Magnetic Field Decay in Magnetars & implications for evolutionary links

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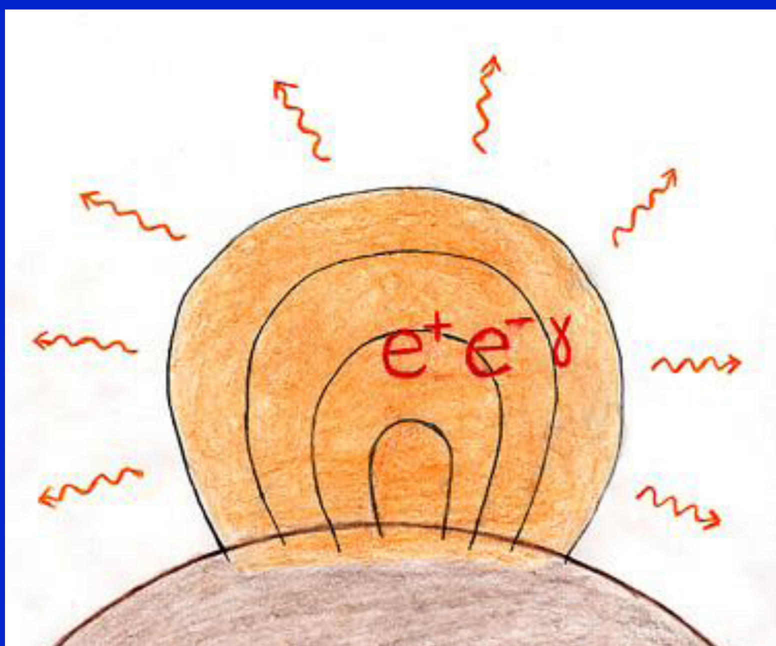


39th COSPAR Scientific Assembly, Mysore, India, July 19, 2012

Outline of the talk:

- Motivation & brief introduction
- Observational evidence for magnetar B-field decay
- Field decay: main properties **(true vs. spin-down age)** & observational constraints on dipole field decay
- $L_X > |\dot{E}_{B,dipole}|$ ➔ another energy source is required
- ➔ Internal field decay? requires $B_{internal,i} \gtrsim 10^{16}$ G
- Implications for evolutionary links
- Conclusion

Motivation

X-ray emission of magnetars is powered by the decay of their super-strong magnetic field:

a) eventually test this hypothesis;

b) best objects to study B-field decay

"Magnetar-like" emission from unsuspected magnetars:

Additional degree of freedom besides dipole field?

Link between different classes of high-B NSs (SGRs, AXPs, "transient" AXP/SGRs, XDINs,...)

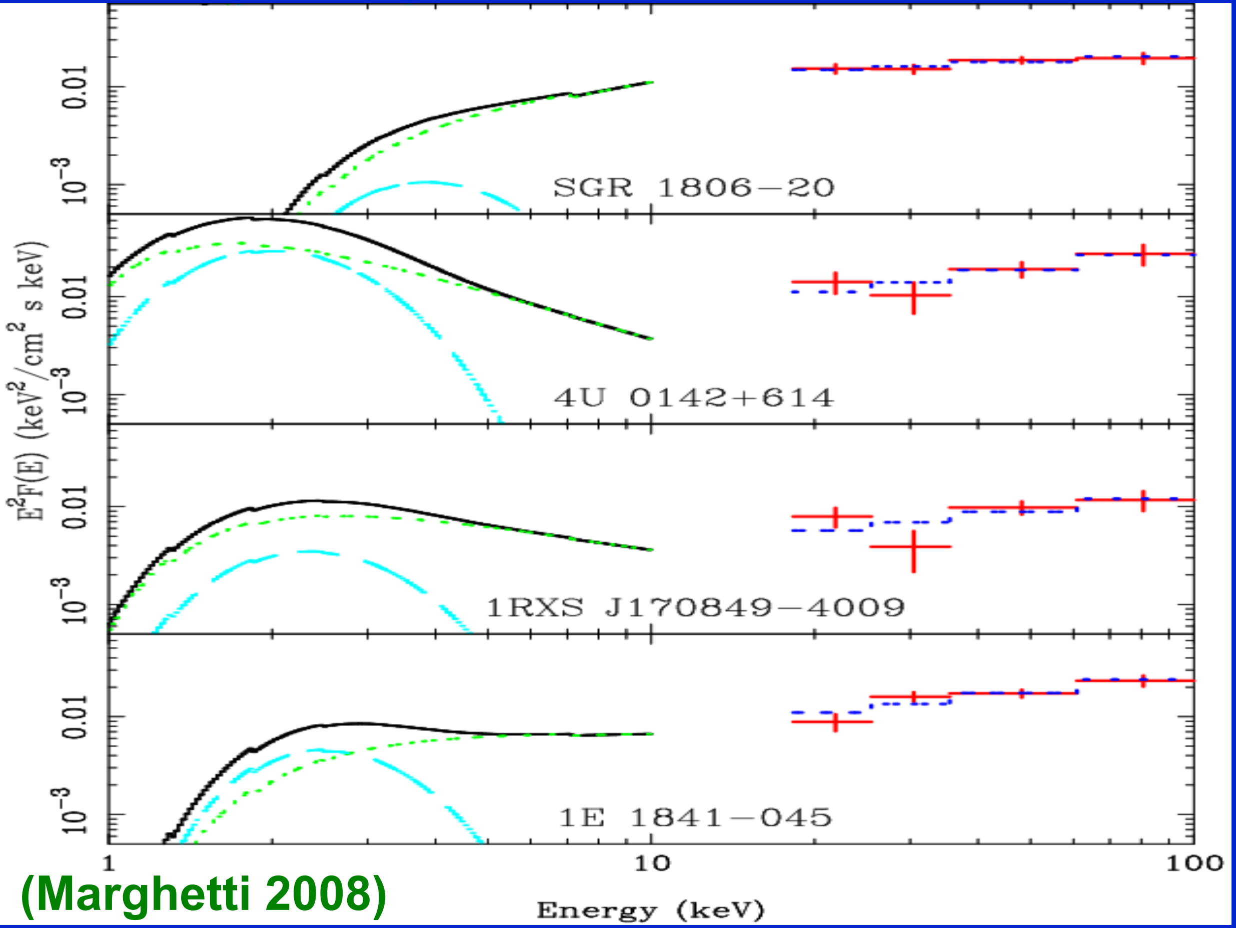
Dall'Osso, JG & Piran 2012, MNRAS, 422, 2878

Source Classes

AXPs/SGRs: Persistent X-ray emission ≫ dE_{rot}/dt

Thermal → kT = (0.5-0.7) keV

Hard-X spectral tails (up to 150 keV)



(Marghetti 2008)

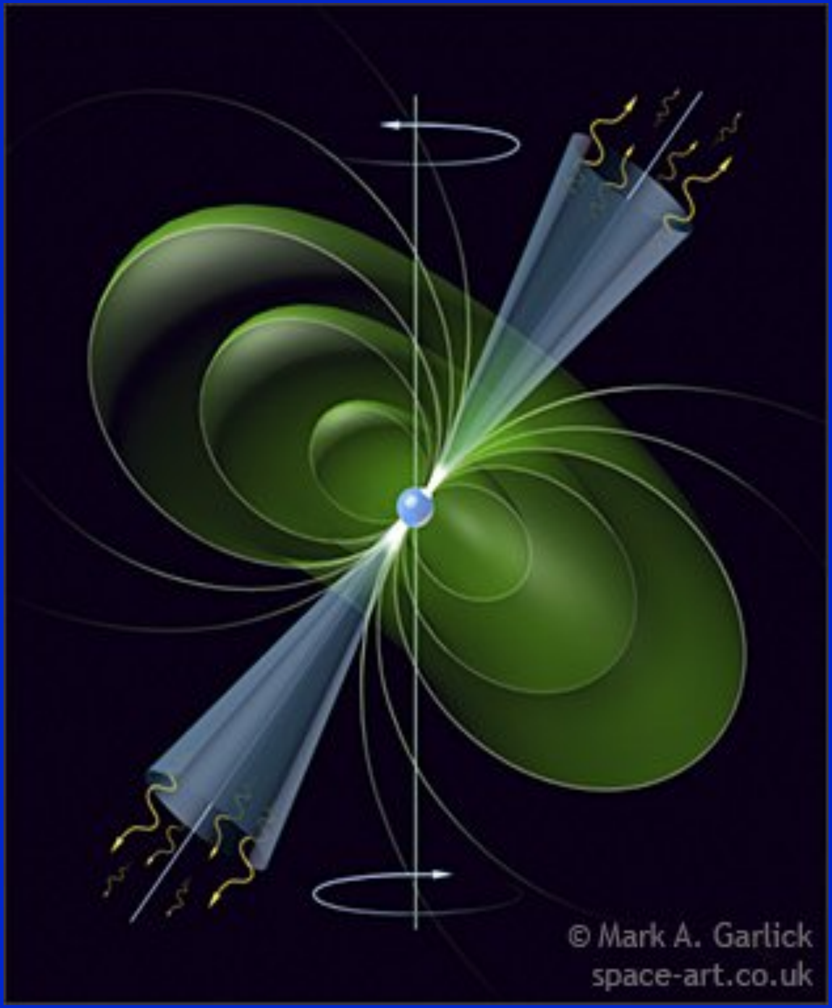
Source Classes

AXPs/SGRs: Persistent X-ray emission $\gg dE_{rot}/dt$
Thermal → $kT = (0.5\text{-}0.7)$ keV
Hard-X spectral tails (up to 150 keV)

Transients: Quiescent X-ray emission $\lesssim dE_{rot}/dt$
Thermal → $kT = (0.4\text{-}0.5)$ keV + $A \ll A_{NS}$
In outburst: X-ray emission $\gg dE_{rot}/dt$
& decays over years

X-ray Dim Isolated Neutron stars (XDINs):
Prototypical Isolated Neutron Stars,
Nearly perfect thermal spectra and
Stable X-rays $kT = (0.04\text{-}0.1)$ keV

PULSARS: BACK TO BASICS



Magnetic dipole spindown:

$$\dot{\Omega} = K\, B_d^{\,2}\, \Omega^3$$

$$K_{vacuum} = 2R^6 \sin^2\theta_B / 3Ic^3$$

$$K_{plasma} = R^6 (1+\sin^2\theta_B)/Ic^3$$

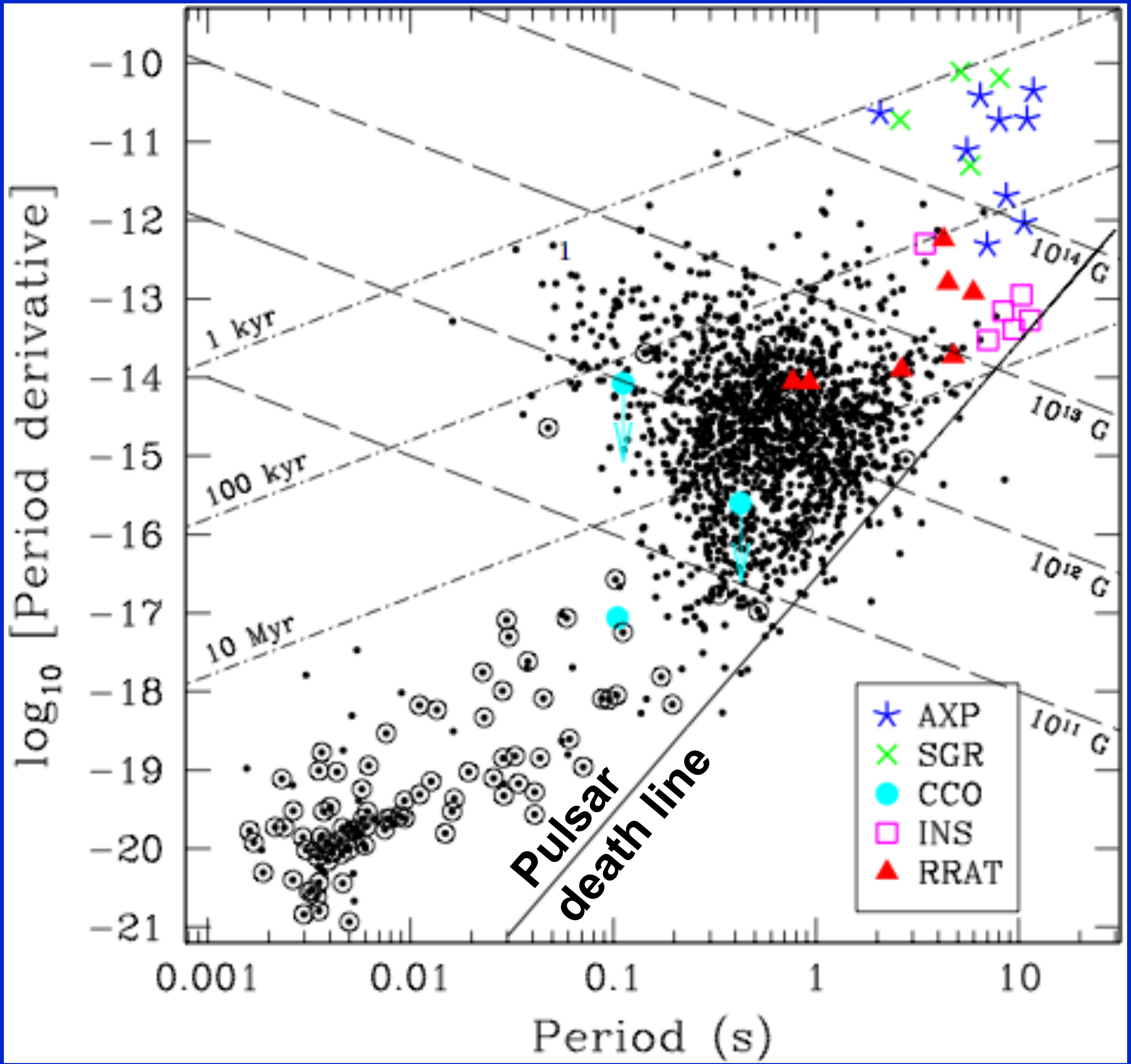
Characteristic (spindown) Age

$$\tau_c = -\Omega/2\dot{\Omega} = P/2\dot{P}$$

$$B_d = 3.2\times10^{19} (P[s]\ \dot{P})^{1/2}\ G$$

$$= 3.2\times10^{19} P[s] (2\tau_c[s])^{-1/2}\ G$$

An observational perspective:



P - $\dot{P}$ diagram for 1704 objects, including 1674 RPPs (small black dots).

Magnetars have some of the lowest spins, despite being the most luminous. A lower-B NS would be over the death line & thus no longer a RPP.

RPP = roation powered pulsar
CCO = central compact object
INS = XDIN
RRAT = rotating radio transient

(Kaspi 2010)

An observational perspective:

SGR0418+5729: discovered by Fermi/GBM on 9 June 2009 through 2 weak bursts **(Van der Horst et al. 2010)**

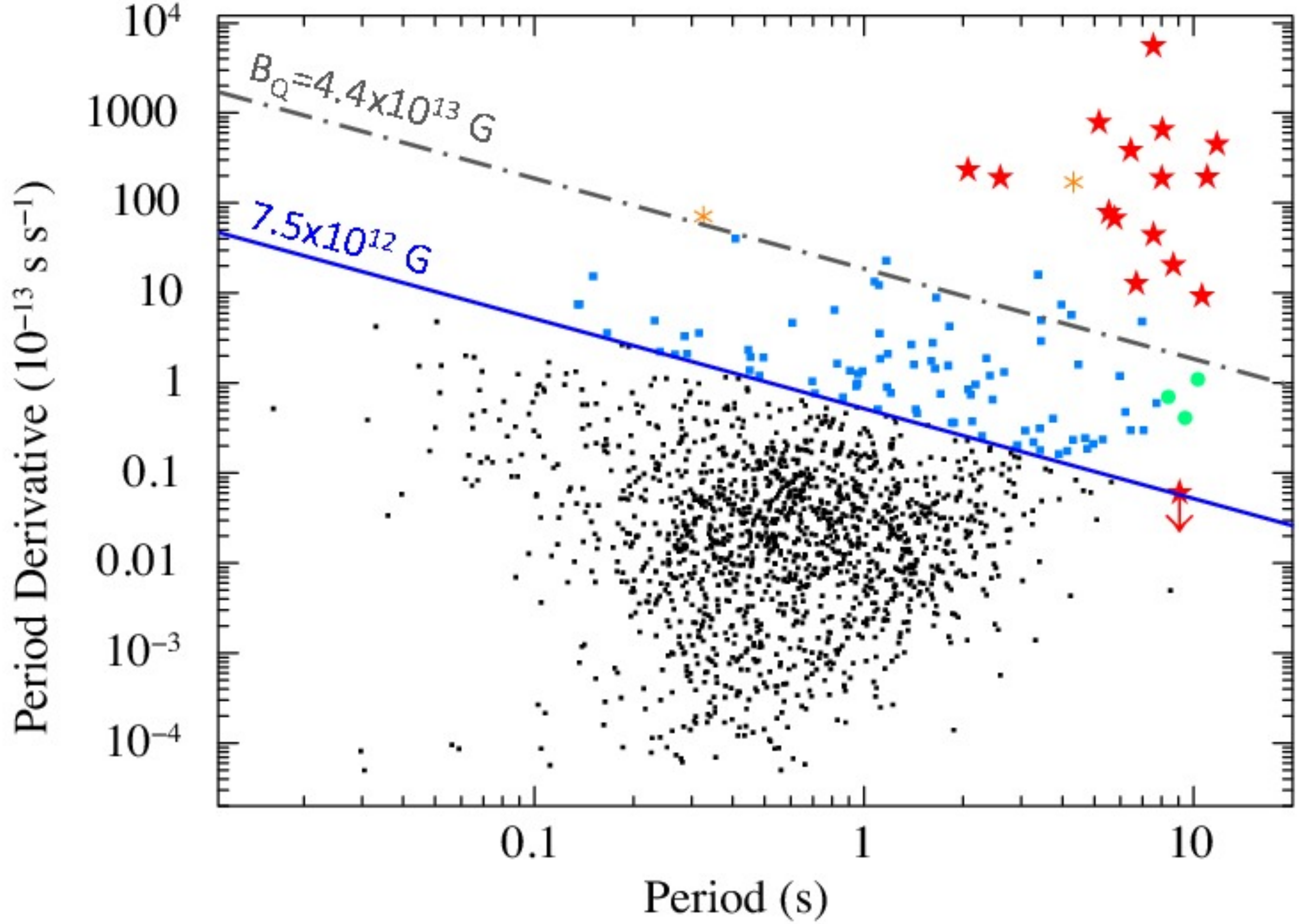
+

It displayed long-lasting enhanced X-ray emission & a spin period of $P \approx 9.1$ s **(Esposito et al. 2010)**

By 23 Sep. 2010 its F_X decreased by $\times 10^3$ to 6×10^{31} erg/s. Hot thermal emission ($kT \approx 0.67$ keV) & very small emission region ($R \approx 0.1$ km) **(Rea et al. 2010)**

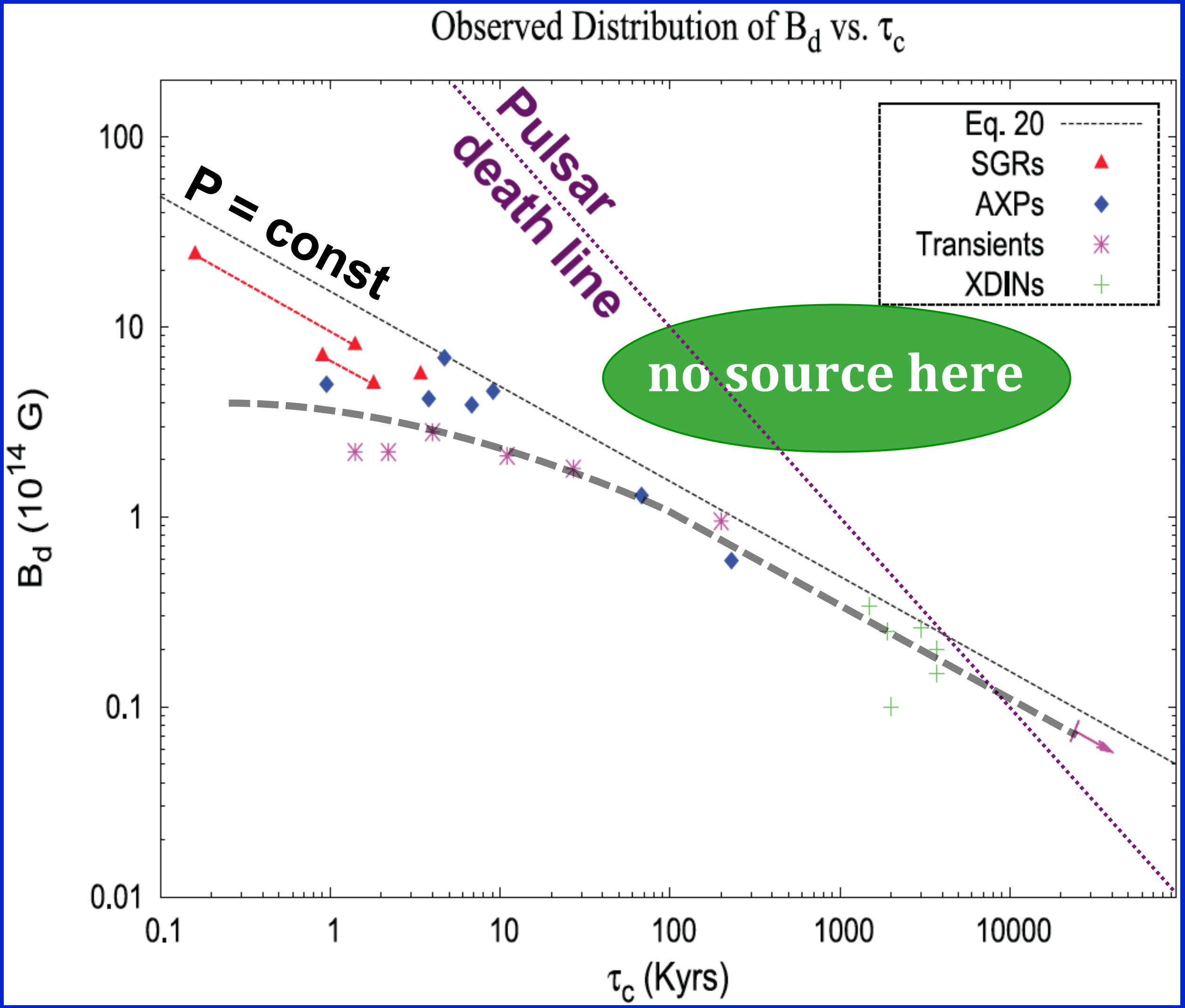
No period derivative measured: $\dot{P} < 6\times 10^{-15}$ s/s
→ $B_{dipole} < 7.5\times 10^{12}$ G & $\tau_c > 2.4\times 10^{7}$ yrs
(Rea et al. 2010)

An observational perspective:



(Rea et al. 2010)

A physical perspective:



(Dall'Osso, JG & Piran 2012)

(7 SGRs, 11 AXPs, 6/7 XDINs)

No high-B_d objects With an old τ_c

(B_d = dipole B-field
τ_c = spin-down age)

There is a limiting spin period: $P \lesssim 10$ s

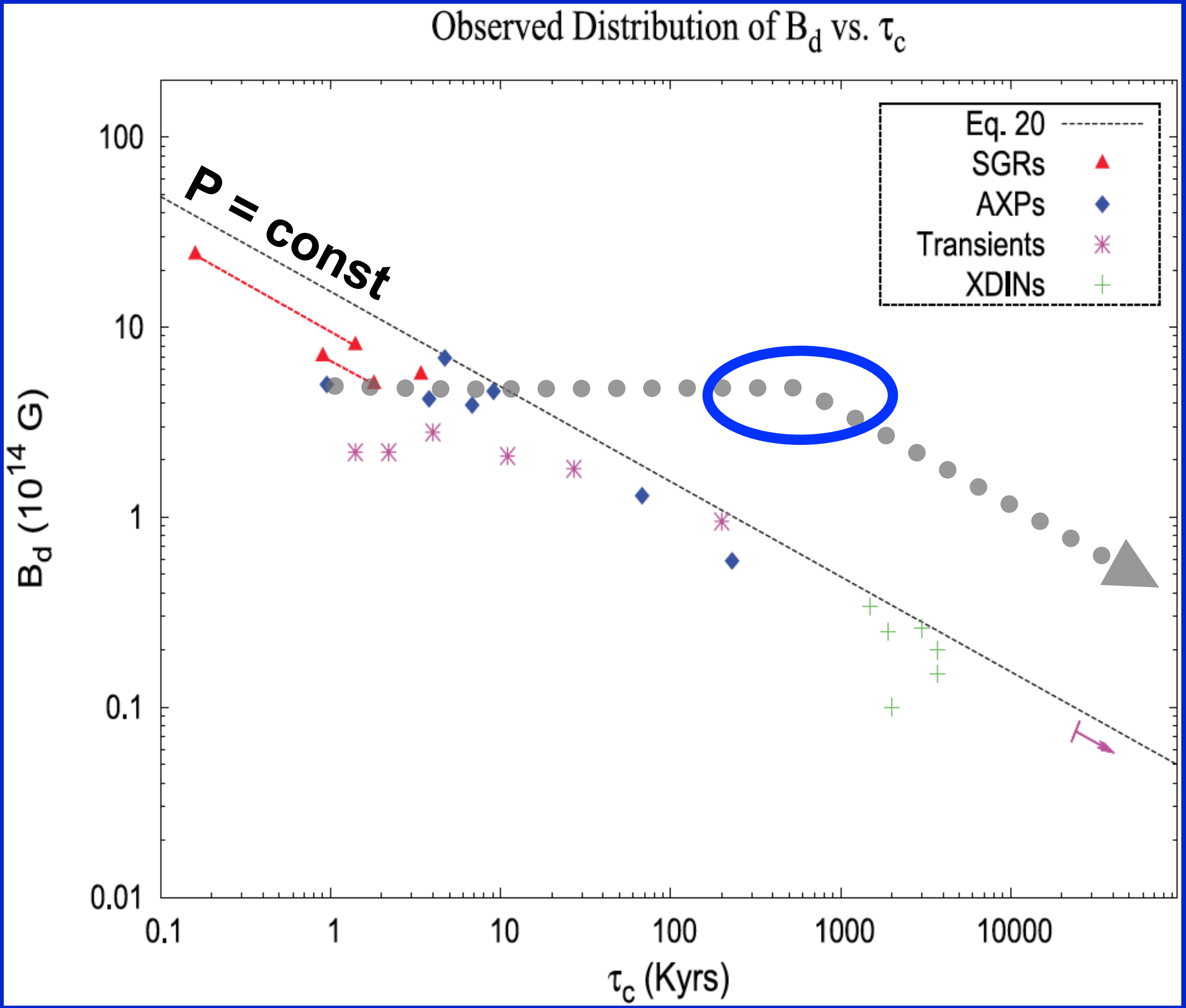
It is expected if B_d decays fast enough:

$\dot{B}_d \propto B_d/\tau_d$

$\tau_d \propto B^{-\alpha}$ with $\alpha < 2$

(Colpi et al. 2000)

Could this be a selection effect? Unlikely!



(Dall'Osso, JG & Piran 2012)

- For $\tau_c = \text{const}$, larger B_d is easier to detect

SGRs are detected through their bursts: Before B_d decays a lot, $\tau_c \sim t$ ➔ more sources at larger τ_c

If bursts follow B_d ➔ SGRs should be detected mostly with $P \gg 10\,\mathrm{s}$

If bursts ~~follow~~ B_d how do they "know" to stop at $P > 10\,\mathrm{s}$?

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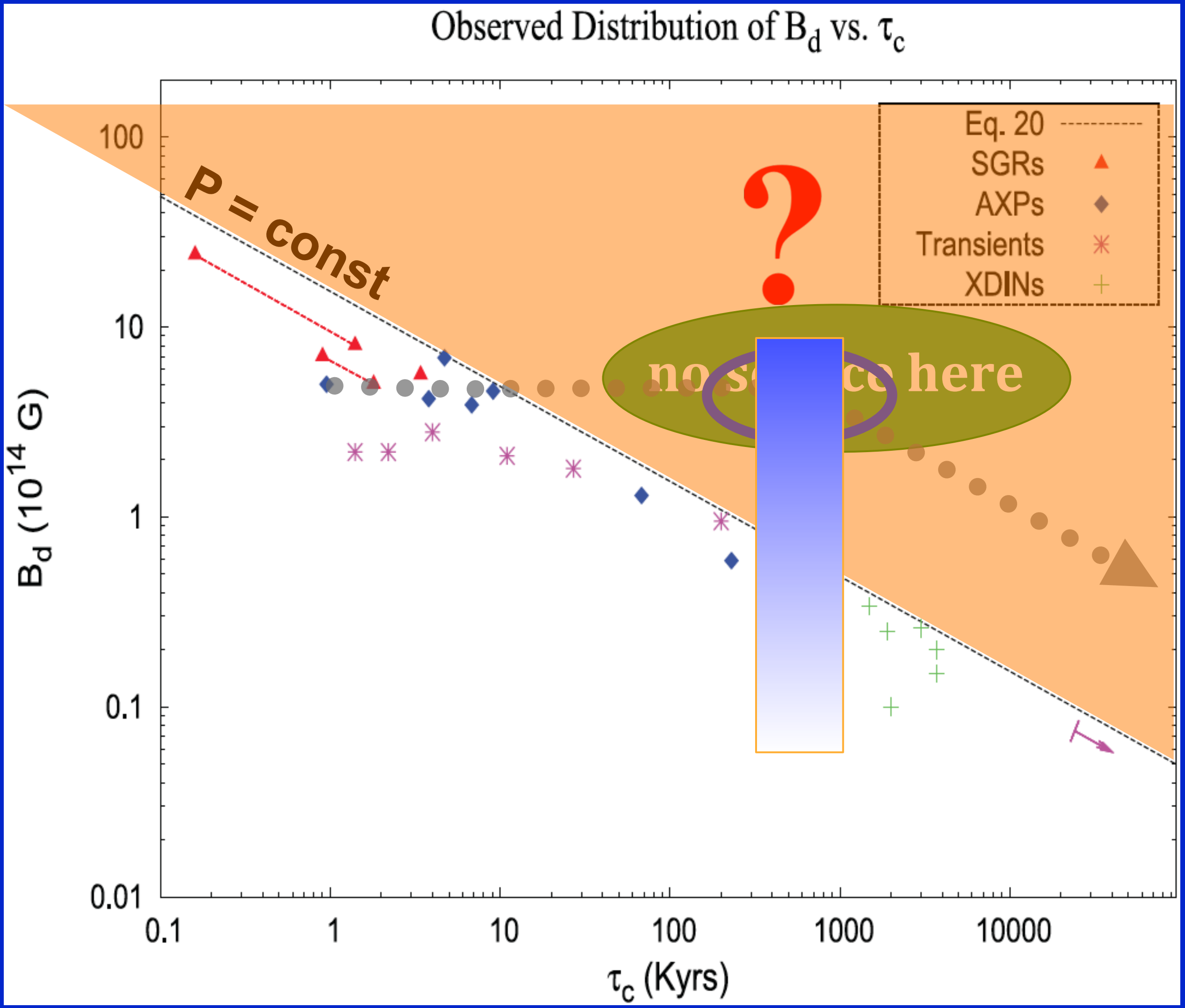

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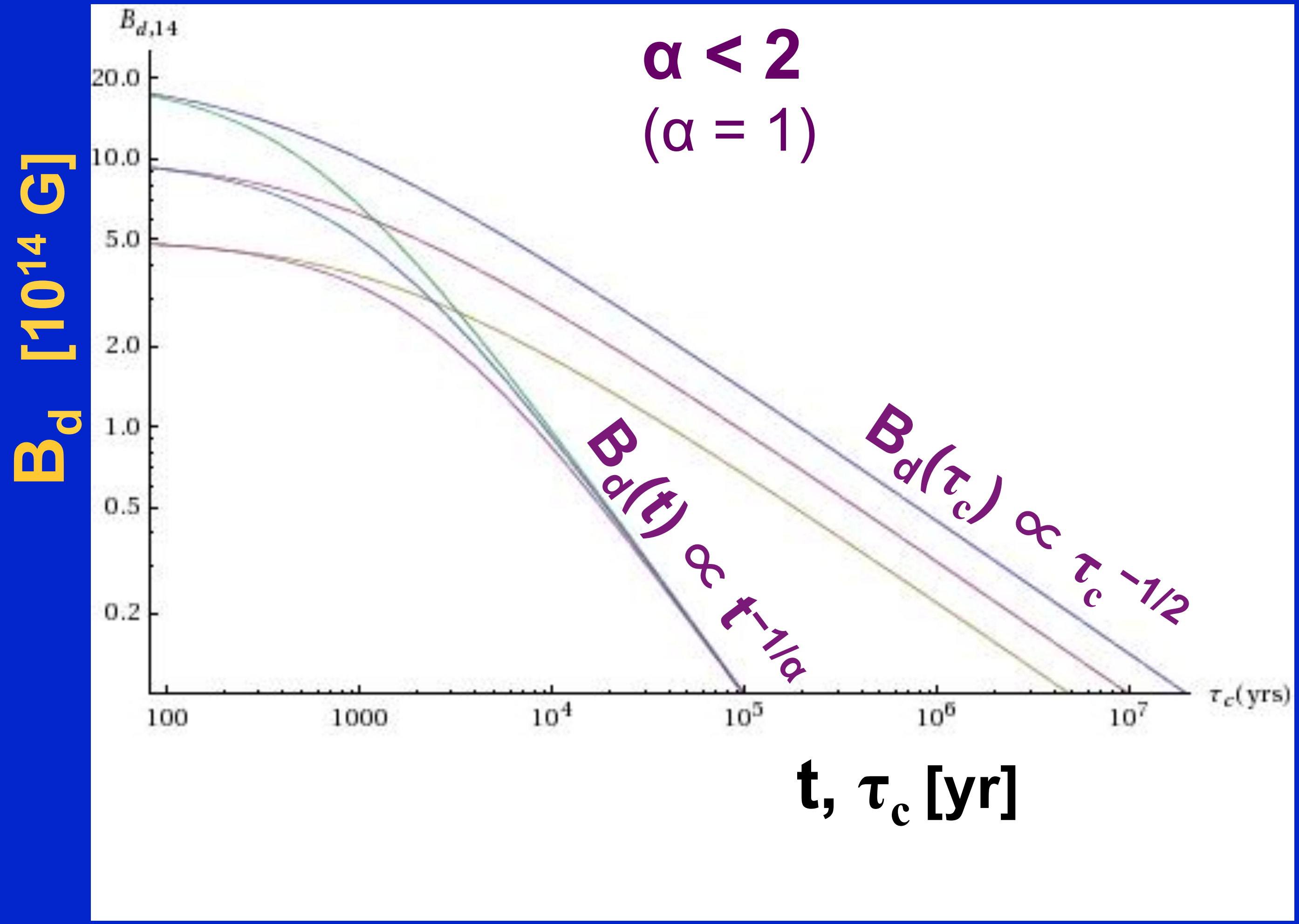
If bursts ~~follow~~ B_d how do they "know" to stop at $P > 10\,s$?

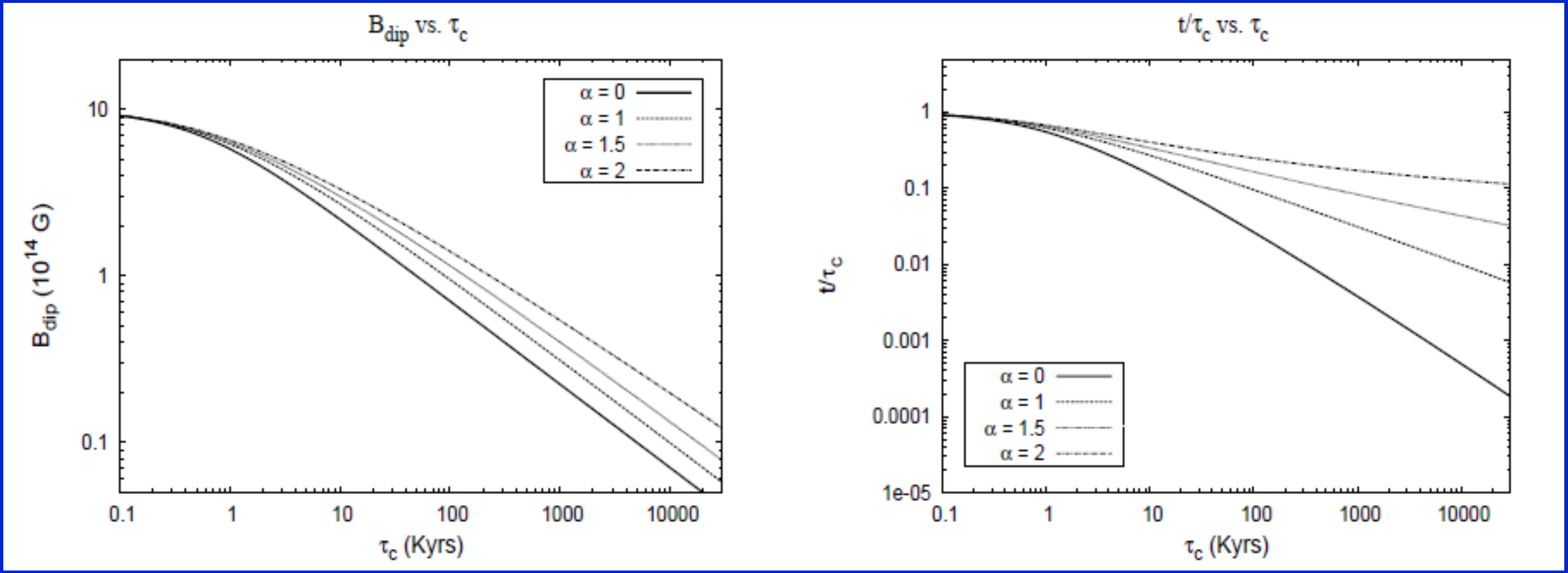
Dipole field decay: parameterized model

$\dot{B}_d \propto B_d/\tau_d \propto B_d^{1+\alpha}$, $\tau_d \propto B^{-\alpha}$ with $\alpha < 2$



Dipole field decay: parameterized model

Once B_{dip} decays significantly, true age $t \ll$ spin-down age τ_c



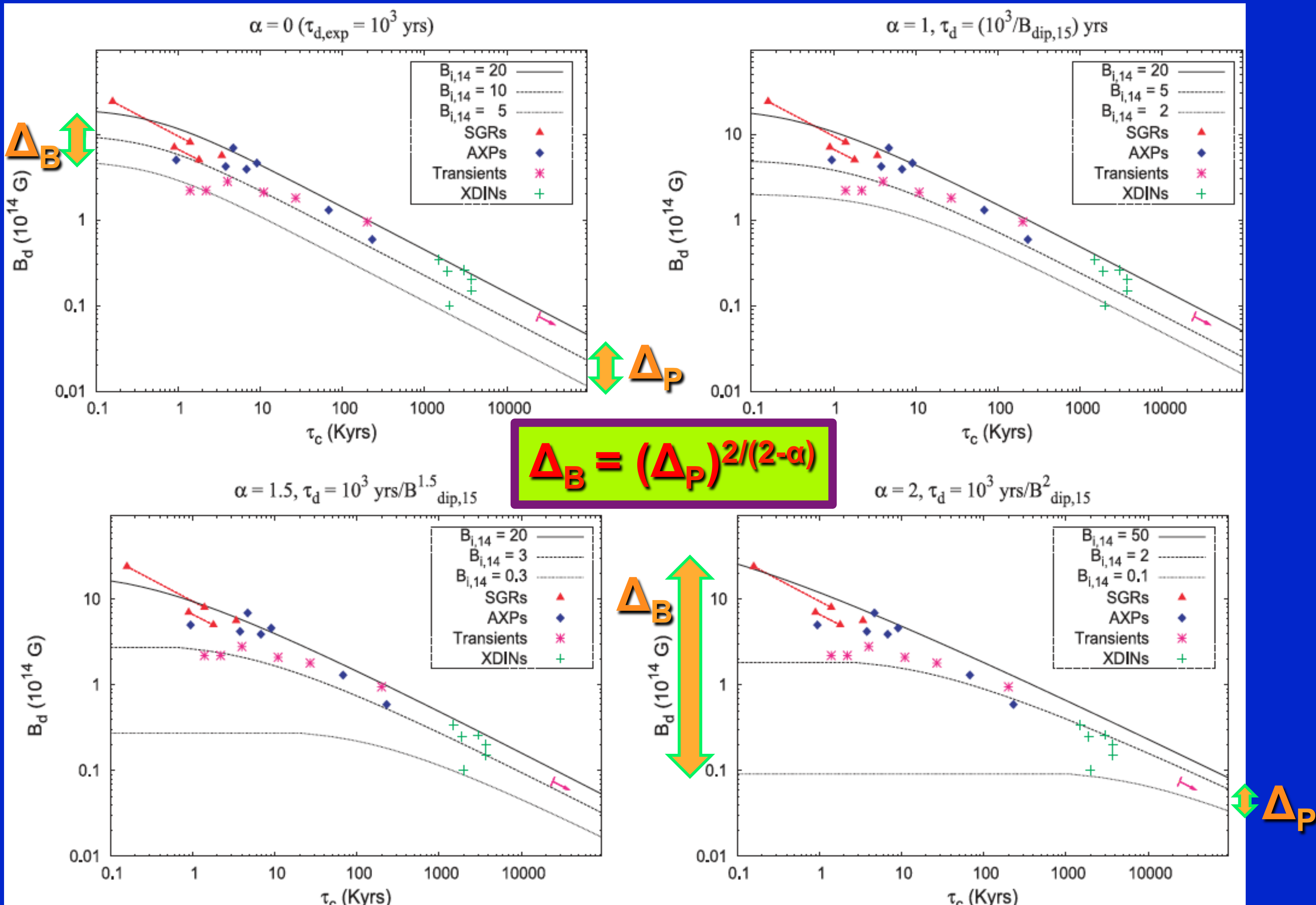
$$B_d \propto P\,\tau_c^{-1/2}$$

For $t \gg \tau_{d,i}$, $\alpha < 2$:

$$B_d \propto t^{-1/\alpha} \propto \tau_c^{-1/2}$$

$$t/\tau_c \propto \tau_c^{(\alpha-2)/2}$$

Dipole decay modes vs. Observations



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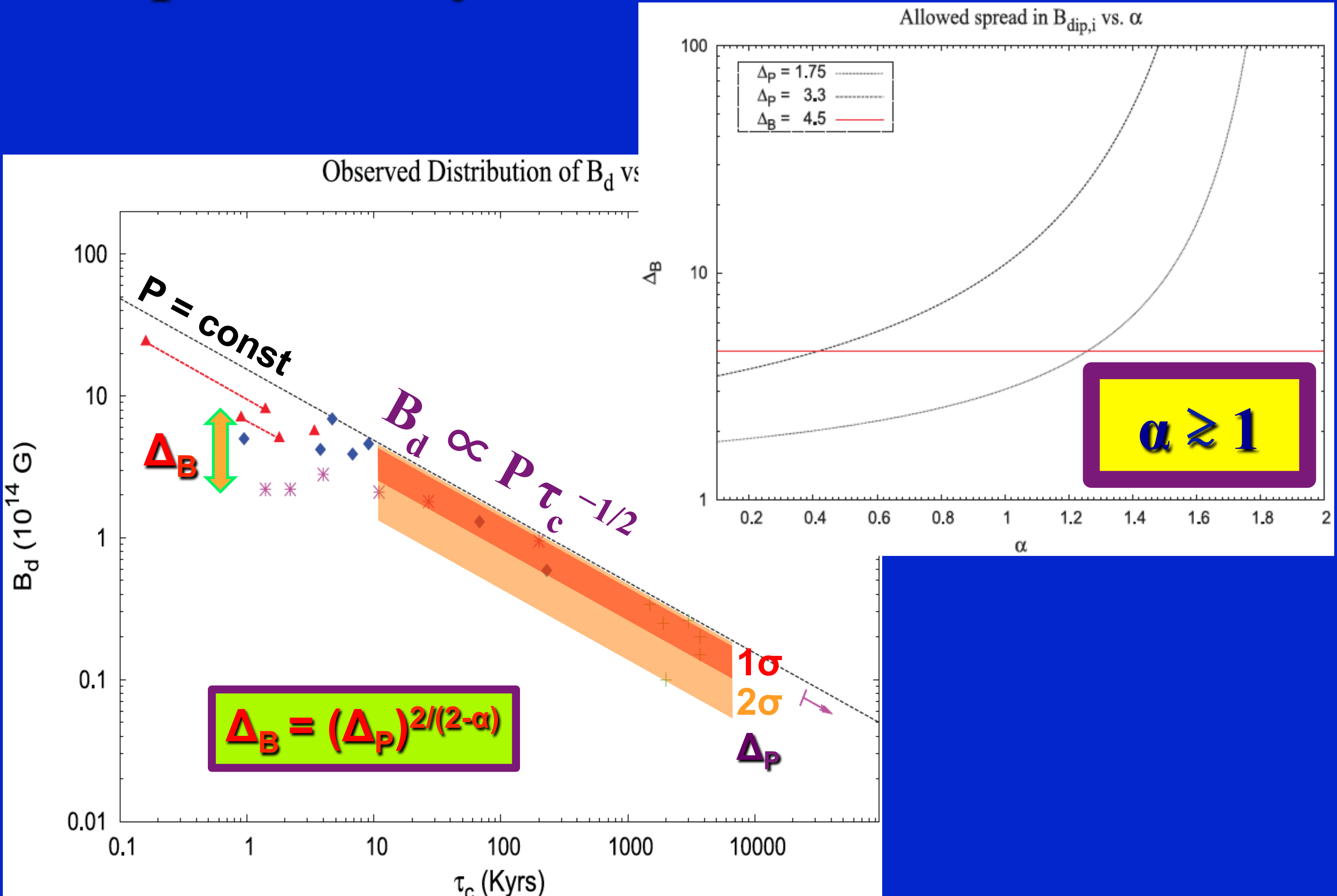

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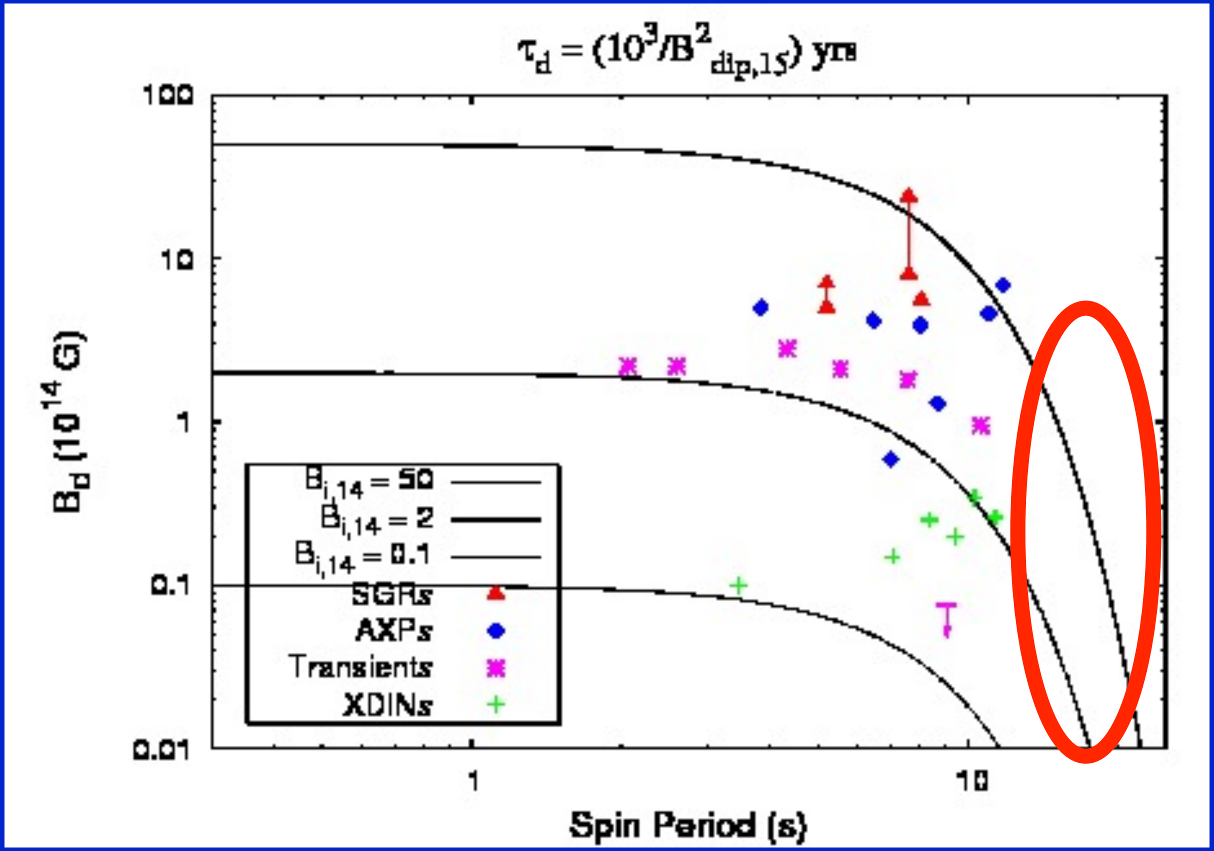
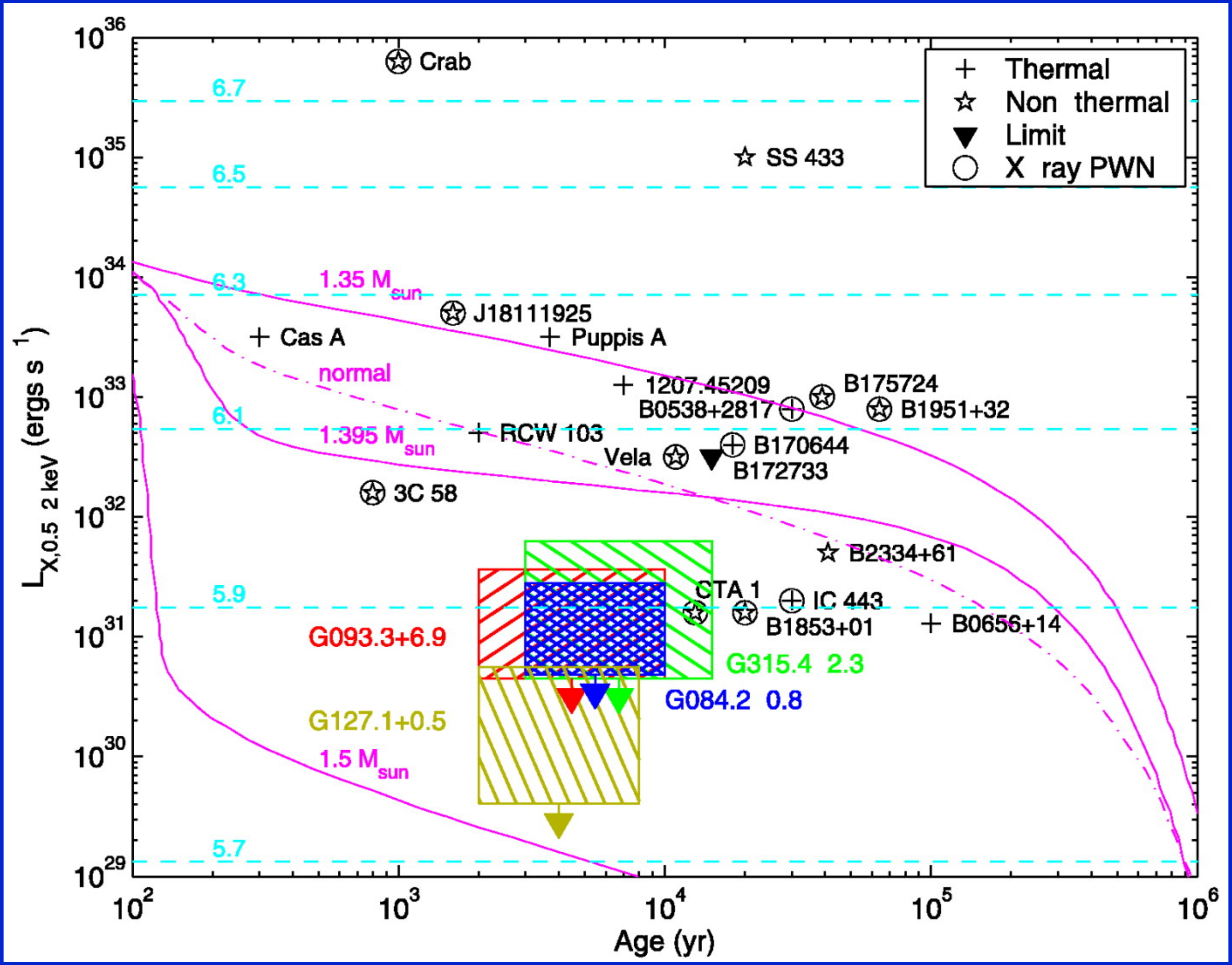


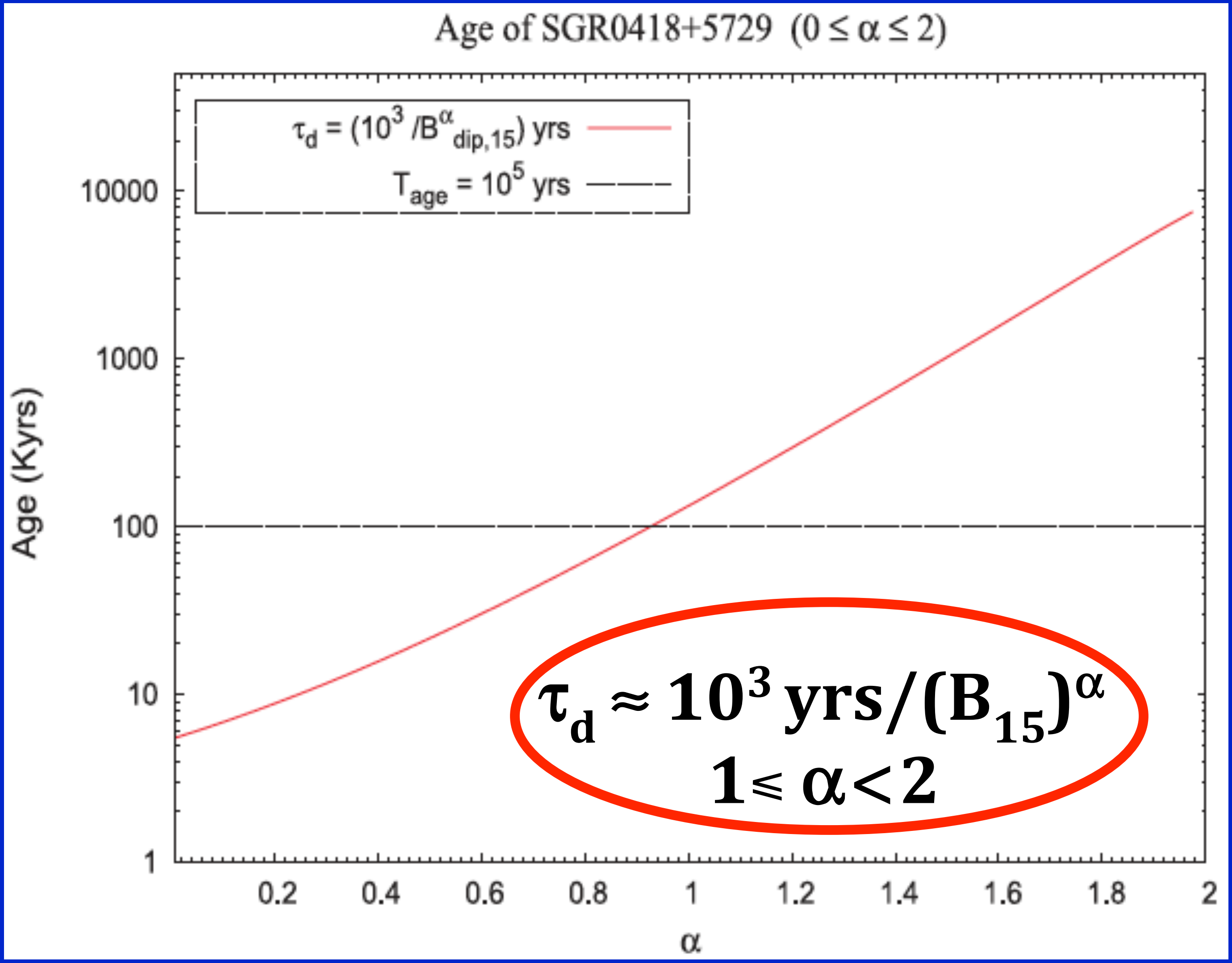
α < 2

Age constraints on the field decay



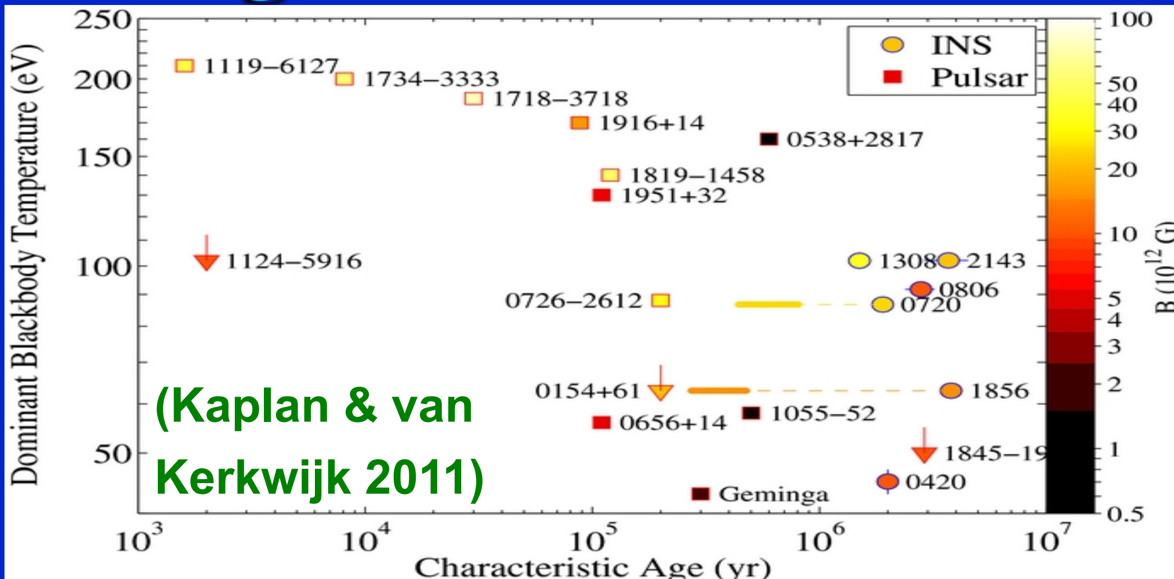
(Kaplan 2004)

Age constraints on the field decay



$L_X(0.5\text{-}10\ \mathrm{keV}) < 6\times10^{31}$ erg/s → **$t > 10^5$ yr**

Age constraints on α from XDINs



(Kaplan & van Kerkwijk 2011)

$L_X \approx$ few $\times 10^{31}$ erg/s

$kT < 0.1$ keV $\approx 10^6$ K

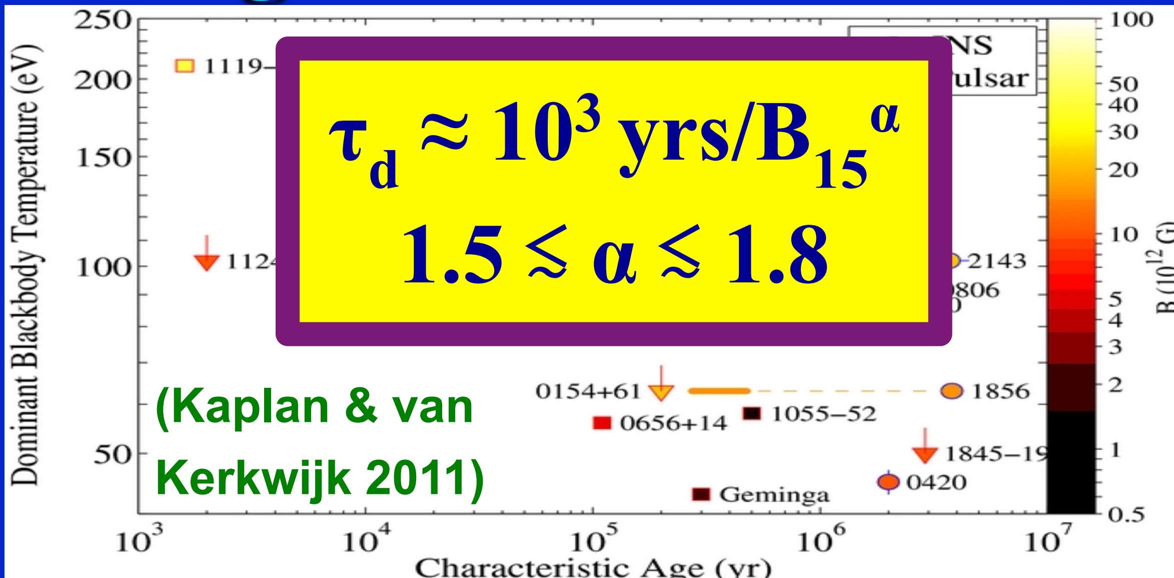
➔ ages $t \lesssim 10^5$ yrs

$(t/\tau_c \lesssim 0.1)$

➔ $\alpha \gtrsim 1.5$

Name	τ_c [kyr]	t_{age} [kyr] ($\alpha = 1$)	t_{age} [kyr] ($\alpha = 1.5$)	kT_{eff} [eV]
RXJ 1308	1500	30	100	102
RXJ 0806	3000	40	160	96
RXJ 0720	1900	42	160	90
RXJ 2143	3700	50	200	100
RXJ 1856	3700	66	350	63
RXJ 0420	2000	100	580	44

Age constraints on α from XDINs



$\tau_d \approx 10^3$ yrs$/B_{15}^{\alpha}$

$1.5 \lesssim \alpha \lesssim 1.8$

$L_X \approx$ few $\times 10^{31}$ erg/s

$kT < 0.1$ keV $\approx 10^6$ K

➔ ages $t \lesssim 10^5$ yrs ($t/\tau_c \lesssim 0.1$)

➔ $\alpha \gtrsim 1.5$

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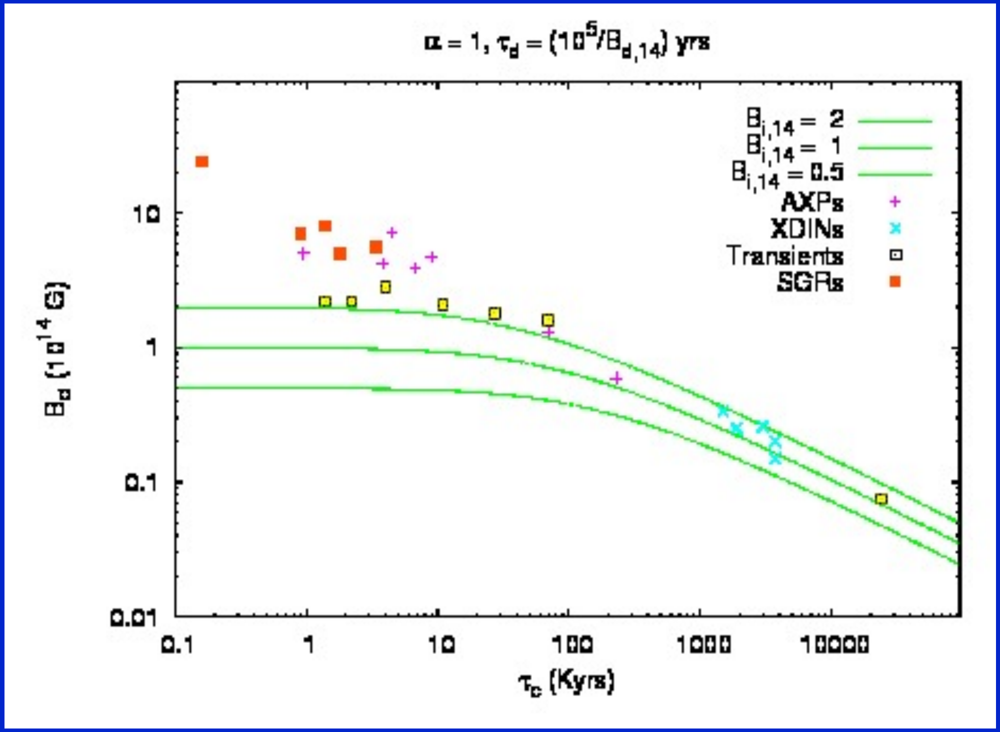
Dipole field decay: physical models

Hall Decay of the magnetic field in the NS crust is expected to operate fast enough at large B

$$\tau_d \sim 10^4 \text{ yrs} / B_{15} \quad (\alpha = 1)$$

(Goldreich & Reisenegger 1992; Cumming et al. 2004)



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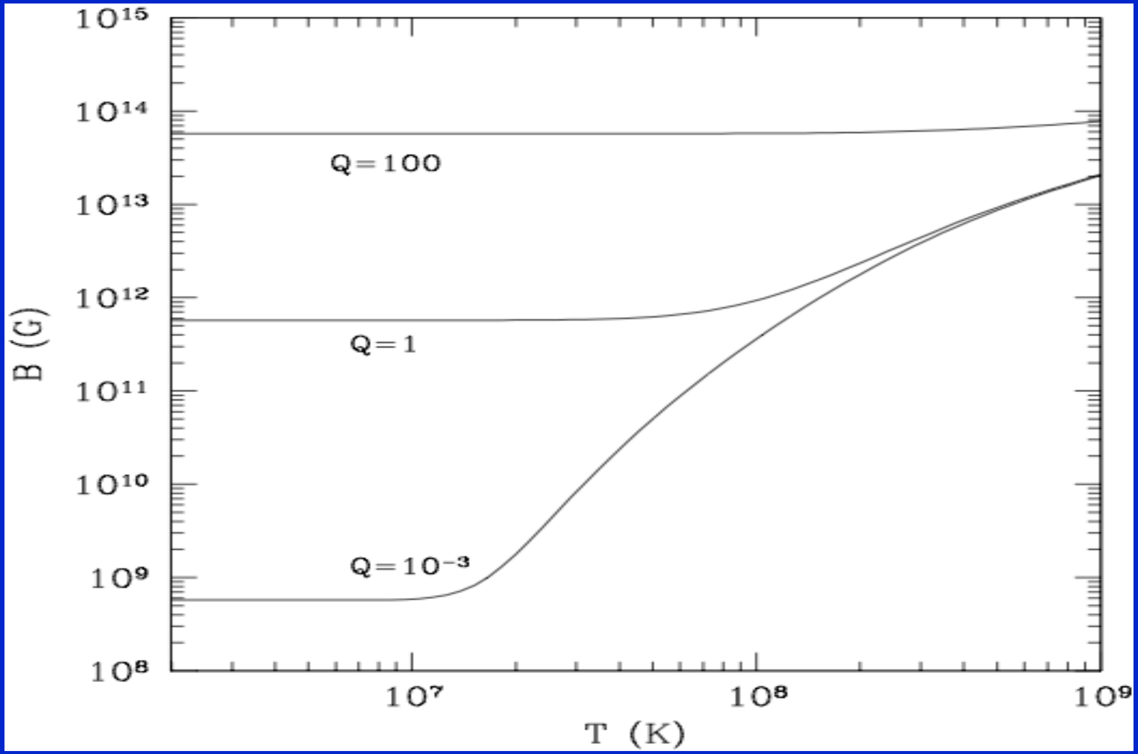

B-field above which the Hall effect dominates over direct Ohmic decay

Q = crust impurity parameter

(Cumming et al. 2004)

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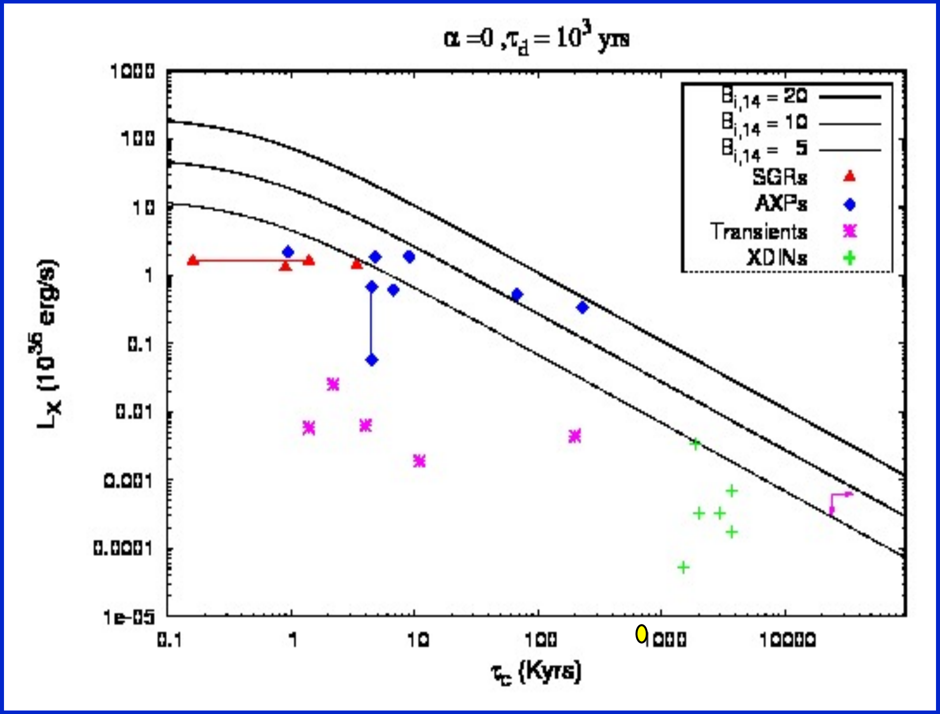
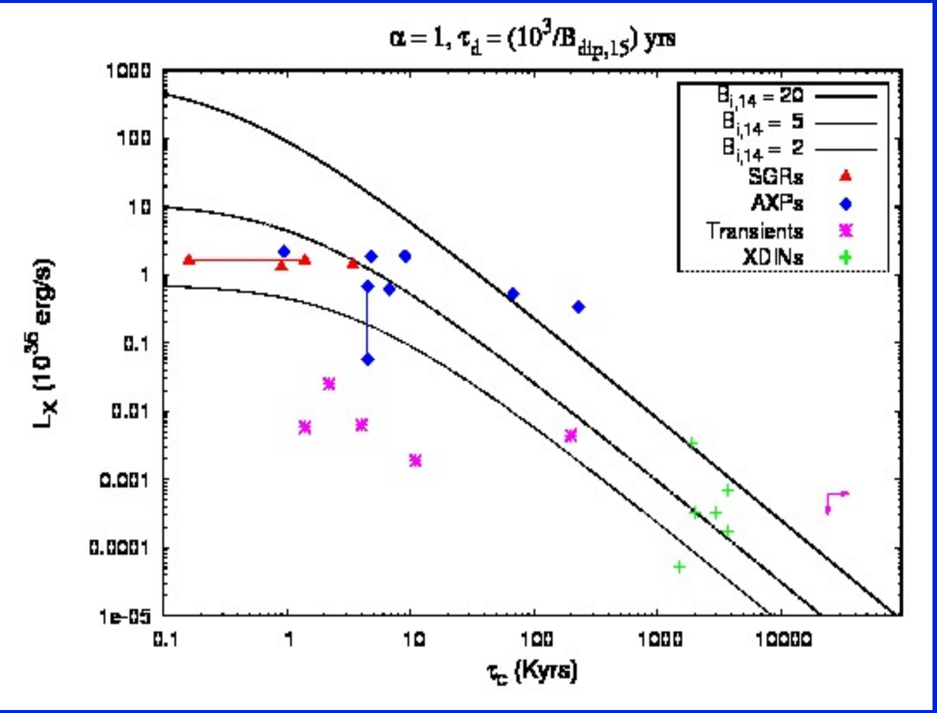
B-independent Ohmic decay + diffusion in deep crust gives a power-law decay, $B \propto t^{-1/\alpha}$ with $1.5 \leq \alpha \leq 1.8$ and $\tau_{d,i} \approx 10^4 \rho_{i,12}$ yrs ~~$\propto$~~ $B_i^{-\alpha}$ ➔ $\alpha_{eff} = 0$, $\Delta_B = \Delta_P$ ➔ problematic!

(Urpin, Changmugam & Sang 1994 […]→ Urpin & Yakovlev 2008)

Luminosity Evolution vs. Dipole Decay

New observable: L_X(2-10 keV)

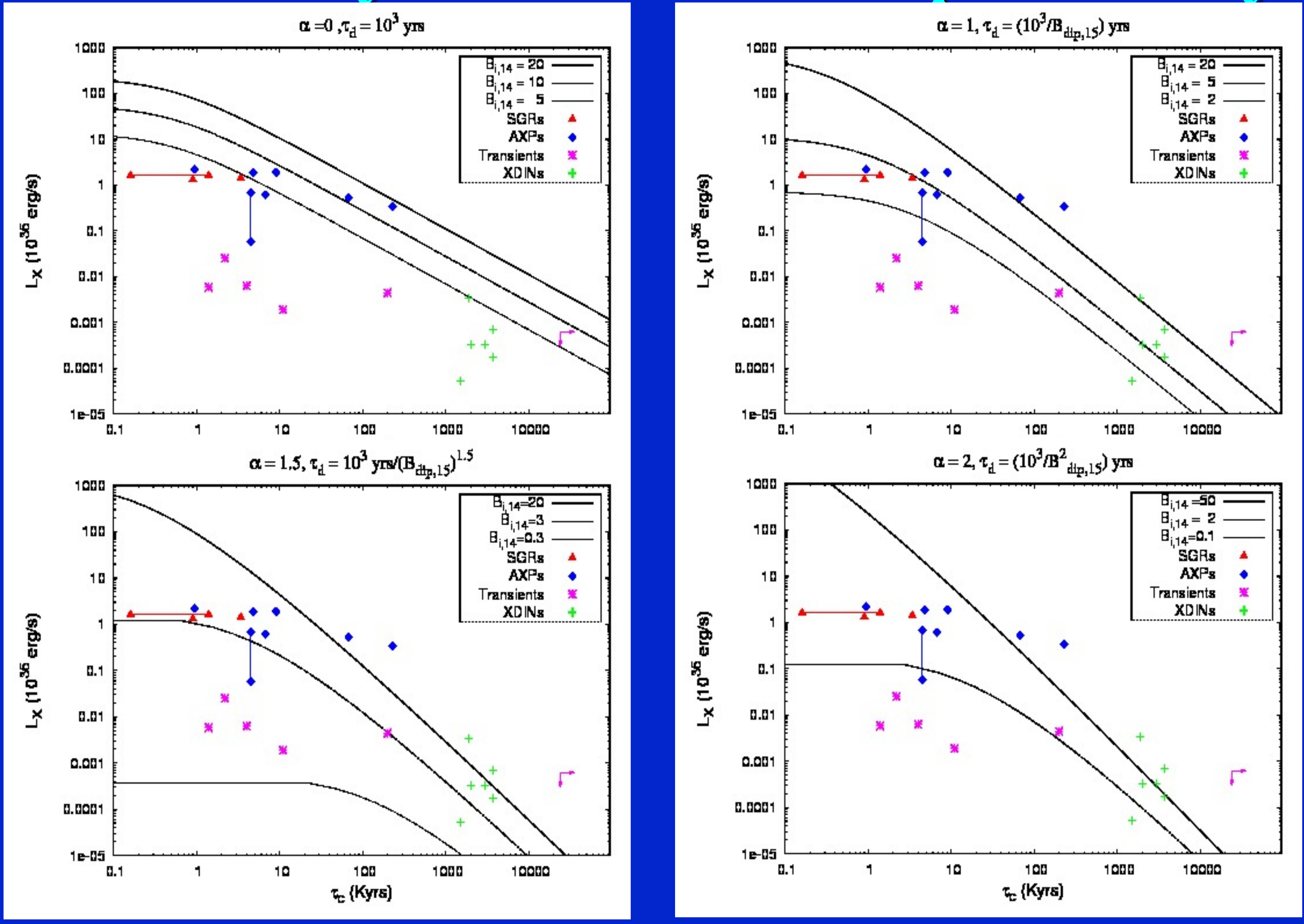




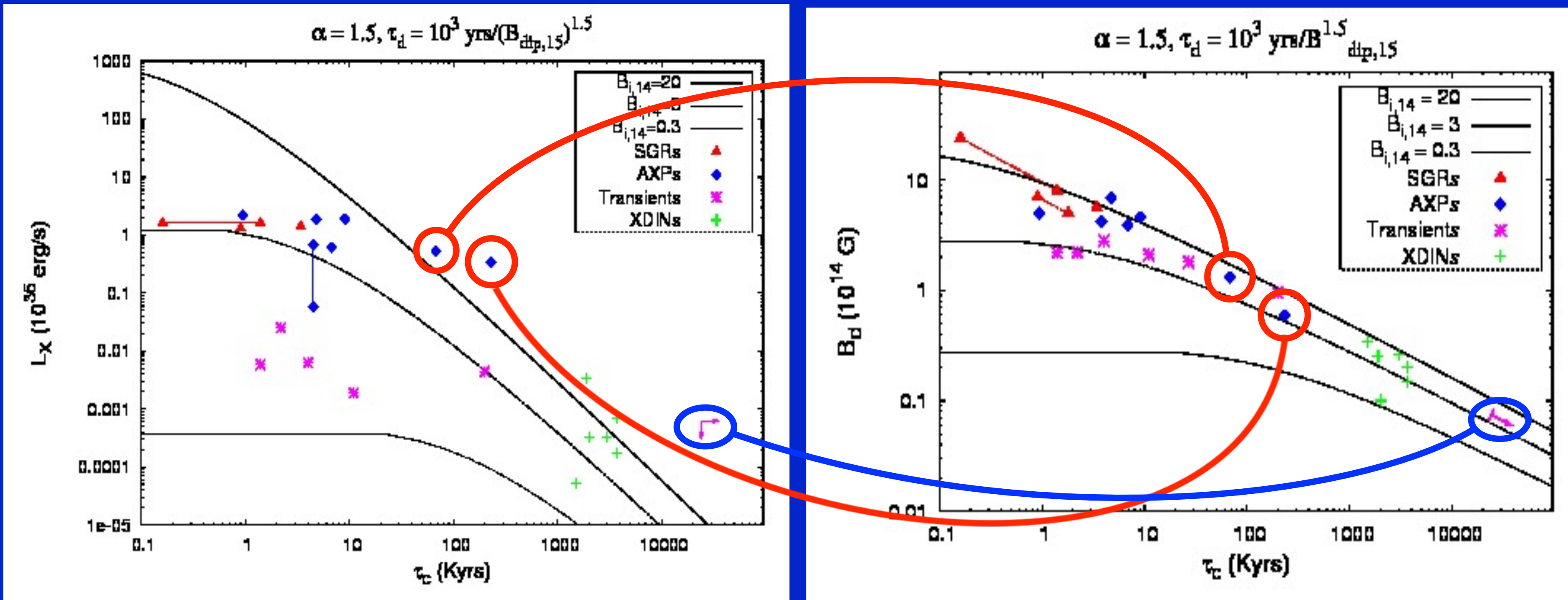
$$E_{B,d} \sim R^3 B_d^{\,2}$$

$$|\dot{E}_{B,d}| = L_B \sim R^3 B_d^{\,2+\alpha}/A$$

Luminosity Evolution vs. Dipole Decay



Luminosity Evolution vs. Dipole Decay

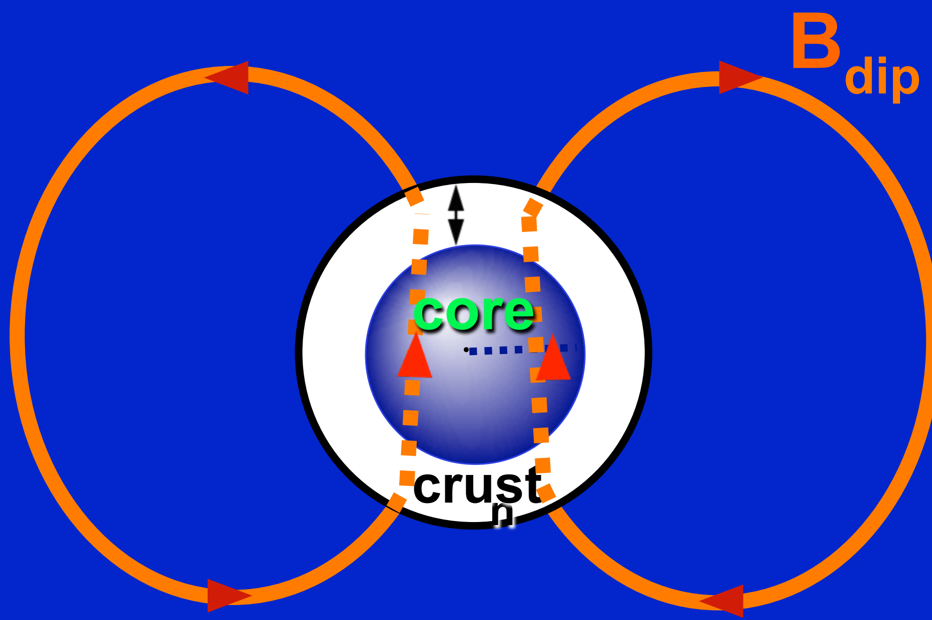


- We use L_X(2-10 keV) ~ (0.3-0.5) $L_{X,bol}$ ➔ bolometric + GR corrections imply $L_{X,intrinsic}$ ~ several × L_X(2-10 keV)
- L_B also goes to other channels (bursts, ν's) ➔ conservative

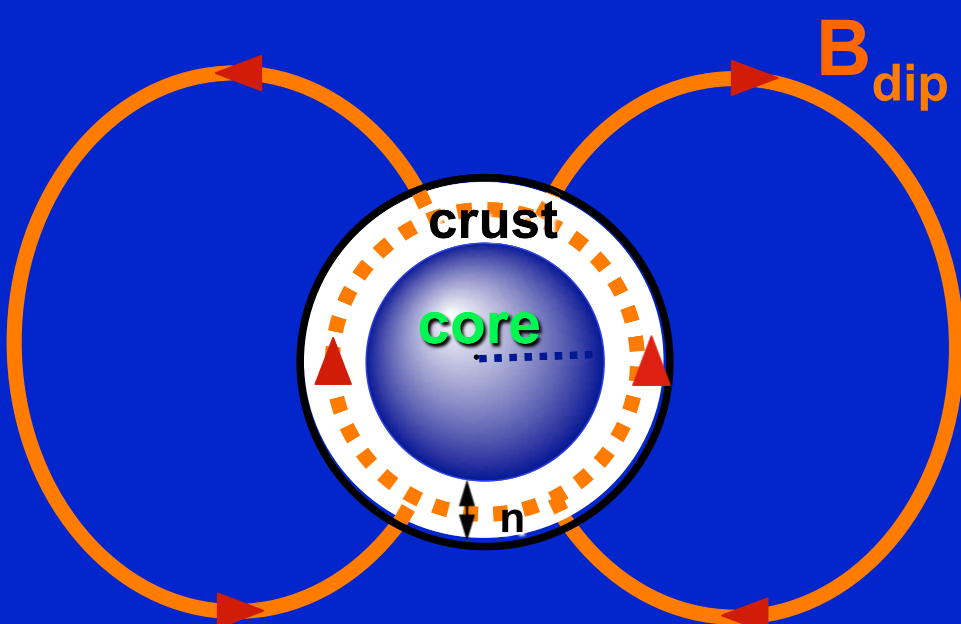
Decay of the Dipole Field does not match L_X evolution

In particular it cannot power sources @ $\tau_c \gtrsim 10^5$ yrs

Interior Field



1. Decay of the interior field releases heat in the core, which is conducted to the surface, producing a quasi-thermal emission



2. Interior field is confined to the crust, and/or core field does not decay (condensed phase?)

Decay of Internal Field: toy models

Ambipolar diffusion in the NS core

$$L_{\rm B,int} = (R_*^3/3)B_{\rm int}^2/\tau_{\rm d,int} \approx 10^{38} B_{\rm int,16}^{16/5} R_{*,6}^3 \text{erg s}^{-1}$$

$$\frac{dU^-}{dt} \simeq 9.6 \times 10^{20}\ T_9^8\ \rho_{15}^{\frac{2}{3}} \text{ erg cm}^{-3}\text{s}^{-1}$$

$$T_{8,\rm eq}^{(\rm s)} \simeq 2.7\ B_{15}^{2/5} \left(\frac{\rho_{15}}{0.7}\right)^{-2/3}$$

$$T_{\rm s} \simeq 1.17 \times 10^6 \text{ K} \left[(7\zeta)^{9/4} + \left(\frac{\zeta}{3}\right)^{5/4}\right]^{1/4}$$

where $\zeta \equiv T_{\rm c,9} - 0.001\ g_{14}^{1/4}(7\ T_{\rm c,9})^{1/2}$ and $g_{14} \approx 1.87$ is the surface gravity.

$$L_{\rm X,\infty} = \left(1 - \frac{2GM_*}{R_* c^2}\right) L_{\rm X} \approx 10^{33} \text{ erg s}^{-1} \left[(7\zeta)^{9/4} + \left(\frac{\zeta}{3}\right)^{5/4}\right]$$

Decay of Internal Field: toy models

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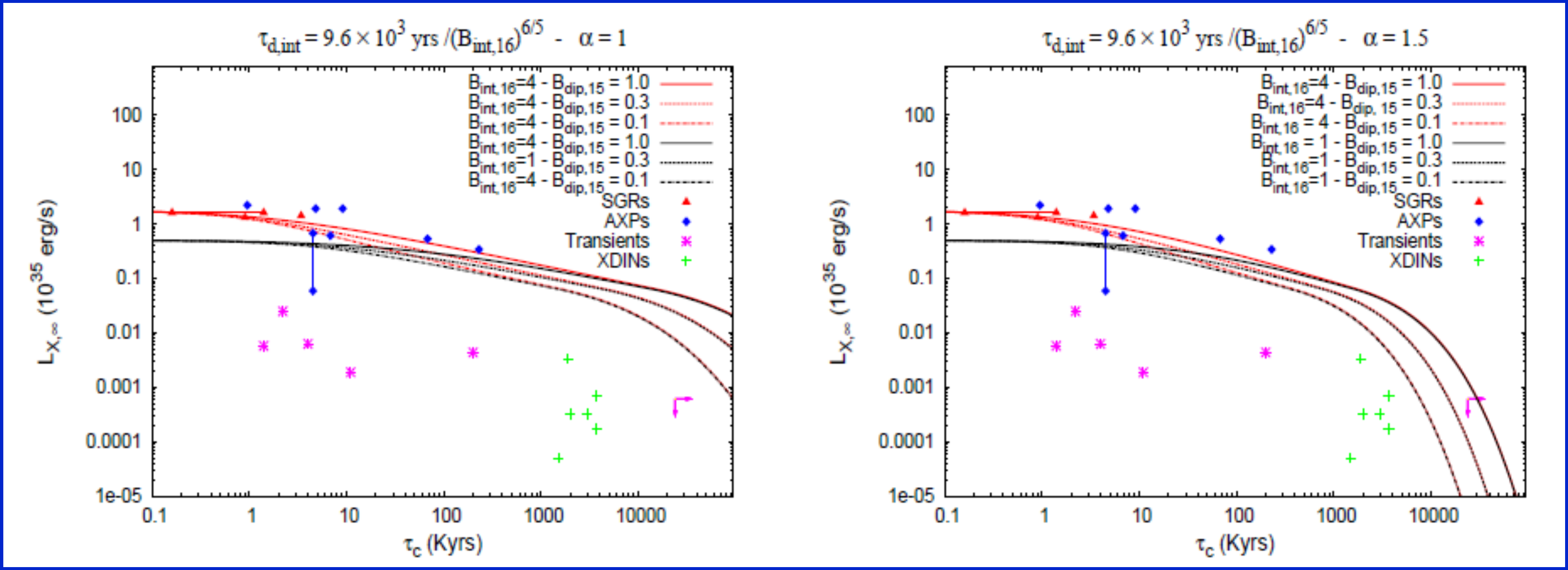
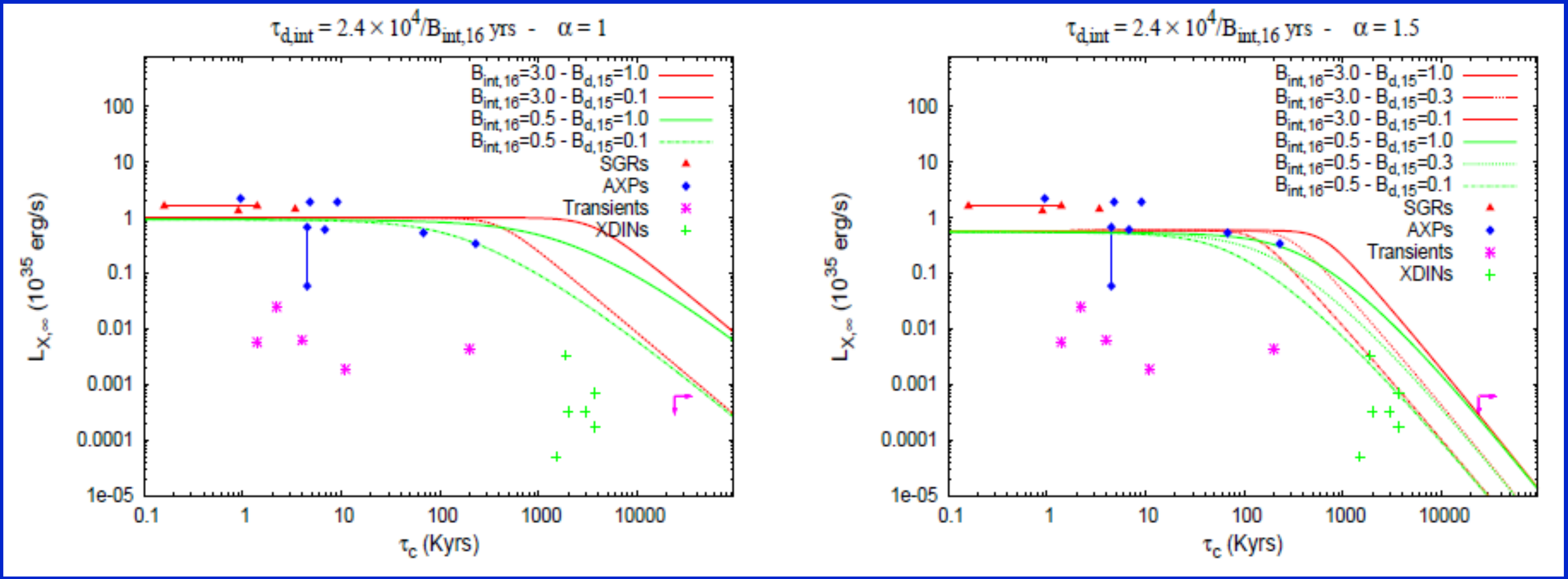


Decay of Internal Field: toy models

Hall decay of internal field in the deep crust

$$L_{\mathrm{B,int}}^{(I)} \approx 2 \times 10^{36} B_{16}^{3} R_{*,6} \ \mathrm{erg\ s^{-1}}$$

(Arras, Cumming & Thompson 2004)



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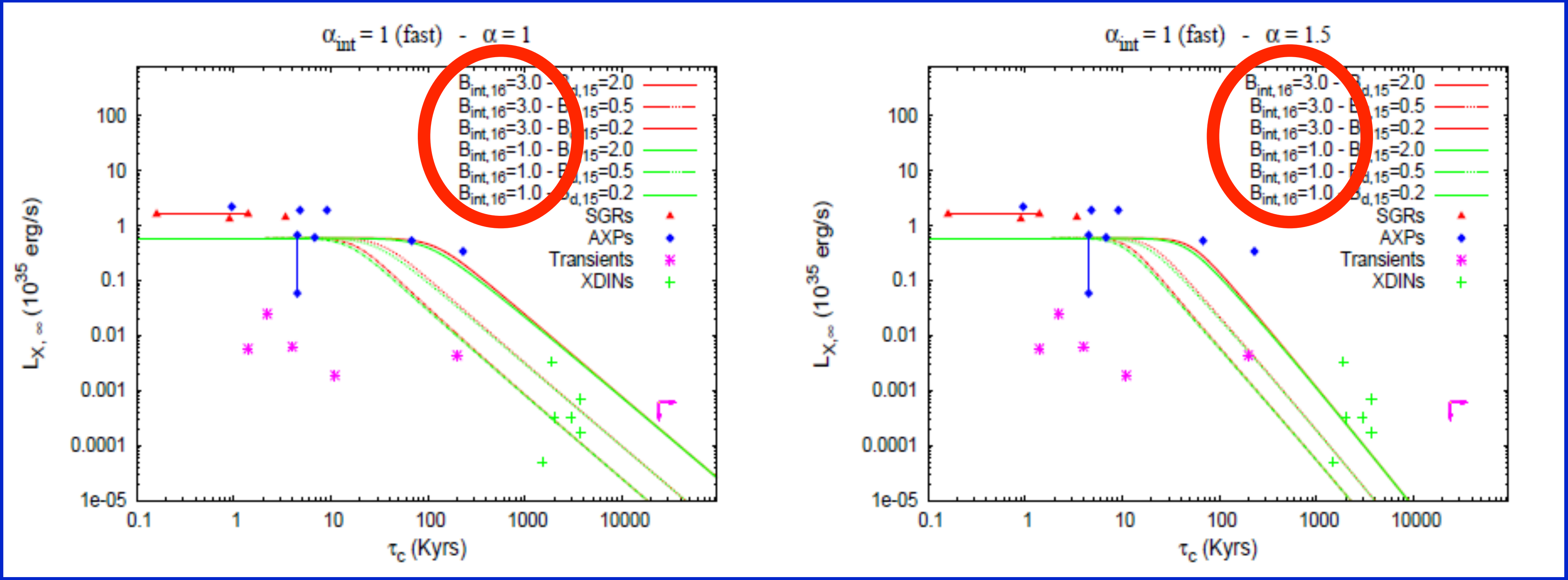
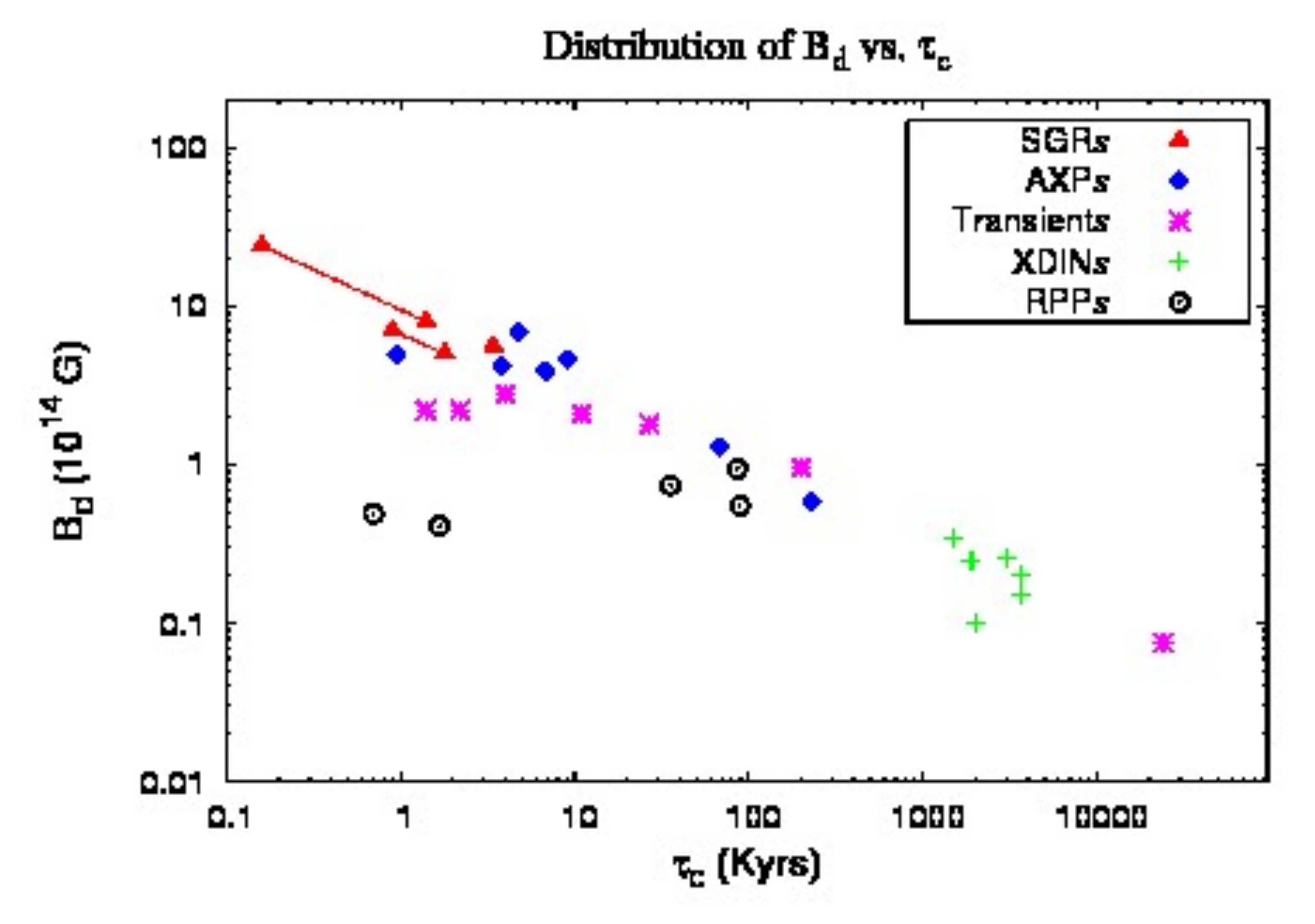
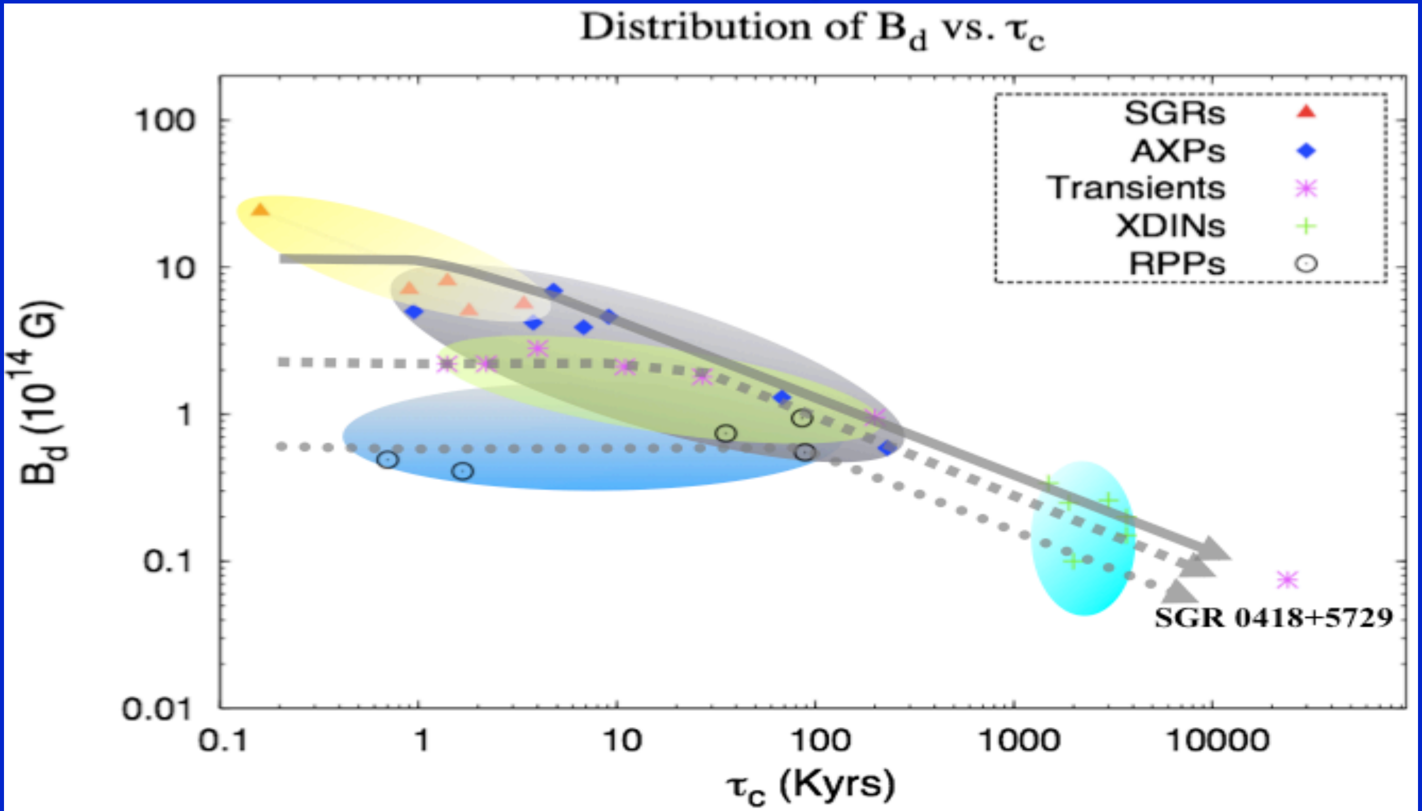
$B_{\rm int,i} \gtrsim 10^{16}$ G



Adding Sources



Evolutionary Links:

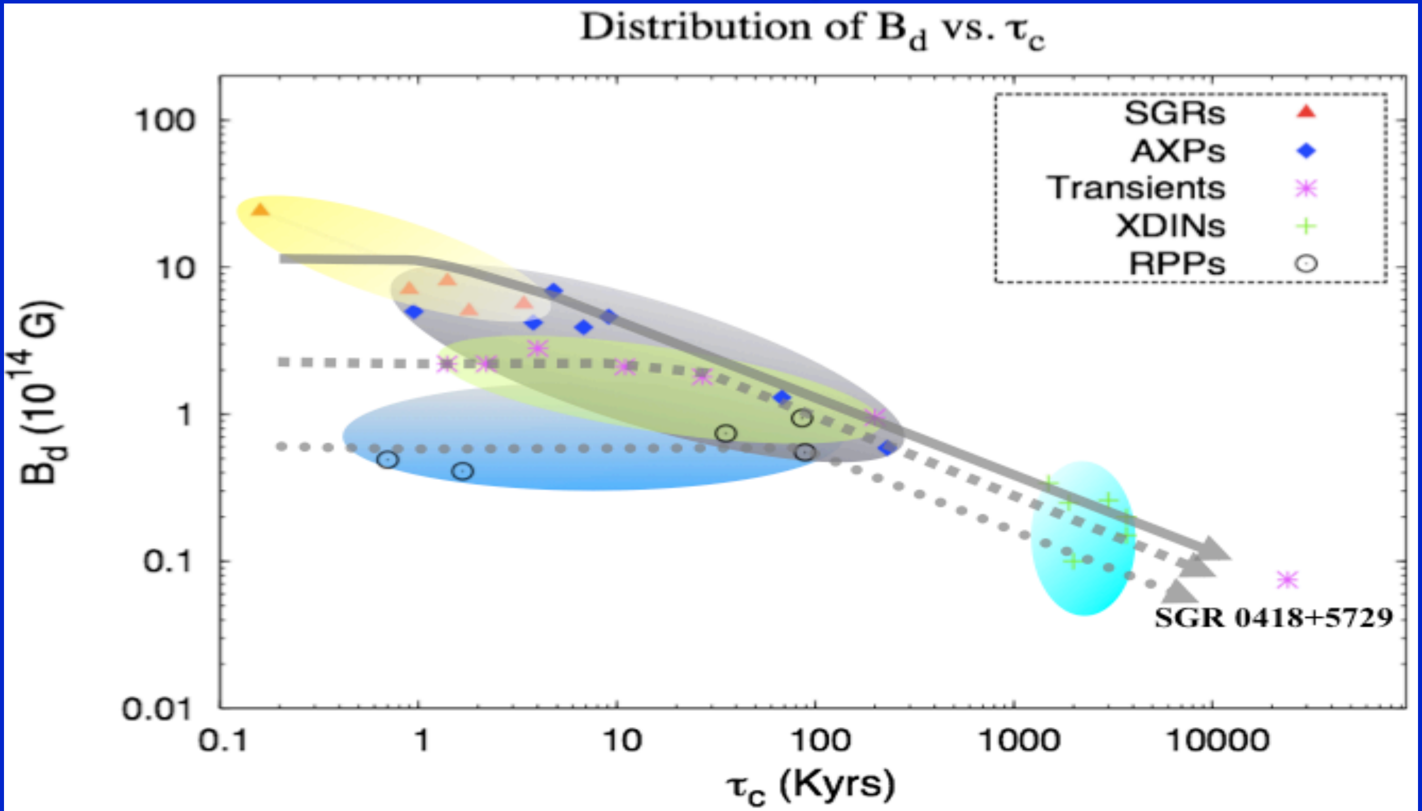


1. **SGR/AXP branch** **(Kouveliotou et al. 1998)**: **SGR ➔ AXP ➔ XDIN?**
   $B_{d,i} \sim 10^{15}$ G, $B_{int,i} \gtrsim 10^{16}$ G; early **$L_X \sim 10^{35}$ erg/s** $\ll$ **$L_{B,int}$** (ν-limited)
2. **Transient branch: Trnasient SGR/AXP ➔ ???**
   $B_{d,i} \sim 2\times10^{14}$ G, $L_{X,quiescent} \ll L_{B,dip}$ ➔ $B_{int,i} \sim$?, $L_{X,outburst} \sim L_{X,SGR/AXP}$

➔? ordered **$B_{int,i} \gtrsim 10^{16}$ G** suppresses quiescent heat conduction to surface

◆ **$B_{int,SGR/AXP}$ ➔ α-Ω dynamo, $B_{int,transient}$ ➔ ???** (remnant field?)

Evolutionary Links:



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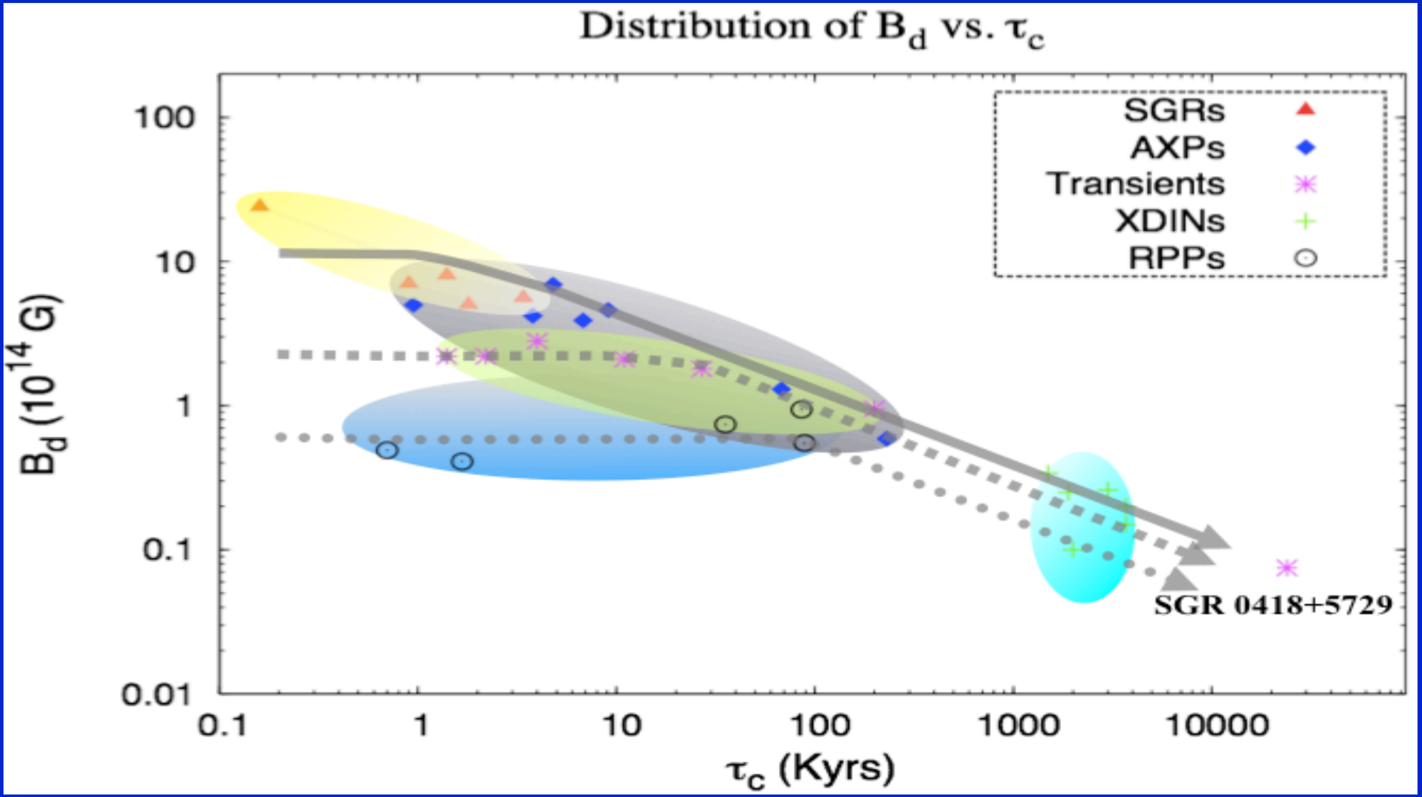
3. **High-B RPP ➔ XDIN?**

Sources of interest:



SGR J0418+5729: **$B_{d,i} \sim (3\text{-}5)\times10^{14}$ G**, **while currently $t_{age} \sim 1\text{-}2$ Myr,**
$B_d \sim (4\text{-}7)\times10^{12}$ G, $B_{int} \sim (1\text{-}2)\times10^{14}$ G (for $B_{int,i} \gtrsim 10^{16}$ G) &
$L_{B,int} \sim L_X \sim (4\text{-}10)\times10^{30}$ erg/s

XDINs: **$t_{age} \sim 0.1\text{-}0.6$ Myr, $B_{d,i} \sim (0.3\text{-}20)\times10^{14}$ G, L_X** likely remnant heat (**$L_{B,int}$** might contribute a little); no evidence for **B_{int}** → ? related to other high-B NSs without bursting activity (RPP, CCO?)

Conclusions:

- We find strong observational evidence of dipole field decay on $\sim 10^3$ yr timescale for strongest magnetars, $B_{dip,i} \sim 10^{15}$ G
- Dipole field decay index **α**, defined by $\dot{\mathbf{B}}_\mathbf{d} \propto \mathbf{B}_\mathbf{d}^{1+\alpha}$, is in the range **$1 \leq \alpha < 2$**, and more likely **$1.5 \lesssim \alpha \lesssim 1.8$**
- Once B_{dip} decays significantly, true age $\ll$ spin-down age
- $\mathbf{L}_{\mathbf{X,persistent}} > |\dot{\mathbf{E}}_{\mathbf{B,dipole}}|$ → another energy source is required → likely internal field decay: requires $\mathbf{B}_{\mathbf{internal,i}} \gtrsim 10^{16}$ G
- Evolutionary tracks:
  - SGR/AXP branch
  - Transient branch
  - High-B RPP → XDIN branch?