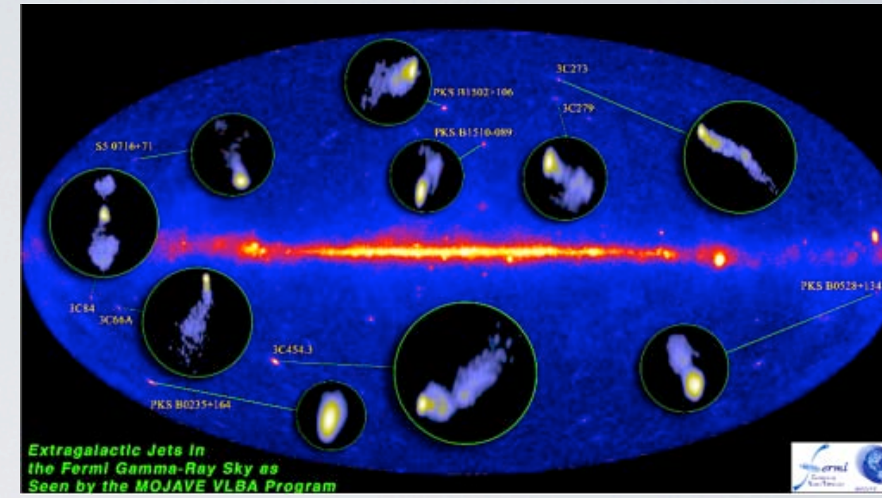


# Faraday rotation in MOJAVE blazar jets

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with
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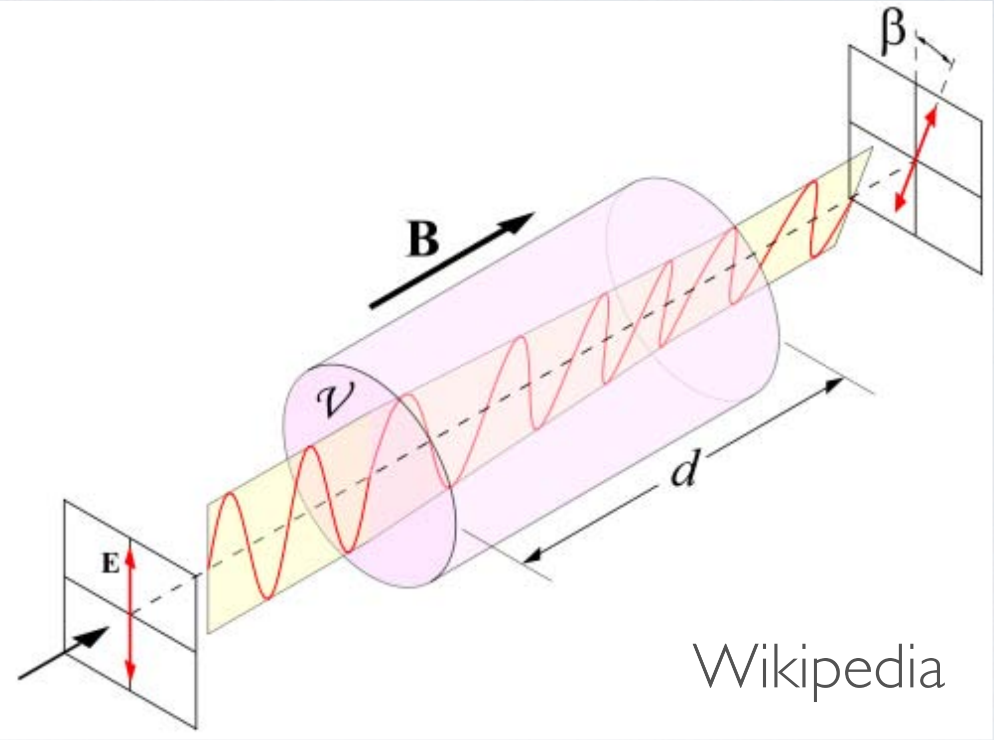
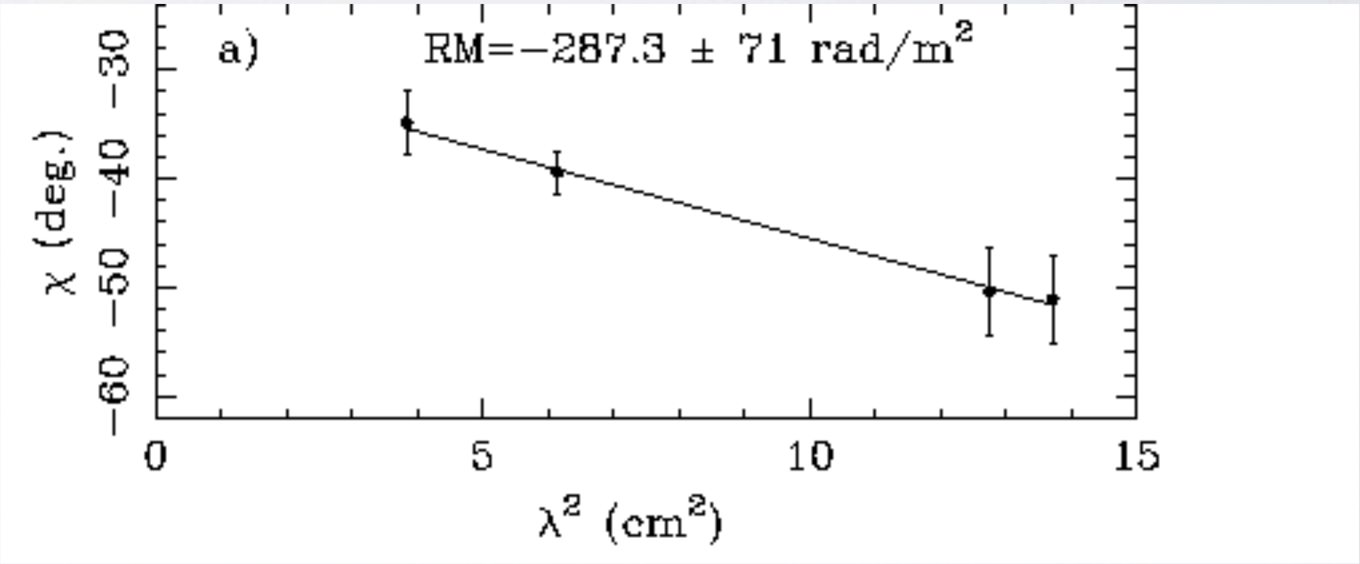
Alexander Pushkarev and Tuomas Savolainen

# FARADAY ROTATION

- Linearly polarized wave is a sum of right and left hand circularly polarized waves
- In magnetized plasma the waves travel at slightly different speeds causing a phase offset
- The plane of polarization gets rotated
- Strongly wavelength dependent

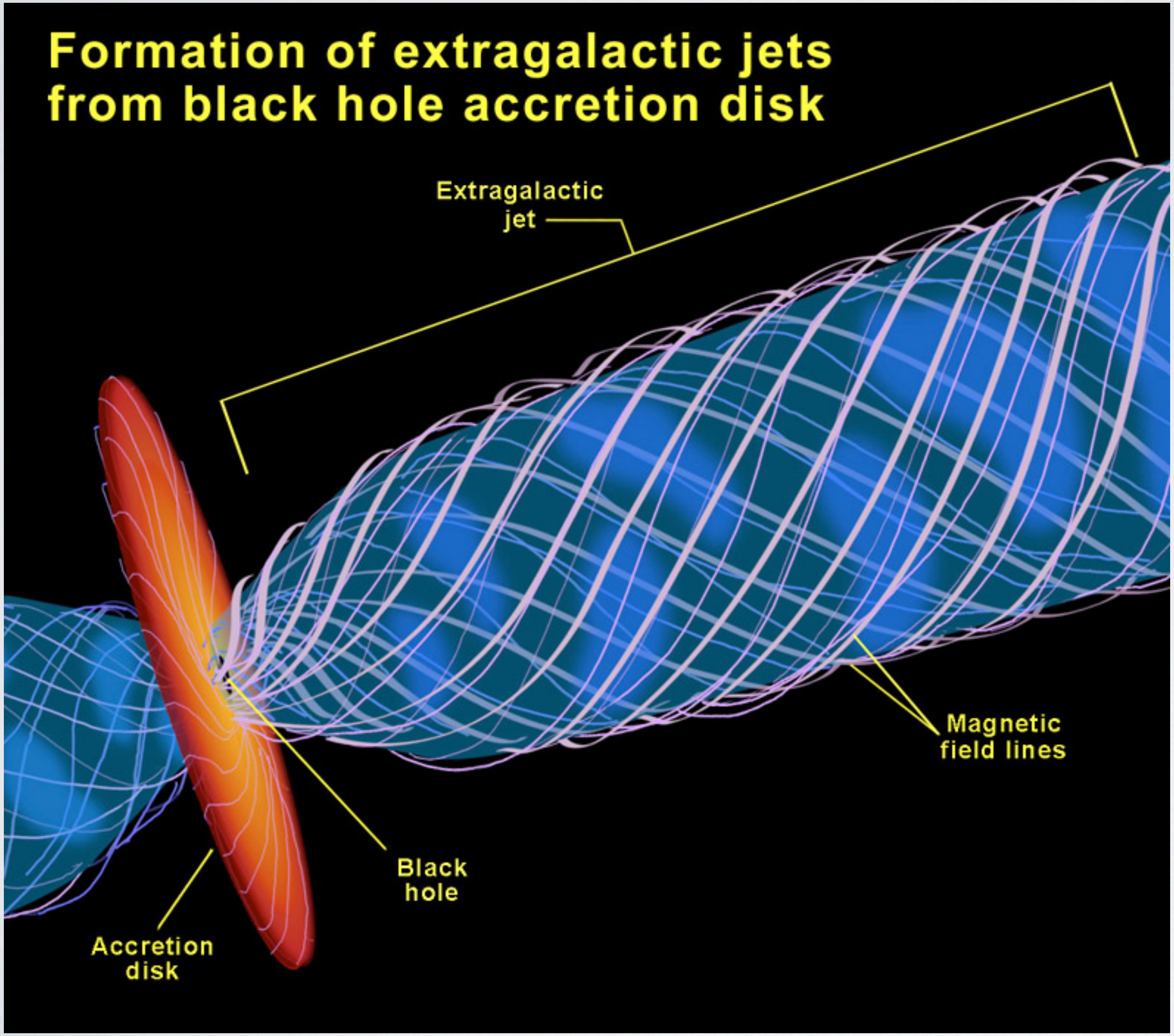



$\chi_{obs} = \chi_0 + \mathrm{RM}\,\lambda^2$

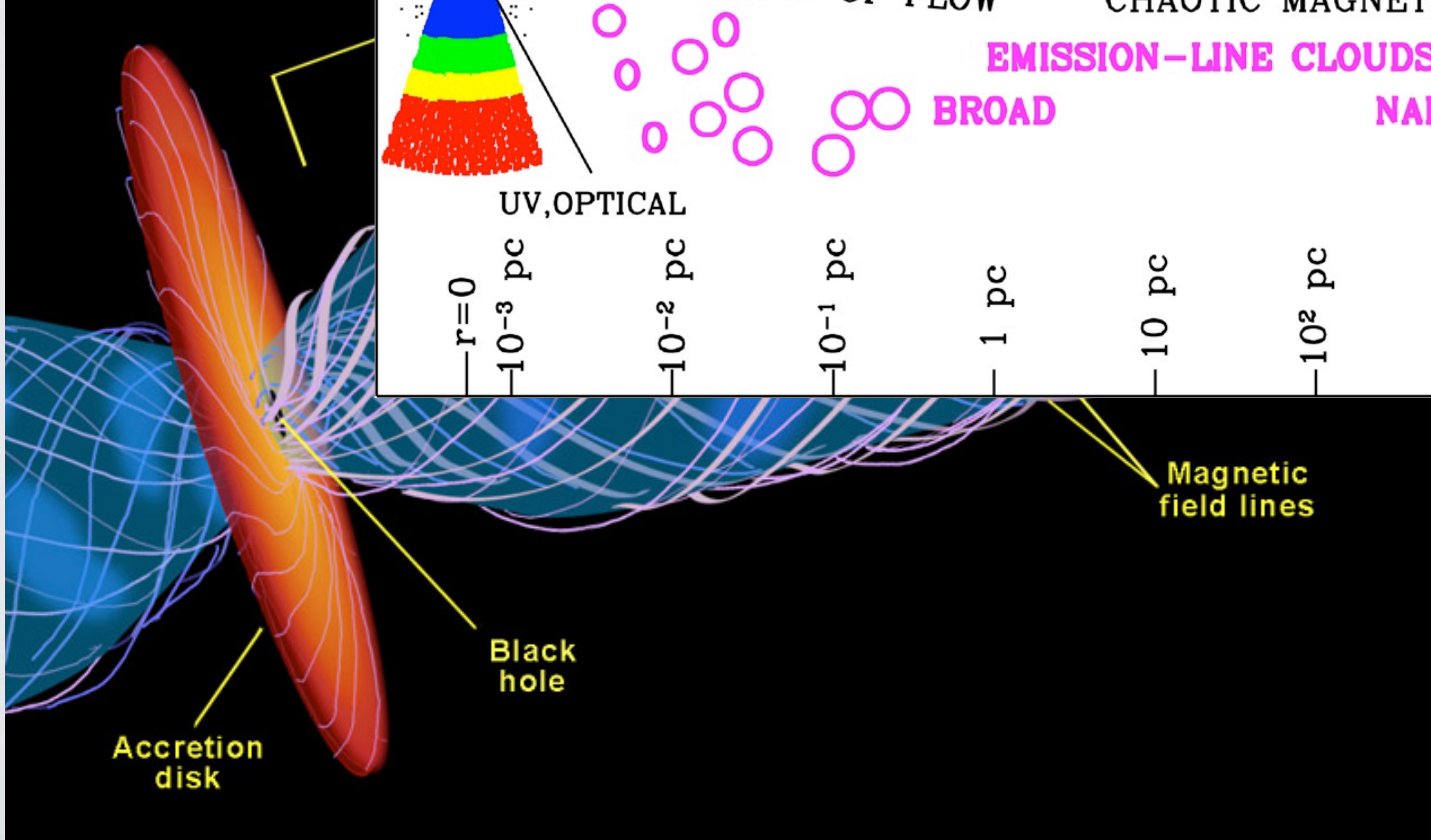
$\mathrm{RM} \sim \int n_e B_{||}\, dl$

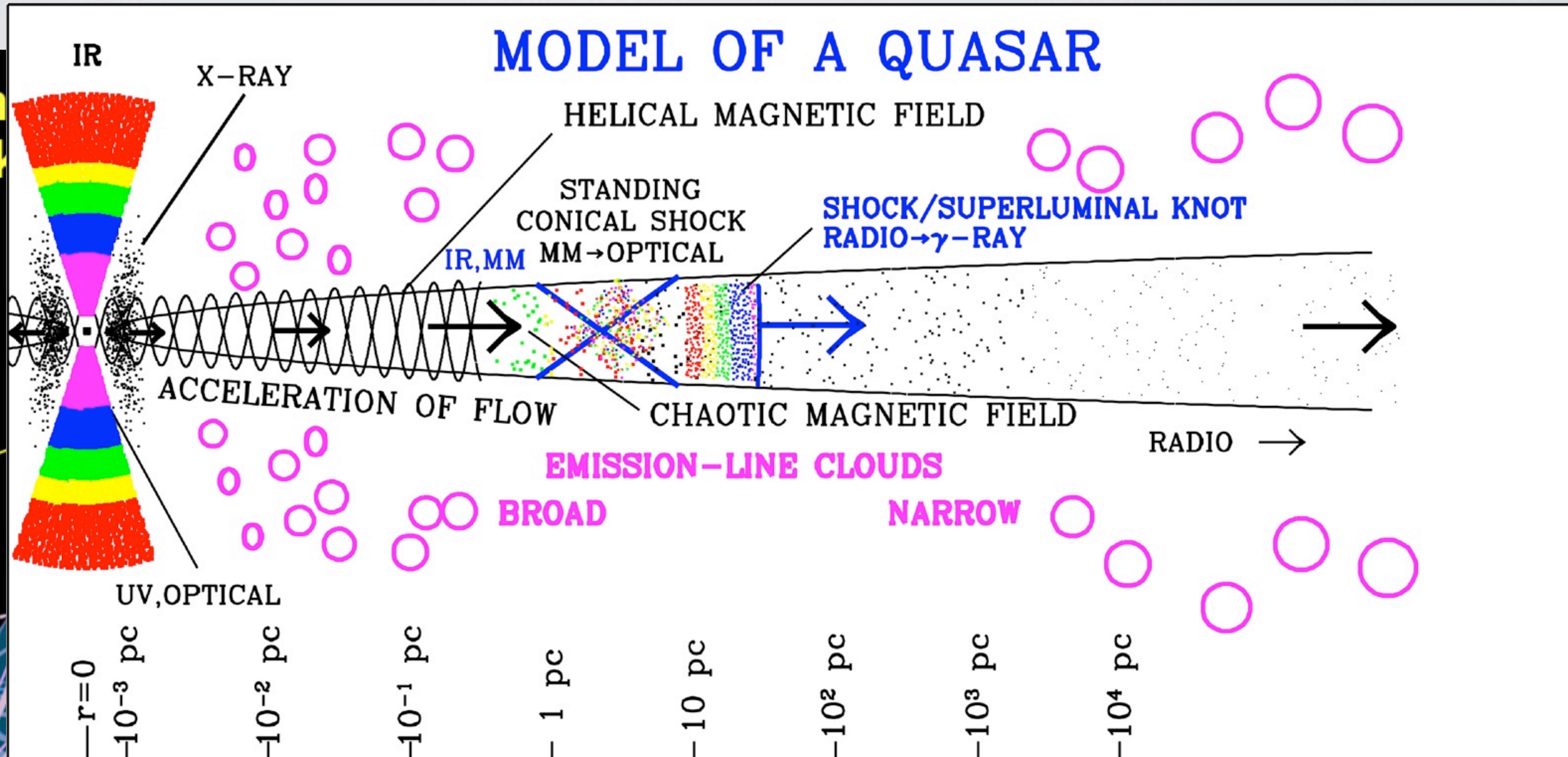
# MAGNETIC FIELD STRUCTURE




Credit: NASA and Ann Field (Space Telescope Science Institute)

# MAGNETIC FIELD STRUCTURE



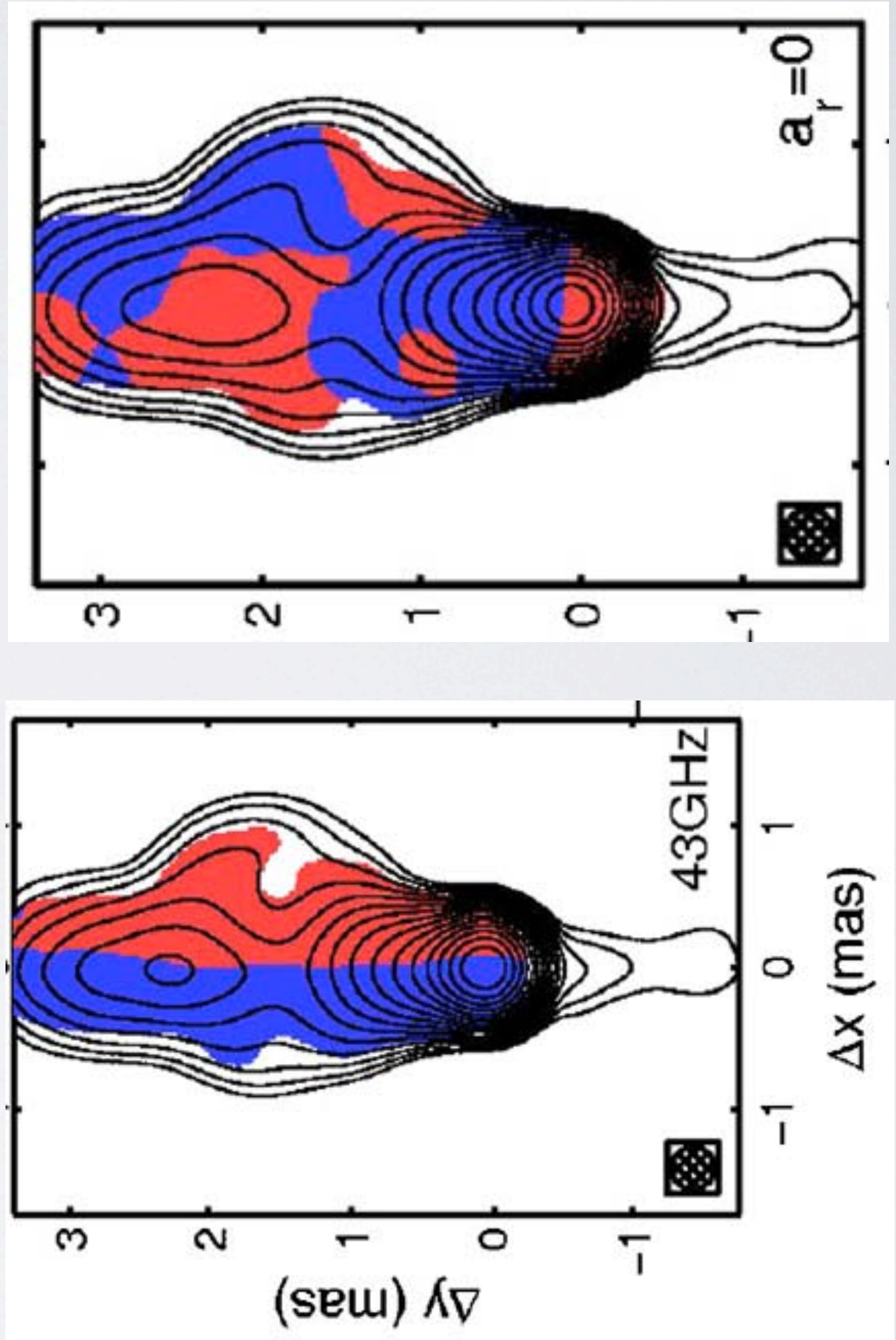




Credit: A. Marscher

Credit: NASA and Ann Field (Space Telescope Science Institute)

# WHAT DO WE GAIN WITH FRM OBSERVATIONS?

- True direction of the magnetic field
  - RM of 500 rad/m$^2$ rotates the EVPA by ~10$^o$ at 15 GHz and by 40$^o$ at 8 GHz
- Direction of the line of sight component of the B-field in the rotating plasma
- Amount of Faraday depolarization
  - internal or external screen?
- Distance dependence
  - more material close to the core?




Broderick & McKinney 2010

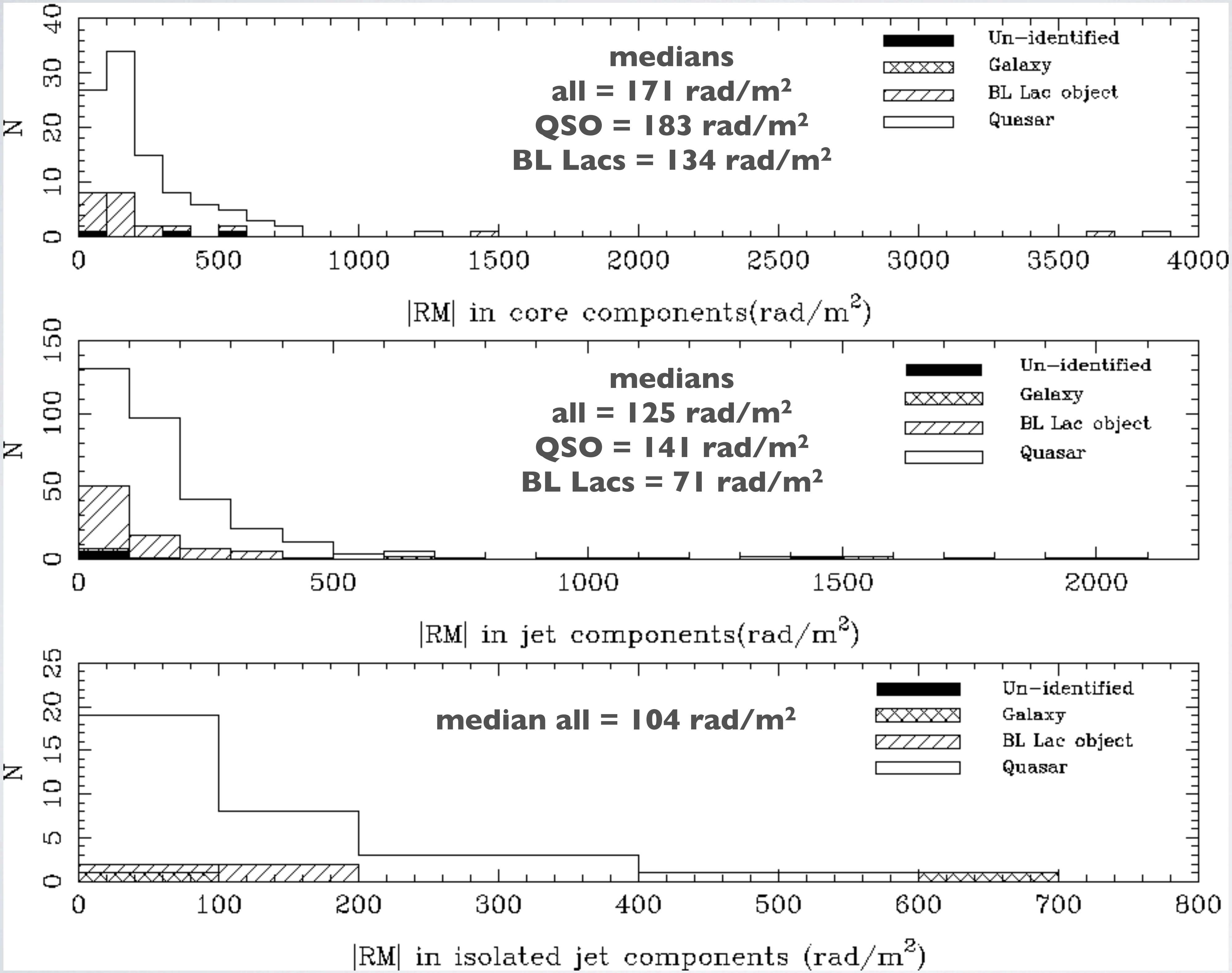
Sign of Faraday rotation = direction of line of sight components of the B-field

# OUR SAMPLE AND OBSERVATIONS

- 191 sources from the MOJAVE program
- 12 epochs with the VLBA in 2006
- 15, 12, 8.4 and 8.1 GHz
- 211 observations (20 sources were observed twice)
- 159 maps with significant polarization to calculate RM maps

➡ Largest sample so far studied for pc-scale Faraday rotation

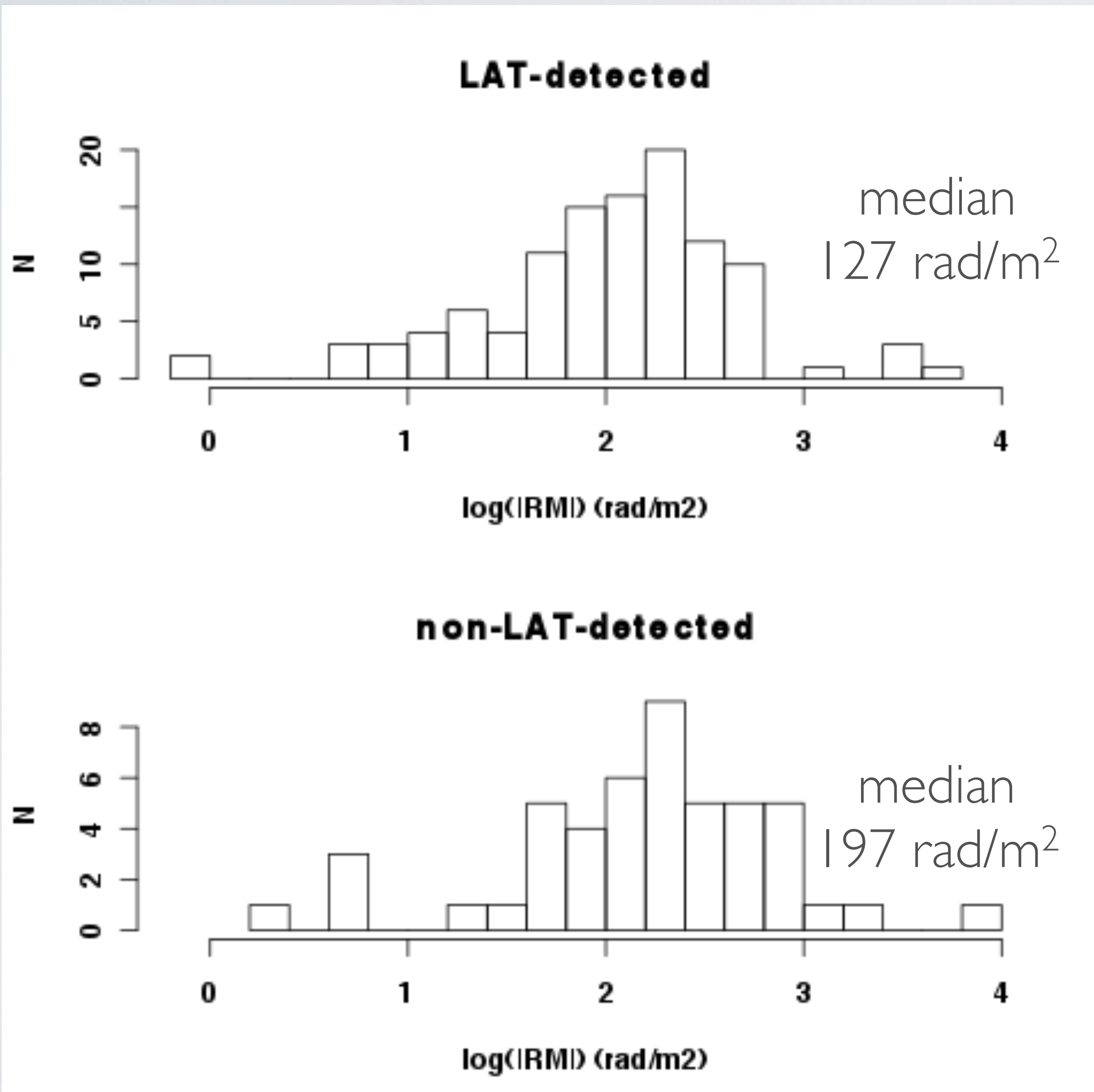
# CORE VS. JET RM




- In the majority of sources RM is less than 500 rad/m$^2$ which would rotate EVPAs at 15 GHz by about 10° and at 8 GHz by 40°
- Core and Jet distributions differ significantly with higher RM in the cores
- Quasar and BL Lac core difference not significant but jets differ significantly

Hovatta et al. 2011 in preparation

# IS THERE A RM AND GAMMA-RAY CONNECTION?



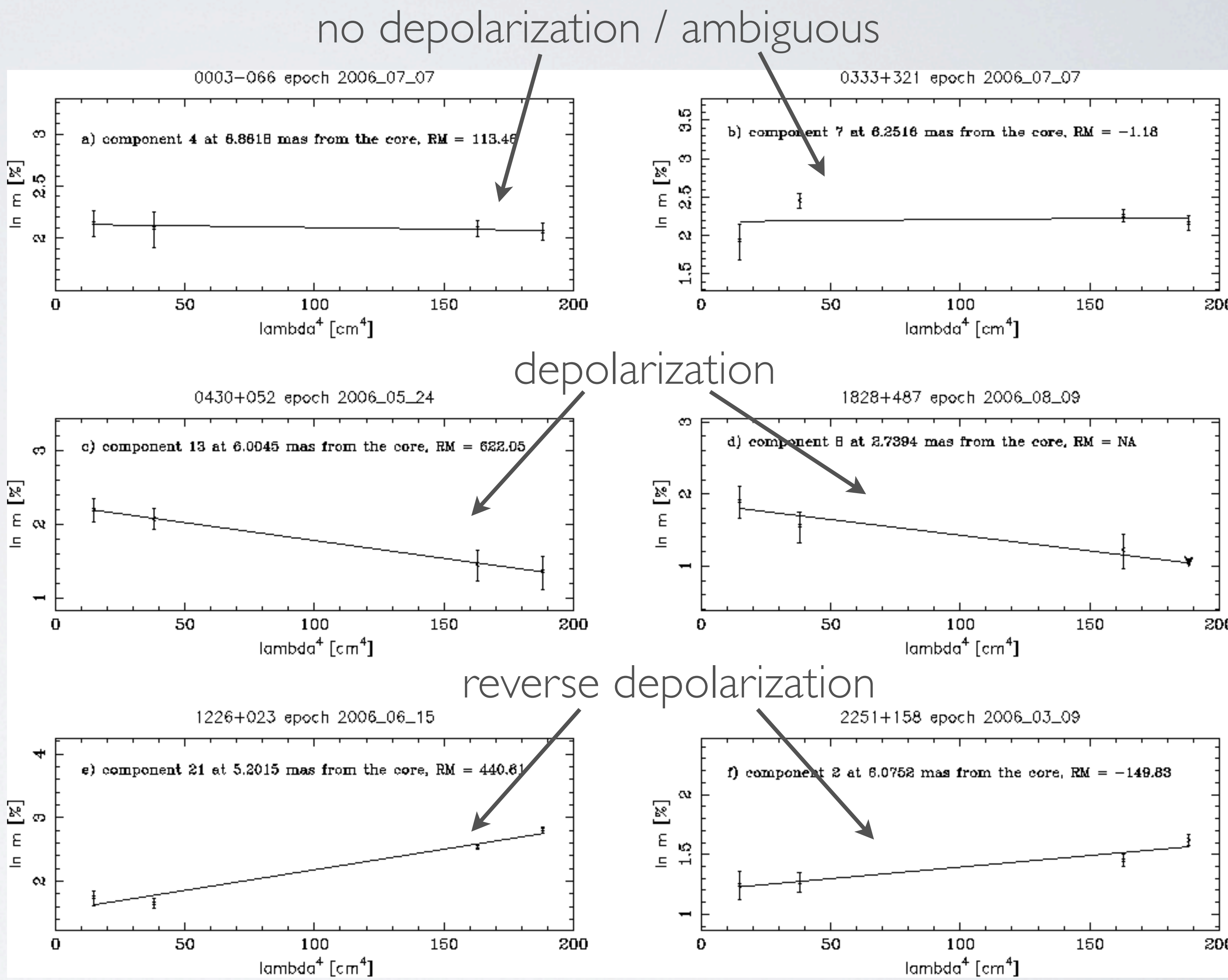

- 119 LAT detected sources with 131 RM observations
    - 111 with detected RM
- 72 non-detected sources with 80 RM observations
    - 48 with detected RM
- K-S test p = 0.12
    - no significant difference
- Higher RM detection rate in LAT-detected due to correlation between gamma-ray flux and polarized flux density in radio (Lister et al. 2011, Kadler et al. in prep.)

# WHERE IS THE FARADAY SCREEN?

- Internal to the jet?
  - low-energy end of the synchrotron emitting electrons
  - ✔ could explain fast RM variations easily
  - according to the standard Burn 1966 model causes severe depolarization at total rotations larger than $45^\circ$ ($\approx$ 800 rad/$m^2$ between 8.1 and 15.3 GHz)
    - ✔ what about other magnetic field configurations and number of lines of sight?
- External to the jet?
  - Far away screen: Galactic Faraday rotation, intergalactic clouds, narrow line region of the AGN
    - ✔ Rotation measures should not vary over time scales of years
  - Screen interacting with the jet: bending jet, sheath around the jet
    - ✔ Variability on time scales of years possible but difficult to explain very fast variations

# DEPOLARIZATION OBSERVATIONS ARE THE CLUE

- Internal and external depolarization formulae follow the same form for RM < 800 rad/m$^2$
  - $m = m_0 \exp(-b\lambda^4)$
- Possible to fit for depolarization
- Slope b of the fit is the amount of depolarization
- Relation to RM depends on the model



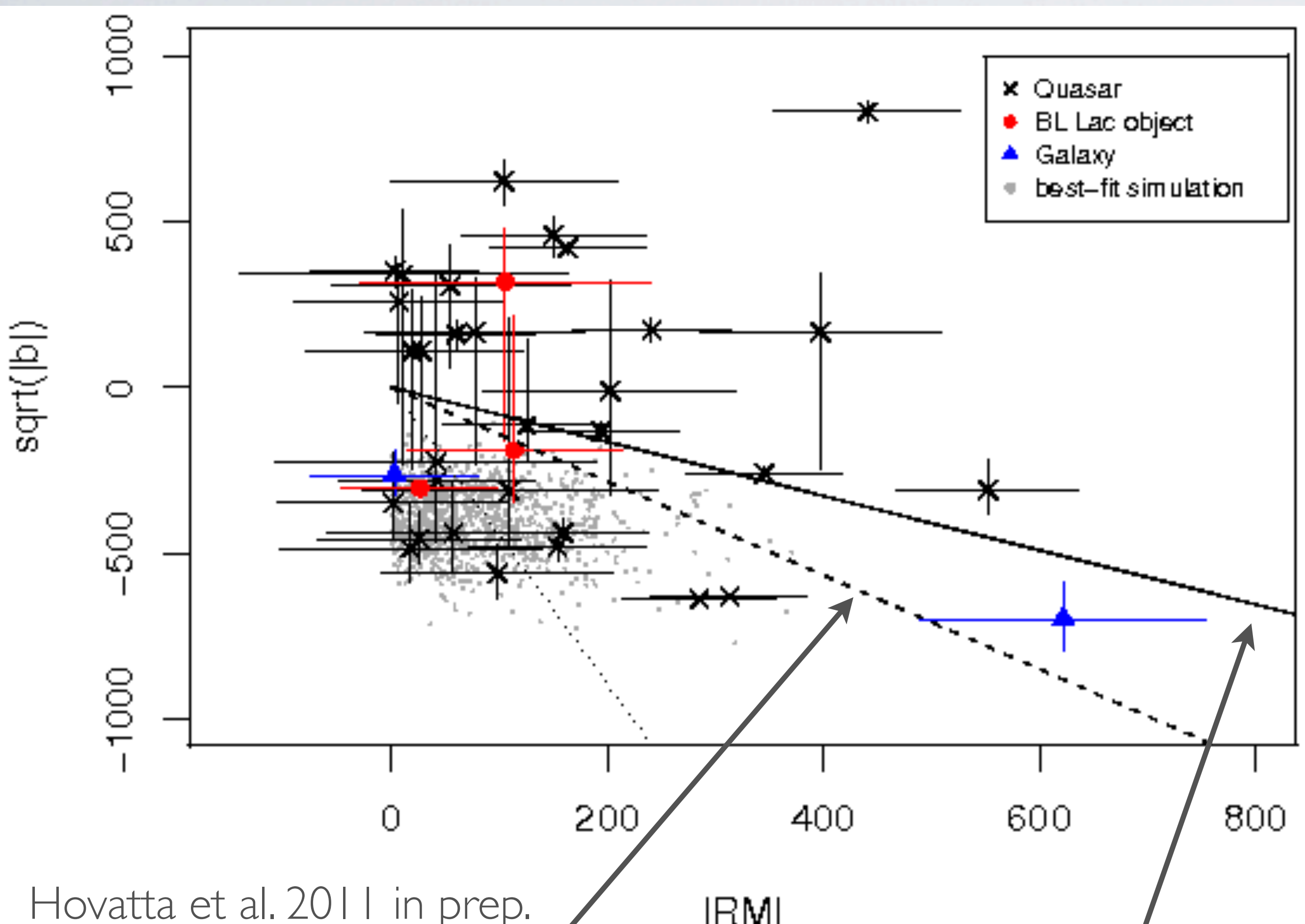

$$\ln m = \ln m_0 - b\lambda^4$$

Hovatta et al. 2011 in preparation

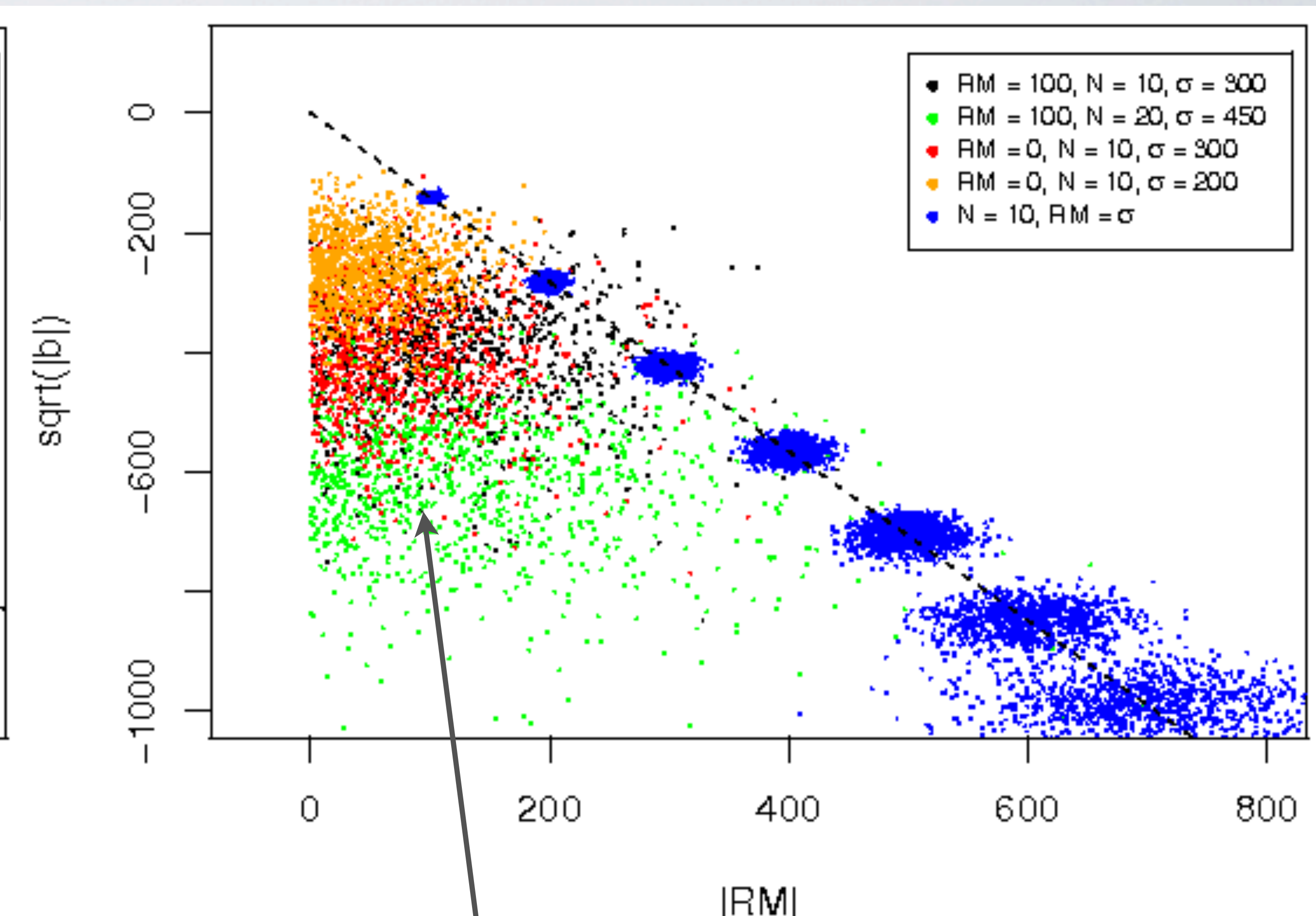
# DEPOLARIZATION MODELS

Fitted depolarization values against RM for isolated optically thin jet components

Simulations for external Faraday depolarization




Hovatta et al. 2011 in prep.



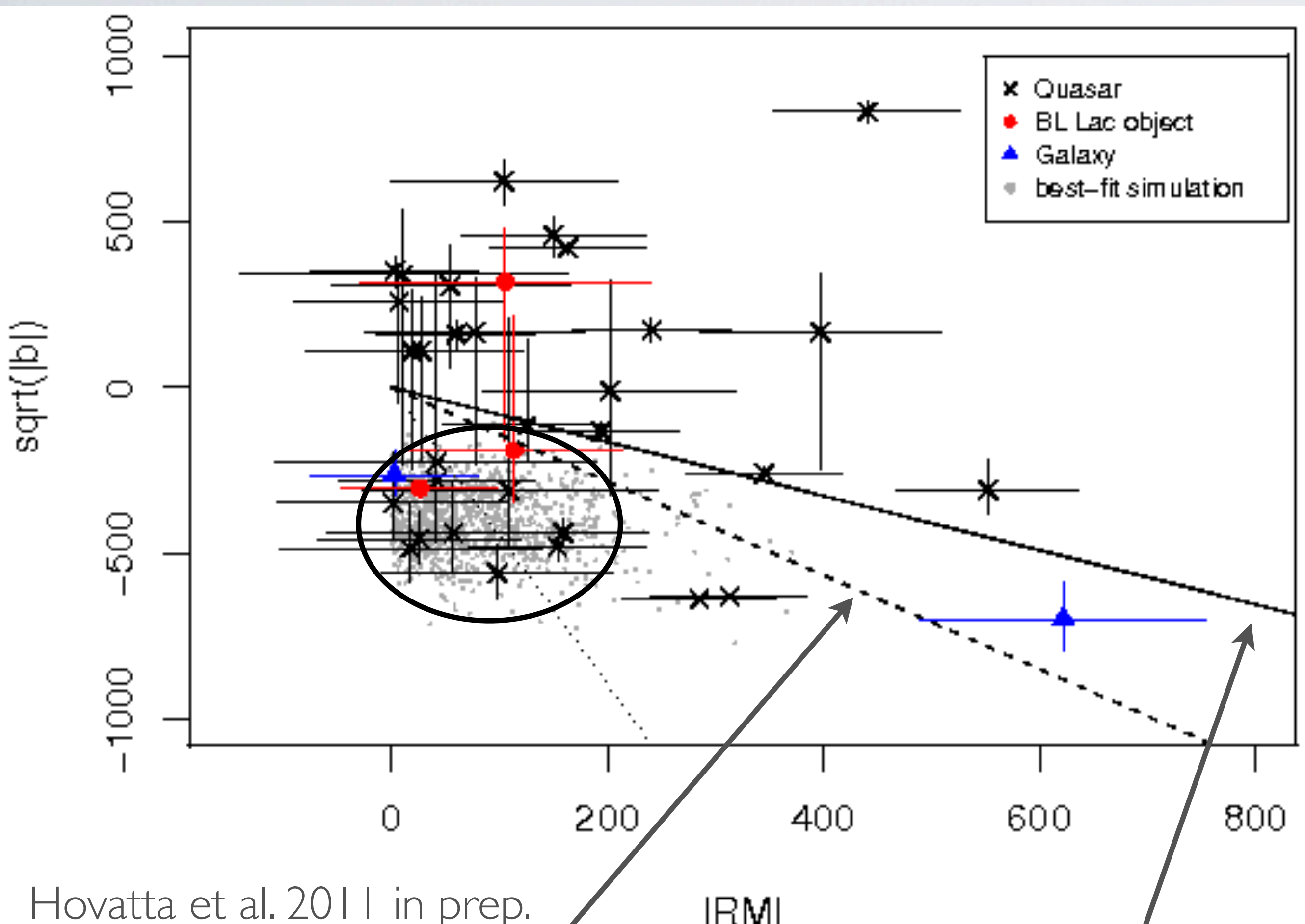

External Faraday depolarization when scale of random RM fluctuations σ is the same as observed RM. Then $b = \sigma^2 = RM^2$

Internal Faraday depolarization $b = 2RM^2$

Small number of lines of sight

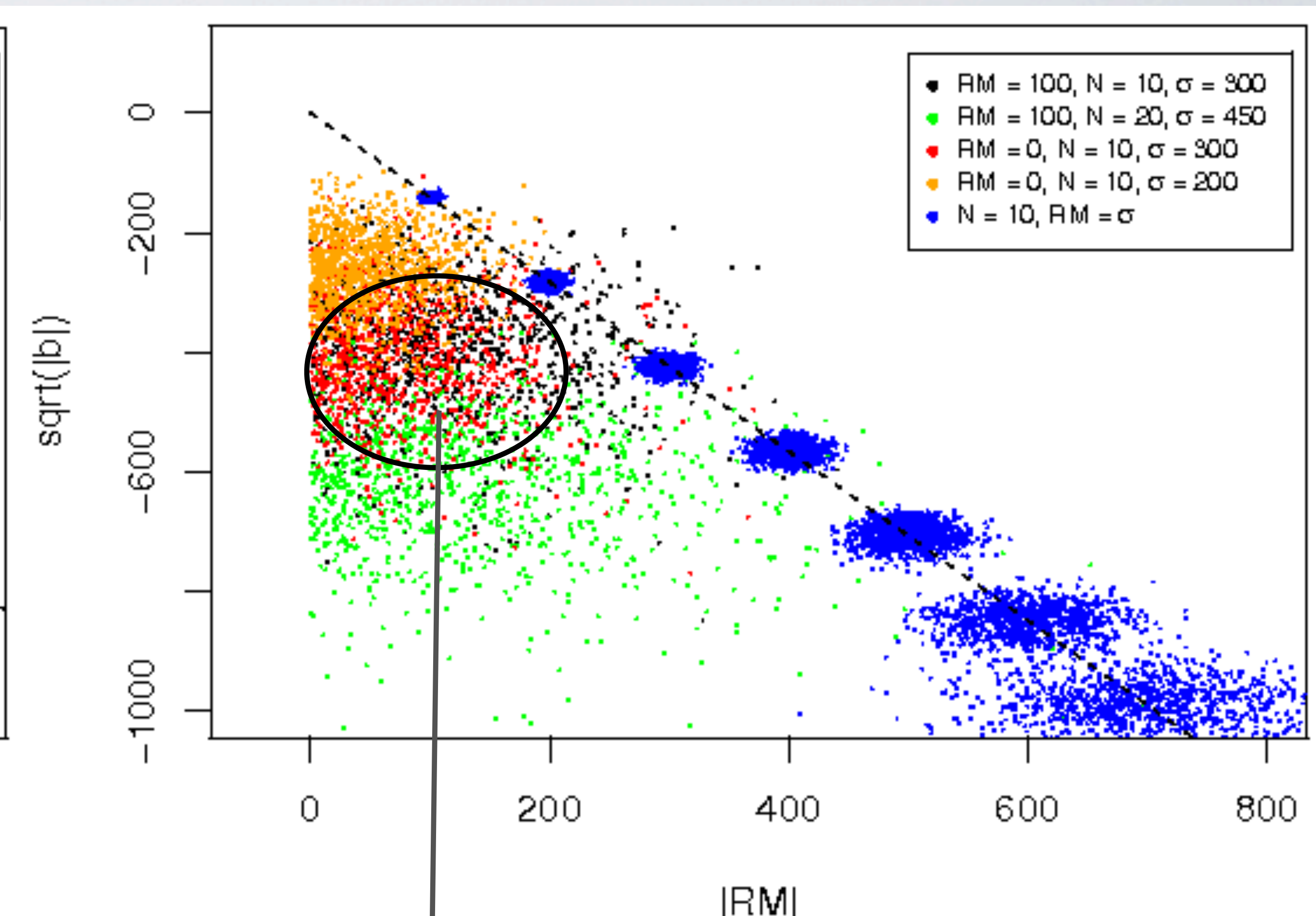
# DEPOLARIZATION MODELS

Fitted depolarization values against RM for isolated optically thin jet components




Hovatta et al. 2011 in prep.

Simulations for external Faraday depolarization




External Faraday depolarization when scale of random RM fluctuations $\sigma$ is the same as observed RM. Then $b = \sigma^2 = RM^2$

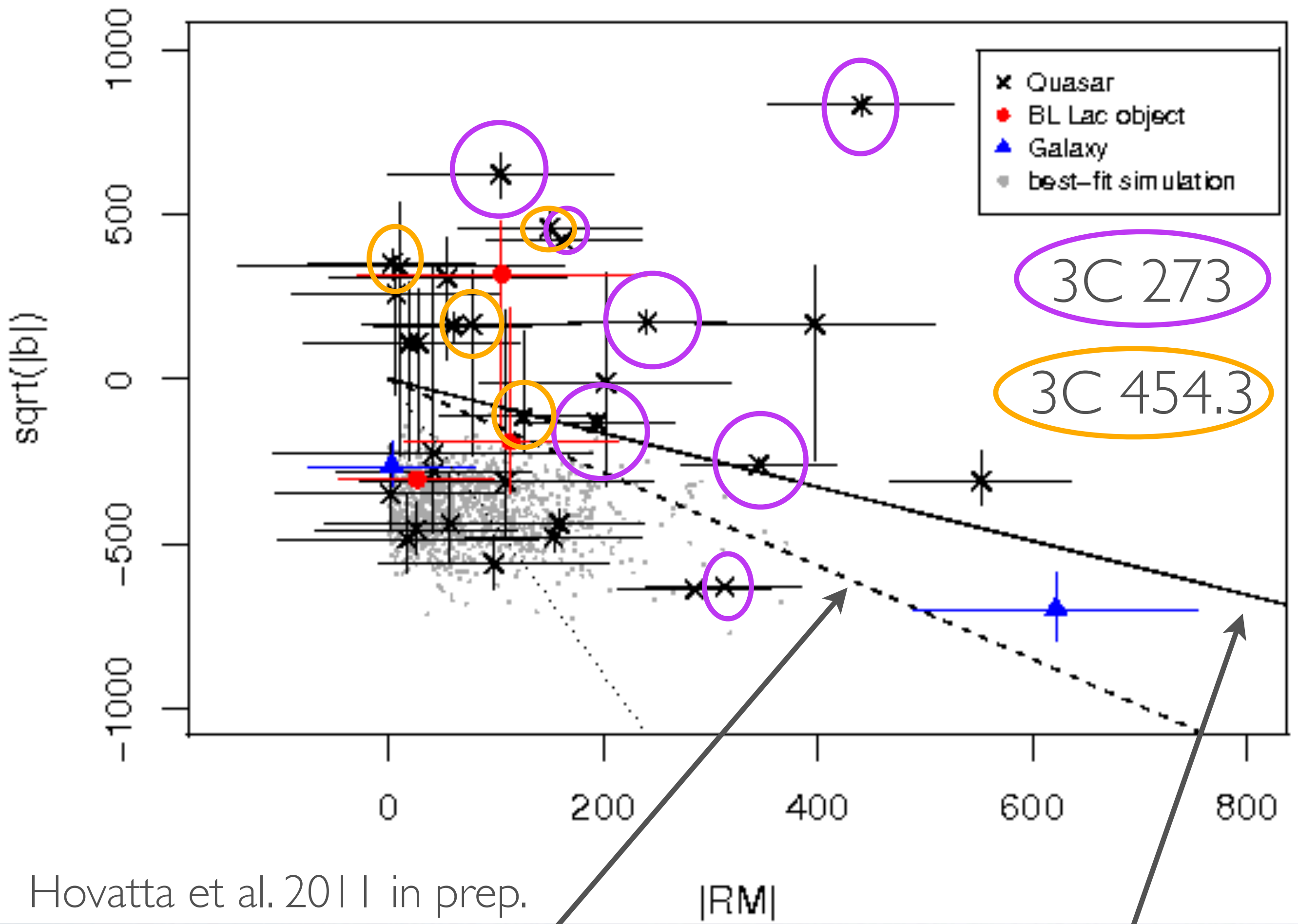
Internal Faraday depolarization $b = 2RM^2$

Random external Faraday screen can explain most of our observed depolarization

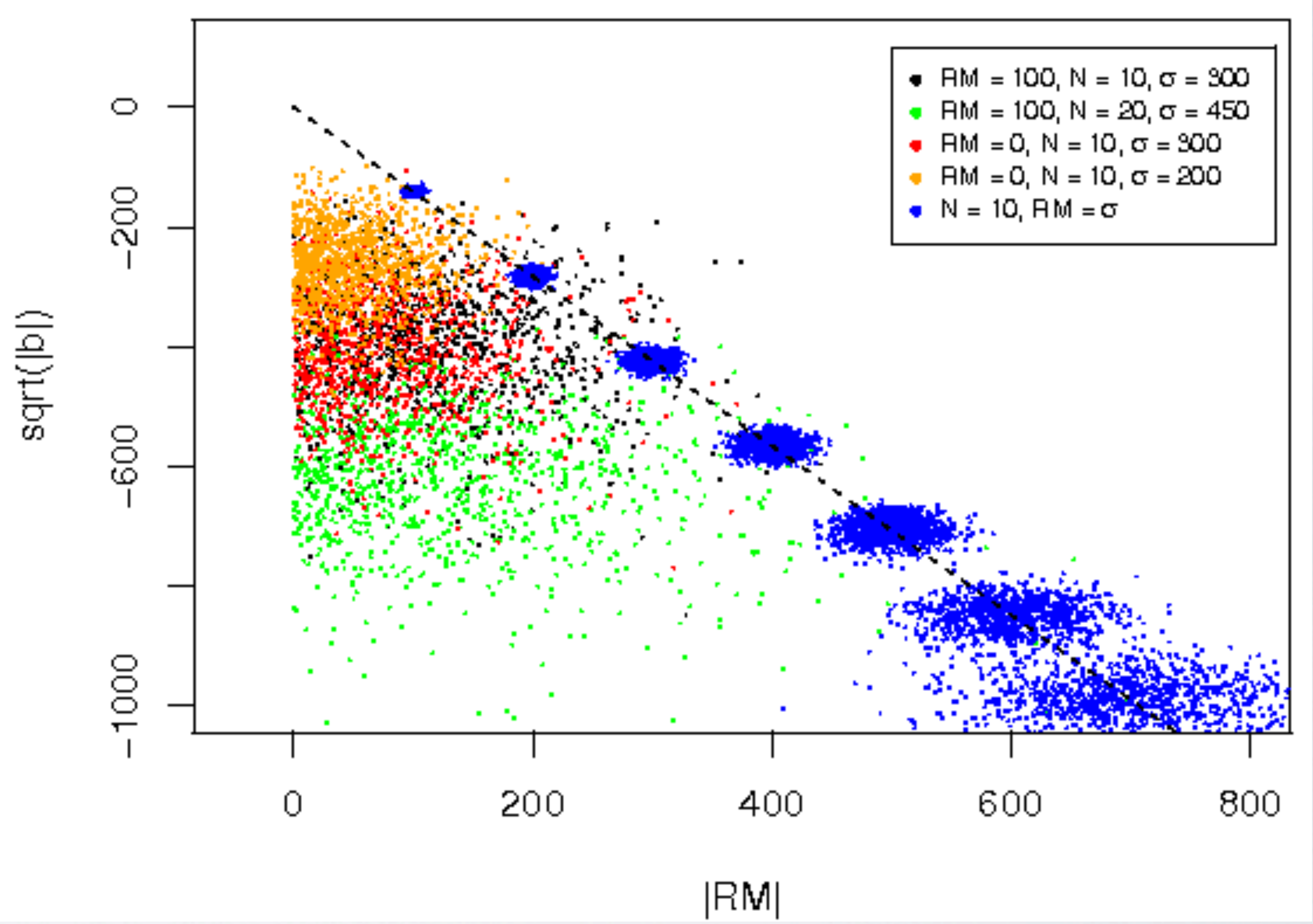
# DEPOLARIZATION MODELS

Fitted depolarization values against RM for isolated optically thin jet components

Simulations for external Faraday depolarization




Hovatta et al. 2011 in prep.




External Faraday depolarization when scale of random RM fluctuations $\sigma$ is the same as observed RM. Then $b = \sigma^2 = RM^2$

Internal Faraday depolarization $b = 2RM^2$

Internal Faraday rotation is needed to explain the polarization in 3C 273 and 3C 454.3 and solves the fast variability too!

# SIMULATED RM MAPS

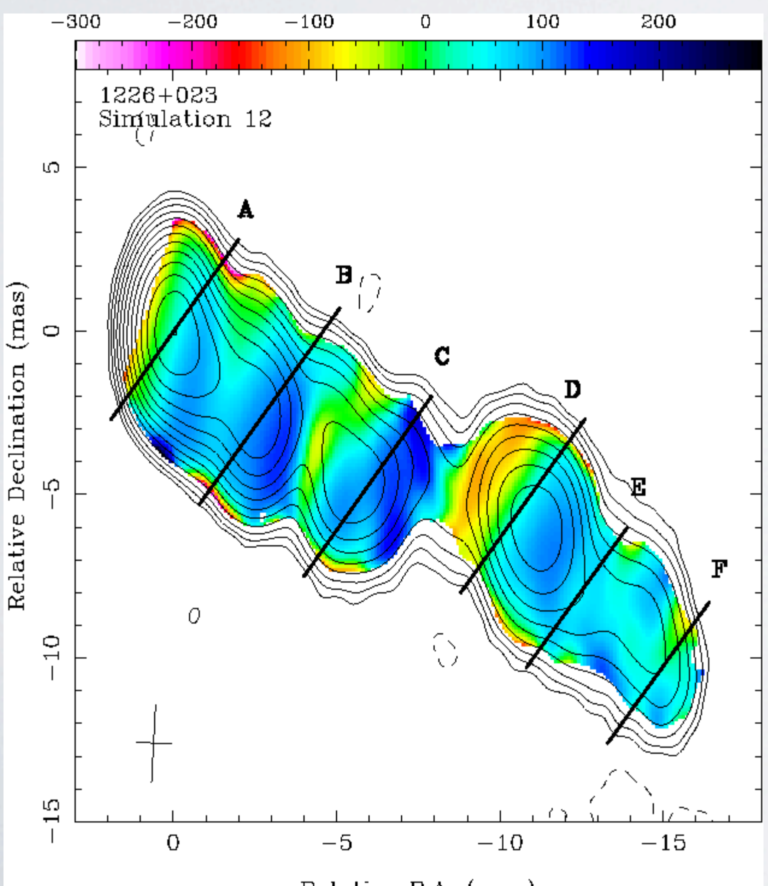
- Simulations of polarization and RM errors and estimating the significance of RM gradients

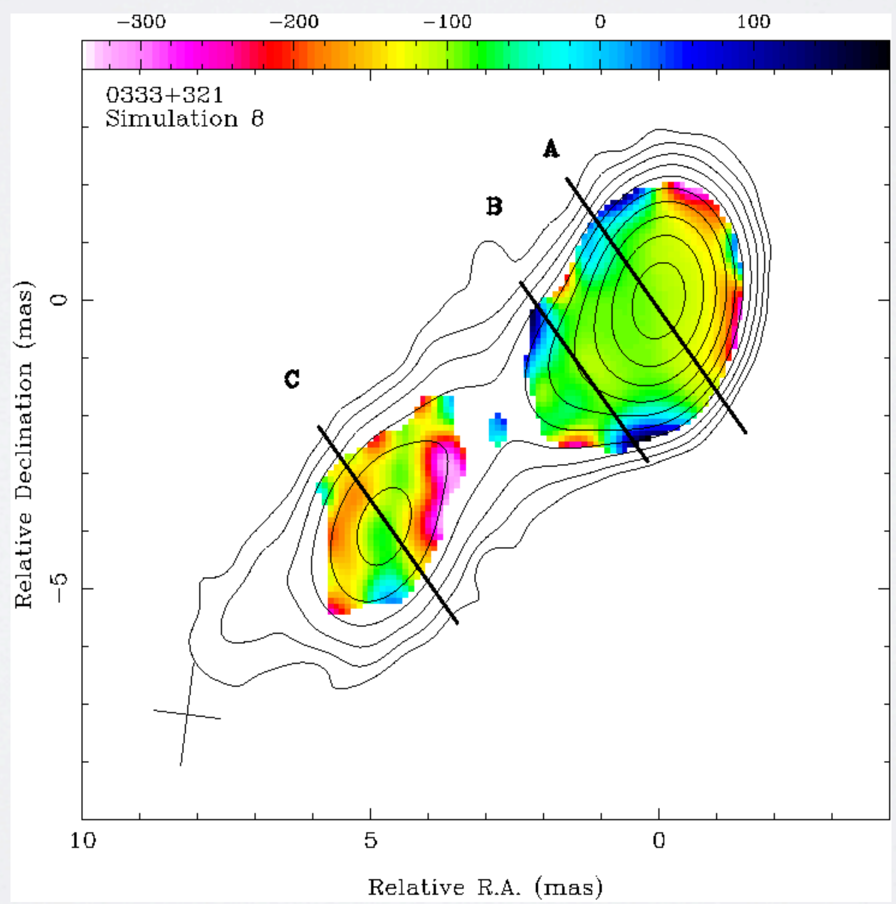
➡ trying to solve the issue of controversial RM gradients (see e.g. Taylor & Zavala 2010)

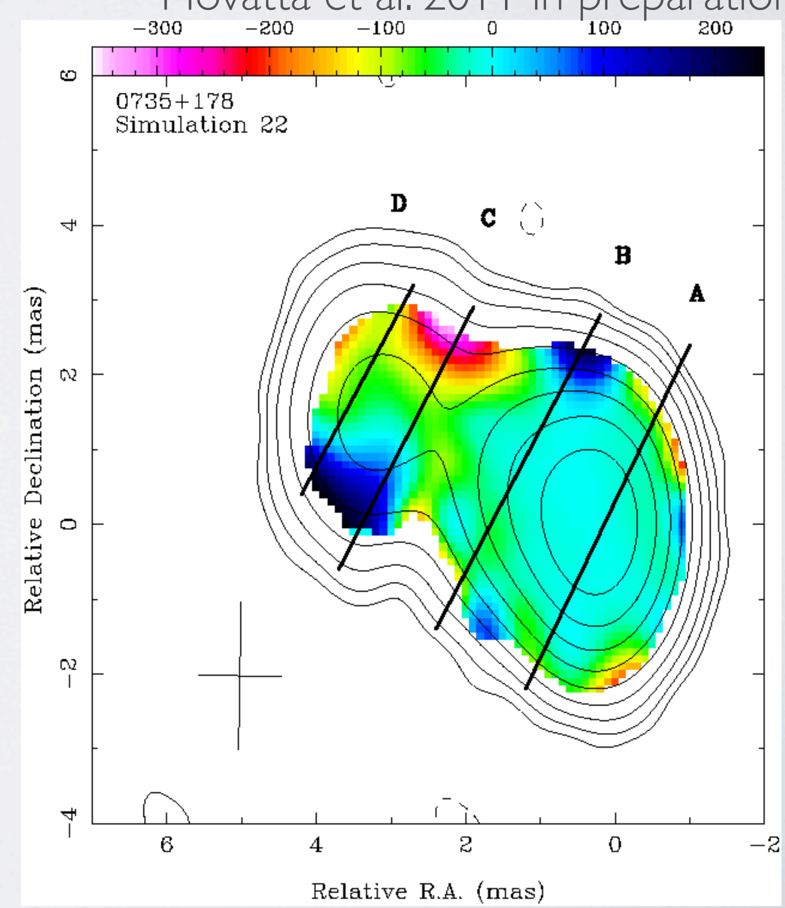
- simulated RM maps using total intensity structure of 3 real sources
  - 1000 simulations with random noise of the same order as in real data

➡ how large spurious gradients can appear in RM maps due to noise and finite beam size

Hovatta et al. 2011 in preparation

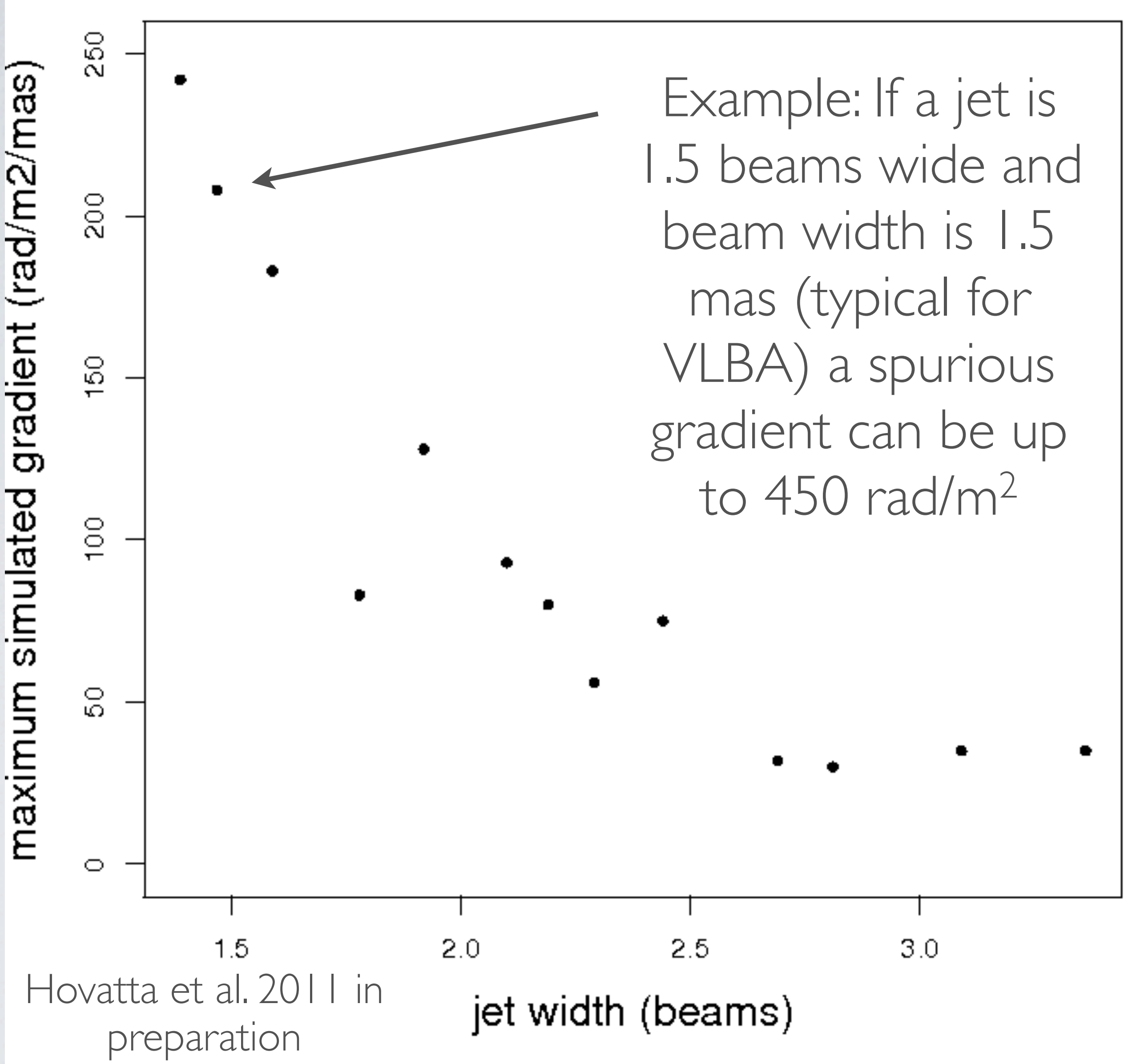


# SIMULATION RESULTS

maximum spurious gradient in1000 simulations

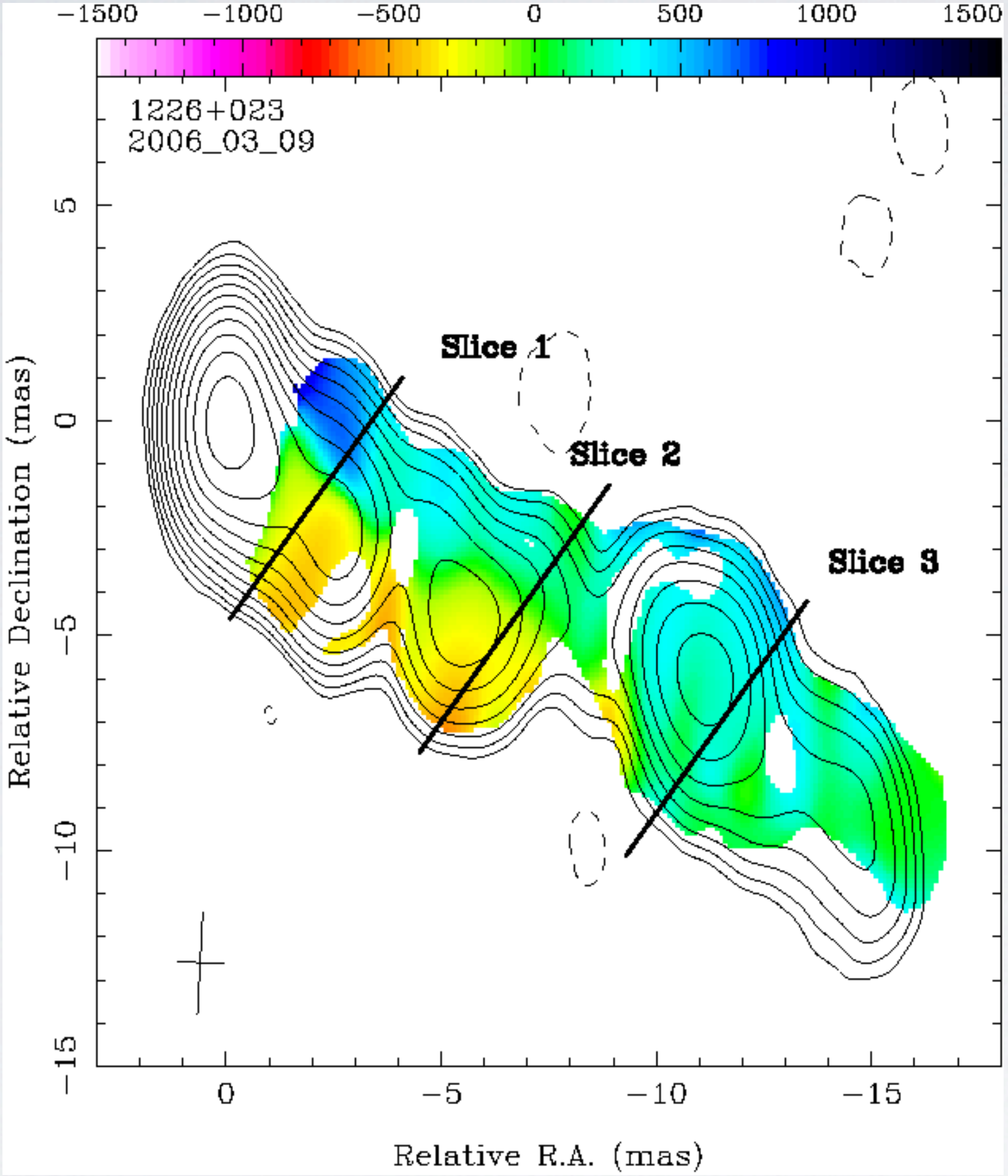


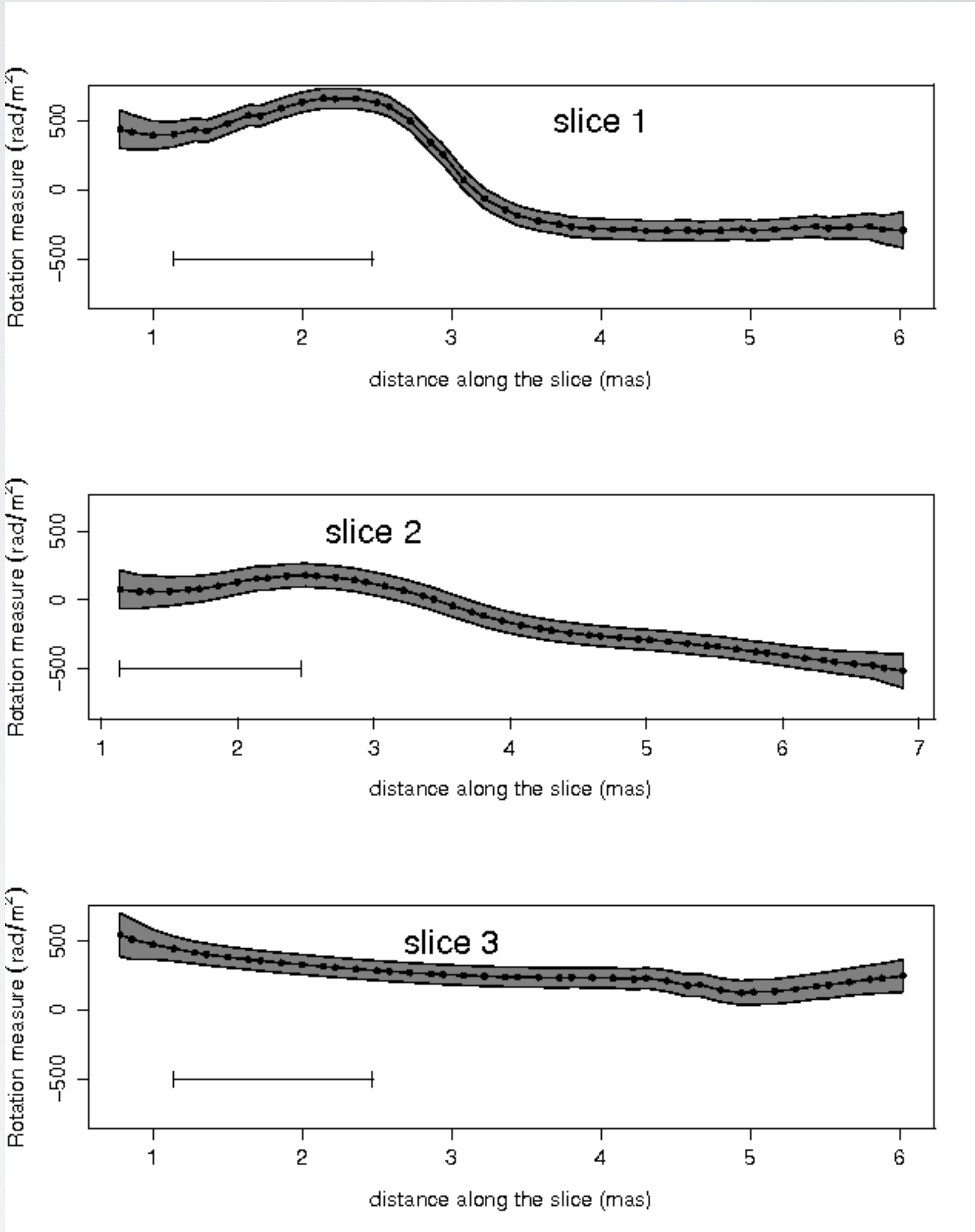

Hovatta et al. 2011 in preparation

- Jet needs to be at least 1.5 beams wide in polarization but preferably > 2.
- Less than 2 beams requires the use of 3σ limit (i.e. change in RM is more than 3 times the error of the RM at the edges of the jet). 1σ is never enough.
- σ should be determined from the variance-covariance matrix of the RM fit where errors in EVPA are calculated using error propagation from U and Q rms values

# RM GRADIENTS IN OUR SAMPLE

3C 273



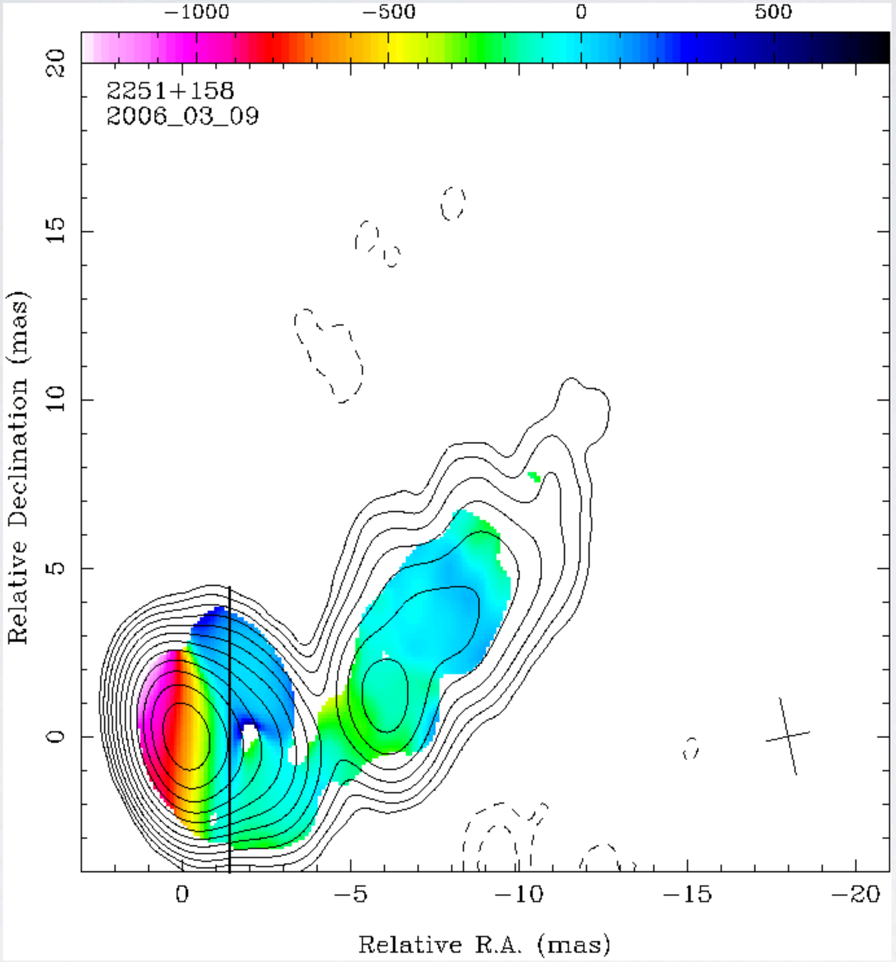



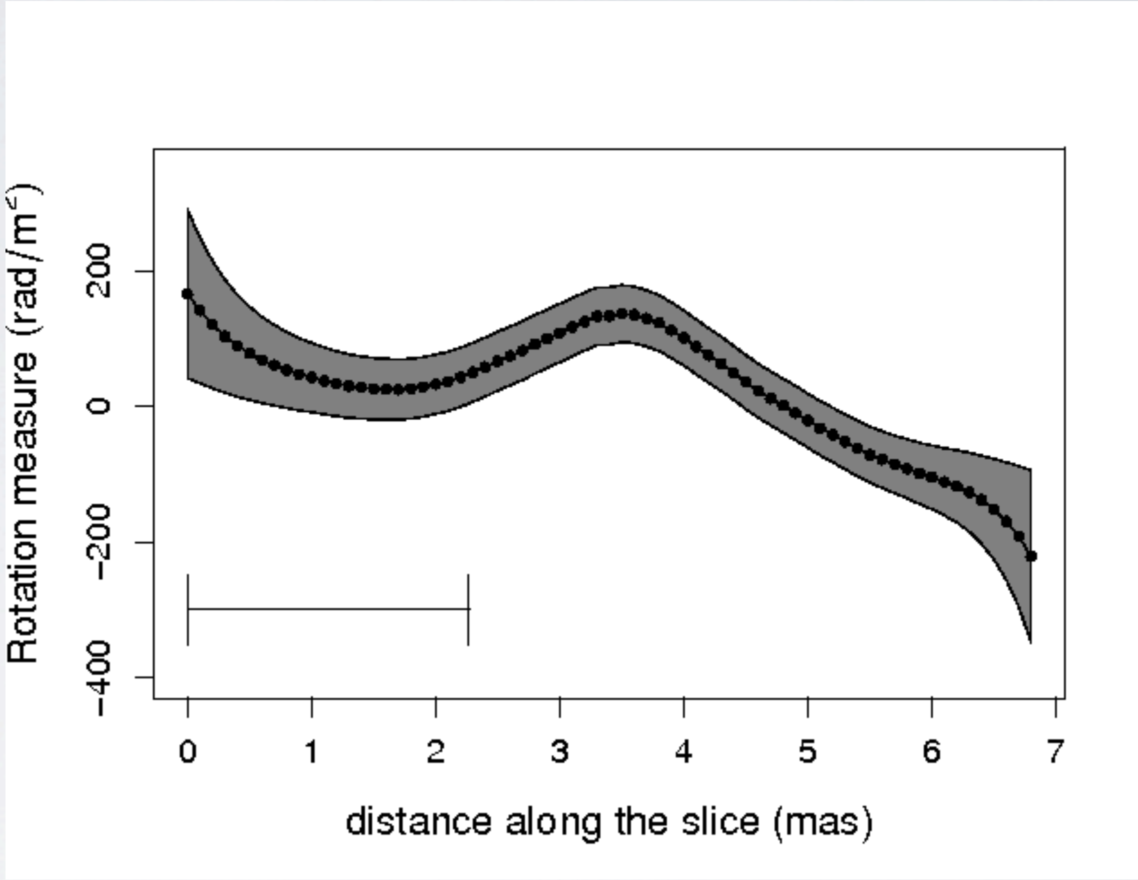

Hovatta et al. 2011
in preparation

- Changed significantly since the Asada et al. 2002,2008 and Zavala & Taylor 2005 results
  - different jet direction
- Our two epochs 3 months apart show significant variability -> hard to explain with external Faraday screen

# RM GRADIENTS IN OUR SAMPLE

3C 454.3

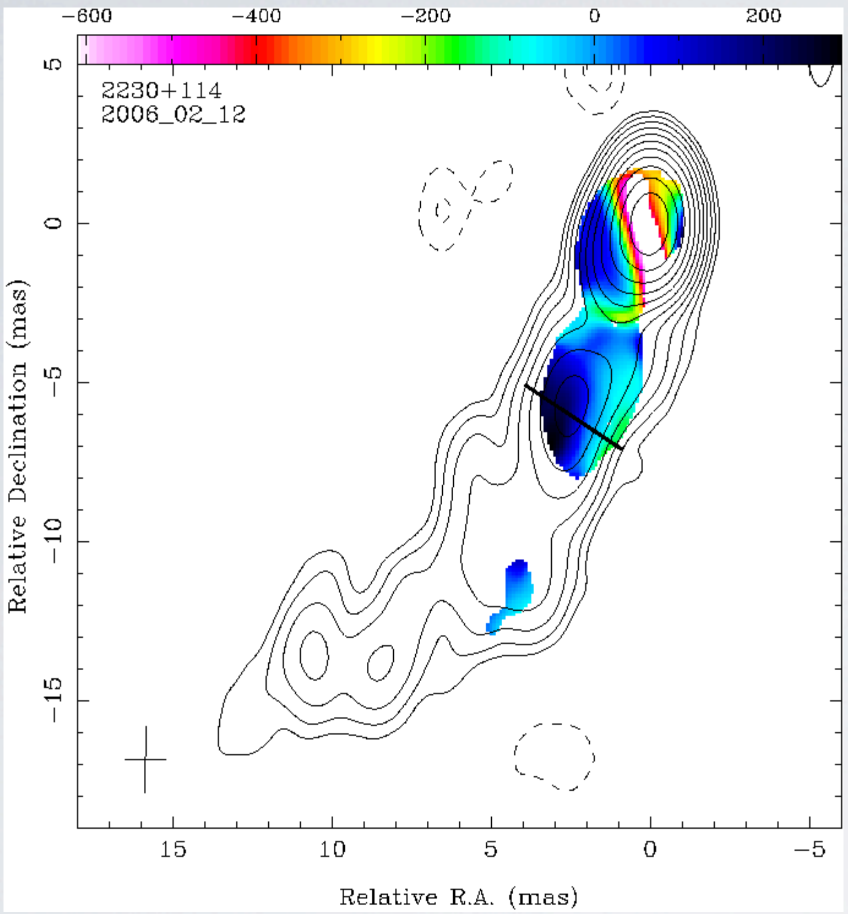


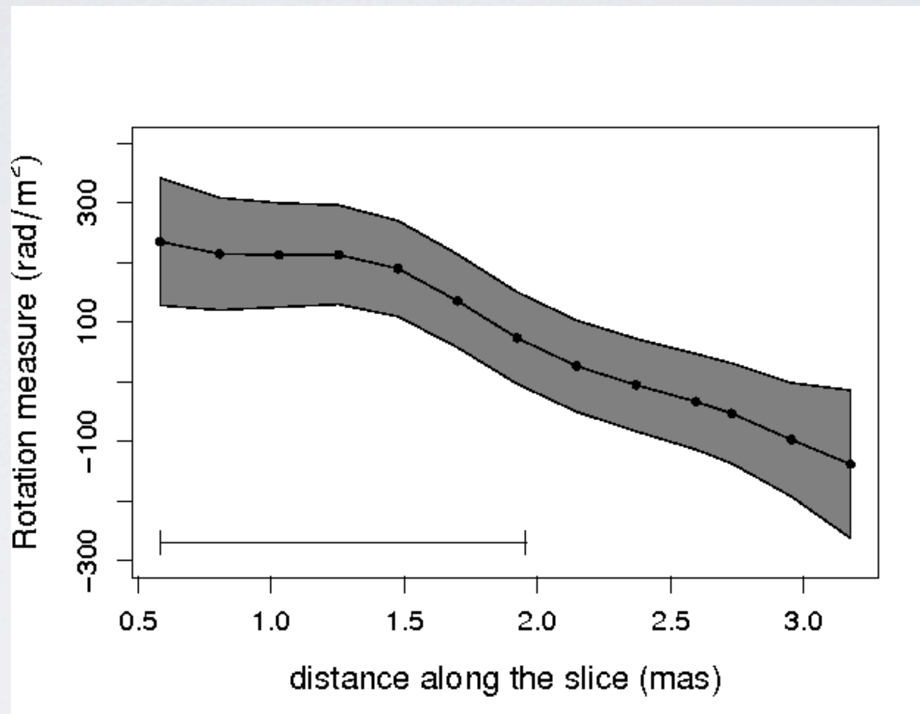

Hovatta et al. 2011 in preparation

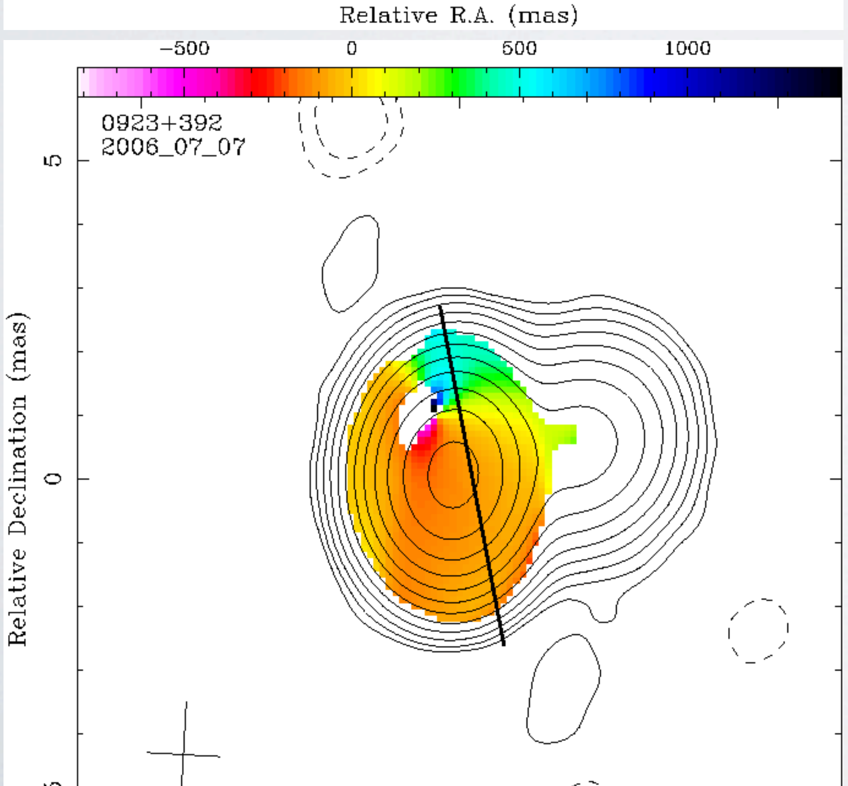
- Not as remarkable as in 3C 273 but still significant (jet is 3 beams wide, change in RM > 3σ)
- Together with total intensity, polarization and spectral index results seems to follow a model with large scale helical magnetic field in the jet (Zamaninasab et al. in preparation)
- Variability over times scales of 3 months -> difficult for external Faraday rotation models

# RM GRADIENTS IN OUR SAMPLE



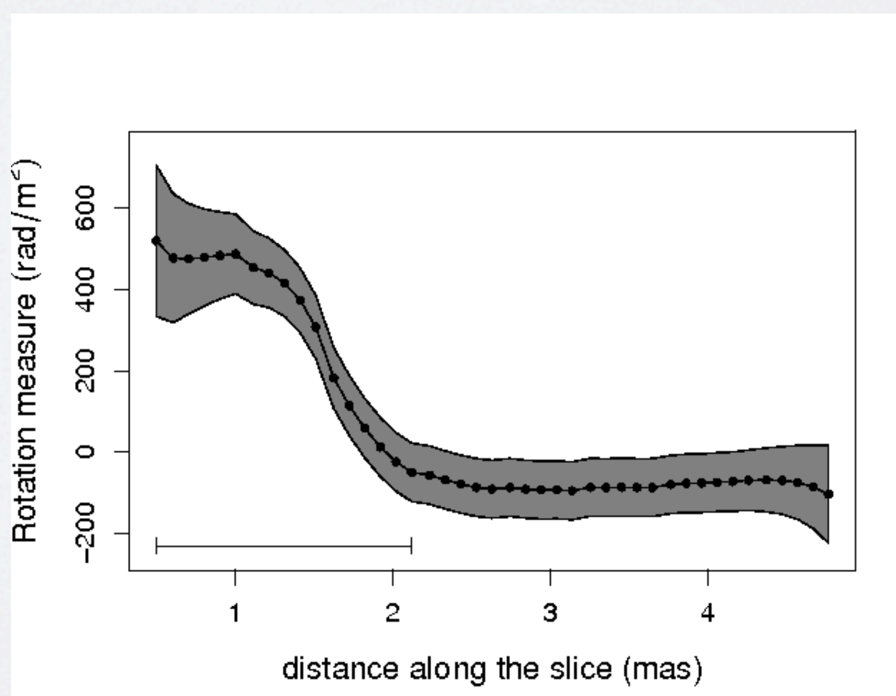

## 2230+114




Hovatta et al. 2011 in preparation

## 0923+392




- 2230+114 polarized jet is 1.9 beams wide but gradient is visible only in a small region
  - need follow-up observations
- 0923+392 sharp gradient in a location where the jet bends
  - interaction with external medium?

# SUMMARY

- In the majority of the sources RMs are less than 500 rad/m$^2$ which rotates 15 GHz EVPAs only by 10° but at 8 GHz the rotation is already 40°
- Magnitude of Faraday rotation diminishes as a function of distance from the core

- There seems to be no direct correlation between gamma-ray emission and Faraday rotation but FRM observations are important for finding the true B-field orientation during gamma-ray flares.

- The jet RMs of most of the sources have not changed over time scales of years -> could be produced by external random screens which is also supported by our depolarization observations.
- In 3C 273 and 3C 454.3 internal Faraday rotation could explain the fast variations, which is also supported by depolarization observations in these two sources
  - Simulations of internal Faraday rotation in different magnetic field configurations are ongoing (Homan et al. in preparation)

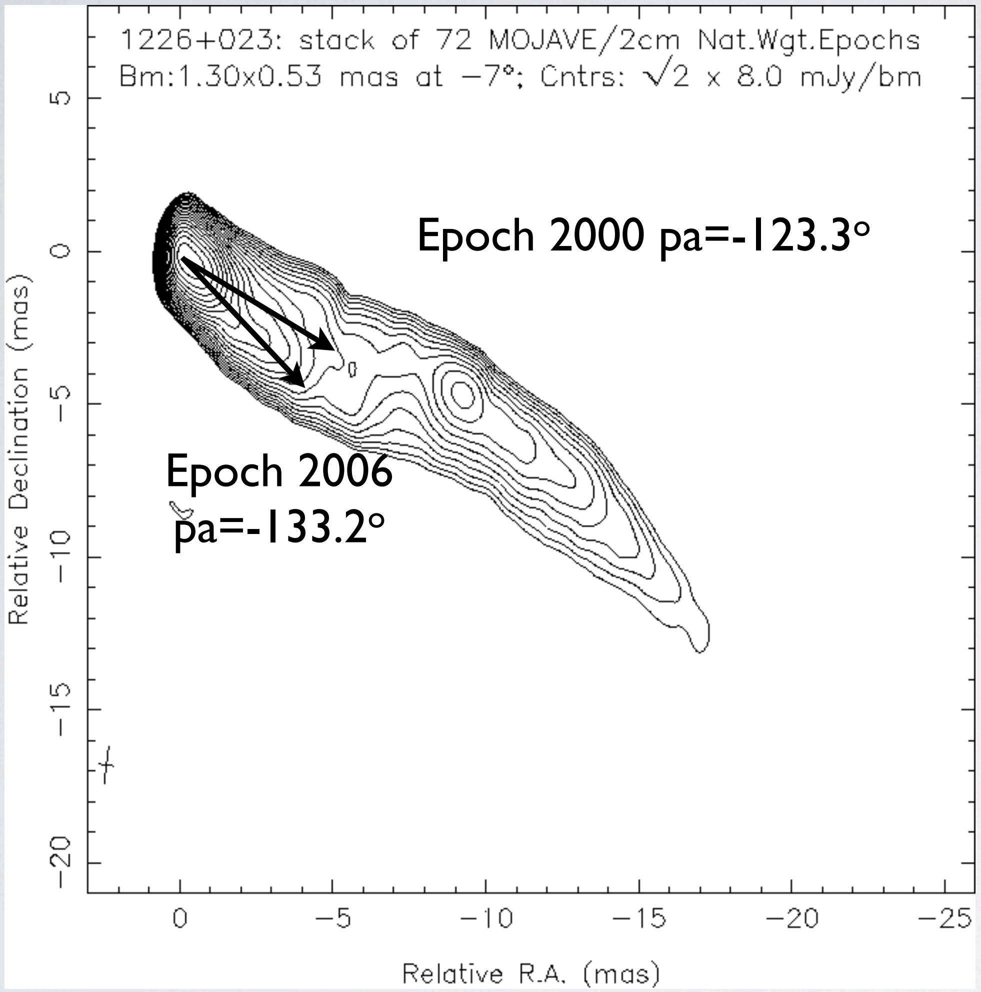
- Our simulations show that the jet needs to be preferably at least 2 beams wide in polarization when transverse RM gradients are studied
  - We detect significant transverse gradients in 3C 273, 3C 454.3, 2230+114 and 0923+392

# TIME VARIABILITY OF FARADAY ROTATION

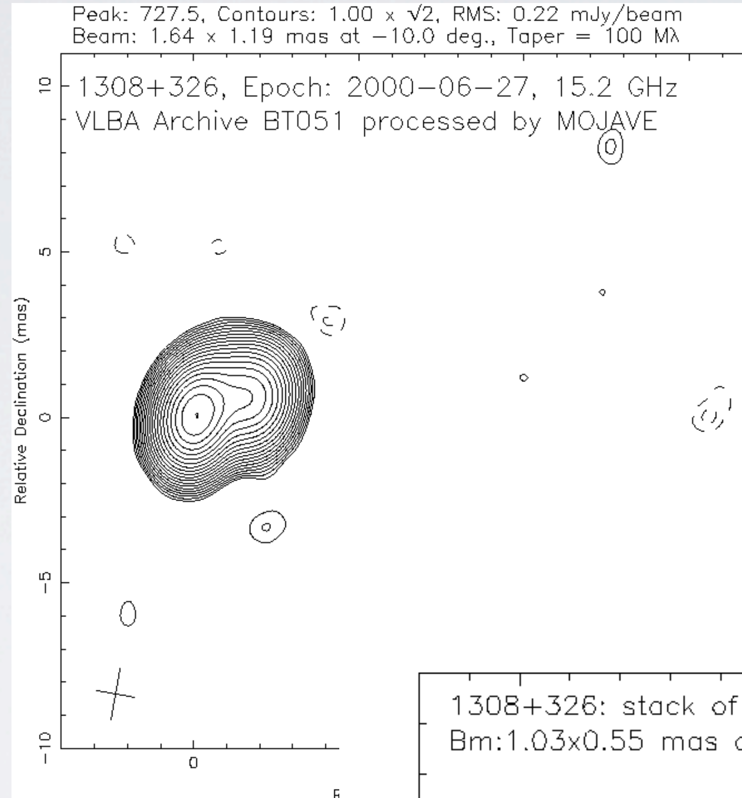
- Comparison to earlier studies, especially Taylor 1998, 2000 Zavala & Taylor 2003,2004, O'Sullivan & Gabuzda 2009
- RMs in the cores of AGN vary from epoch to epoch
  - multiple components blending within the finite beam
- In most of the sources variable jet RMs can be explained with different part of the Faraday screen being illuminated at different times
  - Significant variations in the jet RMs seen on time scales of 3 months in 3C 273 and 3C 454.3 and on time scales of years in 2230+114
    - Internal rotation or interaction between jet and a sheath

# CHANGE OF JET APPEARANCE

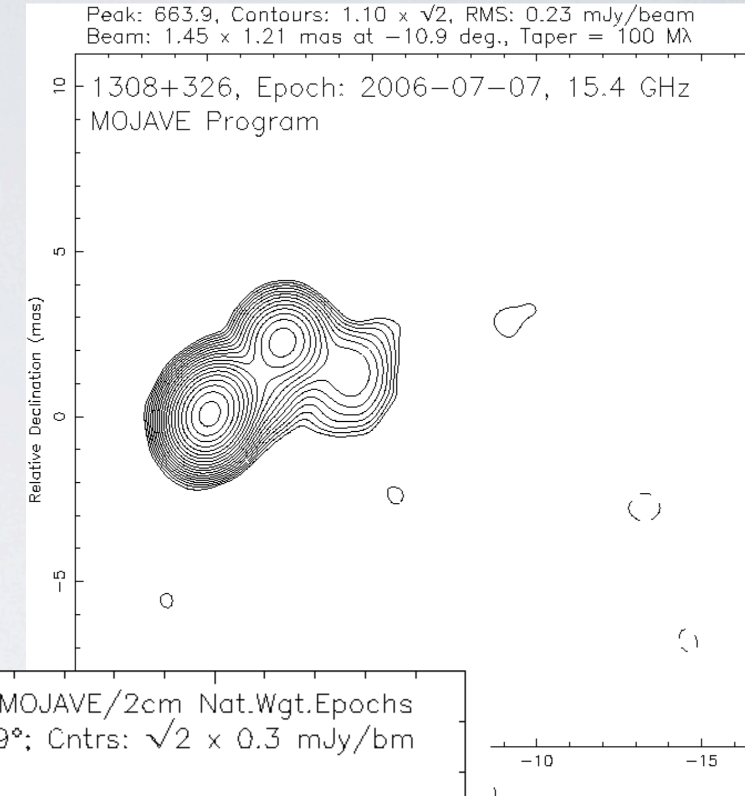
Stacked image of 3C 273

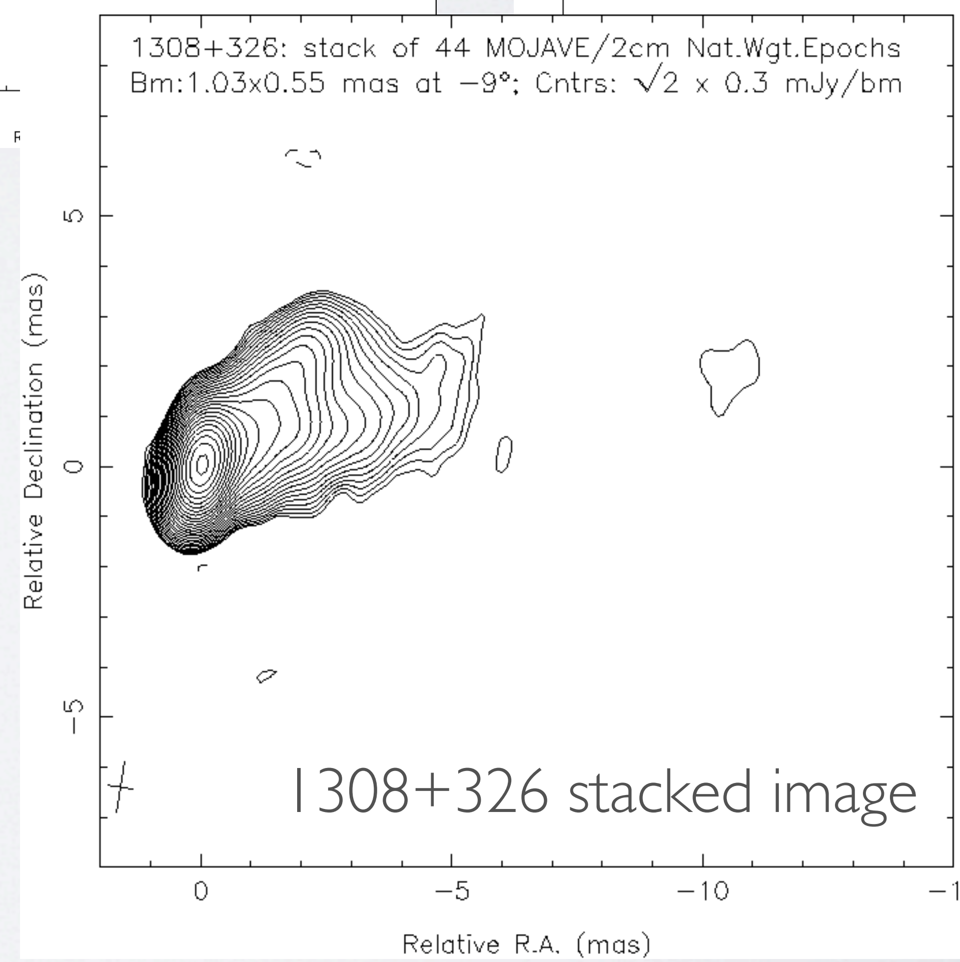



1308+326 Z&T 2000 epoch




1308+326 MOJAVE 2006 epoch




Over time scales of years the components probe a different region of the jet and the Faraday screen. (see also Gomez et al. 2011)