

MAGNETARS AND THE X-RAY SKY



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Agència
de Gestió
d'Ajuts
Universitaris
i de Recerca

Nanda Rea



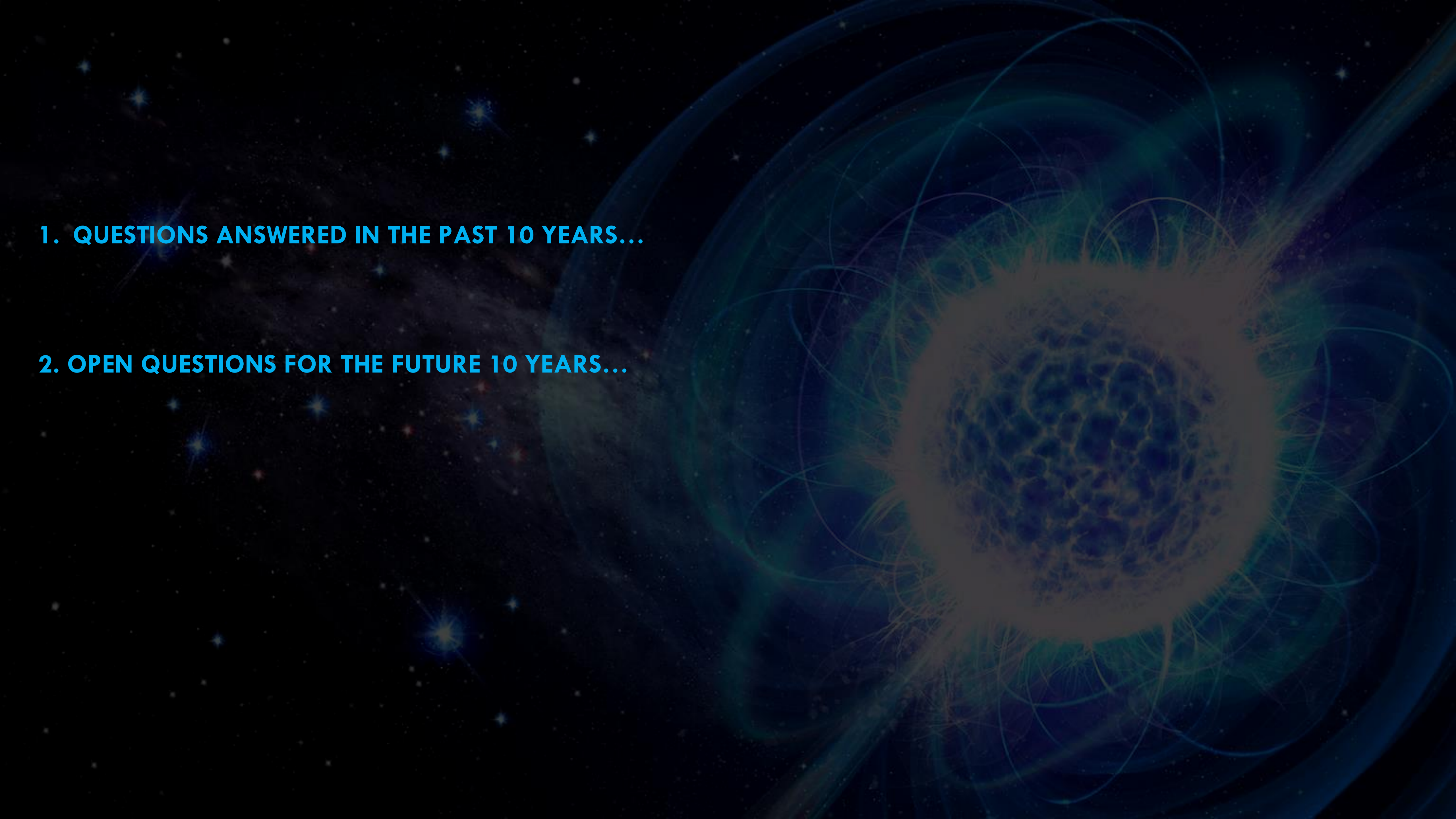
Institute of
Space Sciences



CSIC

IEEC



The background of the slide is a deep space image featuring a complex network of glowing, interconnected lines in shades of blue, green, and yellow, resembling a cosmic web or a neural network. A bright, dense cluster of these lines is visible on the right side, with a glowing orange and yellow core. The left side of the image is darker, showing a field of distant stars and galaxies.

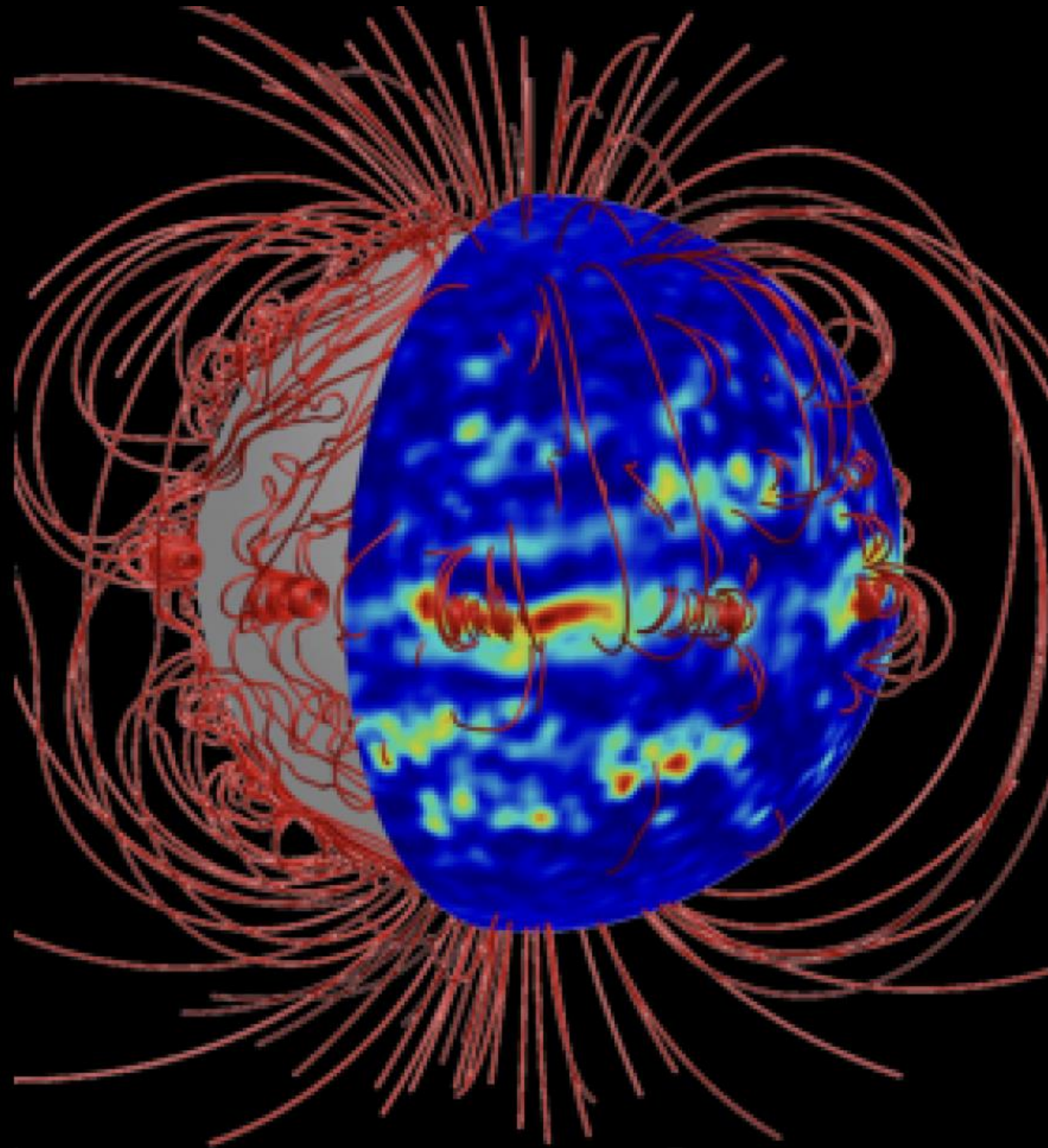
1. QUESTIONS ANSWERED IN THE PAST 10 YEARS...

2. OPEN QUESTIONS FOR THE FUTURE 10 YEARS...

1. QUESTIONS ANSWERED IN THE PAST 10 YEARS...

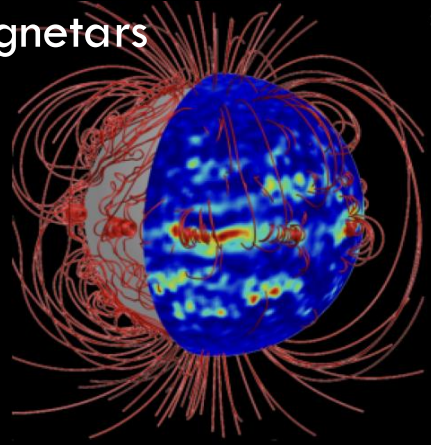
- **WHY AREN'T ALL PULSARS BEHAVING SIMILARLY?**
- **HOW COMMON ARE STRONG MAGNETIC FIELDS?**

WHAT IS A MAGNETAR?



THE ISOLATED PULSAR POPULATION

Magnetars



MAGNETARS

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

Thermal XDINSs



THERMAL NSs (XDINS)

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

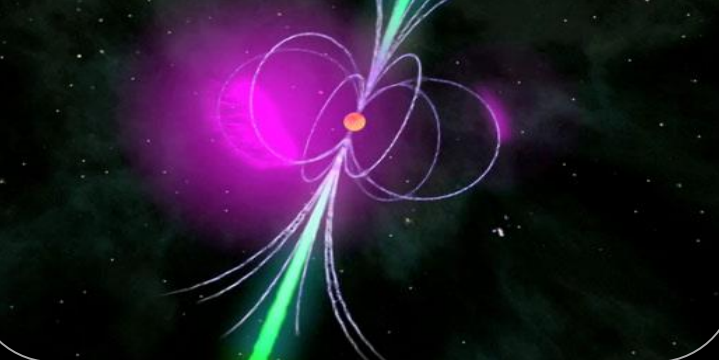
Central Compact Objects



CENTRAL COMPACT OBJECTS

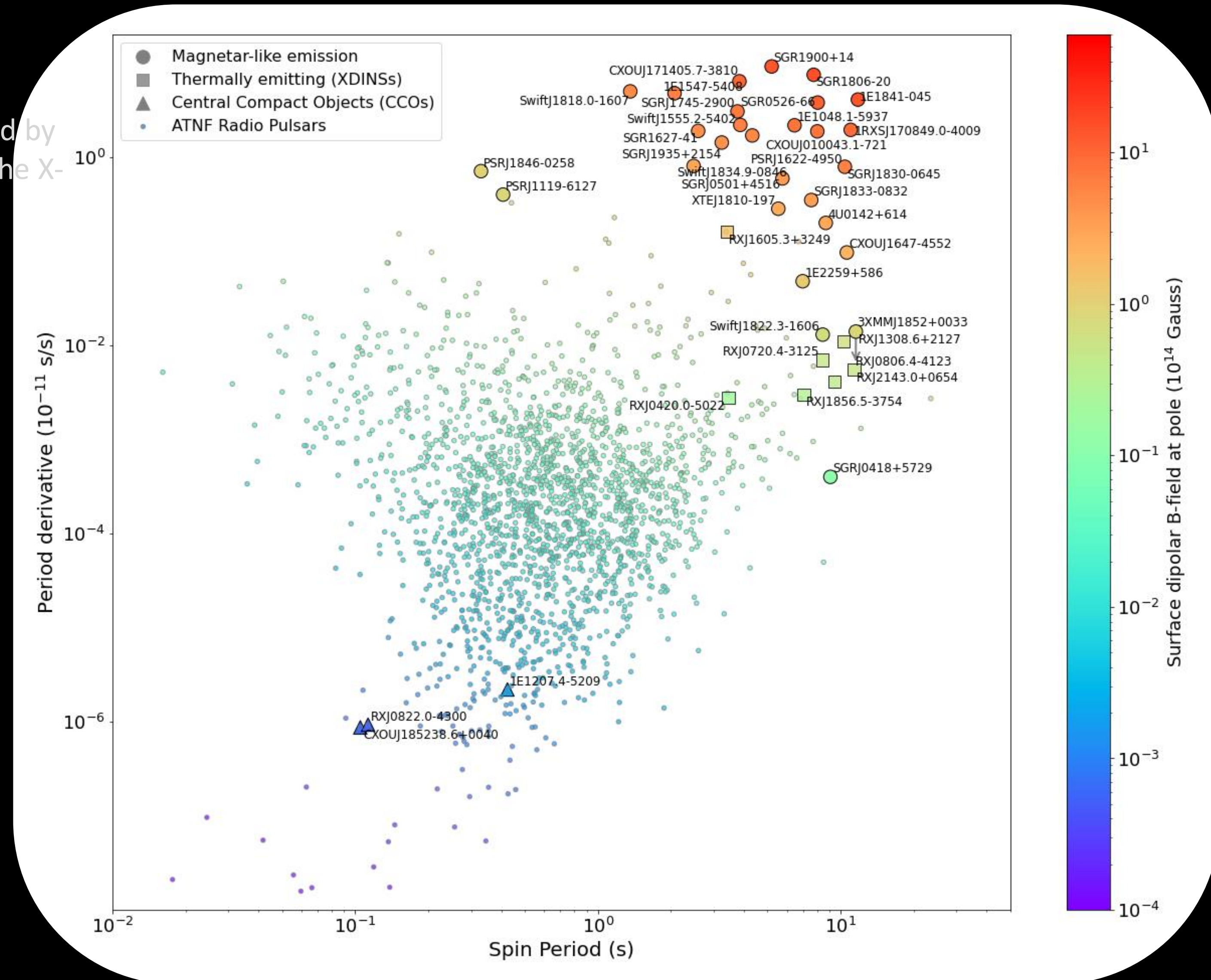
Powered by magnetic energy. Young, with bright SNRs. Typically emitting in the X-rays.

Rotational Powered Pulsars



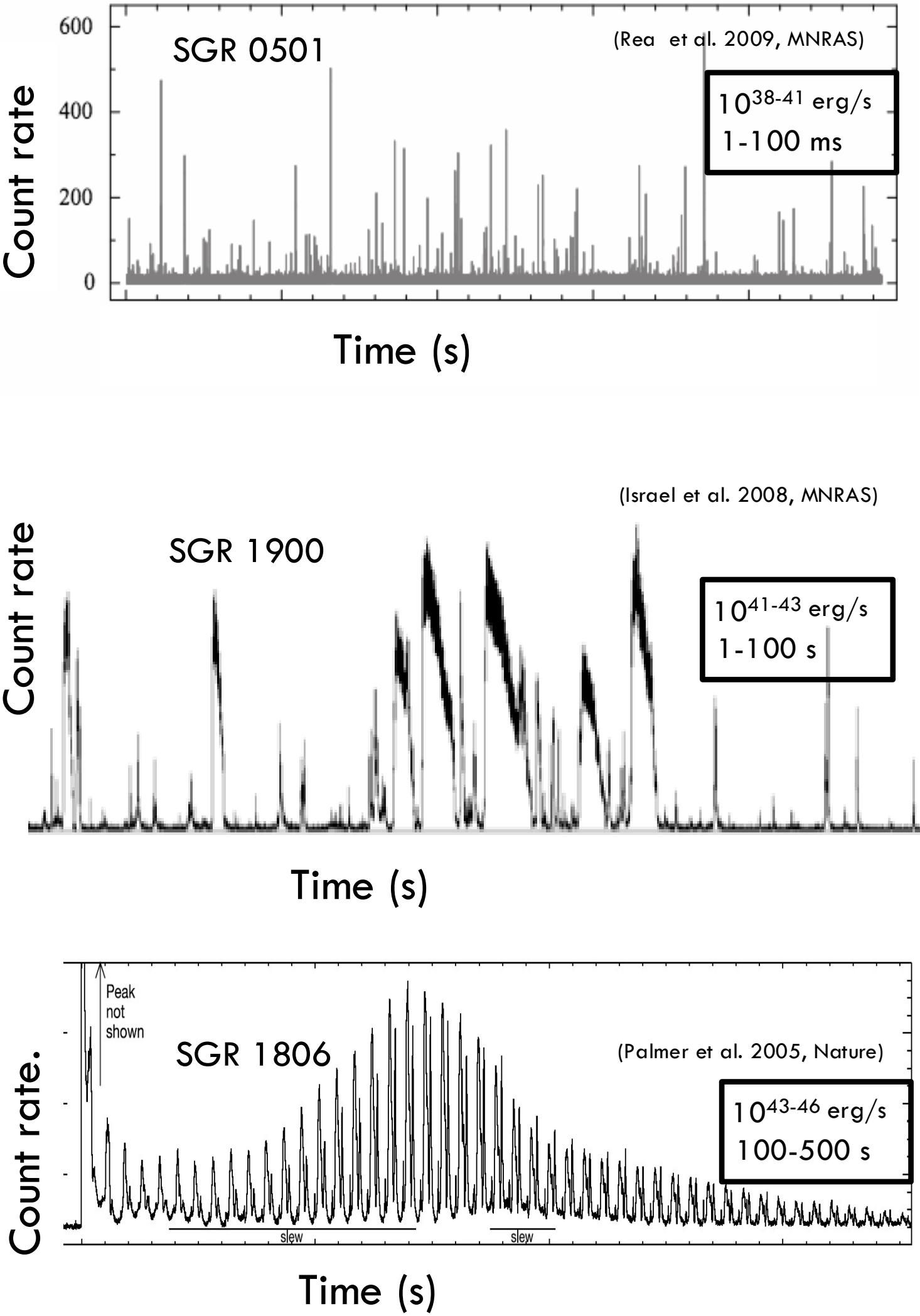
ROTATIONAL POWERED PULSARS

Powered by rotational energy. Typically emitting in radio.

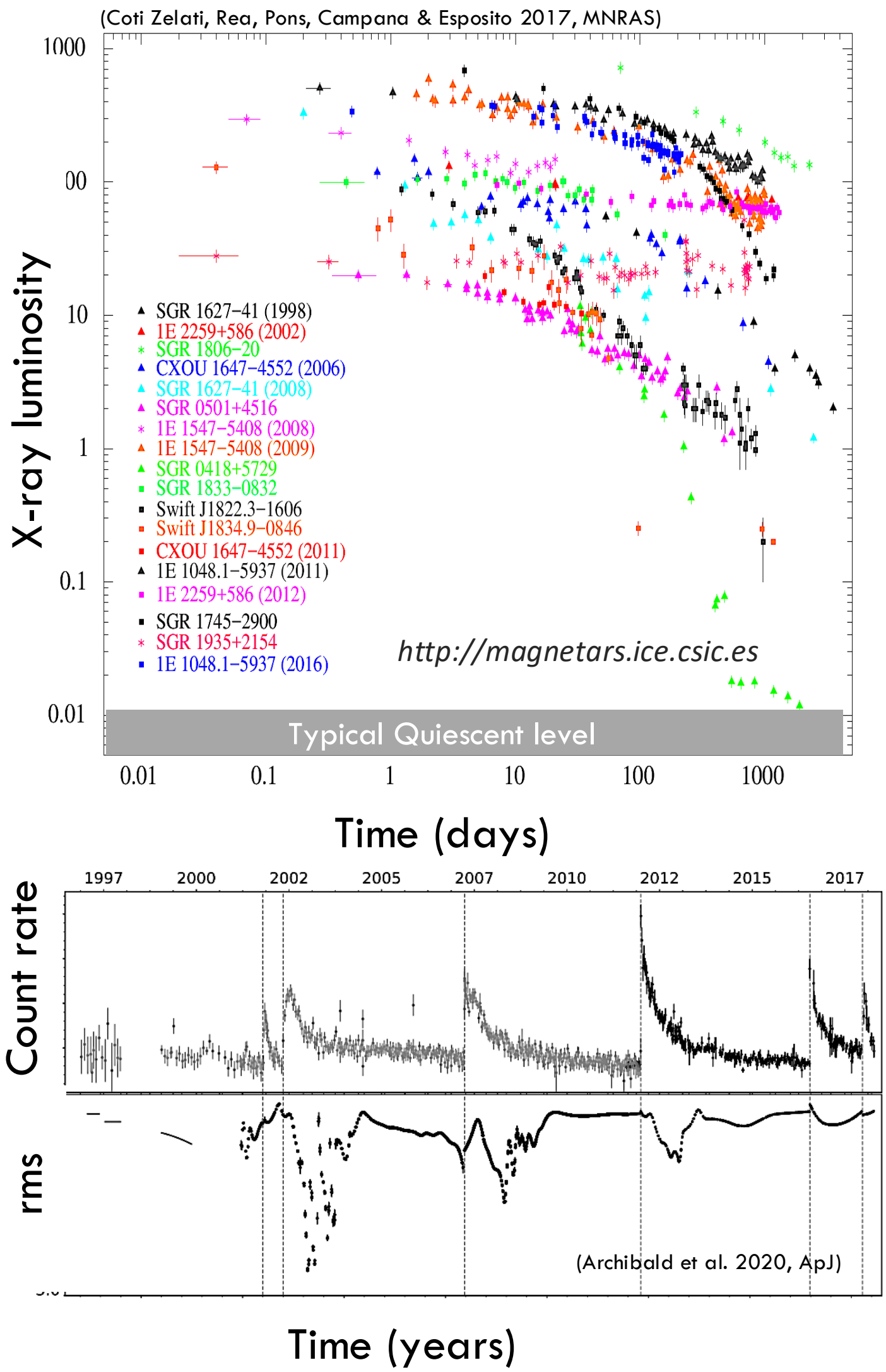


MAGNETAR OUTBURSTS AND FLARES

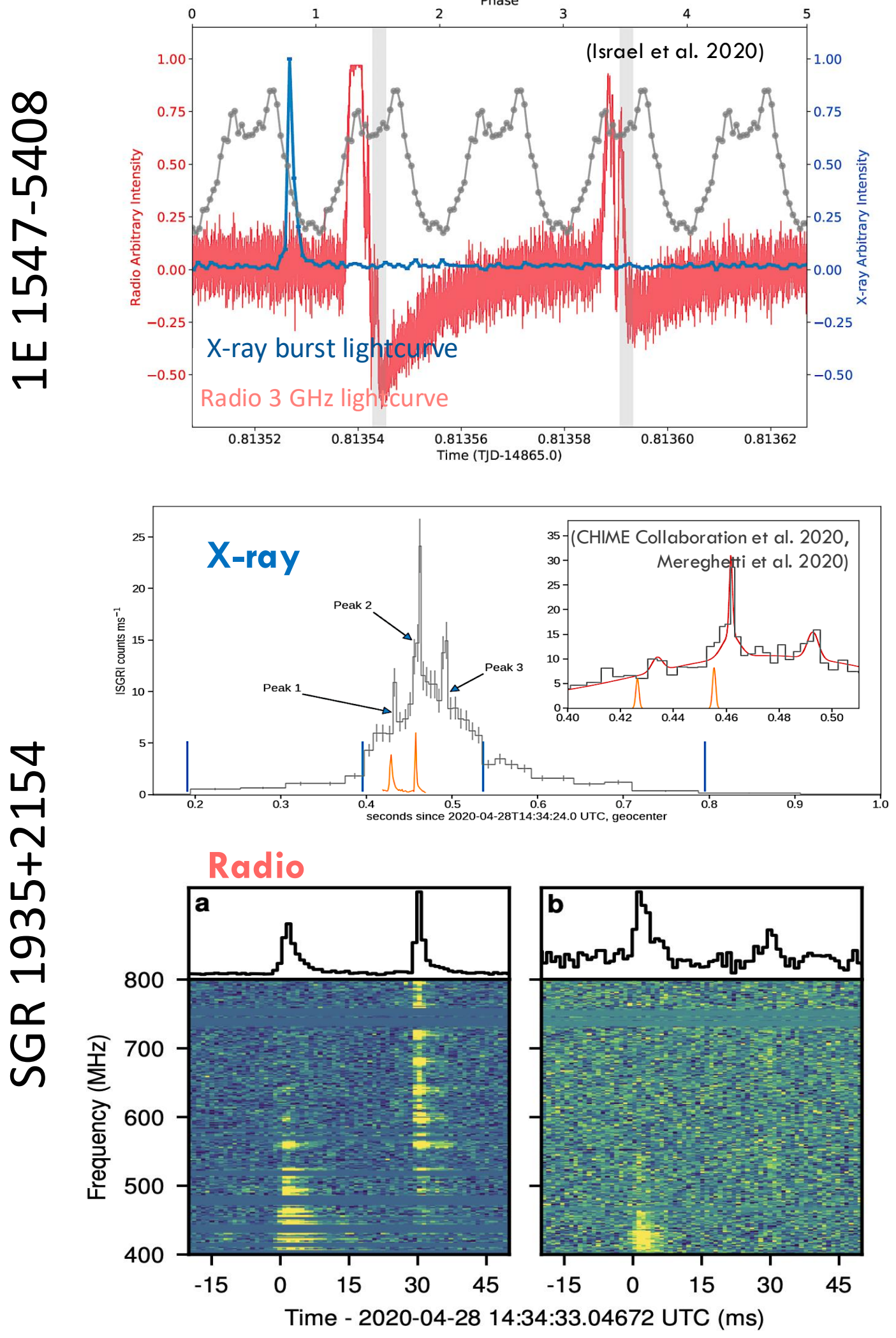
FLARING ACTIVITY



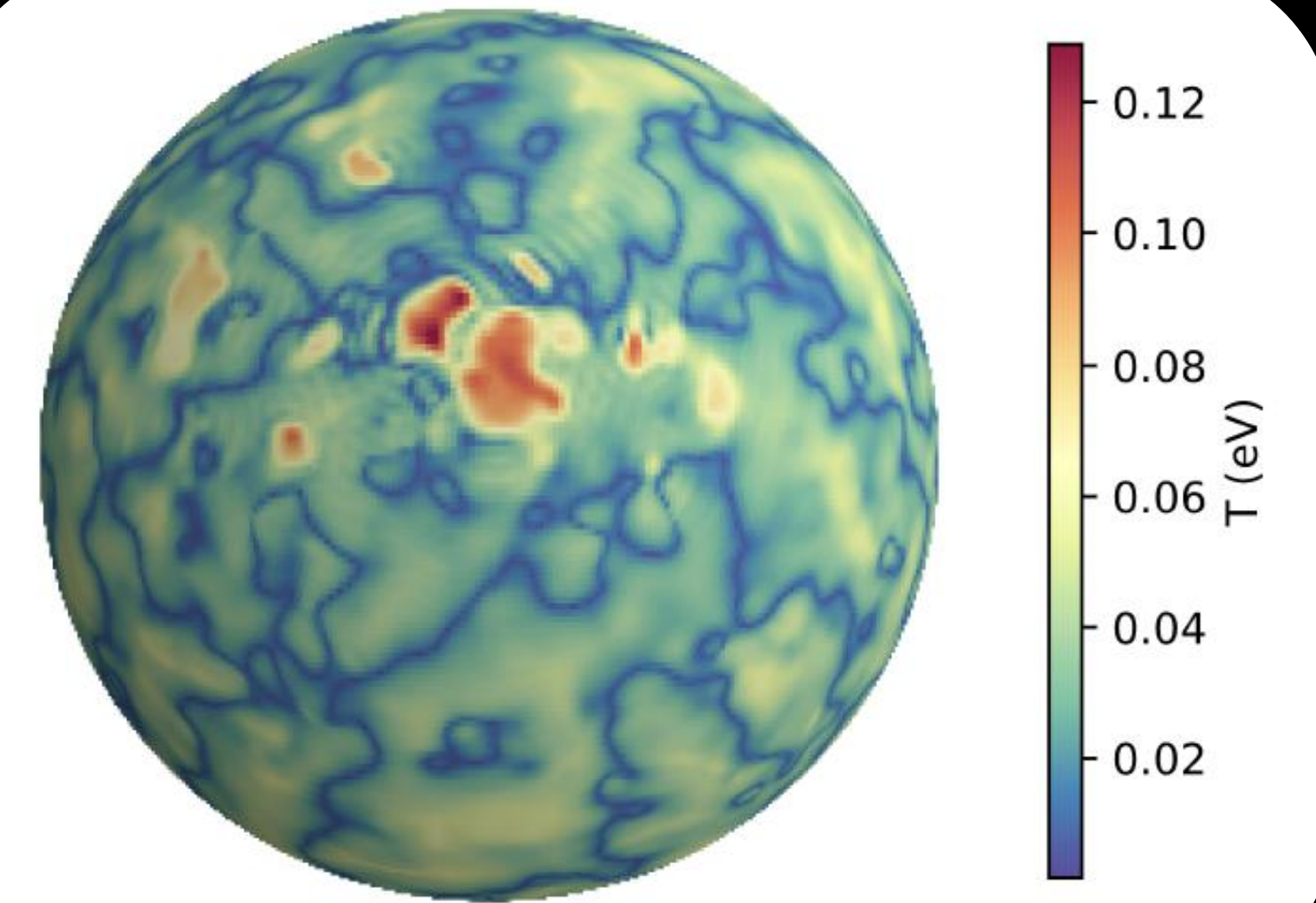
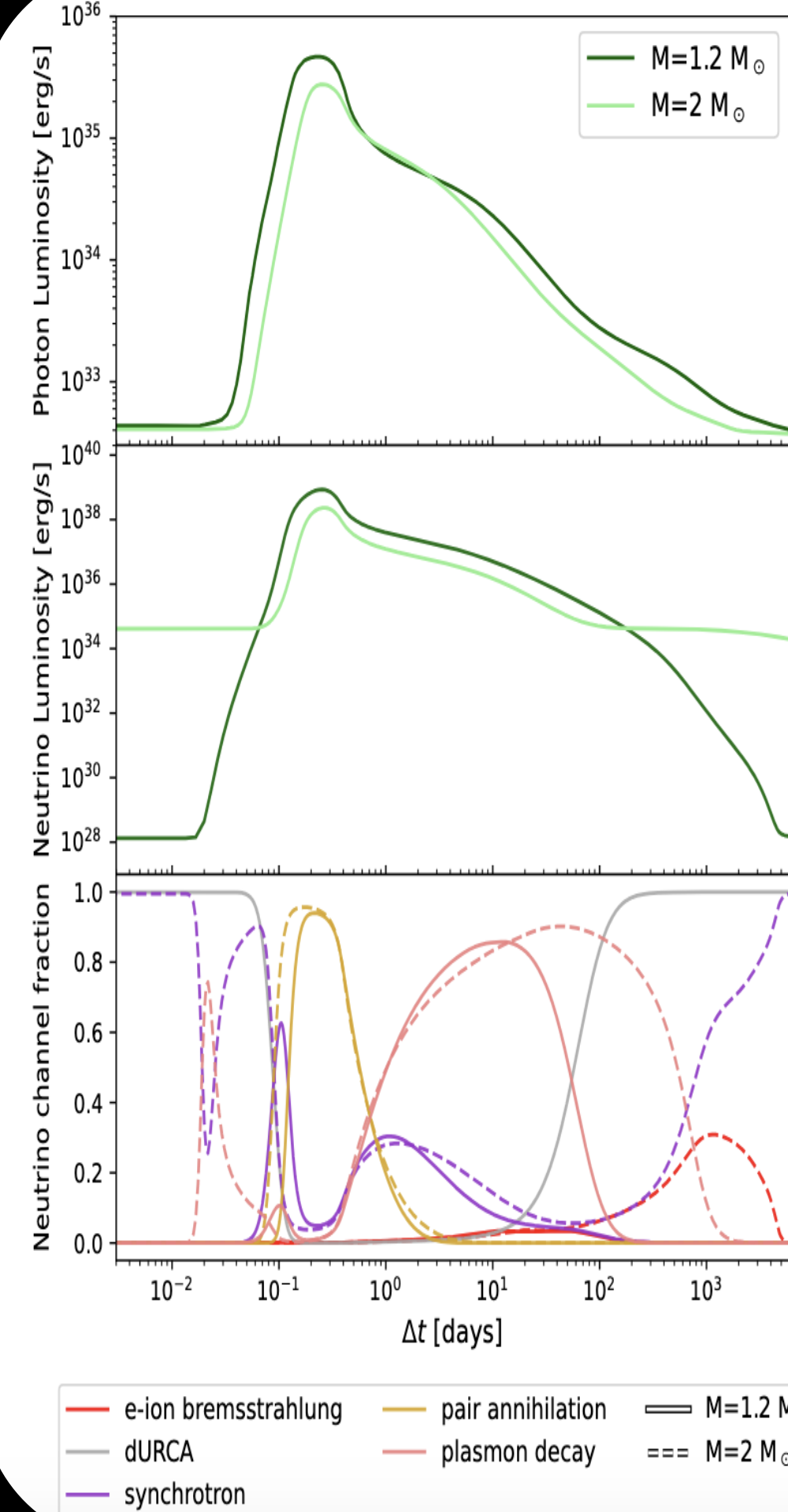
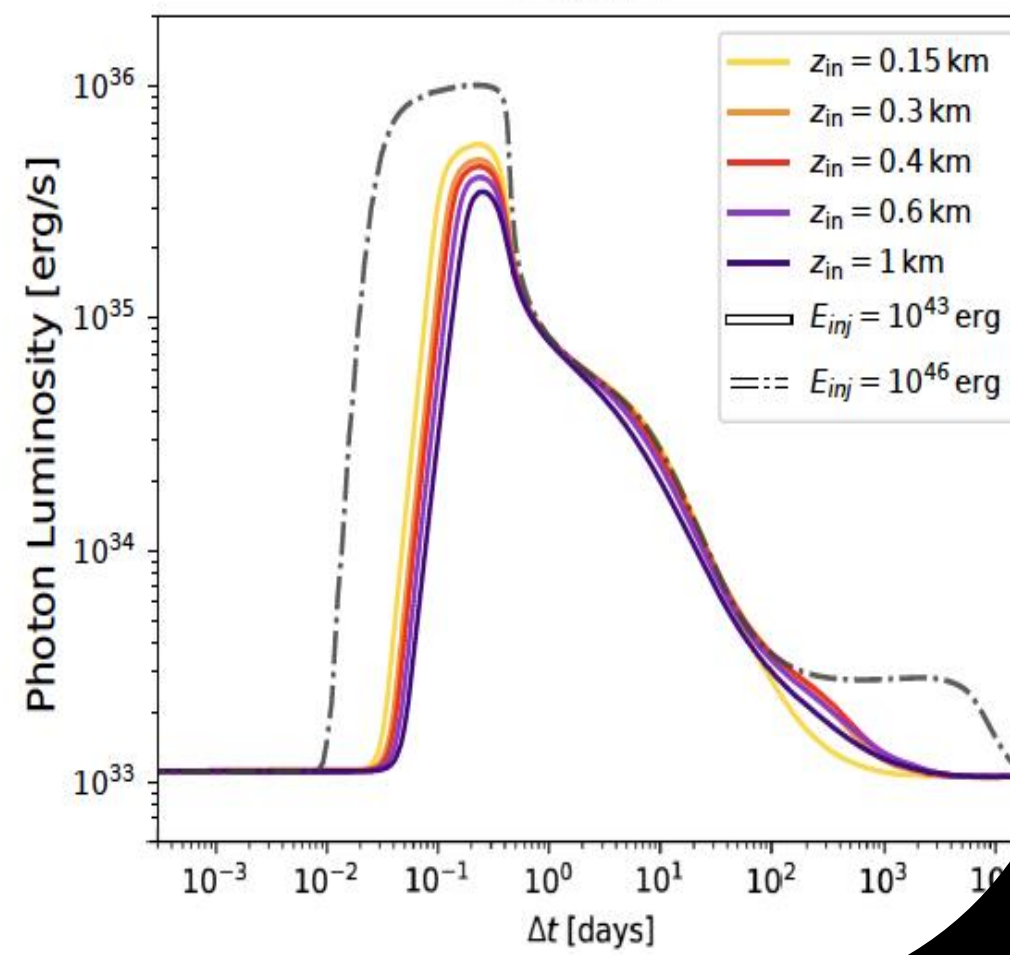
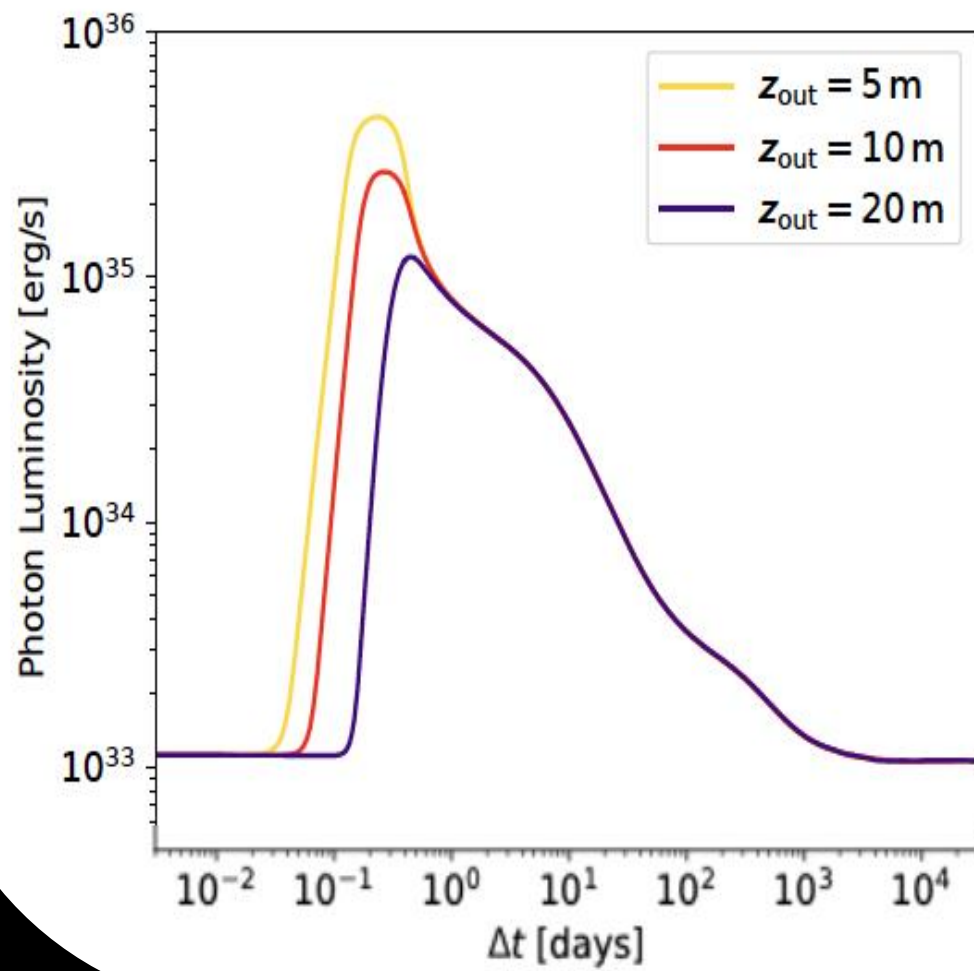
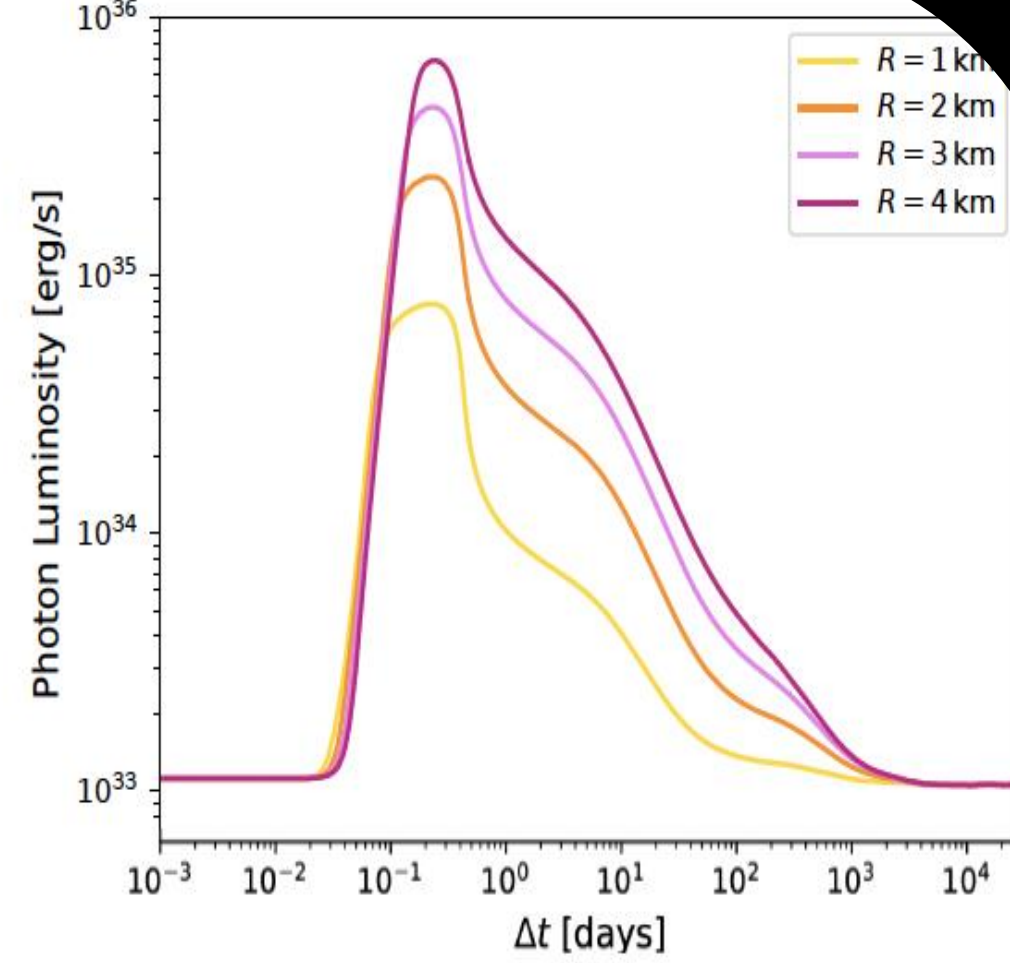
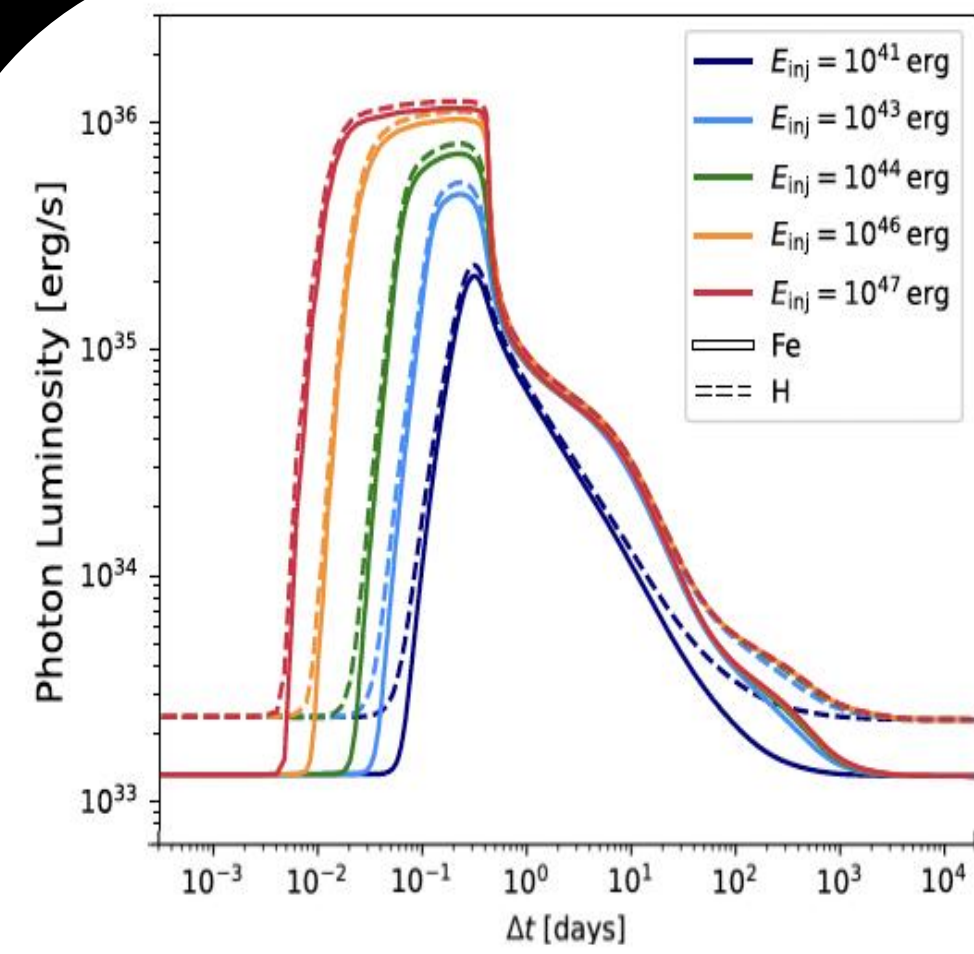
OUTBURST ACTIVITY



RADIO ACTIVITY

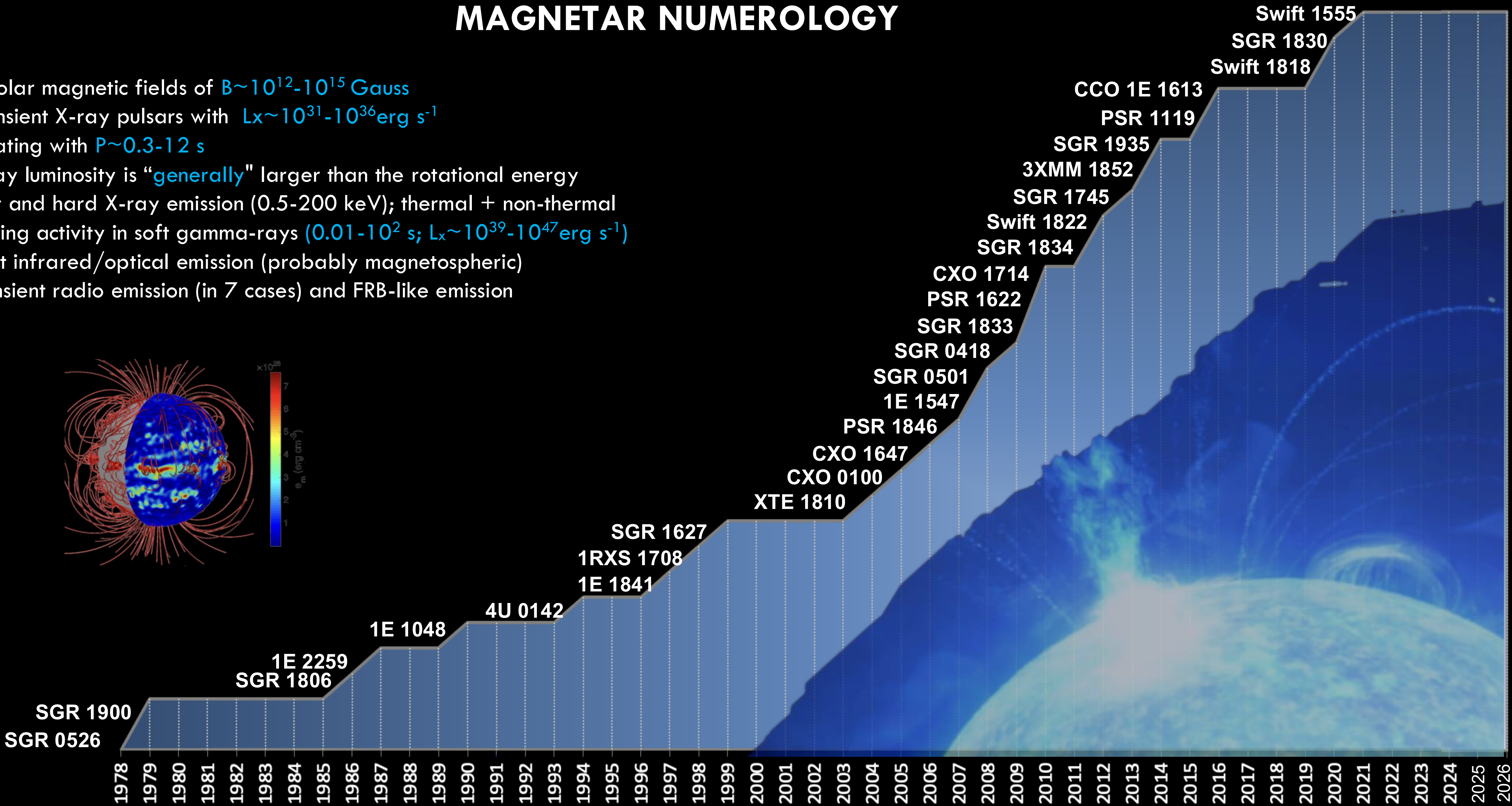


MAGNETAR OUTBURSTS: MODELLING



MAGNETAR NUMEROLOGY

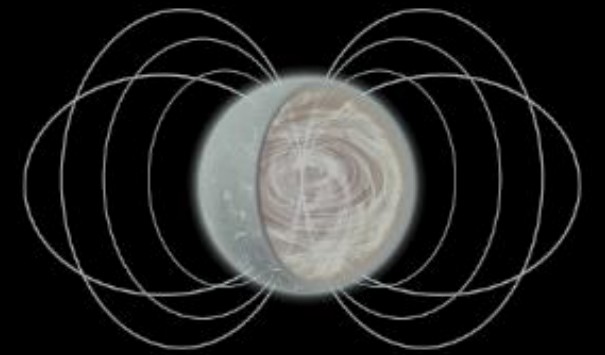
- Dipolar magnetic fields of $B \sim 10^{12} - 10^{15}$ Gauss
- Transient X-ray pulsars with $L_x \sim 10^{31} - 10^{36} \text{ erg s}^{-1}$
- Rotating with $P \sim 0.3 - 12 \text{ s}$
- X-ray luminosity is “generally” larger than the rotational energy
- Soft and hard X-ray emission (0.5-200 keV); thermal + non-thermal
- Flaring activity in soft gamma-rays ($0.01 - 10^2 \text{ s}$; $L_x \sim 10^{39} - 10^{47} \text{ erg s}^{-1}$)
- Faint infrared/optical emission (probably magnetospheric)
- Transient radio emission (in 7 cases) and FRB-like emission



CONCLUSIVE UNIFICATION THE PULSAR POPULATION

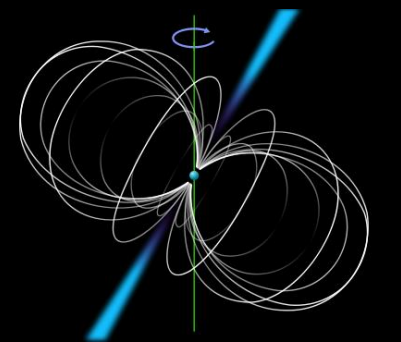
1. Magnetars were discovered having low dipolar B-fields and strong magnetic structures.

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



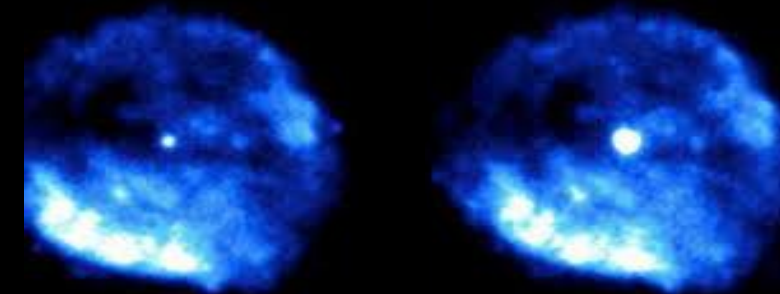
2. Two young rotational powered pulsars (PSR1846 and PSR1119) showed magnetar activity.

(Gavril et al. 2008, Nature; Kumar & Safi-Harb, 2008, ApJ; Archibald et al. 2016, ApJ; Sathyaprakash et al. 2023, ApJ)



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

(Rea et al. 2016, ApJ Letters; D'Ai et al. 2016, MNRAS; Borghese et al. 2018, ApJ)

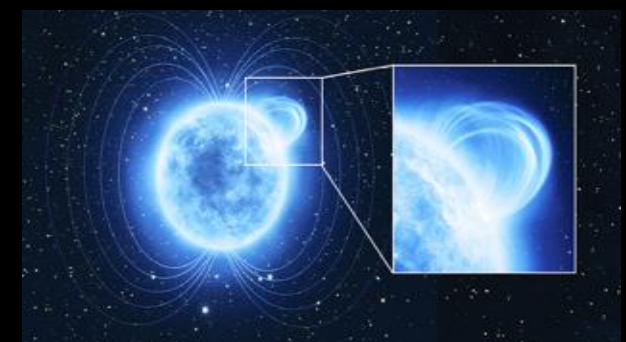


quiescence

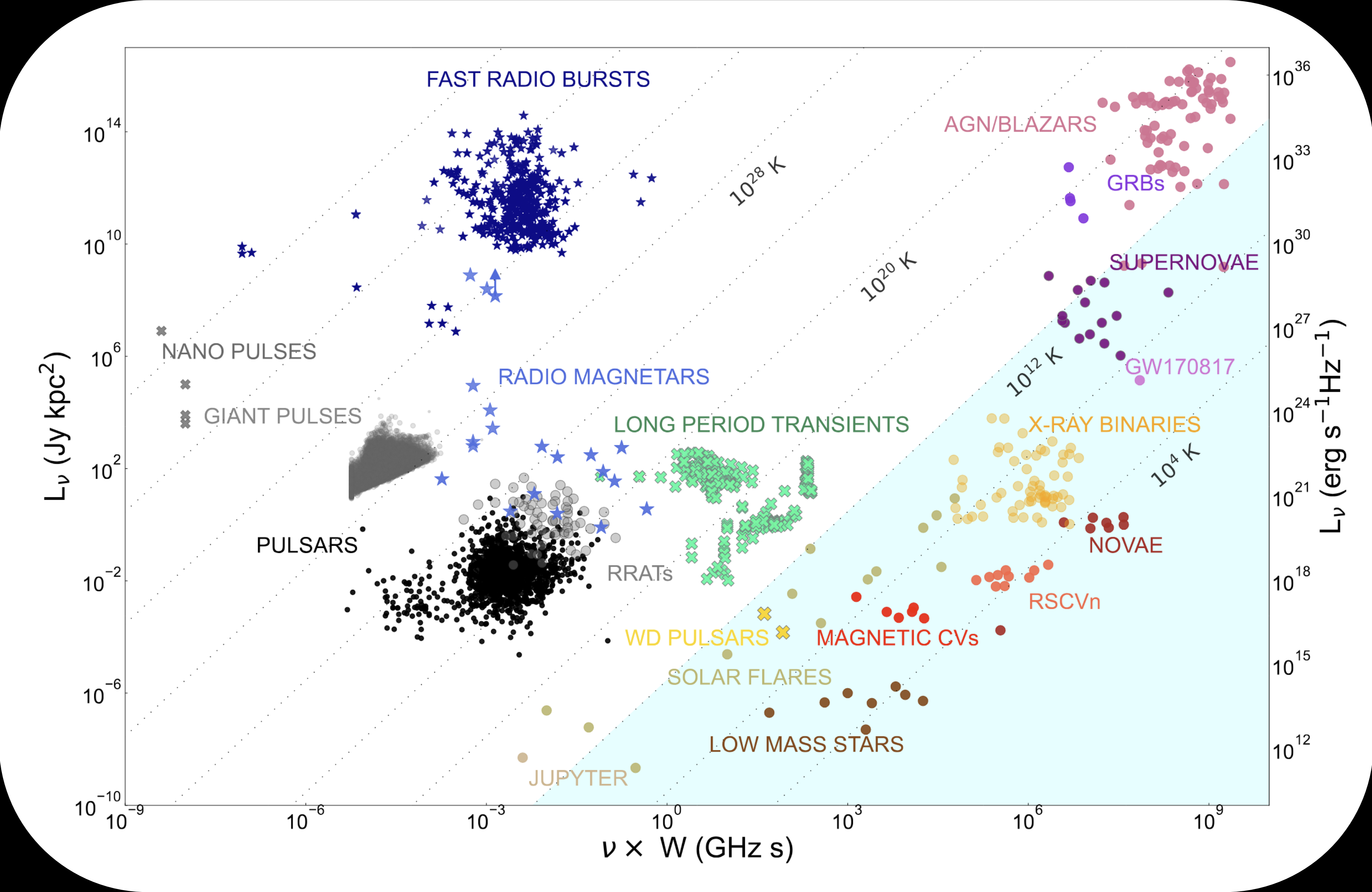
outburst

4. Two X-ray Dim Isolated Neutron Stars show evidence of strong magnetic structures.

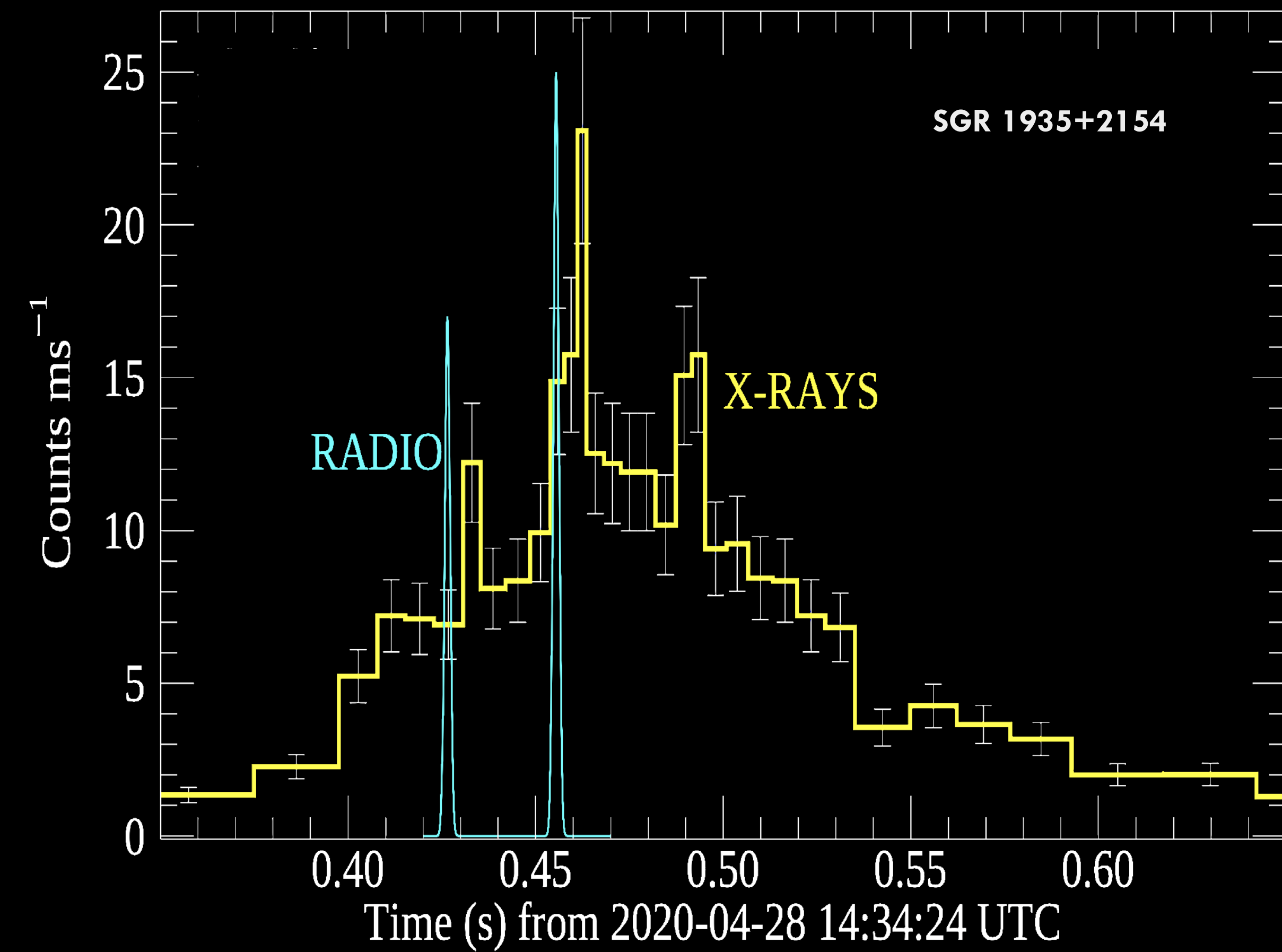
(Borghese et al. 2015, 2017, ApJ)



THE RADIO TRANSIENT SKY



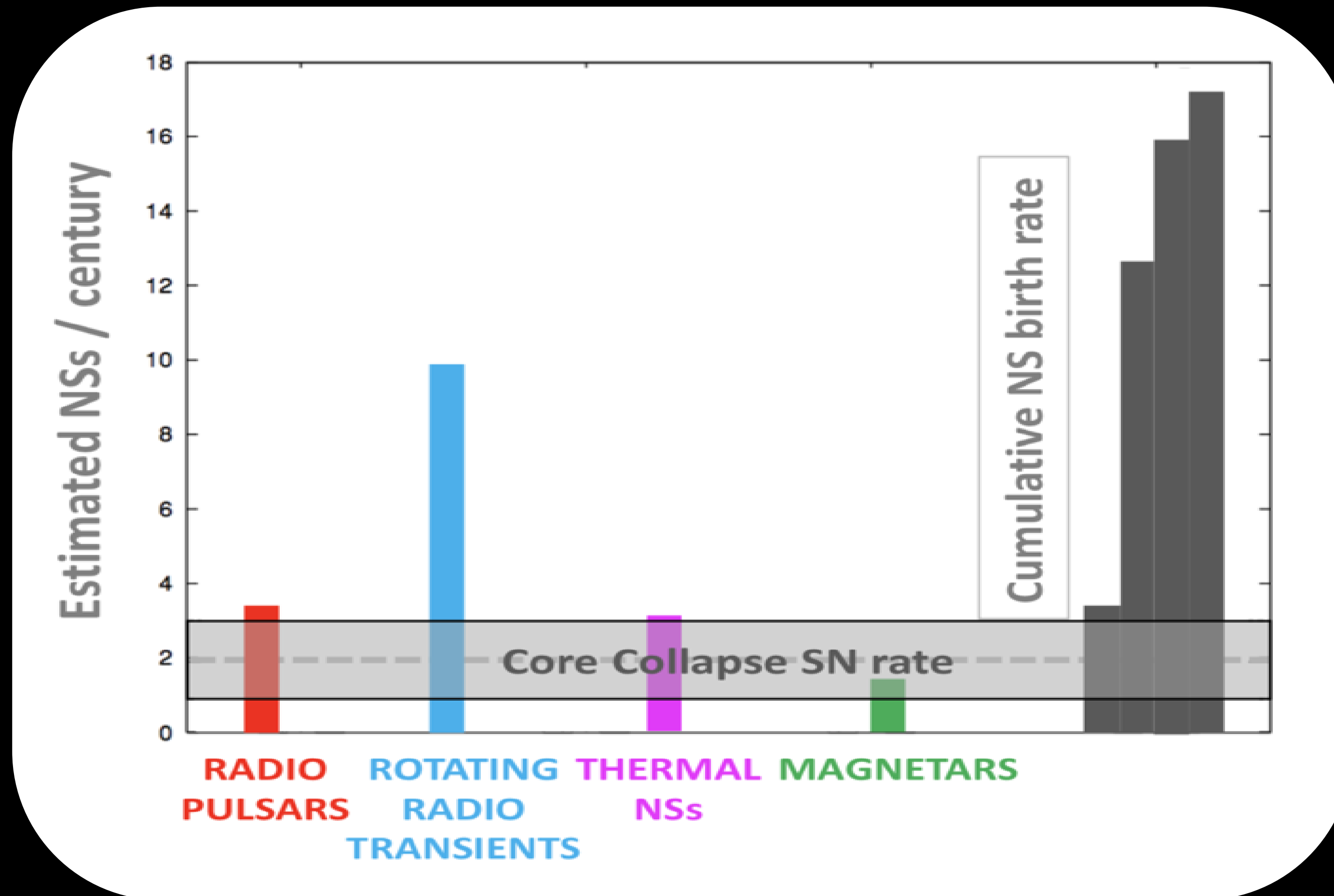
THE FRB-MAGNETAR CONNECTION



1. QUESTIONS ANSWERED IN THE PAST 10 YEARS...

- WHY AREN'T ALL PULSARS BEHAVING SIMILARLY?
 - HOW COMMON ARE STRONG MAGNETIC FIELDS?
-
- DO WE HAVE ENOUGH SNe FOR SO MANY DIFFERENT NS CLASSES?
 - WHAT DID WE LEARN ABOUT MAGNETARS' FORMATION RATE?

NS CLASSES AND CC SN RATES



Adapted from Keane & Kramer 2008, MNRAS

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

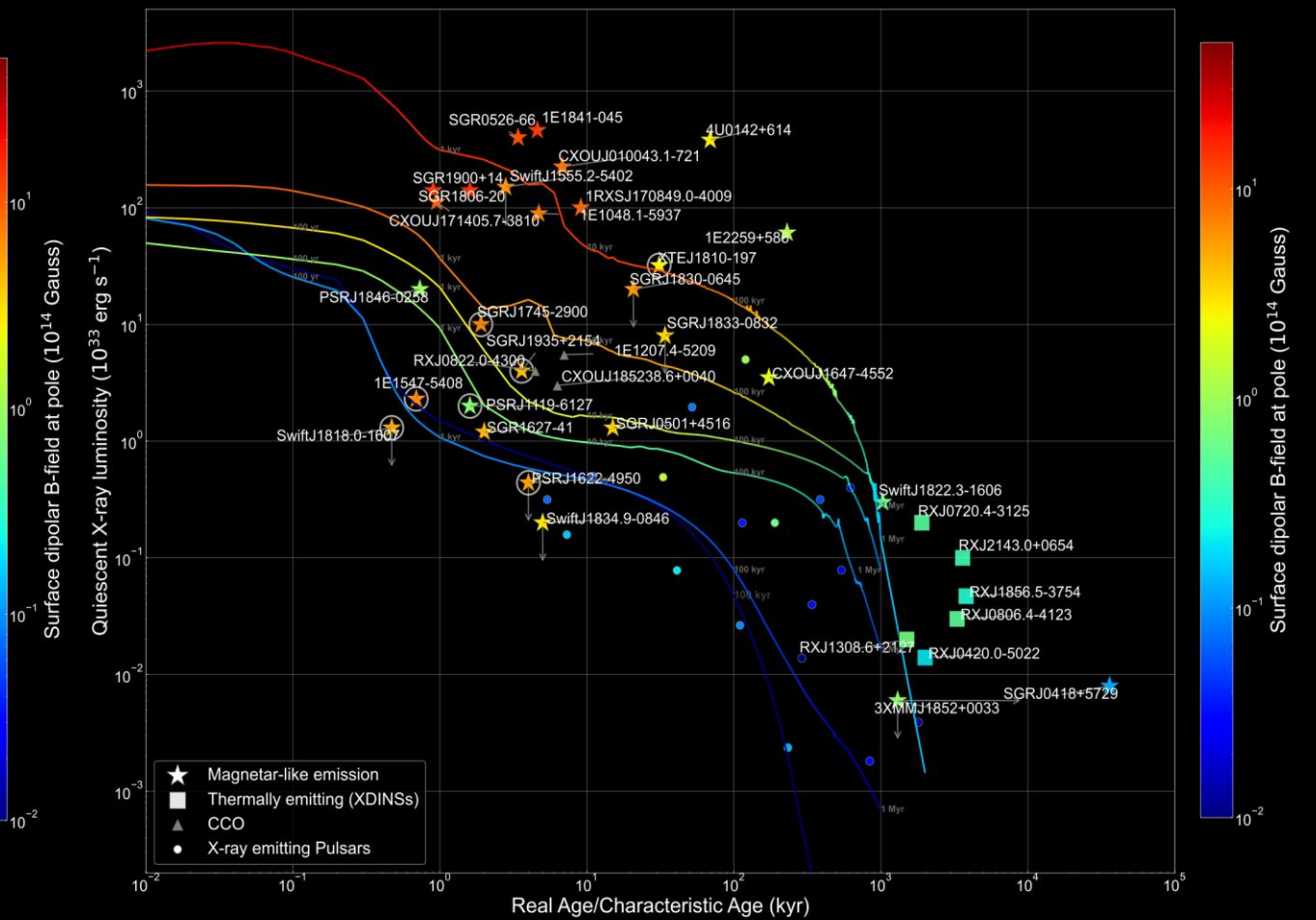
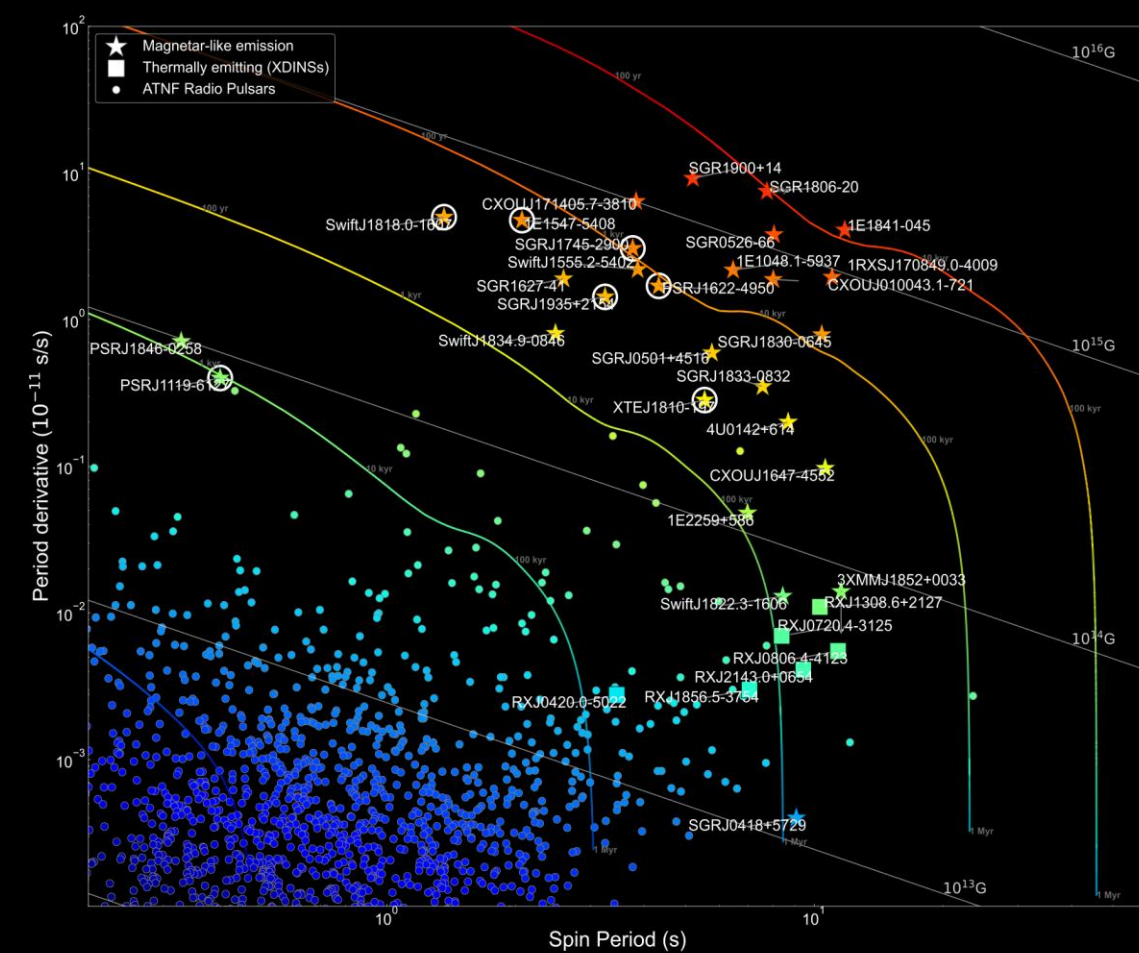
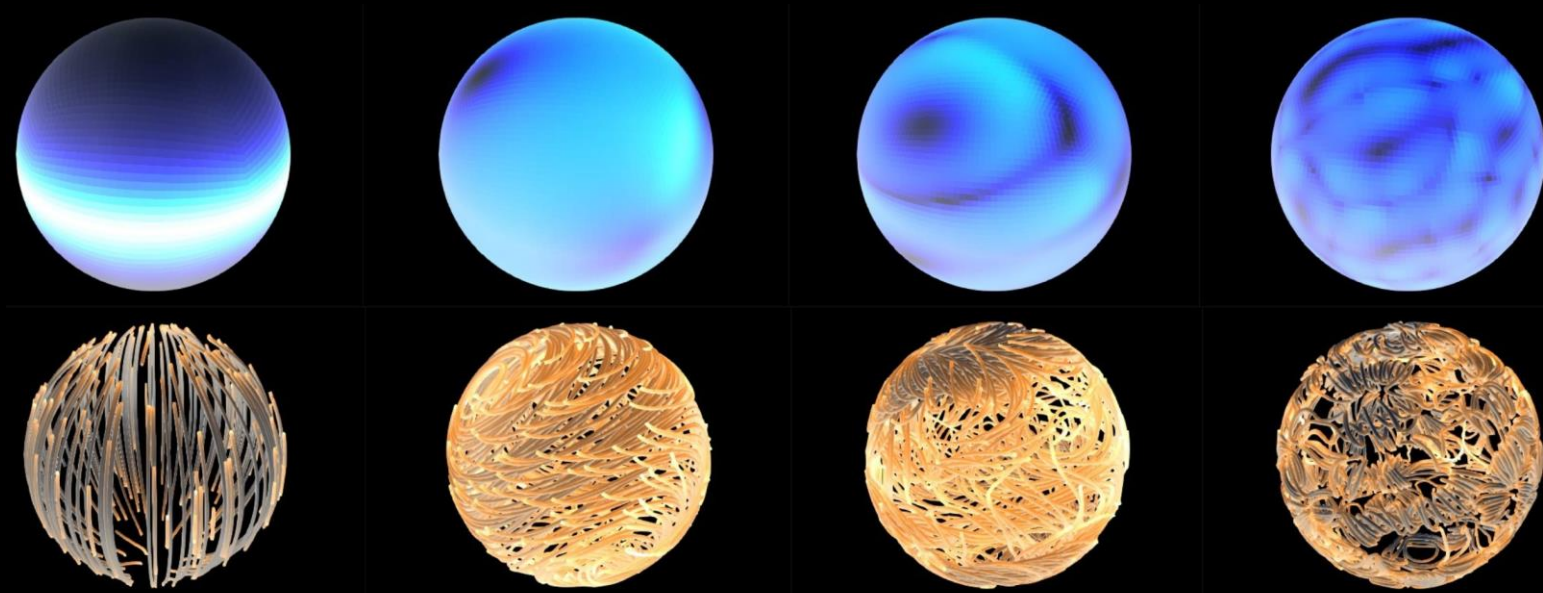
$$C_v e^\nu \frac{\partial \mathbf{T}}{\partial t} + \nabla \times [-k \times \nabla (e^\nu \mathbf{T})] = e^{2\nu} [H - Q]$$

ENERGY BALANCE EQUATION

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

HALL INDUCTION EQUATION

Electrical Resistivity

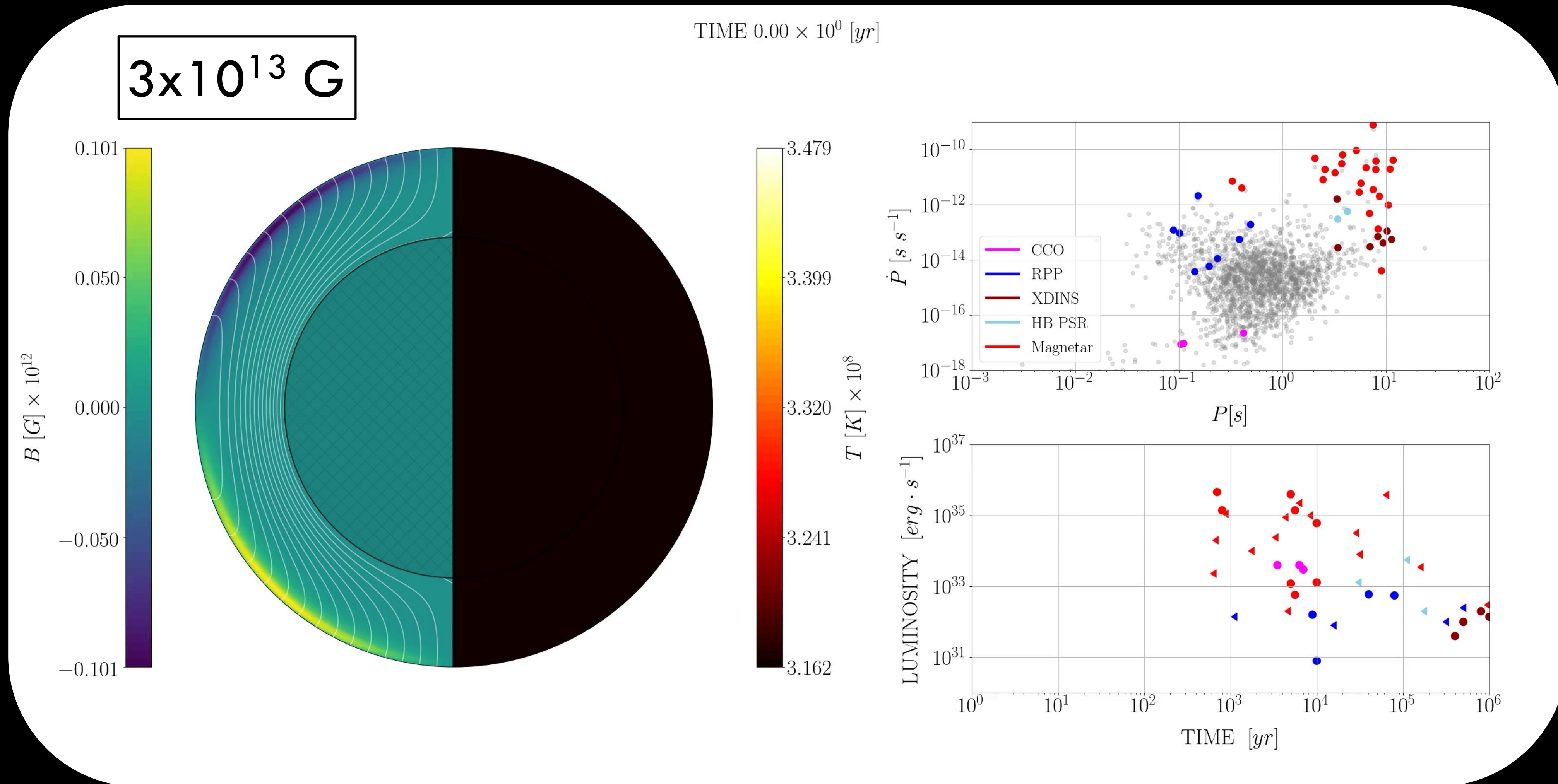


MATINS: Dehman et al. 2023, Ascenzi et al. 2024

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

Rea & De Grandis 2025, Elsevier, Astrophysics encyclopedia

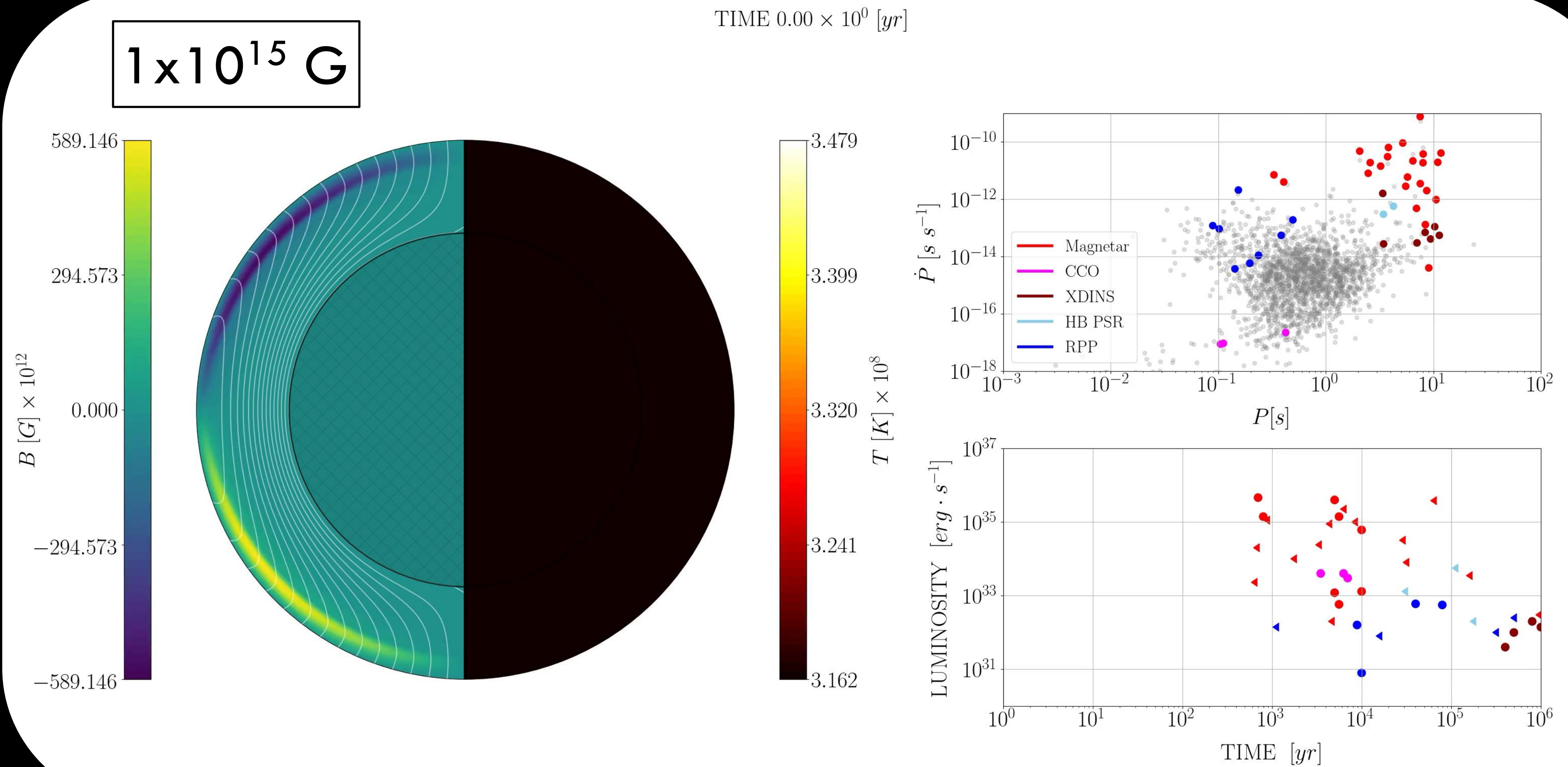
NEUTRON STAR EVOLUTION: 3D eMHD SIMULATIONS



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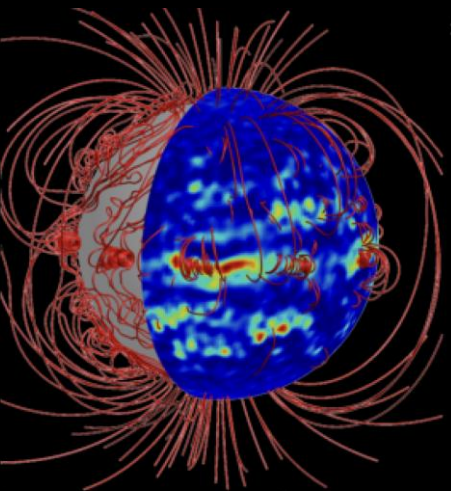
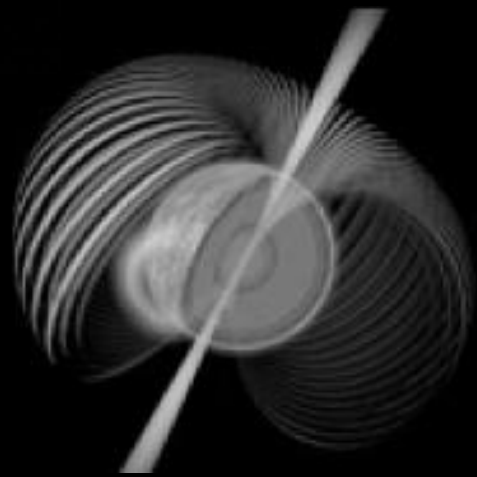


MATINS: Dehman et al. 2023, Ascenzi et al. 2024

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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



WHAT DO WE LEARN ON SNe JUST FROM THE DATA...

1. If CC SN birthrate ~ 1 per century, the sample is complete, implying $\sim 60\%$ of neutron stars are born as magnetars.

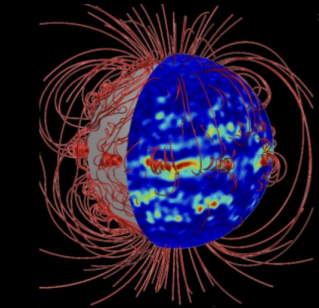
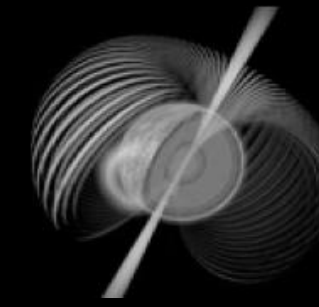
→ the SN rate is necessarily >1 per century!

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

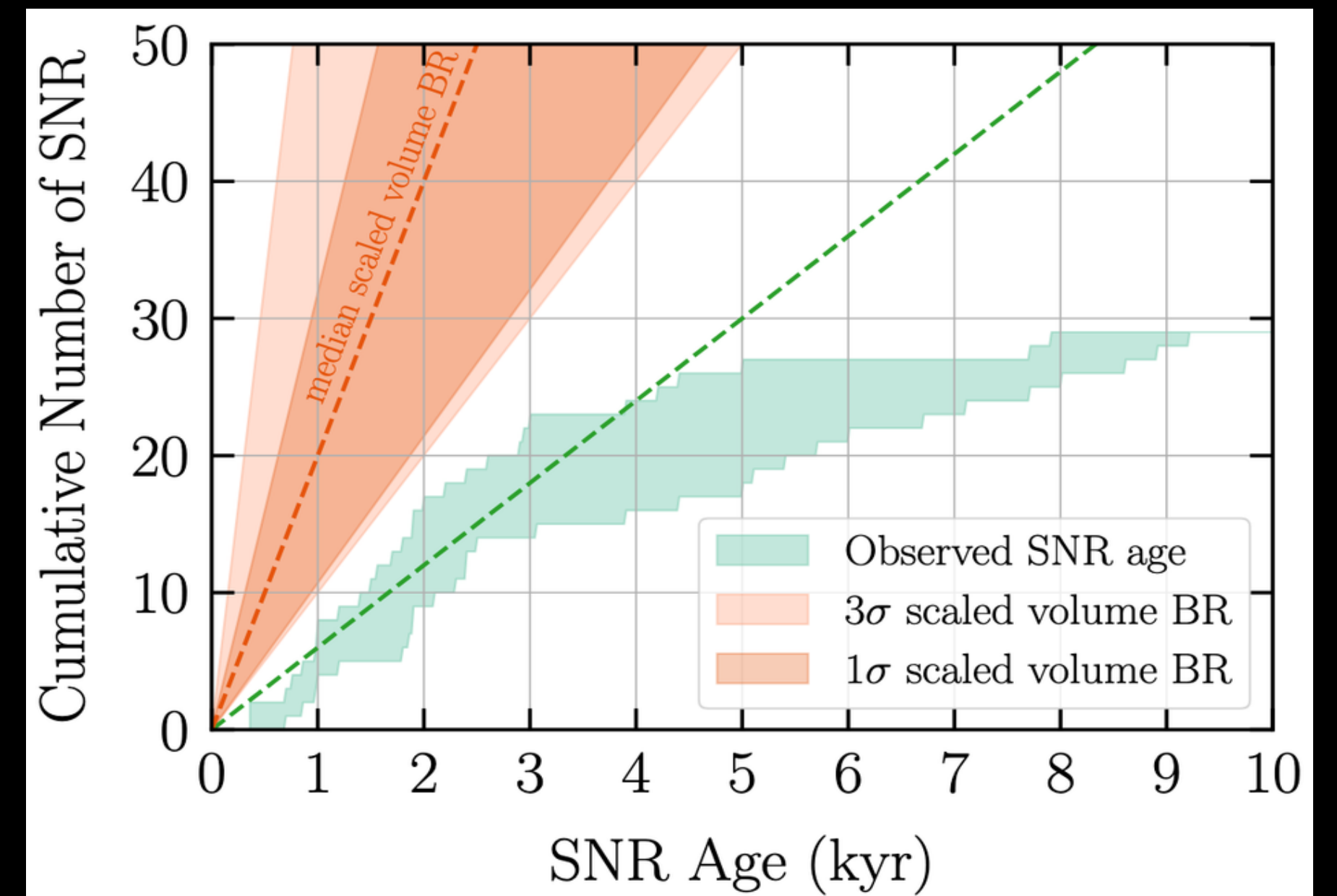
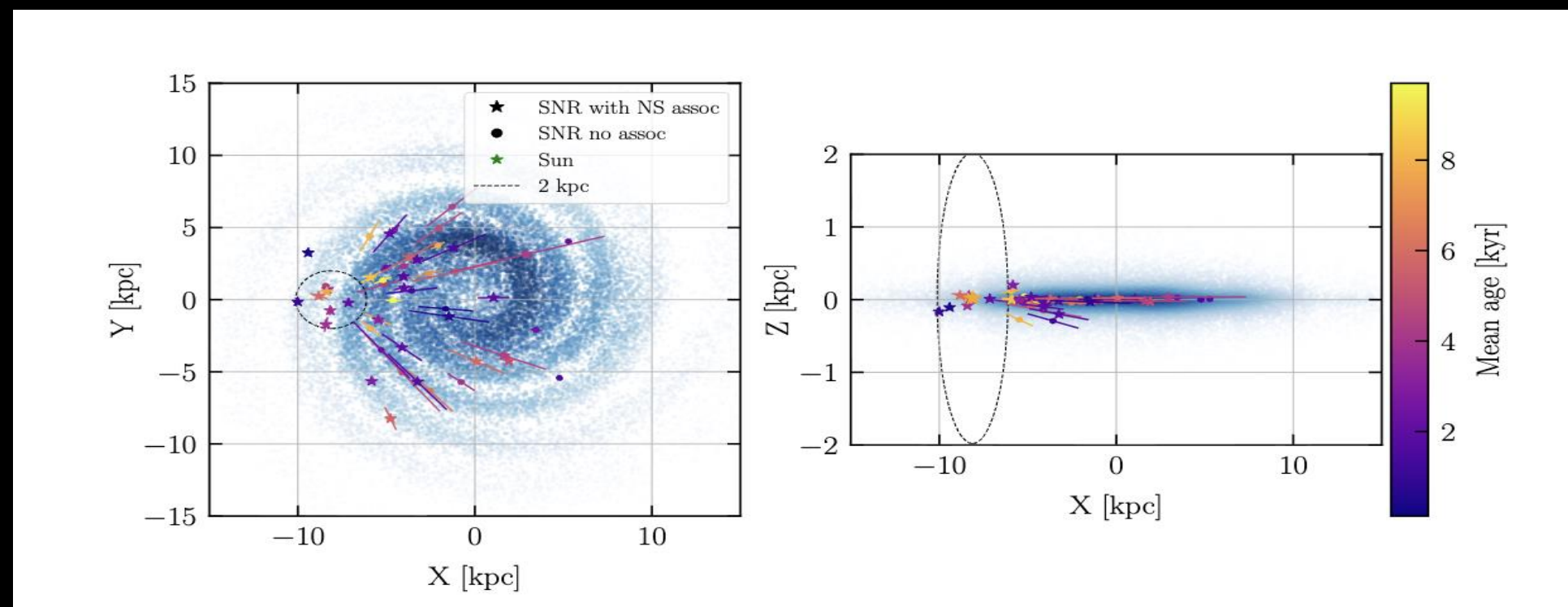
3. Assuming we observed all CC SNe within 2 kpc (certainly a lower limit), rescaling for the whole Galaxy we obtain a SN rate of

$> 2.01^{+1.90}_{-0.96}$ NS/century.

→ the SN rate is >2 per century!



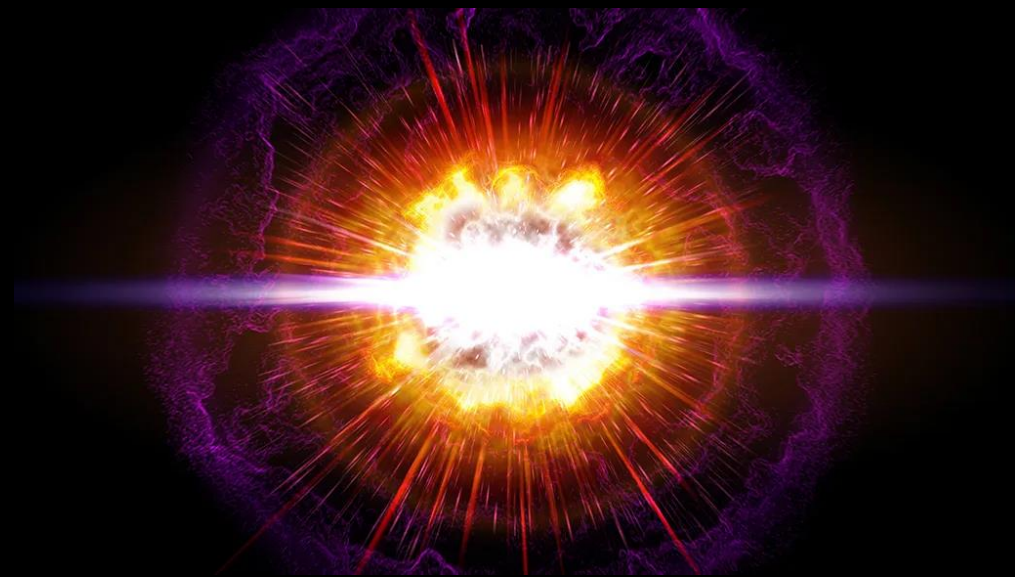
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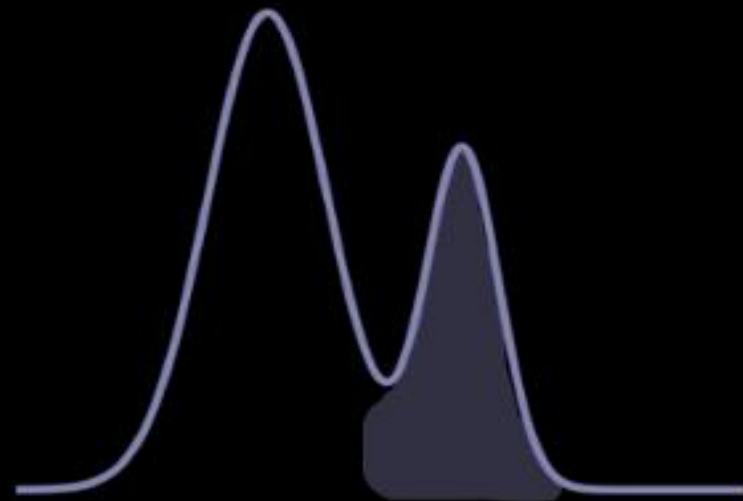


POPULATION SYNTHESIS SIMULATIONS OF NEUTRON STARS

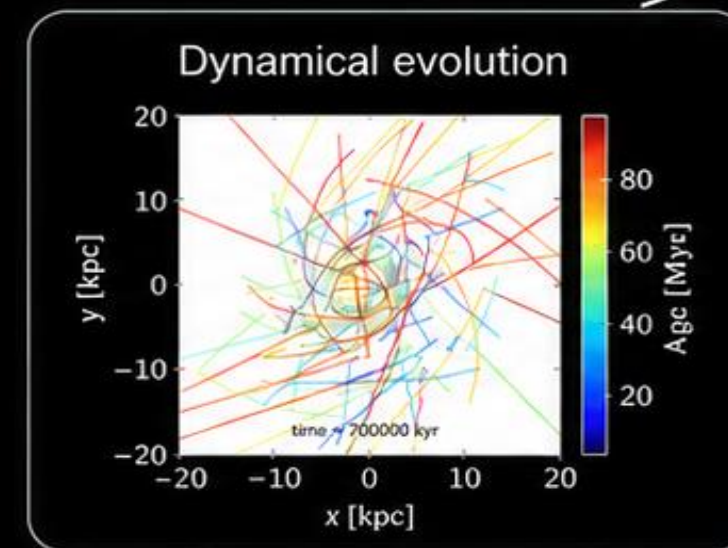
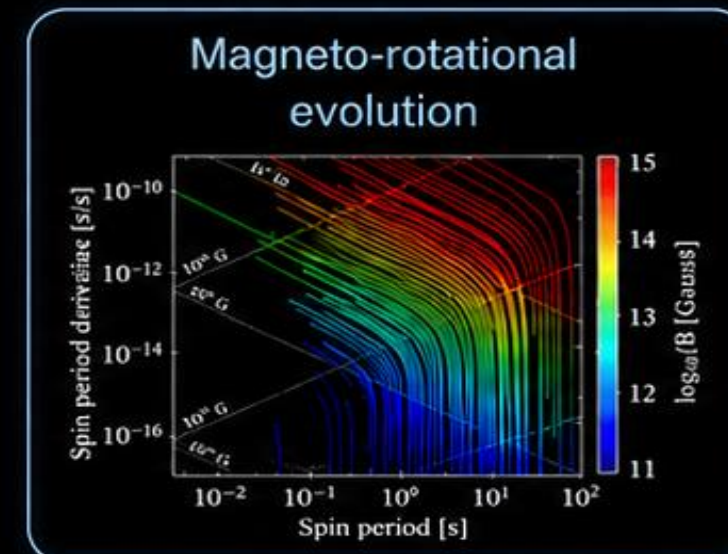
BIRTH PROPERTIES



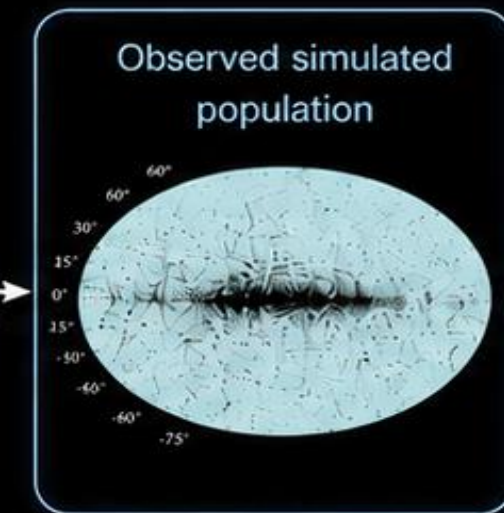
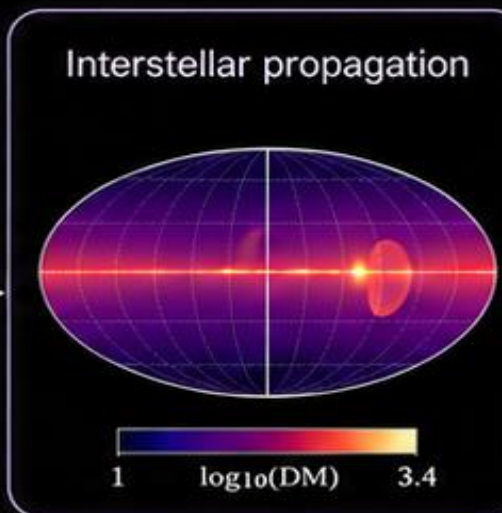
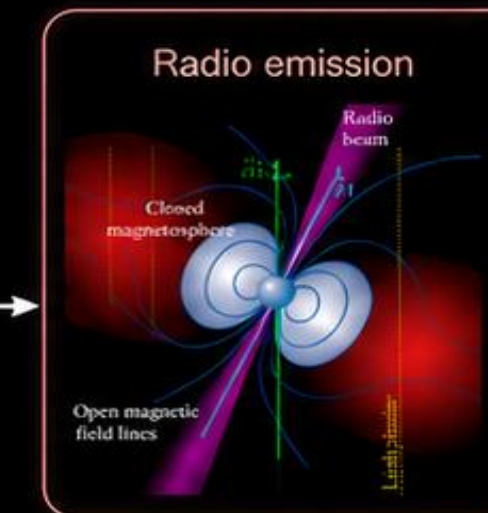
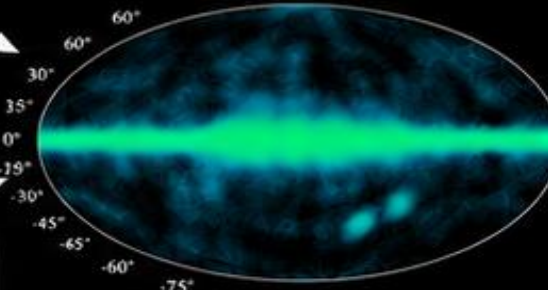
MAGNETAR RATIO



Initial magnetic field

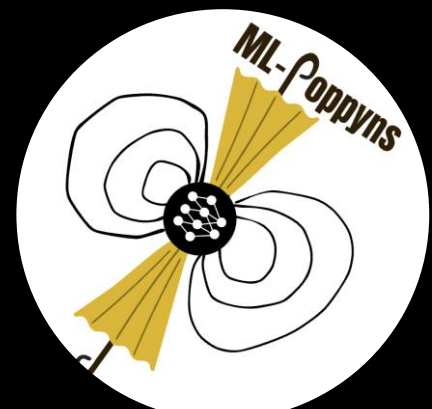


Full population



Survey sensitivities and
observational biases
sky coverage
radiometer equation
pulsar detections

Compare simulations
with observations
Constrain physics



Graber et al. 2024, ApJ; Pardo et al. 2025, ApJ; Pardo et al. 2026, Nature Astronomy in press

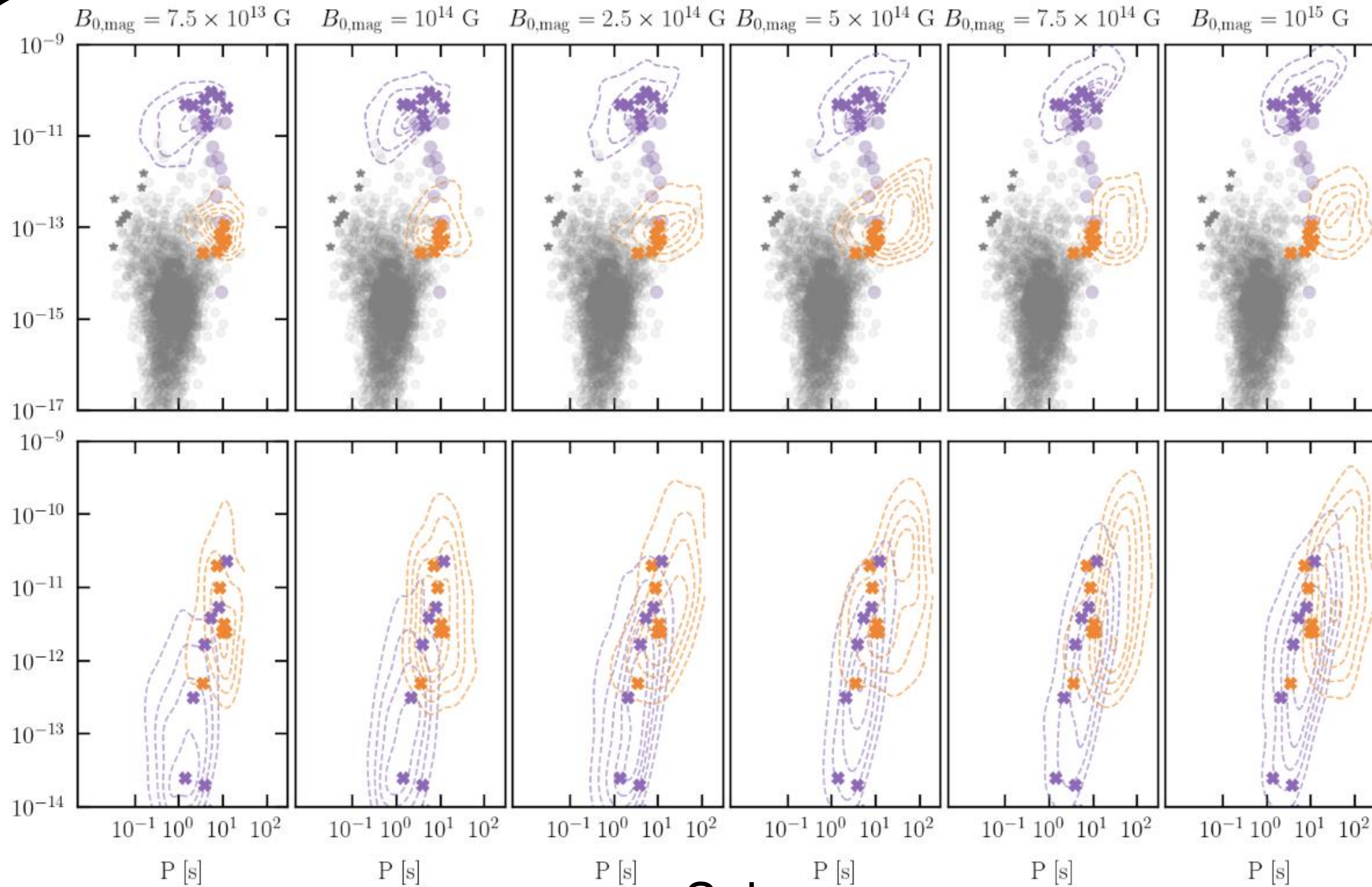
https://ice-csic-astroexotic.github.io/code/ml_poppyns/



POPULATION SYNTHESIS SIMULATIONS OF NEUTRON STARS

Spin derivative

X-ray flux

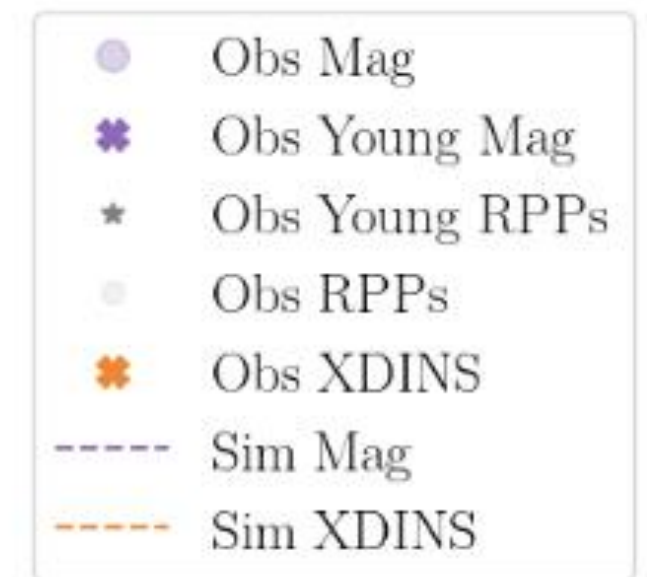


B-field

Magnetars

XDINSs

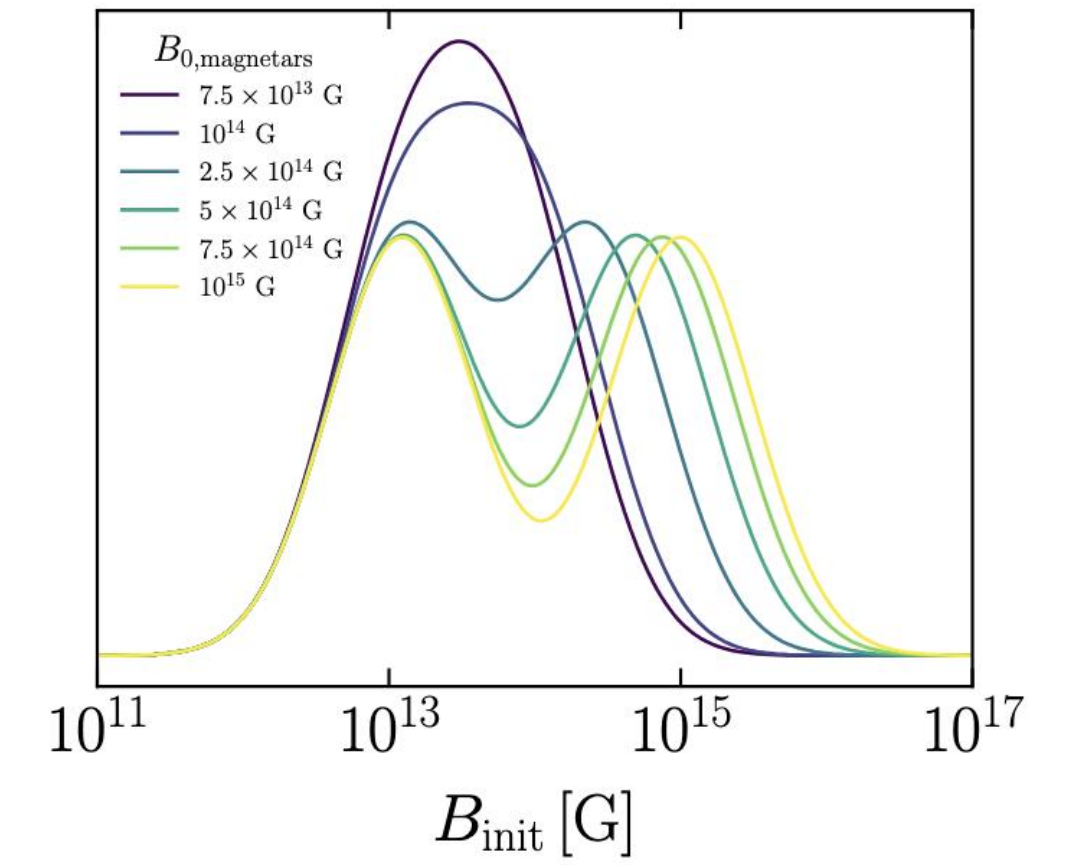
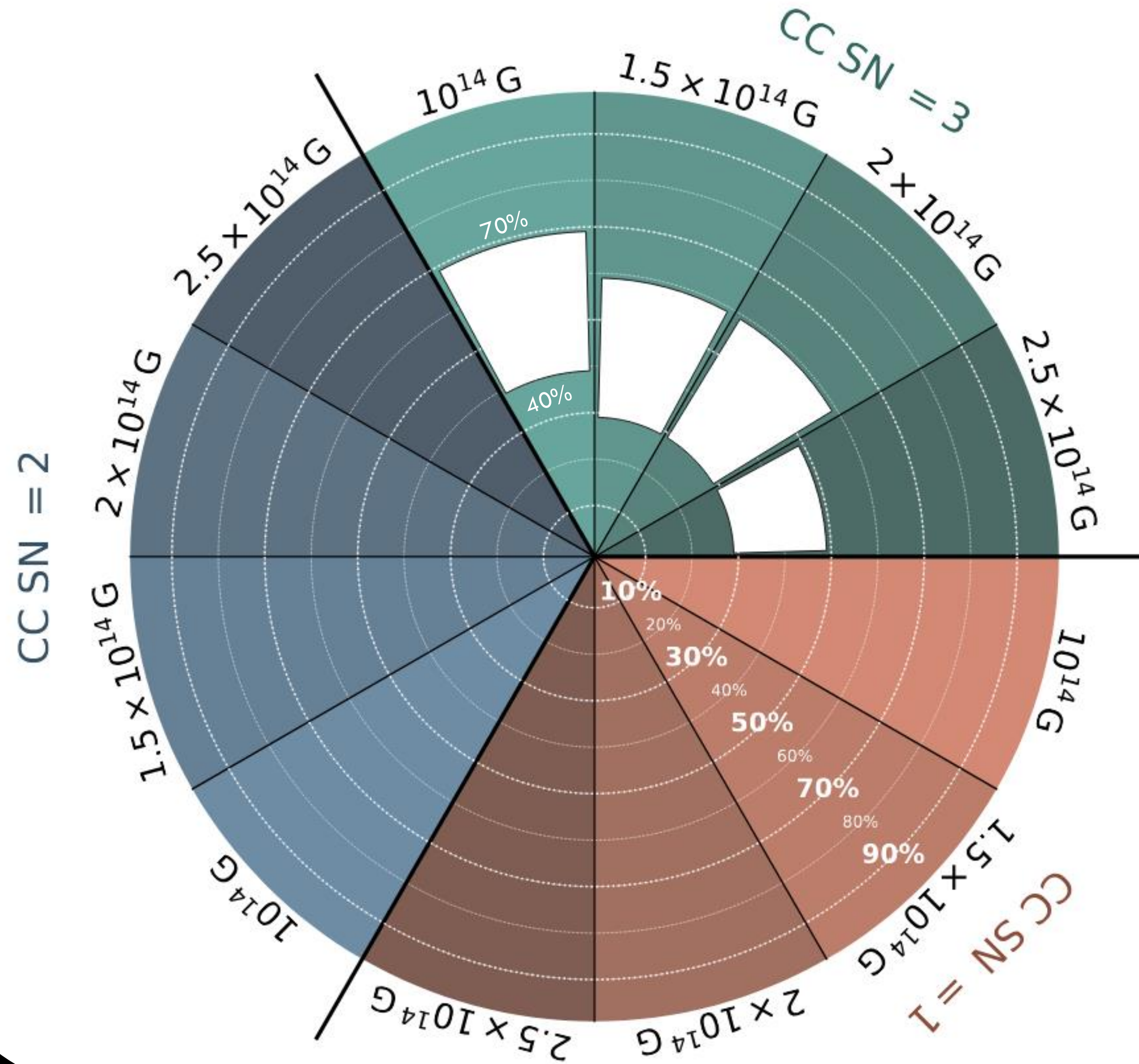
Radio Pulsars



Spin



CONSTRAINS ON CC RATES AND MAGNETAR FRACTION



1. QUESTIONS ANSWERED IN THE PAST 10 YEARS...

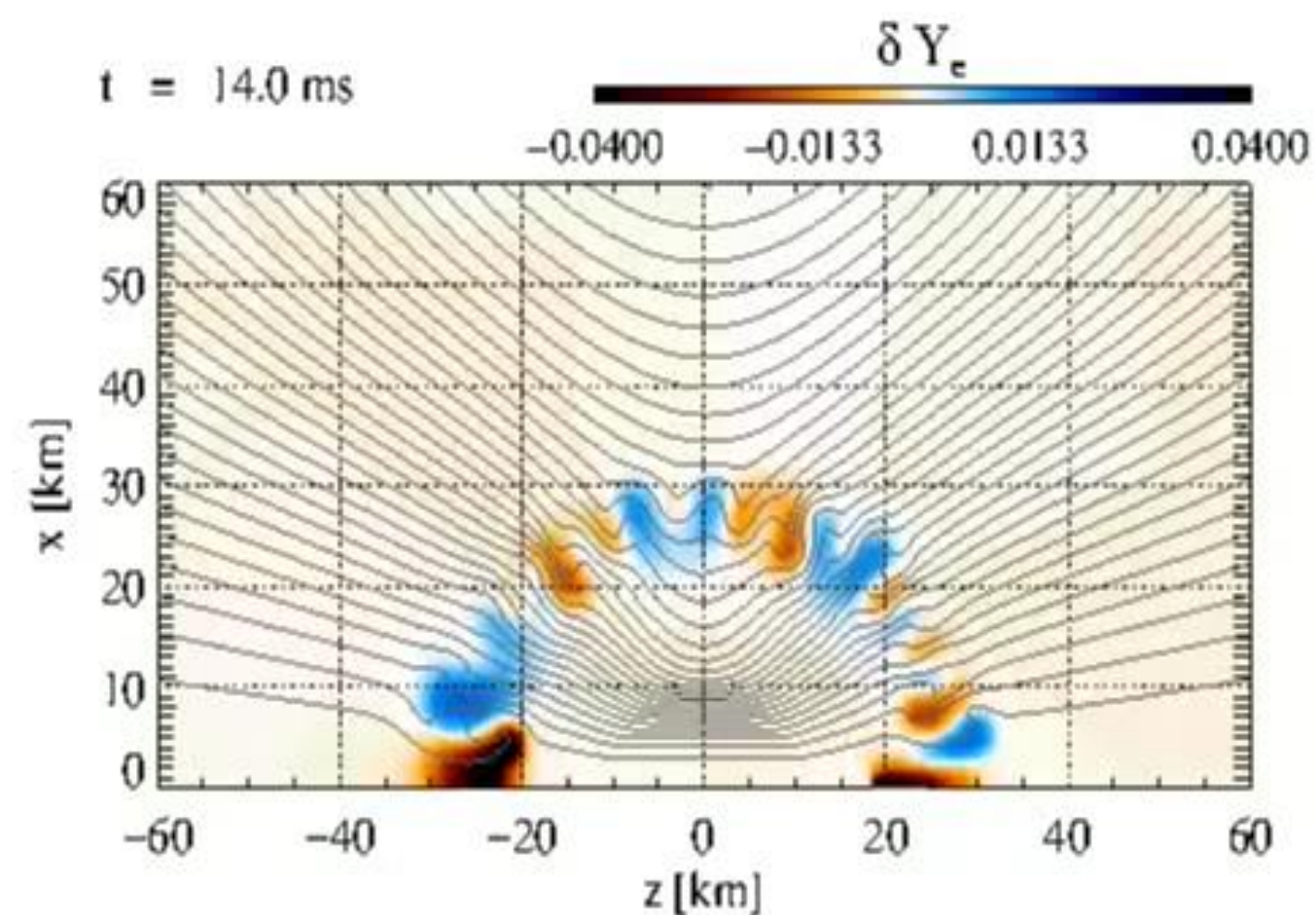
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- WHAT DID WE LEARN ABOUT MAGNETARS' FORMATION RATE?

2. OPEN QUESTIONS FOR THE FUTURE 10 YEARS...

- **HOW THESE HIGH DIPOLAR FIELDS ARE CREATED IN SNe?**
- **HOW ARE THEY RELATED TO THEIR PROGENITORS? WHERE ARE THE BINARIES?**

MAGNETAR FIELD FORMATION

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



Obergaulinger, Aloy & Janka 2015, MNRAS

Observationally...

- Proper motions for ~ 9 objects: 100-300 km/s range
- A few magnetars coincident with massive star clusters
- One case: a wind blown bubble 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

1. QUESTIONS ANSWERED IN THE PAST 10 YEARS...

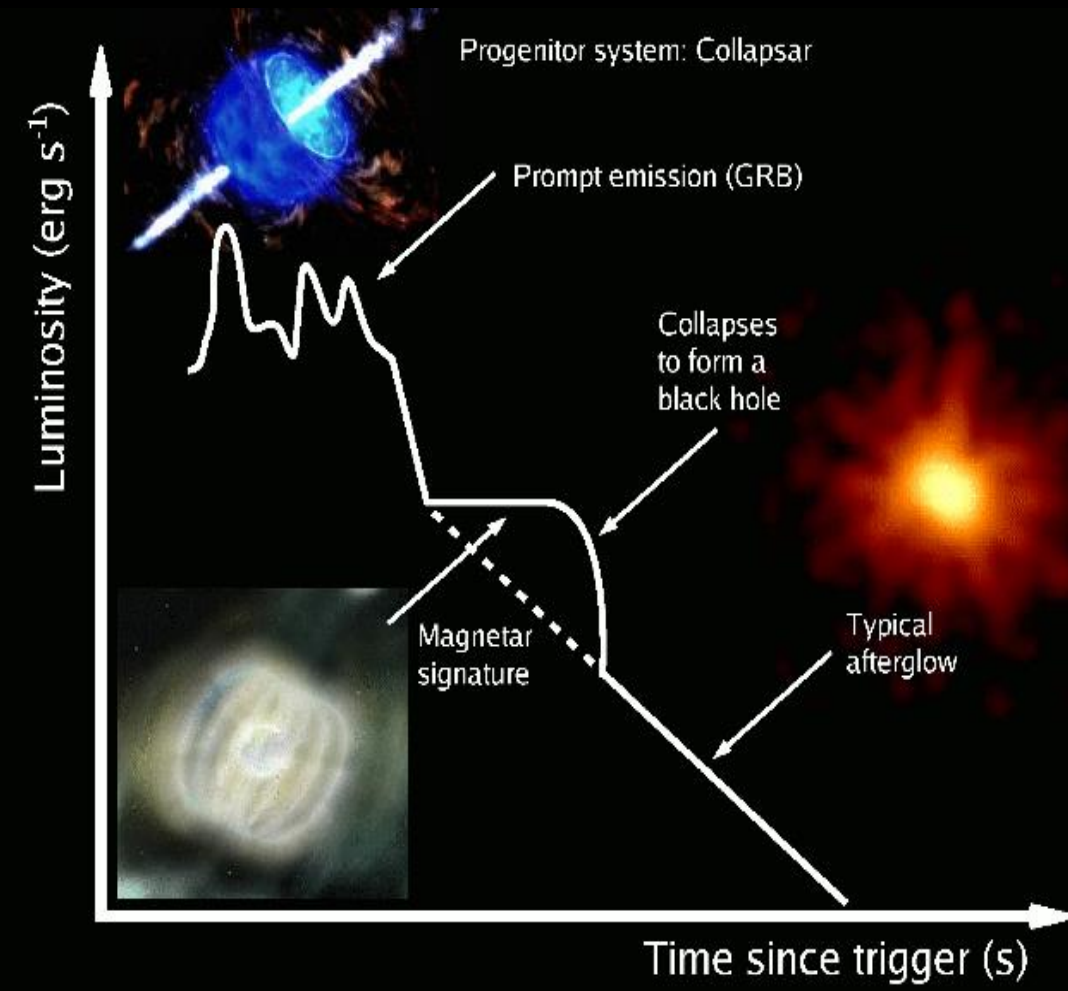
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- WHAT DID WE LEARN ABOUT MAGNETARS' FORMATION RATE?

2. OPEN QUESTIONS FOR THE FUTURE 10 YEARS...

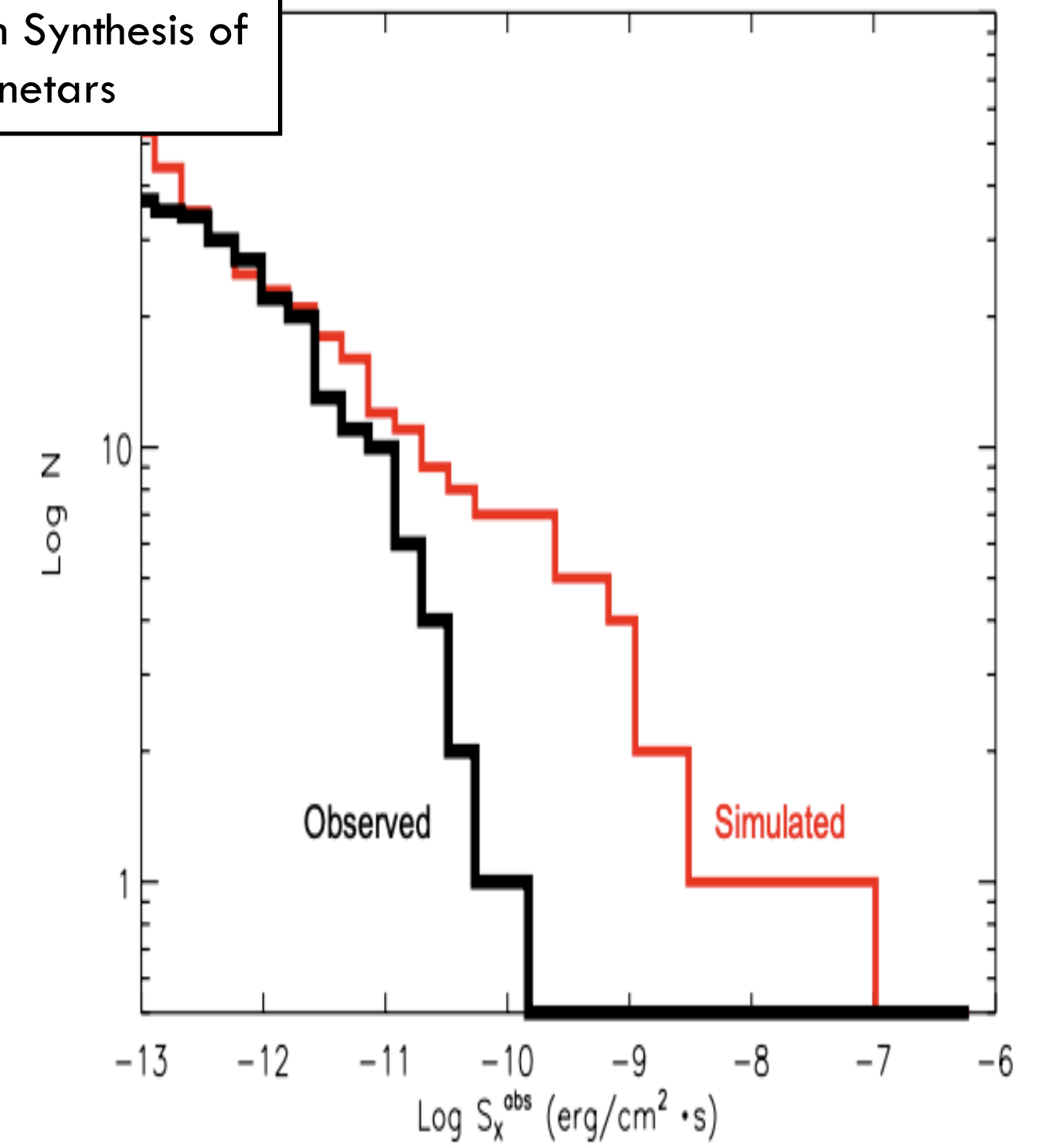
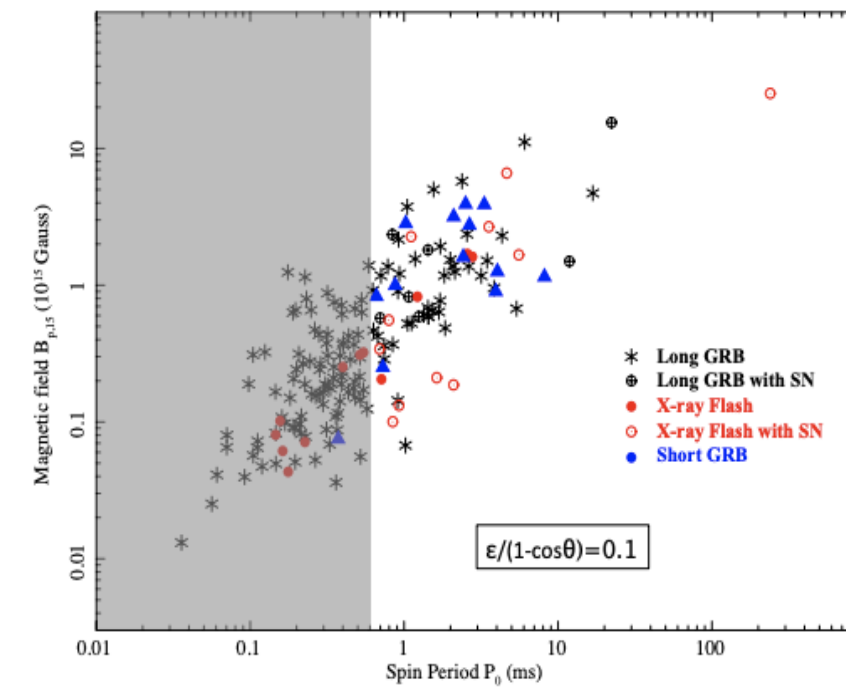
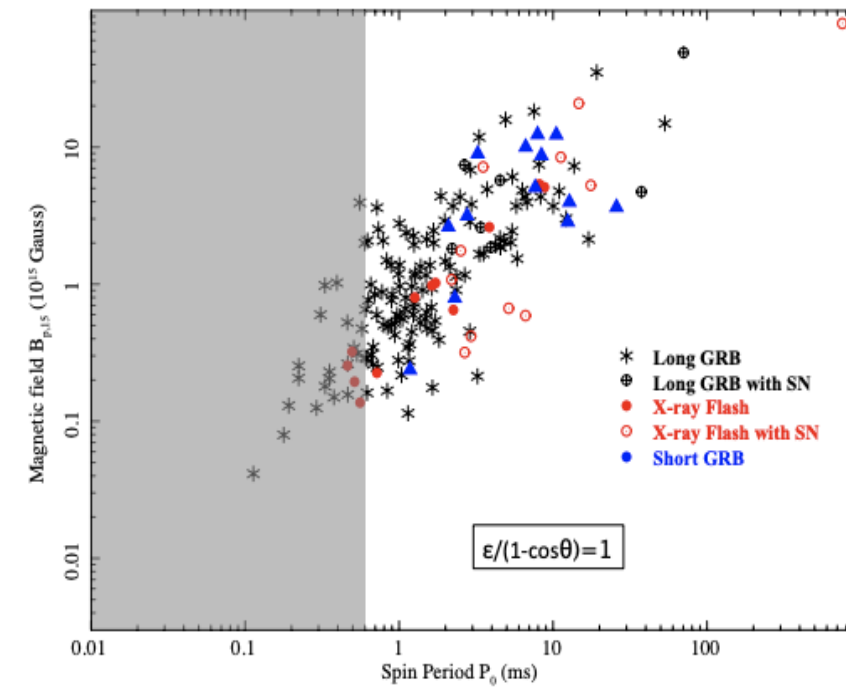
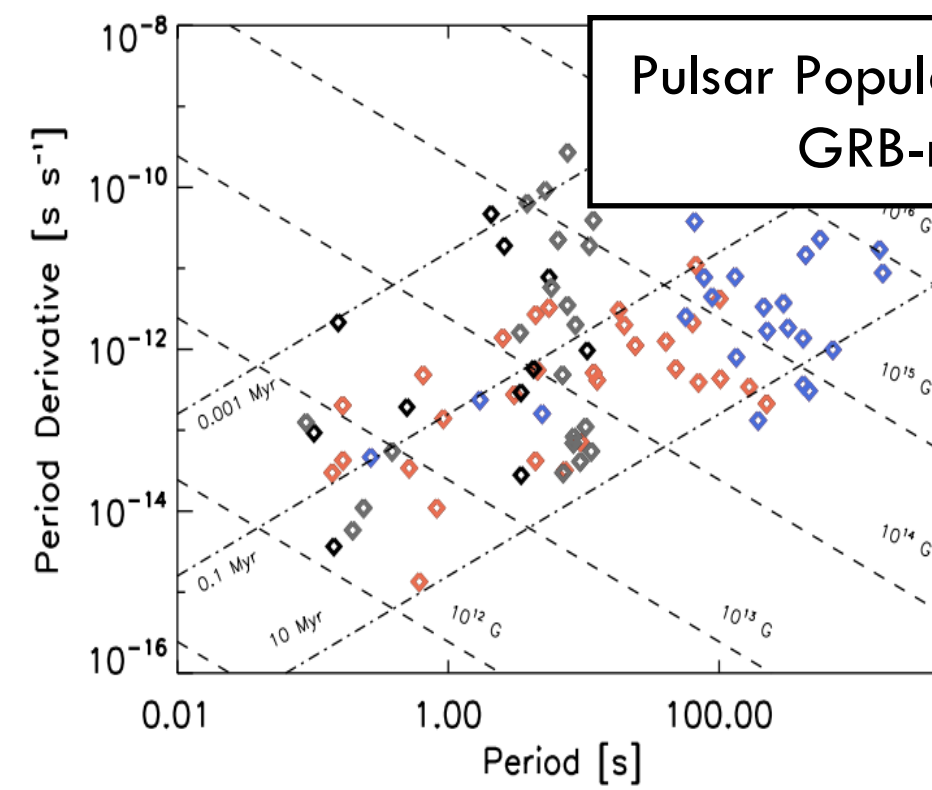
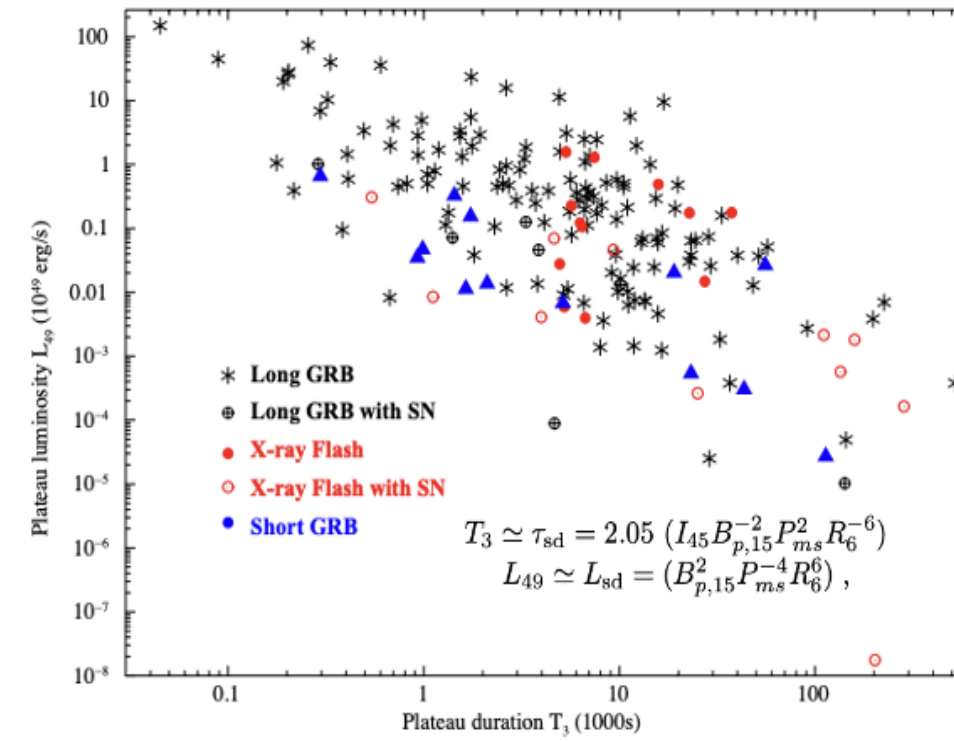
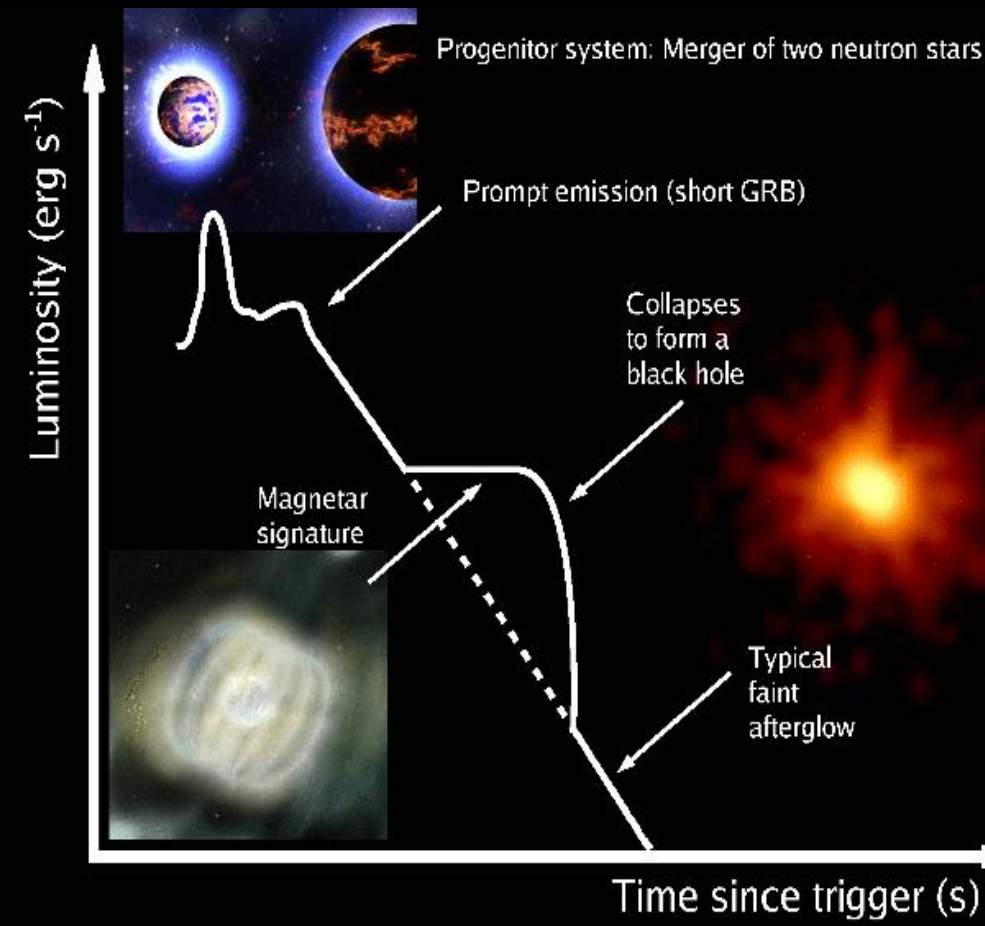
- HOW THESE HIGH DIPOLAR FIELDS ARE CREATED IN SNe?
 - HOW ARE THEY RELATED TO THEIR PROGENITORS? WHERE ARE THE BINARIES?
-
- **WHAT CAN WE LEARN FROM MAGNETARS FOR GRBs AND FRBs?**

GAMMA-RAY BURSTS AND MAGNETARS

Collapsar model for Long-GRBs

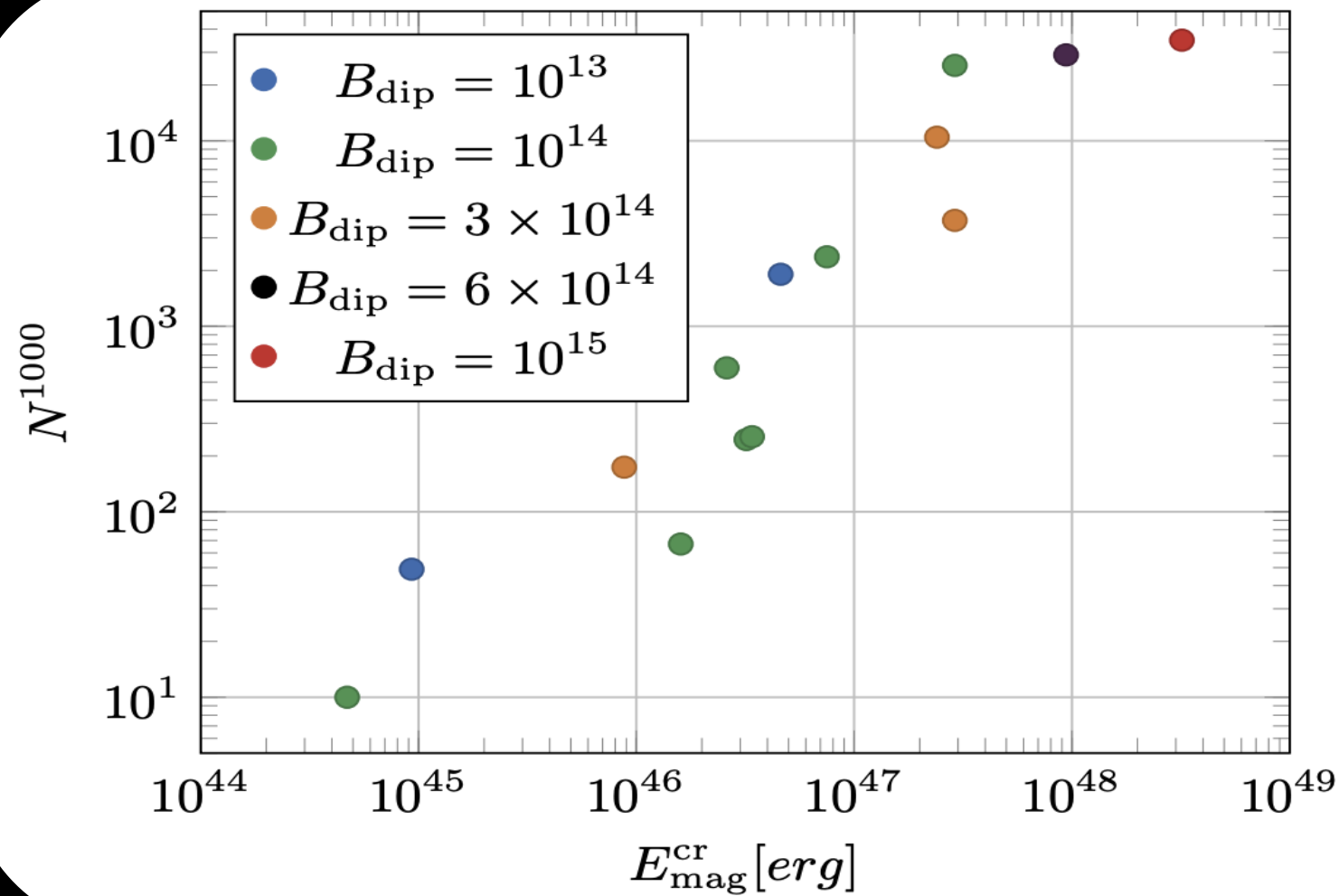
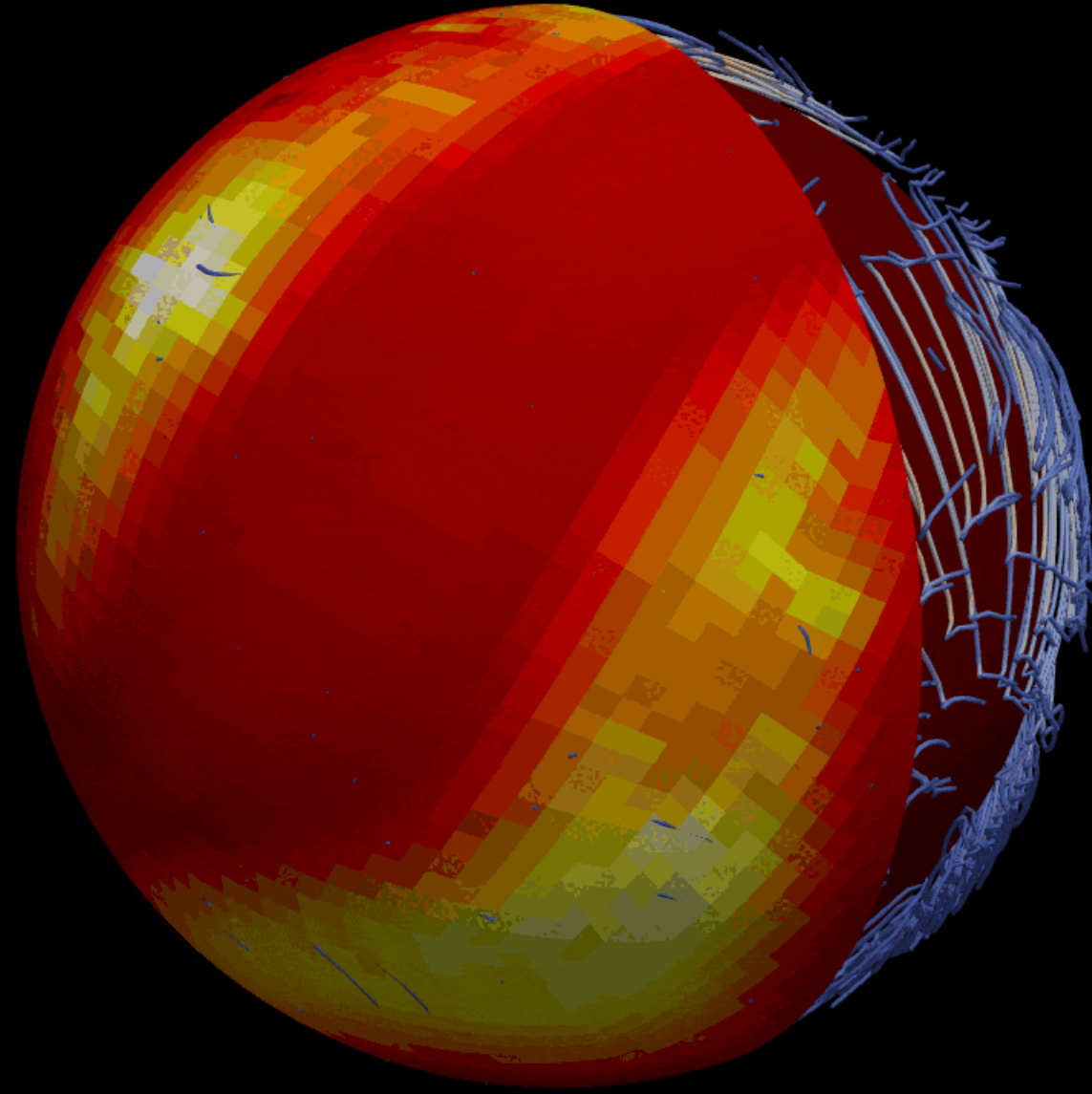


Binary mergers for Short-GRBs

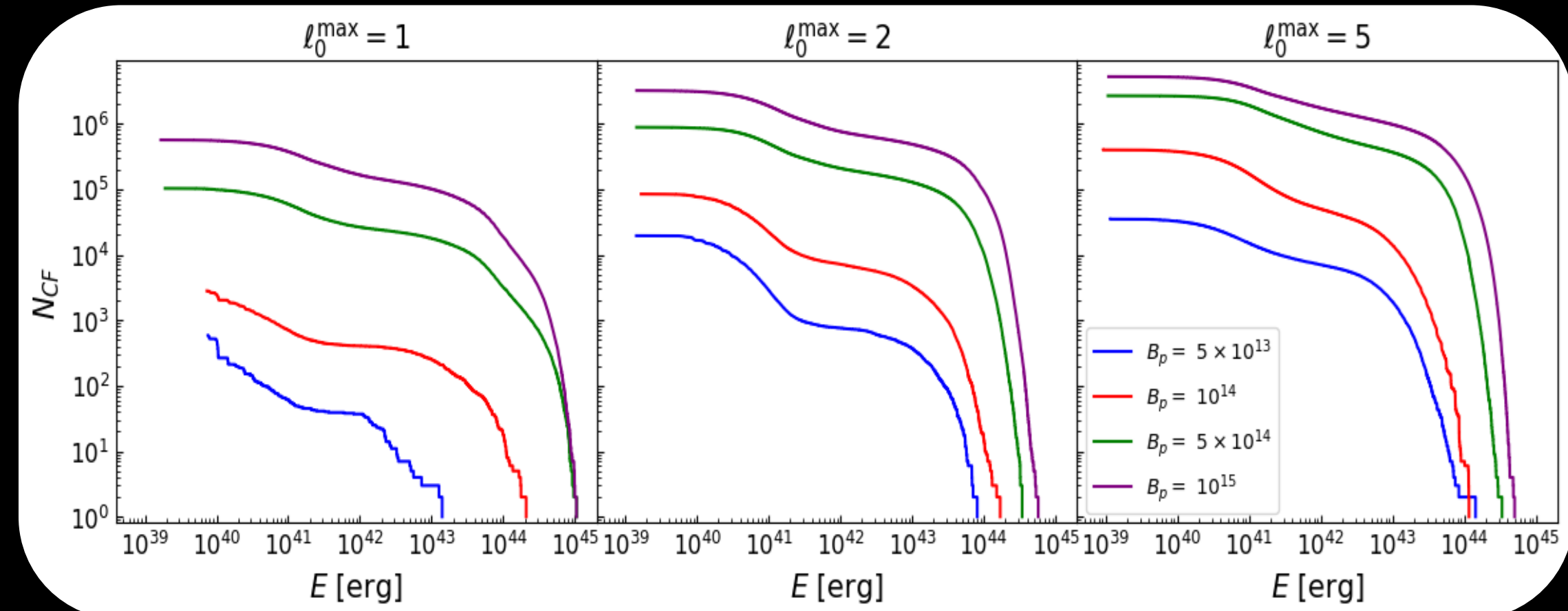
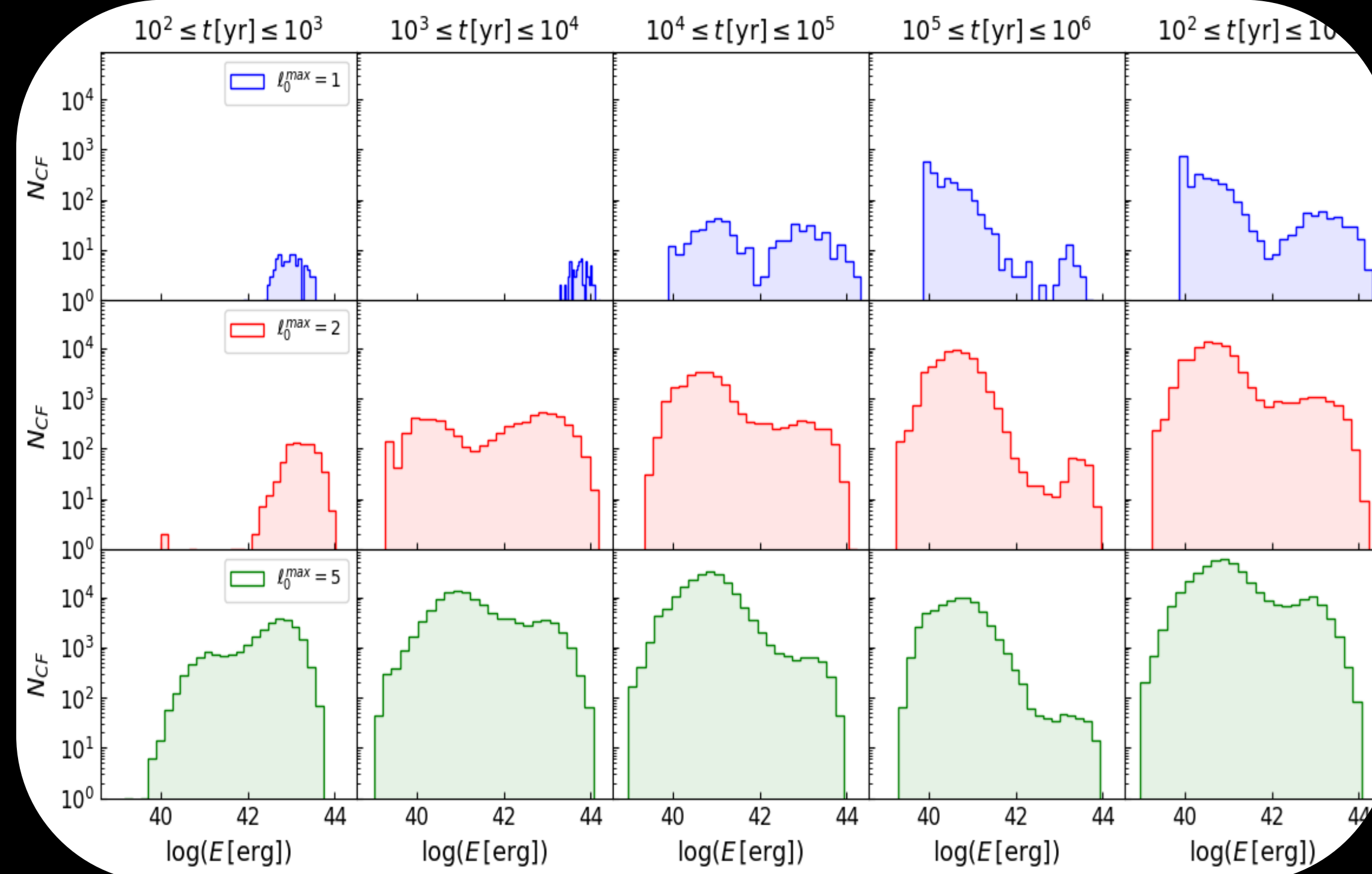


GRB-magnetars are too magnetic at birth compared to the typical population in our Galaxy.

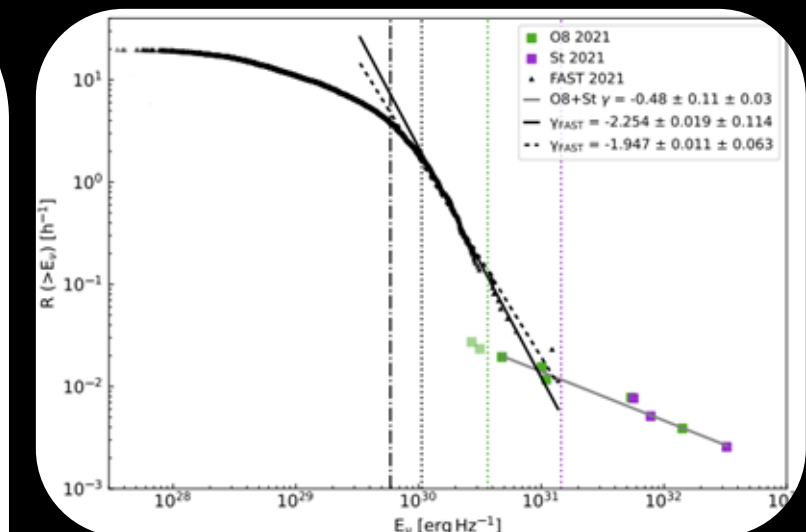
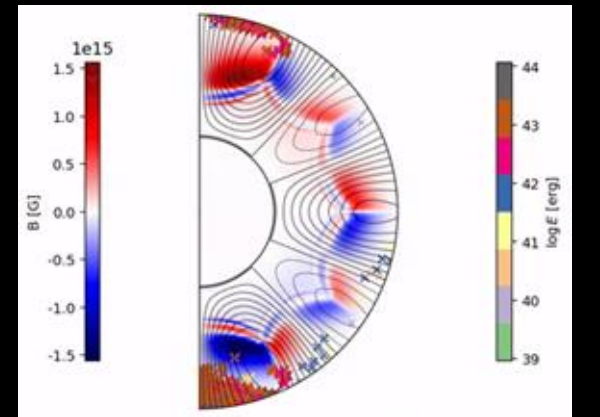
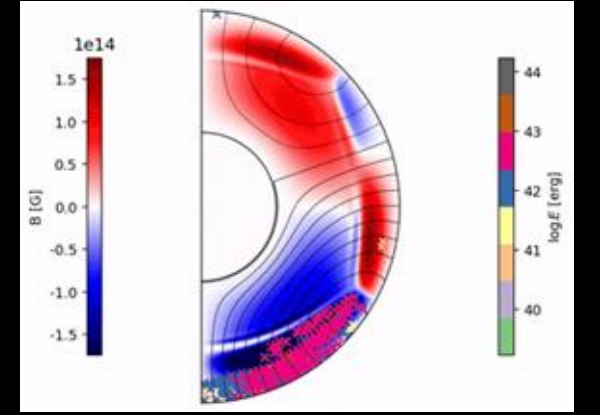
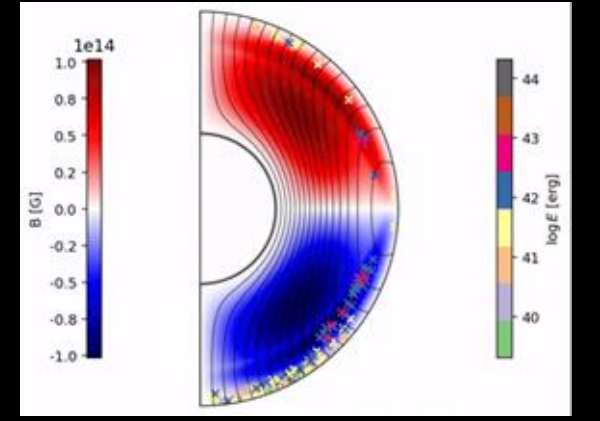
FAST RADIO BURSTS AND MAGNETARS



Dehman, Vigano, Rea et al. 2020, ApJ Letters;
see also Lander 2023, ApJ Letters

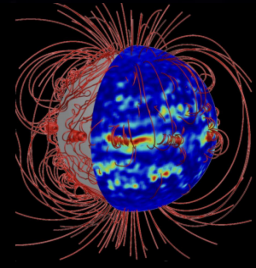


Ricci, De Grandis, Rea et al. 2026, in prep

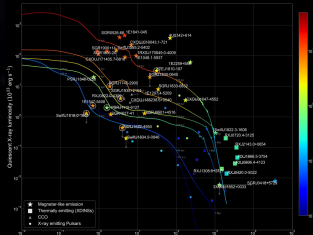


Kirsten, Oud-Boukattine,
Hermann et al. 2023,
Nature Astronomy

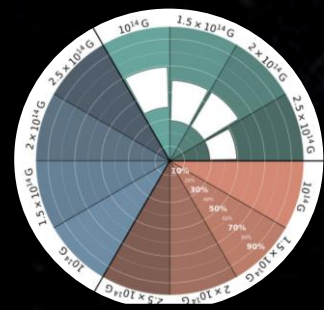
1. QUESTIONS ANSWERED IN THE PAST 10 YEARS...



Strong and tangled fields are ubiquitous in the pulsar population.

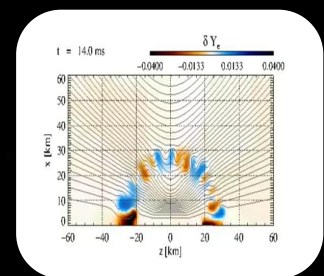


Neutron star classes evolve and different classes are related evolutionary via B-field evolution.

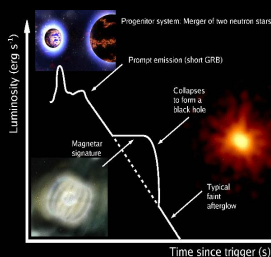


Core-collapse SNe in our Galaxy should be >2 per century and magnetar fraction should be around $\sim 50\%$ depending on the initial field distribution and rates.

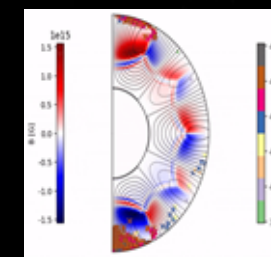
2. OPEN QUESTIONS FOR THE FUTURE 10 YEARS...



Dipolar field re-ordering and the role of binarity (if any).



Exact role of magnetars in long and short GRBs, and connection with SLSNe.



Constraining the number and energetics of FRBs by modelling crustal failures and magnetar population for different galaxies and metallicities.

THANKS!!!



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