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Investigation for the magnetic pair-creation process in the WD's magnetosphere

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Outline

1. Motivation
2. Polar gap accelerator of white dwarf pulsar scenmario
3. Death-line and pair-creation cascade

1. Motivation

(I) Rapidly spinning and highly magnetized WD.

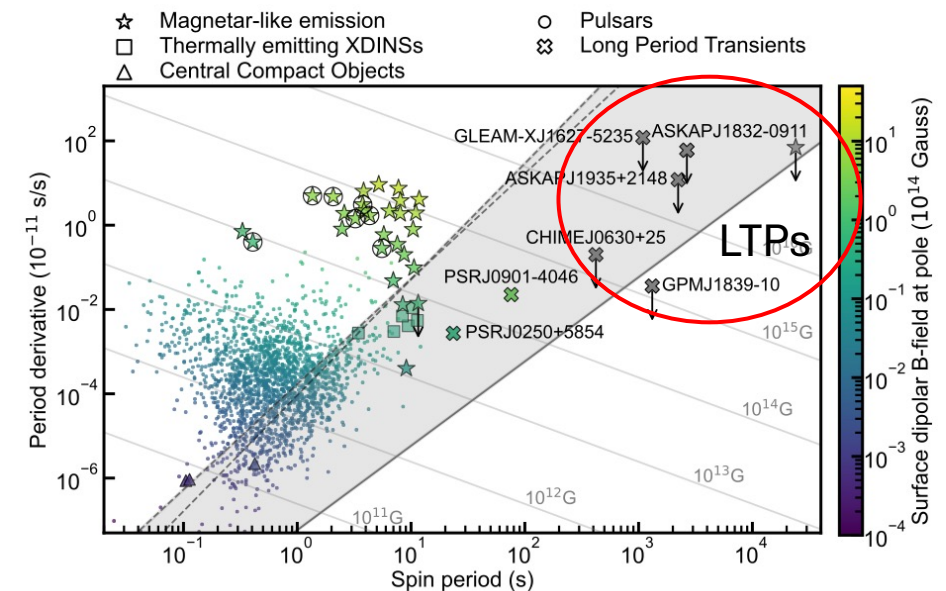
- AR Scorpii type binary.
- *Isolated* massive WDs.

(II) Long Period Radio Transients (LPTs)

- 7 minutes – 3 hours periods.
- Three WD binary systems.

→ Investigating the possibility of **rotation-powered activity** and **death line** of WD pulsars.

System	Class	WD mass ($M_{\odot}$)	Spin period	Magnetic field	Emission
AR Scorpii (2016 Marsh et al.)	Binary (3.6h)	$\approx 0.8\text{--}1.3$	117 s	uncertain ($\sim 10^2\text{--}10^3$ MG, est.)	Non-thermal (radio - X-ray)
J1912-4410 (2023 Pelisoli et al.)	Binary (4.0h)	$\gtrsim 1.0$	318 s	uncertain	Non-thermal (radio- X-ray)
SDSS J2211+1136 (2021 Kilic et al.)	Isolated	1.27	70.3 s	15 MG	
ZTF J1901+1458 (2021 Caiazzo et al.)	Isolated	1.33-1.36	416 s	600-900 MG	Pulsed X-ray

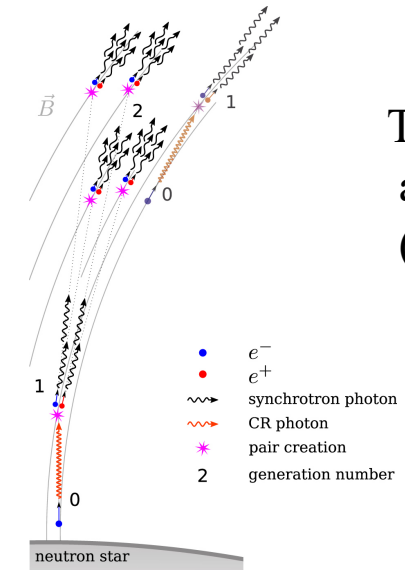


1. Motivation

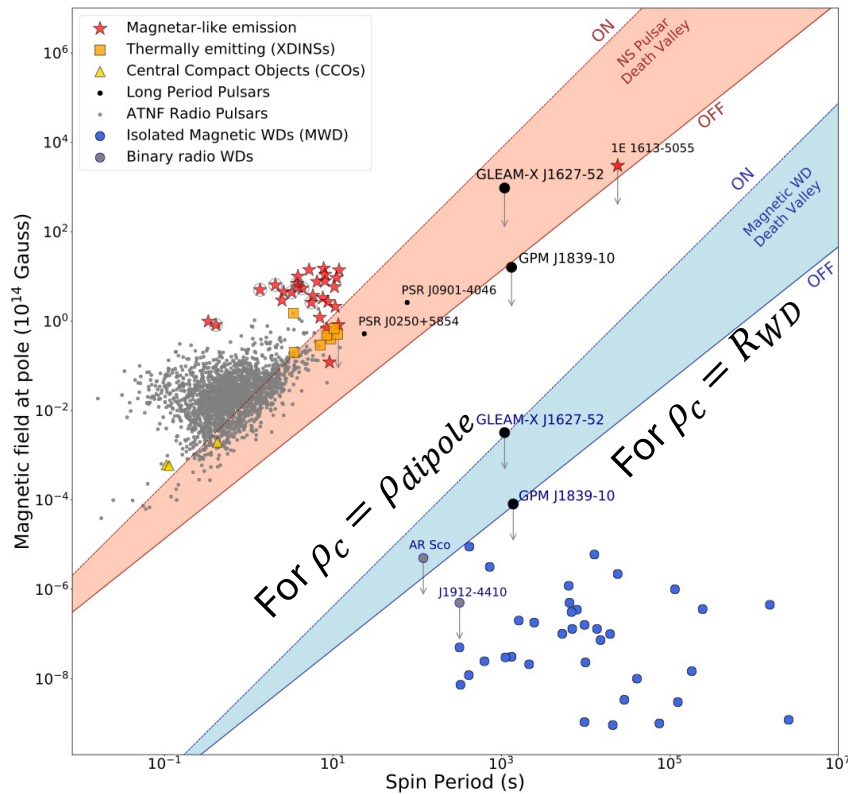
- **Previous death-line model of WD**
 - Ruderman and Sutherland model (1975)

$$B_s = 3 \times 10^4 \left(\frac{P}{1s} \right)^{\frac{13}{8}} \left(\frac{R_{WD}}{5 \cdot 10^8 cm} \right)^{-\frac{21}{8}} \left(\frac{\rho_c}{R_{WD}} \right)^{1/2} G$$

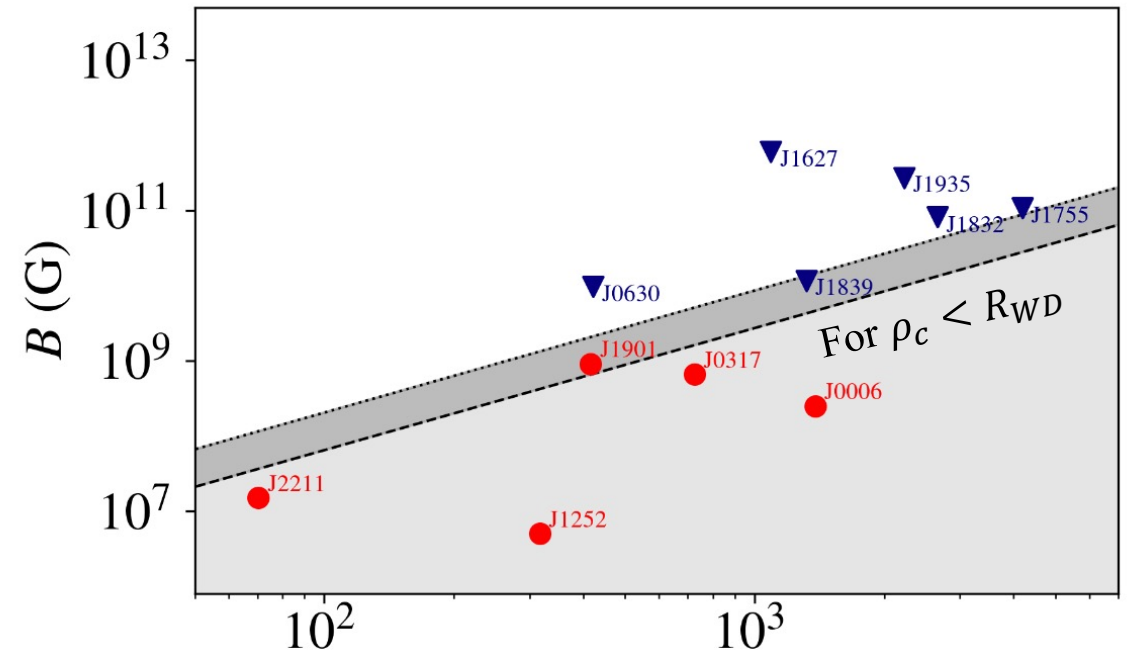
ρ_c : curvature radius



Timokhin
and Harding
(2015)



Rea et al. 2024



Malheiro et al. 2026

1. Motivation

- **Three assumption in Ruderman and Sutherland model**

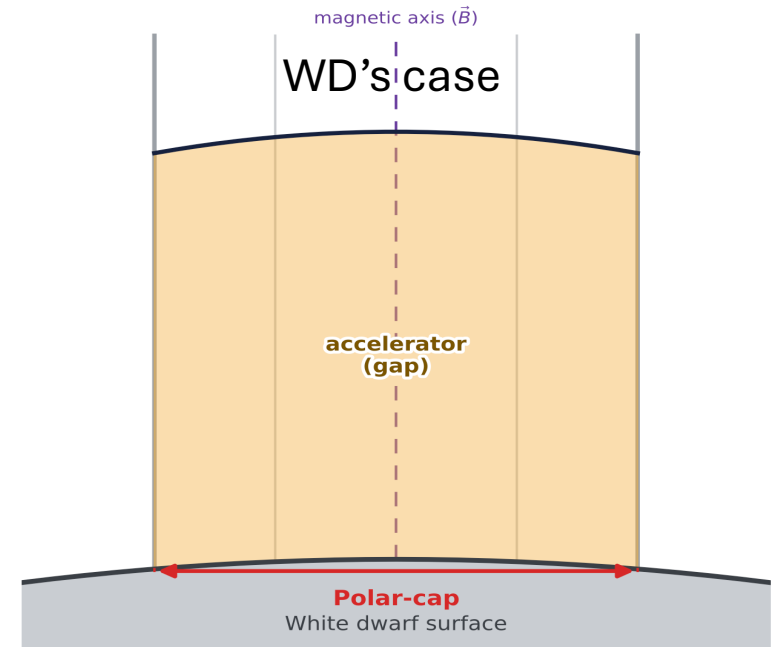
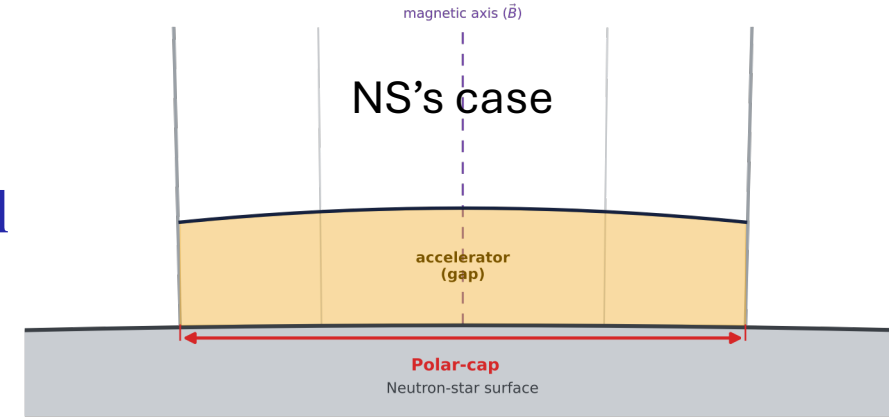
(1) Vacuum gap electric field : $E_{\parallel,RS} = \frac{2\Omega B_s}{c} S$

(2) Small gap $\ll$ Polar cap size

(3) Negligible curvature radiation loss: $\gamma(s) = \frac{e\Delta\Phi_{gap}}{m_e c^2}$

- Assumptions (2) and **especially (3)** will not hold for WD' magnetic field ($B_s < 10^{10} G$)
- Pair creation is more restrictive than previously thought.

→ **Investigation for more realistic death-line.**



2. Polar gap size

Pair-creation front

- Travel distance to emission point, ℓ_{acc}
- Mean free path of the magnetic pair-creation, ℓ_{MFP}

$$\frac{E_\gamma}{2m_e c^2} \frac{B}{B_{QED}} \sin\theta_\gamma = \chi_m, \sin\theta_\gamma \sim \frac{\ell_{MFP}}{\rho_c}$$

$$\text{Gap size} = \text{Min}[\ell_{acc}(s) + \ell_{MFP}(s)]$$

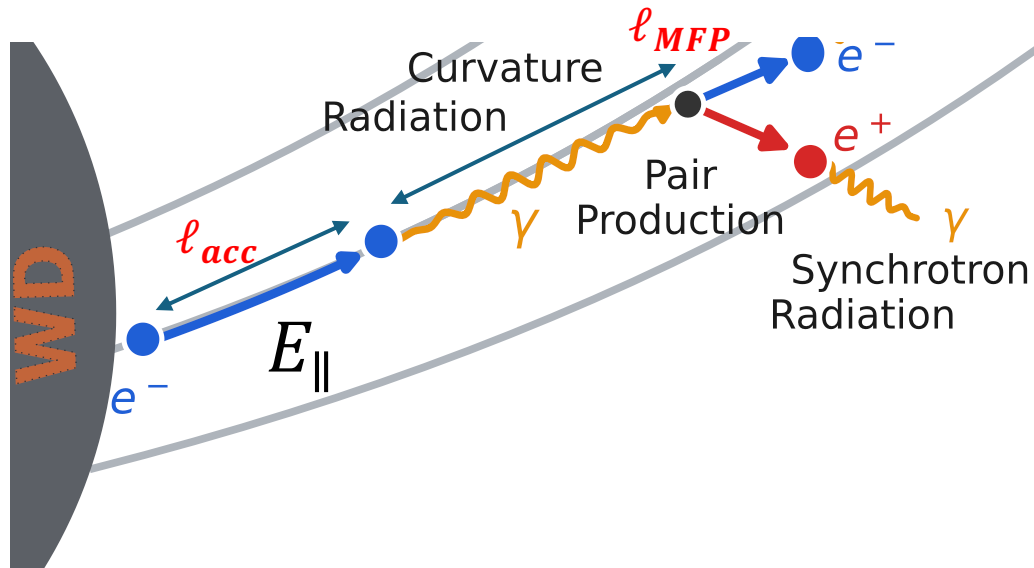
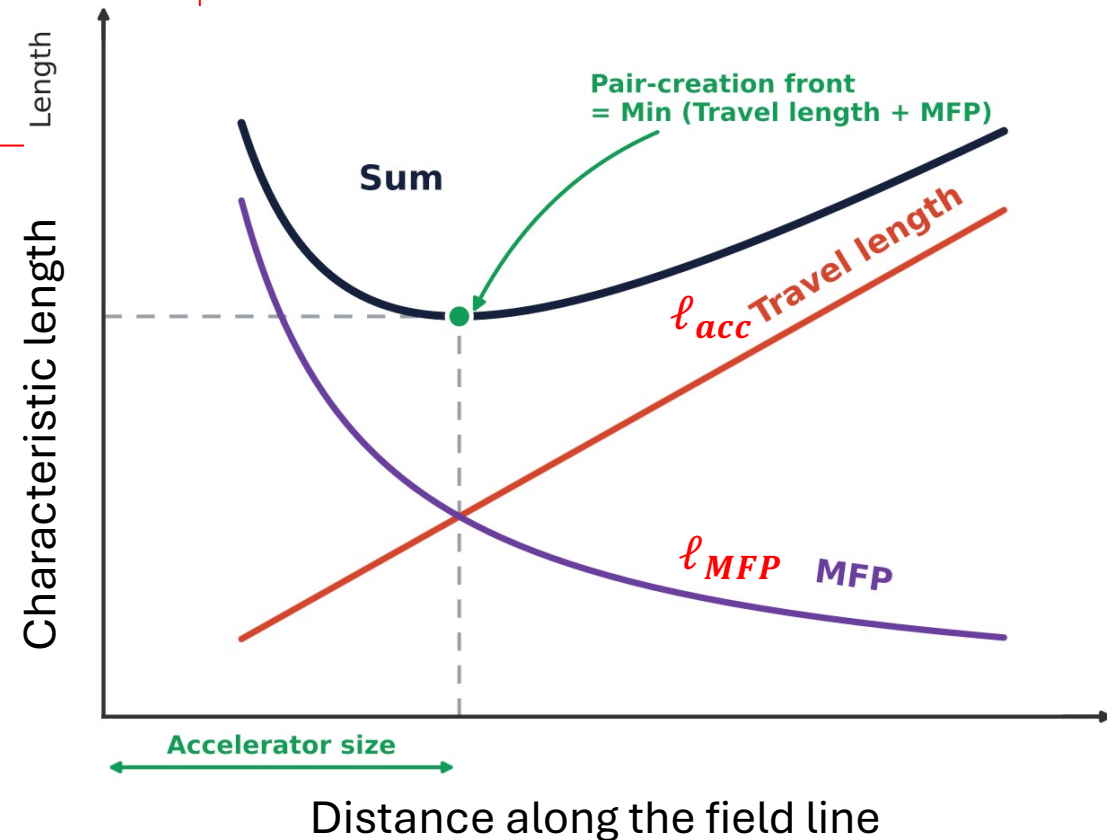


Fig. Schematic diagram for determination of accelerator size



2. Polar gap size

Polar gap size vs. Magnetic field strength

Case 1: Assuming no curvature loss: $\gamma(s) = \frac{e\Delta\Phi(s)}{m_e c^2}$

Case 2: Saturation motion due to energy loss.

$$\gamma(s) = \left(\frac{3E_{\parallel}(s)\rho_c^2(s)}{2e} \right)^{1/4}$$

- The gap size is set by shorter length.
- Critical magnetic field

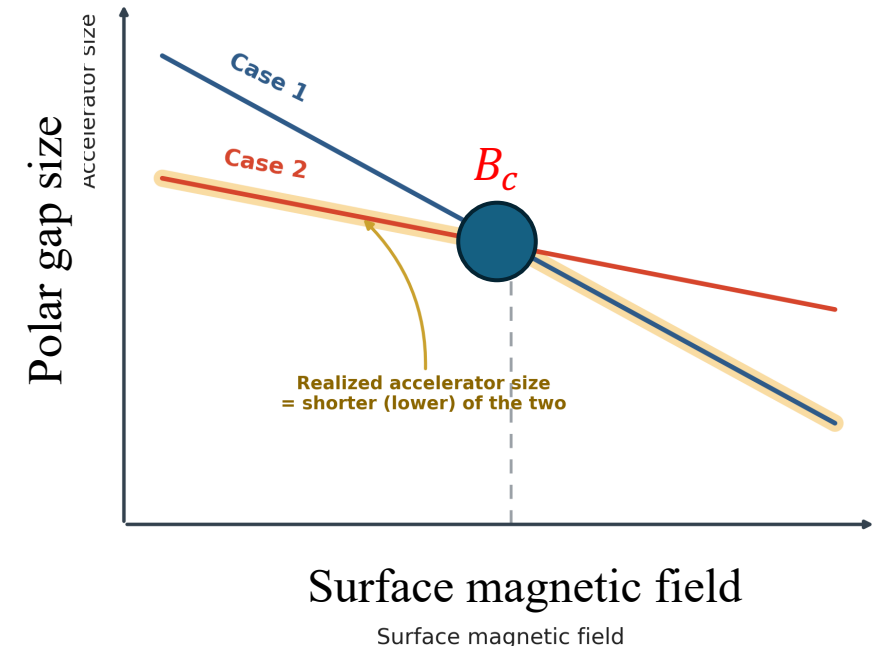
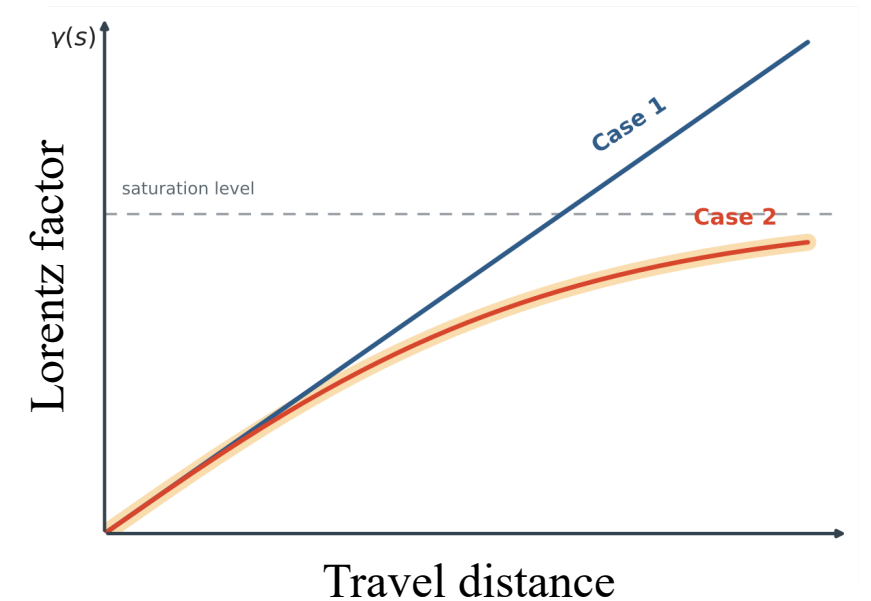
$$B_c \sim \frac{8}{3} \alpha_f \chi_m B_{QED} \sim 5 \times 10^{10} \left(\frac{\chi_m}{0.05} \right) G$$

- Independent of spin period and ρ_c .

α_f : fine structure constant

B_{QED} : $4.4 \times 10^{13} G$

Death-line with influence of curvature energy loss

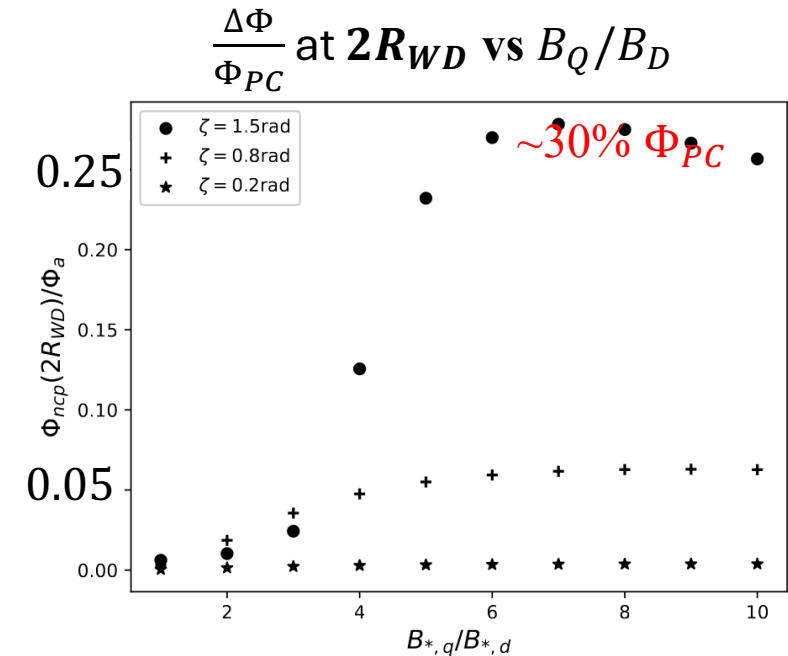
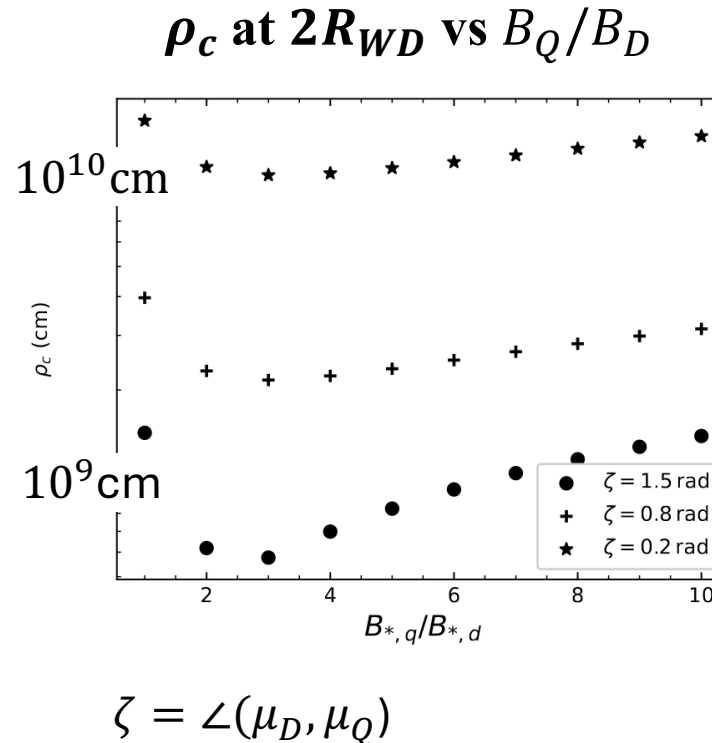
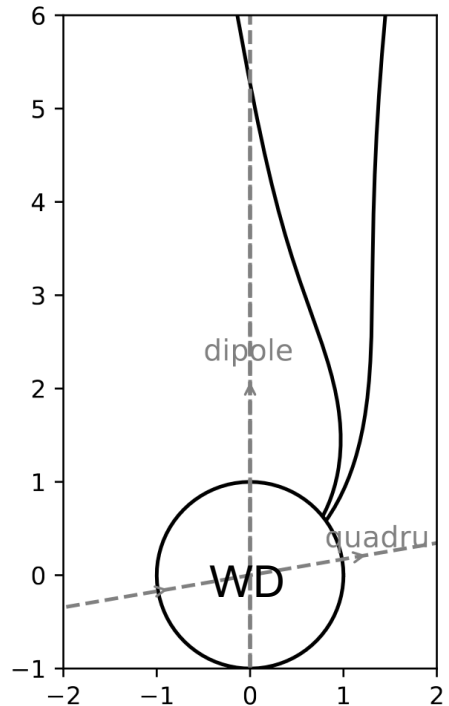
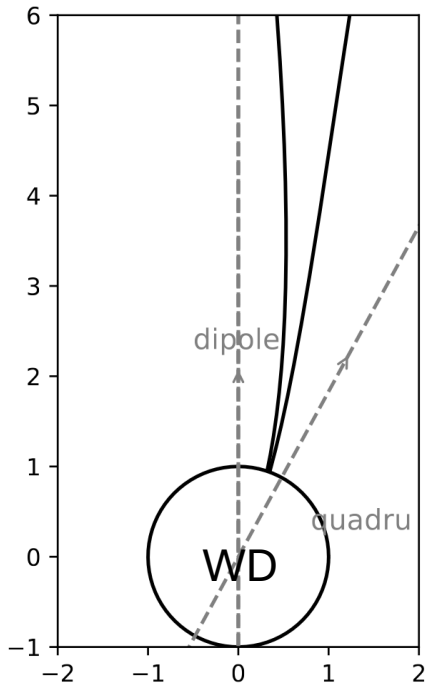
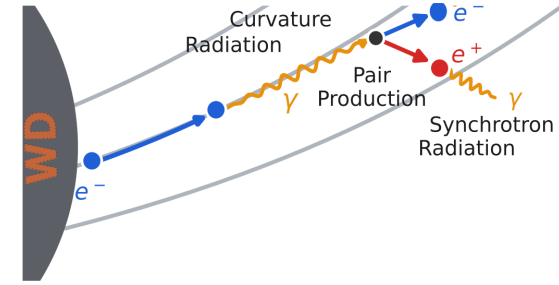


3. Cascade calculation

Space-Charge limited flow: $\Delta\Phi(s) \sim \Phi_{pc} \left(1 - \frac{\rho_{GJ}(s)}{\rho_{GJ}(R_*)}\right)$ (Scharlemann et al. 1979)

Magnetic field geometry: Dipole field + Quadrupole field

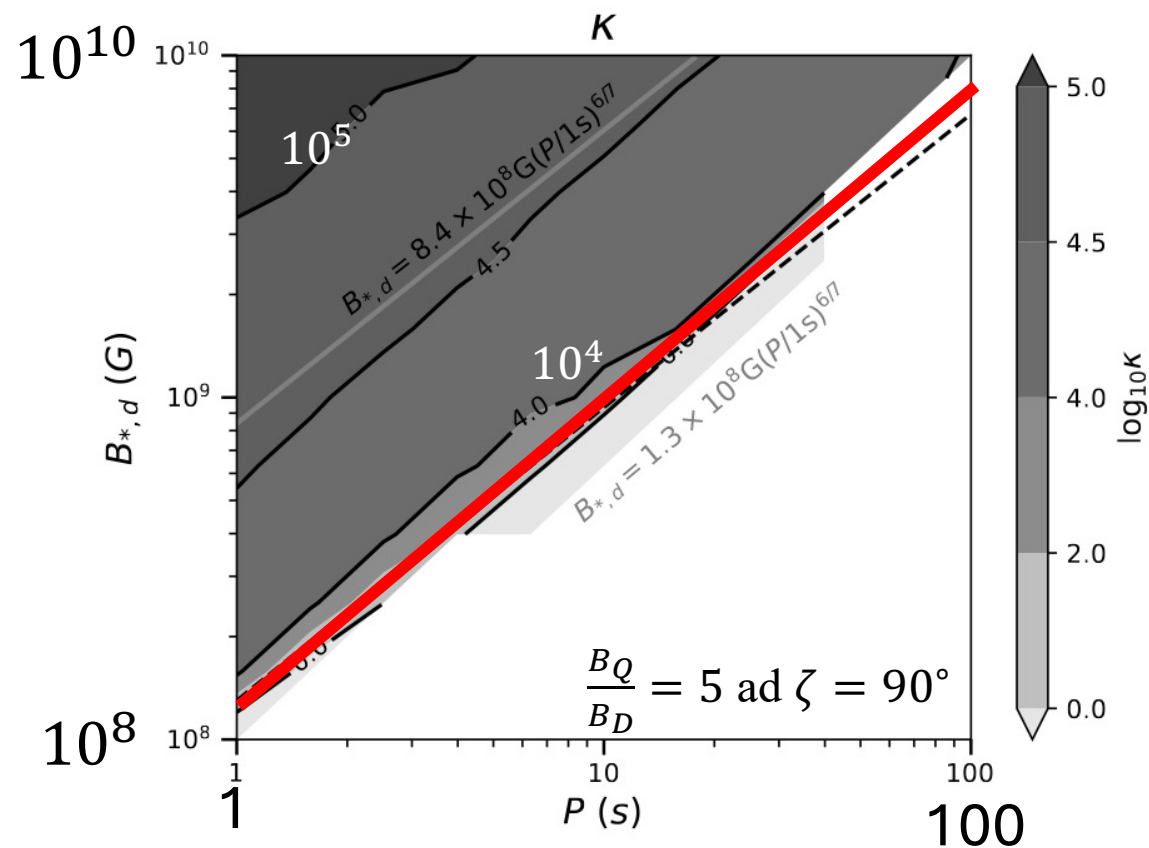
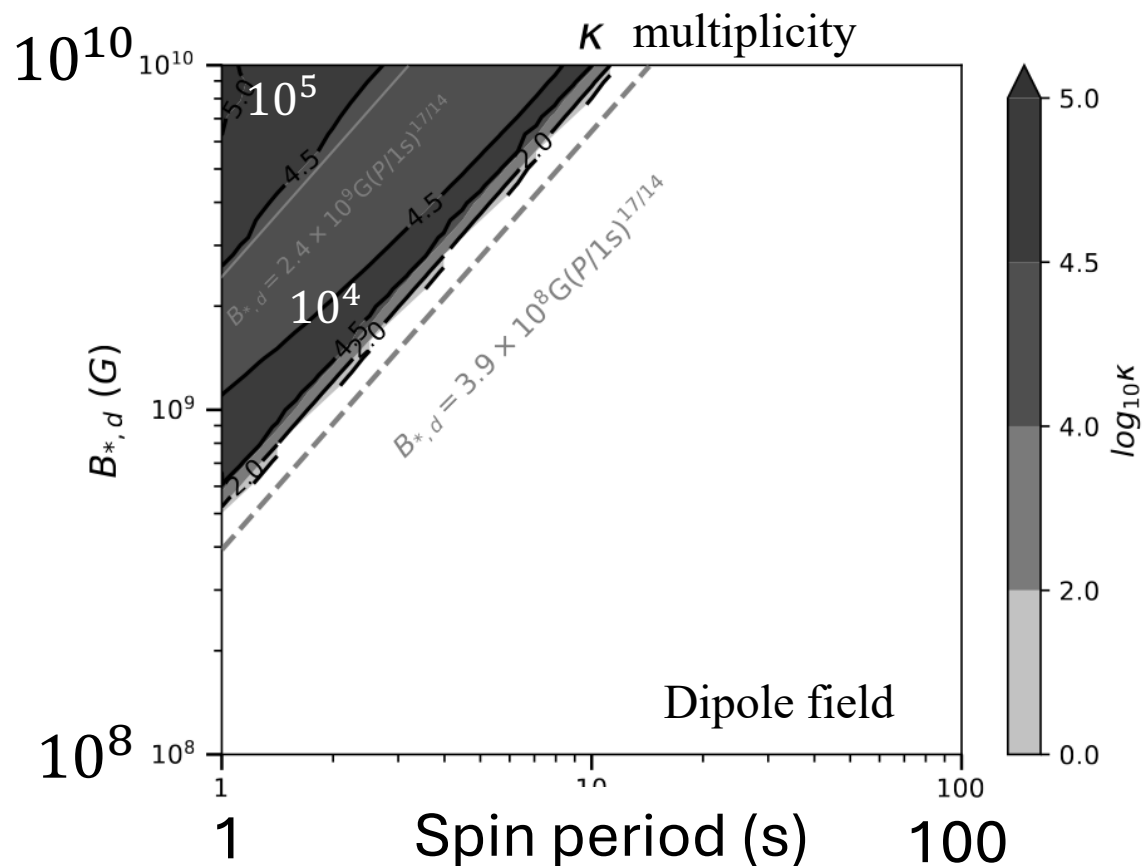
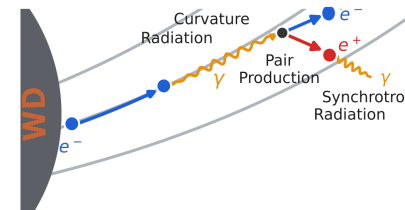
- Strength ratio $\beta = B_Q/B_D$ is model parameter.
- ✓ Curvature radius is reduced to $\rho_c \sim R_{WD}$.
- ✓ Potential drop enhances to $\Delta\Phi_{max} \sim 30\% \Phi_{PC}$



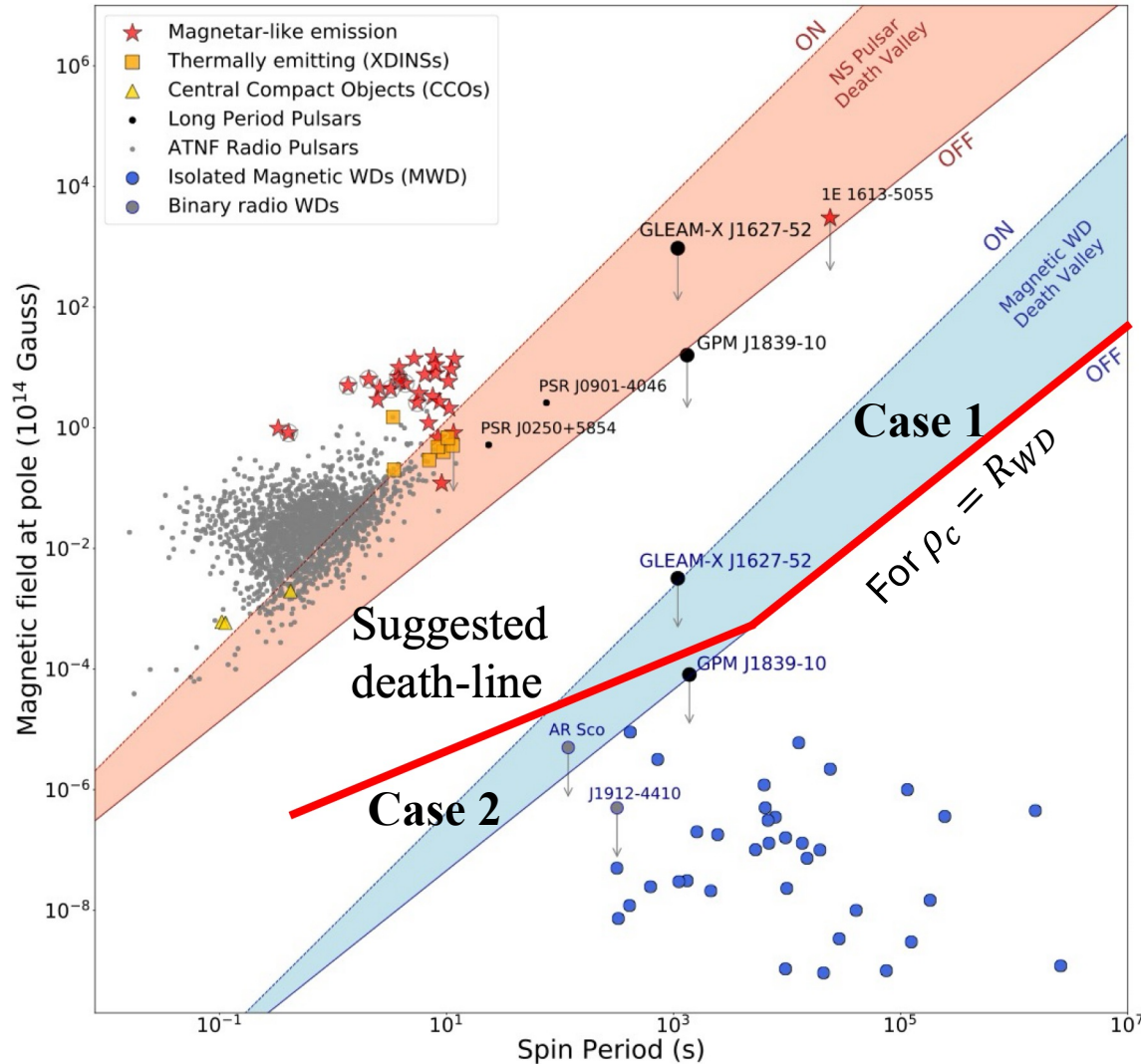
3. Cascade calculation

Physical processes (one-dimensional model)

- Space-Charge limited flow $\Delta\Phi(s) \sim \Phi_{pc} \left(1 - \frac{\rho_{GJ}(S)}{\rho_{GJ}(R_*)}\right)$ (Scharlemann et al. 1979)
- Magnetic pair-creation process.
- Curvature radiation process.
- Synchrotron radiation.



3. Cascade calculation



- Death-line for $B_D < 5 \times 10^{10} \text{G}$.

$$B_d \sim 6.2 \times 10^8 (3 + 2\beta)^{-\frac{4}{6}} \left(\frac{P}{1s}\right)^{6/7} \text{G}$$
- All known white dwarfs lie below the death line.
- The white dwarf pulsar scenario has difficulty explaining the observed LPTs.

Summary

- Death line of the white dwarf pulsar scenario
- Curvature energy loss plays an important role.
- The pair-creation process is more restrictive than previously thought.
- Death-line for $B_D < 5 \times 10^{10} \text{ G}$.

$$B_d \sim 6.2 \times 10^8 (3 + 2\beta)^{-\frac{4}{6}} \left(\frac{P}{1s} \right)^{6/7} \text{ G}$$