THE ROLE OF FALLBACK DISCS IN THE LONG-TERM EVOLUTIONARY LINKS BETWEEN THE ISOLATED NEUTRON STAR POPULATIONS

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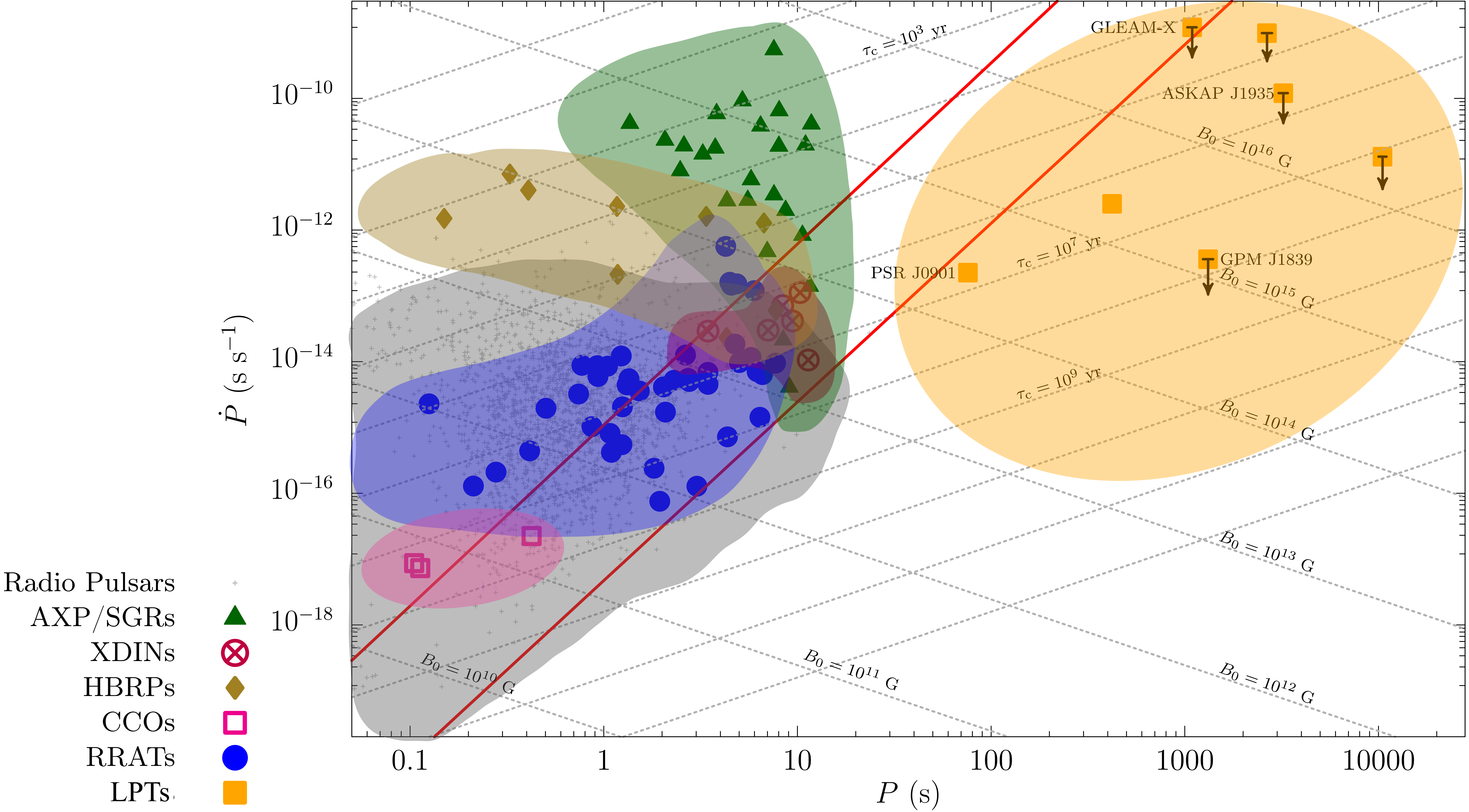
Isolated Neutron Star Populations

- **Anomalous X-ray Pulsars (AXPs)**
- **Soft Gamma Repeaters (SGRs)**
- **Dim Isolated Neutron Stars (XDINs)**
- **“High-Magnetic-Field” Radio Pulsars (HBRPs)**
- **Central Compact Objects (CCOs)**
- **Rotating Radio Transients (RRATs)**
- **Long-period Pulsars (LPPs) – Long-period Radio Transients (LPTs)**


GLEAM-X
ASKAP J1935
GPM J1839
PSR J0901
$\tau_c = 10^3$ yr
$\tau_c = 10^7$ yr
$\tau_c = 10^9$ yr
$B_0 = 10^{16}$ G
$B_0 = 10^{15}$ G
$B_0 = 10^{14}$ G
$B_0 = 10^{13}$ G
$B_0 = 10^{12}$ G
$B_0 = 10^{11}$ G
$B_0 = 10^{10}$ G
10^{-10}
10^{-12}
10^{-14}
10^{-16}
10^{-18}
$\dot{P}$ (s s^{-1})
0.1
1
10
100
1000
10000
P (s)
Radio Pulsars +
AXP/SGRs ▲
XDINs ⊗
HBRPs ◆
CCOs □
RRATs ●
LPTs ■

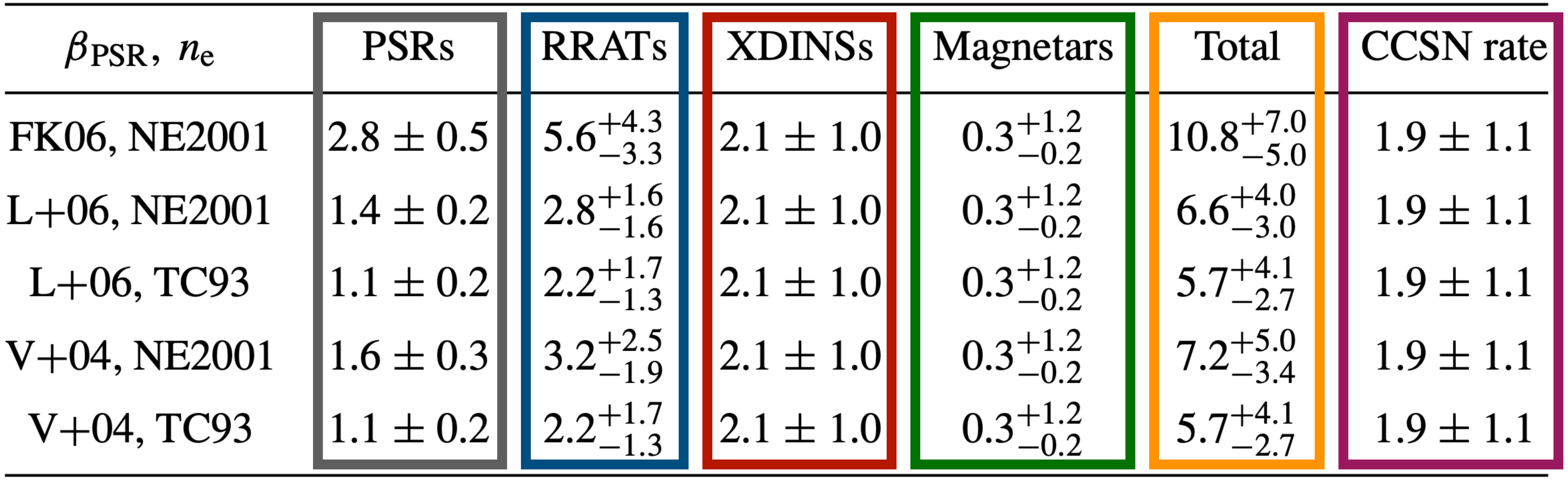
Birth Rate Problem

- **Galactic Supernova Rate:** $\beta_{\mathrm{CCSN}} \sim (1.9 \pm 1.1)\ \mathrm{century}^{-1}$

  (Diehl et al., 2006; Faucher-Giguère & Kaspi, 2006; Keane & Kramer, 2008; Popov et al., 2006; Rozwadowska, Vissani, & Cappellaro, 2021)

- $\beta_{\mathrm{RRATs}} \gtrsim \beta_{\mathrm{PSRs}} \sim \beta_{\mathrm{XDINs}} \sim \beta_{\mathrm{CCSN}} \Rightarrow \beta_{\mathrm{TOT}} > \beta_{\mathrm{CCSN}}$

  (Vranesevic et al. 2004; Lorimer 2005; Faucher-Giguére & Kaspi 2006; Popov et al. 2006; Kean & Kramer 2008)



β_{PSR}, n_e	PSRs	RRATs	XDINSs	Magnetars	Total	CCSN rate
FK06, NE2001	2.8 ± 0.5	$5.6^{+4.3}_{-3.3}$	2.1 ± 1.0	$0.3^{+1.2}_{-0.2}$	$10.8^{+7.0}_{-5.0}$	1.9 ± 1.1
L+06, NE2001	1.4 ± 0.2	$2.8^{+1.6}_{-1.6}$	2.1 ± 1.0	$0.3^{+1.2}_{-0.2}$	$6.6^{+4.0}_{-3.0}$	1.9 ± 1.1
L+06, TC93	1.1 ± 0.2	$2.2^{+1.7}_{-1.3}$	2.1 ± 1.0	$0.3^{+1.2}_{-0.2}$	$5.7^{+4.1}_{-2.7}$	1.9 ± 1.1
V+04, NE2001	1.6 ± 0.3	$3.2^{+2.5}_{-1.9}$	2.1 ± 1.0	$0.3^{+1.2}_{-0.2}$	$7.2^{+5.0}_{-3.4}$	1.9 ± 1.1
V+04, TC93	1.1 ± 0.2	$2.2^{+1.7}_{-1.3}$	2.1 ± 1.0	$0.3^{+1.2}_{-0.2}$	$5.7^{+4.1}_{-2.7}$	1.9 ± 1.1

(Kean & Kramer 2008)

Birth Rate Problem

- **Galactic Supernova Rate:** $\beta_{\mathrm{CCSN}} \sim (1.9 \pm 1.1)\ \mathrm{century}^{-1}$

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  (Vranesevic et al. 2004; Lorimer 2005; Faucher-Giguére & Kaspi 2006; Popov et al. 2006; Kean & Kramer 2008)

- **Evolutionary links between these NS populations**

  (Faucher-Giguère & Kaspi, 2006; Popov et al., 2006; Keane & Kramer, 2008; Gullón et al., 2014; Kaspi & Kramer, 2016; Johnston & Karastergiou, 2017; Beniamini et al., 2019; Jawor & Tauris, 2022)

Models

- Magnetar Model
- **Fallback Disc Model**

Very Brief Introduction of Magnetar Model

- Rotating NS in a vacuum
- Slowing down by purely magnetic dipole torque; $\Gamma_{\rm dip} = I\dot{\Omega} = -\frac{2}{3}\frac{\mu^2\Omega_*^3}{c^3}$
- $B_0 \sim 6.4 \times 10^{19}\sqrt{P\dot{P}} \gtrsim 10^{14}$ G
- Field Decay —> Heating of the Crust —> Observed $L_{\rm X}$

(Duncan & Thompson, 1992; Thompson & Duncan, 1995)

Fallback Disc Model

- **Disc-field interaction**

- **Dominant Torque –> Disc Torque (Γ_{D})**

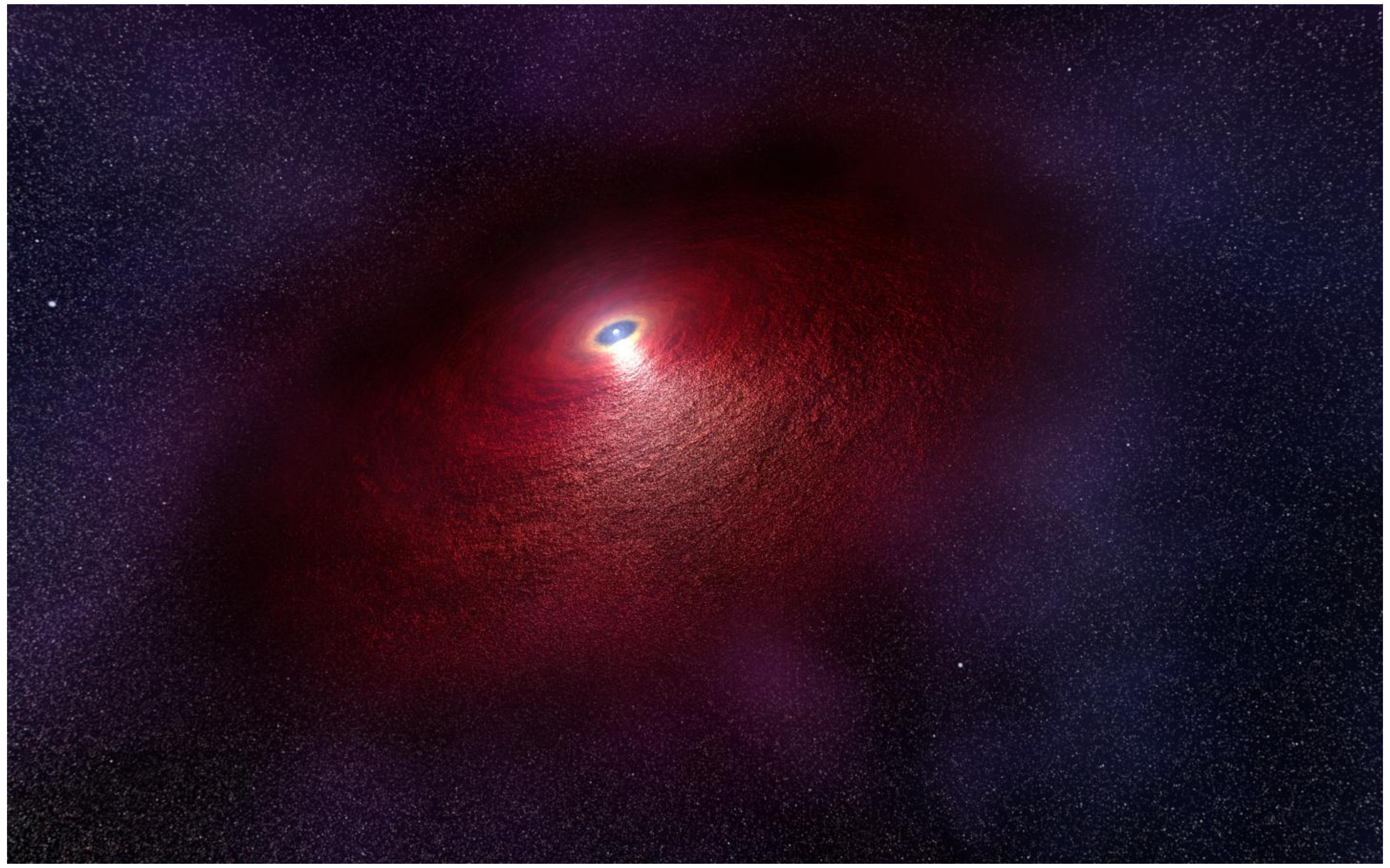
- $\Gamma_{\mathrm{D}} = \frac{\mu^2}{r_{\mathrm{in}}^3}\left(\frac{\Delta r}{r_{\mathrm{in}}}\right), \mu = BR_{\mathrm{NS}}^3$

- **Source of L_{X}**
  - $L_{\mathrm{acc}} = GM\dot{M}_*/R$ and $L_{\mathrm{cool}} -> L_{\mathrm{X}} = L_{\mathrm{acc}} + L_{\mathrm{cool}}$

(Ertan & Çalışkan 2006; Ertan et al. 2007; Ertan & Erkut 2008; Ertan et al. 2009)

Fallback Discs

- **After SNe, some of the ejected matter could fall back** (Chevalier, 1989; Colgate, 1971; Woosley et al., 2002; Zel'dovich et al., 1972)
- **If** this matter **has sufficient angular momentum**, **a fallback disc could form** around the newly born NS (Michel & Dessler 1981; Michel 1988; Mineshige et al. 1997; Perna et al. 2014)



Fallback Disc Model

- Proposed to explain the observed P clustering and L_{X} of AXPs (Chatterjee et al. 2000)
- The model could explain the observed properties of other young NS populations too (Alpar 2001)

Fallback Disc Model

- **Solving the disc diffusion equation with α (0.045) prescription**
- **The model includes the effects of:**
  - X-ray irradiation of the disc, $\boldsymbol{C = (1 - 7) \times 10^{-4}}$
  - Contribution of the $\boldsymbol{L_{\mathrm{cool}}}$ into the irradiation (Page et al. 2006, 2009)
  - Inactivation of the disc at low temperatures ($\boldsymbol{T_{\mathrm{P}} = 50 - 150\ \mathrm{K}}$)

(Ertan & Çalışkan 2006; Ertan et al. 2007; Ertan & Erkut 2008; Ertan et al. 2009)

Inner Disc (r_{in})

- $\boldsymbol{R_{\mathrm{in,max}}^{25/8}\ |1 - R_{\mathrm{in,max}}^{-3/2}|\ \simeq\ 1.26\ \alpha_{-1}^{2/5}\ M_{1.4}^{-7/6}\ \dot{M}_{\mathrm{in,16}}^{-7/20}\ \mu_{30}\ P^{-13/12}}$
  - $R_{\mathrm{in,\ max}} = r_{\mathrm{in,\ max}}/r_{\mathrm{co}}, \quad \alpha_{-1} = (\alpha/0.1), \quad M_{1.4} = (M/1.4\ M_{\odot})$
  - $\dot{M}_{\mathrm{in,16}}\ =\ \dot{M}_{\mathrm{in}}/(10^{16}\ \mathrm{g\ s^{-1}}), \quad \mu_{30} = \mu/(10^{30}\ \mathrm{G\ cm^{3}})$
- $\boldsymbol{r_{\mathrm{in}} = r_{\eta} = \eta\ r_{\mathrm{in,max}}}$, where $\eta \lesssim 1$

Ertan Ü., 2017, MNRAS, 466, 175
Ertan Ü., 2018, MNRAS, 479, L12
Ertan Ü., 2021, MNRAS, 500, 2928

Rotational Phases

Strong Propeller (SP) Phase

- $r_\eta = r_{\rm in} > 1.26\, r_{\rm co} = r_1$

No mass accretion ($\dot{M}_* = 0$)

Pulsed Radio emission is allowed!

- $L_{\rm acc} = 0$ and $L_{\rm X} = L_{\rm cool}$
- $$\Gamma_{\rm tot} = \frac{\mu^2}{r_{\rm in}^3}\left(\frac{\Delta r}{r_{\rm in}}\right) + \cancel{\Gamma_{\rm dip}}$$

Weak Propeller (WP) Phase

- $\mathbf{1.26}\ r_{\rm co} = r_1 \geq r_{\rm in}$

Mass accretion from $r_{\rm in} = r_{\rm co}$

Ordinary Radio Pulses are Expected to be quenched!

- $L_{\rm X} = L_{\rm acc} + L_{\rm cool}$
- $\Gamma_{\rm SU} \simeq \dot{M}_* \sqrt{GMr_{\rm in}}\ , \quad (\dot{M}_* = \dot{M}_{\rm in})$
- $\Gamma_{\rm tot} = \Gamma_{\rm D} + \Gamma_{\rm SU} + \cancel{\Gamma_{\rm dip}}$

LONG-TERM EVOLUTIONARY LINKS BETWEEN THE ISOLATED NEUTRON STAR POPULATIONS

Disc parameters

$\alpha = 0.045,\ T_{\rm P} = 50\ \mathrm{K},$

$C = 1 \times 10^{-4}$

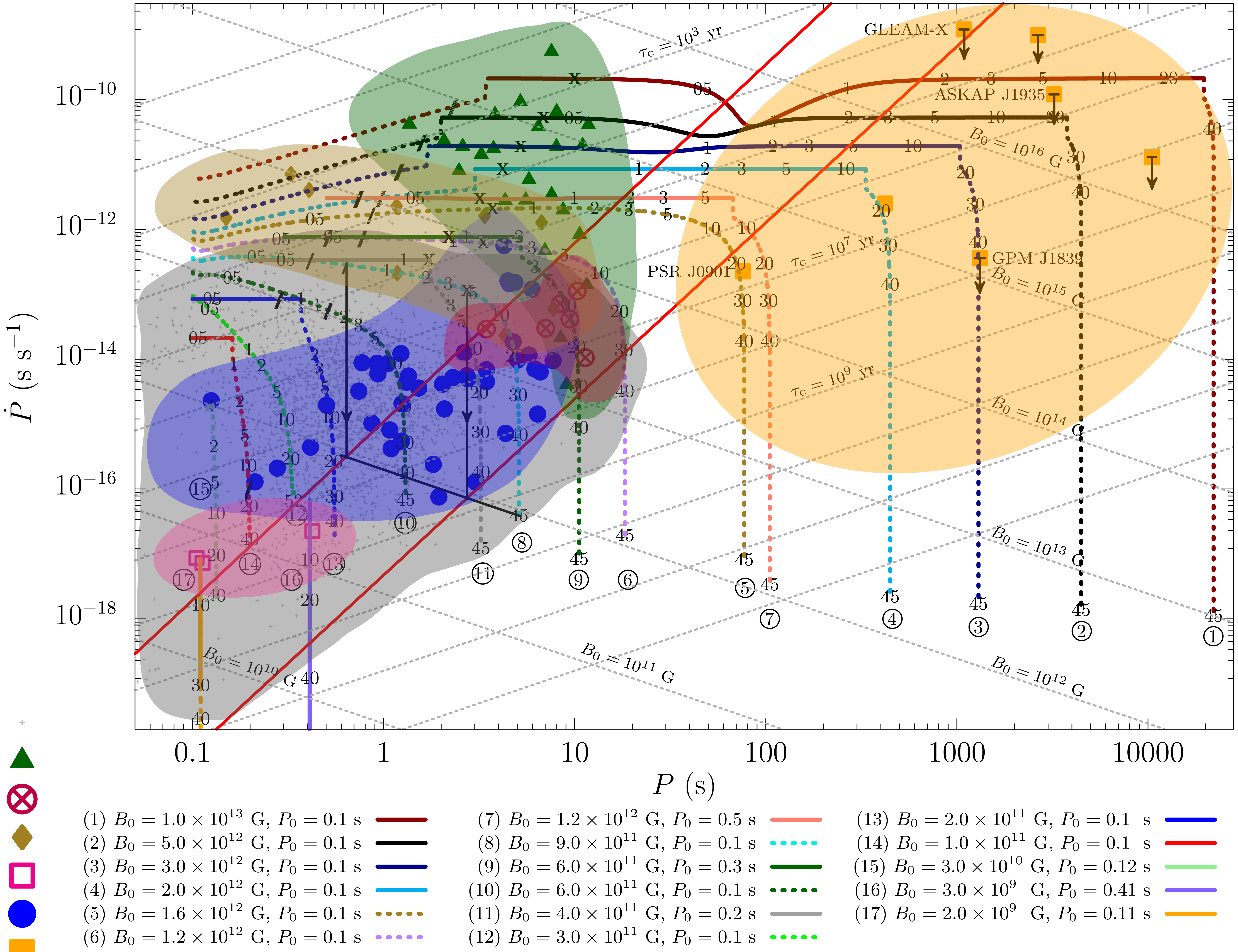
$L_{\rm cool,\,max}$ is used

Initial Conditions

$P_0 = 0.1 - 0.5\ \mathrm{s}$

$M_{\rm d} \simeq 1 \times 10^{-5}\ M_{\odot}$

$\boxed{B_0 = 2 \times 10^9 - 1 \times 10^{13}\ \mathrm{G}}$



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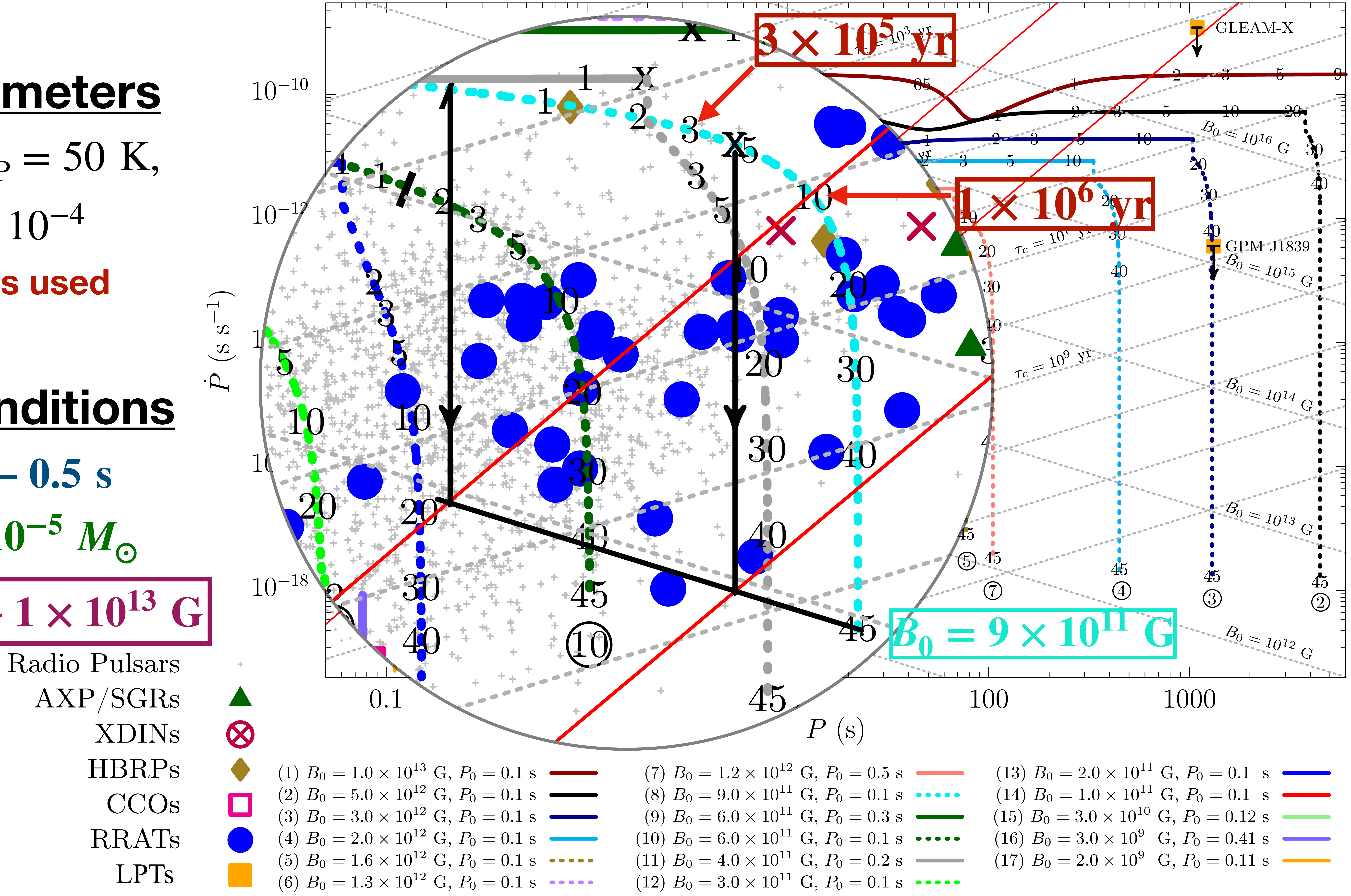


3×10^5 yr

1×10^6 yr

$B_0 = 9 \times 10^{11}$ G

Initial Conditions

$P_0 = 0.1 - 0.5$ s

$M_\mathrm{d} \simeq 1 \times 10^{-5}\ M_\odot$

$B_0 = (1.2 - 10) \times 10^{12}$ G

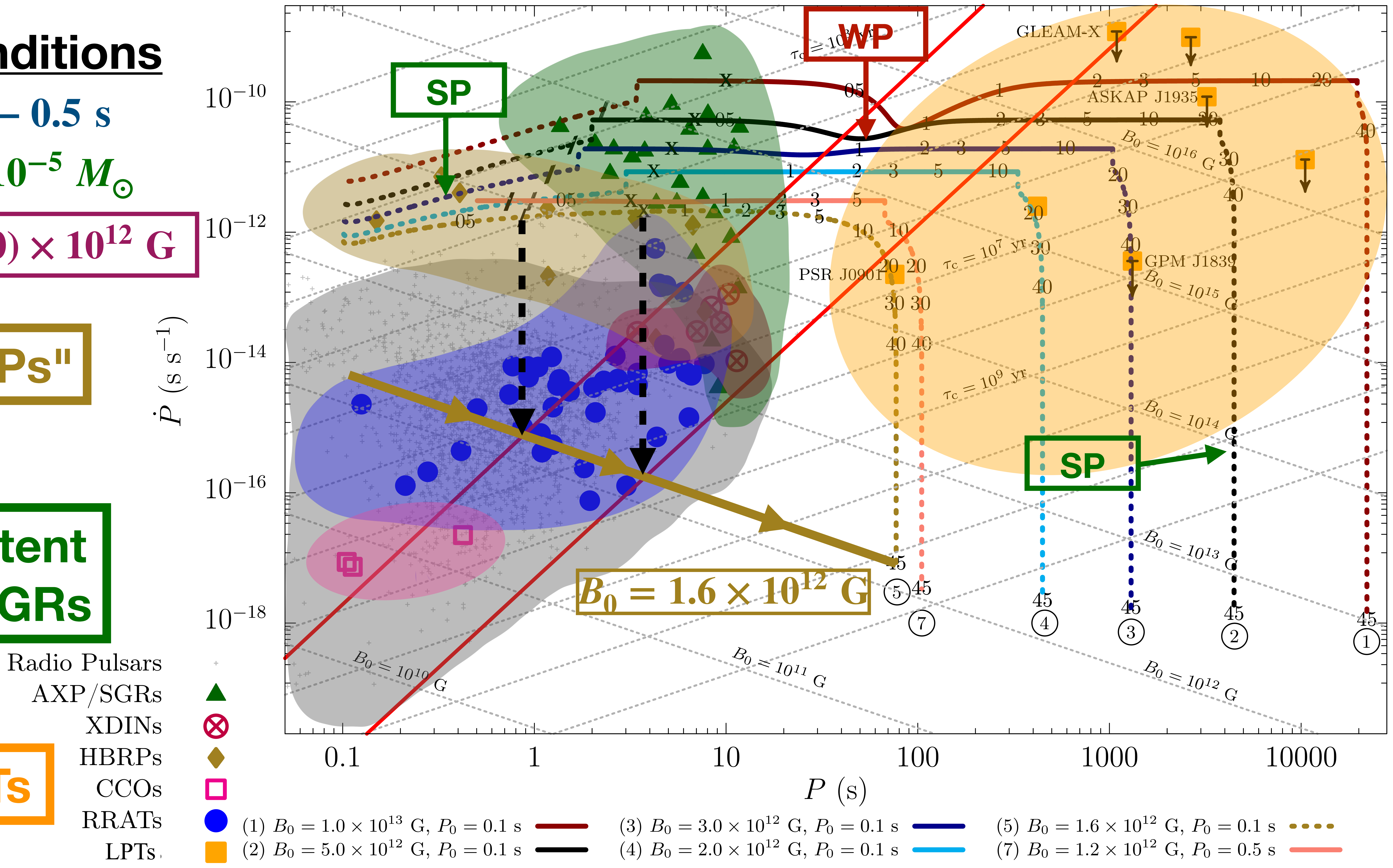
"HBRPs"

↓

Persistent AXP/SGRs

↓

LPTs



Initial Conditions

$P_0 = 0.1 - 0.3$ s

$M_\mathrm{d} \simeq 1 \times 10^{-5}\ M_\odot$

$B_0 = (4 - 13) \times 10^{11}$ G

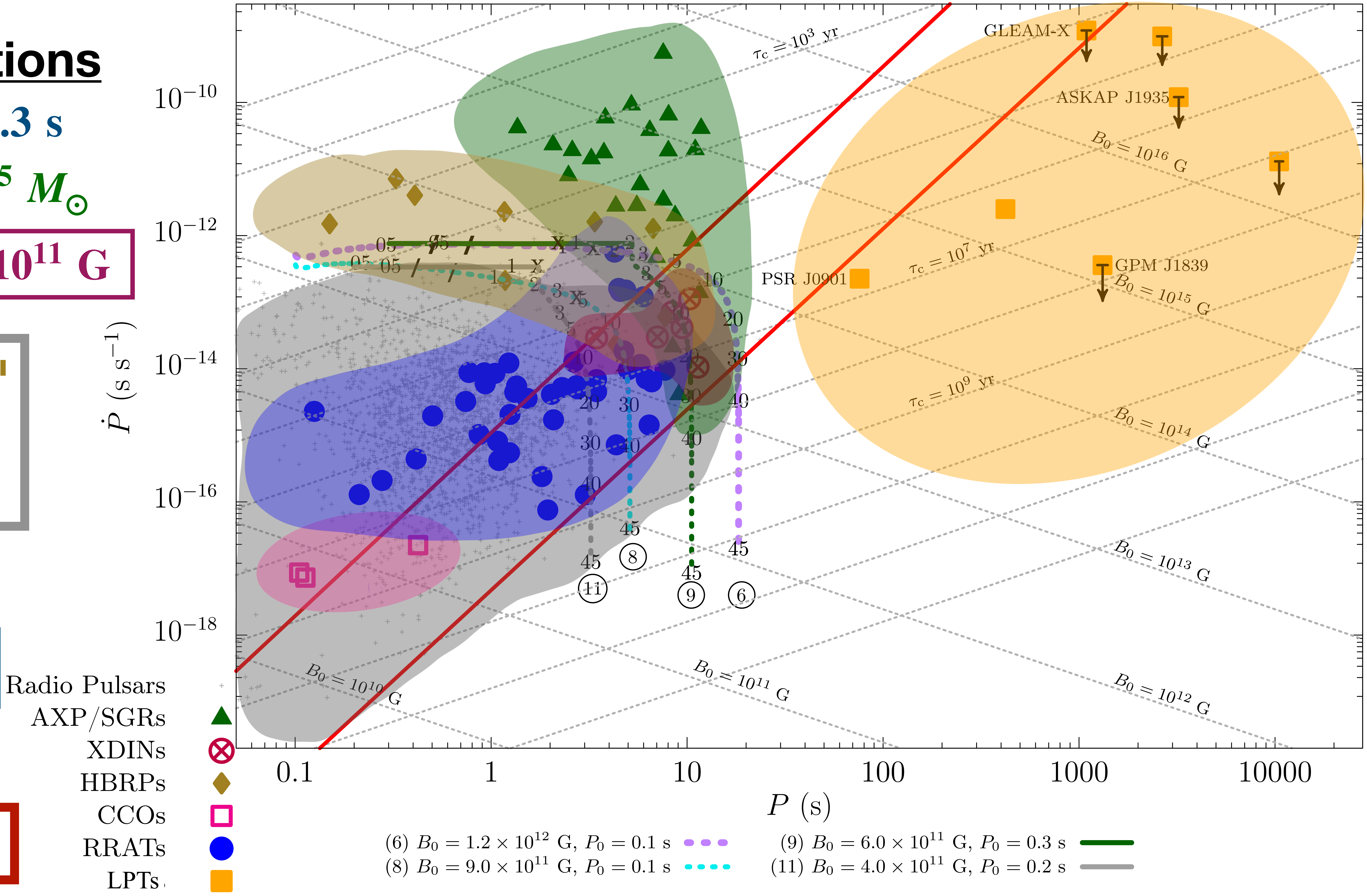
"HBRPs"
and/or
RPs

↓

RRATs

↓

XDINs



Initial Conditions

$P_0 \sim 0.1$ s

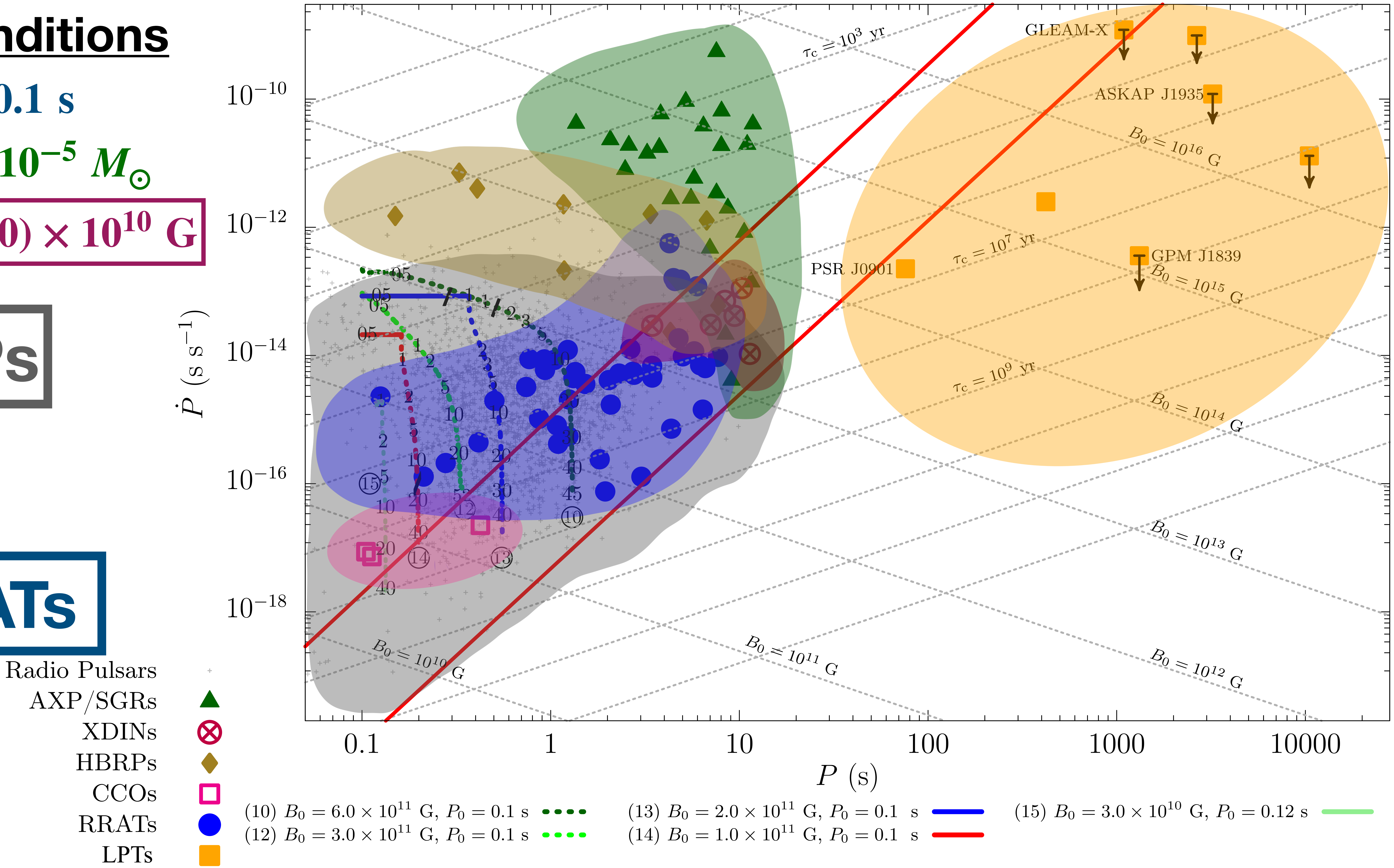
$M_\mathrm{d} \simeq 1 \times 10^{-5}\ M_\odot$

$\boxed{B_0 = (3.0 - 6.0) \times 10^{10}\ \mathrm{G}}$

RPs

↓

RRATs



RPs

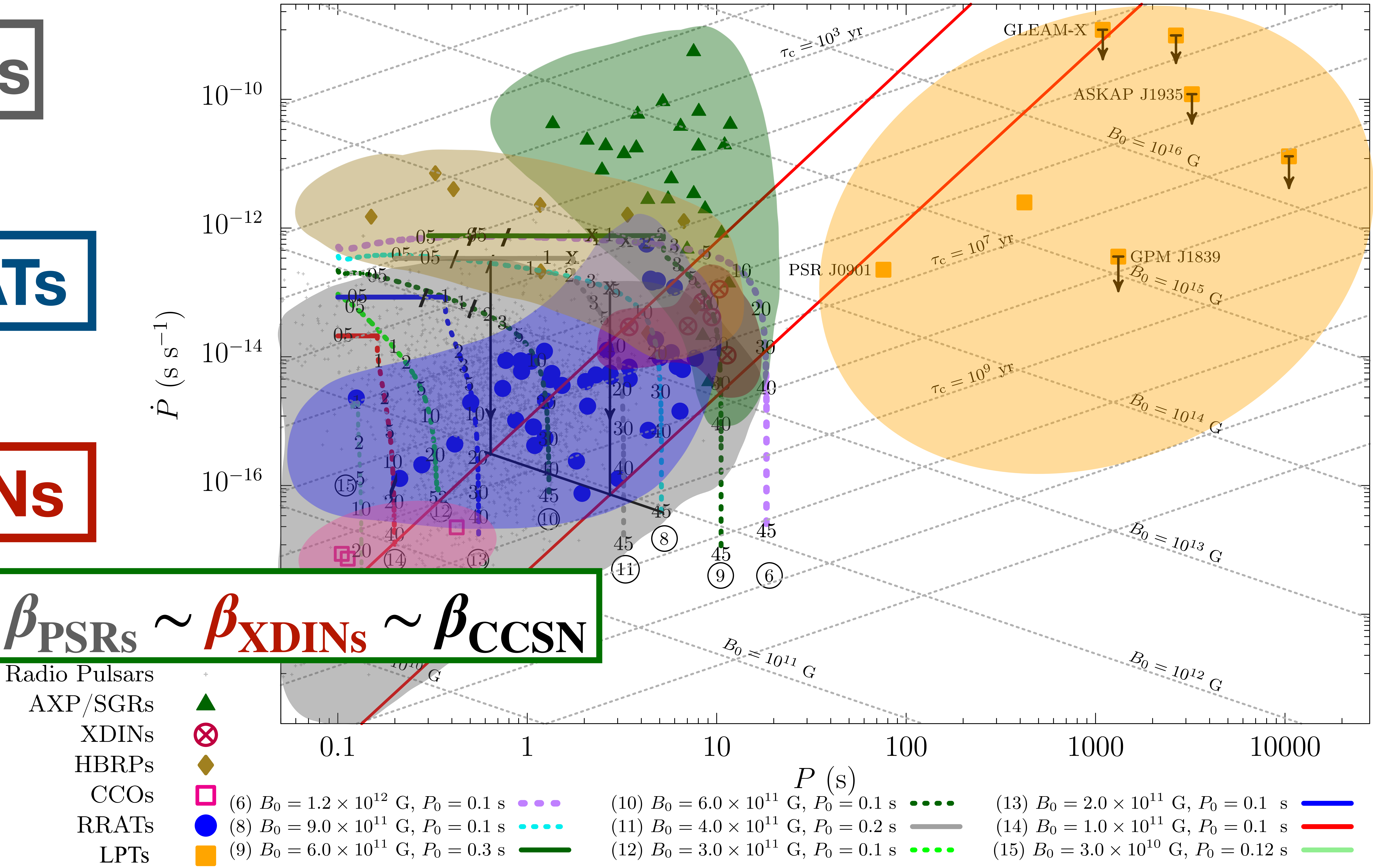
↓

RRATs

↓

XDINs

$$\beta_{\mathbf{RRATs}} \gtrsim \beta_{\mathbf{PSRs}} \sim \beta_{\mathbf{XDINs}} \sim \beta_{\mathbf{CCSN}}$$



How could sources emit Radio Pulses below the Pulsar Death Valley?

How could sources emit Radio Pulses below the Pulsar Death Valley?

- **Enhancement of the magnetic flux of the open field lines through the magnetic poles of the star** (Parfrey, Spitkovsky & Beloborodov 2016, 2017)
- $\Delta V_{\max} \approx \dfrac{BR^3\Omega^2}{2c} = \dfrac{\Omega\phi_0}{2\pi c}$ and $\phi_0 = \pi R(\Omega R/c)B$
- **$\boldsymbol{\Delta V_{\max} \approx 10^{12}}$ V –> For ordinary radio pulses**
- $\phi_{\rm open} = \zeta \dfrac{r_{\rm LC}}{r_{\rm in}} \phi_0$ and $L_{\rm open} = \zeta^2 \left(\dfrac{r_{\rm LC}}{r_{\rm in}}\right)^2 L_0$

Initial Conditions

$P_0 = 0.11 - 0.41$ s

$M_d \simeq 1.6 \times 10^{-6}\ M_\odot$

$B_0 = (3 - 4) \times 10^9$ G

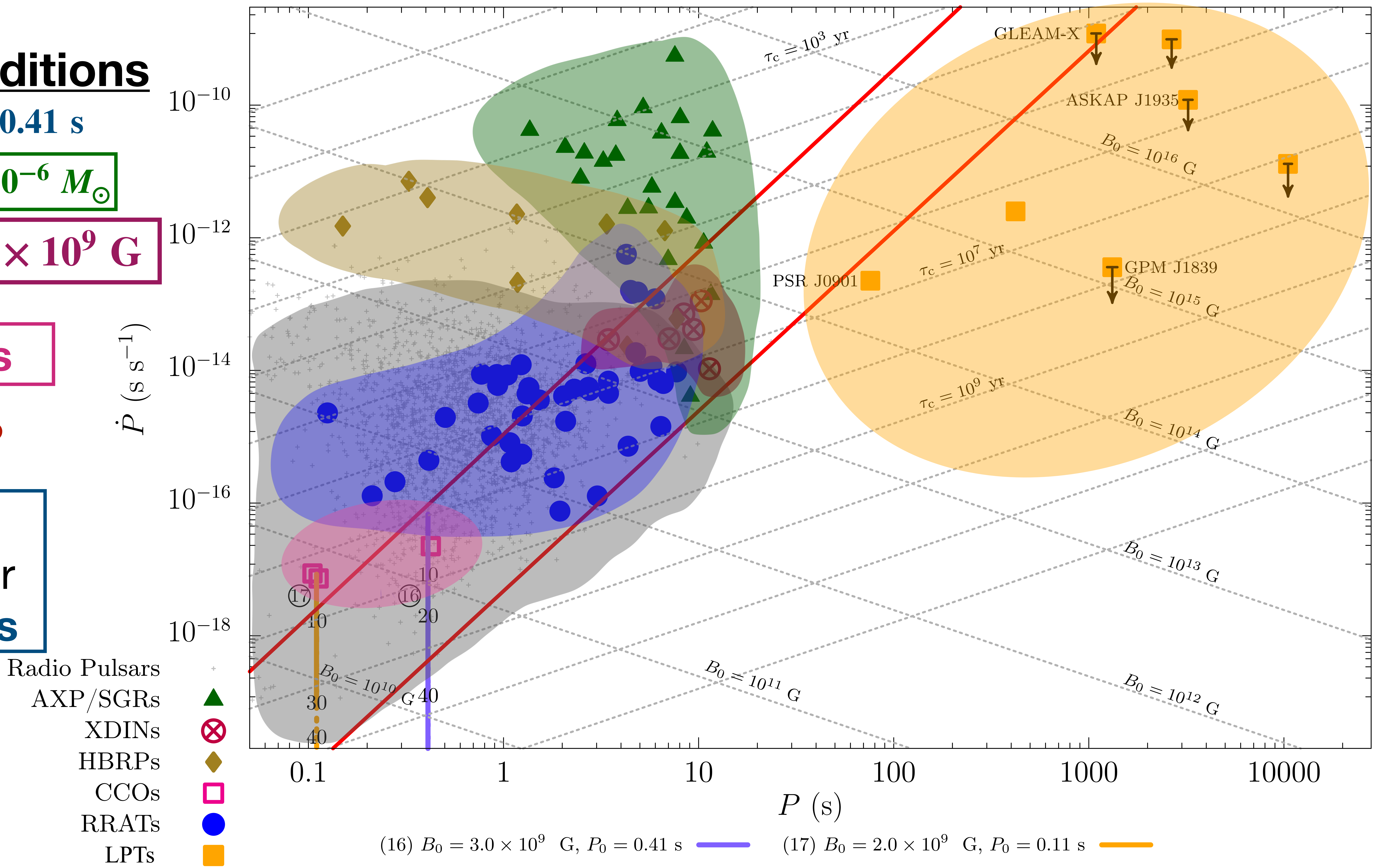
CCOs

↓ ? ?

RPs

and/or

RRATs



Initial Conditions

$P_0 = 0.11 - 0.41$ s

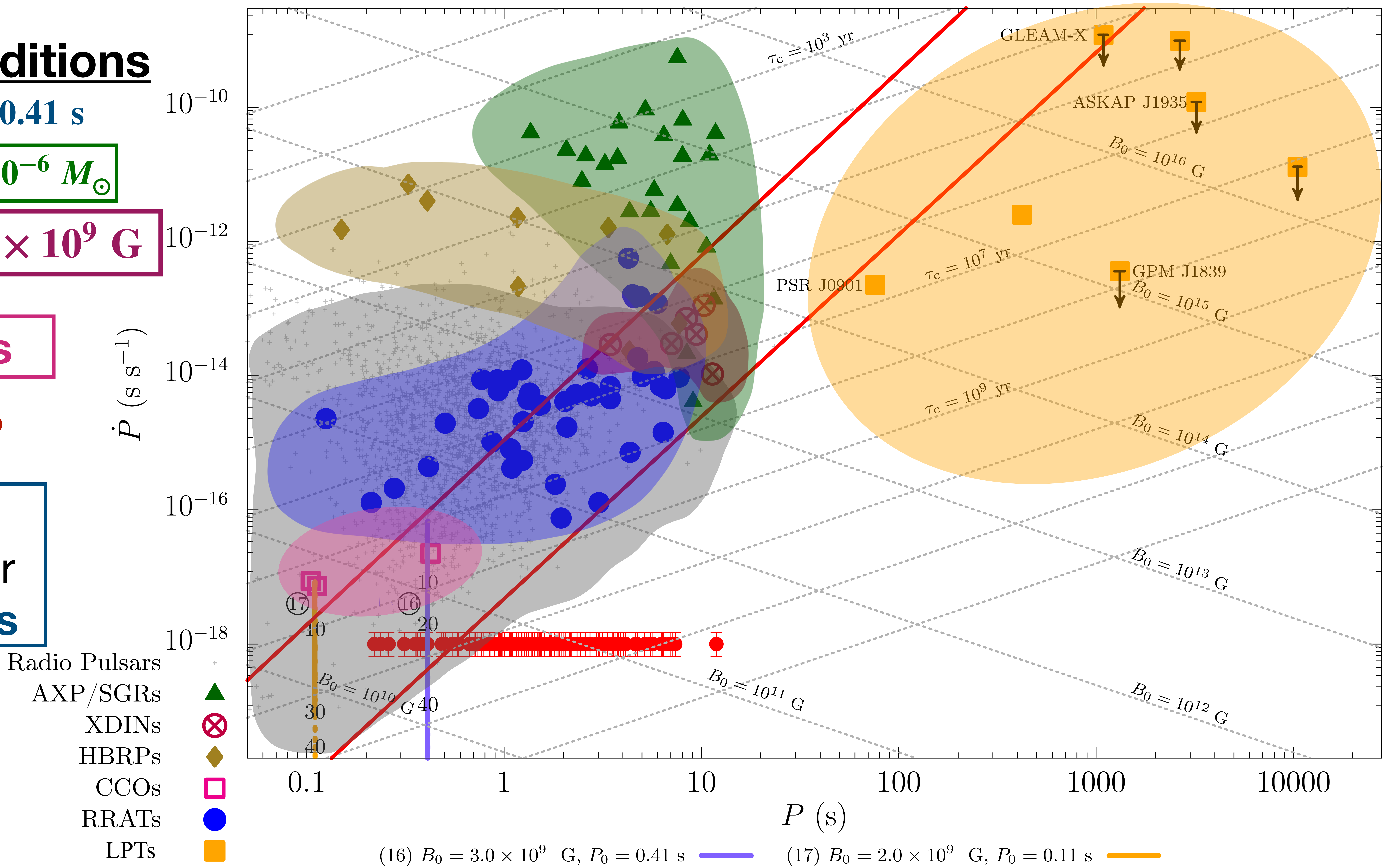
$M_\mathrm{d} \simeq 1.6 \times 10^{-6}\ M_\odot$

$B_0 = (3-4) \times 10^9$ G

CCOs

? ↓ ?

RPs and/or RRATs



Initial Conditions

$P_0 = 0.11 - 0.41$ s

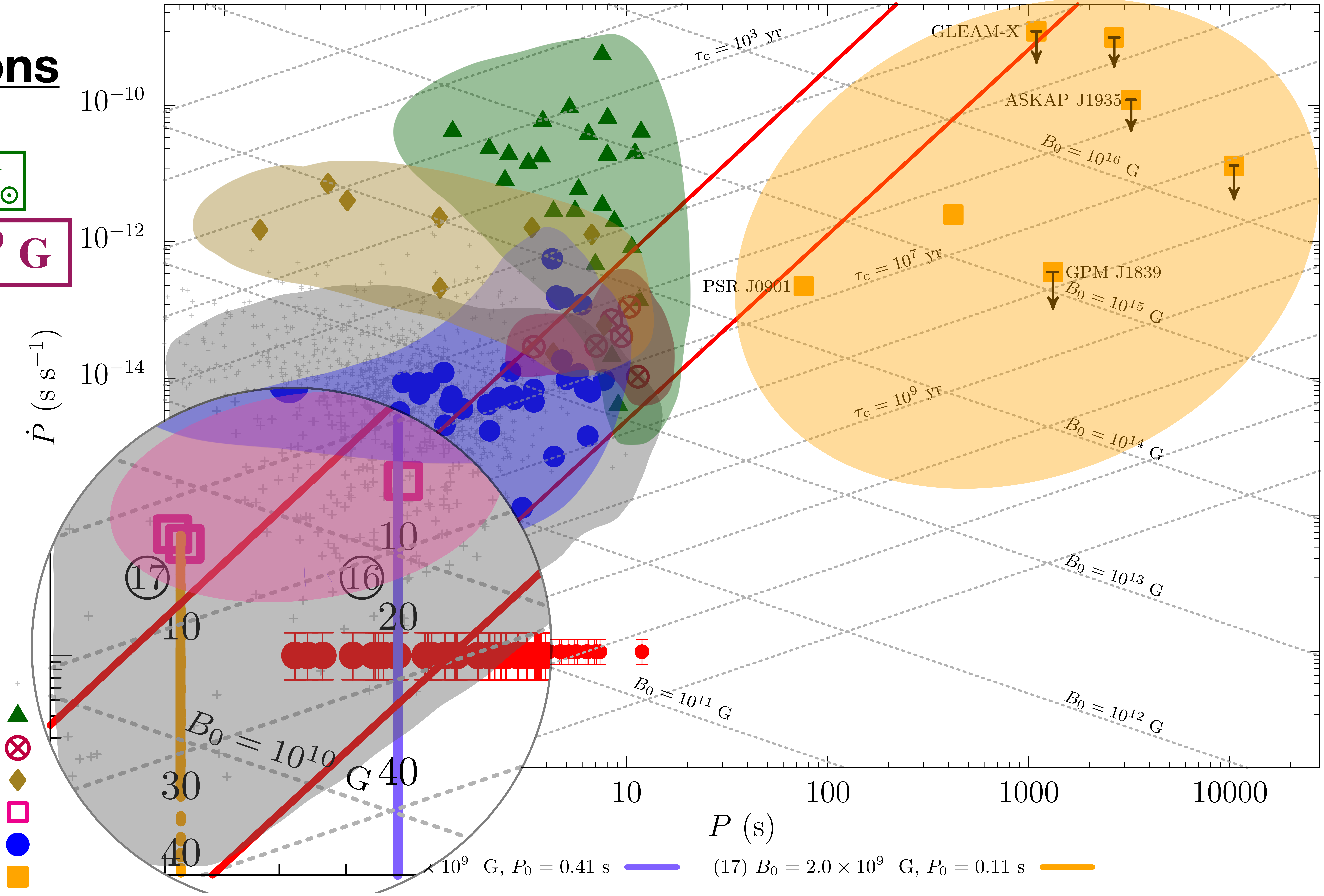
$\boxed{M_\mathrm{d} \simeq 1.6 \times 10^{-6}\ M_\odot}$

$\boxed{B_0 = (3 - 4) \times 10^9\ \mathrm{G}}$

CCOs

? ↓ ?

RPs
and/or
RRATs



Conclusions

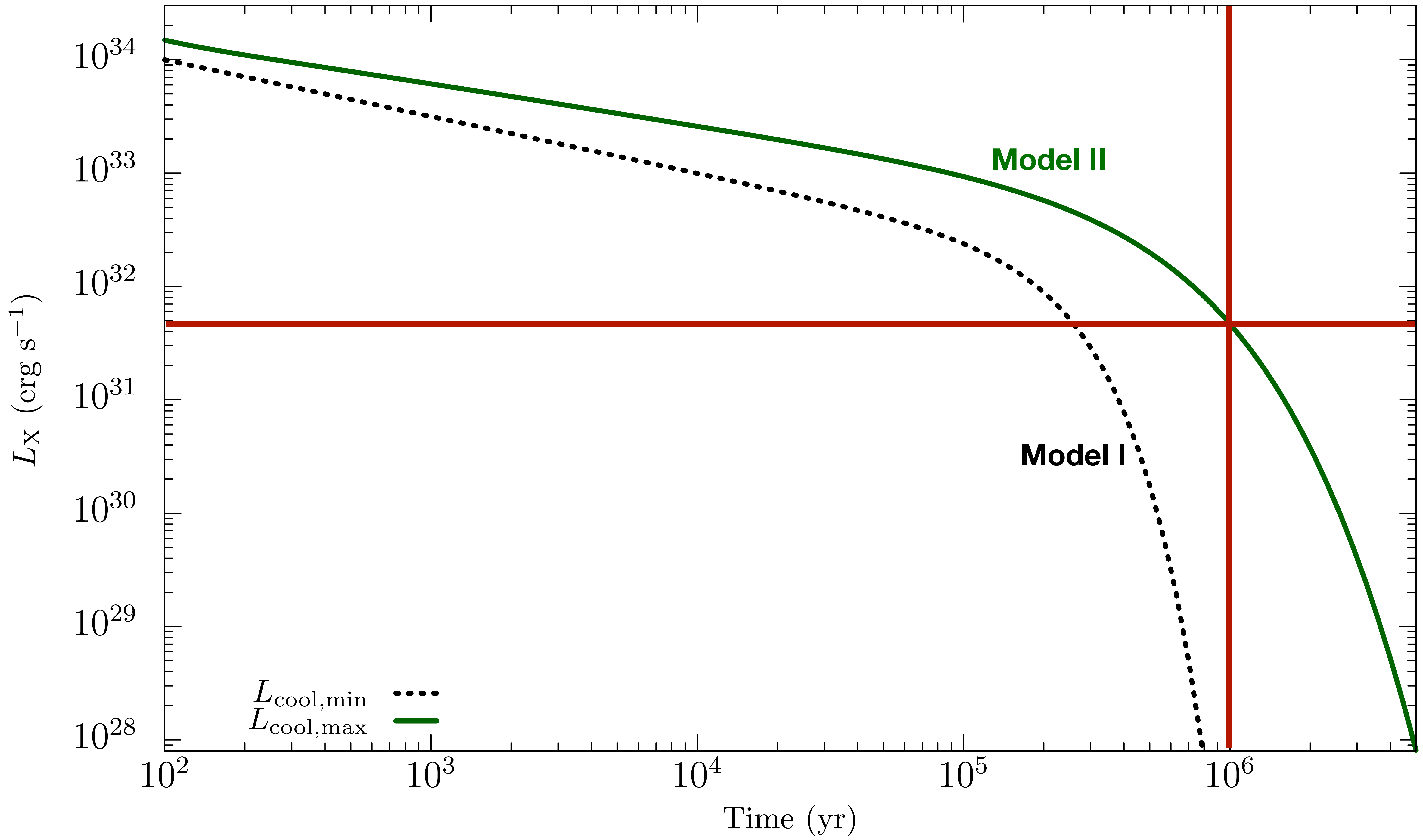
- The rotational properties of isolated NS populations can be reproduced:
  - **As a natural outcome of differences in the initial conditions** P_0, M_d, and B_0 in a single picture
  - Continuous B_0 distribution (a few $10^9 - 10^{13}$ G)
- Our simulations indicate **significant evolutionary connections** between the NS families especially **RRATs**, **XDINs**, and **RPs**
- **RRATs** have evolutionary connections with almost all other populations (**except persistent AXP/SGRs** and **LPPs**)
- **Our detailed model results provide concrete support to earlier predictions to account for the long-lasting birth-rate problem**

Bonus Conclusion

- Our results are in good agreement with the **estimated braking indices (n)** of the sources.

Thank you

Theoretical Cooling Curves



(Page et al. 2009)

Effects of the Initial Conditions on the Long-term Evolution

- **Initial Period: P_0**

- **Disc Mass: M_d**

- **Magnetic Dipole Field Strength: B_0**

Initial Period (P_0)

Model Parameters

$$\alpha = 0.045,\ T_{\rm P} = 50\ {\rm K},$$

$$C = 1 \times 10^{-4}$$

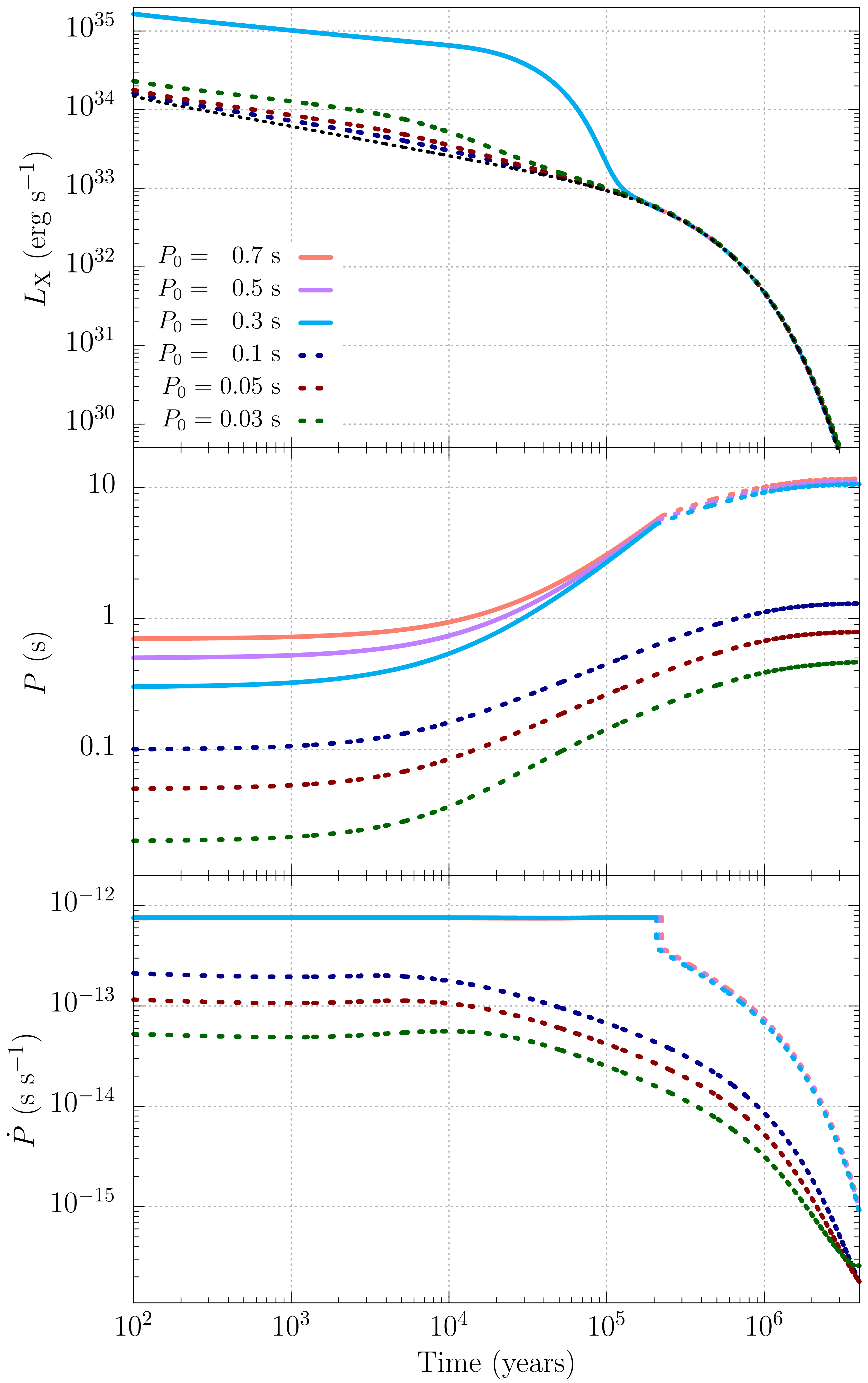
$$\Delta r / r_{\rm in} = 0.25,\ \eta = 0.7,\ \xi = 0.7$$

Initial Conditions

$$\boldsymbol{P_0 = 0.03 - 7\ {\rm s}}$$

$$\boldsymbol{M_{\rm d} = 9.6 \times 10^{-6}\ M_\odot}$$

$$\boldsymbol{B_0 = 6 \times 10^{11}\ {\rm G}}$$



Disc Mass (M_d)

Model Parameters

$\alpha = 0.045,\ T_\mathrm{P} = 50\ \mathrm{K},$

$C = 1 \times 10^{-4}$

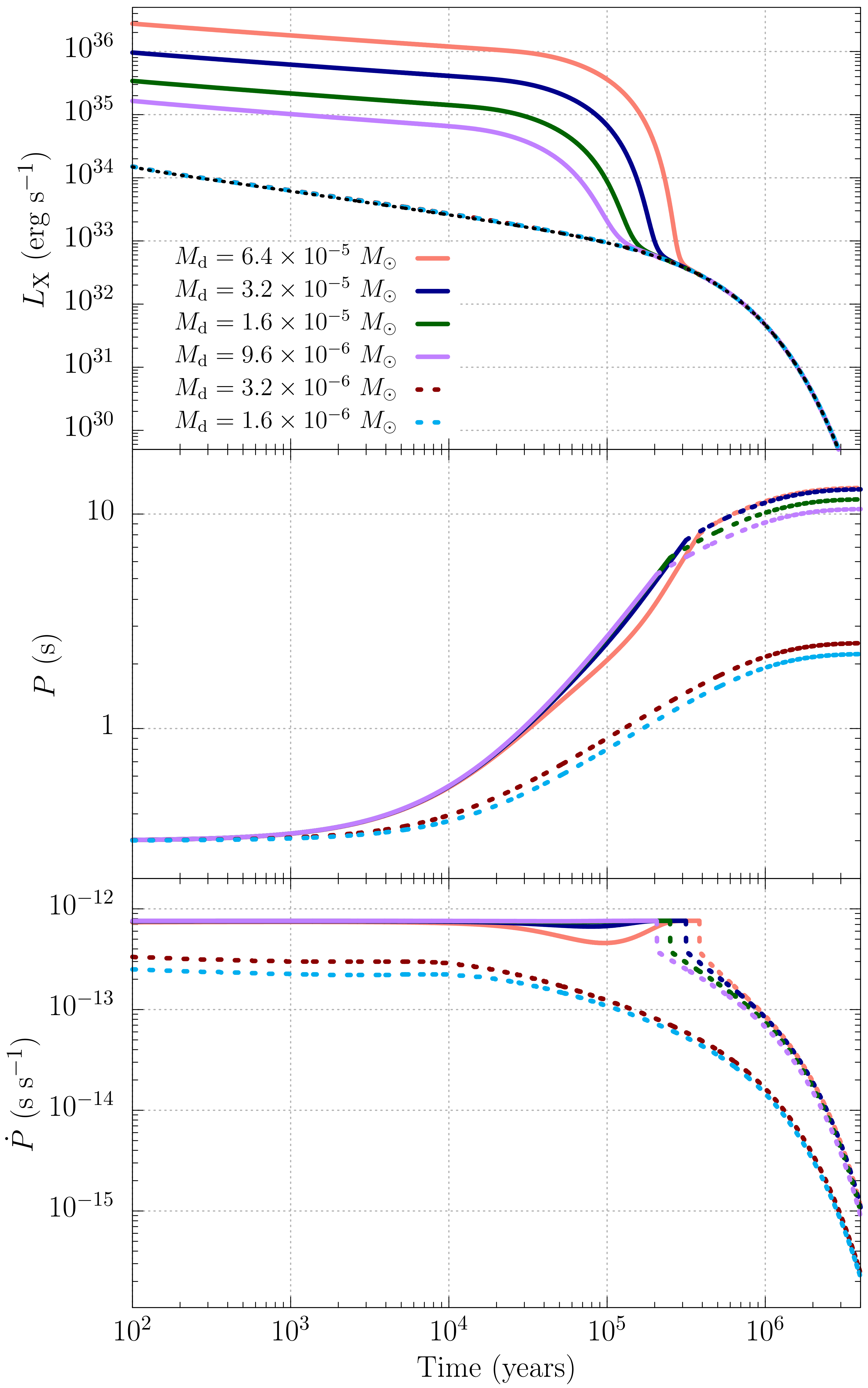
$\Delta r / r_\mathrm{in} = 0.25,\ \eta = 0.7,\ \xi = 0.7$

Initial Conditions

$\boldsymbol{P_0 = 0.3\ \mathrm{s}}$

$\boldsymbol{M_\mathrm{d} = 1.6 \times 10^{-6} - 6.4 \times 10^{-5}\ M_\odot}$

$\boldsymbol{B_0 = 6 \times 10^{11}\ \mathrm{G}}$



Magnetic Dipole Field Strength, B_0

Model Parameters

$$\alpha = 0.045,\ T_{\mathrm{P}} = 50\ \mathrm{K},$$

$$C = 1 \times 10^{-4}$$

$$\Delta r / r_{\mathrm{in}} = 0.25,\ \eta = 0.7,\ \xi = 0.7$$

Initial Conditions

$$\boldsymbol{P_0 = 0.3\ \mathrm{s}}$$

$$\boldsymbol{M_{\mathrm{d}} = 9.6 \times 10^{-6}\ M_{\odot}}$$

$$\boldsymbol{B_0 = 2 \times 10^{10} - 1 \times 10^{13}\ \mathrm{G}}$$