PSR B0943+10:
Mode switch, Polar cap geometry
And Orthogonally polarized radiation

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(Published by *ApJ.* 2024.9.20)

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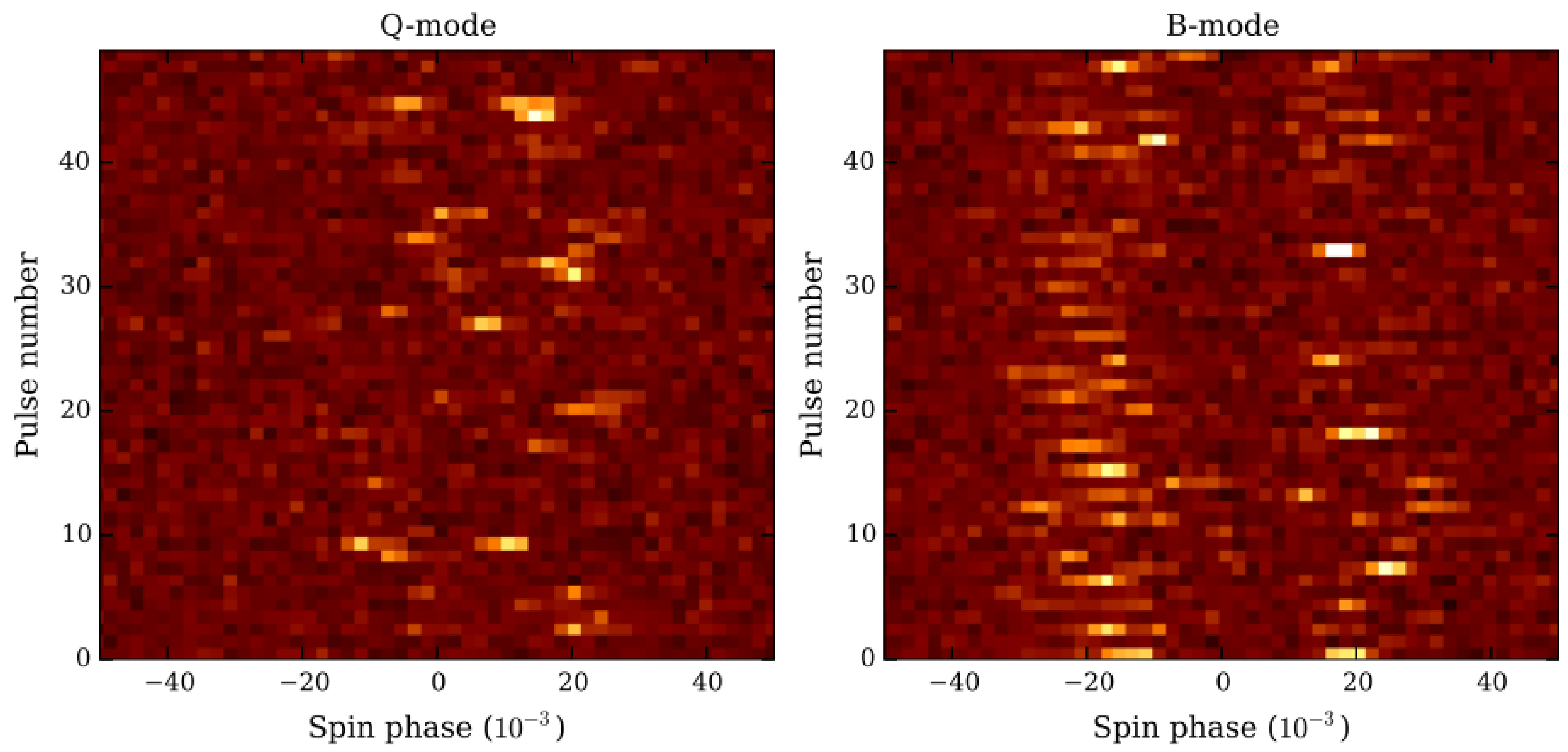
2024.10

I. Introduction

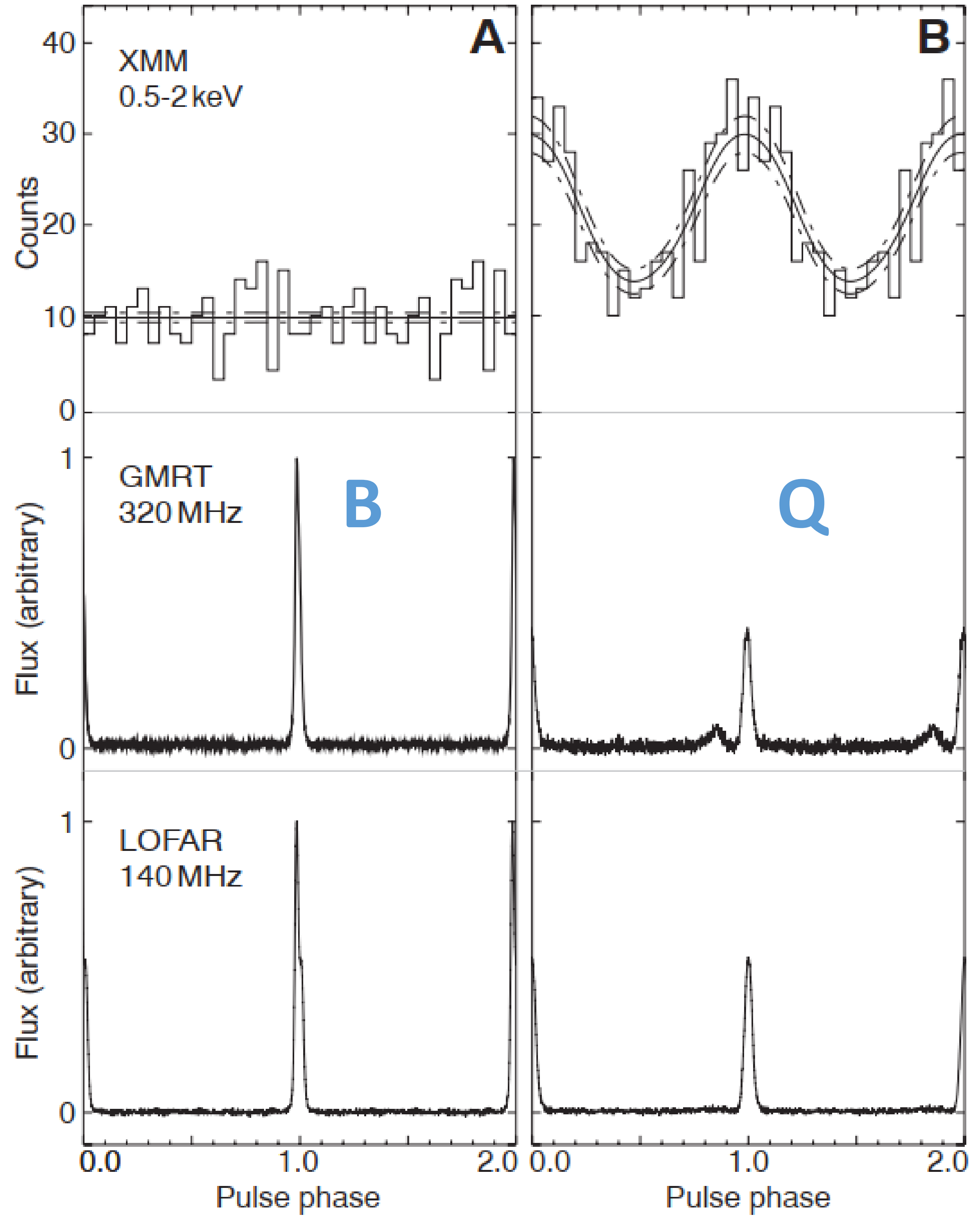
Basic radiation facts on PSR J0946+0951 (B0943+10):

P ≈ 1.1s, Pdot ≈ 10^{-15}, DM ≈ 15 pc*cm^{-3}, RM ≈ 14.1 m^{-2} (PSRCAT)

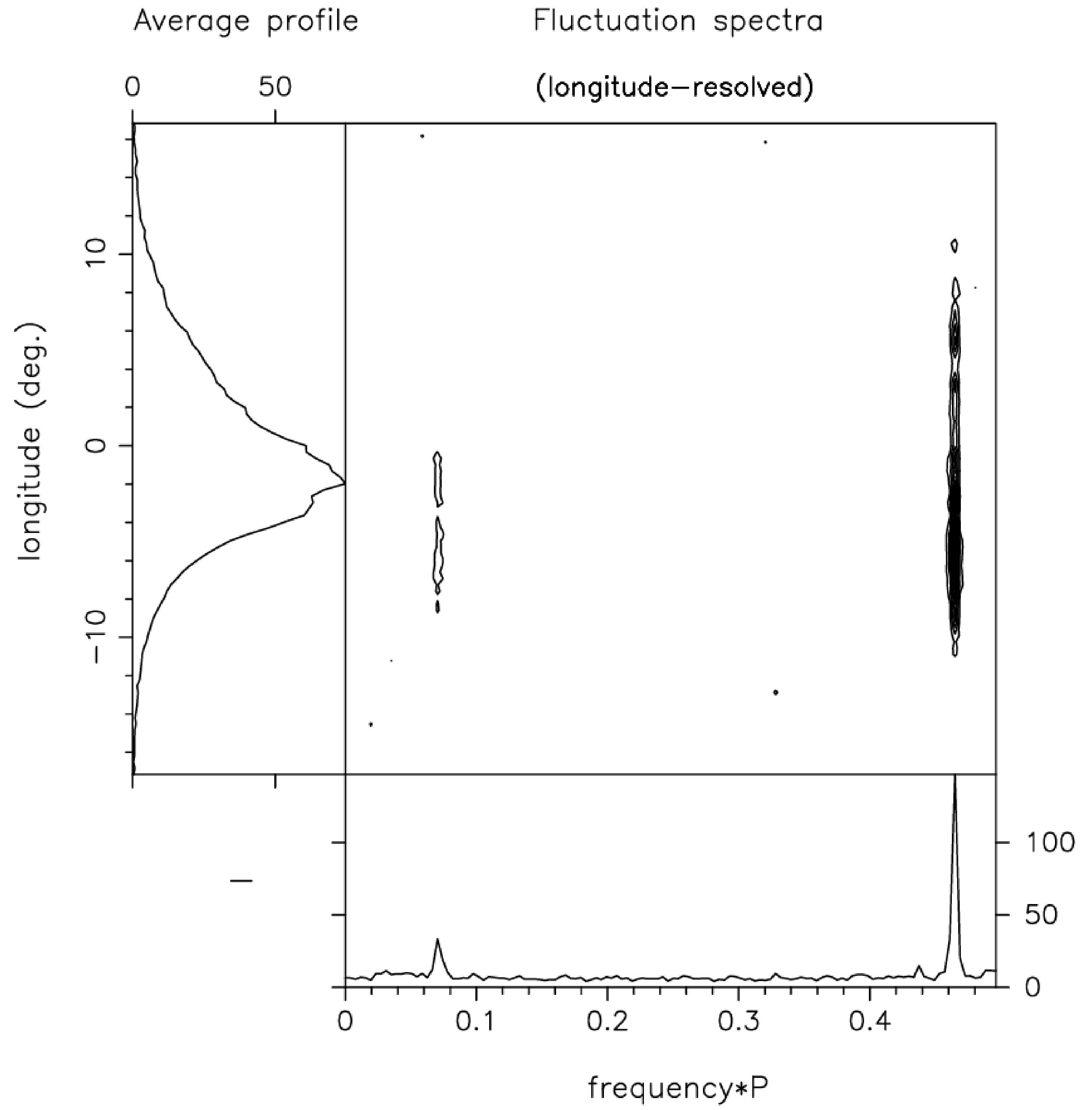
·Mainly two stable modes: B (burst, with **drifting subpulses**) and Q (quiet, disorganized, but with strong thermal(?) X-ray pulsation)



Bilous et al. 2018 *A&A*
(LOFAR 25-80MHz)

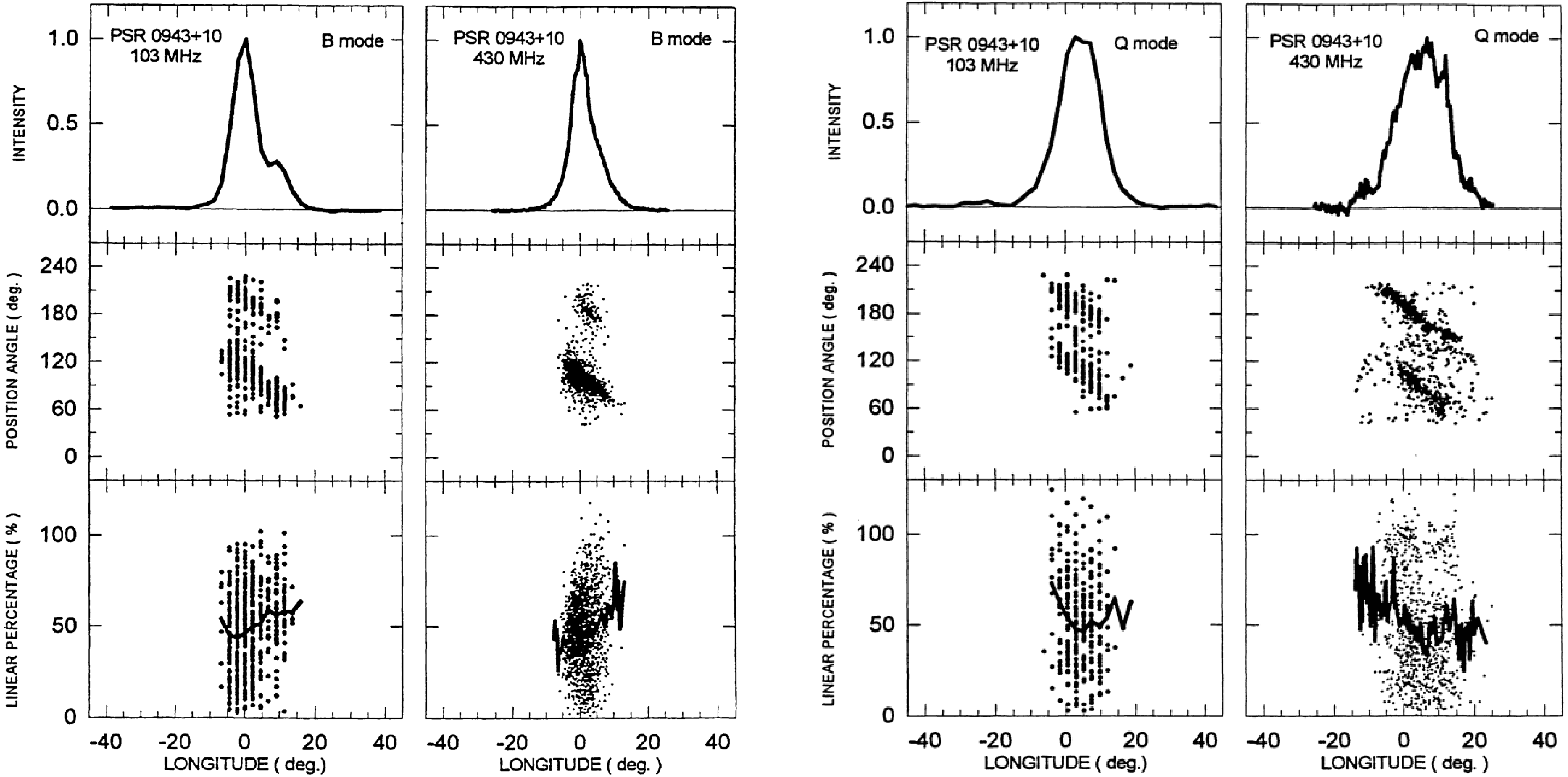


Hermsen et al. 2013 *Science*



Deshpande & Rankin 2001 *ApJ*
(Arecibo 430MHz, LRFS)

B-to-Q mode switch: OPMs' proportion changes with modes and frequencies.
OPM: Orthogonal Polarization Modes.



Suleymanova et al. 1998 *JApA*

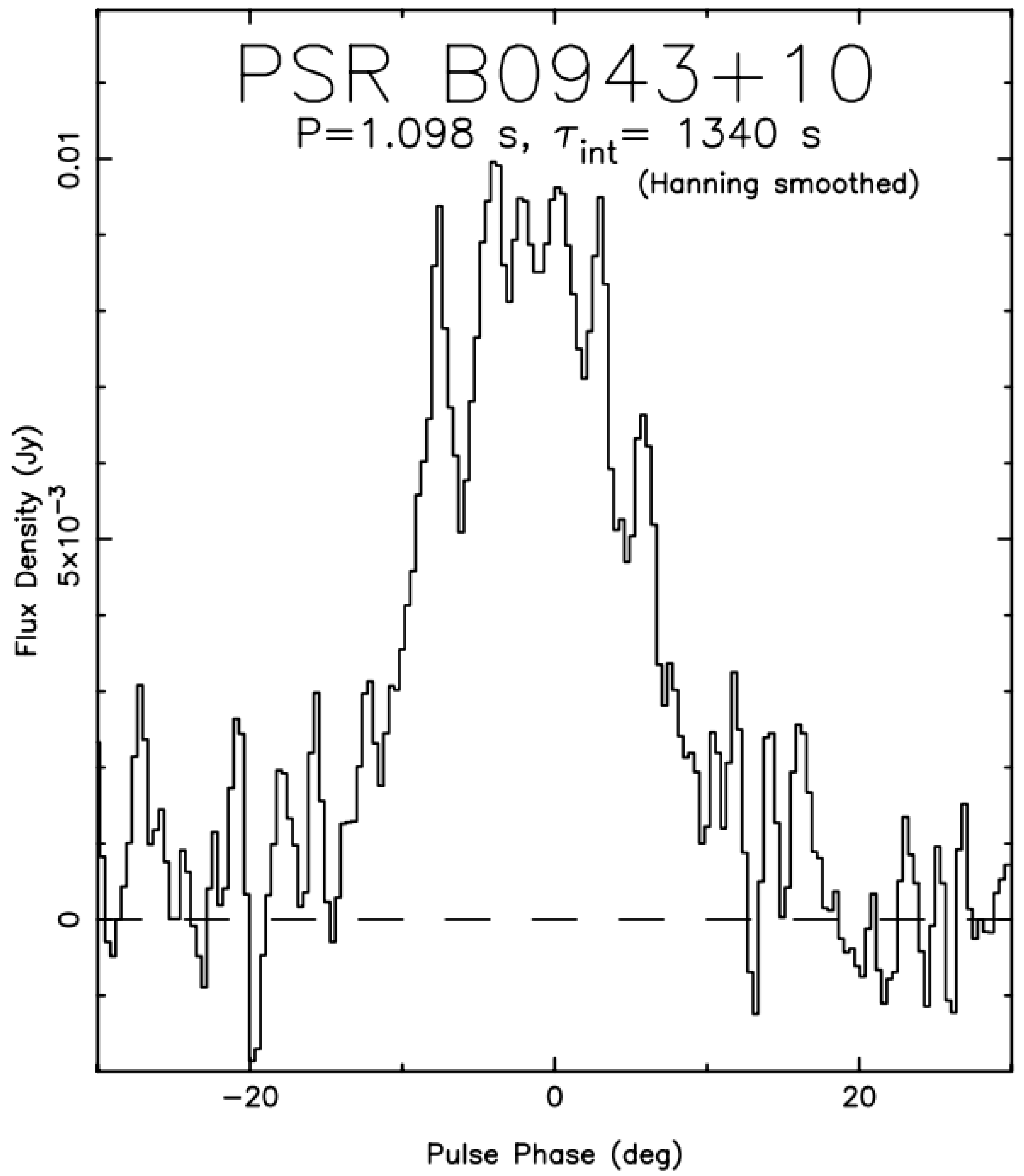
Study B0943+10's radiation properties with FAST data:

Theoretical motivation:

(1) Origin of mode switch
(2) Explanation to radio & X-ray emission synchronization

Observational motivation:

(1) No detailed study of B0943+10 above 1GHz
(2) No good enough estimation of radiation geometry



(Arecibo 1.418GHz)

Weisberg et al. 1999 *ApJS*

Source	Suleymanova et al. (1998)	Deshpande & Rankin (2001)	Backus et al. (2010)
Frequency (MHz)	102.5 and 430	102.5 and 430	327 and 430
R_{PA} (deg/deg)	$-2.4 \sim -3.6$	−2.7	−3.0
α (deg)	…	11.58	…
β (deg)	…	−4.29	…

II. Observation

4 sessions by FAST (2022-2023)   PI: Shunshun Cao and Zhichen Pan (20220517)

Observe Date	Source Name	RA	Dec	Backend	Observation Mode	Observation Duration (s)
2022-09-02	J0946+0951	09:46:07.60	+09:51:55.0	psr	Tracking	3000
2022-05-17	J0946+0951	09:46:07.60	+09:51:55.0	psr	SwiftCalibration	7335
2023-08-27	J0946+0951	09:46:07.60	+09:51:55.0	psr	Tracking	2720
2023-08-16	J0946+0951	09:46:07.60	+09:51:55.0	psr	Tracking	3280

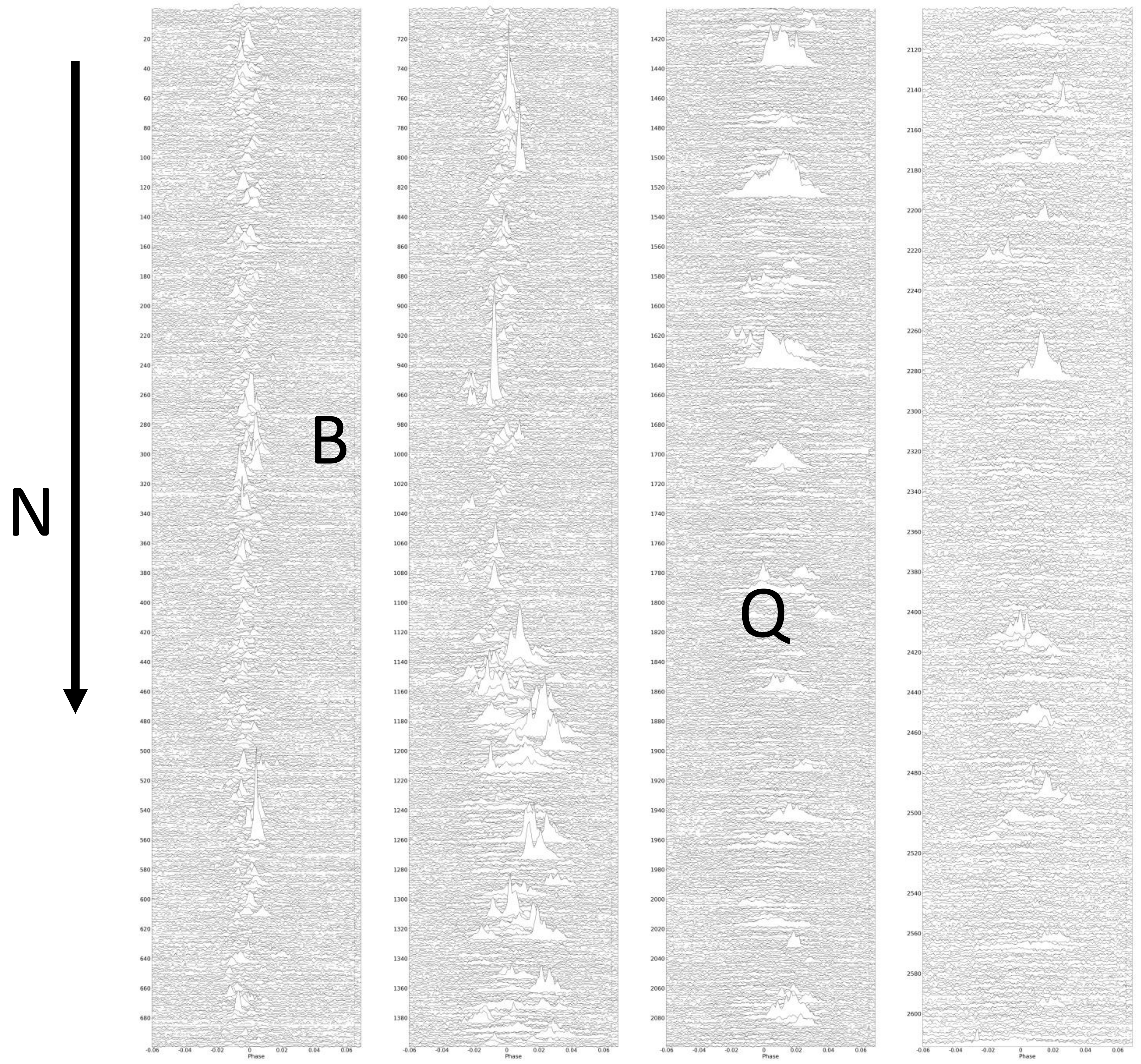
https://fast.bao.ac.cn/observation_log/observed_source_search

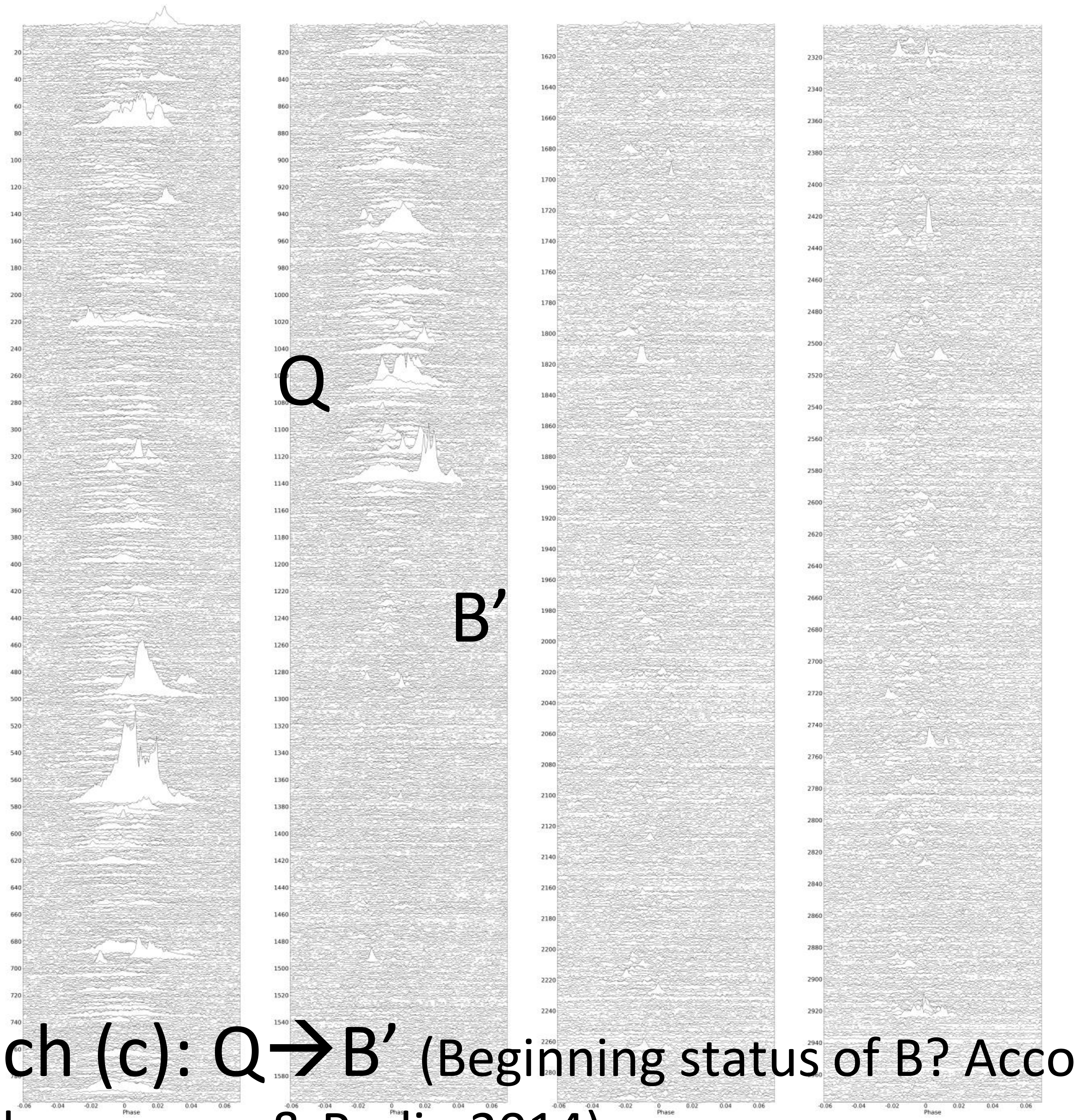
Data processing: DSPSR, PSRCHIVE and TEMPO2 software packages.

III. Results

Epoch (a): pure Q   Epoch (d): pure B

Modes and Mode switches (analyzed with a decomposition method in appendix)

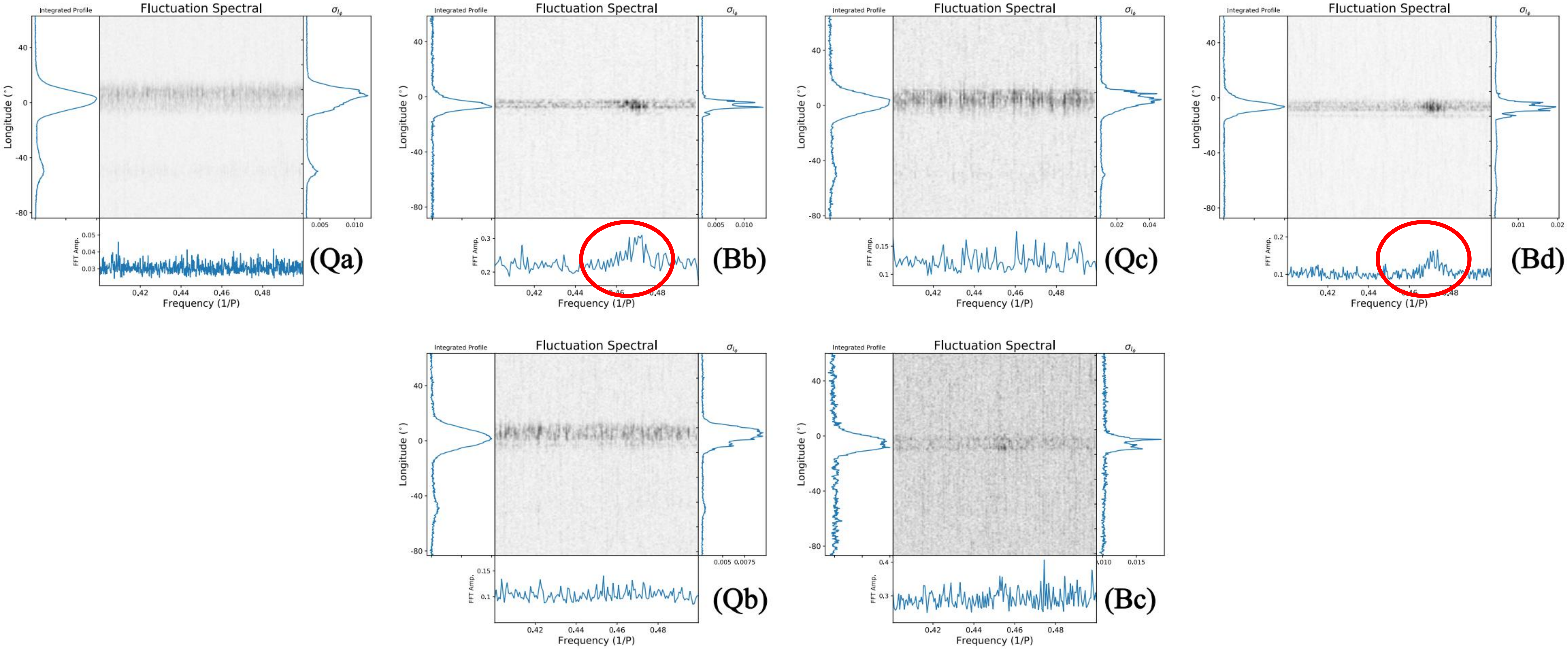




Epoch (c): Q→B’ (Beginning status of B? According to Suleymanova & Rodin 2014)

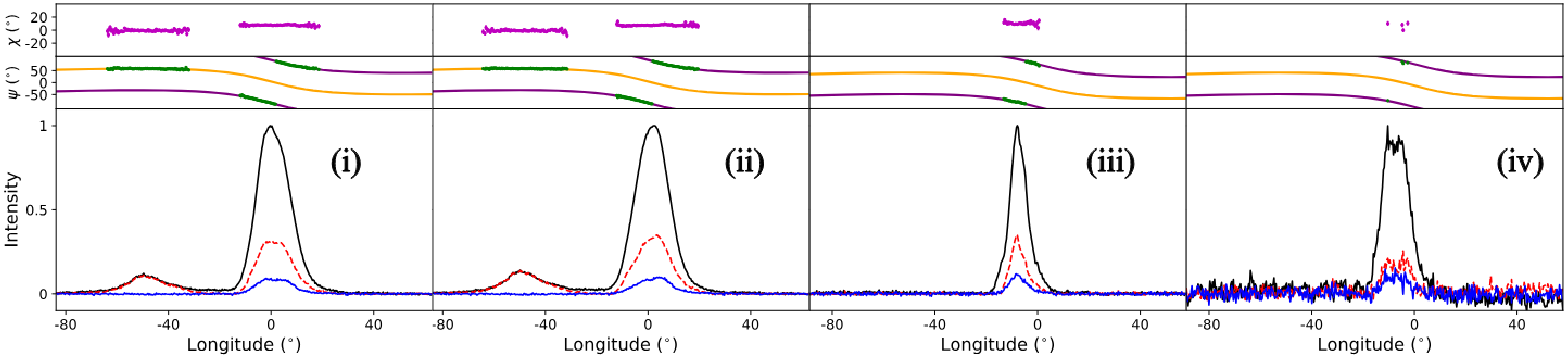
Epoch (b): B→Q

Longitude (Phase)



LRFS (Longitude Resolved Fluctuation Spectral) of all modes’ pulses.
The drifting B modes have peaks around 0.47cycle/period.

Profiles: with good **TWO orthogonal** RVM fitting (yellow & purple curves).



Total (14521 pulses) Q mode B mode B' mode

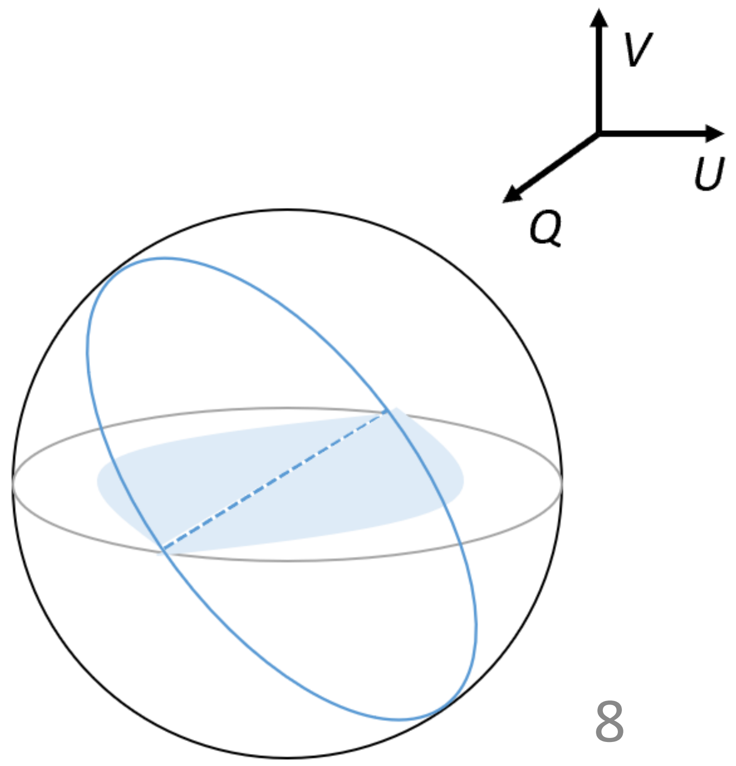
Dots:

Green – Polarization position angle (PA)

$$\psi = \frac{1}{2}\arctan(\frac{U}{Q})$$

Purple – Ellipticity angle (EA)

$$\chi = \frac{1}{2}\arcsin(\frac{V}{\sqrt{U^2+Q^2+V^2}})$$



Lines:

Black – Intensity (I)

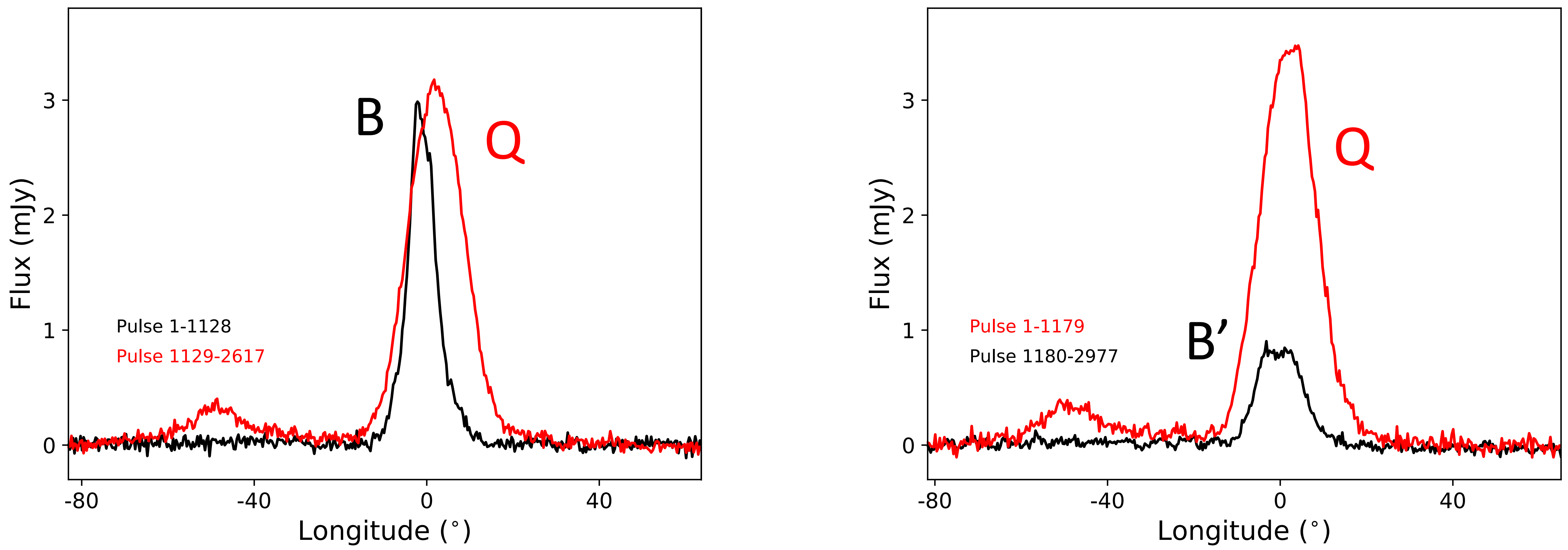
Red – Linear polarization $L = \sqrt{Q^2+U^2}$

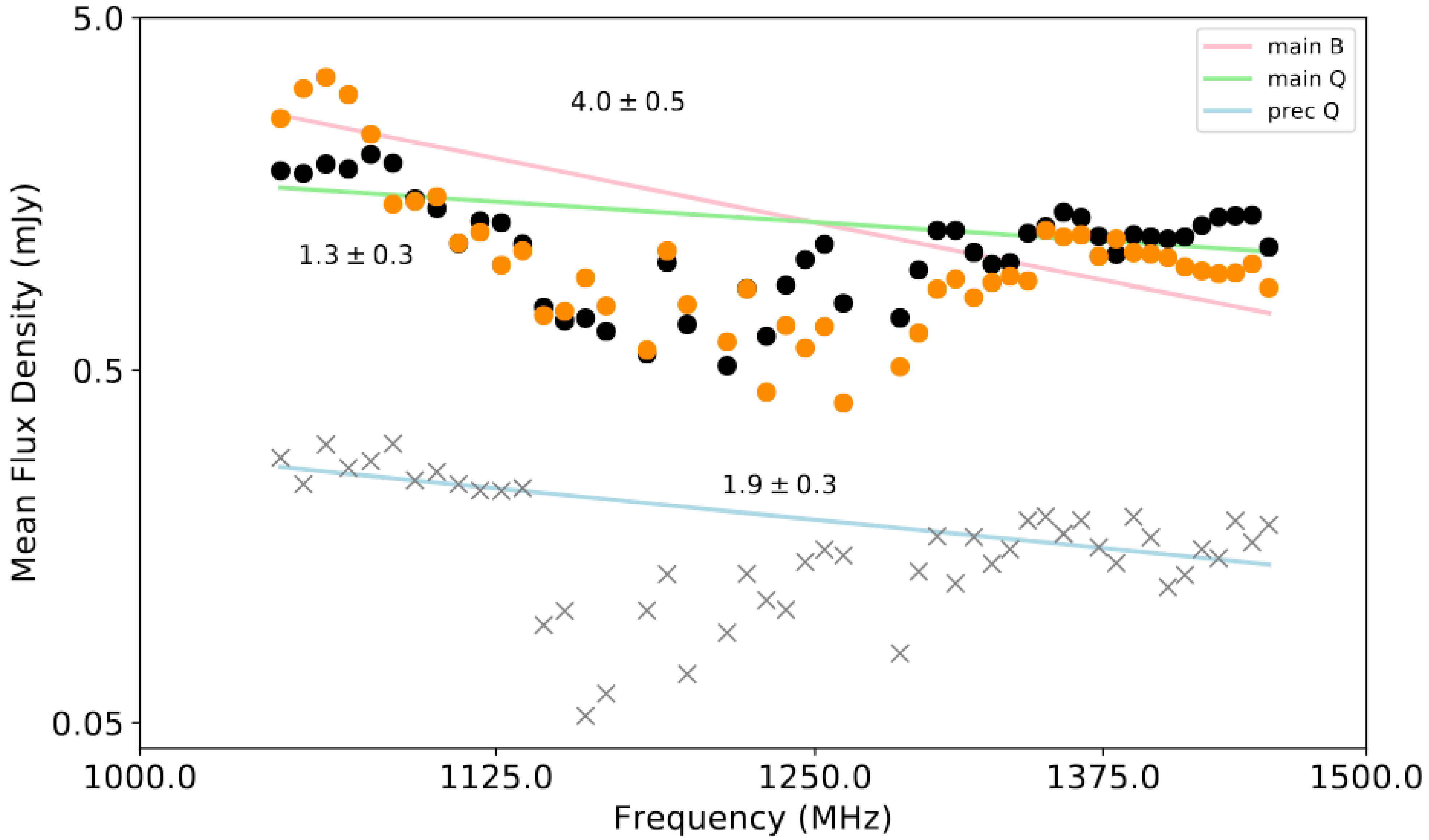
Blue – Circular polarization (V)

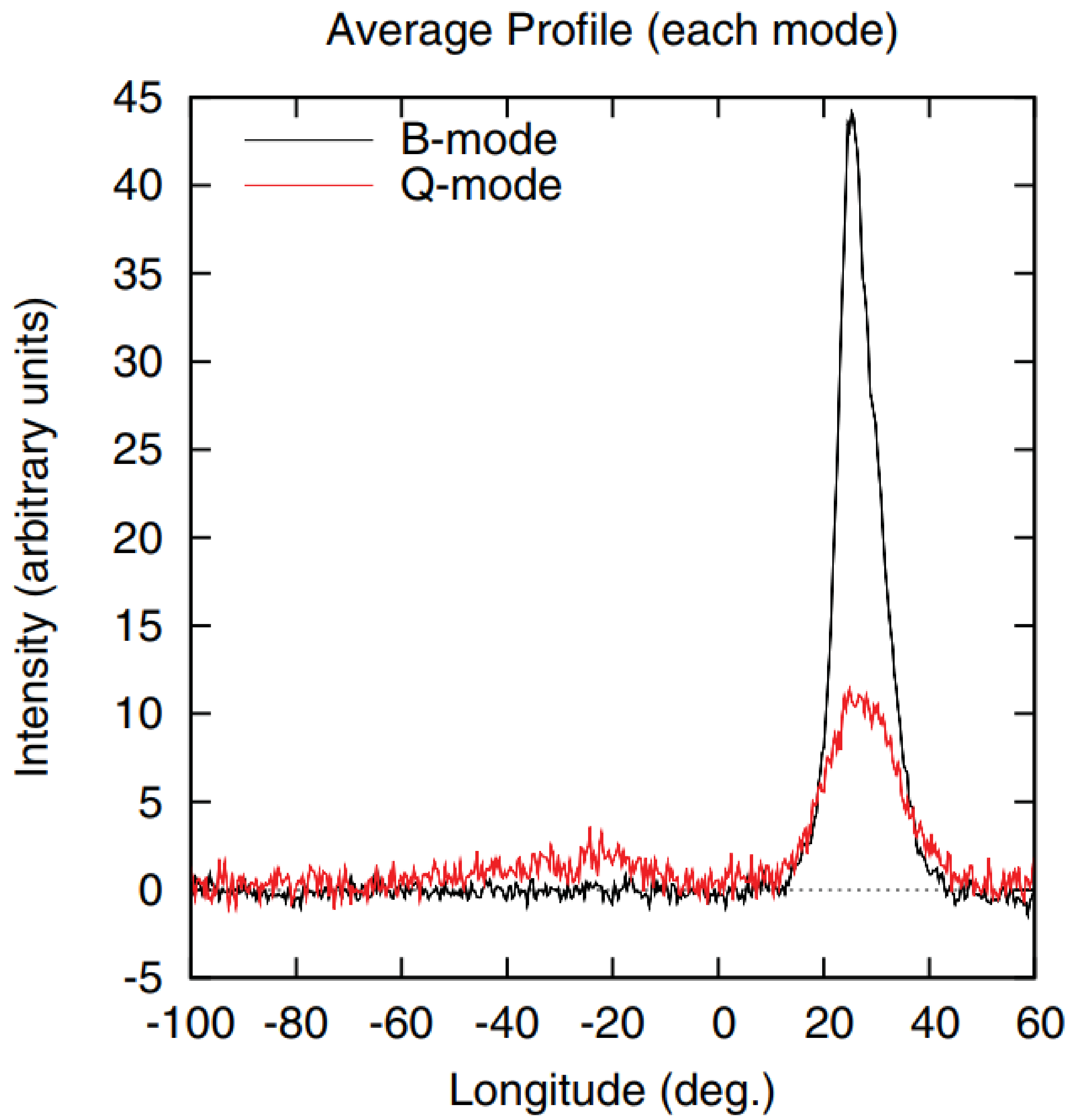
Precursor and Main pulse: orthogonally polarized.

Flux density estimation: $I_\phi = \frac{\mathrm{SNR} \cdot T_{\mathrm{sys}}}{G} \sqrt{\frac{\mathrm{nbin}}{2 \times \mathrm{bandwidth} \times t_{\mathrm{obs}}}}$

G & T_{sys} from Jiang et al. 2020 *RAA*







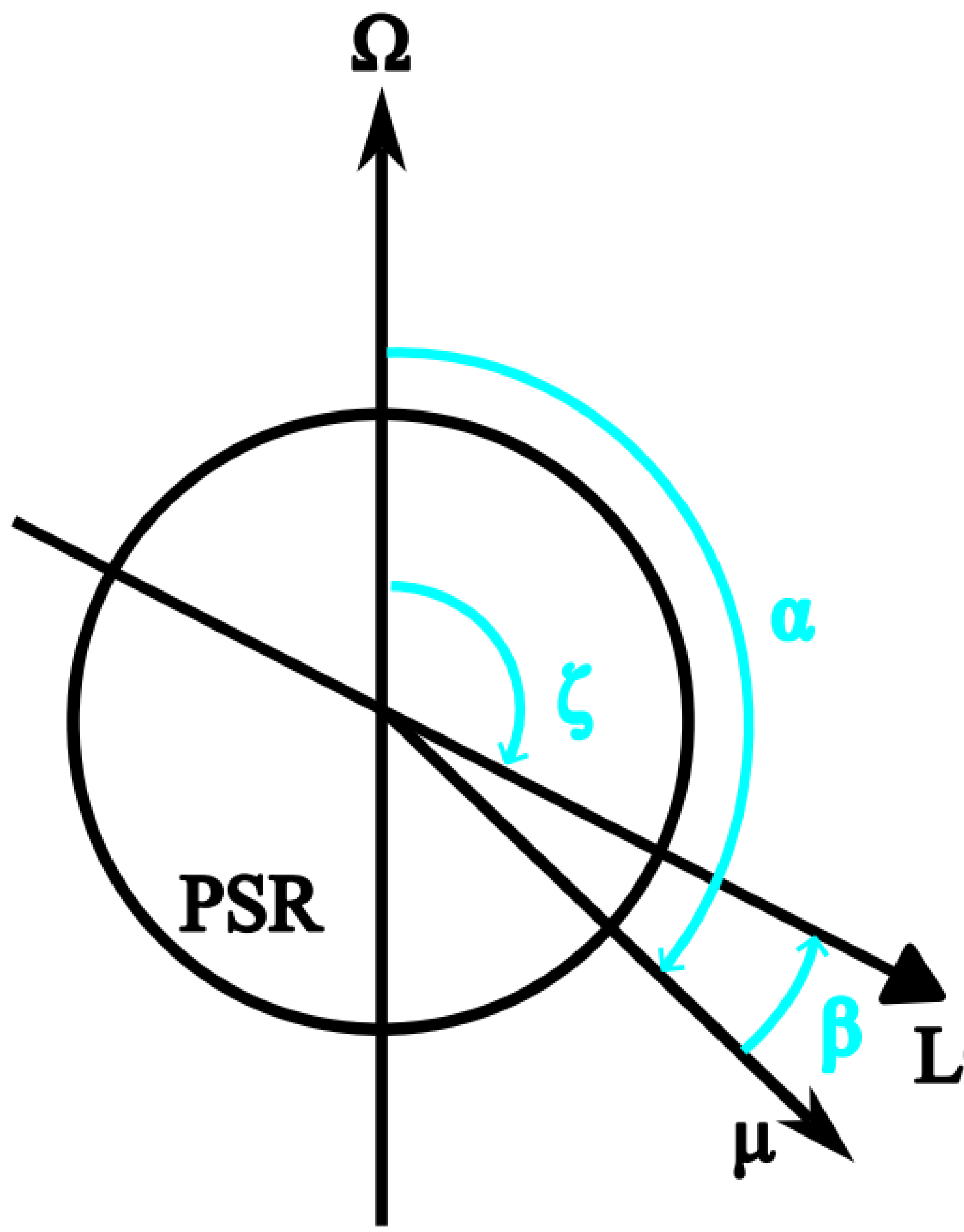
Backus, Mitra and Rankin 2011 *MNRAS*

(GMRT 325MHz)

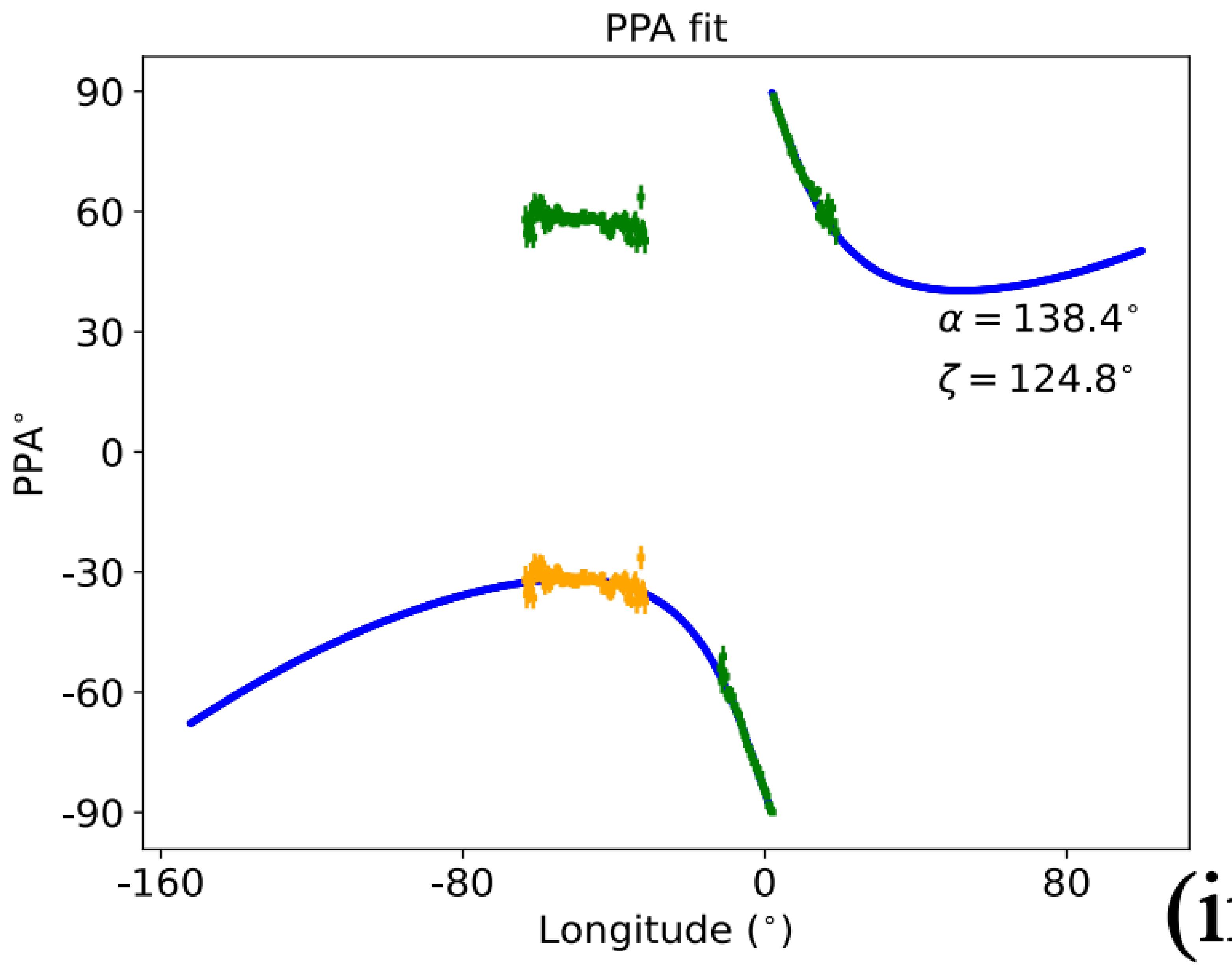
B and Q: different in frequency evolution.

Profiles: with good **TWO orthogonal** RVM fitting.

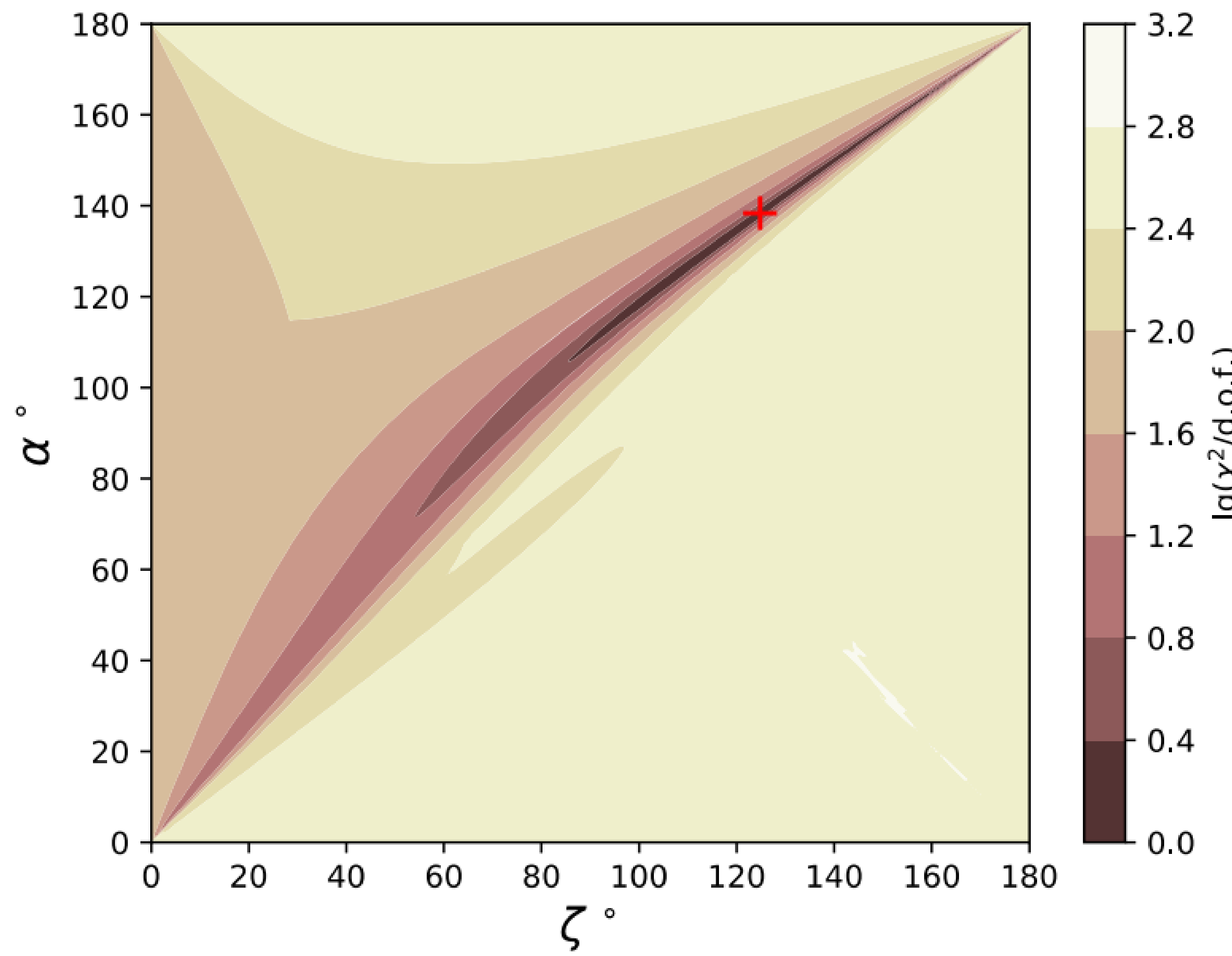
$$\tan(\psi - \psi_0) = \frac{\sin(\phi - \phi_0)\sin\alpha}{\sin\zeta\cos\alpha - \cos\zeta\sin\alpha\cos(\phi - \phi_0)}$$



(i)



(ii)



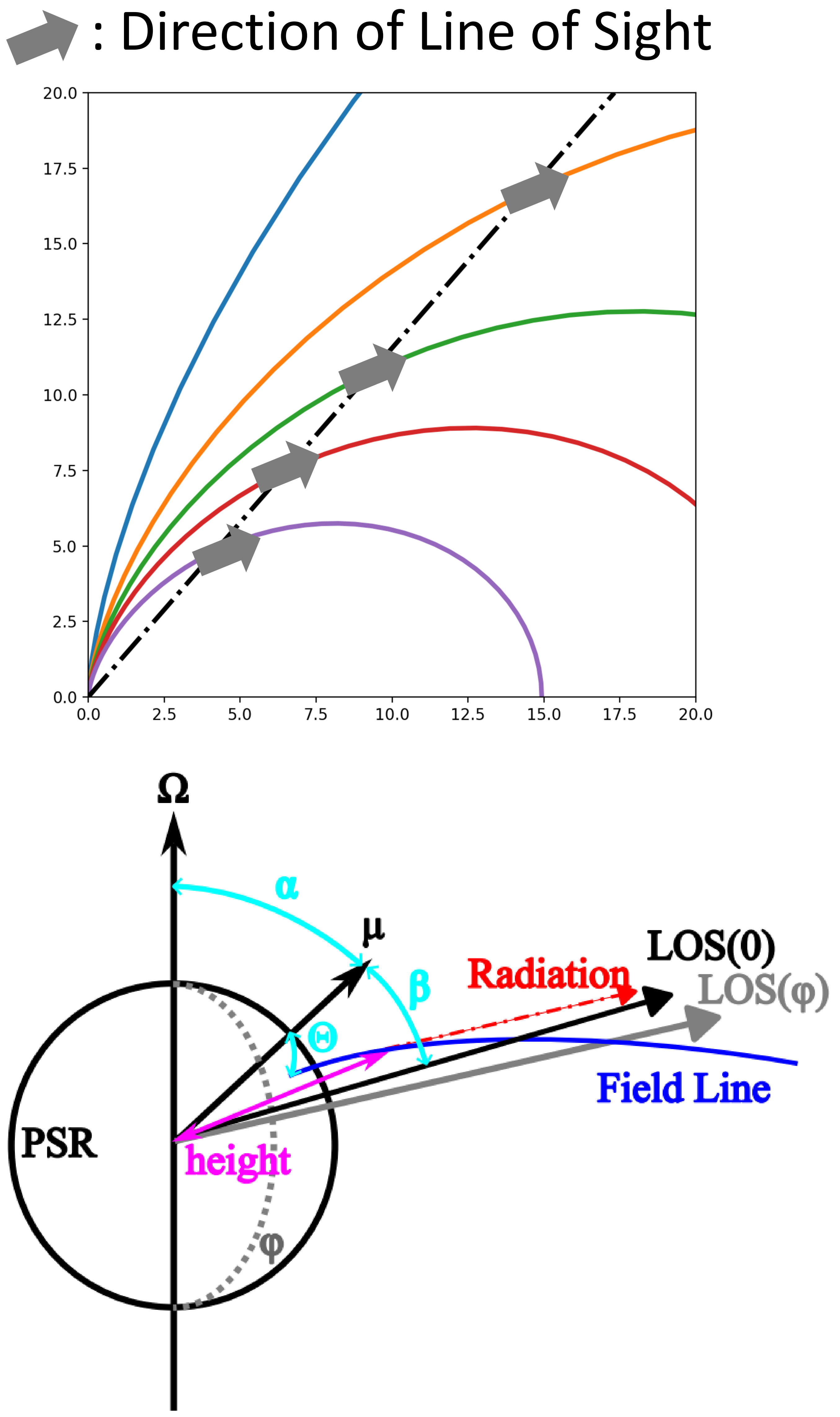
(iii)

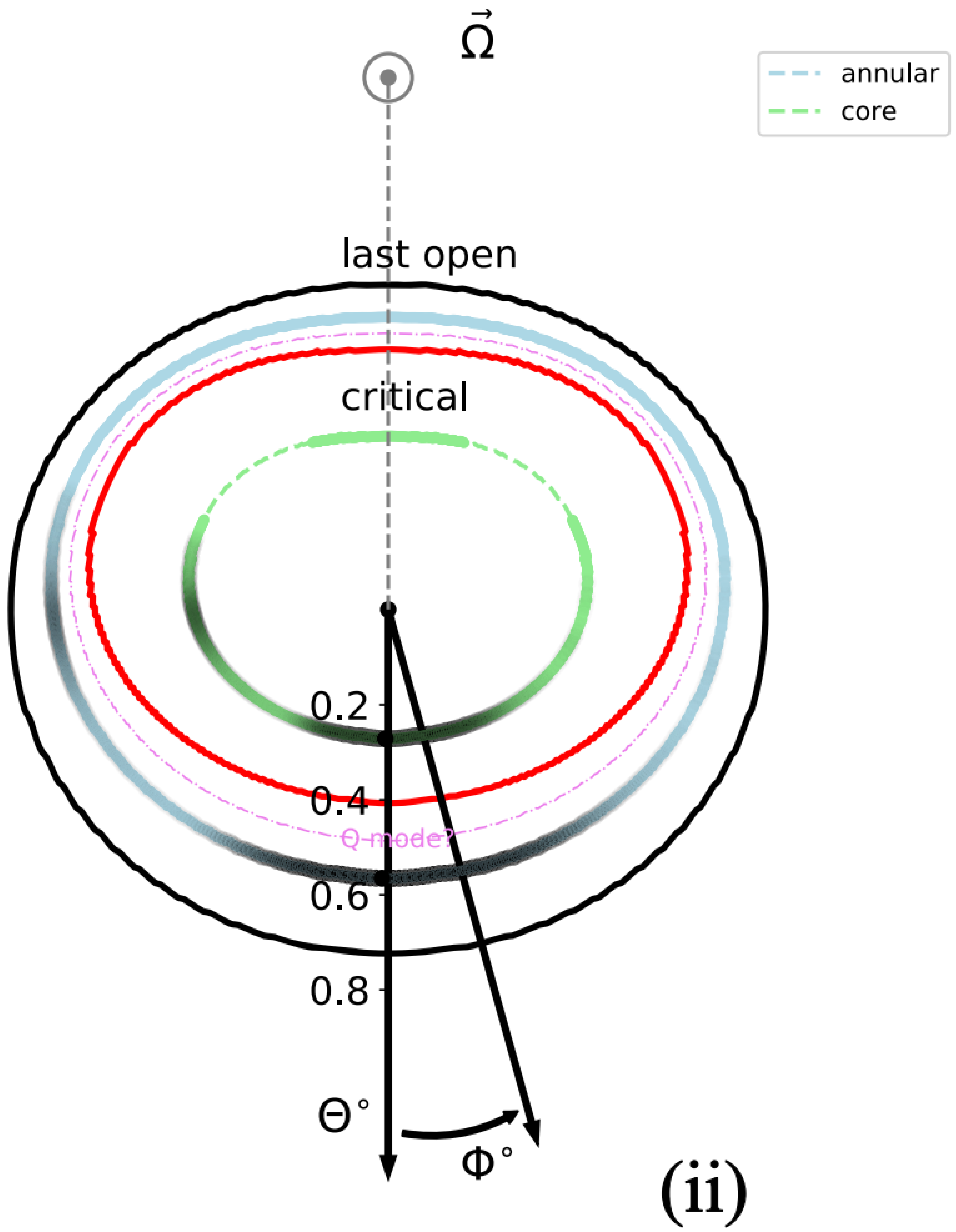
With FAST data, the wide longitude range of on-pulse region makes RVM fitting possible.
Inclination angle: α = 138 ± 2 deg, Impact angle: β = -14 ± 4 deg.

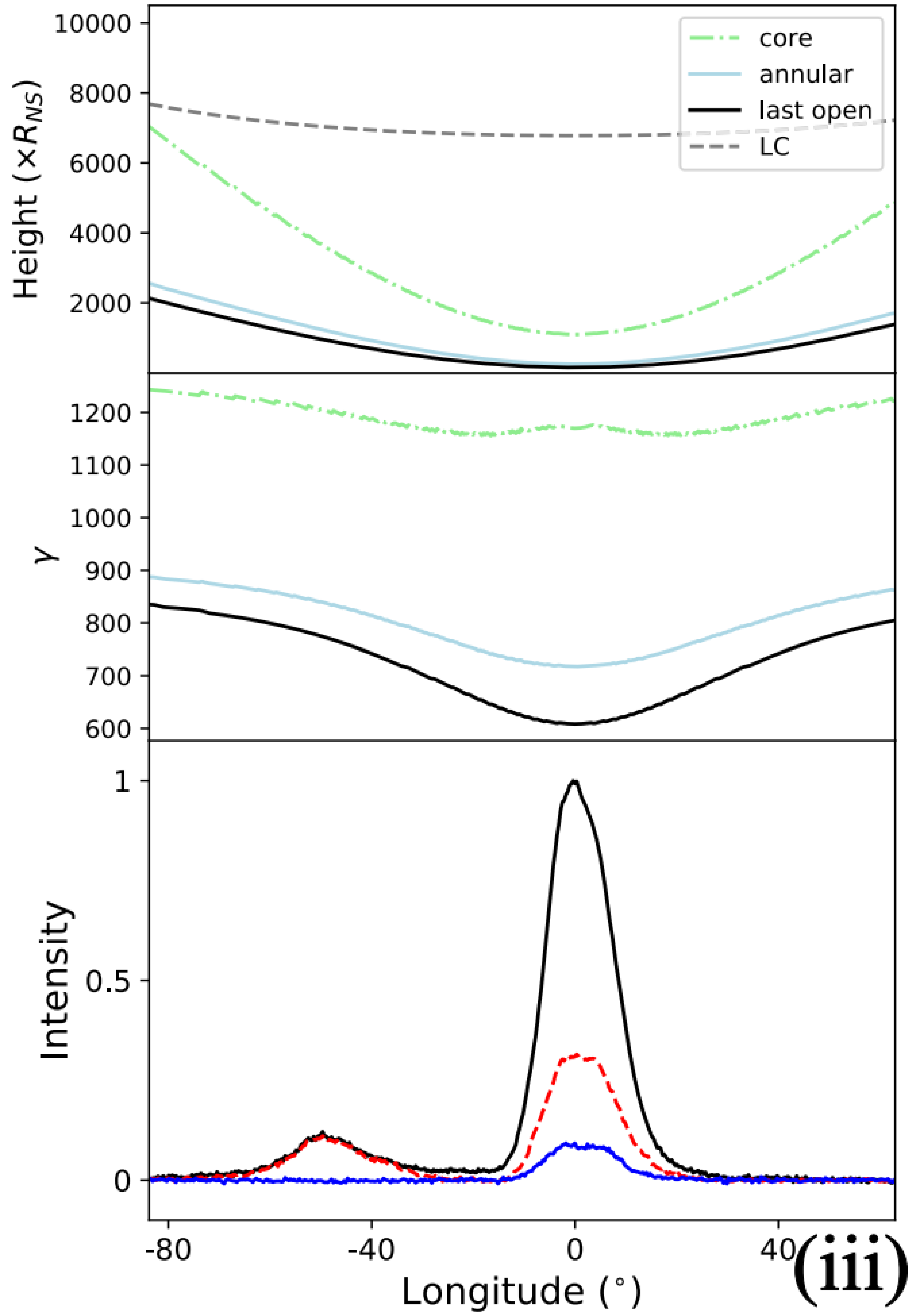
Precursor and Main pulse: orthogonally polarized.

Geometry → Pulse profile mapping to pulsar surface (method by Wang et al. 2023 *ApJ.*):
Choose a group of magnetic field lines, and mark their feet on polar cap region.

$$f_c = \frac{1}{2\pi}\frac{3c\gamma^3}{2\rho_c}$$

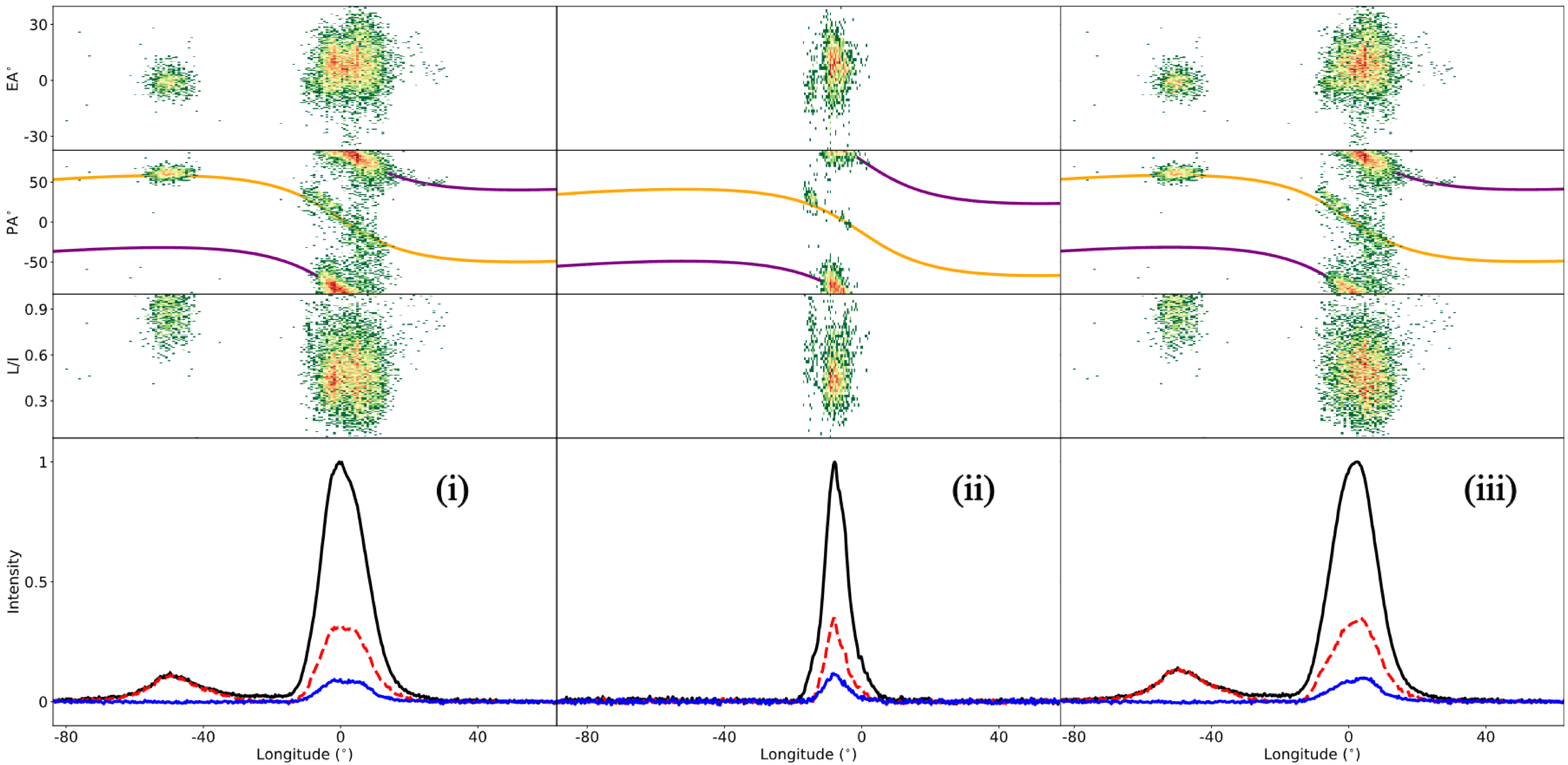






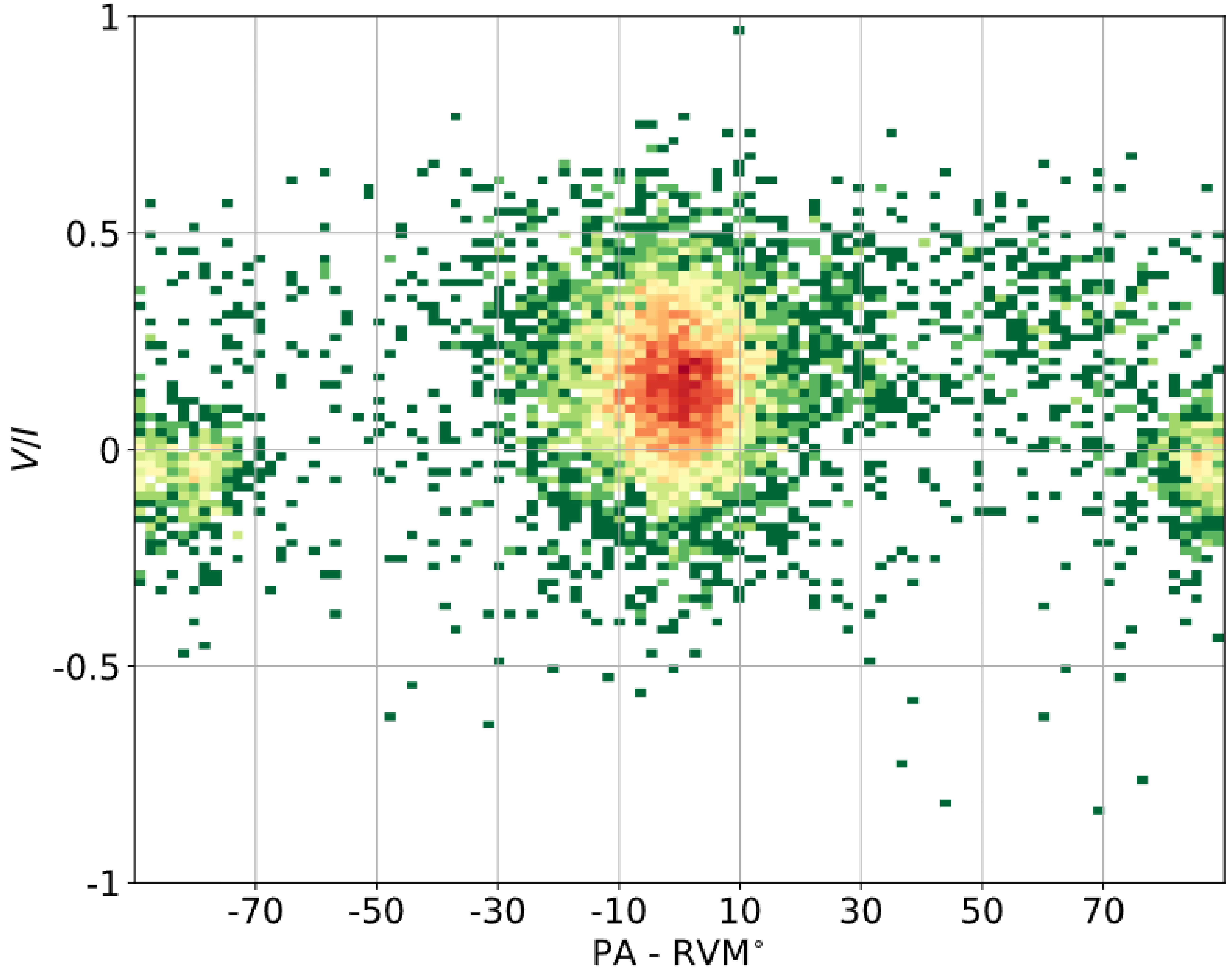
Based on Qiao et al. 2004 ApJ.

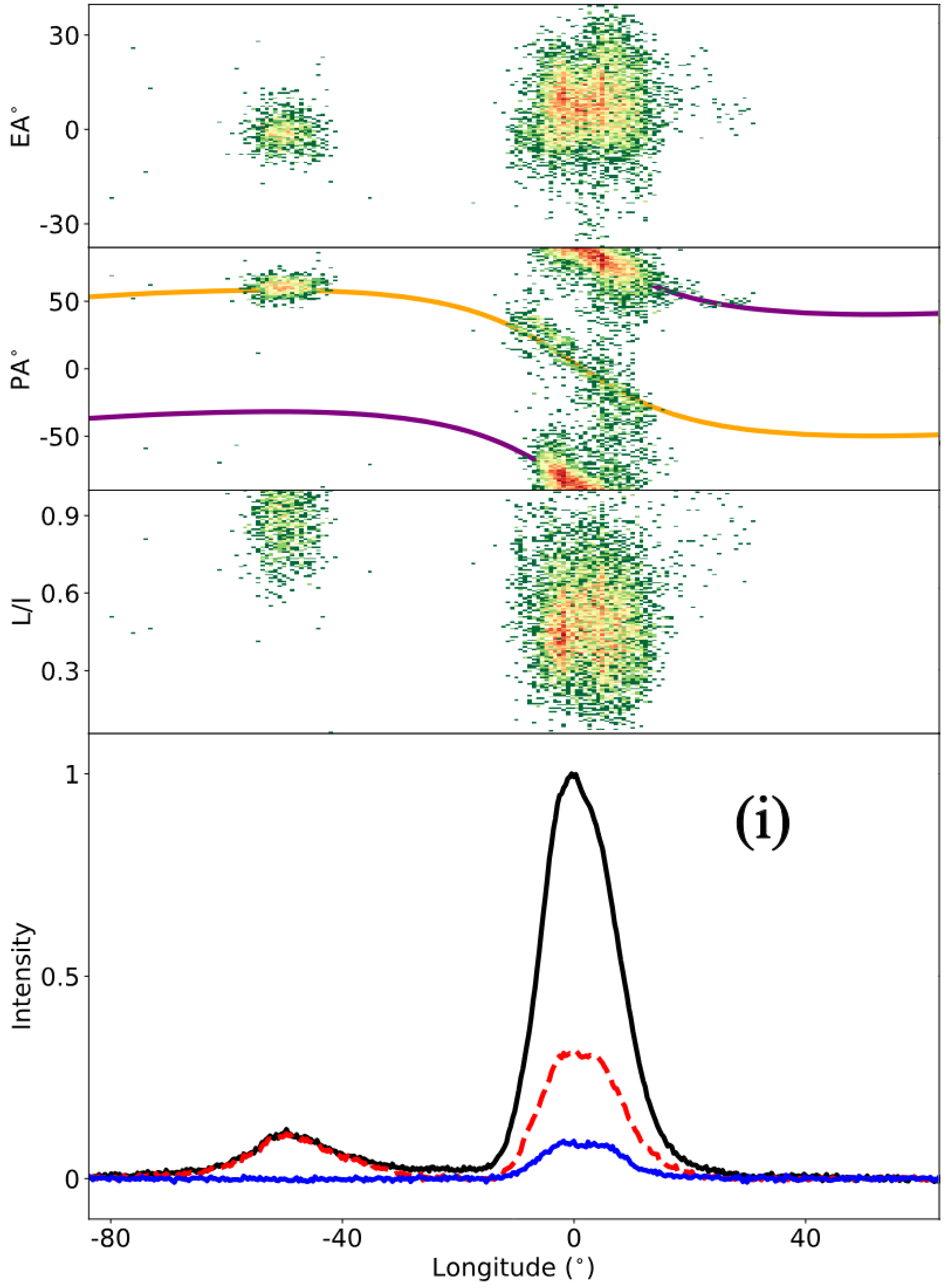
➔Single pulses' distributions of L/I, PA and EA (of all, B and Q).



PA distribution reveals OPMs (PA patches around 0° & 90°)

PA and V/I distribution (for main pulse component):



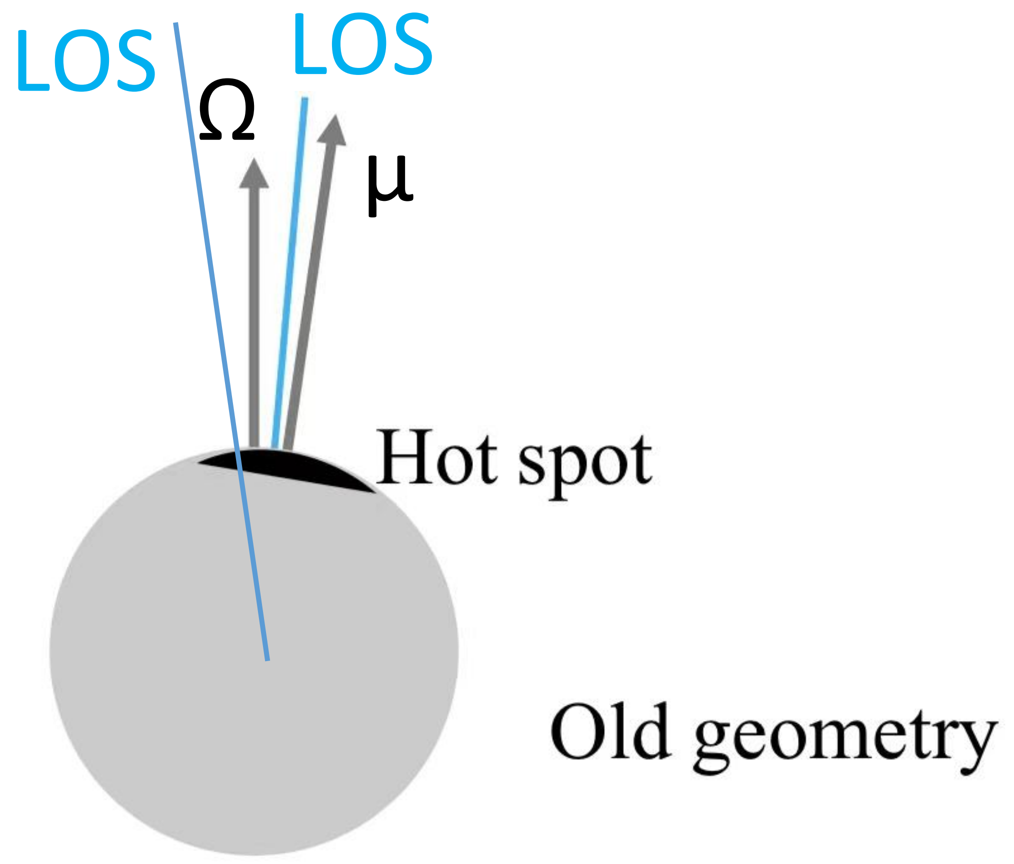


Different orthogonal modes tend to have **different** sign(V) and |V|.

IV. Discussion

(i) Understand Radio & X-ray emission synchronization:

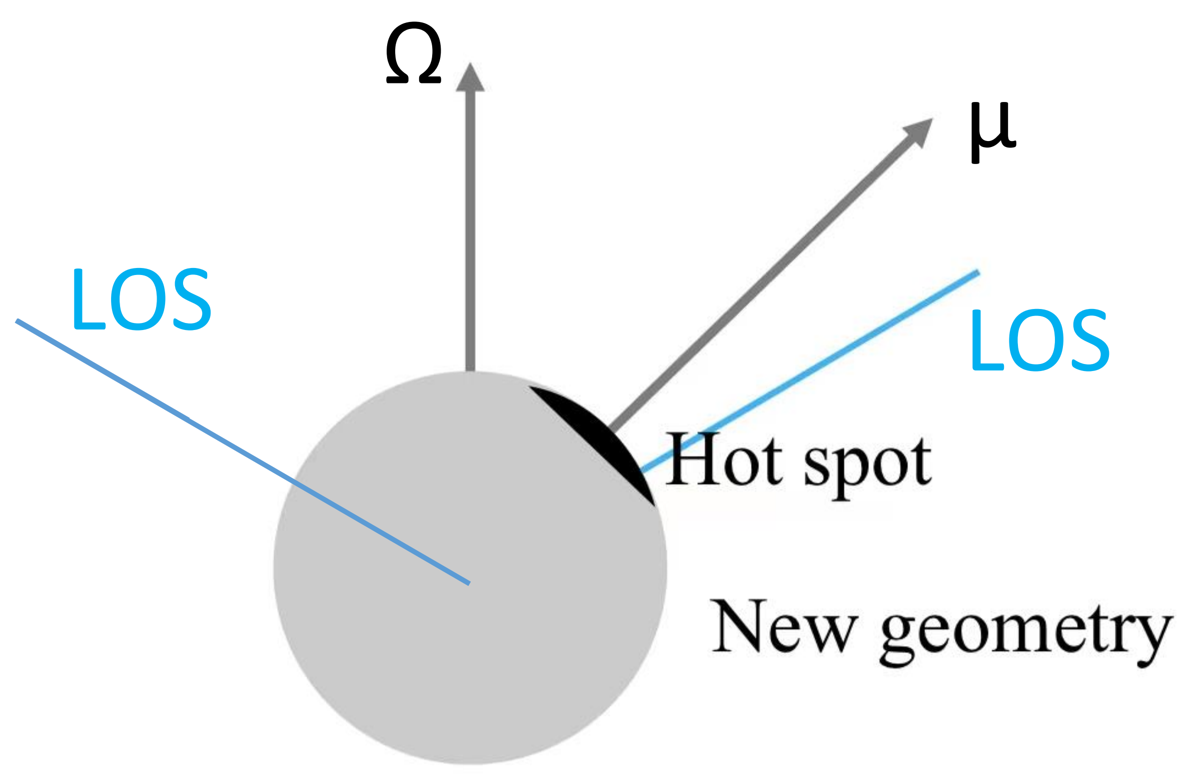
Former geometry estimation:
α ≈ 12°, β ≈ -5°
(Rankin & Deshpande 2001)
➔Hard to produce thermal X-ray pulsation

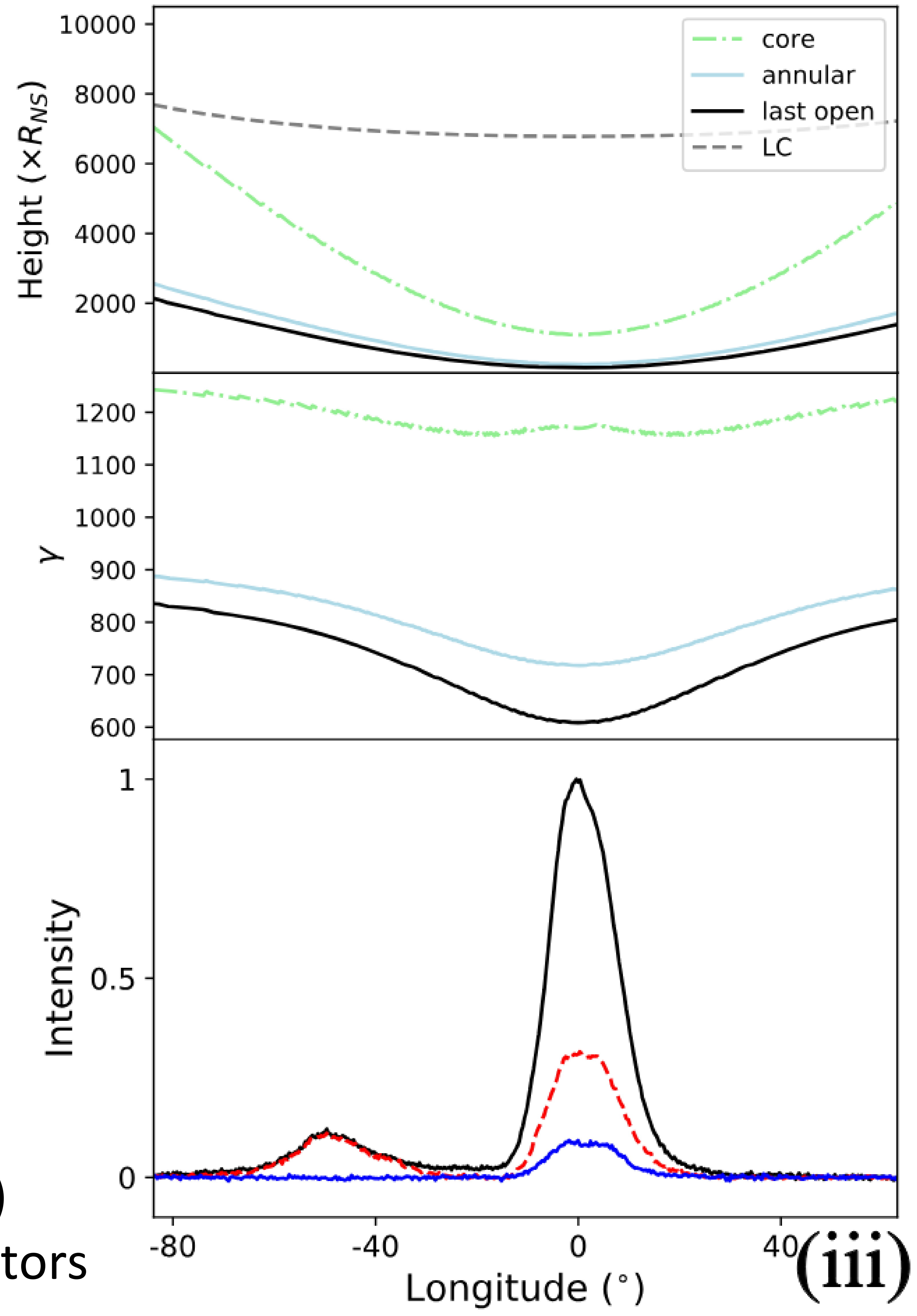


New derived geometry:
α = 138° (42°), β = 14°

LOS: line of sight.

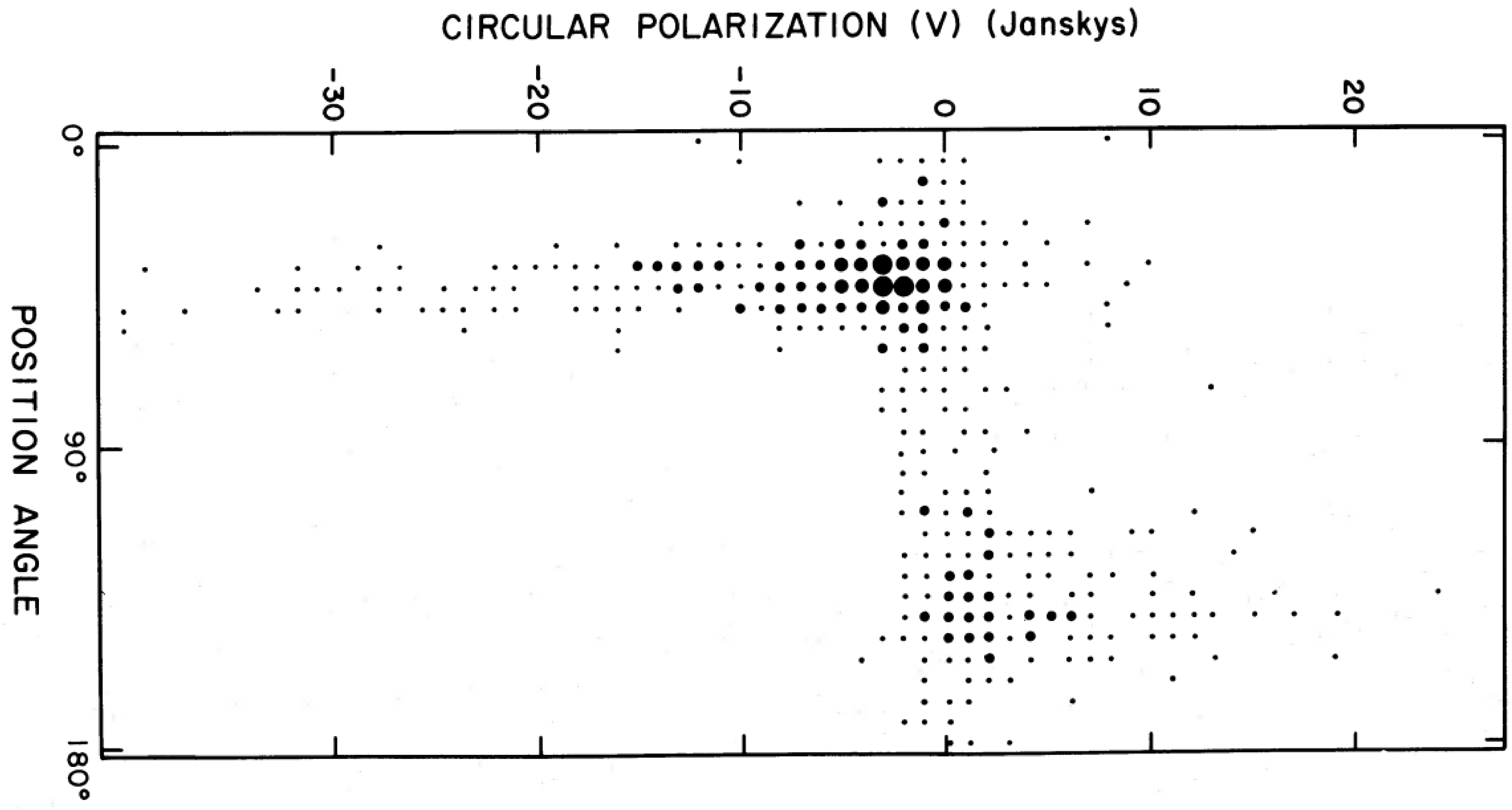
Make X-ray modulation more possible

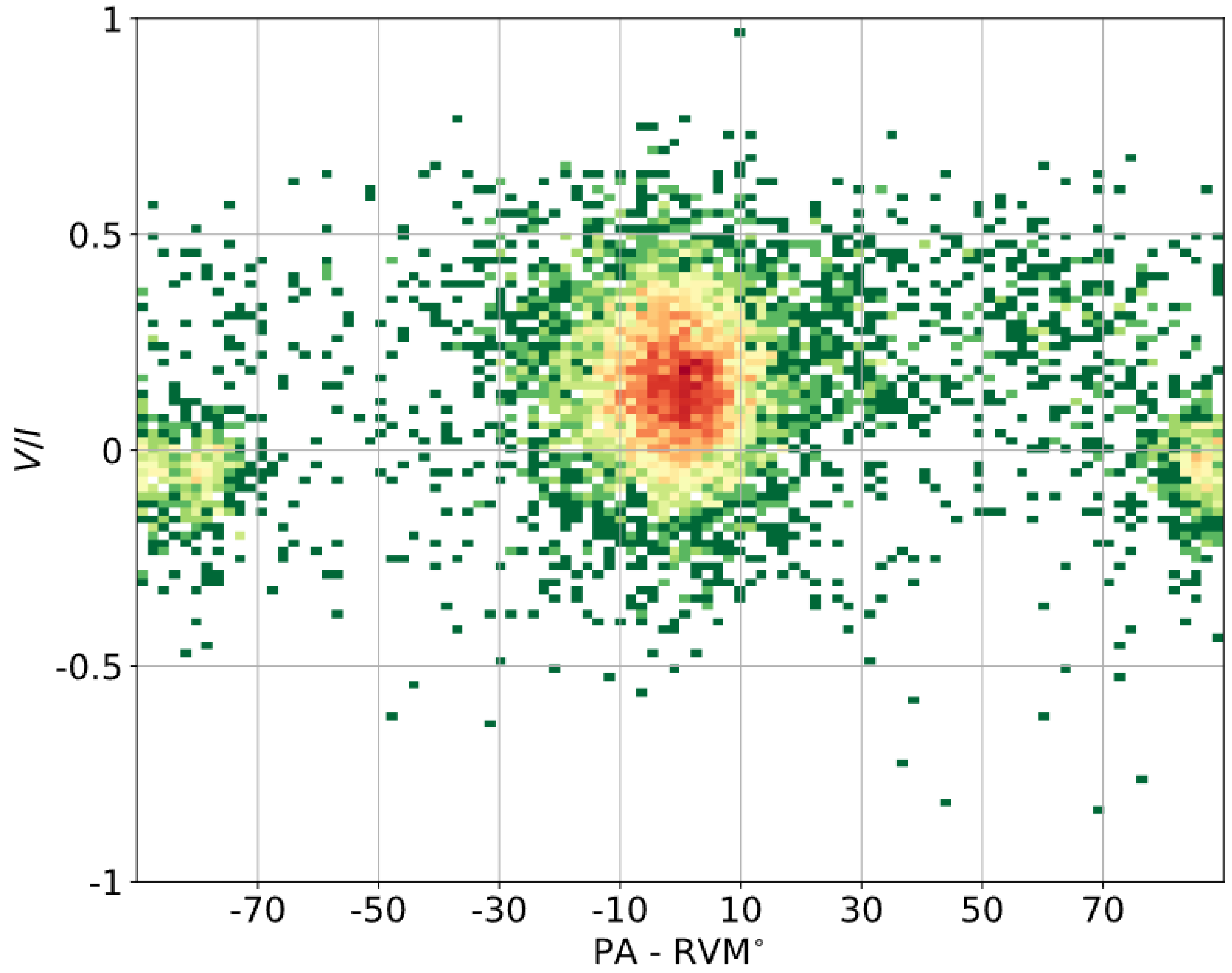




Precursor component (in Q)
has larger initial Lorentz factors
➔hotter hotspot
➔➔X-ray pulsation brighter in Q mode?

(ii) OPM v.s. V: A similar pattern (on single pulses) is found in B2020+28 (Cordes, Rankin, Backer 1978, *ApJ*).





OPMs in plasma physics/optics: Ordinary mode (O) & Extraordinary mode (E)

Two questions:

(1) Why ±V for O mode and E mode?

(2) Why |V| different for O mode and E mode?

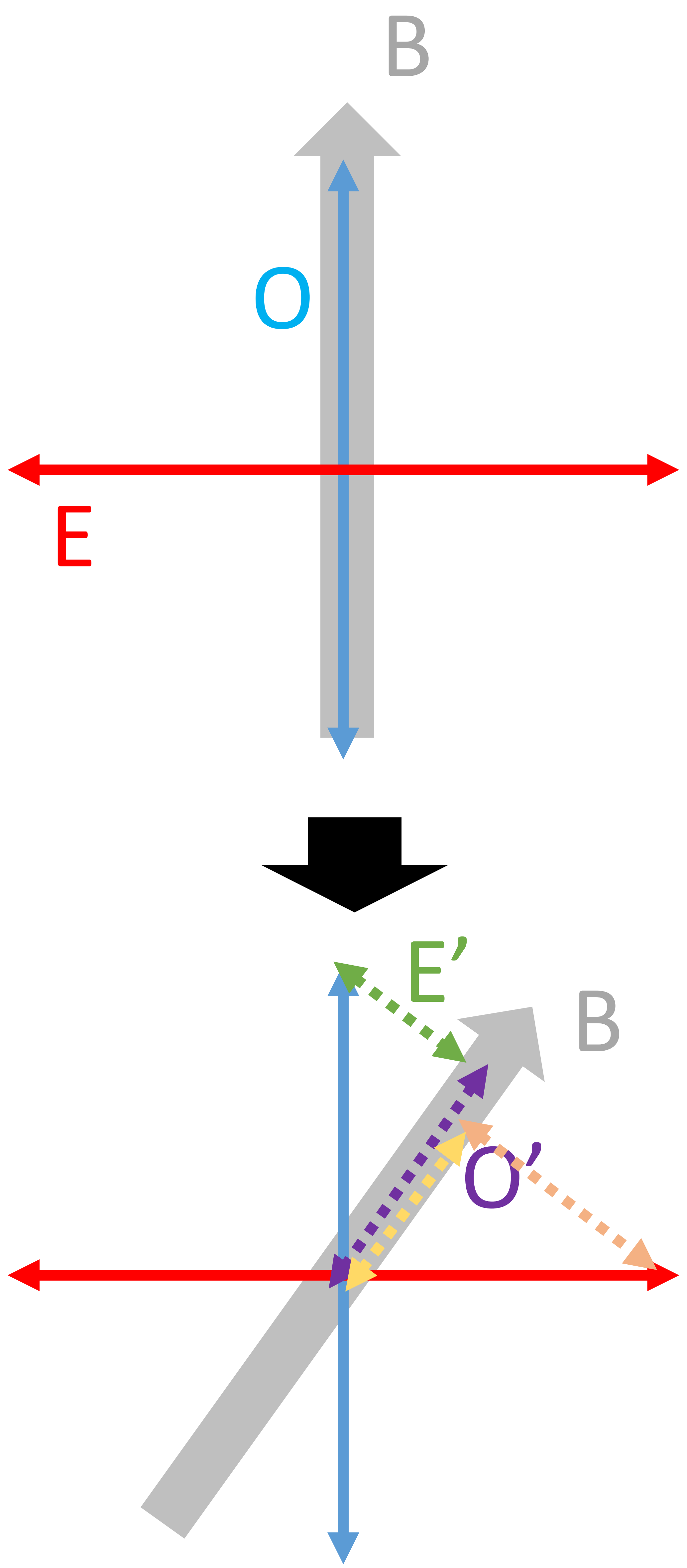
Look at how V changes during propagation
(take uniform medium for e.g.)

$$\frac{\mathrm{d}\mathbf{S}}{\mathrm{d}s} = \begin{pmatrix} \varepsilon_I \\ \varepsilon_Q \\ 0 \\ \varepsilon_V \end{pmatrix} - \begin{pmatrix} \eta_I & \eta_Q & 0 & \eta_V \\ \eta_Q & \eta_I & \rho_V & 0 \\ 0 & -\rho_V & \eta_I & \rho_Q \\ \eta_V & 0 & -\rho_Q & \eta_I \end{pmatrix} \mathbf{S} \qquad \boldsymbol{S} = (I, Q, U, V)^{\mathrm{T}}$$

Huang & Shcherbakov 2011, *MNRAS*   Ignore emission ε.

$$\frac{dV}{ds} = -\eta_V I + \rho_Q U - \eta_I V$$

For OPMs, $PA_O = PA_E + 90°$, $U_O = -U_E$, $Q_O = -Q_E$
(O = Ordinary mode, E = Extraordinary mode)
➔±V comes from Faraday conversion (mode coupling)
➔Different |V| comes from absorption term?
$\Delta(|V|/I) \sim 2\eta_V s$



Mode coupling ➔ V.

B modes and Q modes: different freq evolution!

New geometry: better understanding X-ray pulsation!

Main pulse and precursor: different origin?

OPM v.s. V and single pulses: propagation matters.

Mode switch 🡐?🡐 Magnetosphere change🡐?🡐 Pulsar surface change

Thank you for your attention ☺

Way to identification profile evolution:
Search for eigen modes (Hao et al. submitted) based on MLE.

i-th sub-integration

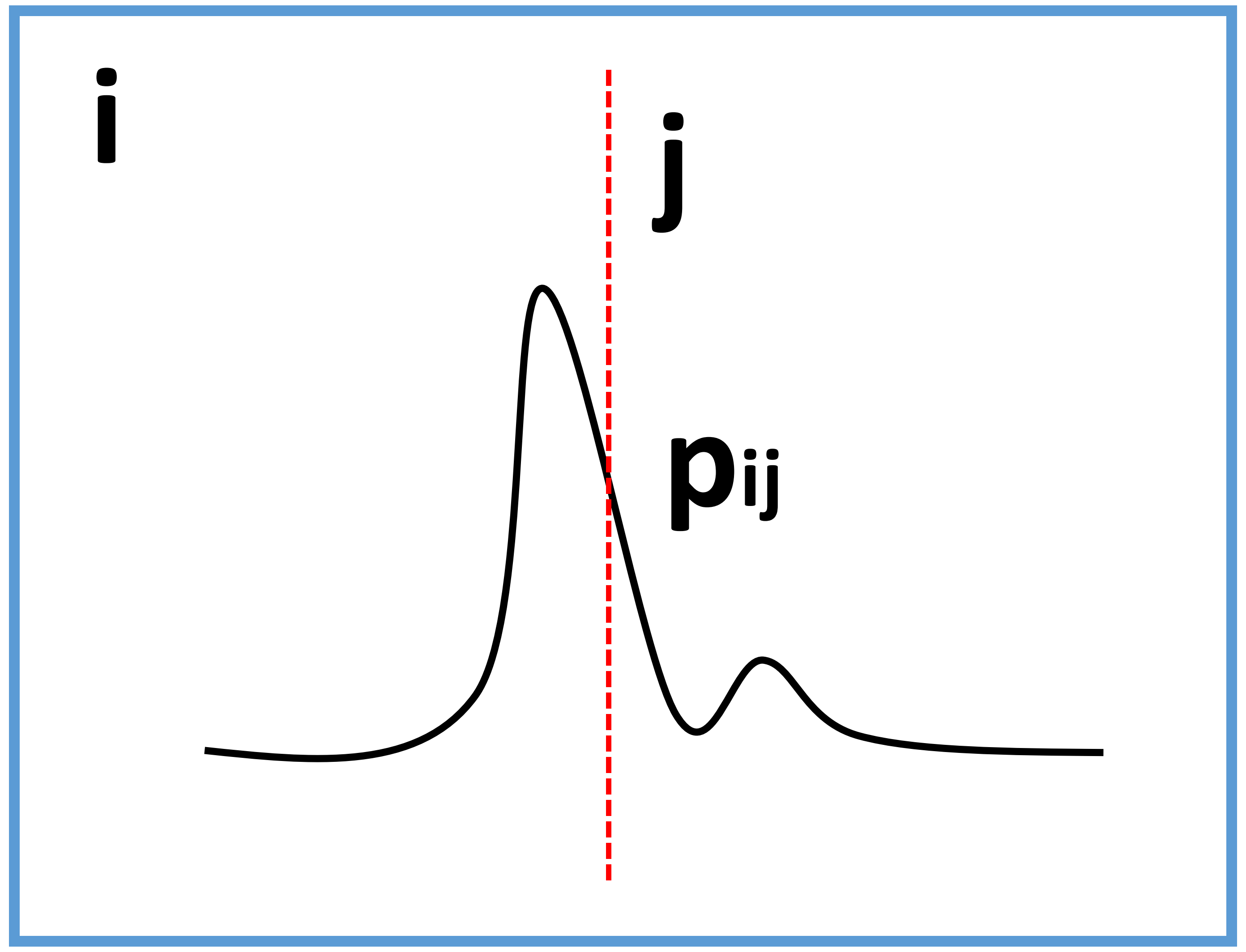
Phase j ➔ pij

$$p_{ij} = \alpha_i f_j + \beta_i g_j + n_{ij}$$

$\alpha_i f_j$: "eigen mode" 1

$\beta_i g_j$: "eigen mode" 2

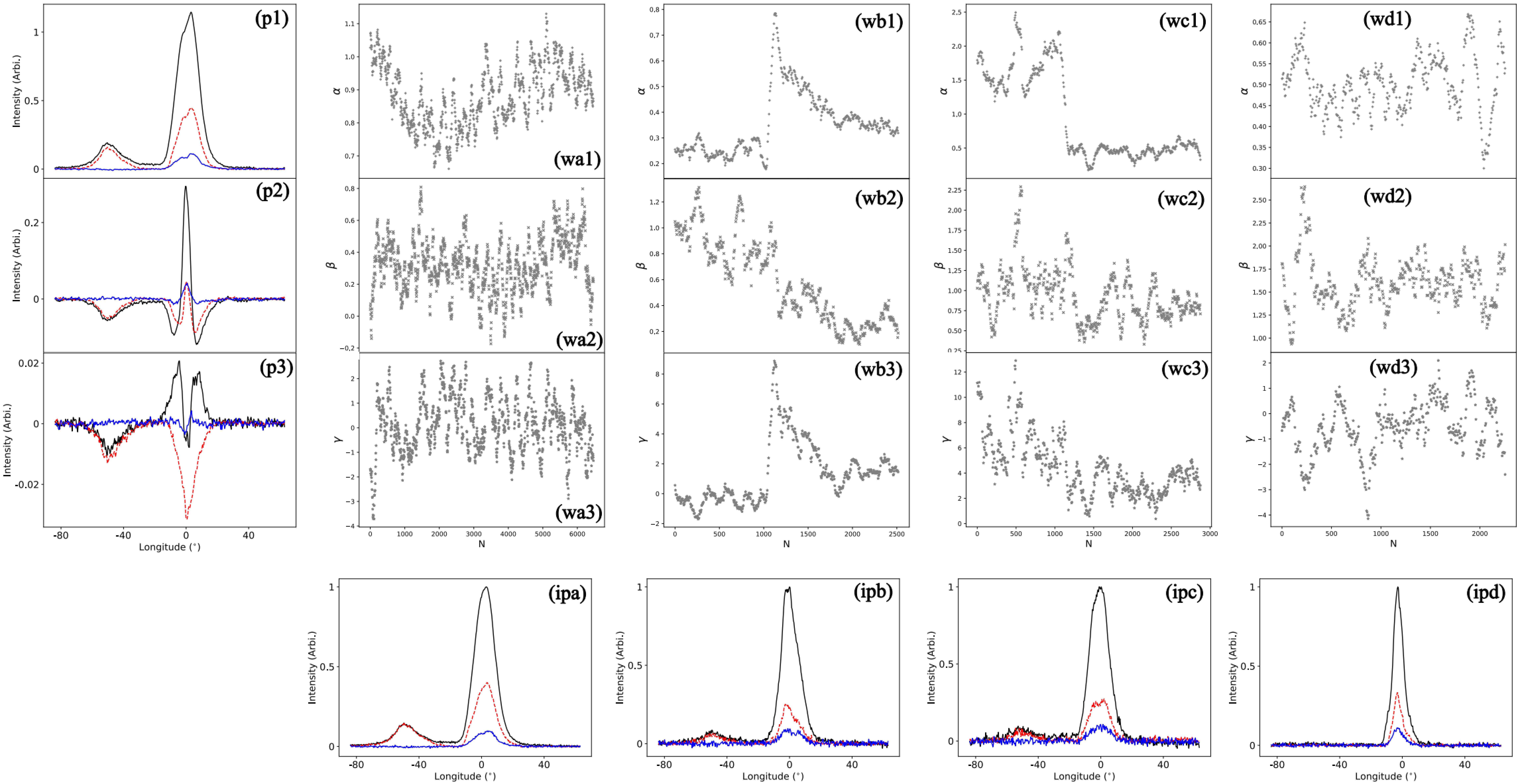
n_{ij}: Measurement noise



Assume the measurement noise follow the Gaussian distribution.

Likelihood: $\Lambda \propto e^{-\frac{1}{2}\sum_i \sum_j \left(\frac{p_{ij}-\alpha_i f_j - \beta_i g_j}{\sigma_i}\right)^2}$

$\partial\Lambda/\partial\alpha_i = 0, \partial\Lambda/\partial\beta_i = 0, \partial\Lambda/\partial f_j = 0$, and $\partial\Lambda/\partial g_j = 0$.


(p1)
(p2)
(p3)
(wa1)
(wa2)
(wa3)
(wb1)
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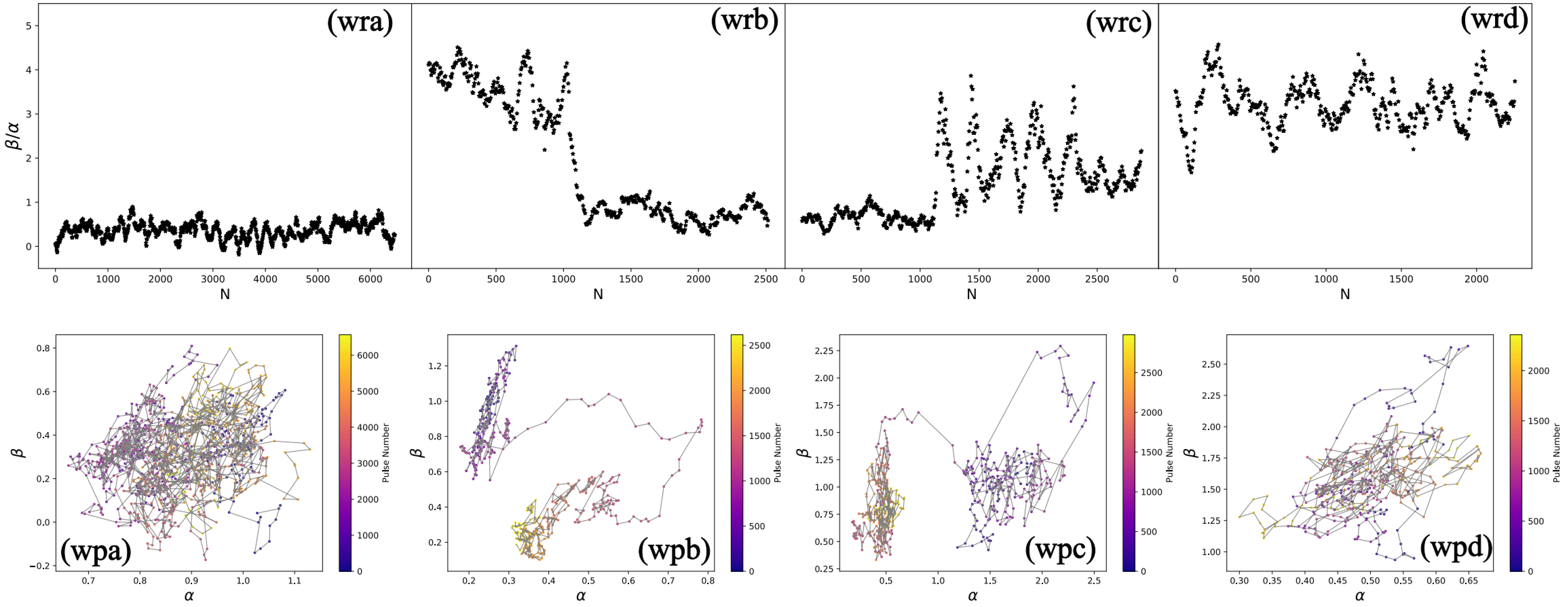
(wc1)
(wc2)
(wc3)
(wd1)
(wd2)
(wd3)
(ipa)
(ipb)
(ipc)
(ipd)
Intensity (Arbi.)
Longitude (°)
N
α
β
γ



(wra)
(wrb)
(wrc)
(wrd)
β/α
N
(wpa)
(wpb)
(wpc)
(wpd)
α
β
Pulse Number