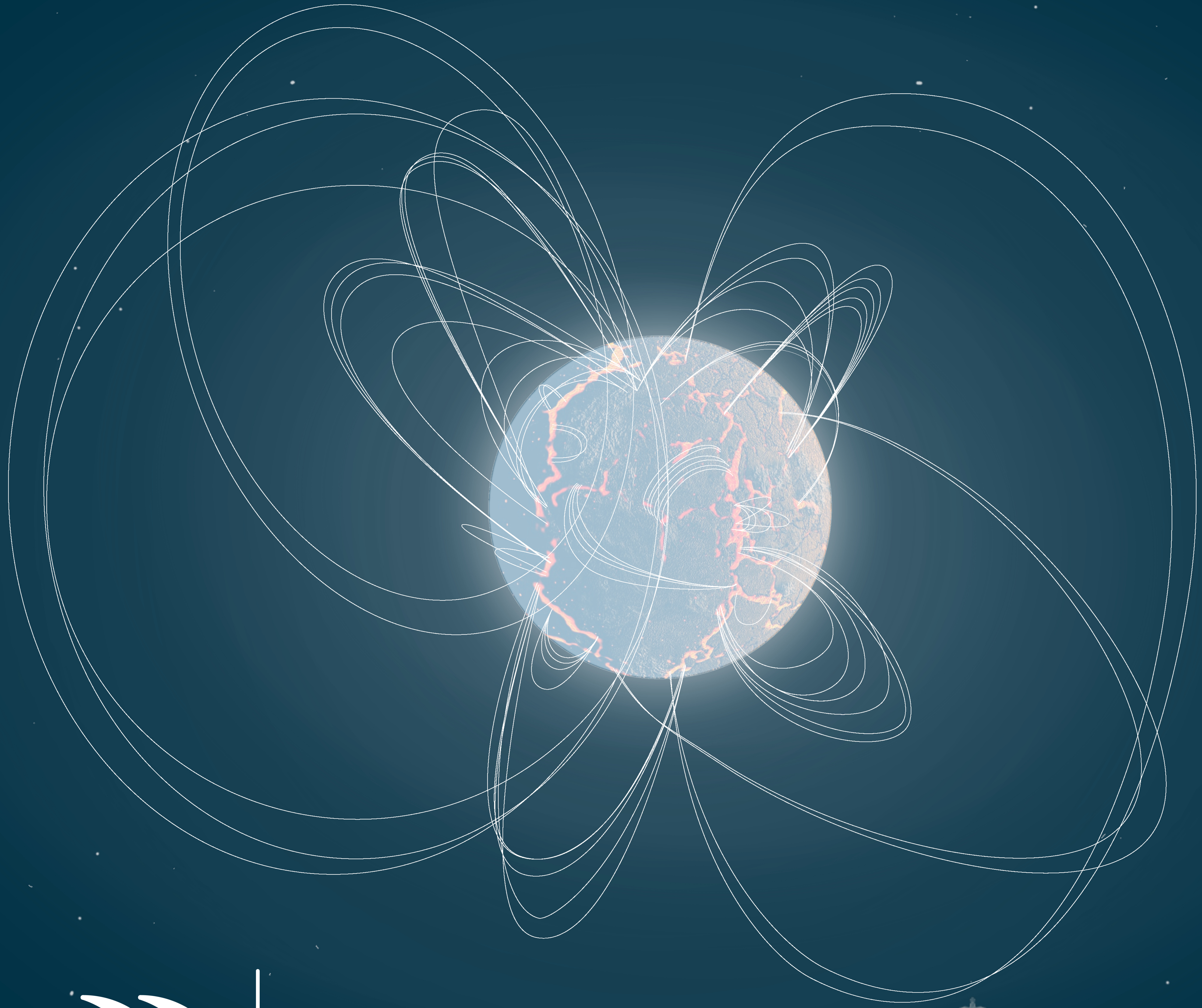
# PULSARS: MAGNETIC MONSTERS AT NUCLEAR DENSITY




*Nanda Rea*

Institute of Space Sciences

CSIC IEEC

*Barcelona, Spain*



erc

European Research Council

Established by the European Commission

MAGNESIA

MAGNETAR CENSUS

The Impact of Highly Magnetic Neutron Stars in the Explosive and Transient Universe

cost

EUROPEAN COOPERATION IN SCIENCE & TECHNOLOGY

GOBIERNO DE ESPAÑA

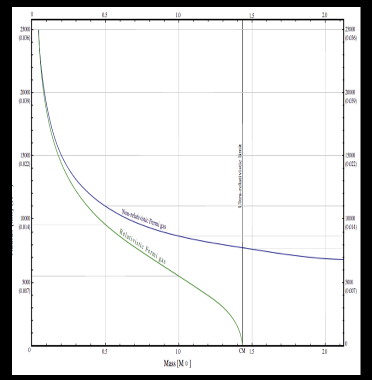
MINISTERIO DE CIENCIA, INNOVACIÓN Y UNIVERSIDADES

Agència de Gestió d'Ajuts Universitaris i de Recerca

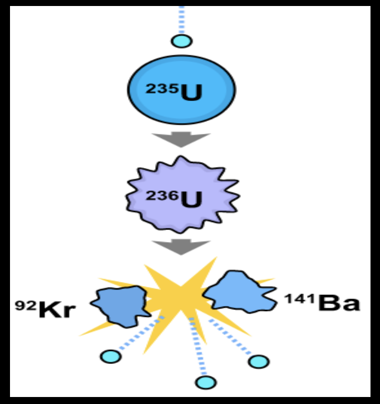
AGAUR

# EARLY HISTORY

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

- 1932 Chadwick discovers the neutron, recognized as a new elementary particle.
(Chadwick1932, proceedings of the RAS)

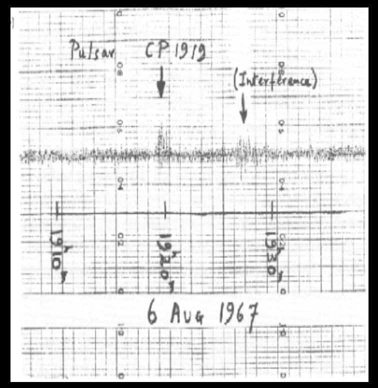




- 1934 Baade & Zwicky proposed the existence of NS, they predicted their formation due to supernova explosion and their radius of ~10 km .
(Baade & Zwicky 1934, Proc.Nat.Acad.Sci.)

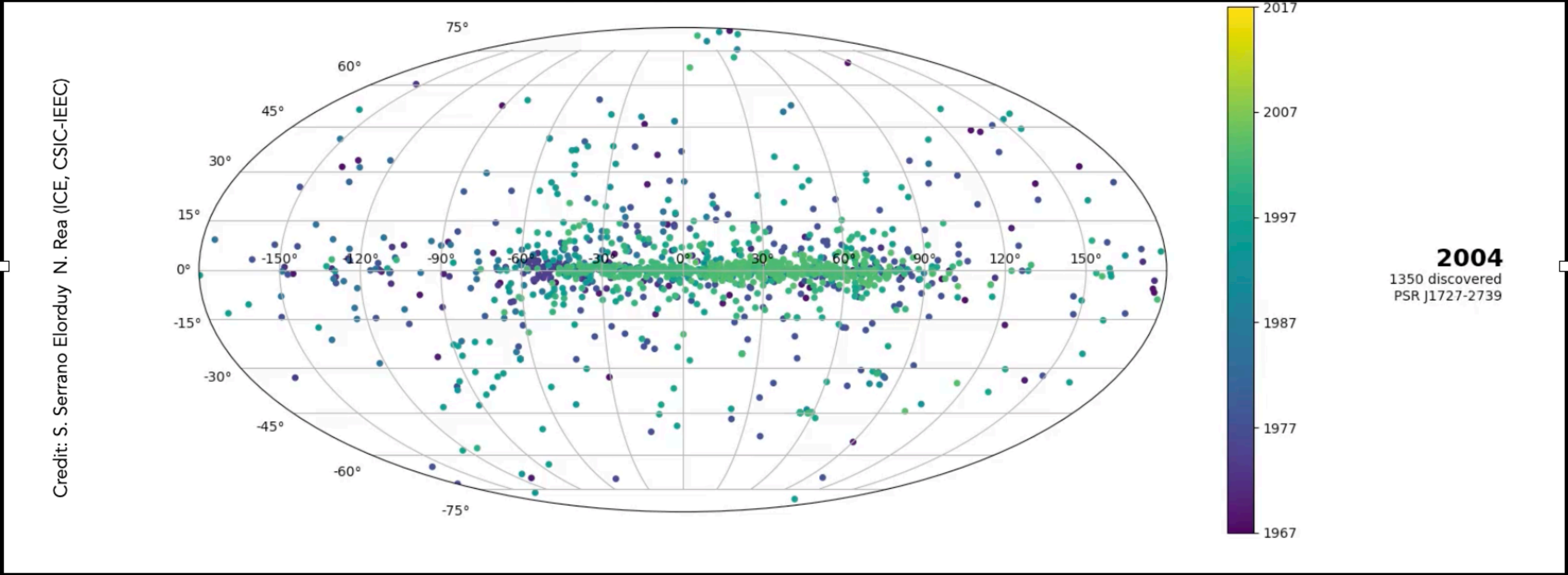

- 1939 Oppenheimer & Volkoff defined the first equation of state for a NS of mass ~1.4 $M_{\odot}$, a radius of ~10 km and a density of ~$10^{14}$ gr/cm$^3$
(Oppenheimer & Volkoff 1939, Phys.Rev)


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


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




# 50 YEARS OF PULSARS

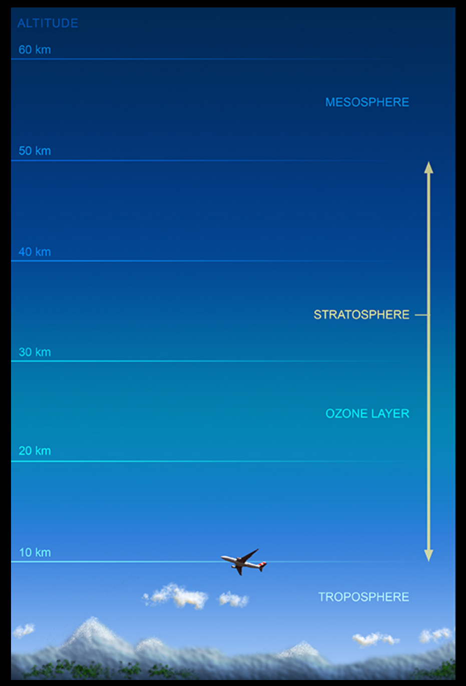


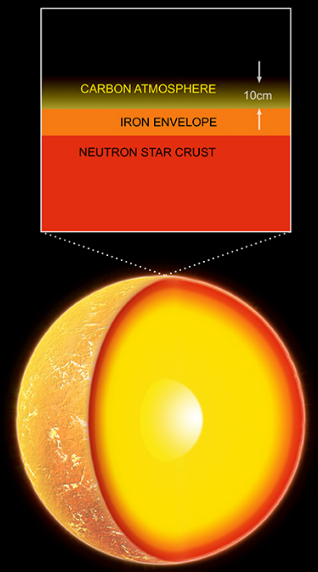

Rea 2017, Nature Astronomy, Vol. 1 p 827

# WHY NEUTRON STARS ARE IMPORTANT?

…AND THEY KEEP BUSY NUCLEAR PHYSICISTS, ASTROPHYSICISTS, THEORETICAL PHYSICISTS, PARTICLE PHYSICIST AND SPACE ENGINEERS?

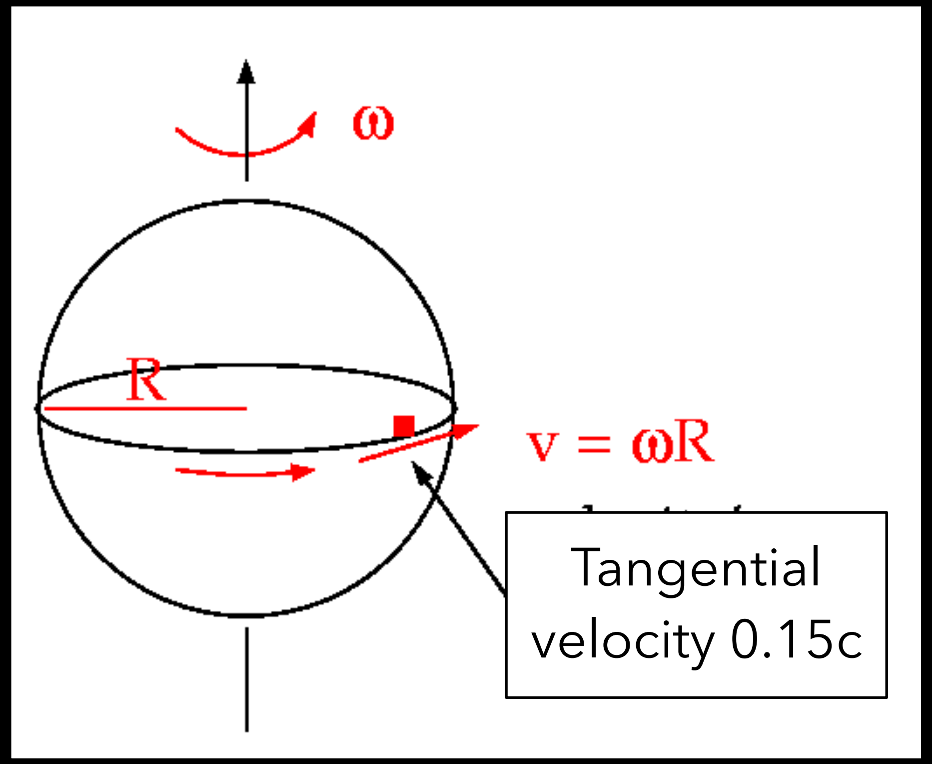
# RECORD GUINNESES



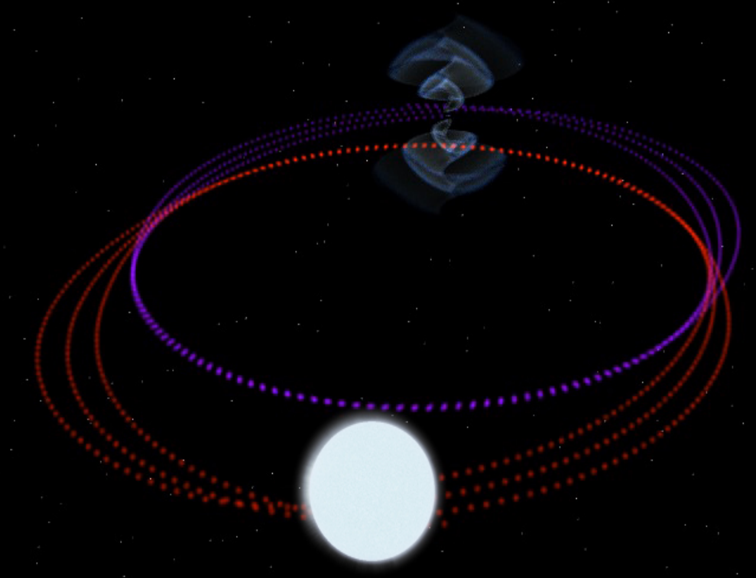

## The densest rigid body known to date:

As dense as a nucleus, with a central pressure $10^{25}$ times the atmospheric pressure on Earth.




## The fastest known rotating body in the Universe:

1.3959546744700354+/-0.0000000000000003ms



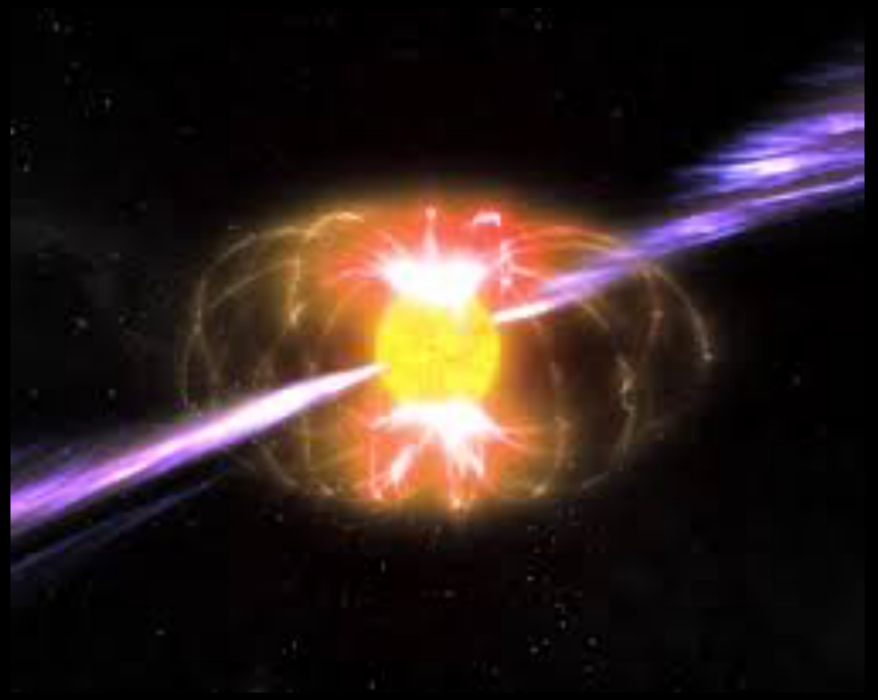
## The roundest known circle in the Universe:

Is the orbit of the pulsar PSR J1909-3744 around a normal star. It is round to 5micron (1/10 of a human hair) to 567000km.

# RECORD GUINNESES

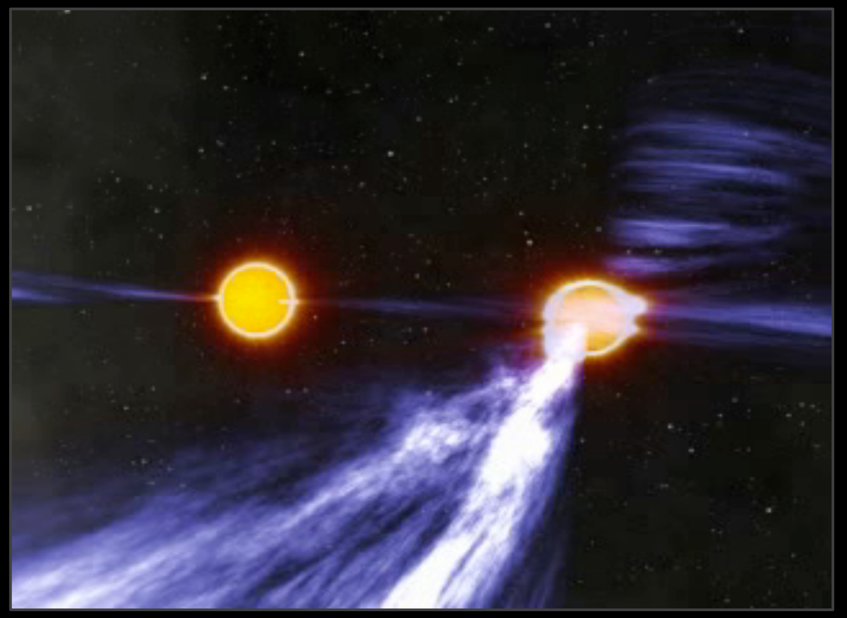
The most stable clocks in the Universe:

Pulsar arrivals are so precise and stable that beats atomic and quantum optical clocks.



The most magnetic objects in the Universe:

The magnetar SGR 1806-20 has a magnetic field of $\sim 10^{15}$ , about $10^{8}$ times larger than the highest B-field we can produce on Earth.



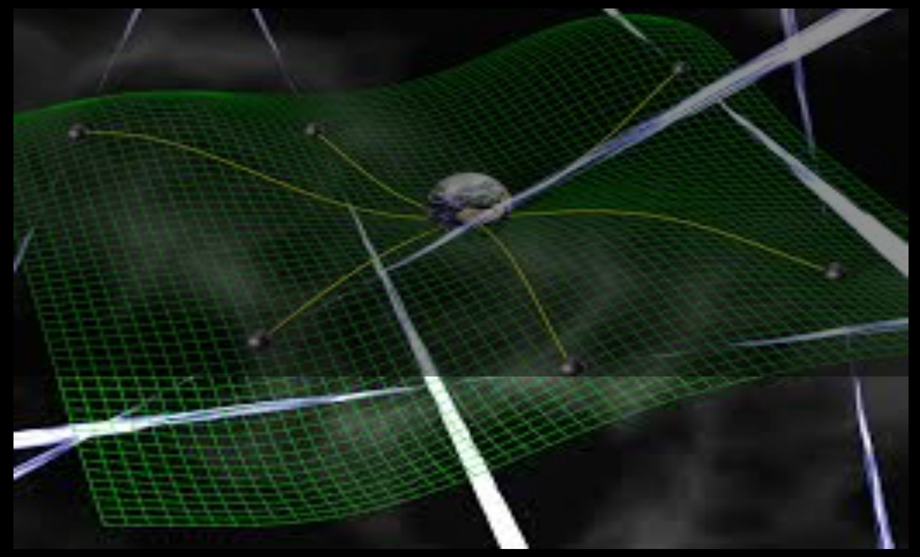
The most precise tests of General Relativity:

Binary pulsar systems holds the Guinness for having tested GR at 0.02% confidence level. Einstein is right so far…

# RECORD GUINNESES

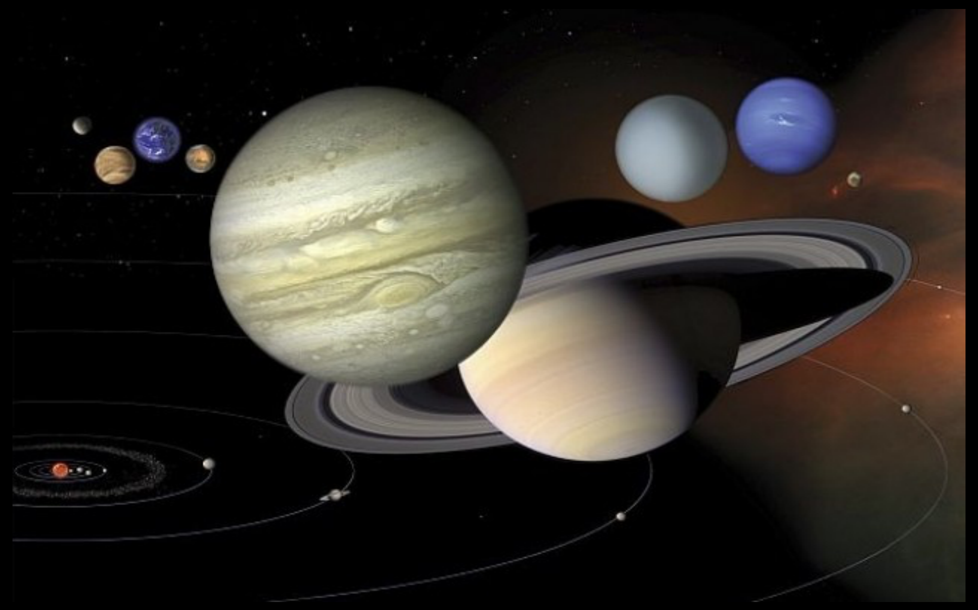
A natural Gravitation Waves detector:

Observing regularly millisecond pulsars we might detect GWs (International Pulsar Timing Array).



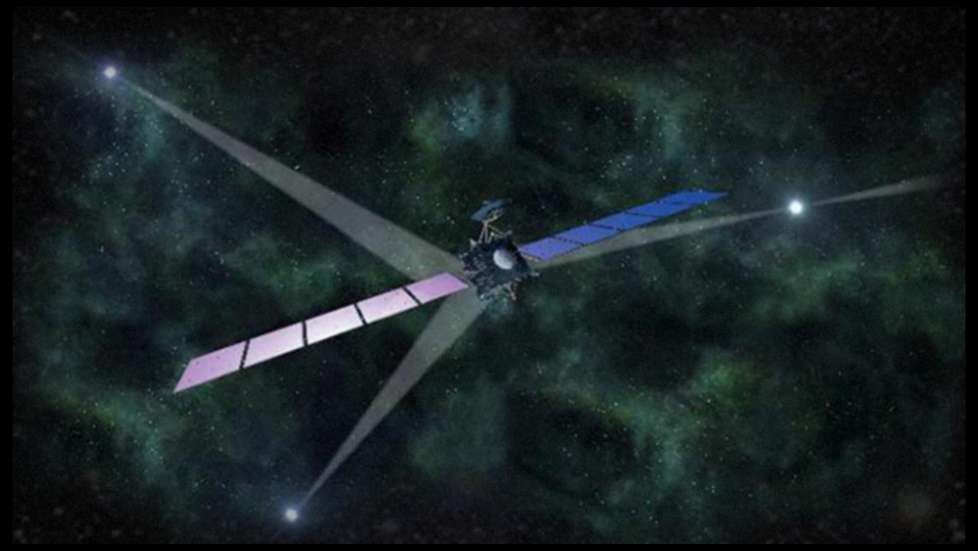
The least expensive Solar System planet mass determination:

Observing pulsars systematically planet masses are measured as precisely as dedicated satellites.

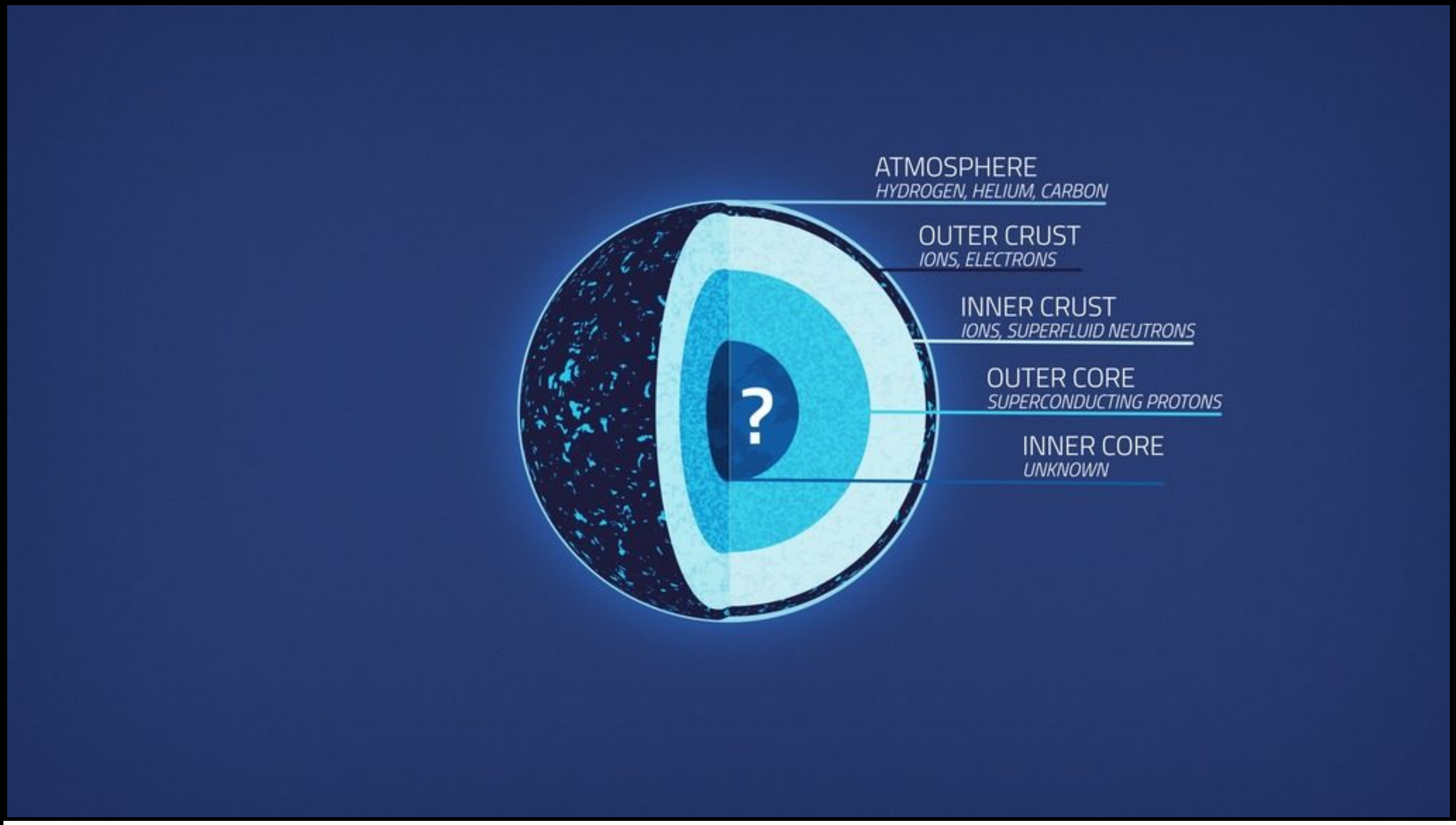


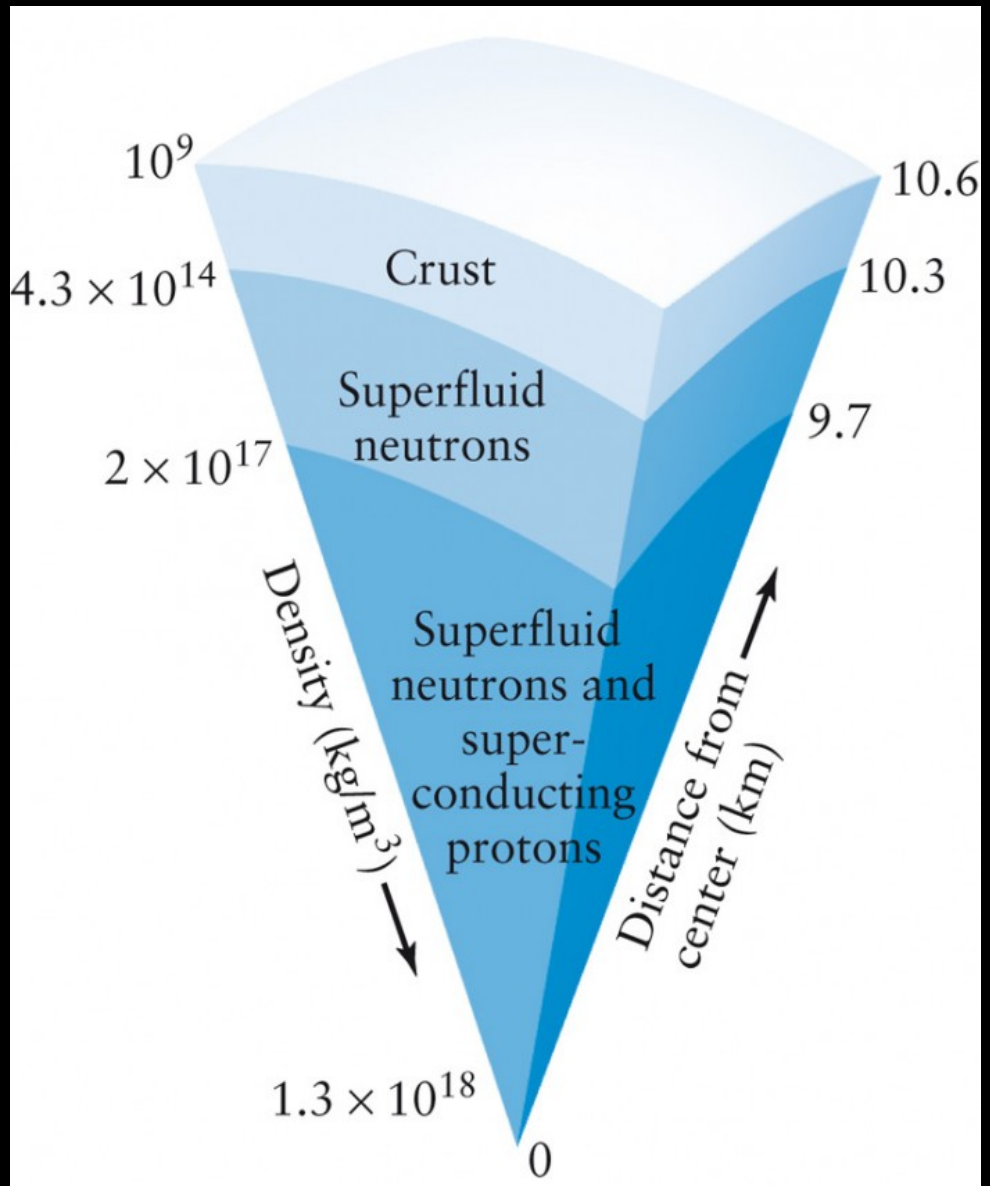
Our future GPS in space:

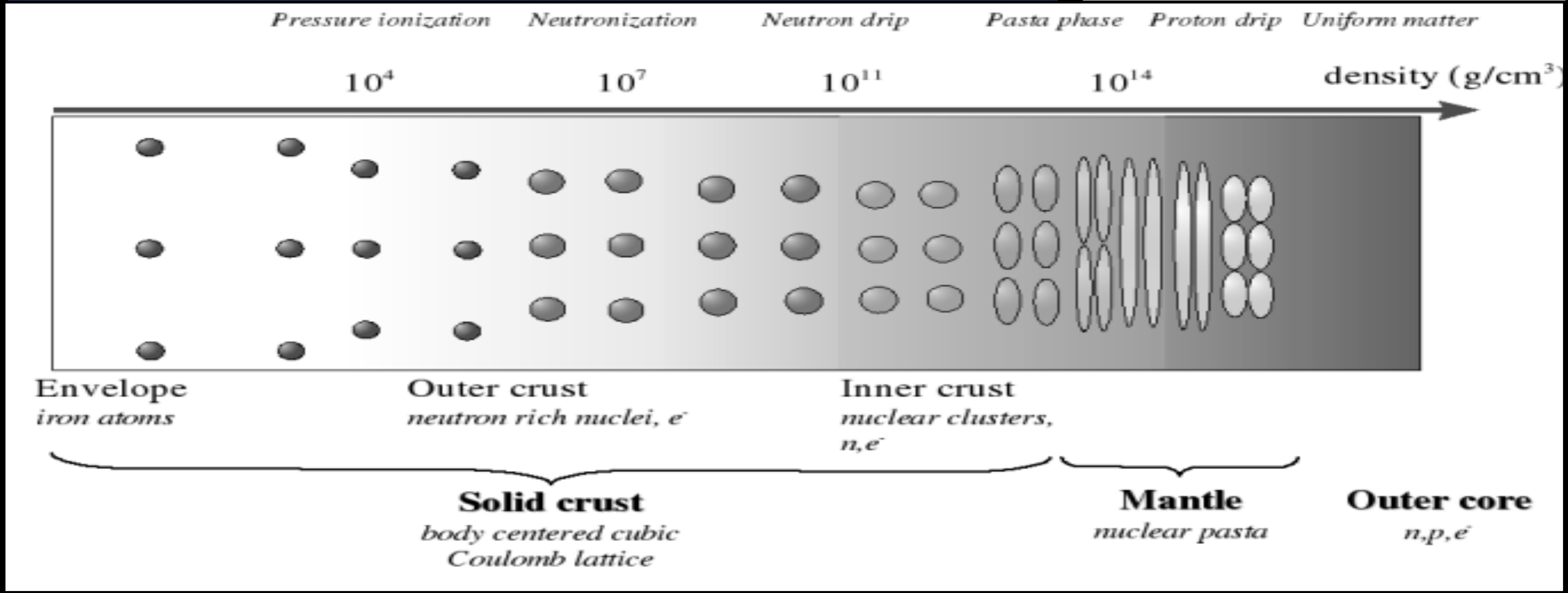
Pulsar clocks are so precise that will be our unique GPS system when travelling in space with no connection with Earth.



# A NEUTRON STAR FROM INSIDE



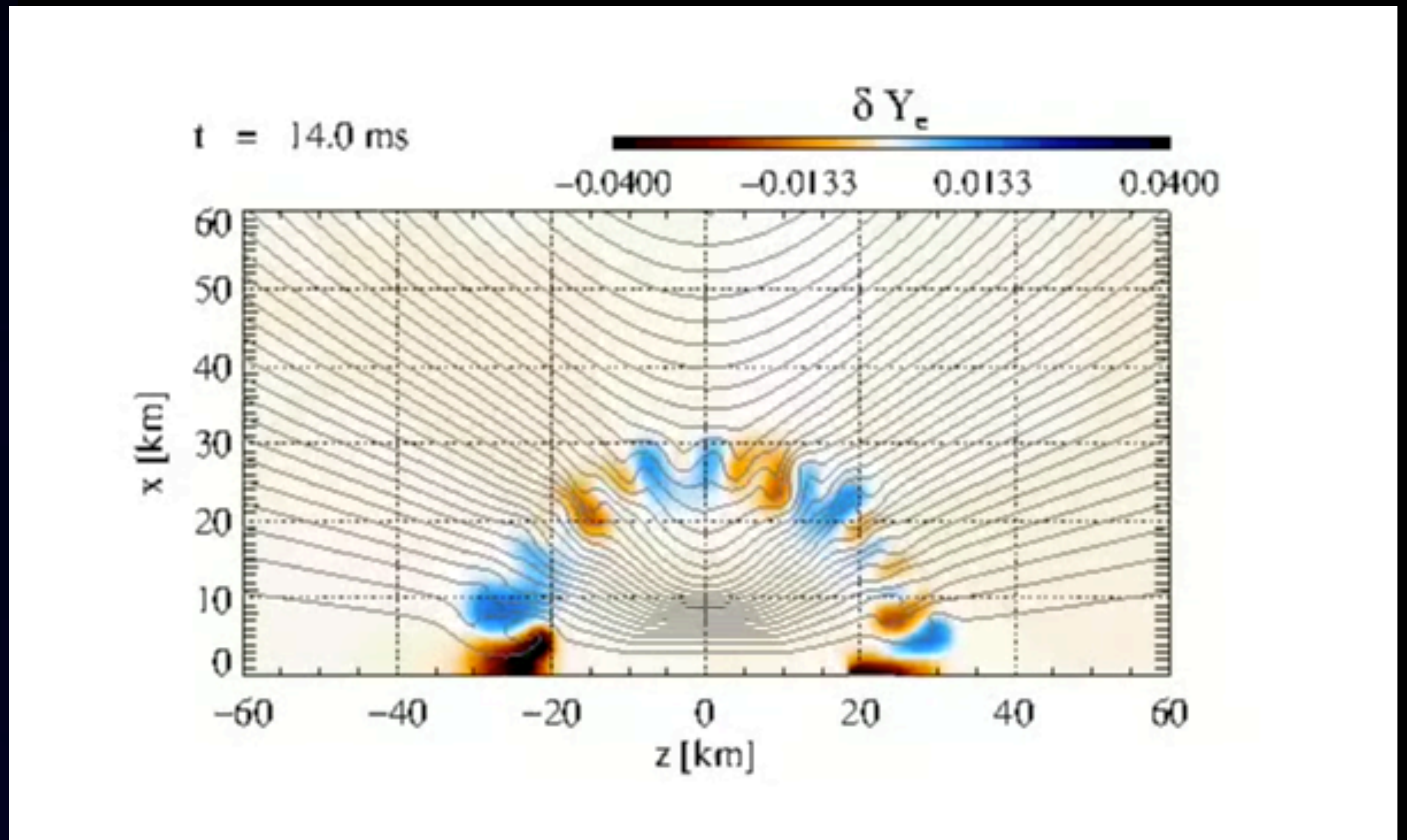



# MAGNETIC FIELD FORMATION IN PULSARS

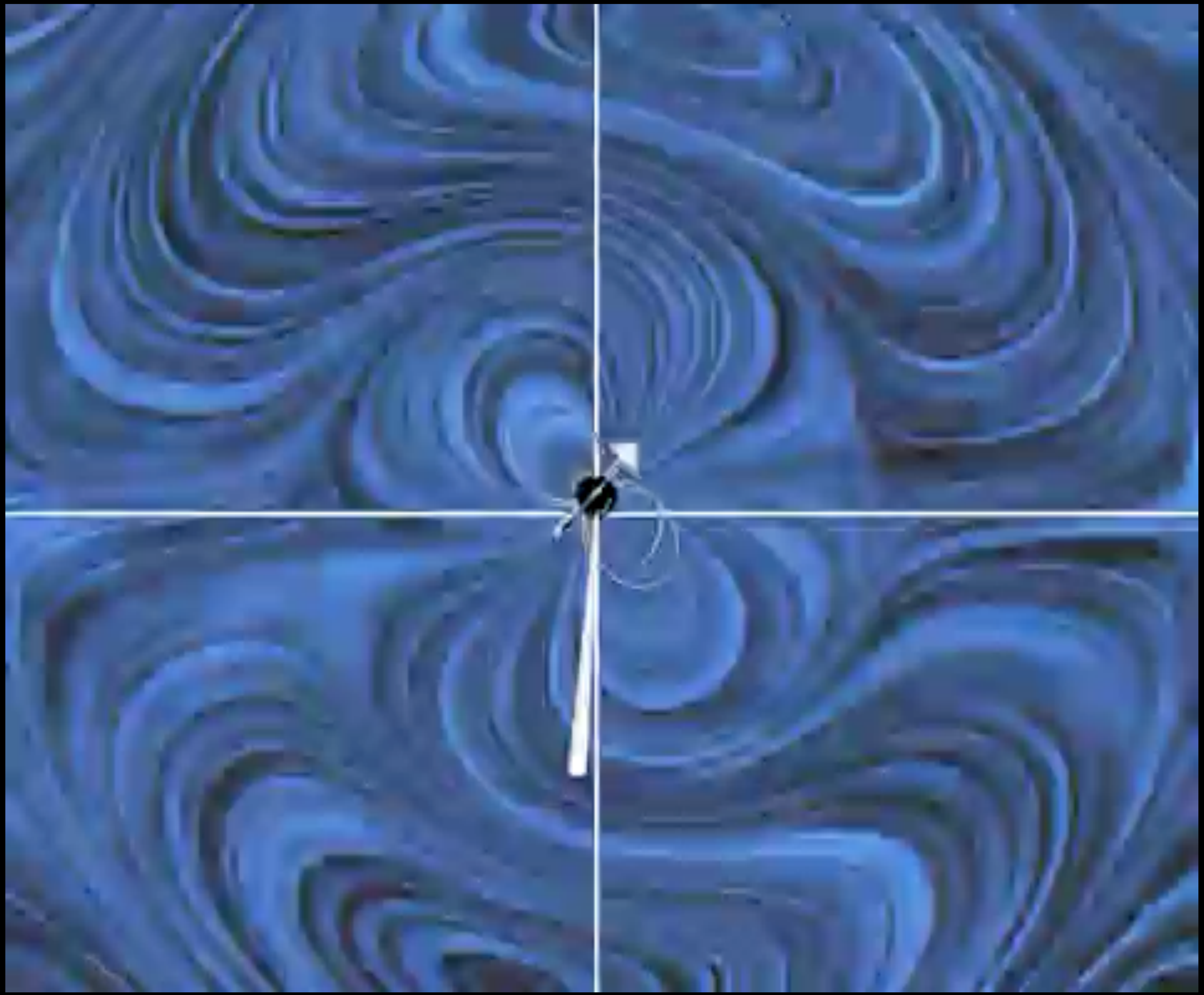
- Via dynamos/instabilities in the stellar core
- As fossil fields from a magnetic progenitor

Massive Cluster Westerlund 1 in X-ray




(Obergaulinger, Janka & Aloy 2015, MNRAS)

# MAGNETIC FIELD ESTIMATE



Rotating magnetic dipole

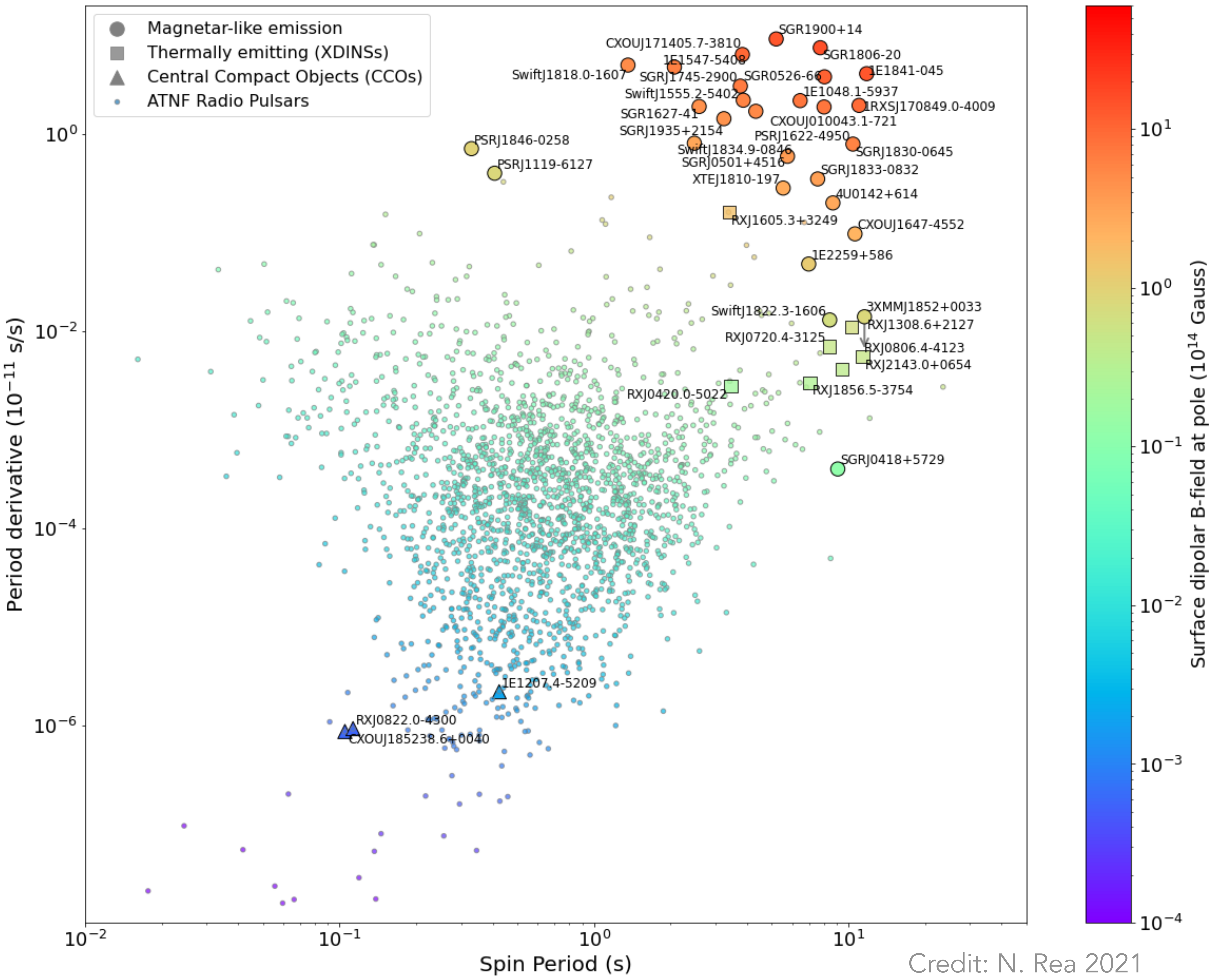
$$\dot{E}_{rot} = I_{ns}\Omega_s\dot{\Omega}_s = -\frac{4\pi^2 I_{ns}\dot{P}_s}{P_s^3}$$

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

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

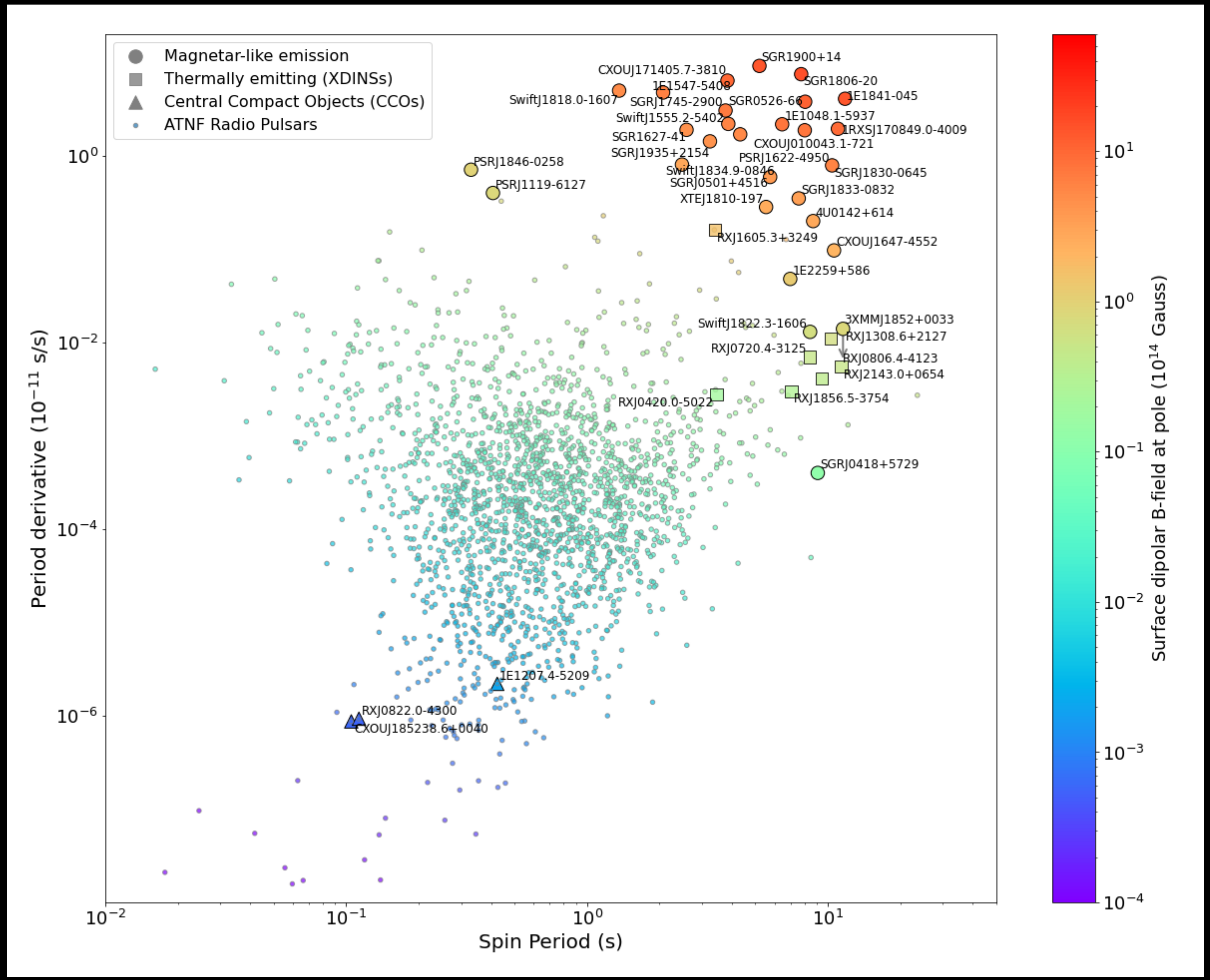
# THE ISOLATED PULSAR POPULATION

Many neutron star classes emitting rotational and magnetic energy, thermally and/or non-thermally.




Credit: N. Rea 2021

# 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. Close-by. Typically emitting in the X-rays.

## CENTRAL COMPACT OBJECTS

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

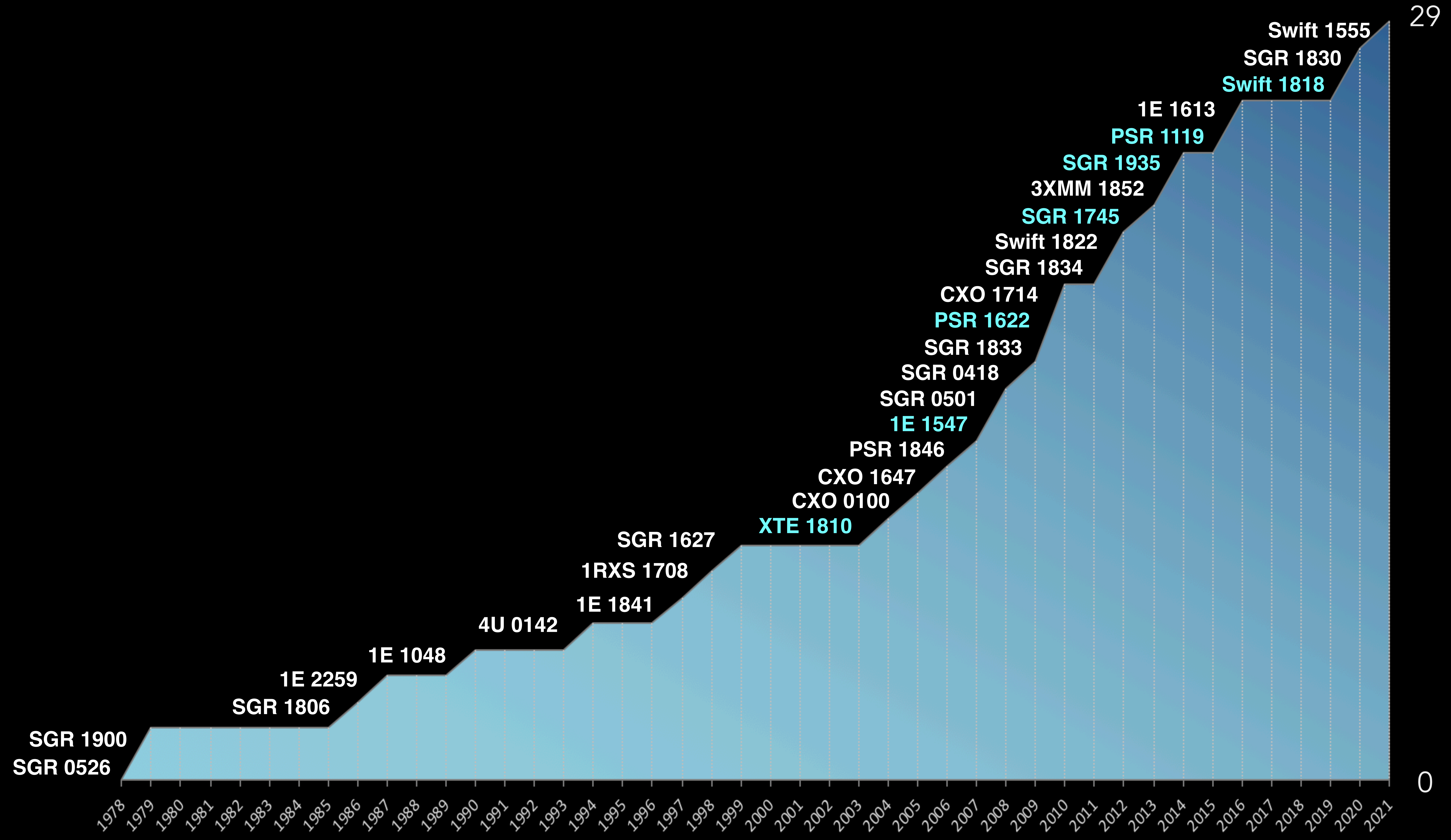
## ROTATIONAL POWERED PULSARS

Powered by rotational energy. Typically emitting in radio.

## ROTATING RADIO TRANSIENTS

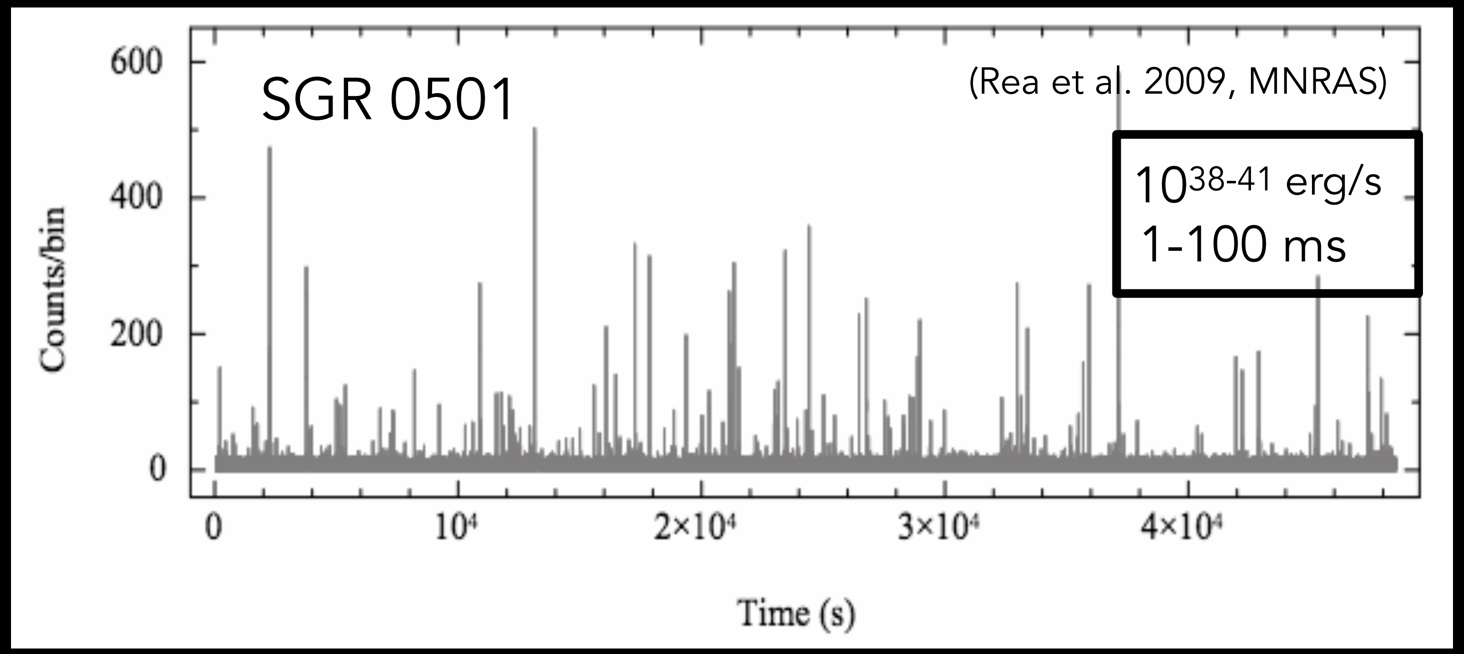
Powered by rotational energy. Single-pulses. Typically emitting in radio.

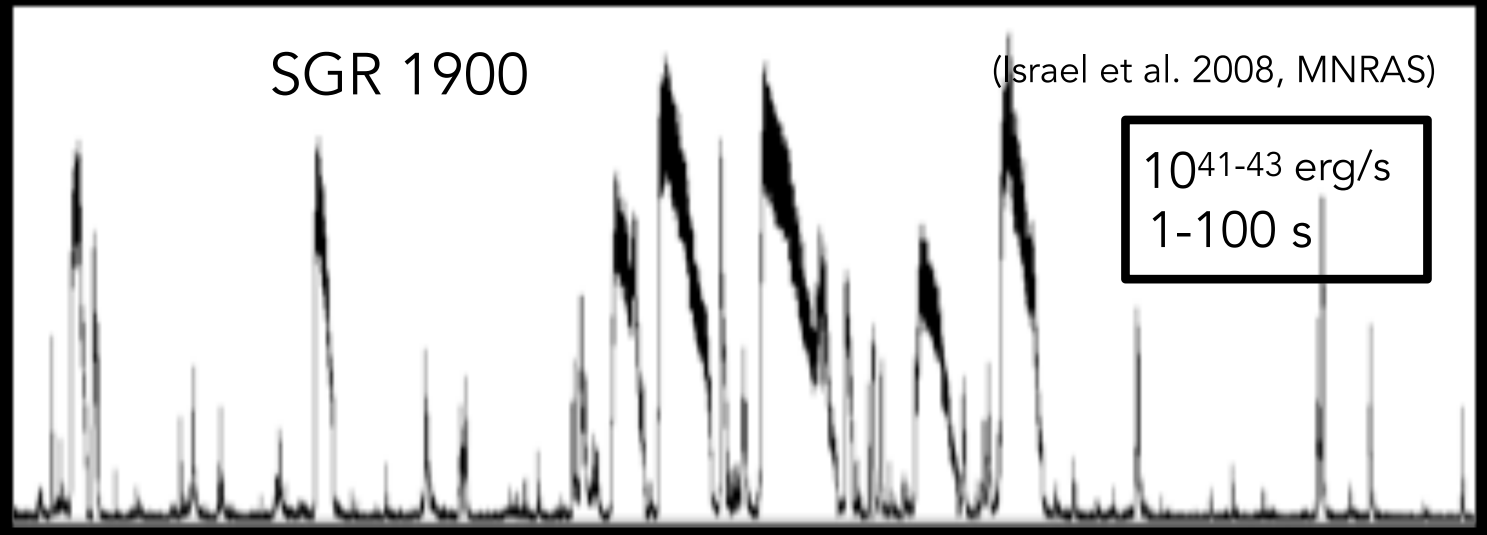
# MAGNETARS NOW

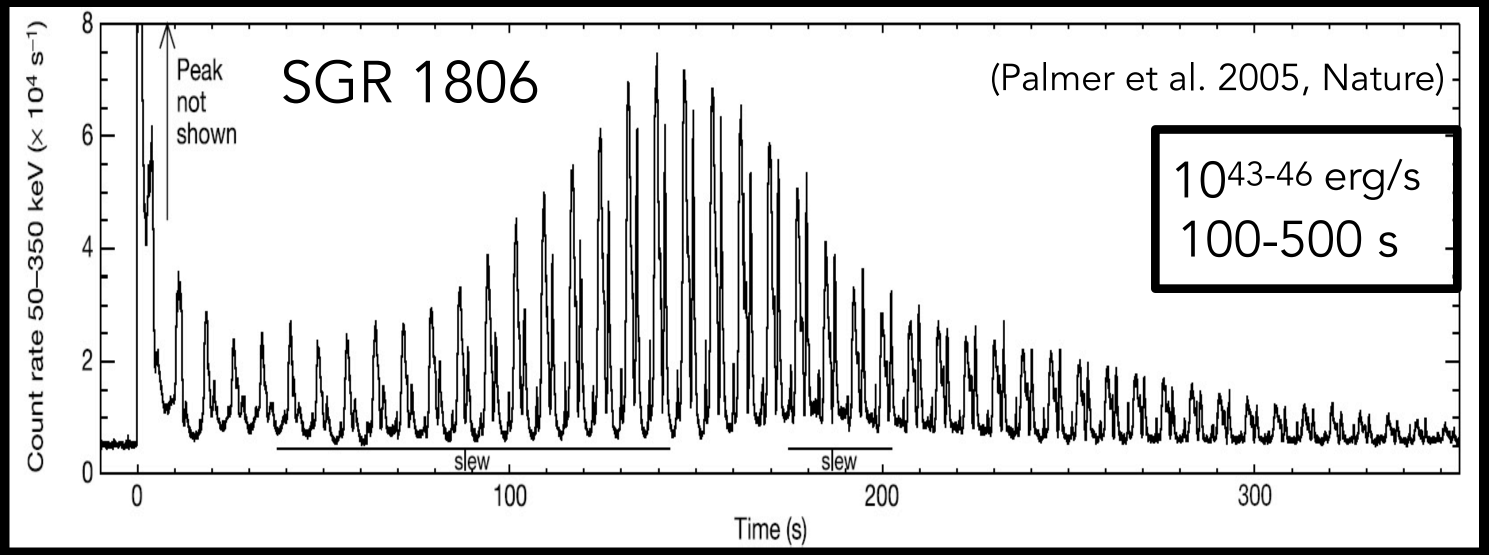


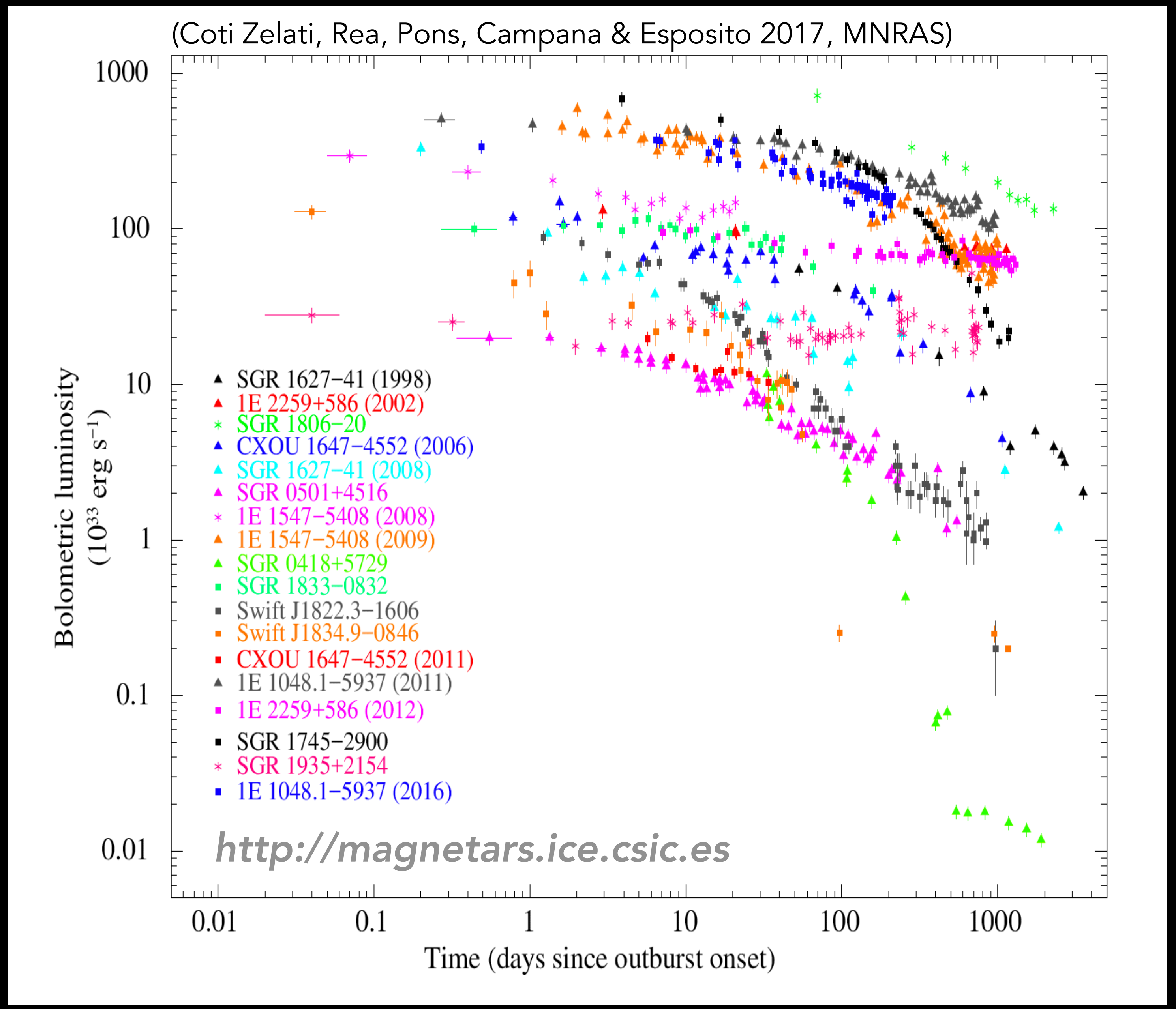
# MAGNETAR OUTBURSTS AND FLARES

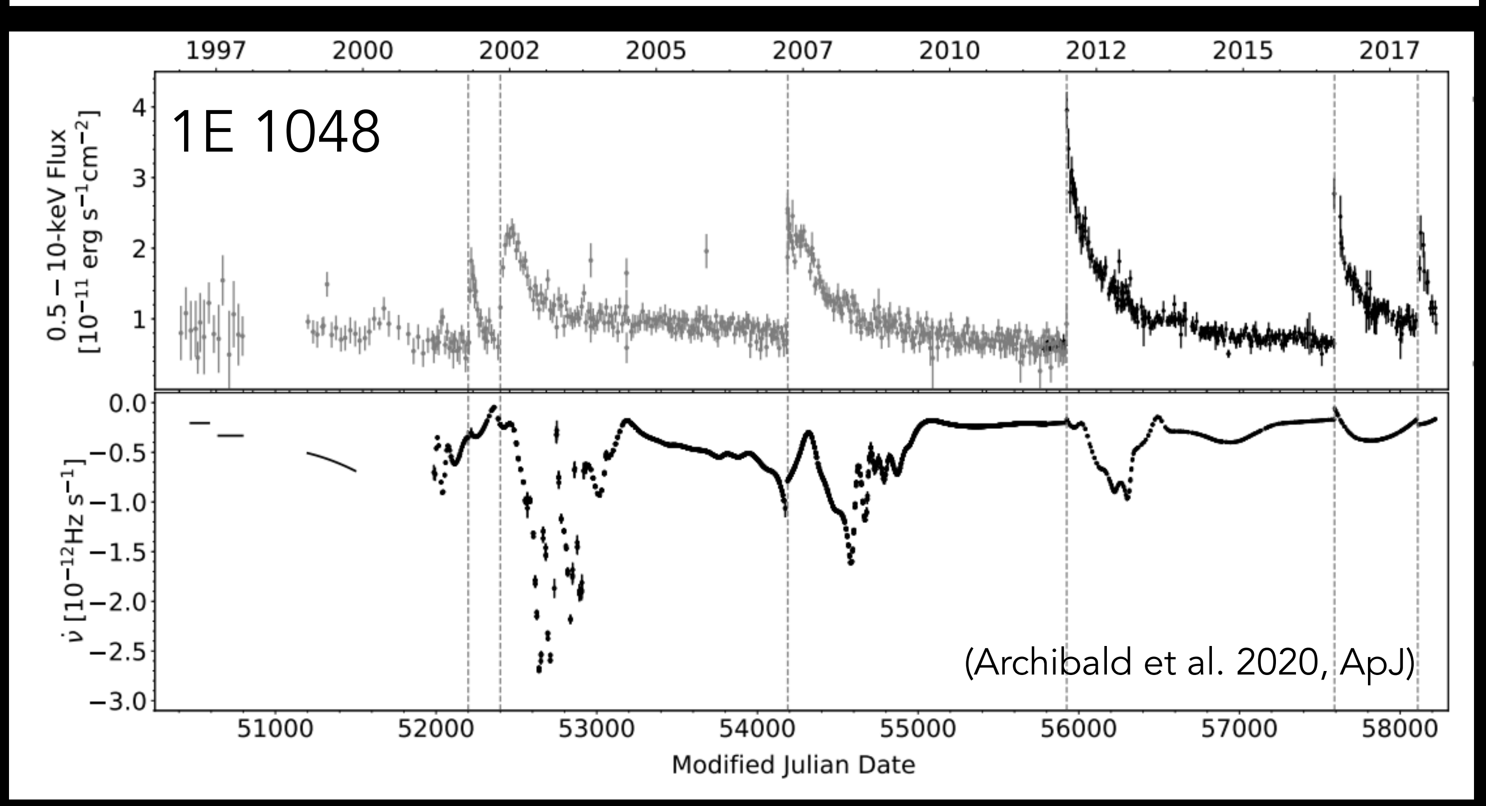
## FLARING/OUBURST ACTIVITY



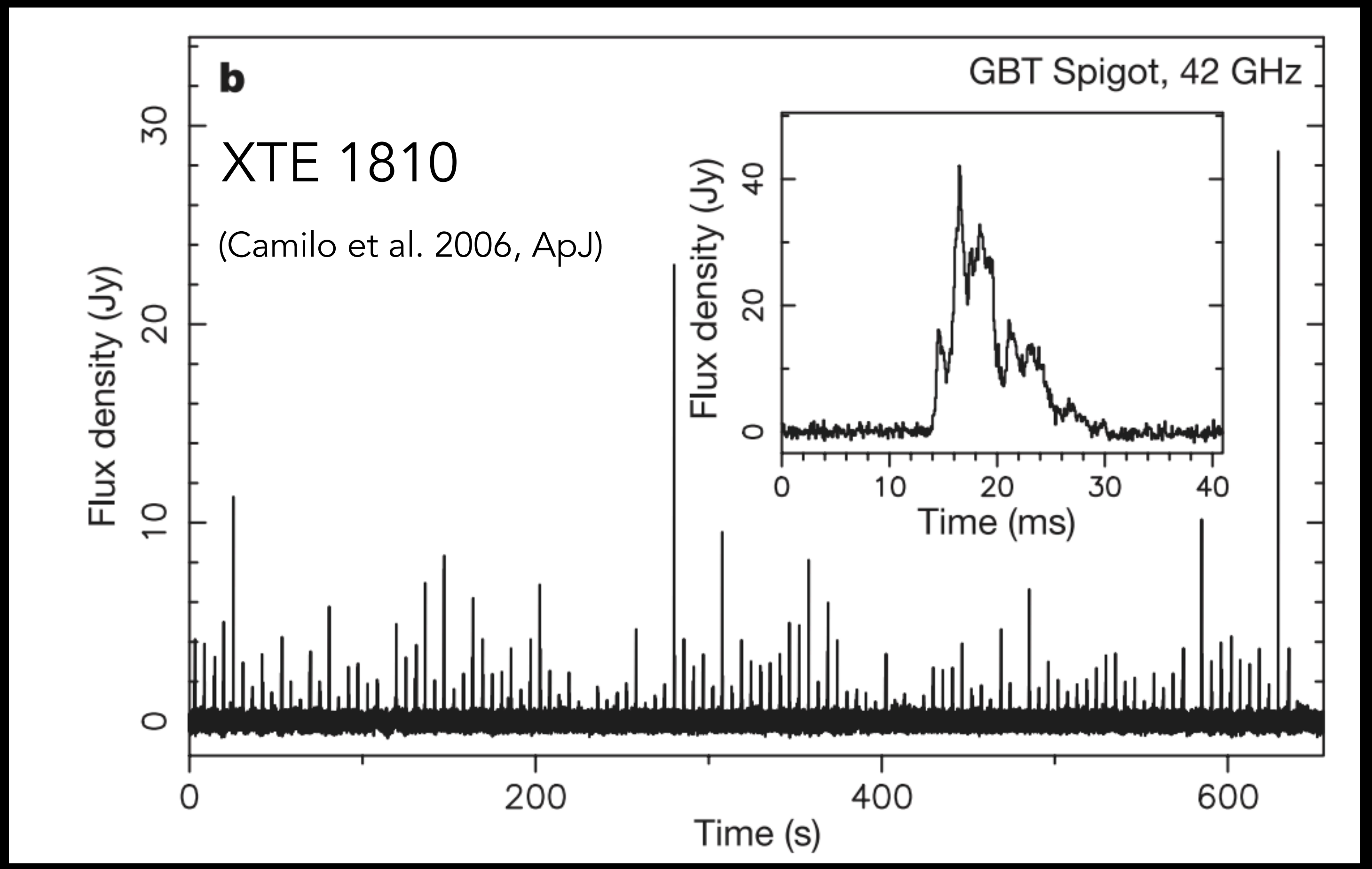



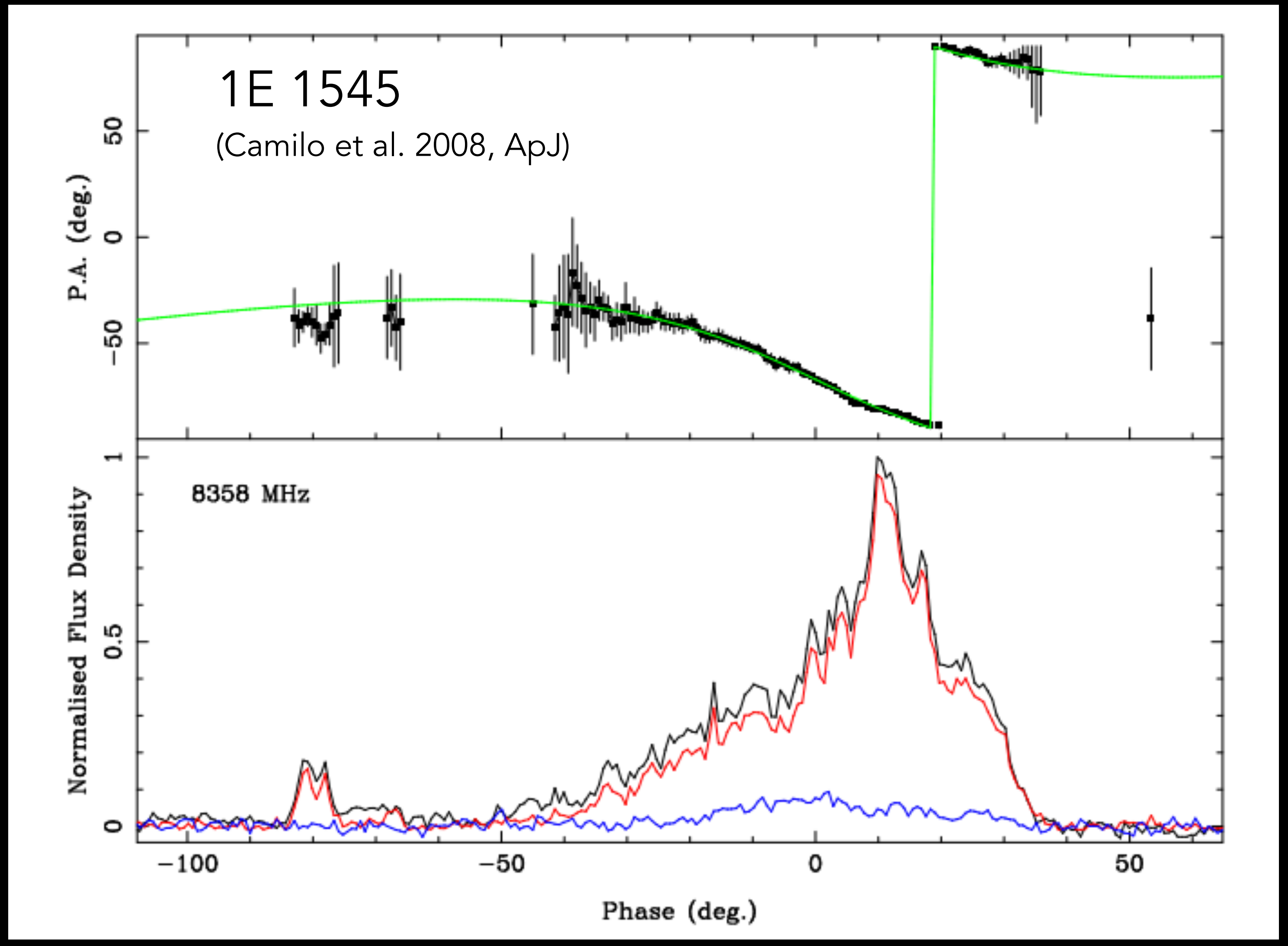




## RADIO ACTIVITY



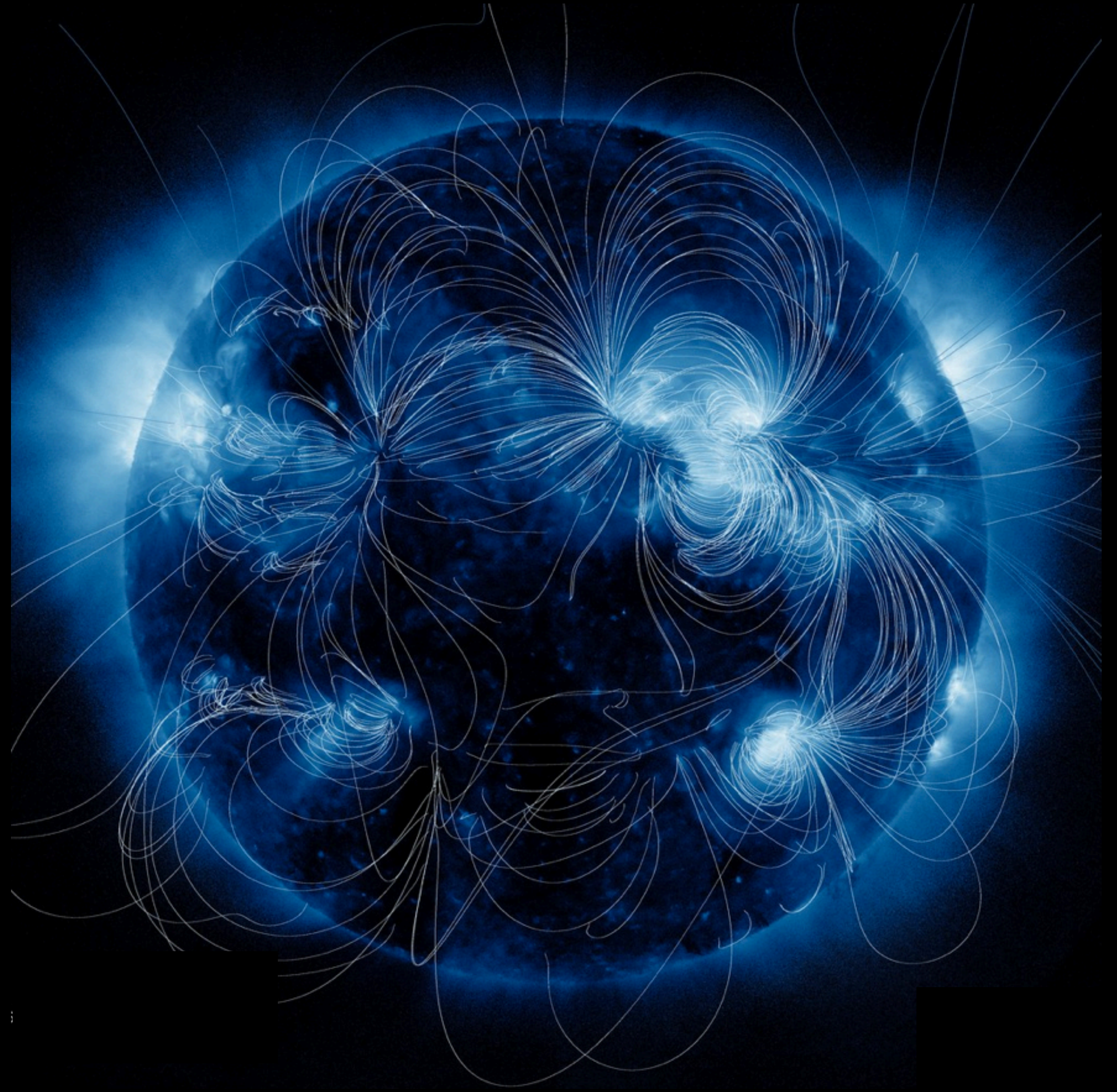



# MAGNETARS

- TANGLED FIELDS. Magnetars have highly twisted and complex magnetic field morphologies, both inside and outside the star.

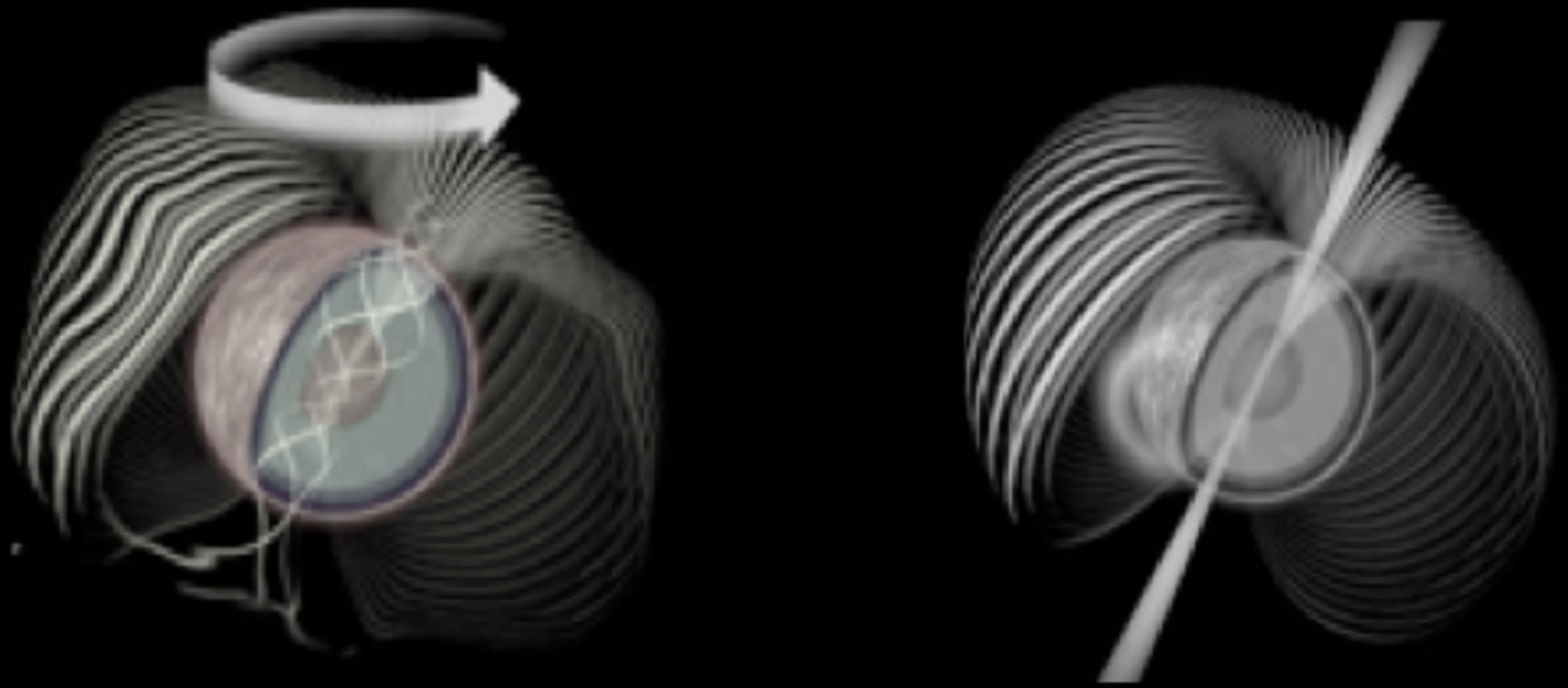
- STEADY EMISSION. Magnetar magnetospheres are filled by charged particles trapped in the twisted field lines, interacting with the surface thermal emission through resonant cyclotron scattering.

- FLARES. Twisted magnetic fields might locally (or globally) stress the crust (either from the inside or from the outside). Plastic motions and/or returning currents convert into crustal heating causing large outbursts.



Magnetars

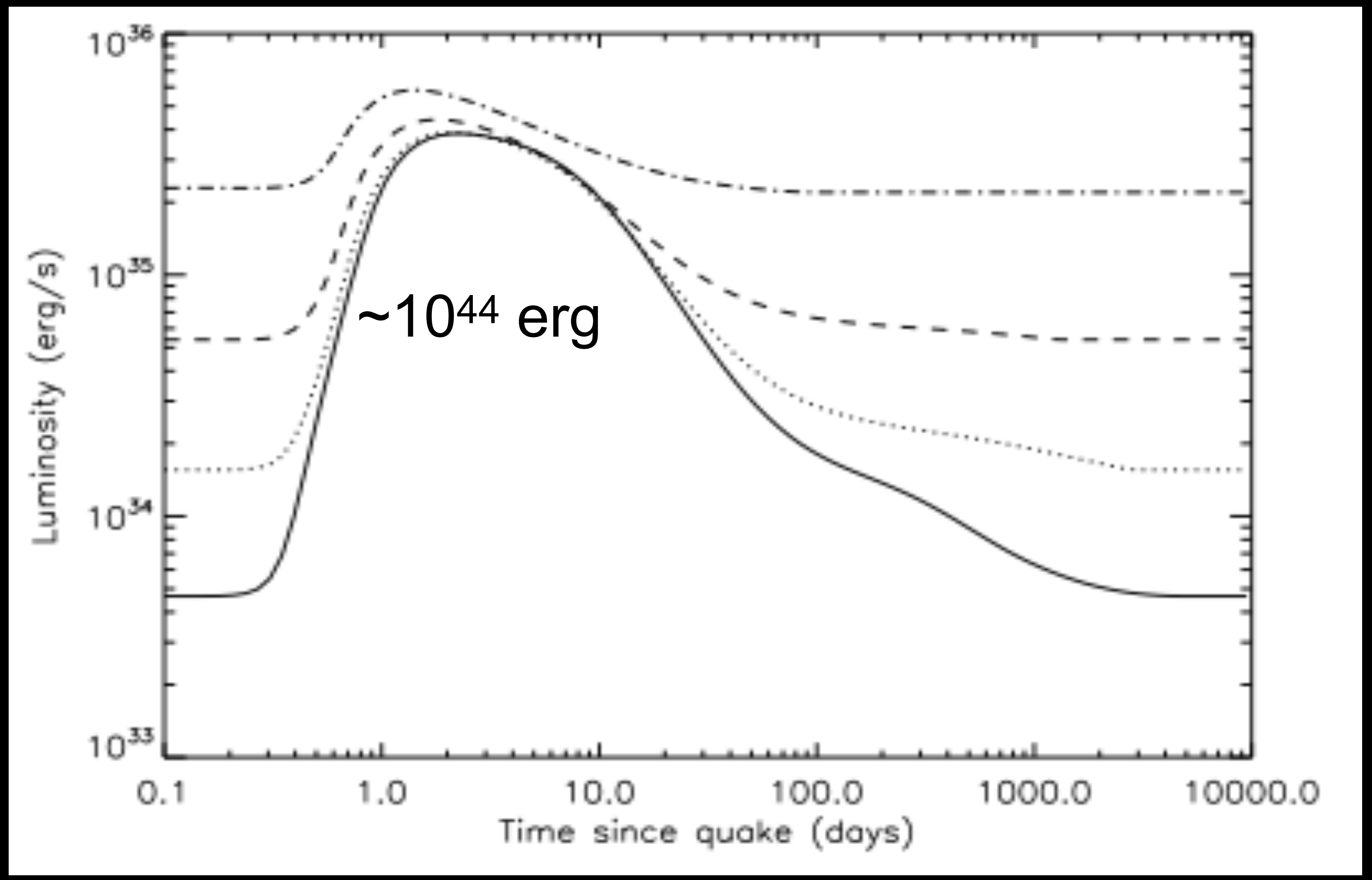
Normal Pulsars



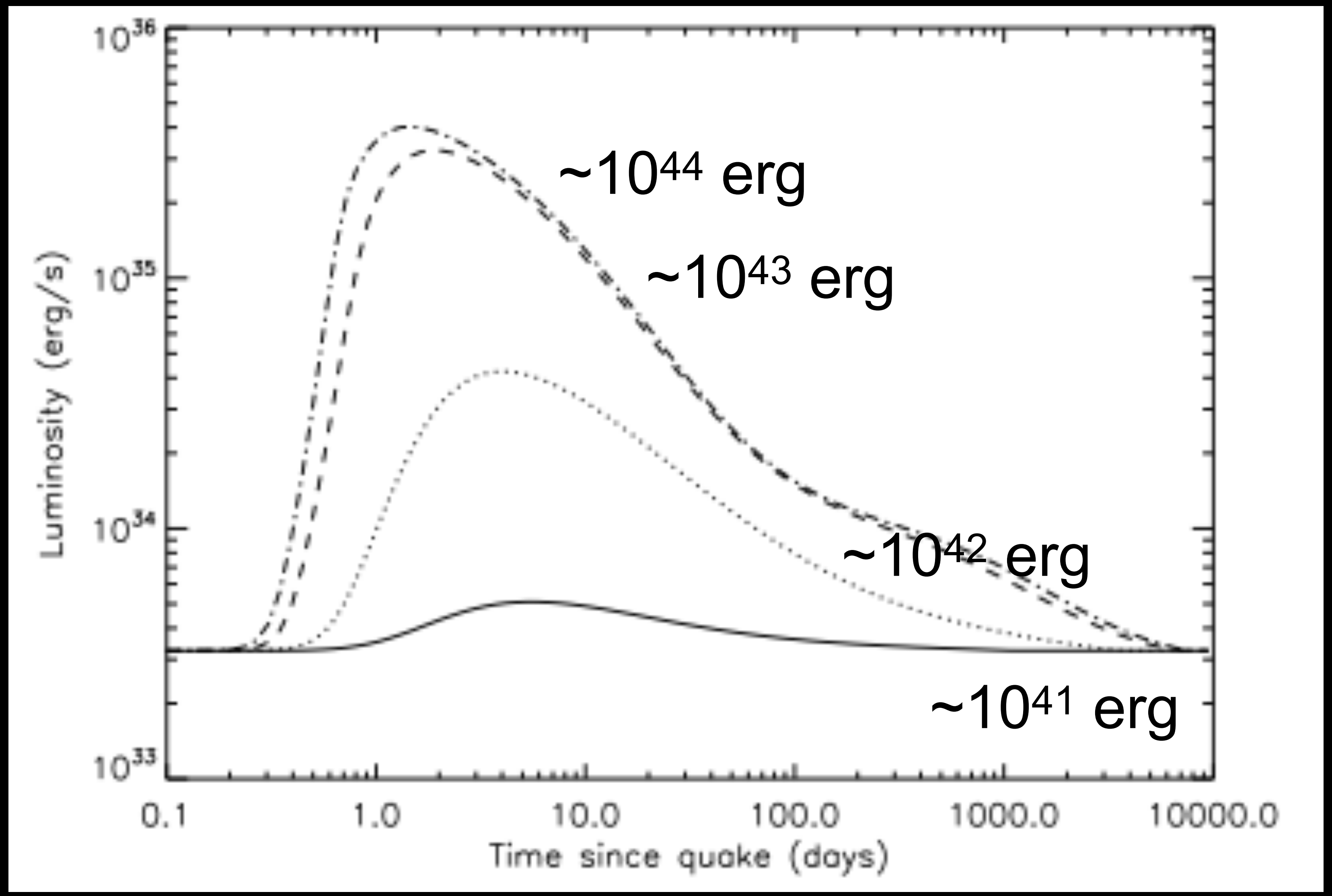
(Rea & Esposito 2011; Kaspi & Beloborodov 2017; Esposito, Rea & Israel 2021)

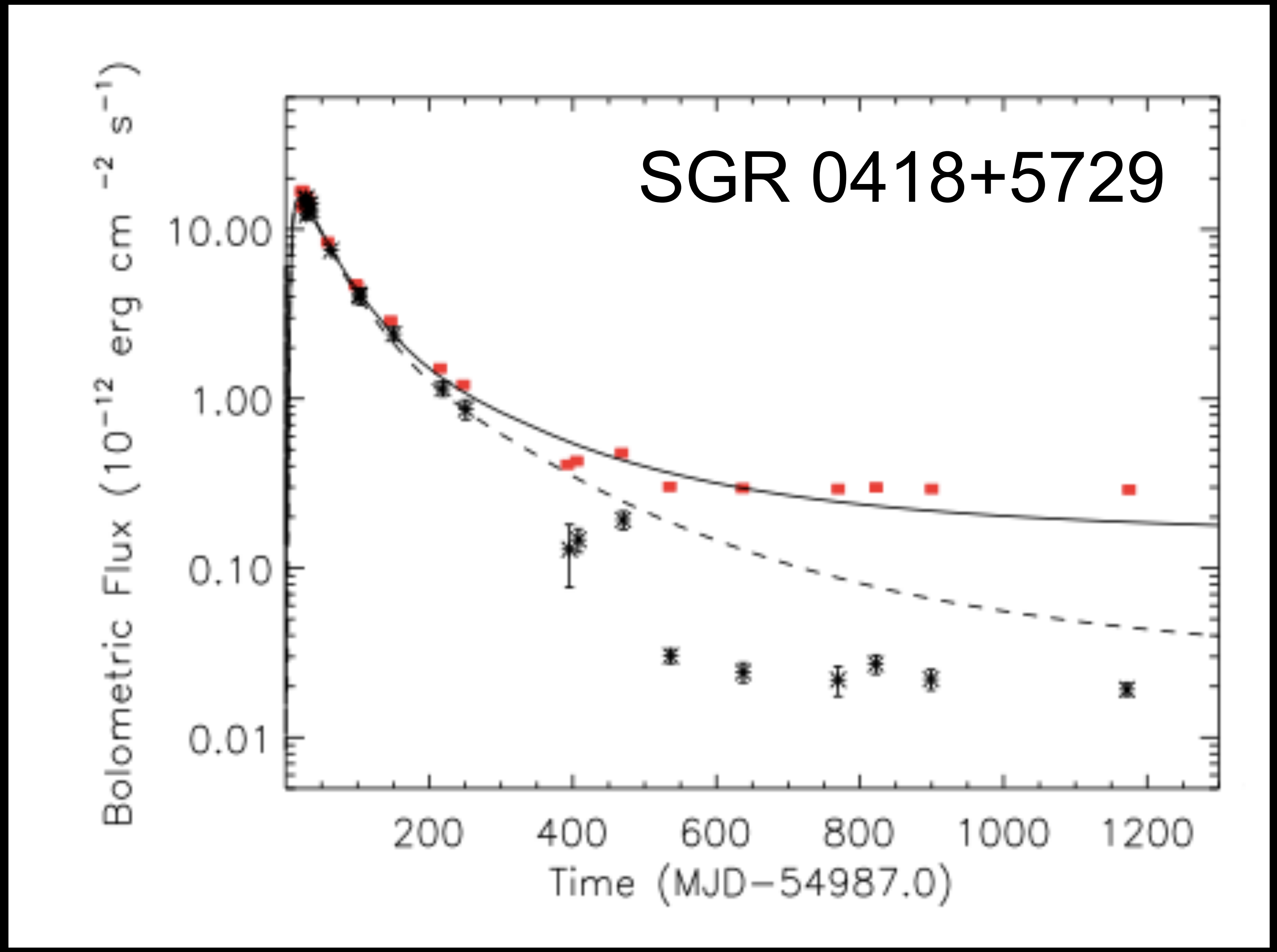
# MODELLING MAGNETAR COOLING

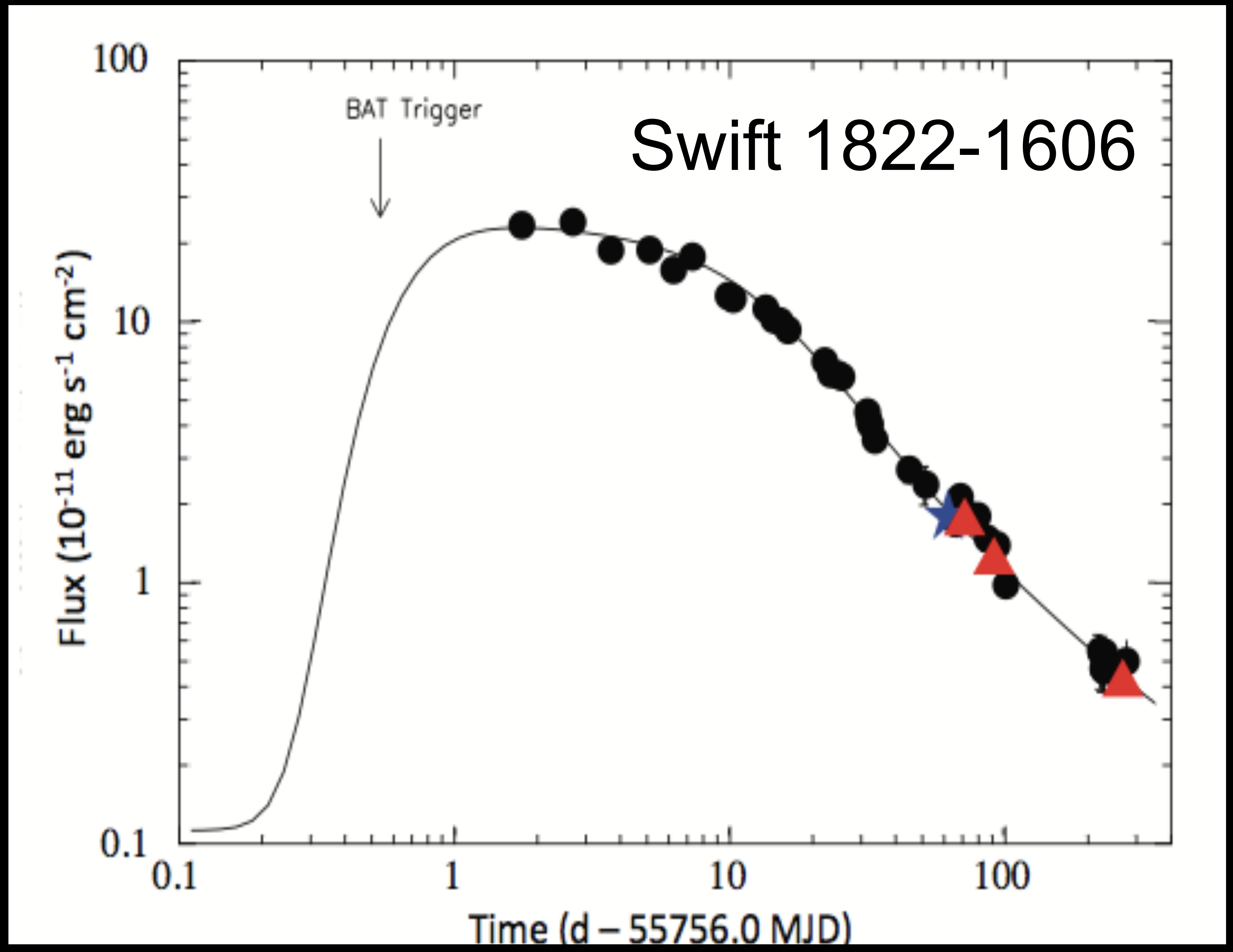
Varying initial quiescent luminosity




Varying injected energy



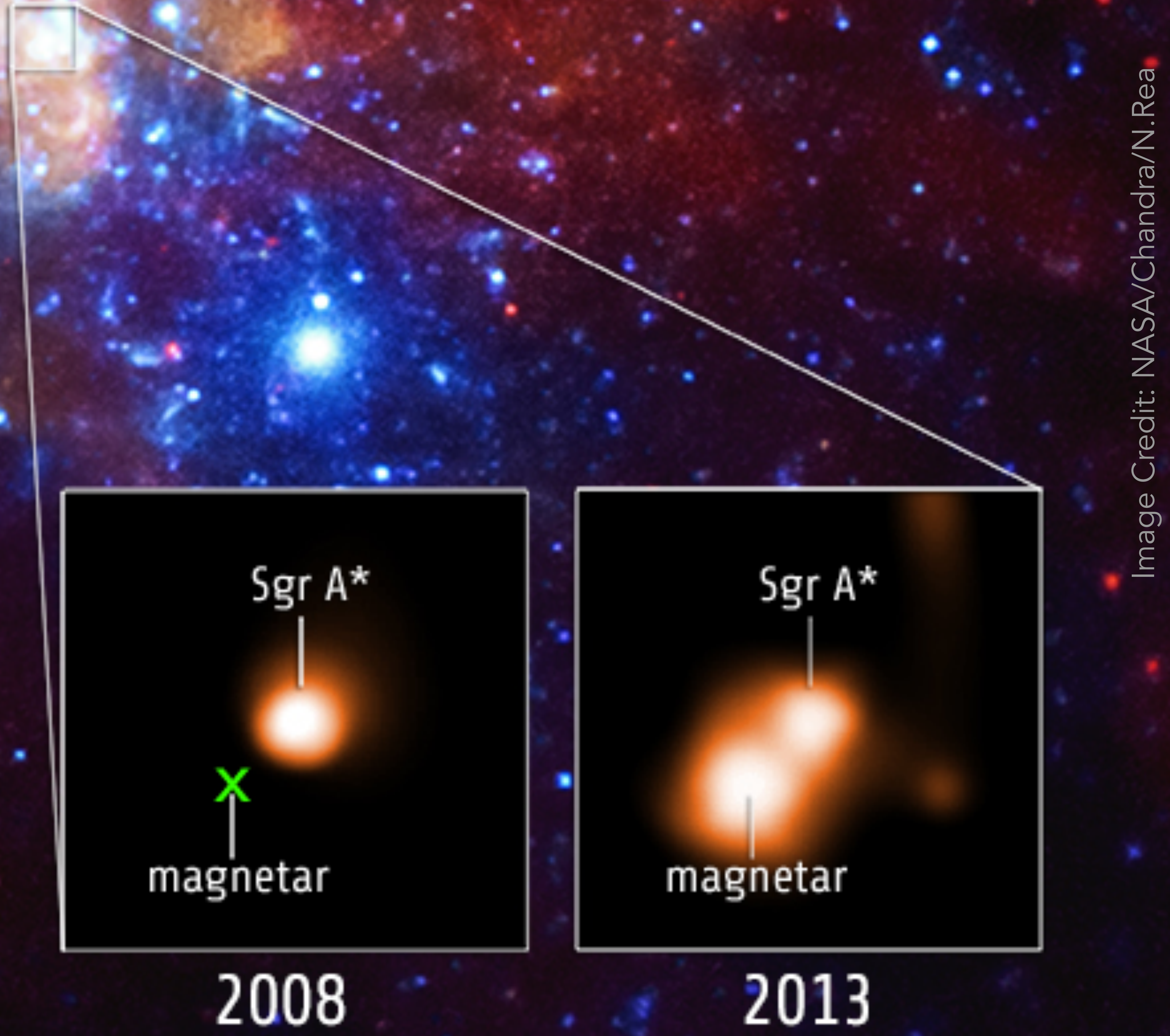




(Pons & NR 2012; NR et al. 2012, 2013)

# THE GALACTIC CENTER MAGNETAR

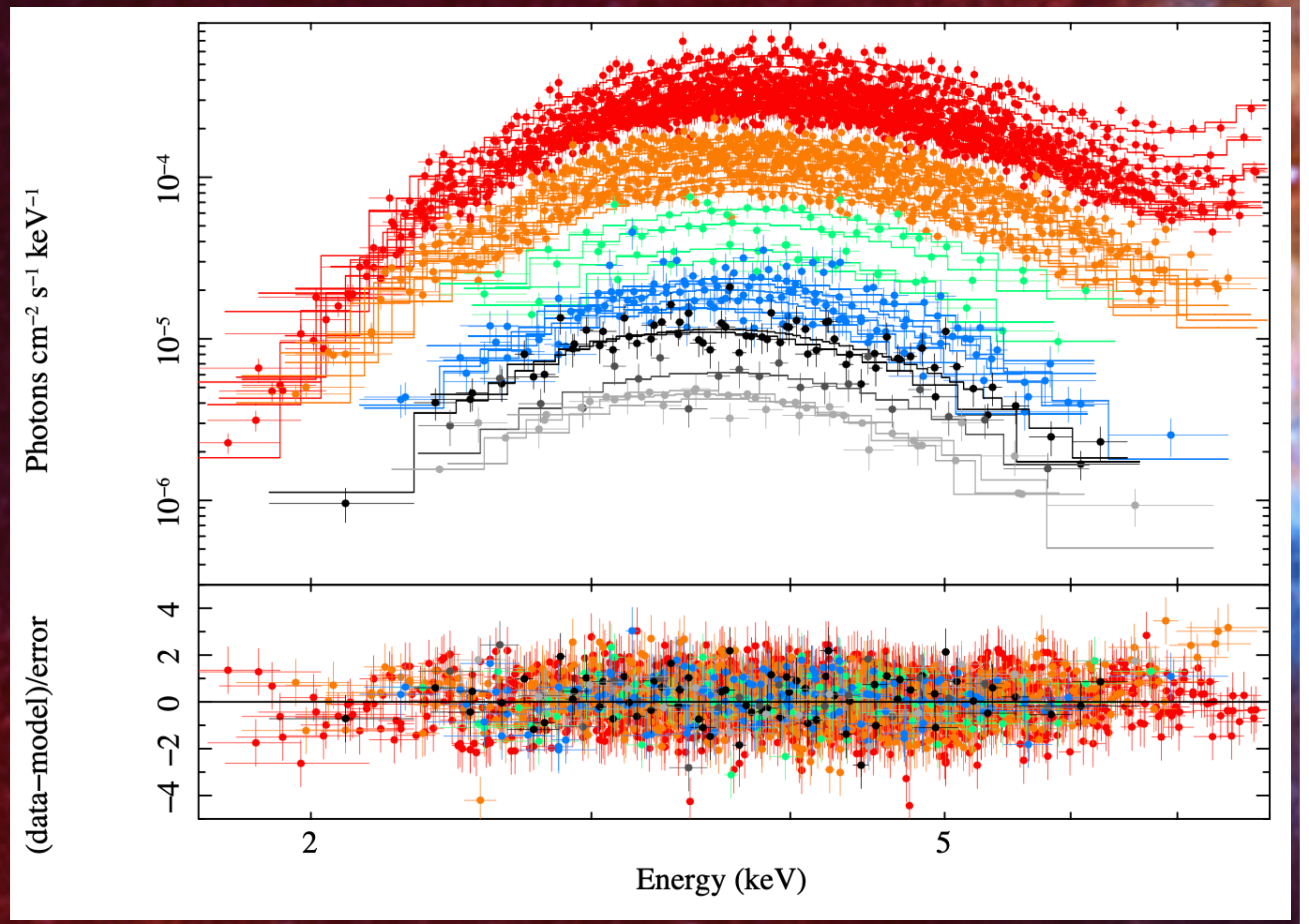
**A magnetar at a 2.4" projected distance from SgrA*!**

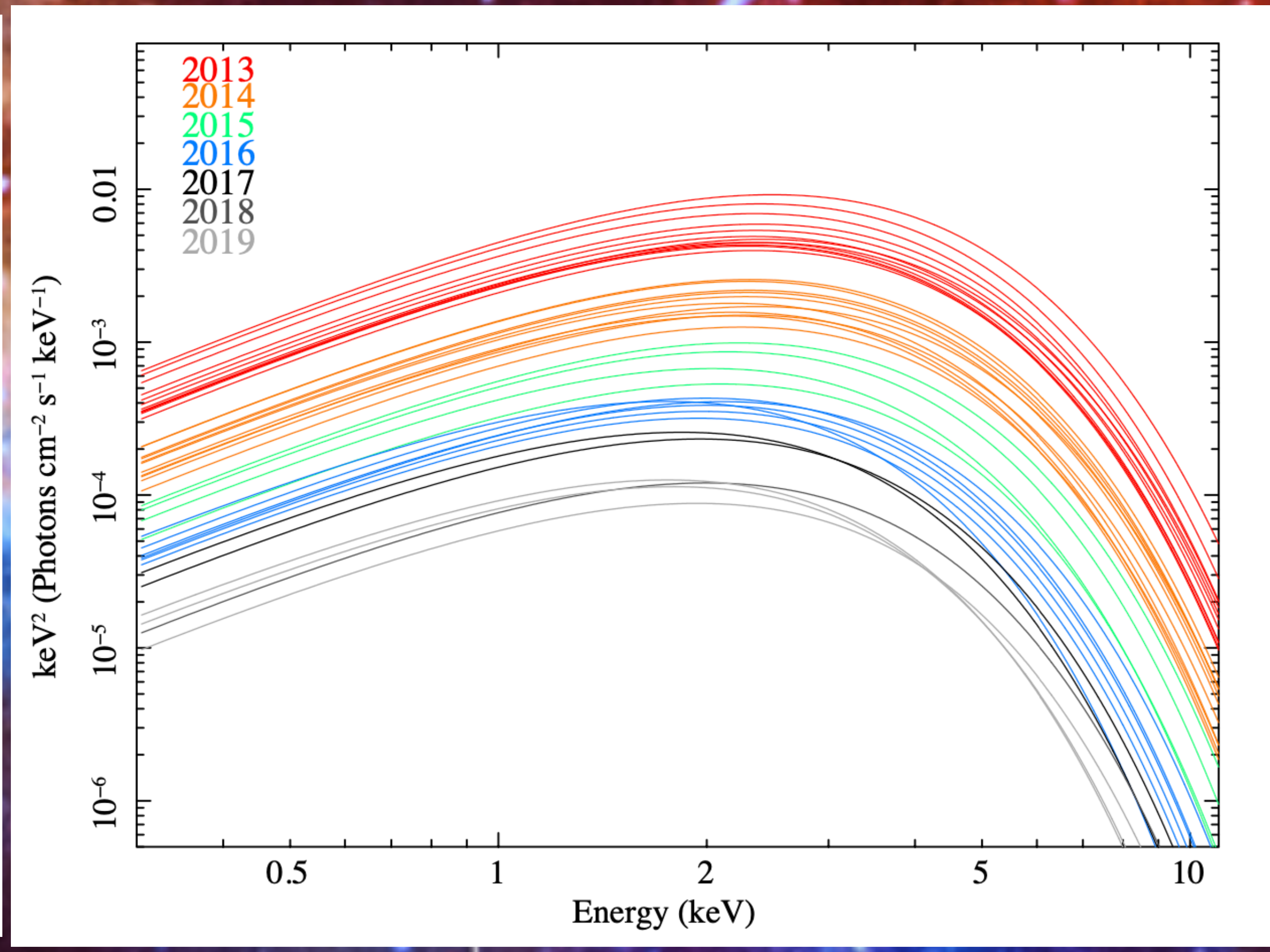
**d = 0.09+/-0.02 pc** (90% CL)
for D=8.3 kpc



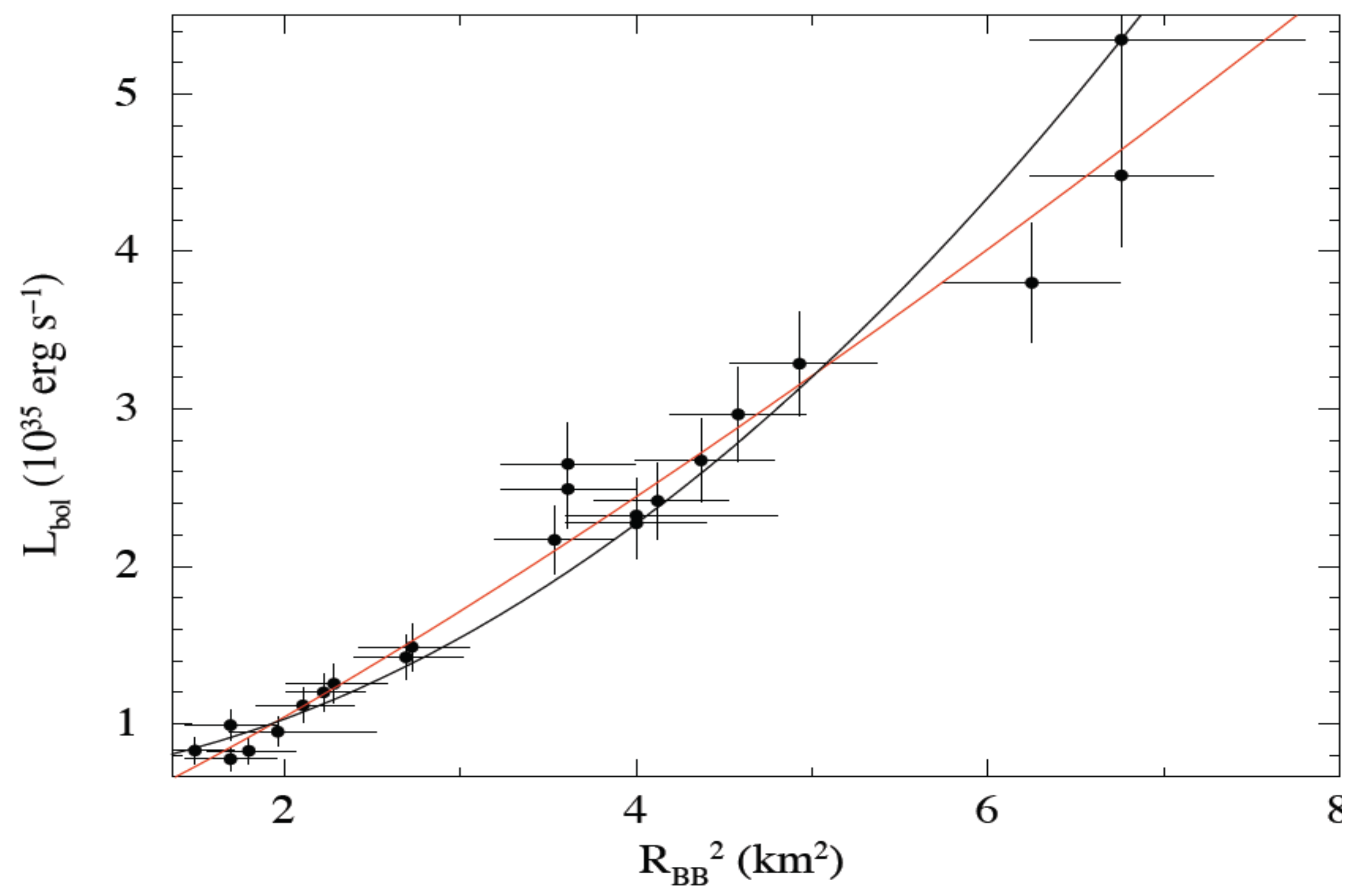

(NR al. 2013, Mori et al. 2013; Kaspi et al. 2014)

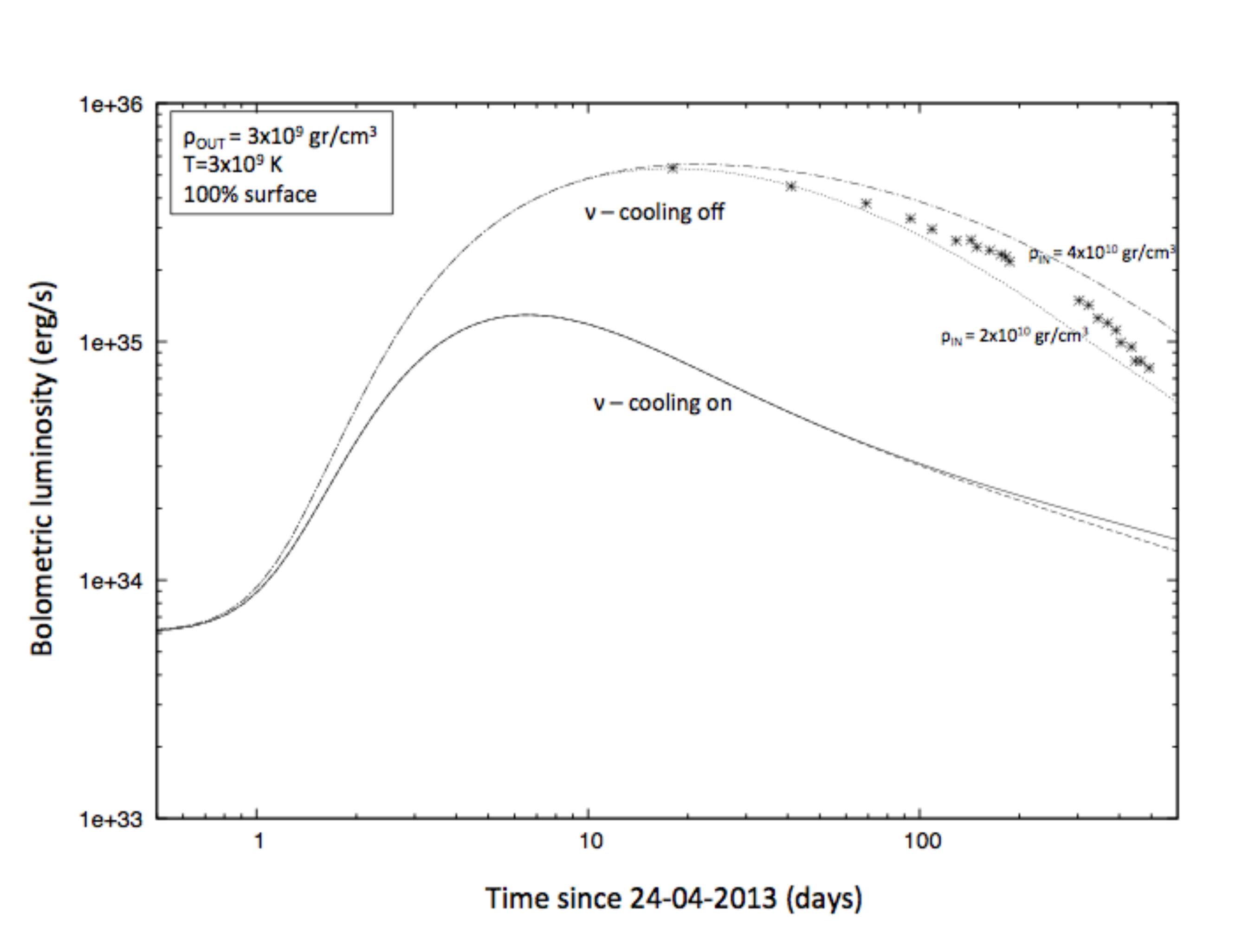
# THE GALACTIC CENTER MAGNETAR




A perfect example of surface cooling, but challenging our models!

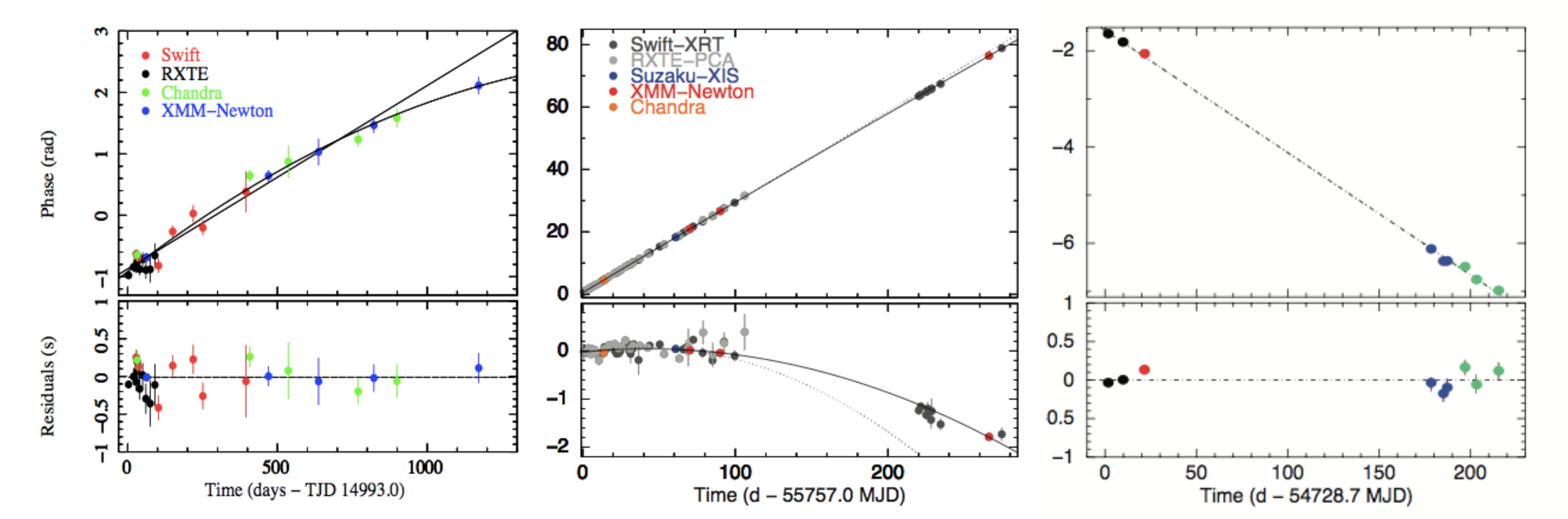



(Coti Zelati, NR, Turolla et al. 2017; NR, Coti Zelati, Vigano', et al. 2020)

# VERY OLD MAGNETARS: i.e. LOW FIELD MAGNETARS

B = 6.2x10[12] G    B = 2.3x10[13] G    B < 4x10[13] G




**SGR J0418+5729**

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

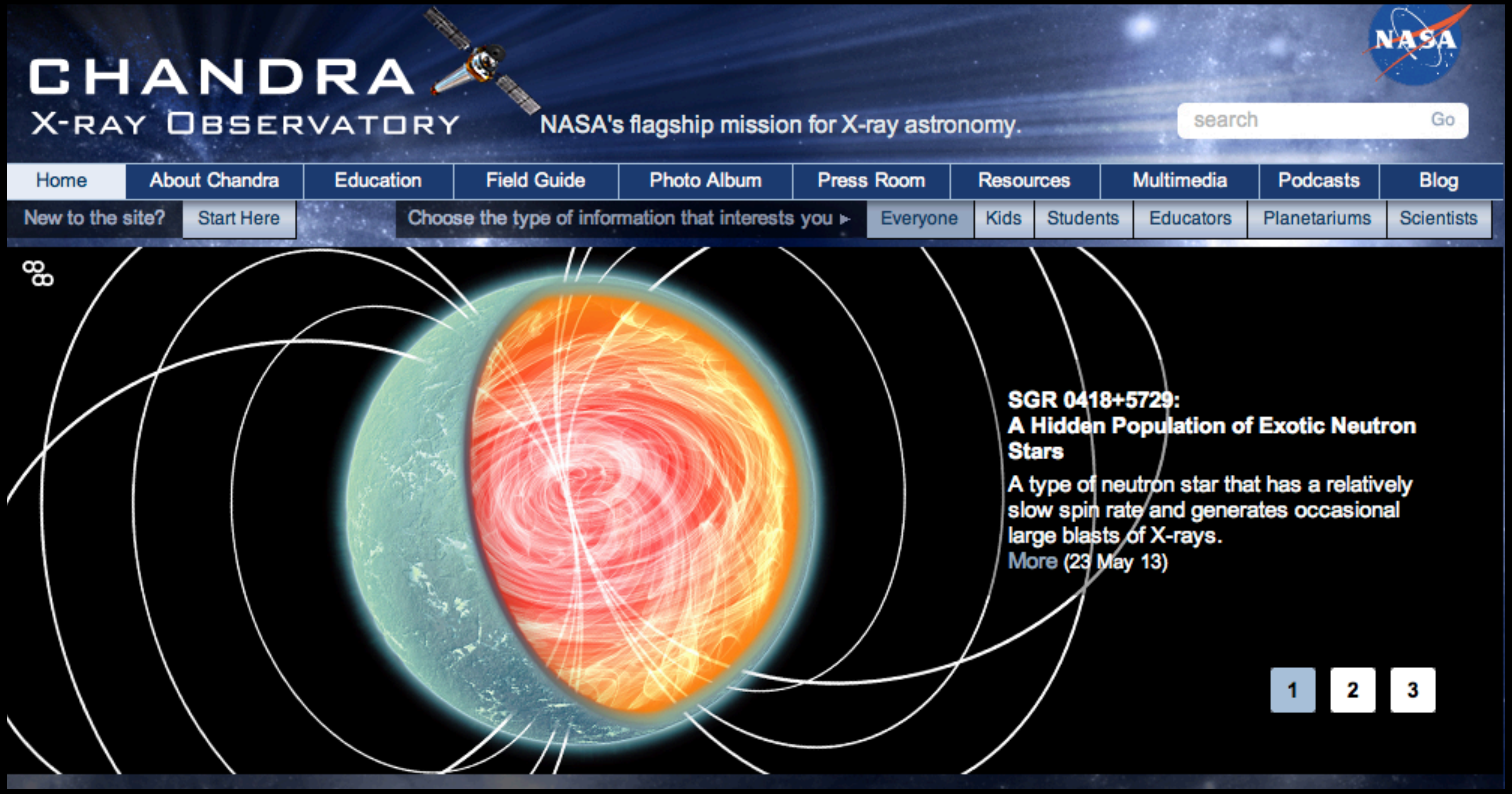
**Swift J1822-1606**

NR et al. 2012, ApJ
Scholtz et al. 2012, ApJ

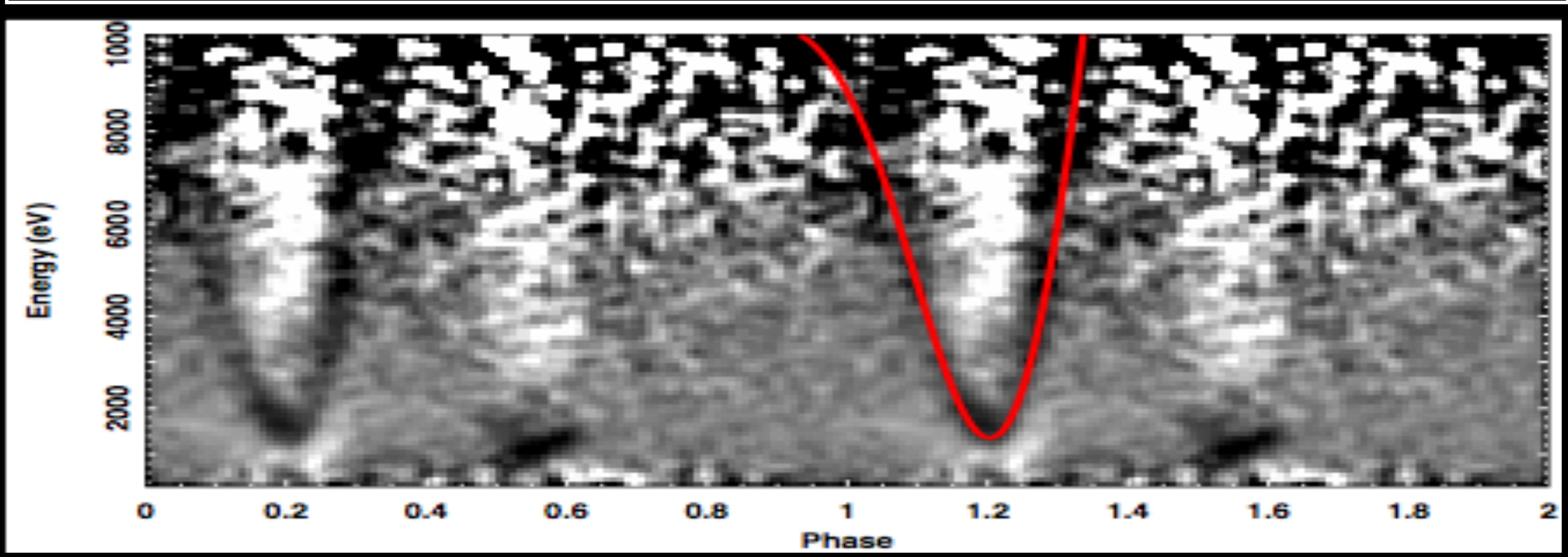
**3XMM J1852+0033**

NR et al. 2014, ApJL
Zou et al. 2014, ApJL

# LOW FIELD MAGNETARS: SPECTRAL LINES

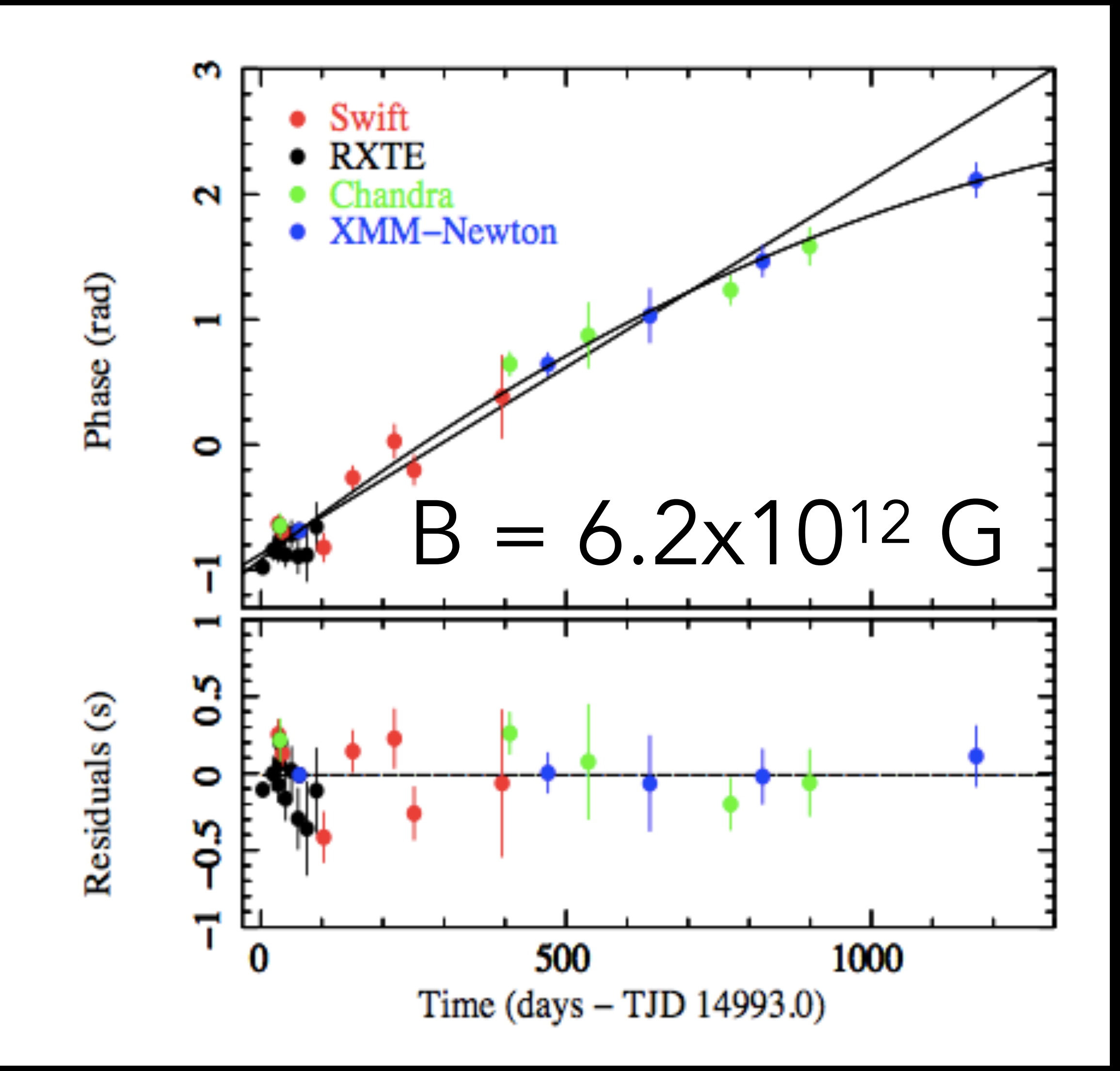


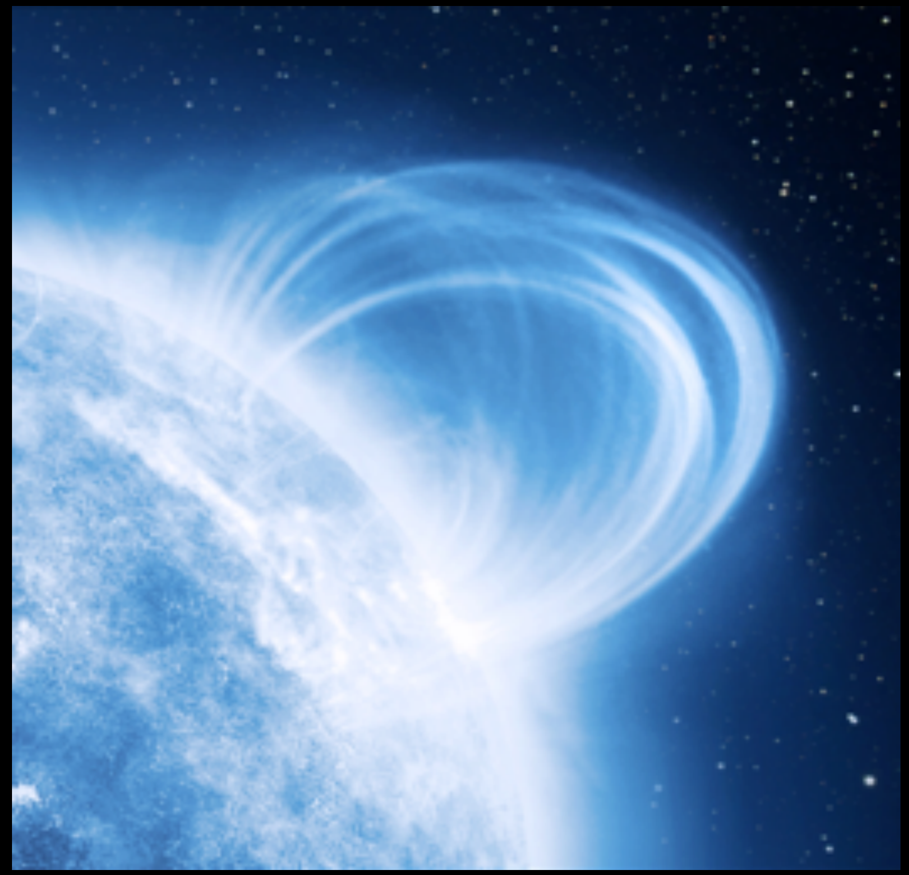

During the outburst peak SGR0418 showed a phase variable absorption feature




(Tiengo et al. 2013, Nature)

## SGR J0418+5729



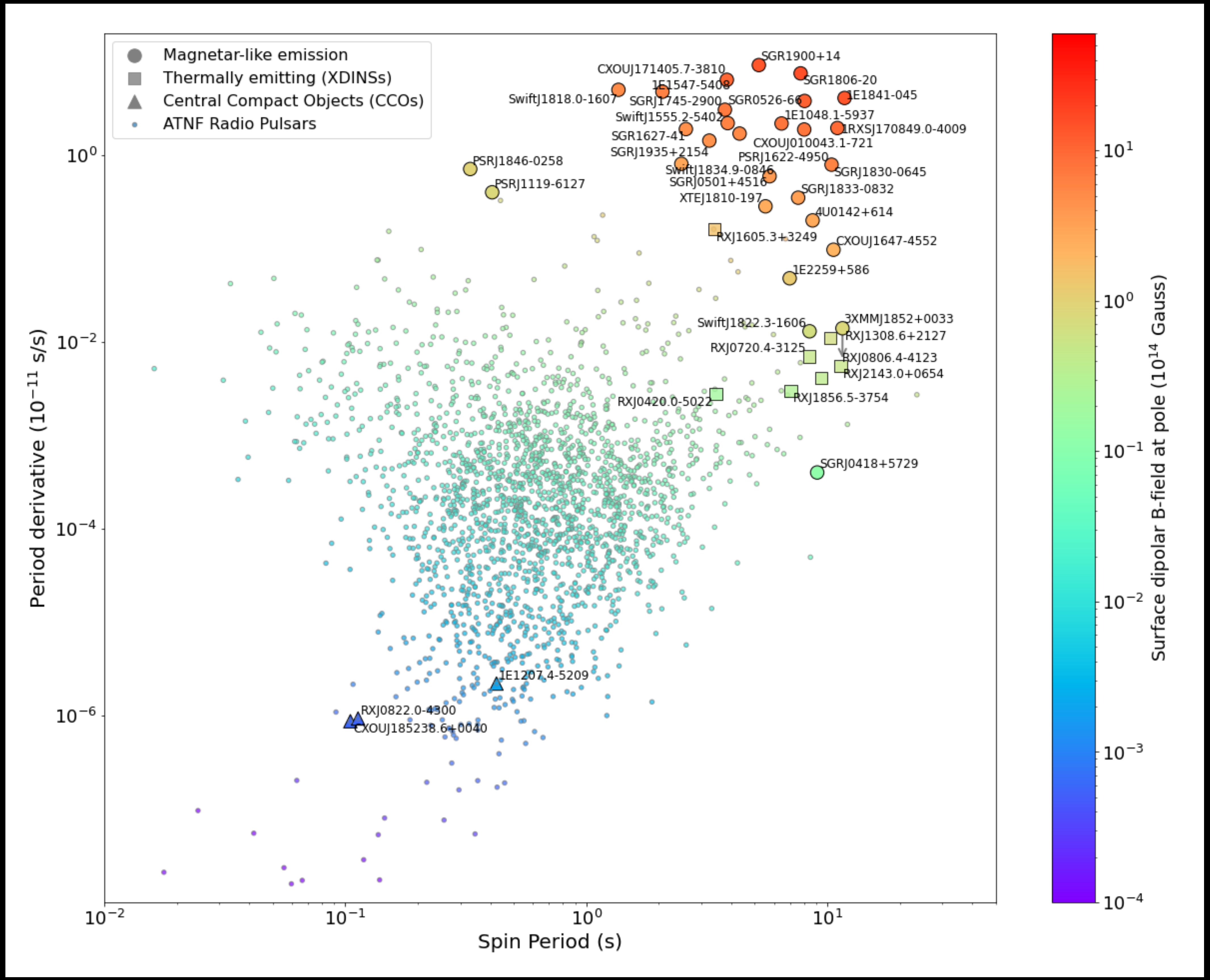
$E_{cycl,p}$= 0.6 $B_{14}$ keV

⇒ $B_{loop}$ ~ (2-20) x $10^{14}$ G

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

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

# 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. Close-by.
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

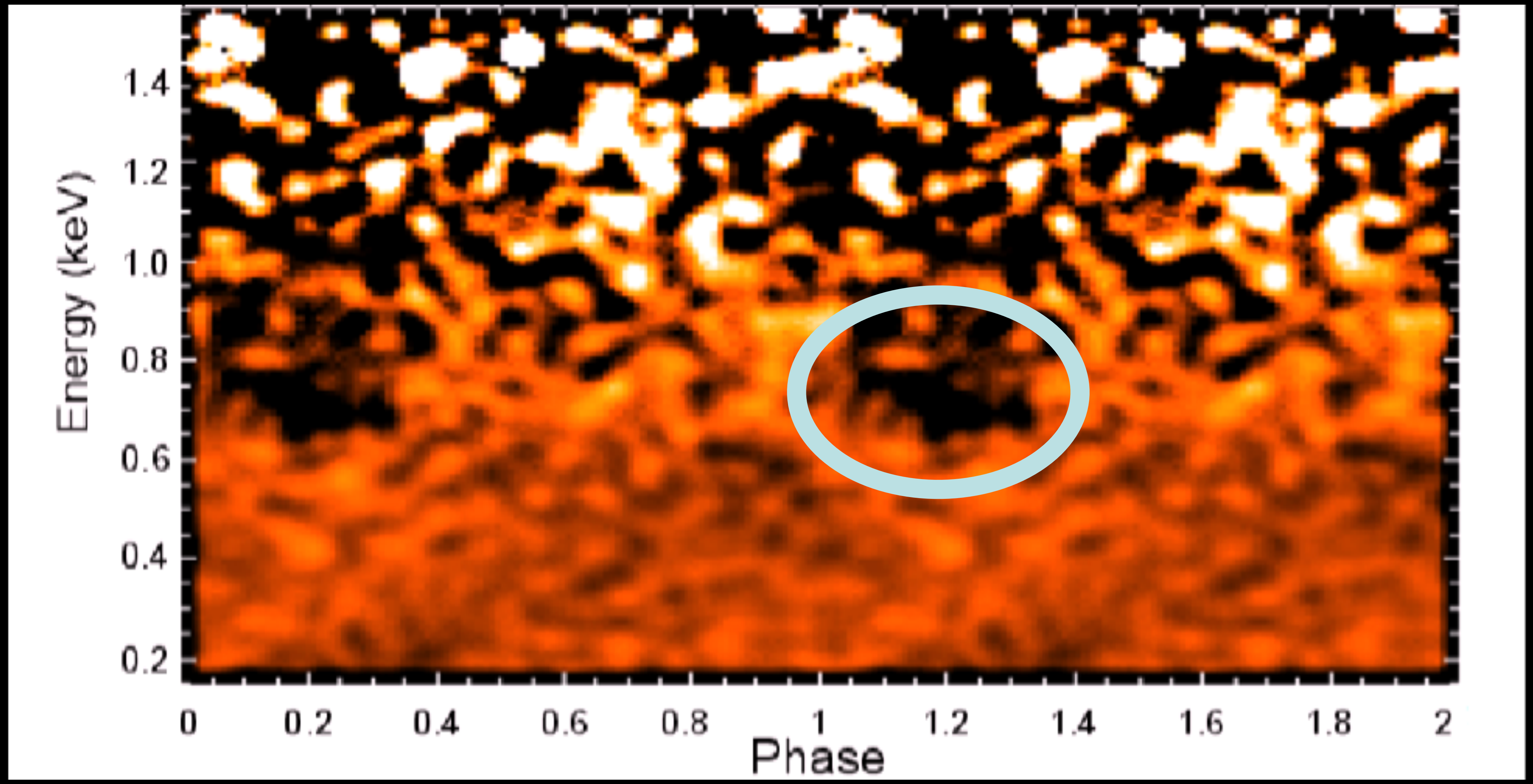
Powered by rotational energy.
Typically emitting in radio.

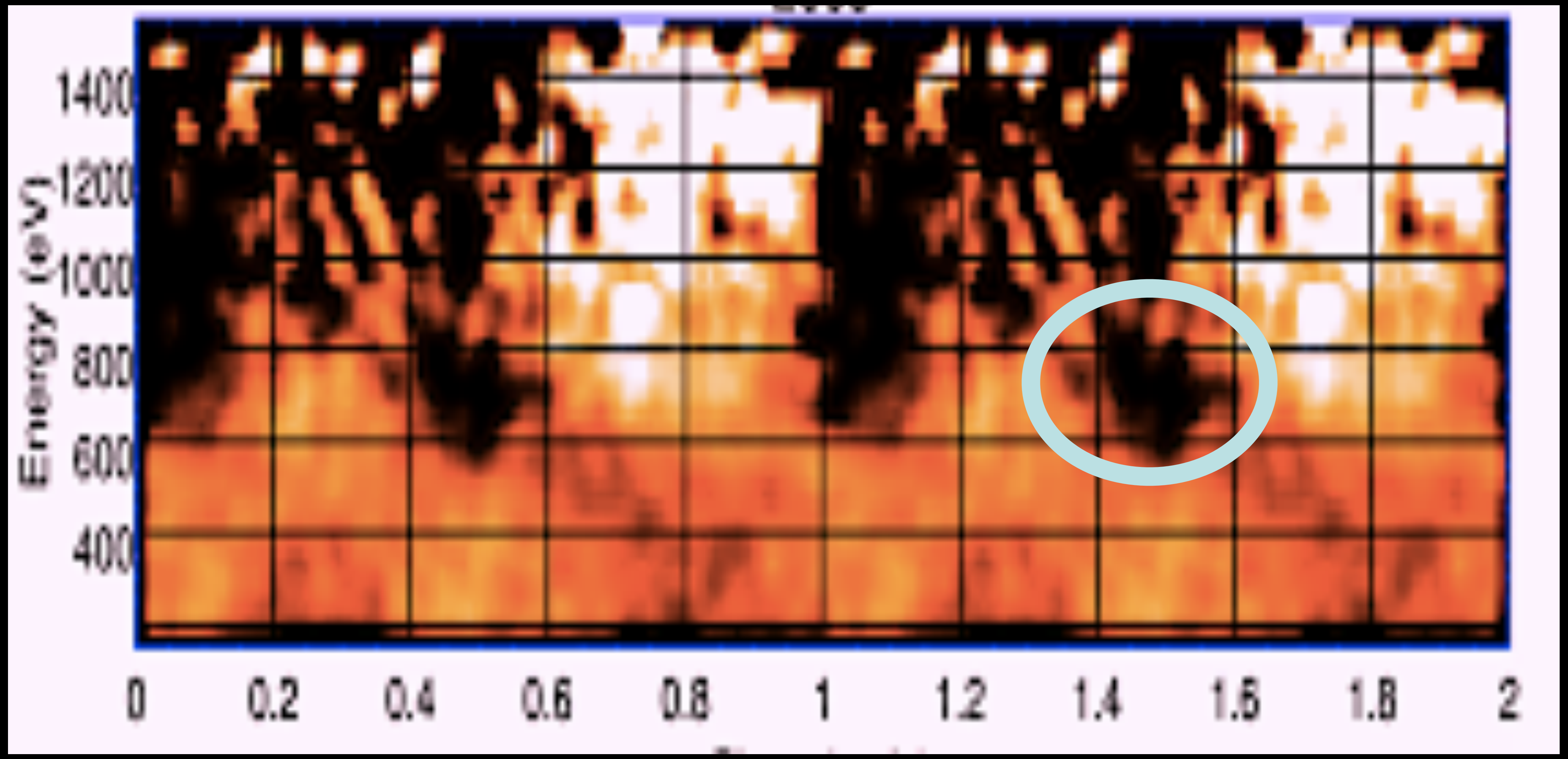
## ROTATING RADIO TRANSIENTS

Powered by rotational energy. Single-pulses.
Typically emitting in radio.

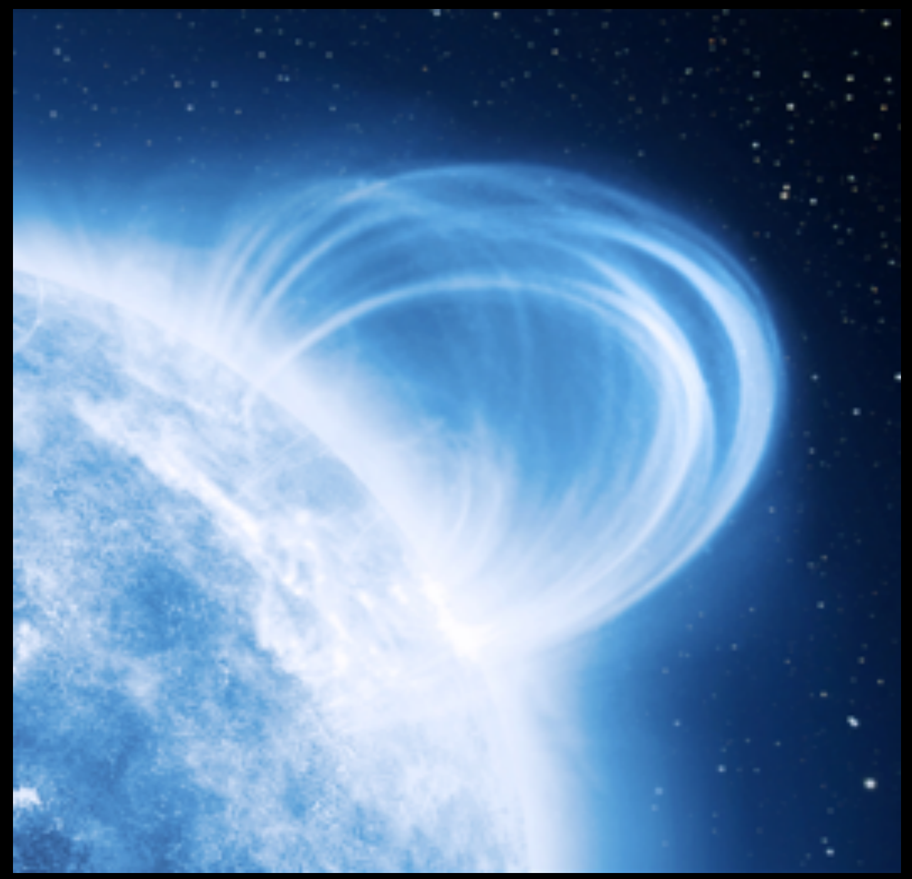
# THERMAL EMITTING NEUTRON STARS (XDINSs)

Systematic search for narrow phase-dependent absorption features in all XDINSs:
two found in the spectrum of RX J0720.4-3125 and RX J1308+2127



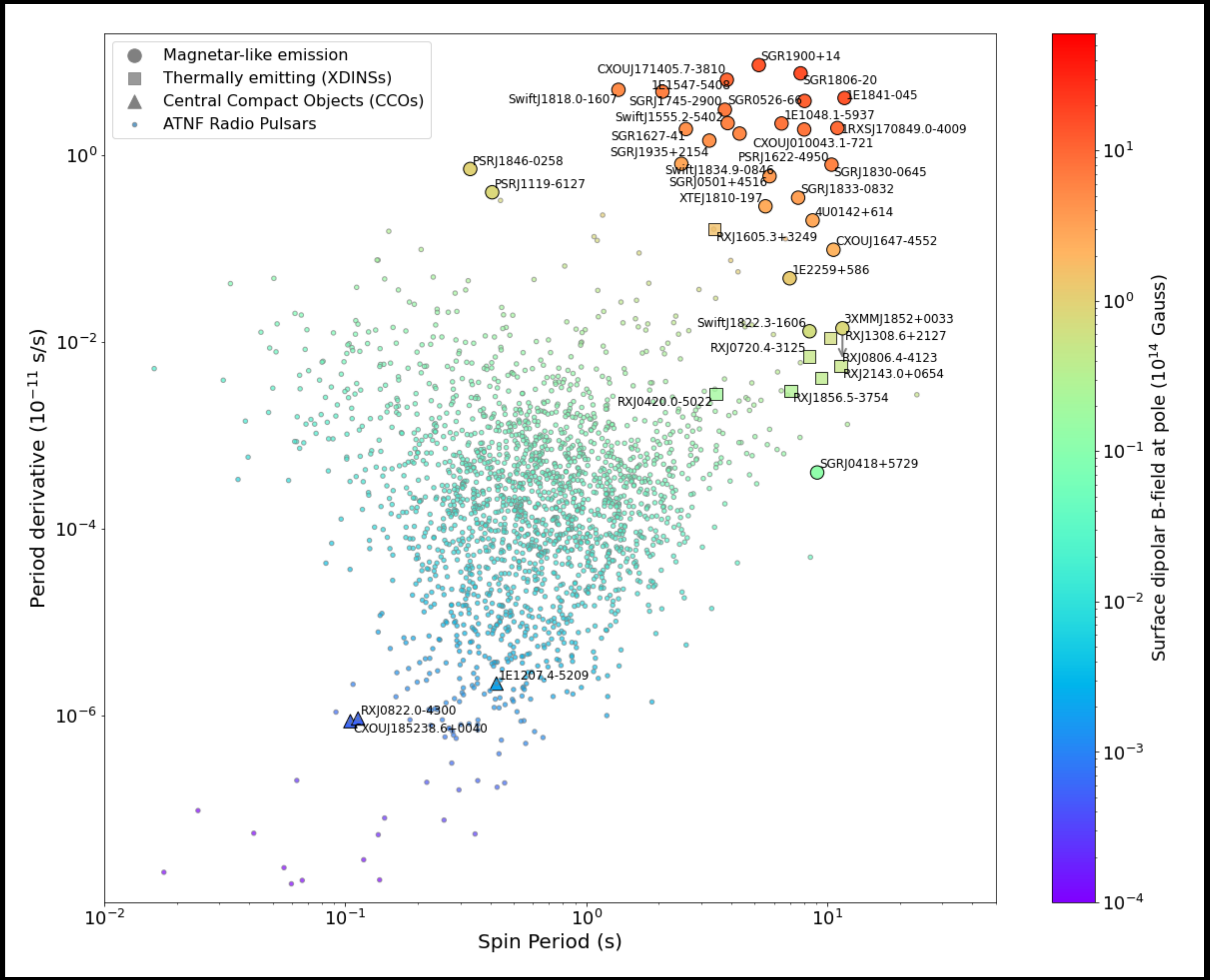

**Similar to the low-field magnetar, XDINSs have dipolar fields of $10^{13}$ Gauss, and loops reaching $10^{14}$ Gauss.**



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

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

# 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. Close-by.
Typically emitting in the X-rays.

## CENTRAL COMPACT OBJECTS

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

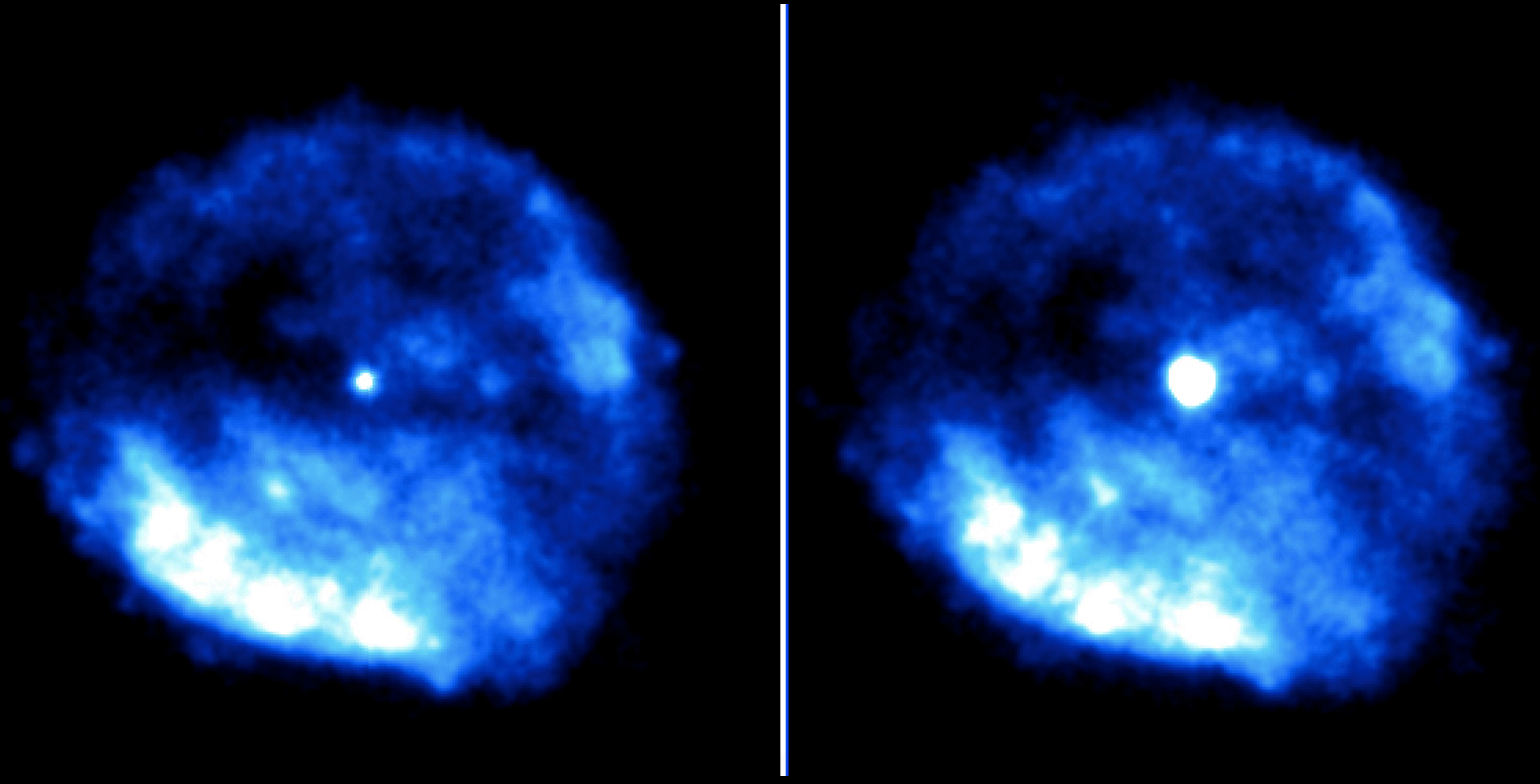
## ROTATIONAL POWERED PULSARS

Powered by rotational energy.
Typically emitting in radio.

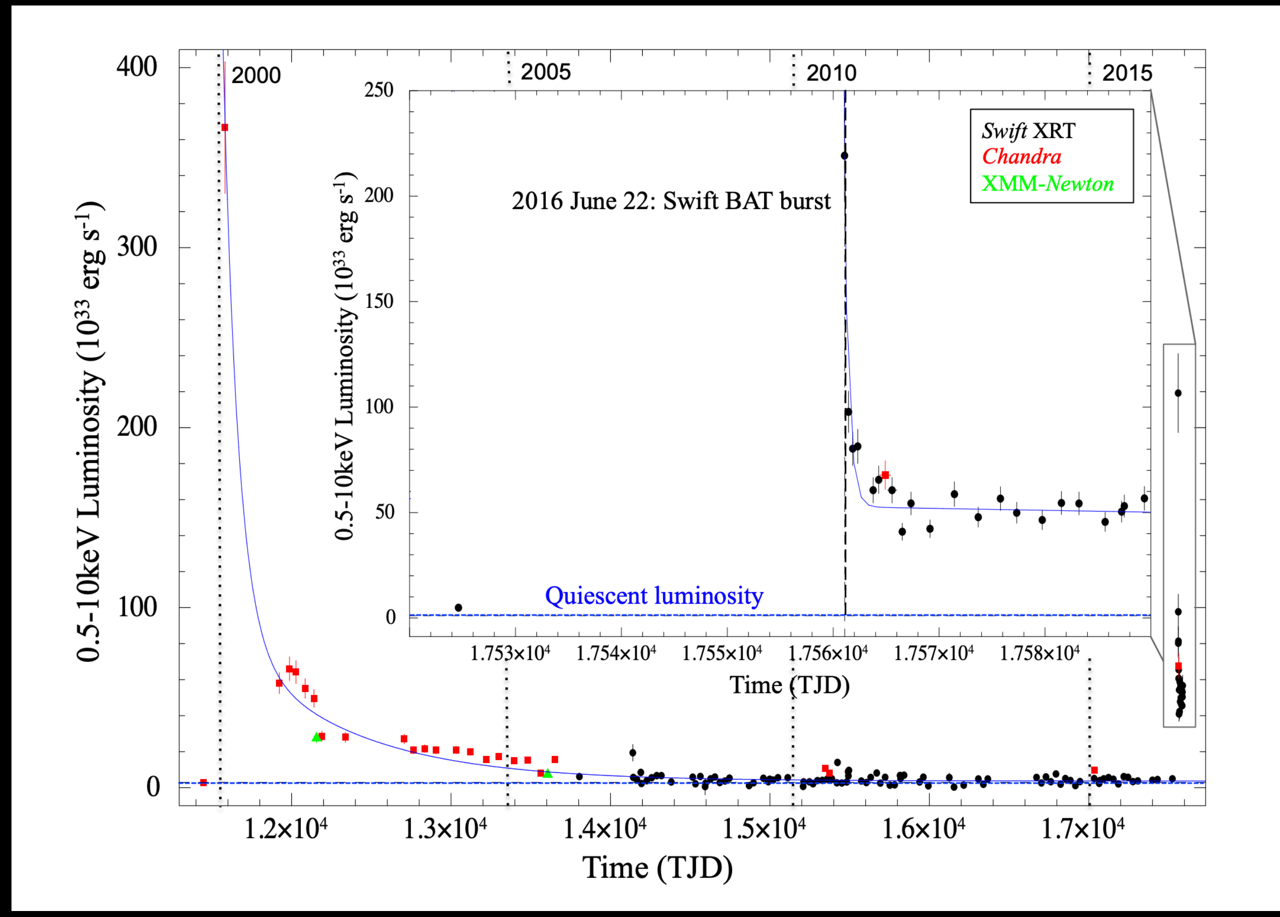
## ROTATING RADIO TRANSIENTS

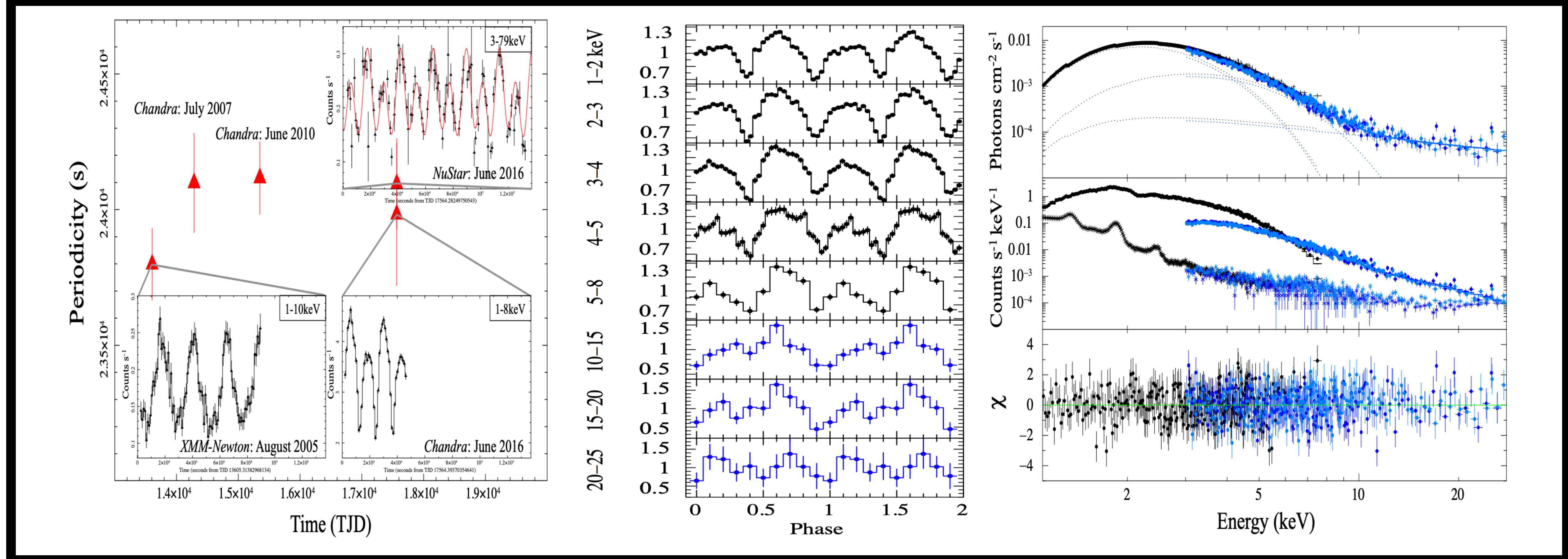
Powered by rotational energy. Single-pulses.
Typically emitting in radio.

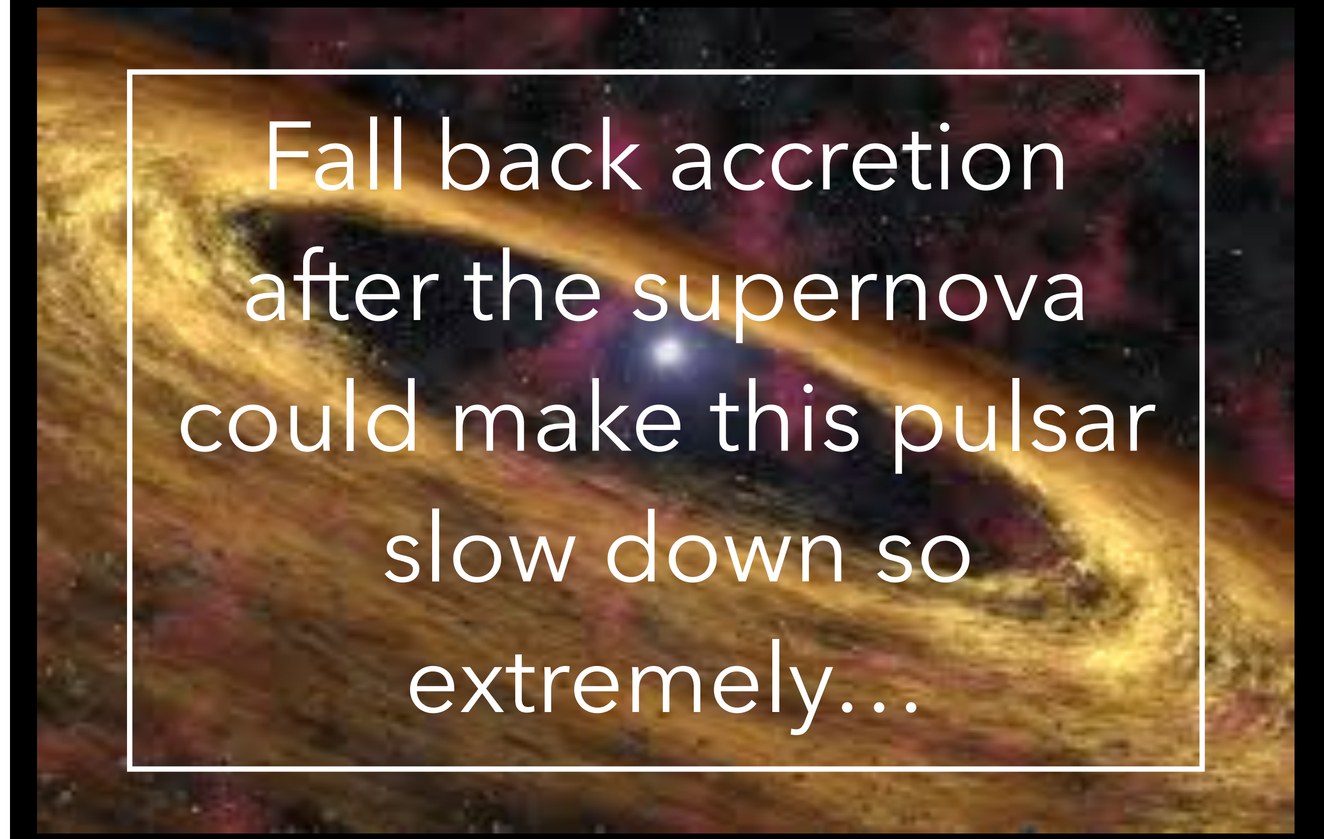
# NEW MAGNETAR EMISSION FROM UNEXPECTED SOURCES: RCW103




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

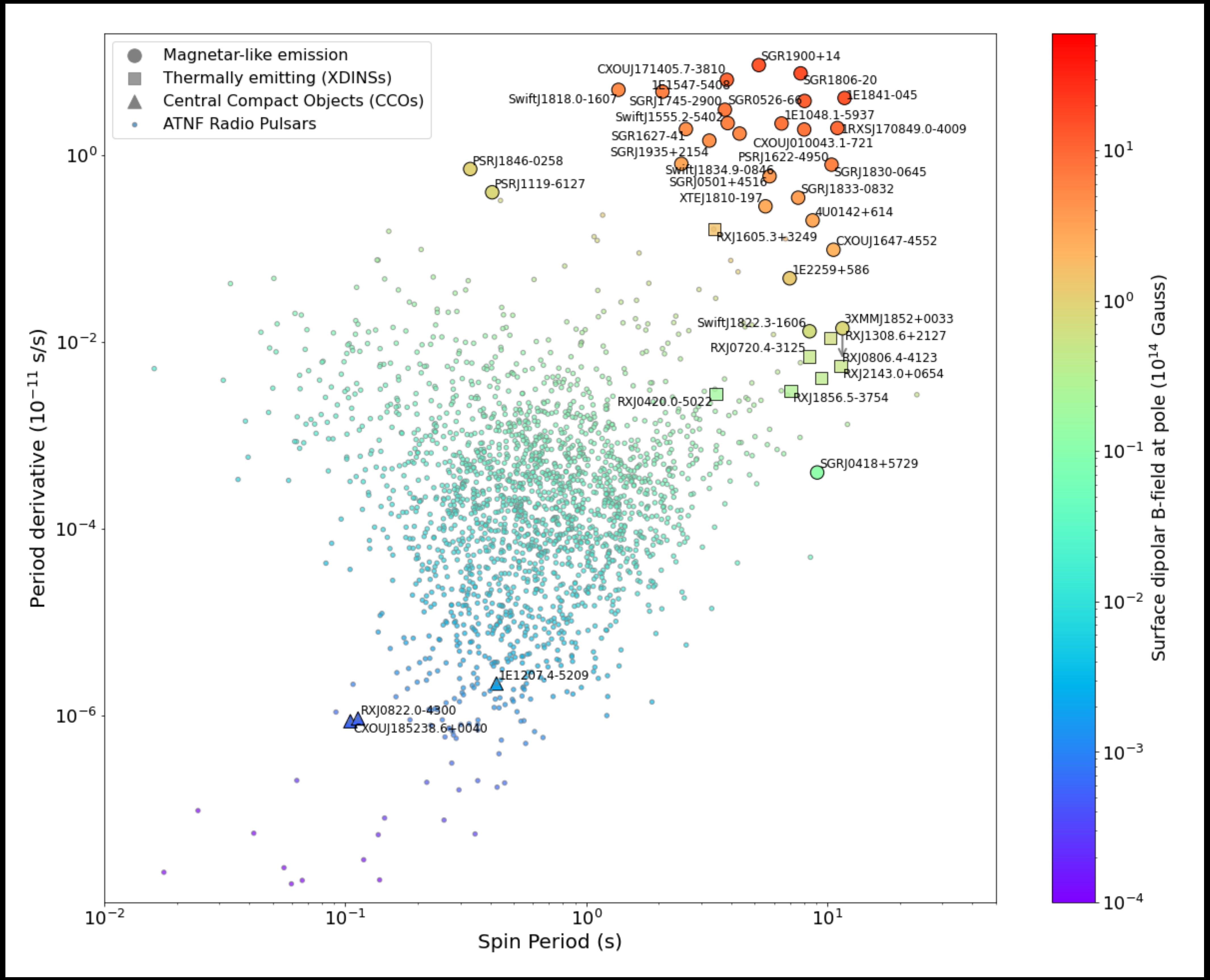



(D'Ai et al. 2016; NR, Borghese, Coti Zelati et al. 2016, Ho & Andersson 2016, Borghese, NR, Coti Zelati et al. 2018)

# 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. Close-by.
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.

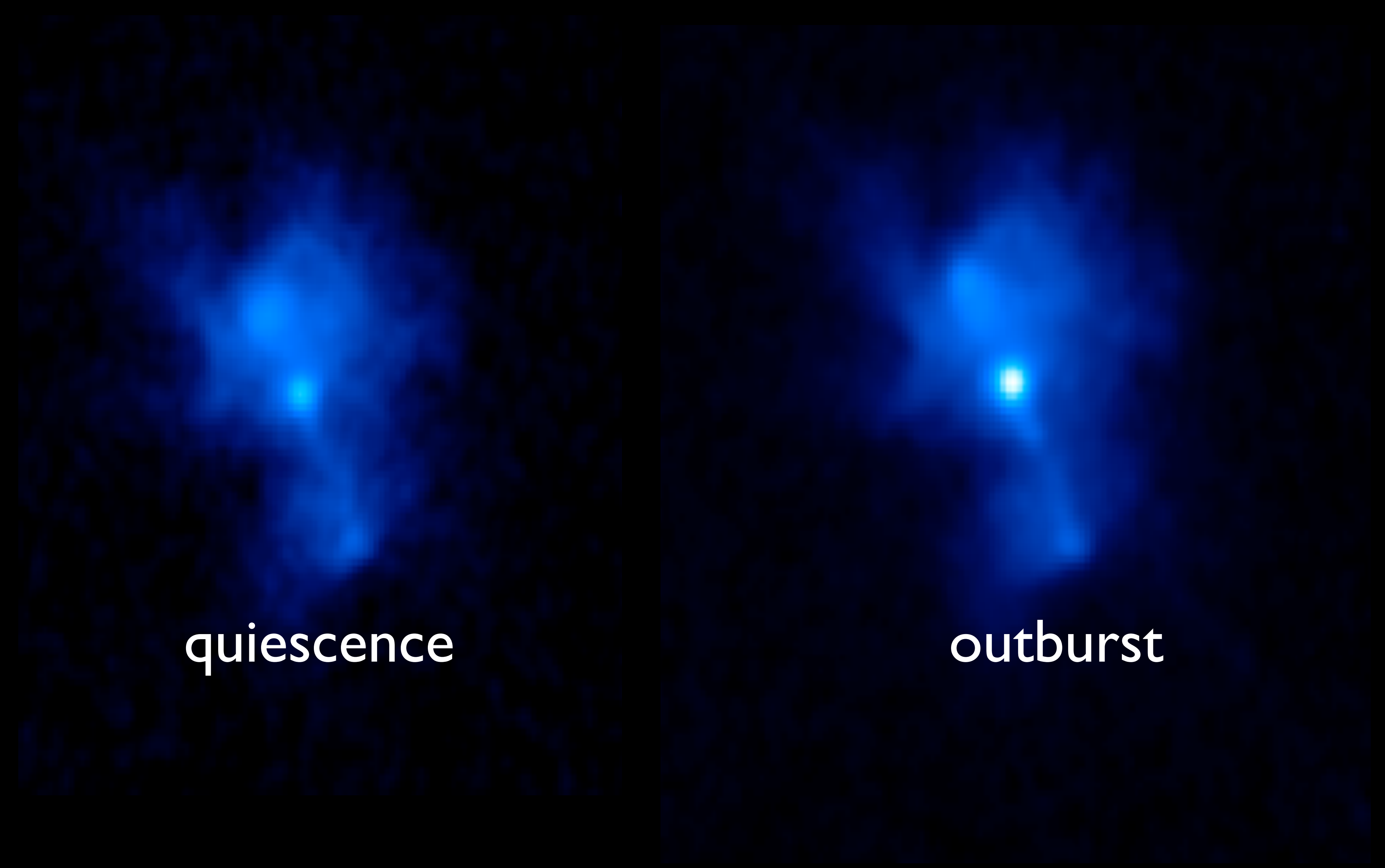
## ROTATING RADIO TRANSIENTS

Powered by rotational energy. Single-pulses.
Typically emitting in radio.

# HIGH-B PULSARS

## *PSR 1846-0258*

- rotational power of Edot~8x$10^{36}$ erg/s
- magnetic fields ~5x$10^{13}$ - Gauss
- Kes75, with a powerful PWN
- X-ray rotational powered pulsar
- Showed SGR-like bursts and outburst in 2008, 2020



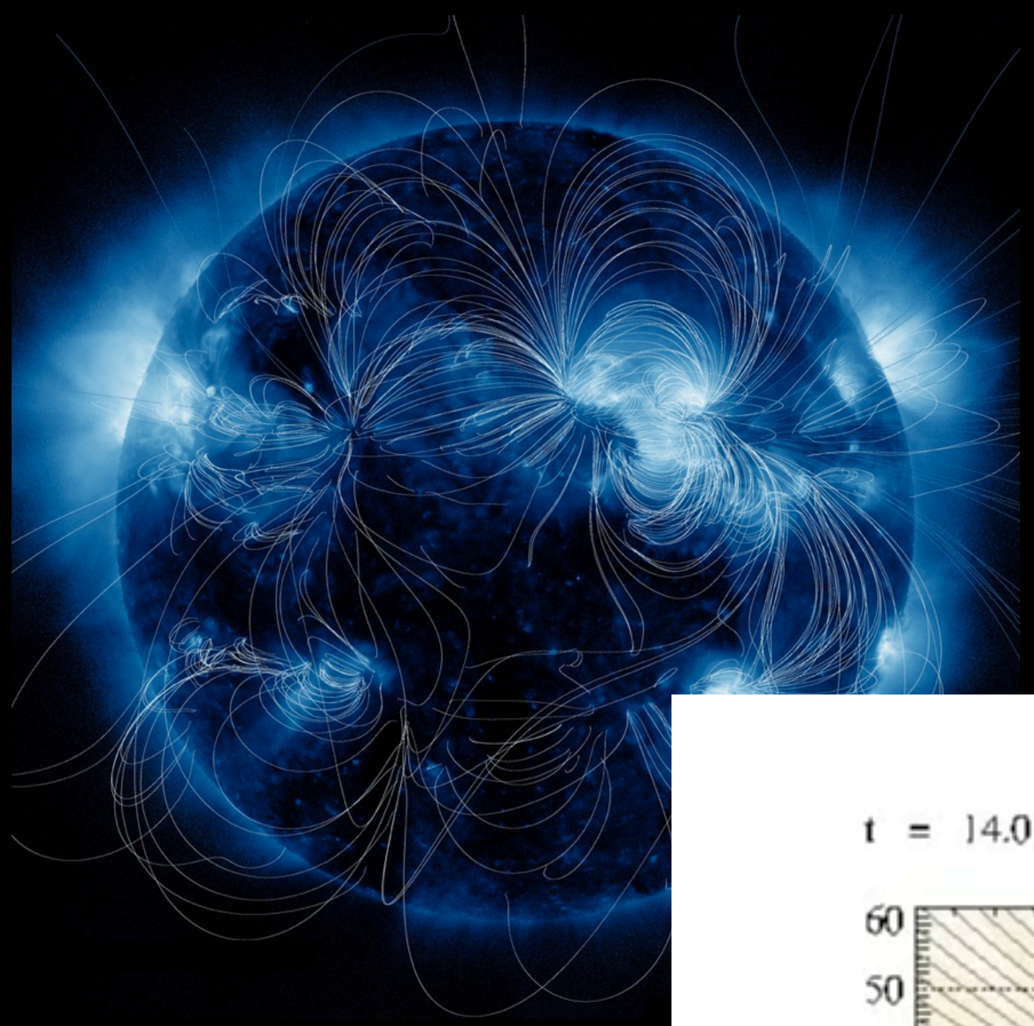

## *PSR 1119-6127*

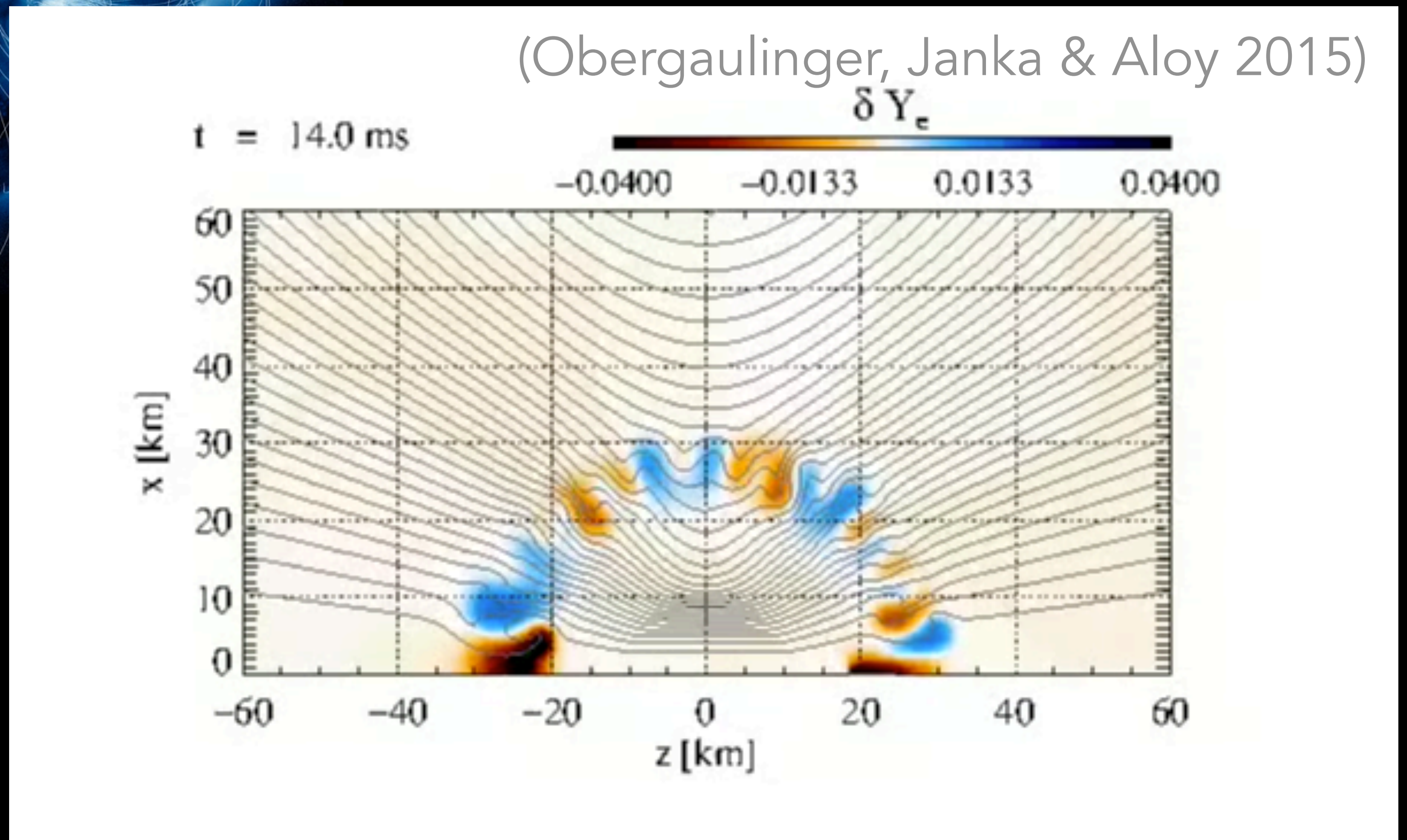
- rotational power of Edot~2.3x$10^{36}$ erg/s
- magnetic fields ~4x$10^{13}$ - Gauss
- with a PWN
- Radio/X-ray rotational powered pulsar
- Showed SGR-like bursts and outburst in 2016

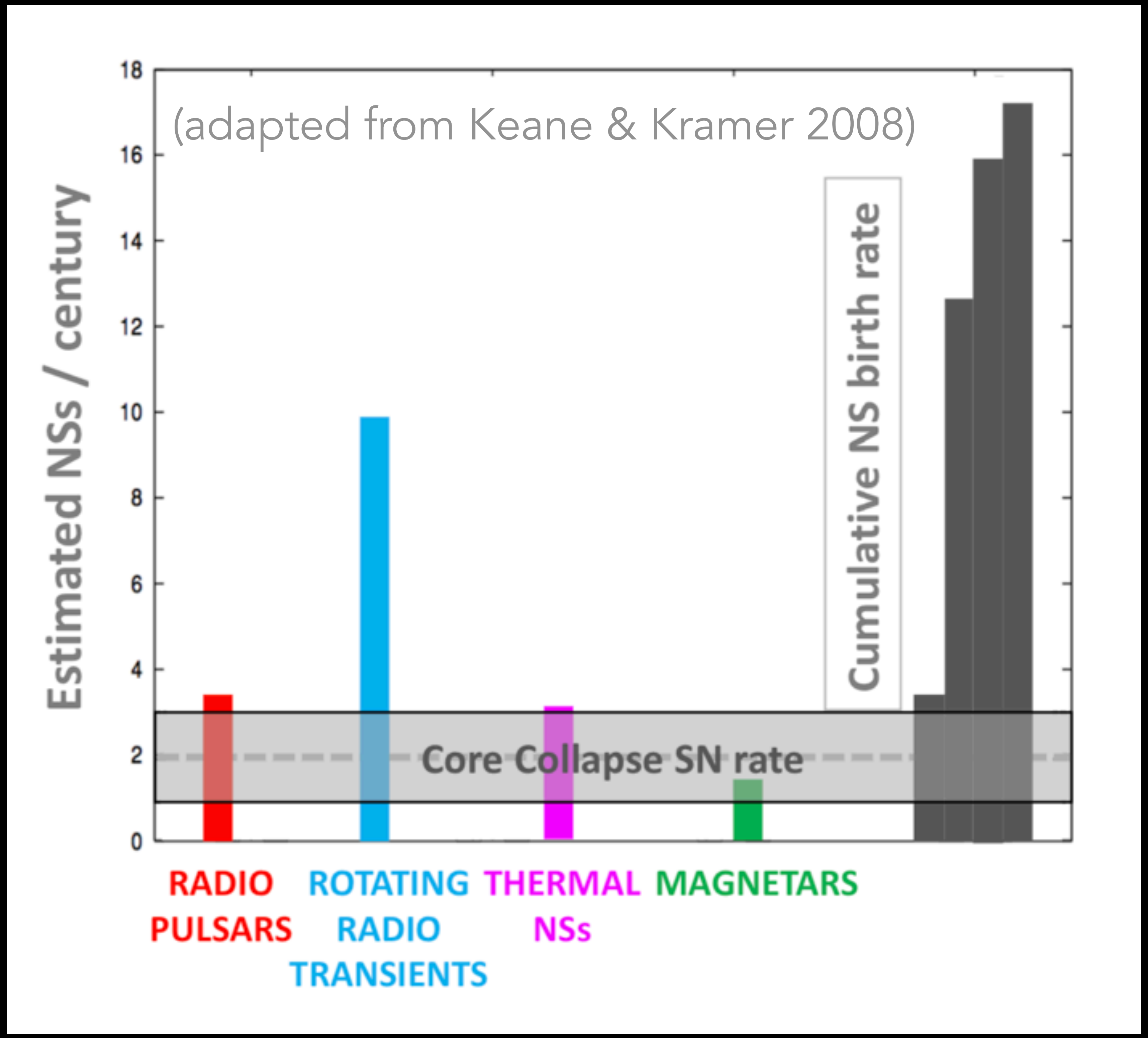
**Two canonical pulsars showed magnetar-like activity!**

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

# CONSEQUENCES NS BIRTH PROPERTIES AND SN RATES

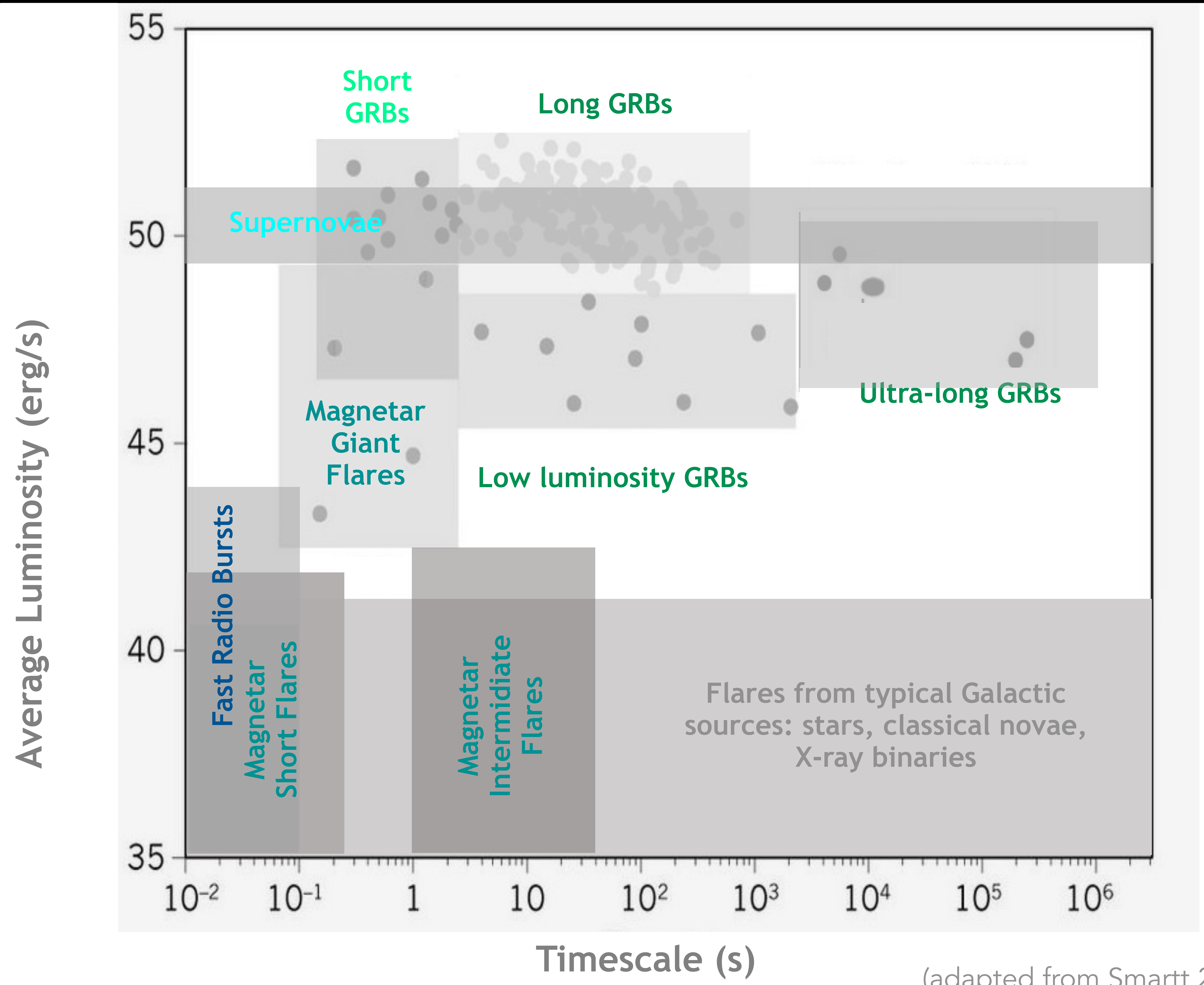





1. Magnetar-like emission is way more diffuse than thought before.
2. Neutron star classes cannot have independent formation, there should be an evolutionary model scenario.

# THE UNIVERSE MOST ENERGETIC TRANSIENTS




(adapted from Smartt 2015)

# NEUTRON STAR EVOLUTION

We need to solve the thermal and magnetic evolution of a neutron star over > Myr timescales…

Thermal evolution: energy balance equation

Specific heat — Thermal conductivity — Neutrino emissivity

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

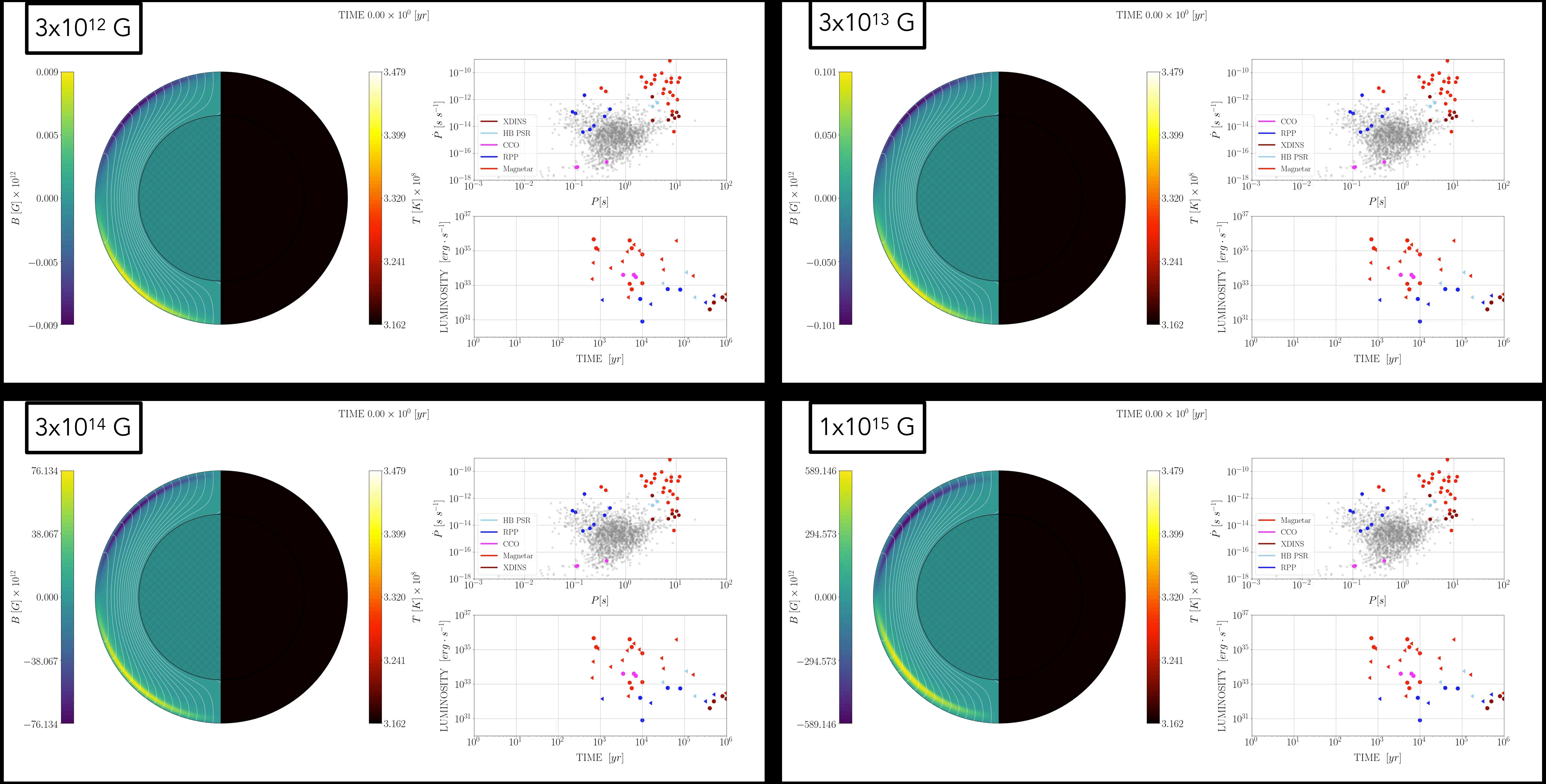
Magnetic evolution: Hall induction equation

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

Hall induction

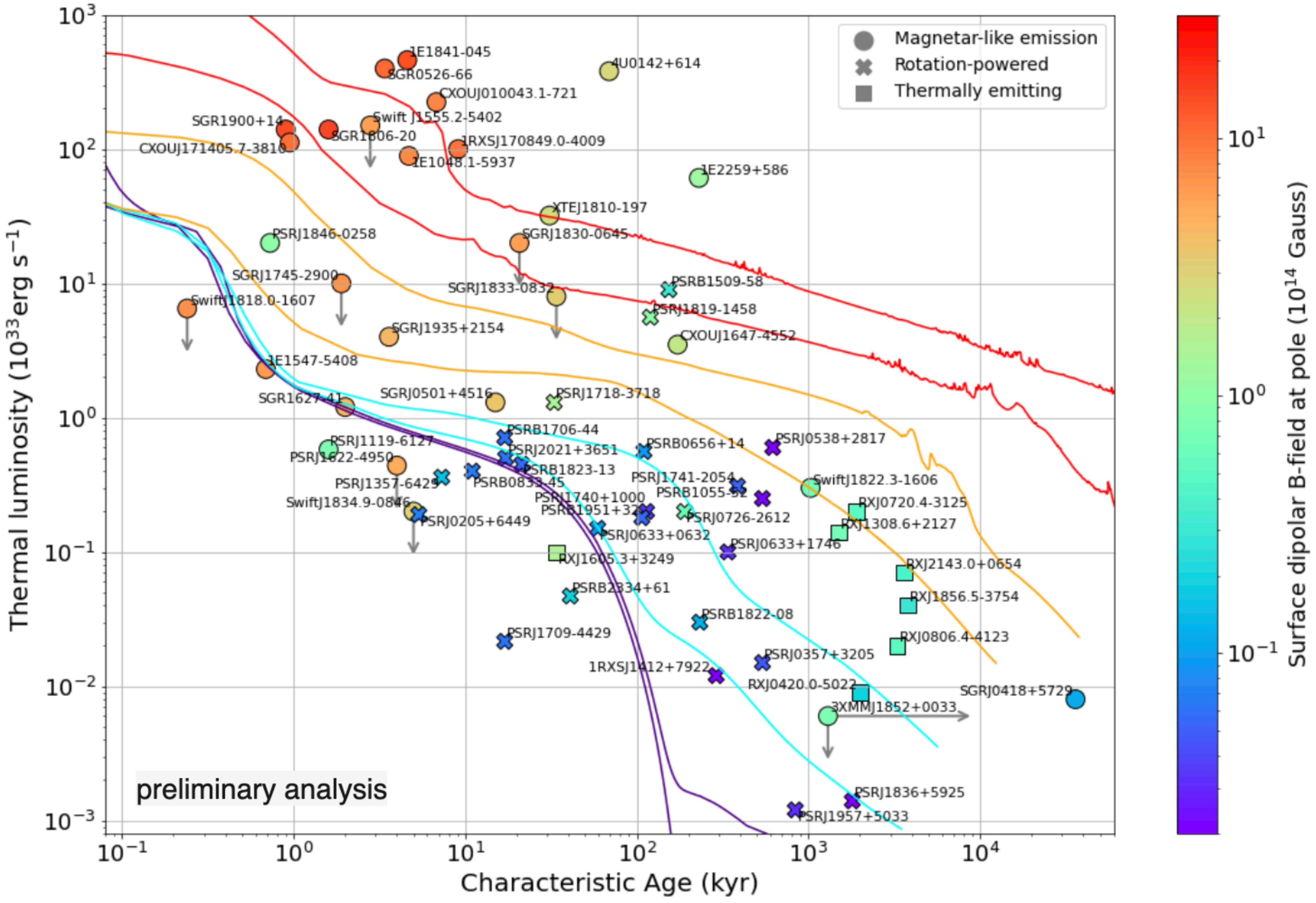
Electrical resistivity: strongly depends on T

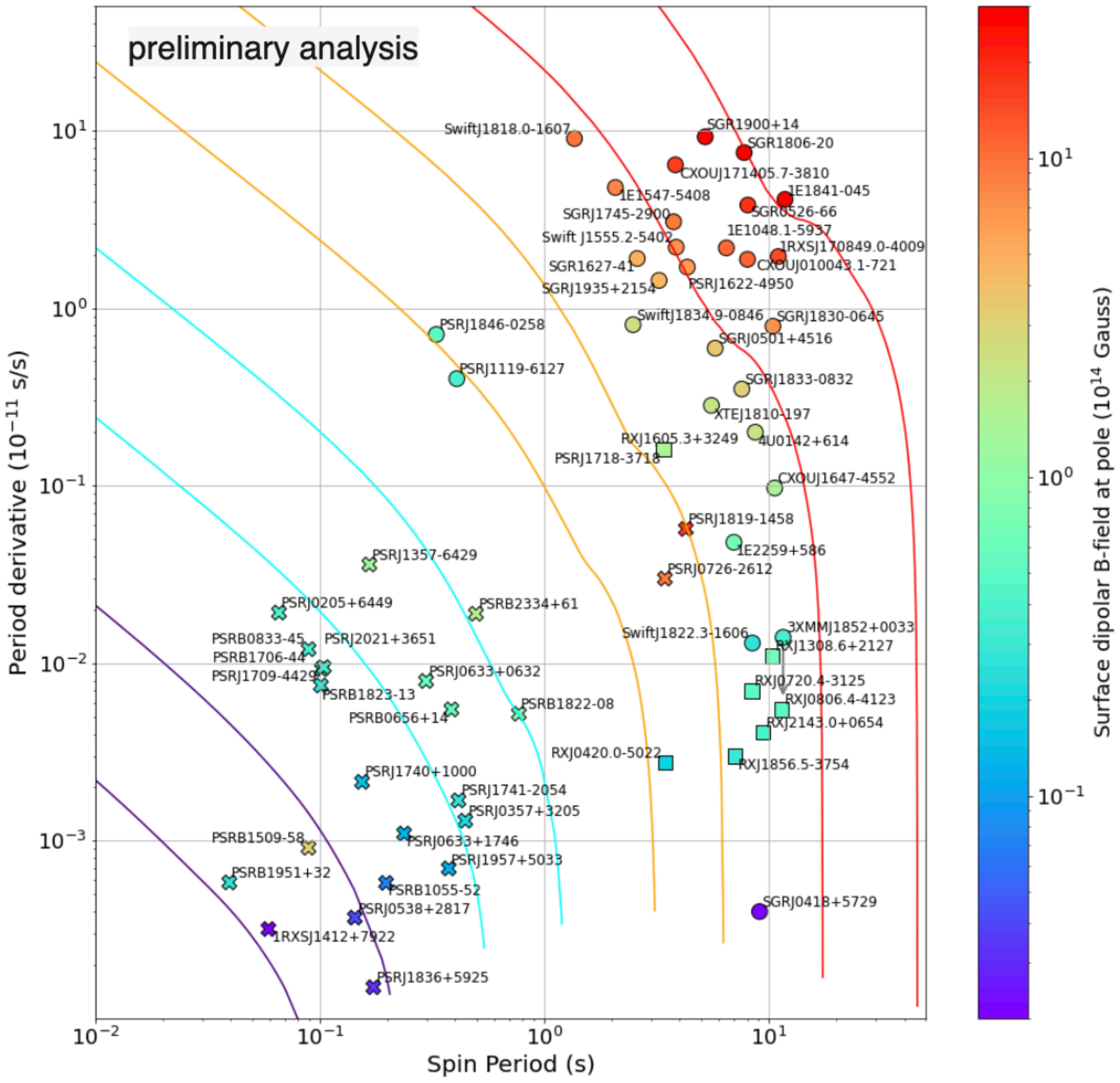
# UNIFIED EVOLUTIONARY SCENARIO FOR DIFFERENT PULSARS




(Vigano, Pons, Miralles 2012; Vigano, NR, Pons et al. 2013; Pons & Vigano 2020; Vigano, Garcia-Garcia, Dehman, et al. 2020)

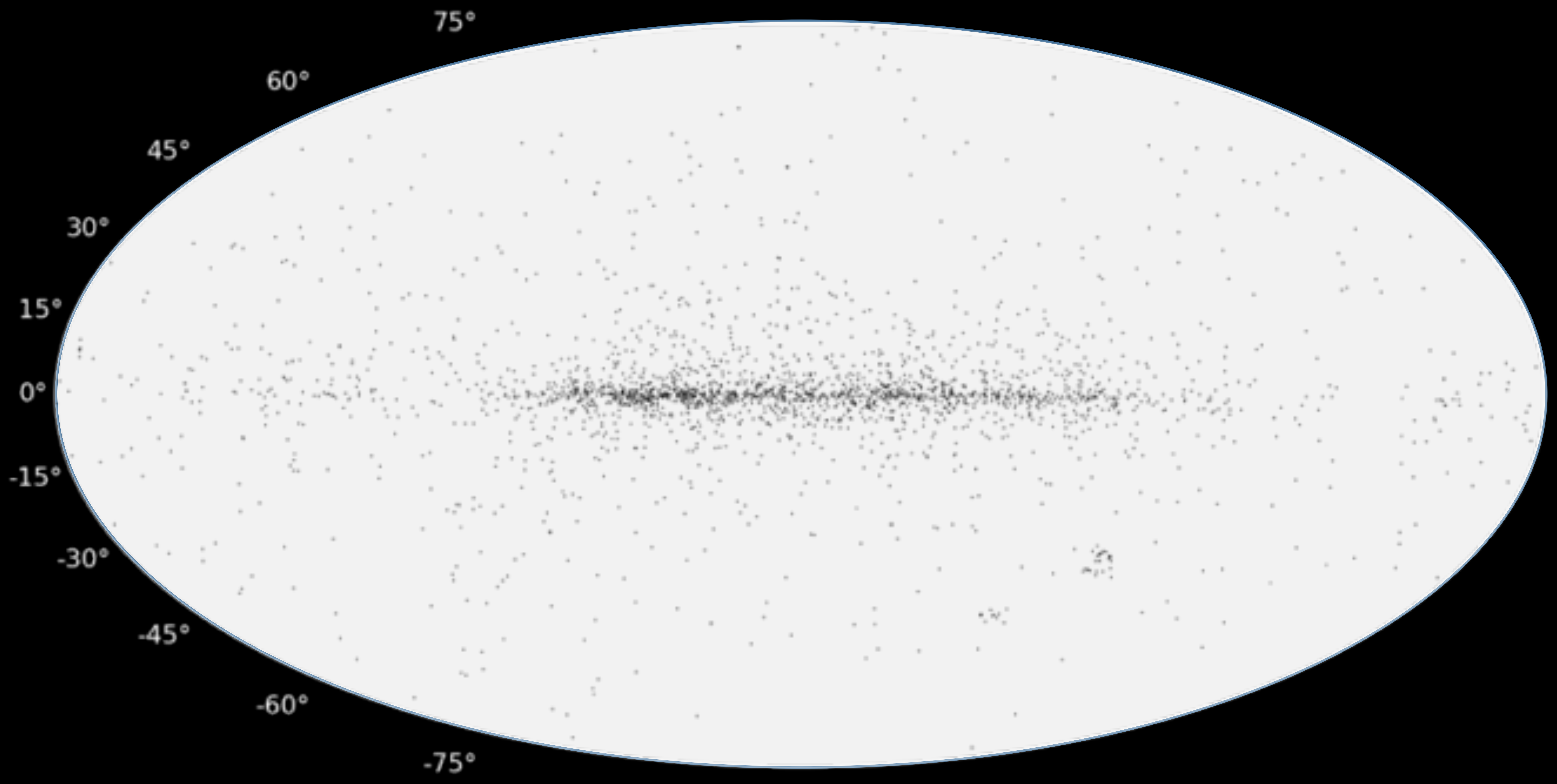
# UNIFIED EVOLUTIONARY SCENARIO FOR DIFFERENT PULSARS



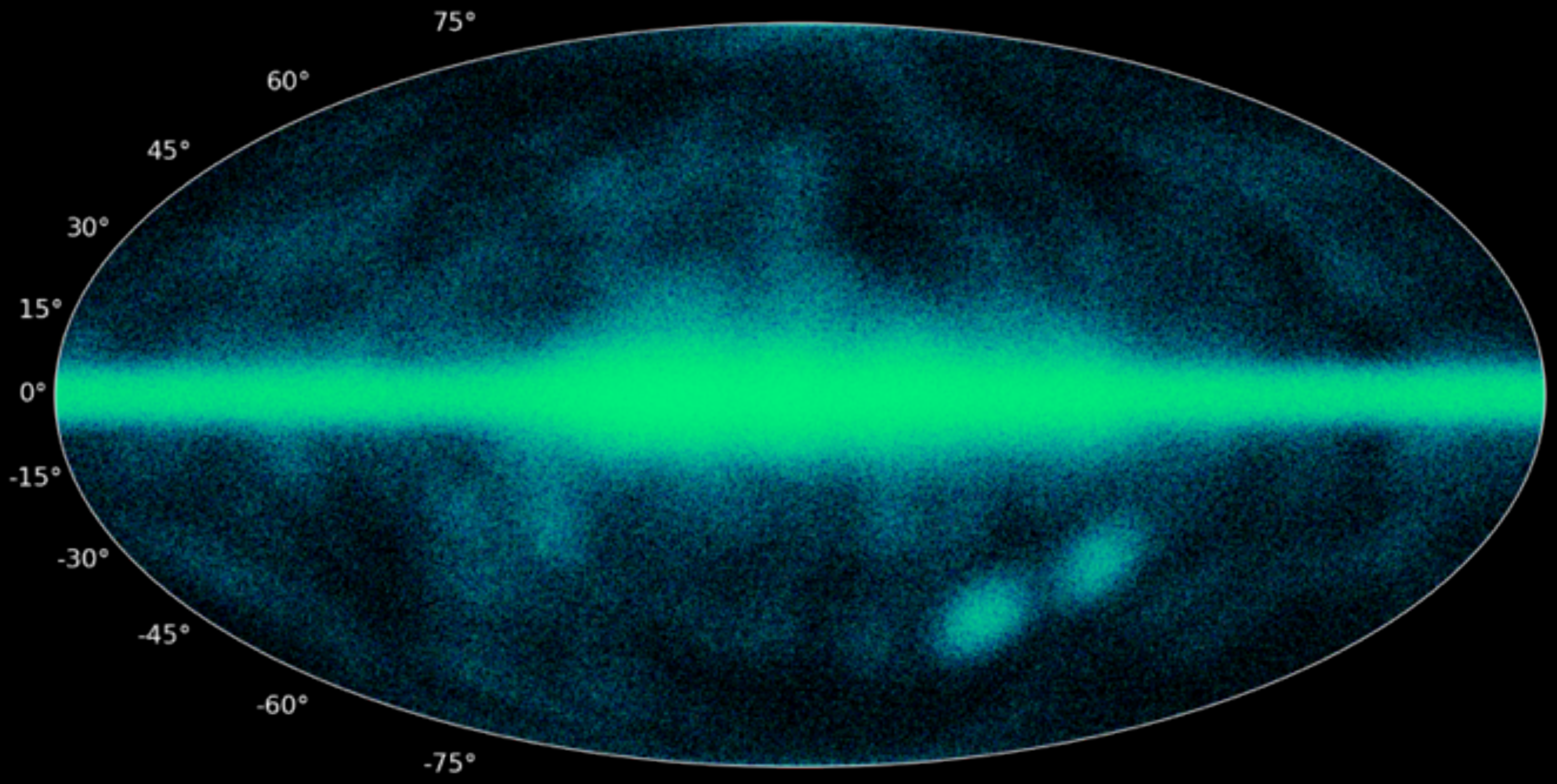




(Dehman, Rea, Viganó & Pons 2022, in prep)

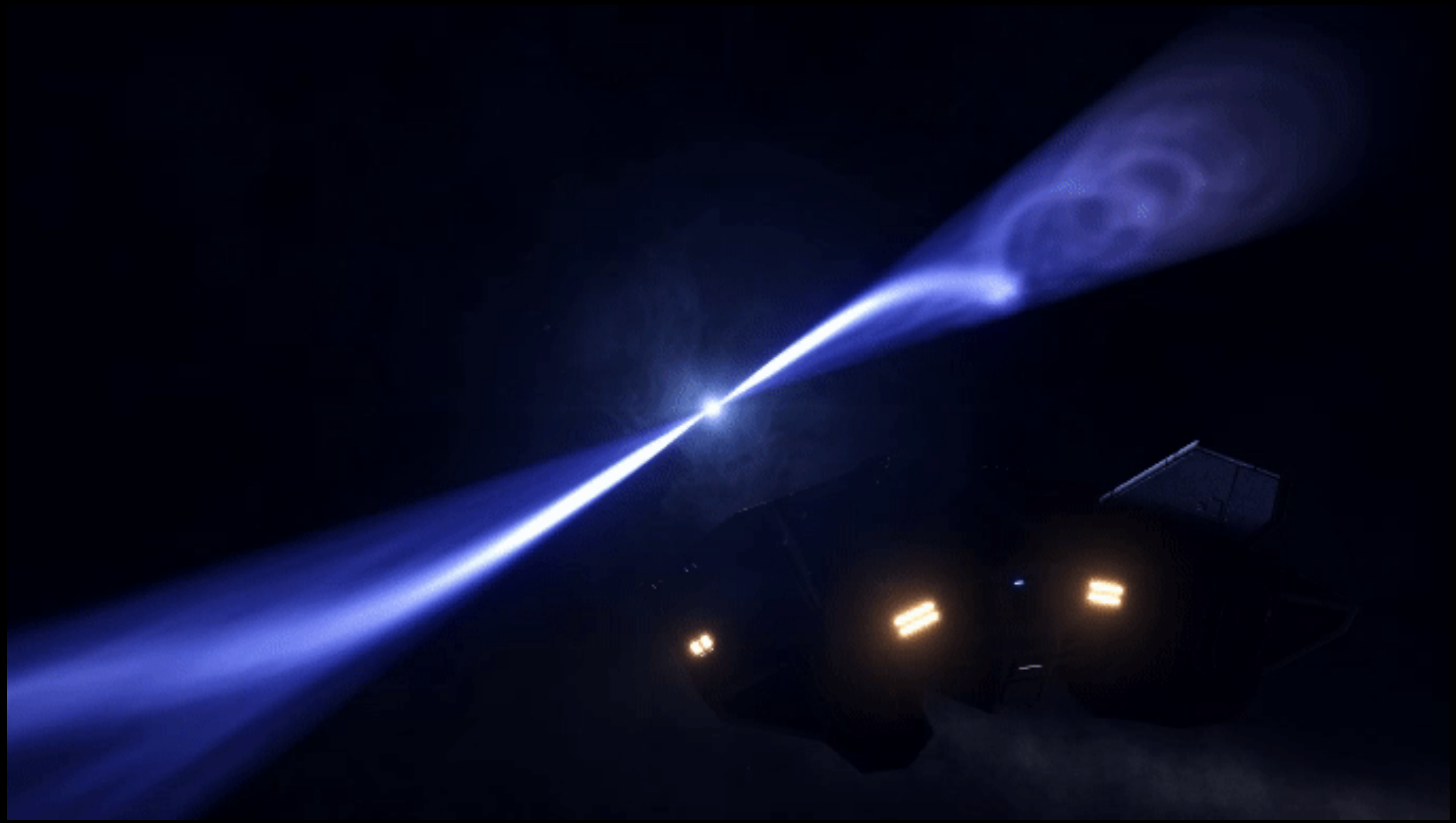
# OBSERVED NEUTRON STAR POPULATION IN 2022



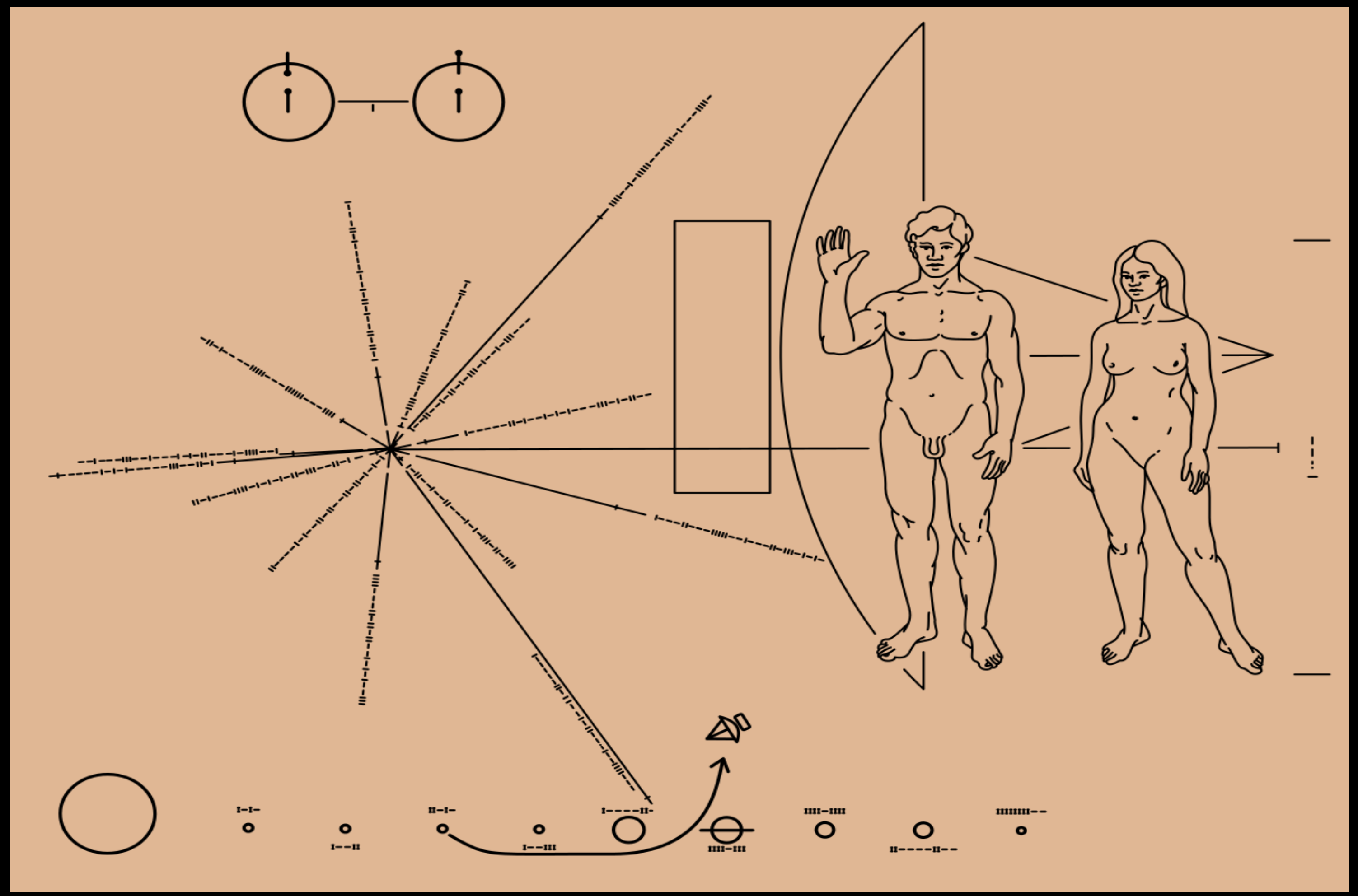
# EXPECTED NEUTRON STAR POPULATION...



# PULSARS AS GPS FOR DEEP SPACE TRAVEL

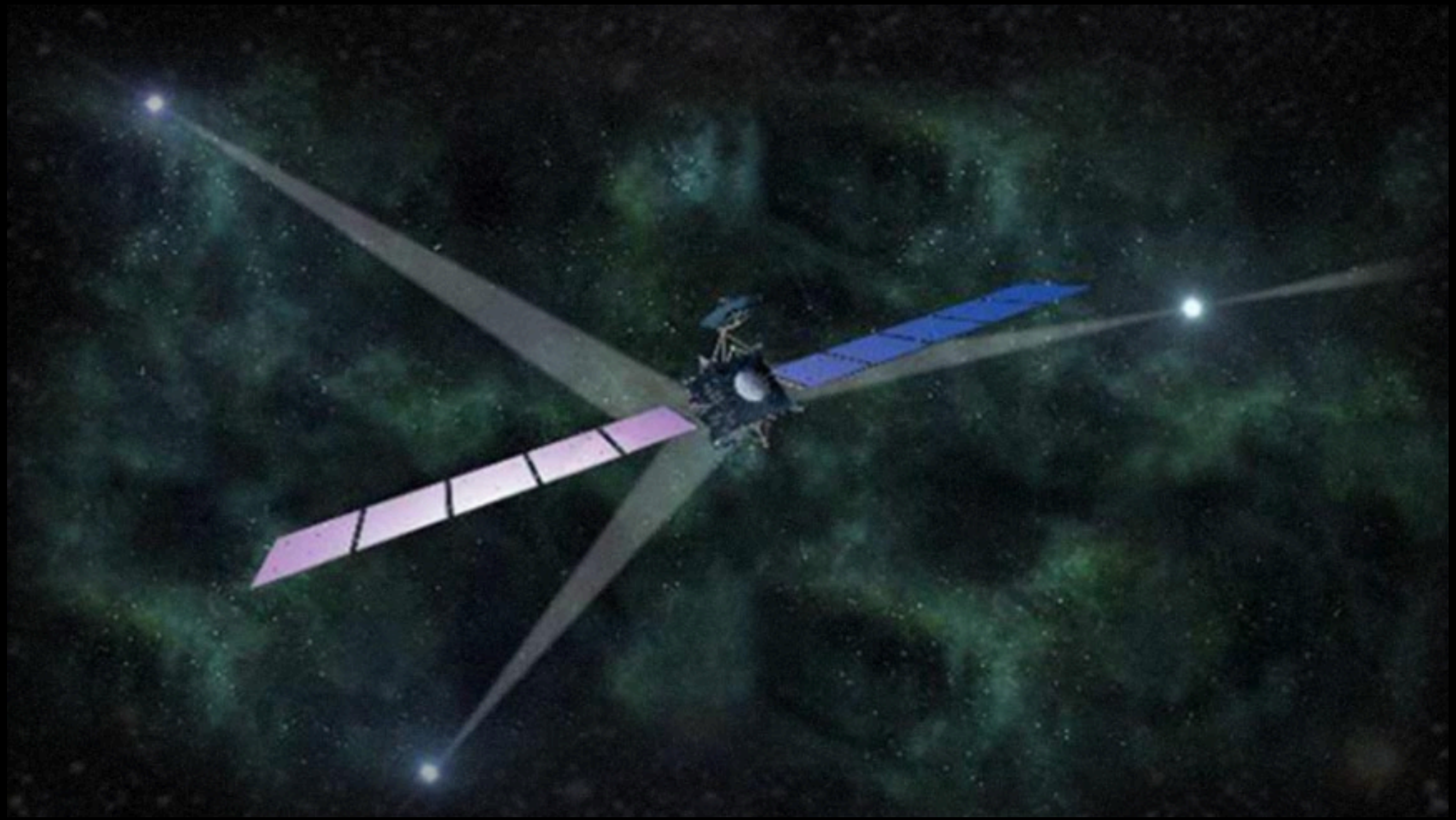
# PULSARS AS GPS FOR DEEP SPACE TRAVEL

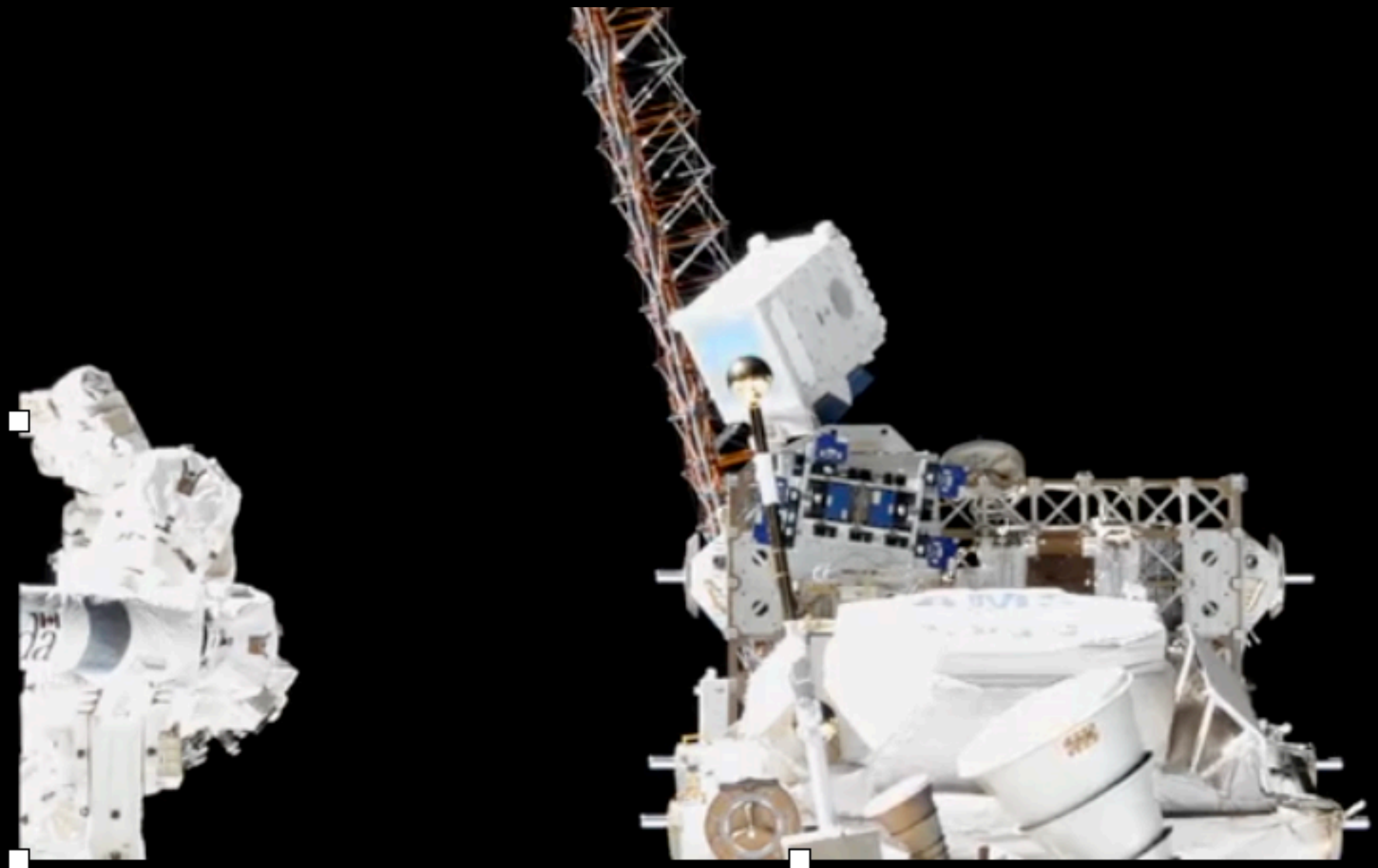


The Pioneer plaques are a pair of aluminium plaques which were placed on board the 1972 Pioneer 10, 1973 Pioneer 11 spacecrafts, featuring a pictorial image in case either Pioneer 10 or 11 is intercepted by extraterrestrial life.


NASA's Voyager 1, launched 35 years ago with various messages from the Earth, is on the verge of moving into interstellar space. It has a Golden Record on-board in case it will be intercepted by extraterrestrial life .

# PULSARS AS GPS FOR DEEP SPACE TRAVEL





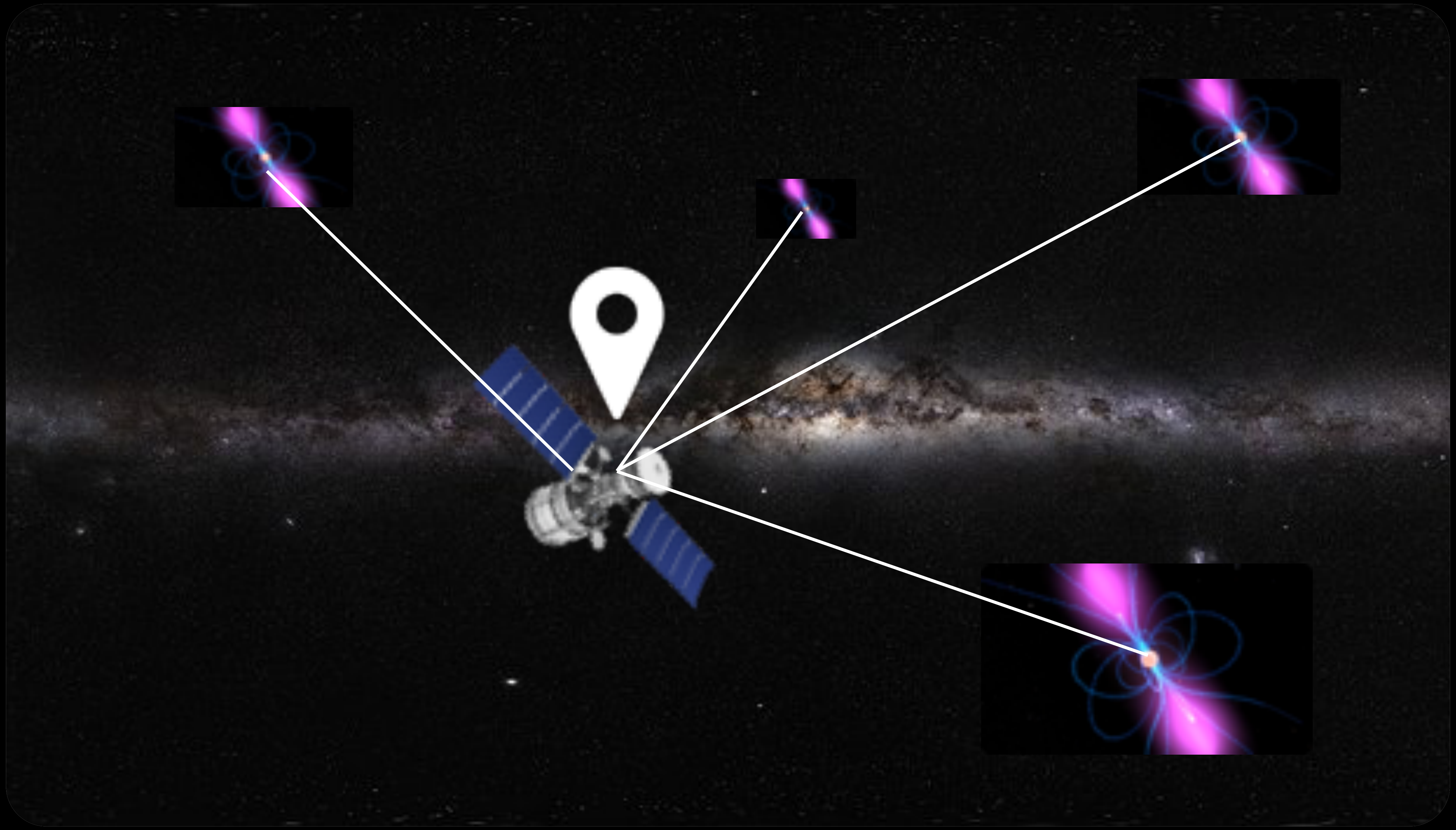
(NICER collaboration, Nature 2018)

On January 2018 the first test of this pulsar GPS system has been successfully performed using the SEXTANT instrument onboard NICER, hosted by the International Space Station that orbits around Earth at slightly more than 17,500 mph. Within eight hours of starting the X-ray pulsar timing experiment, via timing 14 X-ray millisecond pulsars, the algorithm converged on a location with an error of 10 miles.

PULSARS AS GPS: NEXT GENERATION INSTRUMENTS

**PODIUM**

50x15x15 $cm^3$

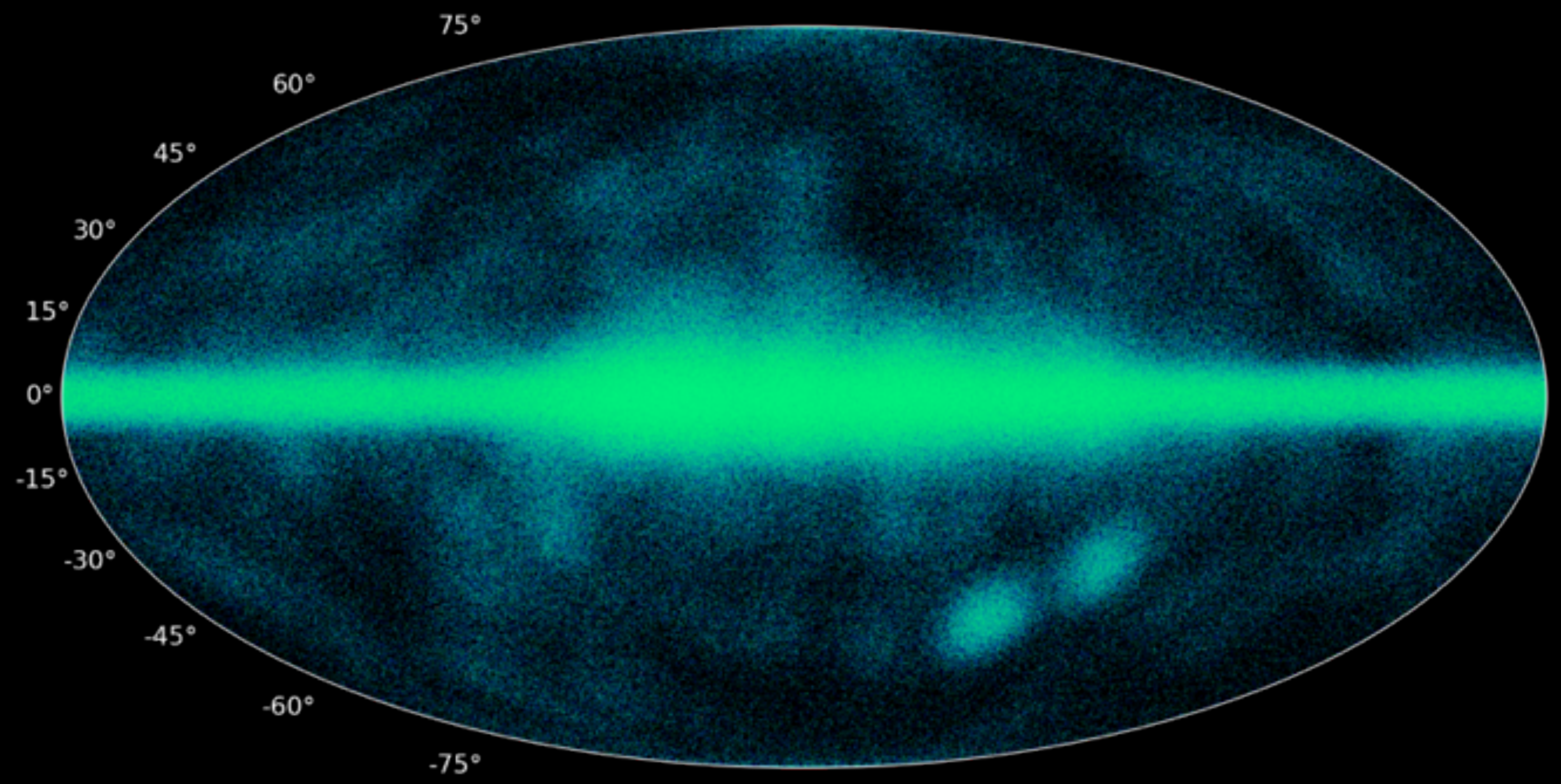
# CONCLUSIONS

+ All neutron star classes have shown magnetar-like activity. We need to understand their characteristics and behaviour in our Galaxy to be able to relate them to rates and emission properties of the extra-Galactic transients.

+ The different classes of neutron stars can be unified in a simple evolutionary scenario, invoking field decay in objects with different initial B-field strength, configuration and age: there is no SN-rate problem!

+ PULSARS ARE COSMIC GIFTD!

- Study dense matter
- Test our physics under extreme magnetic fields
- Test General Relativity and alternative theories
- Detect gravitational waves and their EM counterparts
- Use them as Gravitational Wave Detectors
- Use them as GPS for deep space travels



Credit: N. Rea and S. Serrano 2021

# THANKS!

*Dr. Vanessa Graber*
*Dr. Emilie Parent*


*Dr. Daniele Viganò*
*Dr. Francesco Coti Zelati*


*Dr. Alice Borghese*
*Mr. Michele Ronchi*


*Ms. Clara Dehman*
*Mr. Abubakr Ibrahim*


*Dr. Stefano Ascenzi*
*Dr. Rajath Sathyaprakash*


*Mr. Celsa Pardo*
*Mr. Albert Herrando*



European Research Council
Established by the European Commission

MAGNESIA
MAGNETAR CENSUS
The Impact of Highly Magnetic Neutron Stars in the Explosive and Transient Universe

cost
EUROPEAN COOPERATION IN SCIENCE & TECHNOLOGY

GOBIERNO DE ESPAÑA
MINISTERIO DE CIENCIA, INNOVACIÓN Y UNIVERSIDADES

AGAUR
Agència de Gestió d'Ajuts Universitaris i de Recerca