FPS8, 西安

From isolated magnetars to accreting magnetars

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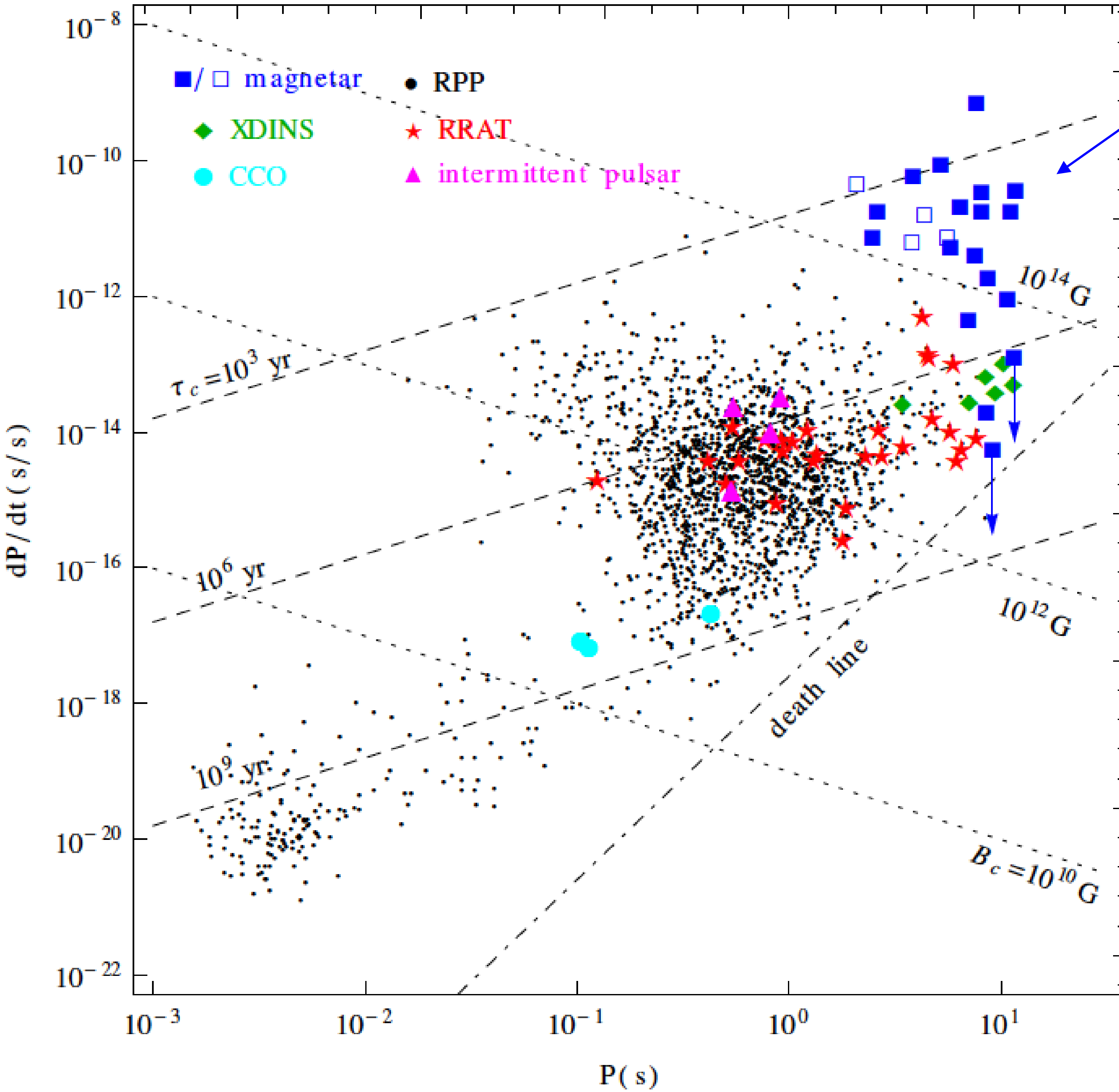
History of pulsars

- 1967: discovery of pulsars (Hewish, Bell et al.)
- ~1970: X-ray pulsars (accreting neutron stars in binary systems, Giacconi et al.)
- 1982: millisecond pulsars (Backer et al.)
  Recycled neutron stars via low mass X-ray binaries
- 1990s: magnetar (Thompson/Duncan, Kouveliotou et al.)
  - Where are accreting magnetars?

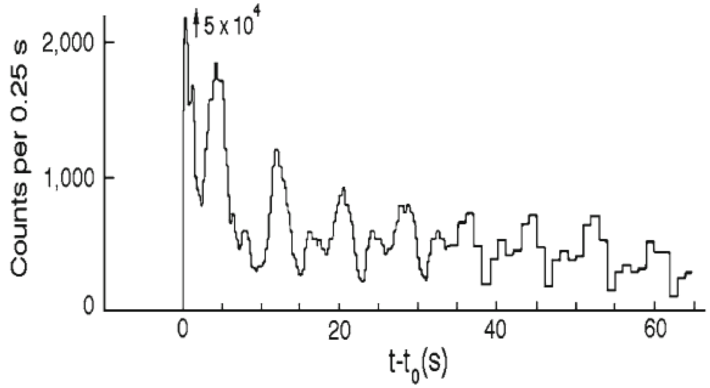


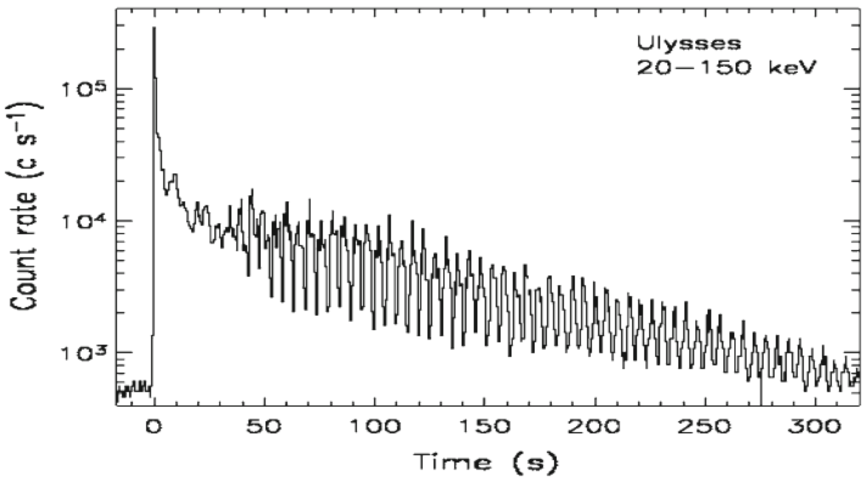
Magnetars my favorite!

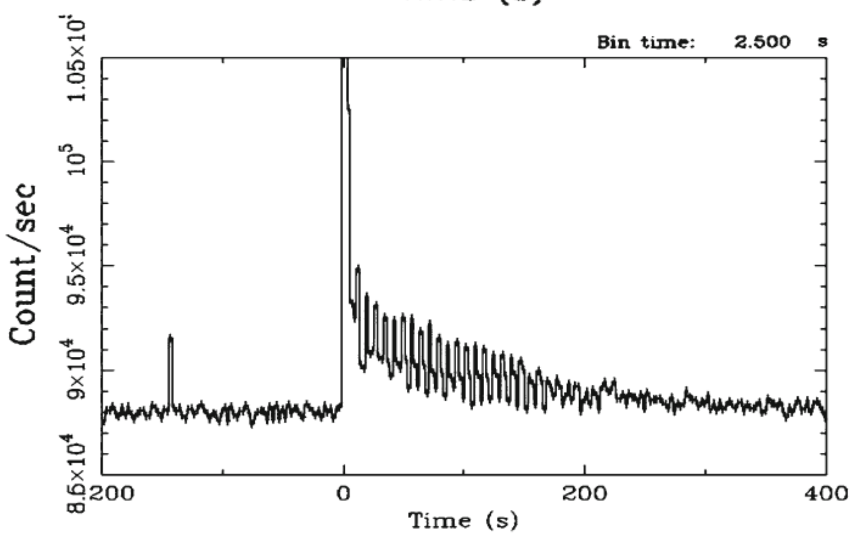
Tong & Wang 2014

Traditional magnetar model (Mereghetti 2008)

- Magnetar =
  1. young NS (SNR & MSC)
  2. $B_{dip} > B_{QED} = 4.4 \times 10^{13}$ G (braking)
  3. $B_{mul} = 10^{14}$ - 10^{15} G (burst and super-Eddington luminosity and persistent emission)







Giant flares of magnetars (Mereghetti 2008):

1. Spike+pulsating tail (hundreds of seconds)

2. 10^4 times super-Eddington during the tail (10^42 erg s^-1)

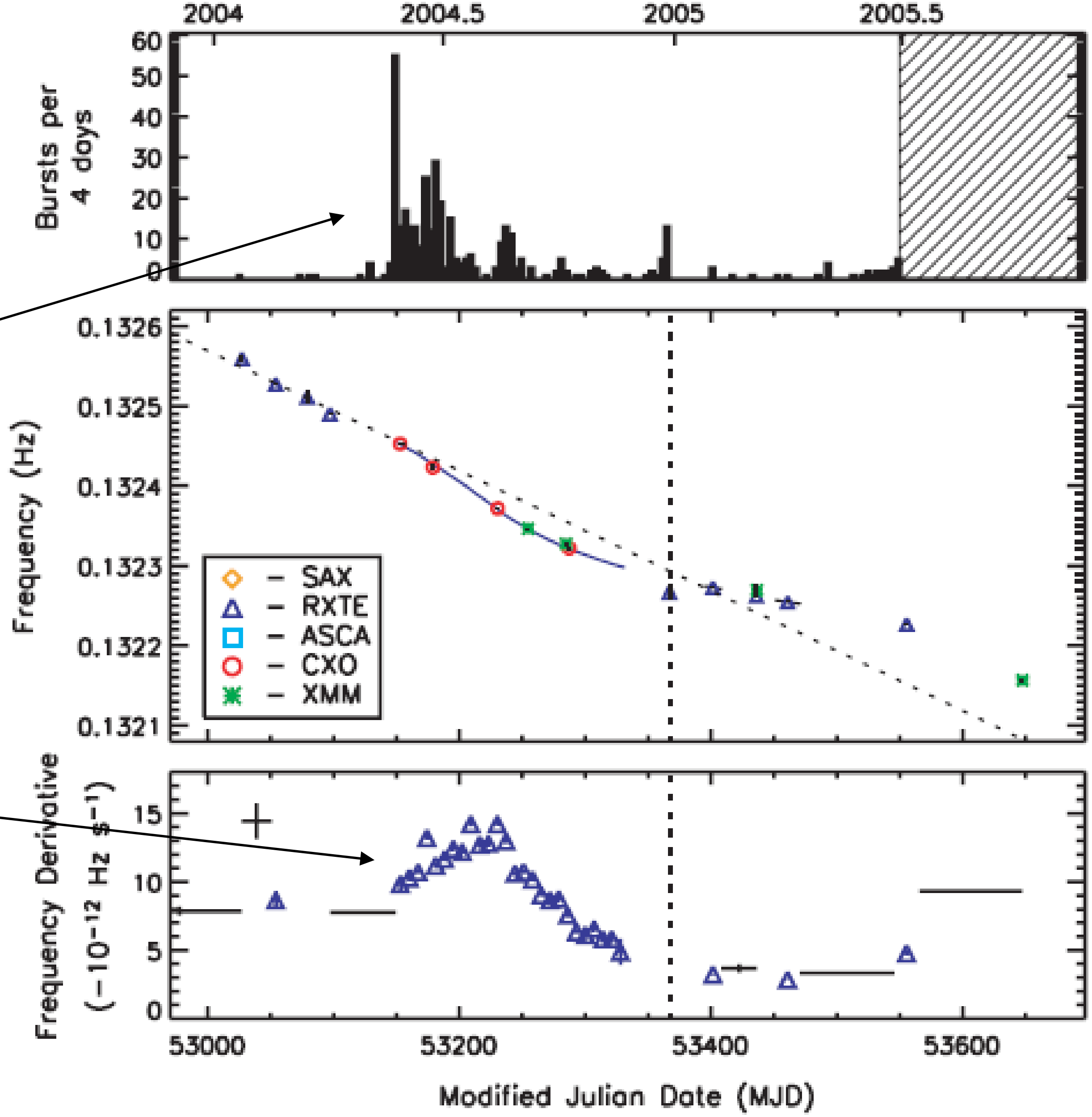
Explanation: 10^15 G magnetic field as the energy power and cause of super-Eddington luminosity

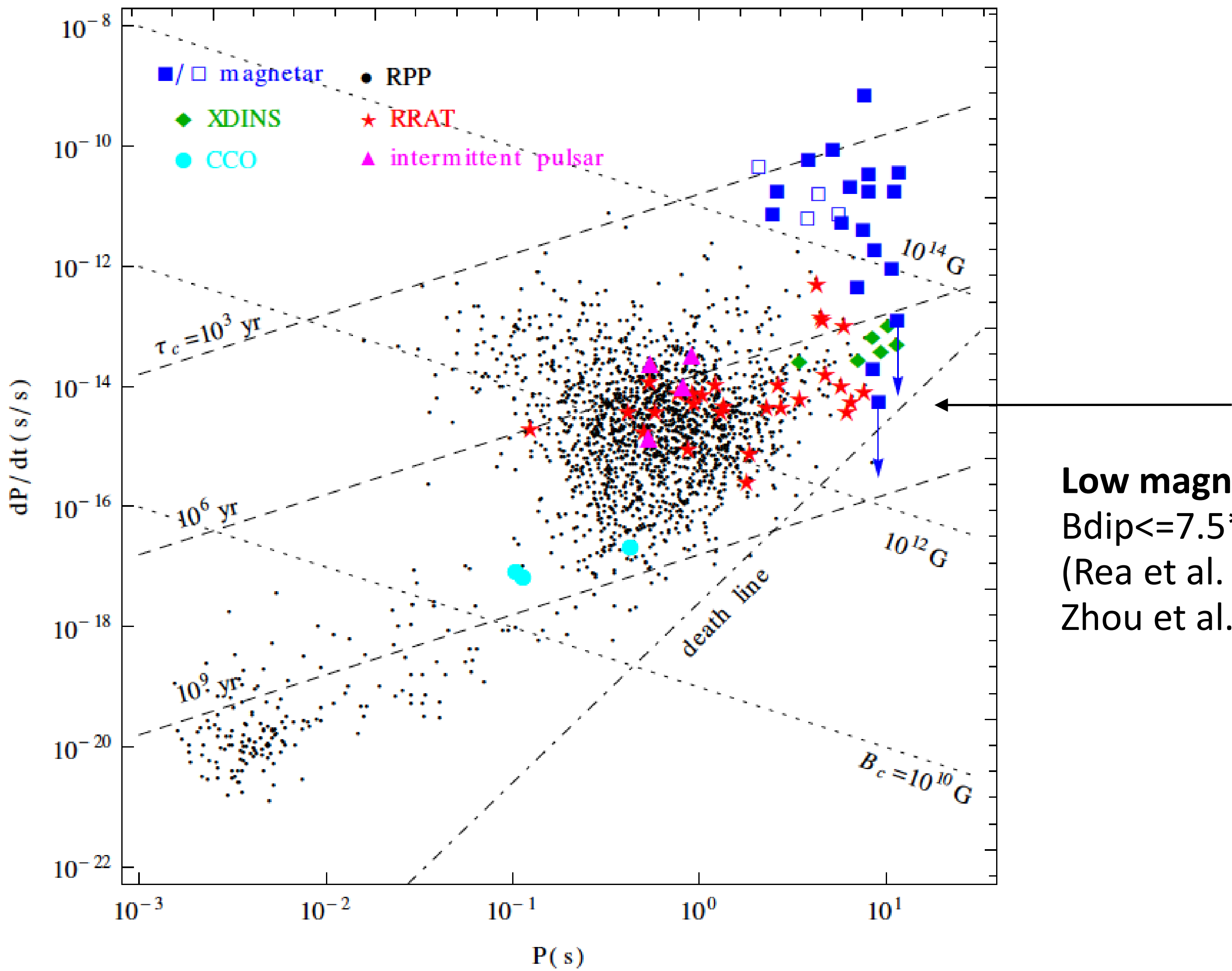
Restless magnetars:

Woods+ 2007

bursts

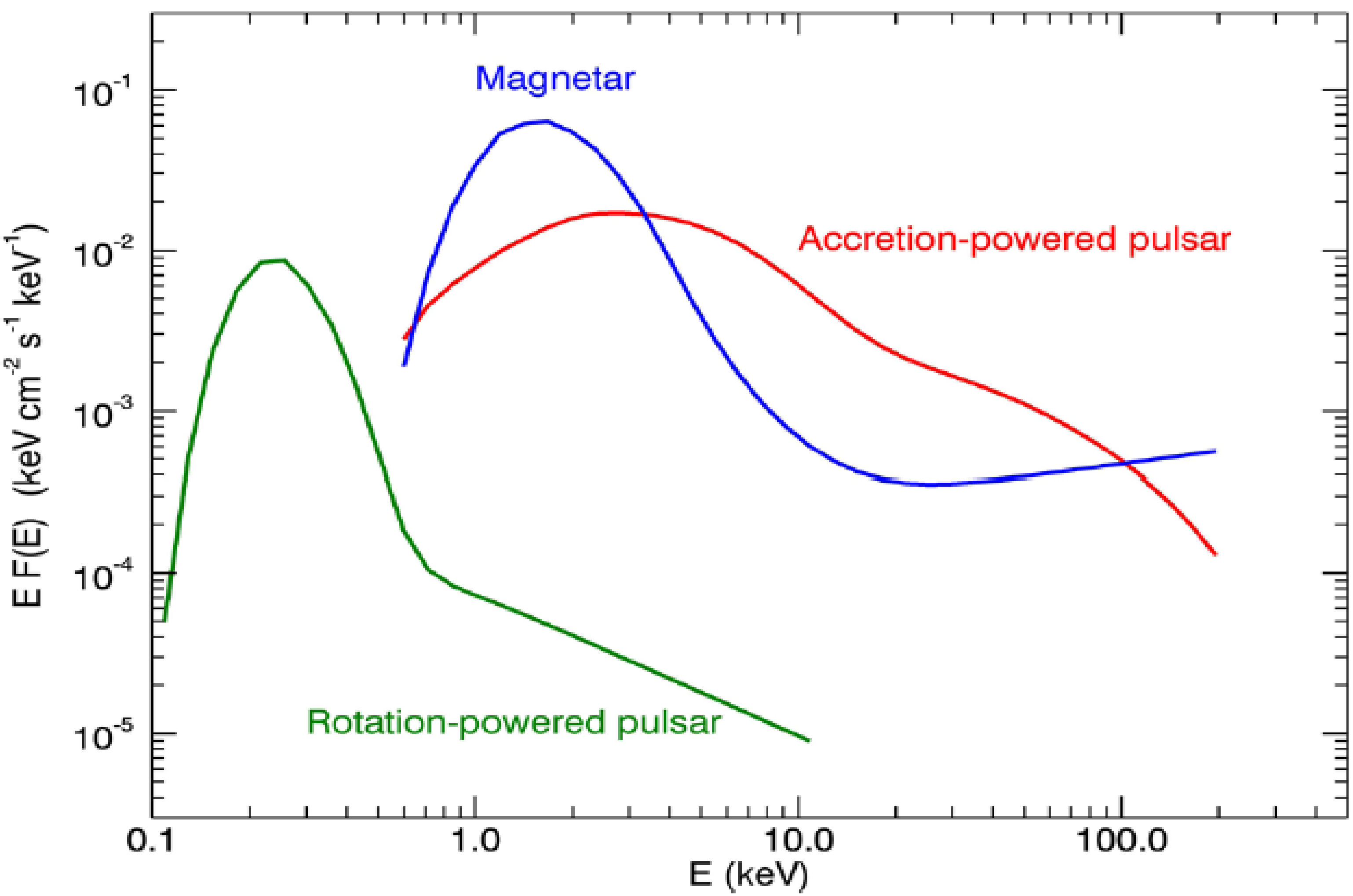
A period of enhanced spindown





Low magnetic field magnetar
Bdip<=7.5*10^12 G
(Rea et al. 2010, 2012;
Zhou et al. 2014)

Mereghetti et al. (2015): comparison between different kinds of objects



Previous works: (1/2)

- On Fermi observations of magnetars

  Tong+ 2010, **ApJL**
  2011, **ApJ**
  (total citations: 31)

- Wind braking of magnetars

  Tong+ 2012, **ApJL**
  2013, **ApJ (**citatons 50+**)**
  2013a/b, **RAA**
  2014, **ApJ**
  2015, **RAA**
  2016, **RAA**
  (total citations: 120+)

- Wind braking of pulsars

  Li+ 2014, **ApJ**

  Kou & Tong 2015, **MNRAS**
  (citations 21**)**

  Kou+ 2016, **RAA**

  Ou+ 2016, **MNRAS**

  Tong+ 2017, **ApJ**

  Kou+ 2019, **ApJ**

  (total citations: 60+)

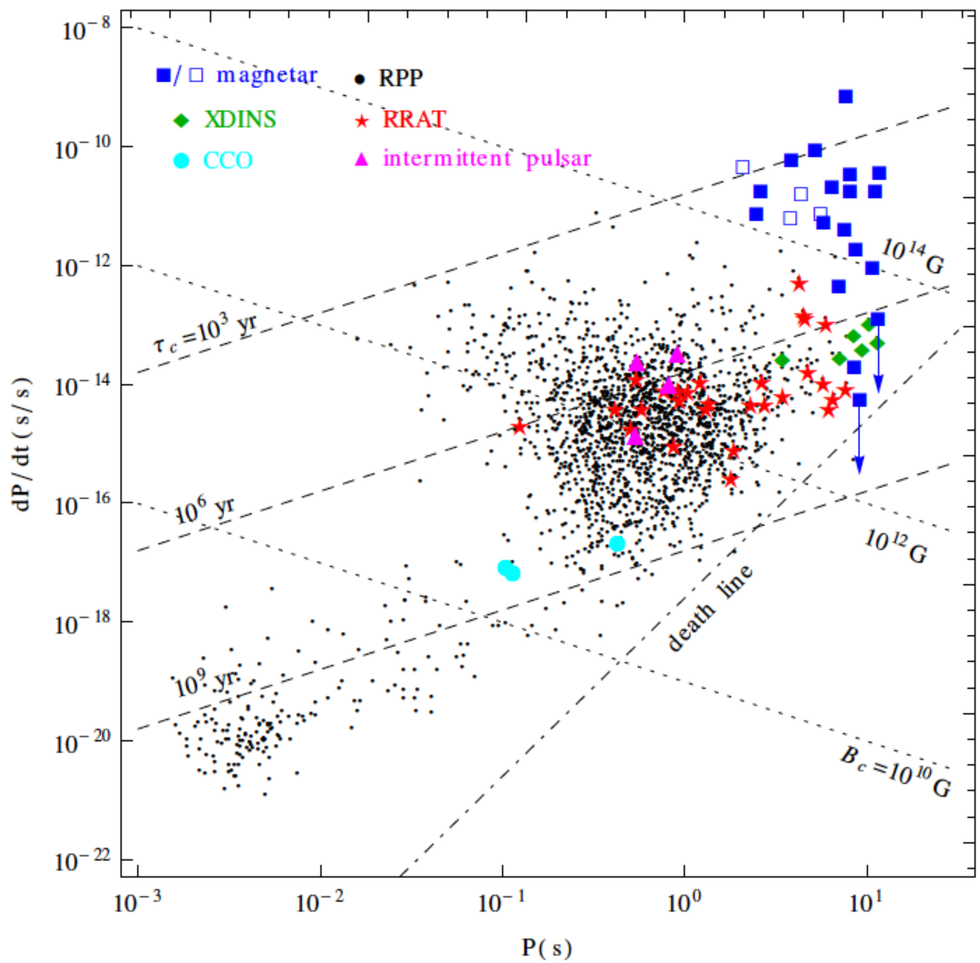
  (H.Tong mainly as the corresponding author)

Previous works (2/2)

- Accreting magnetars
  Tong 2015, **RAA (**citations: 22**)**;
  2016, **ApJ**;
  Tong & Wang 2019, ***MNRAS***
  (total citations: 35)

- Others: Tong+ 2018, “A magnetically driven origin for the low luminosity GRB 170817A associated with GW170817”, RAA (citations: 4)

工作1



The key difference between magnetars and rotation-powered pulsars:
multipole magnetic field!

Not their positions on the P-Pdot diagram (not the dipole magnetic field)

Evidence for strong multipole field in accreting systems (Tong & Wang 2014):
1. magnetar burst
2. hard X-ray tail
3. Ultra-luminous X-ray pulsar (late in 2014)

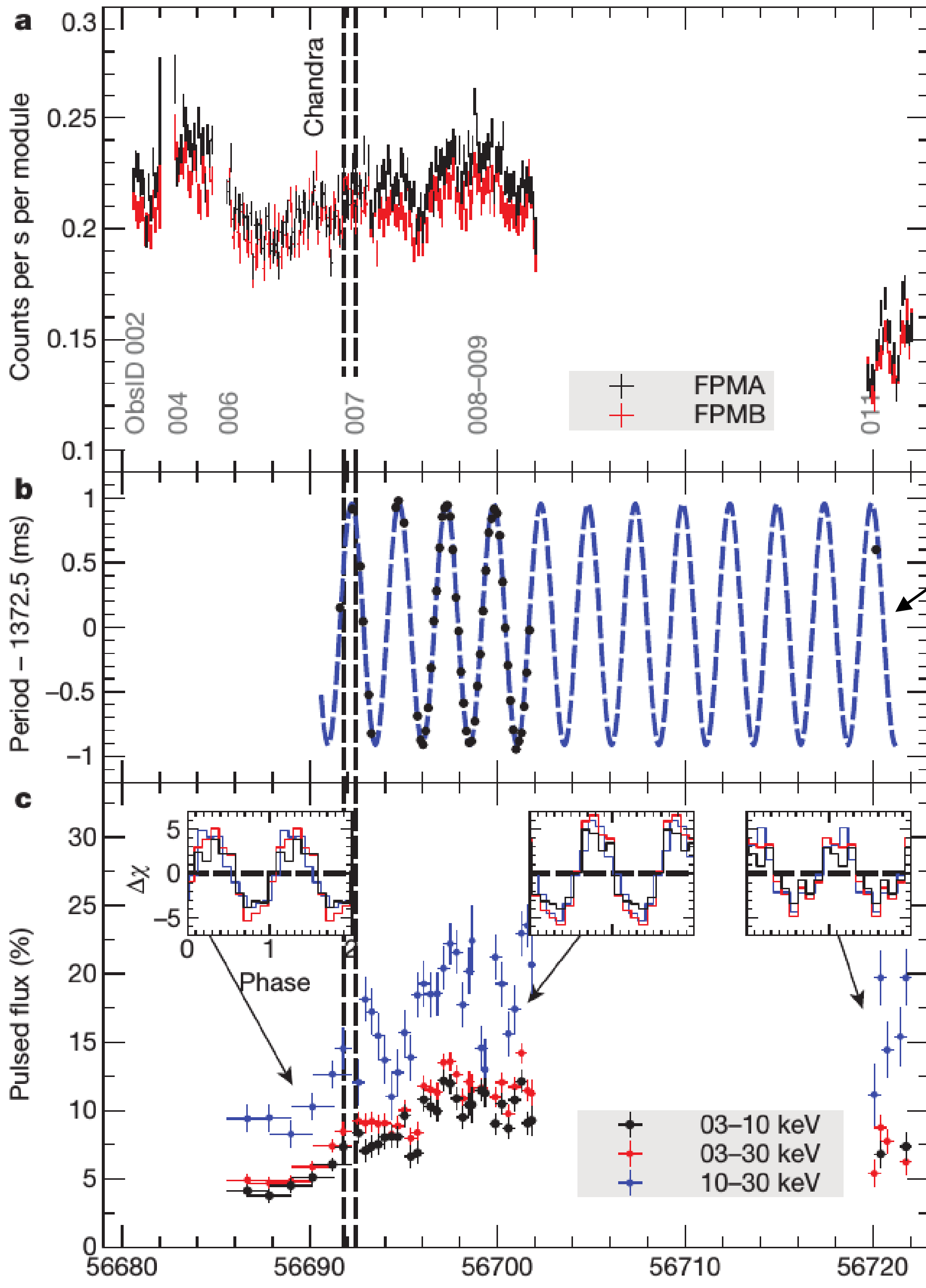
LETTER

doi:10.1038/nature13791

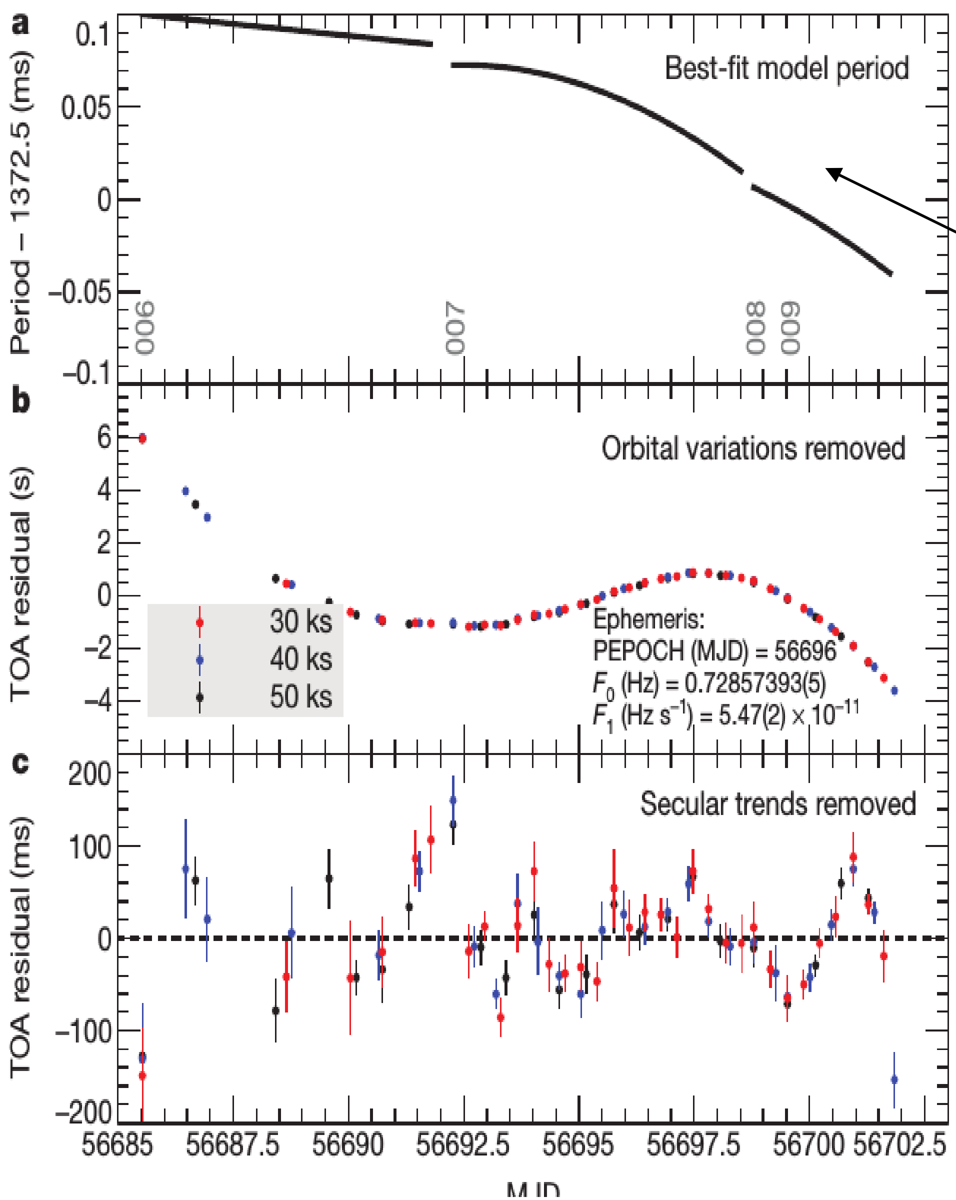
An ultraluminous X-ray source powered by an accreting neutron star

M. Bachetti[1,2], F. A. Harrison[3], D. J. Walton[3], B. W. Grefenstette[3], D. Chakrabarty[4], F. Fürst[3], D. Barret[1,2], A. Beloborodov[5], S. E. Boggs[6], F. E. Christensen[7], W. W. Craig[8], A. C. Fabian[9], C. J. Hailey[10], A. Hornschemeier[11], V. Kaspi[12], S. R. Kulkarni[3], T. Maccarone[13], J. M. Miller[14], V. Rana[3], D. Stern[15], S. P. Tendulkar[3], J. Tomsick[6], N. A. Webb[1,2] & W. W. Zhang[11]

Bachetti et al. 2014



Pulsation (1.37 s) modulated
By the orbital motion (2.5 day)



Bachetti et al. 2014

The neutron star is spinning up!
Pdot=-2*10^-10
Typical accretion-power X-ray pulsars

Problem & Difficulity:
How to explain the super-Eddington luminosity (10^40 erg s^-1) and spin-up rate?

Accreting magnetar

Models: accreting magnetar

- Observation: Bachetti et al. (arXiv:1410.3590) and subsequent ones

1. Eksi et al. (arXiv:1410.5205): accreting magnetar, smaller torque during accretion equilibrium
2. Lyutikov (1410.8745): accreting magnetar, super-Eddington accretion
3. Kluzniak & Lasota (1411.1005): ULX pulsar-->millisecond pulsar
4. **Tong (1411.3168): accreting low magnetic field magnetar**
5. Christodoulou et al. (1411.5434): accreting normal neutron star
6. Dall'Osso et al. (1412.1834): accreting magnetar
7. Mushtukov et al. (1506.03600): maximum luminosity of 10^40 erg s^-1
8. **Pan et al. (1510.08597)**: evolution of accreting magnetars

10. King & Lasota (1601.03738): beaming
11. Fragos et al. (1501.02679), Shao & Li (1502.03905): formation

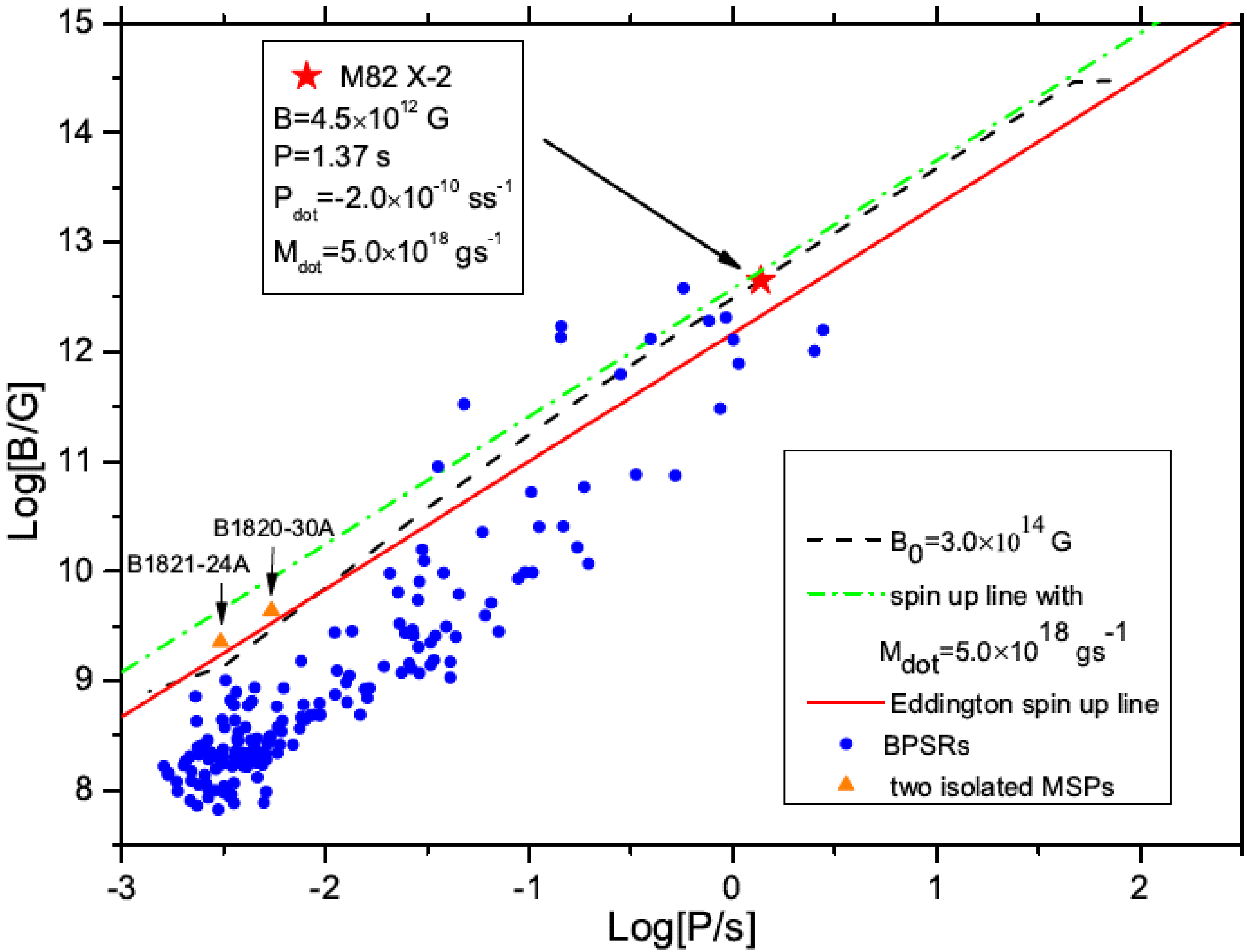
工作2

Accreting low magnetic field magnetar

- Aged magnetars are more like to be low magnetic field magnetars (10^6 yrs old; consistent with population synthesis)
- Super-Eddington luminosity due to the presence of strong multipole field (e.g.,10^14 G)
- Rotational behaviors due to the interaction of much lower dipole field (10^12 G) with the accretion flow

Tong 2015, RAA (citation 20)

Pan et al. 2015



工作3

Four ULX pulsars up to now:
(1)All show near sinusoidal pulse profile;
(2) NGC 5907 ULX pulsar has X-ray luminosity as high as 2*10^41 erg s^-1
(3) NGC 300 ULX1 showed a rapid period evolution

Table 1. The main parameters of four ULX pulsars: the observed luminosity $L_{\rm x,iso}$, period P, period derivative $\dot{P}$, and the derived dipole magnetic field $B_{\rm p}$ assuming $b = 0.2$ and $\eta = 0.1$.

ULX name	$L_{\rm x,iso}$ (erg s^{-1})	P (s)	$\dot{P}$ (s/s)	$B_{\rm p}$ (G)	References
M82 X-2	10^{40}	1.37	-2×10^{-10}	2.1×10^{10}	Bachetti et al. 2014
NGC7793 P13	10^{40}	0.42	-3.5×10^{-11}	2×10^{11}	Fürst et al. 2016; Israel et al. 2017a
NGC5907 ULX	2×10^{41}	1.137	-5×10^{-9}	6×10^{12}	Israel et al. 2017b
NGC300 ULX1	4.7×10^{39}	31.6	-5.56×10^{-7}	6.7×10^{13}	Carpano et al. 2018

Consistent with our “accreting low magnetic field magnetar” model
Tong & Wang 2019 MNRAS

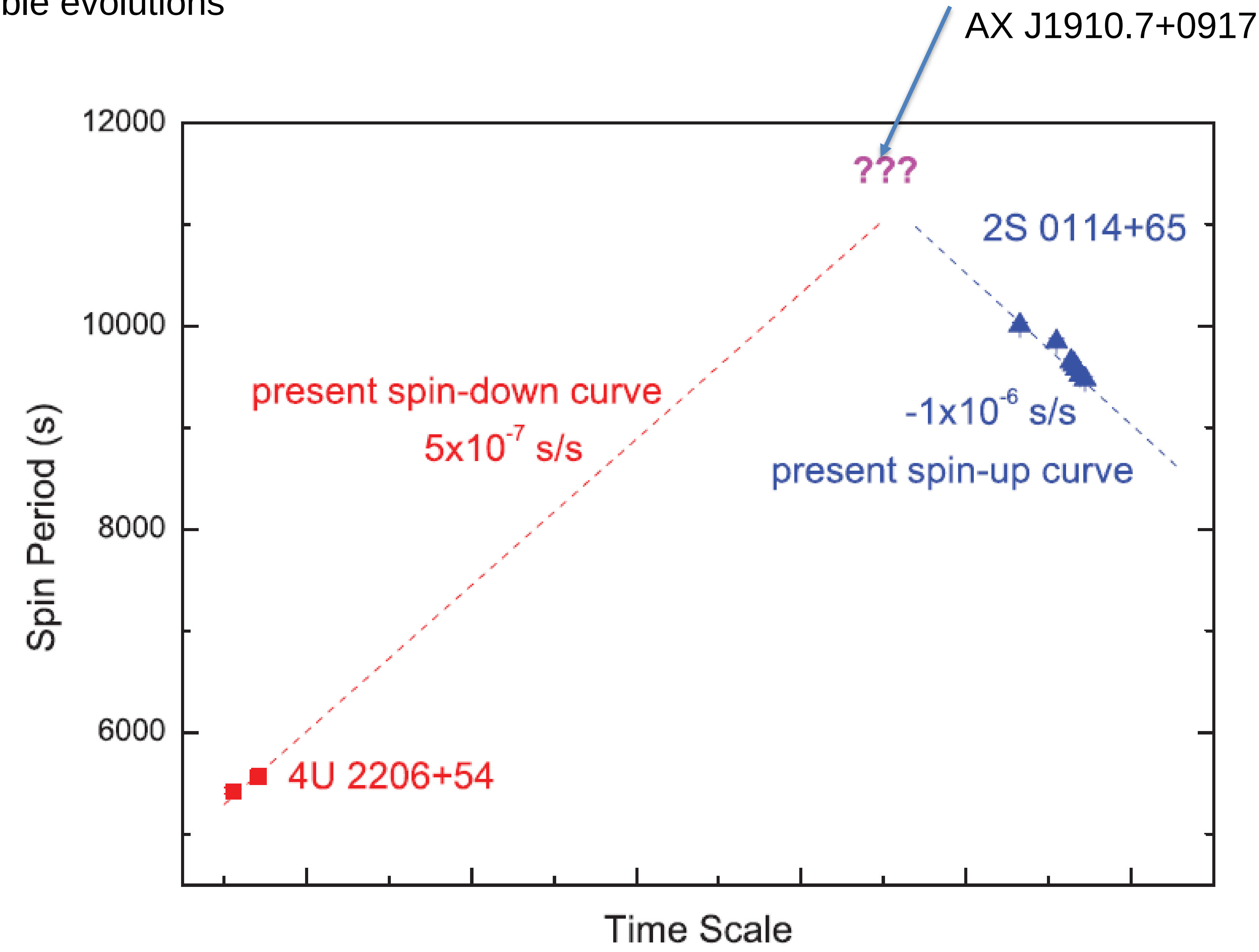
The slowest pulsation X-ray pulsar

- AX J1910.7+0917
- Pspin ~ 10 hours (3.6*10^4 s)
- Lx ranges from 1.7*10^34 -10^36 erg s^-1
- May be un accreting magnetar (B=4*10^15 G) With low mass accretion rate (Mdot ~ 10^14)
- Indirect support: 4U 0114+61 (Pspin~9500s) (Sanjurjo-Ferrrin et al. 2017); magnetar in SNR RCW 103 (Pspin~6.7 hours) (Rea+2016; D'Ai+2016; Tong+ 2016)
- Possible transient disk in action in AX J1910
- Predictions: magnetar-like activities in AX J1910

3 kinds of accreting magnetars

- **ULX pulsars: high mass accretion rate,** decay of dipole magnetic field→accreting low-B magnetar
- **Slow pulsation X-ray pulsars** (AX J1910.7+0917, 4U 0114+65, 4U 2206+54, SFXTs): **low mass accretion rate** (Sanjurjo-Ferrrin et al. 2017; Reig et al. 2012;Bozzo et al. 2008)
- **Slow pulsations X-ray pulsars in SMC** (P~1000s): **intermediate mass accretion rate** (Klus+2014; Ho+2014)

Possible evolutions



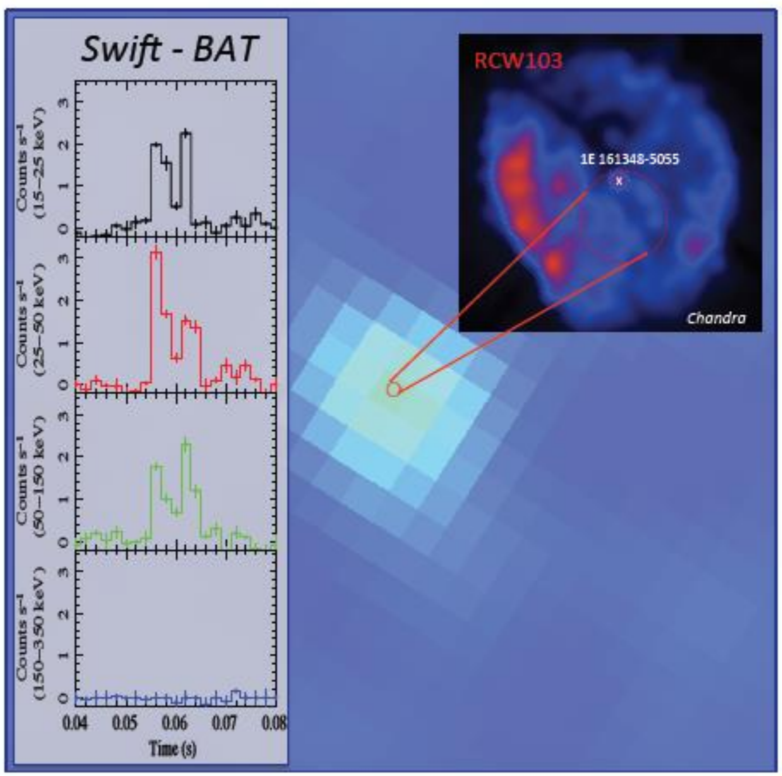
Seven signatures of accreting magnetars (Tong & Wang 2019 and references therein)

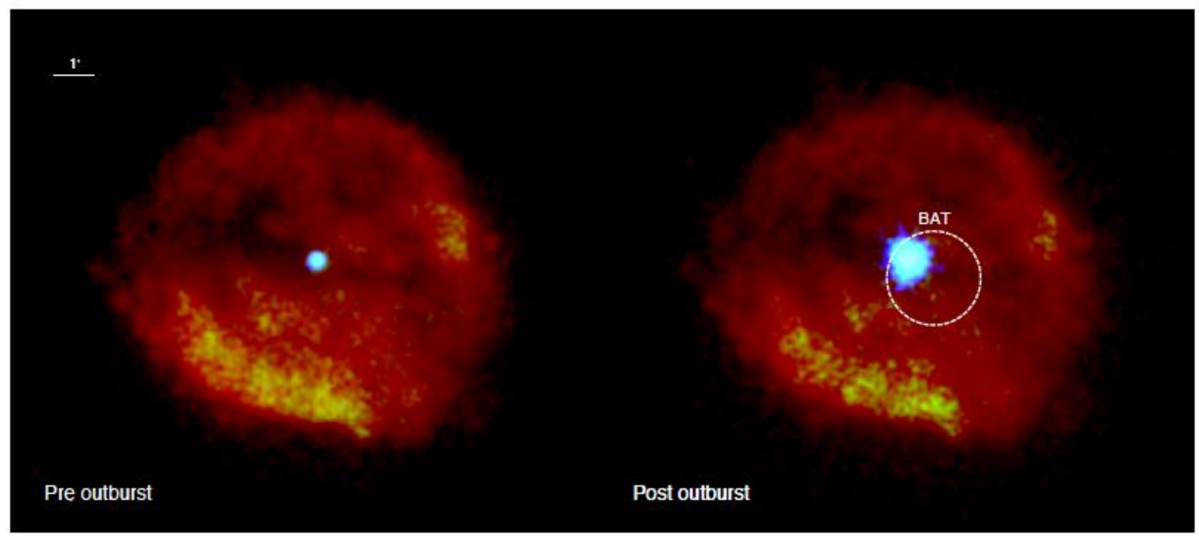
1. Magnetar-like outburst
2. Hard X-ray tail
3. ULX pulsars
4. Cyclotron line observations (if the final magnetic field is in the magnetar range)
5. Switch between the accretion phase and propeller phase (if the final magnetic field is in the magnetar range)
6. ULX sources with pulsar-like spectra
7. Slow pulsation X-ray pulsars

工作4：magnetar accretion from a fallback disk:

Magnetar activities from the CCO in RCW 103

- Rea et al. arXiv:1607.04107; D'Ai et al. arXiv:1607.04264 (appear the same day on the arXiv)





Nature of CCO in RCW 103

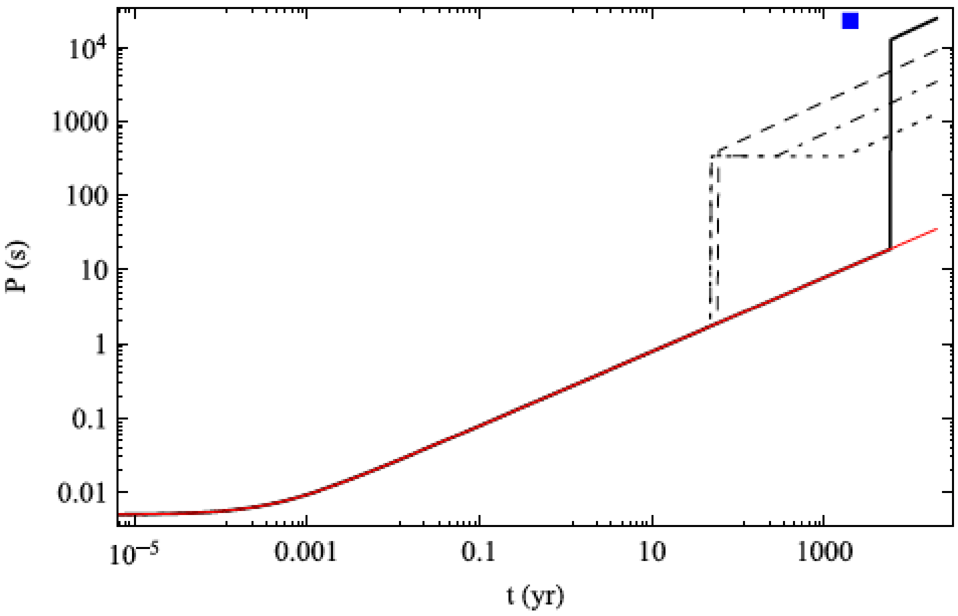
1. a magnetar!
2. a very special magnetar compared with magnetars, CCOs, normal neutron stars and accreting neutron stars: the longest spin period (6.6 hours) (at that time)!
3. a magnetar braked down by a fallback disk in the past?

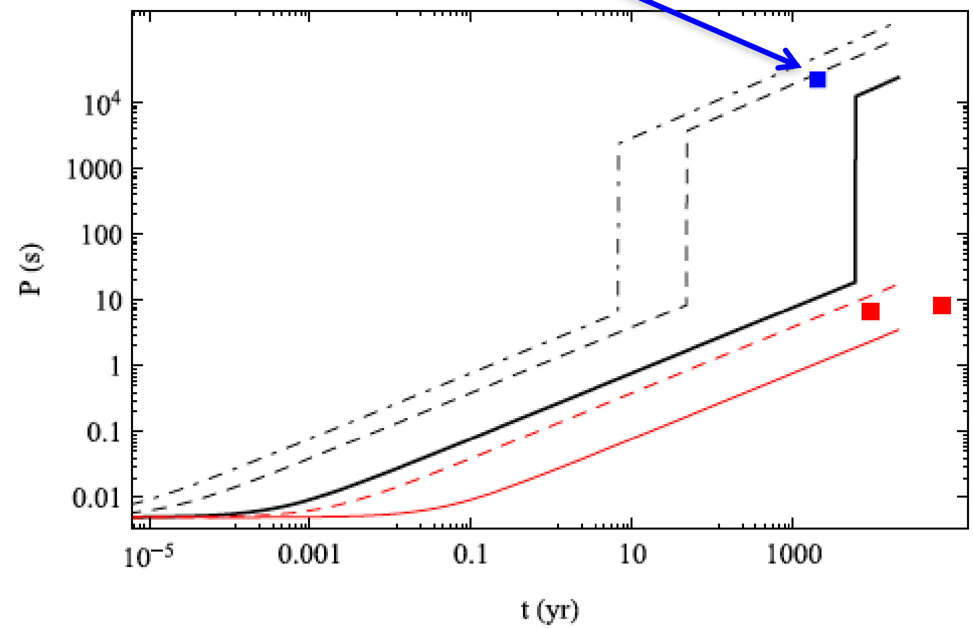
$$\begin{aligned} \dot{M}_{\rm acc} &= \dot{M}_{\rm Edd}, \qquad 0 < t < t_{\rm eq}, \\ &= \dot{M}_{\rm Edd}\left(\frac{t}{t_{\rm eq}}\right)^{-\alpha}, \quad t \geqslant t_{\rm eq}. \end{aligned}$$

Rotational evolution of magnetars in the presence of a fallback disk:
for different masses of the disk (left) and different magnetic field of the magnetar (right)

Only for **a high disk mass** (10^-5 Msun) and **high dipole field** (5*10^15 G), the magnetar will be spun down significantly by the fallback disk

Tong et al. 2016





Summary： Accreting magnetars

1. ULX pulsars: accreting magnetars in binary system? Accreting low-B magnetar?
2. Slow pulsations X-ray pulsars: accreting magnetar with low mass accretion rate? Possible evolution link?
3. CCO magnetar: magnetars braked down by a fallback disk

They are all accreting magnetars. They are all magnetars!

Many observations (e.g. glitch & anti-glitch)! Many opportunities!

Thanks!