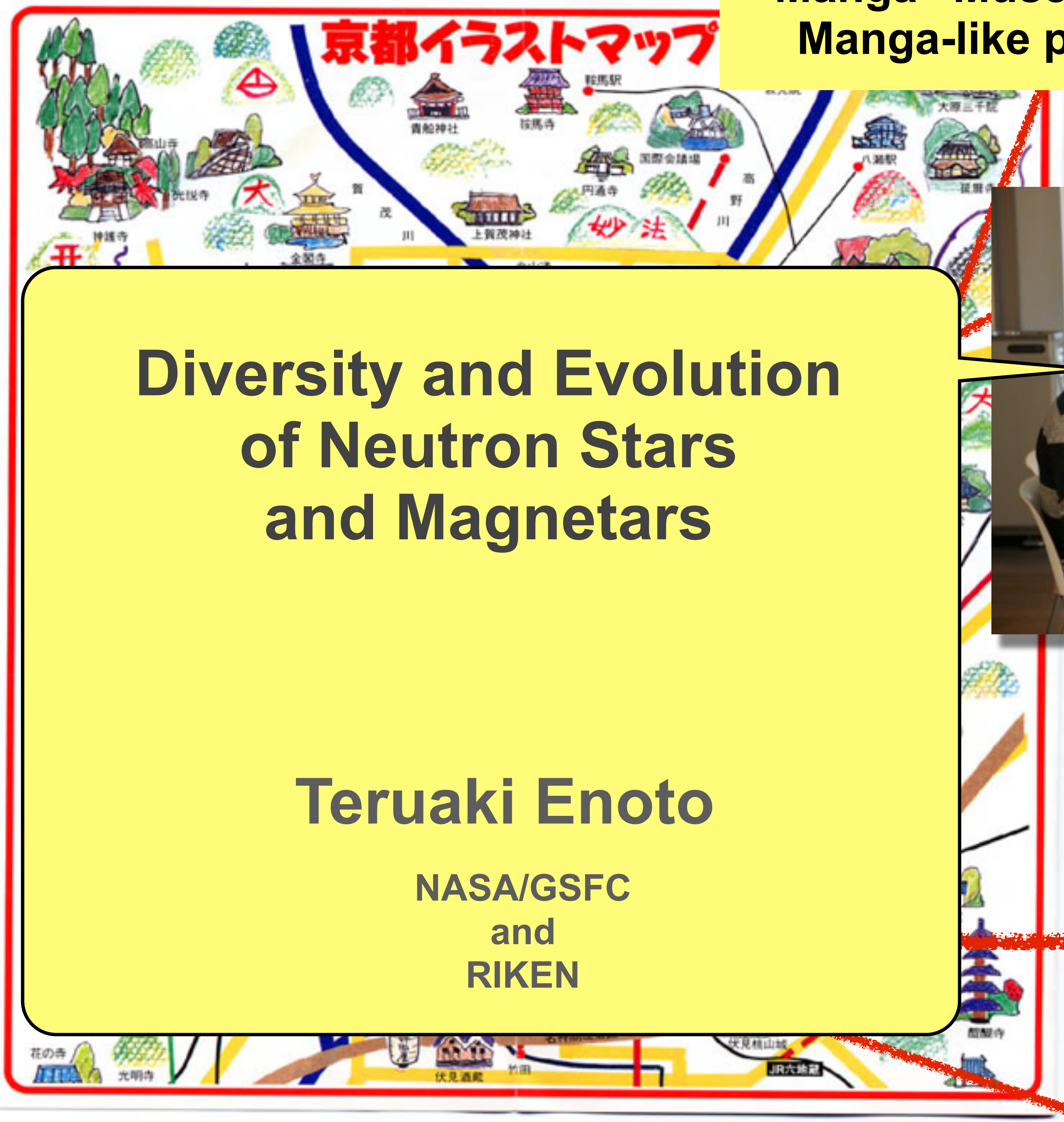
One of my favorit

“Manga” Museum
Manga-like portrait (1000yen, weekend)



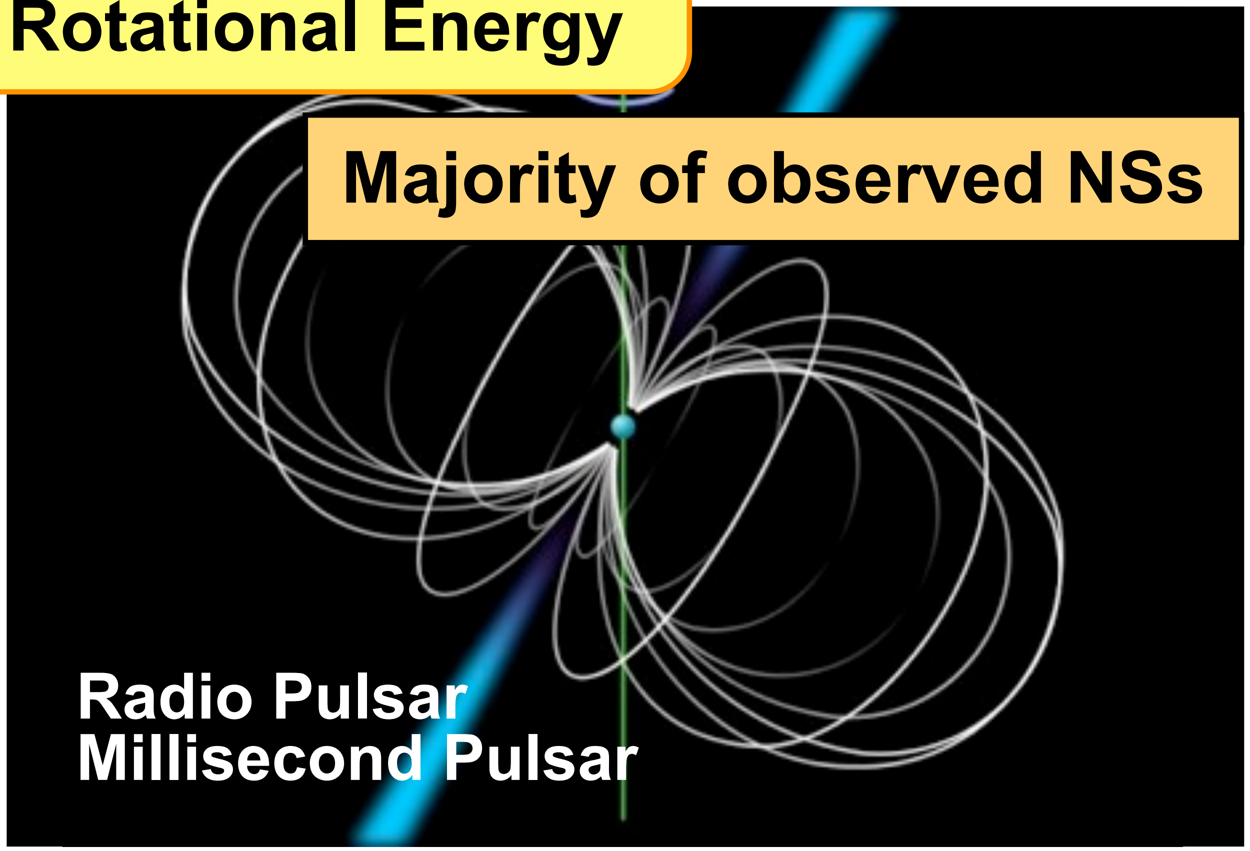
Diversity and Evolution of Neutron Stars and Magnetars

Teruaki Enoto

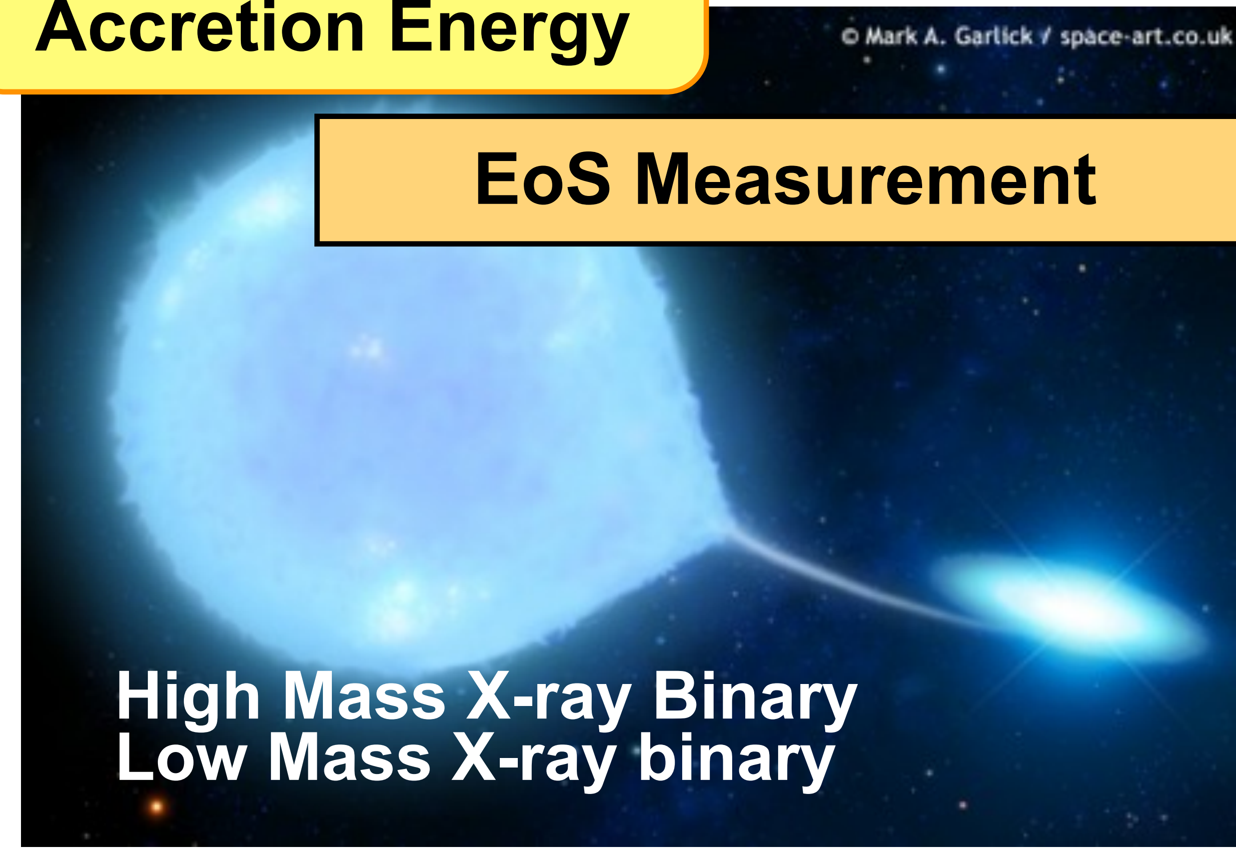
NASA/GSFC
and
RIKEN

Diversity of Neutron Star; Energy Source

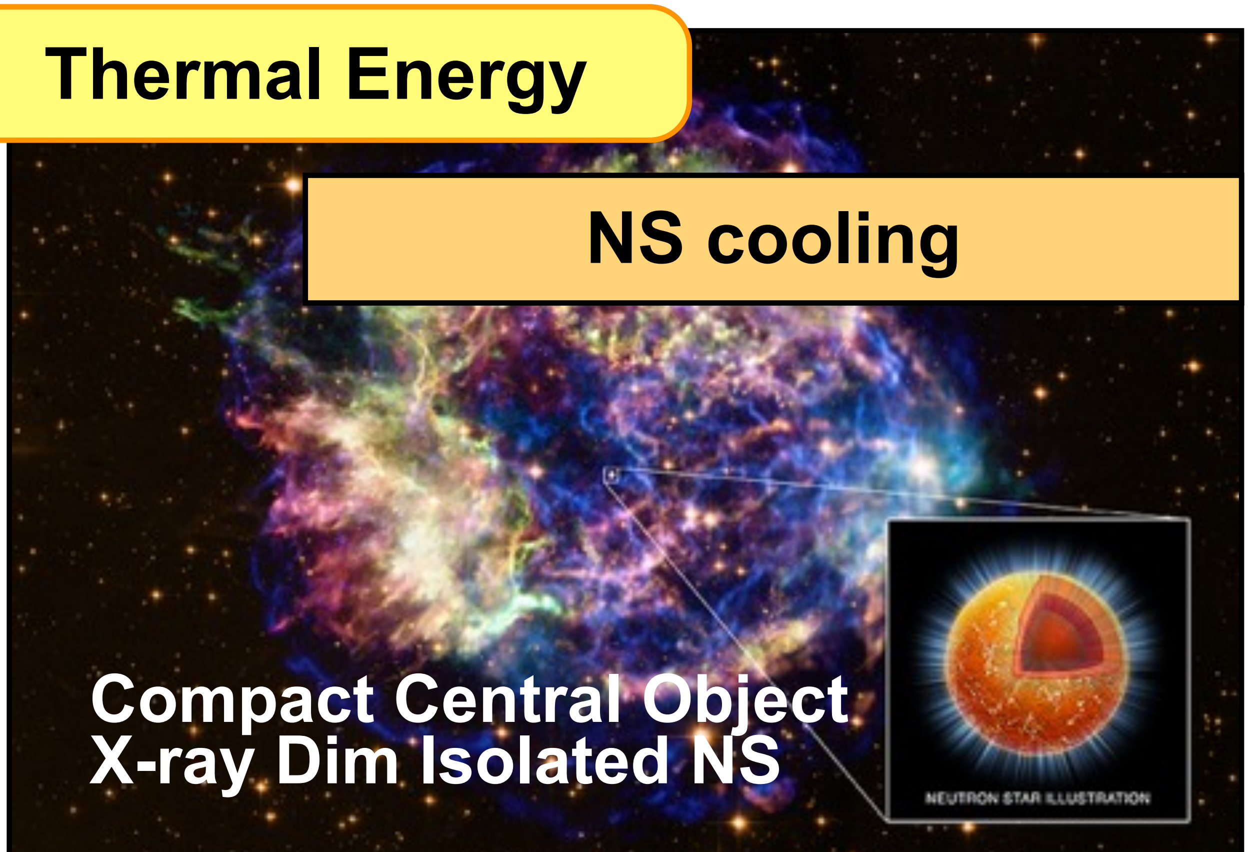
Rotational Energy



Accretion Energy



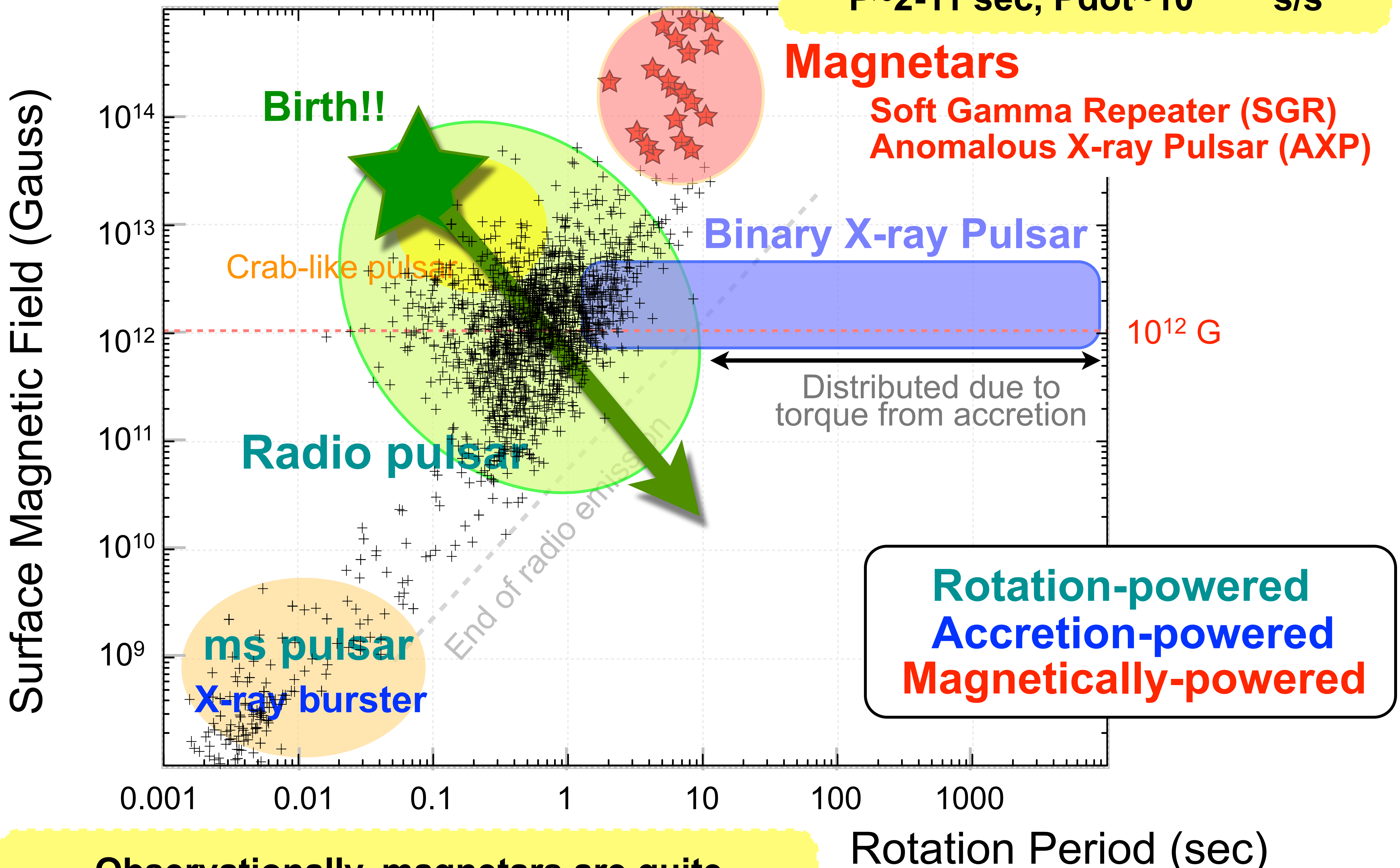
Thermal Energy



Magnetic Energy $B \sim 10^{14\text{-}15}$ G

Diversity of Neutron Stars

P~2-11 sec, Pdot~$10^{-12\text{-}10}$ s/s

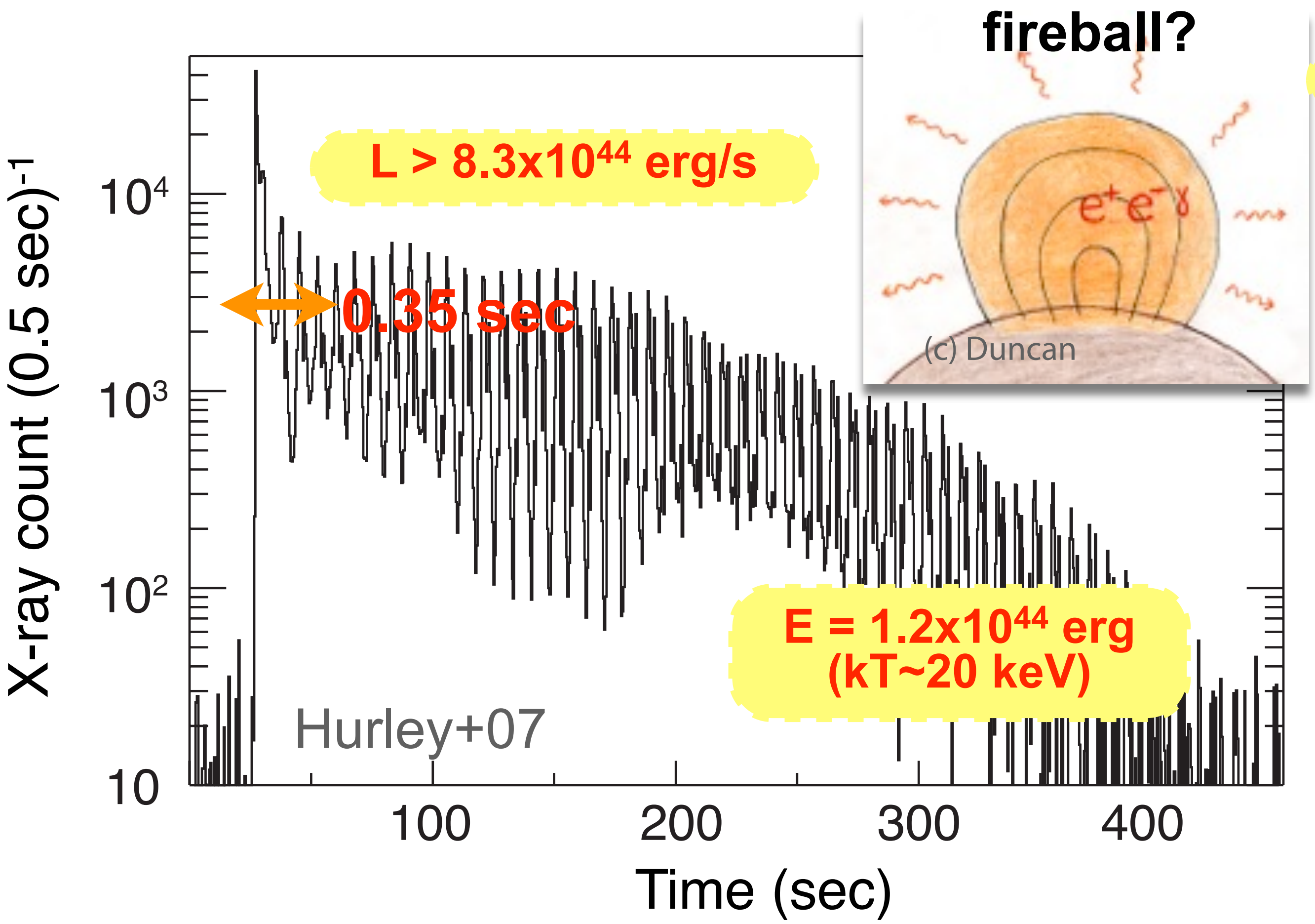


Observationally, magnetars are quite different from nominal radio pulsars.

Properties of Magnetars

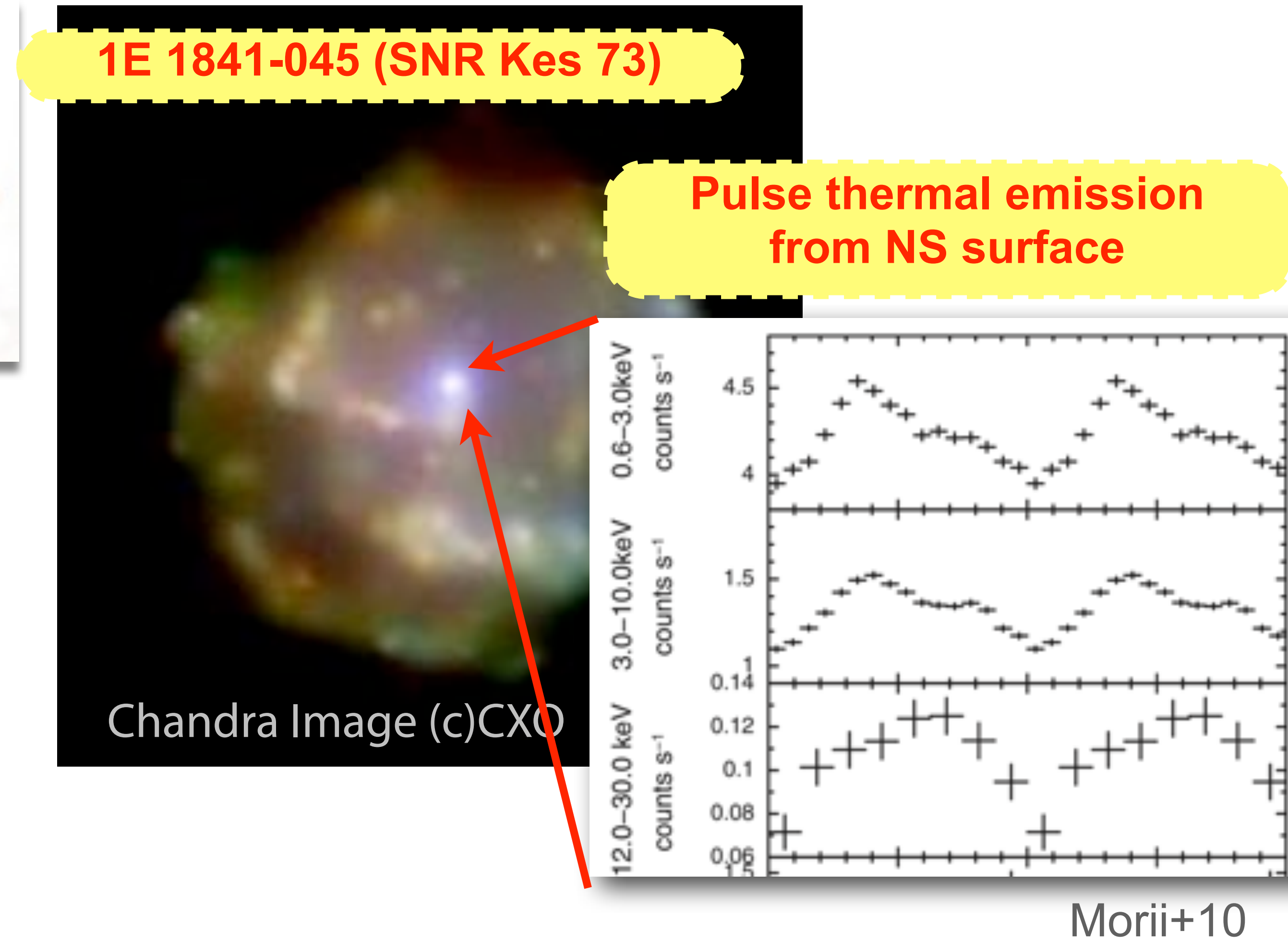
Soft Gamma Repeater

Giant Flare SGR 1806-20 (2004)



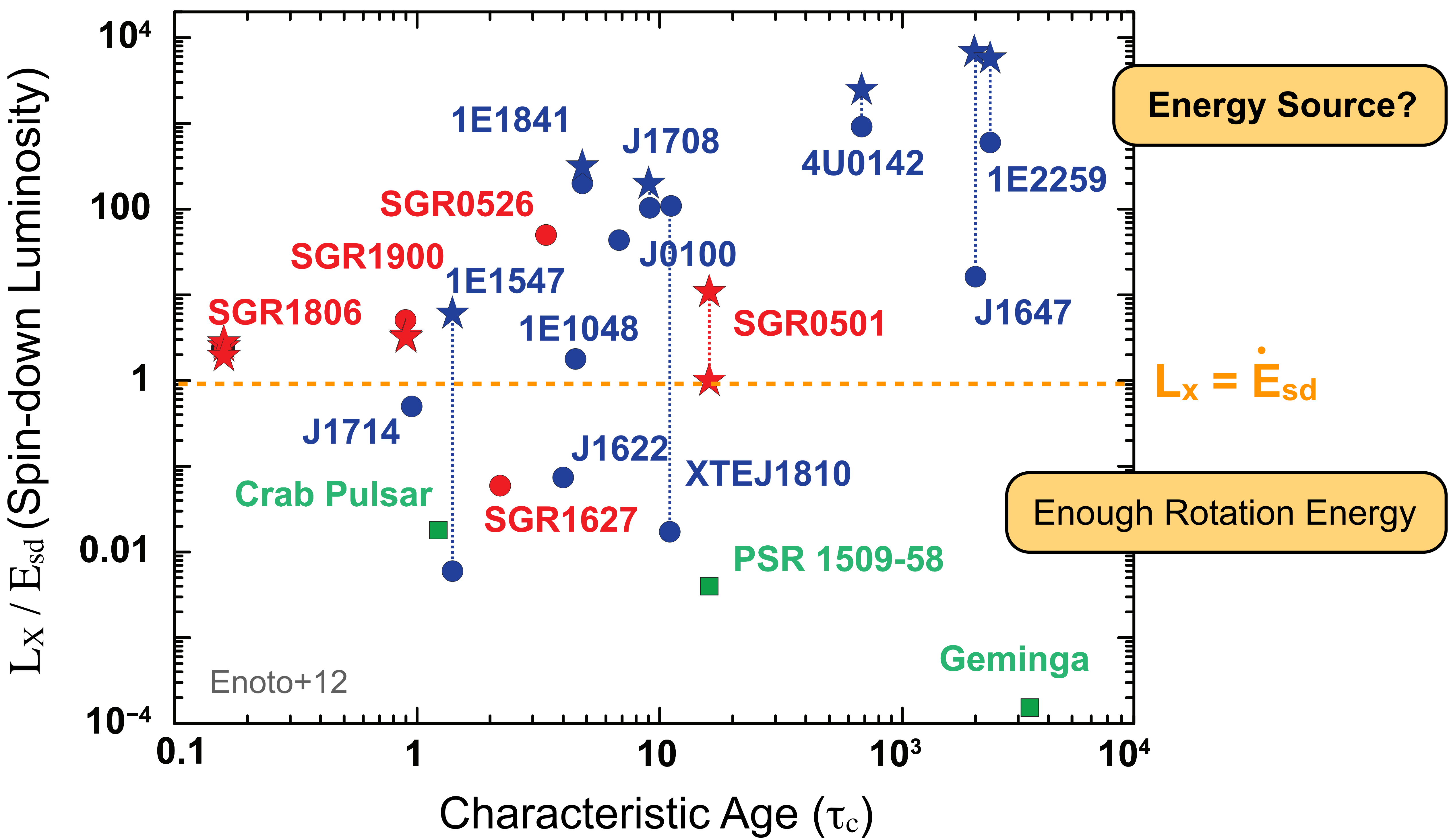
Anomalous X-ray Pulsar

Bright X-ray source (w SNR)



- Dipole magnetic field B_d~10$^{14\text{-}15}$ G via *P*-*P*dot measurements
- Supper Eddington giant flares, short bursts, and X-ray outbursts
- Distinctive soft and hard X-ray spectra
- Connection to extra-galactic events (GRBs etc)

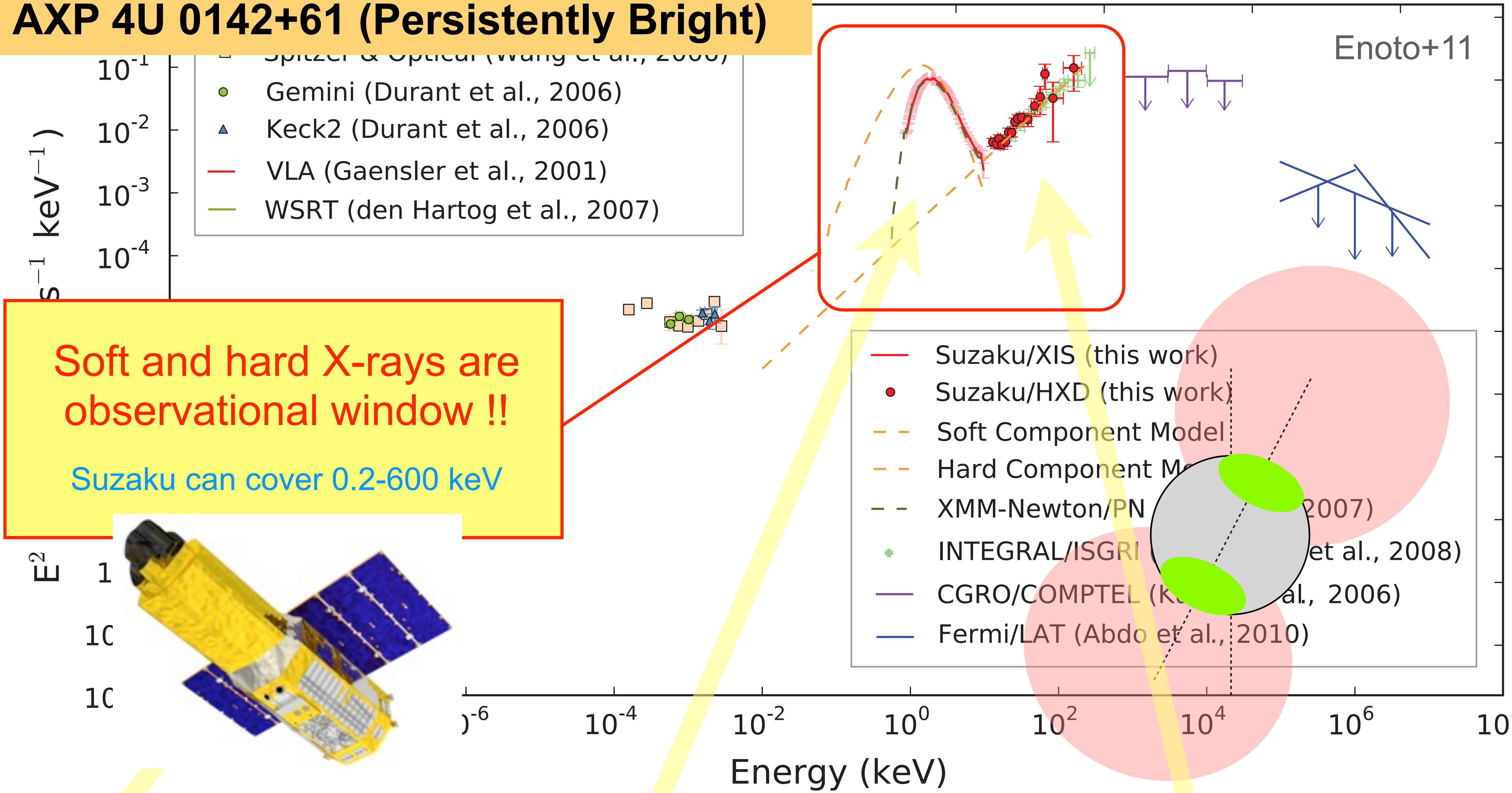
Persistent X-ray Luminosity of SGR/AXP



L_X >> Spin-down E_{sd}, no evidence for a binary companion (e.g., Kaspi+99)
Magnetars hypothesis; Magnetically-powered Pulsars? (Thompson & Duncan, 95)

Magnetar Multi-wavelength Emissions

AXP 4U 0142+61 (Persistently Bright)



Soft and hard X-rays are observational window !!

Suzaku can cover 0.2-600 keV

No radio emission

Photon splitting in high-B suppresses the e+/e- pair creation and radio emission?

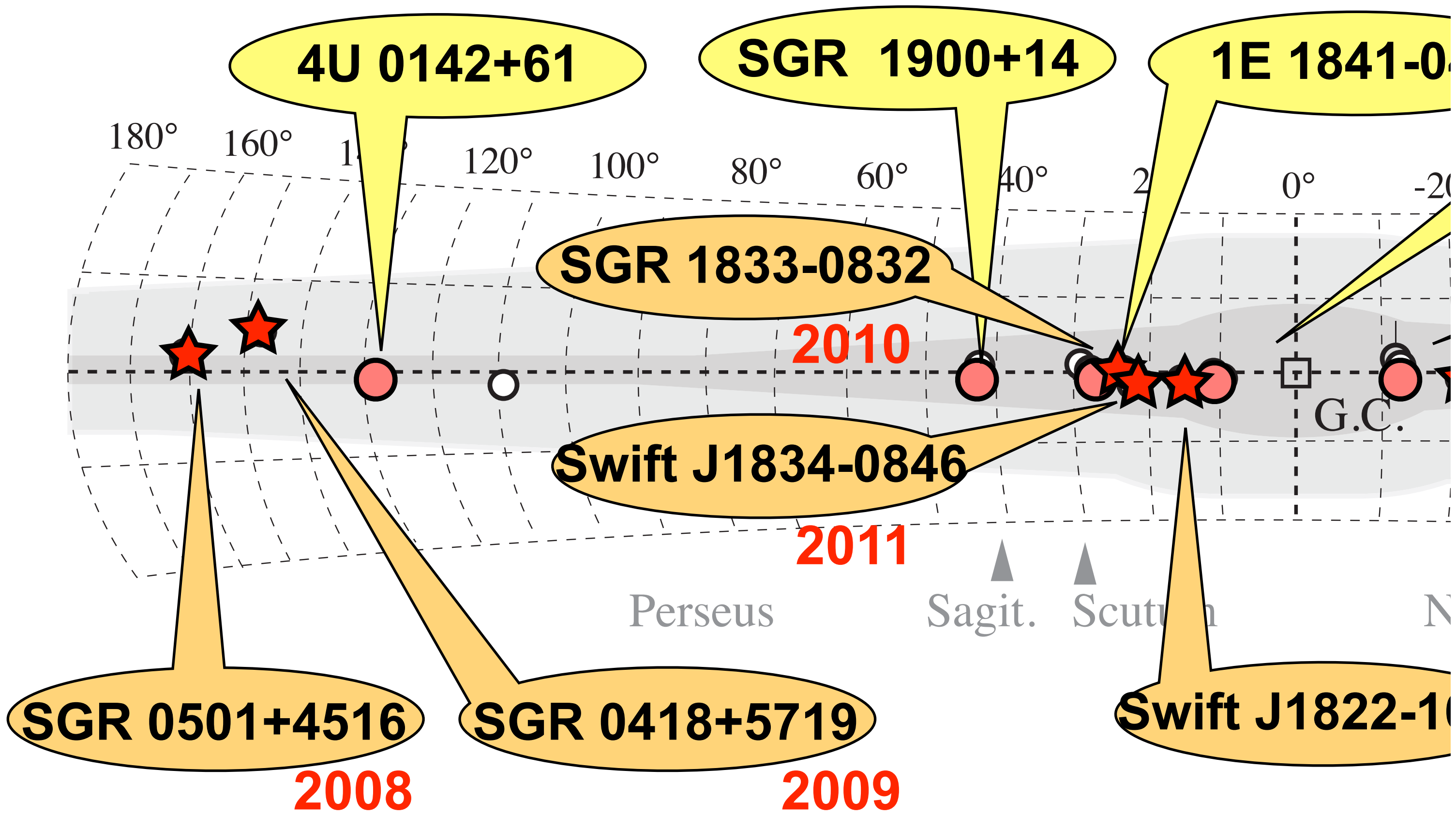
Pulsed thermal emission

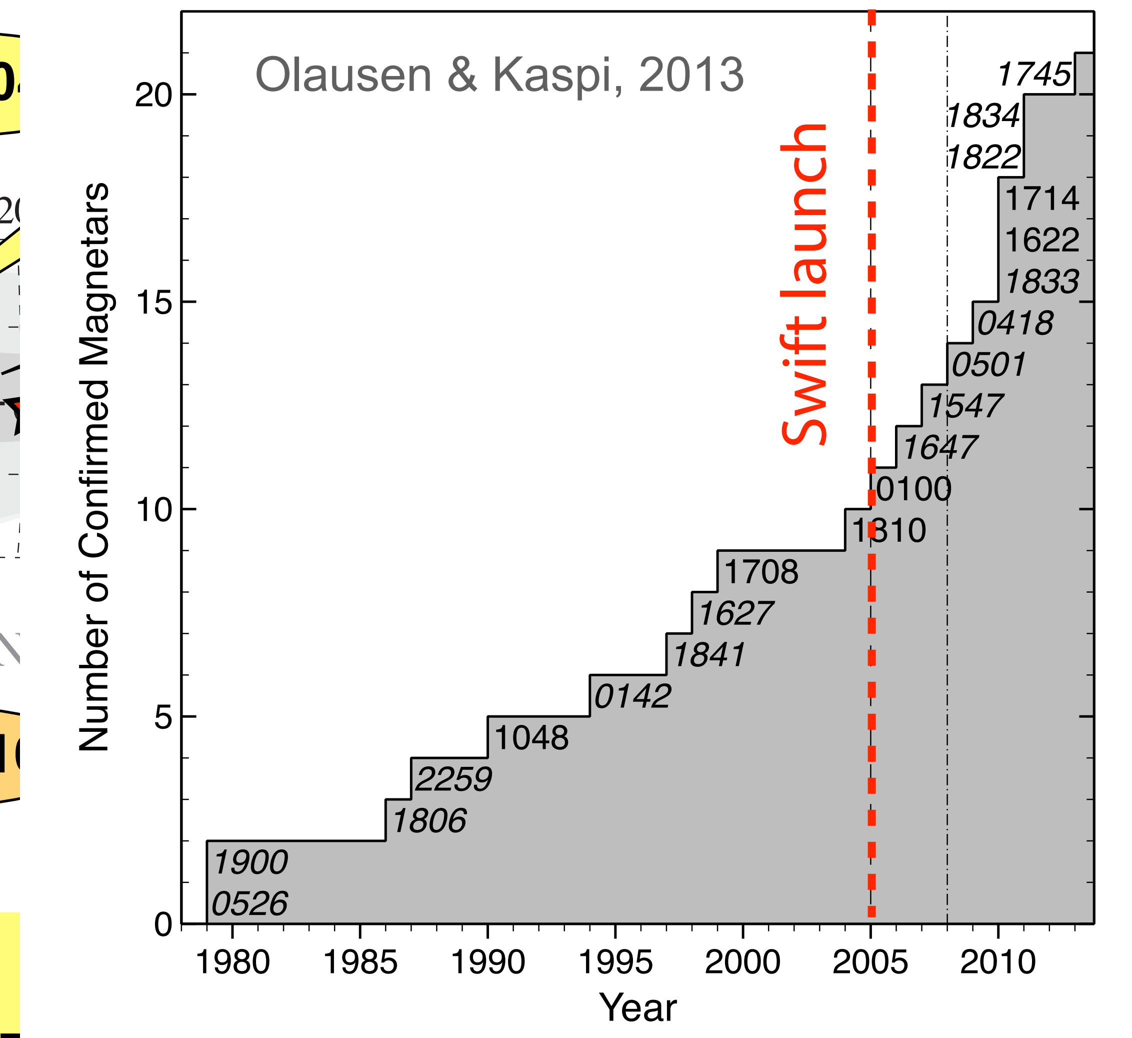
from hot NS surface.
Quasi-BB $kT \sim 0.3$ keV
heated by the interior field

Pulsed hard X-rays

Discovered by INTEGRAL
hard photon index $\Gamma \sim 1$
upper limit >750 keV

Discoveries of Transient Magnetars



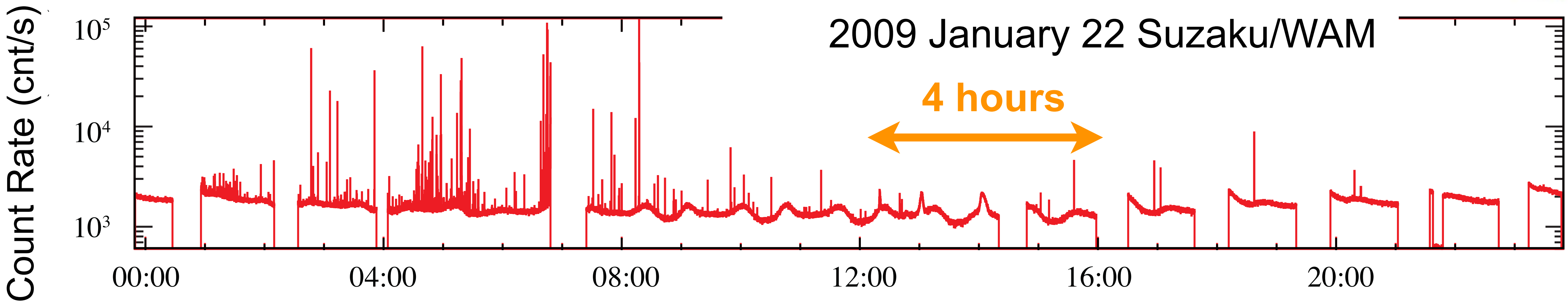


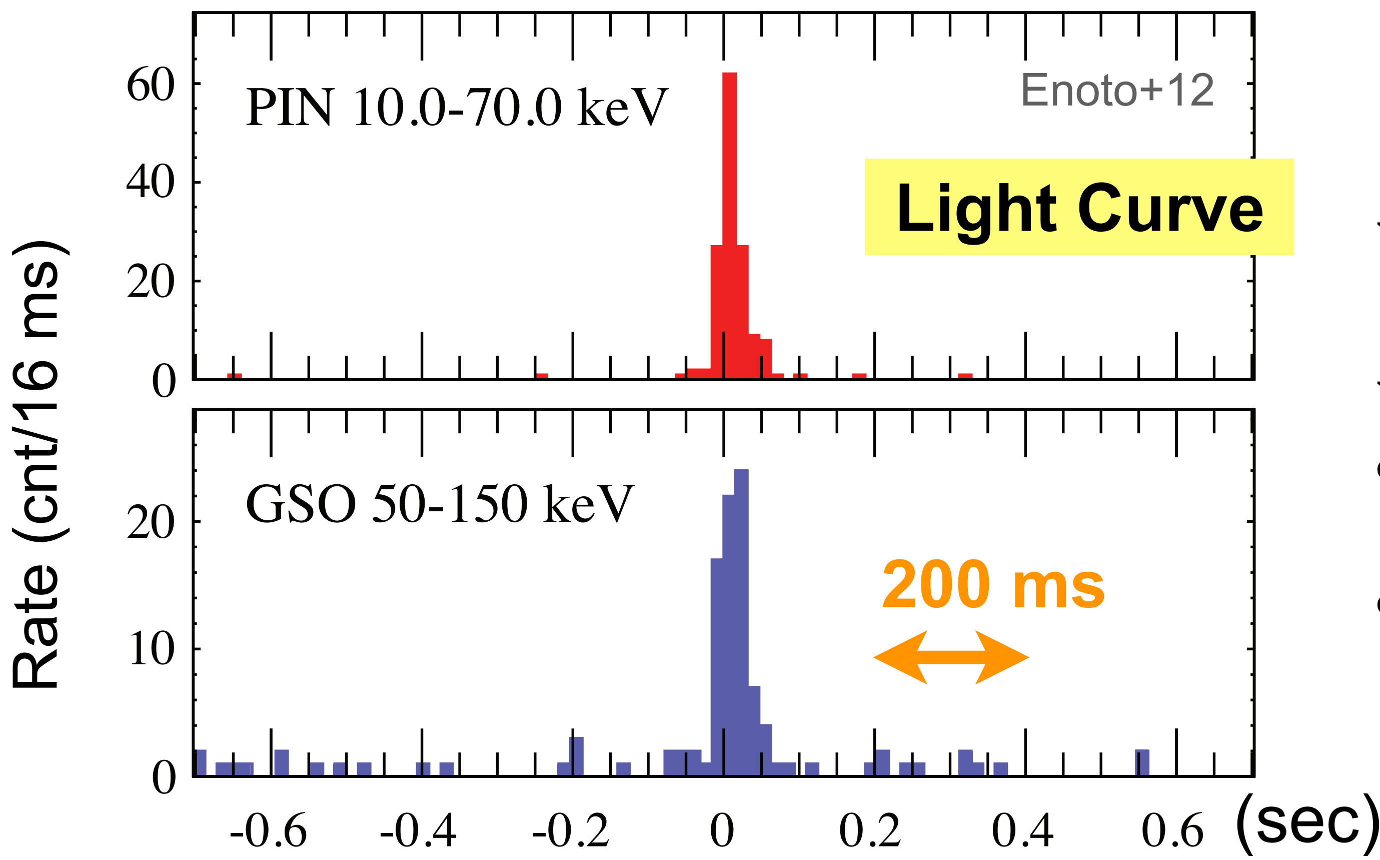
1. New magnetars have been discovered, 1-2 new per year
   - ⇒ **Swift satellite (for the GRB) detects short bursts from magnetars.**
   - ⇒ **X-ray, optical, and radio follow-up observations within a week.**
   - ⇒ **Bright new X-ray source are confirmed with multiple short bursts.**
2. Magnetar population is much larger than we previously thought.

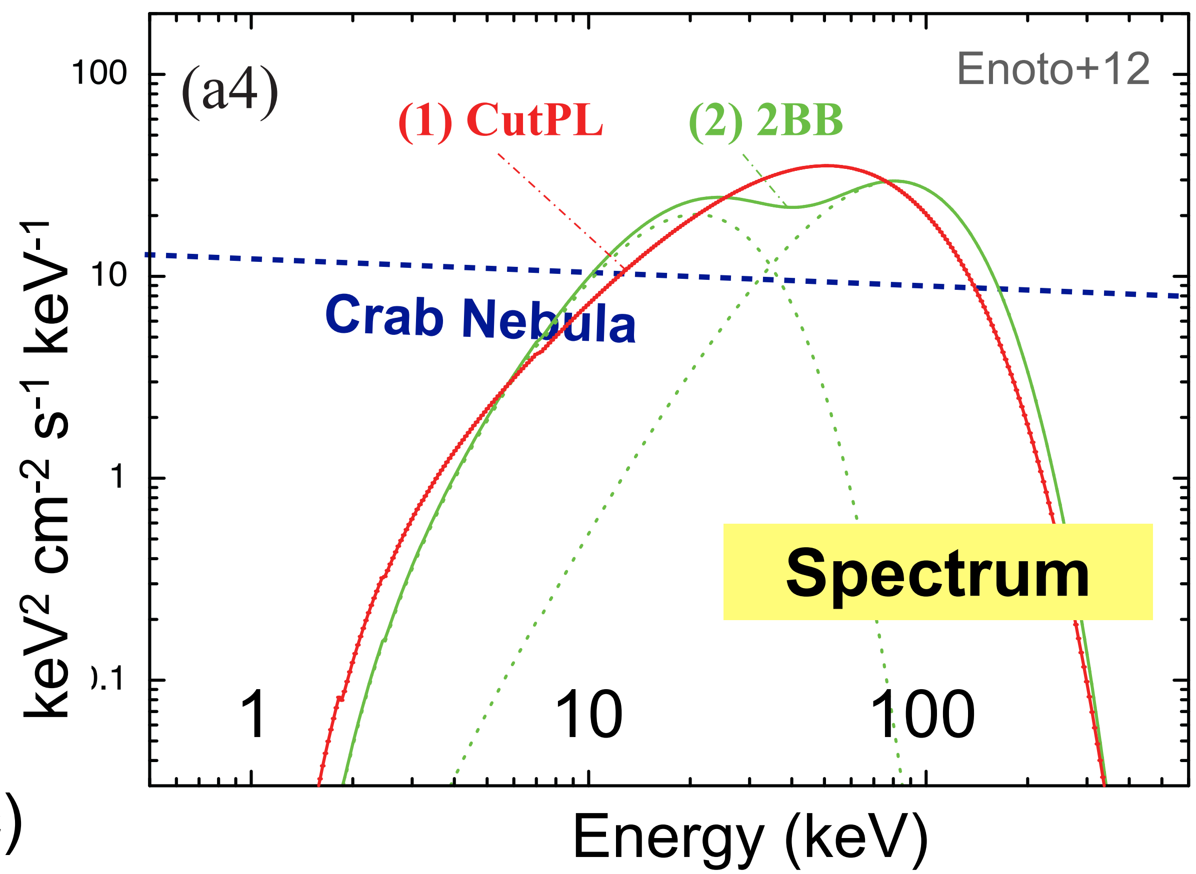
Challenge to provide a more unified characterization !!

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

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





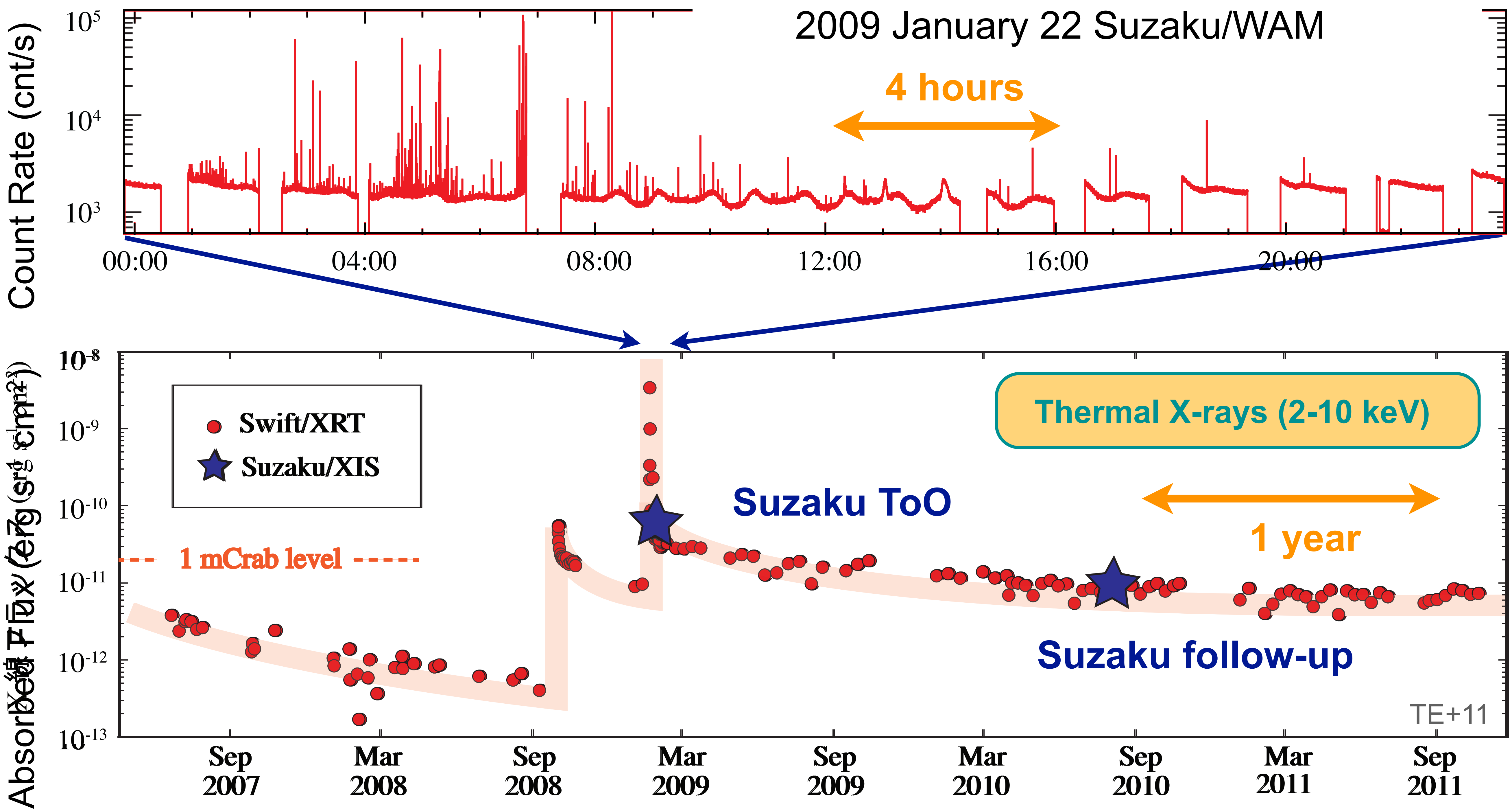


Feature1: Recurrent Bright Short Burst

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

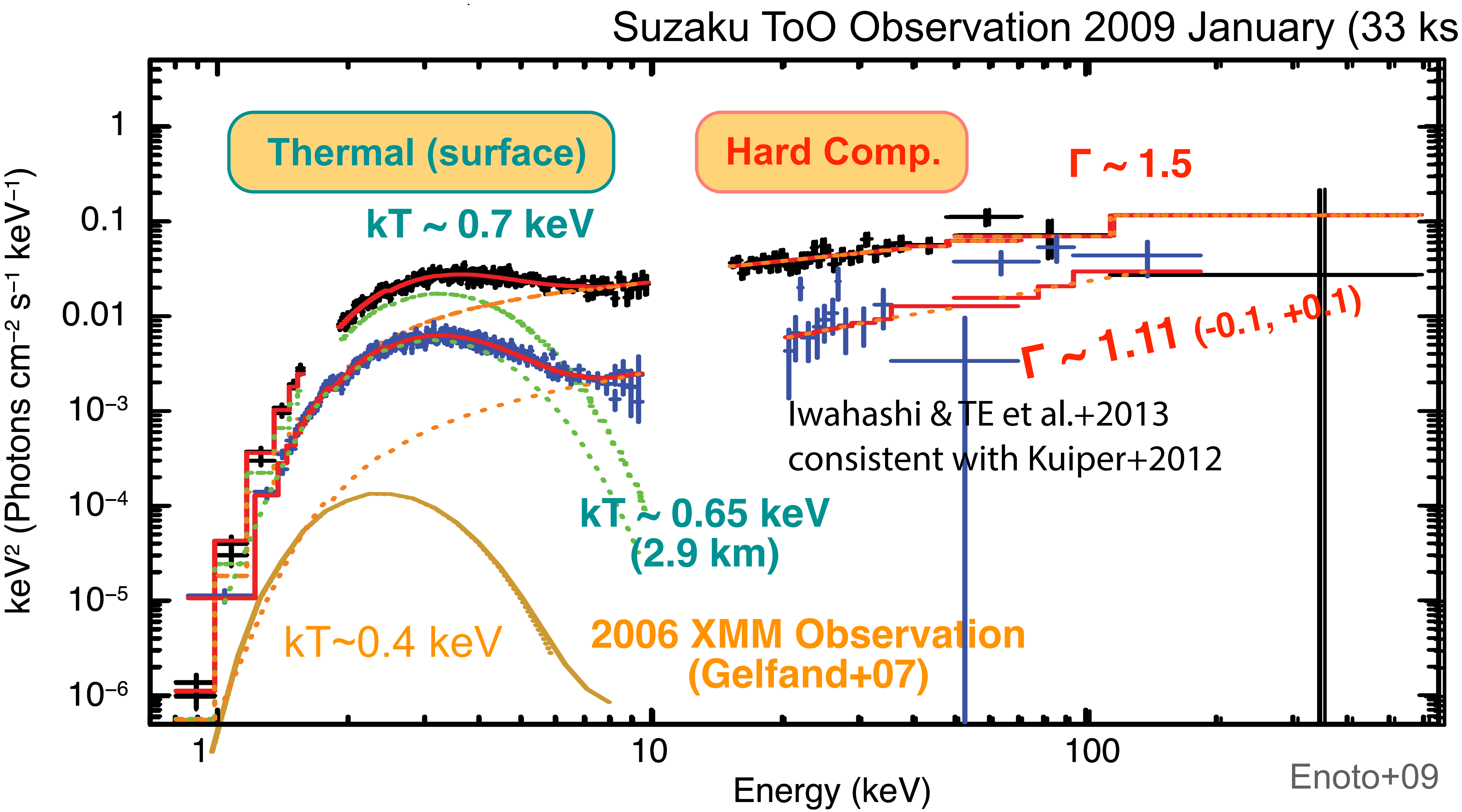
X-ray Outburst of AXP 1E 1547.0-5408 (2)

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



Feature2: Persistent X-ray becomes brighter by 2-3 orders of magnitude.

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

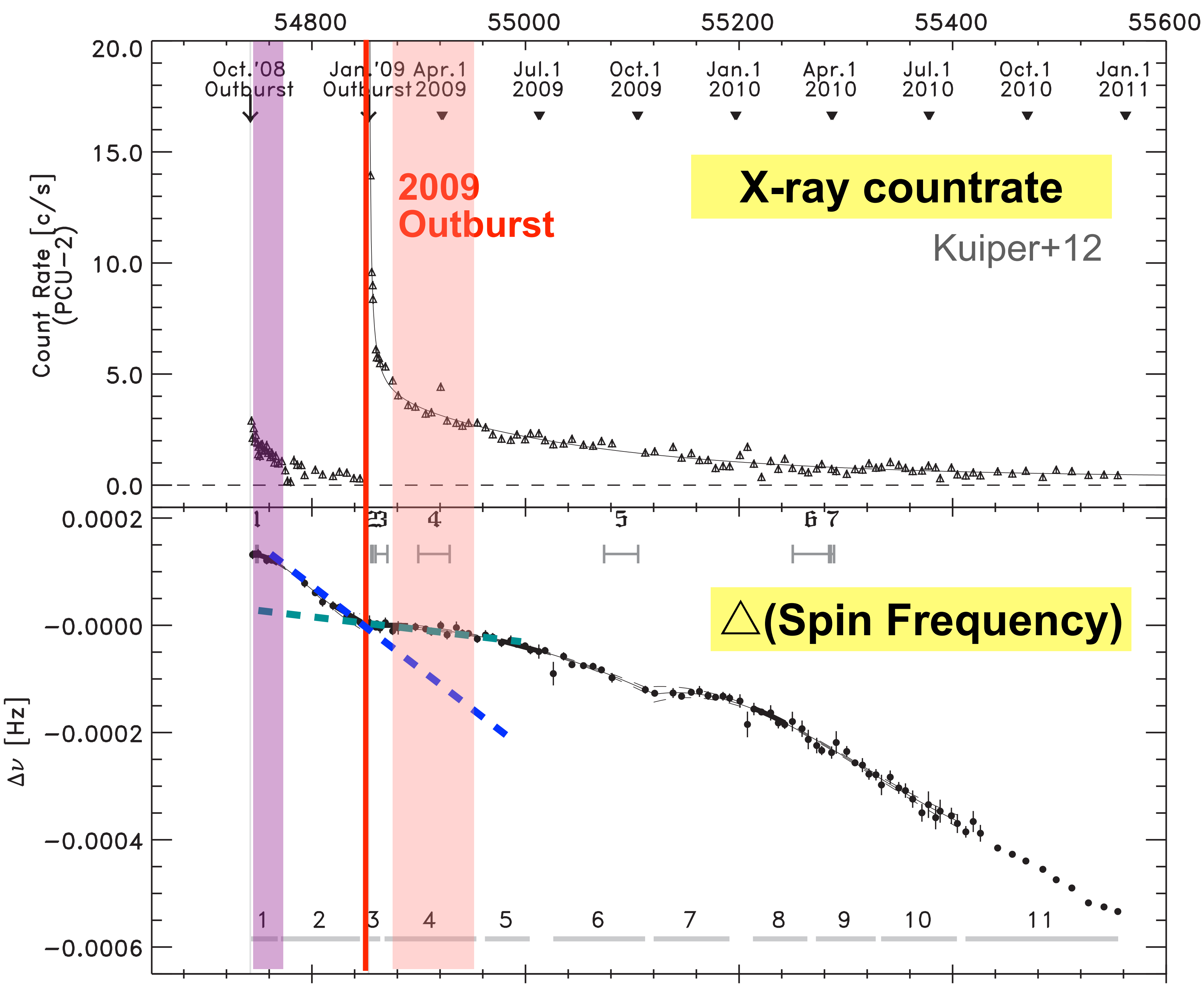


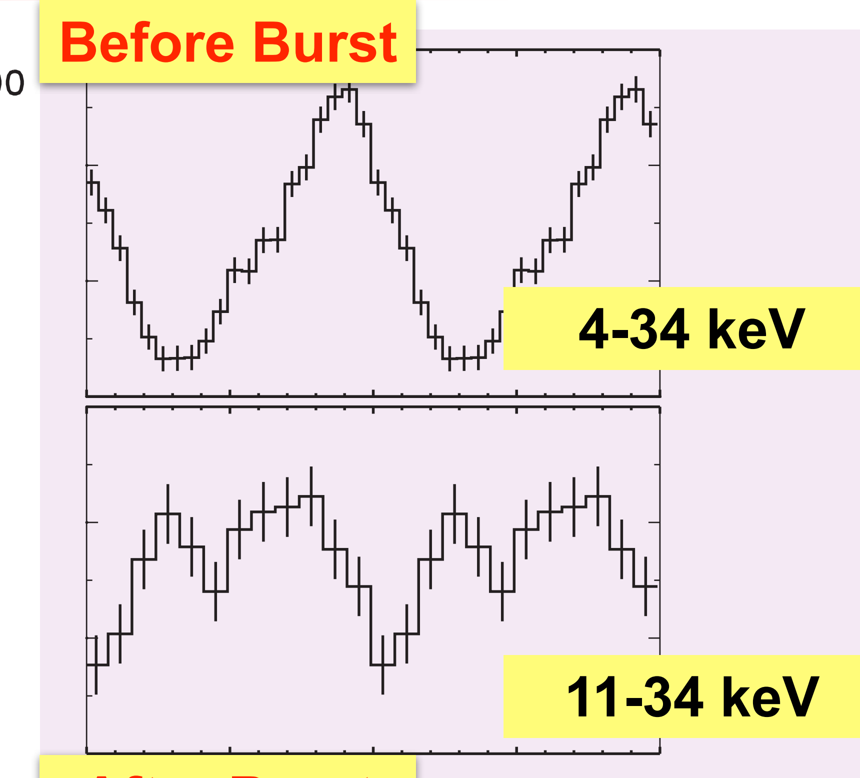
Hard X-rays were clearly discovered during the magnetar outburst with Suzaku.

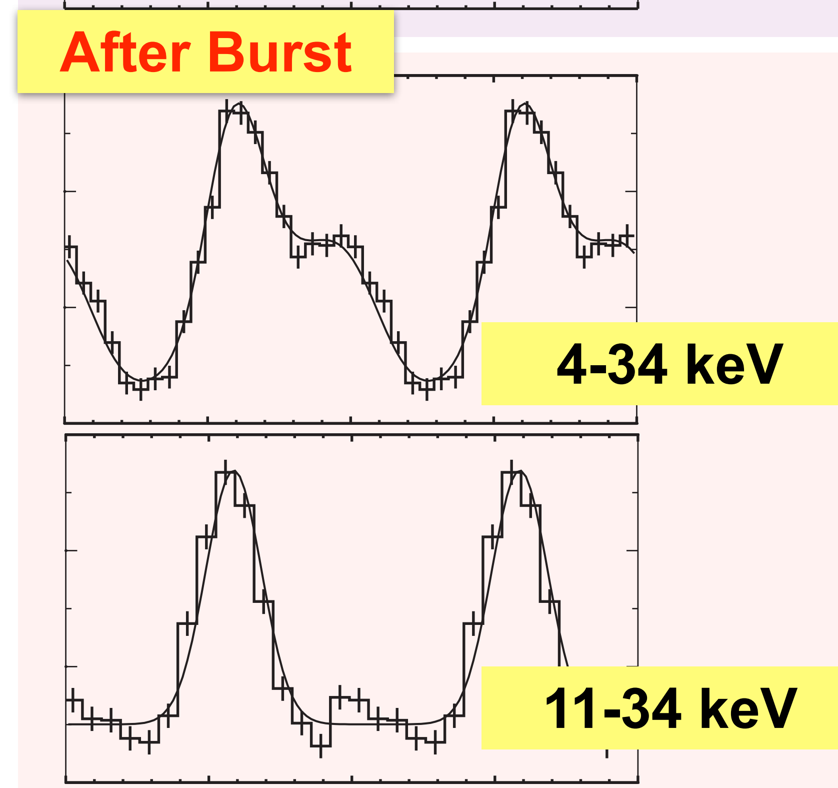
Feature2: Persistent X-ray becomes brighter by 2-3 orders of magnitude

Both components (soft thermal + hard X-rays) become brighter

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



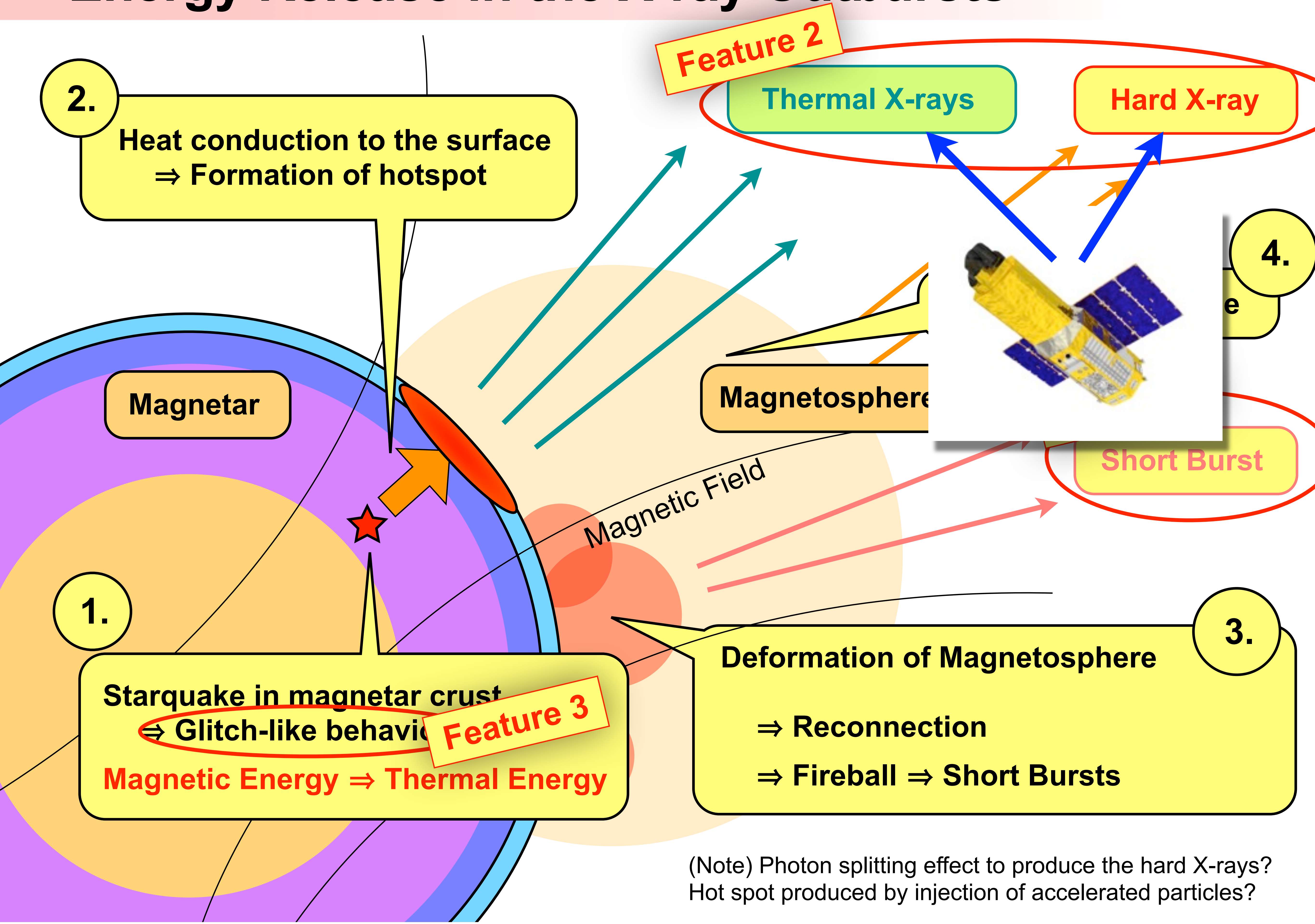




Feature3: Pulse profile changes at the outburst $(\triangle\dot{\nu}/\nu = -0.69 \pm 0.07)$

⇒ Hot spot location was changed?

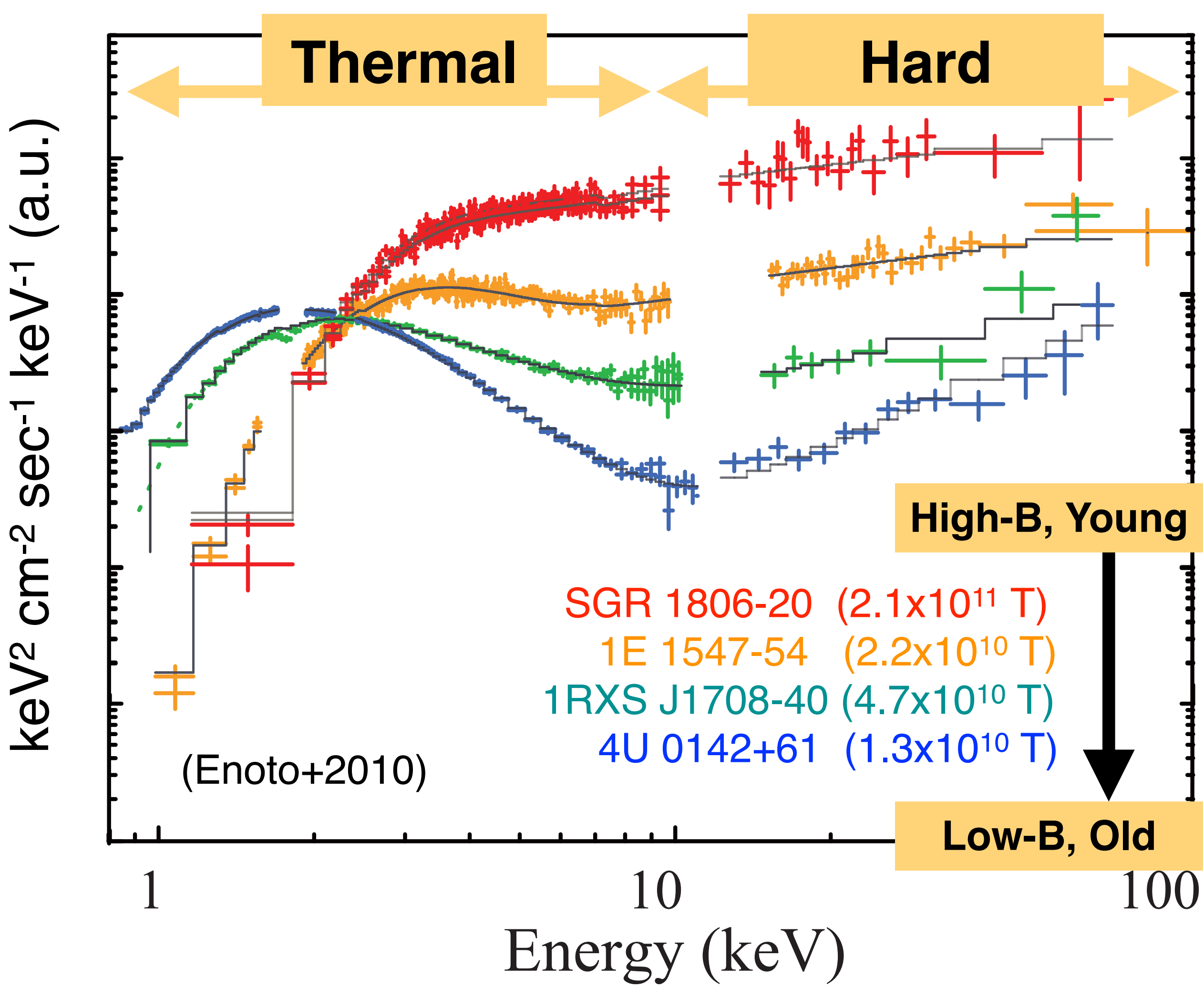
Energy Release in the X-ray Outbursts

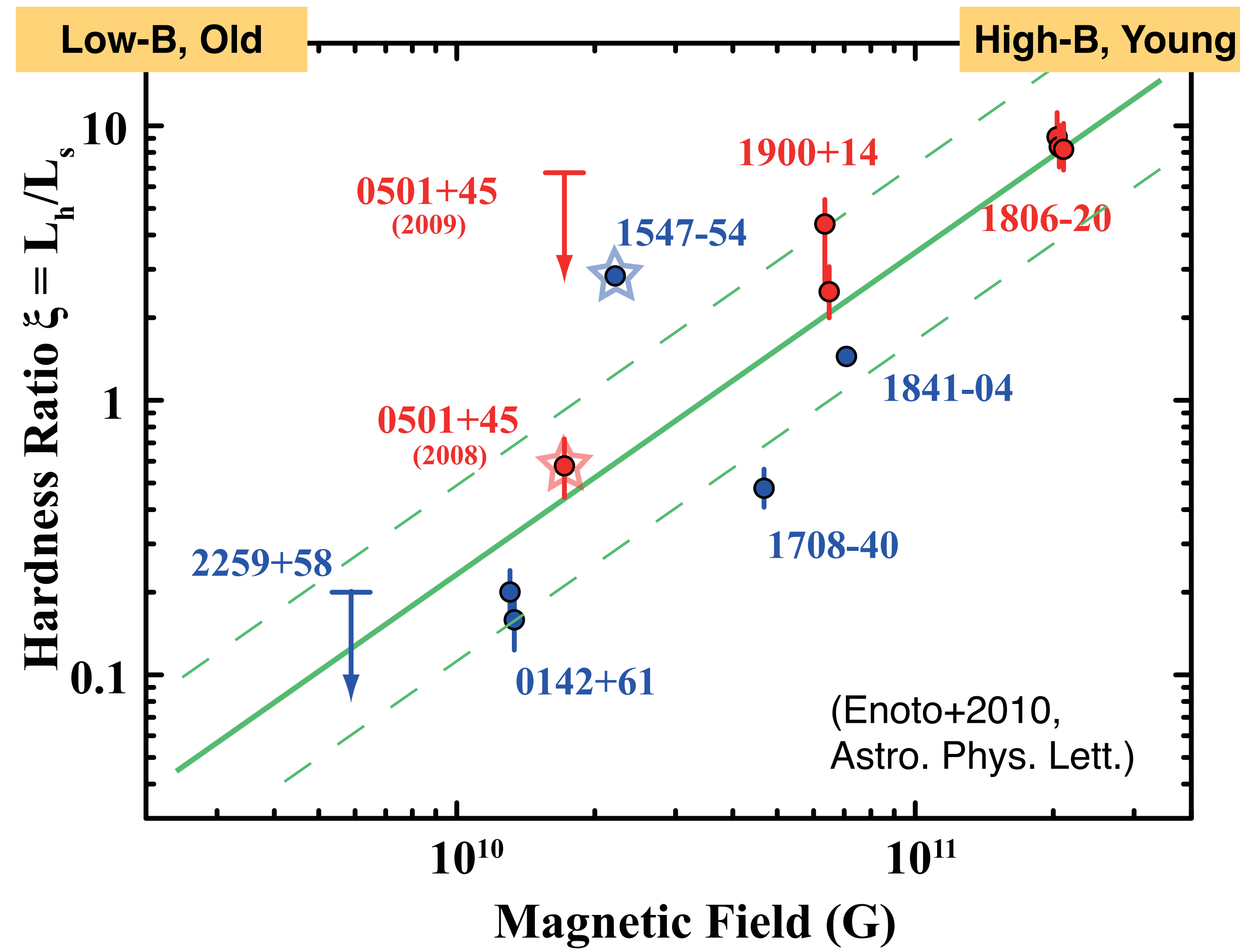


(Note) Photon splitting effect to produce the hard X-rays?
Hot spot produced by injection of accelerated particles?

Broadband X-ray Spectra vs. Magnetic Field

Suzaku performed "Magnetar Key Project" and detected the "hard X-ray component" from ~7 magnetars.



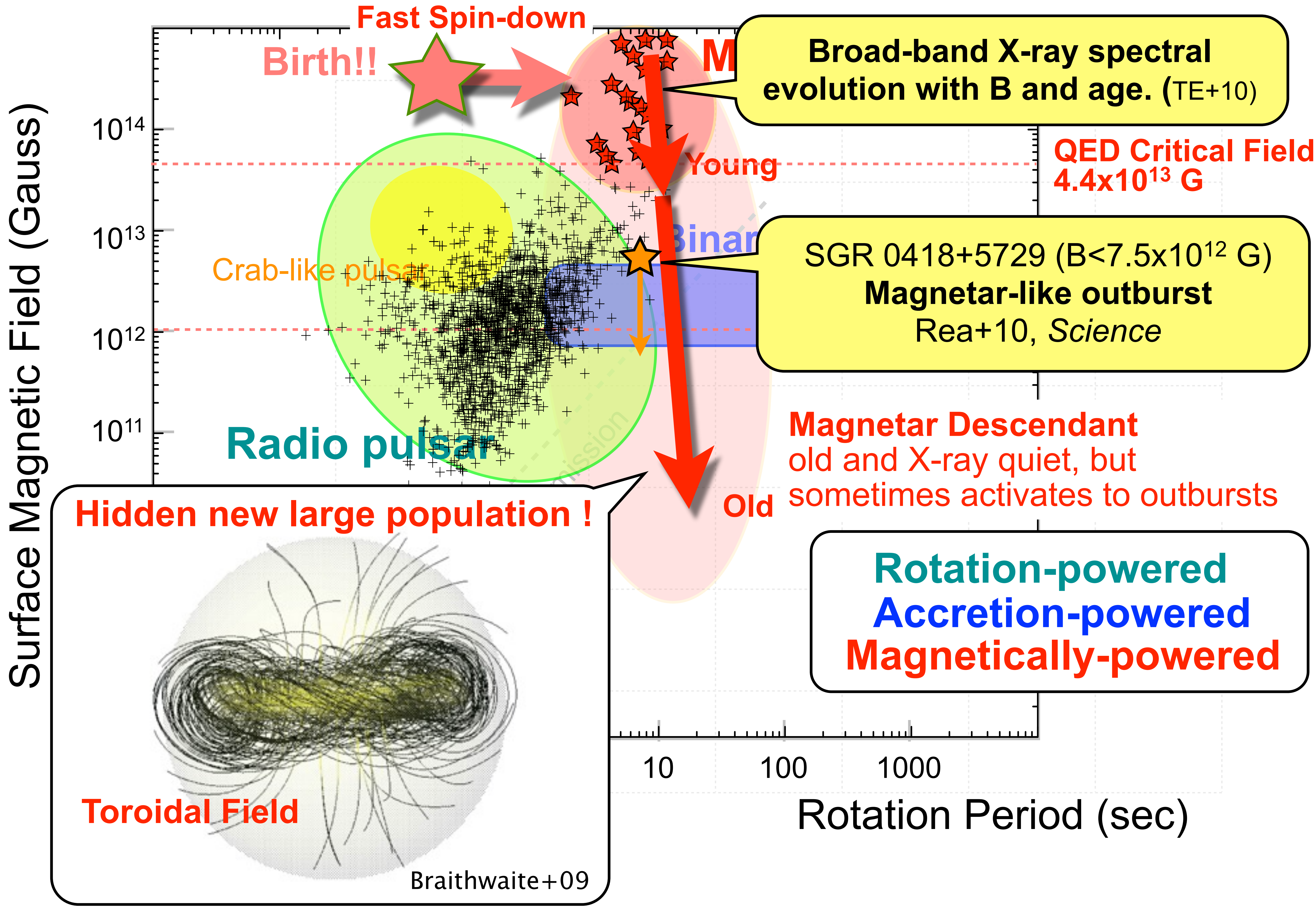


Luminosity of the hard X-ray component is found to be positively correlated with their magnetic field derived by Period *P* and its derivative P_{dot}.

2 Types of Magnetars (SGR & AXP) show broad-band X-ray spectral evolution !

One key feature of the hard X-ray emission mechanism.

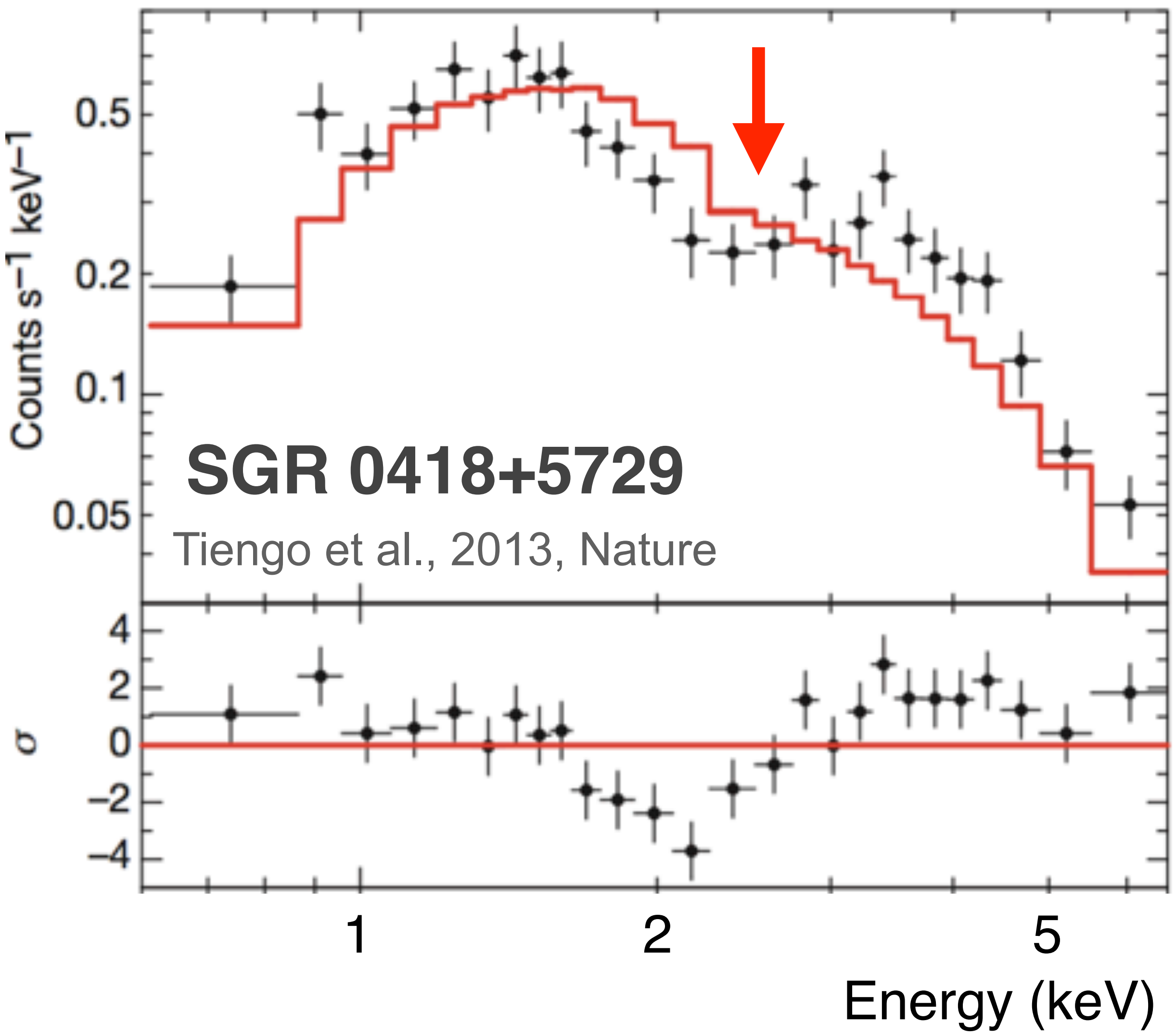
Diversity of Neutron Stars

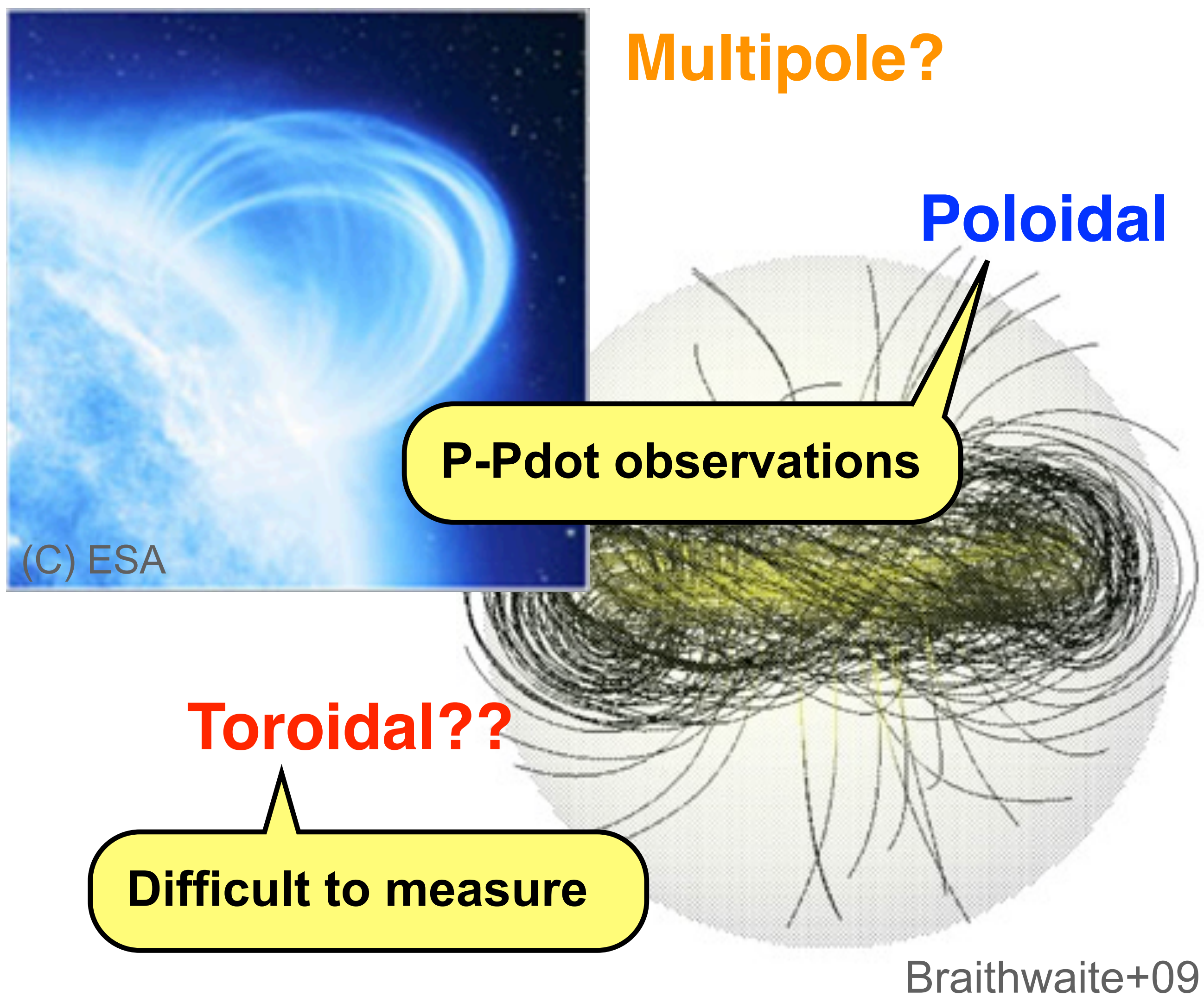


Signatures of Toroidal Field: Low-B Magnetar

- Low-B_d magnetars ($B_d < 3.3 \times 10^{13}$ G): SGR 0418+5729 and Swift J1822.3-1606
  - Magnetar burst activity requires high-B field than measured $B_d \sim 6 \times 10^{12}$ G.
  - Short-burst originates from reconnection? Higher multipoles?
- Discovery of proton(?) cyclotron signature in SGR 0418+5729
  - Strong multiple signature with $B > 2 \times 10^{14}$ G near the NS surface
- Simulations of the toroidal field inside the NS (e.g., wound-up at the birth)

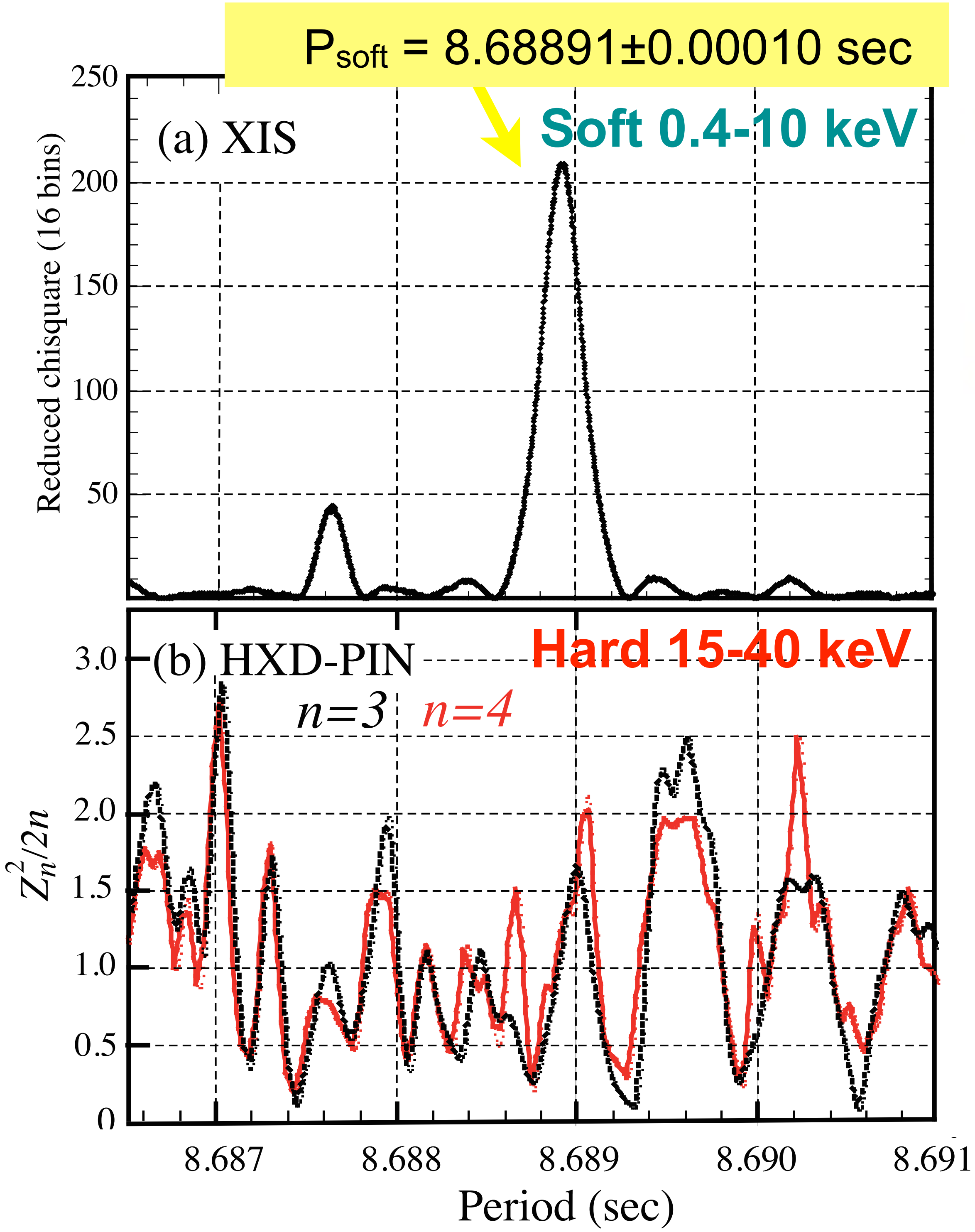
Energy source of magnetars = Poloidal + "Toroidal" Magnetic field ?

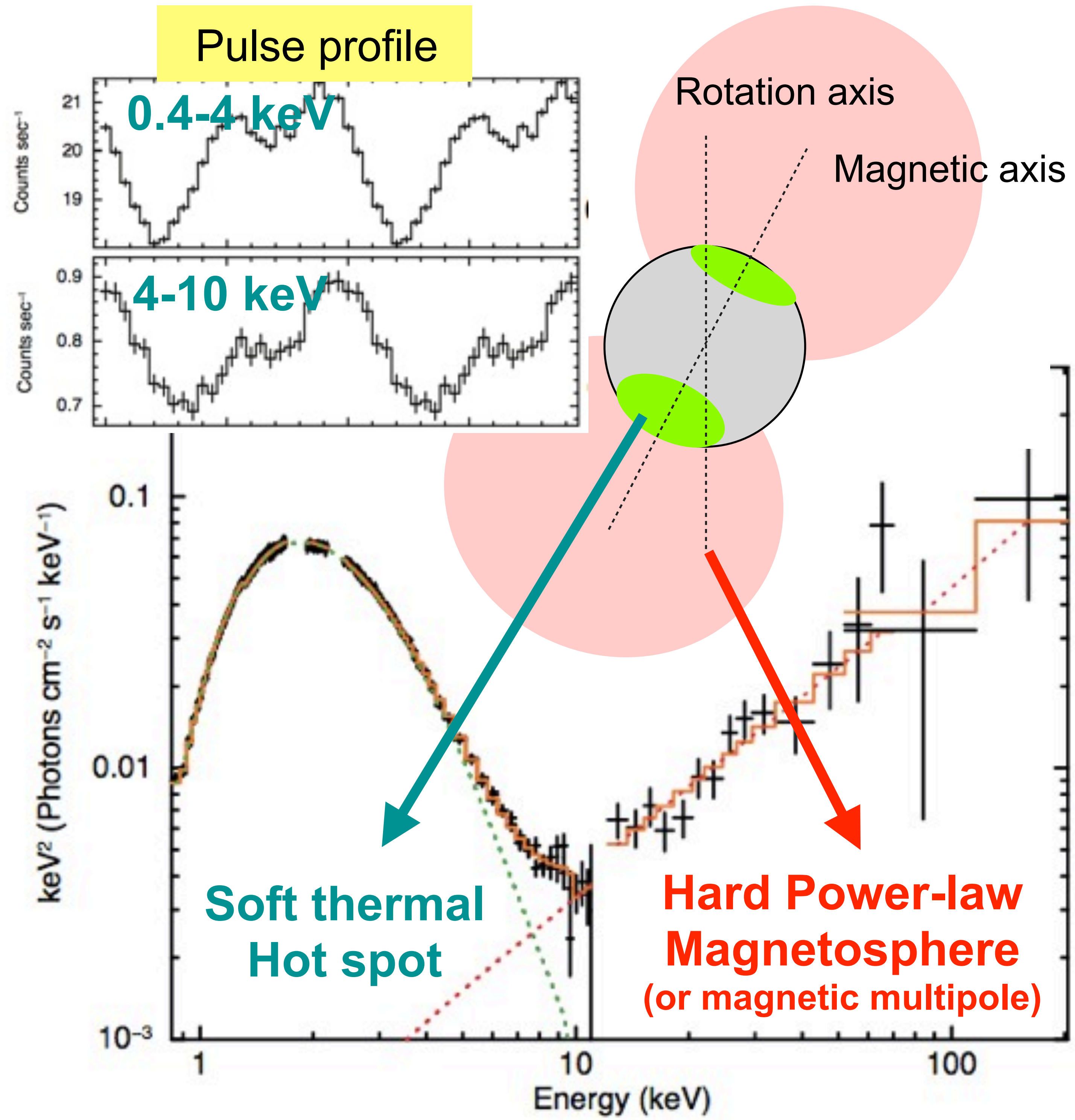




Soft and Hard X-ray Pulsation: 4U 0142+61

Famous and prototypical AXP: B_d~1.3×10^{14} G. Observed in 2007 and 2009 (both ~100 ksec)



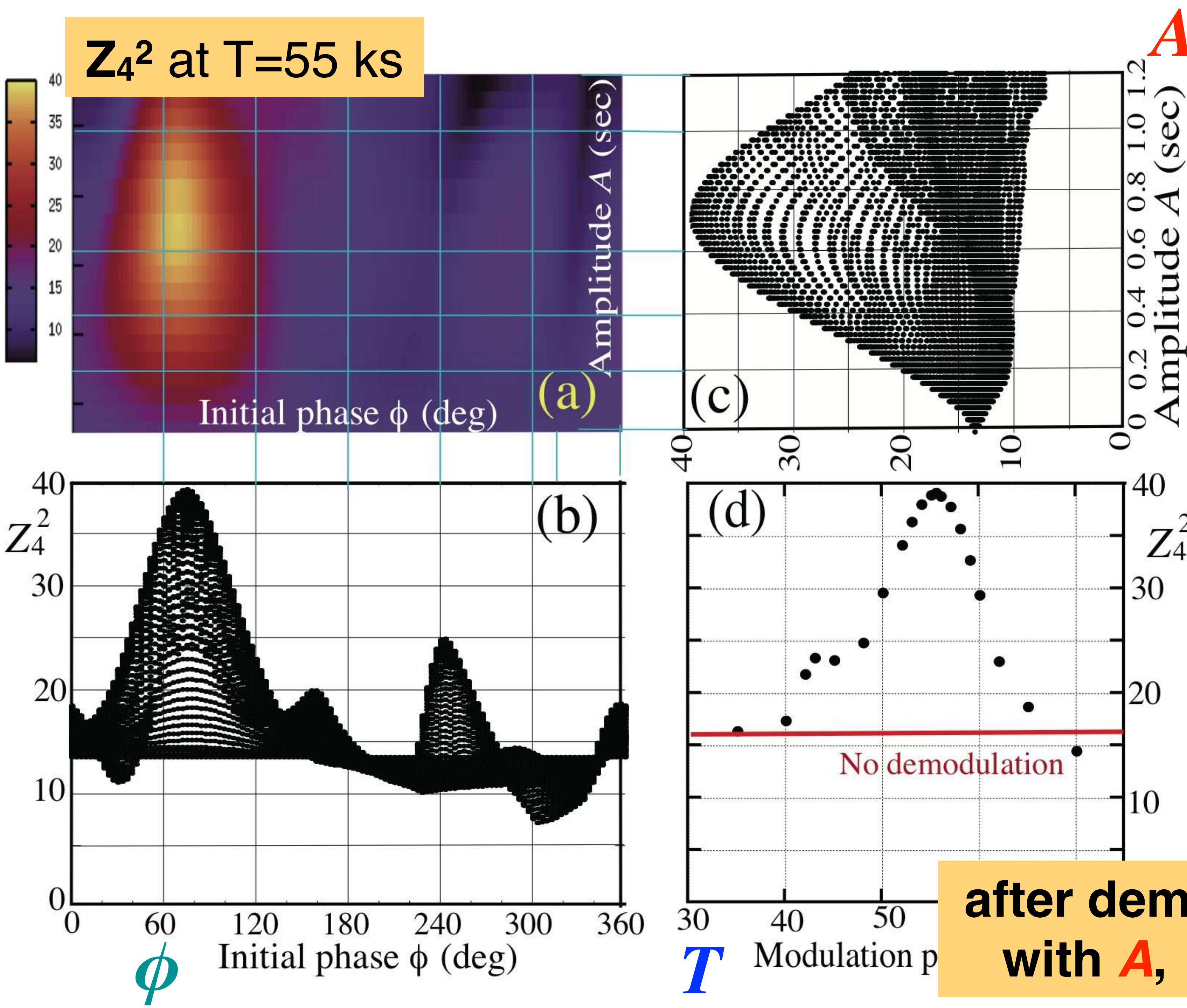


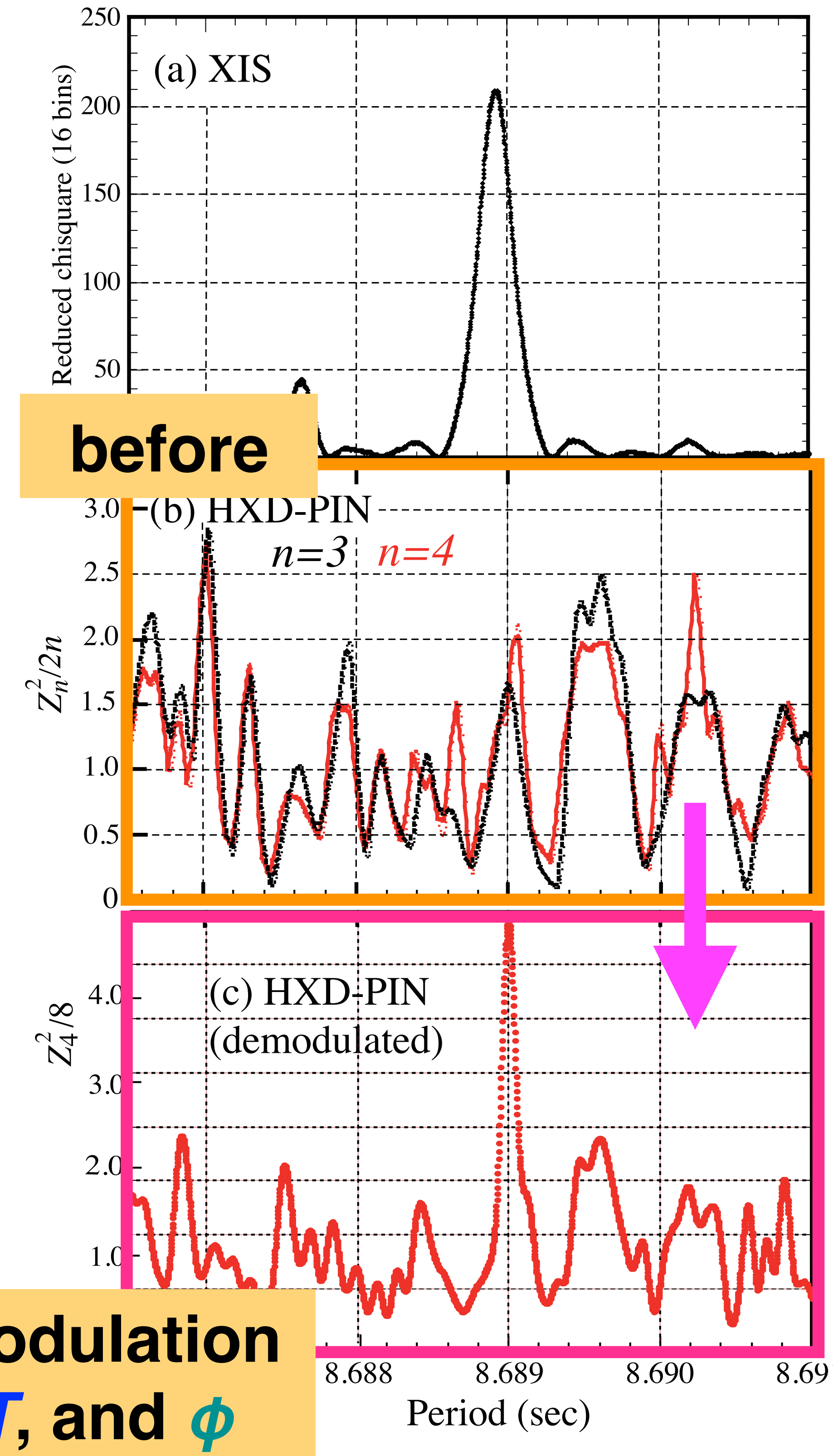
8.69 sec pulsation signal was weak in hard X-rays in the 2009 observation.

Makishima & Enoto et al., submitted

Slow Phase Modulation?

Assuming $\triangle t = A \sin(2\pi\, t/T - \phi)$ and search A, T, ϕ





Hard X-ray (15-40 keV) shows phase modulation by A=0.7 sec with a T~1.5 h.

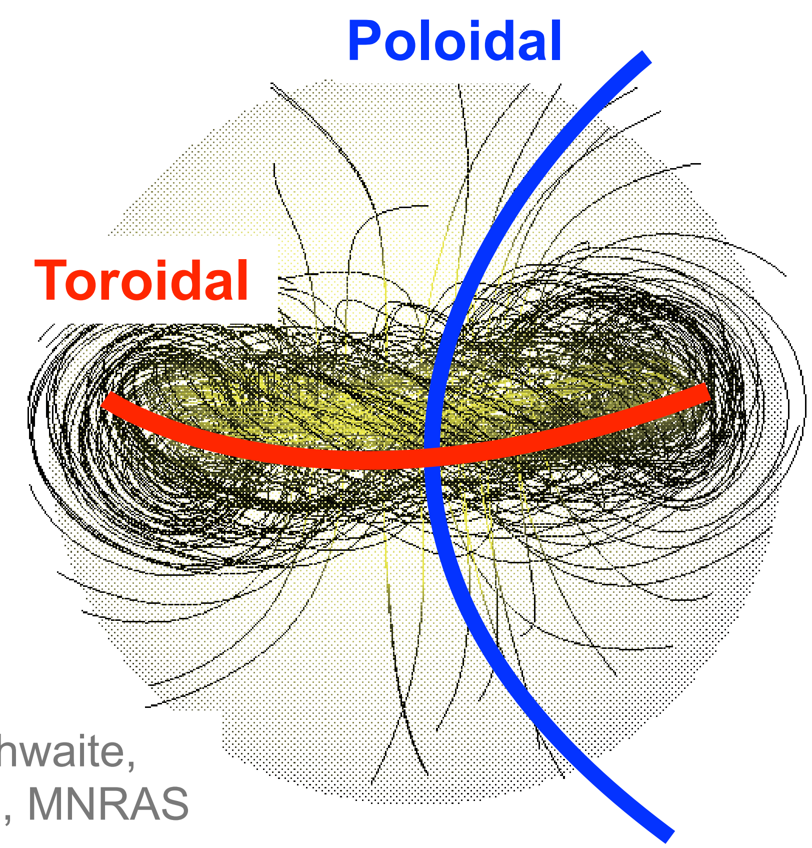
Makishima & Enoto et al., submitted

Interpretation of the Slow Phase Modulation

- **Statistically significant?: YES**
  - Chance probability (Z_4^2=39.2) ~ 4×10^{-6}. (Z_2, Z_3, and Z_4 gave consistent results)
- **Instrumental effect or noise?: NO**
  - Blank-sky data and bright Crab Nebula: Z_4^2 <30
- **Doppler effect of a hidden binary companion? : NO**
  - observed T and A gives $M_c \sim 0.12 M_{sun}/\sin i$ >~ 0.1M_{sun}
  - Inconsistent with pulsed optical properties (likely to emerge from a NS)
- **Free Precession of Isolated NS??**
  - **Poloidal field B_d**
    - can be measured from P and Pdot
    - makes a star the "**oblate**" shape
  - **Toroidal field B_t**
    - can not be measured from P and Pdot
    - makes a star the "**prolate**" shape

$$\epsilon = \frac{\triangle I}{I} \simeq k \times 10^{-4} \left(\frac{B_t}{10^{16}\ \mathrm{G}} \right)^2$$

k=4~9 (Determined by EoS), e.g., Gualtieri et al., 2011

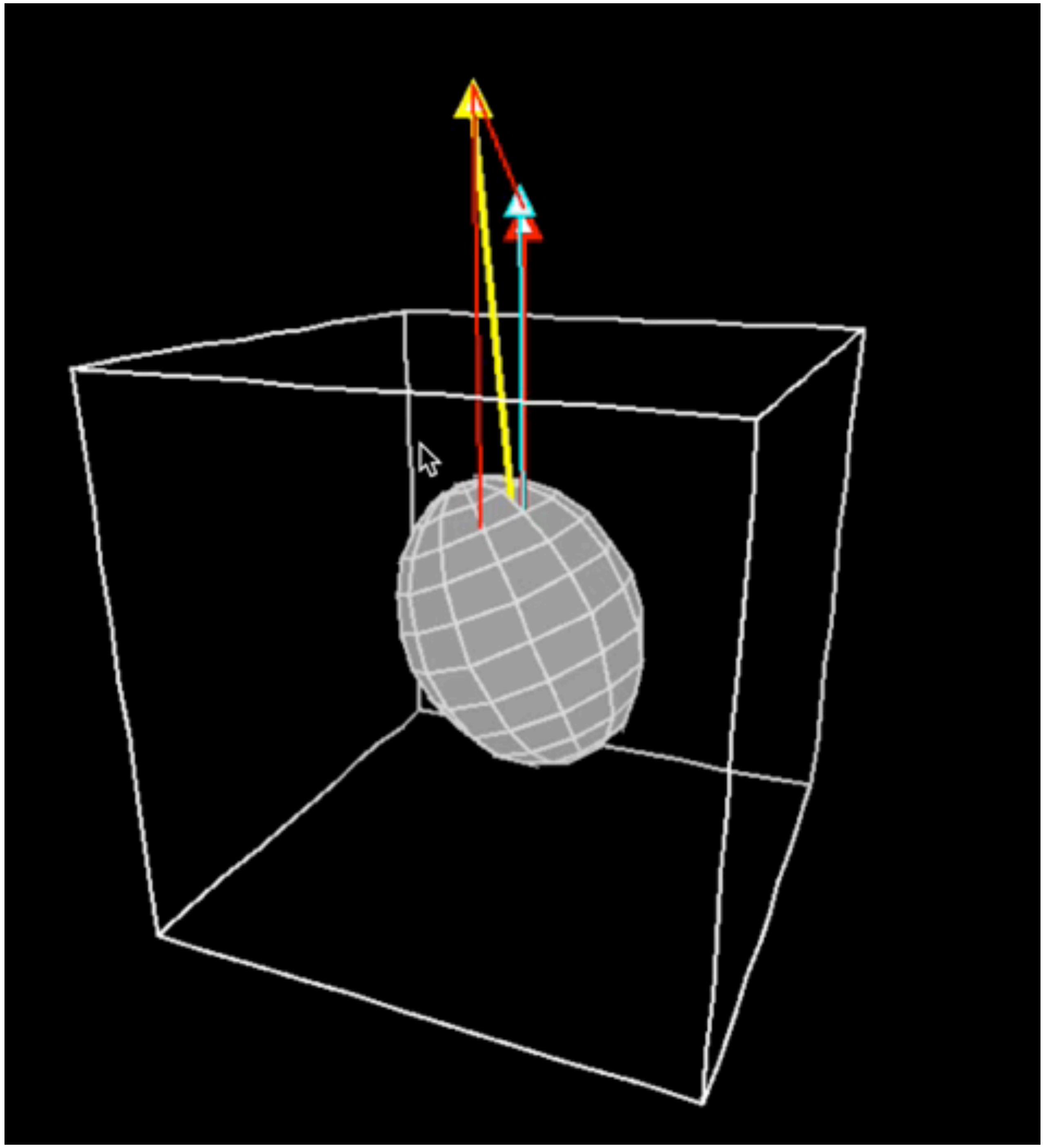


Braithwaite, 2009, MNRAS

NS with strong B_t is deformed into a prolate shape with $\epsilon \sim 10^{-3\sim-4}$

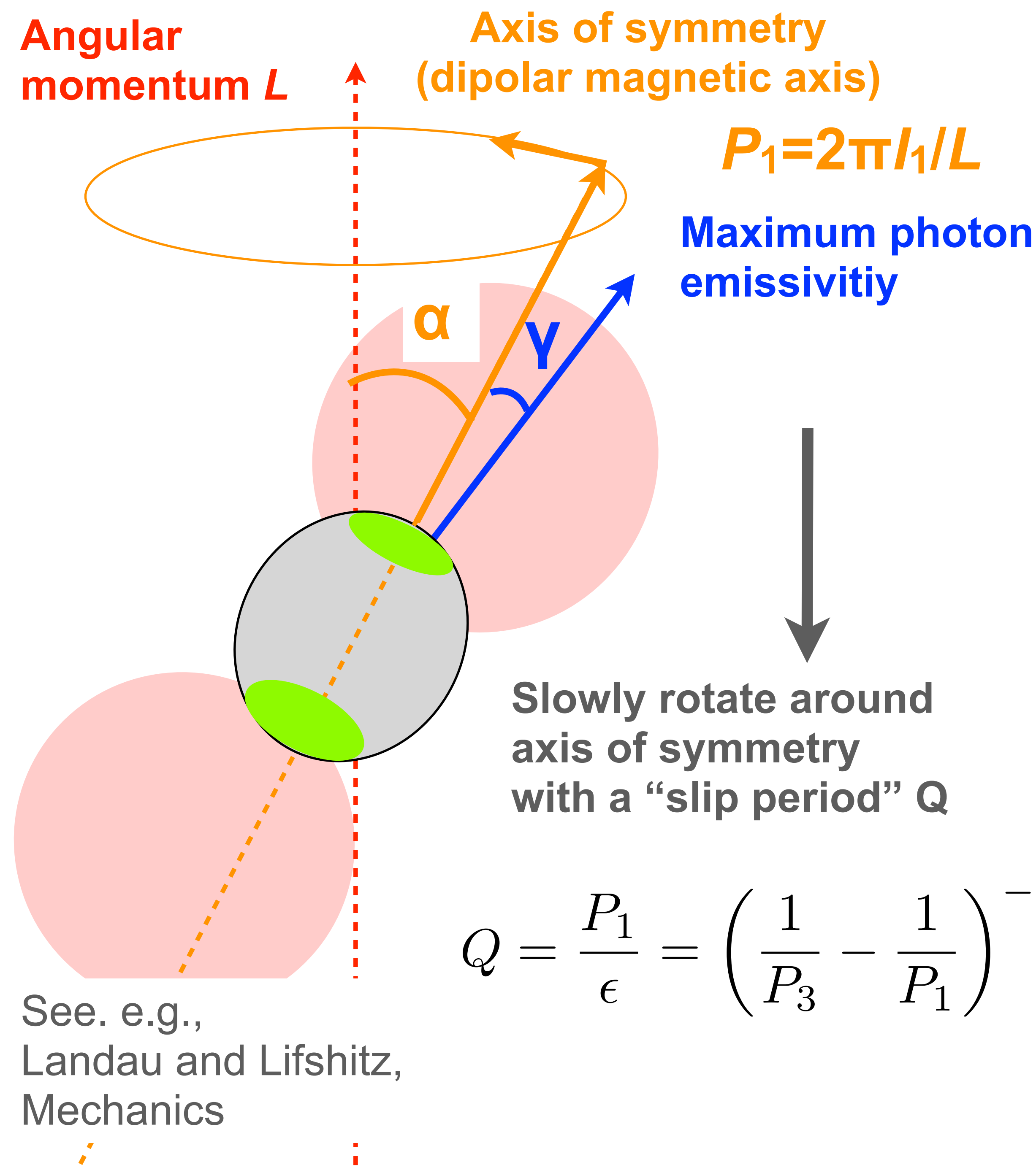
Makishima & Enoto et al., submitted

Free Precession of Axisymmetric Rigid Body



(C) http://faculty.ifmo.ru/butikov/Applets/Precession.html

Three vectors and two angles



$$Q = \frac{P_1}{\epsilon} = \left(\frac{1}{P_3} - \frac{1}{P_1}\right)^{-1}$$

See. e.g., Landau and Lifshitz, Mechanics

Pulse-phase modulation become detectable when the NS is axisymmetric **(ε≠0)** and has a finite wobbling angle **(α≠0)**, and its emission peak direction is deviated from the symmetry axis **(γ≠0)**. **[asymmetry ε]=[Spin period P]/[slip period Q]**

Makishima & Enoto et al., submitted

Evidence on the Toroidal Magnetic Field

Rotation period

$$\epsilon = \frac{P_1}{Q} = \frac{P_{\rm hard}}{T} \sim 1.6 \times 10^{-4}$$

Slip period Phase modulation

$$\epsilon = \frac{\triangle I}{I} \simeq k \times 10^{-4} \left(\frac{B_t}{10^{16}\ \rm G}\right)^2$$

k=4~9 (Determined by EoS)

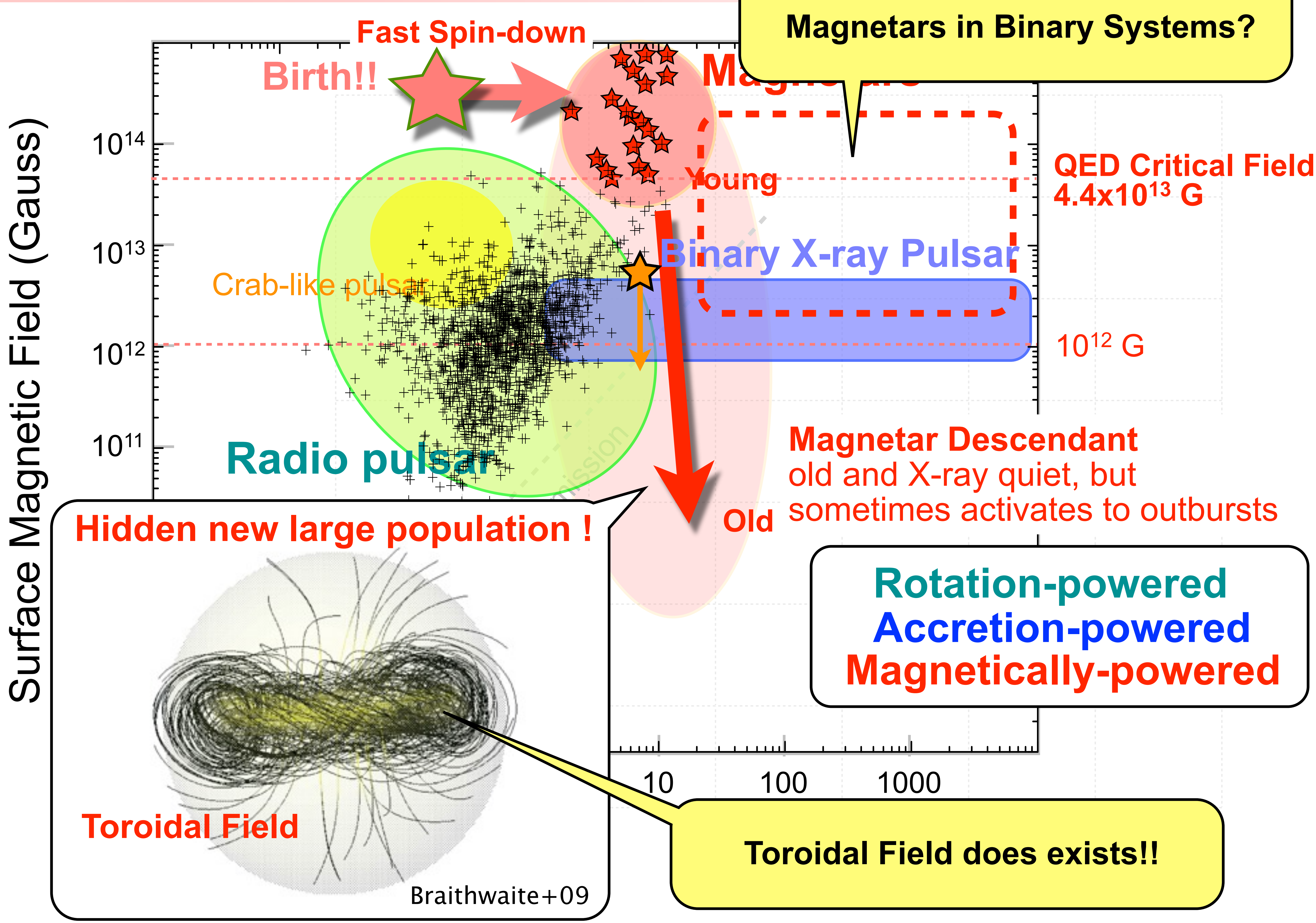
Observational evidence for toroidal field, B_t~$10^{15\text{-}16}$ G, inside the NS.

- Why 4U 0142+61 shows such a signature?
  - Two components (Soft and Hard X-rays) is effectively used to detect the signature.
  - γ≠0 is fulfilled. B-field configulation (multipole component) may wander around on the star.
- Comparing other types of X-ray pulsars?
  - Accretion-powered: forced precession
  - Fast-rotating: centrifugal force makes the NS oblate and precession would be damped.

Evidence for the toroidal magnetic field is suggested by the Suzaku observation.

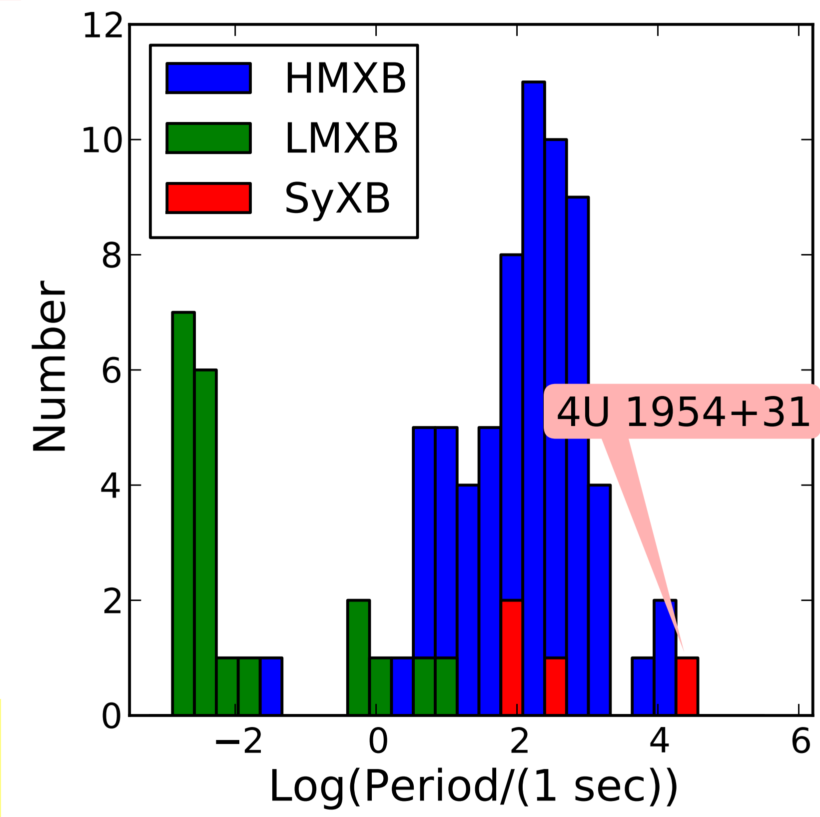
Makishima & Enoto et al., submitted

Diversity of Neutron Stars

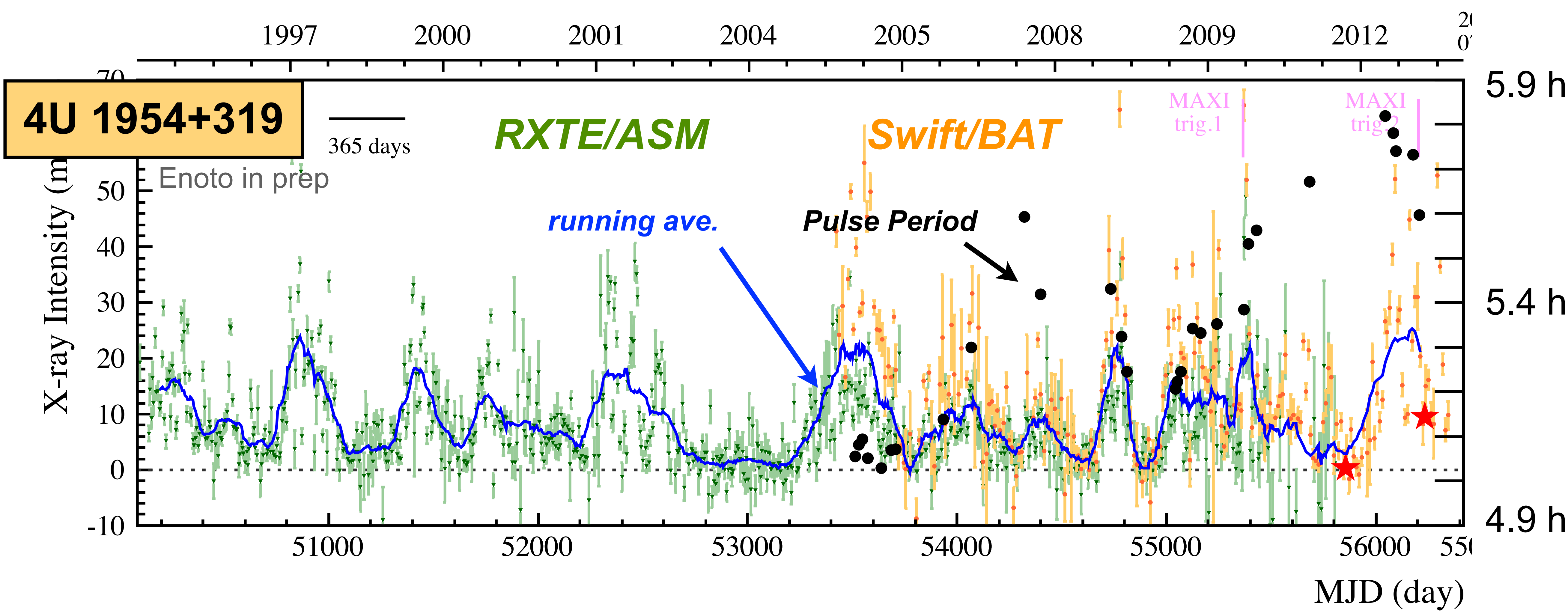


Magnetars in X-ray Binaries?

- Long Period Pulsars in X-ray Binaries
  - P~1.6 hour (IGR J16358-4726; Patel+2007)
  - P~1.6 hour (4U 2206+54; Reig+2002)
  - P~2.7 hour (4U 0114+65; Li+1999)
  - P~5.4 hour (4U 1954+319; Corbet+2008)
- Standard accretion theory (Gosh & Lamb 1979)
  - $P_{eq} \approx 7\mu_{30}^{6/7}\dot{M}_{16}^{-3/7}$ s, ⇒ B~$10^{14\text{-}16}$ G?



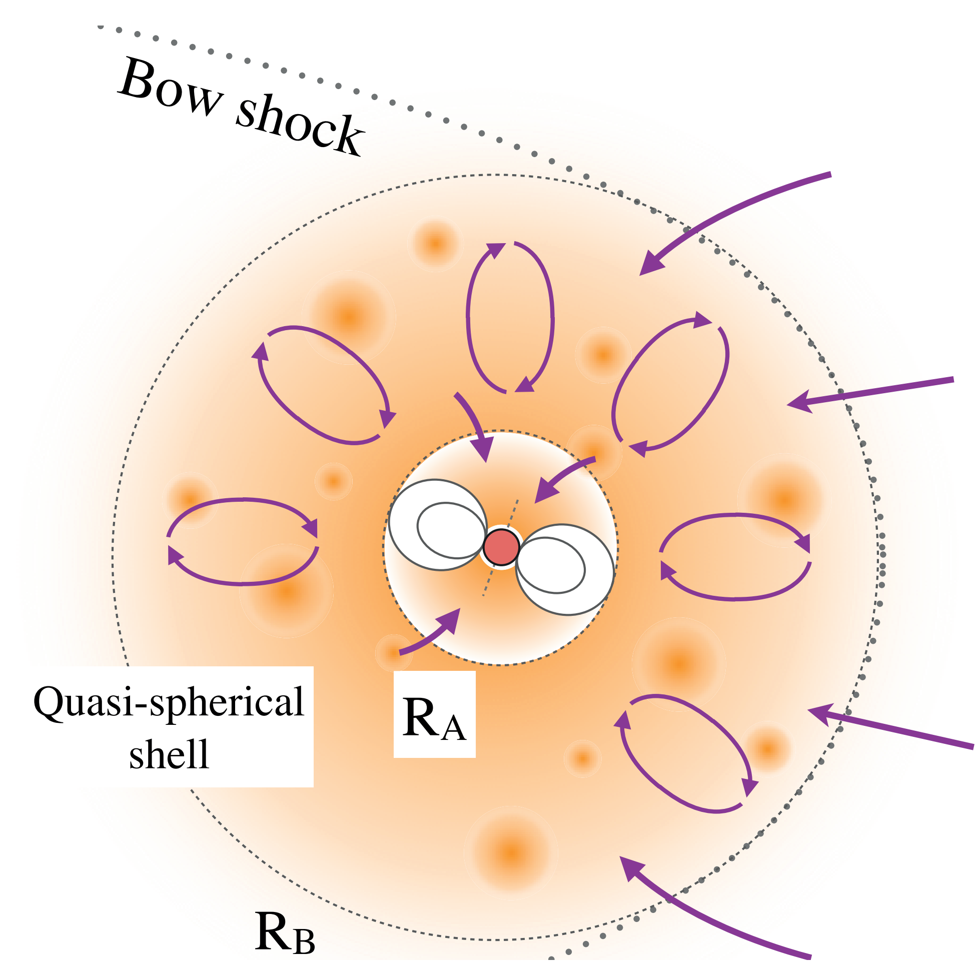
Magnetars? Or alternative new accretion theory?

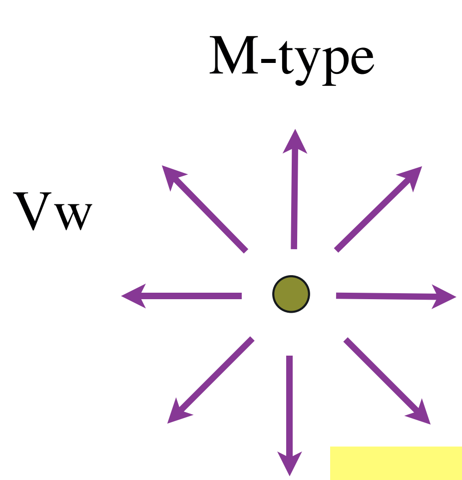


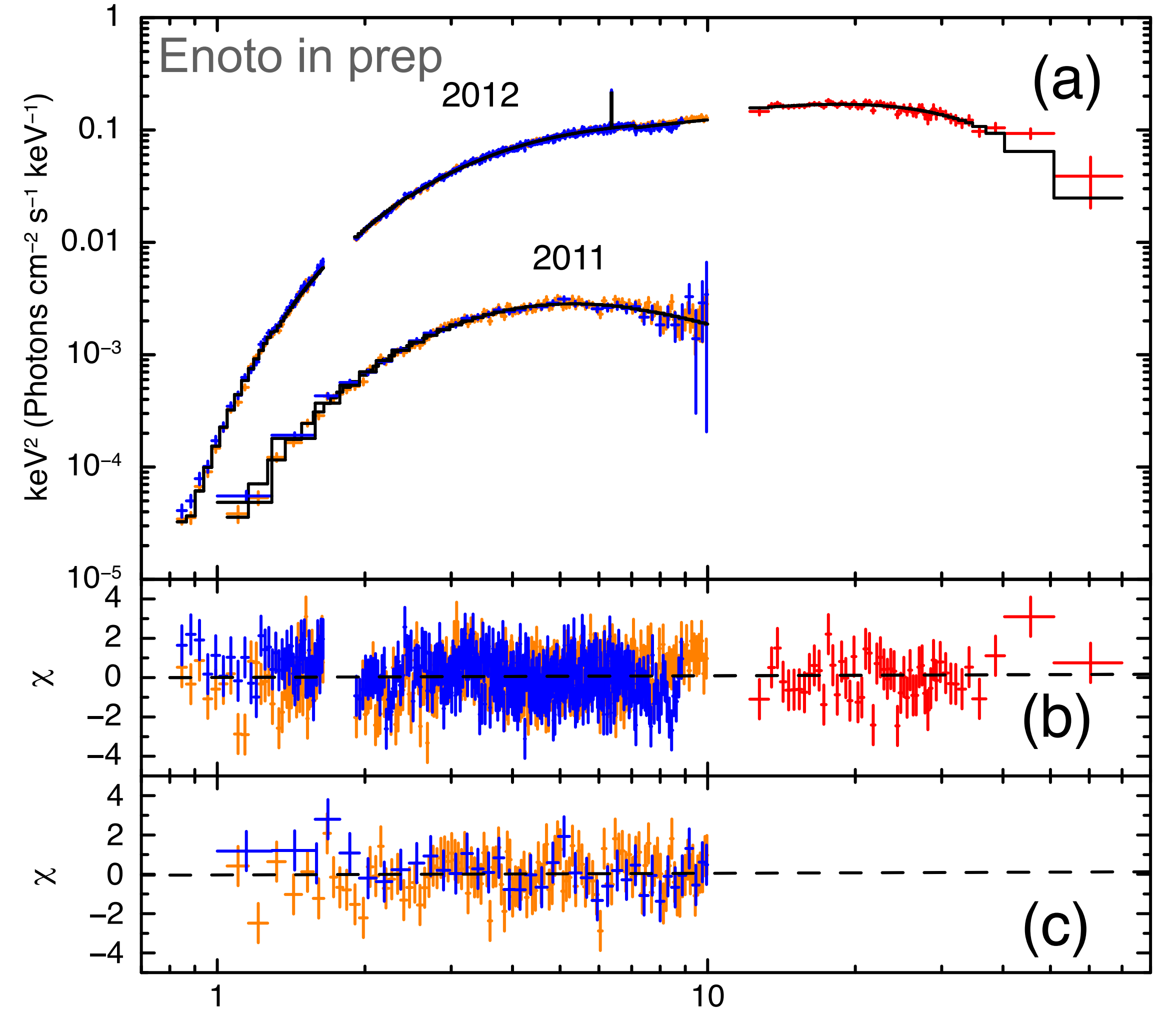
Slowest Rotating X-ray Pulsar 4U 1954+319

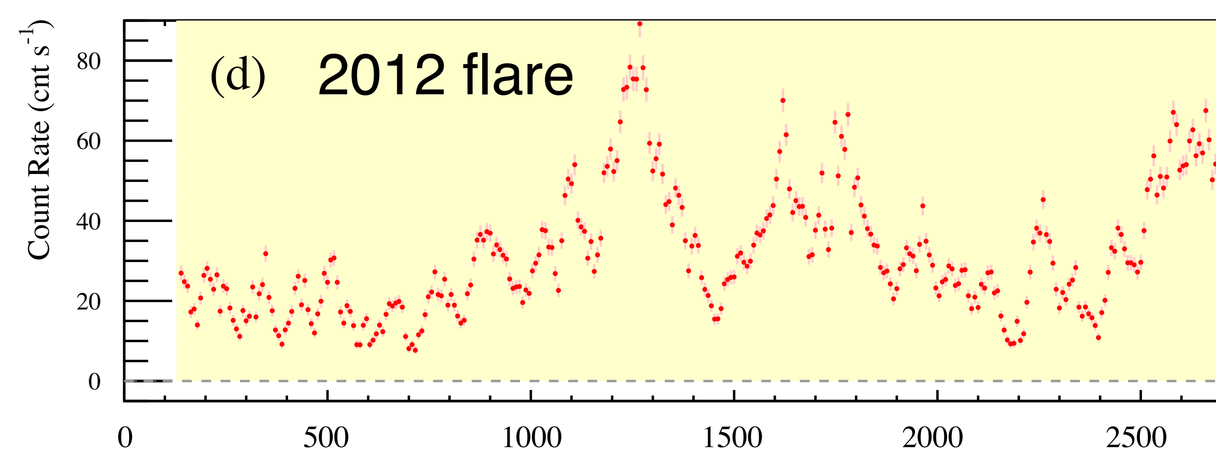
- Observational Property with Suzaku
  1. Slowest spin period P~5.4 hour
  2. High pulsed fraction 50-90%
  3. ~100 sec shot-like burst
  4. Hard X-ray spectrum
- Magnetars? ⇒ No burst activity
- Quasi-spherical accretion (Shakura+2010)?

$$P_{\rm eq} \simeq 13000\ \mu_{30}^{12/11} \dot{M}_{16}^{-4/11} v_8^4 \left(\frac{P_{\rm orb}}{100\ {\rm day}}\right)\ {\rm s},$$







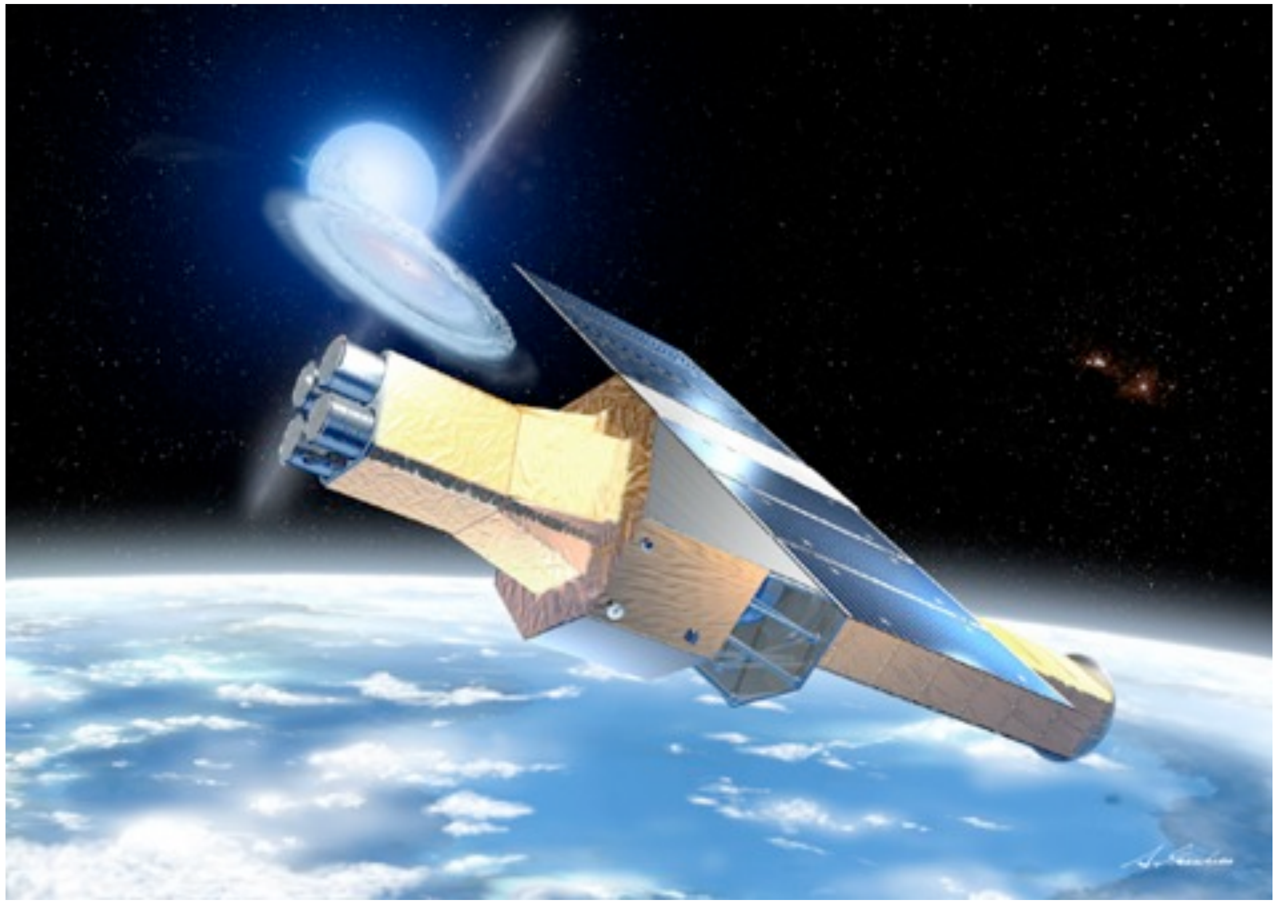


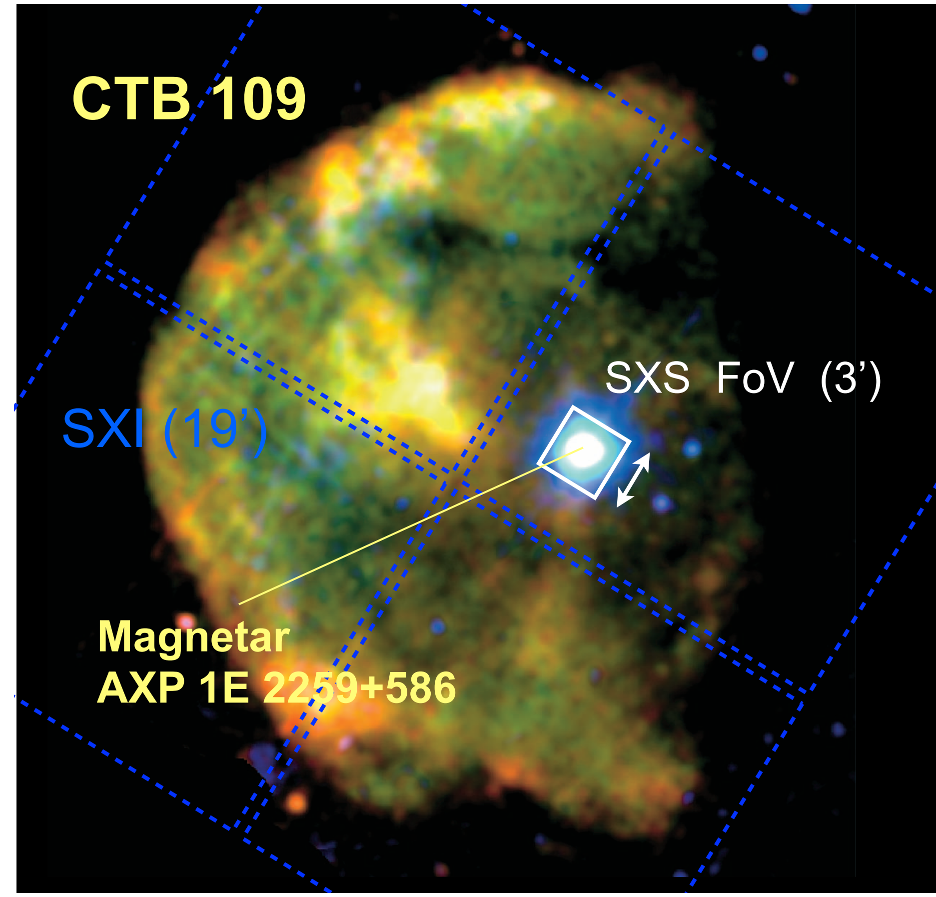
Long spin pulsar ~ $10^{12\text{-}13}$ G pulsar ?

Enoto to be submitted

Next X-ray Observatory: ASTRO-H

Broad-band and high resolution spectroscopy: Japan-US collaboration

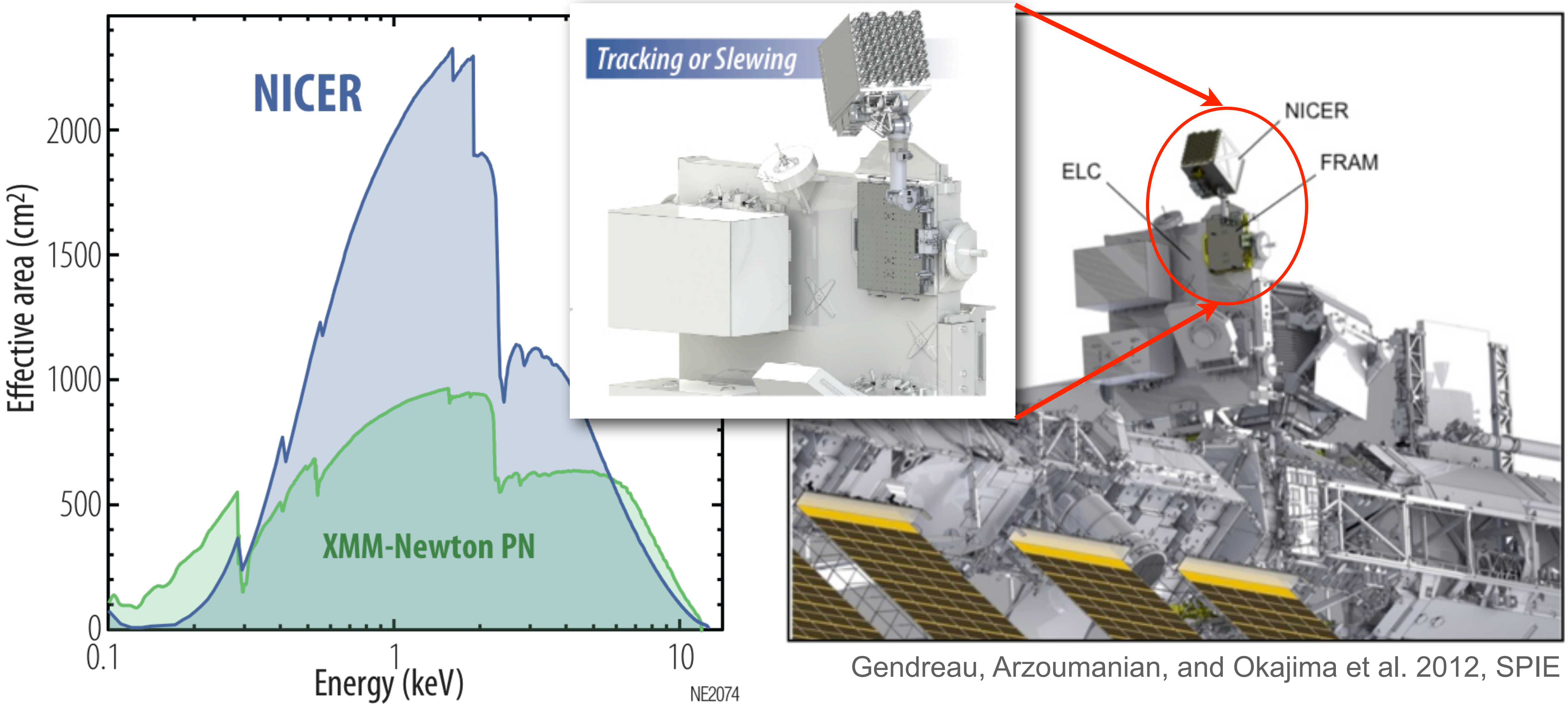




- Broad-band (0.2-600 keV) spectroscopy with high sensitivities.
- High energy resolution (a few eV) in the soft X-ray band using the calorimeter.
- Science challenges towards NSs and magnetars
  - Search for proton cyclotron from magnetars and determine the B field.
  - Study of NS and magnetar atmosphere models
  - Precise measurements of supernova remnant of magnetars: Their birth environment
  - Hard X-ray power-law and their origin related with QED physics.

Neutron star Interior Composition ExploreR (NICER)

Approved as a NASA Explorer Mission of Opportunity



Gendreau, Arzoumanian, and Okajima et al. 2012, SPIE

- Soft X-ray (0.2-12 keV) timing (<300 ns reso.) spectroscopy with a large effective area
- 56 modules of Grazing-incidence optics coupled with silicon drift detectors
- Payload to the International Space Station (ISS) in 2016
- High precision measurement of NS Mass and Radius: the EoS and NS interior
    - Phase-resolved spectroscopy method of NS hot spots, Shapiro delay in X-rays

Summary

- Recent discoveries of transient magnetars have increased number of the “magnetar” class.
- The non-thermal hard X-ray component was discovered both in persistent magnetars and transient sources.Relative luminosity between soft and hard X-ray components shows spectral evolution as a function of the magnetic field and age.
- 1.5-hour phase modulation was detected. This is interpreted as a free precession due to toroidal magnetic field embedded in the magnetar interior.
- Long period pulsars were recently discovered in X-ray binaries. These become magnetars if following to the standard accretion theory, but can be regarded as $10^{12\text{-}13}$ G pulsars if different accretion model are assumed.