MAGNETARS AND LONG PERIOD TRANSIENTS

Nanda Rea

Institute of Space Sciences

CSIC
Consejo Superior de Investigaciones Científicas

IEEC

In collaboration with Natasha Hurley-Walker, Andy Wang, Francesco Coti Zelati, Michele Ronchi, Celsa Pardo, Alessio Marino and many others….

erc
European Research Council
Established by the European Commission

GOBIERNO DE ESPAÑA
MINISTERIO DE CIENCIA, INNOVACIÓN Y UNIVERSIDADES

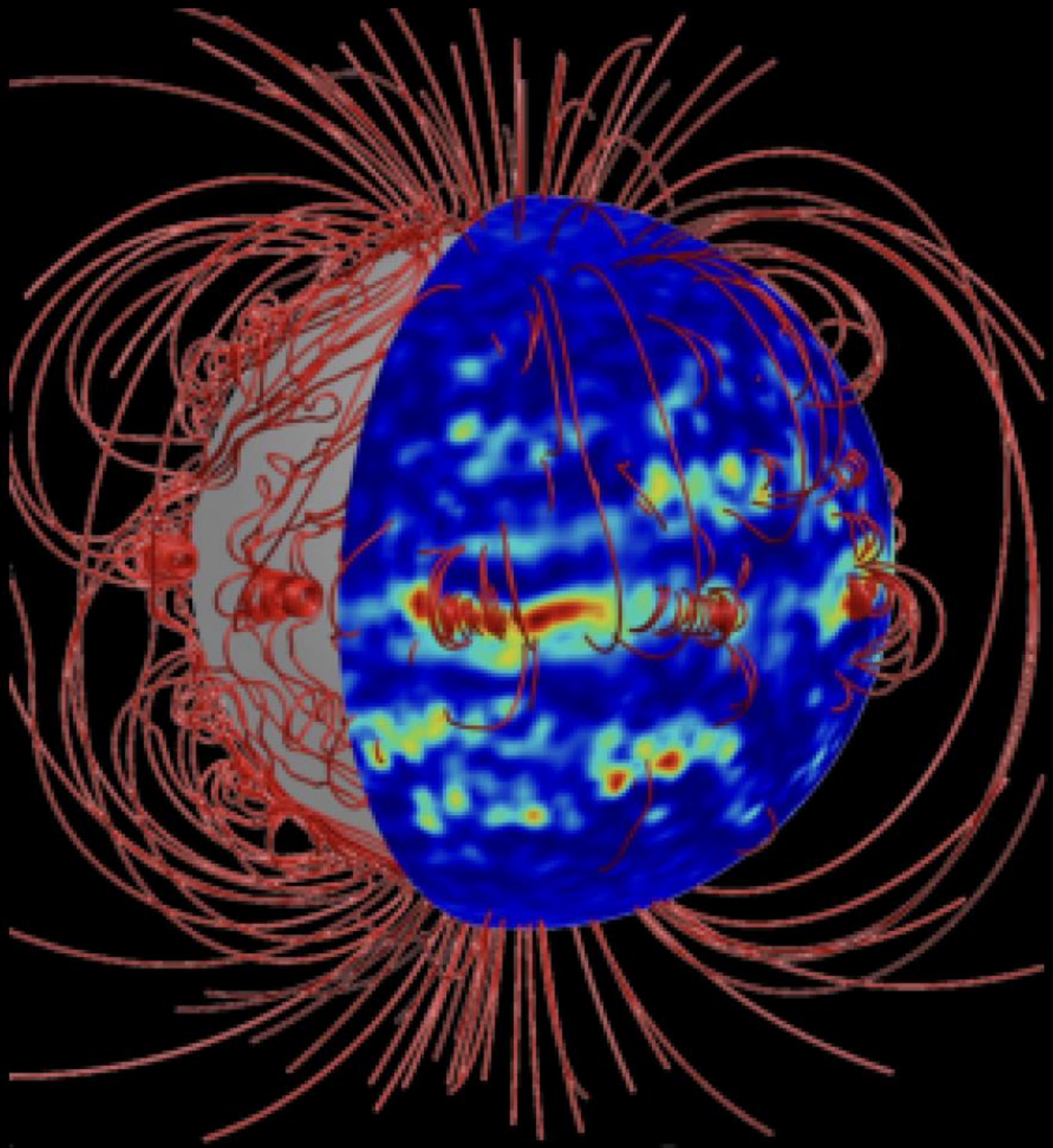
AGAUR
Agència de Gestió d'Ajuts Universitaris i de Recerca

- MAGNETARS AND THE PULSAR POPULATION

- MAGNETAR BIRTH RATES AND EVOLUTION

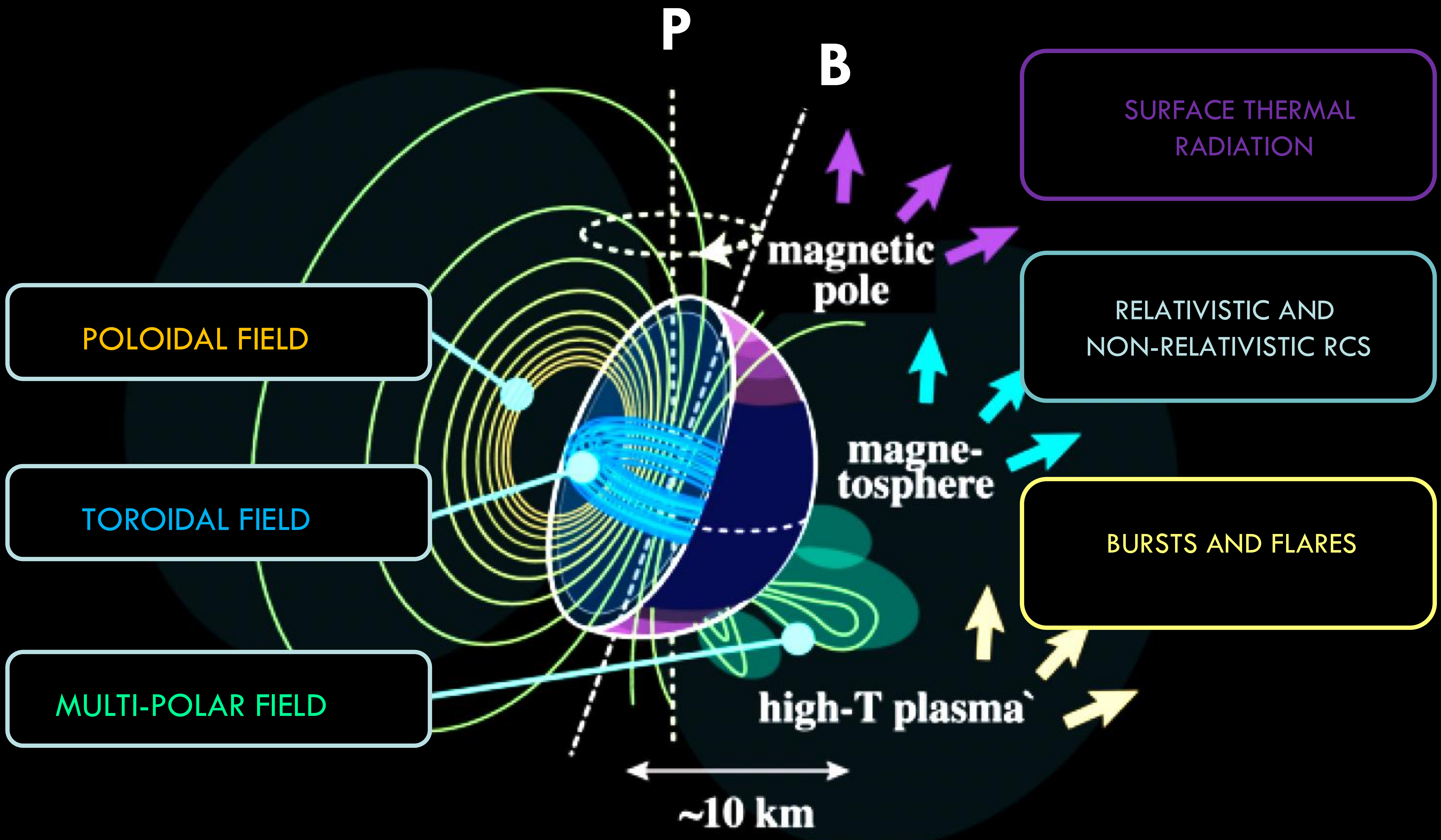
- LONG PERIOD TRANSIENTS

WHAT IS A MAGNETAR?



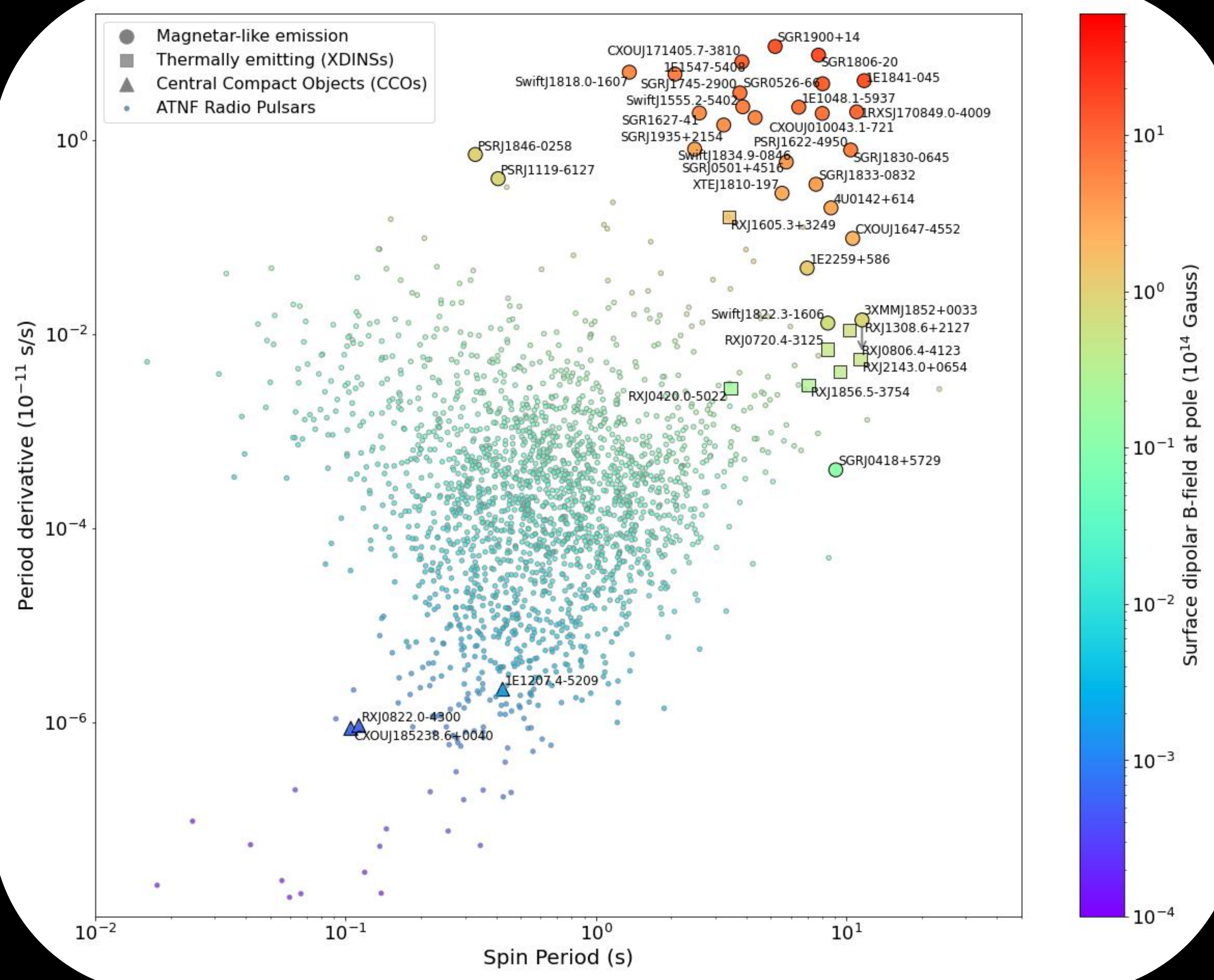
(Gougouliatos et al. 2014)

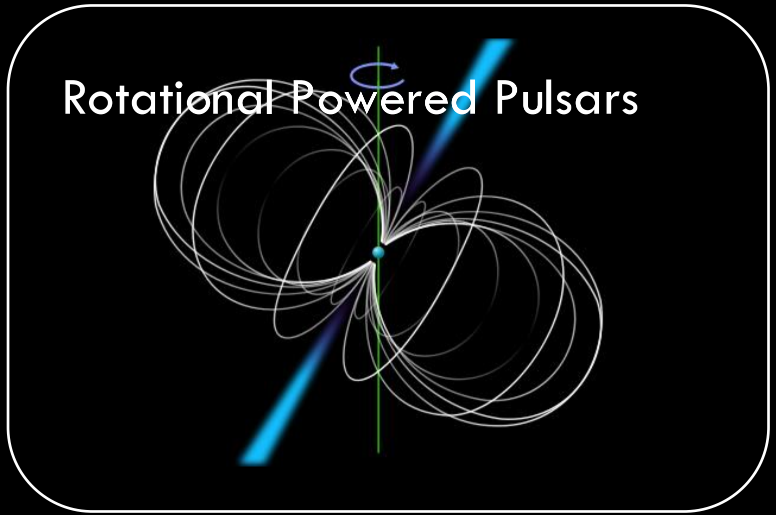
MAGNETAR GENERAL EMISSION CHARTOON



(adapted from Enoto et al. 2019)

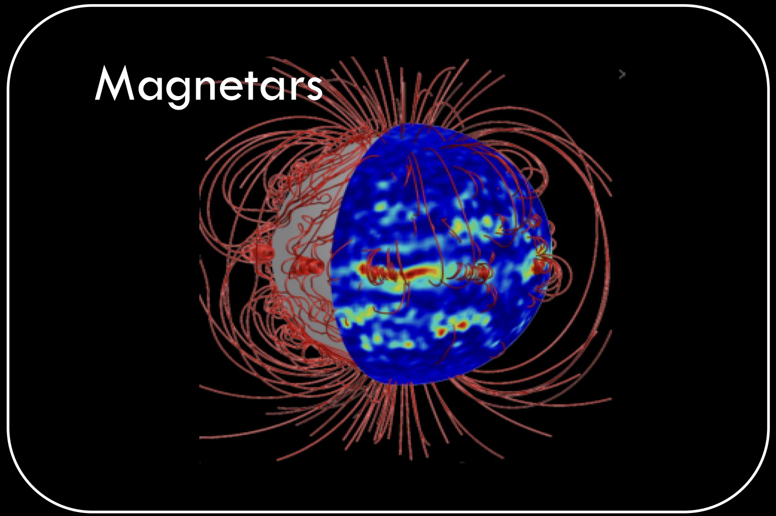
THE ISOLATED PULSAR POPULATION





ROTATIONAL POWERED PULSARS

Powered by rotational energy.
Typically emitting in radio.

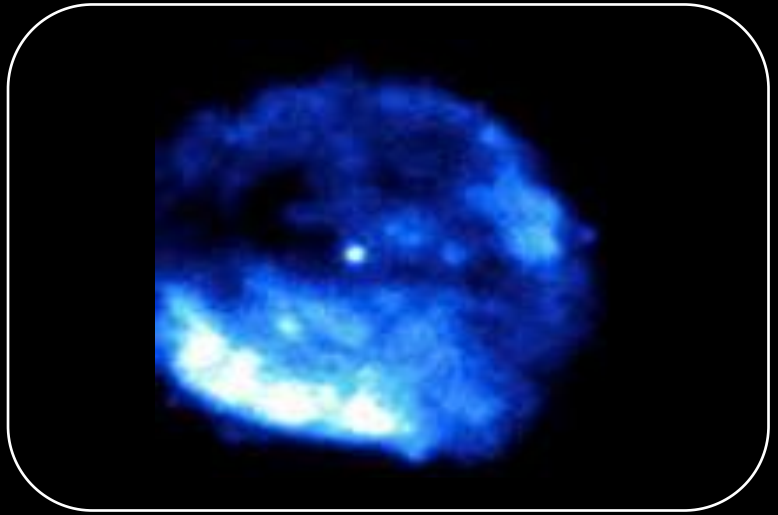


MAGNETARS

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

THERMAL NSs (XDINS)

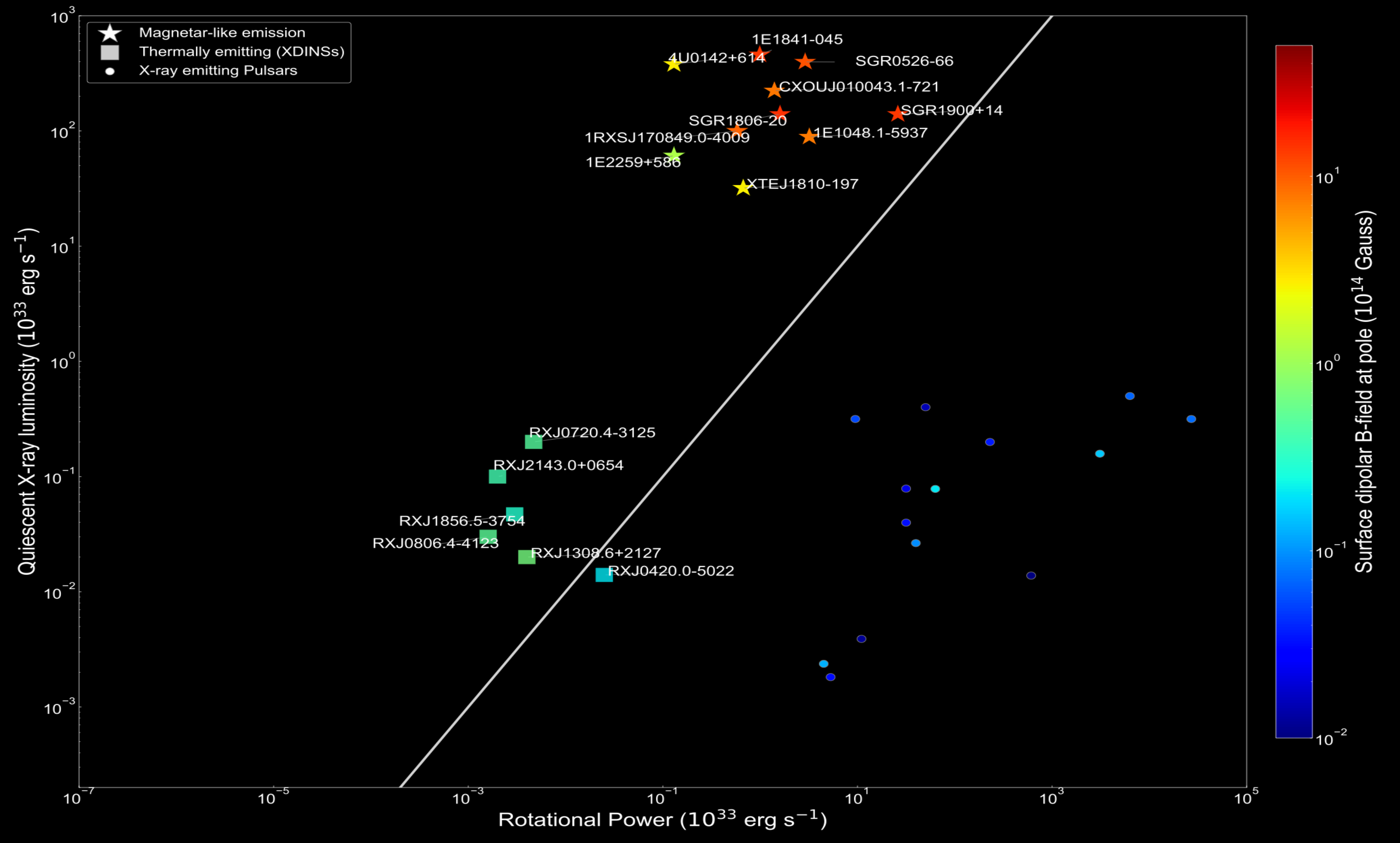
Powered by magnetic energy.
Old, almost pure blackbodies.
Typically emitting in the X-rays.

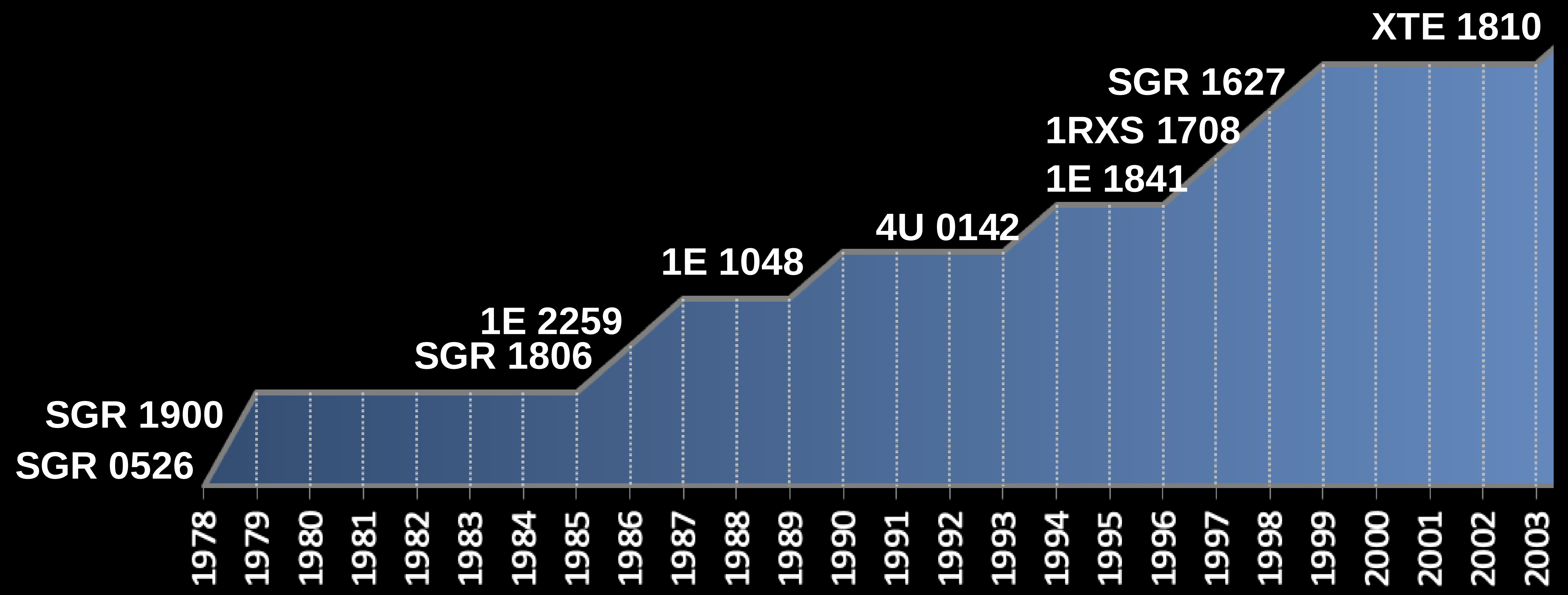


CENTRAL COMPACT OBJECTS

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

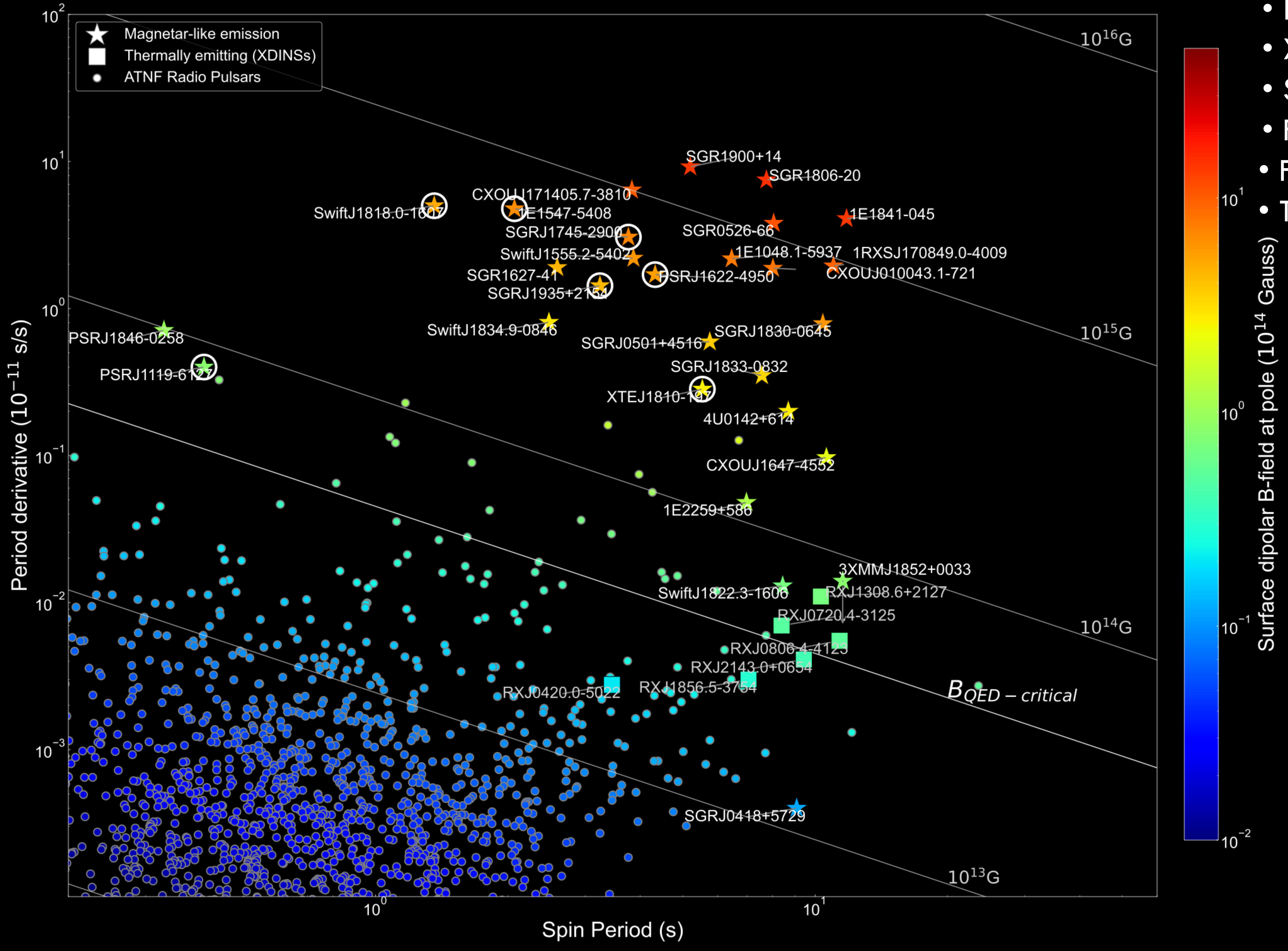
MAGNETAR NUMEROLOGY YEARS AGO…



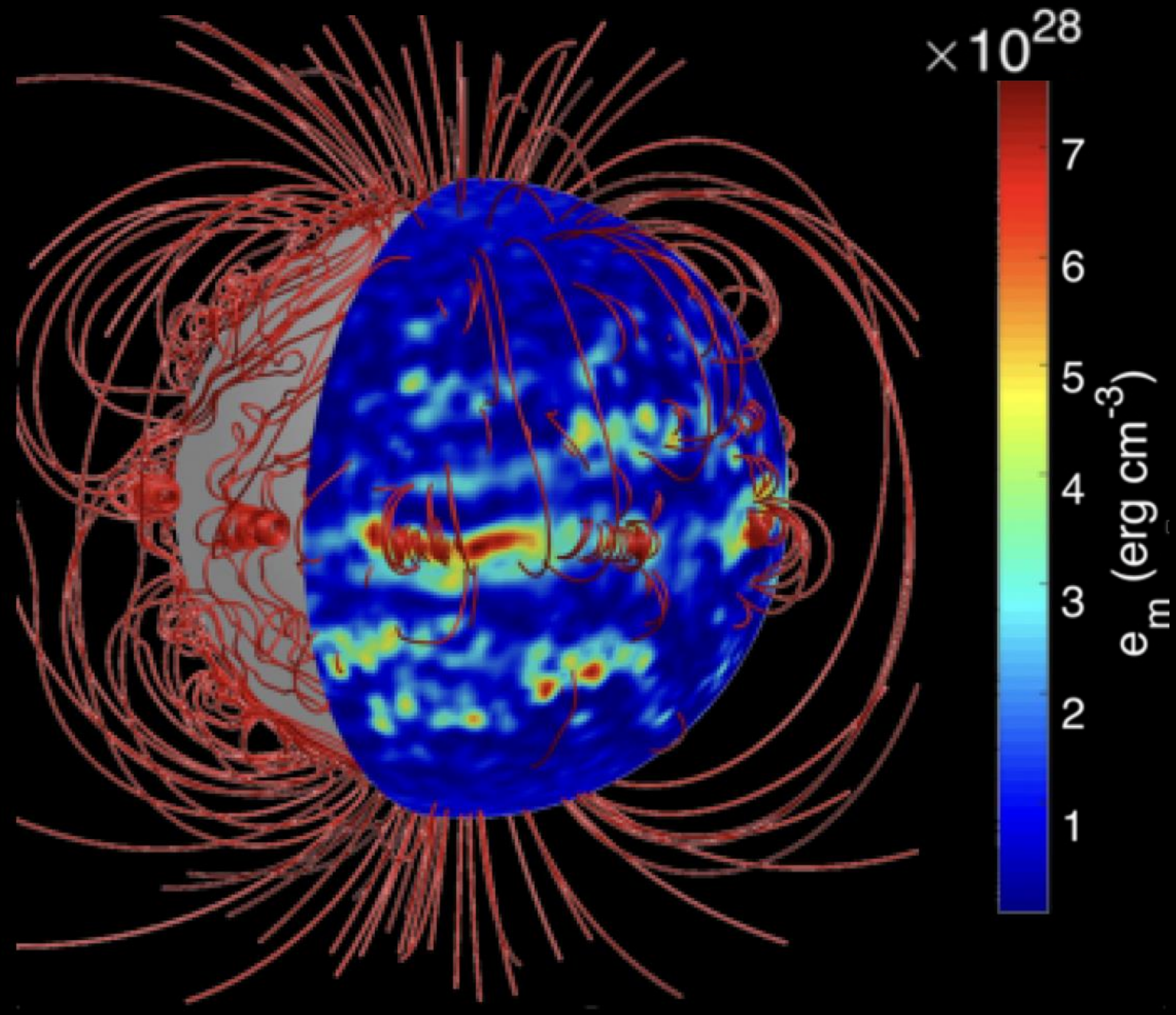


MAGNETAR NUMEROLOGY NOW!

MAGNETARS PROPERTIES



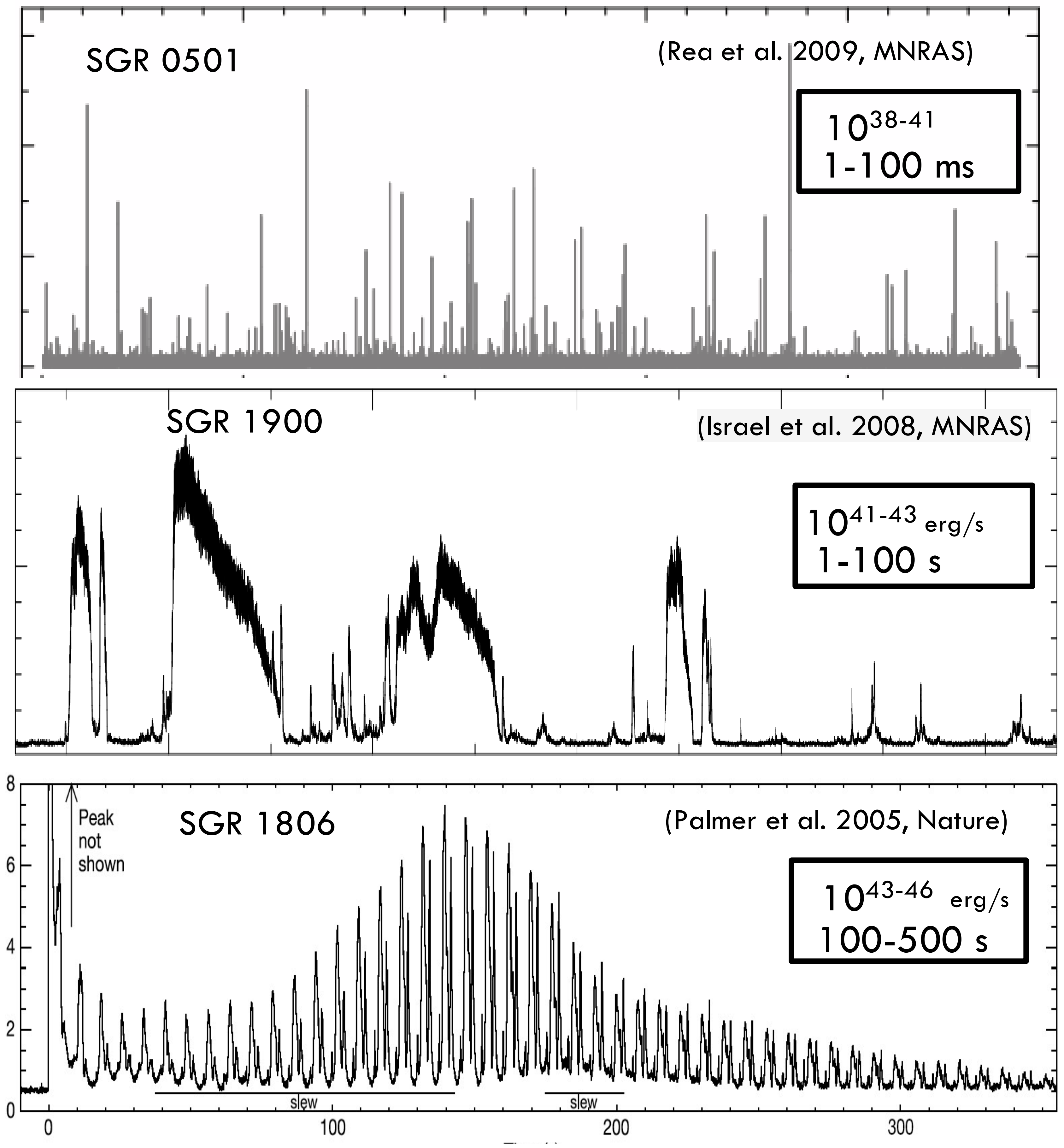
- Dipolar magnetic fields of $B\sim10^{12}$-10^{15} Gauss
- Transient X-ray pulsars with $L_x\sim10^{31}$-10^{36} erg s^{-1}
- Rotating with P~0.3-12 s
- Large Glitches
- X-ray luminosity is "generally" larger than the rotational energy
- Soft and hard X-ray emission (0.5-200 keV); thermal + non-thermal
- 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



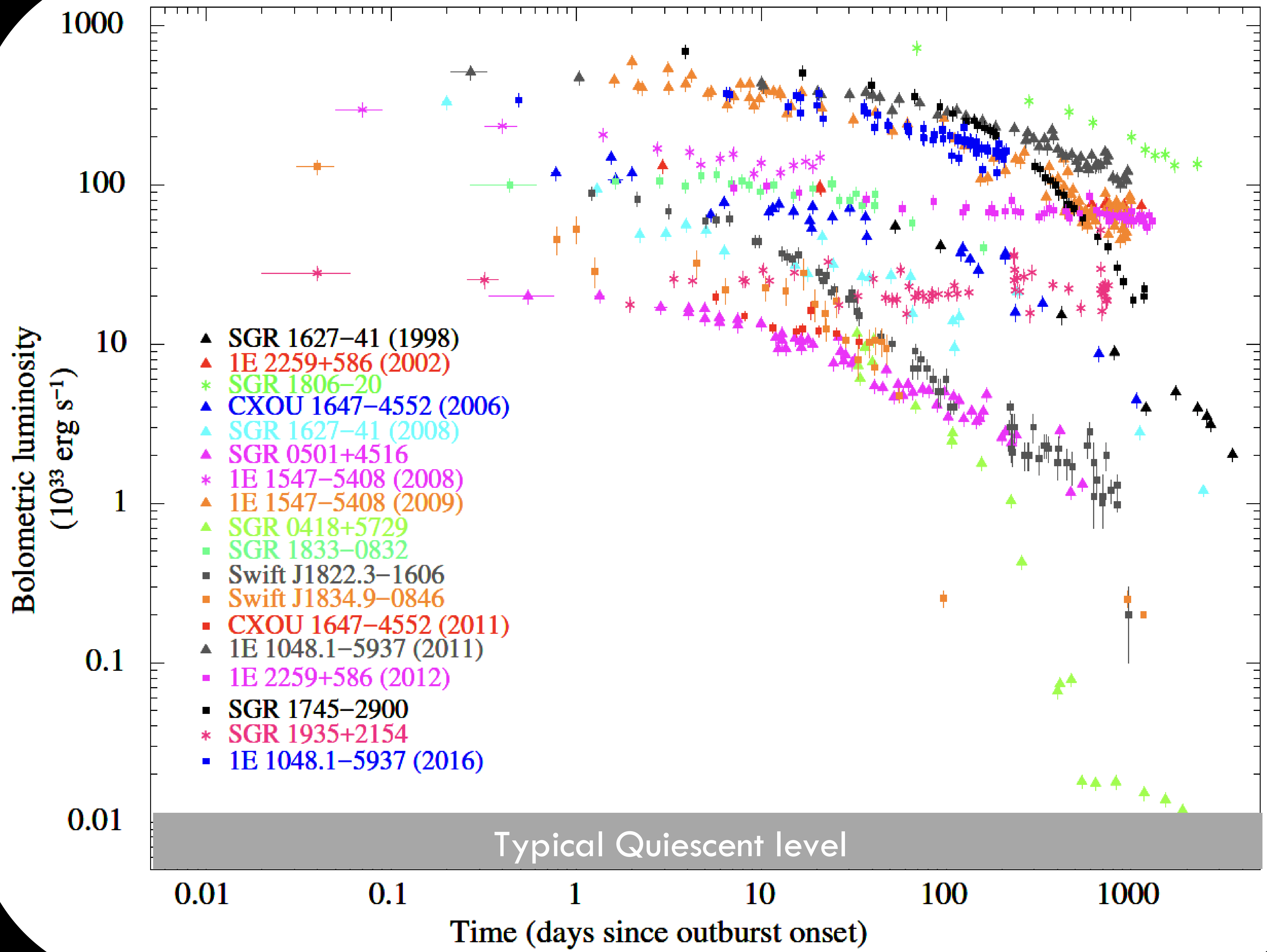
(recent reviews: Kaspi & Beloborodov 2017, Esposito, Rea & Israel 2021, Rea & De Grandis 2025)

MAGNETAR OUTBURSTS AND FLARES

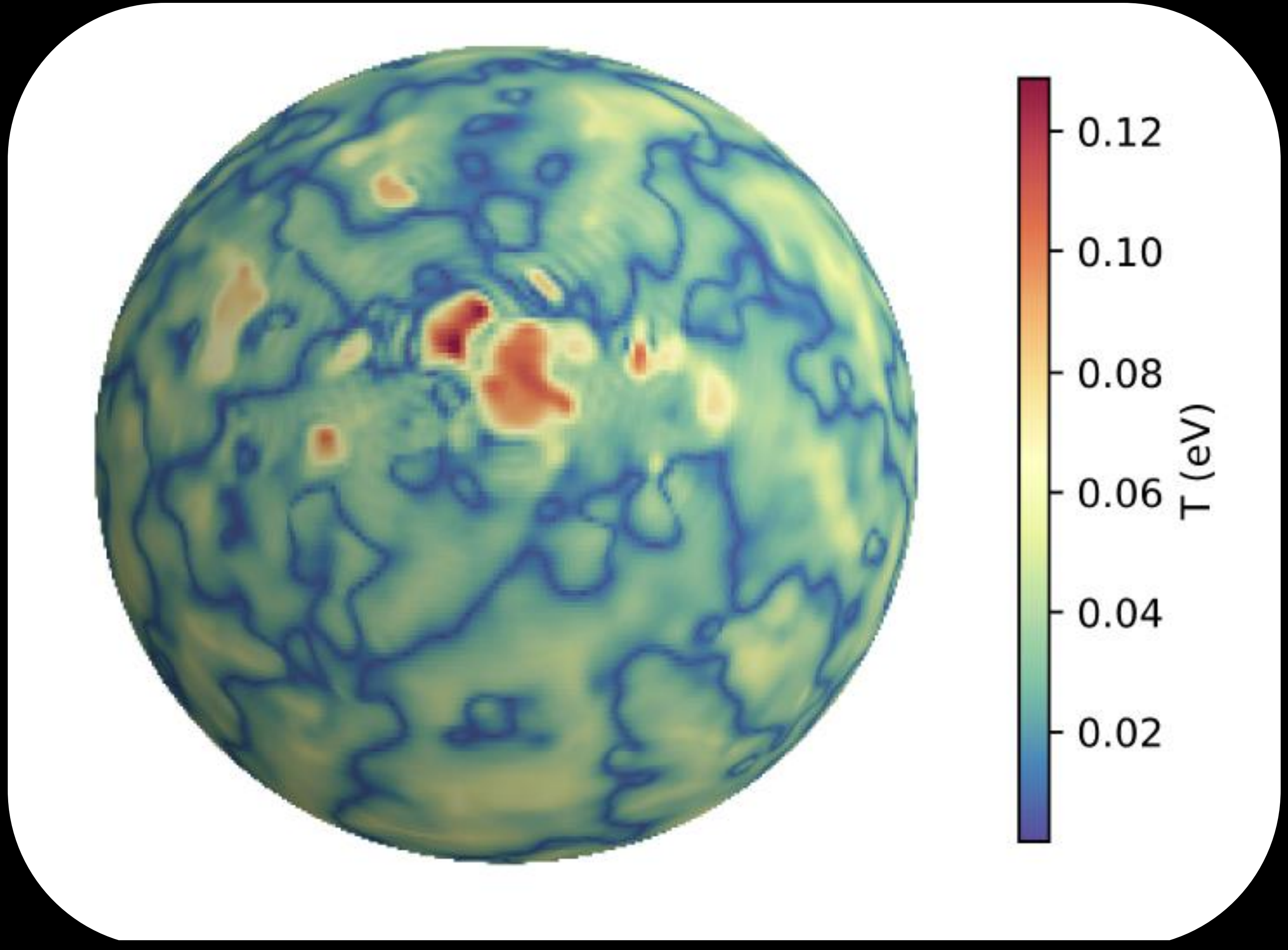
crustal failures, surface heating, magnetospheric bundles, reconnection…

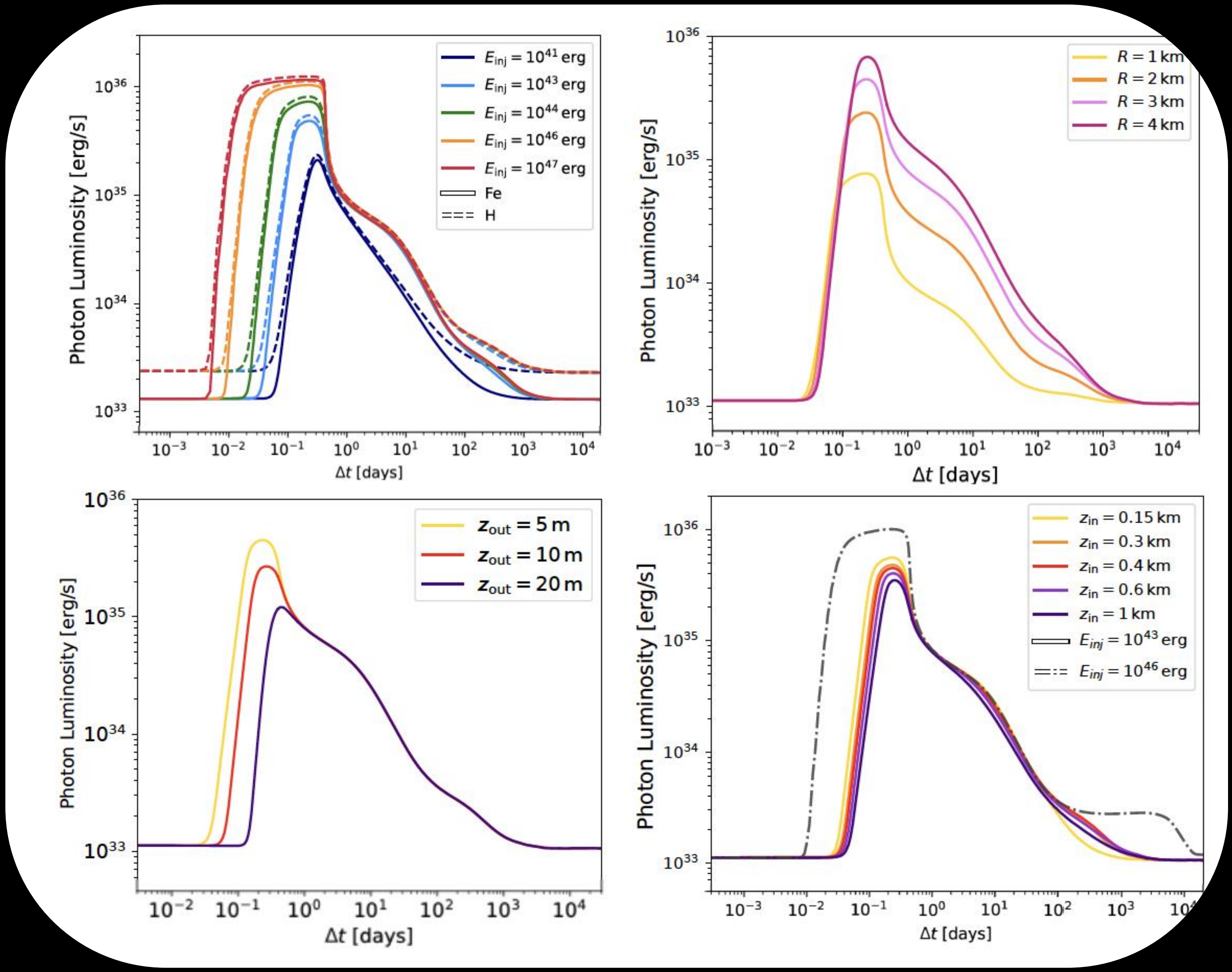


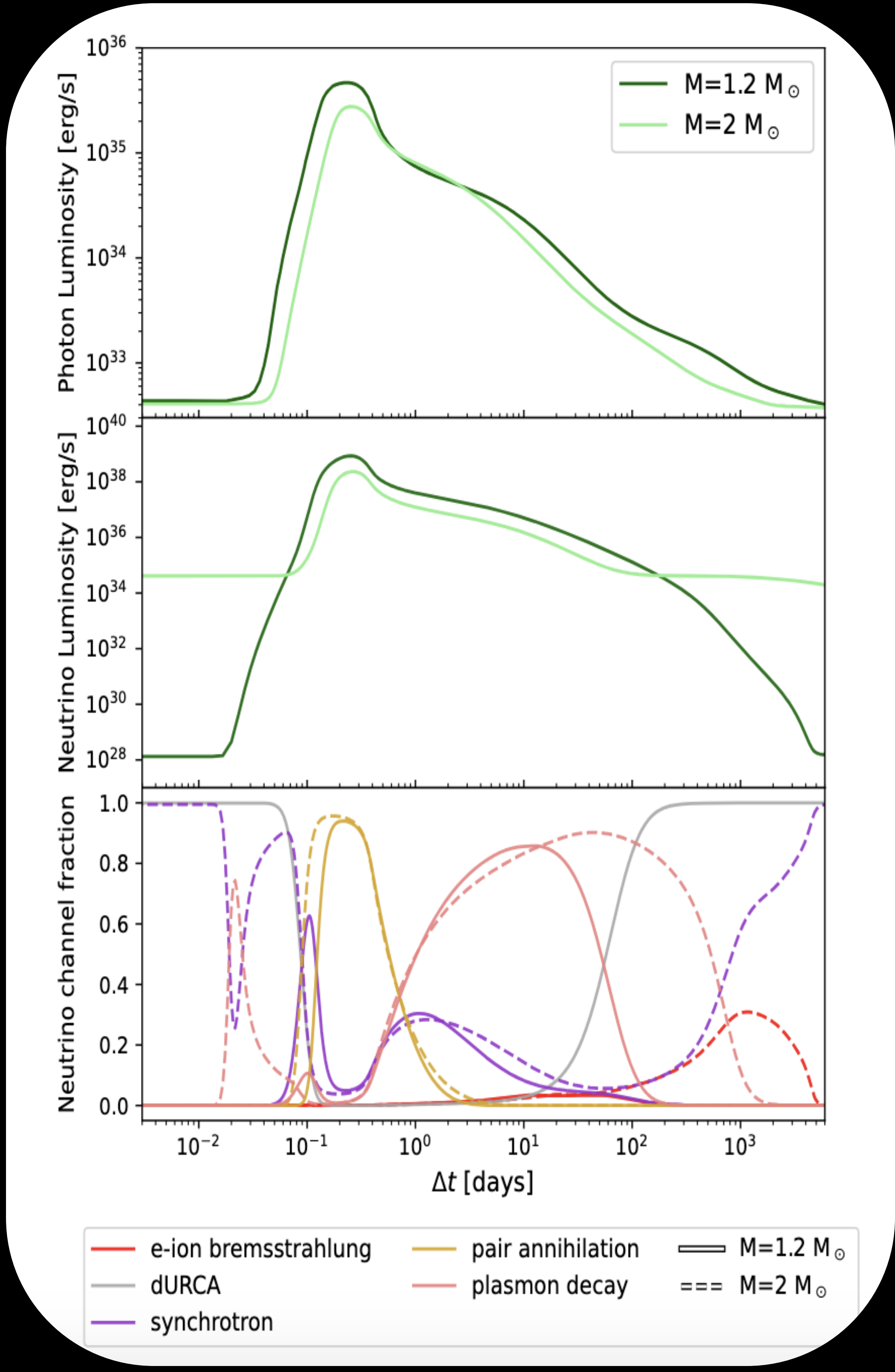
Internal or external trigger?



MAGNETAR OUTBURSTS: MODELLING

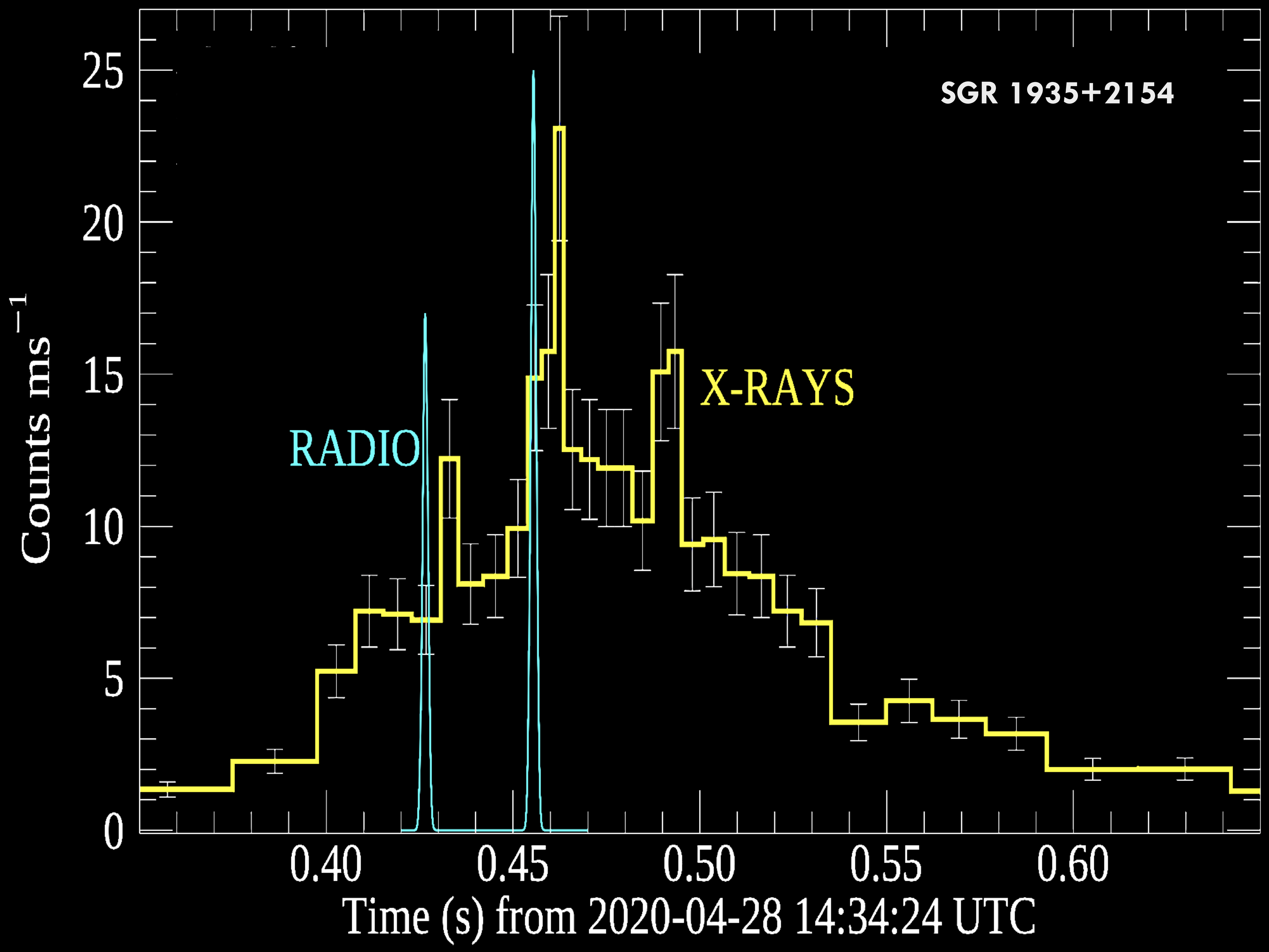


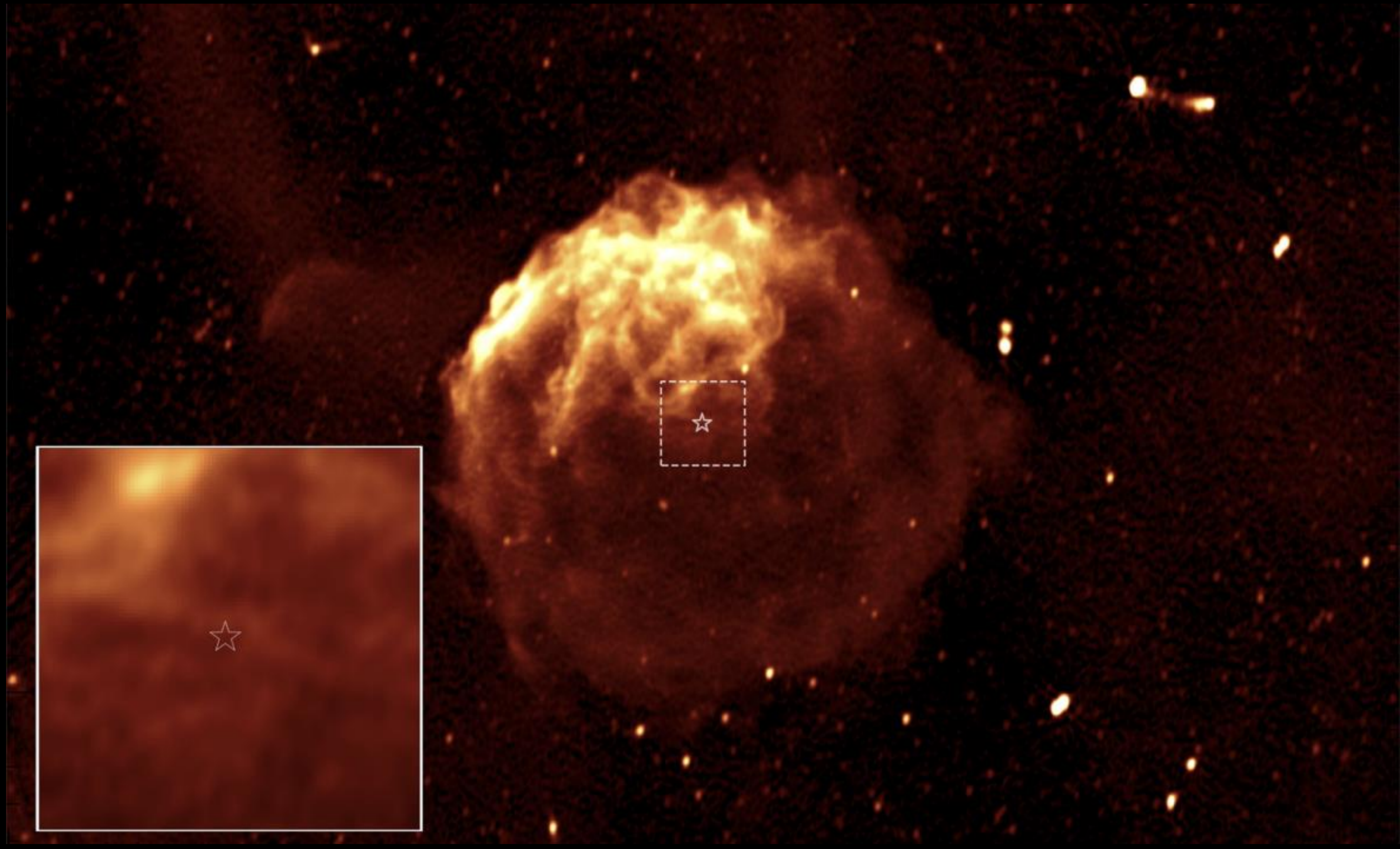




(De Grandis, Rea, Kovlakas, et al. 2025 submitted)

THE FRB-MAGNETAR CONNECTION

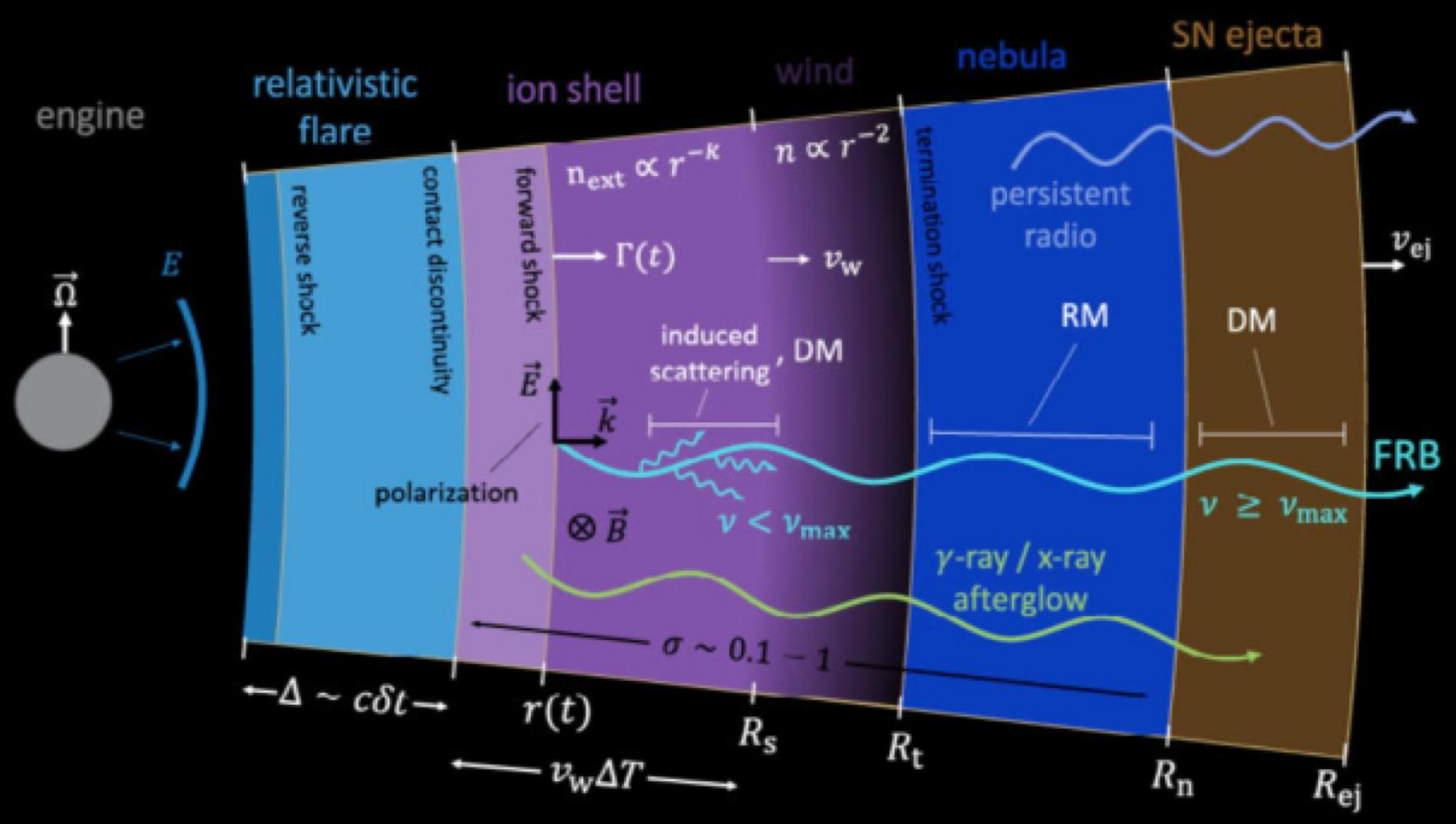




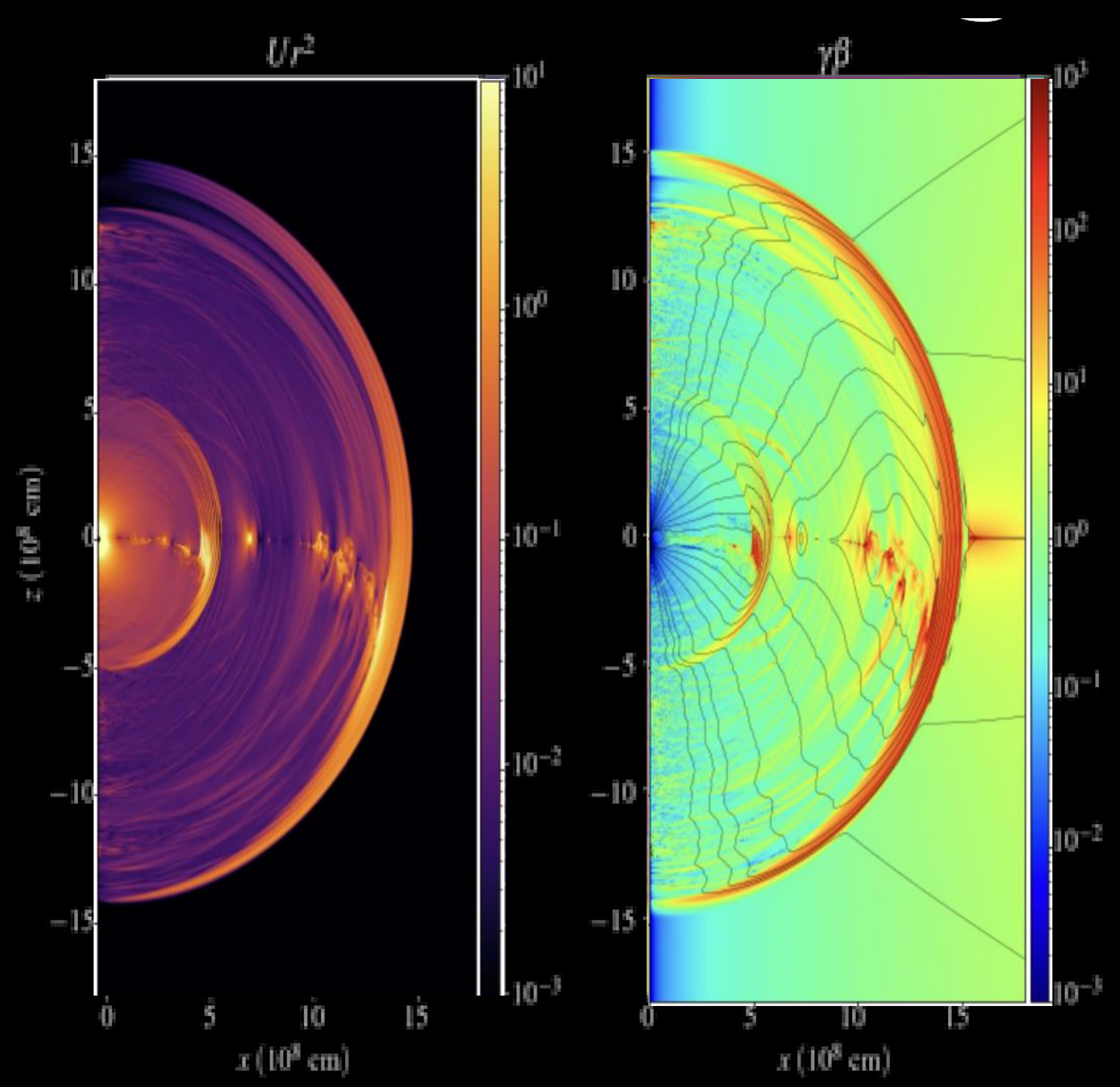
Bailes et al. 2021

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

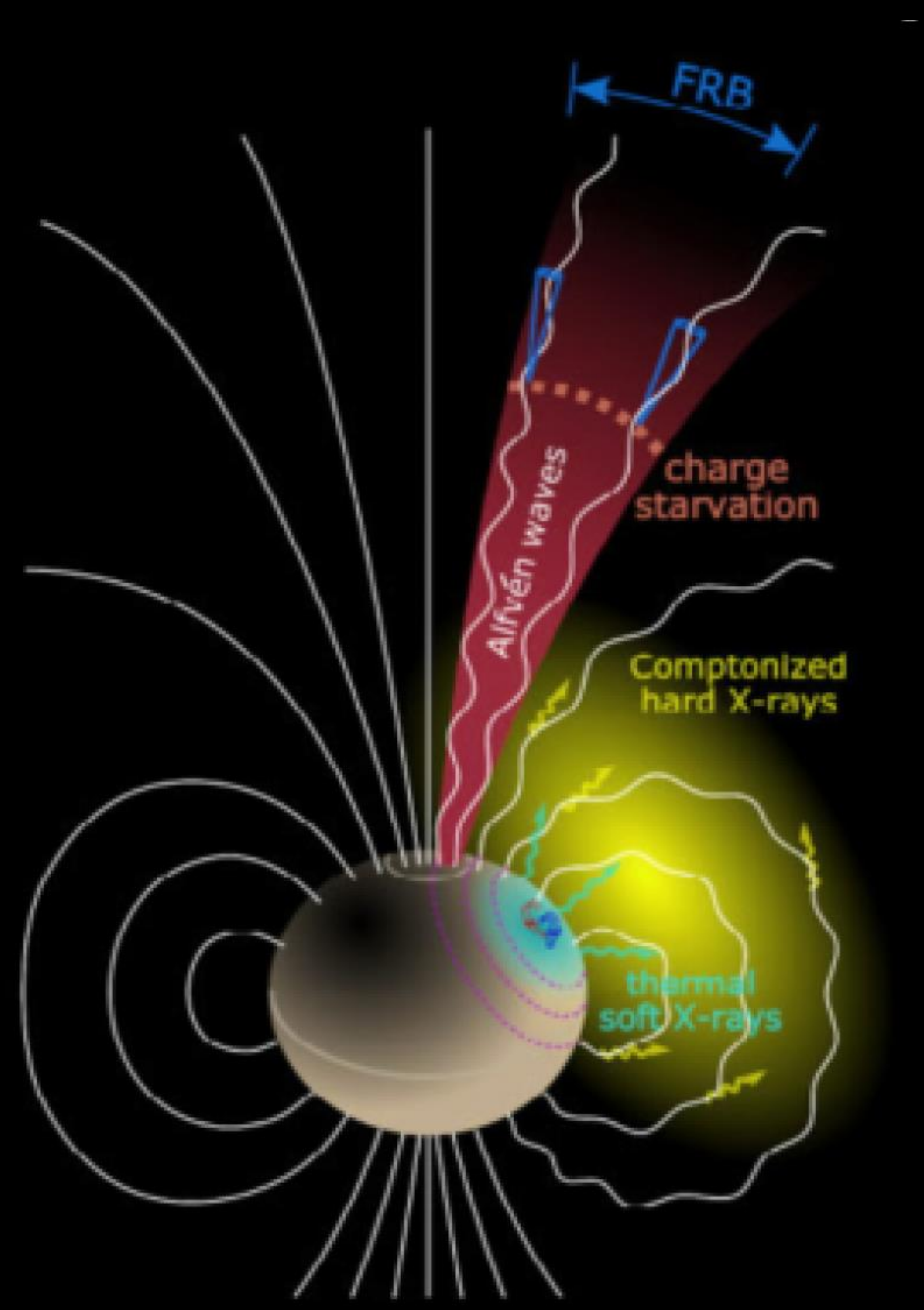
THE FRB-MAGNETAR CONNECTION



Metzger et al. 2019



Yuan et al. 2020

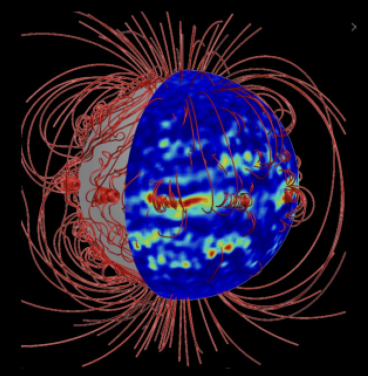


Lu et al. 2020

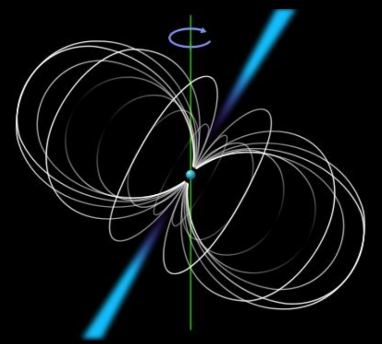
Shock models or magnetospheric models

SMOKING GUNS ….

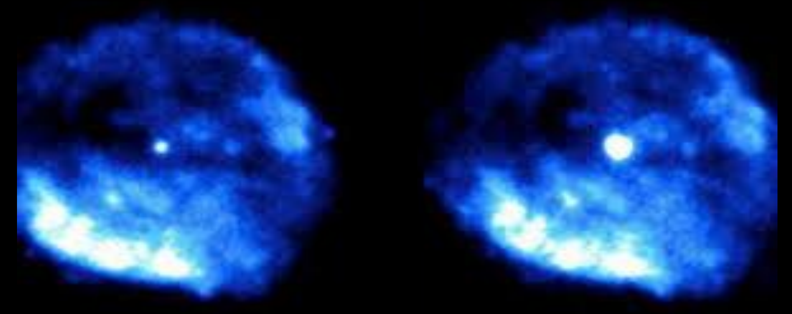
1. Magnetars were discovered having low dipolar B-fields and strong magnetic structures.
   (Rea et al. 2010, Science; 2012, 2013, 2014, ApJ; Tiengo et al. 2013, Nature)



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)

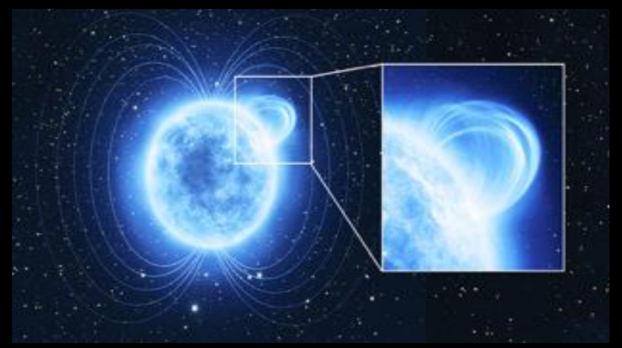


3. A central compact object (CCO) with a 6.4hr period showed magnetar-like activity.
   (Rea et al. 2016, ApJ Letters; D'Ai et al. 2016, MNRAS; Borghese et al. 2018, ApJ)

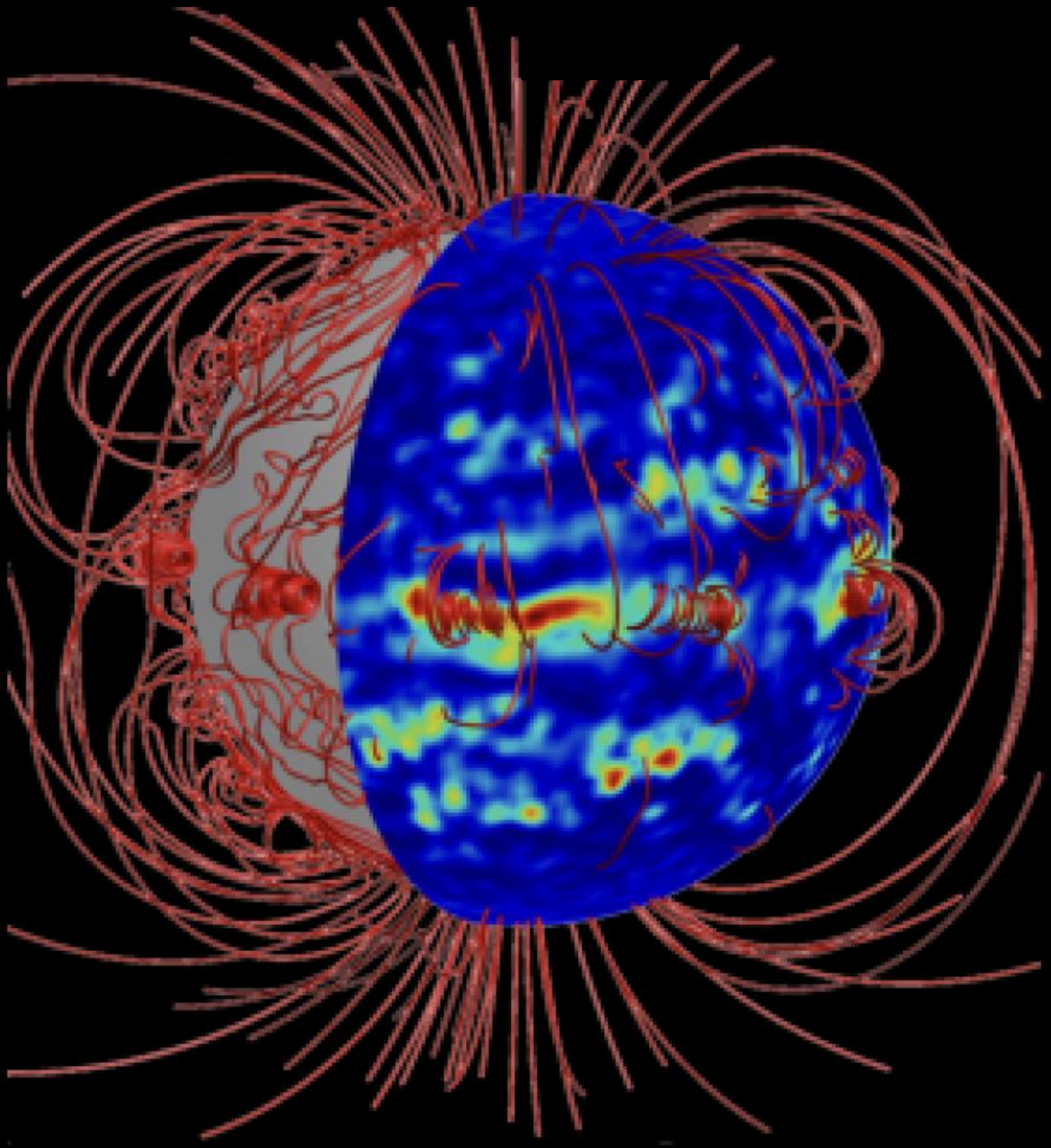


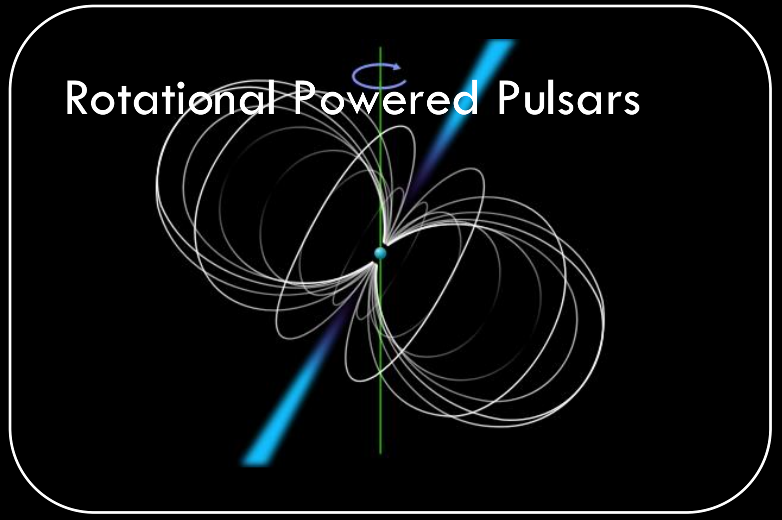
quiescence outburst

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



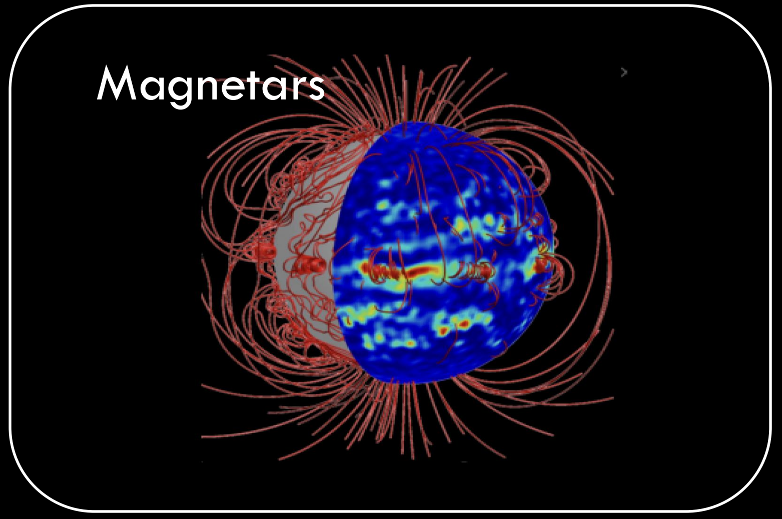
MAGNETAR ACTIVITY IS PRESENT IN ALL ISOLATED NEUTRON STAR CLASSES





ROTATIONAL POWERED PULSARS

Powered by rotational energy.
Typically emitting in radio.

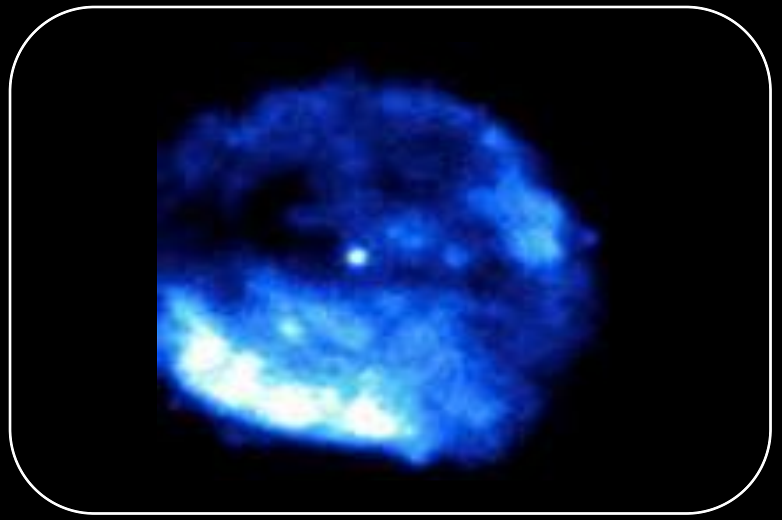


MAGNETARS

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

THERMAL NSs (XDINS)

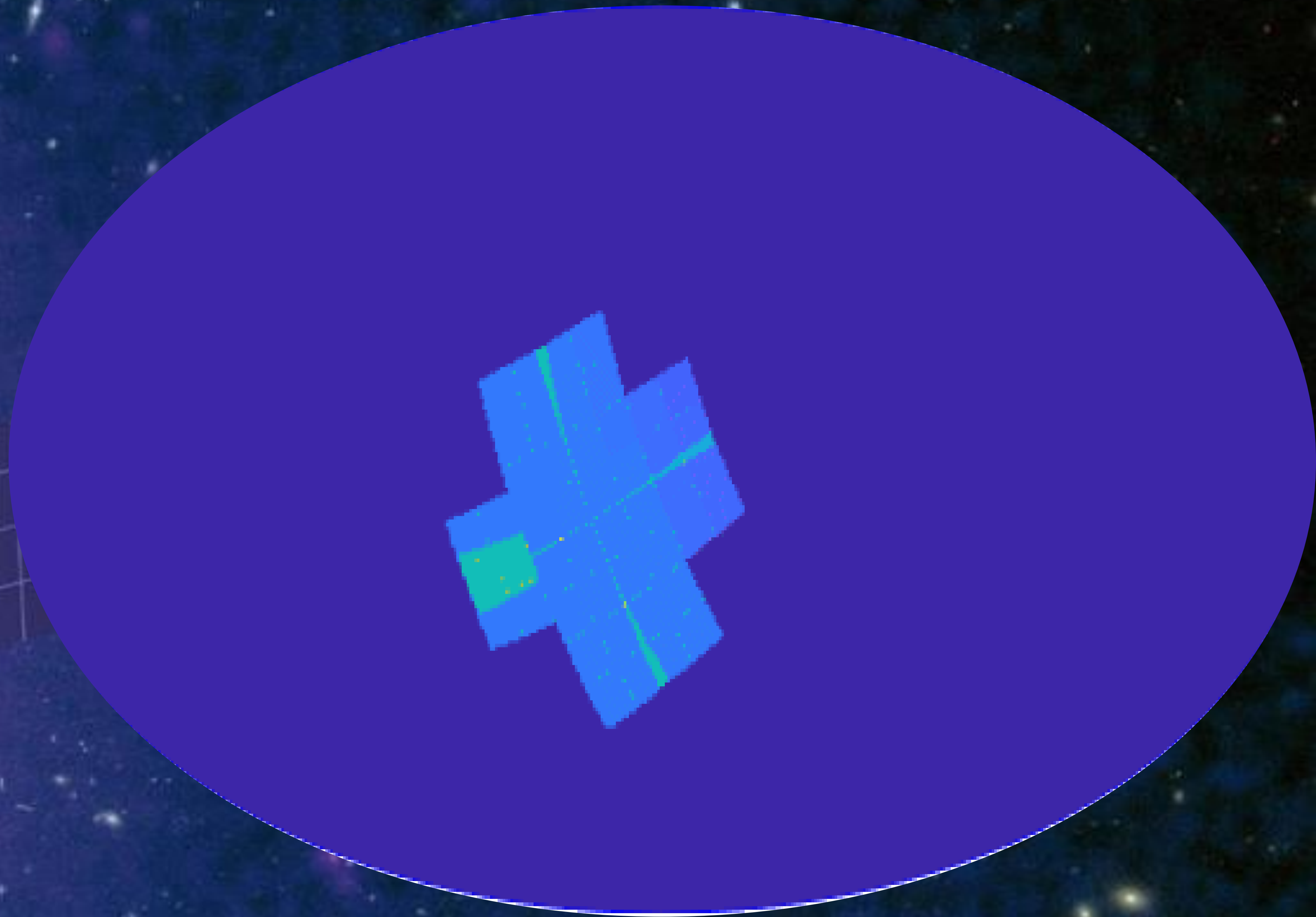
Powered by magnetic energy.
Old, almost pure blackbodies.
Typically emitting in the X-rays.

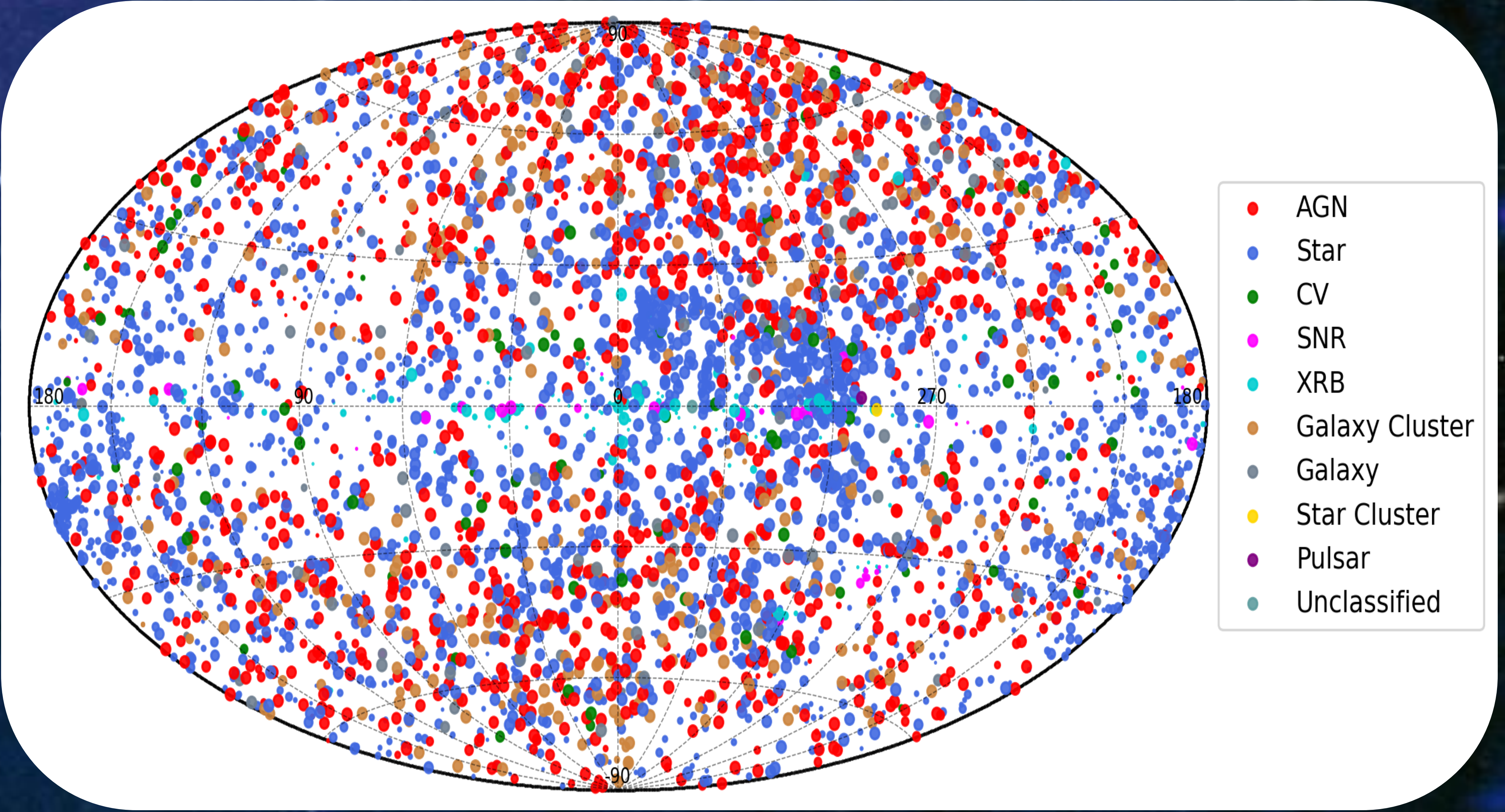


CENTRAL COMPACT OBJECTS

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

EINSTEIN PROBE





Launched in Jan 2024

- Bright sources detected with WXT: ~6847
- Transients: ~130 with high S/N
- New X-ray sources detected with FXT: ~20,000

- MAGNETARS AND THE PULSAR POPULATION

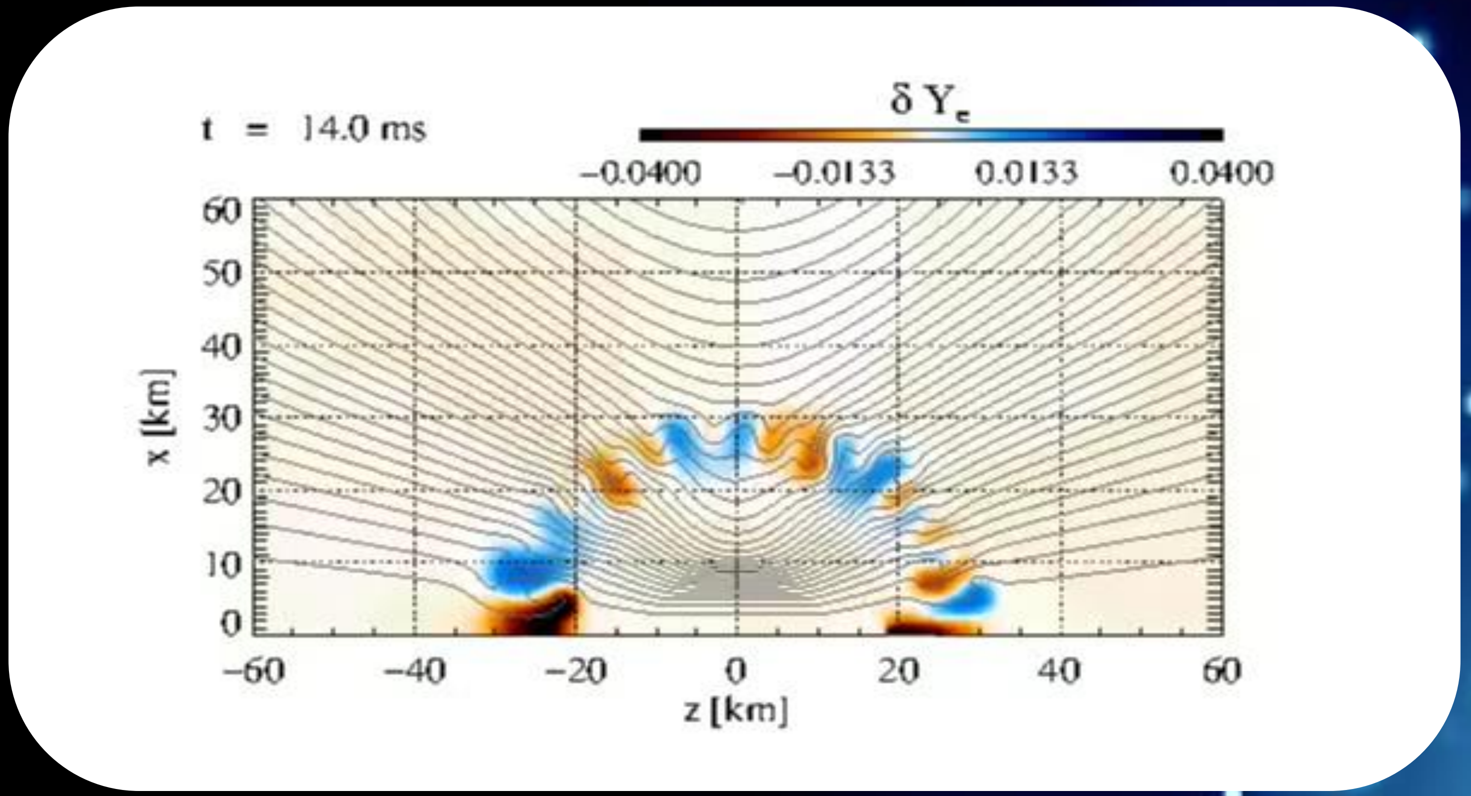
- MAGNETAR BIRTH RATES AND EVOLUTION

- LONG PERIOD TRANSIENTS

MAGNETAR BIRTH

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

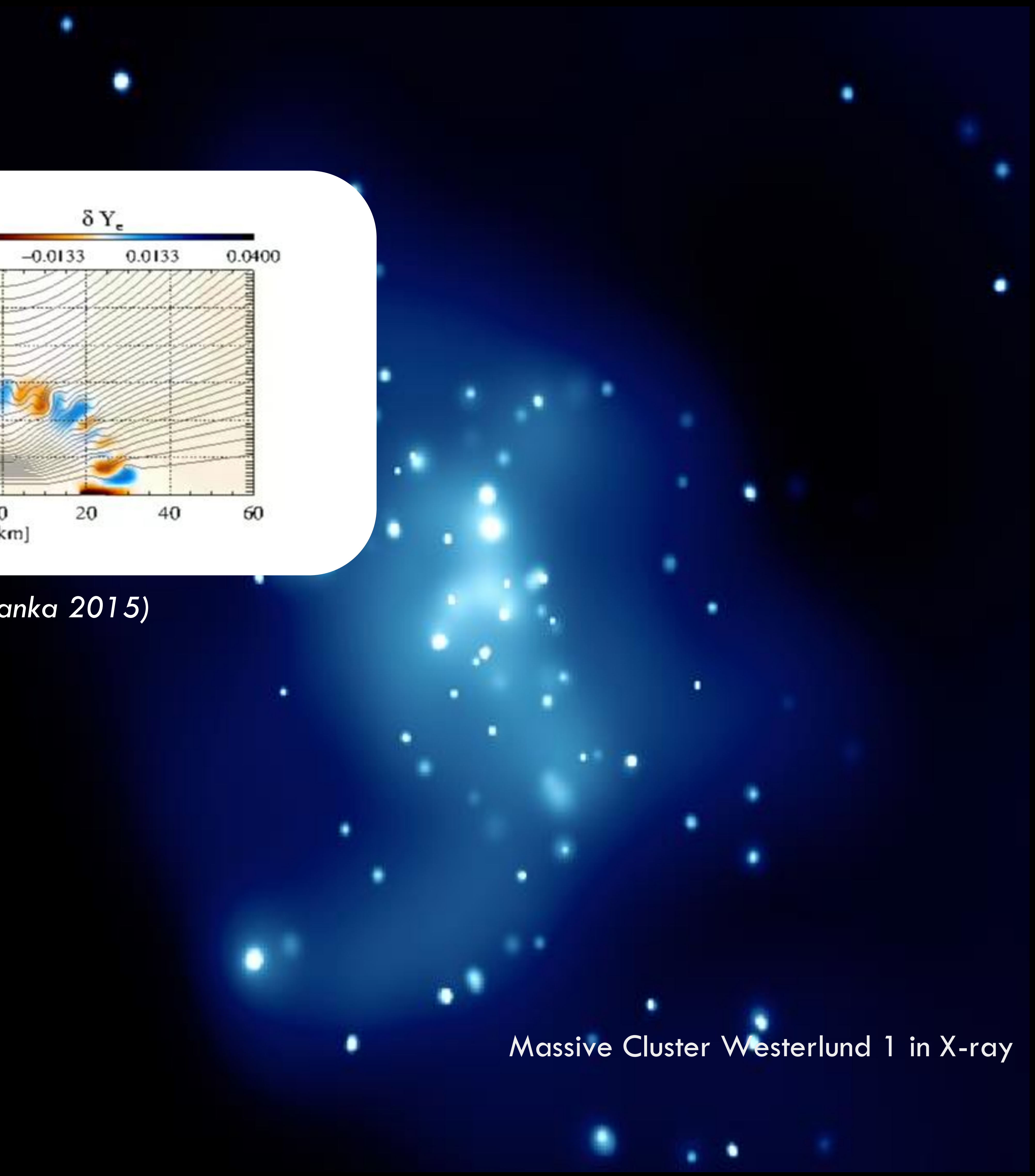
- via dynamos in the stellar core
- as fossil fields from a magnetic progenitor
- from massive star binary progenitors



(Obergaulinger, Aloy & Janka 2015)

Observationally…

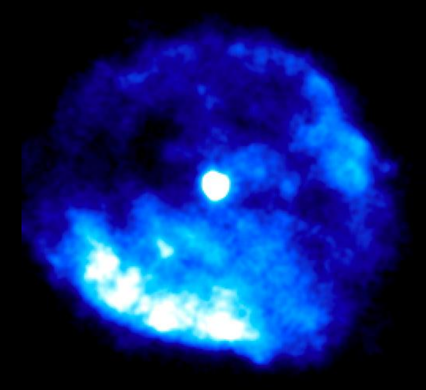
- Proper motions for ~9 objects: 100-300 km/s range
- A few magnetars coincident with massive star clusters
- One case: a wind blown boubble observed in radio
- One case: a run-away massive star close-by is detected.
- ~6 confirmed SNRs, 3 more possibly associated

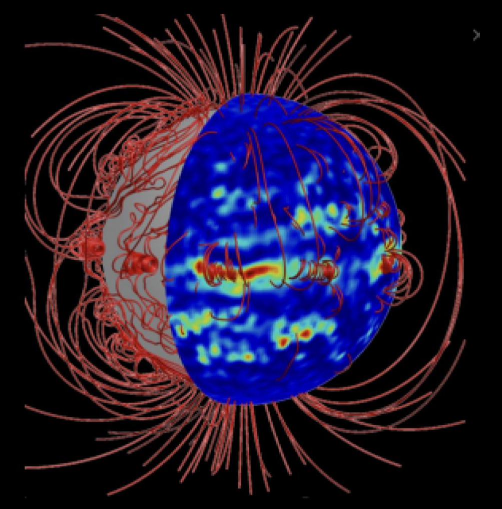


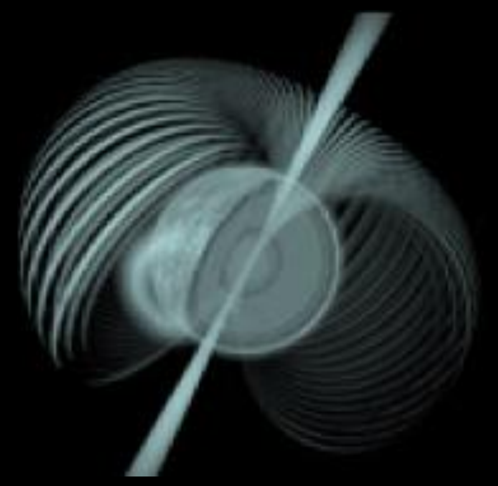
Massive Cluster Westerlund 1 in X-ray

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

VERY YOUNG NEUTRON STARS IN OUR GALAXY





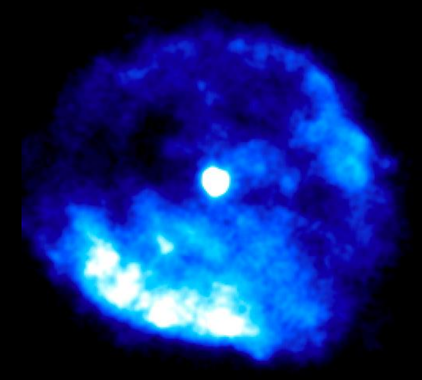


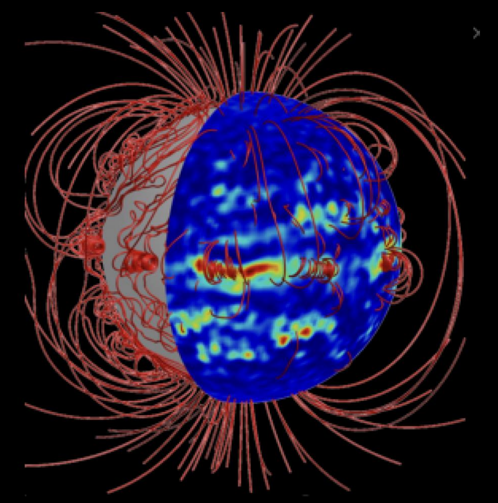
source	radio	association	class	tau_real(kyr)	tau_c(kyr)	ref_age_real	distance(kpc)
CXOJ232327.9+584842		SNR CasA	CCO	0.32		SNR	3.4
XMMUJ172054.5-372652		G350.1-0.3	CCO	0.6		SNR	6.1
CXOJ160103.1-513353		G330.2+1.0	CCO	0.8		SNR	5.0
1WGAJ1713.4-3949		G347.3-0.5	CCO	1.6		SNR	1.3
1E161348-5055		SNR RCW103	CCO	2.0		SNR	3.3
1E1841-045		SNR Kes73	Magnetar	0.7	4.6	SNR	8.5
SGR1806-20		W31 open cluster	Magnetar	0.8	1.6	PM	8.7
SwiftJ1818.0-1607	TRUE		Magnetar		0.47		4.8
1E1547-5408	TRUE	SNR G327.24-0.13	Magnetar		0.69	SNR	4.5
PSRJ1846-0258			Magnetar		0.73		6.0
CXOUJ171405.7-3810		SNR CTB37B	Magnetar		0.95	SNR	13.2
SGRJ1745-2900	TRUE	Galactic Center	Magnetar		1.9		8.3
PSRJ0205+6449	TRUE	3C58	RPP	0.83	5.37	SNR	3.2
PSRB0531+21 (Crab)	TRUE	Crab	RPP		1.26	SNR	2
PSR B1509-58		G320.4-1.2	RPP		1.57	SNR	4.4

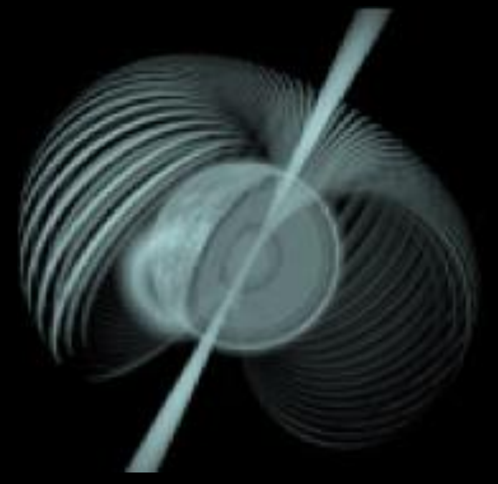
Among the ~20 neutron stars we should have with ~2kr we know 15 of them already…

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

VERY YOUNG NEUTRON STARS IN OUR GALAXY







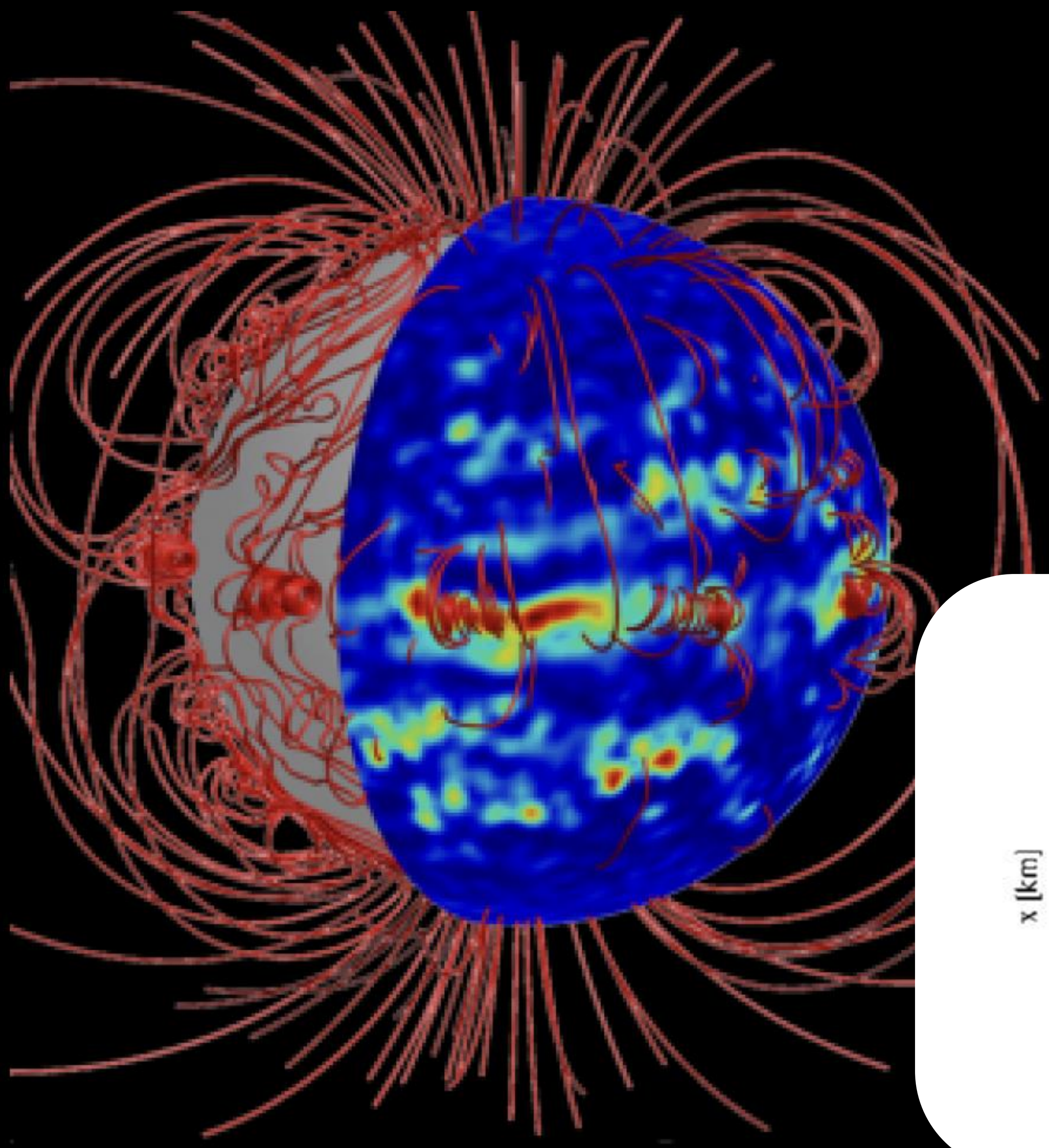
source	radio	association	class	tau_real(kyr)	tau_c(kyr)	ref_age_real	distance(kpc)
CXOJ232327.9+584842		SNR CasA	CCO	0.32		SNR	3.4
XMMUJ172054.5-372652		G350.1-0.3	CCO	0.6		SNR	6.1
CXOJ160103.1-513353		G330.2+1.0	CCO	0.8		SNR	5.0
1WGAJ1713.4-3949		G347.3-0.5	CCO	1.6		SNR	1.3
1E161348-5055		SNR RCW103	CCO	2.0		SNR	3.3
1E1841-045		SNR Kes73	Magnetar	0.7	4.6	SNR	8.5
SGR1806-20		W31 open cluster	Magnetar	0.8	1.6	PM	8.7
SwiftJ1818.0-1607	TRUE		Magnetar		0.47		4.8
1E1547-5408	TRUE	SNR G327.24-0.13	Magnetar		0.69	SNR	4.5
PSRJ1846-0258			Magnetar		0.73		6.0
CXOUJ171405.7-3810		SNR CTB37B	Magnetar		0.95	SNR	13.2
SGRJ1745-2900	TRUE	Galactic Center	Magnetar		1.9		8.3
PSRJ0205+6449	TRUE	3C58	RPP	0.83	5.37	SNR	3.2
PSRB0531+21 (Crab)	TRUE	Crab	RPP		1.26	SNR	2
PSR B1509-58		G320.4-1.2	RPP		1.57	SNR	4.4

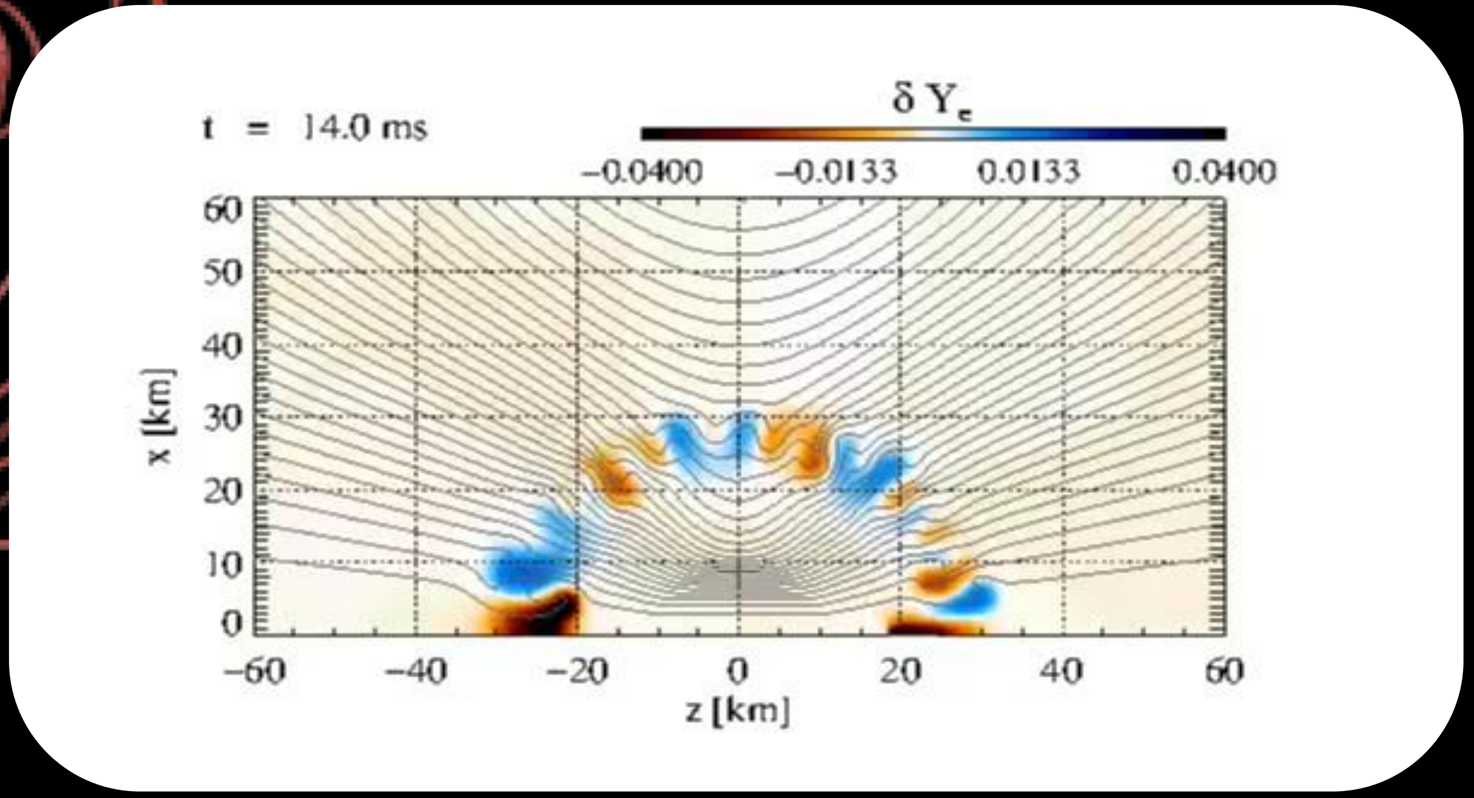
Among the ~20 neutron stars we should have with ~2kr we know 15 of them already…

This means (with no population synthesis models involved…) that in the past 2kyr our Galaxy created mostly ~50% Magnetars, ~30% Central Compact Objects and 20% Rotational Powered Pulsar.

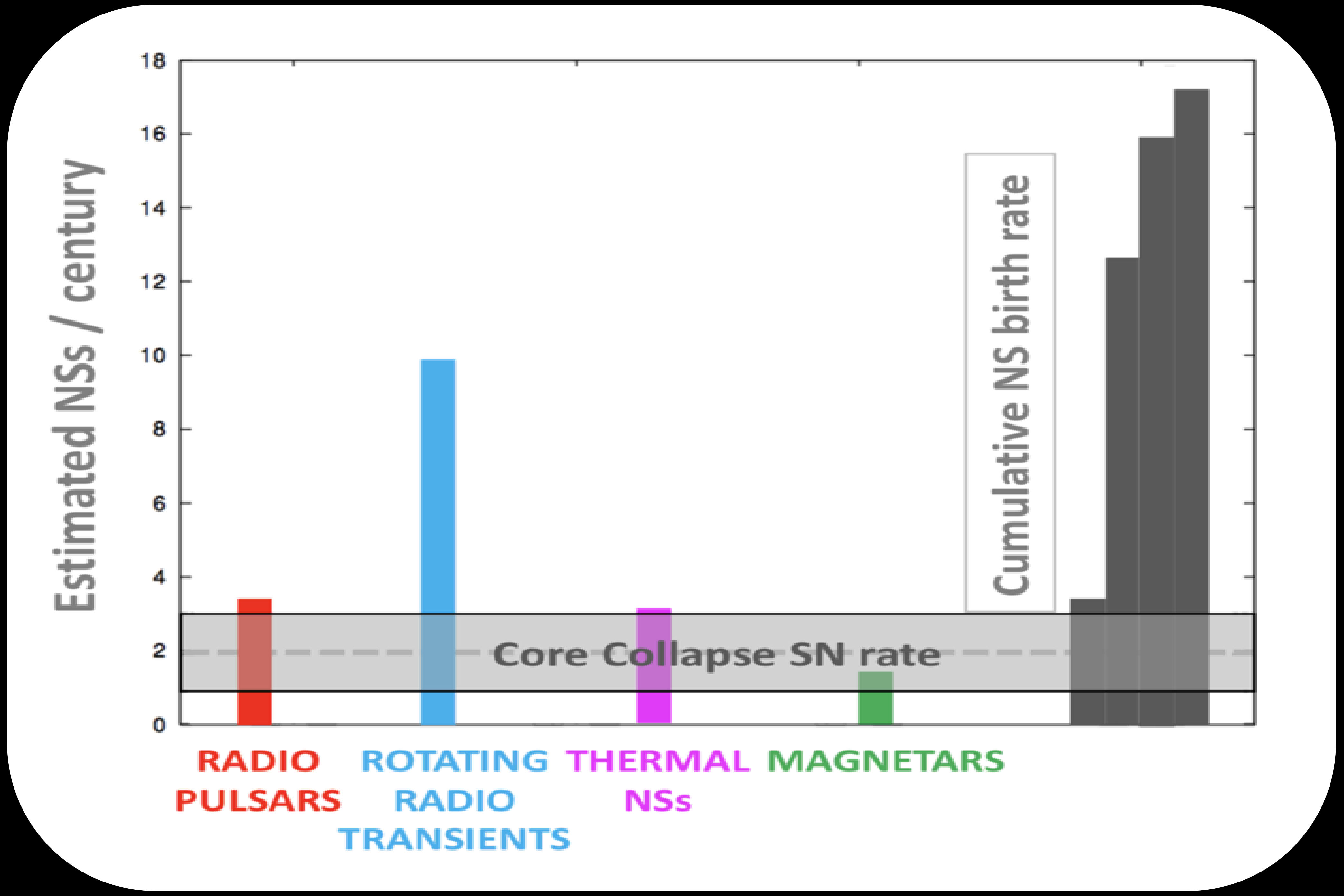
(Rea, Pardo, Ronchi et al. 2025 in prep)

NEUTRON STARS 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, and their birth rate is very high.

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

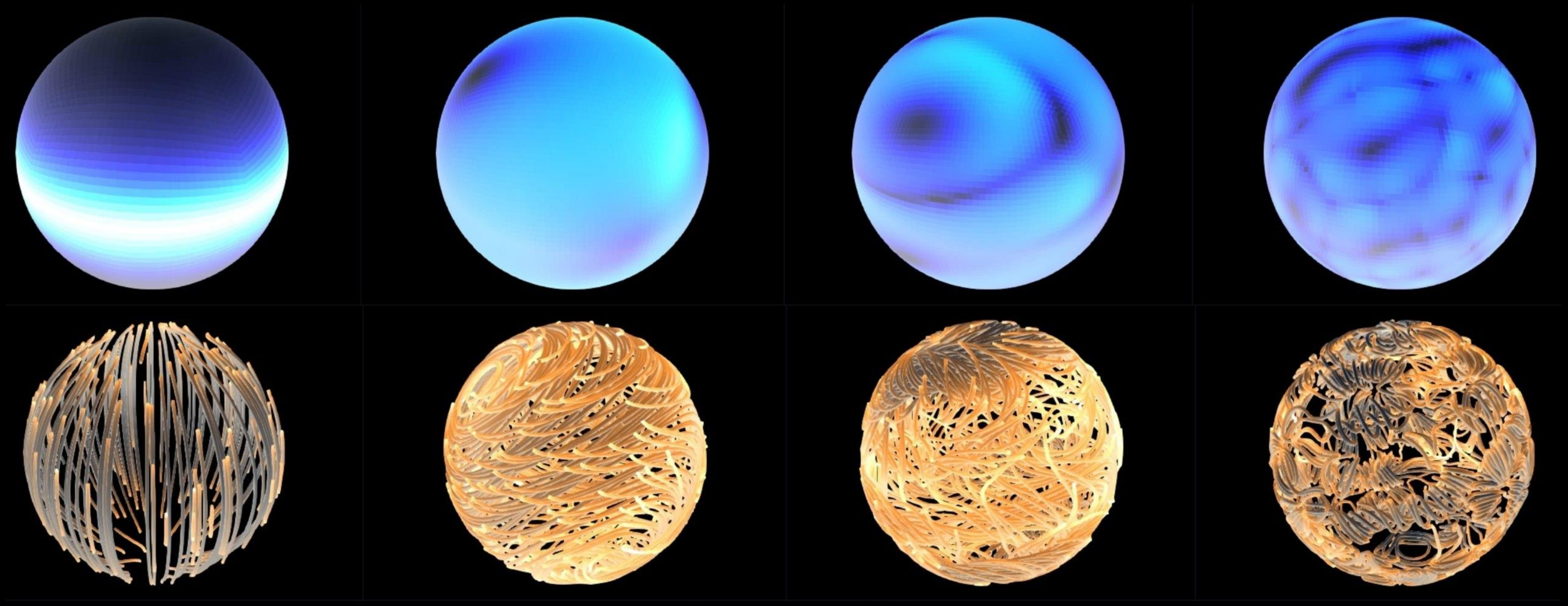
$$C_v e^{\nu} \frac{\partial \mathbf{T}}{\partial t} + \nabla \times [-k \times \nabla(e^{\nu}\mathbf{T})] = e^{2\nu}[H - Q]$$

ENERGY BALANCE EQUATION

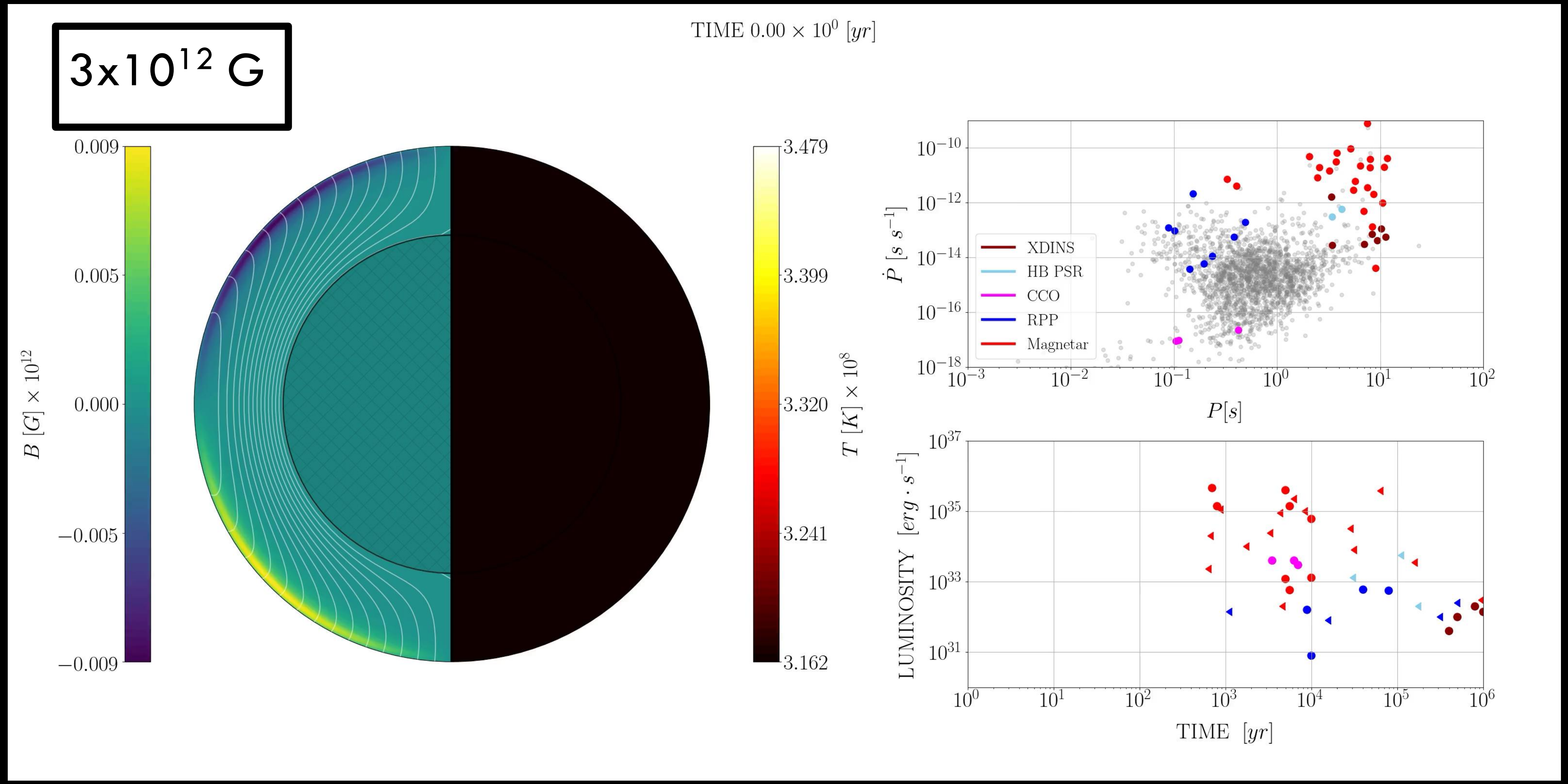
$$\frac{\partial \mathbf{B}}{\partial t} = -\nabla \times \left\{ \eta \nabla \times (e^{\nu}\mathbf{B}) + \left[\frac{c e^{-\nu}}{4\pi e n_e} \nabla \times (e^{\nu}\mathbf{B}) \right] \times (e^{\nu}\mathbf{B}) \right\}$$

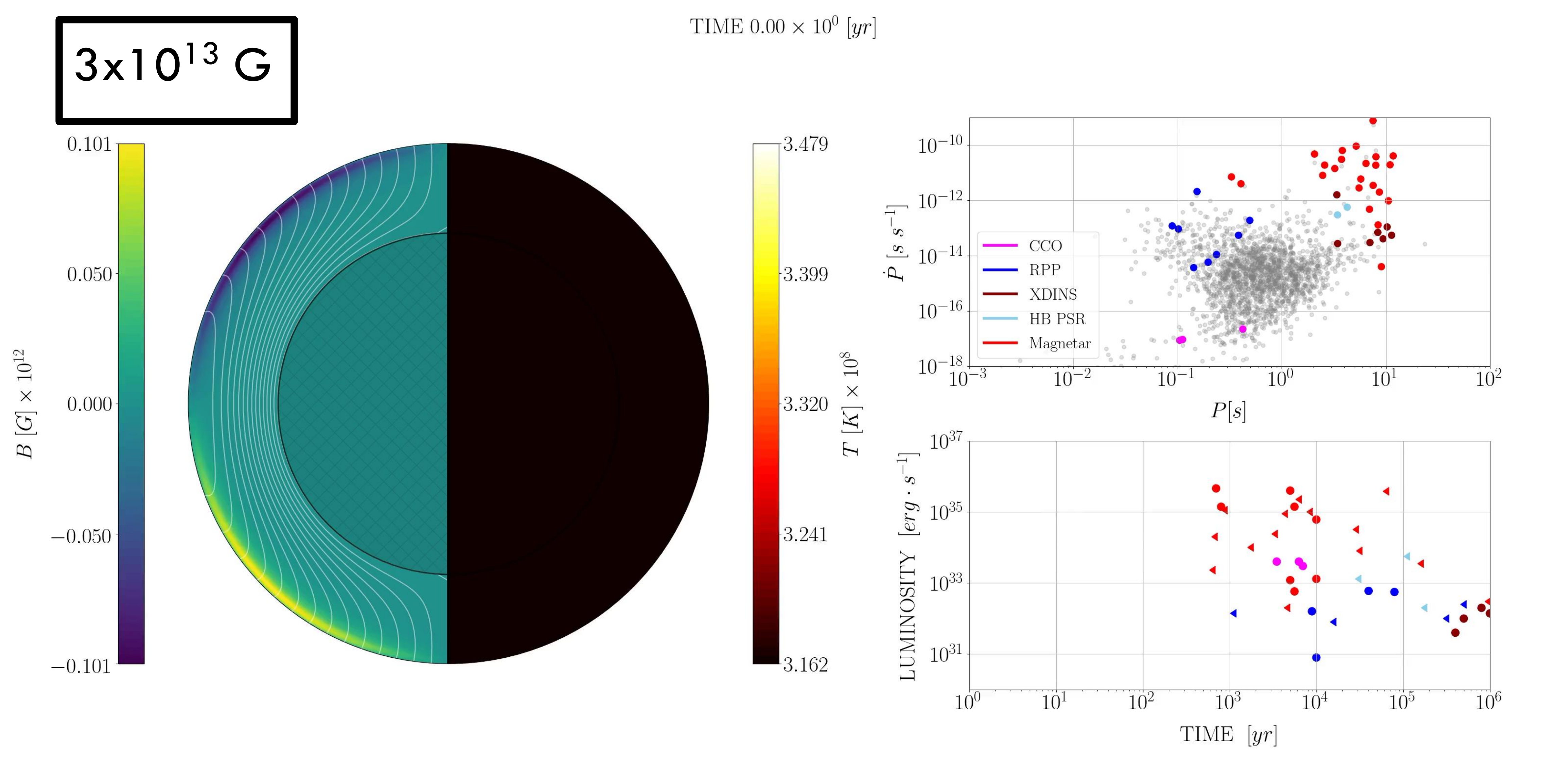
HALL INDUCTION EQUATION

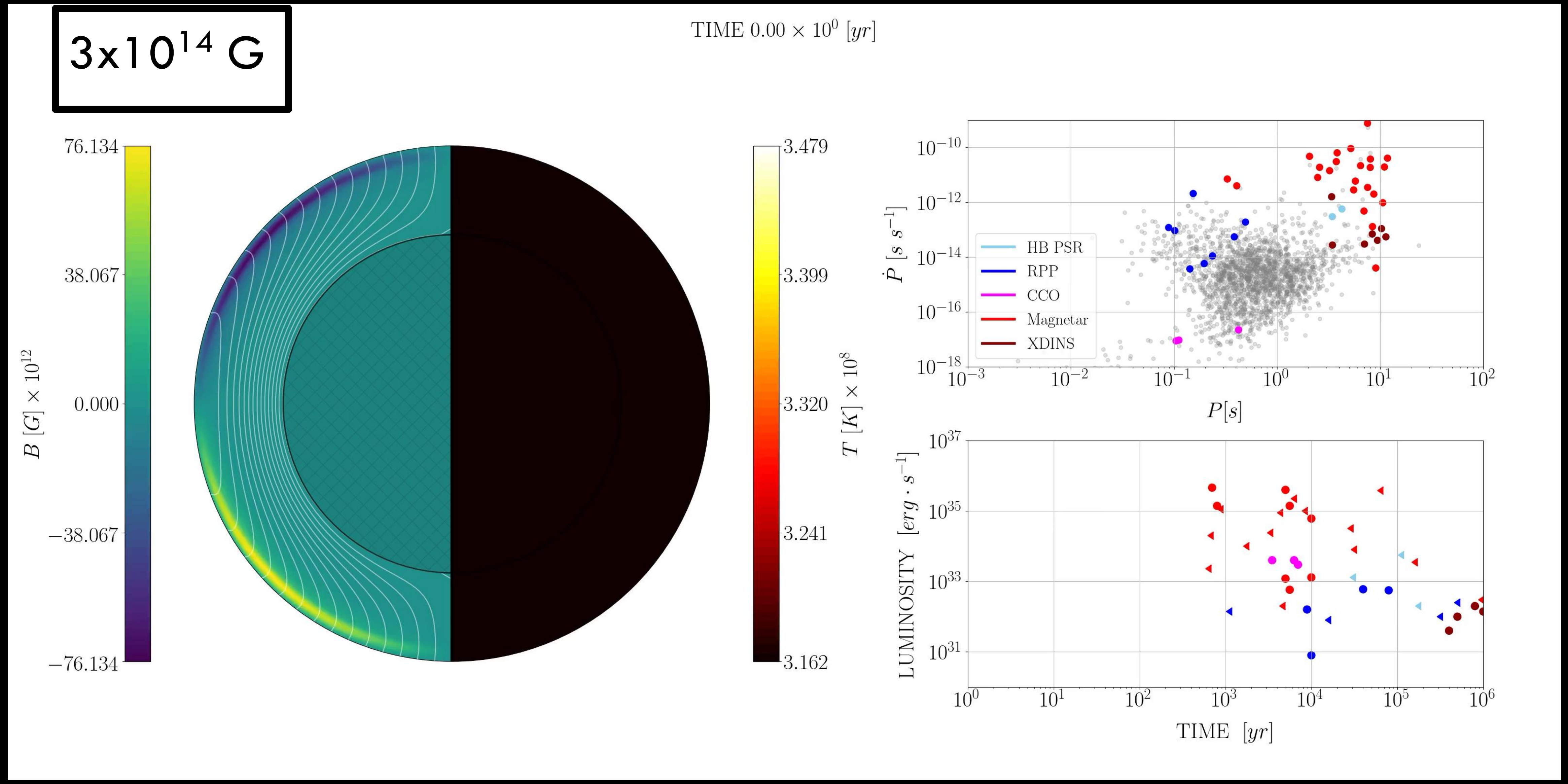
Electrical Resistivity

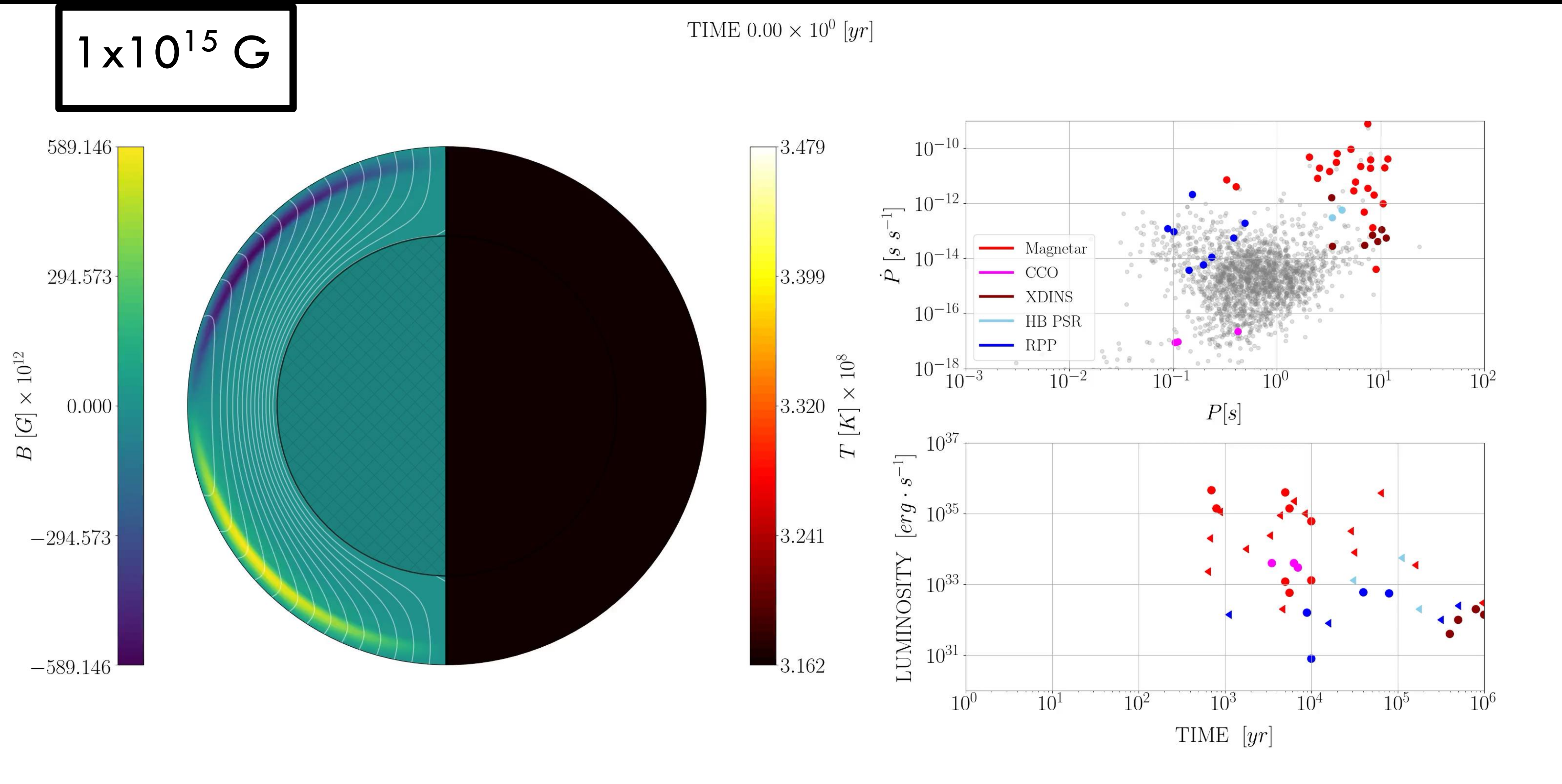


NEUTRON STAR EVOLUTION: eMHD SIMULATIONS







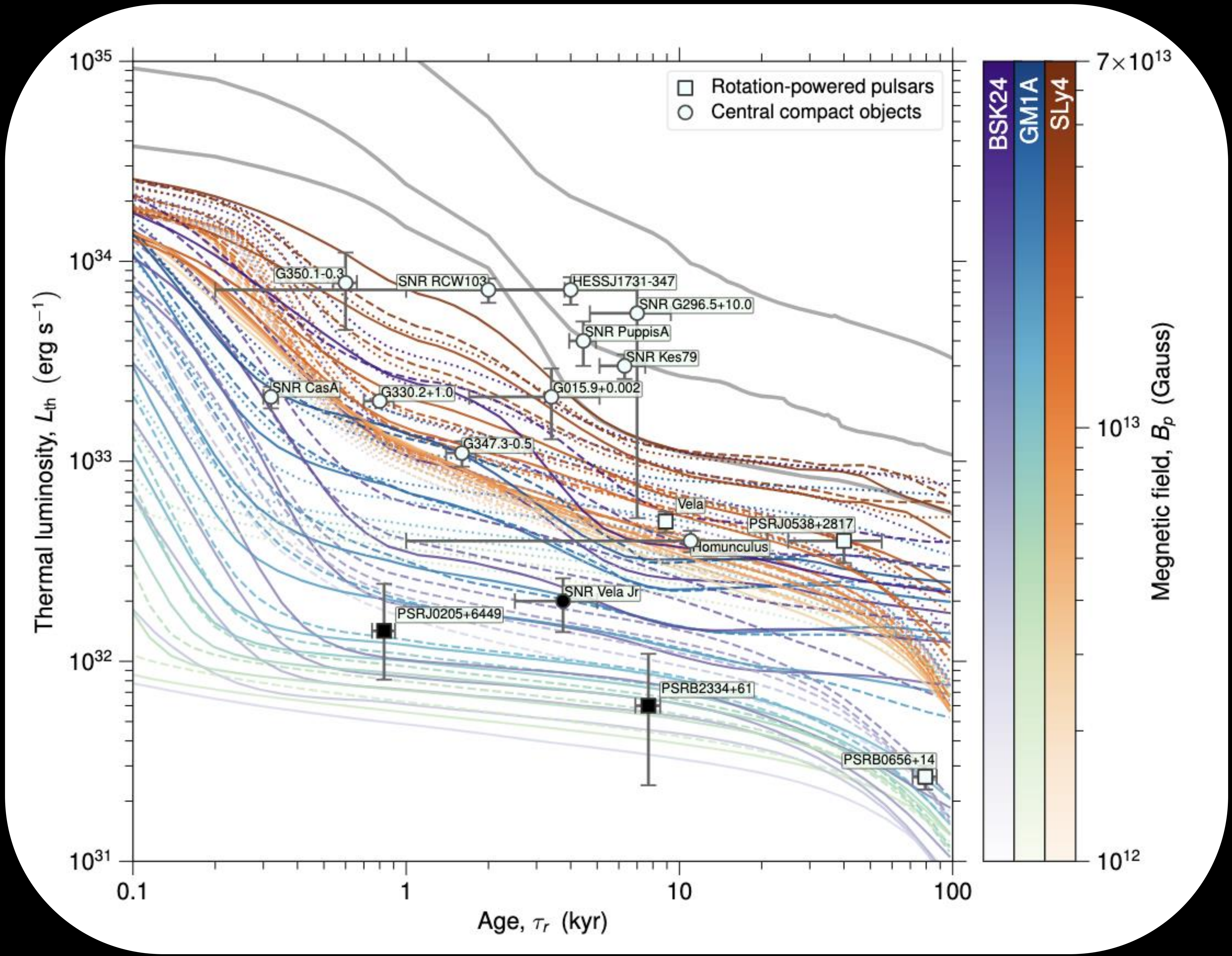


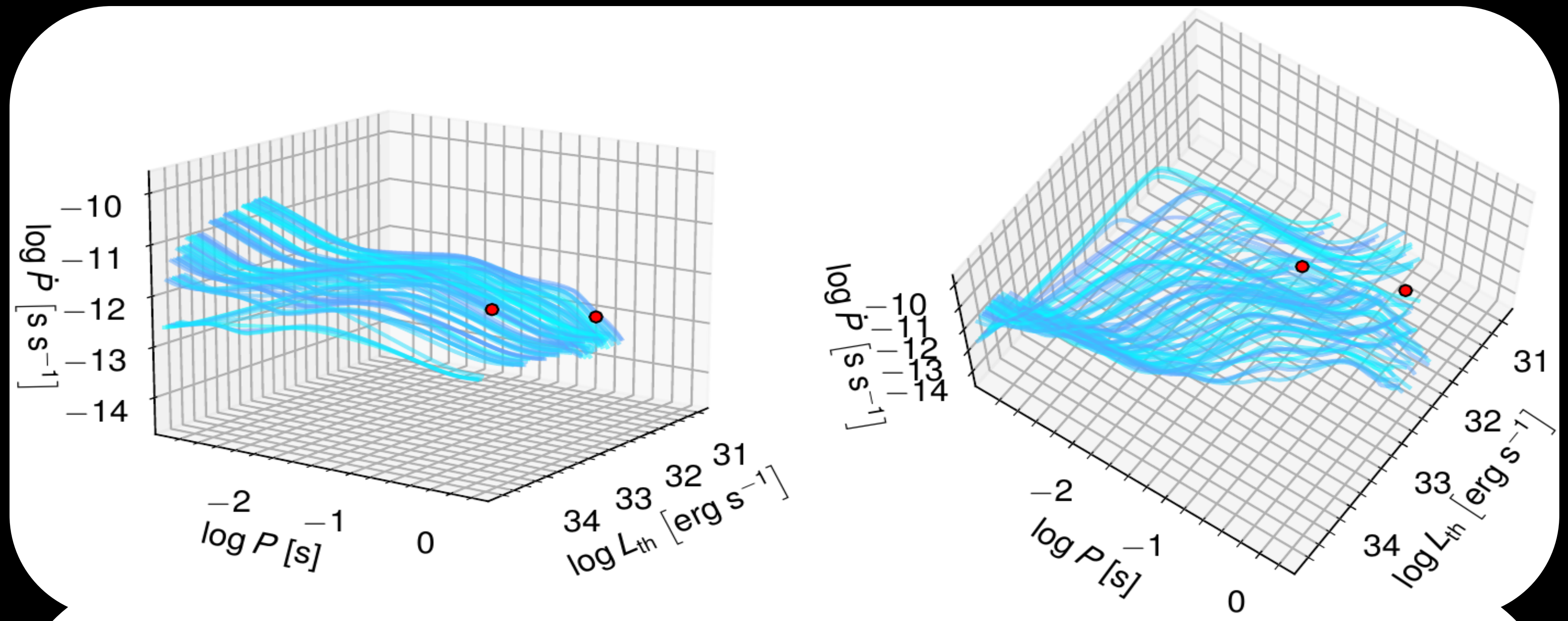
(Dehman et al. 2023, Ascenzi et al. 2024: MATINS - first 3D MT-code with microphysics)

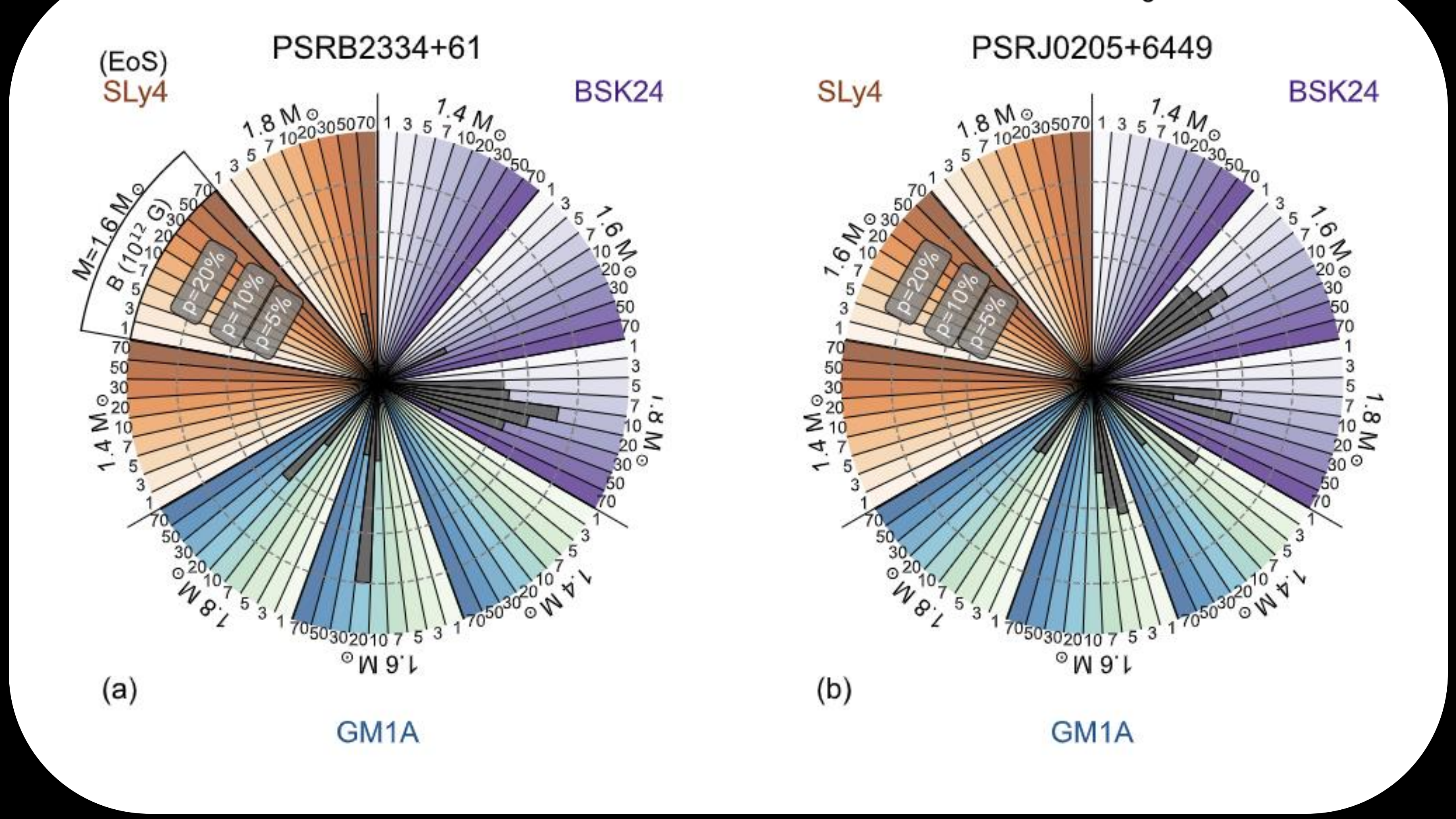
NEUTRON STAR FIELD EVOLUTION

(Rea & De Grandis 2025, Elsevier encyclopedia)

NEUTRON STAR FIELD EVOLUTION: CONSTRAINING EoS





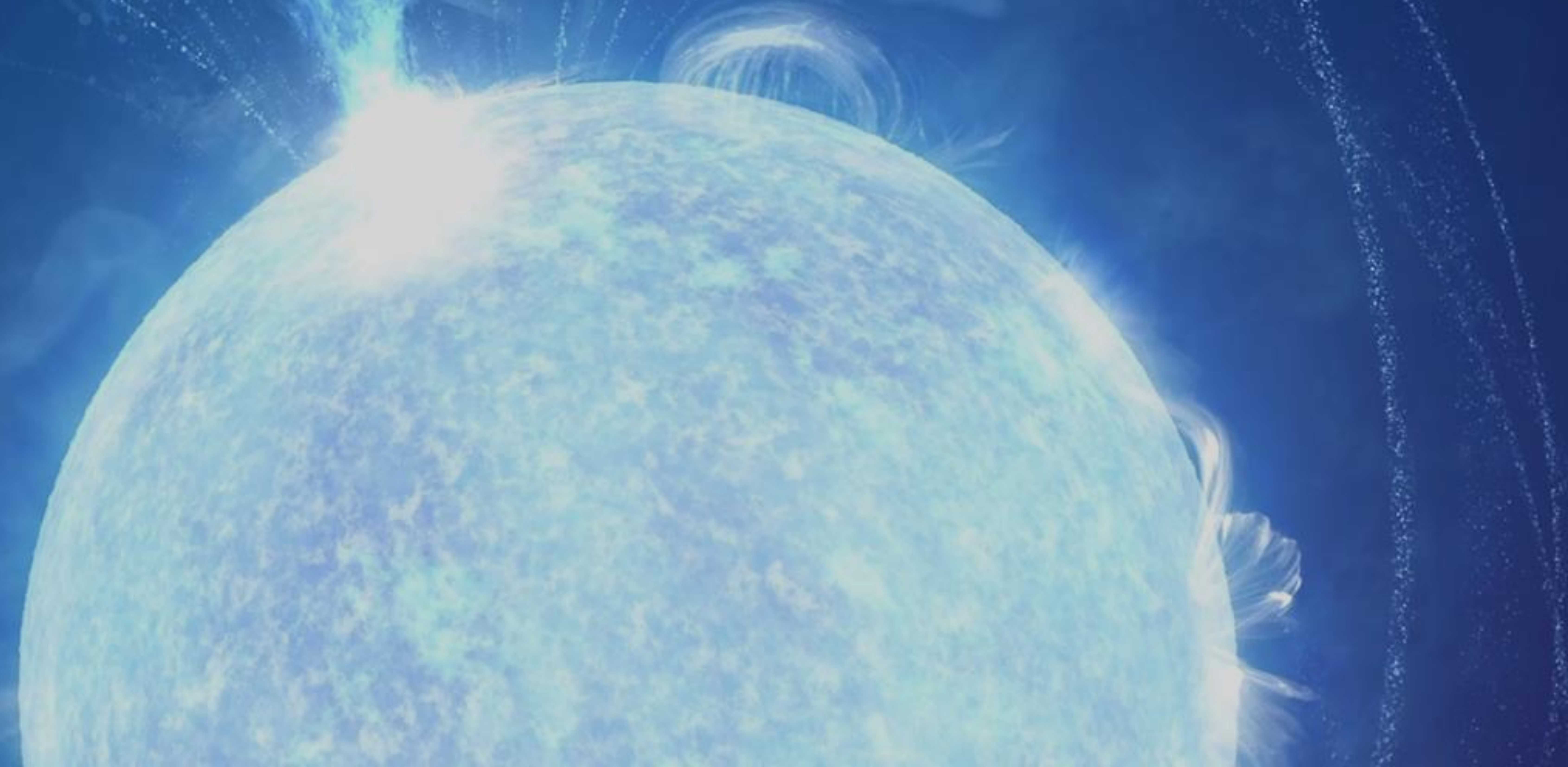


FAT COOLING NECESSARY FOR THE NS EoS AT LEAST FOR HIGH MASSES, to explain the three young and cold NSs.

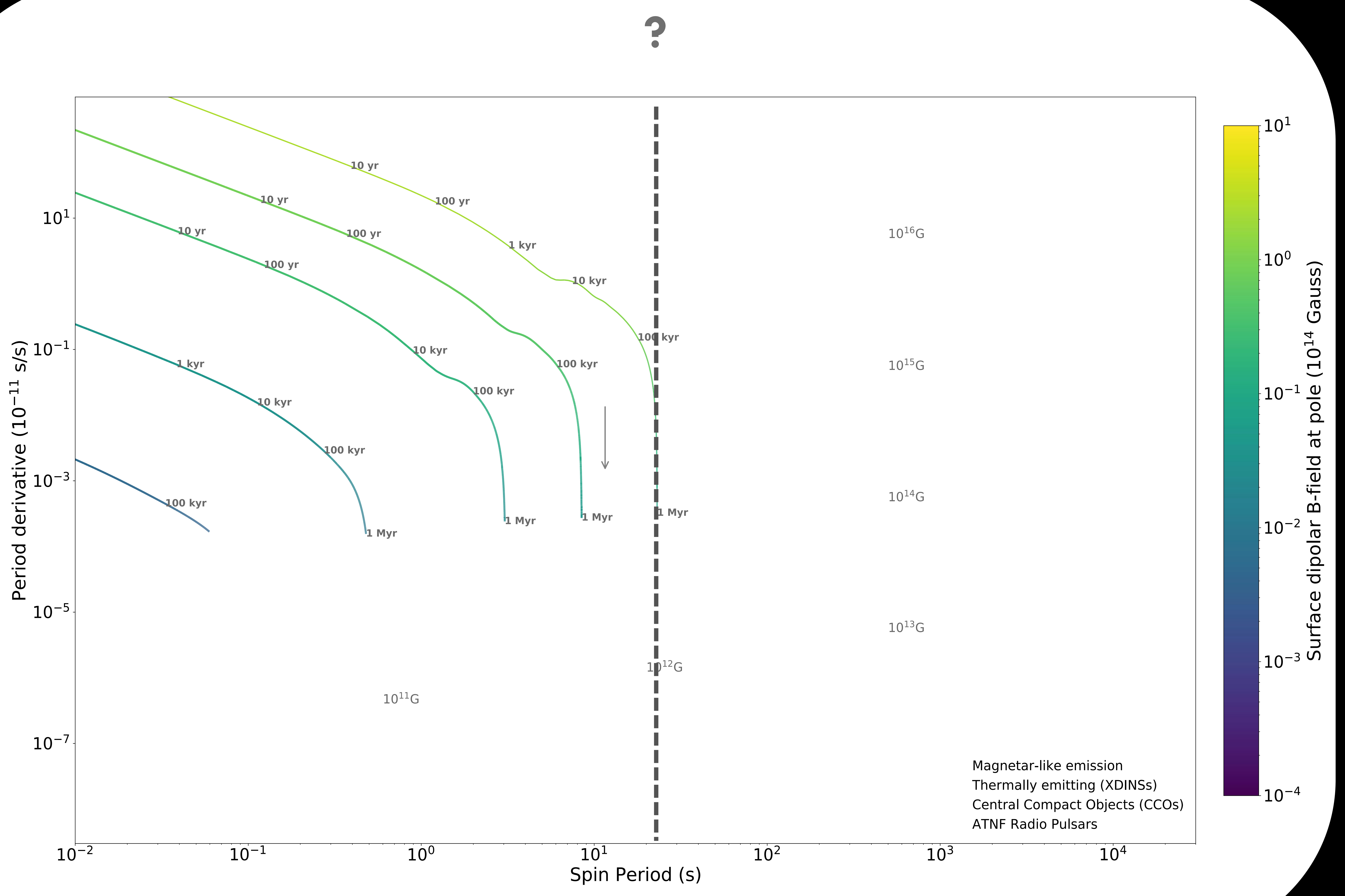
This excludes 75% of the current proposed EoS (in the Compose catalog).

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

- MAGNETARS AND THE PULSAR POPULATION
- MAGNETAR BIRTH RATES AND EVOLUTION
- LONG PERIOD TRANSIENTS

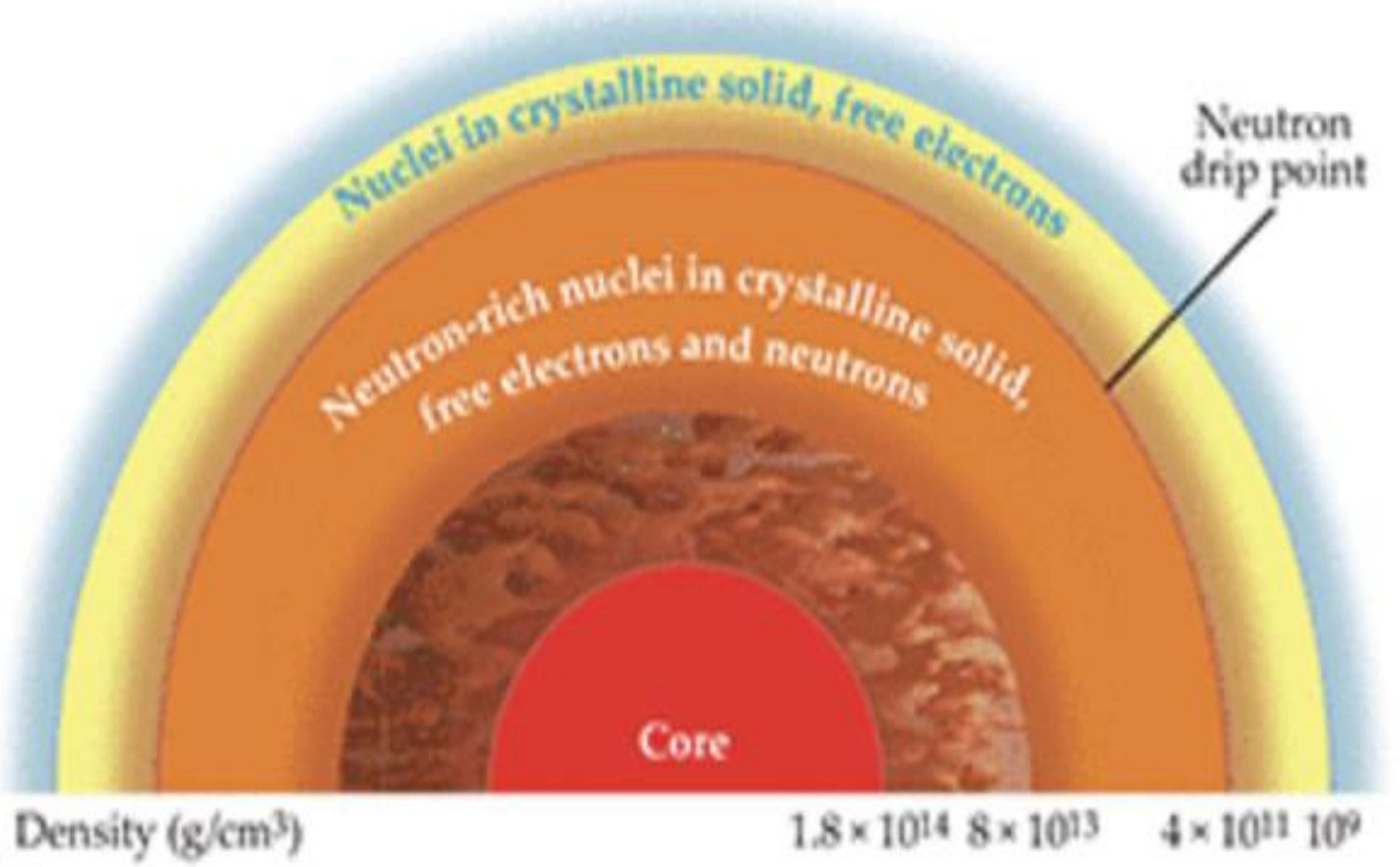


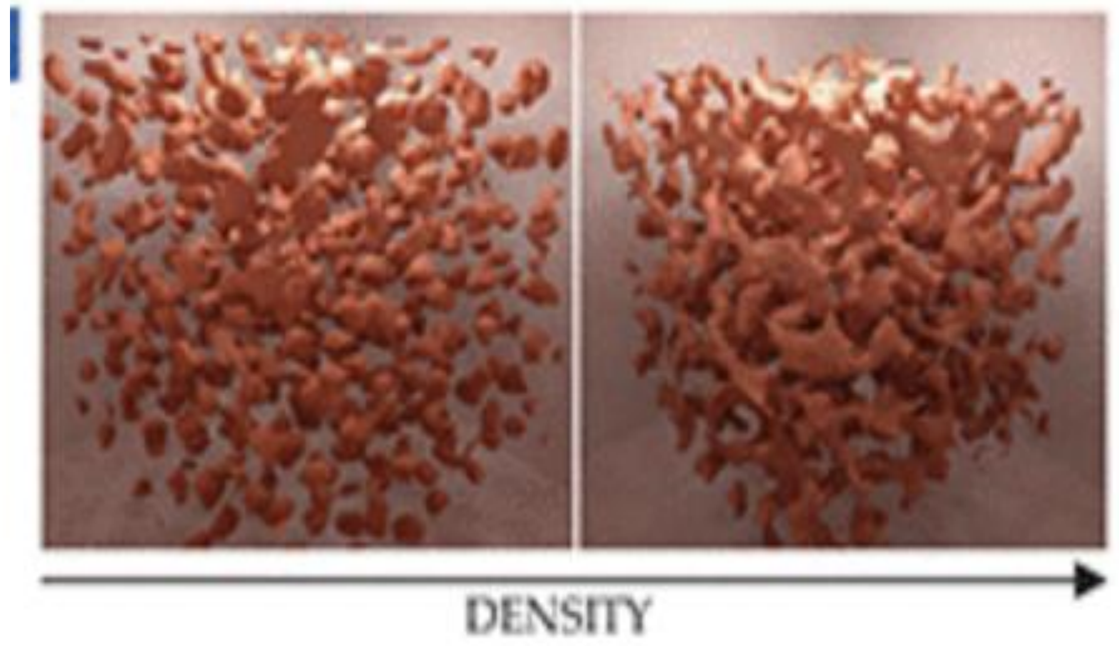
THE ISOLATED PULSAR POPULATION SPIN DISTRIBUTION



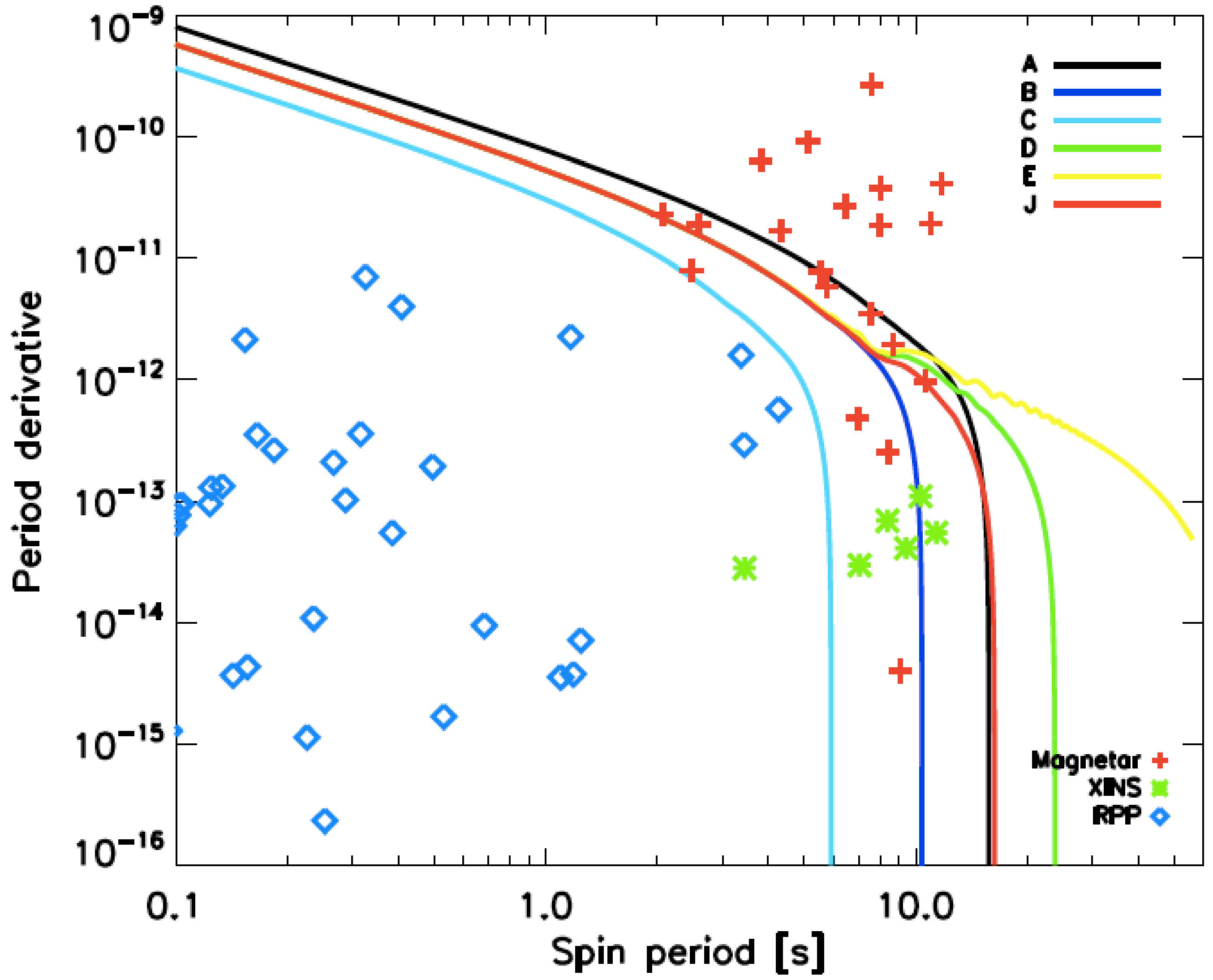
THE INNER CRUST HIGH RESISTIVITY IS DRIVING THE SPIN DISTRIBUTION

(Rea 2015, Physics Today)

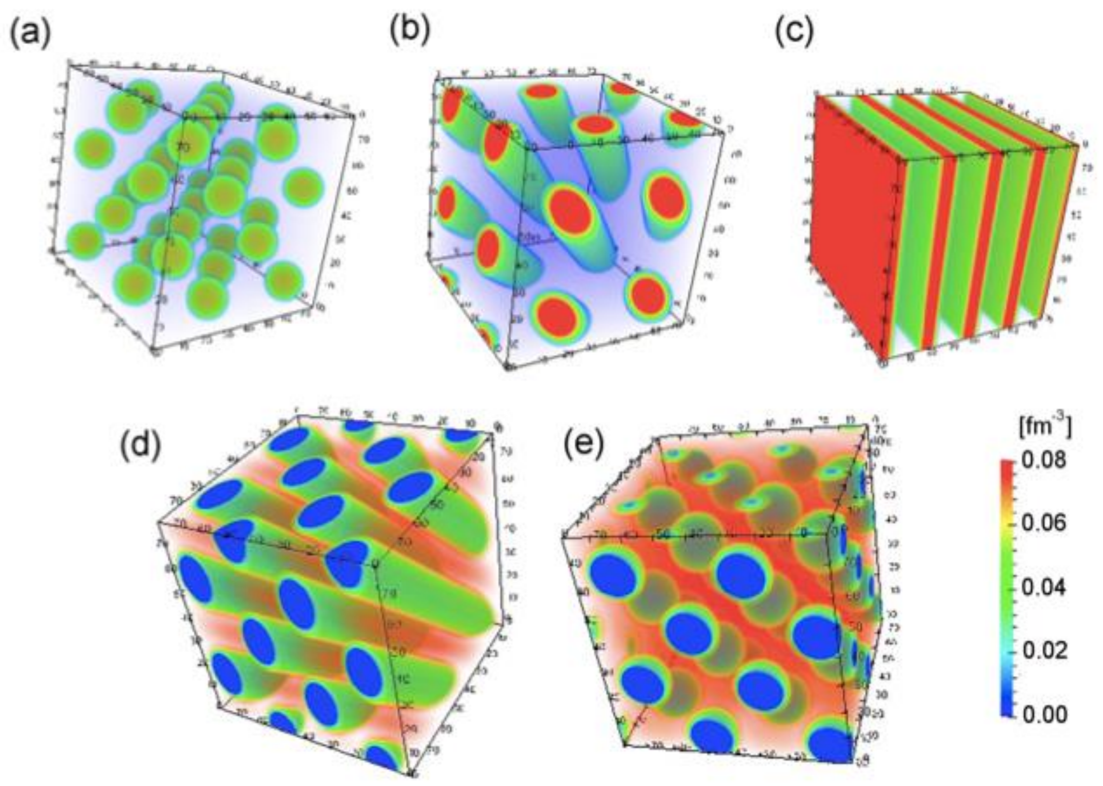




Model	$M[M_\odot]$	I_{45}	ΔR_{crust} [km]	ΔR_{pasta} [km]	Q_{max}
A	1.10	0.962	0.94	0.14	100
B	1.40	1.327	0.70	0.10	100
C	1.76	1.755	0.43	0.07	100
D	1.40	1.327	0.70	0.10	10
E	1.40	1.327	0.70	0.10	0.1
J	1.40	1.327	0.70	0.0	23

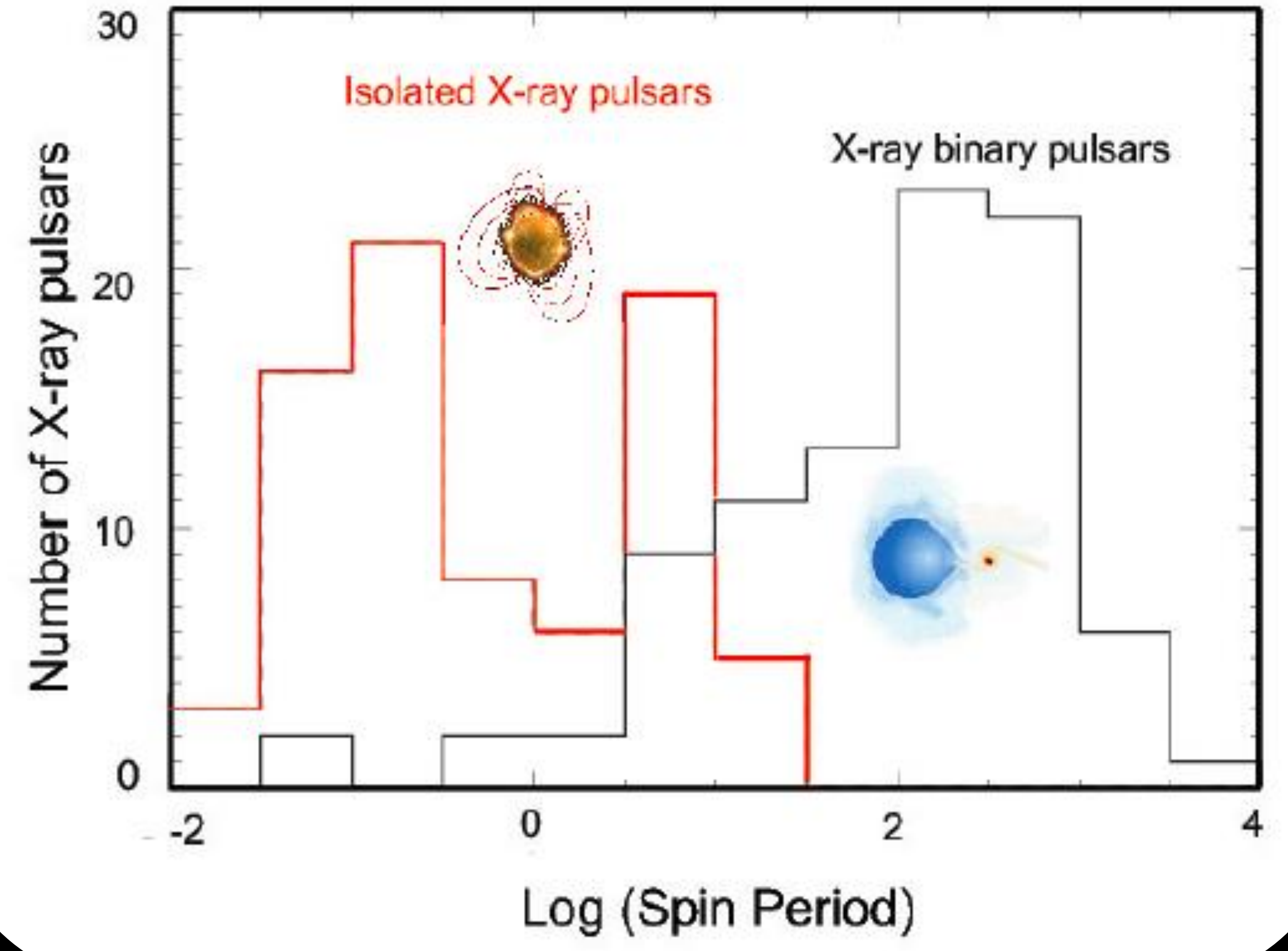


(Pons, Vigano' & Rea 2013 *Nature Physics* 9, 431)

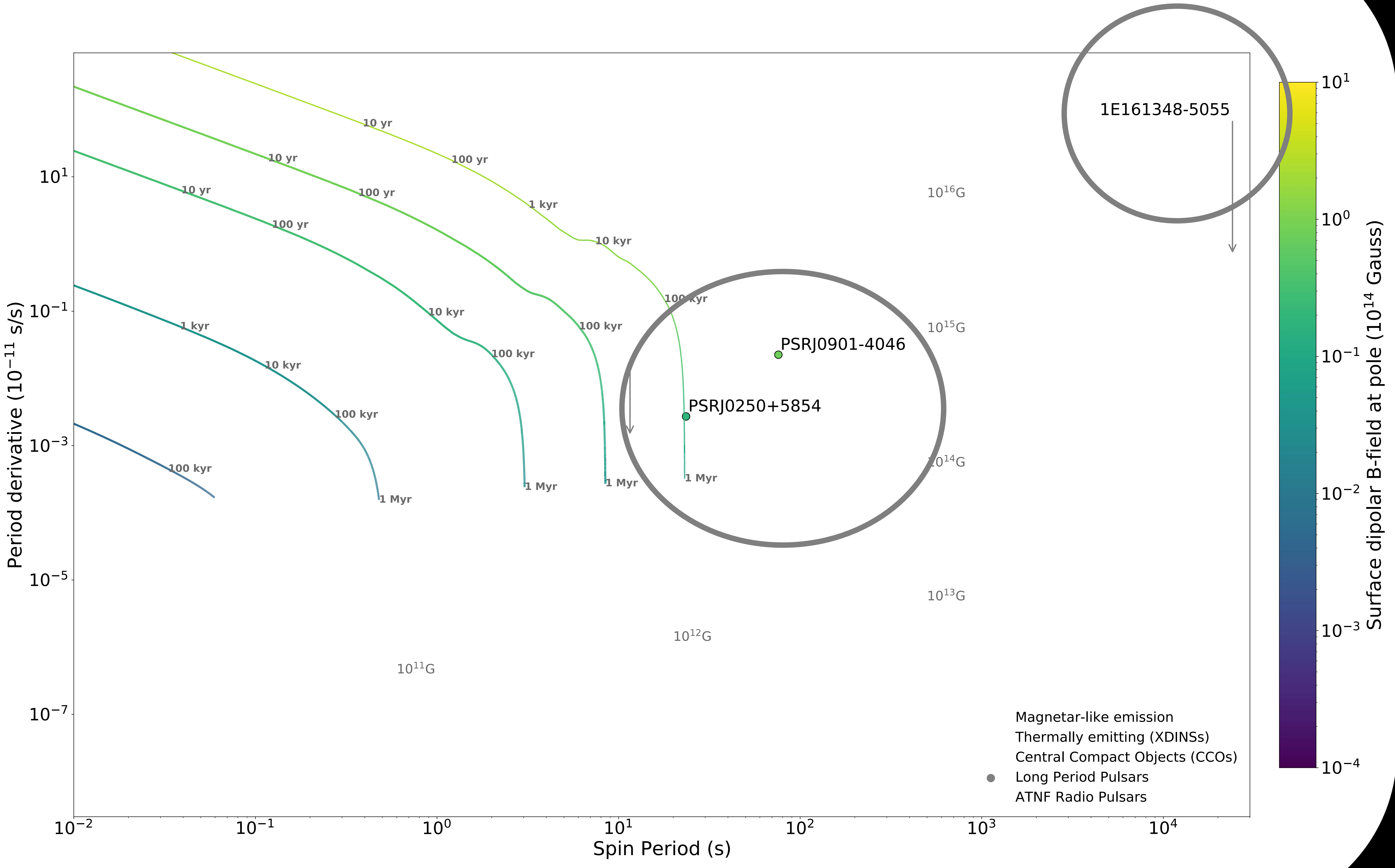


(Okamoto et al. 2013)

Magnetar spin limit as an observational evidence of the existence of the Nuclear Pasta phase of matter. At densities > 10^{13} gr cm^{-3} nuclei are favoured in pasta shapes (rods, slabs, bubbles).

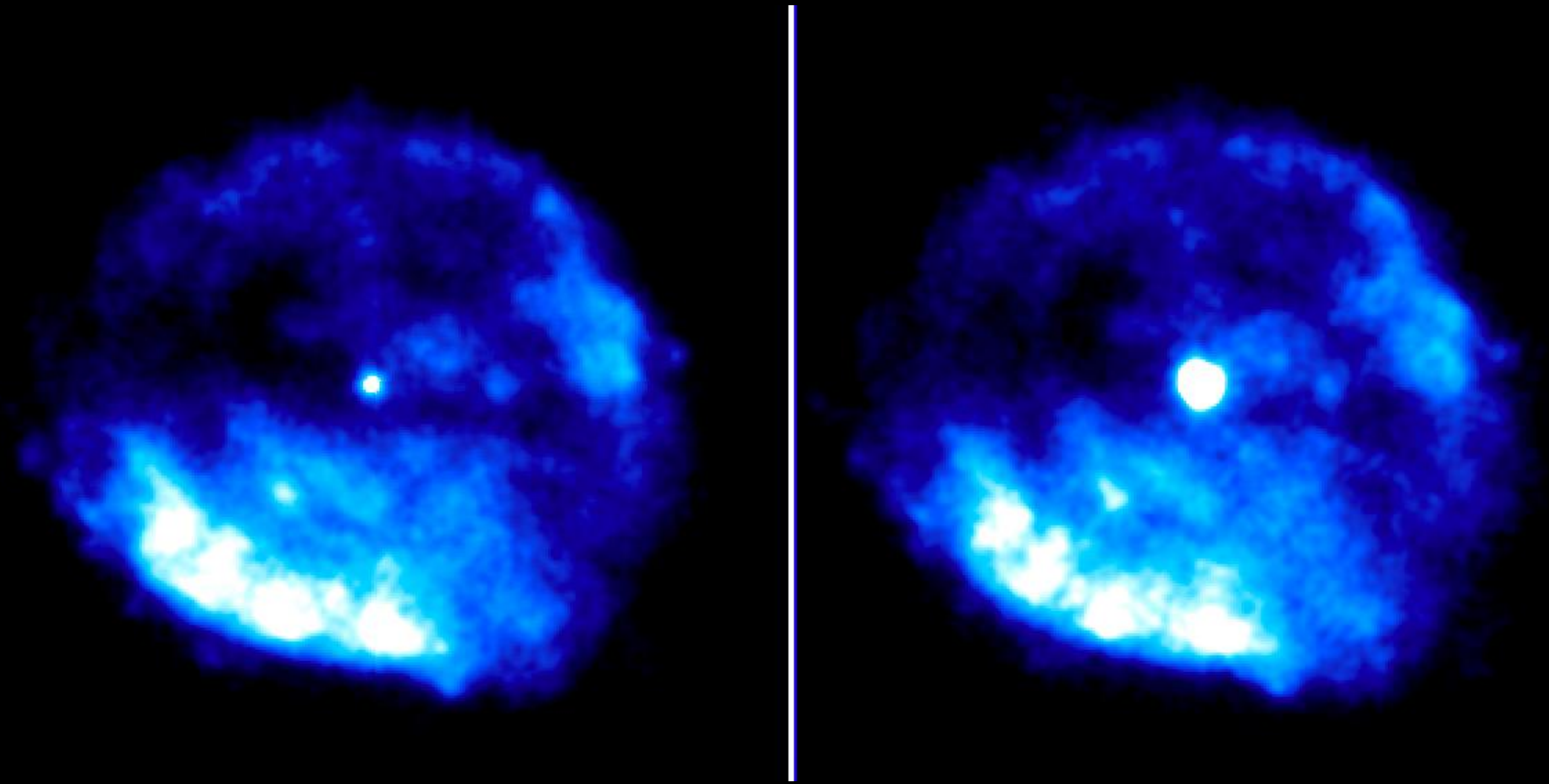


THE ISOLATED PULSAR POPULATION SPIN DISTRIBUTION

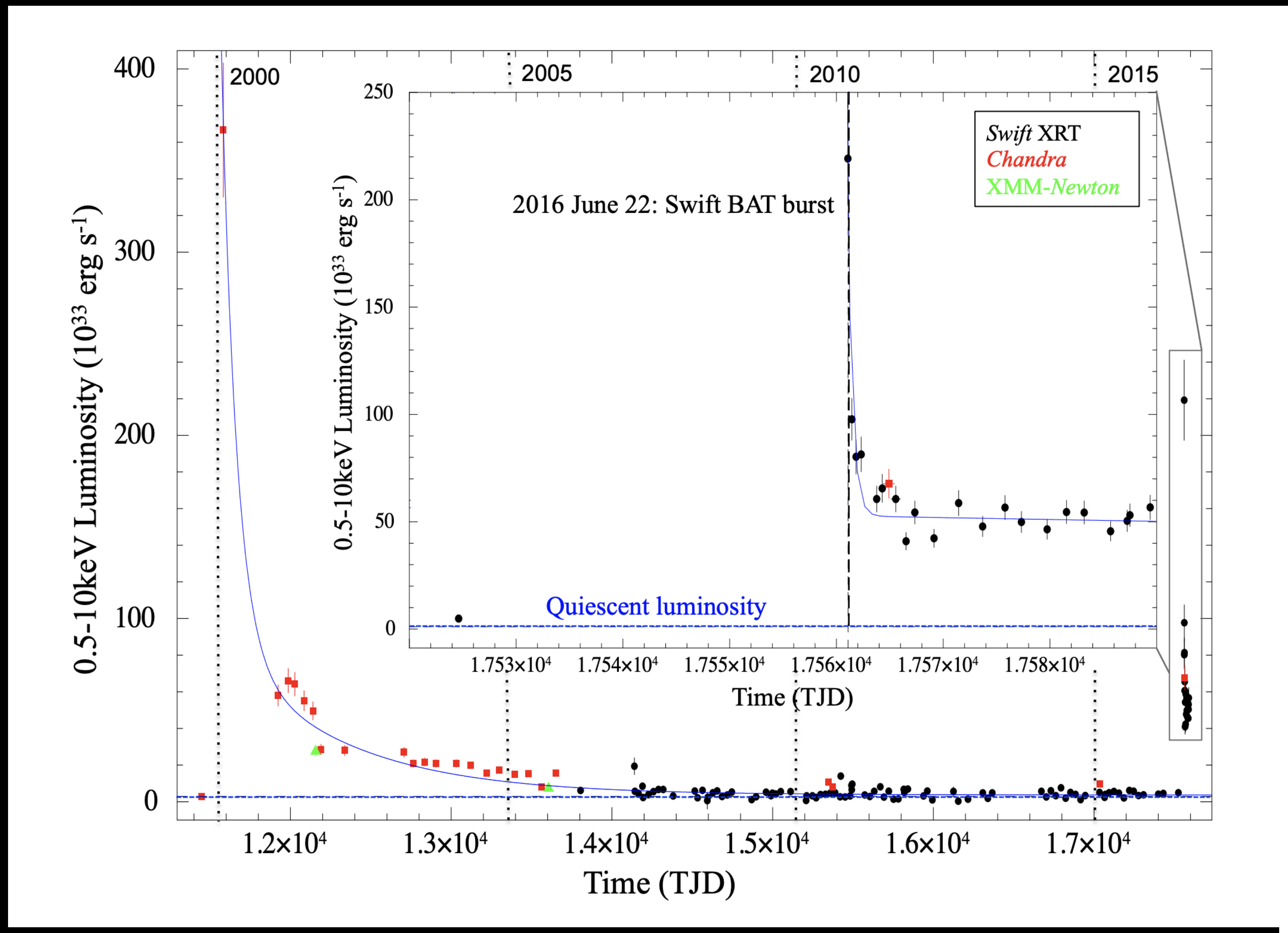


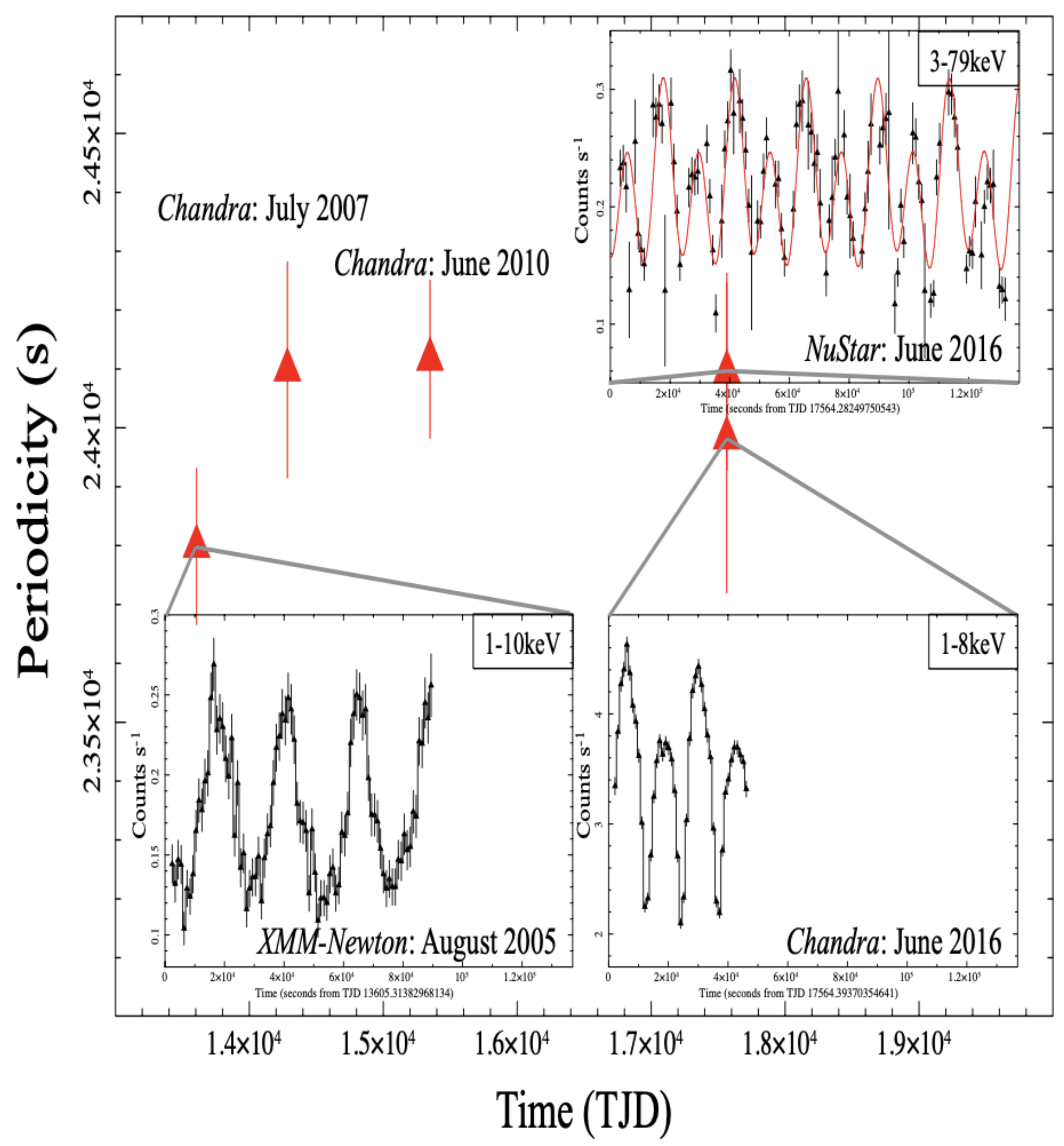
(Tan et al. 2018, ApJ; Caleb et al. 2022, *Nature Astronomy; De Luca et al. 2006, MNRAS, Rea et al. 2016, ApJL*)

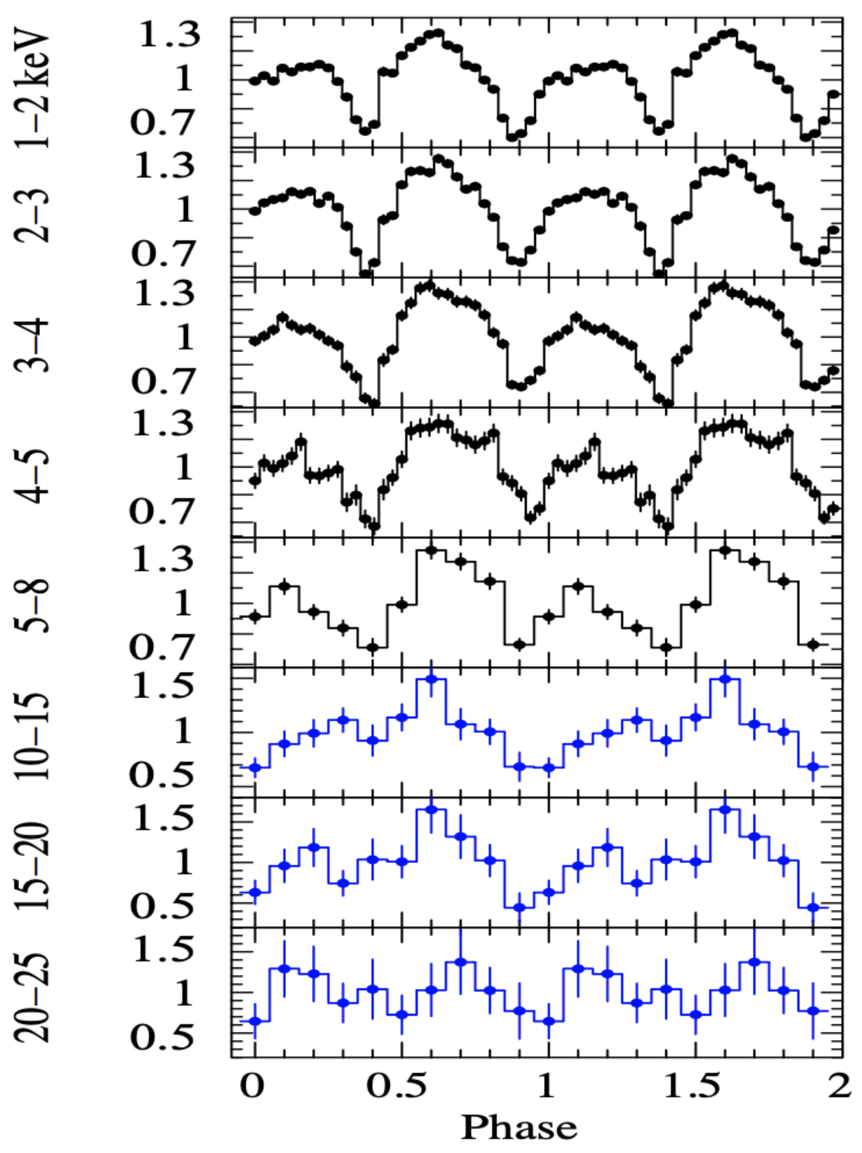
A MAGNETAR WITH A 6.4hr SPIN PERIOD IN THE CCO RCW103

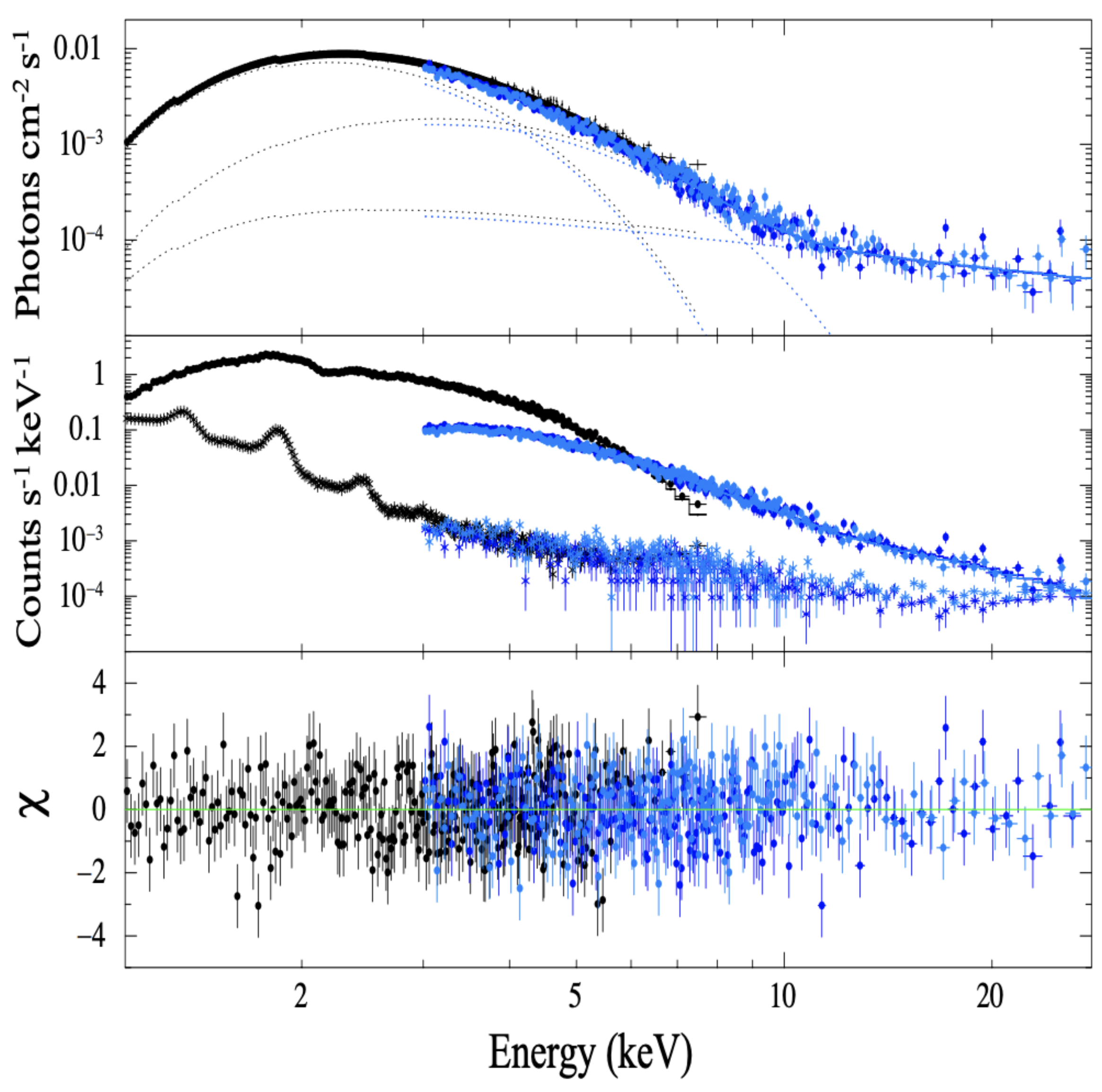


Fall back accretion after the supernova could make this pulsar slow down so extremely…





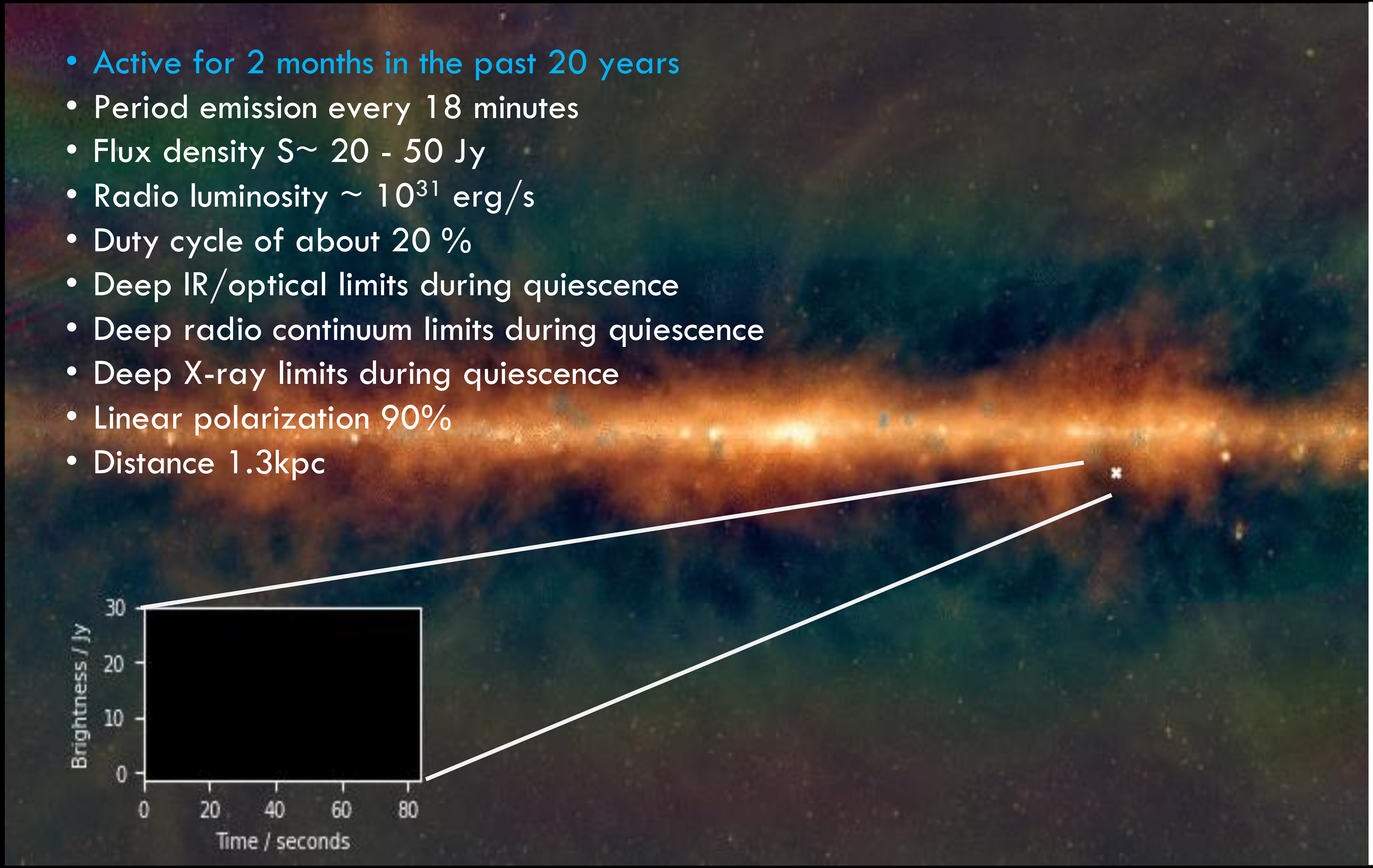


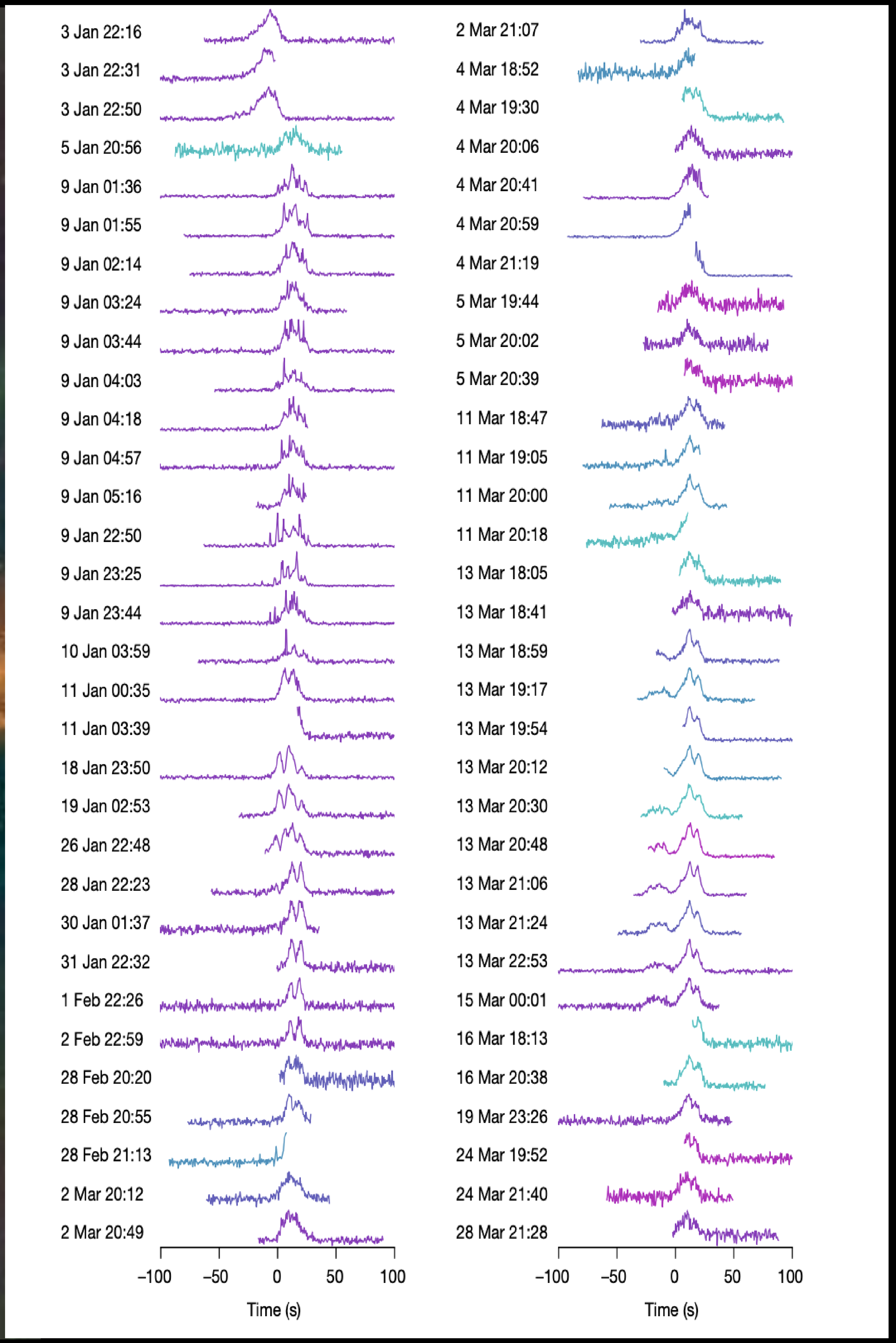


(Rea et al. 2016, D'Ai et al. 2016, Ho & Andersson 2016, Borghese et al. 2018)

LONG PERIOD TRANSIENT: GLEAM-X J1627

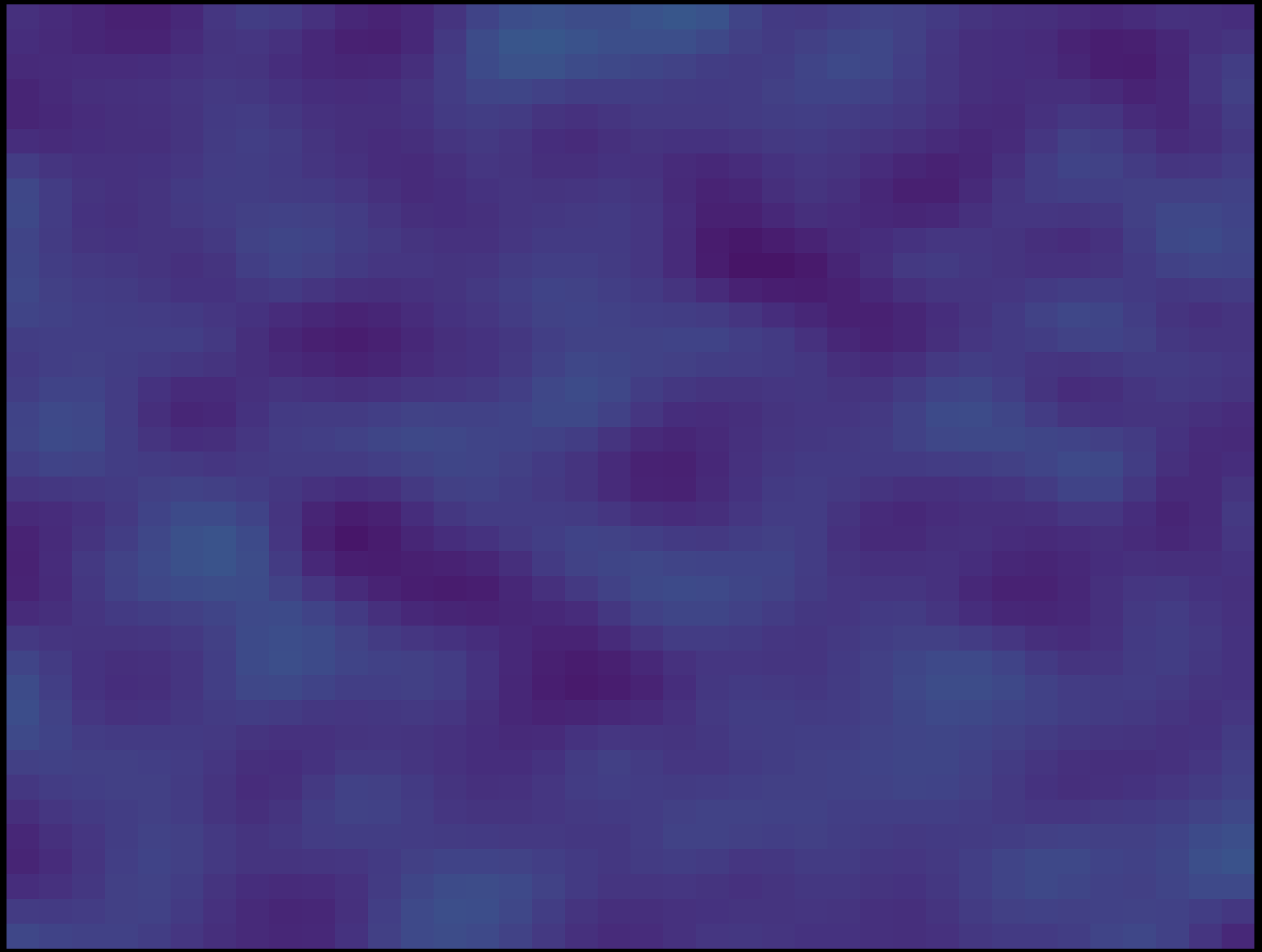
- Active for 2 months in the past 20 years
- Period emission every 18 minutes
- Flux density S~ 20 - 50 Jy
- Radio luminosity ~ 10^{31} erg/s
- Duty cycle of about 20 %
- Deep IR/optical limits during quiescence
- Deep radio continuum limits during quiescence
- Deep X-ray limits during quiescence
- Linear polarization 90%
- Distance 1.3kpc

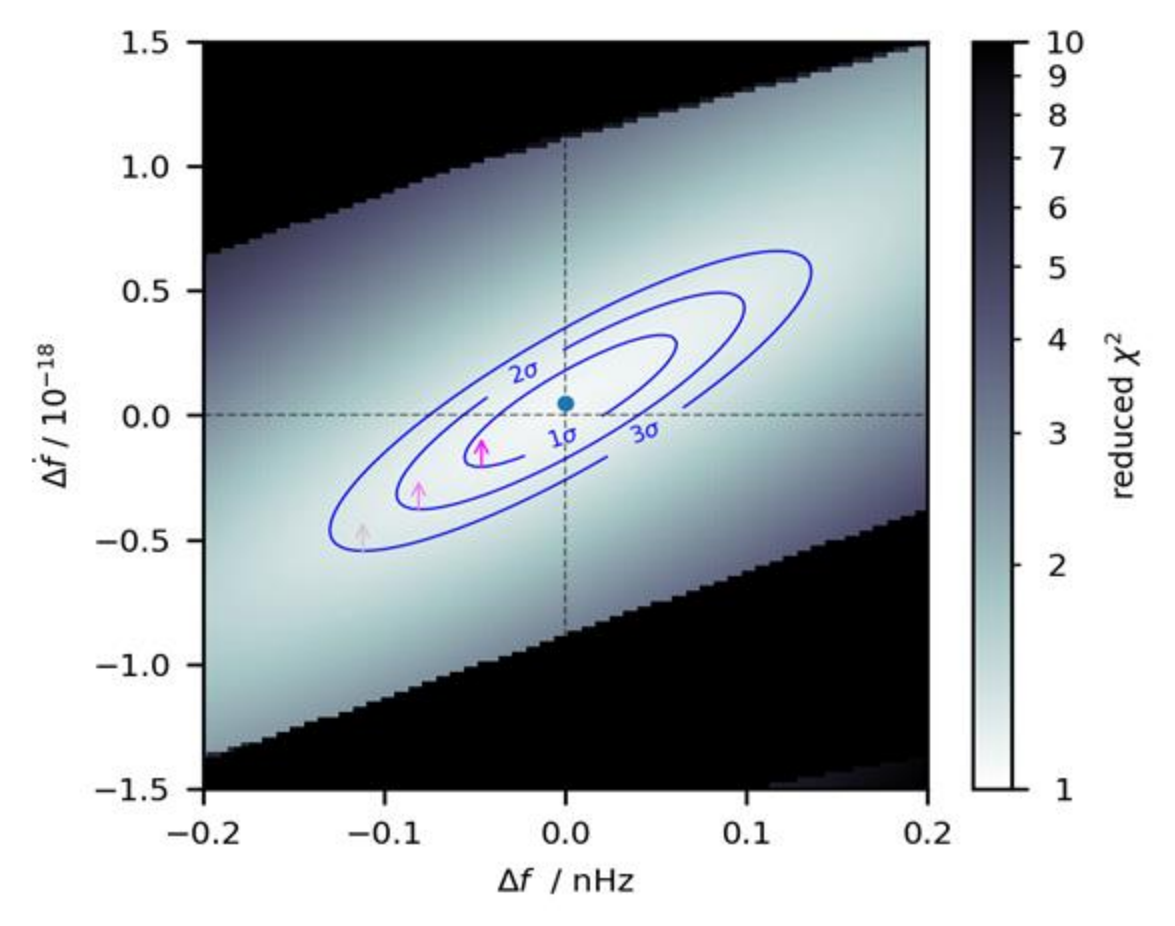




(Hurley-Walker , Zhang, Bahramian, et al. 2022, Nature)

LONG PERIOD TRANSIENT: GPM J1839-10

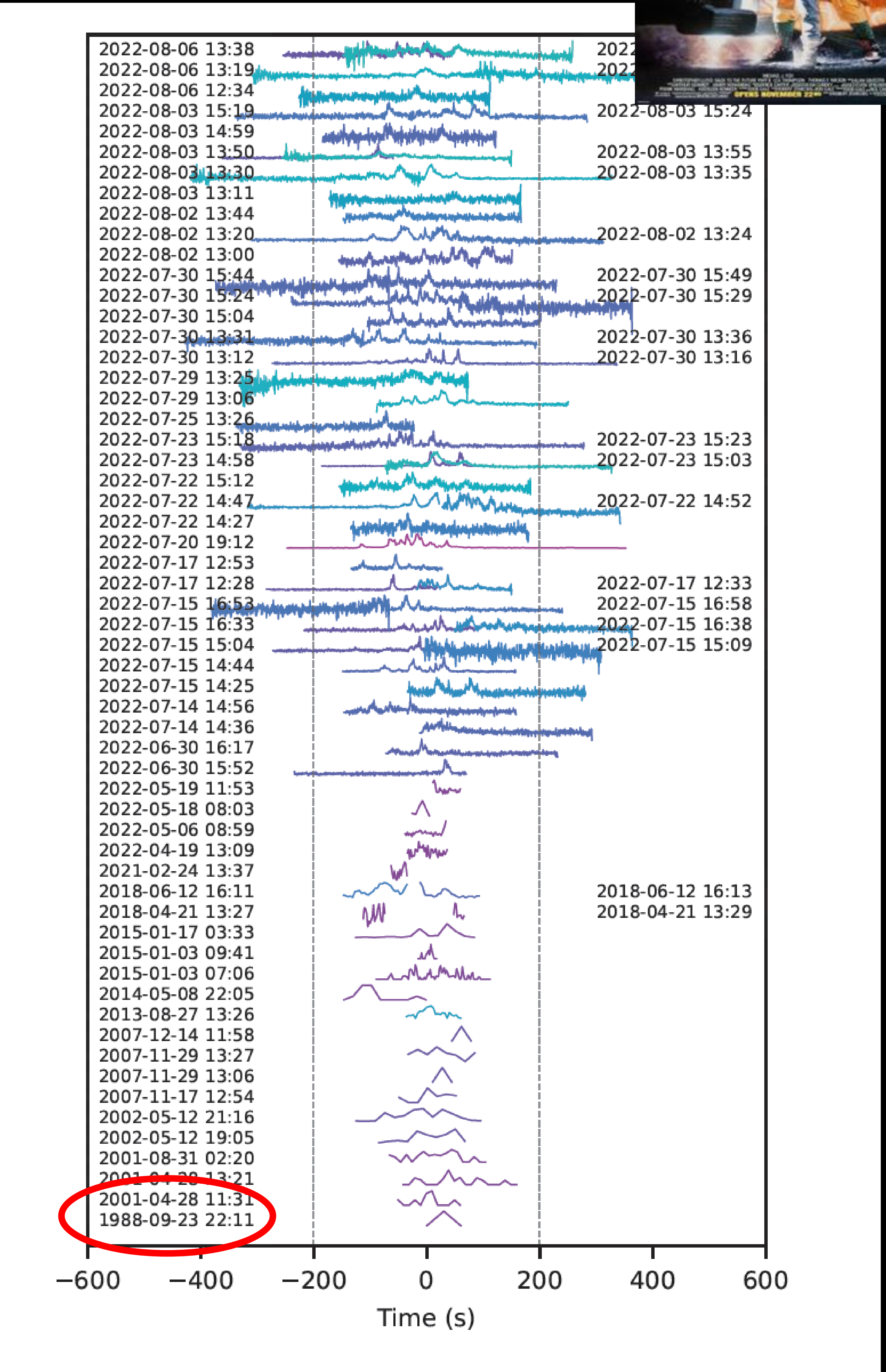




$$L_{\rm spin} = \frac{4\pi^2 I \dot{P}}{P^3}$$

$$L_{\rm spin} < 10^{24}\,{\rm erg\,s^{-1}}$$

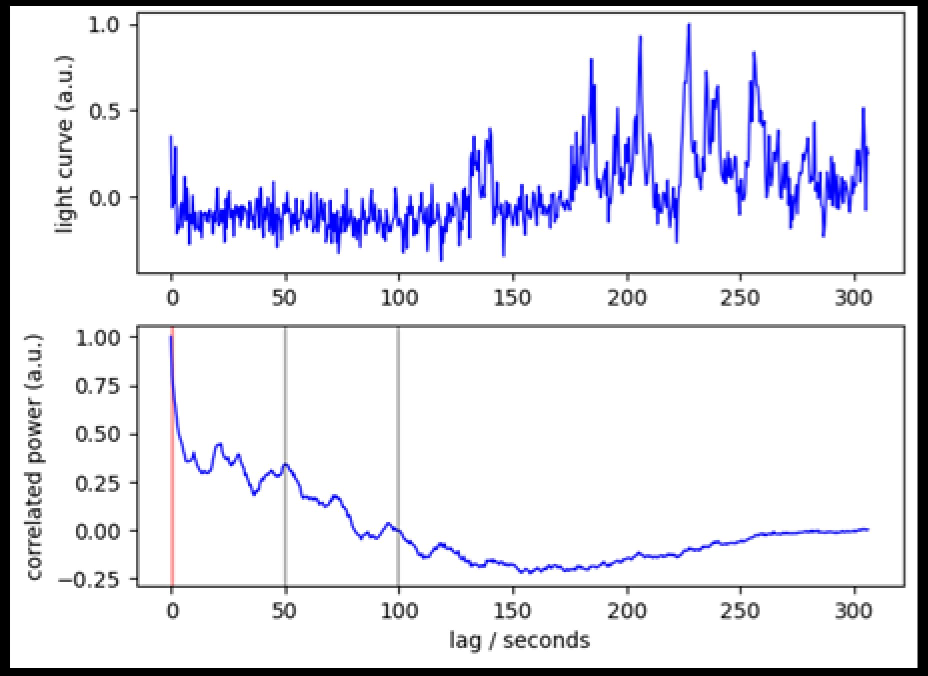
L_{radio} ~ 10^{28} erg/s !



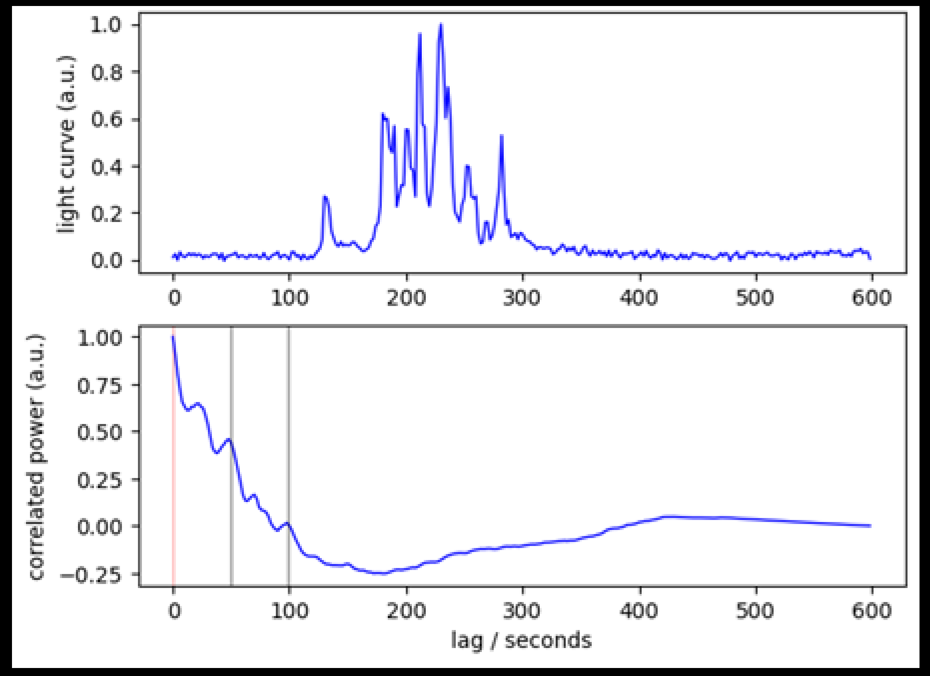
- Active since 30 years!!
- Period emission every 21 minutes
- Duty cycle of about 10-40 %
- A possible faint IR/optical
- Radio/X limits during bursts
- Linear polarization ~20%
- Distance 5.7kpc

(Hurley-Walker, Rea, McSweeney et al. 2023, *Nature*)

LONG PERIOD TRANSIENT: GPM J1839-10

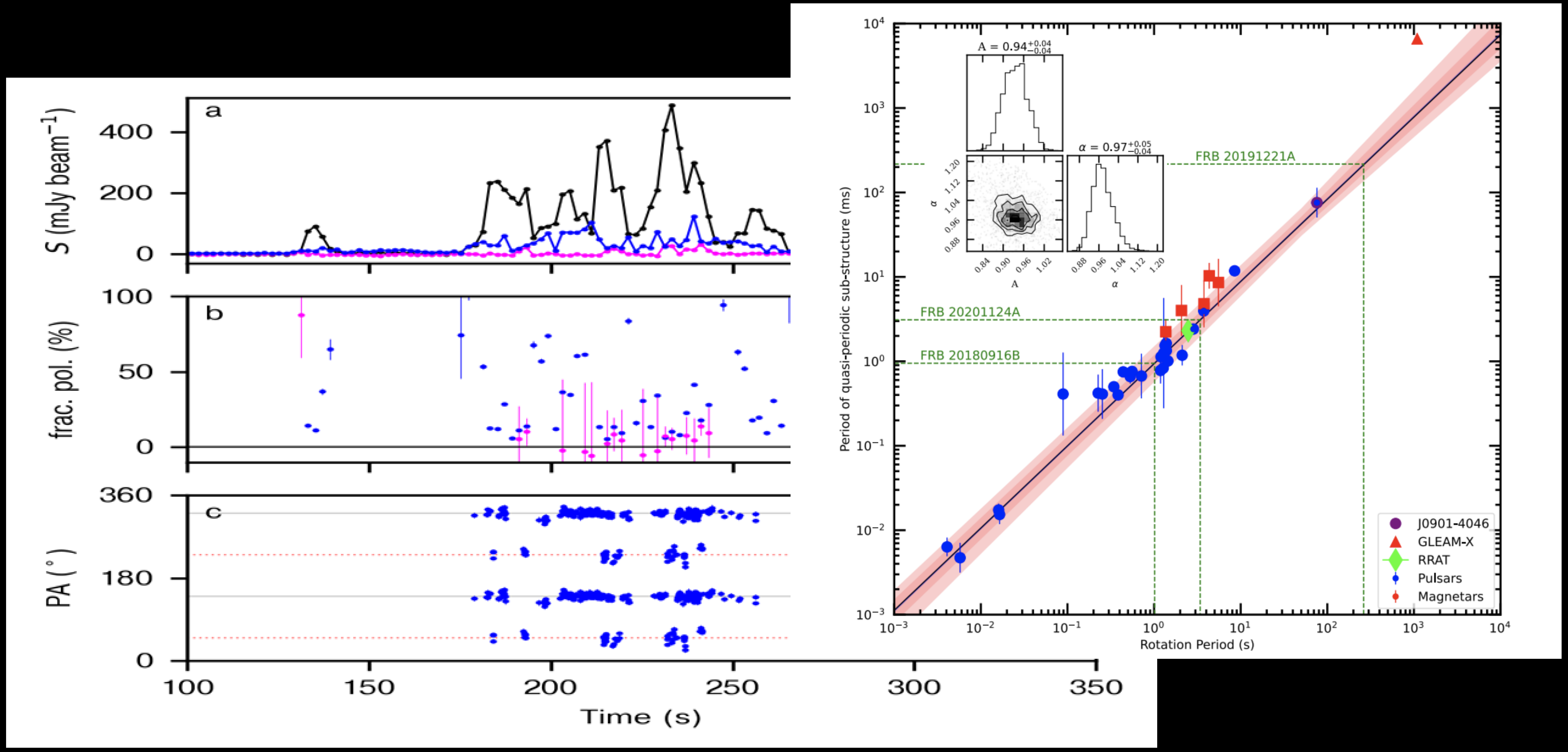


MWA, 154 MHz



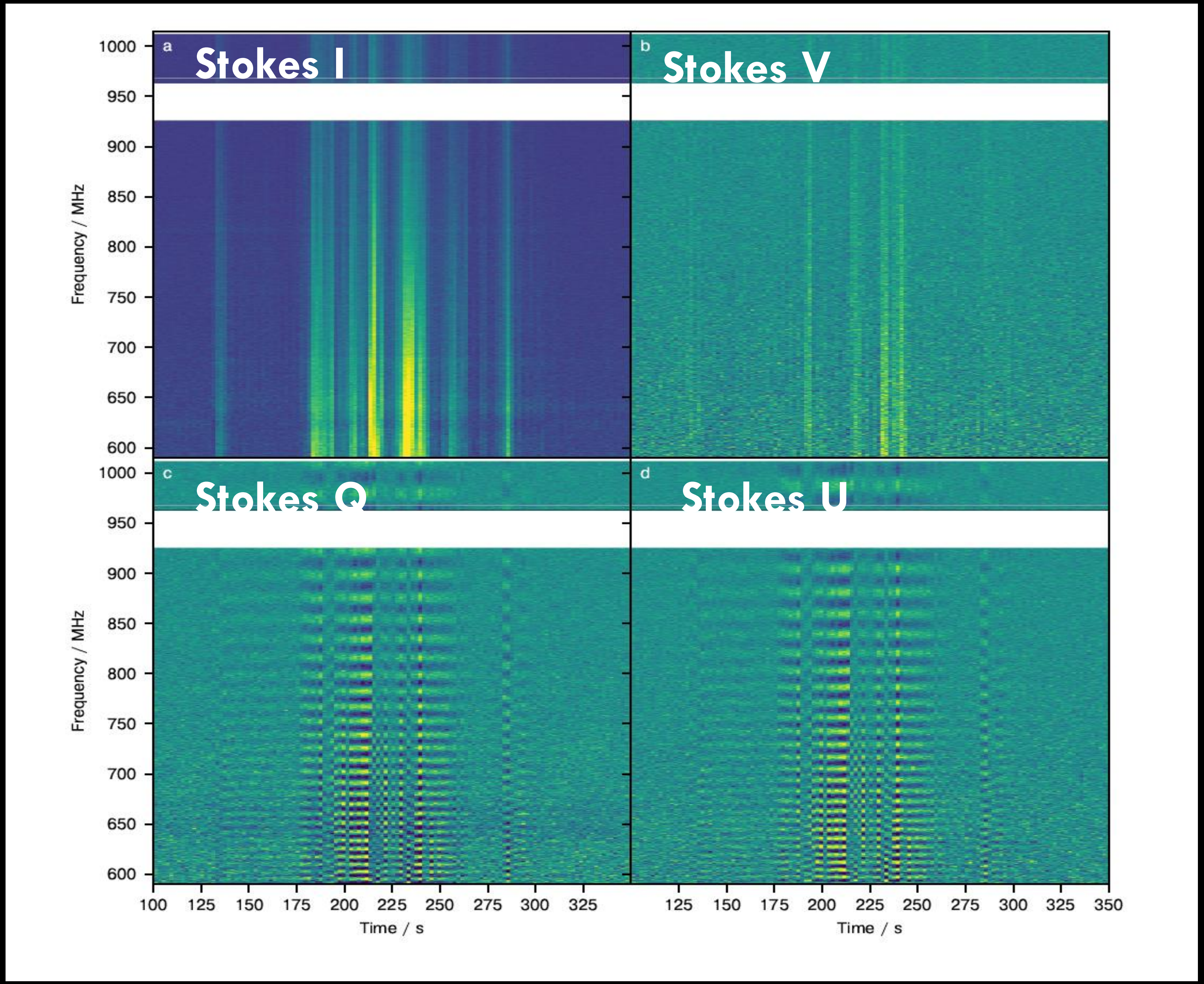
MeerKAT, UHF

Quasi-periodic oscillation: ~25 s = 20 milliperiods



From PTUSE: substructure lasts ~a few ms

(Kramer, Liu, Desvignes et al. 2023, *Nature Astronomy*)



Fractional polarisation:

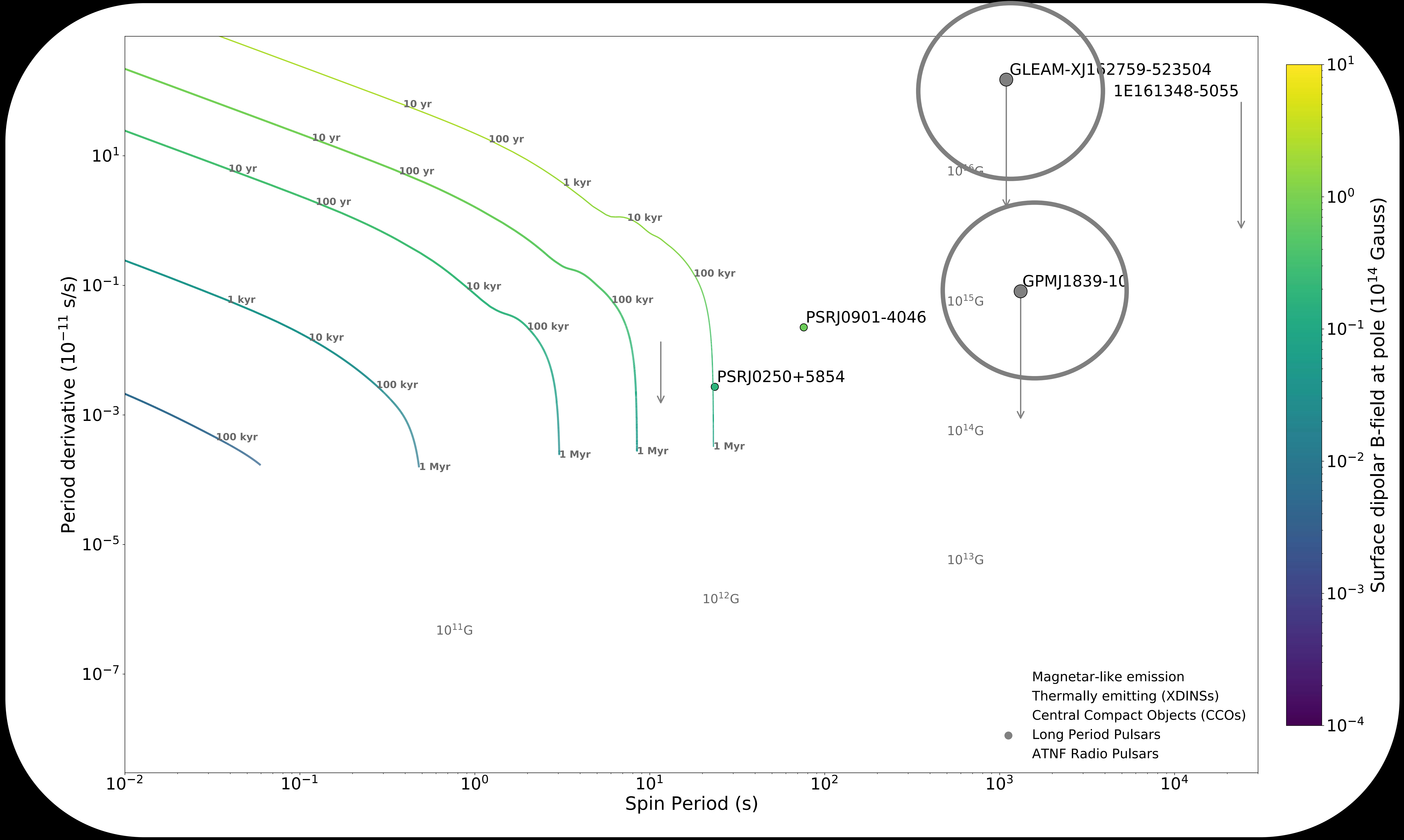
Linear ~ 5 — 20 %; Circular ~ 5 — 10%

Phase suddenly flips by 180 degrees. Orthogonal polarization modes?

Very flat polarisation angle (similarities with GLEAM-X J1627 and many magnetars and FRBs)

(Hurley-Walker, Rea, McSweeney et al. 2023, *Nature*)

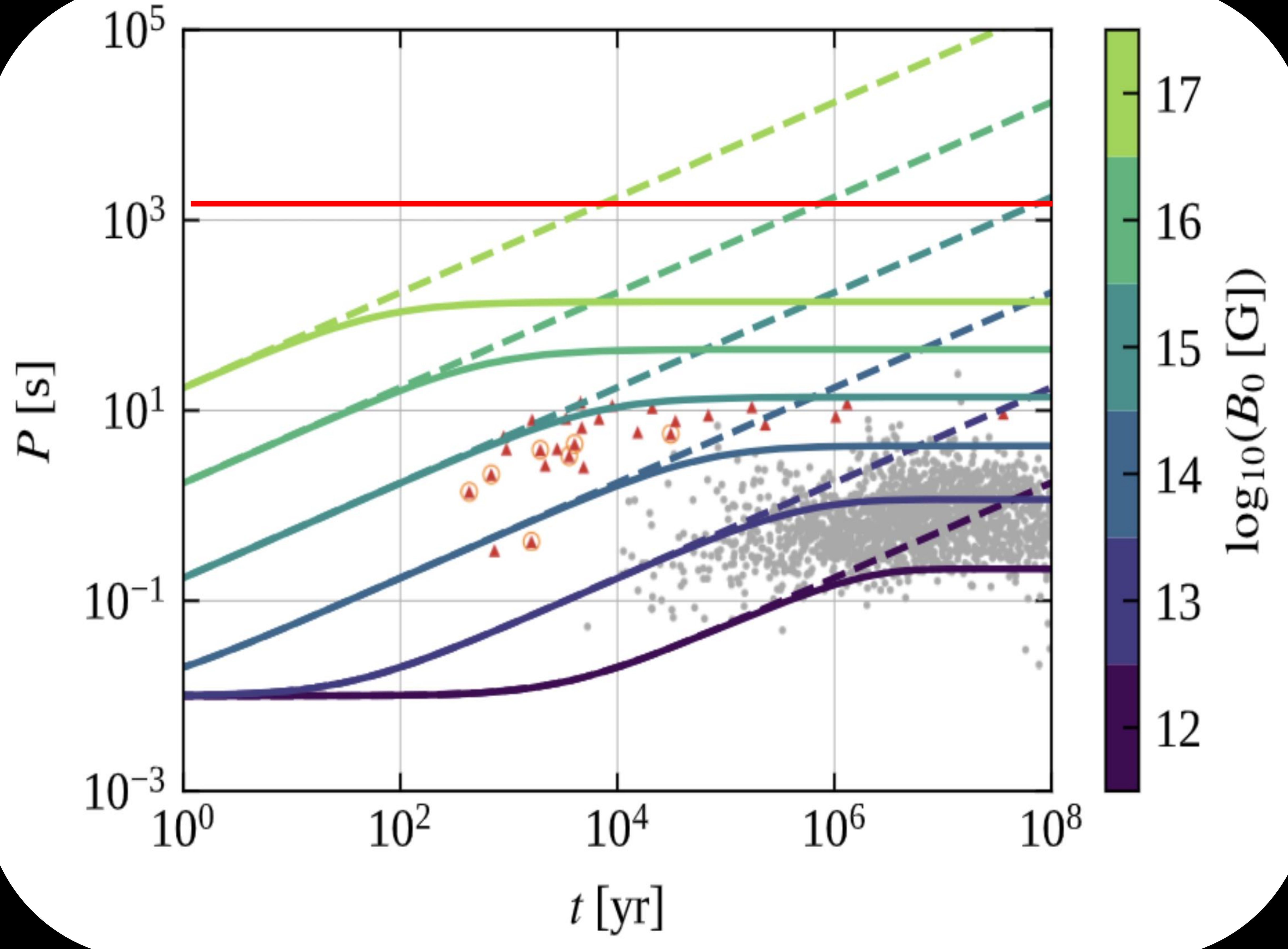
THE ISOLATED PULSAR POPULATION SPIN DISTRIBUTION?

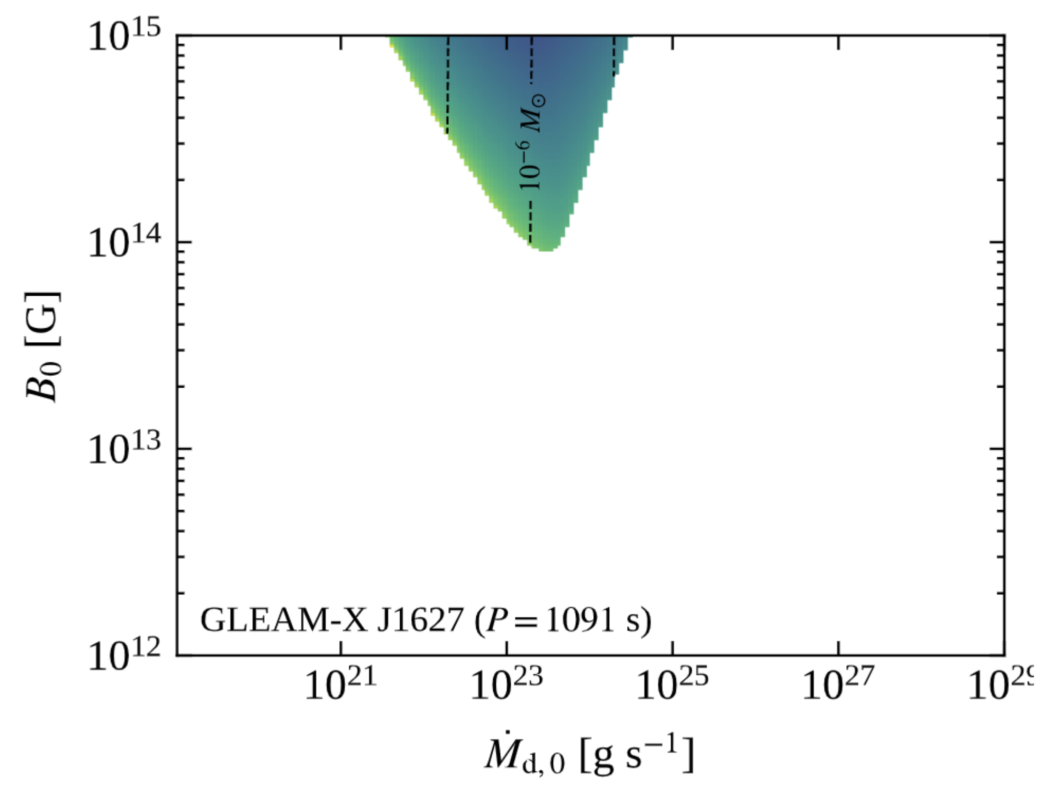


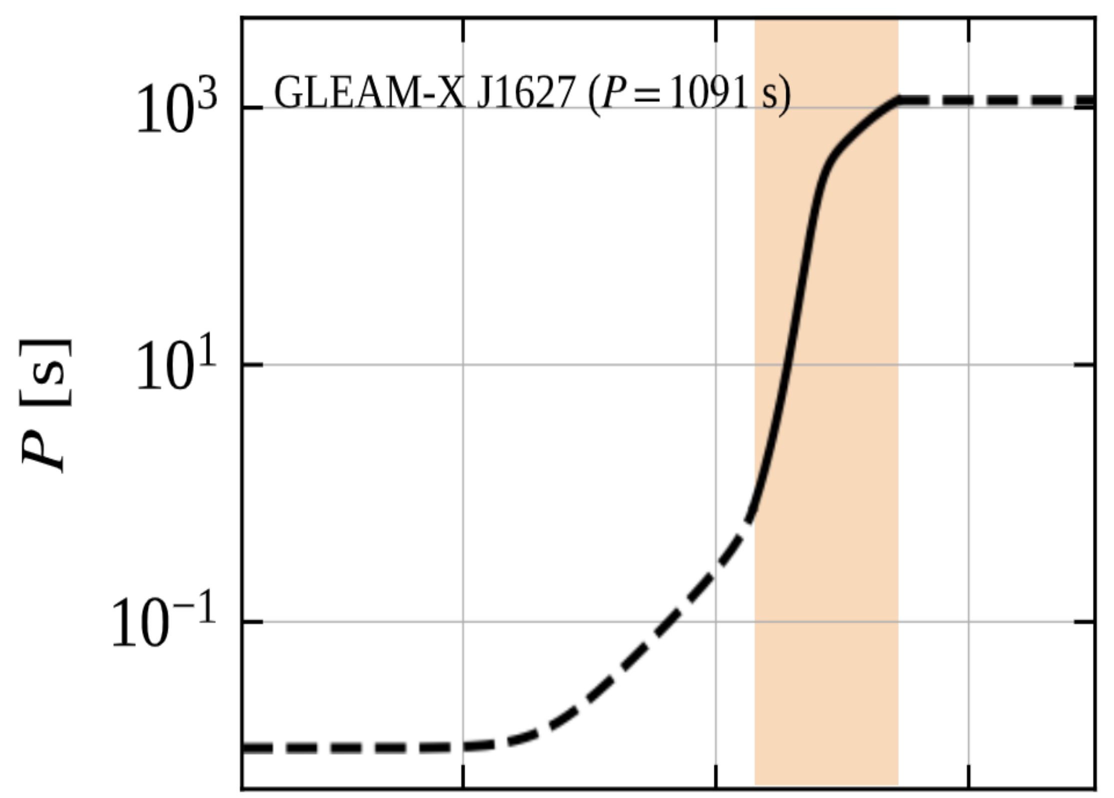
(Hurley-Walker, Rea, McSweeney et al. 2023, *Nature*)

WHAT CAN LONG PERIOD TRANSIENTS BE?

LONG PERIOD TRANSIENTS: SLOWING DOWN VIA FALL-BACK



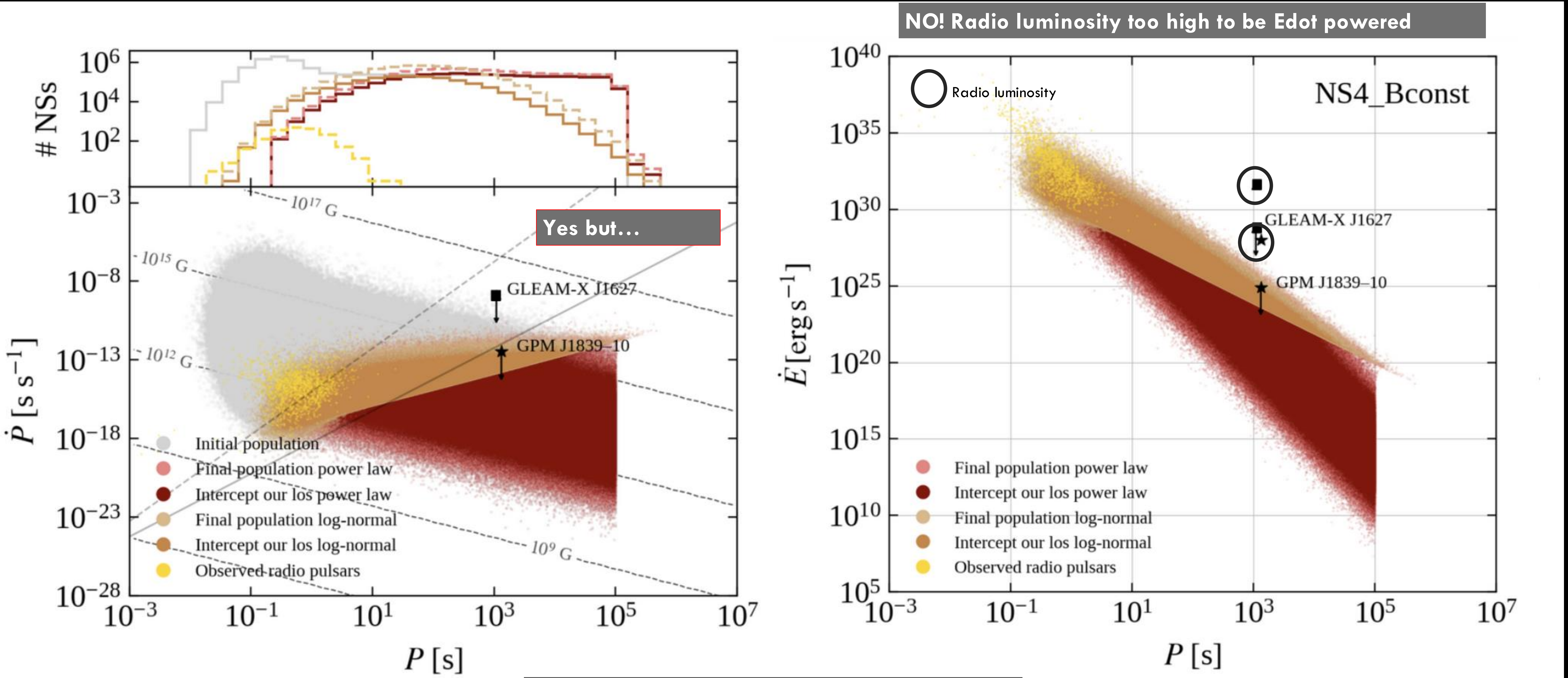




Fall back accretion after the supernova could make these (and other) pulsars slow down extremely fast…

(Ronchi, Rea, Graber et al. 2022, ApJ; Gencali, Ertan, Alpar et al. 2022, MNRAS)

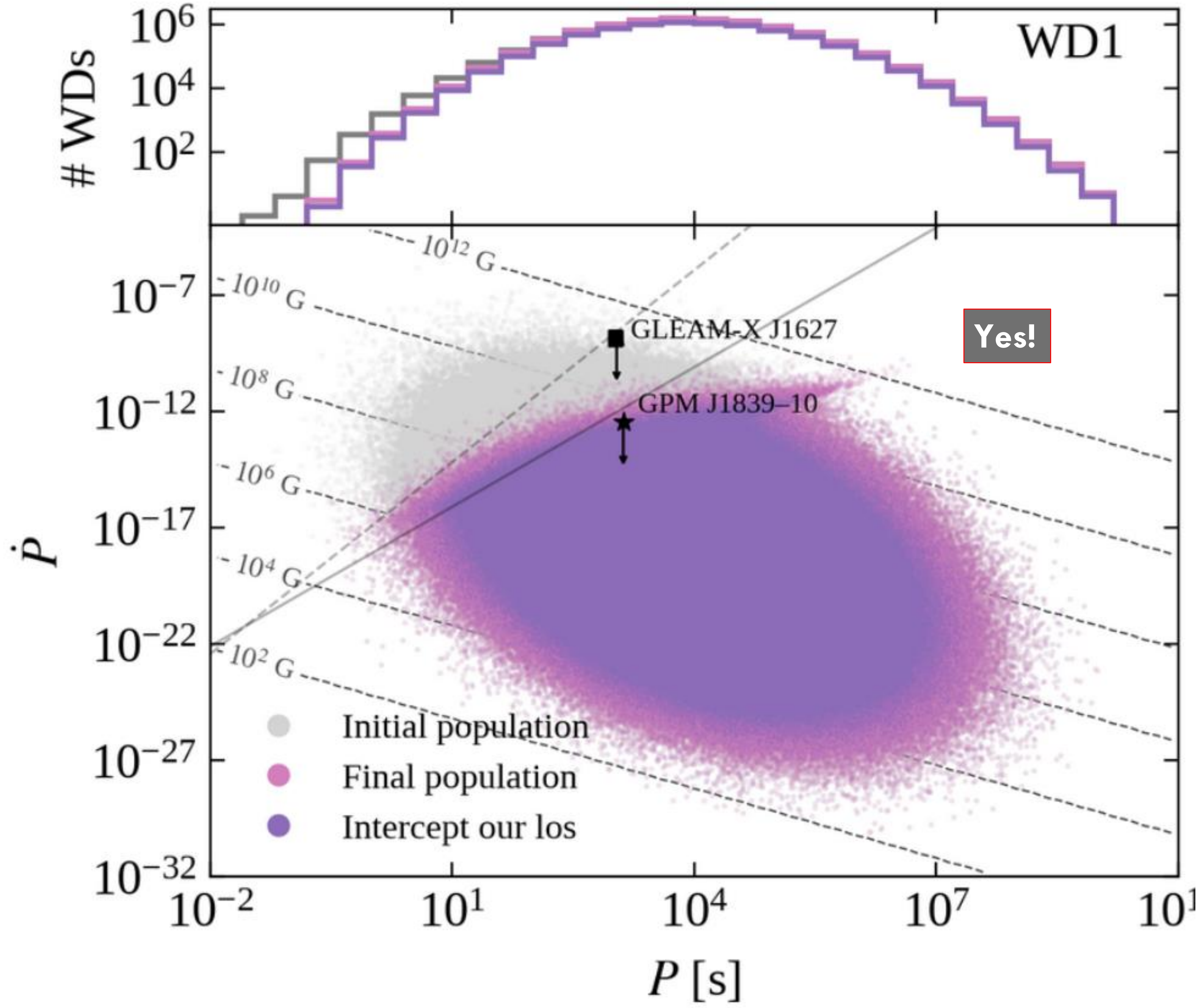
LONG PERIOD TRANSIENTS: SLOWING DOWN VIA FALL-BACK

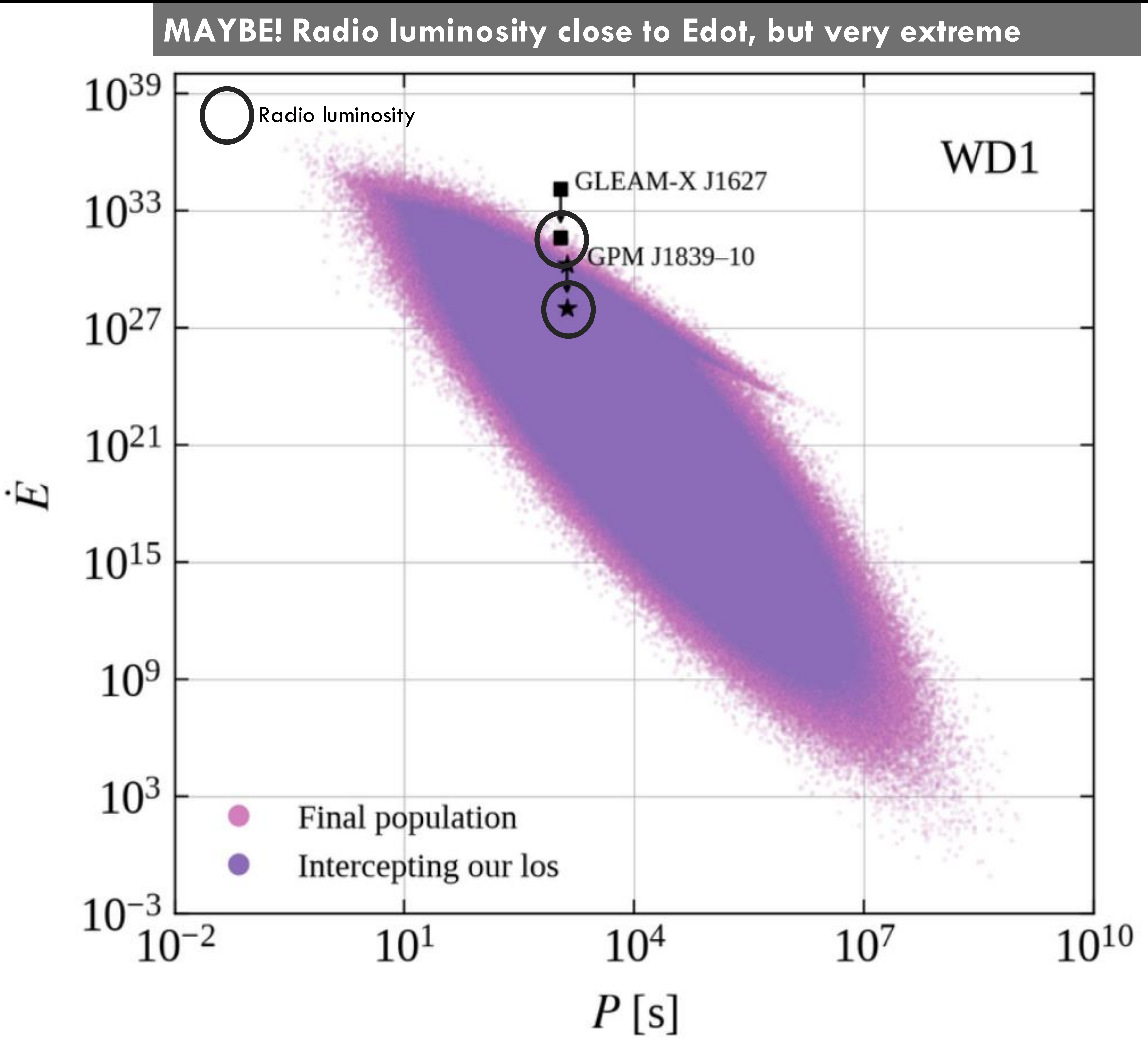


Mimicking a fall-back disk period distribution

(Rea, Hurley-Walker, Pardo et al. 2024, ApJ)

LONG PERIOD TRANSIENTS: SLOWING DOWN AS AN ISOLATED WD





(Rea, Hurley-Walker, Pardo et al. 2024, ApJ)

White dwarfs dipolar evolution

CHALLENGING MODELS FOR PULSAR-LIKE RADIO EMISSION

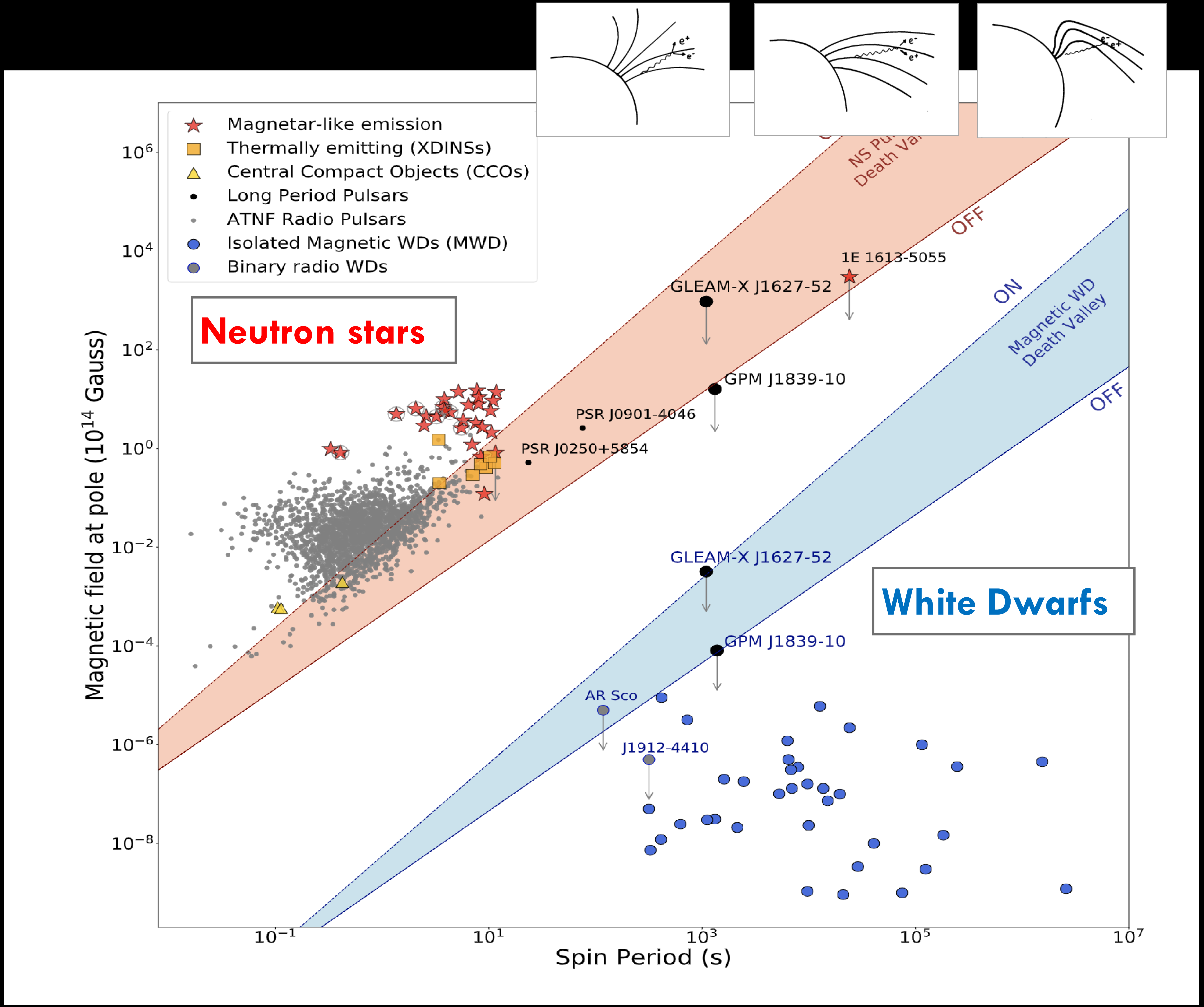
Death lines for pair production

$$\left(\frac{e\Delta V}{mc^2}\right)^3 \frac{\hbar}{2mcr_c} \frac{h}{r_c} \frac{B_s}{B_g} \approx \frac{1}{15}$$

$$\Delta V_{\max} \approx \frac{B_p R^3 \Omega^2}{2c^2}$$

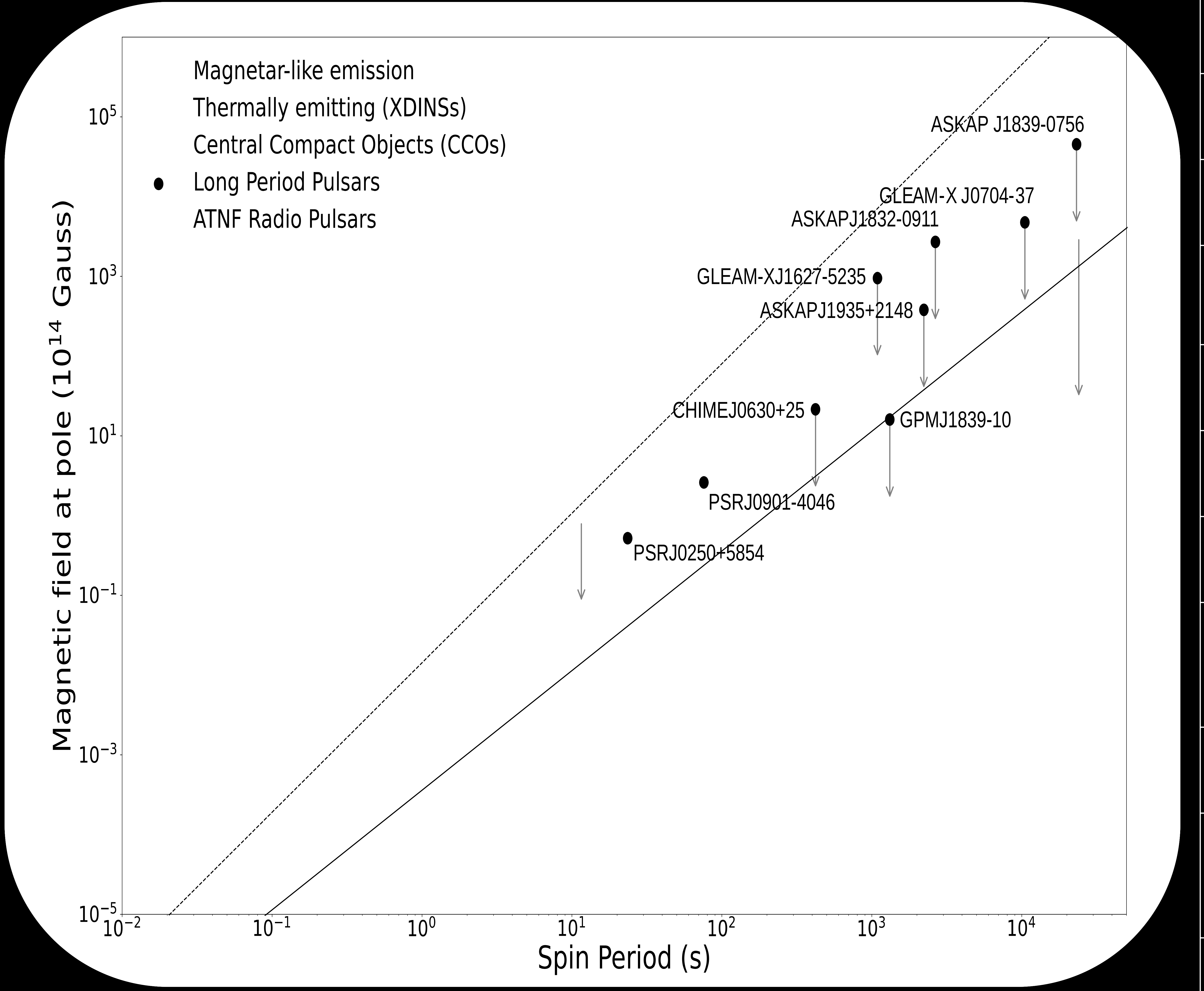
(Ruderman & Sutherland 1975,
Cheng & Ruderman 1993,
Zhang et al. 2000)

GPM J1839 challenges both isolated NS and WD classical pulsar-like dipolar emission scenarios.



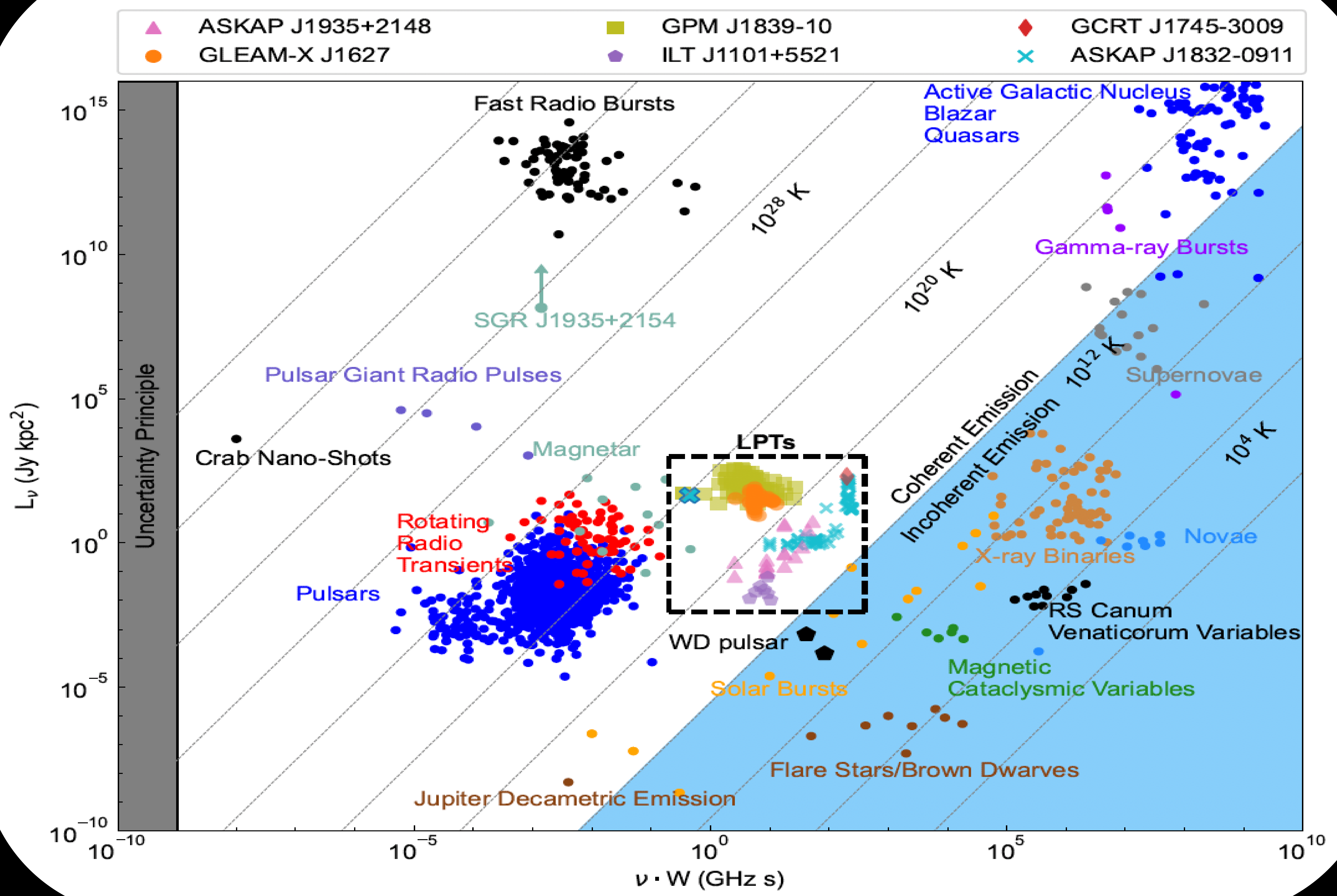
(Hurley-Walker, Rea, McSweeney et al. 2023, *Nature;* Rea, Hurley-Walker, Pardo et al. 2024, ApJ)

… AND WE KEEP FINDING MORE AND MORE



Name	Periodicity (seconds)	Distance	Comments
CHIME J0630+25	421.3 (7 min)	170 pc	Only few bursts…
GLEAM-X J0704-37	10496.6 (2.9 hr)	400 pc	WD + Mdwarf Polar-like
ILT J1101+5521	7531.2 (2.0 hr)	504 pc	WD + Mdwarf Polar-like
GLEAM-X J16275-52350	1091.1 (18 min)	1.3 kpc	Active for 3 months
GCRT J1745-300	4620.7 (1.3 hr)	~8 kpc	Only few bursts…
ASKAP J175534.9-252749.1	4186.3 (1.16 hr)	4.7 kpc	
ASKAP J1832-0911	2656.2 (42 min)	4.5kpc	X-ray pulsed counterpart with X-ray outburst
ASKAP J1839-0756	23213.4 (6.5 hr)	4.0 kpc	Interpulse?
ASKAP J193505.1+214841.0	3225.3 (54 min)	4.8kpc	Mode switching
GPM J1839-10	1318.1 (21 min)	5.7 kpc	Active since >30 years

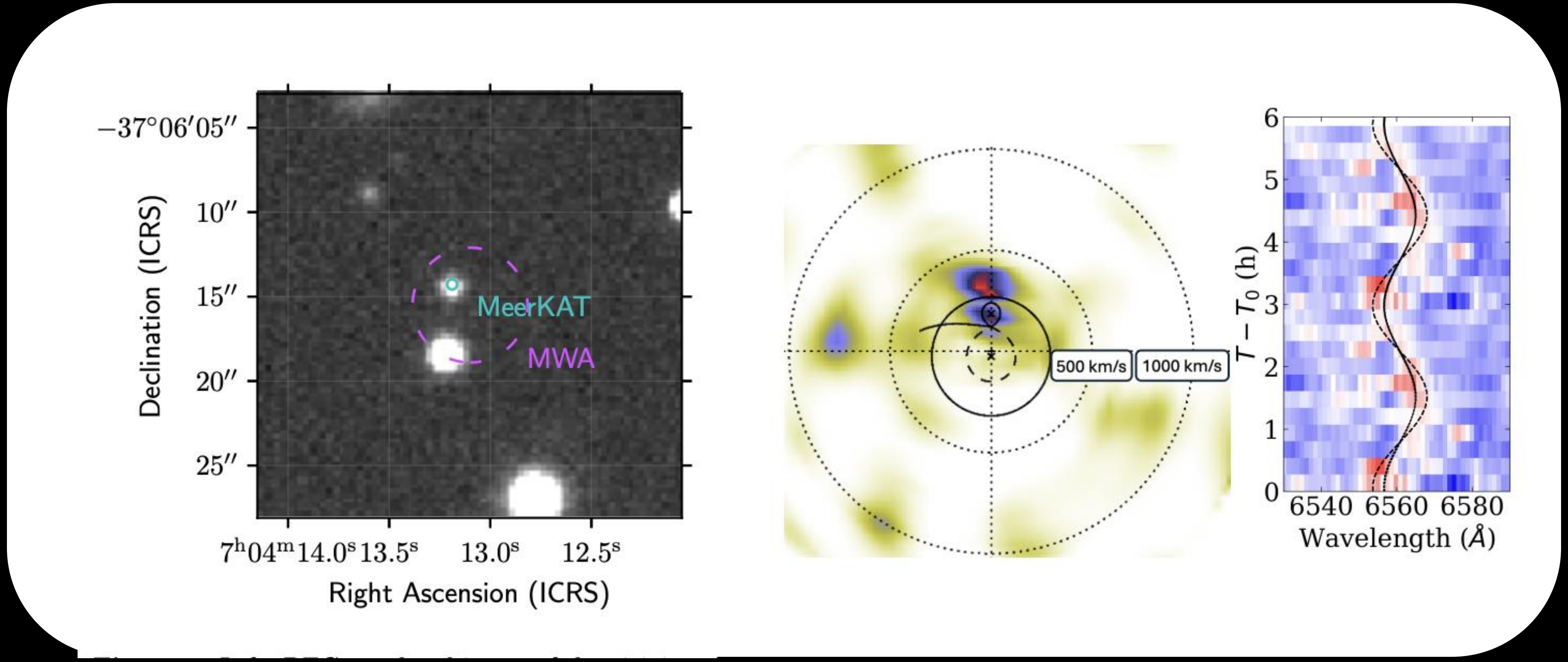
… AND WE KEEP FINDING MORE AND MORE



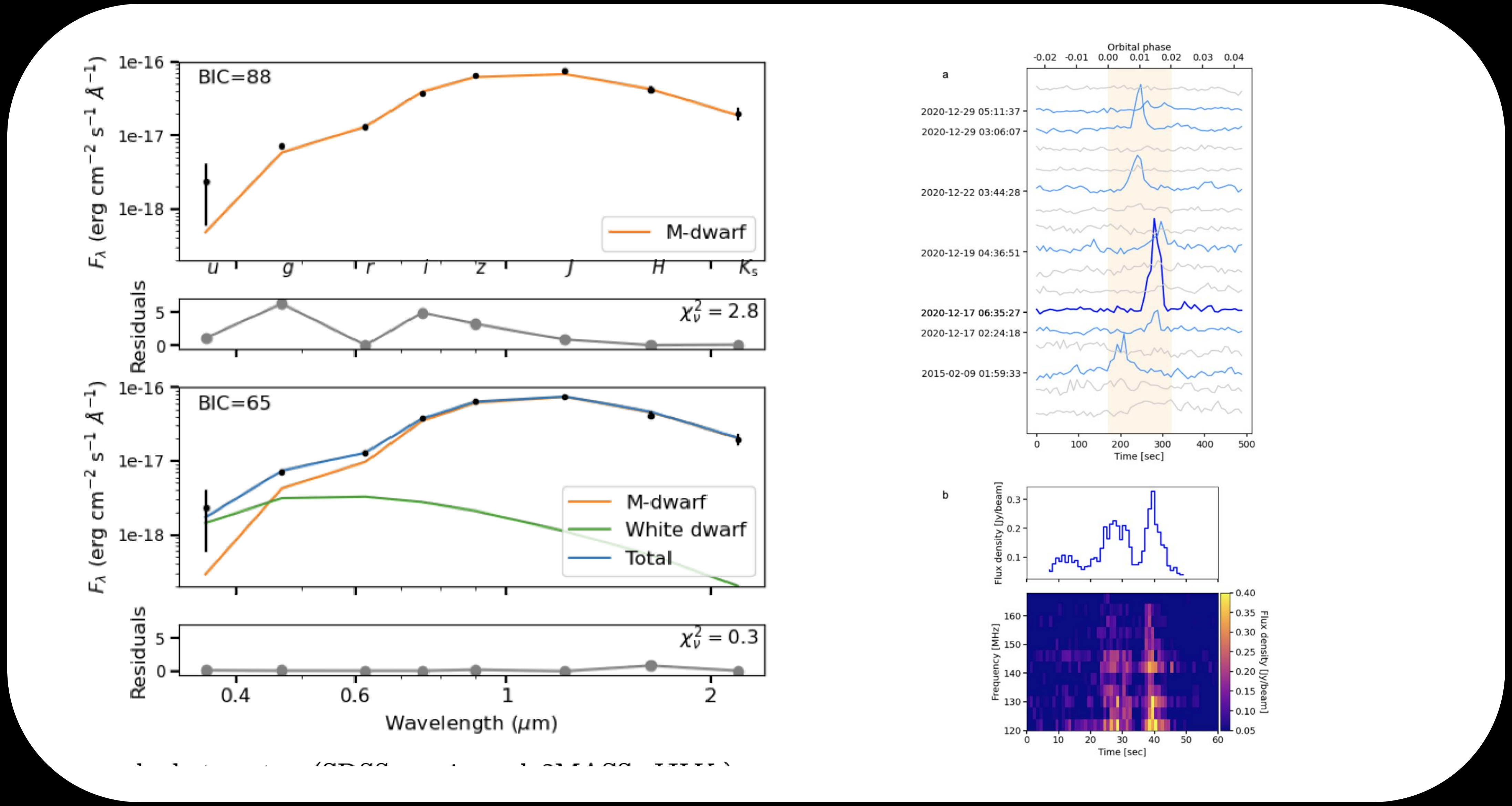
(Wang, Rea, Tong et al. 2025, Nature in press)

LONG PERIOD TRANSIENTS: TWO LPTs IDENTIFIED WITH WD+Mdwarf

GLEAM-X J0704-37 – 2.9 hr



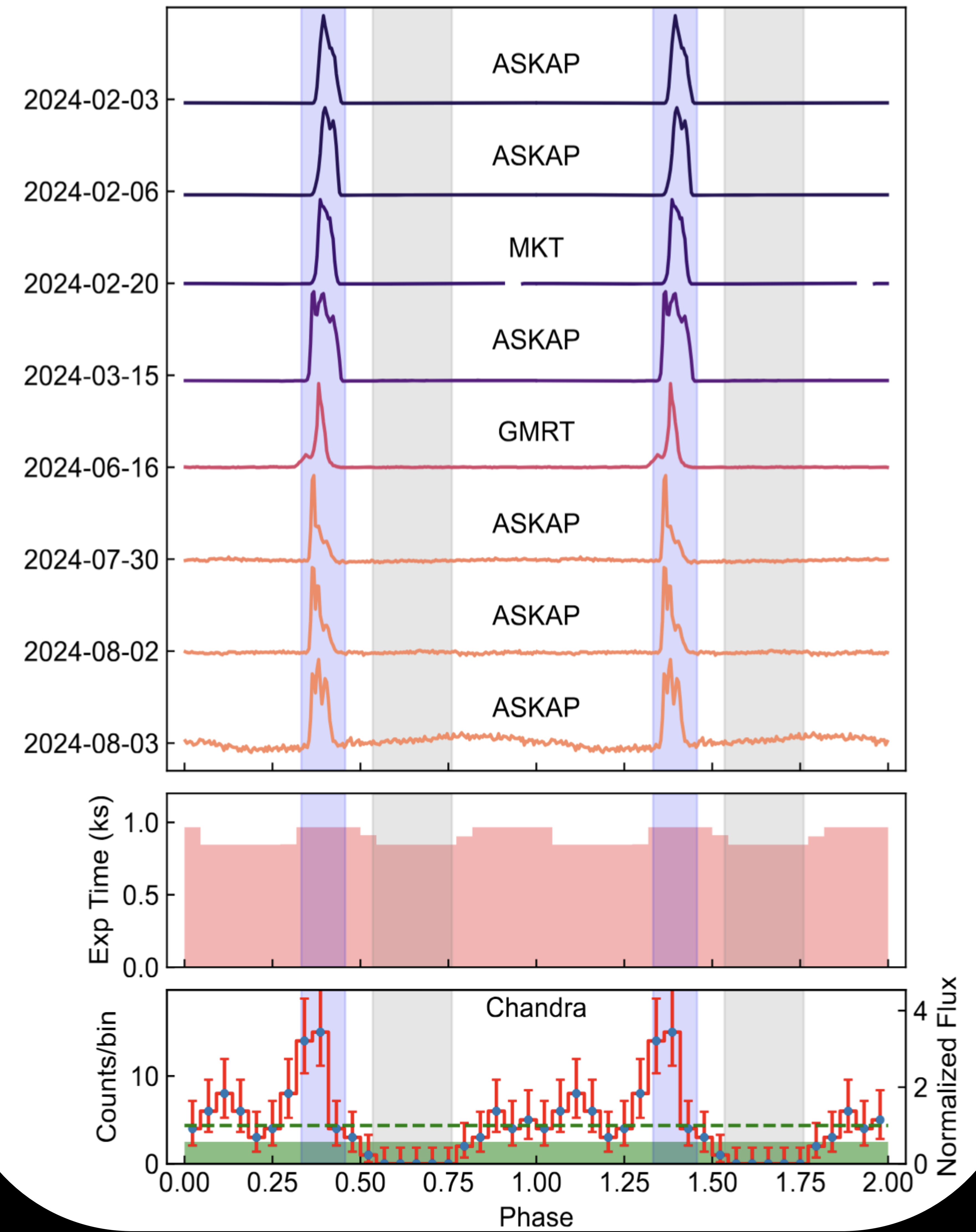
ILT J1101+5521 - 2.0 hr

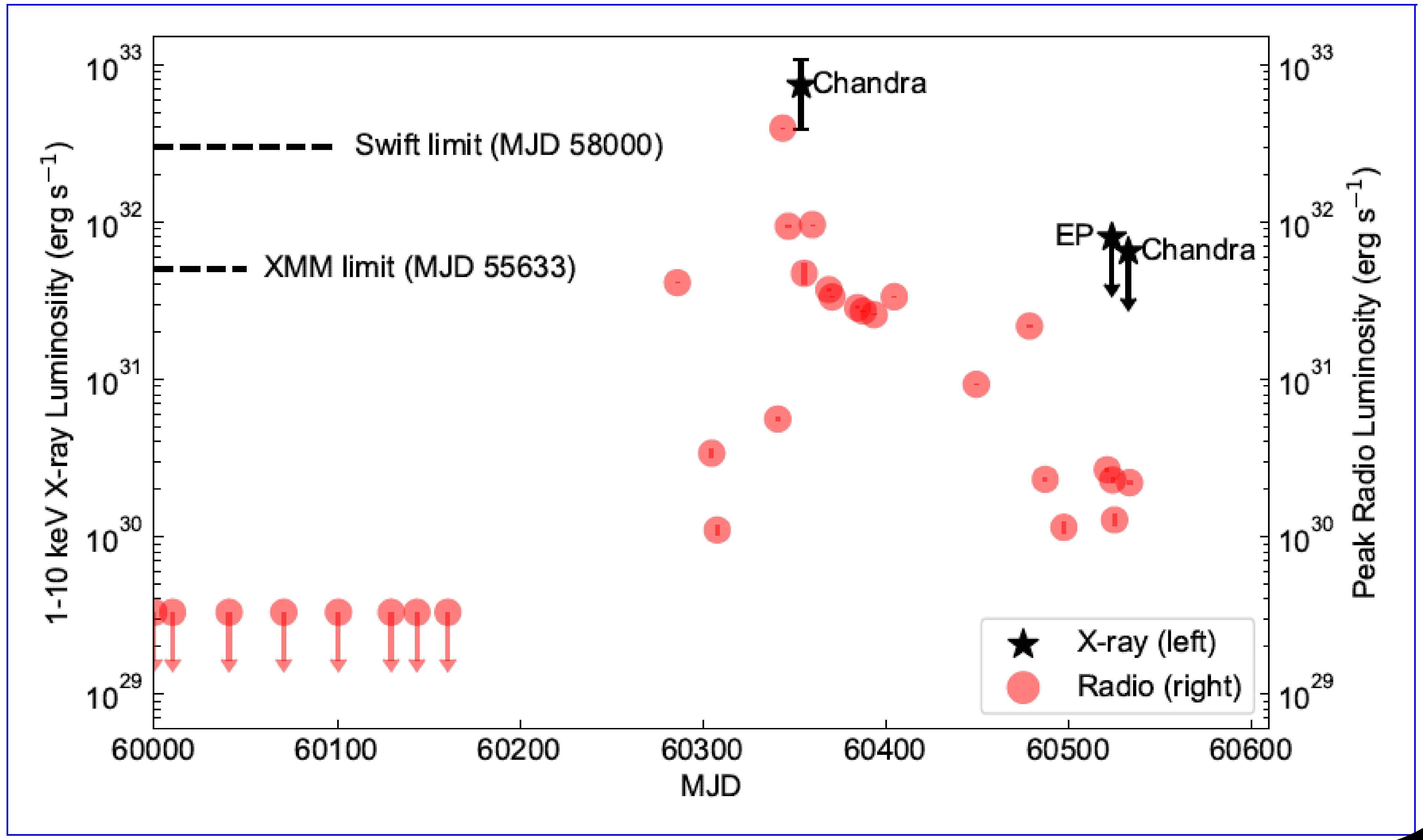


(Hurley-Walker et al. 2024, ApJ Letter; Rodriguez 2025, ApJ; de Ruiter et al. 2024, Nature Astronomy)

LONG PERIOD TRANSIENTS: The X-ray outburst of ASKAP J1832-0911

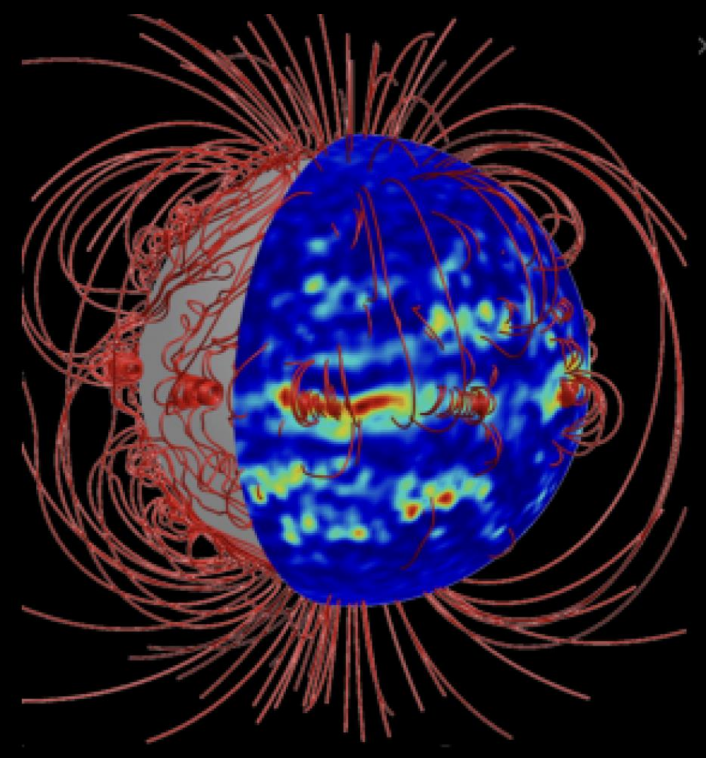
- Active for > 10 months
- Period emission every 44 minutes
- Flux density S~ 0.01 - 20 Jy
- Radio luminosity ~ 10^{32} erg/s
- Duty cycle of about 20 %
- X-ray outburst, pulsed at peak!!!!
- Linear polarization 90%
- Distance 4.5kpc





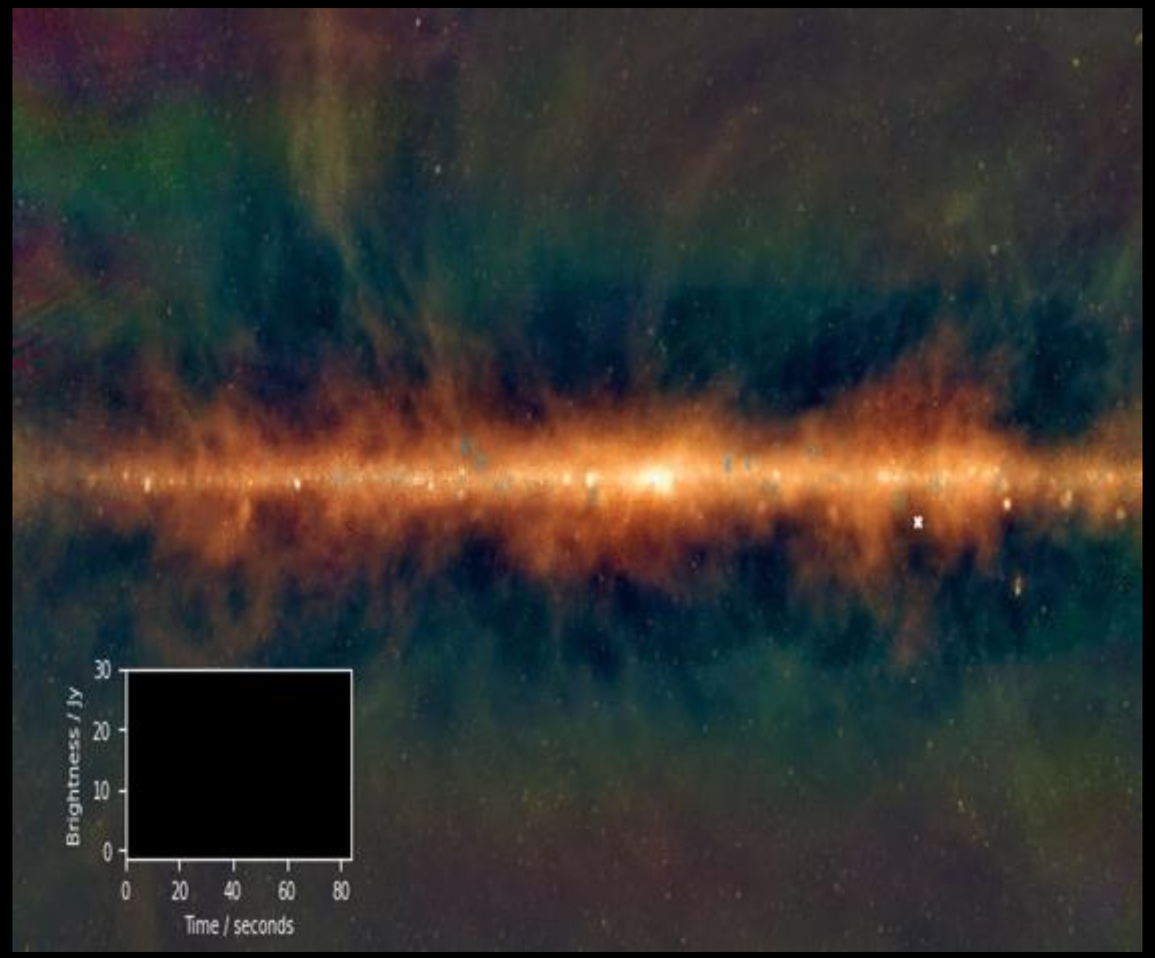
(Wang, Rea, Tong et al. 2025, Nature in press)

SUMMARY



1. Magnetar-like emission is present in all neutron star classes. 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. Our Galaxy has mostly formed magnetars in the past 2000 years. Population studies are currently biased by our ignorance in the magnetar X-ray detection biases and outburst rates.



3. Long Period Transients have been discovered at high rate. Two of them are confirmed WD+Mdwarf binaries, one showed a transient X-ray emission. Are they all binary WD systems? or there is still room for a very slow magnetar in there?

4. How is the Long Period Transients' bright (50 Jy!!), coherent, transient and highly polarized radio emission produced?