Ultraslow PSR J0901-4046 with an ultrahigh magnetic field of 3.2×10^{16} G

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Reporter: 曹顺顺
(Shunshun Cao)

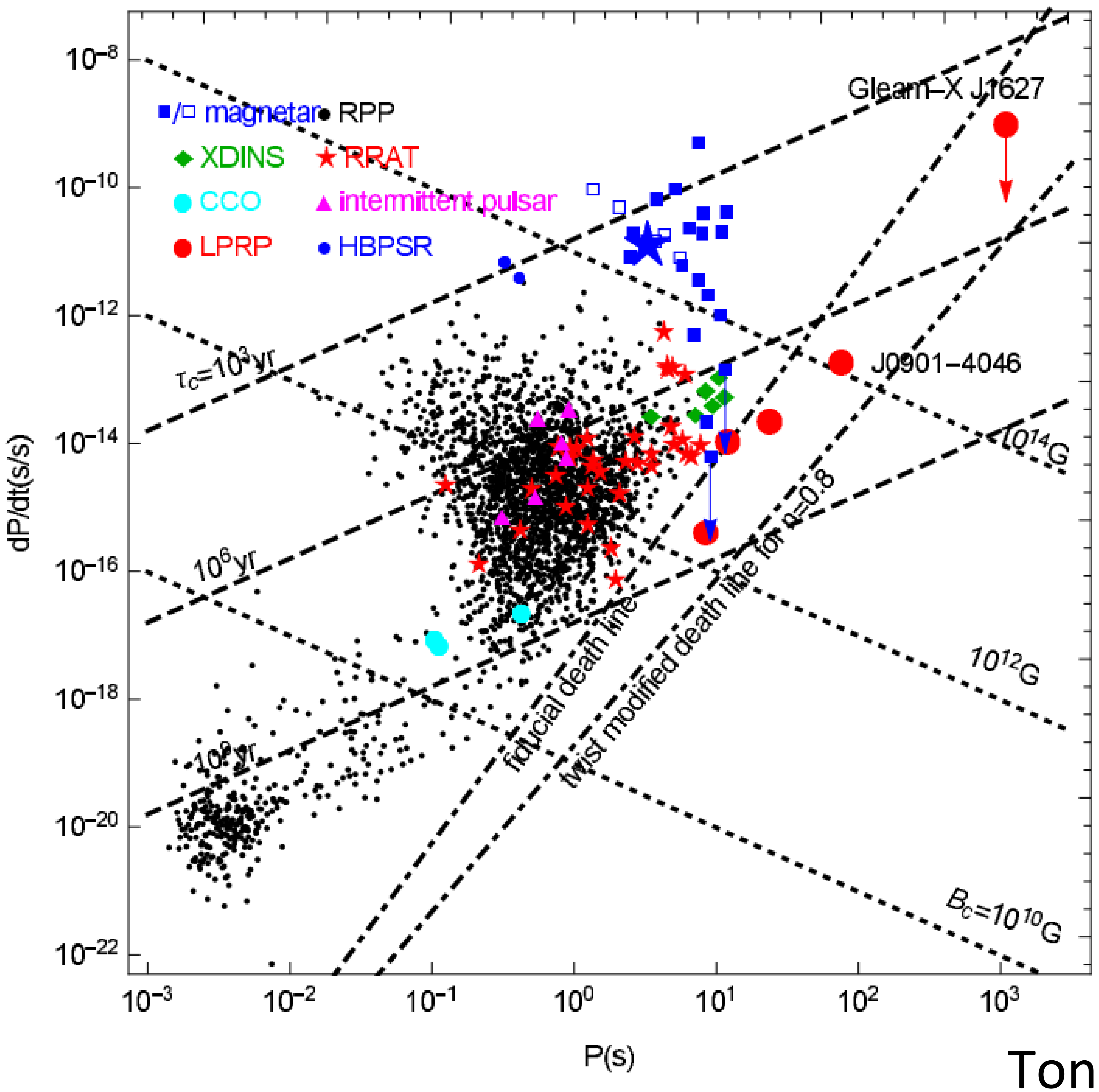
Contents

I. Background

What periods and period derivatives should a radio pulsar have?

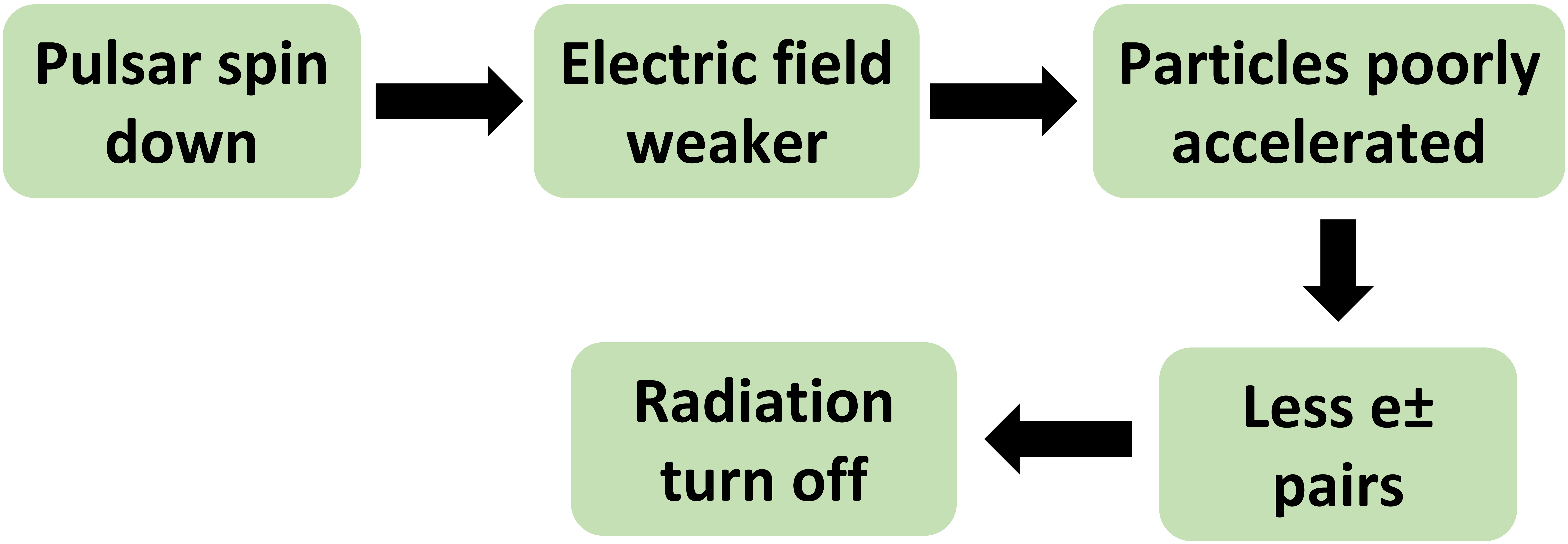
——Related to radiation/turn-off mechanism. Death lines exist.

Example:



Tong 2022

The fiducial death line (Ruderman & Sutherland 1975):



Quantitatively:

Maximum potential drop above polar cap: $$\Phi_{\max} \approx \frac{B_p R^3 \Omega^2}{2c^2}$$

Surface dipole magnetic field strength: $$B_p = \frac{1}{\sin\alpha} \left(\frac{3 I c^3 P \dot{P}}{2\pi^2 R^6} \right)^{1/2}$$

Take $\Delta V = \Phi_{\max}$ = 10^{12} V, we get a relation between P and P-dot.

➔➔➔ The fiducial death line.

Different models can give different death lines.

Turn to observation:

nature astronomy

ARTICLES

https://doi.org/10.1038/s41550-022-01688-x

Check for updates

Discovery of a radio-emitting neutron star with an ultra-long spin period of 76 s

Manisha Caleb[1,2,3,14] ✉, Ian Heywood[4,5,6,14] ✉, Kaustubh Rajwade[1,7], Mateusz Malenta[1], Benjamin Willem Stappers[1,14], Ewan Barr[8], Weiwei Chen[8], Vincent Morello[1], Sotiris Sanidas[1], Jakob van den Eijnden[4], Michael Kramer[1,8], David Buckley[9,10,11], Jaco Brink[9,10], Sara Elisa Motta[12], Patrick Woudt[10], Patrick Weltevrede[1], Fabian Jankowski[1], Mayuresh Surnis[1], Sarah Buchner[6], Mechiel Christiaan Bezuidenhout[1], Laura Nicole Driessen[1,13] and Rob Fender[4]

A pulsar with 76s period discovered on 2020.9.27 by MeerKAT.
Published on 2022.5.30

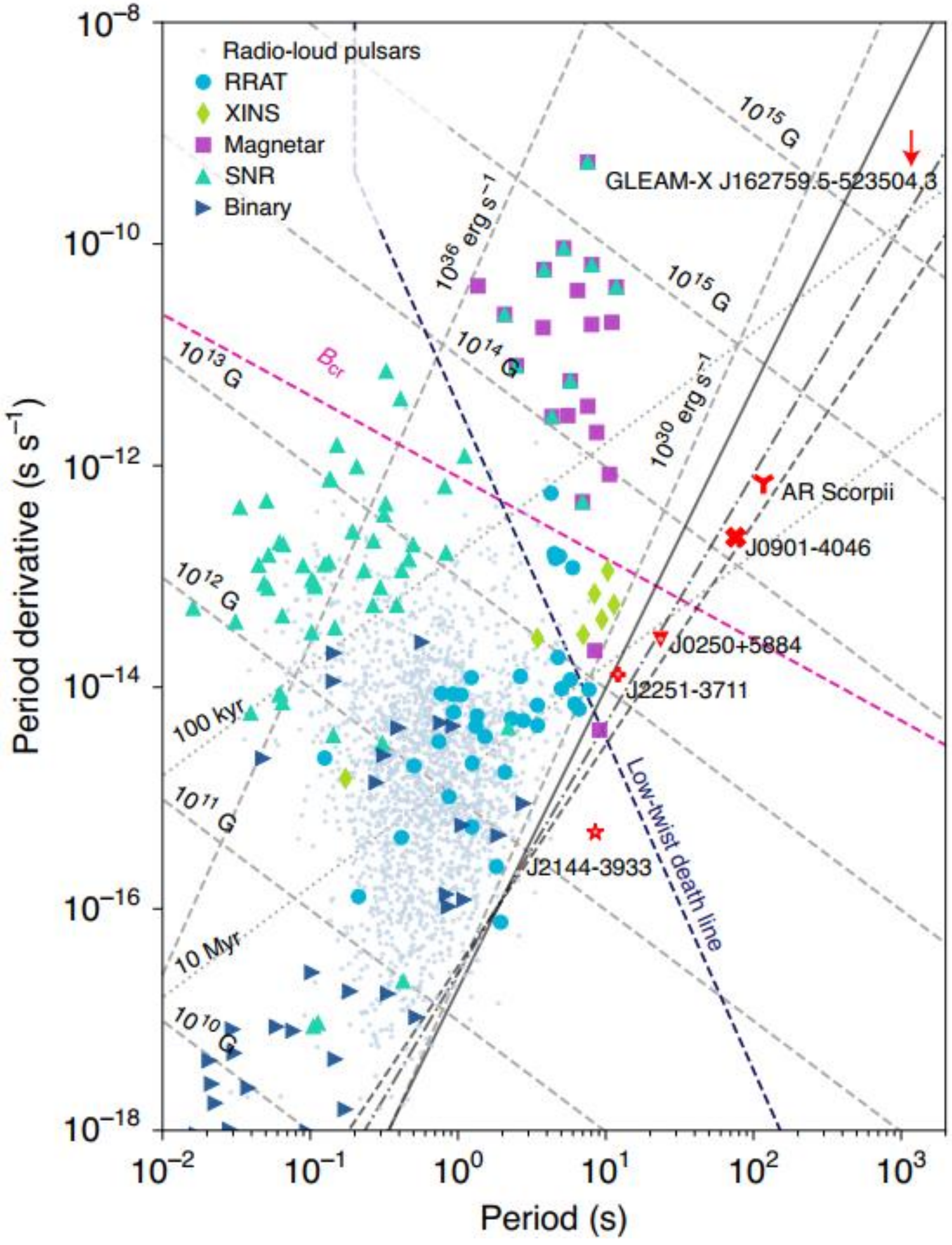
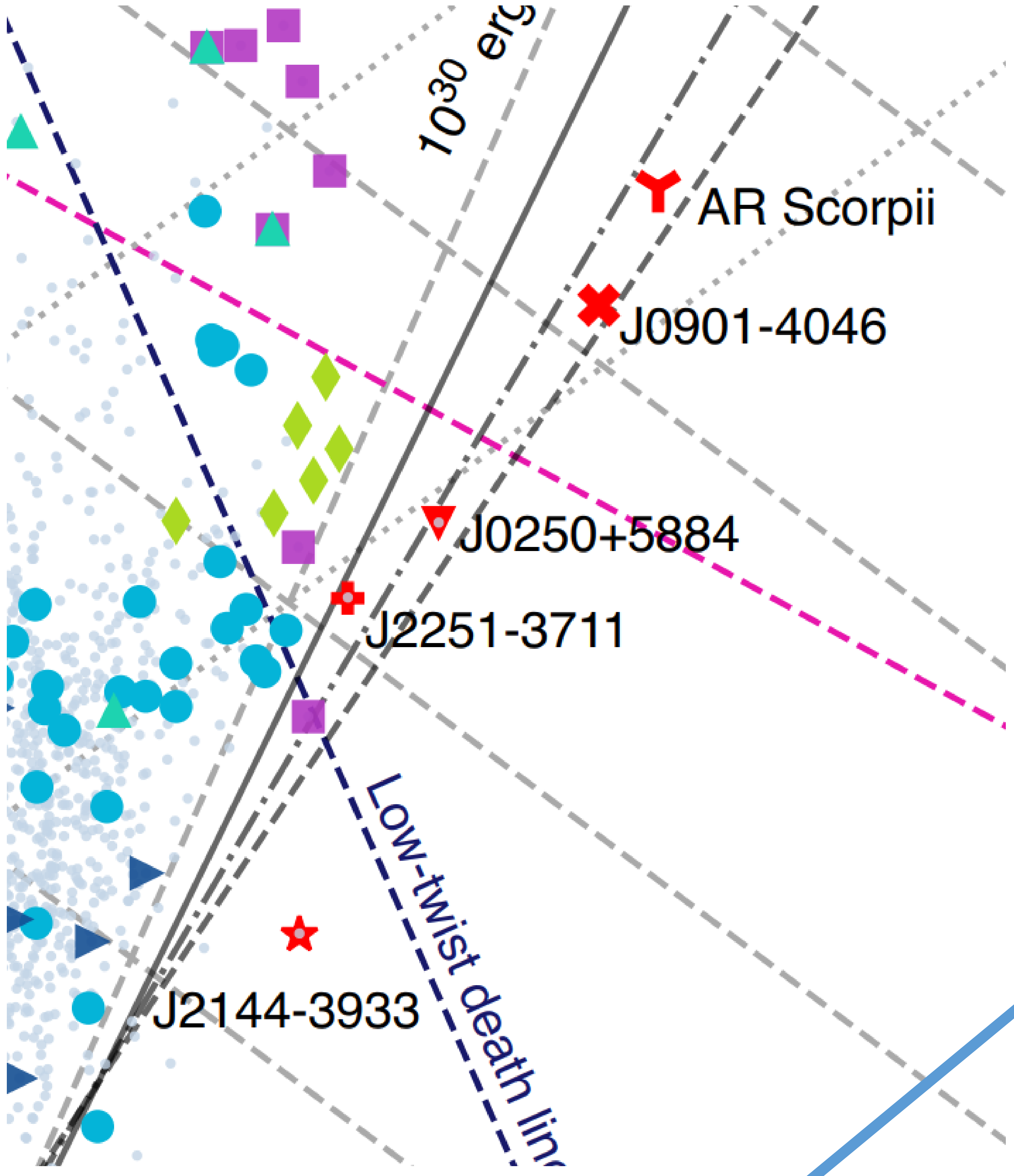
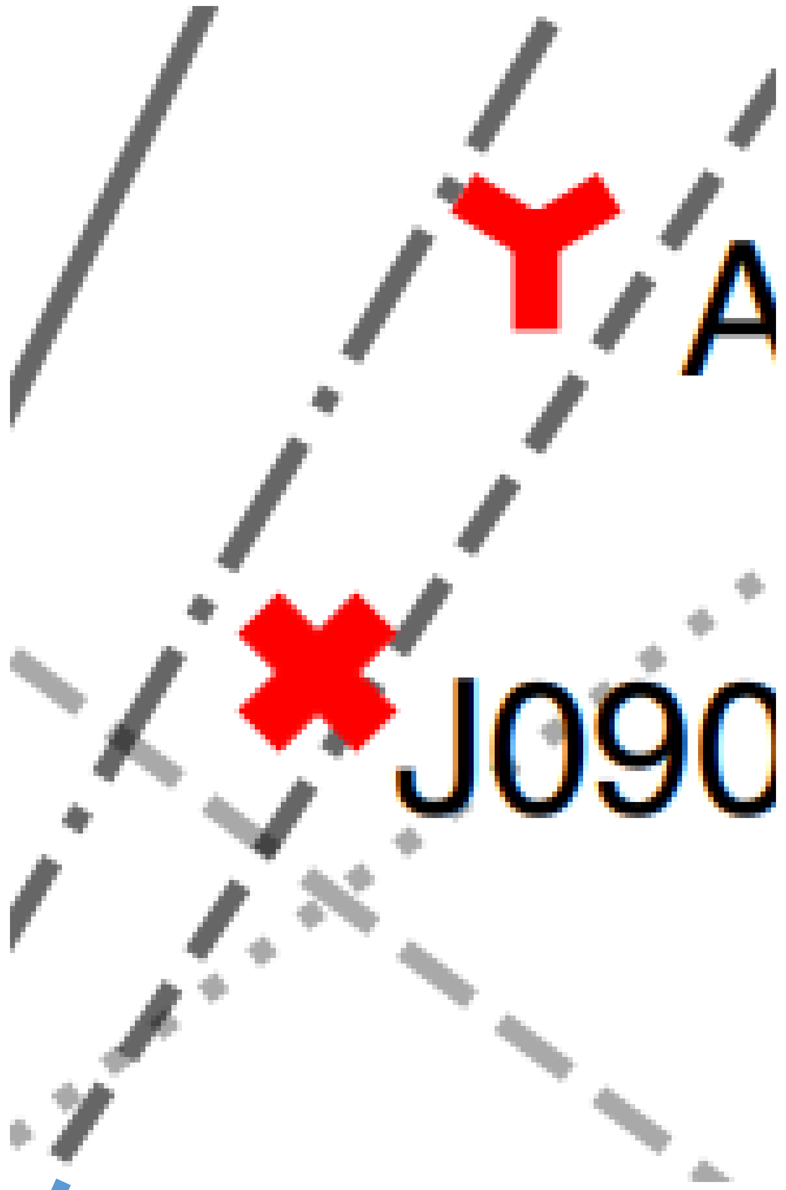


Fig 1 in Caleb et al. 2022





Death line of inner vacuum gap model

Death line of space charge limited flow model (with multipole field)

Pulse period, P	$75.88554711 \pm (6 \times 10^{-8})$ s
Period derivative, $\dot{P}$	$(2.25 \pm 0.1) \times 10^{-13}$ s s^{-1}

➔➔➔Surface dipole magnetic field strength (take α=90°):

$$B_{\mathrm{p}} = \frac{1}{\sin\alpha}\left(\frac{3Ic^3 P\dot{P}}{2\pi^2 R^6}\right)^{1/2} \approx 1.3 \times 10^{14}\ \mathrm{G}$$

Above $B_{cr} = m_e^2 c^3 / e\hbar \approx 4.4 \times 10^{13}\ \mathrm{G}$

➔➔➔ Should be radio-quiet…?

This paper: re-investigating its magnetic field.

II. Magnetic field estimation

(1) A more realistic α angle

$$\sin\alpha = \frac{5.2^\circ P^{-0.5}}{W_{10}^{1\ \mathrm{GHz}}}$$

➔➔➔α ≈ 10°

(2) Lorentz factors γ

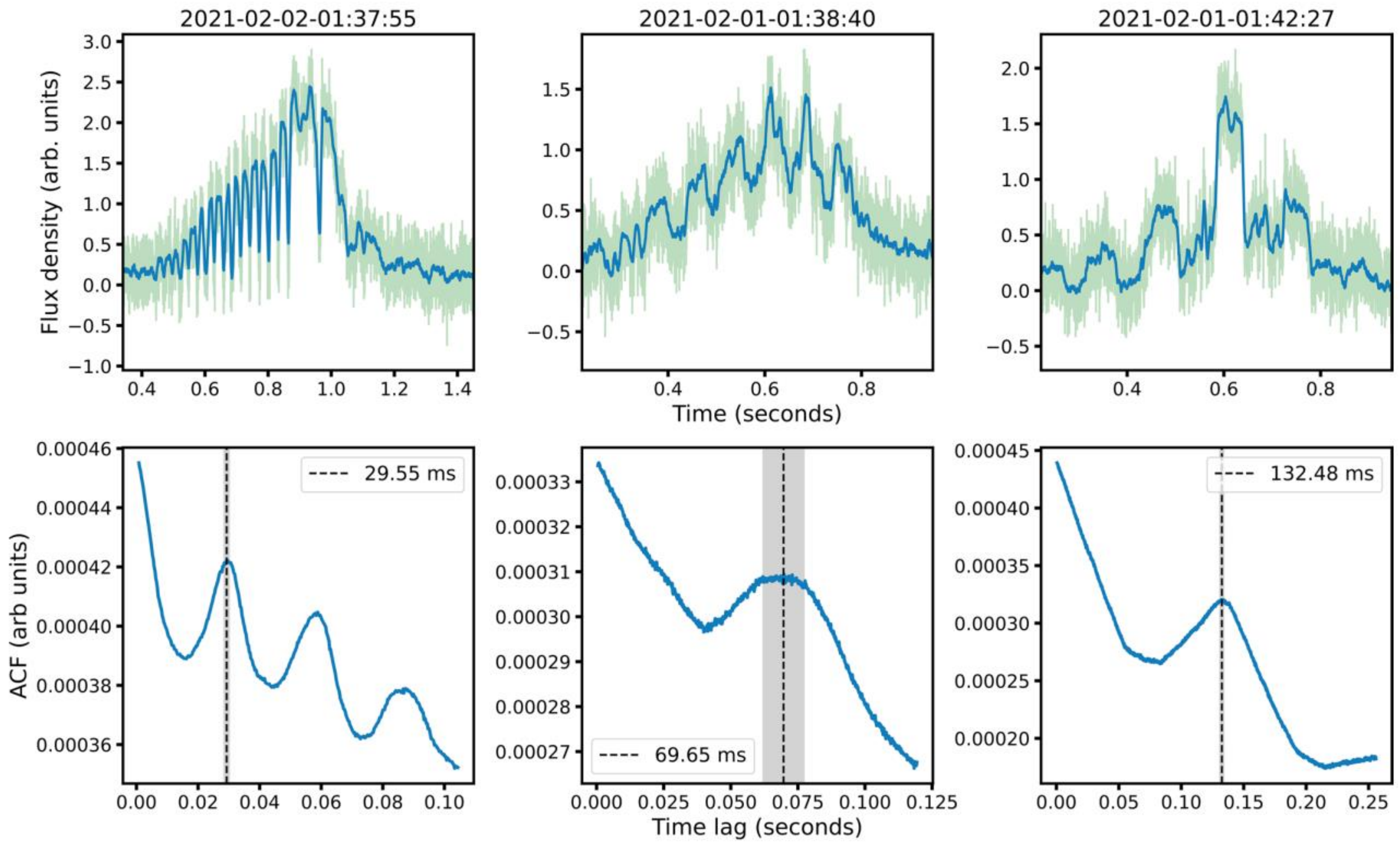
(2.1) From micro pulses:

Median width: $w_\mu \sim 49\ \mathrm{ms}$

Gil 1982&1986:

Particles' curvature radiation

➔micro pulses



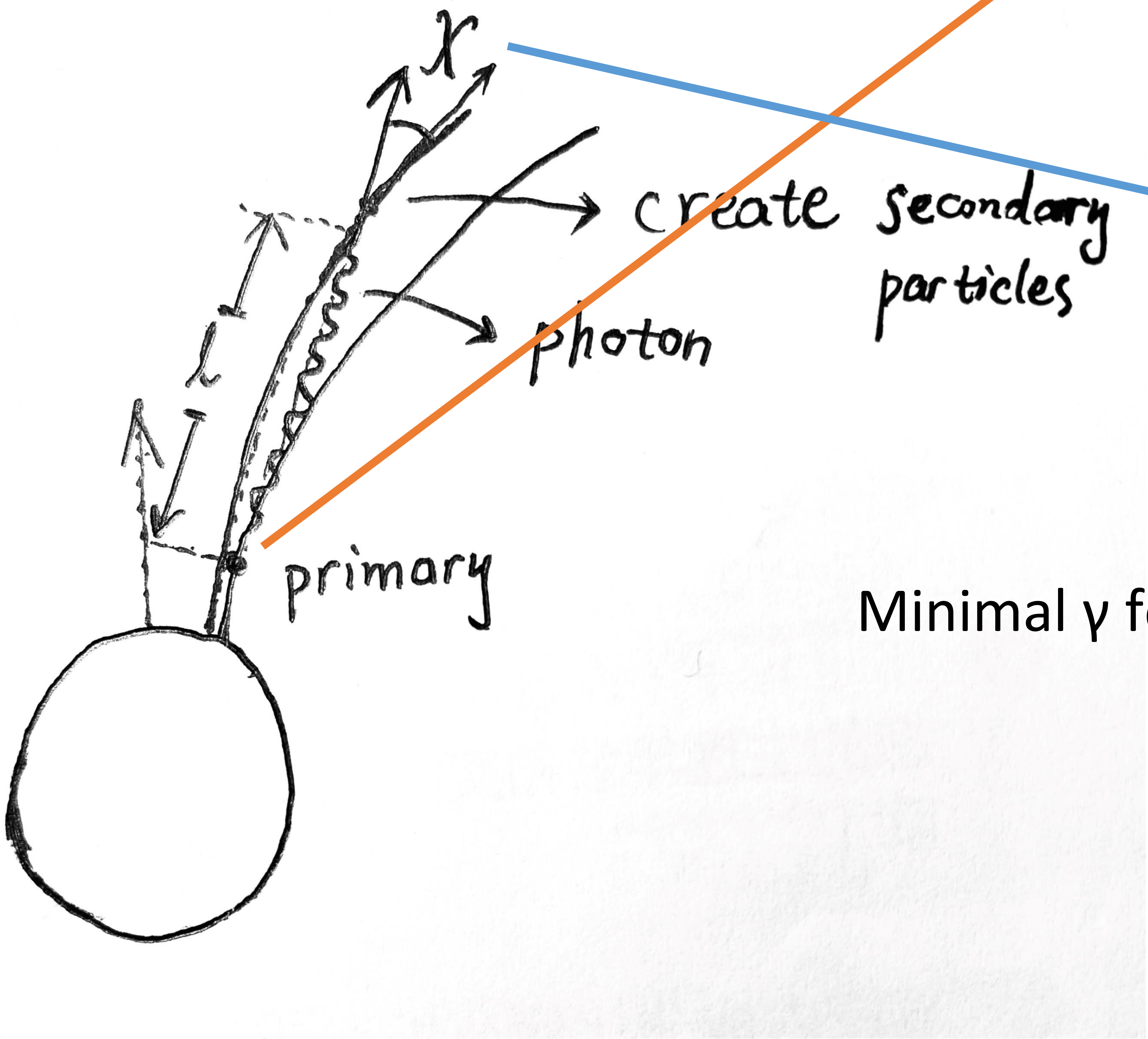
From Caleb et al. 2022 supplementary

Radiation opening angle: $\phi_\mu = 2/\gamma$

➔Micro pulse width: $w_\mu \ (\mathrm{rad}) = \phi_\mu / \sin\alpha$

➔➔γ of radiating particles: $\gamma = \dfrac{P}{\pi w_\mu \sin\alpha} \approx 2700.$

(2.2) From pair cascade:



Suppose radiation happens at s*RLC from magnetic axis (0<s<1).
Mitra & Rankin 2002: s=0.5

$$\chi = l/\rho_0(1 + l/R_{\rm ns})$$

$$\rho_0 = (4/3s)(R_{\rm ns}R_{\rm lc})^{0.5}$$

Minimal γ for secondary particles:

$$\gamma_{\rm min} = \frac{4}{3s}\left(\frac{R_{\rm lc}}{R_{\rm ns}}\right)^{0.5} \approx 1600$$

➔➔➔ Now estimating γ_0 of primary particles:

$$\varepsilon_{\rm ph} = (3/2)\hbar c \gamma_0^3/\rho_0 = 2\gamma m_e c^2$$

➔➔➔

$$\gamma_0 \approx 5.3 \times 10^7 \qquad \gamma_{0\,\min} \approx 4.5 \times 10^7$$

(3) Relating γ_0 with surface magnetic field:

Accelerating potential: $U = \frac{BR_{NS}^3}{2R_{LC}^2}(1-s^2)(1-\rho/\rho_{GJ}) \approx \frac{BR_{NS}^3}{2R_{LC}^2}(1-s^2)$

And we have: $eU=\gamma_0 mc^2$

➔➔➔ $$B = \frac{8}{3}\frac{\gamma_0 m_e c^2 R_{\rm lc}^2}{eR_{\rm ns}^3 \cos\alpha} \approx 3.2 \times 10^{16}\ {\rm G} \qquad B_{\min} \approx 2.7 \times 10^{16}\ {\rm G}$$

III. Discussion

(1) Why J0901-4046 radio active ?

Baring & Harding 1998: Photon “splitting’ forbids NS with B > B_{cr} to be radio active.
(Photons’ energy decreases, banning pair cascade)

Istomin & Sob’yanin 2007: **but** photons’ polarization affects splitting…

Demanding:

$$B \gtrsim \frac{P^{7/3}}{\cos\alpha} 10^{12}\ \mathrm{G}$$

For J0901-4046’s condition: $B \gtrsim B_{\rm death} \approx 2.5 \times 10^{16}\ \mathrm{G}$

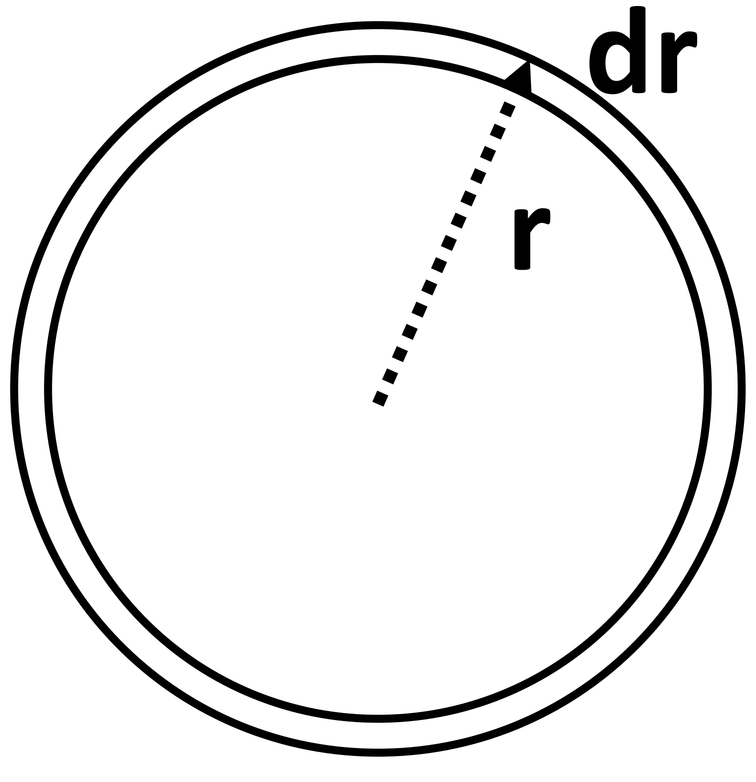
$$B_{\rm p} \approx 1.3 \times 10^{14}\ \mathrm{G} \qquad (\times)$$

$$B = \frac{8}{3} \frac{\gamma_0 m_e c^2 R_{\rm lc}^2}{e R_{\rm ns}^3 \cos\alpha} \approx 3.2 \times 10^{16}\ \mathrm{G}. \qquad (\surd)$$

(2) About J0901-4046’s spinning down:

B >> Bp ➔ spinning down not mainly due to vacuum dipole radiation.

Consider potential distribution near polar cap surface:



$$\left(\frac{1}{r}\frac{\partial}{\partial r}r\frac{\partial}{\partial r}+\frac{\partial^2}{\partial z^2}\right)\Psi=-4\pi(\rho_e-\rho_{GJ})$$

Ignore the change along z axis: $V = U[1-(r/R_{\rm pc})^2]\cos\alpha$

$$U=\frac{BR_{NS}^3}{2R_{LC}^2}(1-s^2)(1-\rho/\rho_{GJ})\approx\frac{BR_{NS}^3}{2R_{LC}^2}(1-s^2)$$

Introduce current I: $dI = 2Irdr/R_{\rm pc}^2$

Power: $dW = V\,dI$ $W = \int dW = (1/2) U I \cos\alpha$

A pulsar has two polar caps: $\dot{E} = U I \cos\alpha$

Observed E-dot: $2.0 \times 10^{28}\ \mathrm{erg\,s^{-1}}$

➔➔➔ $I = \frac{3}{4} \frac{e\dot{E}}{\gamma_0 m_e c^2} \approx 56\ \mathrm{MA}$

Physically: Lorentz force slows down the pulsar.

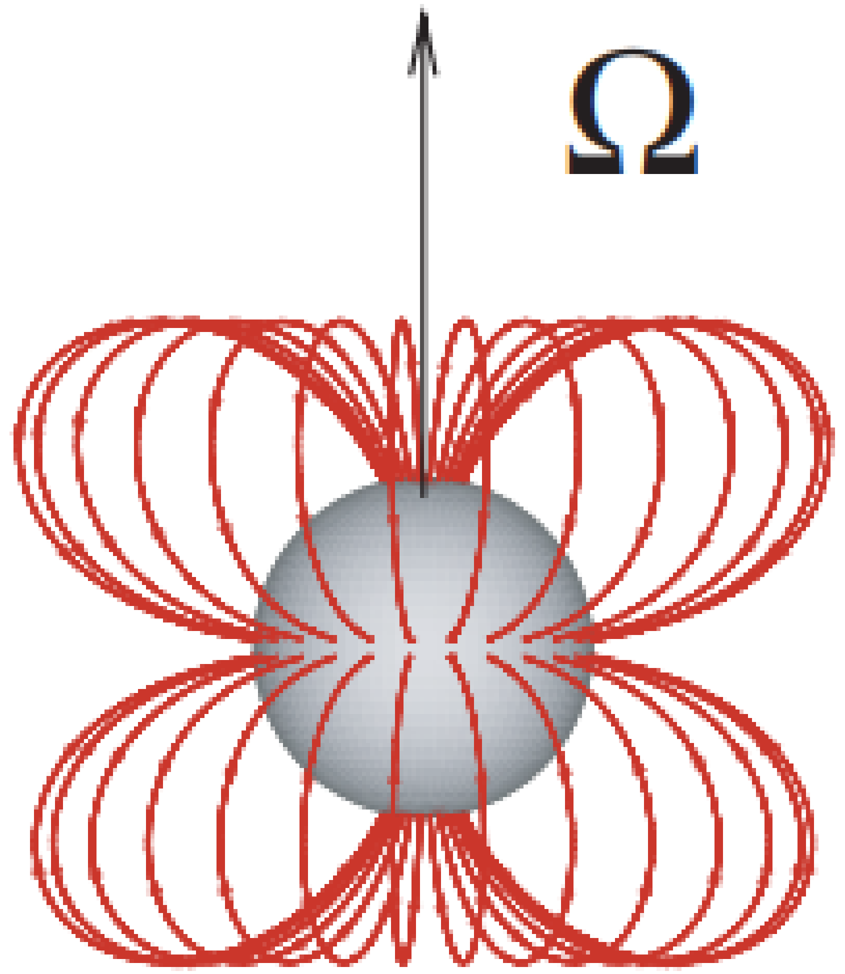
(3) Multipole (quadrupole) magnetic field:

$$B_r = 3D(3\cos^2\theta - 1)/4r^4$$

$$B_\theta = 3D\sin\theta\cos\theta/2r^4$$

➔➔ $B_{\mathrm{q}} \approx 3.1 \times 10^{23}$ G Unrealistic

➔ No global quadrupole



Long, Romanova and Lovelace 2007

Still possible if local multipole field together with a global dipole…

Thank you for your attention