Diversity of Magnetized Neutron Stars

Theoretical Astrophysics
Tohoku University

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(Tohoku Univ. & Aoyama Gakuin Univ.)

Enoto, SK & Shibata "*Observational diversity of magnetized neutron stars*"
Submitted to Reports on Progress in Physics

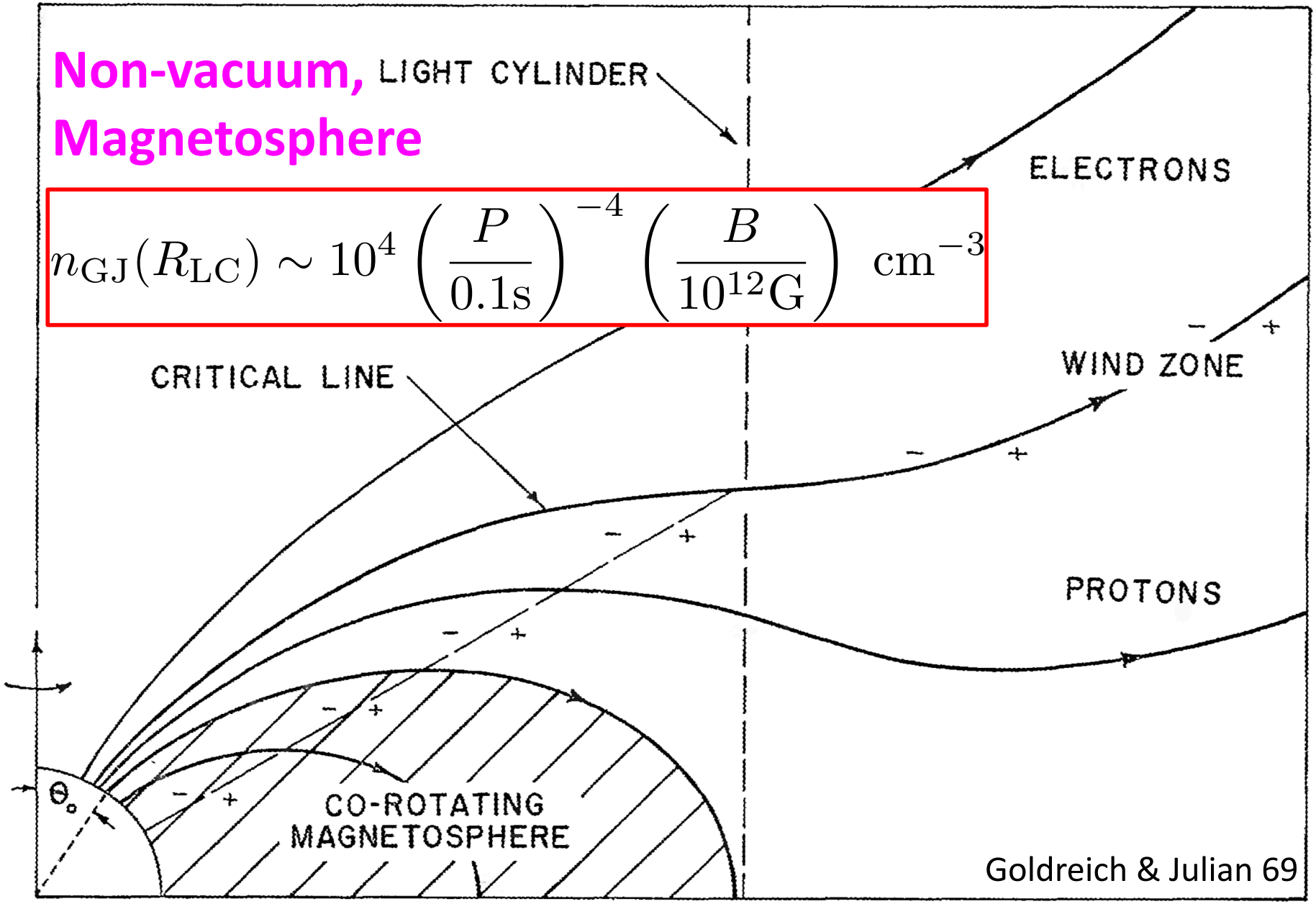
Contents

The 50th Anniversary

Goldreich-Julian model

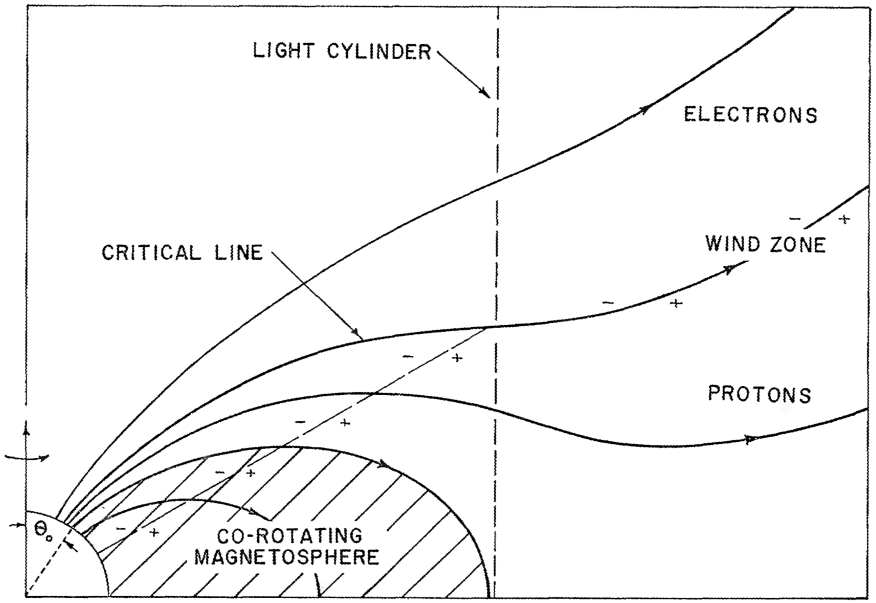
Non-vacuum, Magnetosphere

$$n_{\rm GJ}(R_{\rm LC}) \sim 10^4 \left(\frac{P}{0.1{\rm s}}\right)^{-4} \left(\frac{B}{10^{12}{\rm G}}\right) \ {\rm cm}^{-3}$$



Goldreich & Julian 69

Standard Picture



Goldreich & Julian 69

Energy source : Rotation energy

Magnetic field : Stationary poloidal dipole field

Braking mechanism : Magnetic braking

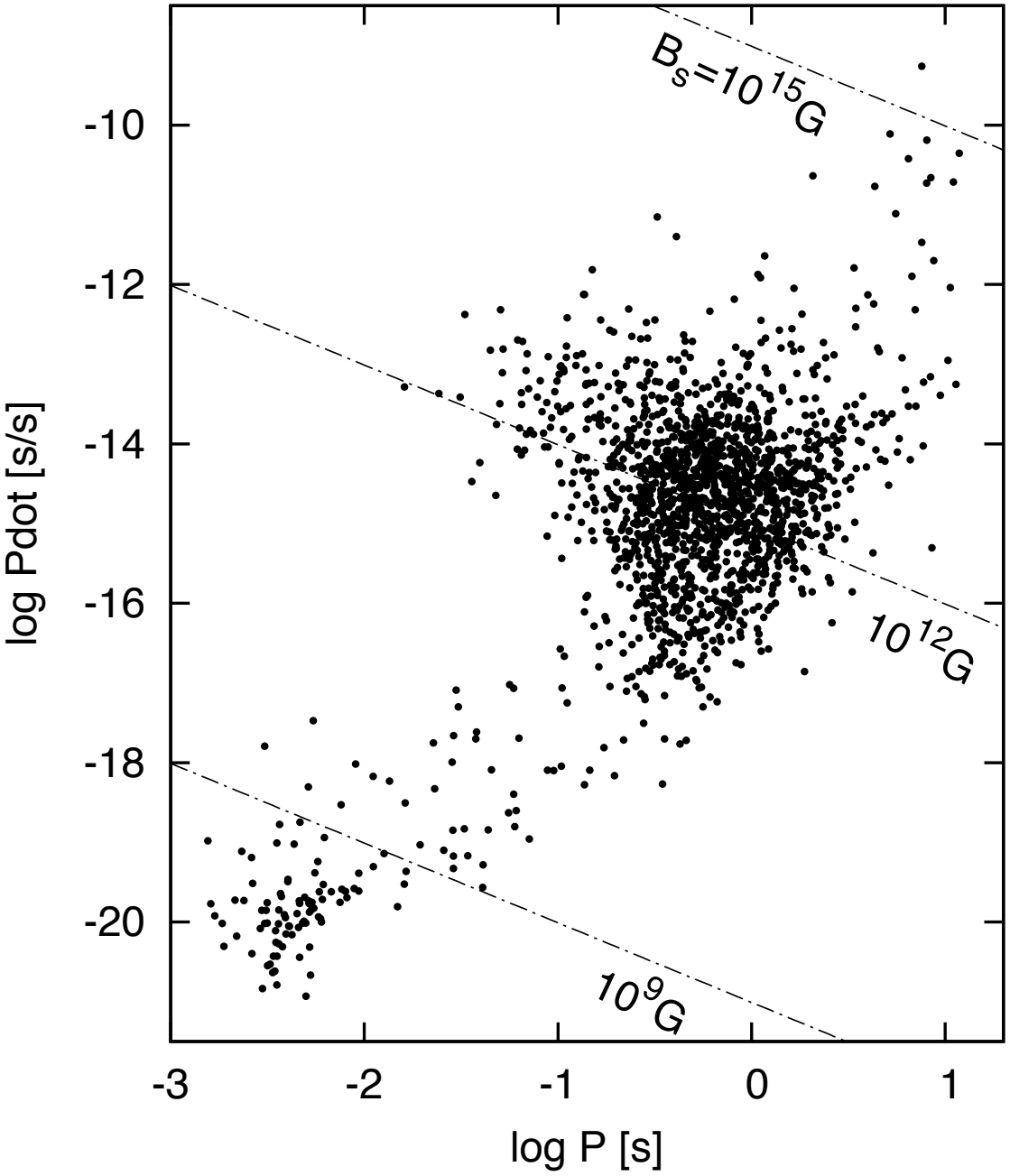
Plasma supply : Pair cascade
→ EM radiation

Rotating magnetized object ($n >> n_{GJ}$)
→ Plasma co-rotation due to unipolar induction
→ Plasma outflow at a certain outer radius
→ Formation of a centrifugal wind with a velocity of $r\Omega$

Rotational period P and magnetic field B determine the braking properties.

Standard Picture

Pulsars = Rotating magnetized isolated neutron stars



Dipole B-field

$$B_{\rm s} \sim 3.2 \times 10^{12} \sqrt{P_0 \dot{P}_{-14}}\ {\rm G}$$

Spin-down Luminosity

$$L_{\rm sd} \sim 4.4 \times 10^{32} P_0^{-3} \dot{P}_{-14}\ {\rm erg\ s^{-1}}$$

Characteristic age

$$\tau_{\rm c} \sim 1.6 \times 10^{6} P_0 \dot{P}^{-1}\ {\rm yr}$$

$$P_0 \equiv P/1{\rm s}$$

$$\dot{P}_{-14} \equiv \dot{P}/10^{-14}{\rm ss}^{-1}$$

Standard Picture

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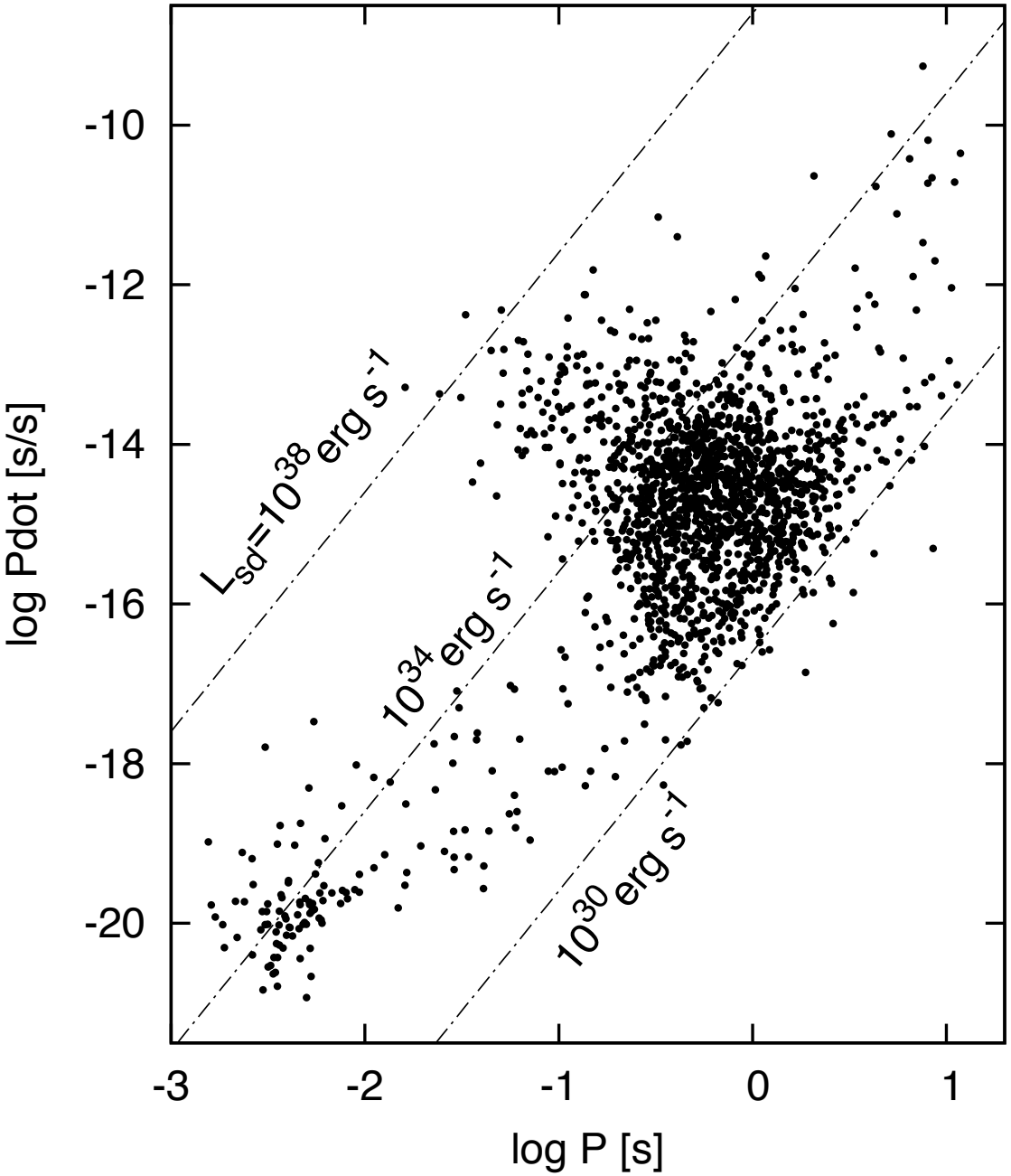

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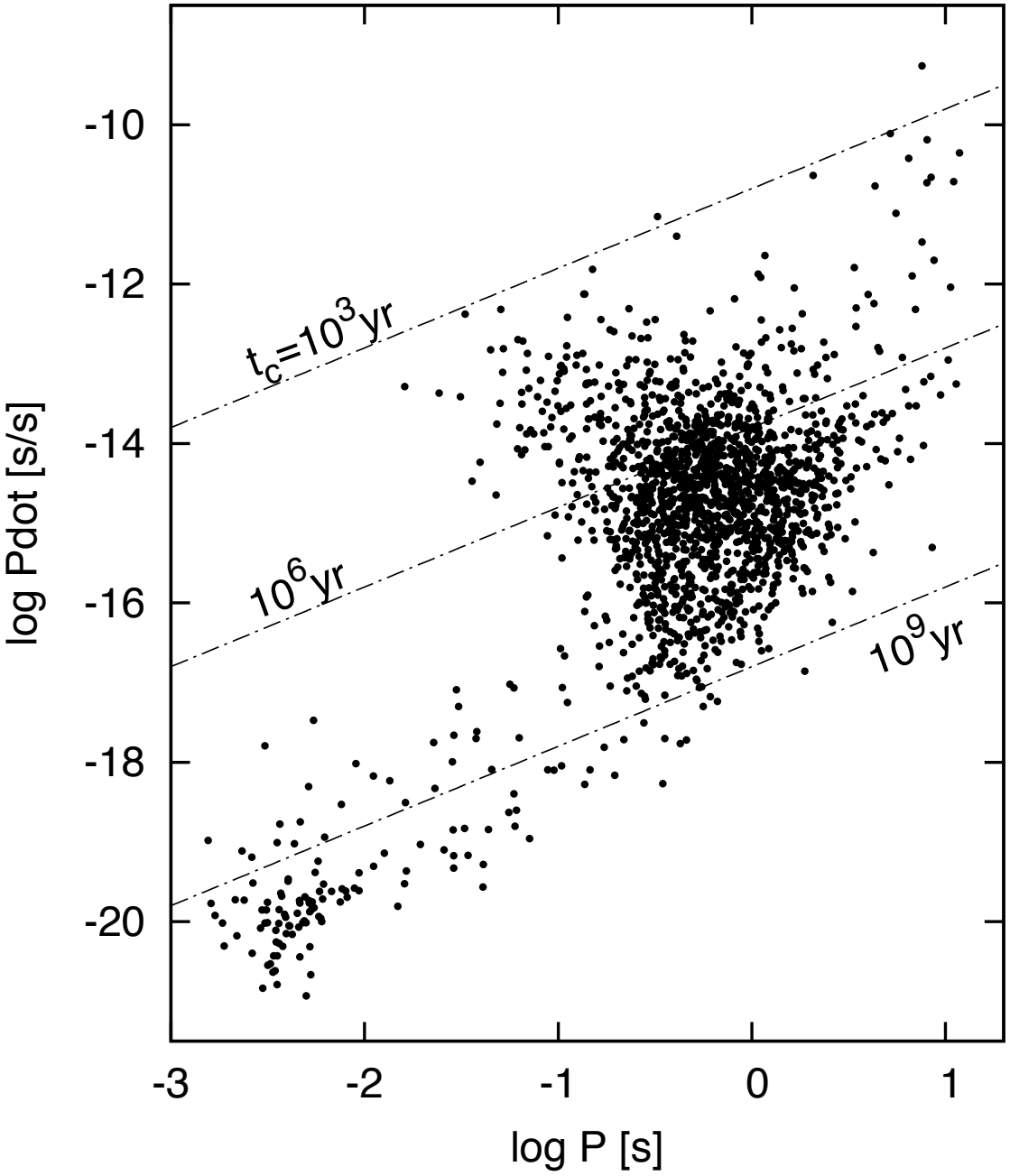

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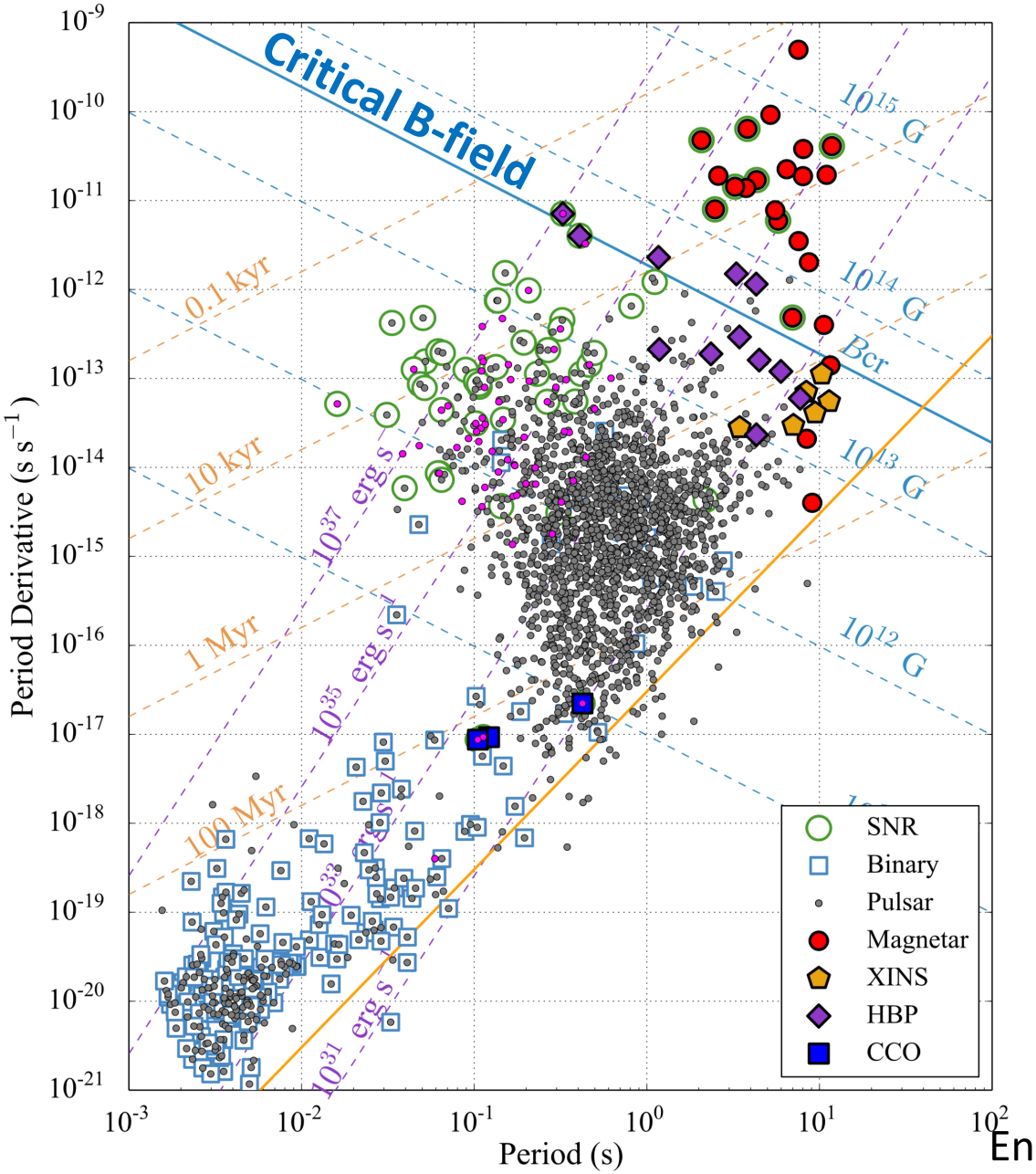
Standard Picture

P and B determine the braking properties.



Energy source
: Rotation energy

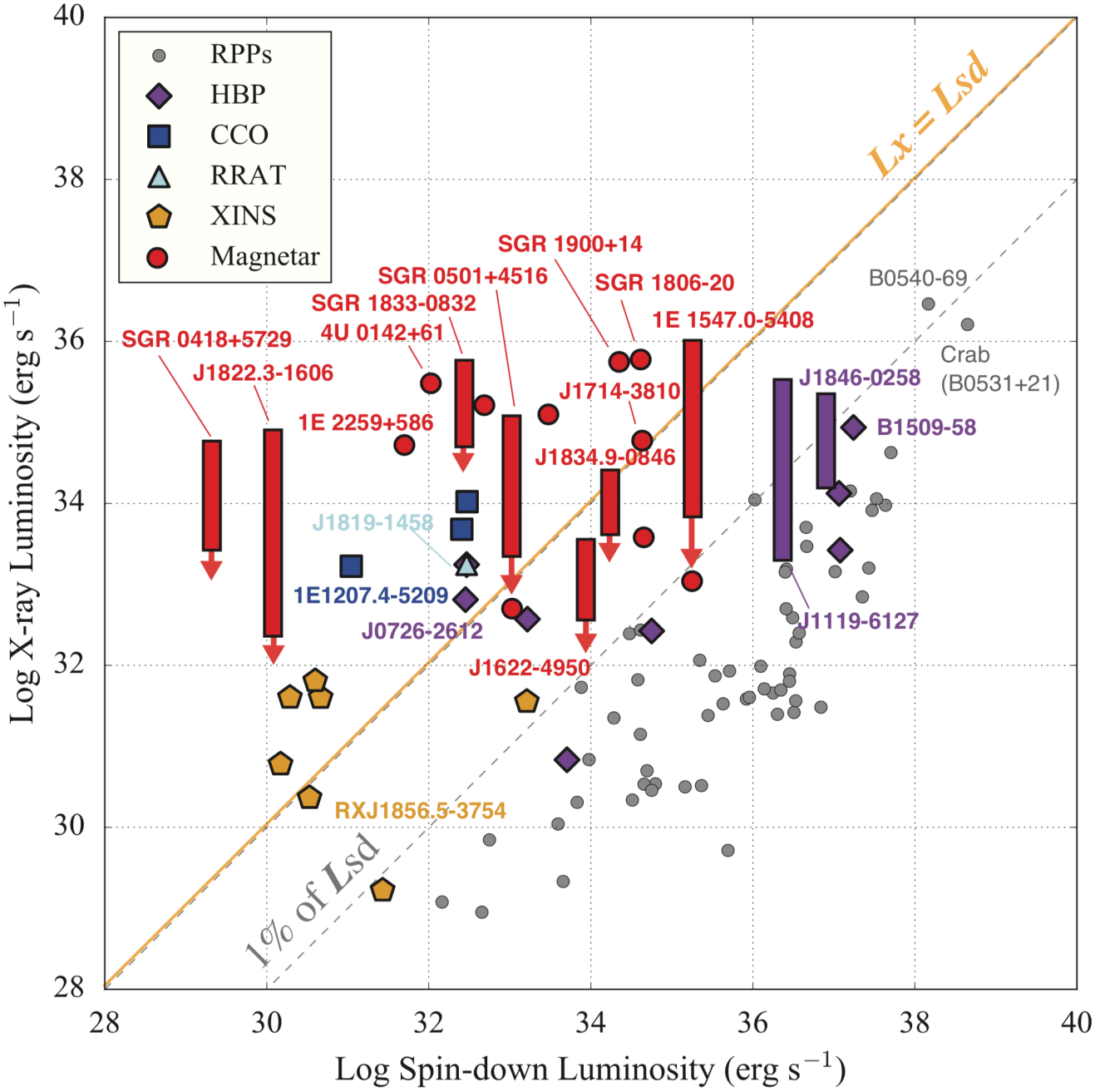
Magnetic field
: Stationary poloidal dipole field

Braking mechanism
: Magnetic braking

Plasma supply
: Pair cascade
→ EM radiation

Enoto, SK & Shibata submitted

Beyond the Standard Picture



Energy source

: Rotation energy

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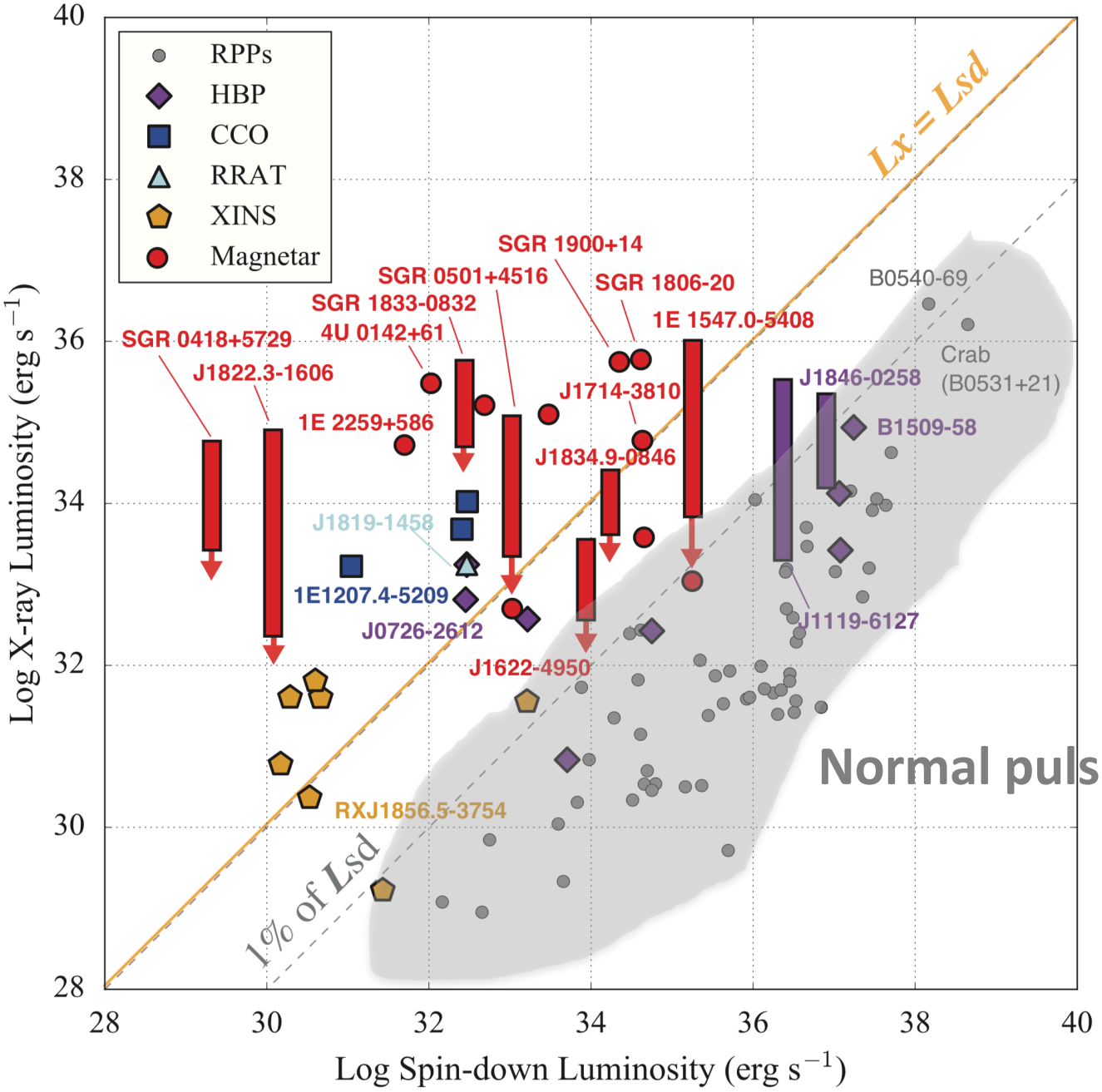
Beyond the Standard Picture



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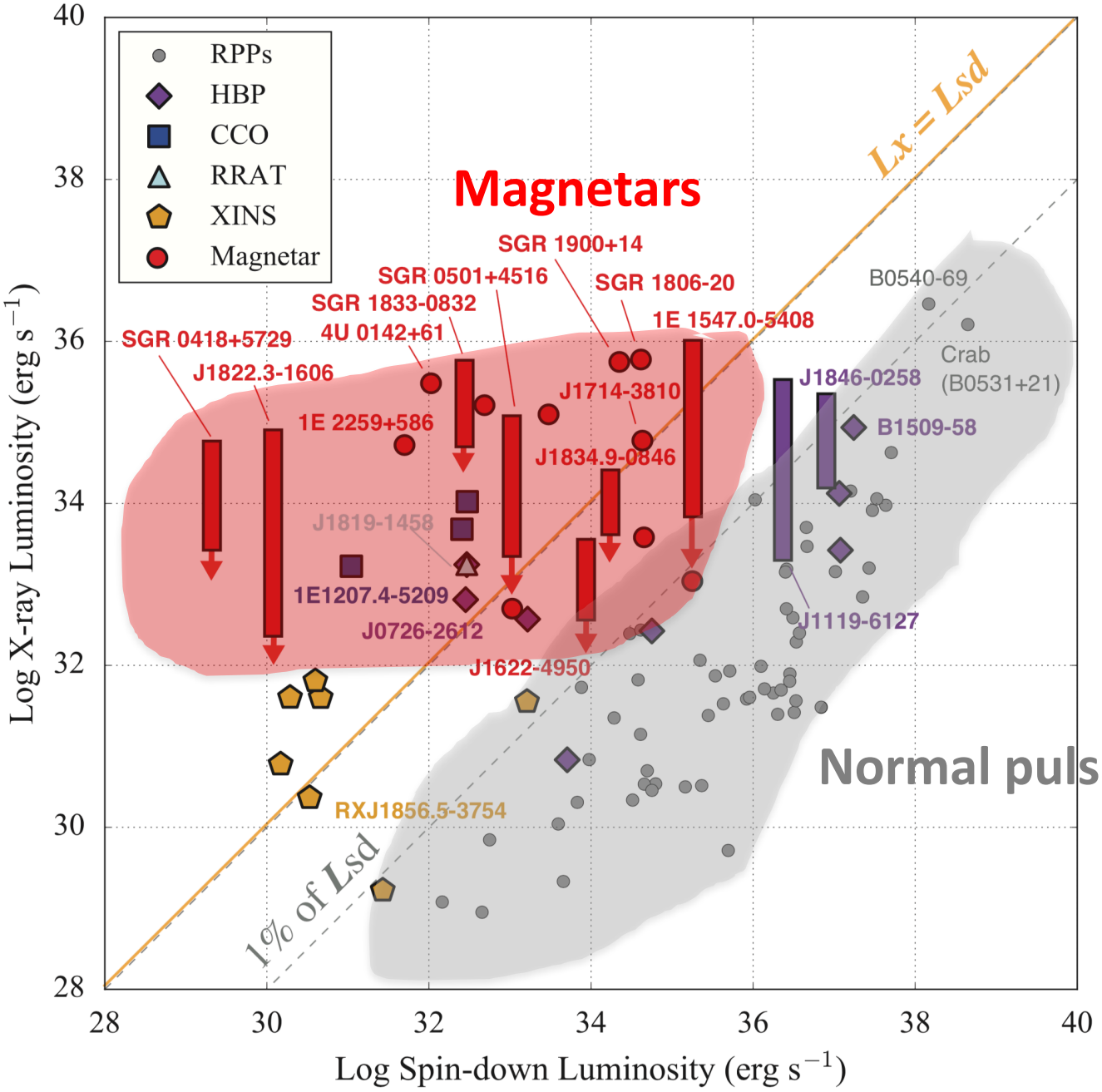

Energy source

: Rotation energy?

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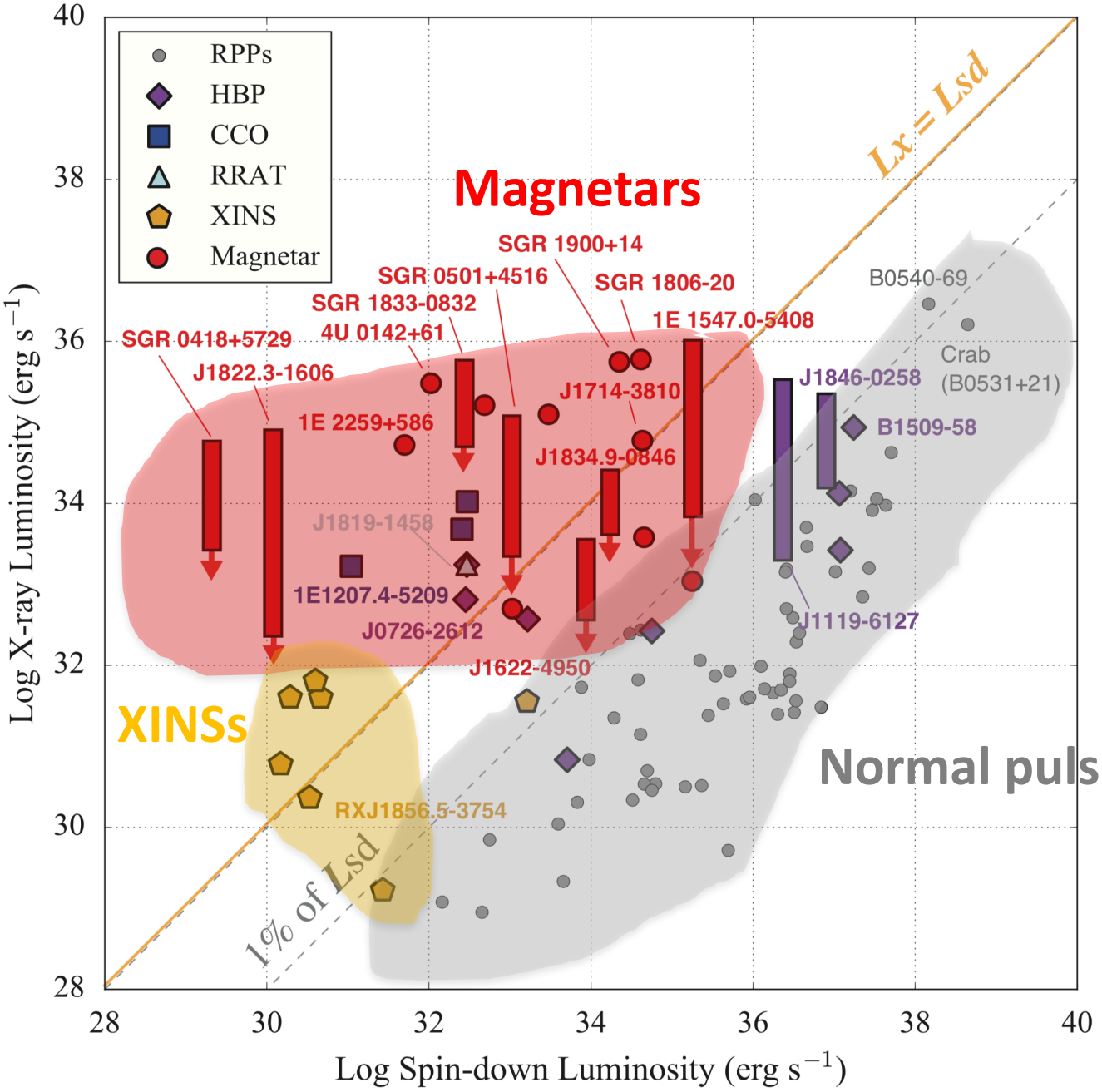

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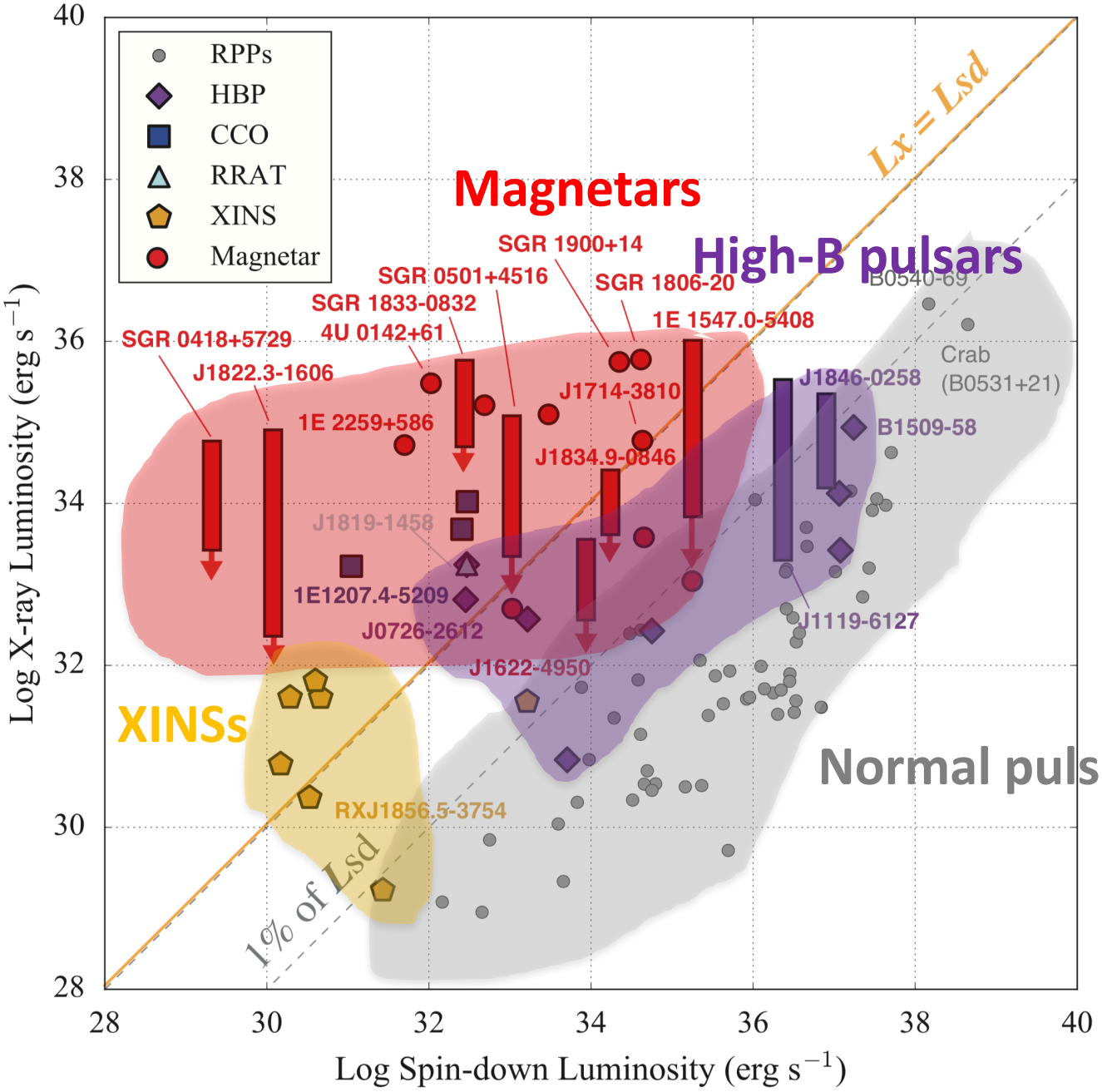

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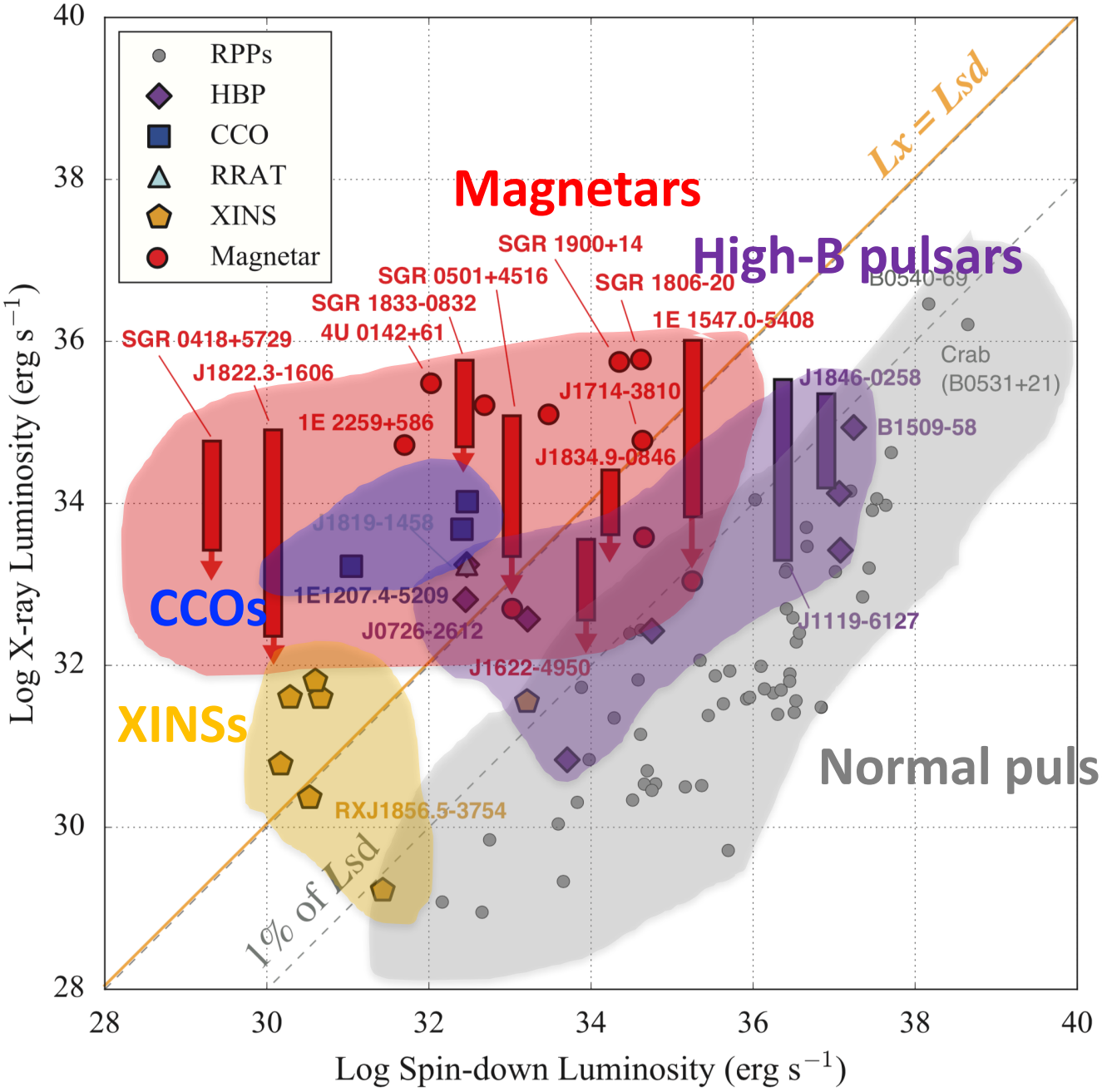
Beyond the Standard Picture

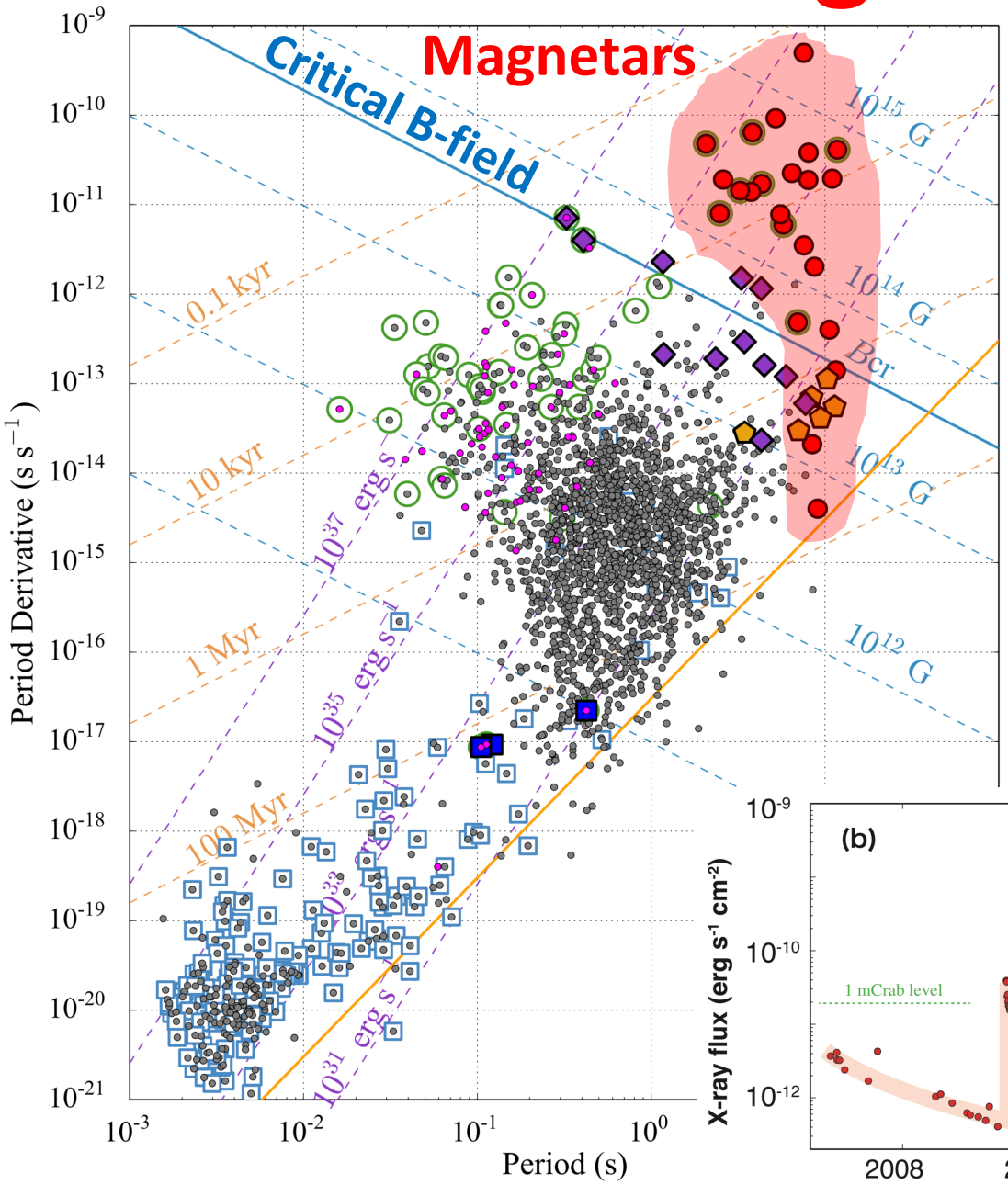


Energy source

: Rotation energy?

Enoto, SK & Shibata submitted

Beyond the Standard Picture : Magnetars



- **Strong B-field**

  $B \sim 10^{14} - 10^{15}$ G $> B_{cr}$

- **Large X-ray luminosity**

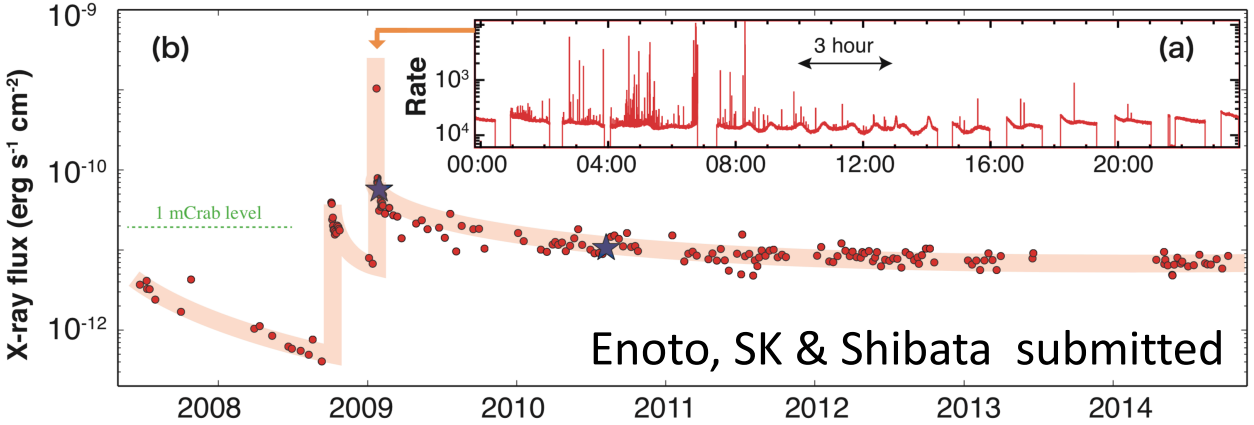
  $L_X \sim 10^{34} - 10^{35}$ erg s^{-1} $> L_{sd}$

- **Flaring activities**

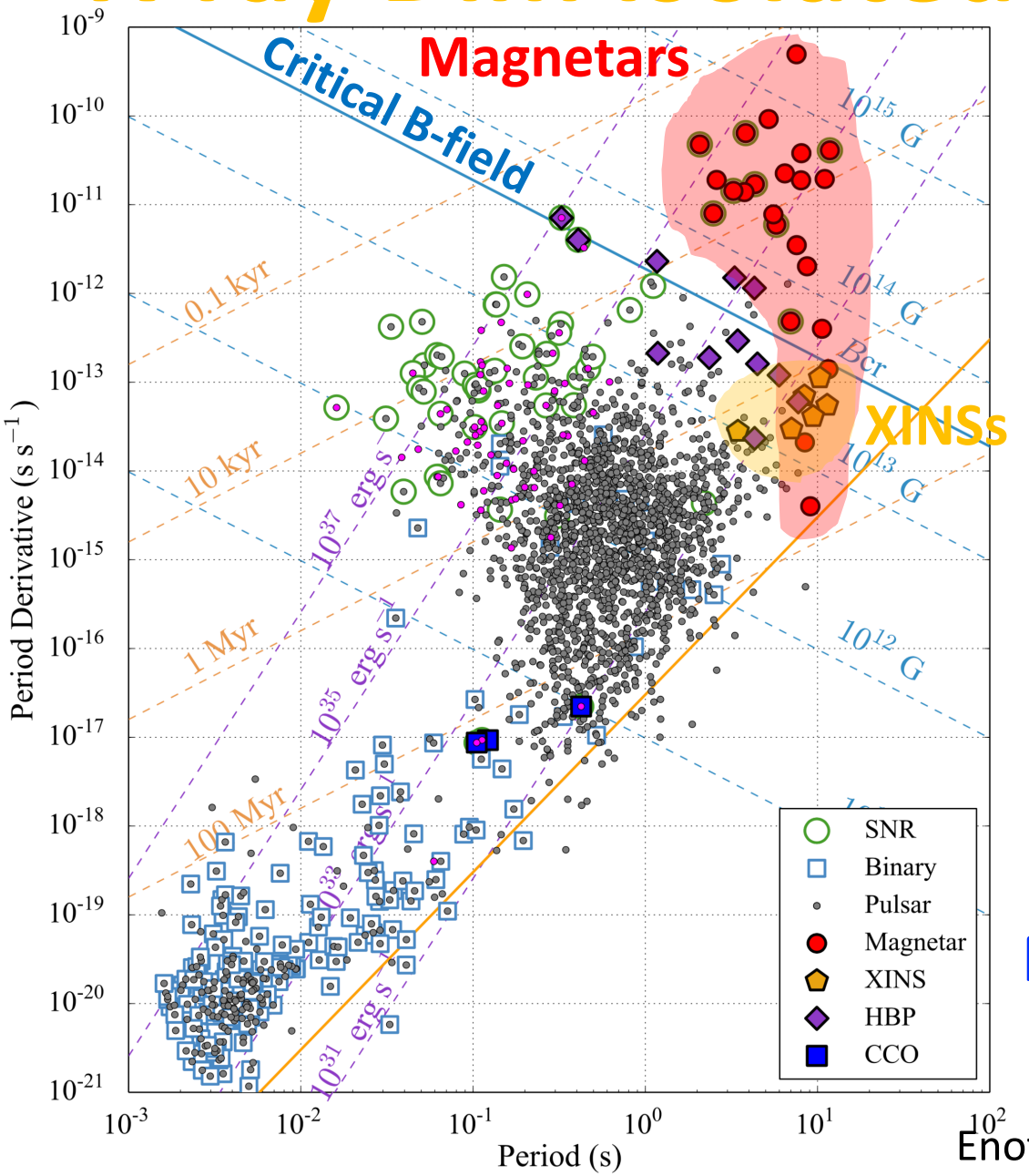
  $E \sim 10^{38} - 10^{46}$ erg

Energy source : B-field?

B-field : Non-stationary?



Beyond the Standard Picture :
X-ray Dim Isolated Neutron Stars

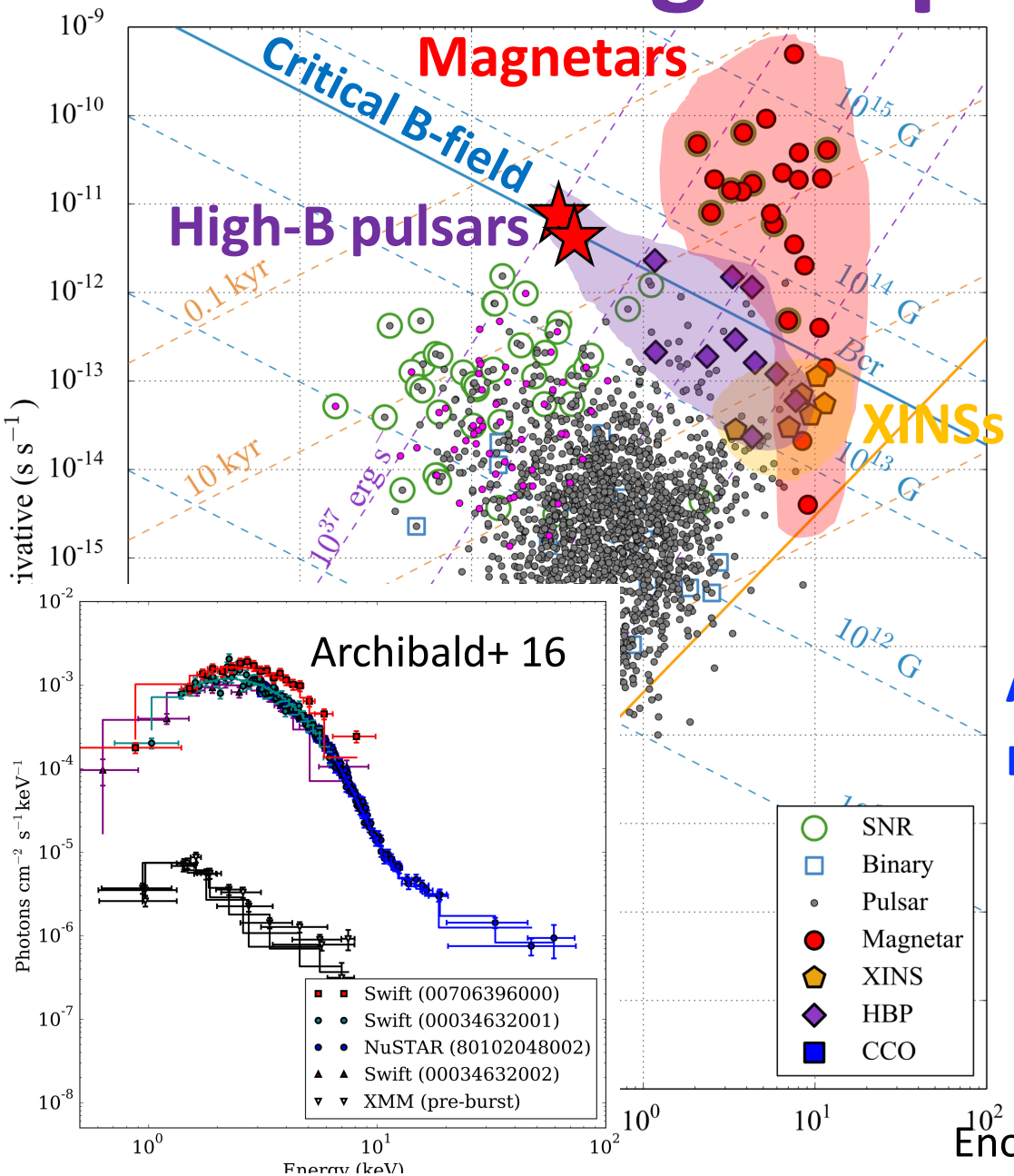


- **High X-ray efficiency**
  $L_X \sim 0.01\text{-}10\ L_{sd}$
- **Strong B-field**
  $B \sim 10^{13}$ G
- **Quasi-BB spectra**
- **No radio pulse, no outburst.**
- **High polarization degree (~16%) in optical (Mignani+ 17)**
- **Absorption feature? (Borghese+ 15, 17)**

Magnetar descendants?

Enoto, SK & Shibata submitted

Beyond the Standard Picture : High-B pulsars

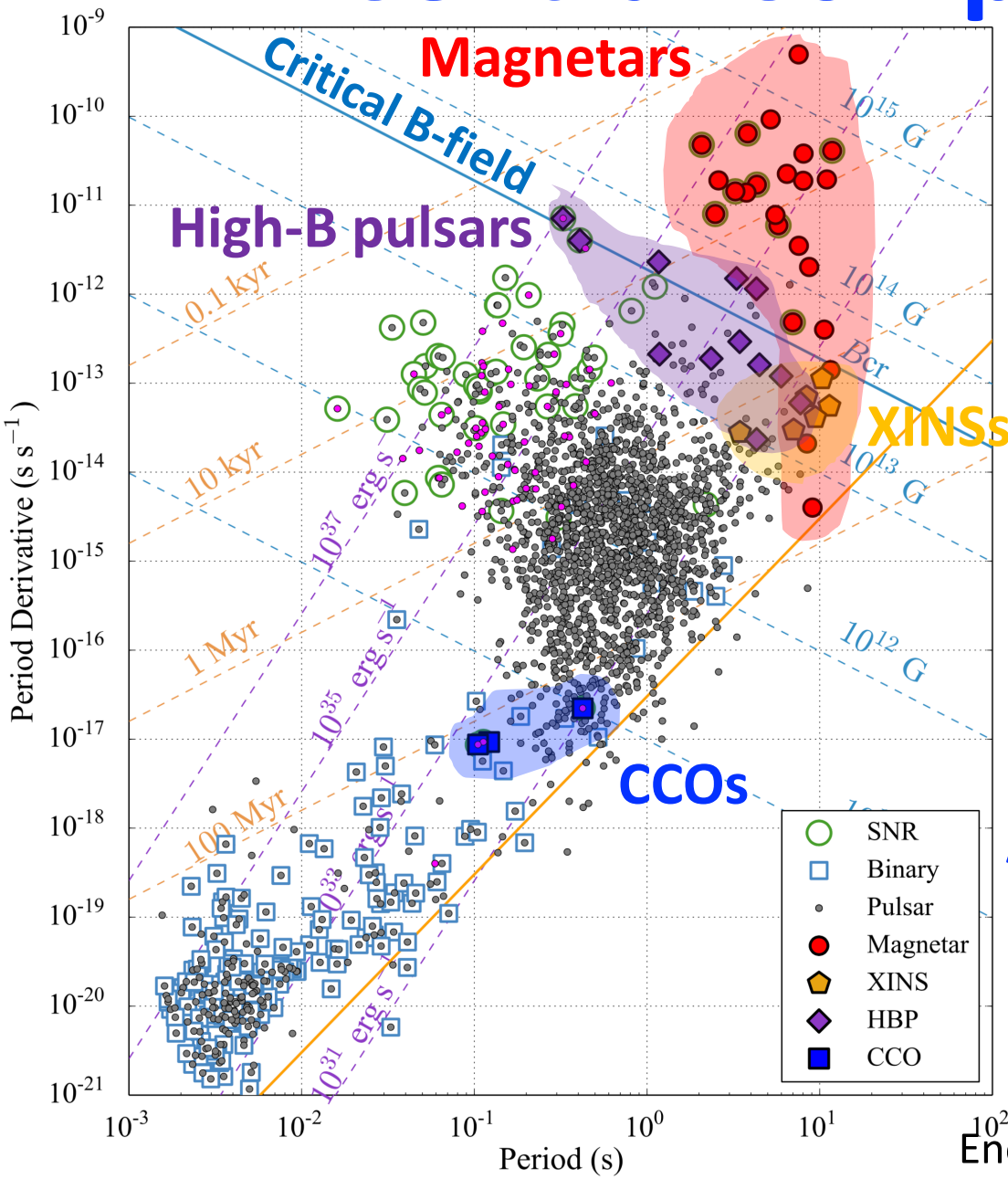


- **Strong B-field**
  B ~ 10^{13} G
- **Relatively high temperature**
- **Magnetar-like outbursts**
  PSRs J1846-0258, J1119-6127
- **Mostly normal PSRs**
  Radio - γ-ray pulses, PWNe

An intermediate class between normal PSRs and magnetars?

Enoto, SK & Shibata submitted

Beyond the Standard Picture : Central Compact Objects



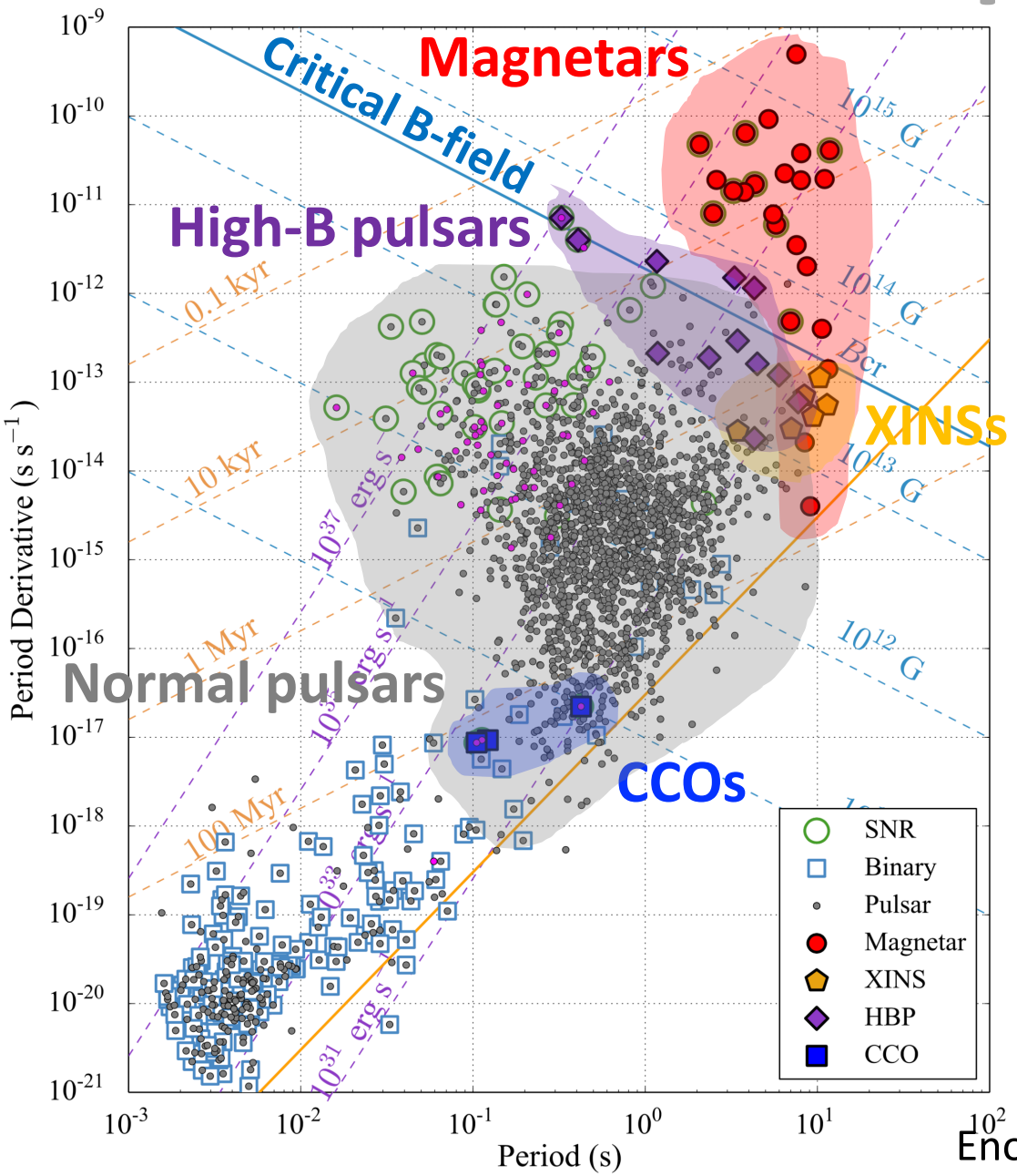
- **Weak B-field**
  B ~ 10^{10} – 10^{11} G
- **Associate with SNRs**
- **No radio pulse, No PWN**
- **Thermal X-ray spectra**
- **Strong B signatures?**
  Large pulsed fraction
  Absorption features
  Two hot spots with different kT

Anti-Magnetars?

Birth rate ~O(0.1) × PSRs

Enoto, SK & Shibata submitted

Beyond the Standard Picture :
Normal pulsars



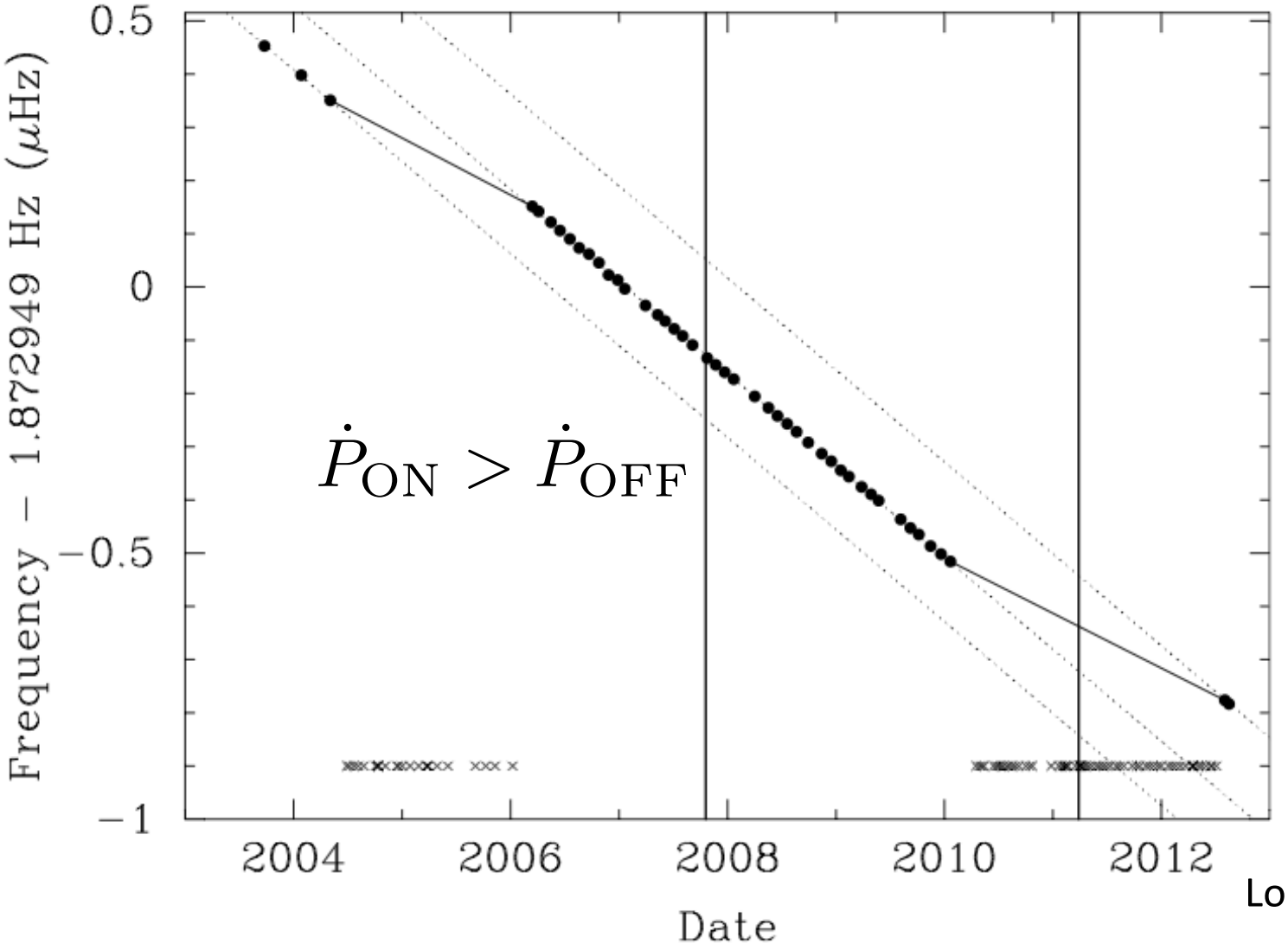
Normal pulsars follow the standard picture?

Enoto, SK & Shibata submitted

Beyond the Standard Picture :

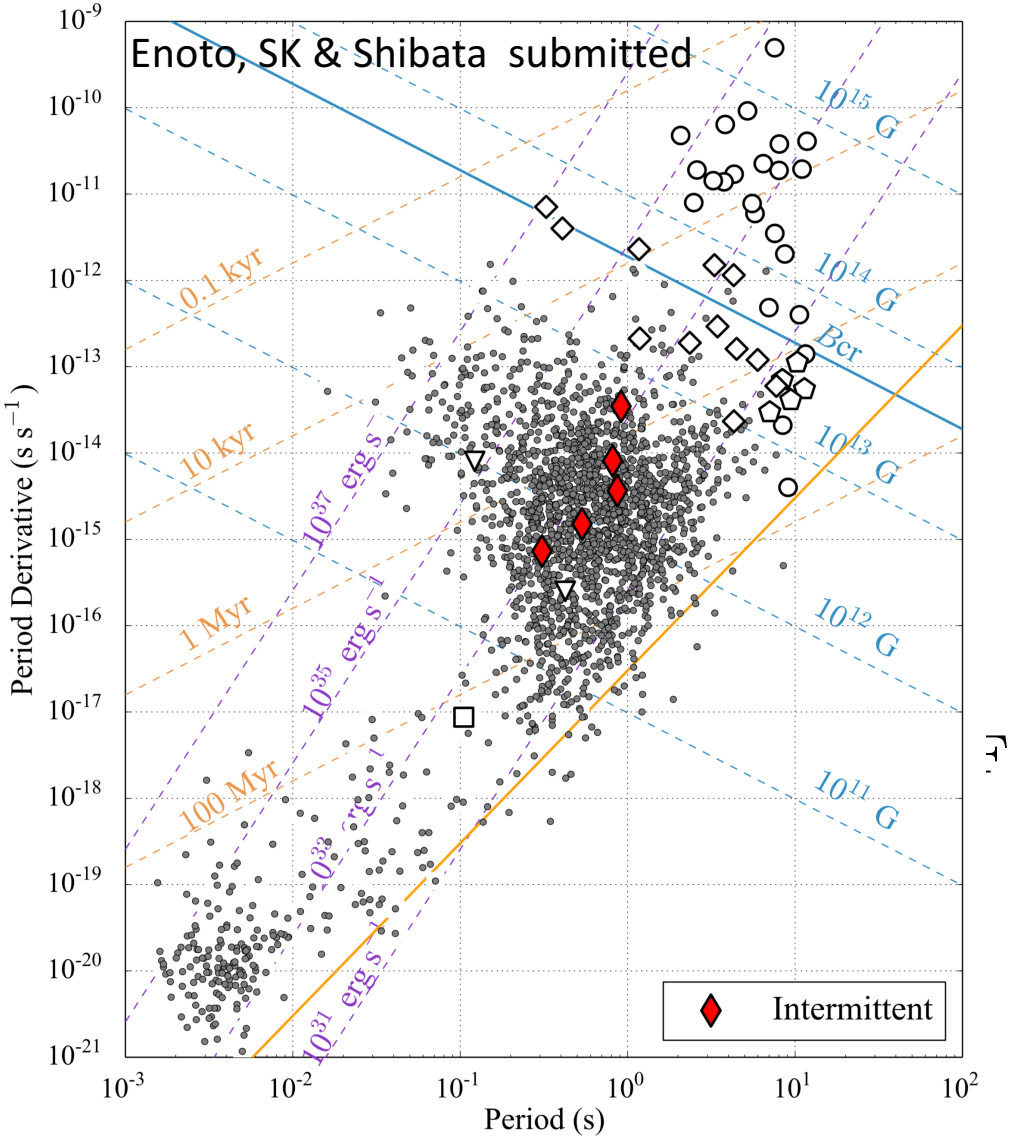
Intermittent Pulsars

Different spin-down states between ON and OFF modes of radio pulse.



Lorimer+ 12

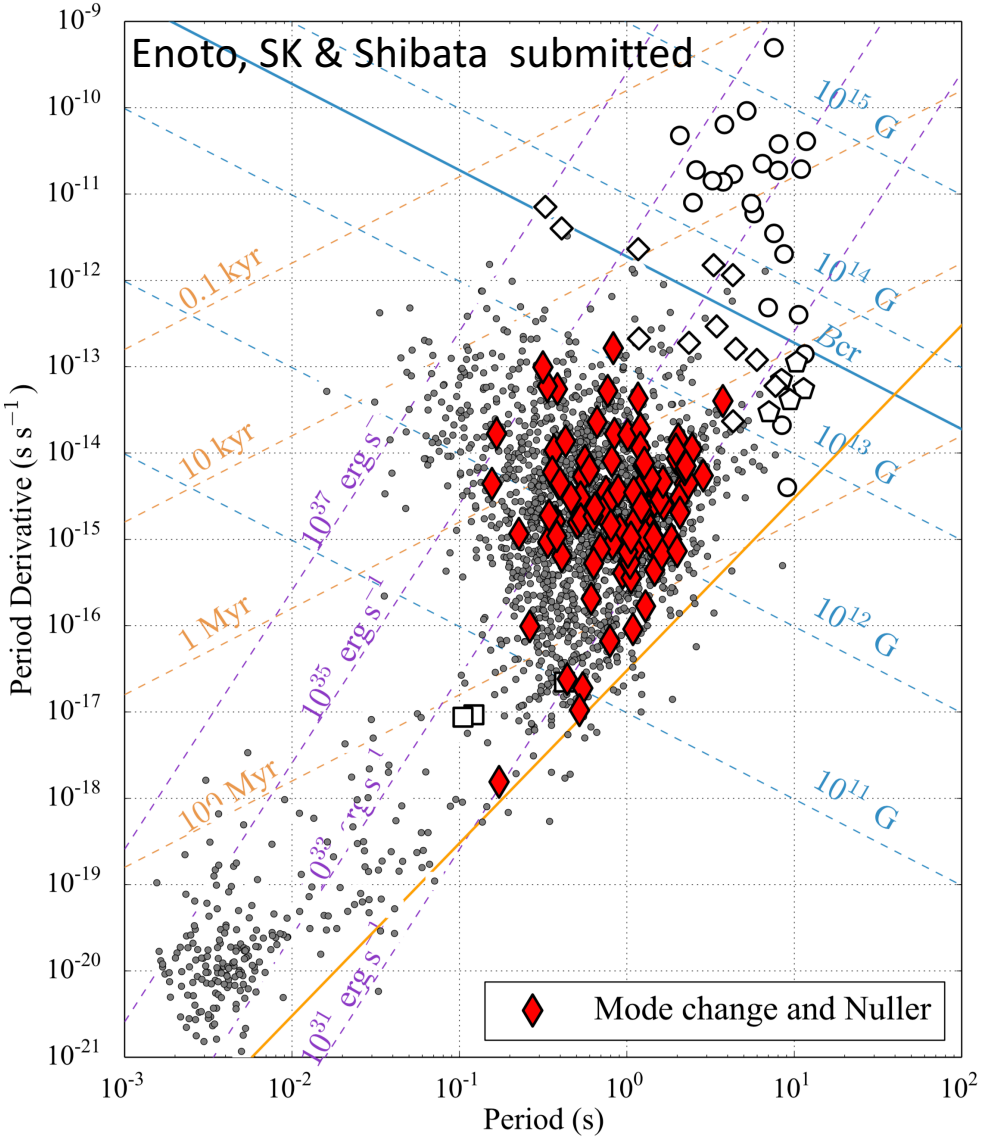
Beyond the Standard Picture :
Intermittent Pulsars



Only 5 pulsars.

Peculiar cases?

Beyond the Standard Picture :
Mode Changing Pulsars

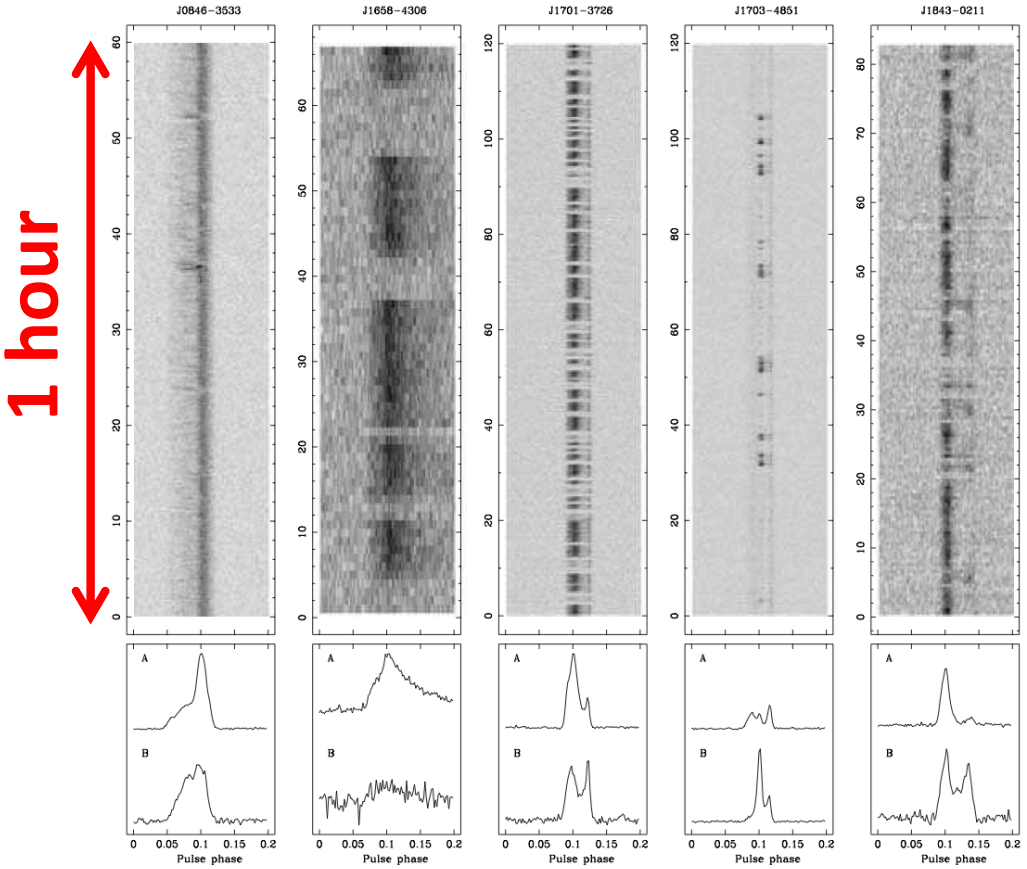


Only 5 pulsars.

Peculiar cases?

→ Maybe No. There are many pulsars with shorter transition timescale.

Wang+ 07



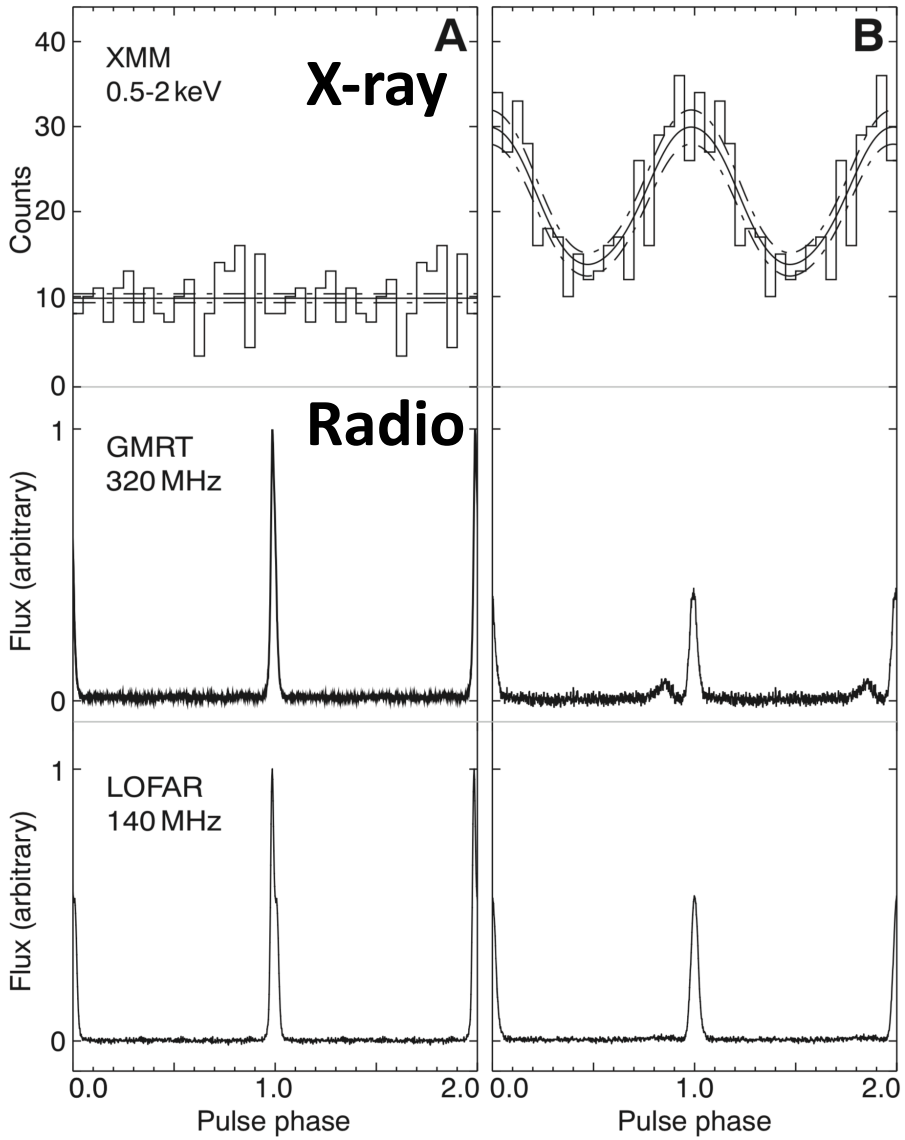
Mode Changing Pulsars

Simultaneous change in both radio and X-ray

→ Change the entire magnetosphere

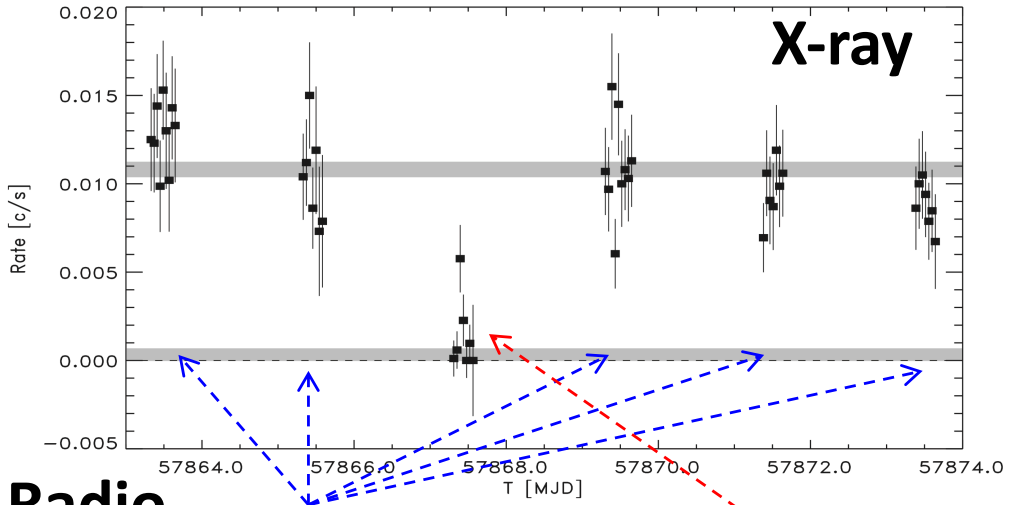
B0943+10

Hermsen+ 13

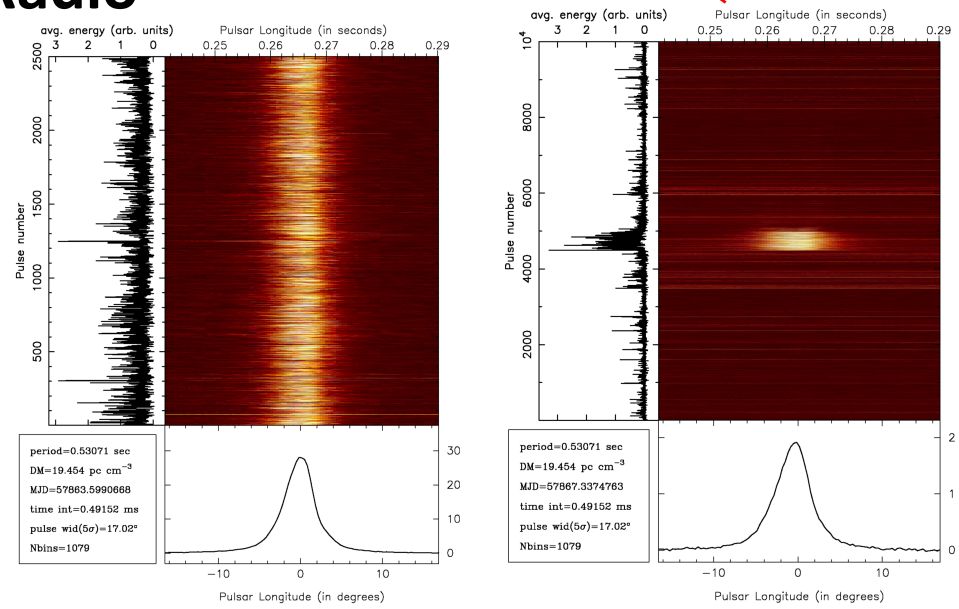


B0823+26

Hermsen+ 18



Radio



Mode Changing Pulsars

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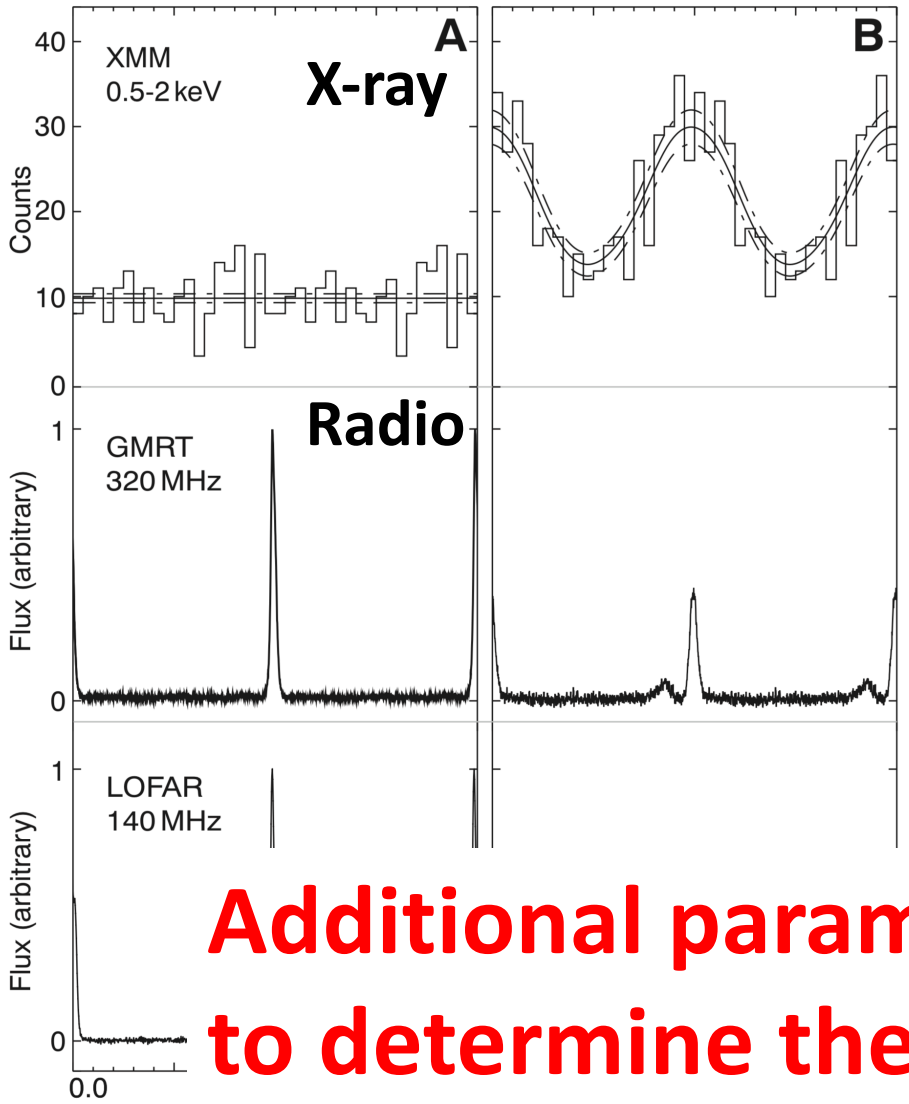

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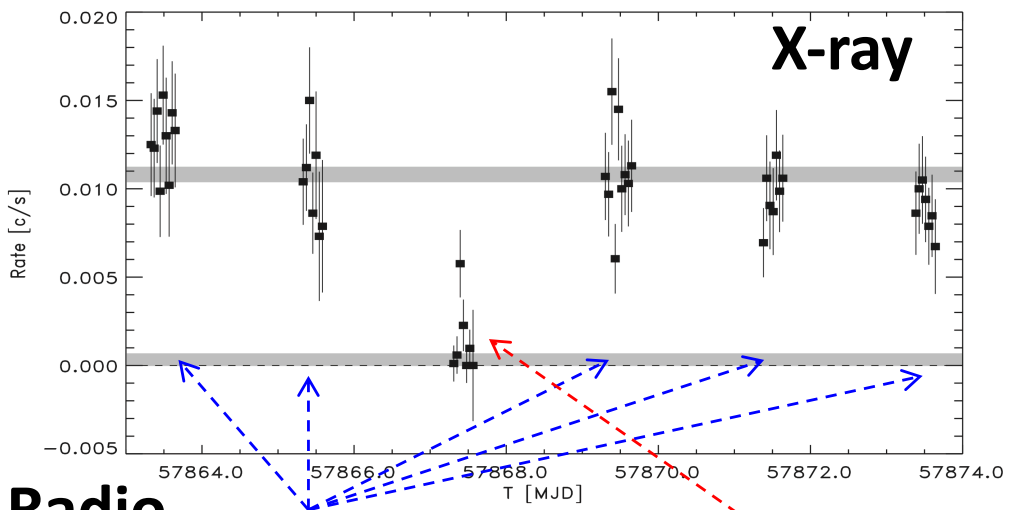
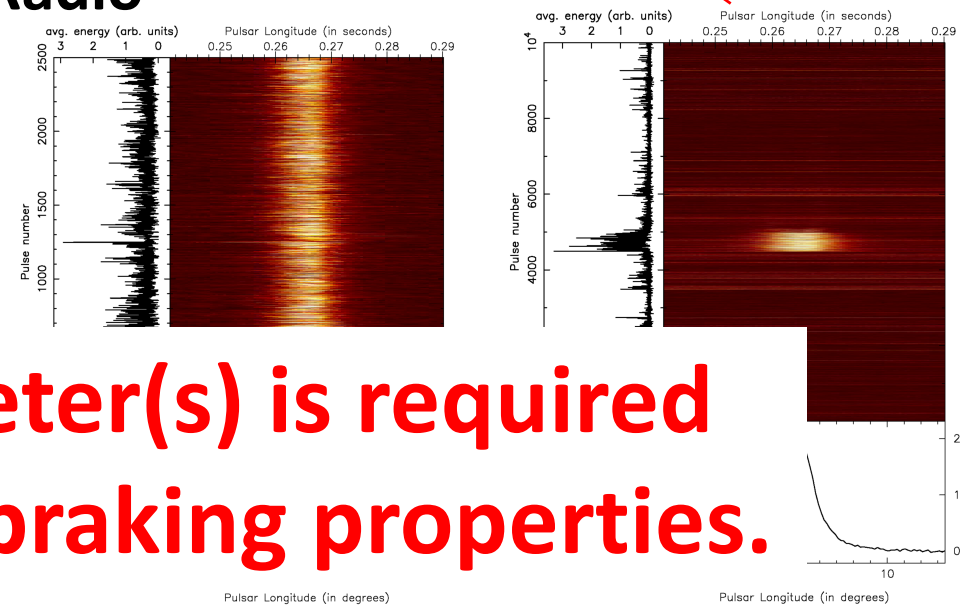
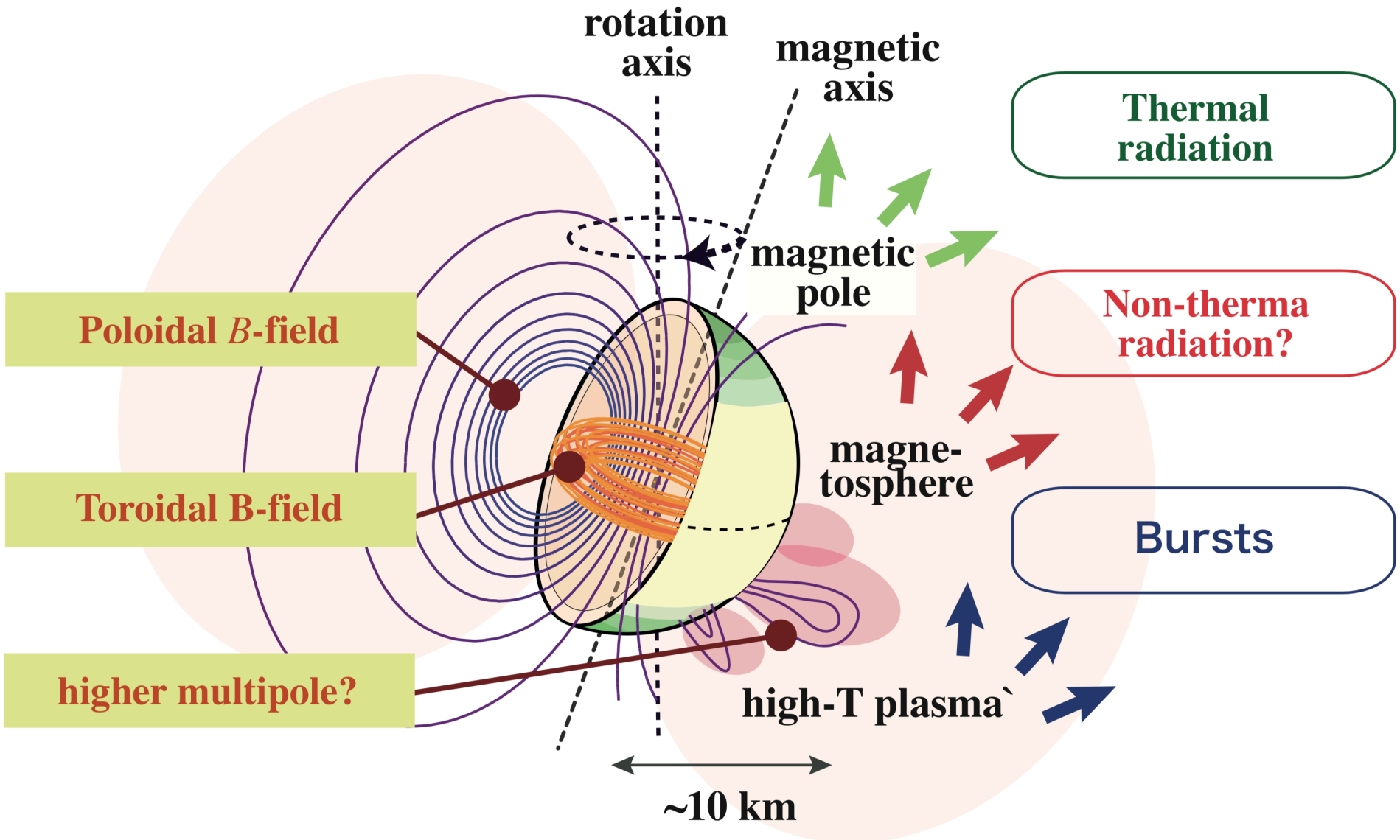


Radio



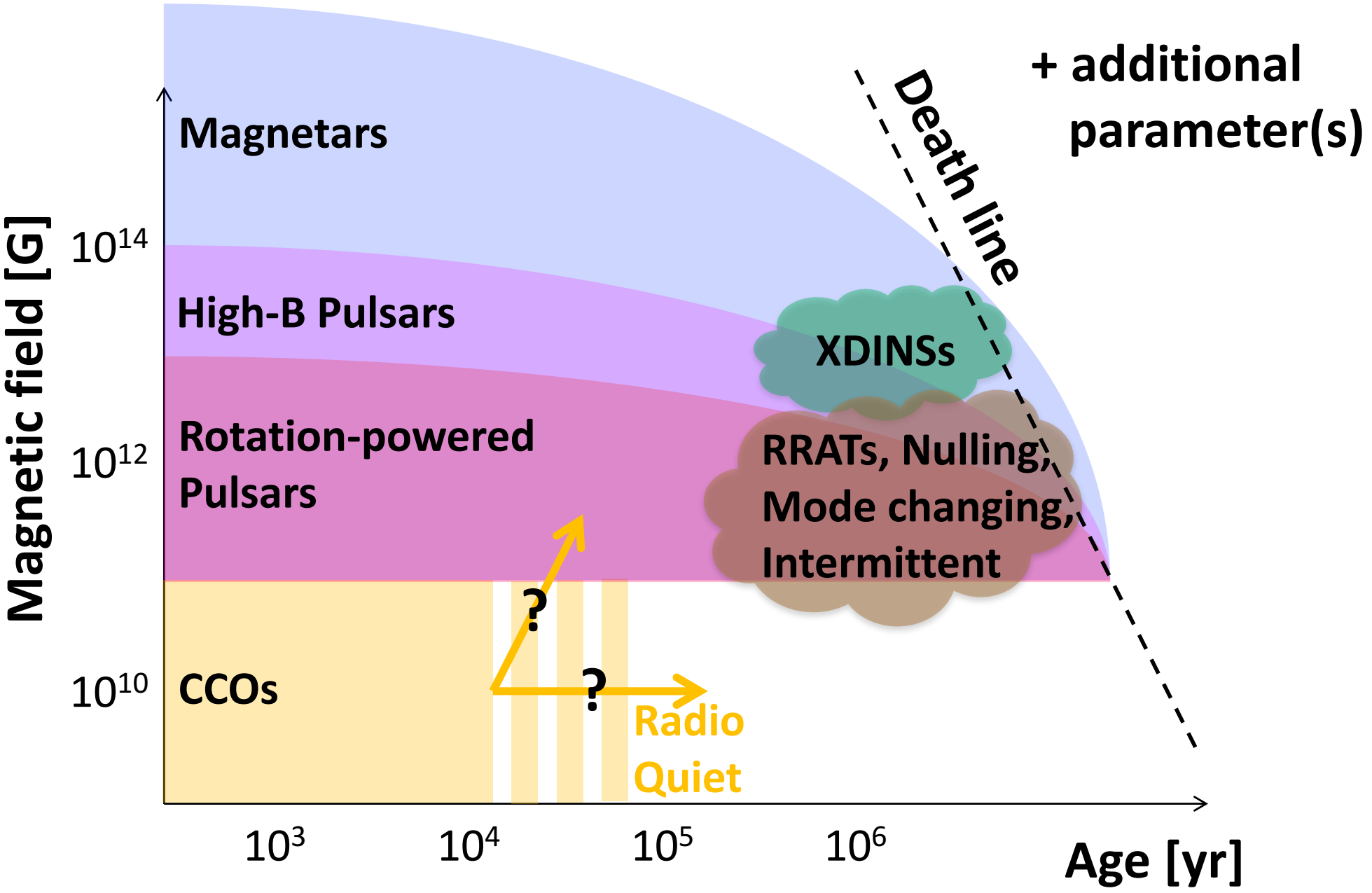
Additional parameter(s) is required to determine the braking properties.

Toroidal and/or Multipole Fields



Enoto, SK & Shibata submitted

Unified Picture?



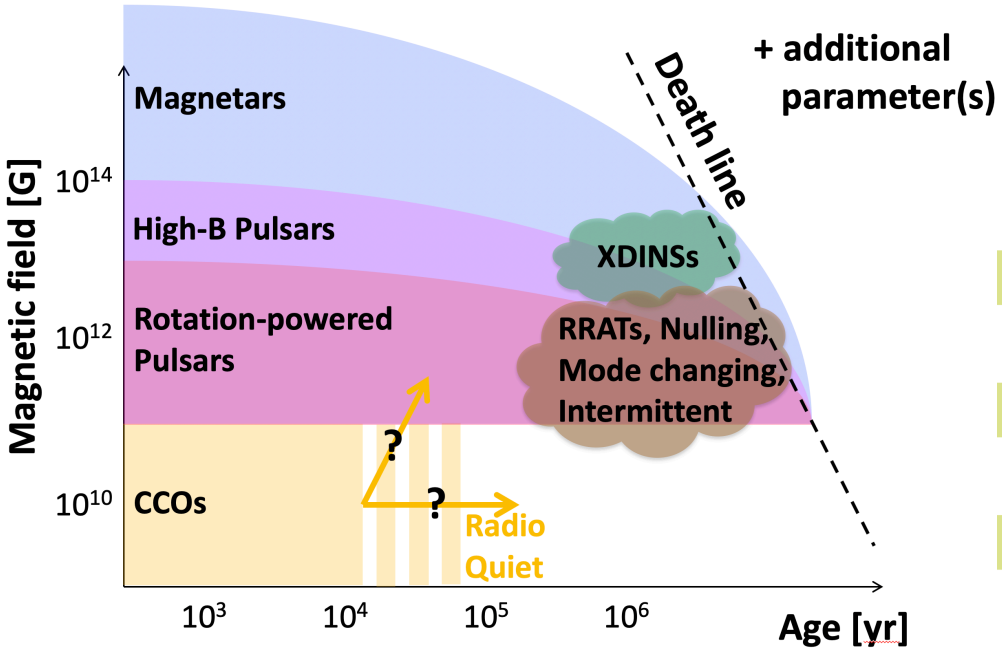
Unified Picture?

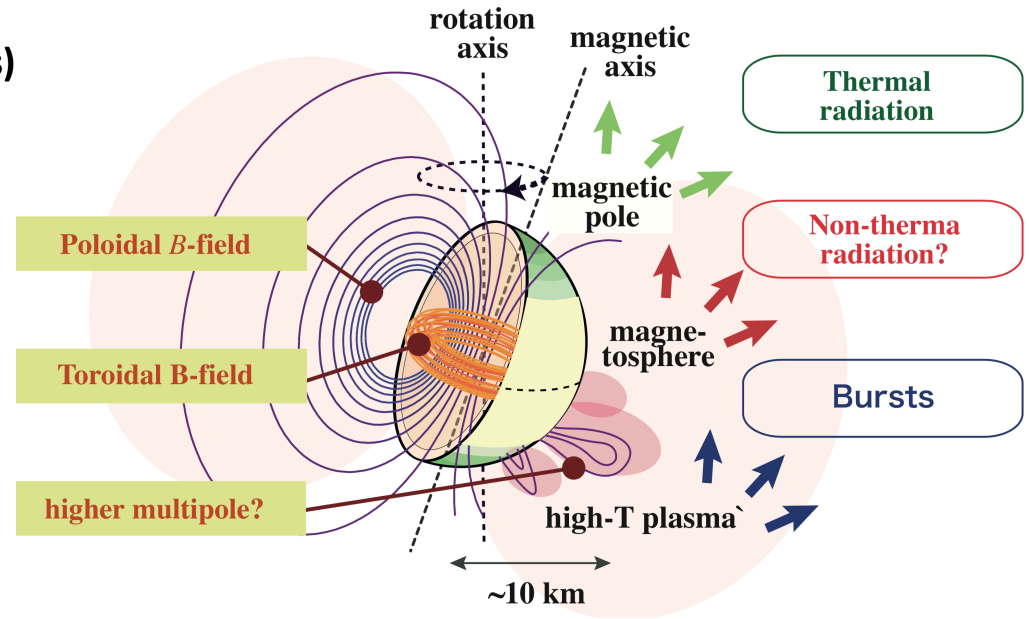
NS diversity ← **Initial condition** + **B-field evolution** + **Pair cascade**

- Mass
- Period
- B-field
- fallback

- Dissipation mechanism
- Mechanical failure or plastic deformation
- Configuration change
- Thermal evolution

- Acceleration
- Radiation
- Pair creation
- Plasma interaction





Observational Prospects

Initial condition

- **SN-SNR-PWN-NS connection (+FRB?)**
- HMXB census

+

B-field evolution

- eROSITA survey
- Long-P pulsars
- Old pulsar heating

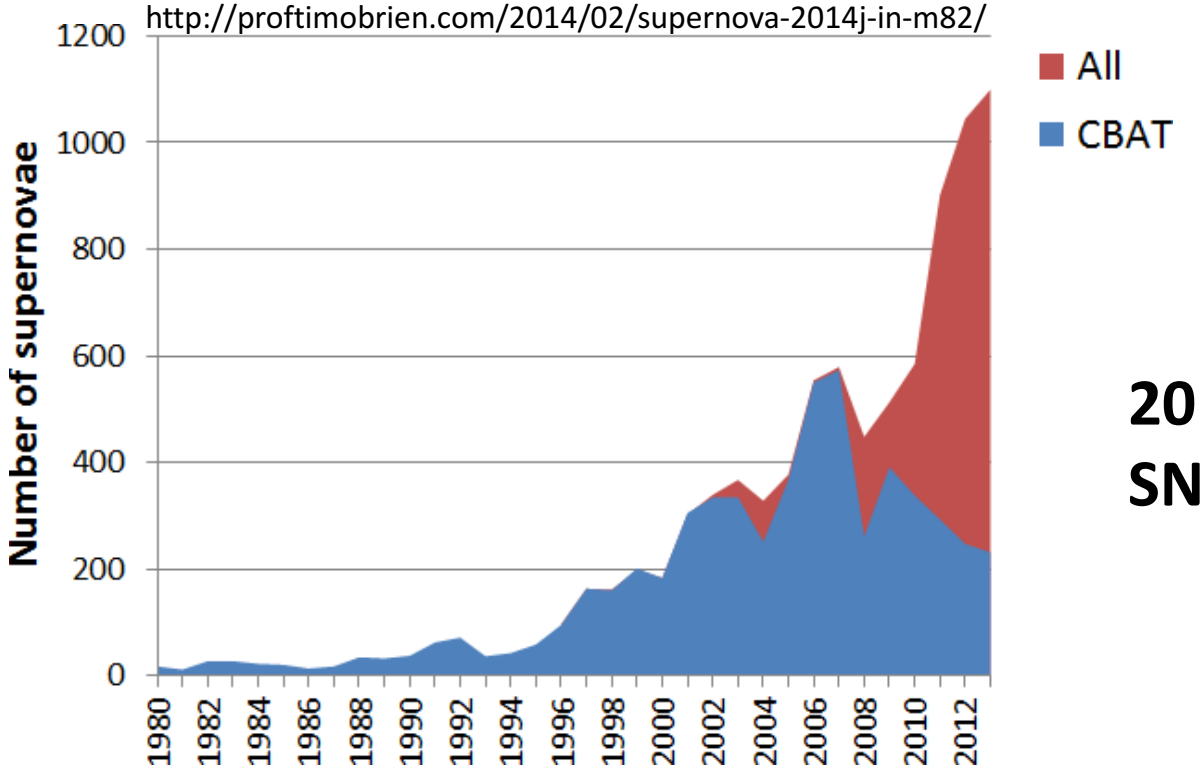
+

Pair cascade

- Polarization
- MSP single pulse
- Low γ-ray pulsars

List of Supernovae

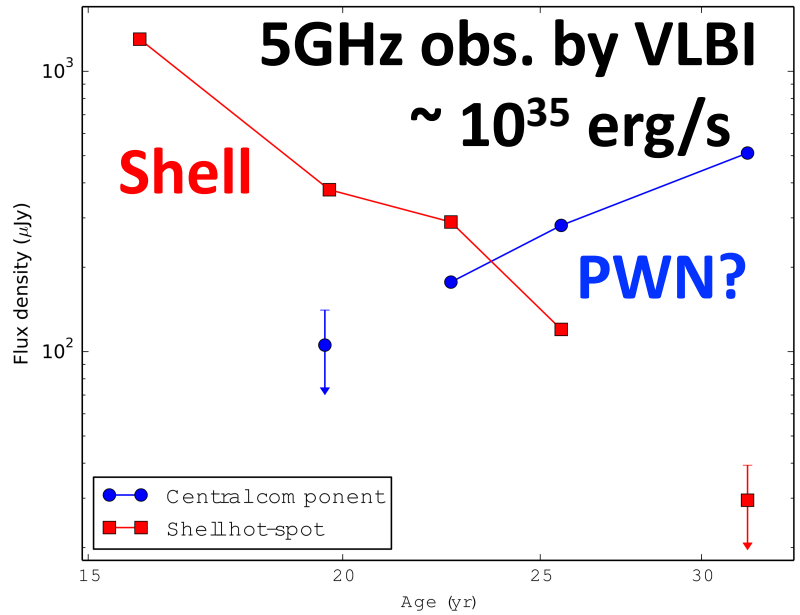
http://proftimobrien.com/2014/02/supernova-2014j-in-m82/

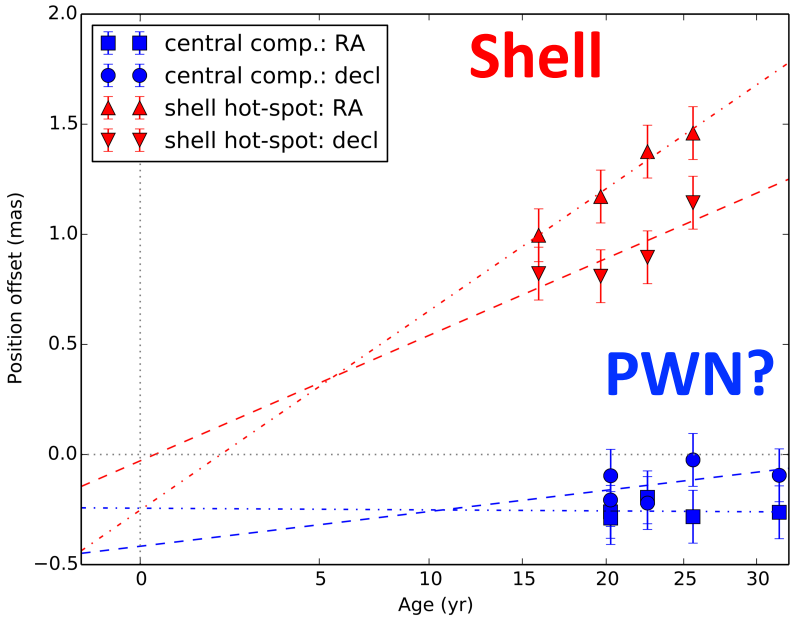


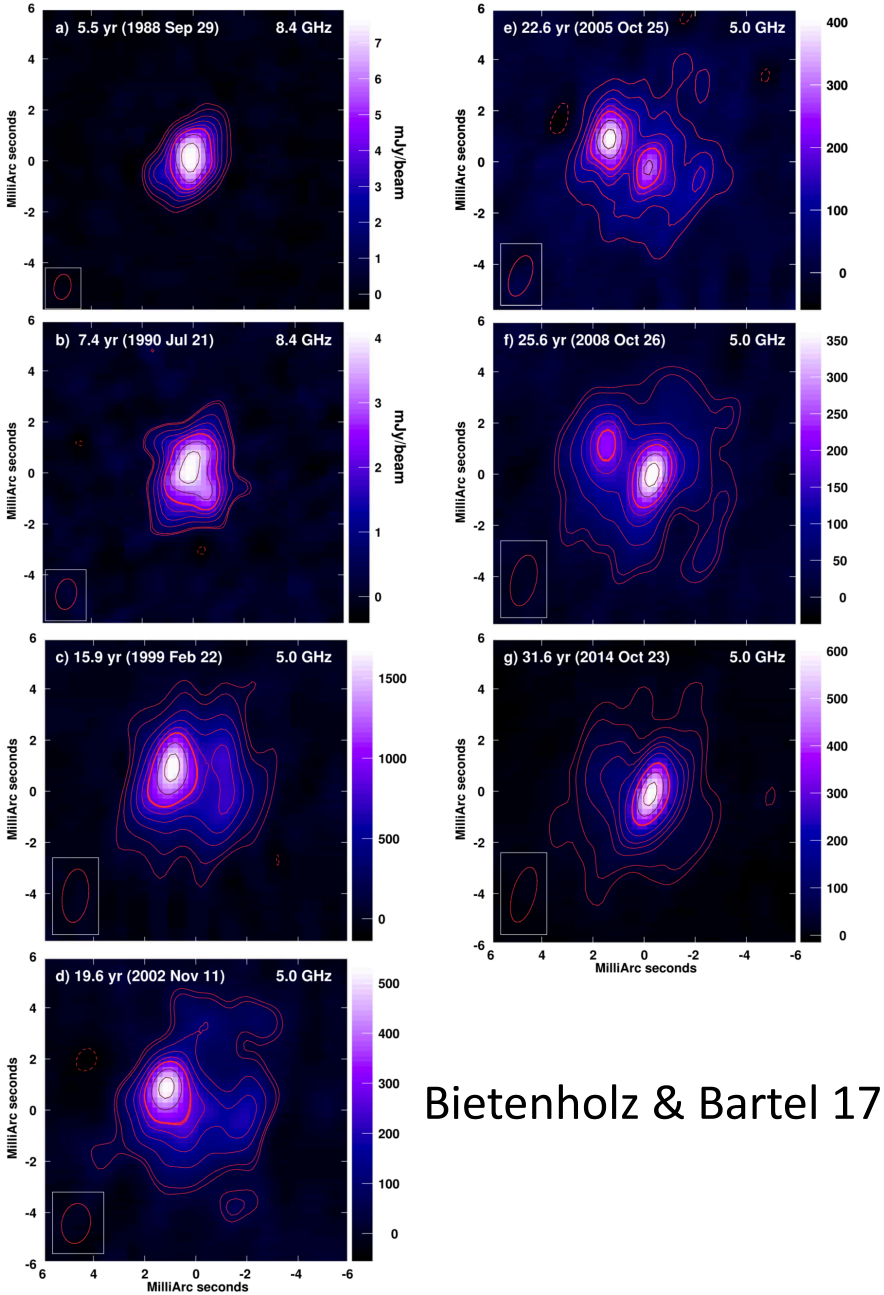
20 yrs since the discovered SNe exceeds 200 per a year.

Observational Prospects

Detection of a PWN candidate from SN1986J





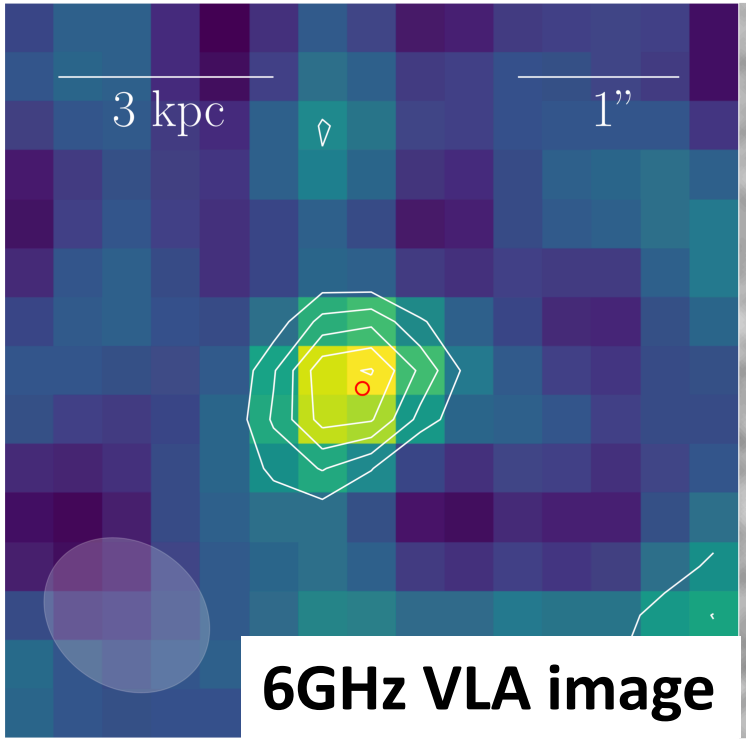


Bietenholz & Bartel 17

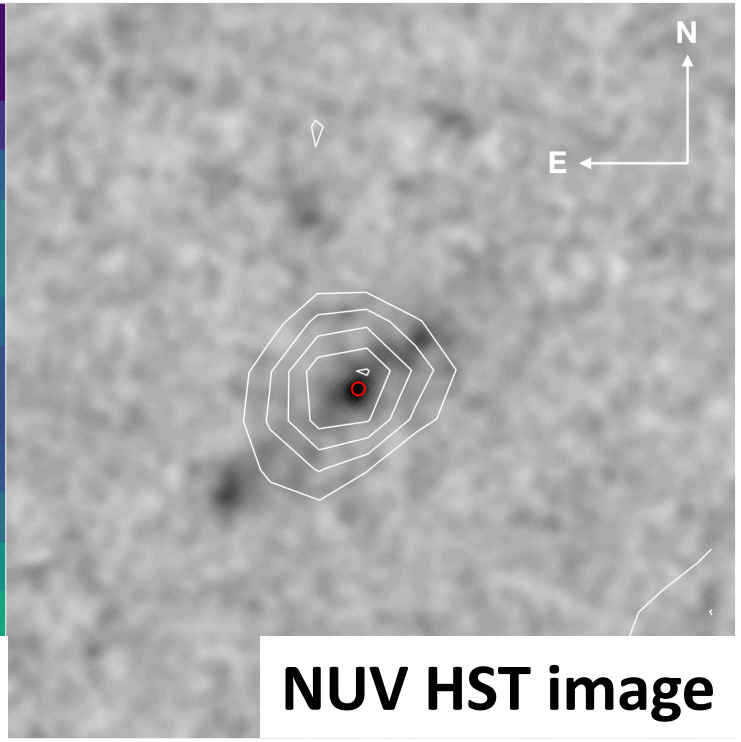
Observational Prospects

Eftekhari+ 19

Detection of a PWN candidate from the type I SLSN



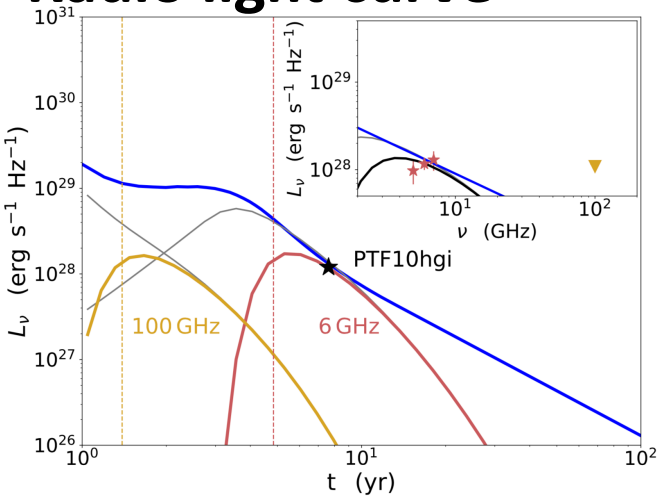
6GHz VLA image

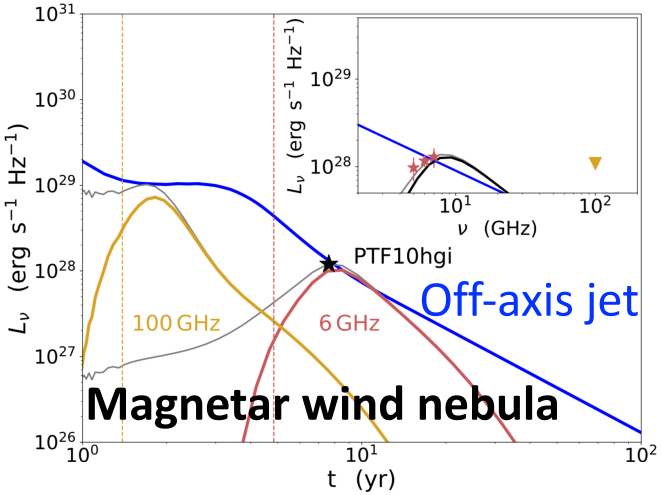


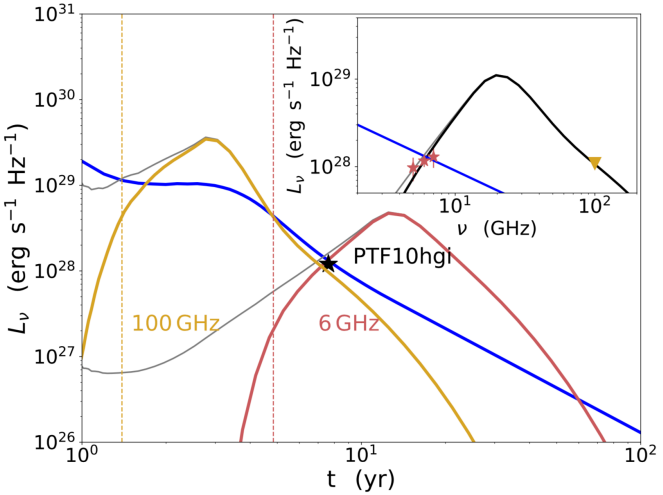
NUV HST image

PTF10hgi
z ~ 0.098
7.5 years
~10^{38} erg/s (6GHz)

Radio light curve



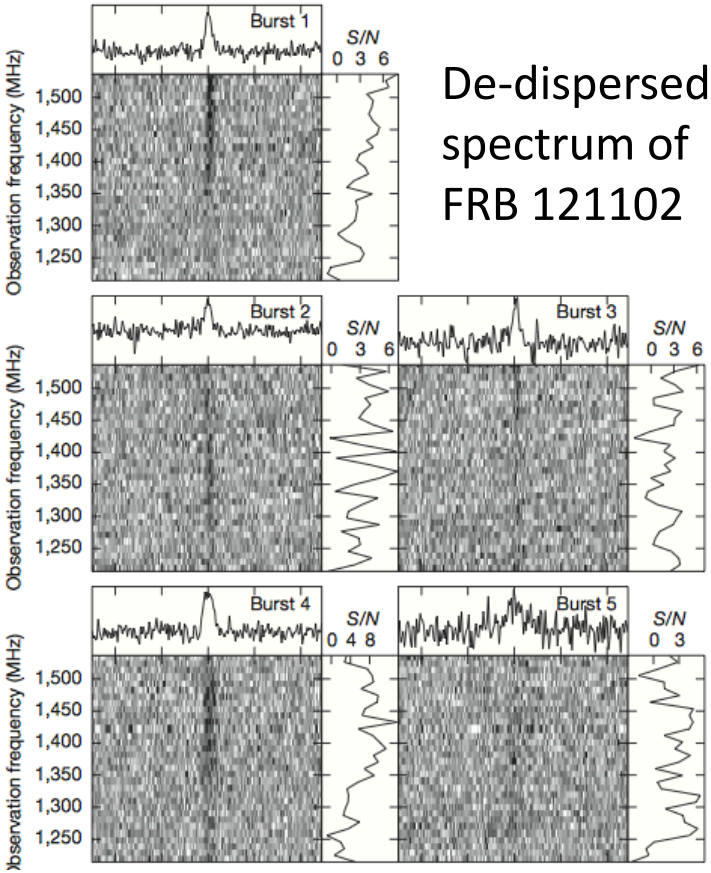




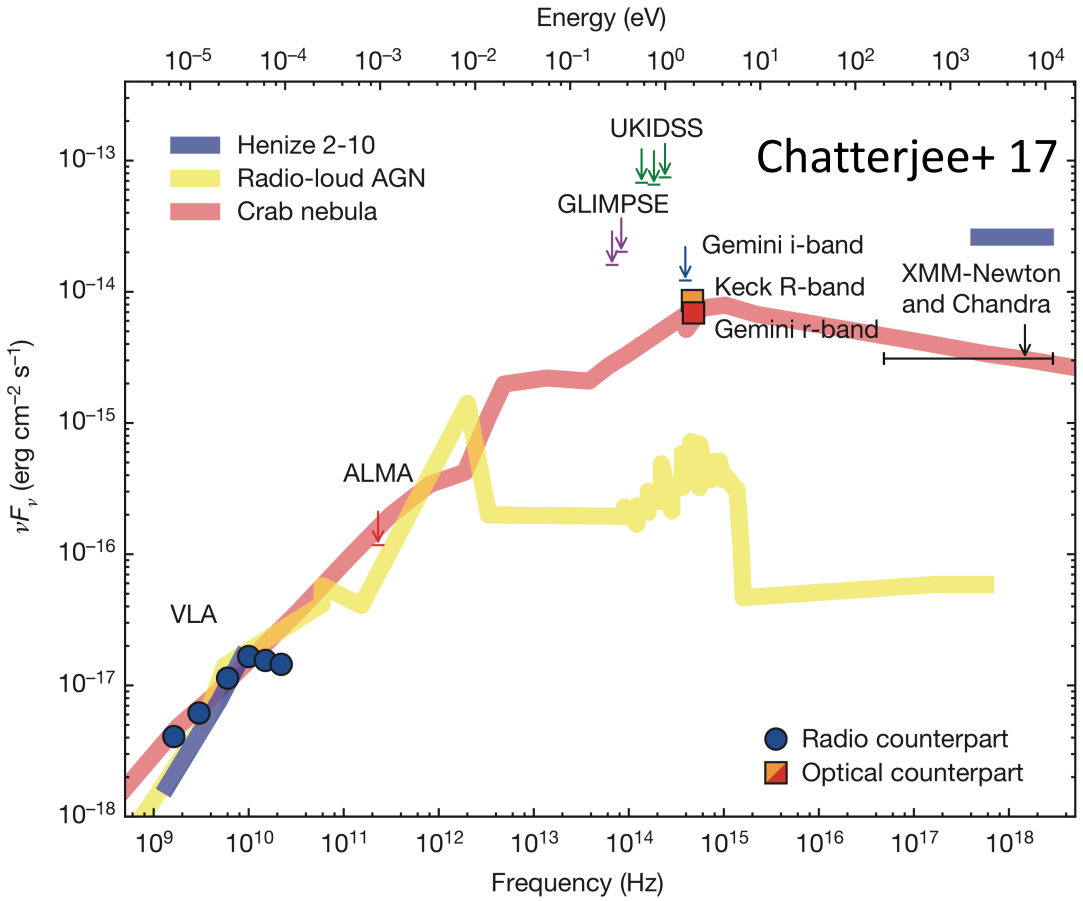
Observational Prospects

A persistent source co-located with the repeating FRB.

Emission is compatible to PWNe.



De-dispersed spectrum of FRB 121102



Luminosity ~ 2×10^{39} erg s^{-1}

Frequency range ~ 1-20 GHz

Flux peak ~ 10 GHz

Variability < 30 %

Observational Prospects

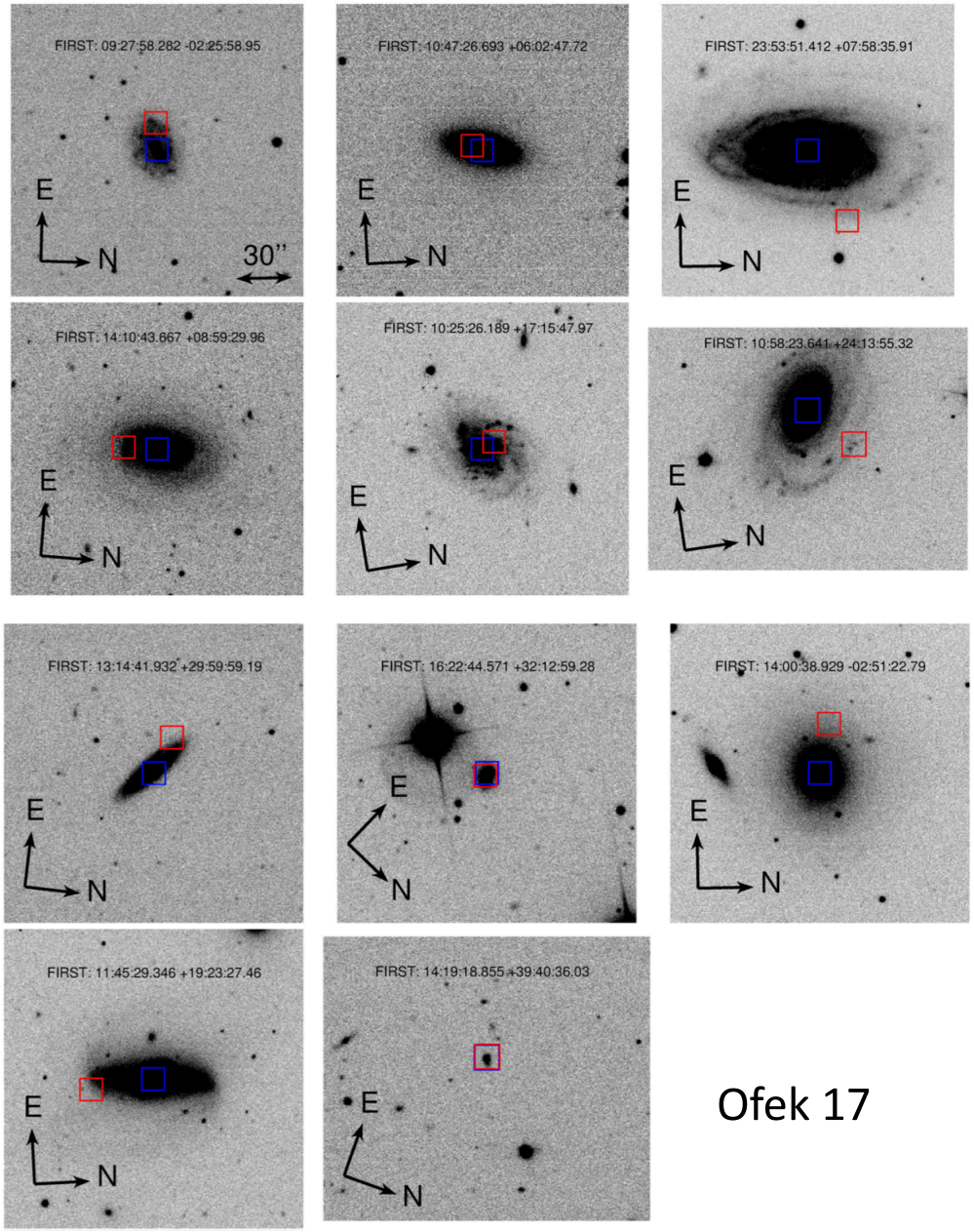
Search for FRB 121102-like radio sources

Sample:
30% of the total galaxy g-band luminosity within <108 Mpc

Picking up persistent sources with radio luminosity > 10% of FRB 121102

Rejecting AGN-like sources

- **11 candidates**
- **Birth rate of $< 5 \times 10^{-7}$ yr^{-1} Mpc^{-3} (assuming lifetime 100 yrs)**
- **Good targets for FRB & young pulsar searches**



Ofek 17