Observational Indication with Suzaku on the Toroidal Magnetic Field inside a Magnetar

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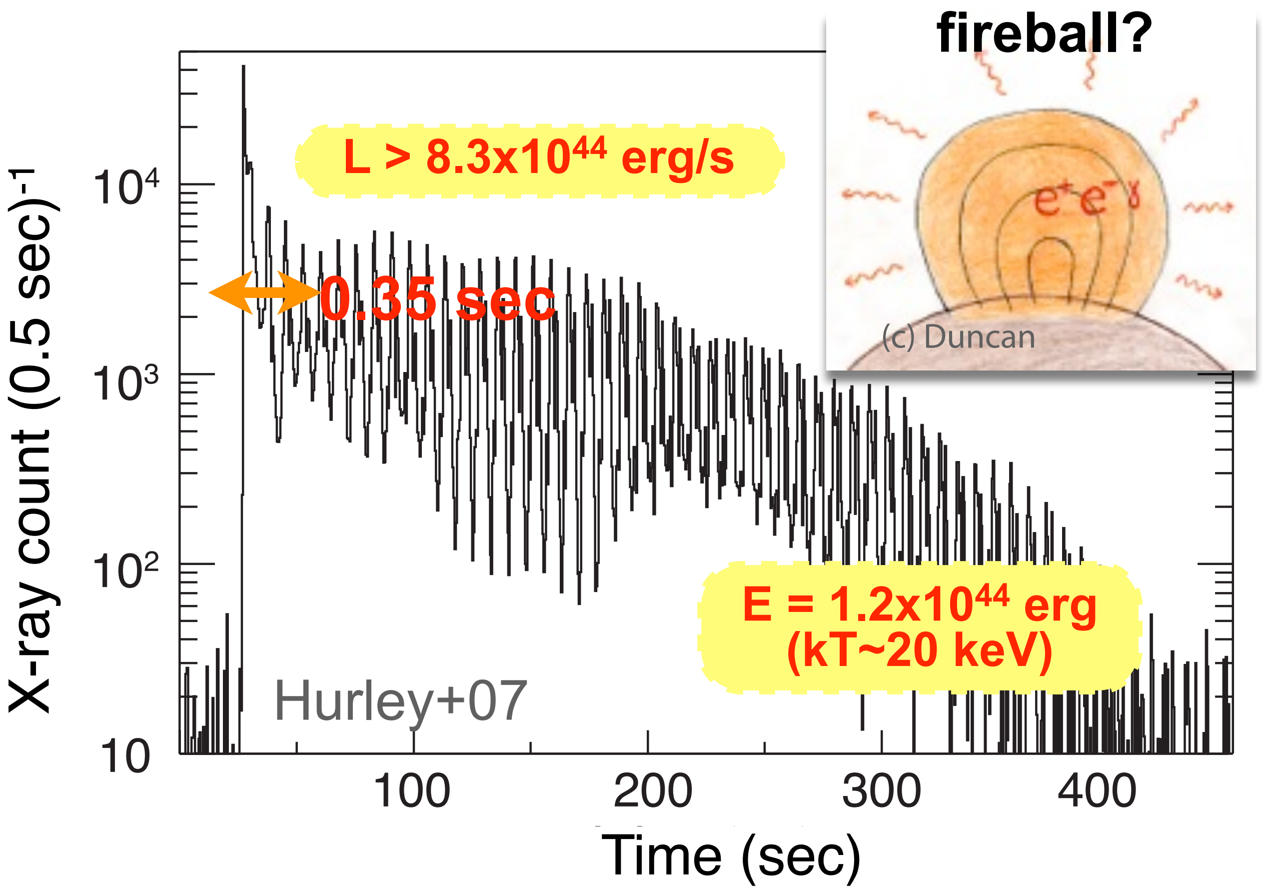
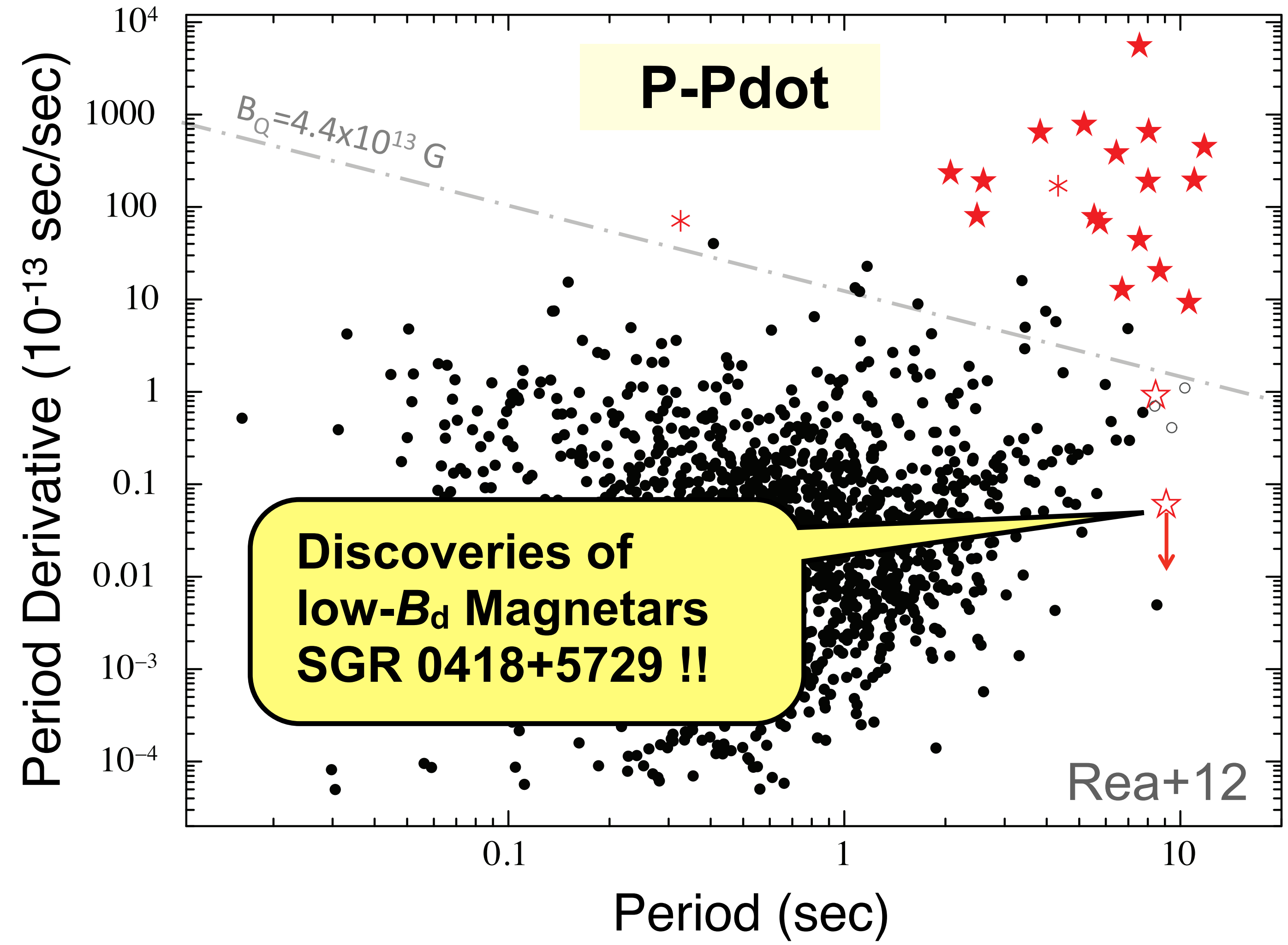
Makishima and Enoto, et al. submitted

Magnetars

Giant Flare in 2004
Soft Gamma Repeater SGR 1806-20





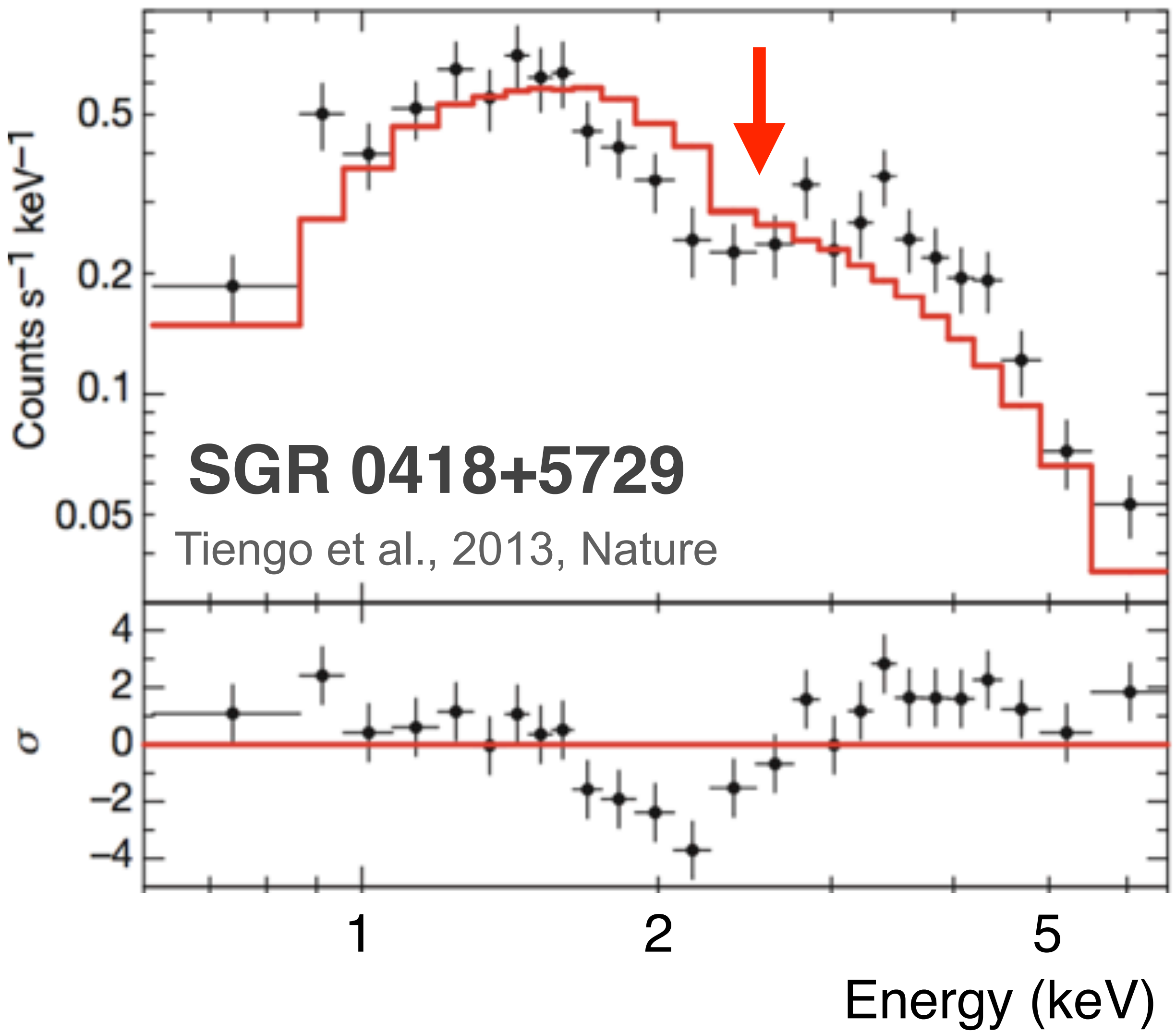
- Soft Gamma Repeaters (SGRs) and Anomalous X-ray pulsars (AXPs)
  - Supper Eddington giant flares, short bursts, and X-ray outbursts
  - Dipole magnetic field B_d~$10^{14\text{-}15}$ G via *P*-*P*dot measurements
  - Bright X-ray emission $L_x >> L_{spin\text{-}down}$, No evidence for optical companion (binary)
  - Connection to extra-galactic events (GRBs etc), GW and NS interior

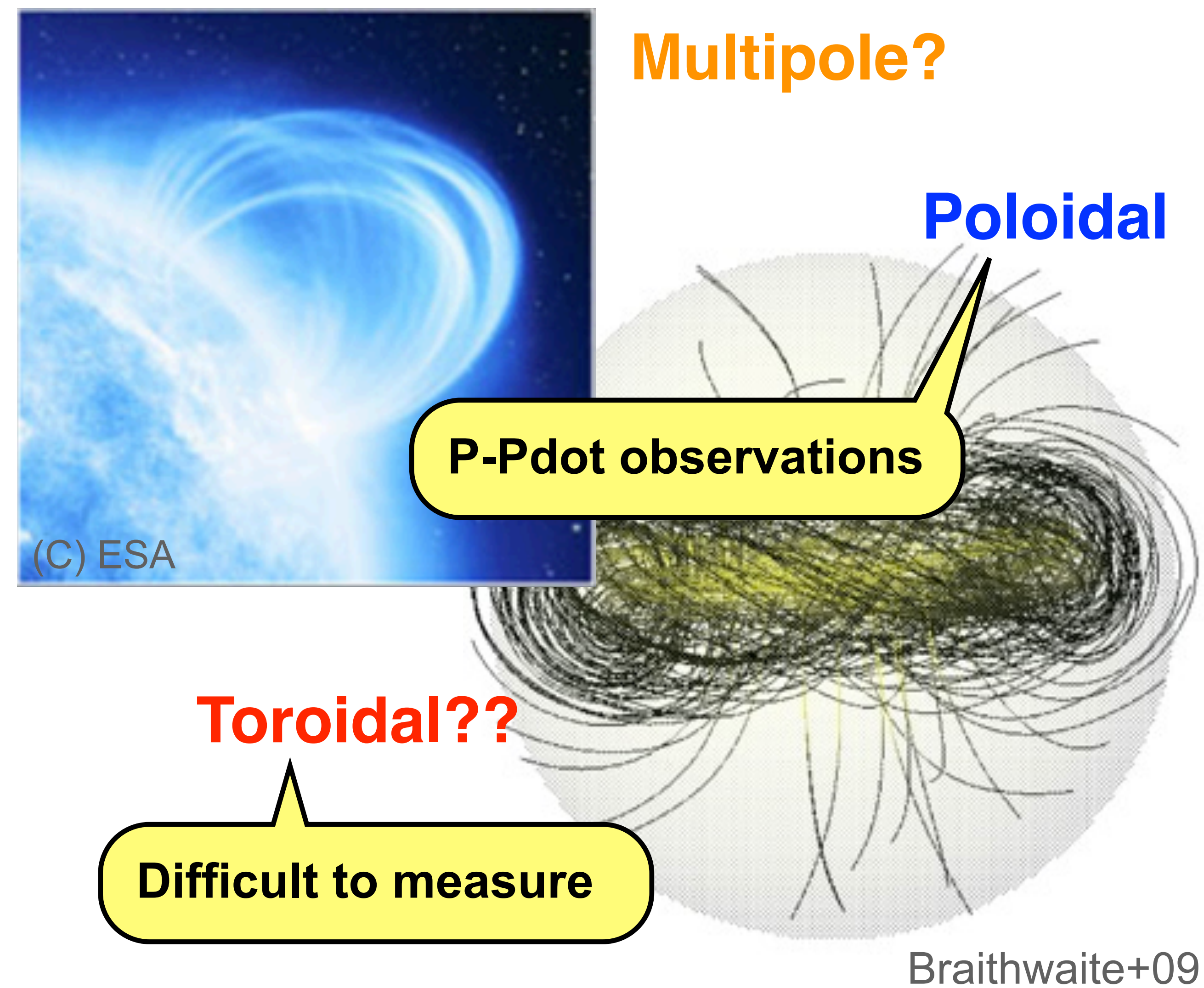
Magnetar activities are supported by dissipation of magnetic energy?

Signatures of Toroidal Field

- Low-B_d magnetars (B_d < 3.3x10^{13} G): SGR 0418+5729 and Swift J1822.3-1606
  - Magnetar burst activity requires high-B field (>B_d~6x10^{12} G)? Toroidal field?
  - Short-burst originates from reconnection? Higher multipoles?
- Discovery of proton(?) cyclotron signature in SGR 0418+5729
  - Strong multiple signature with B>2x10^{14} G near the NS surface
- Simulations of the toroidal field inside the NS (e.g., wound-up at the birth)

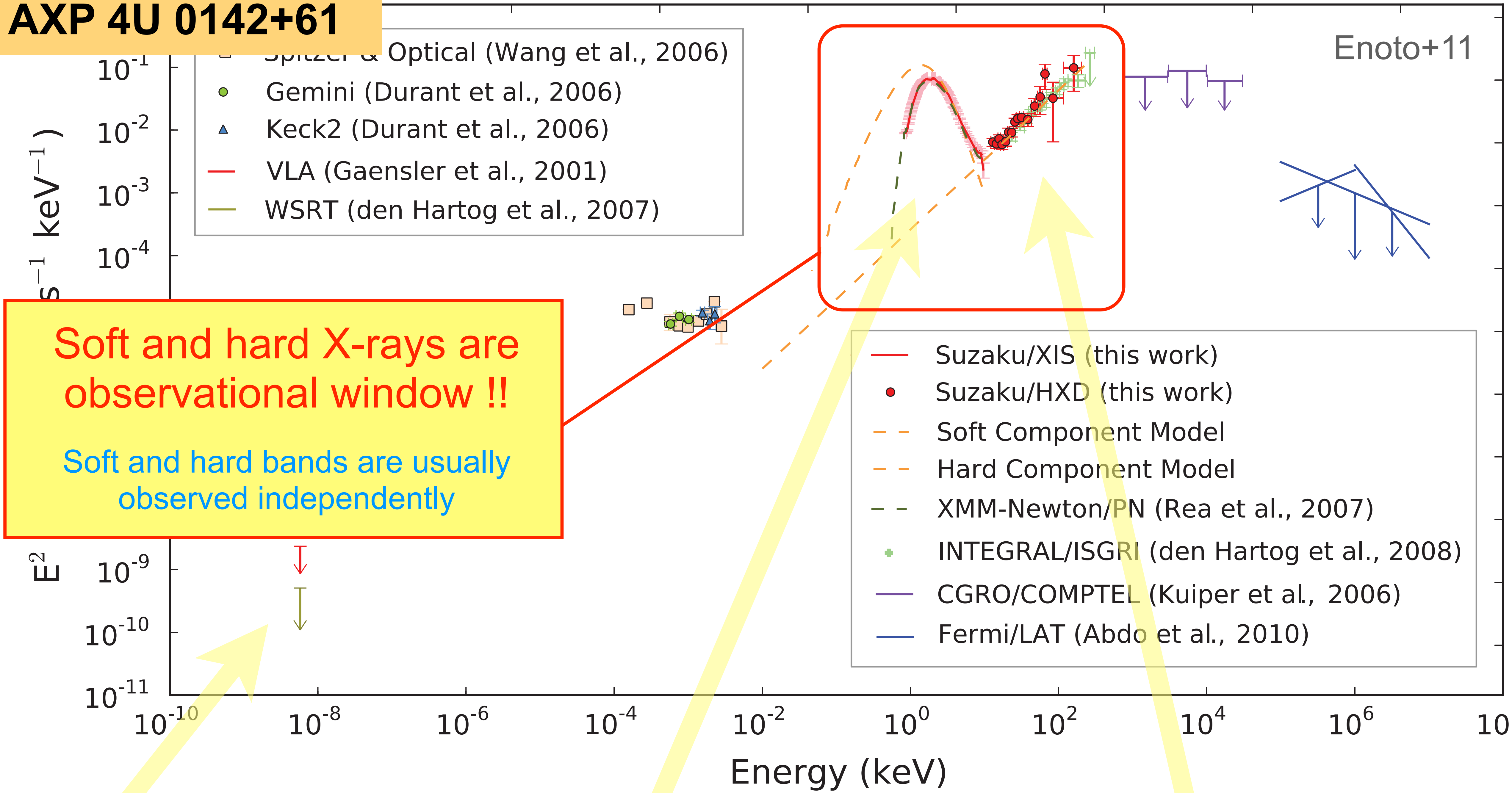
Energy source of magnetars = Poloidal + "Toroidal" Magnetic field ?





Magnetar Multi-wavelength Emissions

AXP 4U 0142+61



Soft and hard X-rays are observational window !!

Soft and hard bands are usually observed independently

No radio emission

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

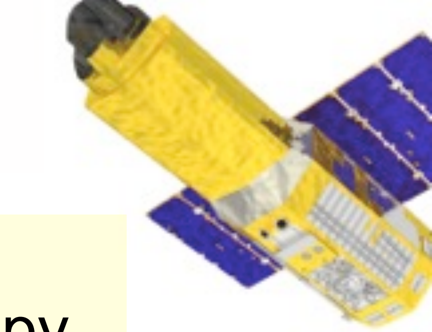
Pulsed thermal emission

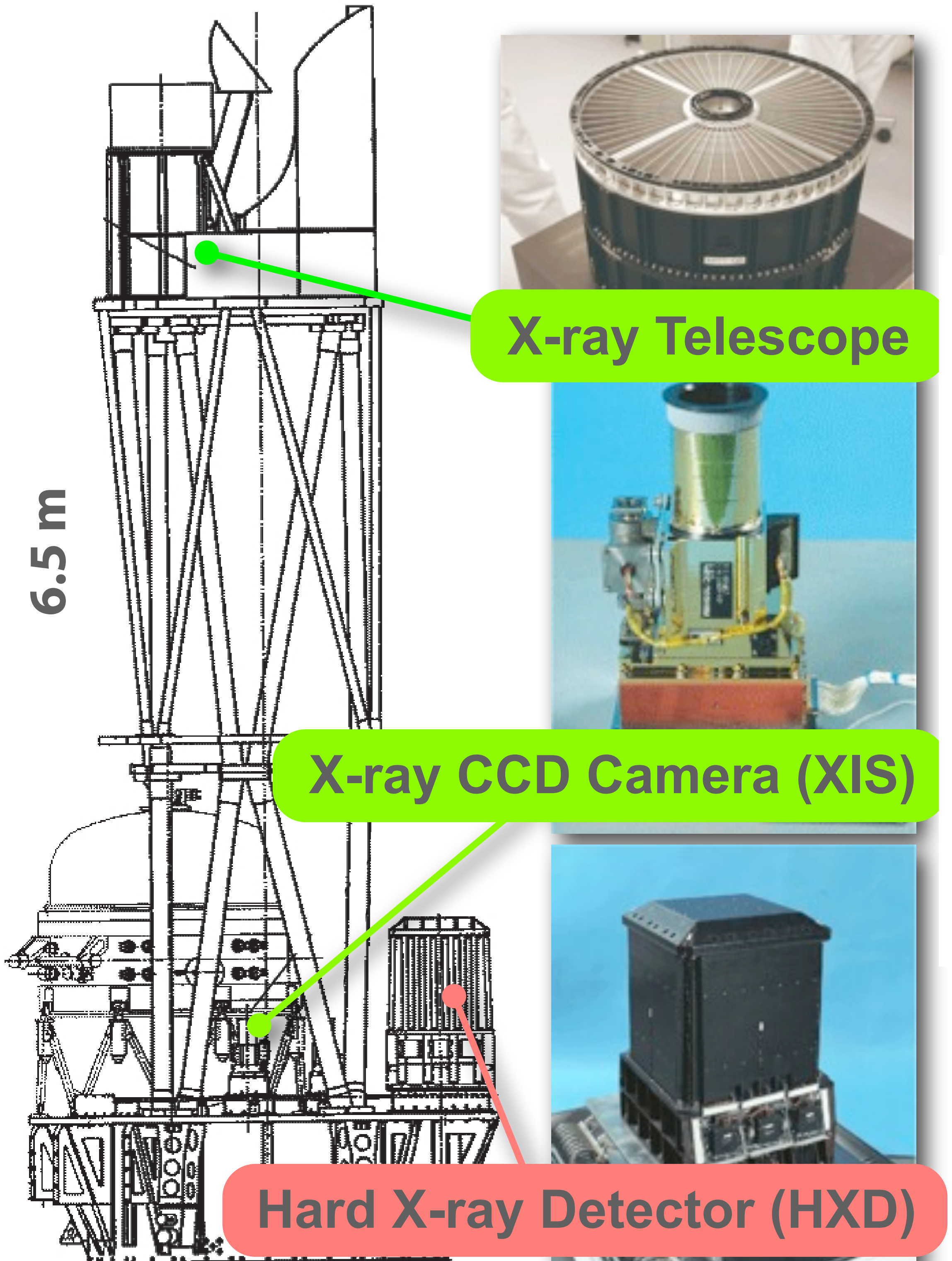
from hot NS surface.
Quasi-BB *kT* ~ 0.3 keV
heated by the interior field

Pulsed hard X-rays

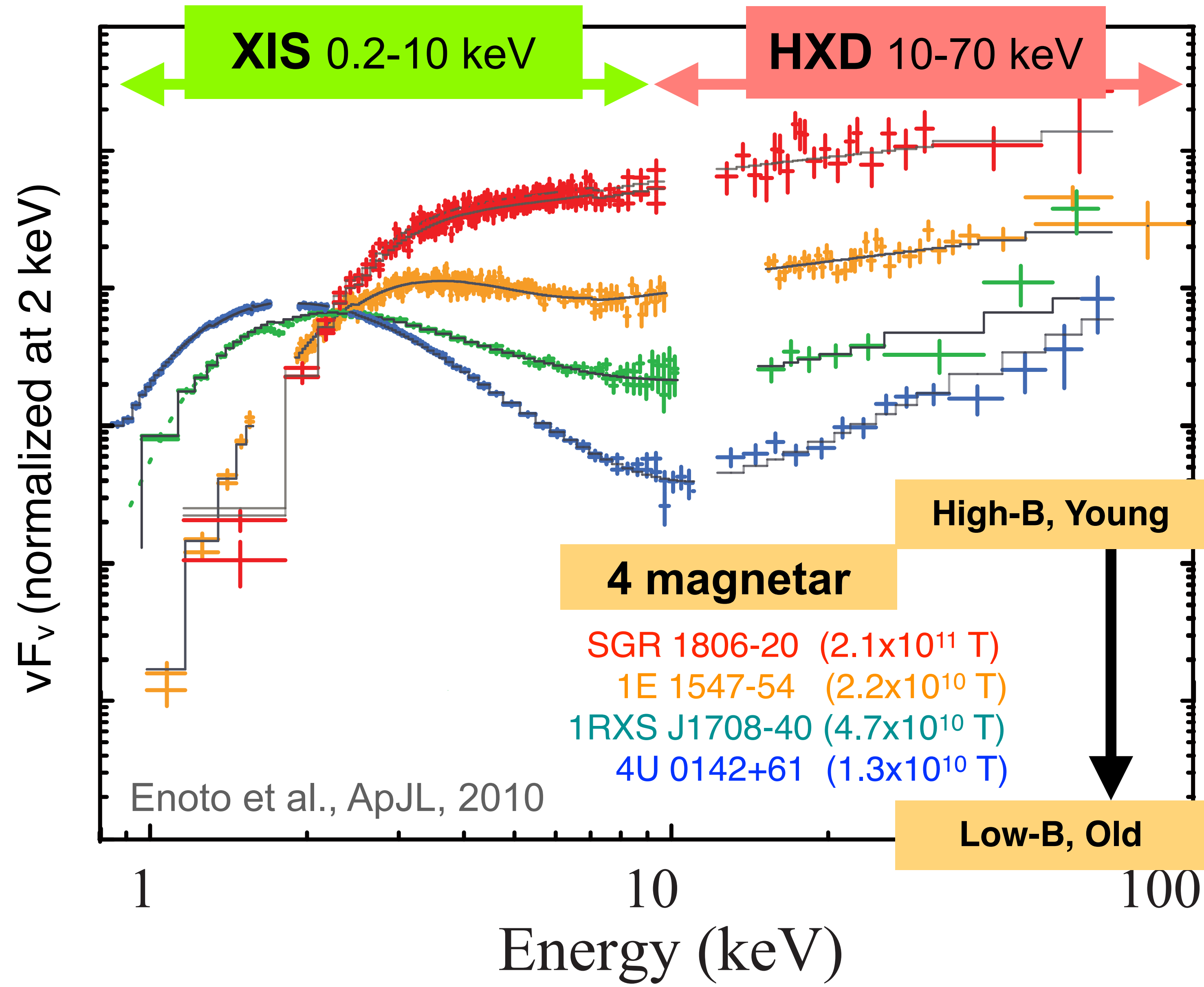
Discovered by INTEGRAL
hard photon index Γ~1
upper limit >750 keV

X-ray Observatory: Suzaku





launched in 2005
0.5--70 keV broadband spectroscopy

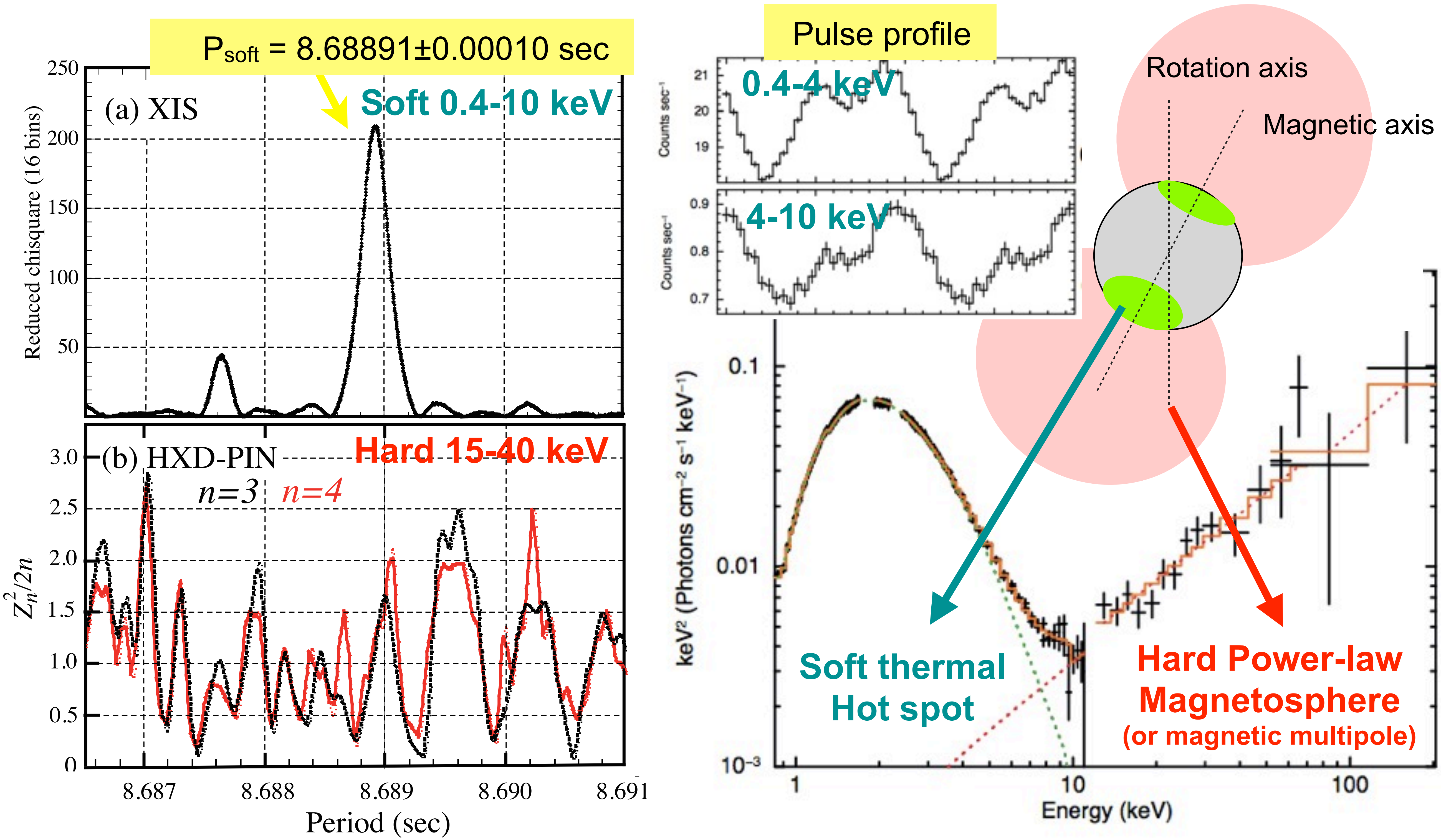


Based on systematic studies of 7 SGRs AXPs, Suzaku revealed that magnetar spectral shape evolves as a function of magnetar characteristic age and magnetic field strength.

Suzaku simultaneously observes soft and hard X-rays with a short exposure.

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)

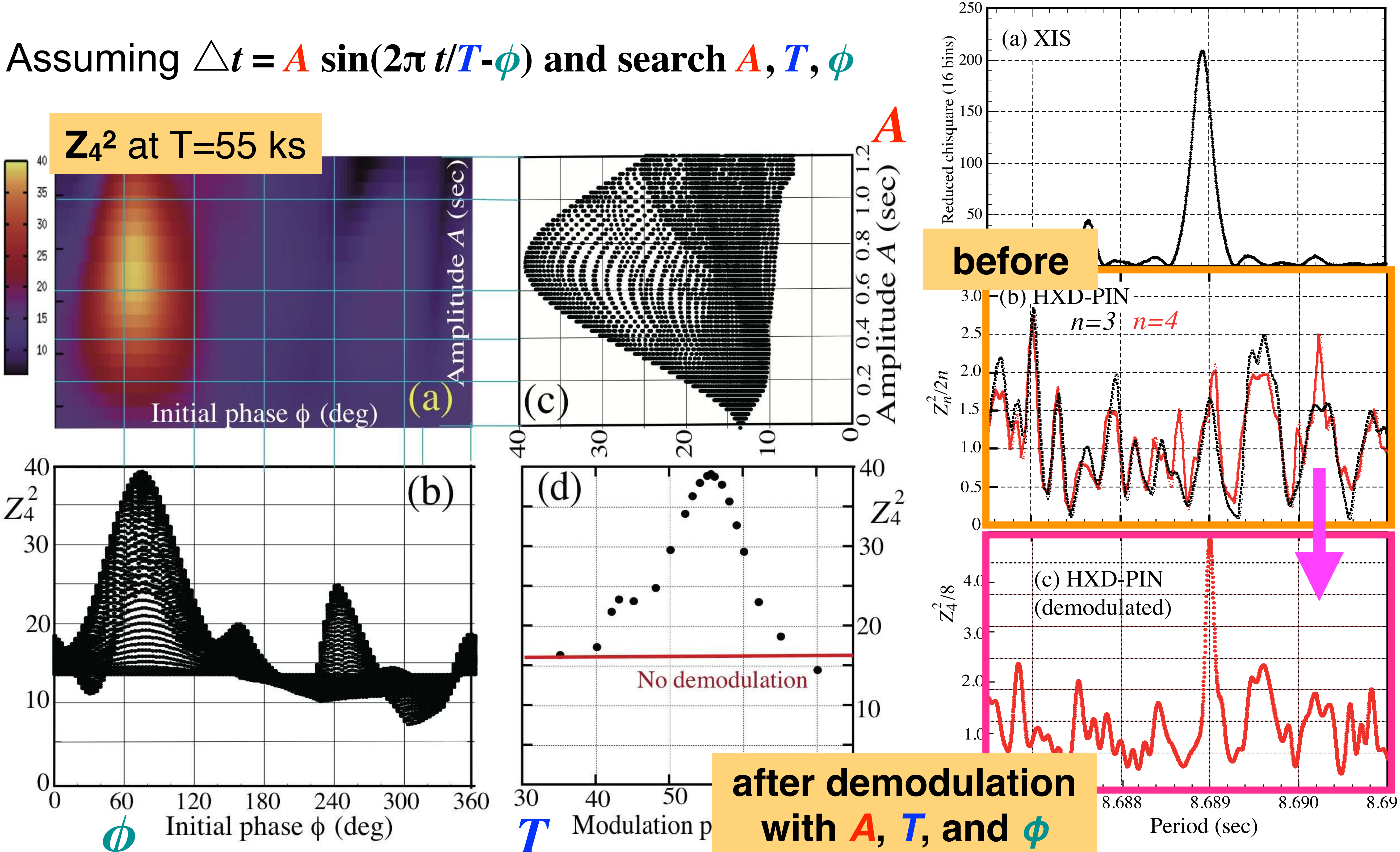


8.69 sec pulsation signal was weak in hard X-rays in the 2009 observation.

Makishima & Enoto et al., submitted

Slow Phase Modulation?

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

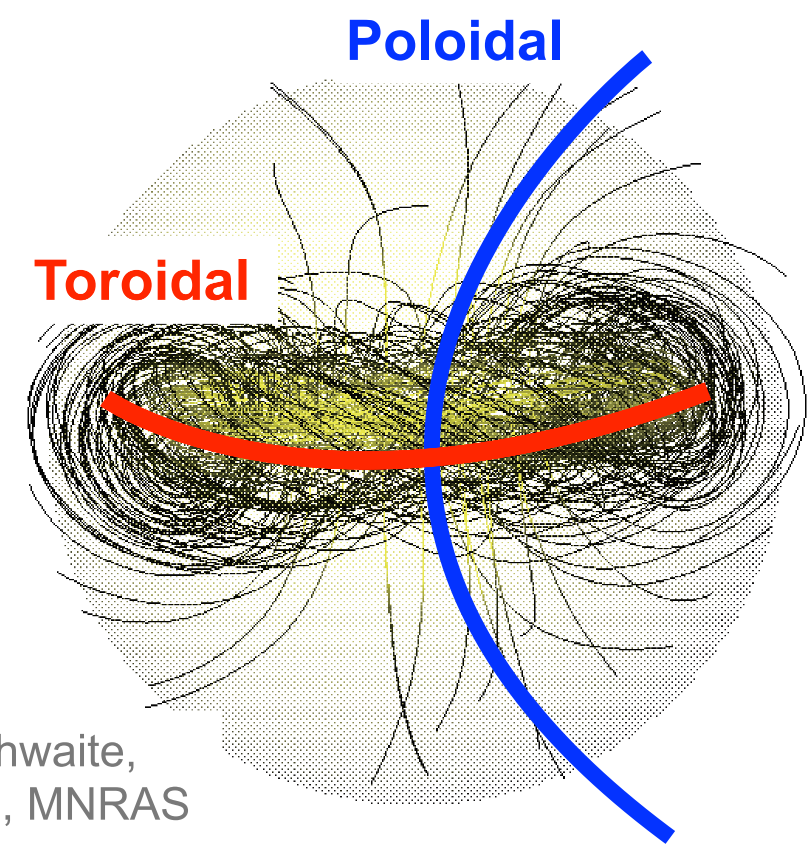


Hard X-ray (15-40 keV) shows phase modulation by A=0.7 sec with a T~1.5 h.

Makishima & Enoto et al., submitted

Interpretation of the Slow Phase Modulation

- **Statistically significant?: YES**
  - Chance probability (Z_4^2=39.2) ~ 4x10^{-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~0.12M_{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



Braithwaite, 2009, MNRAS

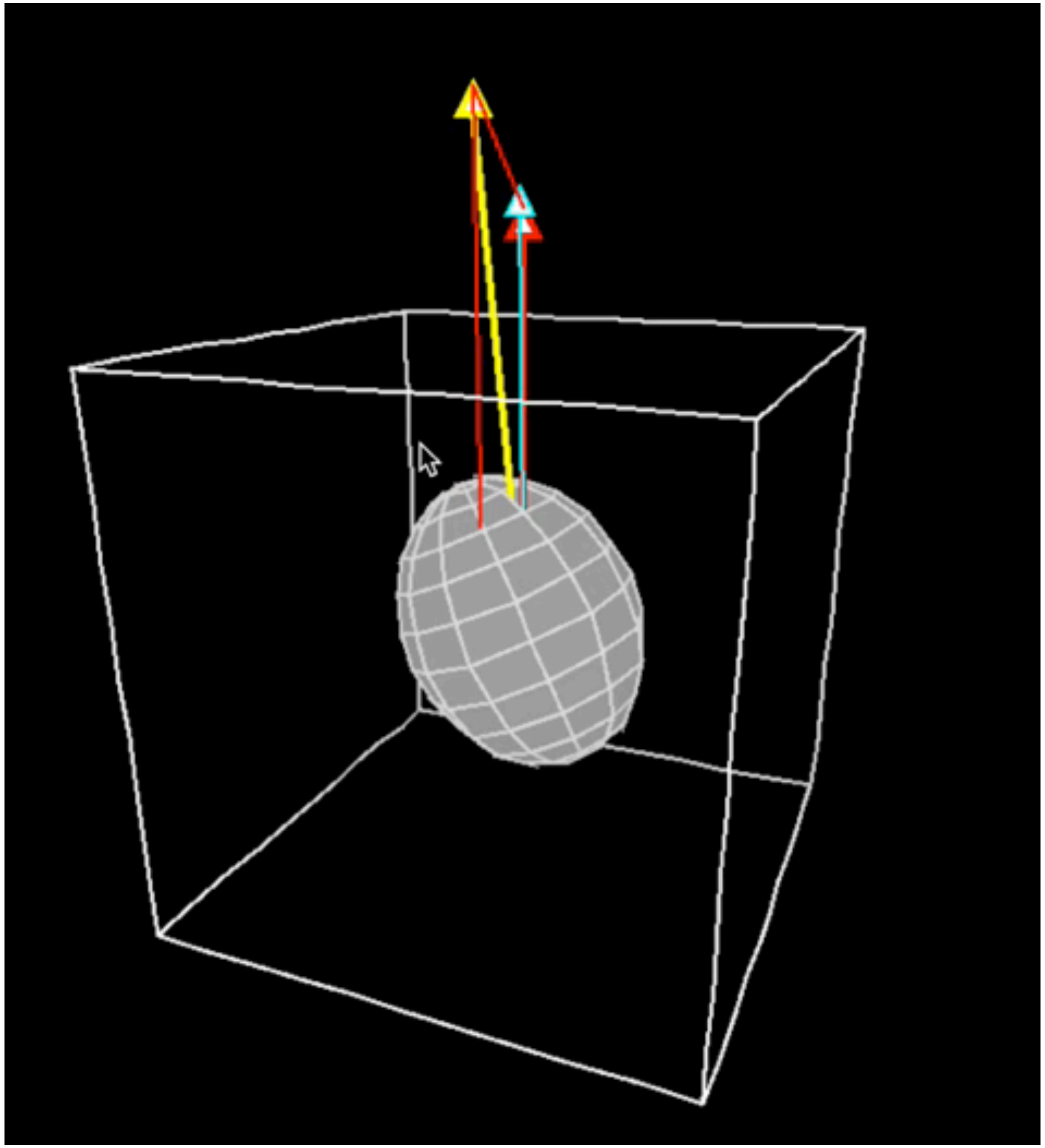
$$\epsilon = \frac{\triangle I}{I} \simeq k \times 10^{-4} \left(\frac{B_t}{10^{16}\ \mathrm{G}} \right)^2$$

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

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

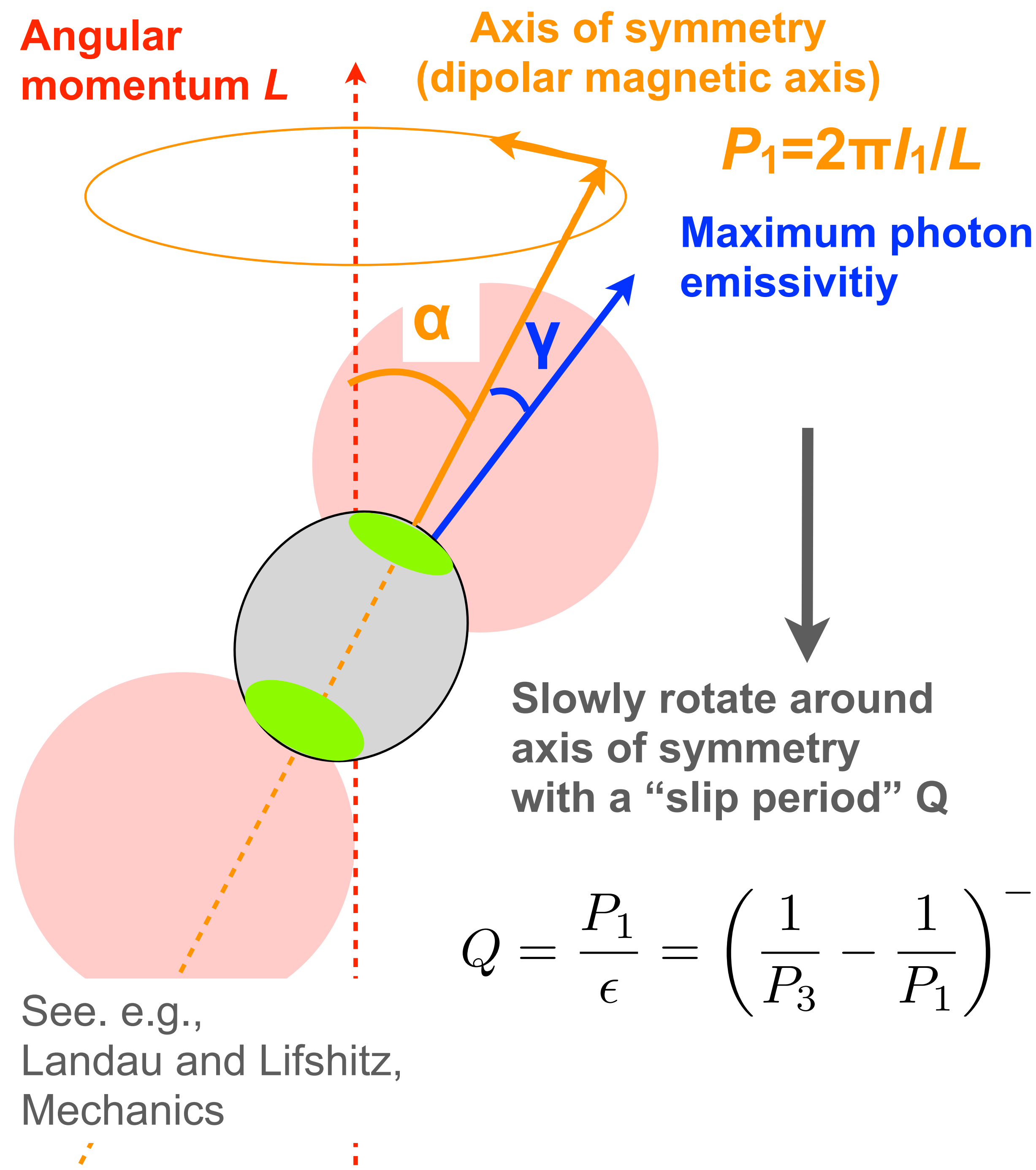
Makishima & Enoto et al., submitted

Free Precession of Axisymmetric Rigid Body



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

Three vectors and two angles



Slowly rotate around axis of symmetry with a "slip period" Q

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

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

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

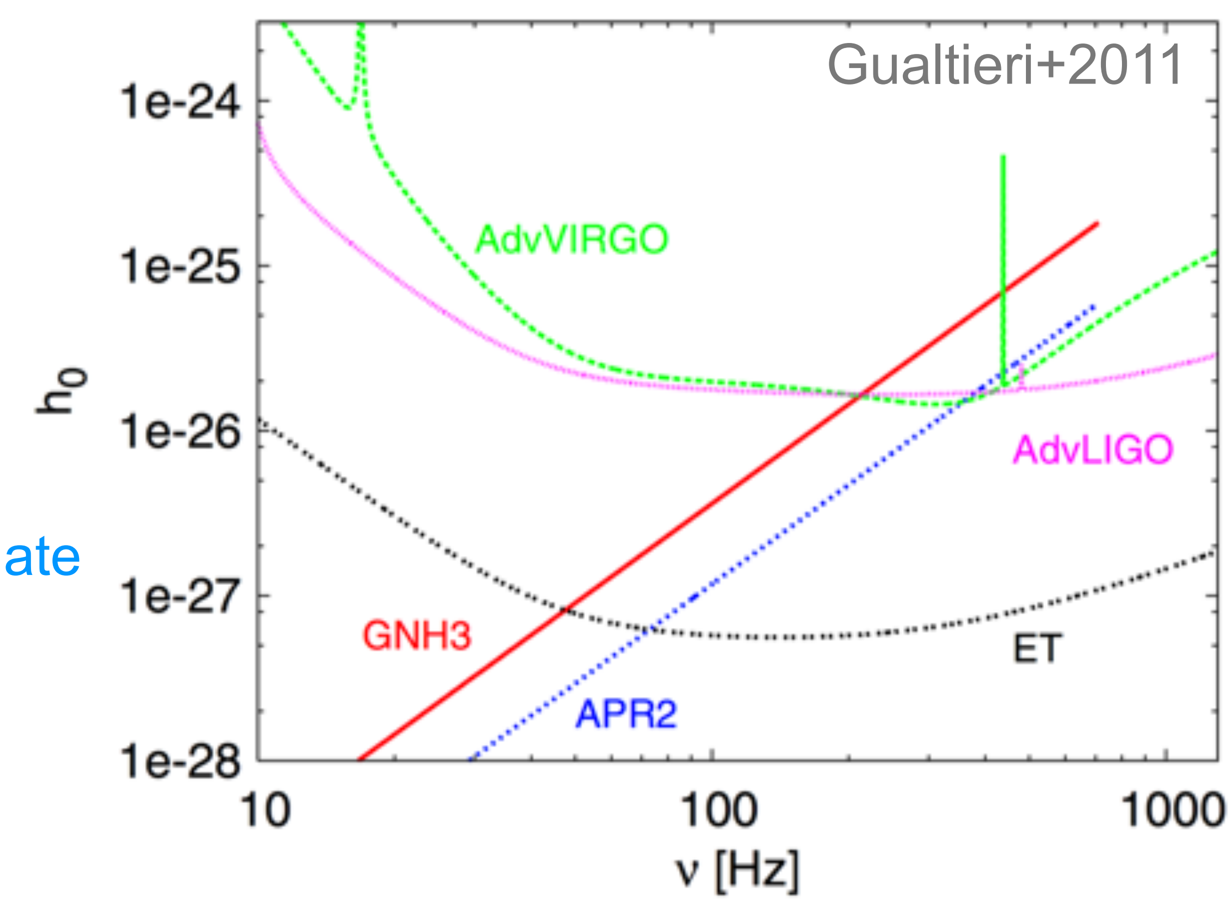
Slip period   Phase modulation

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

k=4~9 (Determined by EoS)

Observational evidence for toroidal field, $B_t \sim 10^{15\text{-}16}$ 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.
- **Gravitational waves from Giant Flare or newly-born magnetars.**

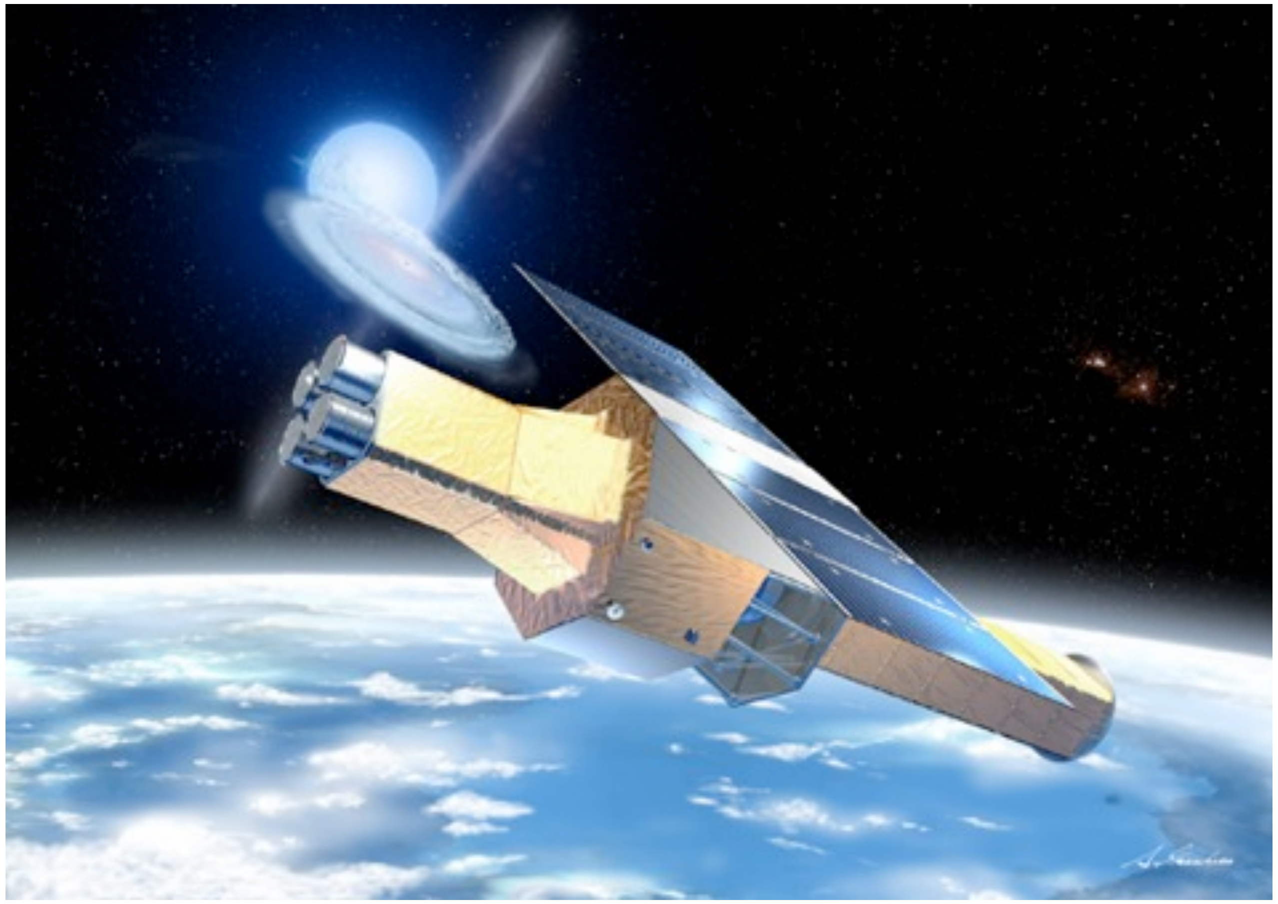


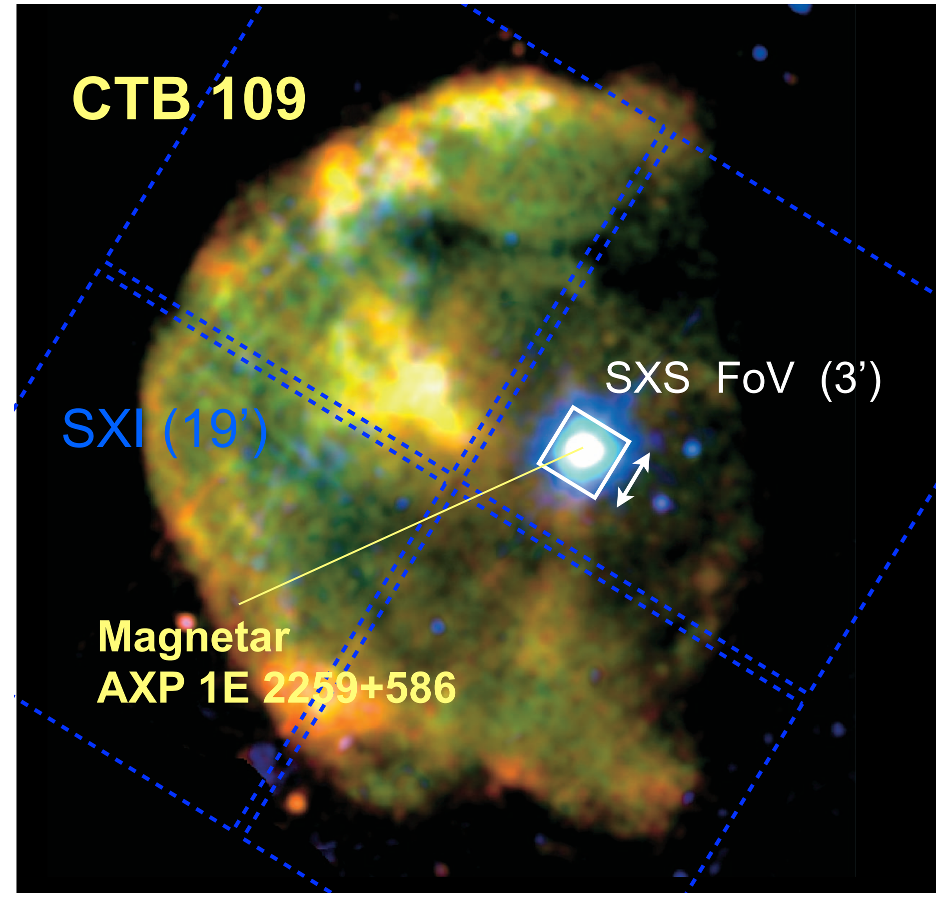
Evidence for the toroidal magnetic field is suggested by the Suzaku observation. Further verification is needed by existing and future X-ray missions.

Makishima & Enoto et al., submitted

Next X-ray Observatory: ASTRO-H

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

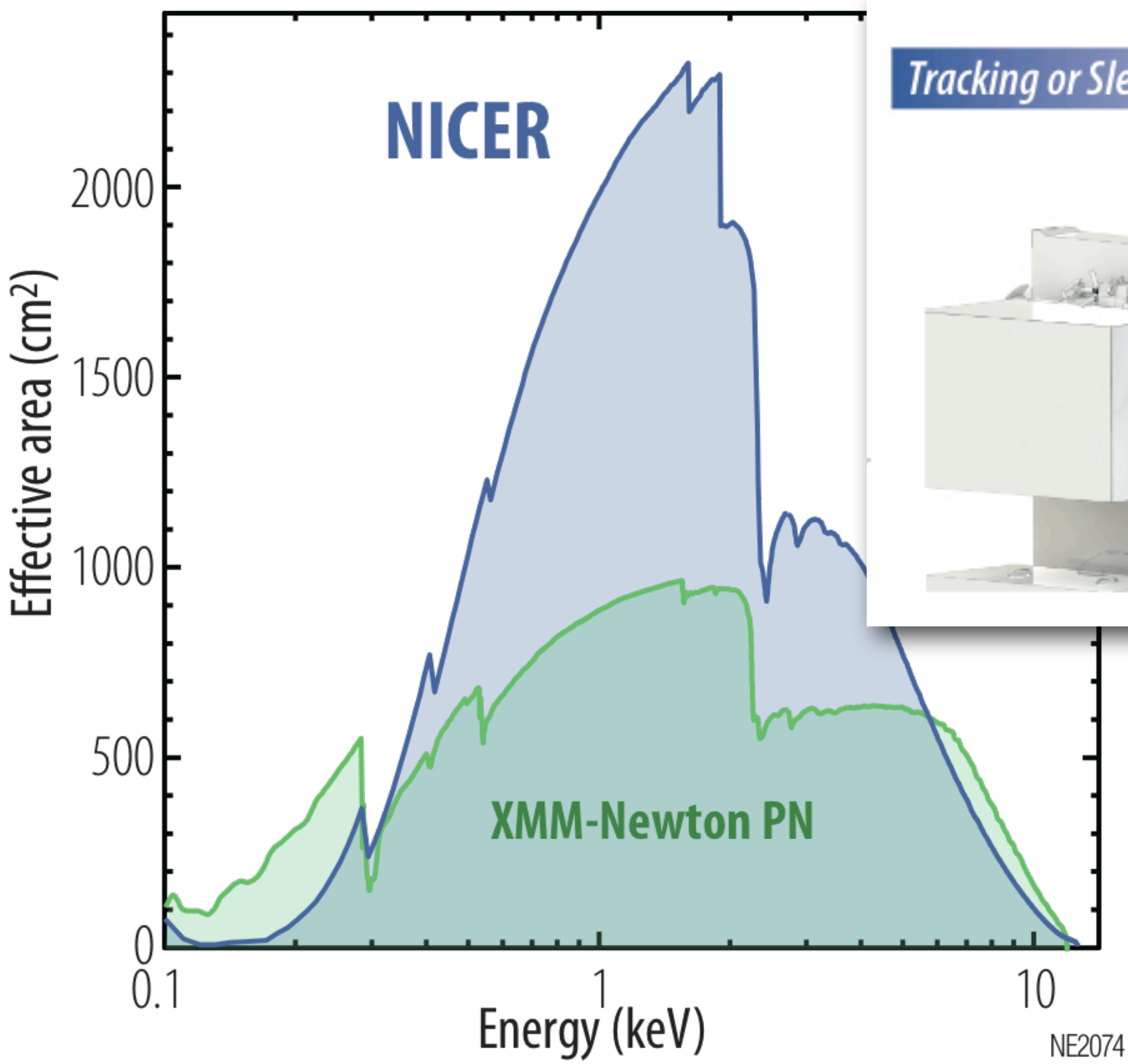


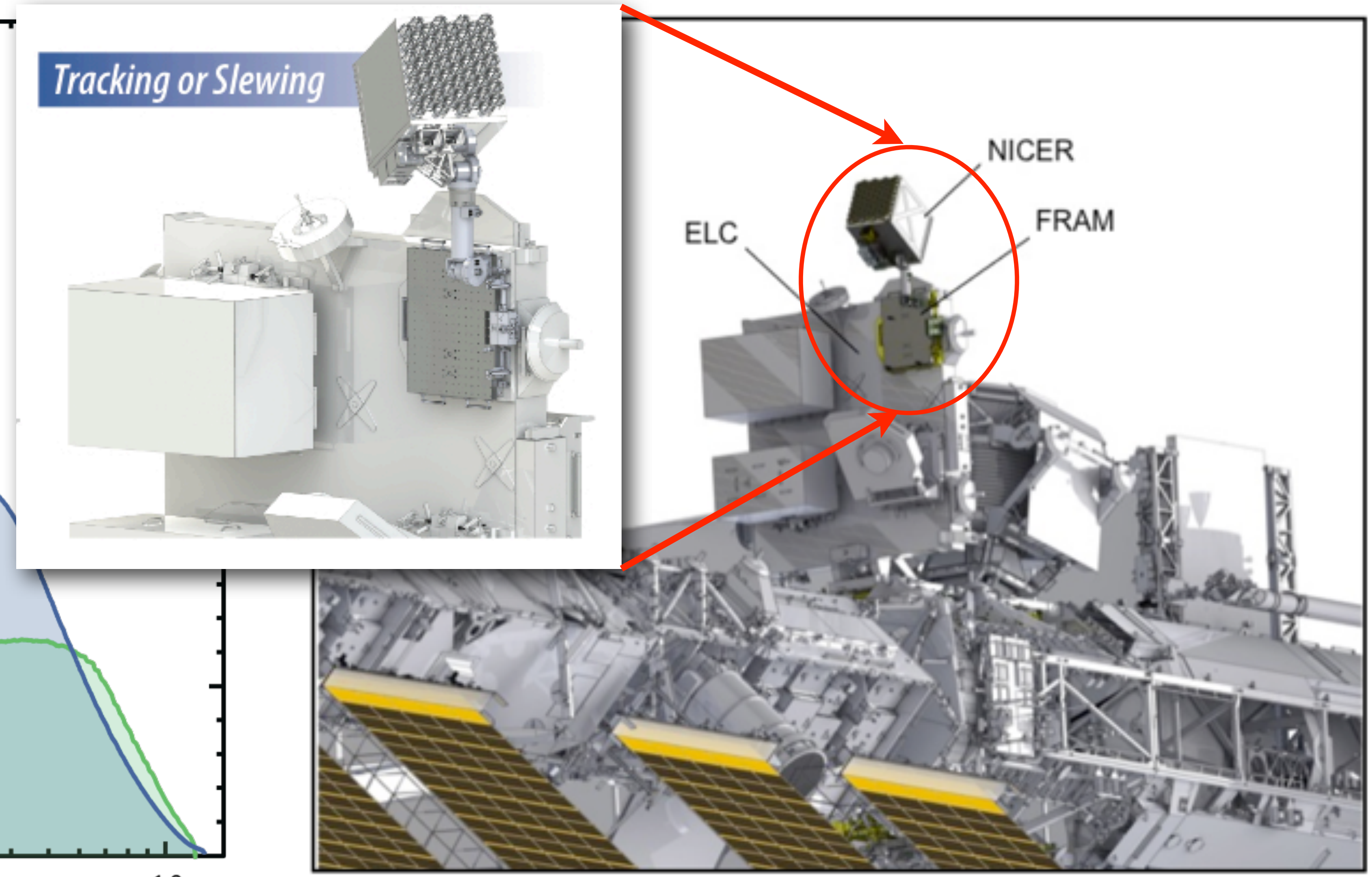


- Broad-band (0.2-600 keV) spectroscopy with high sensitivities.
- High energy resolution (a few eV) in the soft X-ray band using the calorimeter.
- Challenges towards NSs and magnetars
    - Search for proton cyclotron from magnetars and determine the B field.
    - Study of NS and magnetar atmosphere 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 X-ray observations suggest an existence of the toroidal magnetic field embedded in the magnetar interior as an energy source of burst activities.
- Different from the poloidal magnetic field estimated via P and P_{dot}, the toroidal field is difficult to be measured.
- From 8.69 sec magnetar 4U 0142+61, Suzaku detected a signature of a slow phase modulation by ±0.7 sec with a period of ~1.5 hour.
- Taken as evidence for free precession of the magnetar, this object is deformed with a fractional anisotropy of 1.6×10^{-4} in terms of the moment of inertia.
- This magnetar is expected to harbor an intense toroidal field of $B_t \sim 10^{16}$ G to deform the NS prolate shape.