Magnetars

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NASA Goddard SPACE FLIGHT CENTER

OUTLINE

- Basic introduction to Neutron Stars and Magnetars
- Magnetar observational Properties
  - Bursts
  - Persistent emission
  - Outbursts
- Few interesting sources
- Looking ahead into the future

PART 1
Magnetars place in NS Zoo

WHAT IS A MAGNETAR?

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- A sort of Neutron Star — What is a Neutron Star?

DEATH OF A MASSIVE STAR — BIRTH OF A NEUTRON STAR

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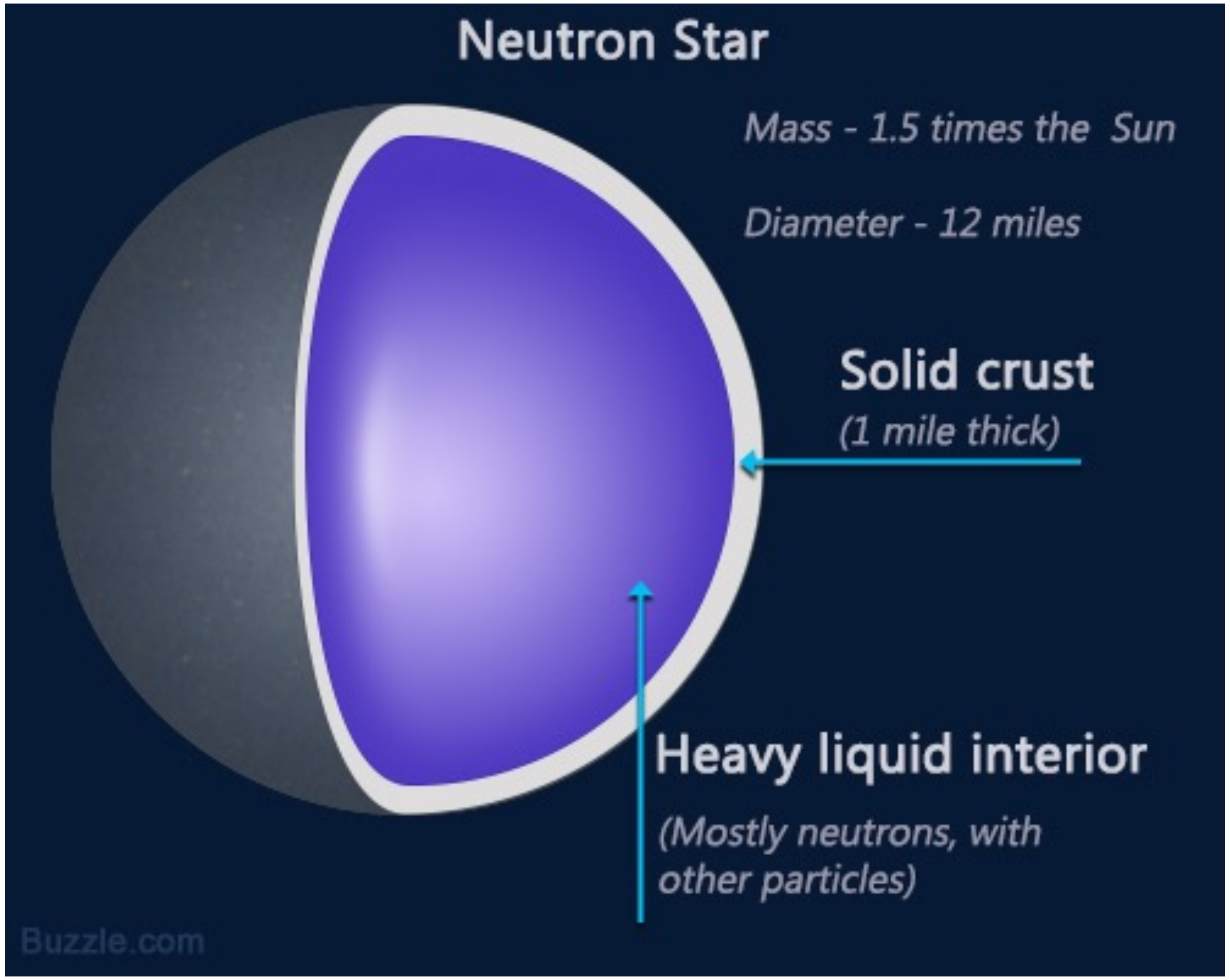


- Conservation of angular momentum:

L = I.W (I: moment of inertia, 2/5 m R^2, W=2.pi.f: angular velocity).

- Conservation of magnetic flux:

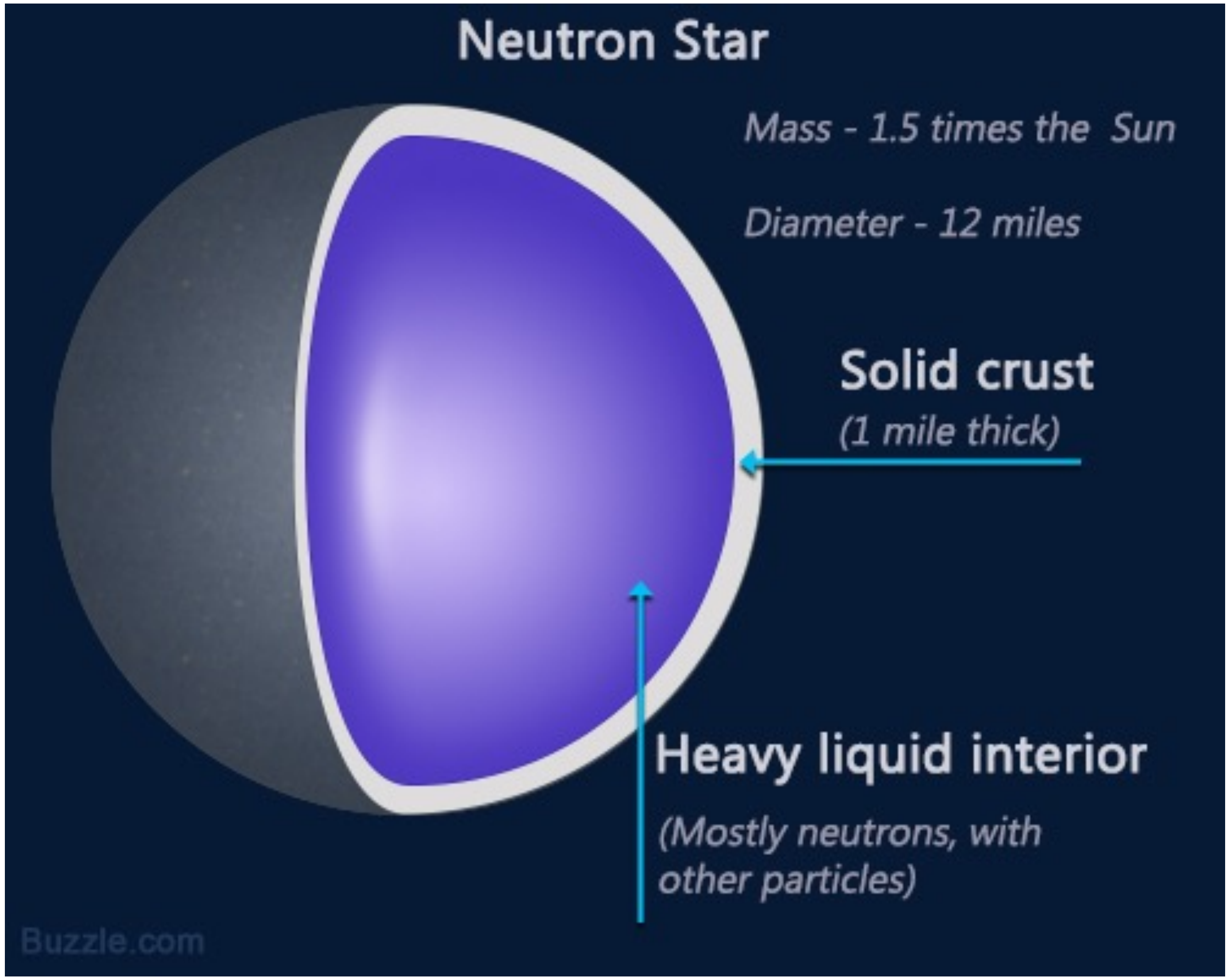
F_B = B.A (B: magnetic field strength, A: area perpendicular to B field).

For instance: A massive star have 5*R_sun = 10^{11} cm. Collapse it to 10^6 cm, increase B field by 10^{10} G, and angular velocity by the same amount.

B_initial = 100 G — B_final = 10^{12} G.

*f*_initial = 1rotation/100days — *f*_final = 1rotation/1ms.

DEATH OF A MASSIVE STAR — BIRTH OF A NEUTRON STAR



Density: 10^{14} g/cm^3

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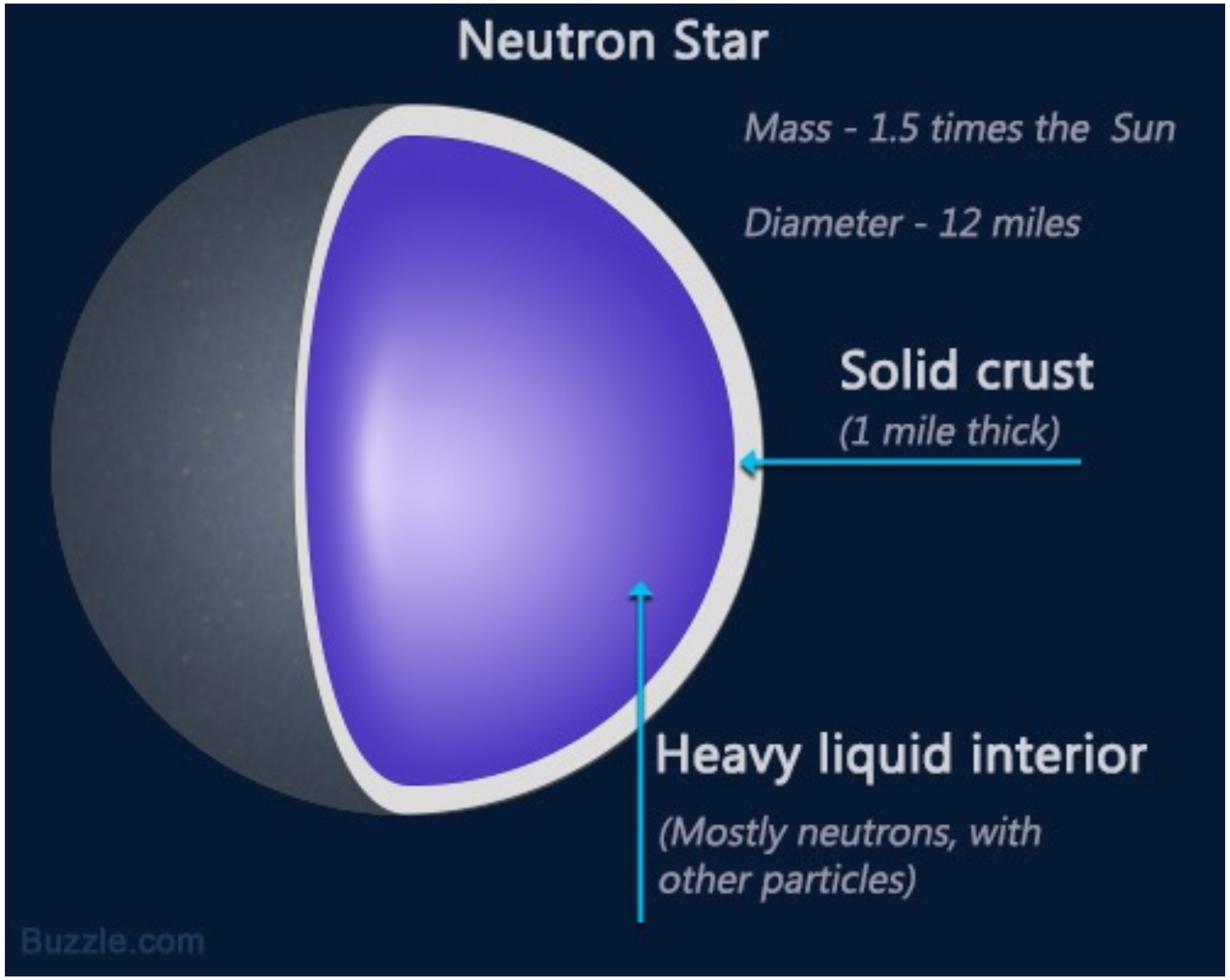

Density: 10^{14} g/cm^3

118 of those
in 1 cm^3!

WHAT IS A MAGNETAR?

- A sort of Neutron Stars — What is a Neutron Star?
    - Remnant of a massive star.
    - Radius ~ 10 km, Mass ~ 1.4 M_sun, B_init ~ 10^{12} G, P_init ~ 1 ms.
- Evolution of neutron stars. What happens to them as they grow mature?

EVOLUTION OF NEUTRON STARS — SIMPLISTICALLY

Due to rapid rotation P, NSs possess large rotational kinetic energy E_{rot}.

NSs also give away very strong radiation and particle fields, as seen below!

You need to get this energy from somewhere, best from E_{rot} —> slow down NS $dP/dt > 0$.

EVOLUTION OF NEUTRON STARS — SIMPLISTICALLY

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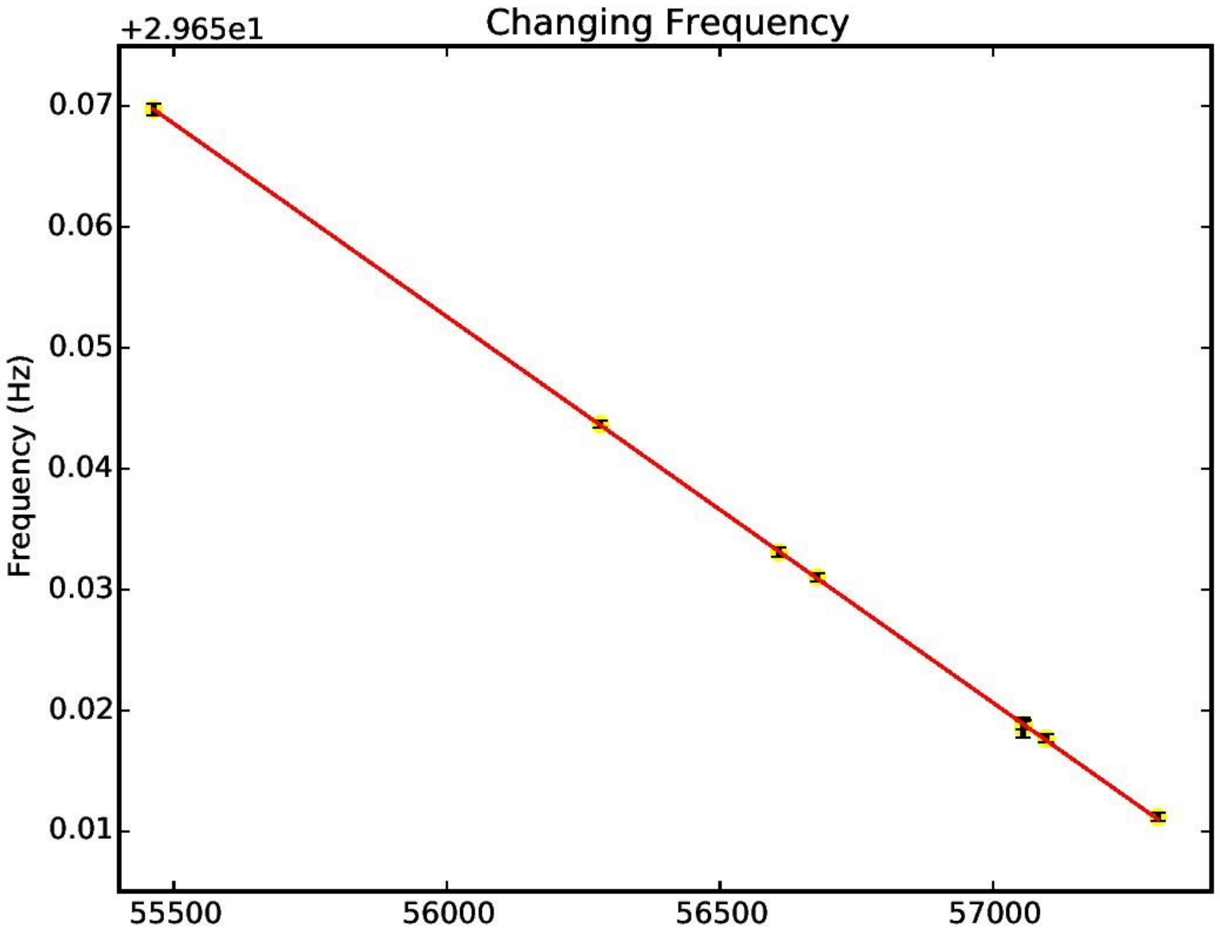
You need to get this energy from somewhere, best from E_{rot} —> slow down NS ***dP/dt > 0.*** This decrease in period is in fact observed and a calculable measure.

Crab: f = 29.6503 Hz, df/dt = -3.7 E-10 Hz/s



EVOLUTION OF NEUTRON STARS — SIMPLISTICALLY

Assuming that the rotational energy loss, **dE_{rot}/dt** is going into dipole radiation **P_{rad}**, we can solve this system, which depends on **P**, **dP/dt**, and surface dipole magnetic field **B**. Hence, we can derive **$B \sim 3.2.10^{19}\ (P.P_{dot})^{1/2}$ G**; Crab: **$B \sim 4.10^{12}$ G**.

Also, knowing the current **P and dP/dt**, we can extrapolate back in time to when **P** was very small, and estimate the age of the neutron star, $\tau = P/2\dot{P}$. ***Crab: ~1300 yr.***

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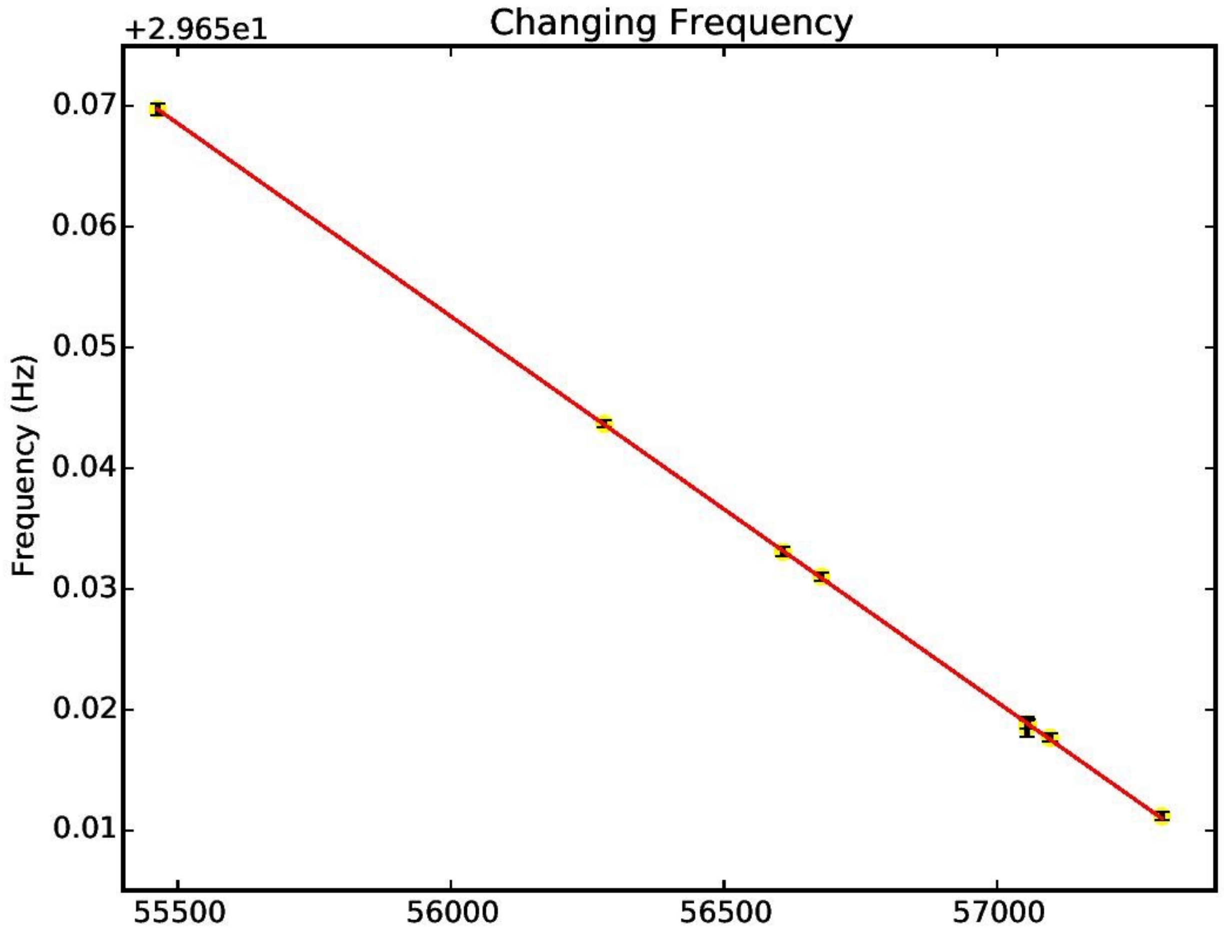

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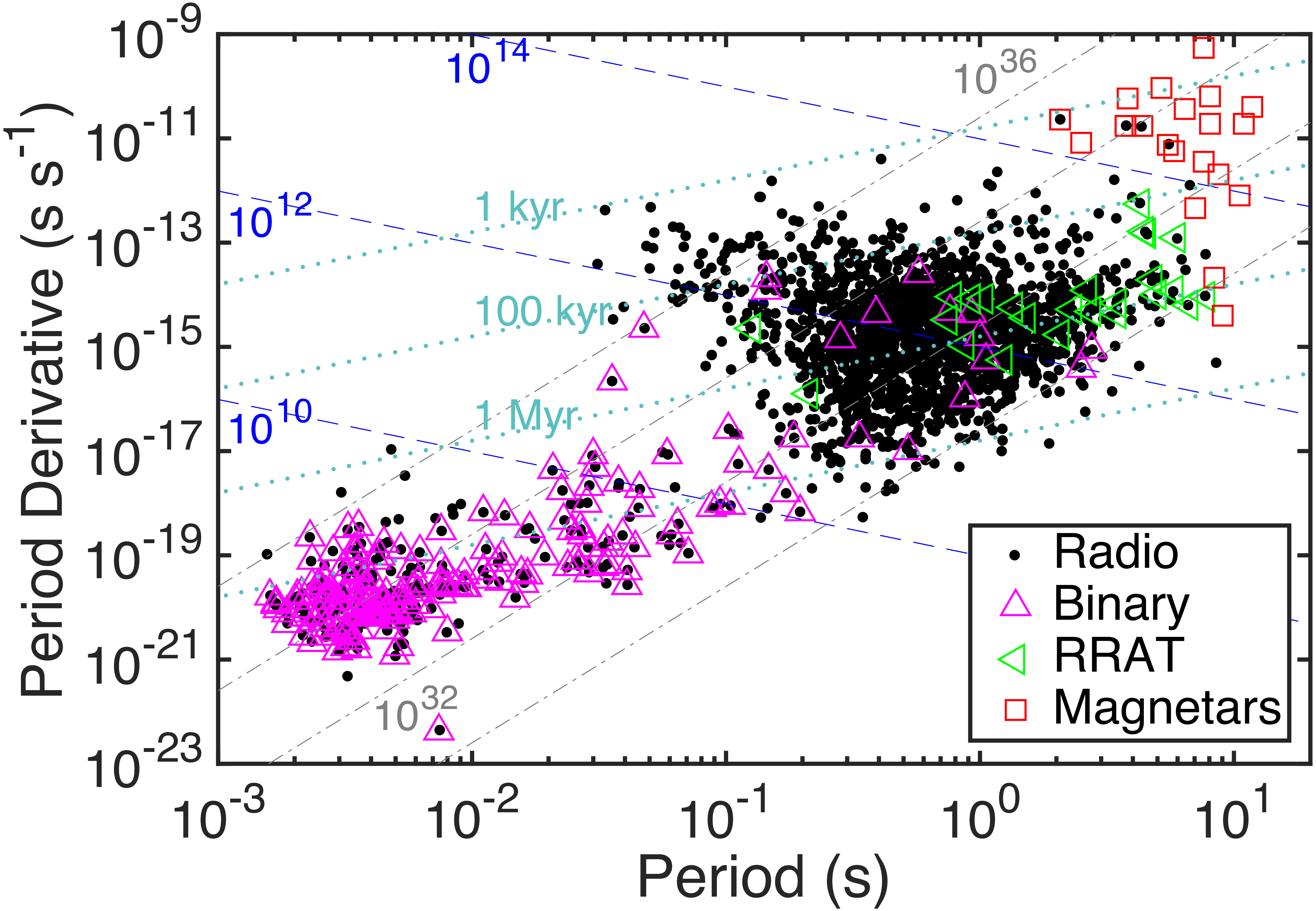
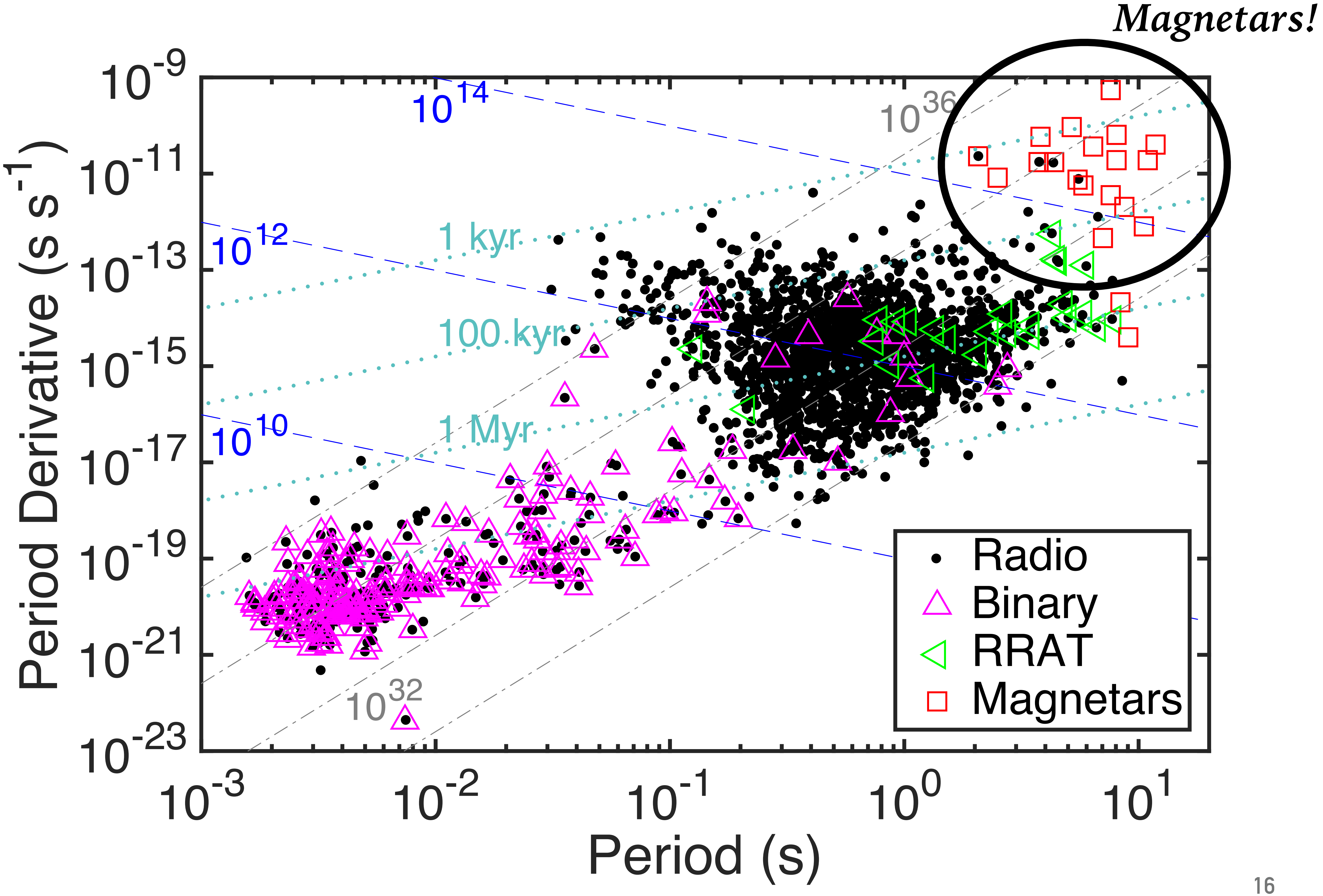
- How does that look for all known (isolated) Neutron Stars?

NEUTRON STARS



MAGNETARS


Magnetars!
Period Derivative (s s^{-1})
Period (s)
10^{-9}
10^{-11}
10^{-13}
10^{-15}
10^{-17}
10^{-19}
10^{-21}
10^{-23}
10^{-3}
10^{-2}
10^{-1}
10^{0}
10^{1}
10^{14}
10^{12}
10^{10}
10^{36}
10^{32}
1 kyr
100 kyr
1 Myr
Radio
Binary
RRAT
Magnetars

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  - 1 population with ***P*** ~ 2-12 seconds! Slow down fast!
  - Surface B-field strength: 10^{14} — 10^{15} G, *Tau* ~1000 — 10000 of years.
  - These are magnetars!

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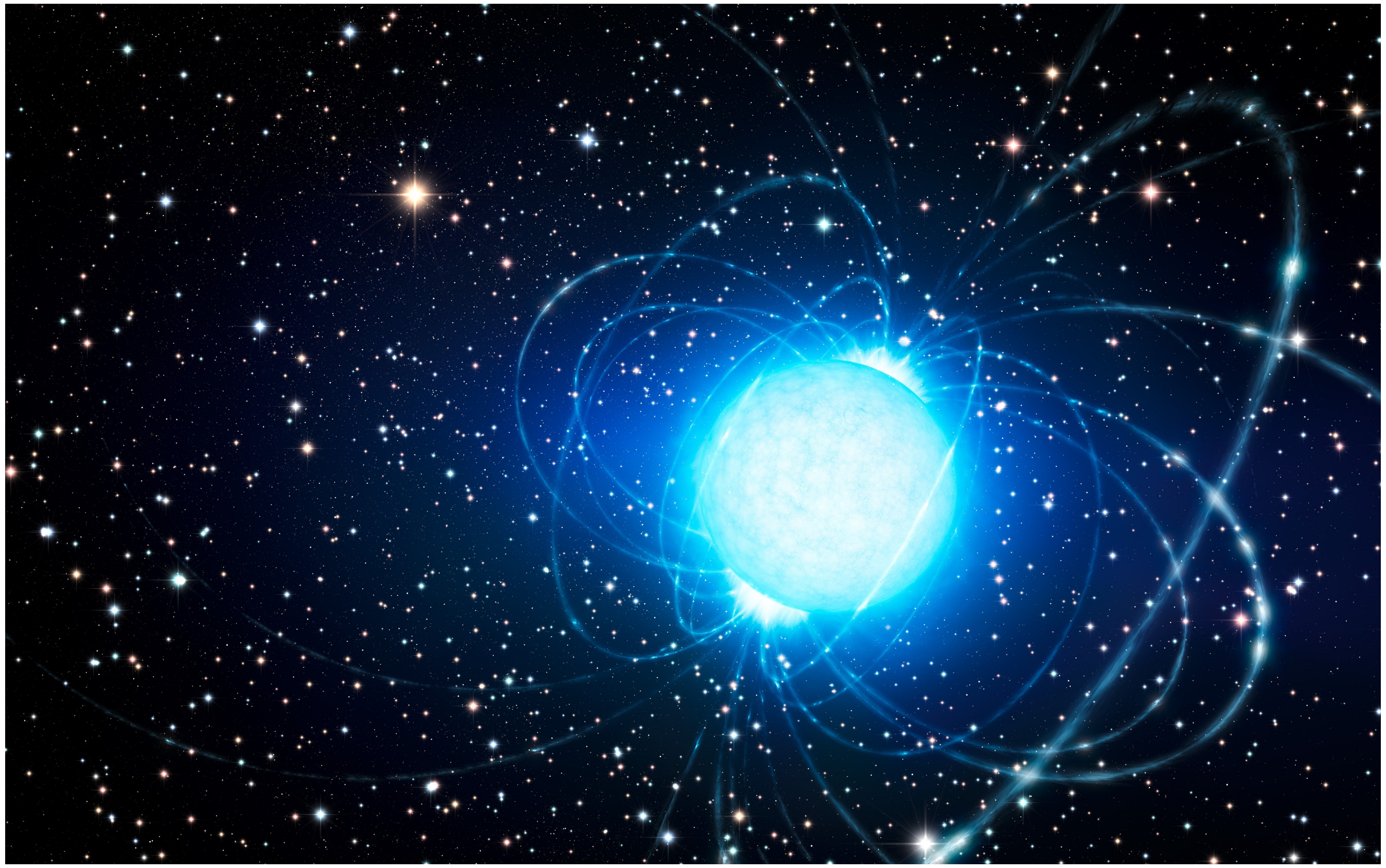

- Conservation of magnetic flux:

F_B = B.A (B: magnetic field strength, A: area perpendicular to B field).

Massive stars come in different flavors, follow a distribution in B-field strengths. Tail of B-field distribution 1000-10000 G

B_initial ~ few 1000 G — B_final ~ $10^{14} - 10^{15}$ G.

1 of few theories of creating magnetars!

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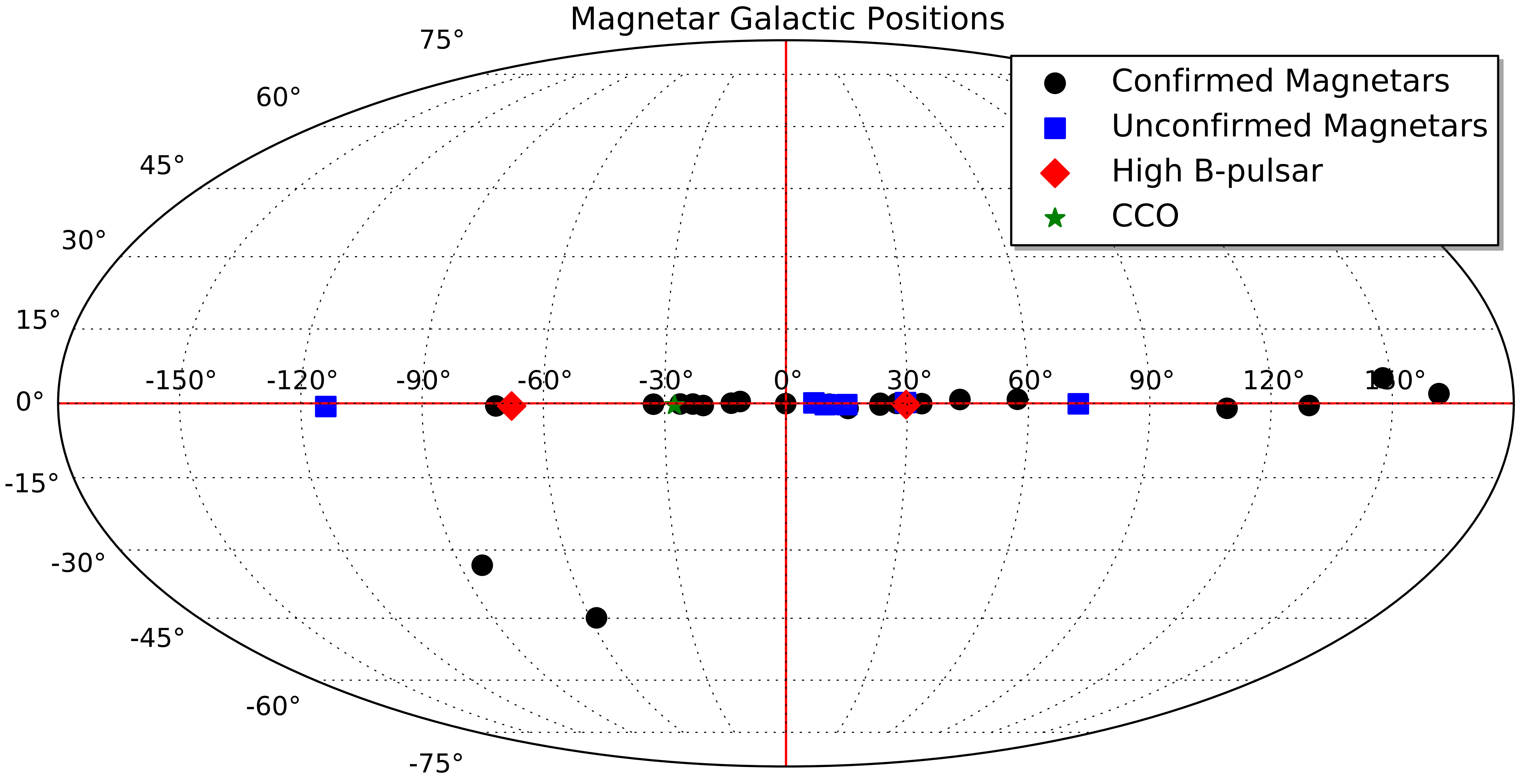
  - These are magnetars! But how are they formed? **Highest B progenitor.**

Magnetars are the most extreme manifestations of Neutron Stars!

28 known in the Galaxy, 1 in LMC, 1 in SMC

MAGNETARS IN THE SKY



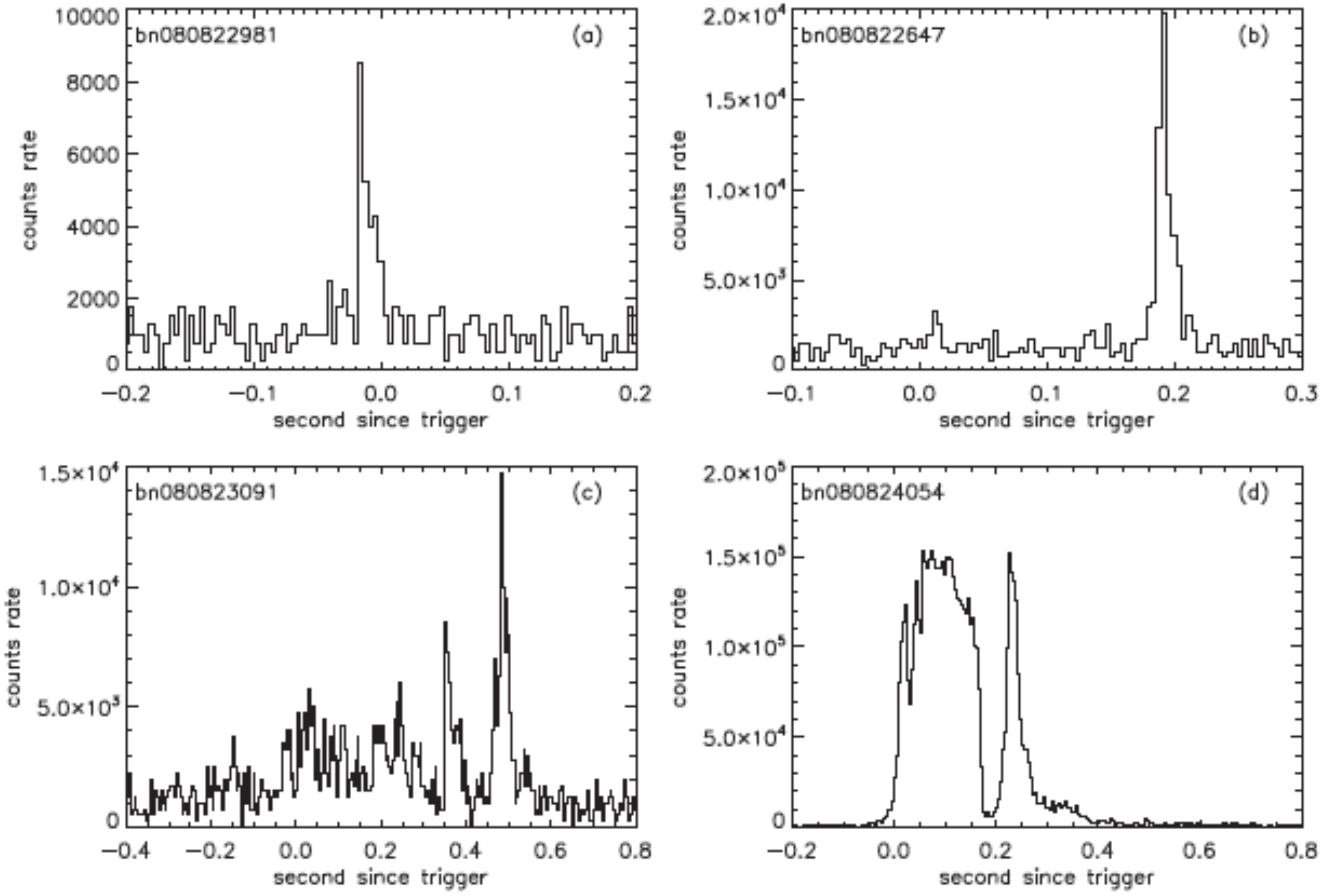
PART 2

Magnetar Observational Properties

Bursts

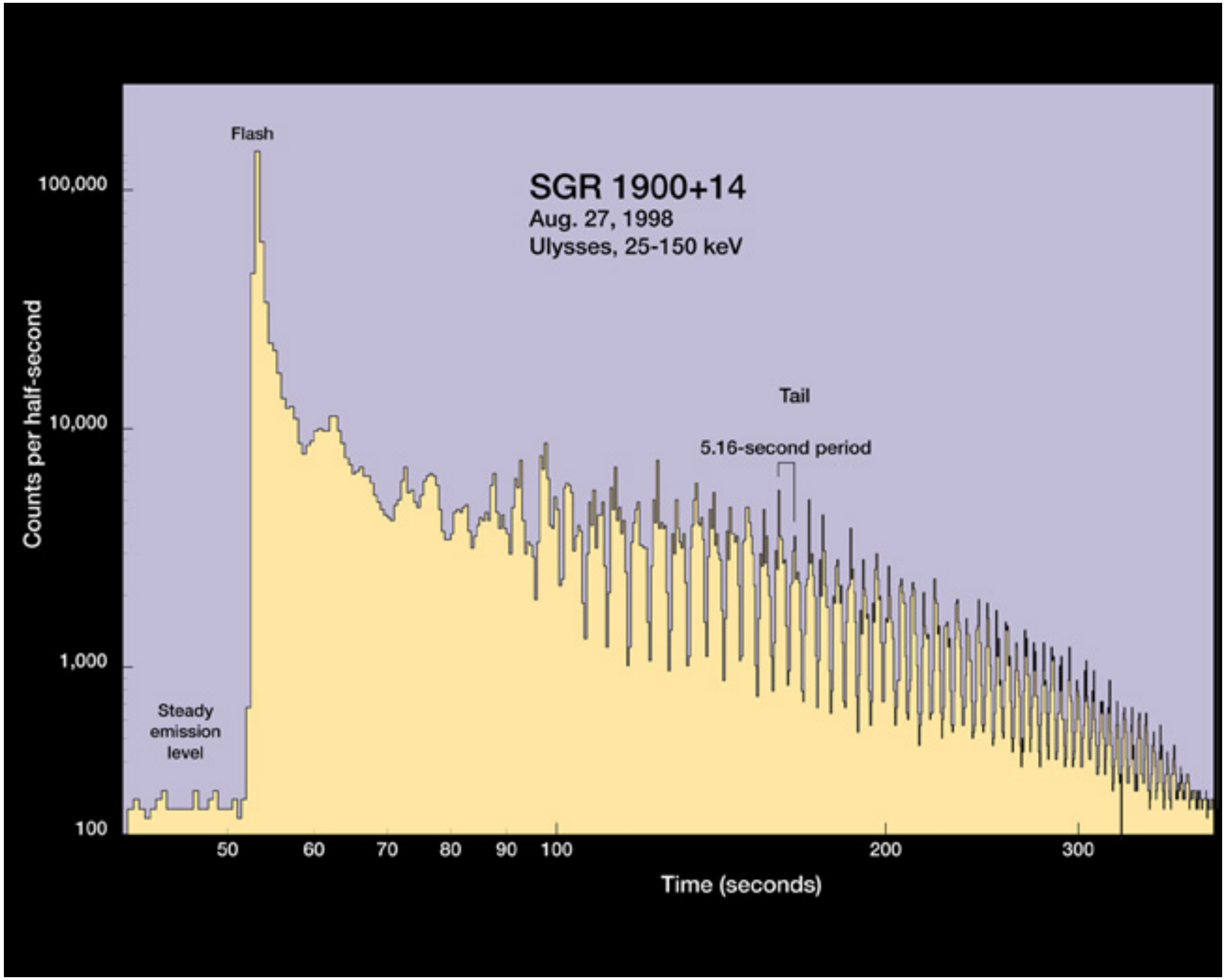
BURSTS

- A very strange peculiar property



- X-/Gamma-ray bursts
- Soft emission, between 1-100 keV, peaking at tens of keV.
- Short lasting ~0.1 s, E~1.0E37-1.0E41 erg.

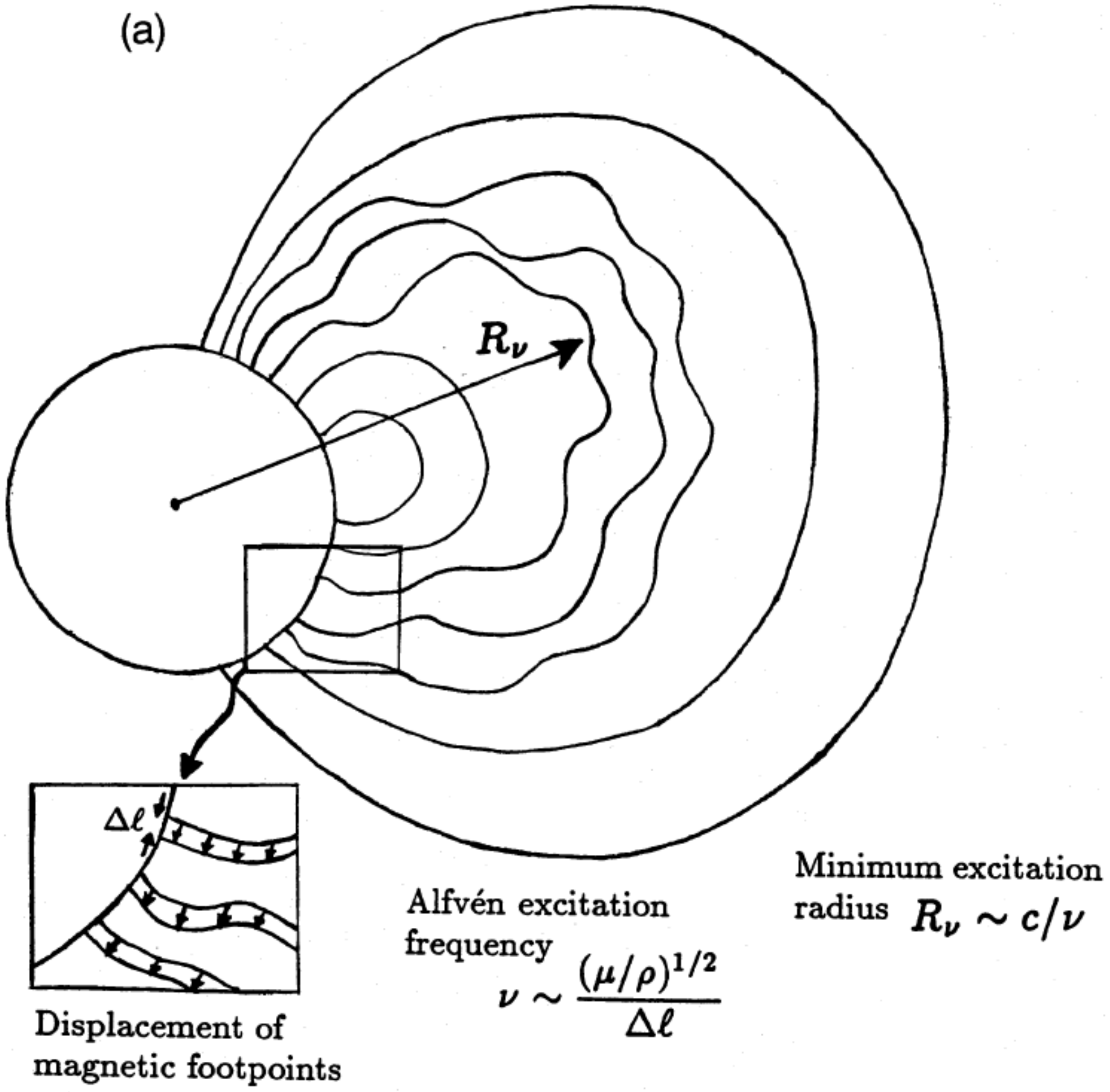
GIANT FLARES

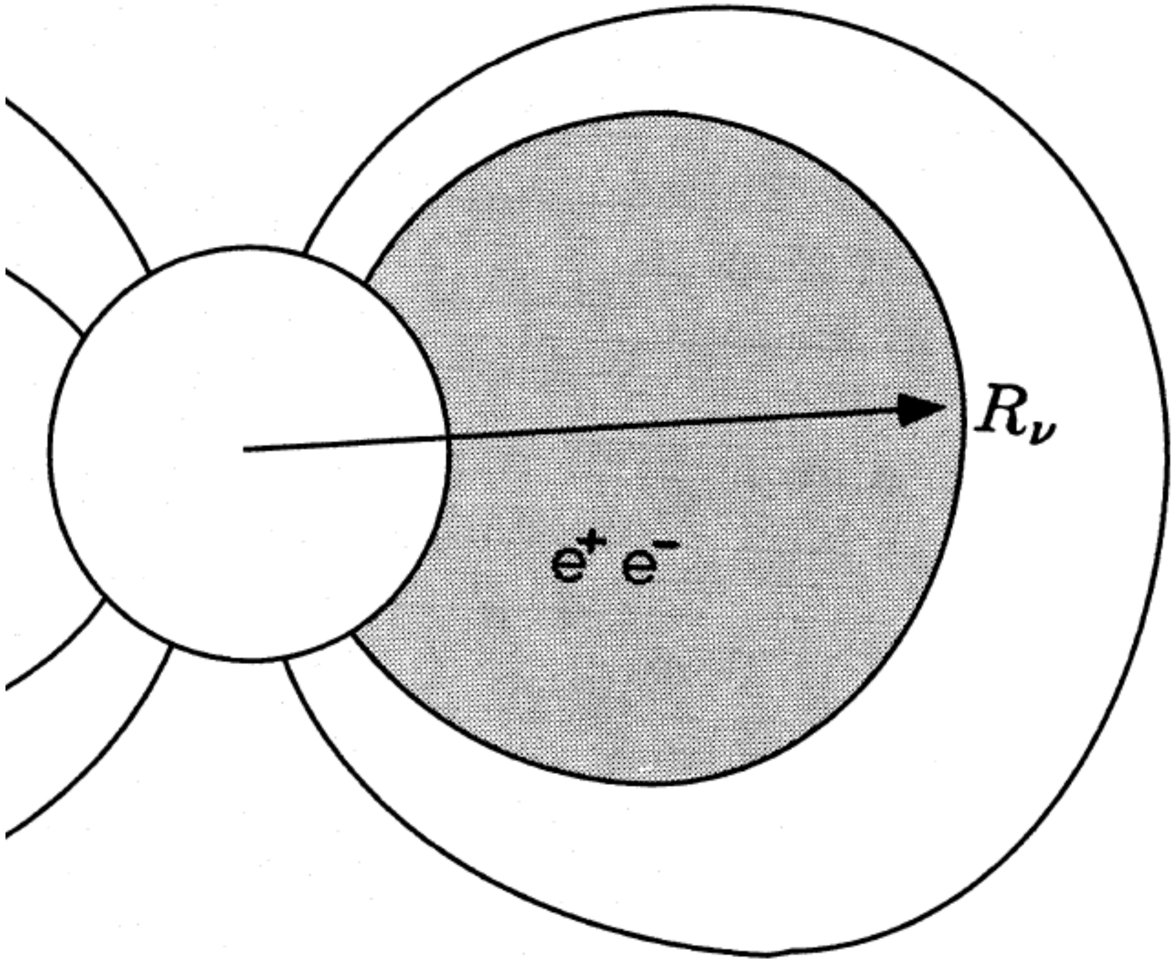


- Giant Flares (3)
- Short (0.5 s), VERY bright spike E~1.0E46 erg.
- Hard spectrum, most photons emitted at energies > 100 keV.
- Long lasting tails (500s).
- Tail energy comparable to spike.

BURST THEORY

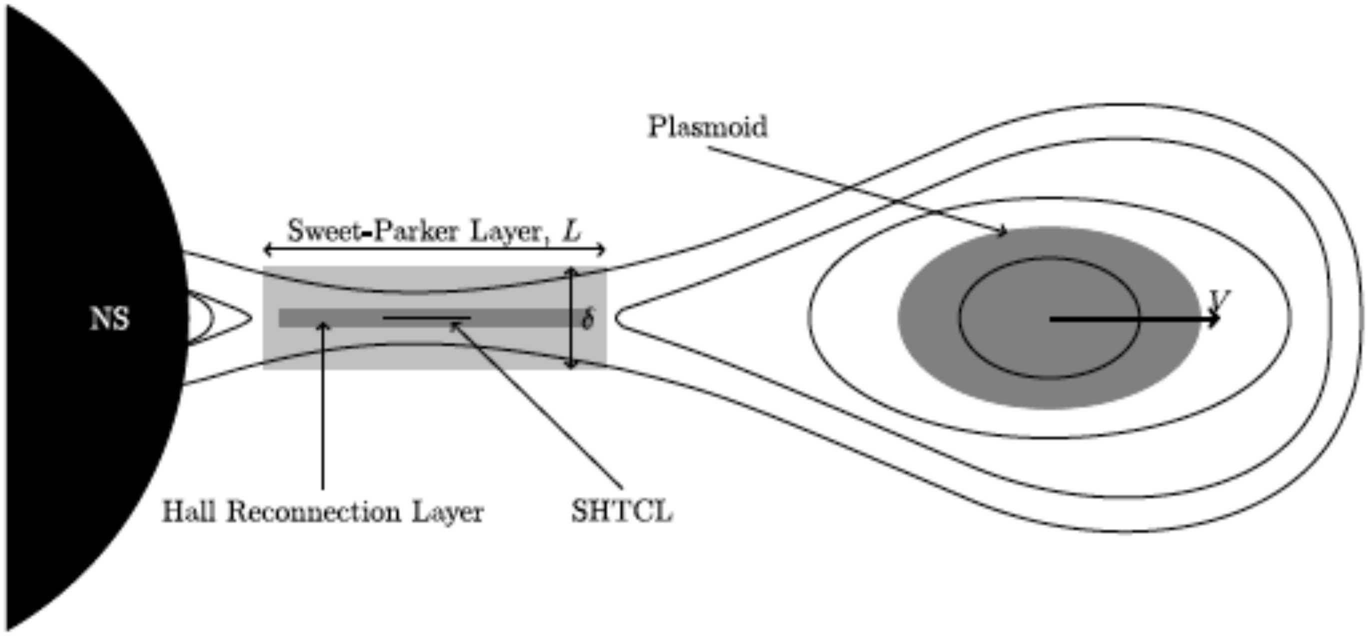
Thompson & Duncan 1995
Heyl & Hernquist 2005





BURST THEORY

Lyutikov 2003, 2006, 2014
Gill & Heyl 2005



Magnetic reconnection in upper magnetosphere
Also predicts the formation of photon-pair plasma fireballs in closed flux lines

5 YEARS GBM CATALOG

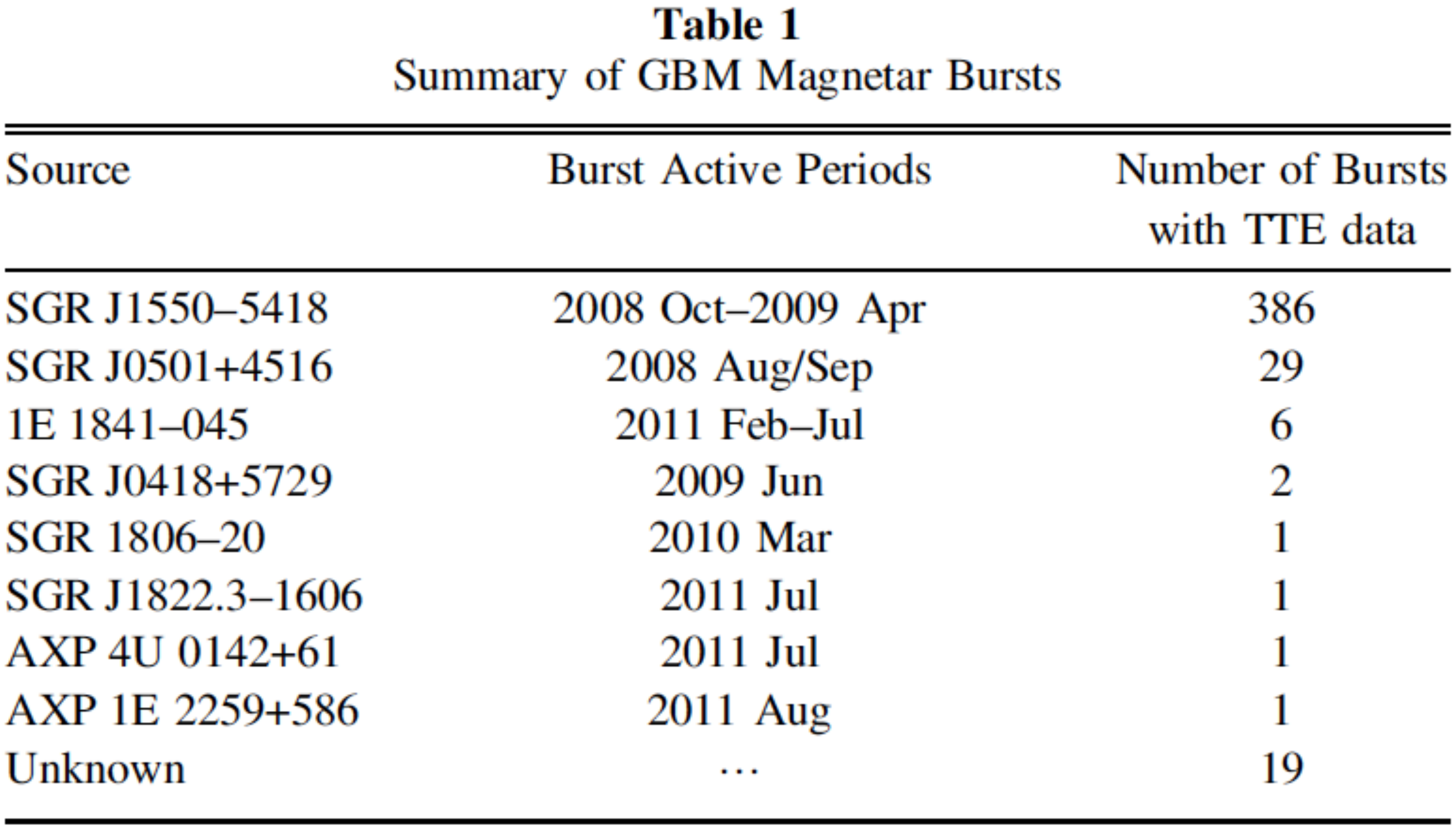


Table 1
Summary of GBM Magnetar Bursts

Source	Burst Active Periods	Number of Bursts with TTE data
SGR J1550–5418	2008 Oct–2009 Apr	386
SGR J0501+4516	2008 Aug/Sep	29
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SGR 1806–20	2010 Mar	1
SGR J1822.3–1606	2011 Jul	1
AXP 4U 0142+61	2011 Jul	1
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Unknown	···	19

5 yr magnetar burst catalog, Collazzi et al. 2015

SGR 1935+2154	2015 Feb-2016 June	>120
4U 0142+61	2015 Feb	~10
1E 1841-045	Scattered	~10
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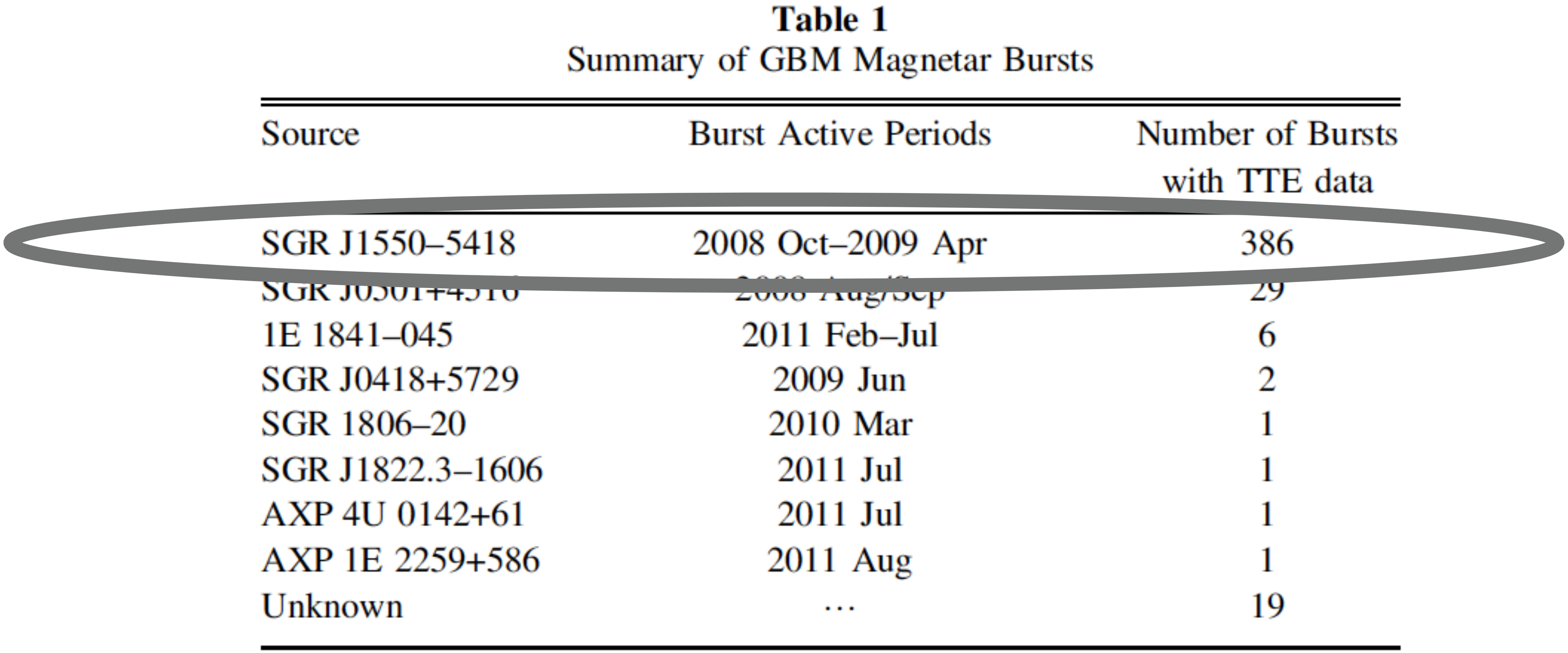
CXOU J164710.2-455216	2017 May	1

5 YEARS GBM CATALOG



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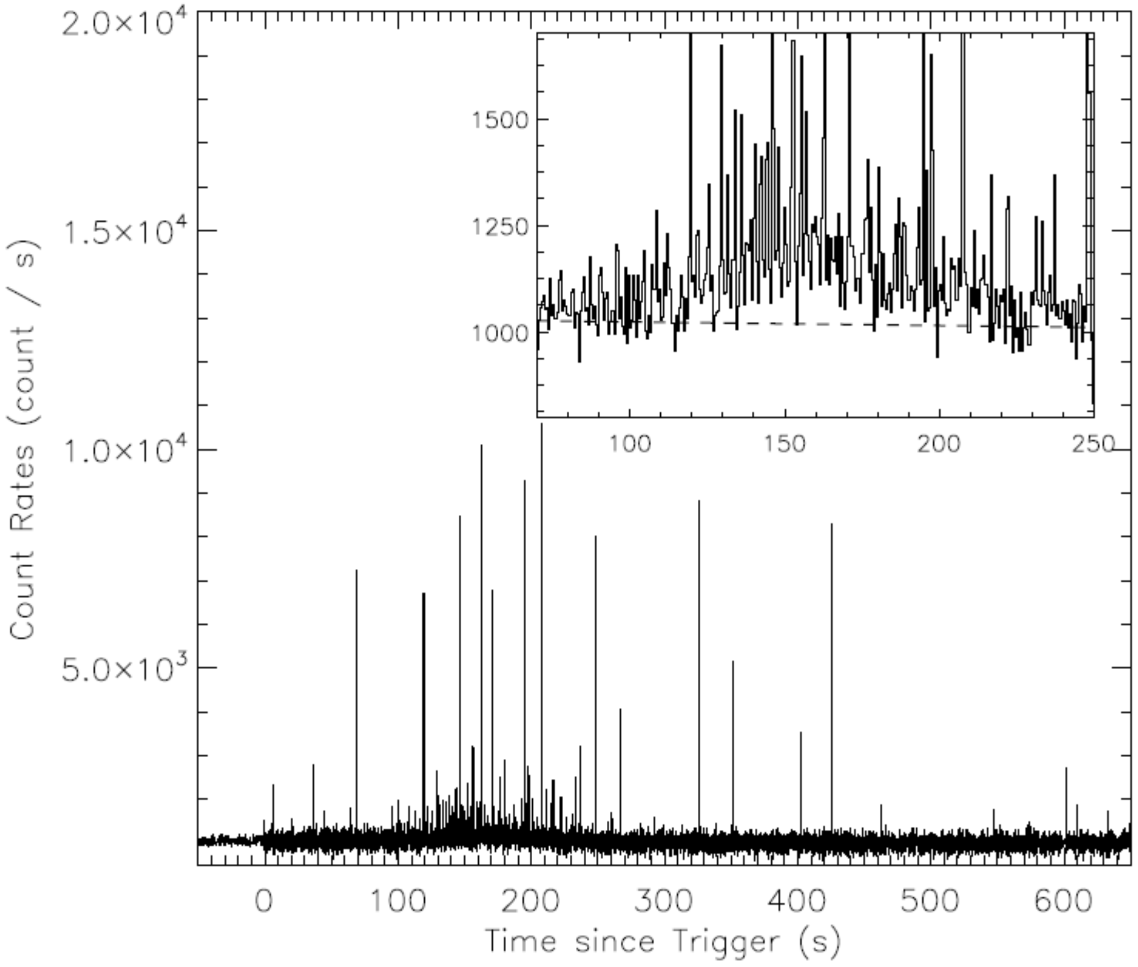
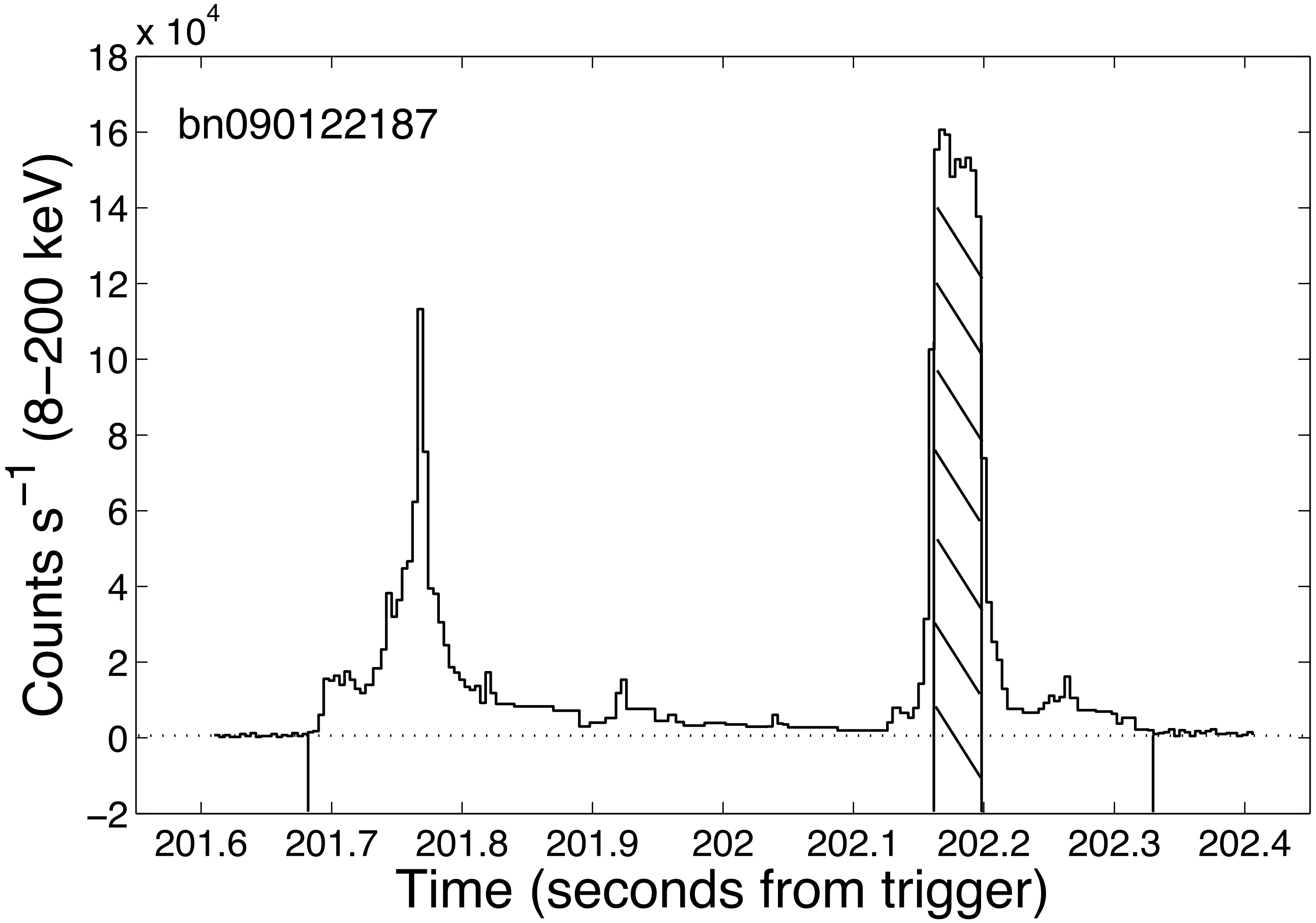
SGR J1550-5418 - GENERAL PROPERTIES

- P = 2.1 s, Pdot = 2.32E-11 s/s, B ~ 2.1E14 G.
- Entered high level of activity in 2008-2009.
    - Hundreds of bursts on 22 January 2009 seen with many high energy instruments — GBM most complete sample (**van der Horst et al. 2012**).

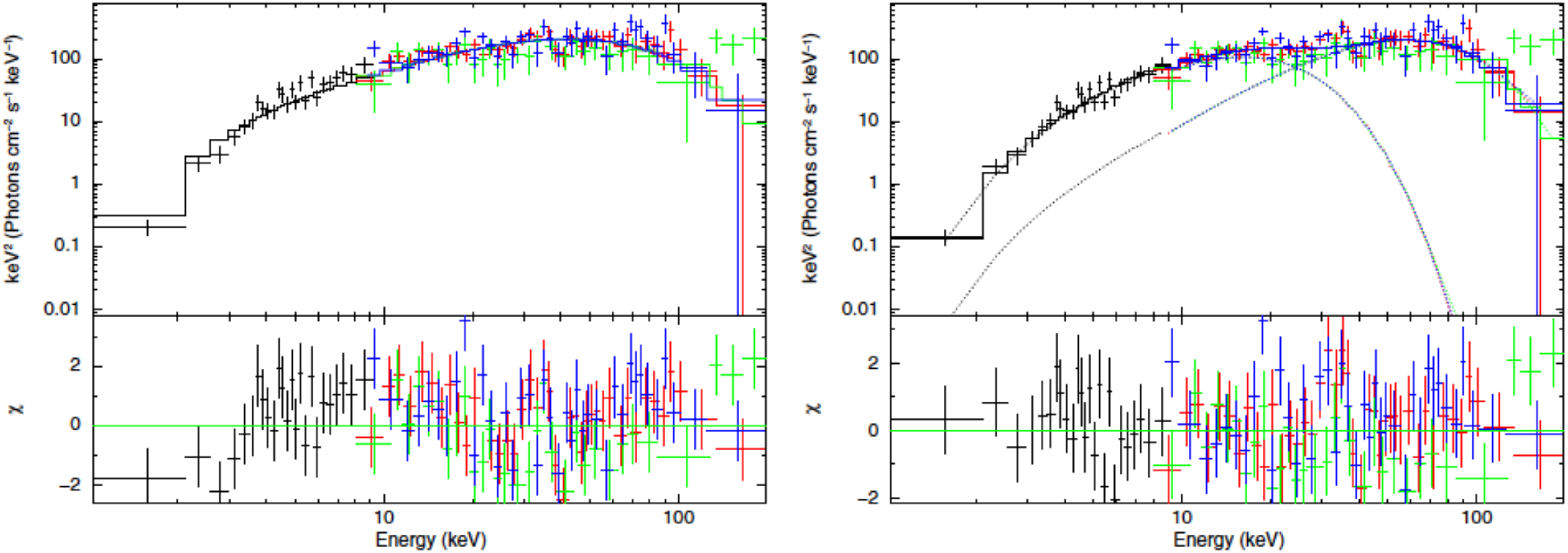


Kaneko et al. 2011



SGR J1550-5418 - SPECTRAL MODELING

Fermi GBM+Swift fit, 1-200 keV



Low-energy residuals with the Comptonized model. Perfect fit with the 2BBs.

$$R^2 = FD^2/\sigma T^4$$

$$kT_{\rm high} \approx 13 \text{ keV}, kT_{\rm low} \approx 6 \text{ keV},$$

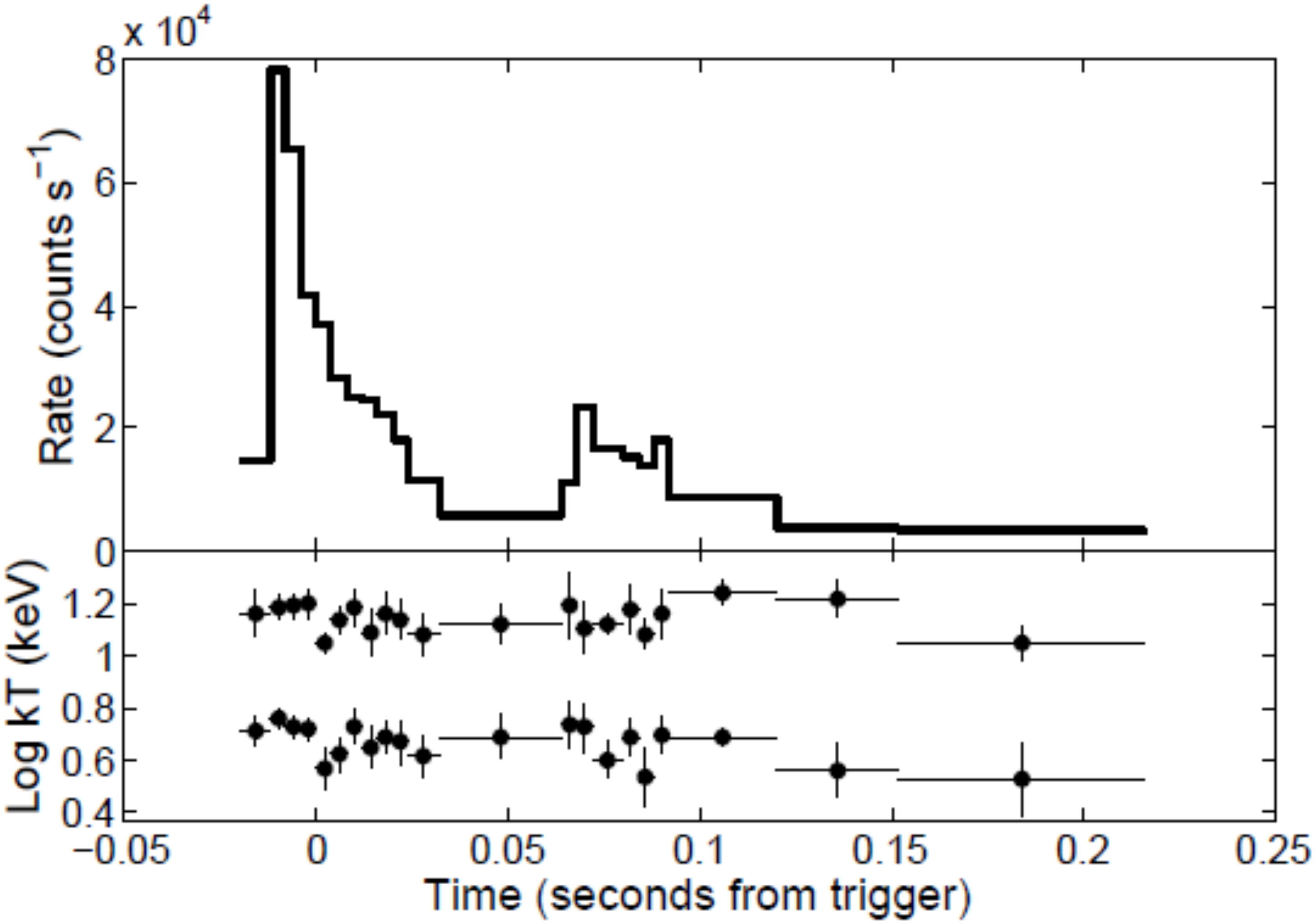
$$R_{\rm high\_kT} \approx 0.3, R_{\rm low\_kT} \approx 17 \text{ km}$$

Could be thought of as footpoints and surface layer of fireball

SGR J1550-5418 - TIME RESOLVED SPECTROSCOPY

Time resolved spectroscopy of 60 brightest bursts

- Bin at >=4ms (achieve 3sigma constraint on kT)
- Fit each bin with 2BB model
- Follow evolution of fit parameters



SGR J1550-5418 – TIME RESOLVED SPECTROSCOPY

Time resolved spectroscopy of 60 brightest bursts

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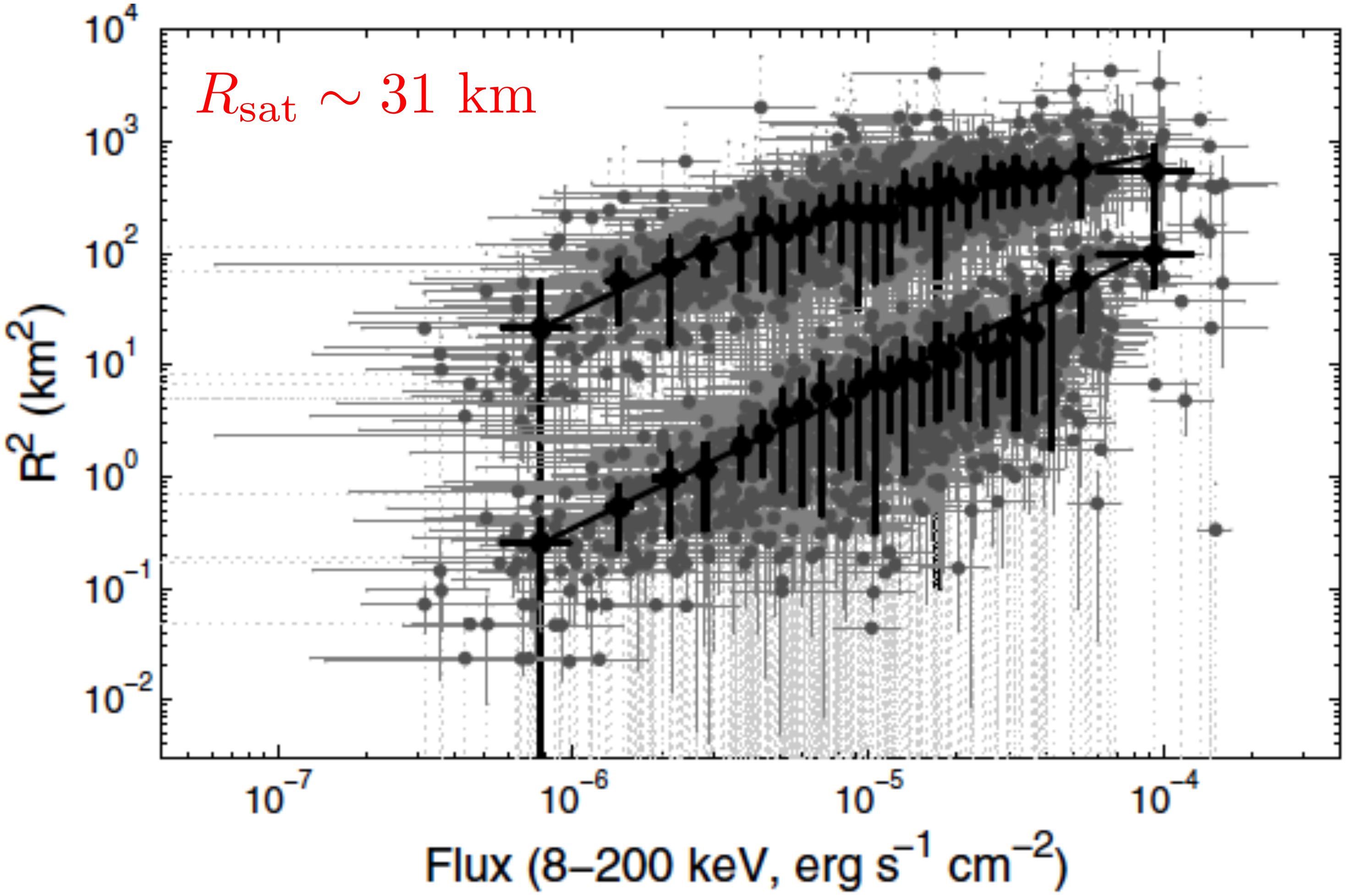
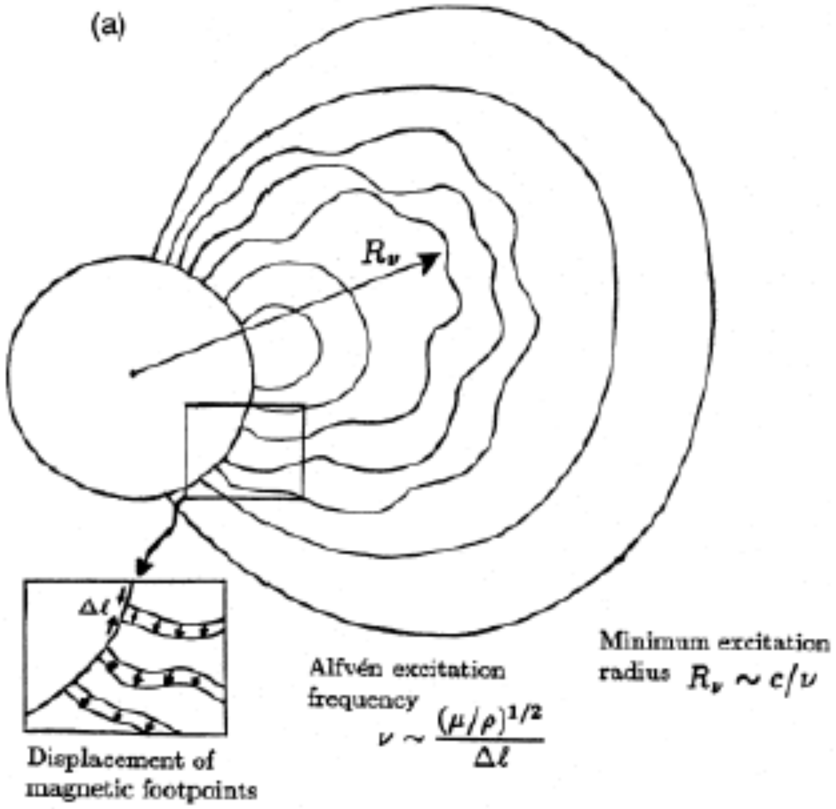
- Radii as a function of flux



$R_{\rm sat} \sim 31$ km



$$R_\nu \sim 10\, B_{15}^{-2} \left(\frac{\theta_{\rm max}}{10^{-3}}\right) \left(\frac{V_\mu}{1.4 \times 10^8}\right) l_5 \text{ km},$$

$R_\nu < R_{\rm sat}$, or insufficient excitation

Younes et al. 2014, ApJ., 785,52, Thompson & Duncan 1995

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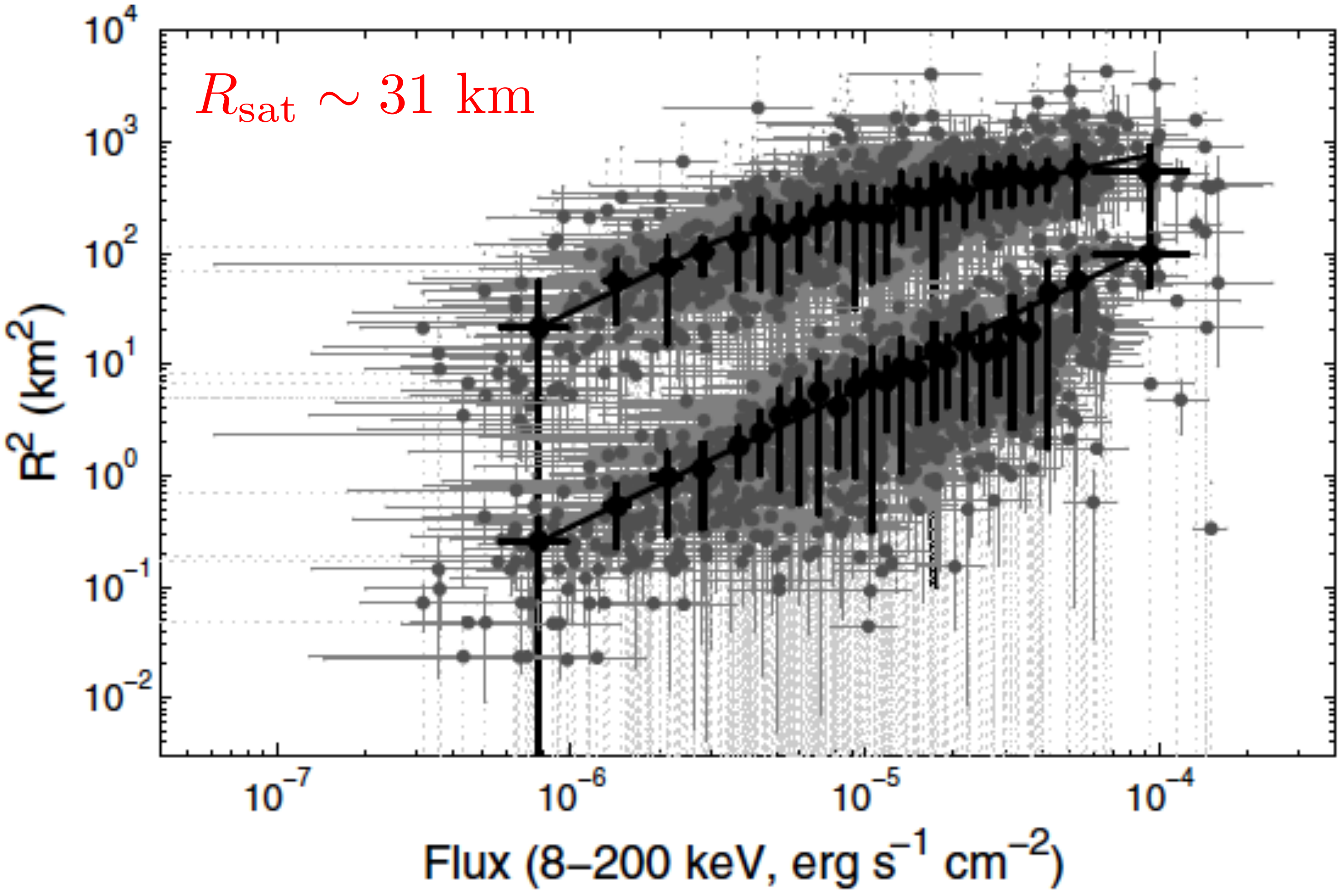

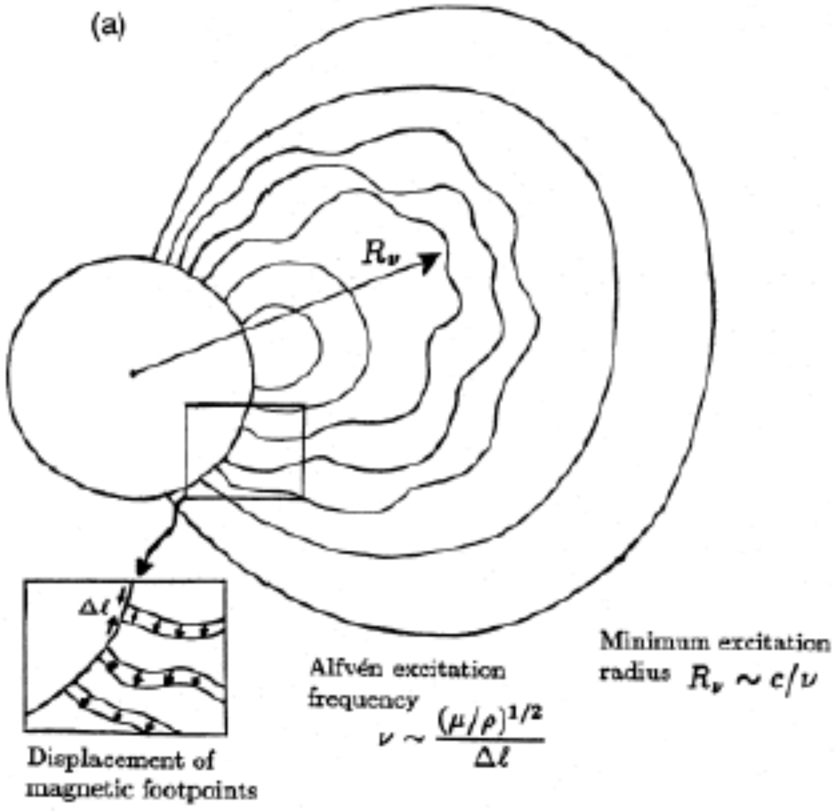

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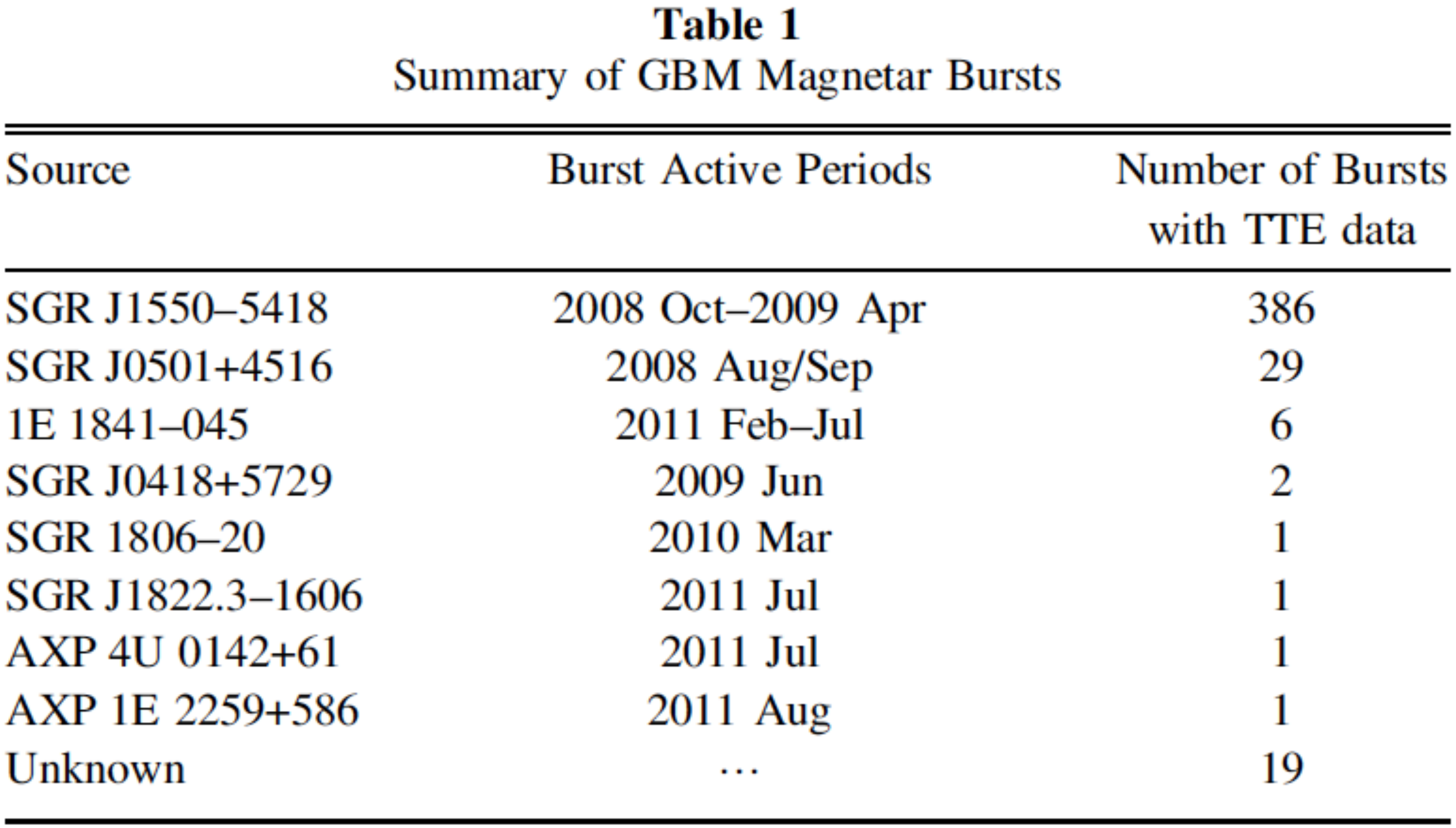
Internal B field strength:

$$B \gtrsim 4.5 \times 10^{15}$$

Younes et al. 2014, ApJ., 785,52, Thompson & Duncan 1995

5 YEARS GBM CATALOG



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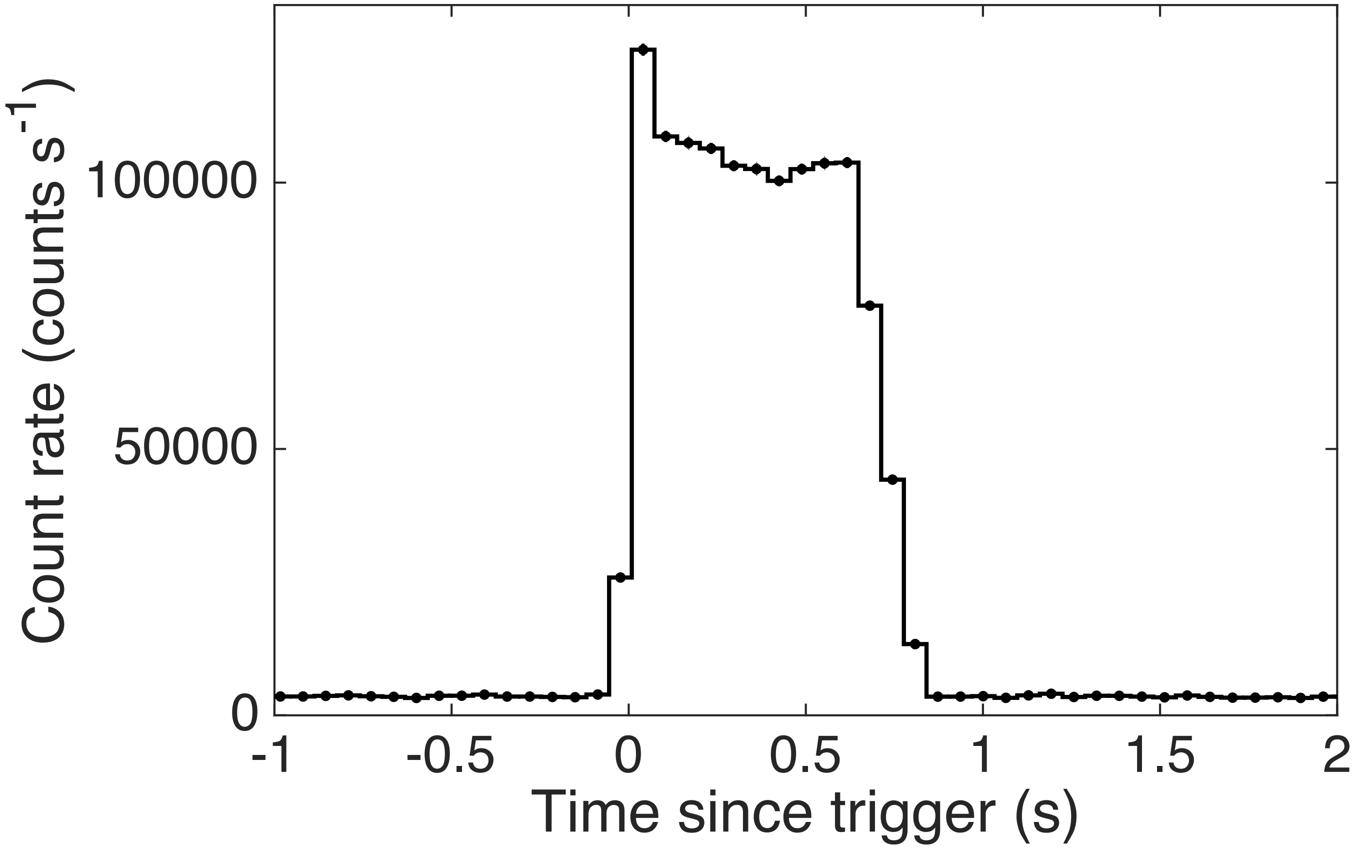
SGR J1935+2154 – GENERAL PROPERTIES

- P = 3.2 s, Pdot = 1.43E-11 s/s, B ~ 2.2E14 G.
- Three burst episodes: Oct. 2014, Feb. 2015, May & June 2016.
  - Almost 100 bursts detected with Fermi GBM during last burst episode.

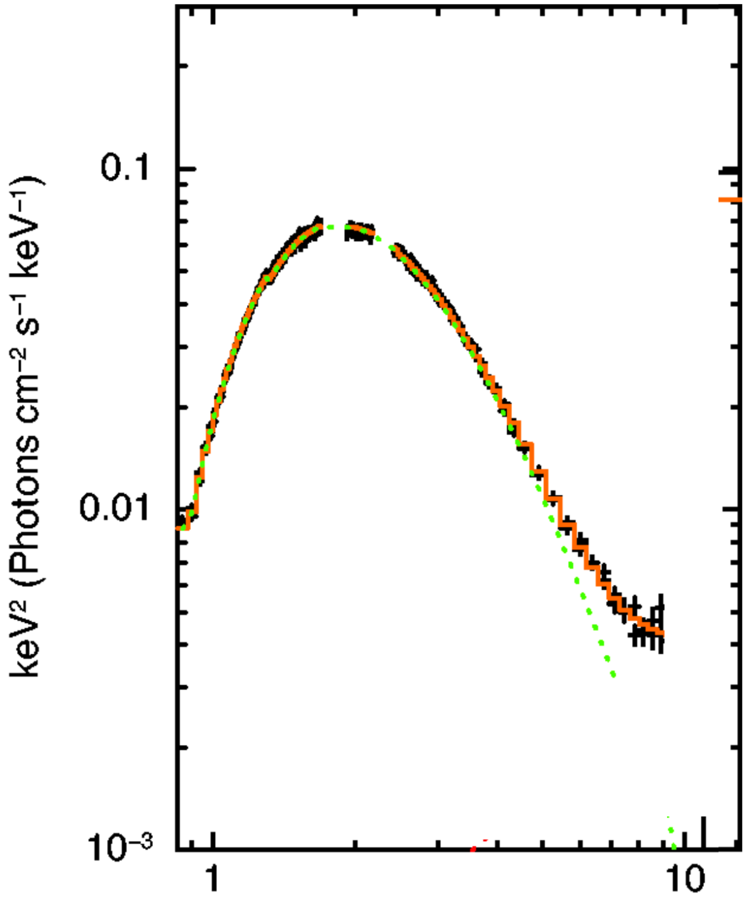


- The brightest burst detected from the source so far.
- Flux ~ 2.5E41 erg/s, Fluence ~ 2.0E41 erg.
- Longer than typical bursts!
- Quick rise, quick decay.
- Flat-top bursts!

Persistent emission

PERSISTENT EMISSION - SOFT X-RAYS

- Brighter, hotter than normal neutron stars



4U 0142+61 — Enoto et al. 2011

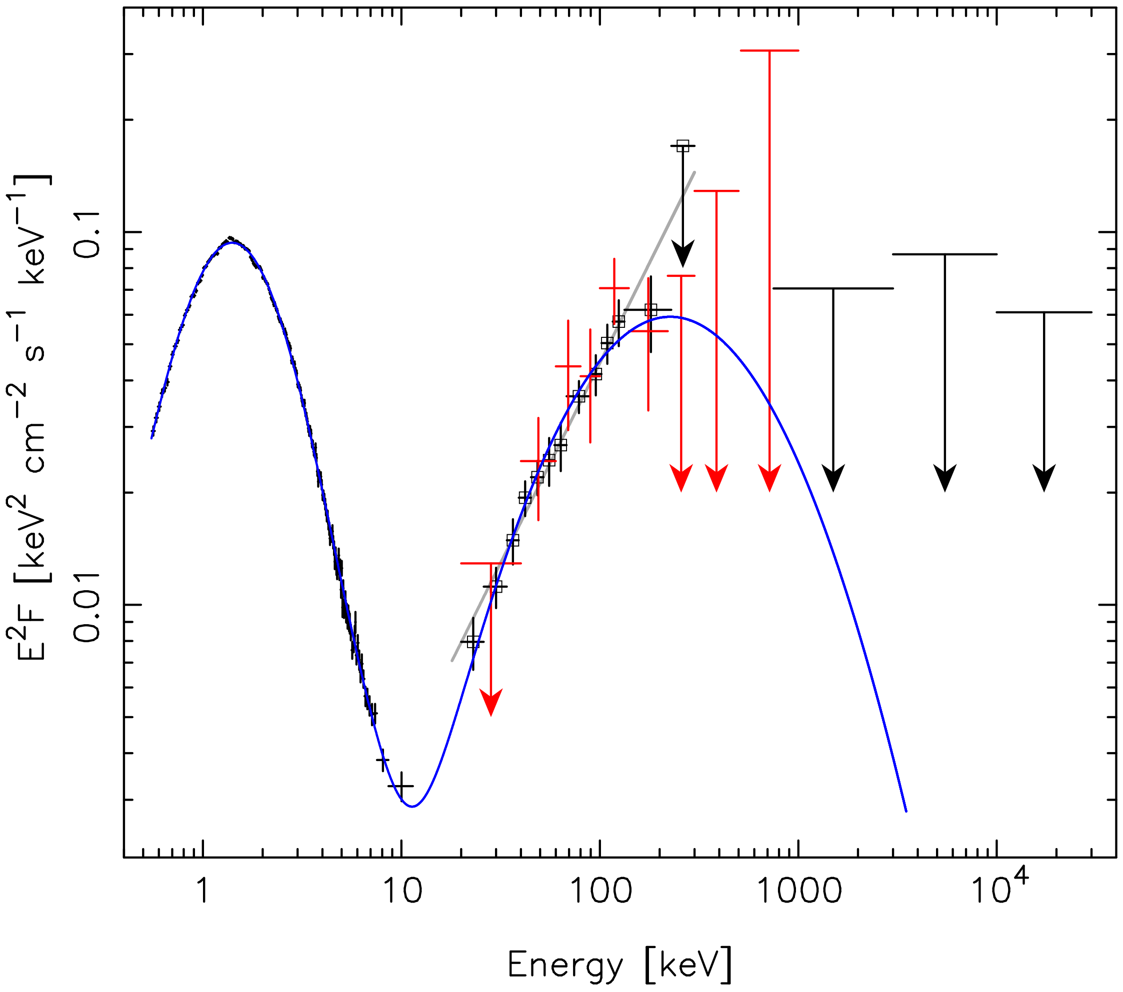
- In Soft X-rays <10 keV:
  - Modified black-body, i.e., blackbody+powerlaw
  - kT=0.5 keV, Gamma=3.0

$$F_\mathrm{X} > \dot{E}_\mathrm{rot}$$

Rotational energy loss cannot power X-ray emission
Decay of super strong B-field is the alternative

PERSISTENT EMISSION - HARD X-RAYS

- Turn over in spectrum at 10 keV

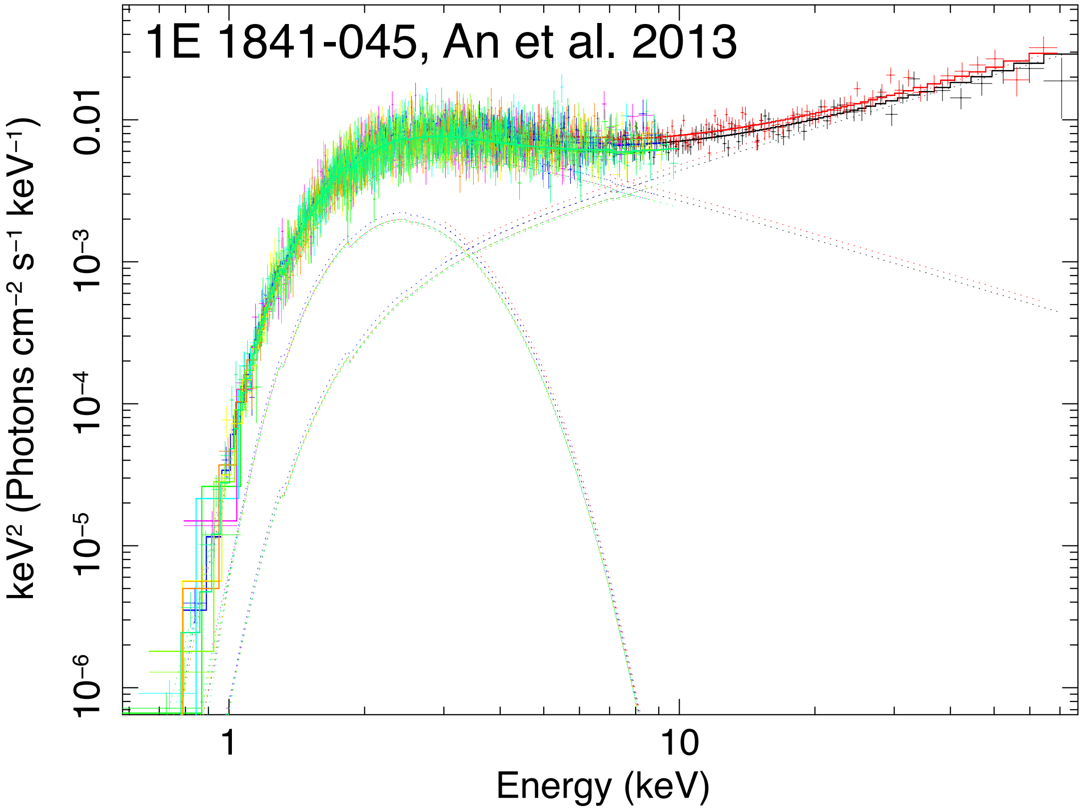


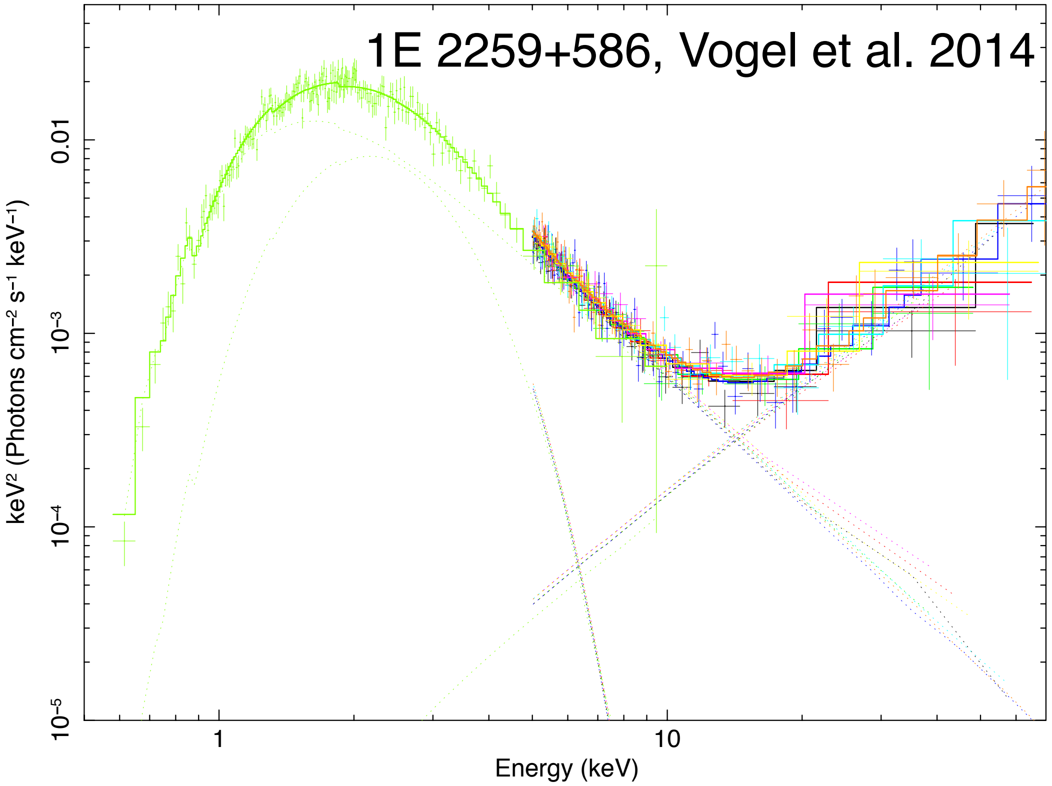
4U 0142+61
Den Hartog et al. 2008

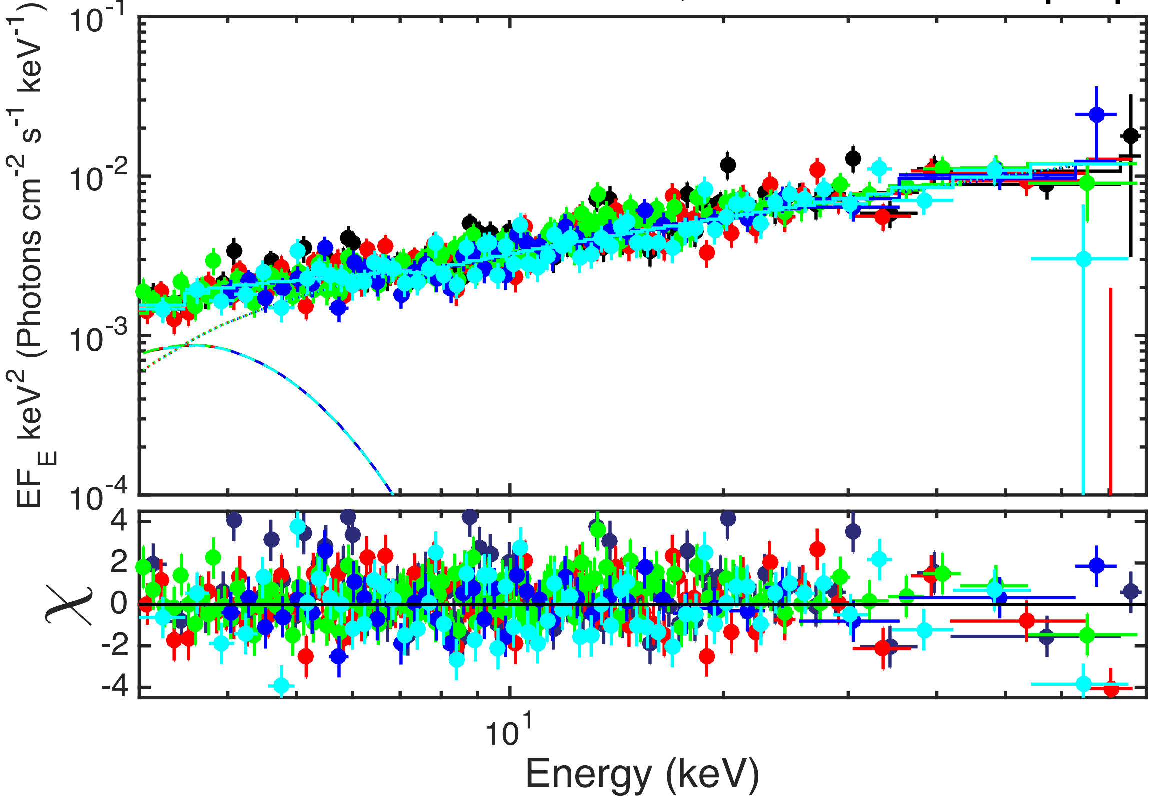
- Hard power-law tail
  - Gamma=1.0

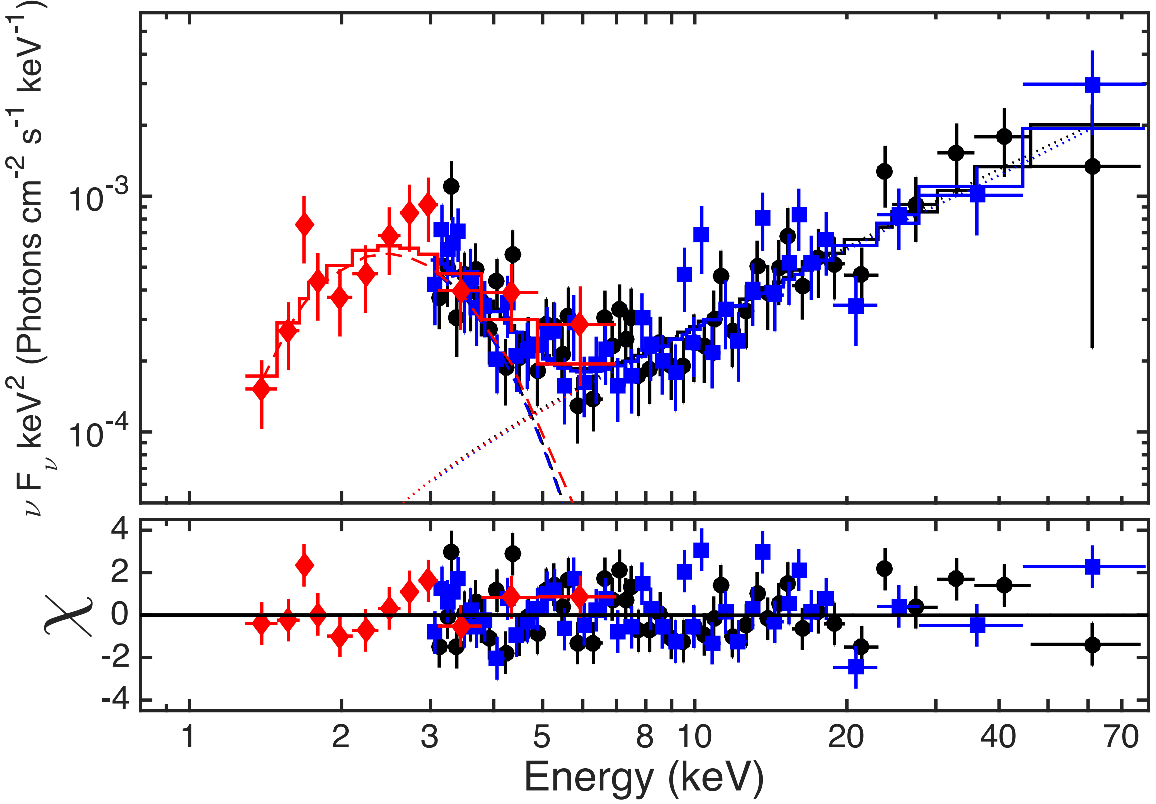
$$F_{\mathrm{X,\ 10-100\ keV}} > F_{\mathrm{X,\ 0.5-10\ keV}}$$

PERSISTENT EMISSION – HARD X-RAYS


1E 1841-045, An et al. 2013

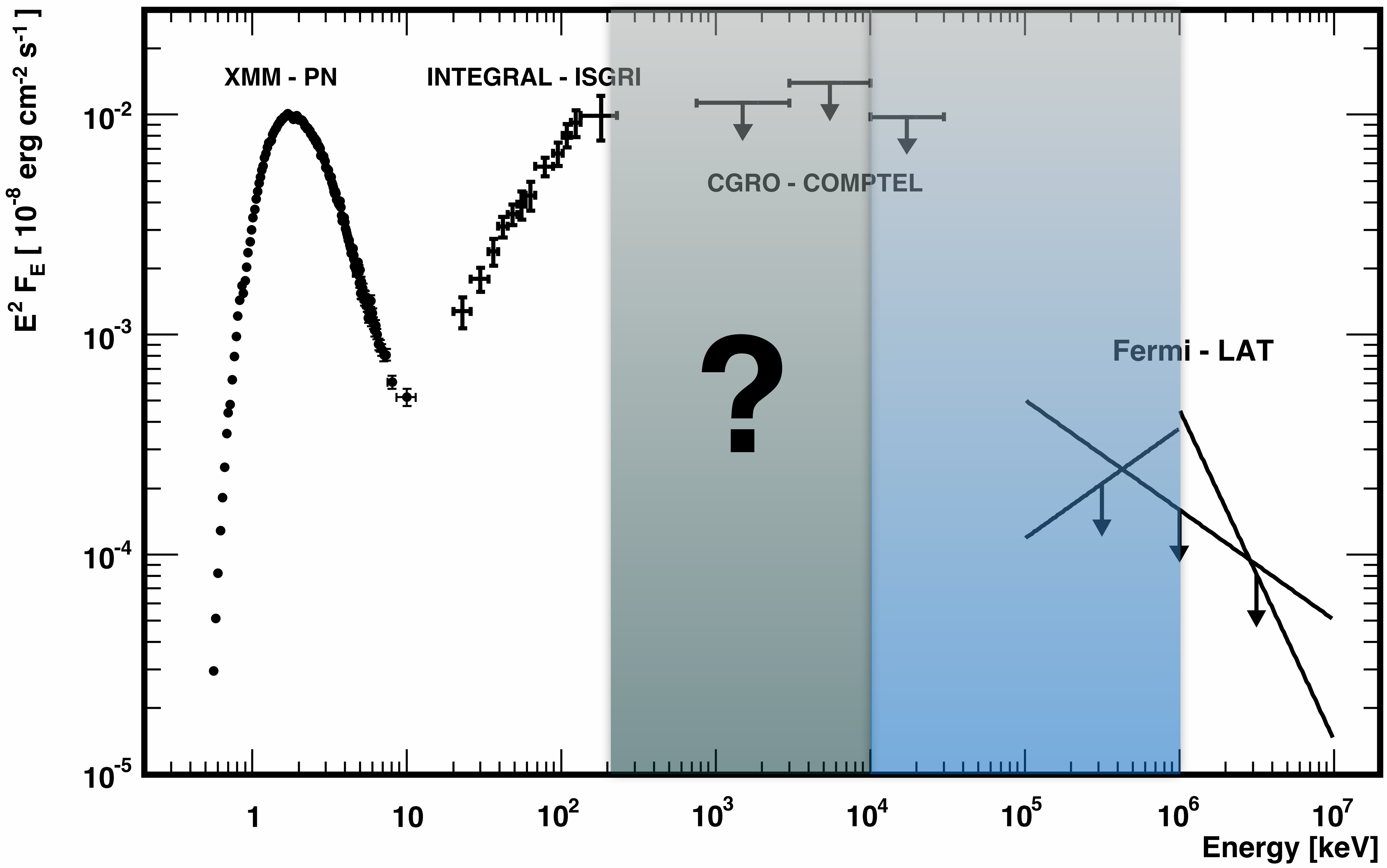

1E 2259+586, Vogel et al. 2014


SGR 1806-20, Younes et al. in prep.

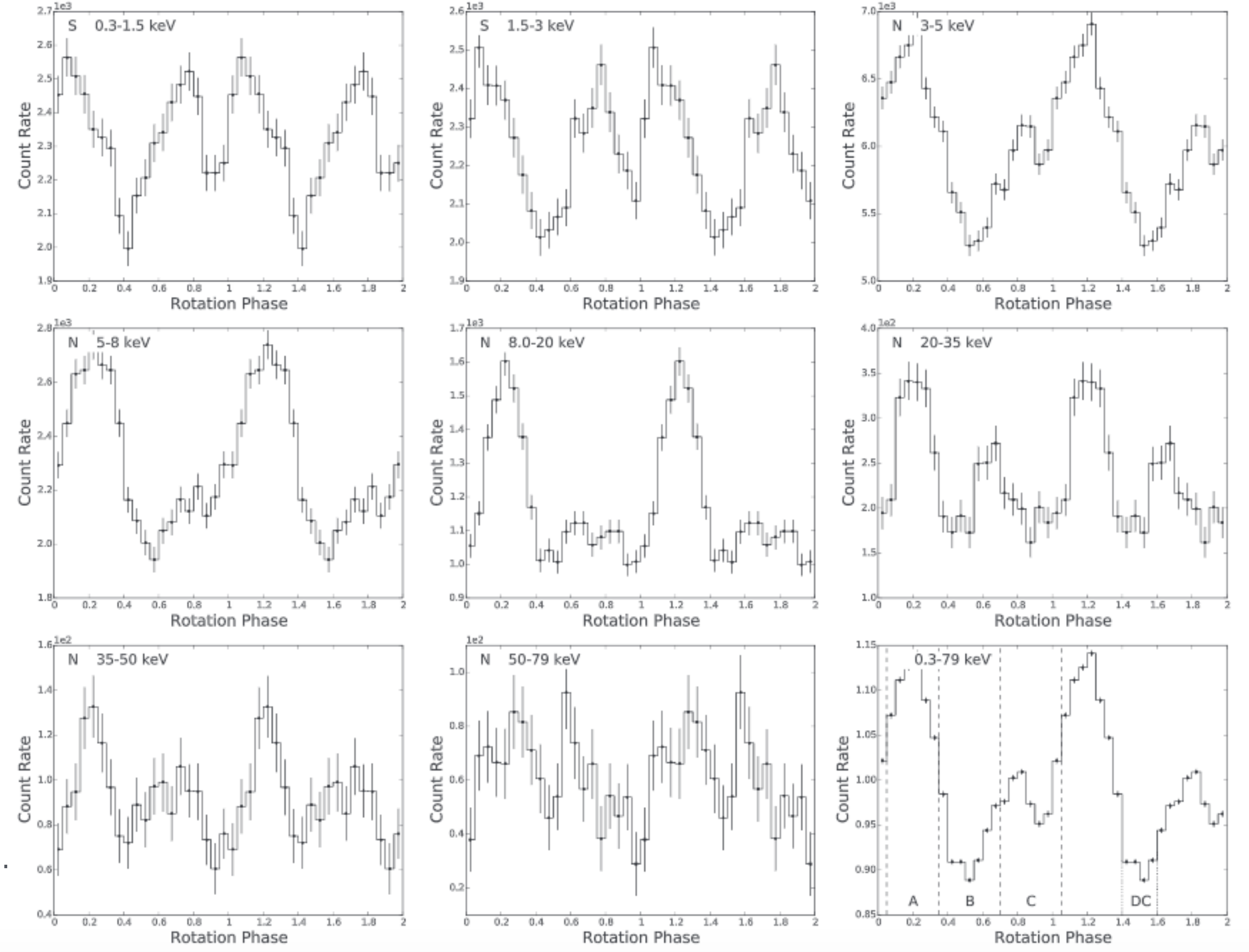

SGR 1935+2154, Younes et al. 2017

FERMI/LAT - GEV GAMMA-RAYS

4U 0142+61, Abdo et al. 2010 (see also Li et al. 2017)

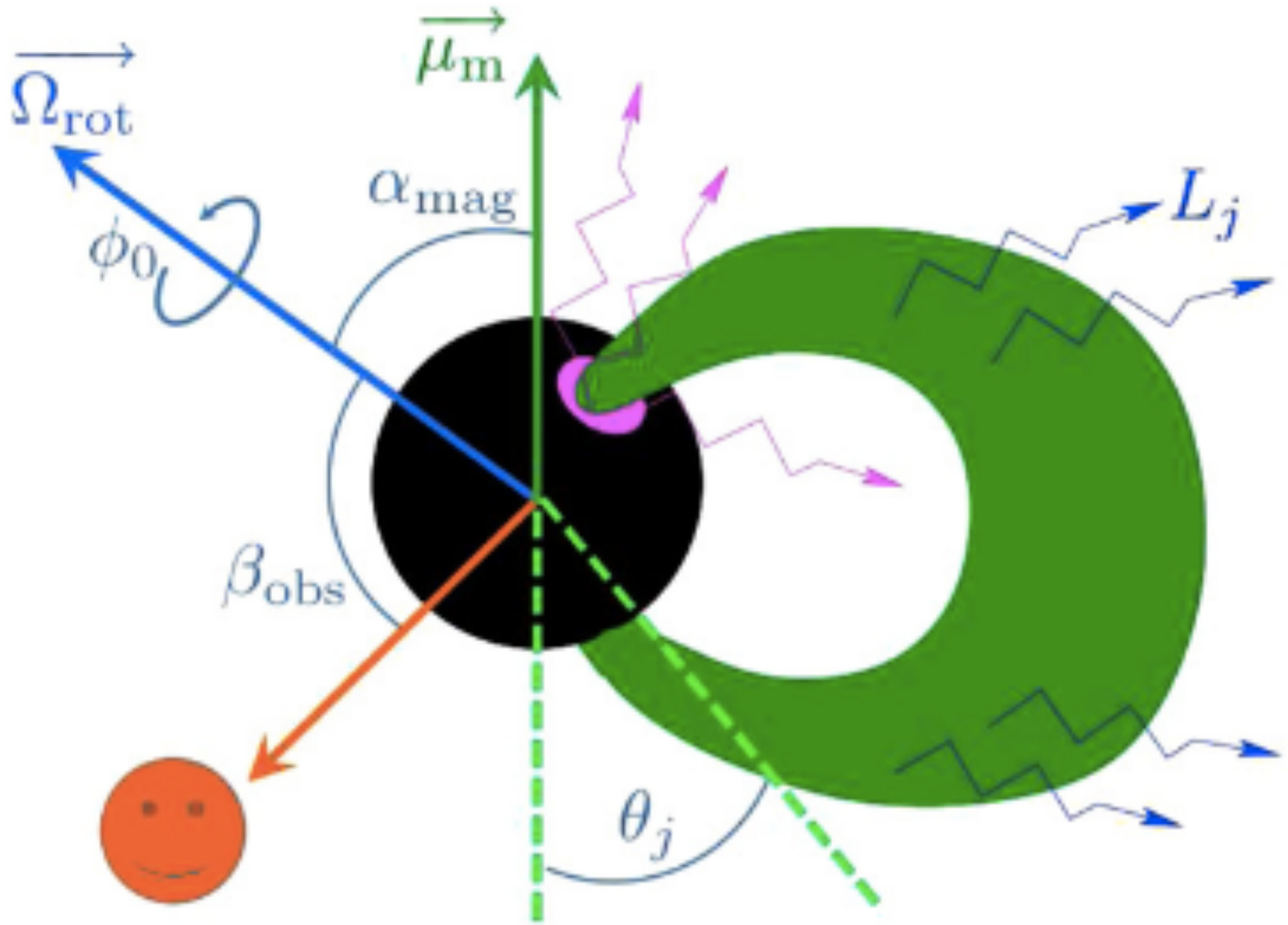


PERSISTENT EMISSION – PULSATIONS



Tendulkar et al. 2015

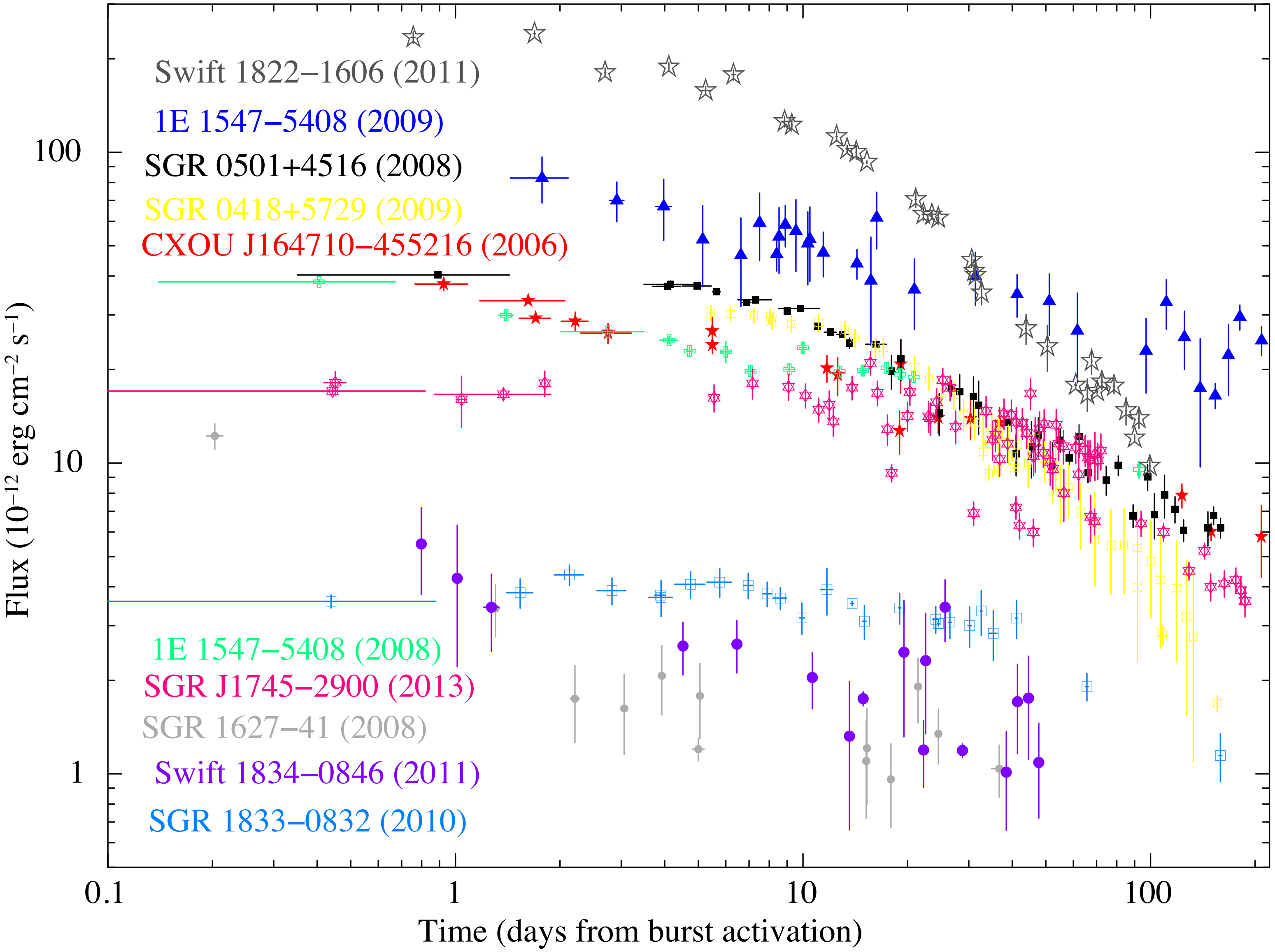
PERSISTENT EMISSION – THEORY



Thompson et al. 2002, Beloborodov 2009, Hascoet et al. 2014
Baring & Harding 2007

Magnetar Outbursts

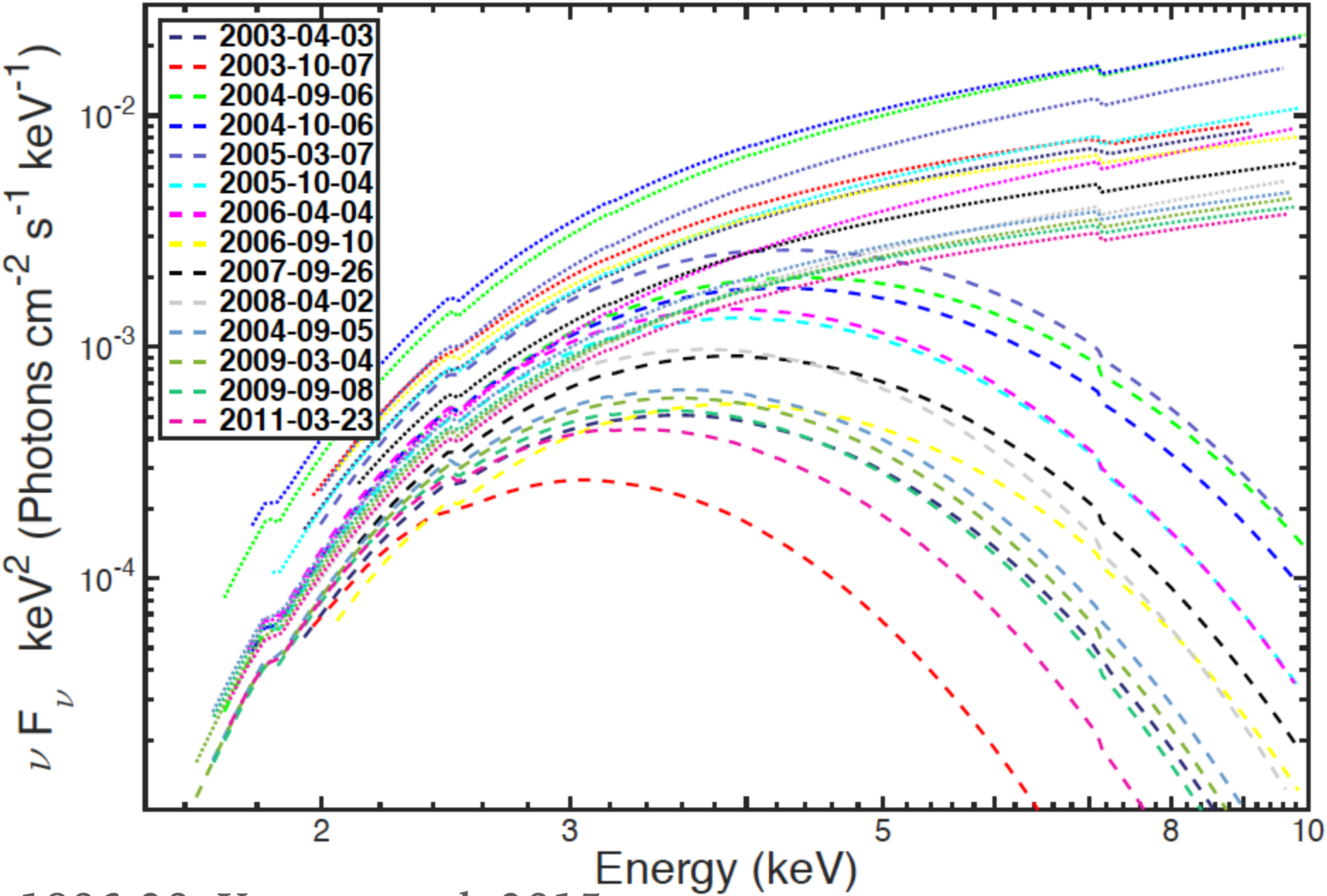
PERSISTENT EMISSION RESPONSE TO BURSTS



Coti Zelati et al. 2015

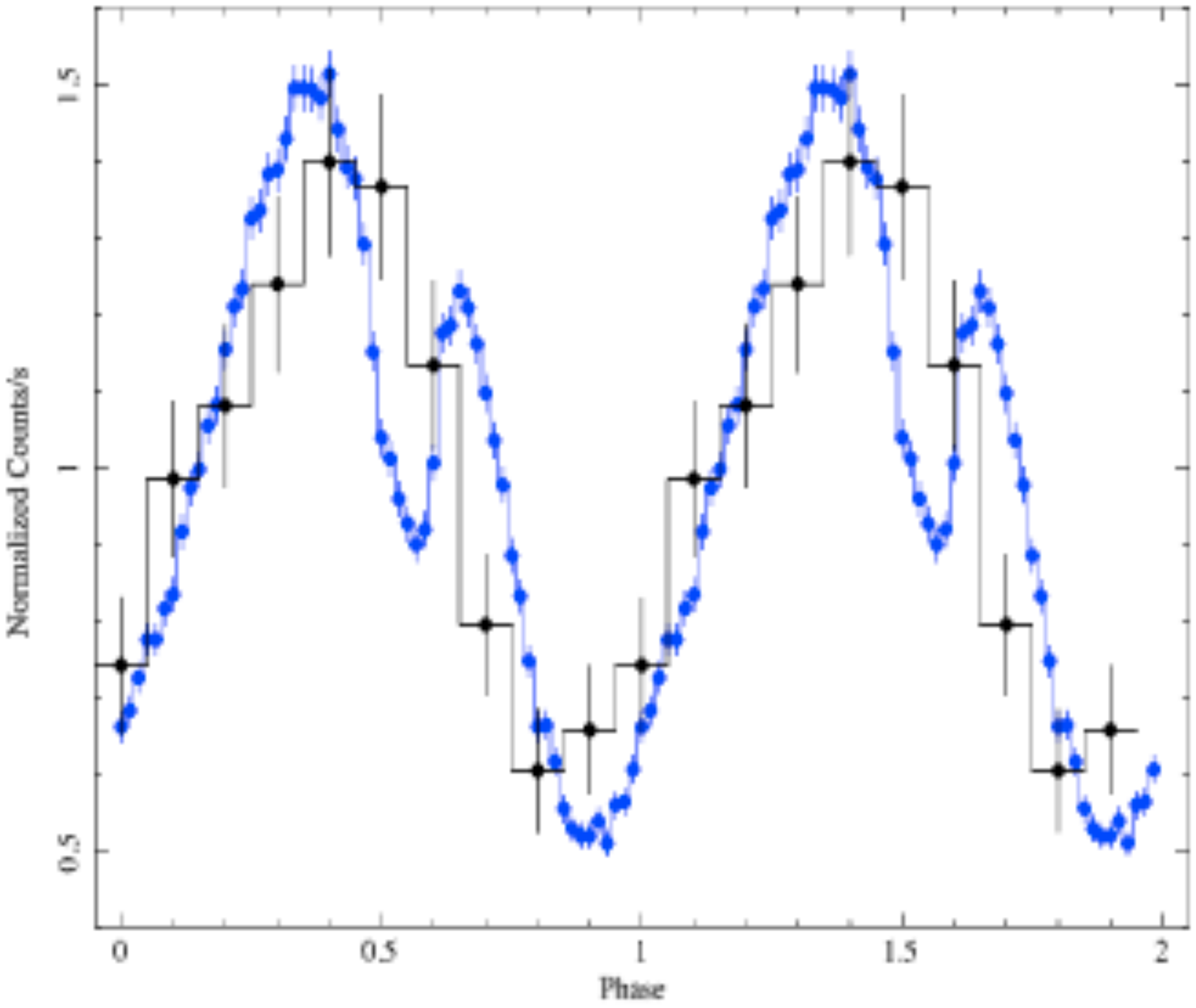
- 0.5-10 keV flux increase by as many as 3 orders of magnitude, also as low as a factor of a few.
- Much harder spectra compared to pre-outburst.
- Change in pulse period, in the form of noise or glitches.
- Change in pulse shape, and pulsed flux.

SGR 1806–20 – FOLLOWING 2004 OUTBURST UP TO 2011

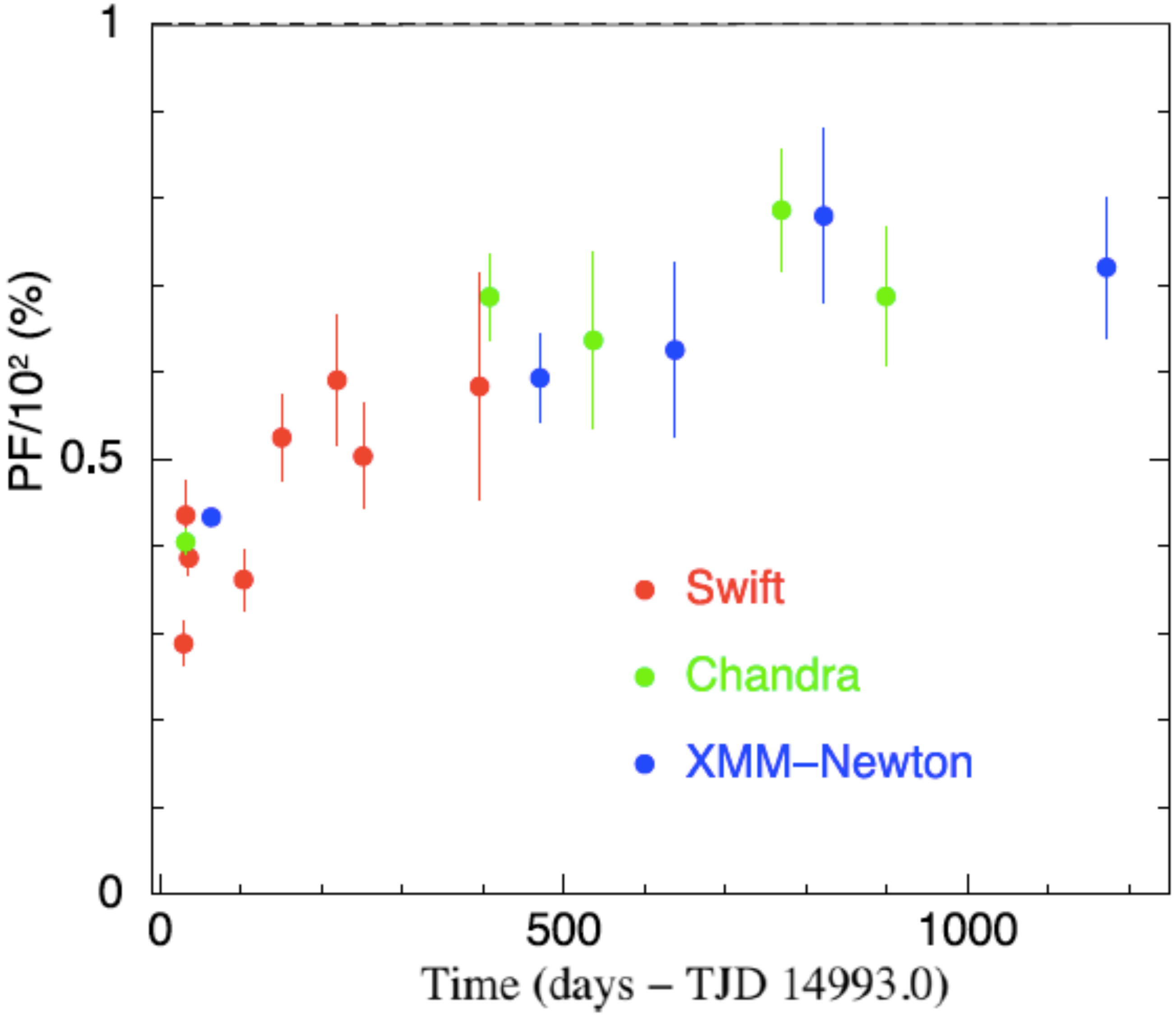


SGR 1806-20, Younes et al. 2015

SGR 0418+5729 - FOLLOWING 2009 OUTBURST



SGR 0418+5729, Rea et al. 2013

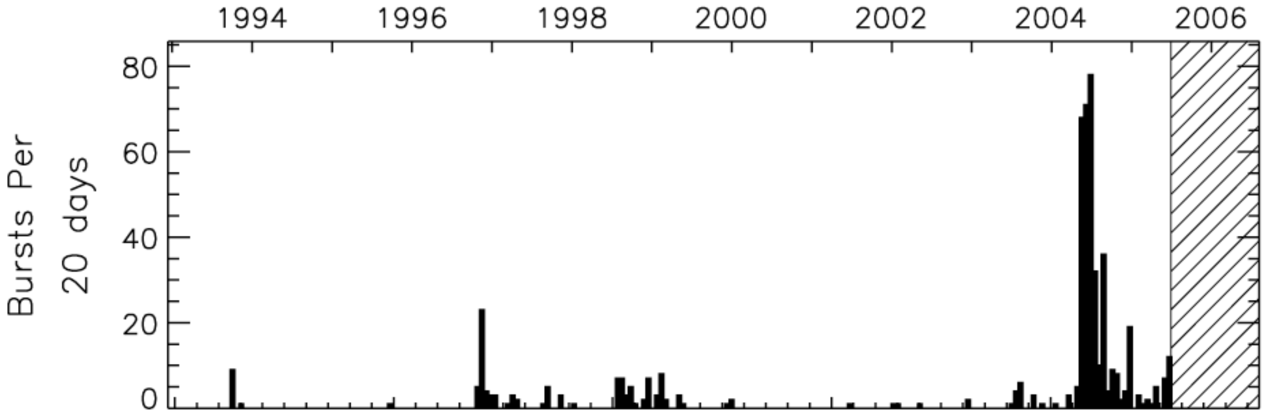


PART 3

Interesting sources

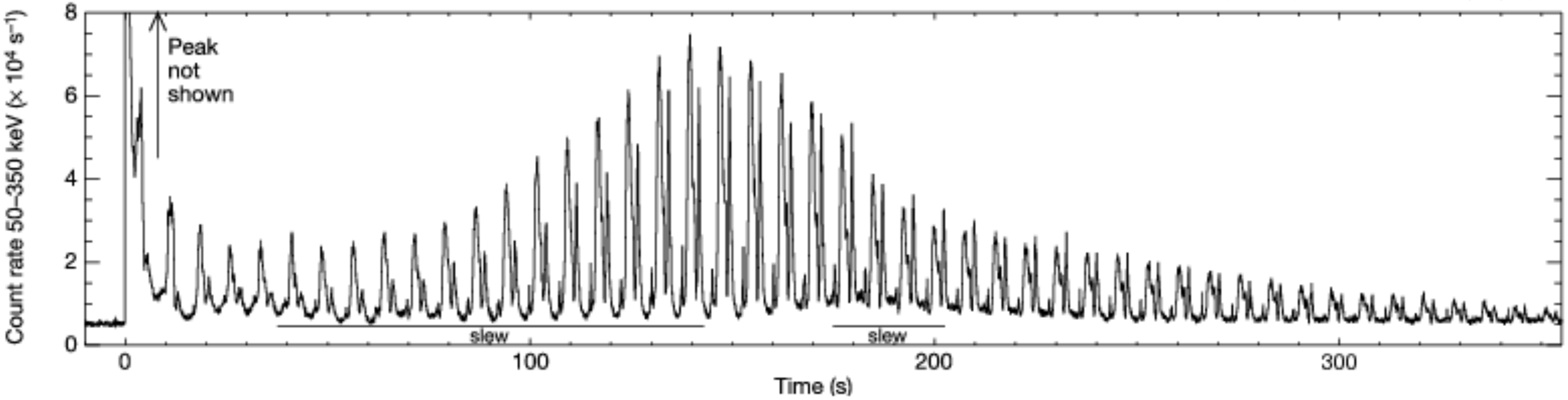
SGR 1806-20 - GENERAL PROPERTIES

- P = 7.5 s, Pdot ~ 3E-10 s/s, B ~ 1.0E15 G, Tau_c ~ 0.24 kyr.
- L_X ~ 1.0E35 erg/s @ 8.7 kpc.
- Prolific burster.

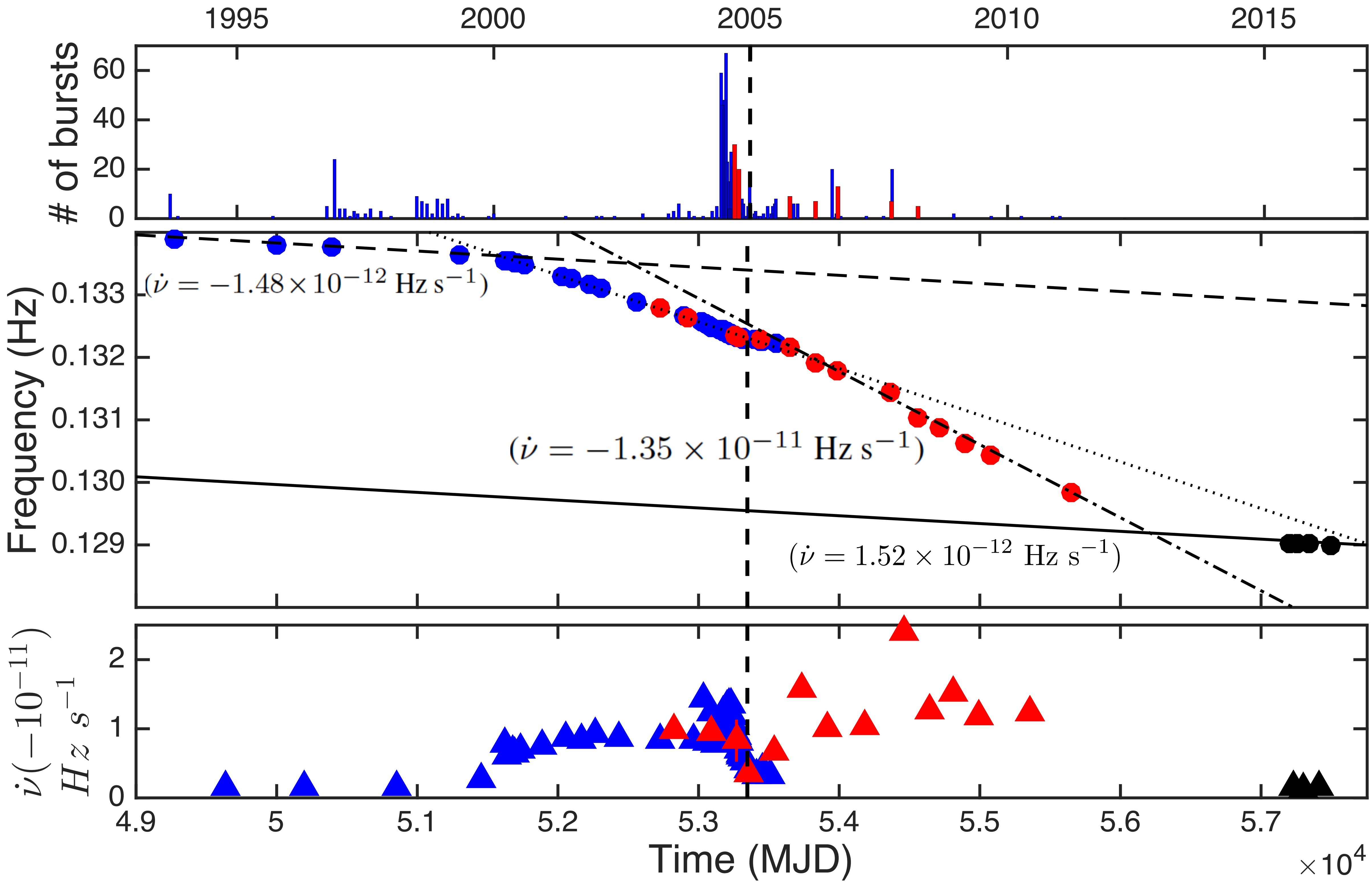


- GF in 2004 December.

Palmer et al. 2005

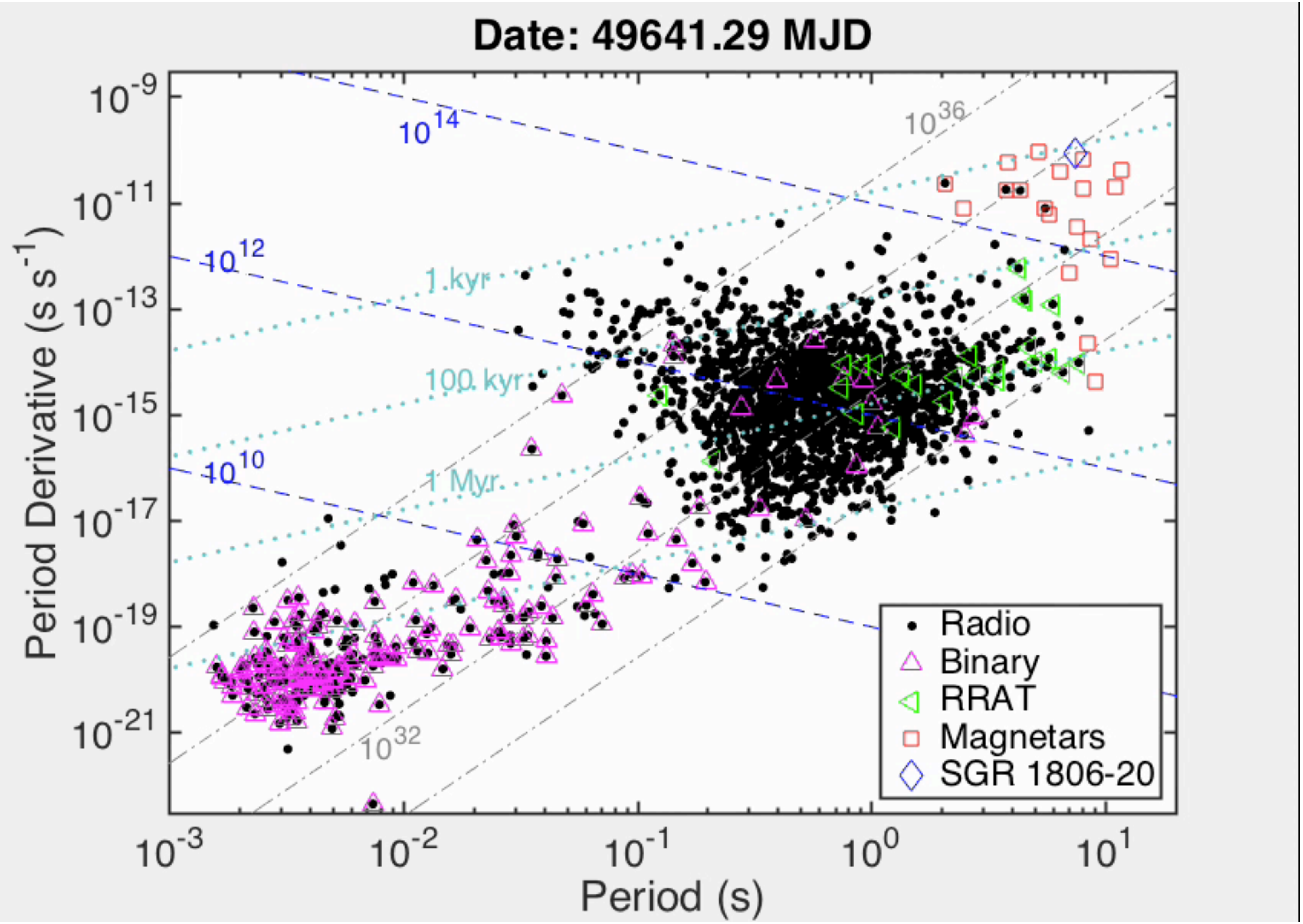


SGR 1806–20 – UP TO MID 2015



Younes et al. 2015, Younes et al. in prep.

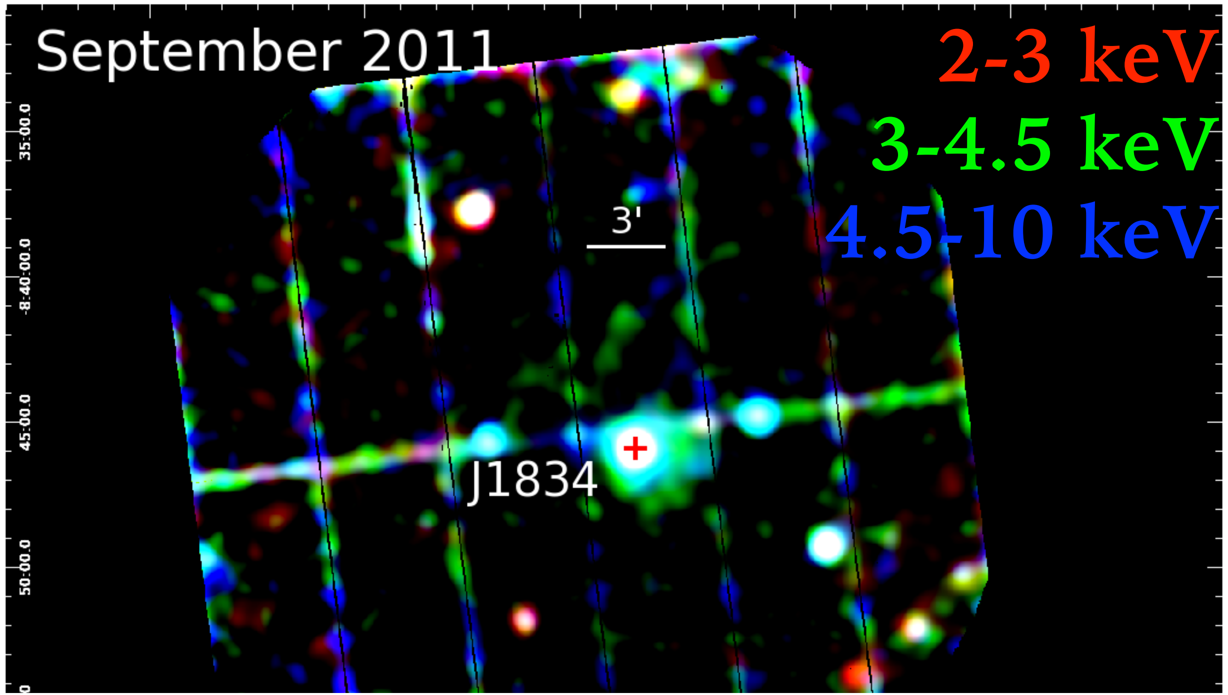
SGR 1806-20 – UP TO MID 2015

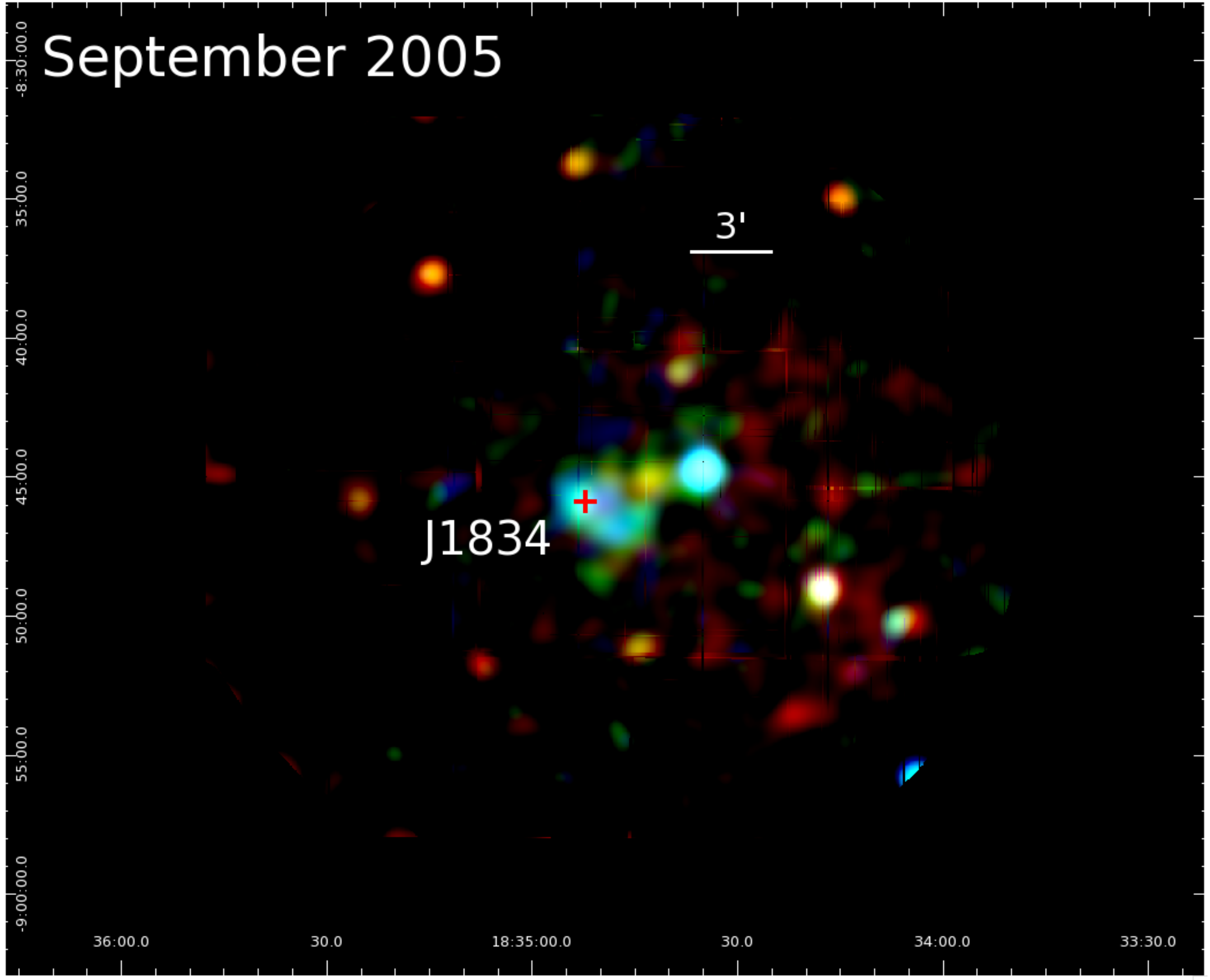


SWIFT J1834.9–0846

- Discovered in 2011 August 7 (Swift/BAT burst).
- $P = 2.48$ s, $P_{dot} \sim 7.96 \times 10^{-12}$ s s^{-1} (Kargaltsev et al. 2012).
- $B \sim 1.4 \times 10^{14}$ G, $\tau \sim 4.9$ kyr.
- $-\dot{E} \sim 2.1 \times 10^{34}$ erg s^{-1}.

SWIFT J1834.9—0846, WHAT IS THE EXTENDED EMISSION?





- Asymmetry.
- Hard spectrum, $\Gamma\sim3.0$ (relative to Magnetar).
- Bright X-ray flux (relative to Magnetar).
  - A Wind Nebula around a Magnetar!

Younes et al. 2012

Esposito et al. 2013

- Absorbed by a Giant Molecular Cloud (GMC); density inhomogeneity.
- Large error bars on spectral shape.
- Large extent; delay in flux decay.
  - Awkward dust scattering halo!

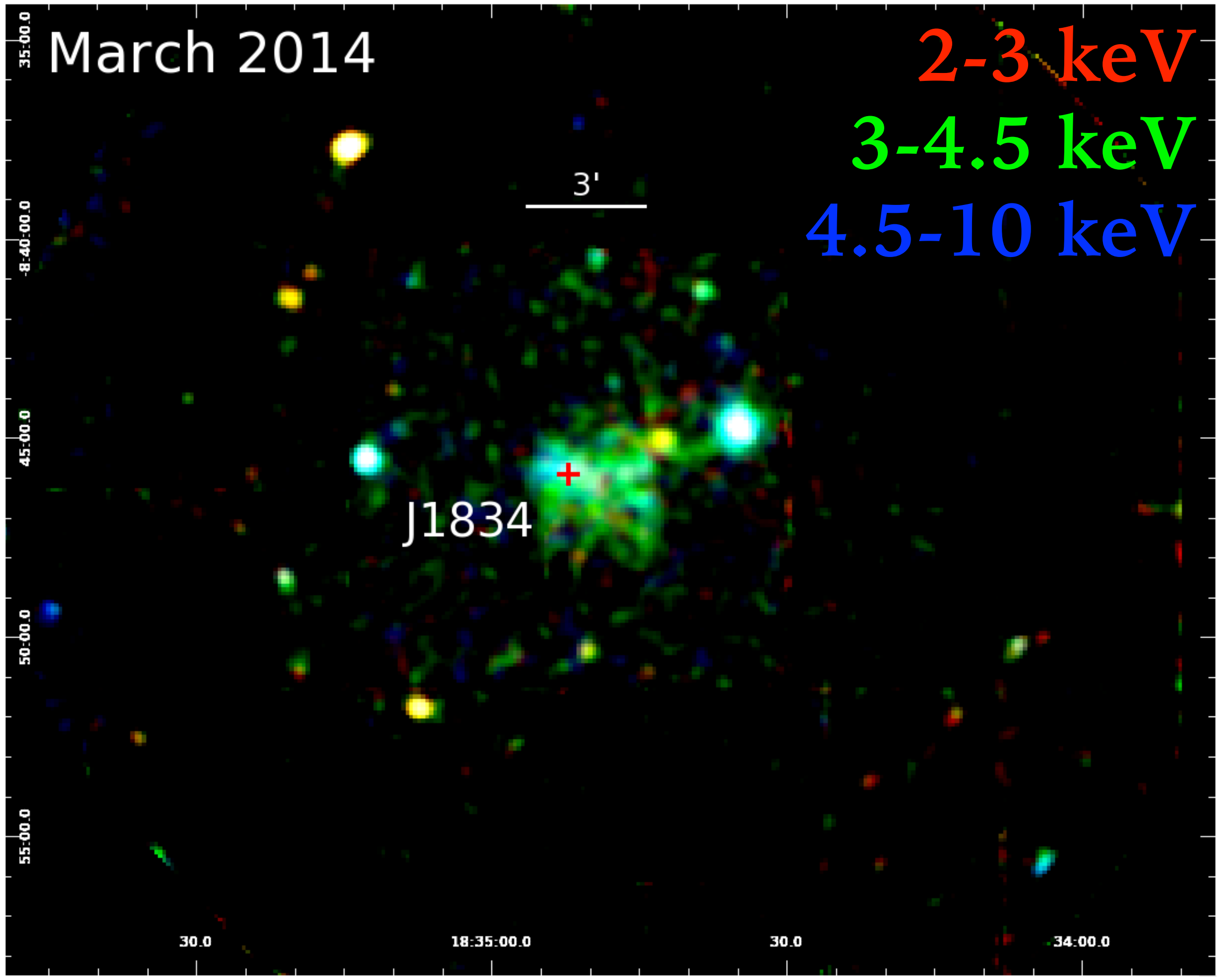
SWIFT J1834.9—0846, NEW XMM-NEWTON DATA

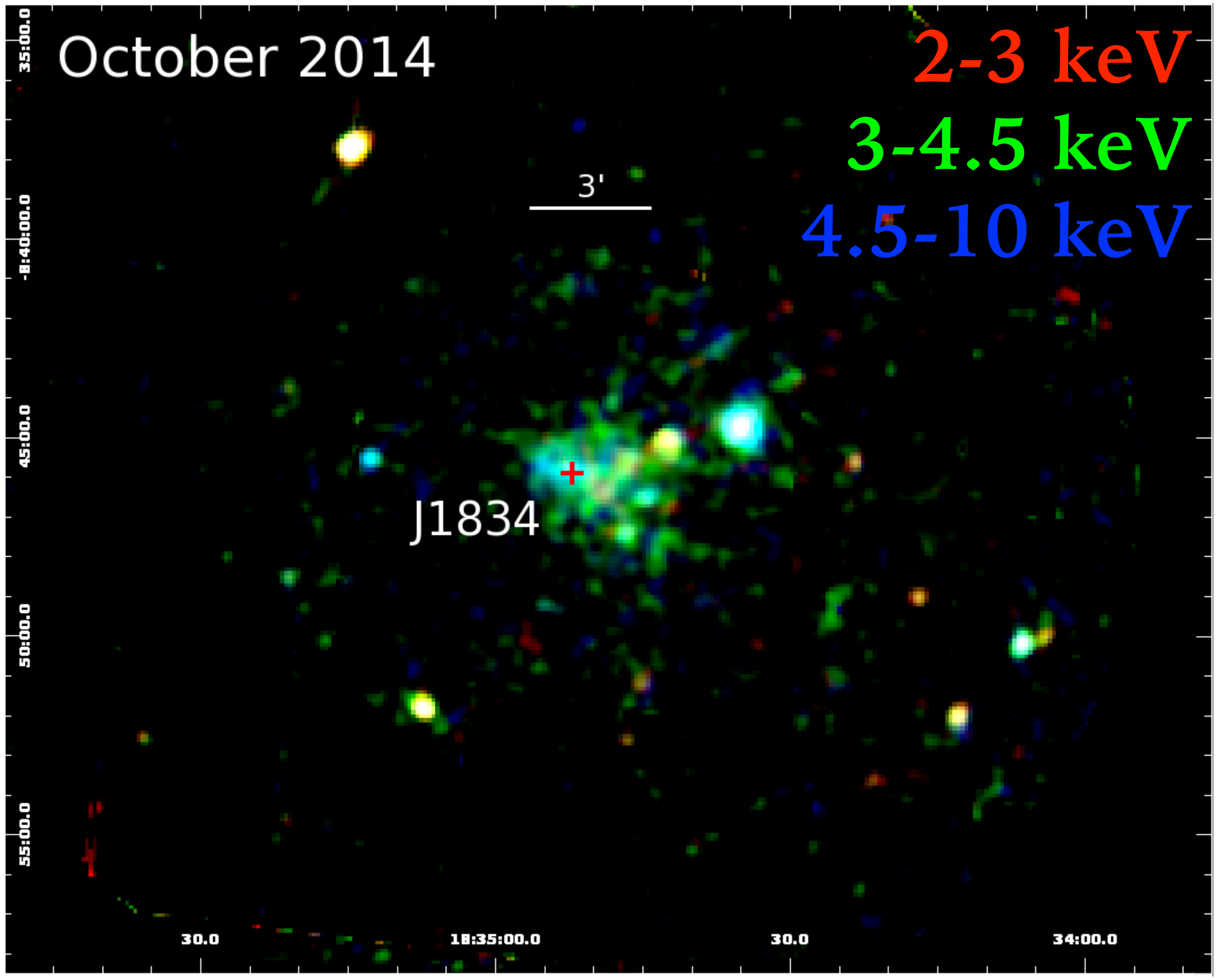
- 2 deep XMM-Newton observations
  - 2014 March 16 — 2.5 yrs after 2011 outburst.

    260 ks between PN (80 ks)/MOS1/MOS2.
  - 2014 October 16 — 3.1 yrs after 2011 outburst.

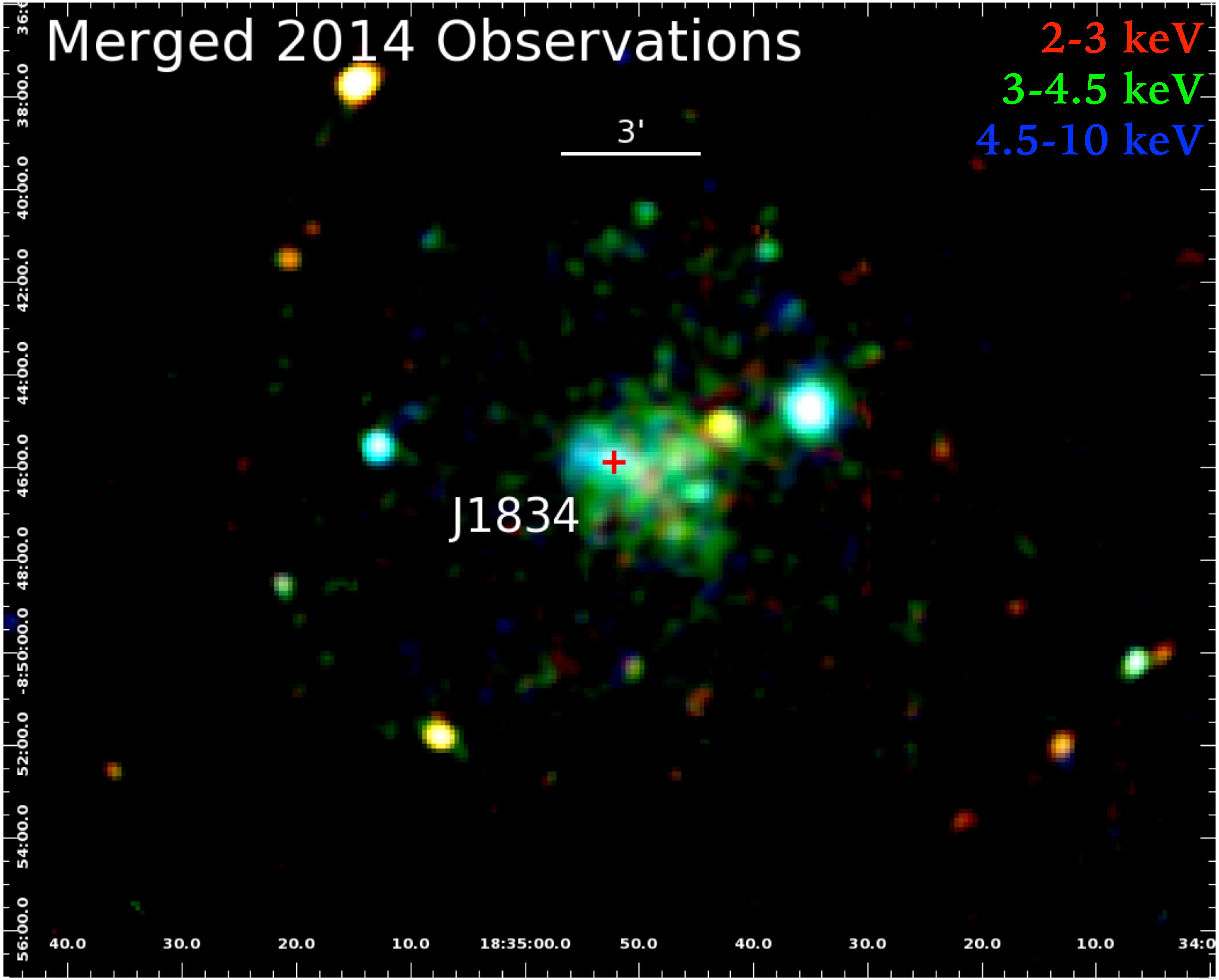
    240 ks between PN (70 ks)/MOS1/MOS2.

SWIFT J1834.9—0846, 2.5 & 3.1 YEARS AFTER DISCOVERY

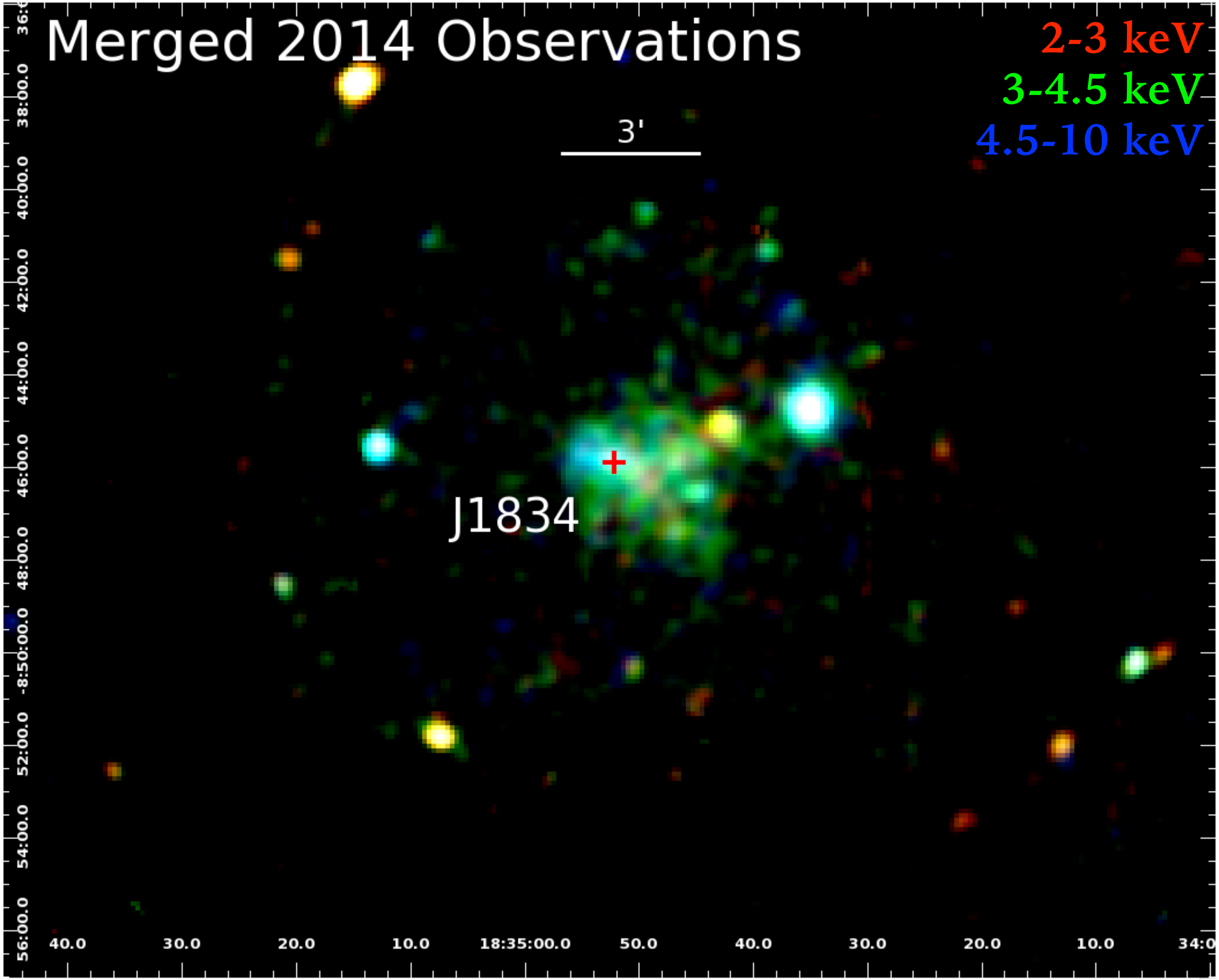




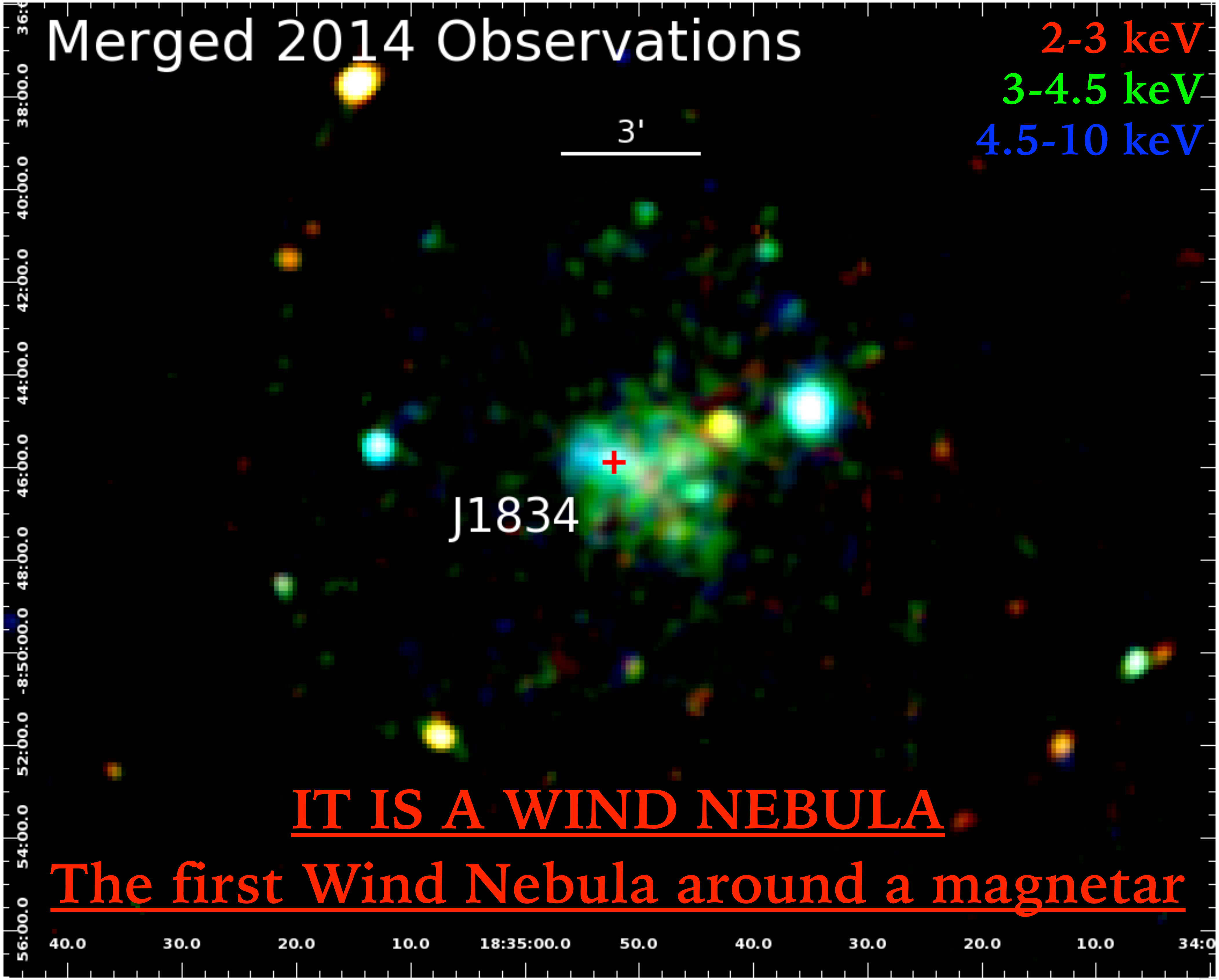
SWIFT J1834.9—0846, 2014 OBS. MERGED



SWIFT J1834.9—0846, WHAT IS THE EXTENDED EMISSION?



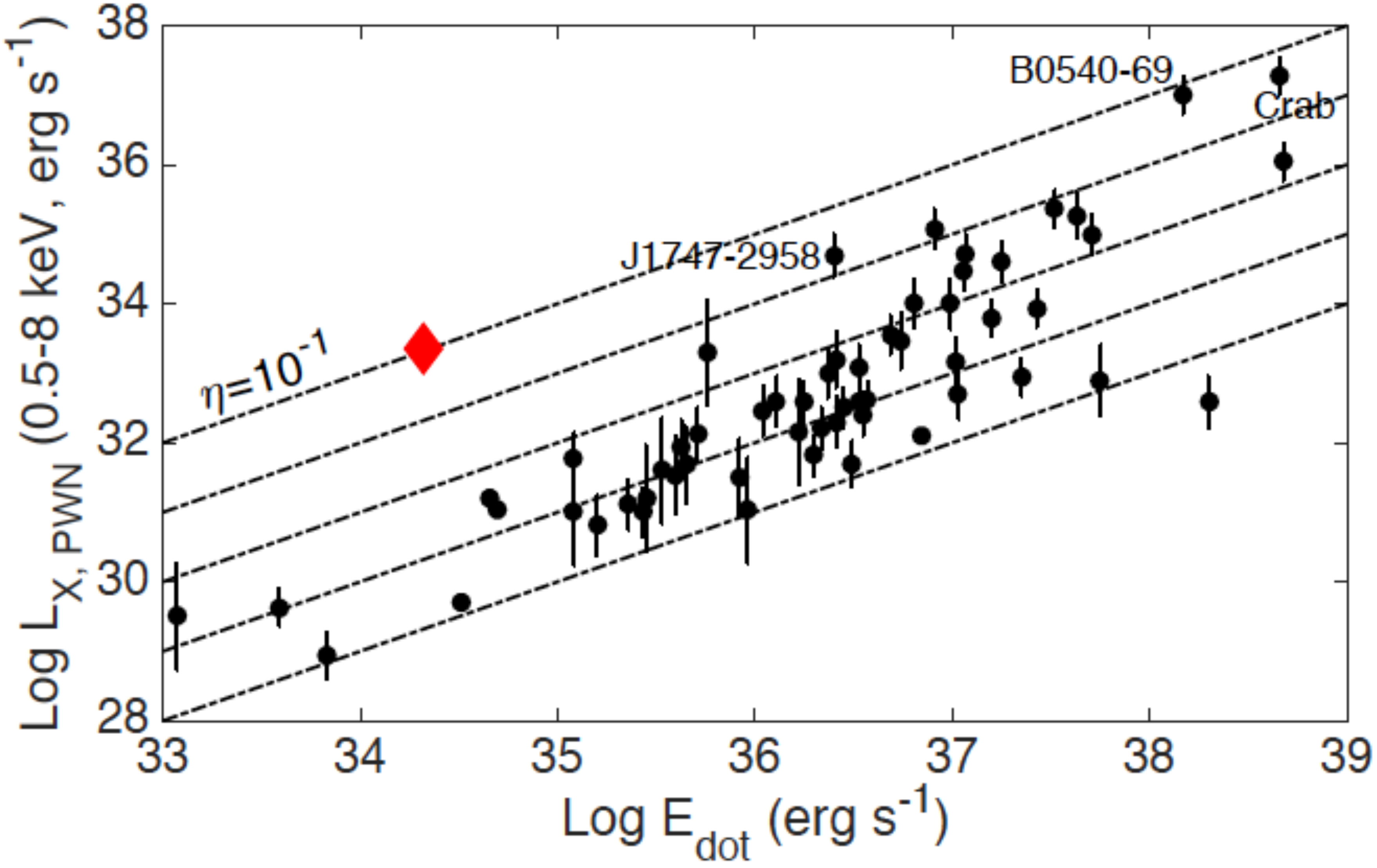
SWIFT J1834.9—0846, WHAT IS THE EXTENDED EMISSION?



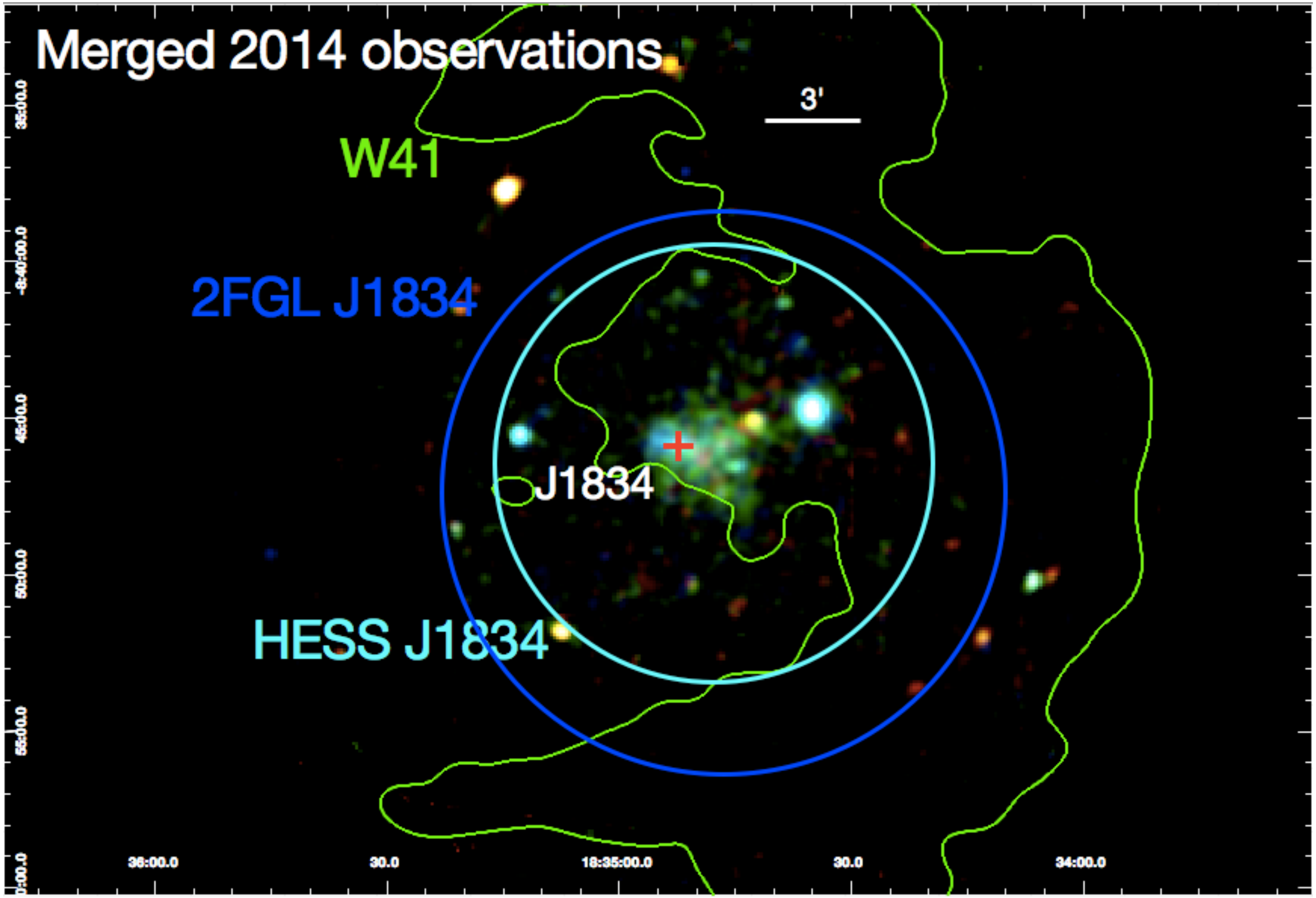
IT IS A WIND NEBULA

The first Wind Nebula around a magnetar

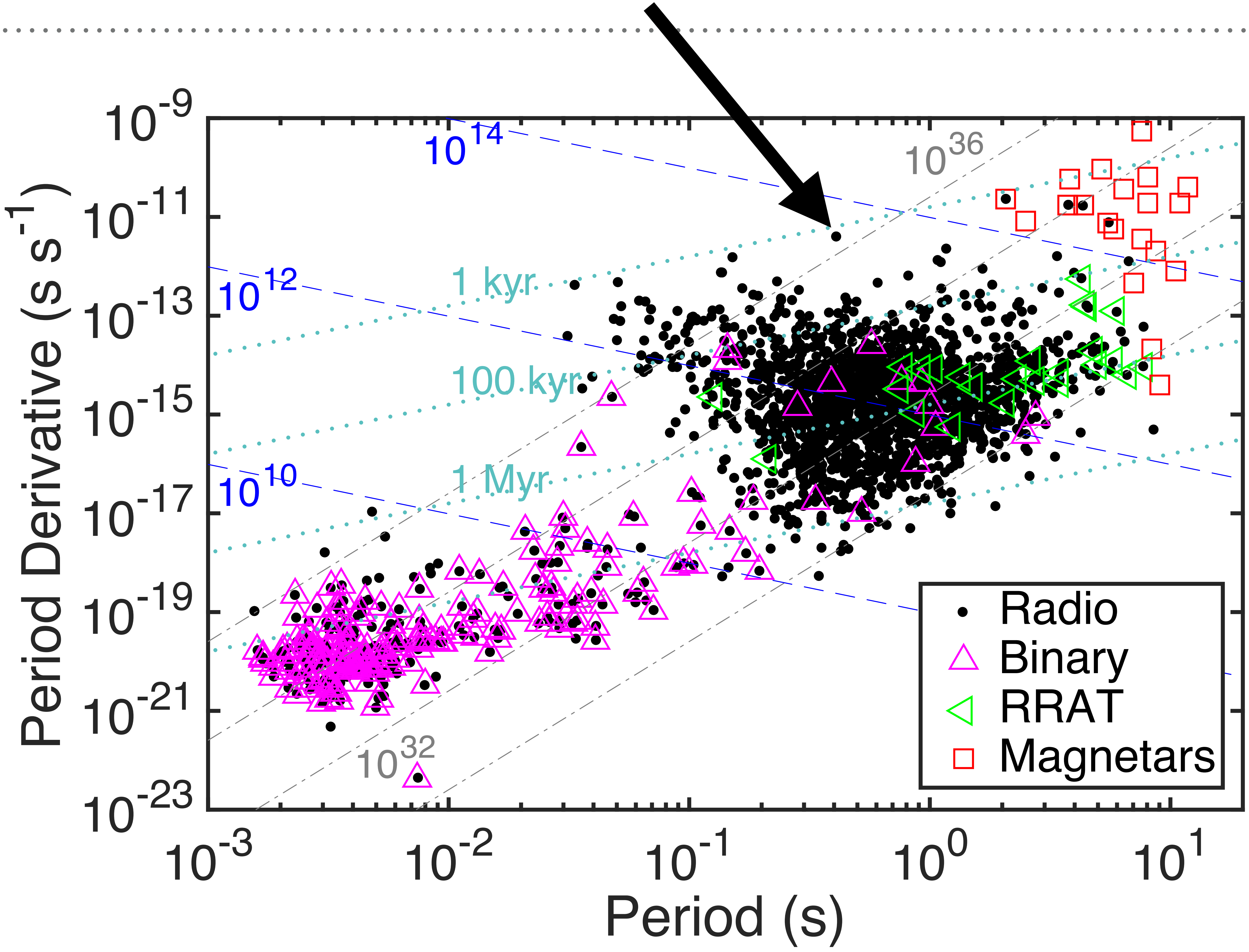
SWIFT J1834.9—0846, COMPARED TO OTHER NEBULA



SWIFT J1834.9–0846 ENVIRONMENT

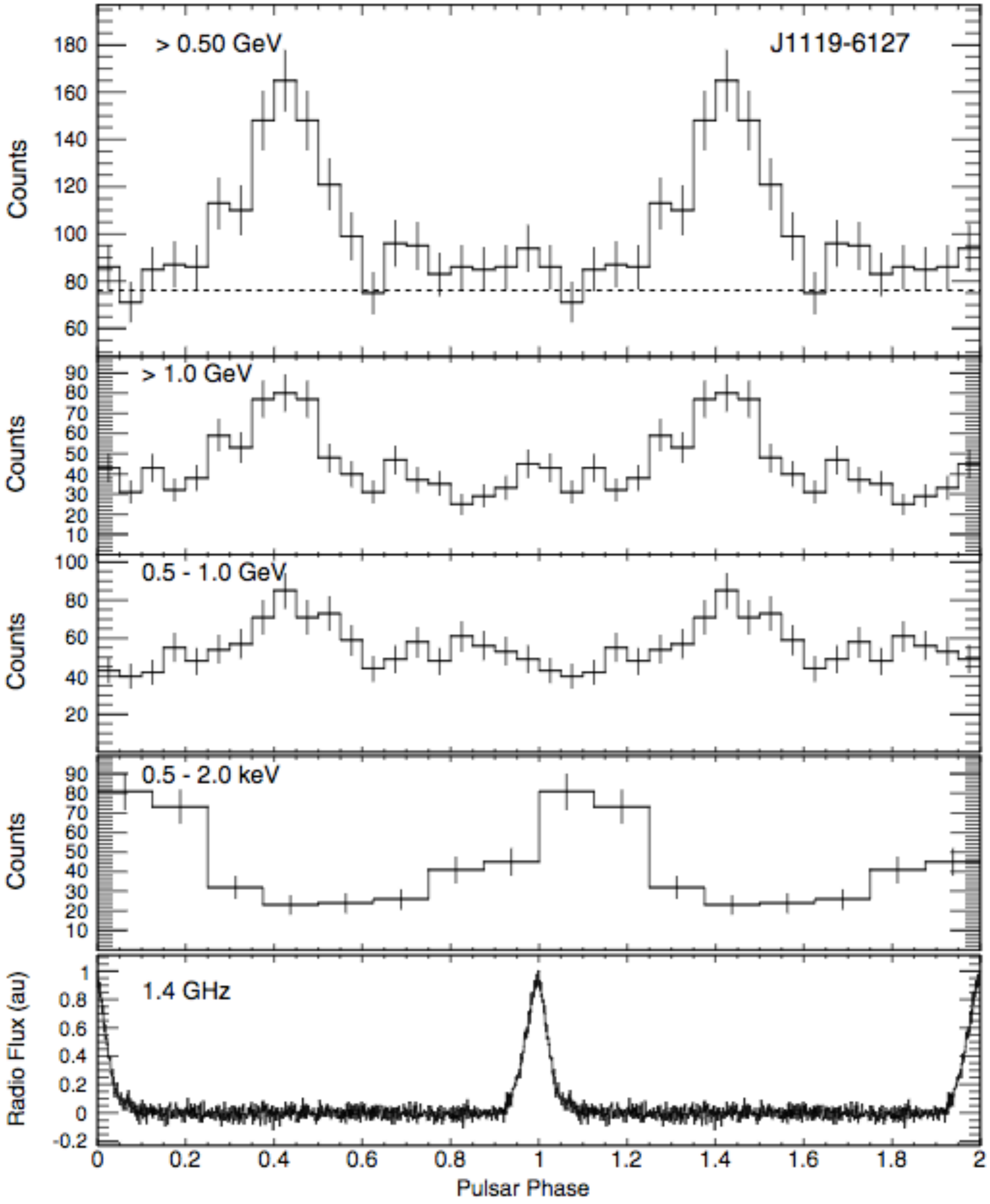


HIGH-B PULSARS — PSR J1119-6127



HIGH-B PULSARS — PSR J1119-6127

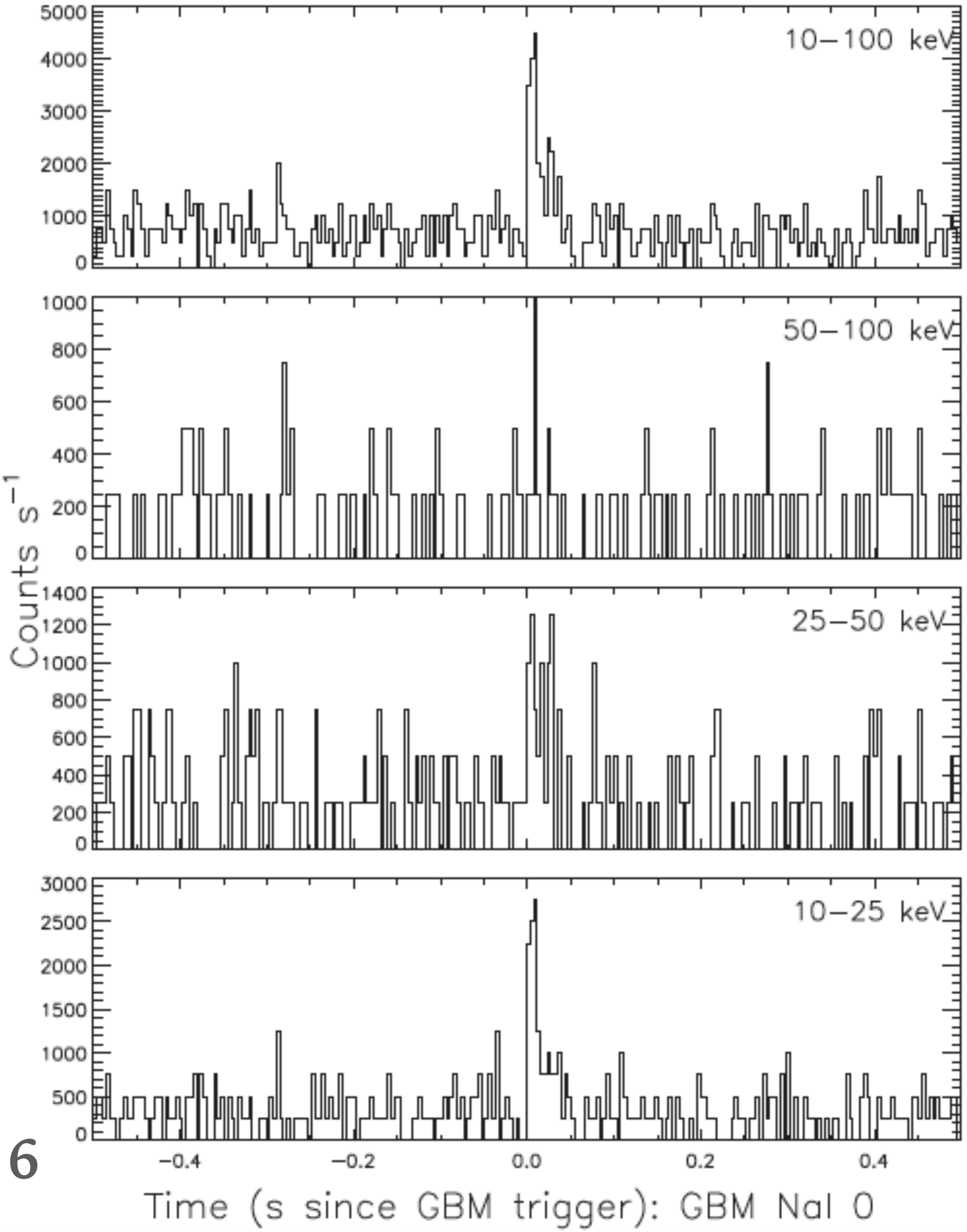
- P = 0.407 s, $P_{dot} \sim 4.0 \times 10^{-12}$ s s^{-1} (Camillo et al. 2000).
- B ~ 4.1×10^{13} G, $\tau \sim 1.6$ kyr.
- $-\dot{E} \sim 2.3 \times 10^{36}$ erg s^{-1}.
- Gamma-ray pulsar!



Parent et al. 2011

HIGH-B PULSARS — PSR J1119-6127

- Emitted magnetar-like bursts on 2016 July 27.
- Accompanied by spin-up glitch, enhancement in persistent X-ray flux, ceasing of radio pulsations.
- Fermi/LAT gamma-ray emission seem to not care about any of this!



Gogus et al. 2016

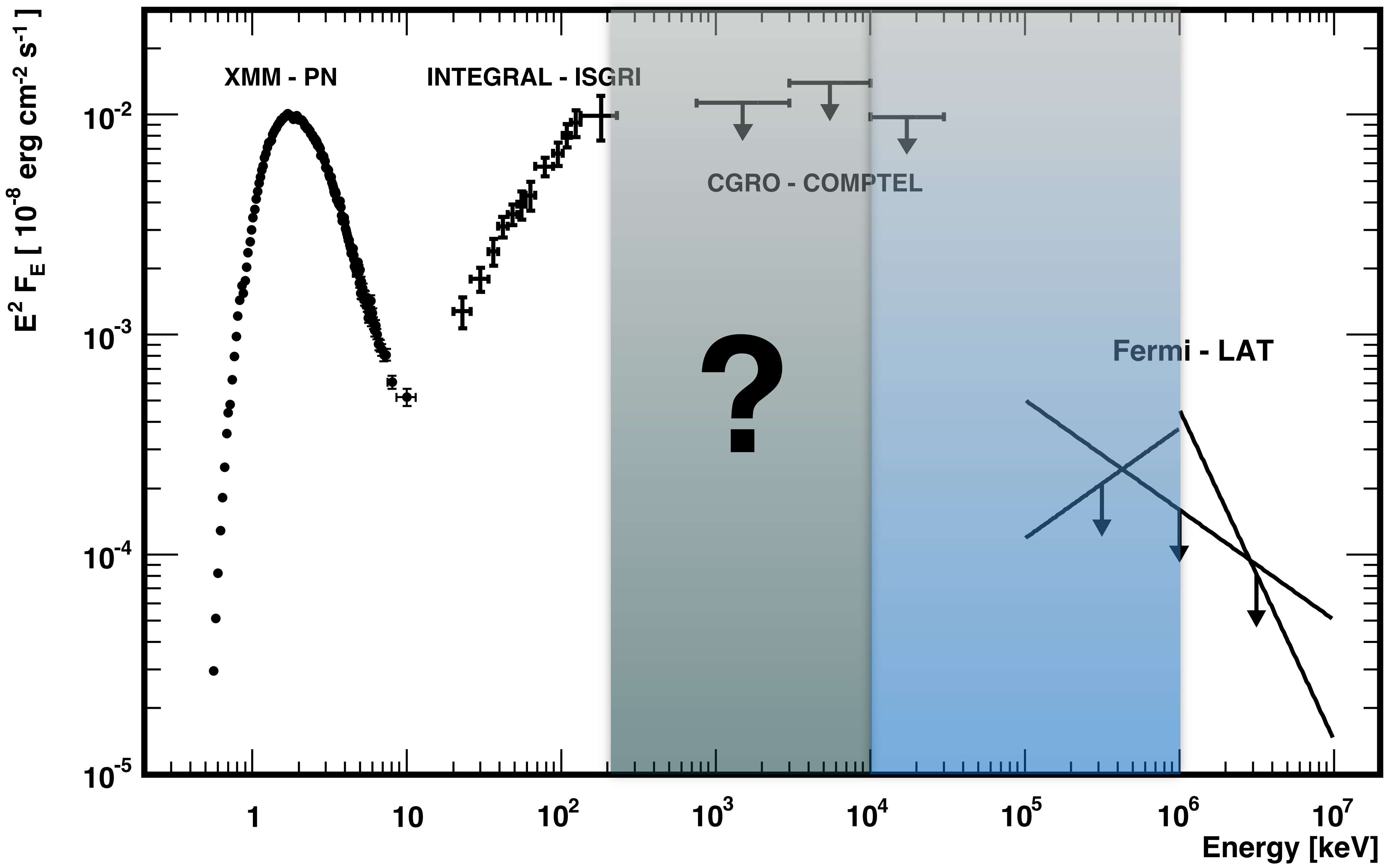
Archibald et al. 2016

PART 4

What the future holds

FERMI/LAT - GEV GAMMA-RAYS

4U 0142+61, Abdo et al. 2010 (see also Li et al. 2017)



MEV OBSERVATIONS OF MAGNETARS — WHY CARE?

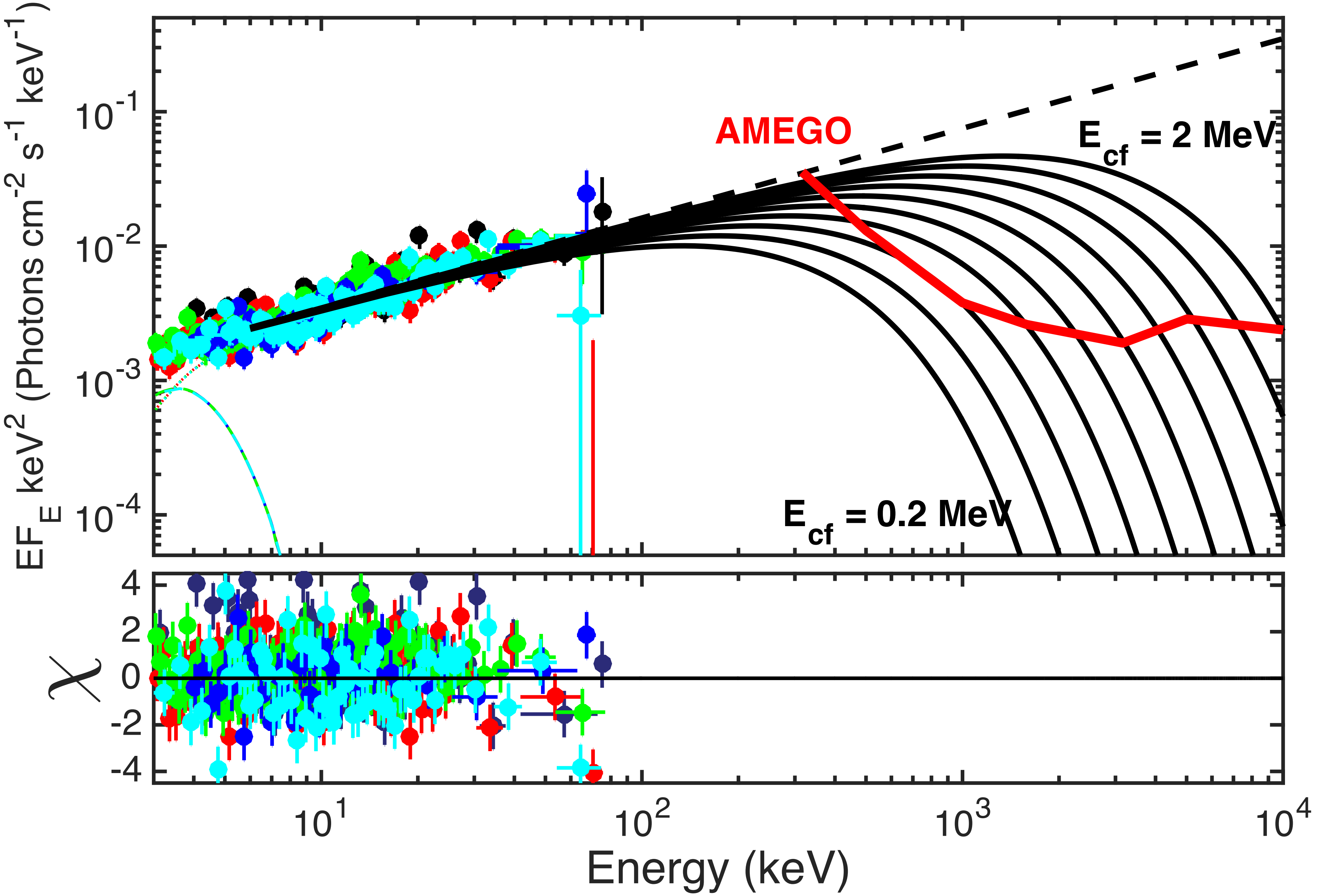
Quiscent/persistent emission:

- Where does the hard X-ray component break?
- What is the total energy budget of magnetars?
- How does the break energy change with phase?
- How do these parameters correlate with spin-down, B-field, age, etc.?
- What about the high-B pulsars? What about the CCO? And the next discovery?

Outburst:

- What is the total energy budget during outburst?
- How does the break energy evolve with time?

MEV OBSERVATIONS OF MAGNETARS — AMEGO



PART 5

Conclusion

CONCLUSION

- Formation?
- Persistent emission?
- Bursts triggering mechanism?
- Radiative transfer in super-strong B field?
- Evolution? Association with RPPs?
- Connection to gamma-ray bursts and super-luminous supernovae?
- Connection to ultra-luminous X-ray sources?
- Connection to Fast Radio Bursts?

THEY EXIST

THANK YOU