MAGNETAR BIRTH RATES, EVOLUTION, AND THEIR IMPRINT IN THE TRANSIENT X-RAY SKY

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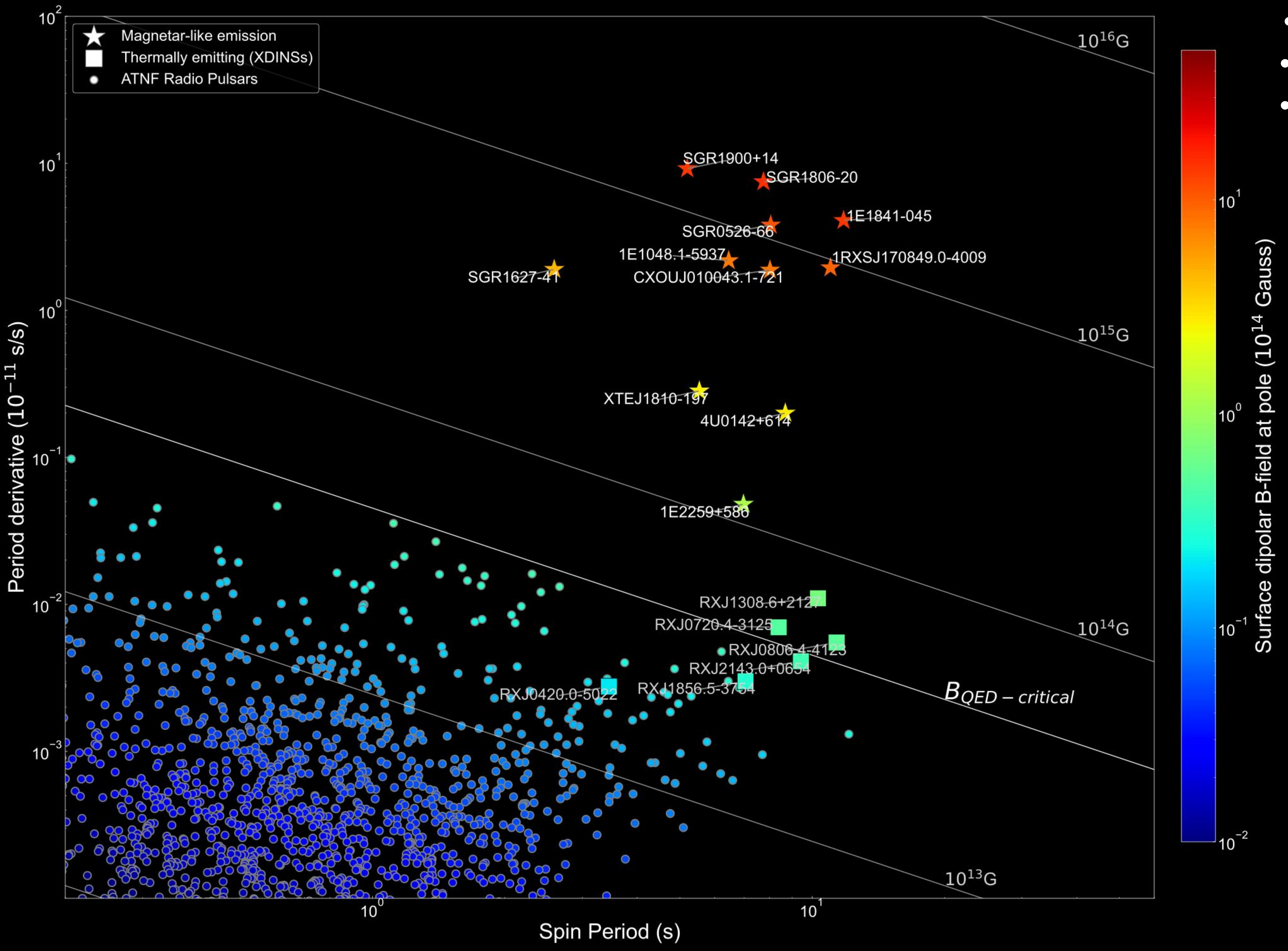
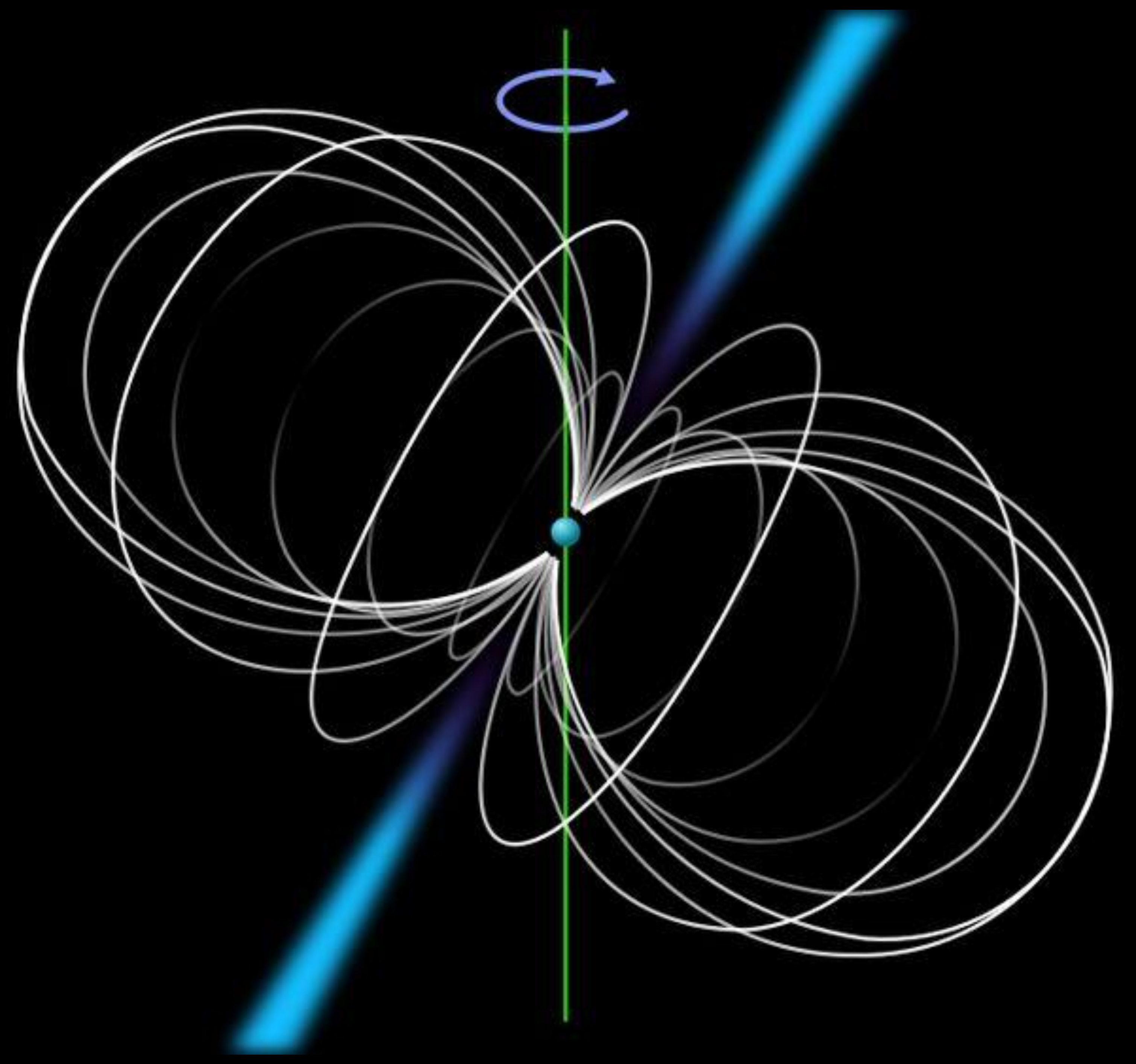
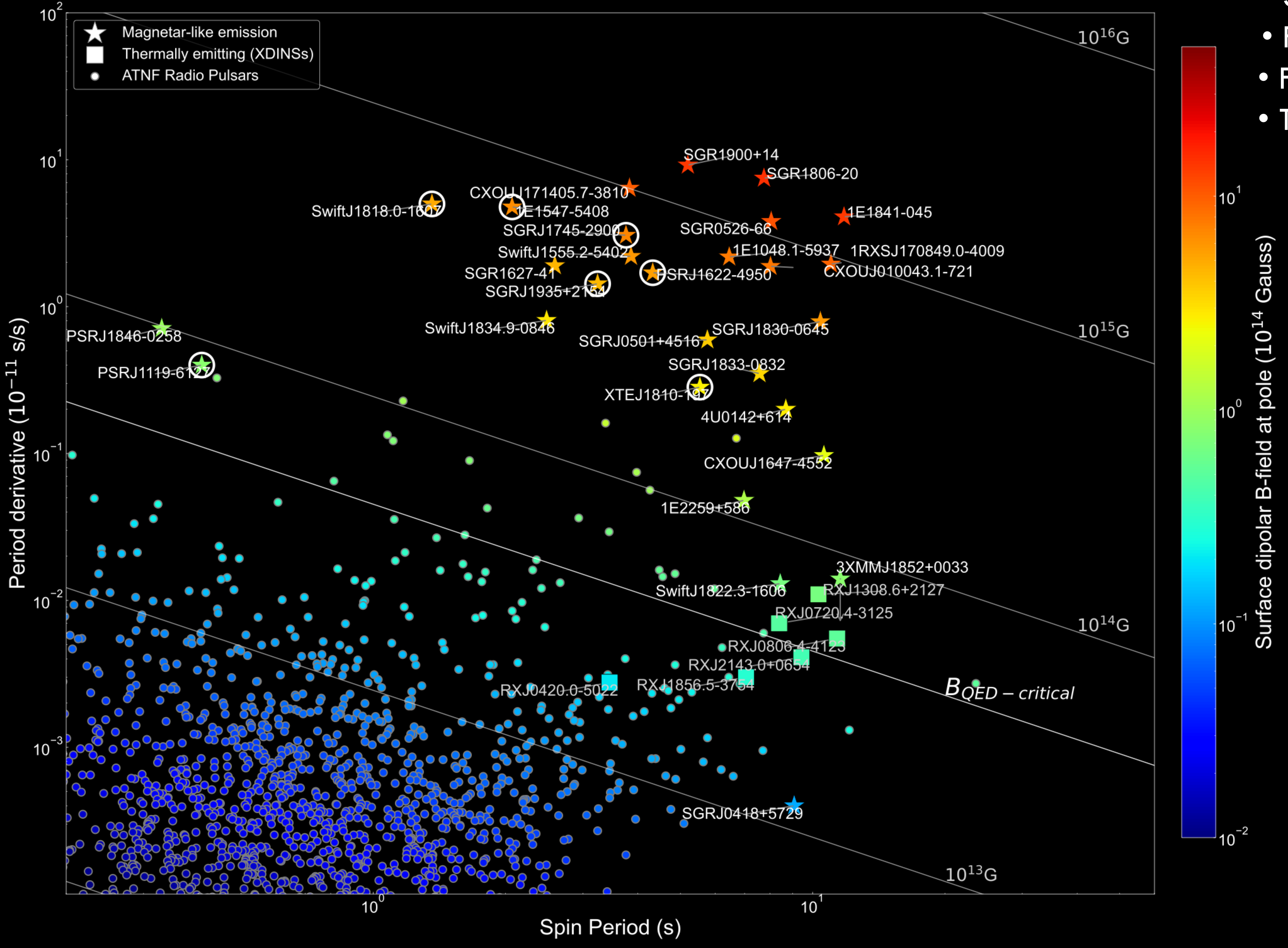
MAGNETARS BEFORE SWIFT…



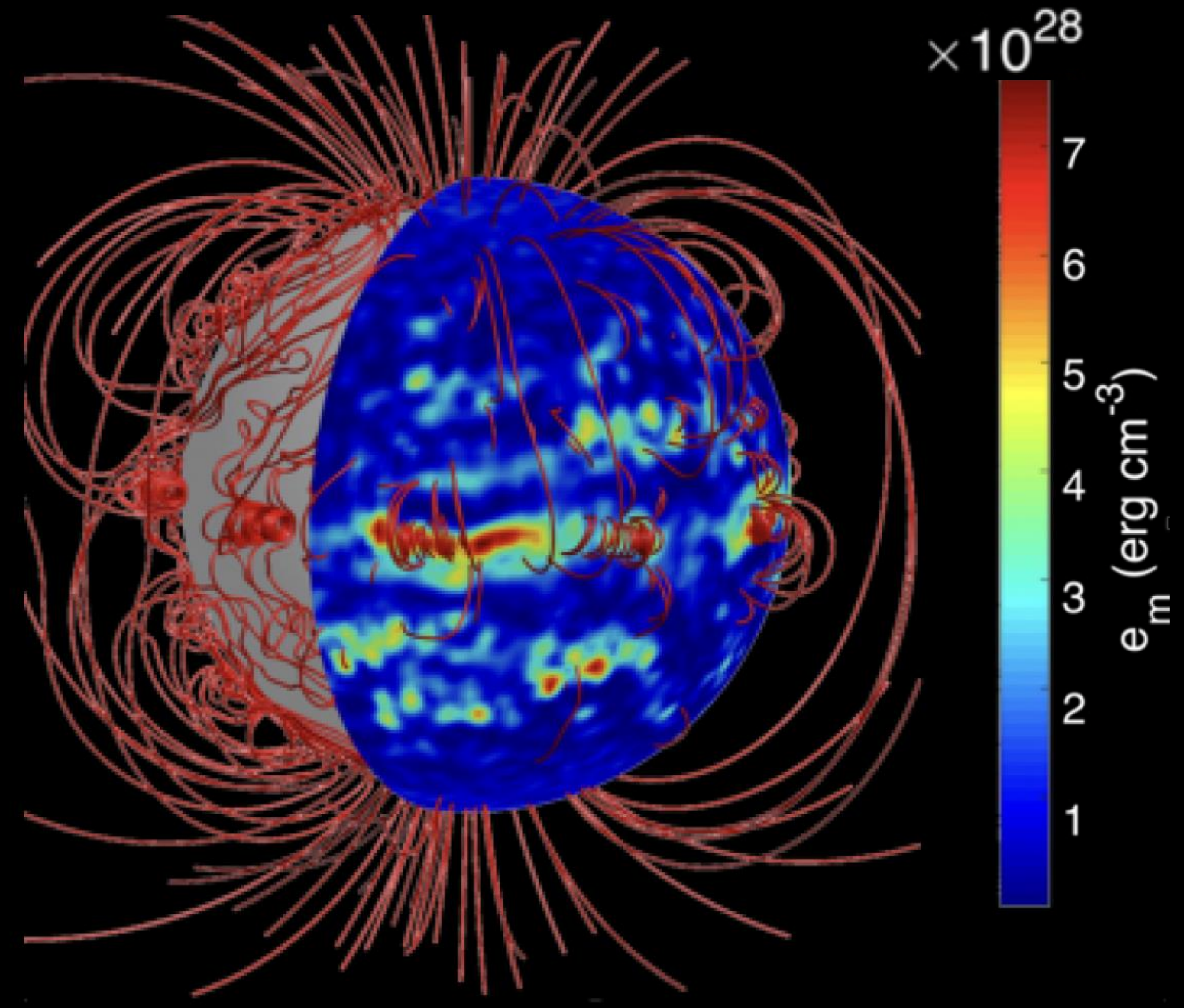
- Dipolar magnetic fields of $B \sim 10^{14}$-10^{15} Gauss
- Steady X-ray pulsars with $Lx \sim 10^{35}$ erg s^{-1}
- Rotating with $P \sim 2$-12 s
- X-ray luminosity larger than the rotational energy loss rate
- Soft X-ray emission
- Flaring activity in soft gamma-rays (0.01-10^2 s; $L_x \sim 10^{39}$-10^{47} erg s^{-1})
- Faint infrared/optical emission



MAGNETARS AT *Swift*20!

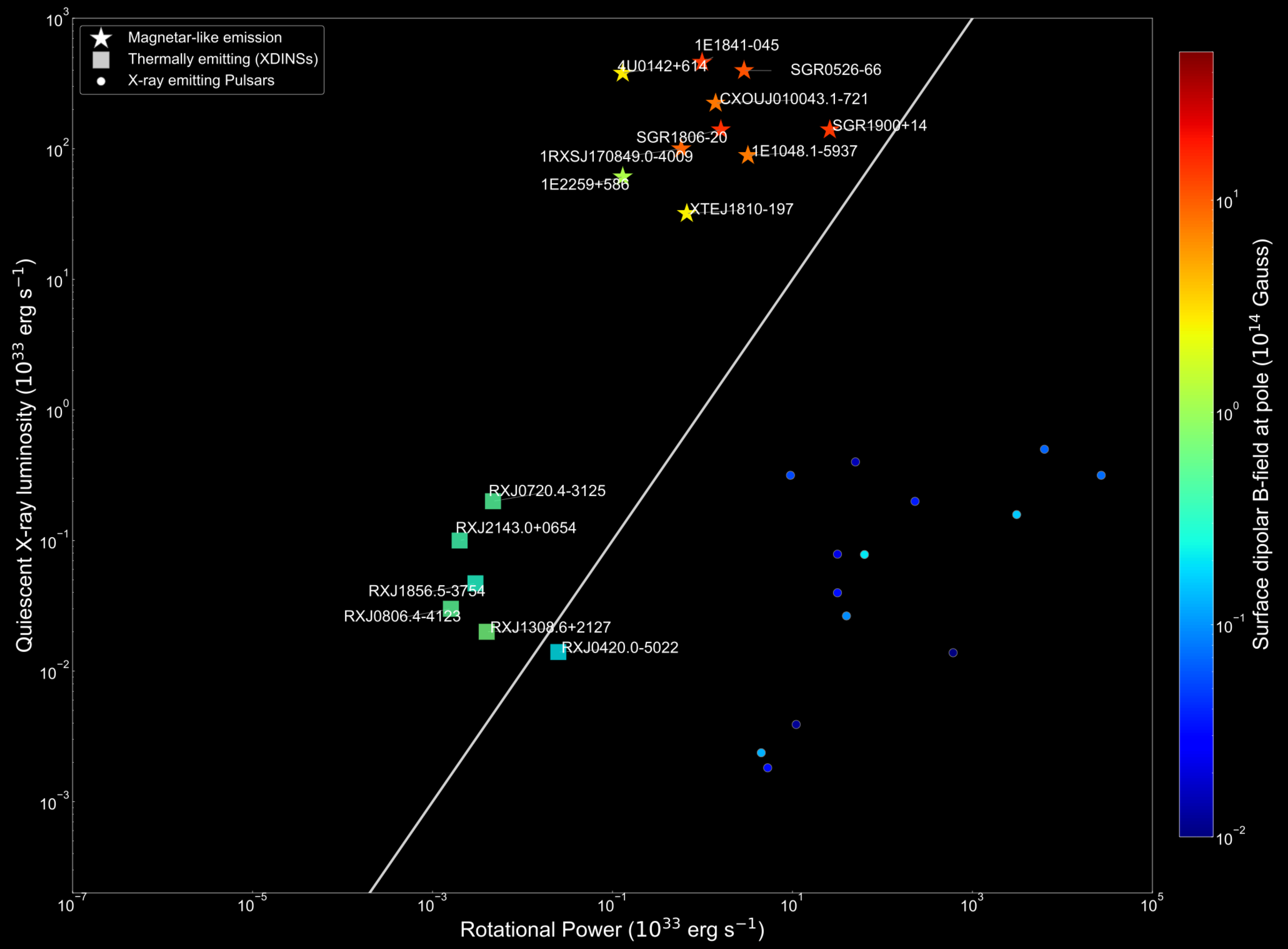


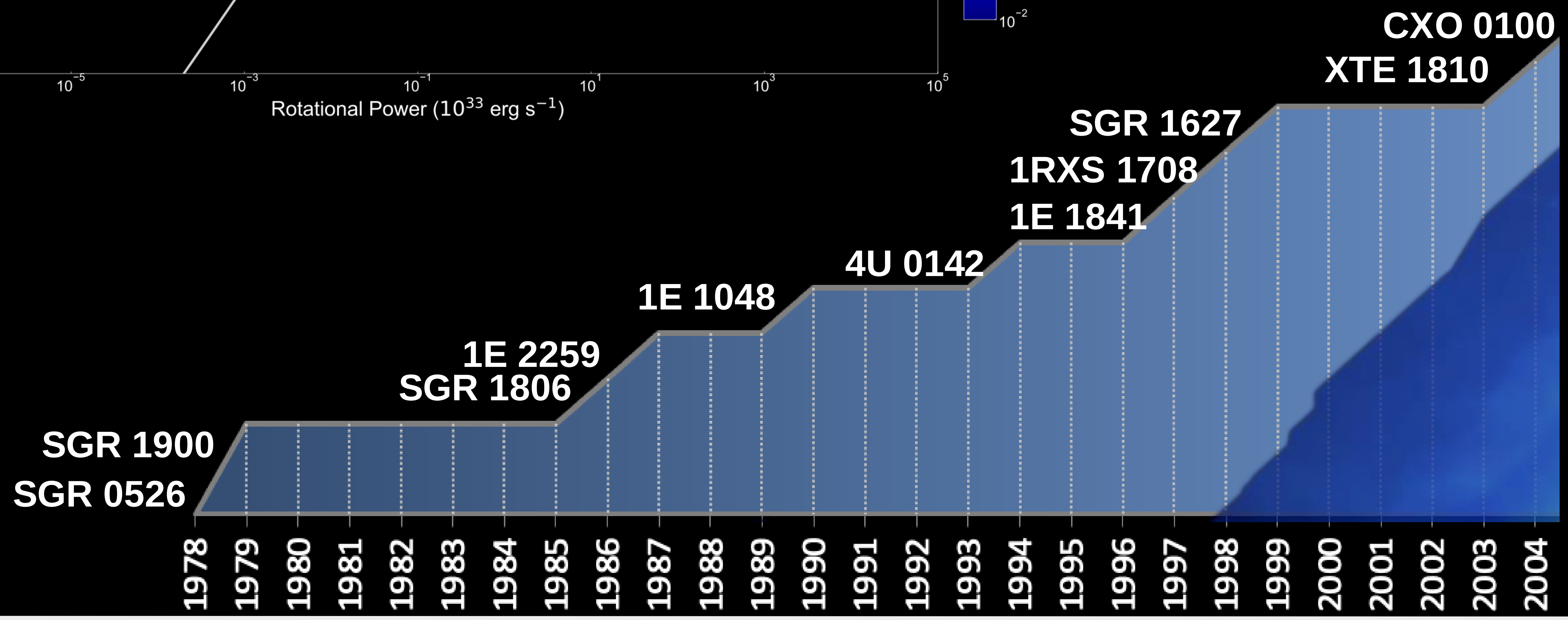
- Dipolar magnetic fields of $B\sim10^{12}$-10^{15} Gauss
- Transient X-ray pulsars with $L_x\sim10^{31}$-10^{36}erg s^{-1}
- Rotating with P~0.3-12 s
- X-ray luminosity is "generally" larger than the rotational energy
- Soft and hard X-ray emission (0.5-200 keV); thermal + non-thermal
- Flaring activity in soft gamma-rays (0.01-10^2 s; $L_x\sim10^{39}$-10^{47}erg s^{-1})
- Faint infrared/optical emission (probably magnetospheric)
- Transient radio emission (in 7 cases) and FRB-like emission



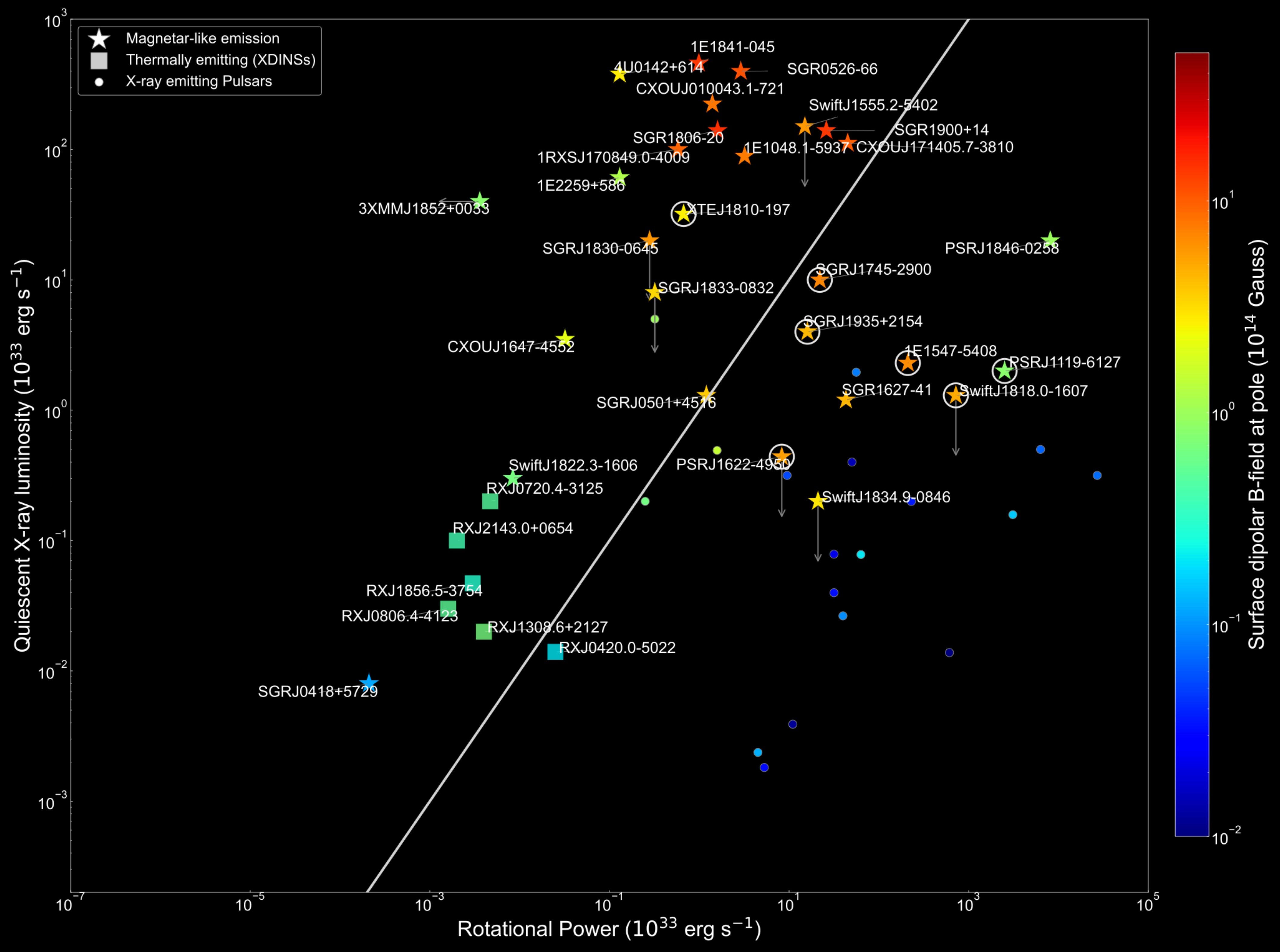
(*Gougouliatos et al. 2014*)

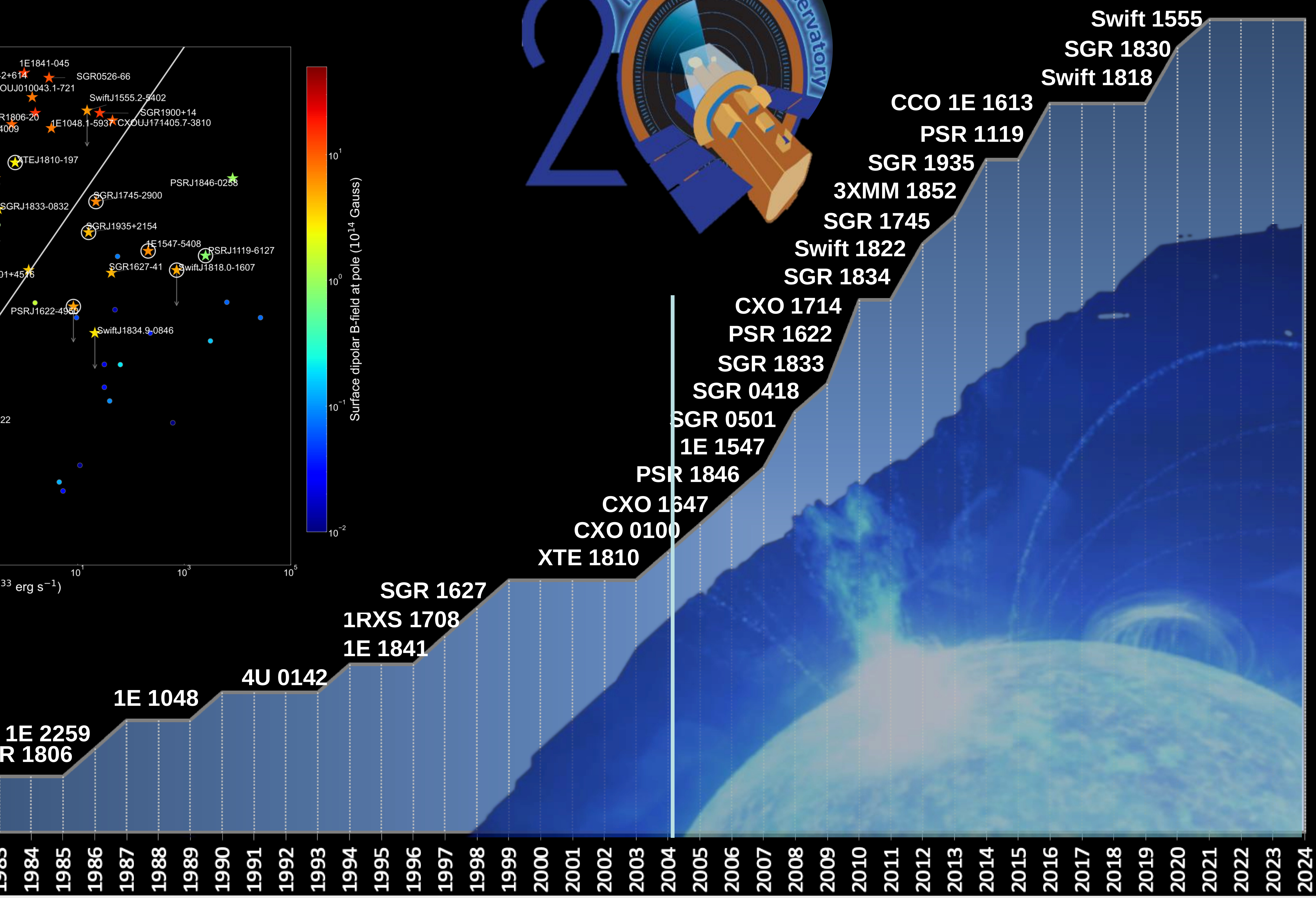
MAGNETAR NUMEROLOGY





MAGNETAR NUMEROLOGY





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MAGNETAR FLARES

Short bursts

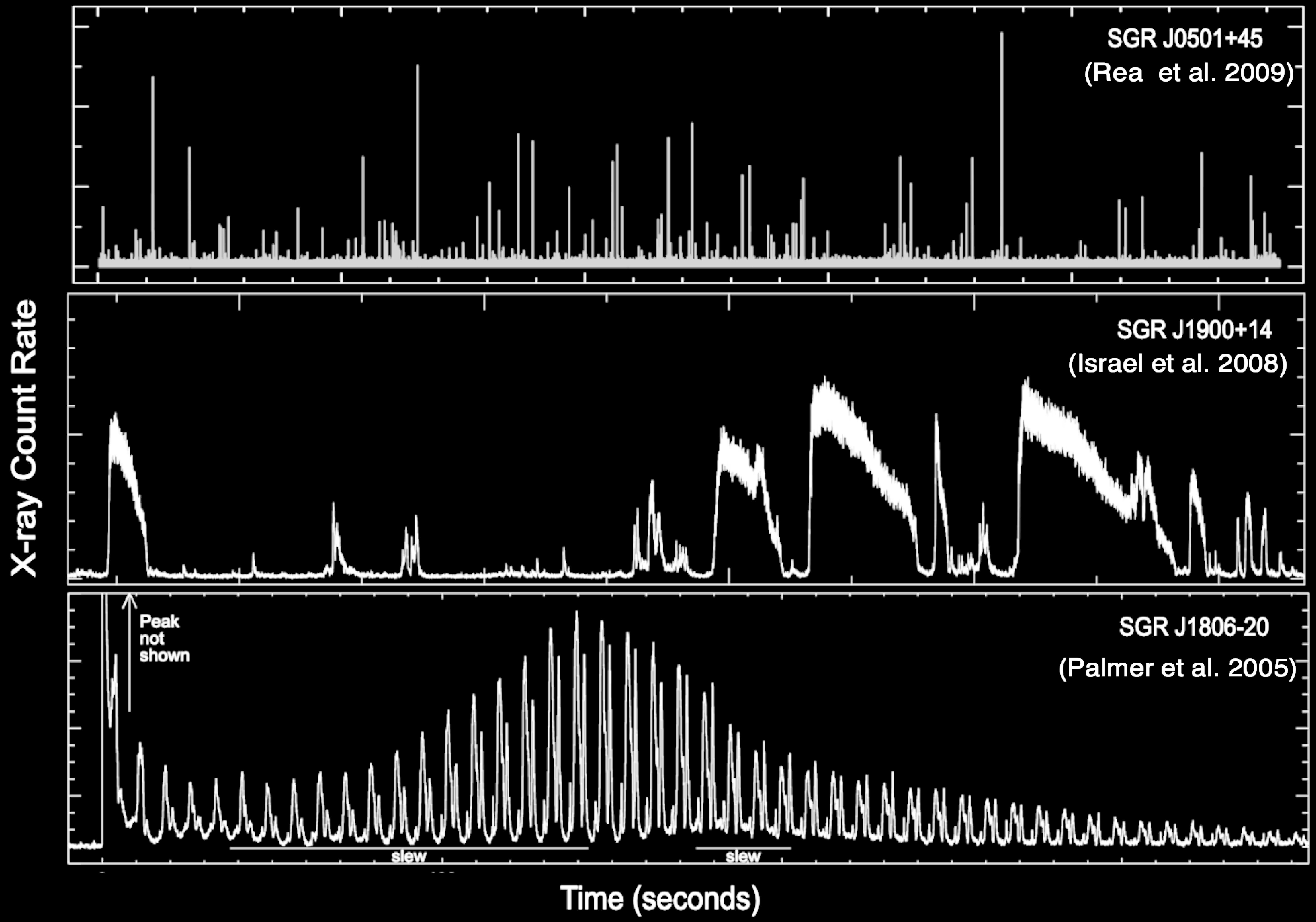
- the most common ones
- they last ~1-100ms
- peak lum ~10^{38-41} ergs/s
- soft γ-rays thermal spectra

Intermediate bursts

- they last ~ 1-40 s
- peak ~10^{41}-10^{43} ergs/s
- abrupt on-set
- Sometimes modulated by the spin period and QPOs
- usually soft γ-rays thermal spectra

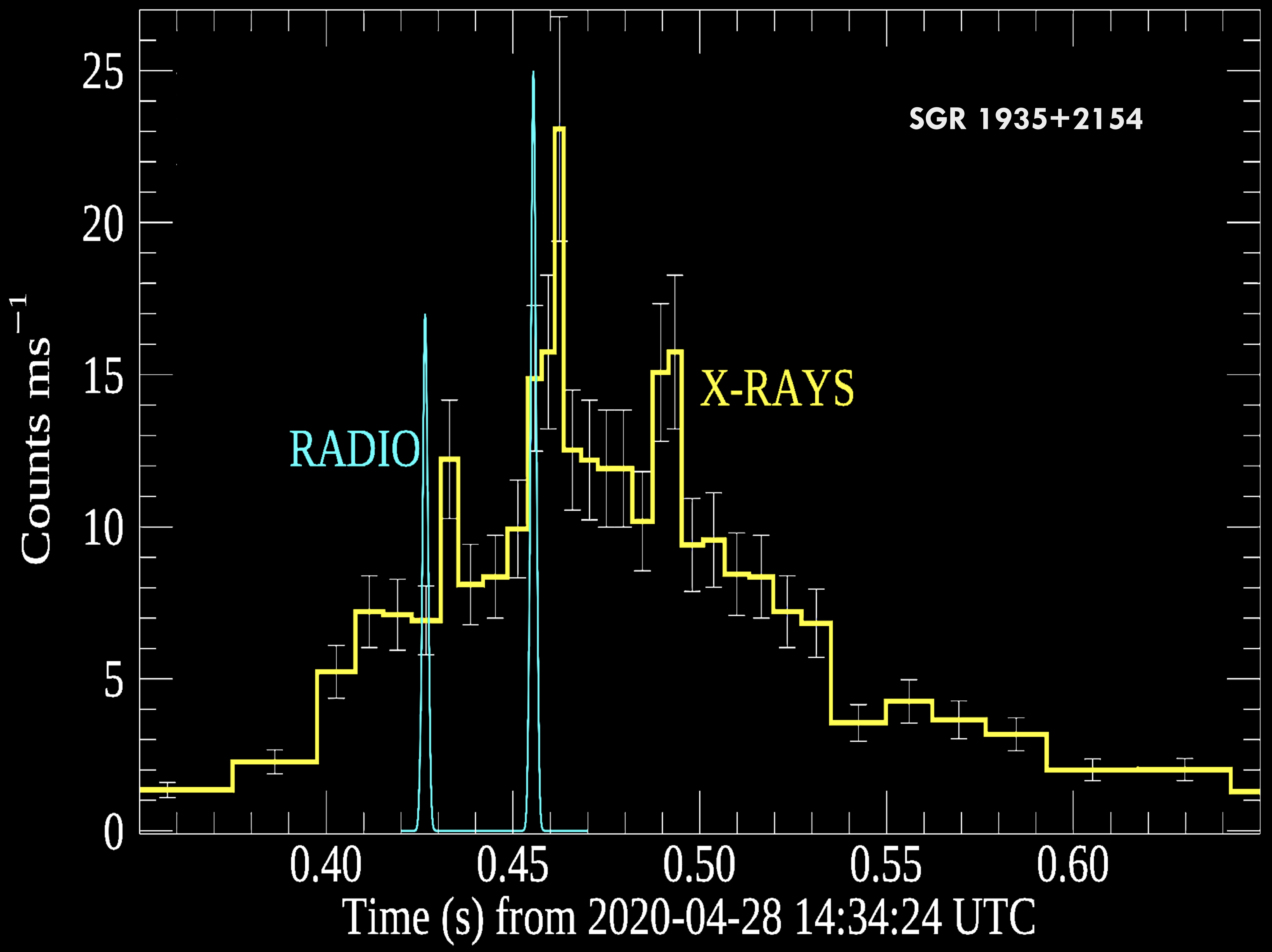
Giant Flares

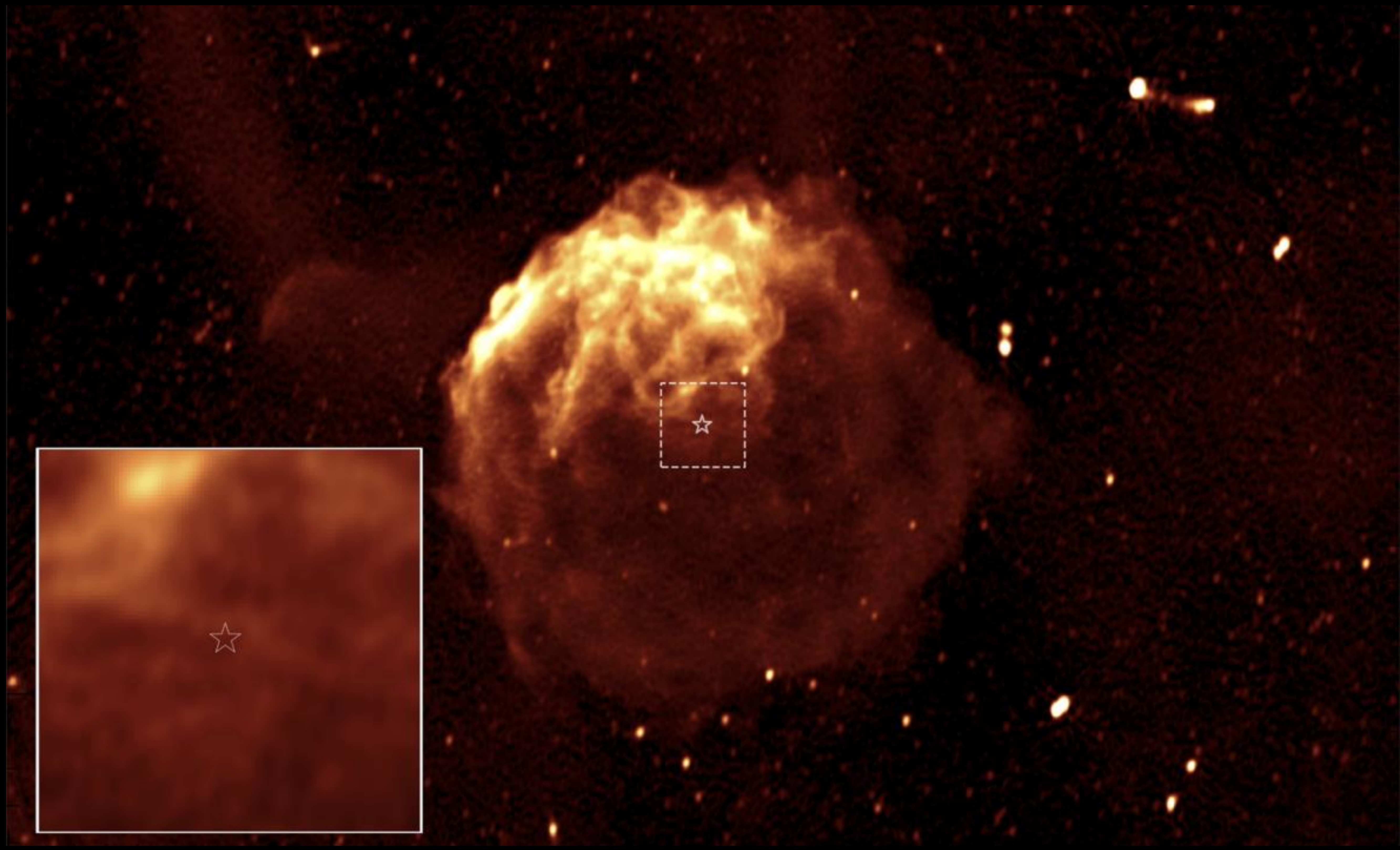
- very rare, every ~15 years
- the peak lasts ~ 1-20ms
- peak lum ~10^{43}-10^{45} ergs/s
- the tail lasts ~100 s
- tail lum ~10^{41}-10^{43} ergs/s
- the peak has a hard spectrum which rapidly become softer in the burst tail
- the tail is modulated by the NS spin pulsations, and QPOs



Ses S. Mereghetti's talk!

THE FRB-MAGNETAR CONNECTION



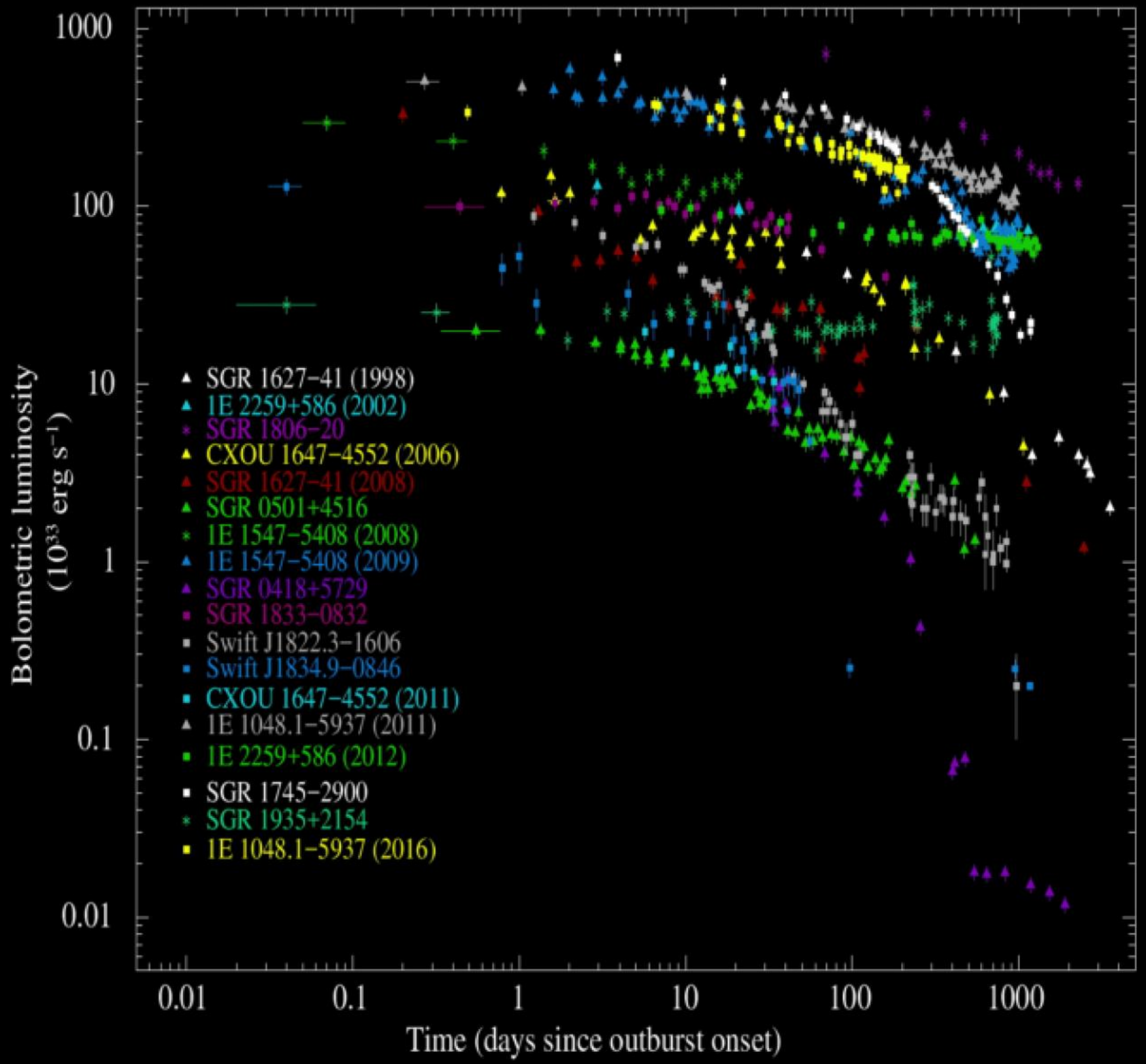


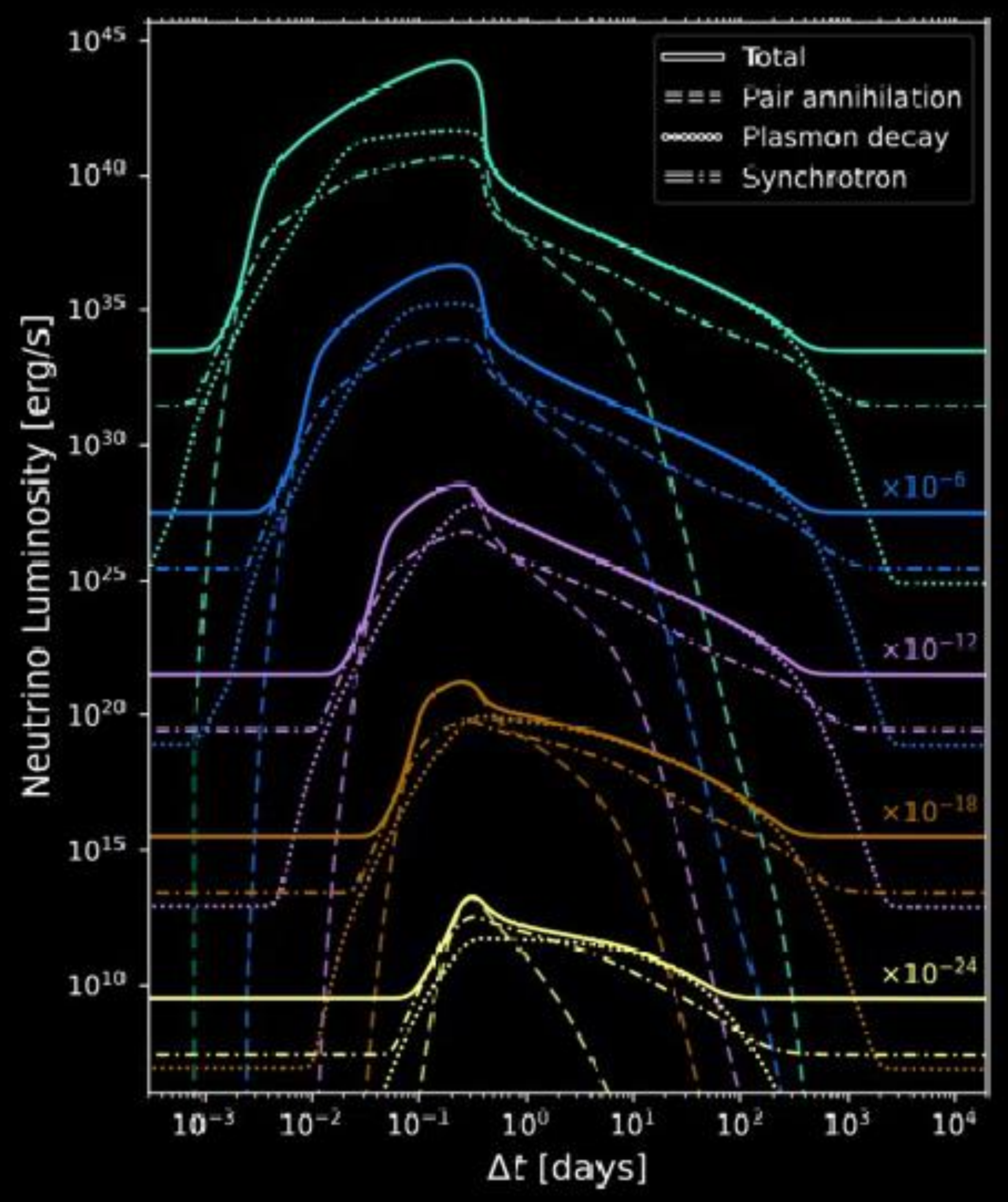
Bailes et al. 2021

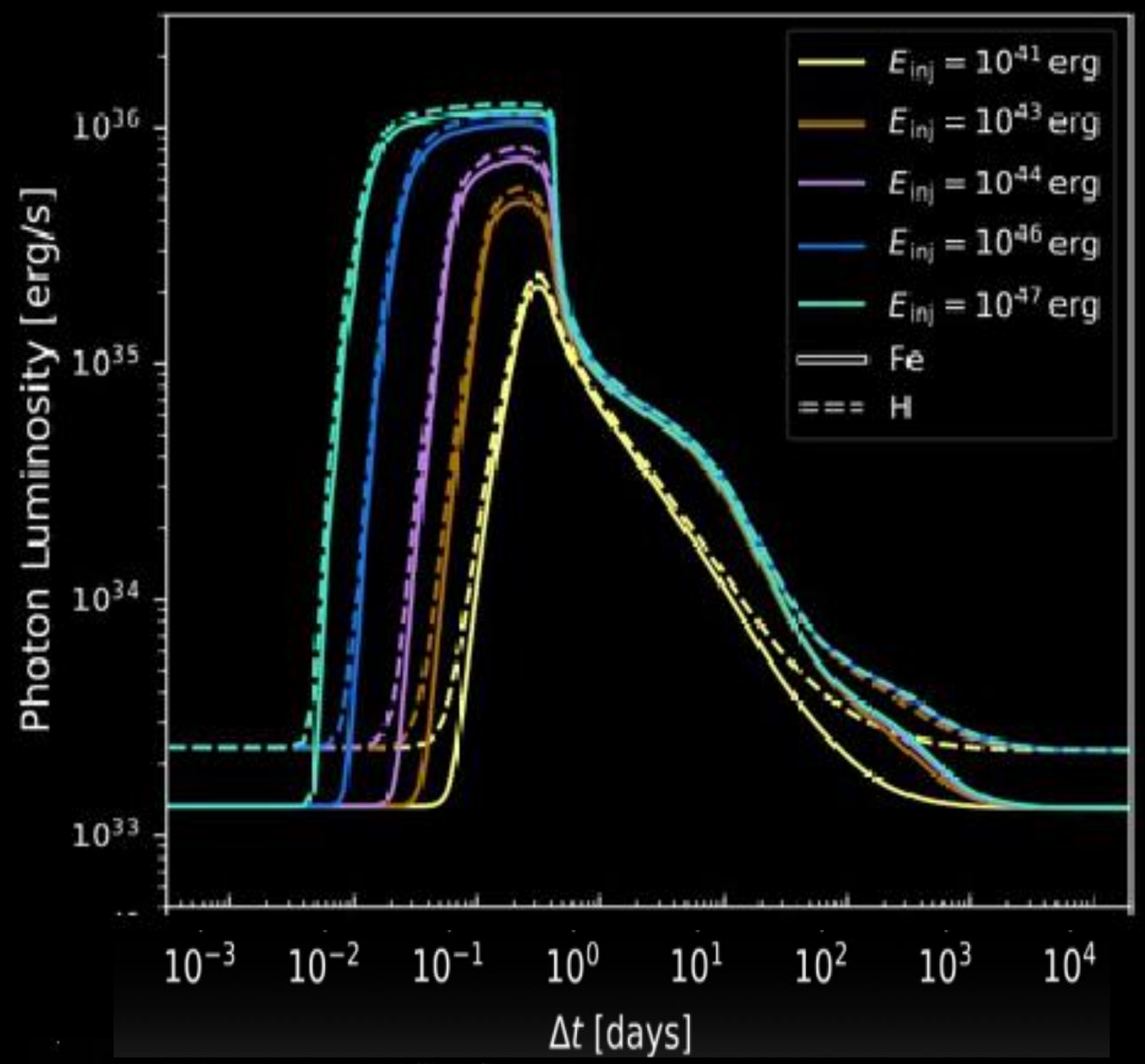
(CHIME Collaboration et al. 2020, Bochenek et al. 2020, Mereghetti et al. 2020, Ridaia et al. 2020, see also Petroff, Hessels & Lorimer 2022)

MAGNETAR OUTBURSTS

Ses F. Coti Zelati's talk!





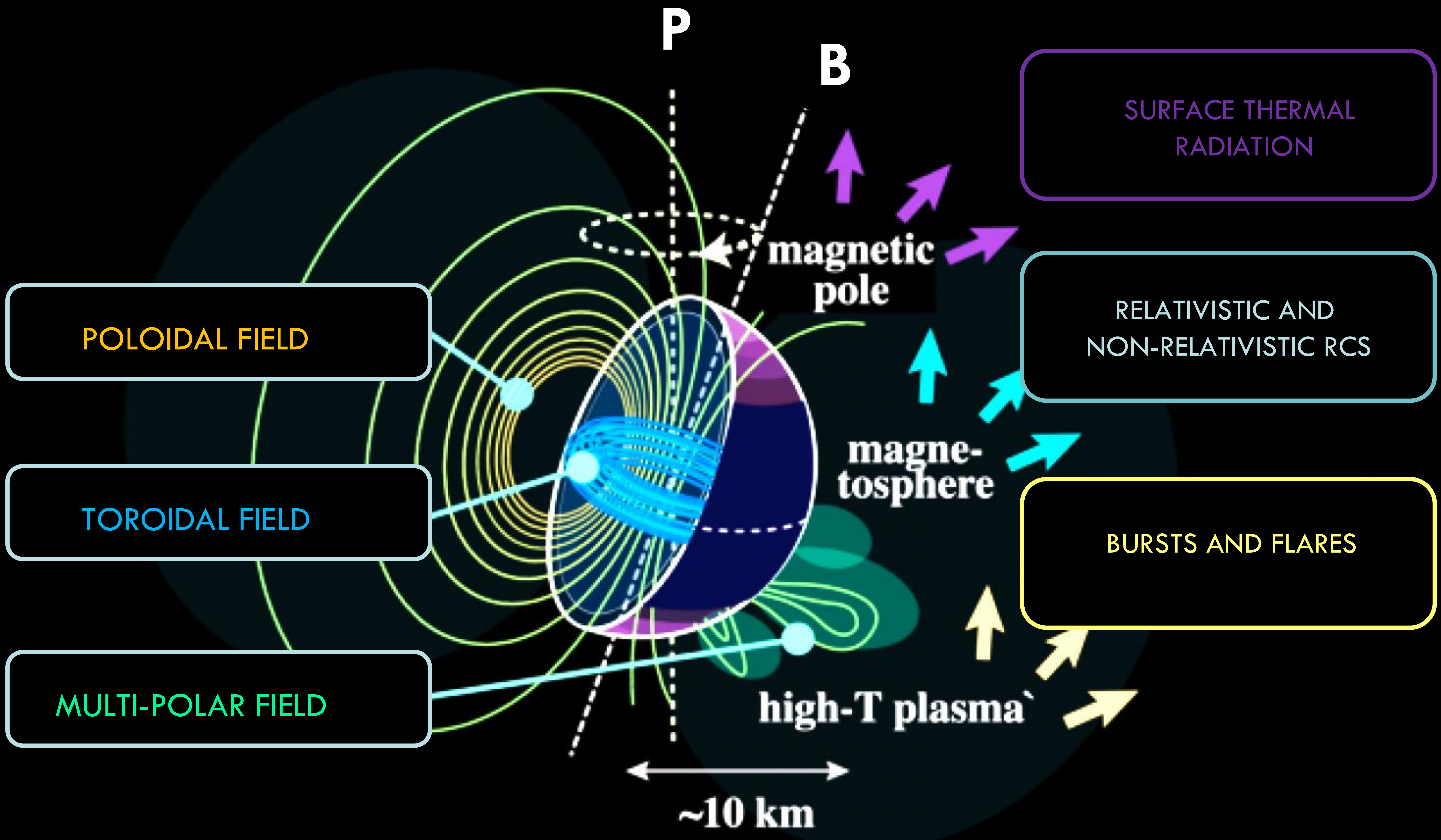


(Coti Zelati, Rea, Pons, Campana & Esposito 2018)

http://magnetars.ice.csic.es

(De Grandis, Rea, Kovlakas, Coti Zelati et al. 2025 submitted)

MAGNETAR GENERAL EMISSION CHARTOON



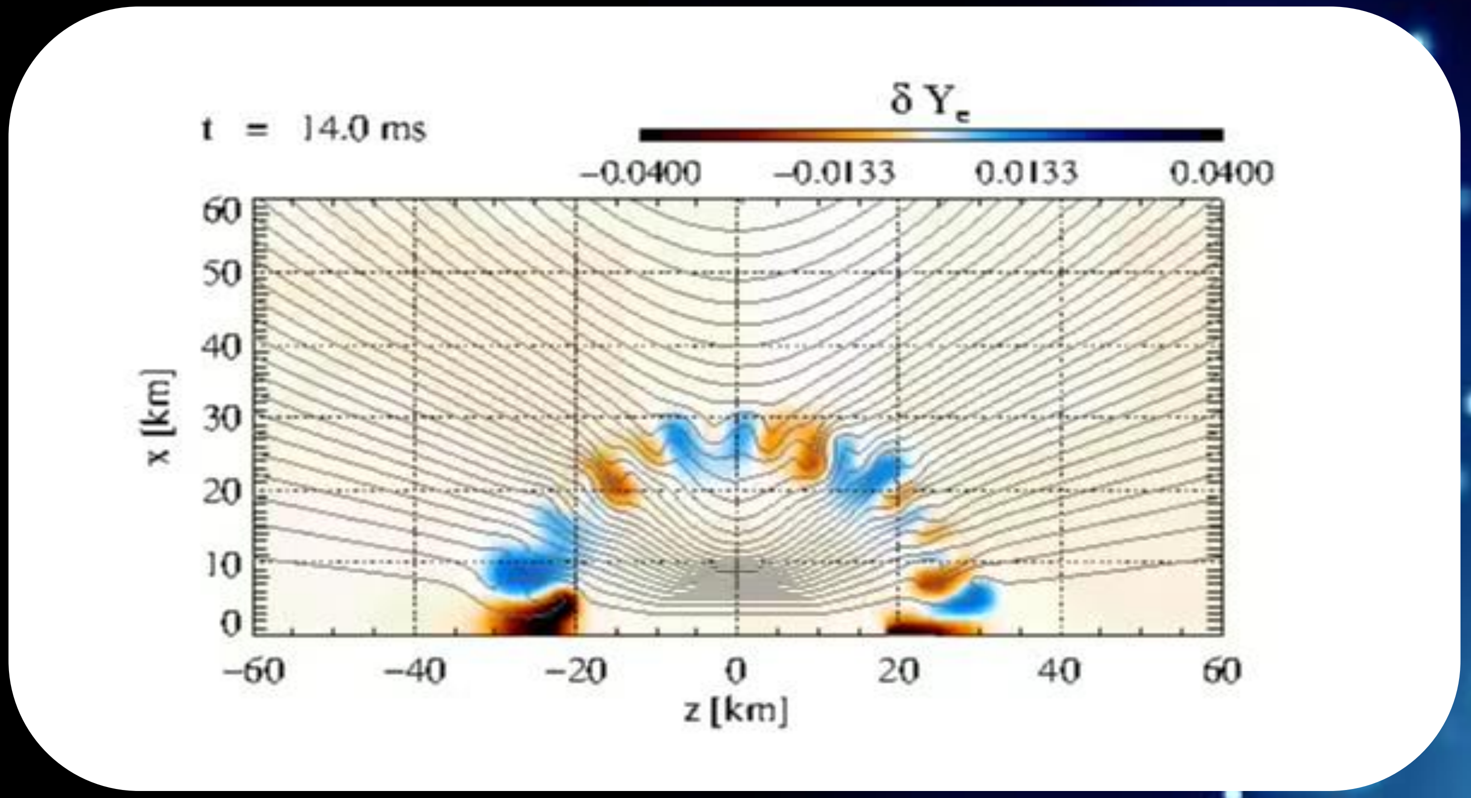
(adapted from Enoto et al. 2019)

MAGNETAR BIRTH RATES, EVOLUTION, AND THEIR IMPRINT IN THE TRANSIENT X-RAY SKY

MAGNETAR BIRTH

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)

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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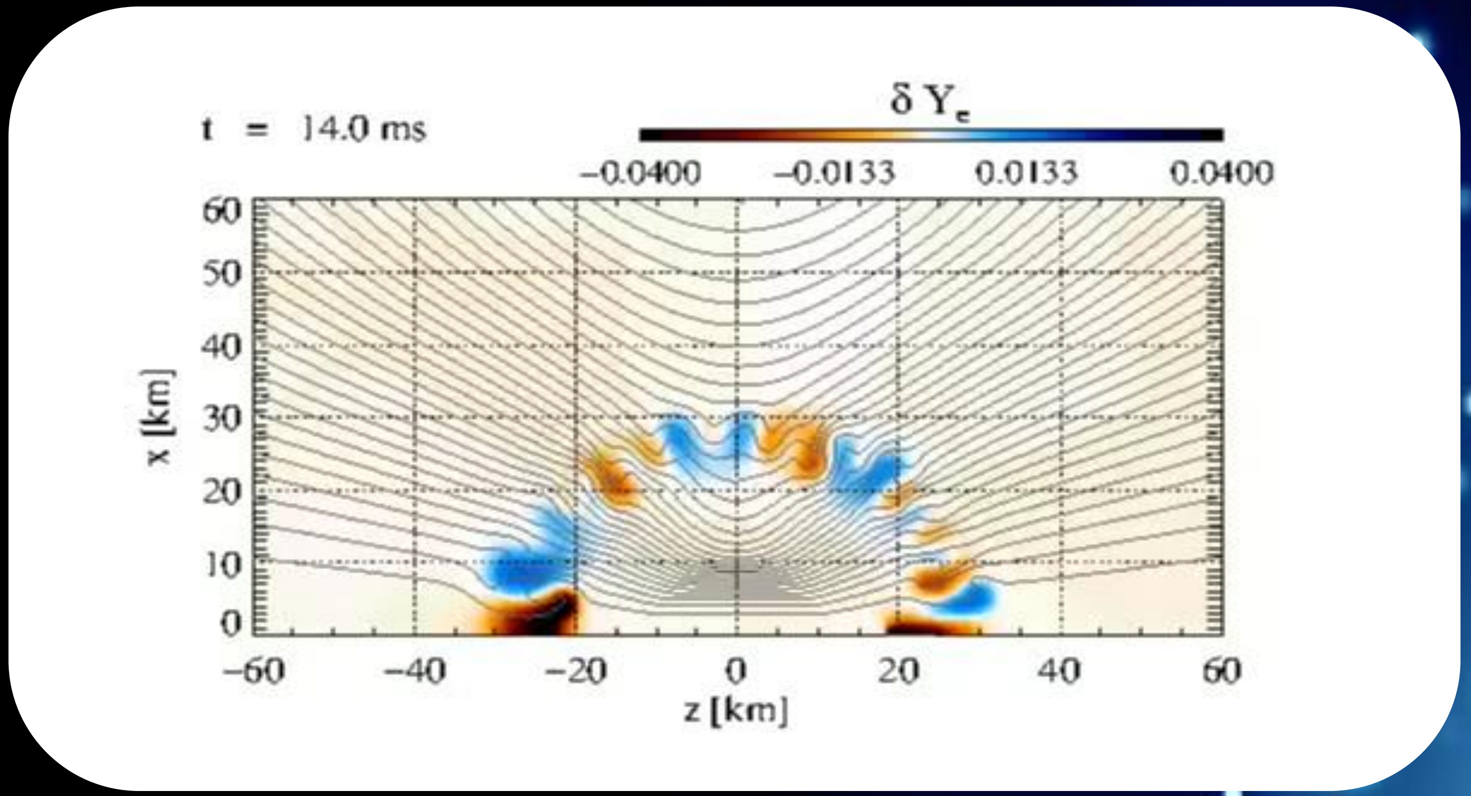


(Obergaulinger, Aloy & Janka 2015)

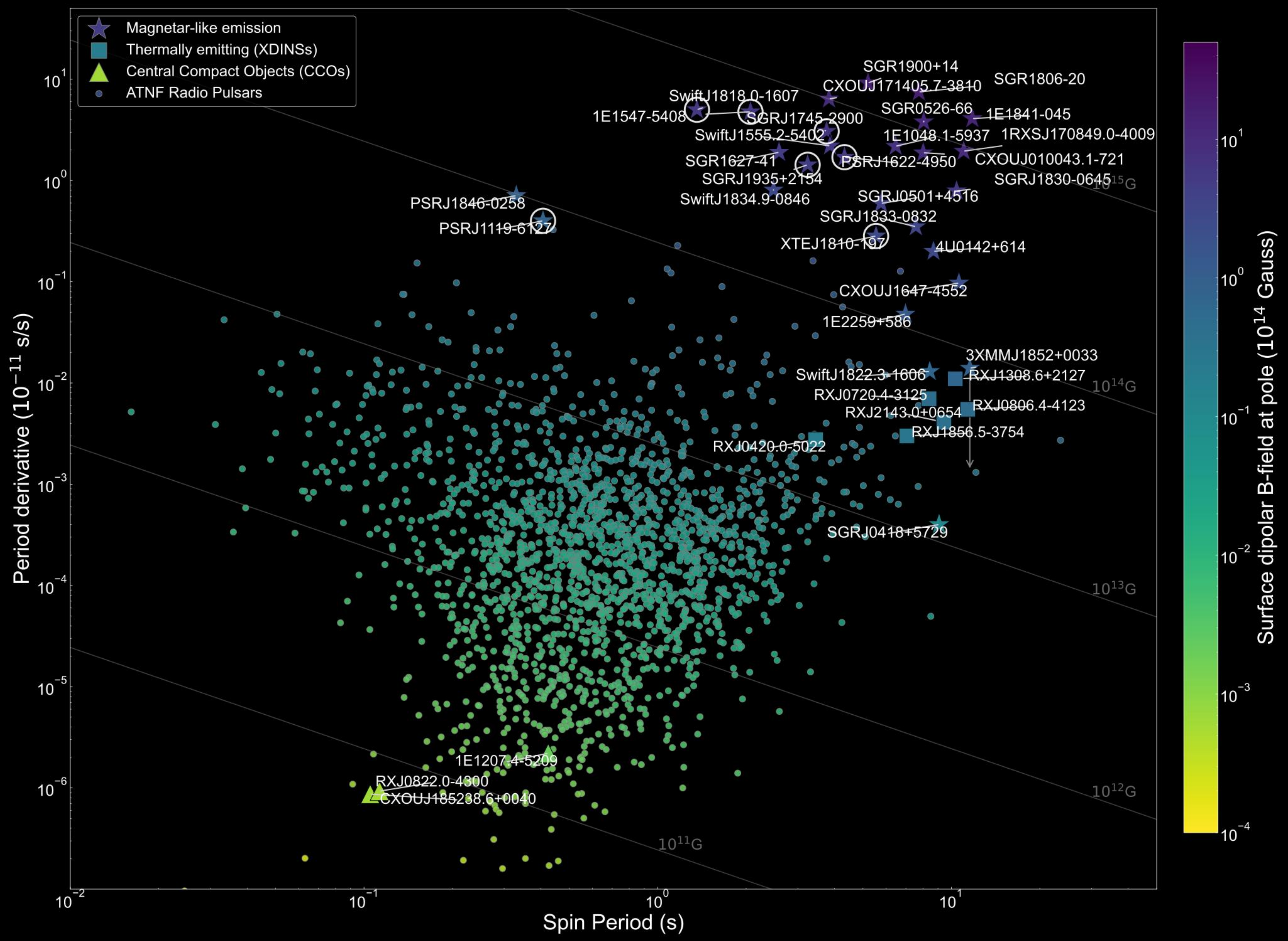
Observationally…

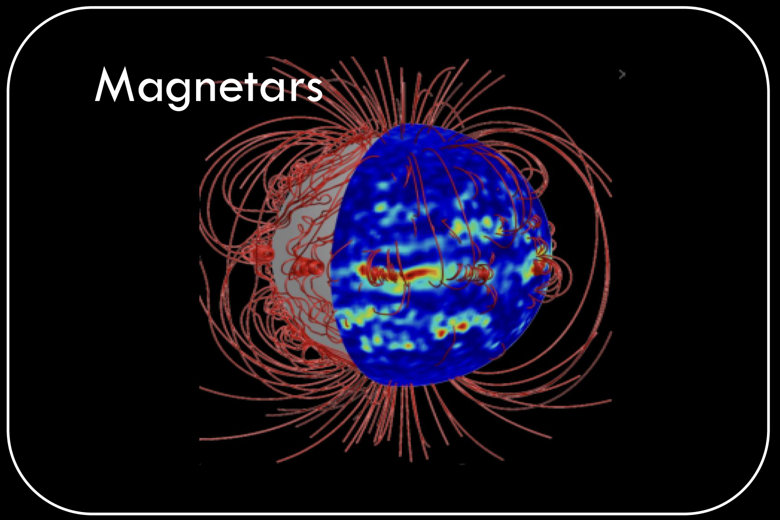
- Proper motions for ~9 objects: 100-300 km/s range
- A few magnetars coincident with massive star clusters
- One case: a wind blown boubble observed in radio
- One case: a run-away star close-by is detected.
- ~6 confirmed SNRs, 3 more possibly associated

Massive Cluster Westerlund 1 in X-ray

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

THE ISOLATED PULSAR POPULATION



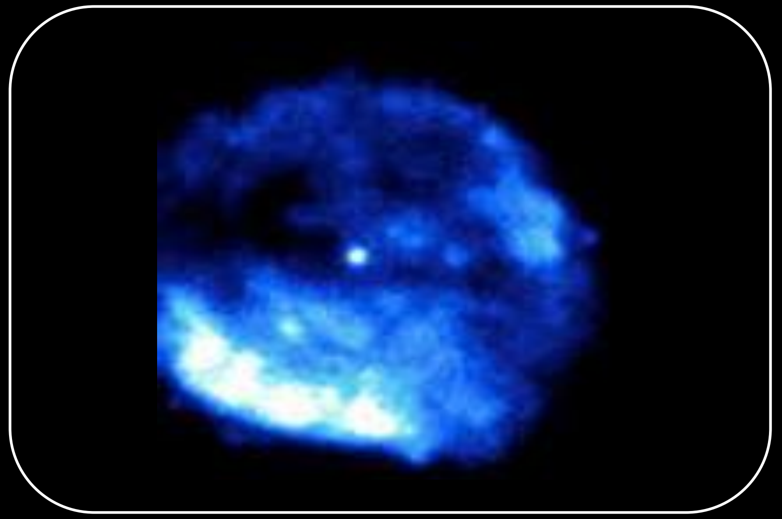


MAGNETARS

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

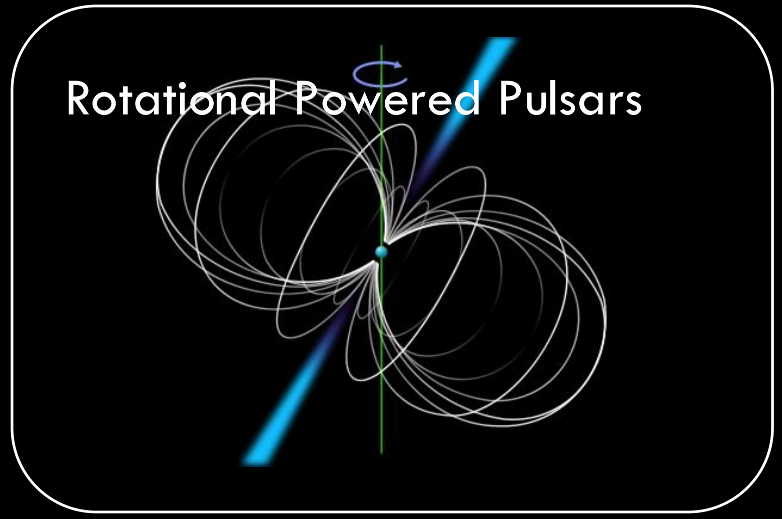
THERMAL NSs (XDINS)

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.

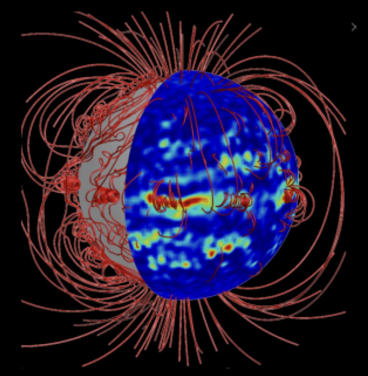


ROTATIONAL POWERED PULSARS

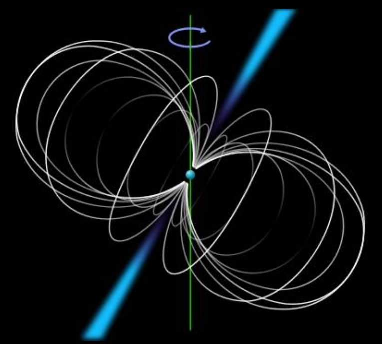
Powered by rotational energy.
Typically emitting in radio.

SMOKING GUNS FOR THE MAGNETAR BIRTH RATE

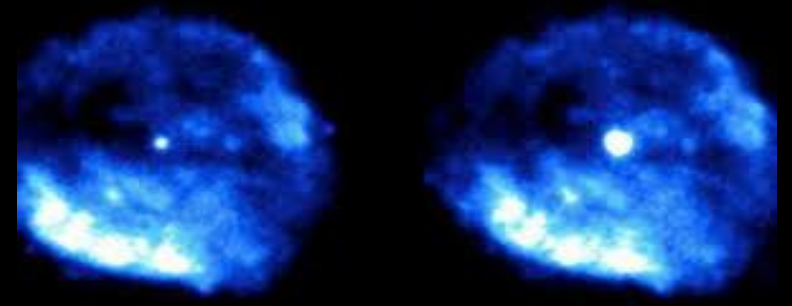
1. Magnetars were discovered having low dipolar B-fields and strong magnetic structures.
   (Rea et al. 2010, Science; 2012, 2013, 2014, ApJ; Tiengo et al. 2013, Nature)



2. Two young rotational powered pulsars (PSR1846 and PSR1119) showed magnetar activity.
   (Gavriil et al. 2008, Nature; Kumar & Safi-Harb, 2008, ApJ; Archibald et al. 2016, ApJ; Sathyaprakash et al. 2024, ApJ)

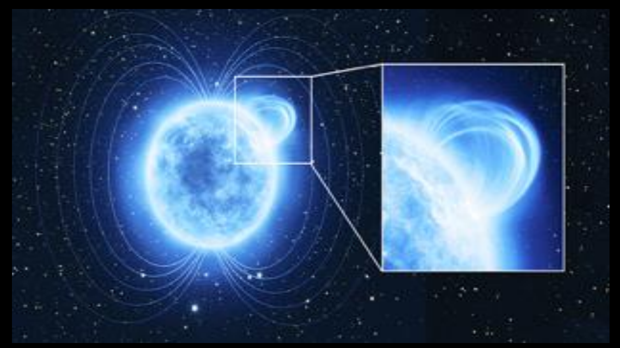


3. A central compact object (CCO) with a 6.4hr period showed magnetar-like activity.
   (Rea et al. 2016, ApJ Letters; D'Ai et al. 2016, MNRAS; Borghese et al. 2018, ApJ)



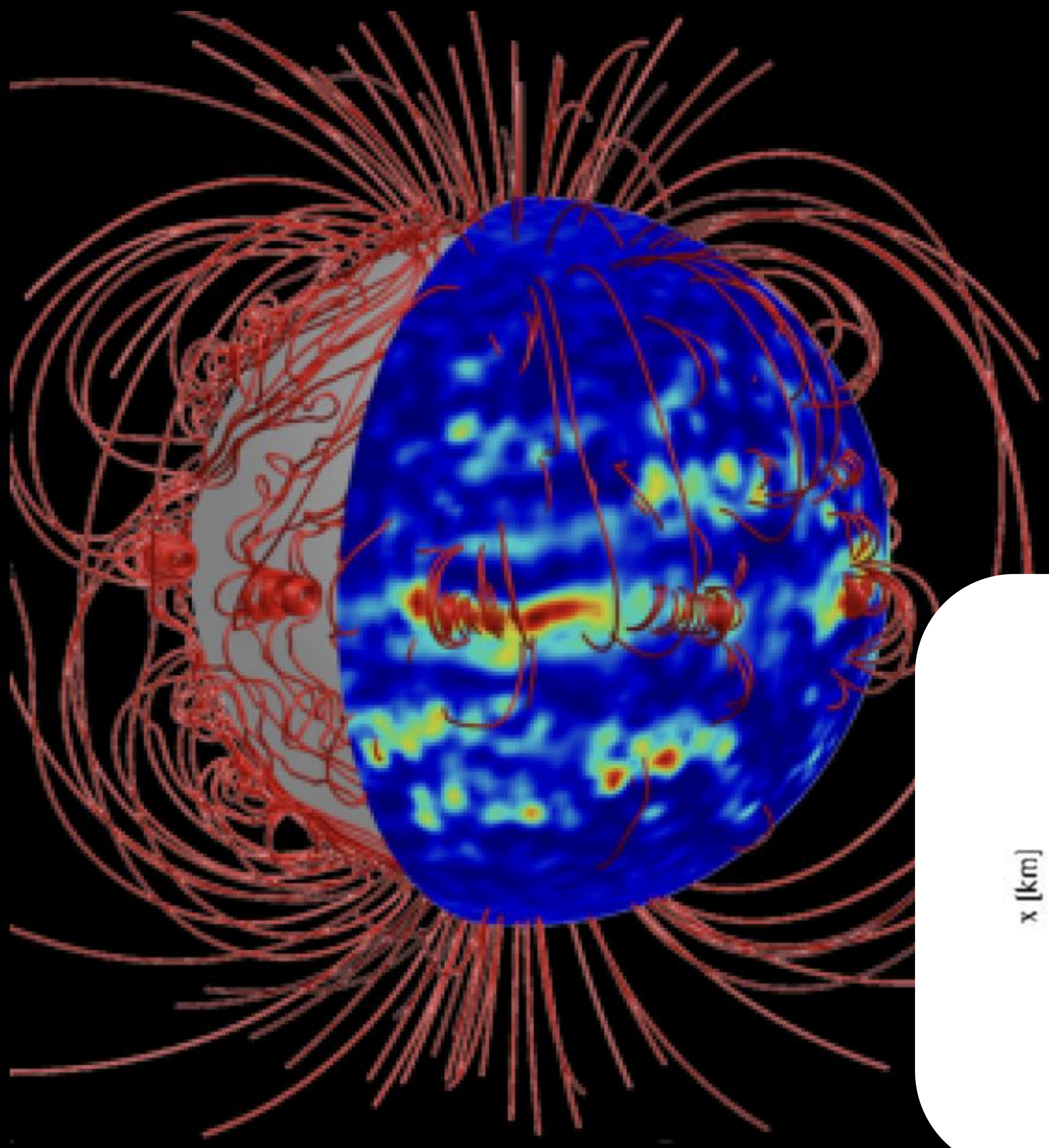
quiescence outburst

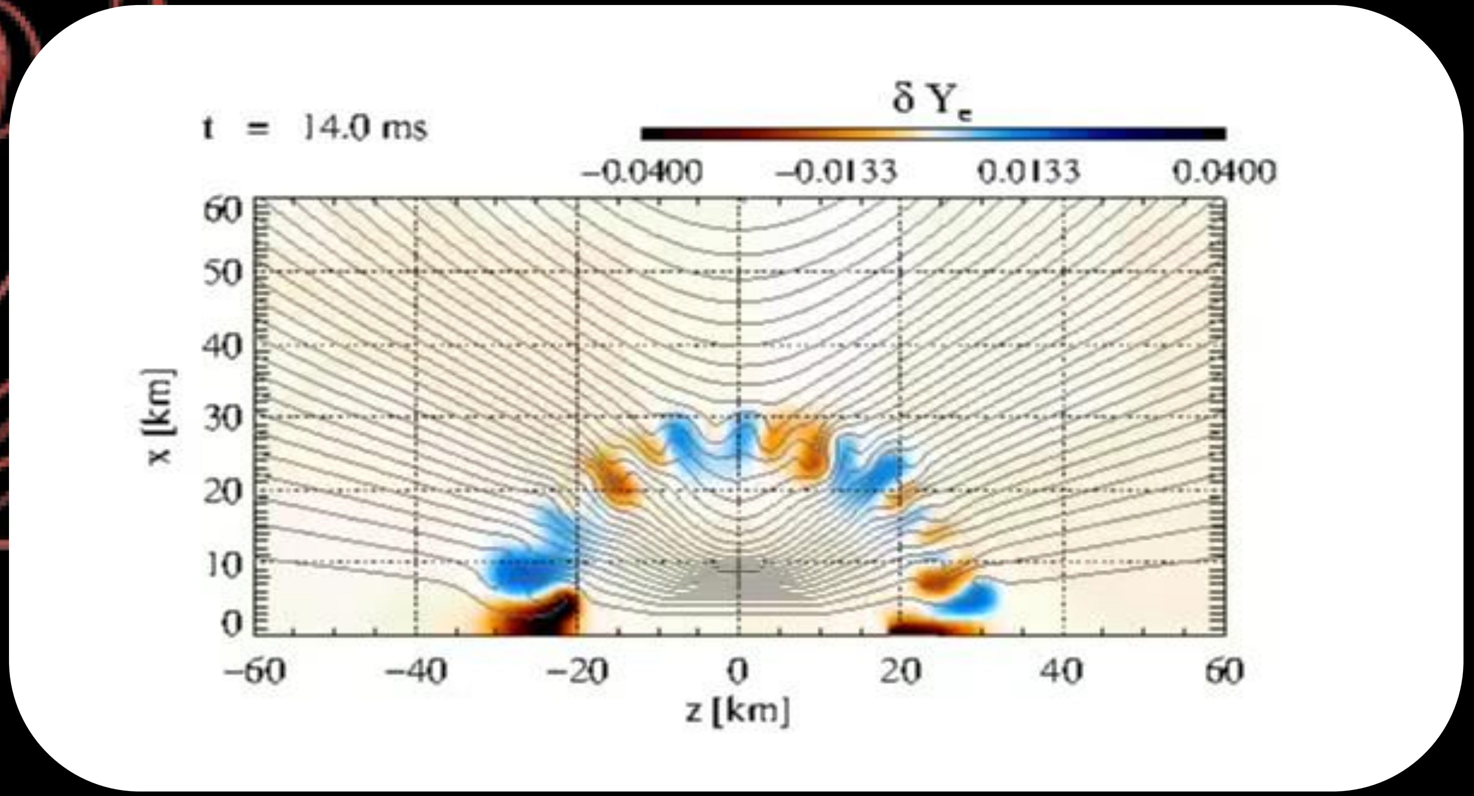
4. Two X-ray Dim Isolated Neutron Stars show evidence of strong magnetic structures.
   (Borghese et al. 2015, 2017, ApJ)



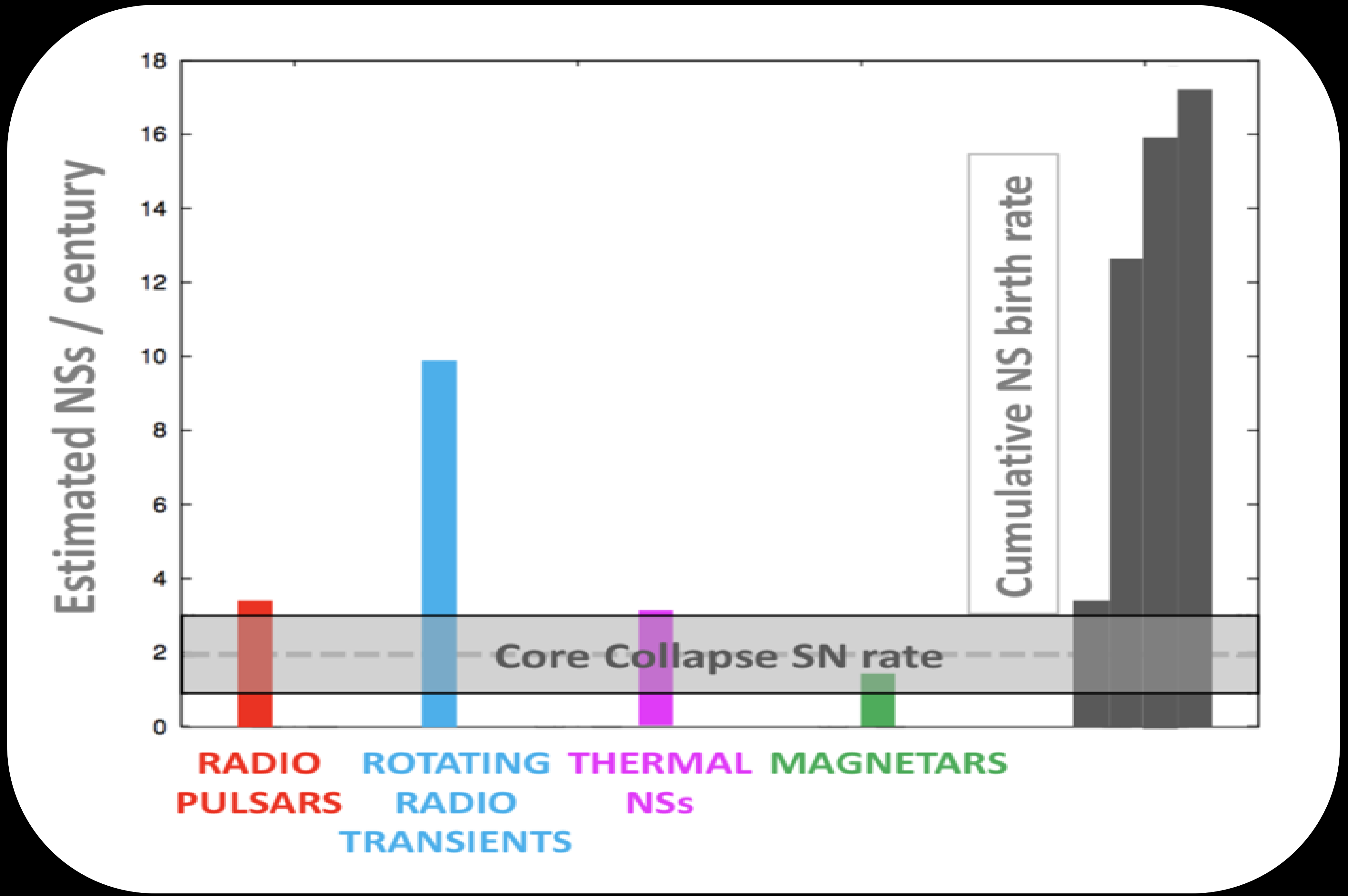
MAGNETAR BIRTH RATES, EVOLUTION, AND THEIR IMPRINT IN THE TRANSIENT X-RAY SKY

NS CLASSES AND CC SN RATES





(Obergaulinger, Janka & Aloy 2015)



(adapted from Keane & Kramer 2008)

1. Magnetar-like emission is present in all neutron star classes.
2. 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

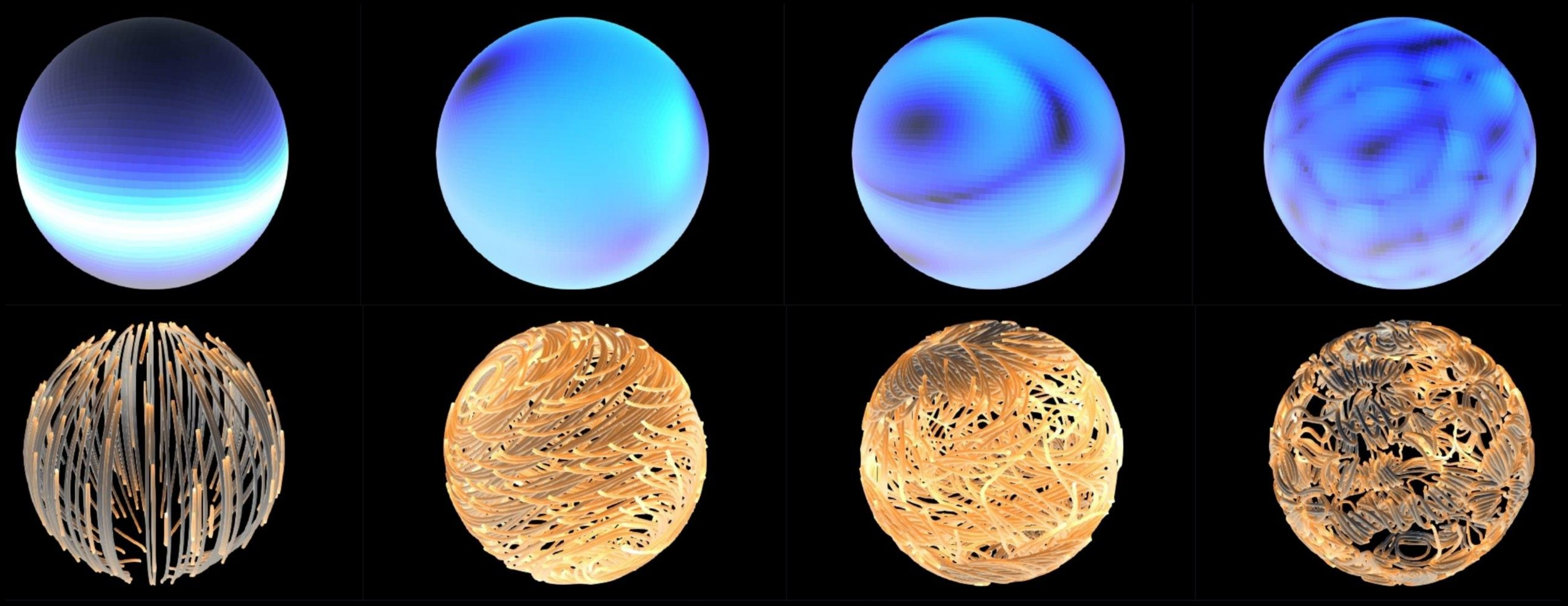
$$C_v e^{\nu} \frac{\partial \mathbf{T}}{\partial t} + \nabla \times [-k \times \nabla(e^{\nu}\mathbf{T})] = e^{2\nu}[H - Q]$$

ENERGY BALANCE EQUATION

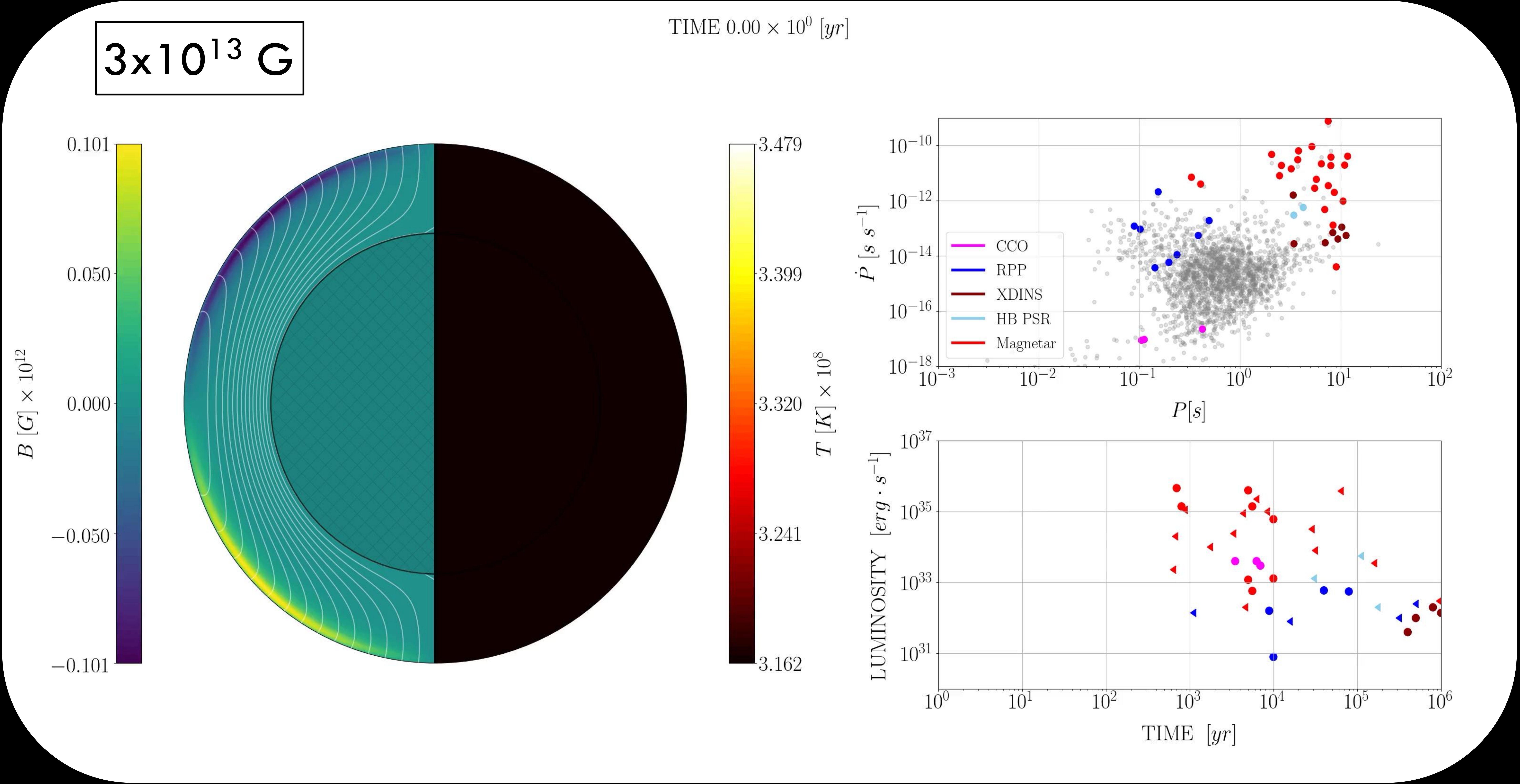
$$\frac{\partial \mathbf{B}}{\partial t} = -\nabla \times \left\{ \eta \nabla \times (e^{\nu}\mathbf{B}) + \left[\frac{c e^{-\nu}}{4\pi e n_e} \nabla \times (e^{\nu}\mathbf{B}) \right] \times (e^{\nu}\mathbf{B}) \right\}$$

HALL INDUCTION EQUATION

Electrical Resistivity

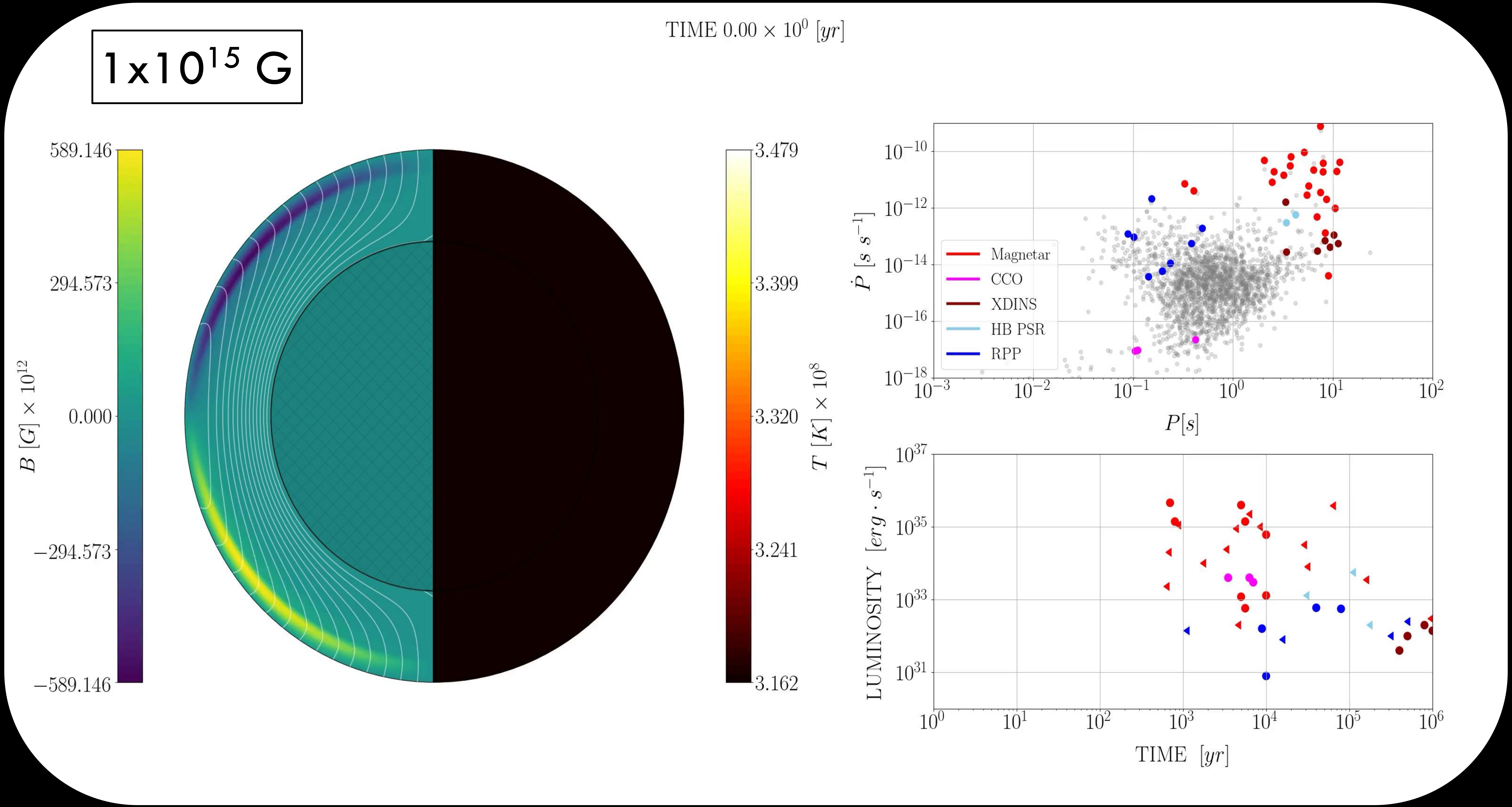


NEUTRON STAR EVOLUTION: eMHD SIMULATIONS



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

NEUTRON STAR EVOLUTION: eMHD SIMULATIONS



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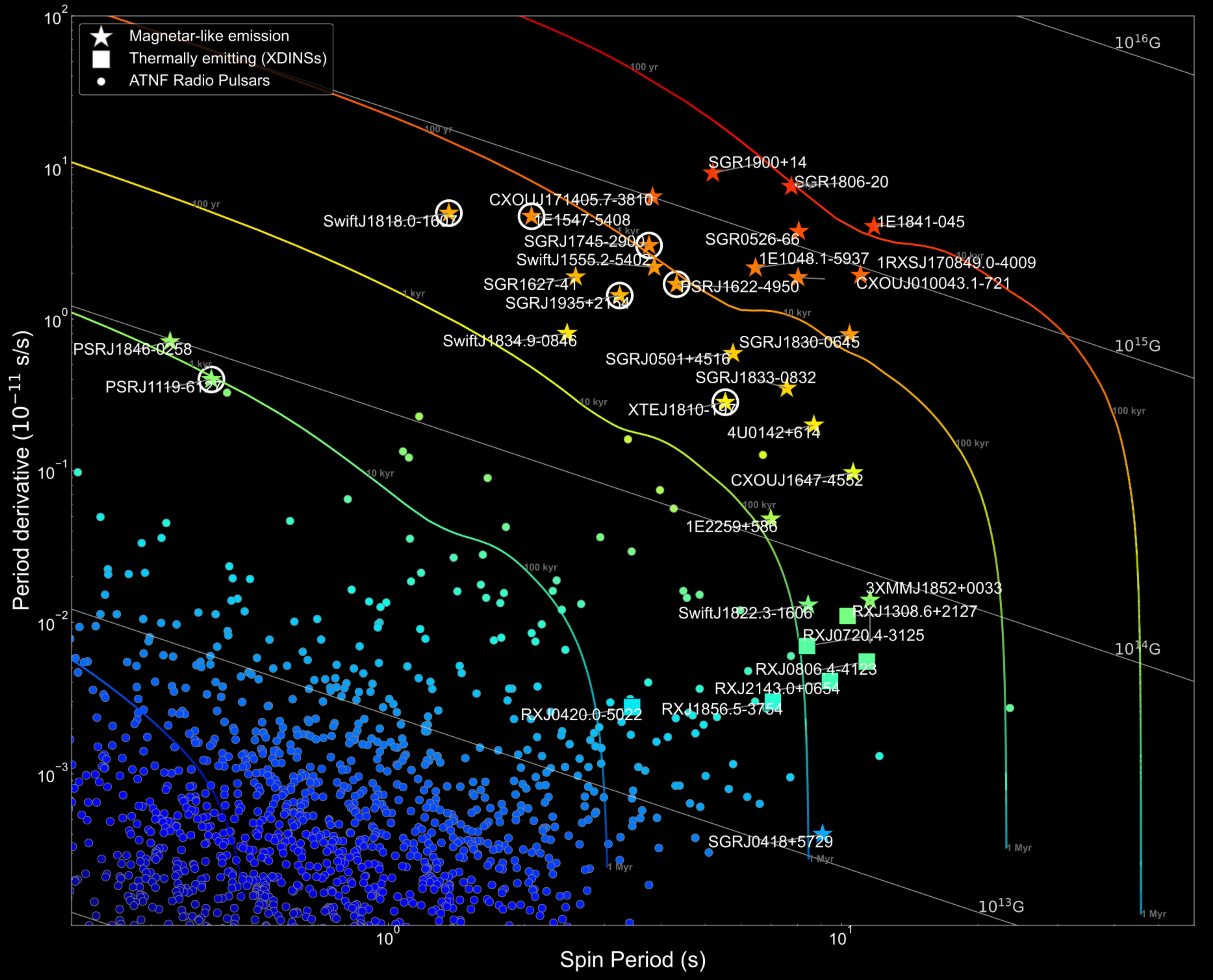
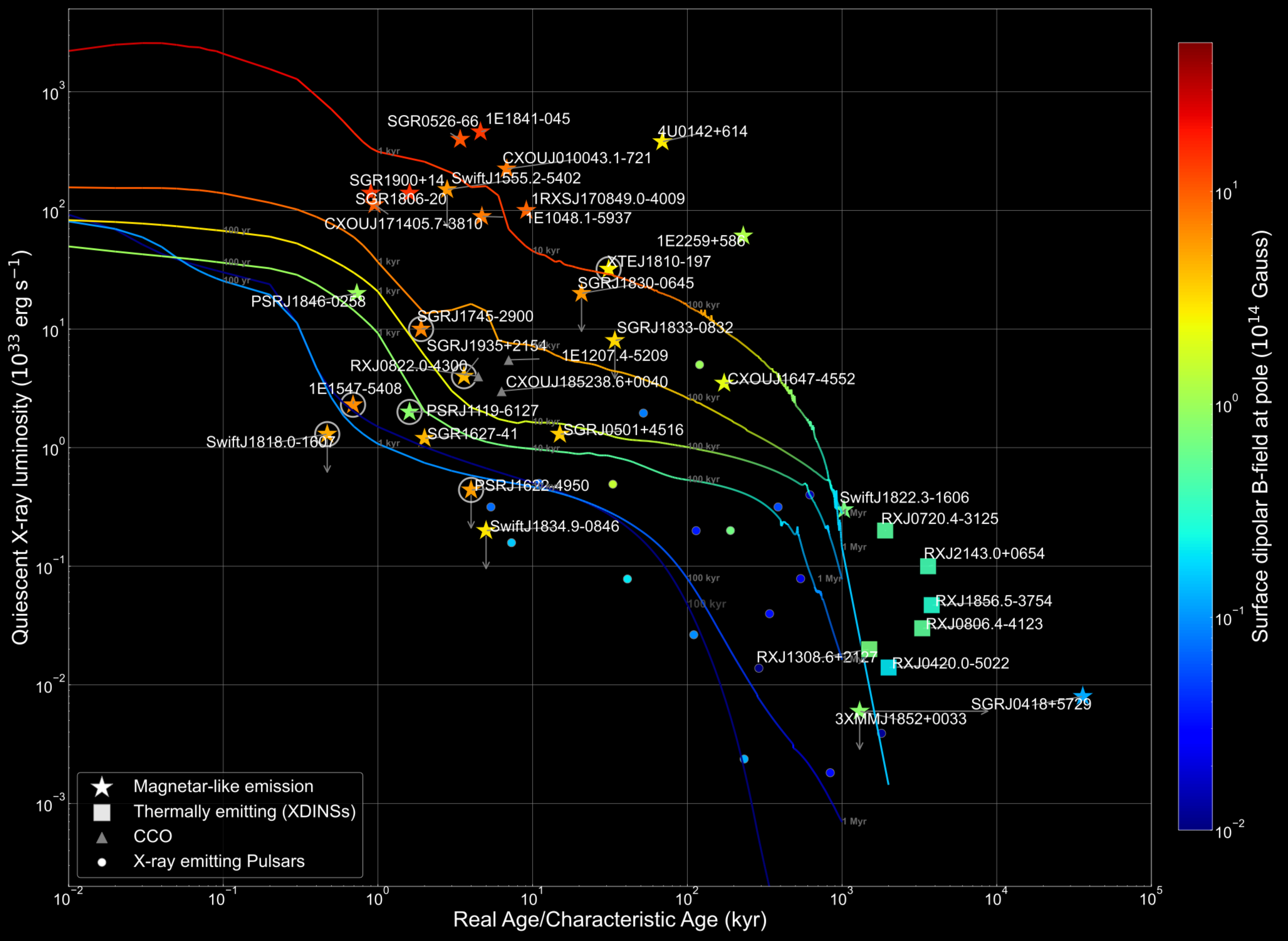
MAGNETARS EVOLUTION

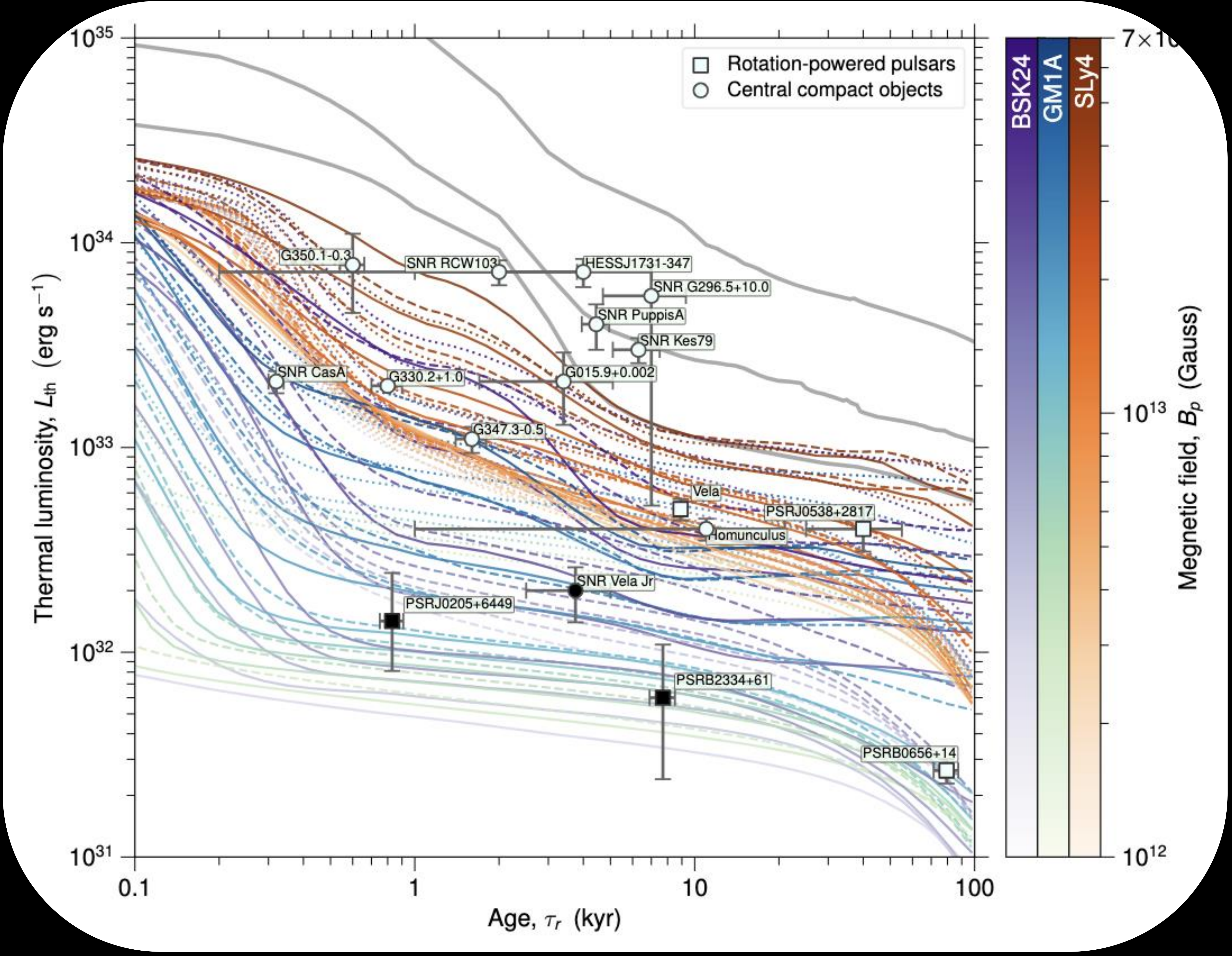


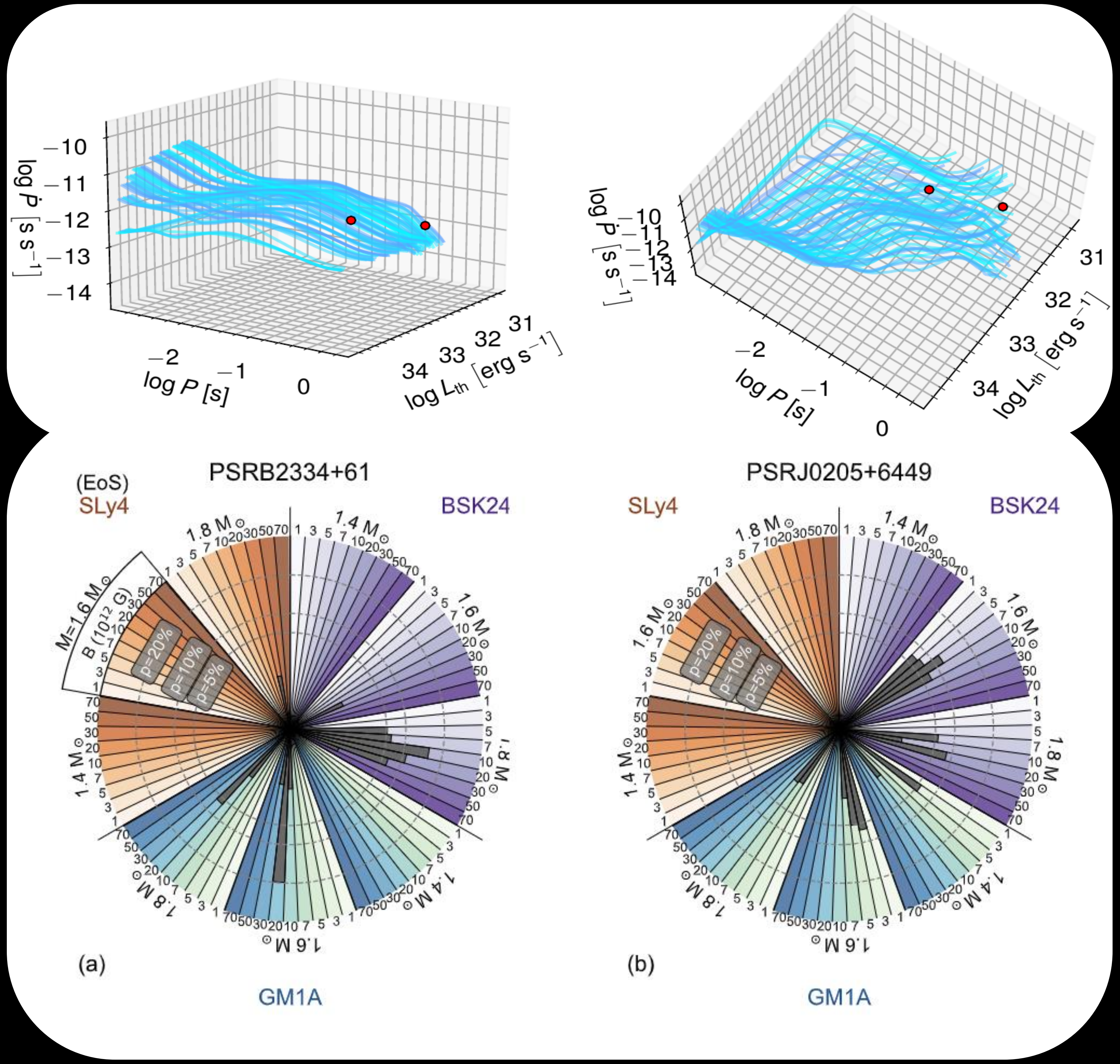


(Rea & De Grandis 2025, Elsevier encyclopedia)

MAGNETARS EVOLUTION: CONSTRAING NS EoS

(Marino, Dehman, Kovlakas, Rea, Pons & Viganó 2024, *Nature Astronomy*)



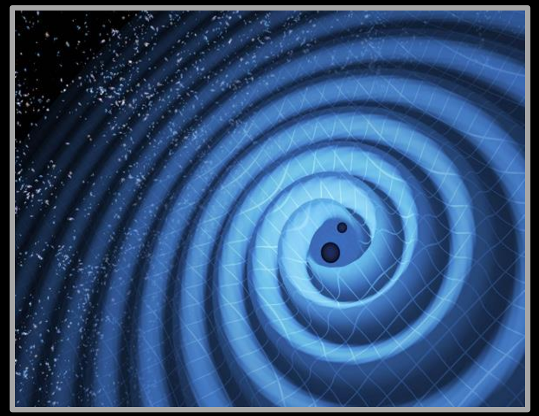


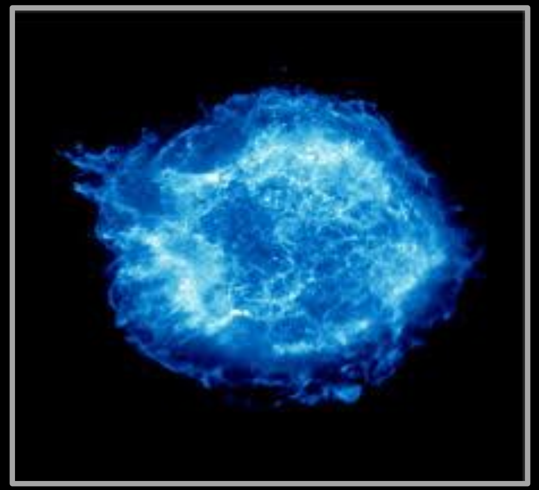
FAT COOLING NECESSARY FOR THE NS EoS AT LEAST FOR HIGH MASSES, to explain the three young and cold NSs.

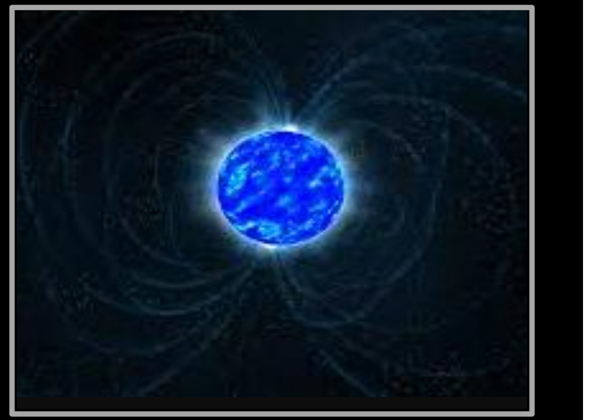
This excludes 75% of the current proposed EoS (in the Compose catalog).

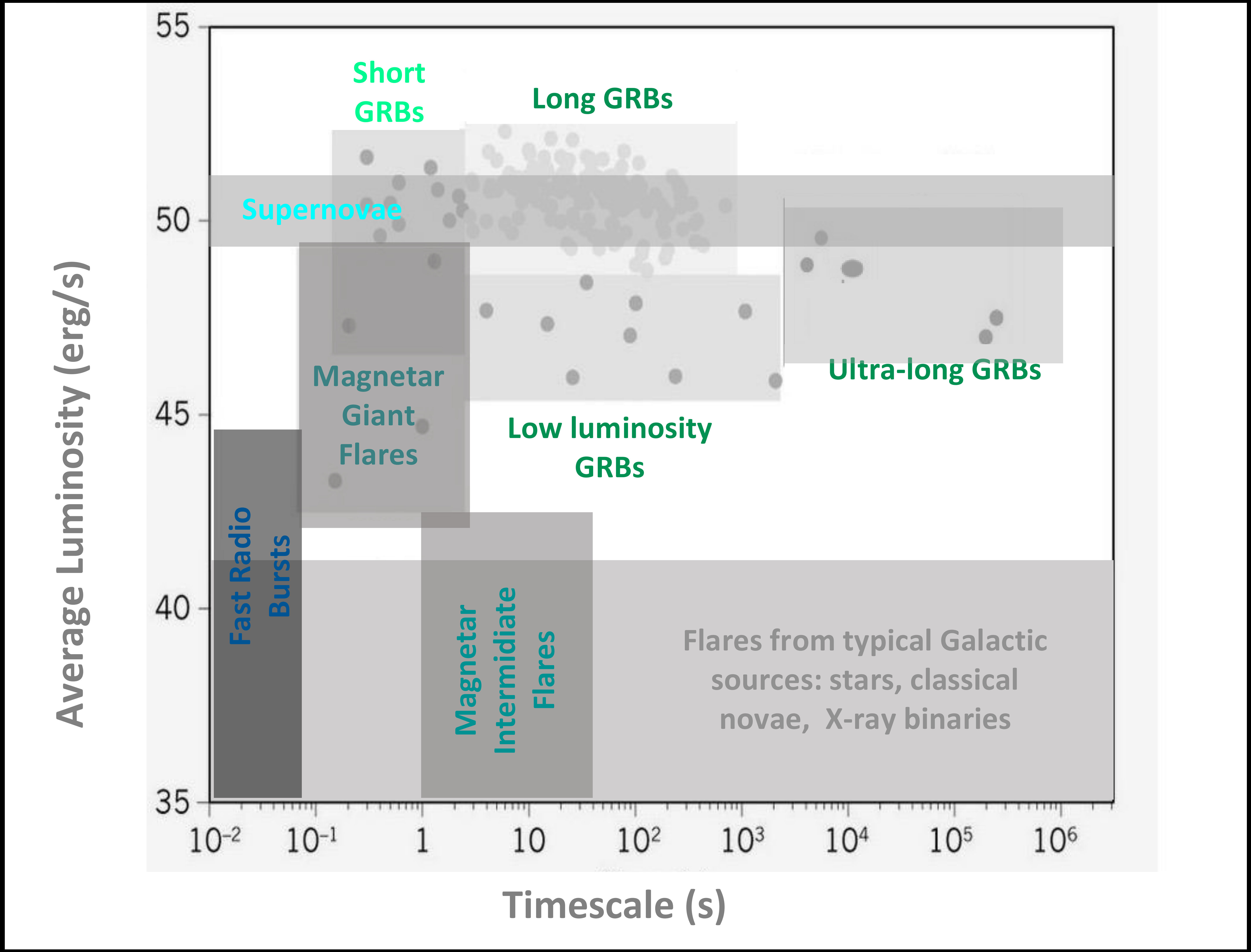
MAGNETAR BIRTH RATES, EVOLUTION, AND THEIR IMPRINT IN THE TRANSIENT X-RAY SKY

MAGNETARS AND THE TRANSIENT HIGH ENERGY SKY



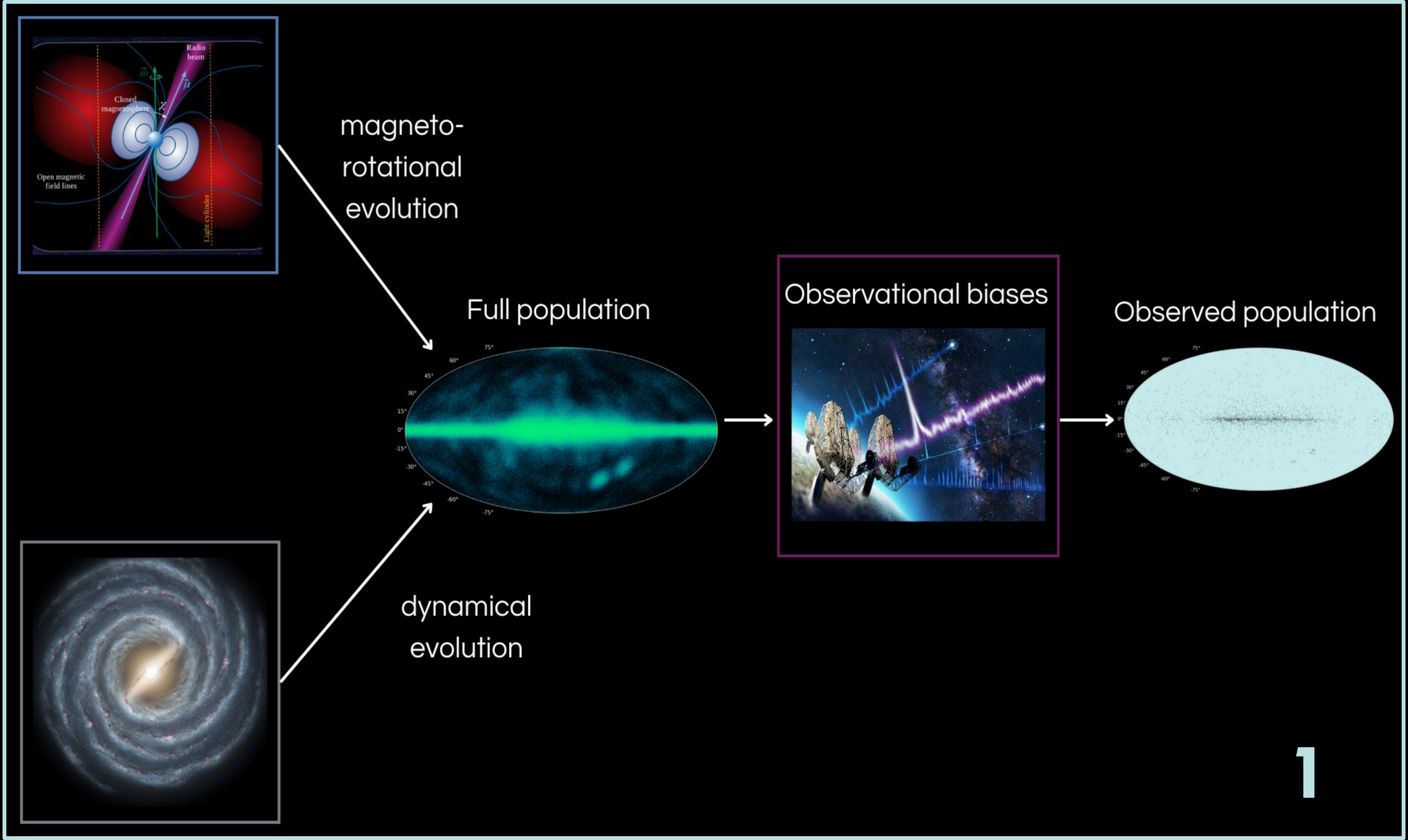


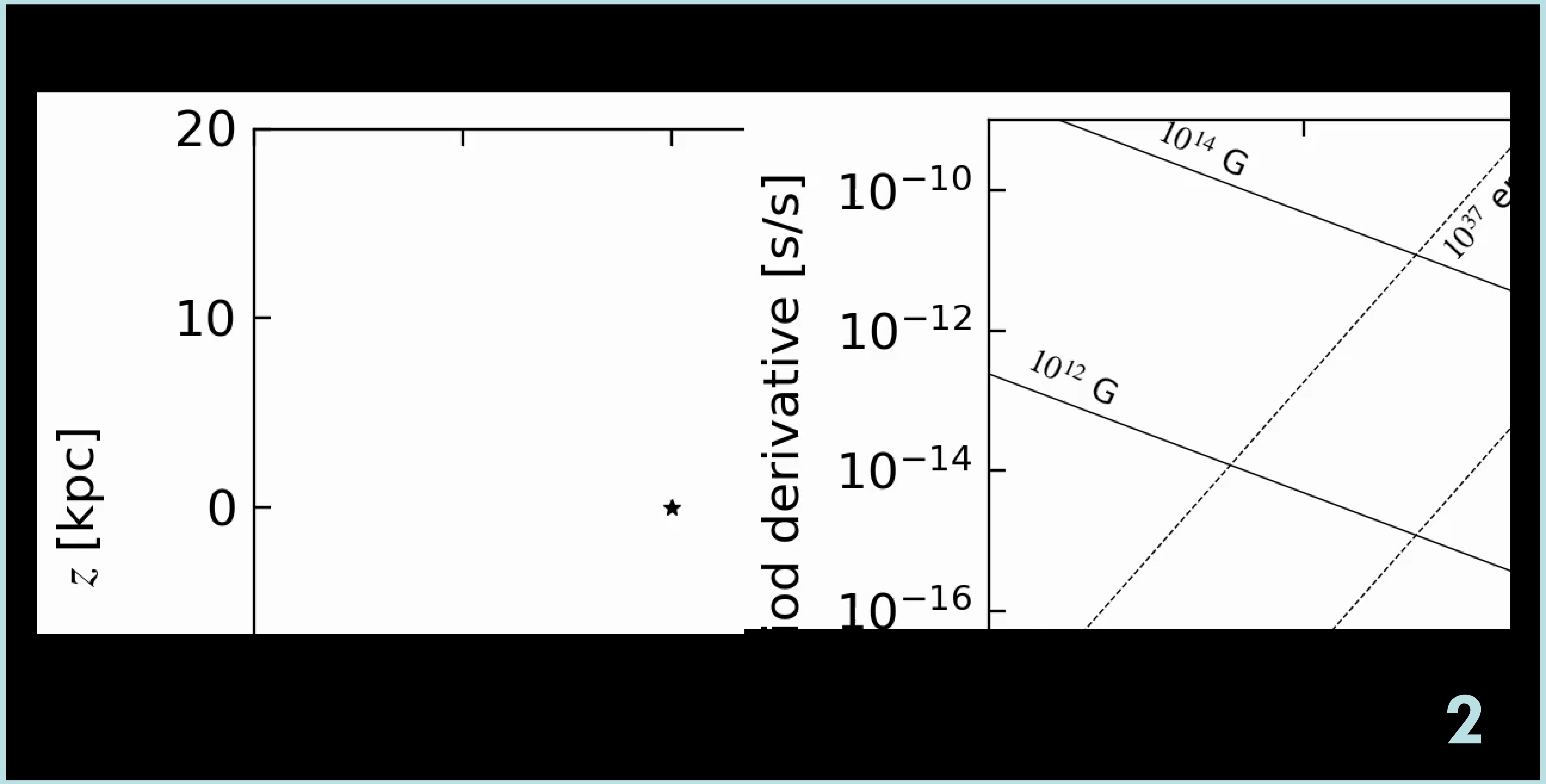


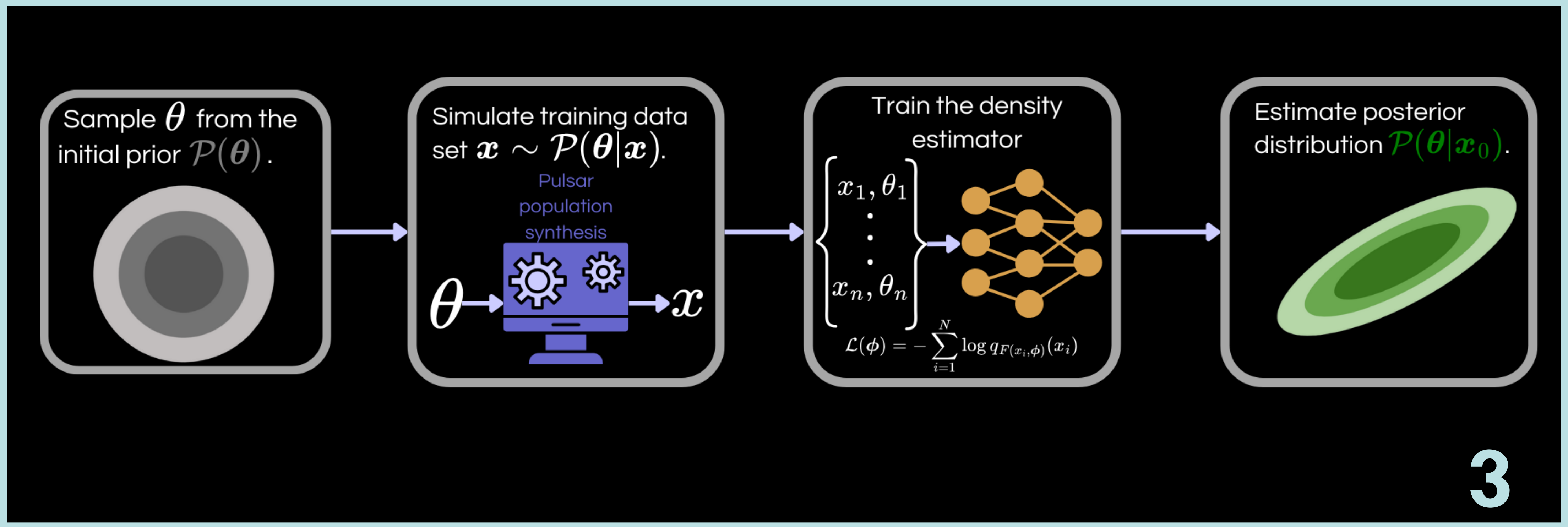


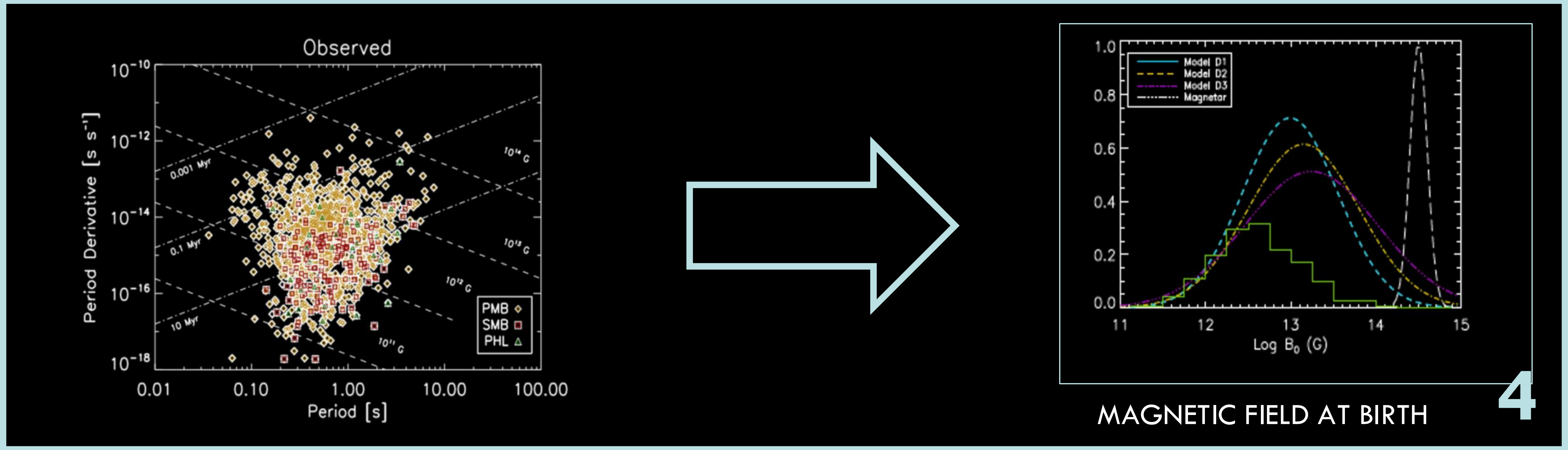
(adapted from Smartt 2015)

CONSTRAINING EXTRA-GALACTIC EVENTS WITH THE MAGNETAR POPULATION





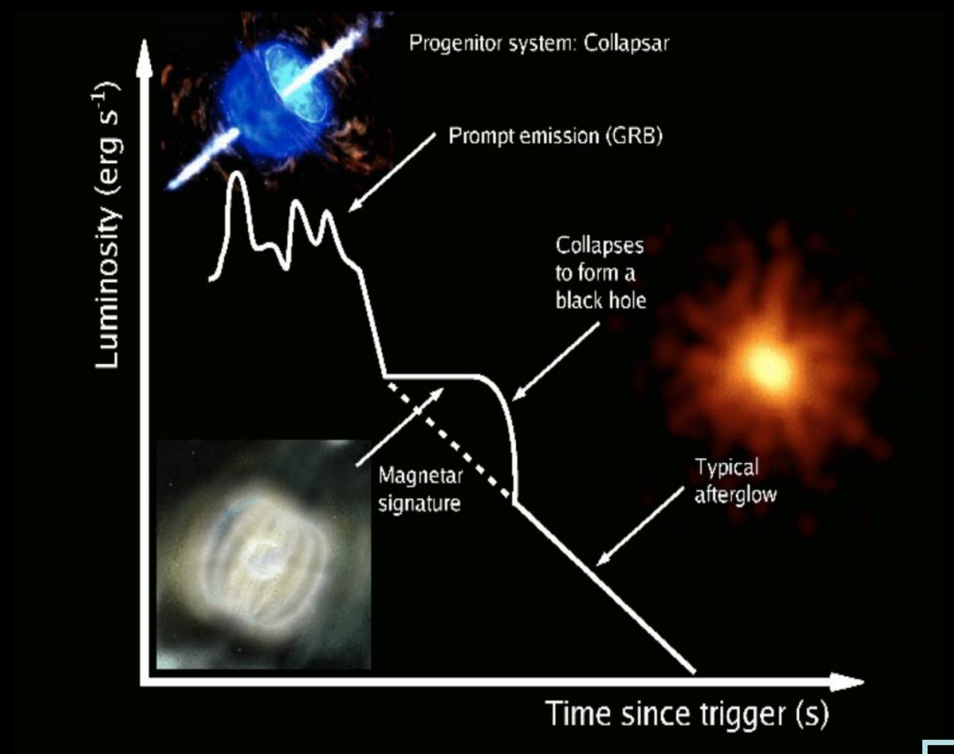


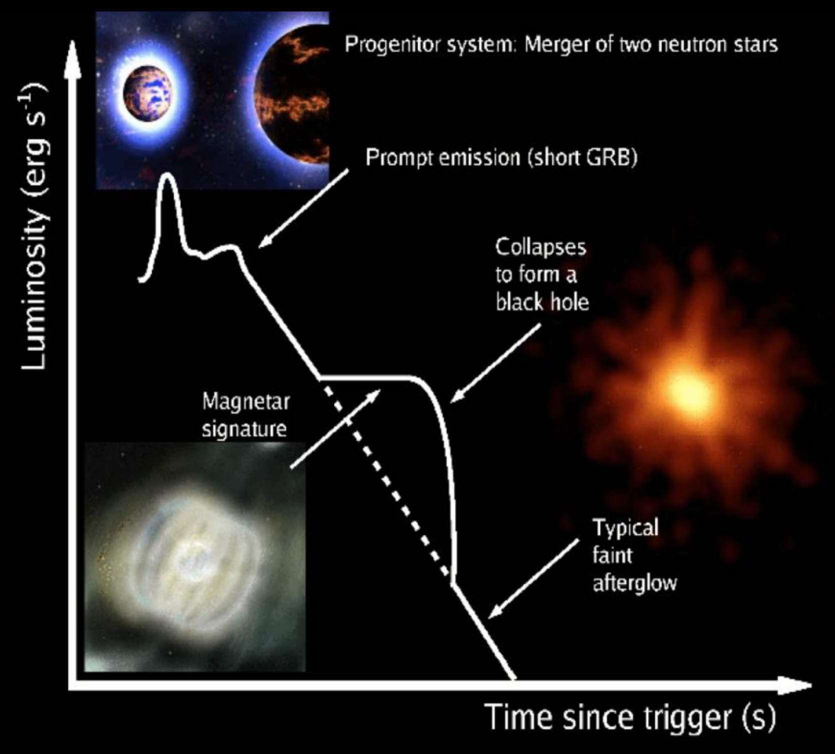


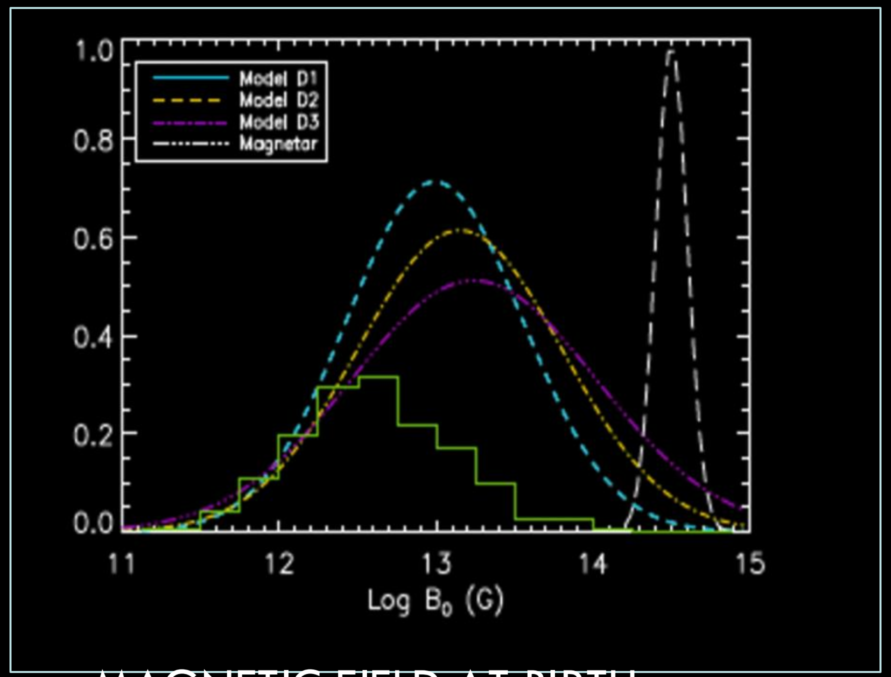
(Ronchi et al. 2022; Graber et al. 2024; Pardo Araujo et al. 2025)

CONSTRAINING EXTRA-GALACTIC EVENTS WITH THE MAGNETAR POPULATION

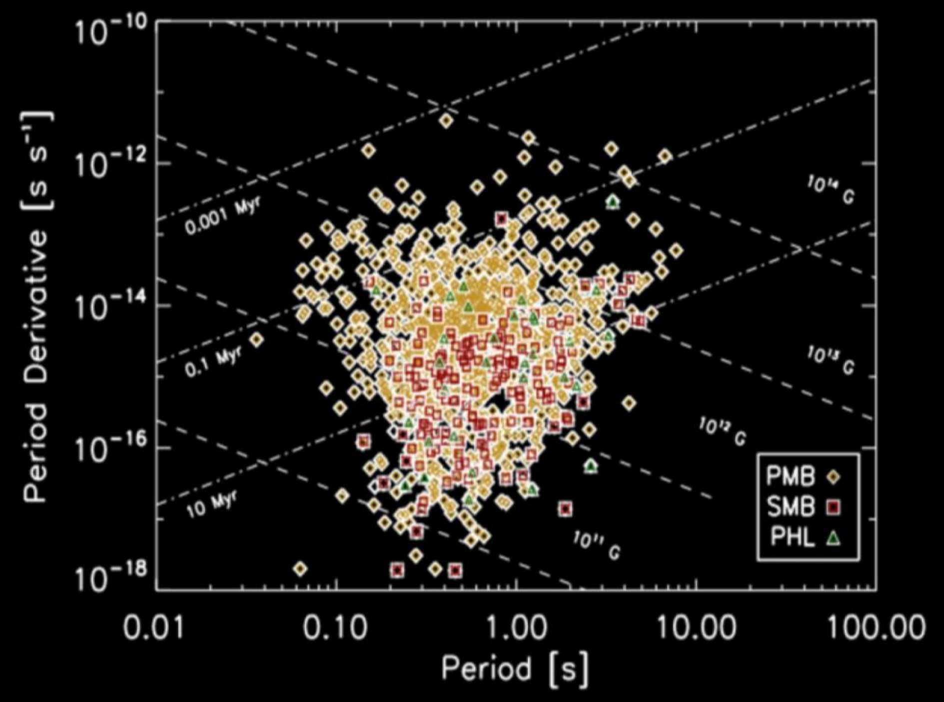
GRB-BORN MAGNETAR DISTRIBUTION

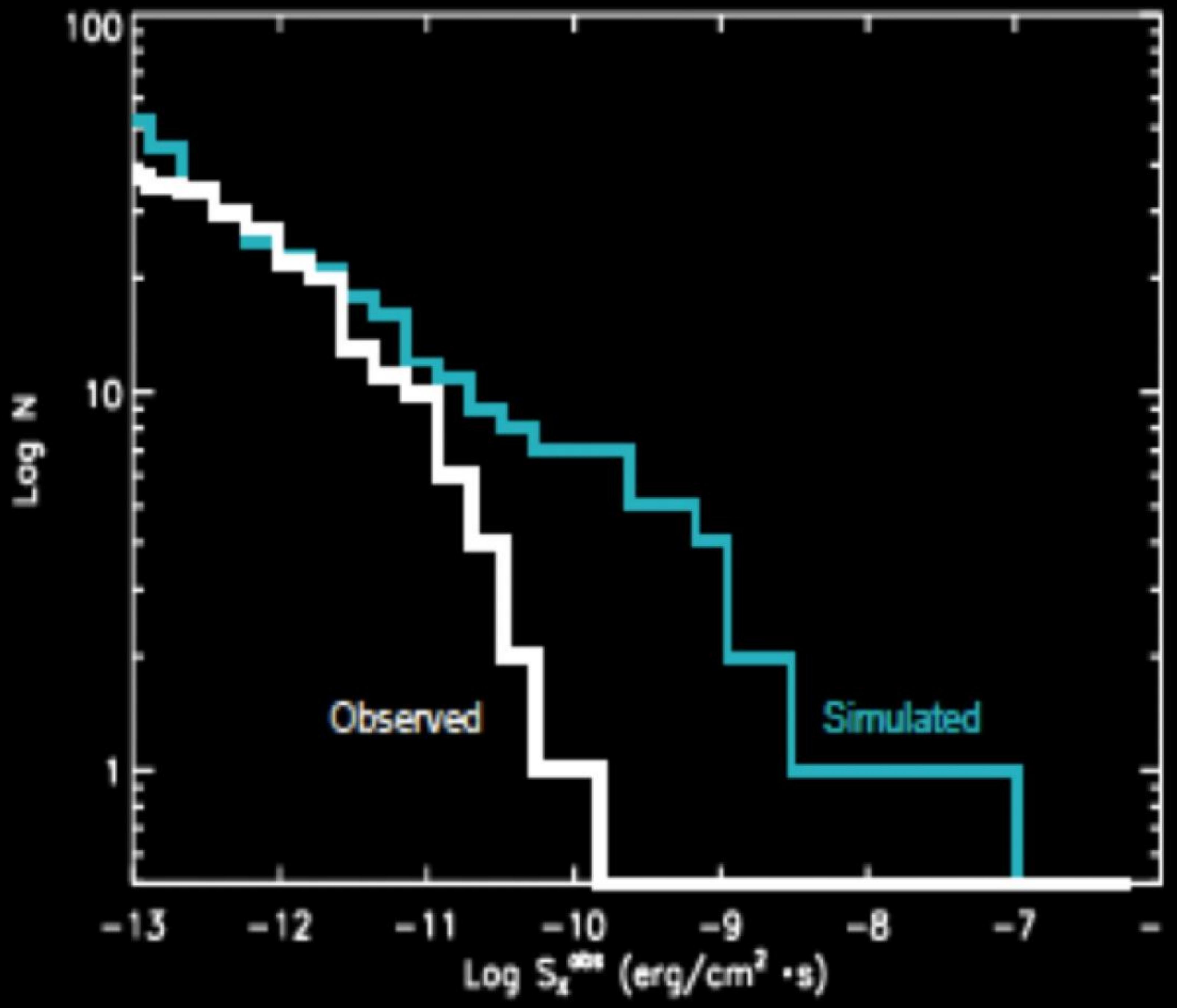






MAGNETIC FIELD AT BIRTH





We do not see GRB-formed magnetars in our Galactic population. If GRB plateaus are due to the formation of a magnetar they have B-fields way higher than our Galactic population.

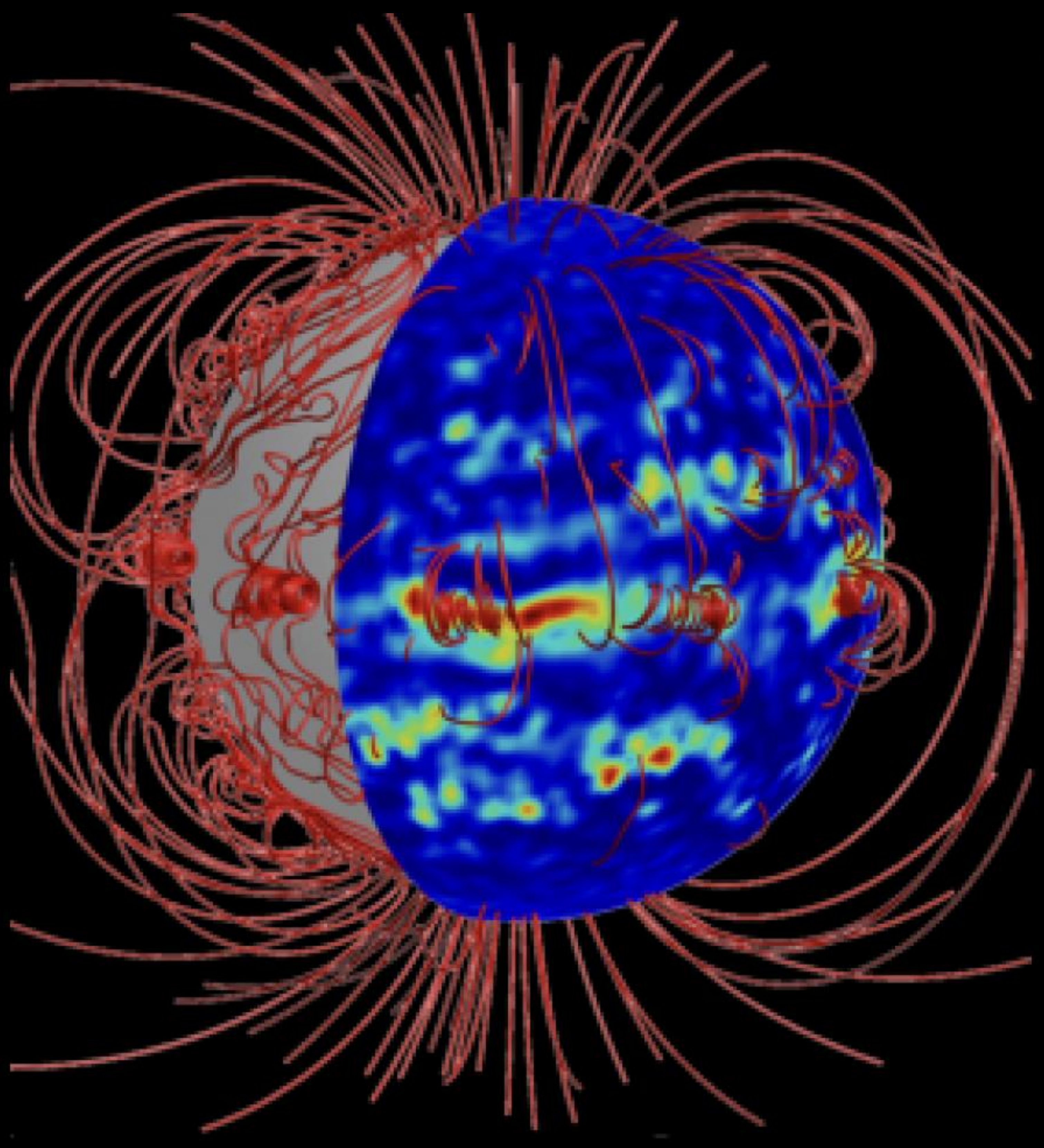
(Rea et al. 2015, Ronchi et al. 2025 in prep)

MAGNETAR BIRTH RATES, EVOLUTION, AND THEIR IMPRINT IN THE TRANSIENT X-RAY SKY

1. Magnetar-like emission is present in all neutron star classes. Thanks to Swift we now know that all are transients despite different outburst rates.

2. Magnetar birth rate in our Galaxy is way higher (up to 80%?) than previously thought and population studies are currently biased by our ignorance in the detection biases and outburst rates.

3. Figuring out magnetar birth rates in our Galaxy via population synthesis study and magneto-thermal simulations is key to try to connect them to GRBs and SLSNe.



THANKS