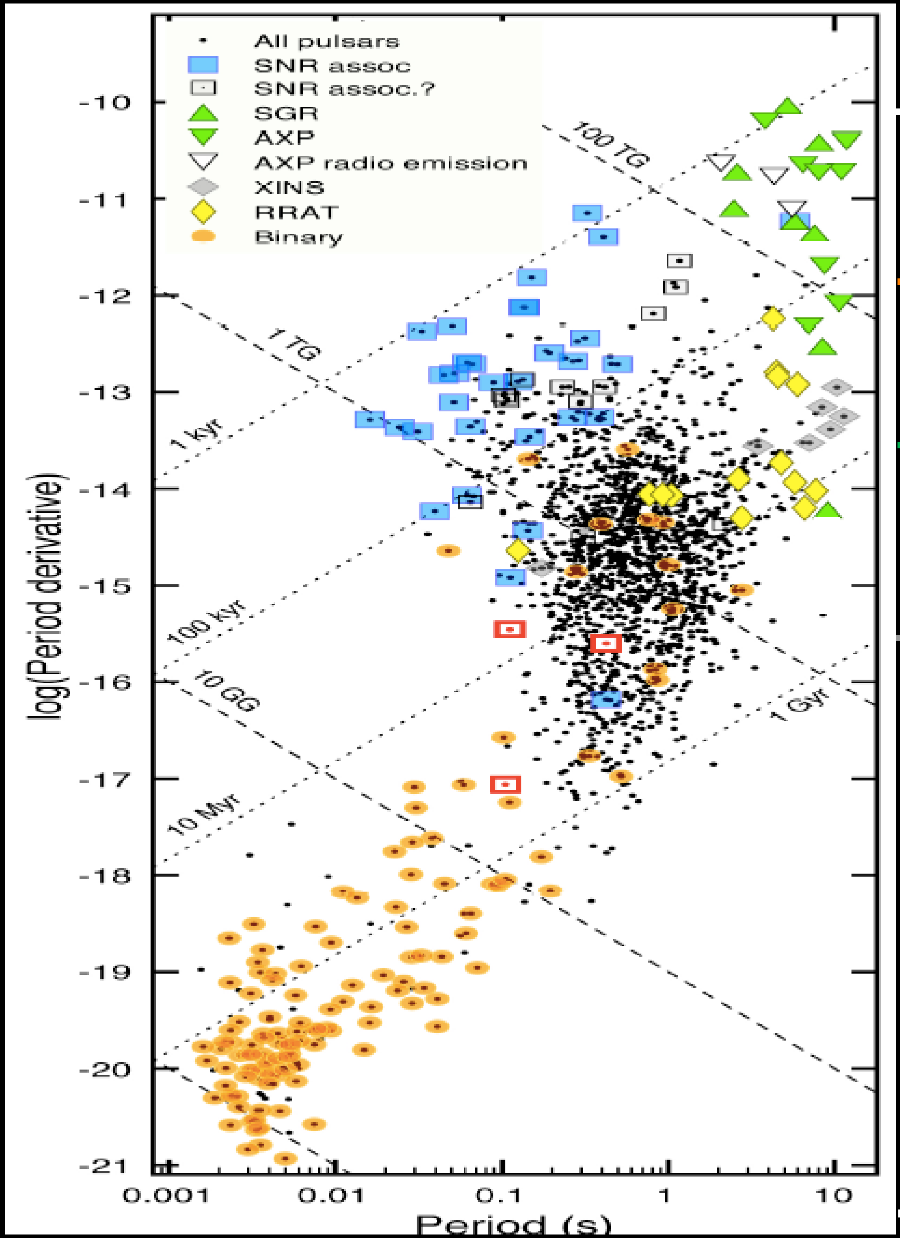
The neutron star zoo: evolution and cooling

NANDA REA

Institute of Space Sciences (ICE), CSIC-IEEC, Barcelona

The Pulsar Bestiary



- Radio pulsars: ~2500

- Binary pulsars: ~60

- Magnetars: ~25

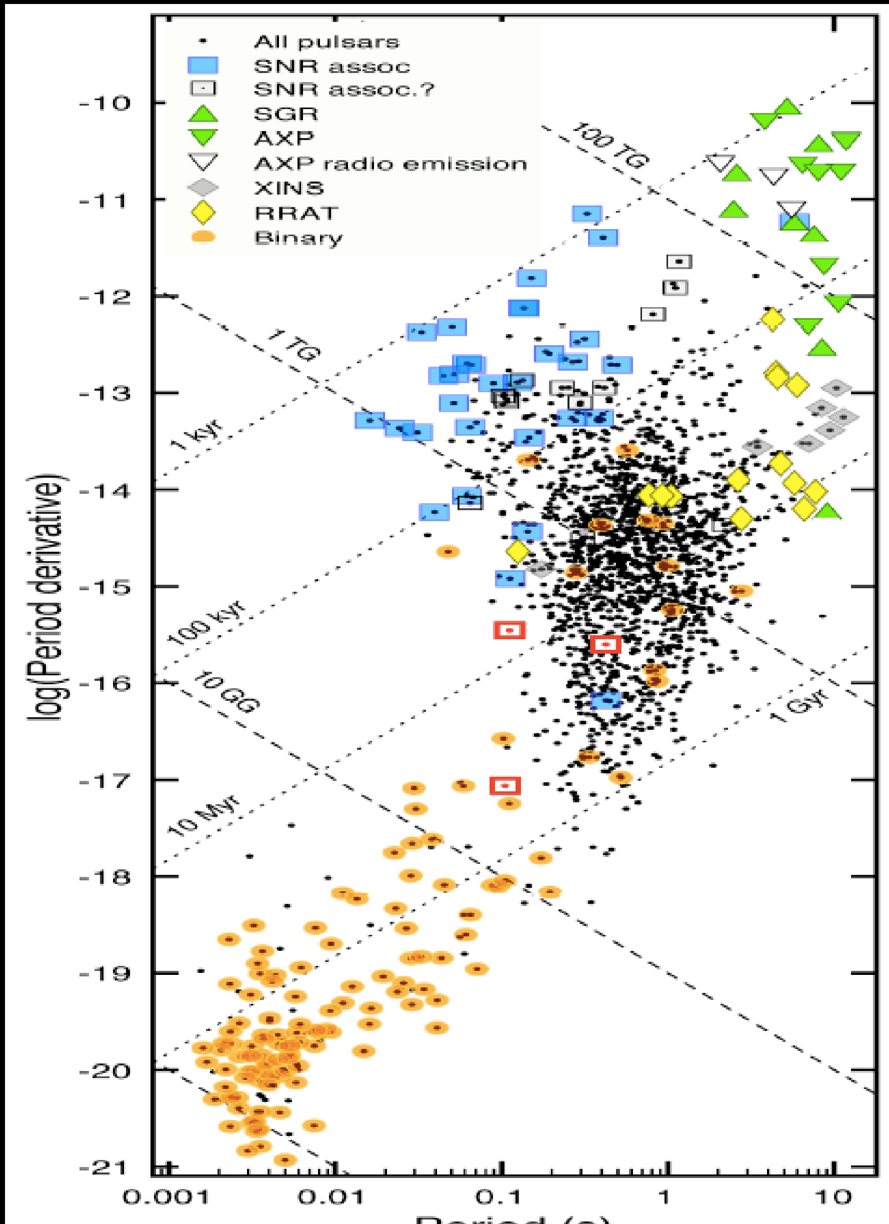
- X-ray Dim Isolated Neutron Stars: ~7

Rotating Radio Transients (RRATs): ~

- Central Compact Objects (CCOs): ~5

… and X-ray binary neutron stars: ~10(

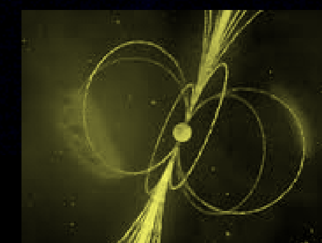
The Pulsar Bestiary



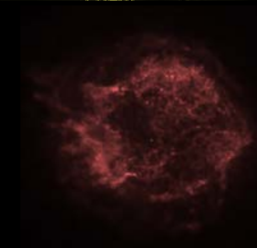
Magnetars: B-powered

XDINS: kT-powered

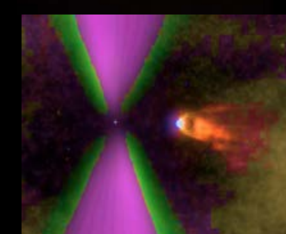
Pulsars and RRATs: rotation-powered



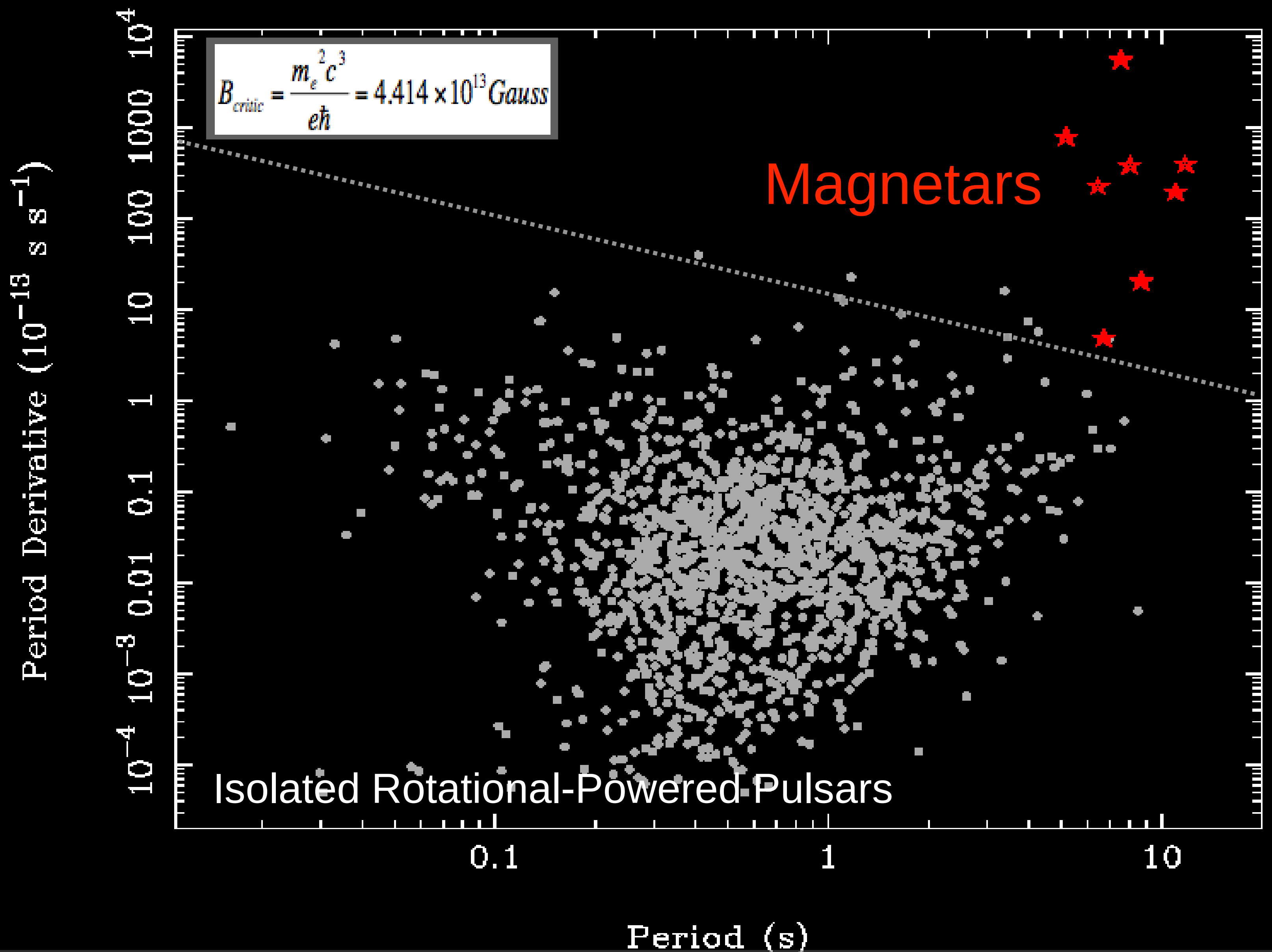
CCOs: kT-powered



Recycled binaries: rotation-powered



A decade ago…

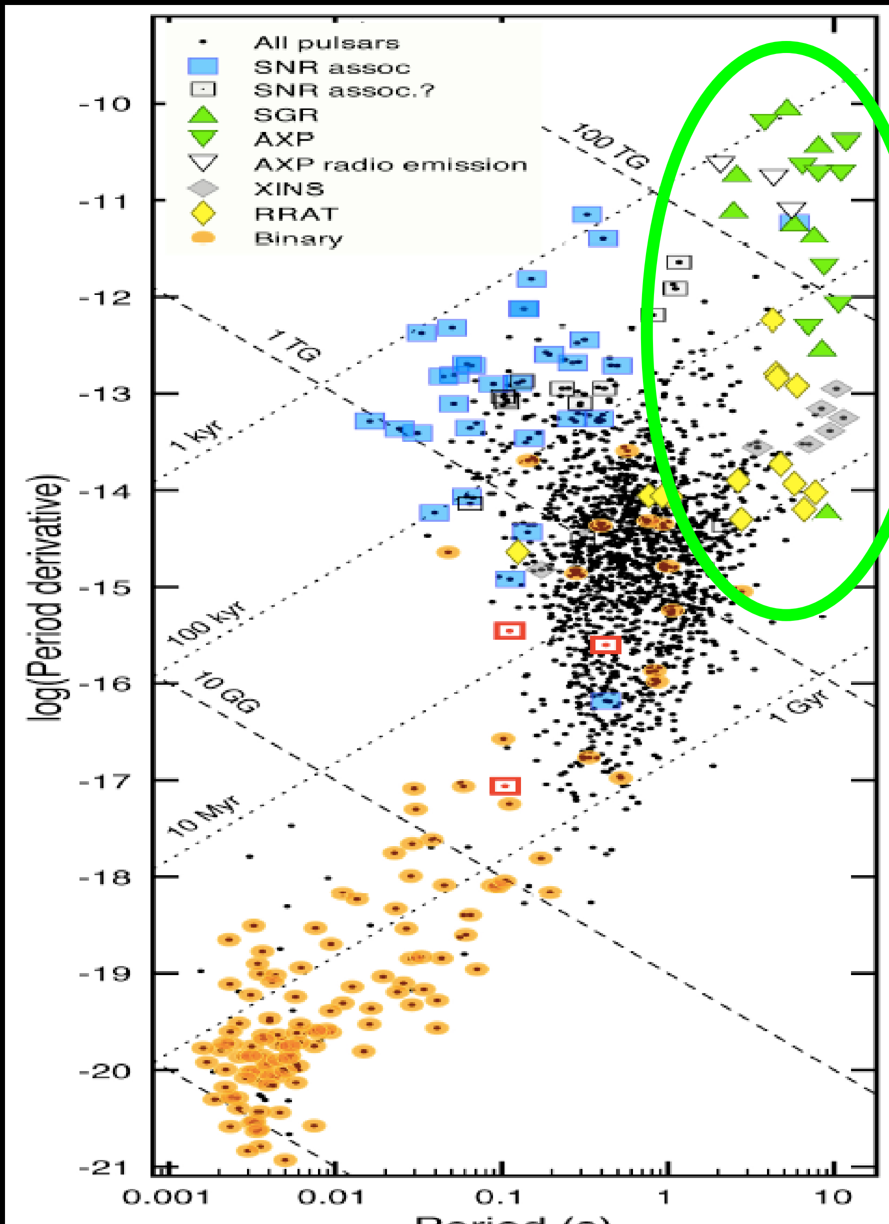


$B_{critic} = \frac{m_e^2 c^3}{e\hbar} = 4.414 \times 10^{13}\,Gauss$
Magnetars
Isolated Rotational-Powered Pulsars
Period Derivative $(10^{-13}\ s\ s^{-1})$
Period (s)
0.1
1
10
10^{-4}
10^{-3}
0.01
0.1
1
10
100
1000
10^{4}

- We observe ~10^{14} Gauss magnetic components in all isolated neutron star classes (not only magnetars).

- All different isolated neutron star manifestations simply depend on B-field strength and configuration at birth, and age.

The Pulsar Bestiary



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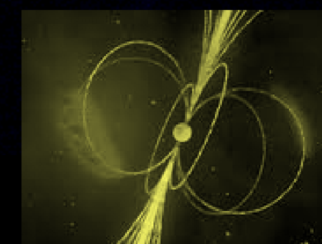
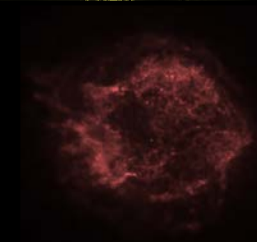
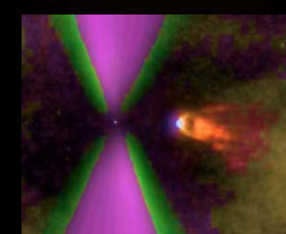


CCOs: kT-powered

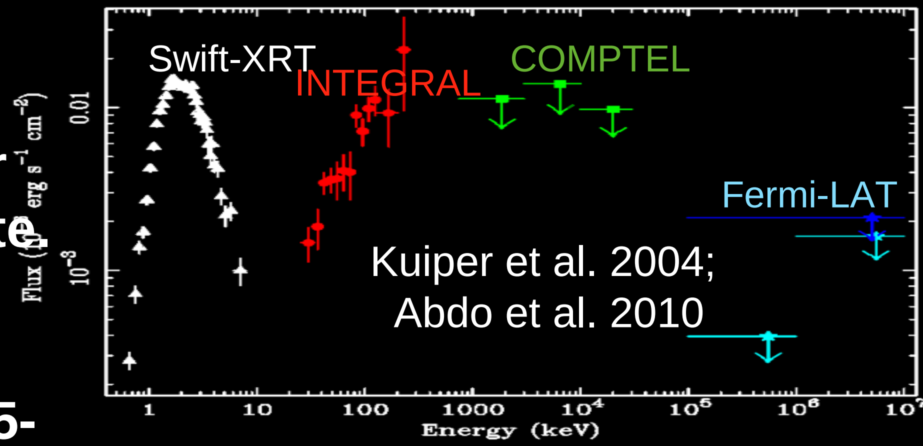


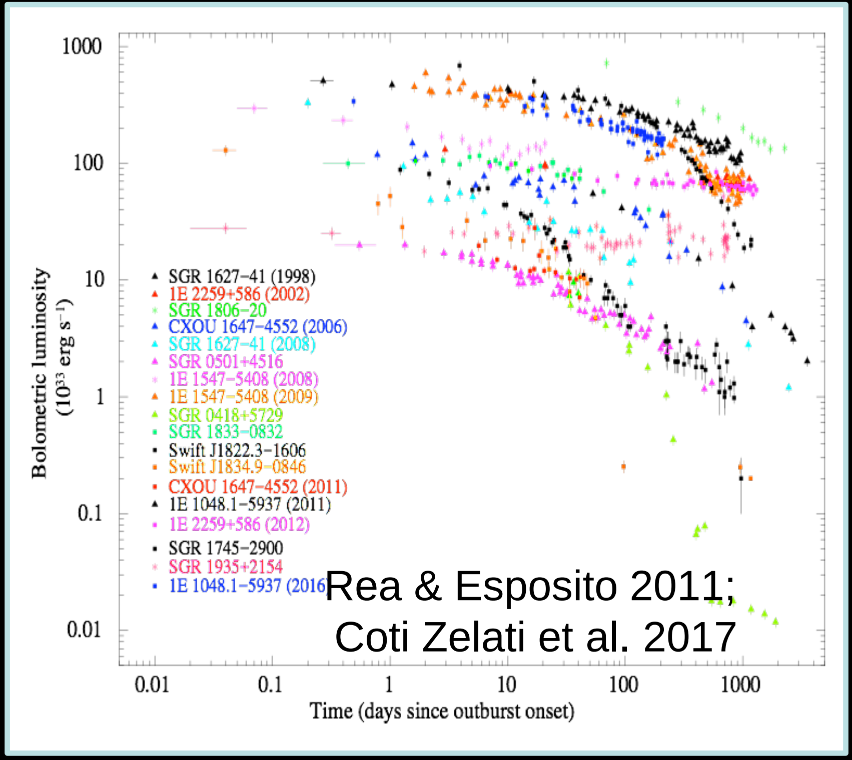
Recycled binaries: rotation-powered



Magnetars

- About 25 X-ray pulsars with $L_X \sim 10^{33} - 10^{36}$ erg s^{-1}
- X-ray luminosity generally larger than the rotational energy loss rate. Often Transients!
- soft and hard X-ray emission (0.5-200 keV); thermal + resonant cyclotron scattering
- rotating with $P \sim 0.3 - 12$ s
- magnetic fields of $\sim 10^{13} - 10^{15}$ G
- flaring activity in soft gamma-rays (0.01 - 10^2 s; $L_X \sim 10^{39} - 10^{47}$ erg s^{-1})
- faint infrared/optical emission
- transient radio emission (in 4 cases)

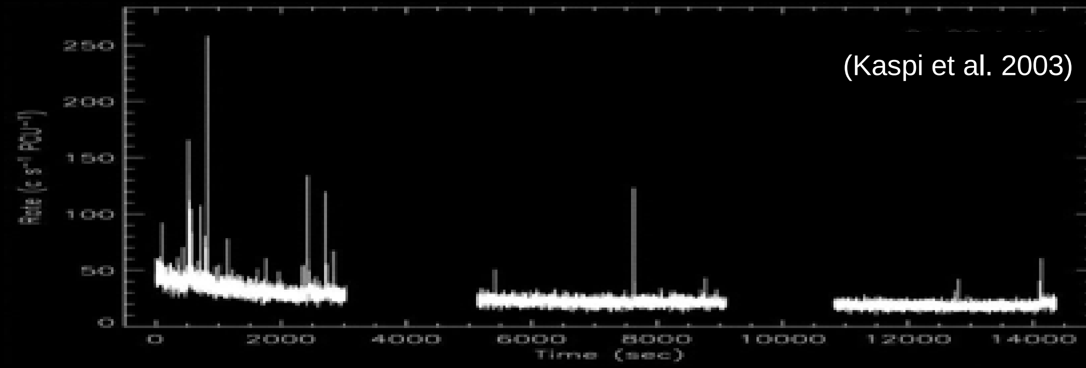




Magnetar flaring activity (timescale: seconds/minutes)

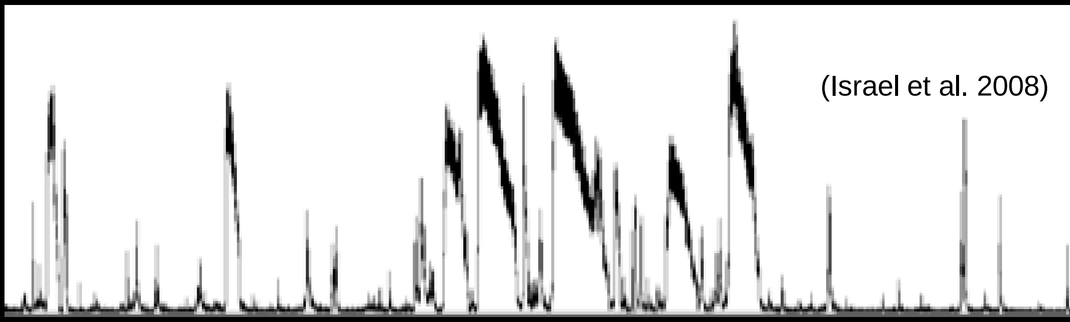
Short bursts

- the most common
- they last ~0.1s
- peak ~10^{41} ergs/s
- soft γ-rays thermal spectra



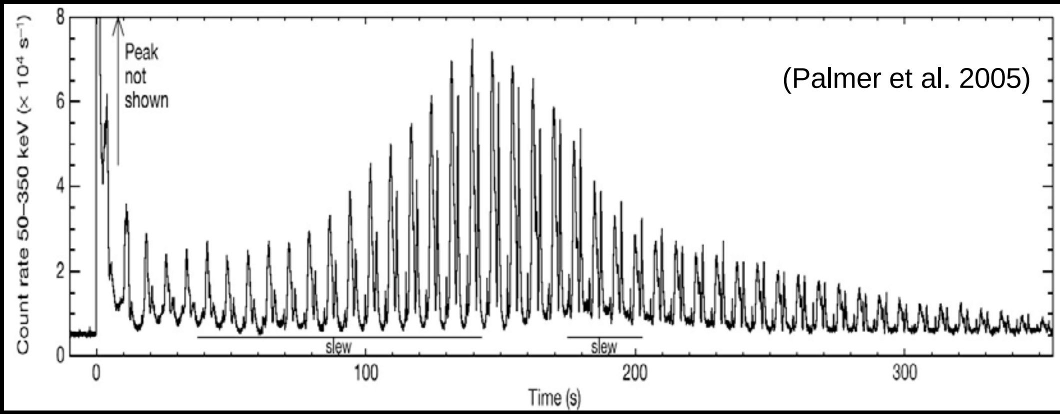
Intermediate bursts

- they last 1-40 s
- peak ~10^{41}-10^{43} ergs/s
- abrupt on-set
- usually soft γ-rays thermal spectra

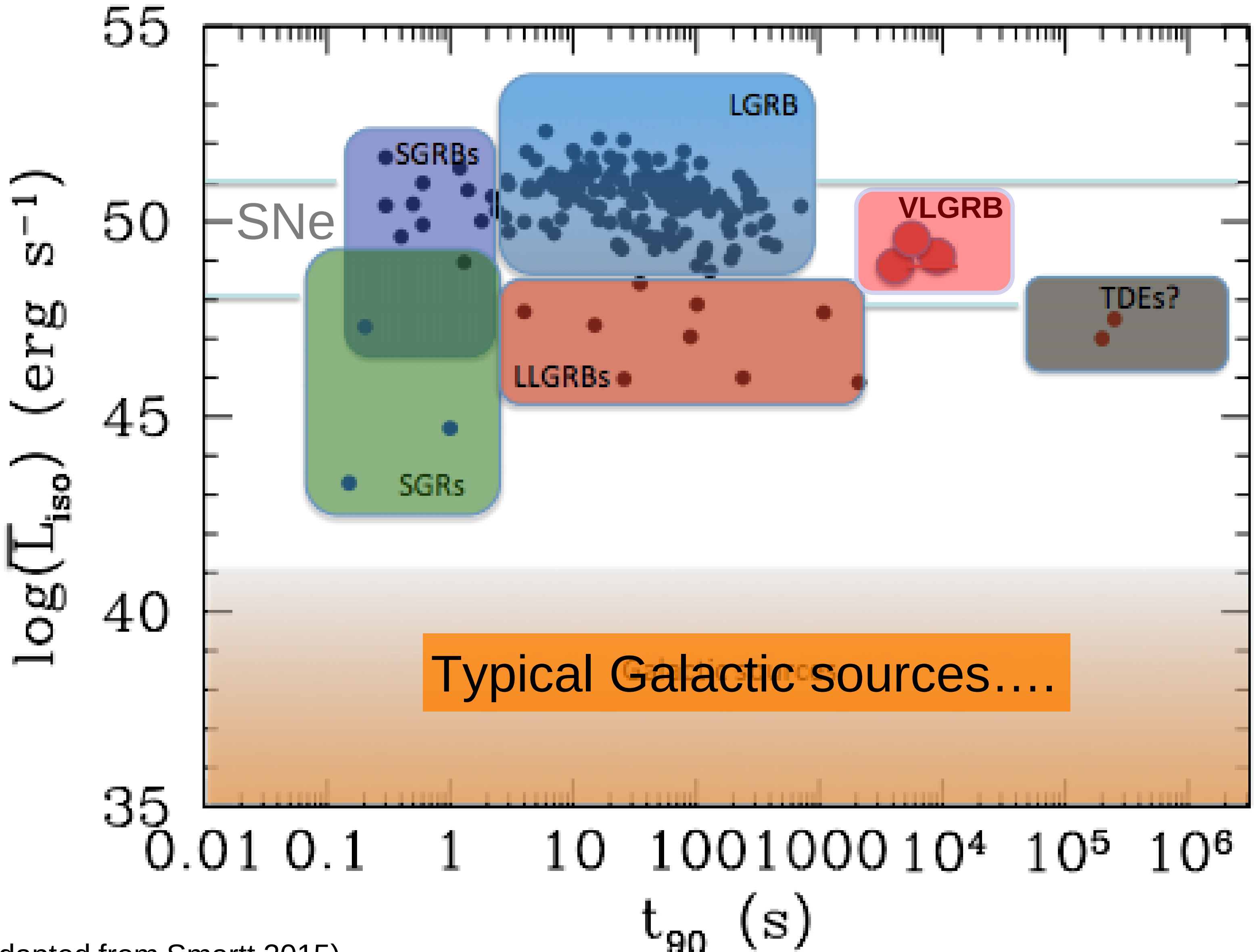


Giant Flares

- their output of high energy is exceeded only by blazars and GRBs
- peak energy > 3x10^{44} ergs/s
- <1 s initial peak with a hard spectrum which rapidly become softer in the burst tail that can last > 500s, showing the NS spin pulsations, and quasi periodic oscillations (QPOs)



Comparison with other energetic transients



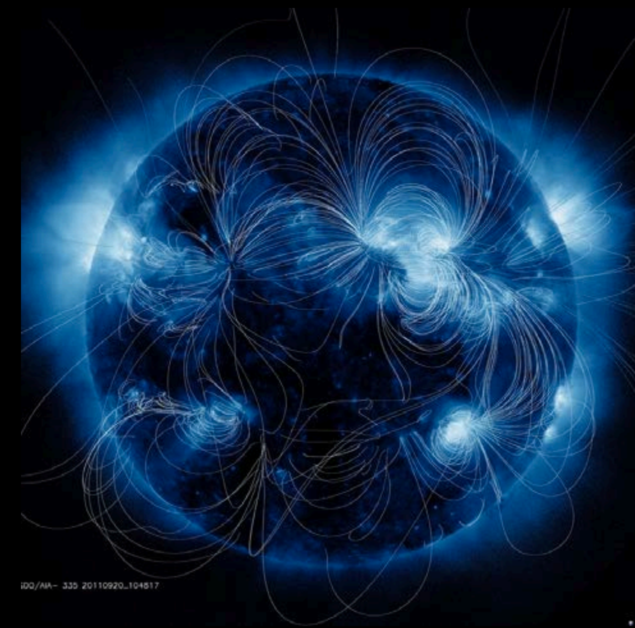
(adapted from Smartt 2015)

Magnetars

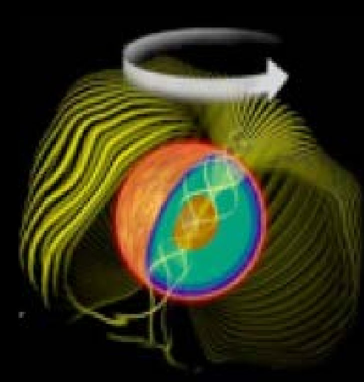
- **Magnetars have highly twisted and complex magnetic field morphologies, both inside and outside the star. The surface of young magnetars are so hot that they are bright in X-rays.**

- **Magnetar magnetospheres are filled by charged particles trapped in the twisted field lines, interacting with the surface thermal emission through resonant cyclotron scattering.**

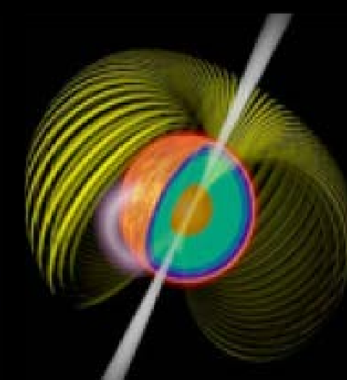
- **Twisted magnetic fields might locally (or globally) stress the crust (either from the inside or from the outside). Plastic motions and/or returning currents convert into crustal heating causing the outburst onset and evolution.**



Magnetars

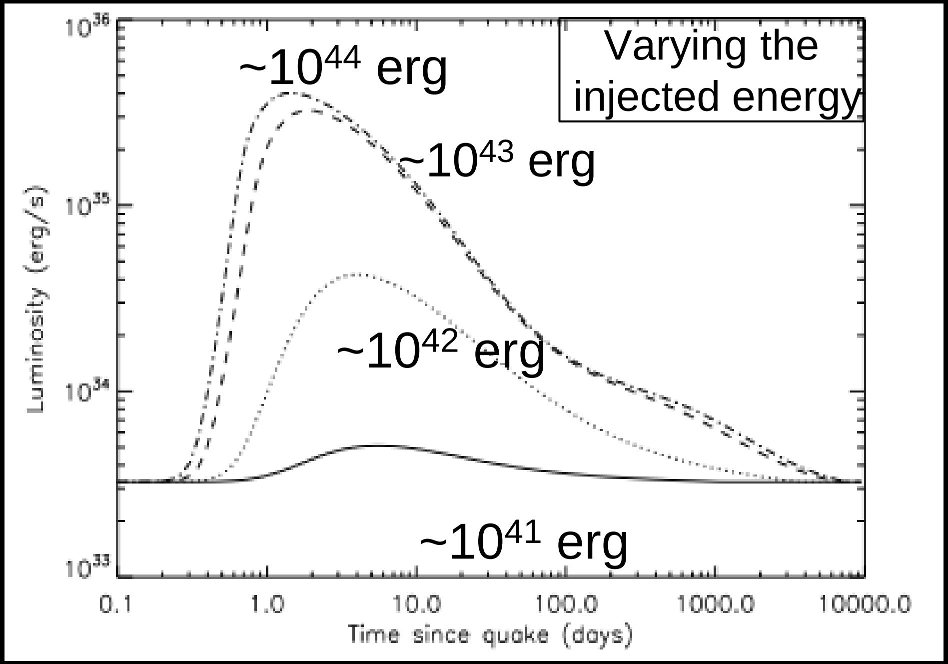


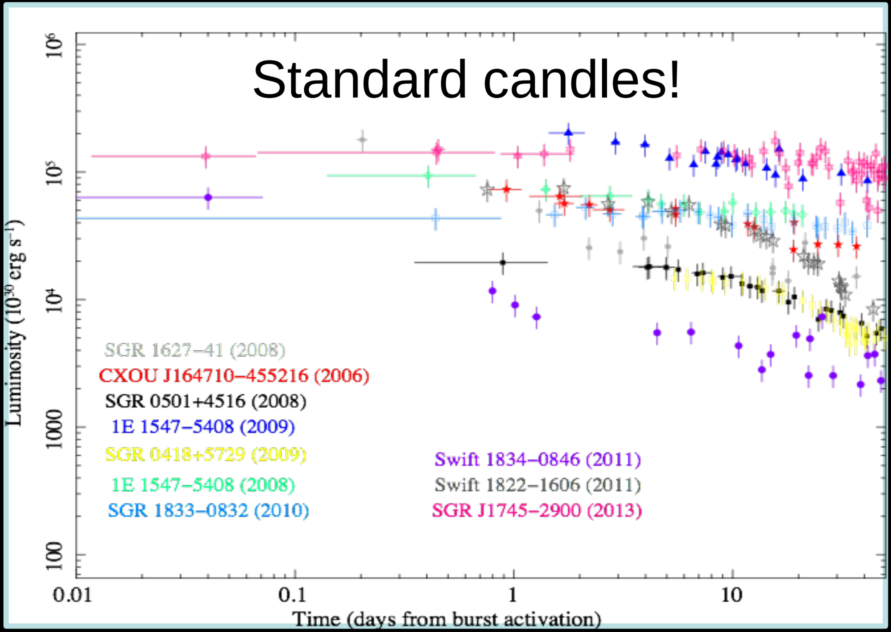
Normal Pulsars

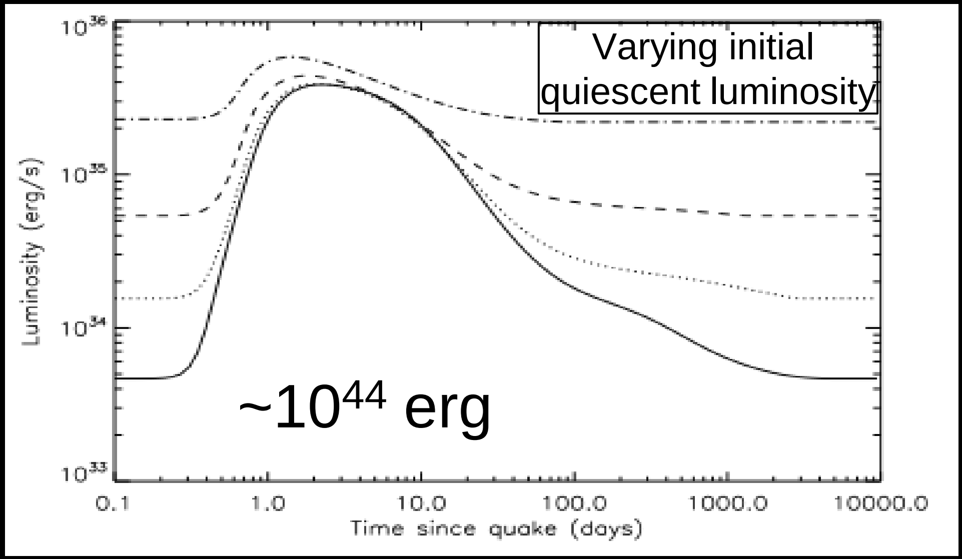


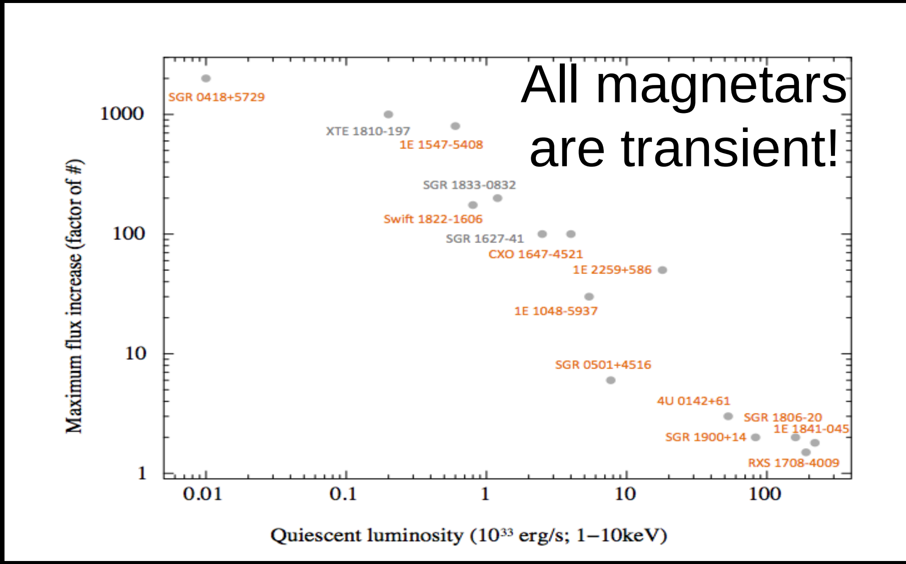
(Thompson & Duncan 1993; Thompson, Lyutikov & Kulkarni 2002; Fernandez & Thompson 2008; Nobili, Turolla & Zane 2008a,b)

Magnetars' outburst modelling: cooling



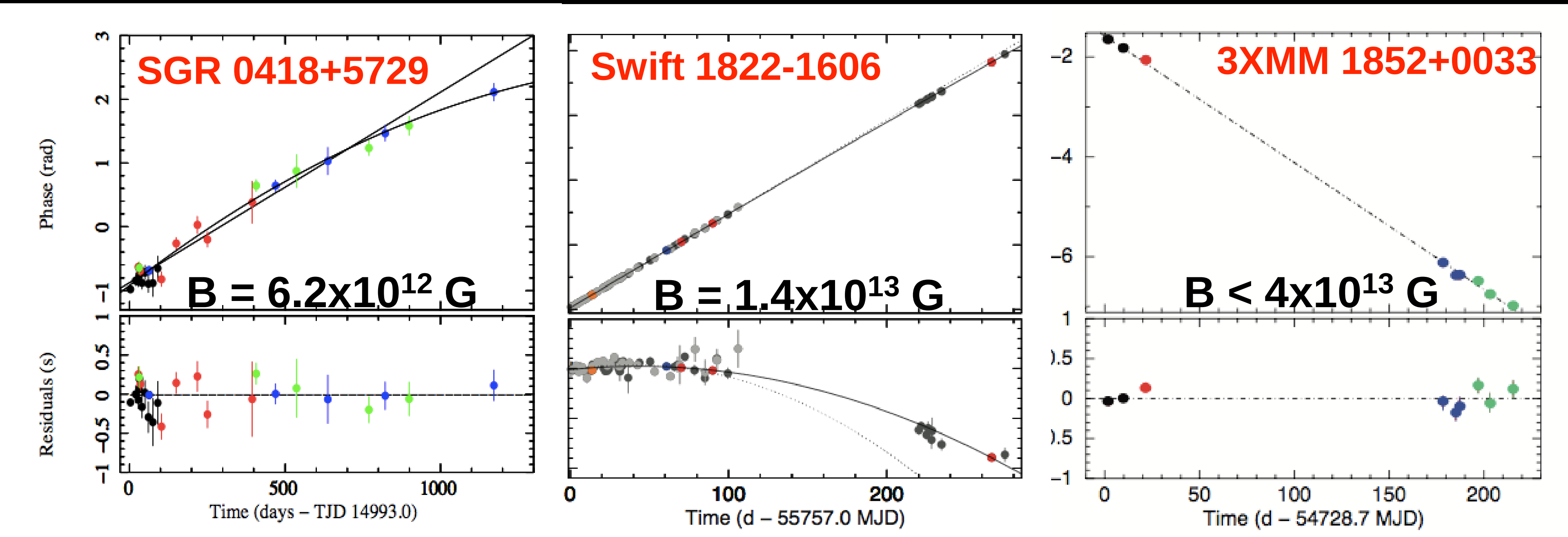


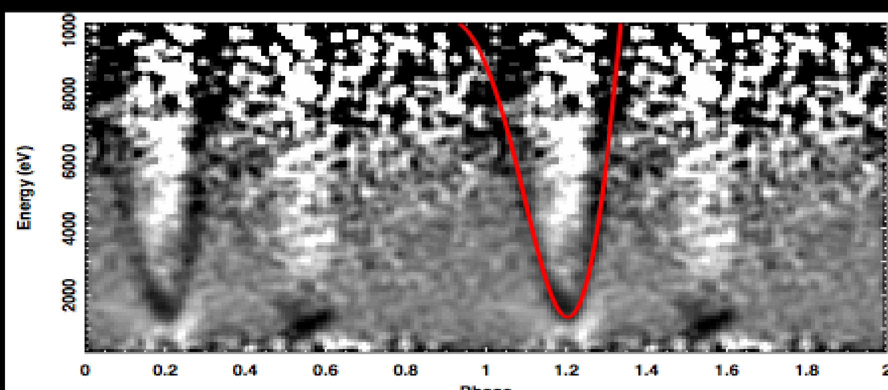




(Pons & Rea 2012, ApJ Letter)

Magnetars with low “external” magnetic fields

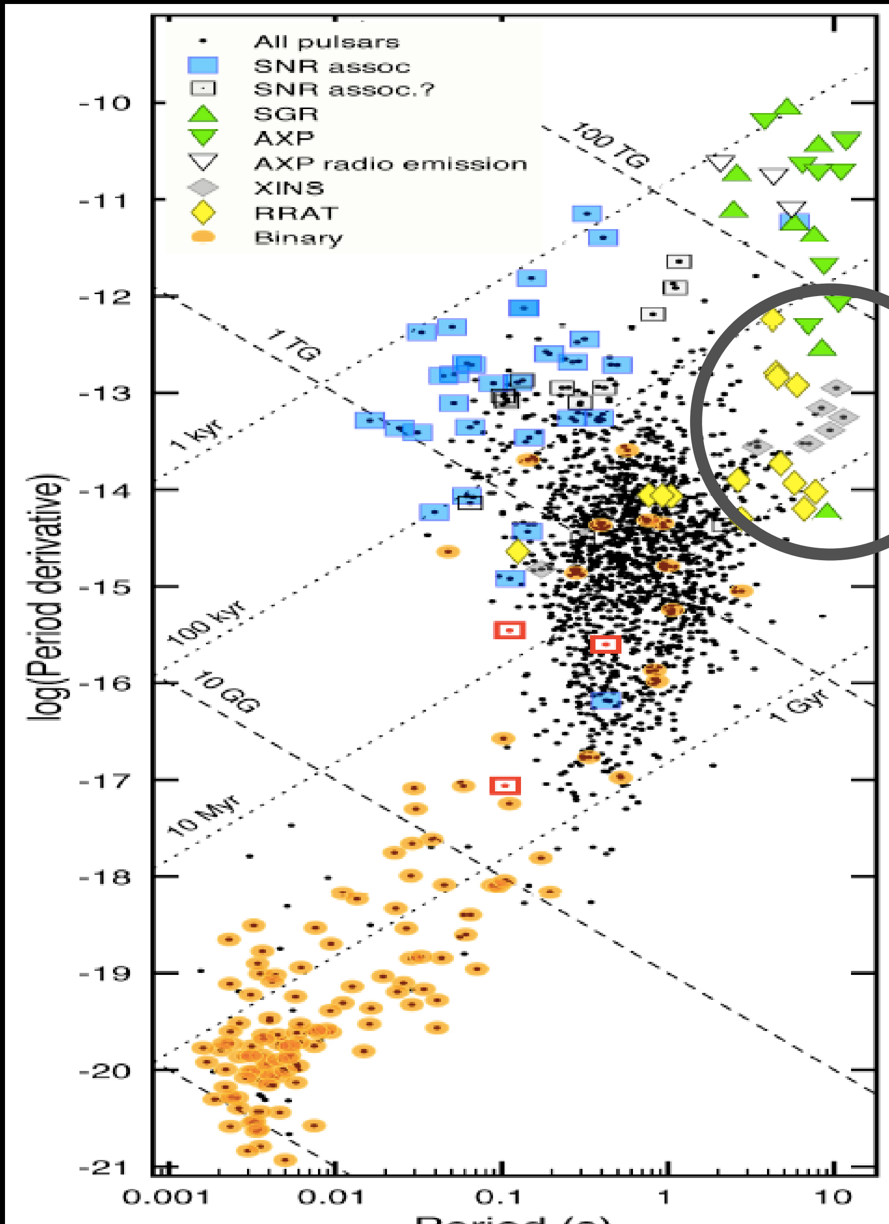




Low-field magnetars have normal external dipolar magnetic fields while keeping strong field component close or inside the crust.

(Rea et al. 2010, Science; Rea t al. 2012, 2013, 2014, ApJ; Tiengo et al. 2013, Nature)

The Pulsar Bestiary



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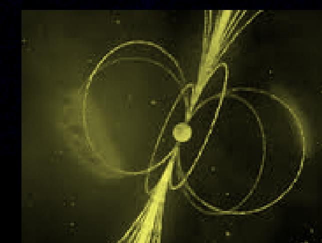
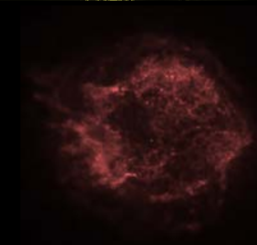
XDINS: kT-powered

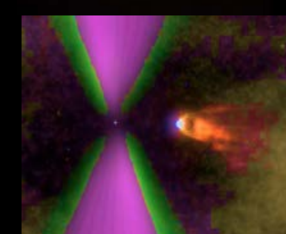
Pulsars and RRATs: rotation-powered



CCOs: kT-powered

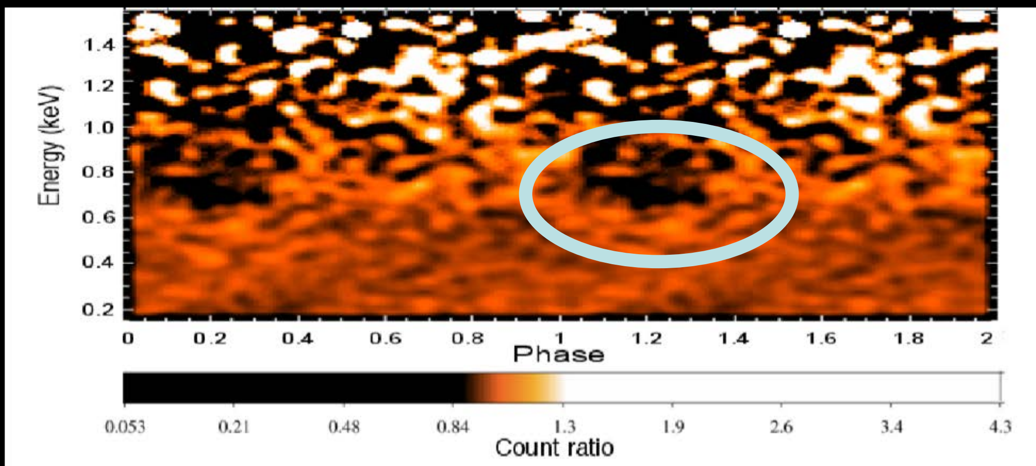


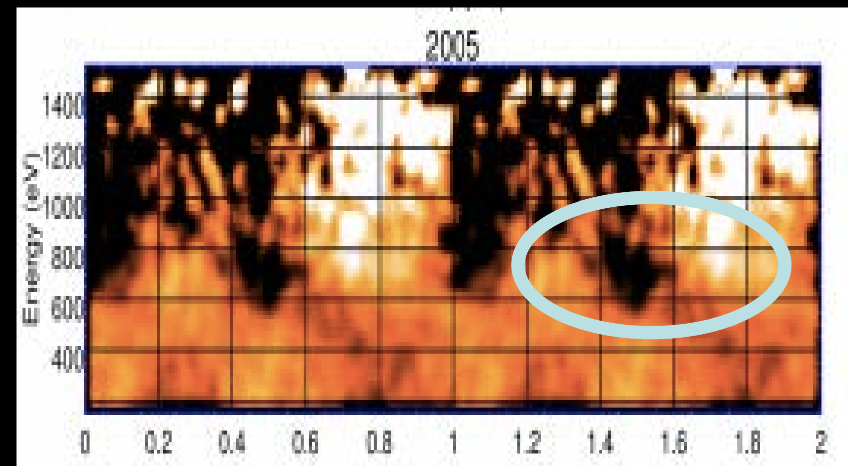
Recycled binaries: rotation-powered



X-ray dim isolated neutron stars (XDINSs)

Narrow feature found in the spectrum of two XDINS:
RX J0720.4-3125 and RX J1308+2127

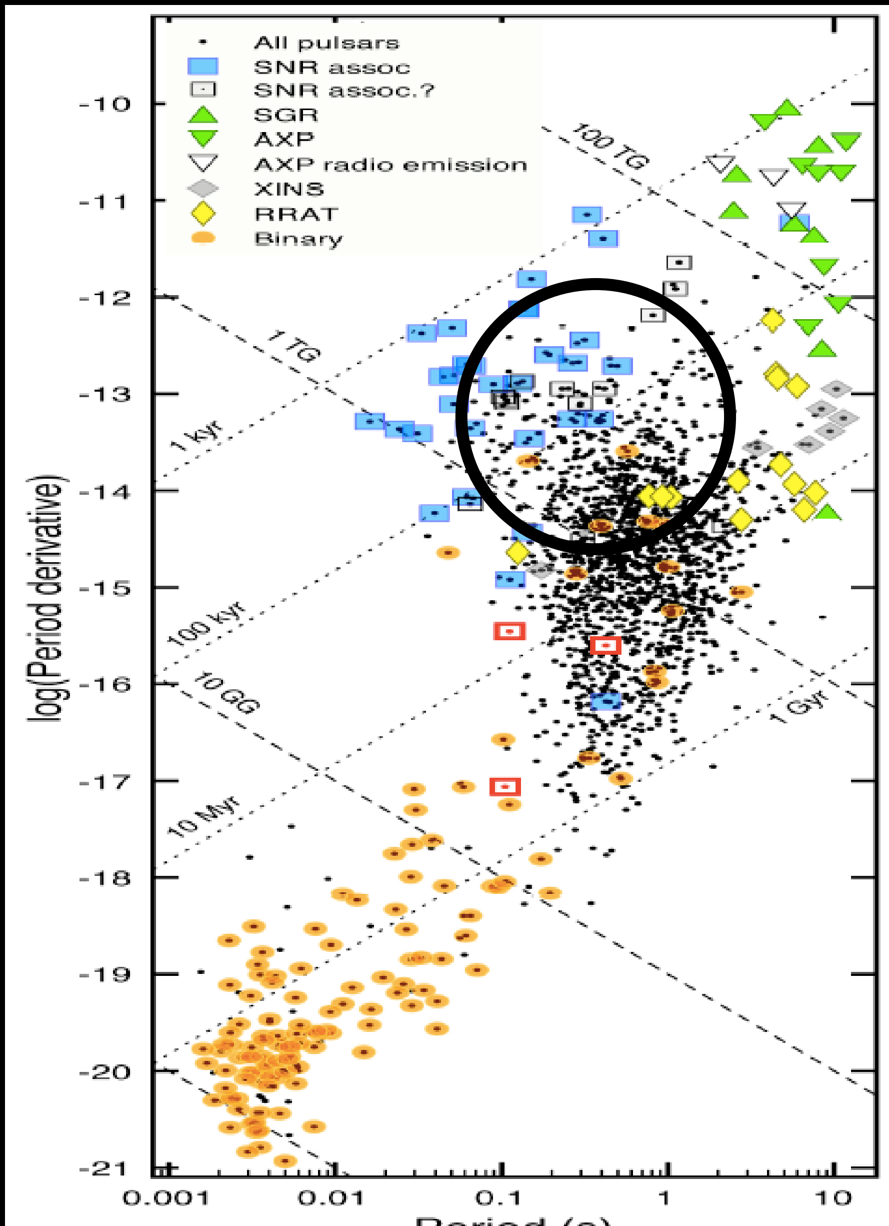




Similar to the spectral feature found in the low-field magnetar SGR 0418+5729.

$B_{loop} \approx 1.8 \times 10^{14}$ G
($B_{dipole} \approx 2.5 \times 10^{13}$ G)

The Pulsar Bestiary



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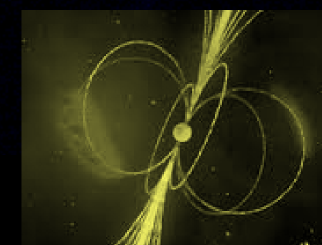
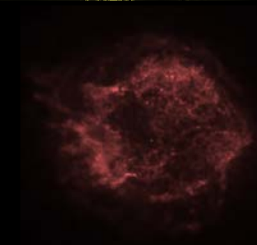
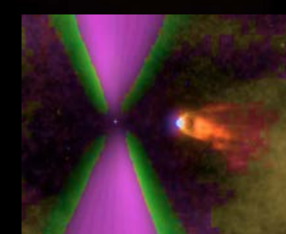


CCOs: kT-powered



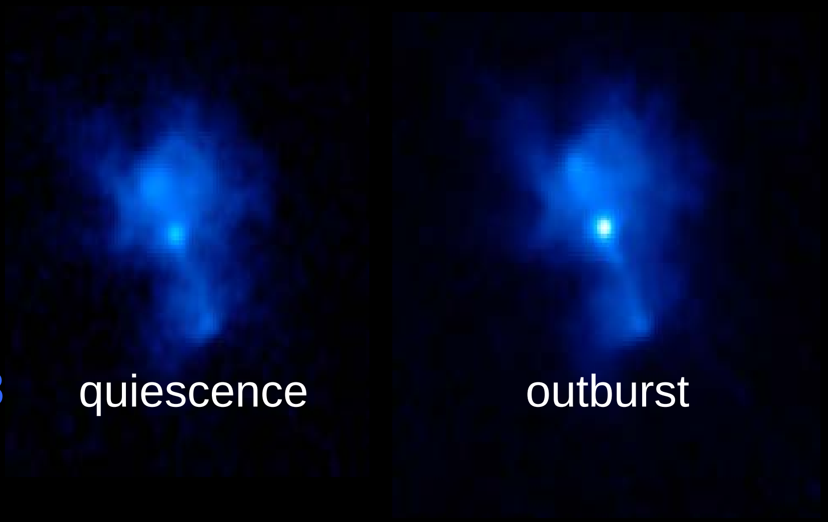
Recycled binaries: rotation-powered



Magnetar-like outbursts from rotational powered pulsars

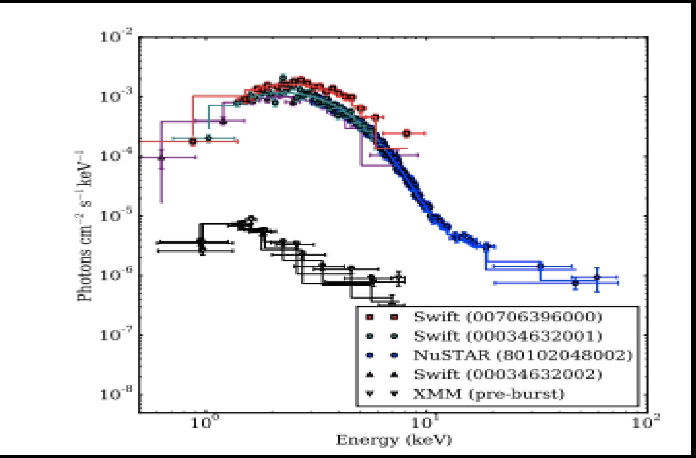
PSR 1846-0258

- rotational power of Edot~8×10^{36} erg/s
- rotating with P ~ 0.3s
- magnetic fields ~5×10^{13} - Gauss
- Kes75 and with a PWN
- X-ray rotational powered pulsar
- Showed SGR-like bursts and outburst in 2008



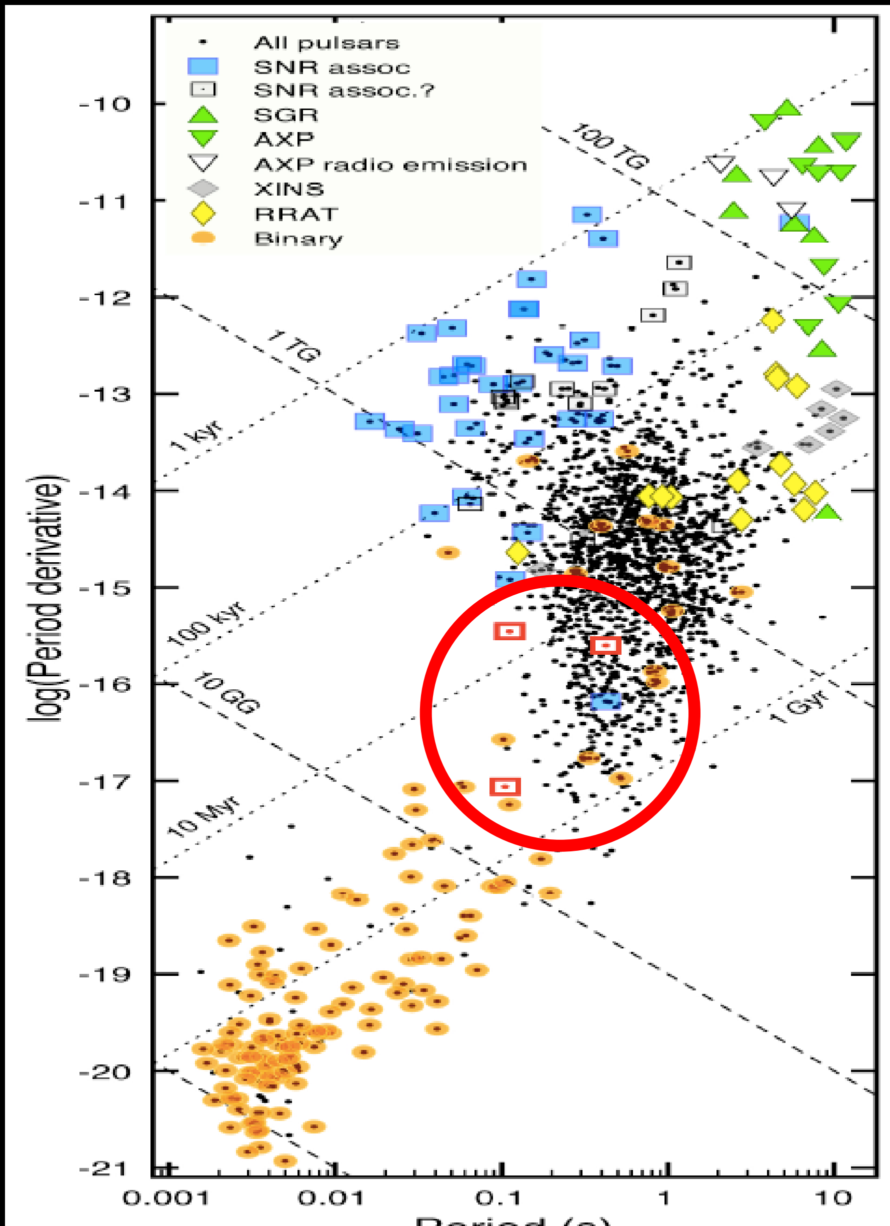
PSR 1119-6127

- rotational power of Edot~2.3×10^{36} erg/s
- rotating with P ~ 0.4s
- magnetic fields ~4×10^{13} - Gauss
- with a PWN
- Radio/X-ray rotational powered pulsar
- Showed SGR-like bursts and outburst in 2016



(Gavriil et al. 2008, Science; Kumar & Safi-Harb 2008, ApJ; Archibald et al. 2016, ApJ; Gogus et al. 2016, MNRAS)

The Pulsar Bestiary



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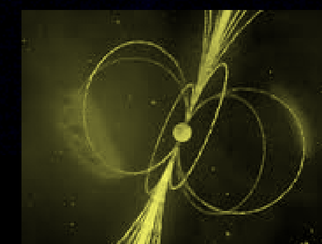
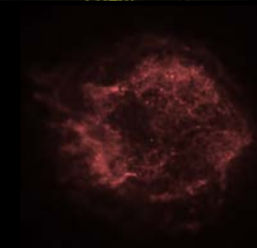
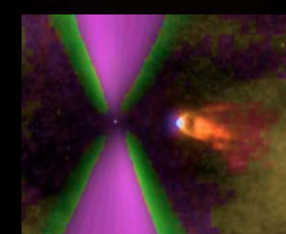


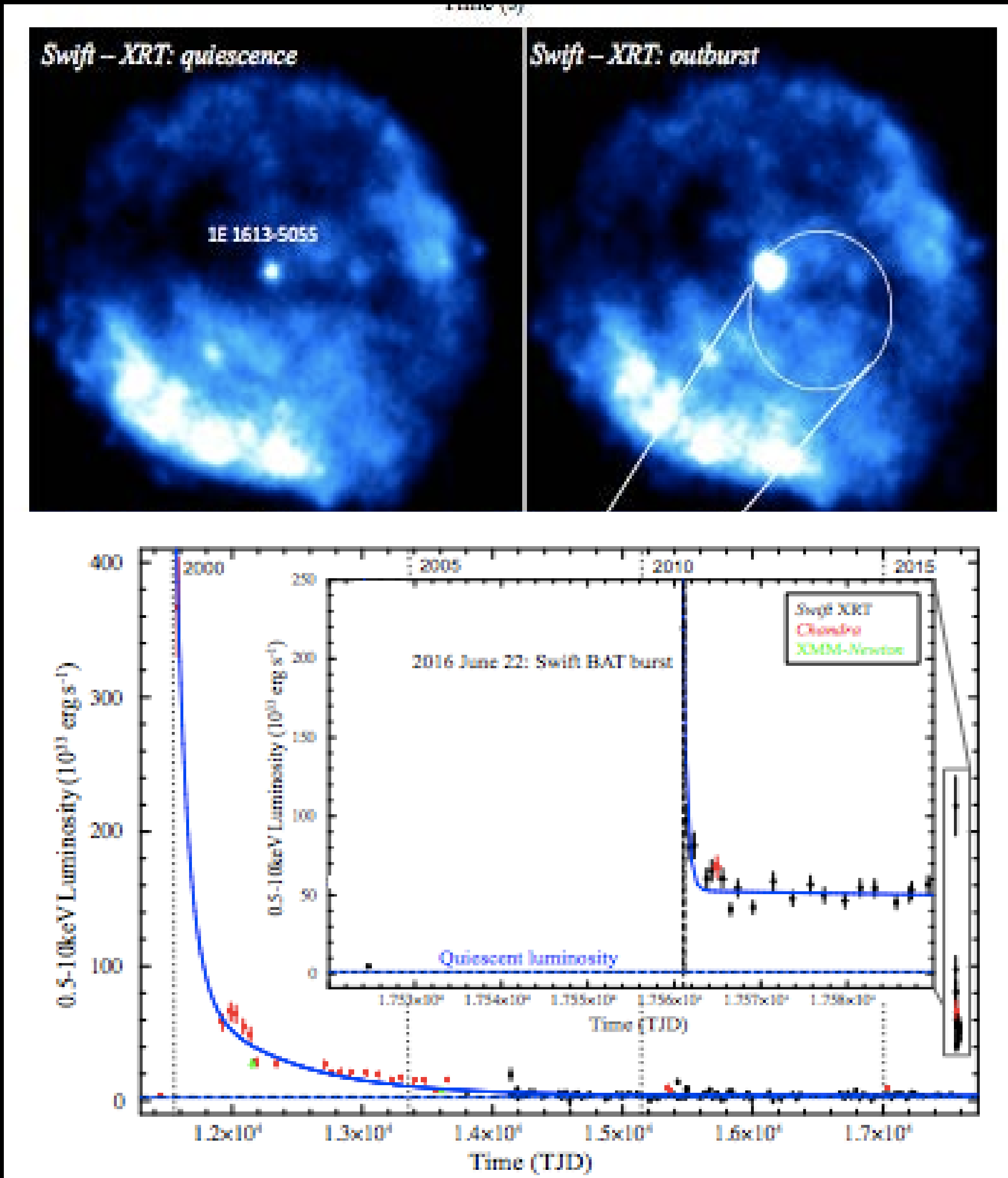
CCOs: kT-powered

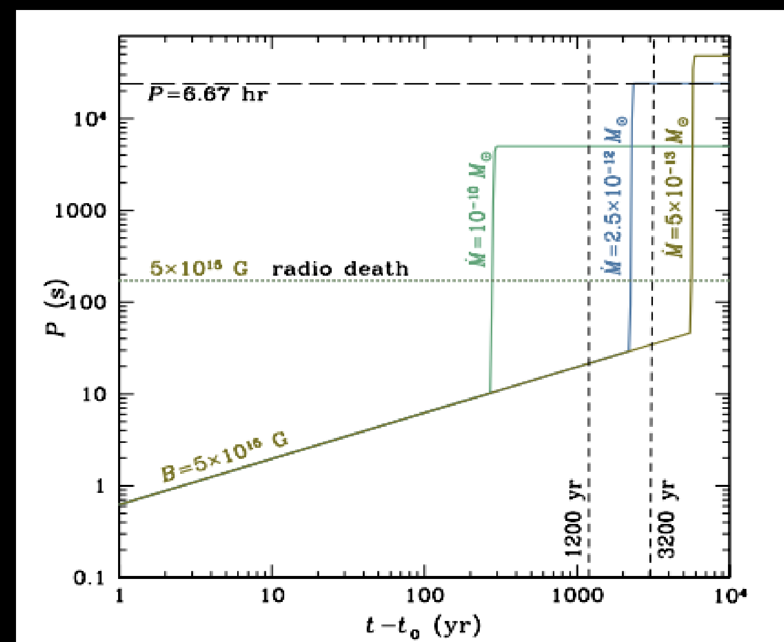


Recycled binaries: rotation-powered



A new magnetar discovered being the slowest isolated pulsar!



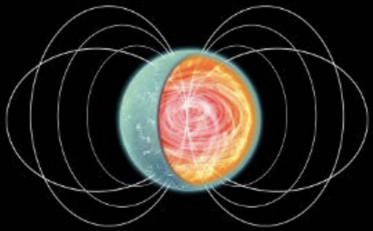


(Rea et al. 2016, ApJ Letters; D'Ai et al. 2016, MNRAS)

Summarizing…

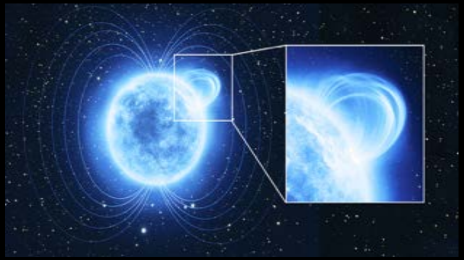
1. Magnetars were discovered having also low dipolar B-fiels and strong magnetic structures.

   (Rea et al. 2010, 2012, 2014, Tiengo et al. 2013)



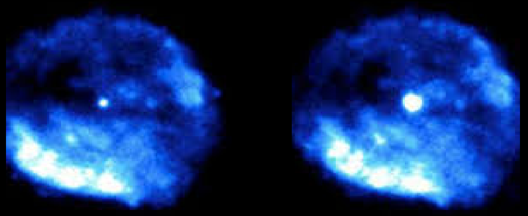
2. Two X-ray Dim Isolated NSs show evidence of strong magnetic structures

   (Borghese et al. 2015, 2017)



3. A central compact object (CCO) with a 6.4hr period showed magnetar-like activity.

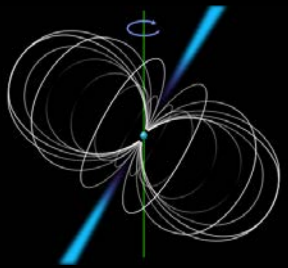
   (Rea et al. 2016; D'Ai et al. 2016)



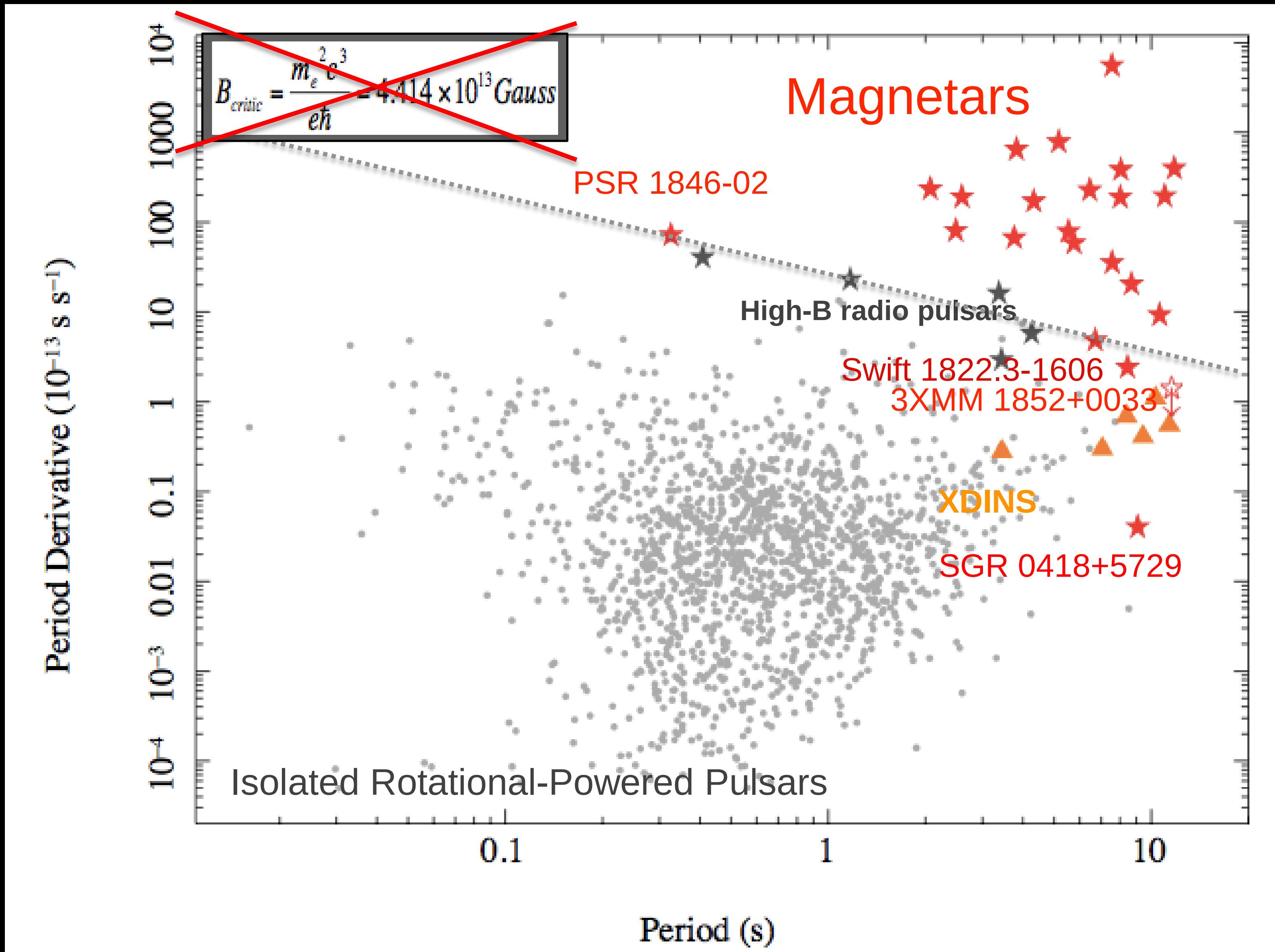
quiescence outburst

4. Two young rotational powered pulsars showed magnetar activity.

   (Gavriil et al. 2008; Kumar & Safi-Harb, 2008; Archibald et al. 2016, Gogus et al. 2016)



Now…



B_critic = m_e^2 c^3 / eħ = 4.414 x 10^13 Gauss
Magnetars
PSR 1846-02
High-B radio pulsars
Swift 1822.3-1606
3XMM 1852+0033
XDINS
SGR 0418+5729
Isolated Rotational-Powered Pulsars
Period Derivative (10^-13 s s^-1)
Period (s)
0.1
1
10
10^4
1000
100
10
1
0.1
0.01
10^-3
10^-4

We need to solve the thermal and magnetic evolution of a neutron star over > Myr timescales…

Thermal evolution: energy balance equation

Specific heat — Thermal conductivity — Neutrino emissivity

$$C_v e^{\Phi(r)} \frac{\partial T}{\partial t} + \vec{\nabla} \cdot \left(-\hat{\kappa} \cdot \vec{\nabla} \left(e^{\Phi(r)} T \right) \right) = e^{2\Phi(r)} Q$$

Magnetic evolution: Hall induction equation

$$\frac{\partial \boldsymbol{B}}{\partial t} = -\boldsymbol{\nabla} \times \left\{ \eta \boldsymbol{\nabla} \times (e^{\nu} \boldsymbol{B}) + \frac{c}{4\pi e n_e} \left[\boldsymbol{\nabla} \times (e^{\nu} \boldsymbol{B}) \right] \times \boldsymbol{B} \right\}$$

Hall induction

Electrical resistivity: strongly depends on T

(Aguilera et al. 2008; Pons et al. 2009; Vigano', Rea, Pons, Perna, Aguilera & Miralles 2013; Elfritz, Pons & Rea 2016, 2017 in prep)

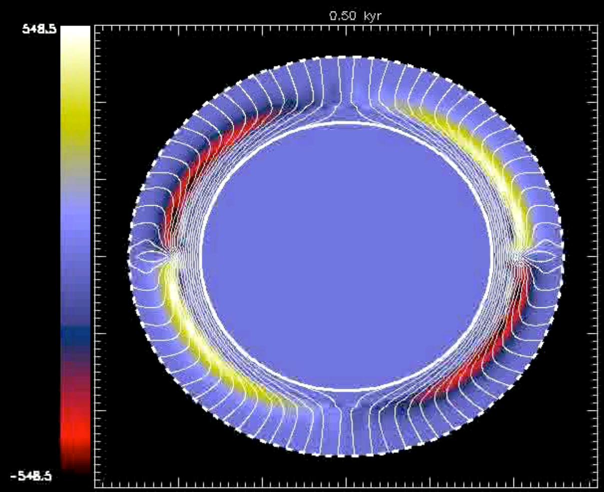
Magnetic properties at birth, and age, drive the different neutron star classes!

Extremely Magnetic Pulsar

Intial conditions:

B_{dip}~10^{15} G (white lines)

B_{int}~ 10^{16} G (colors)

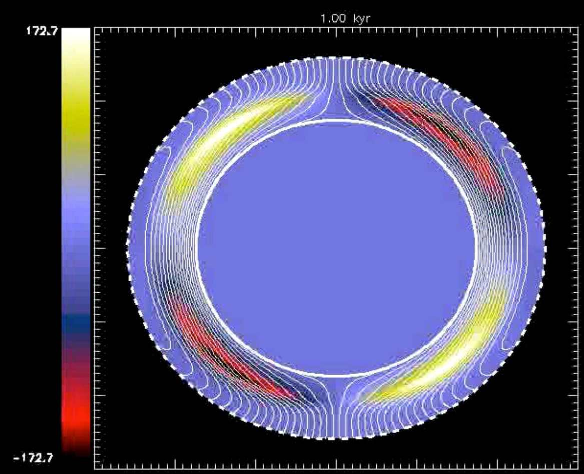


Very Magnetic Pulsar

Initial conditions:

B_{dip}~10^{14} G (white lines)

B_{int}~ 10^{15} G (colors)



Magnetic Pulsar

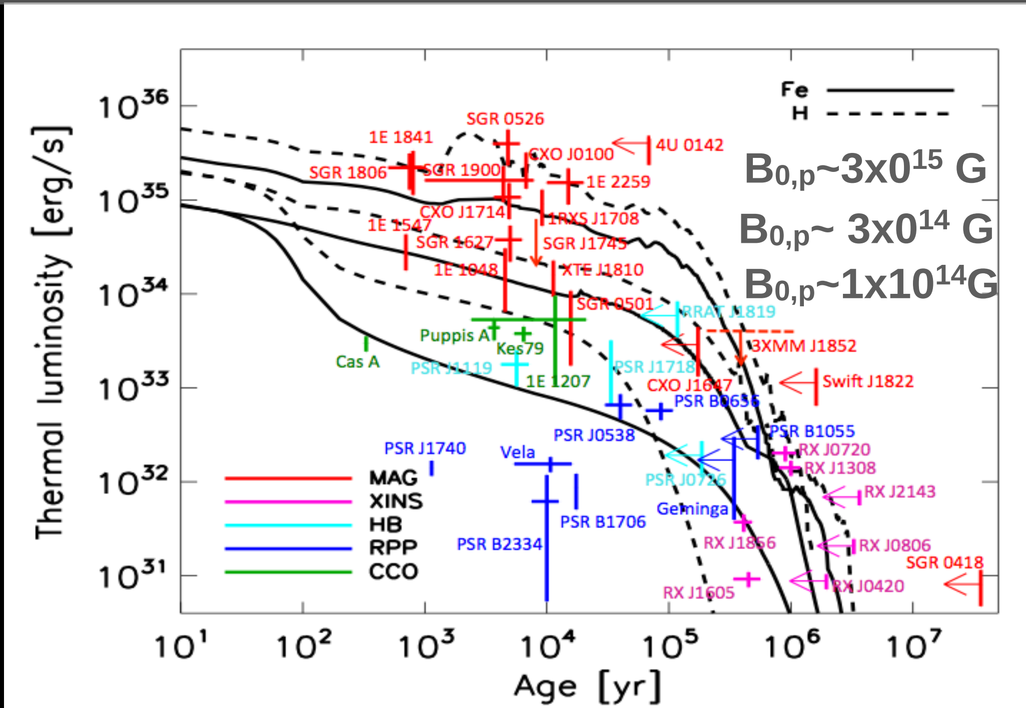
Intial conditions:

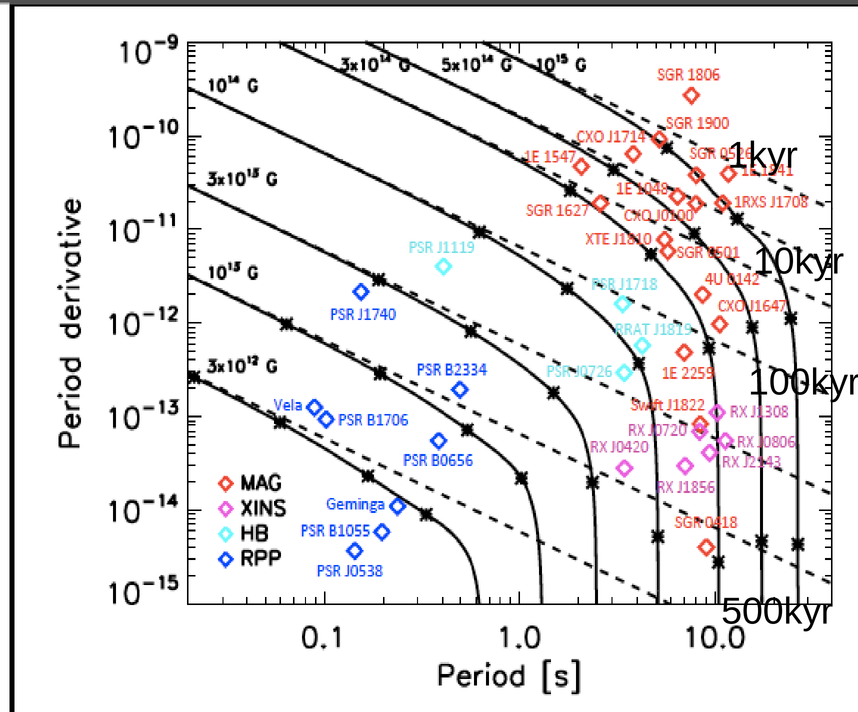
B_{dip}~10^{13} G (white lines)

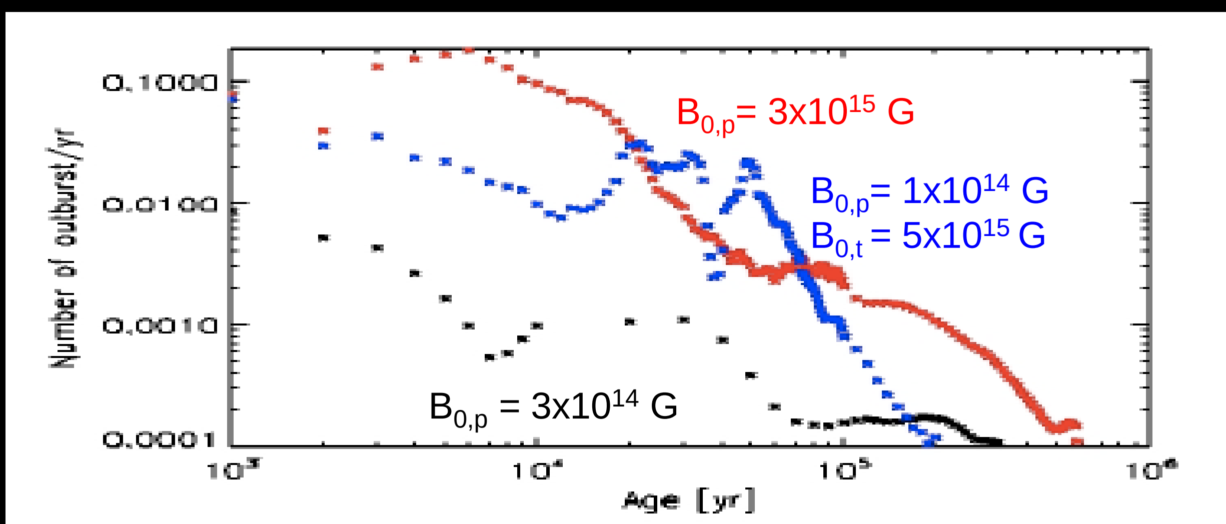
B_{int}~ 10^{14} G (colors)

(Vigano', Rea, Pons, Perna, Aguilera & Miralles 2013; Elfritz, Pons & Rea 2017)

Unified scenario for the Pulsar Bestiary



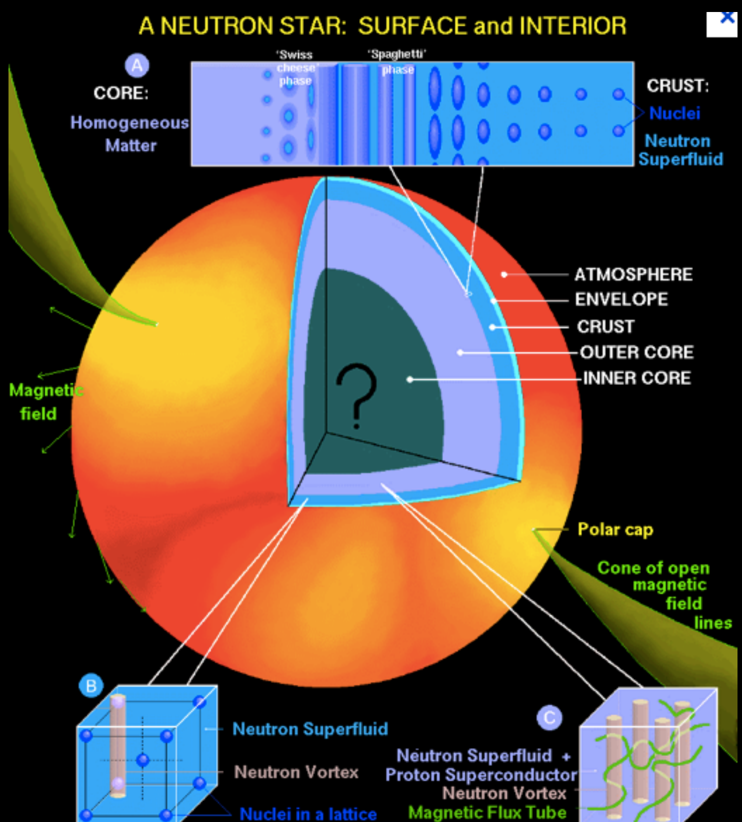


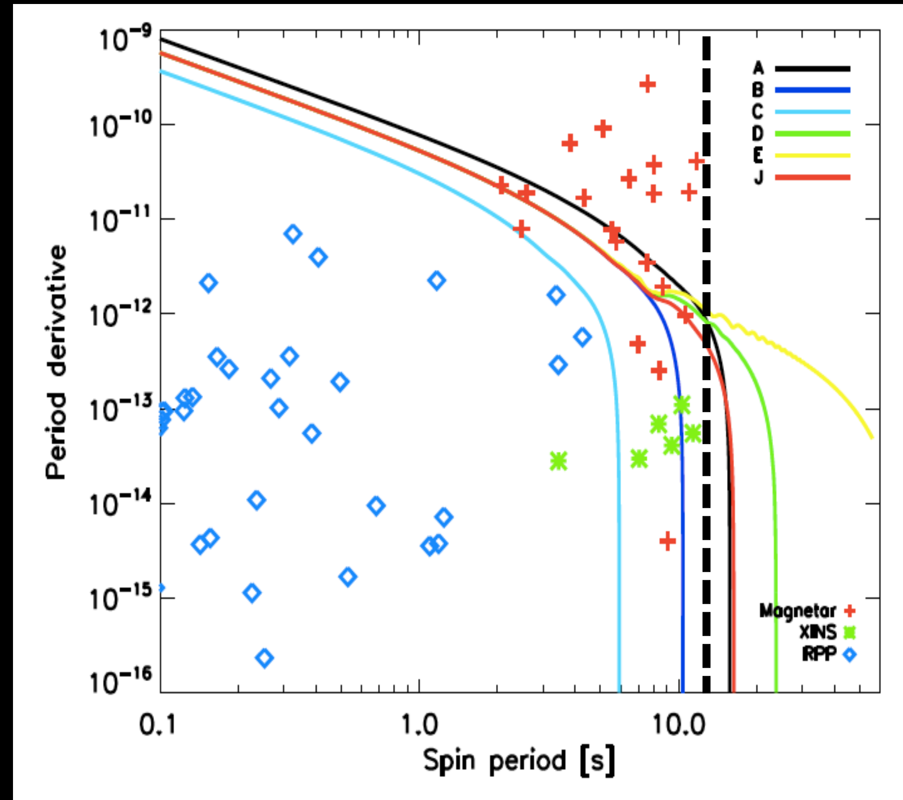


(Vigano', Rea, Pons, Perna, Aguilera & Miralles 2013; Elfritz, Pons & Rea 2017)

Constraining Nuclear Physics with magnetar modelling

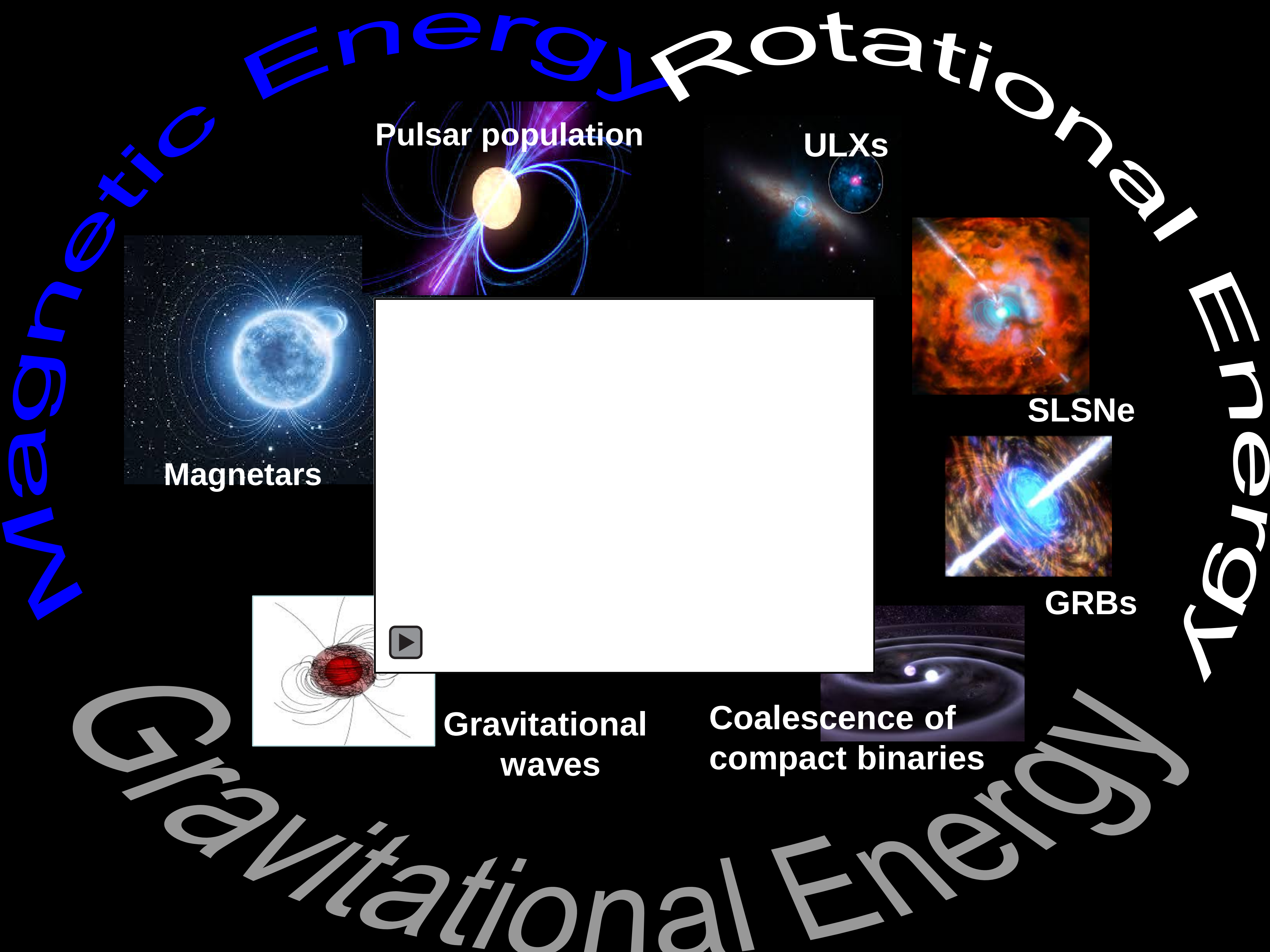
Magnetar spin limit as the first observational evidence of the existence of the Nuclear Pasta phase of matter.





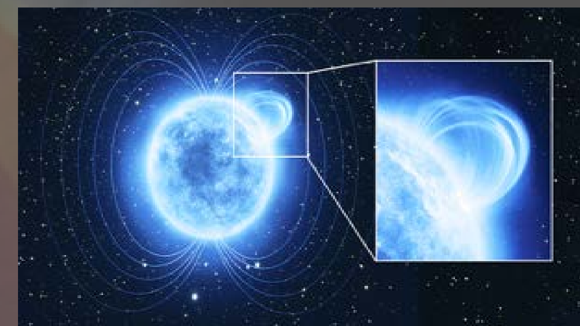
Model	$M[M_\odot]$	I_{45}	ΔR_{crust} [km]	ΔR_{pasta} [km]	Q_{max}
A	1.10	0.962	0.94	0.14	100
B	1.40	1.327	0.70	0.10	100
C	1.76	1.755	0.43	0.07	100
D	1.40	1.327	0.70	0.10	10
E	1.40	1.327	0.70	0.10	0.1
J	1.40	1.327	0.70	0.0	23

(Pons, Vigano' & Rea 2013 *Nature Physics* 9, 431; Rea 2015, Physics Today)

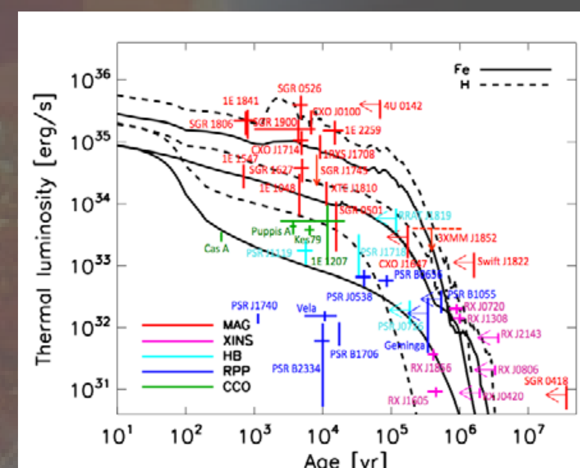


Magnetic Energy
Rotational Energy
Gravitational Energy
Pulsar population
ULXs
SLSNe
GRBs
Magnetars
Gravitational waves
Coalescence of compact binaries

Summary and Conclusions



- We observe ~10^{14} Gauss magnetic components in all isolated neutron star classes (not only magnetars).



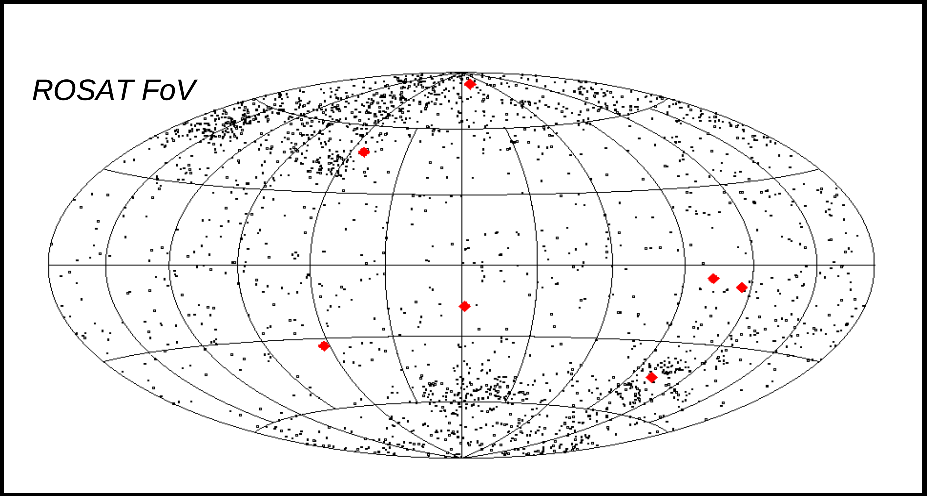
- All different isolated neutron star manifestations simply depend on B-field strength and configuration at birth, and age.

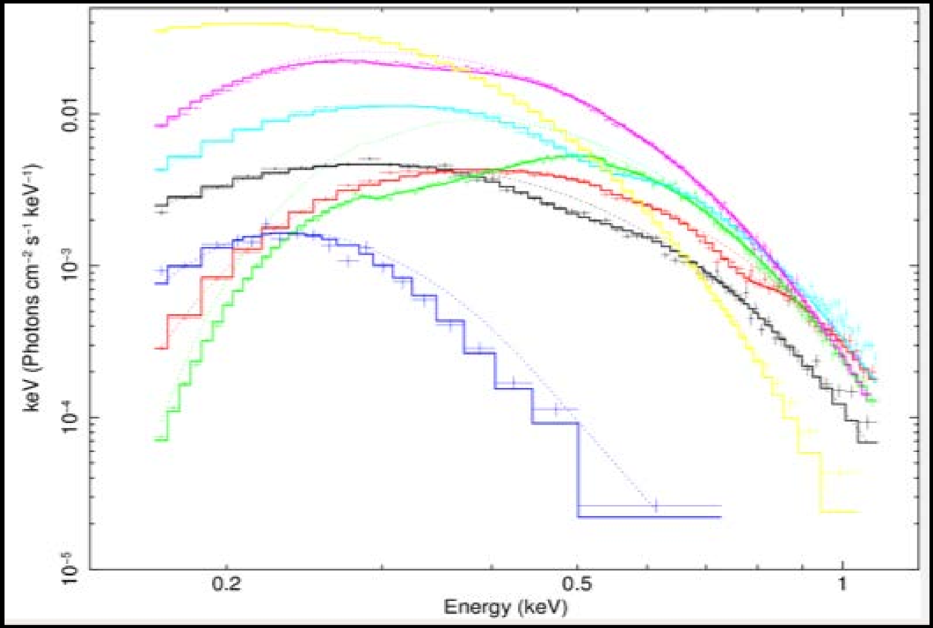
HAPPY BIRTHDAY MARGARITA!

BACK UP SLIDES!
GENERAL

Thermally emitting neutron stars (XDINSs)

- Distances : d<500pc
- Spin periods: P~3-11s
- Magnetic dip-fields: B~10^{13} G
- Age: t~0.1-1 Myr
- Luminosities: Lx~10^{30}-10^{33} erg/s
- Lx >> Rotational energy
- No radio emission
- Fx/Fopt~10^4 - 10^5

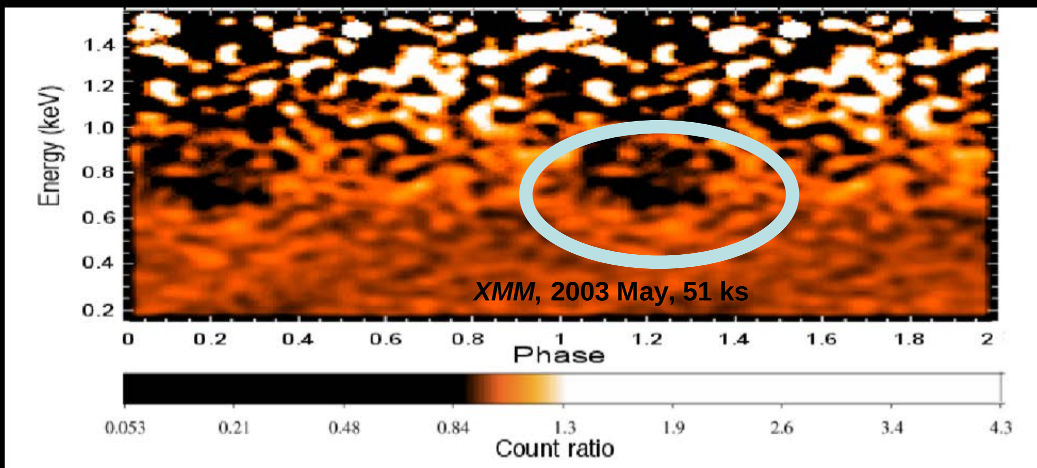


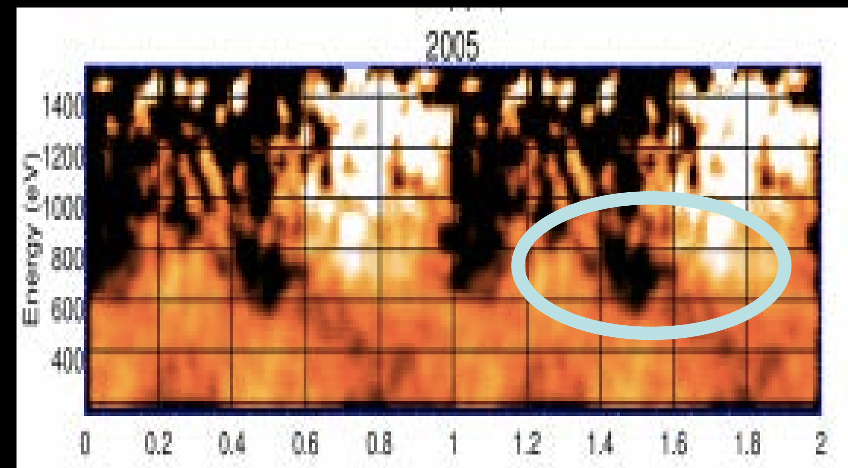


Thermal X-ray spectra (kT_{BB} ~ 40-110 eV) plus
a broad absorption feature (E_{lin} ~ 0.2-0.8 keV)

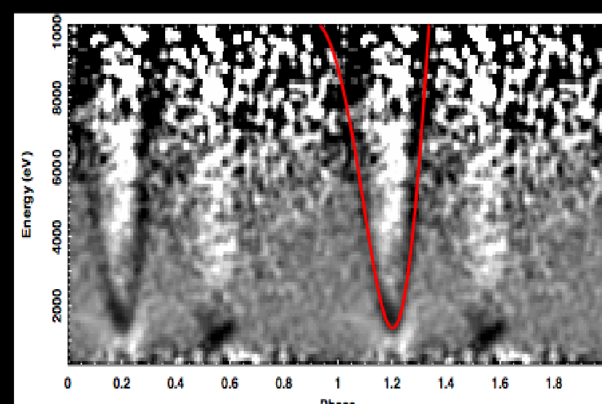
Thermally emitting neutron stars (XDINSs)

Systematic search for narrow phase-dependent absorption features in all XDINSs
Narrow feature found in the spectrum of RX J0720.4-3125 and RX J1308+2127



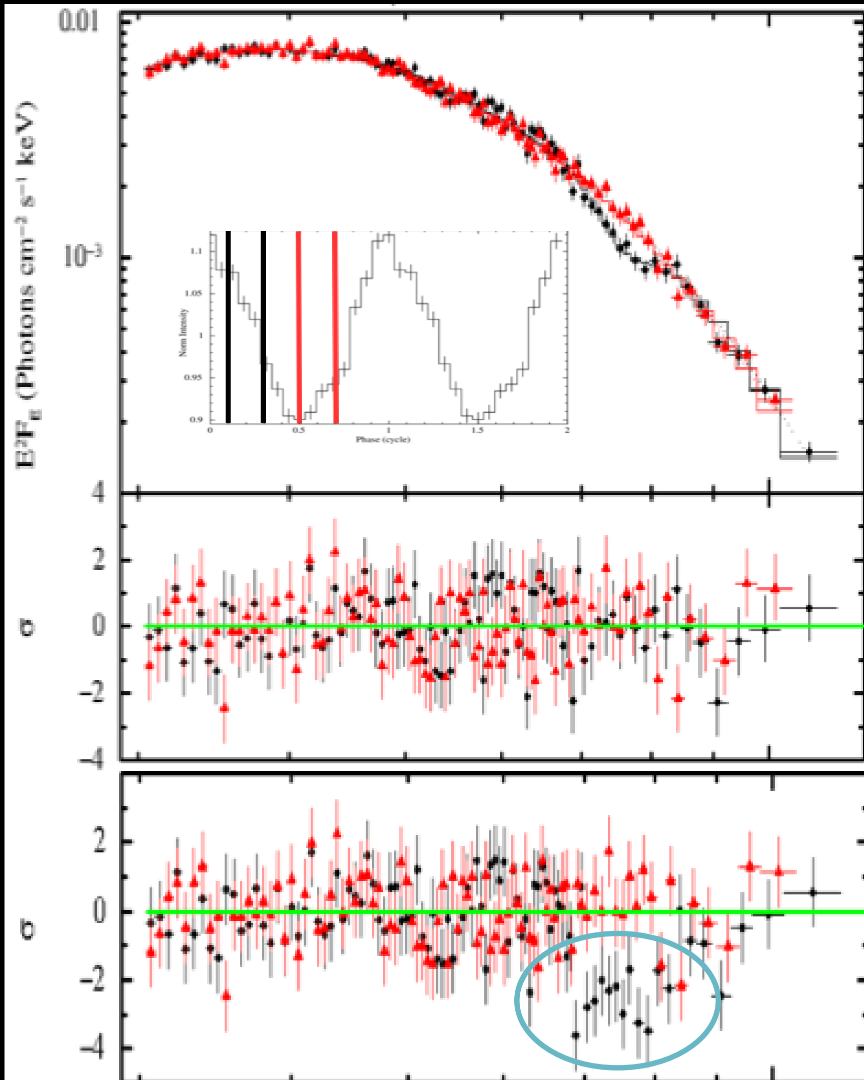


Similar to the spectral feature found in the low-field magnetar SGR 0418+5729.



(Tiengo et al. 2013)

(Borghese, NR et al. 2015, 2017)



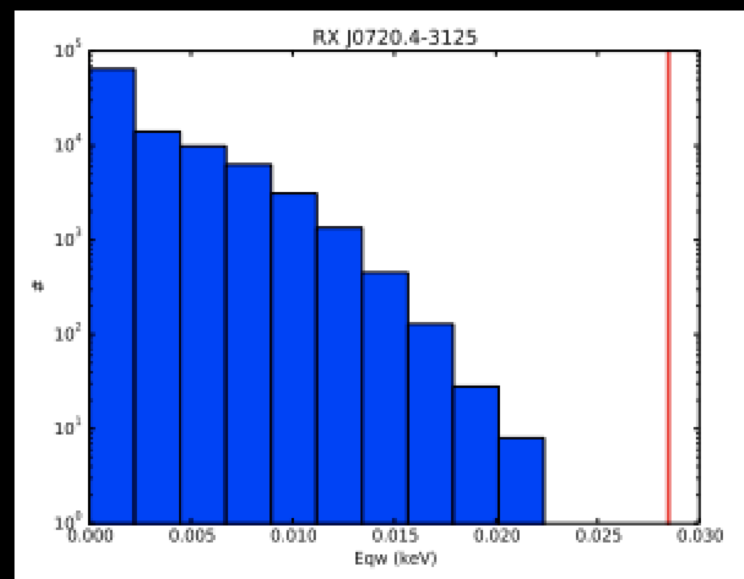
0.3 Energy 1

Phase-dependent line:

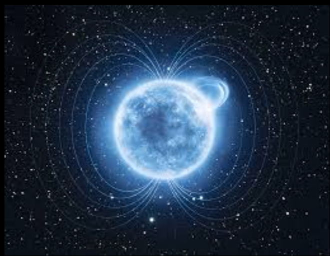
$E_{line} = 745_{-27}^{+17}$ eV

$\sigma_{line} = 42_{-33}^{+51}$ eV

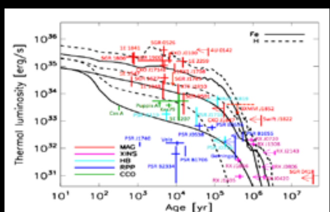
$Eqw = 28_{-11}^{+9}$ eV



Summary and Conclusions

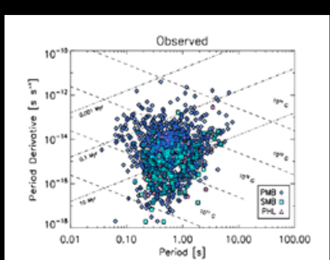


- Magnetars are unique laboratories to study the effects on matter embedded in extreme magnetic fields.



- The different classes of neutron stars can be unified in a simple scenario invocking field decay and thermal evolution in objects with different initial B-field strength, configuration and age.

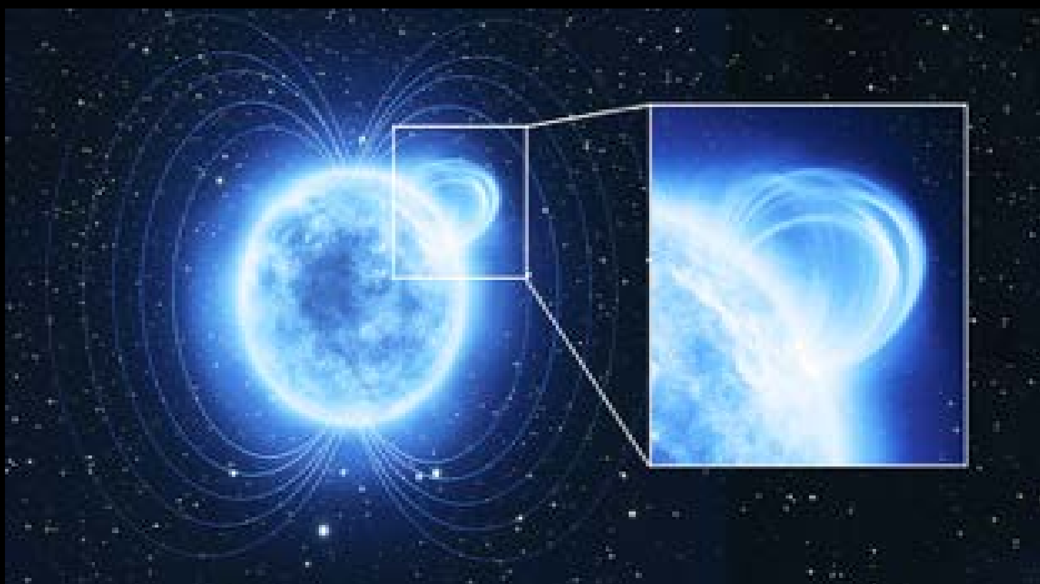
- The intensive follow-up of magnetar outbursts is giving every day new key discoveries, as the low field magnetars and the Galactic center magnetar, or magnetar-like activity from pulsars



- Population synthesis models considering for the first time all neutron star classes, including magnetars, hint to a limiting B-field at birth of ~10^{15} Gauss.

Thermally emitting neutron stars (XDINSs)

Possible origin: proton cyclotron resonant
attering in a small magnetic loop close to the surface



I.e. For RX J0720.4-3125

$$E_{line} = 0.63\ (B_{loop}/10^{14}\ \mathrm{G})\ (1+z)^{-1}\ \mathrm{keV}$$

↓

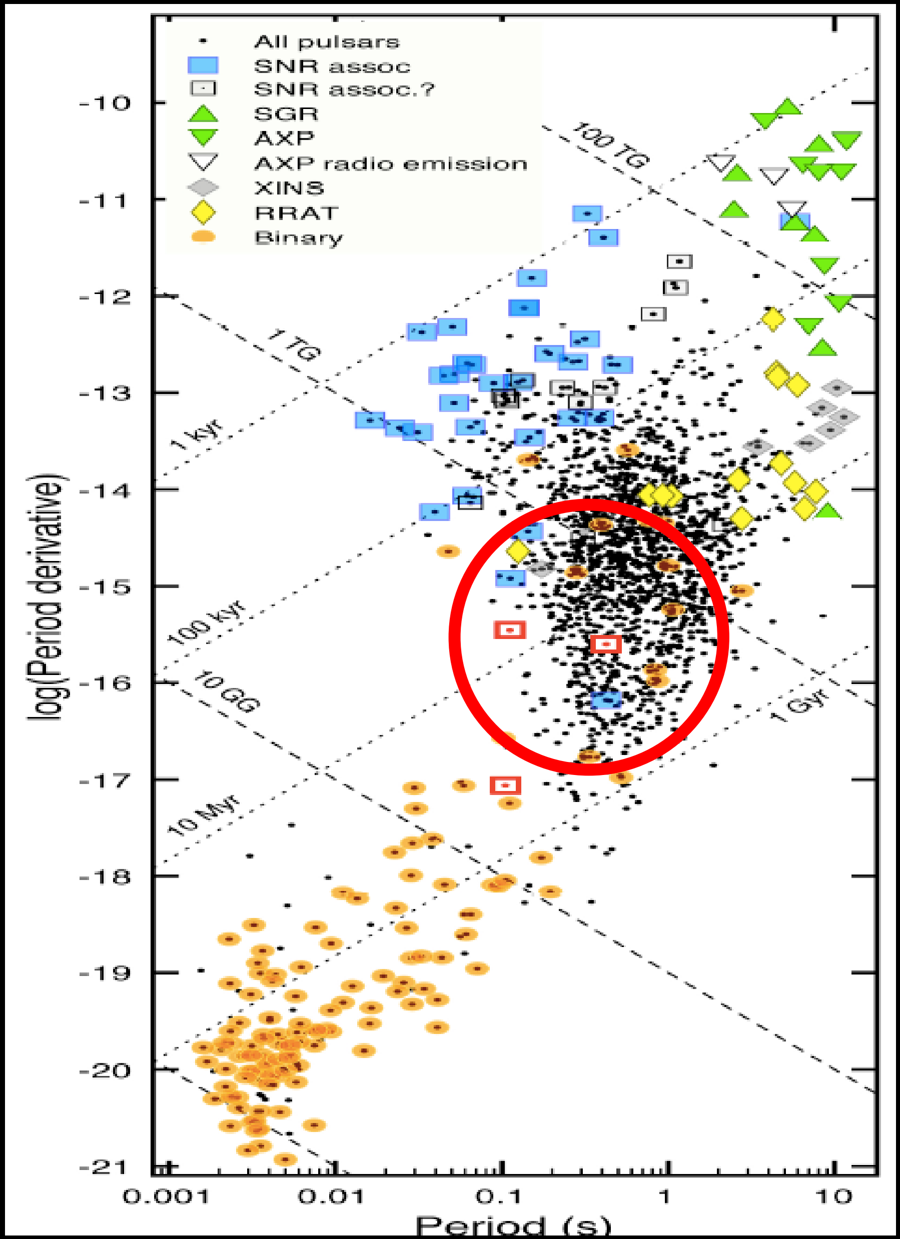
$B_{loop} \approx 1.8 \times 10^{14}$ G

($B_{dipole} \approx 2.5 \times 10^{13}$ G)

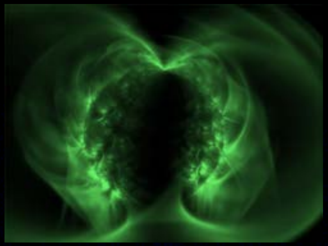
- First observational evidence of a complex magnetic field in the XDINSs
- Evolutionary connection between XDINSs and magnetars.

Discovery of magnetar-like outburst from a Central Compact Object

The Pulsar Bestiary

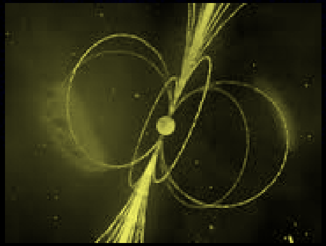


Magnetars: B-powered

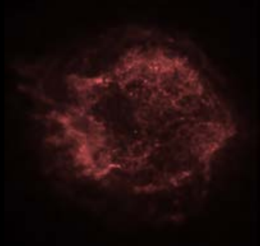


XDINS: kT-powered

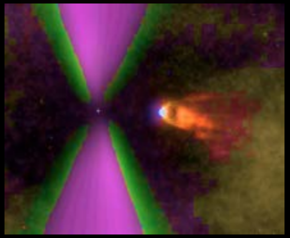
Pulsars and RRATs: rotation-powered



CCOs: kT-powered



Recycled binaries: rotation-powered



Central Compact Objects (CCO)

- Point-like X-ray sources close to centre of SNRs
- No counterparts at other wavelengths.
- Thermal-like emission
- L_X ~ few 10^{33} erg s^{-1}

Cas A

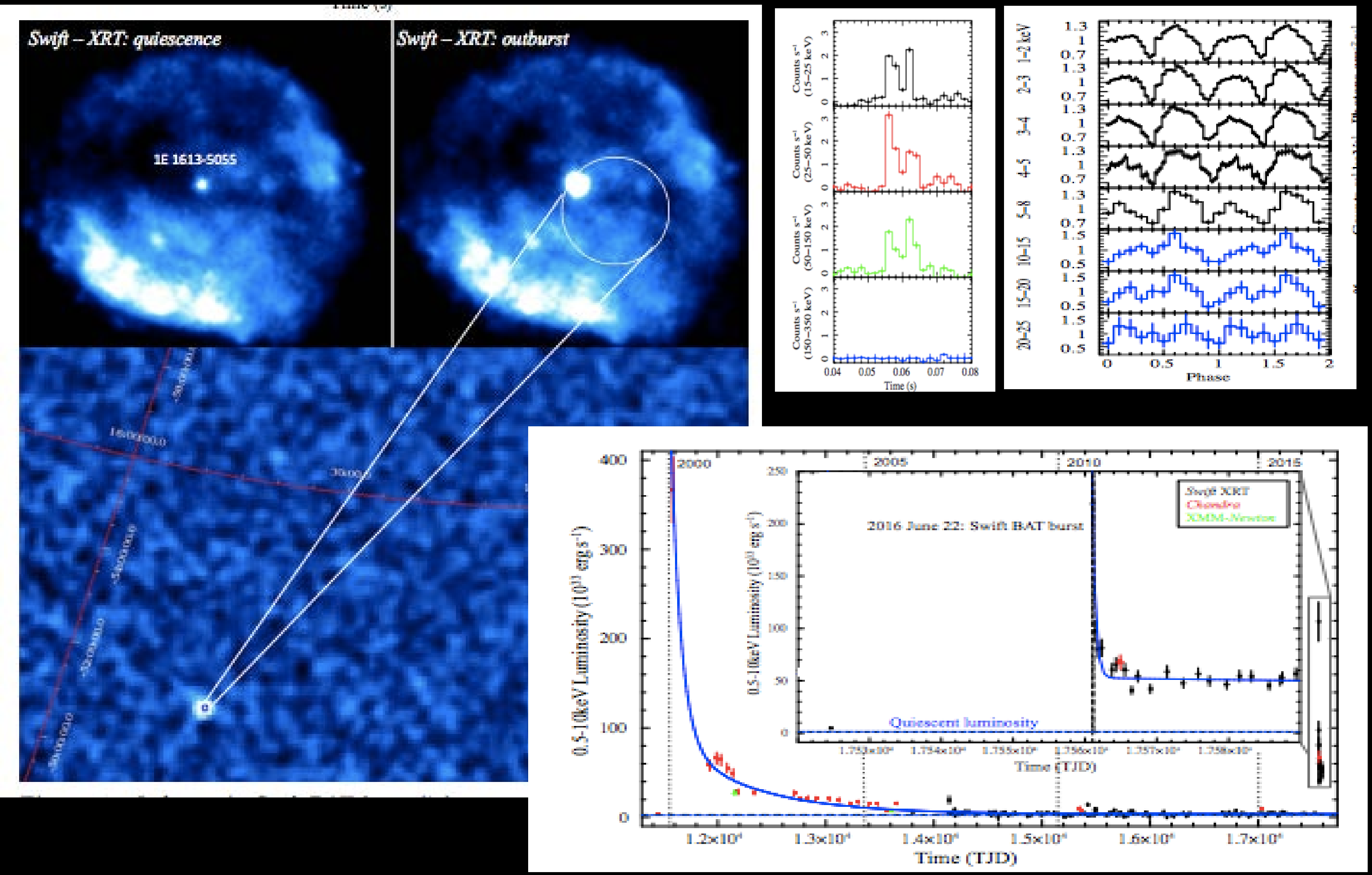
RCW103

Table 1
Central Compact Objects in Supernova Remnants

CCO	SNR	Age (kyr)	d (kpc)	P (s)	f_p[a] (%)	B_s (10^{10} G)	$L_{x,\mathrm{bol}}$ (erg s^{-1})
RX J0822.0−4300	Puppis A	4.5	2.2	0.112	11	2.9	5.6×10^{33}
CXOU J085201.4−461753	G266.1−1.2	1	1	···	<7	···	2.5×10^{32}
1E 1207.4−5209	PKS 1209−51/52	7	2.2	0.424	9	9.8	2.5×10^{33}
CXOU J160103.1−513353	G330.2+1.0	$\gtrsim$3	5	···	<40	···	1.5×10^{33}
1WGA J1713.4−3949	G347.3−0.5	1.6	1.3	···	<7	···	$\sim 1 \times 10^{33}$
XMMU J172054.5−372652	G350.1−0.3	0.9	4.5	···	···	···	3.9×10^{33}
CXOU J185238.6+004020	Kes 79	7	7	0.105	64	3.1	5.3×10^{33}
CXOU J232327.9+584842	Cas A	0.33	3.4	···	<12	···	4.7×10^{33}
2XMMi J115836.1−623516	G296.8−0.3	10	9.6	···	···	···	1.1×10^{33}
XMMU J173203.3−344518	G353.6−0.7	~27	3.2	···	<9	···	1.3×10^{34}
CXOU J181852.0−150213	G15.9+0.2	1–3	(8.5)	···	···	···	$\sim 1 \times 10^{33}$

(Gotthelf et al. 2013)

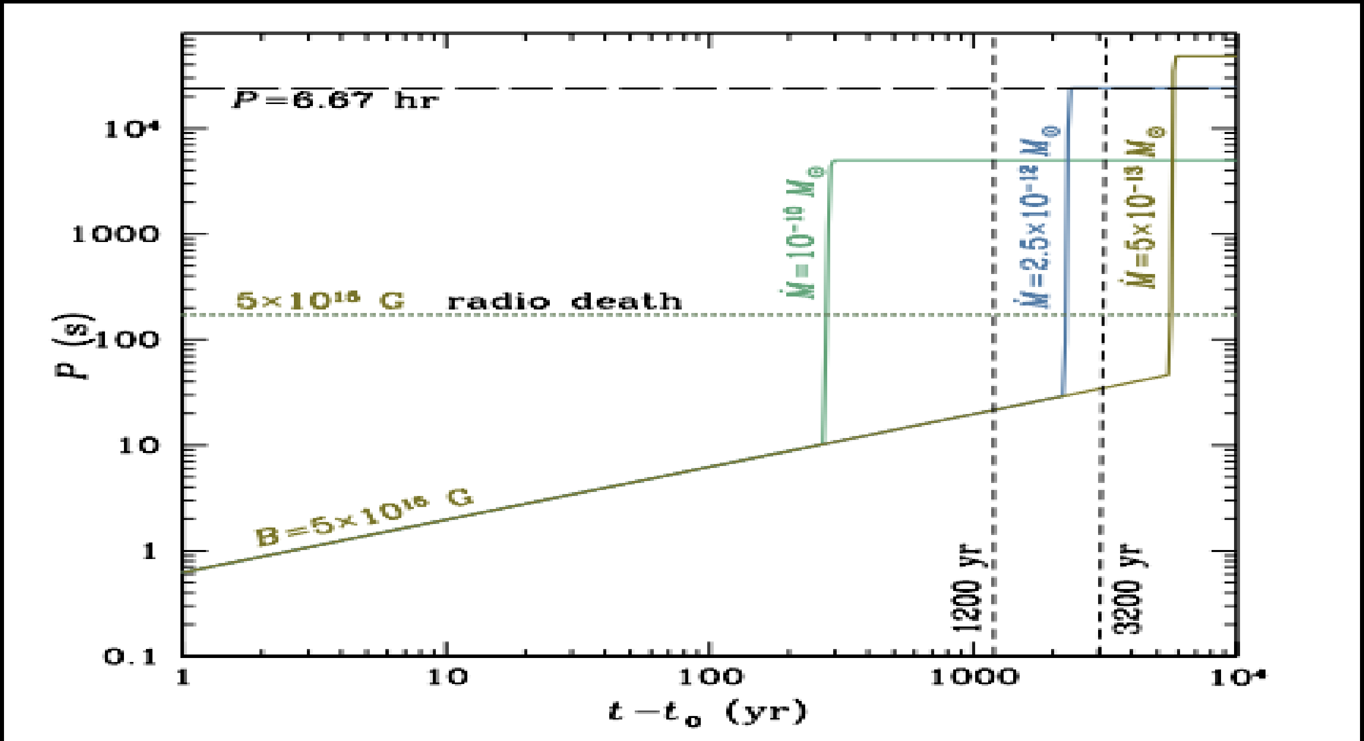
A new magnetar discovered being the slowest isolated pulsar!



(NR et al. 2016, D'Ai et al. 2016)

A new magnetar discovered being the slowest isolated pulsar!

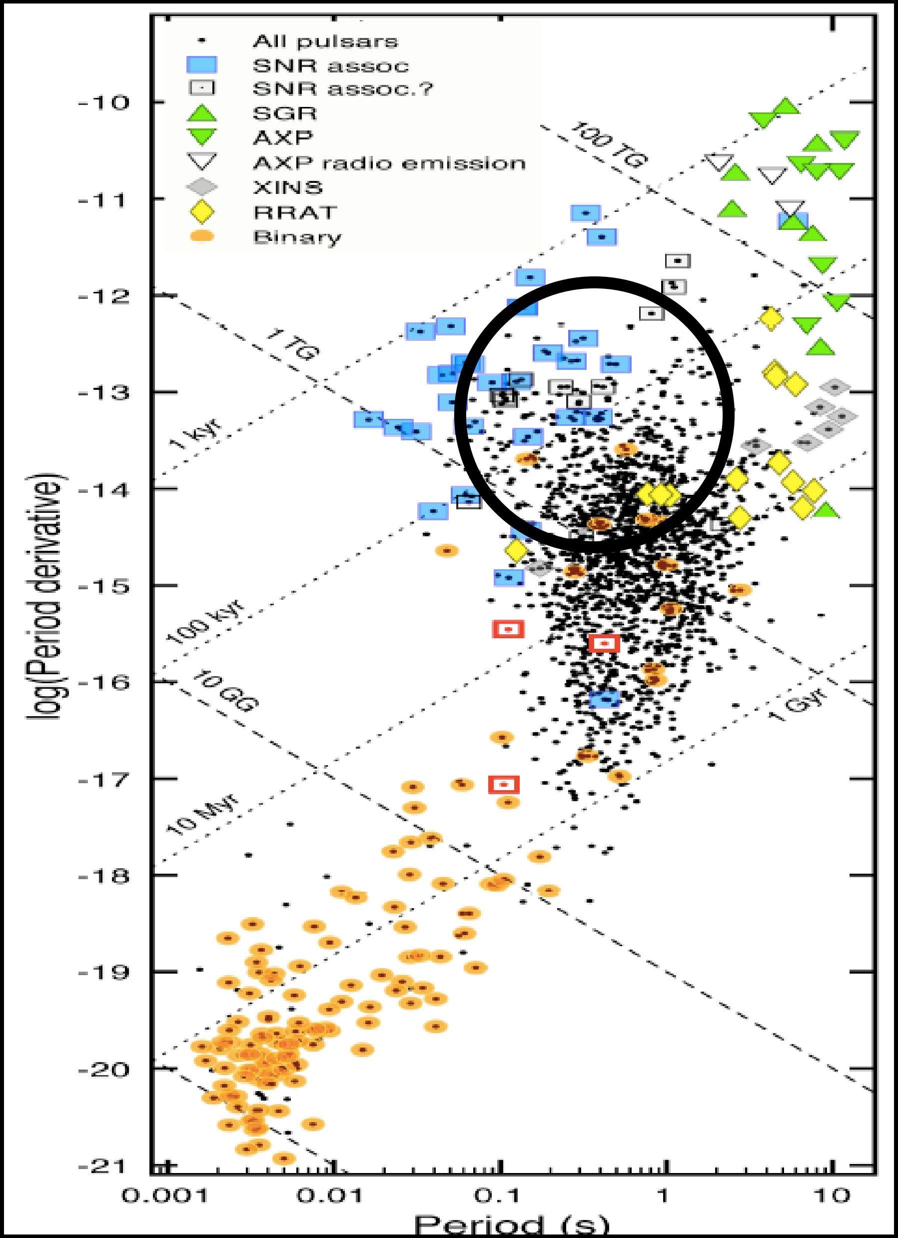
Fall back accretion after the supernova could make this pulsar slow down so extremely…



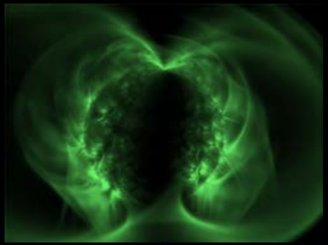
(Li 2007, NR et al. 2016, Ho & Andersson 2016, Tong et al. 2016)

Discovery of magnetar-like outburst from Rotational powered pulsars

The Pulsar Bestiary

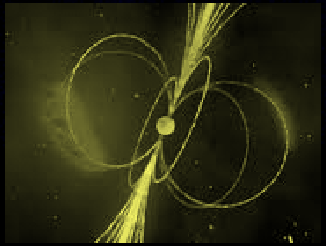


Magnetars: B-powered

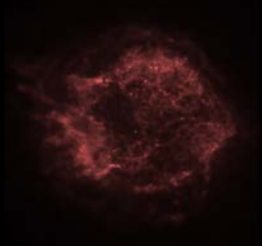


XDINS: kT-powered

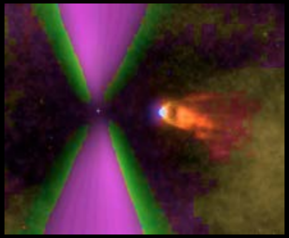
Pulsars and RRATs: rotation-powered



CCOs: kT-powered



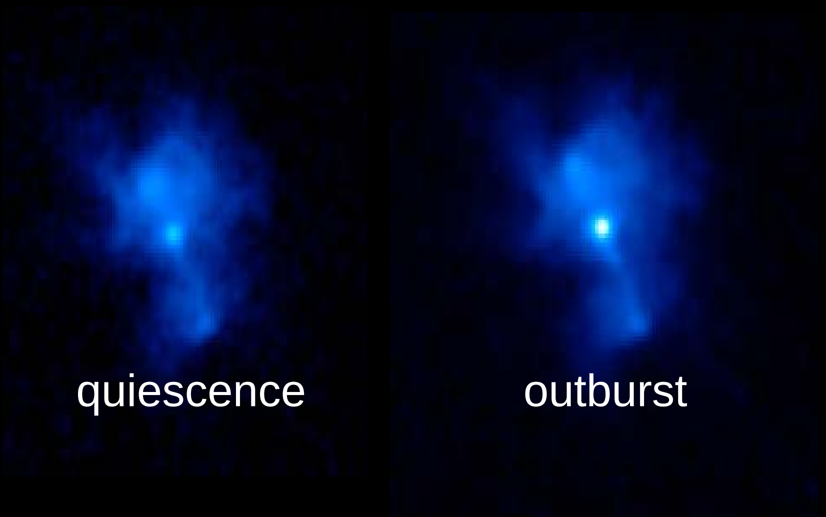
Recycled binaries: rotation-powered



Magnetar-like outbursts from rotational powered pulsars

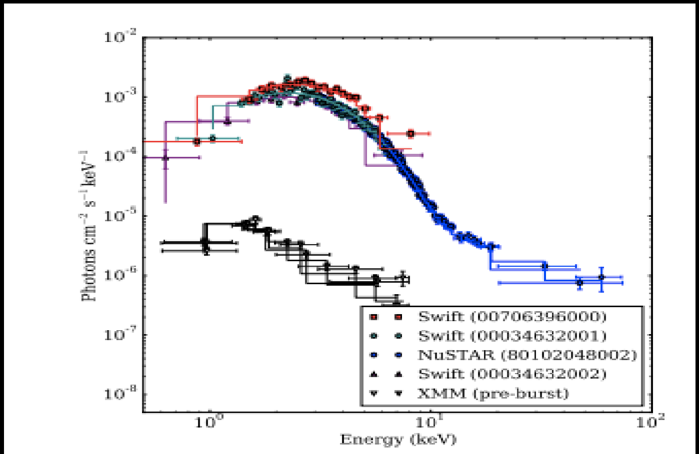
PSR 1846-0258

- rotational power of Edot~8×10^{36} erg/s
- rotating with P ~ 0.3s
- magnetic fields ~5×10^{13} - Gauss
- Kes75 and with a PWN
- X-ray rotational powered pulsar
- Showed SGR-like bursts and outburst in 2008



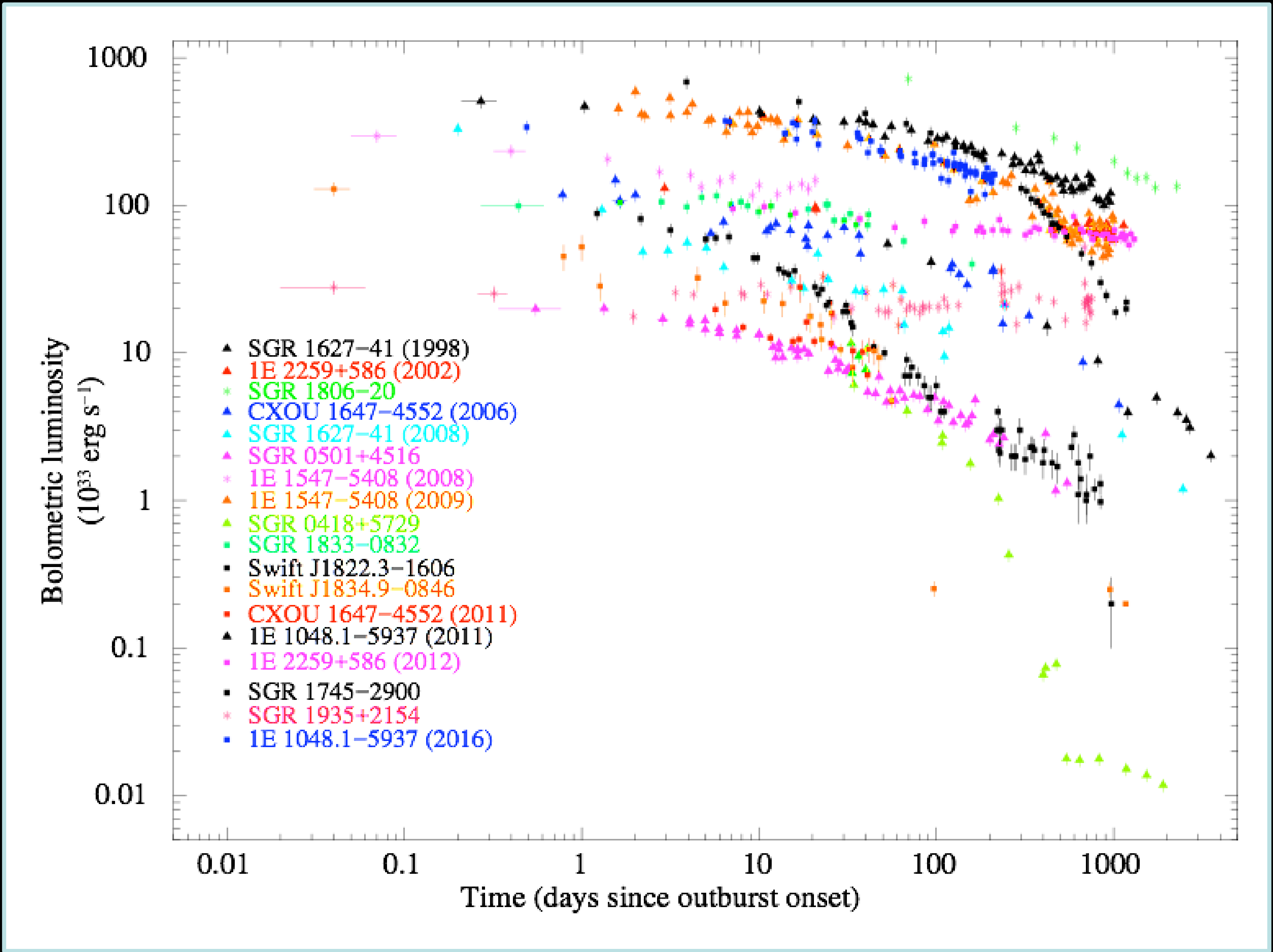
PSR 1119-6127

- rotational power of Edot~2.3×10^{36} erg/s
- rotating with P ~ 0.4s
- magnetic fields ~4×10^{13} - Gauss
- with a PWN
- Radio/X-ray rotational powered pulsar
- Showed SGR-like bursts and outburst in 2016



(Gavriil et al. 2008, Kumar & Safi-Harb 2008, Archibald et al. 2016, Gogus et al. 2016)

Magnetars' outburst events

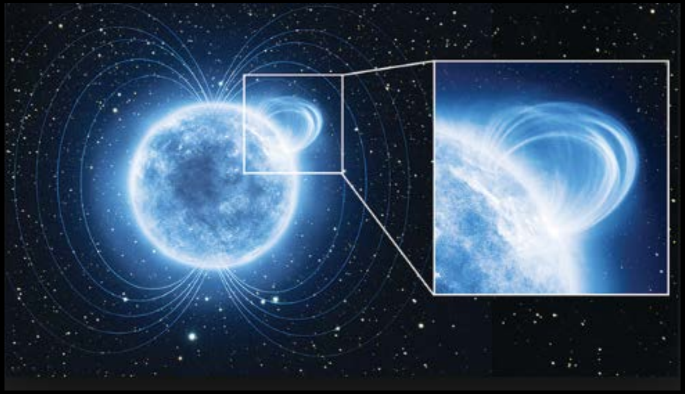


(Coti Zelati, NR, et al. 2017a, in prep)

Magnetars’ outburst mechanisms

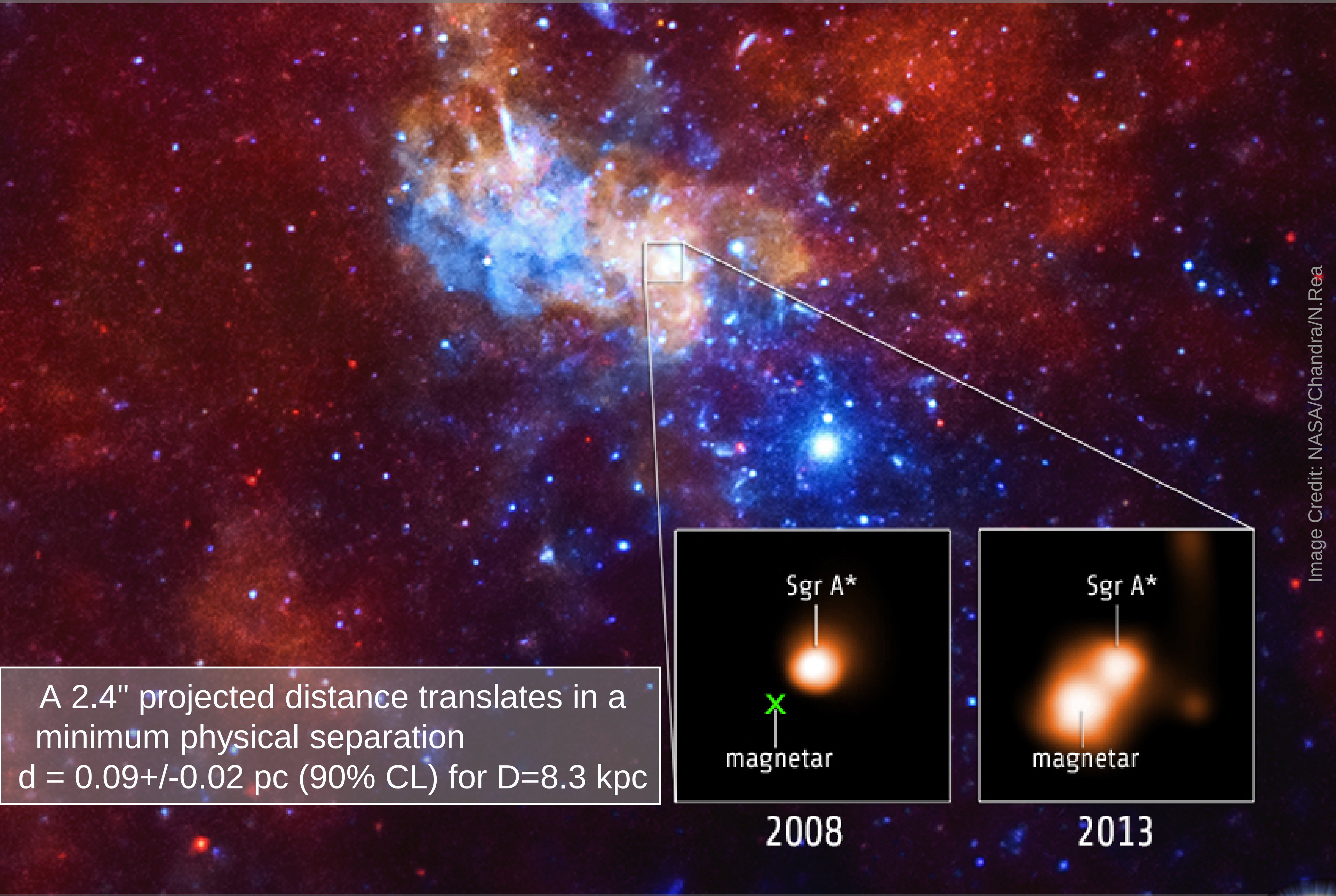
1. **Internal source of heat:** Magnetic fields evolve in the crust and dissipates energy. This changes the stress balance. When the crustal shear breaking strength is exceeded by magnetic stress, the crust breaks, and elastic/magnetic energy is released.

2. **External source of heat:** Magnetic bundles are ubiquitous in magnetars. They can form and dissipate on timescales of months/years. They cause strong particles outflows, and slamming particles heating the magnetar surface.



(Thompson et al. 2002; Beloborodov 2007; Perna & Pons 2011; Pons & Rea 2012; Paffrey, Beloborodov & Hui 2013

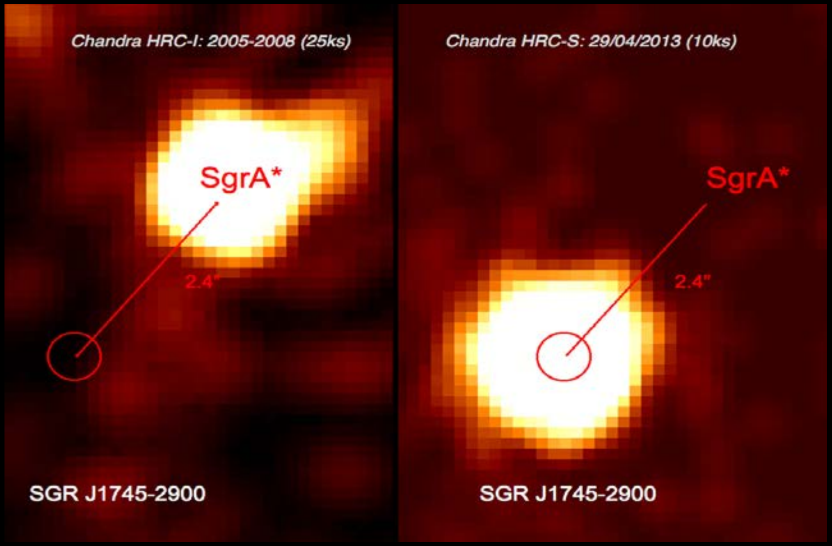
The magnetar in the Galactic Center: SGR 1747-2900



A 2.4" projected distance translates in a minimum physical separation
d = 0.09+/-0.02 pc (90% CL) for D=8.3 kpc

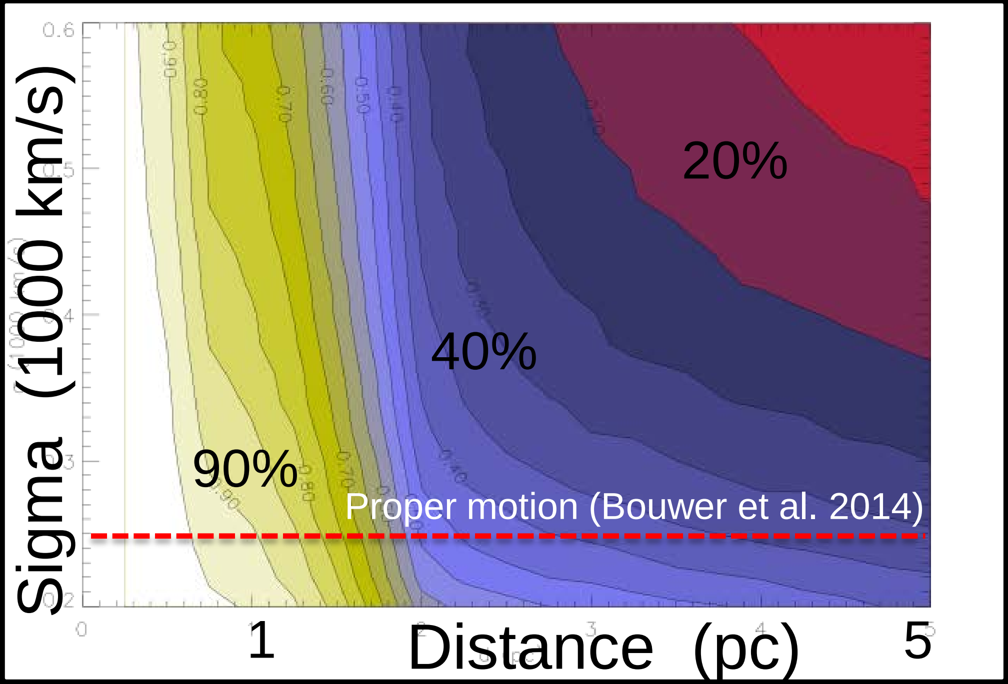
(NR et al. 2013; Kaspi et al. 2014; Coti Zelati et al. 2015, 2017b)

The magnetar in the Galactic Center: SGR 1747-2900

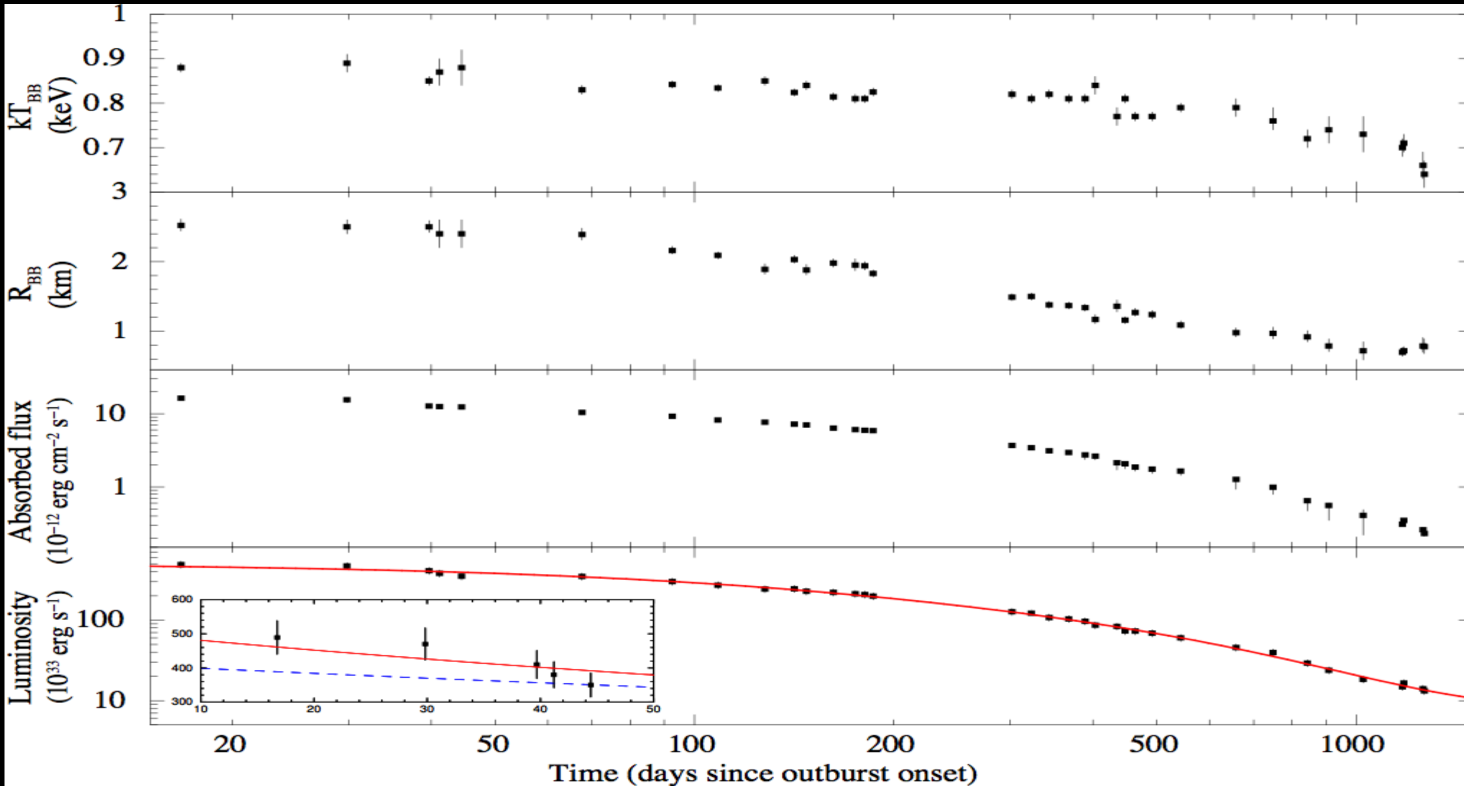


SGR 1745-2900 has, on average, > 90% probability of being bound to the SMBH. Depending on eccentricity and semi-mayor axis, it can have an orbital period from a minimum of 500 yr to several kyrs.

This is the closest neutron star to a supermassive black hole ever detected and expected to be one of the few young neutron star so close to SgrA*.



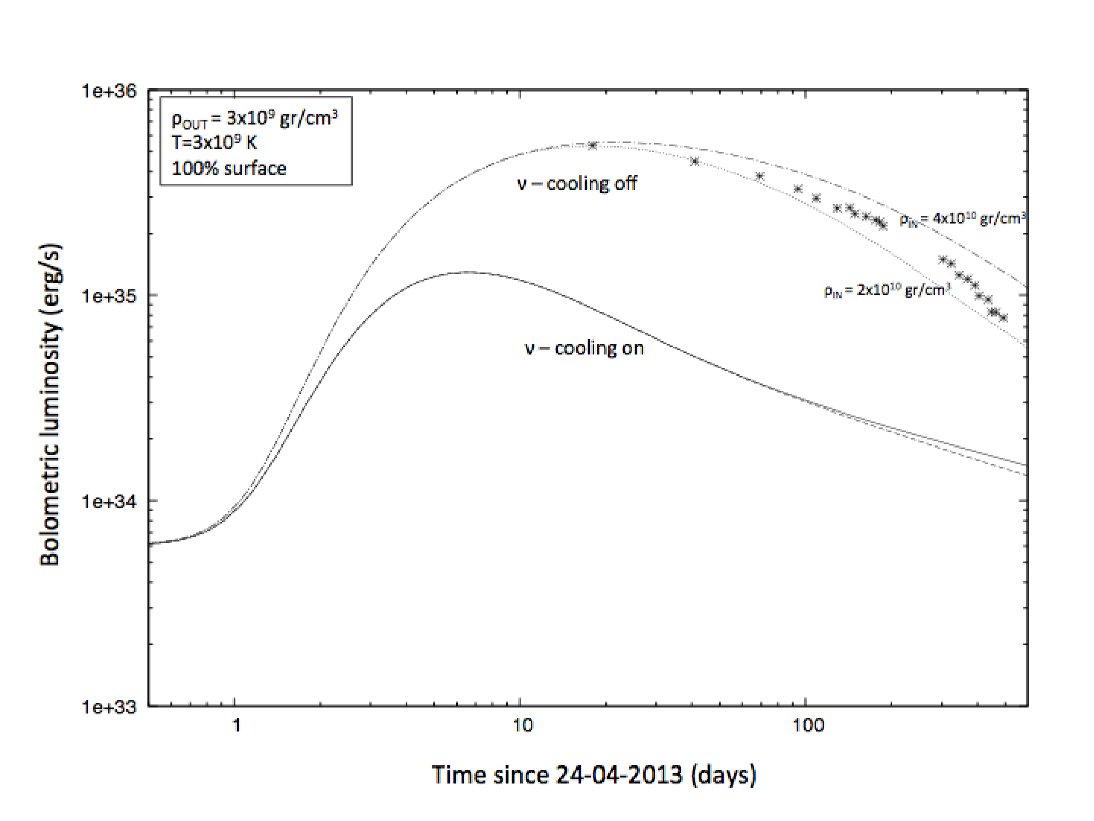
The magnetar in the Galactic Center: SGR 1747-2900



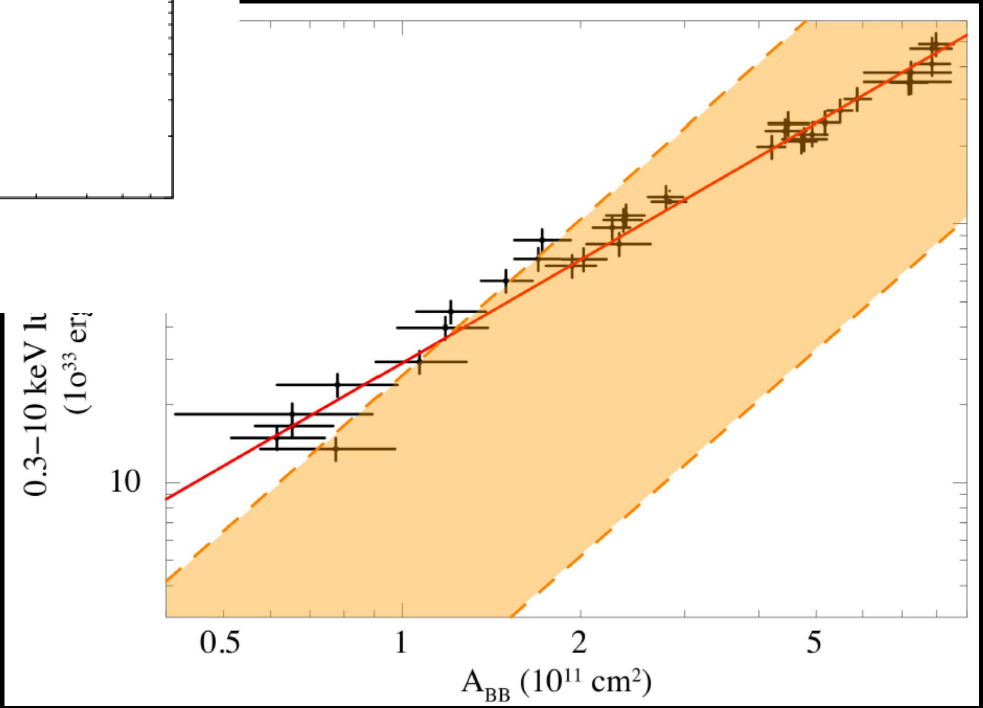
Validity range [MJD]	56 411.6 – 56 475.5	56 500.1 – 56 594.2	56 709.5 – 57 588.5
Epoch T_0 [MJD]	56 424.5509871	56 513.0	56 710.0
$P(T_0)$ [s]	3.7635537(2)	3.76363799(7)	3.763982(3)
$\dot{P}(T_0)$ [s s^{-1}]	$6.61(4) \times 10^{-12}$	$1.360(6) \times 10^{-11}$	$2.96(4) \times 10^{-11}$
$\ddot{P}$ [s s^{-2}]	$4(3) \times 10^{-19}$	$3.7(2) \times 10^{-19}$	$0.67(20) \times 10^{-19}$
$\nu(T_0)$ (Hz)	0.265706368(14)	0.26570037(5)	0.2656761(2)
$\dot{\nu}(T_0)$ [Hz s^{-1}]	$-4.67(3) \times 10^{-13}$	$-9.60(4) \times 10^{-13}$	$-2.09(3) \times 10^{-12}$
$\ddot{\nu}$ [Hz s^{-2}]	$-3(2) \times 10^{-20}$	$-2.6(1) \times 10^{-20}$	$-0.47(11) \times 10^{-20}$
rms residual	0.15 s	0.396 s	2.1 μHz
χ^2_ν (dof.)	0.85 (5)	6.14 (44)	3.16 (18)

Pdot increase by a factor of ~4

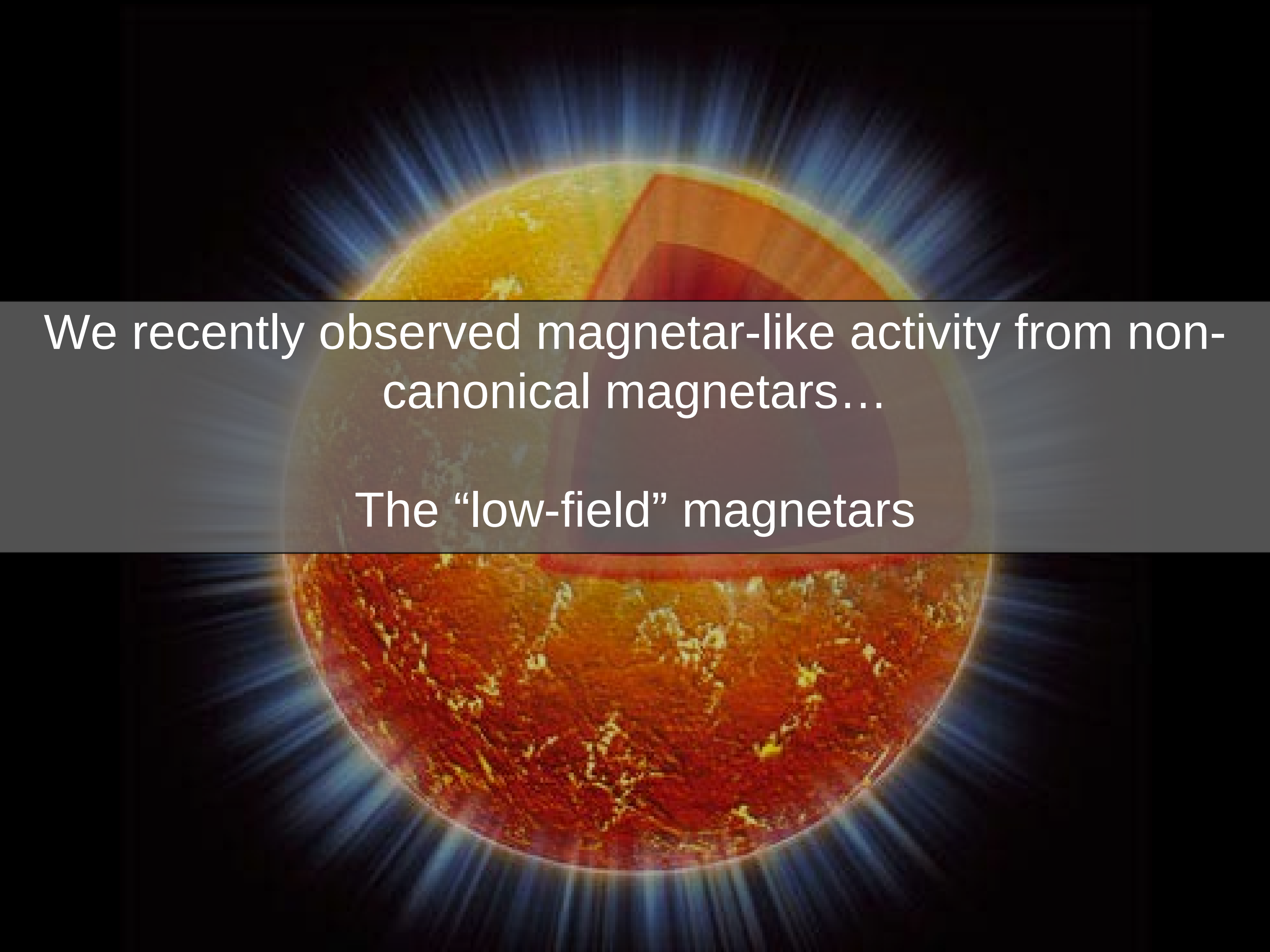
(Coti Zelati, NR, et al. 2017b, in prep)



Cannot be only crustal cooling from a single injection.



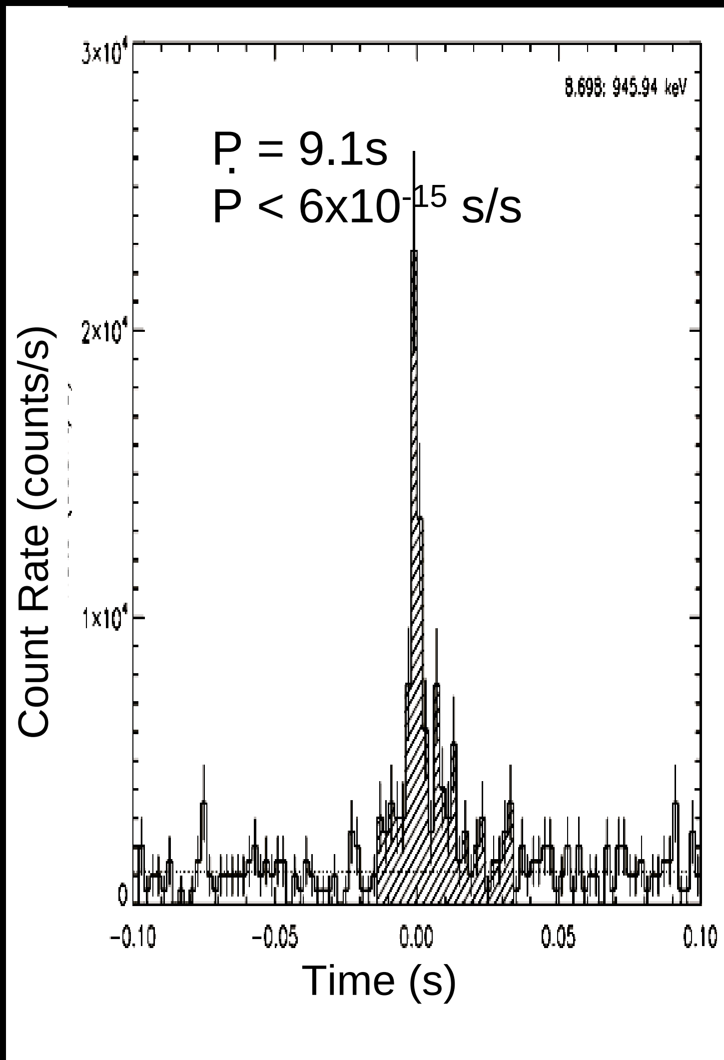
Qualitative agreement with bundle untwisting.



We recently observed magnetar-like activity from non-canonical magnetars…

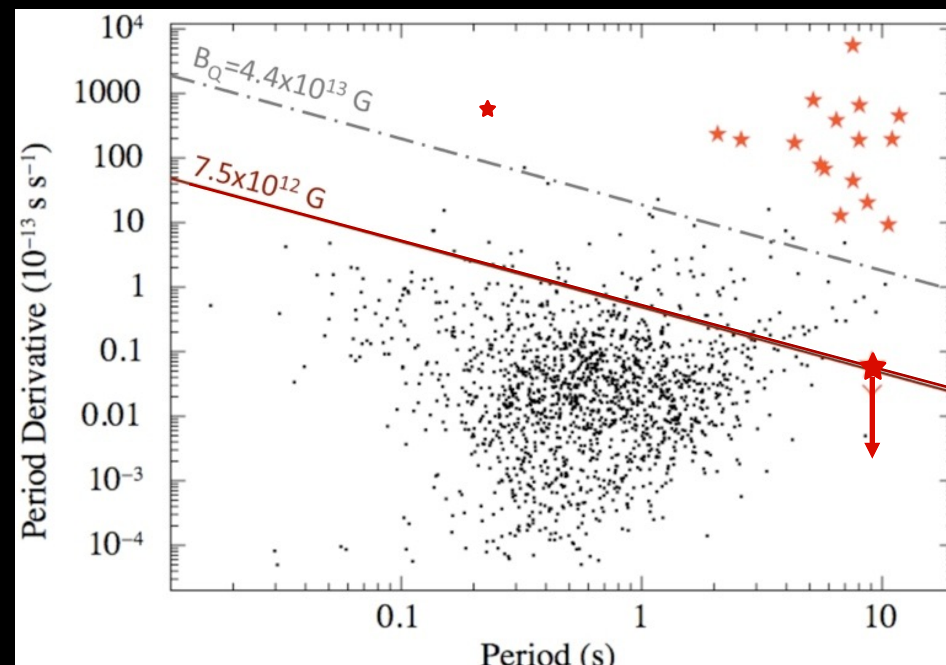
The “low-field” magnetars

Discovery of the first the low field magnetar



A low-magnetic-field Soft Gamma Repeater

N. Rea[1,2*], P. Esposito[3], R. Turolla[4,5], G. L. Israel[6], S. Zane[5], L. Stella [6], C. Kouveliotou[7], S. Mereghetti[8], A. Tiengo[8], D. Götz[9], E. Göğüş[10]



Magnetic field was:
$B < 7.5\times10^{12}$ G

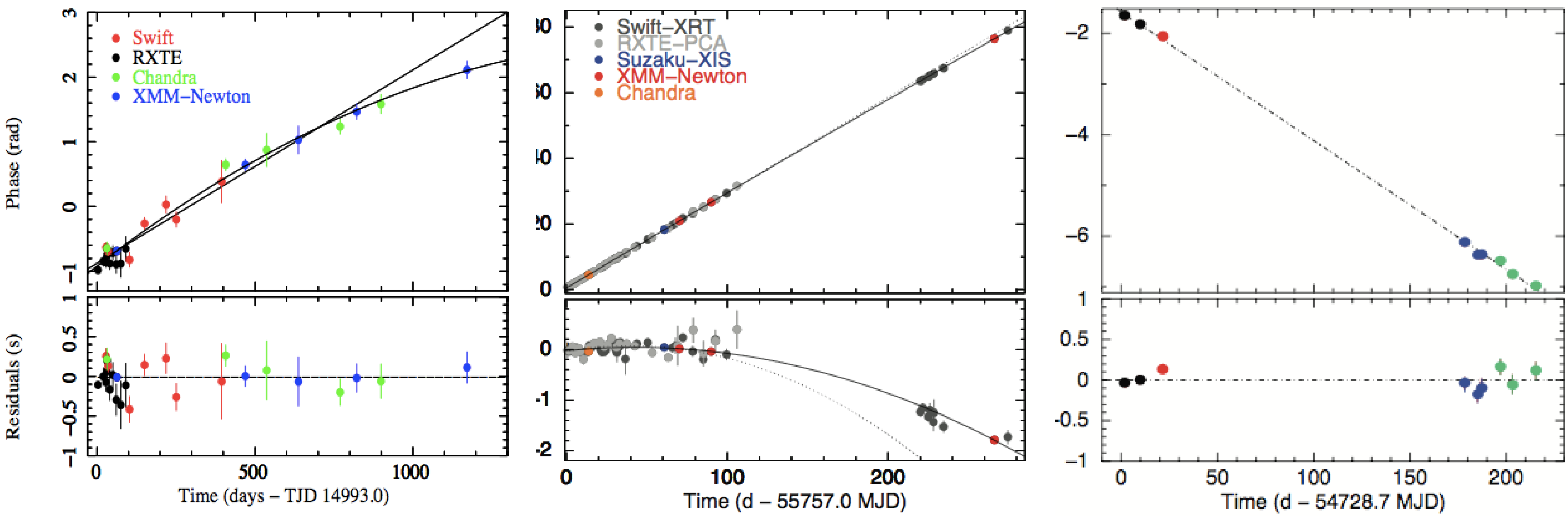
(van der Horst et al. 2010, ApJ; Esposito et al. 2010, MNRAS; NR et. al. 2010, Science)

The low field magnetars: we have three now

$B = 6.2\mathrm{x}10^{12}$ G

$B = 2.3\mathrm{x}10^{13}$ G

$B < 4\mathrm{x}10^{13}$ G



SGR 0418+5729

Esposito et al. 2010, MNRAS
NR et al. 2010, Science
NR et al. 2013, ApJ

Swift 1822-1606

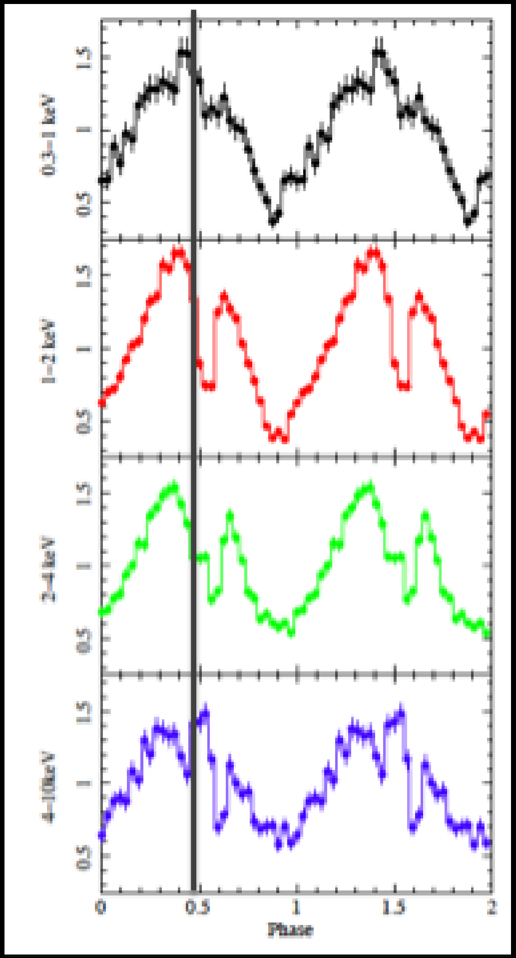
NR et al. 2012, ApJ
Scholtz et al. 2012, ApJ

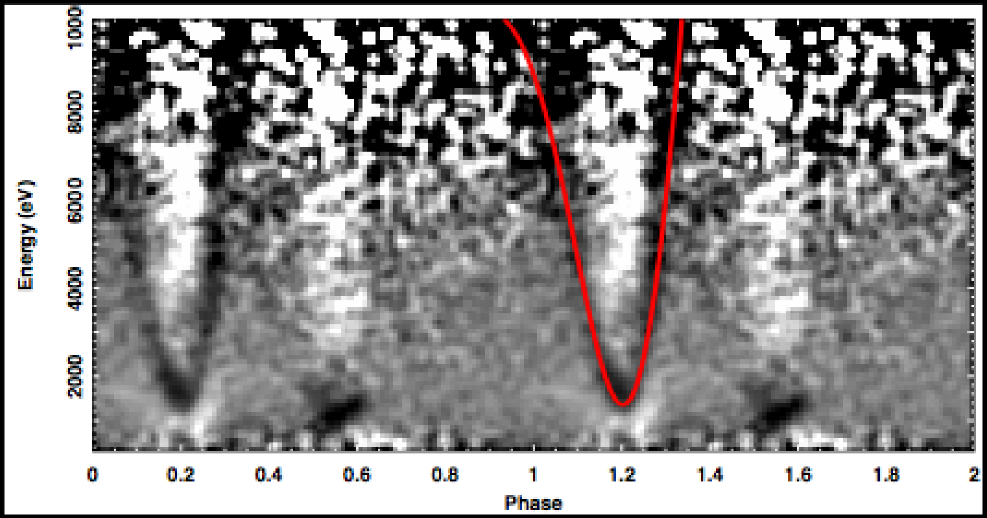
3XMM 1852+0033

NR et al. 2014, ApJL
Zou et al. 2014, ApJL

The low field magnetar: spectral feature

During the outburst peak it showed a phase variable absorption feature





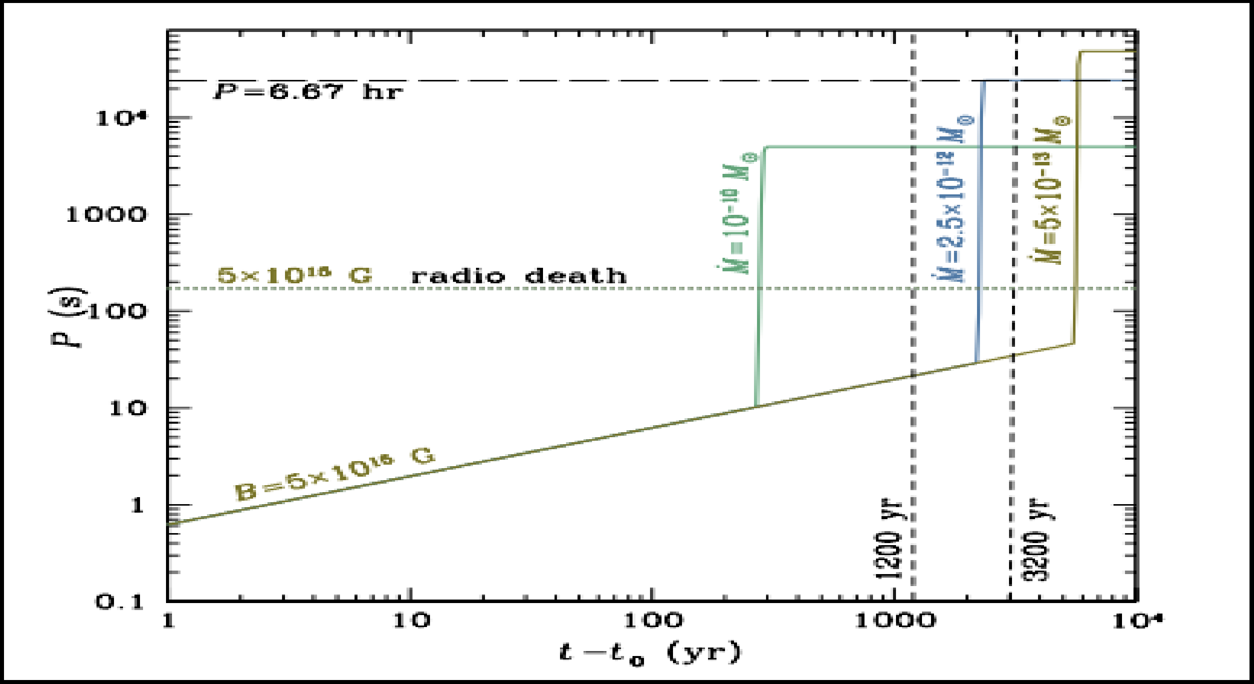
Different geometries can be envisaged, but our toy-model shows that the hypothesis of proton cyclotron resonant scattering in a magnetar loop is a viable scenario.

$E_{cycl,p}$= 0.6 B_{14} keV

⇒ B ~ (2-20) x 10^{14} G

A new magnetar discovered being the slowest isolated pulsar!

Fall back accretion after the supernova could make this pulsar slow down so extremely…

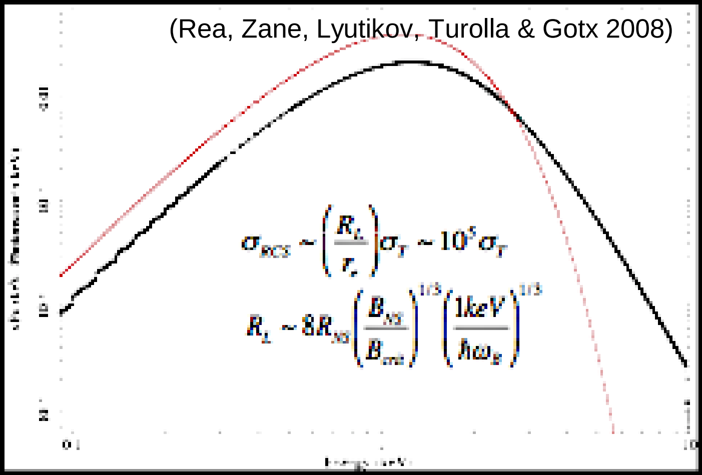


(De Luca et al. 2006; Li 2007, NR et al. 2016, Ho & Andersson 2016, Tong et al. 2016)

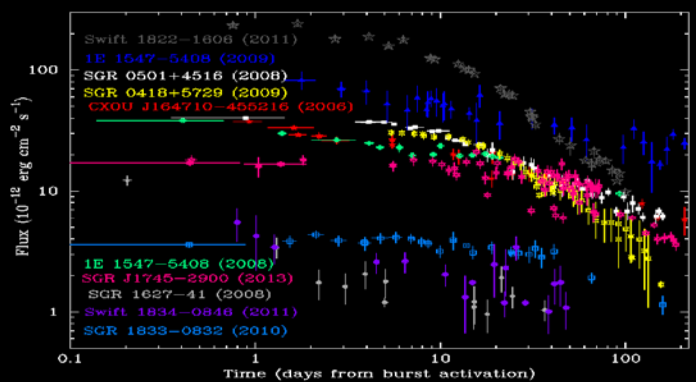
Magnetar-like field structures in X-ray Dim Isolated Neutron Stars

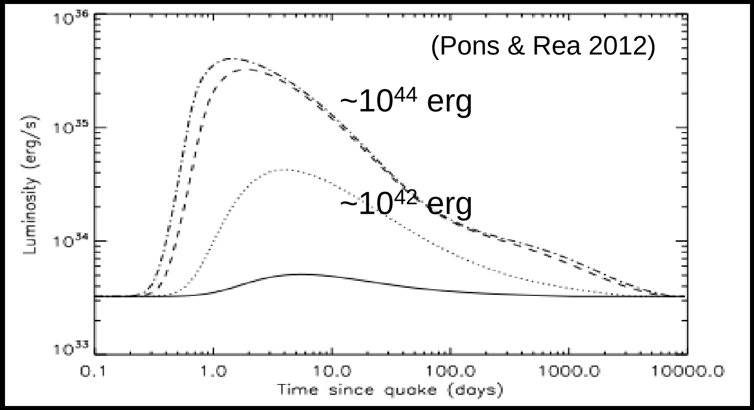
Where do we see the twisted magnetospheres?

1. In their X-ray spectral shape....

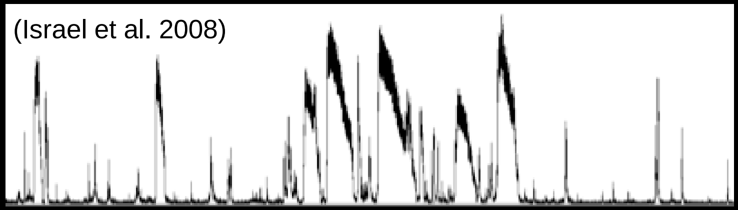


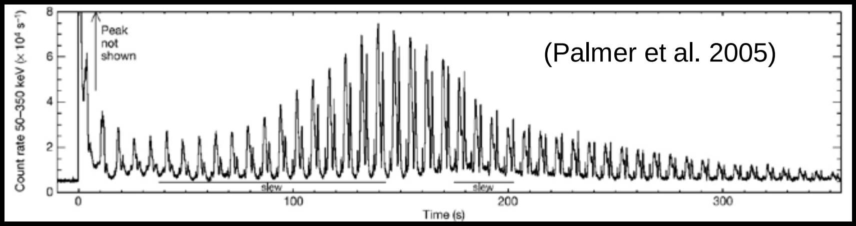
2. In their transient outbursts....



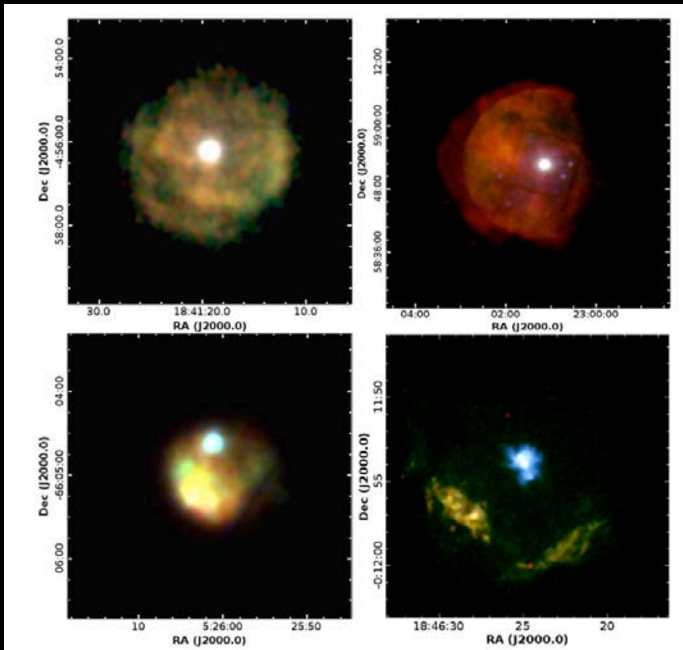


3. In their X-ray/gamma-ray flares...



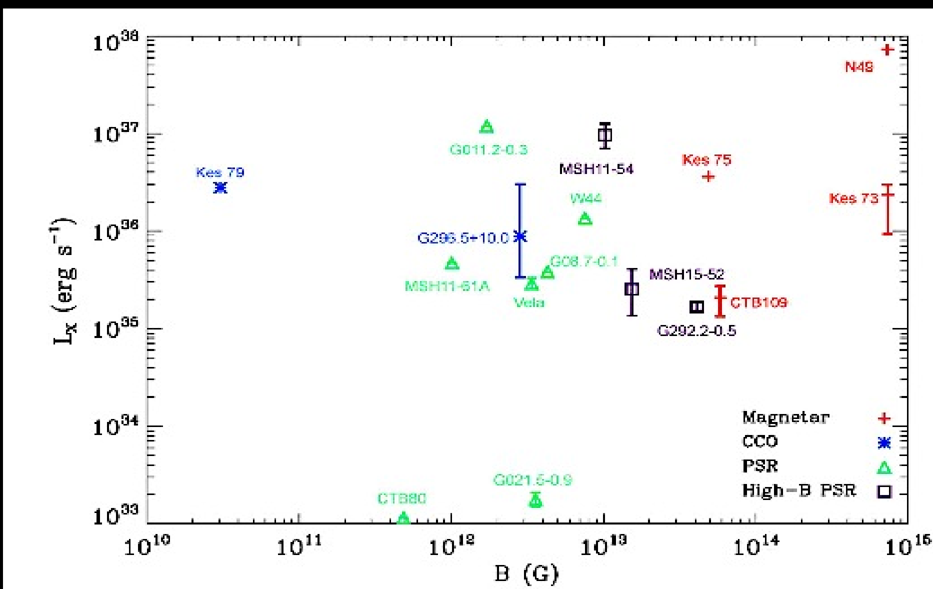


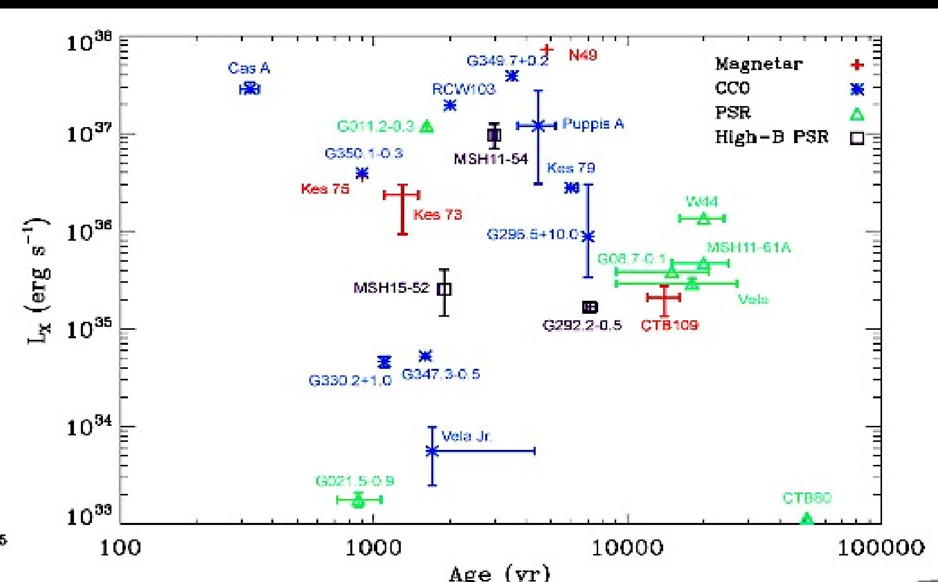
No apparent difference between pulsars and magnetars SNRs



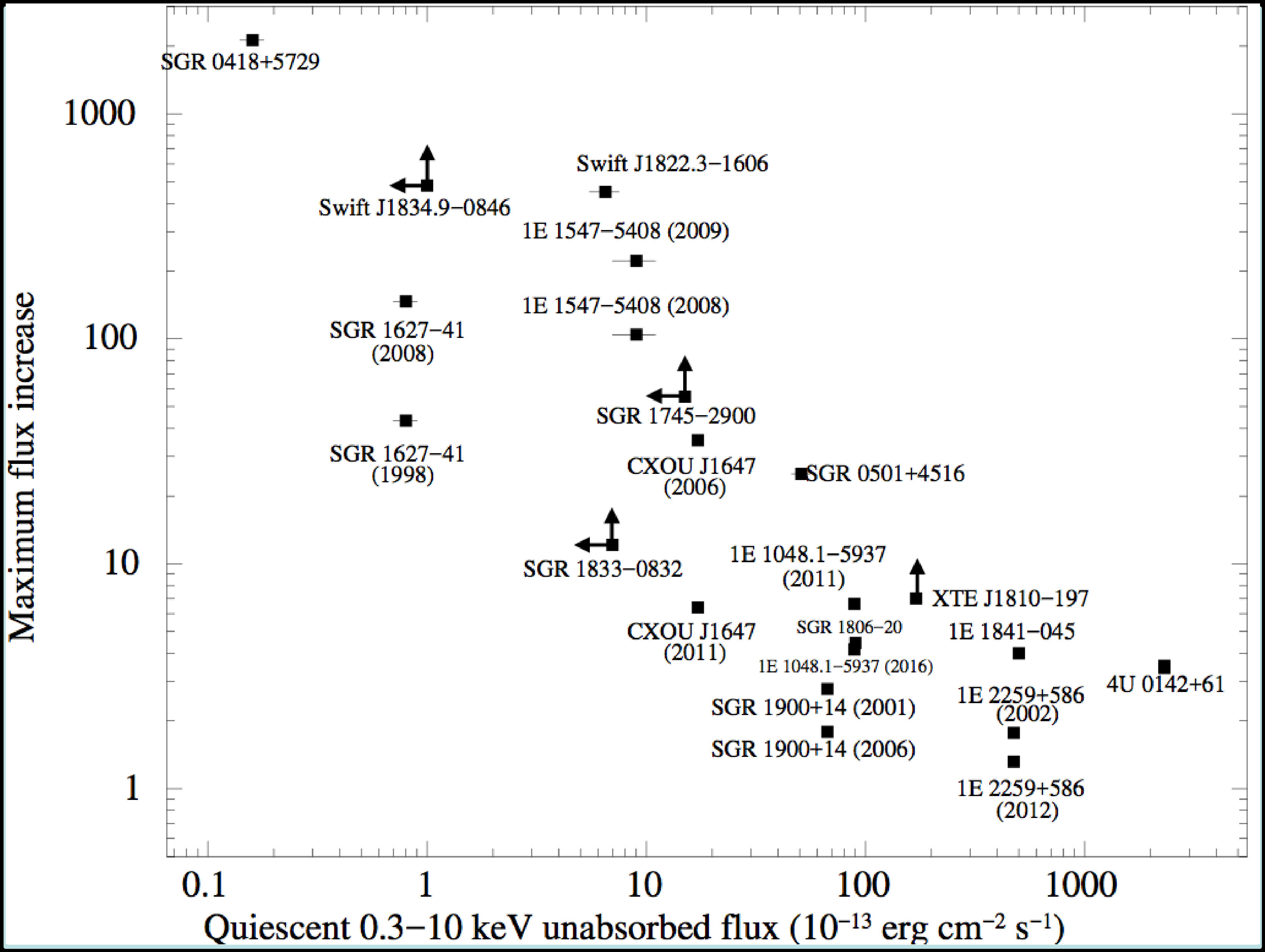
Kes73 –> 1E 1841-045
CTB109 –> 1E 2259+586
N49 –> SGR 0526-66 (LMC)
Kes75 –> PSR 1846-0258

(Vink & Kuiper 2006; Martin, NR, Torres & Papitto 2014, MNRAS)



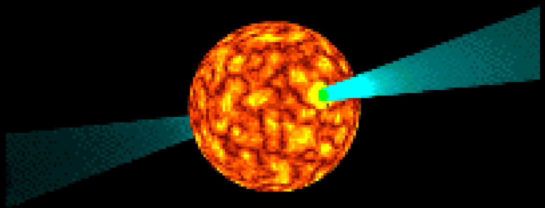


Magnetars' outburst events

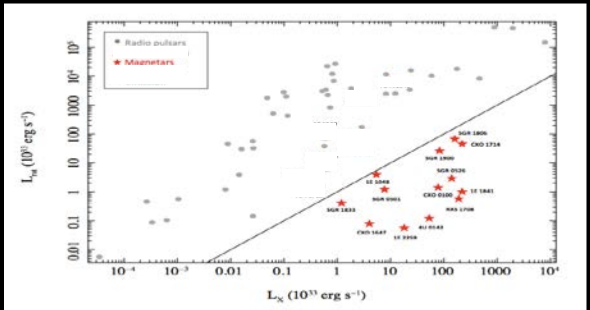


(Coti Zelati, NR, et al. 2017a, in prep)

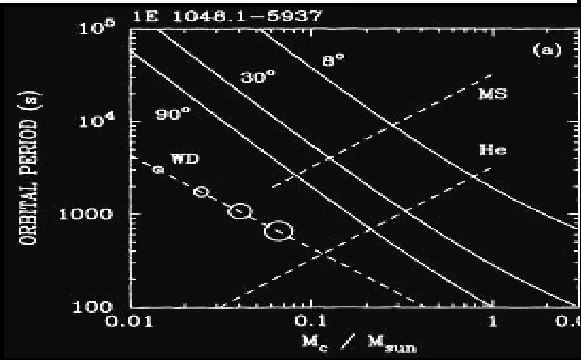
Why they can't be rotational or accretion powered?



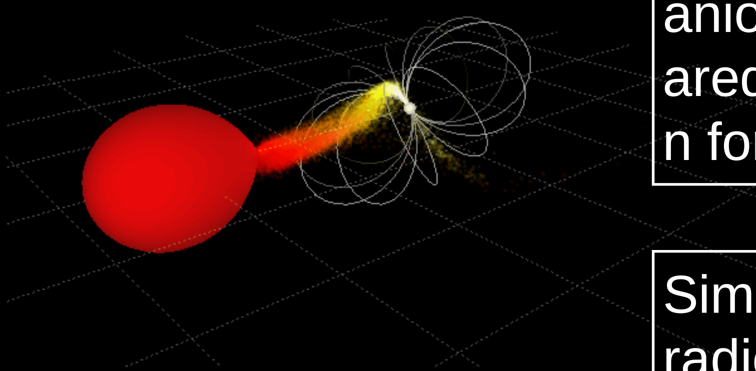
X-ray luminosity in general is exceeding their rotational energy.

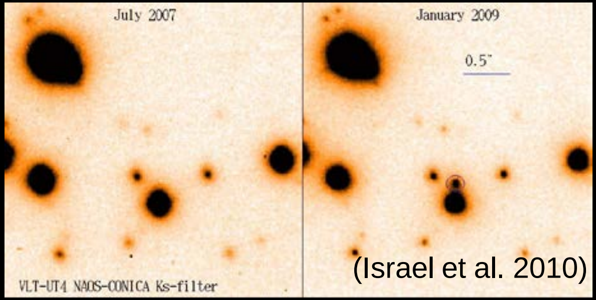


No sign for a binary companion in the timing residuals excluding masses larger than Jupiter.



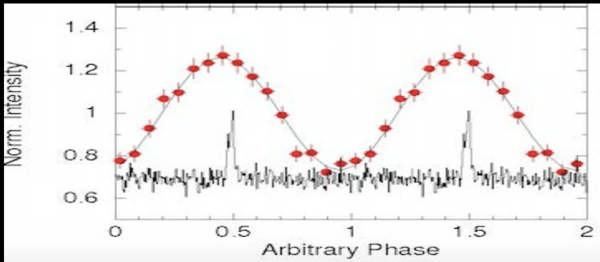
No sign for a binary companion in the opitcal or infrared bands. Too faint even for K or M stars!



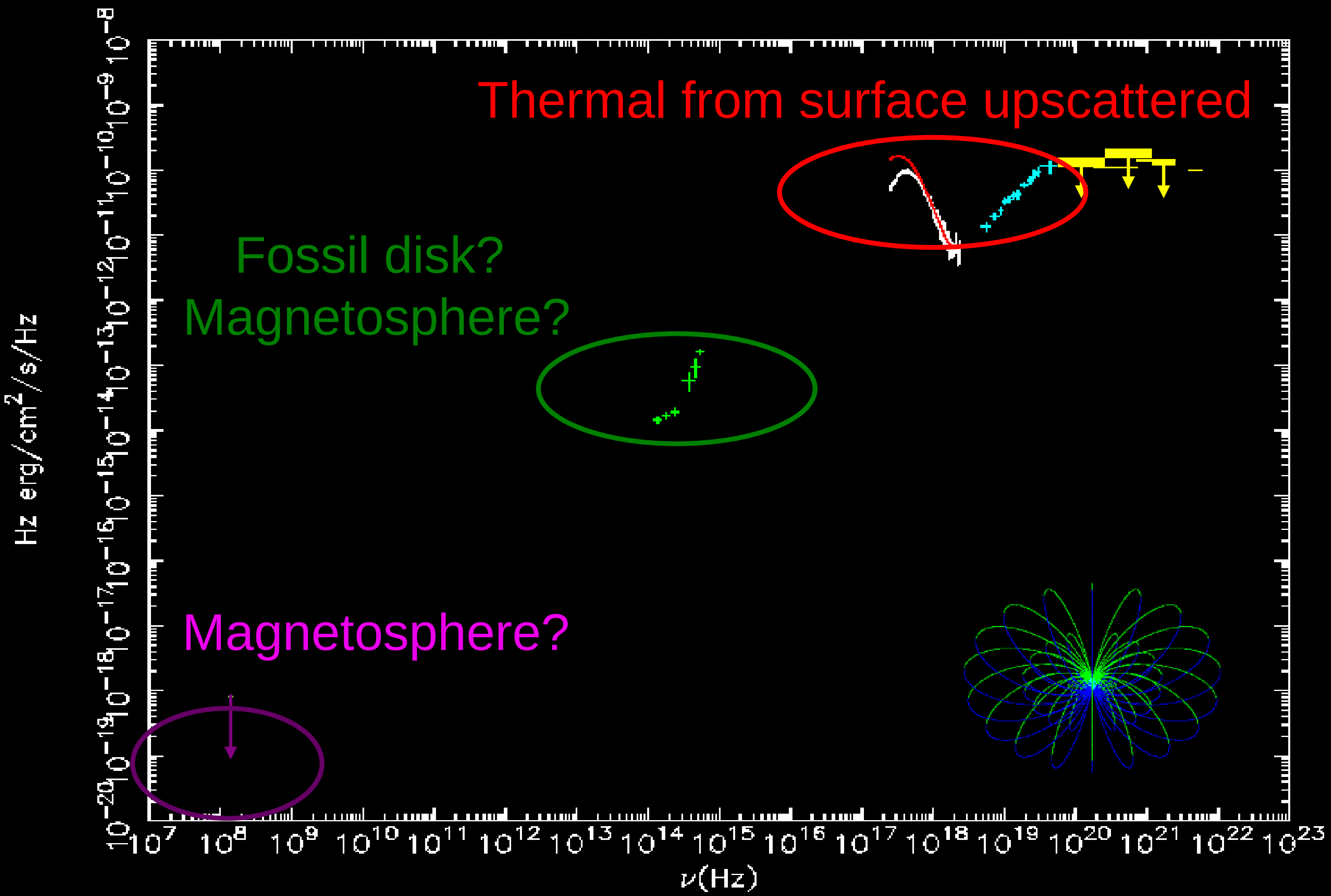


(Israel et al. 2010)

Simultaneous X-ray and radio pulsatations during outbursts: no accretion.



Magnetar typical SED when in quiescence…

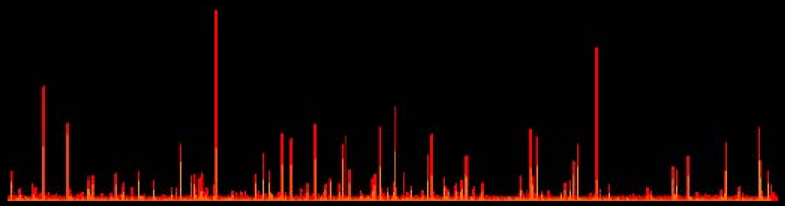


(NR et al. 2007a, ApJ Letter)

How do we discover new magnetars?

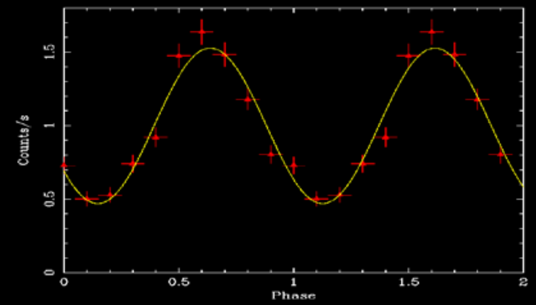
No physical distinction between Anomalous X-ray Pulsars, Soft Gamma Repeaters, and Transient Magnetars: all showing all kind of magnetar-like activity.

Short X/gamma-ray bursts (at the beginning thought to be GRBs)



Soft Gamma Repeaters

Bright X-ray pulsars with 0.5-10keV spectra modelled by a thermal plus a non-thermal component



Anomalous X-ray Pulsars

Bright X-ray transients!

Transients magnetars

(Mereghetti 2008, NR & Esposito 2011 for a review)

….Magnetars… are starting to show up everywhere…

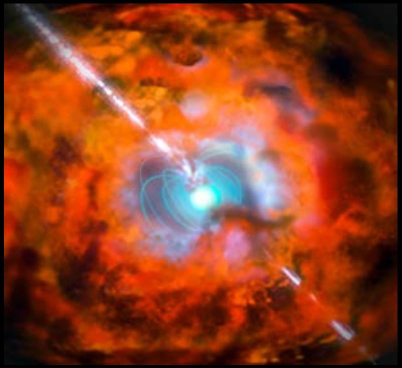
Coalescence of compact binaries

Pulsar population

FRBs

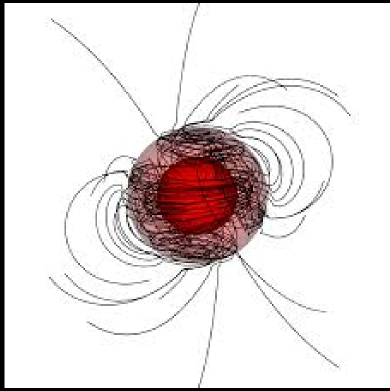
?

Super Luminous supernovae

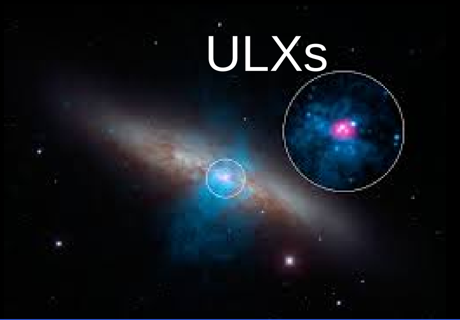


Gamma Ray Bursts

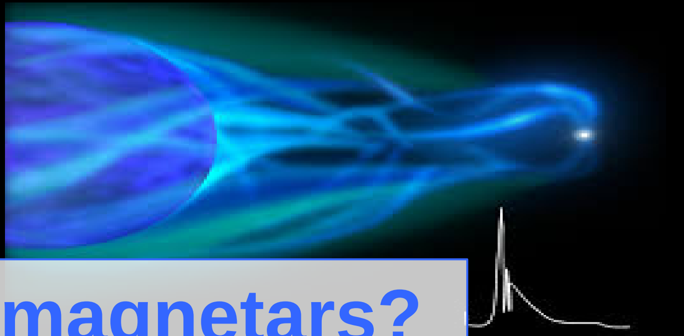
Gravitational waves



ULXs



Super Giant Fast X-ray Transients



Which is the definition of magnetars?

Magnetic field formation in neutron stars

- Via dynamos/instabilities in the stellar core
- As fossil fields from a magnetic progenitor
- From massive star binary progenitors

(Obergaulinger, Janka & Aloy 2015, MNRAS)

Magnetic field estimates

Rotating magnetic dipole

$$\dot{E}_{rot} = I_{ns}\Omega_s\dot{\Omega}_s = -\frac{4\pi^2 I_{ns}\dot{P}_s}{P_s^3}$$

$$P_{dip-rad} = -\frac{2}{3c^3}\left|\ddot{\mu}_d\right|^2 = -\frac{2(B_d R_{ns}^3 \sin(1+\alpha))^2}{3c^3}\left(\frac{4\pi^2}{P_s^2}\right)^2$$

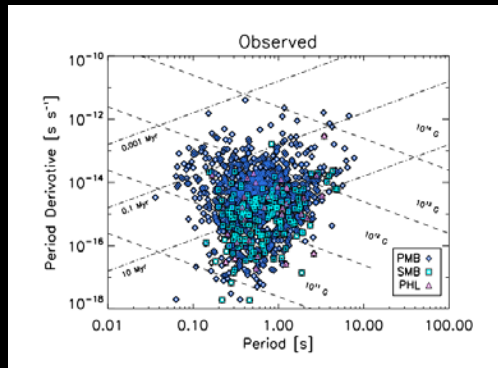
$$B = 3.2 \cdot 10^{19}\sqrt{P\dot{P}} \text{ Gauss.}$$

at the equator

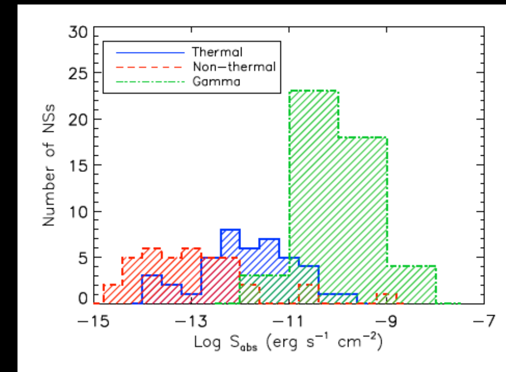
$$\tau = \frac{P}{2\dot{P}}$$

for $P_0 << P$

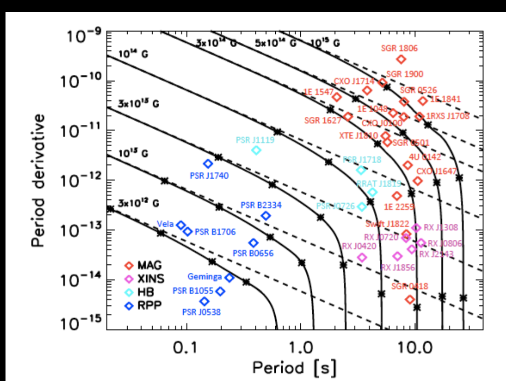
GRB-magnetars vs Galactic magnetars: simulations



Observed Radio Pulsars



Thermal X-ray pulsars (magnetars, XDINs, etc)
Non-thermally emitting X-ray pulsars
Gamma-ray pulsars



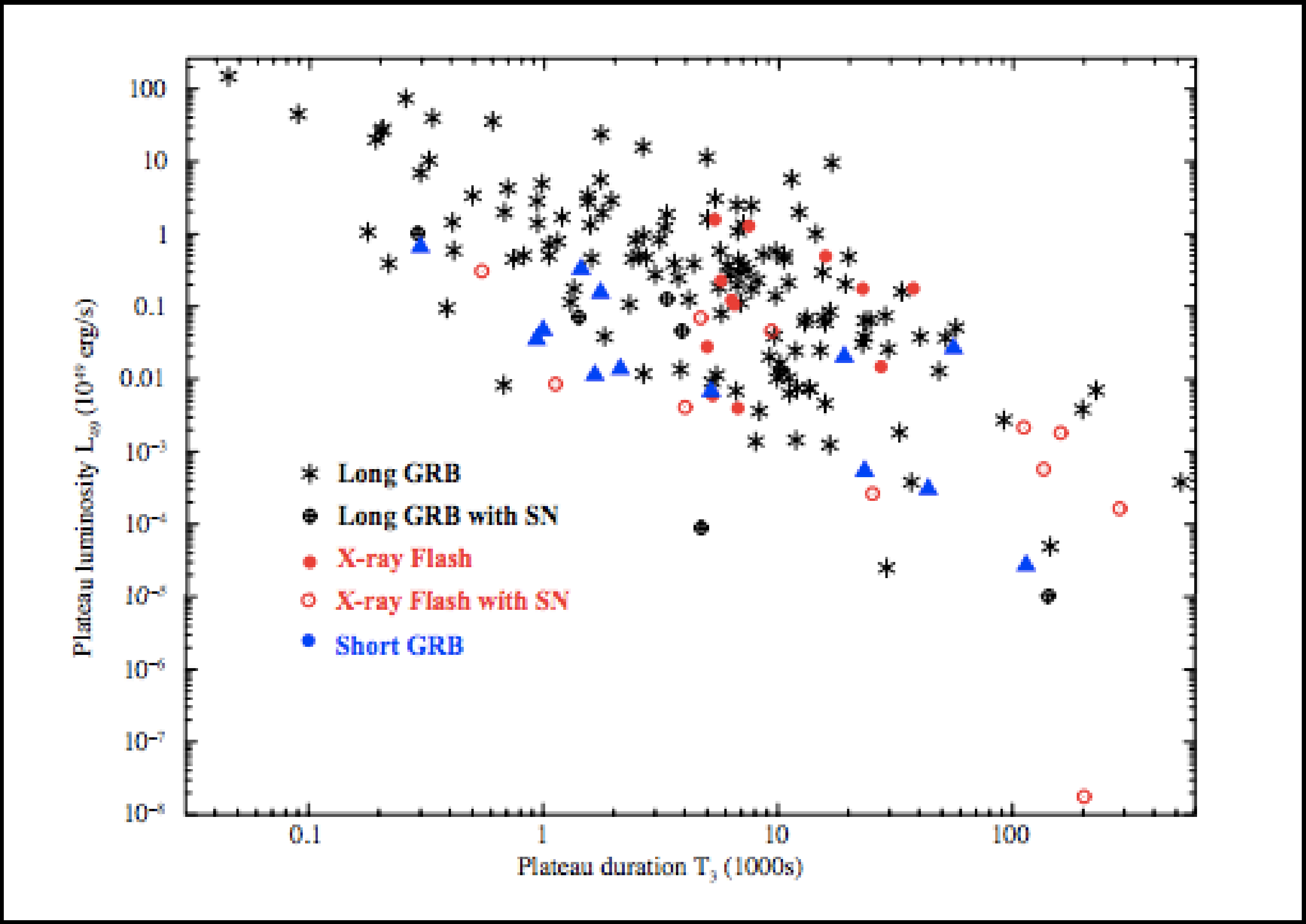
- Age uniformly chosen in → [0, 500 Myr]
- Spatial location related to OB associations of massive stars → Disk (spiral arms) + height.
- Initial velocity (“kick”) due to supernova explosion ($v \sim 500$ km s^{-1})
- P_0 and $\log B_0$ from normal distributions
- Initial inclination angle χ_0 (rotational and magnetic axis) randomly selected.
- Evolution dictated by magneto-rotational models.
- Tested vaccum magnetosphere and with plasma, secular alignment or not.

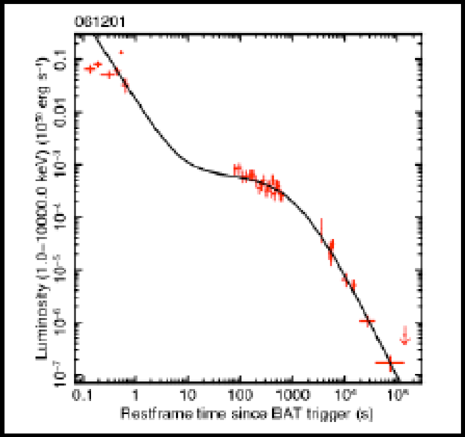
B-field decay models —> Monte-Carlo Simulations —> 2D Kolmogorov-Smirnov test

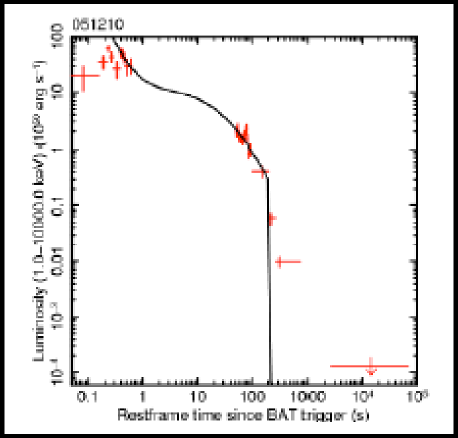
(Fauscher-guitierre & Kaspi 2006; Gonthier et al. 2009; Popov et al. 2010; Pierbattista et al. 2012; Gullon et al. 2014)

Gamma Ray Bursts and magnetars…

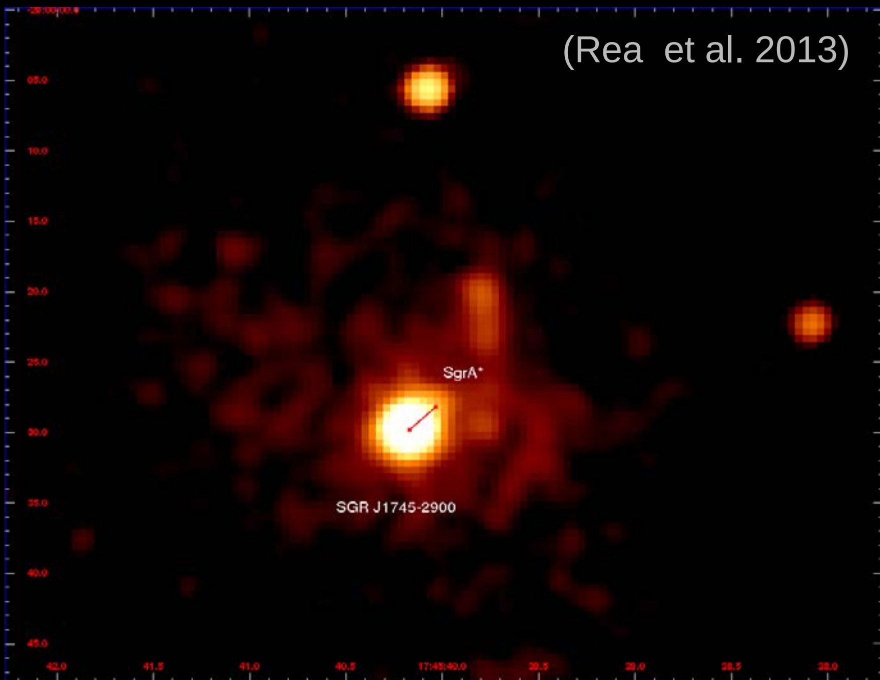
We fitted with a plateau model all Swift GRBs (Long and Short) from launch till August 2014.







The magnetar in the Galactic Center: SGR 1747-2900



$P \sim 3.76$ s

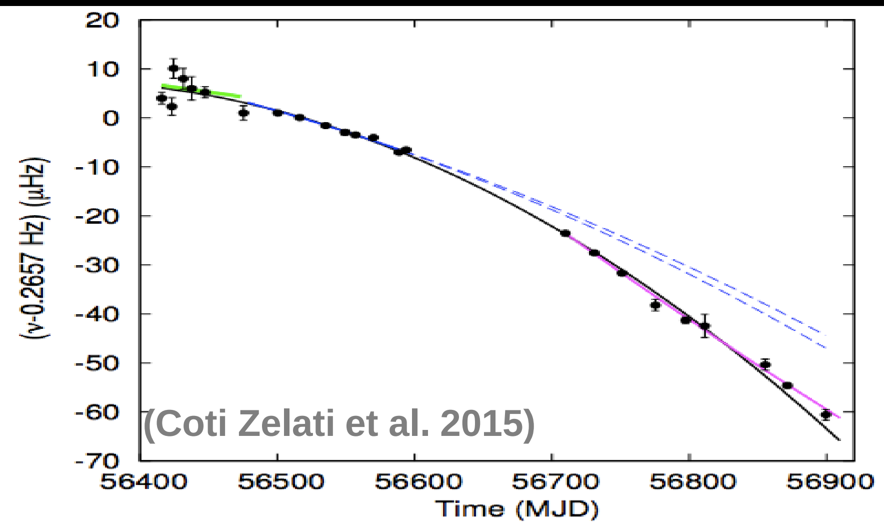
$dP/dt \sim 0.4 - 6.6\times10^{-12}$ s/s

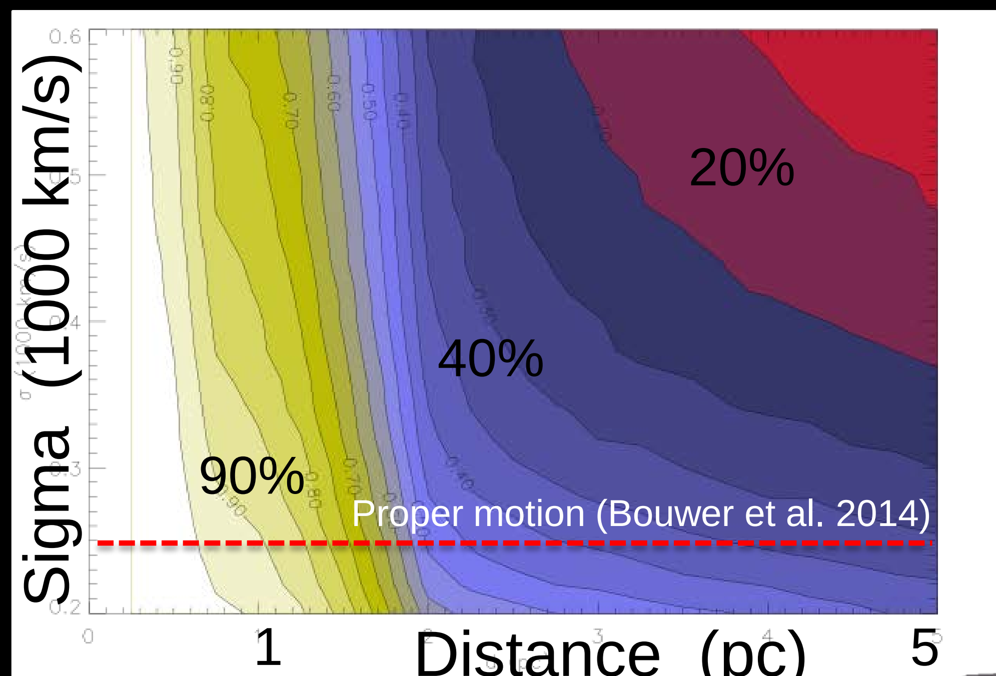
$B_{dip} \sim 2\times10^{14}$ G

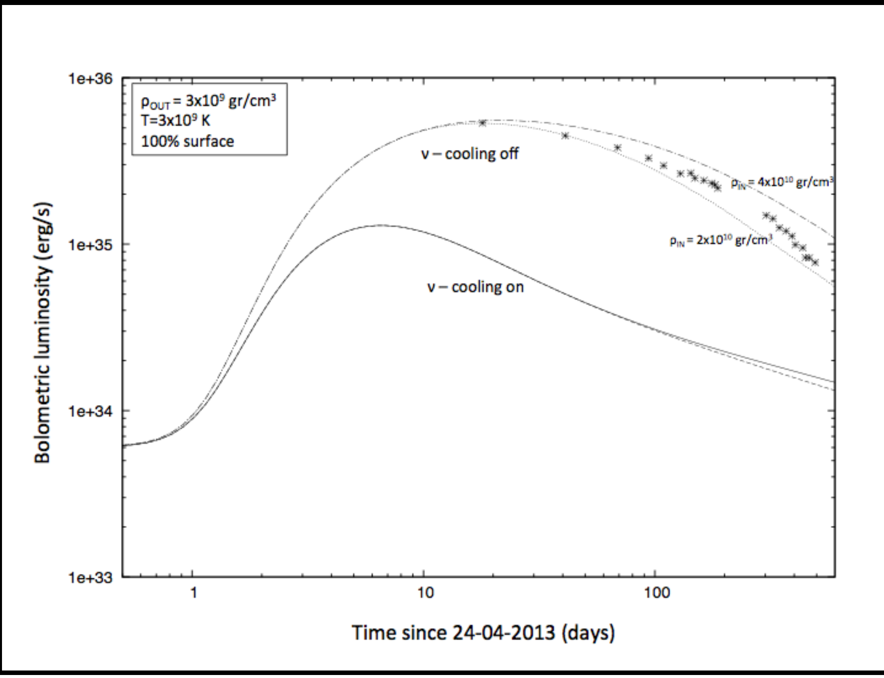
$L_{sd} \sim 5\times10^{33}$ erg/s

$\tau_c \sim 9$ kyr

SGR 1745-2900 has, on average, > 90% probability of being bound to the SMBH.





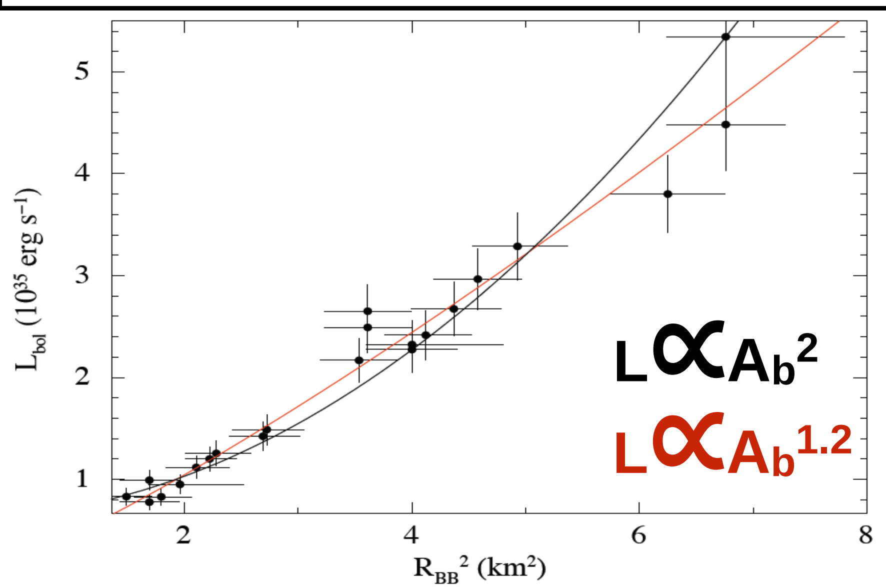


Crustal cooling?

Bad modelling when injecting an energy of 10^{45-46} erg in the inner crust ($\rho_{IN}<\rho<\rho_{OUT}$)

Better modelling if plasmon and synchrotron neutrino emissions are switched off…BUT they should be at work!

Pons & Rea 2012



Bombardment by magnetospheric currents?

Currents in a bundle of twisted field lines keep slamming on to the NS surface and form a hot spot

The bundle untwists, the hot spot cools and shrinks

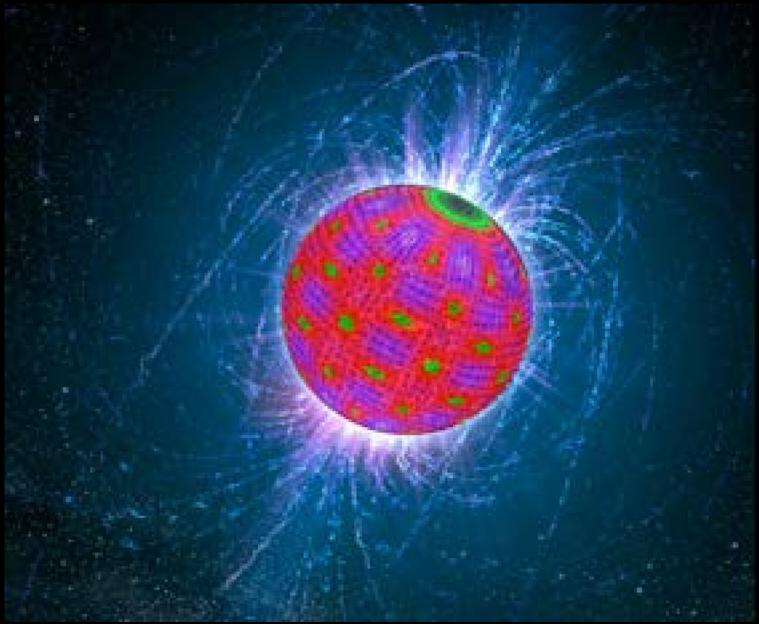
L should decrease as $L \propto A_b^2$

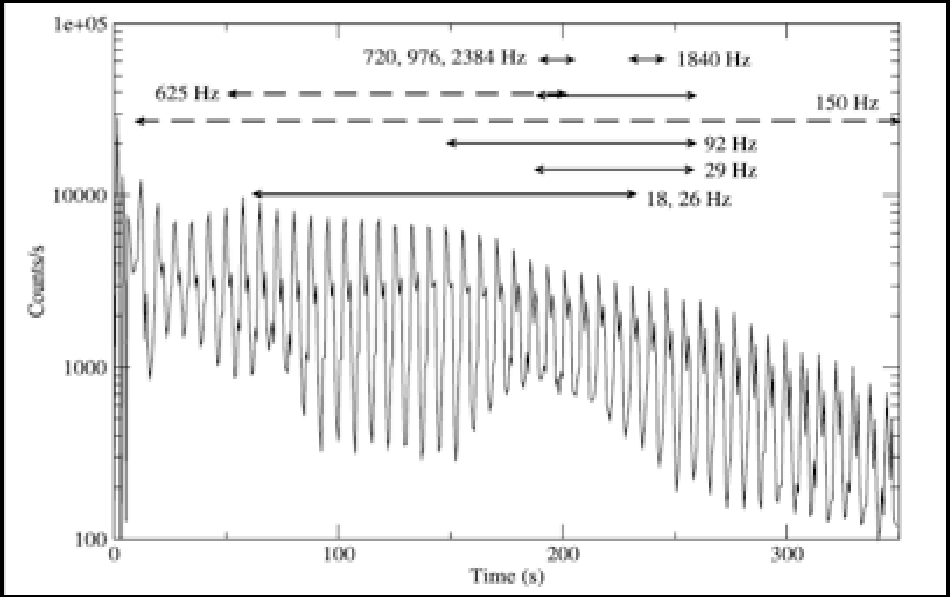
Beloborodov 2009

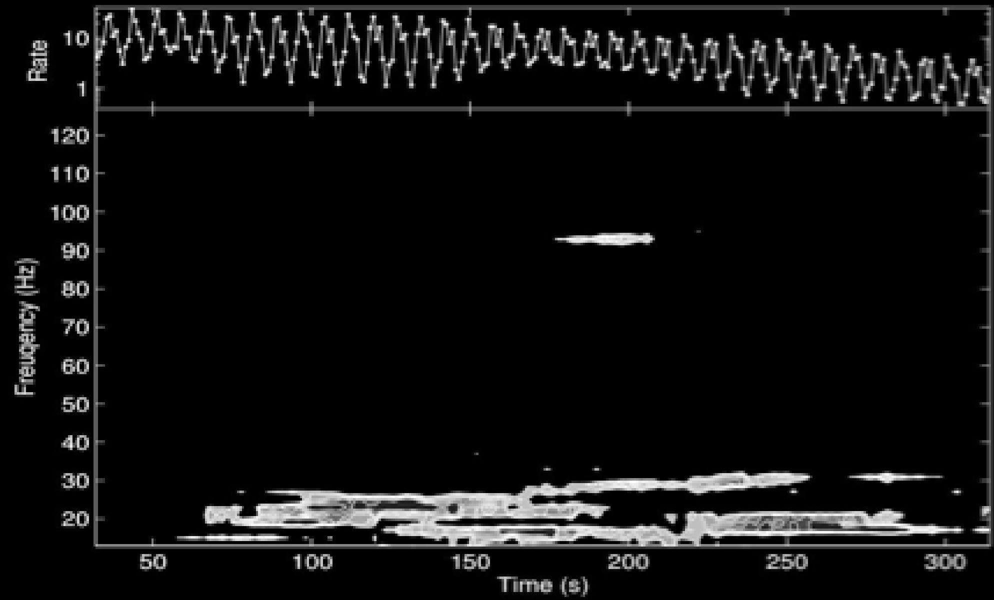
(Coti Zelati et al. 2015)

2. Magnetar flaring activity: quasi-periodic oscillations

•







(Israel et al. 2005; Stromayer & Watts 2006)

Magnetars' outburst events

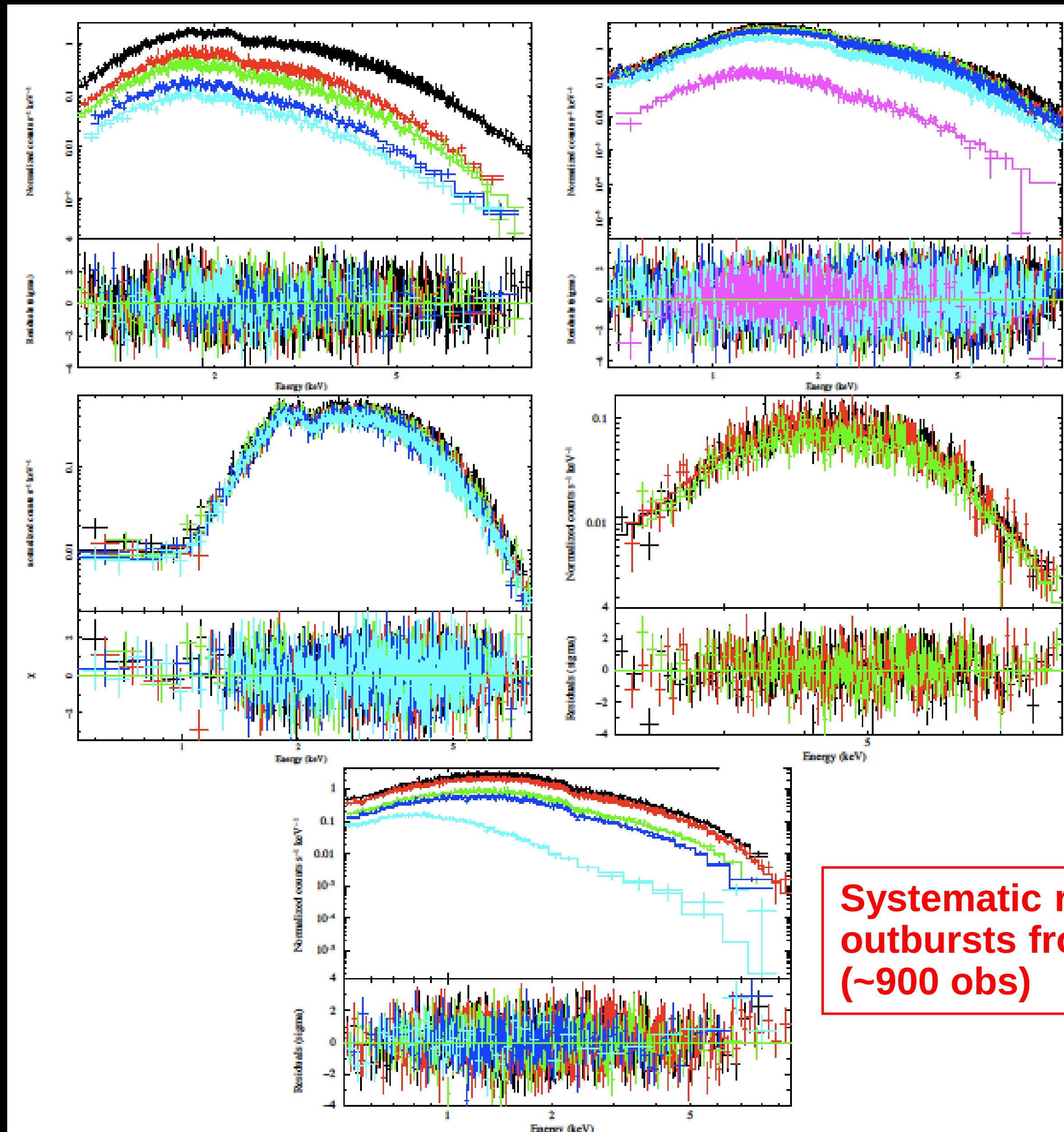
CXOU J1647-4552

SGR 0501+4516

1E 1547-5408

SGR 1833-0832

Swift 1822.3-1606

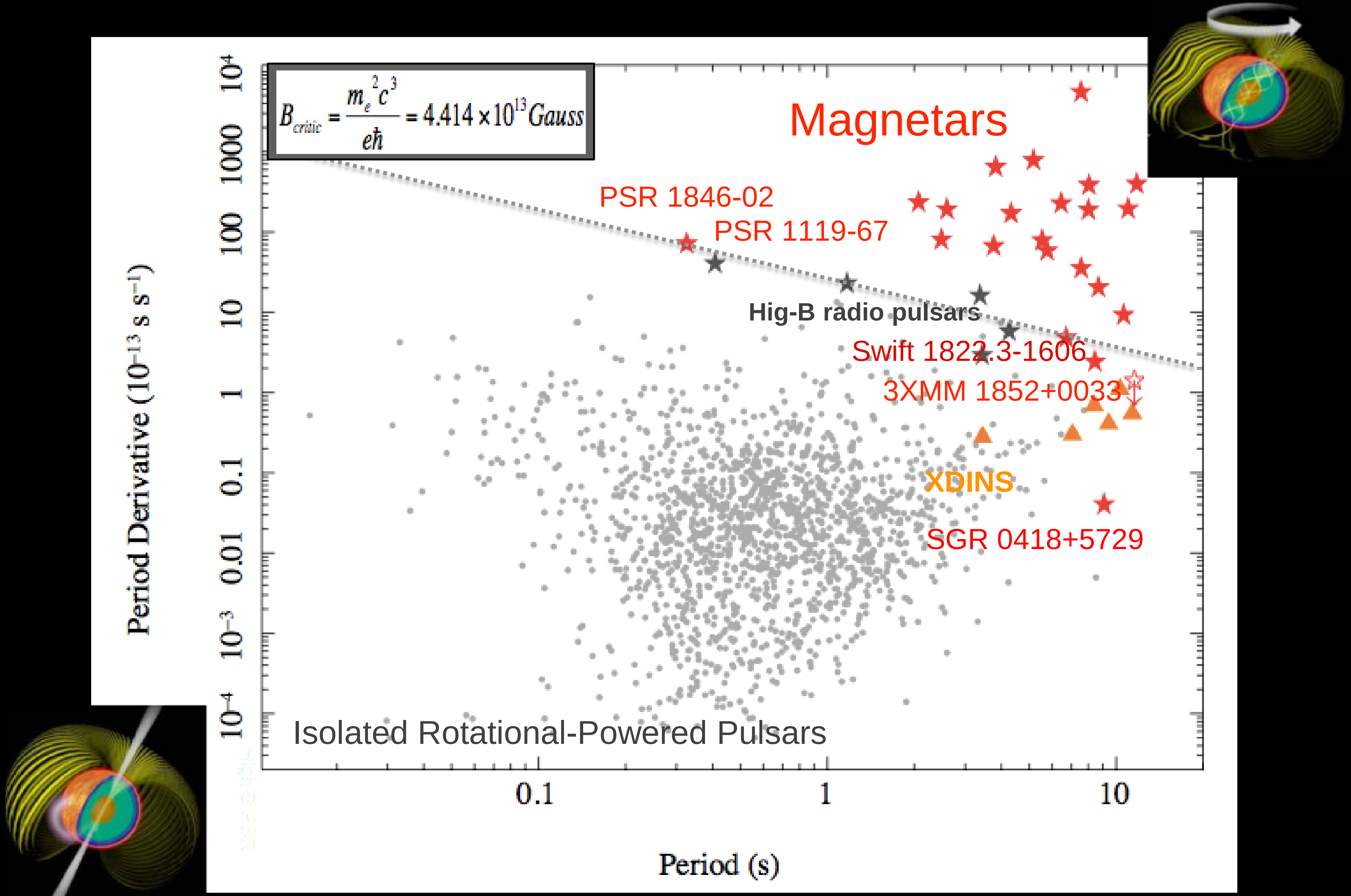


Systematic reanalysis of 19 outbursts from 14 magnetars (~900 obs)

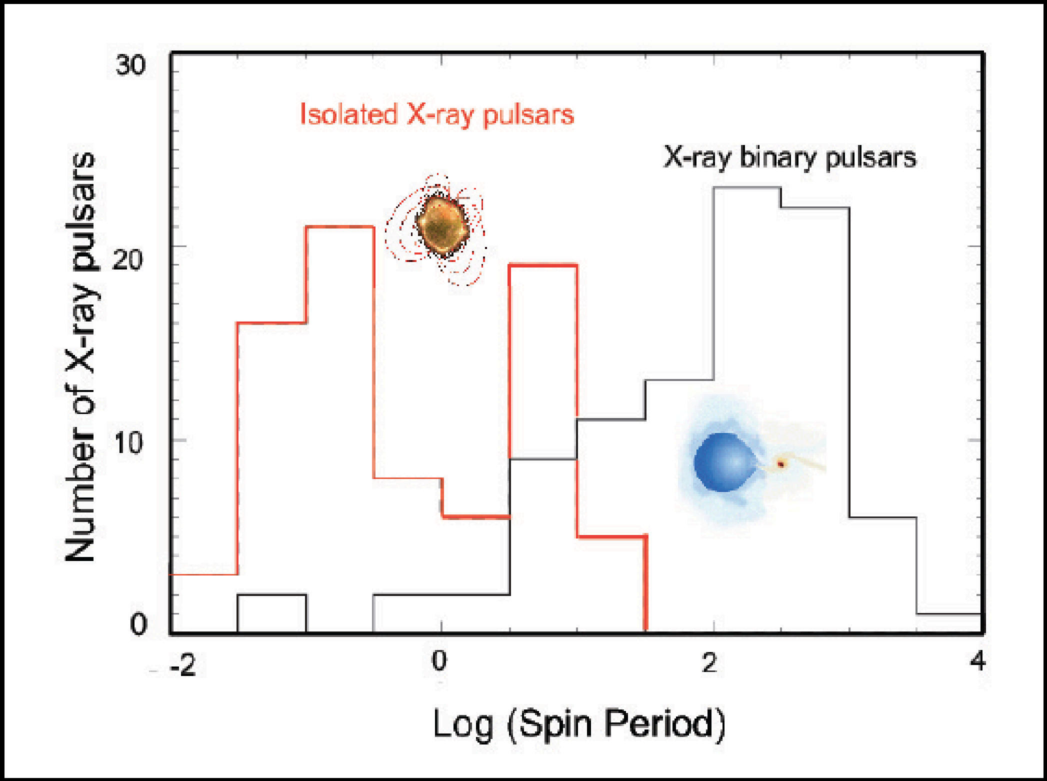
(Coti Zelati, NR, et al. 2017a, in prep)

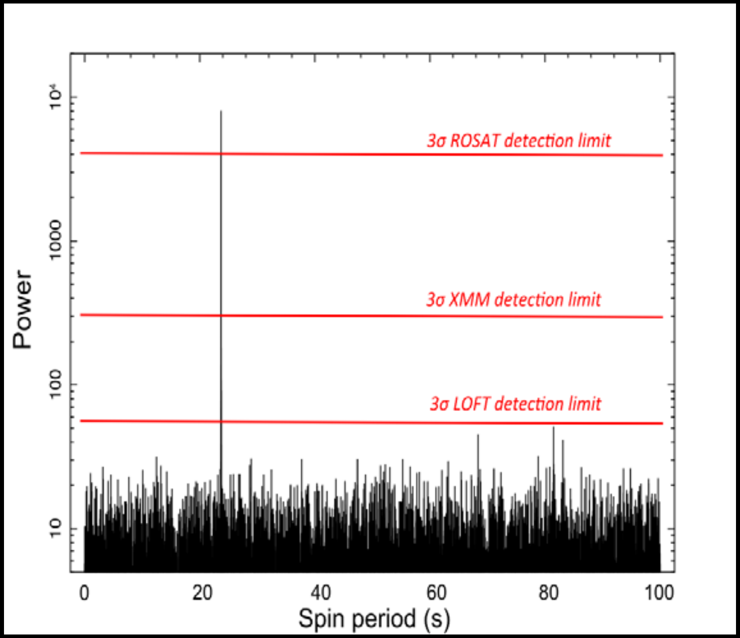
BACK UP SLIDES!
PASTA

Filling the gap around the critical magnetic field…



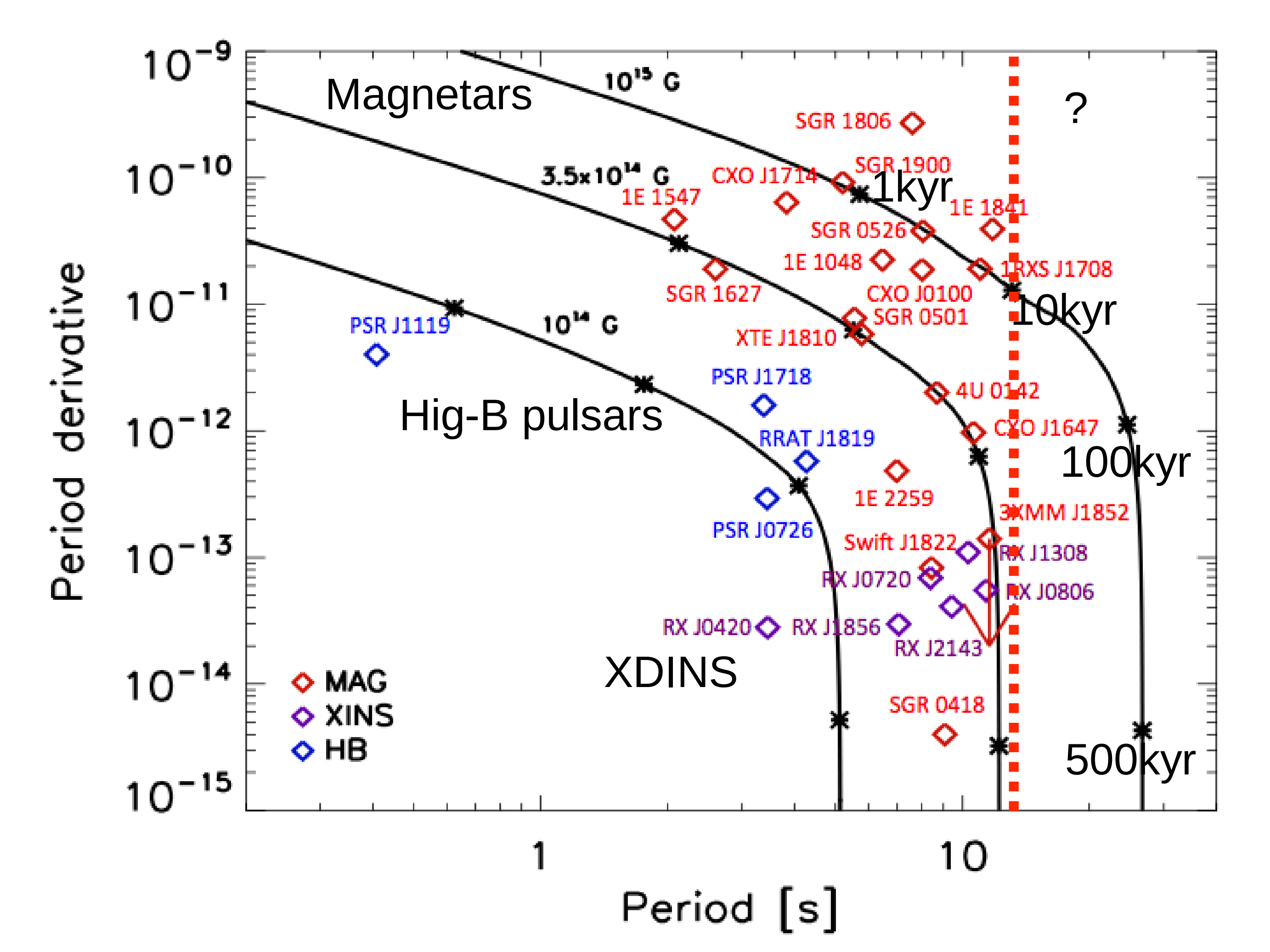
X-ray pulsars are NOT biassed





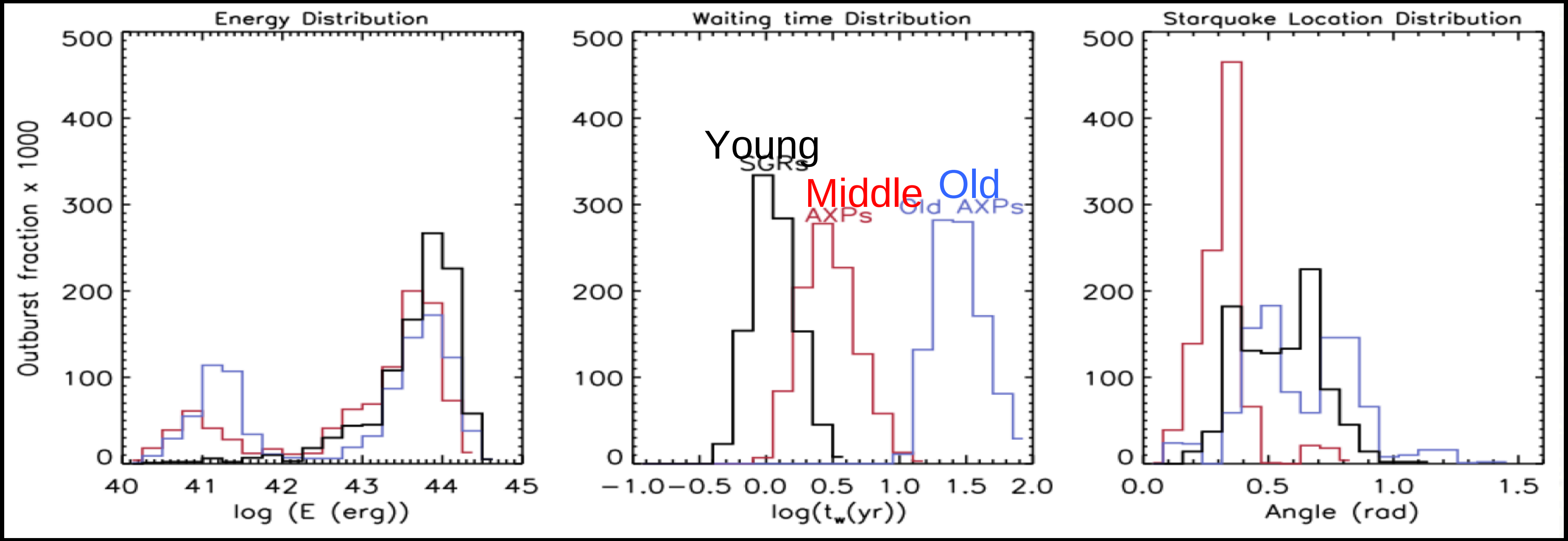
- There are no theoretical or observational biases in the X-ray band for discovering slow X-ray pulsars!

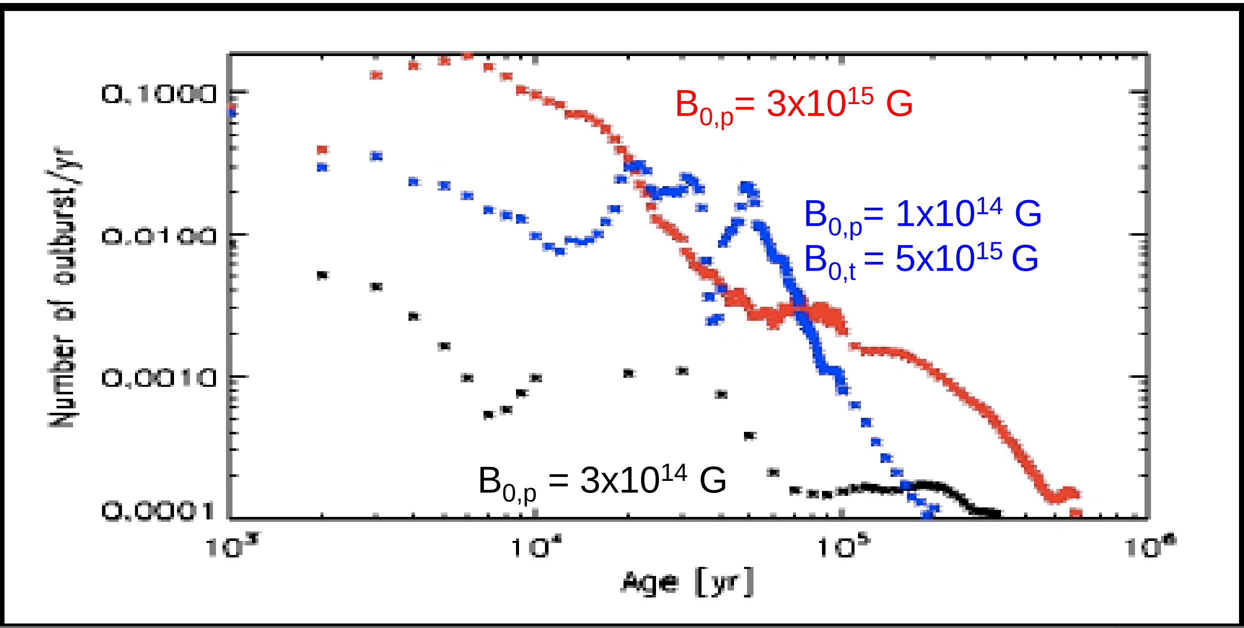
Magnetic field decay drives spin period evolution



Nanda Rea *University of Amsterdam/CSIC-IEEC*

2. Magnetars outburst rates

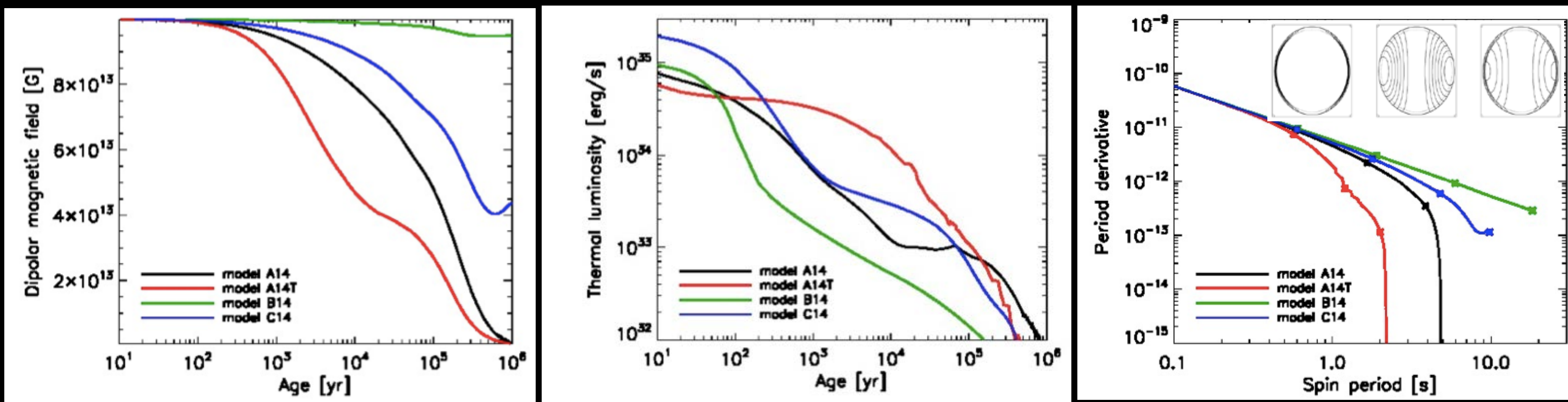


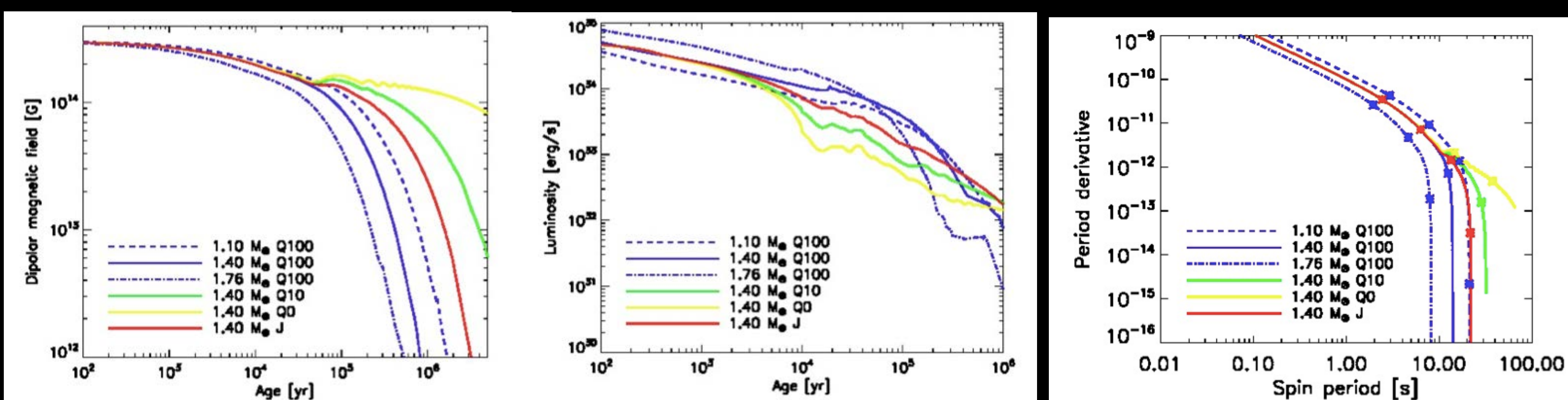


(Perna & Pons 2011; Pons & Perna 2011; Vigano' et al. 2013)

Magneto-thermal 2D MHD simulations

- Changing the B-field configuration: large differences between pure crustal and core fields



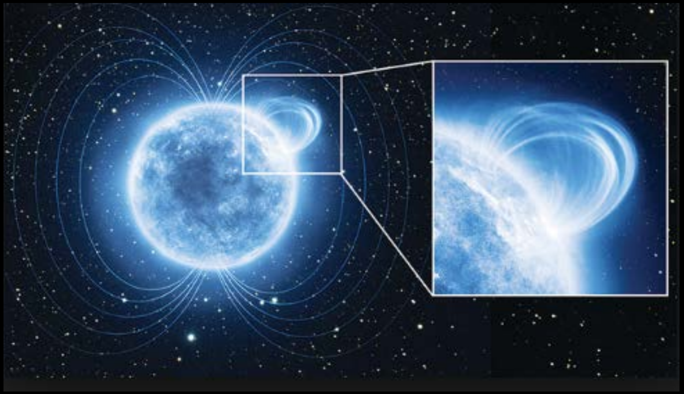


(Pons, Vigano' & Rea 2013 *Nature Physics* 9, 431)

2. Magnetar outburst mechanisms: eventually crustal heating

1. **Internal source of heat:** Magnetic fields evolve in the crust and dissipates energy. This changes the stress balance. When the crustal shear breaking strength is exceeded by magnetic stress, the crust breaks, and elastic/magnetic energy is released.

2. **External source of heat:** Magnetic bundles are ubiquitous in magnetars. They can form and dissipate on timescales of months/years. They cause strong particles outflows, and slamming particles heating the magnetar surface.



(Thompson et al. 2002; Beloborodov 2007; Perna & Pons 2011; Pons & Rea 2012; Paffrey, Beloborodov & Hui 2013)

Magnetic field formation in neutron stars

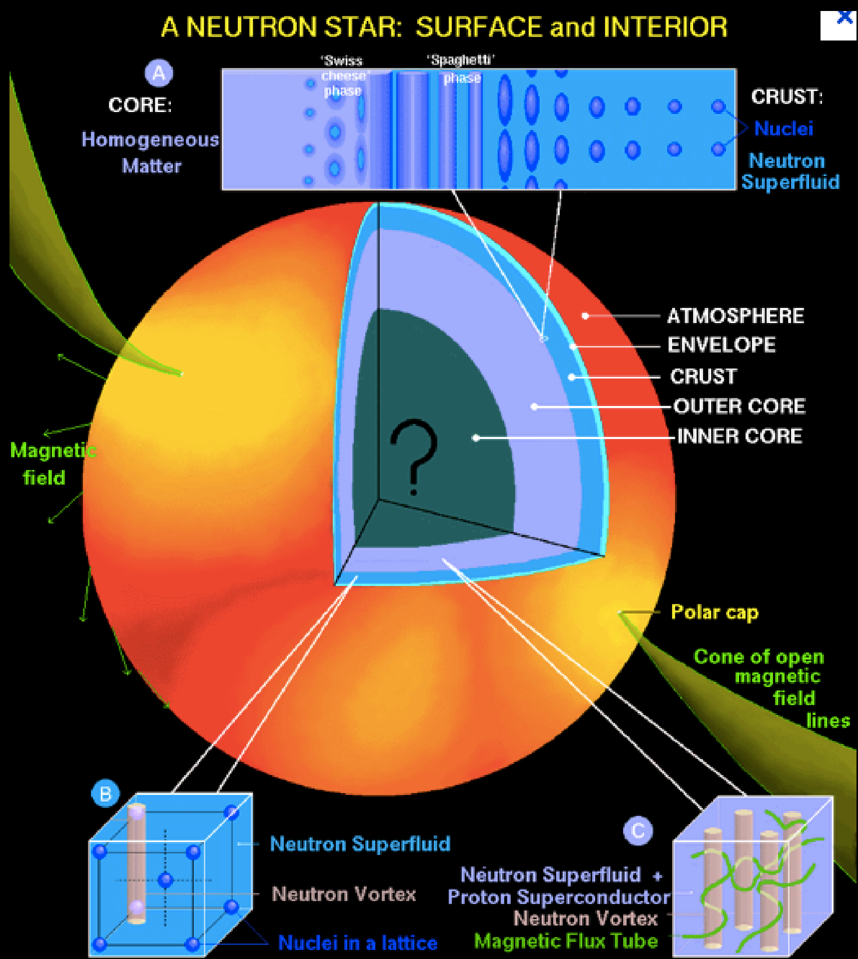
- Via dynamos/instabilities in the stellar core
- As fossil fields from a magnetic progenitor
- From massive star binary progenitors

Observationally…

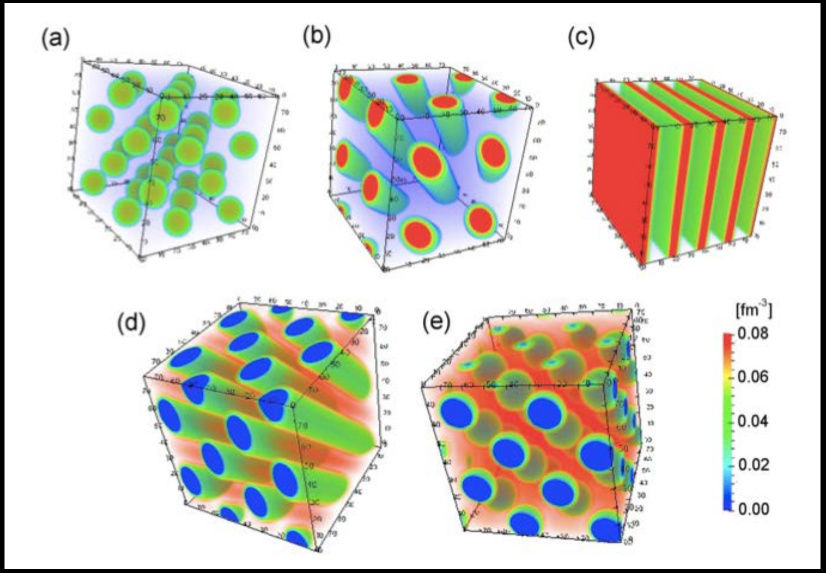
- Proper motions for ~6 objects: 200-300 km/s range
- A few magnetars coincident with massive star clusters
- One case: a wind blown bouble observed in radio
- One case: a run-away star close-by is detected.
- ~6 confirmed SNRs, 3 more possibly associated

What is the crustal impurity: Q*imp*

(Okamoto et al. 2013)



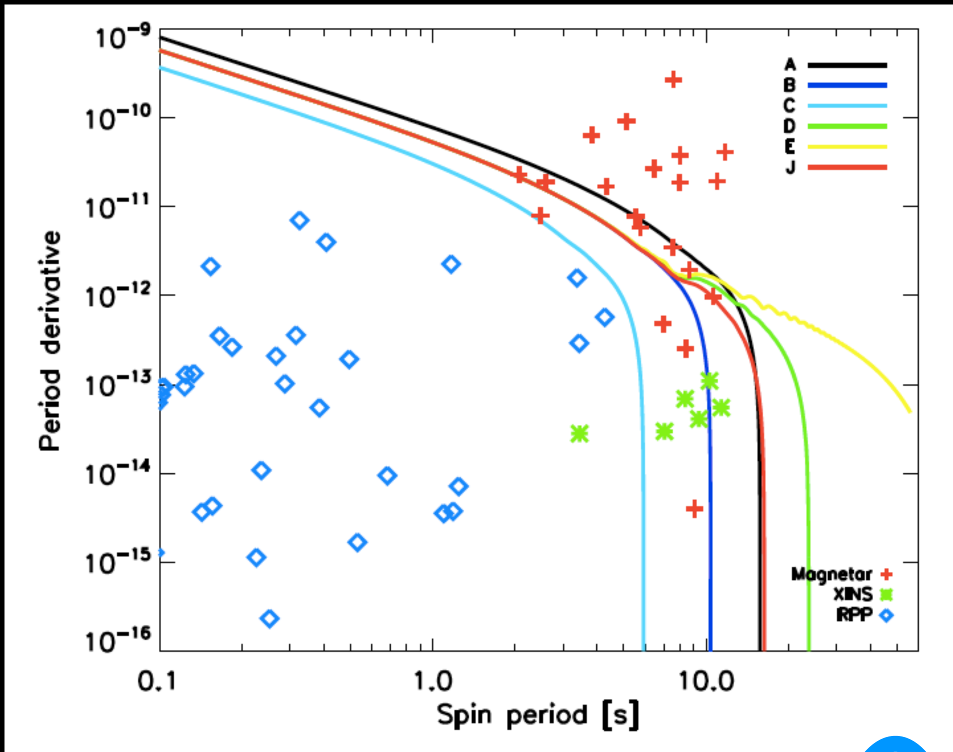
(Page & Reddy 2006)



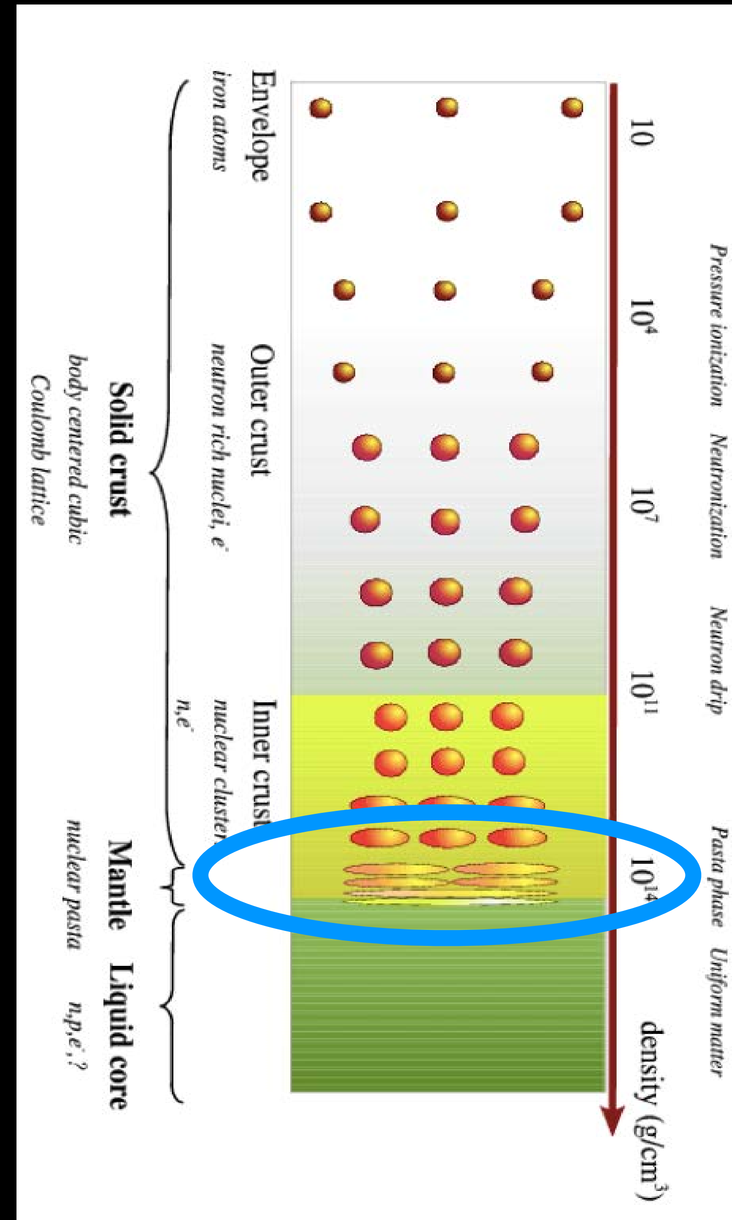
At densities > 10^{13} gr cm^{-3} nuclei are favoured in pasta shapes (rods, slabs, bubbles).

Qimp = $\langle Z^2 \rangle - \langle Z^2 \rangle$: In absence of more detailed calculations, Q*imp* parametrizes the crystal structure.

Constraining crustal composition



Model	$M[M_\odot]$	I_{45}	ΔR_{crust} [km]	ΔR_{pasta} [km]	Q_{max}
A	1.10	0.962	0.94	0.14	100
B	1.40	1.327	0.70	0.10	100
C	1.76	1.755	0.43	0.07	100
D	1.40	1.327	0.70	0.10	10
E	1.40	1.327	0.70	0.10	0.1
J	1.40	1.327	0.70	0.0	23



(Pons, Vigano' & Rea 2013 *Nature Physics* 9, 431)

Neutron drip point

In neutron stars, neutron heavy nuclei are found as relativistic electrons penetrate the nuclei and produce inverse beta decay, wherein the electron combines with a proton in the nucleus to make a neutron and an electron-neutrino:

$$p + e^{-} \rightarrow n + \nu_e$$

As more and more neutrons are created in nuclei the energy levels for neutrons get filled up to an energy level equal to the rest mass of a neutron. At this point any electron penetrating a nucleus will create a neutron which will "drip" out of the nucleus. At this point we have:

$$E_F^n = m_n c^2$$

And from this point onwards the equation

$$E_F^n = \sqrt{(p_F^n)^2 c^2 + m_n^2 c^4}$$

applies, where p_F^n is the Fermi momentum of the neutron. As we go deeper into the neutron star the free neutron density increases, and as the Fermi momentum increases with increasing density, the Fermi energy increases, so that energy levels lower than the top level reach neutron drip and more and more neutrons drip out of nuclei so that we get nuclei in a neutron fluid. Eventually all the neutrons drip out of nuclei and we have reached the neutron fluid interior of the neutron star.

Nuclear Pasta Phase

In astrophysics, **nuclear pasta** is a type of degenerate matter found within the crusts of neutron stars. Between the surface of a neutron star and the quark–gluon plasma at the core, at matter densities of 10^{14} g/cm^3, nuclear attraction and Coulomb repulsion forces are of similar magnitude. The competition between the forces allows for the formation of a variety of complex structures assembled from neutrons and protons. Astrophysicists call these types of structures *nuclear pasta* because the geometry of the structures resembles various types of pasta.[1][2]

Nuclear pasta phases are theorized to exist in the inner crust of neutron stars, forming a transition region between the conventional matter at the surface, and the ultradense matter at the core. Towards the top of this transition region, the pressure is great enough that conventional nuclei will be condensed into much more massive semi-spherical collections. These formations would be unstable outside the star, due to their high neutron content and size, which can vary between tens and hundreds of nucleons. This semispherical phase is known as the *gnocchi phase*.

BACK UP SLIDES!
MAGNETO-THERMAL

3. Magneto-thermal evolutionary models

(Aguilera et al. 2008; Pons et al. 2009; Vigano', Rea, Pons, Perna, Aguilera & Miralles 2013)

Thermal evolution: energy balance equation

Specific heat — Thermal conductivity — Neutrino emissivity

$$C_v e^{\Phi(r)} \frac{\partial T}{\partial t} + \vec{\nabla} \cdot \left(-\hat{\kappa} \cdot \vec{\nabla}(e^{\Phi(r)} T) \right) = e^{2\Phi(r)} Q$$

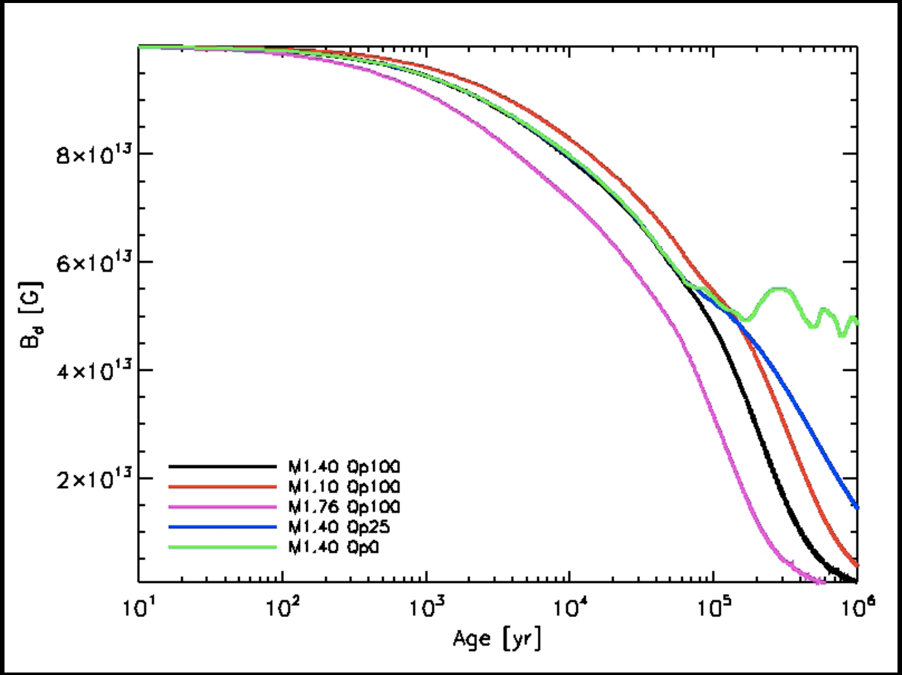
Magnetic evolution: Hall induction equation

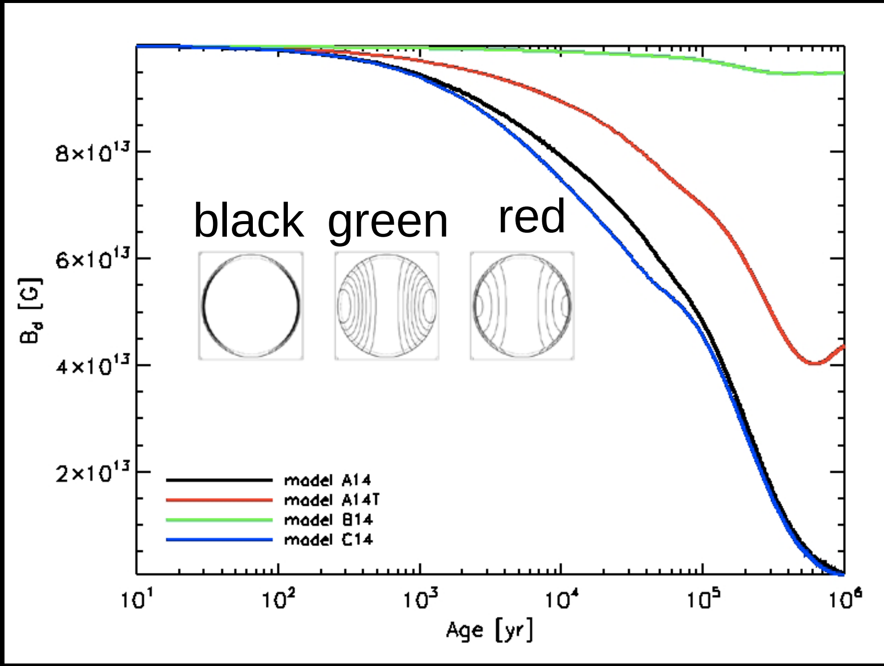
$$\frac{\partial \boldsymbol{B}}{\partial t} = -\nabla \times \left\{ \eta \nabla \times (e^{\nu} \boldsymbol{B}) + \frac{c}{4\pi e n_e} [\nabla \times (e^{\nu} \boldsymbol{B})] \times \boldsymbol{B} \right\}$$

Hall induction

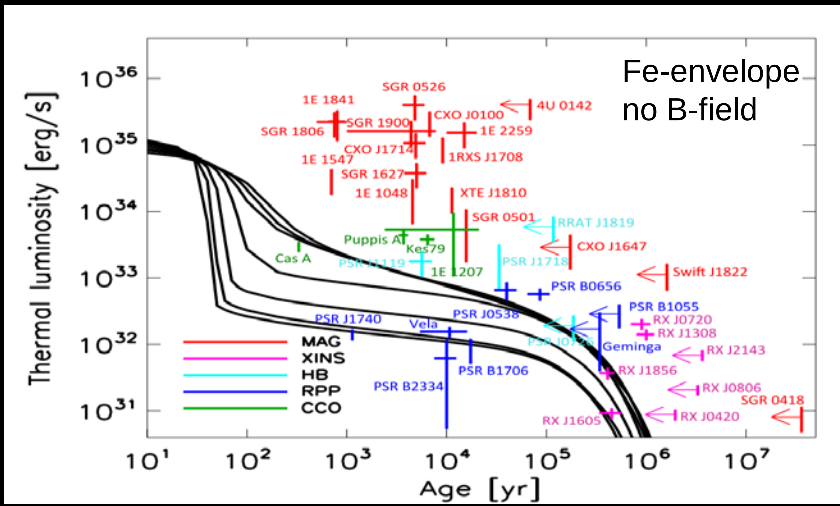
Electrical resistivity: strongly depends on T

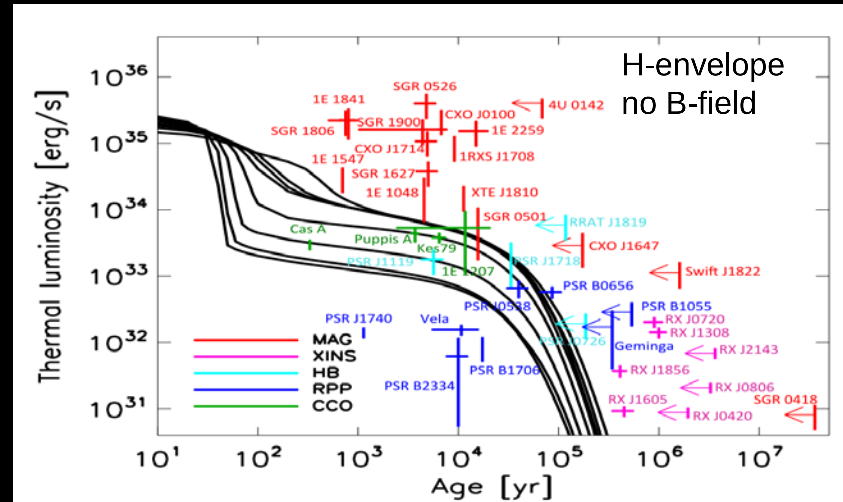
Neutron star cooling models

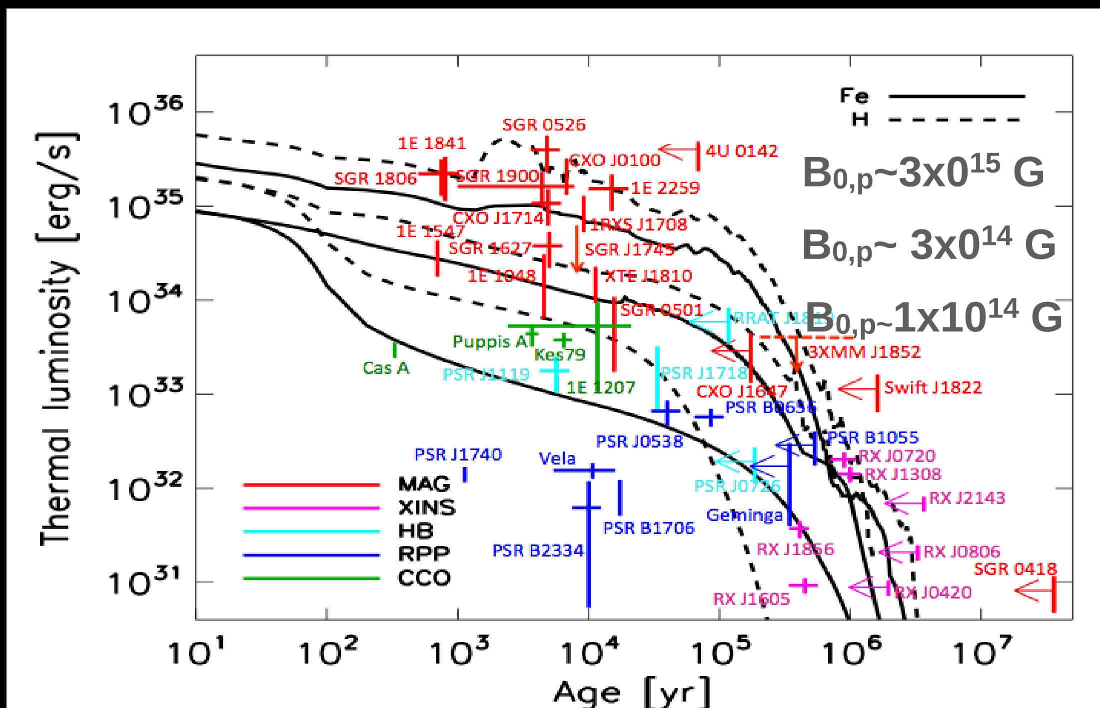




3. Magnetic evolution of neutron stars: toward a unification

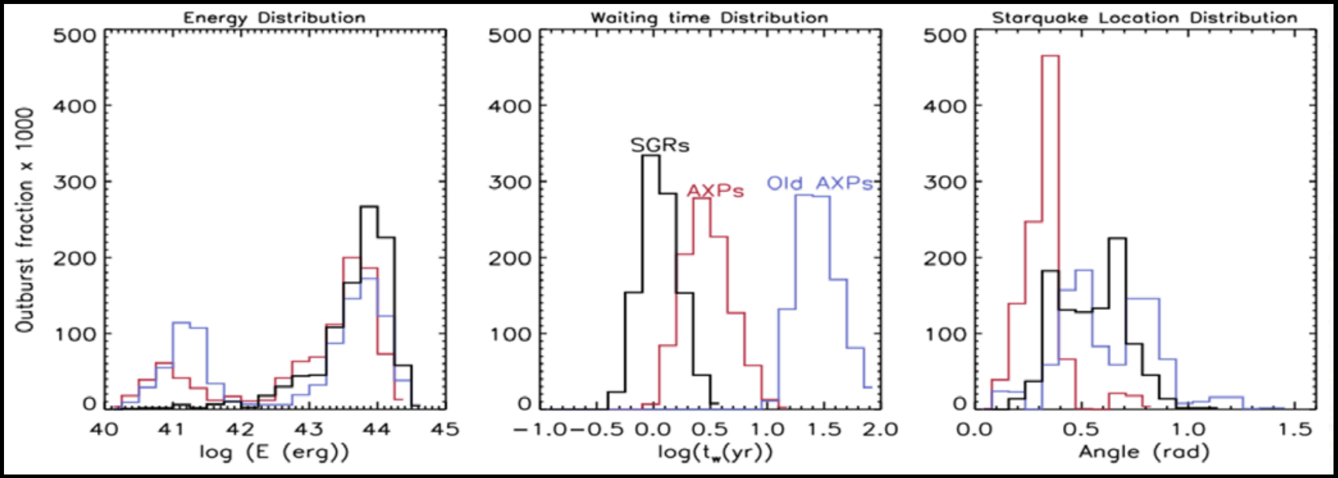


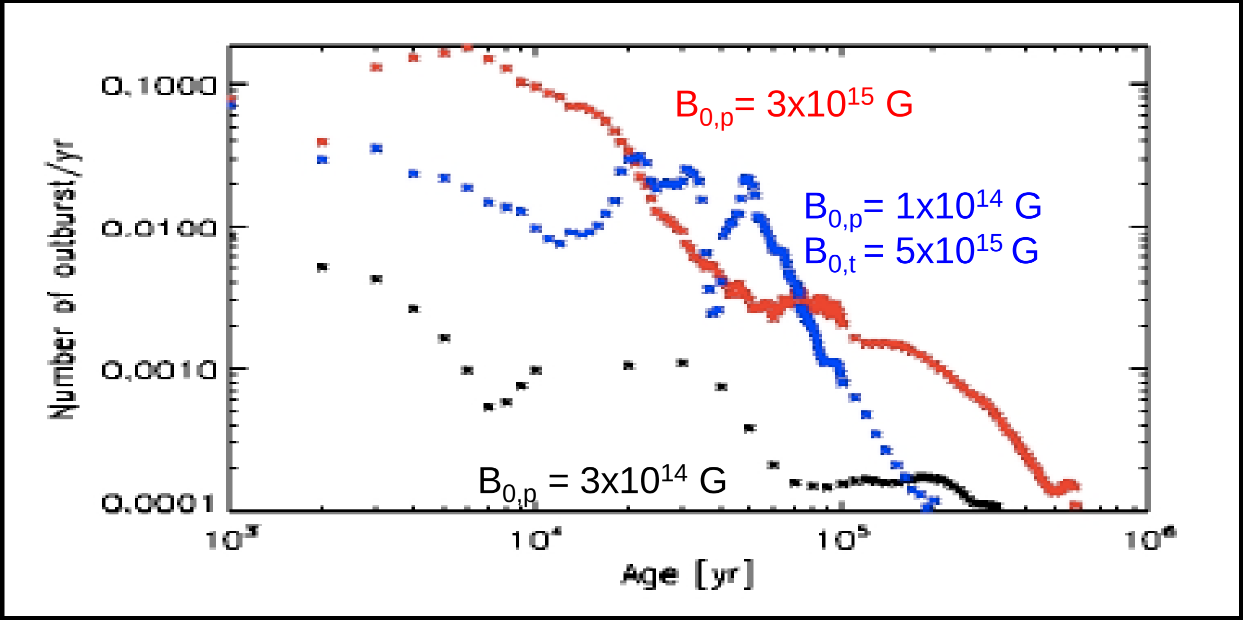




3. Magnetars bursting rate

Can a neutron star with 6x10[12] Gauss dipolar field, as the low-B magnetar SGR 0418+5729, show magnetar-like outbursts and flares?





(Perna & Pons 2011; Pons & Perna 2011; Vigano', Rea, Pons, Perna, Aguilera & Miralles 2013)

3. Magneto-thermal evolutionary models

- Neutron star model (structure, EOS)

- Thermal evolution (energy balance equation): standard theory of cooling of NSs

- Magnetic field decay and Joule heating.

- Magnetic field evolution in the crust: Hall induction equation

- Magnetic field evolution in the core: ambipolar diffusion ? superconducting fluid dynamics, interaction between fluxoids and vortices ? (Elfritz et al. 2015 in prep)

- Microphysics ingredients (thermal conductivity, electrical resistivity, neutrino emission processes, …)

- Elastic/plastic properties of the crust: shear modulus, breaking strength (Horowitz+: crust is much stronger than though !). Necessary to understand starquake activity.

- Put everything in a numerical code. Results from simulations.

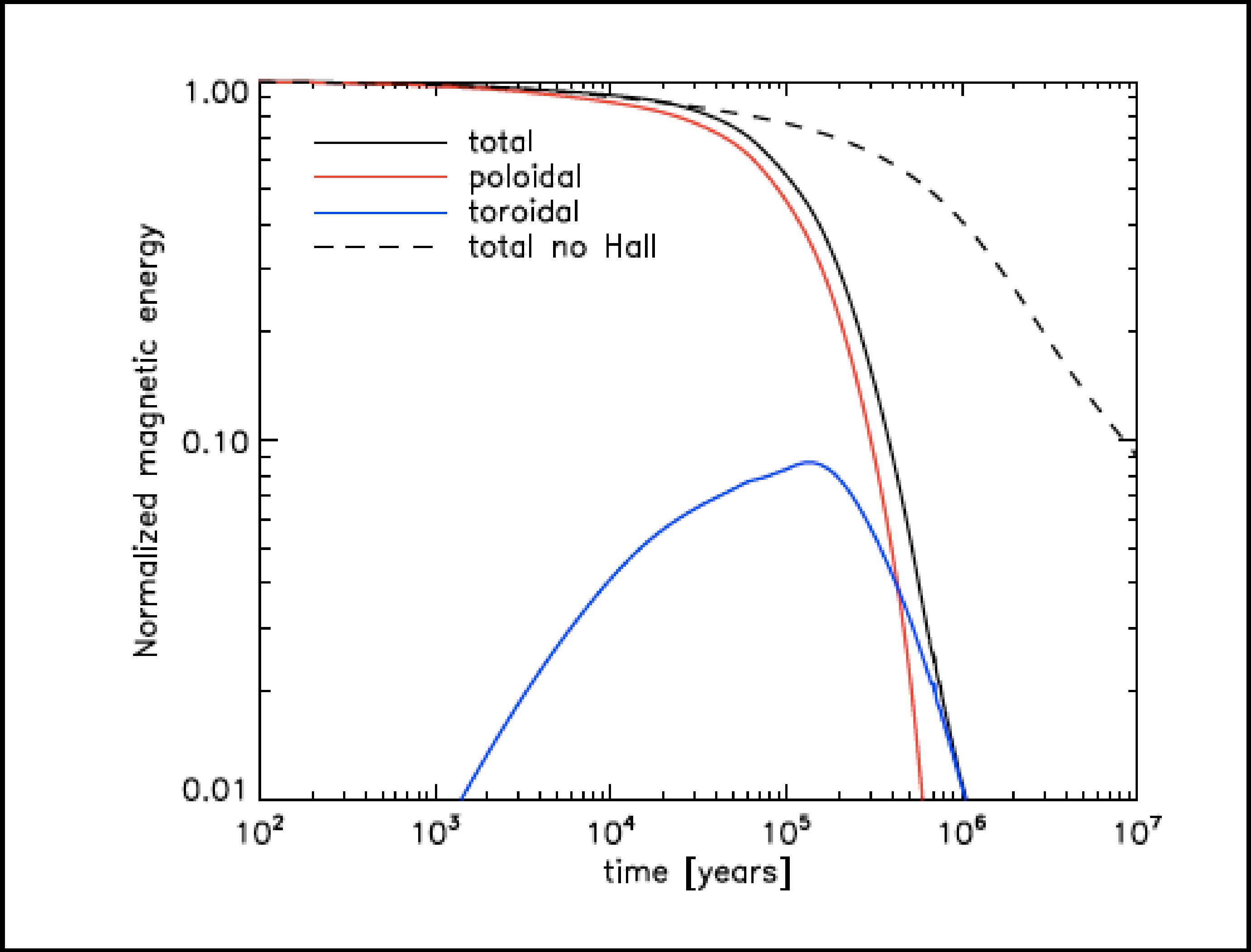
How does temperature affect the B field evolution ?

- In a real NS, the crust is solid. It is appropriate to describe it as a Hall plasma, where ions have very restricted mobility and only electrons can move freely through the lattice.
- The proper equations are Hall MHD. If ions are strictly fixed in the lattice, the limit is known as EMHD (electron MHD)
- There are two basic wave modes: in the homogeneous limit (constant electron density), whistler or helicon waves, and also Hall drift waves in the inhomogeneous case.
- Transition from diffusive to hyperbolic regime depends on temperature.

Hall induction

$$\frac{\partial \boldsymbol{B}}{\partial t} = -\boldsymbol{\nabla} \times \left\{ \eta \boldsymbol{\nabla} \times (e^{\nu} \boldsymbol{B}) + \frac{c}{4\pi e n_e} [\boldsymbol{\nabla} \times (e^{\nu} \boldsymbol{B})] \times \boldsymbol{B} \right\}$$

Electrical resistivity strongly depends on T



1.00
0.10
0.01
Normalized magnetic energy
total
poloidal
toroidal
total no Hall
10^2
10^3
10^4
10^5
10^6
10^7
time [years]

Neutrino processes in the crust

Process	Q_ν [erg cm^{-3}s^{-1}]	Onset	Ref
Core			
Modified URCA (n-branch)			
$nn \to pne\bar{\nu}_e$, $pne \to nn\nu_e$	$8 \times 10^{21}\, \mathcal{R}_n^{MU}\, n_p^{1/3}\, T_9^8$		1
Modified URCA (p-branch)			
$np \to ppe\bar{\nu}_e$, $ppe \to np\nu_e$	$8 \times 10^{21}\, \mathcal{R}_p^{MU}\, n_p^{1/3}\, T_9^8$	$Y_p^c = 0.01$	1
N-N Bremsstrahlung			
$nn \to nn\nu\bar{\nu}$	$7 \times 10^{19}\, \mathcal{R}^{nn}\, n_n^{1/3}\, T_9^8$		1
$np \to np\nu\bar{\nu}$	$1 \times 10^{20}\, \mathcal{R}^{np}\, n_p^{1/3}\, T_9^8$		1
$pp \to pp\nu\bar{\nu}$	$7 \times 10^{19}\, \mathcal{R}^{pp}\, n_p^{1/3}\, T_9^8$		1
e-p Bremsstrahlung			
$ep \to ep\nu\bar{\nu}$	$2 \times 10^{17}\, n_B^{-2/3}\, T_9^8$		2
Direct URCA			
$n \to pe\bar{\nu}_e$, $pe \to n\nu_e$	$4 \times 10^{27}\, \mathcal{R}^{DU}\, n_e^{1/3}\, T_9^6$	$Y_p^c = 0.11$	3
$n \to p\mu\bar{\nu}_\mu$, $p\mu \to n\nu_\mu$	$4 \times 10^{27}\, \mathcal{R}^{DU}\, n_e^{1/3}\, T_9^6$	$Y_p^c = 0.14$	3
Crust			
Pair annihilation			
$ee^+ \to \nu\bar{\nu}$	$9 \times 10^{20}\, F_{\rm pair}(n_e, n_{e^+})$		4
Plasmon decay			
$\tilde{e} \to \tilde{e}\nu\bar{\nu}$	$1 \times 10^{20}\, I_{\rm pl}(T, y_e)$		5
e-A Bremsstrahlung			
$e(A,Z) \to e(A,Z)\nu\bar{\nu}$	$3 \times 10^{12}\, L_{eA}\, Z\, \rho_o\, n_e\, T_9^6$		6
N-N Bremsstrahlung			
$nn \to nn\nu\bar{\nu}$	$7 \times 10^{19}\, \mathcal{R}^{nn}\, f_\nu\, n_n^{1/3}\, T_9^8$		1
Core and crust			
CPBF			
$\tilde{B} + \tilde{B} \to \nu\bar{\nu}$	$1 \times 10^{21}\, n_N^{1/3}\, F_{A,B}\, T_9^7$		7
Neutrino synchrotron			
$e \to (B) \to e\nu\bar{\nu}$	$9 \times 10^{14}\, S_{AB,BC}\, B_{13}^2\, T_9^5$		8

Refs.: (1) Yakovlev & Levenfish (1995); (2) Maxwell (1979); (3) Lattimer et al. (1991); (4) Kaminker & Yakovlev (1994); (5) Yakovlev et al. (2001); (6) Haensel et al. (1996); Kaminker et al. (1999); (7) Yakovlev et al. (1999); (8) Bezchastnov et al. (1997)

Table 4.3: Neutrino processes and their emissivities Q_ν in the core and in the crust, taken from Aguilera et al. 2008. The third column shows the onset for some processes to operate (critical proton fraction Y_p^c). We indicate the normalized temperature $T_9 = T/10^9$ K; detailed functions and precise factors can be found in the references (last column).

Neutrino processes in the crust

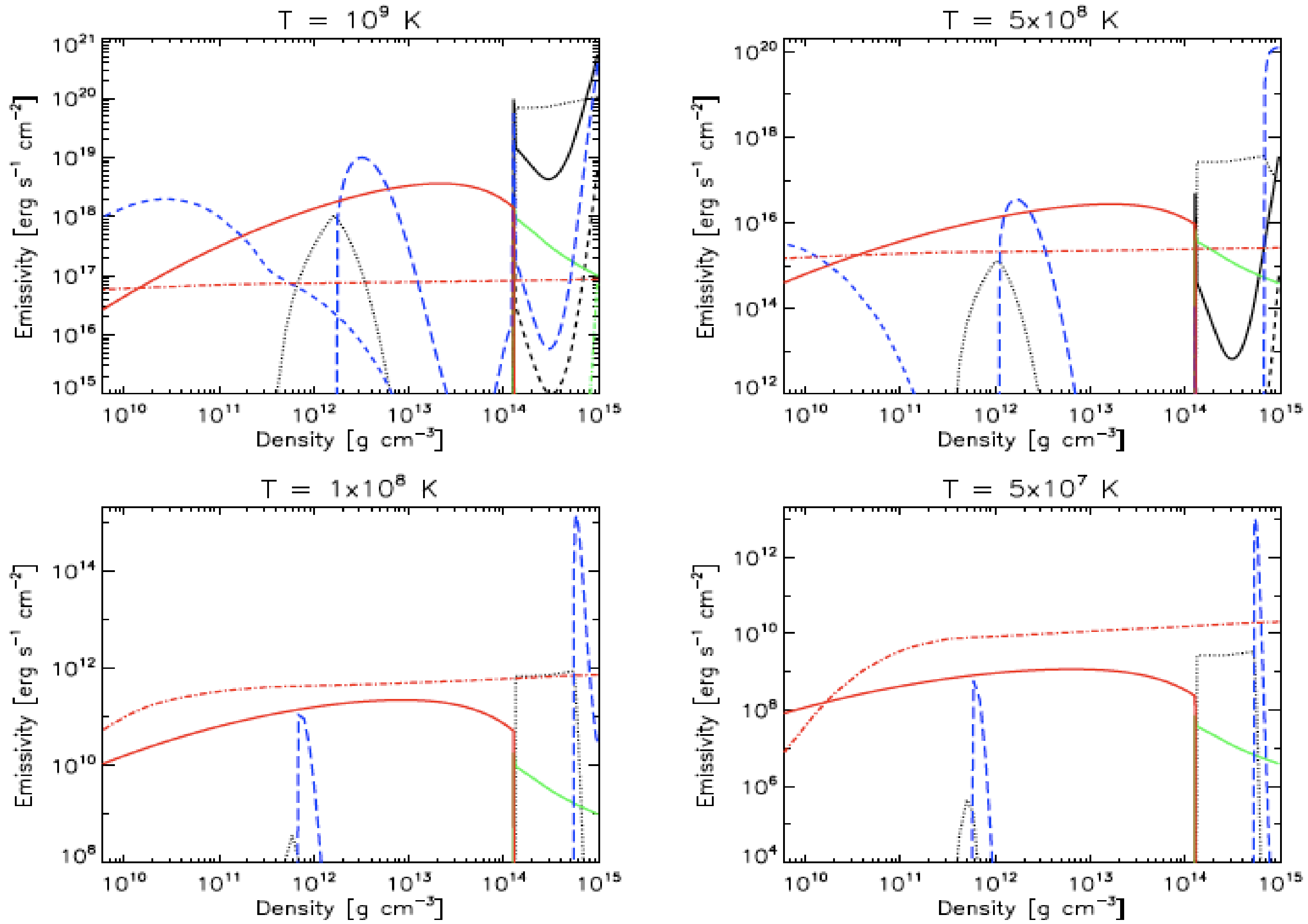


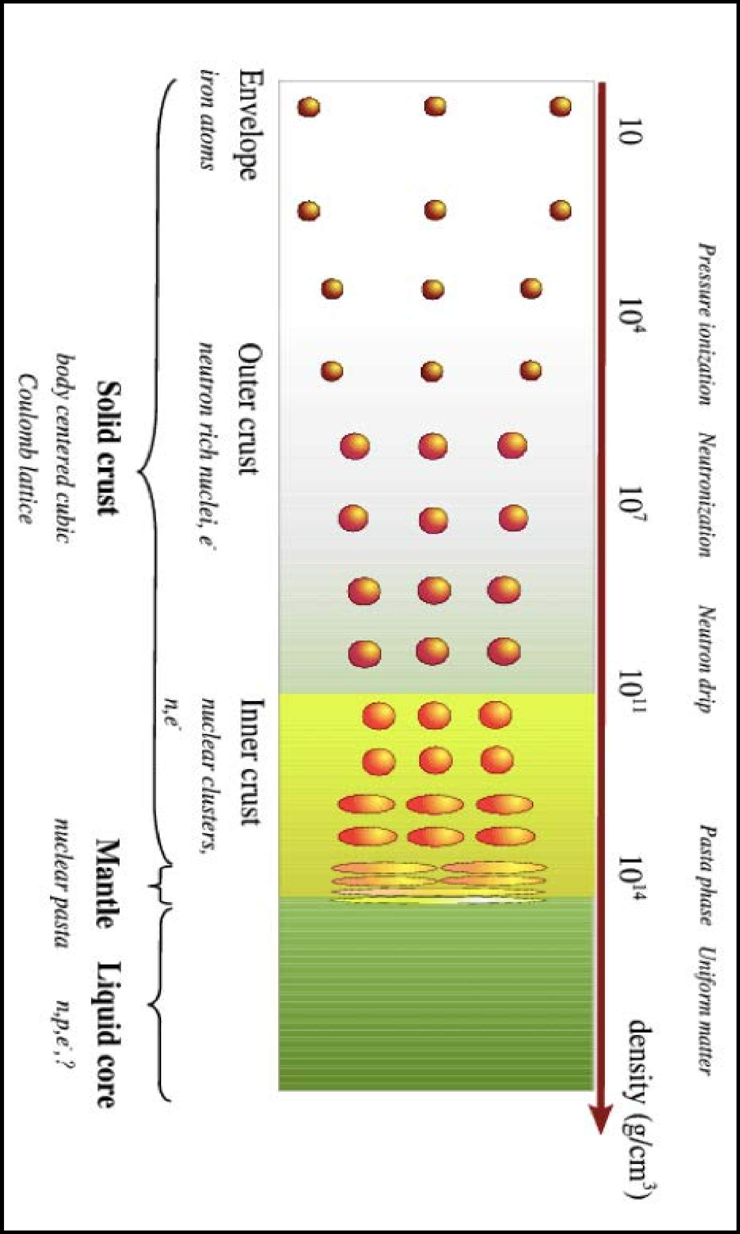
Figure 4.7: Neutrino emissivities in the crust and in the core at the four indicated temperatures, with the chosen equation of state and superfluid gaps (see text), and mass $M = 1.4\ M_\odot$ (no direct URCA). Lines denote: modified URCA (black solid line), n-n Bremsstrahlung (black dots), n-p Bremsstrahlung (black dashes), e-p Bremsstrahlung (green solid), e-A Bremsstrahlung (red solid), plasmon decay (short blue dashes), CPBF (blue long dashes), and ν-synchrotron for $B = 10^{14}$ G (red dot-dashed line).

BACK UP SLIDES!
OUTBURSTS

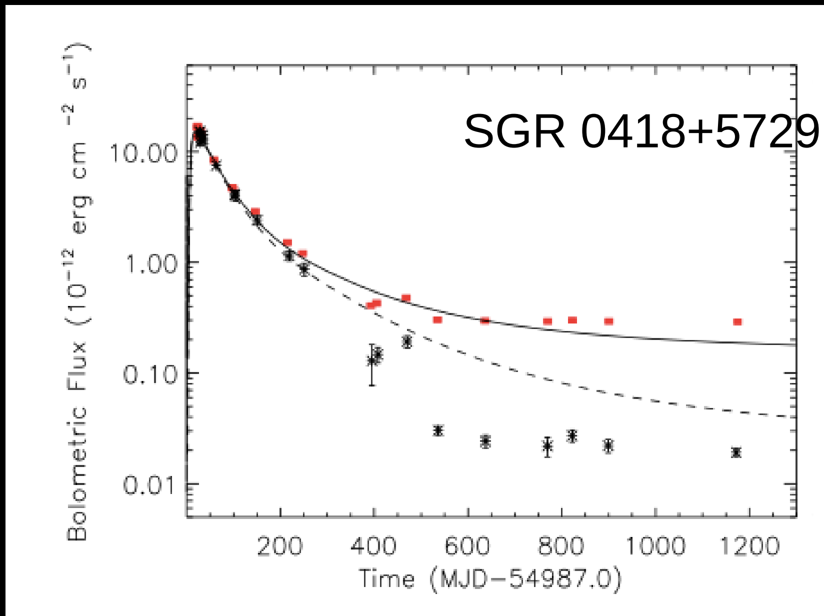
1- Set the stage: derive the steady B-configuration, age, crustal thermal map from P, Pdot, quiescent luminosity.
Magneto-thermal evolutionary models!

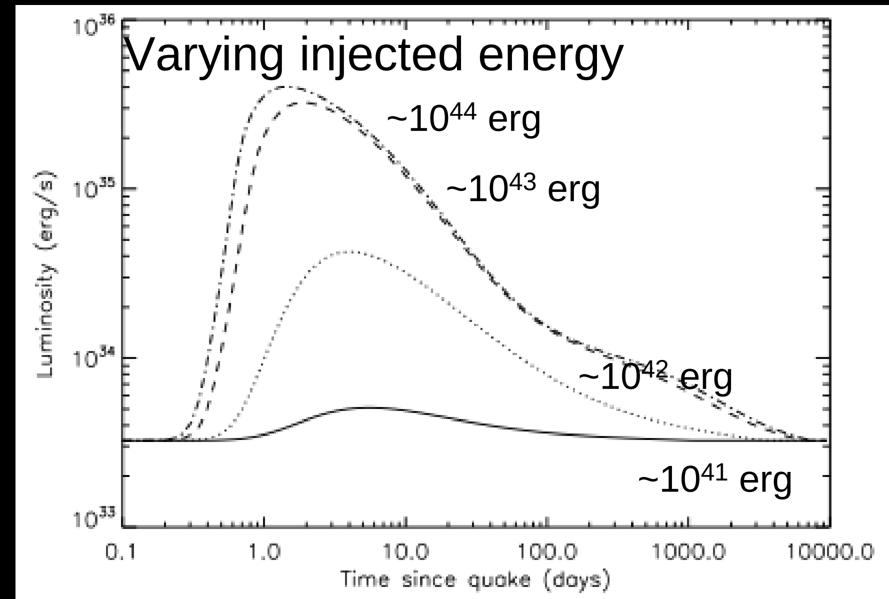
2. A fixed amount of energy is injected in a fraction of the crustal volume.
Parameters: rate, energy and volume (depth and angular size).

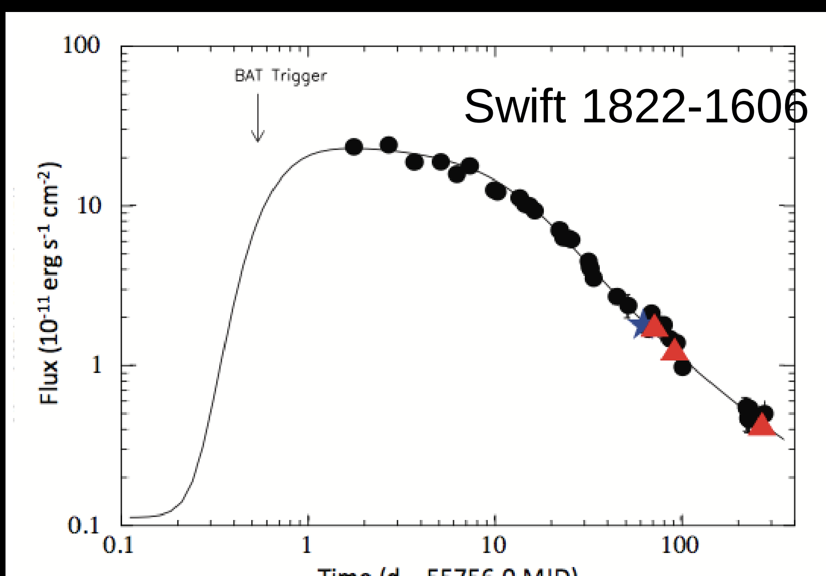
— > We follow the evolution of the thermal structure until it returns to the original state.

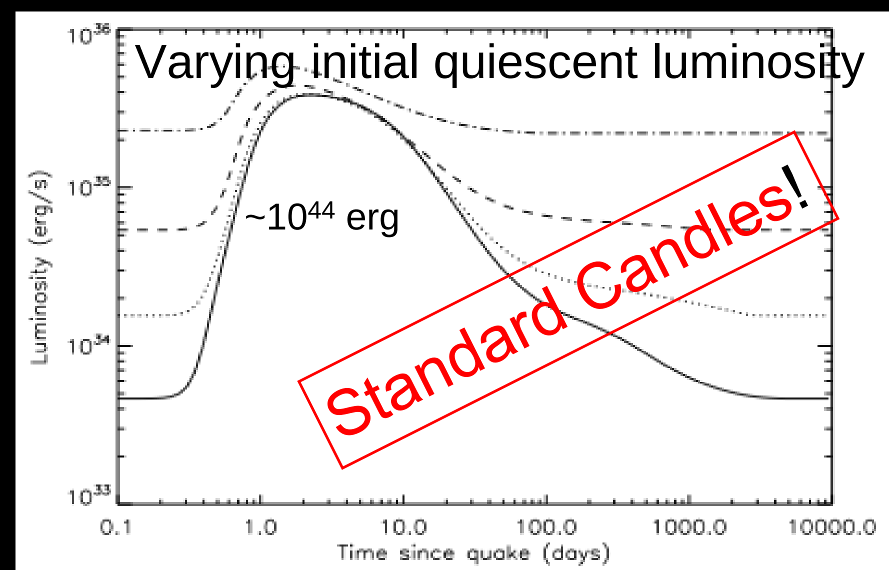


2. Low magnetic-field magnetars: outburst modelling

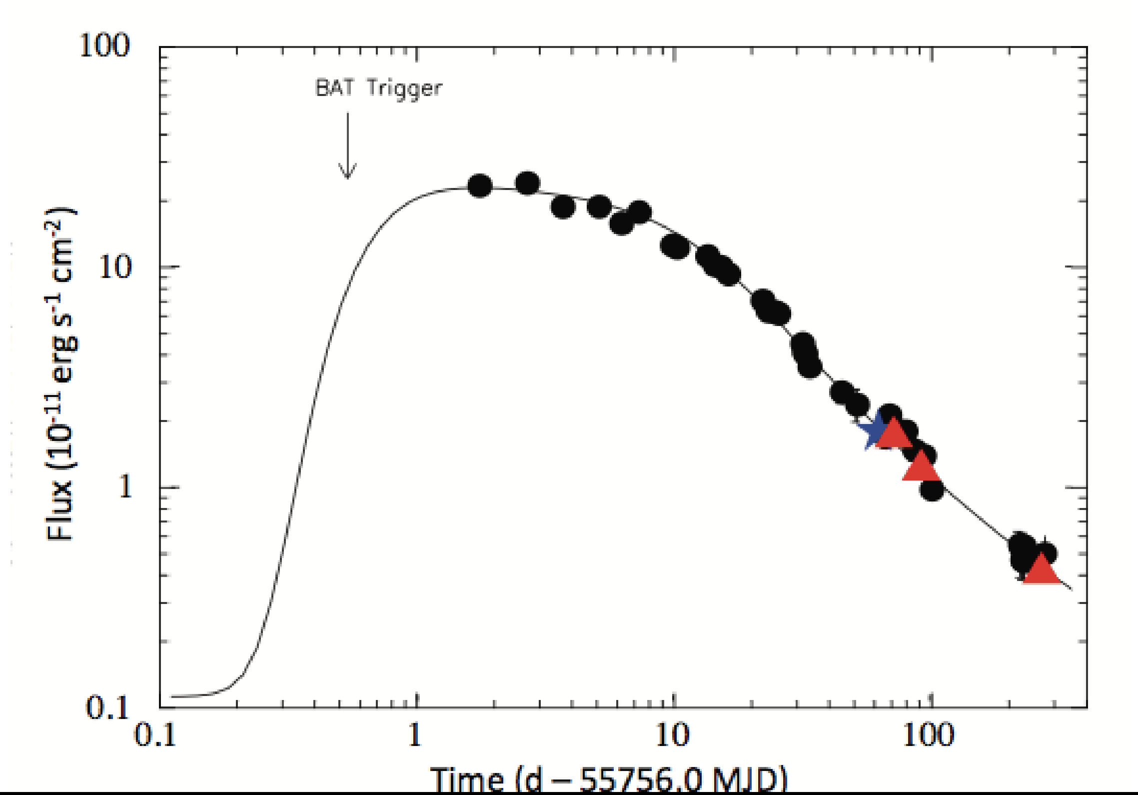








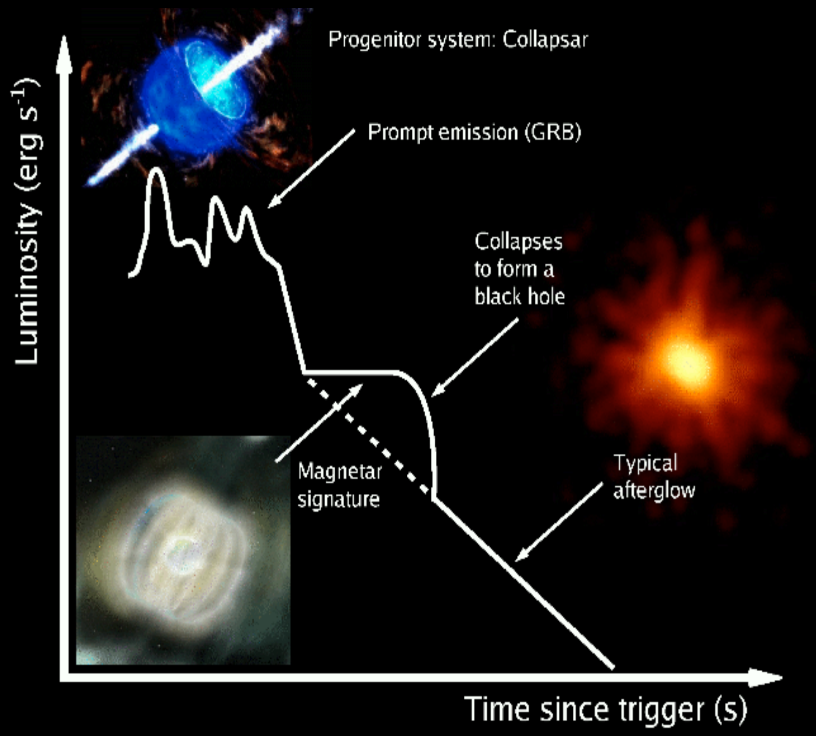
(Pons & Rea 2012; Rea et al.

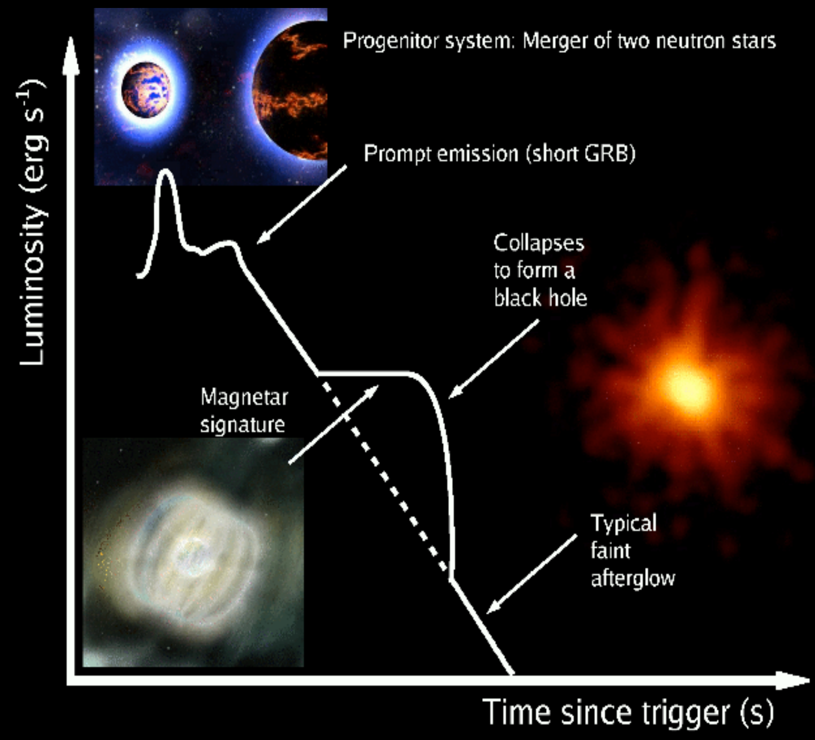


External surface dipolar field from P and Pdot: ~$2x10^{13}$G. Magneto-thermal state consistent with a 0.5 Myr old magnetar, with crustal toroidal field of ~10^{14} G. Outburst due to $4x10^{25}$ erg/cm^3 injected in the outer crust on an ~3km radius hot spot (total energy ~10^{42} erg).

BACK UP SLIDES!
Pop Syth

Some GRBs may be powered by a millisecond highly magnetized pulsar.



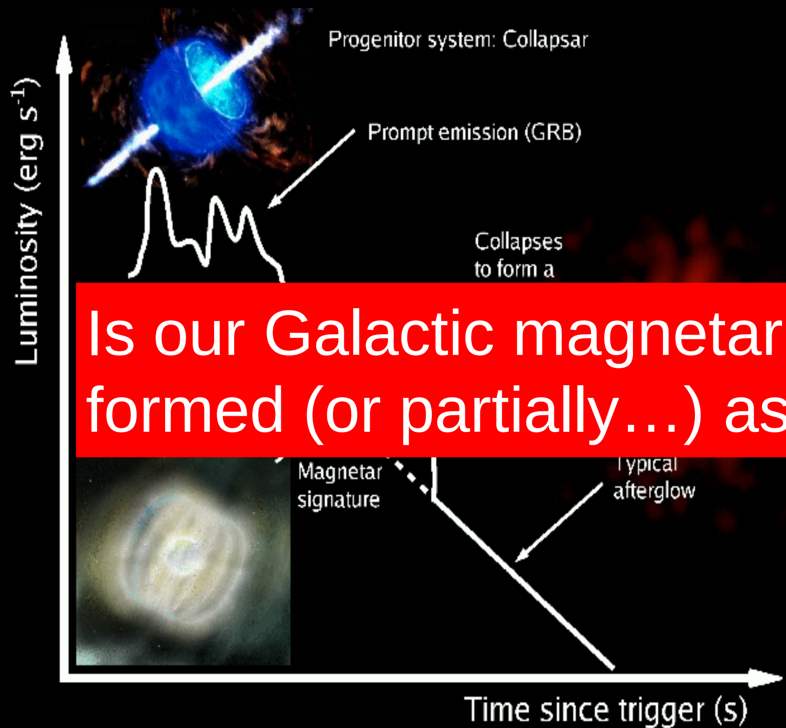


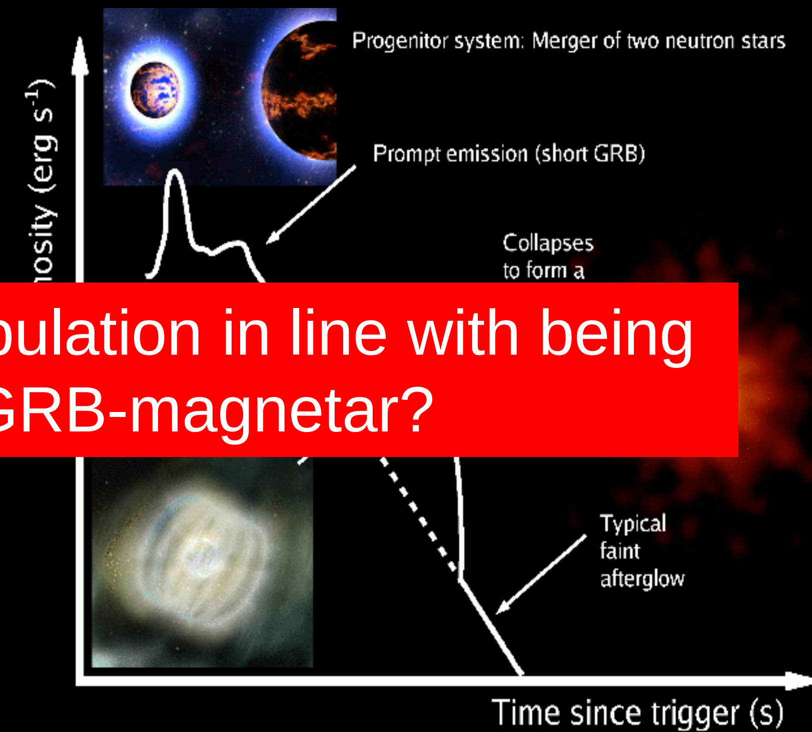
Collapsar model for Long-GRBs

Binary mergers for Short-GRBs

(Usov 1992; Zhang & Meszaros 2002; Dai et al. 200; Metzger 2009, 2011; Rowlinson et al. 2012, 2014)

Some GRBs may be powered by a millisecond highly magnetized pulsar.





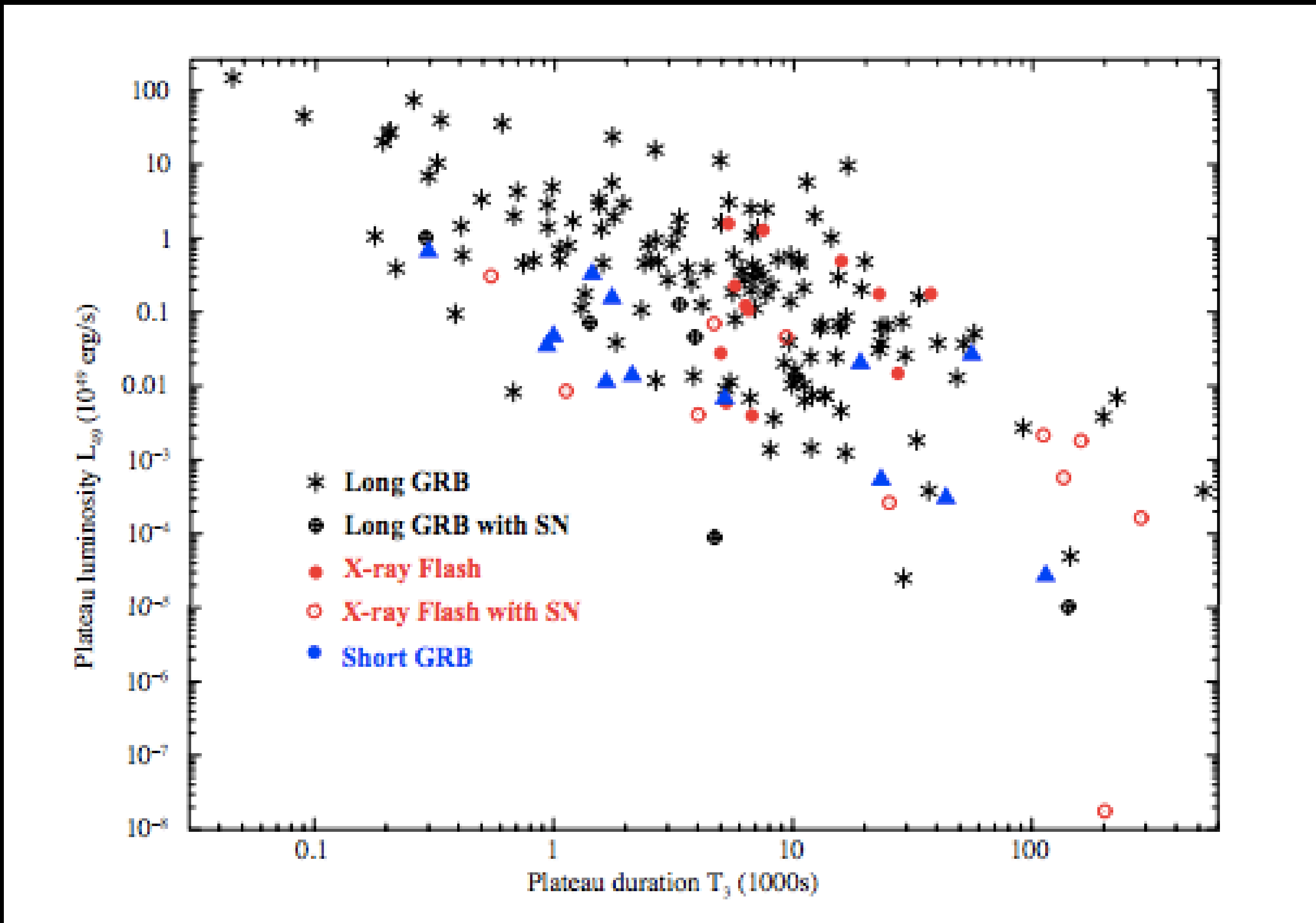
Is our Galactic magnetar population in line with being formed (or partially…) as a GRB-magnetar?

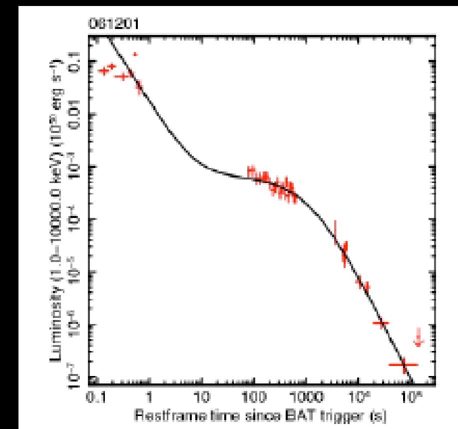
Collapsar model for Long-GRBs

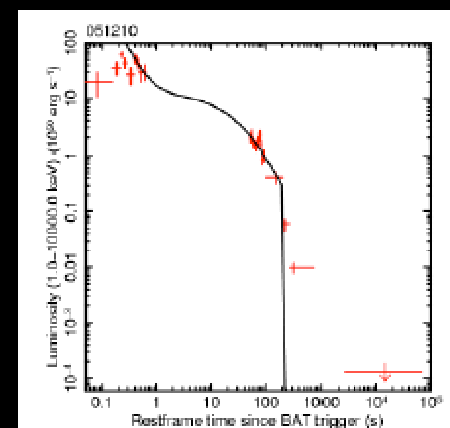
Binary mergers for Short-GRBs

(Usov 1992; Zhang & Meszaros 2002; Dai et al. 200; Metzger 2009, 2011; Rowlinson et al. 2012, 2014)

We fitted with a plateau model all Swift GRBs (Long and Short) from launch till August 2014.

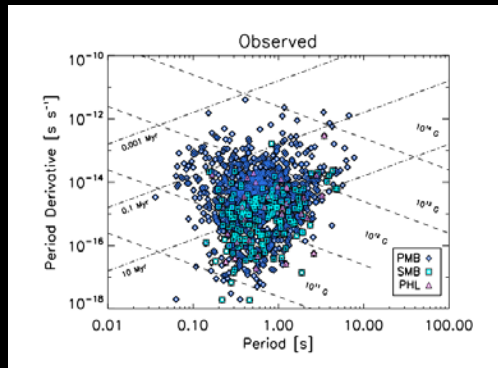






(Rea et al. 2015, ApJ)

3. Multi-band Population Synthesis modelling



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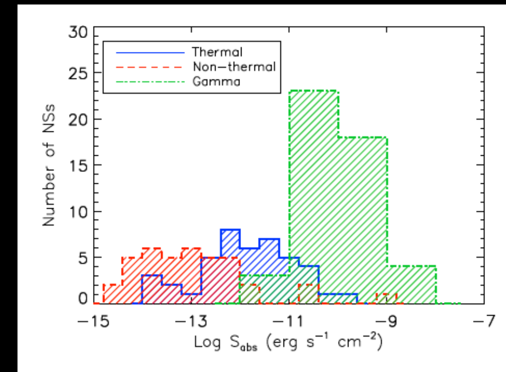
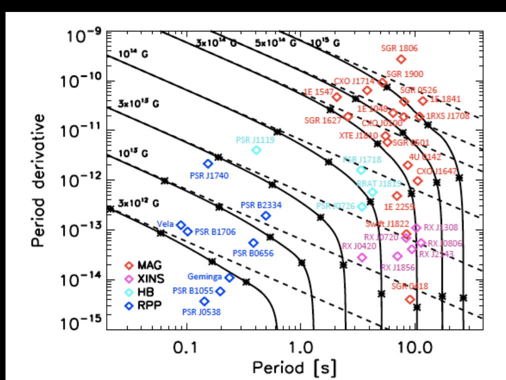


Radio Pulsars

Thermal X-ray pulsars (magnetars, XDINs, etc)
Non-thermally emitting X-ray pulsars
Gamma-ray pulsars

+



- Age uniformly chosen in → [0, 500 Myr]
- Spatial location related to OB associations of massive stars → Disk (spiral arms) + height.
- Initial velocity (“kick”) due to supernova explosion (v ~ 500 km s^{-1})
- P_0 and $\log B_0$ from normal distributions
- Initial inclination angle χ_0 (rotational and magnetic axis) randomly selected.
- Evolution dictated by magneto-rotational models.
- Tested vaccum magnetosphere and with plasma, secular alignment or not.

B-field decay models —> Monte-Carlo Simulations —> 2D Kolmogorov-Smirnov test

(Gullon, Pons, Rea et al. 2015, submitted)

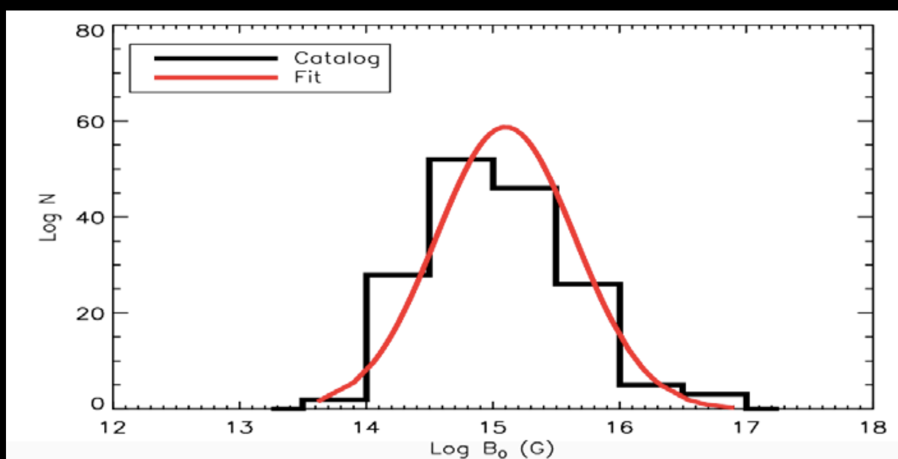
We derive B_0 and P_0 for all GRBs with Swift X-ray plateaus well fit with a magnetar spin-down model.

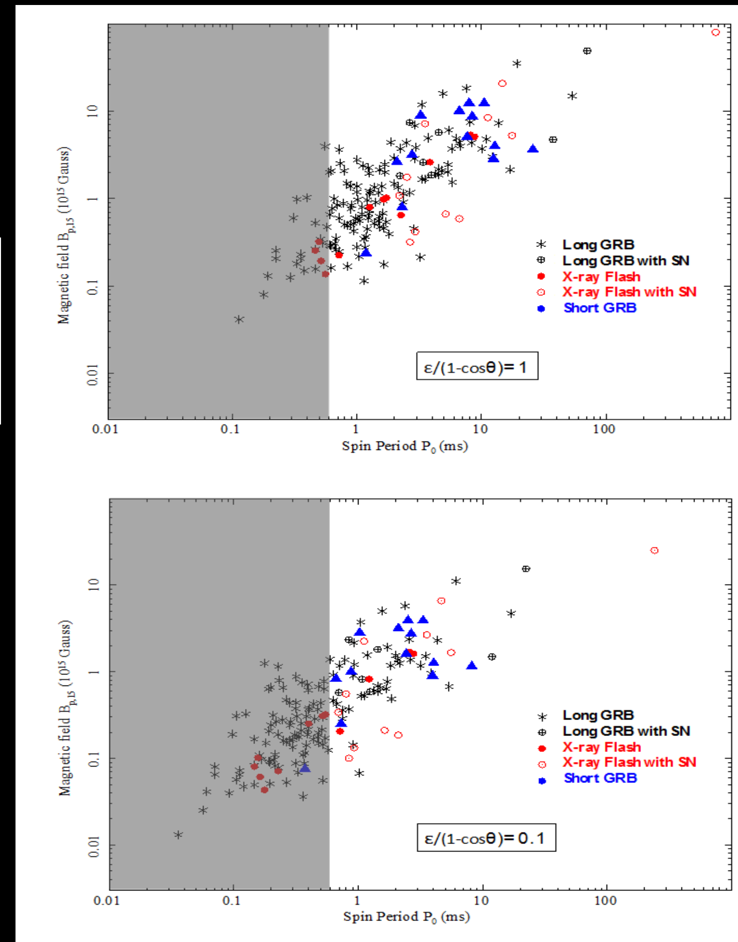
$$T_3 \simeq \tau_{\rm sd} = 2.05\ (I_{45} B_{p,15}^{-2} P_{ms}^{2} R_6^{-6})$$

$$L_{49} \simeq L_{\rm sd} = (B_{p,15}^{2} P_{ms}^{-4} R_6^{6})$$

$$B_{0p,15}^2 \simeq 4.2025 I_{45}^2 R_6^{-6} [L_{\rm sd,49} * \epsilon/(1-\cos\theta)]^{-1} \tau_{\rm sd,3}^{-2}$$
$$P_{0,-3}^2 \simeq 2.05 I_{45} [L_{\rm sd,49} * \epsilon/(1-\cos\theta)]^{-1} \tau_{\rm sd,3}^{-1} \quad ,$$

(Usov 1992; Zhang & Meszaros 2002)

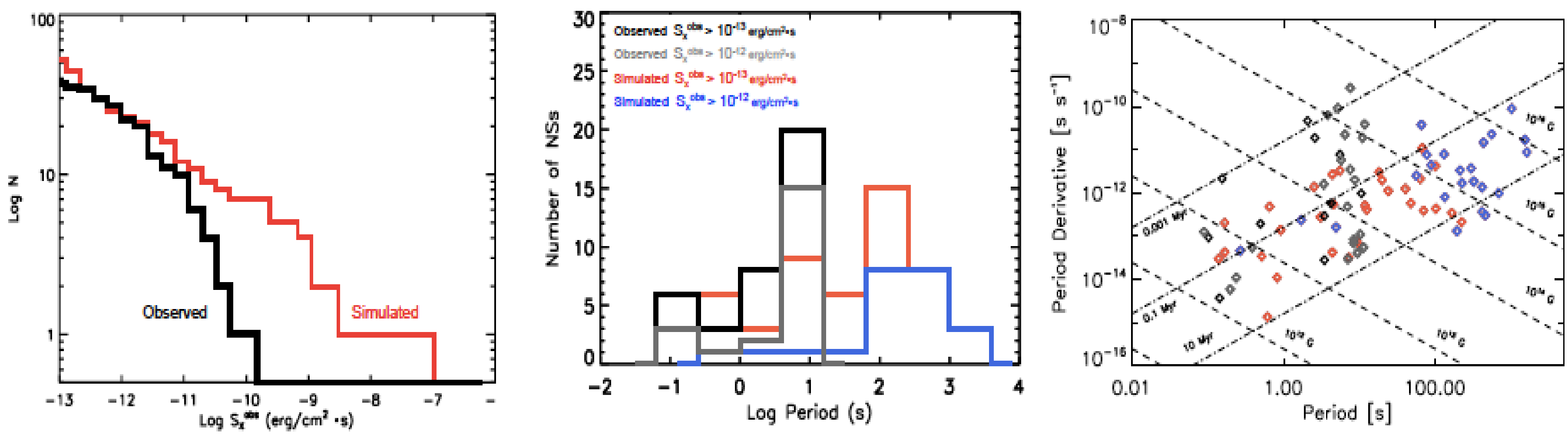




How these B_0 and P_0 compare with the Galactic population of magnetars we know of?

(Rea et al. 2015, ApJ)

4. GRB-magnetars vs Galactic magnetars: simulations

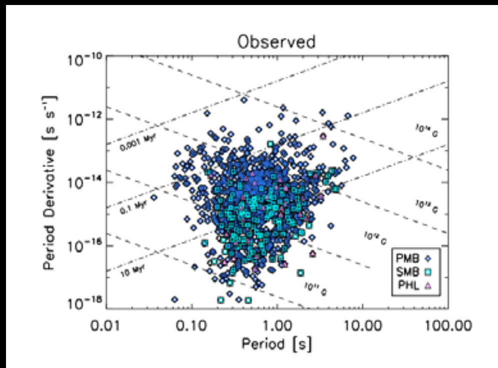


- Simulating 100 SN-Type-GRBs in 1 Myr in the Milky Way we would expect to have now ~25 “observable” magnetars. Numbers ok!

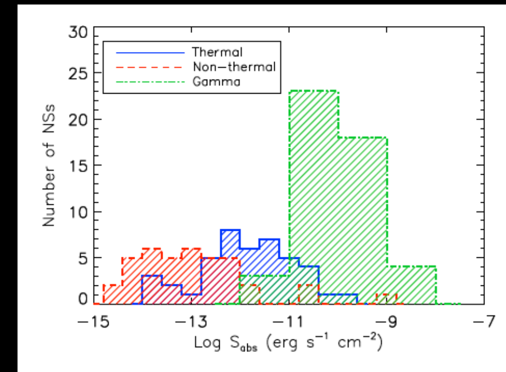
- However, the expected X-ray luminosities and spin period distribution of these GRB-magnetars cannot be reconciled with what observed in our magnetars. Properties are NOT ok!

If GRB plateaus are powered by newly born magnetars (hence being also the central engine), there should exist in Nature “magnetars” formed via typical CC-SNe, and “super-magnetars” via a GRB-SNe.

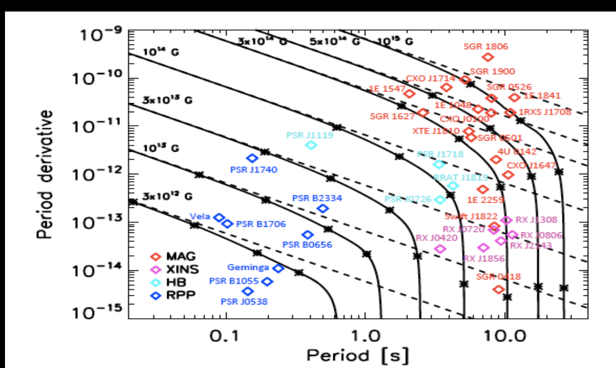
Population Synthesis and magnetars' birth rate



Observed Radio Pulsars



Thermal X-ray pulsars (magnetars, XDINs, etc)
Non-thermally emitting X-ray pulsars
Gamma-ray pulsars



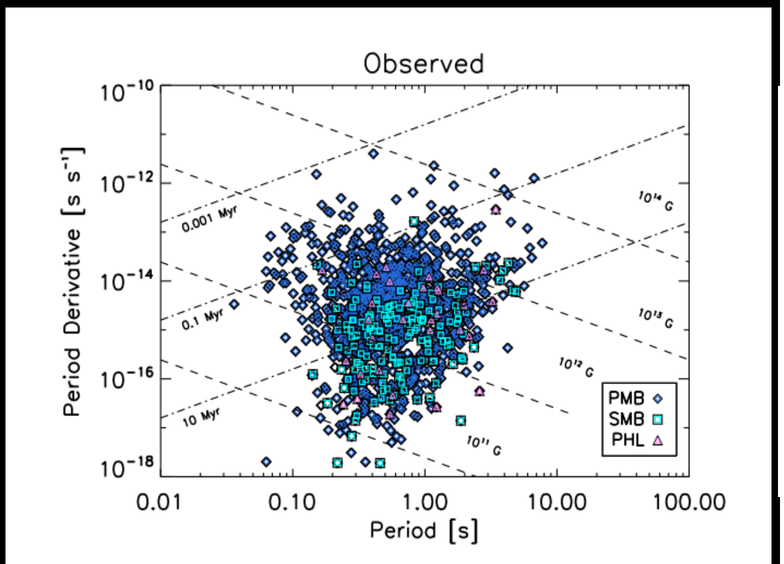
- Age uniformly chosen in → [0, 500 Myr]
- Spatial location related to OB associations of massive stars → Disk (spiral arms) + height.
- Initial velocity ("kick") due to supernova explosion ($v \sim 500$ km s^{-1})
- P_0 and $\log B_0$ from normal distributions
- Initial inclination angle χ_0 (rotational and magnetic axis) randomly selected.
- Evolution dictated by magneto-rotational models.
- Tested vaccum magnetosphere and with plasma, secular alignment or not.

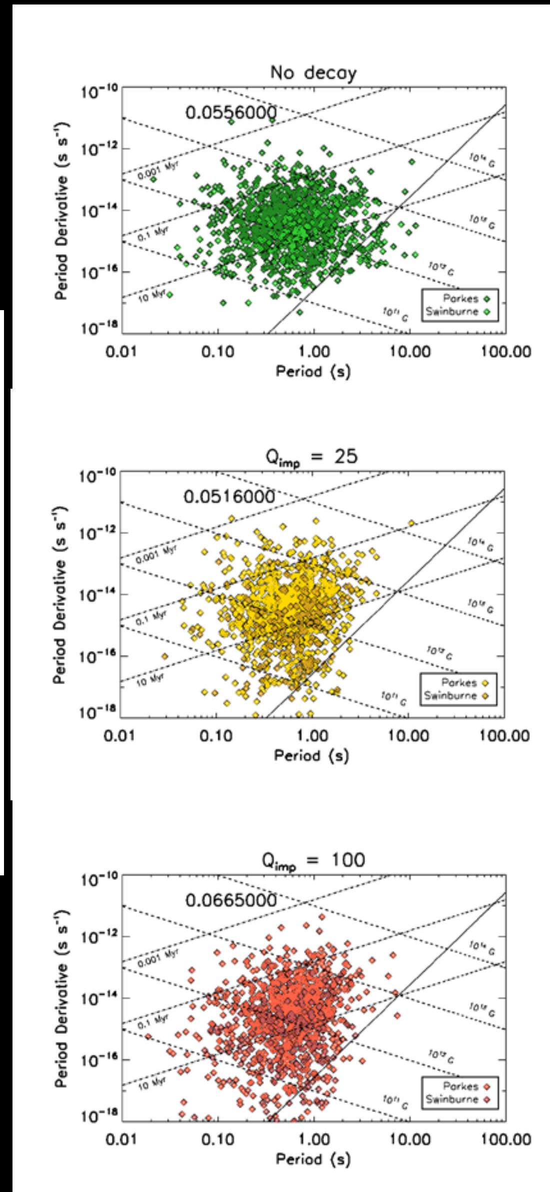
B-field decay models —> Monte-Carlo Simulations —> 2D Kolmogorov-Smirnov test

(Fauscher-guitierre & Kaspi 2006; Gonthier et al. 2009; Popov et al. 2010; Gullon et al. 2014, 2015; Borghese et al. 2017 in prep)

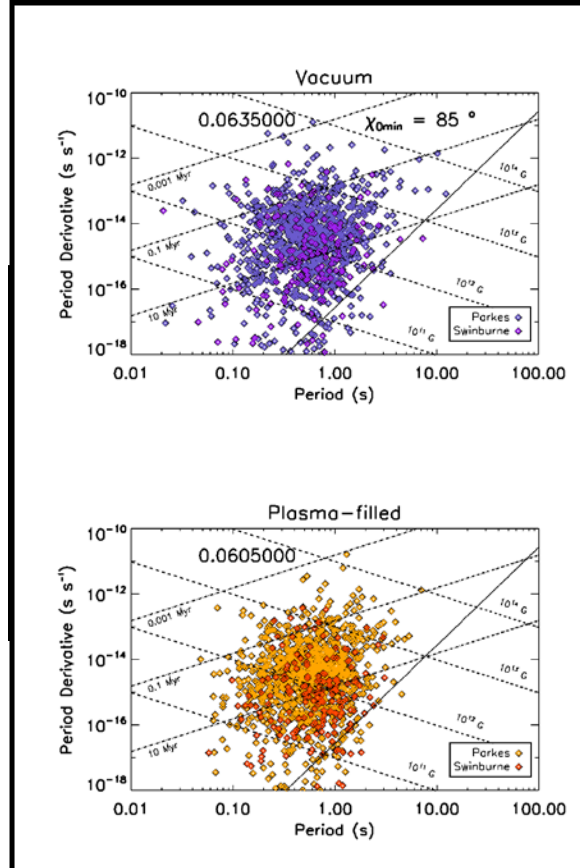
Population Synthesis and magnetars' birth rate

Observed Radio Pulsars

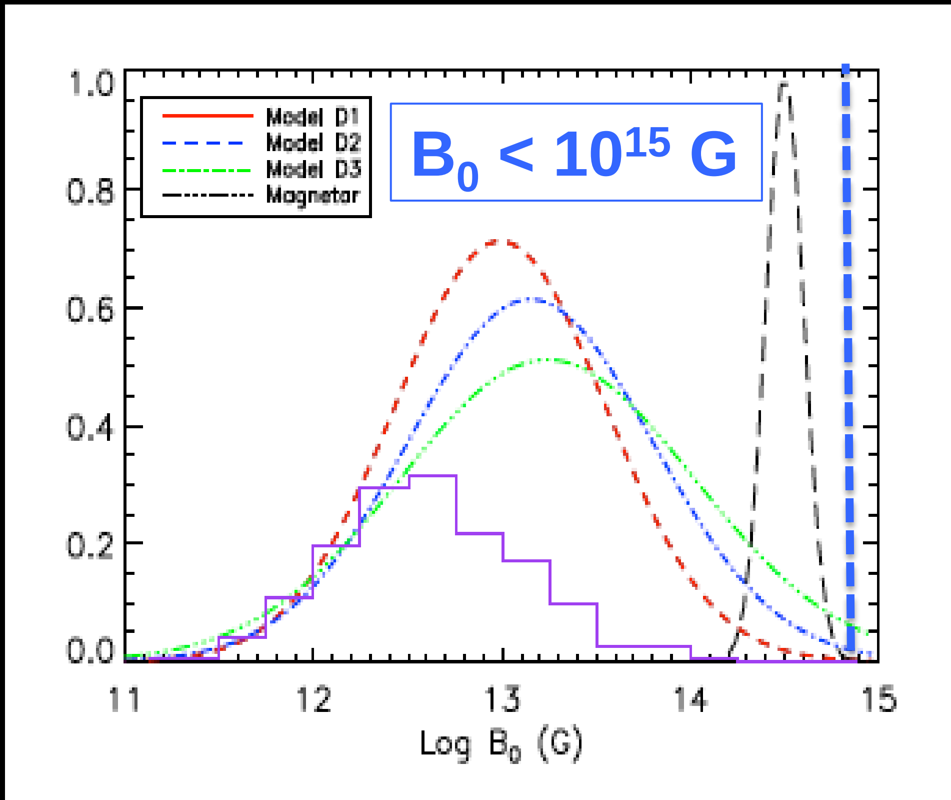


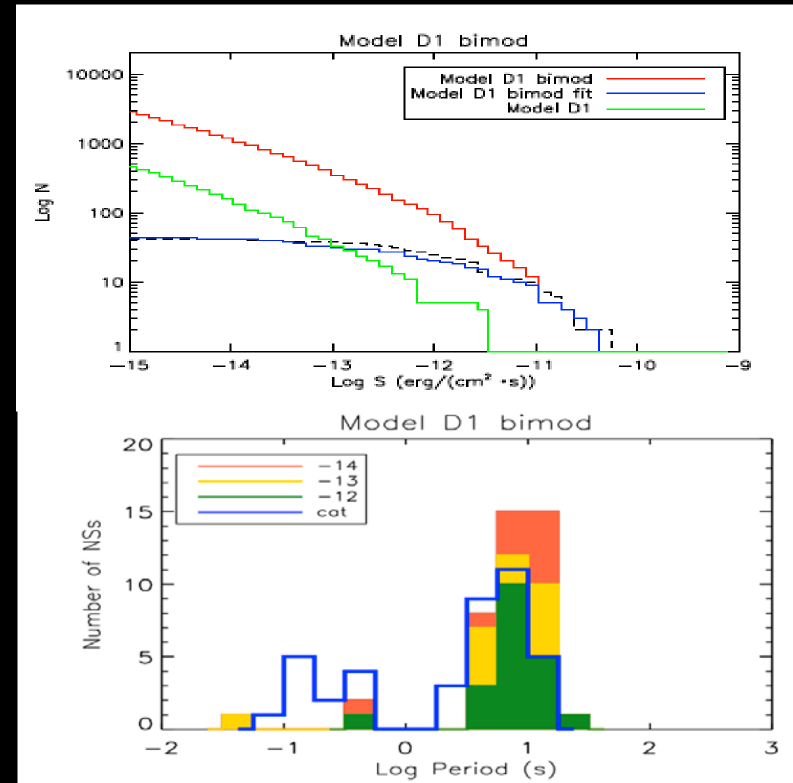


Monte-Carlo simulations



Population Synthesis and magnetars' birth rate





- If the origin of B-field is attributed to MHD instabilities (i.e. any dynamo process relate d to convection), one should expect a saturation when the B-field becomes dynamic ally relevant to suppress the instability.

A bi-modal distribution is preferred to explain the pulsar population + magnetars!

- This might be explained by different progenitors: binaries versus isolated?