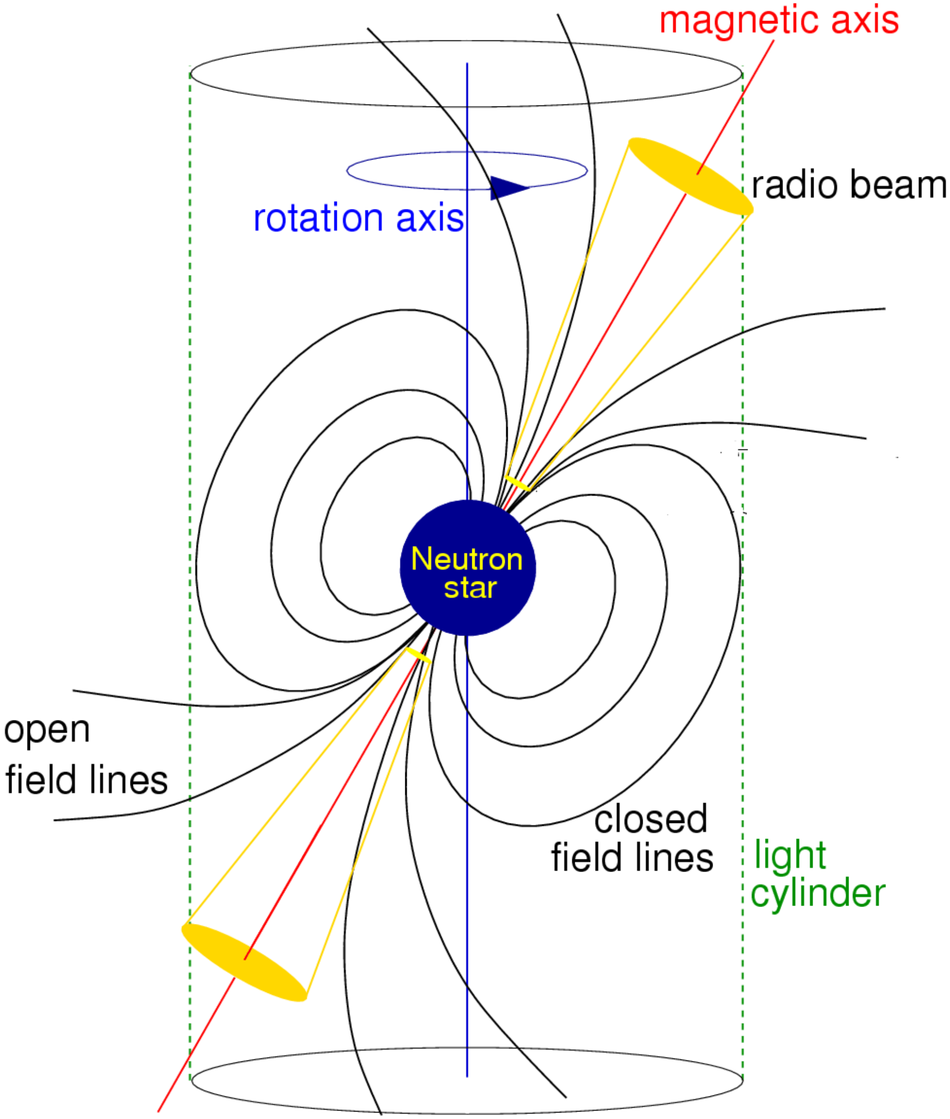
LOFAR's view on B0943+10

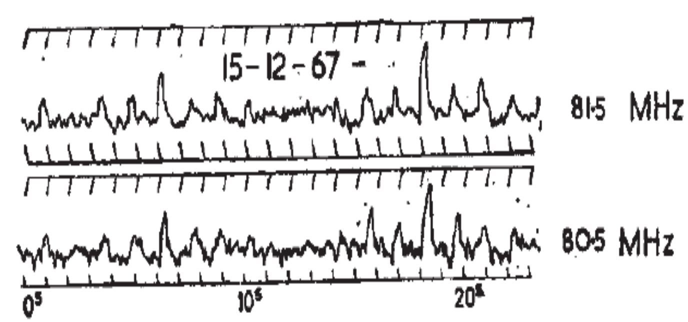
Anya Bilous, Radboud Universiteit Nijmegen

& LOFAR Pulsar Working Group

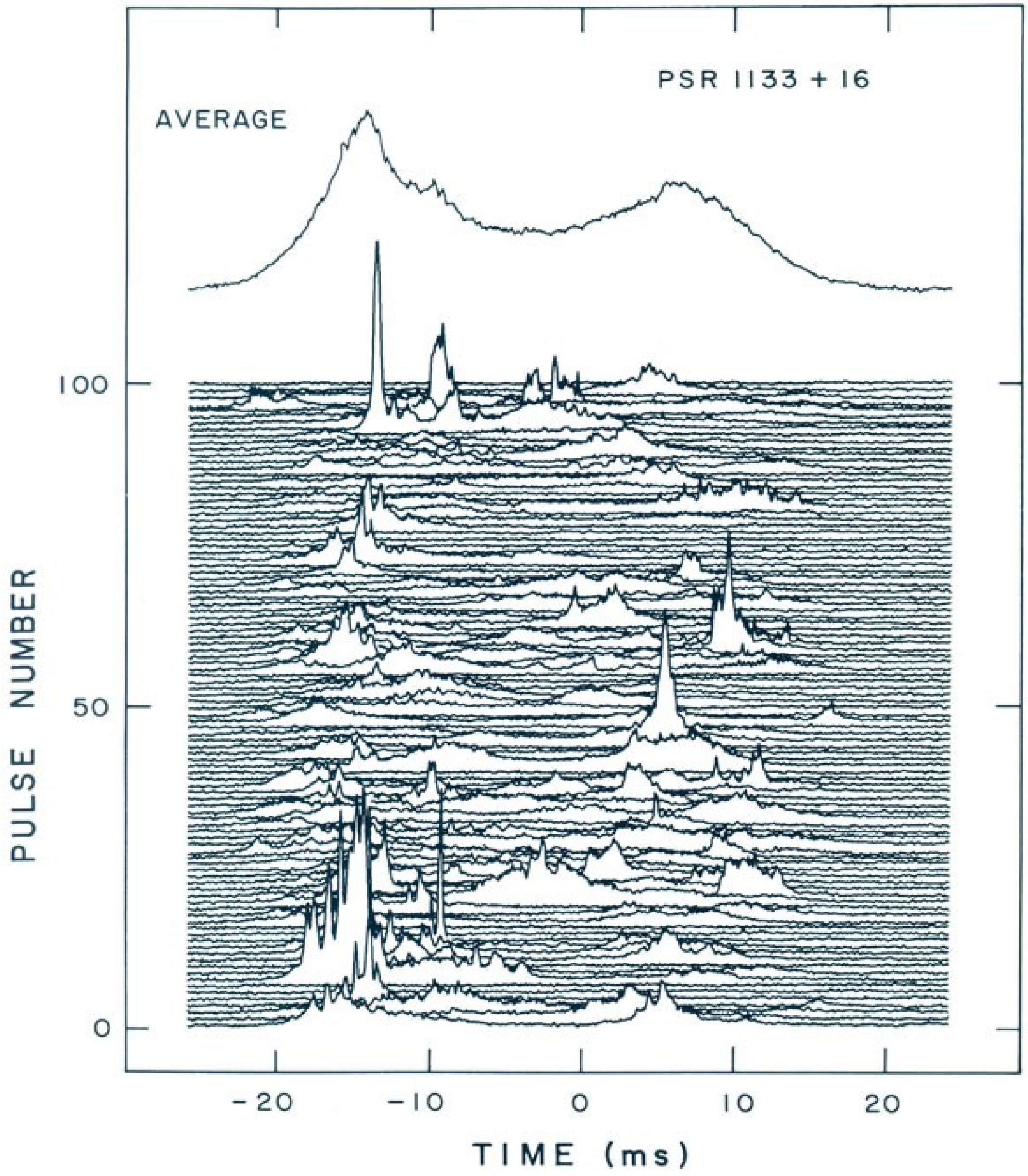
A pulsar:



- Rapidly rotating ball of neutrons
- Strong magnetic field (dipolar)
- Spin and magnetic axes misaligned
- Magnetosphere: particles move along field lines and rotate rigidly with the star
- Light cylinder v_rot = c
- Open field lines – do not close within light cylinder
- Radio pulses: lighthouse effect



Hewish et al, 1968

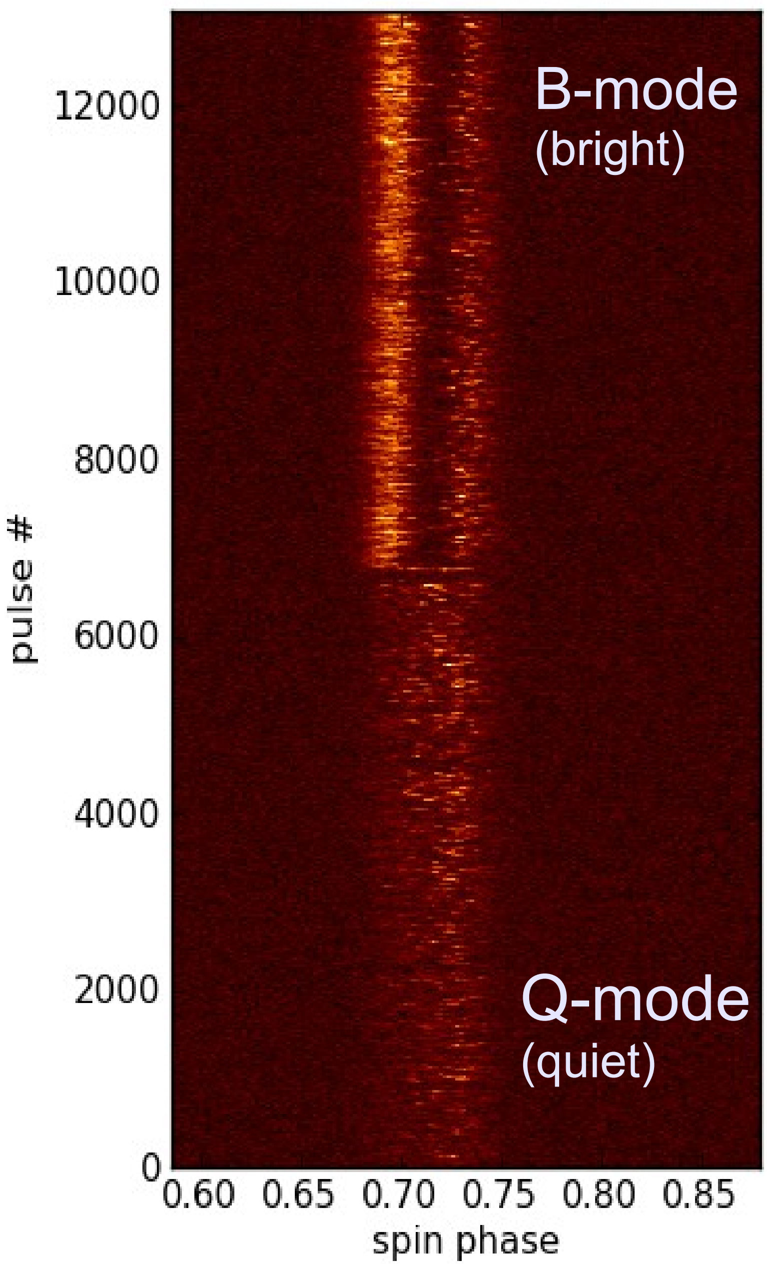


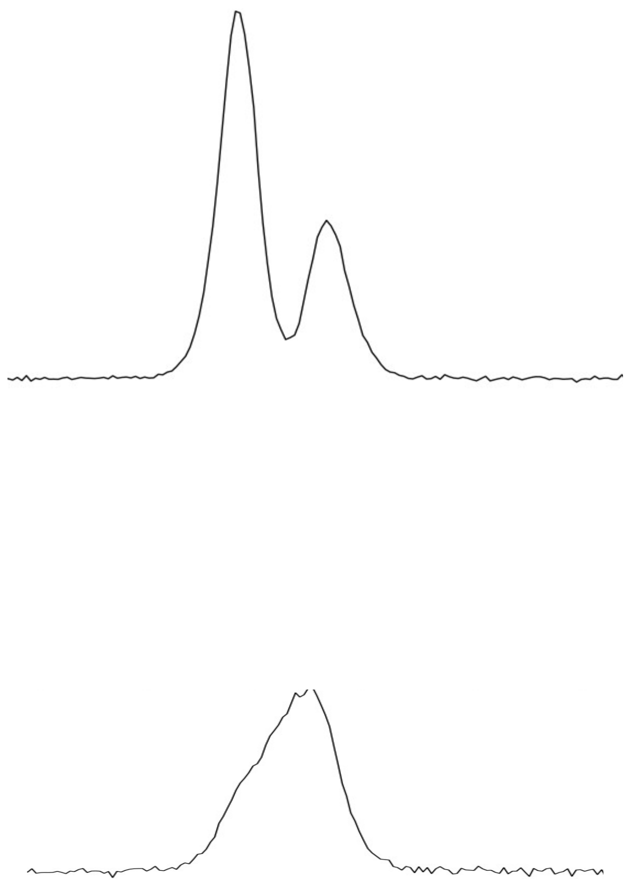
Average profile – stable in time, unique for each pulsar...

But not always!

Mode changing: some pulsars have 2 stable average profiles

Two faces of PSR B0943+10:



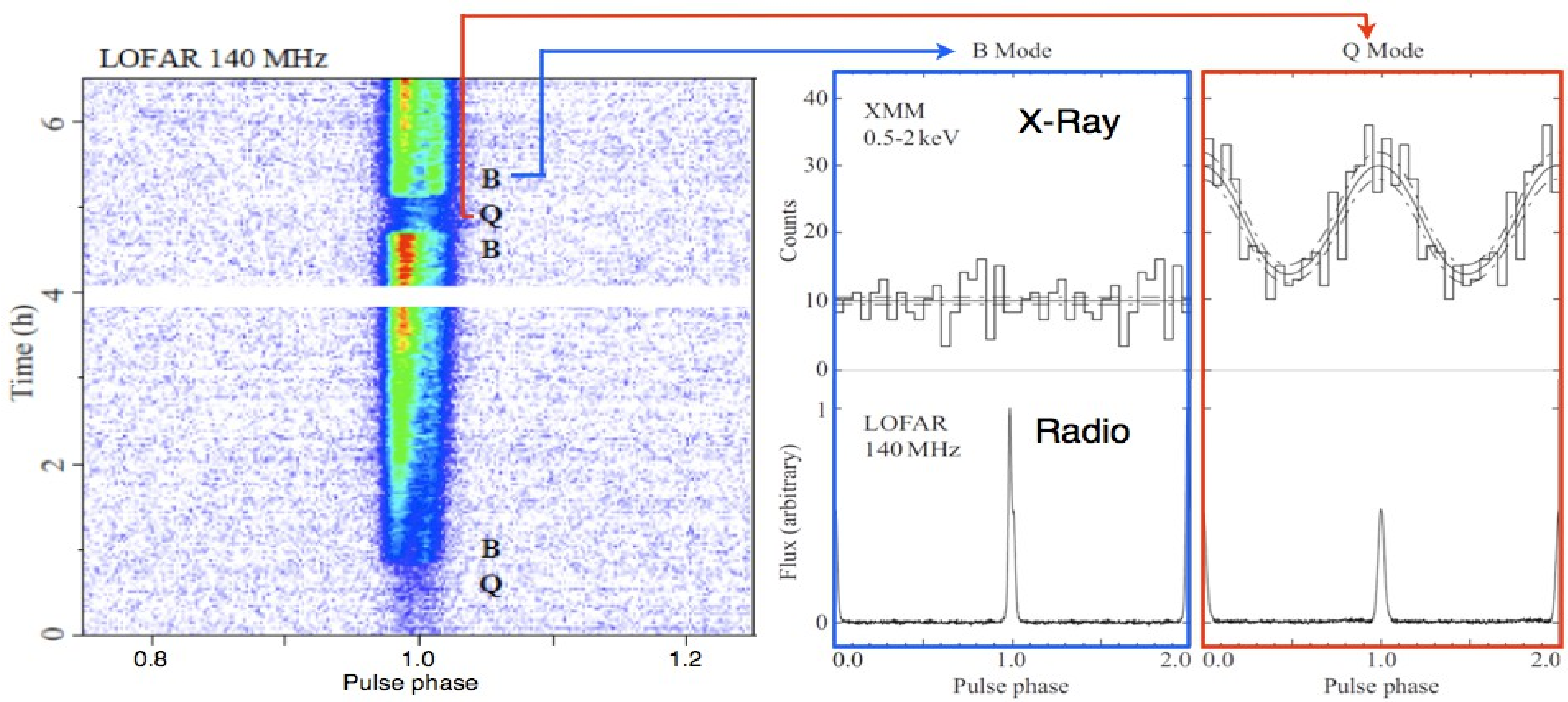


- Different average profiles
- Different single pulses
- Abrupt switch (~1 spin period)
- Manifestation of some global reorganizations in the magnetosphere

Simultaneous observations of B0943+10 in X-rays and radio

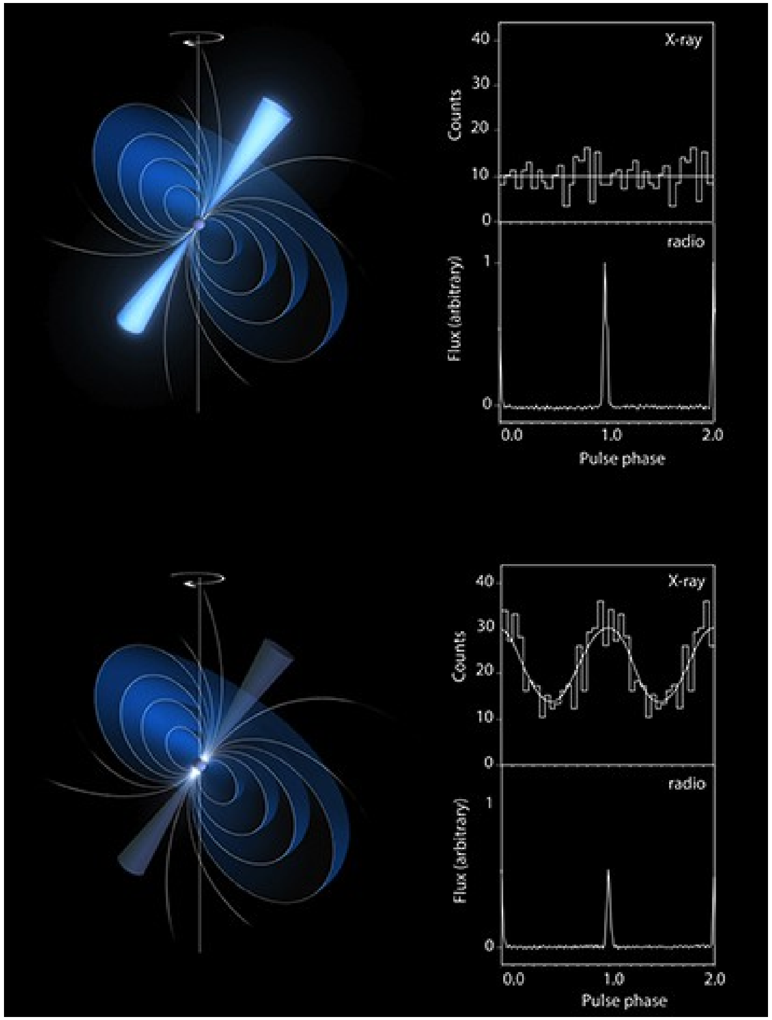
B-mode: bright radio — No thermal X-rays

Q-mode: faint radio — Bright thermal X-rays



Hermsen et al 2013

So what is going on?

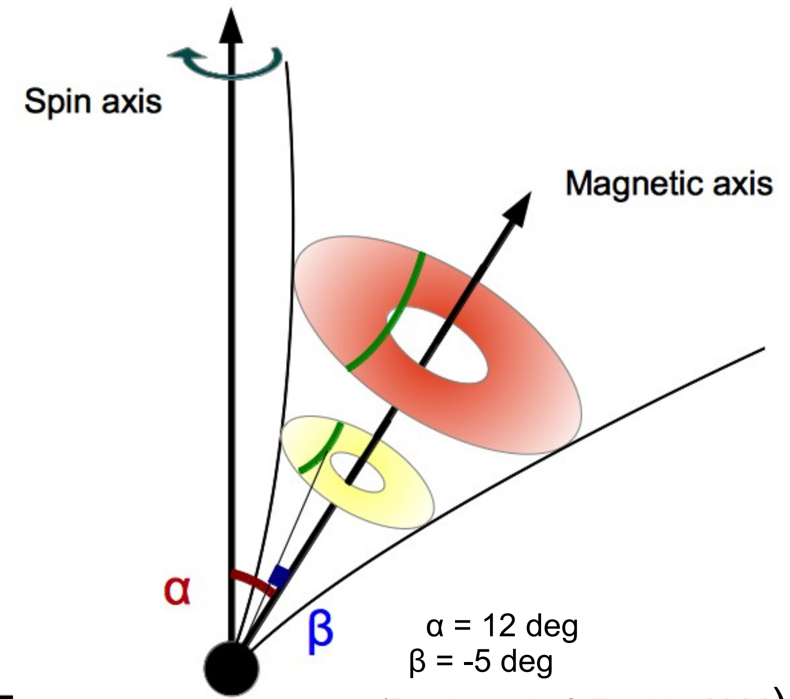


Which parts of the magnetosphere are active in radio in B and Q modes?

http://sci.esa.int/xmm-newton/51320-the-two-states-of-pulsar-psr-b0943-10-as-observed/

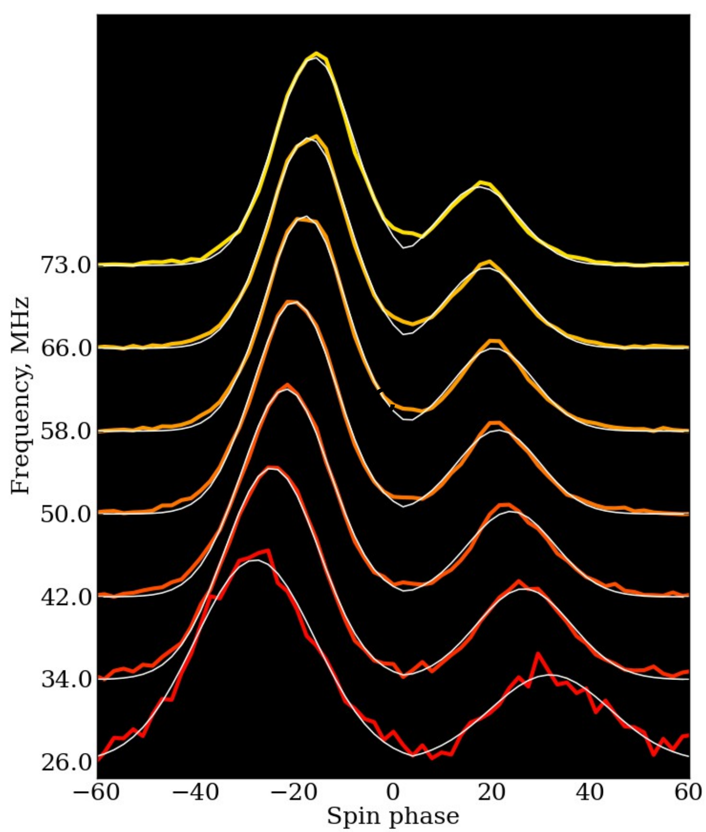
Classical approach:
Radius to frequency mapping

- Photons are emitted tangentially to field lines
- Emission at given frequency comes from a single height

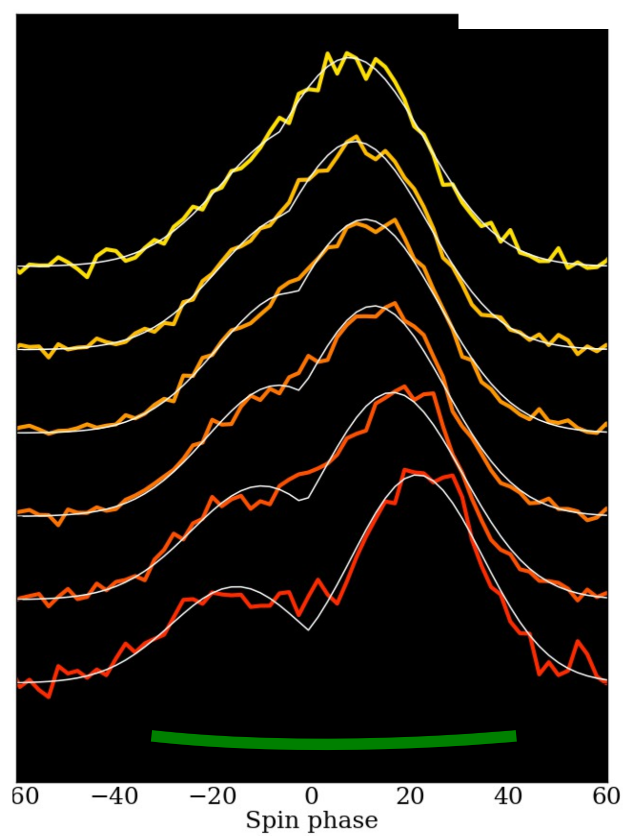


α = 12 deg
β = -5 deg
(Deshpande & Rankin 2001)

B-mode

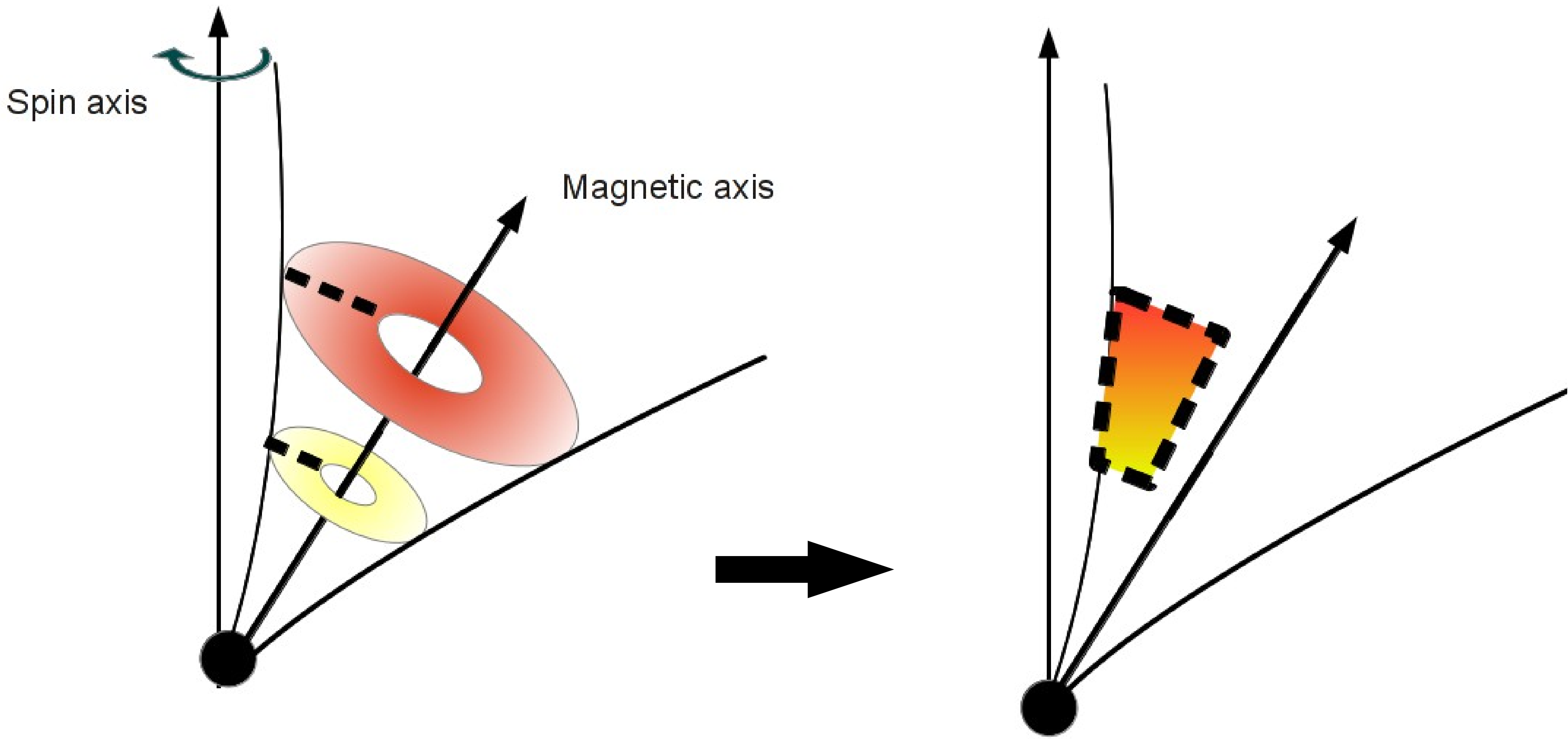


Q-mode

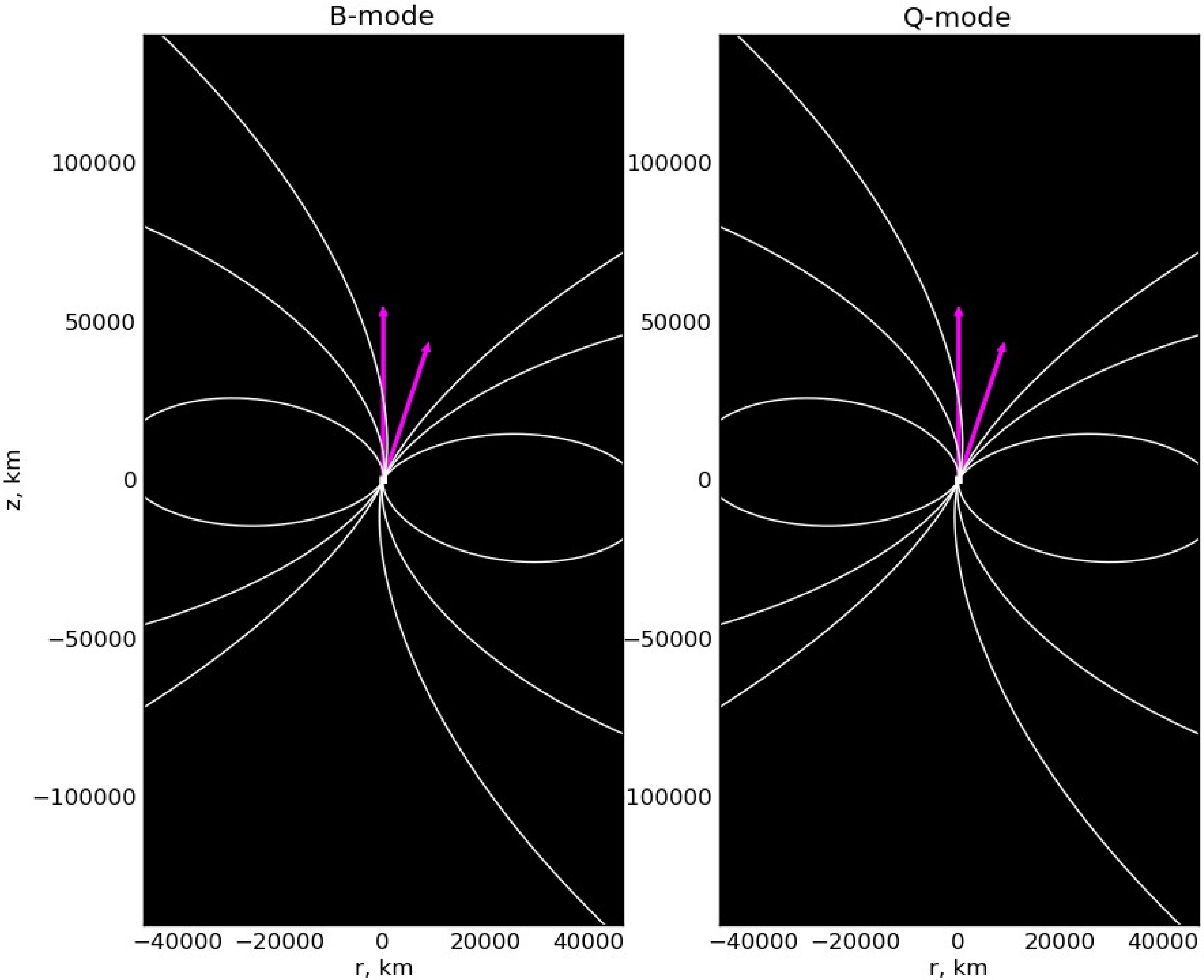


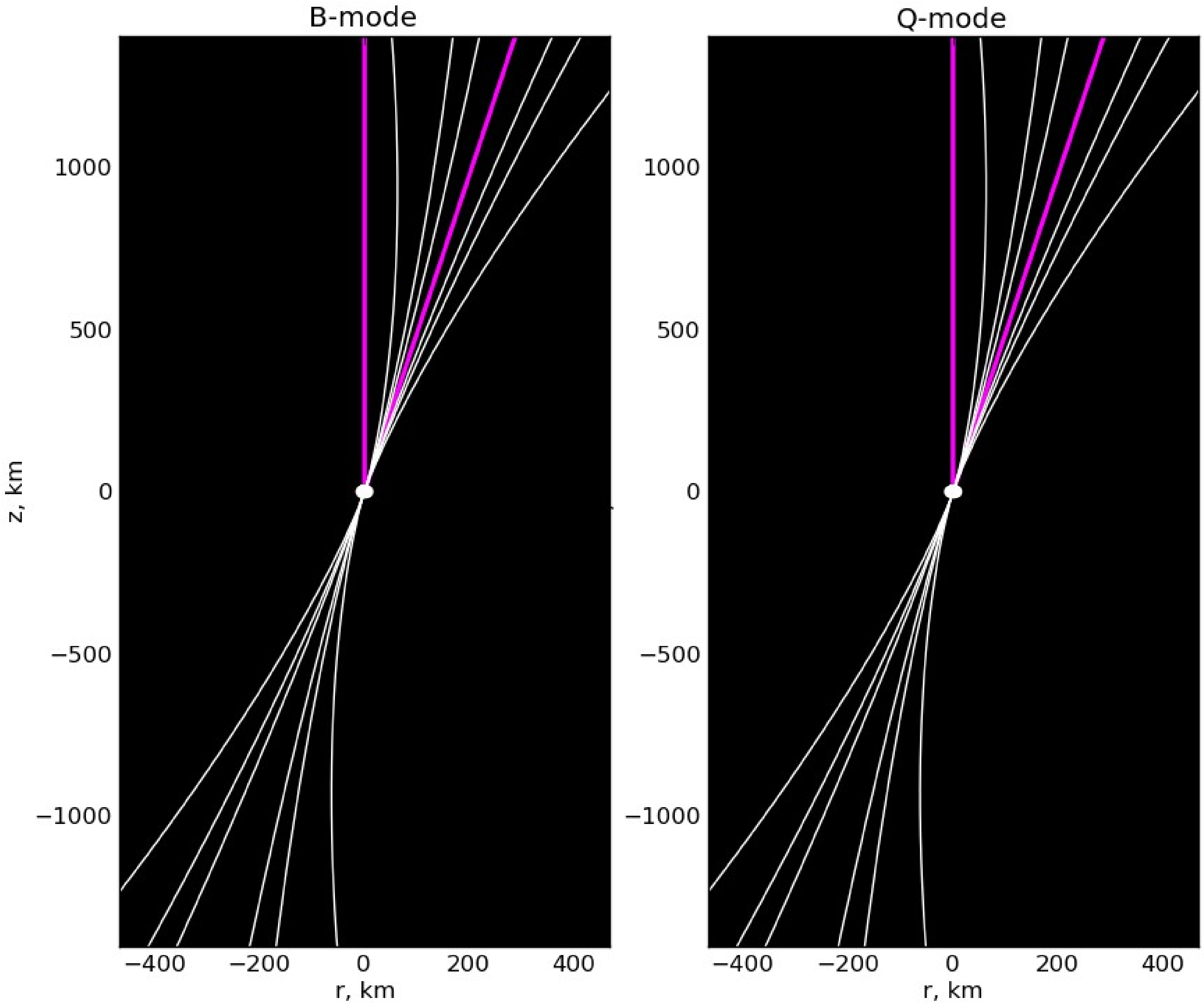
Components merge together – line of sight misses the inner edge of the emission cone

Thanks to high-quality LOFAR data!
(60x bandwidth, 100x observing time comparing to archive low-freq data from the other telescopes)

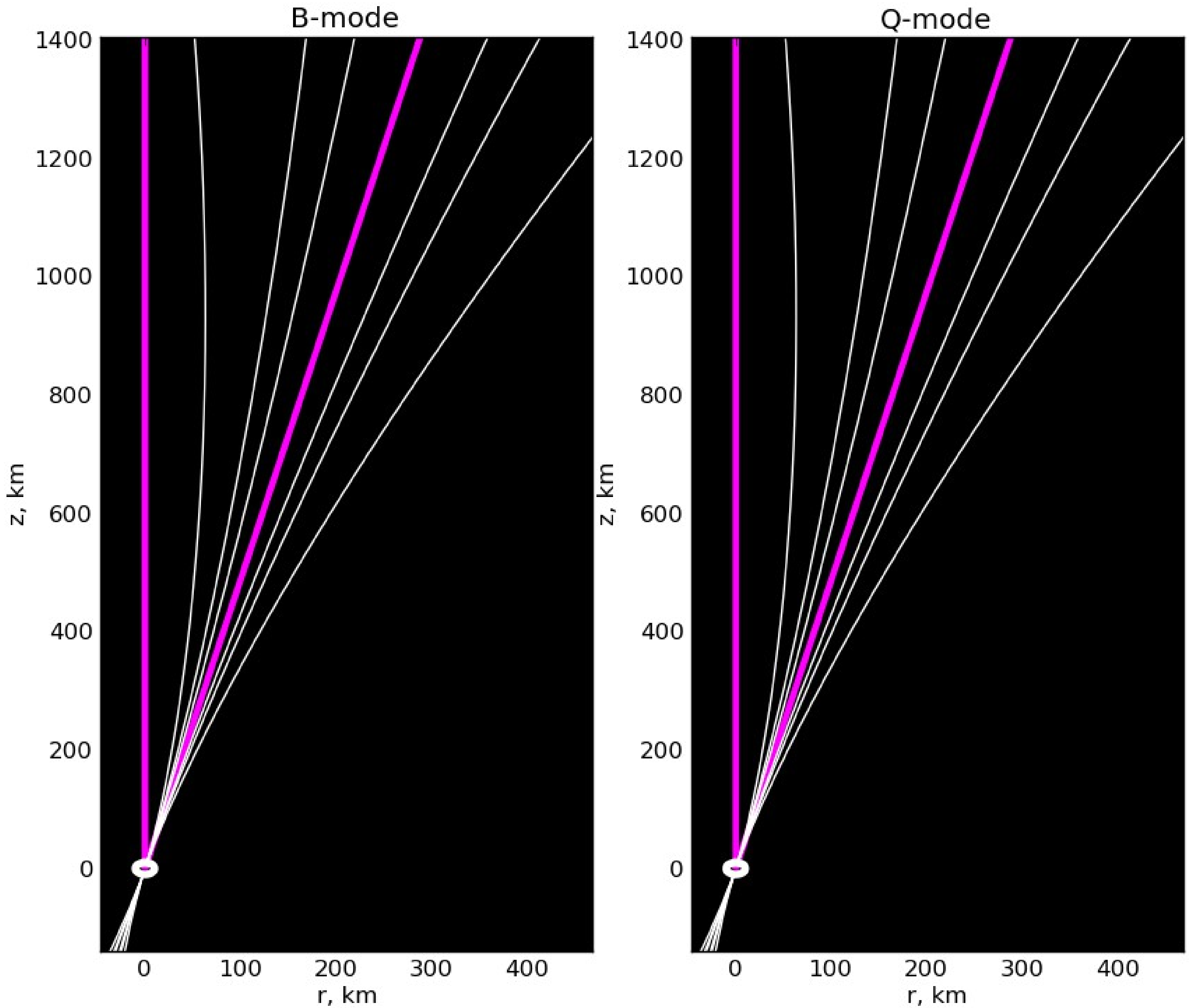


Plotting only the plane defined
by spin and magnetic axes

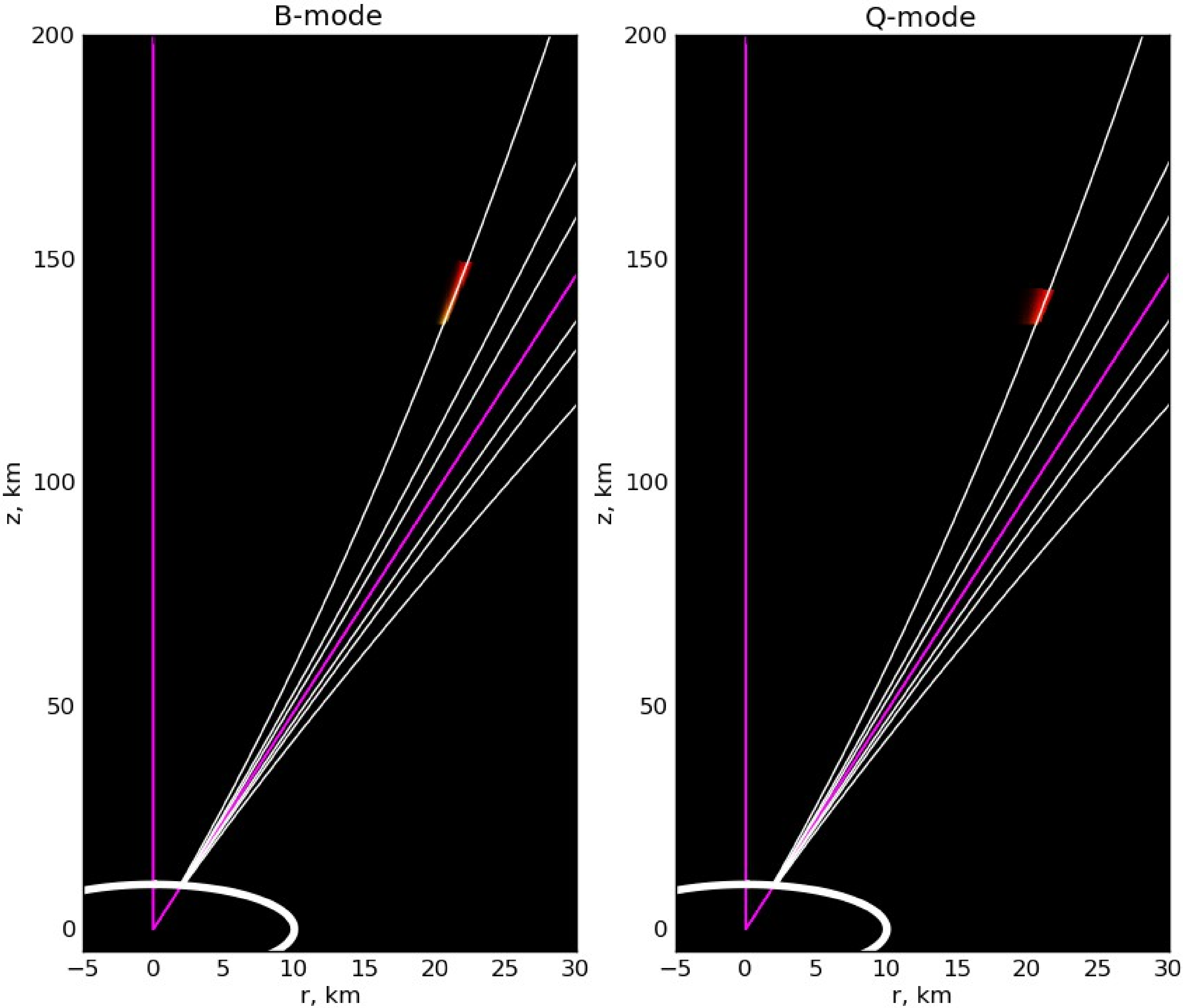

B-mode
Q-mode
100000
50000
0
−50000
−100000
z, km
−40000
−20000
0
20000
40000
r, km



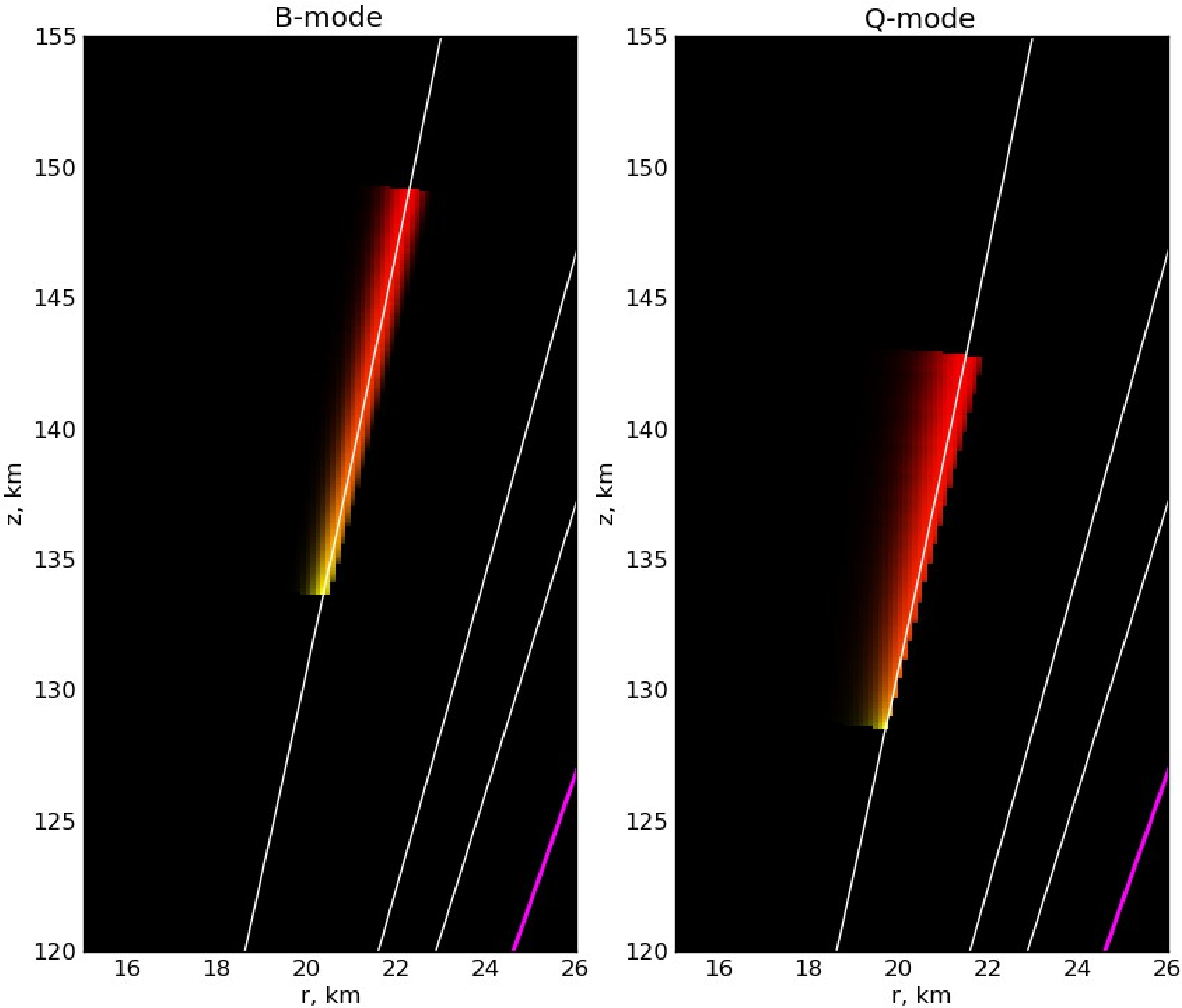
B-mode
Q-mode
z, km
r, km
r, km
1000
500
0
−500
−1000
−400
−200
0
200
400

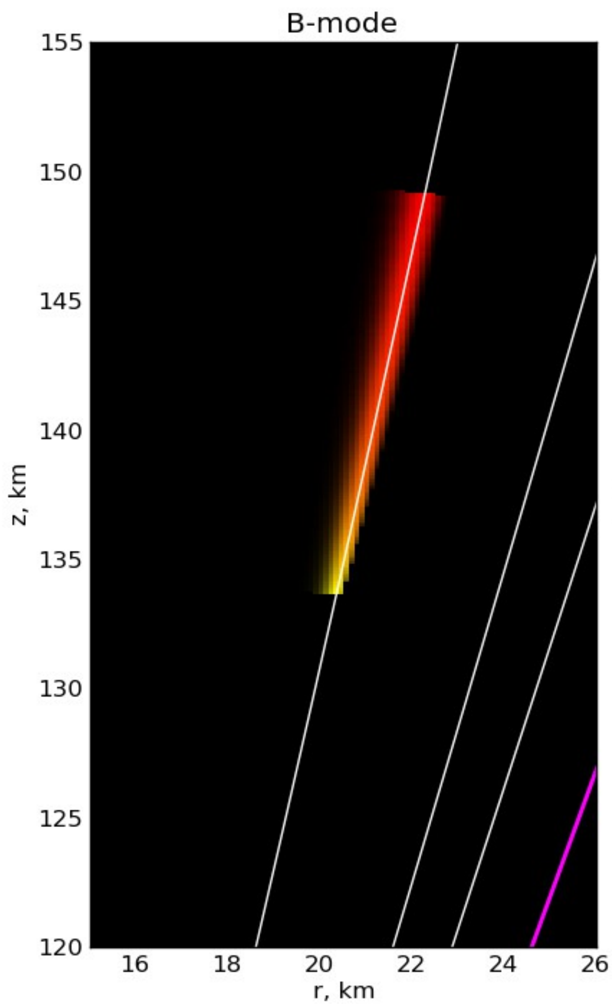


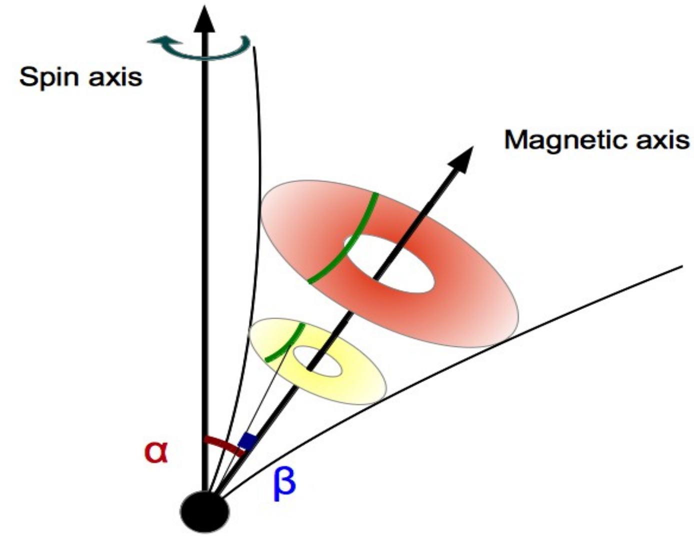
B-mode
Q-mode
z, km
r, km
1400
1200
1000
800
600
400
200
0
100
200
300
400

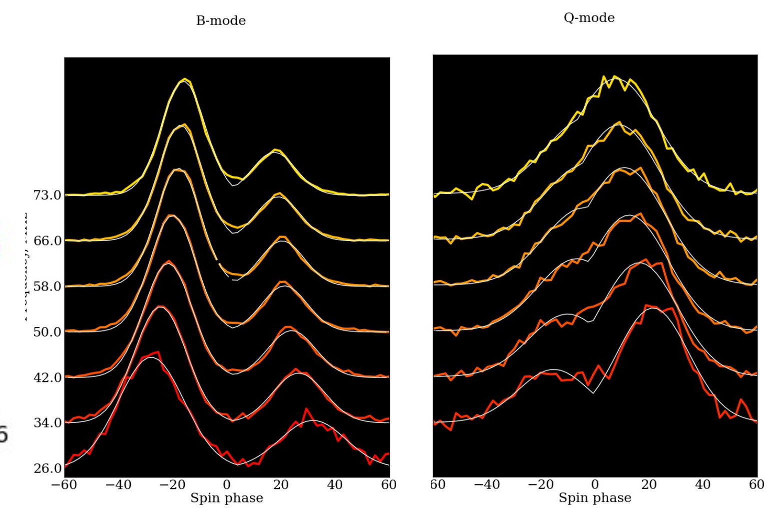


B-mode
Q-mode
z, km
r, km
200
150
100
50
0
−5
0
5
10
15
20
25
30


B-mode
Q-mode
z, km
r, km
155
150
145
140
135
130
125
120
16
18
20
22
24
26



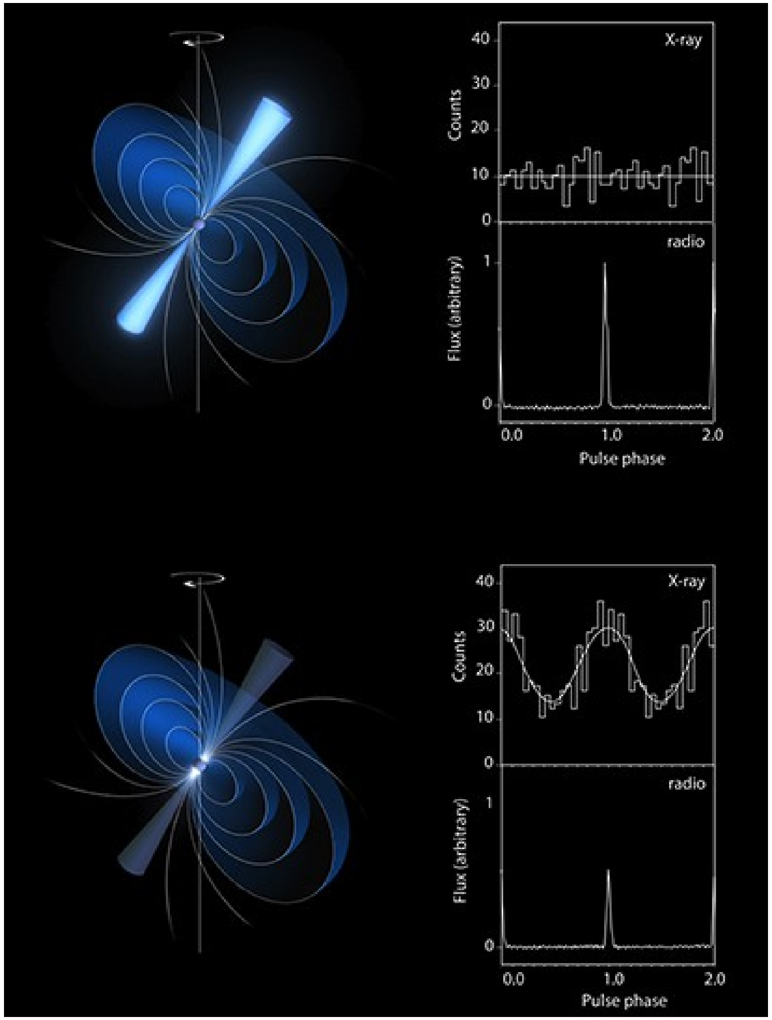




- **For both modes, emission comes from the region close to the star surface.**
- **At any frequency above 20 MHz emission heights between B and Q modes do not differ more than by 6%.**

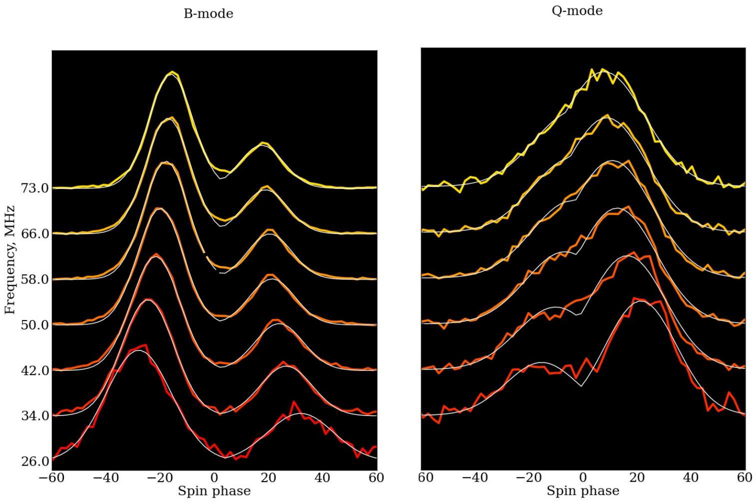
Radius of light cylinder : 52000 km
Radius of the star: 10 km

Which parts of the magnetosphere are active in radio in B and Q modes?

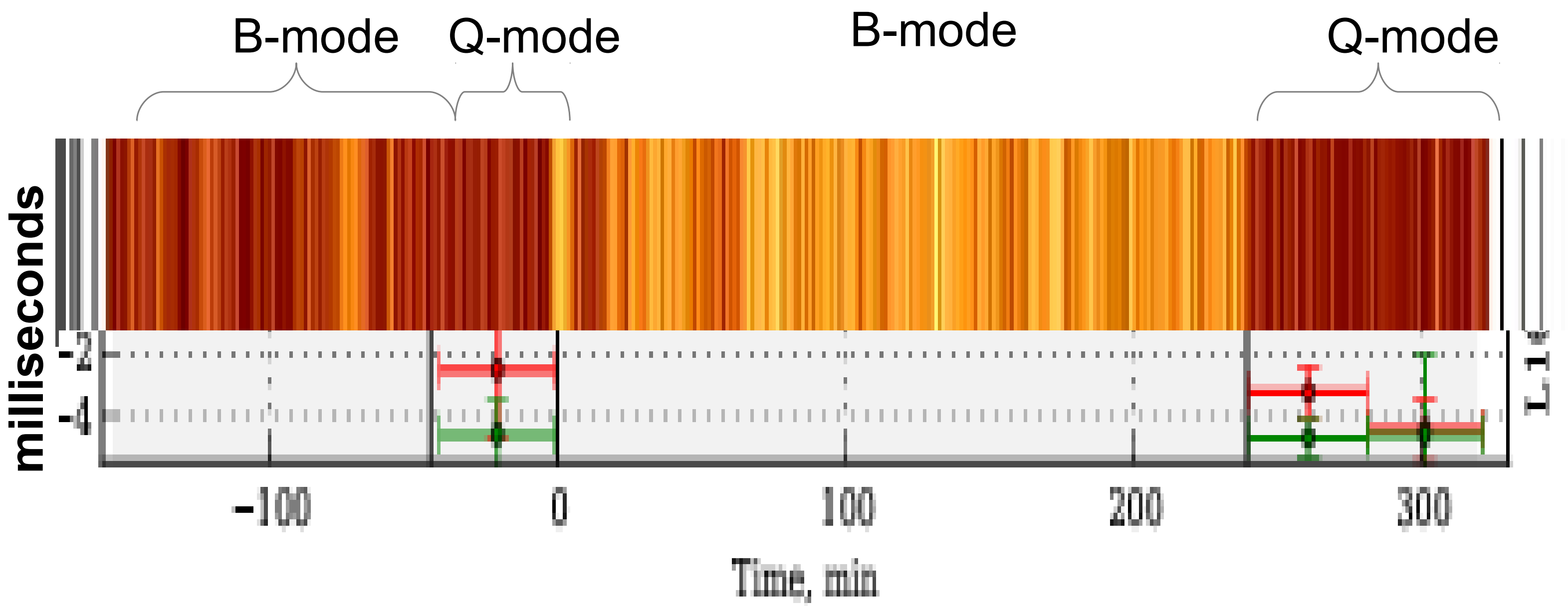


http://sci.esa.int/xmm-newton/51320-the-two-states-of-pulsar-psr-b0943-10-as-observed/

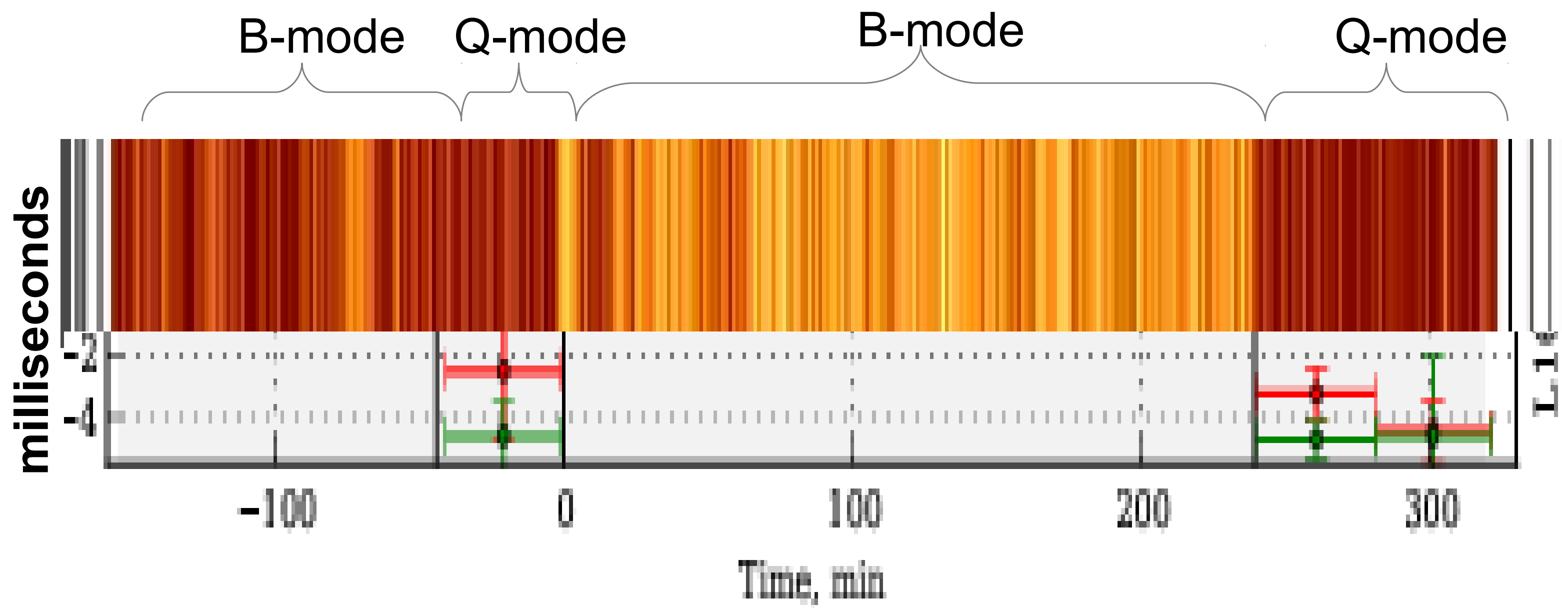
Despite the apparent differences in B and Q appearance, the emission from both modes comes from almost the same (6% difference) range of heights close to stellar surface.

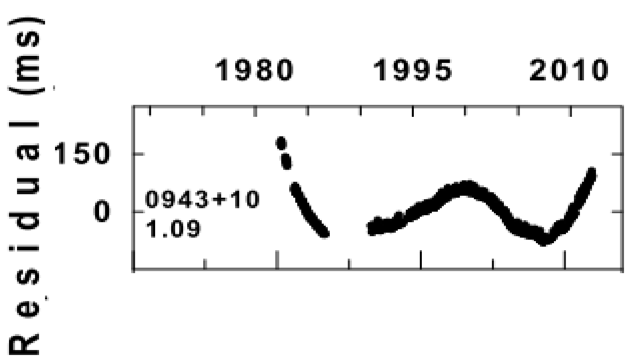


Sign of gradual global changes: systematic delay of the average profile within B-mode

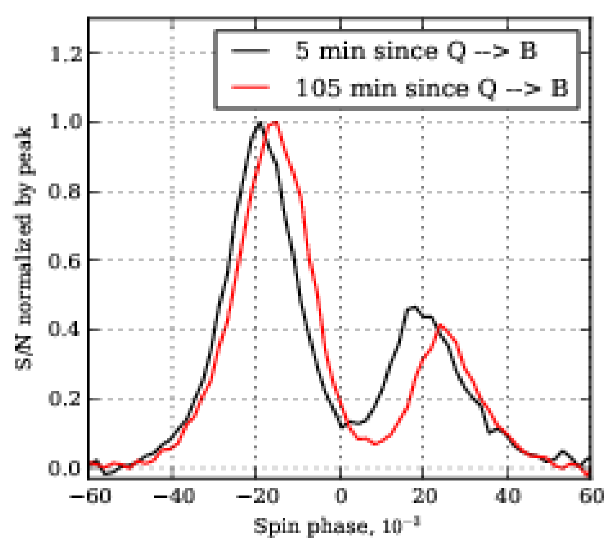


Sign of gradual global changes: systematic delay of the average profile within B-mode

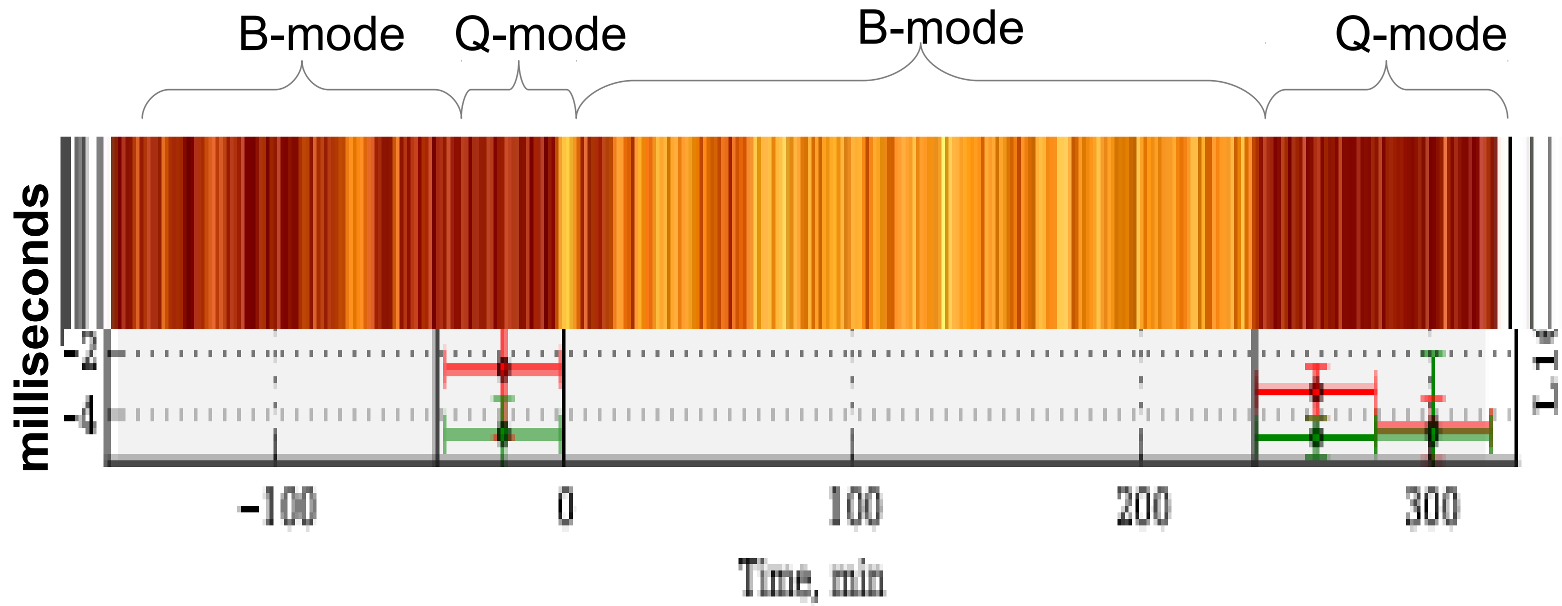




Shabanova et al 2013



Hard to explain with changing spin-down rate (too big and jumps at B to Q transition)

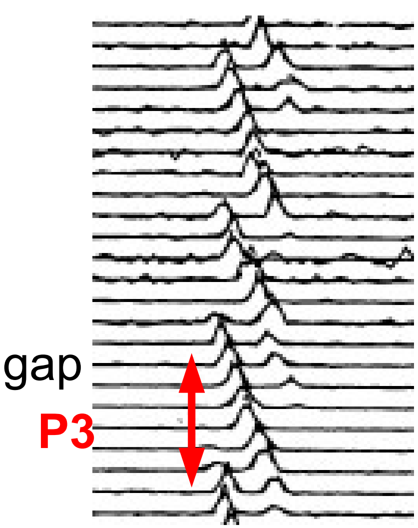


Drift rate of single pulses in B-mode: a completely different phenomena with surprisingly similar dependence on time.

1/P3

1/P3 ~ dV/dr, the horizontal gradient of accelerating potential in the polar gap

(Ruderman & Sutherland 1975, van Leeuwen & Timokhin 2012)



Delay of the B-mode profile – variation of polar gap height?

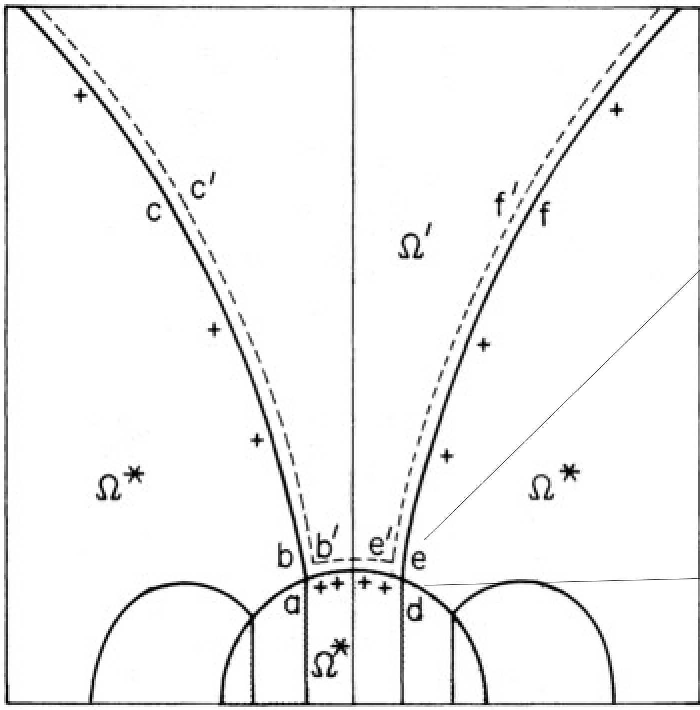
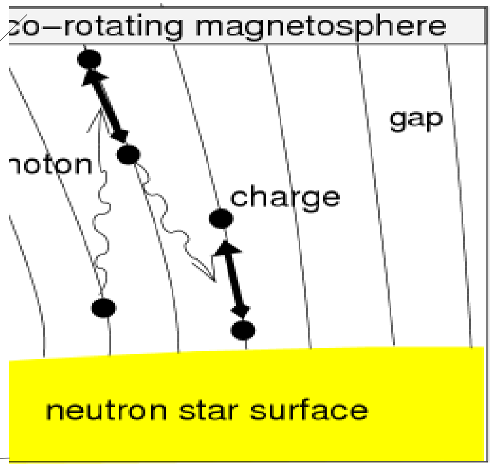
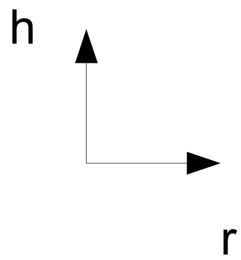


FIG. 2.—Magnetosphere of a rotating neutron star (angular velocity Ω*) with an antiparallel dipole field and a polar gap above the surface in the polar region *ad*. There is zero charge in the magnetosphere between the solid and dashed lines; additional charge is designated only within the star. The magnetosphere between the equator and the cone of *abc* and *def* corotates with the star. The magnetosphere within the cone of *c′b′e′f′* rotates with angular velocity Ω′ < Ω*: Ω′ is constant only along magnetic field lines. Significant departures of **E**·**B** from zero occur only within the polar gap *ab′e′d*.

Ruderman & Sutherland 1975





Potential in the gap: V(r, h)

Plasma above the polar gap rotates with

P < P_star, P = P(gap height)

In order to explain the residuals dh/h~5%, or dV(h)/V(h) ~ 10%

Subpulse drift rate gives 4% variation in dV/dr.

Summary

• Despite the apparent differences in B and Q appearance, the emission from both modes comes from almost the same (6% difference) range of heights close to stellar surface.

• The systematic delay of the profile in B-mode, together with observed variations in subpulse drift rate can provide an important insight into the evolution of the acceleration potential in the polar gap.