Magnetars: the Universe strongest magnets

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Magnetars: the Universe strongest magnets

A bit of history

- 1931 Chandrasekhar argued that WDs collapse at masses > 1.4 $M_\odot$. (Chandrasekhar 1931, ApJ)

- 1934 Baade & Zwicky proposed the existence of NS, they predicted their formation due to supernova explosion and their radius of ~10 km . (Baade & Zwicky 1934, Proc.Nat.Acad.Sci.)

- 1939 Oppenheimer & Volkoff defined the first equation of state for a NS of mass ~1.4 $M_\odot$, a radius of ~10 km and a density of ~10^{14} gr/cm^3 (Oppenheimer & Volkoff, Phys.Rev)

- 1967 Pacini predicted electromagnetic waves from rotating NSs and that such star might be powering the Crab nebula. (Pacini 1967 and 1968, Nature)

- 1967 Hewish & Bell studing interplanetary scintillation observed a periodicity of 1.337s, discovering the first pulsar: PSR 1919+21. (Hewish et al. 1968, Nature)
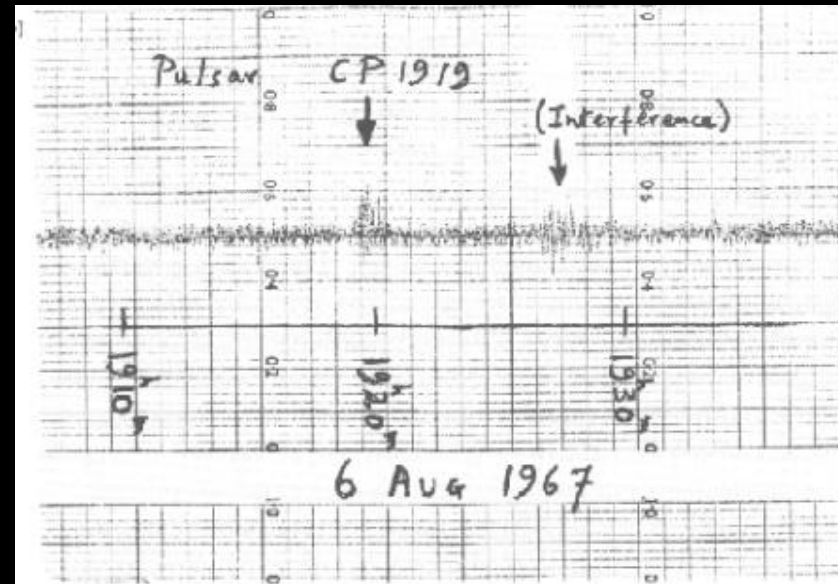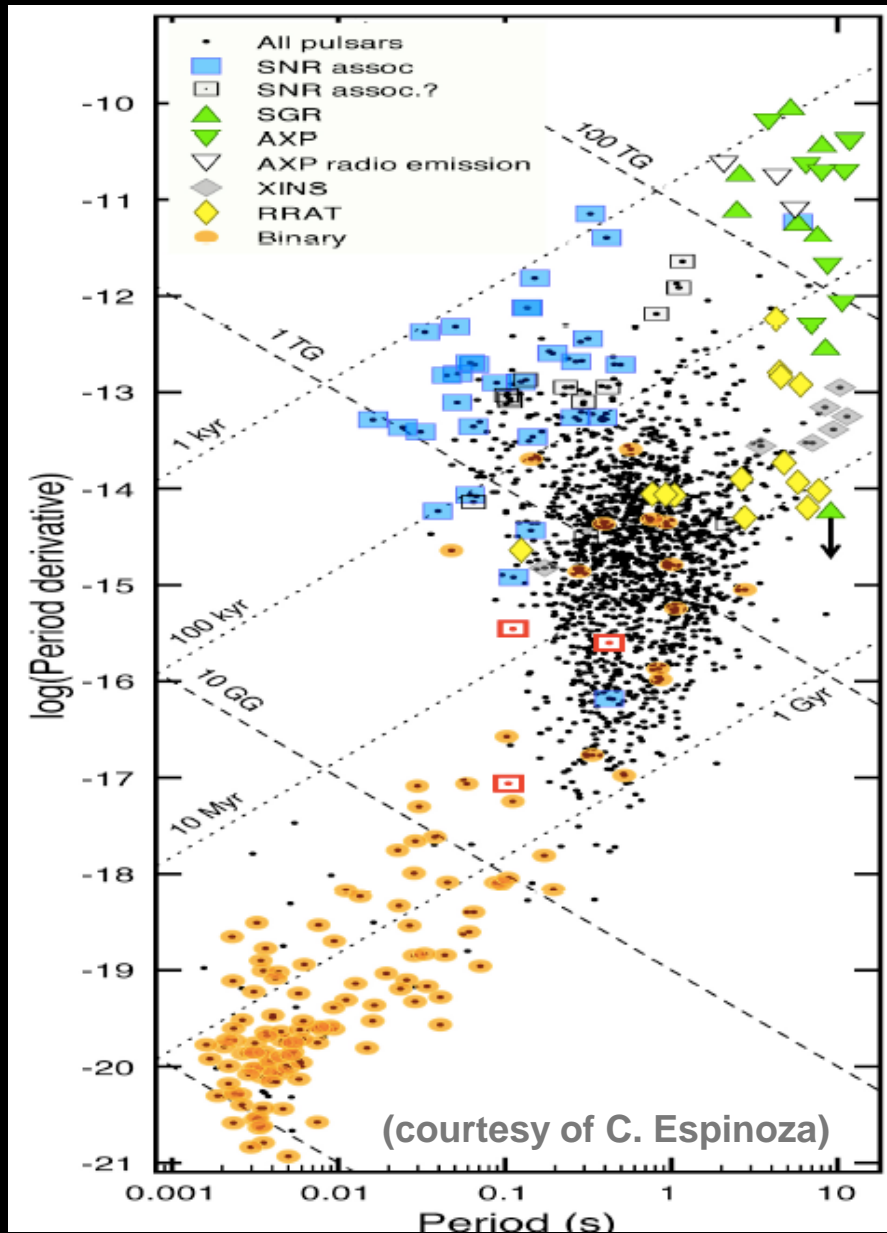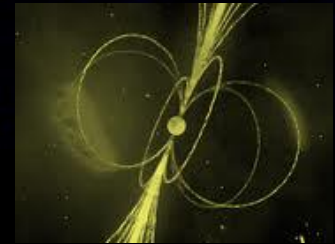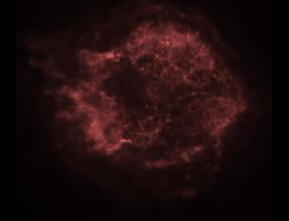
Magnetars: B-powered
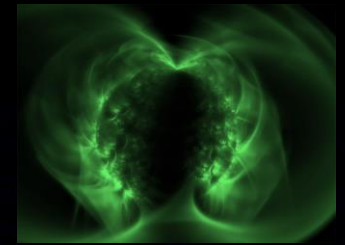
XDINS: kT-powered

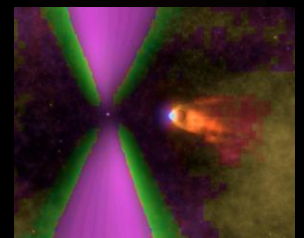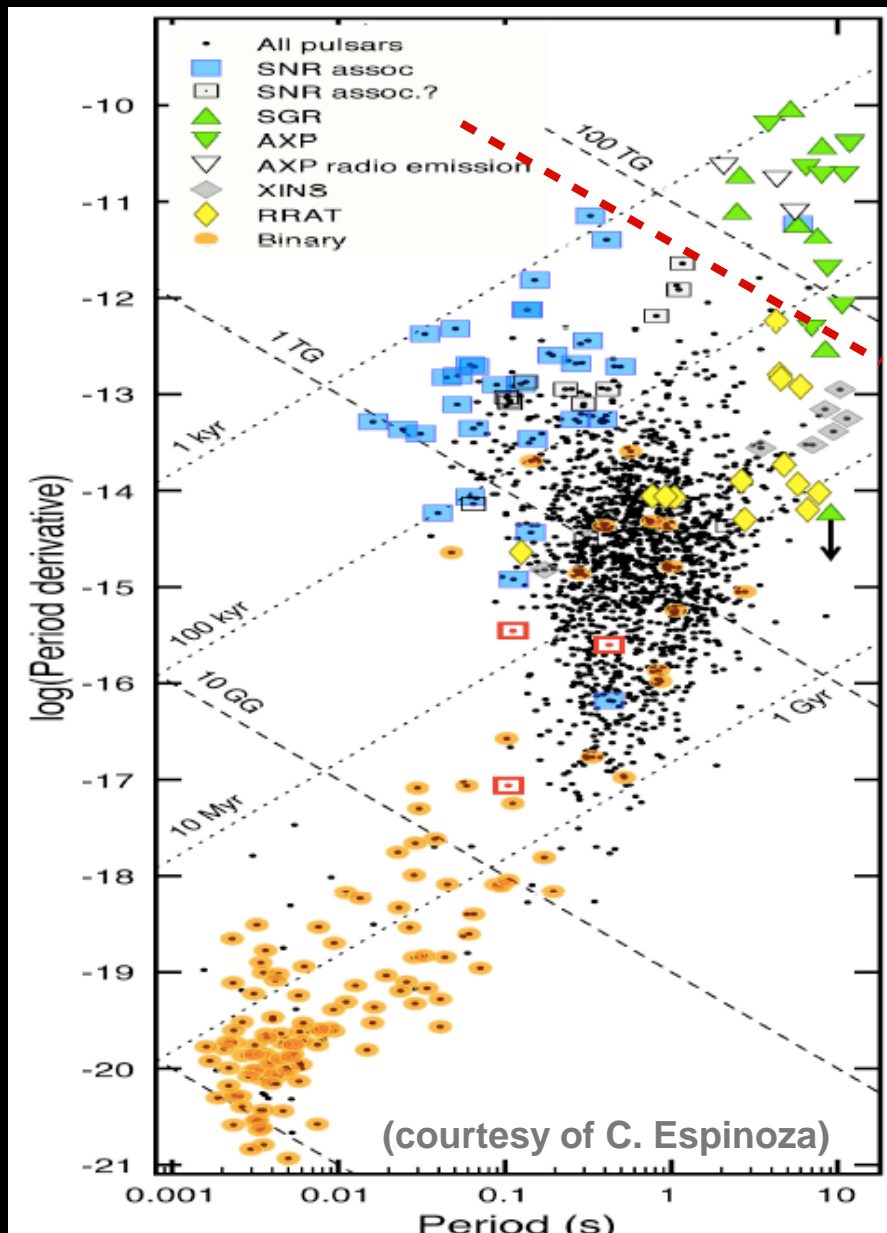Pulsars and RRATs: rotation-powered

CCOs: kT-powered

Recycled binaries: rotation-powered

(courtesy of C. Espinoza)

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The pulsar zoo: B-field estimates

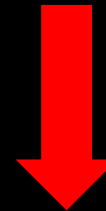(courtesy of C. Espinoza)

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

$$P_{dip-rad} = -\frac{2}{3c^3}\left|\ddot{u}_d\right|^2 = -\frac{2(B_d R_{ns}^3 \sin(1+\alpha))^2}{3c^3}\left(\frac{4\pi^2}{P_s^2}\right)^2$$
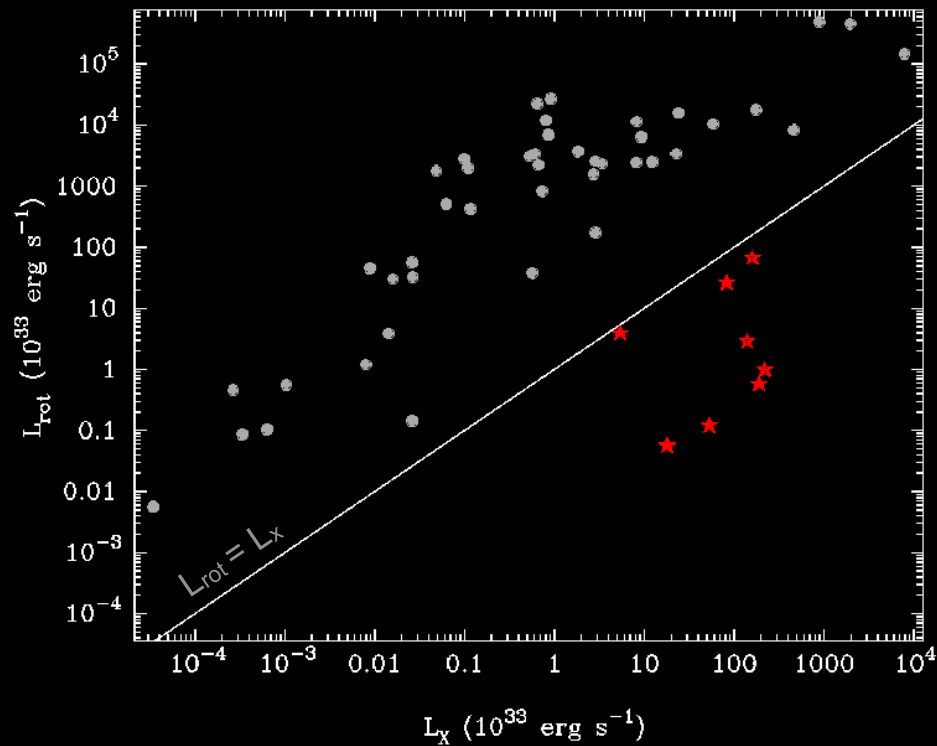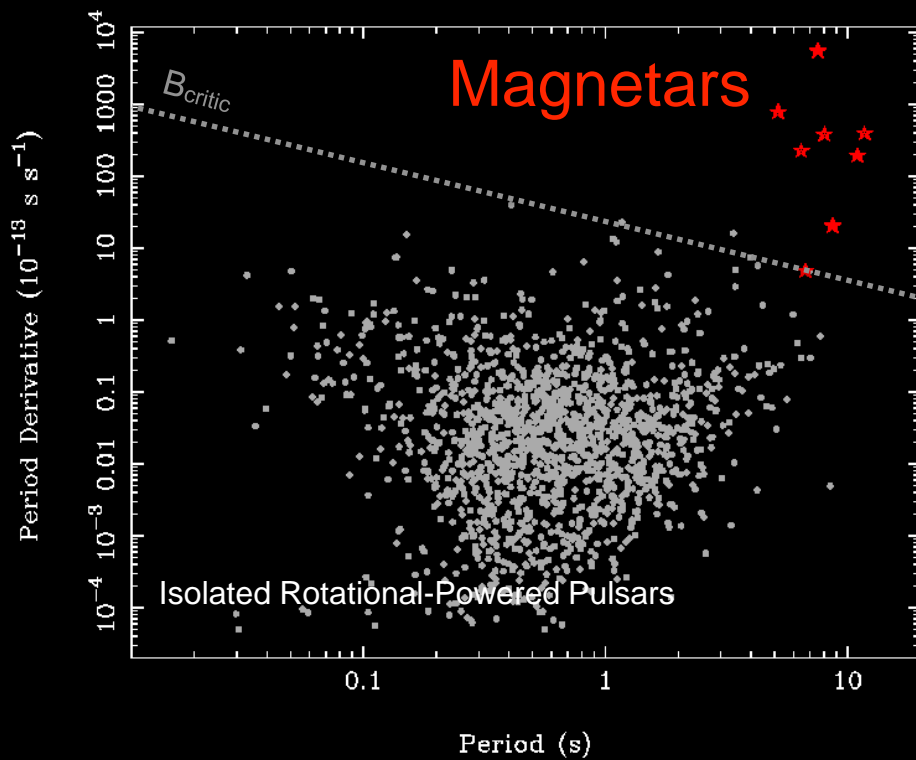
$$B_d \approx 3.2 \times 10^{19}\sqrt{P_s\dot{P}_s}\,Gauss$$

$$B_{critic} = \frac{m_e^2 c^3}{e\hbar} = 4.414\times 10^{13}\,Gauss$$

Critical Electron Quantum B-field

Magnetars: a decade ago…
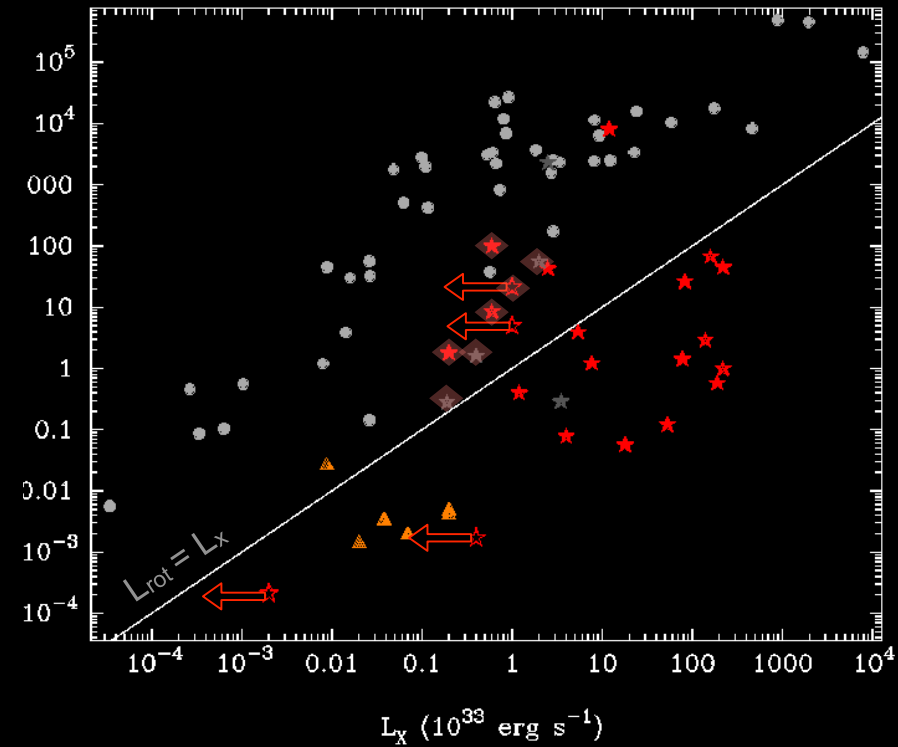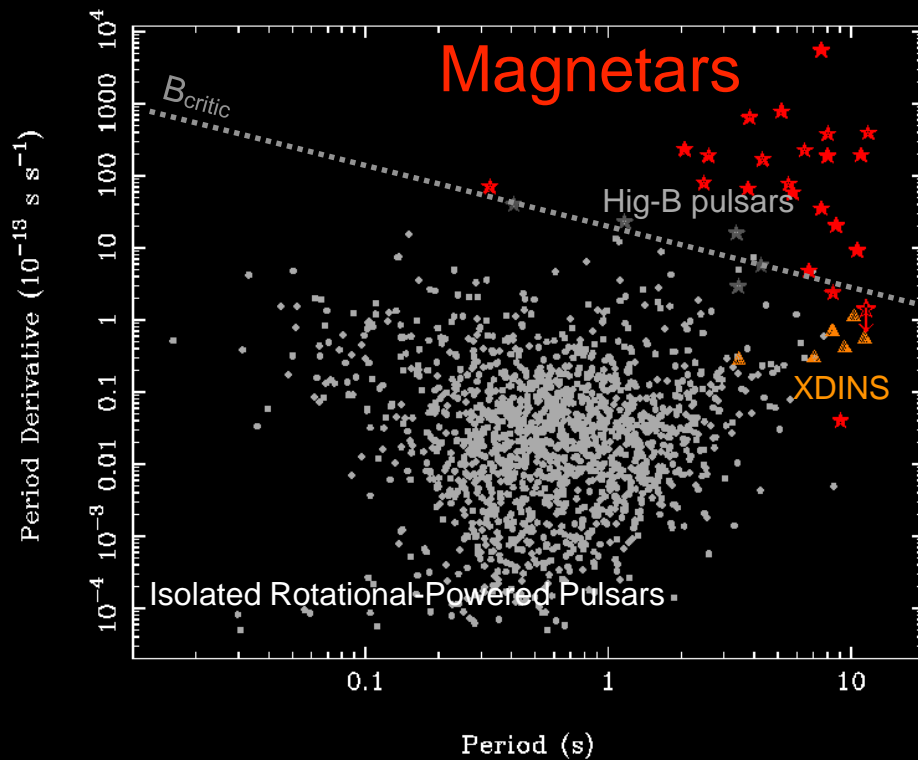
- Magnetic fields > B critical ~4.4x10^{13} Gauss

- X-ray luminosities exceed rotational power

- Stable soft X-ray pulsars with P~5-10s and Lx~10$^{34-35}$ erg/s

- Radio quiet X-ray pulsars

- Magnetic fields NOT always > B critical ~4.4x10^{13} Gauss

- X-ray luminosities does NOT always exceed rot. power

- NOT stable soft and hard X-ray pulsars (P~0.3-10s and Lx~10$^{30-35}$ erg/s)

- NOT radio quiet, but radio on during transient events
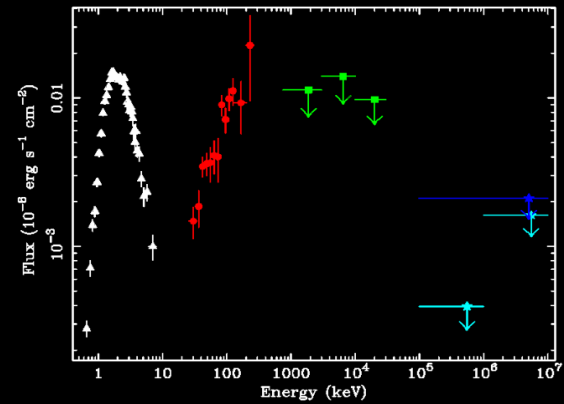
Short bursts

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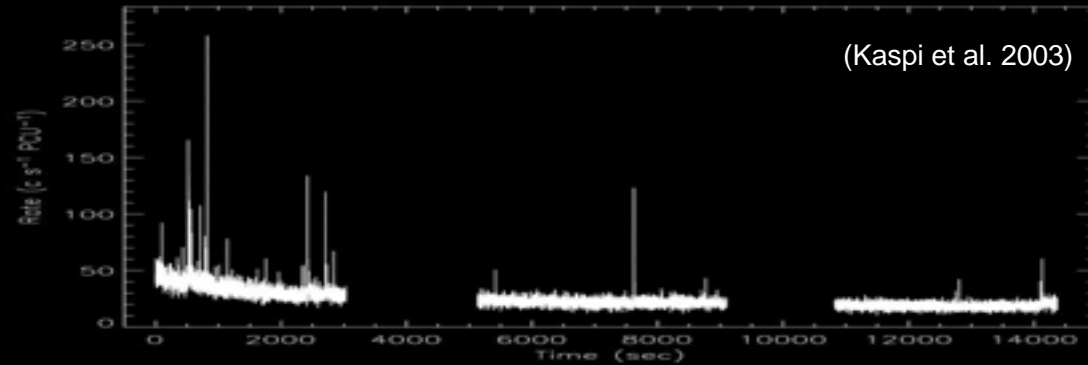- peak ~10^{41} ergs/s
- soft γ-rays thermal spectra

(Kaspi et al. 2003)

Intermediate bursts

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

(Israel et al. 2008)
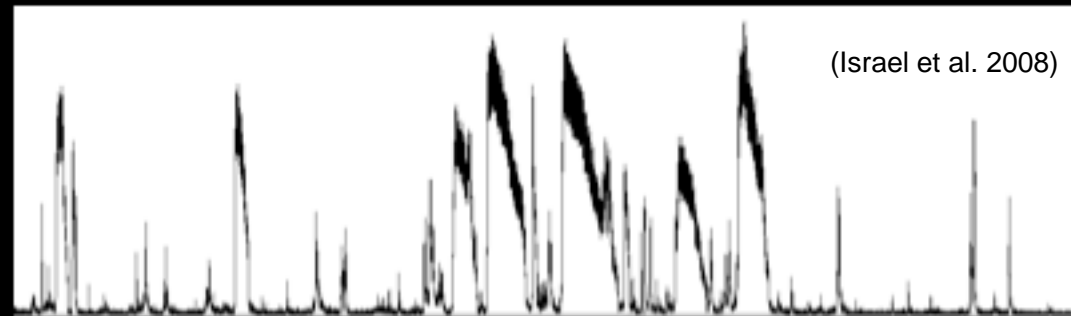
Giant Flares

- their output of high energy is exceeded only by blazars and GRBs
- peak energy > 3×10^{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)
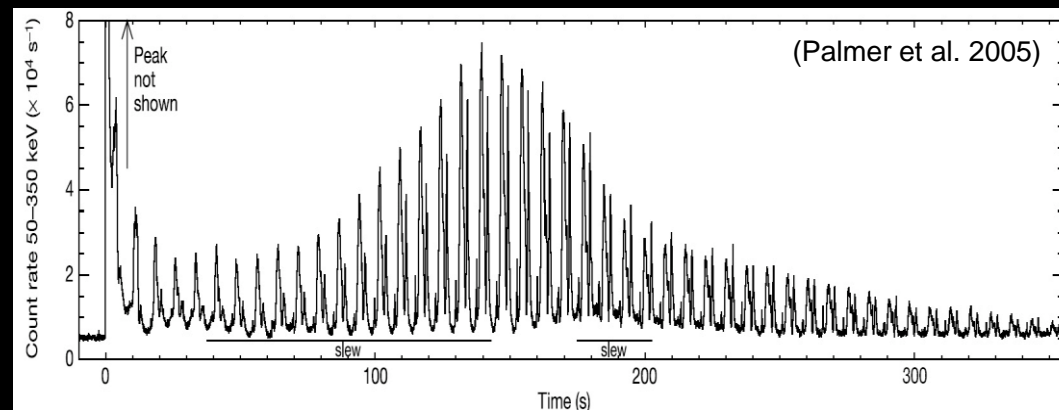
(Palmer et al. 2005)
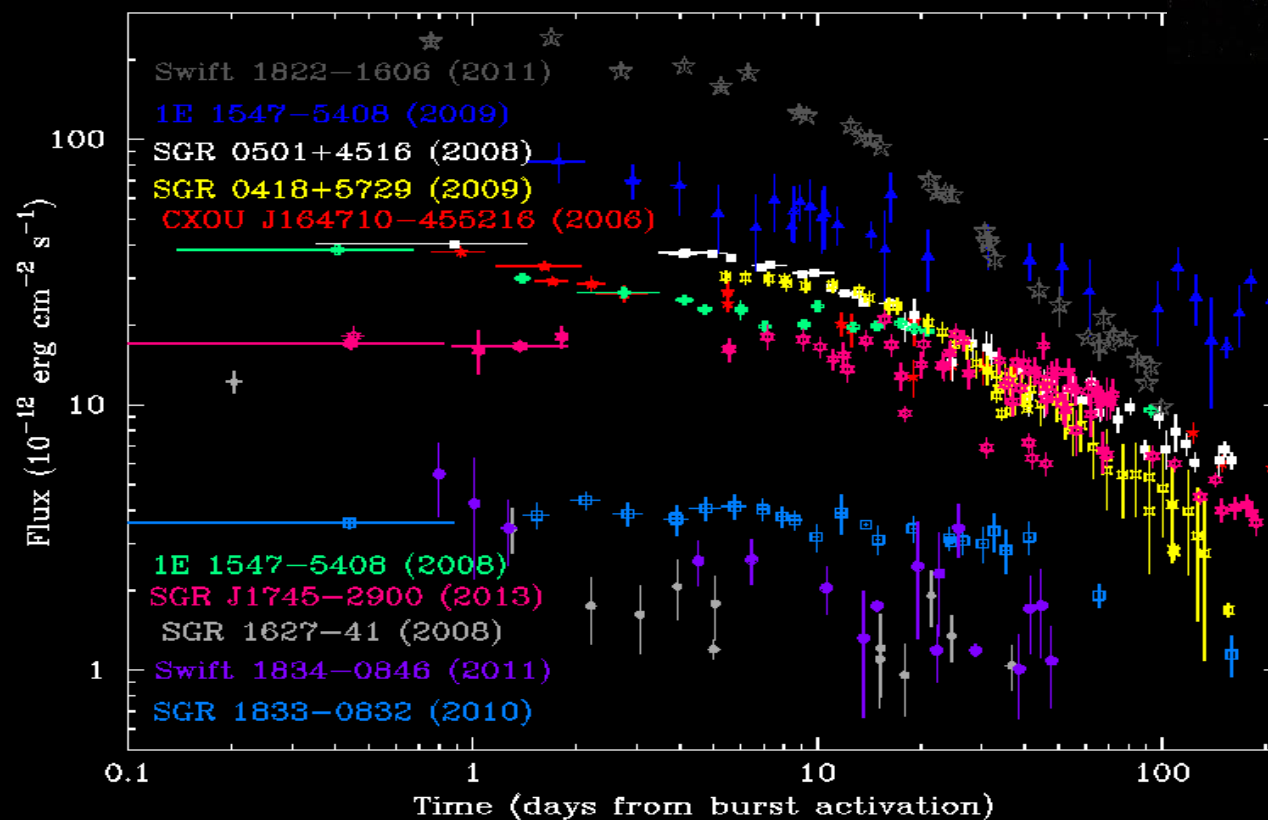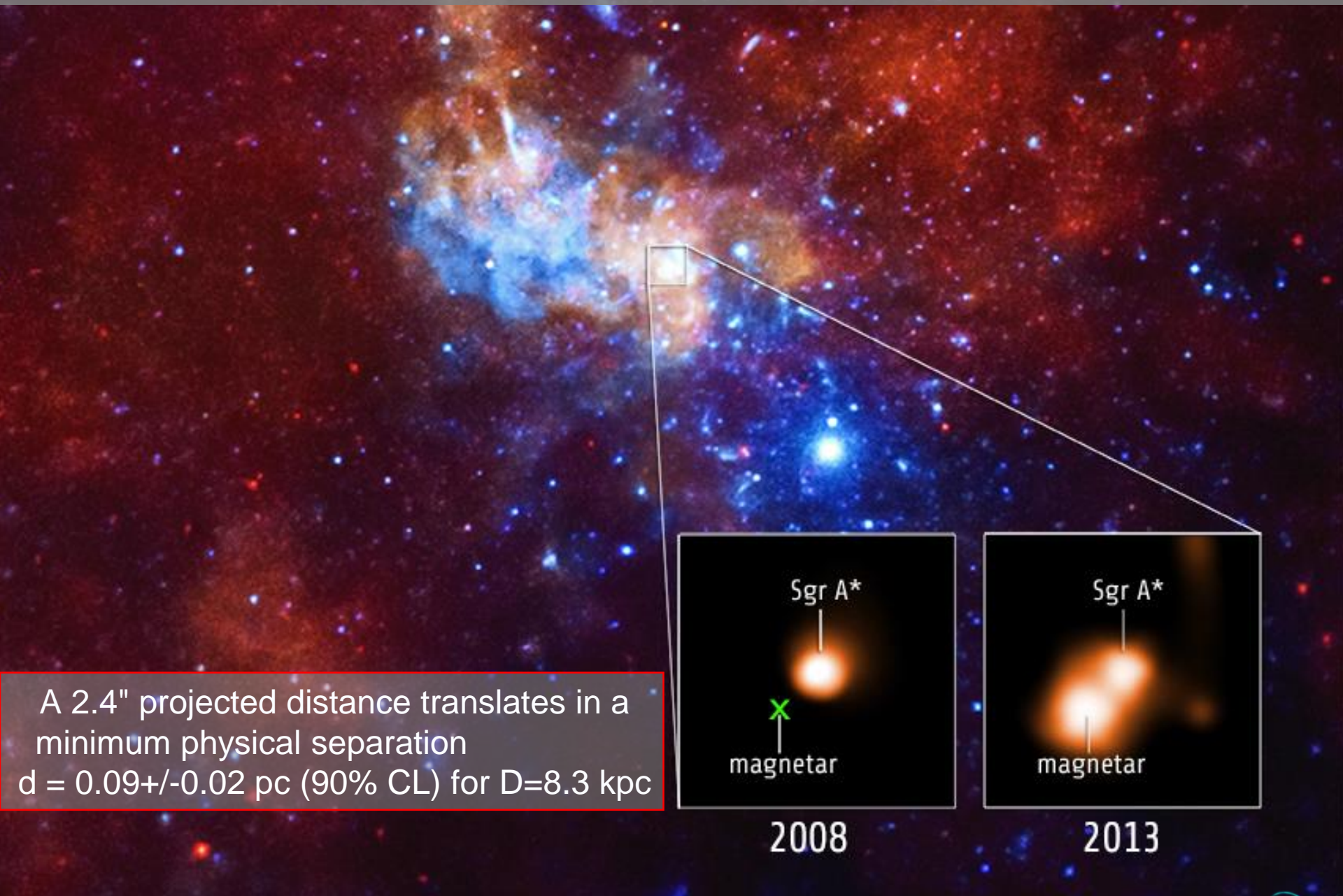
A 2.4" projected distance translates in a minimum physical separation
d = 0.09+/-0.02 pc (90% CL) for D=8.3 kpc

Sgr A*

magnetar

2008

Sgr A*

magnetar

2013

(Mori et al. 2013; Kennea et al. 2013; Rea et al. 2013; Kaspi et al. 2014; Coti Zelati et al. 2015)

EEC
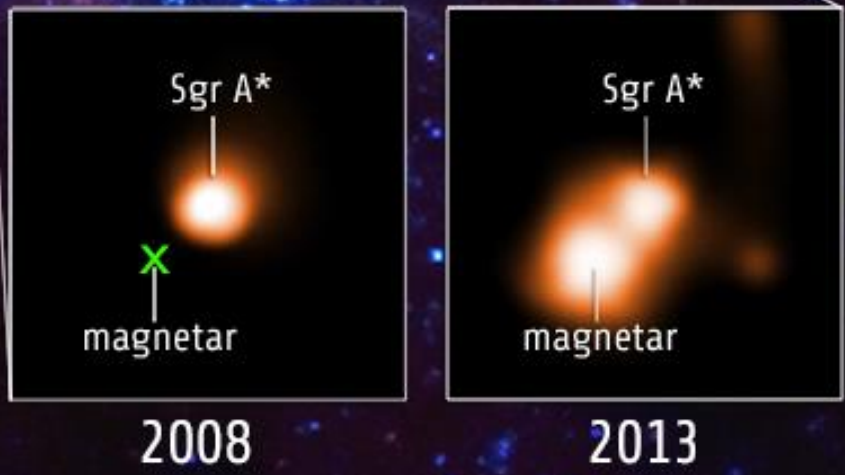
Magnetar theory in a nutshell

- 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.

- Their internal magnetic field is twisted up to 10 times the external dipole. At intervals, stresses build up in the crust which might cause causing glitches, flares...

- Magnetar magnetospheres are filled by charged particles trapped in the twisted field lines, interacting with the surface thermal emission through resonant cyclotron scattering.
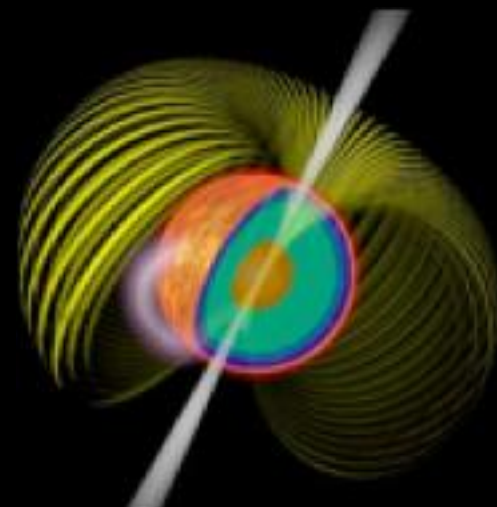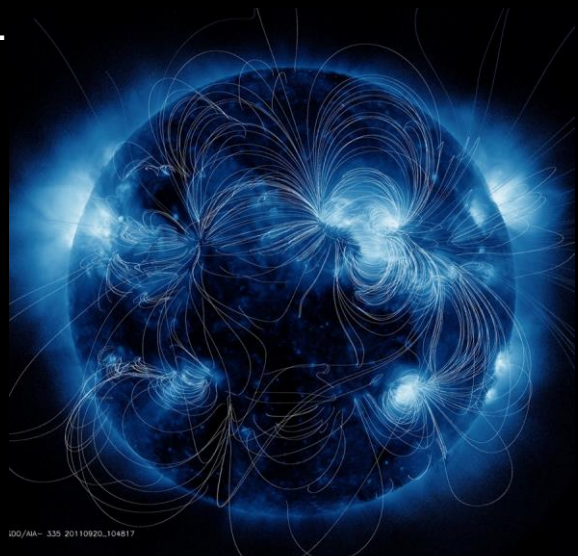
High-B PSR
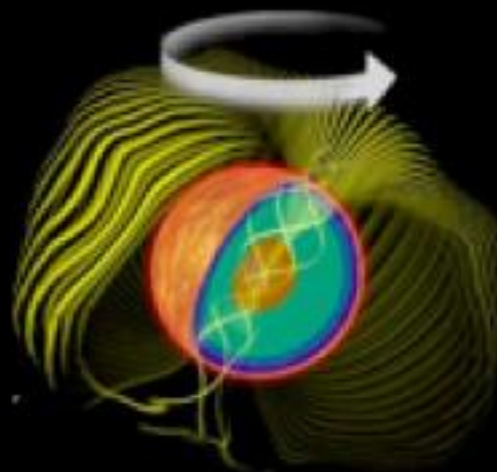
SGR/AXP

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

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1. Magnetars can be radio pulsar during outbursts.

(Camilo et al. 2006, Nature; Camilo et al. 2007, ApJ)
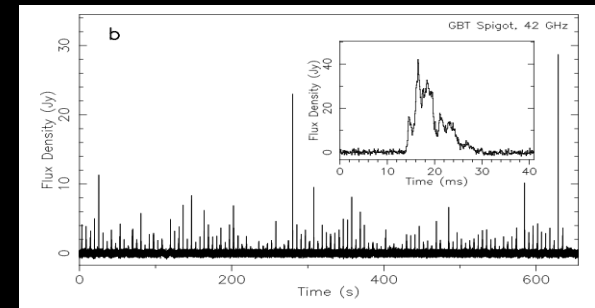
2. A "normal" X-ray pulsar showed magnetar activity.

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

quiescence   outburst

3. Magnetars were discovered having also low B-field.

(Rea et al. 2010, Science; Scholtz et al. 2012; Rea et al. 2012, 2013, 2014 ApJ)

P = 9.1s
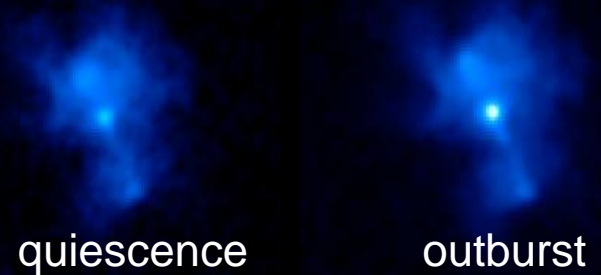$\dot{P}$ < 6x10⁻¹⁵ s/s

B_Q=4.4x10¹³ G

7.5x10¹² G

Magnetic field was:
B < 7.5x10¹² G

(van der Horst et al. 2010, ApJ; Esposito et al. 2010, MNRAS; Rea et al. 2010, Science)
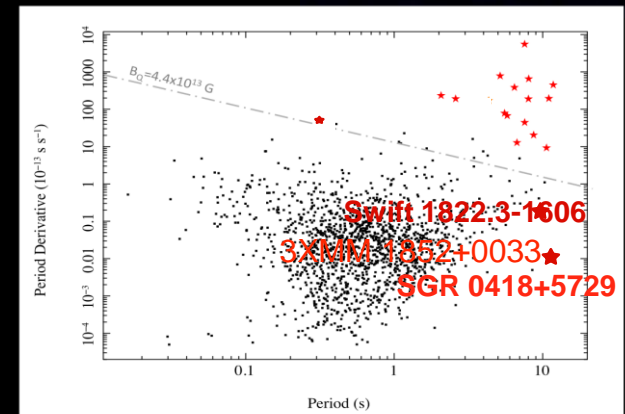
Low magnetic-field magnetars: we have three now!

$B = 6.2 \times 10^{12}$ G $B = 2.3 \times 10^{13}$ G $B < 4 \times 10^{13}$ G
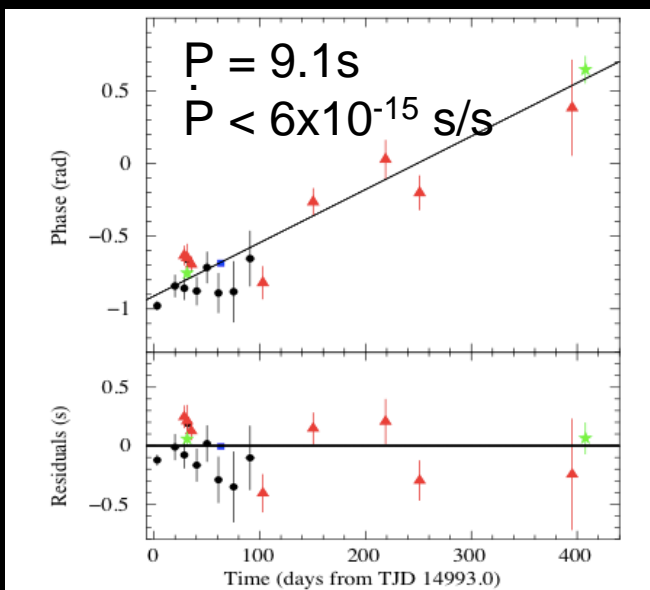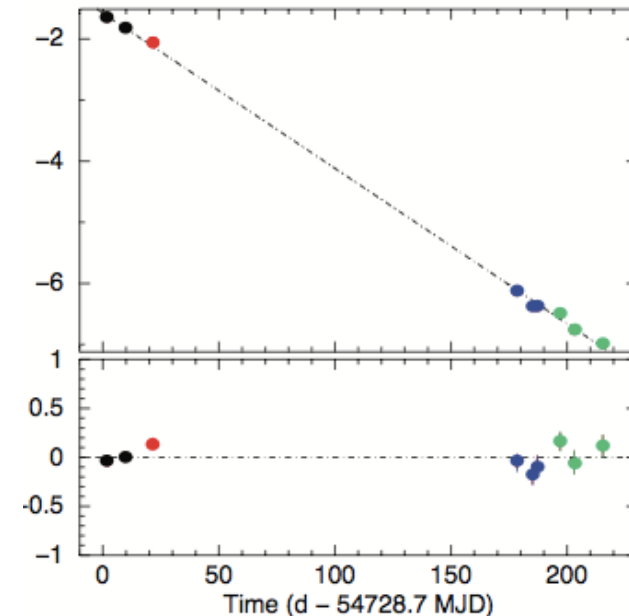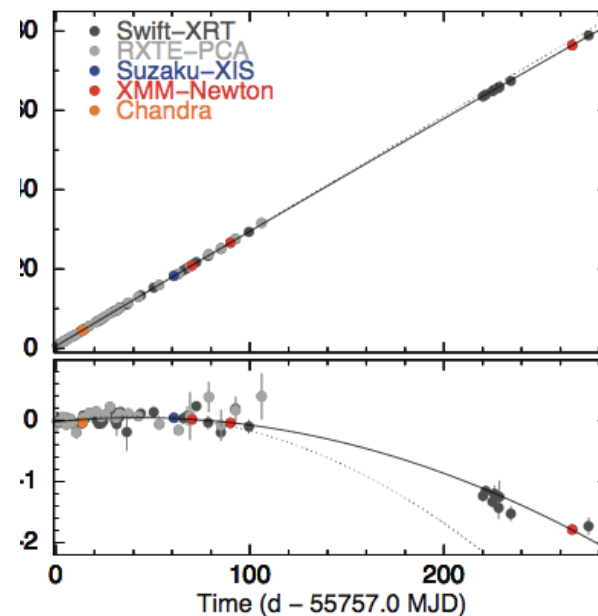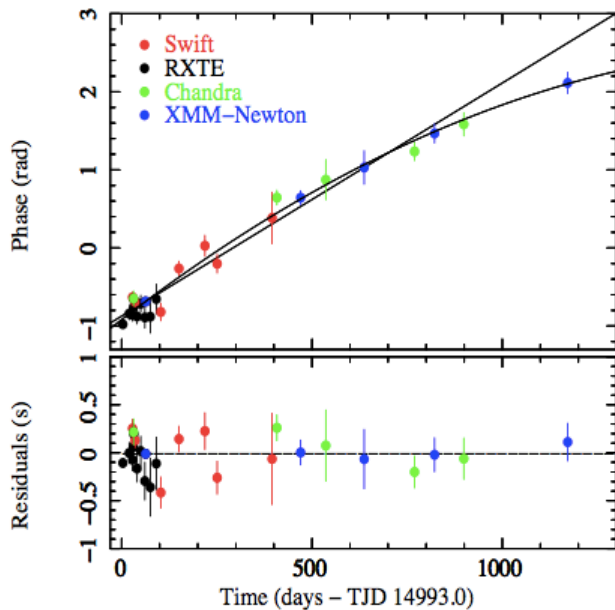

SGR 0418+5729

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

Swift 1822-1606

Rea et al. 2012, ApJ
Scholtz et al. 2012, ApJ

3XMM 1852+0033

Rea et al. 2014, ApJL
Zou et al. 2014, ApJL

Magnetars

B_{critic}

PSR 1846-02

Hig-B pulsars

SGR/AXP

1- No critical field!
2- A continuum of Rotational and B-dominated pulsars

Swift 1822.3-1606
3XMM 1852+0033

XDINS

SGR 0418+5729

ed Rotational-Powered Pulsars

0.1   1

Period (s)

Keane & Kramer, 2008, MNRAS
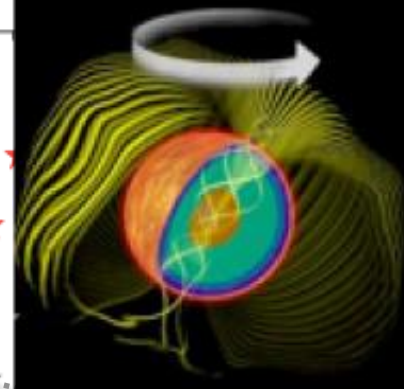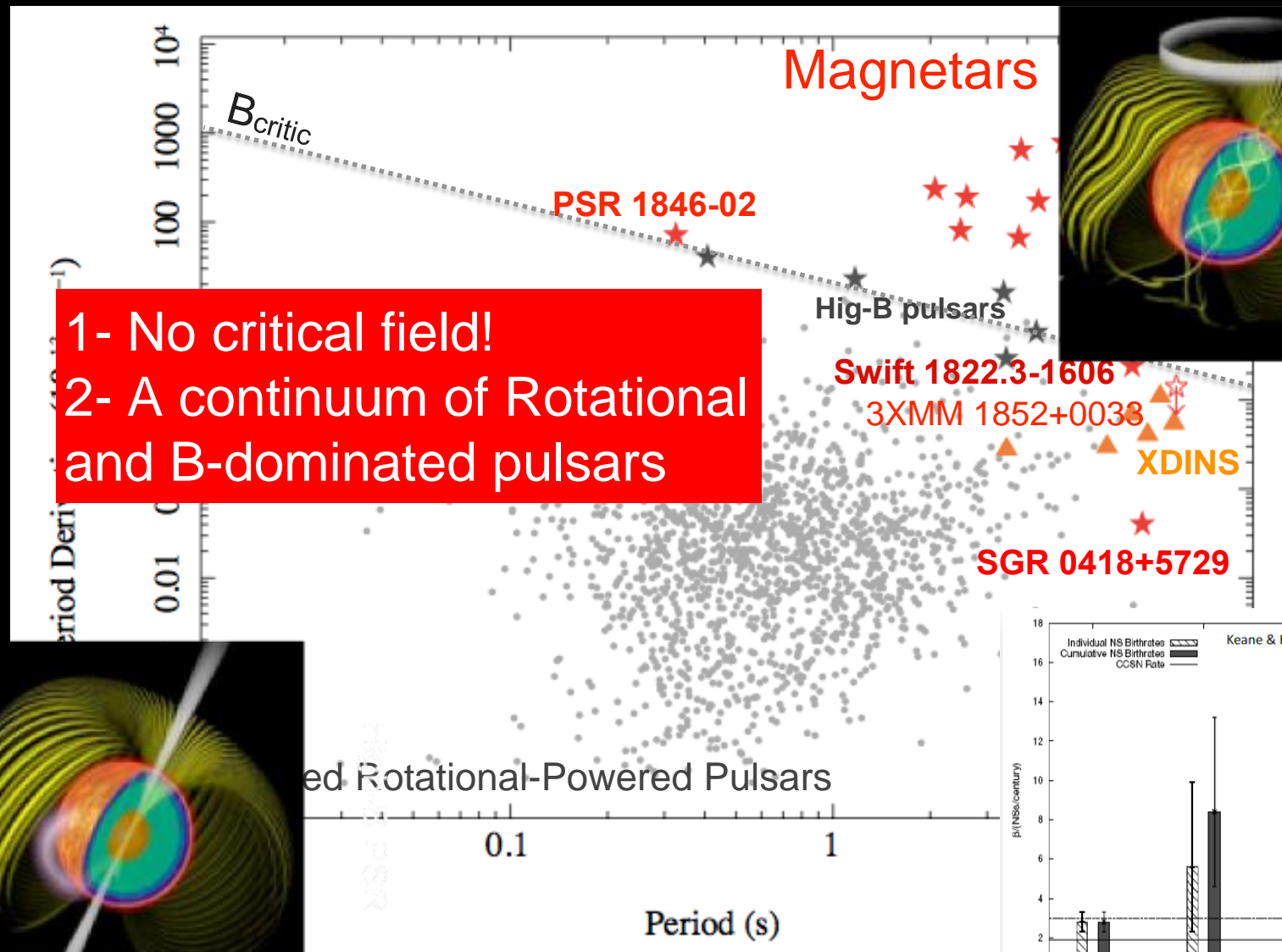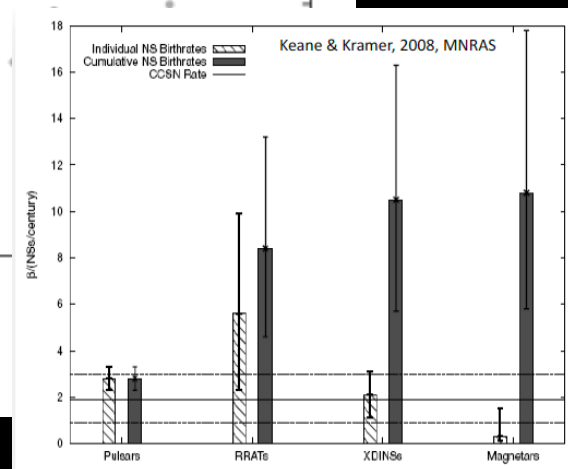
Thermal evolution: energy balance equation

Specific heat   Thermal conductivity   Neutrino emissivity

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

Magnetic evolution: Hall induction equation

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

Hall induction

Electrical resistivity: strongly depends on T

(Aguilera et al. 2008; Pons et al. 2009; Vigano' et al. 2013)

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Normal Pulsar
Intial conditions:
$B_{dip} \sim 10^{13}$ G (white lines)
$B_{int} \sim 10^{14}$ G (colors)
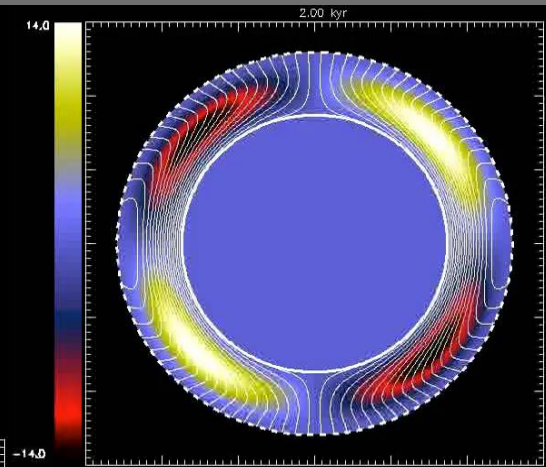
Very Magnetic
Initial conditions:
$B_{dip} \sim 10^{14}$ G (white lines)
$B_{int} \sim 10^{15}$ G (colors)

Extremely Magnetic Pulsar
Intial conditions:
$B_{dip} \sim 10^{15}$ G (white lines)
$B_{int} \sim 10^{16}$ G (colors)
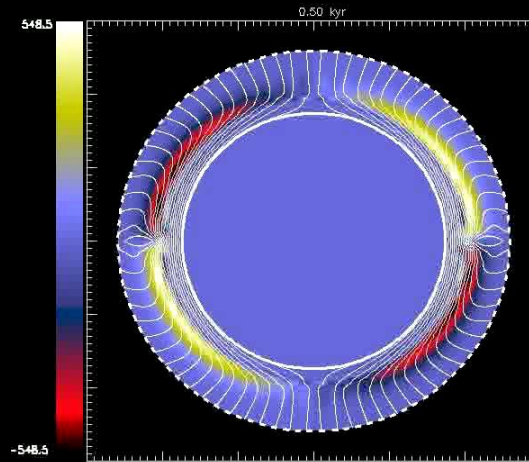
Low B magnetars
are old systemsof
this kind!

Amsterdam/CSIC-IEEC

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.

$$E_{cycl,p} = 0.6\ B_{14}\ keV$$
$$\Rightarrow B \sim (2\text{-}20) \times 10^{14}\ G$$

(Esposito et al. 2010, MNRAS; Rea et al. 2012, ApJ; Tiengo et al. 2013, Nature) *CSIC-IEEC*

Magnetars… are starting to show up everywhere!!!

Pulsar population

Coalescence of compact binaries
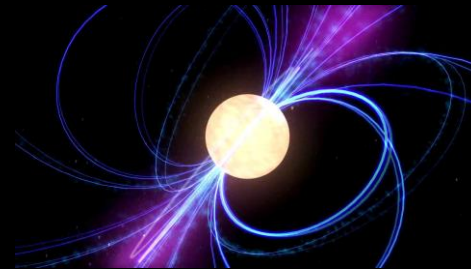
Super Luminous supernovae
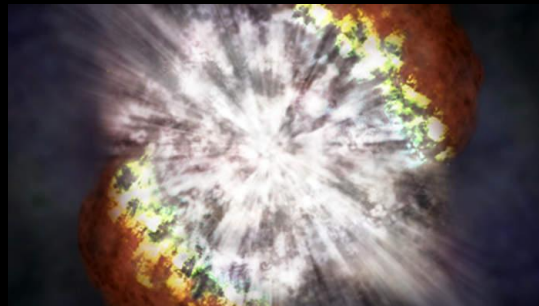
Gamma Ray Bursts
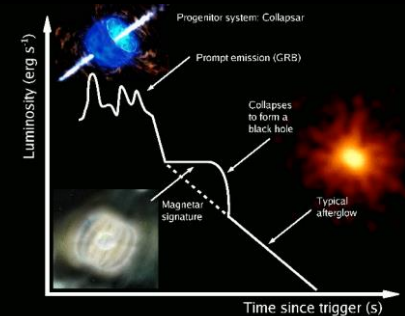
Gravitational waves
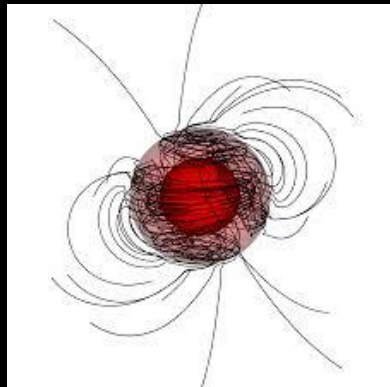
Super Giant Fast X-ray Transients
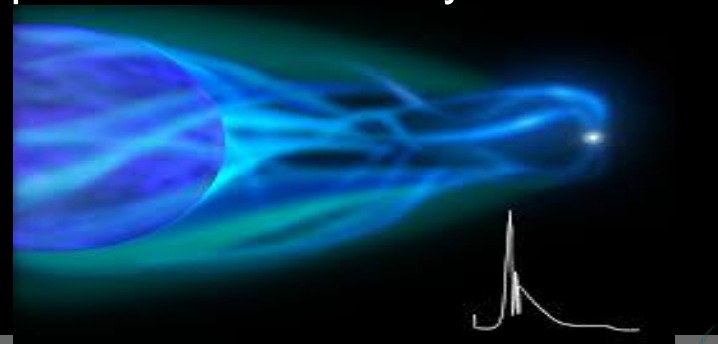
ULXs
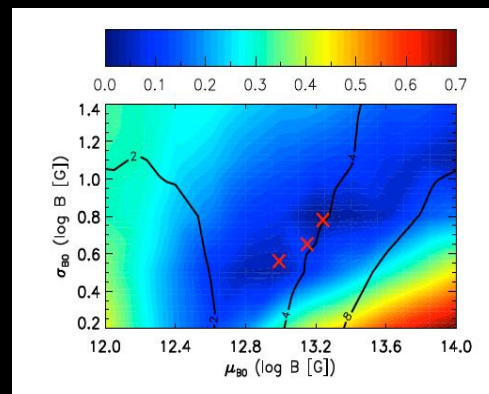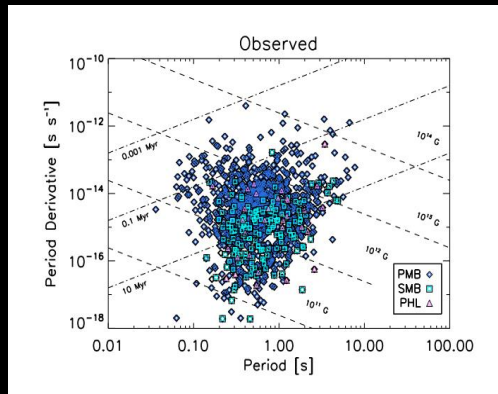
Pulsars Population Synthesis Models using: radio pulsars and all different isolated X-ray pulsar population, comprising magnetars for the first time

$B_0 < 10^{15}$ G
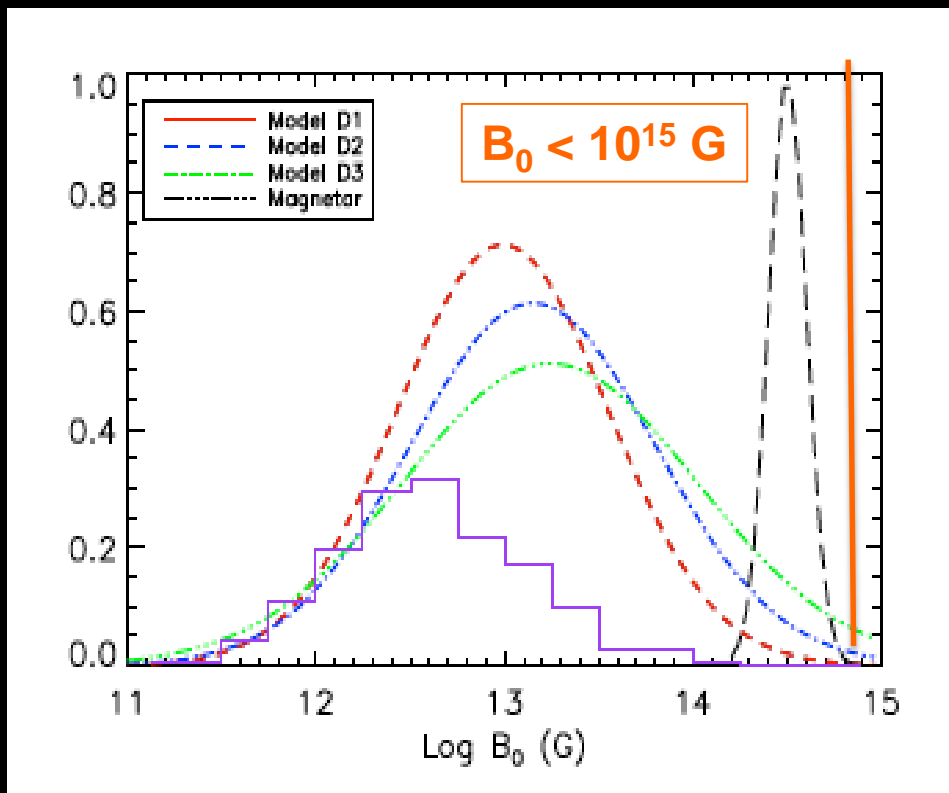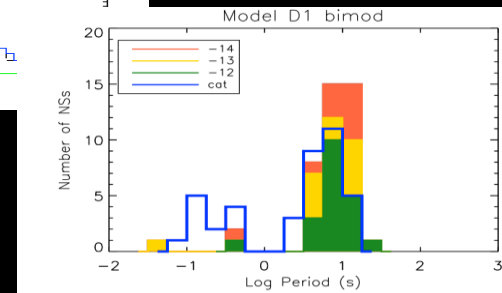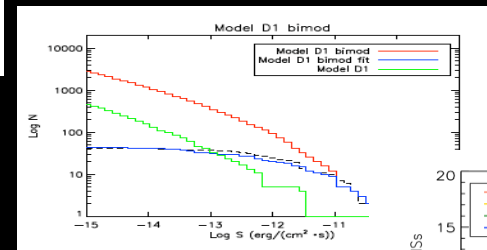
1- Galactic Pulsar distribution of initial B fields cannot be a single Gaussian, and cannot exceed 10^{15} G (in dipole)!

2- ~40% of the pulsar population is born with fields between 10^{14}-10^{15}

(Gullon, Pons, Vigano, Rea, Perna, Miralles 2015, MNRAS)

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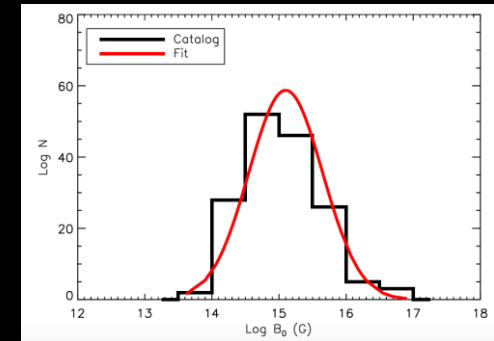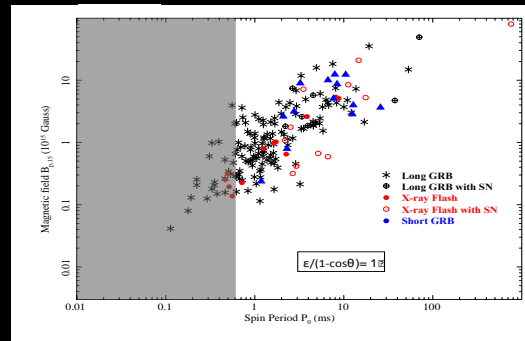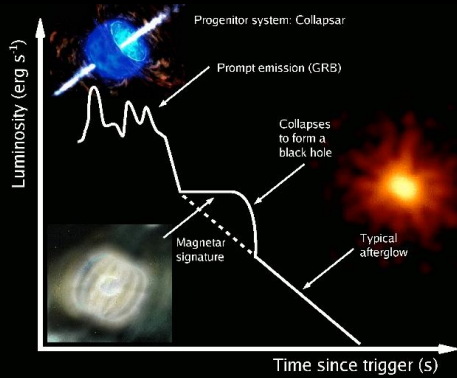
- Simulating 100 SN-Type-GRBs in 1 Myr in the Milky Way we would expect to have now ~25 "observable" magnetars.
- HOWEVER, the expected X-ray luminosities and spin period distribution of these GRB-magnetars CANNOT be reconciled with what observed in our magnetars.

There should exist in Nature "magnetars" and "super-magnetars" if the GRB-magnetar scenario is correct in its present form.
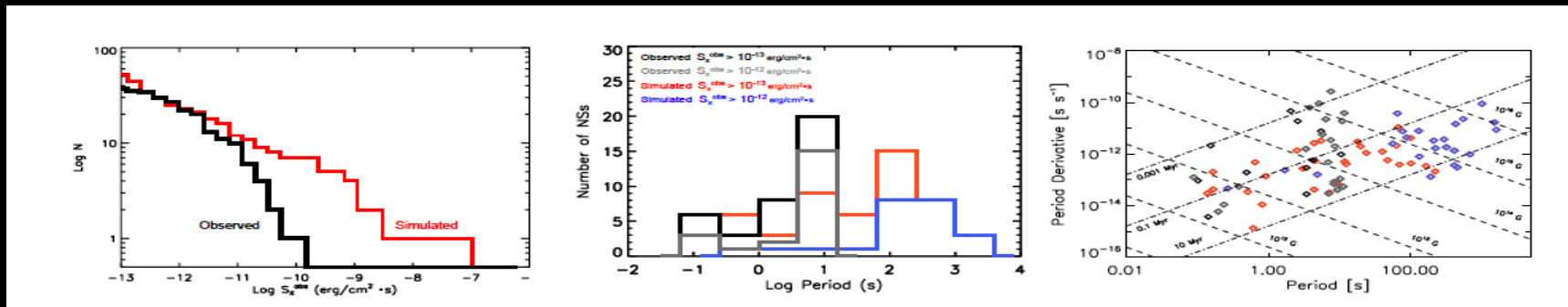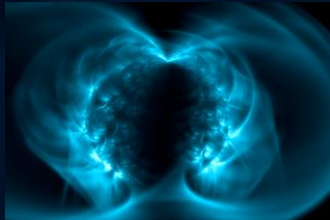
(Rea, Gullon, Pons, Perna, Dainotti, Torres, & Miralles 2015, ApJ)

- Magnetars are unique laboratories to study the effects on matter embedded in extreme magnetic fields.
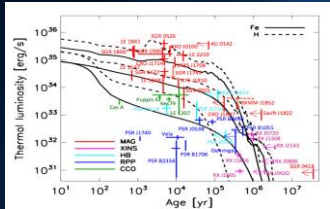
- The different classes of neutron stars can be unified in a simple scenario invocking field decay and thermal evolution in objects with different initial B-field strength, configuration and age.

- The intensive follow-up of magnetar outbursts is giving every day new key discoveries, as the low field magnetars and the Galactic center magnetar.
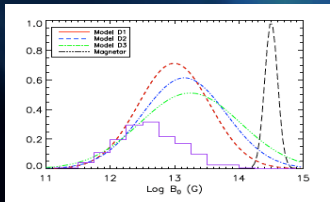
- Population synthesis models considering for the first time all neutron star classes, including magnetars, hint to a limiting B-field at birth of $\sim 10^{15}$ Gauss.

- This limit in the B-field at birth shows that if the GRB-magnetar model is correct, there might be "magnetars" and "super-magnetars" with different origins.

BACK UP SLIDES! GENERAL

GRBs may be powered by a millisecond highly magnetized pulsar.
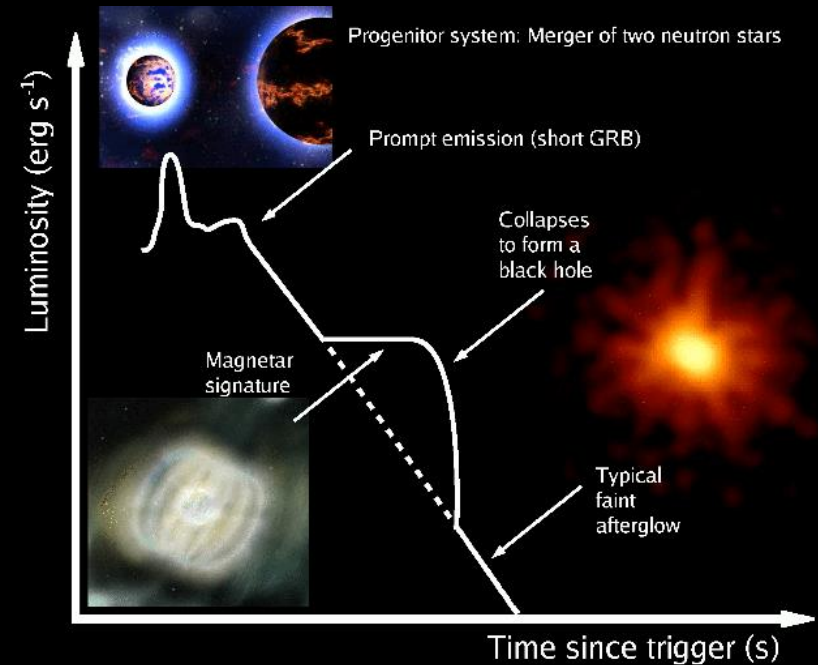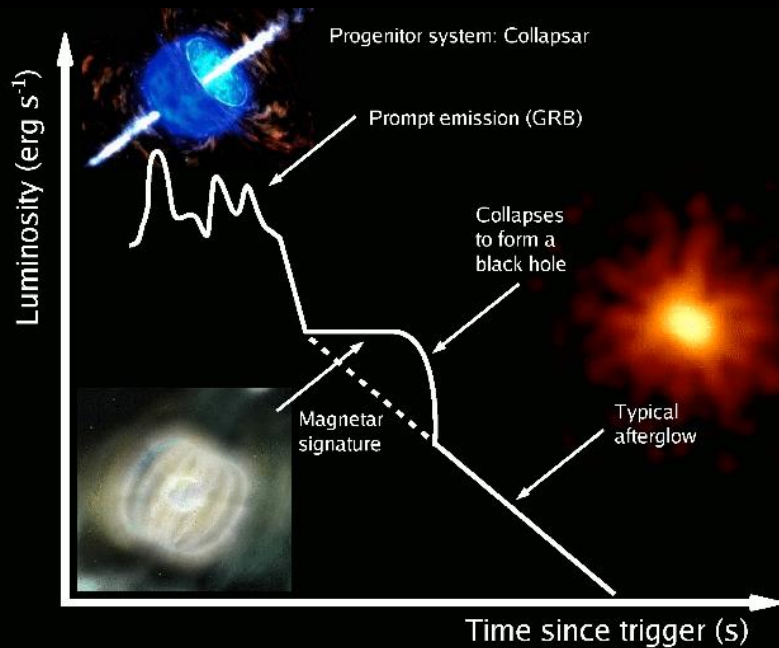
Collapsar model for Long-GRBs

Binary mergers for Short-GRBs

(Usov 1992; Zhang & Meszaros 2002; Duncan & Thompson 1992; Dai et al. 2006 Metzger 2009; Metzger et al. 2011)

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

(Fauscher-guitierre & Kaspi 2006; Gonthier et al. 2009; Popov et al. 2010, Pierbattista et al. 2012; Gullon et al. 2014)
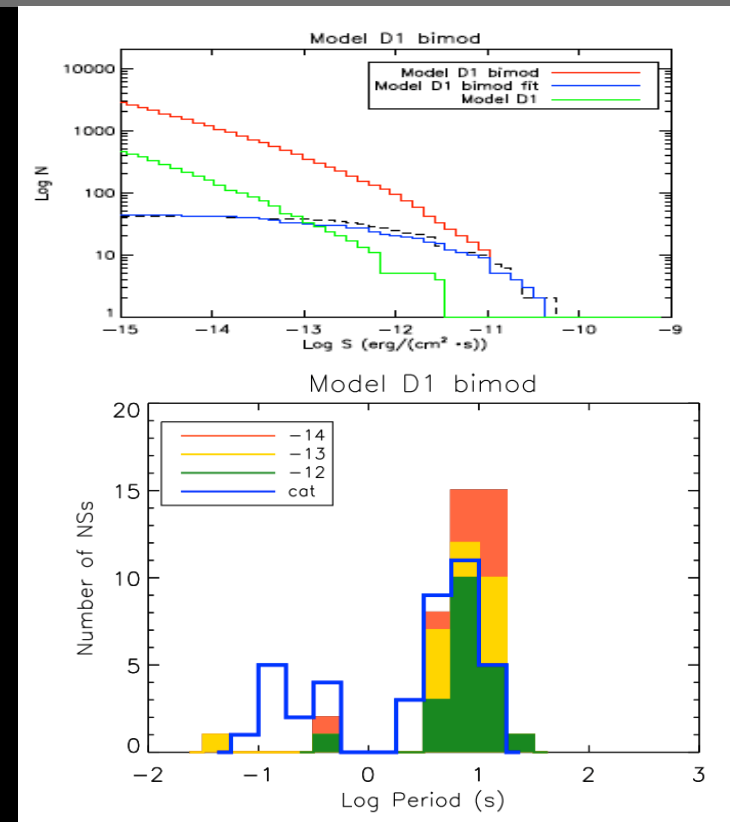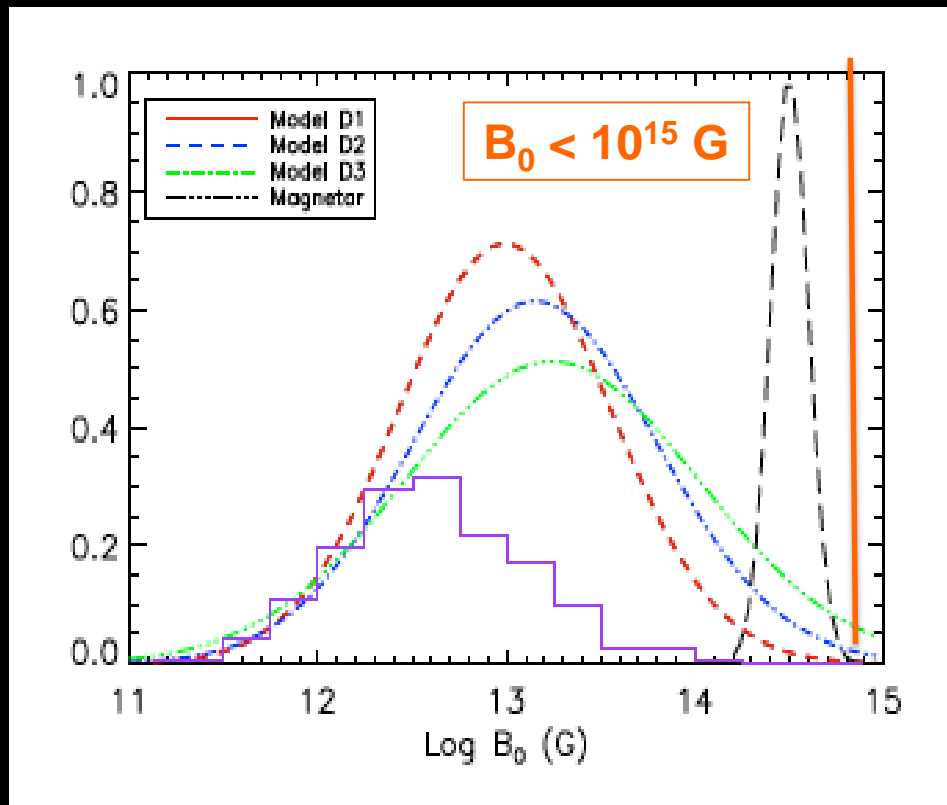
(Gullon, Pons, Miralles, Vigano', Rea, Perna 2015) *Nanda Rea   University of Amsterdam/CSIC-IEEC*

$B_0 < 10^{15}$ G

- If the origin of B-field ia attributed to MHD instabilities (i.e. any dynamo process related to convection), one should expect a saturation when the B-field becomes dynamically 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? GRB-SN versus normal CC-SN?

We fitted with a plateau model all Swift GRBs (Long and Short) from launch till August 2014.
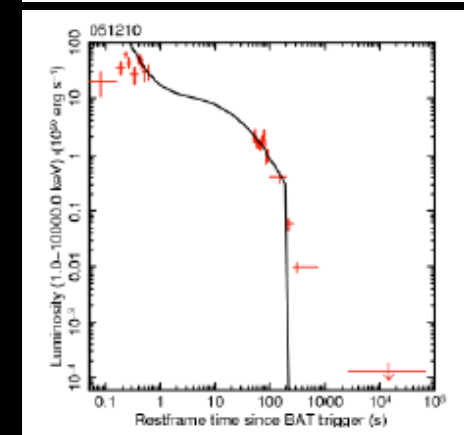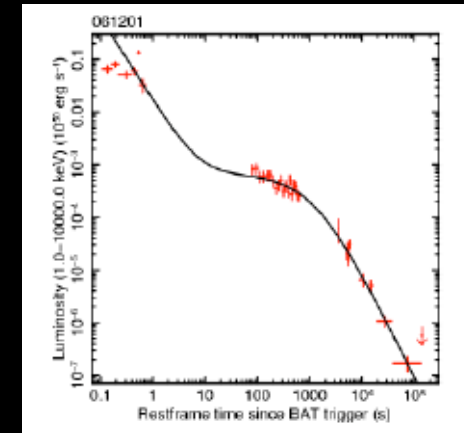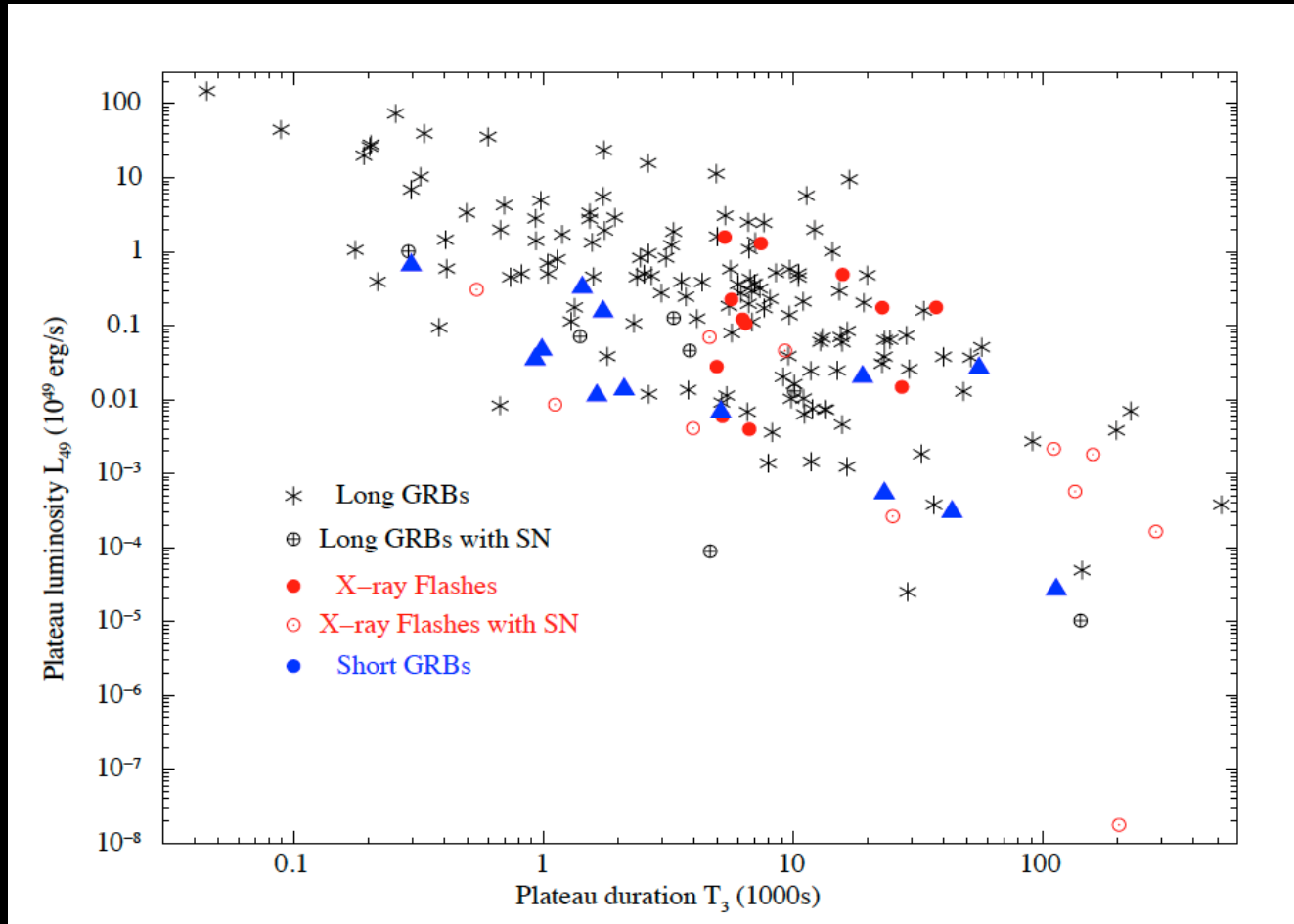
We derive B_0 and P_0 for all GRBs with Swift X-ray plateaus well fit with a magnetar spin-down model.

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

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

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

(Usov 1992; Zhang & Meszaros 2002)
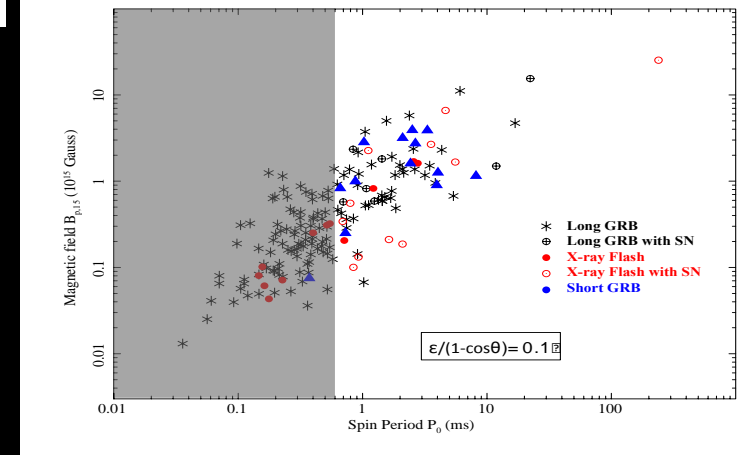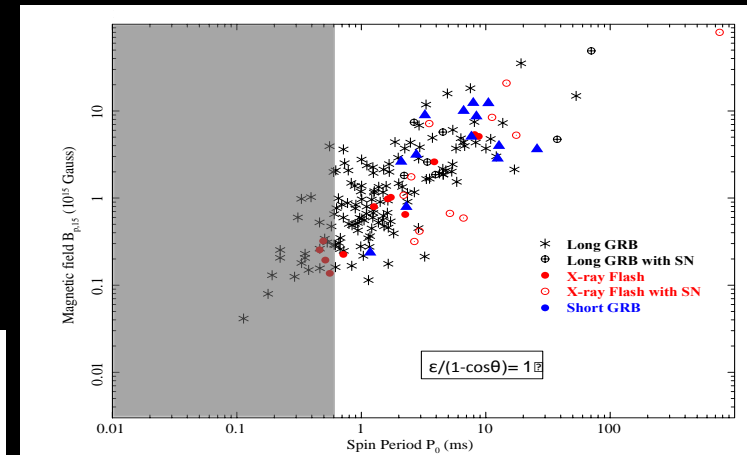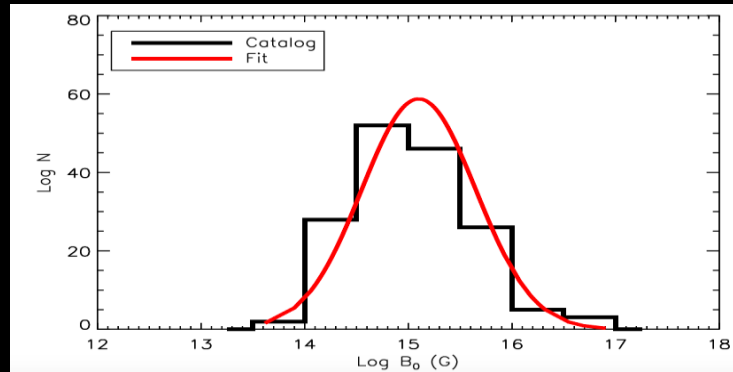
How these B_0 and P_0 compare with the Galactic population of magnetars we know of?

(Rea et al. 2015, ApJ submitted)

Nanda Rea   University of Amsterdam/CSIC-IEEC
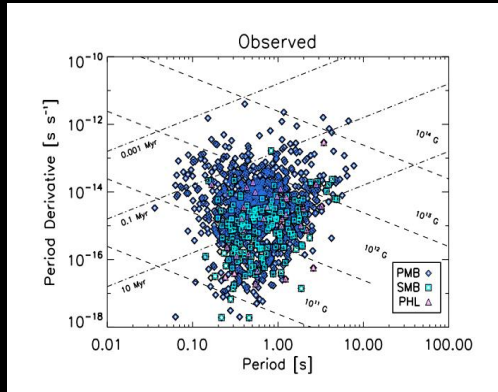
Radio Pulsars
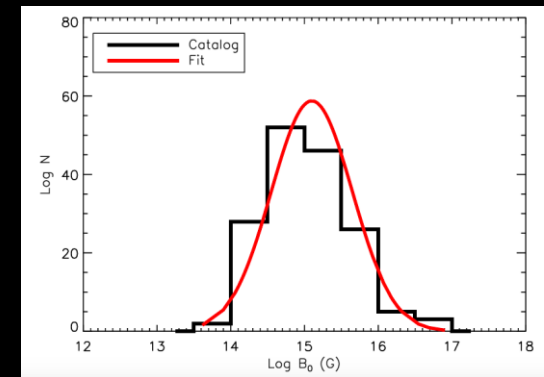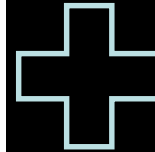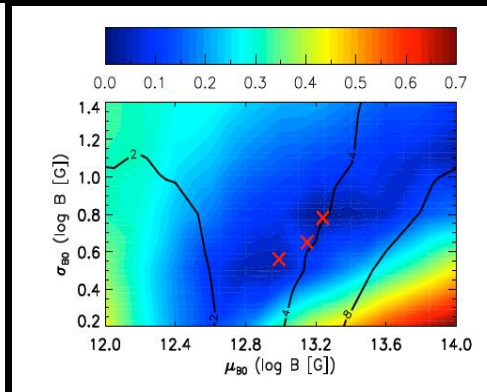
Magnetars from GRBdistribution
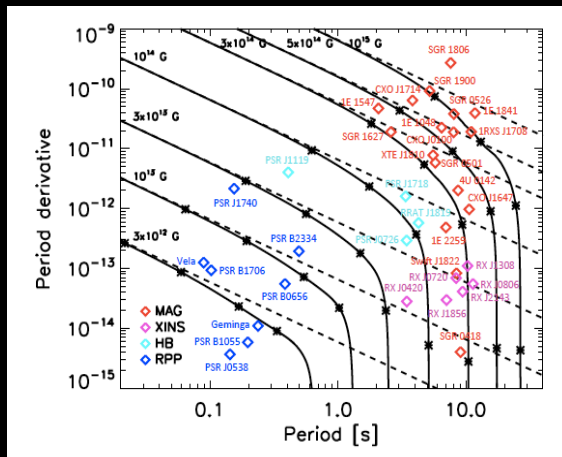
- Age uniformly chosen in → [0, 1 Myr]

- 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})

- B_0 from GRBs distributions + Po from correlation

- Initial inclination angle χ_0 (rotational and magnetic axis) randomly selected.

- Evolution dictated by magneto-rotational models.

B-field decay models —> Monte-Carlo Simulations of Pulsar Population

(Gullon et al. 2014, 2015)

Nanda Rea *University of Amsterdam/CSIC-IEEC*
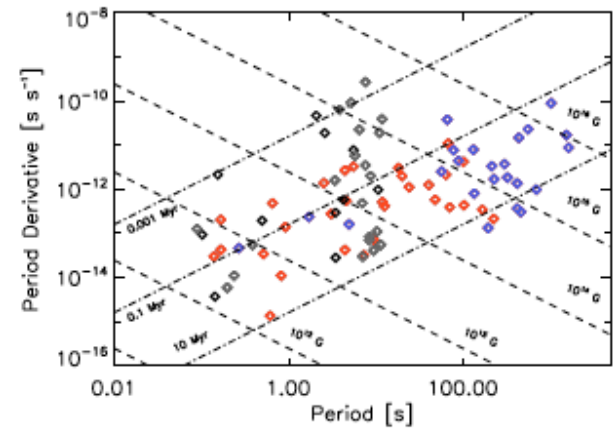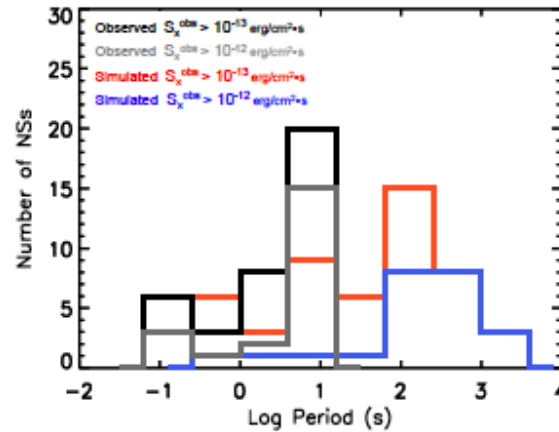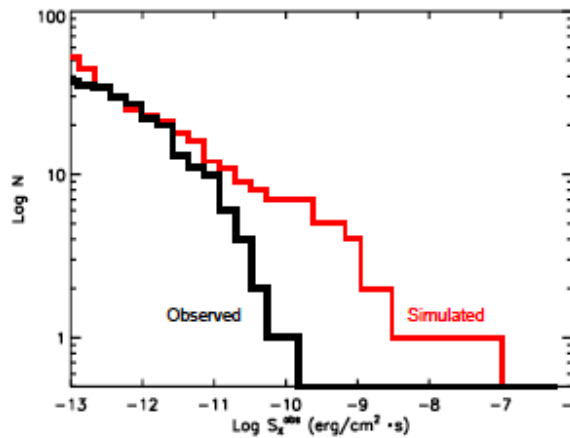
Numbers ok! Simulating 100 GRBs leaving behind a stable magnetar in the past Myr in our Galaxy, correcting for selection effects we would see ~25 objects, compatible with the Galactic population of magnetars.

Properties NOT OK! HOWEVER, their current X-ray luminosities and spin period distribution CANNOT be reconciled with what observed in our magnetars!

→ B0 fields required for GRBs are WAY too large!

(Rea et al. 2015, ApJ submitted)

Nanda Rea   University of Amsterdam/CSIC-IEEC

Our Galactic magnetars DOES NOT come from Gamma-ray bursts!

How many GRB-magnetars can we have in the Milky Way but missing them for selection effects?

a) Two kind of magnetar progenitors are assumed, GRB-ones being different from Galactic magnetar ones (i.e. Metallicity differences?)

a) The No. of stable magnetars produced in the Milky Way via a GRB in the past Myr should be about < 16
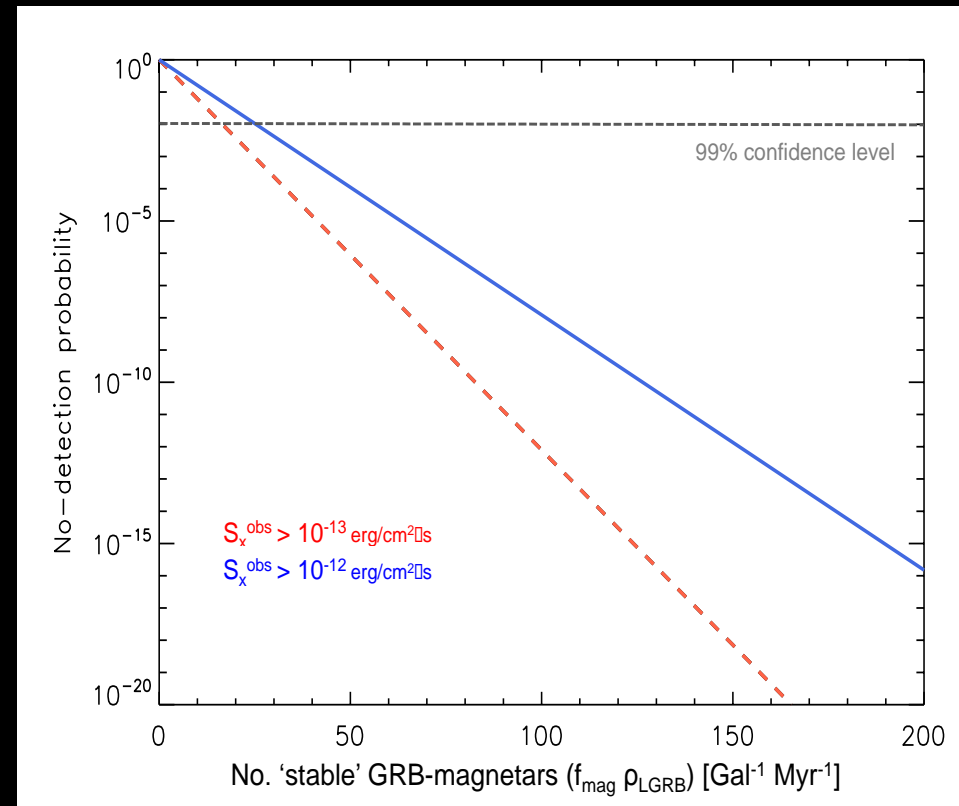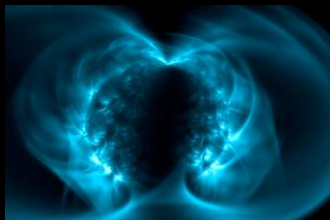
99% confidence level

$S_x^{obs} > 10^{-13}$ erg/cm^2/s

$S_x^{obs} > 10^{-12}$ erg/cm^2/s

No-detection probability

No. 'stable' GRB-magnetars ($f_{mag}\ \rho_{LGRB}$) [Gal^{-1} Myr^{-1}]

(Rea et al. 2015, ApJ submitted)

Nanda Rea   *University of Amsterdam/CSIC-IEEC*

- Magnetars are unique laboratories to study the effects on matter embedded in extreme magnetic fields.
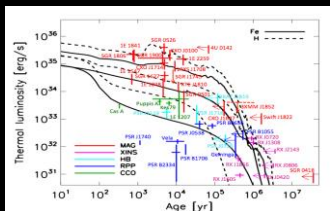
- The different classes of neutron stars can be unified in a simple scenario invoking field decay and thermal evolution in objects with different initial B-field strength, configuration and age.
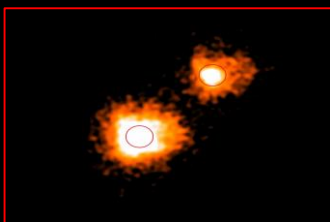
- Our intensive follow-up of magnetar outbursts is giving every day new key discoveries, as the Galactic center magnetar and the low-B magnetars.
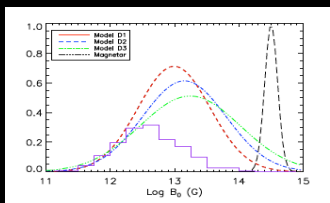
- Population synthesis models considering for the first time all neutron star classes, including magnetars, hint to a limiting B-field at birth of $\sim 10^{15}$ Gauss.

- This limit in the B-field at birth shows that if the GRB-magnetar model is correct, there might be "magnetars" and "super-magnetars" with different origins.

** SN explosions and rates
Study the neutron star population of our Galaxy and B-field distribution at birth, is crucial for SN simulations and rates. SNe should be able to form obiquitously strong internal B.

** GW radiation from newly born magnetars
The GW background radiation produced by the formation of highly magnetic neutron stars is probably underestimated given our recent results.

** Gamma-ray bursts
GRBs are believed to be strongly connected with the formation of magnetars. We are about to show that the ms-magnetar model is not consistent as it is, with the Galactic population of magnetars.

** Massive Stars
If strong-B neutron stars are formed by the explosion of highly magnetic stars, there should be many more of such stars than predicted thus far.
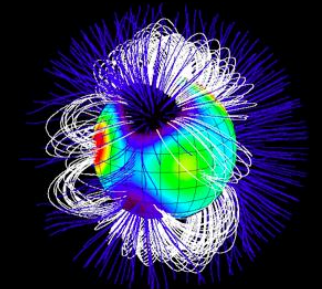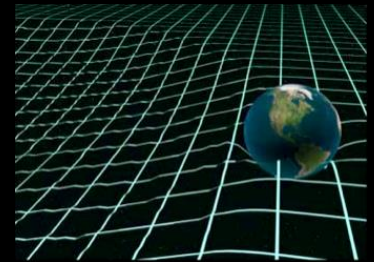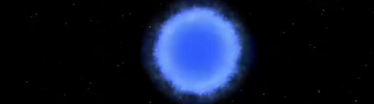
There are big uncertainties on how these huge fields are formed…

- via dynamos in the stellar core

- as fossil fields from a magnetic progenitor

- from massive star binary progenitors

- Connection with Gamma-Ray Bursts???

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

Westerlund 1

(Thompson & Duncan 1993; Ferrario & Winkramasinge 2006; Clark et al. 2014)
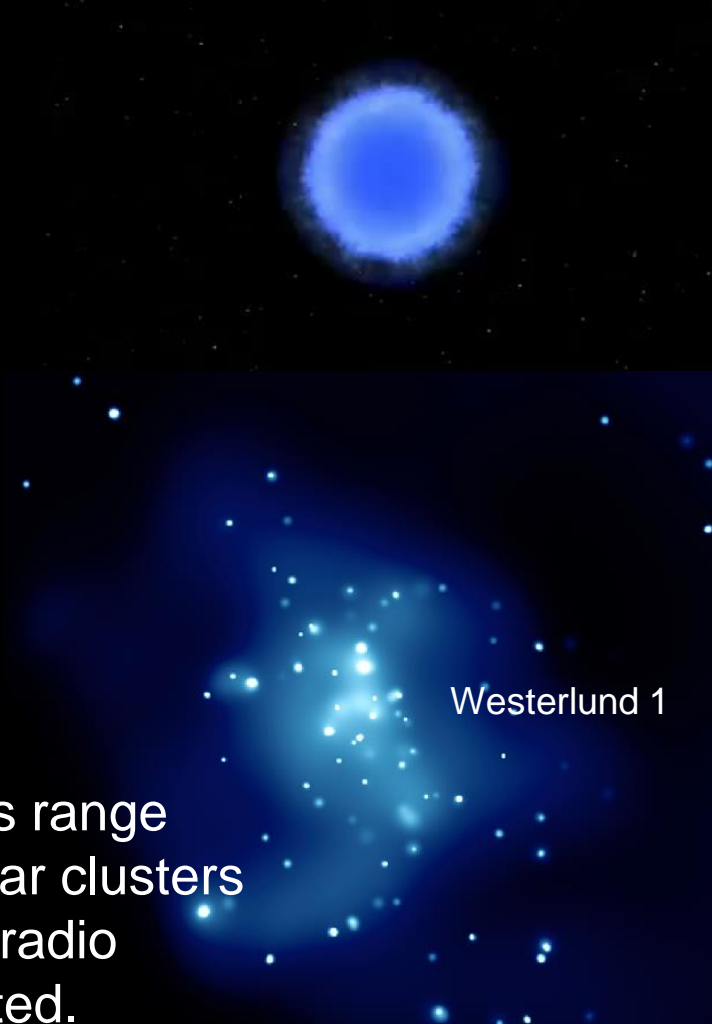
No physical distinction between Anomalous X-ray Pulsars, Soft Gamma Repeaters, and Transient Magnetars: all showing all kind of magnetar-like activity.

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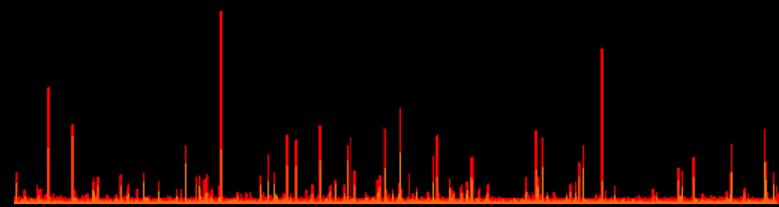
Soft Gamma Repeaters

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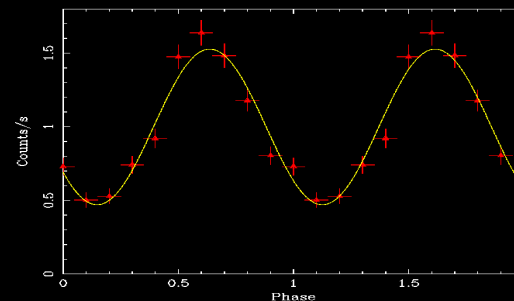
Anomalous X-ray Pulsars

Bright X-ray transients!

Transients magnetars

Some GRBs are believed to form and be powered by a millisecond highly magnetized pulsar: i.e. Millisecond-magnetars
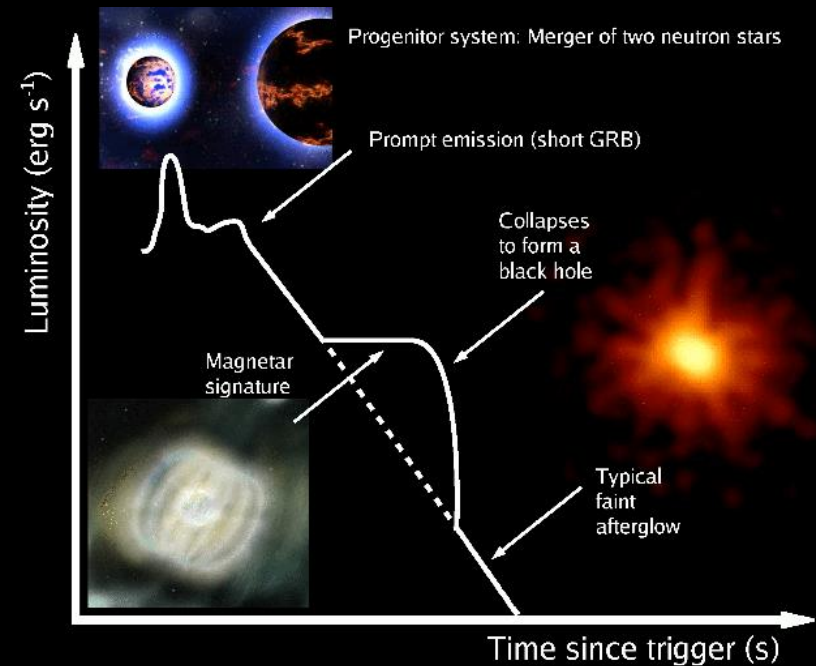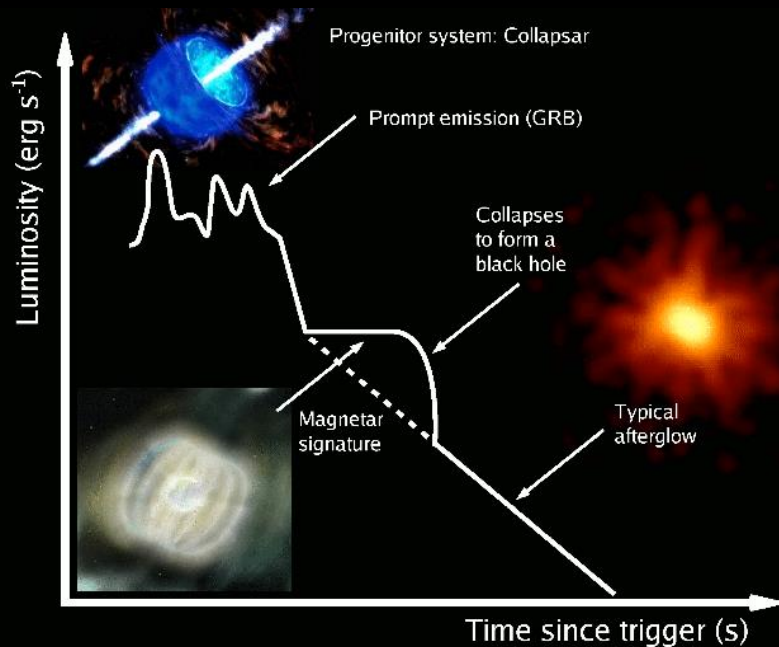
Collapsar model for Long-GRBs

Binary mergers for Short-GRBs

(Usov 1992; Zhang & Meszaros 2002; Metzger et al. 2011;)

-

Nanda Rea *University of Amsterdam/CSIC-IEEC*

(Rea, Zane, Lyutikov, Turolla 2008)

$$\sigma_{RCS} \sim \left(\frac{R_L}{r_e}\right)\sigma_T \sim 10^5 \sigma_T$$

$$R_L \sim 8R_{NS}\left(\frac{B_{NS}}{B_{crit}}\right)^{1/3}\left(\frac{1keV}{\hbar\omega_B}\right)^{1/3}$$

Thermal γ e^- $\gamma^?$ B

Swift 1822−1606 (2011)
1E 1547−5408 (2009)
SGR 0501+4516 (2008)
SGR 0418+5729 (2009)
CXOU J164710−455216 (2006)

1E 1547−5408 (2008)
SGR J1745−2900 (2013)
SGR 1627−41 (2008)
Swift 1834−0846 (2011)
SGR 1833−0832 (2010)

(Pons & Rea 2012)
~10^{44} erg
~10^{42} erg

(Israel et al. 2008)

(Palmer et al. 2005)

$\sim 10^{44}$ erg

$\sim 10^{43}$ erg

$\sim 10^{42}$ erg

$\sim 10^{41}$ erg
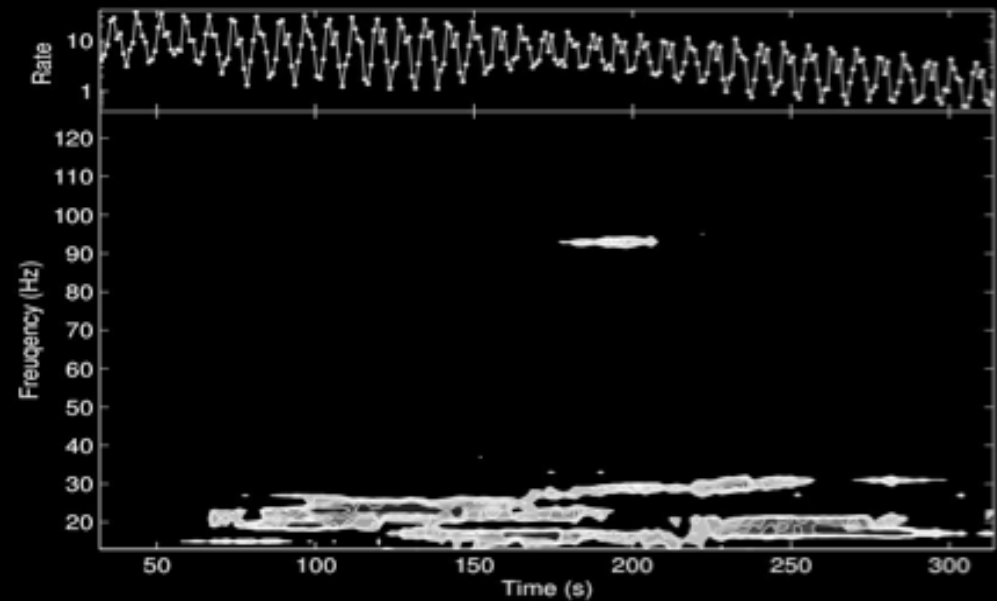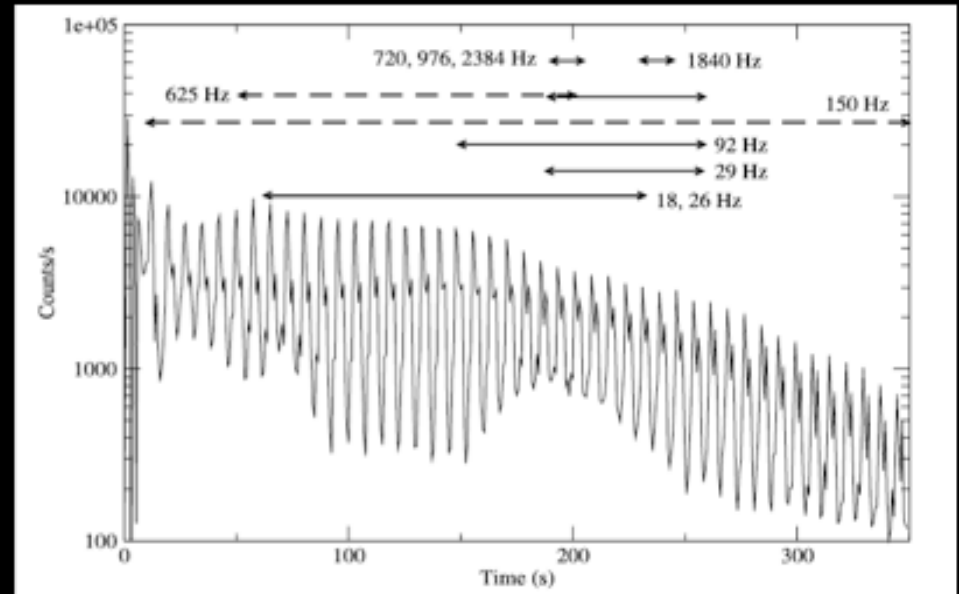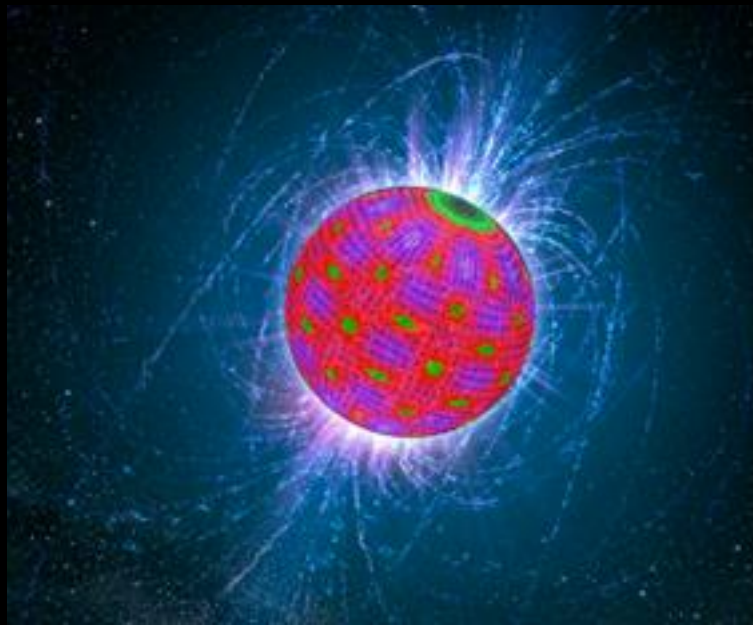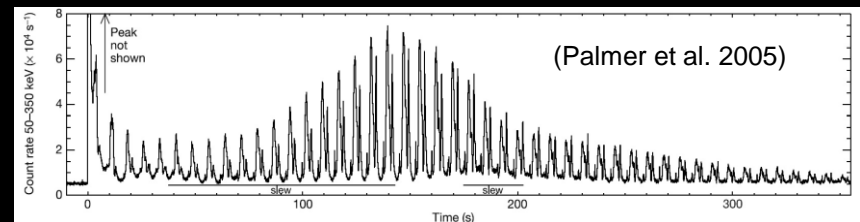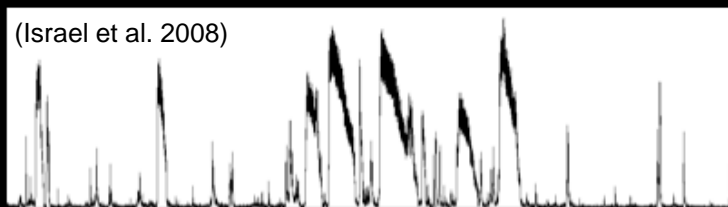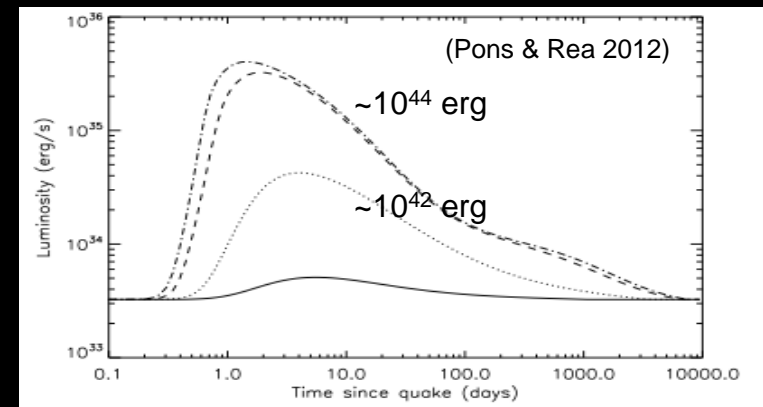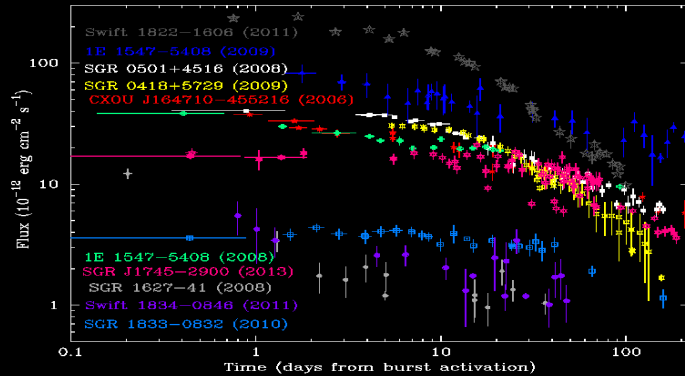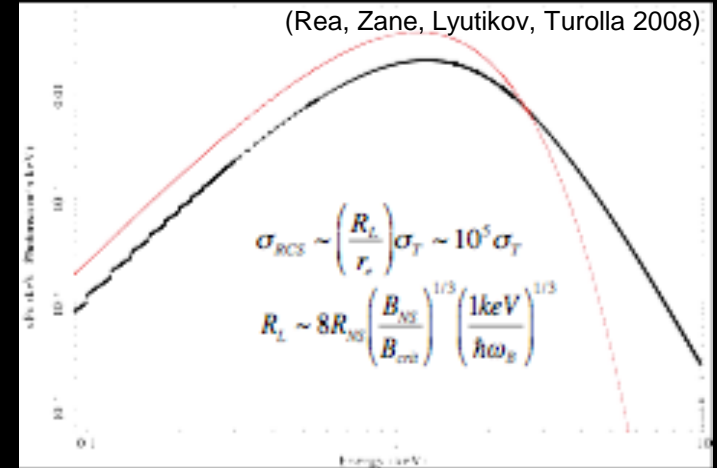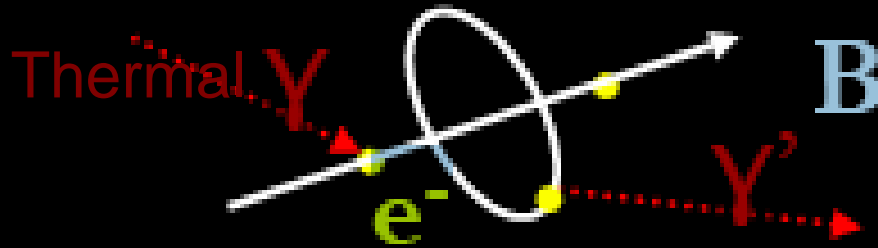
$\sim 10^{44}$ erg
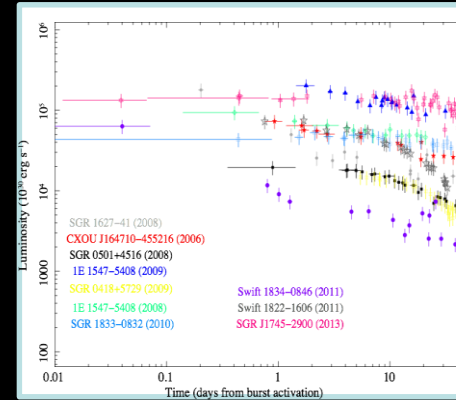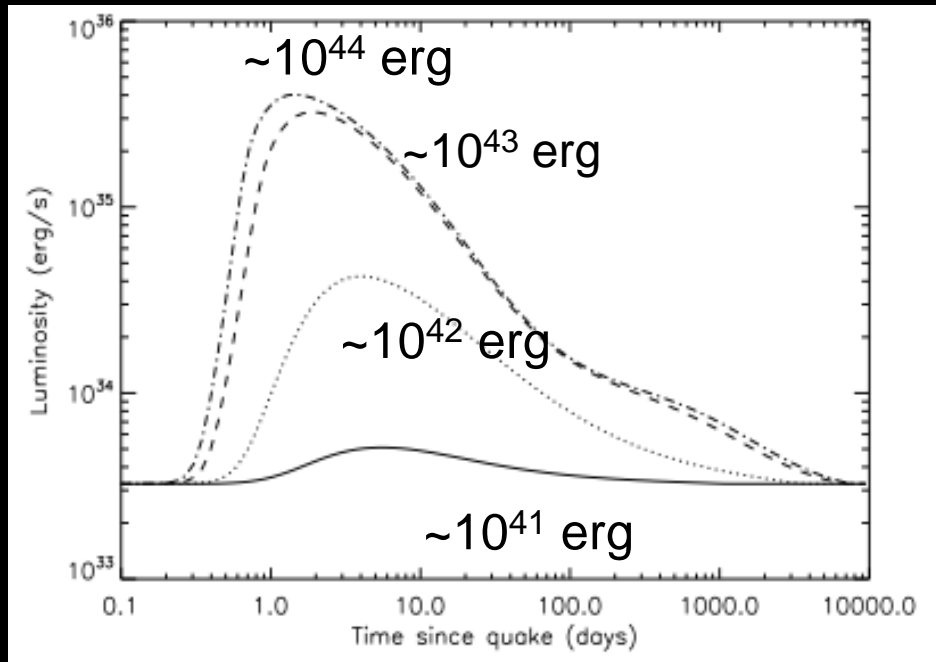
Varying the
injected energy

Standard candles!
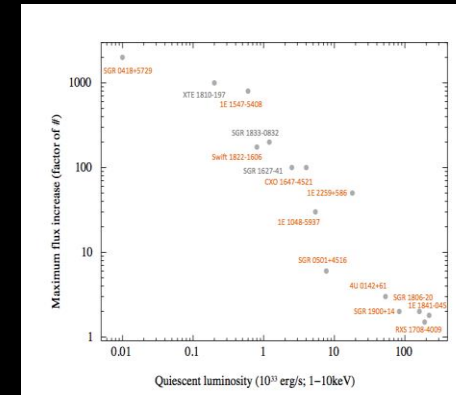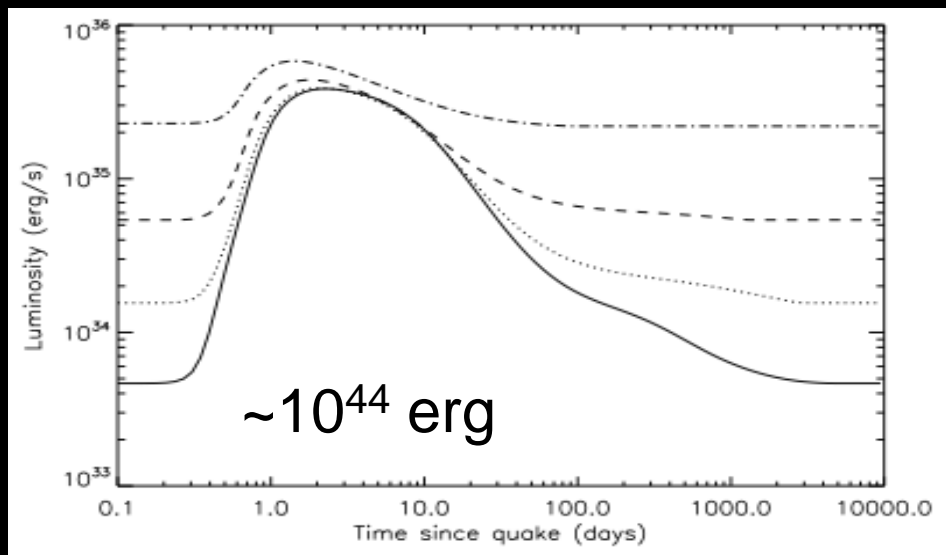
Varying initial
quiescent luminosity

All magnetars are transient!

(Pons & Rea 2012; Rea & Pons 2015 in prep)   *Nanda Rea   University of Amsterdam/CSIC-IEEC*
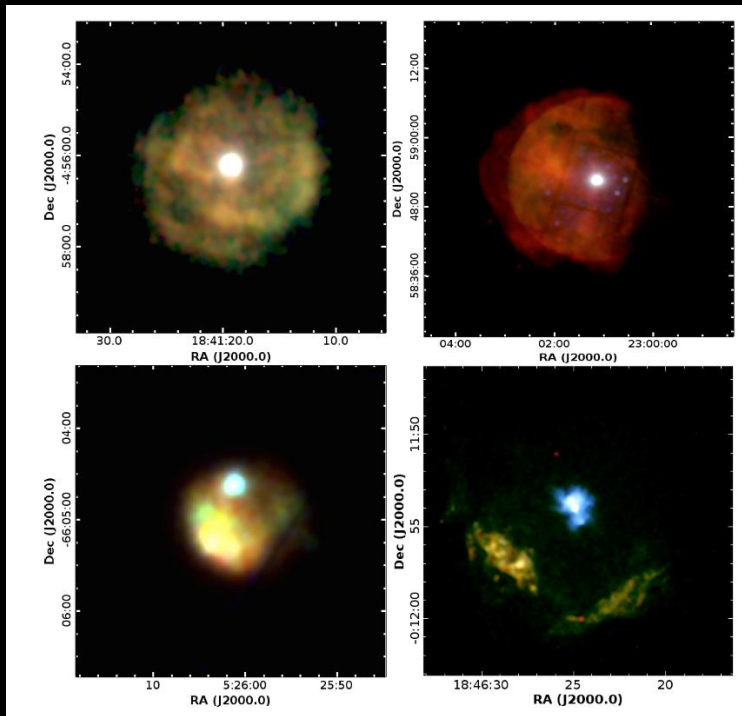
Kes73 –> 1E 1841-045
CTB109 –> 1E 2259+586
N49 –> SGR 0526-66 (LMC)
Kes75 –> PSR 1846-0258

Magnetar SNRs are similar in energetics,
ionization states and detectability,
to normal pulsar SNRs.
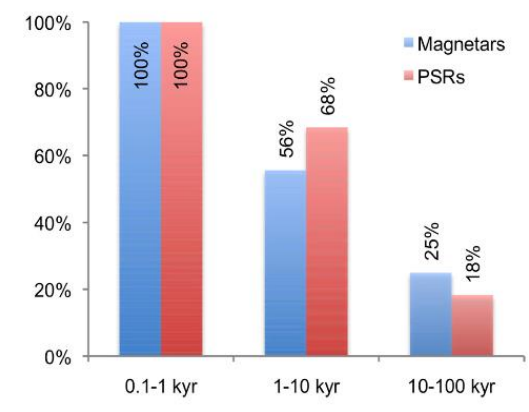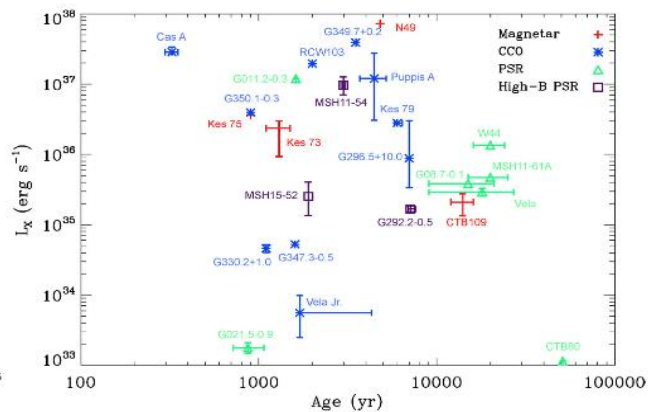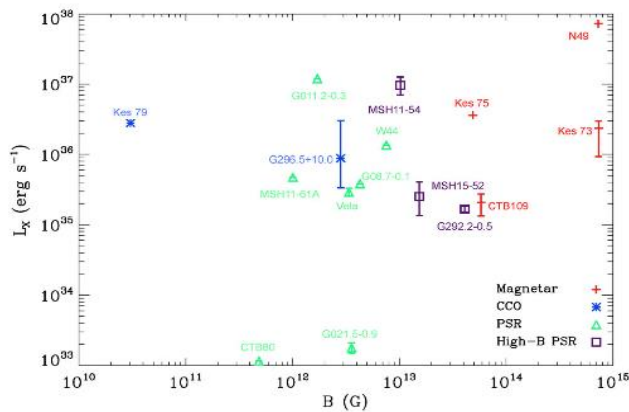
(Palmer et al. 2005)

(Mandea & Balasis 2006, Geophysical Journal)

Nanda Rea *University of Amsterdam/CSIC-IEEC*

(Rea et al. 2013)

SgrA*

SGR J1745-2900

(Coti Zelati et al. 2015)
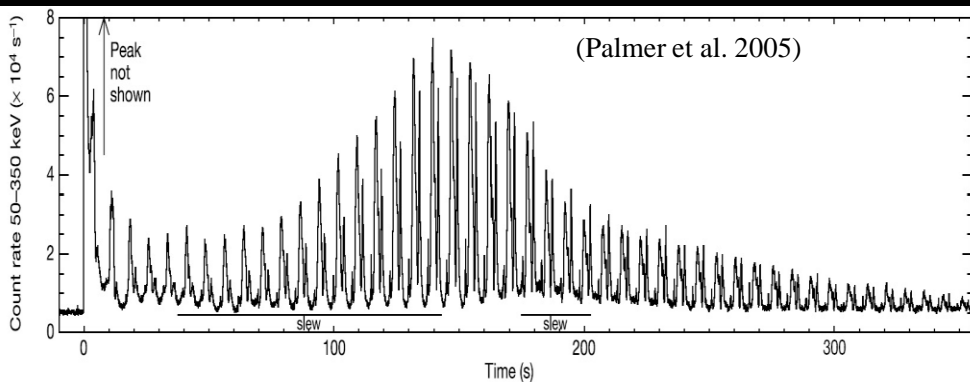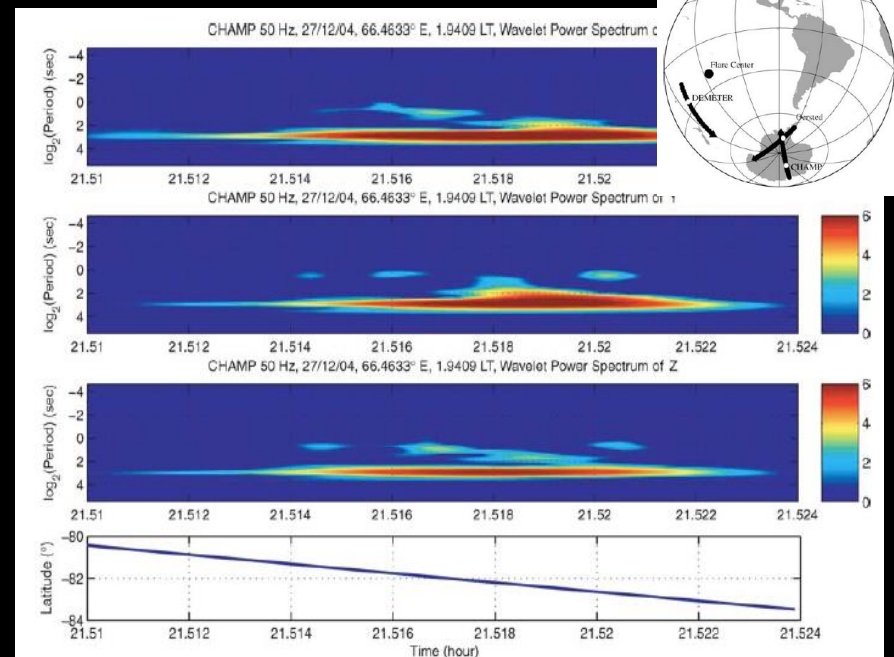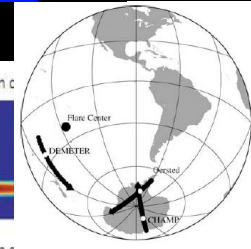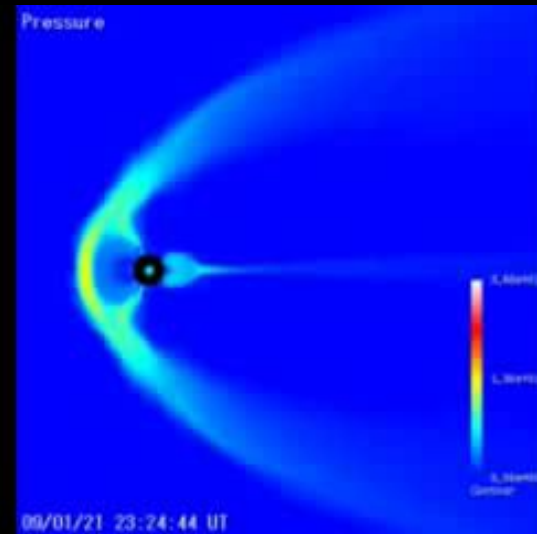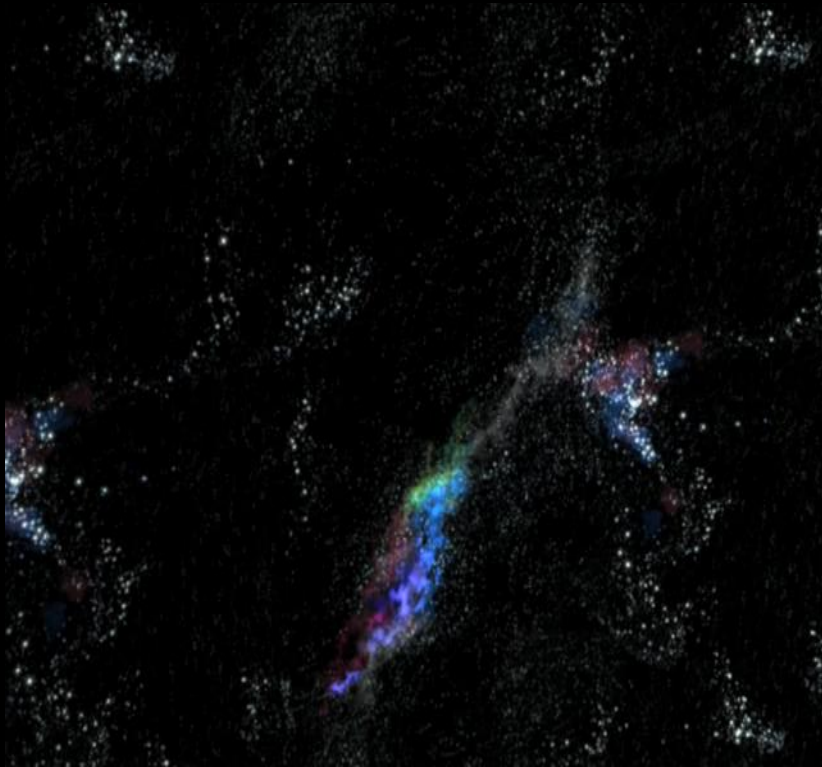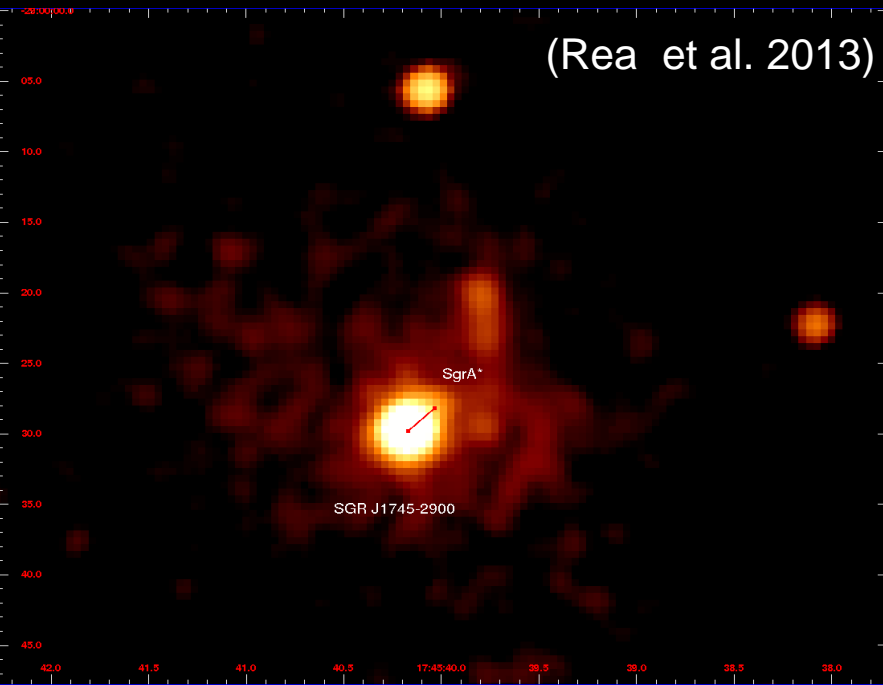
$P \sim 3.76$ s
$\dot{P} \sim 0.4 - 6.6 \times 10^{-12}$ s/s
$B_{dip} \sim 2 \times 10^{14}$ G
$L_{sd} \sim 5 \times 10^{33}$ erg/s
$\tau_c \sim 9$ kyr

- Radio pulsed emission at DM=1750+/-50 pc cm^{-3} (the highest ever detected for a radio pulsar)

- Thermal spectrum: 0.95keV cooled down to 0.85 keV plus faint non-thermal component

- tiny (~1km) hot spot which temperature cools down very slowly

- Column density Nh = 0.98(4)x10^{23} cm^{-2}

- Slow flux decay, a factor of 2-3 in one yr.

Bower et al. 2014
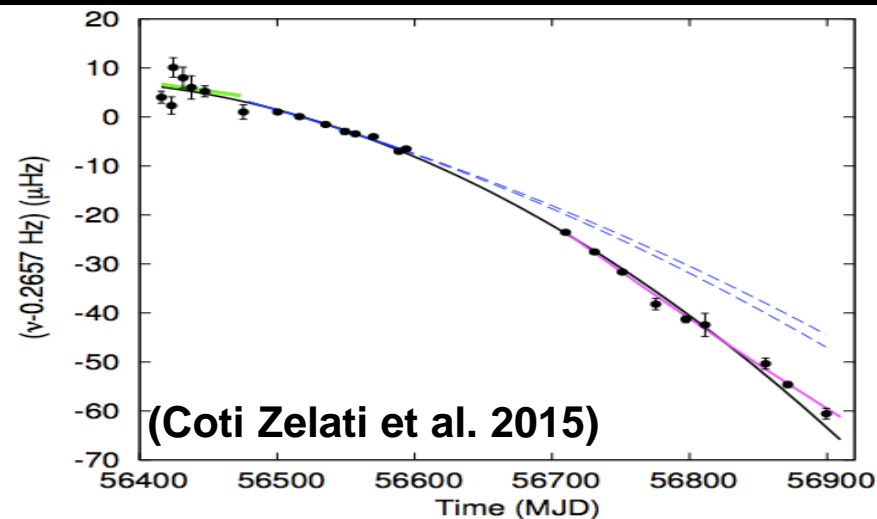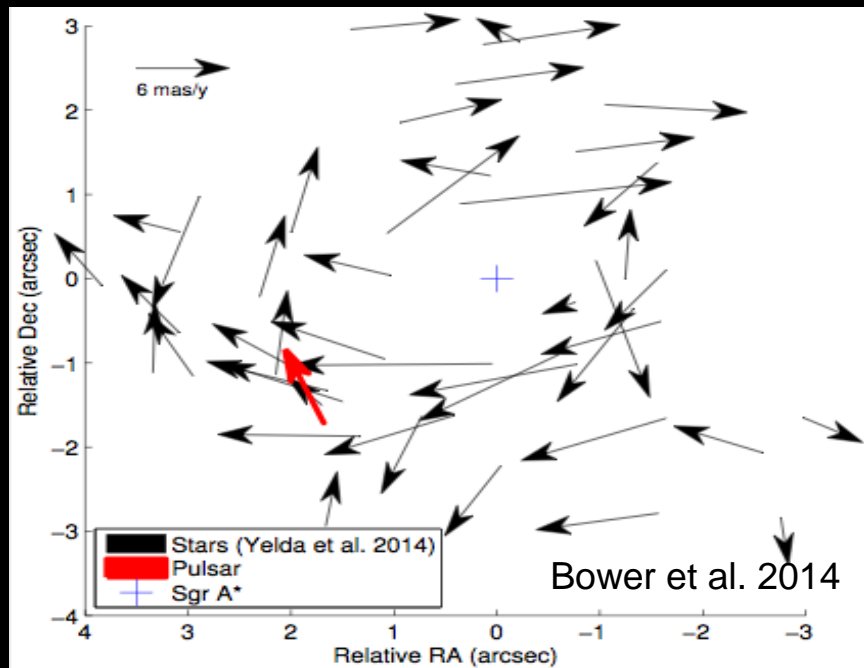
Proper motion from *VLBA* observations

Transverse velocity of 236+/-11 km/s at a position angle 22+/-2 deg East-of-North

Fraction of bound orbits from Monte Carlo N-body simulations

90% probability on average of being bound to the SMBH if born within 1 parsec.

Depending on eccentricity and semi-mayor axis, it can have an orbital period from a minimum of 500 yr to several kyrs.

Adapted from Rea et al. 2013

0.236(11)

Sigma (1000 km/s)

D (pc)

(Coti Zelati et al. 2015)
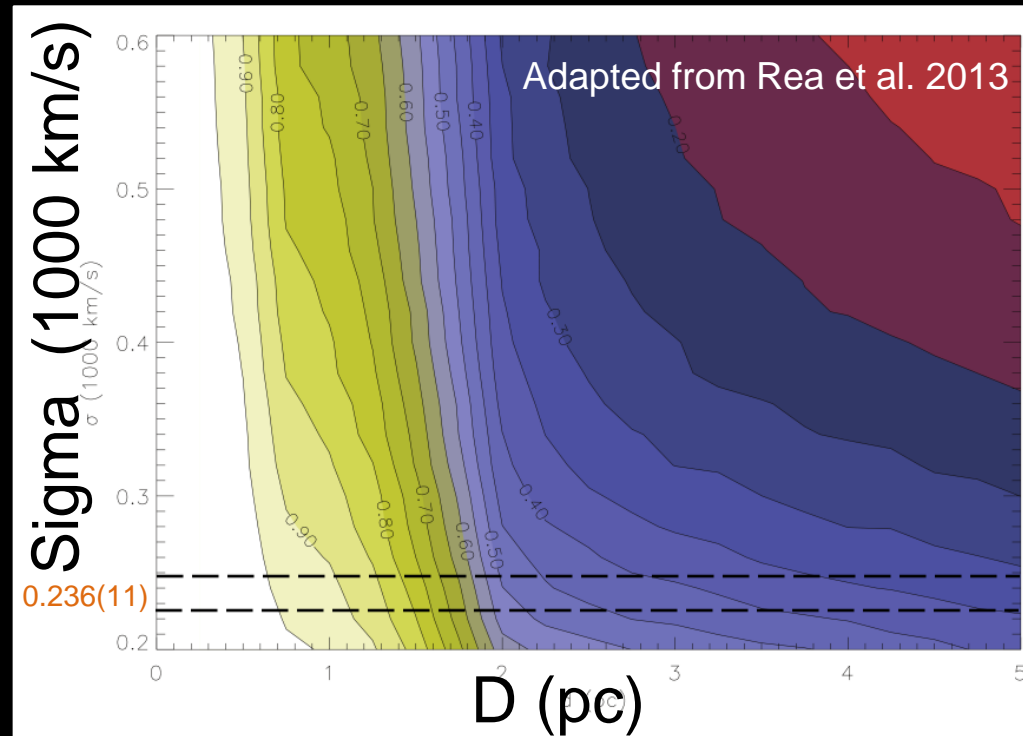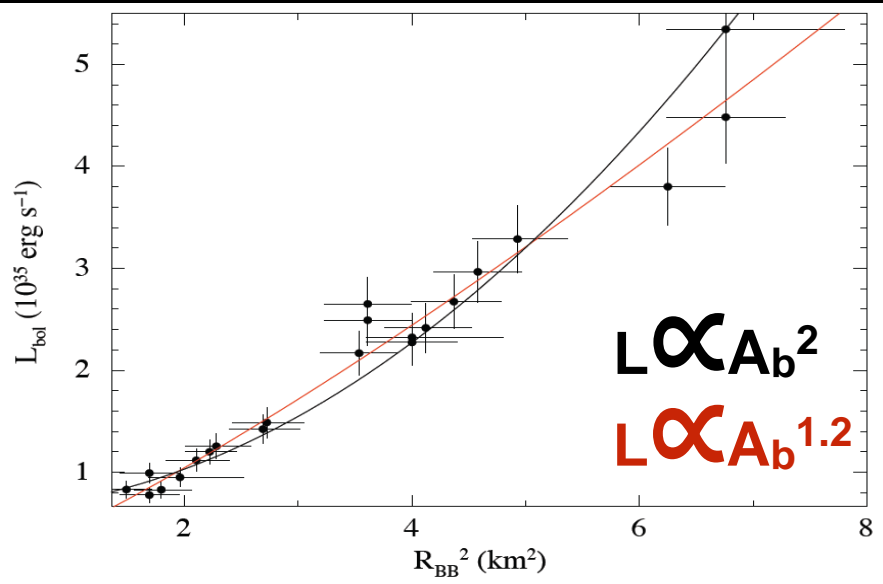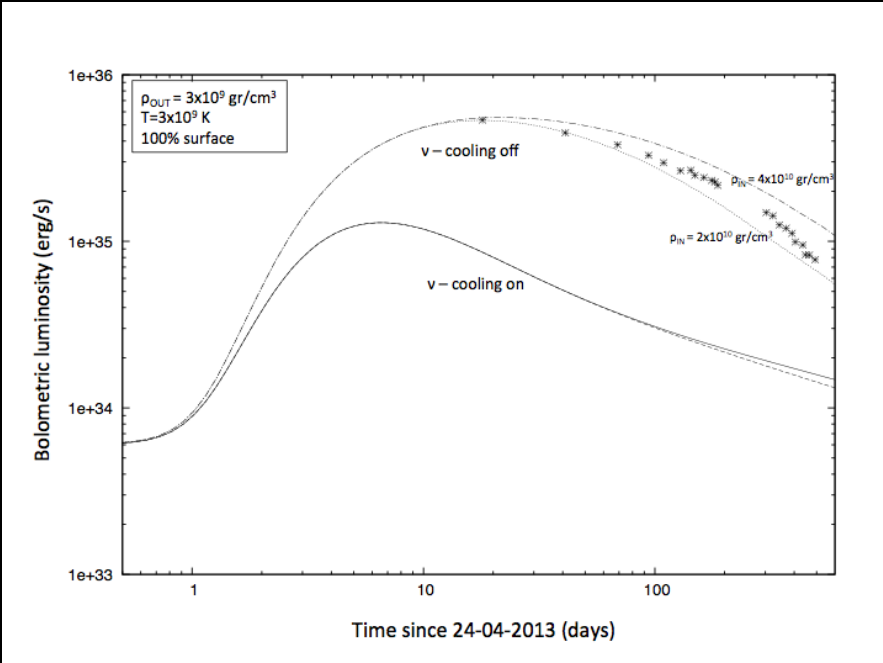
Crustal cooling?

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

$L \propto A_b^2$

$L \propto A_b^{1.2}$
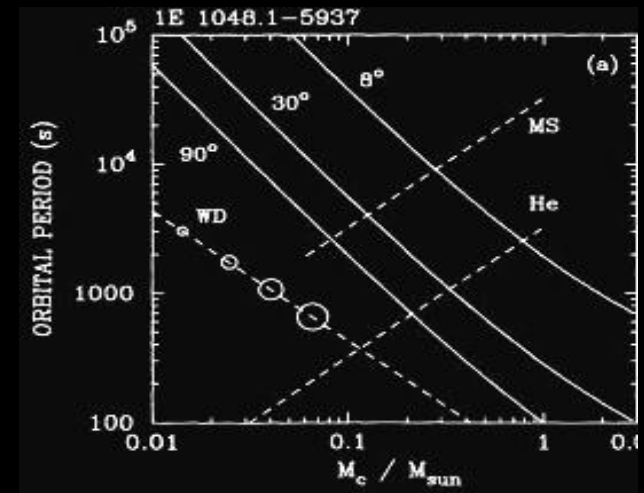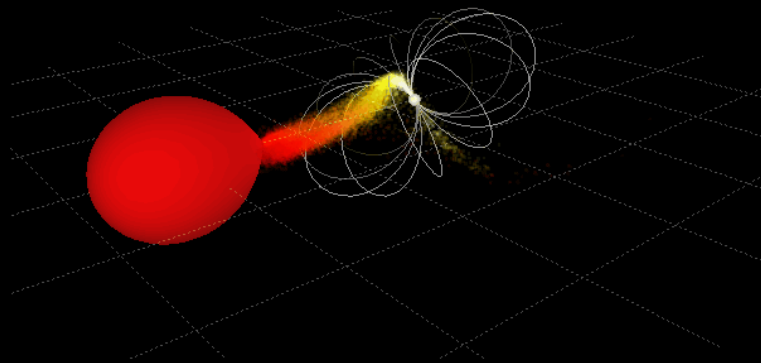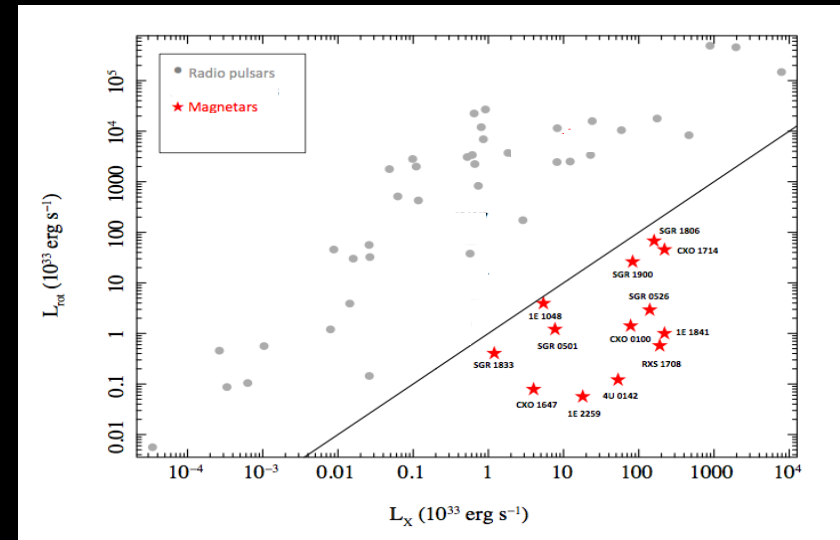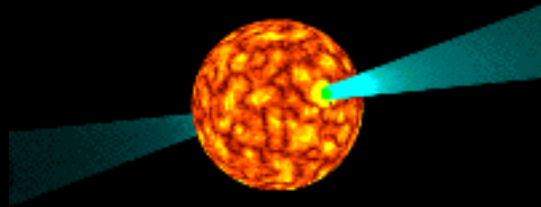
BACK UP SLIDES!
PASTA
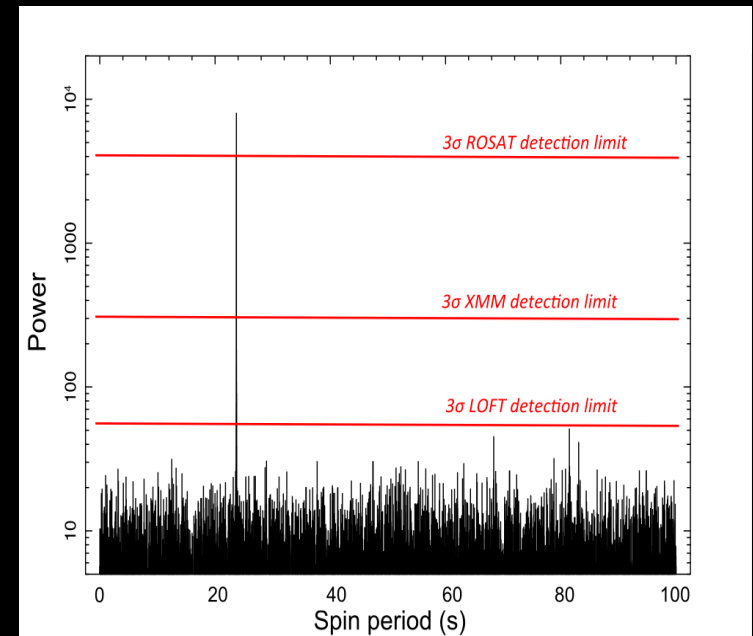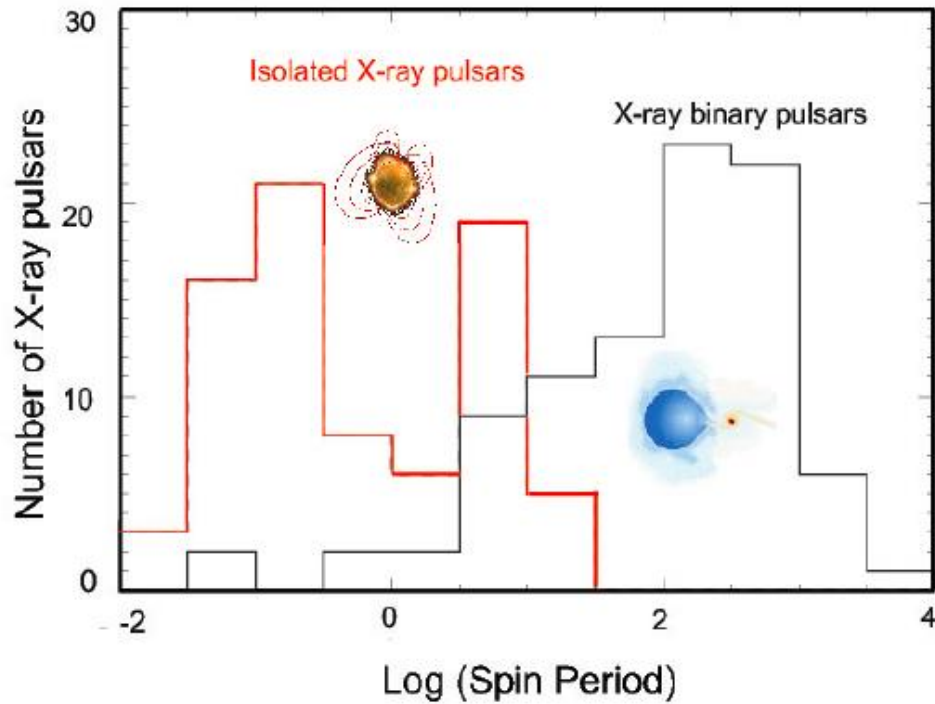
- There are no theoretical or observational biases in the X-ray band for discovering slow X-ray pulsars!

Energy Distribution — Waiting time Distribution — Starquake Location Distribution

Young / SGRs
Middle / AXPs
Old / Old AXPs

$B_{0,p} = 3 \times 10^{15}$ G

$B_{0,p} = 1 \times 10^{14}$ G
$B_{0,t} = 5 \times 10^{15}$ G

$B_{0,p} = 3 \times 10^{14}$ G

(Perna & Pons 2011; Pons & Perna 2011; Vigano' et al. 2013)
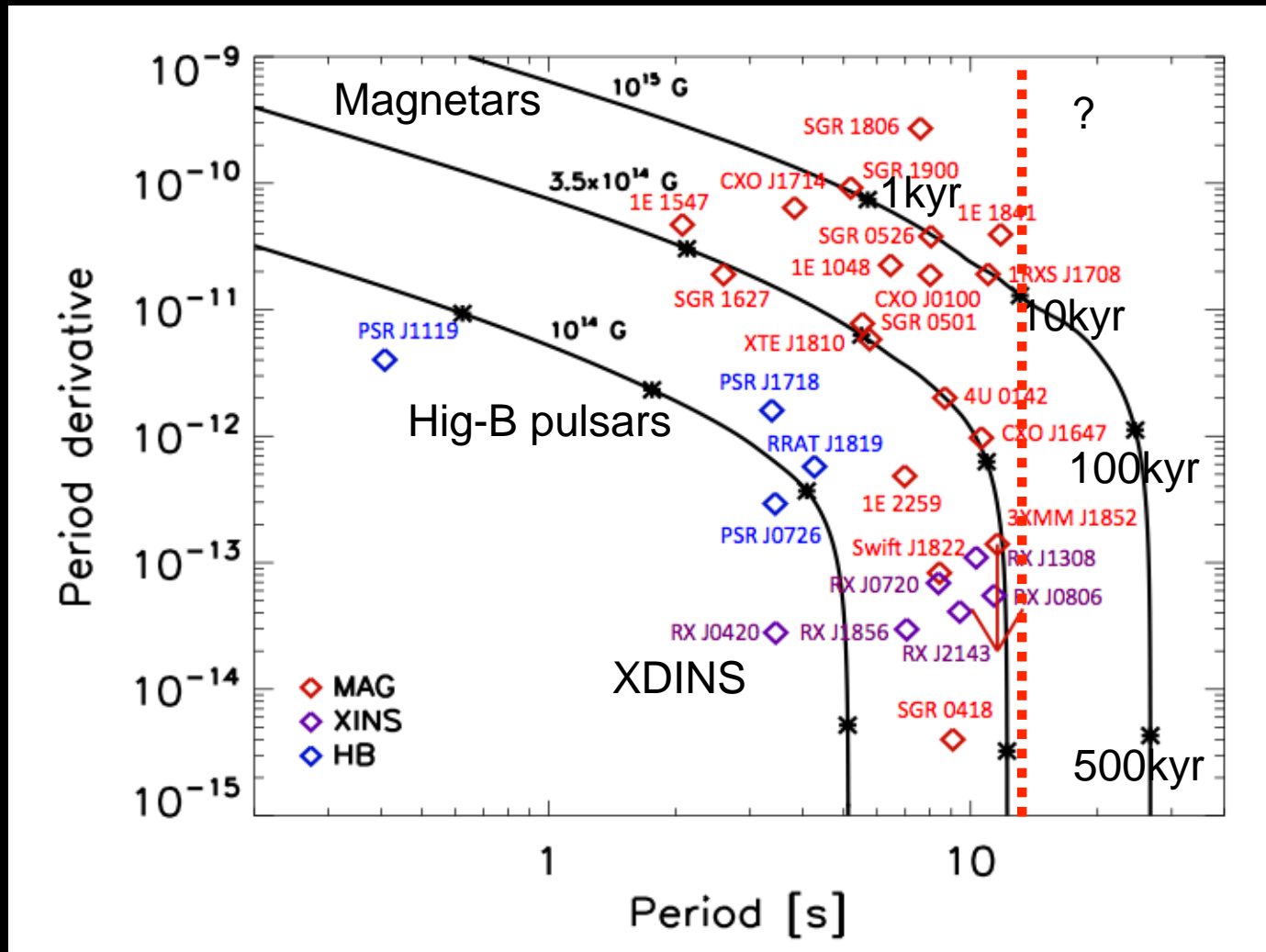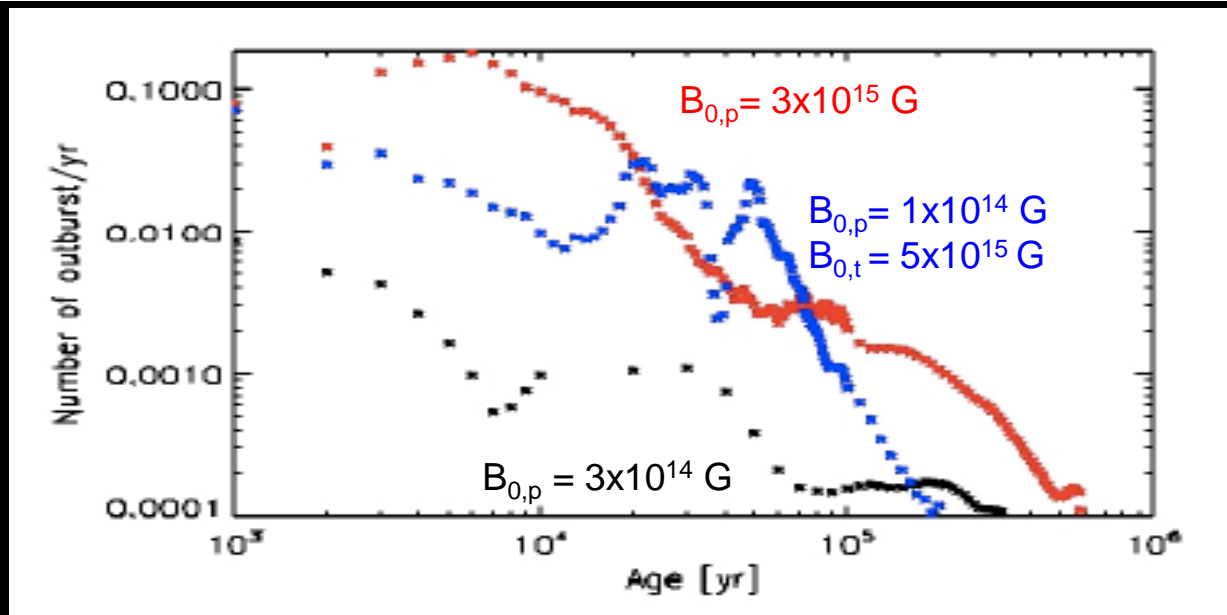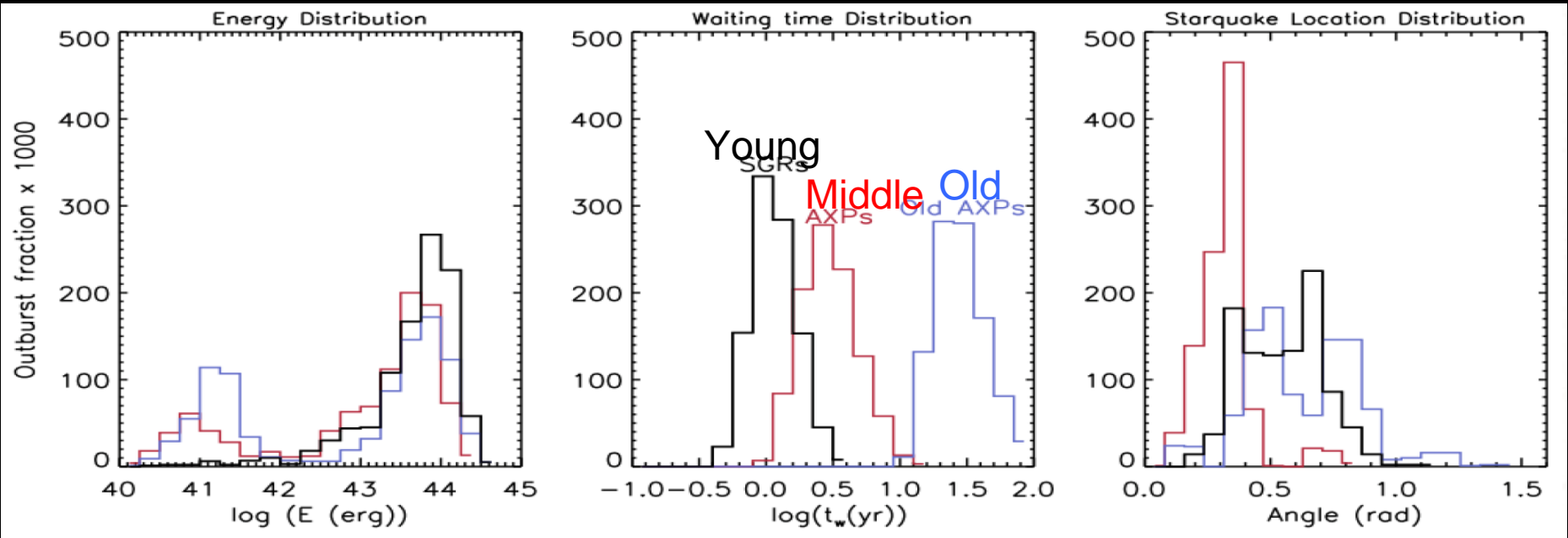
- Changing the B-field configuration: large differences between pure crustal and core fields

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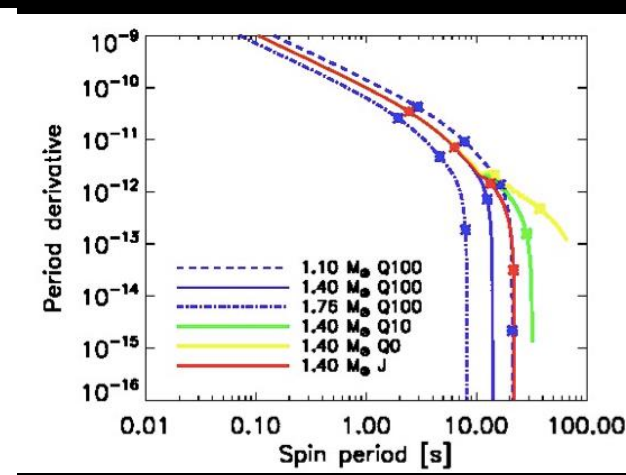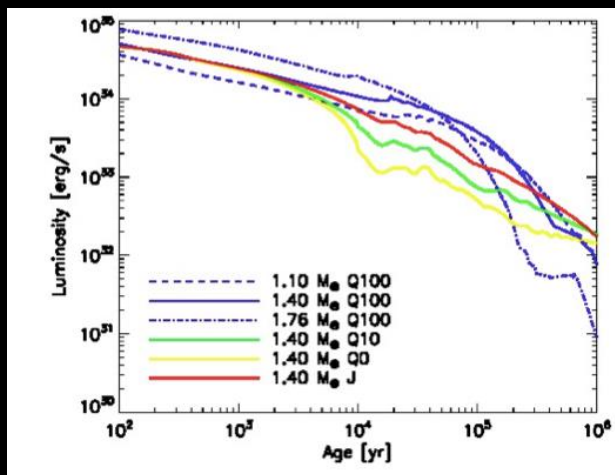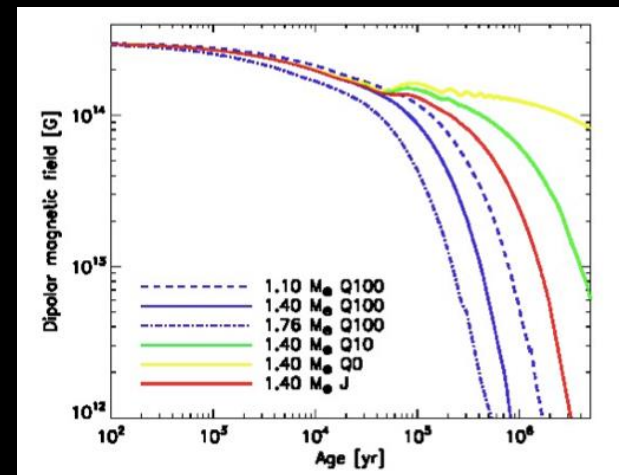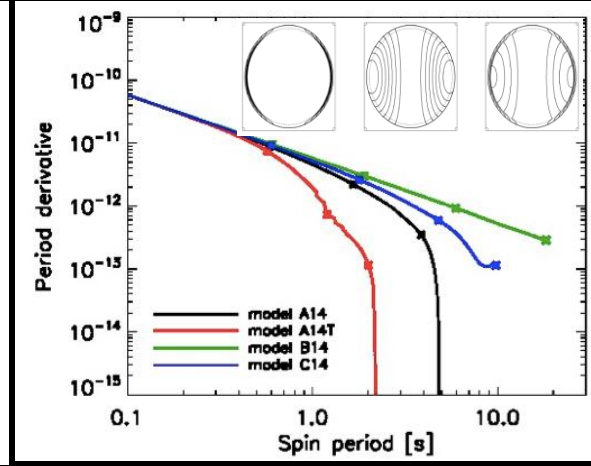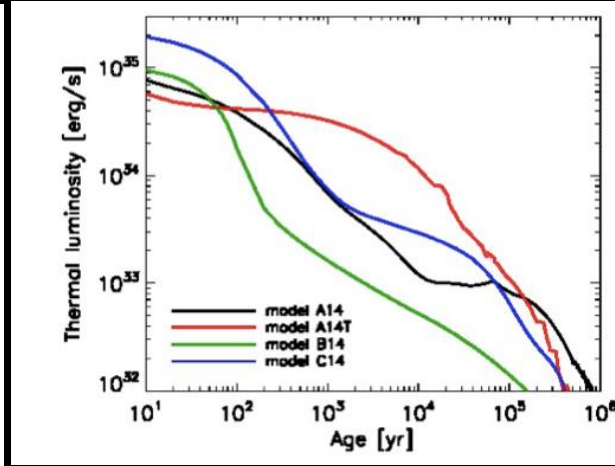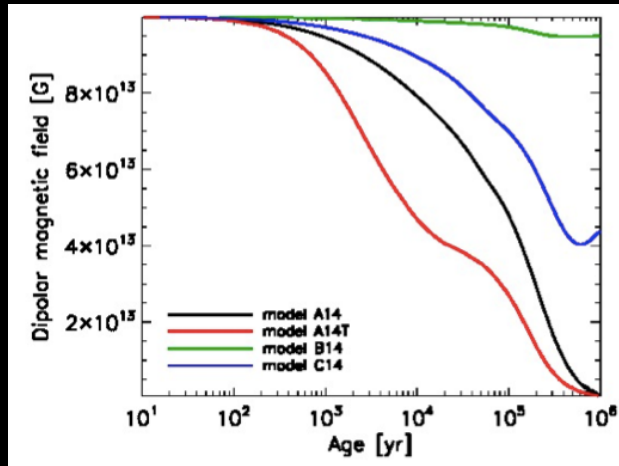
1. **Internal source of heat:** Magnetic fields evolve in the crust and dissipates energy. This changes the stress balance. When the crustal shear breaking strength is exceeded by magnetic stress, the crust breaks, and elastic/magnetic energy is released.

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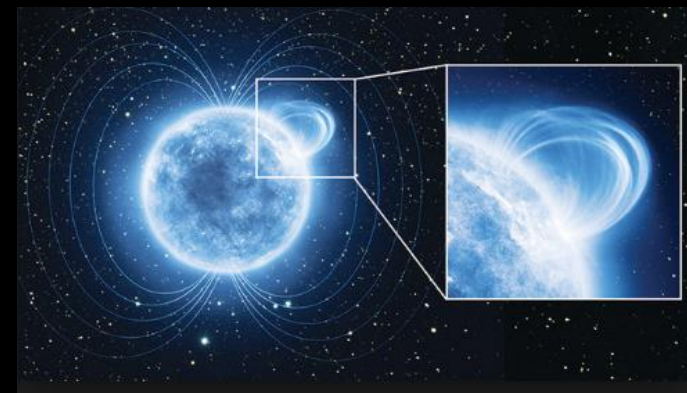
(Thompson et al. 2002; Beloborodov 2007; Perna & Pons 2011; Pons & Rea 2012; Paffrey, Beloborodov & Hui 2013)

(Okamoto et al. 2013)
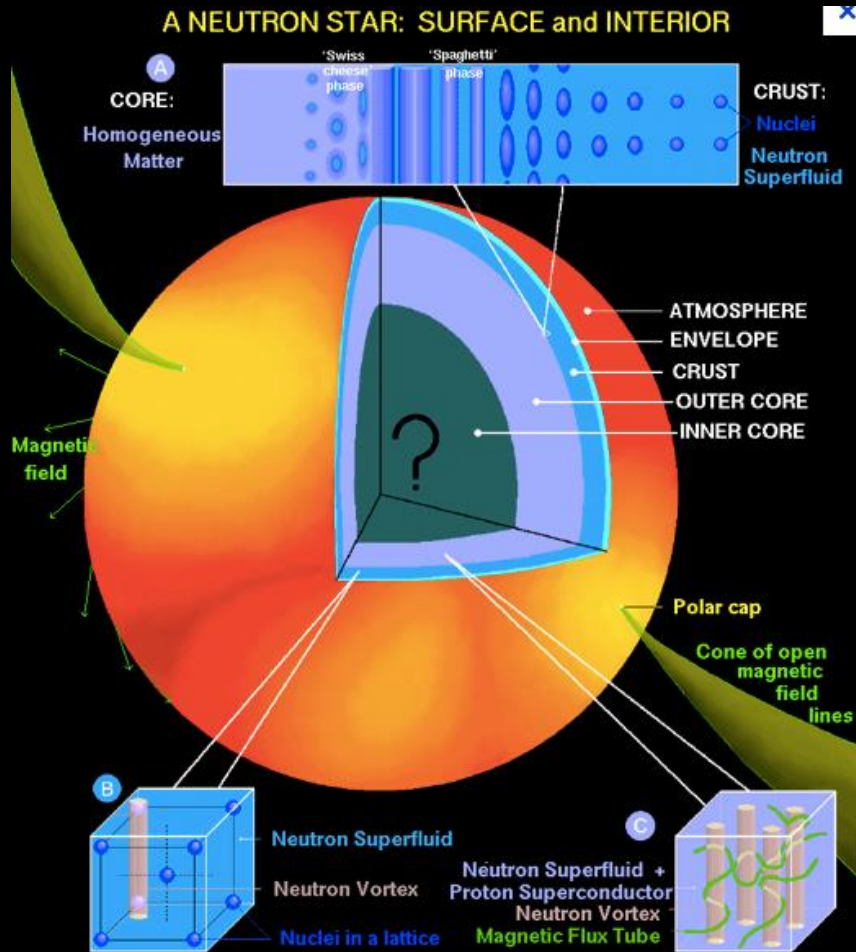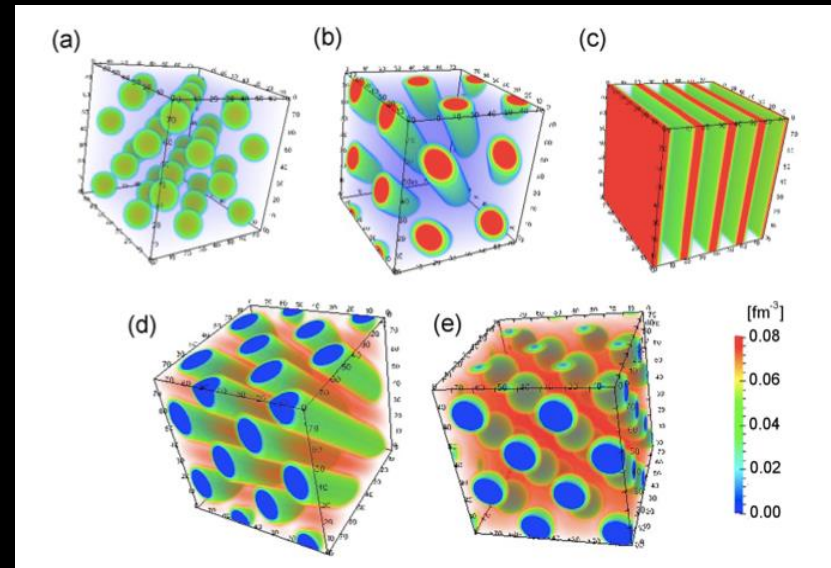
At densities > 10^{13} gr cm^{-3} nuclei are favoured in pasta shapes (rods, slabs, bubbles).

(Page & Reddy 2006)

Qimp = $<Z^2>- <Z^2>$: In absence of more detailed calculations, Qi*mp* parametrizes the crystal structure.
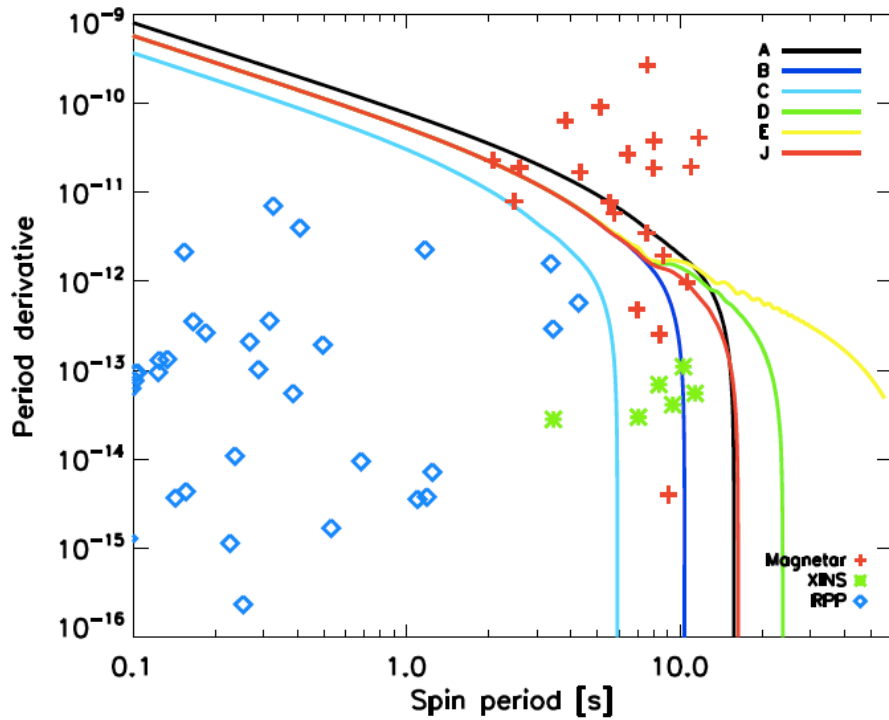
Model	$M [M_\odot]$	I_{45}	ΔR_{crust} [km]	ΔR_{pasta} [km]	Q_{max}
A	1.10	0.962	0.94	0.14	100
B	1.40	1.327	0.70	0.10	100
C	1.76	1.755	0.43	0.07	100
D	1.40	1.327	0.70	0.10	10
E	1.40	1.327	0.70	0.10	0.1
J	1.40	1.327	0.70	0.0	23
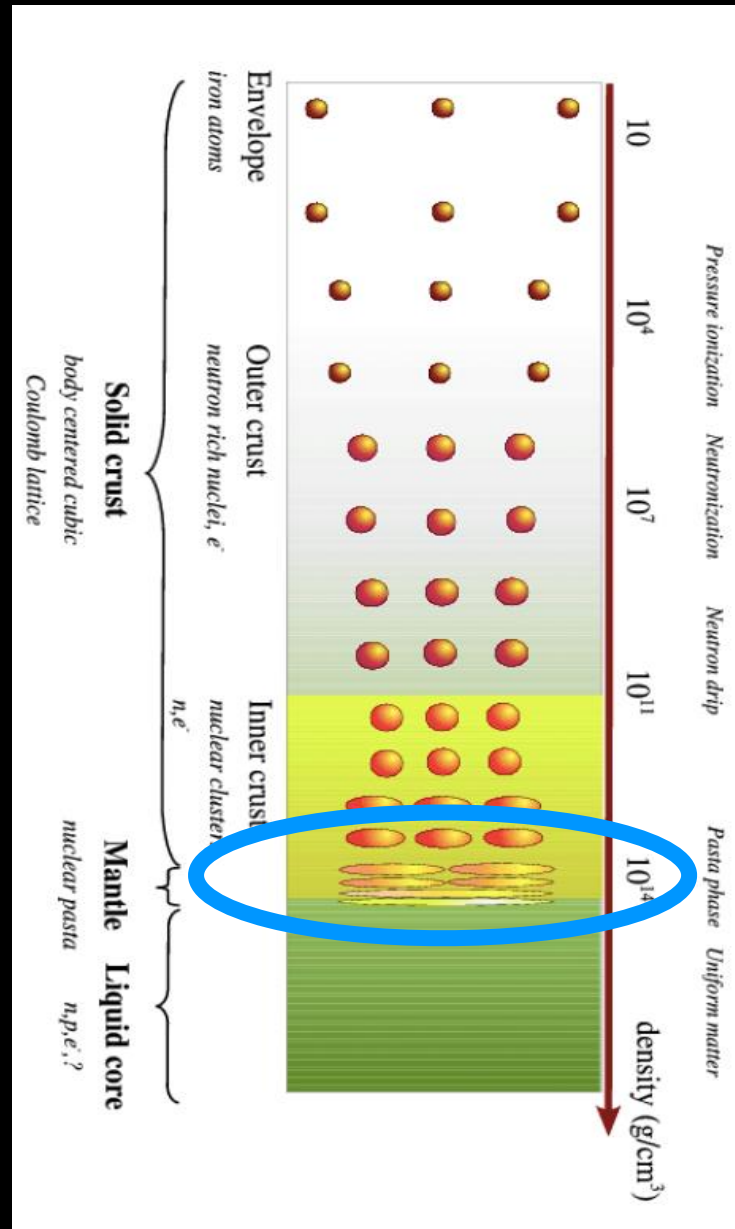
(Pons, Vigano' & Rea 2013 *Nature Physics* 9, 431)

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:
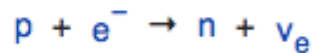
$$p + e^- \rightarrow n + \nu_e$$

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.

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

(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

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

Magnetic evolution: Hall induction equation

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

Hall induction

Electrical resistivity: strongly depends on T
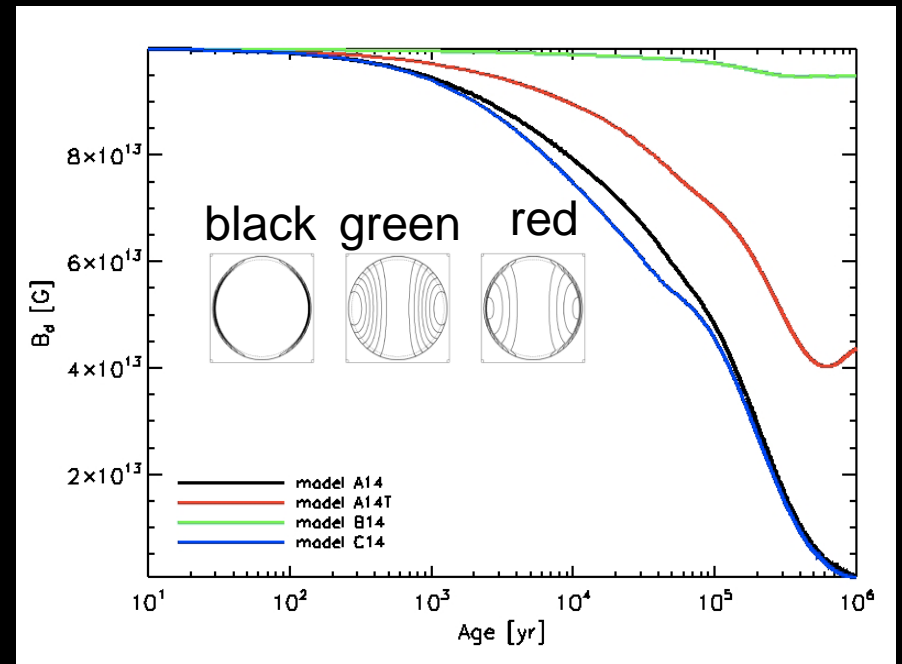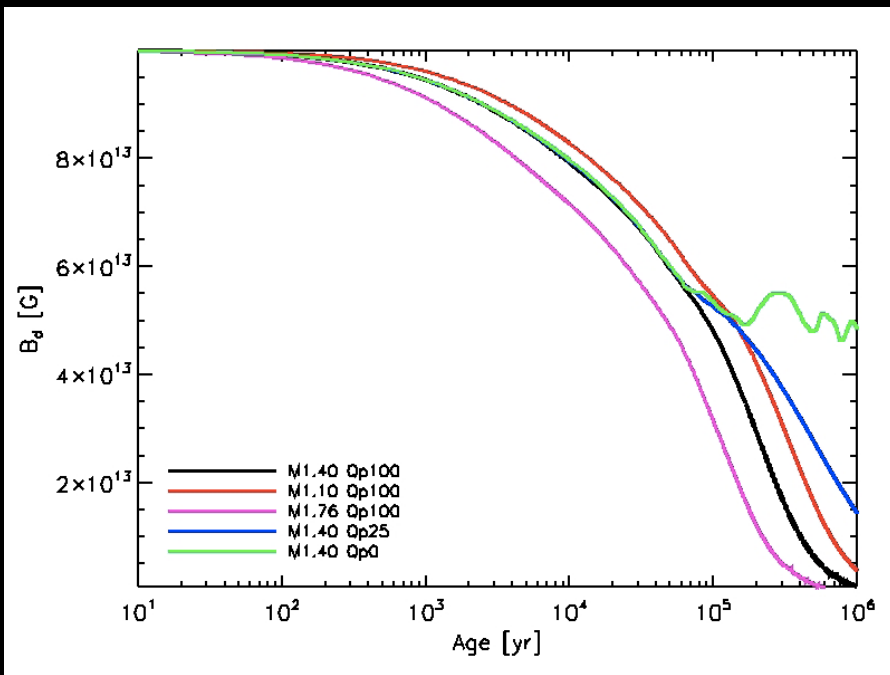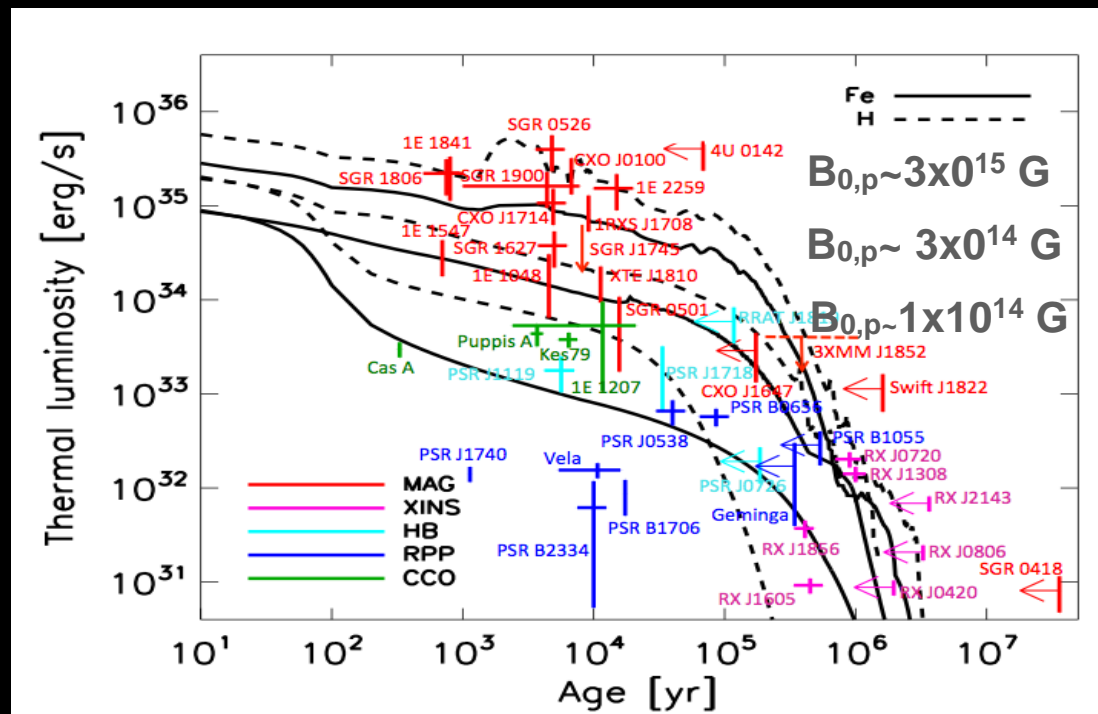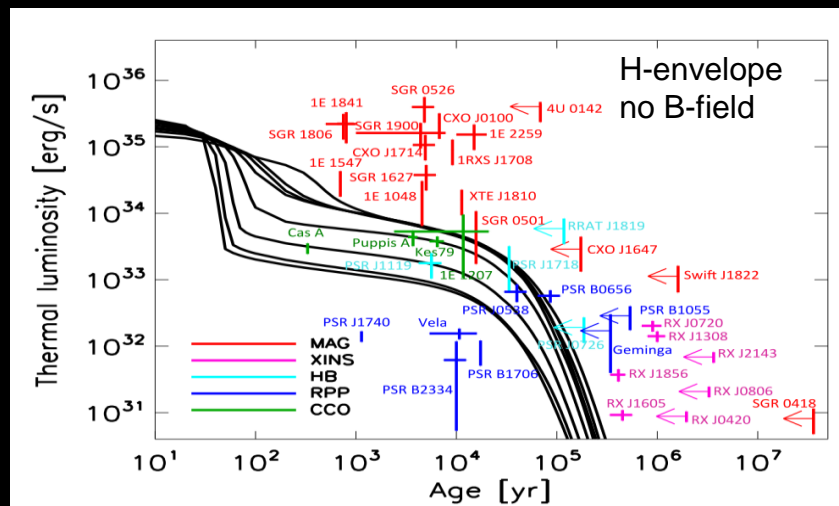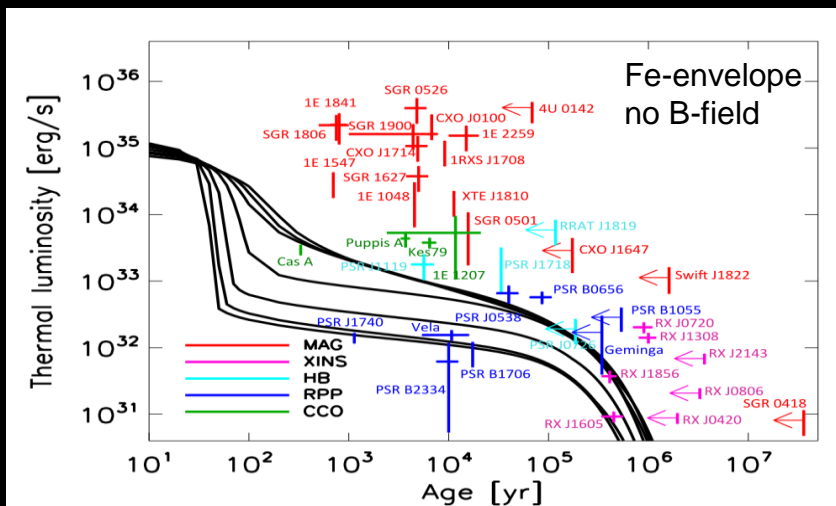
Can a neutron star with 6×10^{12} Gauss dipolar field, as the low-B magnetar SGR 0418+5729, show magnetar-like outbursts and flares?

rdam/CSIC-IEEC
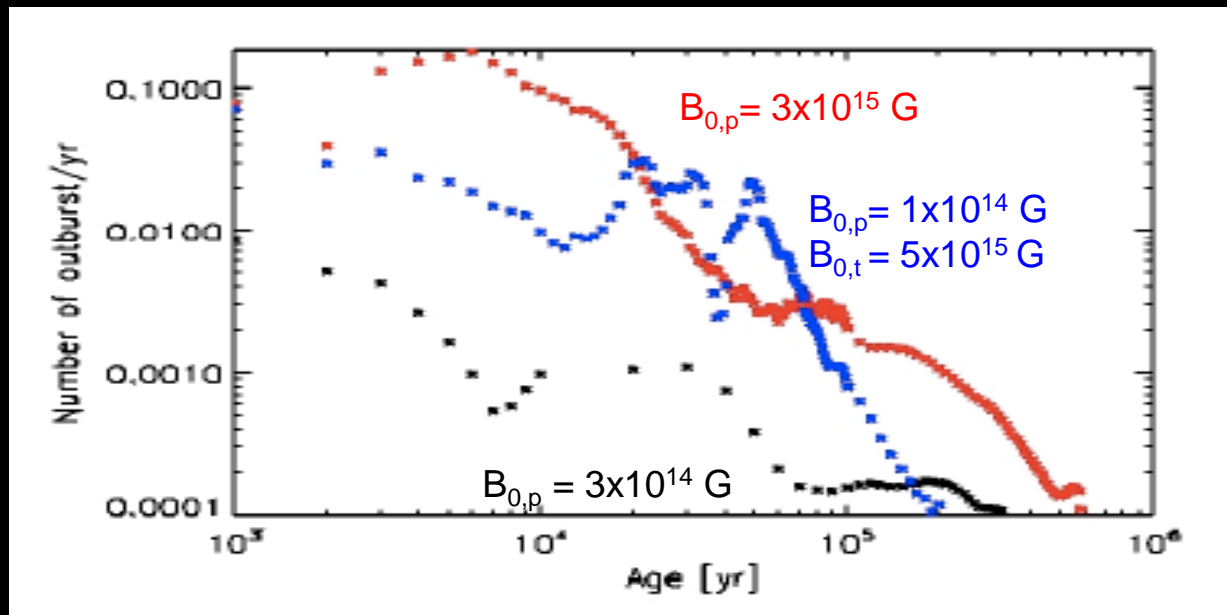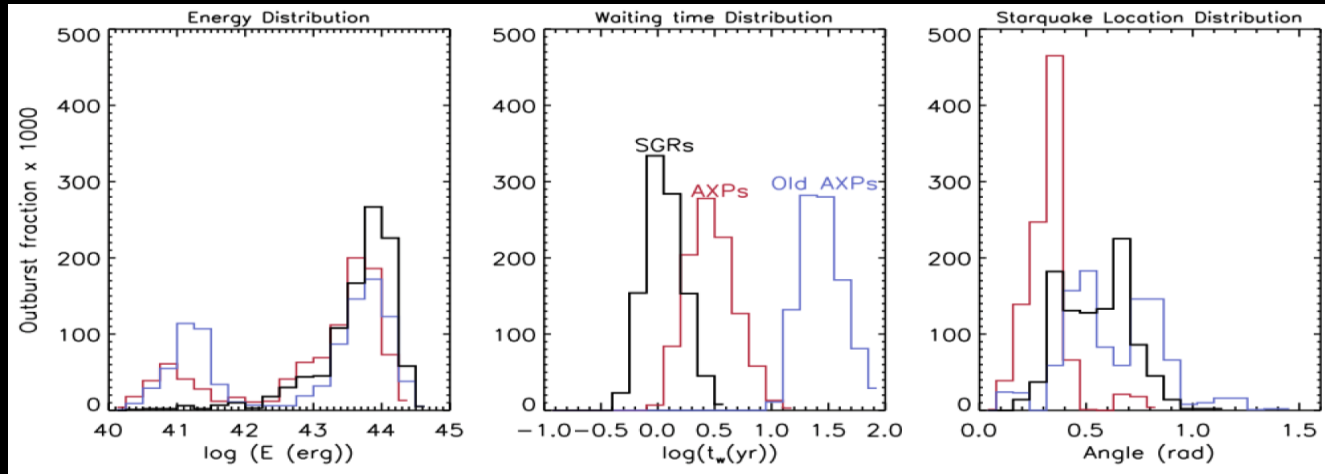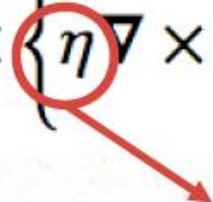
• Neutron star model (structure, EOS)

• 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
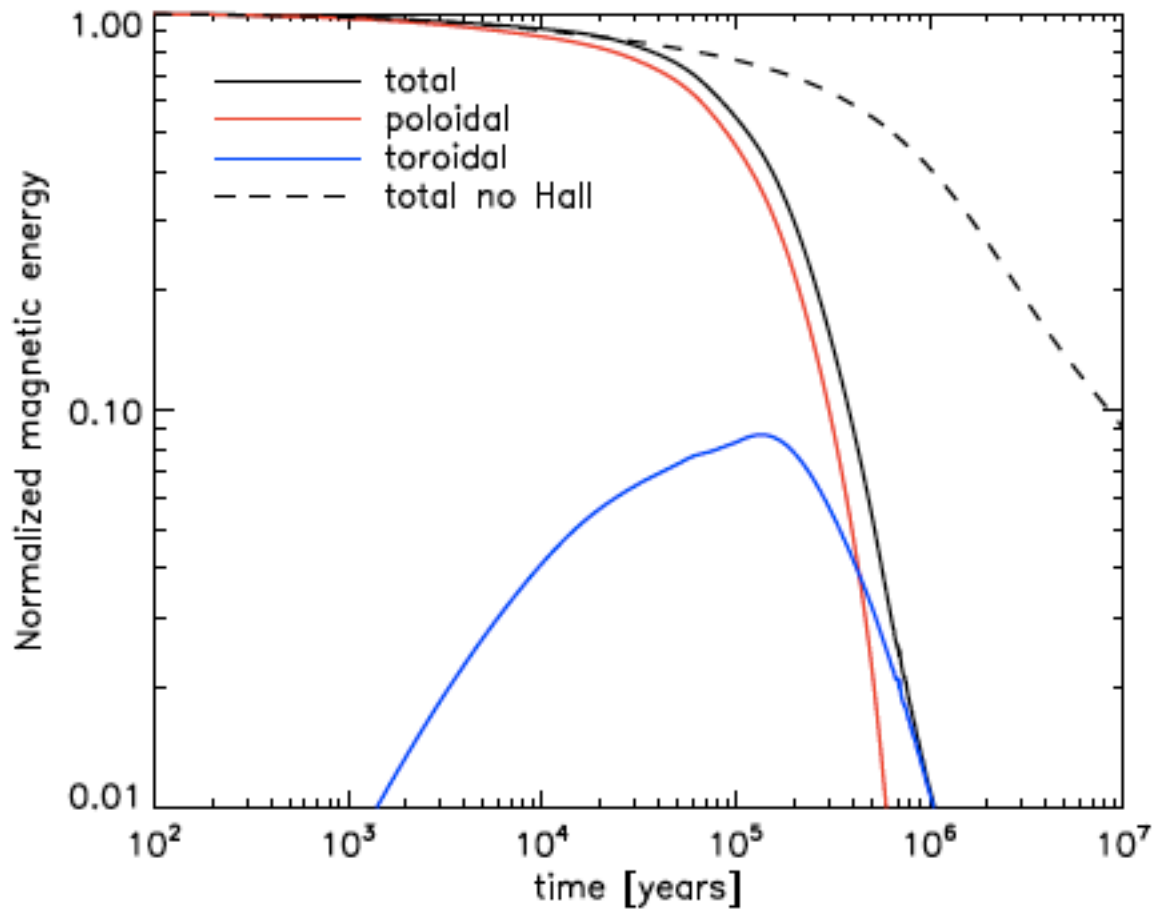
Process	Q_ν [erg cm^{-3}s^{-1}]	Onset	Ref
Core			
Modified URCA (n-branch)			
$nn \to pne\bar{\nu}_e$, $pne \to nn\nu_e$	$8 \times 10^{21}\, \mathcal{R}_n^{MU}\, n_p^{1/3}\, T_9^8$		1
Modified URCA (p-branch)			
$np \to ppe\bar{\nu}_e$, $ppe \to np\nu_e$	$8 \times 10^{21}\, \mathcal{R}_p^{MU}\, n_p^{1/3}\, T_9^8$	$Y_p^c = 0.01$	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			
$ee^+ \to \nu\bar{\nu}$	$9 \times 10^{20}\, F_{\mathrm{pair}}(n_e, n_{e+})$		4
Plasmon decay			
$\tilde{e} \to \tilde{e}\nu\bar{\nu}$	$1 \times 10^{20}\, I_{\mathrm{pl}}(T, y_e)$		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			
$\bar{B} + \bar{B} \to \nu\bar{\nu}$	$1 \times 10^{21}\, n_N^{1/3}\, F_{A,B}\, T_9^7$		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).*
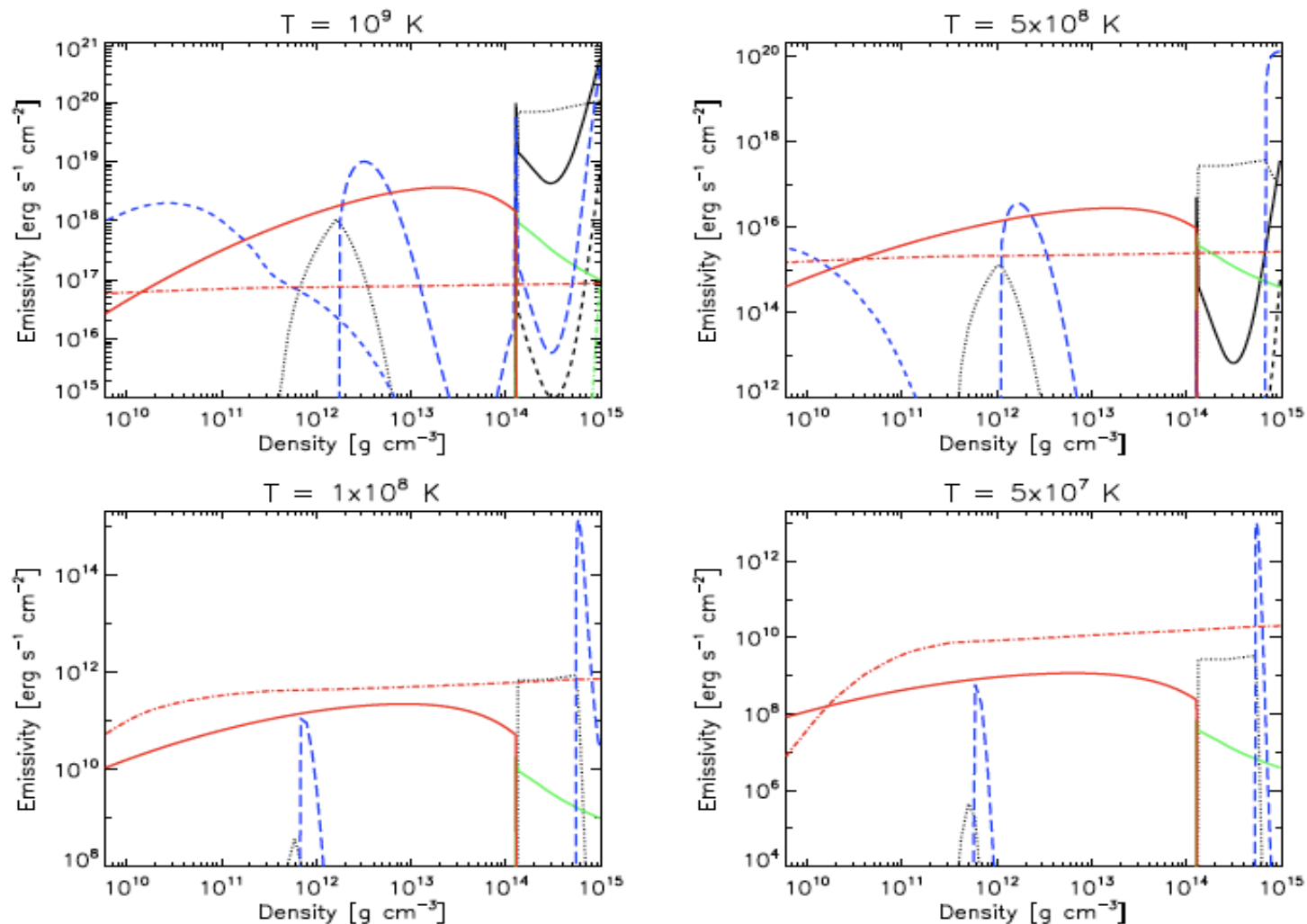
Figure 4.7: *Neutrino emissivities in the crust and in the core at the four indicated temperatures, with the chosen equation of state and superfluid gaps (see text), and mass $M = 1.4\ M_\odot$ (no direct URCA). Lines denote: modified URCA (black solid line), n-n Bremsstrahlung (black dots), n-p Bremsstrahlung (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).*
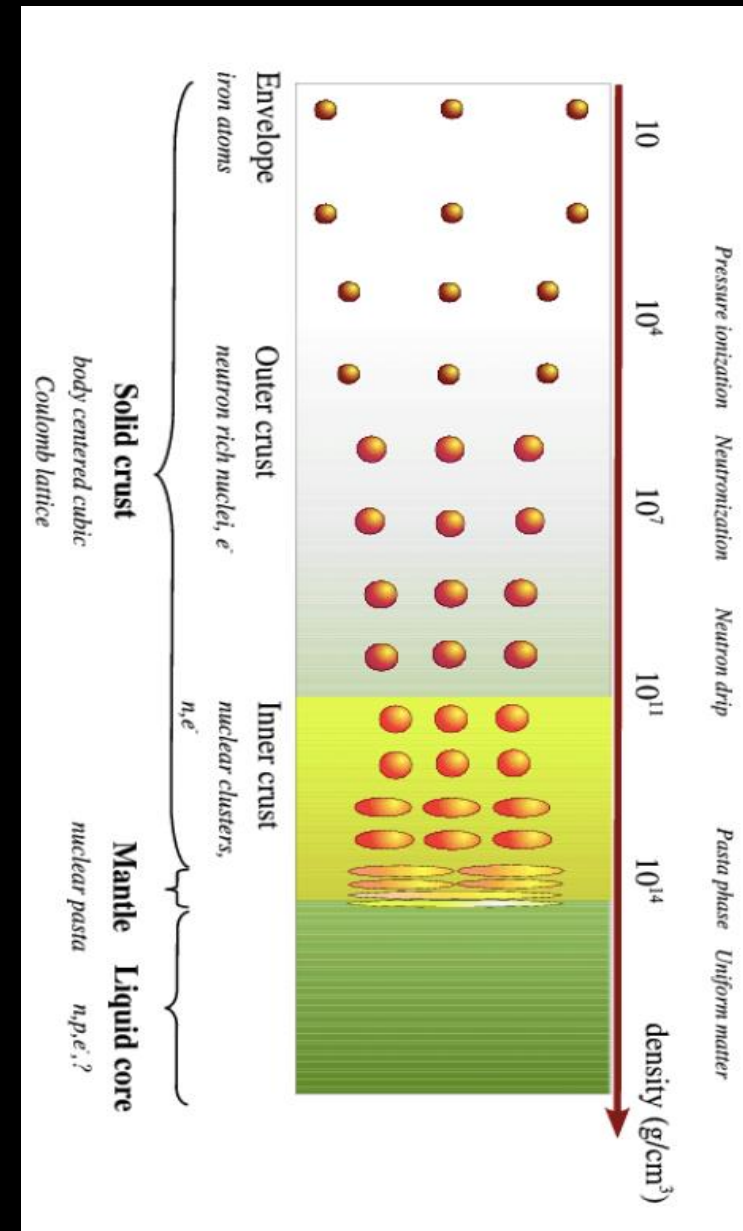
BACK UP SLIDES!
OUTBURSTS

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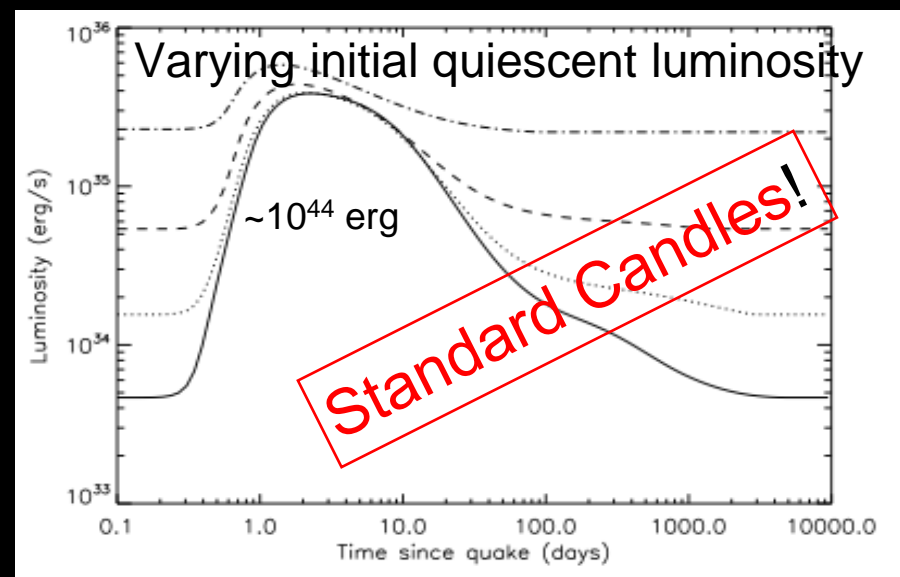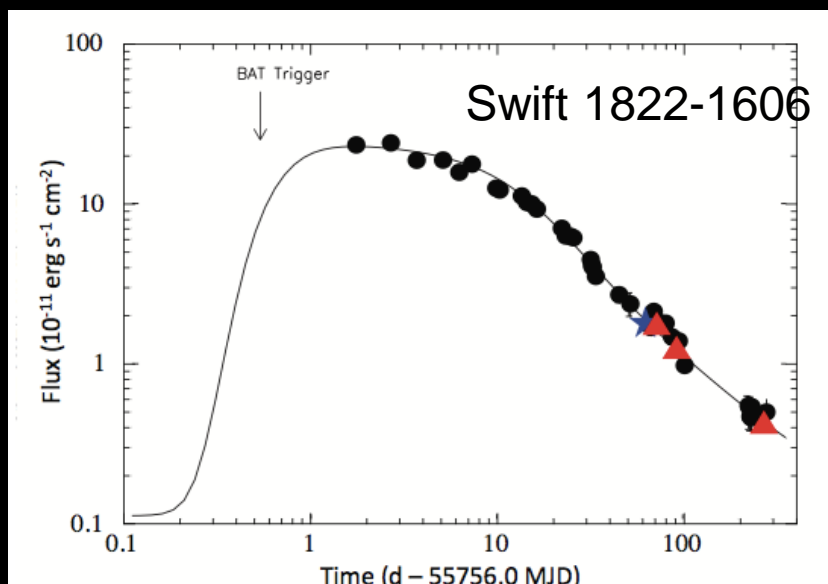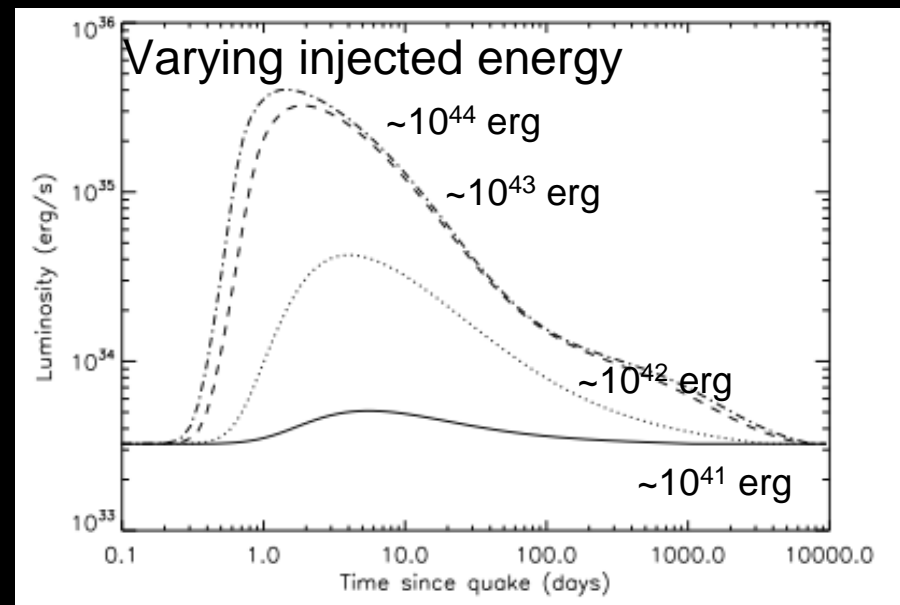Magneto-thermal evolutionary models!

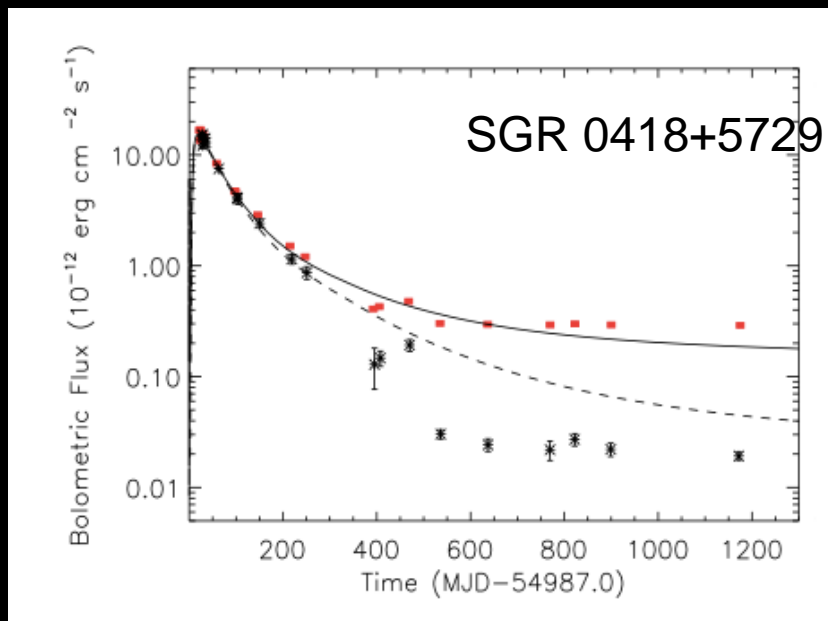2. A fixed amount of energy is injected in a fraction of the crustal volume.
Parameters: rate, energy and volume (depth and angular size).

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

SGR 0418+5729

Varying injected energy

~10^{44} erg

~10^{43} erg

~10^{42} erg

~10^{41} erg

Swift 1822-1606

Varying initial quiescent luminosity

~10^{44} erg

Standard Candles!
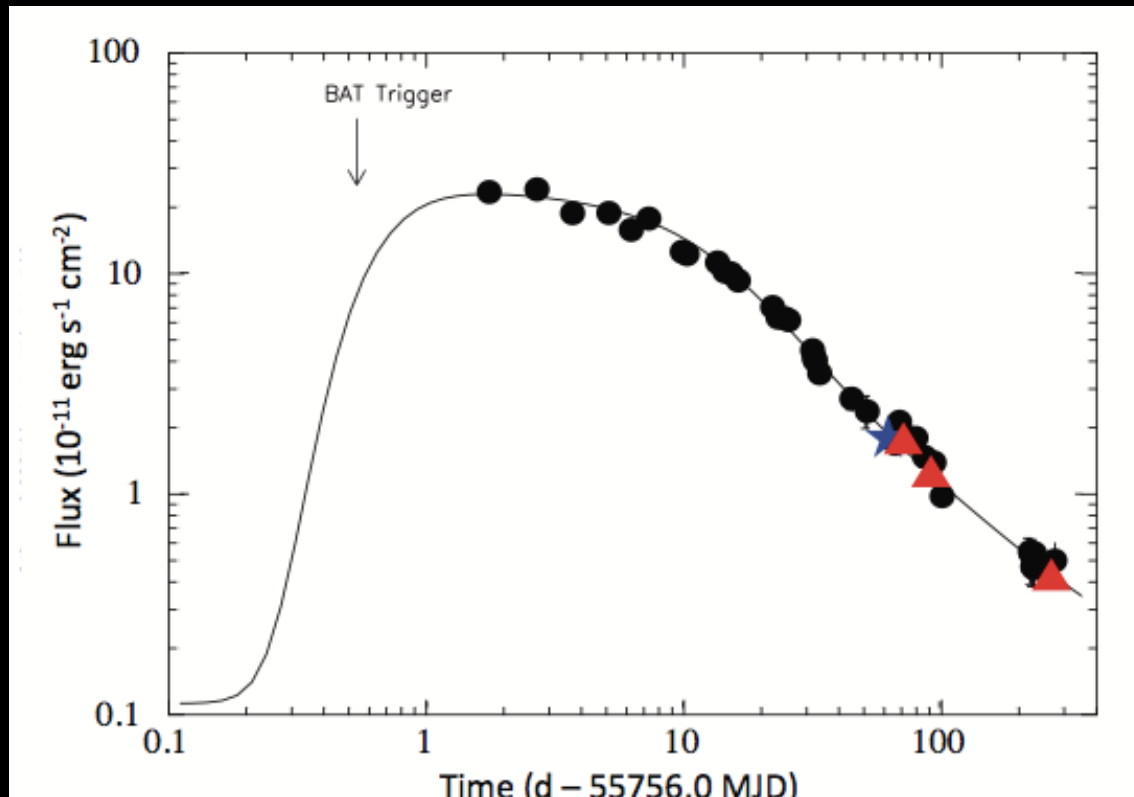
External surface dipolar field from P and Pdot: $\sim 2 \times 10^{13}$ G. Magneto-thermal state consistent with a 0.5 Myr old magnetar, with crustal toroidal field of $\sim 10^{14}$ G. Outburst due to 4×10^{25} erg/cm^3 injected in the outer crust on an ~ 3km radius hot spot (total energy $\sim 10^{42}$ erg).
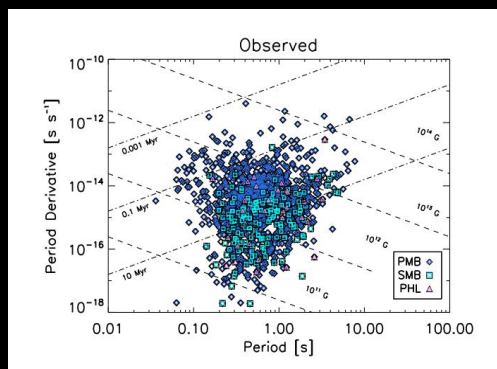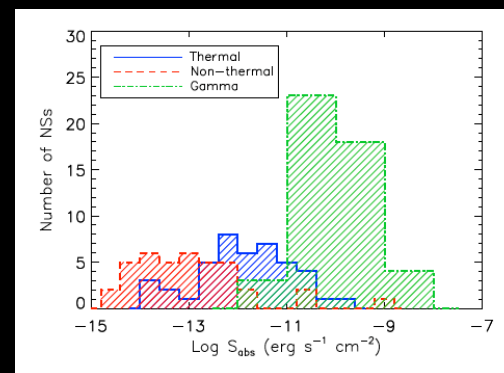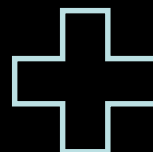
a et al. 2012, 2013; Sholtz et al. 2014)   *Nanda Rea*   *University of Amsterdam*

BACK UP SLIDES!
Pop Syth

Radio Pulsars

+

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

+
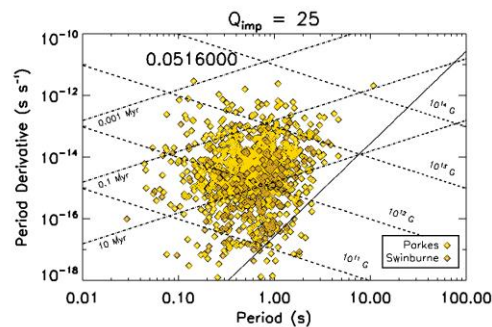

- Age uniformly chosen in → [0, 500 Myr]

- 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

Monte-Carlo simulations

Radio Pulsars

$[\mu_{P_0}, \sigma_{P_0}, \mu_{B_0}, \sigma_{B_0}]$, α, Q_{imp}, alignment (ON/OFF).

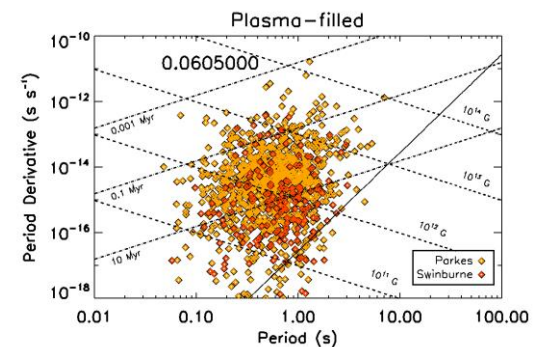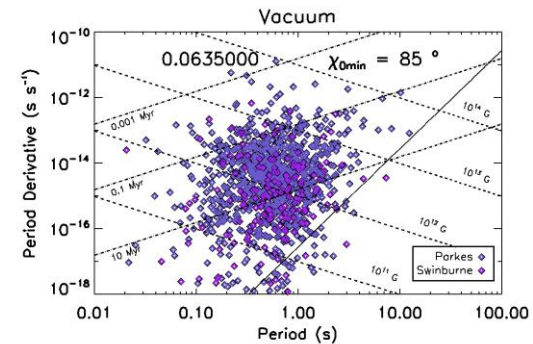| Model	Magnetic field	Envelope	μ_{B_0} $\log B$ [G]	σ_{B_0} $\log B$ [G]	μ_{P_0} [s]	σ_{P_0} [s]	α	n_{br} [century^{-1}]	$\bar{D}$
A	Constant	Heavy elements	12.65	0.50	0.38	0.35	0.50	5.09 ± 0.15	0.072 ± 0.008
B	Decay $Q_{imp}^{ic} = 25$	Heavy elements	13.04	0.55	0.23	0.32	0.44	2.20 ± 0.07	0.068 ± 0.006
C	Decay $Q_{imp}^{ic} = 100$	Heavy elements	13.20	0.72	0.37	0.33	0.41	3.17 ± 0.09	0.062 ± 0.008
D1	Decay $Q_{imp}^{ic} = 25$	Light elements	12.99	0.56	0.16	0.31	0.43	2.63 ± 0.04	0.072 ± 0.009
D2	Decay $Q_{imp}^{ic} = 25$	Light elements	13.15	0.65	0.30	0.23	0.44	3.45 ± 0.09	0.077 ± 0.009
D3	Decay $Q_{imp}^{ic} = 25$	Light elements	13.24	0.78	0.29	0.27	0.42	2.95 ± 0.07	0.08 ± 0.01
E	Decay $Q_{imp}^{ic} = 50$	Light elements	13.13	0.68	0.32	0.19	0.44	3.80 ± 0.11	0.069 ± 0.007

Best fits for period and B-field distributions at birth for radio pulsars should now be compatible with the other neutron star classes: magnetars, x-ray dim isolated neutron stars, gamma-ray pulsars, etc…
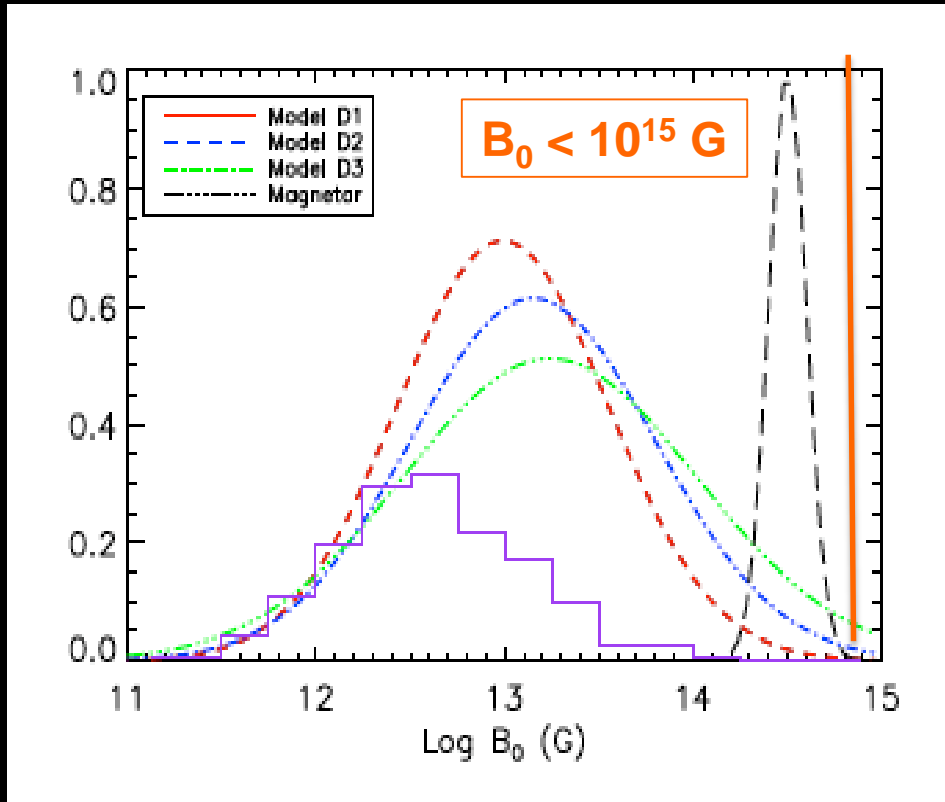
… but none of the Gaussian distributions that best fit the Radio Pulsars population seem to predict correctly the observed samples of the neutron star populations
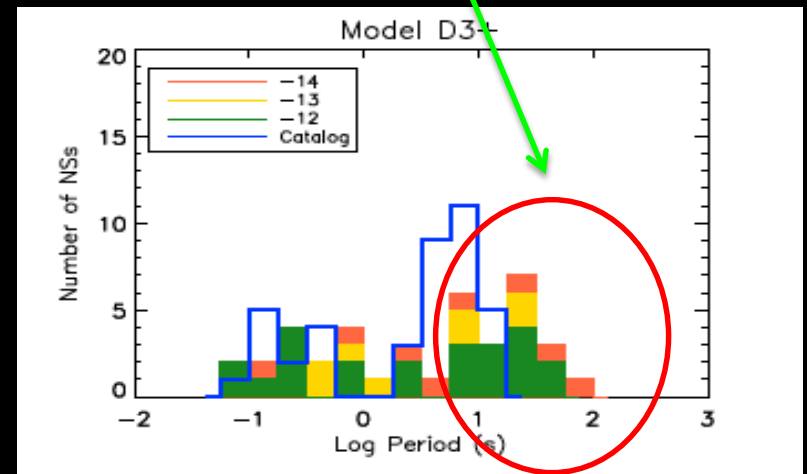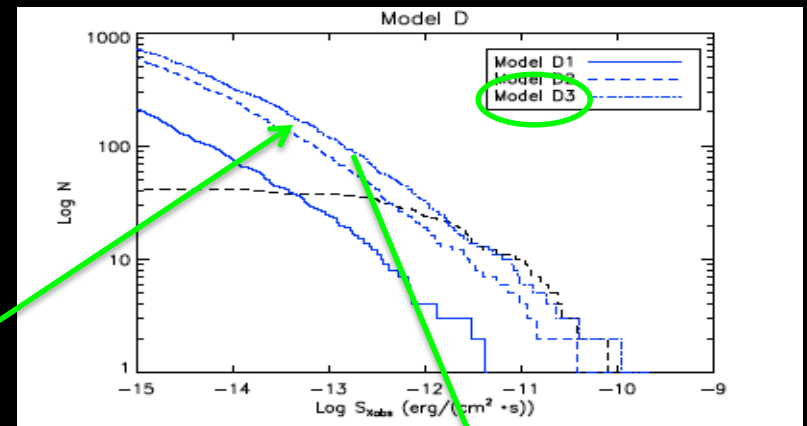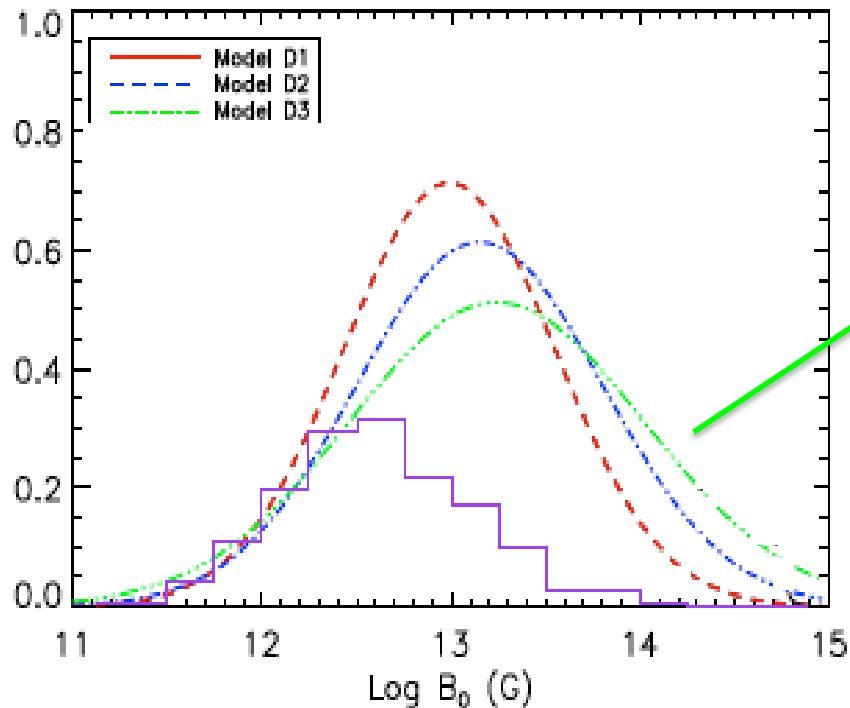
$B_0 < 10^{15}$ G

A bi-modal distribution does work!

- This might be explained by different progenitors: binaries versus isolated?
  GRB-SN versus normal CC-SN?

$B_0 < 10^{15}$ G

- If the origin of B-field ia attributed to MHD instabilities (i.e. any dynamo process related to convection), one should expect a saturation when the B-field becomes dynamically relevant to suppress the instability.

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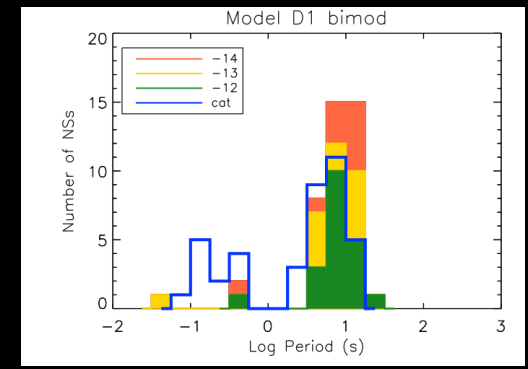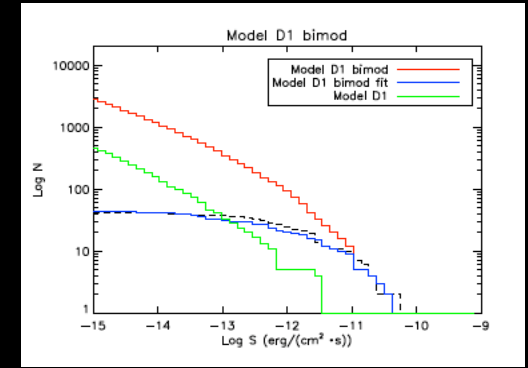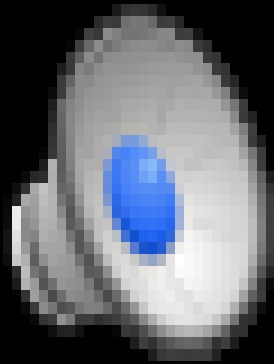- Magnetic field configuration has strong non-dipolar components in every neutron star!

- if the origin of the neutron star magnetic field is attributed to MHD instabilities (any dynamo process related to rotation or convection), one should expect a saturation when the magnetic field becomes dynamically relevant to suppress the instability.We then expect a maximum allowed magnetic field that can be generated this way, which is indeed expect to be of the order of 10^{15} Gauss.

Magnetar general multi-band properties

- X-ray pulsars Lx ~ 10^{33}-10^{36} erg/s

- strong soft and hard X-ray emission

- short X/gamma-ray flares and long outbursts

- pulsed fractions ranging from ~2-80 %

- rotating with periods of ~0.3-12s

- period derivatives of ~10^{-14}-10^{-11} s/s

- magnetic fields of ~10^{13}-10^{15} Gauss

- glitches and timing noise

- faint infrared/optical emission (K~20; sometimes pulsed and transient)

- transient radio pulsed emission

(Abdo et al. 2012)

(Israel et al. 2010)

(Camilo et al. 2006)

(Mereghetti 2008, Rea & Esposito 2011 for a review) *Nanda Rea* *University of Amsterdam/CSIC-IEEC*