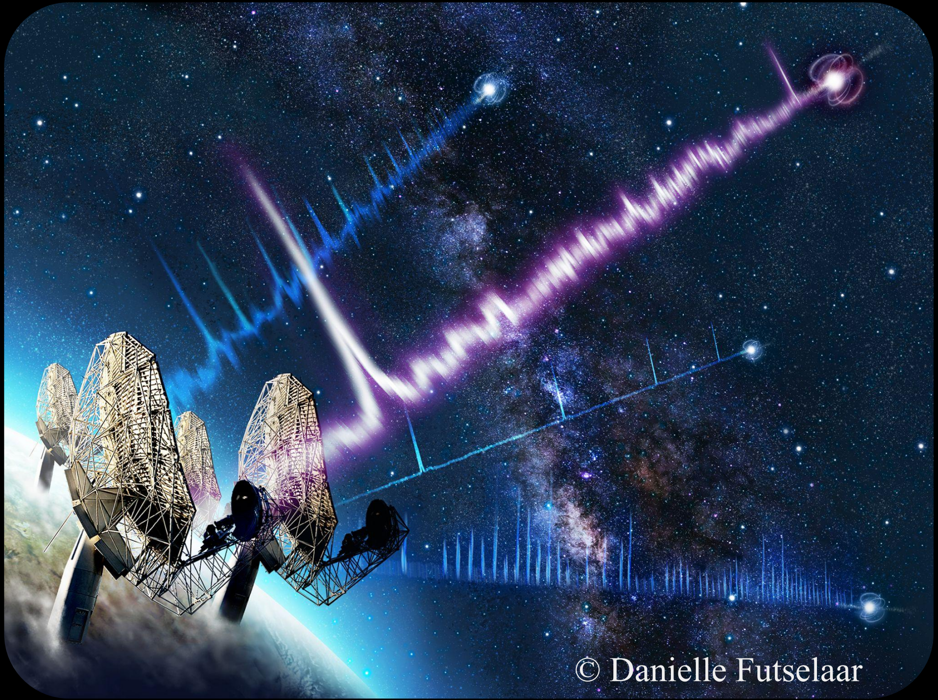


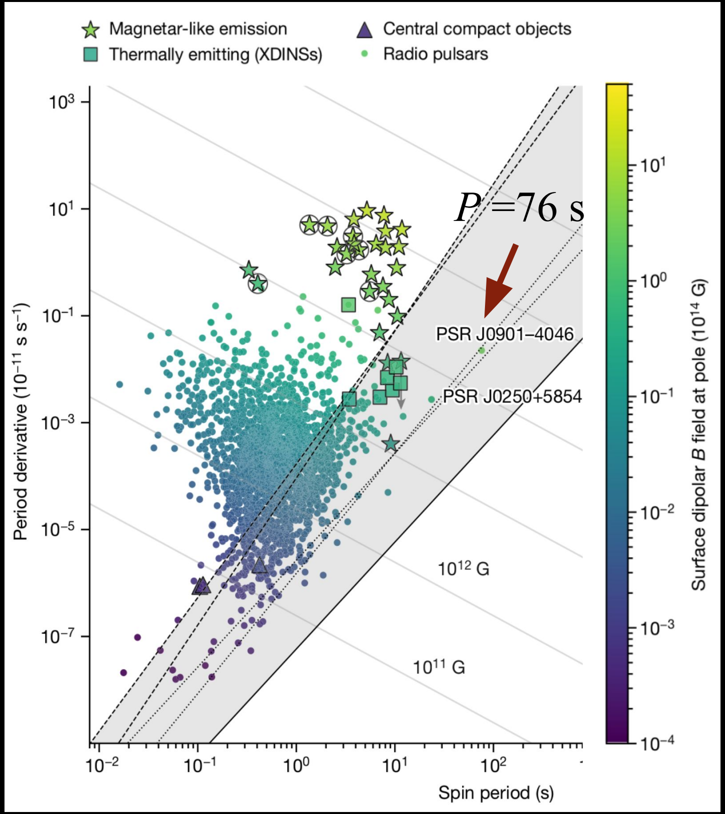
The mystery of long period pulsars

Michele Ronchi

In collaboration with:
Nanda Rea,
Vanessa Graber,
Celsa Pardo Araujo,
Natasha Hurley-Walker

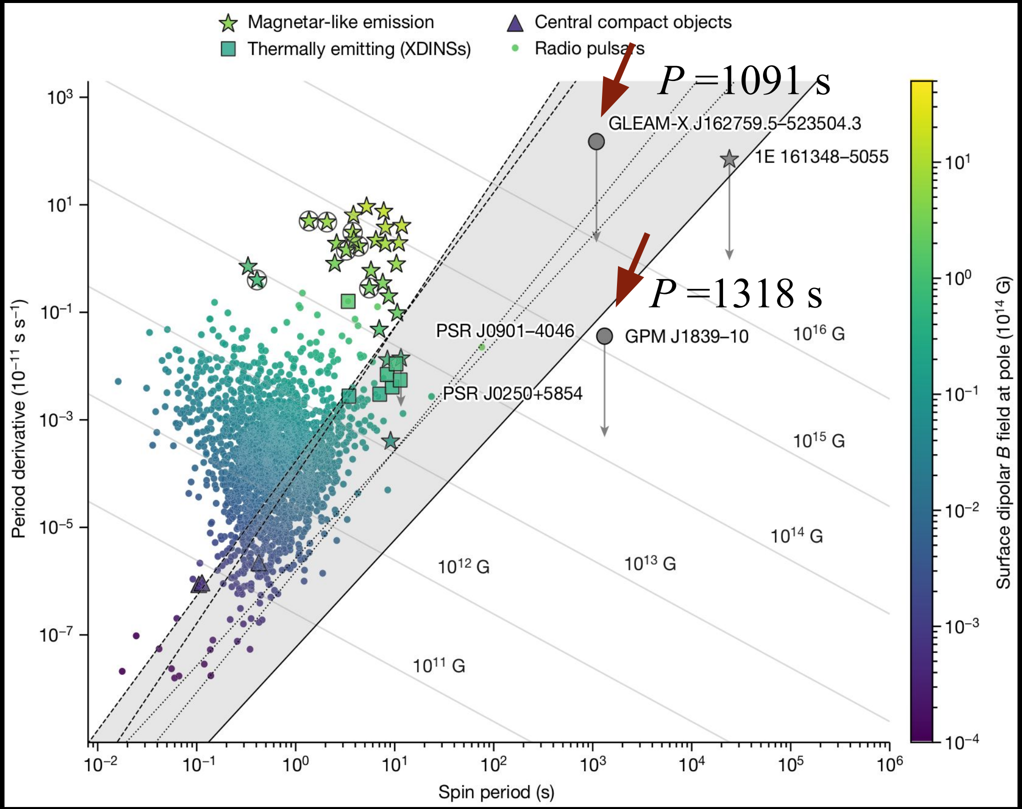
MAGNESIA
erc European Research Council
Institute of Space Sciences
CSIC IEEC
EXCELENCIA MARÍA DE MAEZTU
UAB Universitat Autònoma de Barcelona

Long period pulsars



Long period pulsars in the P-$\dot{P}$ diagram (Hurley-Walker et al. 2022, 2023, Caleb et al. 2022)

Long period pulsars



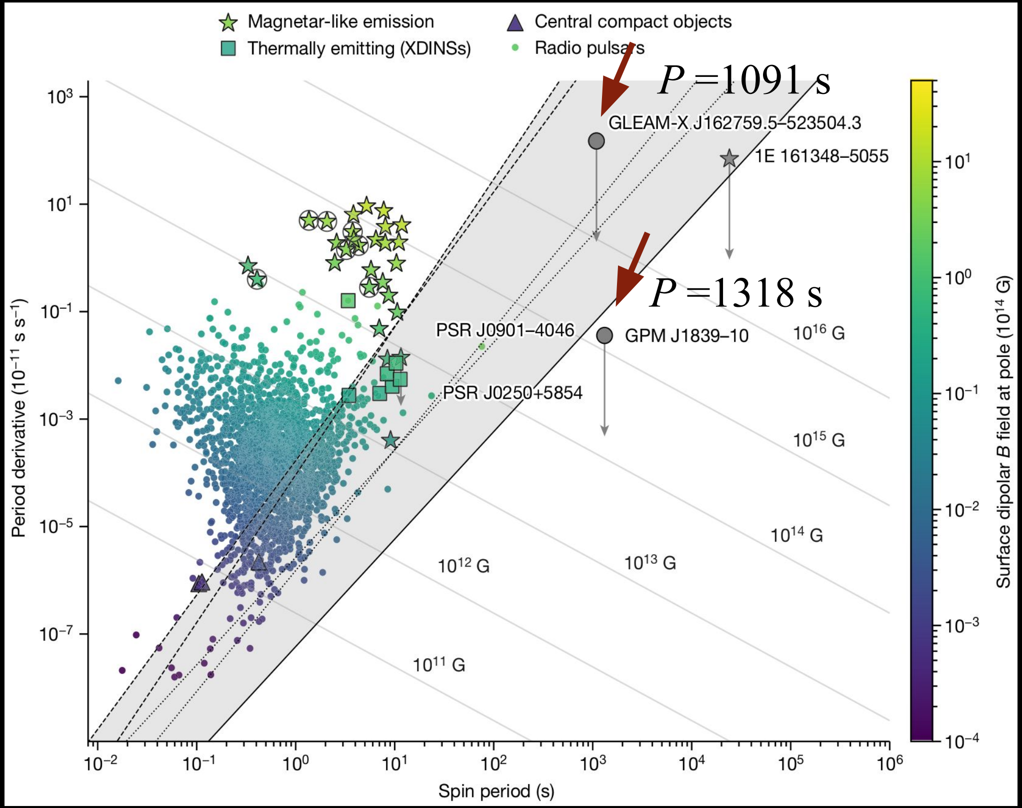
Long period pulsars in the P-$\dot{P}$ diagram (Hurley-Walker et al. 2022, 2023, Caleb et al. 2022)

Properties:

- Spin periods above ~1000 s
- GLEAM-X active for a few months
- GPM J1839 active for at least 30 yrs
- **Magnetar like emission**
  - Highly polarized
  - Spiky and variable pulse profile

See Natasha Hurley-Walker talk

Long period pulsars



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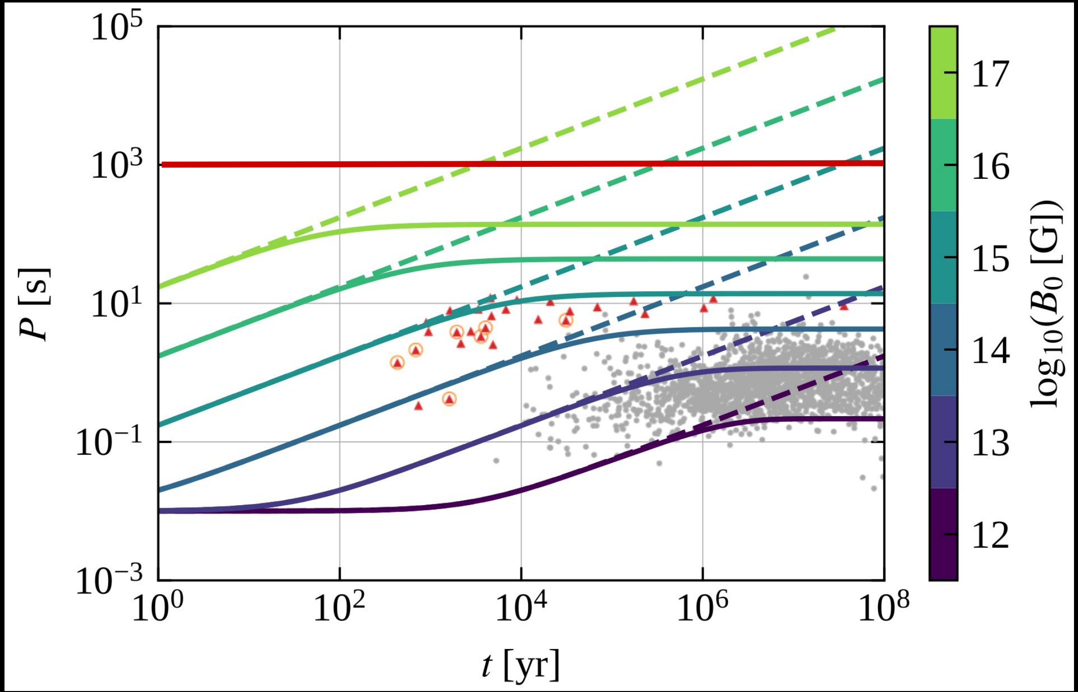
How can we reach such long spin period?

Dipolar spin-down is not enough

Dipolar spin-down evolution with magnetic field decay:

$$\frac{d\omega}{dt} = -\beta B(t)^2 \omega^3$$

Reaching long periods ($\gg$10 s) would require an almost constant (core-dominated?) and extreme magnetic field (> 10^{15} G).

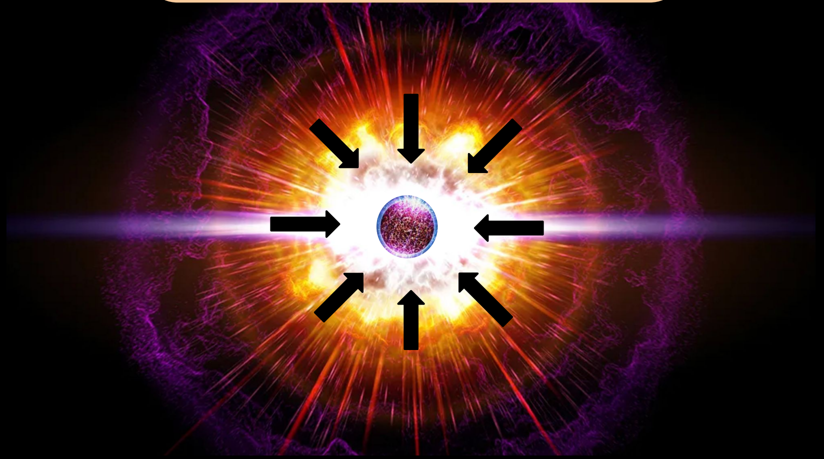


Spin period evolution in the dipolar spin-down model (Ronchi et al. 2022)

Supernova fallback scenario

Fallback from supernova can affect the spin period evolution of a newborn neutron star. (Ronchi et al. 2022, Tong et al. 2023)

Fallback starts on a timescale $t_{\mathrm{fb}} \sim 10$ -100 s post bounce (Janka et al. 2022, Ugliano et al. 2012, Ertl et al. 2016)



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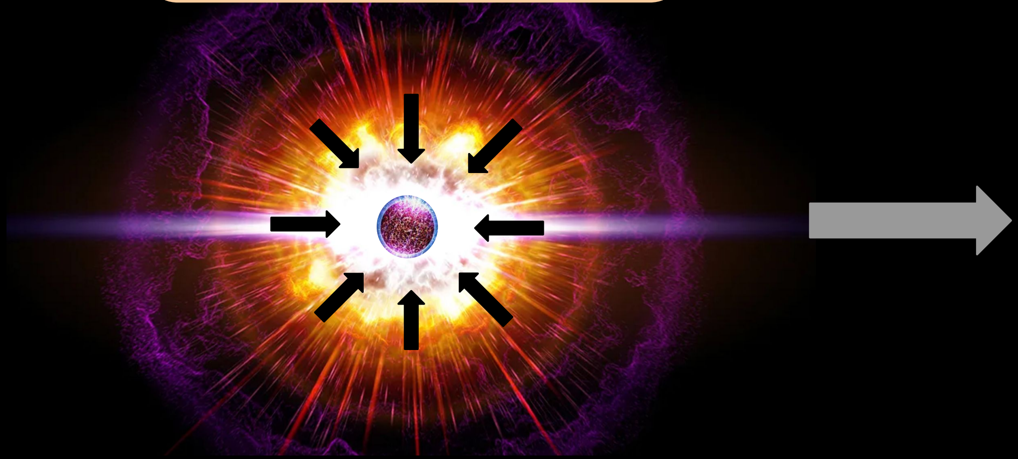
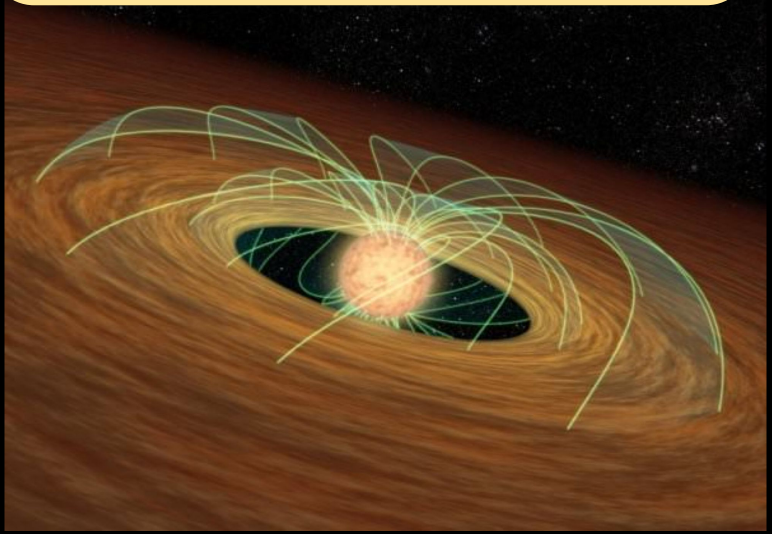


If fallback matter has enough angular momentum it will **circularize to form a disk** on a viscous timescale t_v ~ 2000 s
(Cannizzo et al. 1990, Mineshige et al. 1997, Menou et al. 2001):



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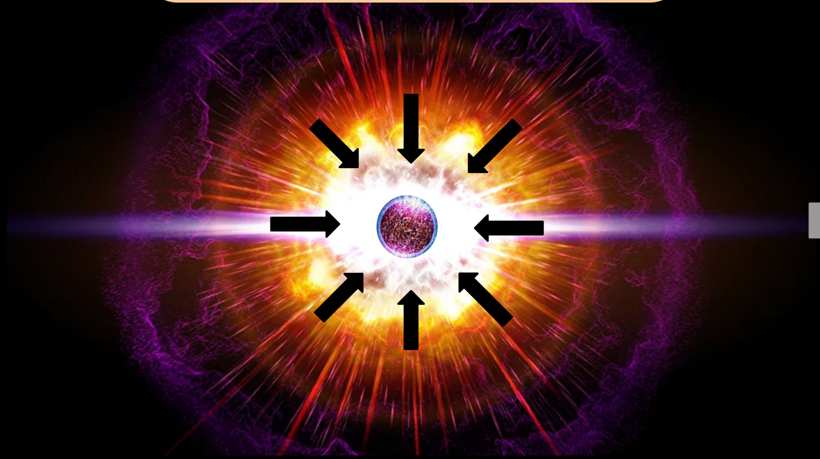

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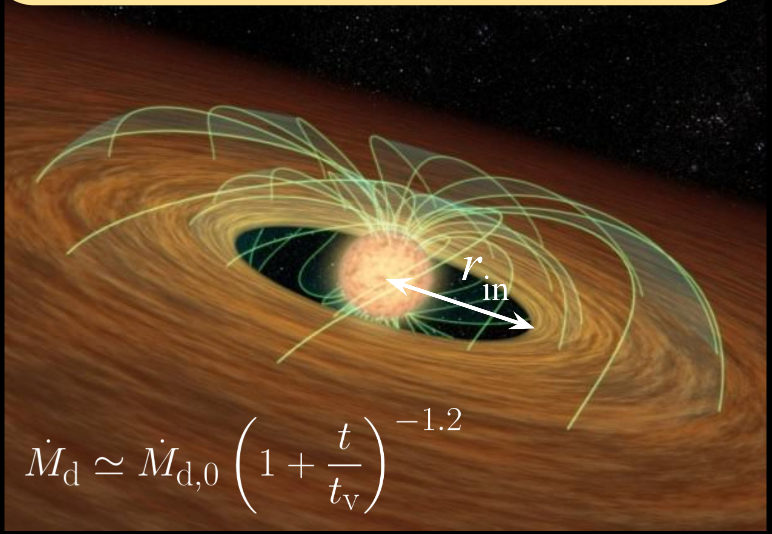


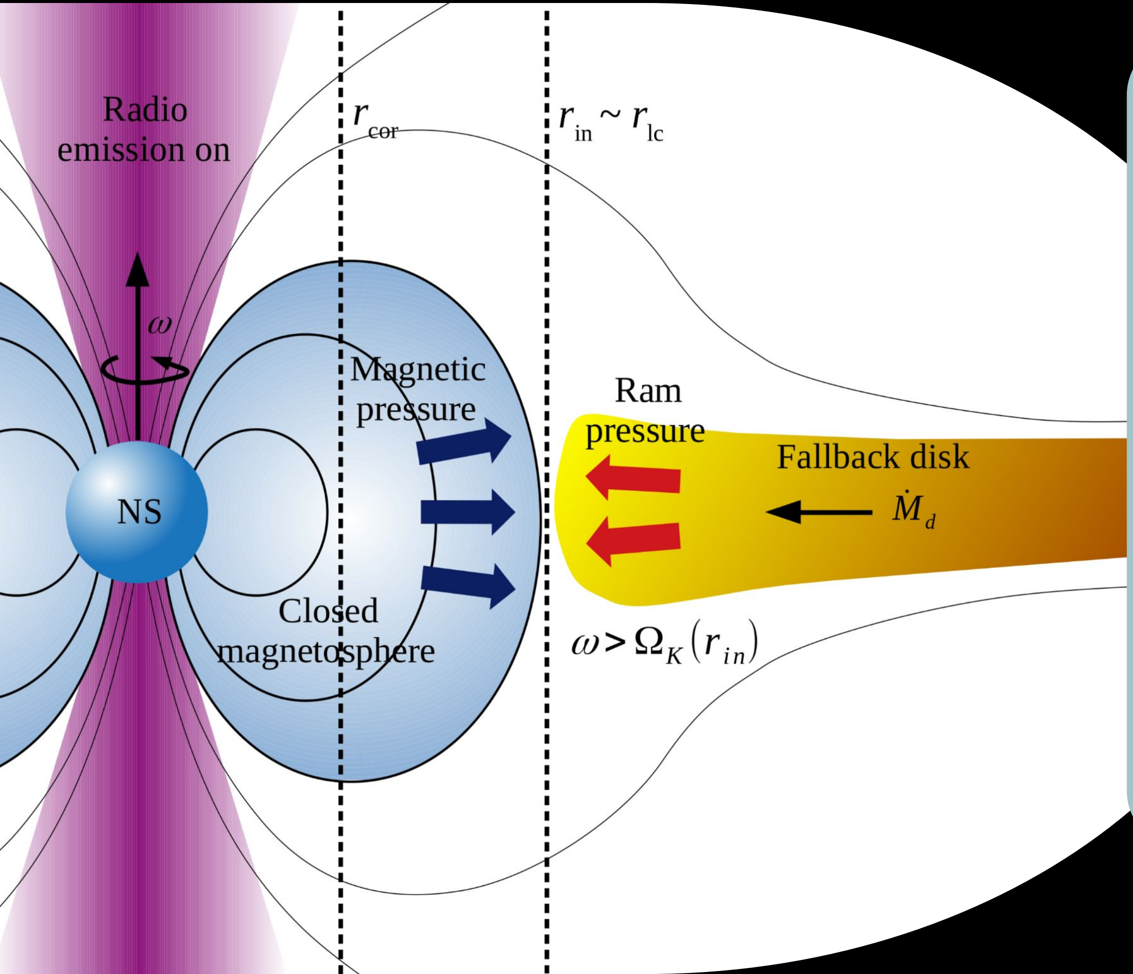
The magnetospheric radius

Magnetospheric (Alfvén) radius

ram pressure of in-falling matter = magnetic pressure

$$r_{\mathrm{m}} \sim \left(\frac{B^4 R_{\mathrm{NS}}^{12}}{G M_{\mathrm{NS}} \dot{M}_{\mathrm{d,in}}{}^2} \right)^{1/7}$$

Ejector phase



The ram pressure is not enough to penetrate the closed magnetosphere. The disk stays **outside the light cylinder**

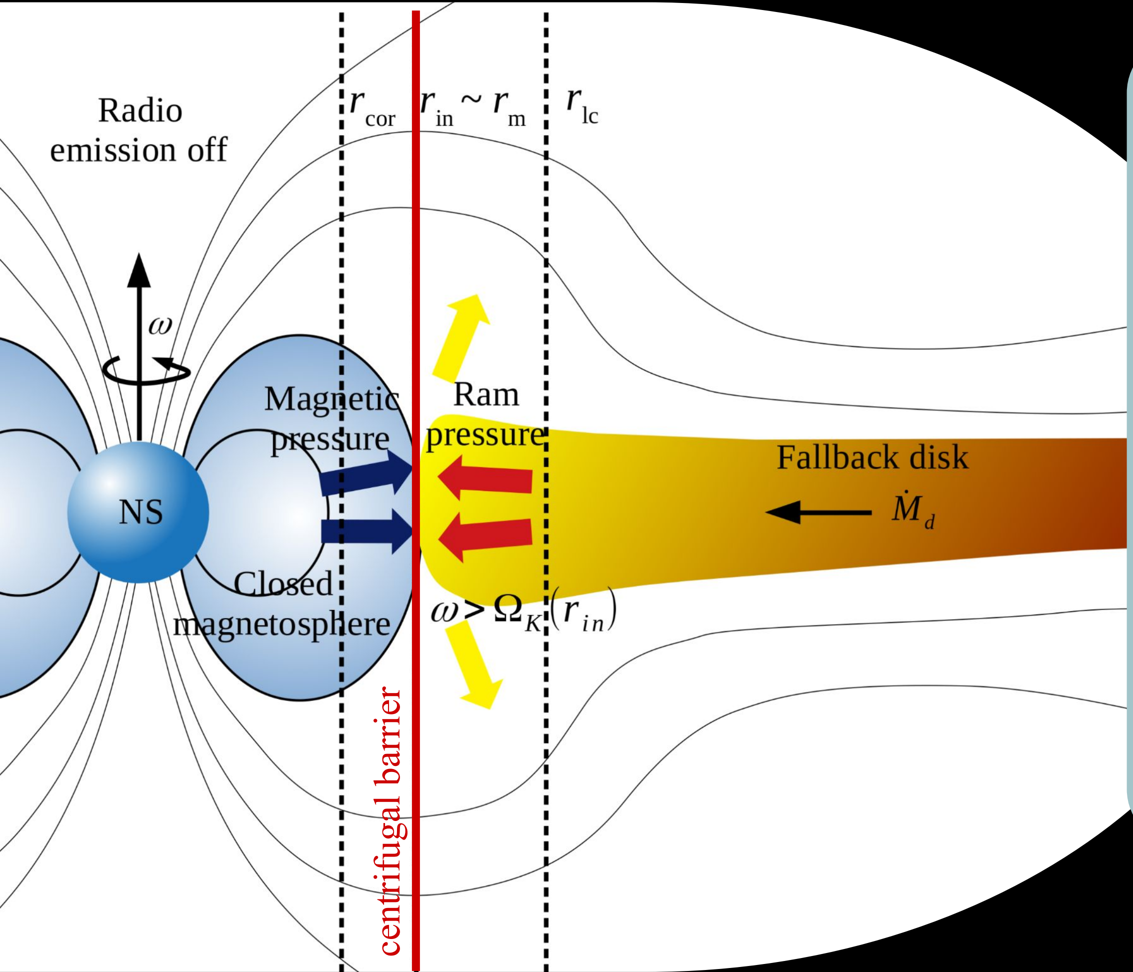
The NS **spins down** mainly by **dipolar electromagnetic losses** (Piro & Ottoman 2011, Parfrey et al. 2016, Metzger et al. 2018).

$$I_{\rm NS}\dot{\omega} = N_{\rm dip} + N_{\rm acc}$$

$$N_{\rm dip} = -I_{\rm NS}\beta \left(\frac{r_{\rm lc}}{r_{\rm in}}\right)^2 B^2\omega^3$$

$$N_{\rm acc} \simeq \dot{M}_{\rm d,in} r_{\rm in}^2 [\Omega_{\rm K}(r_{\rm in}) - \omega]$$

Propeller phase



The ram pressure is enough to penetrate the closed magnetosphere.
BUT the disk **finds a centrifugal barrier**

The NS **spins down** mainly by **propeller torque**
(Piro & Ottoman 2011, Parfrey et al. 2016, Metzger et al. 2018).

$$I_{\rm NS}\dot{\omega} = N_{\rm dip} + N_{\rm acc}$$

$$N_{\rm dip} = -I_{\rm NS}\beta\left(\frac{r_{\rm lc}}{r_{\rm in}}\right)^2 B^2\omega^3$$

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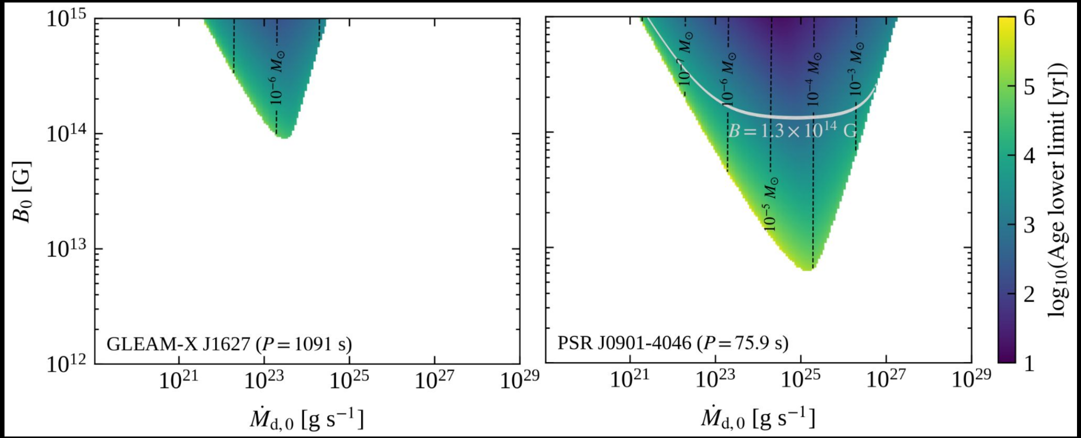
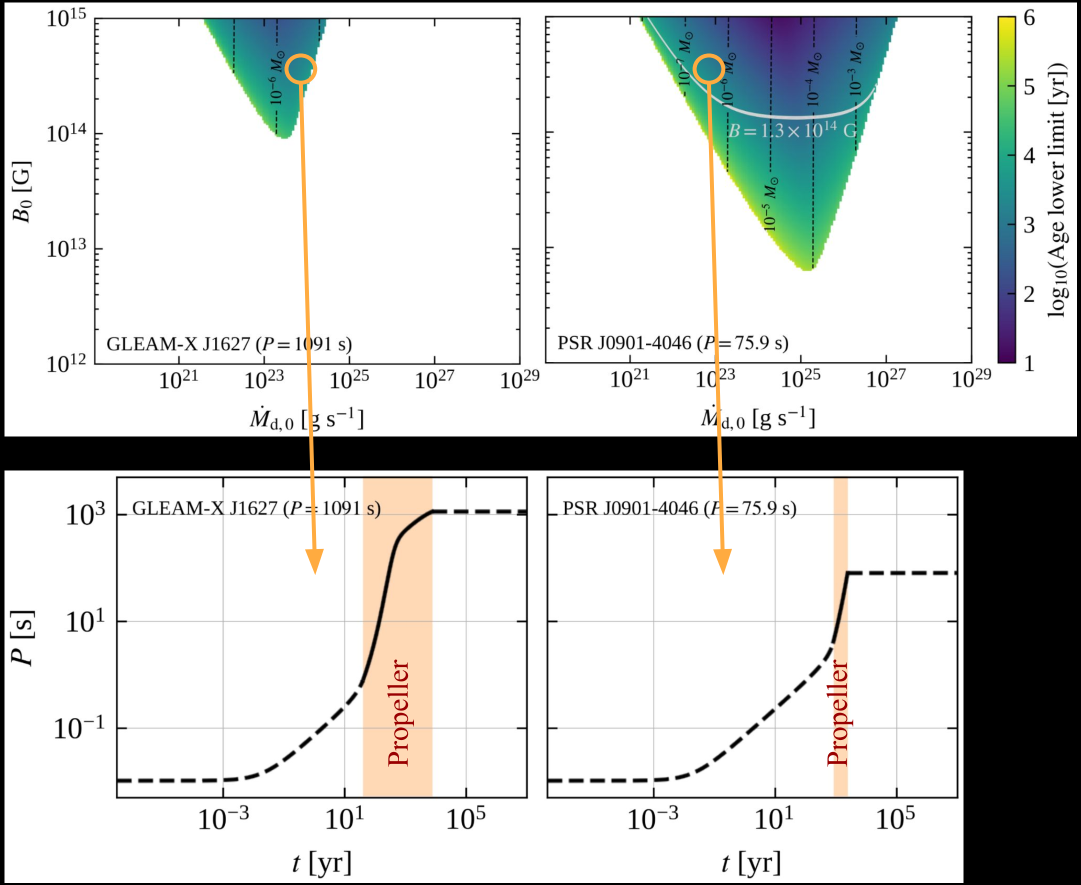
Application to long-period sources



The fallback scenario allows us to relax the physical conditions necessary to reach very long periods (> 1000 s). It requires **magnetar-like magnetic fields** (>10^{14} G) and moderate **accretion rates in line with supernova simulations**.

Application to long-period sources



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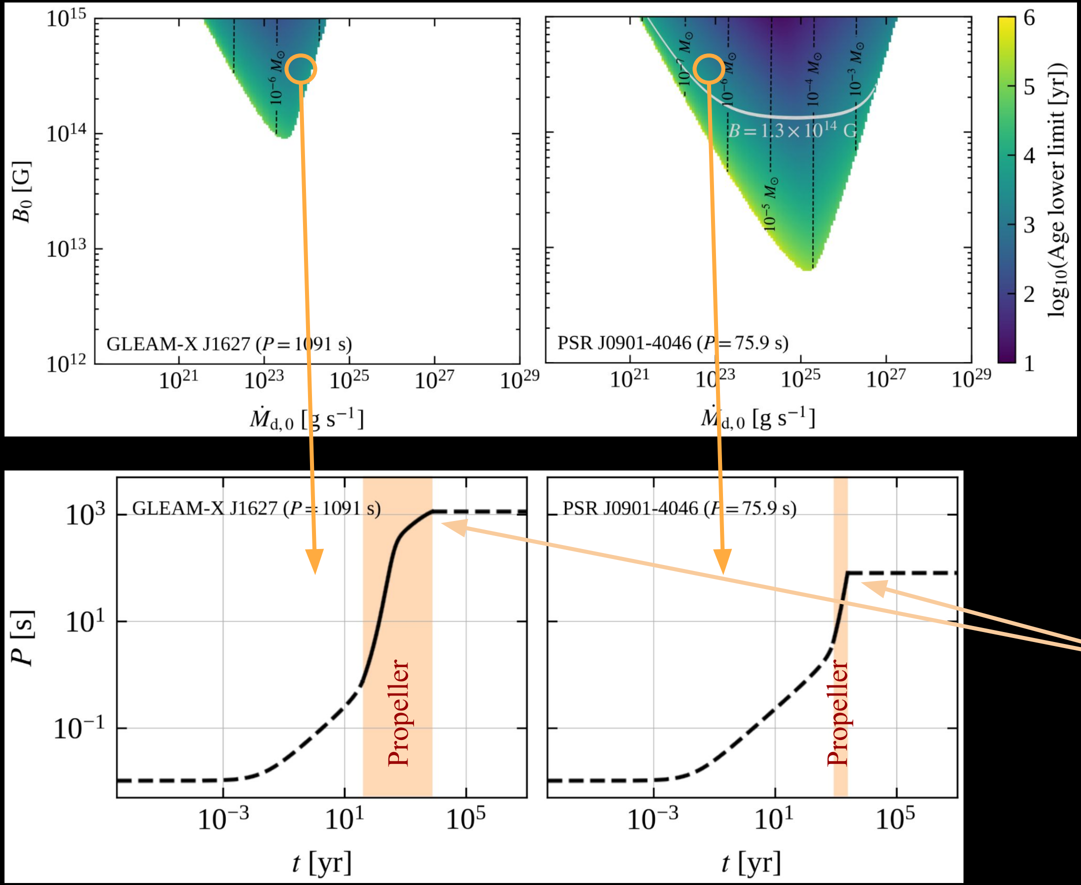
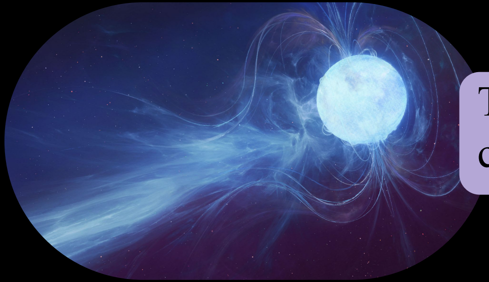


The fallback scenario allows us to relax the physical conditions necessary to reach very long periods (> 1000 s). It requires **magnetar-like magnetic fields** (>10^{14} G) and moderate **accretion rates in line with supernova simulations**.

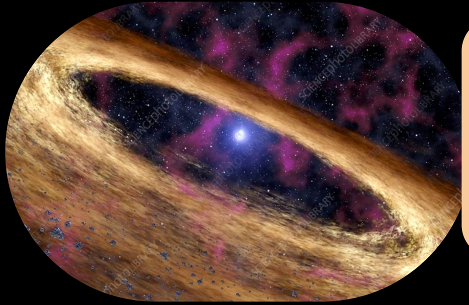
Since GLEAM-X J1627, GPM J1839 and PSR J0901 have been observed as radio pulsars, they should have transitioned to the ejector phase.

Restoring the radio emission



The flaring activity of the magnetar can disrupt or unbind the disk

The fallback disk is consumed by the propeller activity (Ekşi et al. 2005, Romanova et al. 2005)

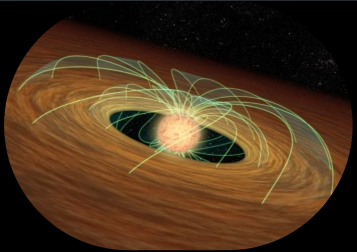


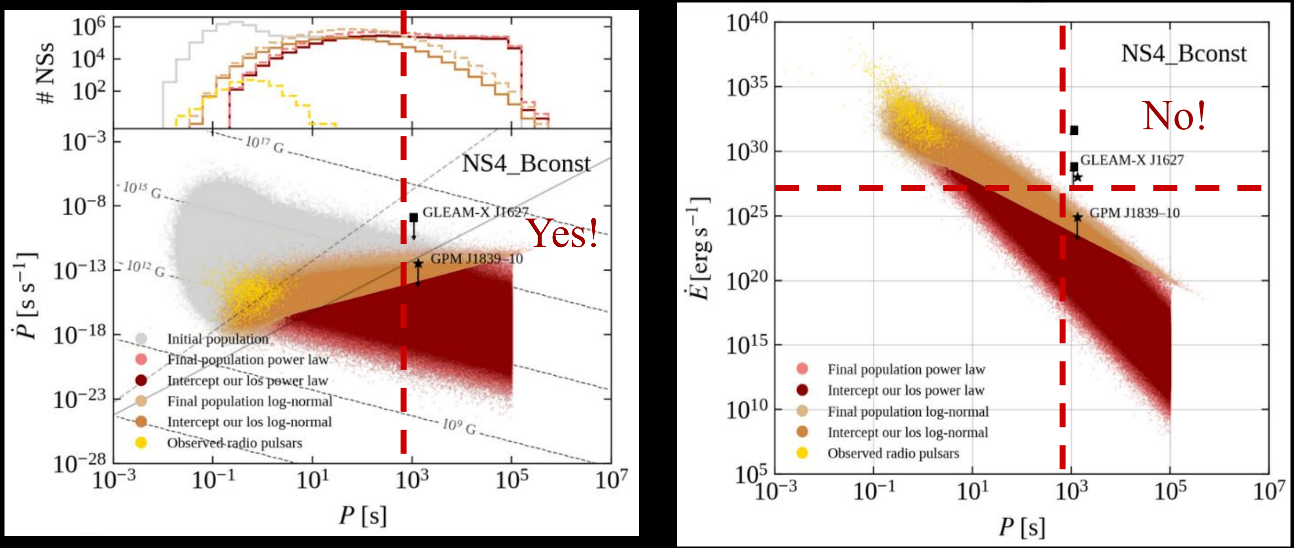
The disk undergoes a **thermal ionization instability**, i.e., becomes too cold to sustain angular momentum transfer and accretion stops (Mineshige et al. 1993, Menou et al. 2001)

From a population synthesis perspective

$$\dot{E}_{\rm rot} = 4\pi^2 I_{\rm NS}\frac{\dot{P}}{P^3}$$

fallback and constant *B*-field

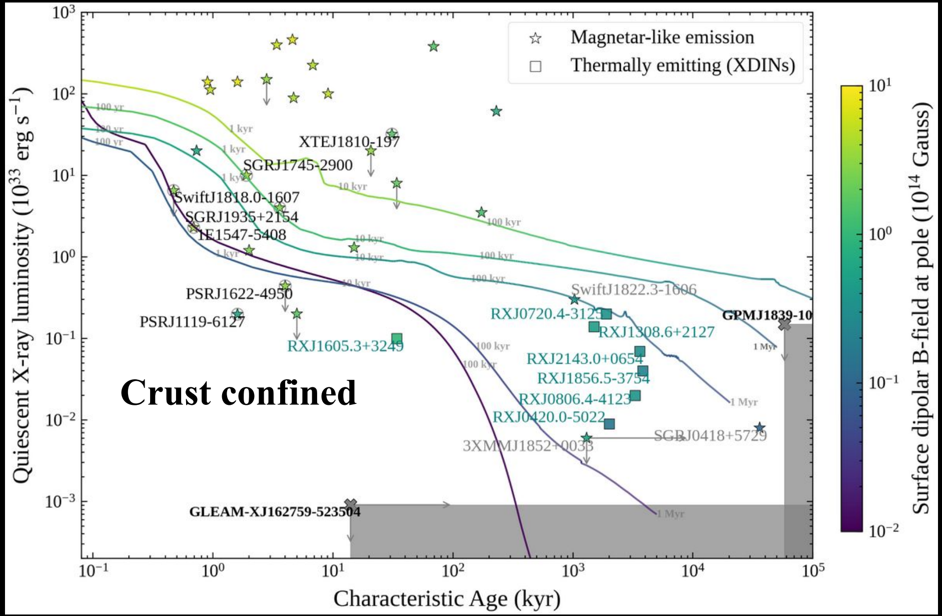


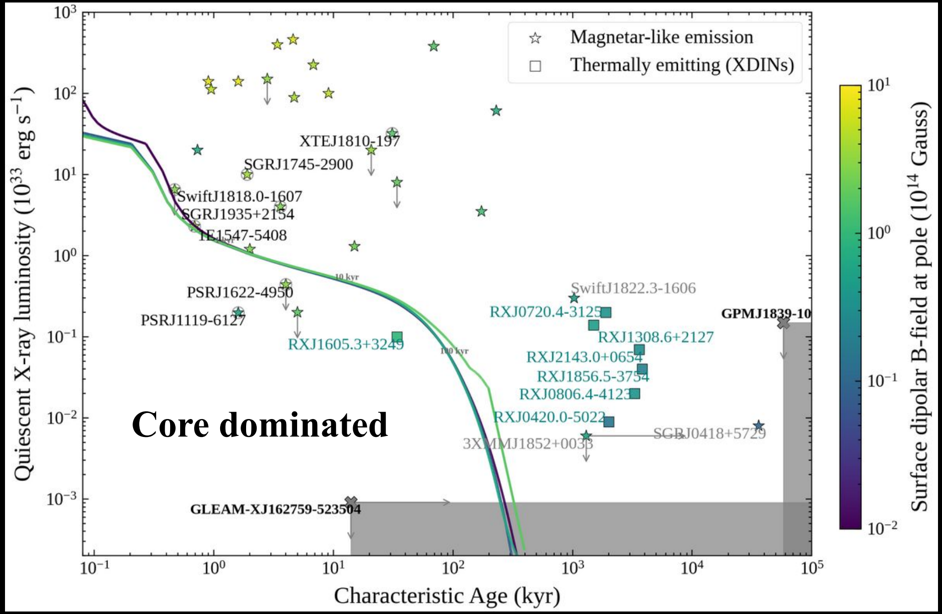


Neutron star population synthesis with fallback (Rea et al. 2024)

Even considering the most extreme scenarios with **constant magnetic field** and **supernova fallback spin-down**, **NSs do not have enough rotational spin-down energy** to power the observed radio emission.

X-ray luminosity limits

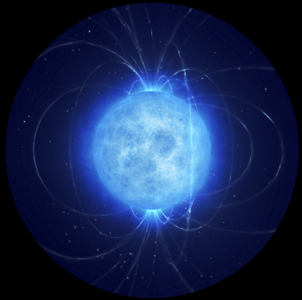




Cooling curves for crustal-confined and core-dominated *B*-field (Viganò et al. 2021, adapted from Rea et al. 2022)

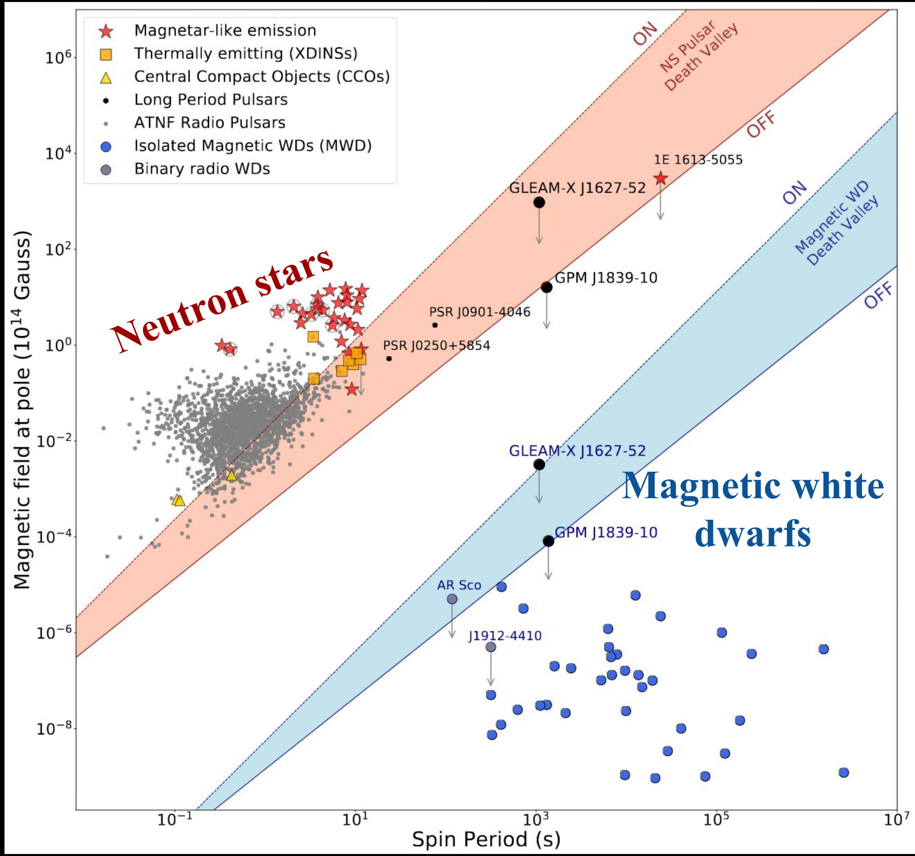
If GLEAM-X J1627 is a magnetar, it is **too cold** to have a crust-confined field.

Magnetic white dwarfs?



~ **600 magnetic WDs** are known to date (Ferrario et al. 2020)

- mass: $M_{\rm MWD} \sim 0.5$ - $1.2\ M_{\odot}$
- radius: $R_{\rm MWD} \sim (4$ - $6) \times 10^8$ km
- spin periods: $P \sim 100$ - 10^7 s
- Magnetic fields: $B \sim 10^3$ - 10^9 G



B-*P* diagram for NSs and MWDs (Rea et al. 2024)

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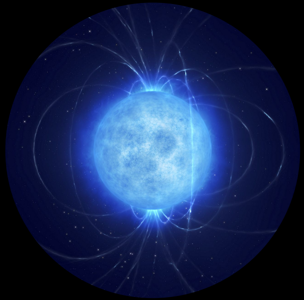

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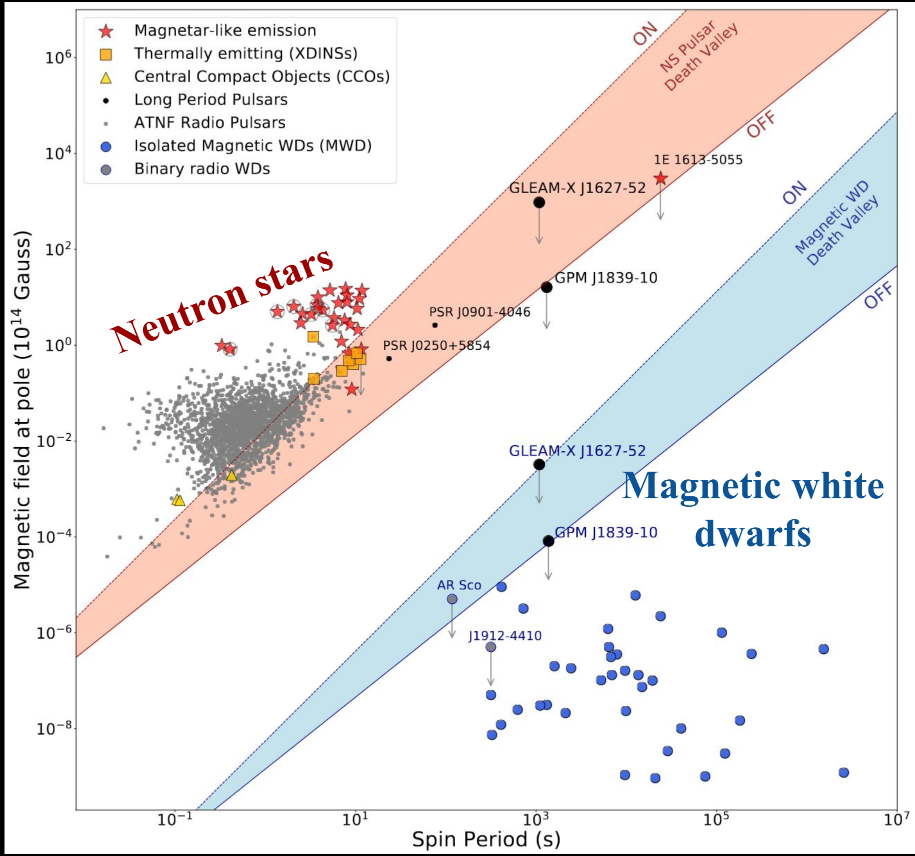
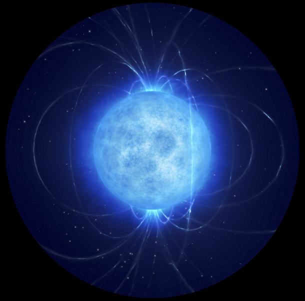
GPM J1839 **challenges models for radio emission** both in the NSs and WDs scenarios



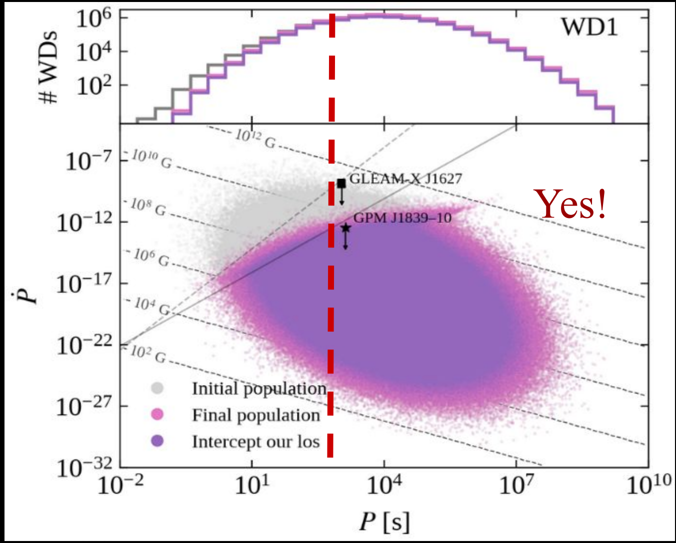
B-*P* diagram for NSs and MWDs (Rea et al. 2024)

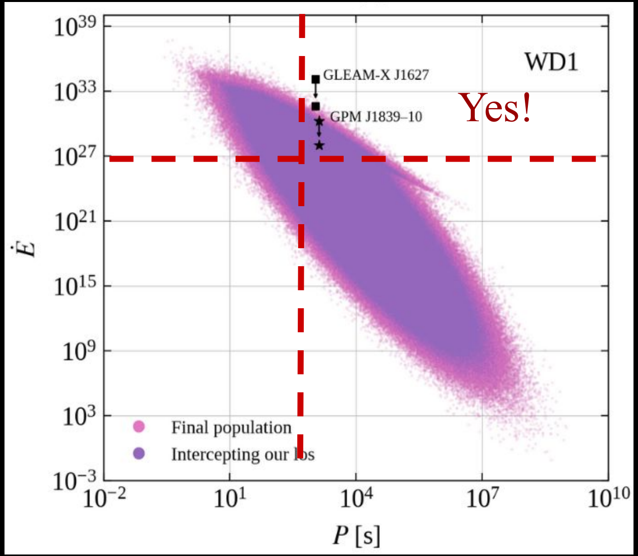
White dwarf population synthesis



We assume a birth rate of 1 per decade (Holberg et al., 2016)

$$\dot{E}_{\rm rot} = 4\pi^2 I_{\rm WD}\frac{\dot{P}}{P^3}$$





White dwarf population synthesis (Rea et al. 2024)

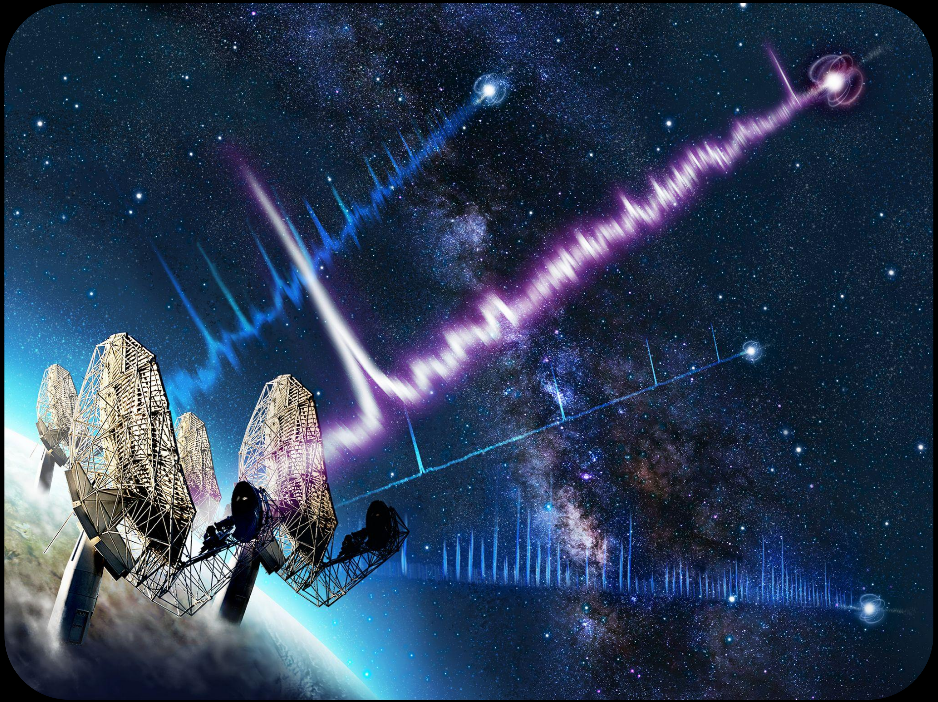
Due to their **higher birth rate and moment of inertia** magnetic white dwarfs have more chances to have the rotational energy budget to power the observed radio emission

The mystery of long-period pulsars

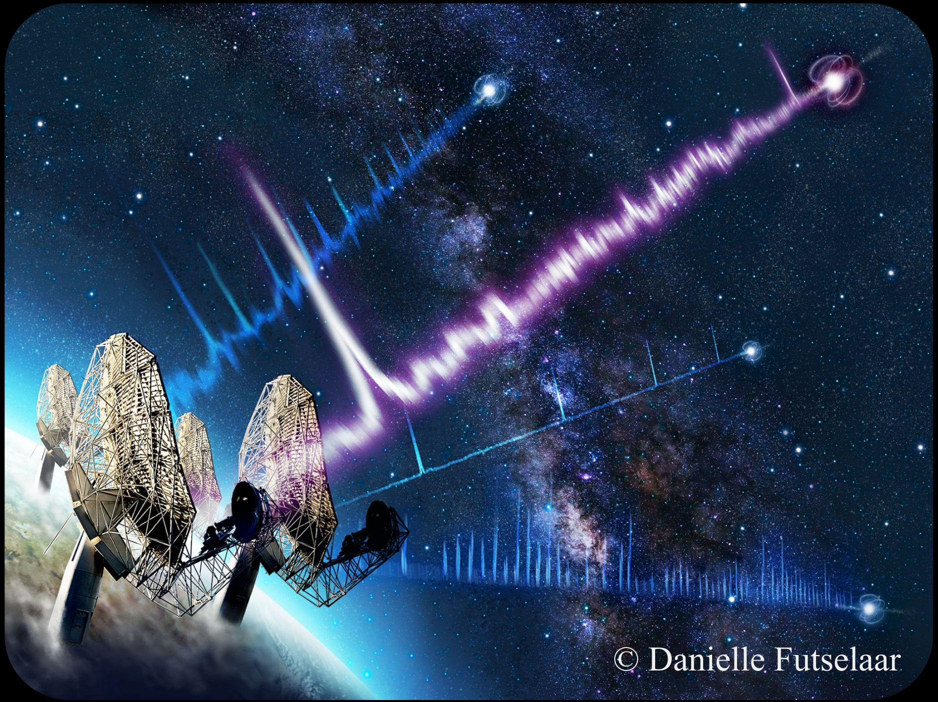
Main conclusion:

The nature of long-period sources is still a mystery, they **challenges our understanding of how radio emission is produced in magnetospheres of compact stars**.

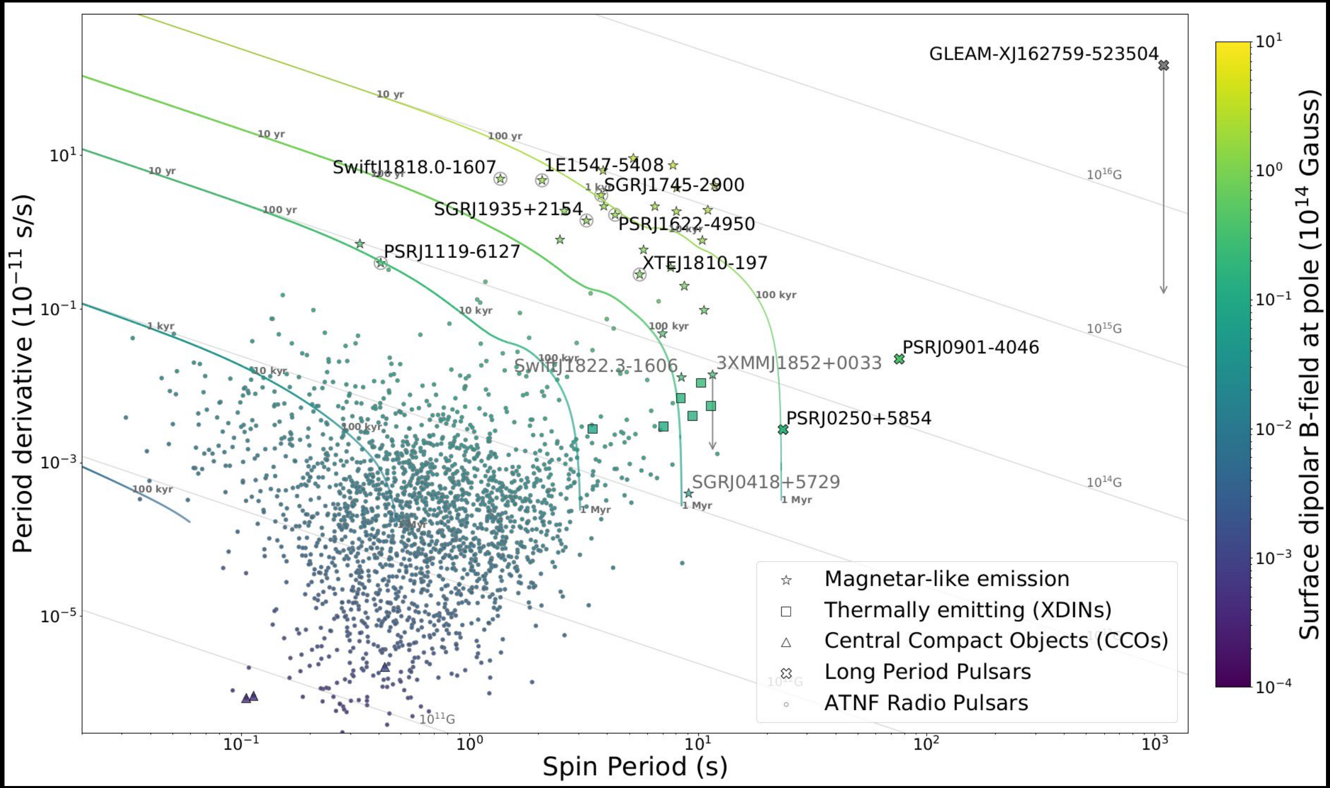
Thank you!



Backup slides

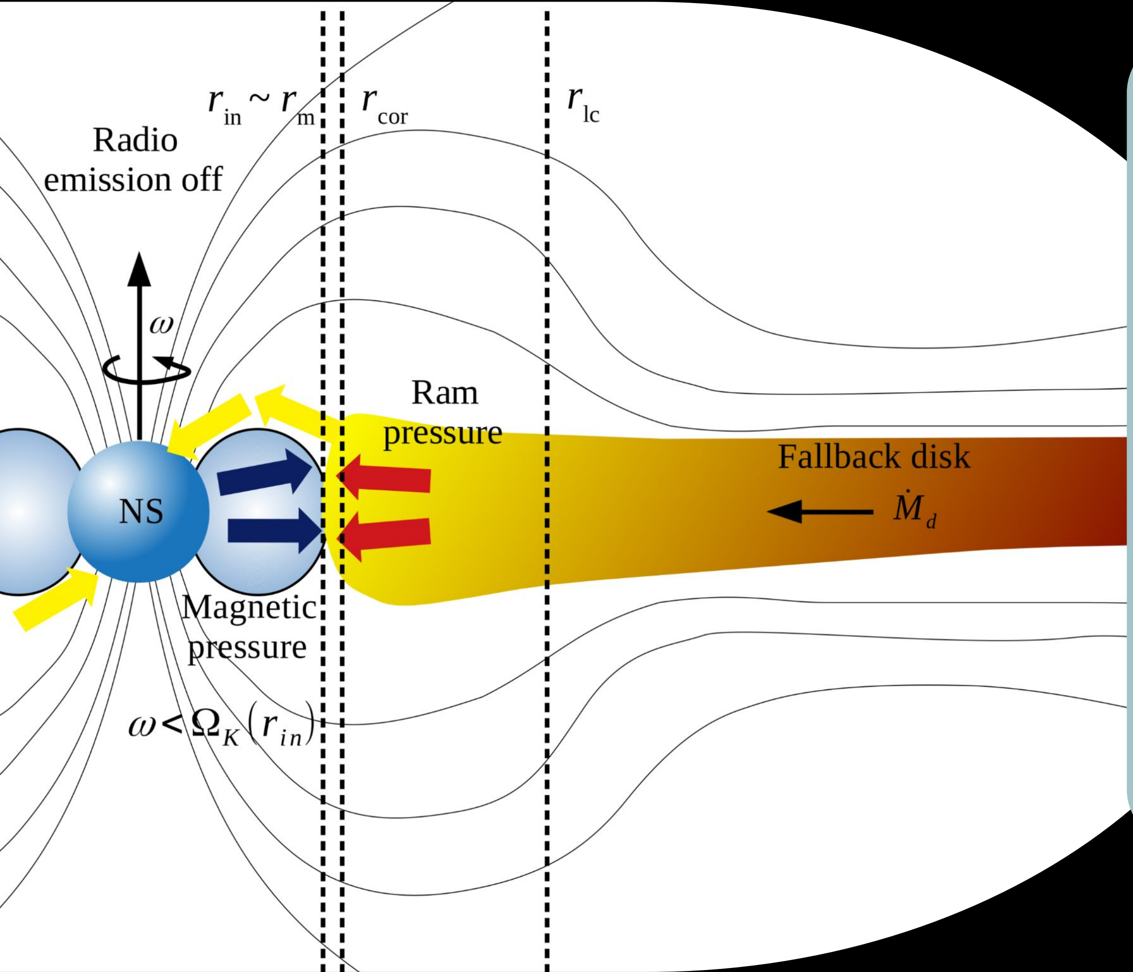


Long period pulsars



Courtesy of Nanda Rea

Accretion phase



The ram pressure is enough to penetrate the closed magnetosphere and the disk **does not find a centrifugal barrier**

The NS **spins up** mainly due to **direct accretion onto the surface** (Piro & Ottoman 2011, Parfrey et al. 2016, Metzger et al. 2018).

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