An Astronomer's Tale

High-dynamic-range Imaging with the Jansky VLA

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Why do HDR?

- “Scientifically useless”?

“Canary in the mine”?
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It's the astrophysics* stupid

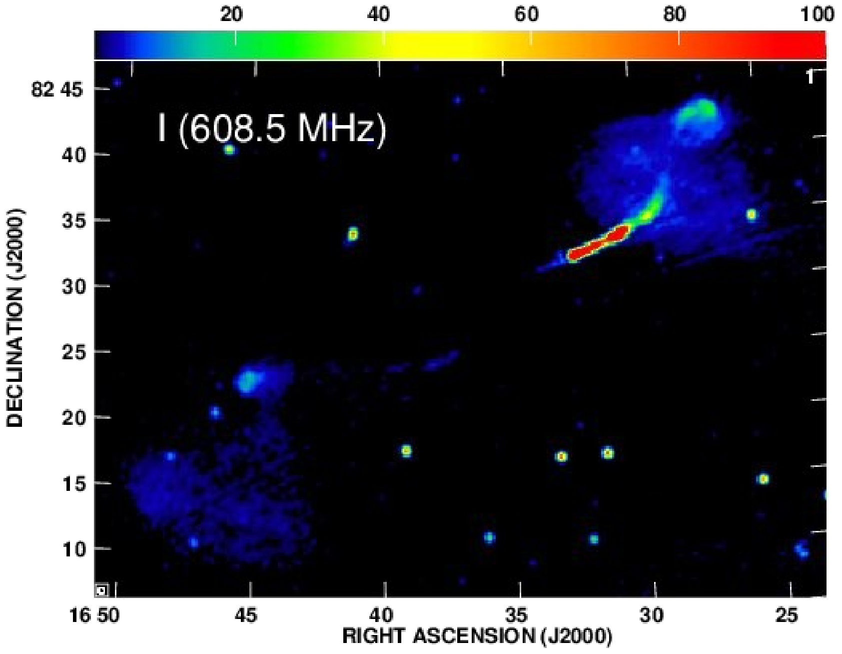
* or chemistry, biology

What do we really, really want?

- High-fidelity imaging of “interesting” structure in IQU(V) as functions of frequency
  - We specify measures of fidelity, but have little idea whether we achieve them in practice
  - The answer is not at the back of the book
- High dynamic range is a necessary, but not sufficient condition for high-fidelity imaging
  - Often add plausible, but unproven conjectures (sparsity off-source, smoothness on-source)
  - Unwelcome subjectivity (CLEAN boxes, ...)
- Nevertheless, let us pick a (relatively tractable) astrophysical problem and see how far we can get

How fast are the jets in NGC 6251?

- NGC 6251 is a nearby giant radio galaxy with twin, but very asymmetrical radio jets
- We think that the intensity differences between the jets are due to special relativistic effects – aberration/Doppler beaming
  - If we can measure the intensity and polarization differences between the jets, then we can estimate the velocity field



WSRT, Mack et al. (1997)

$v \approx c$: Proper motions and Aberration

Flux density in observer's frame at frequency ν

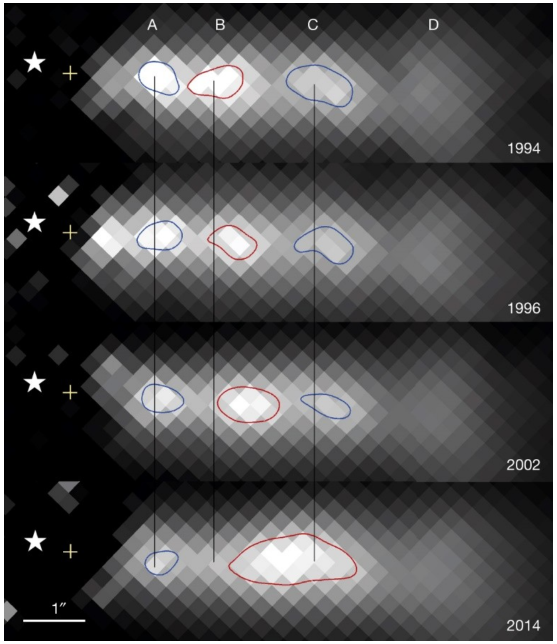
$$S(\theta,\nu) = D^{2+\alpha}\int \varepsilon'(\theta,\nu)\, dV/d^2$$

Doppler factors for antiparallel jets:

$$D_j = [\Gamma(1-\beta\cos\theta)]^{-1} \text{ (approaching)}$$

$$D_{cj} = [\Gamma(1+\beta\cos\theta)]^{-1} \text{ (receding)}$$

$$\sin\theta' = D\sin\theta$$



Meyer et al. (2015)

$\beta_{app} = 1.8 – 7.0$

Approaching jet appears **brighter** and the two jets are observed at **different angles to the line of sight in the flow rest frame** θ'

Polarization depends on θ' – different in the two jets

Jet Models

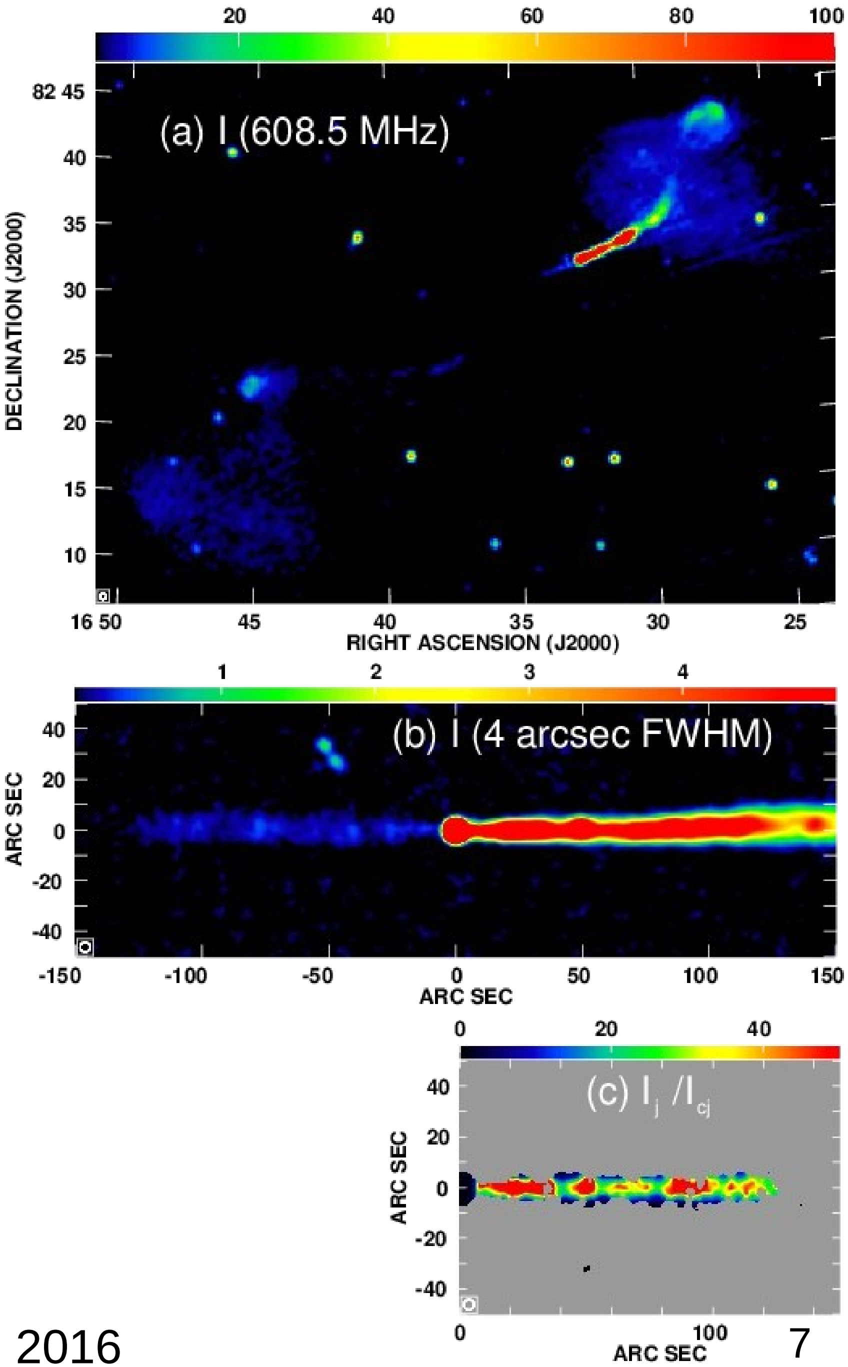
- What distributions of flow velocity, field geometry and rest-frame emissivity are consistent with observations?
- Observe:
  - Deep, high-resolution radio images; IQU, corrected for Faraday rotation
- Assume:
  - Symmetrical, axisymmetric, stationary, relativistic flow
  - Power-law energy distribution, optically-thin synchrotron
- Parametrised model of:
  - Geometry
  - Velocity field in 3D
  - Emissivity
  - Magnetic-field component ratios
- Calculate I, Q, U; optimise

Compare approaching and receding jets

Polarization is crucial!

Laing & Bridle 2002, 2014

Prior Knowledge



Compared with Cygnus A, this is easy:

- point source at the phase/ pointing centre
- low polarization in the core
- fainter emission at larger distances

VLA 1665 MHz

Sidedness ratio image

What images do we need?

- The difficult part
  - Image the counter-jet with good transverse resolution (>5 resolution elements) in IQU with reasonable signal-to-noise in the presence of the (very bright) core
  - Remove the effects of Faraday rotation
- Choice of frequency and configuration
  - Maximum resolution ≈1 arcsec (otherwise resolve out counter-jet emission)
  - Minimum frequency ≈4 GHz (otherwise there is significant variation in Faraday rotation across the beam)
  - Required rms noise ≈1 μJy/beam IQU
  - JVLA: 24 hr, B configuration at 4.5-6.5 GHz (with shorter integrations in C and D configurations for larger scales)
  - 16 spectral windows (spw) each of 64 x 2 MHz channels

Unwelcome news

- Primary beam at 5GHz has HWHM ≈ 230 arcsec at 5.5 GHz
  - Direction-dependent effects important for the main jet
  - Counter-jet will only be detected to ≈ 140 arcsec, so should be minimally affected
- Required dynamic range = 570000:1
  - Need good leakage corrections as well as calibration
- Jansky VLA schedules dynamically
  - We really wanted a 24-hour observation (NGC 6251 is circumpolar) .....
  - but the ******ed referees only gave us B priority ....
  - ..... so were told that the probability of being scheduled was low unless we split the observation into 6-hour blocks – so that's what I did

Data Reduction

- Standard calibration in AIPS (because Rick won't touch CASA)
  - Relatively benign RFI (~8% data flagged); Hanning smooth
  - Quality of polarization calibration surprisingly dependent on choice of reference antenna
    - One observation/spectral window combination needed a different reference antenna from all of the rest – why?
    - Best results for B configuration by using the source as its own leakage calibrator – unpolarized point-like core dominates
- Initial imaging and self-calibration
  - Image, self-calibrate, closure-correct parallel hands for each observation/spectral window separately
  - Subtract model to check for residual RFI
  - Further work until rms <1.25 thermal (image RR, LL, RL, LR separately; remove individual antennas one by one, ...)
  - 2/96 “bad” cross-hand spw/observation combinations dropped at this stage

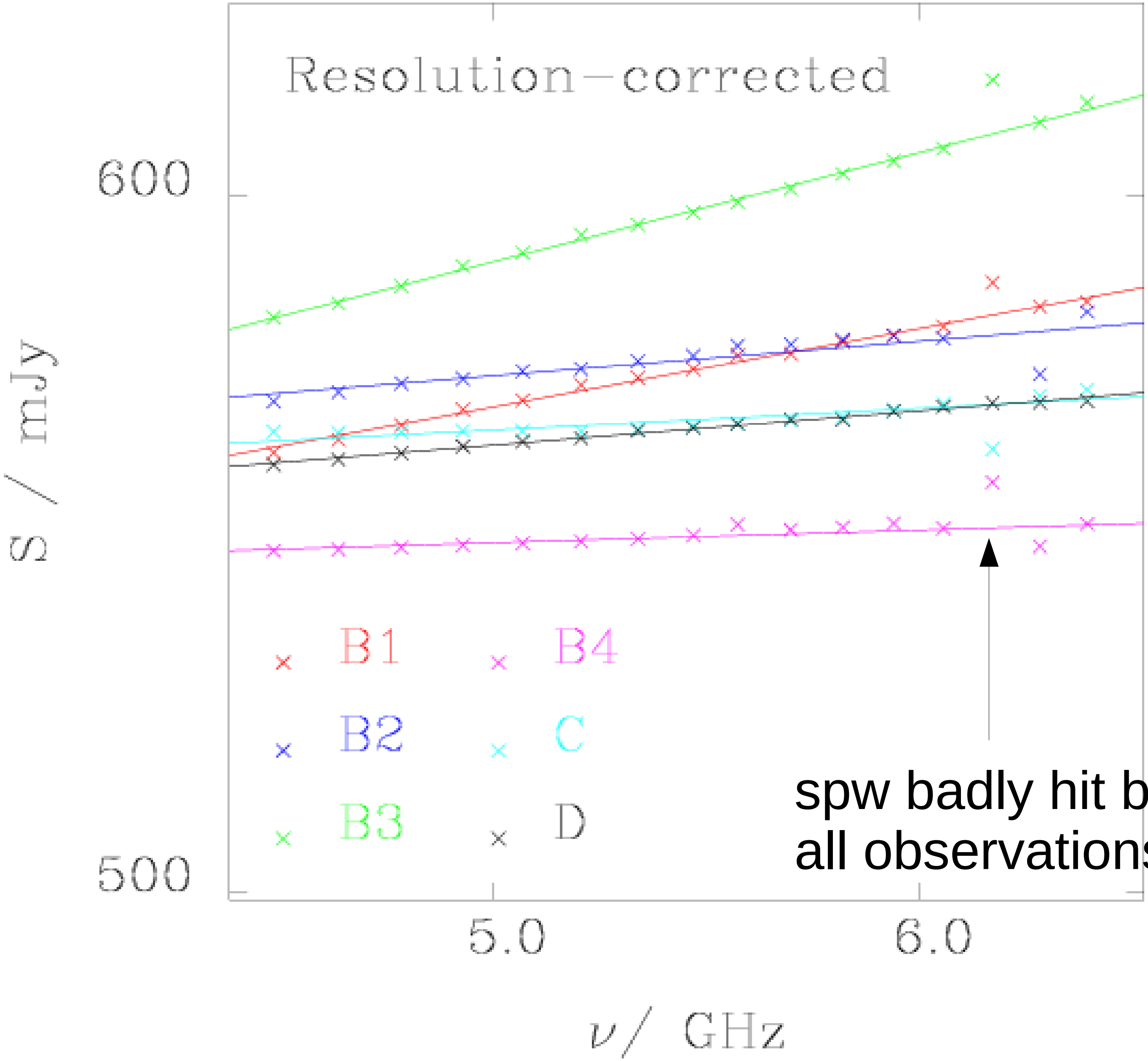
Closure Corrections in RR and LL

- Baseline-dependent (complex) error
- Constant over each observation
  - Solve per channel
  - AIPS BLCHN (also CASA BLCAL, but some bad solutions, so temporarily gave up on this)
- Essential to achieve dynamic range >30000:1 in this frequency range
  - C-band, so cross-polarization is particularly bad (Rick's talk)
- Consistent with second-order D-terms for an unpolarized source (Rick's talk)
- Works for this target because the brightness distribution is dominated by the unpolarized core.

Combining Observations

- Core varies between observations in flux density and spectral index
  - much more than the complex gain calibrator
- Ad hoc procedure
  - For B configuration, measure flux density averaged over each spw
  - Fit power law spectrum for good spw's (no significant curvature detected)
  - Adjust channel-by-channel so that all observations have the same spectrum
  - More complicated for smaller configurations (correction for extended emission)
  - This assumes that the flux scale is constant between observations to a first approximation.
  - Iterative procedure can be used (Laing & Bridle 2002)

Core flux density fits



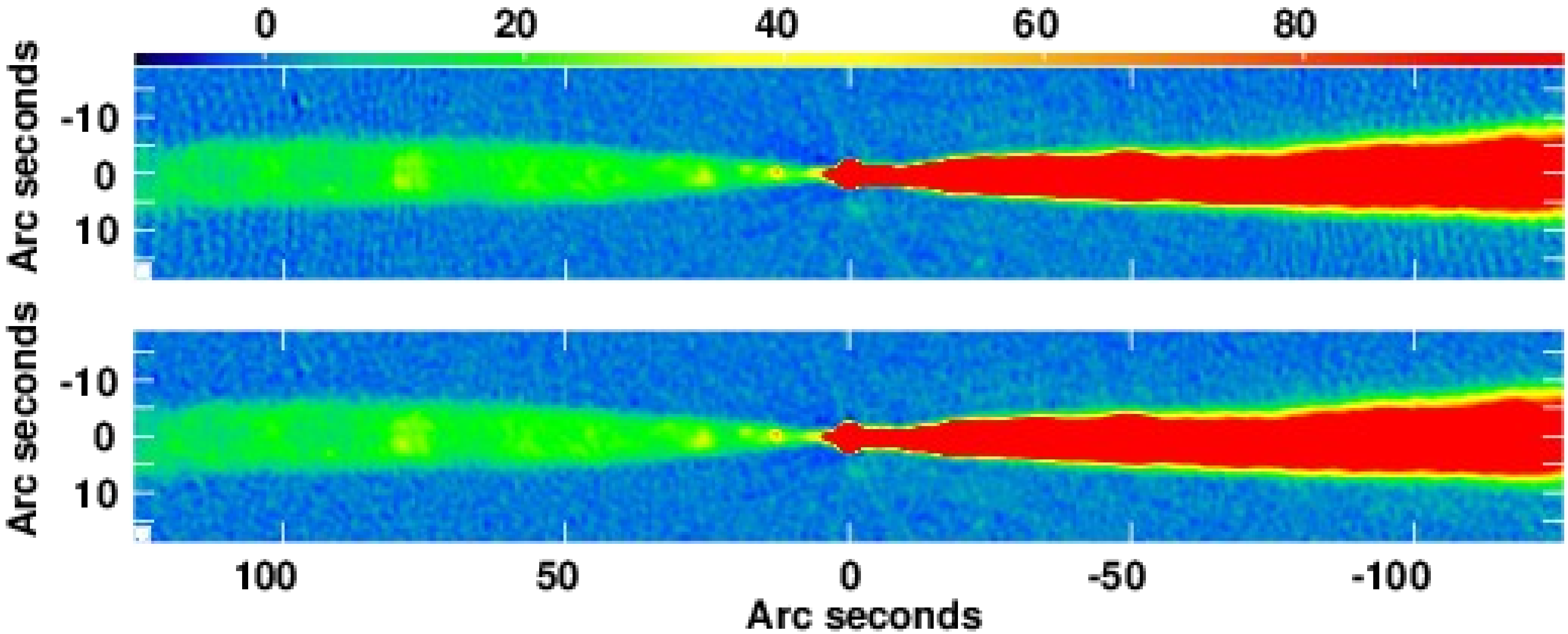
spw badly hit by RFI in all observations

Final self-calibration and Imaging

- Combine in CASA
- Image with MFS, nterms = 2
  - Multiscale CLEAN did not help much for extended emission ...
  - ... which was just as well. There is a problem of large-scale components being fit to inner jet (wider than the mask)
  - Similar issues with AIPS and CASA implementations
  - Led to negative “rails” just outside the jet emission
- Single-scale CLEAN with 250000 iterations worked well
- Final self-calibration and bandpass with spectral model
- Artefacts for inner jet dominated by closely spaced rings centred on the core
  - Much head-scratching
  - Turned out to be quantization of on-line delay corrections

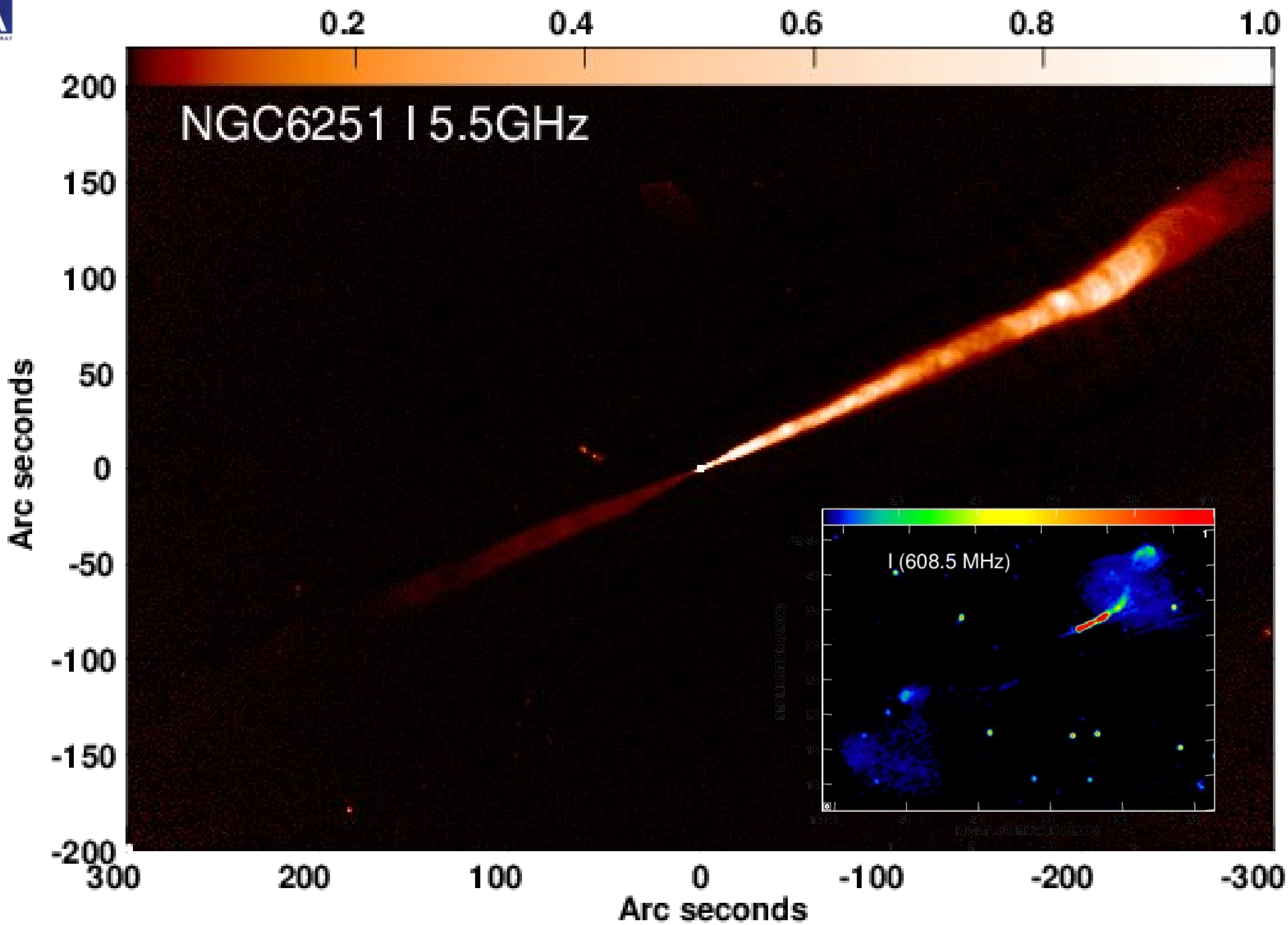
Delay Chunking

Before

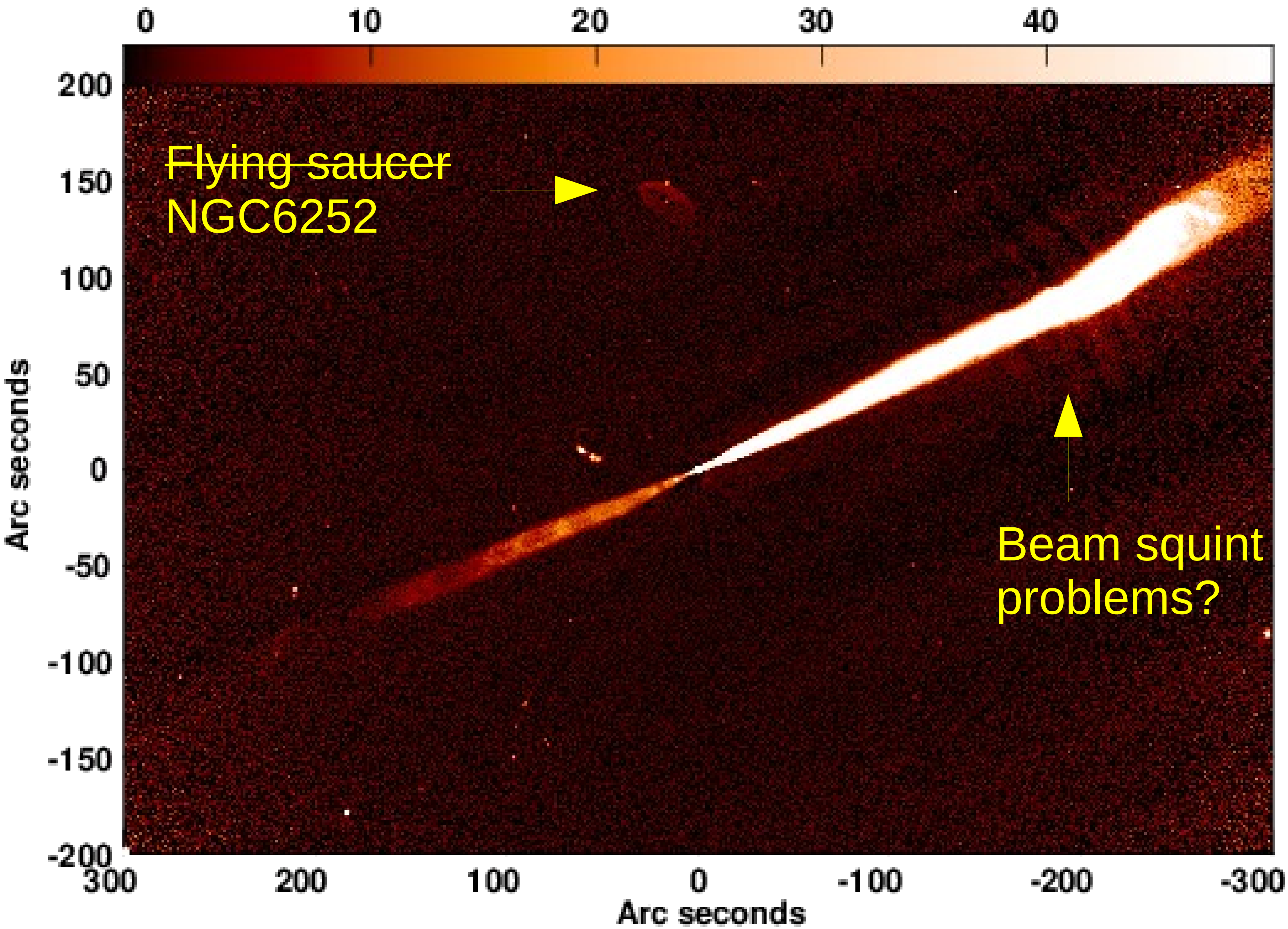


After 1-min delay calibration

Current best image



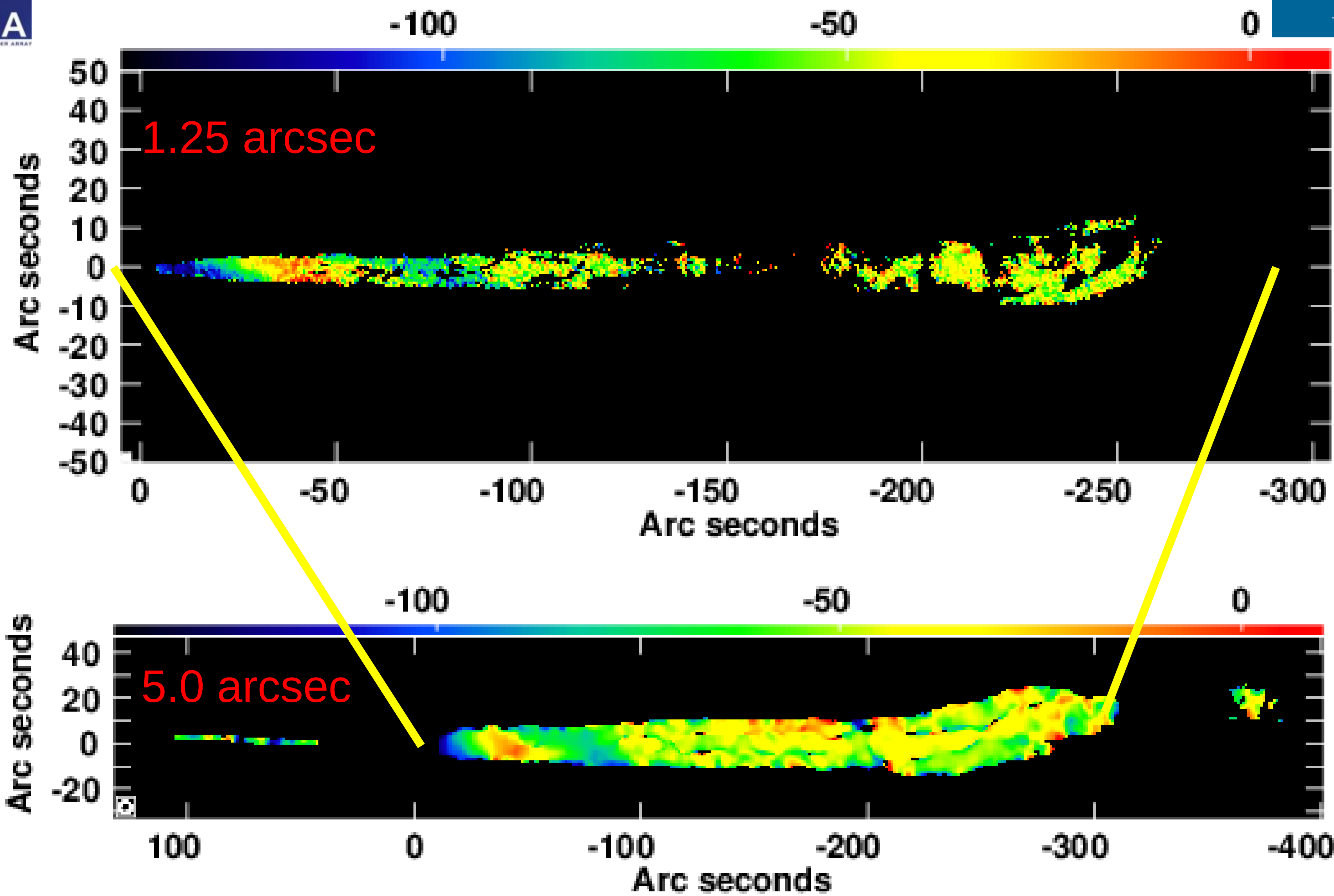
Looking deeper



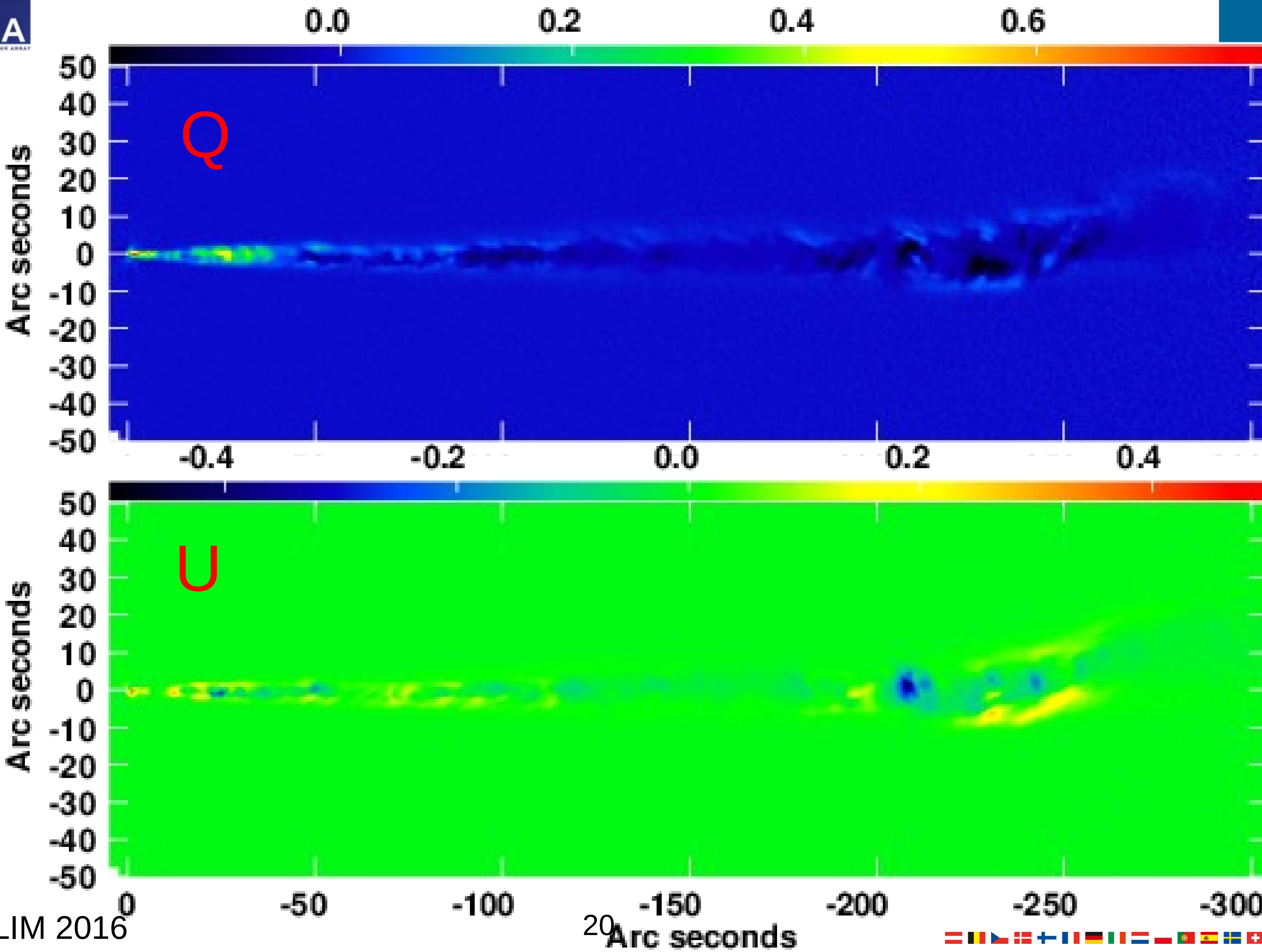
Linear Polarization

- Correction for Faraday rotation across the band is needed
  - Maximum RM ≈ -140 rad m^{-2}
  - Corresponds to 18.5 deg PA rotation across the band
  - Well established to be resolved foreground screen (Perley et al. 1984), so depolarization is negligible
  - Image individual spw's in Q and U, fit RM, correct to zero wavelength and form appropriately weighted sum
  - Only just possible for the counter-jet, by convolving to 5 arcsec resolution
- Artefacts
  - Visible within a few synthesised beams of the core

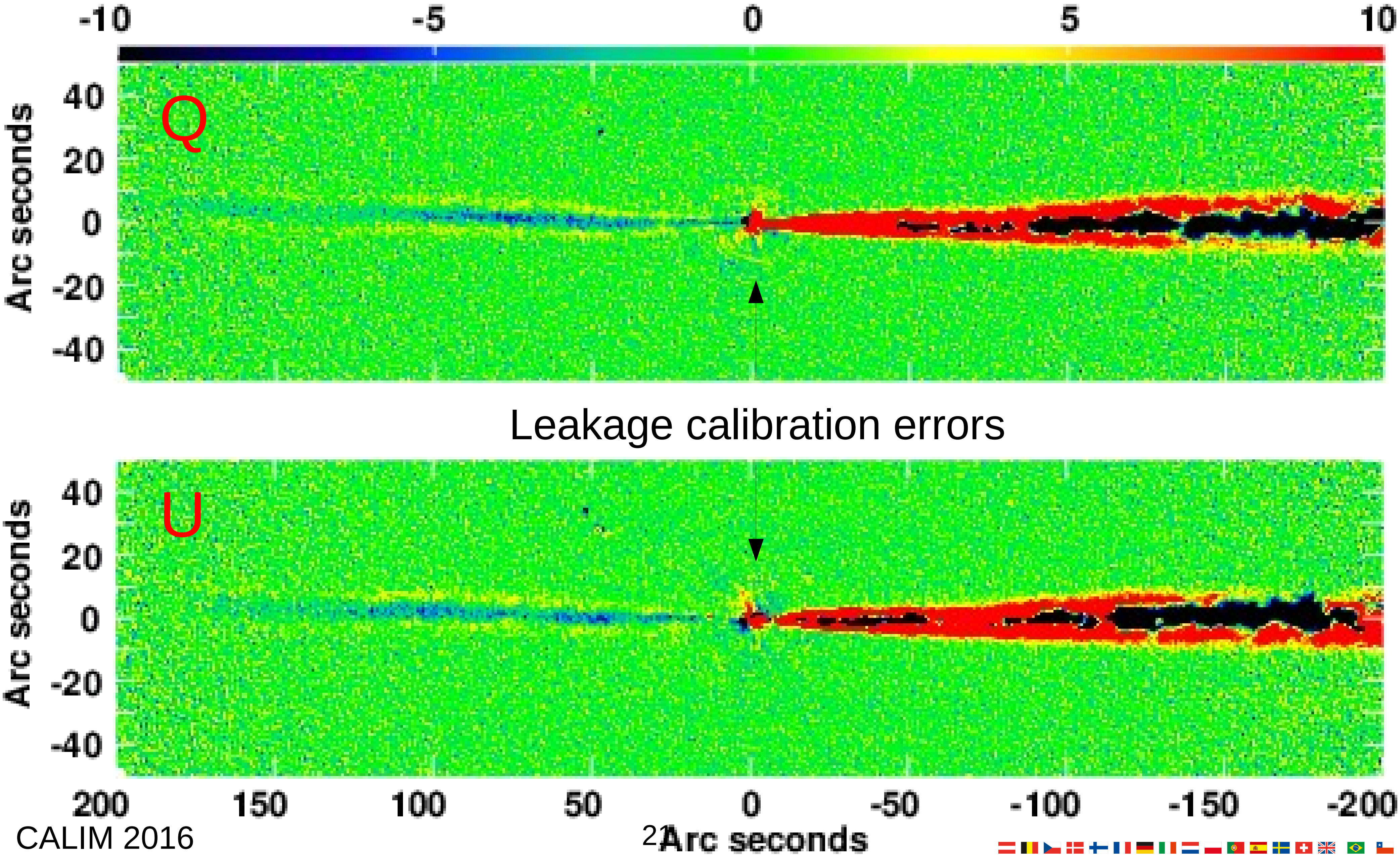
Rotation Measure



Averaged Q and U (main jet)



Deep Q and U (±10 μJy / beam)

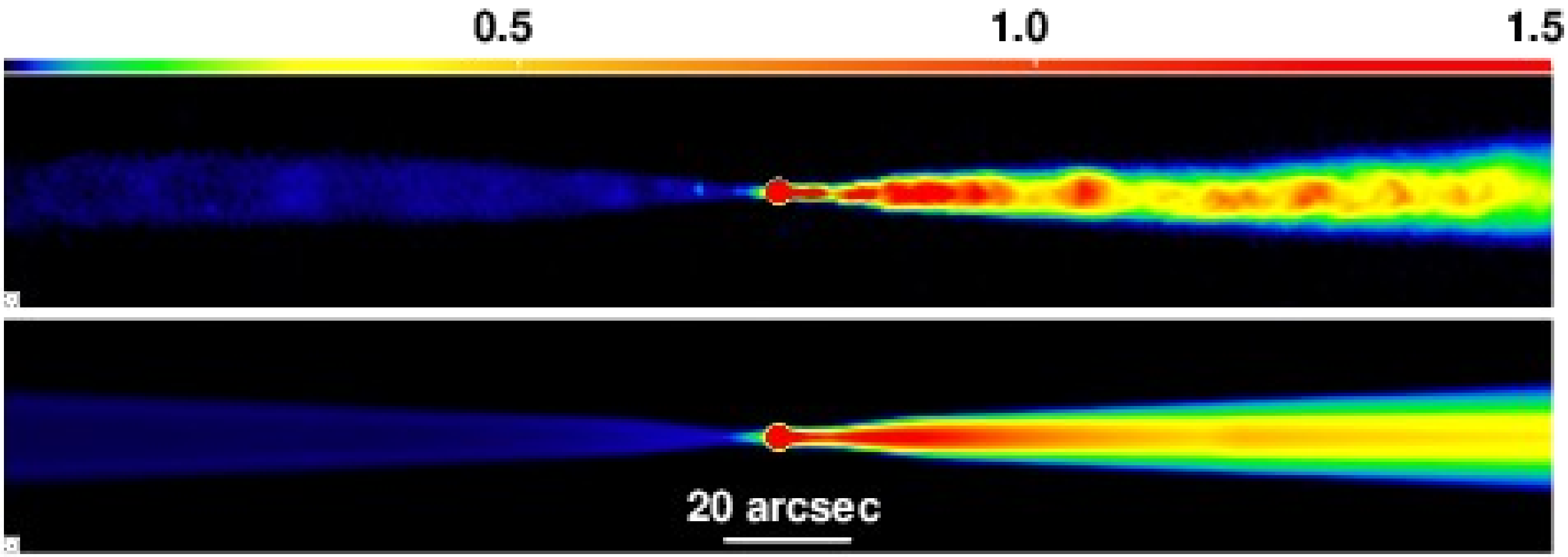


The story so far

- Best images
  - 1.25 arcsec FWHM (Briggs; robust = 0); (wideband)pbcor
  - I CASA MFS nterms = 2
  - QU: image individual spectral windows; fit and remove Faraday rotation; weighted average
  - Off-source rms = 1.2 μJy/beam for all Stokes in centre of field; close to thermal noise
  - Low-level calibration residuals in I, Q and U near the core
  - Otherwise, very few obvious artefacts within ±150 arcsec
- Limitations
  - Clear artefacts associated with bright outer jet knots – likely to be direction-dependent (beam squint)
  - Q and U likely to be very unreliable in the outer parts of the main jet

We can do astrophysics!
I Model Fits ($\theta = 30^o$)

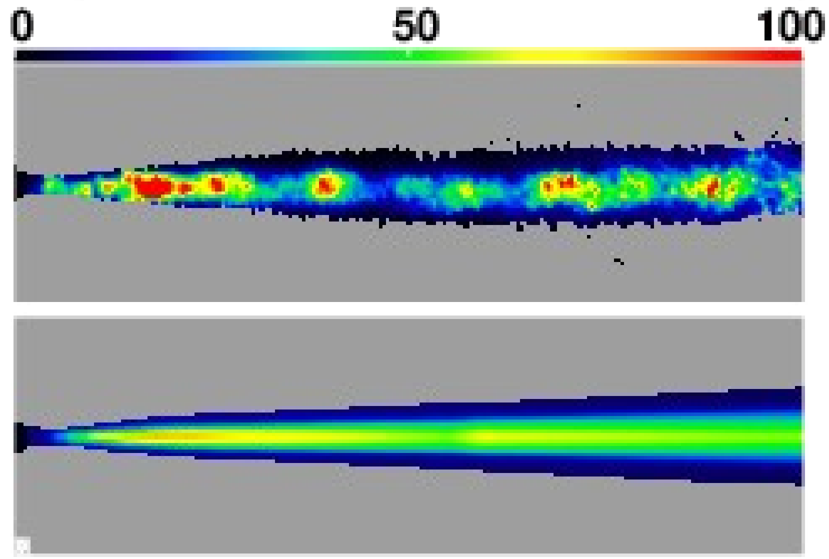
I



Data

Model

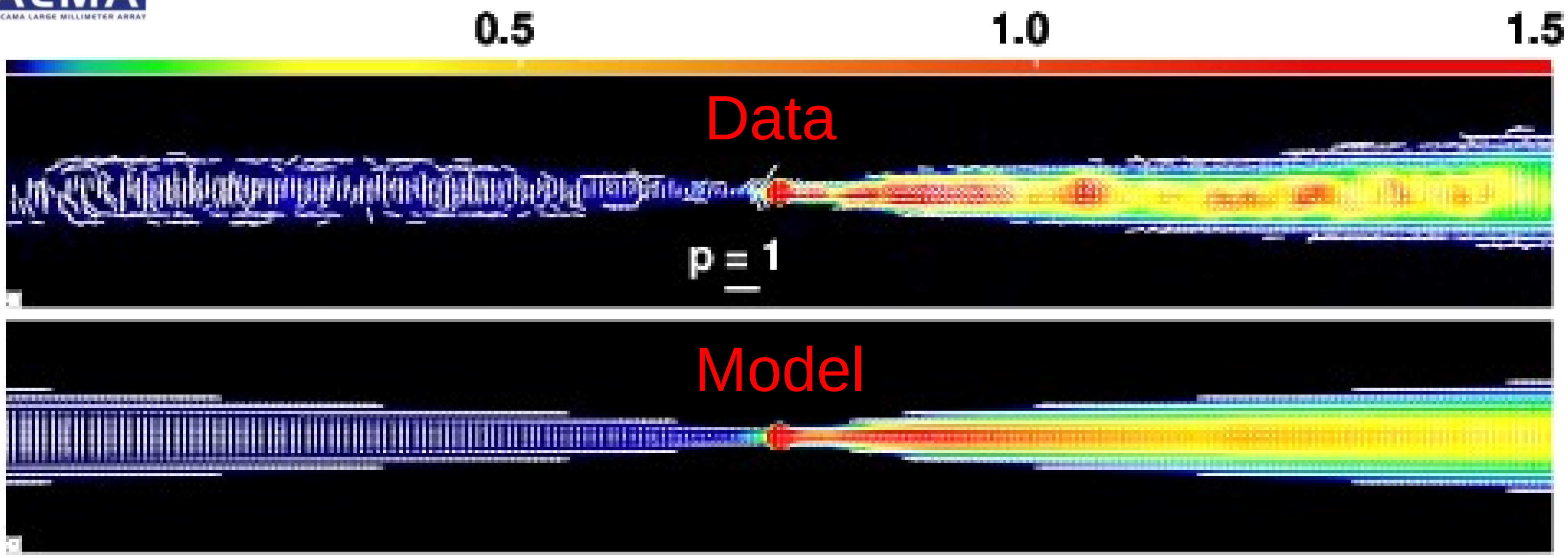
Sidedness ratio



Data

Model

Polarization Model fits

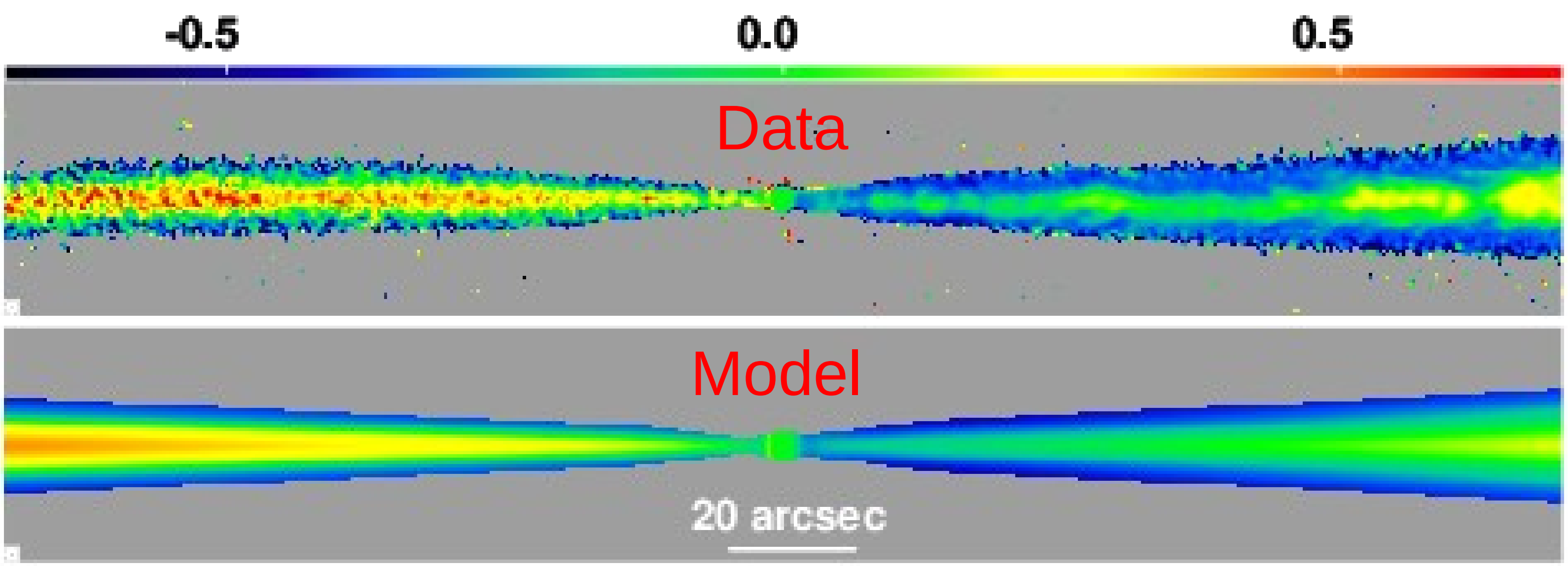


Colour: I

Vector length p

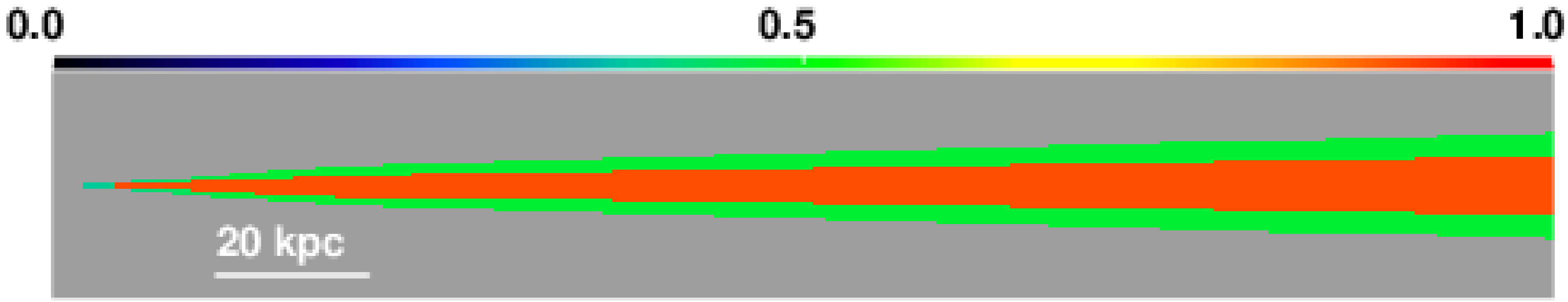
Vector angle χ_0+90^o

Model



Q/I
Axes rotated parallel to jet

Velocity



$\beta = v/c$

Independent longitudinal velocity profiles for spine and layer
No transverse variation in either component

Simplest model:

Spine: constant $\beta \approx 0.89$ ($\Gamma \approx 2.2$)
Layer: $\beta \approx 0.4$ ($\Gamma \approx 1.1$)

.... but cannot exclude faster spine close to the AGN where jets are poorly resolved in width

Wish List 1

- Delay chunking
  - Fix on-line, please
- Leakage and closure corrections
  - These are different manifestations of the same physical effects
  - Consistent and general calibration procedure within the ME framework in CASA (test Dfgen option in CASA polcal)
  - Absolute vs relative D-terms (Perley & Sault)
- Direction-dependent effects
  - Commission A-projection in CASA (Sanjay's talk)
  - Understand VLA Q and U beams (Prasanth's talk)
- AIPS – CASA transfer issues
  - Weights
  - Combined observations

Wish List 2

- Better method to combine observations in the presence of:
  - Variable structure (Urvashi's talk)
  - Flux-scale errors
- MFS algorithms to be aware of Faraday rotation
  - ... at least in the simple case of pure foreground rotation (Faraday dispersion function = constant x Dirac delta)
- Multi-scale CLEAN
  - Dissuade from using large-scale components when they are physically unreasonable

Most, if not all of these are being worked by people at CALIM2016*

*Thanks to Sanjay Bhatnagar, Urvashi Rao, George Moellenbrock and Rick Perley for their help so far.