Evidence for scattering of curvature radiation in radio pulsar profiles

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Reporter: 曹顺顺
(Shunshun Cao)

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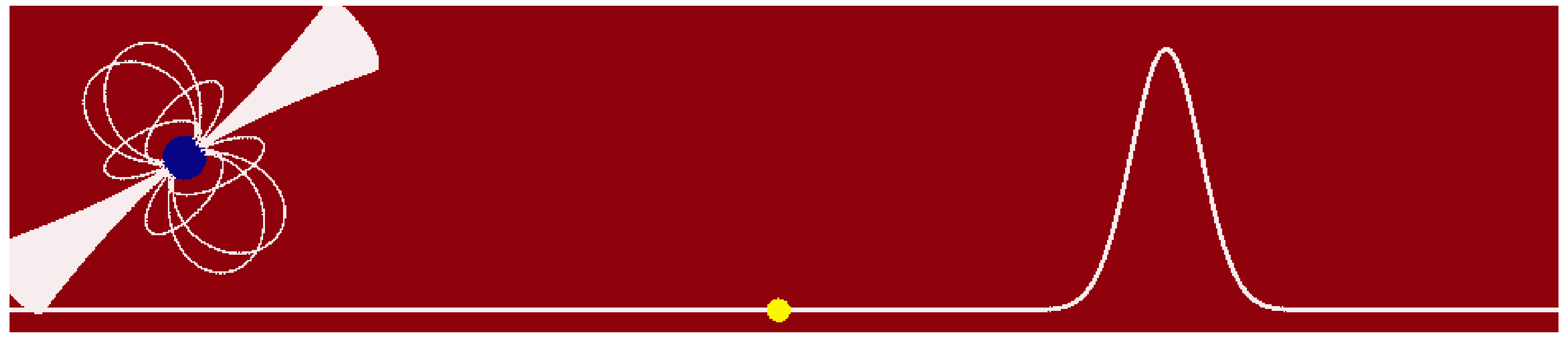
23 pages in total

I. Introduction

Pulsar signal: hundreds of single pulses
➔ integrated profile (usually steady).

Integrated profiles are rich in morphology, and could evolve with frequency.



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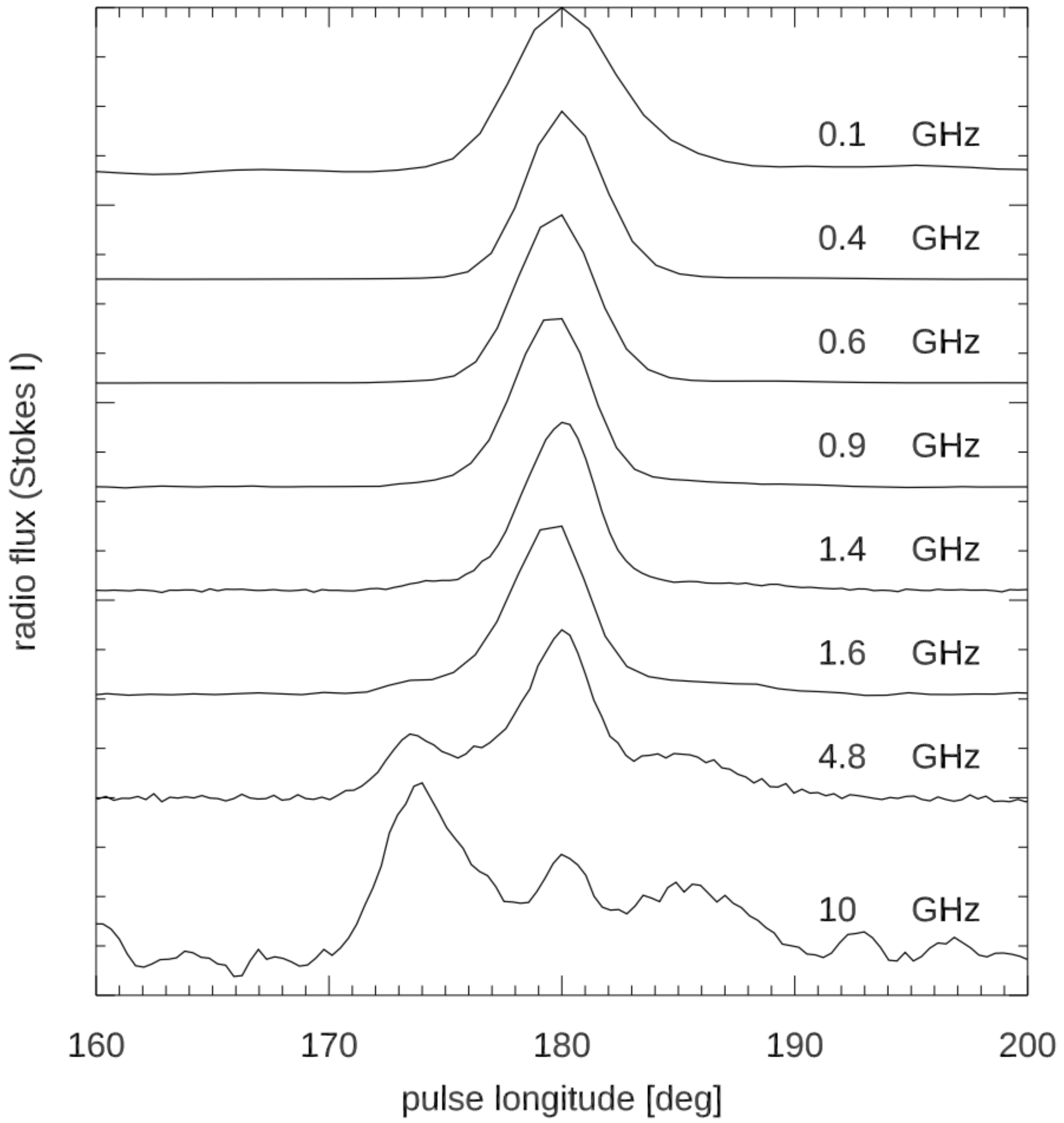

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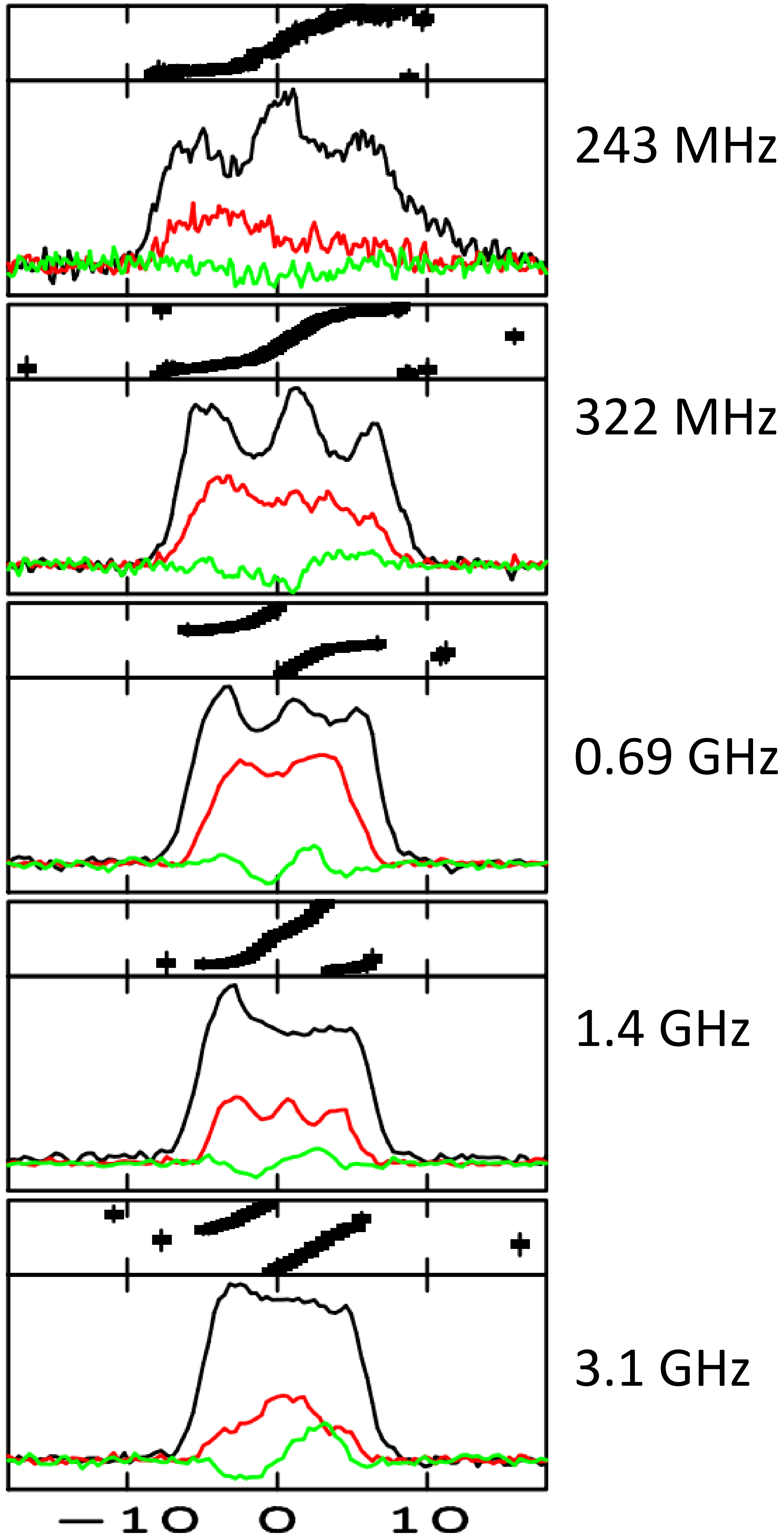
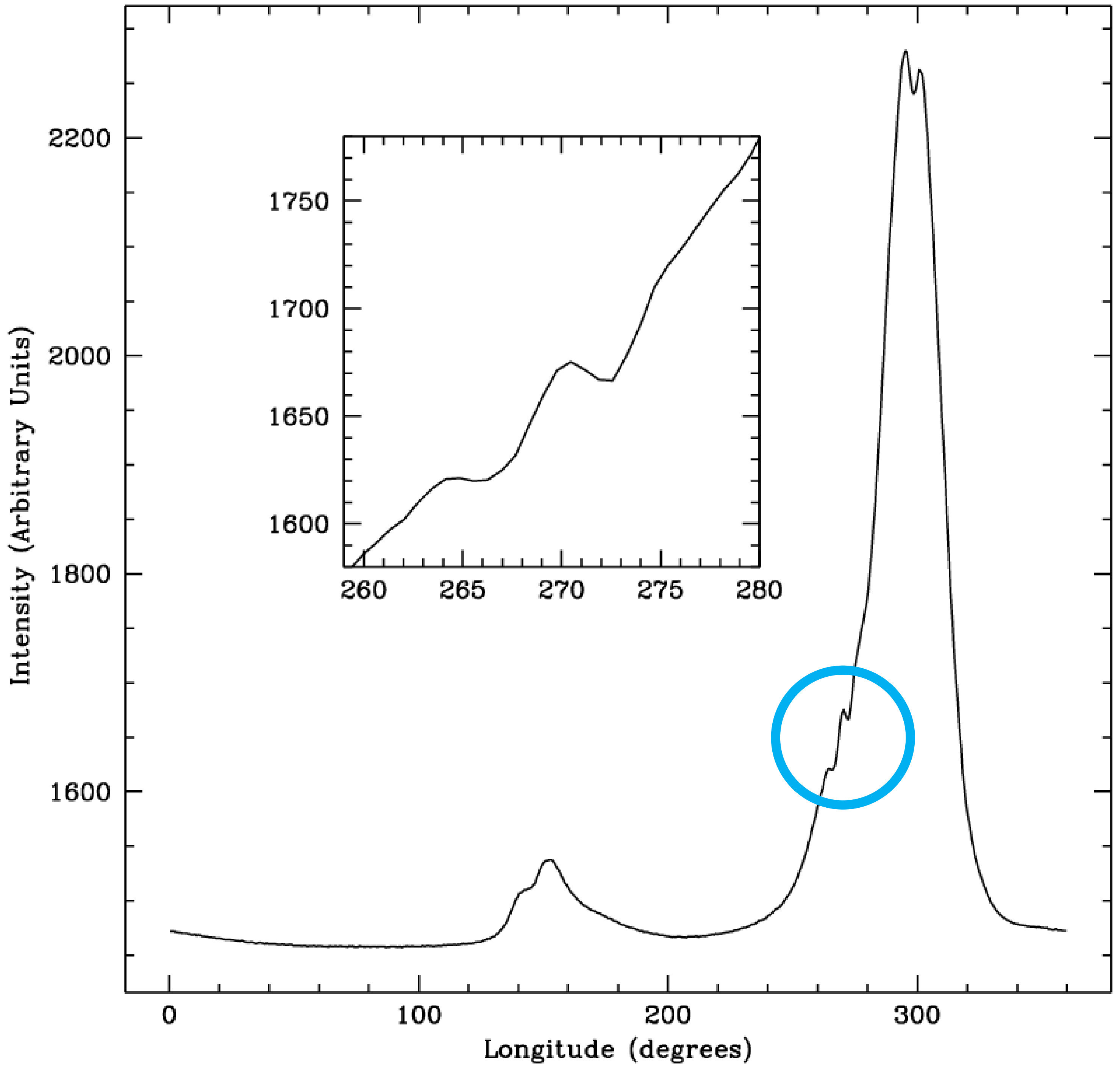


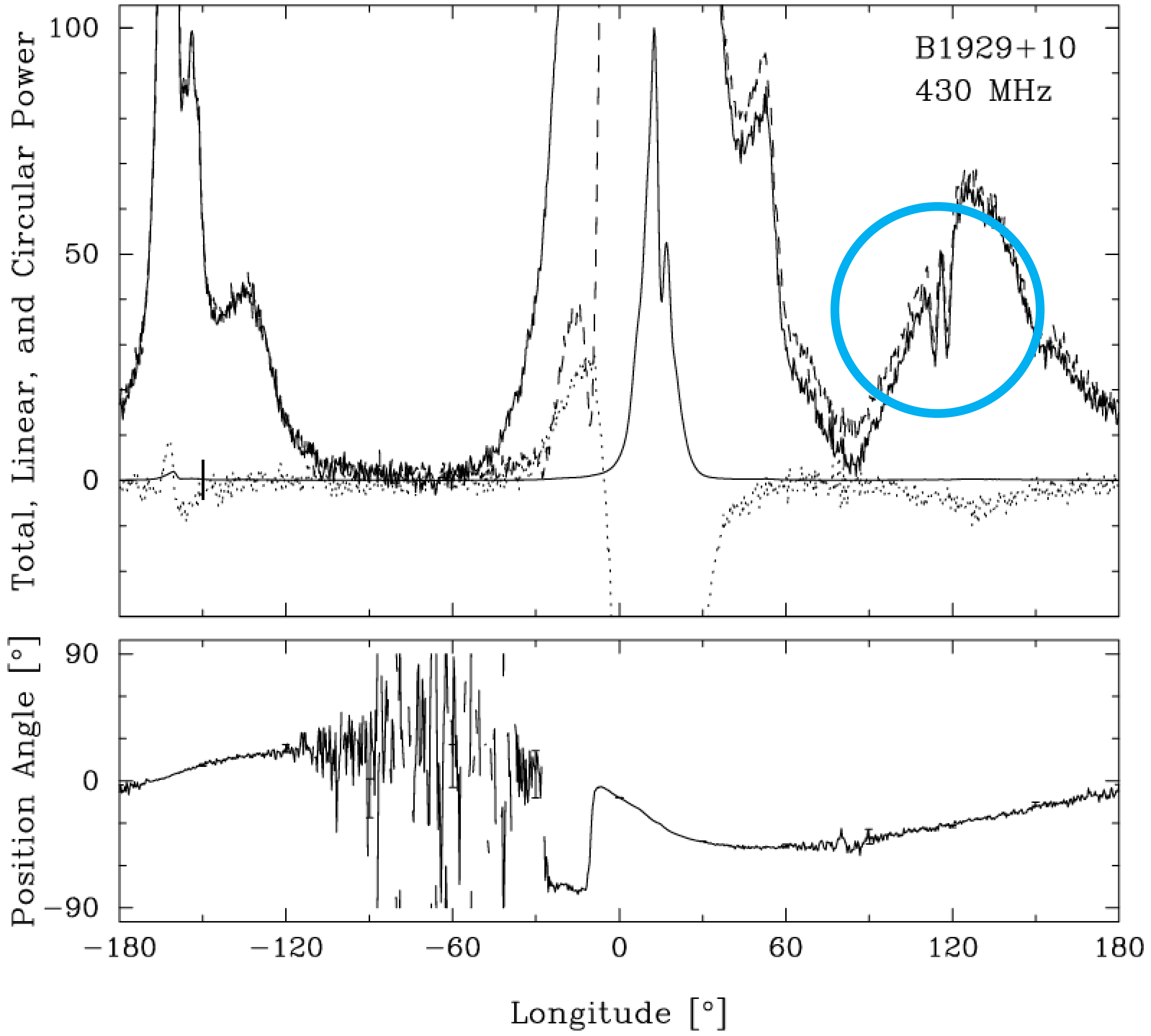
B1700-32

A special kind of profile property: bifurcated components (BCs)

Double notches (DNs):

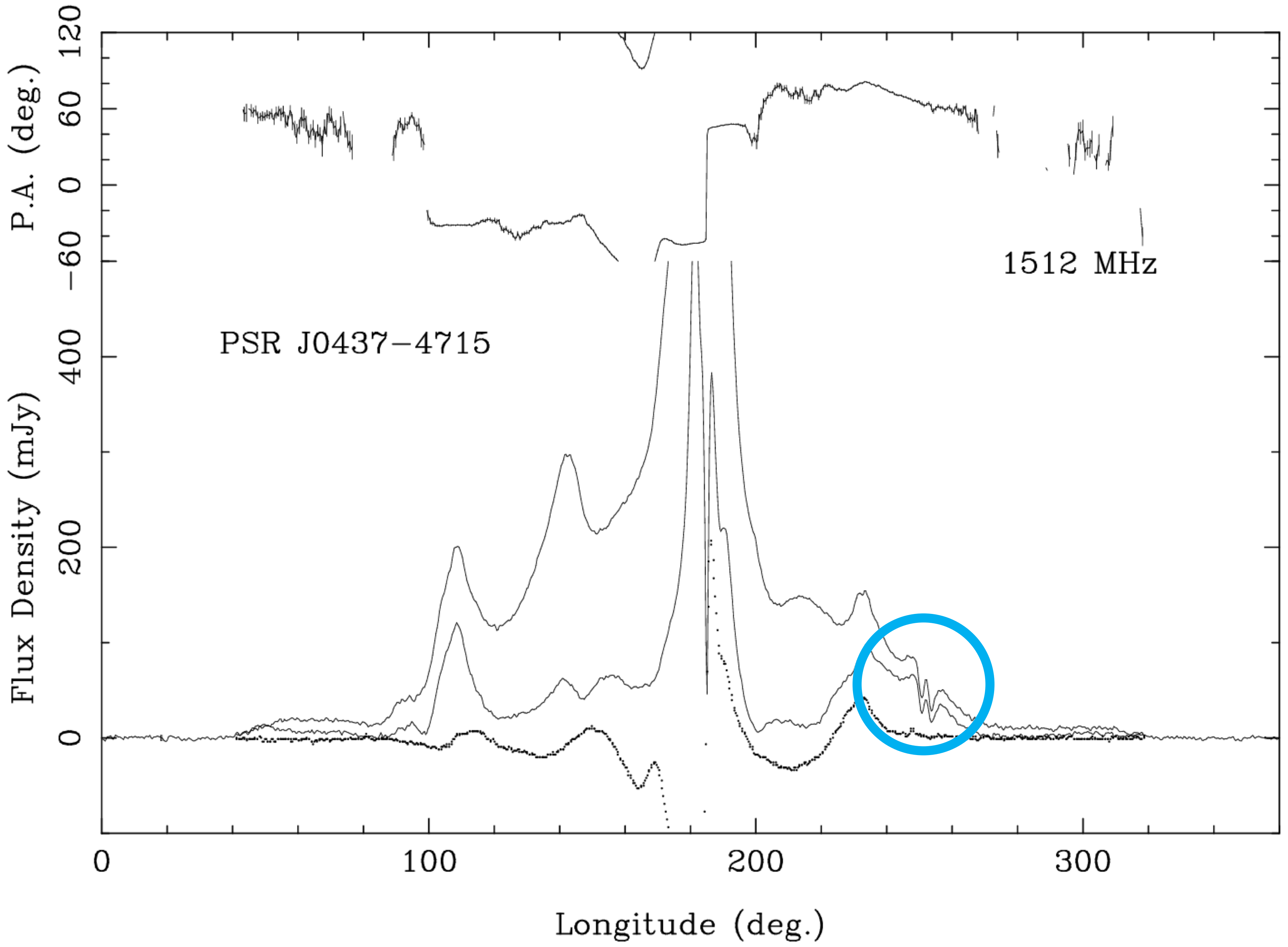


B0950+08, 430 MHz



B1929+10, 430 MHz

McLaughlin & Rankin 2004 *MNRAS*

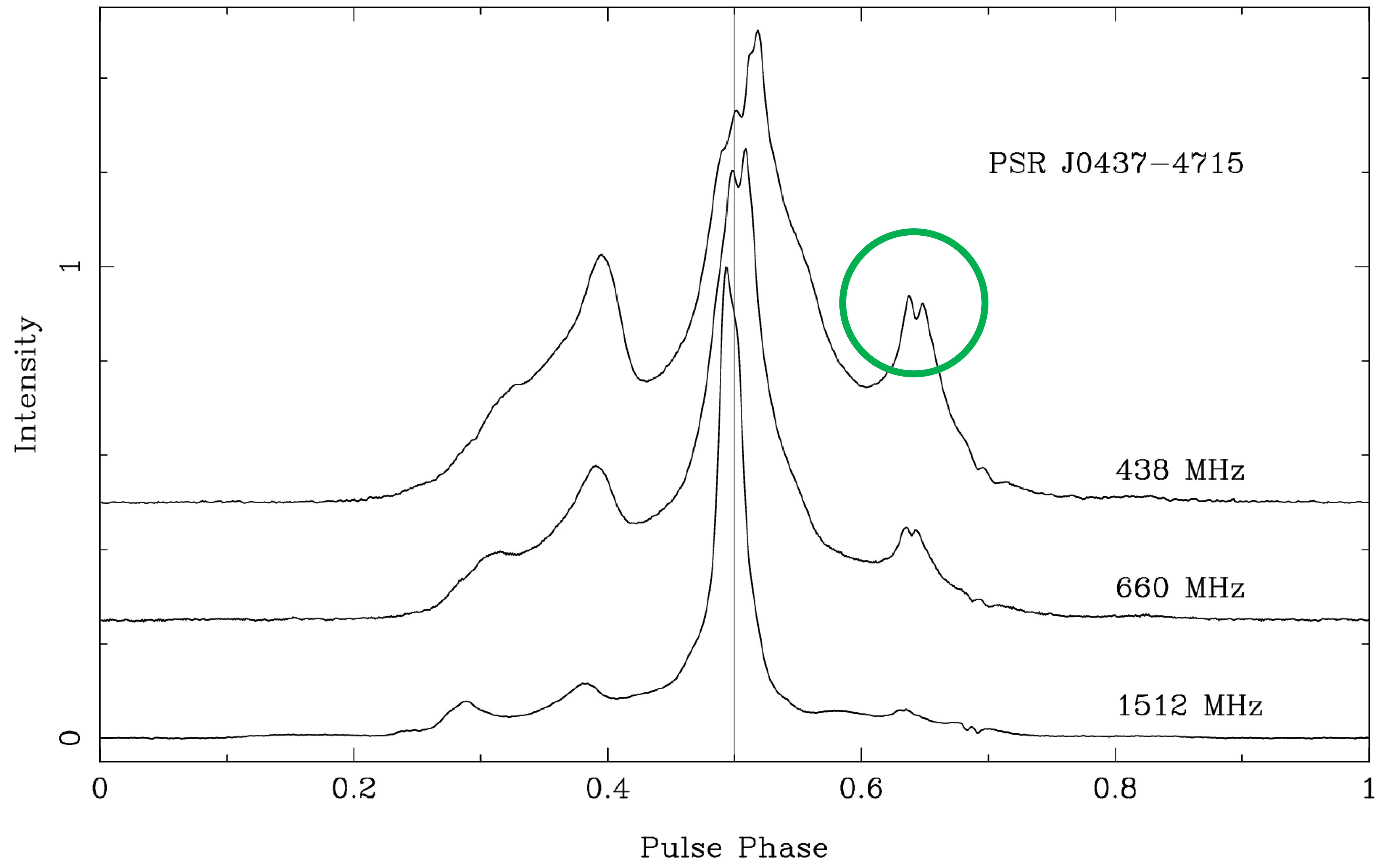


J0437-4715, 1512 MHz

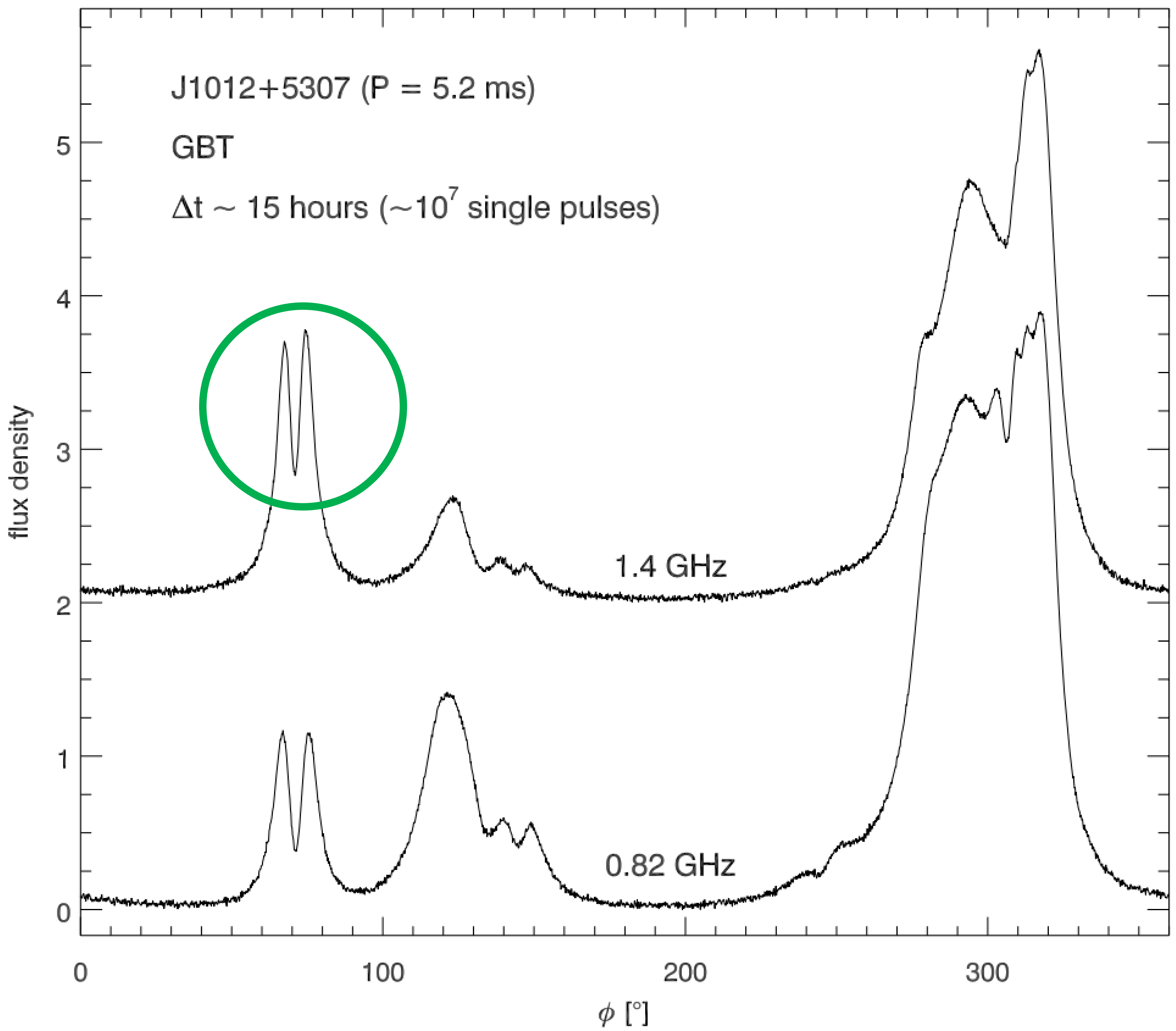
Navarro et al. 1997 *ApJ*

A special kind of profile property: bifurcated components (BCs)

Bifurcated peaks:



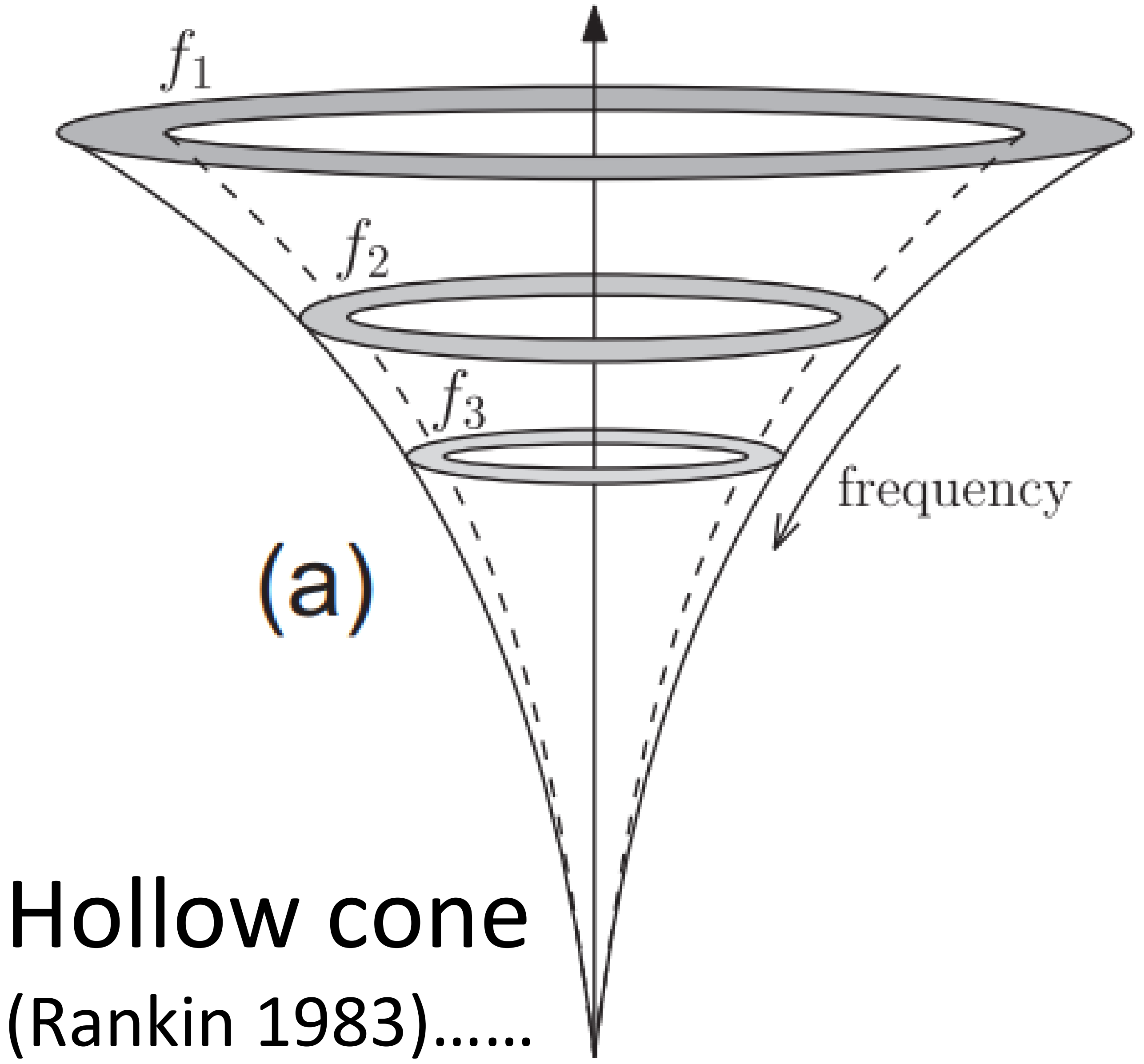
J0437-4715
Navarro et al. 1997 *ApJ*



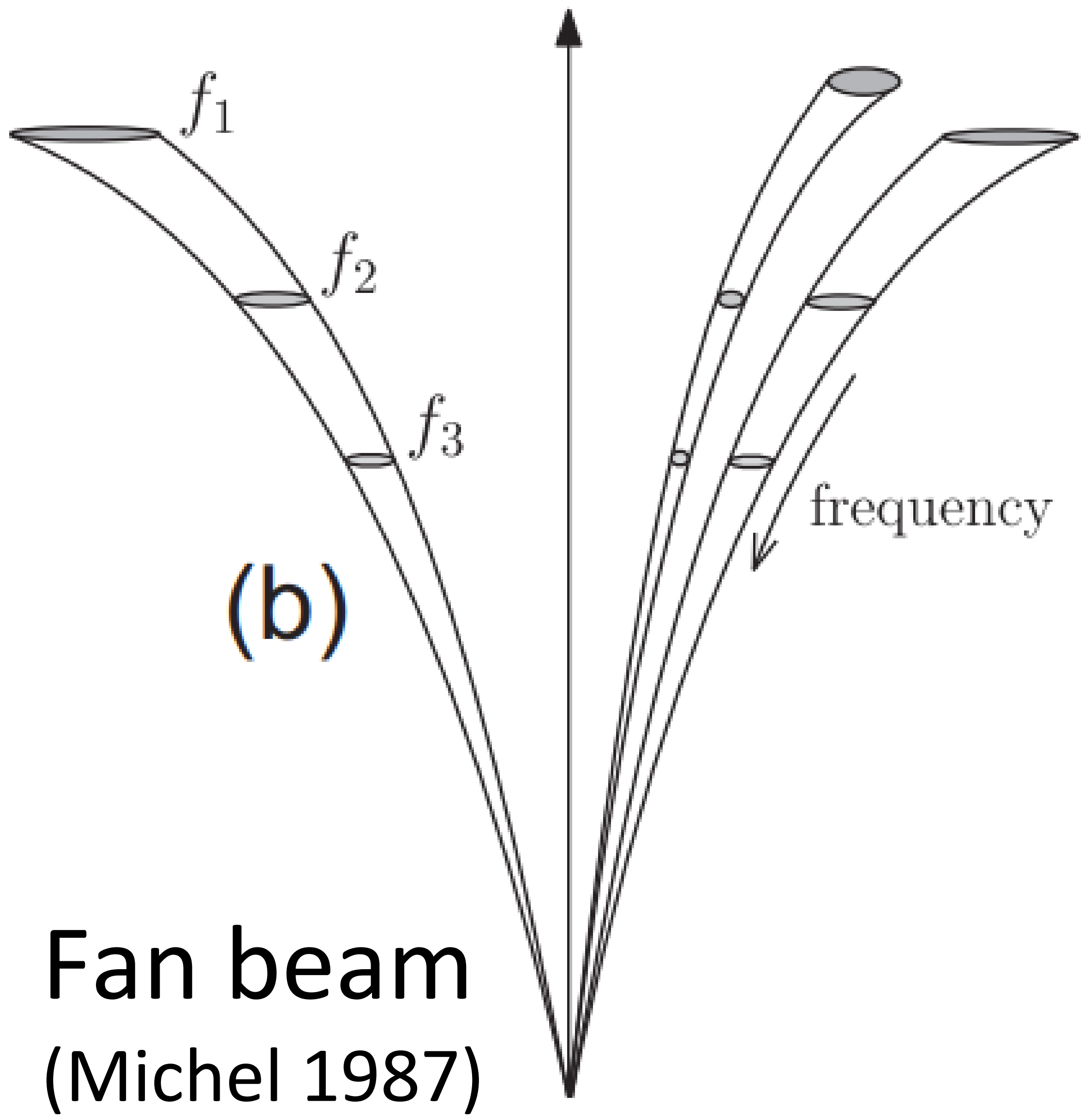
J1012+5307
Dyks, Rudak & Demorest 2010 *MNRAS*

Explanations to phenomena:

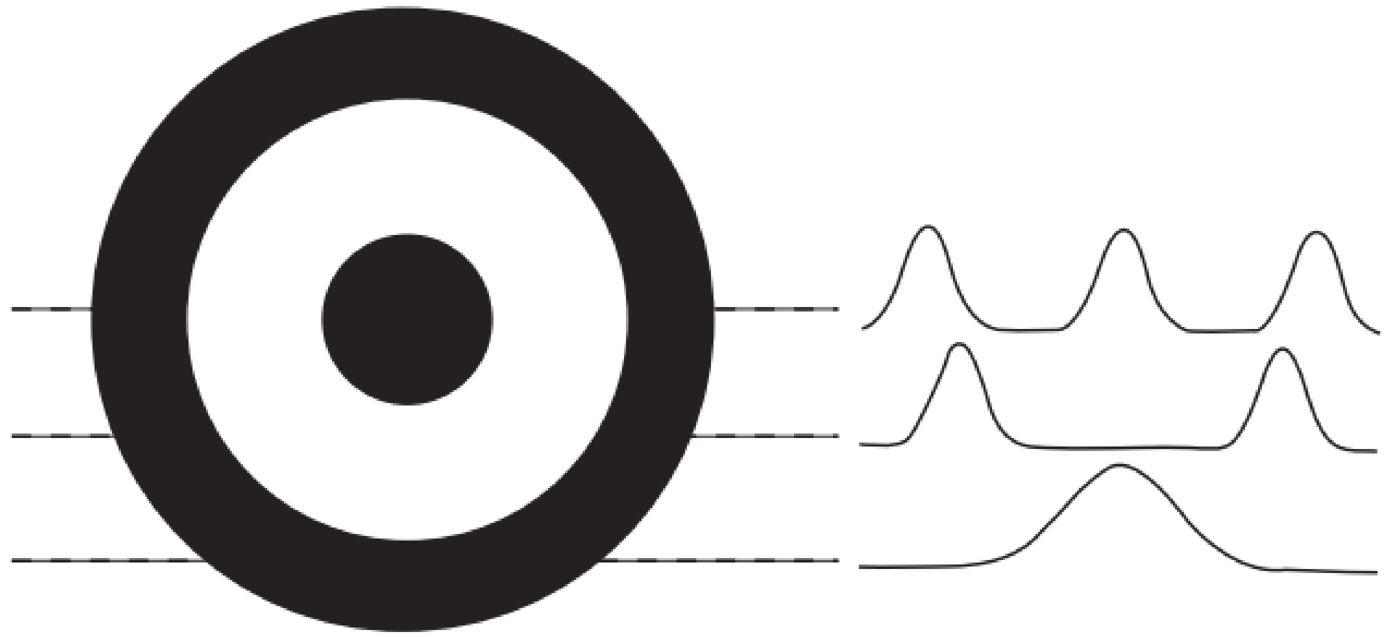
“Conal components” & “Core component”: What’s the physical origin?



Hollow cone
(Rankin 1983)……

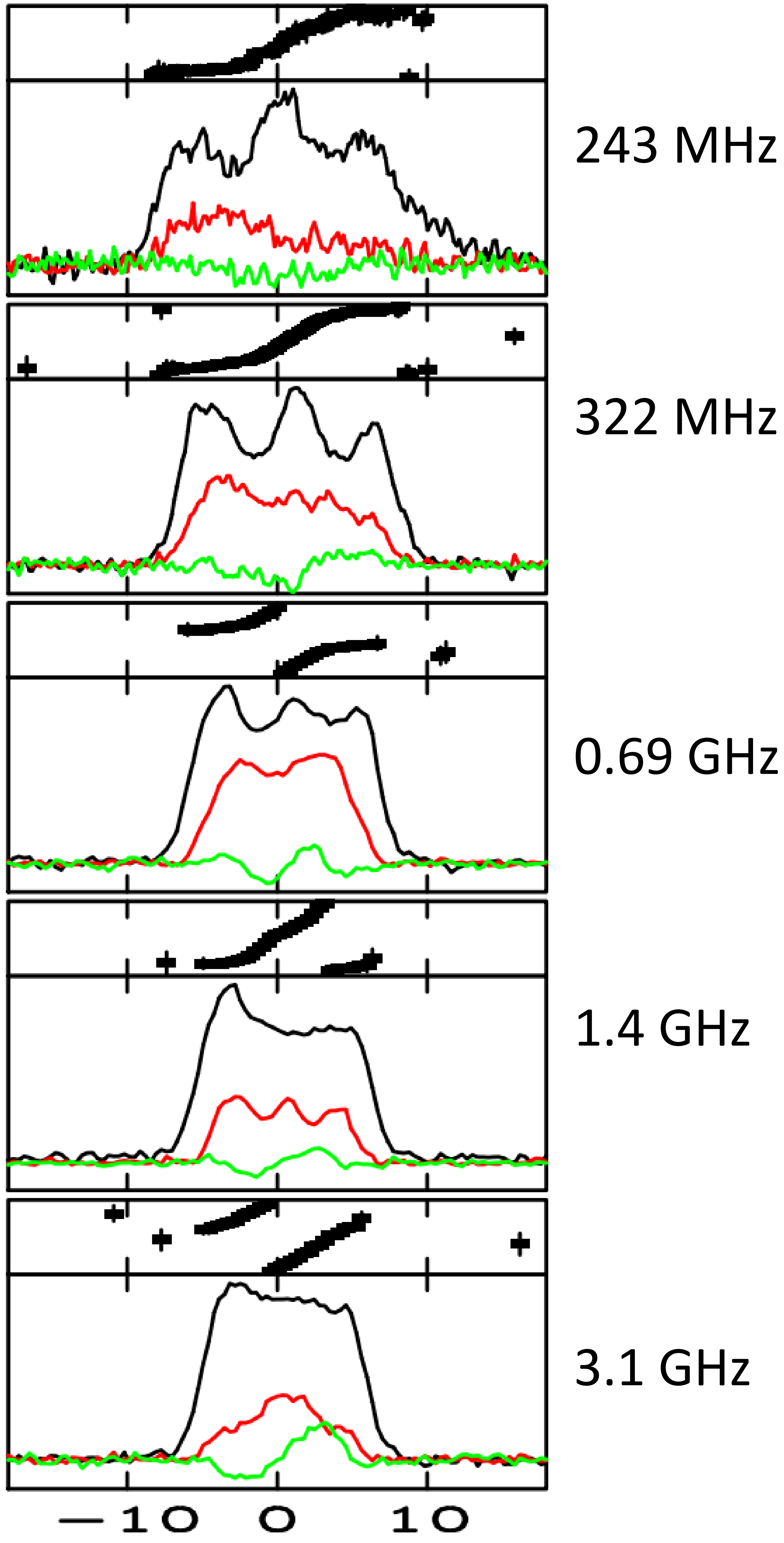


Fan beam
(Michel 1987)
(Dyks, Rudak & Demorest 2010)
(Wang et al. 2014)……



From *Pulsar Astronomy*

Emission of different frequencies may come from different heights
➔ Radius-to-frequency mapping (RFM)



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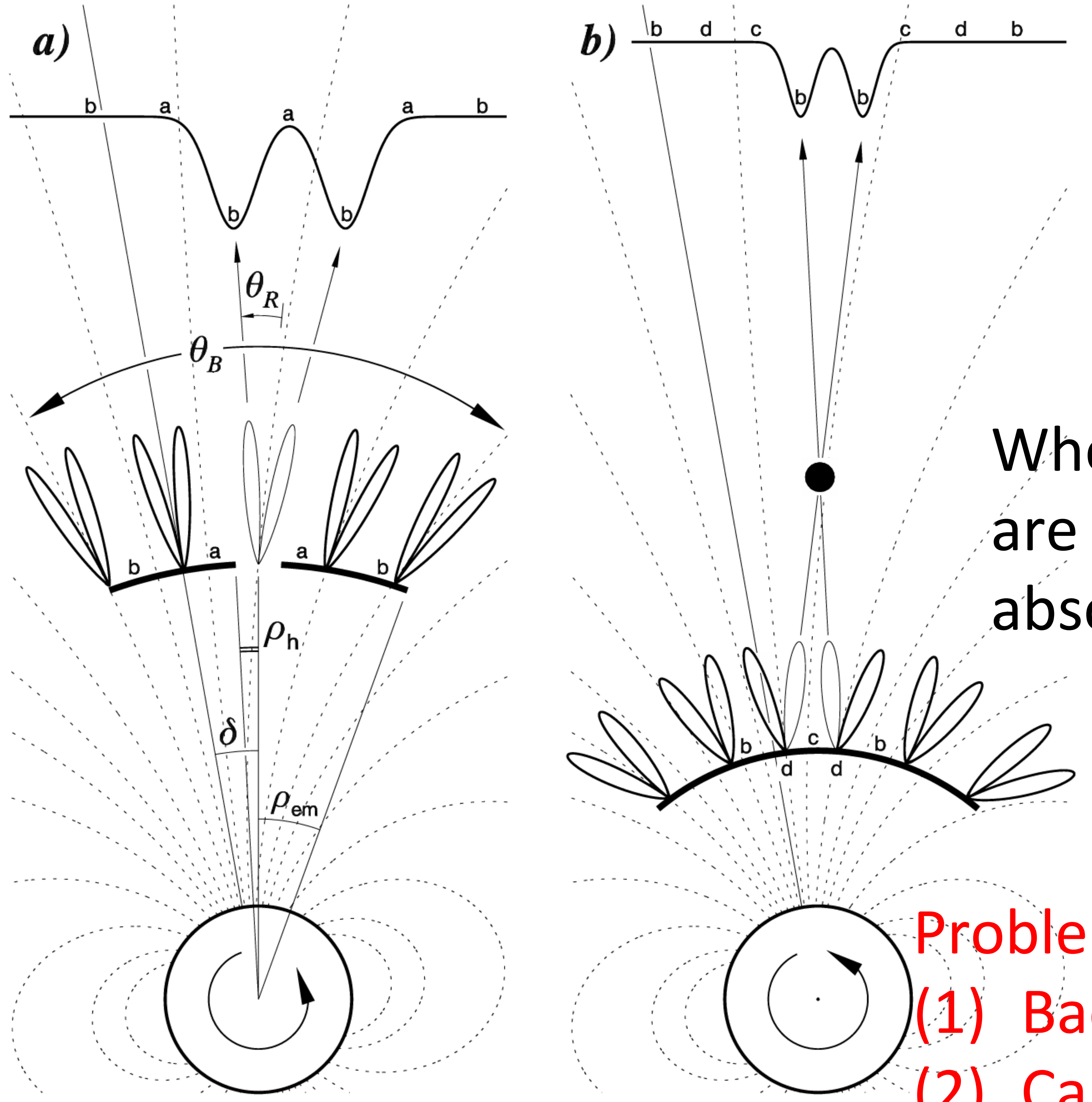
Explanations to phenomena:

What’s behind bifurcated components?

Dyks, Rudak & Rankin 2007 *A&A*: direction of acceleration?

Emission from parallel-accelerated particles is naturally bifurcated.



When part of emission particles are lost or part of emission is absorbed, double notches appear.

Problem (Dyks, Rudak, Demorest 2010):

(1) Bad fitting of J1012+5037 (1.4 GHz).

(2) Cannot produce too deep notch.

Dyks, Rudak & Rankin 2007 *A&A*

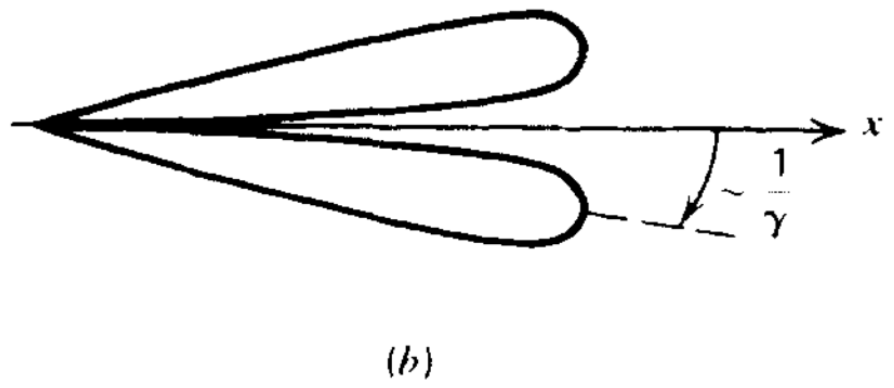


***Figure 4.11b** Angular distribution of radiation emitted by a particle with parallel acceleration and velocity.*

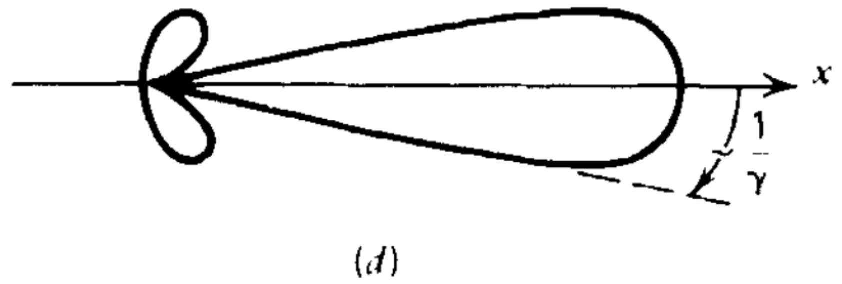
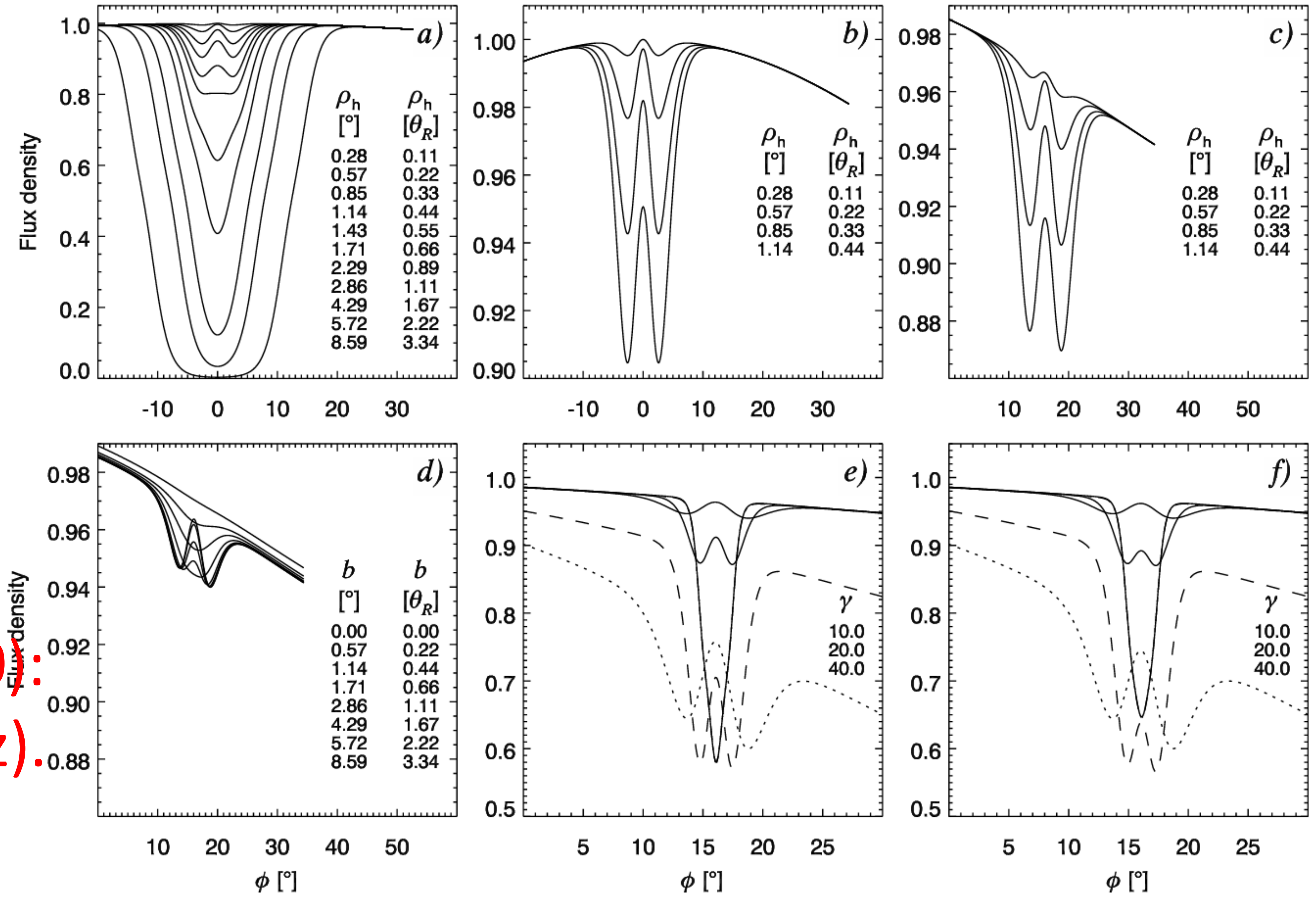


***Figure 4.11d** Angular distribution of radiation emitted by a particle with perpendicular acceleration and velocity.*

From Rybicki & Lightman

Radiative Processes in Astrophysics



Dyks, Rudak & Rankin 2007

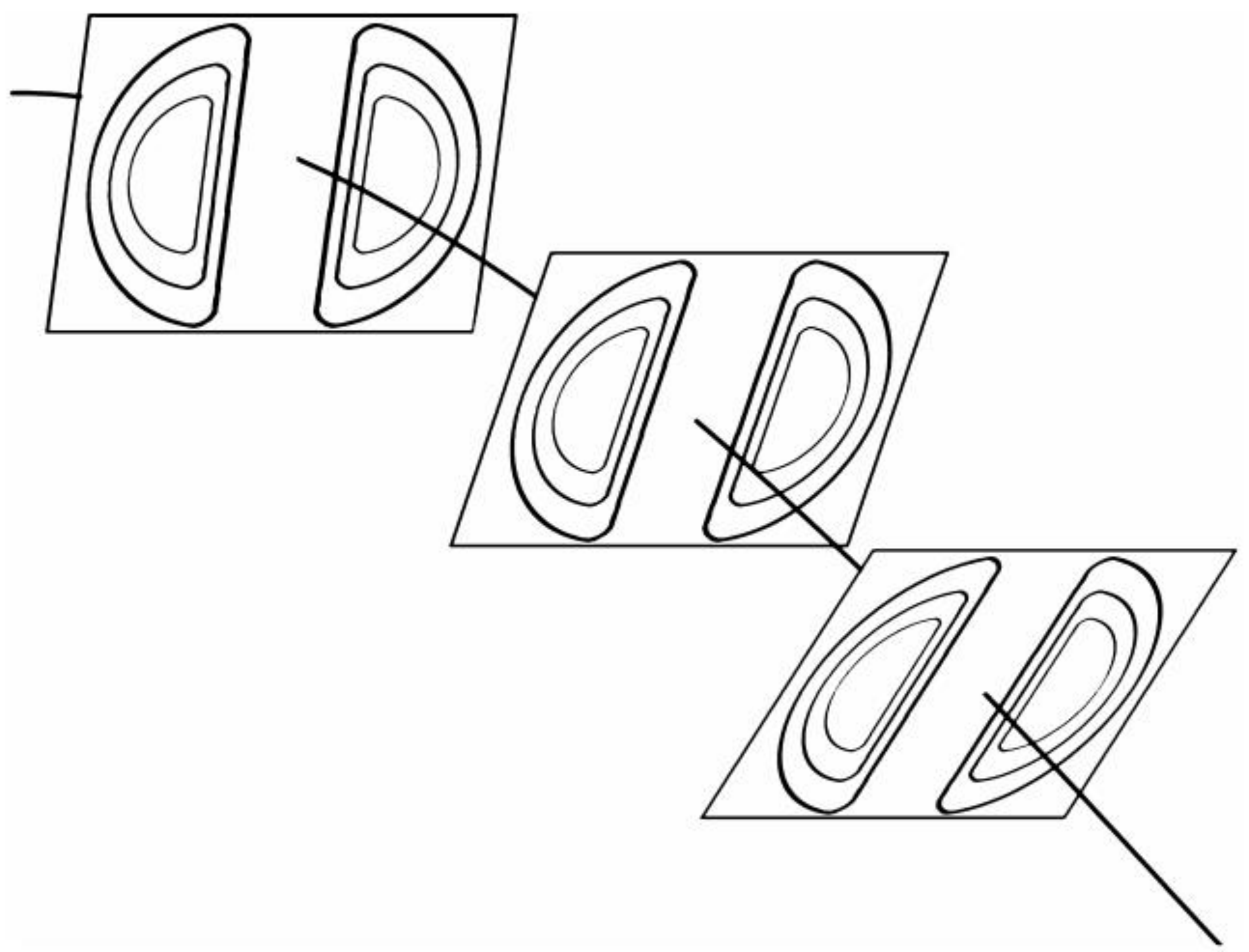
Explanations to phenomena:

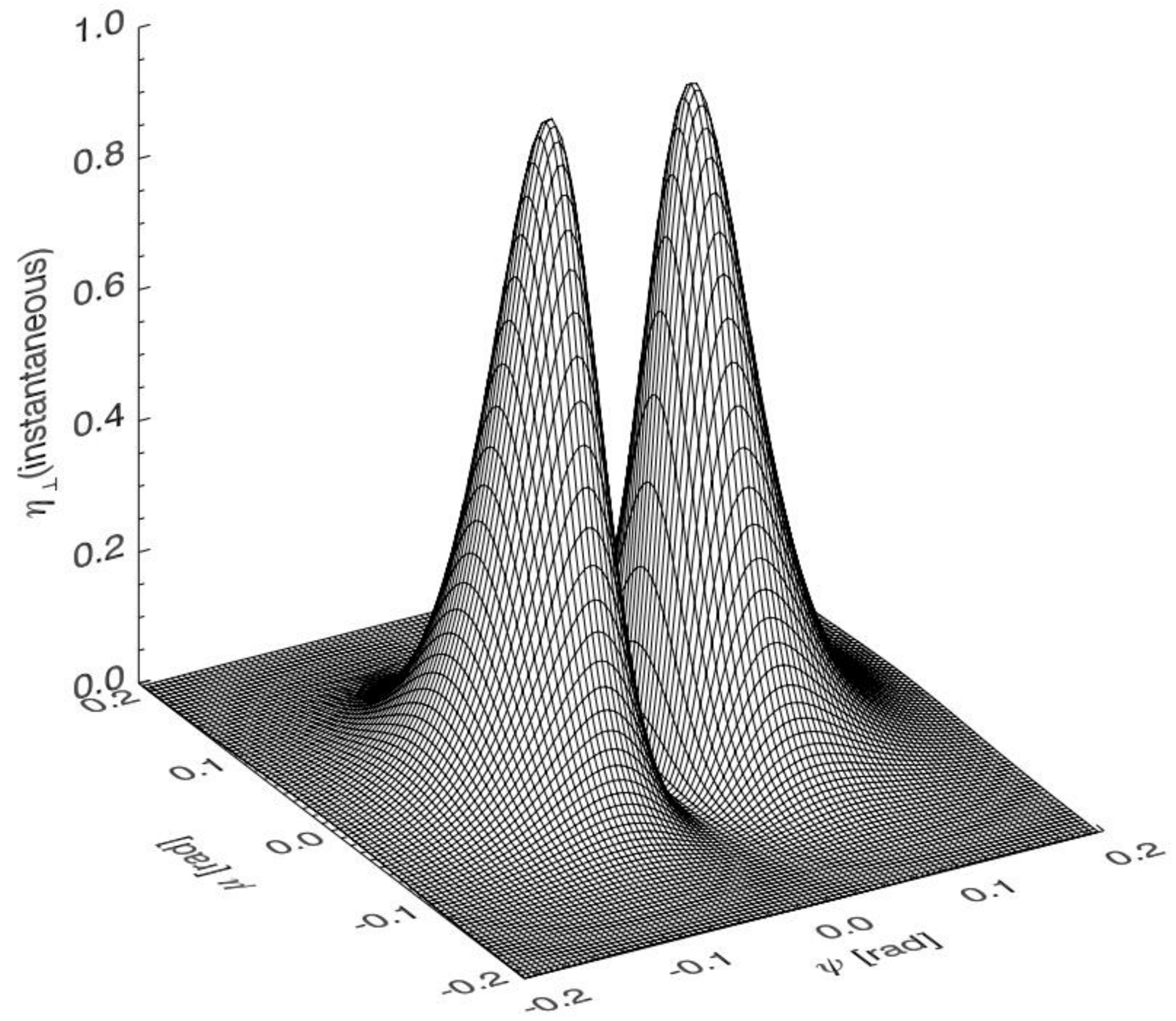
$$\eta_{\rm crv} = \eta_{\parallel} + \eta_{\perp}$$
$$= \frac{q^2\omega^2}{3\pi^2 c}\left(\frac{\rho}{c}\right)^2 \left[\xi^2 K_{2/3}^2(y) + \xi\ K_{1/3}^2(y)\sin^2\psi\right],$$

What's behind bifurcated components?

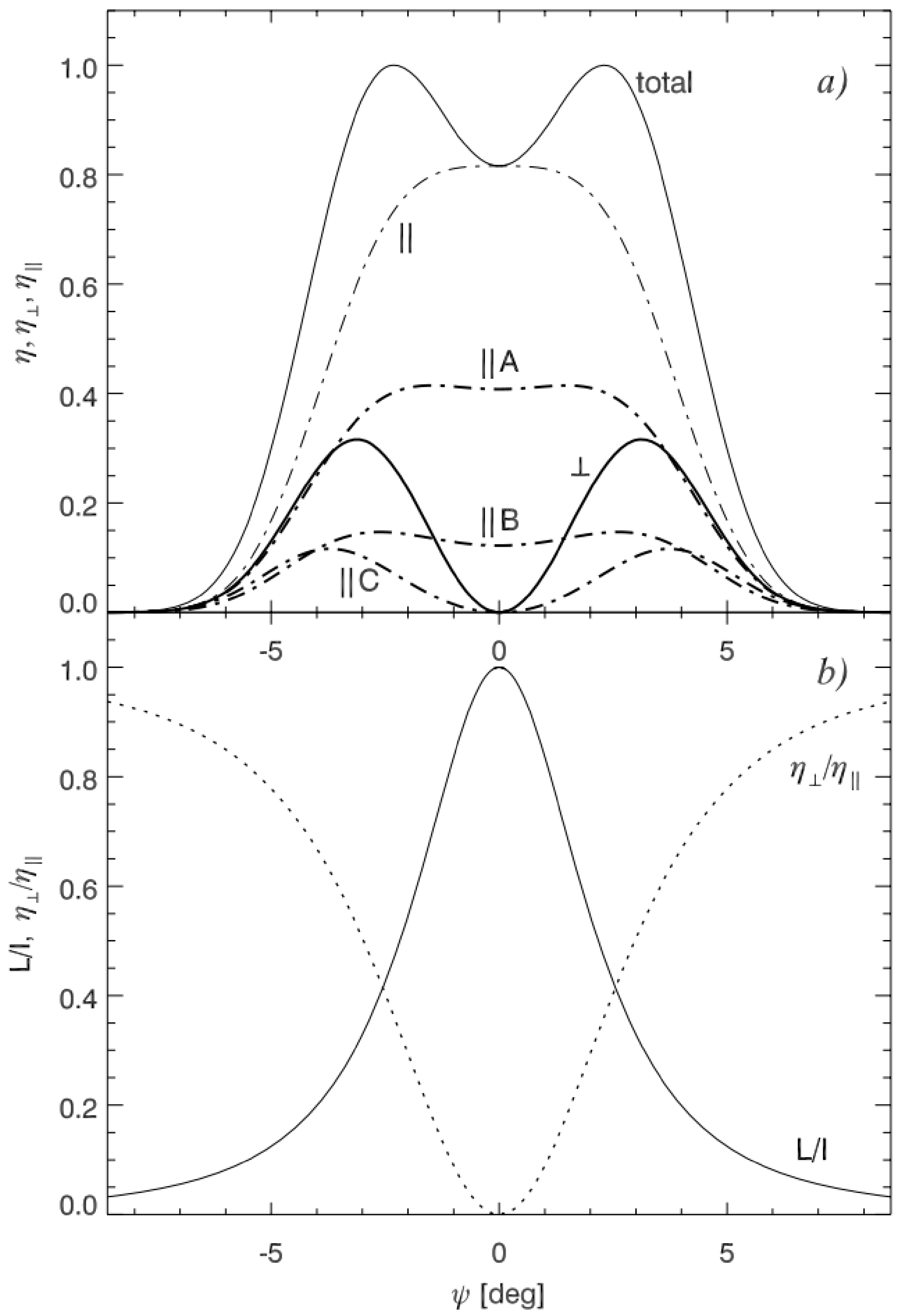
Dyks, Rudak & Demorest 2010 MNRAS: consider partial absorption of curvature radiation cone?

Emission polarized in electron's trajectory plane is more easily absorbed.
➔ radiation becomes bifurcated.





Dyks, Rudak & Demorest 2010



Dyks, Rudak & Demorest 2010

Problem (Dyks 2023):
(1) Too narrow profile

Dyks 2023: consider profiles being modified by inverse Compton scattering (ICS).

ICS: high energy electrons give energy to photons.

When $\gamma h\nu \ll m_e c^2$ is satisfied (always true for pulsar radio waves) in ICS, $\nu_1 = \gamma^2 \nu_0$.

ICS changes the radiation cone morphology, and spectral properties.

II. Basic Model for Conal Structure

A photon goes through several following stages in pulsar magnetic field:

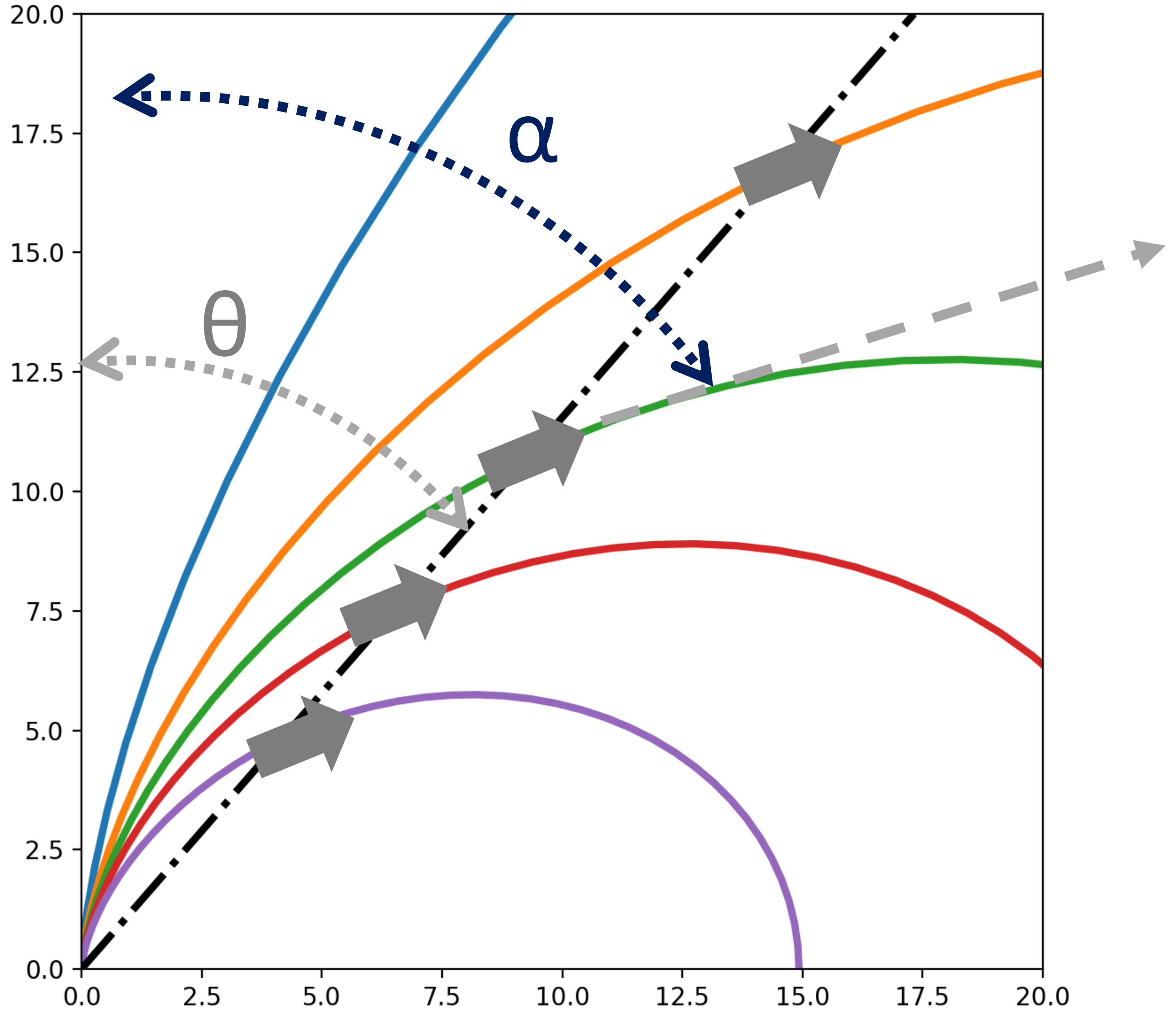
(i) Emitted at some point r_{em};

(ii) Propagate through a mean free path η_{sc};

(iii) Scattered by electrons moving along local B field.

Assume scattered photons propagate in the direction of scattering electron.

⇔ in the direction of local B field.



Drawn by CSS.

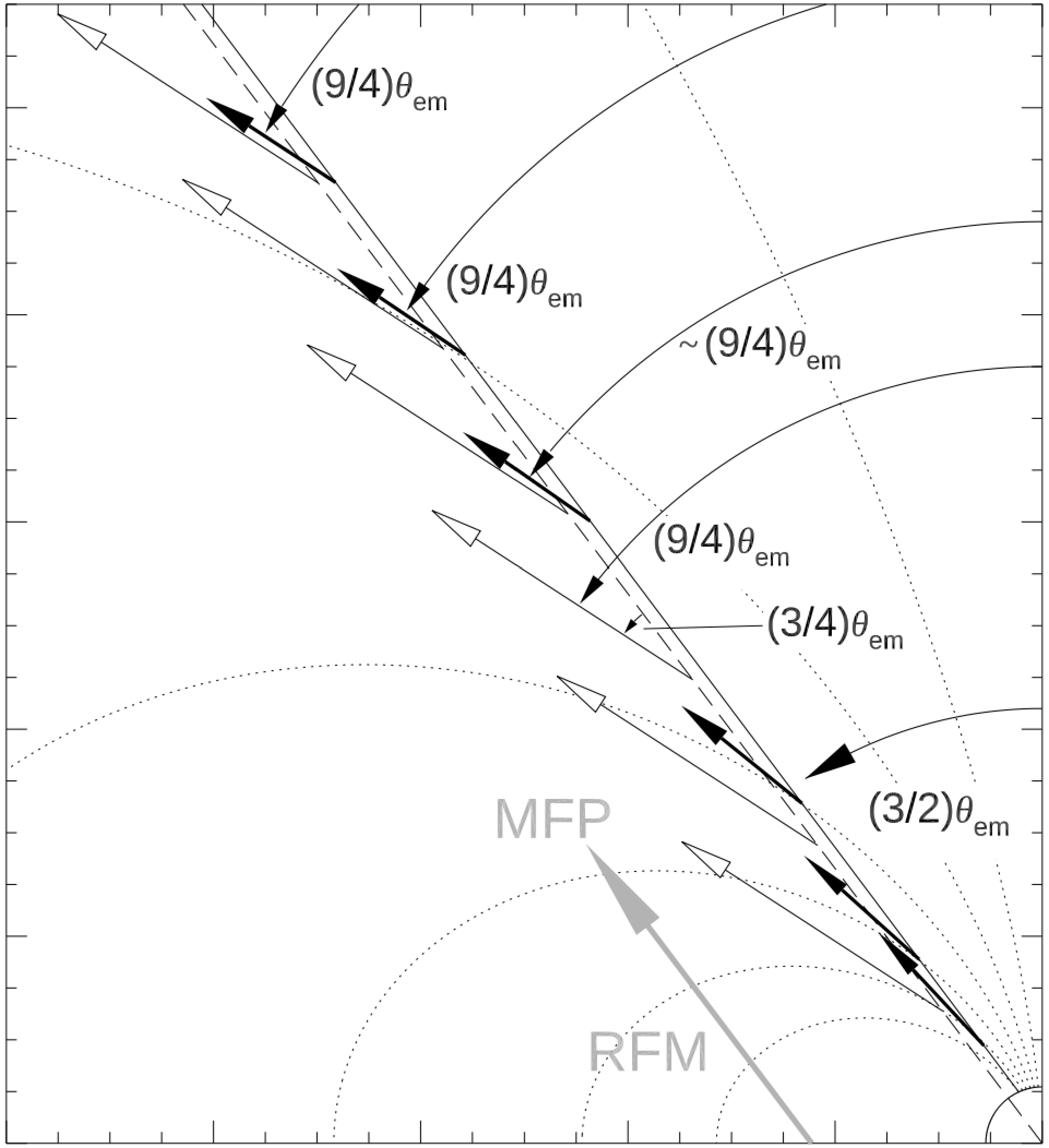
Important property of dipolar field:

Tangential direction α only depends on polar angle θ.

$$\tan\alpha = \frac{3\sin\theta\cos\theta}{2\cos^2\theta - \sin^2\theta}$$

When θ << 1 and α << 1: α = 3/2 θ.

Apply to formation of conal emission:



Emission point

Dashed line:

Initial emitting direction (goes through pulsar centroid).

Black solid line:

Initial emitting direction (from emitting point).

White-tip arrows:

B-field directions for points on the dashed line.

Black-tip arrows:

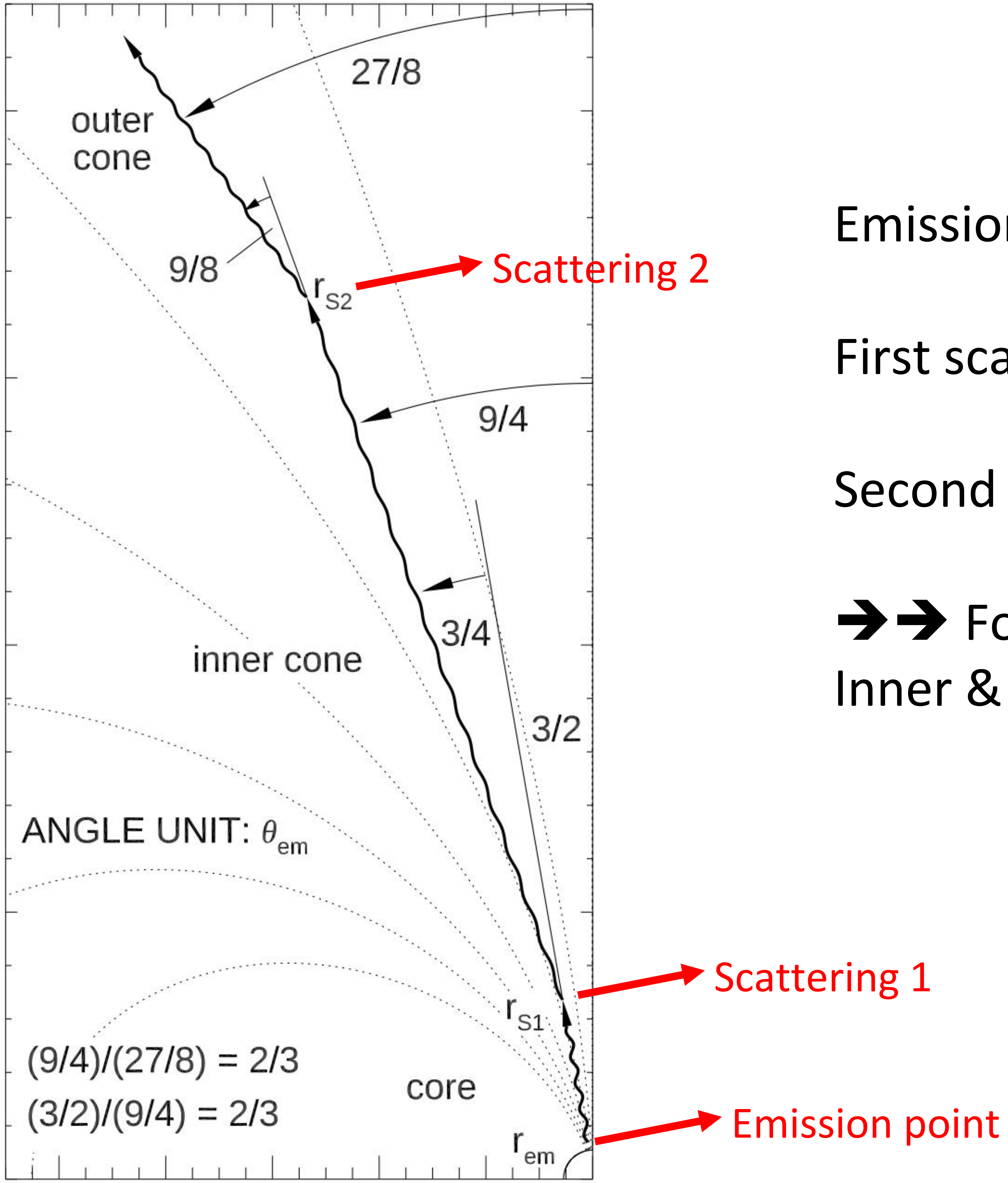
B-field directions for points on the black solid line.

(i.e. ray propagating direction after scattered at this point)

When mean free path of photon is large enough ($\eta_{sc} >> r_{em}$), $\alpha = (3/2)*(3/2)\ \theta$

$= 9/4\ \theta$.

If there's second order scattering:



Emission: α = 3/2 θ

First scattering: α = (3/2)*(3/2) θ = 9/4 θ

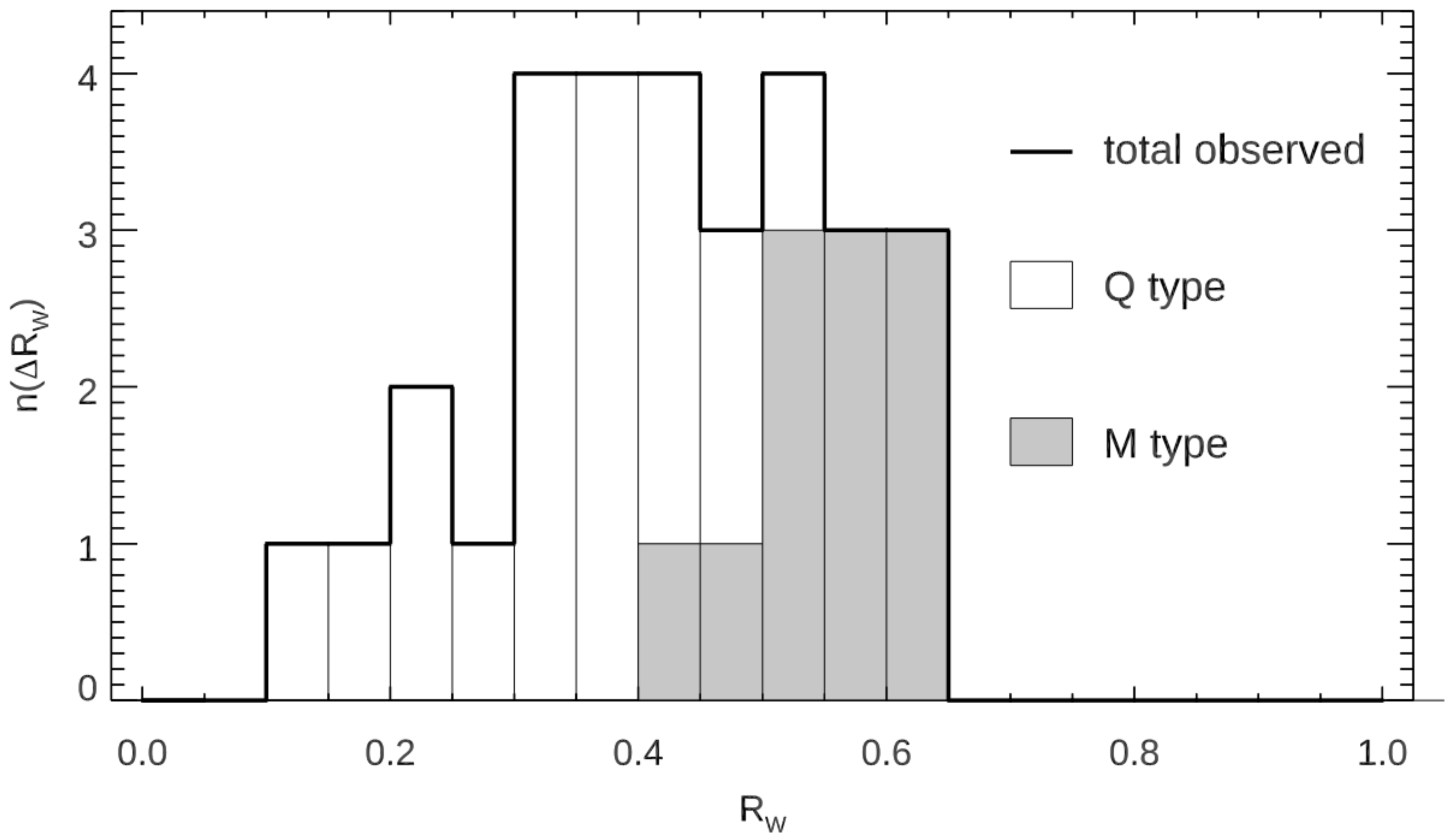
Second scattering: α = (3/2)*(3/2)*(3/2) θ = 27/8 θ

➔➔ Form inner & outer cones.

Inner & Outer cones' width ratio: $$R_{\rm io} = \frac{3}{2}\theta_{\rm em}\left(\frac{9}{4}\theta_{\rm em}\right)^{-1} = \frac{2}{3}$$

Comparison with data:

$$R_{\rm io} = \frac{3}{2}\theta_{\rm em}\left(\frac{9}{4}\theta_{\rm em}\right)^{-1} = \frac{2}{3}$$



R smaller than 2/3

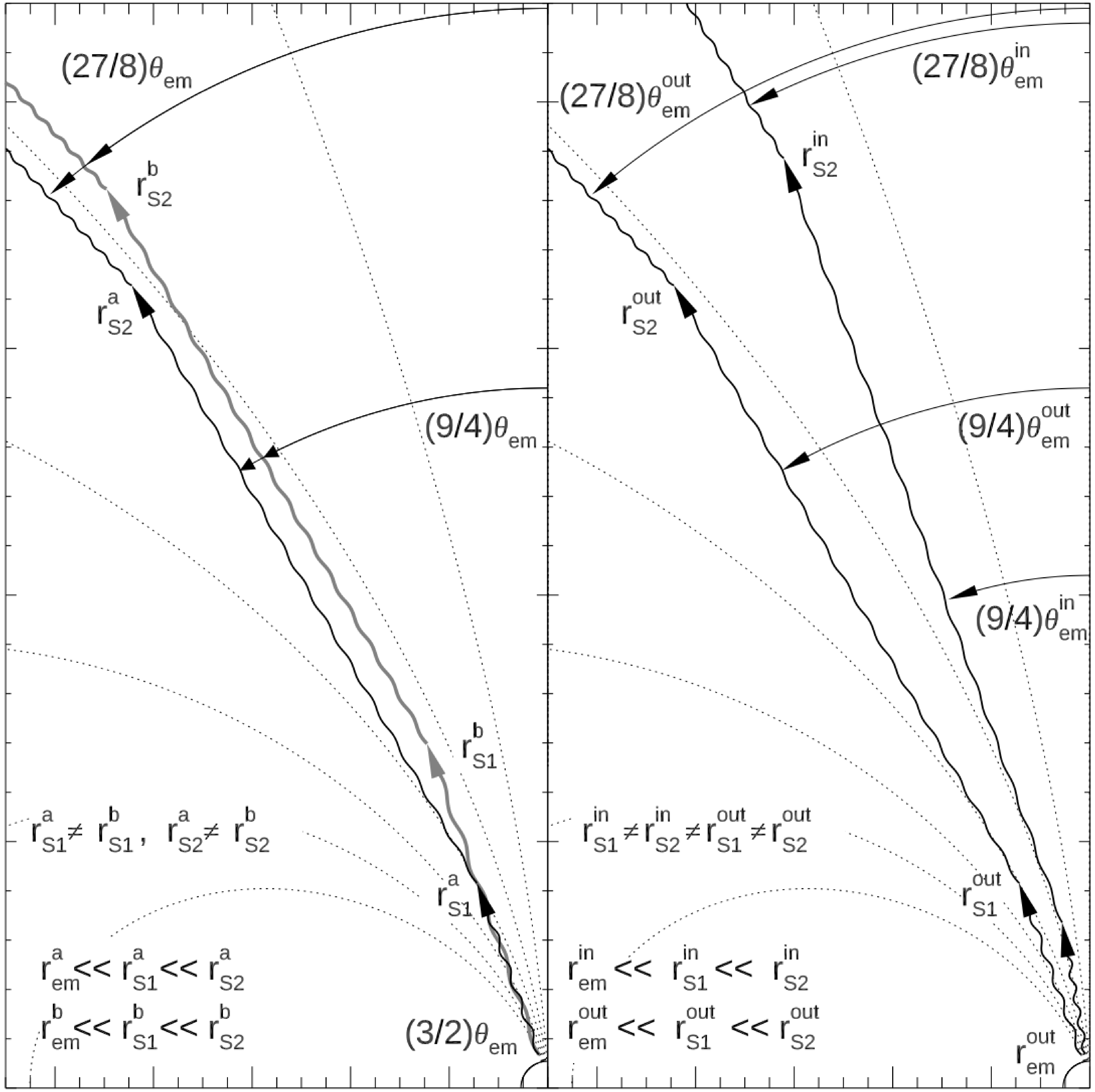
➔ Beam suppression?

Statistics from Dyks & Pierbattista 2015

Q type: 4-components profile

M type: 5-components profile

Two kinds of ray scattering with long enough mean free path:



Left: two rays emitted at same polar angle;
Right: two rays emitted at different polar angle.

➔Forms double cones or core-cone.

Dipolar magnetic field configuration confirms scattering angles to be independent of scattering radii.
➔Non-dipolar: could still be valid for any l-pole star-centered field.

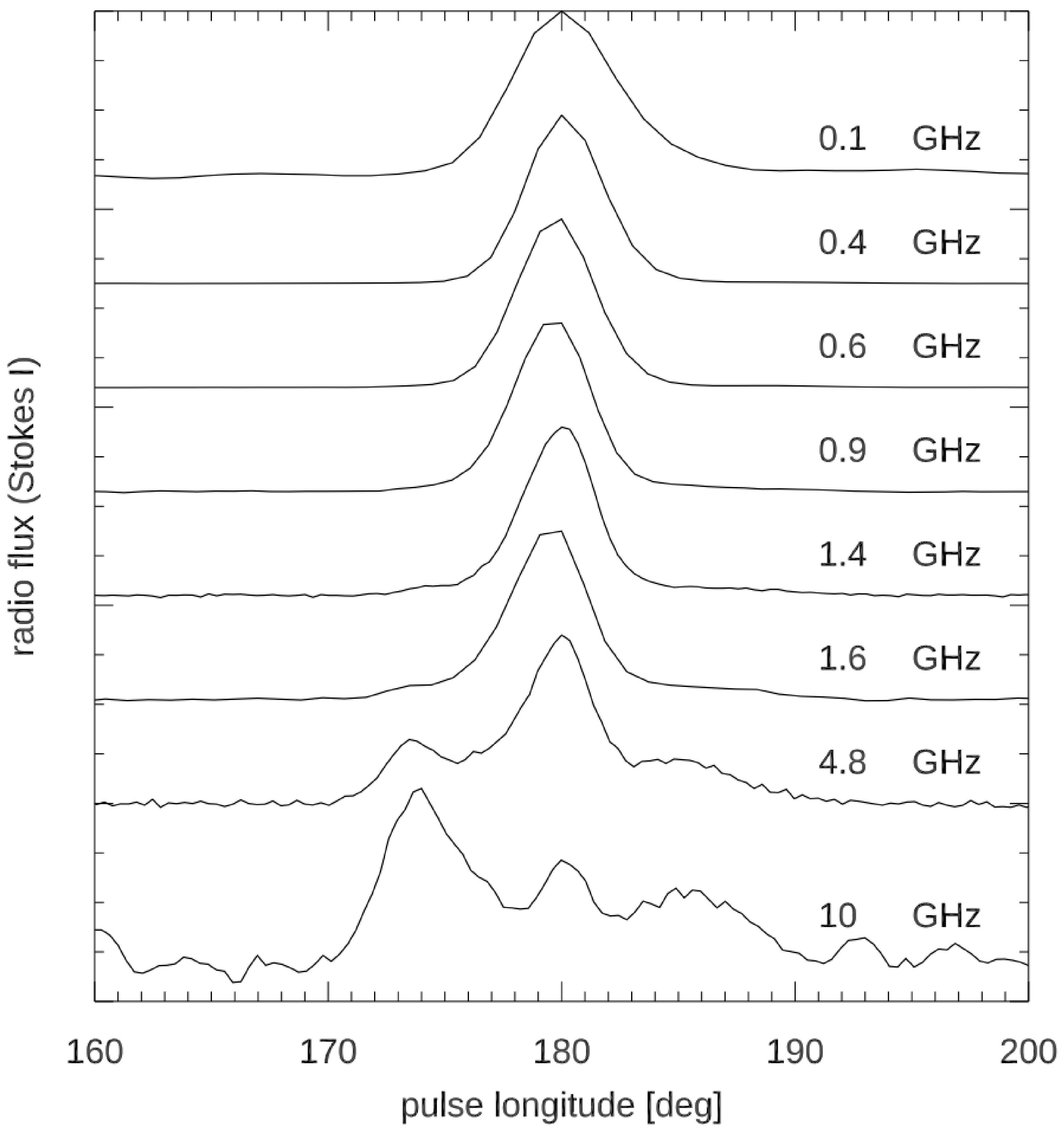
$$B_r = B_{lj}\left(\frac{R_*}{r}\right)^{2+l} P_l(\cos\theta_B) \approx B_{lj}\left(\frac{R_*}{r}\right)^{2+l},$$

$$B_\theta = -\frac{B_{lj}}{l+1}\left(\frac{R_*}{r}\right)^{2+l} dP_l(\cos\theta_B)/d\theta_B \approx B_{lj}\frac{l}{2}\left(\frac{R_L}{r}\right)^{2+l}\theta_B,$$

Arons & Scharlemann 1979 *ApJ.*

$$\theta_x \approx \frac{B_\theta}{B_r} = -\frac{\mathrm{d}P_l(\cos\theta)/\mathrm{d}\theta}{(l+1)P_l(\cos\theta)} \approx \frac{l}{2}\theta$$

III. ICS' impact on profiles' frequency dependence



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Conal components appear at high frequency:

They are scattered and blueshifted.
($\nu_1 = \gamma^2 \nu_0$)

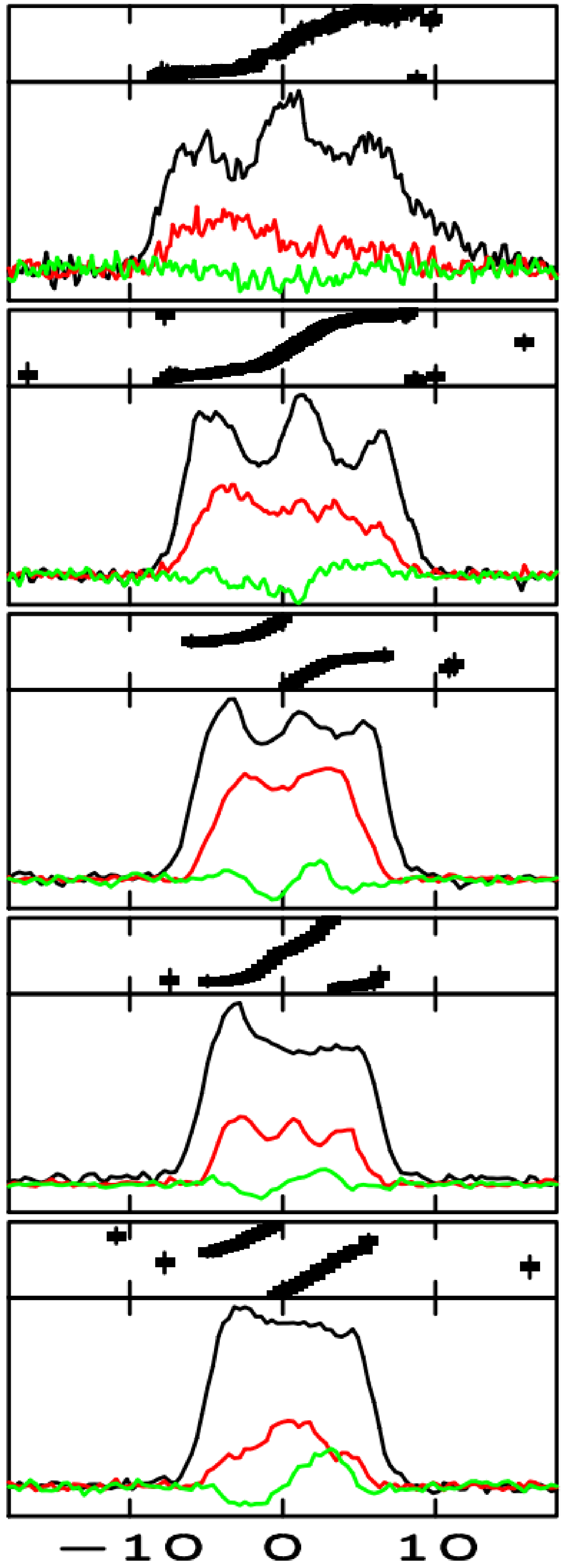
Different polarization modes are differently scattered
➔ Different dominating modes for core/conal components

Mean free path should decrease with frequency:

Higher frequency ➔ lower scattering height

➔➔ Smaller scattering angle

➔➔ Narrower profile



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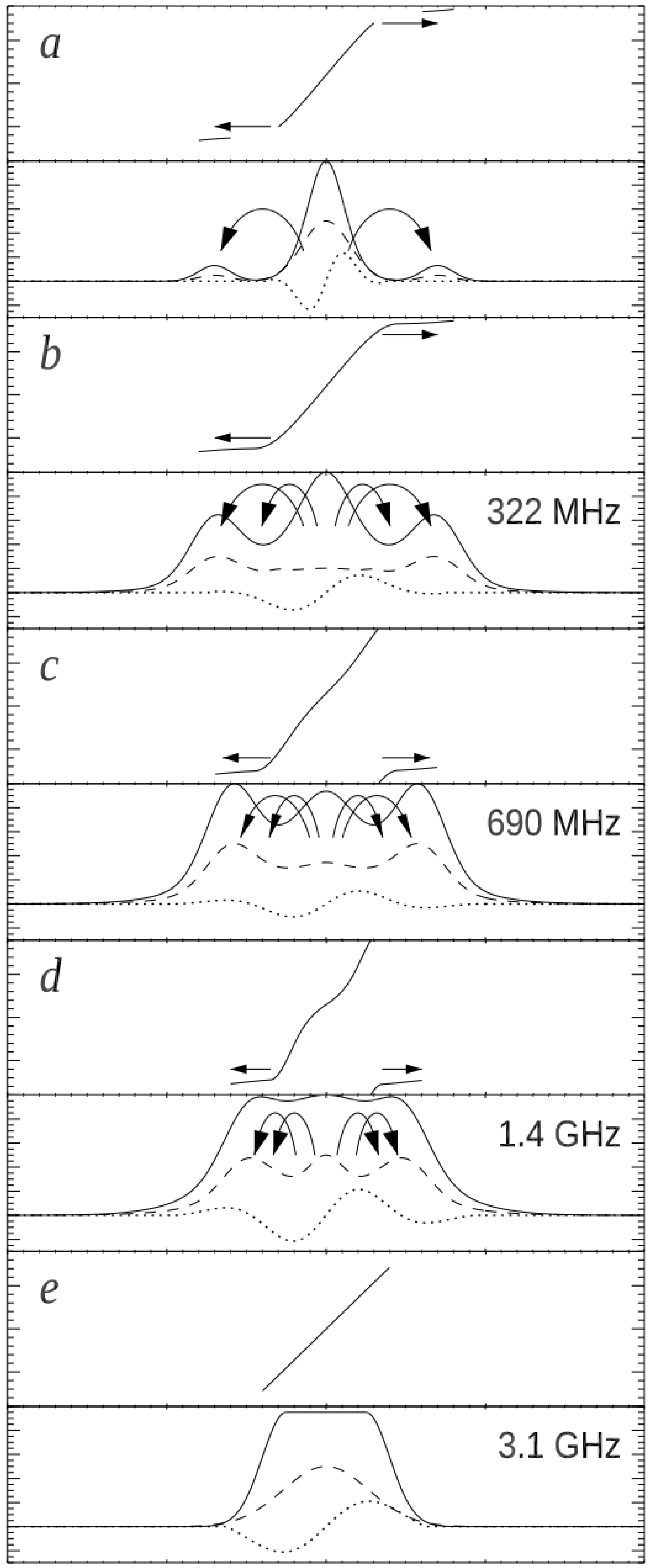

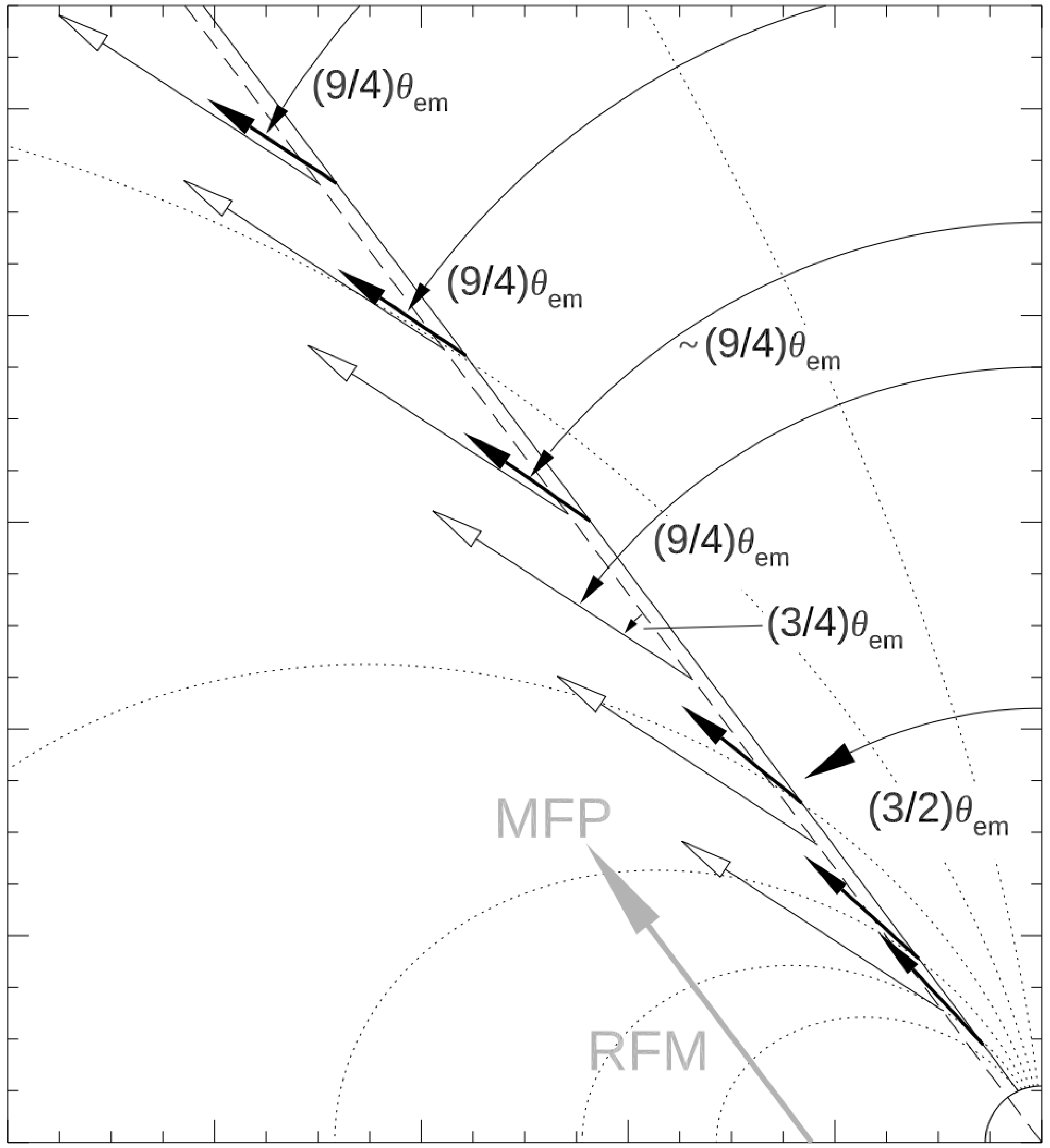

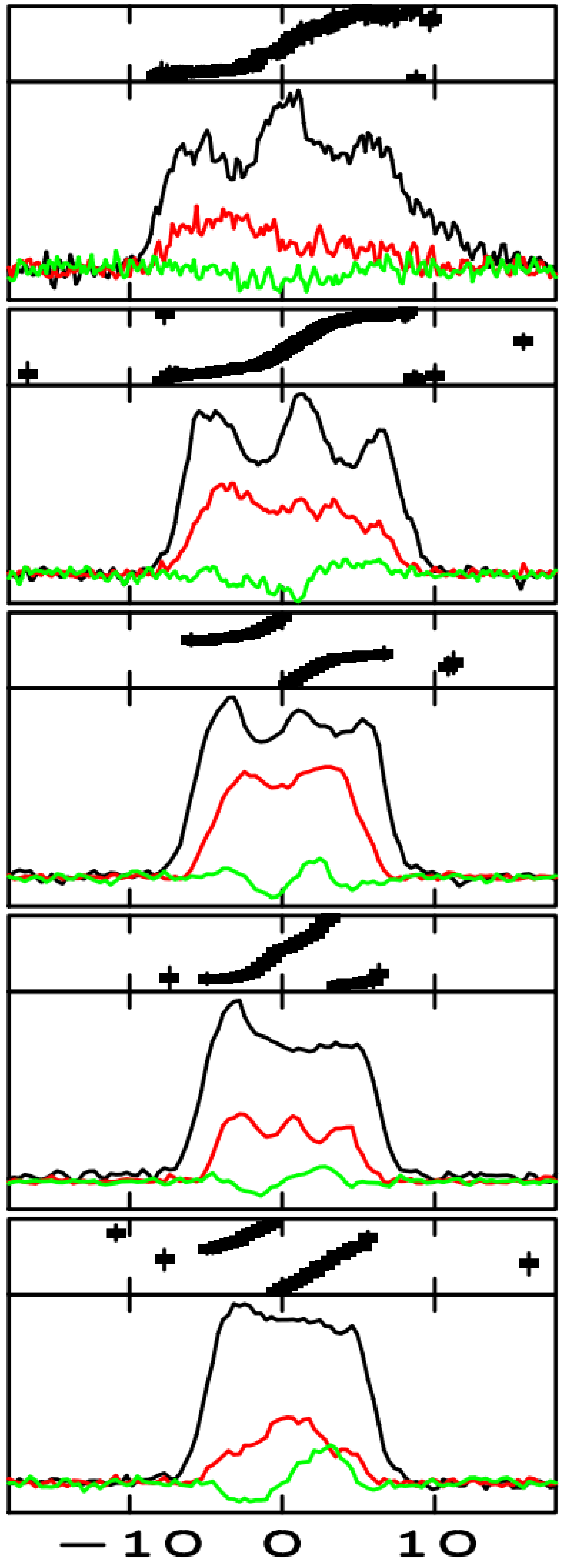

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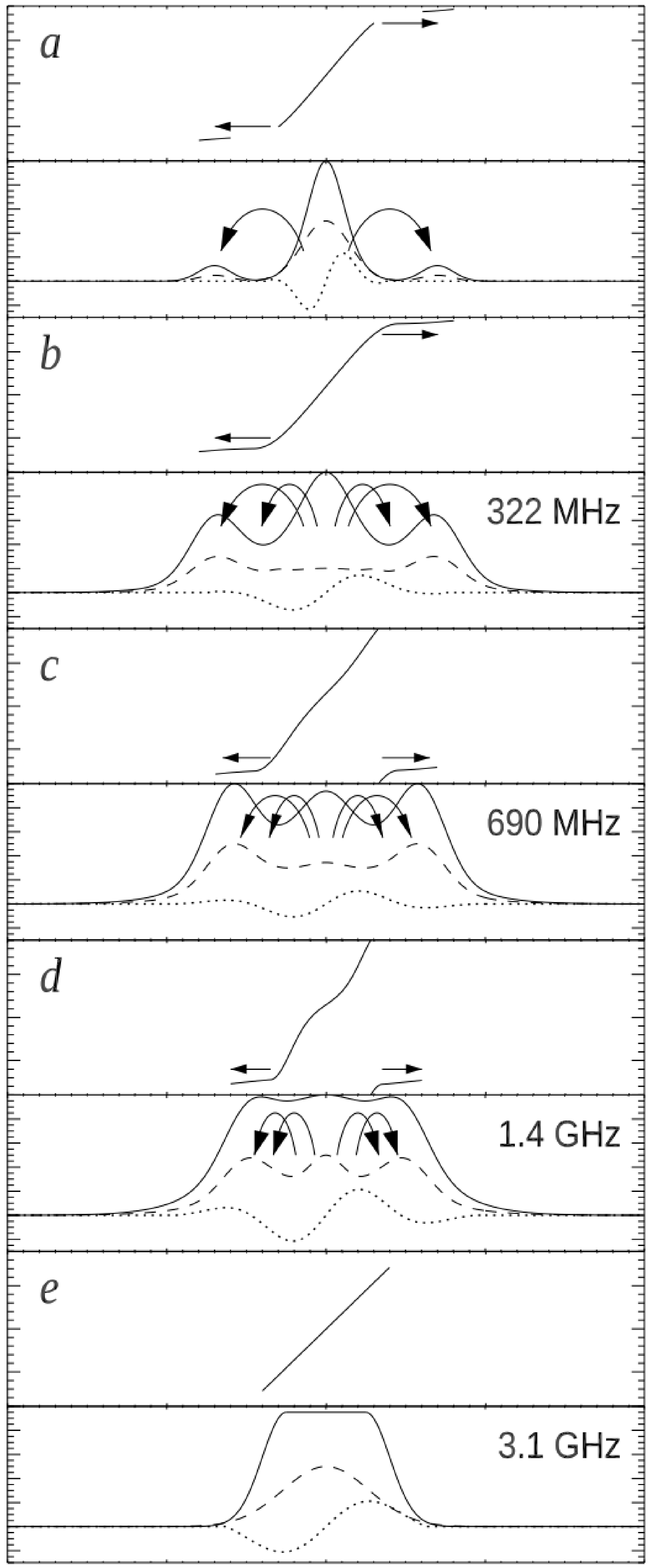
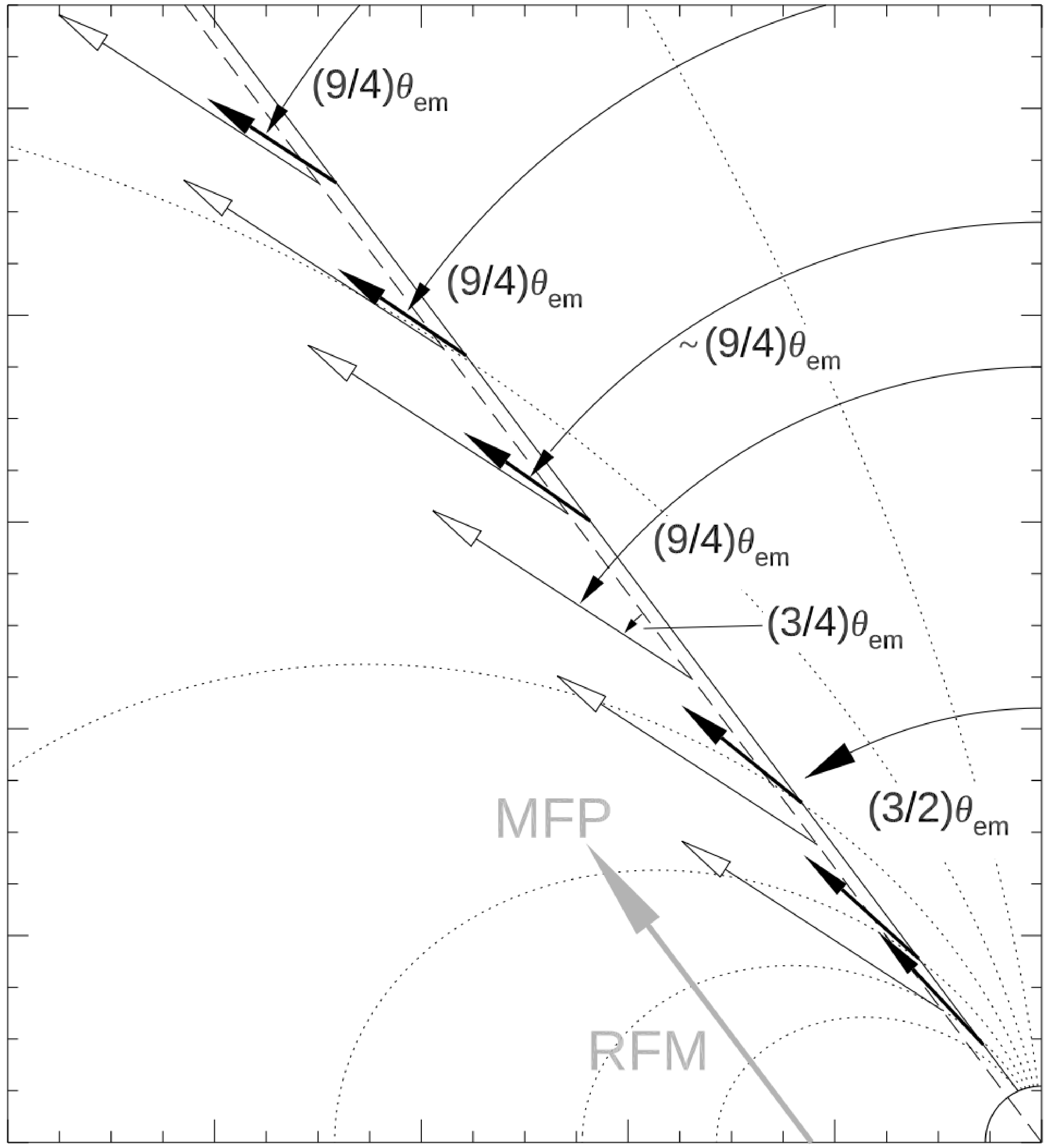


Mean free path should decrease with frequency:

Higher frequency ➔ lower scattering height

➔➔ Different scattering angle

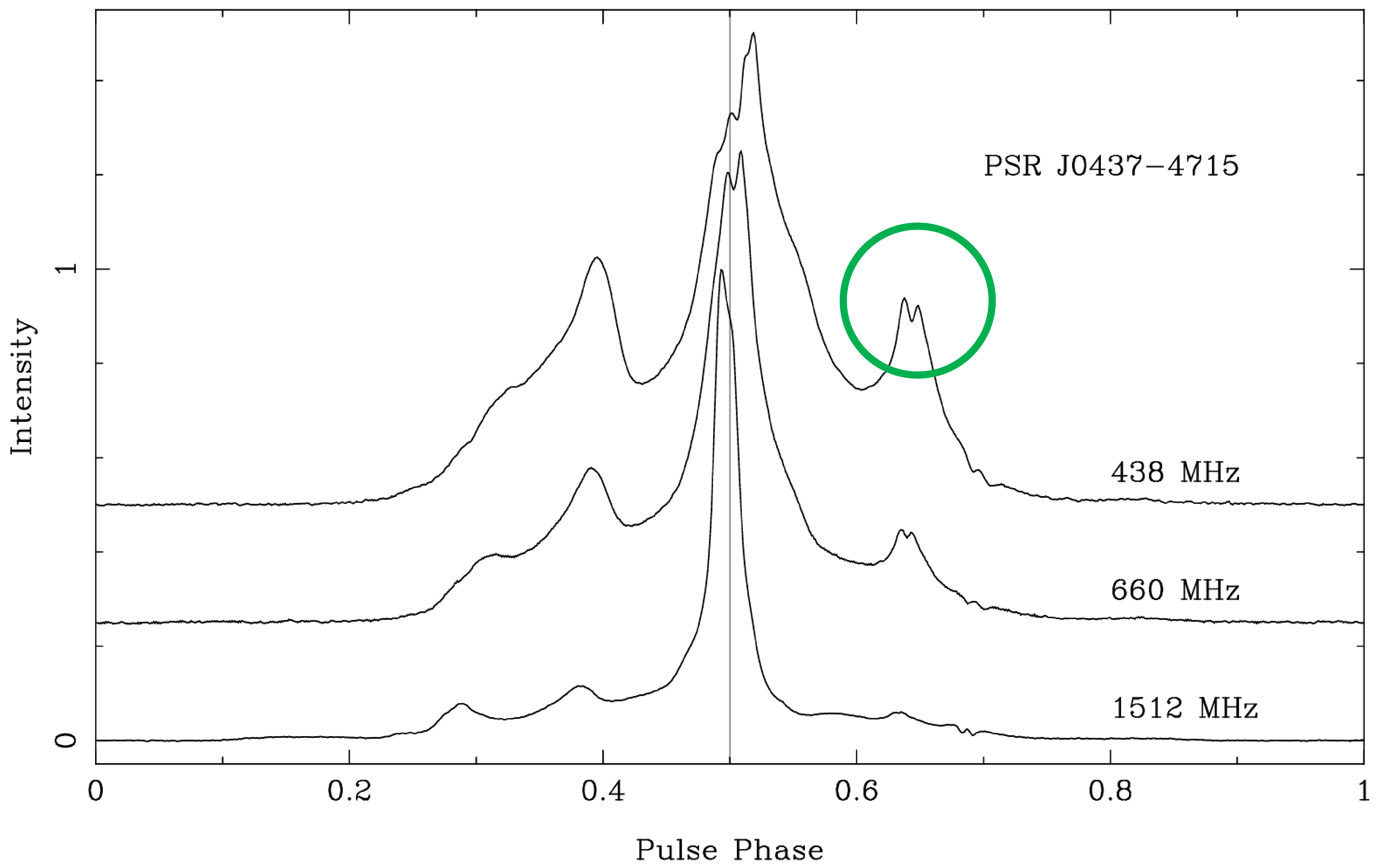
➔➔ Components' merging



IV. Understand Bifurcated components

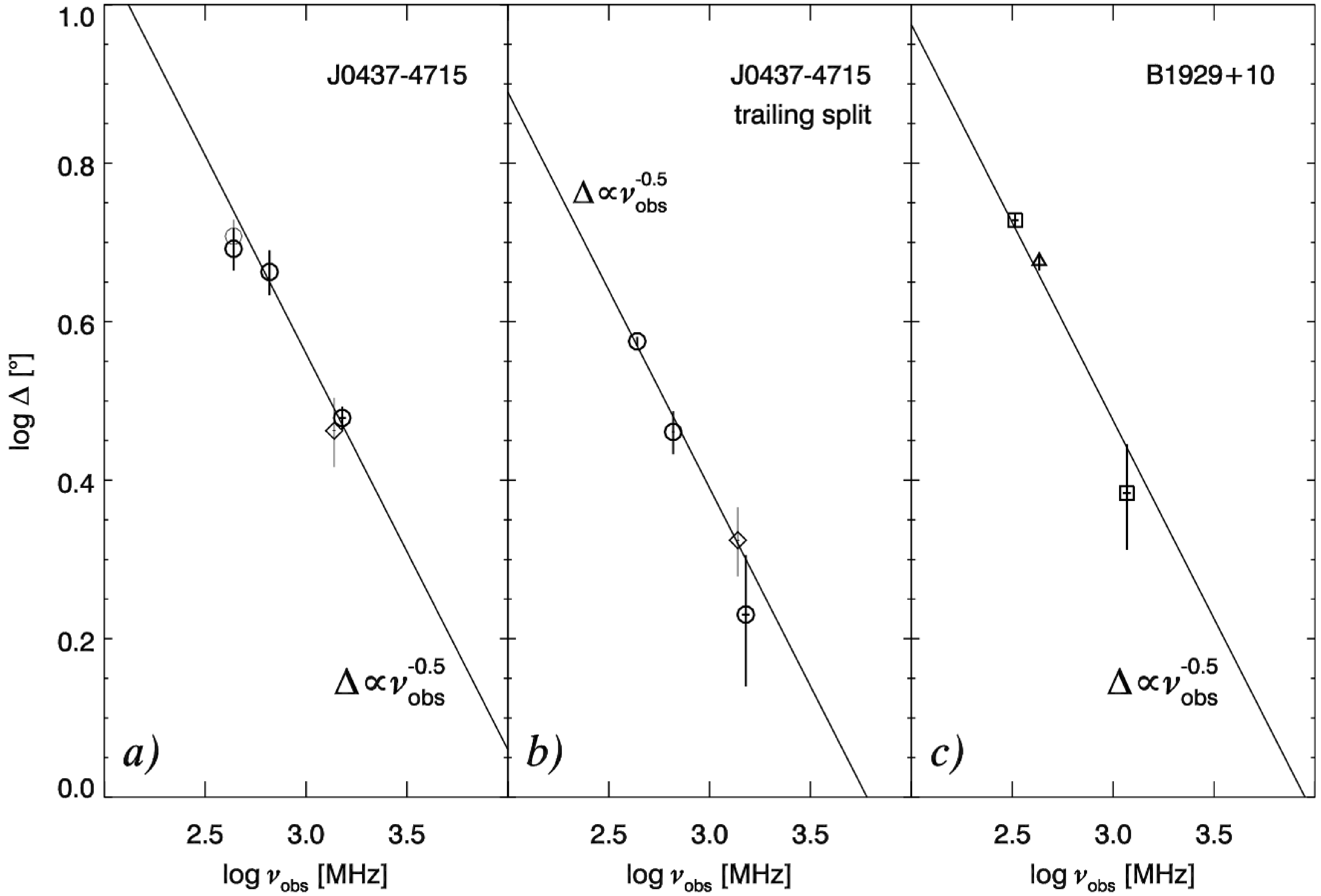
Two types of bifurcated components:

(1) Narrow conal components merging quickly with increasing frequency $\Delta \propto \nu^{-1/2}$



J0437-4715

Navarro et al. 1997 *ApJ*



Dyks, Rudak & Rankin 2007 *A&A*

Two types of bifurcated components:
(1) Narrow conal components merging quickly with increasing frequency $\Delta \propto \nu^{-1/2}$

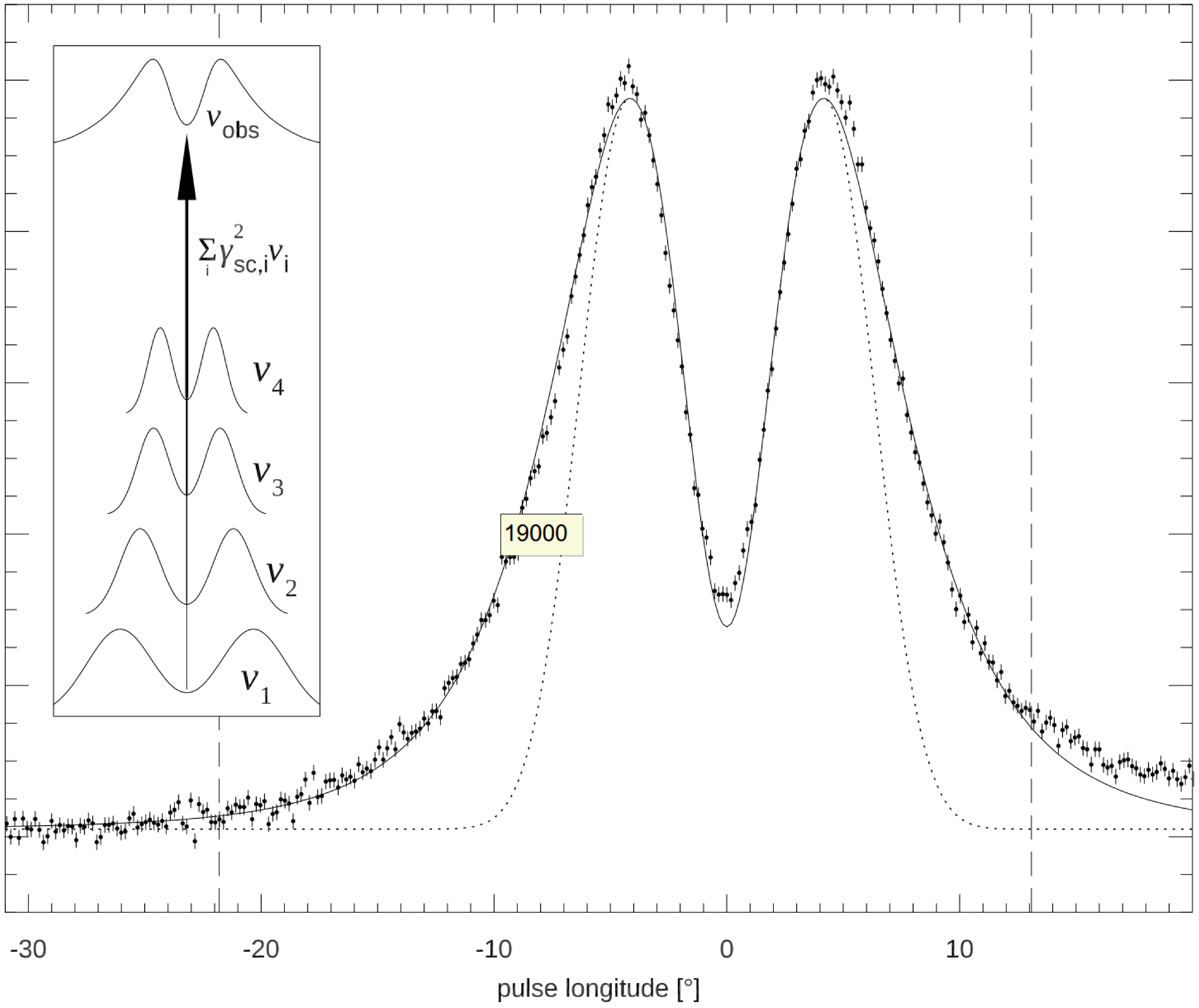
This kind of bifurcated components are scattered by electron flow of very small velocity direction spread. $\Delta \hat{v} \ll 1/\gamma_{sc}$

Beam width / components' separation: $\Delta \propto 1/\gamma_{sc}$ (1/Lorentz factor of scattering particles).

For ICS: $\nu_{obs} \approx \gamma_{sc}^2 \nu_{em}$

➔ $\Delta \propto (\nu_{em}/\nu_{obs})^{1/2}$

Two types of bifurcated components:
(2) Wide, strong, and symmetric bifurcated components, merging with frequency slower.



$$\Delta \propto \nu^{-0.35}$$

The larger width results from scattering by particles with larger velocity spread.

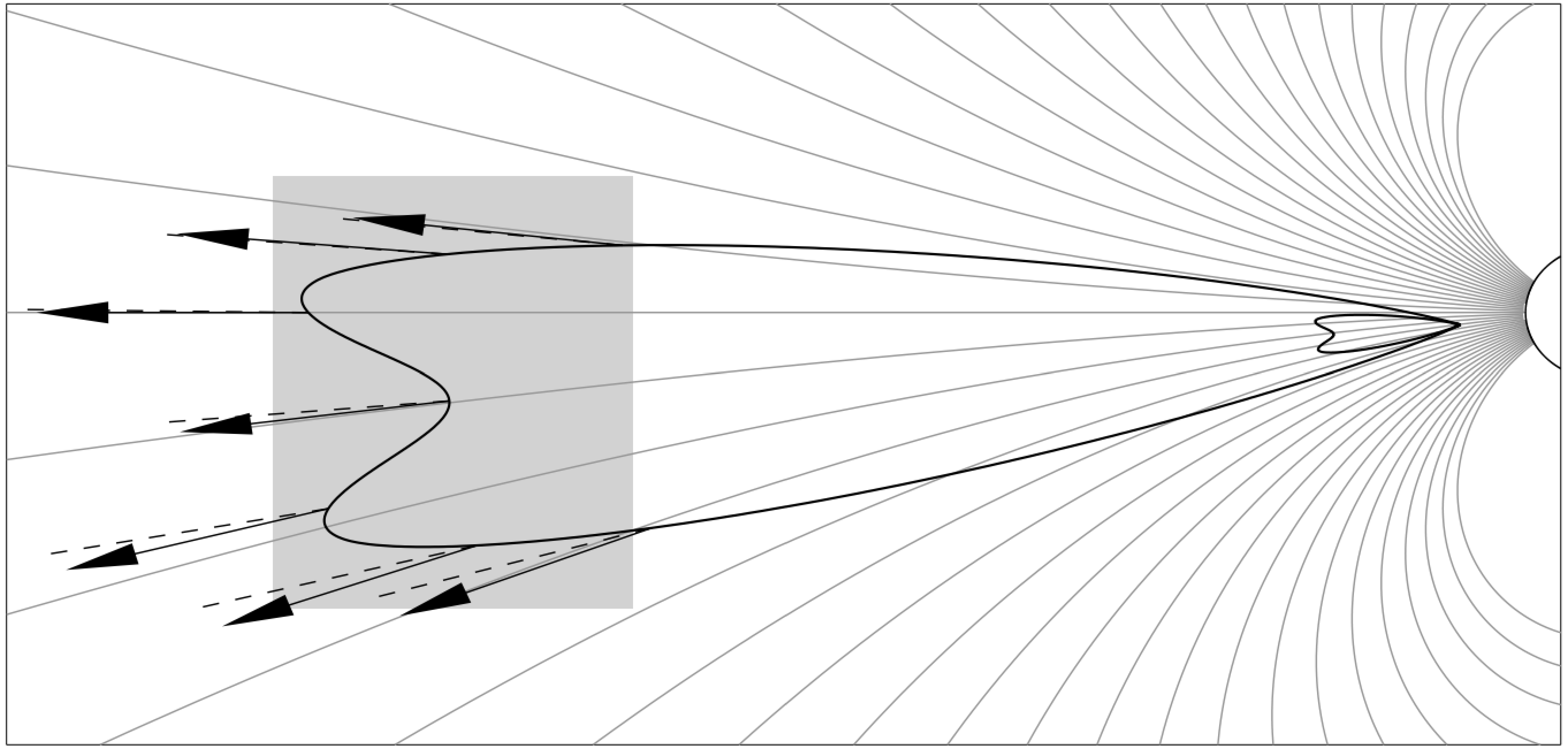
$$\Delta \hat{v} \gg 1/\gamma_{sc}$$

Dotted line: frequency-resolved curvature radiation beam (with only O-mode)

Solid line: frequency-integrated…
(frequency-integrated performs better)

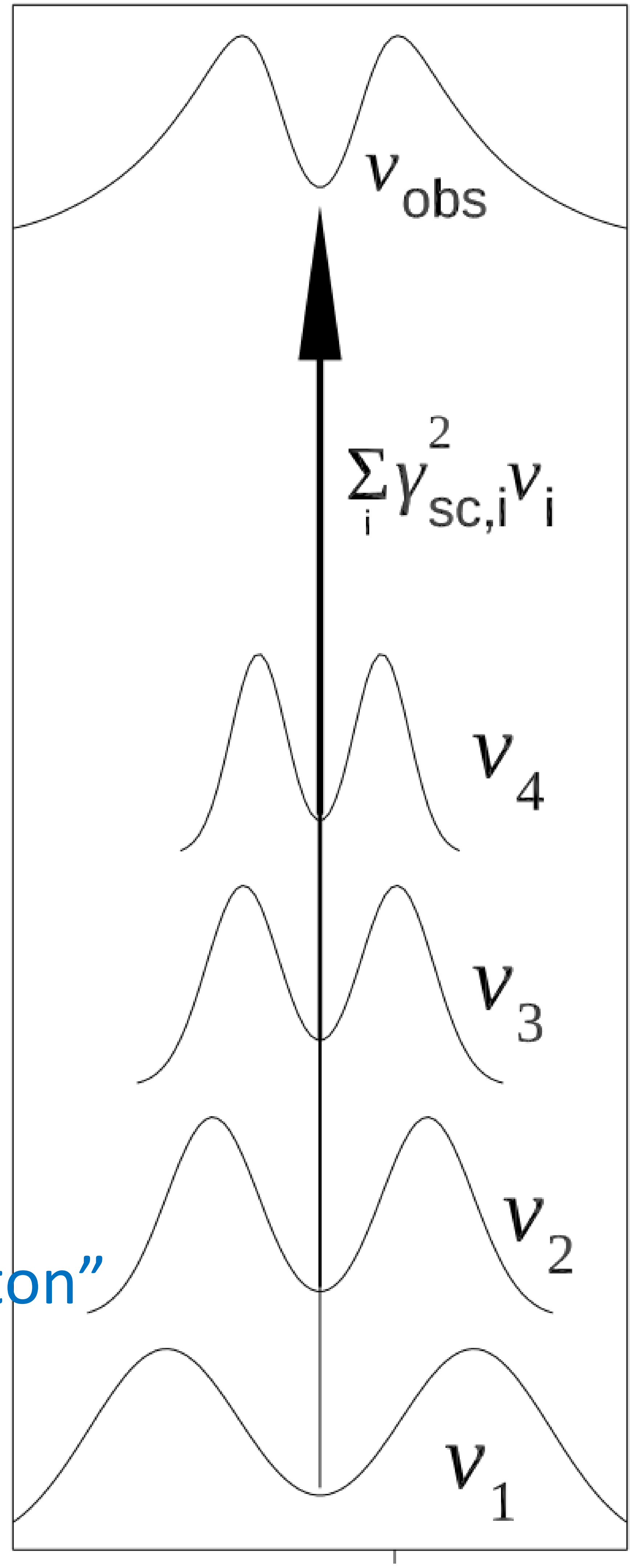
Two types of bifurcated components:

(2) Wide, strong, and symmetric bifurcated components, merging with frequency slower.



The larger width results from scattering by particles with larger velocity spread.

$$\Delta\hat{v} \gg 1/\gamma_{\rm sc}$$



"Curvature self-Compton"

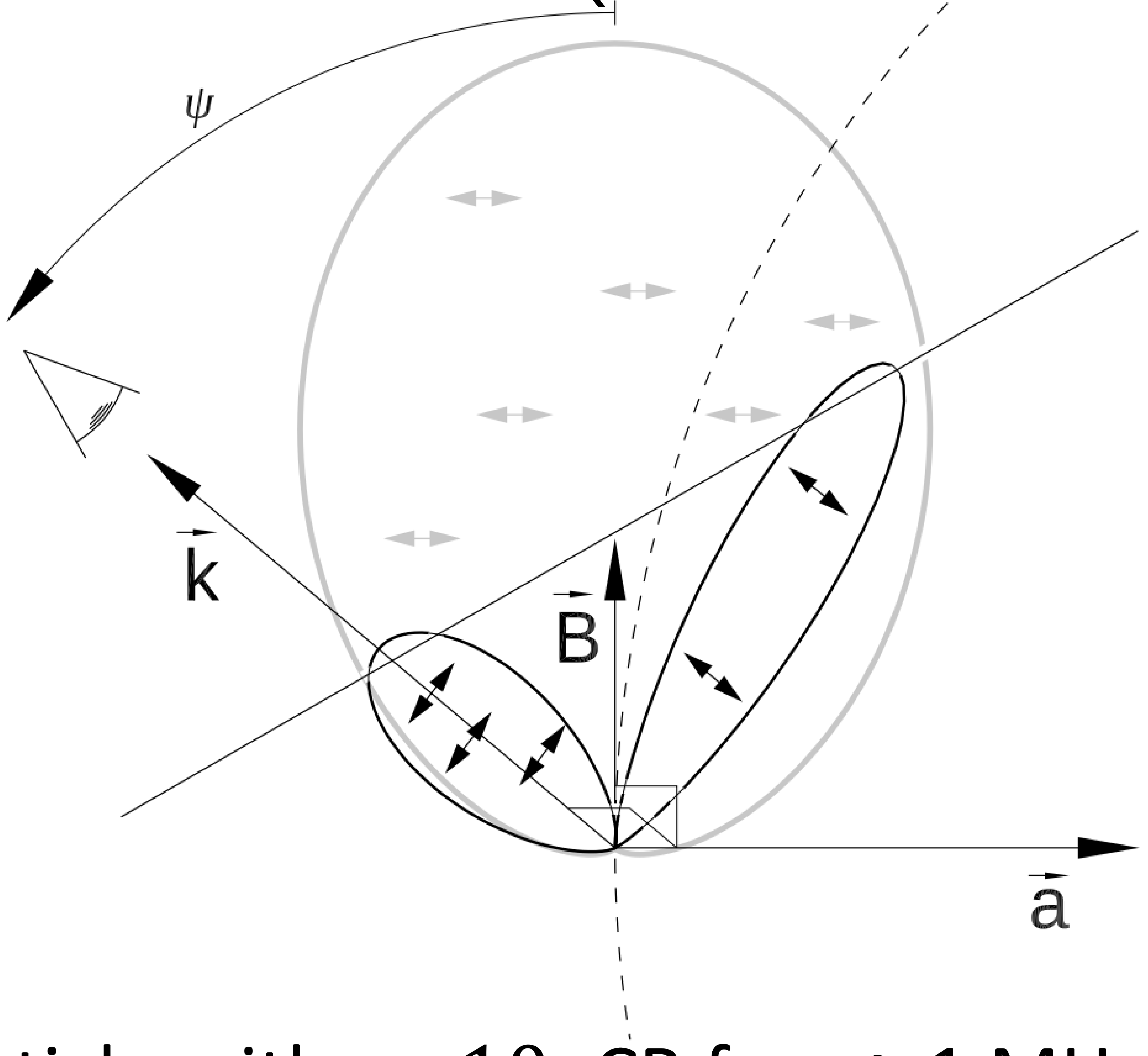
Profiles of different frequencies could be blueshifted
To a same frequency 🡐 origin of "frequency-integrated" CR beam.

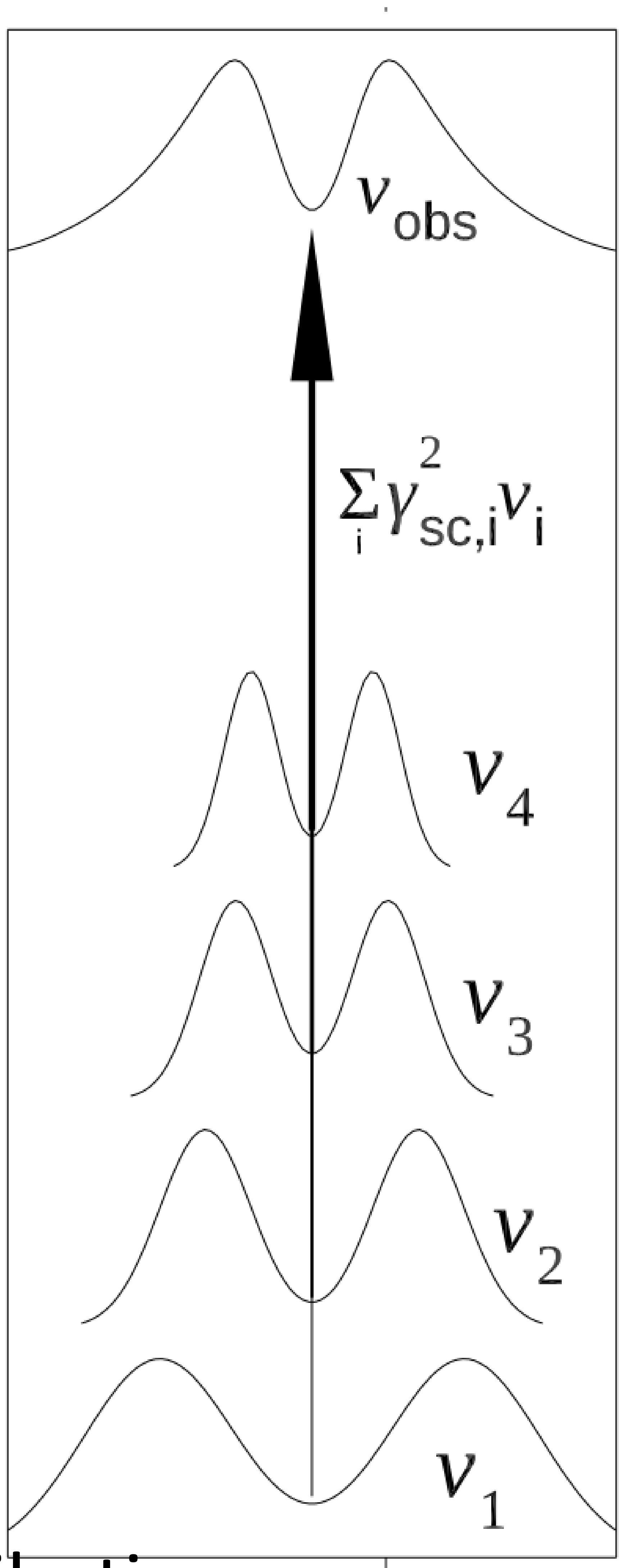
Two types of bifurcated components:

(2) Wide, strong, and symmetric bifurcated components, merging with frequency slower.

ICS of curvature radiated beam: components polarized within $\boldsymbol{k} \times \boldsymbol{B}$ plane could be effectively scattered.

(But not absorbed yet…?)





Emitting particle with $\gamma{\sim}10$: CR freq ~ 1 MHz.

Observed frequency ~ 1GHz ➔ $\gamma_{sc}{\sim}30$.

Scattering particles and emitting particles could have same energy distribution.

V. Discussion

(1) Implications for subpulse modulation:

Scattering modifies beam structure & spectral properties.

➔ Temporal variations of electron energy spectrum could lead to flux modulation.

(2) Cones or fan beams?

The answer is ambivalent at present…

The geometry behind conal structure may not be conal because of scattering.

Summary: ICS of curvature radiation in pulsar magnetic field could explain conal structures and bifurcated components.

Thank you for your attention ☺