# Magnetic Activities of Magnetars and X-ray Observations
# マグネターの磁気活動とX線観測

*Overview of the NS diversity, magnetars, and future projects*

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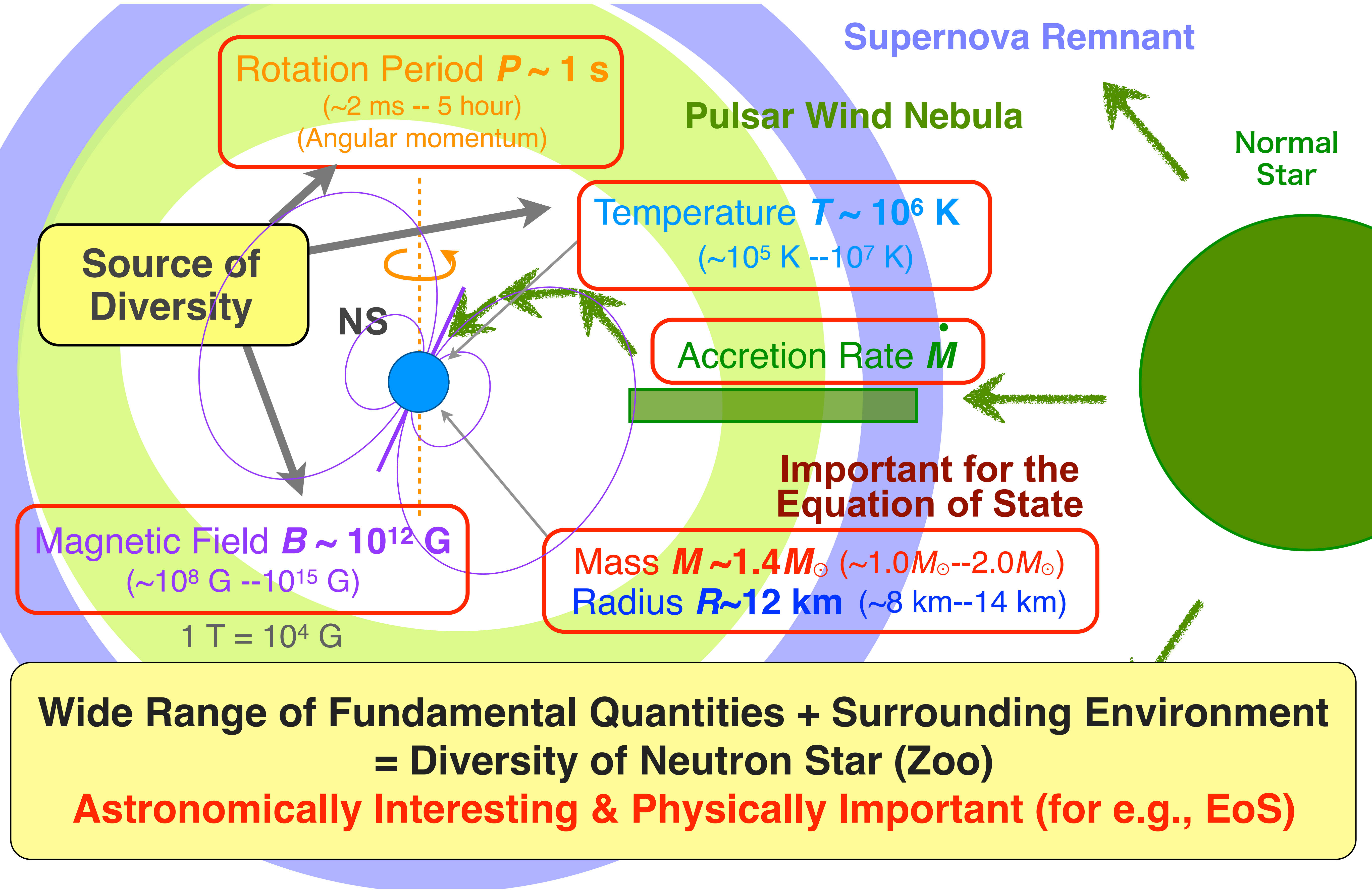
第２回 DTA シンポジウム
「コンパクト天体の活動性と磁気的性質」

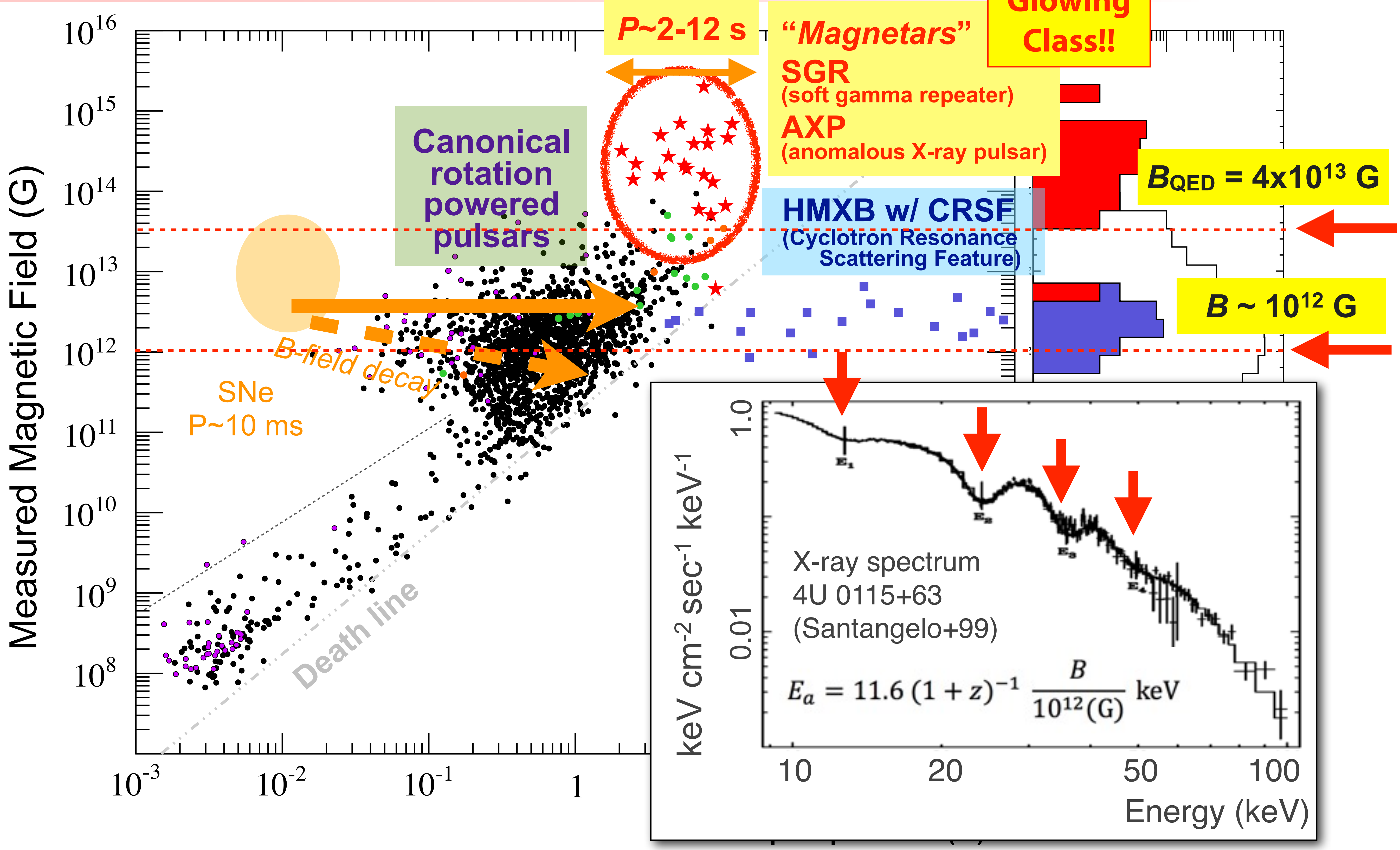
# Neutron Stars: Lab. for the Fundamental Physics

Dense nuclear matter, strong gravity, rapid rotation, and strong magnetic field




**Wide Range of Fundamental Quantities + Surrounding Environment**
**= Diversity of Neutron Star (Zoo)**
**Astronomically Interesting & Physically Important (for e.g., EoS)**

# Magnetic Field and Evolution of NSs

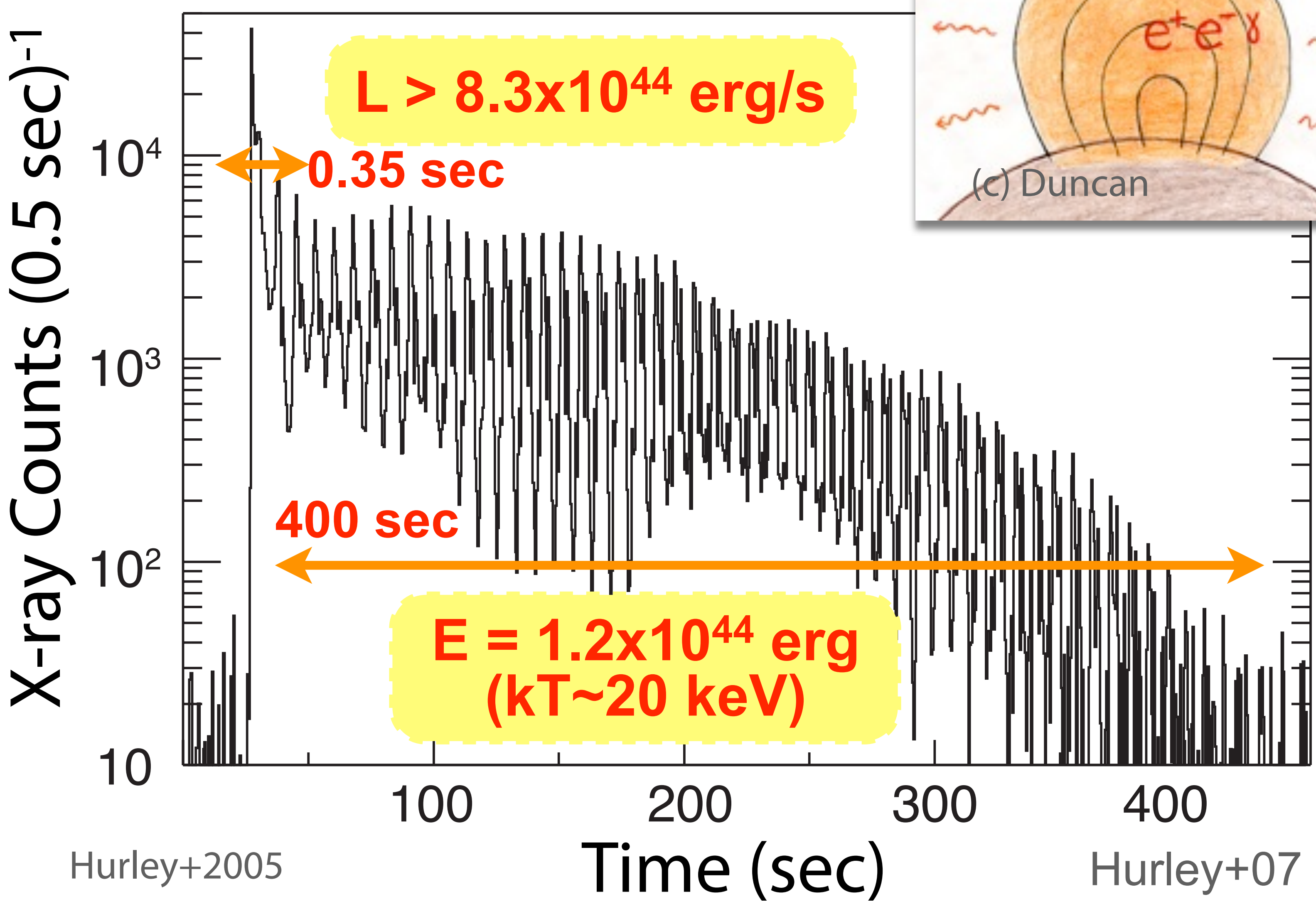


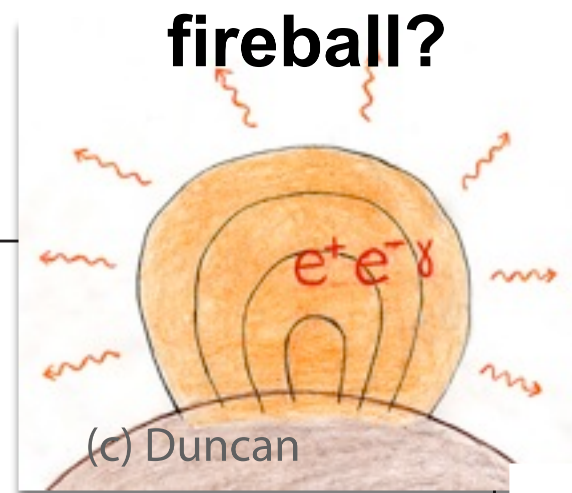

**Strongly magnetized NSs has been implied in recent studies.**

# Soft Gamma Repeater (SGR)

**Discovered by "Giant Flares" or recurrent burst activities. ~ 5 SGRs**

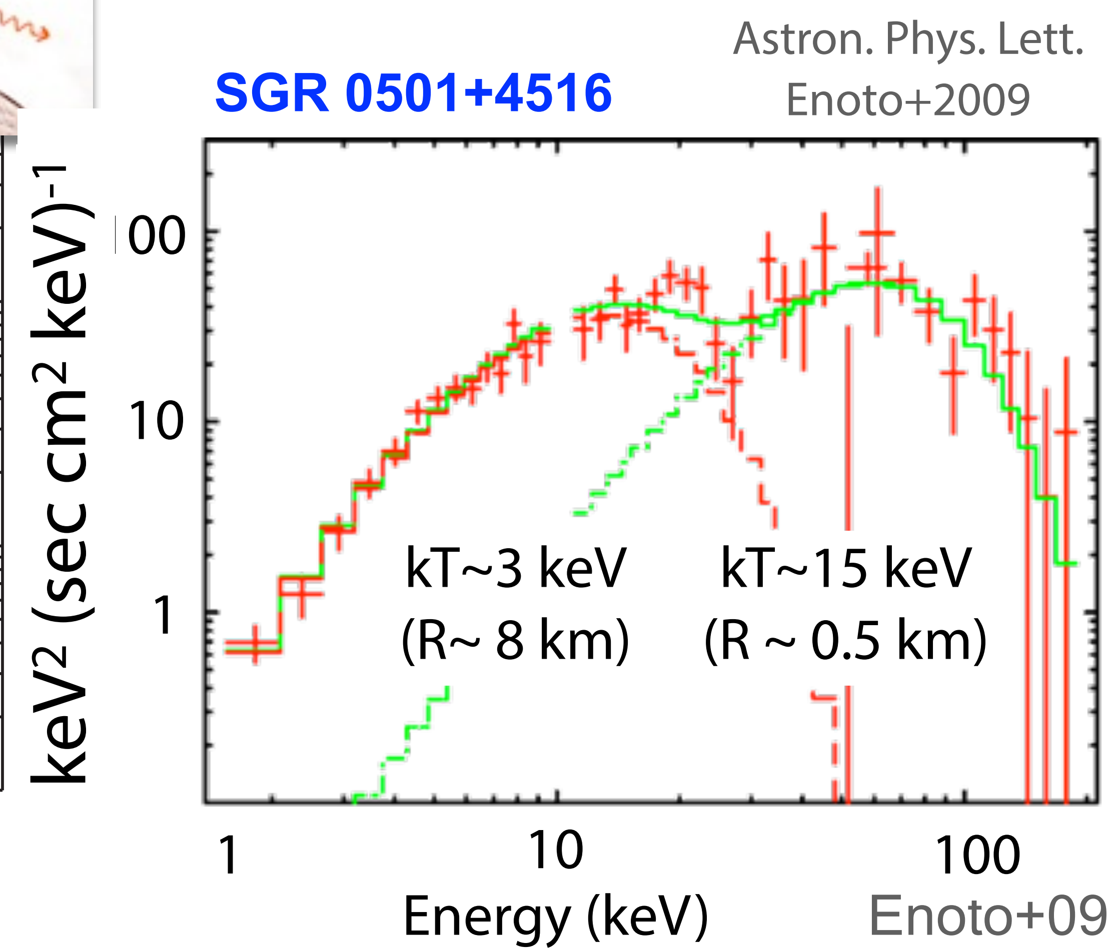
**Giant Flare (3 events)**




**Short Bursts**

a few hundred millisecond
empirically two Blackbody




- **Exceeding the Eddington Luminosity (~$10^{38}$ erg/s) by ~6 orders of magnitudes**
- **B > $10^{14}$ G is required to confine a few dozen keV plasma for ~400 sec**

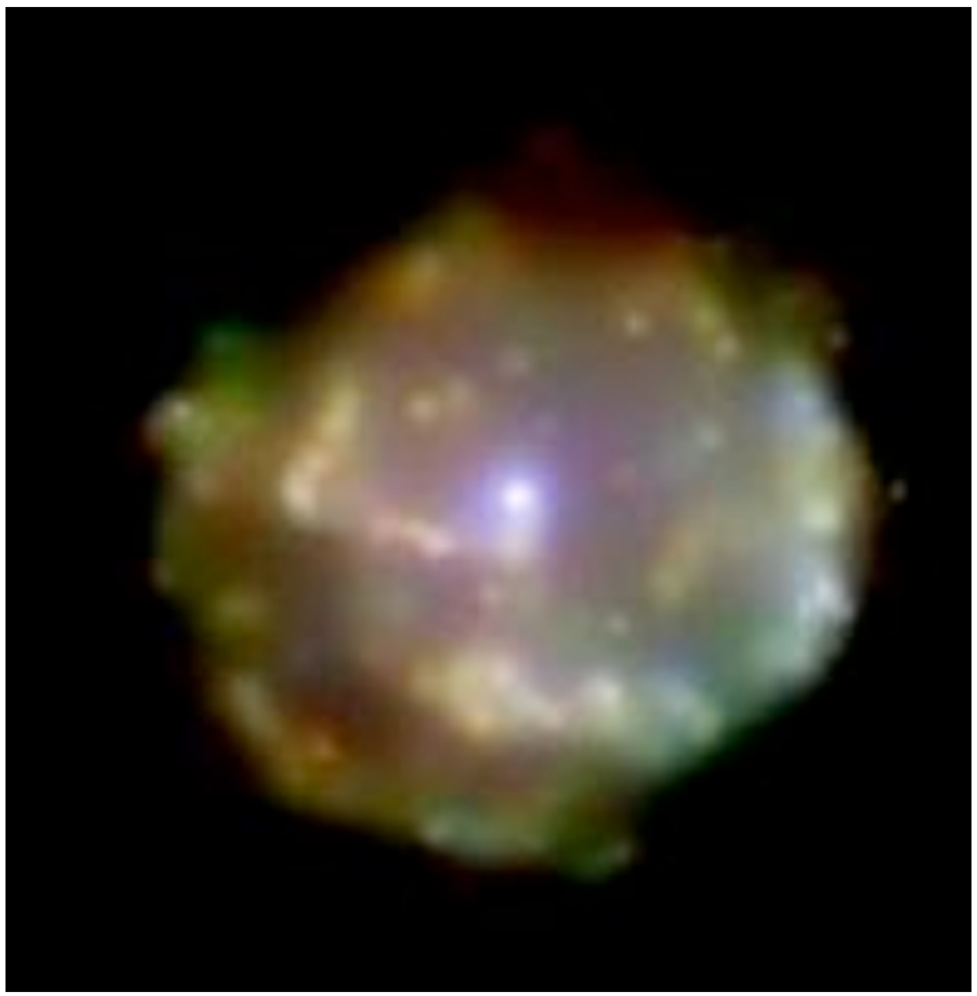
# Anomalous X-ray Pulsar (AXP)

**Discovered as pulsed bright persistent X-ray sources. ~15 AXPs**

**Associated with SNR**

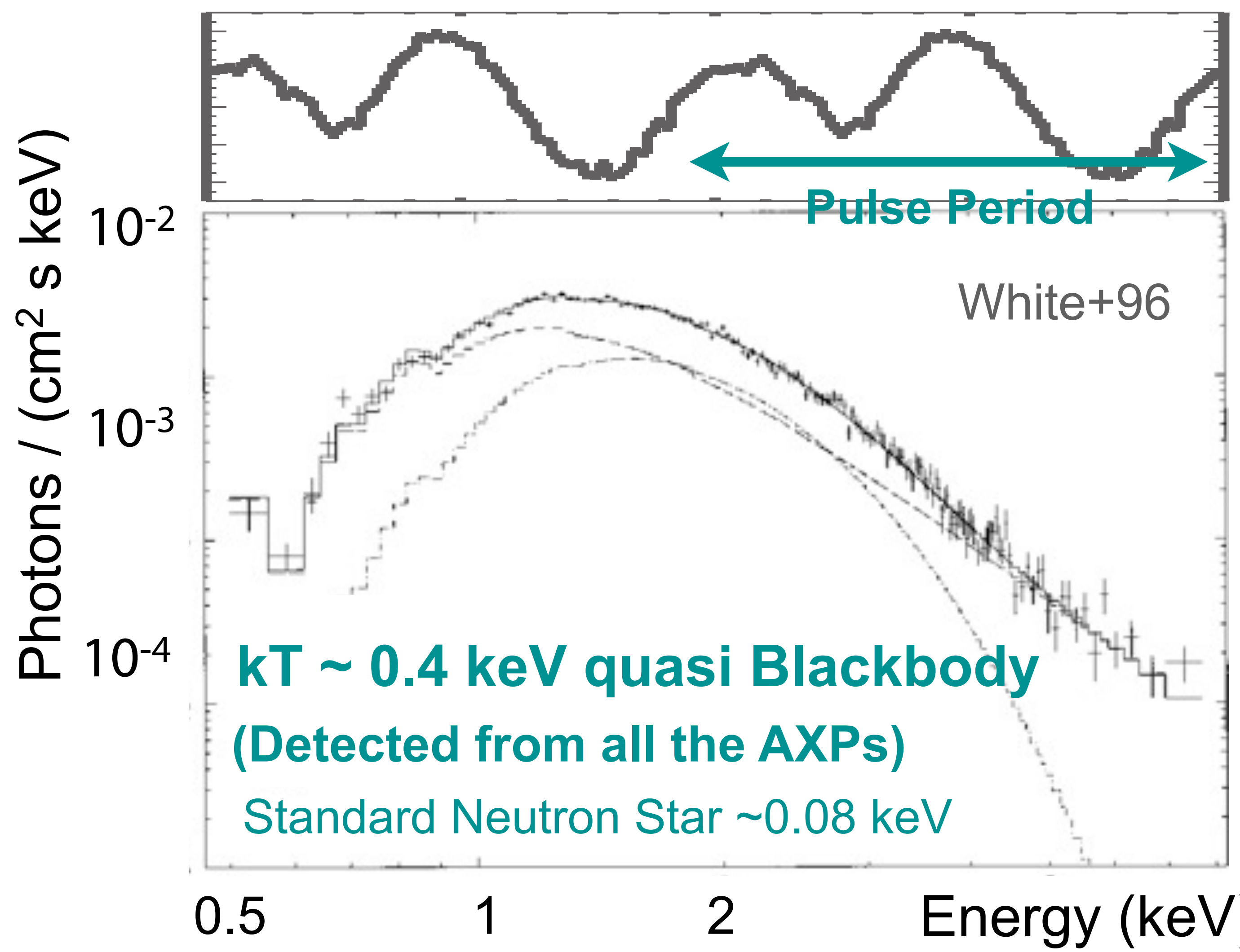
**Persistent X-ray Emission**

**1E 1841-045 (SNR Kes73)**



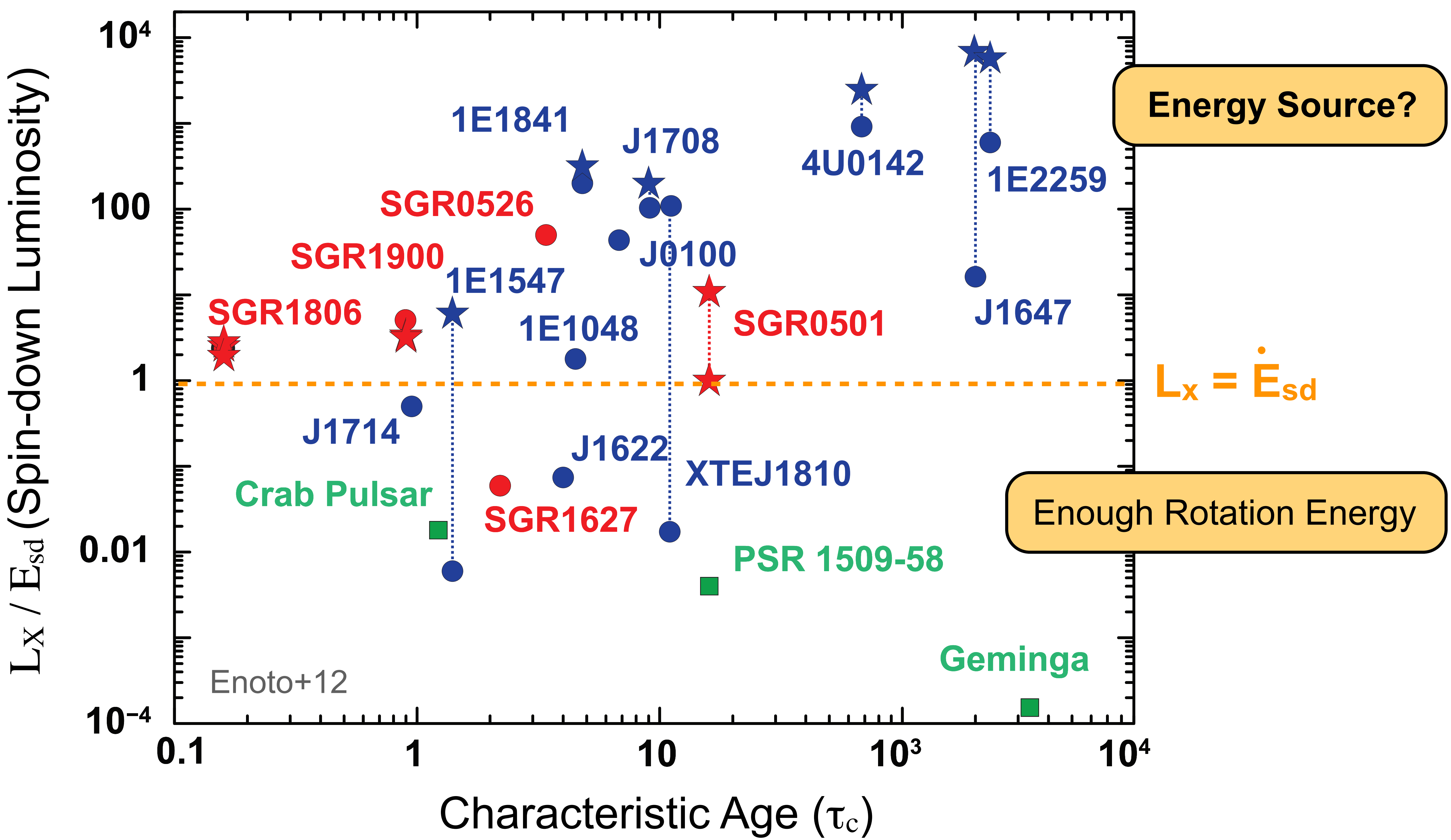
Chandra Image (c)CXO

**4U 0142+61**




**- Exceeding the Spin-down luminosity by ~2 orders of magnitudes ($L_x >> L_{sd}$)**

# Persistent X-ray Luminosity of SGR/AXP




$L_X$ >> Spin-down $E_{sd}$, no evidence for a binary companion (e.g., Kaspi+99)
Magnetars; Magnetically-powered Pulsars?

# “Magnetar Hypothesis”

“SGRs and AXP are ultra-strongly magnetized NSs with $B \sim 10^{14\text{-}15}$ G powered by their stored magnetic energy in the stellar interior.”

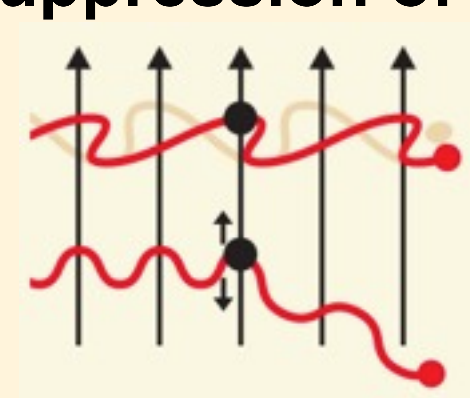
Thompson & Duncan+95, 96

1. SNR association, slow P and large Pdot ⇒ Young ($\tau$<100 kyr) & $B \sim 10^{14\text{-}15}$ G
2. $L_x$ >> $L_{sd}$ by 2-3 orders of mag. ⇒ Not rotation-powered pulsars
3. No evidence of binary system ⇒ Not accretion-powered pulsars
4. Marginal “proton” cyclotron resonance ⇒ Suggests B > $10^{14}$ G
5. Peculiar burst activities ⇒ Magnetic dissipation (e.g., reconnections)??
6. Super-Eddington giant flares ⇒ B > $10^{14}$ G & suppression of $\sigma$

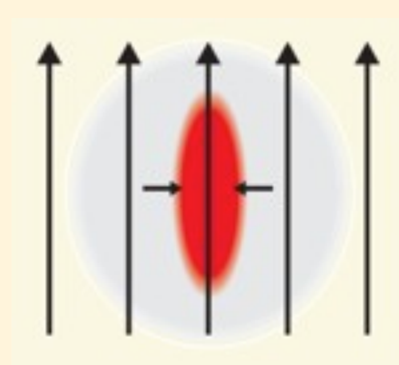
**QED Critical Field**

$$\hbar \frac{eB}{m_e c} = m_e c^2 \Rightarrow B_{QED} = 4.4 \times 10^{13}\ \text{G}$$

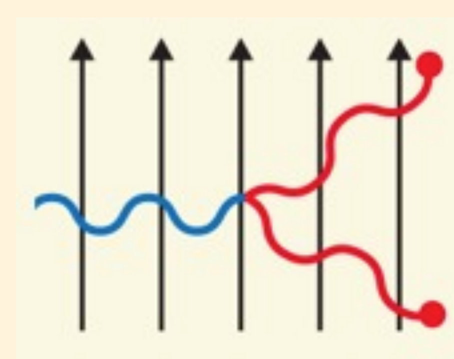
**Suppression of σ**



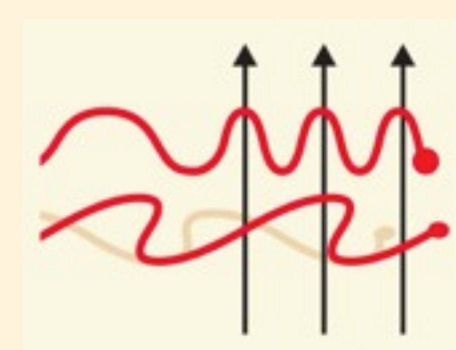
**Distortion of atom**



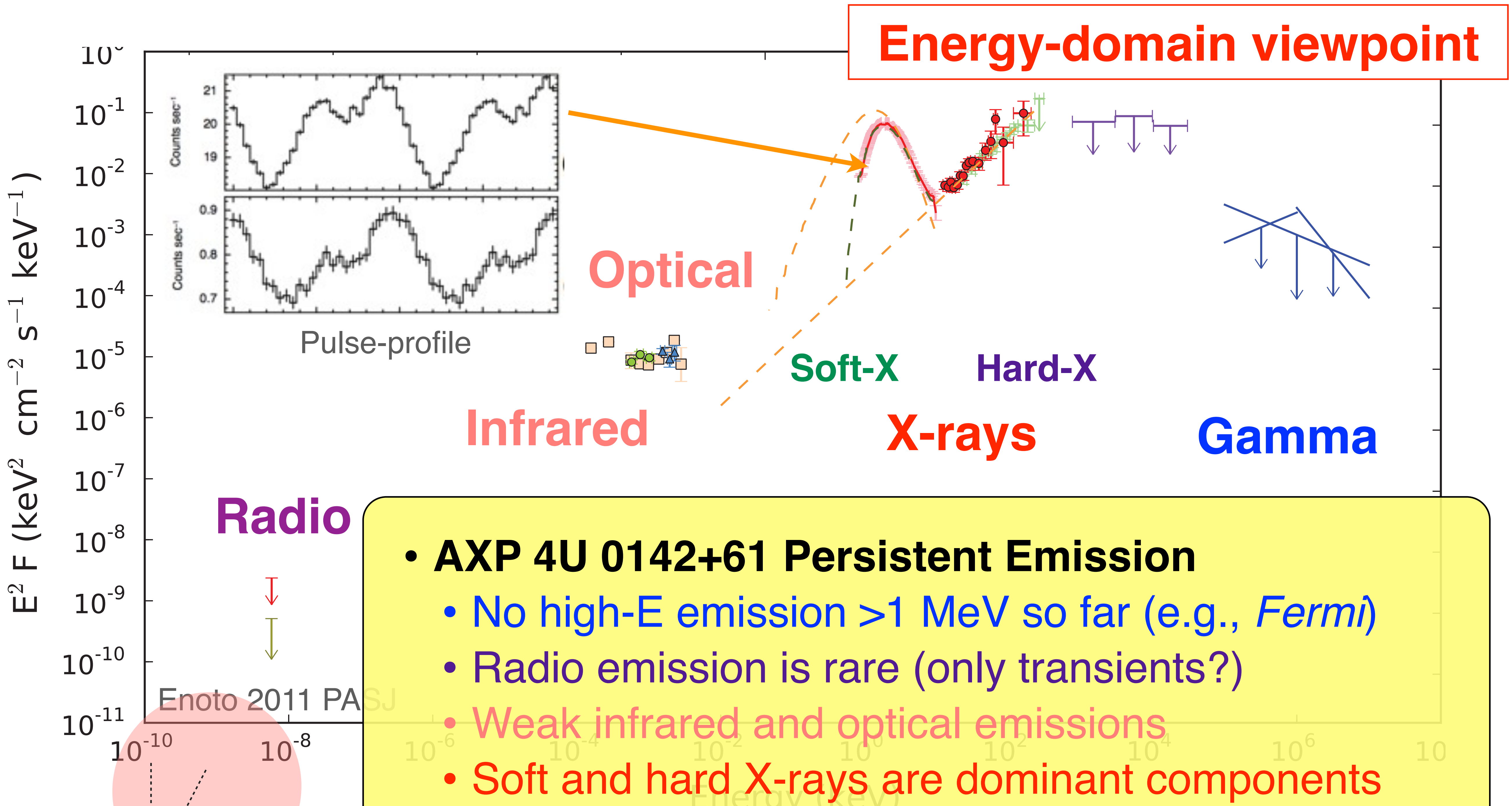
**Photon Splitting**

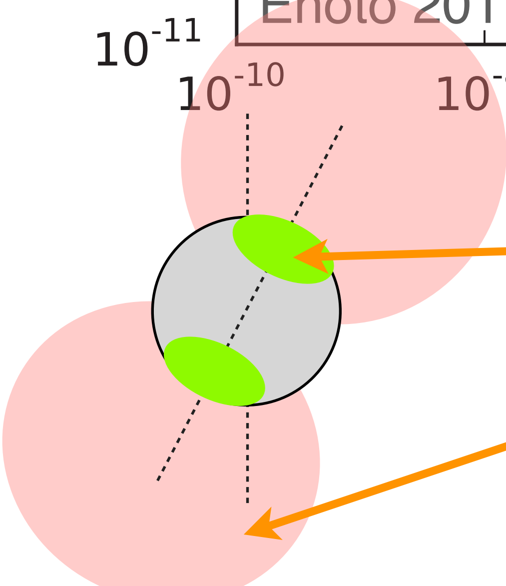


**Birefringence**



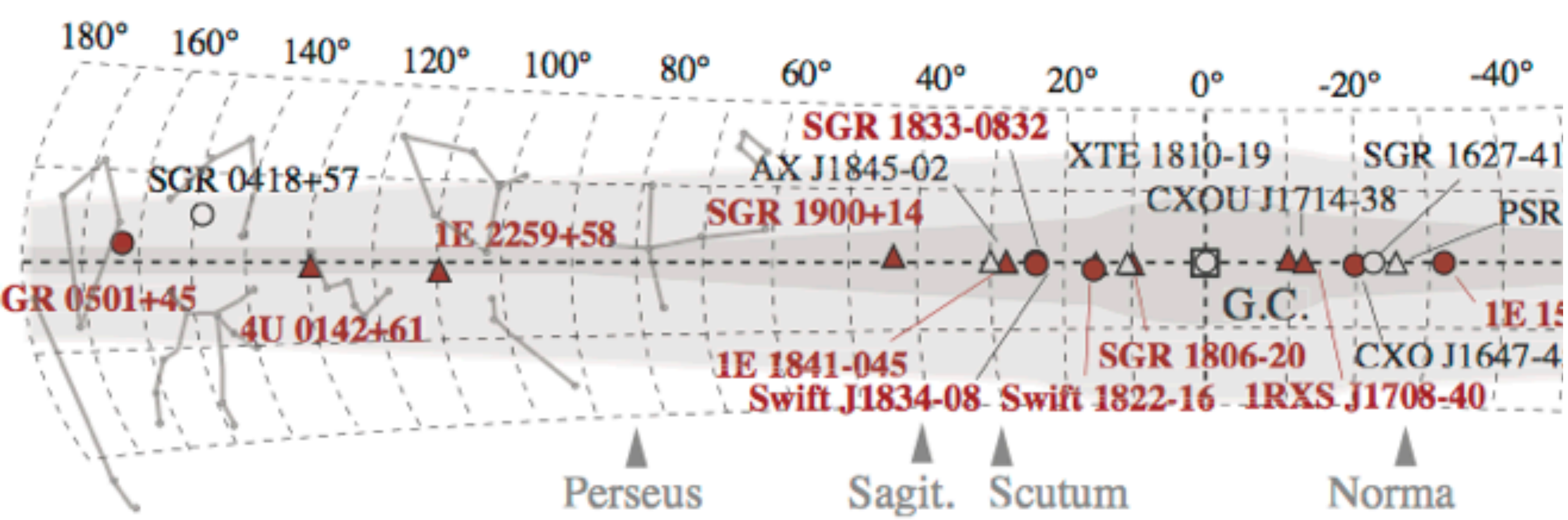
# Multi-wavelength Emissions of the Magnetar Class

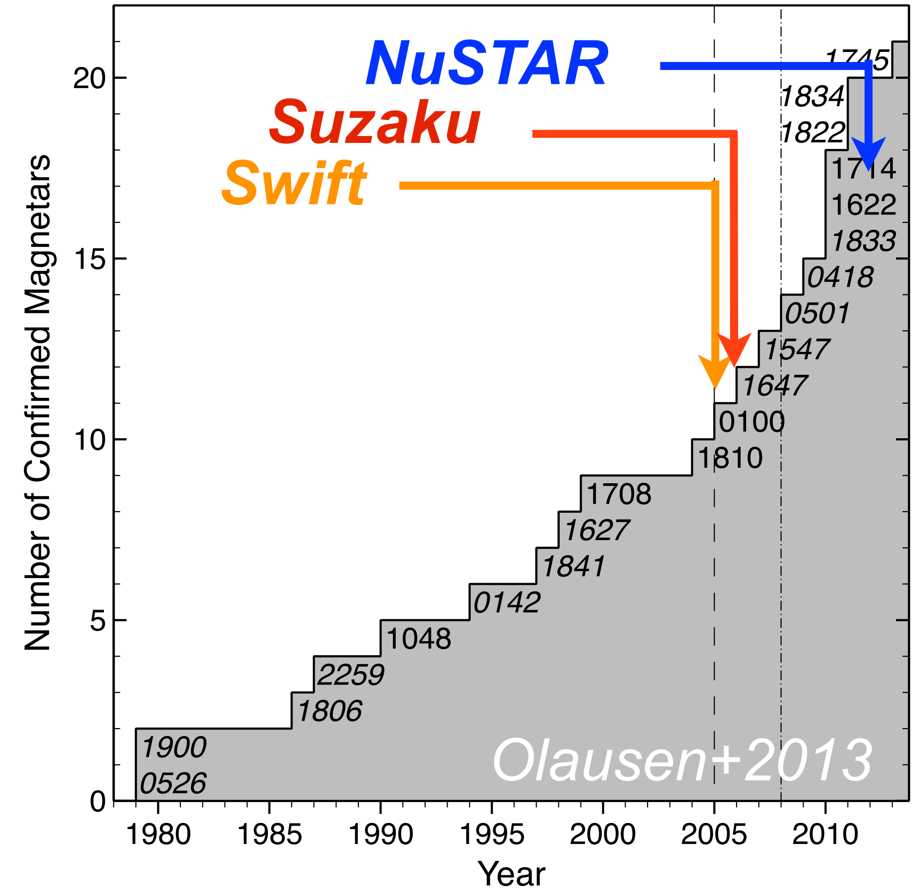


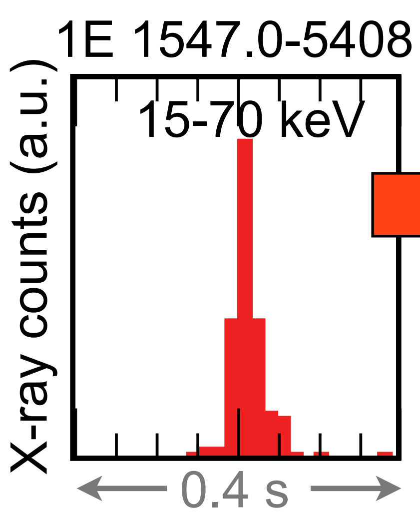
- **AXP 4U 0142+61 Persistent Emission**
  - No high-E emission >1 MeV so far (e.g., *Fermi*)
  - Radio emission is rare (only transients?)
  - Weak infrared and optical emissions
  - Soft and hard X-rays are dominant components
    - Soft-X: quasi-black body kT~0.3 keV
    - Hard-X: non-thermal Γ~1? cutoff > 750 keV?
    - Both components are highly pulsed.
- (Almost) all the magnetars exhibit the soft emission.

# Discoveries of New Magnetars



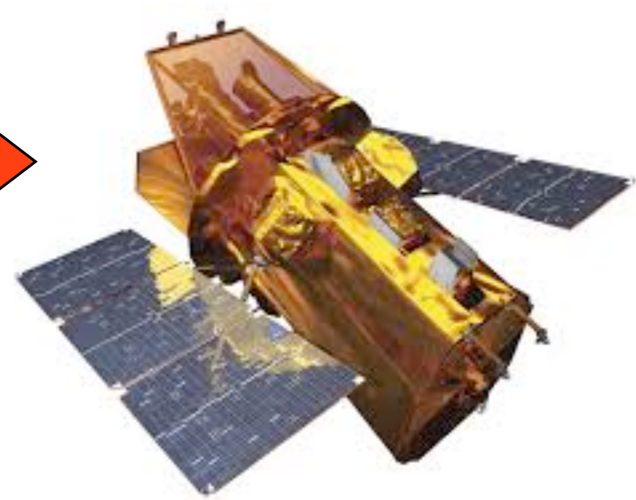




*Swift* has detected 1-2 magnetar outbursts per year increasing number of confirmed magnetars (~20).




TE+10

**Swift**

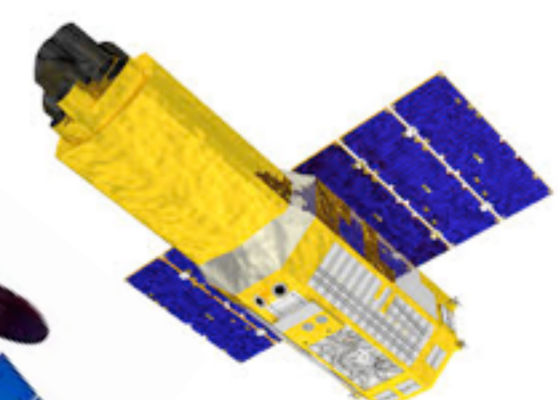


**Burst detection**
**Prompt follow-up**

**Chandra**

**Precise localization**

**Suzaku**



**Hard X-ray detection**

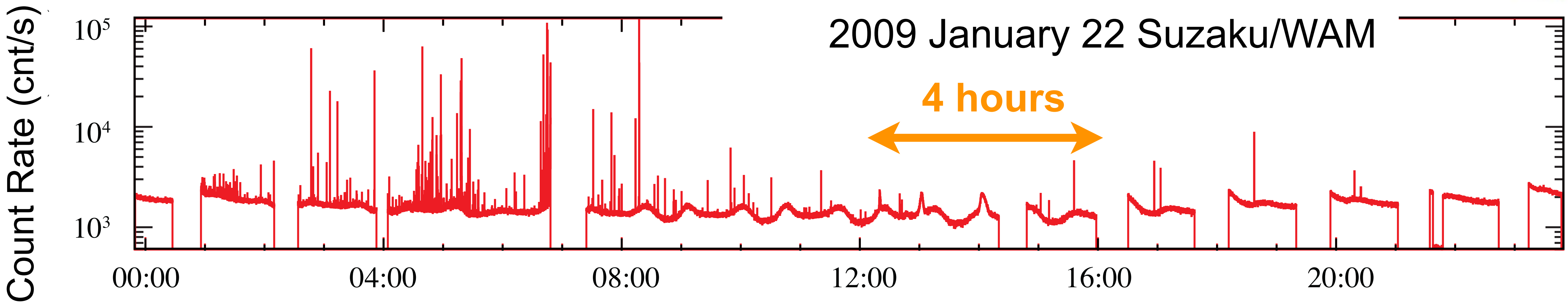
**RXTE**

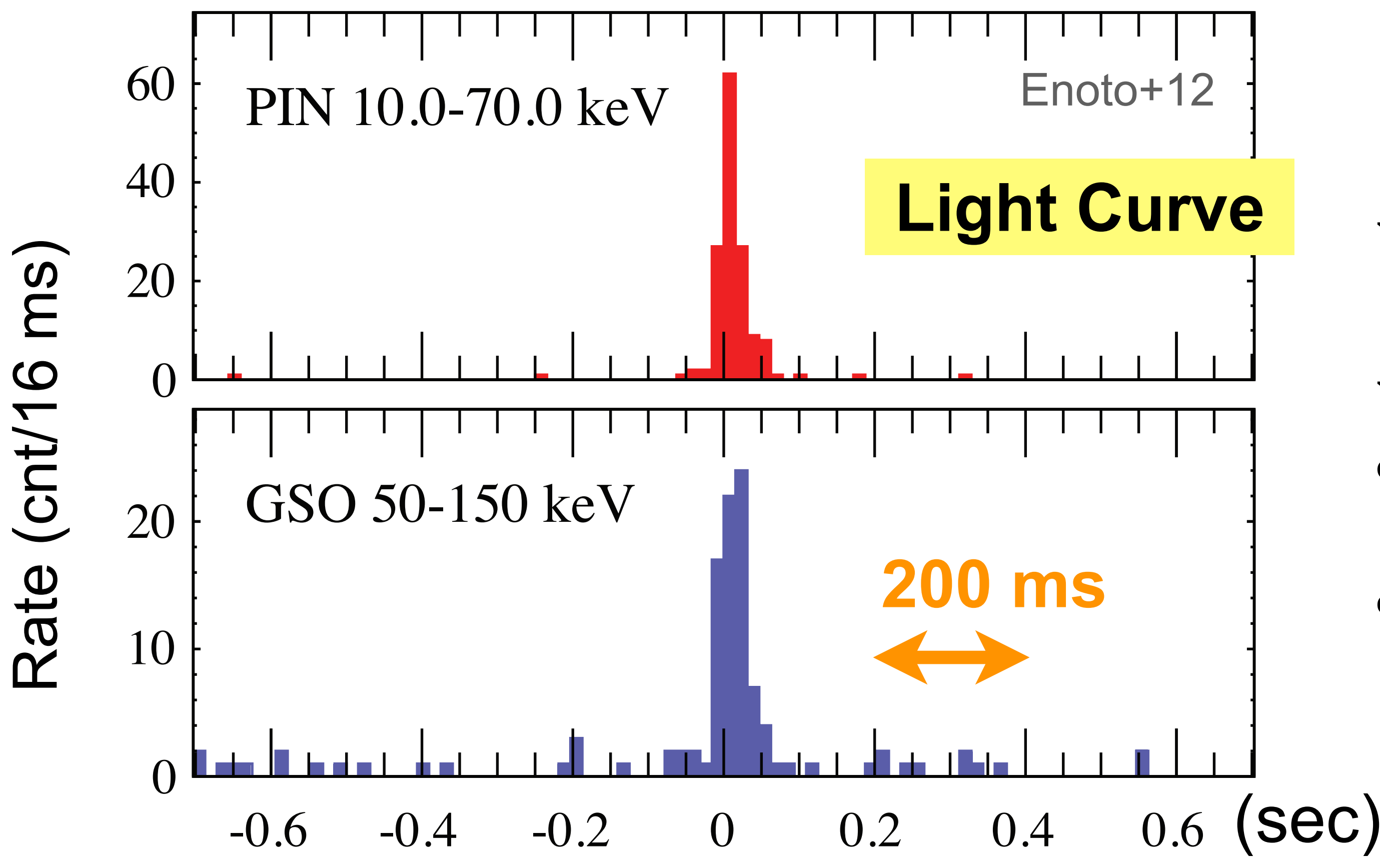
**Period measurement**

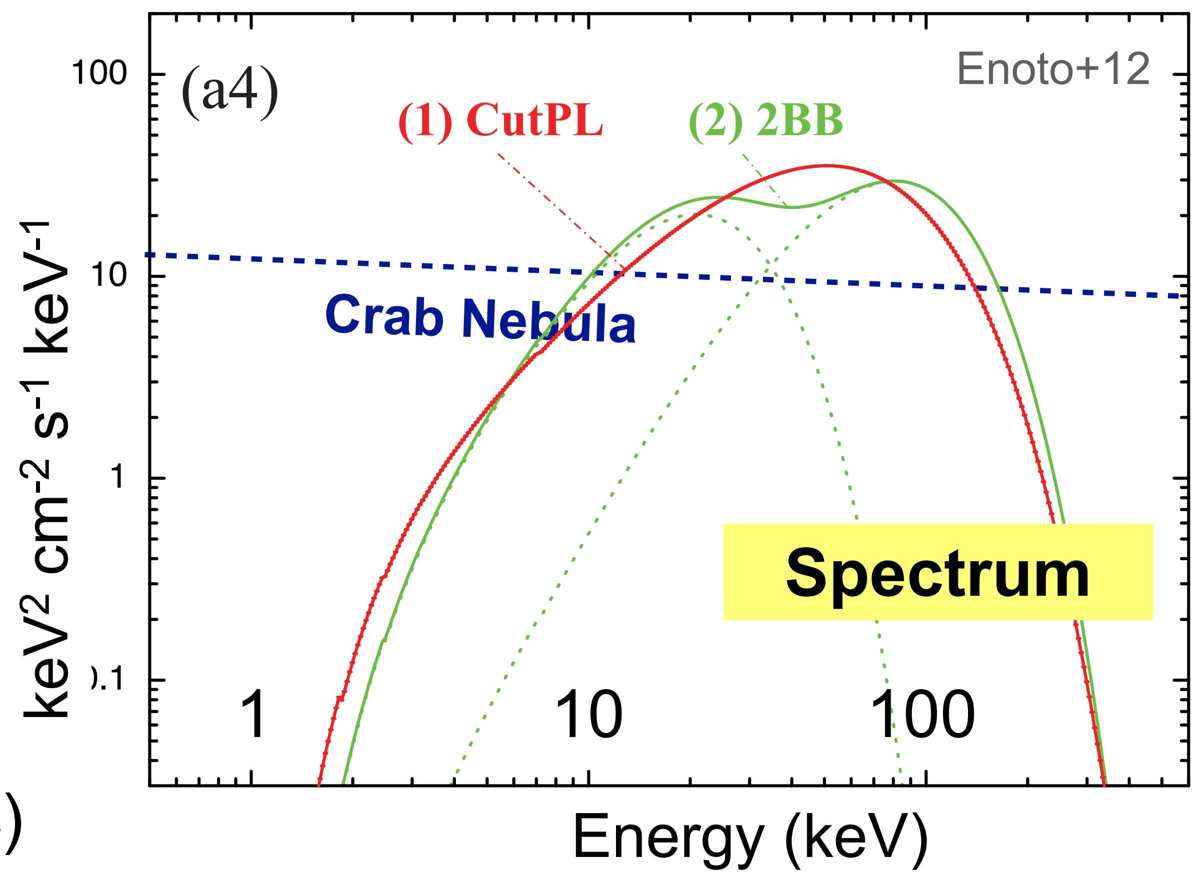
**Magnetars are a glowing new class of NS: A key to understand NS diversity.**

# X-ray Outburst of AXP 1E 1547.0-5408 (1)

Known as a fast rotation faint AXP (P~2 sec)



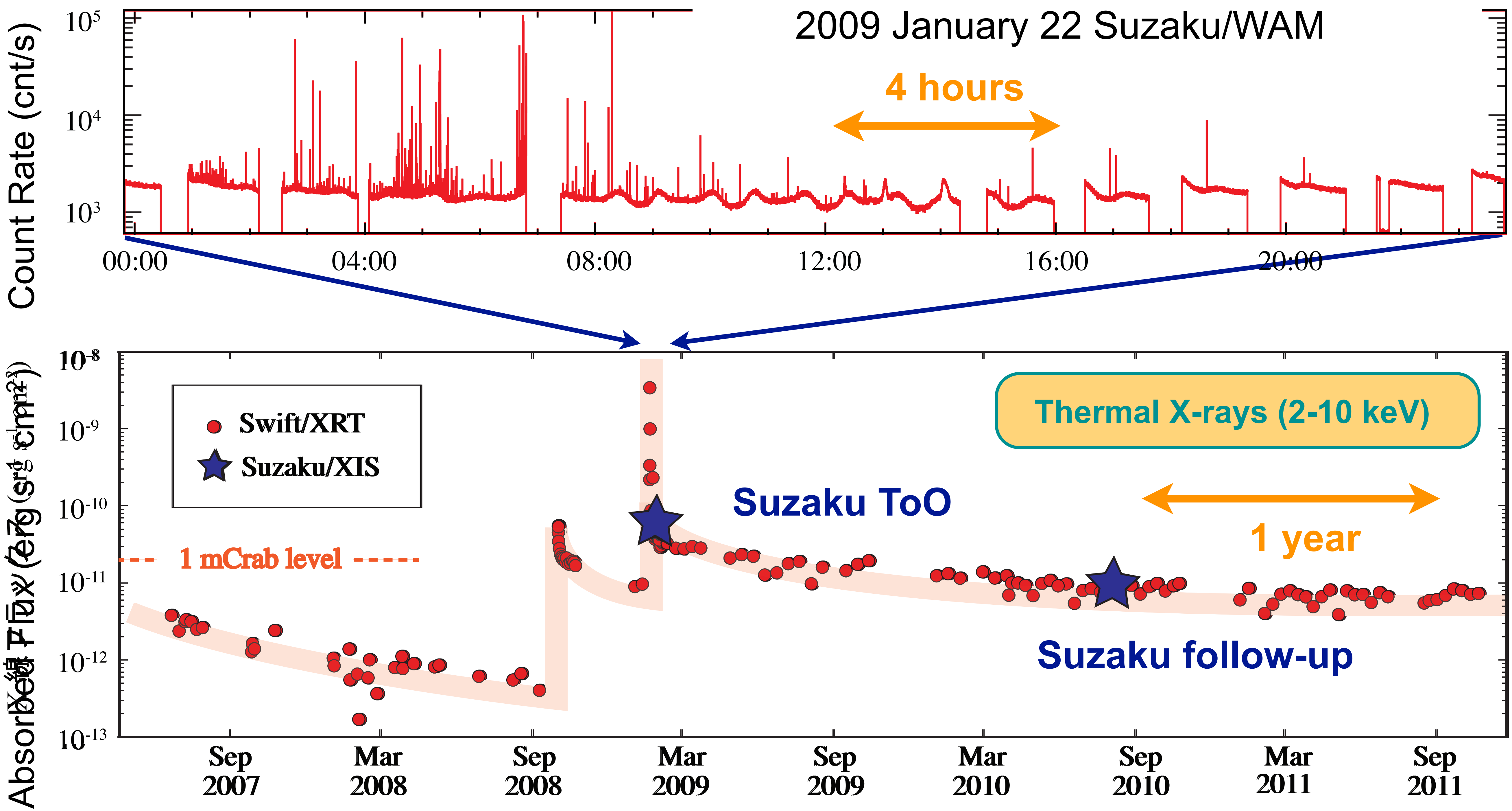




**Feature1: Recurrent Bright Short Burst**

Duration ~100-500 ms, (Empirically) Two blackbody spectrum (kT ~ 4, 11 keV)

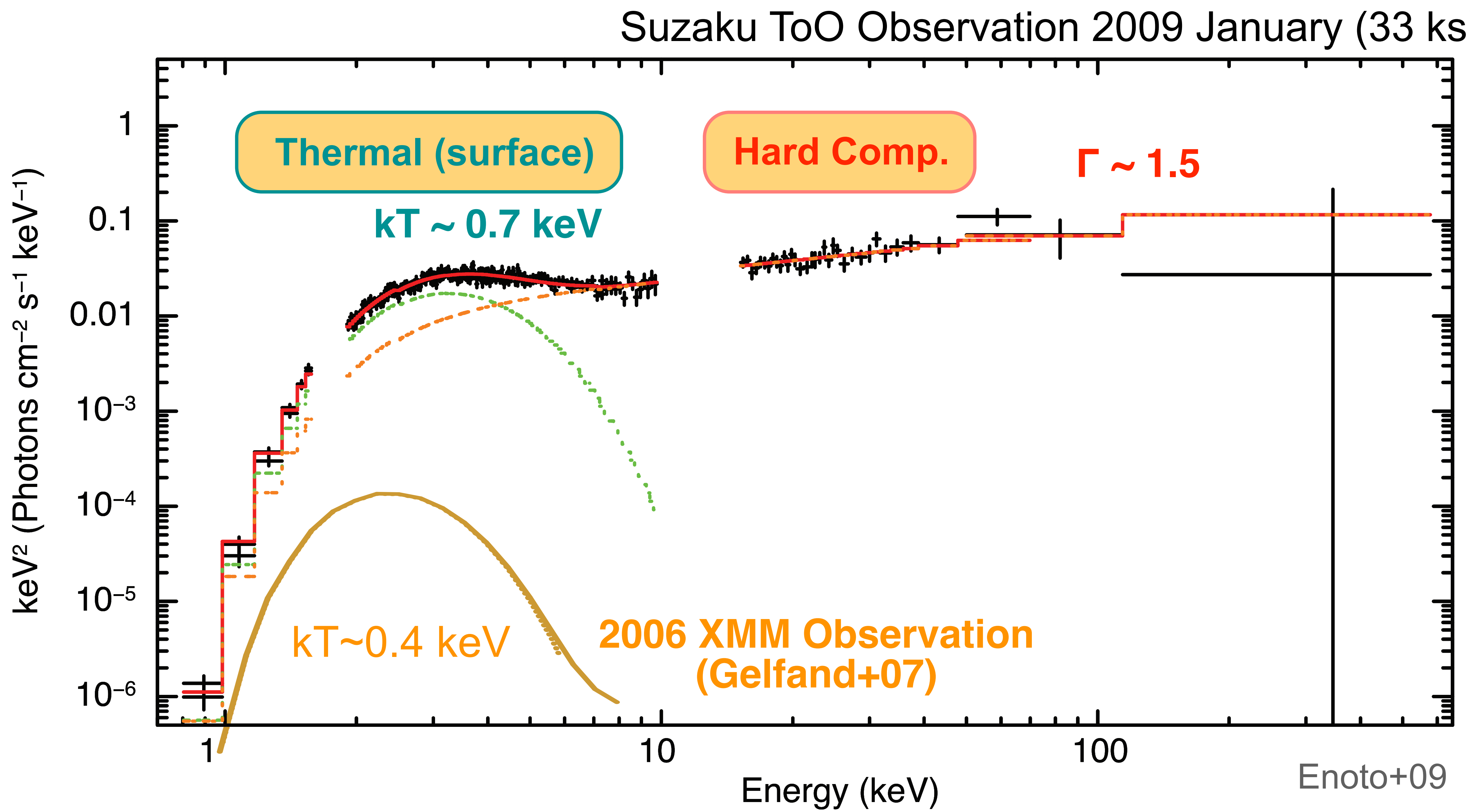
# X-ray Outburst of AXP 1E 1547.0-5408 (2)

Known as a fast rotation faint AXP (P~2 sec)




**Feature2: Persistent X-ray becomes brighterby 2-3 orders of magnitude.**

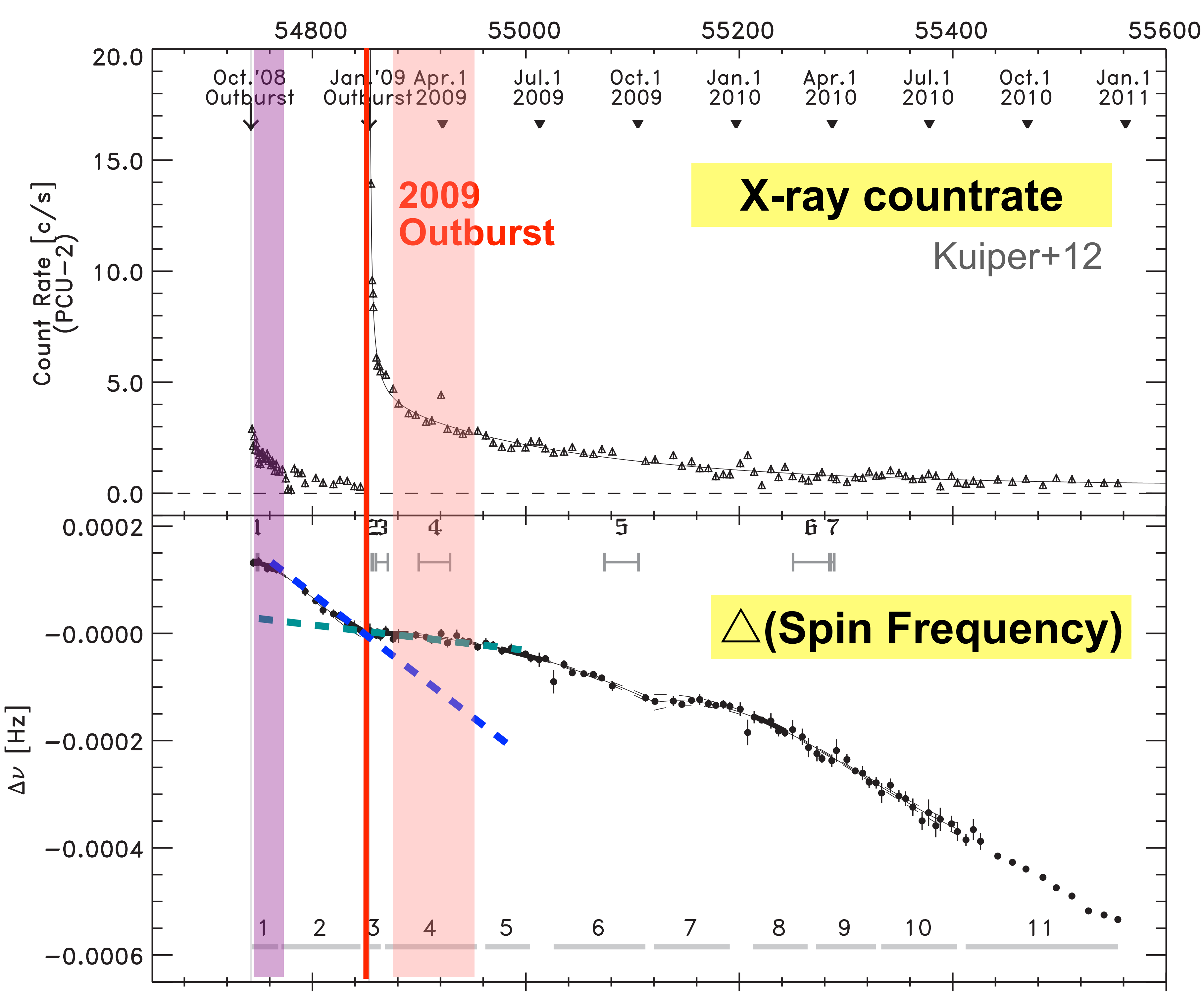
# X-ray Outburst of AXP 1E 1547.0-5408 (3)

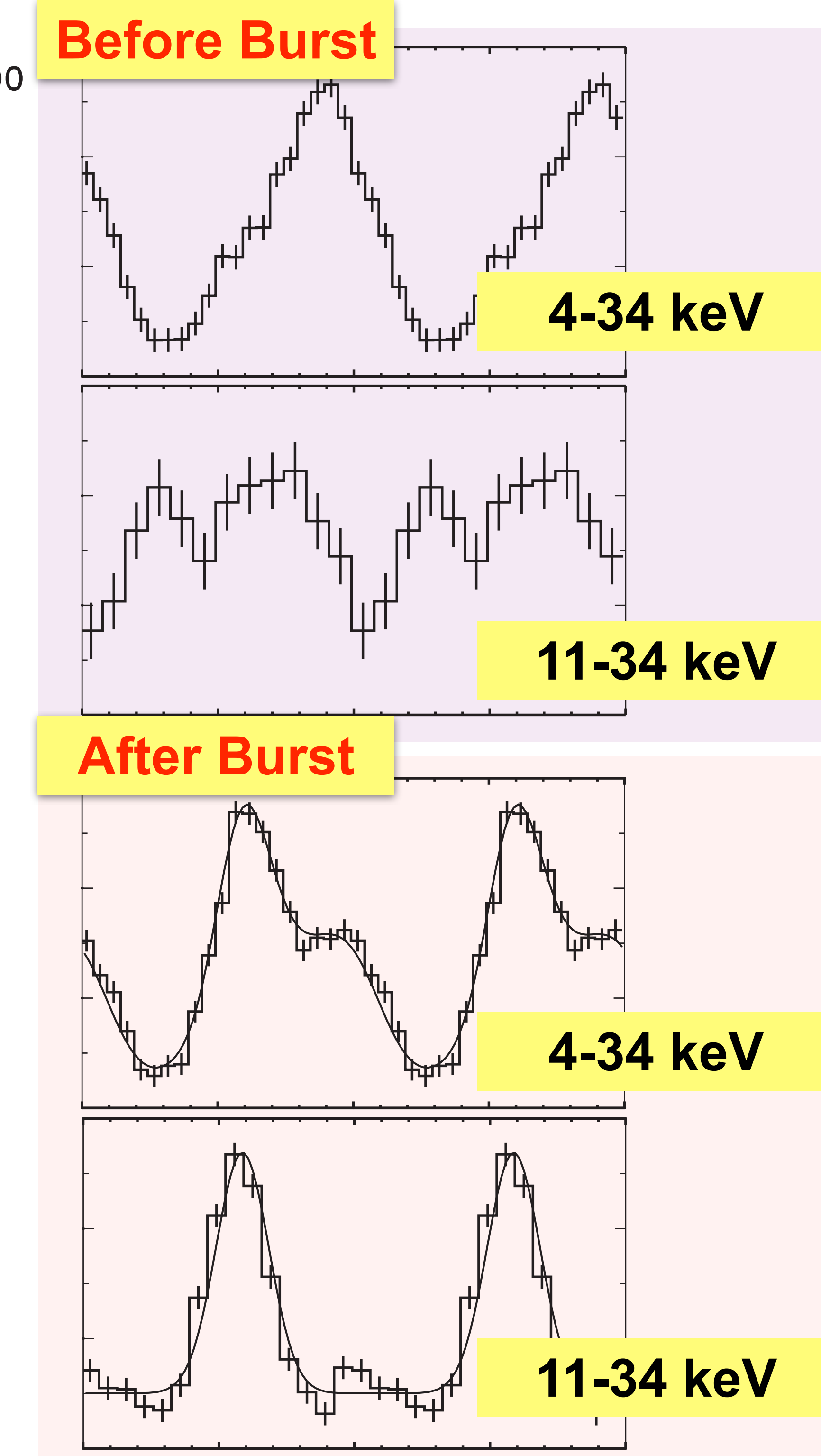



Hard X-rays were clearly discovered during the magnetar outburst.
Follow-up observation confirmed the hard component one year after the outburst.

**Feature2: Persistent X-ray becomes brighter by 2-3 orders of magnitude**
Both components (soft thermal + hard X-rays) become brighter

# X-ray Outburst of AXP 1E 1547.0-5408 (4)

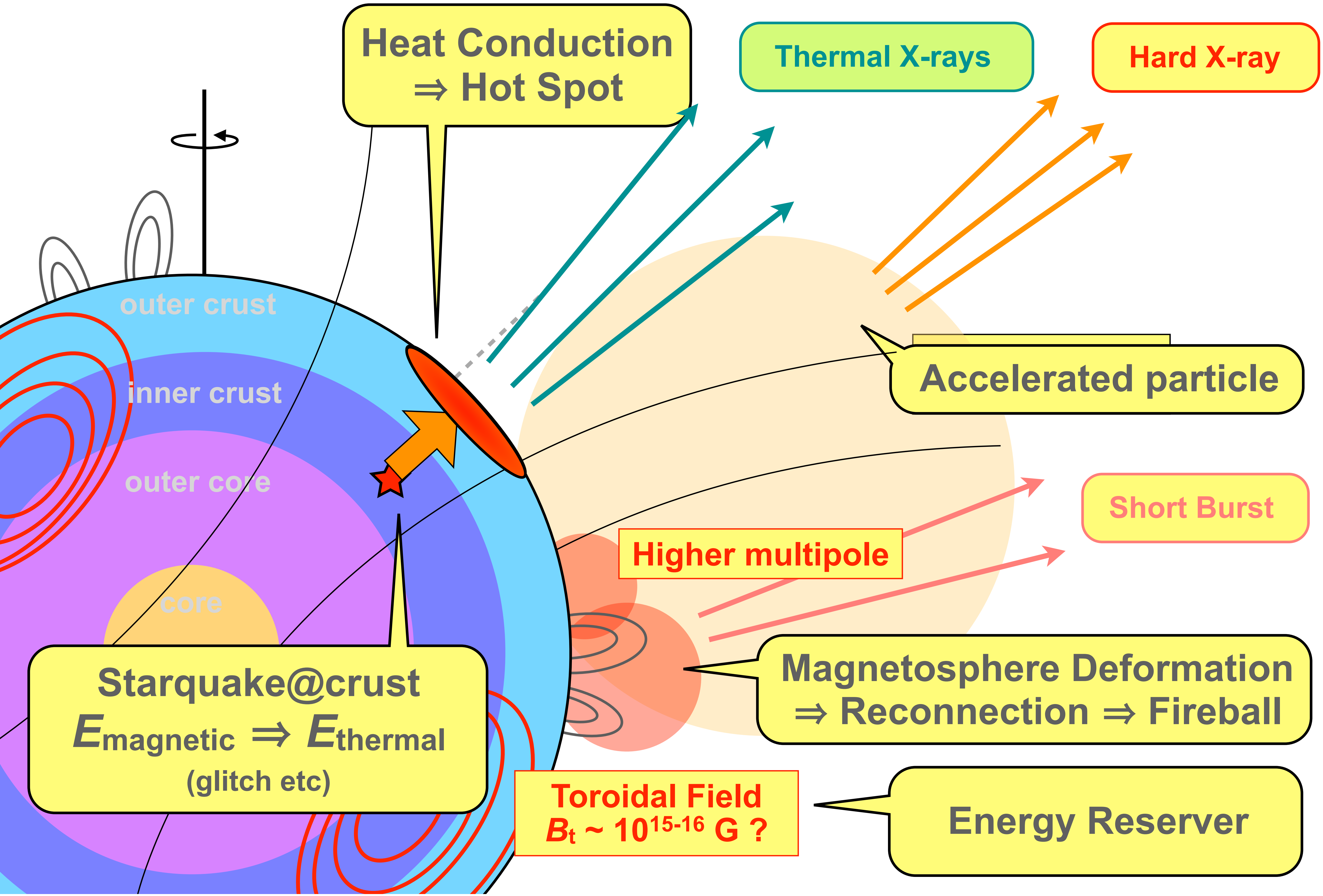


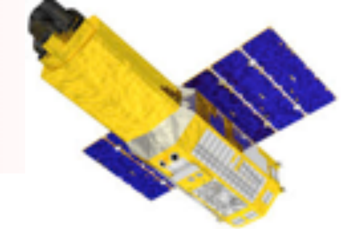

**Feature3:** **A frequency derivative jump at the outburst (** $\triangle\dot{\nu}/\nu = -0.69 \pm 0.07$ **)**

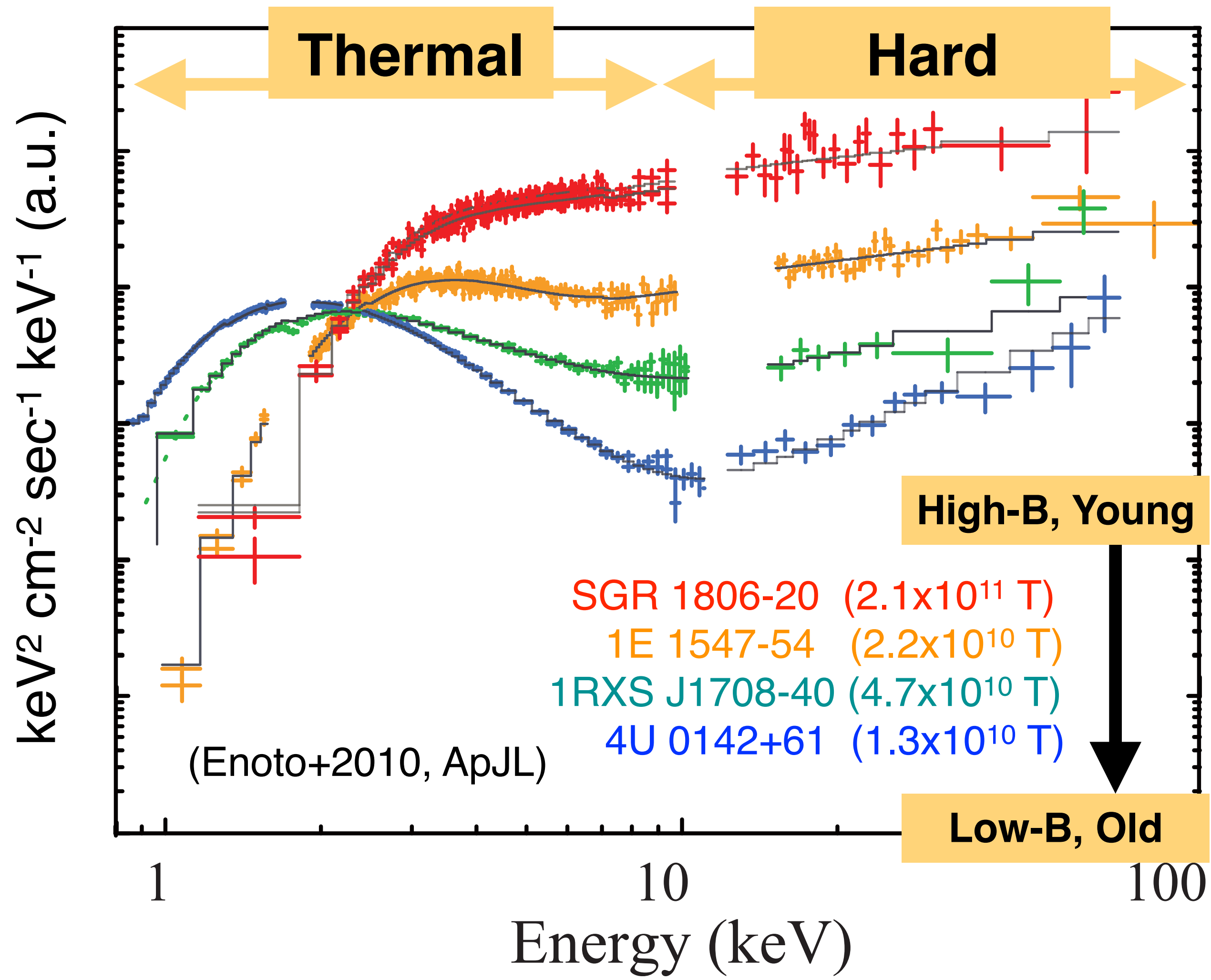
Pulse profile change around the onset of the burst ⇒ Hot spot?

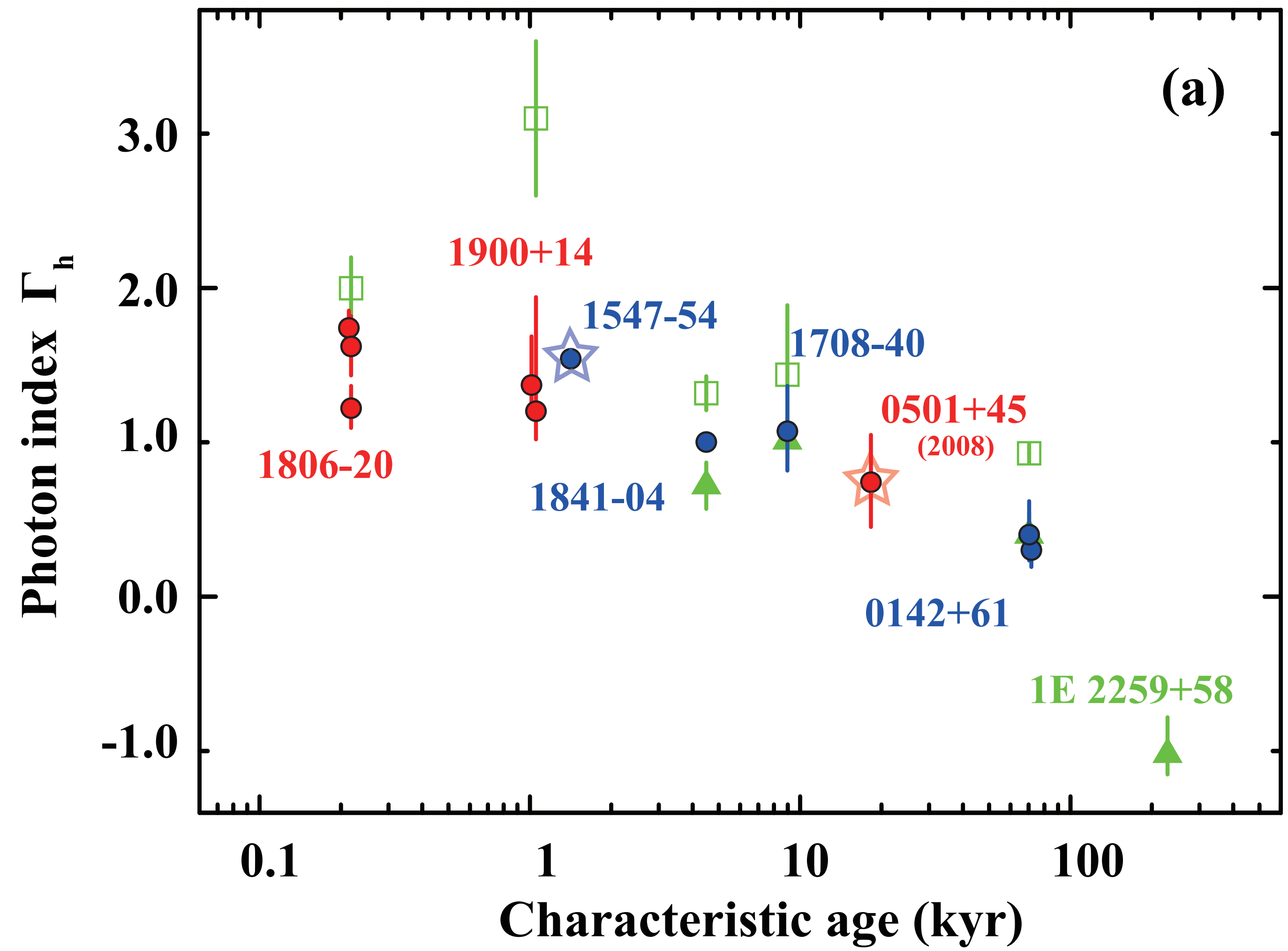
# Magnetar Outbursts



# Surface and Magnetospheric Emission






Magnetospheric hard X-rays were detected from 7 sources (+1 candidate).

- Ratio of soft and hard X-ray luminosities ($\xi = L_h / L_s$) is found to be positively correlated with *B*-field by period *P* and its derivative $P_{dot}$.
- Photon index of hard X-rays becomes harder toward low *B*-field old sources.

Spectral **EVOLUTION** as a function of ***B*-field**.

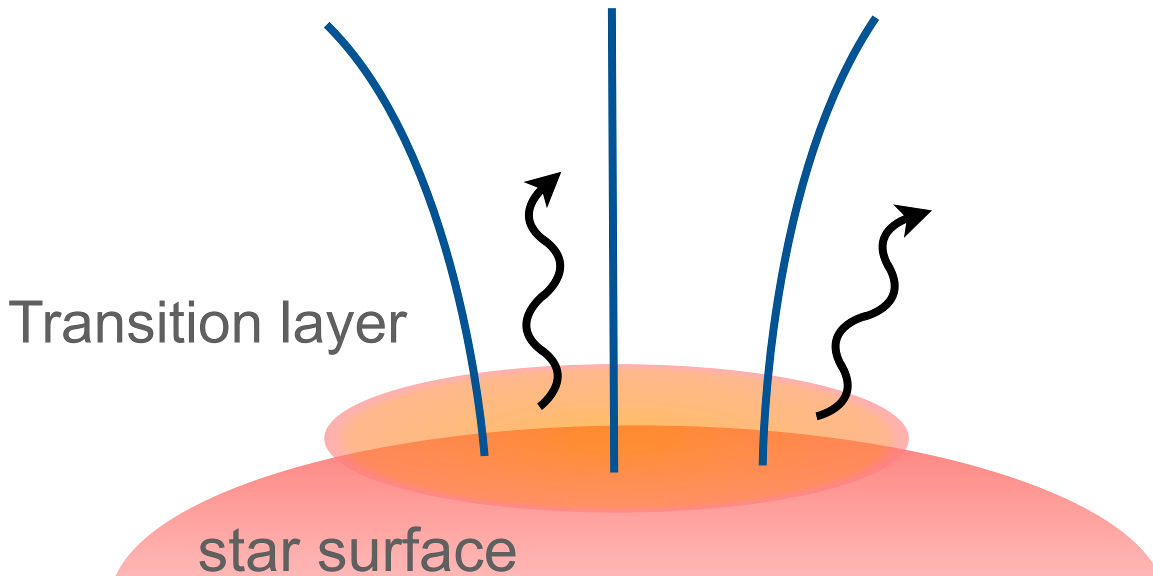
(*e.g., photon-splitting down-cascade in the QED field magnetosphere?*)

*TE et al., ApJL, 2010*

# Hard X-ray emission mechanism

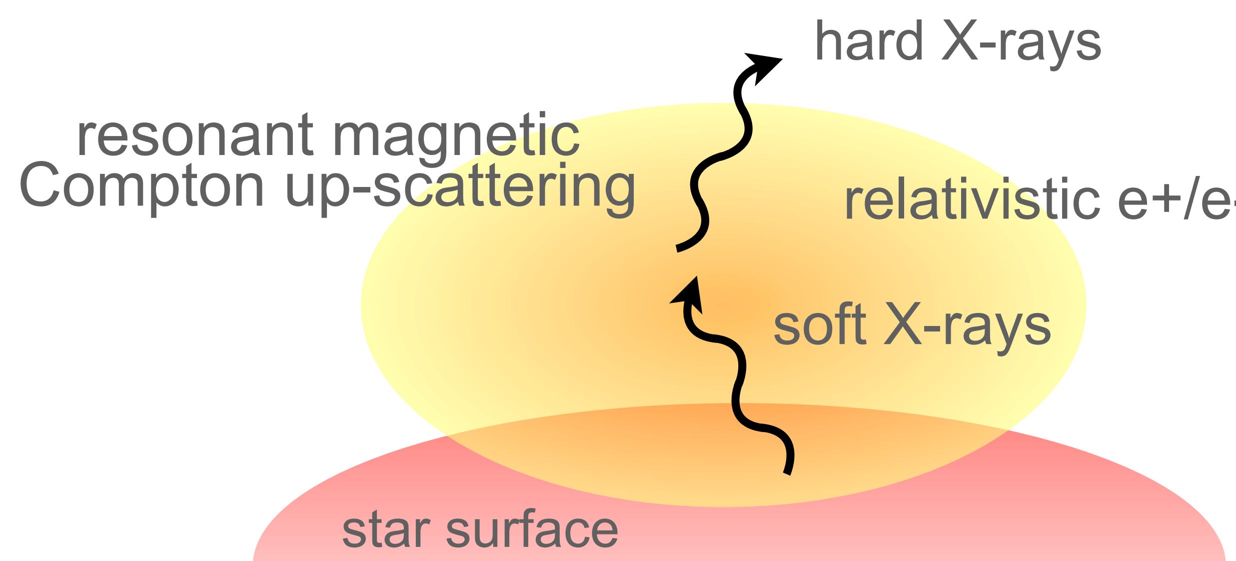
## Thermal Bremsstrahlung ?

(Thompson & Beloborodov 05)



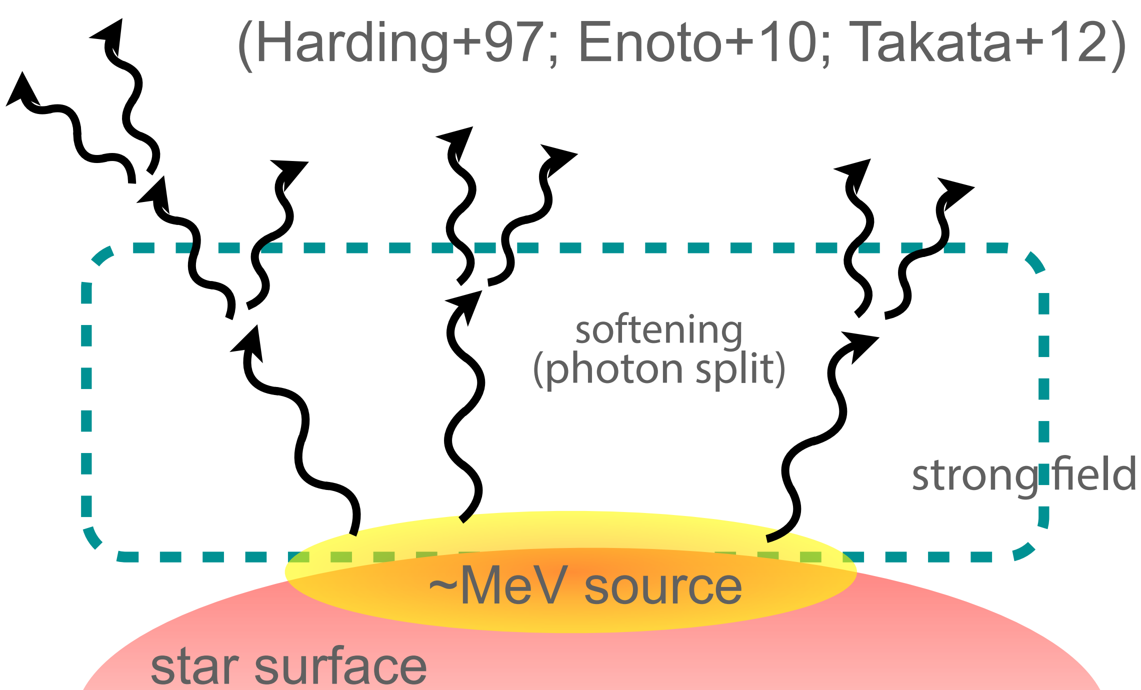

## Resonant Compton up-scattering?

(Baring & Harding 07)




## Photon Splitting Effect?

(Harding+97; Enoto+10; Takata+12)

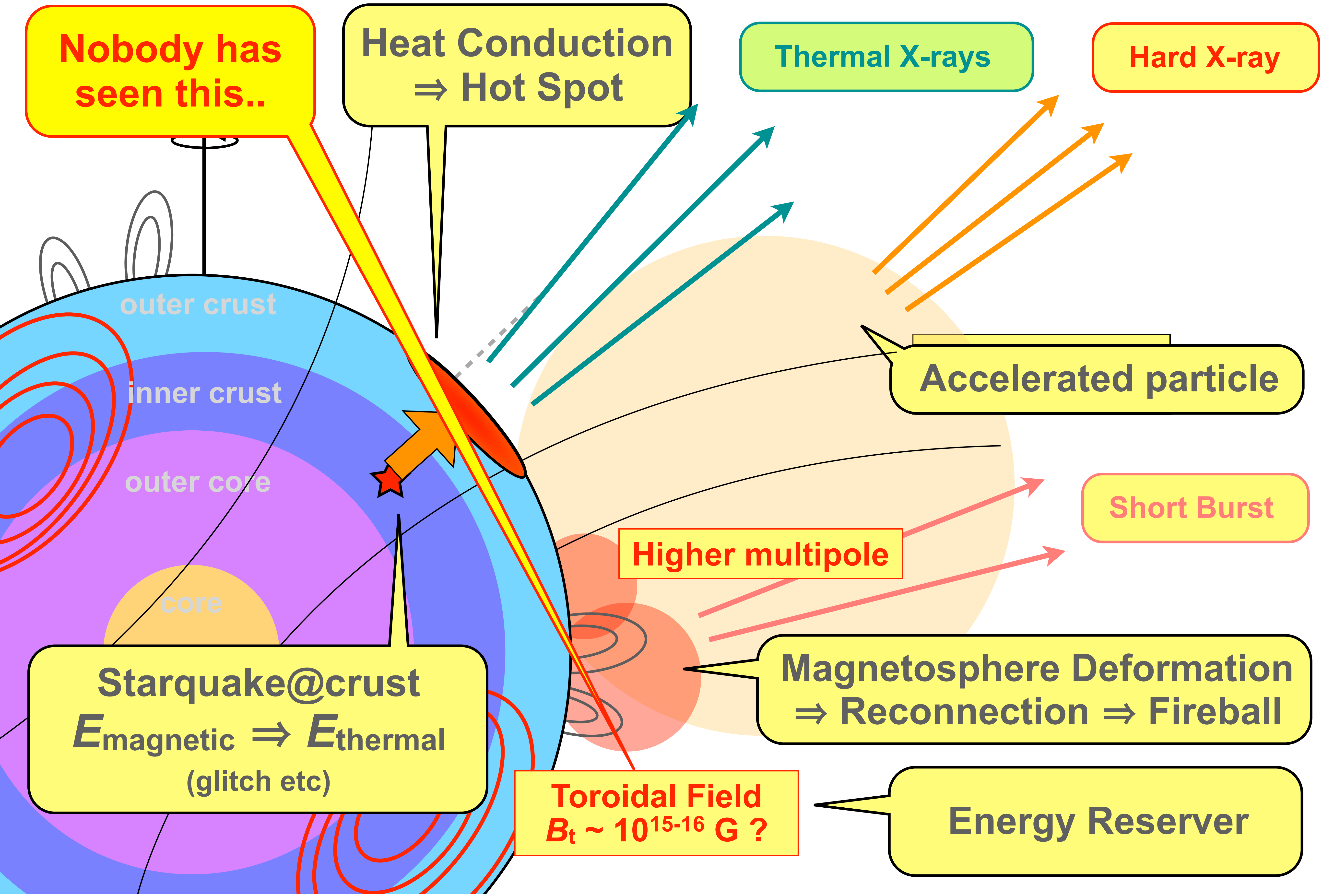



**No model has not yet explained the observed properties of magnetars.**

**Observational & theoretical progress is strongly required.**

And also other models;
Heyl & Hernquist 2007
Trumper+2010
Kuiper+2006

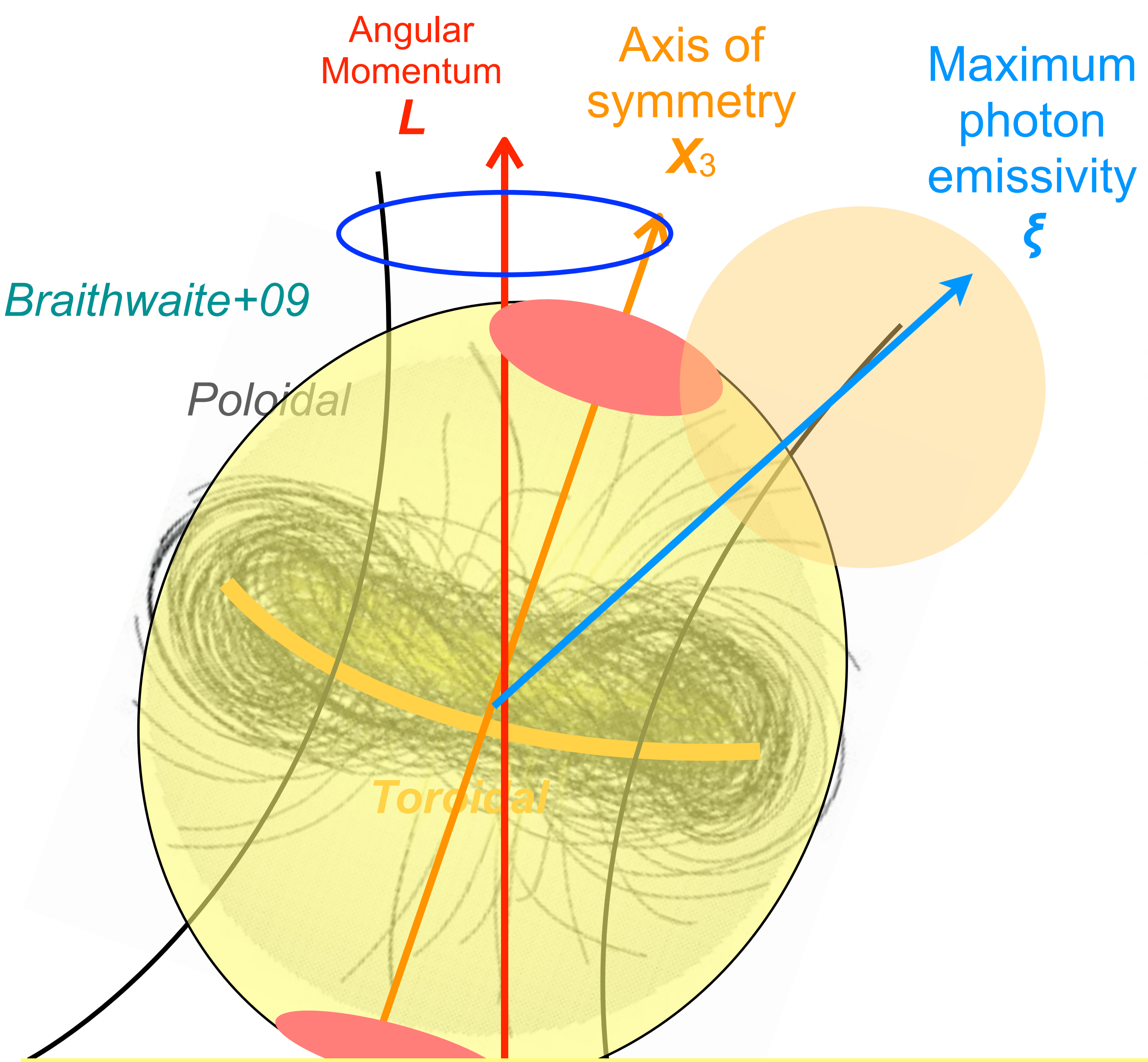
# Magnetar Outbursts

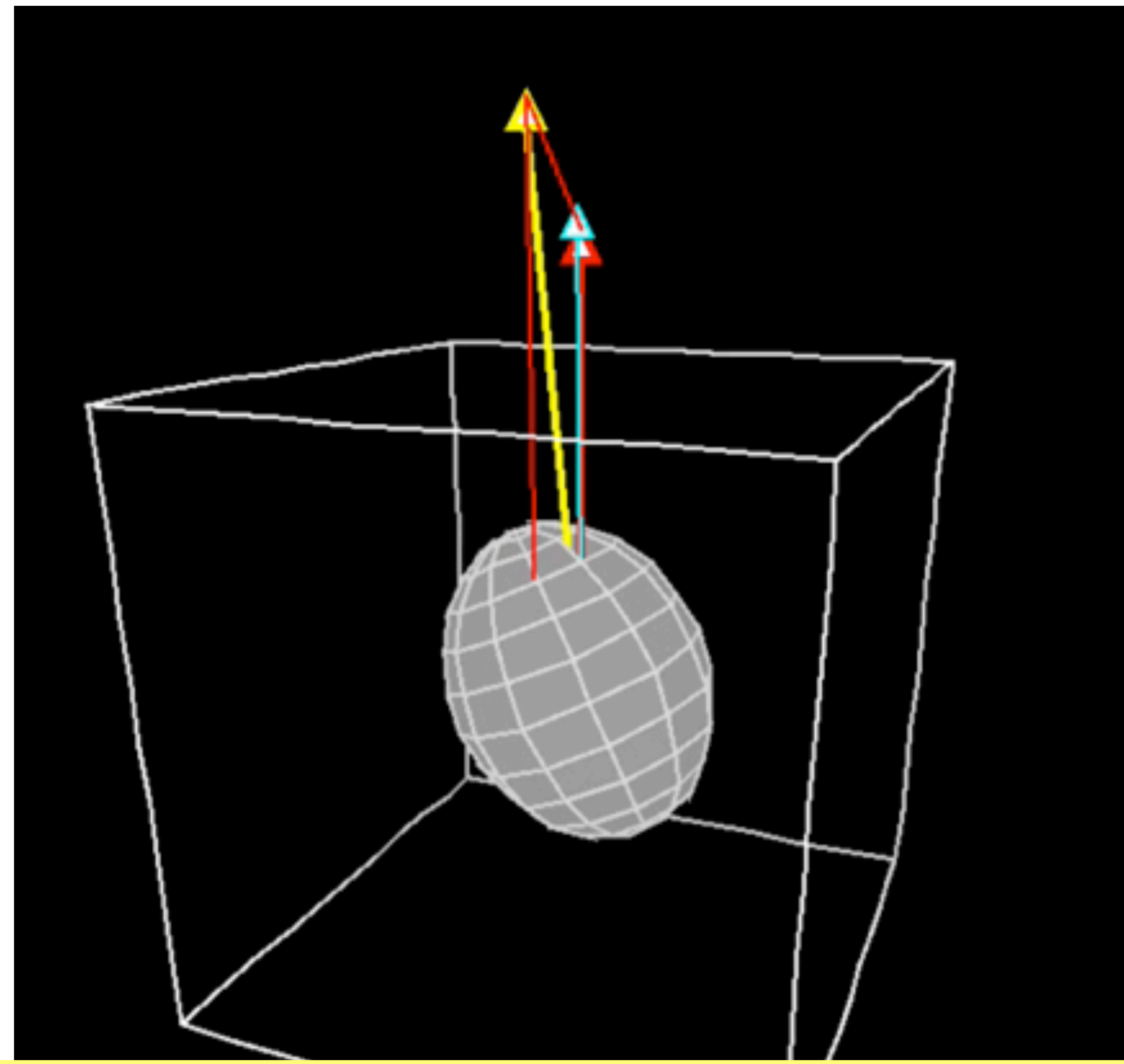


# Toroidal Magnetic Field

**Huge energy reserver is needed inside the magnetars**

**⇒ Strong toroidal Field inside NSs? (can not be measured by *P*-$P_{dot}$)**



**Free Precession with period *Q***

**Toroidal B-field ⇒ Prolate shape**

$$\epsilon = \frac{\Delta I}{I} \sim 10^{-4} \left( \frac{B_t}{10^{16}\,\mathrm{G}} \right)^2$$

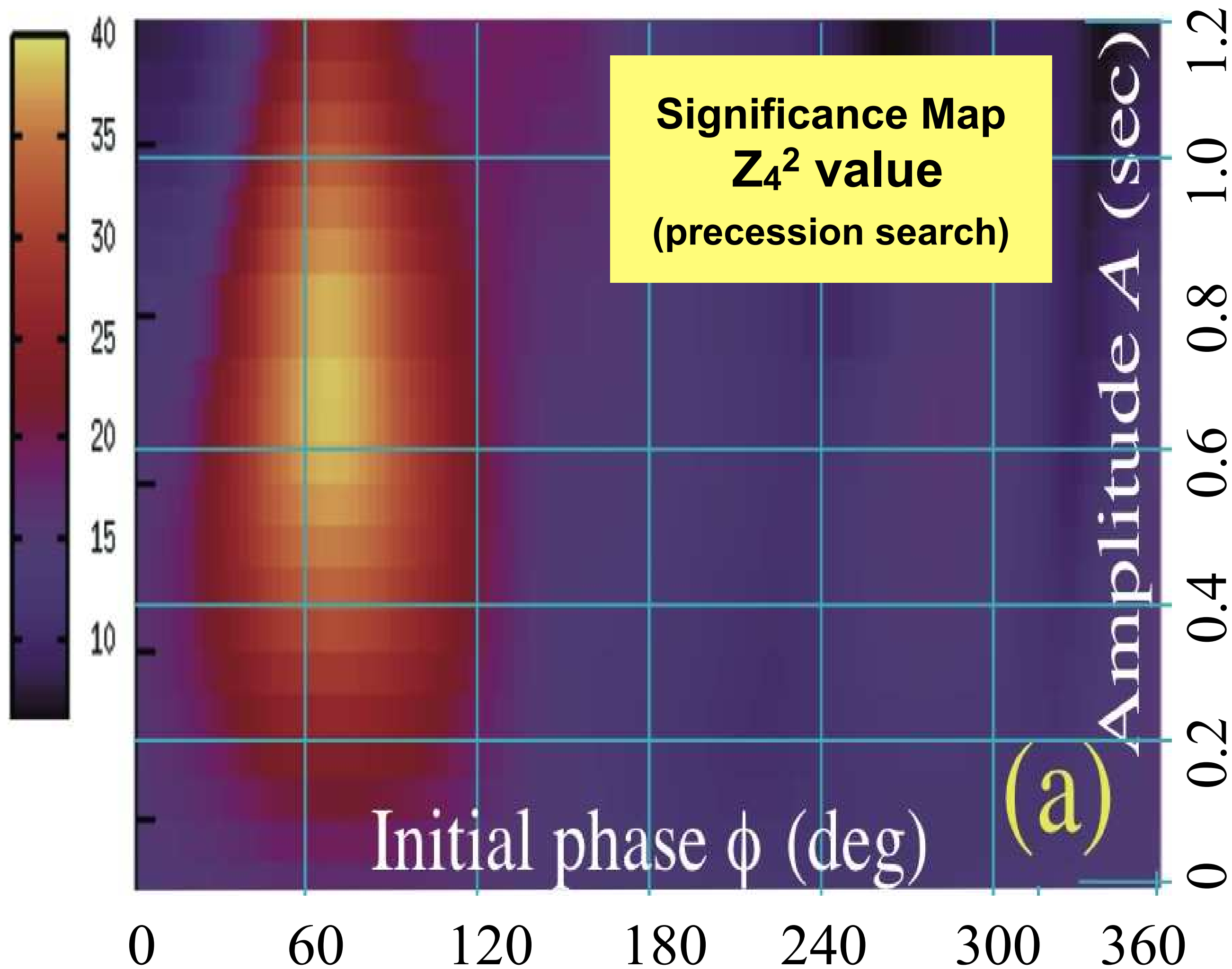
$X_3 \neq \xi$

$$Q = \frac{P_{\mathrm{spin}}}{\epsilon}$$

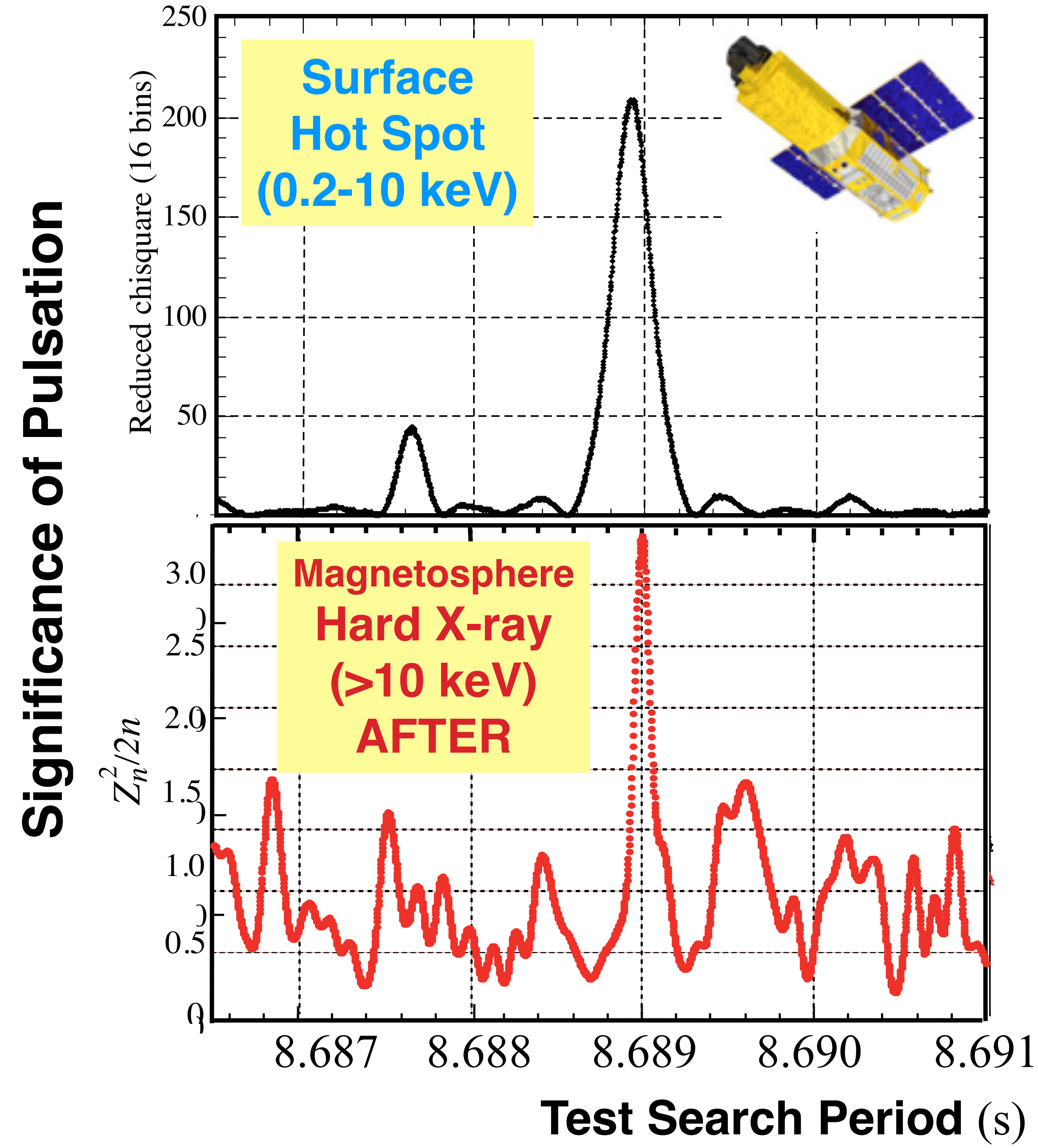
(see., e.g., Landau & Lifshitz textbook)

# Evidence for Precession

Prototypical AXP 4U 0142+61 ($P$=8.69 s, Poloidal field $B_d$~1.3x$10^{14}$ G)




Hard X-ray shows a sinusoidal, $T$=1.5 hour, phase modulation (amplitude 0.7 s)



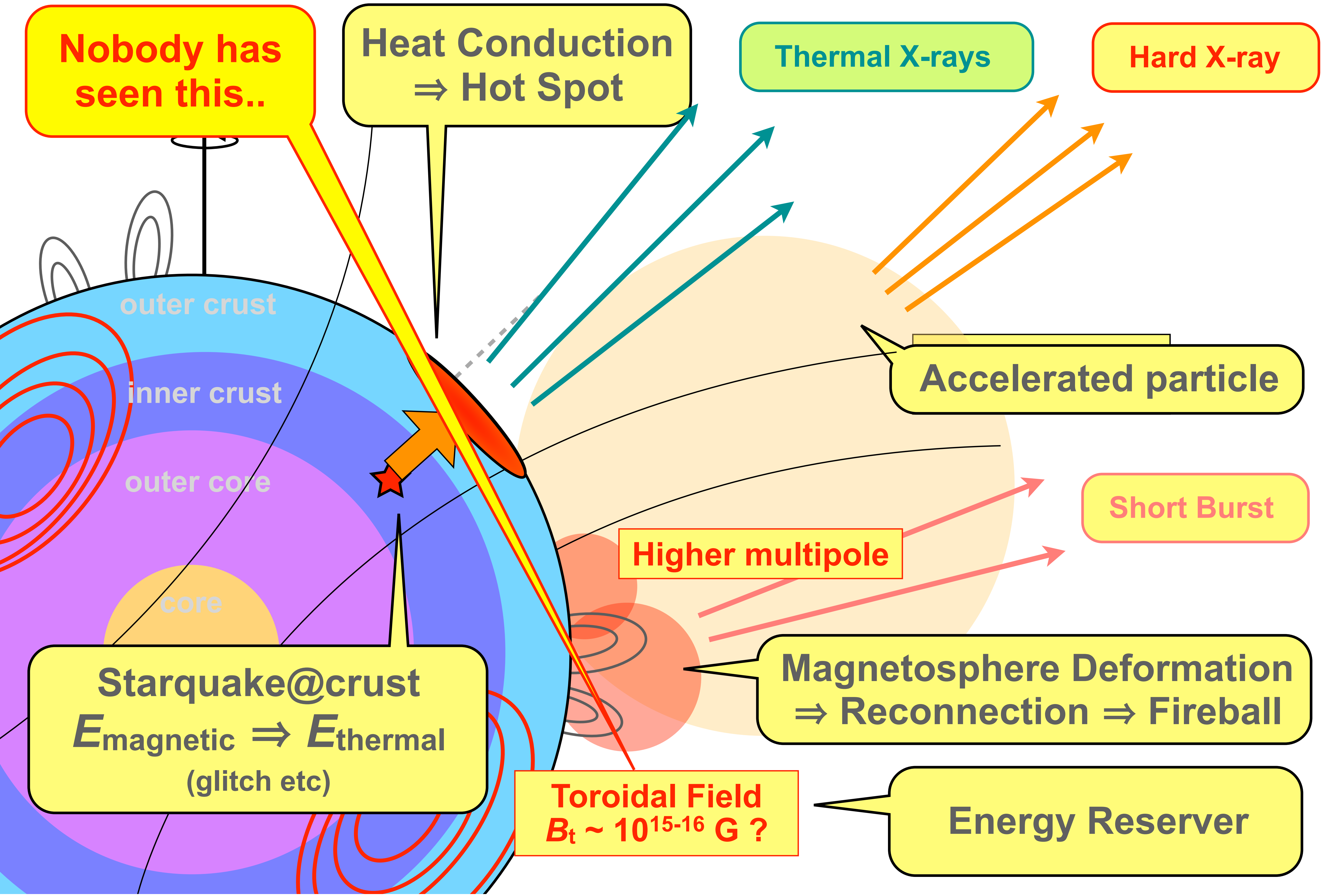

*Makishima, TE et al., PRL, 2014*

$$\epsilon \sim \frac{8.69\,\mathrm{s}}{1.5\,\mathrm{h}} \sim 1.6 \times 10^{-4}$$

→ Toroidal $B$-field $B_t$ ~ $10^{16}$ G

$$\epsilon \sim 10^{-4}(B/10^{16}\,\mathrm{G})^2$$

# Magnetar Outbursts



# Hot spots heated by the internal *B*-field?

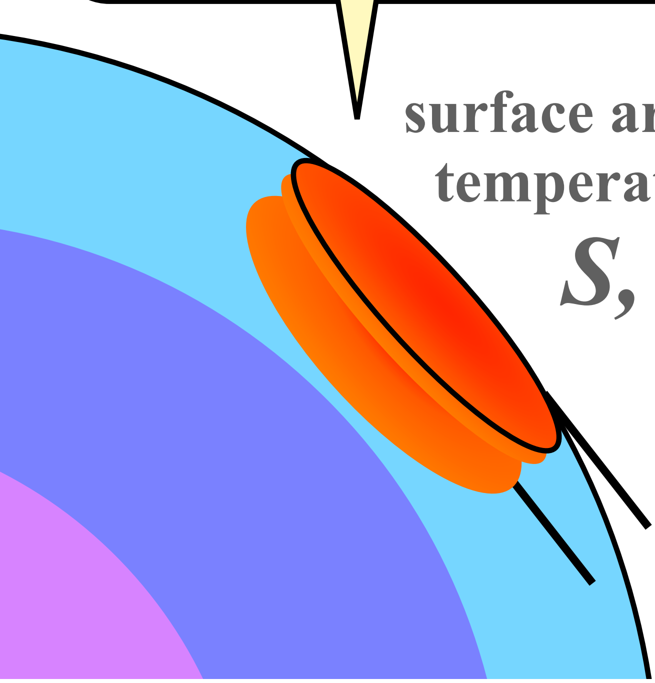
**$E_{magnetic} \Rightarrow E_{thermal}$**

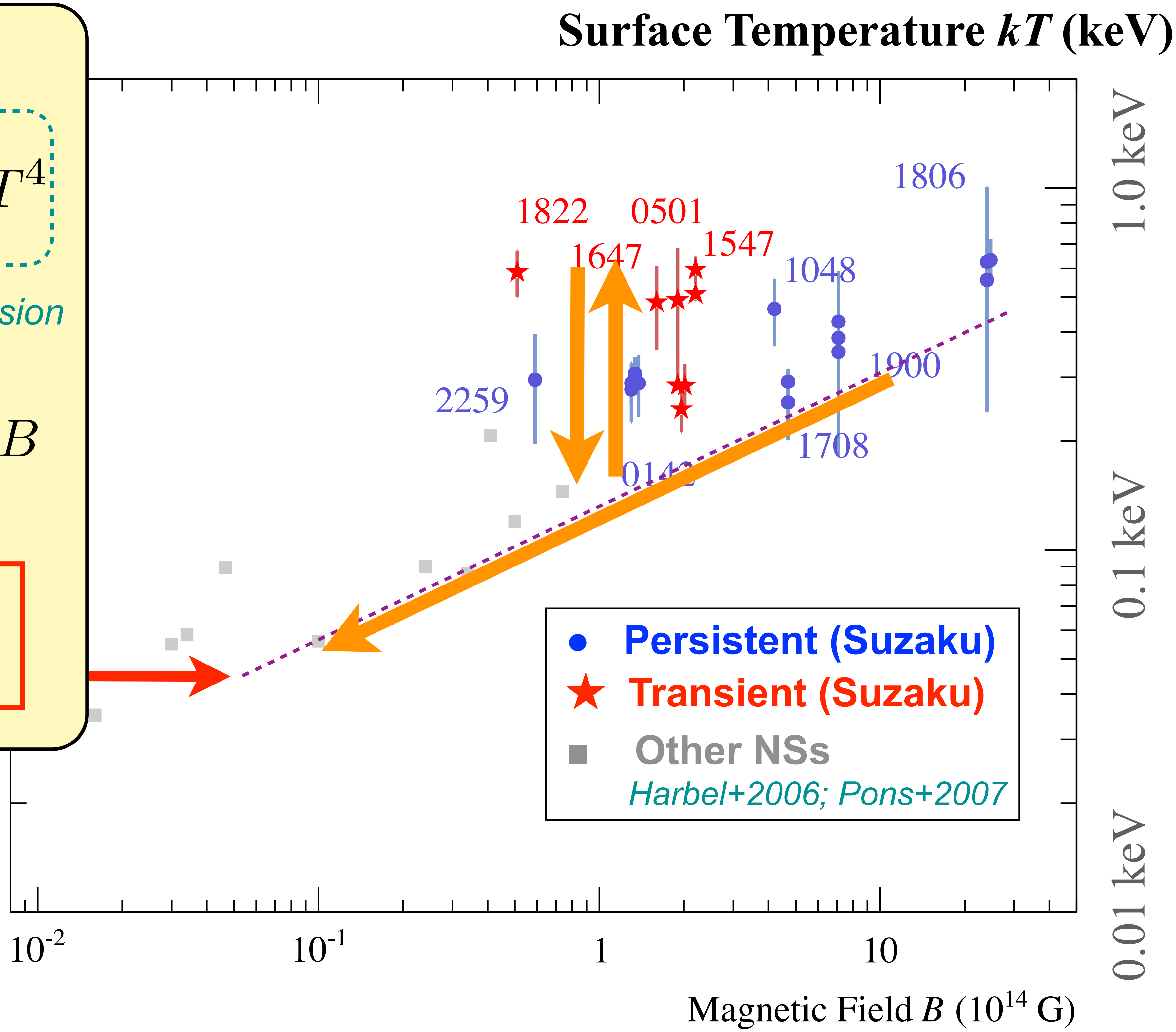
$$S \triangle R \frac{d}{dt}\left(\frac{B^2}{8\pi}\right) = S\sigma T^4$$

volume — *B-field dissipation* — *emission*

**Field decay:** $\frac{dB}{dt} = -aB$

$$kT \sim B^{+0.5}$$

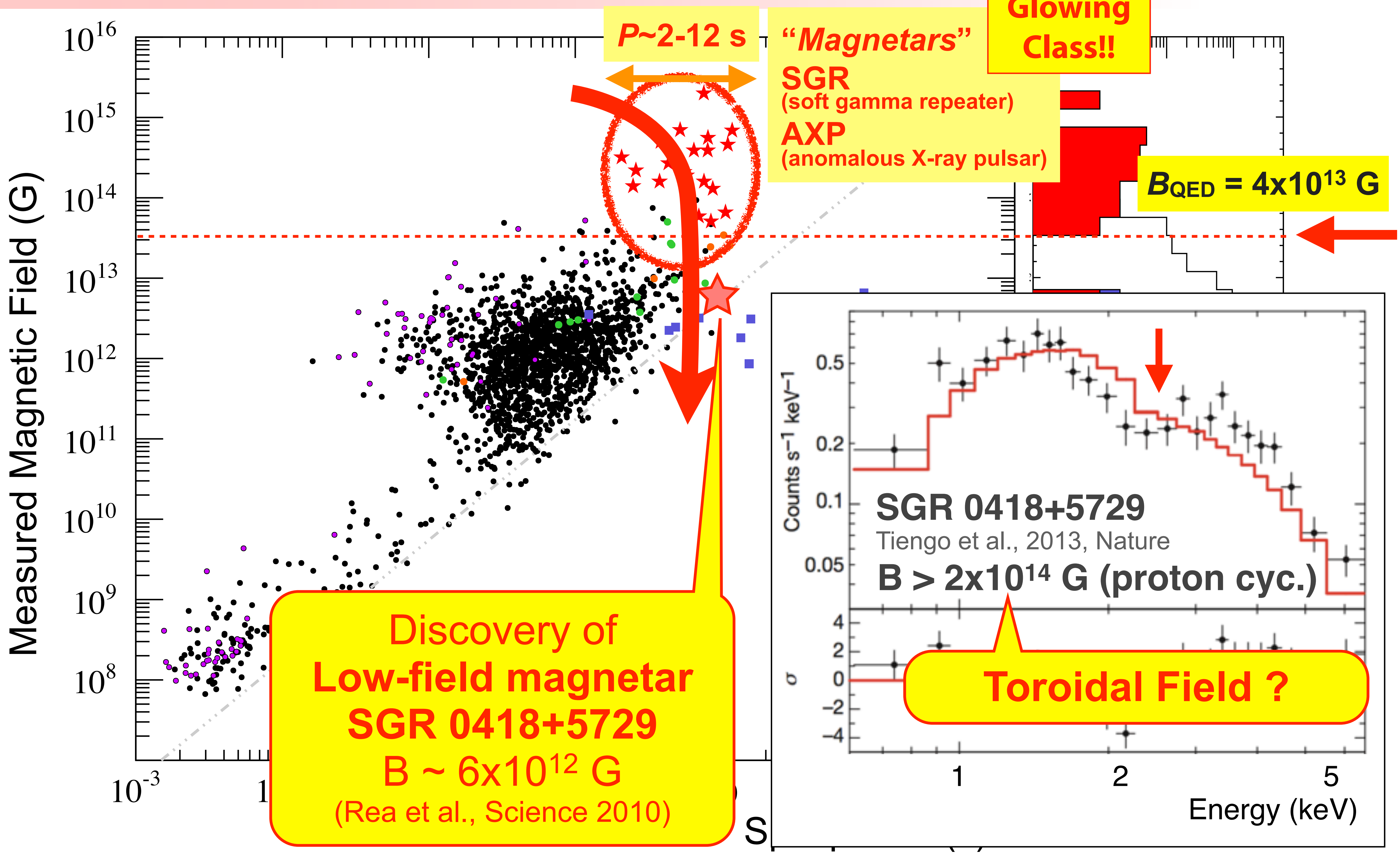



**One support for the magnetic energy dissipation**

*Enoto+in prep*

# Discoveries of Low-Field Magnetars




**Population of hidden magnetars is larger than previously expected?**

# Summary

- **Magnetic field (B~$10^{8\text{-}15}$ G) is one of origins of the NS diversity.**
  **B~$10^{8\text{-}15}$ G に及ぶ磁場が中性子星の多様性を作り出すひとつの要因である。**

- **There is growing evidence that some compact objects are powered by the stored huge magnetic energy with *B*~$10^{14\text{-}15}$ G.**
  **$10^{14\text{-}15}$ Gを超える磁場をエネルギー源とする星の存在が確立しつつある。**

  *Examples:*
  - Evolution of surface & magnetospheric radiation (Enoto et al., ApJL 2010)
  - Toroidal field indicated by NS free precession (Makishima et al., PRL 2014)
  - Low-field magnetars with a cyclotron feature (Tiengo et al., Nature, 2013)

- **Complementary two X-ray observatories will be launched soon**
  **相補的な２つのＸ線観測ミッションが 2015, 2016年に打ち上げられる。**
  - 2015: ASTRO-H, High resolution spectroscopy + wide-band
  - 2016: NICER, Large effective area + high time resolution.