Inverse Compton scattering of curvature radiation as the origin of radio pulsar beam geometry

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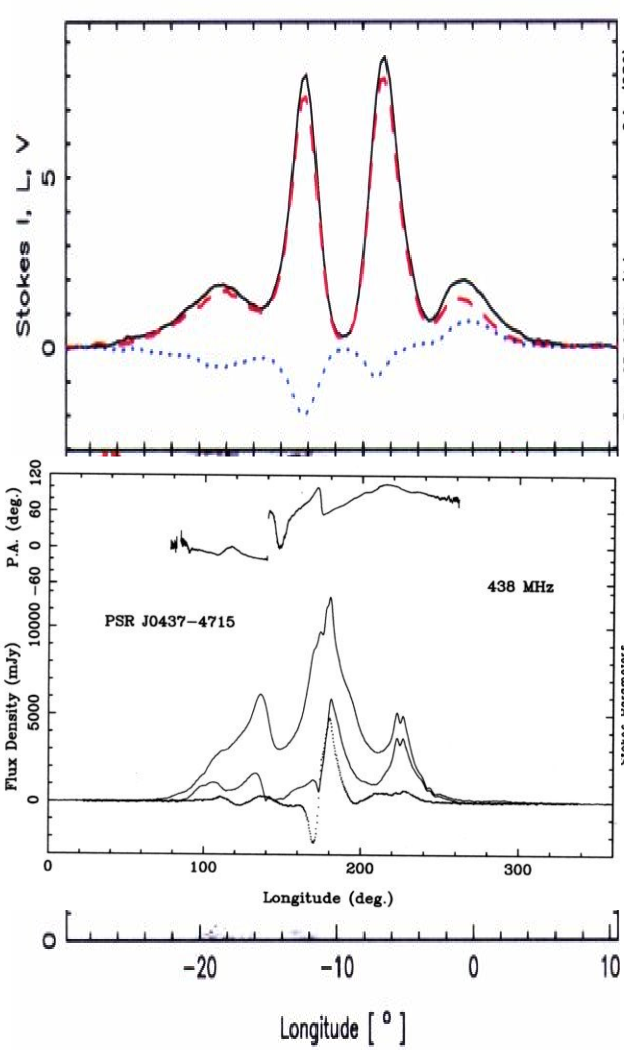
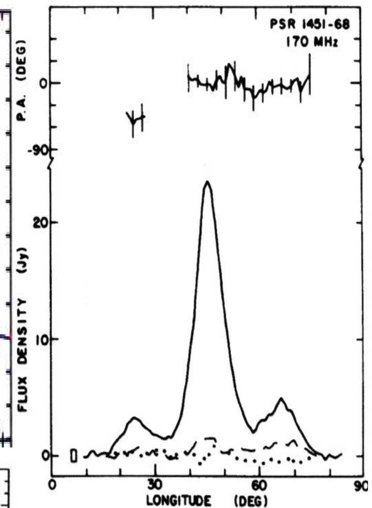
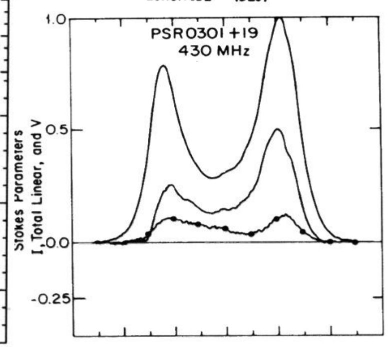
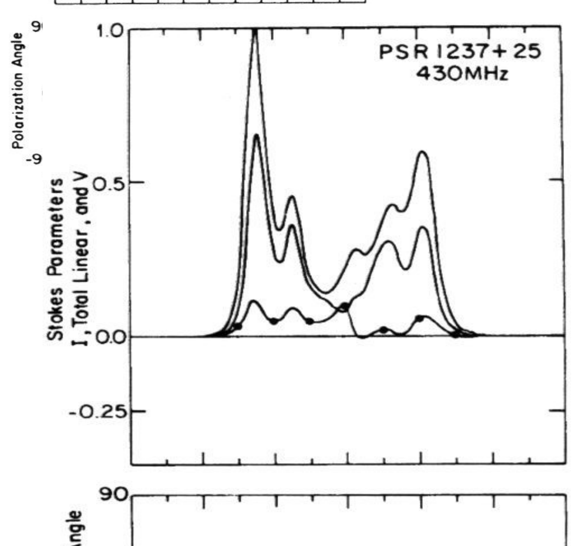
Photo by Richard Sidey

Average profiles of radio pulsars
have **left-right symmetry**:



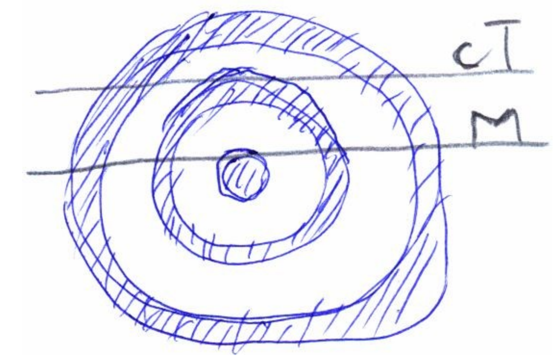




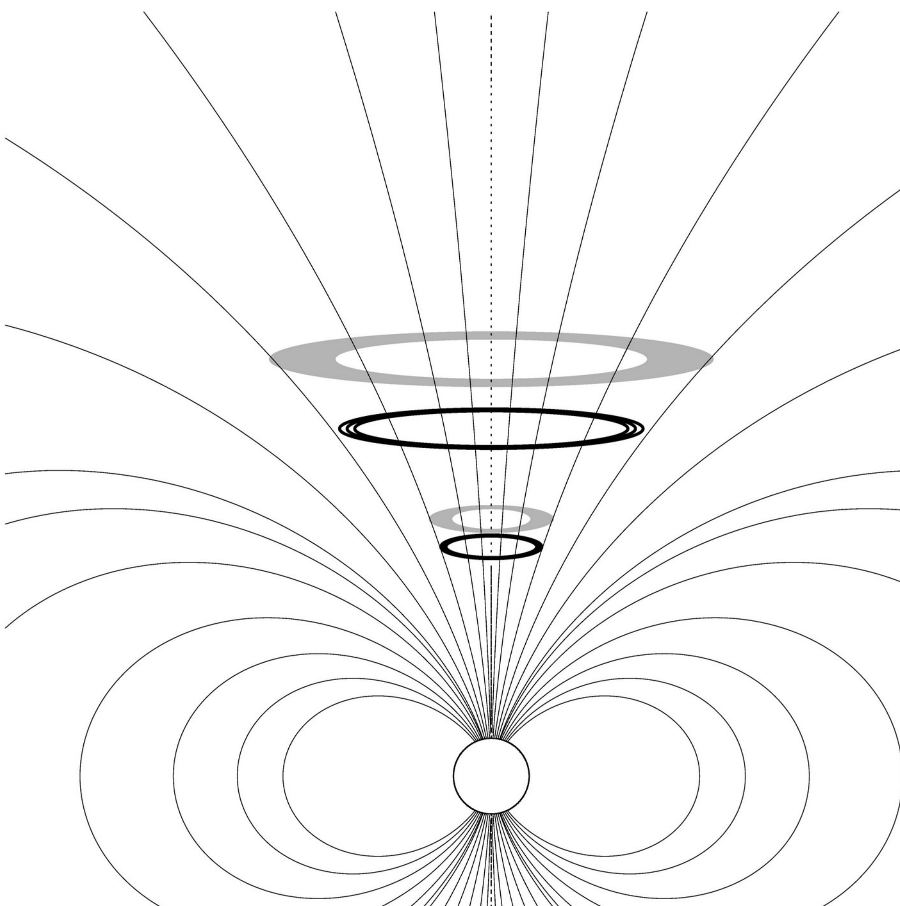


Rankin 83, Teixeira et al. 2015
Navarro et al. 1997

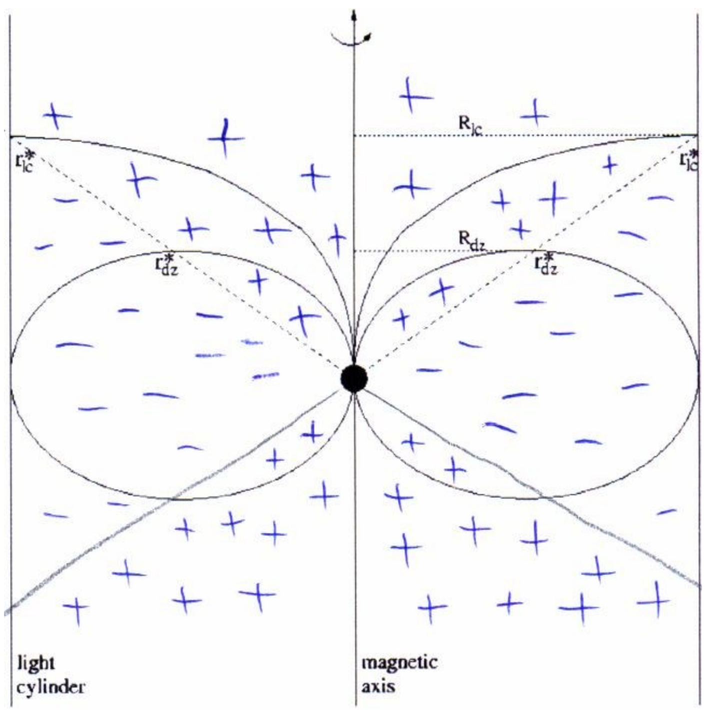
=> **nested cone model** (RS75, Backer76, Rankin 82)



Cones from separated levitating rings?
(Gangadhara & Gupta 2001)

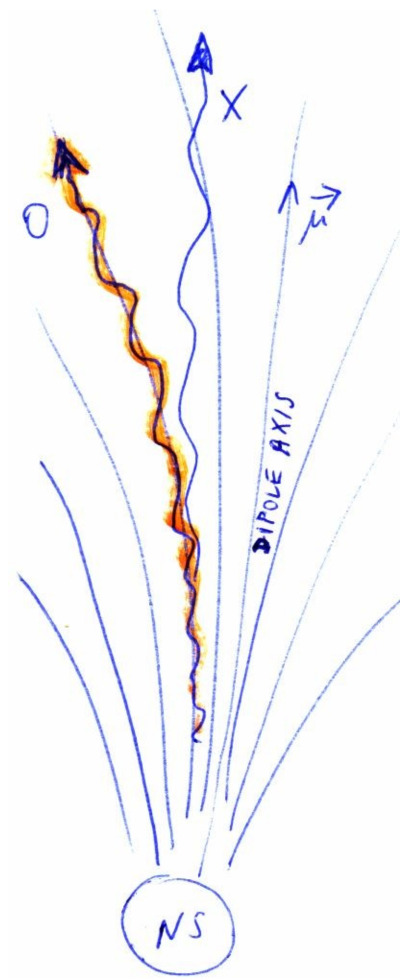


Three models for nested cone geometry



Critical and last open lines
(Wright 2003)
Cone size ratio = 0.75 – 0.82
Observed: 0.74 – 0.87
Rankin method: several steps,
strong/dubious assumptions

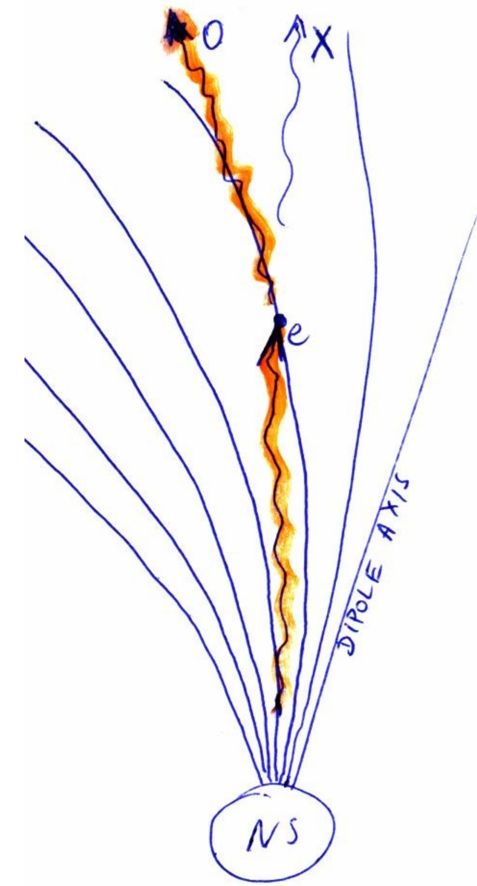
Why core polarized as X mode?



Refraction: X mode core

No special cone size
Only one cone?

How to discern from...



Scattering: X mode core
Lyubarskii & Petrova, Blandford

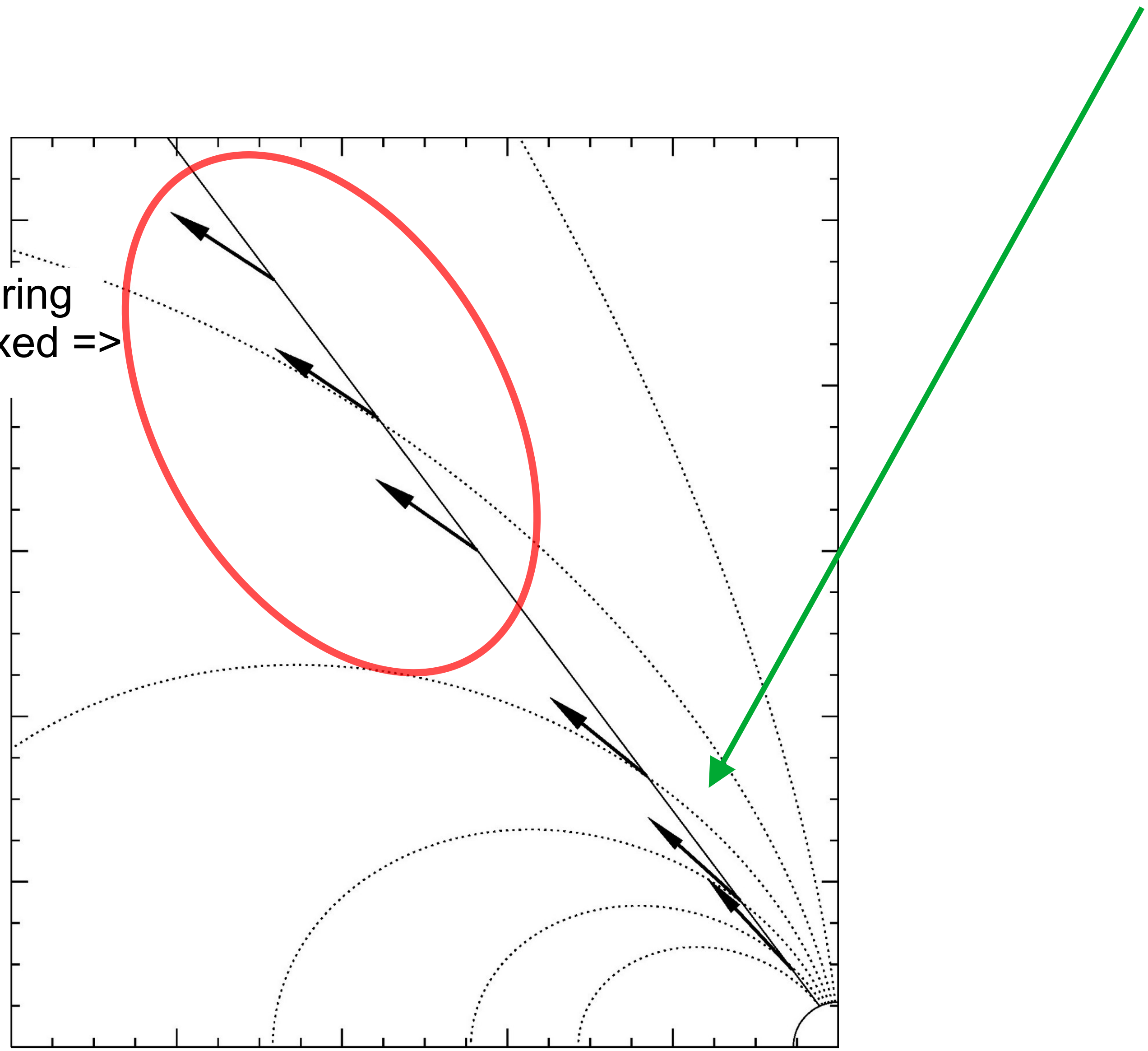
So far applied
for unusual features
(precursors, backward
interpulses)

Can work for the cones?

Universal scattering angle

Rays emitted tangent to B cross B at angle that increases with scattering altitude...

...but soon the scattering angle gets fixed =>

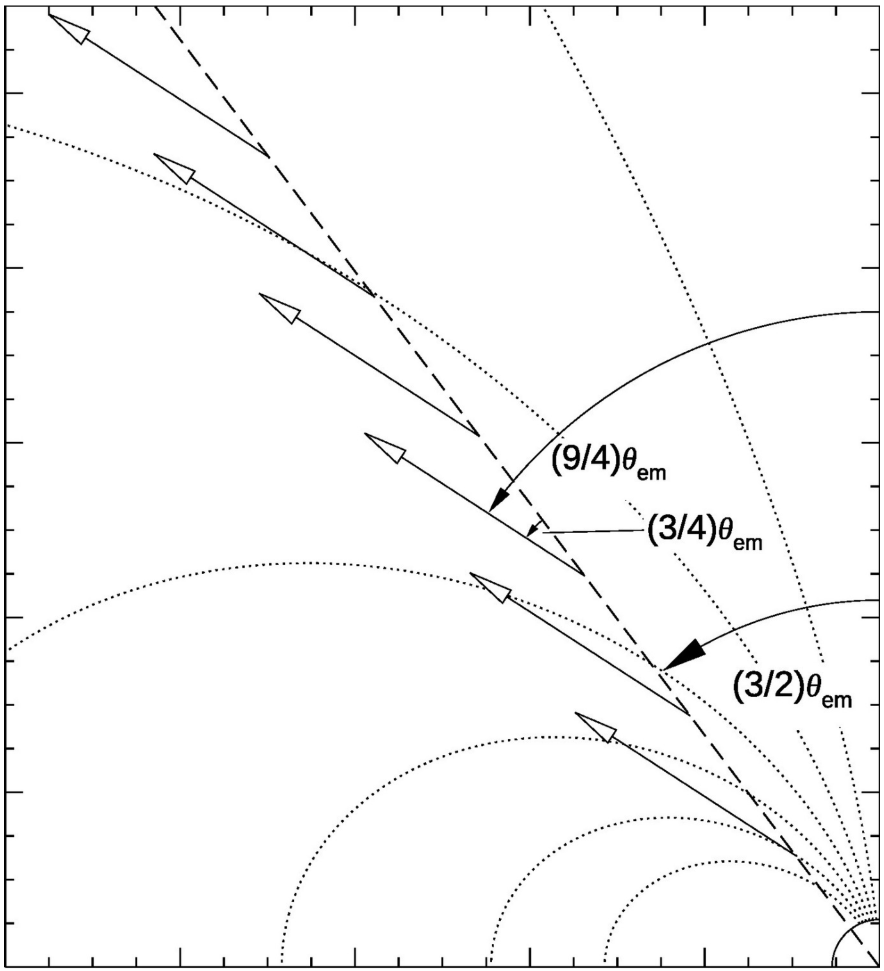


radio waves scattered along local B => in the same direction regardless of scat. altitude or MFP

INNER TO OUTER CONE SIZE RATIO = 2/3

Local dipolar B crosses a radial line at a fixed angle

Far from frame origin any line is radial
(approximately)



local crossing angle = half of the polar angle of propagation

(independent of r)

Original polar angle + Scattering angle = Final polar angle

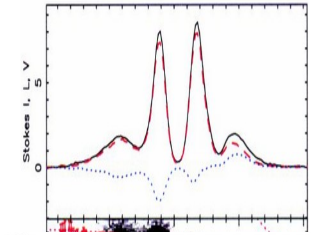
$$3/2 \quad + \quad 3/4 \quad = \quad 9/4$$

$$= 3/2 \times 3/2$$

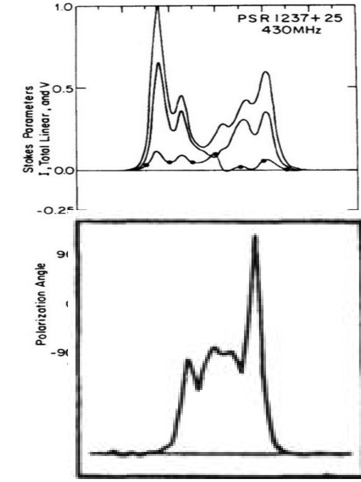
= 1.5 times larger than original

=> inner to outer cone size ratio = 2/3

Conal radii: **rhoin, rhoout** – directly not measurable
unknown: Dipole tilt alpha, sightline distance from beam center beta

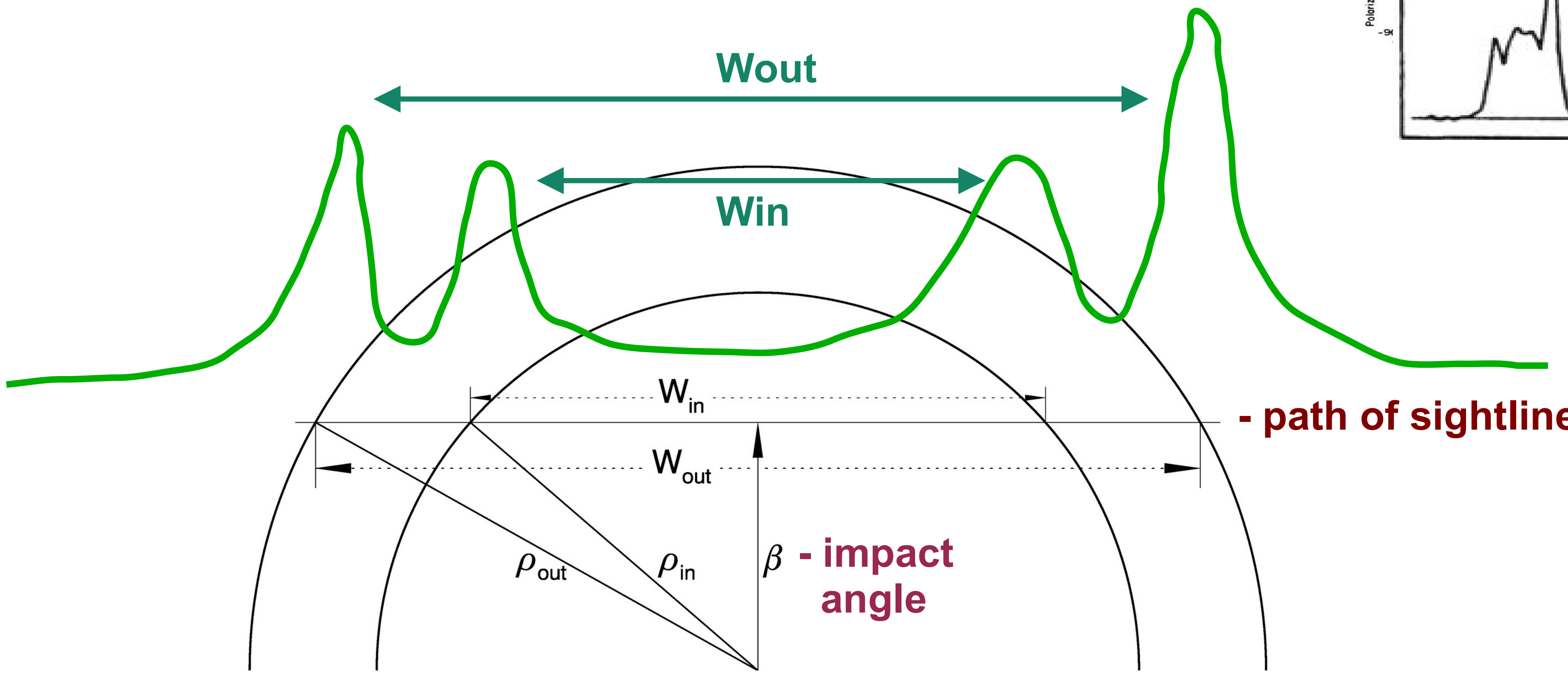


Peak-to-peak separations (widths): **Win, Wout** - directly measurable
for inner and outer pair of components.



Measure the **RATIO** of the widths: **Rw = Win / Wout**

for all Q and M pulsars (with 4 and 5 components)

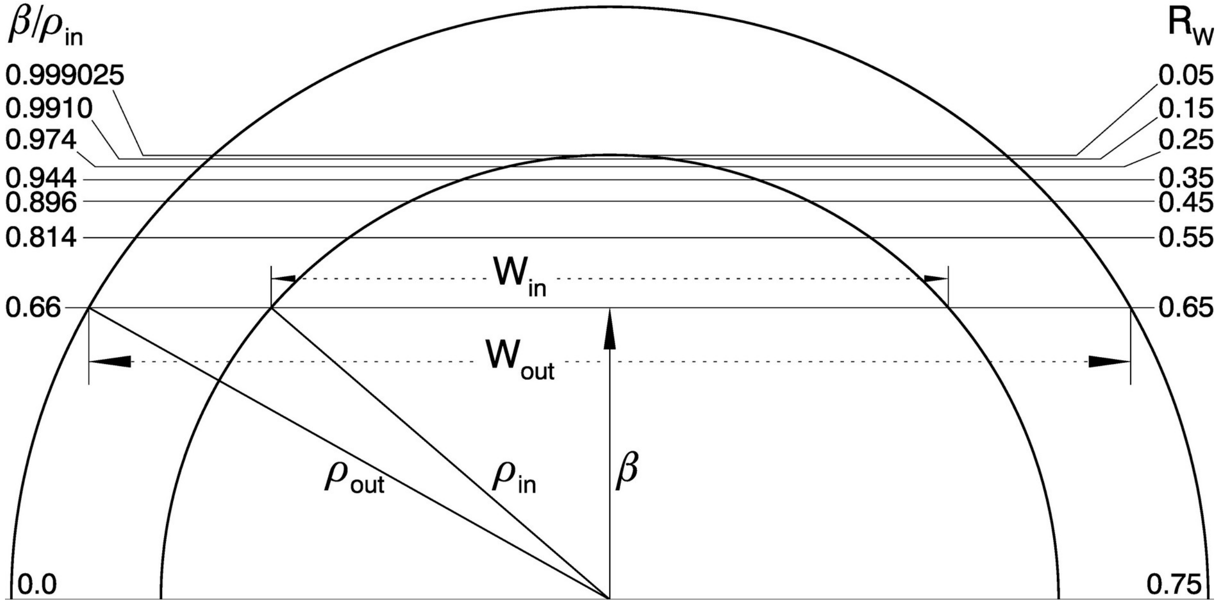


DP2015: Distribution of Rw ratio does not depend on alpha, P, r_em, nu

W_{in} = 0 when the line of sight is just grazing the inner cone
W_{in} = max for the central cut

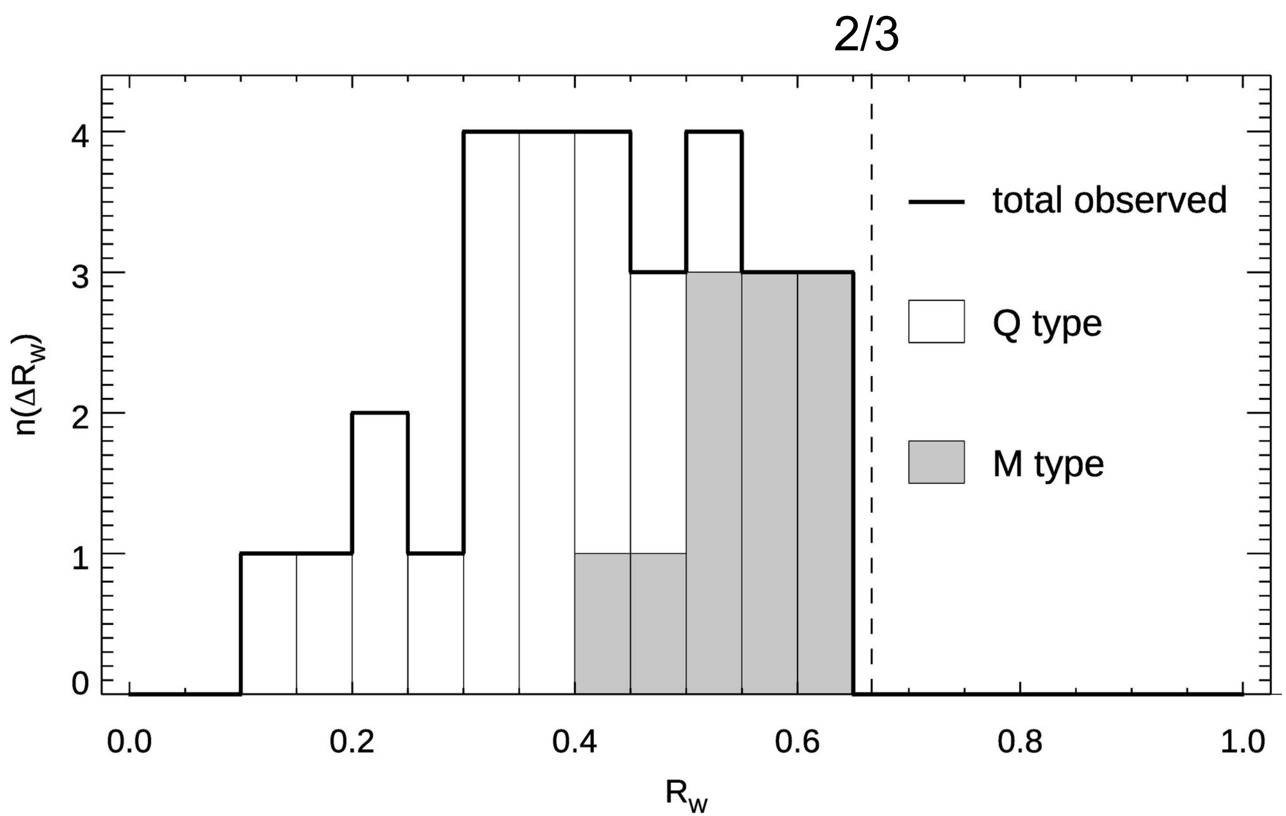
For the central traverse through the beam Rw is maximal and equal to the cone size ratio

Rw = W_in / W_out



Dyks & Pierbattista 2015

Observed Rw distribution:
(30 pulsars of Q and M type)

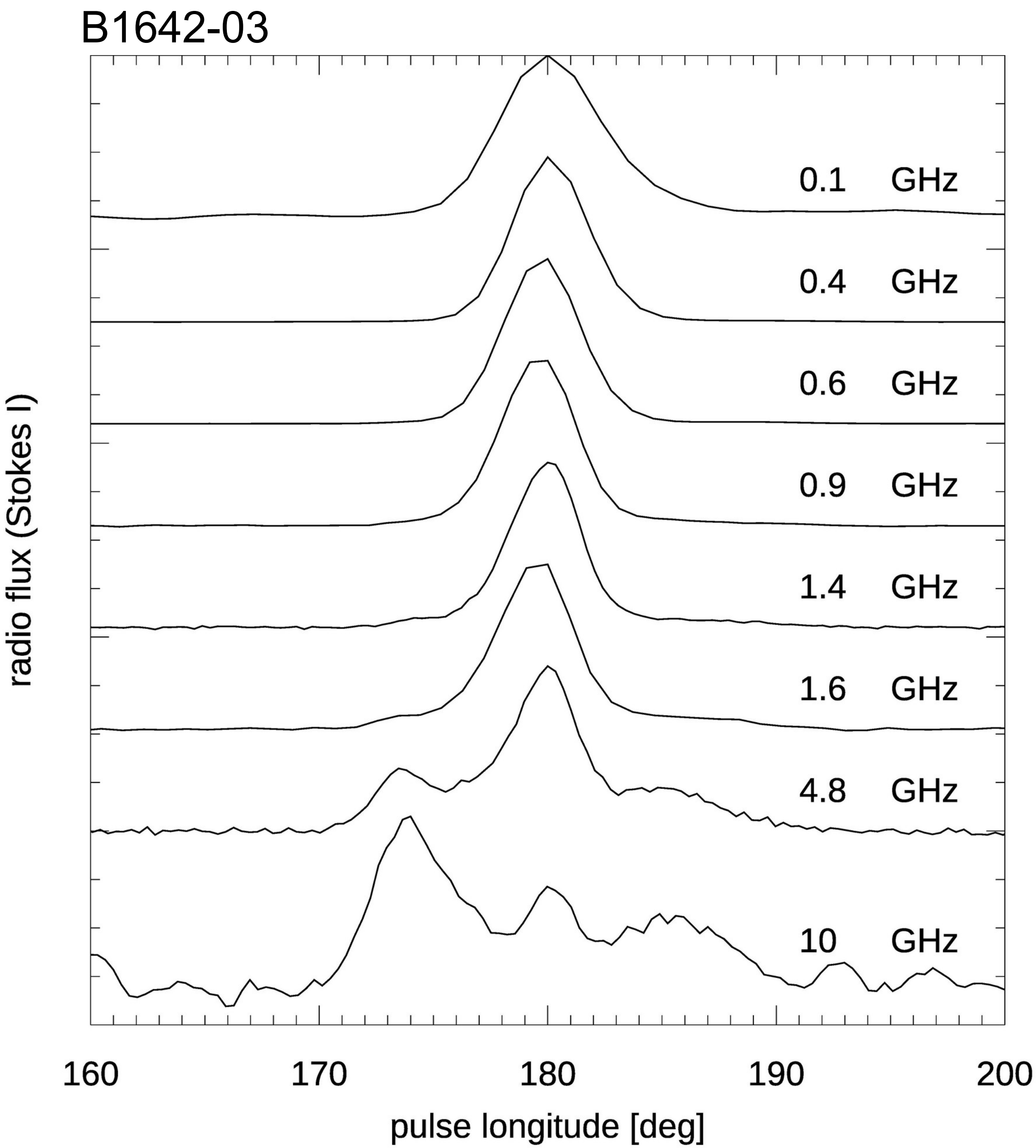


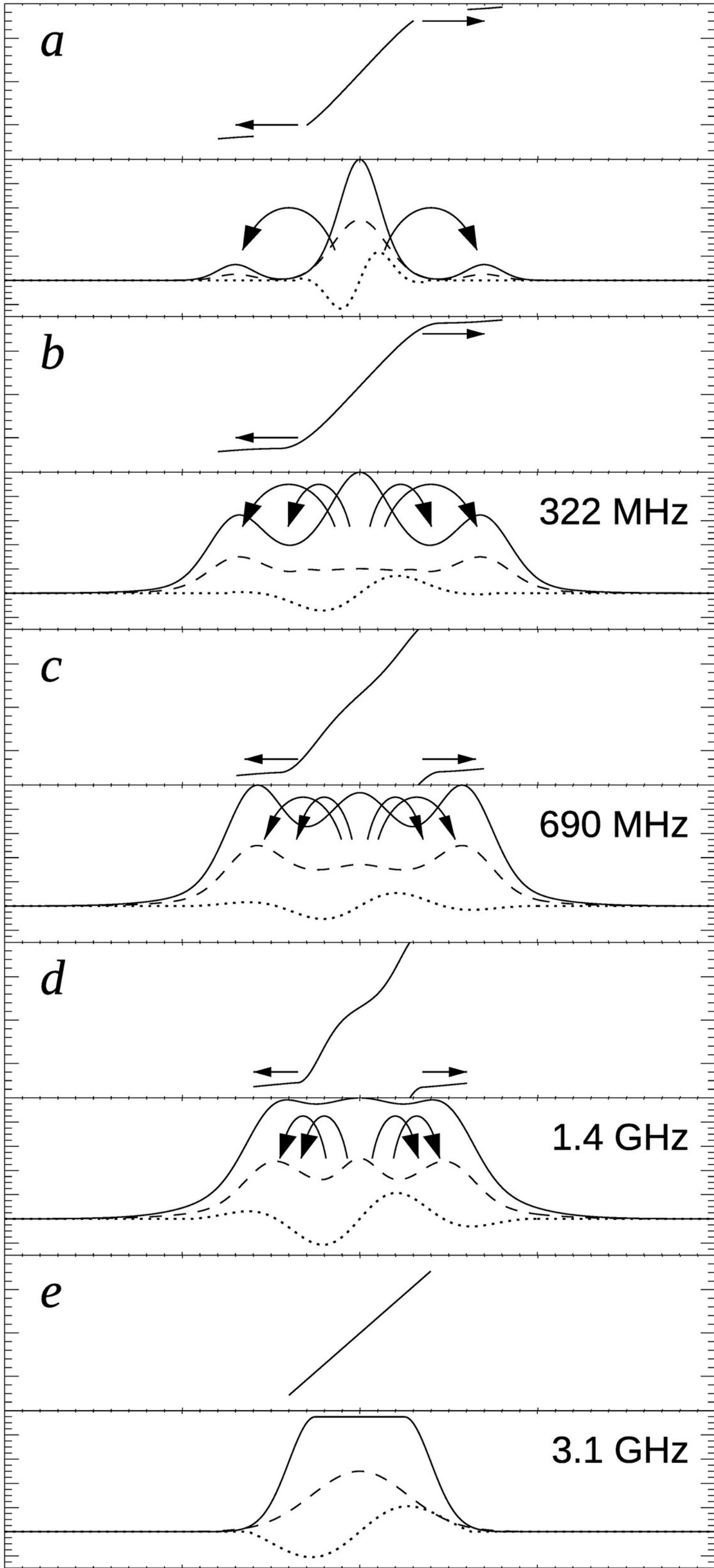
DP2015, D2023

Three objects with the maximum value = 0.63

S_t profiles: conals emerge at high nu

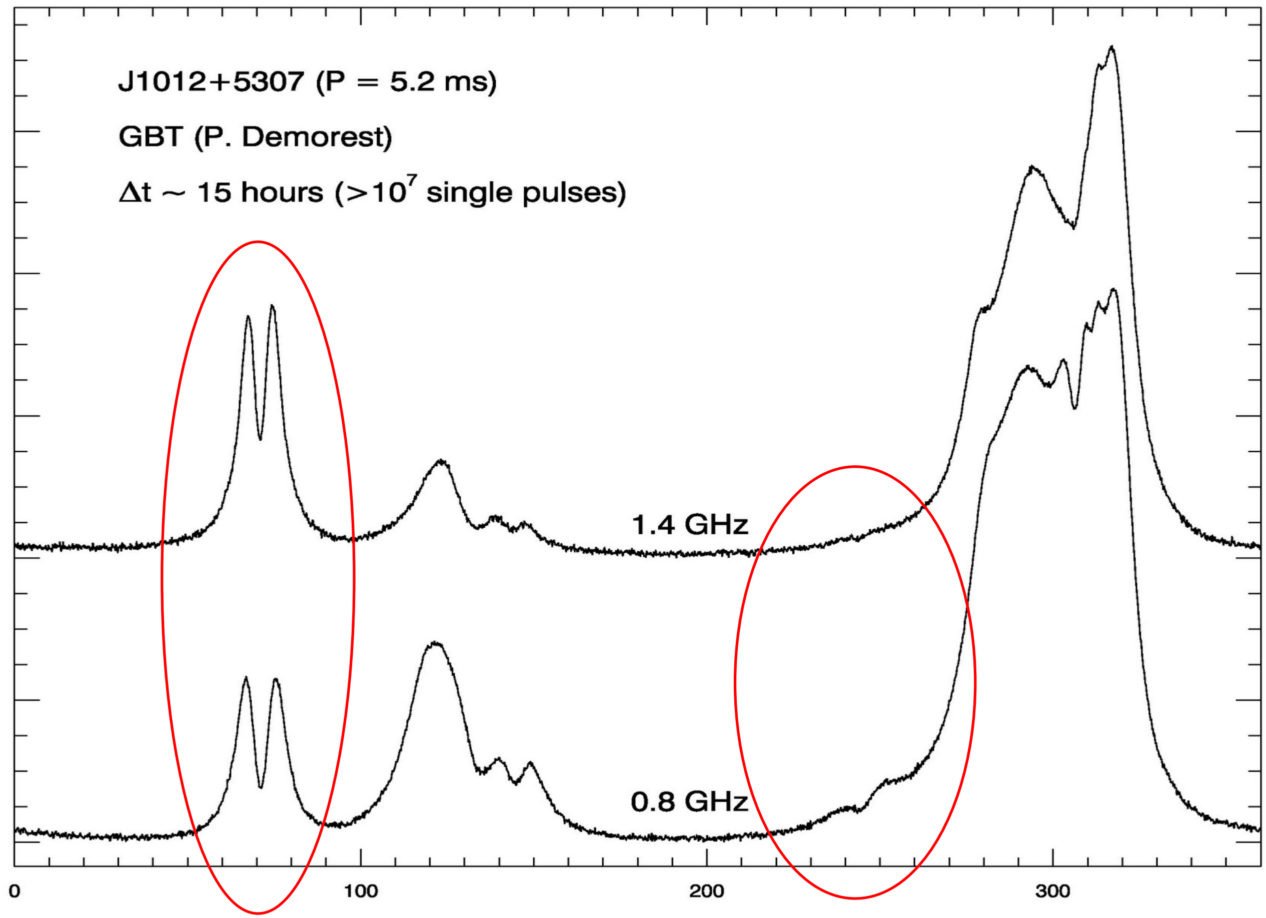
=> blueshifted by the scattering: $\nu_{obs} \sim \gamma^2 \nu_{em}$





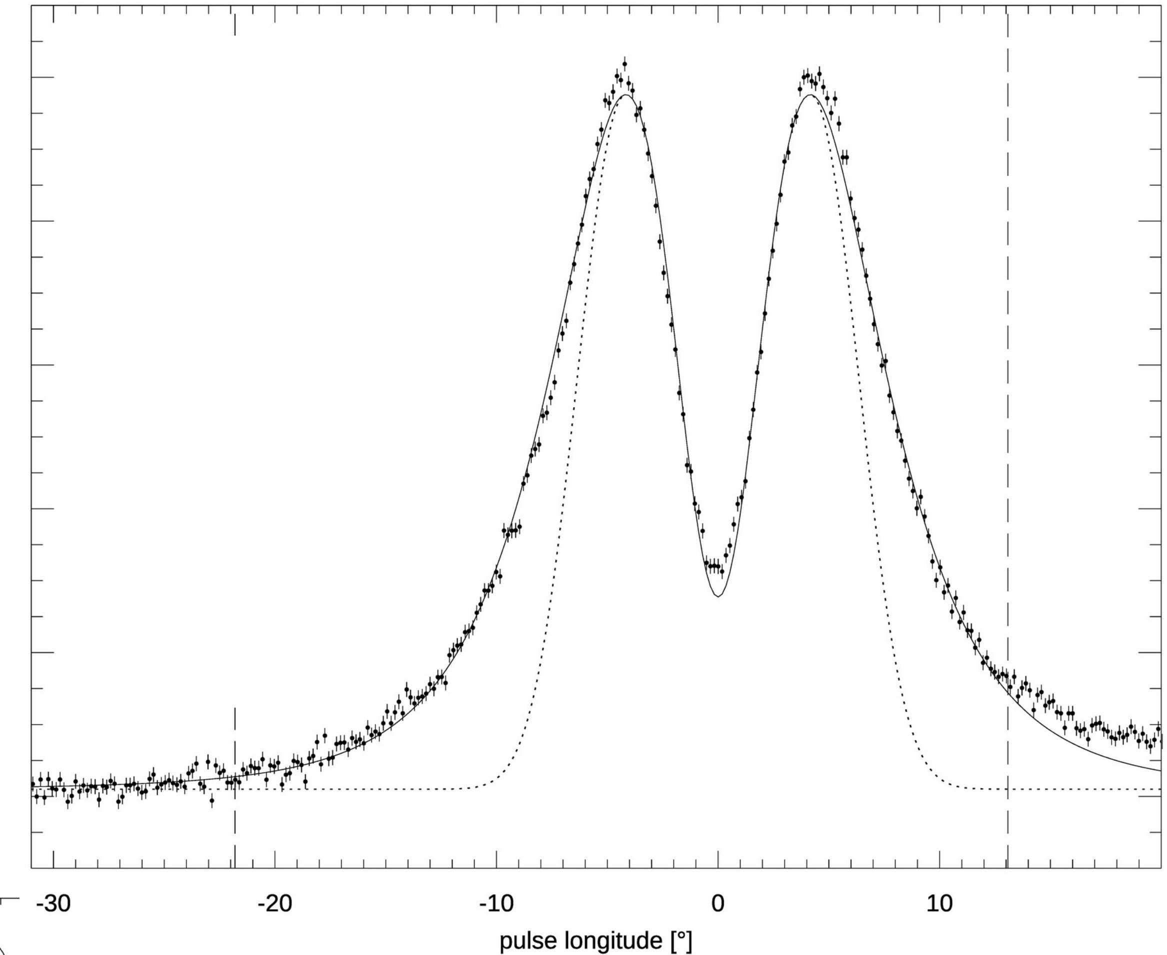
Bifurcated components (BCs)

Bifurcated components of Type 2: wide (8 deg), resolved, merging as curvature radiation microbeam (at $\nu_{obs}^{-1/3}$), shape similar to nu-integrated CR microbeam

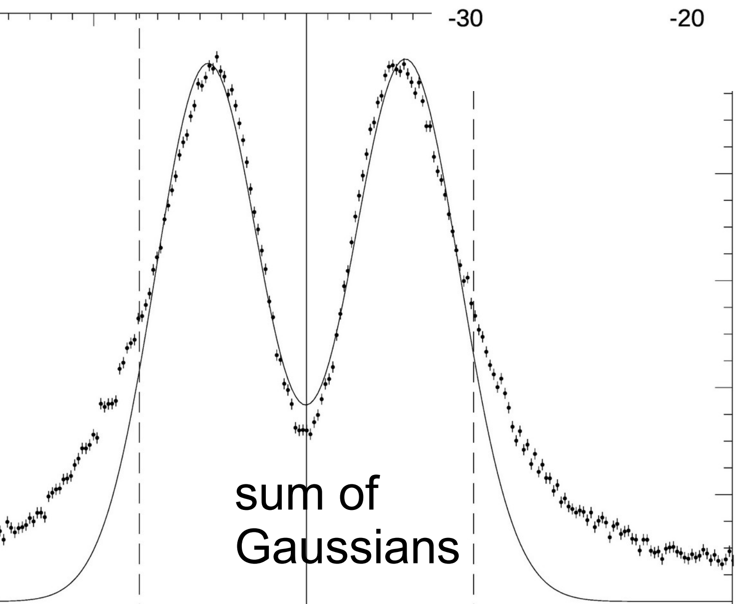


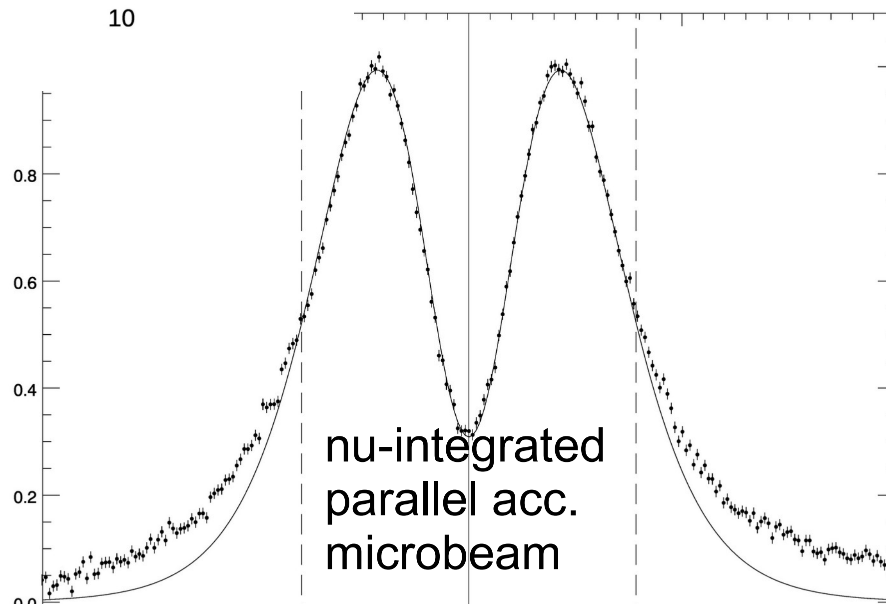
Curvature radiation microbeam directly revealed in average pulse profile**?**

Nu-resolved BC is well modelled by **nu-integrated** CR microbeam



chi2/dof=3.6





Why **nu-integrated** beam almost reproduces the **nu-resolved** BC?

Why observed BC **ten times wider** than expected?

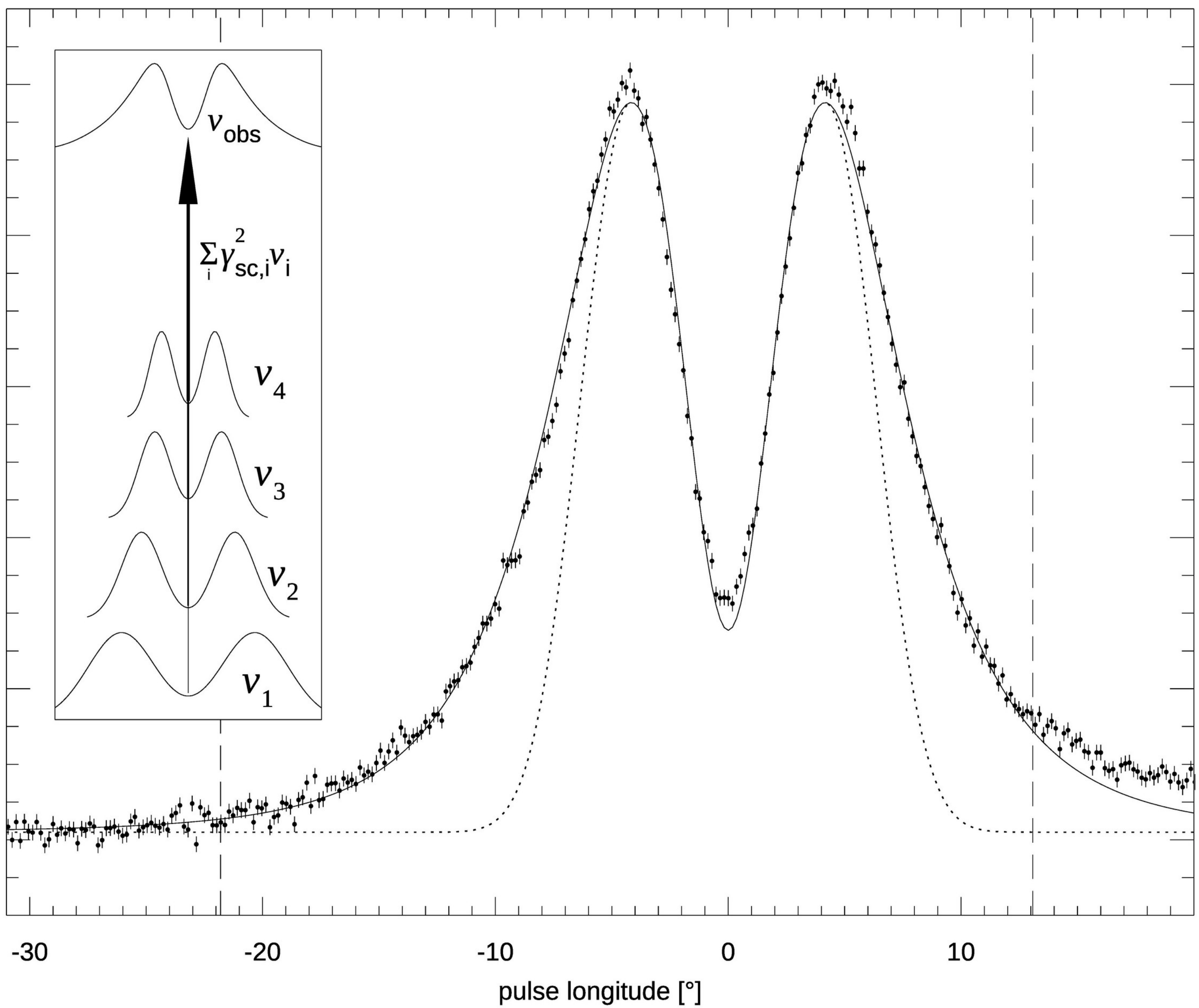
CR microbeam size:

$$\Delta \simeq \frac{0.8^{\circ}}{\nu^{1/3}\,\rho_7^{1/3}\,\sin\delta_{cut}\,\sin\xi}$$

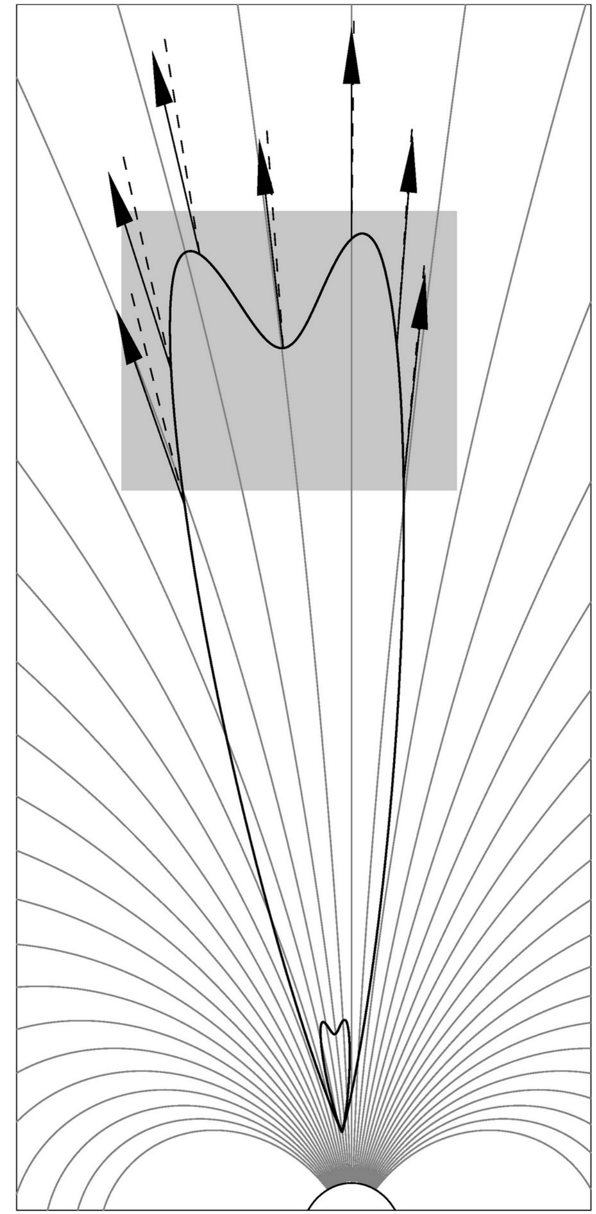
Observed: 8 deg

Spectral stacking: $\nu_{obs} = \gamma_i^2 \nu_{em,i}$

=> for each nu_em there exists such gamma that the scattered radiation reaches the same narrow observed frequency band



Microbeam copying through the **ray-to-ray scattering**



Different rays are **locally scattered** along local velocity, but the scattered flux is proportional to the incident flux

=> the microbeam is transported to high frequency with the wide low-nu width preserved

New phenomenon: **Doppler magnification**

(transportation of intensity pattern in the frequency space)

Shock: the sacred **relativistic beaming formula:**

Δ = 1/gamma

is not always applicable!

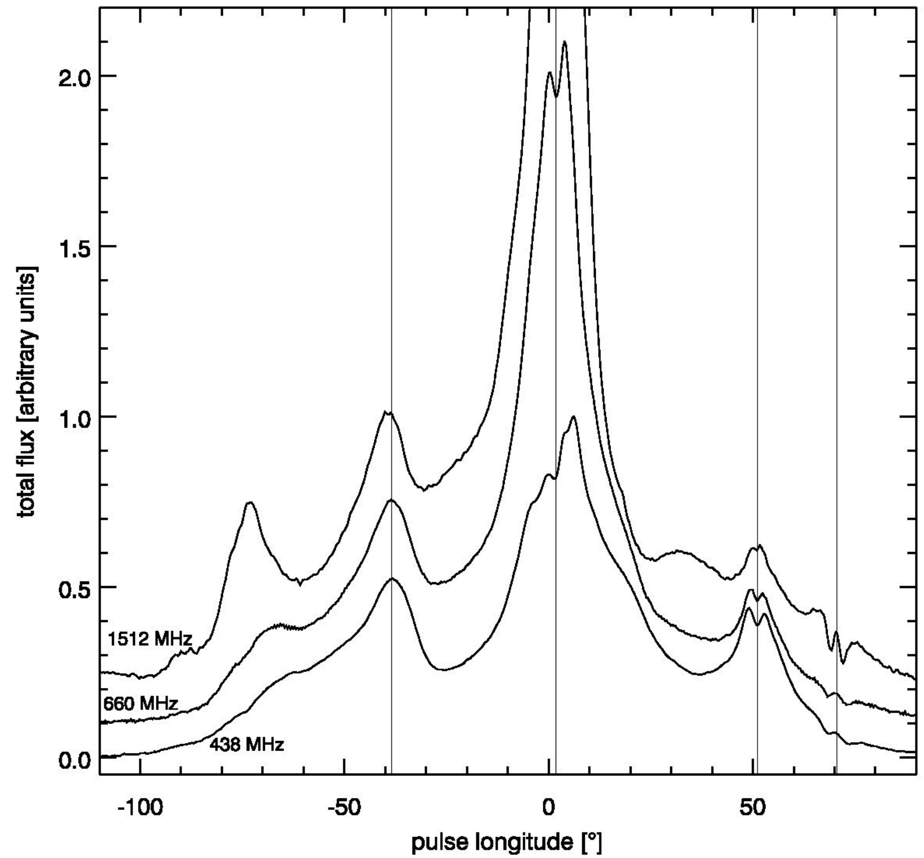
Bifurcated components (BCs):

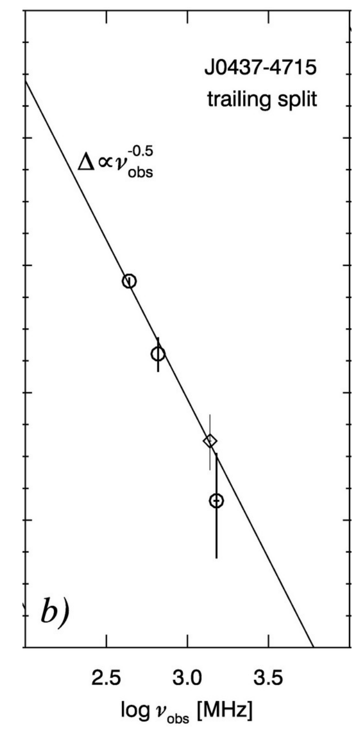
Type 1: narrow, blurred and merging at $\nu_{obs}^{-1/2}$

Scattering: $\nu_{obs} \sim \gamma^2 \nu_{em}$

microbeam width: $\Delta \sim \frac{1}{\gamma}$

=> $\Delta \sim \nu_{obs}^{-1/2}$





This is scattering in the limit of narrow spread of electron velocity directions

Conclusions

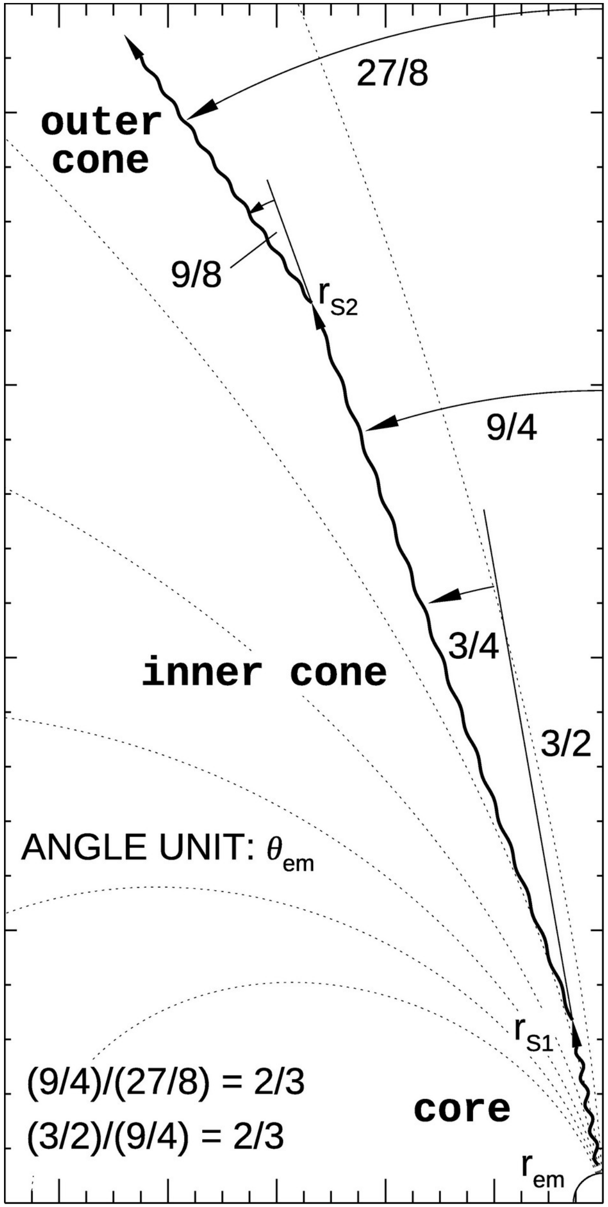
The radio emission mechanism is ICS of CR (curvature-self-Compton radiation)

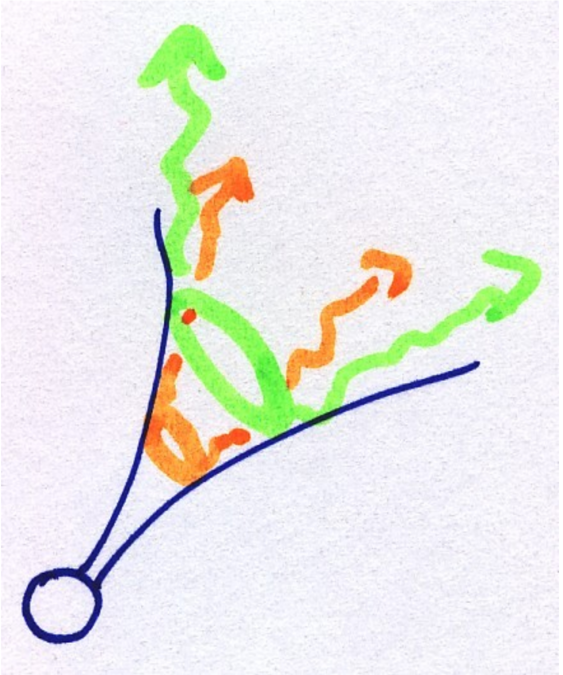
Scattering can explain:
- nested cones of appropriate size ratio
- some types of radius-to-frequency mapping
- bifurcated components
  - much wider than expected at 1 GHz
  - with nu-integrated shape
  - merging with nu at the rate of -1/2
- makes the energy requirements much lower (a few orders of magnitude)

CR microbeam explains:
- the look and nu-dependence (narrowing at -1/3) of BCs

Shocking news: 1/gamma not always applicable
because the microbeam pattern can be Doppler-shifted in frequency

Outer cone emission from higher r than inner cone (which is higher than core)

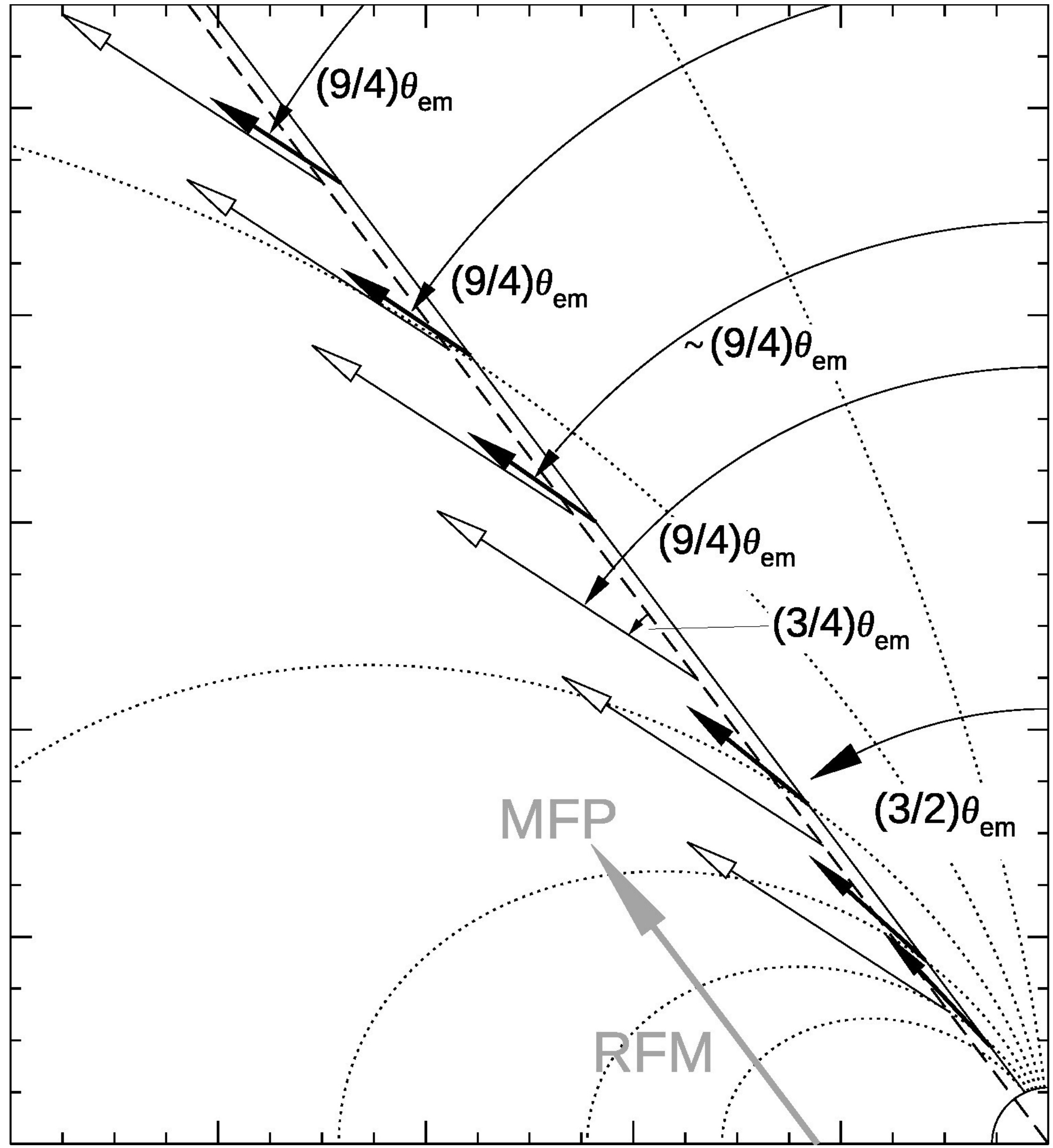




Separated emission rings invoked from the core lag interpreted as the aberration and retardation effect
(Gangadhara & Gupta 2001)

The levitating rings = average regions of scattering of different orders

Previous figures superposed:
- for arbitrary MFP the rays are scattered at the same angle (3/2)theta_i
- recursive argument => cone size ratio = 2/3 (inner to outer)



Far from origin any line is radial

(approximately)

Short-MFP scattering at no special angle => boxy profiles