Circular polarization of AGNs on the parsec VLBI scales

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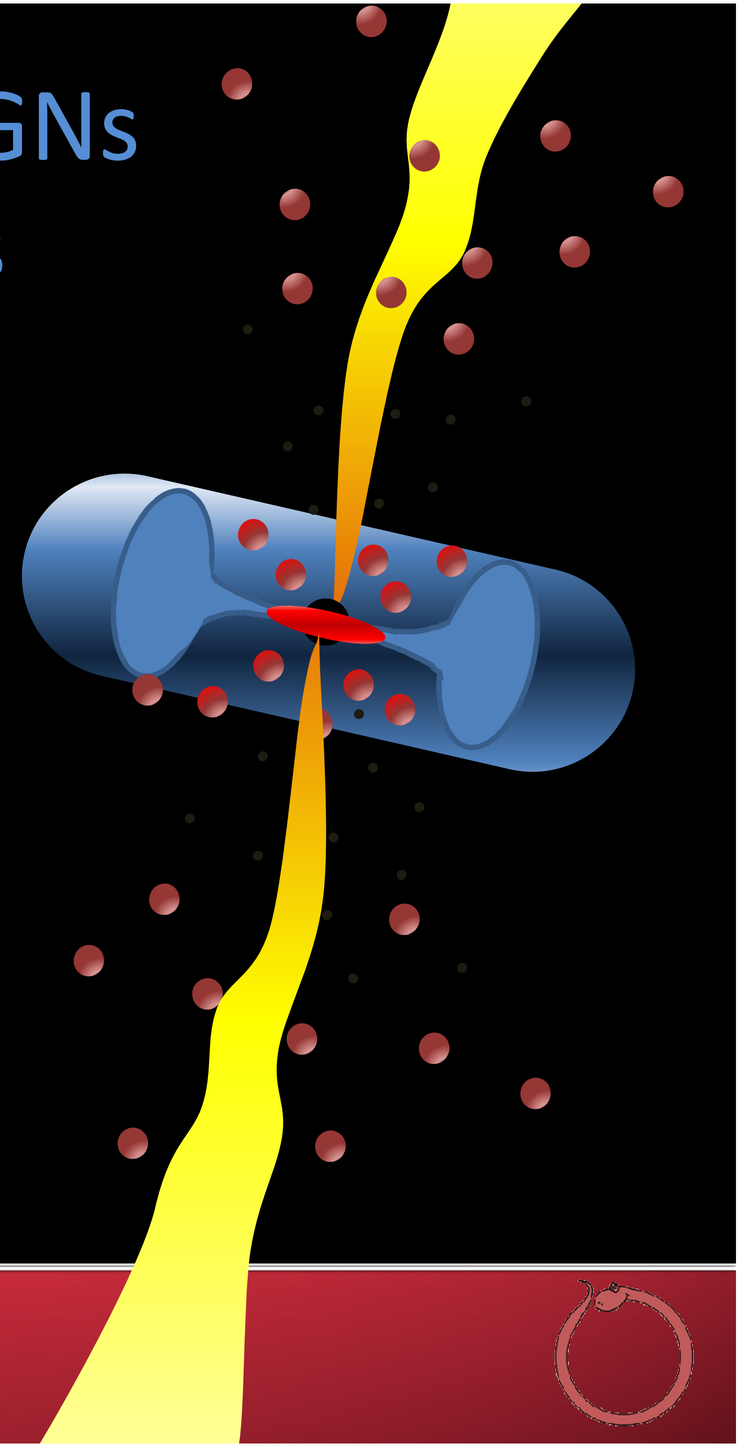

Young European Restless Astronomers Conference,
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Contents

VLBI Studies of AGN jets

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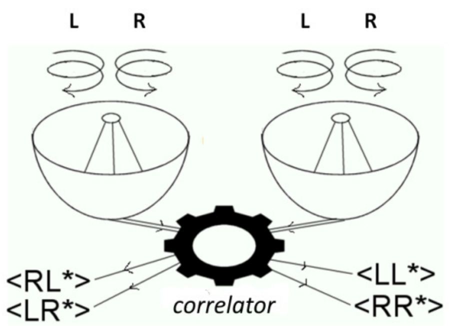
VLBI Studies of AGN jets

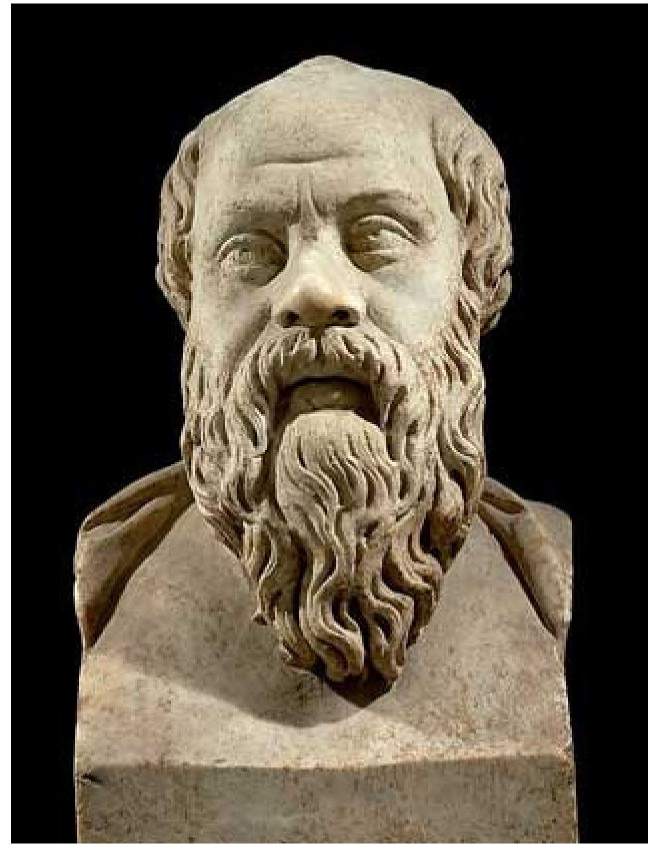
- High resolution mapping (up to 10^{-5} arcseconds)
  - Jet morphology, intensity profiles
- Multiple epochs
  - Variability
  - Jet kinematics
- Multiple frequencies (mm - dm)
  - Spectral index maps, core shifts
  - Birth of the new jet components
- Linear polarization (LP)
  - LP distribution
  - LP variability
  - LP spectra
  - Rotation measure maps



We don't know (or at least quarrel):

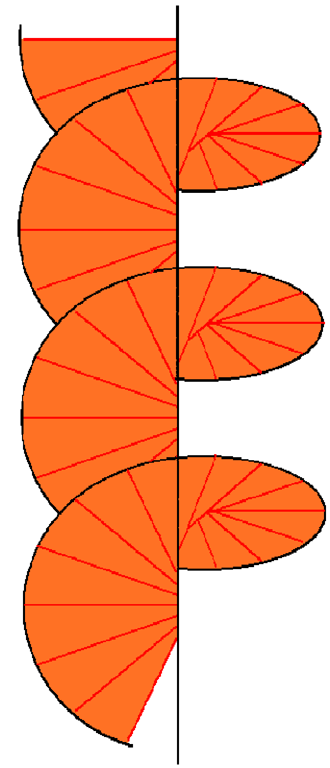
- Jet generation mechanism
- Jet plasma composition (e^-p^+ or e^-e^+ plasma)
- Particle acceleration mechanism
- Particle density
- Particle energy spectra
- Total jet power
- Jet expansion angle
- Angle of jet inclination to the LOS

Magnetic field:
- magnitude
- large-scale polarity
- geometry
- degree of order
- variability



«I know that I know nothing»
-Socrates

Circular polarization (CP) is what we were missing!



- **Doesn't change in interstellar medium**
- **Very sensitive to various internal jet parameters**

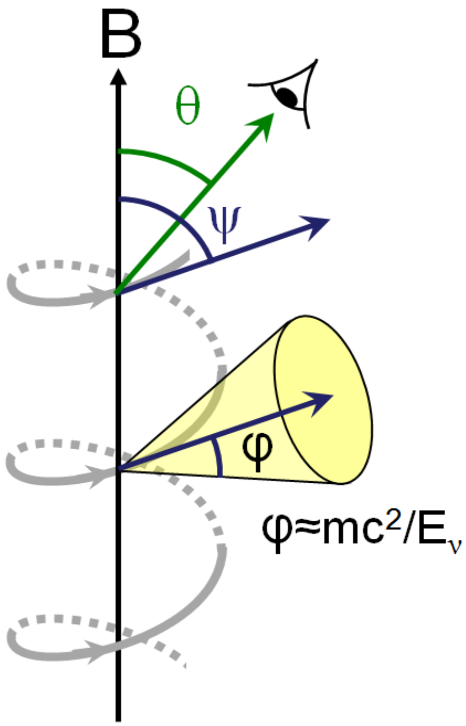
Typical CP degrees in AGNs are **tenths of a percent**. Maximum values **do not exceed several percents**.

Special methods of calibration are required.

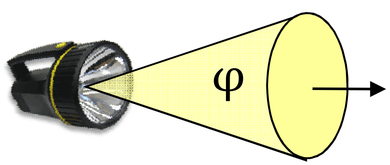
Gain-transfer (Homan & Wardle, 1999)
Separate calibration (Vitrishchak & Gabuzda, 2007)

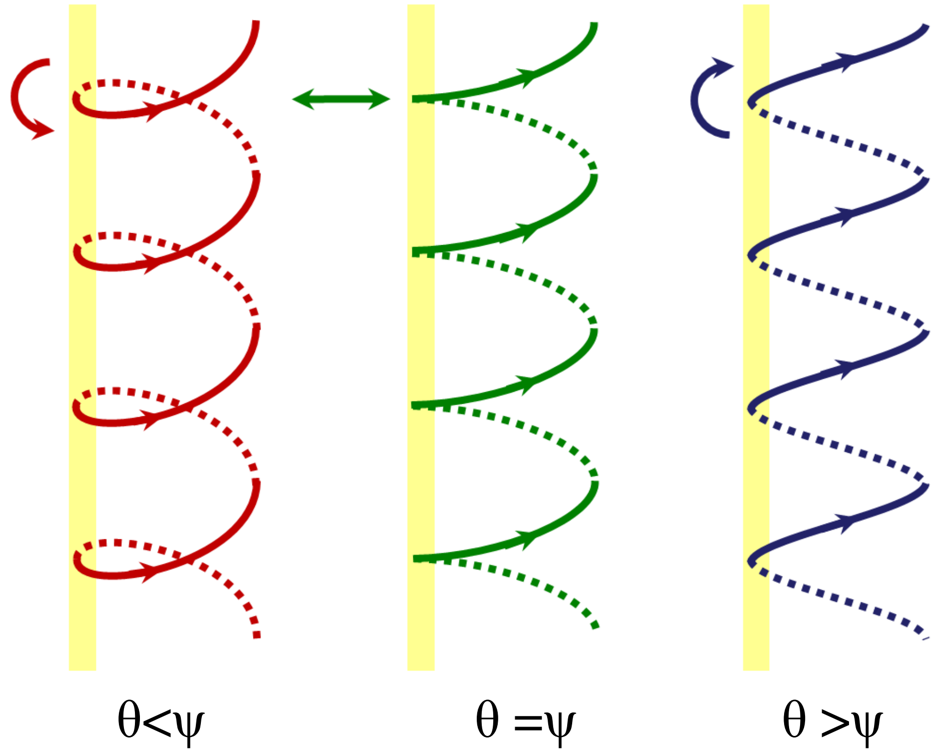
"Circular polarization: comprehensive walkthrough" (Vitrishchak, 2009)

Circular polarization:
Direct synchrotron emission



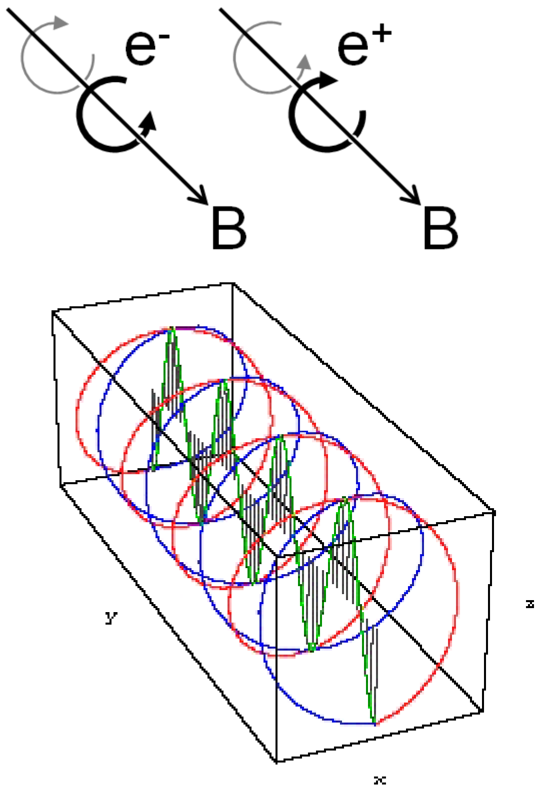
Half of the emission goes to $\varphi \sim 1/\gamma$





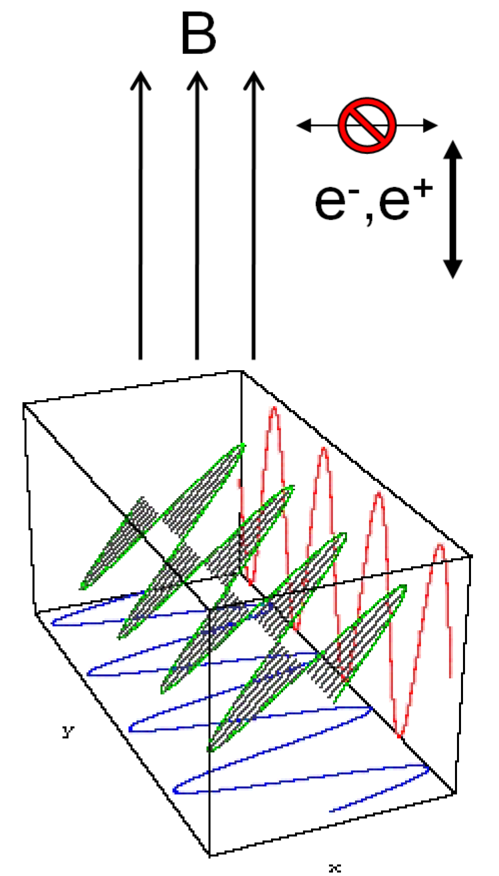
- In e^-e^+ plasma CP=0
- **Strong uniform B-field required ($V \propto B_{\parallel}^{1/2}$)**
- For uniform model source $V_{max} \propto \nu^2$

Faraday effects



Faraday Rotation

Faraday Conversion (Cotton-Muton effect)

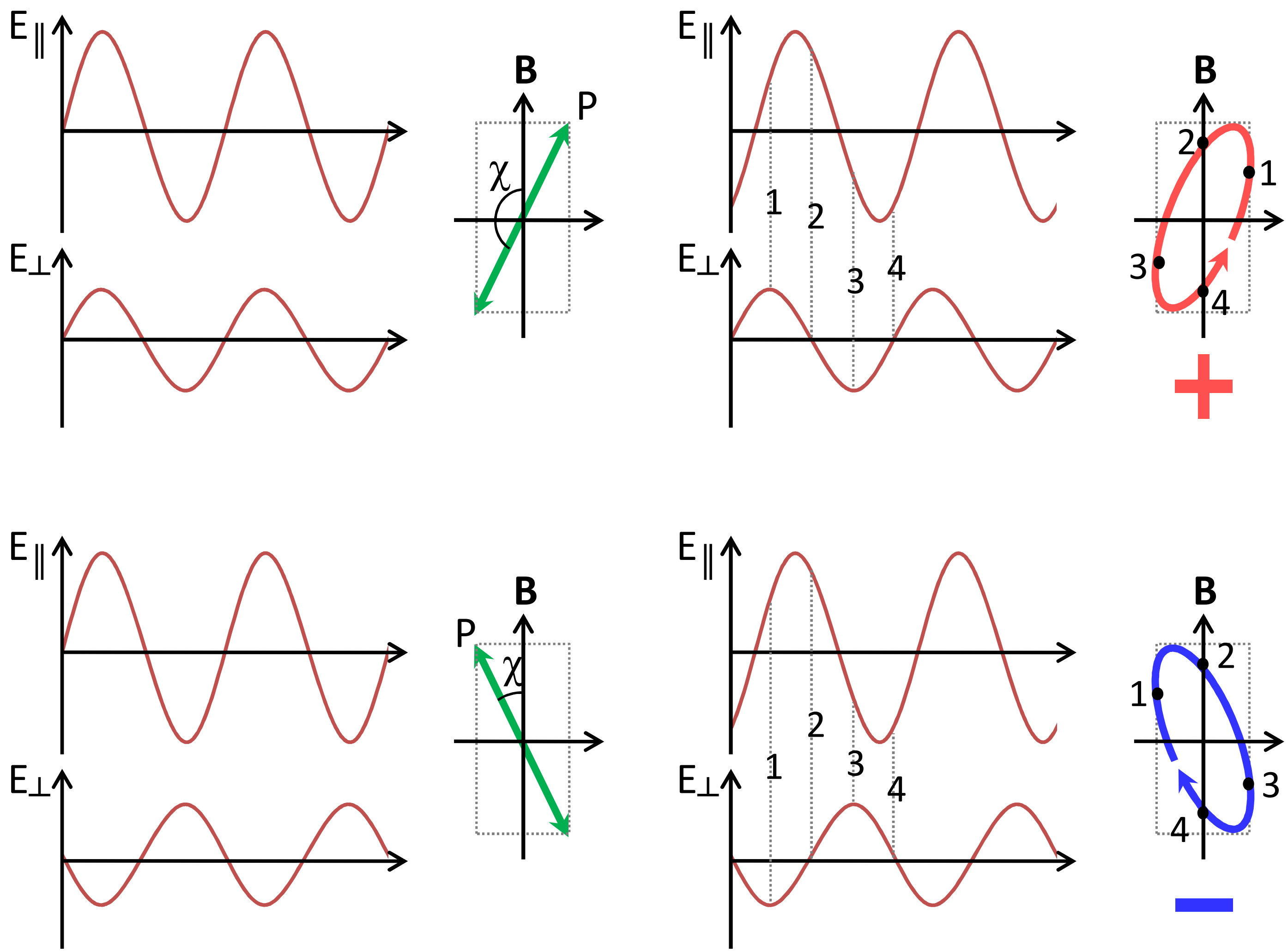


- Parallel (to the LOS) magnetic field component needed
- e^- and e^+ contribute with opposite sign, no rotation in e^-e^+ plasma

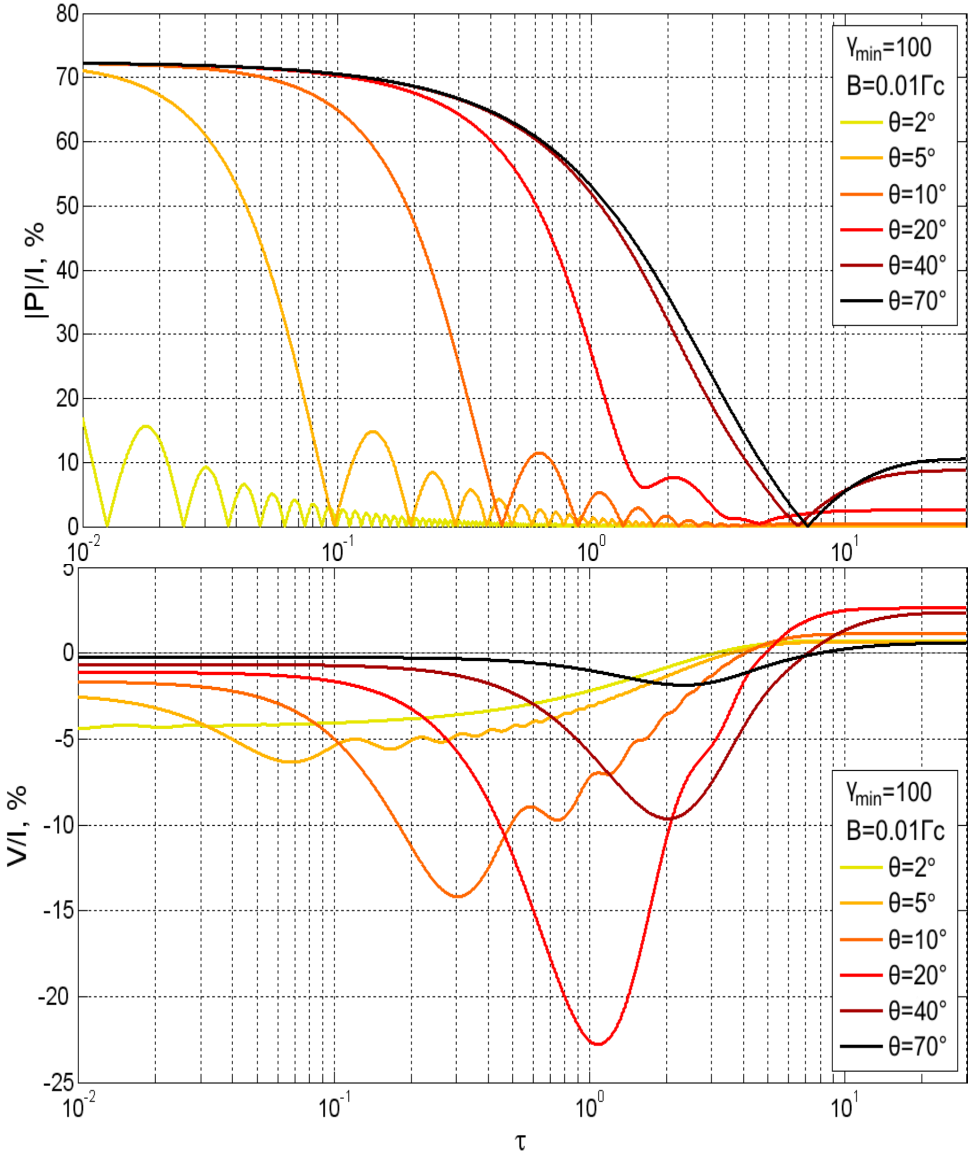
- Transversal (to the LOS) magnetic field component needed
- e^- and e^+ both contribute with the same sign

Videos from Beckert & Falcke

Circular polarization:
Conversion from linear polarization



Circular polarization:
Conversion from linear polarization. Homogenous source



Very sensitive on:

- Plasma composition
- Magnetic field
- Lower end of particle energy distribution
- Particle acceleration mechanism
- Optical depth

Can produce huge degrees of CP!

Internal conversion requires:

- internal faraday rotation

AND / OR

- changing transversal B-field component along the LOS inside the source

Observations

Most reliable (recent) results:

Homan & Lister, 2006. (MOJAVE, 15GHz) **133** AGNs at 15GHz
92 QSO: **28** CP detections >2σ, **30±6%**
22 BL Lacs: **5** CP detections >2σ, **23±10%**

Vitrishchak & Gabuzda, 2007 (15GHz) **29** AGNs: **3** QSO, **26** BL Lacs
continued in
Vitrishchak et. al., 2008 (15, 22, 43GHz) **59** AGNs: **24** QSO, **35** BL Lacs

25 QSO: **9** CP detections >2σ, **36±12%**
46 BL Lacs: **7** CP detections >2σ*, **15±6%**

* two objects with reliable detection at formal level of 1.9σ were added

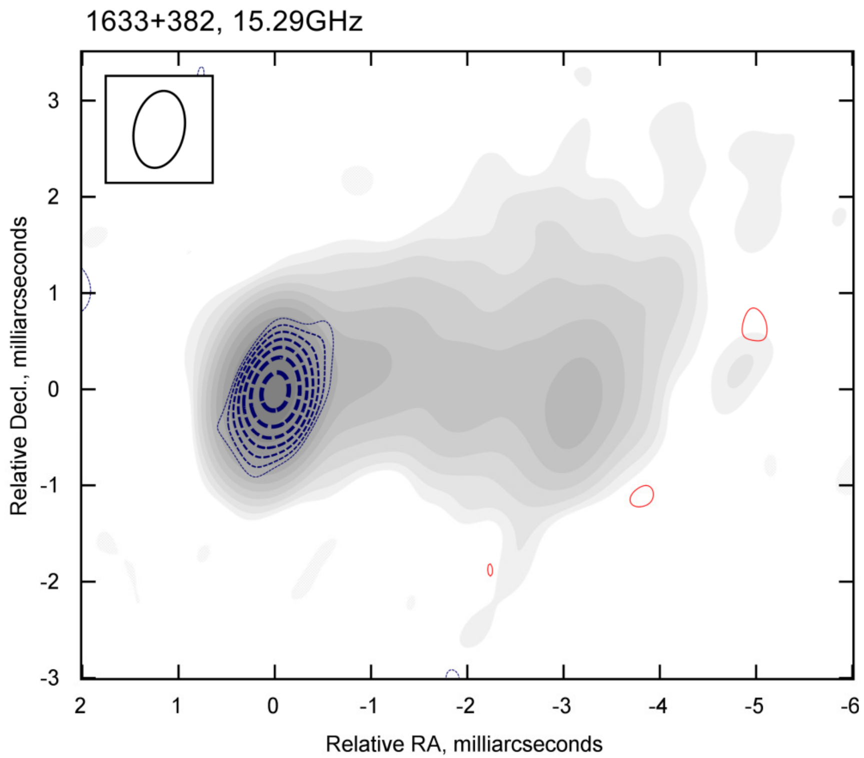
Typical CP detections

- Typical CP degrees in the VLBI-core region – **tenths of a percent** (max. 0.86% in 3C279)
- CP degrees on the jet edges (if observed) reach **several percents**

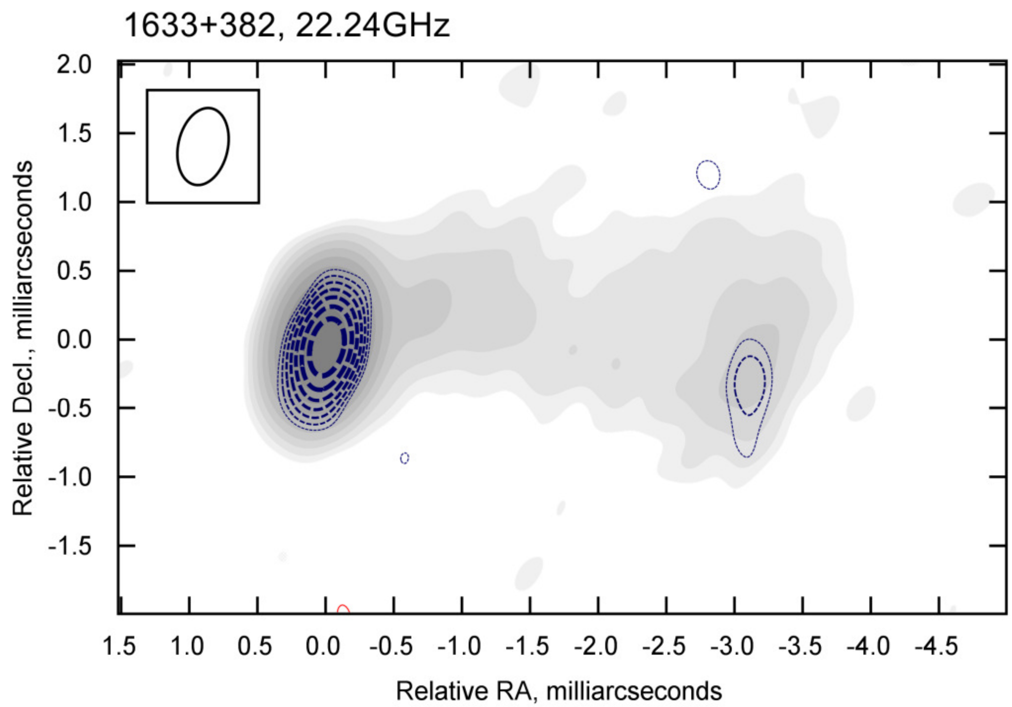
➡ If CP generated directly via synchrotron emission very strong B-fields **(~1G)** are required

- In most cases CP is observed in the “optically” thick VLBI-core

Typical CP maps
Peak in VLBI-core



V_{peak}=-8.5 mJy/Beam
I_{max}=2629 mJy/Beam
V levels: $\times\sqrt{2}$ from ±0.9 mJy/Beam
I levels: $\times 2$ from ±1.5 mJy/Beam



V_{peak}=-23.2 mJy/Beam
I_{max}=2686 mJy/Beam
$\times\sqrt{2}$ from ±2.1 mJy/Beam
$\times 2$ from ±3.3 mJy/Beam

Typical CP detections

- Typical CP degrees in the VLBI-core region – **tenths of a percent** (max. 0.86% in 3C279)
- CP degrees on the jet edges (if observed) reach **several percents**

➡ If CP generated directly via synchrotron emission very strong B-fields **(~1G)** are required

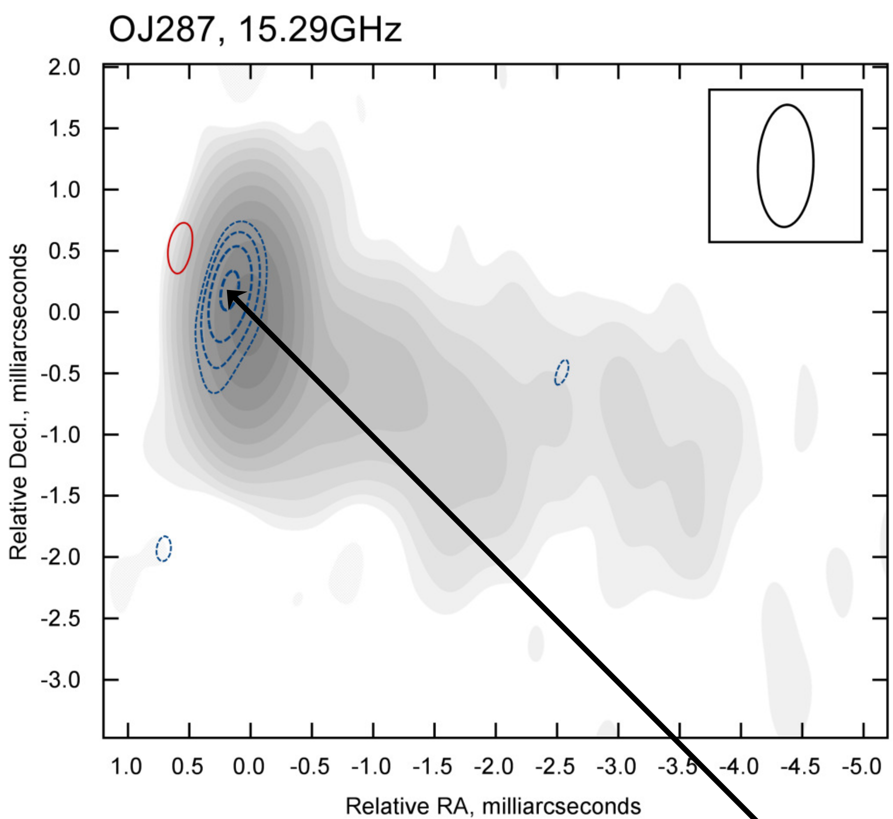
- In most cases CP is observed in the "optically" thick VLBI-core
- CP peak is sometimes shifted from the full intensity peak towards the SMBH – to even more "optically" thick regions.

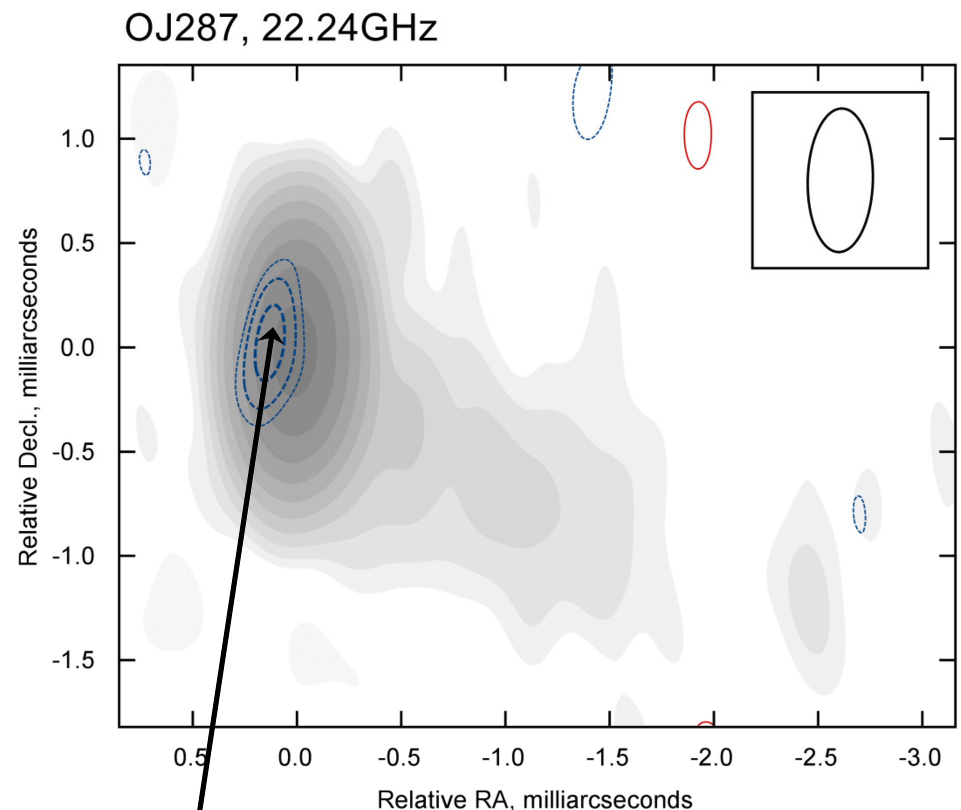
➡ Internal depolarization is weak:

- **Highly ordered B-field**
- **Internal Faraday rotation is small or absent (which is more likely)**

➡ **More likely e^-e^+ plasma** ➡ **CP only via conversion in changing B-field**

Typical CP maps
Peak is shifted towards SMBH





V_{peak}=-5.8 mJy/Beam
I_{max}=3117 mJy/Beam
V levels: $\times\sqrt{2}$ from ±1.9 mJy/Beam
I levels: $\times 2$ from ±2.2 mJy/Beam

CP peak is shifted towards SMBH

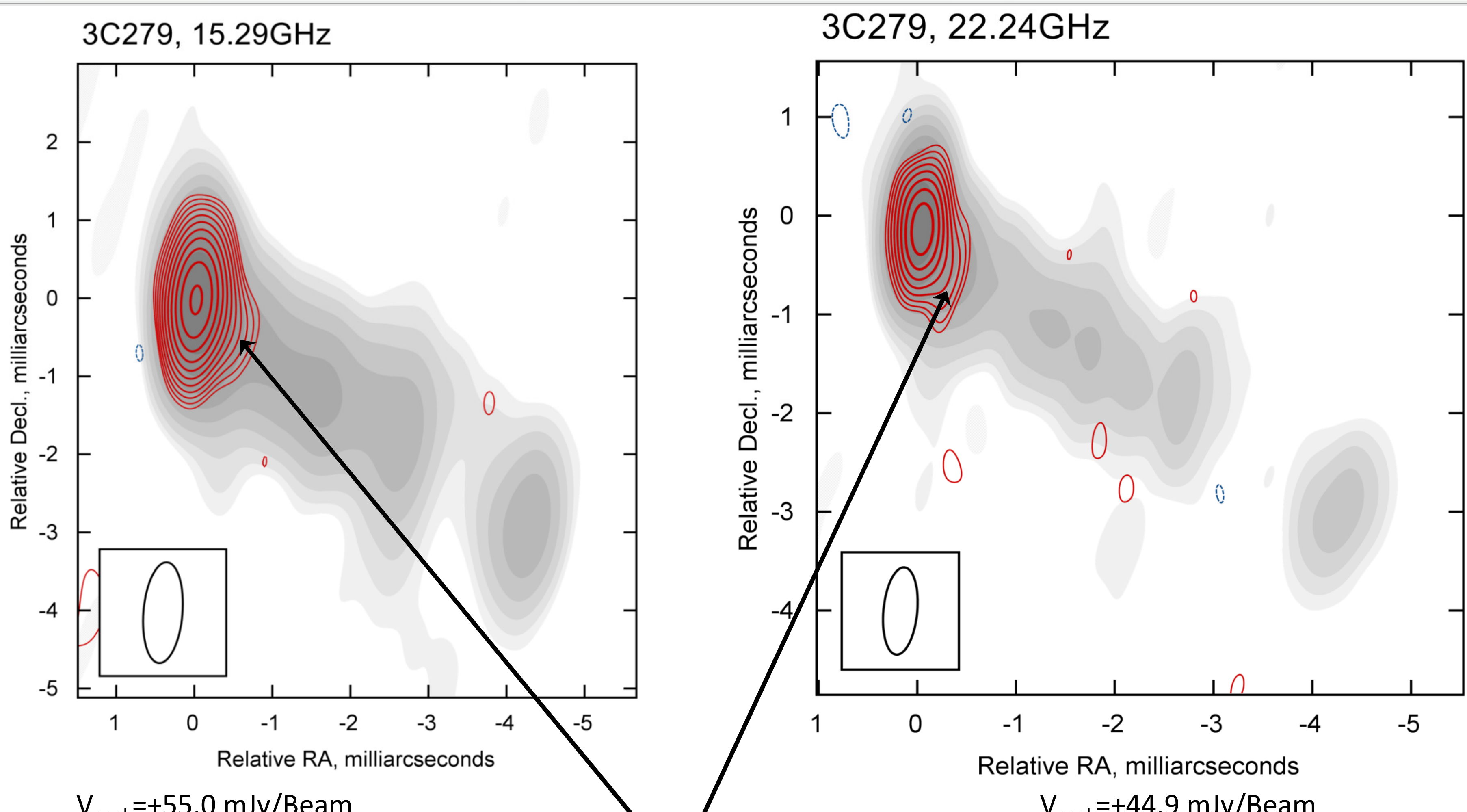
V_{peak}=-6.5 mJy/Beam
I_{max}=3174 mJy/Beam
V levels: $\times\sqrt{2}$ from ±2.8 mJy/Beam
I levels: $\times 2$ from ±4.7 mJy/Beam

Resolved CP signal
Parallel structure

- Prolonged CP structures stretching from “optically” thick VLBI-core to “optically” thin inner jet are detected for several sources

➡ CP generation works within wide range of plasma parameters ➡ **More likely no internal Faraday rotation (very sensitive to parameters)** ➡ **More likely e^-e^+ plasma** ➡ **CP only via conversion in changing B-field**

Resolved CP signal example
Parallel structure



V_{peak}=+55.0 mJy/Beam
I_{max}=6659 mJy/Beam
V levels: ×√2 from ±1.7 mJy/Beam
I levels: ×2 from ±13.1 mJy/Beam

CP in optically thin region

V_{peak}=+44.9 mJy/Beam
I_{max}=7271 mJy/Beam
V levels: ×√2 from ±3.1 mJy/Beam
I levels: ×2 from ±15.3 mJy/Beam

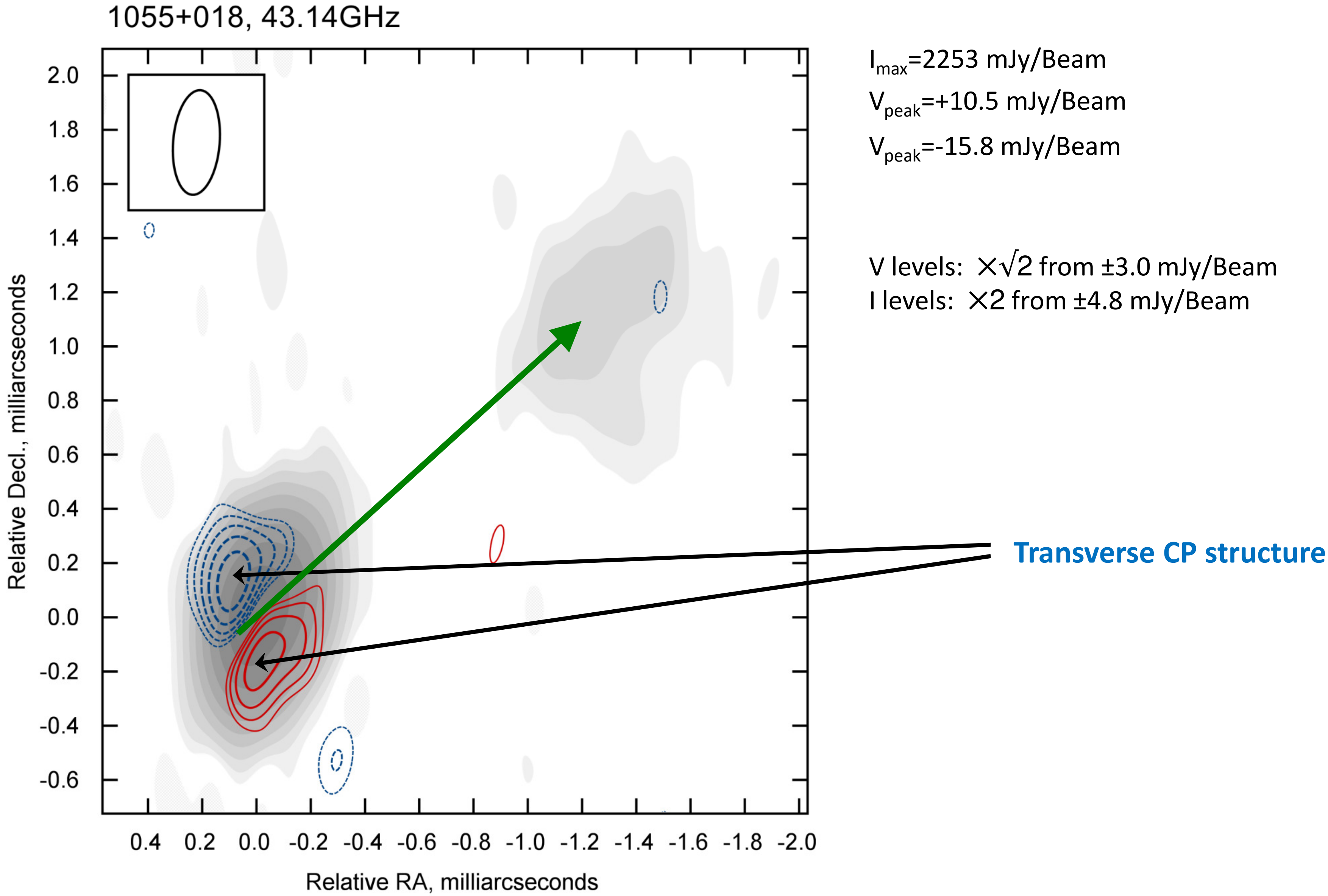
Resolved CP signal
Transverse structure

• Anti-symmetric CP structures with high degrees and different signs of CP on the different edges of jet were detected in some of the sources

➡ Toroidal B-field component present (typical for toroidal or spiral B-field geometries)

➡ **(at least) CP generation via conversion in changing B-field works for sure**

Resolved CP signal
Transverse structure

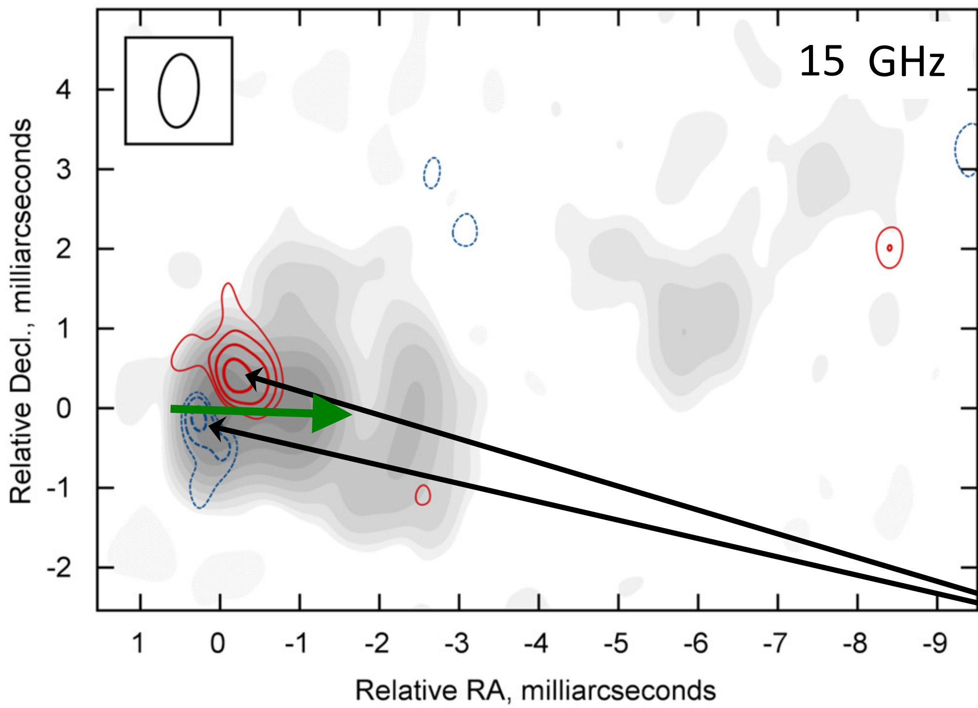


I_{max}=2253 mJy/Beam
V_{peak}=+10.5 mJy/Beam
V_{peak}=-15.8 mJy/Beam

V levels: $\times\sqrt{2}$ from ±3.0 mJy/Beam
I levels: $\times 2$ from ±4.8 mJy/Beam

One more…

2251+158
15 & 22 GHz



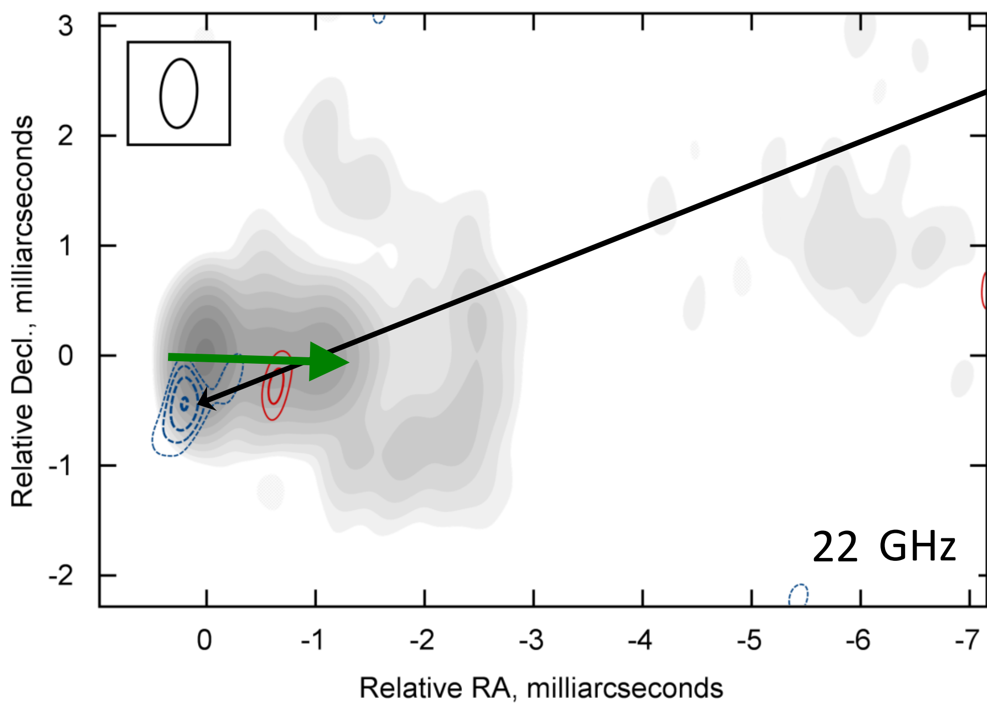
V_{peak}=+4.9 mJy/Beam

V_{peak}=-3.3 mJy/Beam

I_{max}=3117 mJy/Beam

V levels:
×√2 from ±1.5 mJy/Beam
I levels:
×2 from ±9.6 mJy/Beam

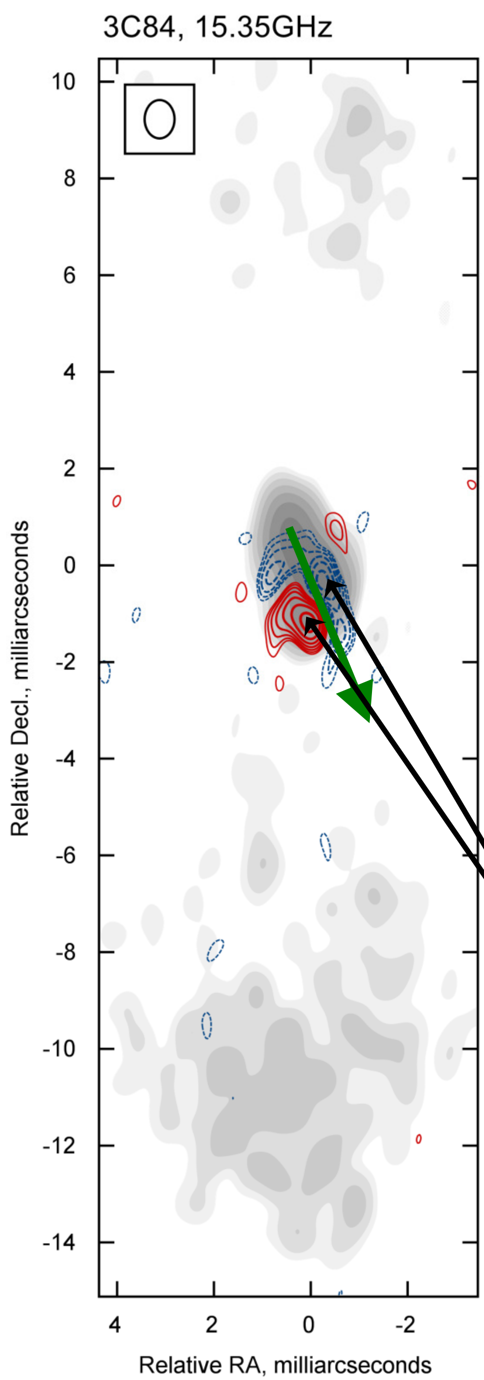
Transverse CP structure

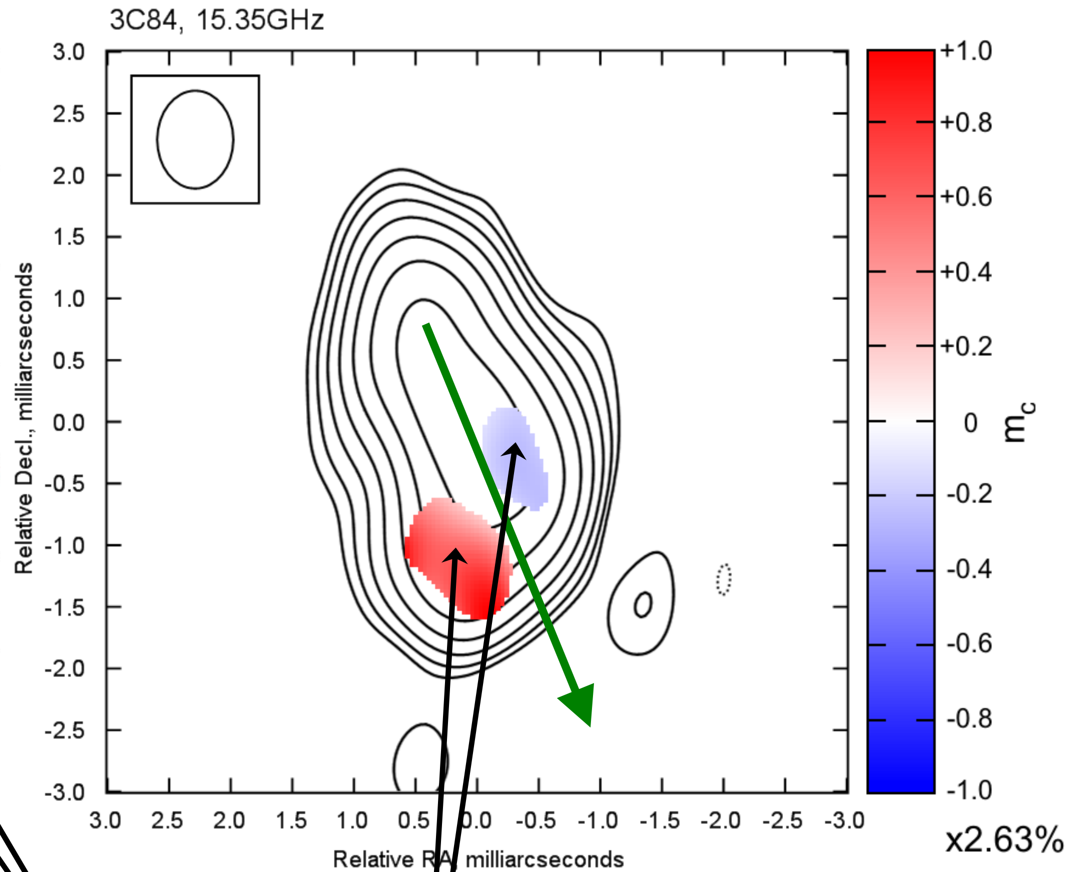


V_{peak}=-11.3 mJy/Beam

I_{max}=4830 mJy/Beam

V levels:
×√2 from ±4.6 mJy/Beam
I levels:
×2 from ±7.7 mJy/Beam





Transverse CP structure

V_{peak}=+22.1 mJy/Beam
V_{peak}=-15.5 mJy/Beam
I_{max}=2802 mJy/Beam

V levels:
×√2 from ±2.9 mJy/Beam
I levels:
×2 from ±25.3 mJy/Beam

More, more…

radiogalaxy 3C84 (0316+413)

Multi-epoch observations

• For **all** the sources observed on several epochs the sign of CP persisted throughout the epochs

• For most of the sources CP degree persisted as well (within the error limits)

➡ **Parameters responsible for CP generation (e.g. ordered B-field geometry) are persistent on the timescales of at least several years**

• For several objects change in CP signal correlated with the major change in the total source flux between the epochs. This can relate to the CP variability, blazar activity and new jet component emerging.

Multi-frequency observations

We measured CP in 41 AGNs on 15, 22 and 43 GHz
CP was detected on 2 or 3 frequencies in 11 objects

- No obvious common frequency dependence was found

- Only 2 sources out of 11 has shown the $V_{peak} \sim \nu^2$ dependence (characteristic for direct CP generation via synchrotron emission)

➡ **Conversion mechanism at least dominates**

- From 9 AGNs with CP detected on both 15 and 22GHz, 8 has shown the same sign on both frequencies.

- From 7 AGNs with CP detected on both 22 and 43GHz, 5 has shown opposite sign on these frequencies.

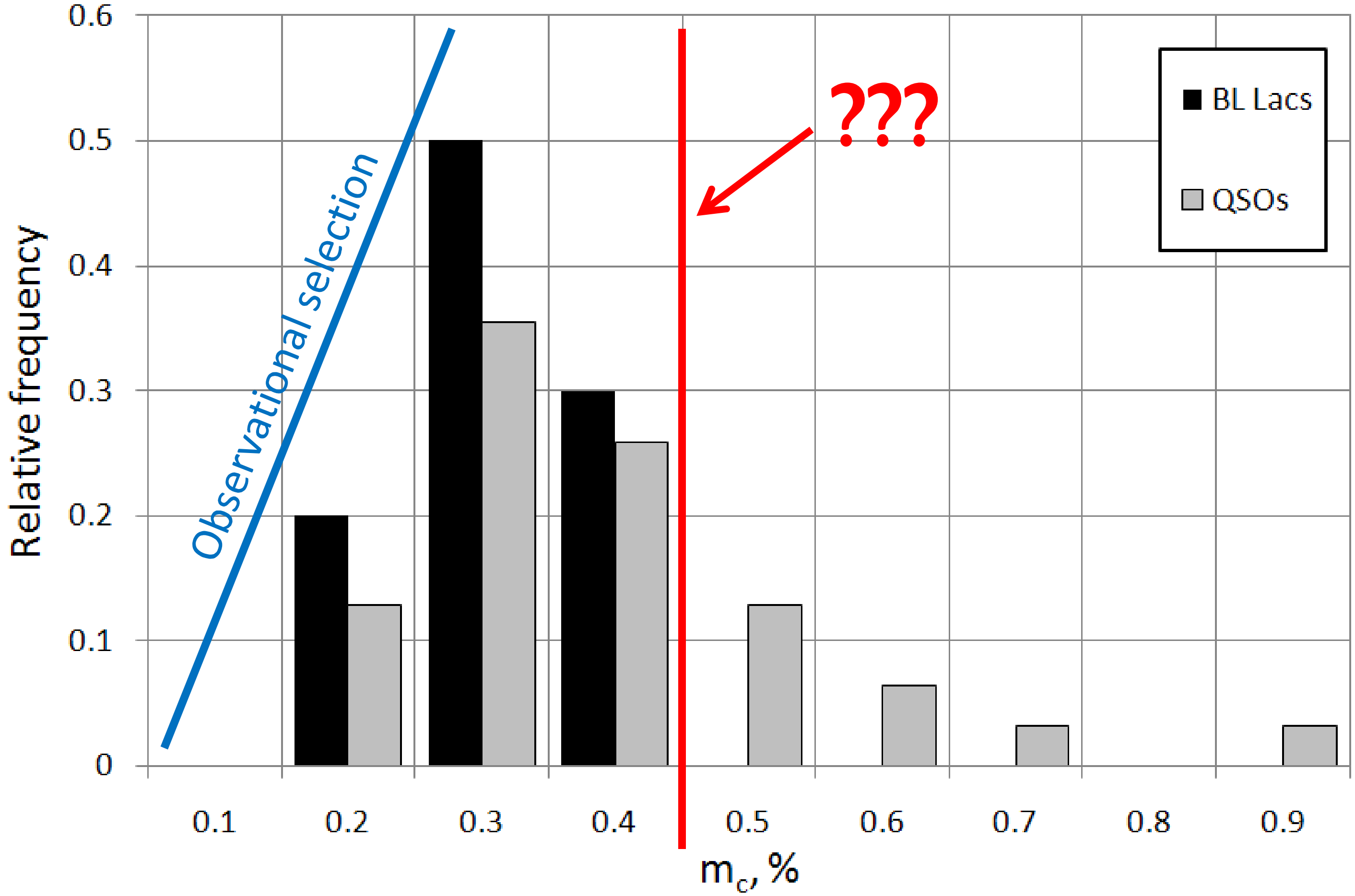
Sign changes with frequency can be explained by conversion mechanism

On QSOs and BL Lacs…

Still popular opinion that the only difference between QSO and BL Lacs is in the jet inclination angle to the line of sight **is wrong.** Moreover, average inclination angles for HPQ (FSRQ) and BL Lacs jets are roughly **the same**

- Average QSO **luminosity** is higher
- Thermal emission from the **disk** and **broad lines** in QSO spectra
- **Morphology of jets:** QSO: FR II, BL Lacs: usually FR I
- QSO activity is related to merging of gas redundant systems
- **Distance**: QSO are more distant (young)
- Different jet **linear polarization structure** on VLBI scales
- **Rotation measures in the VLBI-cores** are higher for QSO

CP degrees
for QSO and BL Lacs



Different plasma?

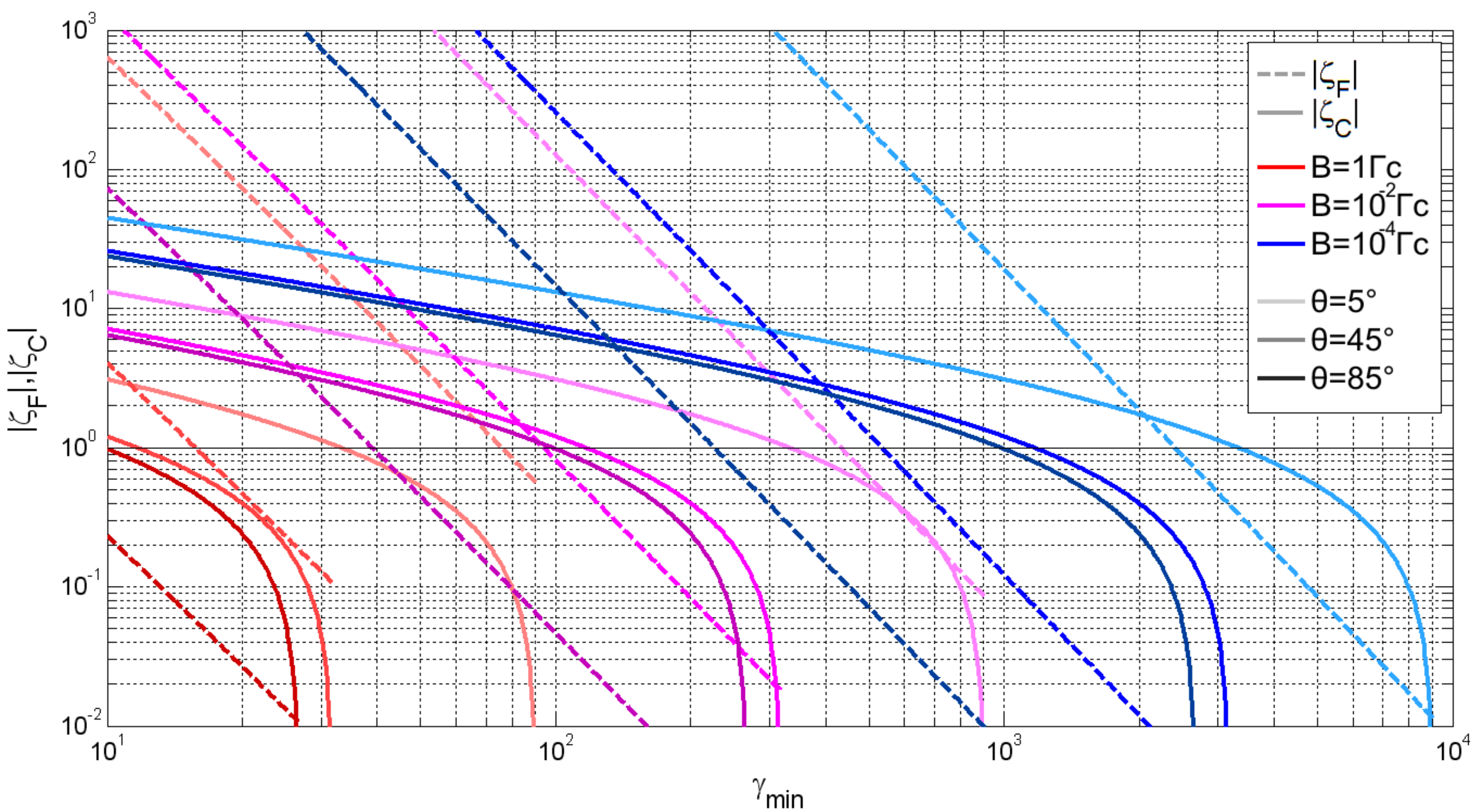
Accretion rate in BL Lacs is small => **Blandford-Znajek?** =>? e^-e^+ plasma dominates in BL Lacs?

In e^-e^+ plasma the only way to create CP is through **conversion in medium with changing transverse component of the B-field** along the LOS, which requires special field geometries

In e^-p^+ B plasma direct CP generation via synchrotron emission and Faraday Rotation act as well, allowing to produce higher degrees of CP

In QSOs dense emission from disk + more dense CMB (higher z) => **particle energies are lower?**

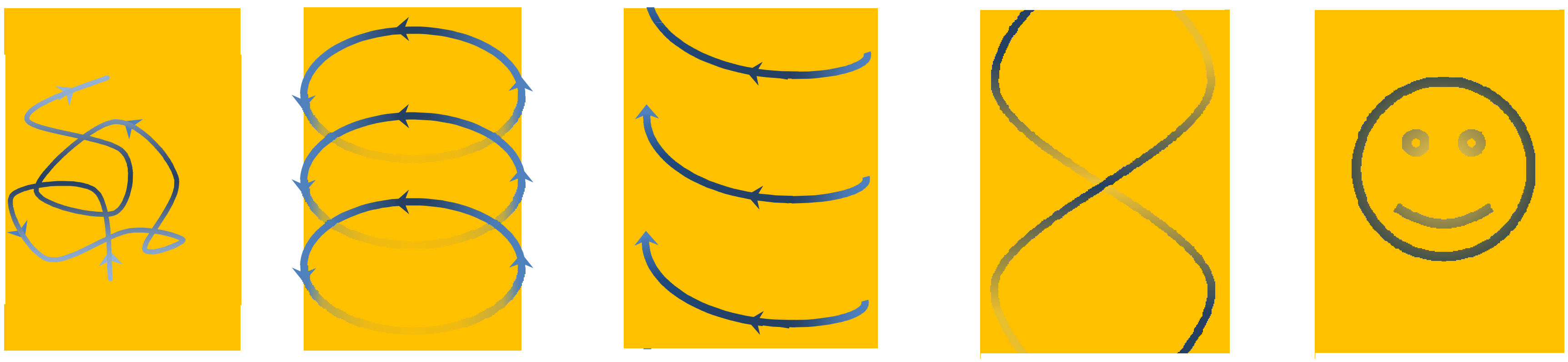
The slowest (more light weighted) particles play the main role in Faraday rotation and conversion



Different magnetic field?

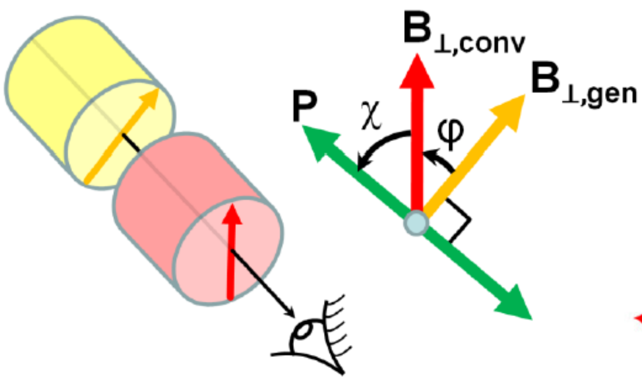
QSOs and BL Lacs may have different magnetic field properties

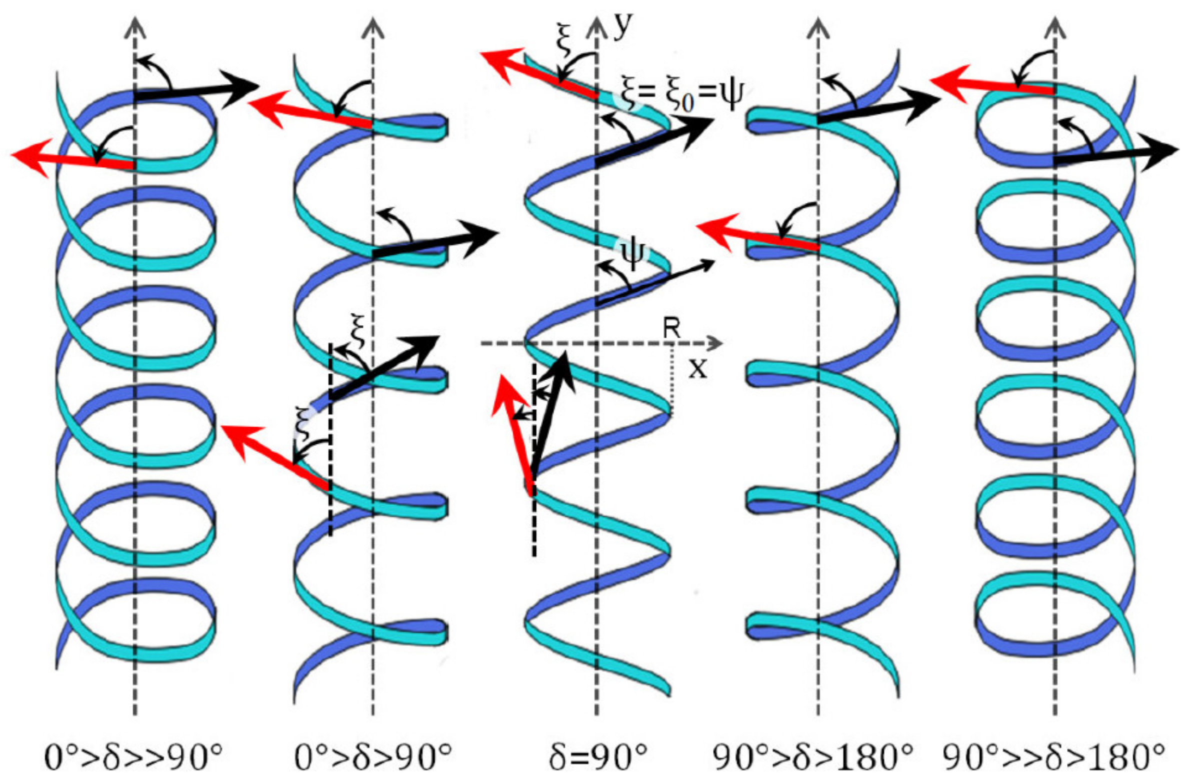
Observations of linear polarization (T.V.Cawthorne, J.F.C.Wardle, D.H.Roberts, D.C.Gabuzda, ApJ, 416, p.519, 1993) support this hypothesis

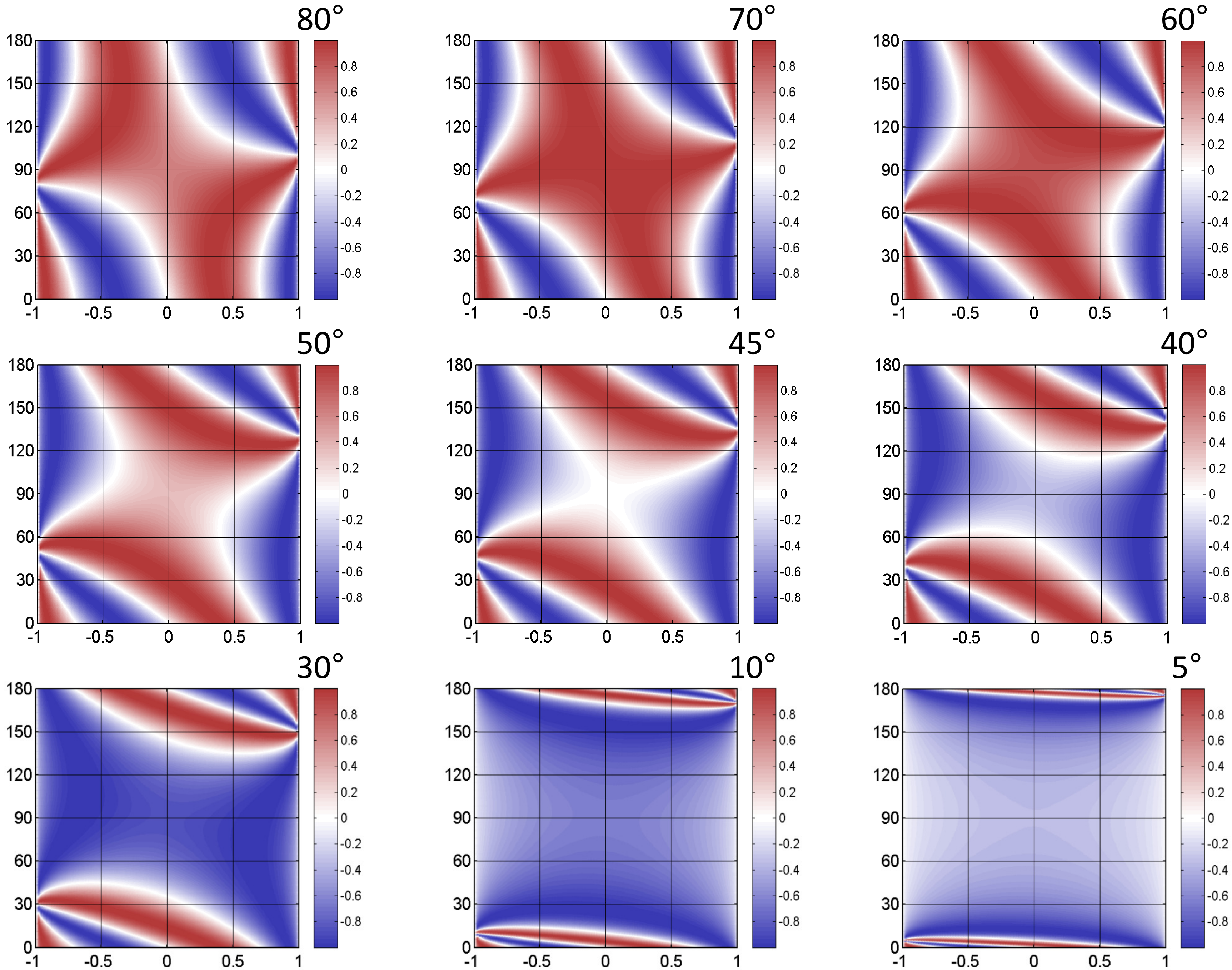


Simplest "helical skin" B-field model

LP is generated in the back layer of the jet
and then is converted into CP on the front layer

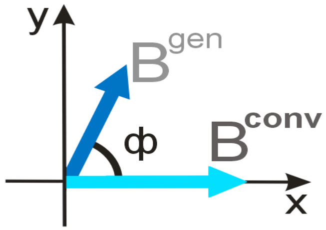


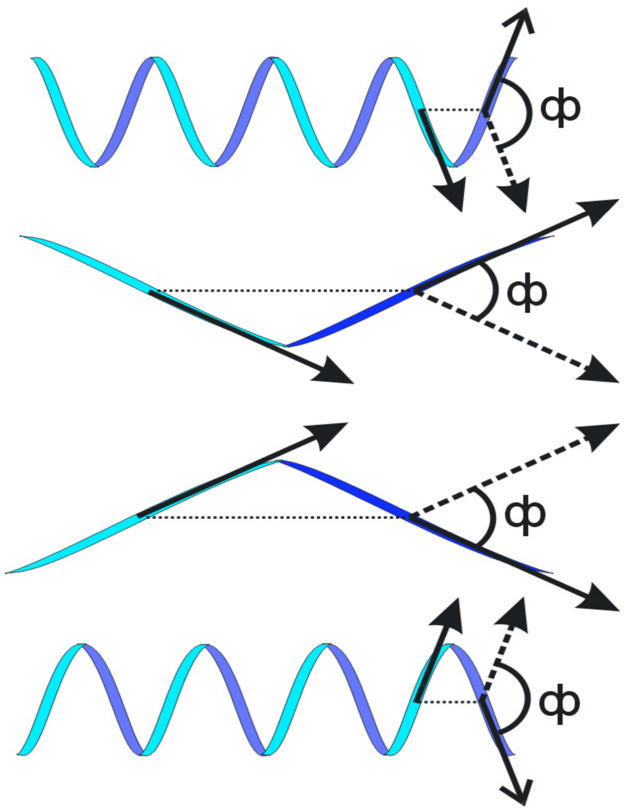




80°
70°
60°
50°
45°
40°
30°
10°
5°
180
150
120
90
60
30
0
-1
-0.5
0
0.5
1
0.8
0.6
0.4
0.2
0
-0.2
-0.4
-0.6
-0.8

CP sign depends only on pitch angle regime and helicity



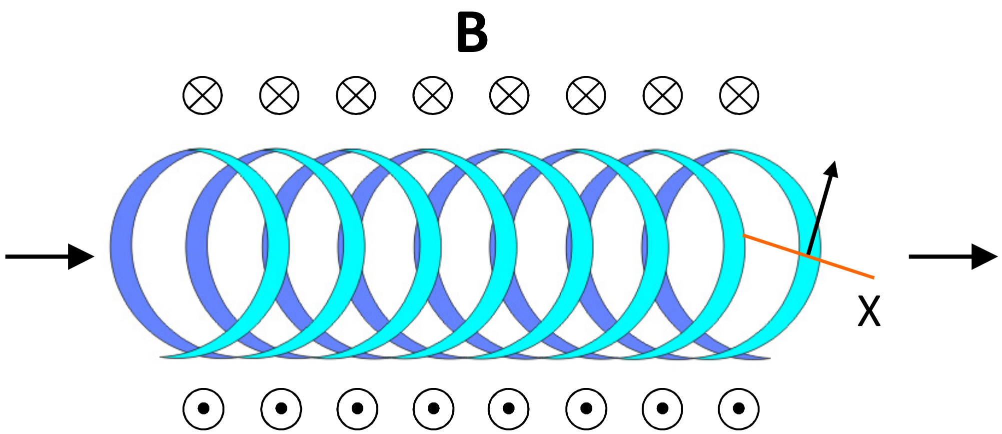


+ 90°<ϕ<180°
Right helicity
Large pitch-angles

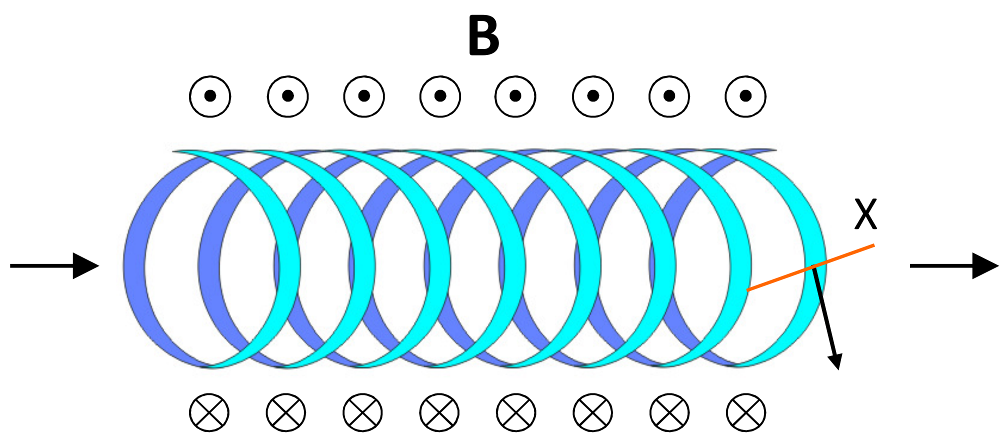
− 0°<ϕ<90°
Right helicity
Small pitch-angles

+ -90°<ϕ<0°
Left helicity
Small pitch angles

− -180°<ϕ<-90°
Left helicity
Large pitch-angles



Left helicity



Right helicity

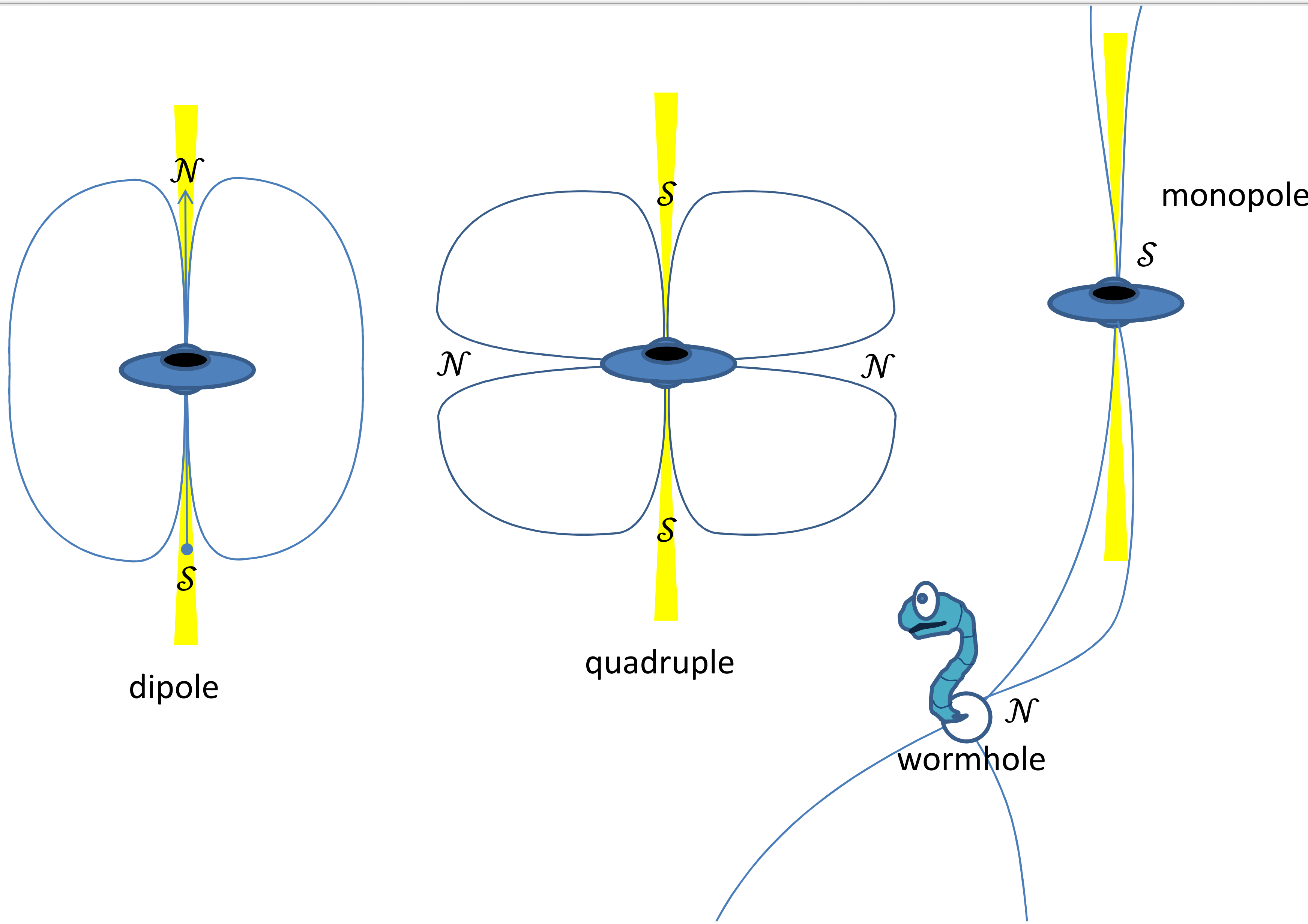
Measured CP sign VS calculated CP sign

AGN	B	Pitch-angle	Helicity	Predicted CP sign	Observed CP (%)	Match
0735+178	⊥	Large	Left	–	-0.30	✓
1156+295	⊥/H	Large	Left	–	-0.27	✓
3C273	||	Small	Right	–	-0.45	✓
3C279	⊥	Large	Left	+	+0.86	✓
3C345	||	Small	Left	+	+0.17	✓
1749+096	⊥	Large	Left	–	-0.42	✓
2230+114	||	Small	Right	–	-0.48	✓
2251+158	⊥/C	Large	Right	+	+0.23	✓

CP from Homan & Wardle (1999), Homam & Lister (2006), Vitrishchak & Gabuzda (2007)

RM from Taylor (1998, 2000), Zavala & Taylor (2003), Gabuzda et al. (2007)

Crazy stuff



$\mathcal{N}$
$\mathcal{S}$
dipole
$\mathcal{S}$
$\mathcal{N}$
$\mathcal{N}$
$\mathcal{S}$
quadruple
monopole
$\mathcal{S}$
$\mathcal{N}$
wormhole

Conclusions

CP is the new "band" in VLBI studies of AGNs

Generated CP signal is **sensitive to many internal parameters** of AGN jets: plasma composition, particle energy distribution and acceleration mechanism, magnetic field properties, e.t.c. Together with the other data, CP can be used to estimate these parameters.

The most likely mechanism of CP generation is **conversion** from the linear polarization while propagating through the **medium with changing transverse B-field** along the LOS

While some important qualitative conclusions can be made even now (like the evidence of toroidal magnetic field component in AGN jets), it is clear that the most promising way lies through **numerical modeling** of AGN jets, solving the radiation transfer problem and comparing the results with real observations.

AGN CP database is still in its "stone age" and lots need to be done to effectively use it in statistical studies, still even now we can make some preliminary conclusions like pointing at the difference between QSOs and BL Lacs