CNOC XII – Cefalù 26-30 September 2022

Long-period pulsars as possible outcomes of supernova fallback accretion

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Ronchi M., Rea N., Graber V., Hurley-Walker N., 2022, ApJ 934 184

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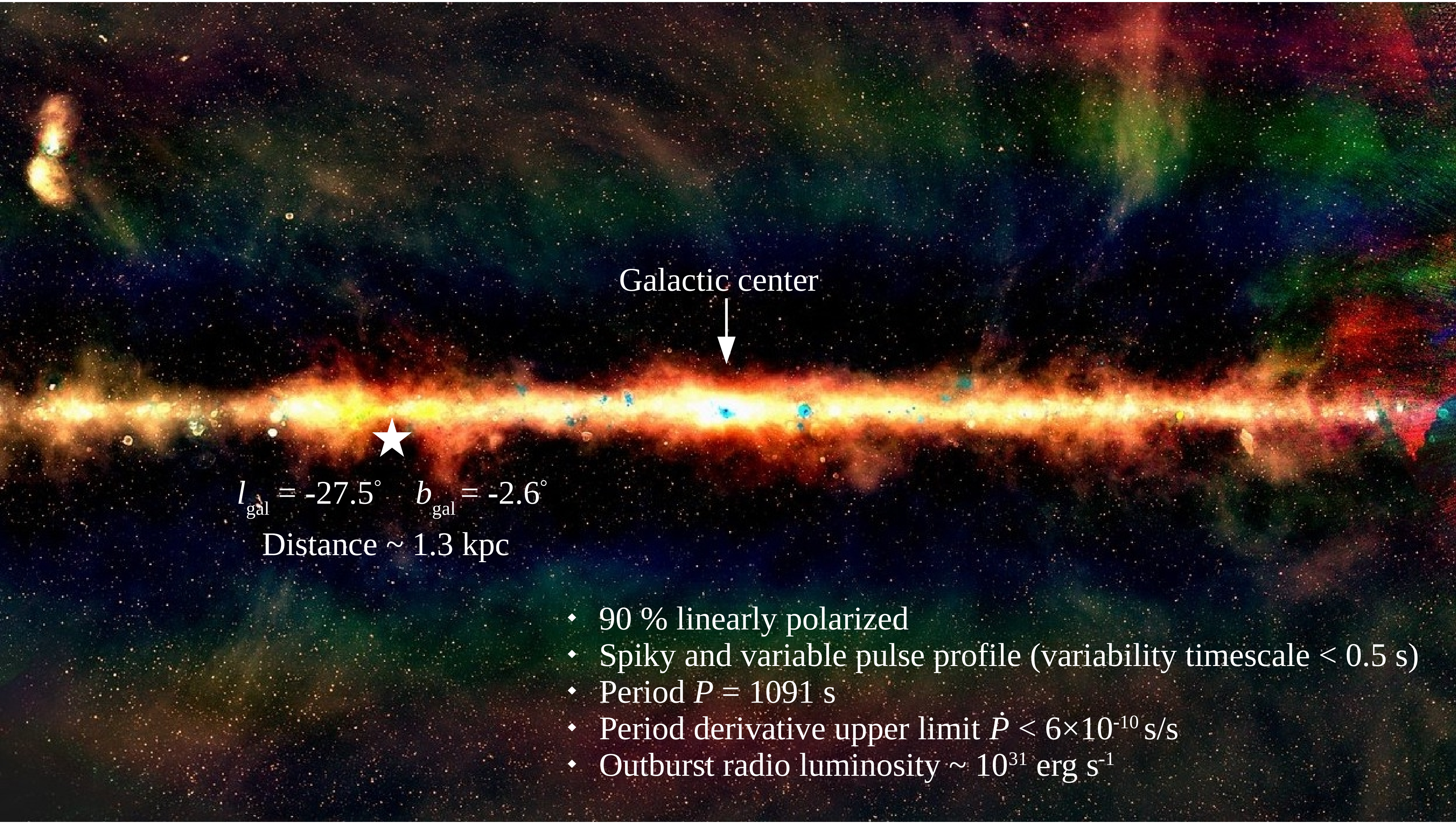
An unusual periodic transient

GLEAM-X J162759.5-523504.3

Hurley-Walker et al., *Nature*, volume 601, pages 526–530 (2022)



- 90 % linearly polarized
- Spiky and variable pulse profile (variability timescale < 0.5 s)
- Period P = 1091 s
- Period derivative upper limit $\dot{P} < 6\times10^{-10}$ s/s
- Outburst radio luminosity ~ 10^{31} erg s^{-1}

GLEAM-X radio survey, 72 - 231 MHz
Wayth et al. 2015, 2018

Credit: Natasha Hurley-Walker (ICRAR/Curtin) and the GLEAM Team

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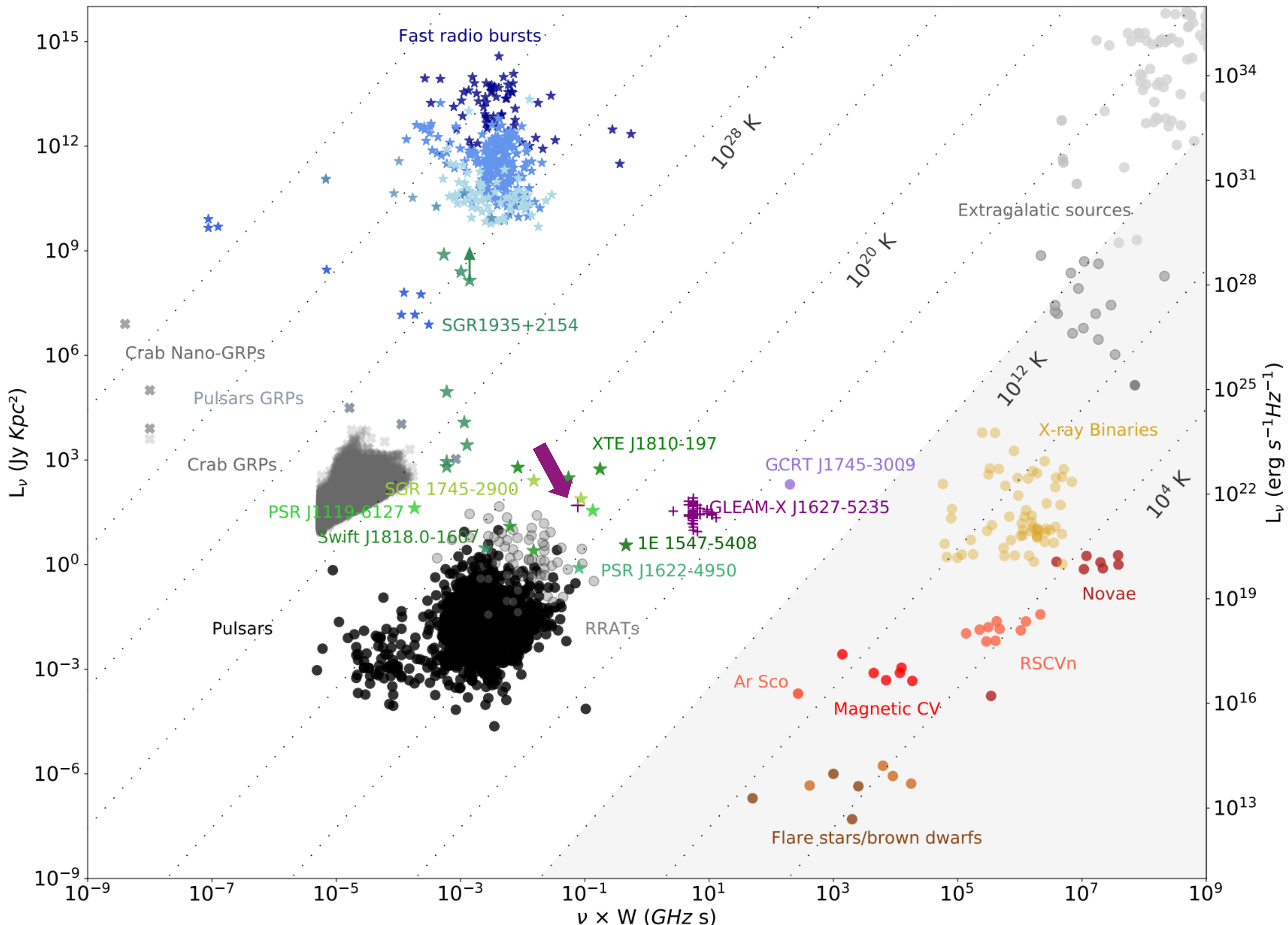
An unusual neutron star?

High radio luminosities
Small duration timescales → Non-thermal, coherent emission mechanism → Strong magnetic fields



Rea et al. (2022) submitted ApJ
Adapted from Pietka et al. (2015)

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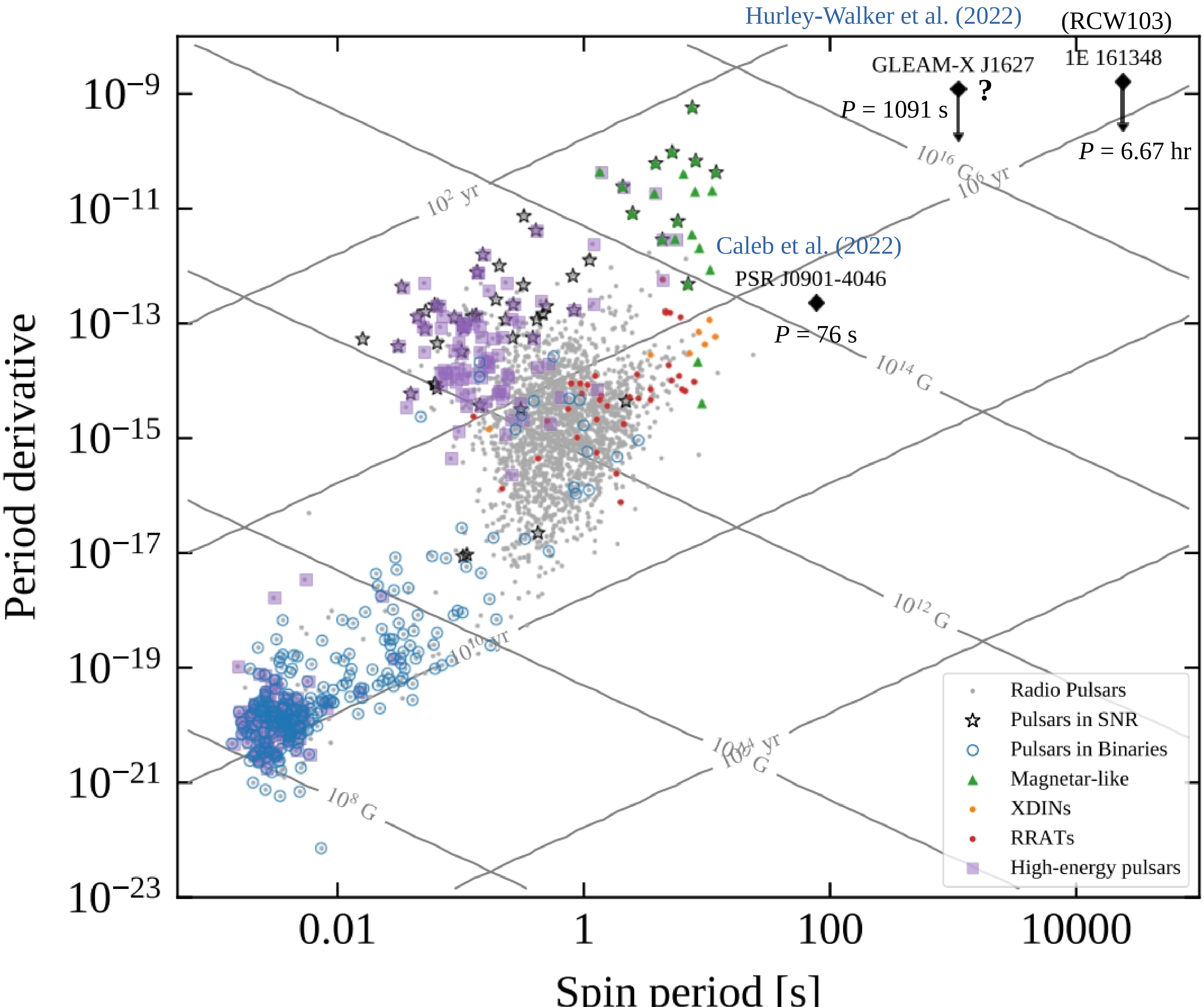
Slowly-spinning neutron stars?



Tuhoy et al. (1980)
De Luca et al. (2006)
Ho et al. 2017
Xu et al. 2019

Data from ATNF catalog

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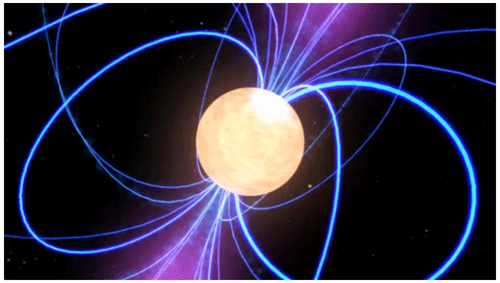


Credits: NASA

Electromagnetic dipolar torque

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

Where $\beta \sim 1.5 \times 10^{-41}$ s G^{-2}

For magnetic field dissipating in the neutron star crust:

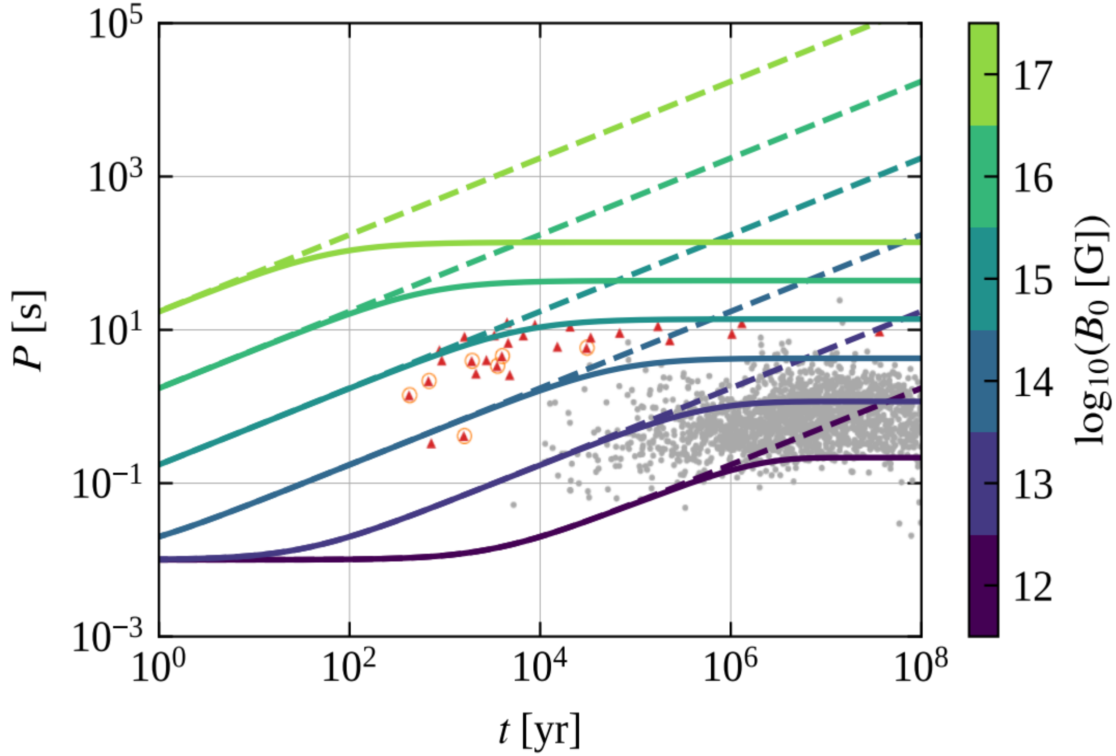
$$\frac{dB}{dt} \sim -\frac{B}{\tau_{Ohm}} - \frac{B^2}{B_0 \, \tau_{Hall,0}}$$

$$\tau_{Hall} \sim 6.4 \times 10^4 \, yr \left(\frac{n_e}{10^{35}\, cm^{-3}} \right) \left(\frac{L}{1\, km} \right)^2 \left(\frac{B_0}{10^{14}\, G} \right)^{-1}$$

$$\tau_{Ohm} \sim 4.4 \times 10^6 \, yr \left(\frac{\sigma}{10^{24}\, s^{-1}} \right) \left(\frac{L}{1\, km} \right)^2$$

Cumming et al. (2004)
Aguilera et al. (2008)
Gourgouliatos & Cumming (2014)

Data from the Magnetar Outburst Online Catalog and ATNF Catalog



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

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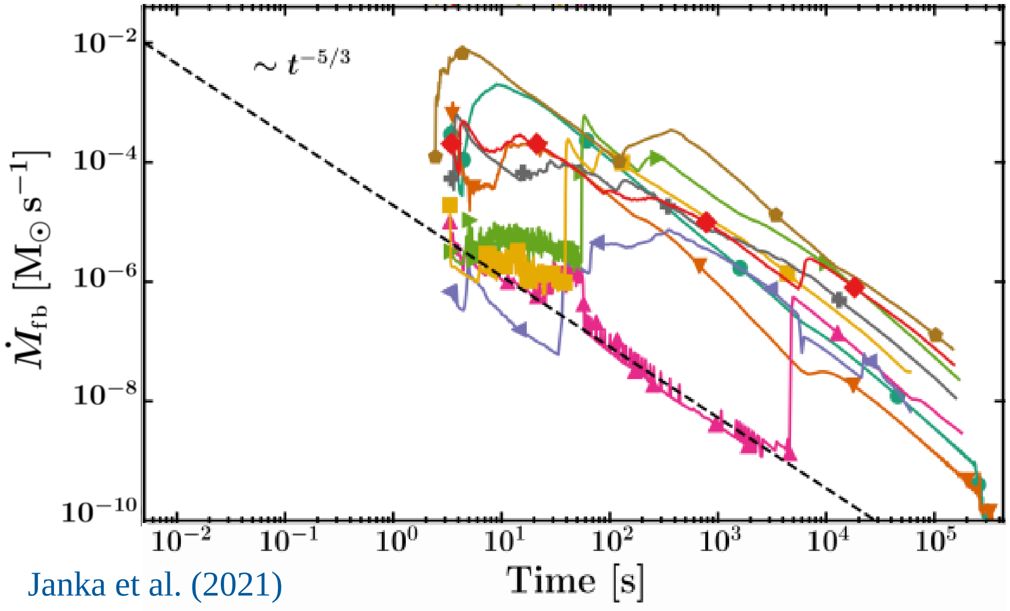
Supernova fallback scenario

Chatterjee et al. (2000)
Ertan et al. (2009)
Benli & Ertan (2016)

fallback starts on a timescale
t_{fb} ~ 10 -100 s post bounce



Janka et al. (2021)
Ugliano et al. (2012)
Ertl et al. (2016)

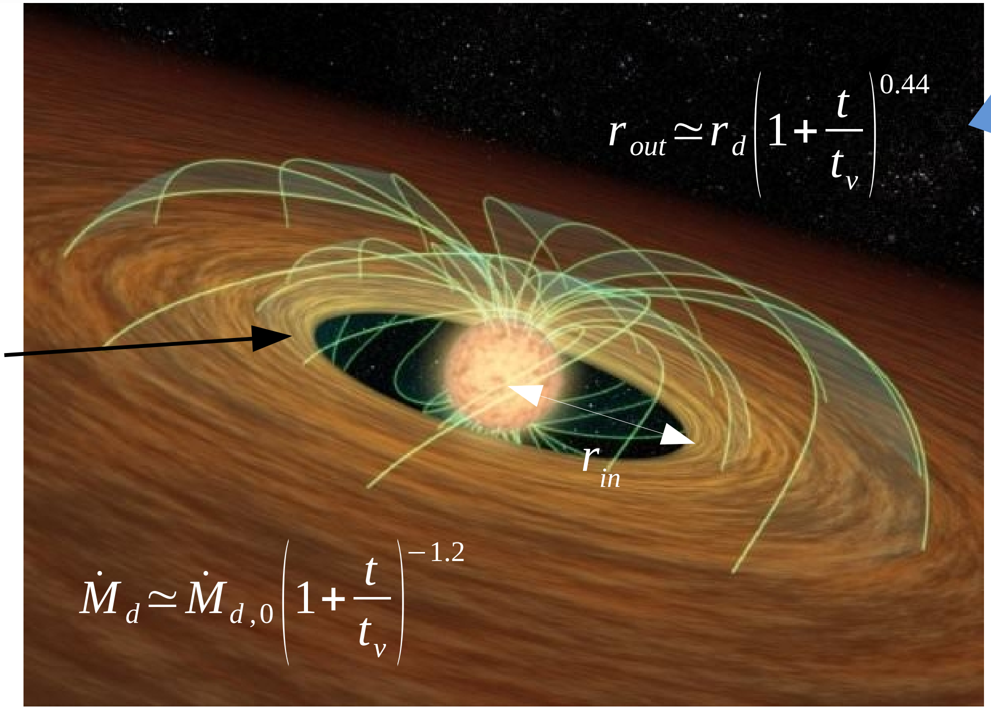
If fallback matter has enough angular momentum it will circularize to form a disk on a viscous timescale:

$$t_v \simeq 2\times10^3 \left(\frac{T_d}{10^6\,K}\right)^{-1} \left(\frac{R_d}{10^8\,cm}\right)^{1/2} s$$

T_d is a typical disk temperature
R_d is the circularization radius

Cannizzo et al. (1990)
Mineshige et al. (1997)
Menou et al. (2001)

Credits: NASA/JPL-Caltech



$$r_{out} \simeq r_d \left(1+\frac{t}{t_v}\right)^{0.44}$$

$$\dot{M}_d \simeq \dot{M}_{d,0} \left(1+\frac{t}{t_v}\right)^{-1.2}$$

At the inner radius of the disk the accretion rate is limited by the Eddington limit

The angular momentum transport inside the disk is driven by MHD turbulence which in turn depends on the ionization state of the disk and therefore on its opacity.

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Accretion onto a magnetized compact star

Magnetospheric (Alfvén) radius

ram pressure of in-falling matter
=
magnetic pressure

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

Light cylinder radius

Corotation speed
~
Speed of light

$$r_{lc} = \frac{c}{\omega}$$

Corotation radius

Keplerian speed
=
Corotation speed

$$r_{cor} = \left(\frac{G M_{NS}}{\omega^2} \right)^{1/3}$$

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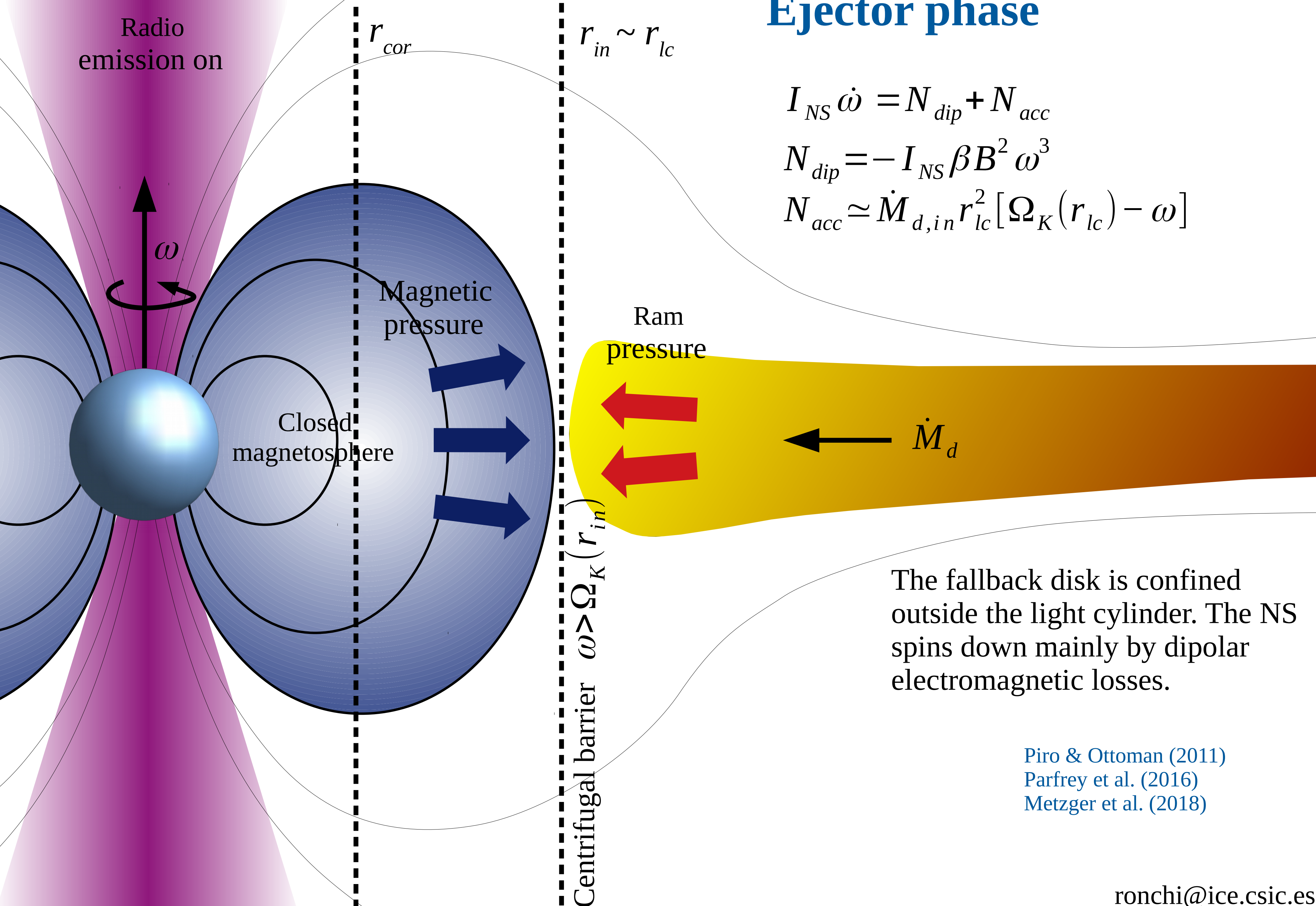
Supernova fallback model: Ejector phase



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

$$N_{dip} = -I_{NS}\,\beta B^2 \omega^3$$

$$N_{acc} \simeq \dot{M}_{d,in}\, r_{lc}^2 \left[\Omega_K(r_{lc}) - \omega\right]$$

The fallback disk is confined outside the light cylinder. The NS spins down mainly by dipolar electromagnetic losses.

Piro & Ottoman (2011)
Parfrey et al. (2016)
Metzger et al. (2018)

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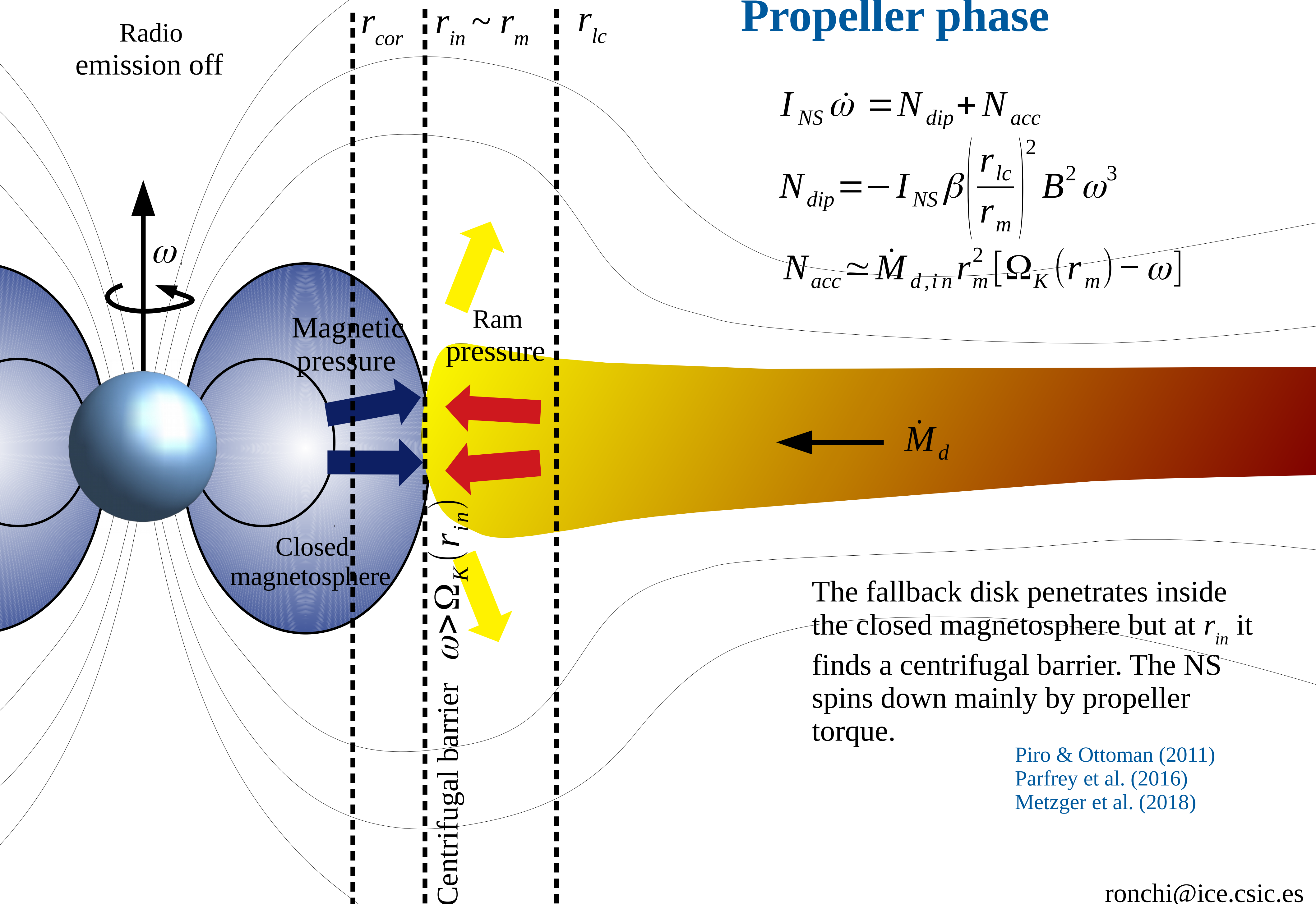
Supernova fallback model: Propeller phase

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

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

$$N_{acc} \simeq \dot{M}_{d,in}\, r_m^2 \left[\Omega_K(r_m) - \omega\right]$$



The fallback disk penetrates inside the closed magnetosphere but at r_{in} it finds a centrifugal barrier. The NS spins down mainly by propeller torque.

Piro & Ottoman (2011)
Parfrey et al. (2016)
Metzger et al. (2018)

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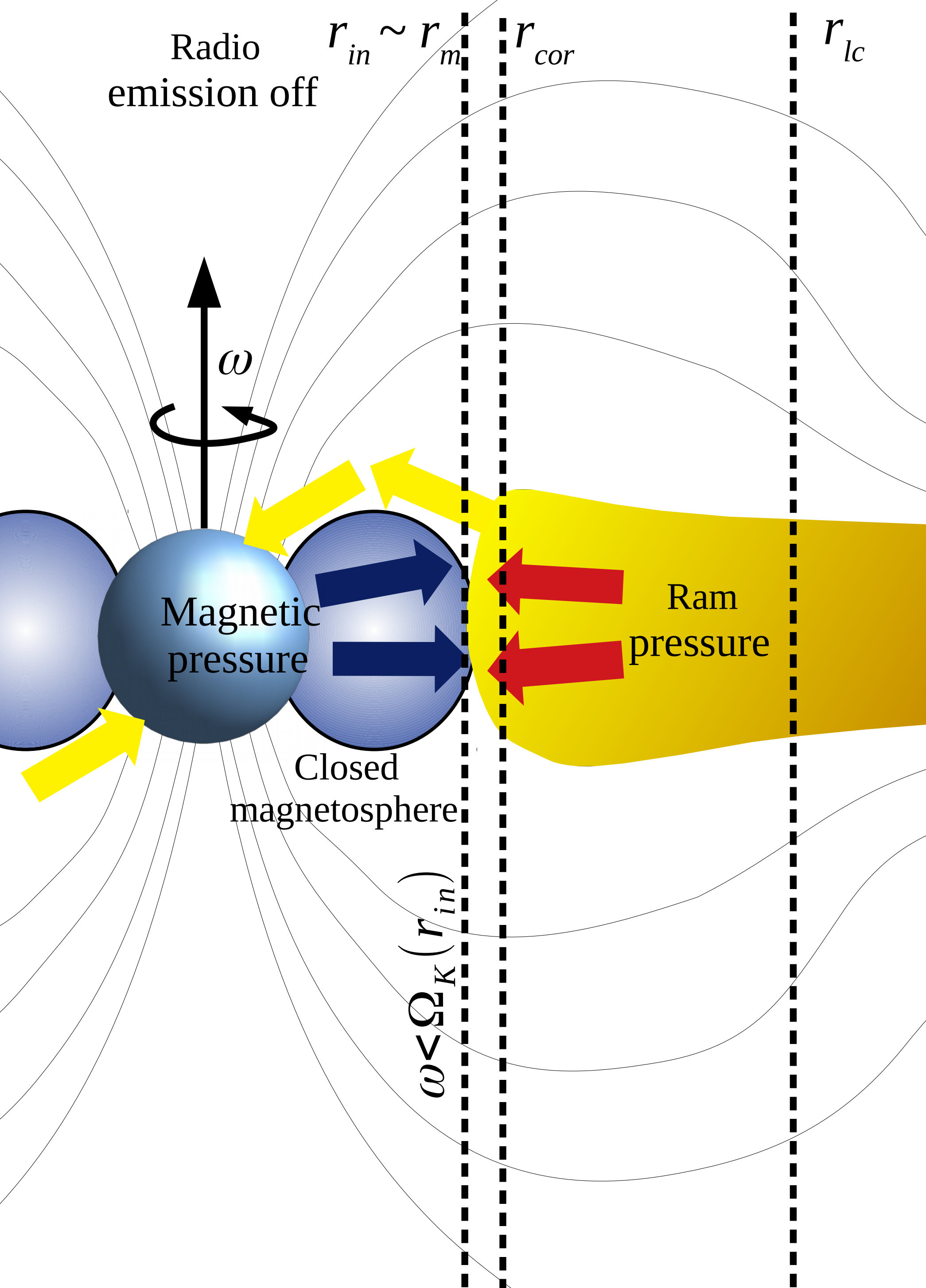
Supernova fallback model: accretion phase



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

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

$$N_{acc} \simeq \dot{M}_{d,in}\, r_m^2 \left[\Omega_K(r_m) - \omega\right]$$

The fallback disk penetrates inside the closed magnetosphere and it is super-Keplerian at r_{in}. The NS spins up and accretes on the surface.

Piro & Ottoman (2011)
Parfrey et al. (2016)
Metzger et al. (2018)

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Supernova fallback model: evolution example

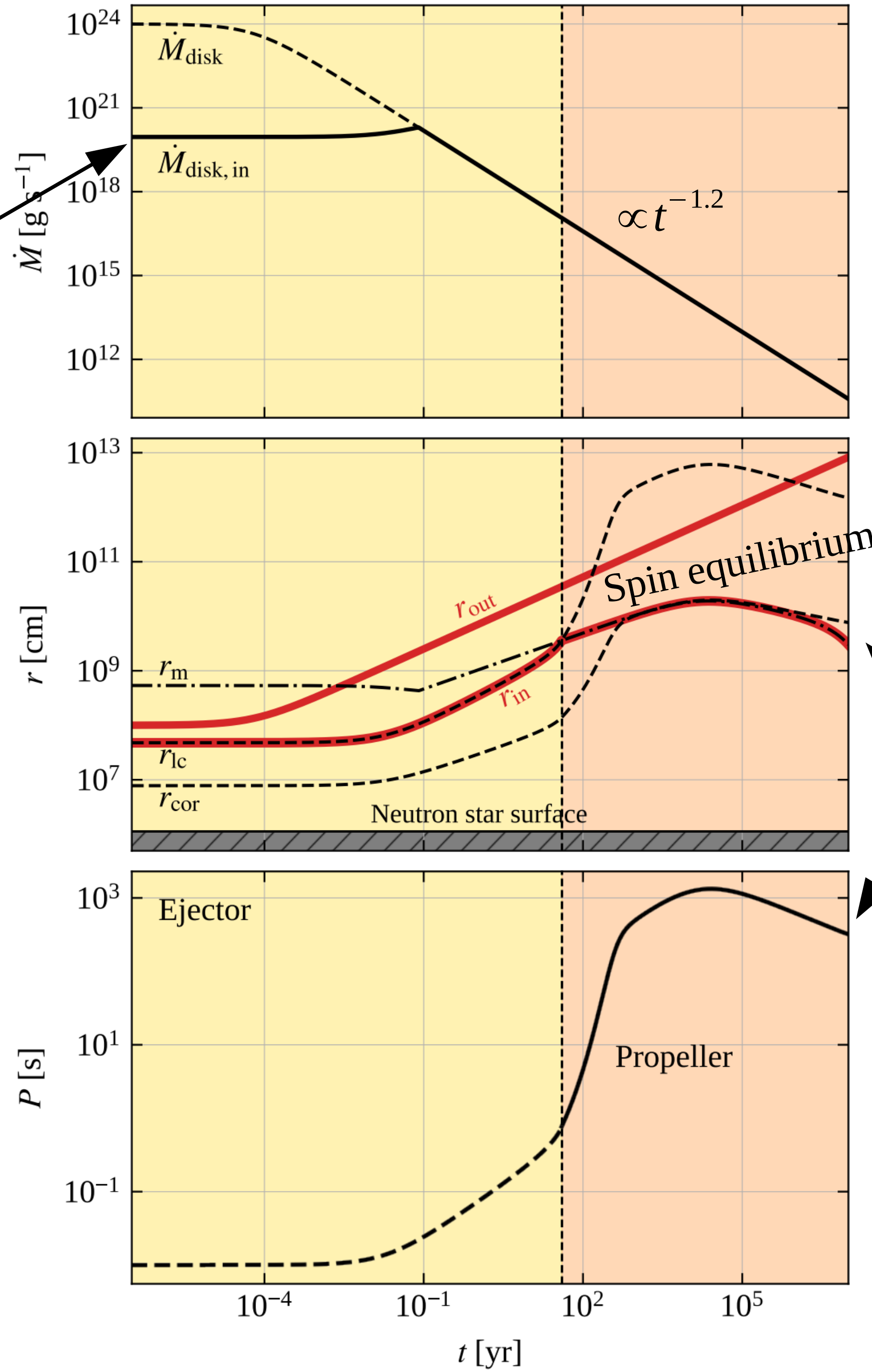
The accretion rate at the inner radius is limited by the Eddington luminosity

Initial conditions:

$P_0 = 0.01\,s$

$B_0 = 4\times10^{14}\,G$

$\dot{M}_{d,0} = 10^{24}\,g\,s^{-1}$



Evolution of the accretion rate

Evolution of the critical radii

Effect of the magnetic field decay

Evolution of the spin period

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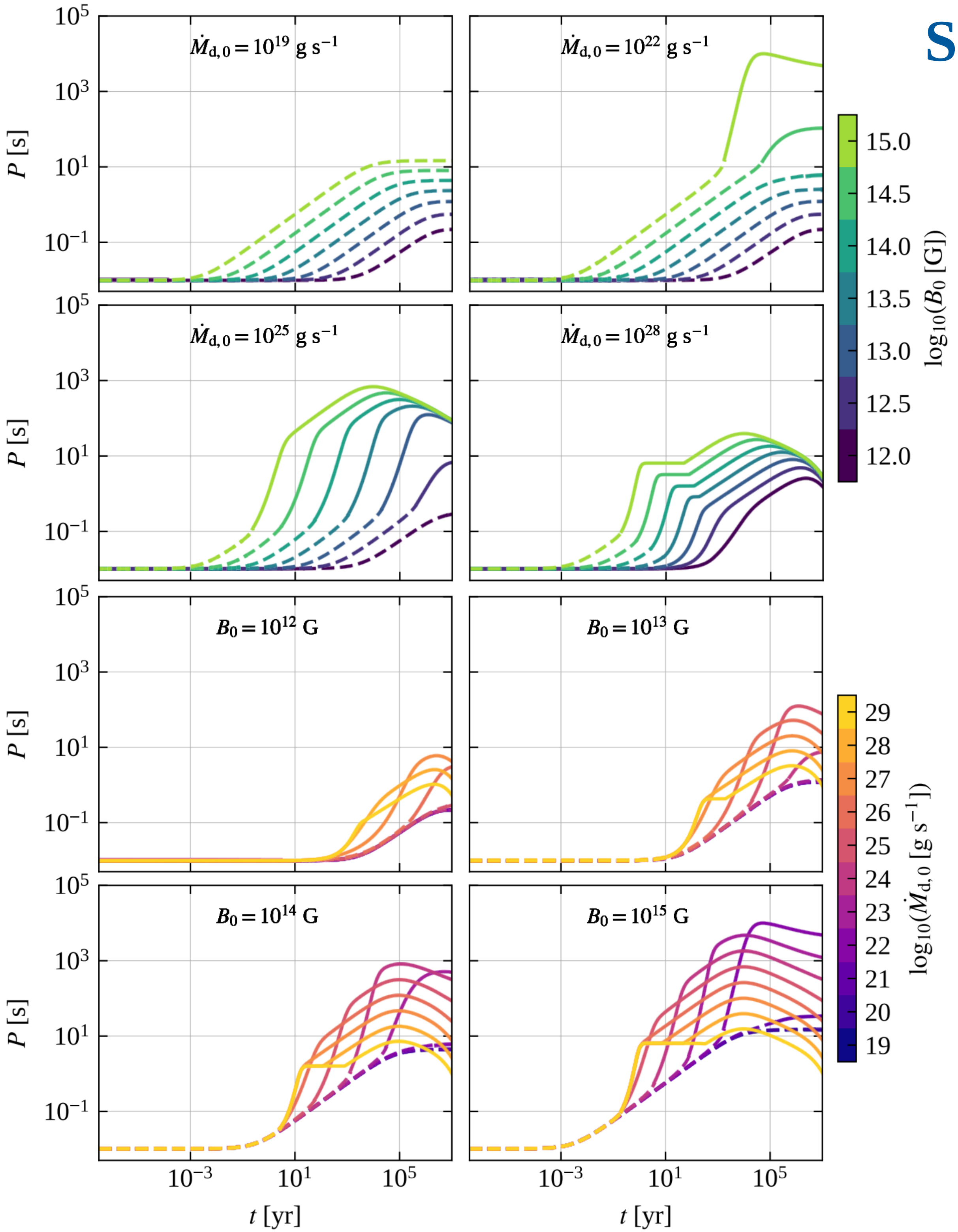
Supernova fallback model: evolution example



Too low or too high disk accretion rates do not allow the star to reach very long spin periods

Typical magnetic fields of normal pulsars do not allow the star to reach very long spin periods. Magnetar field strengths are needed!

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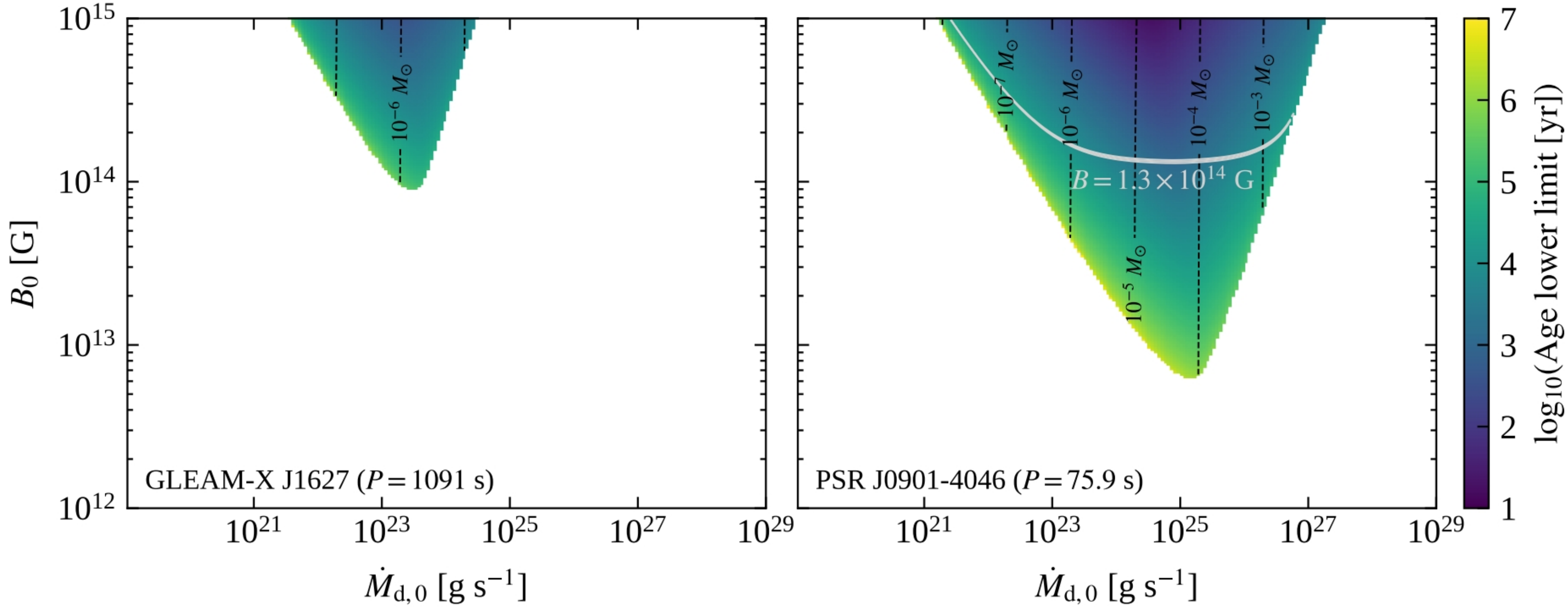
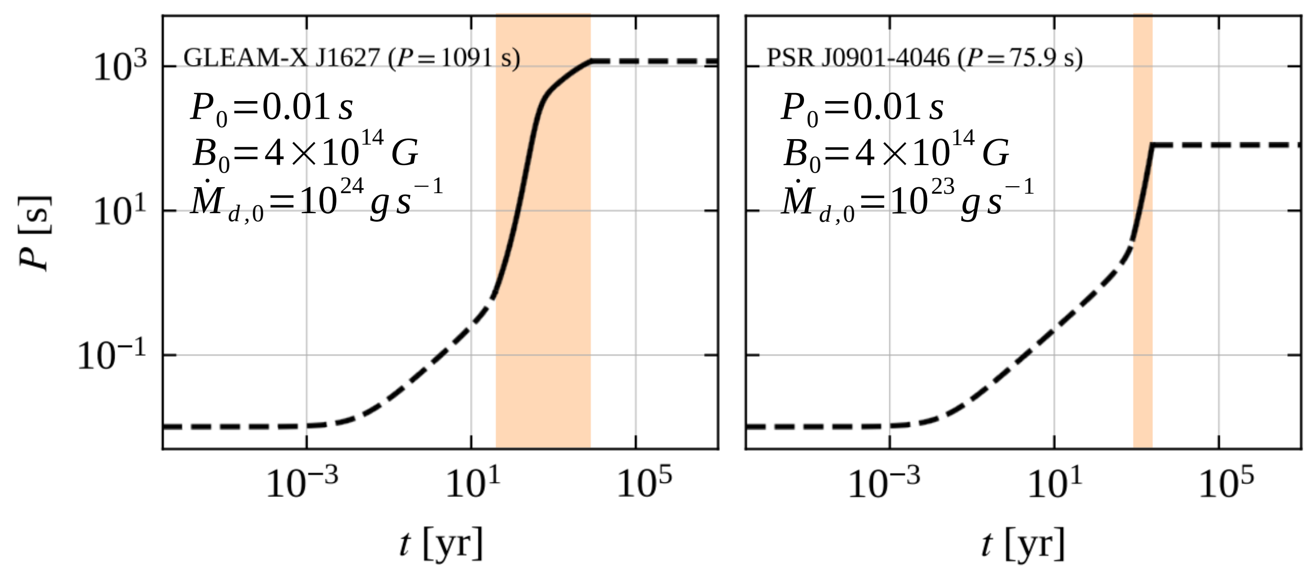
Application to GLEAM-X J162759 and PSR J0901–4046





GLEAM-X J162759 and PSR J0901–4046 have been observed as a radio pulsar. They should have transitioned to the ejector phase.

The fallback scenario allows us to relax the physical conditions necessary to reach very long periods (> 100 s). It requires magnetar-like magnetic fields (~10^{14} G) and accretion rates in line with supernova simulations.

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Restoring the radio emission

We need to stop the accretion flow in the disk. How?

- 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
  Mineshige et al. (1993), Menou et al. (2001)

Critical accretion rate: $\dot{M}_{d,crit} \sim 10^{16}\, g\, s^{-1}$

$t_n \sim 10^3 - 10^4$ yr

A recombination front propagates into the disk starting from the outer edges.

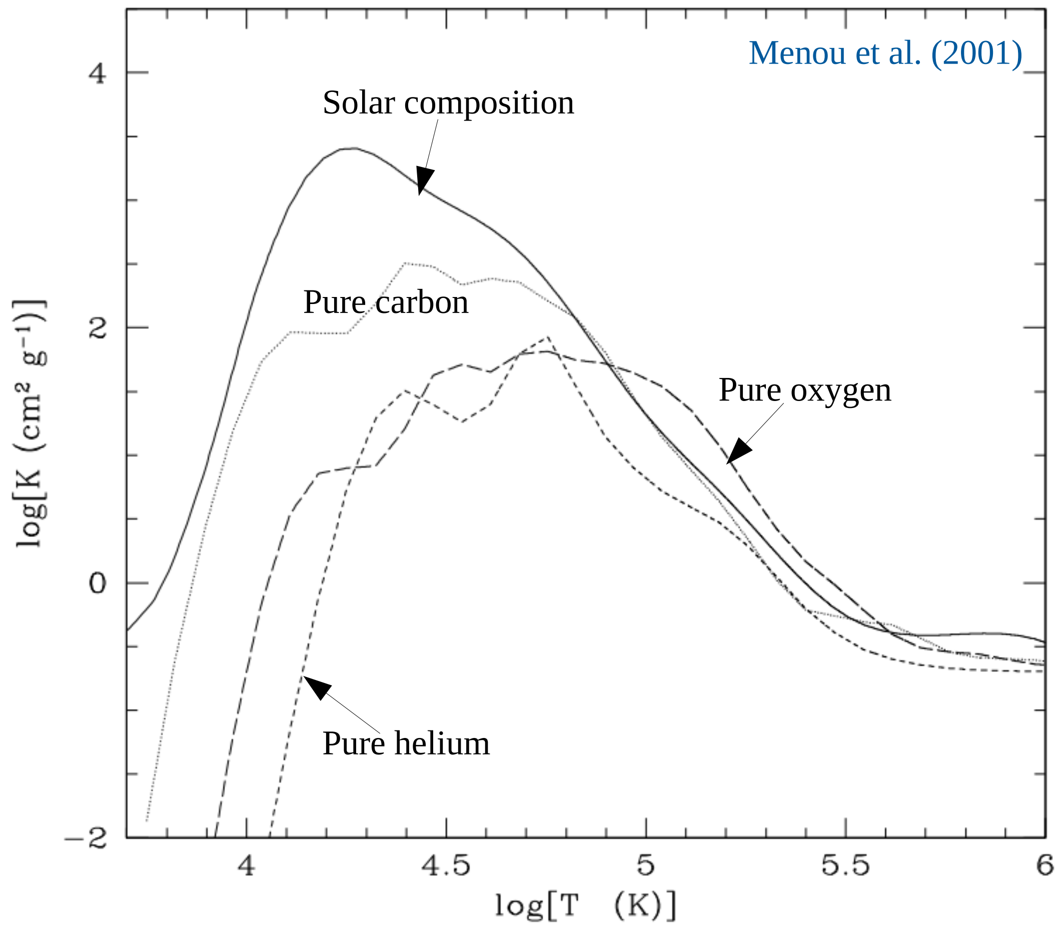
↓

Viscous and magnetic properties are altered, effective angular momentum transport is inhibited.

↓

Accretion stops, the disk becomes inactive.

Rosseland-mean opacities as a function of temperature. The opacity drop at $T_{crit} \sim 10^4$ K corresponds to the last available free electron.



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Summary & Conclusions

Electromagnetic dipolar spin-down is not enough

Reaching long period (> 100 s) requires an almost constant (core-dominated?) and extreme magnetic field (> 10^{15} G).

Interaction with fallback disk

The fallback scenario allows to relax the physical conditions necessary to reach long period at relatively young ages. It requires magnetars-like magnetic fields (> 10^{14} G) and accretion rates (~ 10^{22} - 10^{27} g s^{-1}) in line with supernova simulations.

Application to GLEAM-X J1627 and PSR J0901–4046

They could be magnetars with $B > 10^{14}$ G that have experienced fallback accretion with initial accretion rate ~ 10^{23} - 10^{25} g s^{-1}

The fallback disk could be disrupted, consumed or become inactive on timescales of 10^{3-4} yr so that the radio emission mechanism can be reactivated.

A multi-wavelength study of GLEAM-X J1627 revealed no evident optical/IR counterpart and put a stronger constrain on the X-ray luminosity of ~10^{30} erg/s (Rea et al. 2022 submitted ApJ)

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Thank you for your attention!

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Multiband observation of GLEAM-X J162759

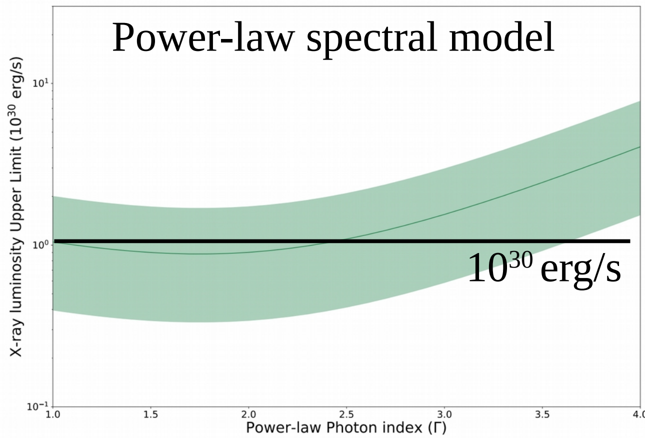
Rea et al. (2022) submitted

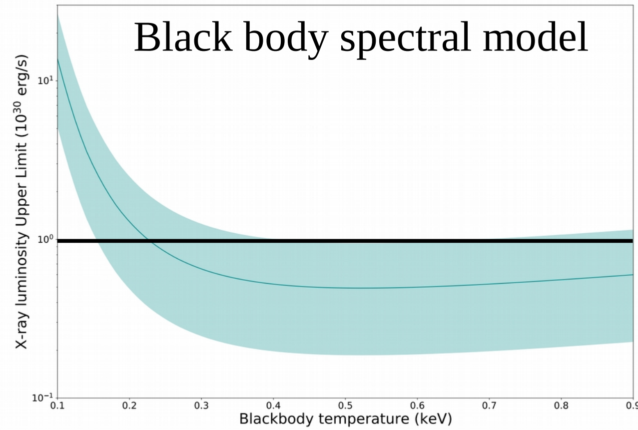
No optical/IR counterpart found in archival data →

- If in a binary system, a stellar companion should be detectable.
- If a WD it should be cold but highly magnetic.

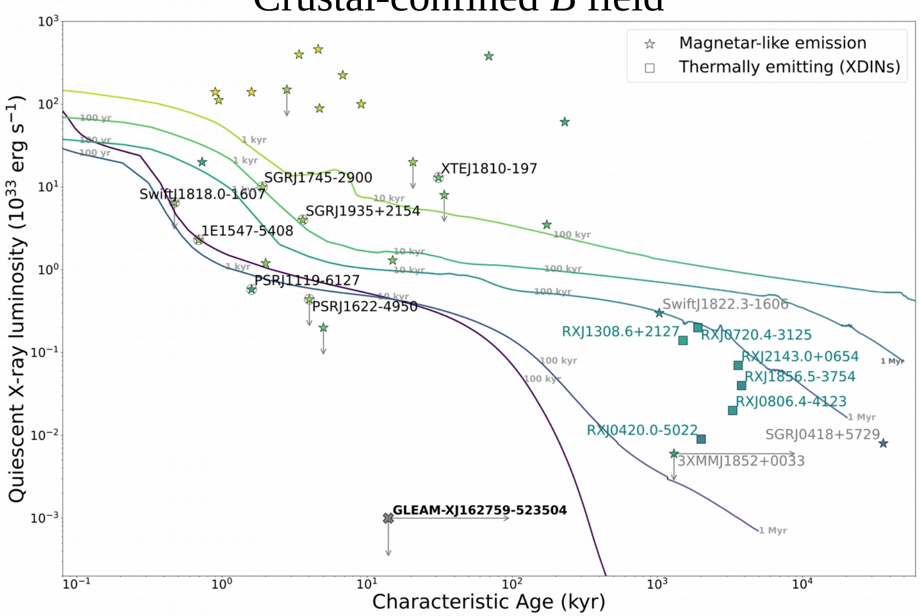
More costringent X-ray luminosity upper limit:

~ 10 hr observations with Chandra X-ray Observatory in the energy range 0.3 – 8 keV

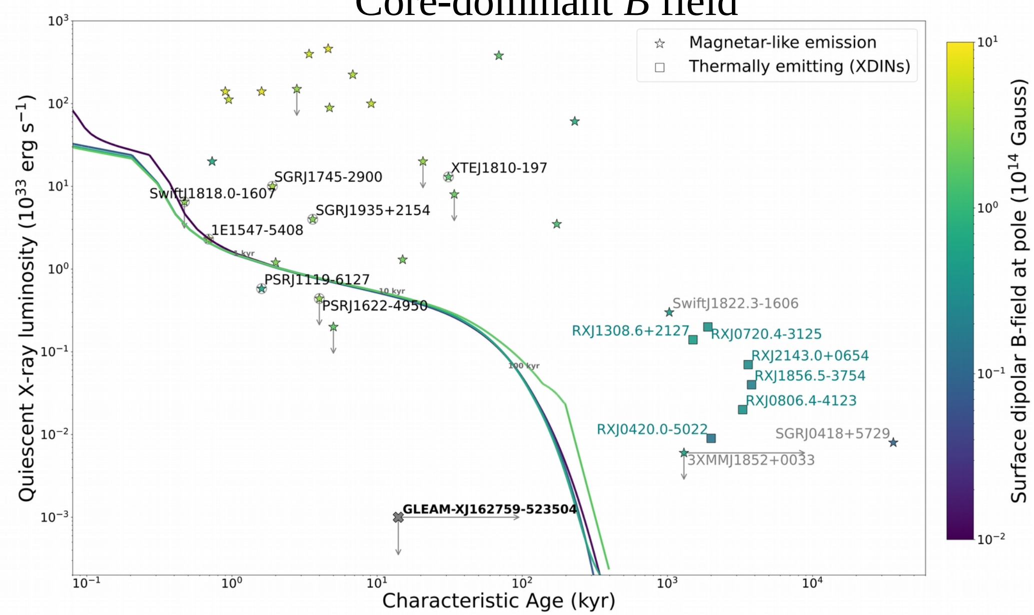




Crustal-confined *B* field



Core-dominant *B* field



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Alternative theories on GLEAM-X nature

Ekşi et al. (2022)

the observed periodicity could be caused by a precessing magnetar deformed by a strong toroidal magnetic field component.

Loeb et al. (2022)

hot, strongly magnetized subdwarf spinning nearly at the breakup limit, most likely following an accretion episode from a companion.

Katz (2022)

strongly magnetized white dwarf emitting coherent curvature radiation.

See also Gencali et al. 2022 for an alternative neutron star – disk interaction model and Tong 2022 for an interesting discussion on the nature of GLEAM-X.