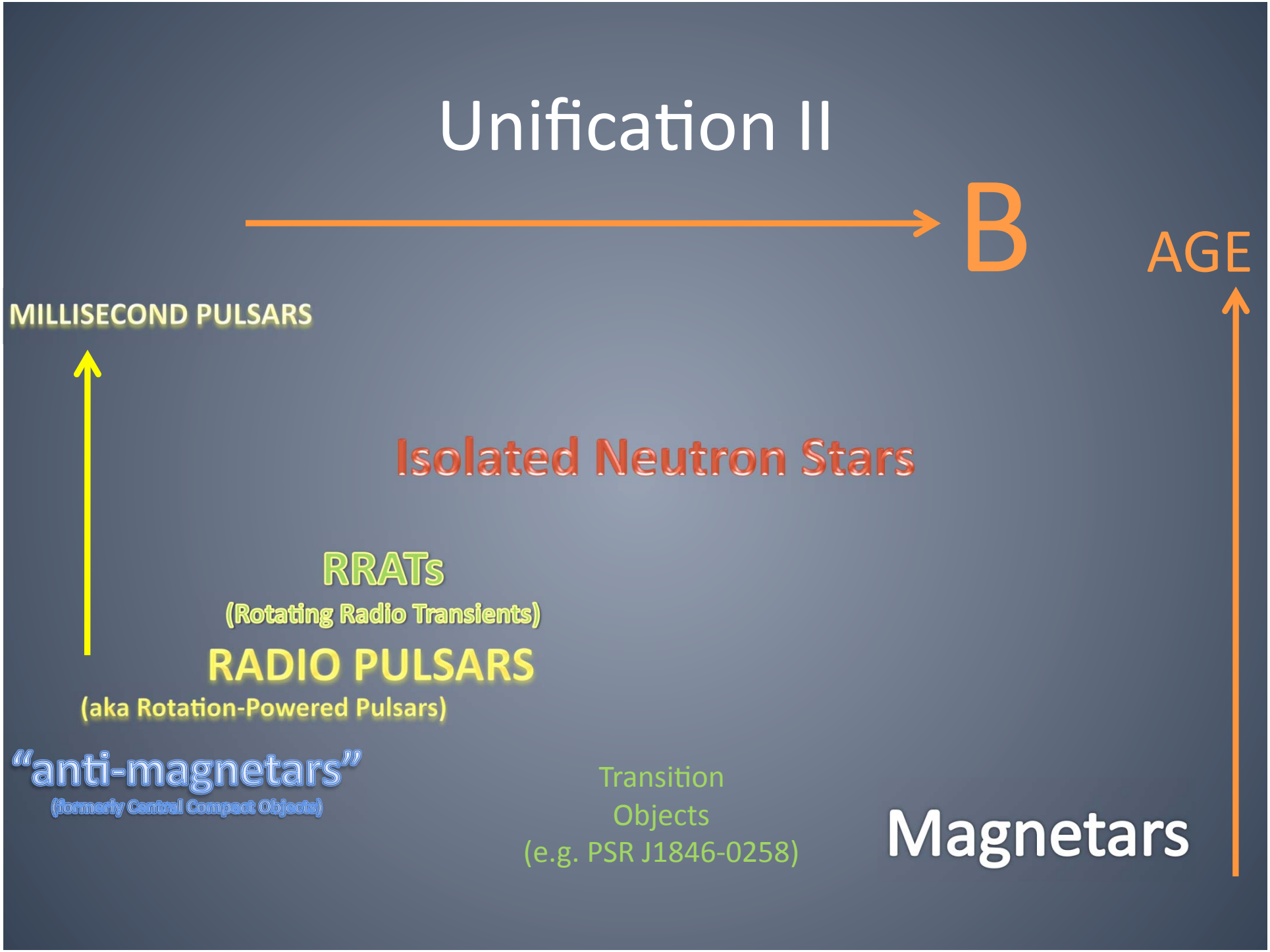
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RADIO PULSARS
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"anti-magnetars"
(formerly Central Compact Objects)
Transition
Objects
(e.g. PSR J1846-0258)
Magnetars

Unification: One Very Rough and Incomplete Possibility

(aka "going out on a limb")

Chandra Tests of Unification Scheme: The Next Decade

- High-B radio pulsars: solidify magnetar connection
  - Deep observations for spectra
  - Monitoring for variations
  - ToO obs at glitch epochs
- Magnetar outburst relaxation: constrain magnetar models, compare with other outbursts
- Monitor INS to study spectral changes, features
- Time new INSs
- Measure proper motions (already some)
- Other ideas??

THANKS TO CXO TEAM FOR ALL THEIR EFFORTS ESP IN SCHEDULING TOOs