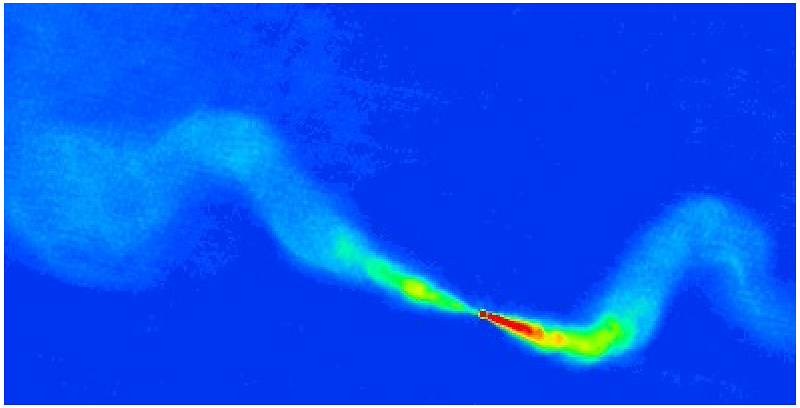
Synchrotron Polarization with ALMA

Robert Laing (ESO)



Synchrotron radiation basics

Ultrarelativistic electrons (positrons) spiralling in a magnetic field

- Spectrum of radiation from a single electron is broad, peaked around the critical frequency ν_c/Hz = 4.2 x $10^{10}\gamma^2$(B/T)
- Electron energy distribution typically a power law

$$n(E)\, dE = n_0\, E^{-(2\alpha+1)}\, dE$$

- Intensity spectrum (if optically thin) is then also a power law with $I(\nu) \propto \nu^{-\alpha}$ with $\alpha \geq 0.5$
- High degrees of linear polarization are possible, up to a maximum $(3\alpha+3)/(3\alpha+5) \approx 0.7$ for an ordered field
- Emissivity $\propto (B\sin\theta)^{\alpha+1}$ for a uniform field at angle θ to the line of sight

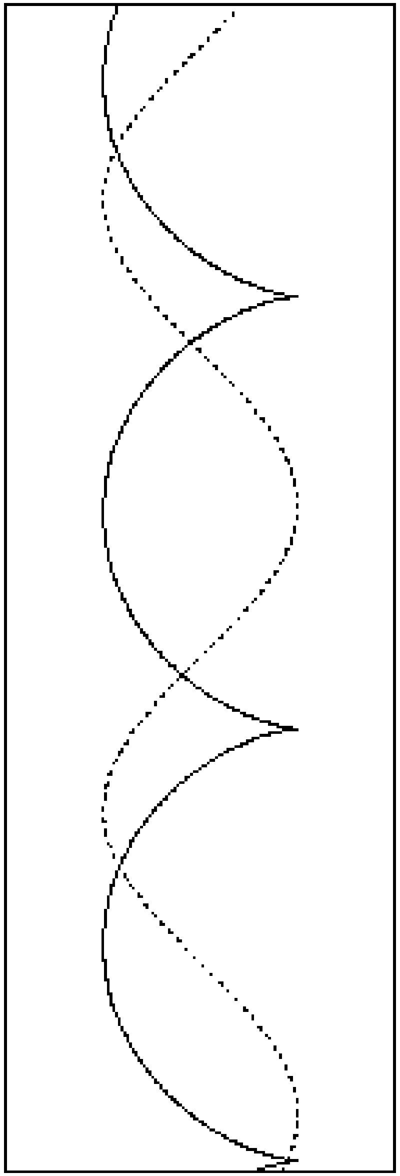
Synchrotron basics (2)

- For a uniform field, the polarization **E**-vector is perpendicular to the projection of the field on the sky (if there are no propagation effects)
- What I call the **apparent field direction** is the perpendicular to the observed **E**-vector in the absence of propagation effects

What can we learn from observations of synchrotron polarization?

- Field structure
  - Integration along the line of sight
  - 3D structure is not a fully determined problem, but we can eliminate some specific models
- Vector ordering
  - Synchrotron emission does not distinguish between + and - field directions
  - Can be hard to tell a 'grand design' (e.g. helical) field from one which is disordered on small scales, but anisotropic
- Trace shocks and compression
  - **B** components perpendicular to shock/compression wave are amplified

Grand Design Helical Fields?

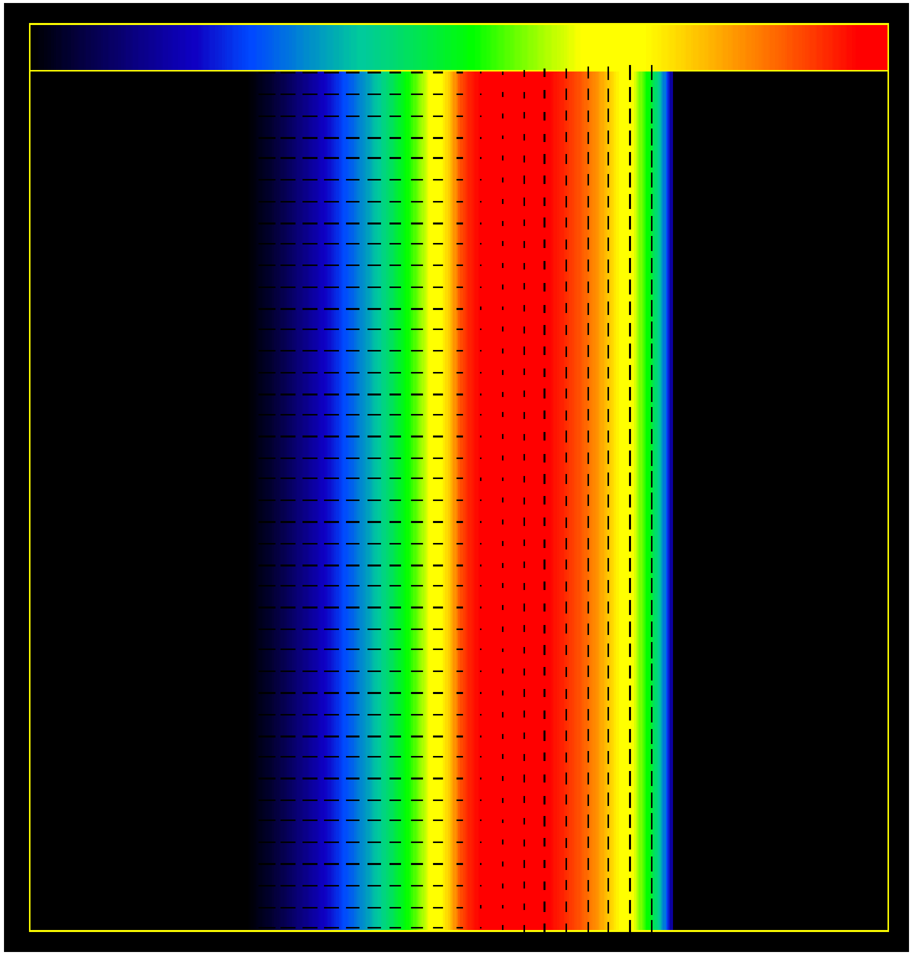


Helical fields generally produce brightness and polarization distributions which have asymmetric transverse profiles

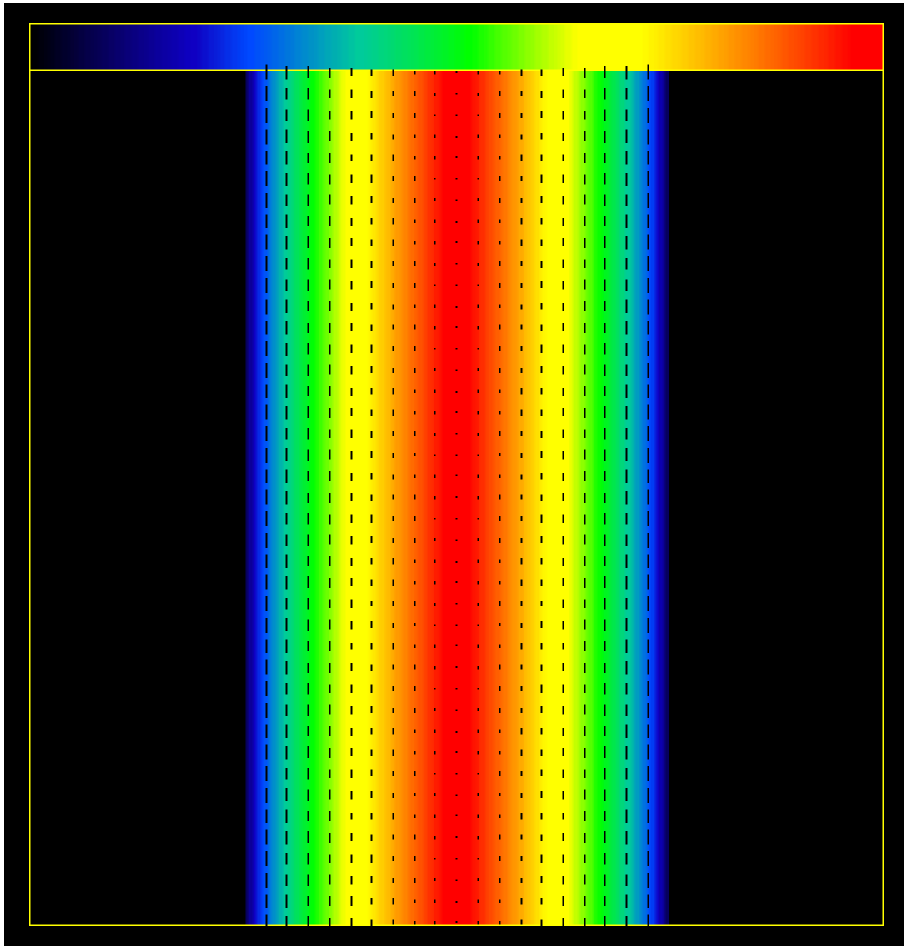
The profiles are symmetrical only if:
- there is no longitudinal component or
 the jet is at 90^{o} to the line of sight in the **rest frame of the emitting material**

Helical Fields

$\theta = 45^o$



$\theta = 90^o$



Synchrotron emission from a helical field with pitch angle 45^o

An application: modelling relativistic jets

Why bother?

Relativistic jets in AGN accelerate highest energy particles
Deposit energy and momentum in IGM/ICM (feedback)

Why these objects?

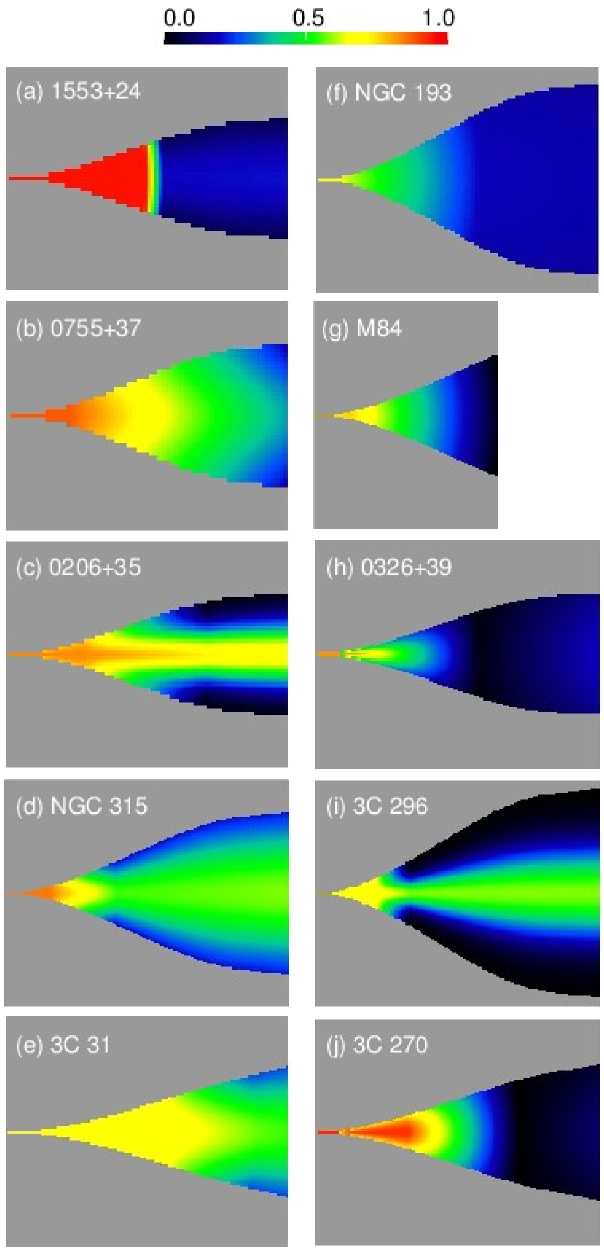
Low accretion rate radio galaxies
Jets are primary channel of AGN energy output
Nearby, bright in radio → lots of detail

How?

Deep VLA images in I, Q and U
Jet flows are relativistic and intrinsically symmetrical
Approaching and receding sides appear different in I and linear polarization (aberration)
Model geometry, velocity field, particle distribution, B-field structure

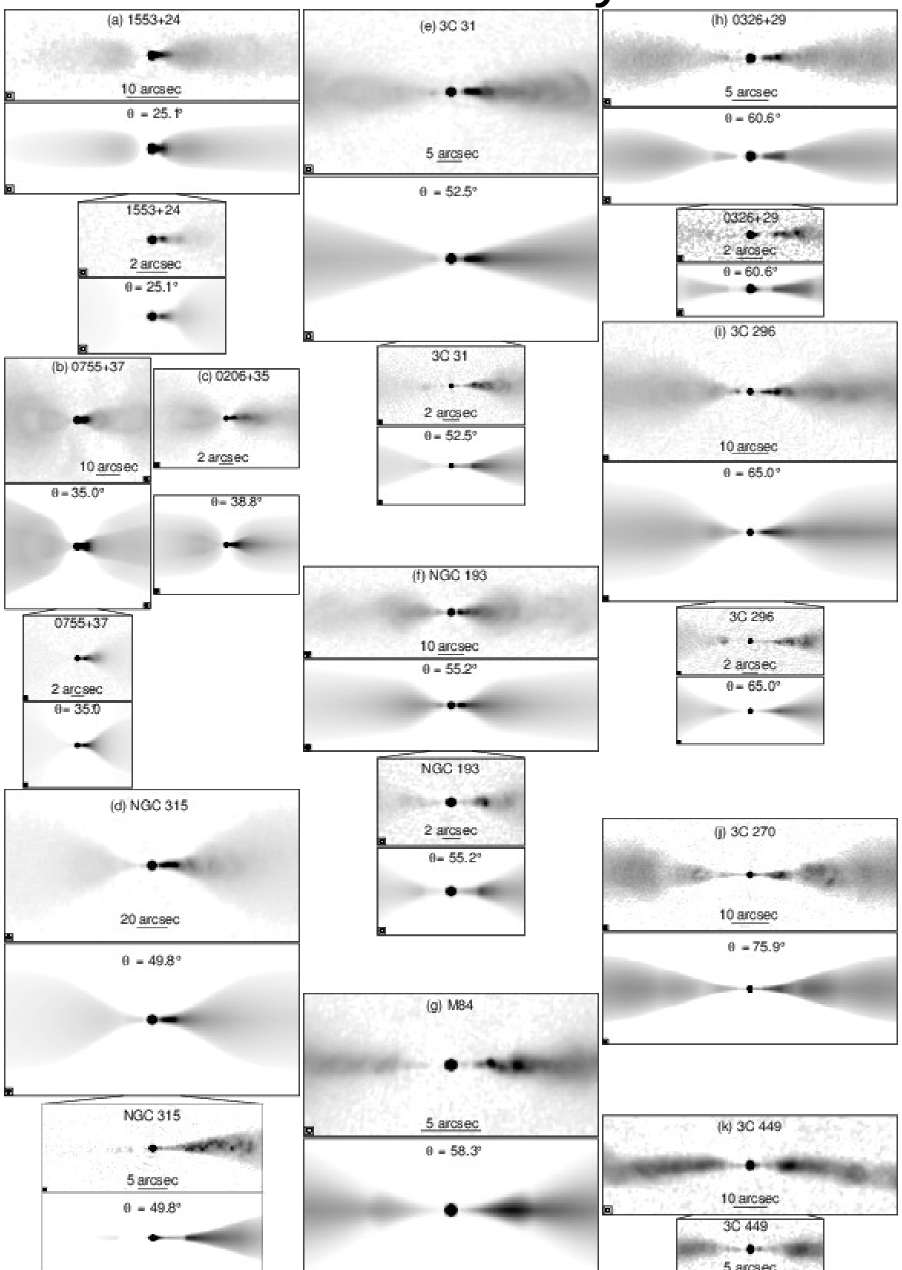
What do we learn?

Geometry: measure inclination
Velocities: jets decelerate and interact with IGM
Fields: longitudinal+toroidal → toroidal
Particle acceleration: depends on jet speed

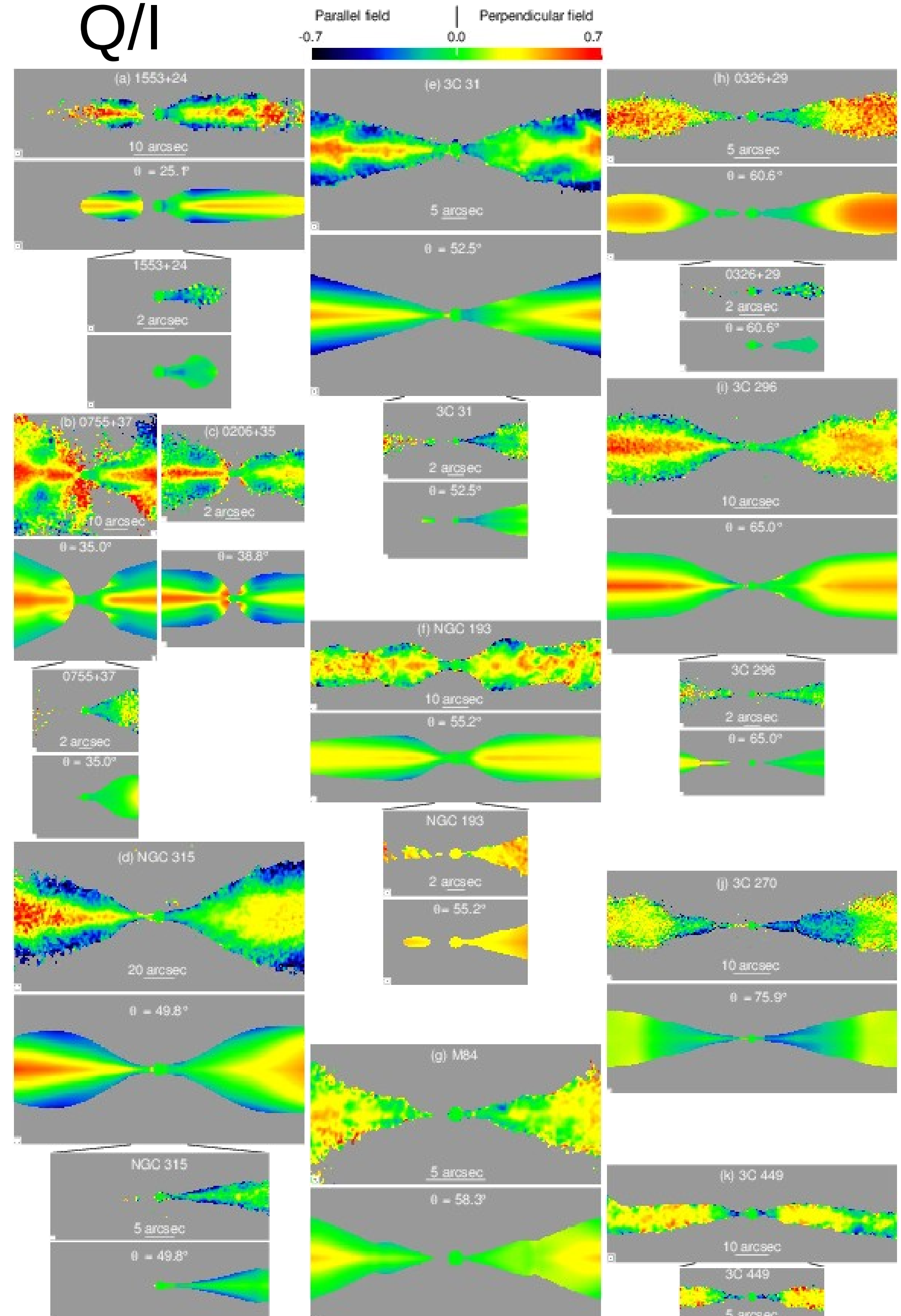


Model Fits

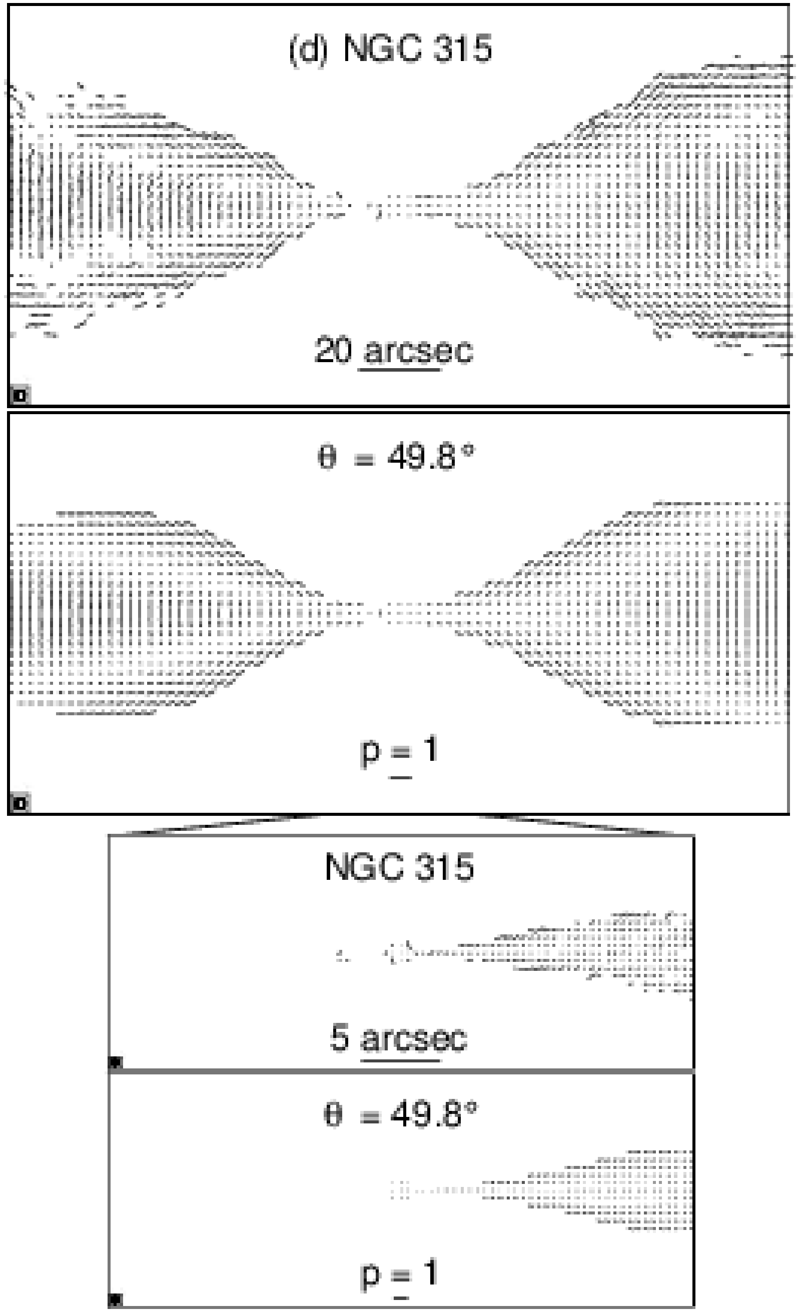
Total Intensity I



Q/I



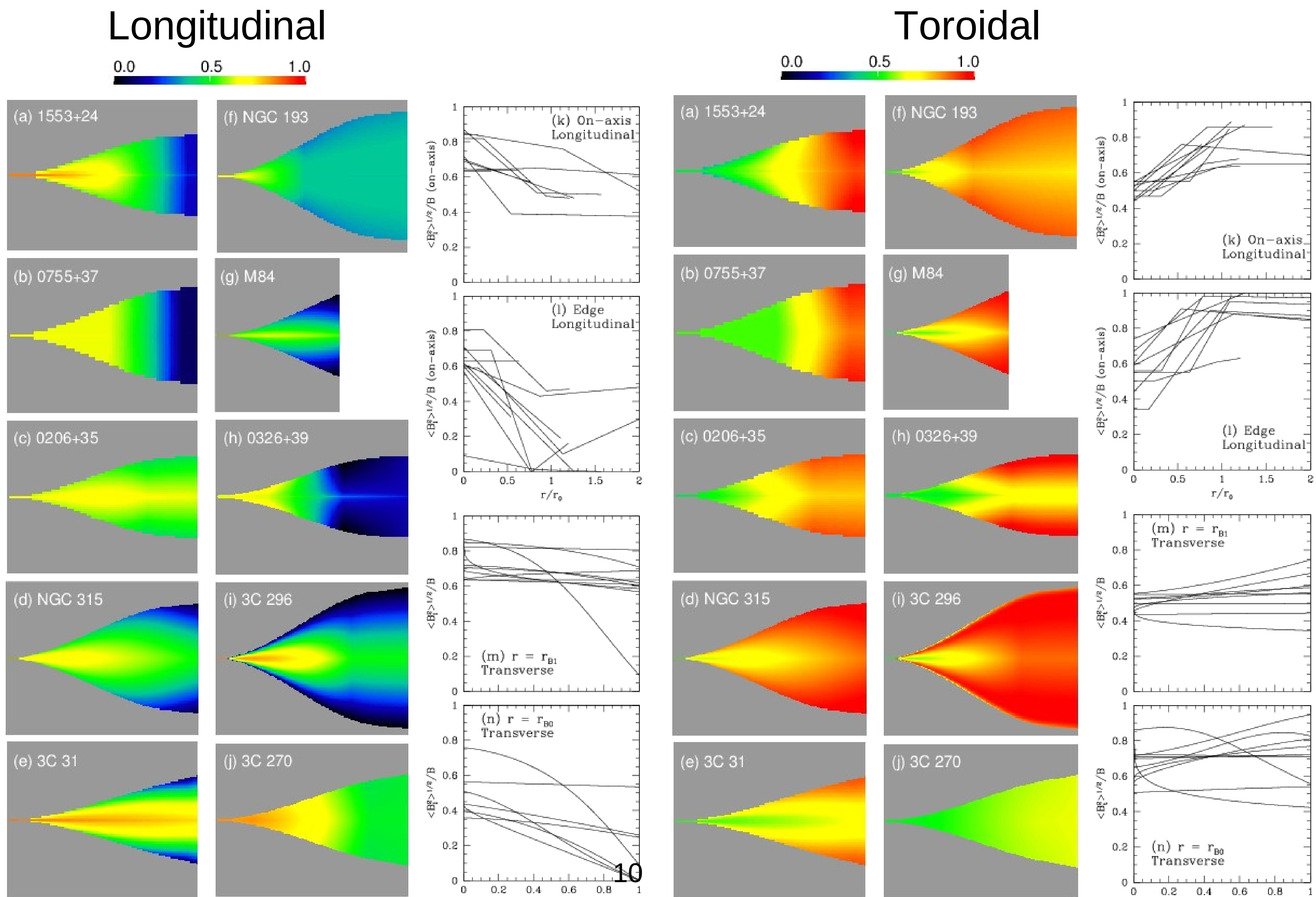
Observed and model vectors



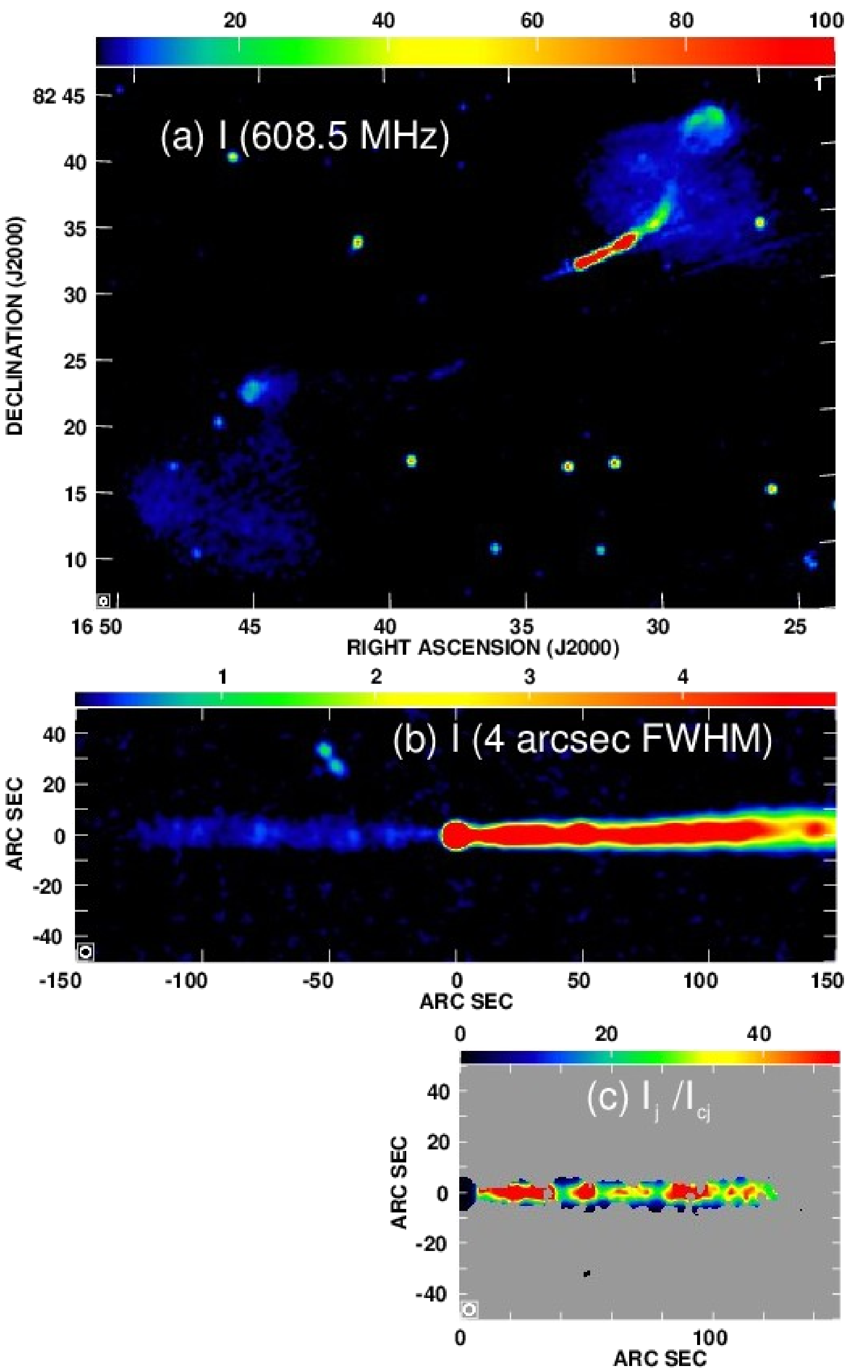
Vector length proportional to p = P/I

Along the apparent magnetic field

Field components



What next?



All jets we have modelled so far are low-luminosity and decelerate

We suspect that powerful quasar jets remain relativistic on scales up to 100's of kpc, but have no good constraints

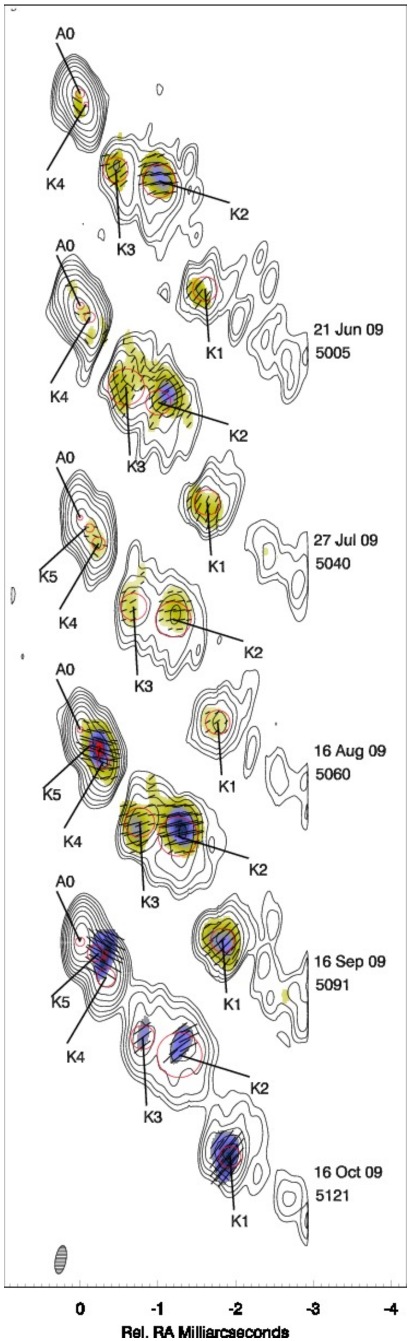
Need higher spatial resolution (0.05-0.1 arcsec) and better sensitivity

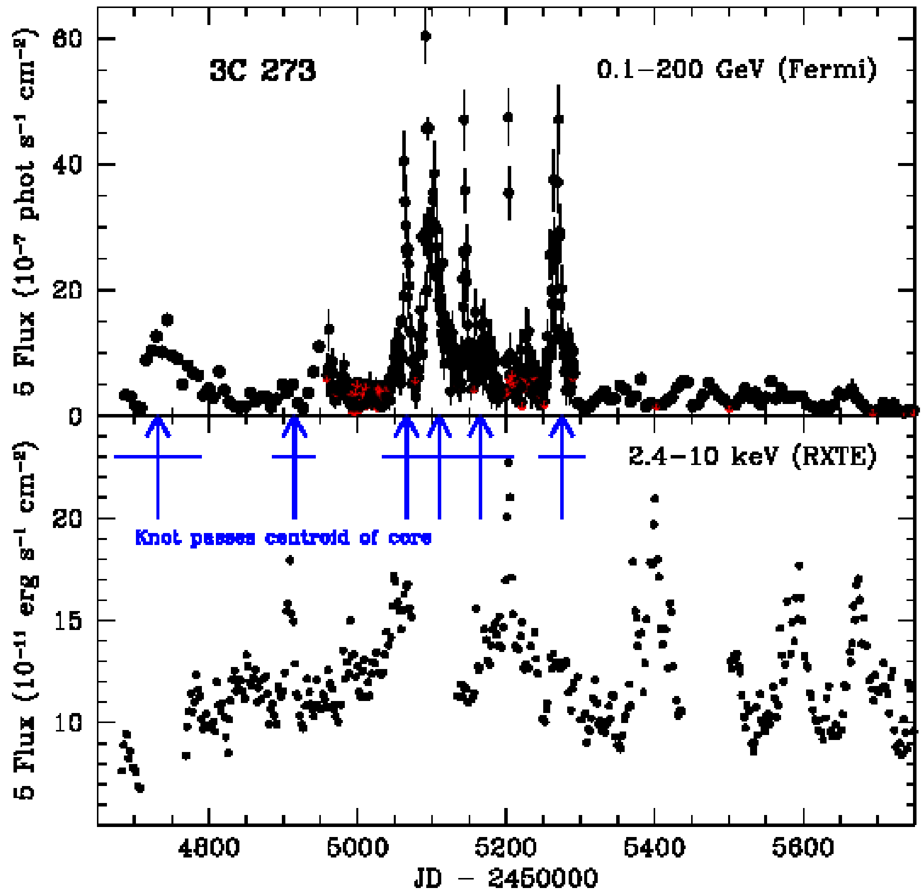
This is extremely hard even with JVLA

What about ALMA?

- Optically thin synchrotron emission has a $\nu^{-0.5}$ or steeper spectrum, and system temperatures/atmosphere are worse at high frequencies, so why observe with ALMA?
  - Resolution (mm VLBI)
  - Emission is optically thick, scattered or free-free absorbed at longer wavelengths
  - Faraday rotation is too high at longer wavelengths
  - There are real differences in structure between mm and cm (or m) wavelengths

mm-wave and γ-ray emission



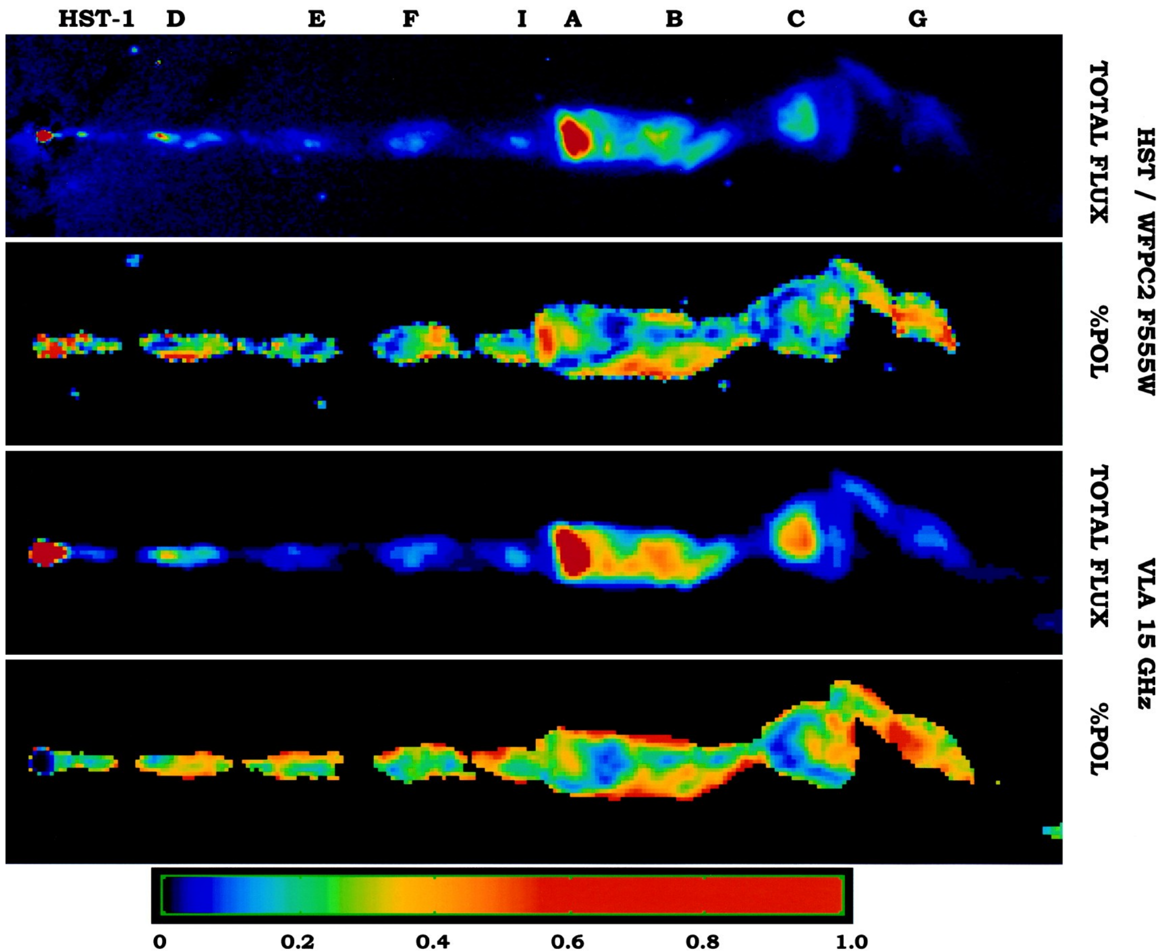


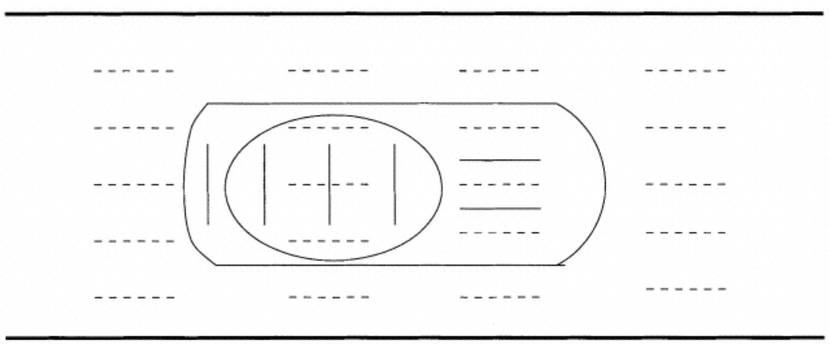
Marscher et al. (2012)

- AGN cores = optically thick jet bases; variable
- Polarization gives apparent field in brightest components (just optically thin at a given frequency}
- Combine with VLBI (new components, jet direction)

Structural differences?

- Differences in jet polarization are observed between (e.g.) radio and optical bands in M87 (Perlman et al. 1999)





Higher energy electrons trace different field structures?

Frequencies differ by a factor of 40 000

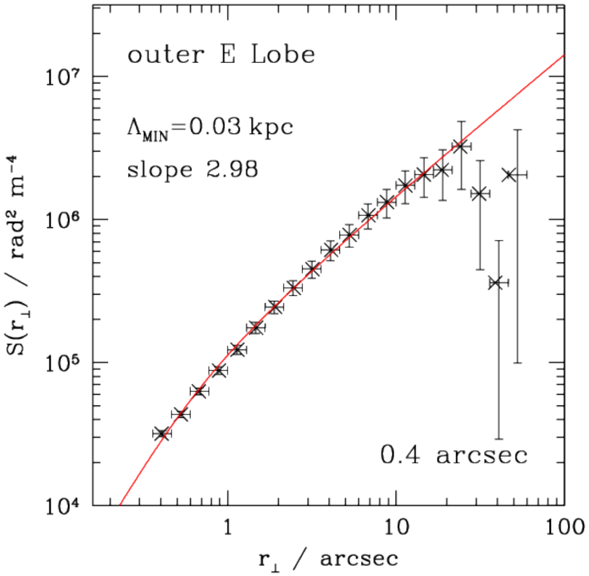
Faraday rotation

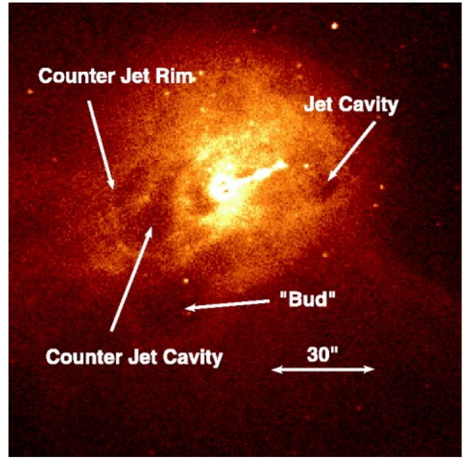
- Rotation of plane of linear polarization as radiation passes through a magnetised (thermal) plasma
- Normal modes are circularly polarized; propagation speeds are different

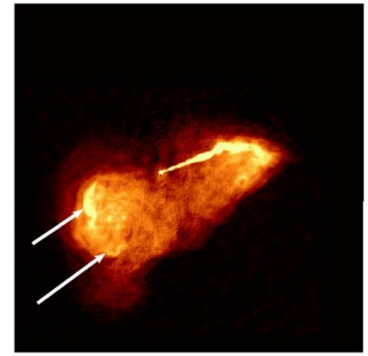
$$\Delta\Psi_{[\mathrm{rad}]} = \Psi(\lambda)_{[\mathrm{rad}]} - \Psi_{0\,[\mathrm{rad}]} = \lambda^2_{[\mathrm{m}^2]}\,\mathrm{RM}_{[\mathrm{rad\,m}^{-2}]}\,,$$

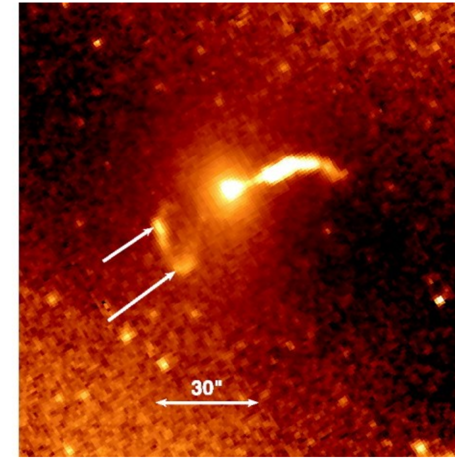
$$\mathrm{RM}_{[\mathrm{rad\,m}^{-2}]} = 812\int_0^{L\,[\mathrm{kpc}]} n_{e[\mathrm{cm}^{-3}]}\,B_{z[\mu\mathrm{G}]}\,\mathrm{d}z_{[\mathrm{kpc}]}\,,$$

M87: Central cD of Virgo Cluster





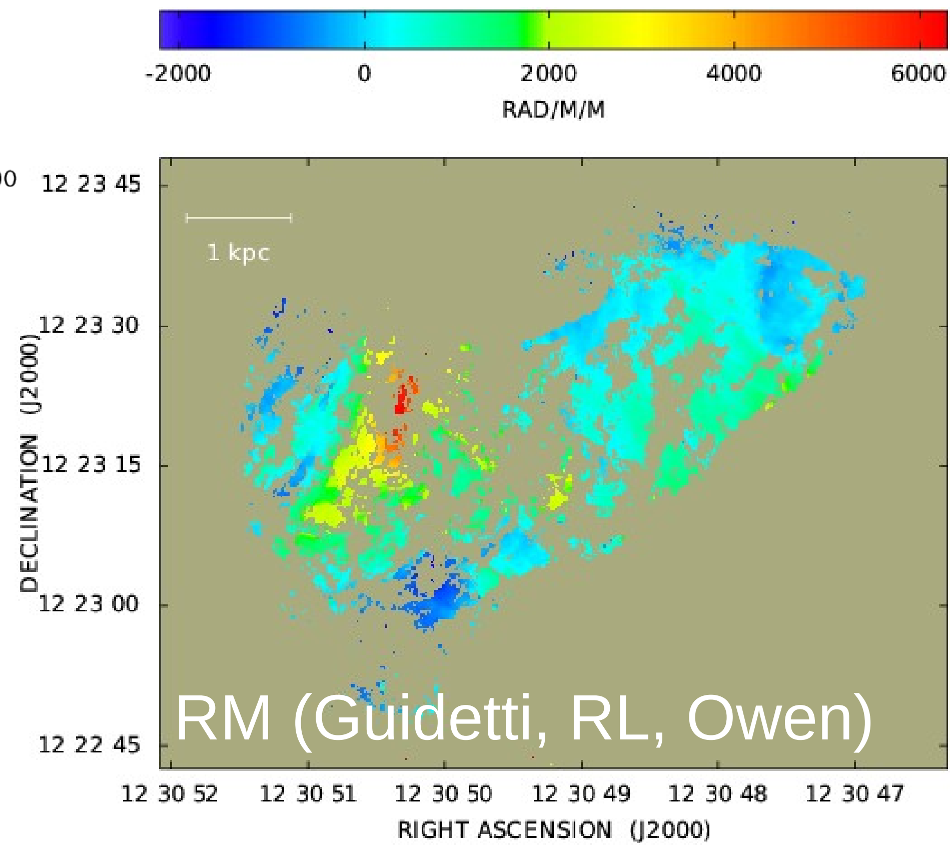




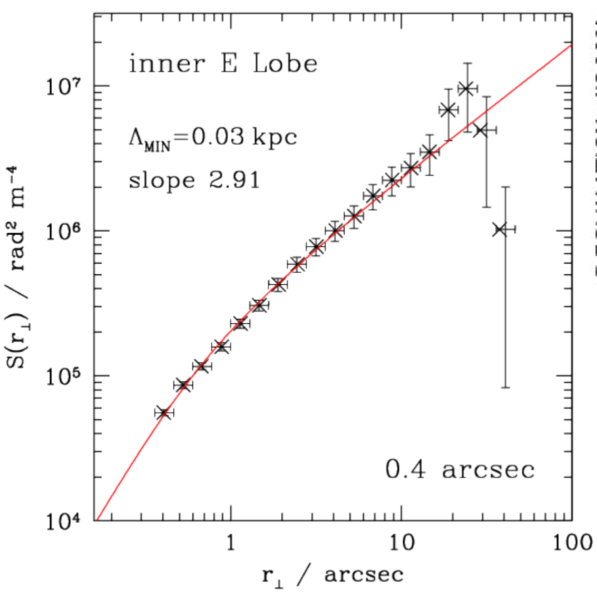
Chandra
(Forman et al. 2007)

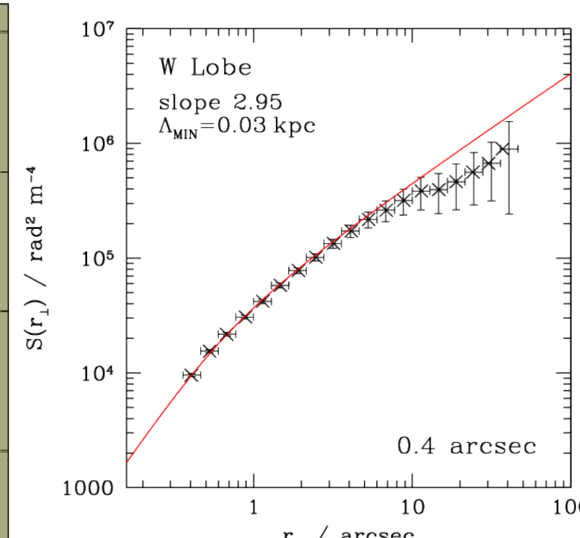
VLA

Spitzer IRAC



RM (Guidetti, RL, Owen)

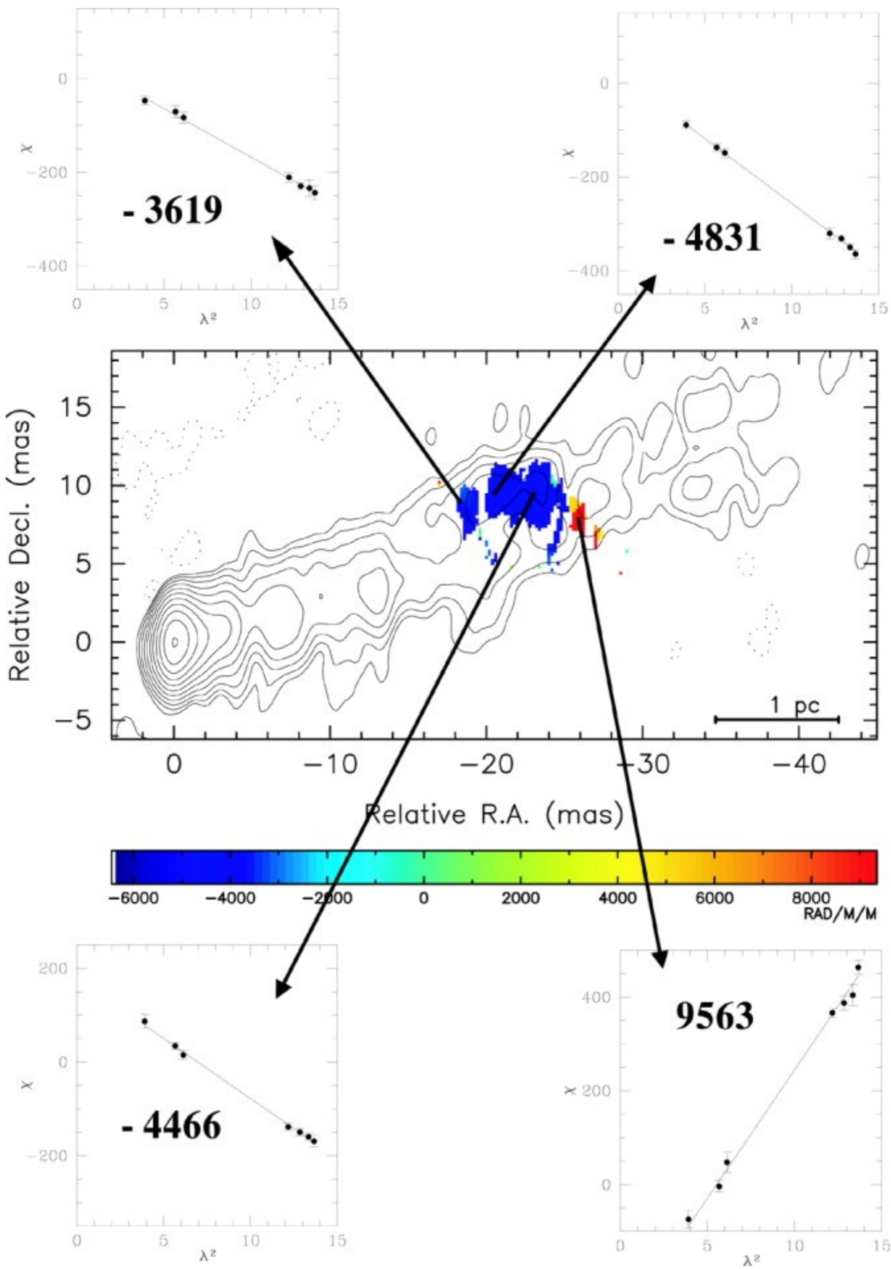




Observe M87 in ALMA Band 3?

- Faraday rotation across Band 3 is only 3^o for RM = 10000 rad m^{-2} (the maximum on kpc scales for M87 – typical for cool core clusters)
- Therefore good for intrinsic field structure; less so for imaging Faraday rotation
- But there may be denser gas close to the nucleus

RM variations on sub-pc scales

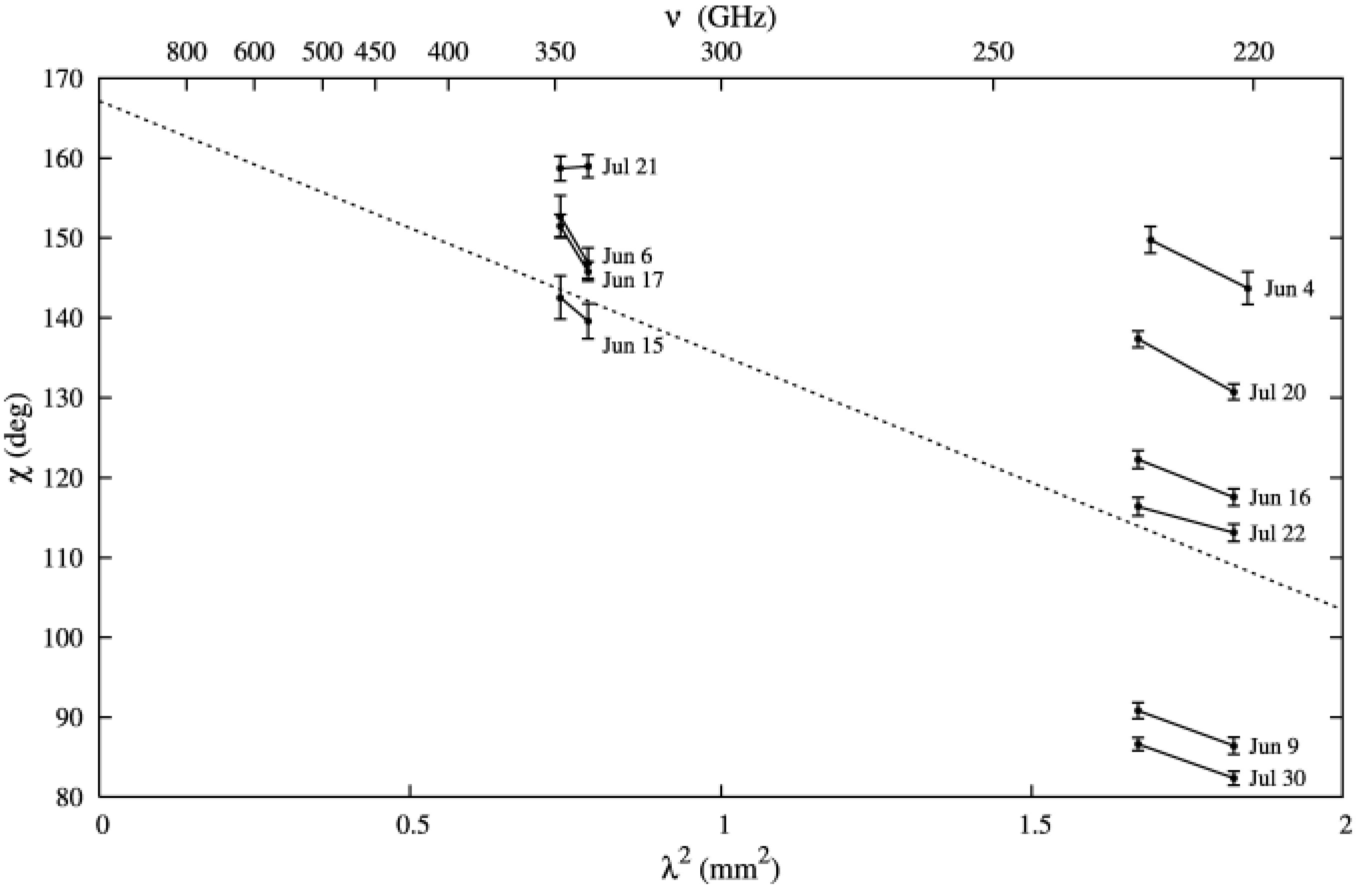


Zavala & Taylor (2002)

Large variations in RM across jet

What are we looking through?

Galactic Centre



Marrone et al. (2007)
SMA

RM = -5.6 x 10^5 radm^{-2}

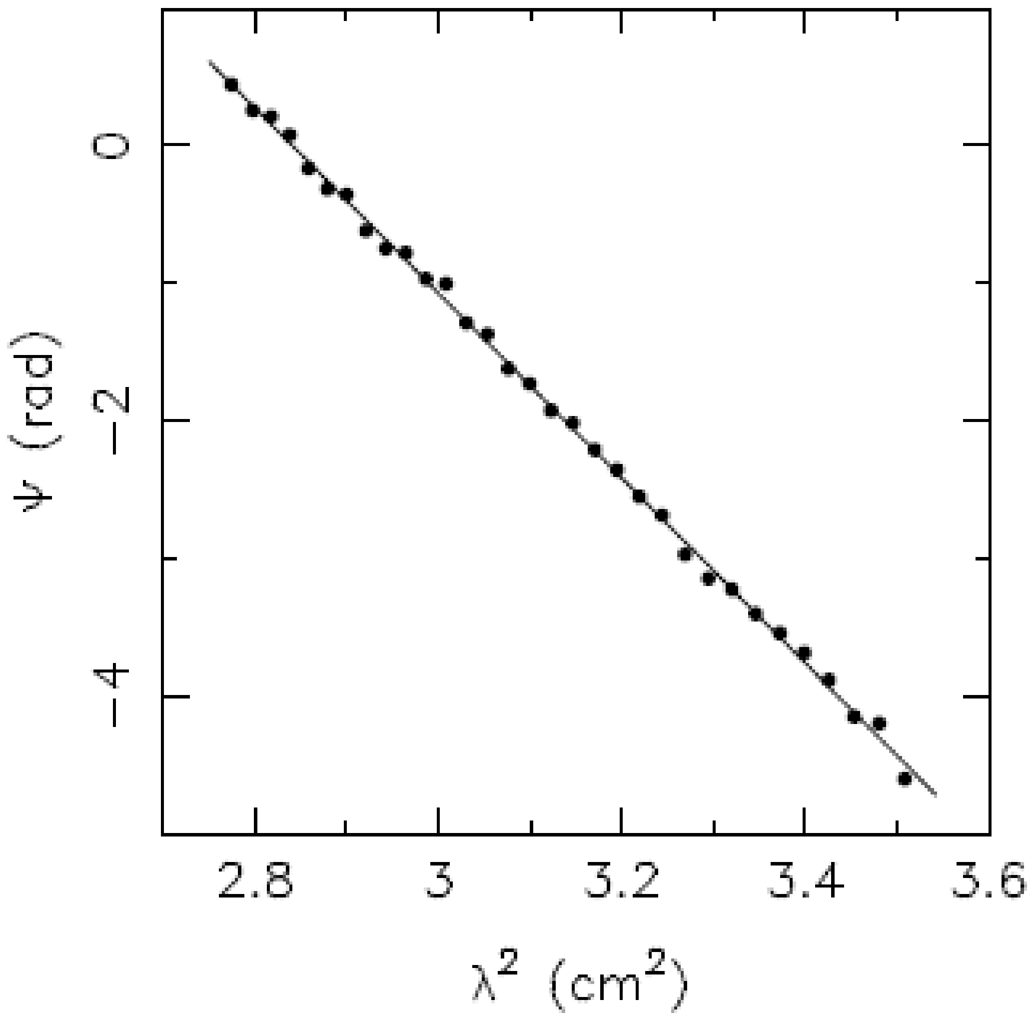
Translates to a limit on accretion rate if B is in equipartition

$10^{-9} – 10^{-7}$ $M_\odot$ /yr
(depends on geometry)

Poor λ^2 fits, complicated by variability

Can we do this for other accreting systems, using jets as background sources?

Galactic Centre Magnetar



Magnetar near the Galactic Centre

Shannon & Johnston (2013)

RM = -6.7 x 10^4 rad m^{-2}

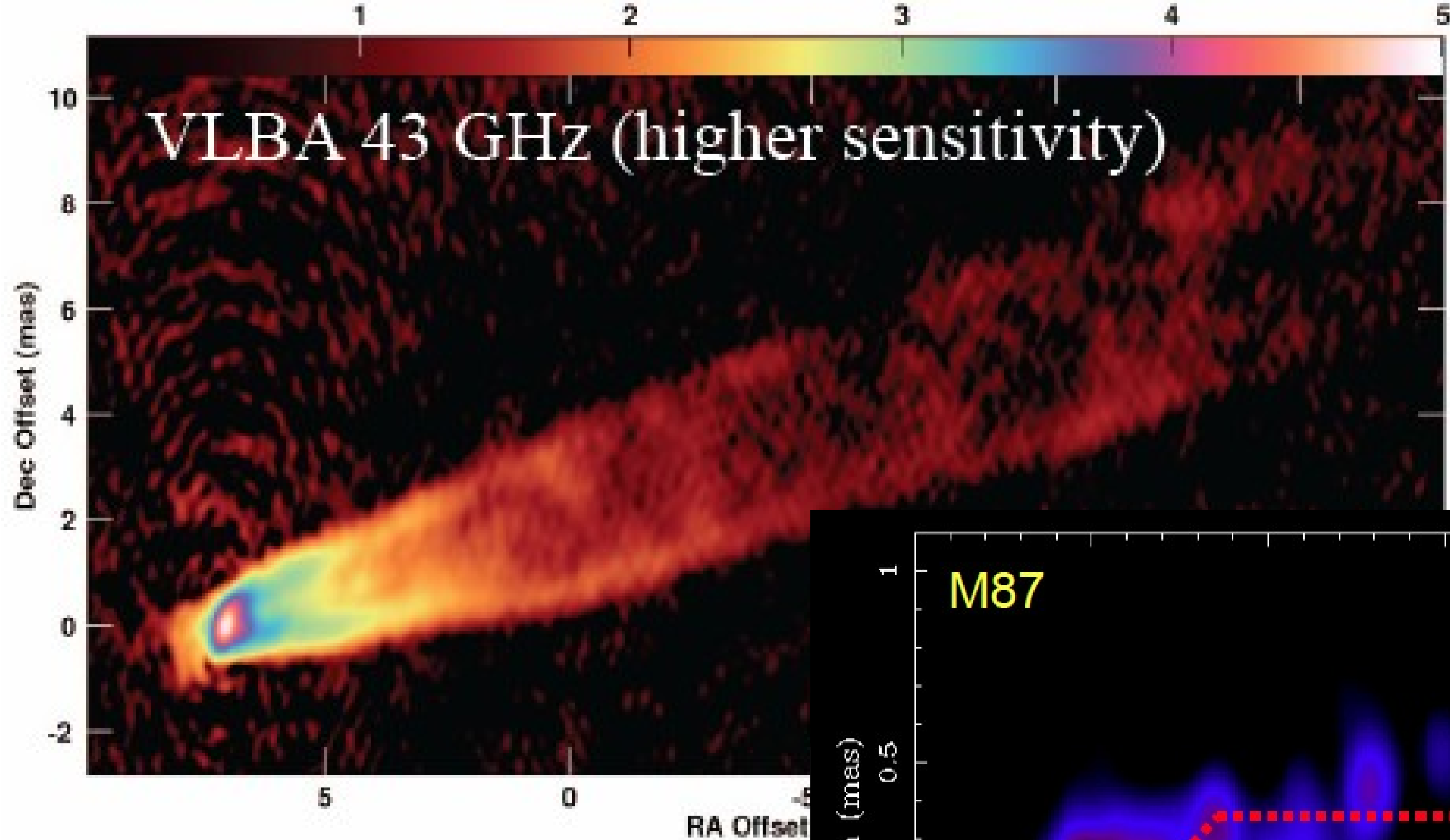
Observing Strategy for Faraday rotation

- For a point background source, can just increase the frequency resolution to the point that there is negligible rotation across a channel (cf. magnetar) – not much advantage in going to high frequency
- If the background source is resolved, and Faraday rotation varies across it, then depolarization is inevitable. Need to increase the observing frequency and/or resolution so that variations across the beam are small (and linear)
- Modern interferometers (VLA, ALMA) all have many spectral channels even in wide-band modes, so can use RM synthesis (Brentjens & de Bruyn 2005, Burn 1966)
- This does not help without good spatial resolution: cannot then distinguish variations of foreground rotation across the beam from mixed thermal and relativistic particles.

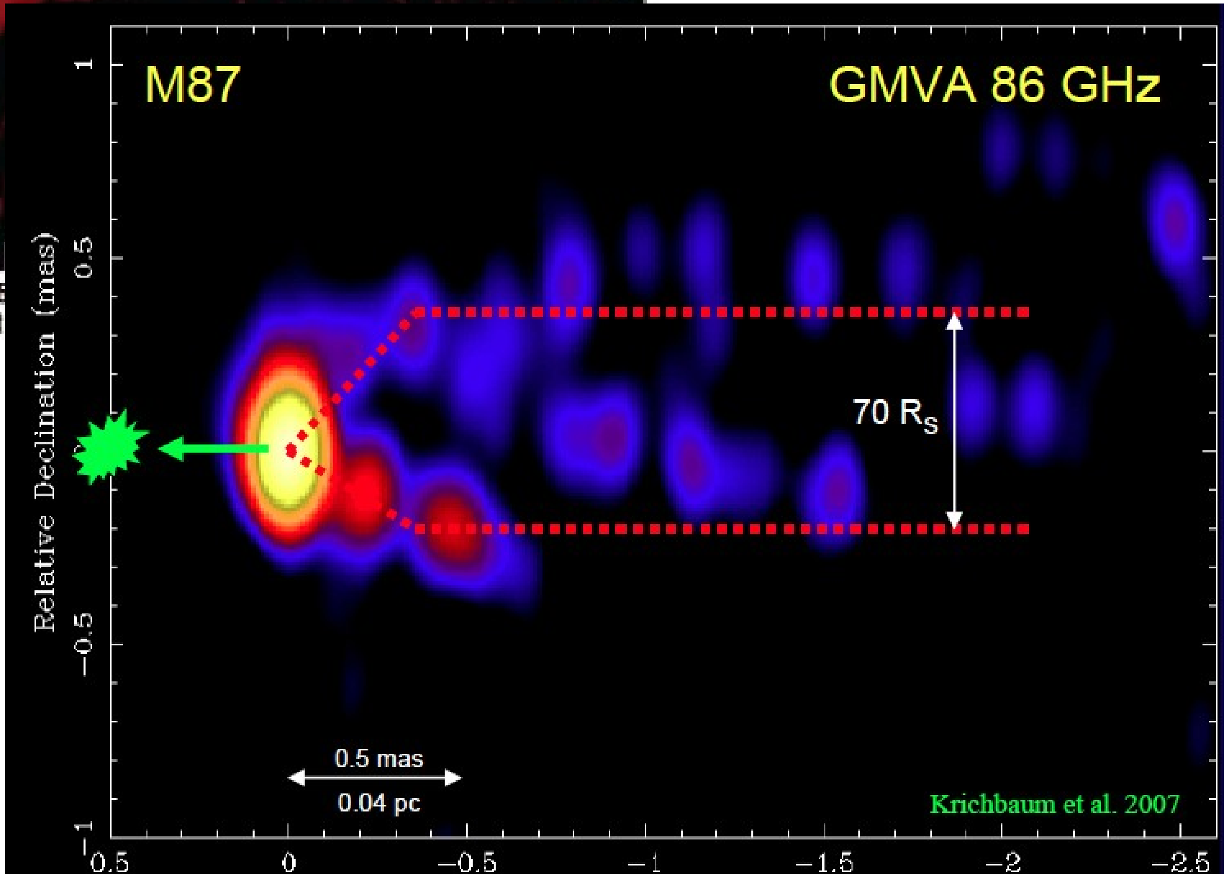
VLBI with ALMA

- ALMA phasing project
  - Phase up ALMA for use in VLBI
  - Ongoing (MIT Haystack/NRAO/MPIfR/OSO/...)
- Science targets
  - Sgr A* event horizon
  - M87 jet formation region
- Polarization?
  - Observations in full polarization possible
  - Initial 230-GHz observations have been made

M87 on sub-pc scales

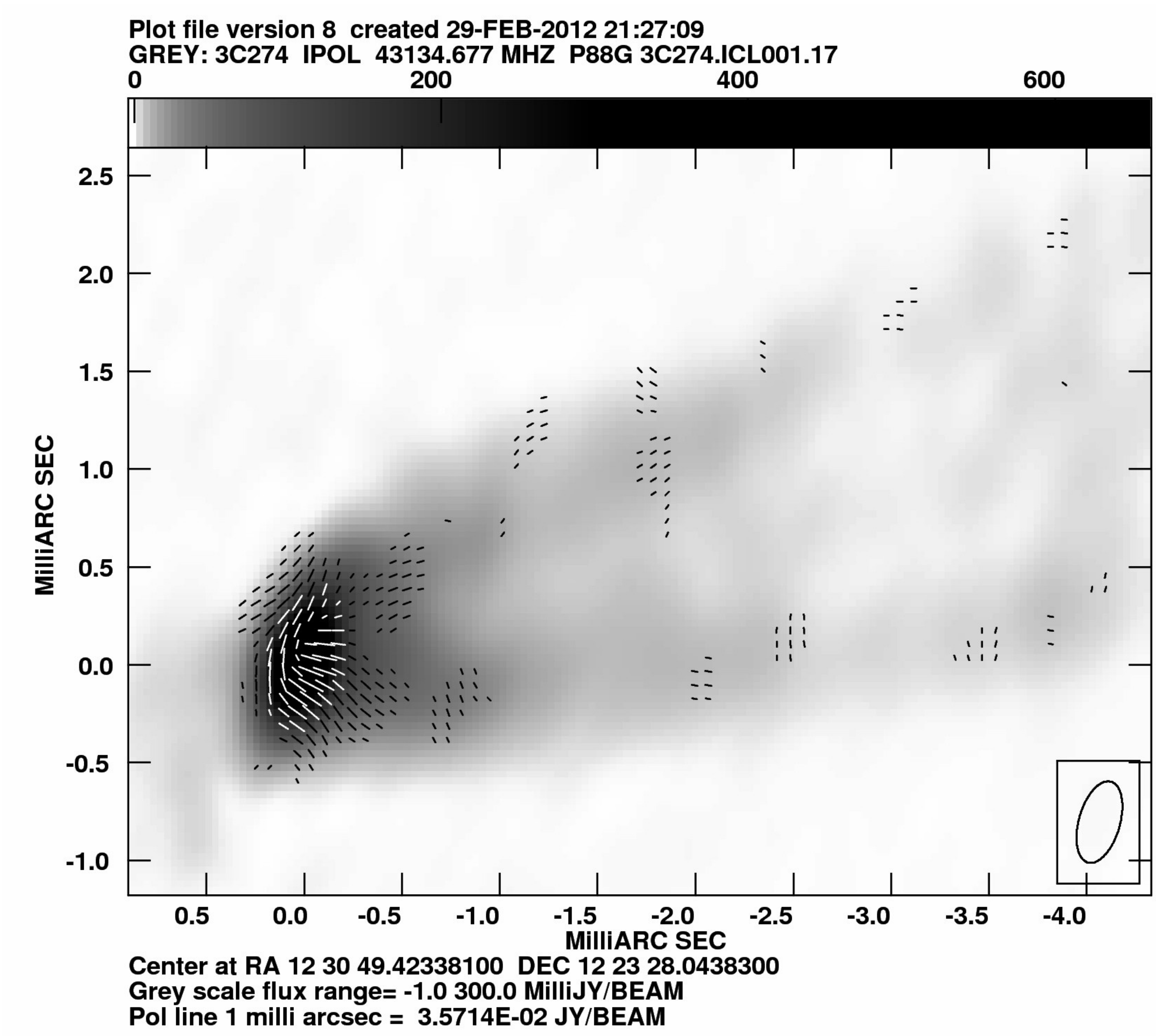


Walker et al.



Krichbaum et al.

sub-pc polarization of M87



1 mas = 0.08 pc
= 140 R_s

Polarization detected, so Faraday rotation cannot be too extreme

Can probably see the counter-jet in linear polarization

Craig Walker

Two Key Projects

- Probe magnetic fields in accretion flows through observations of Faraday rotation
  - Magnetic fields are essential in all models of accretion disc viscosity (MRI), but almost no observational constraints
  - Enormous Faraday rotations even in low-accretion rate flows (Galactic Centre)
  - Not observed in blazars (geometry?). so look at side-on systems using pc-scale jets as background sources
  - Try low accretion AGN (ADAF and relatives) + Sgr A*
- Image the jet and counter-jet of M87 on ~$10R_S$ scales in linear polarization
  - Apply symmetrical relativistic jet models → flow field
  - Simultaneously, measure proper motions
  - Test jet formation models, which predict field structure

More topics

- Magnetic fields in bases of jets which are optically thick, show free-free absorption or extreme Faraday rotation at cm wavelengths
- Blazar polarization monitoring; correlations with high-energy emission
- Circular polarization (probably from linear → circular conversion)
- Imaging of large-scale, optically-thin synchrotron emission is probably not a good idea.