FROM BIRTH TO BURST: NEUTRON STAR DIVERSITY AND THEIR LINK TO SUPERNOVAE, GRBs and FRBs

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CSIC
Consejo Superior de Investigaciones Científicas

IEEC

erc
European Research Council
Established by the European Commission

GOBIERNO DE ESPAÑA
MINISTERIO DE CIENCIA, INNOVACIÓN Y UNIVERSIDADES

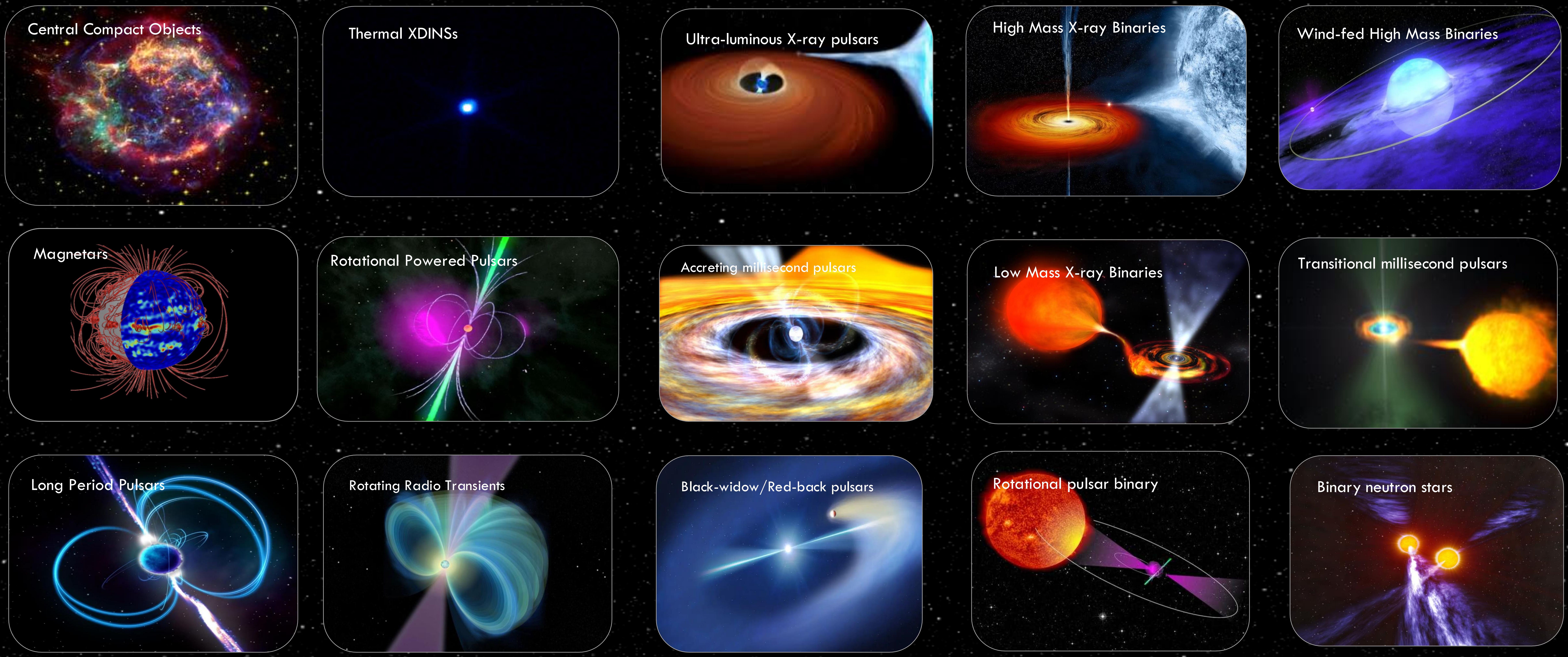
1. WHY AREN'T ALL PULSARS BEHAVING SIMILARLY? HOW COMMON ARE STRONG MAGNETIC FIELDS?

2. DO WE HAVE ENOUGH SNe FOR SO MANY DIFFERENT NS CLASSES?

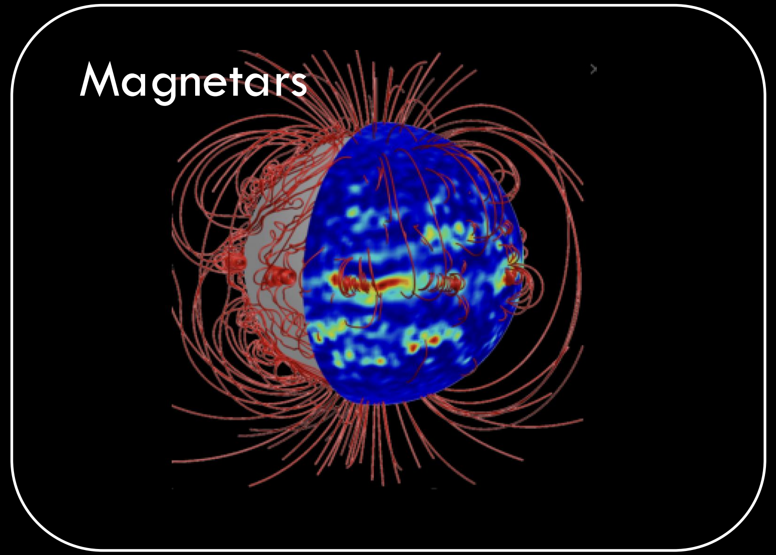
3. WHAT DID WE LEARN FROM THE OBSERVED NSs ABOUT THEIR BIRTH AND SN RATES?

4. HOW CAN WE USE THEM TO CONSTRAIN FRBs AND GRBs?

NEUTRON STAR SYSTEMS



THE ISOLATED PULSAR POPULATION



MAGNETARS

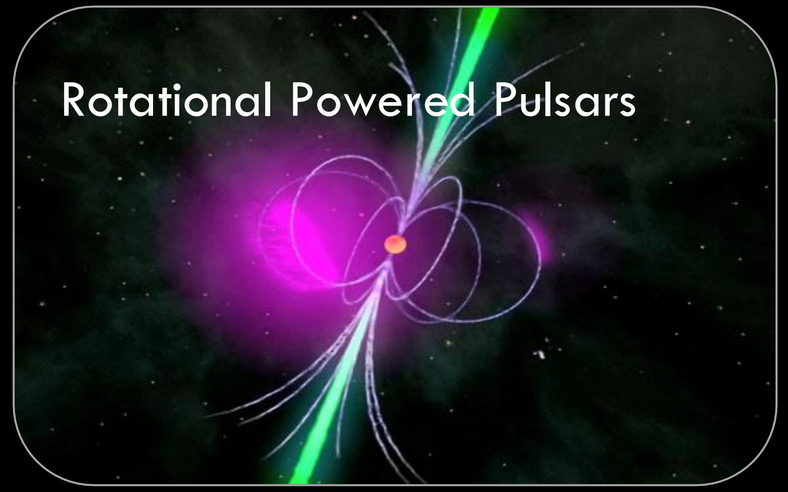
Powered by magnetic energy. Characterized by outbursts and flares. Typically emitting in the X-rays.

THERMAL NSs (XDINS)

Powered by magnetic energy.
Old, almost pure blackbodies.
Typically emitting in the X-rays.

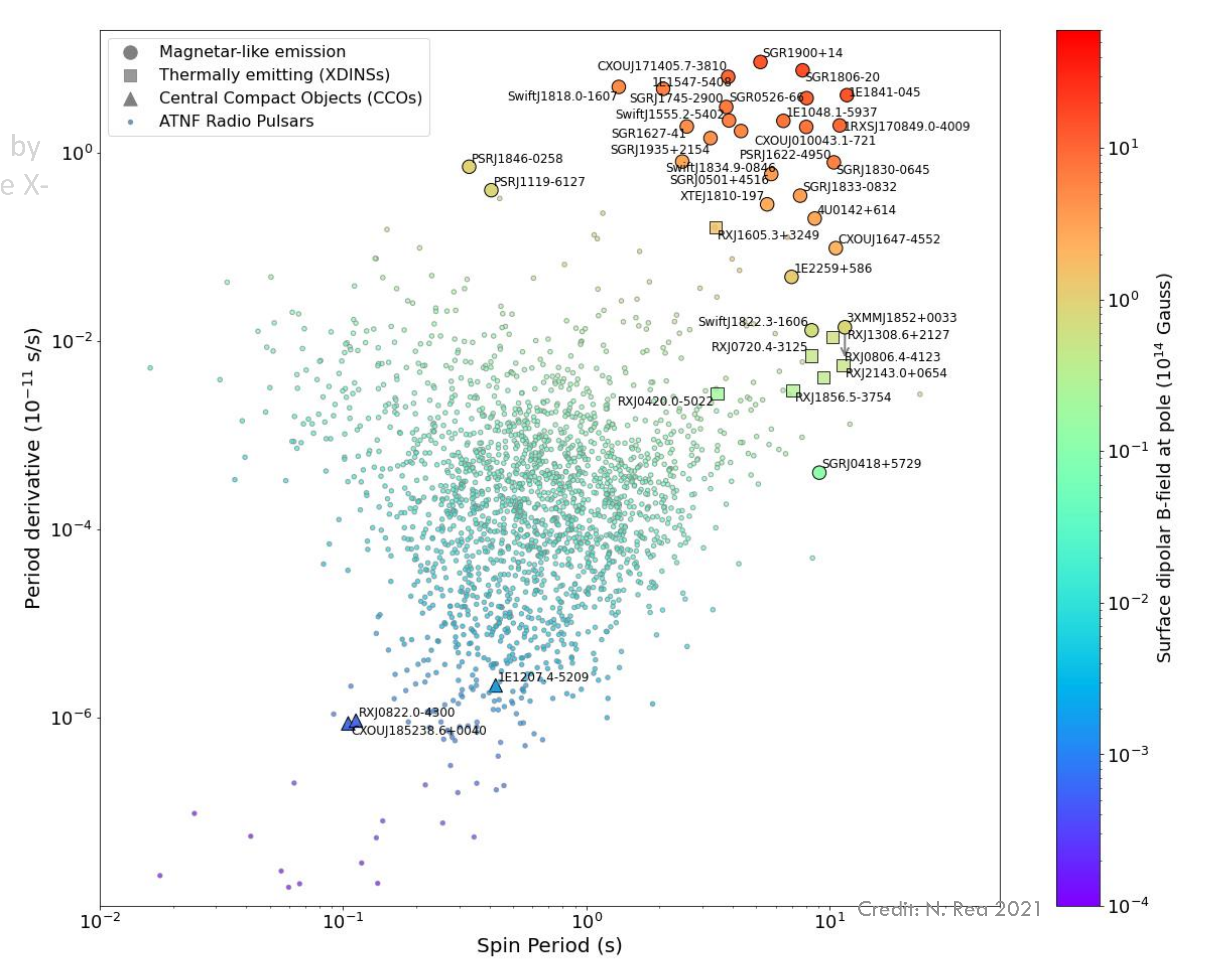
CENTRAL COMPACT OBJECTS

Powered by magnetic energy.
Young, with bright SNRs.
Typically emitting in the X-rays.

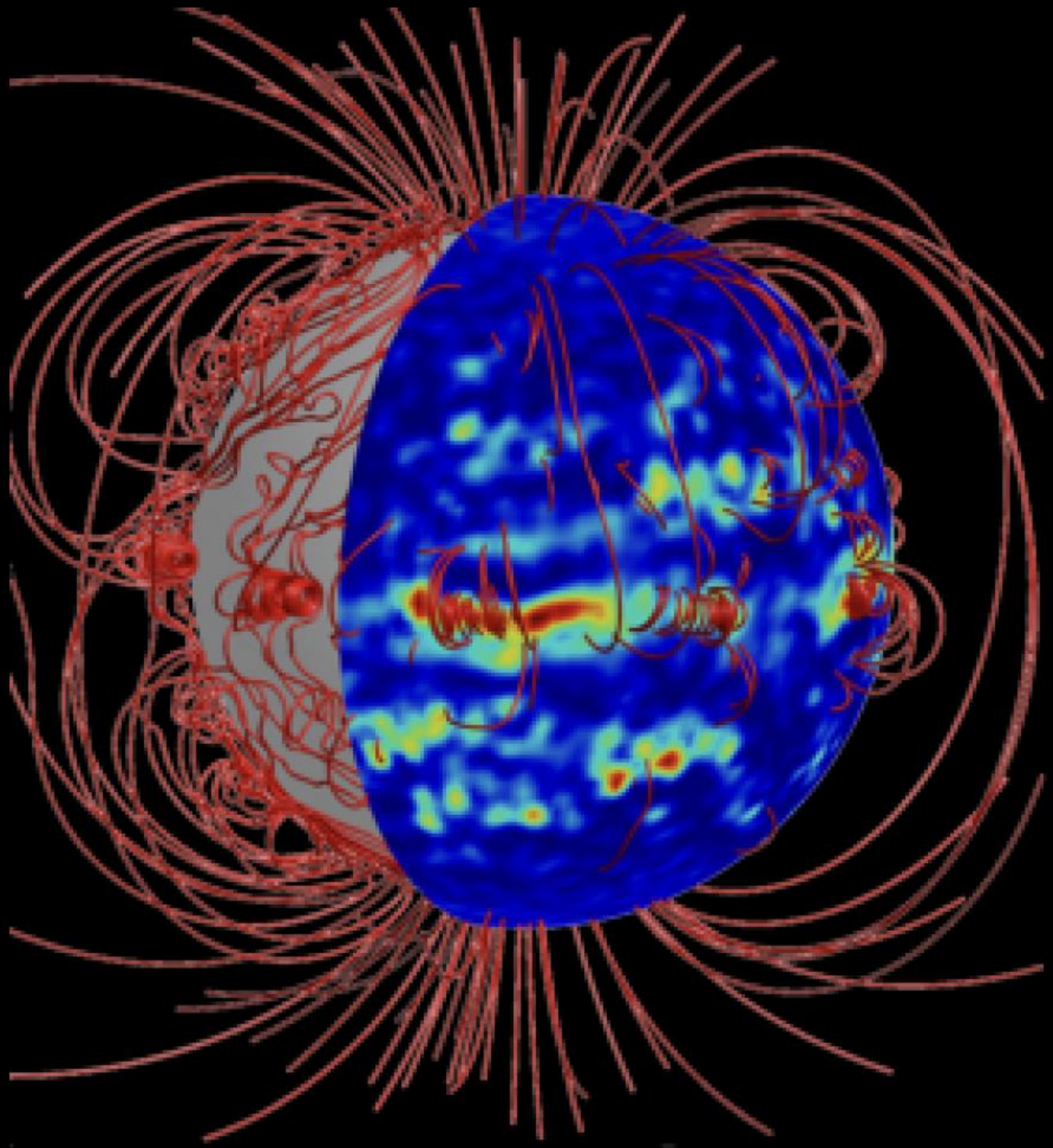


ROTATIONAL POWERED PULSARS

Powered by rotational energy.
Typically emitting in radio.

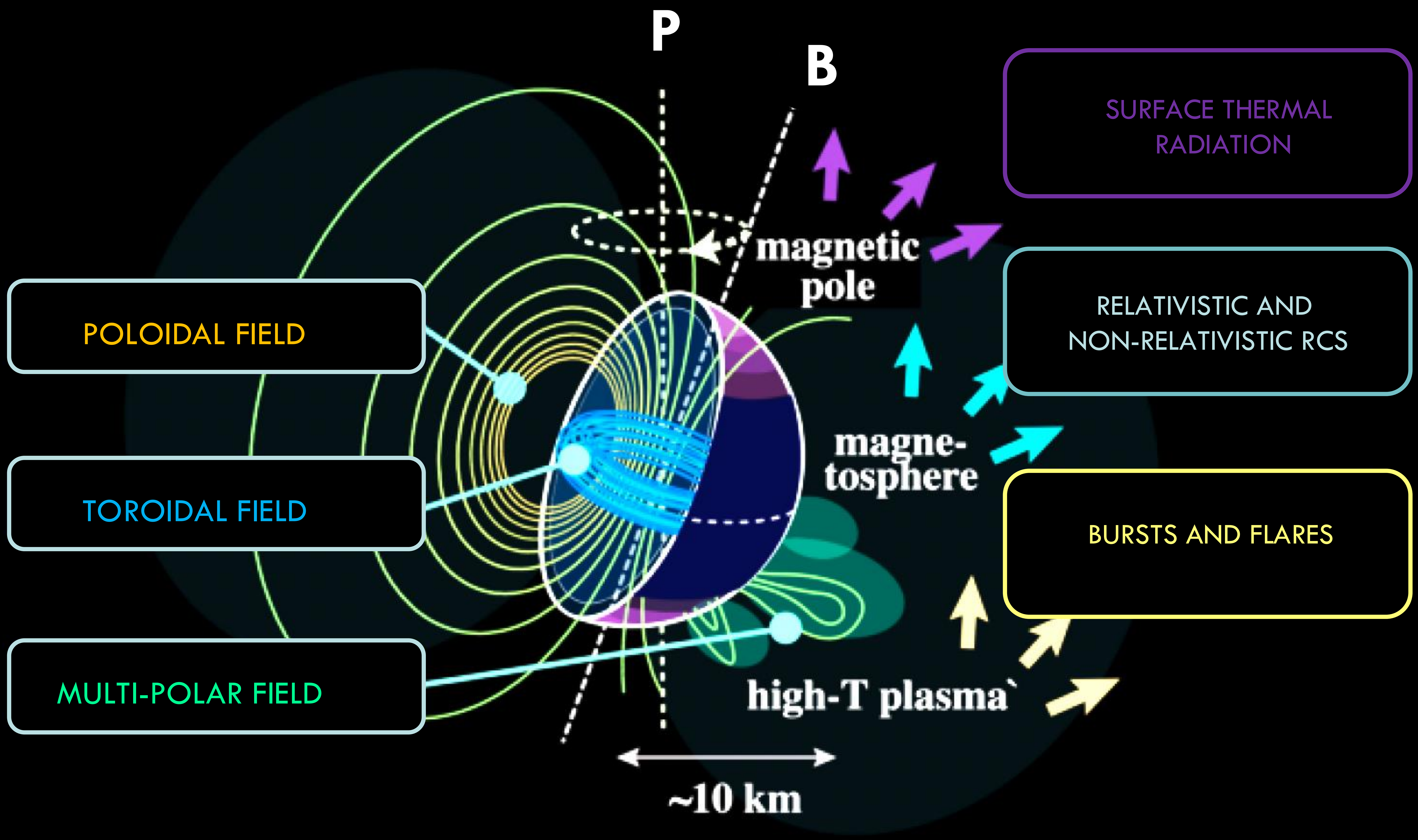


WHAT IS A MAGNETAR?



(Gougouliatos et al. 2014)

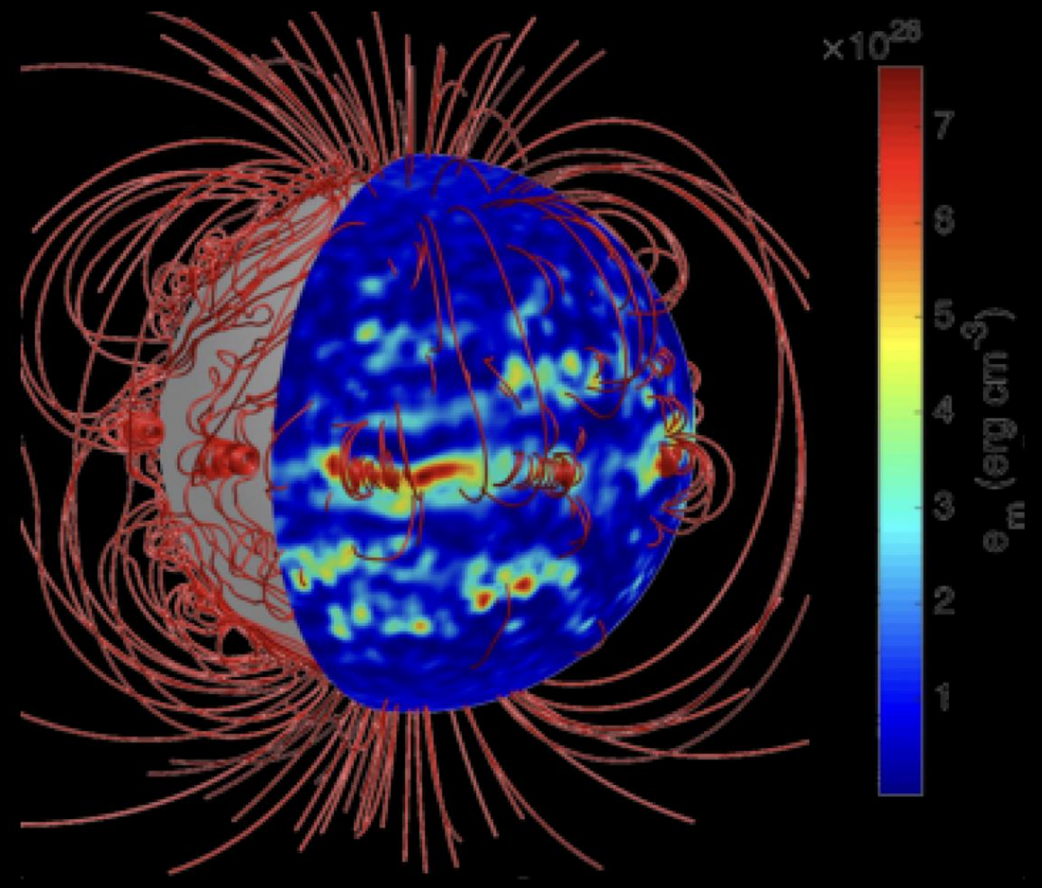
MAGNETAR GENERAL EMISSION CHARTOON

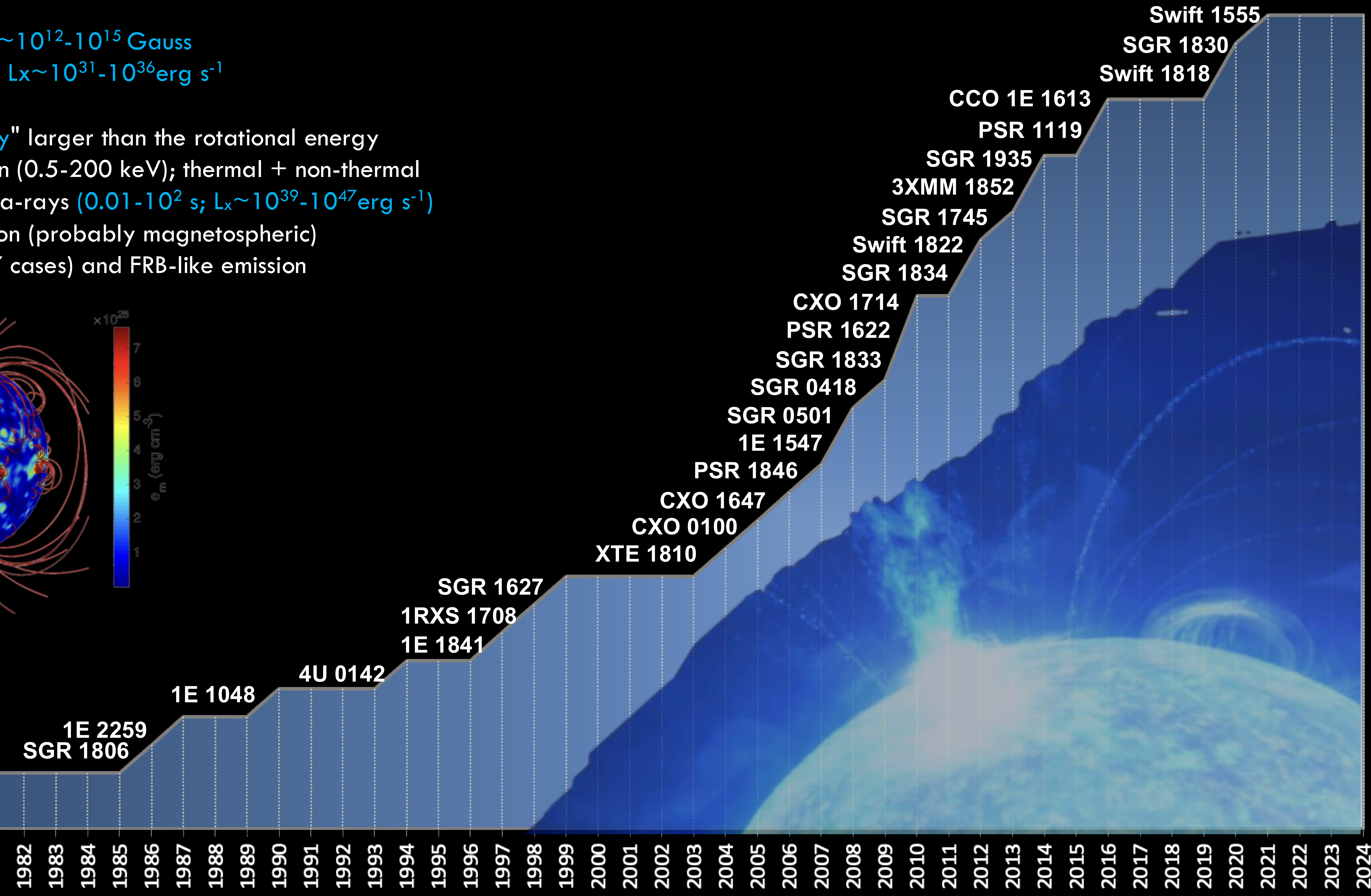


(adapted from Enoto et al. 2019)

MAGNETAR NUMEROLOGY

- Dipolar magnetic fields of $B \sim 10^{12}$-10^{15} Gauss
- Transient X-ray pulsars with $L_x \sim 10^{31}$-10^{36} erg s^{-1}
- Rotating with P~0.3-12 s
- X-ray luminosity is "generally" larger than the rotational energy
- Soft and hard X-ray emission (0.5-200 keV); thermal + non-thermal
- 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 (probably magnetospheric)
- Transient radio emission (in 7 cases) and FRB-like emission

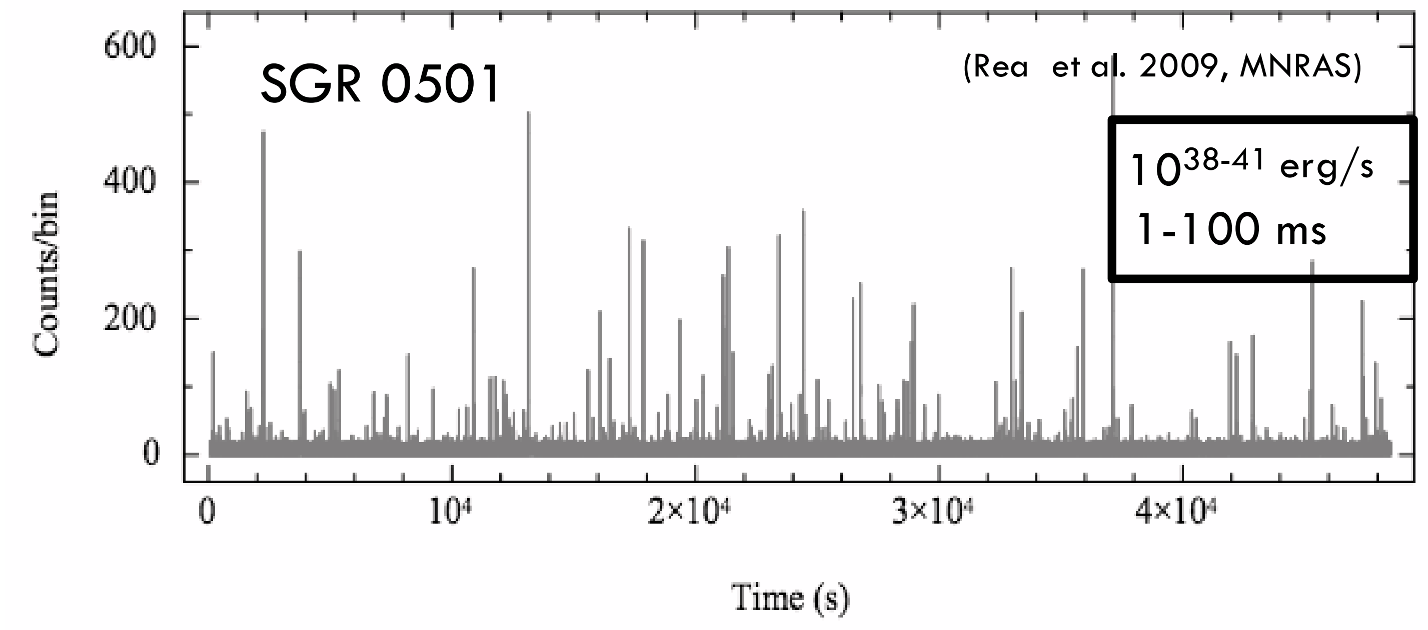


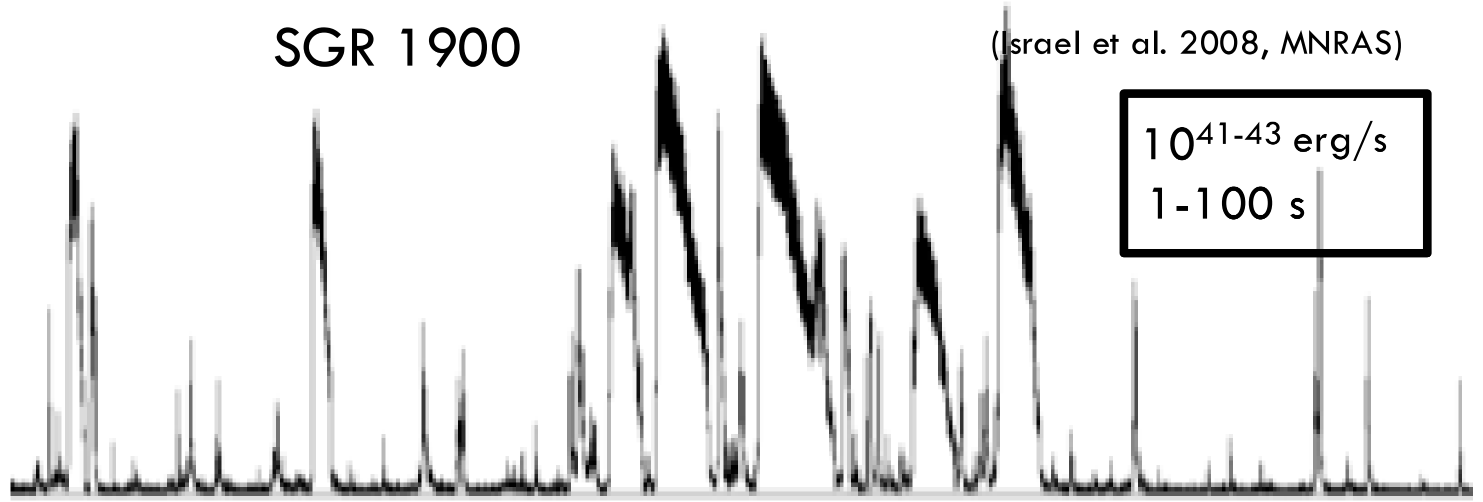


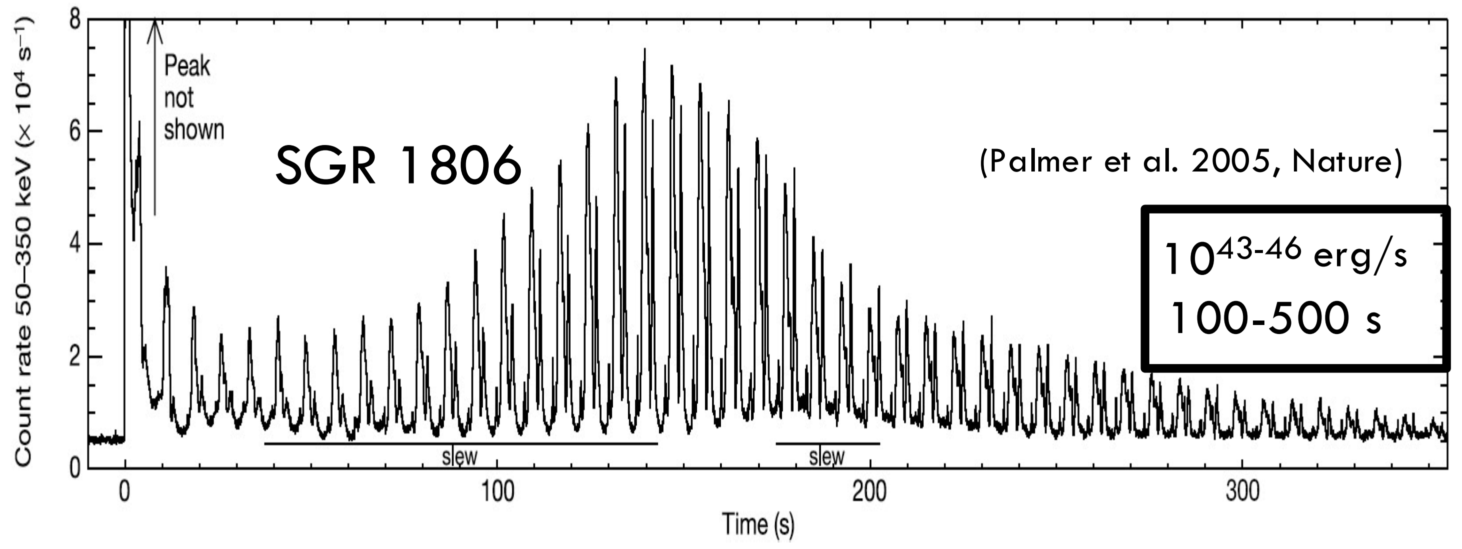
(Rea & De Grandis 2026)

MAGNETAR OUTBURSTS AND FLARES

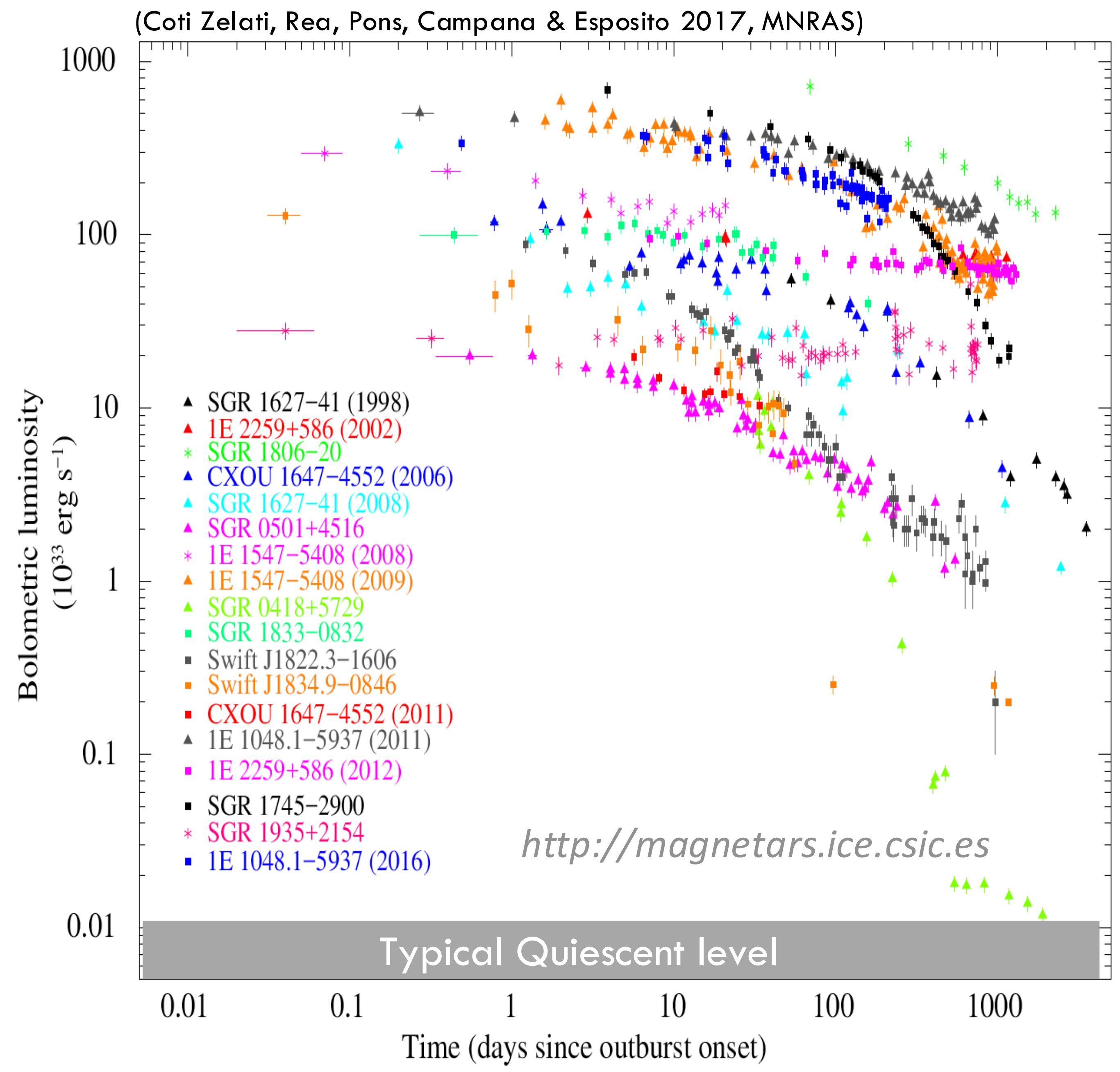
FLARING ACTIVITY

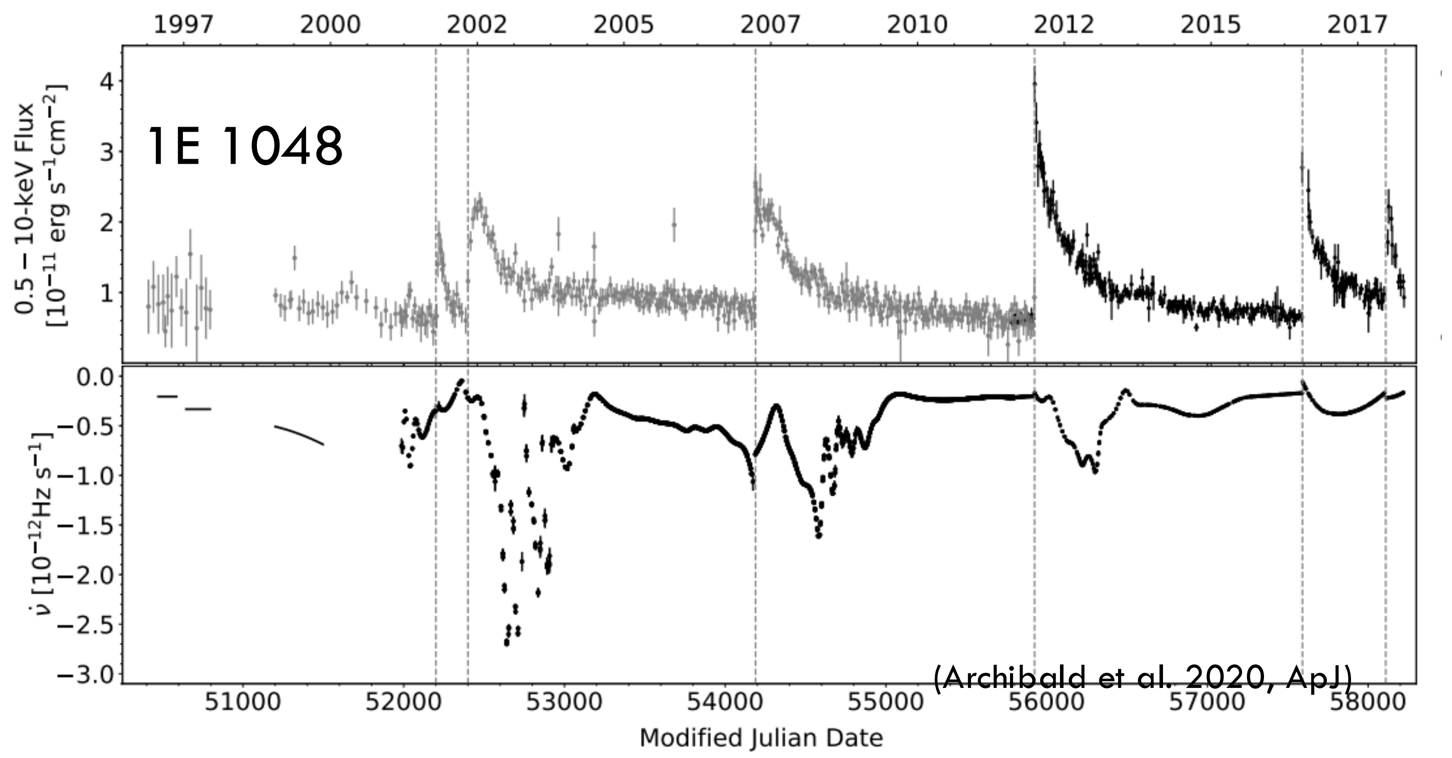






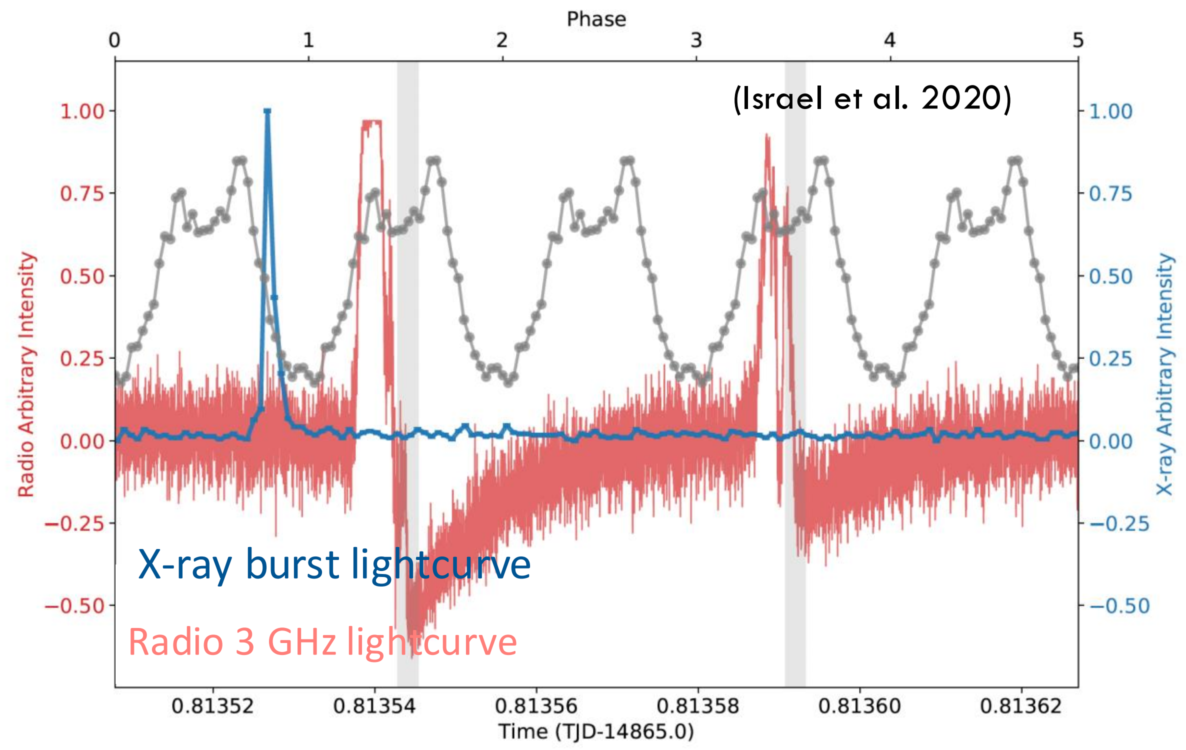
OUBURST ACTIVITY



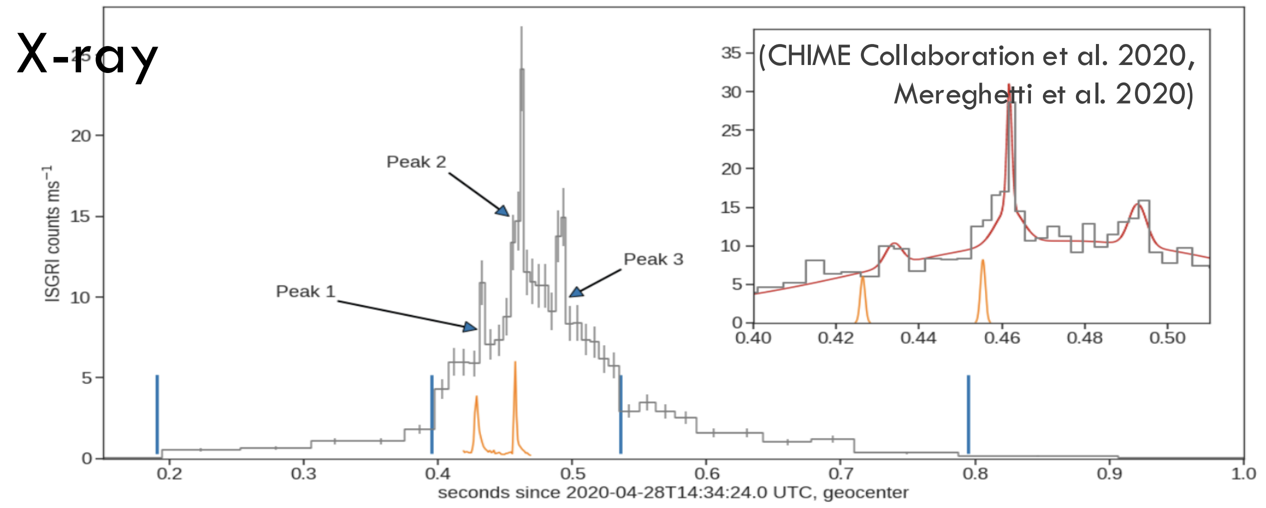


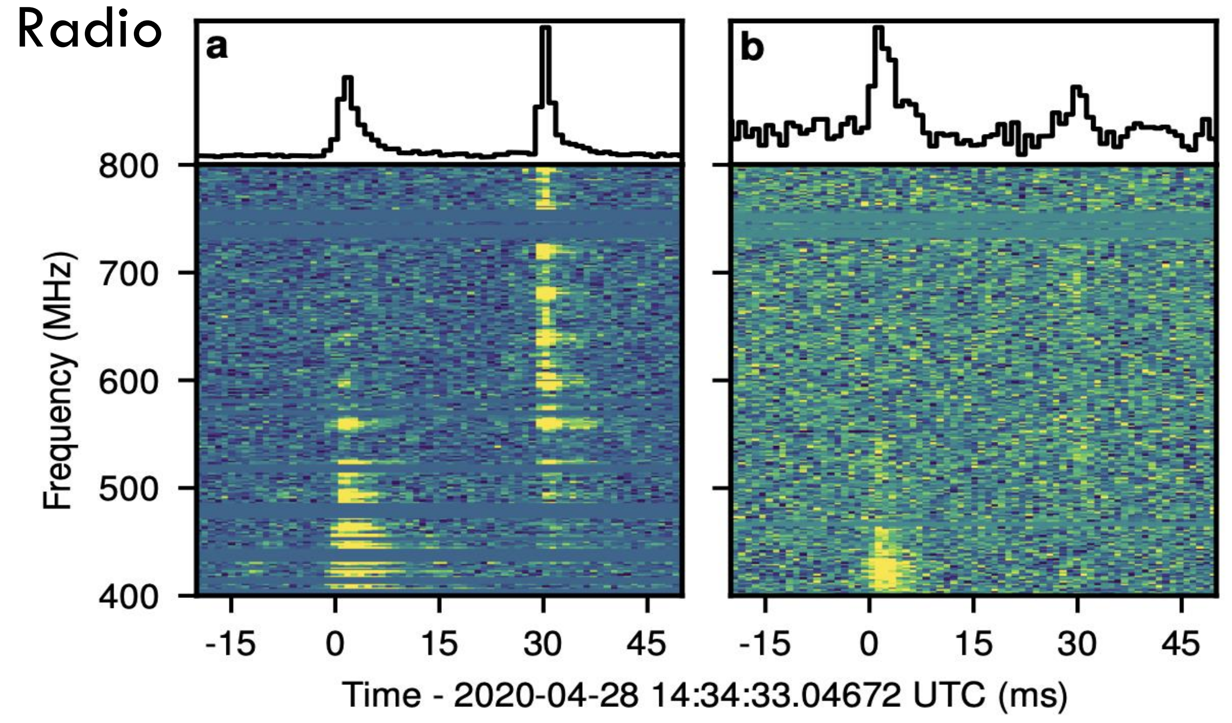
RADIO ACTIVITY

1E 1547-5408

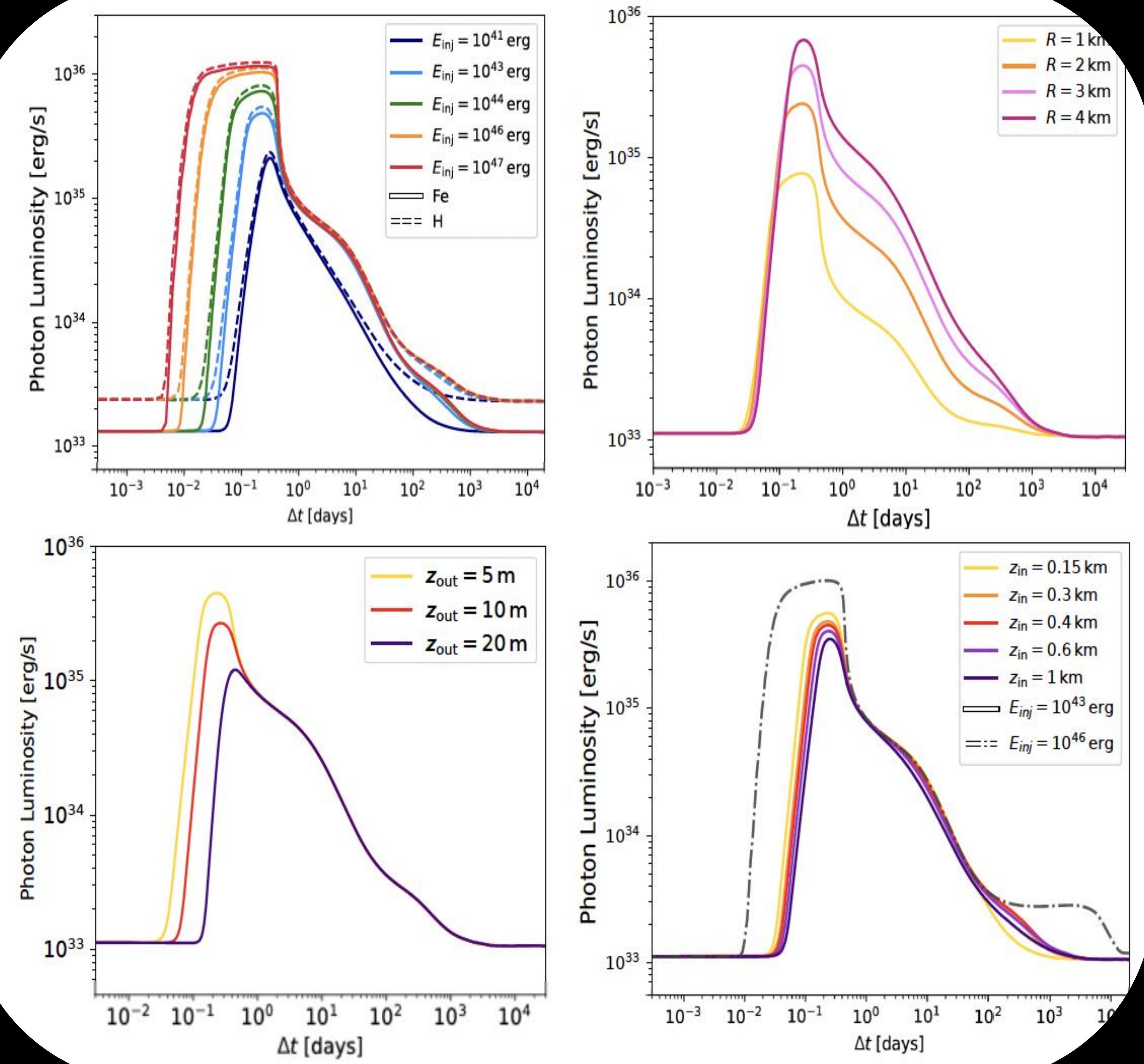


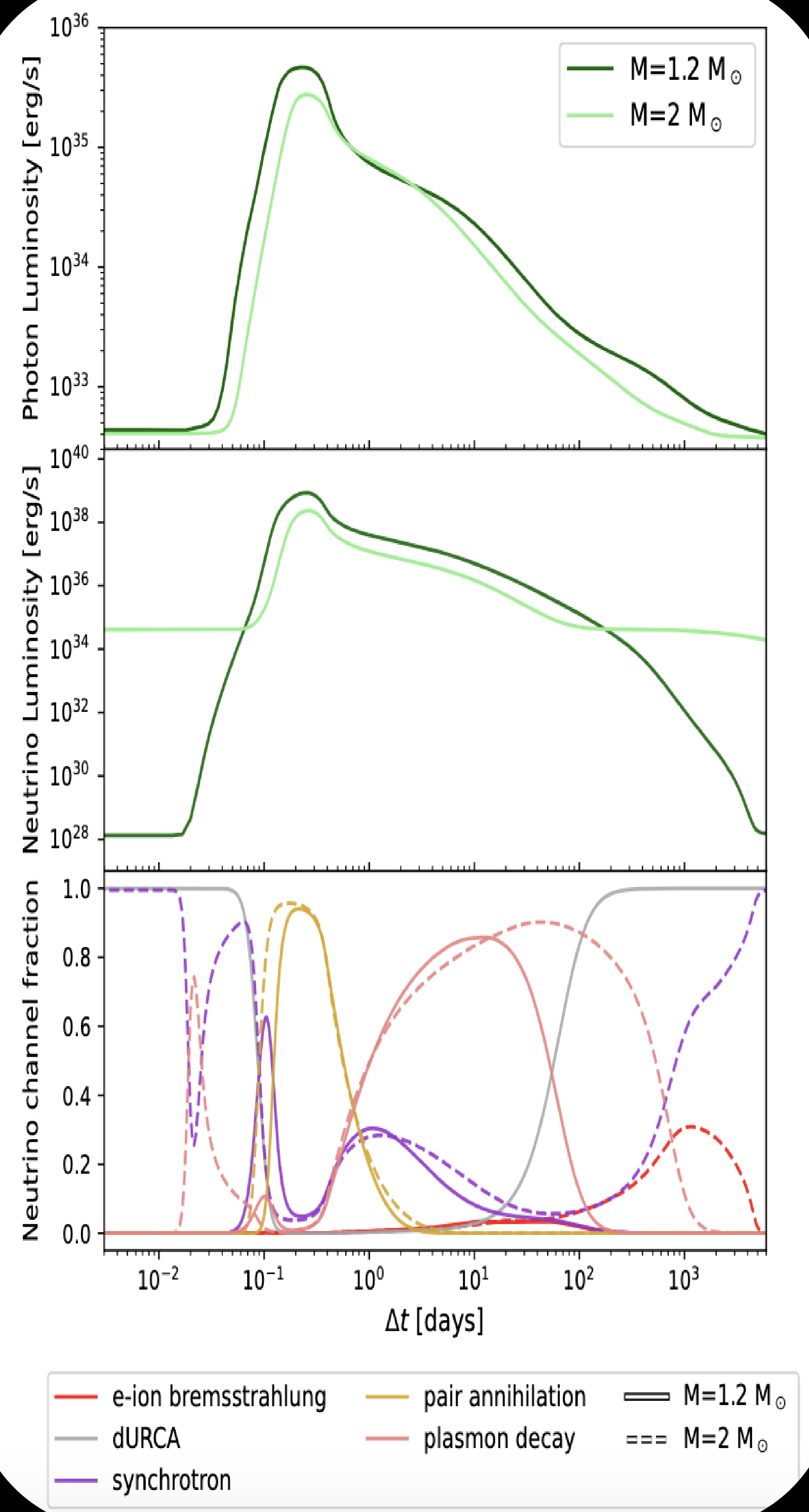
SGR 1935+2154

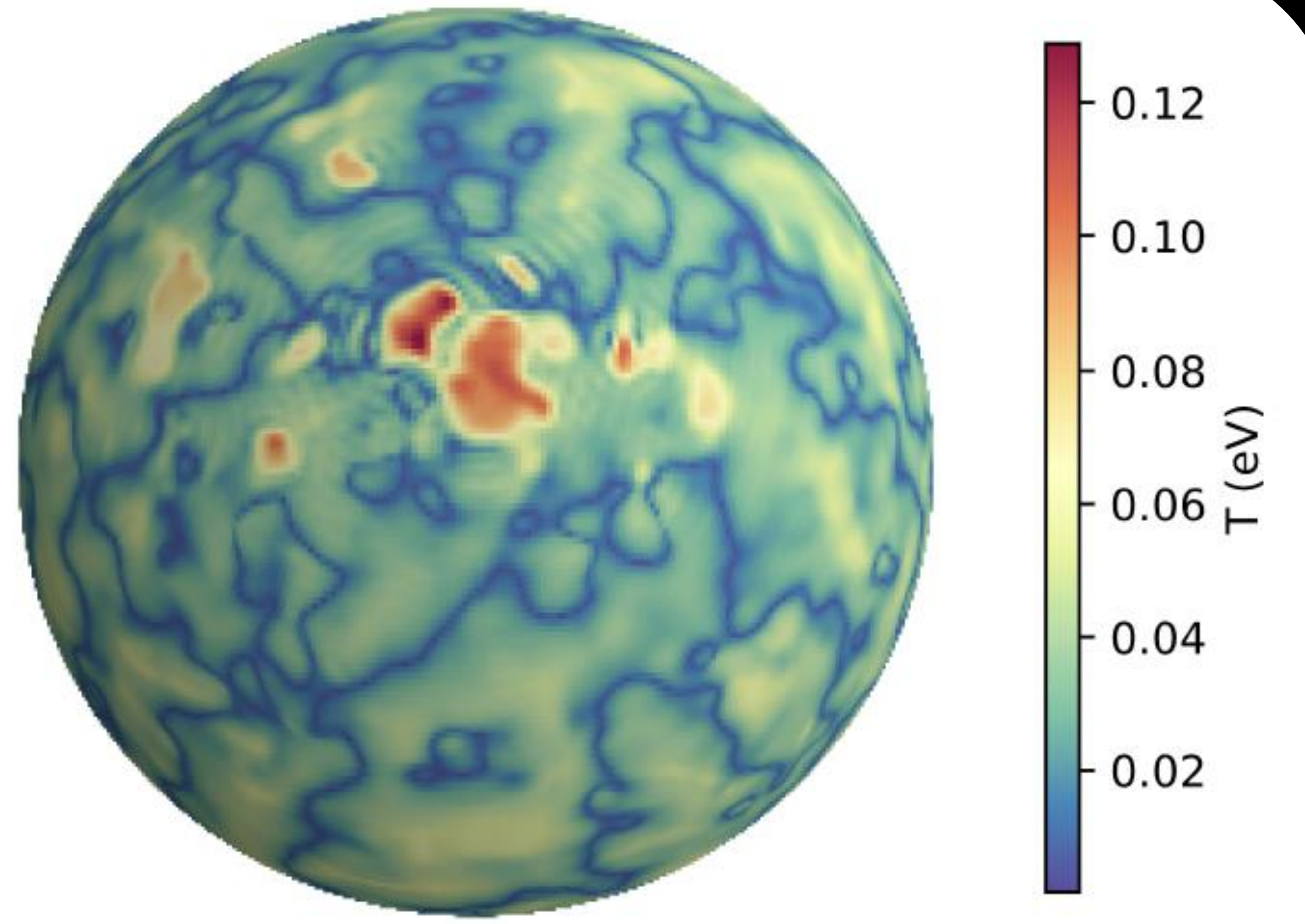




MAGNETAR OUTBURSTS: MODELLING

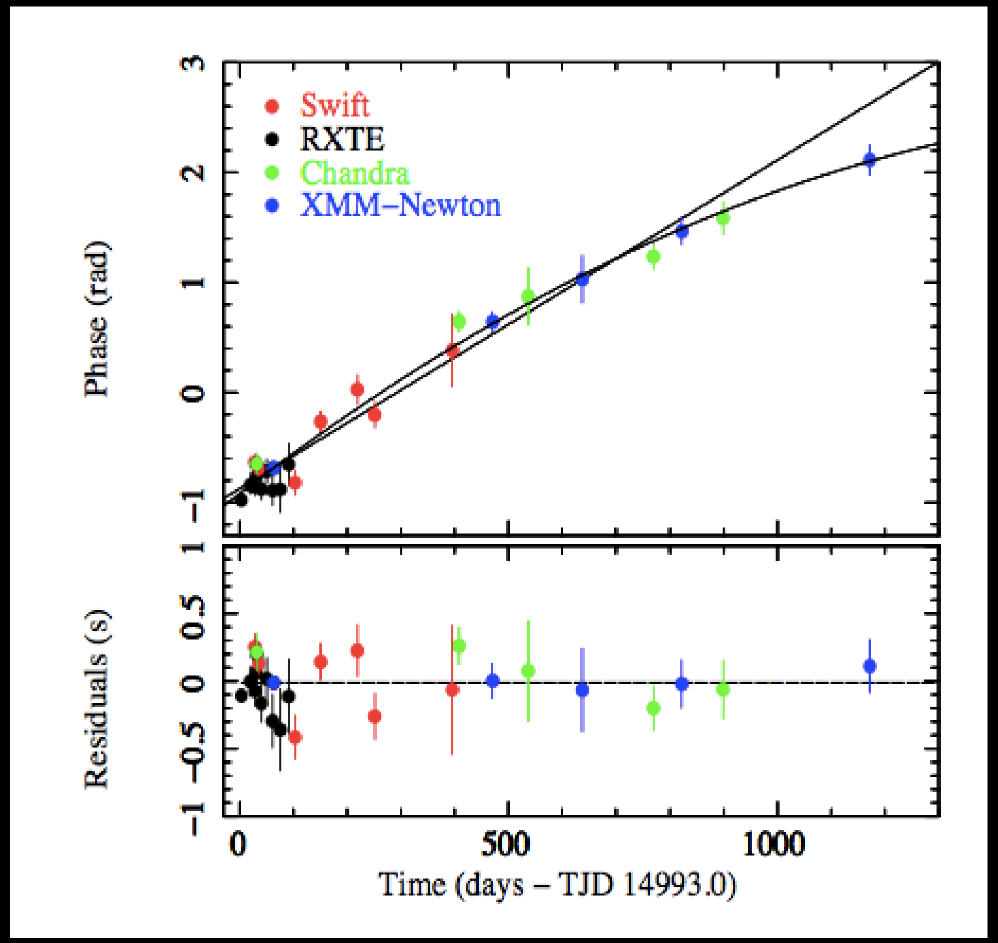






(De Grandis, Rea, Kovlakas, et al. 2025)

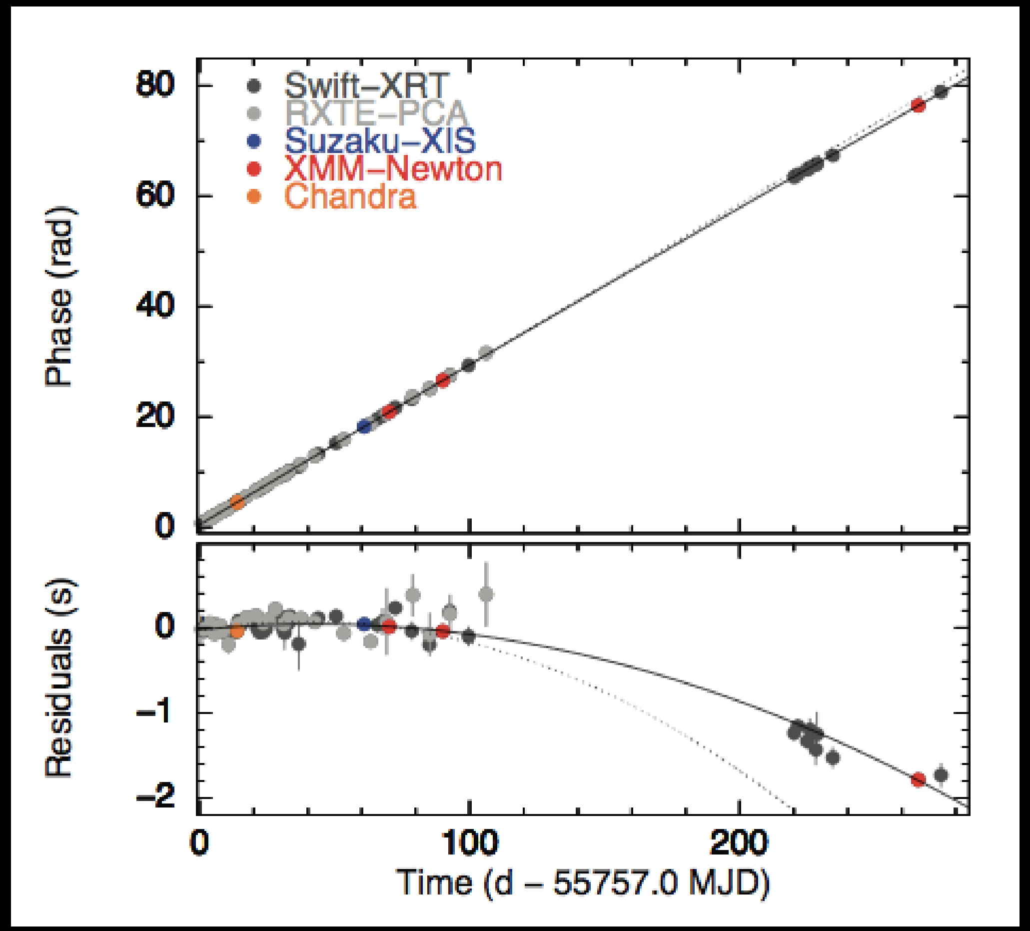
“LOW FIELD" MAGNETARS



B = 6.2×10^{12} G

SGR J0418+5729

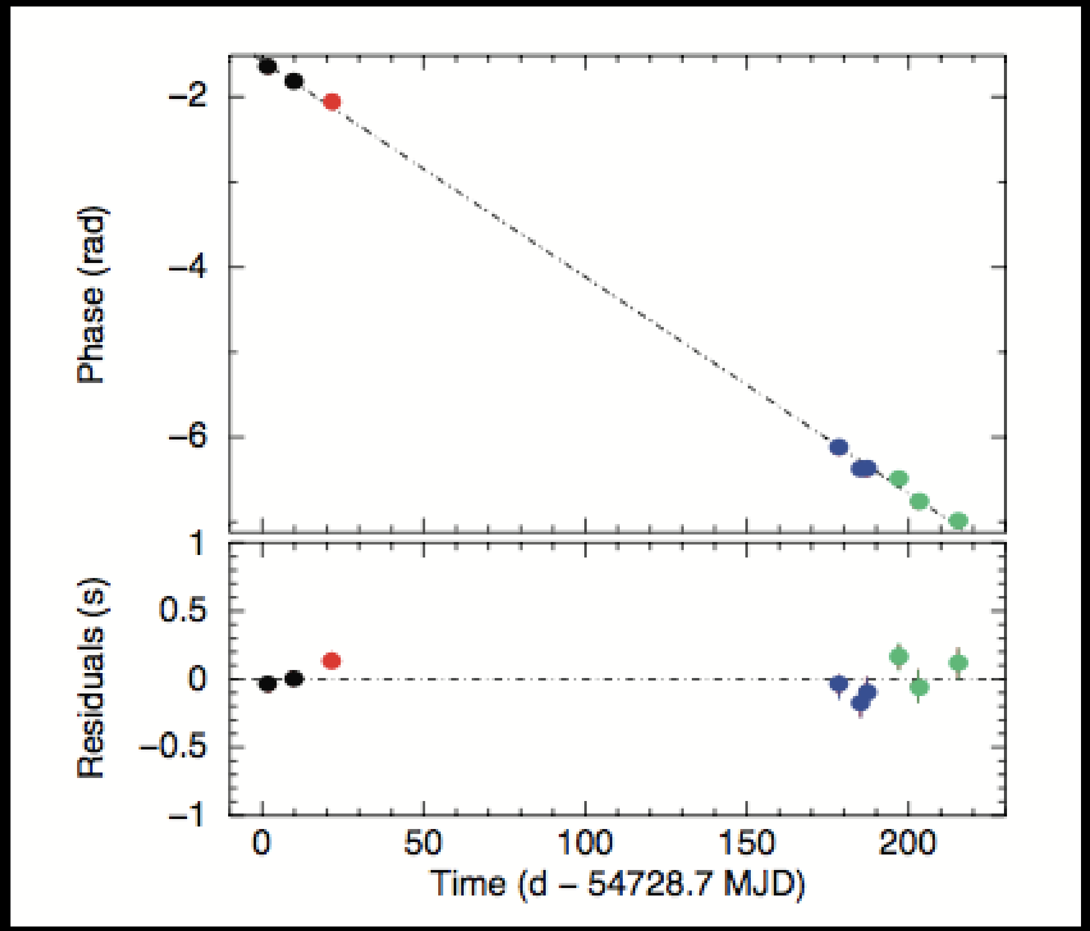
Rea et al. 2010, Science
Rea et al. 2013, ApJ



B = 2.3×10^{13} G

Swift J1822-1606

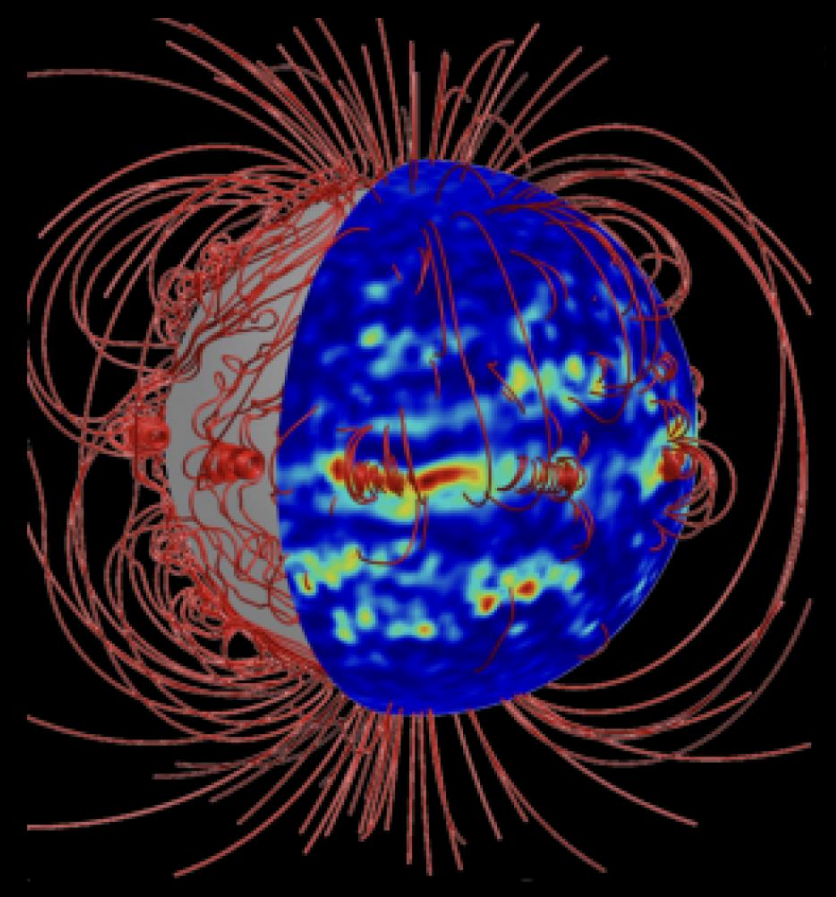
Rea et al. 2012, ApJ
Scholtz et al. 2012, ApJ



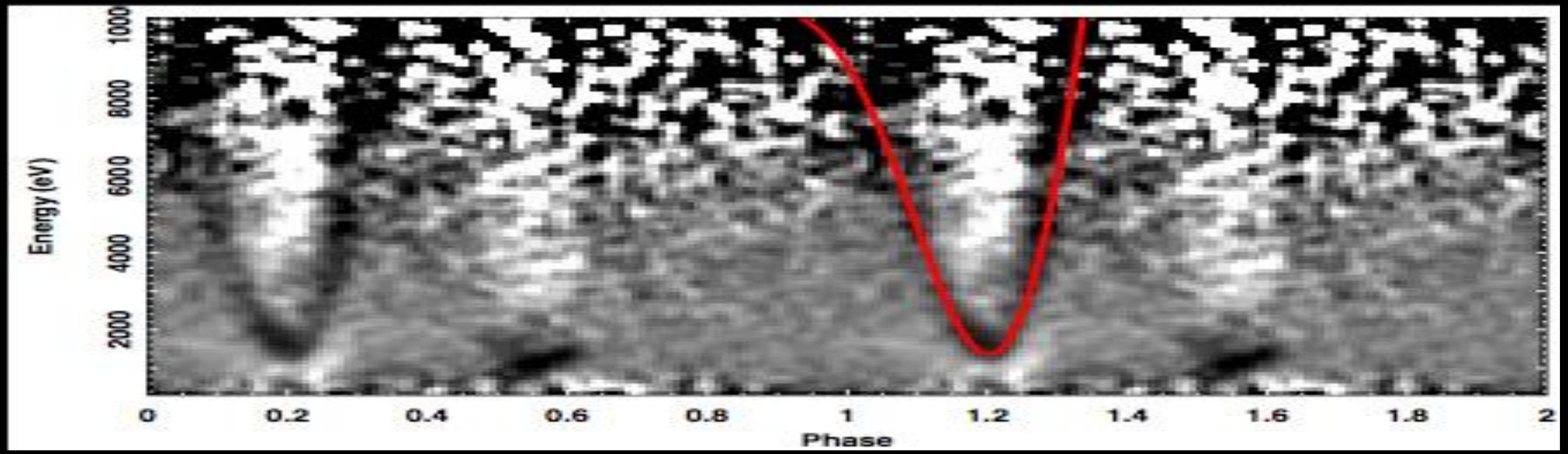
B < 4×10^{13} G

3XMM J1852+0033

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



A magnetar with a dipolar field of 10^{12} Gauss, and loops reaching 10^{14} Gauss.

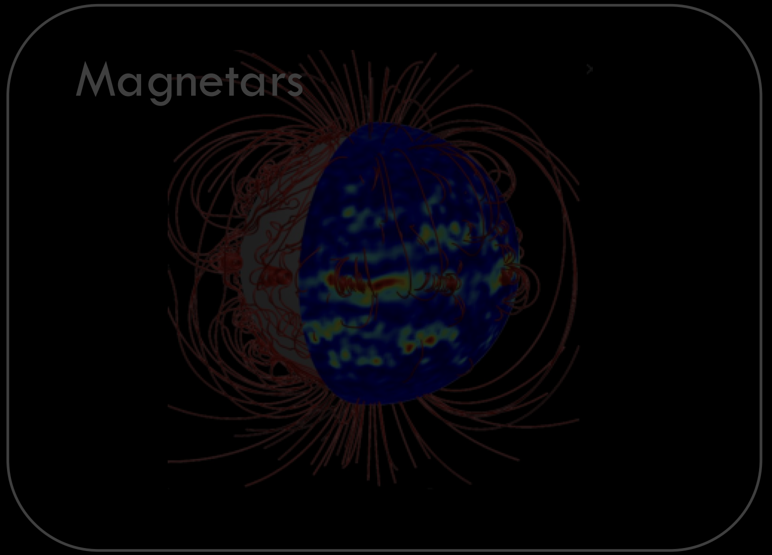


Tiengo et al. 2013, Nature

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

$\Rightarrow B_{loop} \sim (2\text{-}20) \times 10^{14}$ G

THE ISOLATED PULSAR POPULATION



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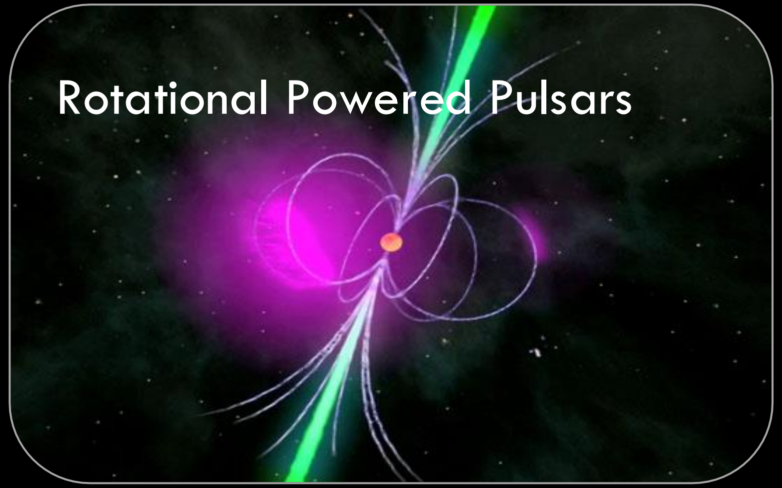

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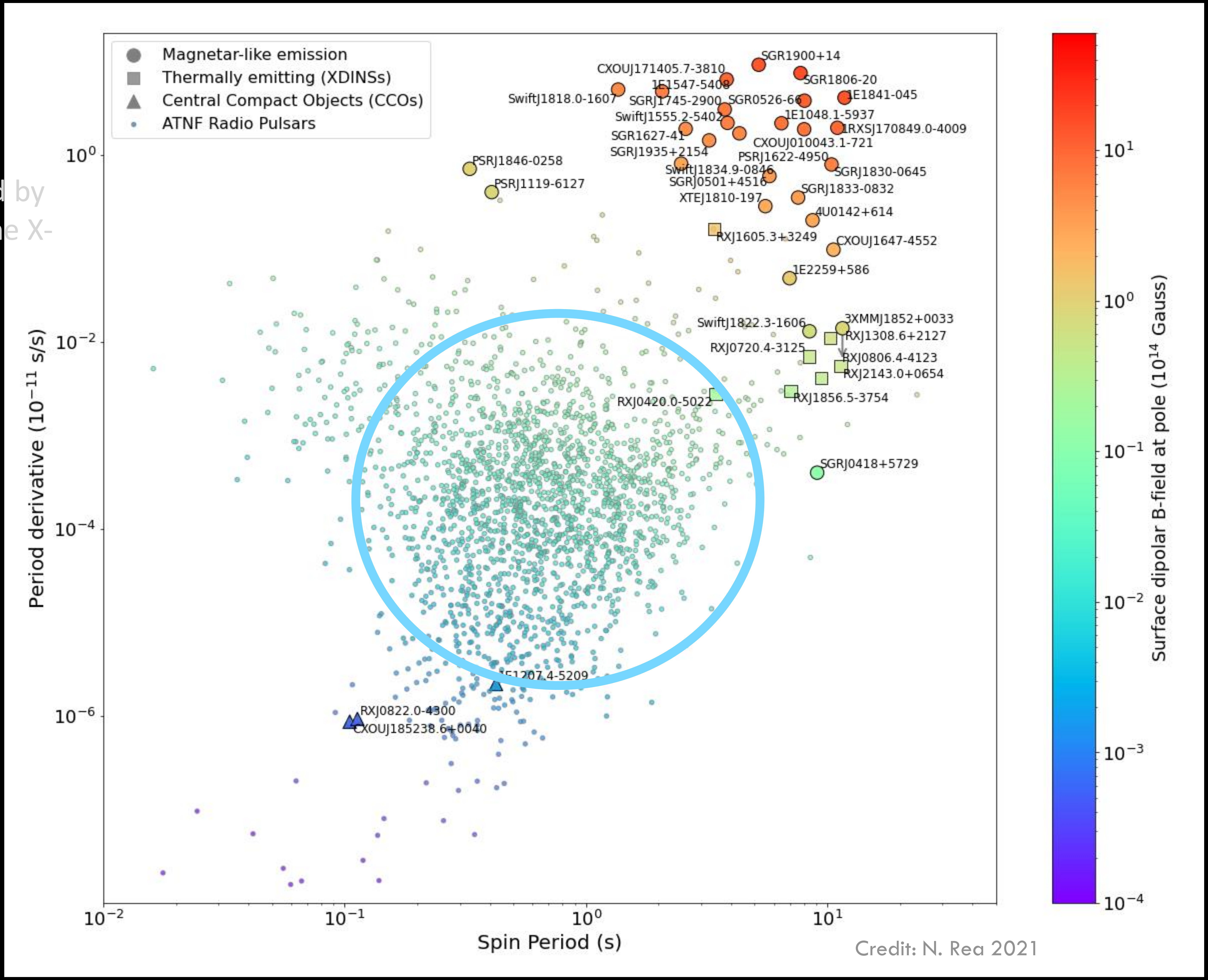
Typically emitting in radio.



Credit: N. Rea 2021

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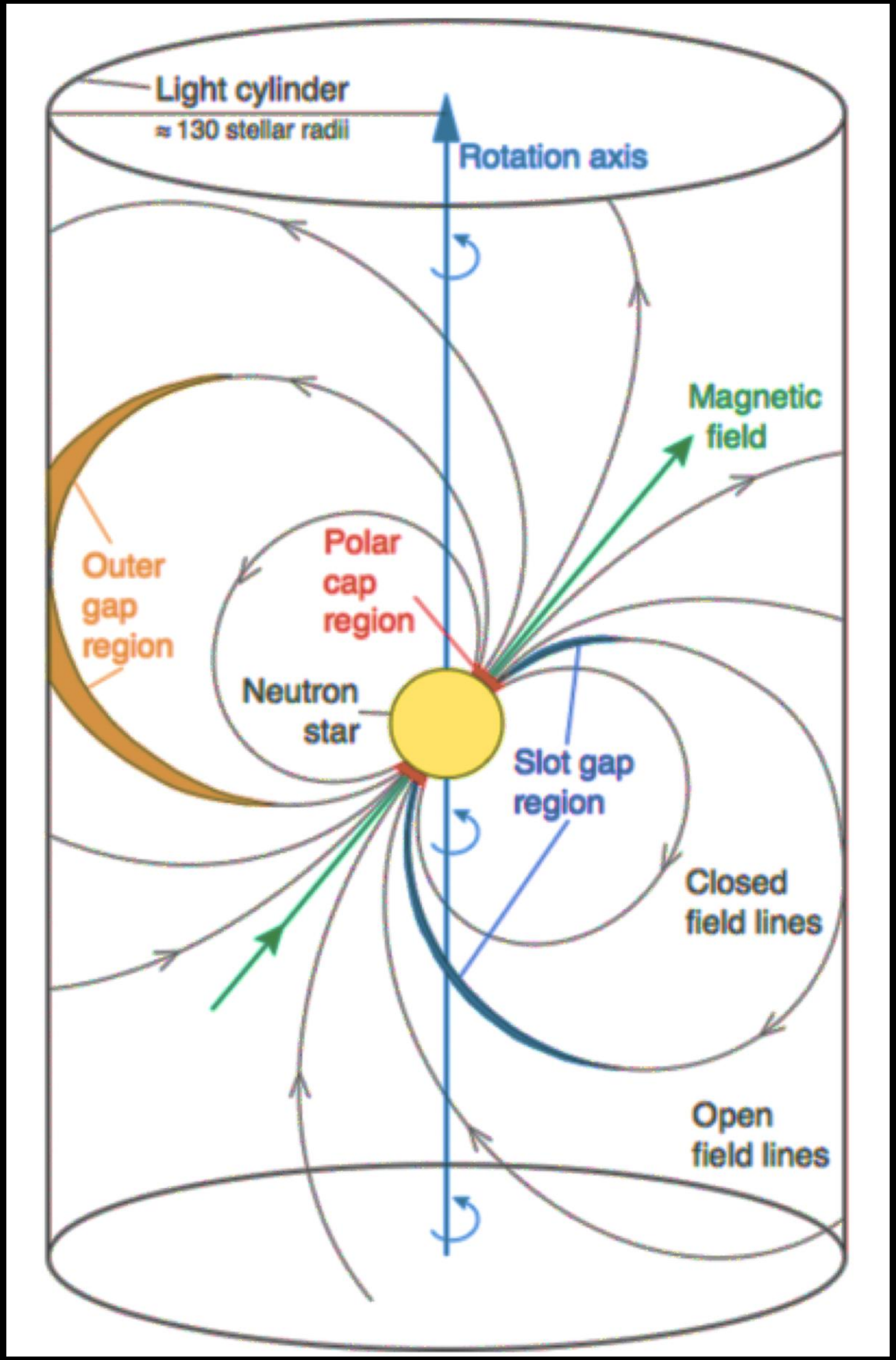
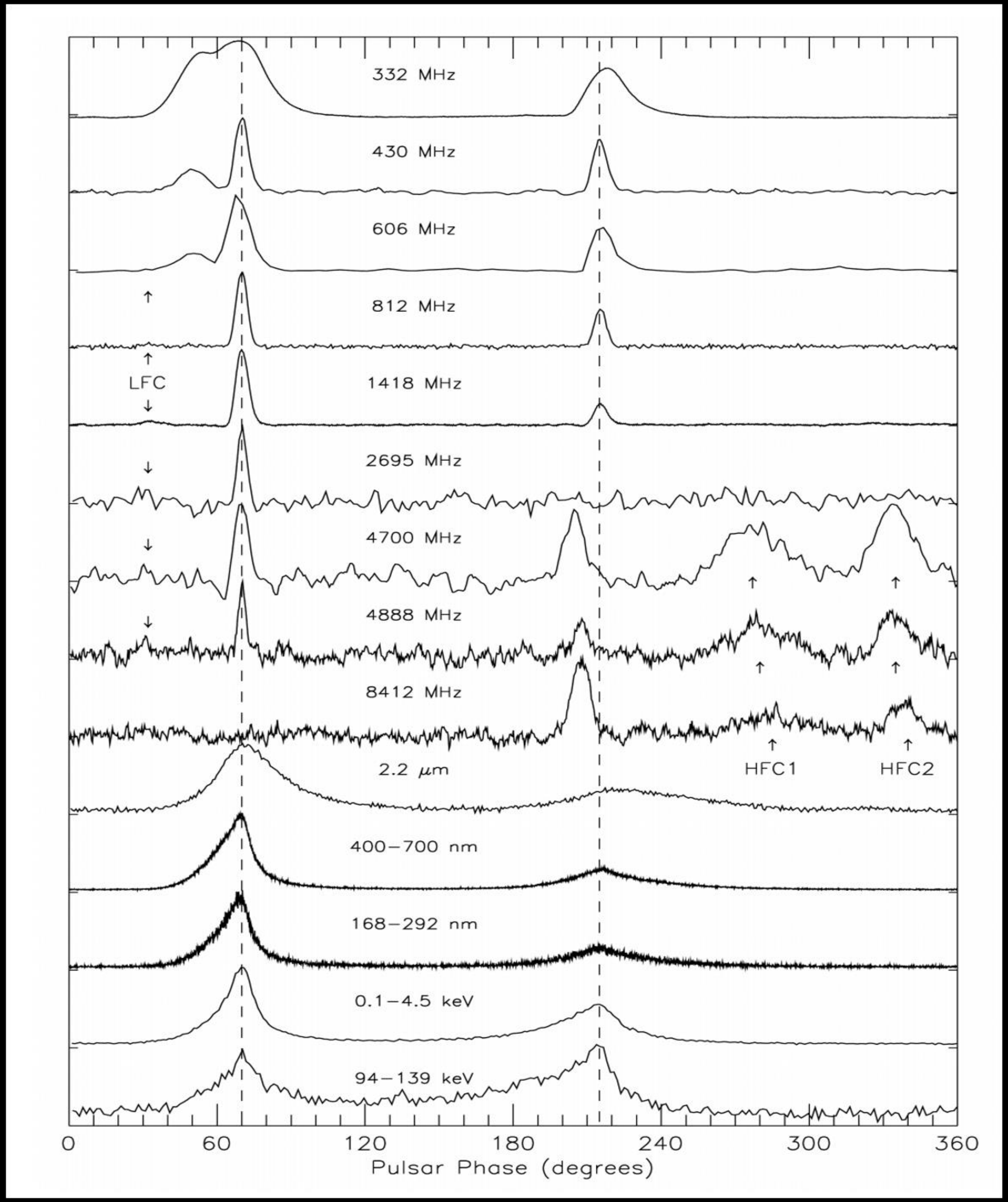




$$\dot{E}_{rot} = I_{ns}\Omega_s\dot{\Omega}_s = -\frac{4\pi^2 I_{ns}\dot{P}_s}{P_s^3}$$

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

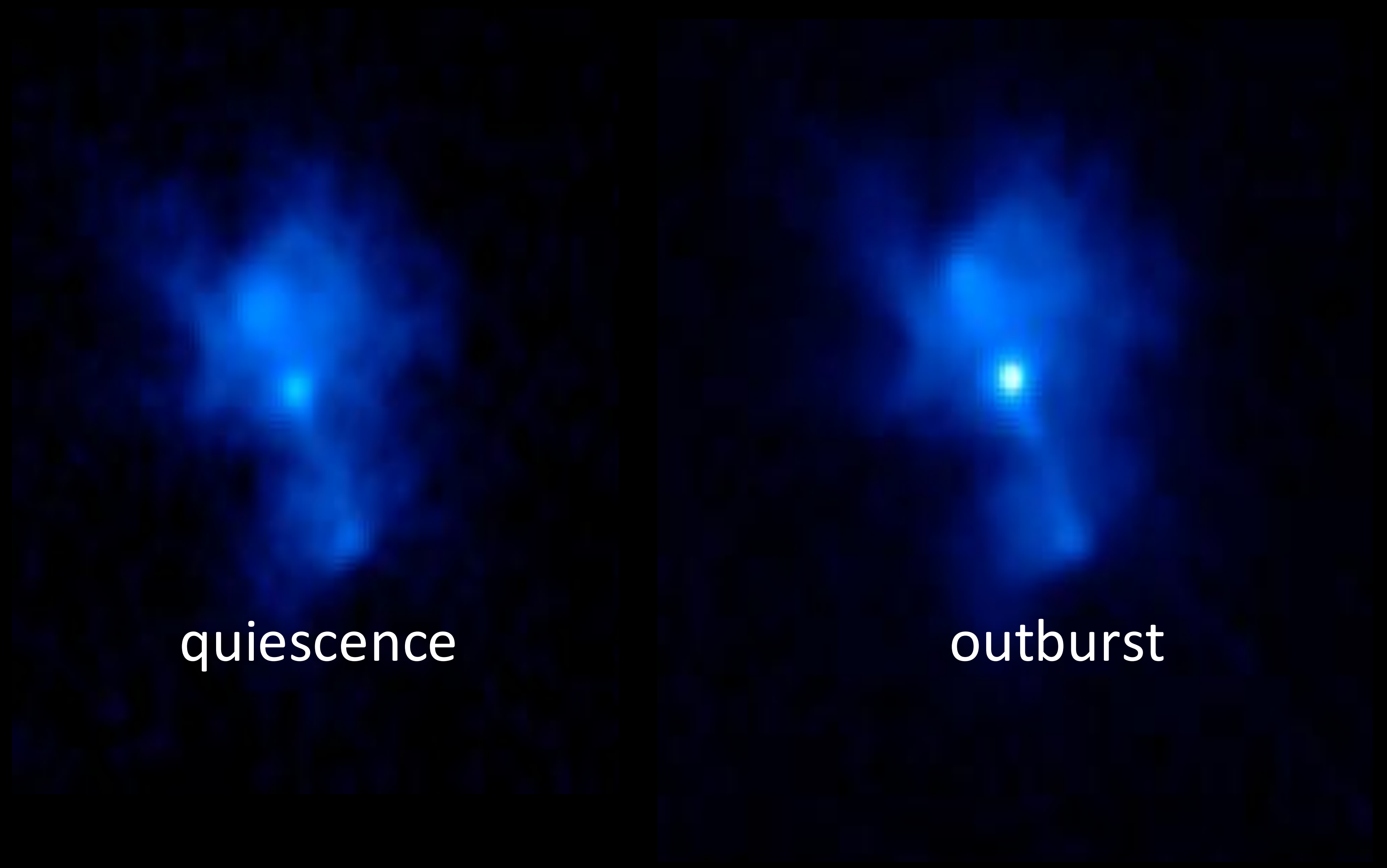
$$B = 3.2 \cdot 10^{19}\sqrt{P\dot{P}}\ \text{Gauss.}$$

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

HIGH-B ROTATIONAL POWERED PULSARS

PSR 1846-0258

- rotational power of Edot~$8x10^{36}$ erg/s
- magnetic fields ~$5x10^{13}$ - Gauss
- Kes75, with a powerful PWN
- X-ray rotational powered pulsar
- Showed SGR-like bursts and outburst in 2008, 2020



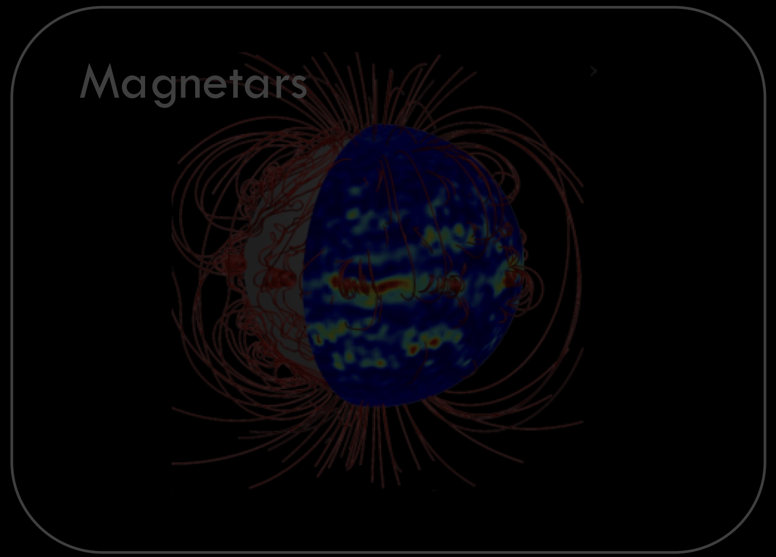
PSR 1119-6127

- rotational power of Edot~$2.3x10^{36}$ erg/s
- magnetic fields ~$4x10^{13}$ - Gauss
- with a PWN
- Radio/X-ray rotational powered pulsar
- Showed SGR-like bursts and outburst in 2016

Two canonical rotational powered pulsars showed magnetar-like activity!

(Gavriil et al. 2008, Kumar & Safi-Harb 2008, Archibald et al. 2016, 2017; Gogus et al. 2016, Sathyaprakash et al. 2022)

THE ISOLATED PULSAR POPULATION



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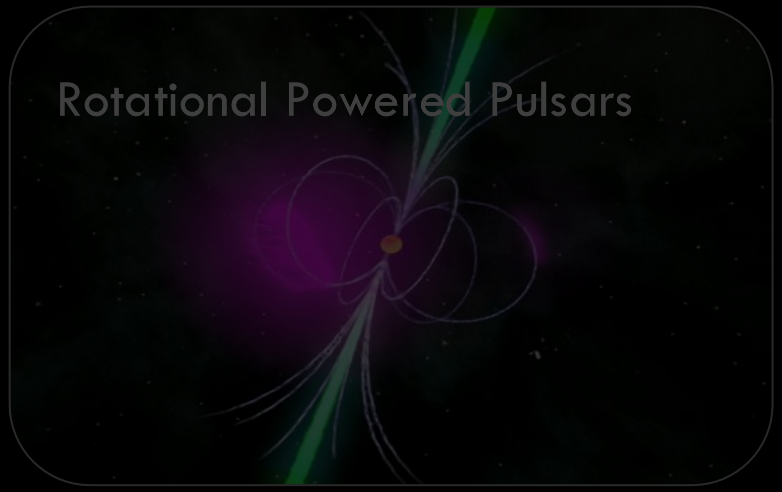

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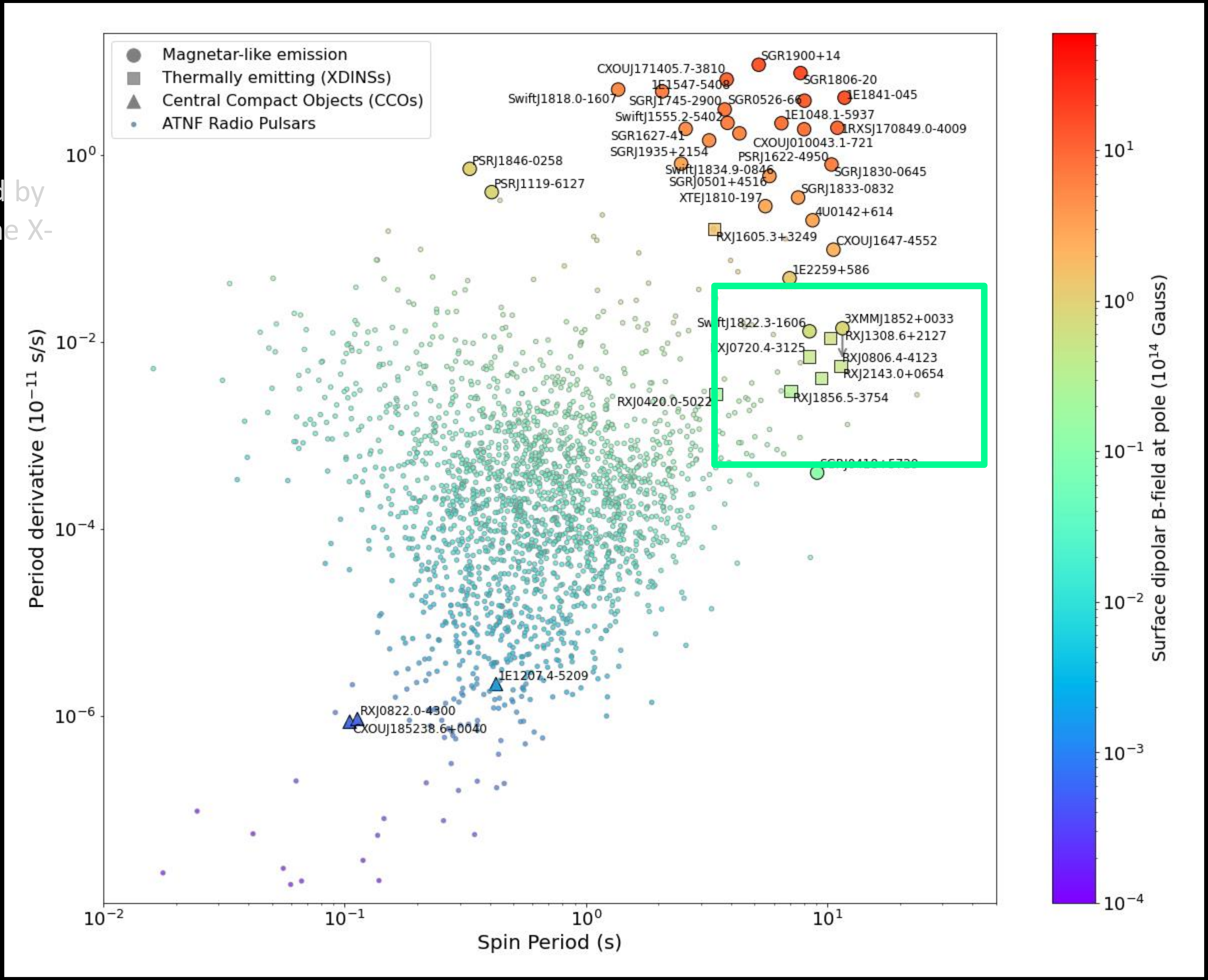
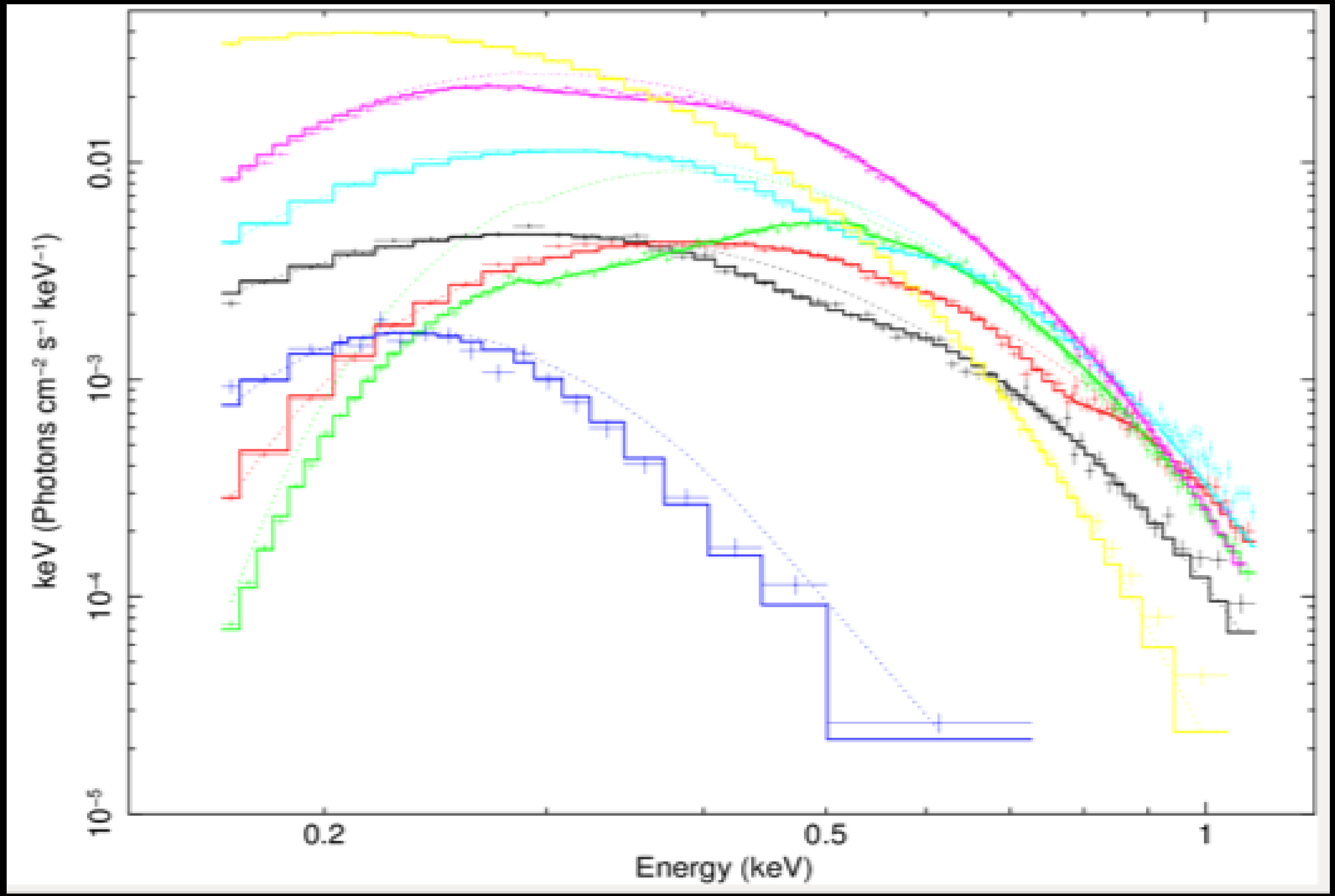
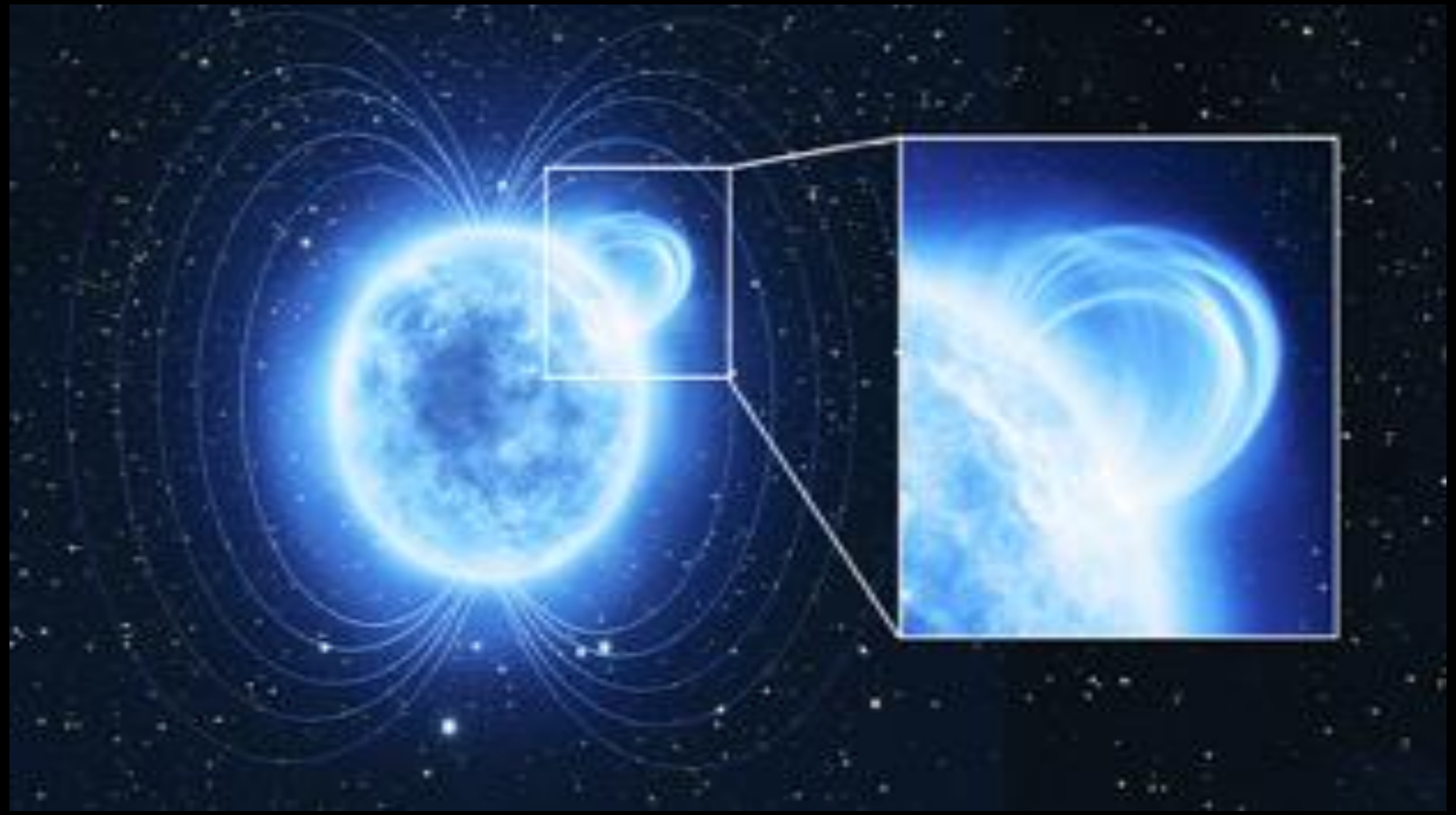
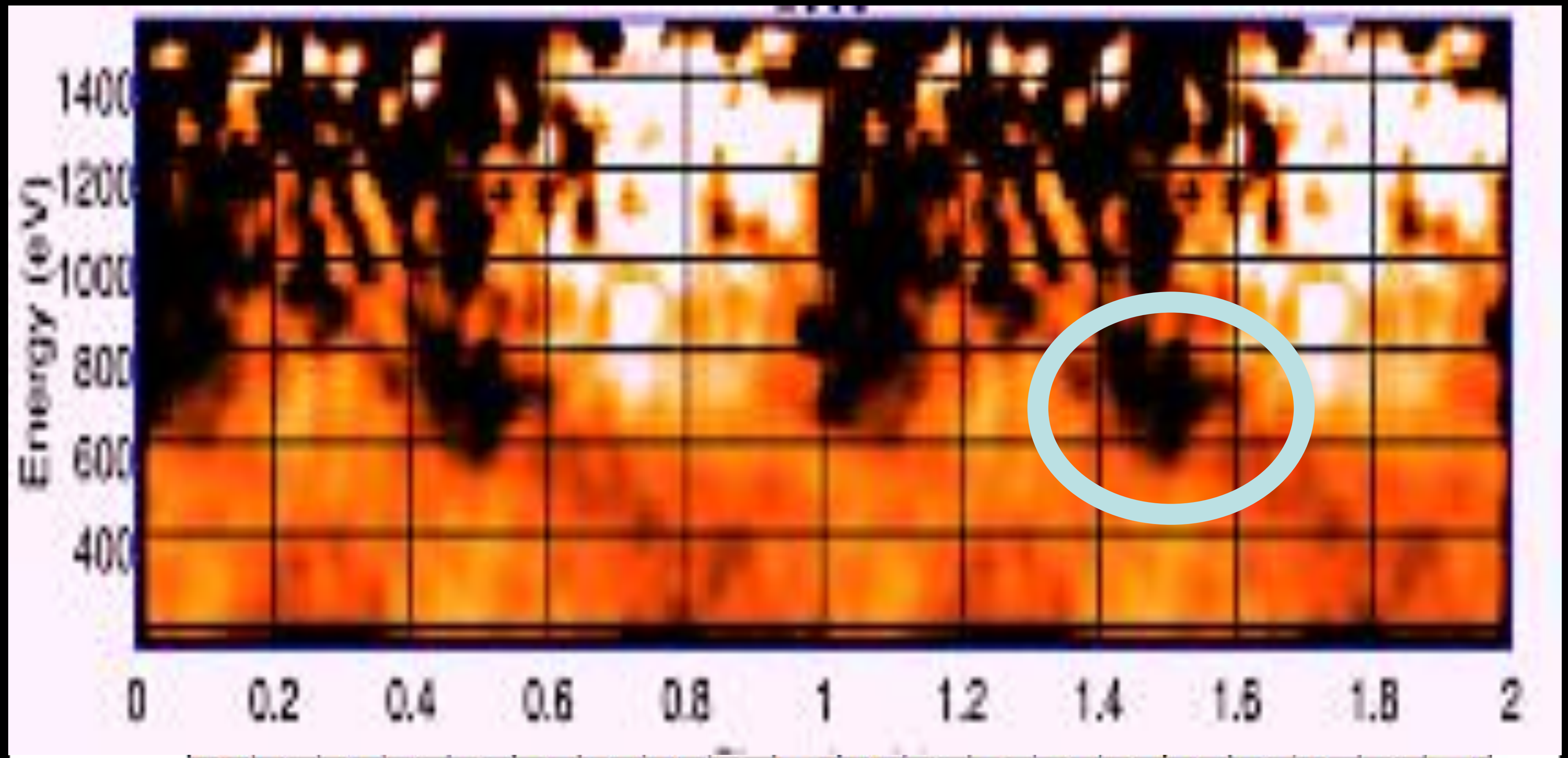


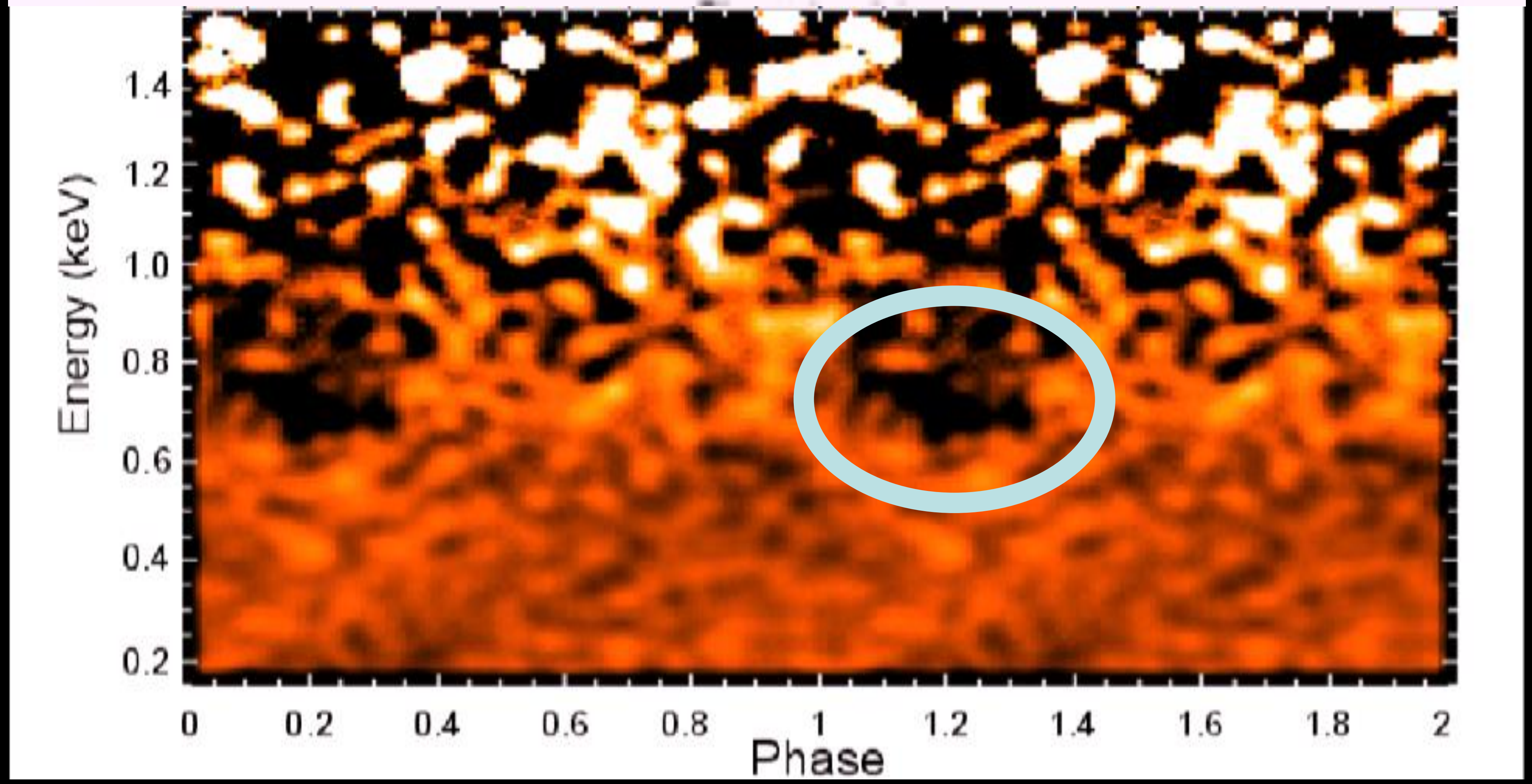
THERMAL EMITTING NEUTRON STARS (XDINSs)





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





Similar to the low-field magnetar, XDINSs have dipolar fields of 10^{13} Gauss, and loops reaching 10^{14} Gauss.

(Borghese, Rea, Coti Zelati et al. 2015, 2017)

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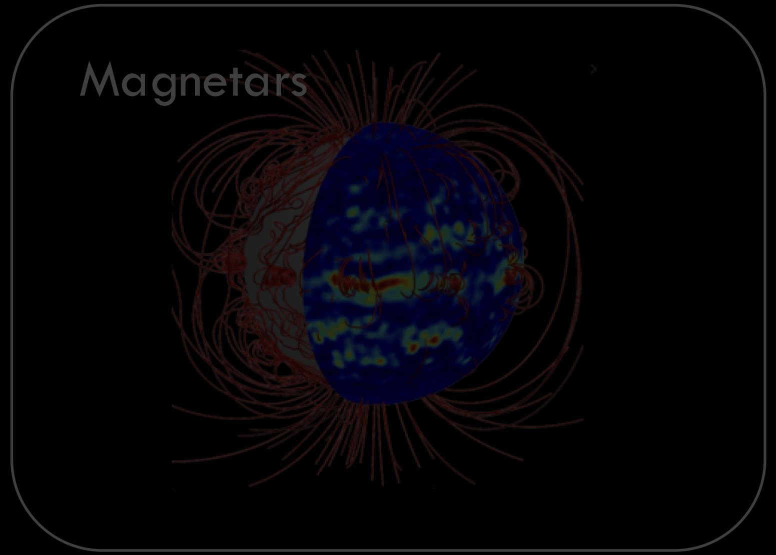

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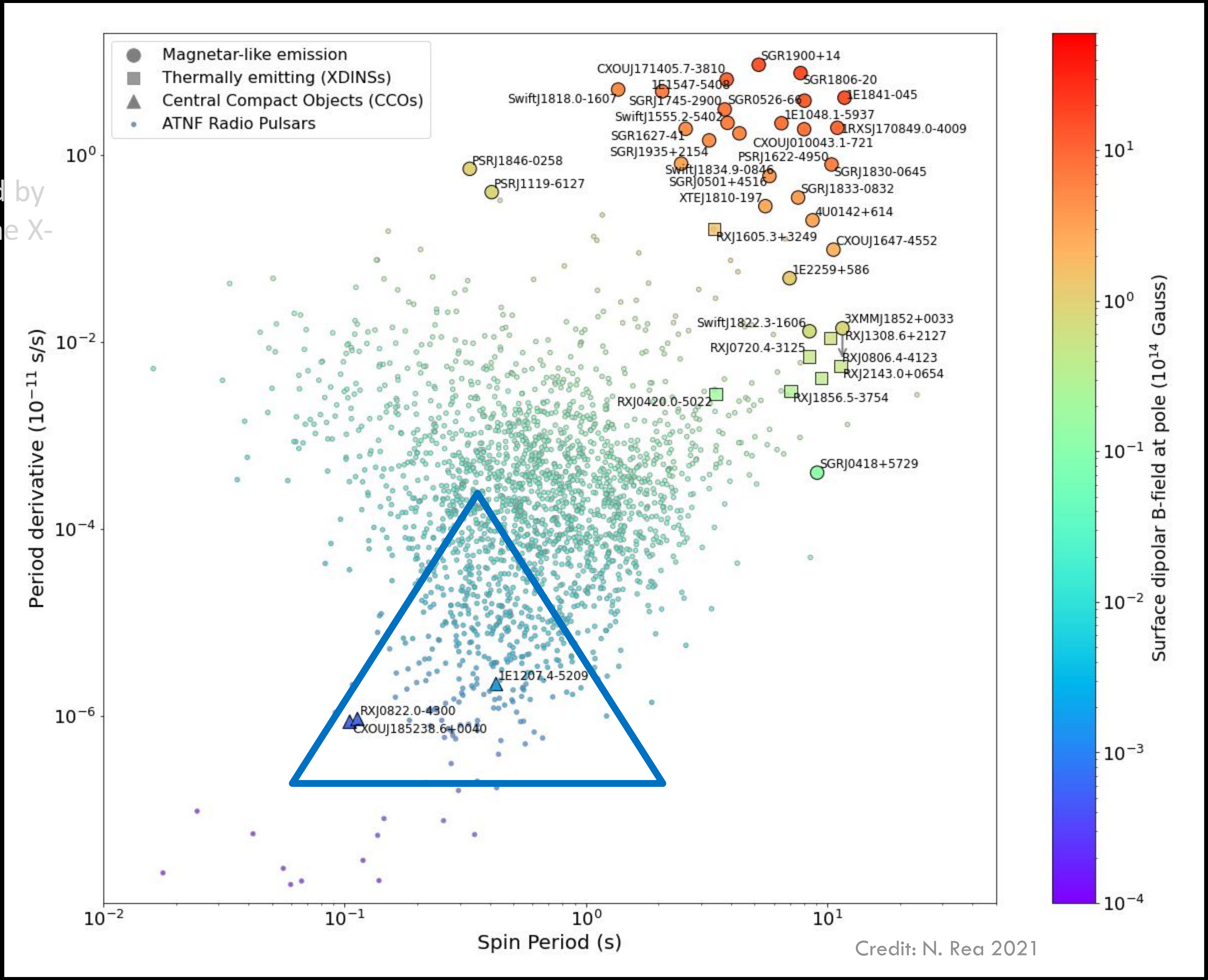
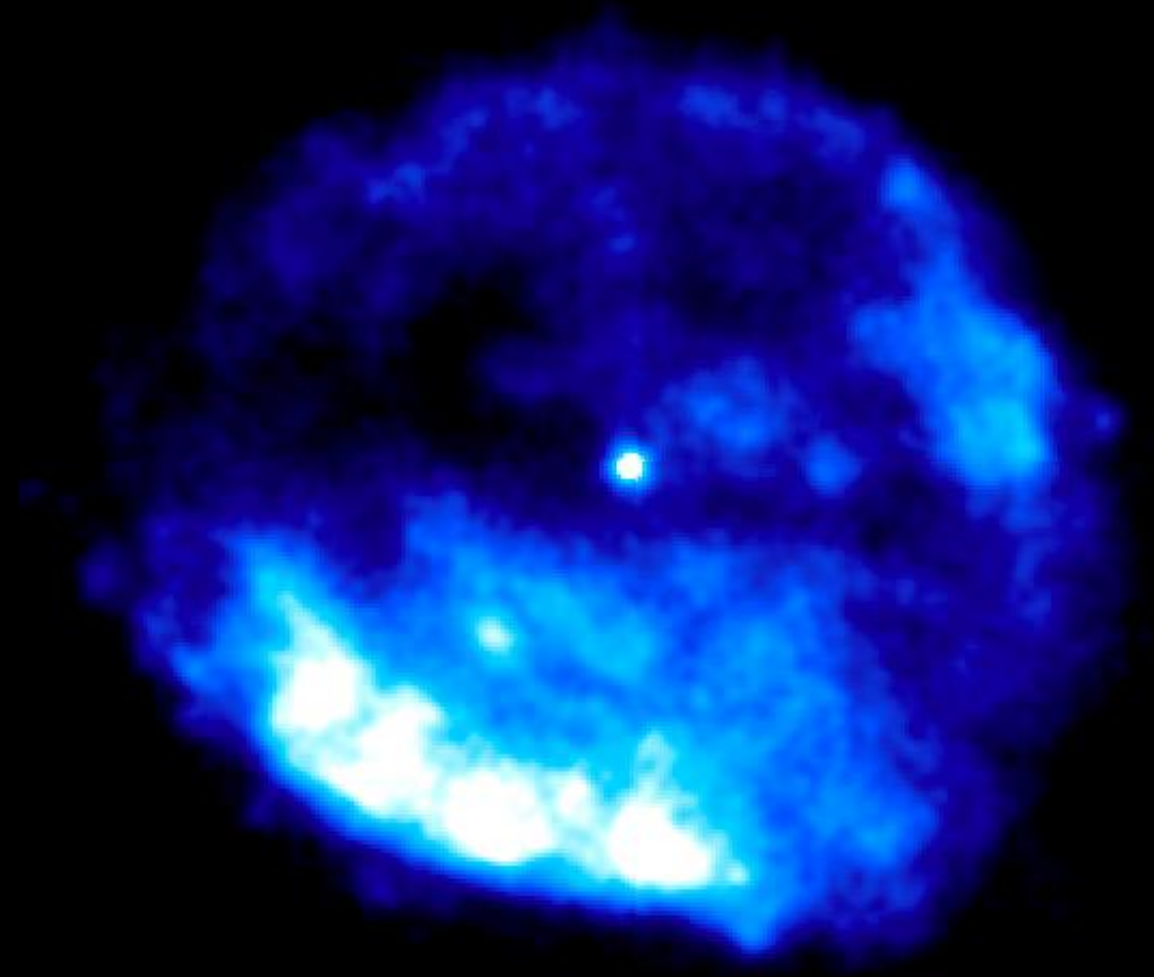


CENTRAL COMPACT OBJECTS



RCW103

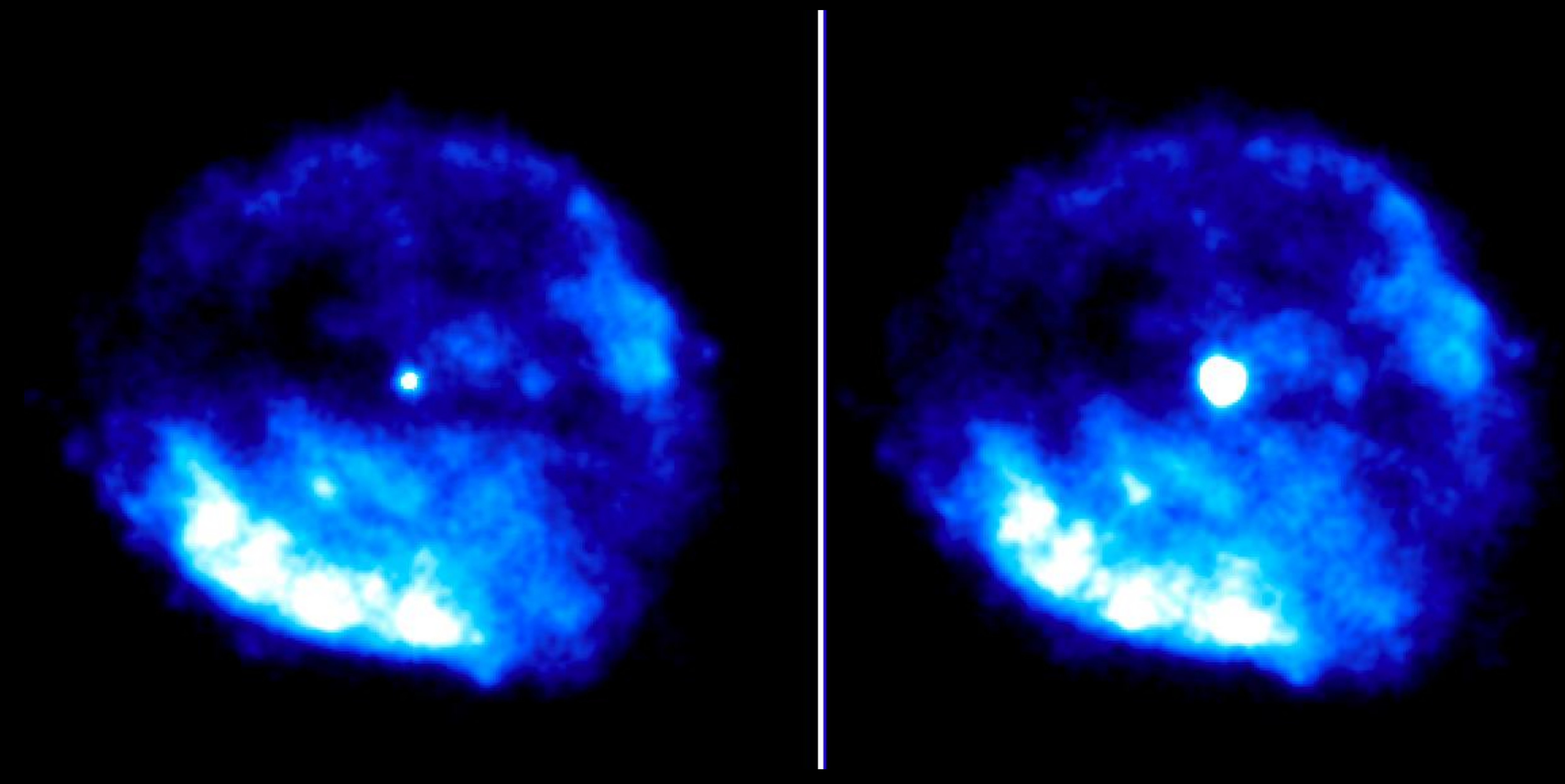
CasA

- 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}

Table 1
Central Compact Objects in Supernova Remnants

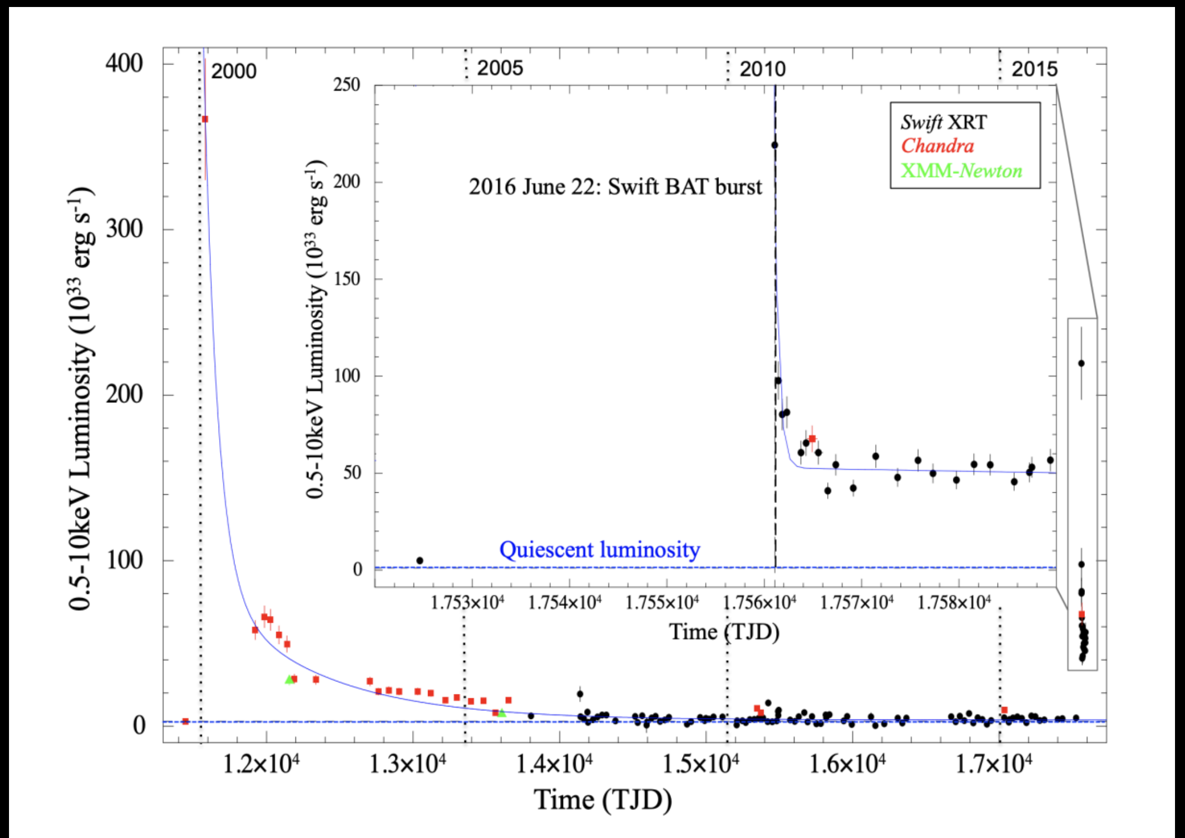
CCO	SNR	Age (kyr)	d (kpc)	P (s)	f_p[a] (%)	B_s (10^{10} G)	$L_{x,bol}$ (erg s^{-1})
RX J0822.0−4300	Puppis A	4.5	2.2	0.112	11	2.9	5.6×10^{33}
CXOU J085201.4−461753	G266.1−1.2	1	1	…	<7	…	2.5×10^{32}
1E 1207.4−5209	PKS 1209−51/52	7	2.2	0.424	9	9.8	2.5×10^{33}
CXOU J160103.1−513353	G330.2+1.0	$\gtrsim 3$	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)	…	…	…	$\sim 1 \times 10^{33}$

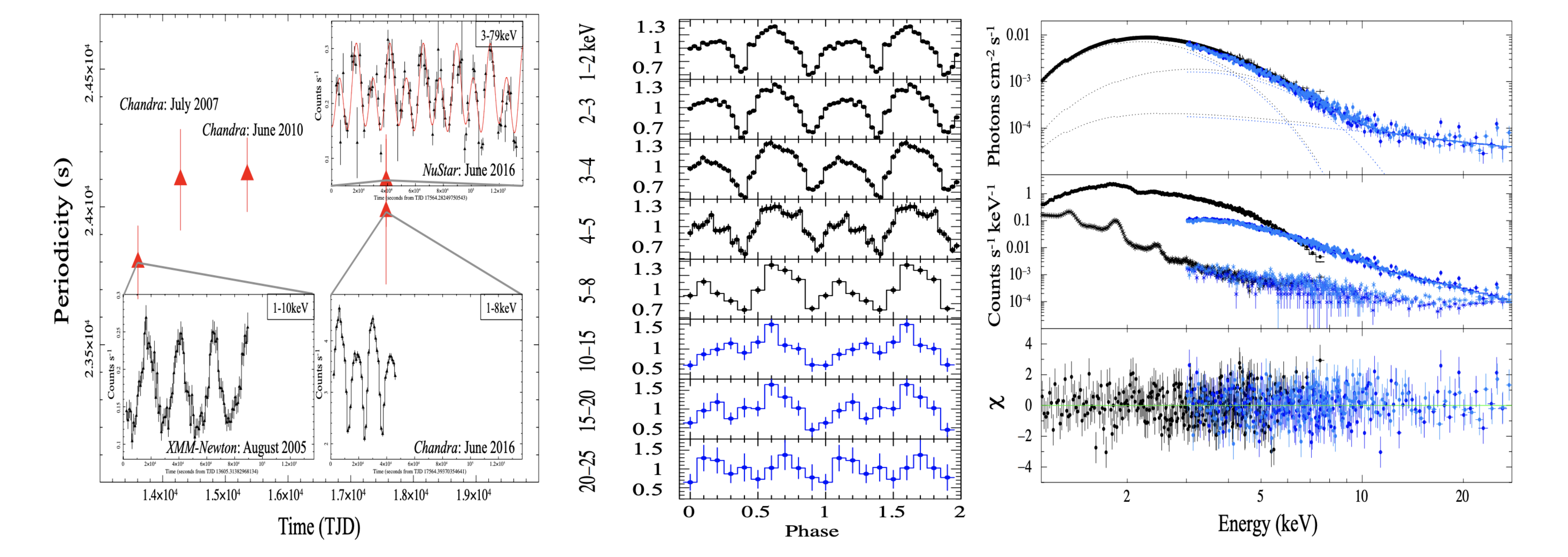
CENTRAL COMPACT OBJECTS



A magnetar-like event from a CCO with a 6.4hr spin-period!

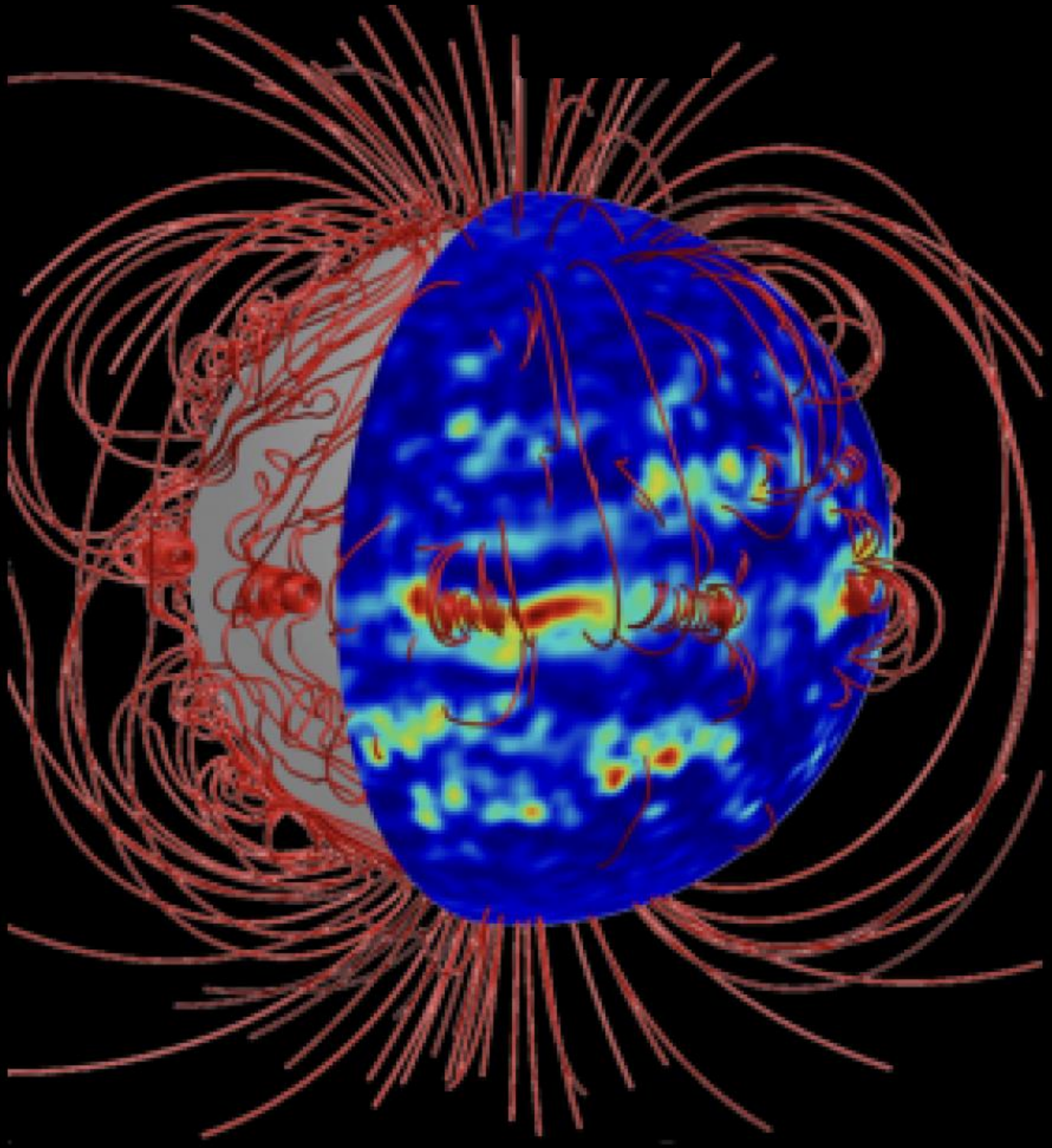
Fall back accretion after the supernova could make this pulsar slow down so extremely…

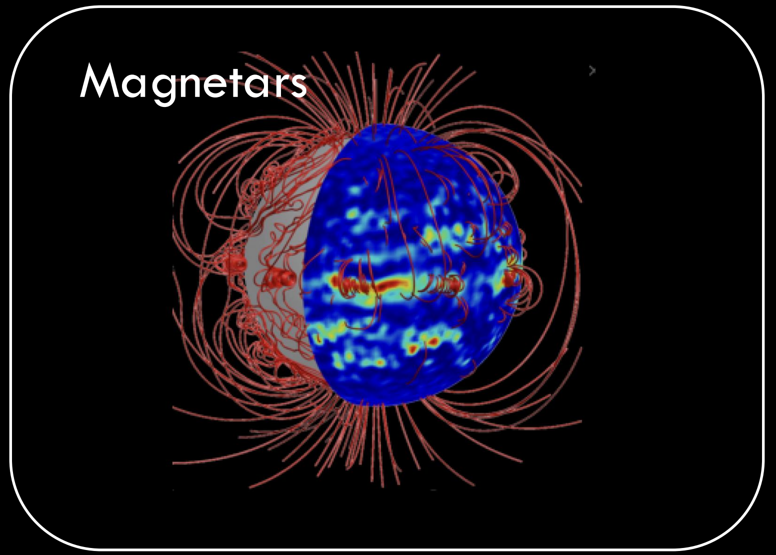




(D'Ai et al. 2016; Rea et al. 2016, Ho & Andersson 2016, Borghese et al. 2018)

MAGNETAR ACTIVITY IS PRESENT IN ALL ISOLATED NEUTRON STAR CLASSES





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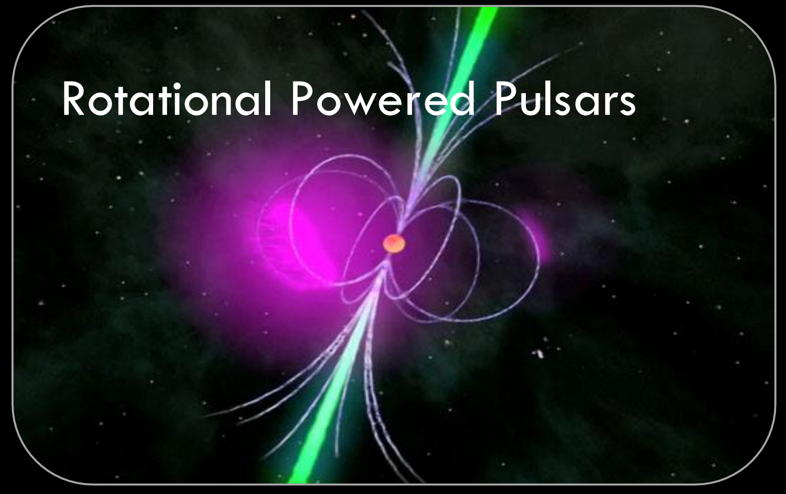

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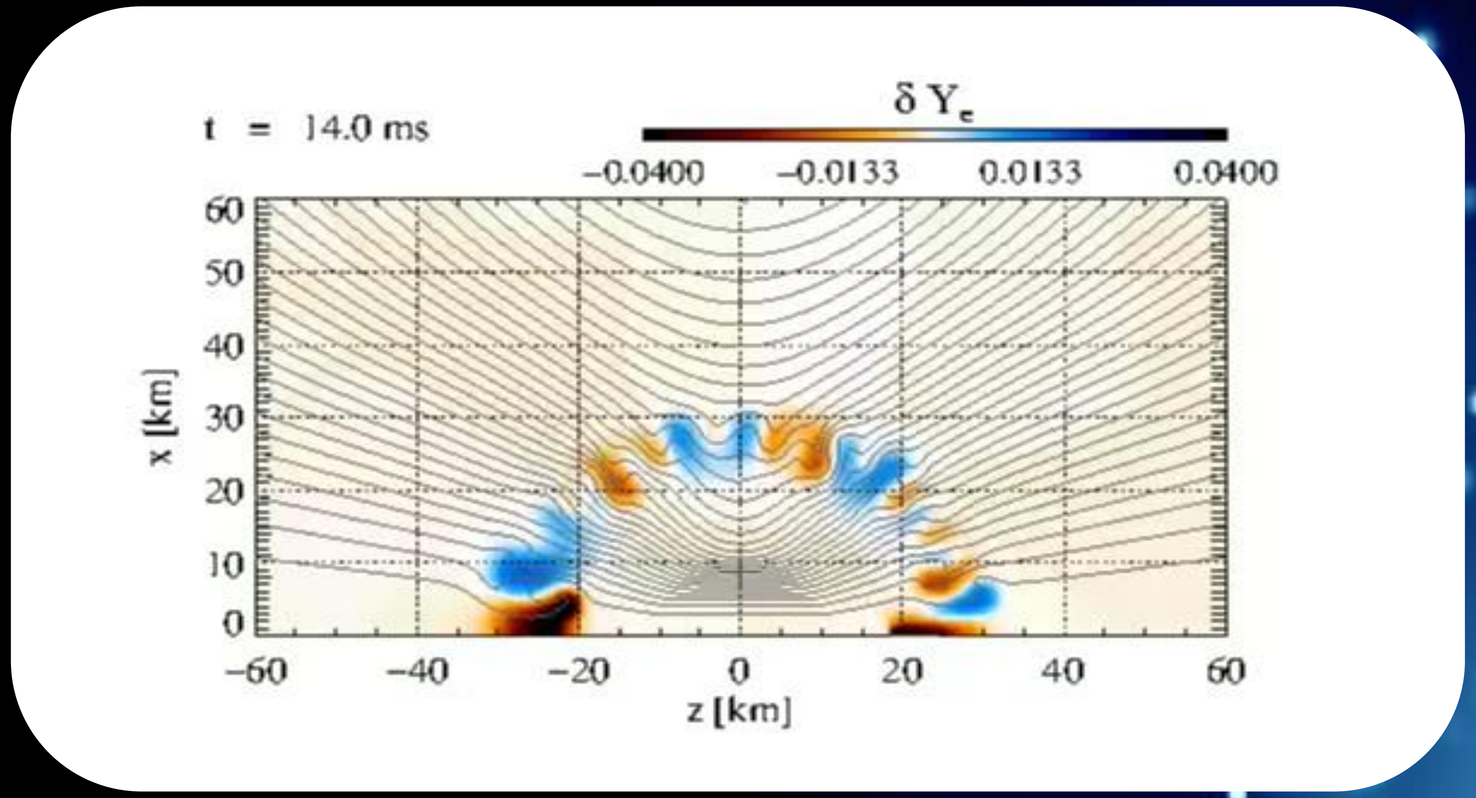
MAGNETIC FIELD FORMATION

There are big uncertainties on how these huge fields are formed…

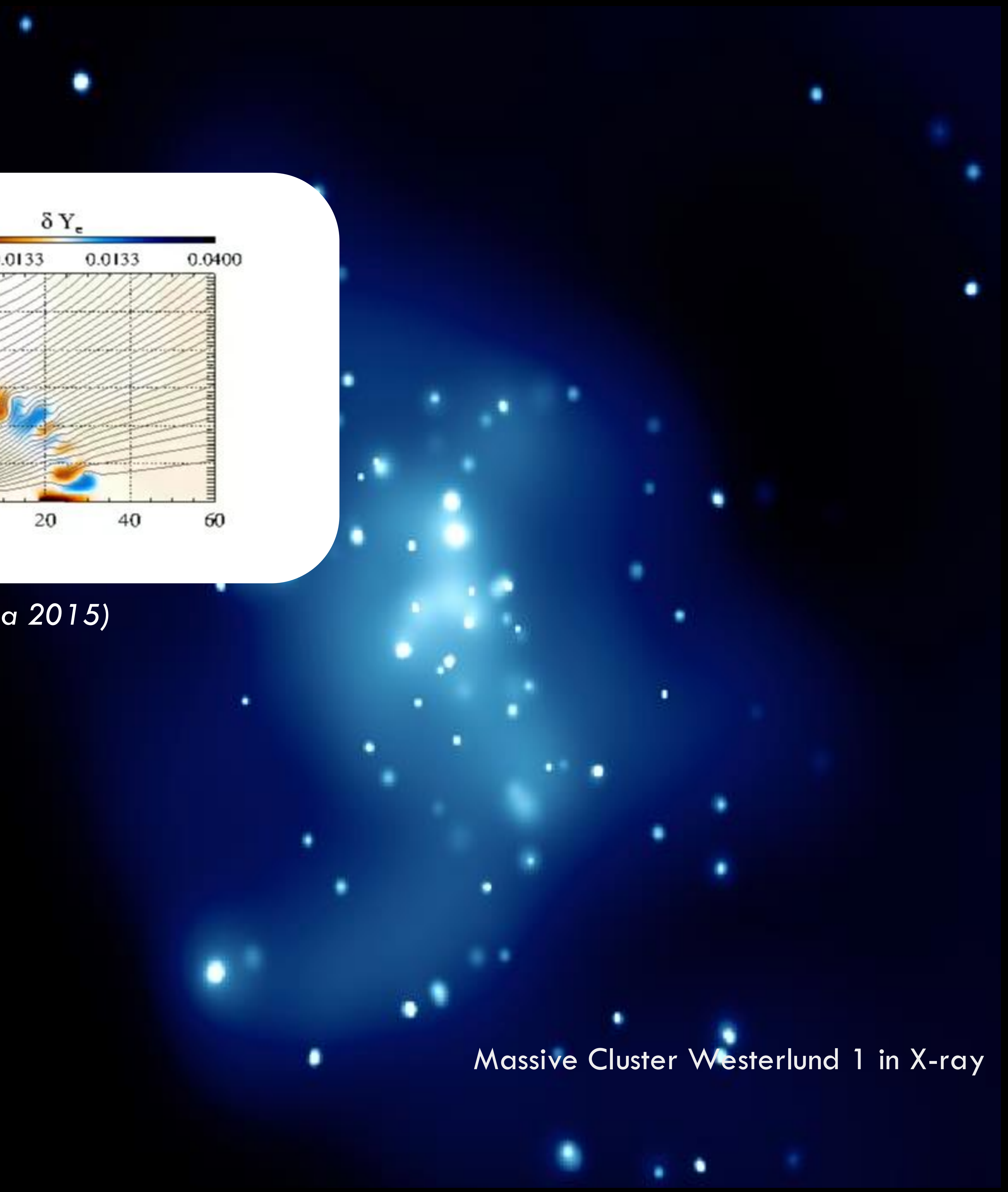
- via dynamos in the stellar core
- as fossil fields from a magnetic progenitor
- from massive star binary progenitors



(Obergaulinger, Aloy & Janka 2015)

Observationally…

- Proper motions for ~9 objects: 100-300 km/s range
- A few magnetars coincident with massive star clusters
- One case: a wind blown boubble observed in radio
- One case: a run-away star close-by is detected.
- ~6 confirmed SNRs, 3 more possibly associated



Massive Cluster Westerlund 1 in X-ray

(Thompson & Duncan 1993; Ferrario & Winkramasinge 2006; Clark et al. 2014, Chrimes et al. 2025)

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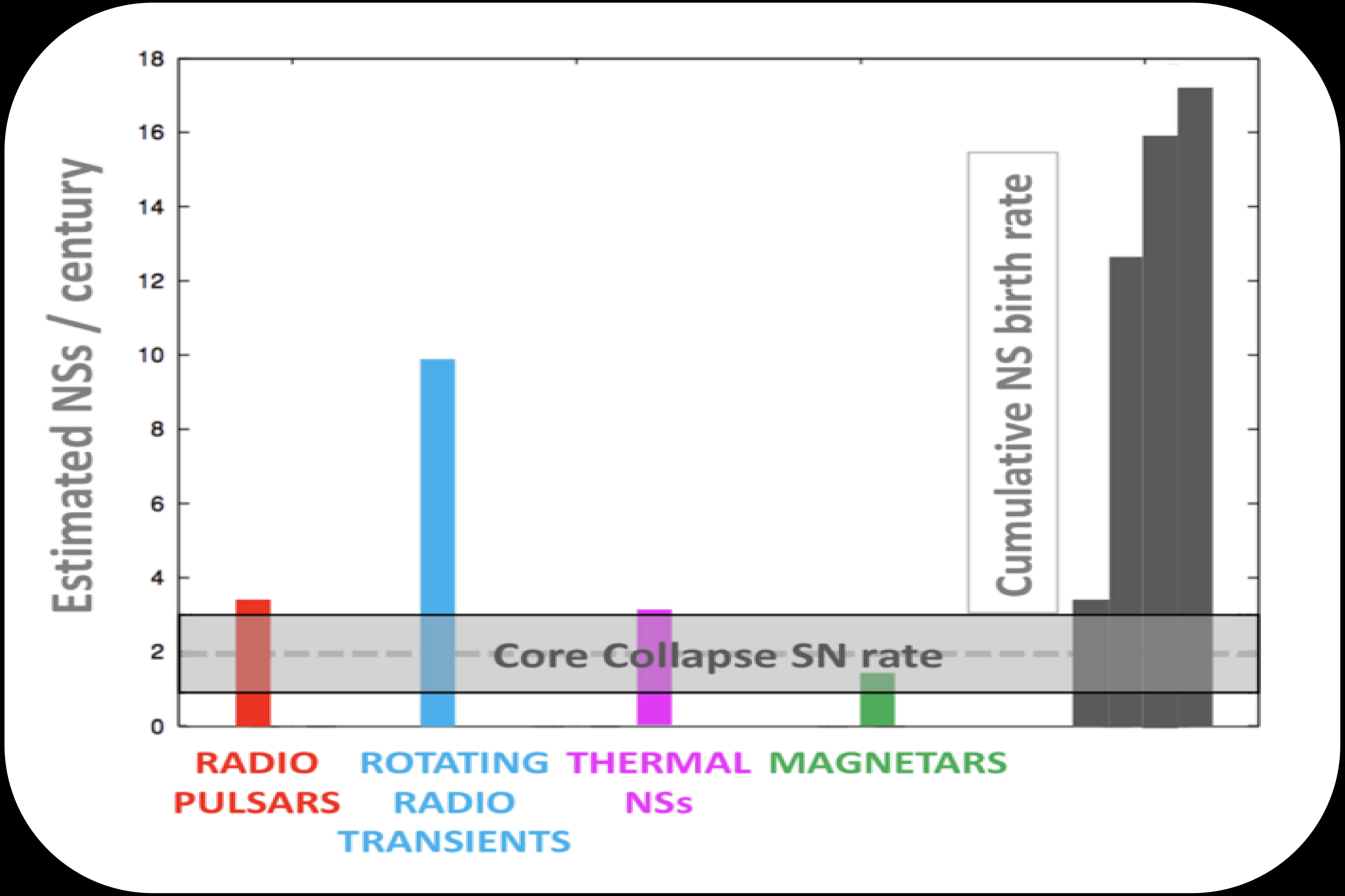
4. HOW CAN WE USE THEM TO CONSTRAIN FRBs AND GRBs?

NS CLASSES AND CC SN RATES



(adapted from Keane & Kramer 2008)

Neutron star classes cannot have independent formation, there should be an evolutionary model scenario.

NEUTRON STAR EVOLUTION: 3D eMHD SIMULATIONS

Specific heat — Thermal conductivity — Joule heating — Neutrino emissivity

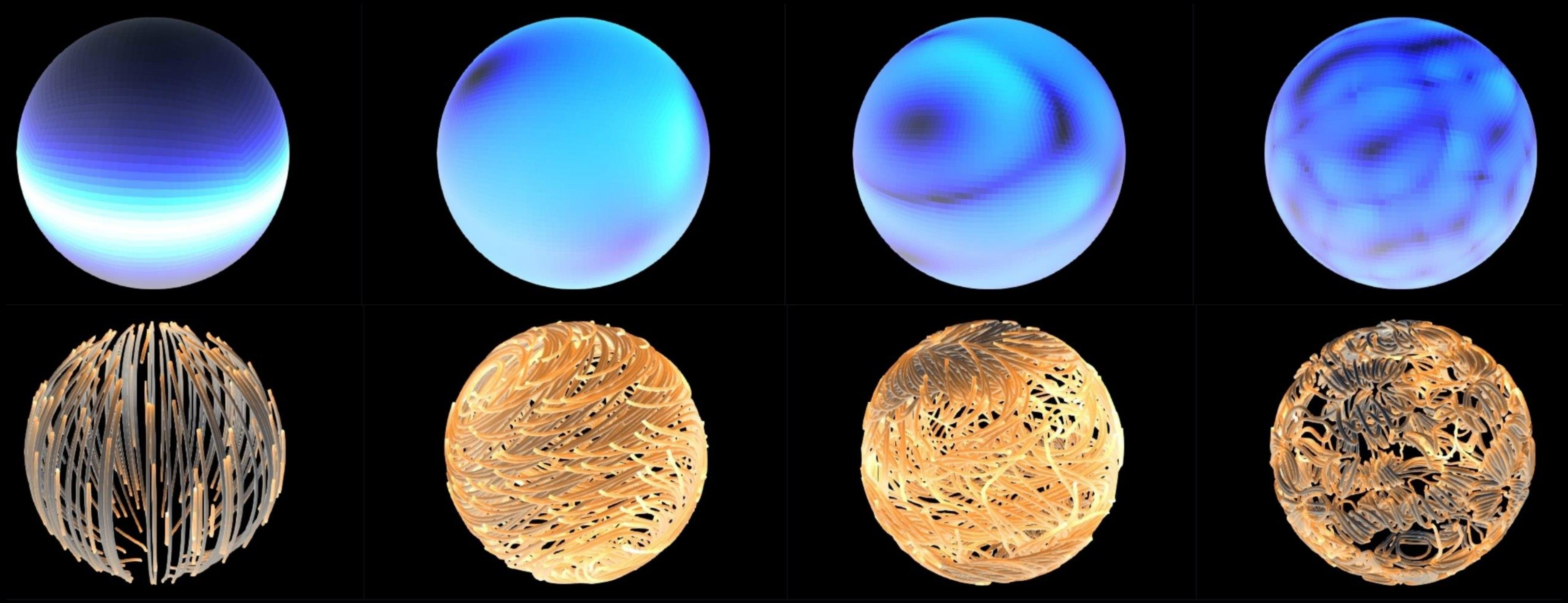
$$C_v e^{\nu} \frac{\partial \mathbf{T}}{\partial t} + \nabla \times [-k \times \nabla(e^{\nu}\mathbf{T})] = e^{2\nu}[H - Q]$$

ENERGY BALANCE EQUATION

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

HALL INDUCTION EQUATION

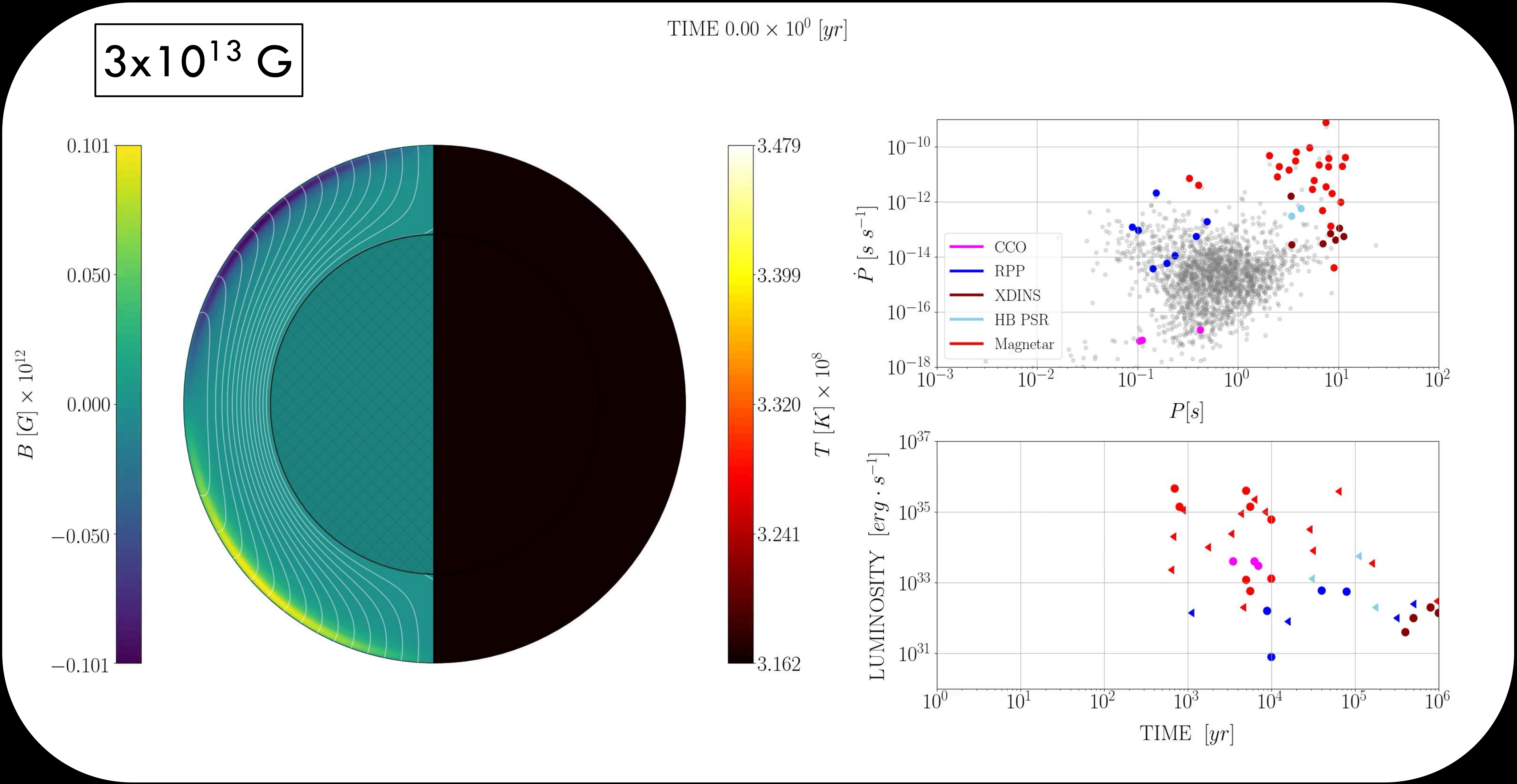
Electrical Resistivity



MATINS: Dehman et al. 2023, Ascenzi et al. 2024

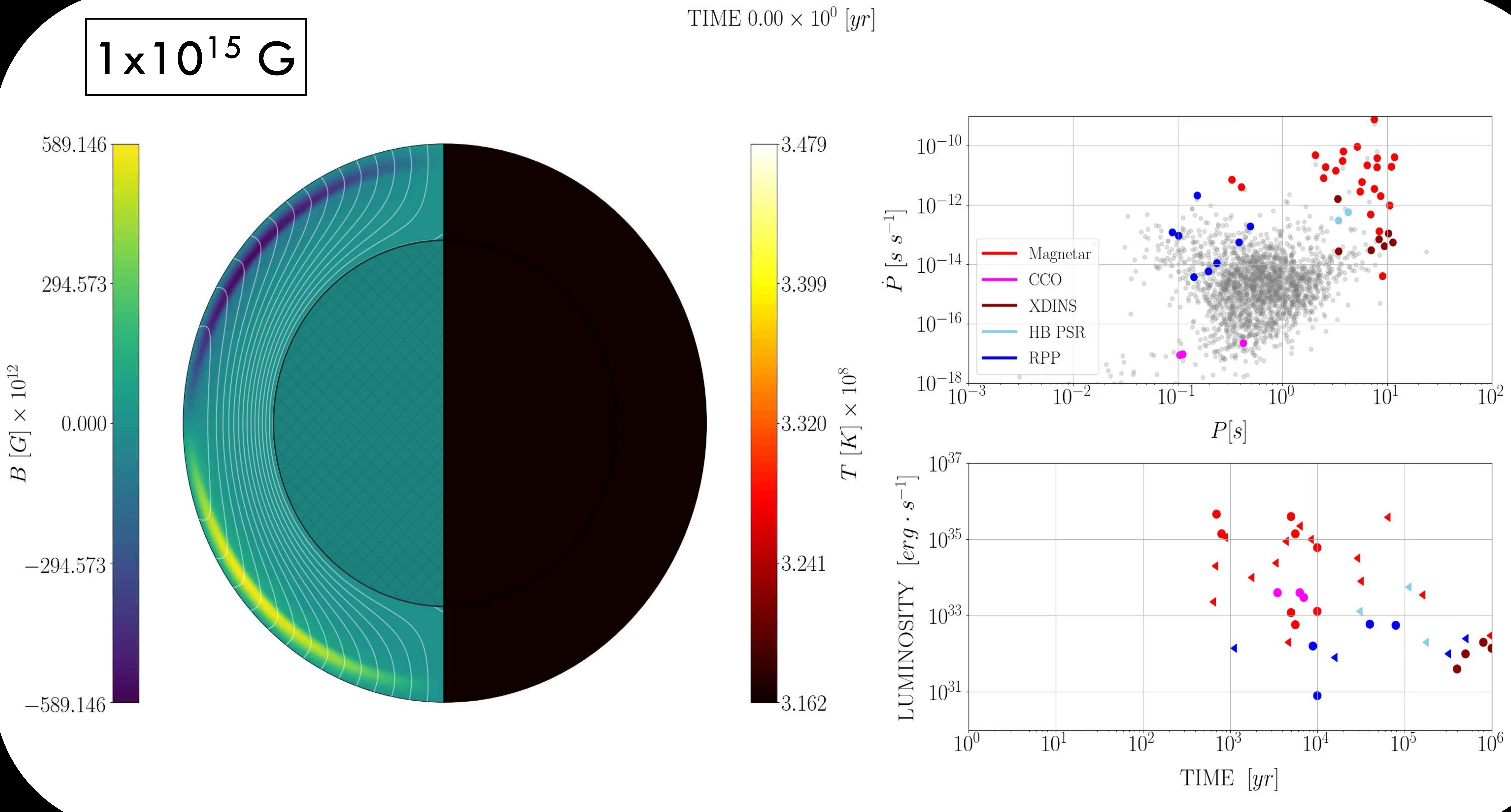
https://ice-csic-astroexotic.github.io/code/matins/

NEUTRON STAR EVOLUTION: eMHD SIMULATIONS



(Viganò et al. 2013, Dehman et al. 2023, Ascenzi et al. 2024: MATINS - first 3D MT-code with microphysics)

NEUTRON STAR EVOLUTION: eMHD SIMULATIONS



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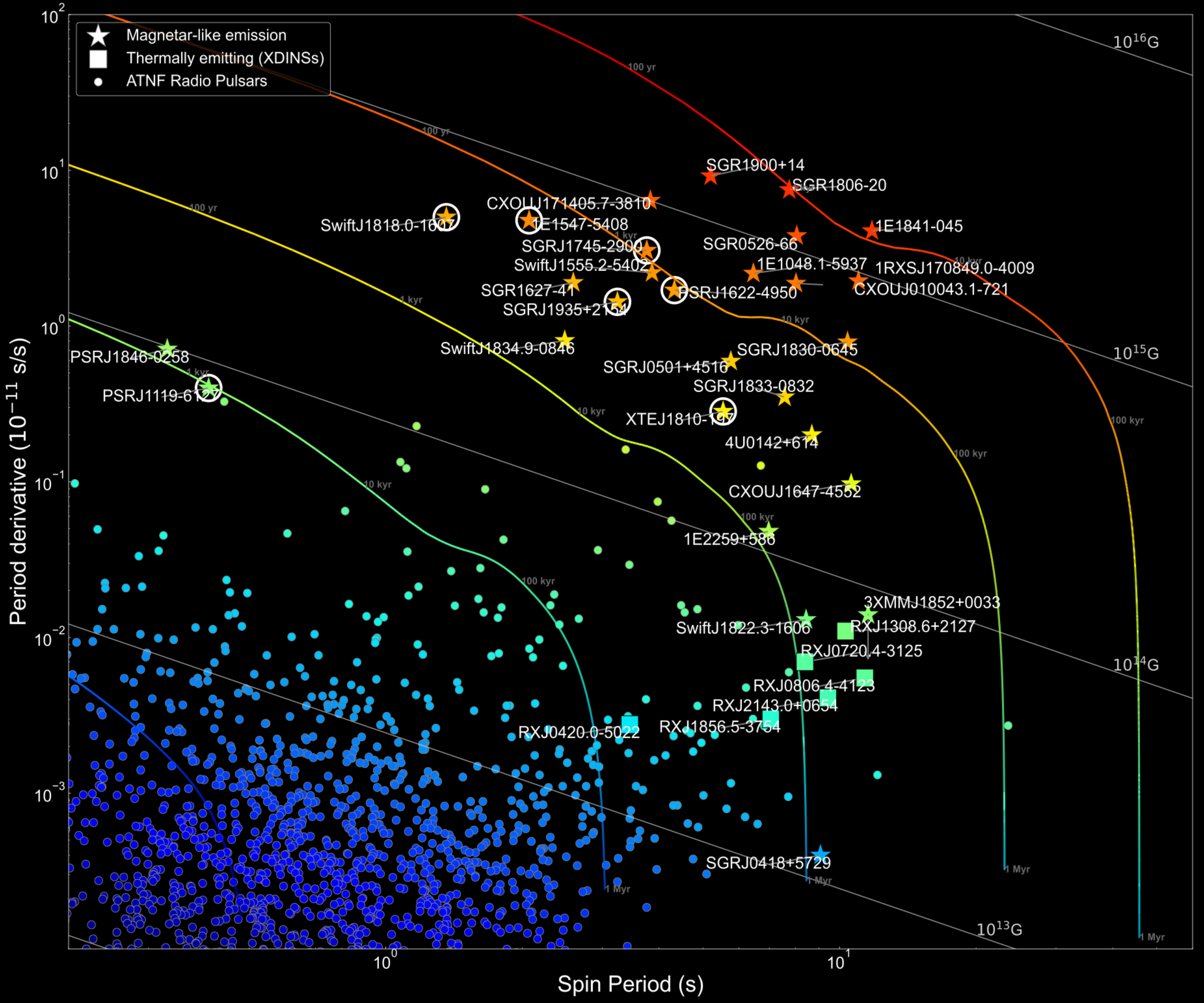
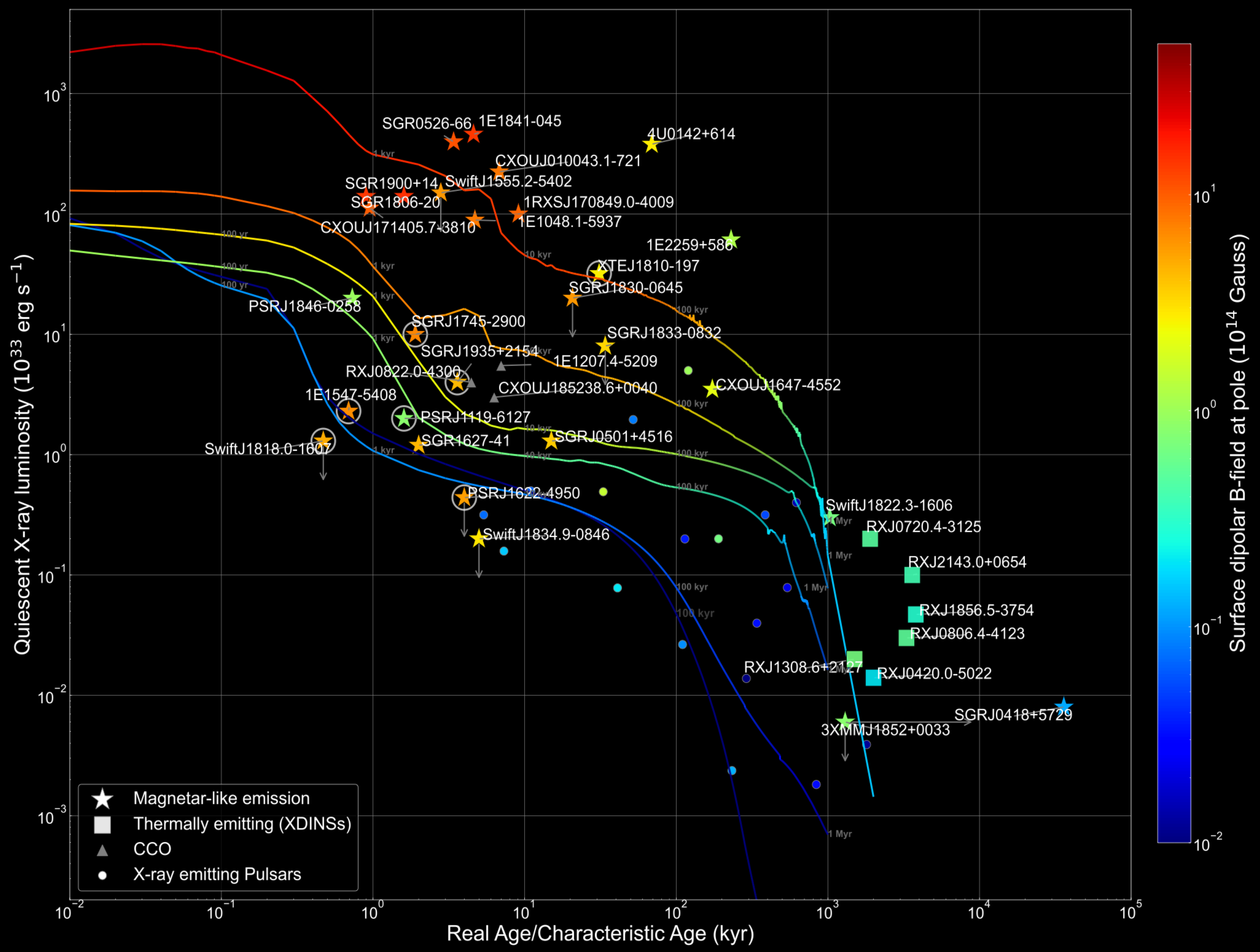




(Rea & De Grandis 2025, Elsevier encyclopedia)

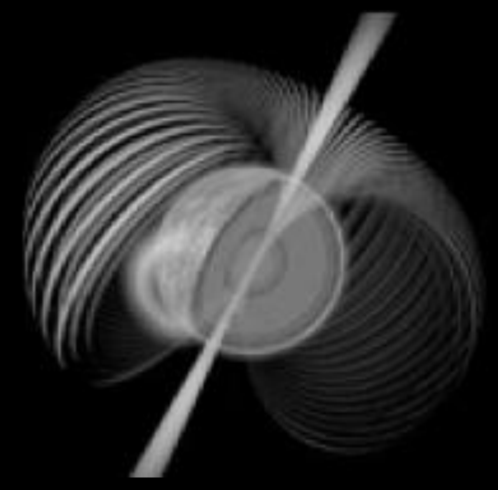
1. WHY AREN'T ALL PULSARS BEHAVING SIMILARLY? HOW COMMON ARE STRONG MAGNETIC FIELDS?

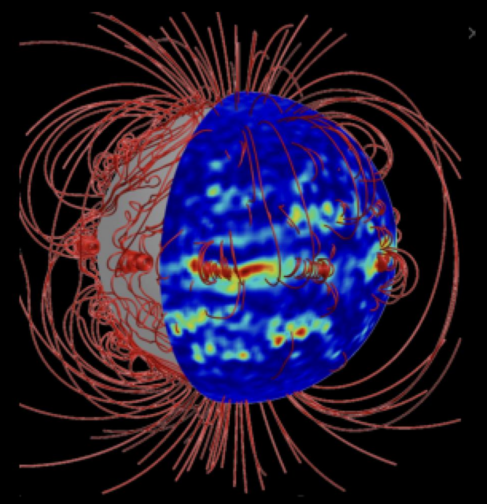
2. DO WE HAVE ENOUGH SNe FOR SO MANY NS CLASSES?

3. WHAT DID WE LEARN FROM THE OBSERVED NSs ABOUT THEIR BIRTH AND SN RATES?

4. HOW CAN WE USE THEM TO CONSTRAIN FRBs AND GRBs?

VERY YOUNG NEUTRON STARS IN OUR GALAXY





N	SNR	NS	SNR Age [kyr]	τ_c [kyr]	B_{dip} [10^{14} G]	Type
1	G000.9+00.1	J1747-2809	1.9	5.31	0.038	RPP (R)
2	G011.2-00.3	J1811-1925	1.4–2.4	23.3	0.023	RPP (X)
3	G012.8-00.0	J1813-1749	1.2	5.58	0.032	RPP (R,X)
4	G021.5-00.9	J1833-1034	1.55–1.8	4.85	0.048	RPP (R,γ)
5	G054.1+00.3	J1930+1852	1.5–2.4	2.89	0.137	RPP (R,X)
6	G130.7+03.1	J0205+6449	0.84	5.37	0.048	RPP (R,X,γ)
7	G184.6-05.8 (Crab)	J0534+2200	0.97	1.26	0.051	RPP (R,X,γ)
8	G310.6-01.6	J1400-6325	1.0–2.5	12.7	0.015	RPP (R,X)
9	G320.4-01.2	B1509-58	1.9	1.58	0.206	RPP (R,X,γ)
10	G027.4+00.0	1E1841-045	0.75–2.1	4.60	9.382	Magnetar (X)
11	G029.7-00.3	J1846-0258	1.69–1.85	0.73	0.654	Magnetar (X)
12	G292.2-00.5	J1119-6127	4.2–7.1	1.6	0.545	Magnetar (R,X)
13	G327.2-00.1	1E1547-5408	0.8	0.69	4.245	Magnetar (R,X)
14	G348.7+00.3	CXOUJ171405.7-3810	0.65–16.8	0.95	6.689	Magnetar (X)
15	G042.8+00.6	SGR1900+14	110	0.9	9.345	Magnetar (X)
16	–	SGR1806-20	–	1.6	10.301	Magnetar (X)
17	–	SGRJ1745-2900	–	1.9	4.583	Magnetar (R,X)
18	–	SwiftJ1818.0-1607	–	0.47	3.523	Magnetar (R,X)
19	G111.7-02.1	CXOJ232327.9+58	0.32–0.35	–	–	CCO
20	G330.2+01.0	CXOJ160103.1-513	< 1	–	–	CCO
21	G332.4-00.4	1E161348-5055	2.0–4.4	–	–	CCO
22	G347.3-00.5	1WGAJ1713.4-3949	1.8–2.4	–	–	CCO
23	G350.1-00.3	XMMUJ172054.5-37	< 0.7	–	–	CCO

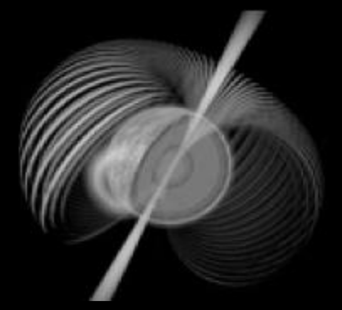
(Pardo, Rea, Ronchi & Graber 2026, Nature Astronomy submitted)

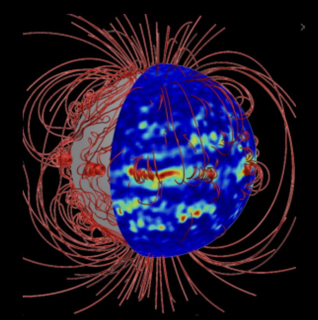
WHAT DO WE LEARN ON SNe JUST FROM THE DATA…

1. If CC SN birthrate ~ 1 per century, the sample is complete, implying ~60% of neutron stars are born as magnetars.
→ the SN rate CANNOT be 1 per century for sure!

2. In the past 2000 yr our Galaxy created mostly ~40% Magnetars, ~20% Central Compact Objects and 40% Rotational Powered Pulsar.

3. Assuming we observed all CC SNe within 2 kpc (certainly a lower limit), rescaling for the whole Galaxy we obtain a SN rate of $2.01^{+1.90}_{-0.96}$ NS/century.
→ the SN rate CANNOT be 2 per century for sure!





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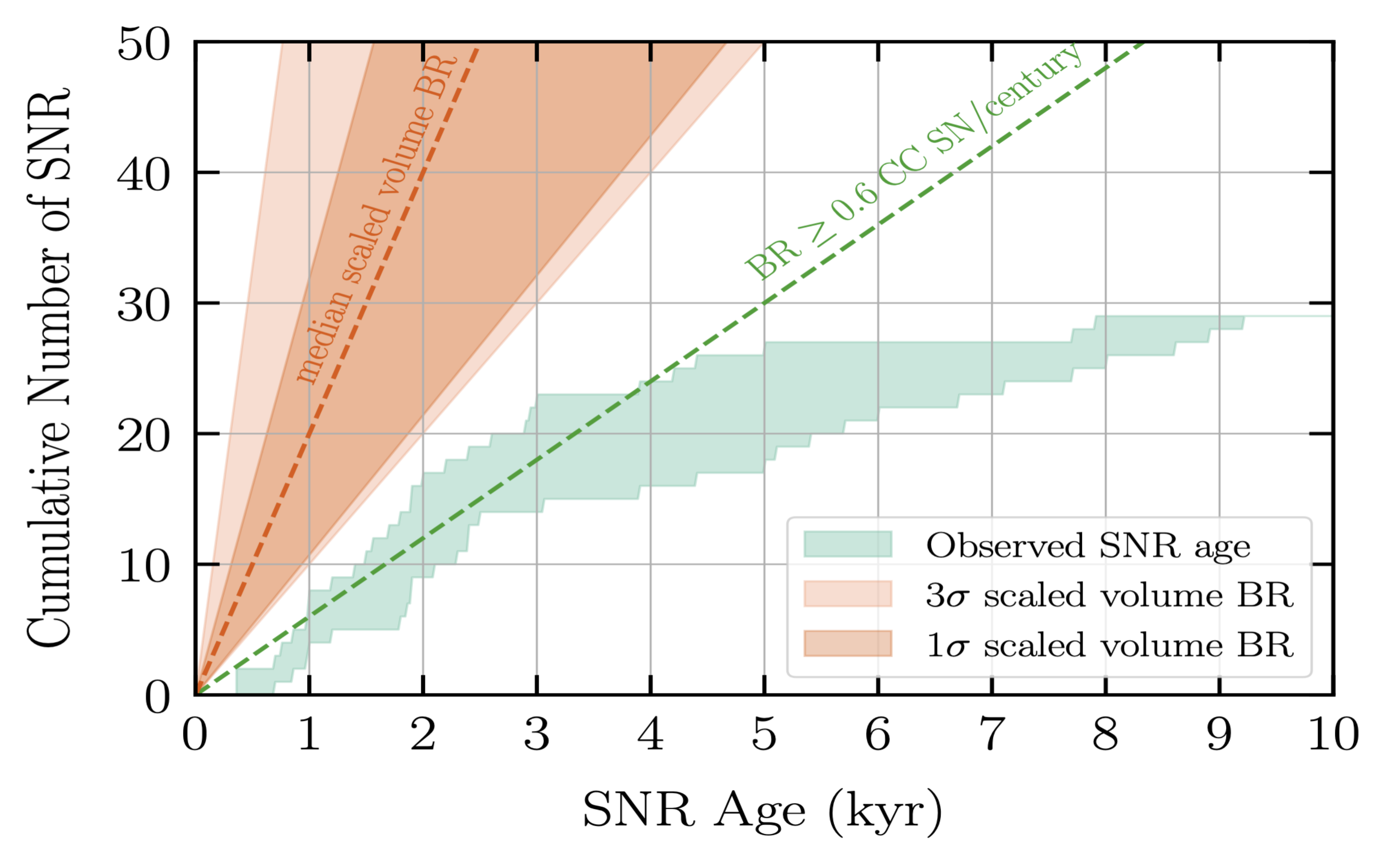
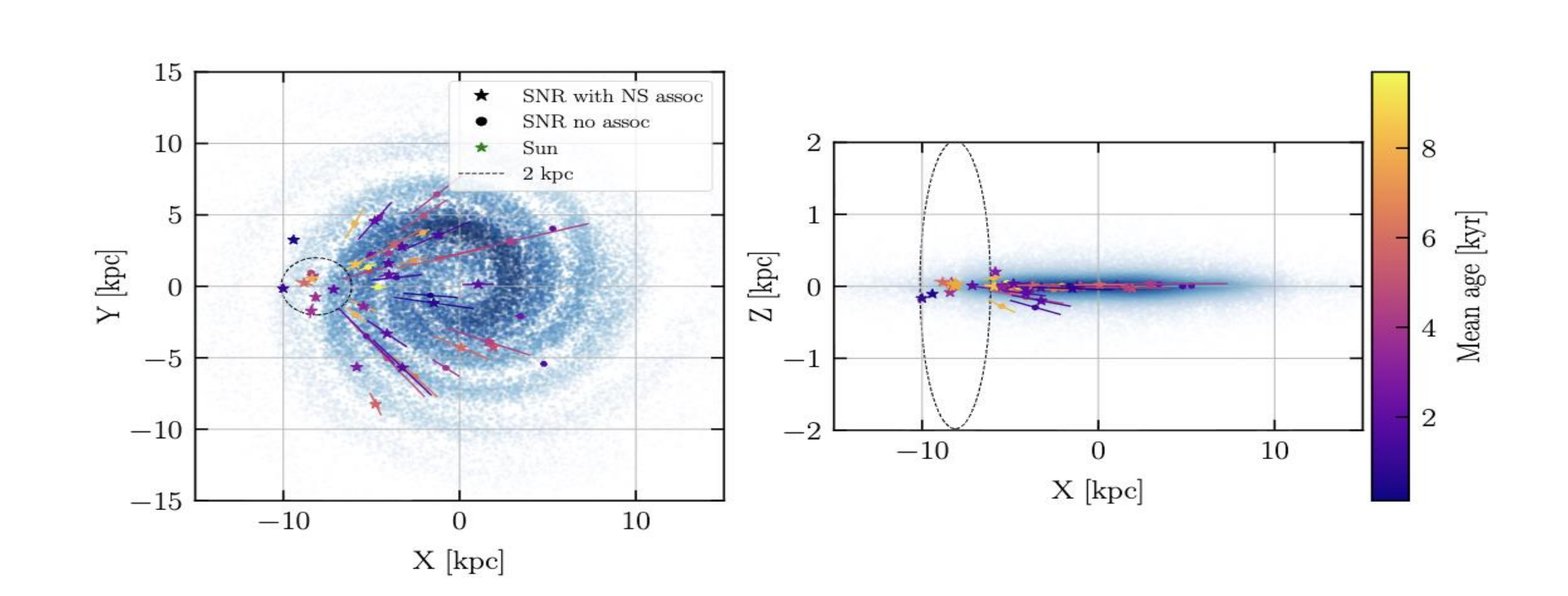


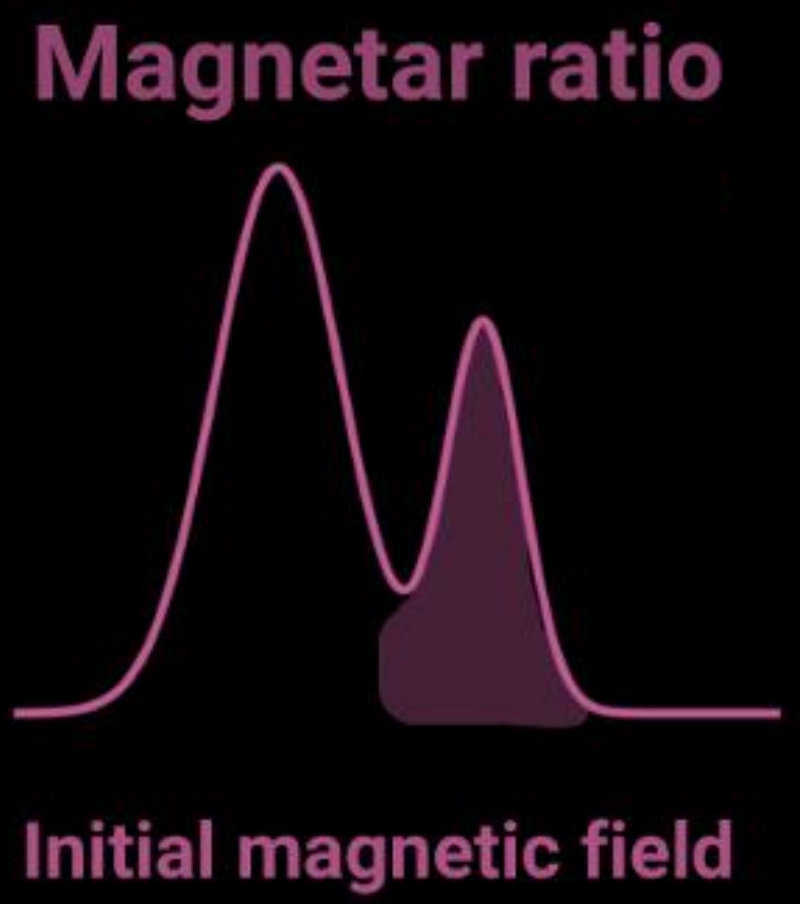


(Pardo, Rea, Ronchi & Graber 2026, Nature Astronomy submitted)

PROPER POPULATION SIMULATIONS ARE NEEDED THOUGH…

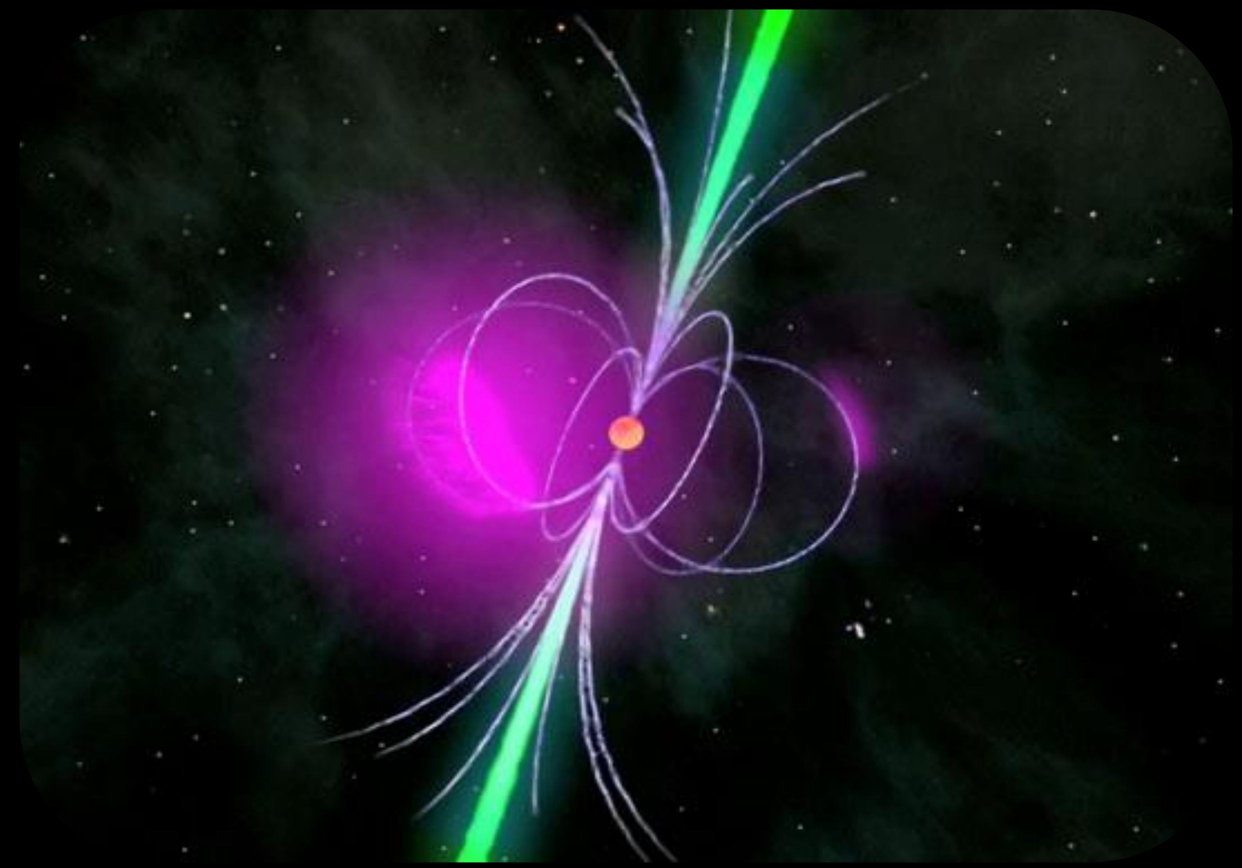
BIRTH PROPERTIES

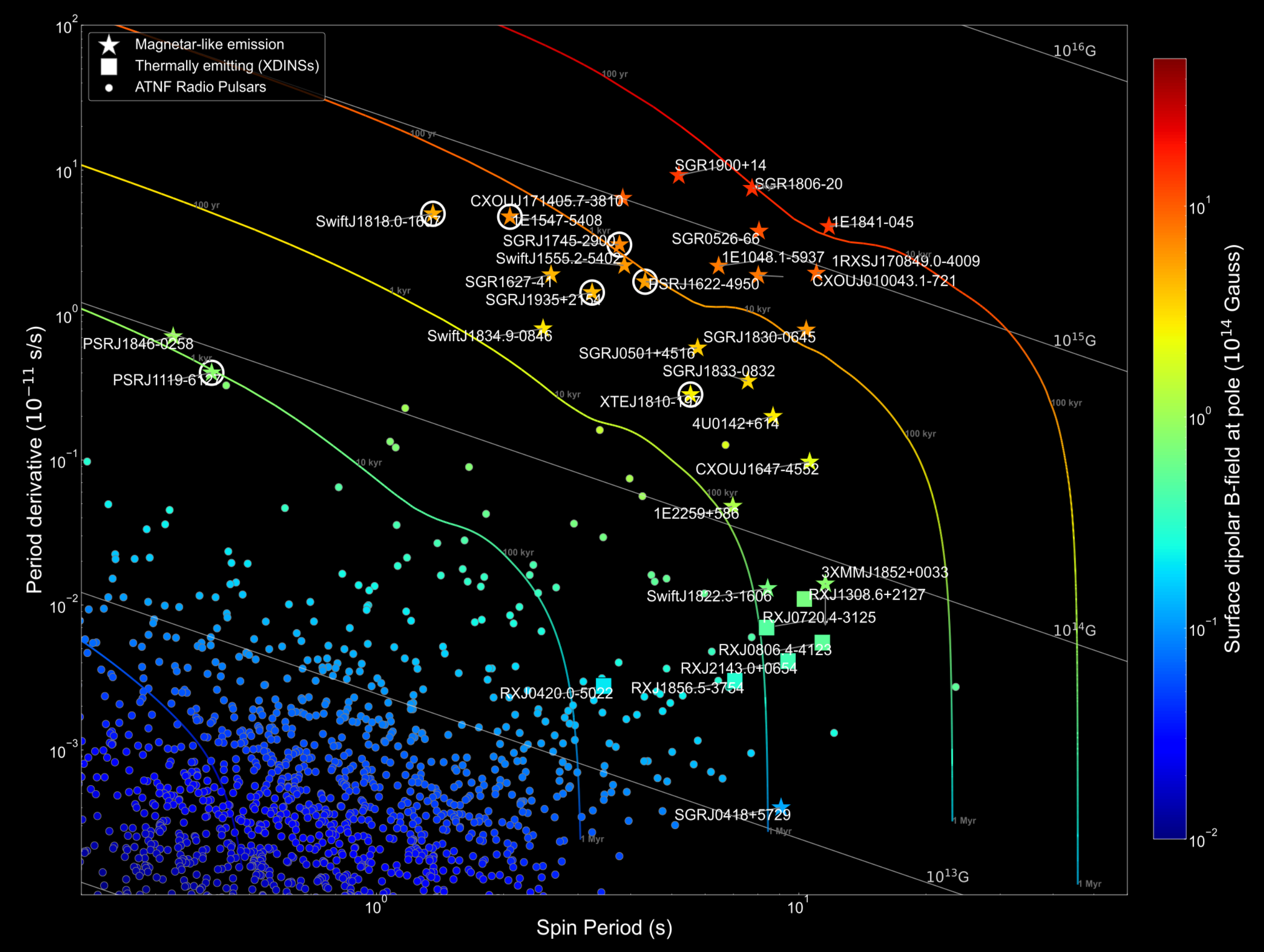
CC SN rate



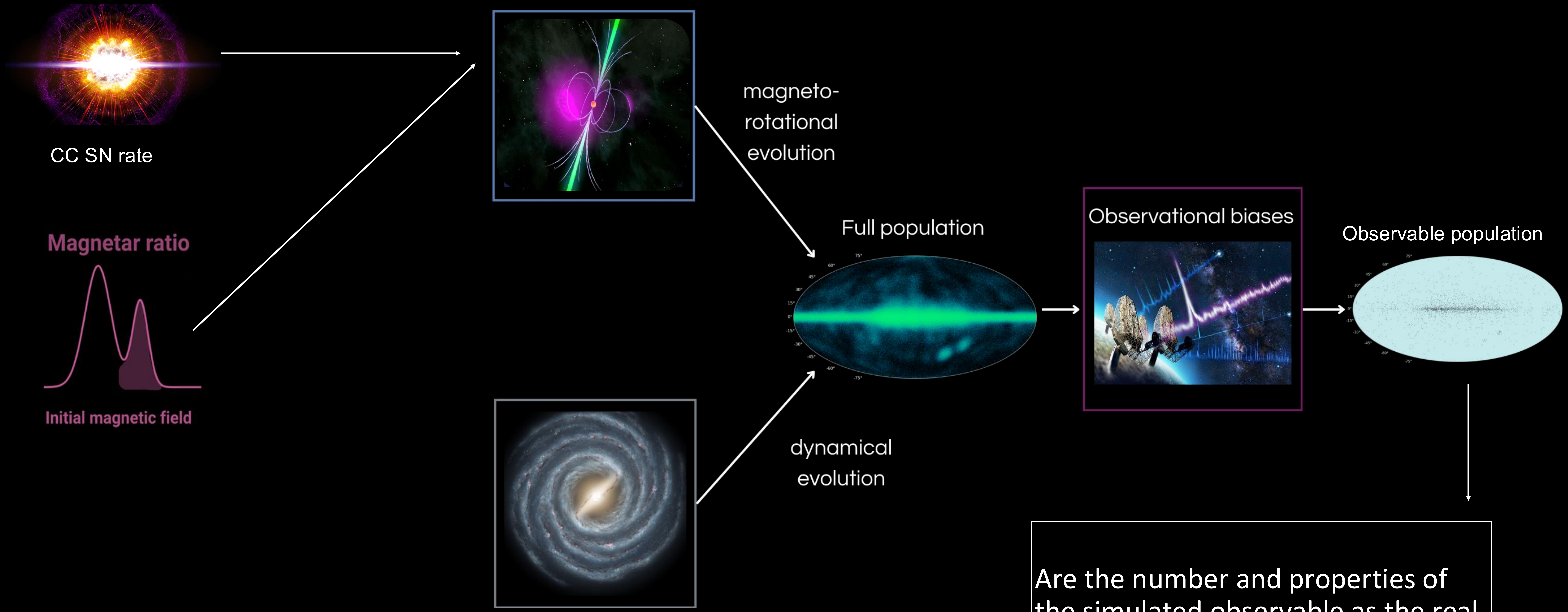
ENVIRONMENT

EVOLUTION





POPULATION SYNTHESIS SIMULATIONS OF NEUTRON STARS

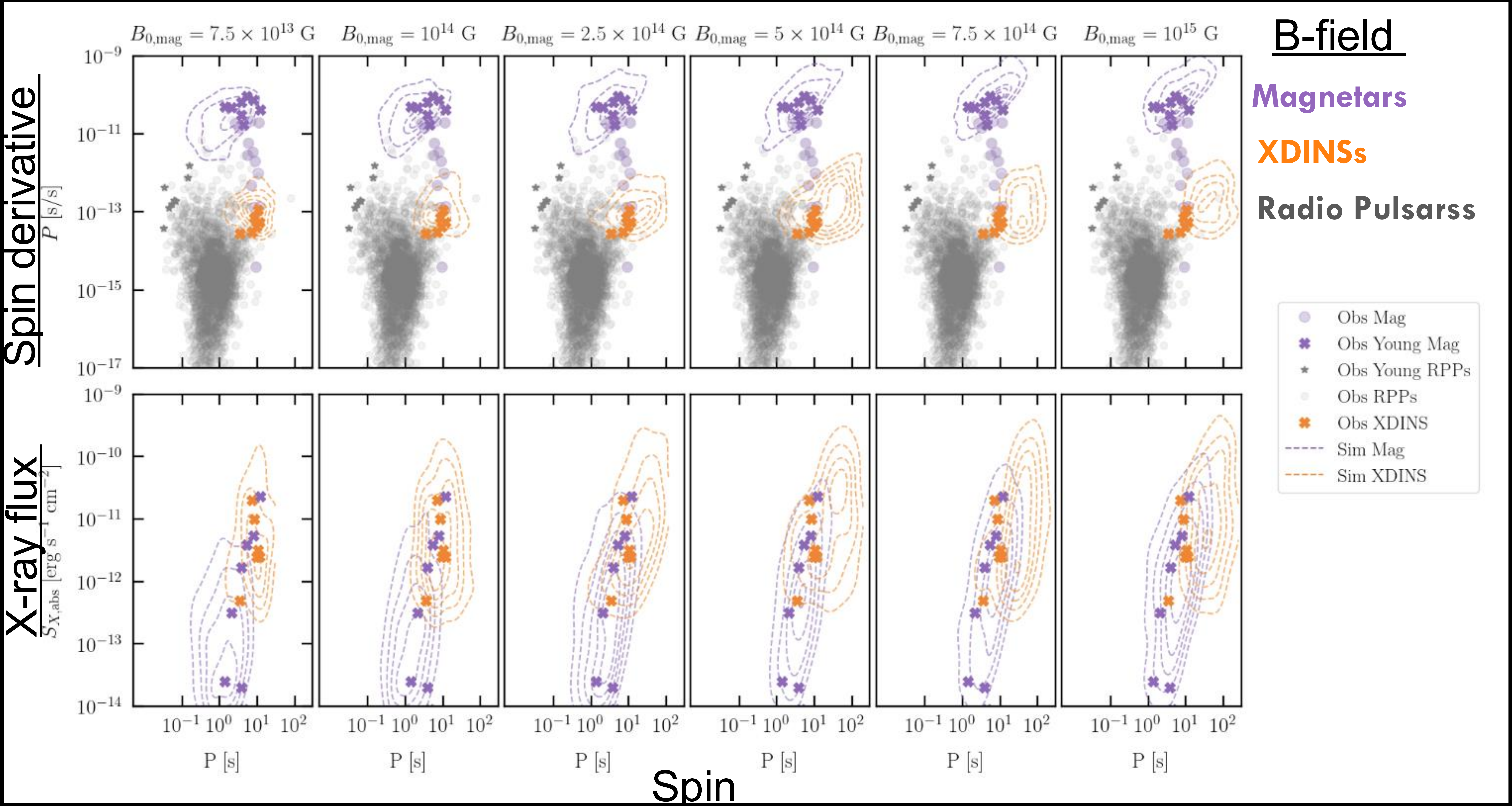


Are the number and properties of the simulated observable as the real observed ones?

MLPoppyns: Ronchi et al. 2022, Graber et al. 2024, Pardo-Araujo et al. 2025

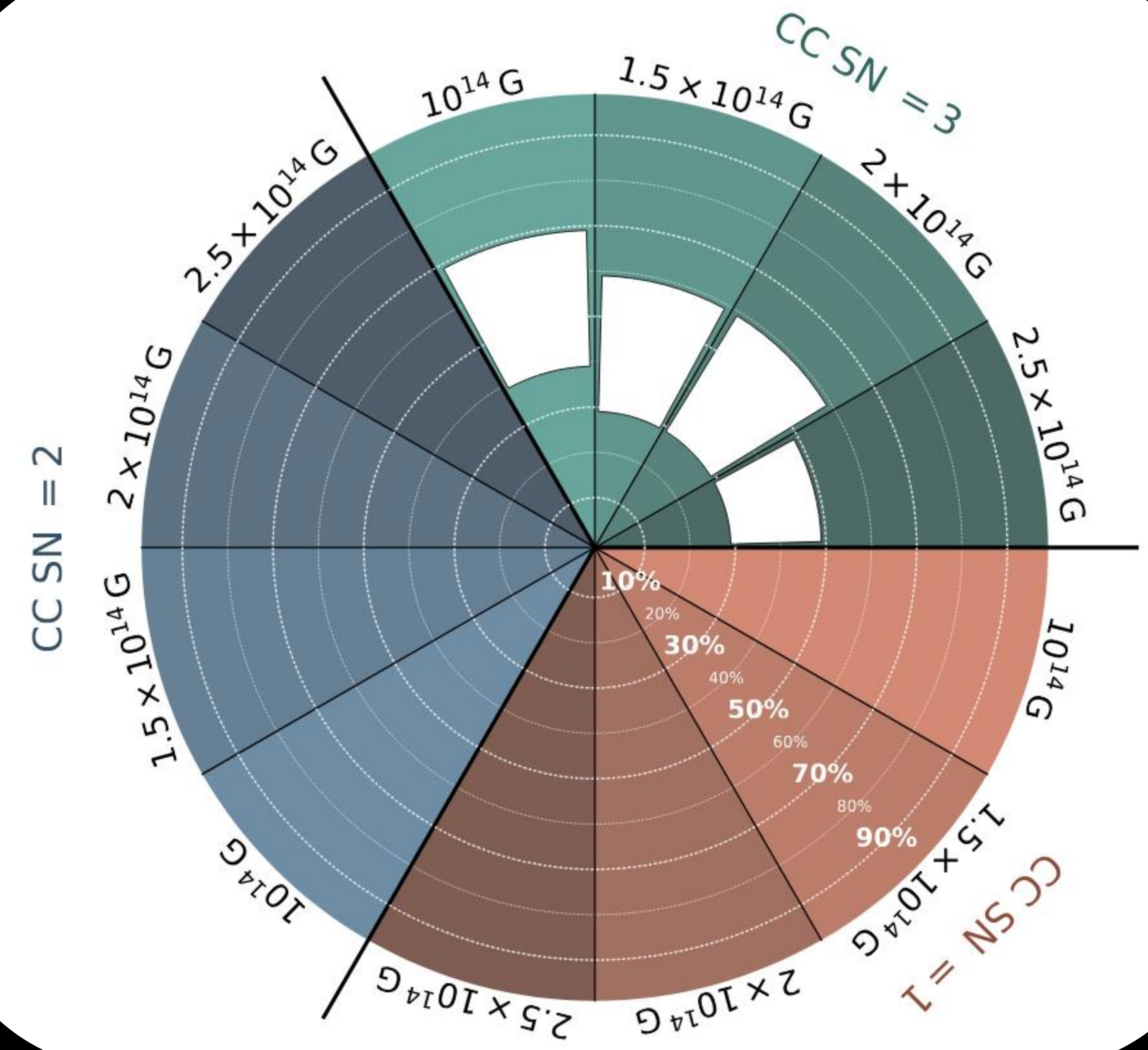
https://ice-csic-astroexotic.github.io/code/ml_poppyns/

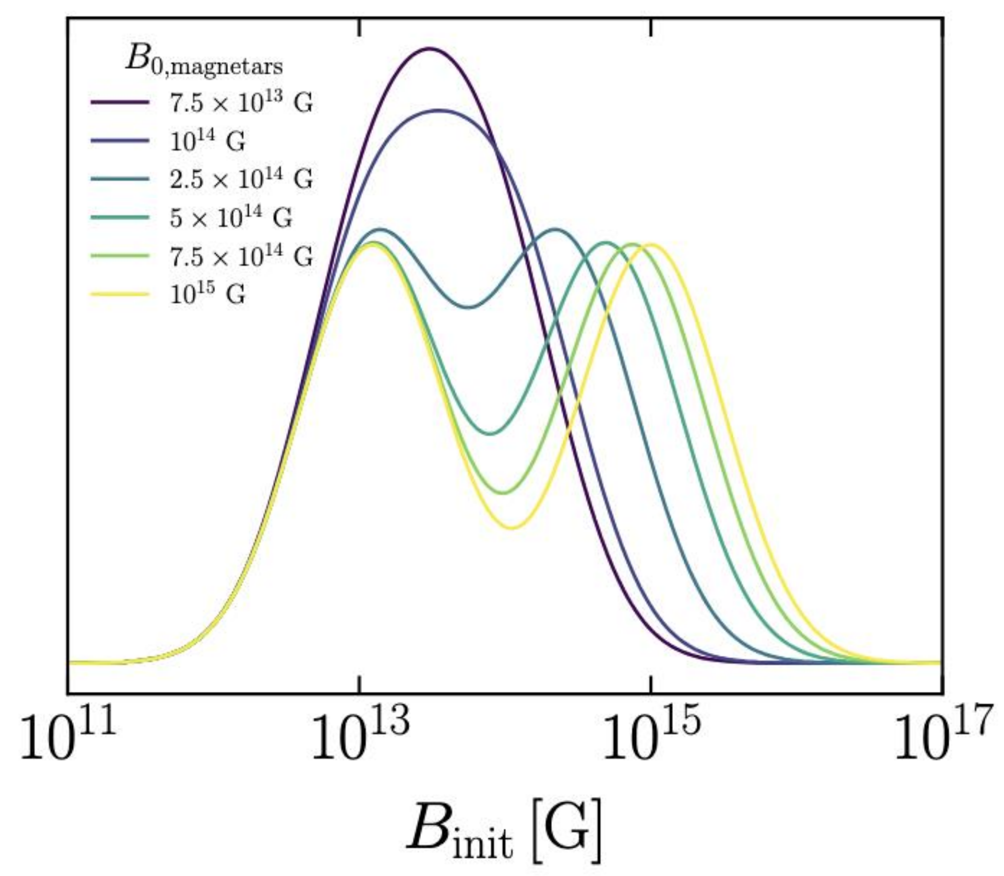
POPULATION SYNTHESIS SIMULATIONS OF NEUTRON STARS



(Pardo, Rea, Ronchi & Graber 2026, Nature Astronomy submitted)

CONSTRINS ON CC RATES AND MAGNETAR FRACTION





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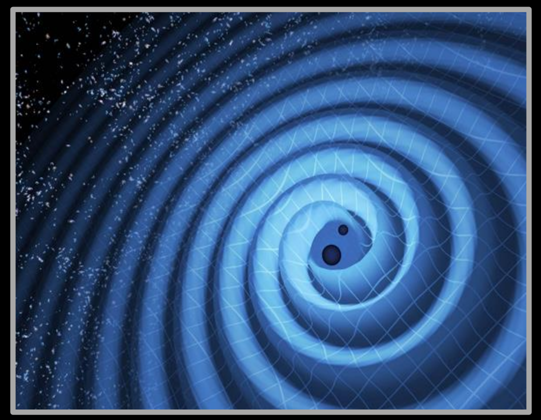
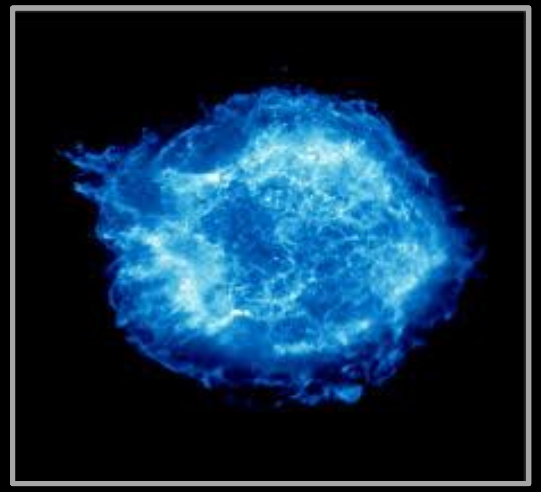
2. DO WE HAVE ENOUGH SNe FOR SO MANY NS CLASSES?

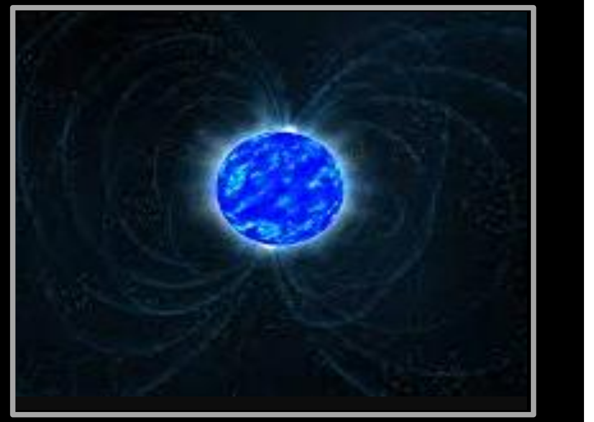
3. WHAT DID WE LEARN FROM THE OBSERVED NSs ABOUT [illegible] BIRTH AND SN RATES?

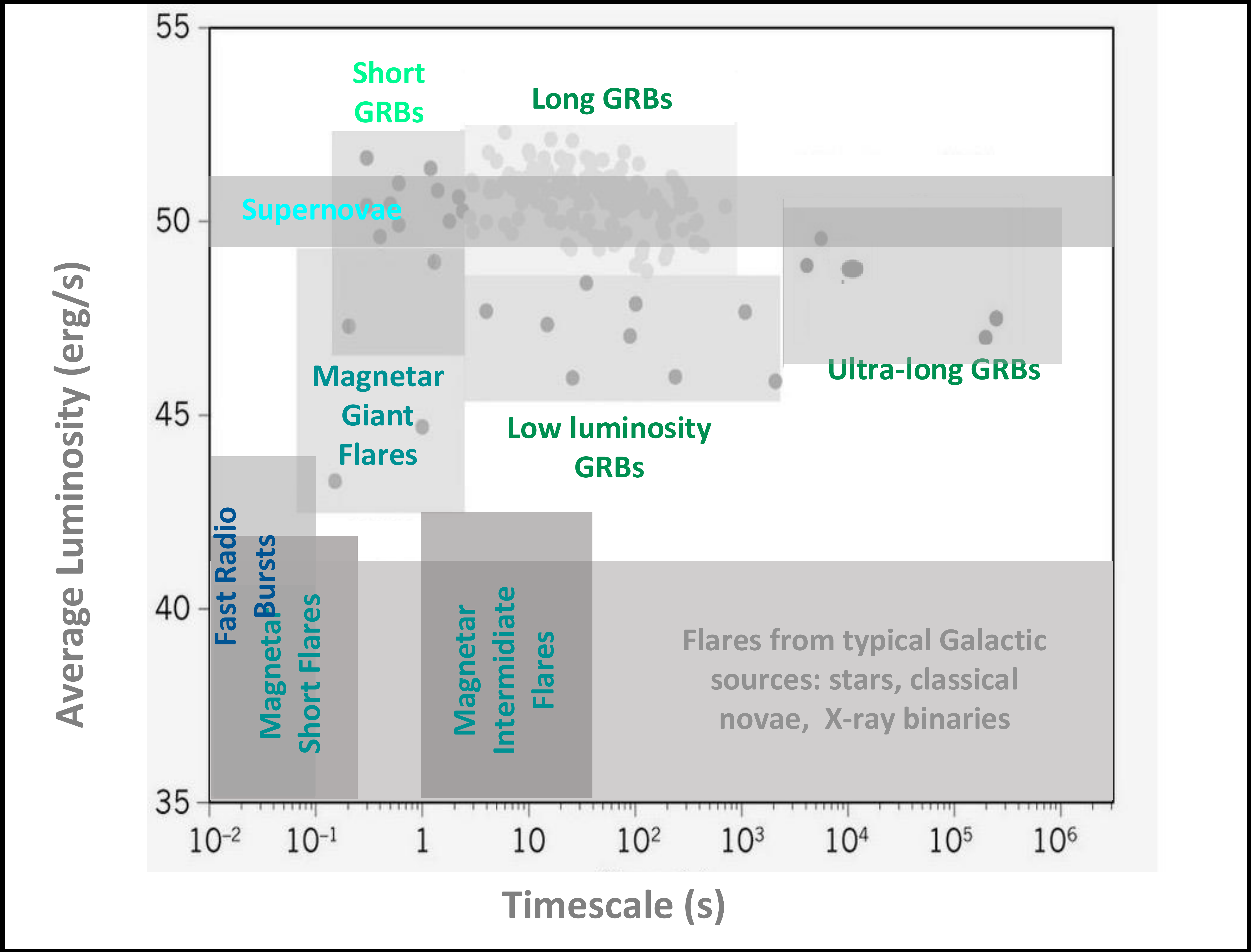
4. HOW CAN WE USE THEM TO CONSTRAIN GRBs and FRBs?

THE UNIVERSE MOST ENERGETIC TRANSIENTS



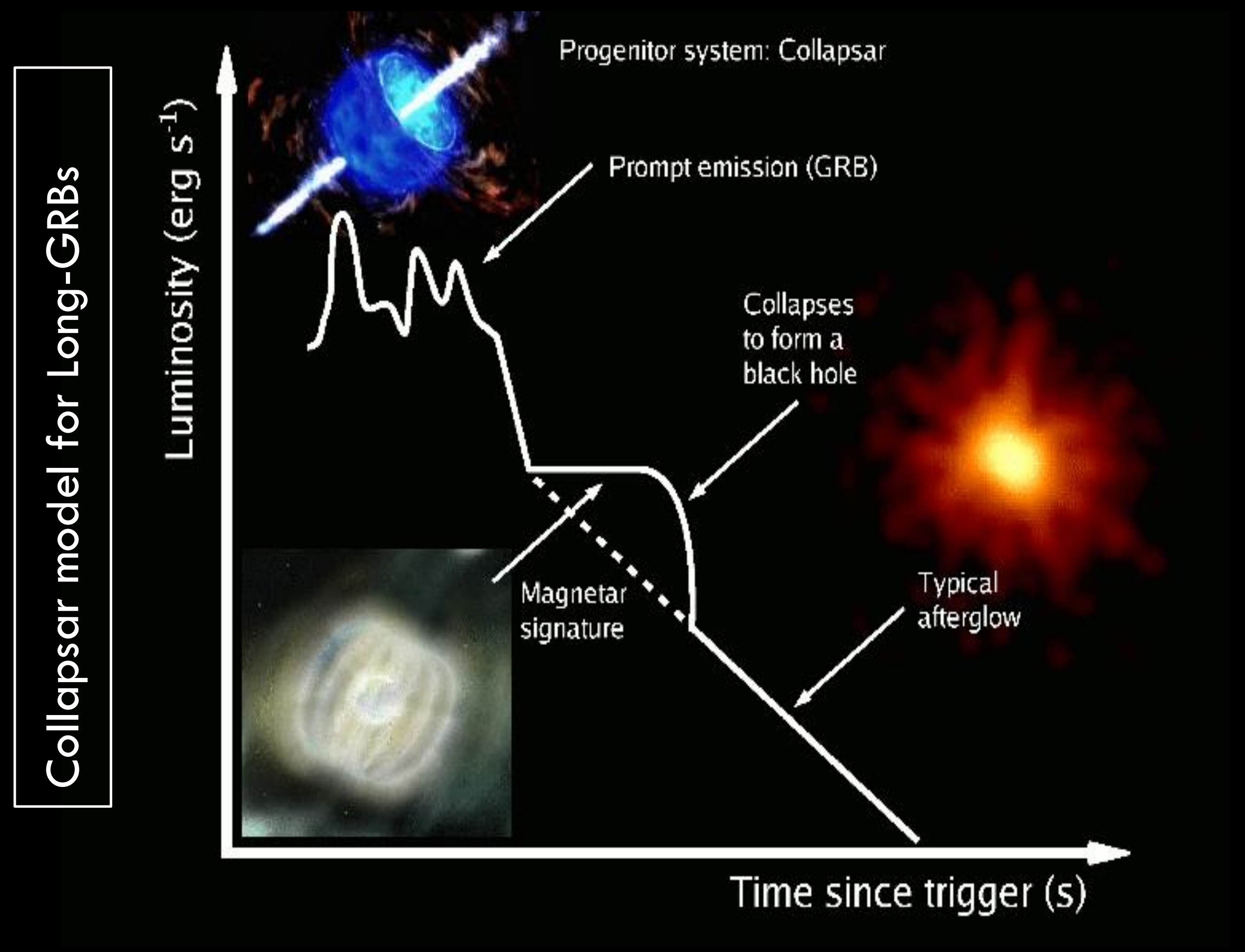


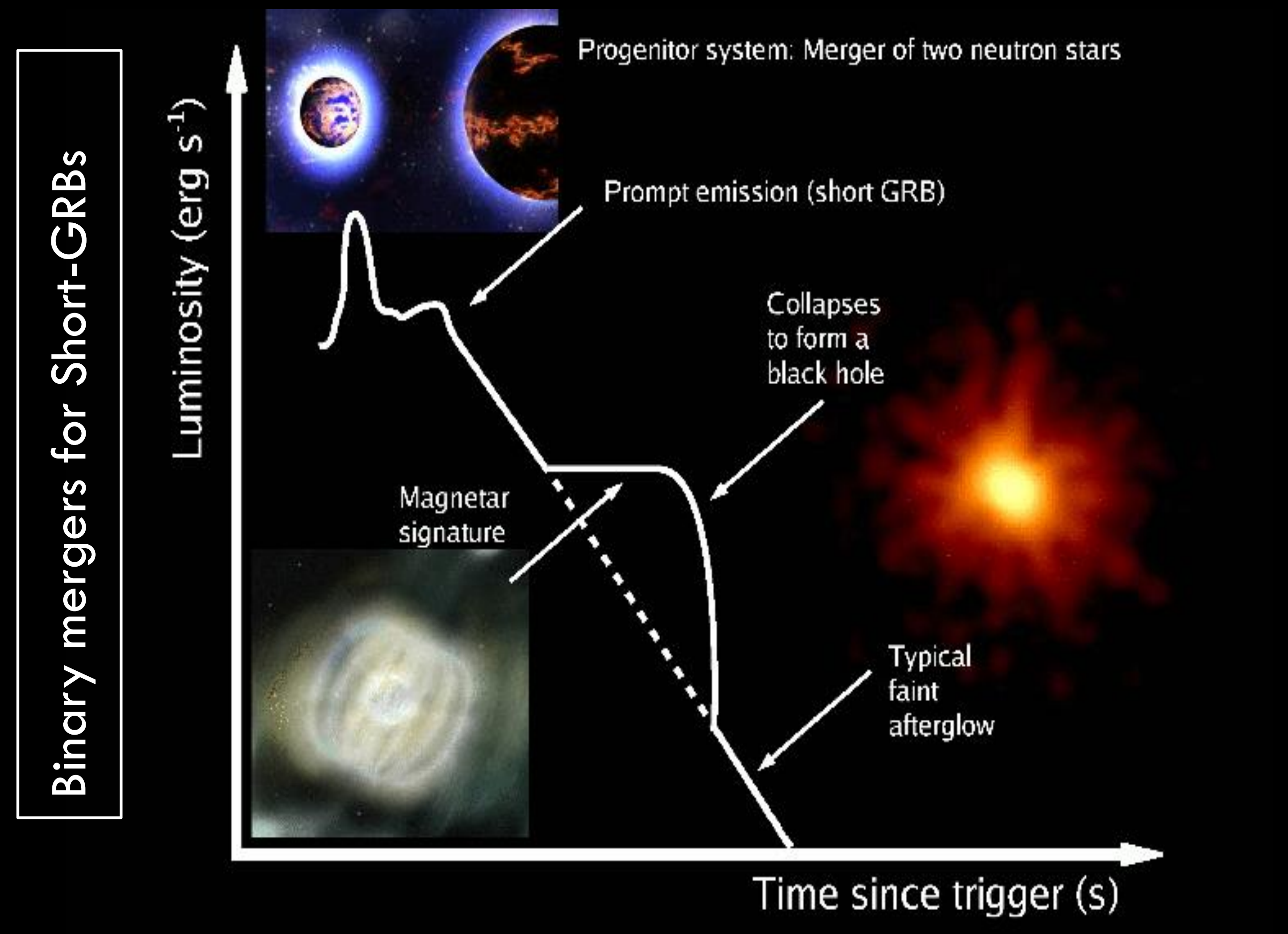


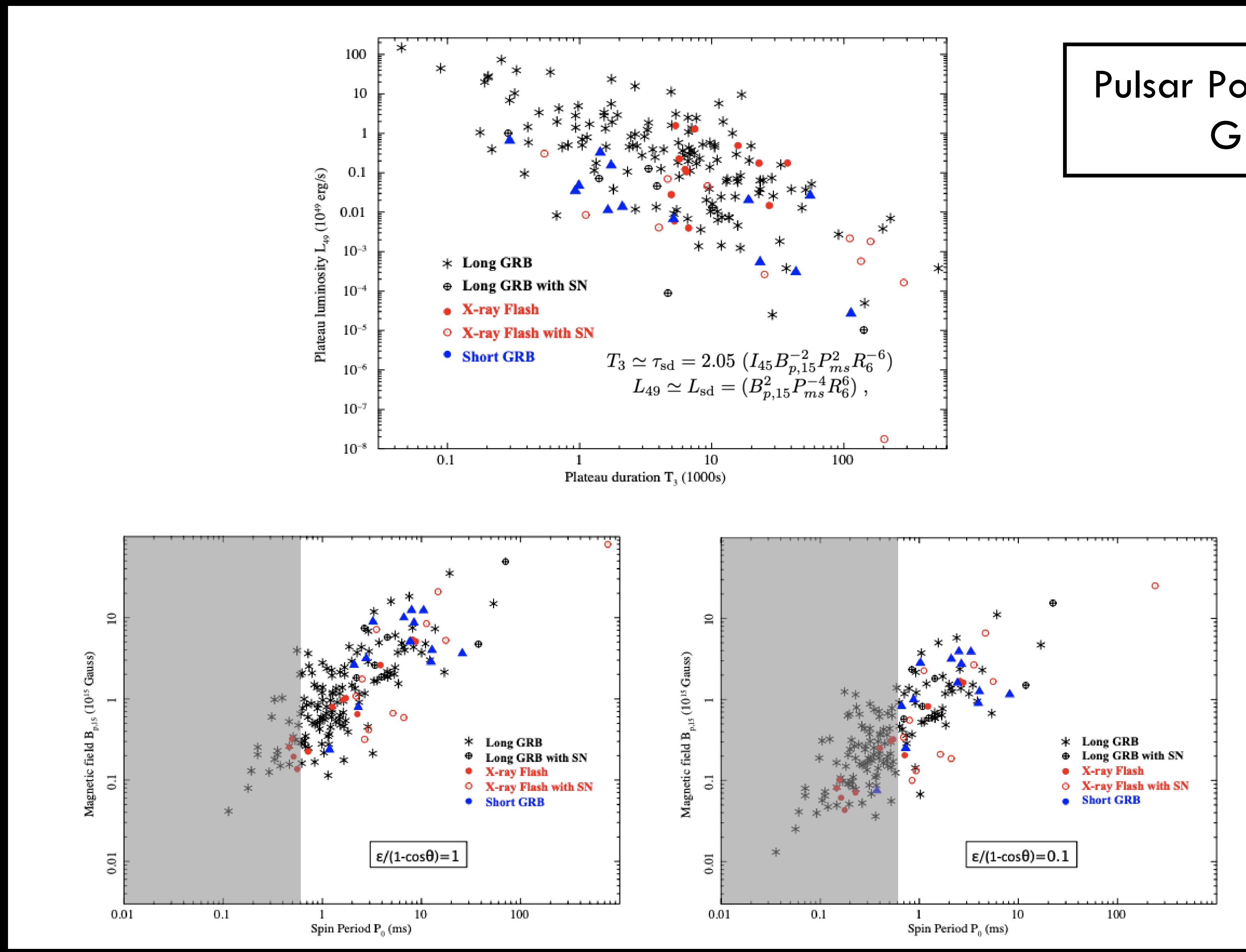


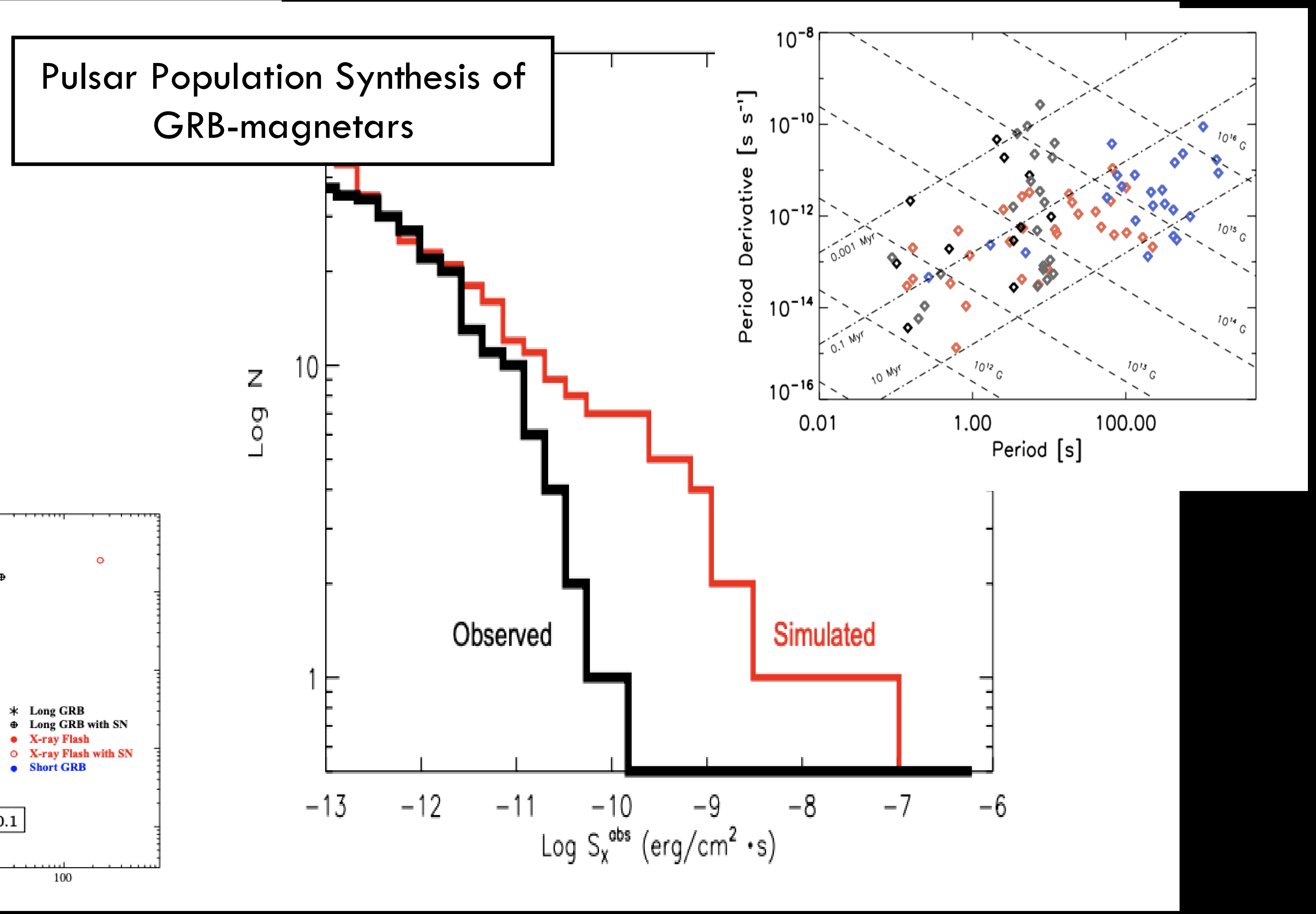
Adapted from Smartt 2015

GAMMA-RAY BURSTS AND MAGNETARS







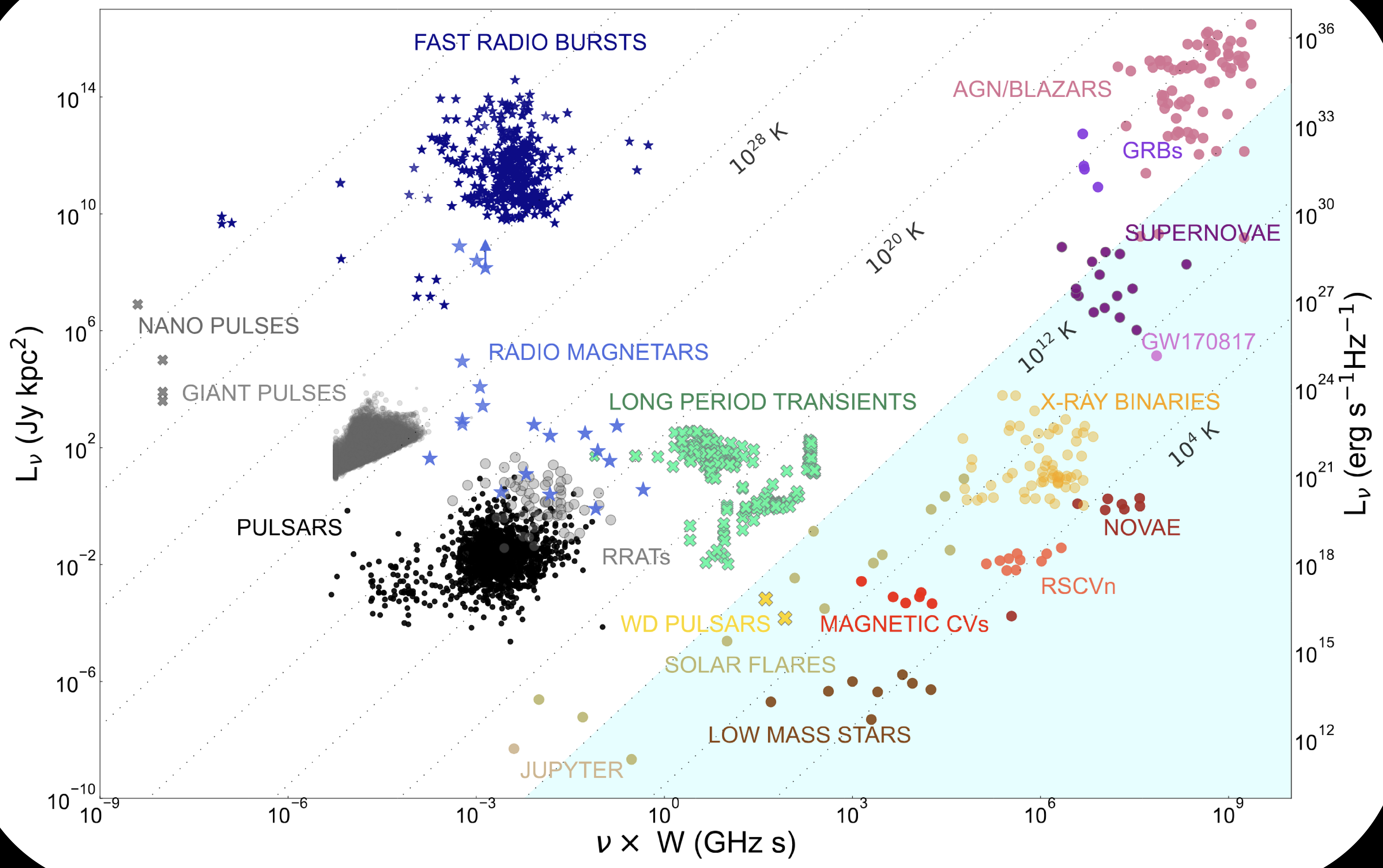


Simulating 100 magnetar-GRBs with B0 distributed as derived from Swift GRB plateaus in the past 1 Myr in the Milky Way, we would expect to have now ~25 "observable", but the expected X-ray luminosities and spin period distribution of these GRB-magnetars cannot be reconciled with what observed in our magnetars.

Our Galactic magnetars cannot have GRB progenitors

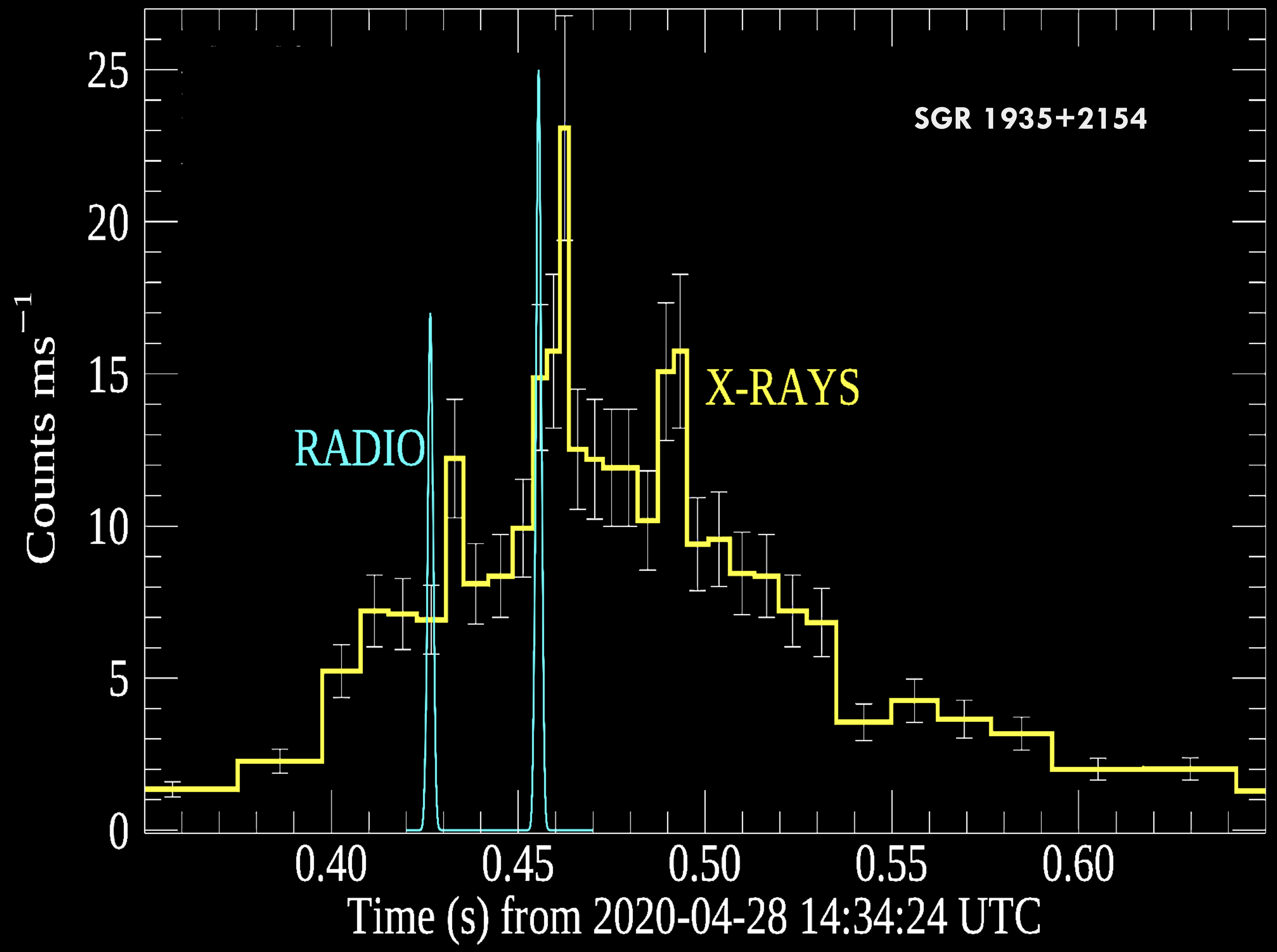
(Rea et al. 2015, Pardo et al. 2026 in prep)

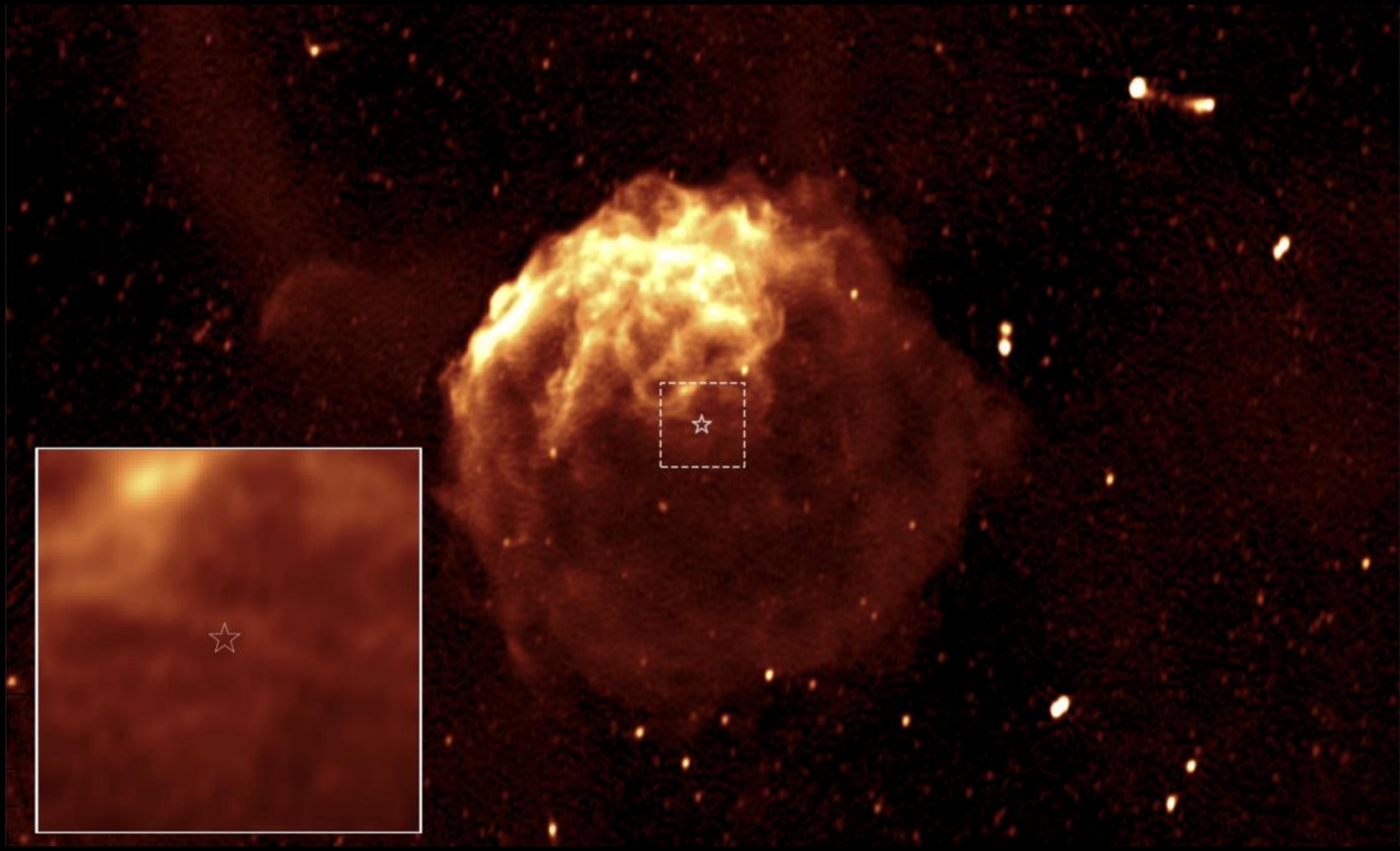
THE UNIVERSE RADIO TRANSIENTS



Rea, Hurley-Walker & Caleb 2026, review in press arXiv:2601.10393

THE FRB-MAGNETAR CONNECTION

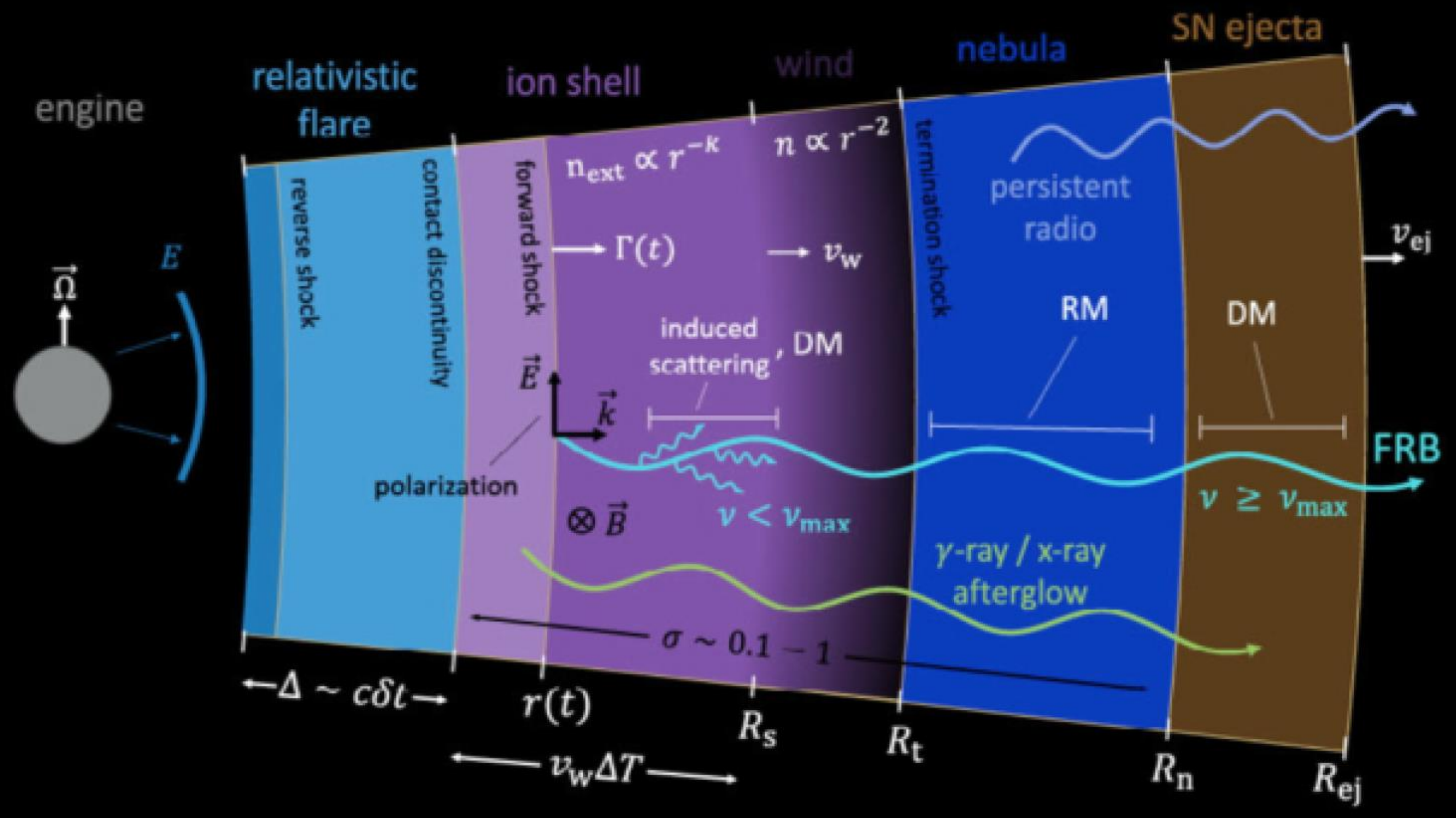




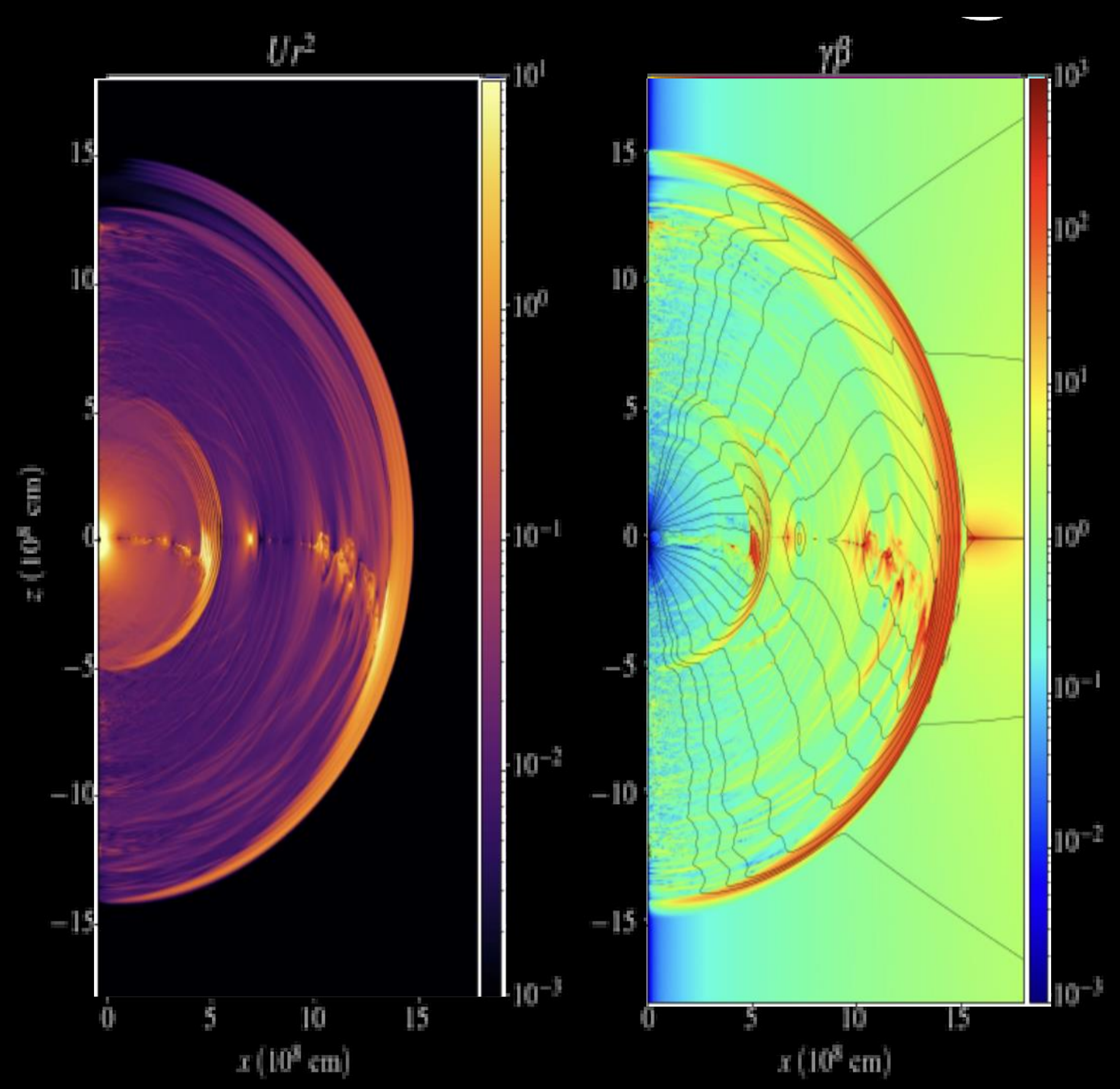
Bailes et al. 2021

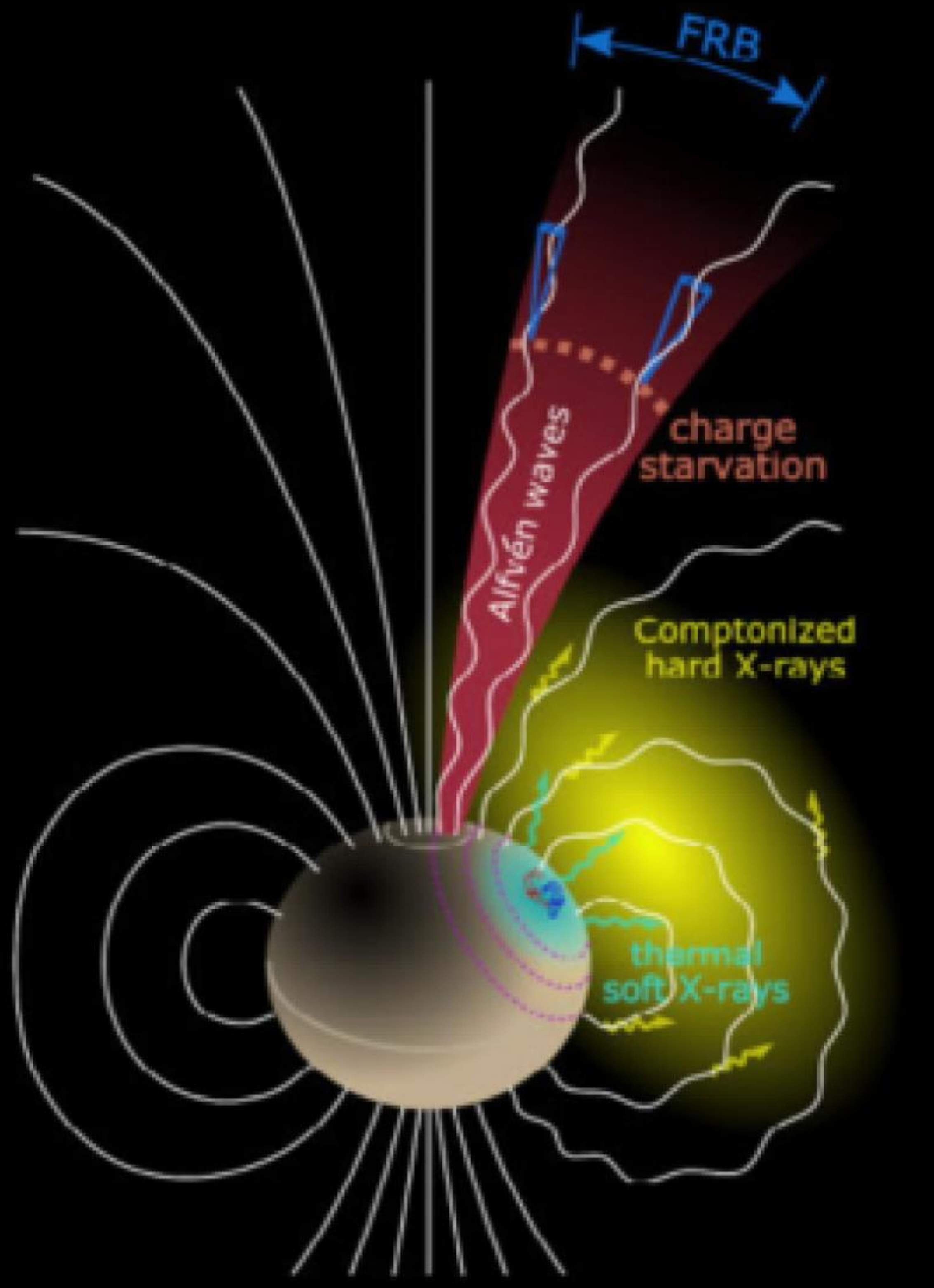
(CHIME Collaboration et al. 2020, Bochenek et al. 2020, Mereghetti et al. 2020, Ridaia et al. 2020, see also Petroff, Hessels & Lorimer 2022)

THE FRB-MAGNETAR CONNECTION



Metzger et al. 2019


Yuan et al. 2020

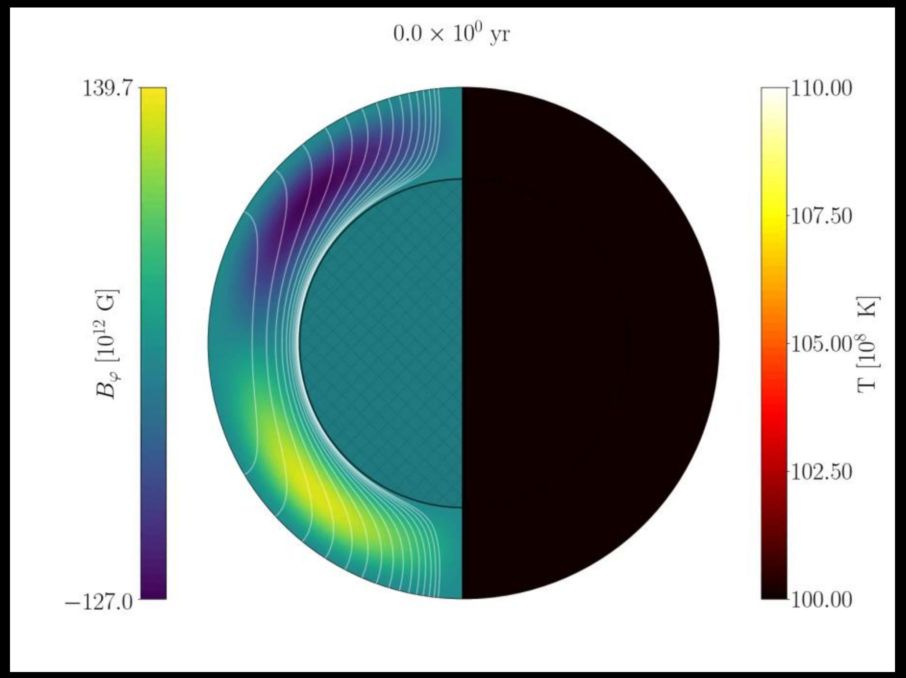


Lu et al. 2020

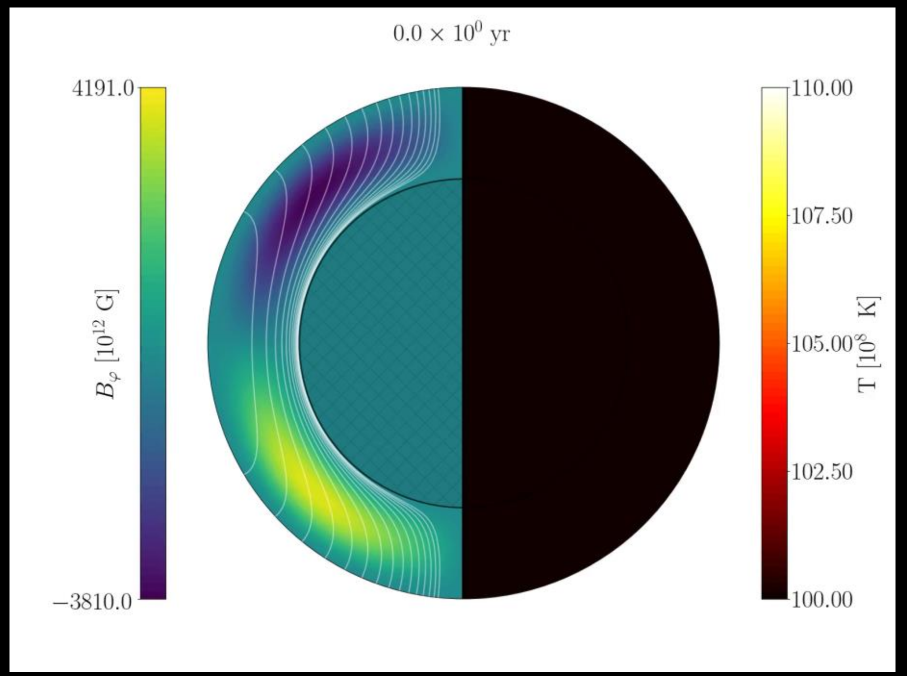
Shock models or magnetospheric models

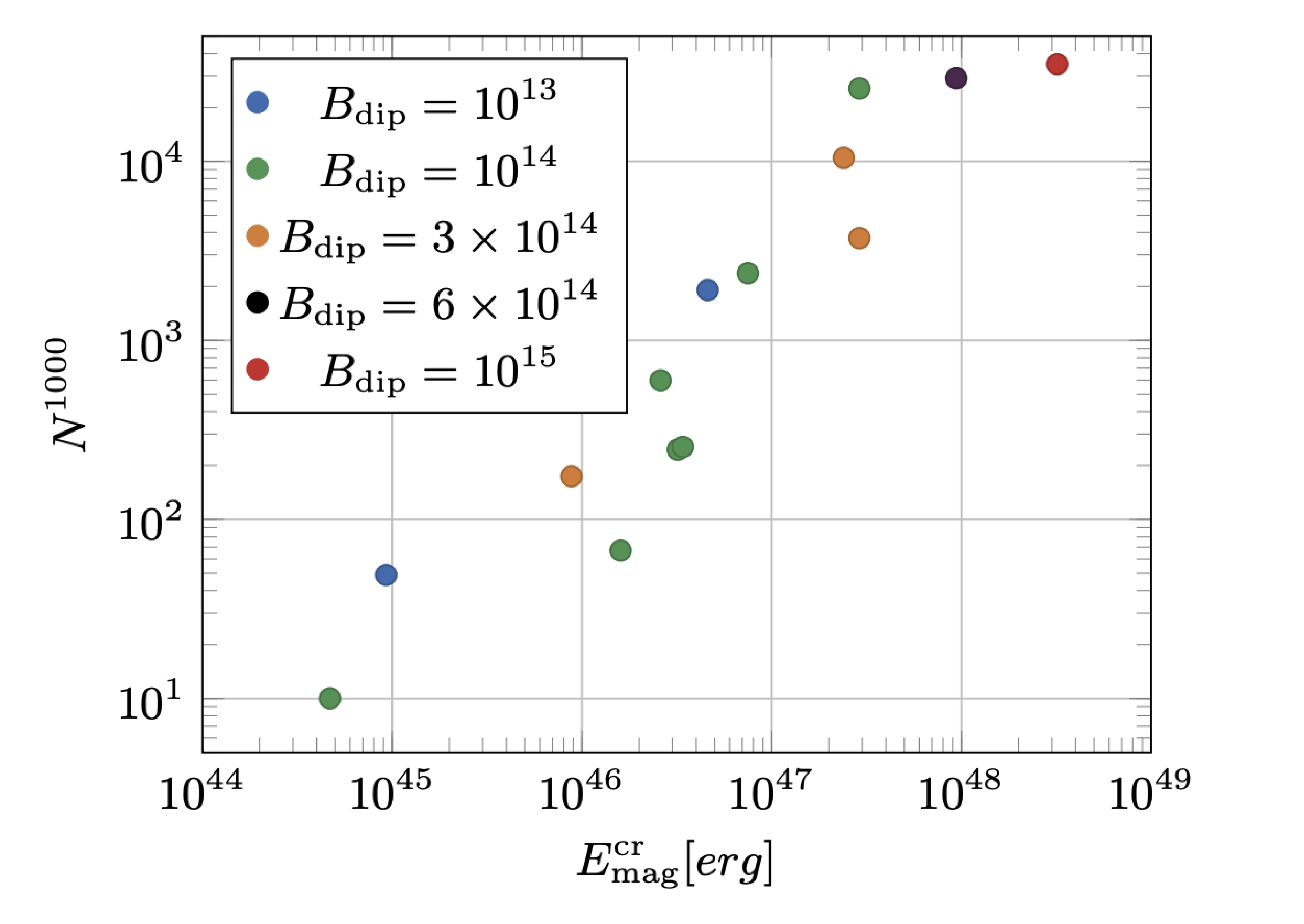
FAST RADIO BURSTS AND MAGNETARS

CrDipL
E_{dip} ~10^{13}G
$E_{cr,\,mag}$ ~10^{44}erg
No events in 1kyr

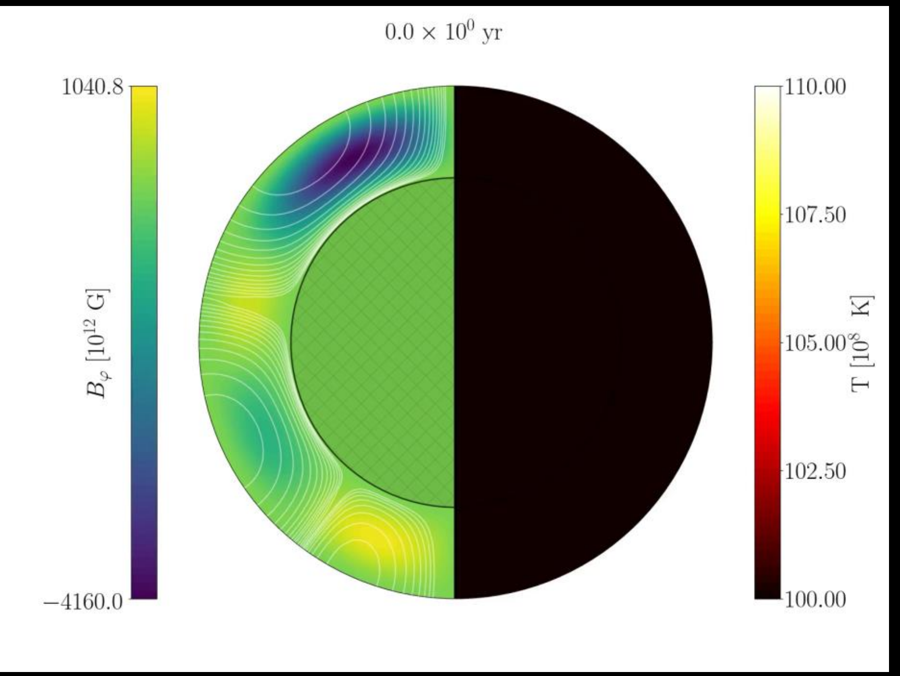


CrDipH
E_{dip} ~3x10^{14}G
$E_{cr,\,mag}$ ~3x10^{47}erg
First event in 0.4yr

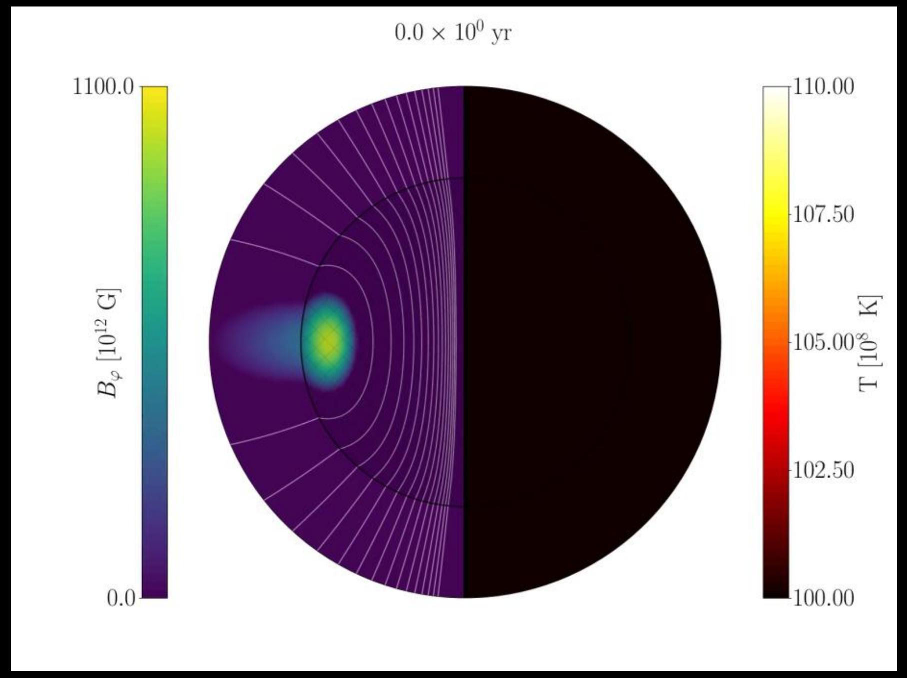




CrMultiT
E_{dip} ~10^{13}G
$E_{cr,\,mag}$ ~10^{46}erg
First event in 0.7yr



CoDipL
E_{dip} ~10^{14}G
$E_{cr,\,mag}$ ~5x10^{44}erg
First event in 13yr

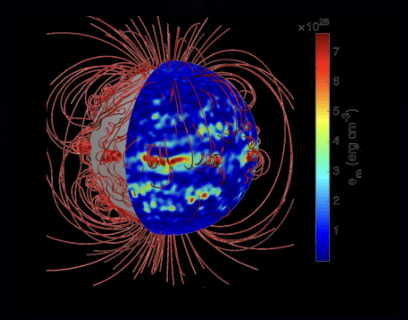


The crustal magnetic energy is the driving parameter to estimate the crustal failure rate.
B-configuration mainly affects the waiting time.

(Dehman et al. 2020)

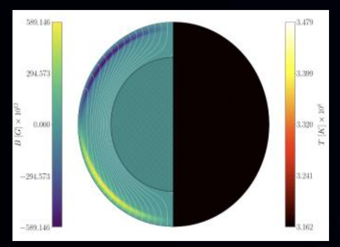
CONCLUSIONS

1. WHY AREN'T ALL PULSARS BEHAVING SIMILARLY? HOW COMMON ARE STRONG MAGNETIC FIELDS?



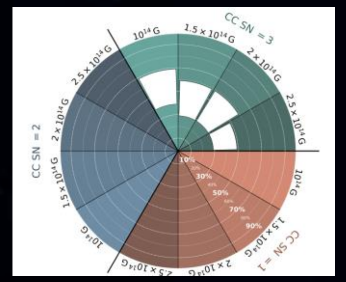
Strong and tangled fields are ubiquitous in the pulsar population!

2. DO WE HAVE ENOUGH SNe FOR SO MANY NS CLASSES?



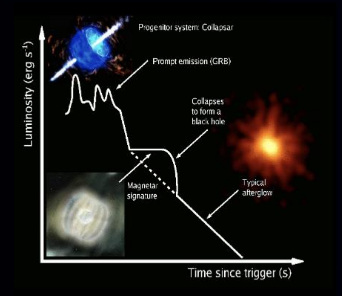
No, we have not enough SNe to explain all classes independently, they are evolutionary related and we can predict how with magneto-thermal simulations how.

3. WHAT DID WE LEARN FROM THE OBSERVED NSs ABOUT THEIR BIRTH AND SN RATES?



We learned that CC SNe in our Galaxy should be >2 per century (possibly around 3). Magnetar fraction should be around ~50% depending on the initial field distribution and SN-CC rates.

4. HOW CAN WE USE THEM TO CONSTRAIN GRBs and FRBs?



Yes! We can constrain population rates and energetics (not single events).


THANKS