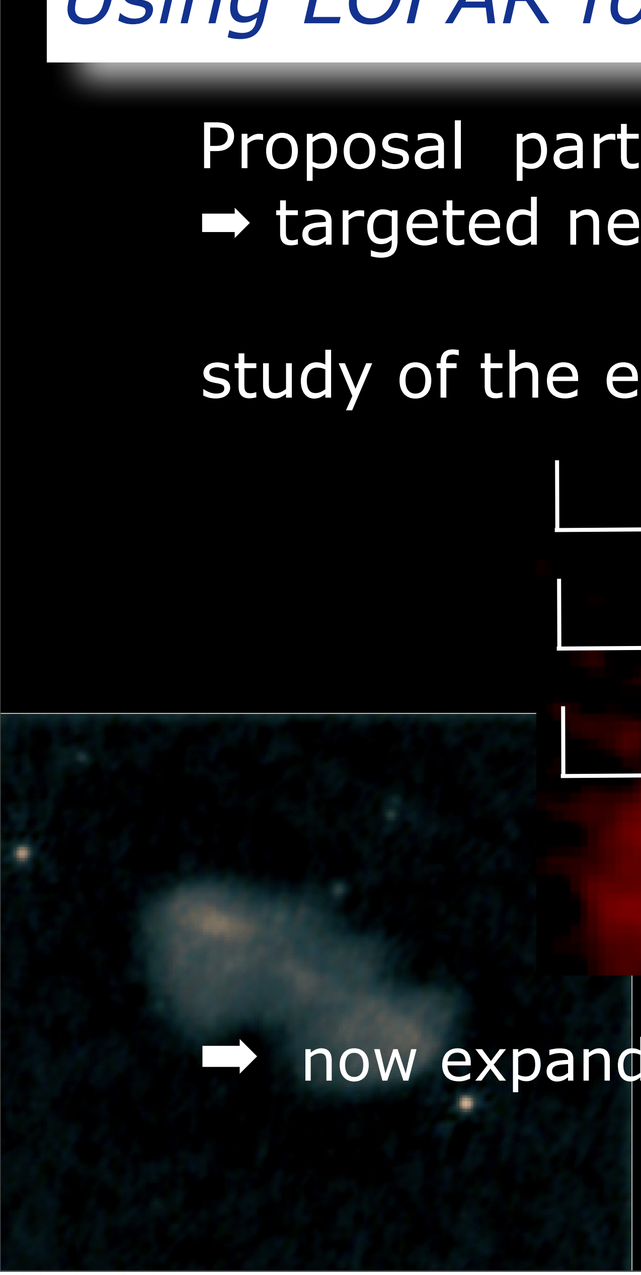
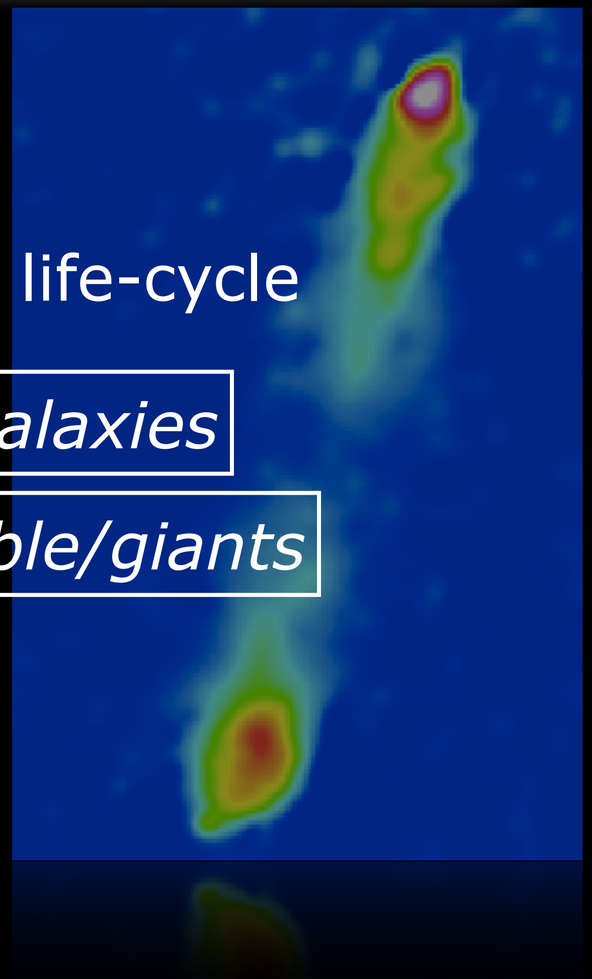
Status of the project (Cycle 0, 1, 2):
Using LOFAR for detailed studies of AGN and AGN physics

Proposal part of the survey group
➡ targeted nearby known radio sources:

study of the energetics, spectral properties and and life-cycle

- *3CR radio galaxies*
- *double-double/giants*
- *relics*





➡ now expanding to serendipitous objects in the fields

Targets

- **3C31** (Heesen et al.) **3C223** (Harwood et al.)
- **3C452** => Brienza, Godfrey & Harwood
- **NGC6152** (Cantwell & Shulevski)
- other giant/dd **3C236** => Shulevski (Orru`)
- **3C388** => Godfrey, Brienza
- serendipitous **Blob1** => Brienza et al. in prep
- **J1431** (Shulevski thesis), **B2 0924+35** Shulevski thesis)
- Results from Cycle 2 (Brienza et al.) => B2 0258+35 (also commissioning data Shulevski et al.), 3C317 etc.

Who is working on the data:

Southampton: Judith Croston, Volker Heesen, Therese Cantwell, Jeremy Harwood (now ASTRON) => using different imaging pipeline

ASTRON/Groningen: Aleksandar Shulevski, RM, Marisa Brienza, Leith Godfrey, Nicolas Vilchez   => all involved in testing imaging pipeline

Observing strategy

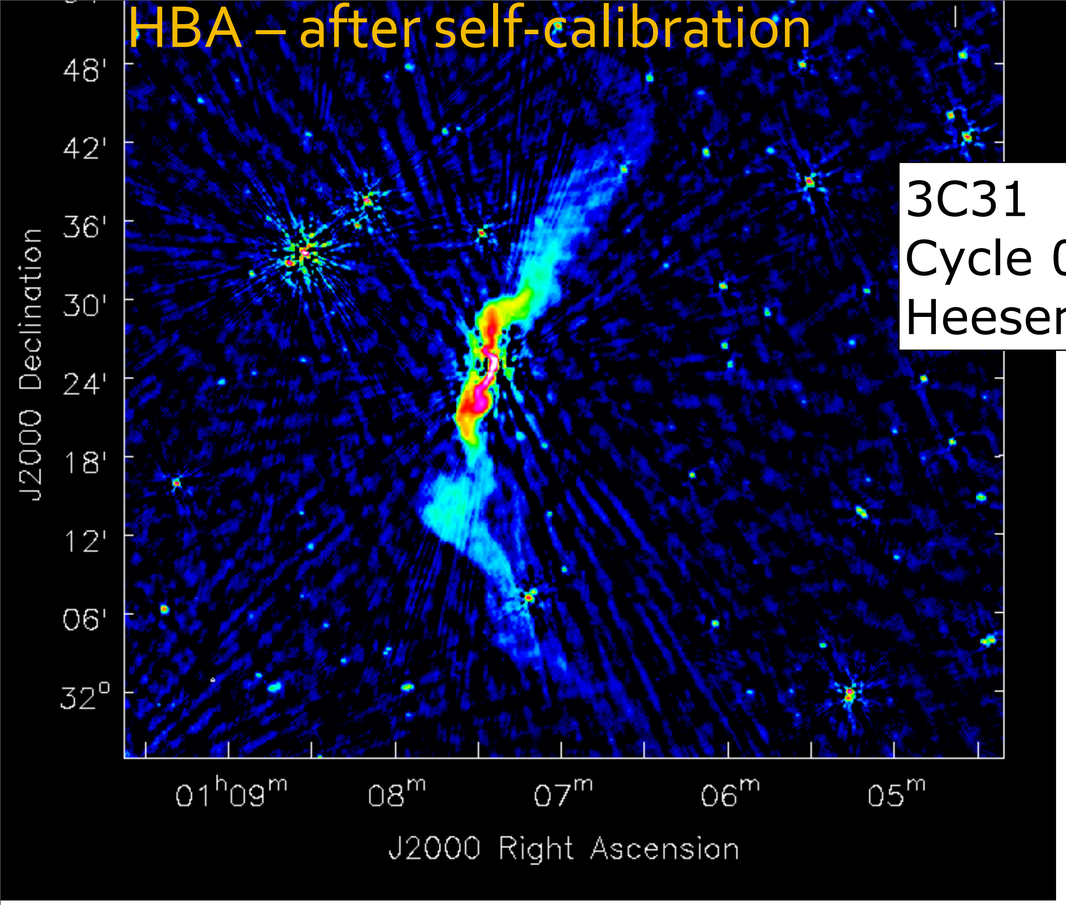
- HBA observations interleaved calibrator-sources (2-11/30min). Quite a lot of time spent on calibrator → important to know stability of the system and accurate flux scale

- LBA: part of the band on a calibrator (3C196, 3C295...) => work on LBA data is lagging behind.

- We did not request night time → investigating the effect of this, so far it seems to be not too bad for HBA but we need to check LBA!

- Pre-processing done initially by pipeline

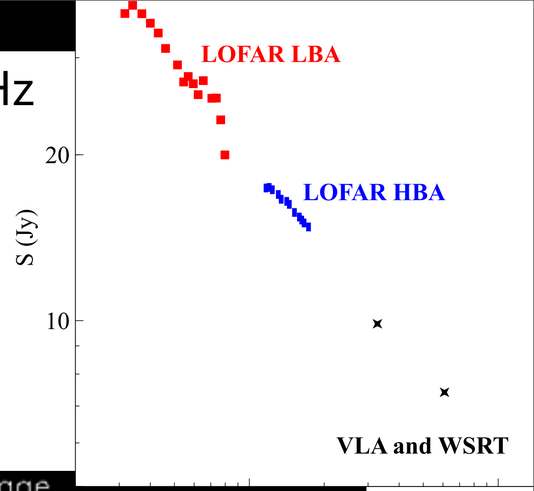
- Raw data kept only for Judith's sources and moved to Southampton
- Other datasets: kept the pre-processed, averaged data => we are moving most of the datasets to the cluster @ASTRON *FLITS* (10 nodes, 200 Tb).

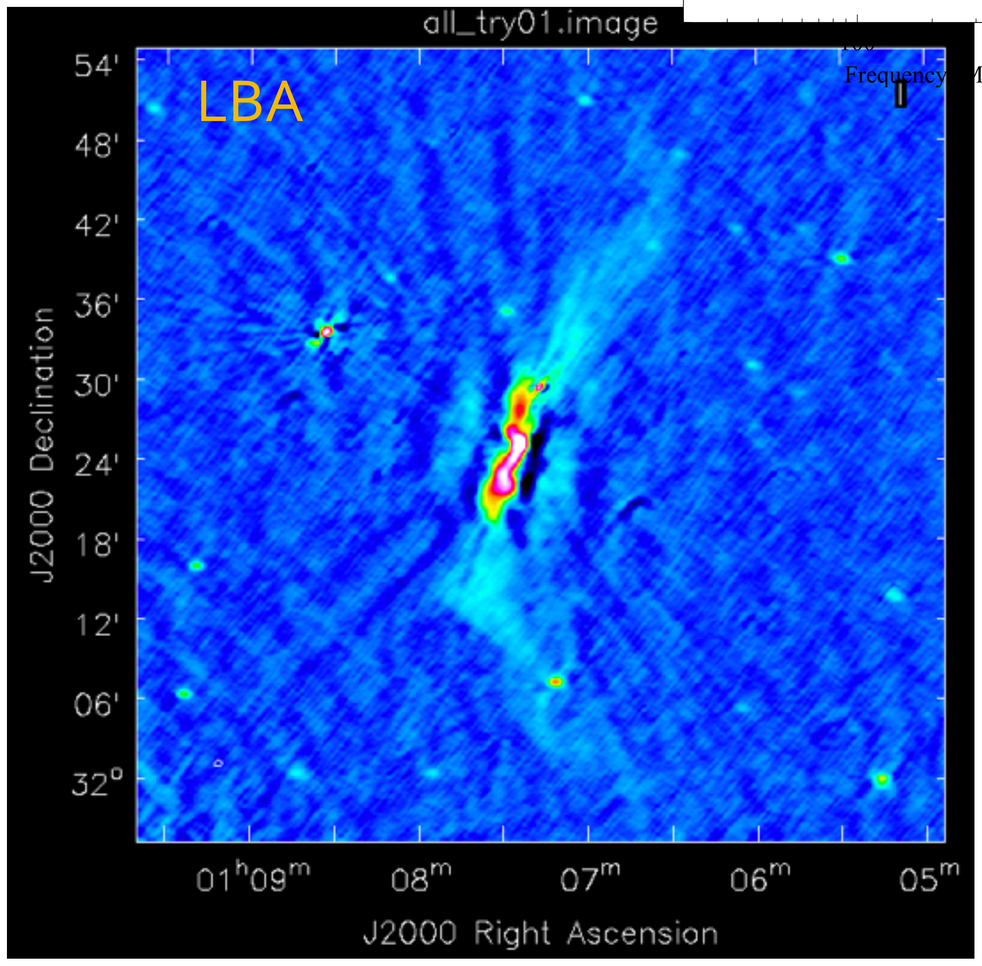


3C31
Cycle 0
Heesen & Croston

- Combined HBA data @ 144 MHz
- RMS noise ~1–2 mJy
- ~18 arcsec resolution
- Peak flux: 6 Jy
- Cleaned with CASA
  - Multi–scales, <13 arcmin
  - Nterms=1 (no SI fitting)

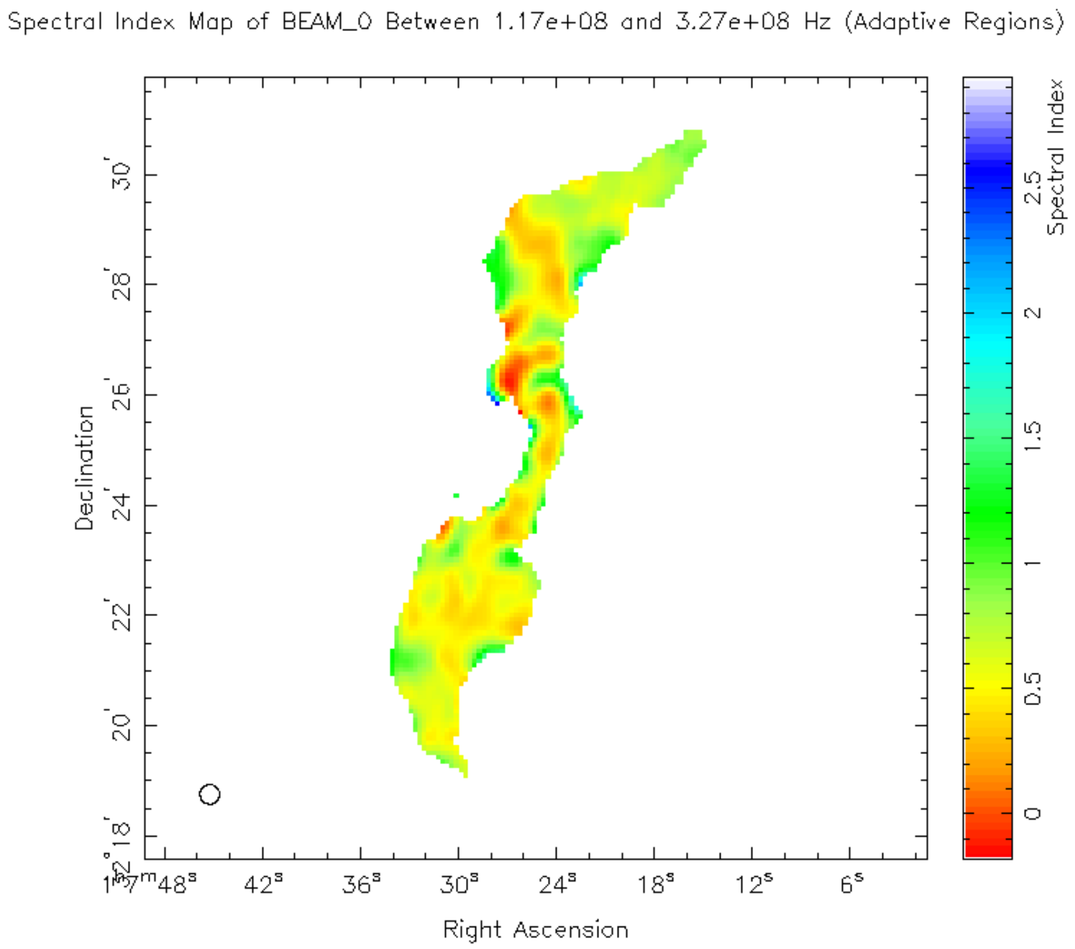
- Combined LBA data @ 60 MHz
- RMS noise 6 mJy
- ~40 arcsec resolution
- Peak flux: 36 Jy
- Cleaned with CASA
  - As for HBA



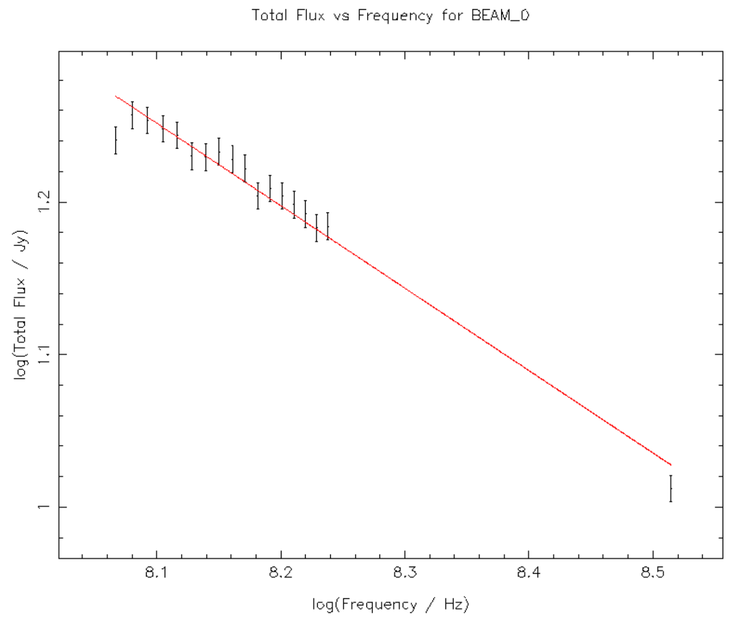


Spectral index

with BRATS (=Broad Band Radio Analysis Tools) See Harwood et al. 2013, MNRAS, 435, 3353



Spectral index = –0.54
(115–330 MHz)



(1) In the inner regions (around <100 kpc) the integrated spectrum appears to extrapolate back from GHz frequencies, with a spectral index of around 0.6

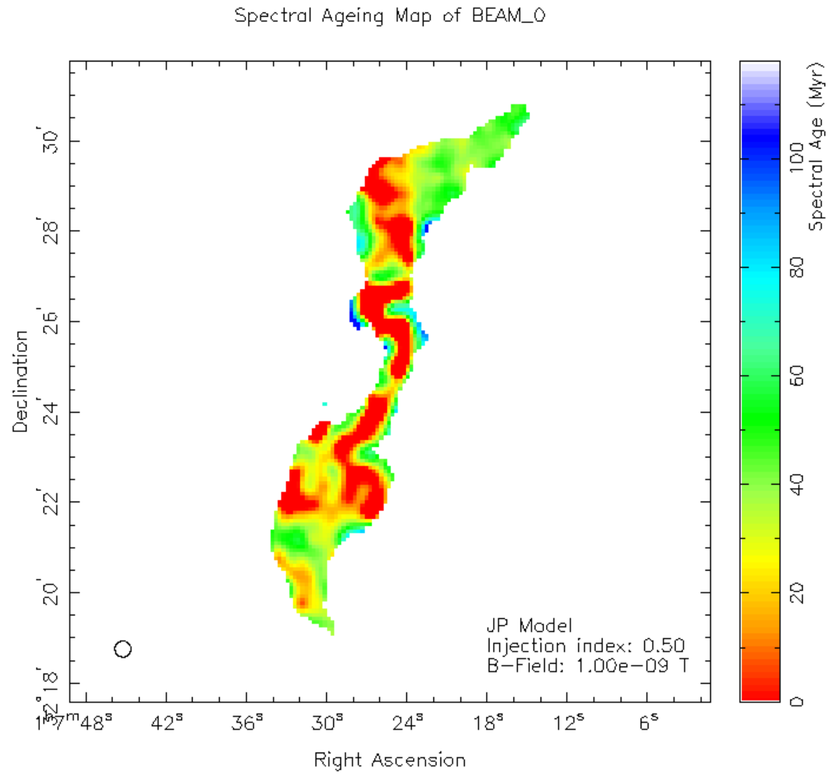
There is no indication of any additional particle population at low energies. The lack of further flattening could be interpreted as support for the role of relativistic shocks in accelerating the jet particles (rather than non-relativistic shocks, which predict alpha_inj=0.5),

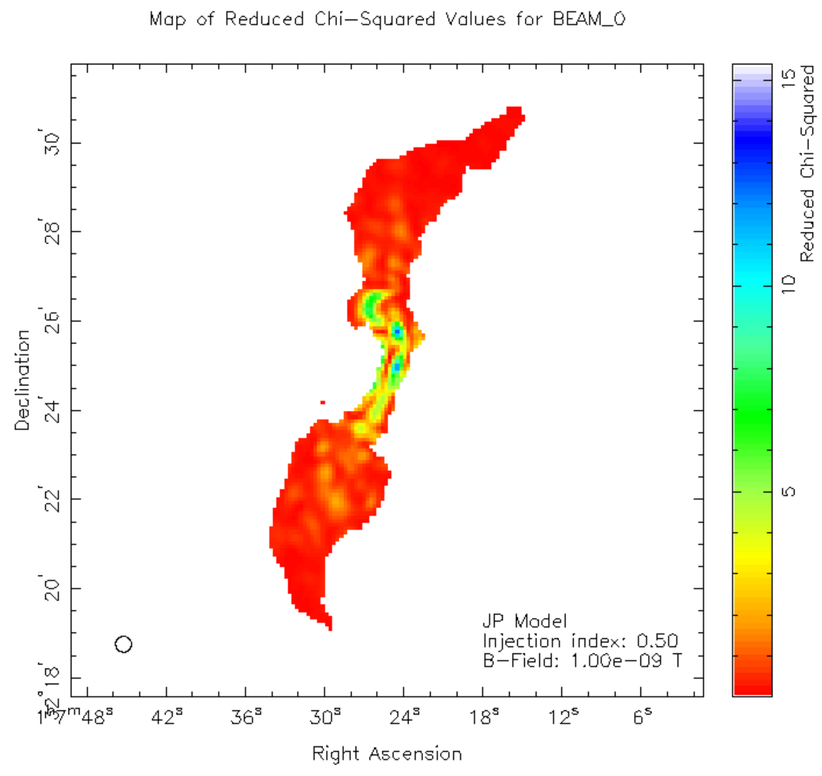
Spectral ageing

with BRATS (=Broad Band Radio Analysis Tools) See Harwood et al. 2013, MNRAS, 435, 3353

the normalisation in age to be finalised

Paper Heesen et al in prep





(2) spectral steeping as a function of distance between 140 MHz and 330 MHz => investigating the best way to model the dynamical evolution via spectral age modelling but also taking into account X-ray pressure constraints.

3C223 – Data quality

3C223
Cycle 0
Harwood & Croston

- Example off-source RMS:
  - HBA 0.78 mJy / beam at 140 MHz
  - LBA: 12.4 mJy / beam at 51.6 MHz

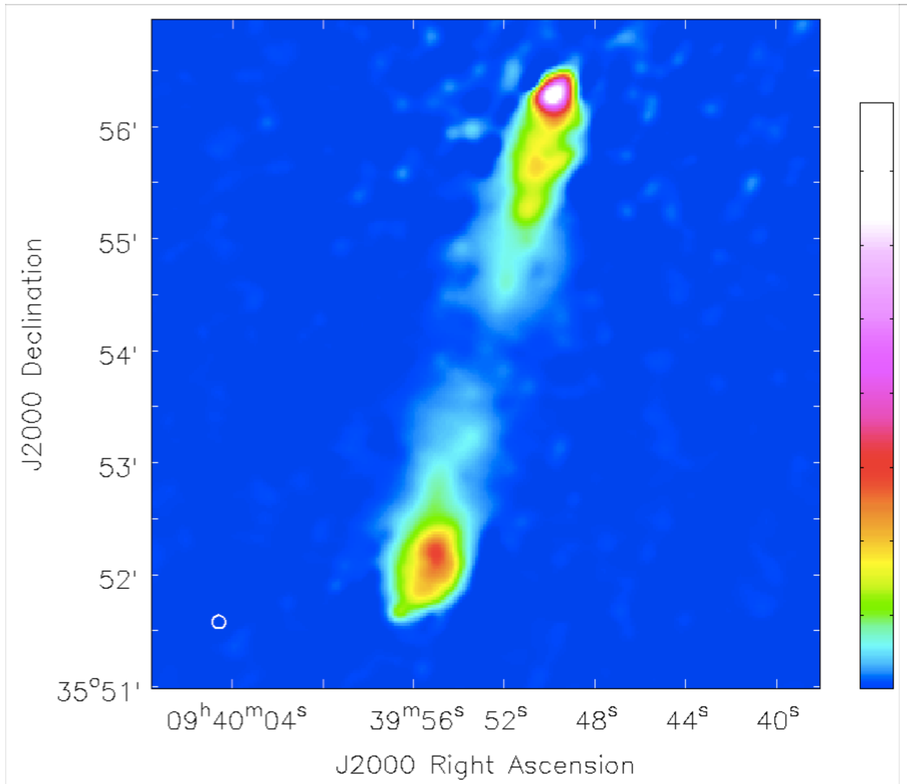
- 6 (usable) images at HBA (7 MHz bandwidth)

- 1 image at LBA (12 MHz bandwidth)

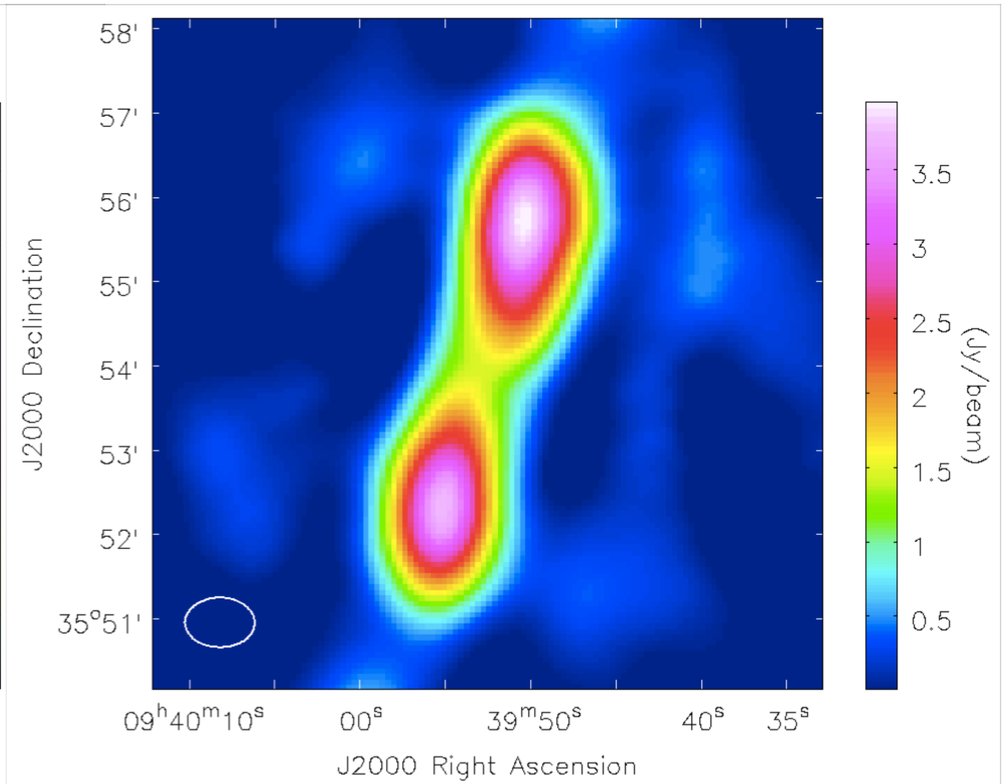
- Integrated flux correct to within ~5% compared to Orru 2010 (extrapolated from 73.8 MHz)

- Noise peaks in the northern lobe currently limit full spectral age model fitting (self-cal doesn't appear to be help!)

- Interesting science still possible, even with the noise



3C223 at 140 MHz (7 MHz Bandwidth)

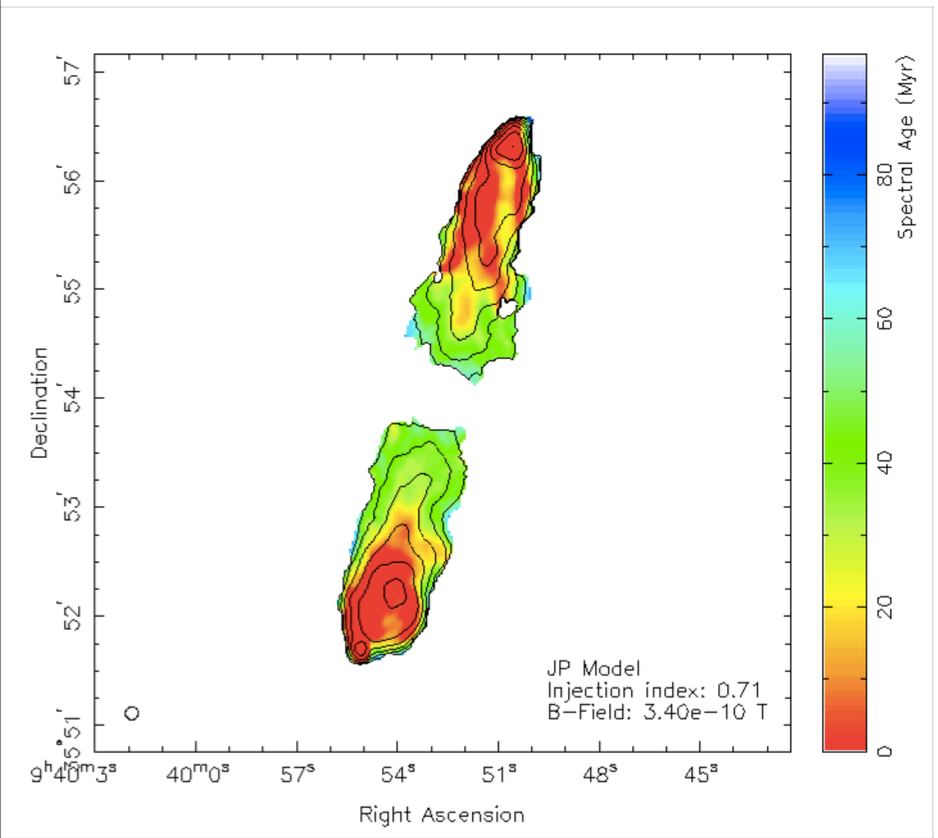


3C223 at 51.6 MHz (12 MHz Bandwidth)

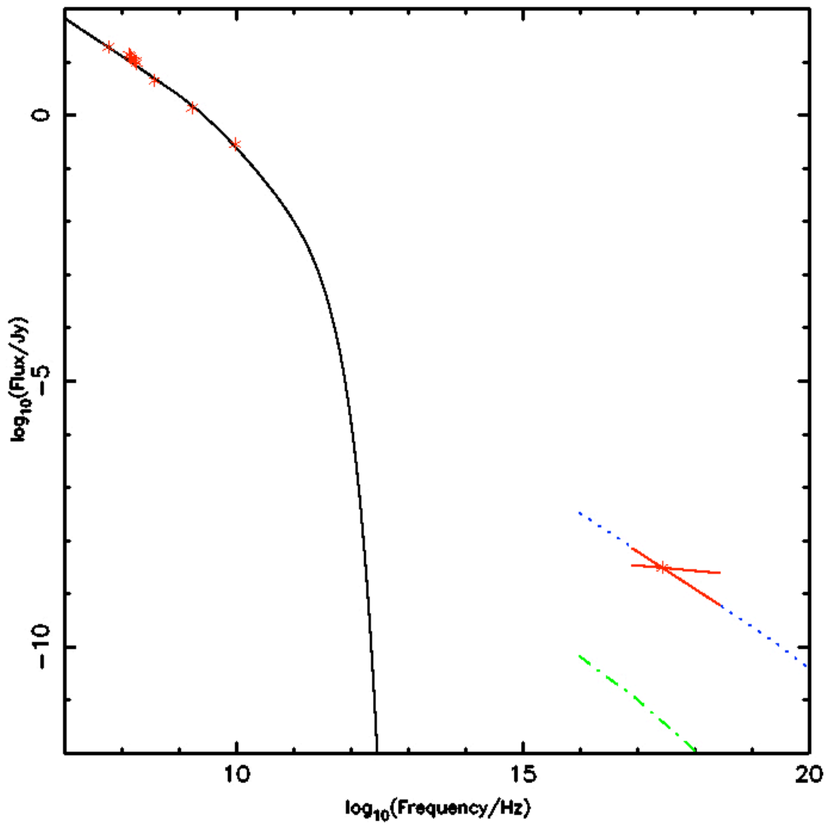
3C223 – Results

- Confirmation at low frequencies of the higher than expected initial electron energy distribution (injection index > 0.7 for 3C223) in FR-II galaxies found by Harwood et al. (2013)
- Synchrotron / inverse-Compton modelling using the updated LOFAR data finds the total lobe energy content is greater by a factor of ~2 compared to the original analysis by Croston (2004)
- This puts the lobes of 3C223 in pressure balance with the external medium (previously thought to be under pressured)
- The same assumption about the low energy electron population has also been applied to a wider sample (Croston 2005). It may therefore apply to the FR-II population as a whole!
- Can this solve the pressure balance issue seen in many galaxies?
- 3C223 results now published in thesis (http://uhra.herts.ac.uk/handle/2299/14409) + proceedings India

Synchrotron / inverse-Compton model fitting of 3C223



Spectral age map of 3C223 (JP model)



Red X: Integrated flux densities
Solid black line: Model synchrotron emission
Red bow tie: X-ray observation constraints
Blue dotted line: Model iC/CMB emission
Green dot-dashed line: Model SSC emission

Note:
Being well constrained at low frequencies means reliable injection indices (previous slide).
Being poorly constrained at higher frequencies means large age errors on the ages.
The high noise levels around the northern lobe mean the spectral morphology is unreliable (fine in the southern lobe)

3C223 – Future work

- Attempt to improve noise levels around the northern lobe of current HBA images of 3C223

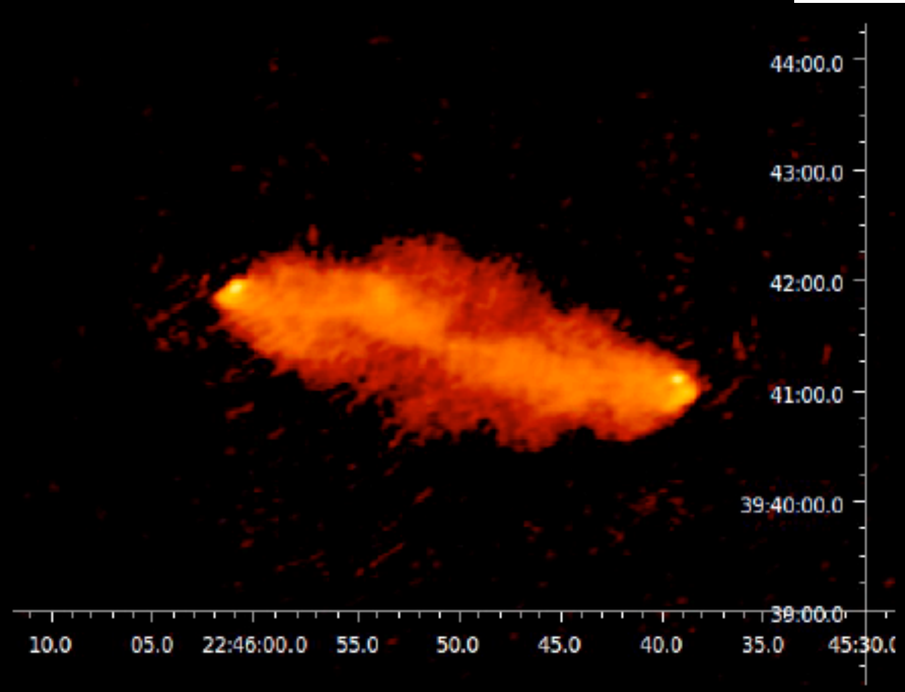
- Obtain additional (science quality) LBA images from current dataset

- Additional sources (e.g. 3C452) required to see if these finding are more general to the FR-II population (in progress)

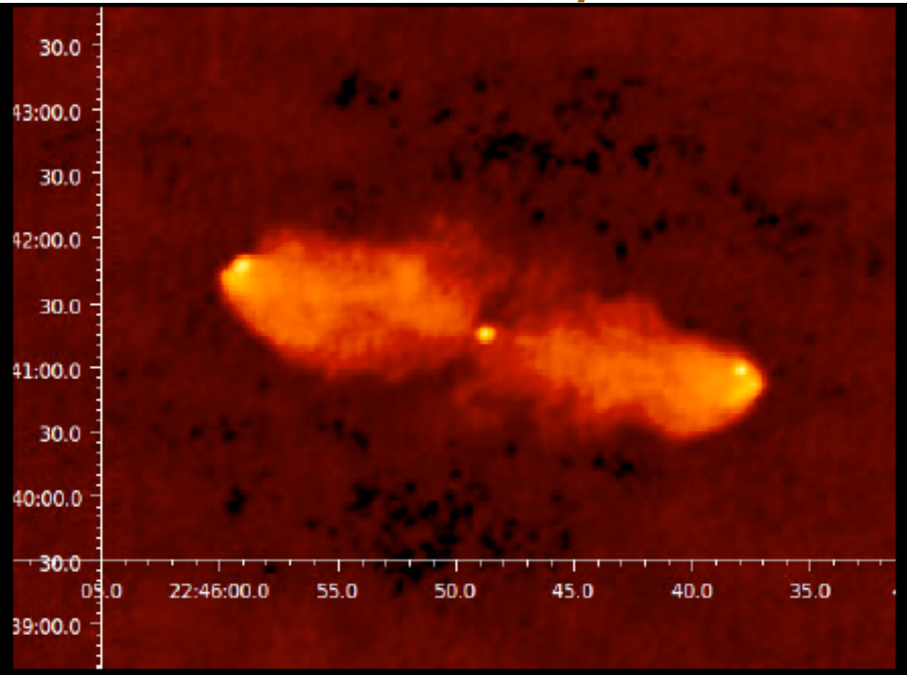
- Final results should be published within 6 -12 months

3C452 Marisa Brienza & Leith Godfrey (Cycle 0)

Planned a similar study as 3C223 (with J. Harwood)



LOFAR 150 MHz



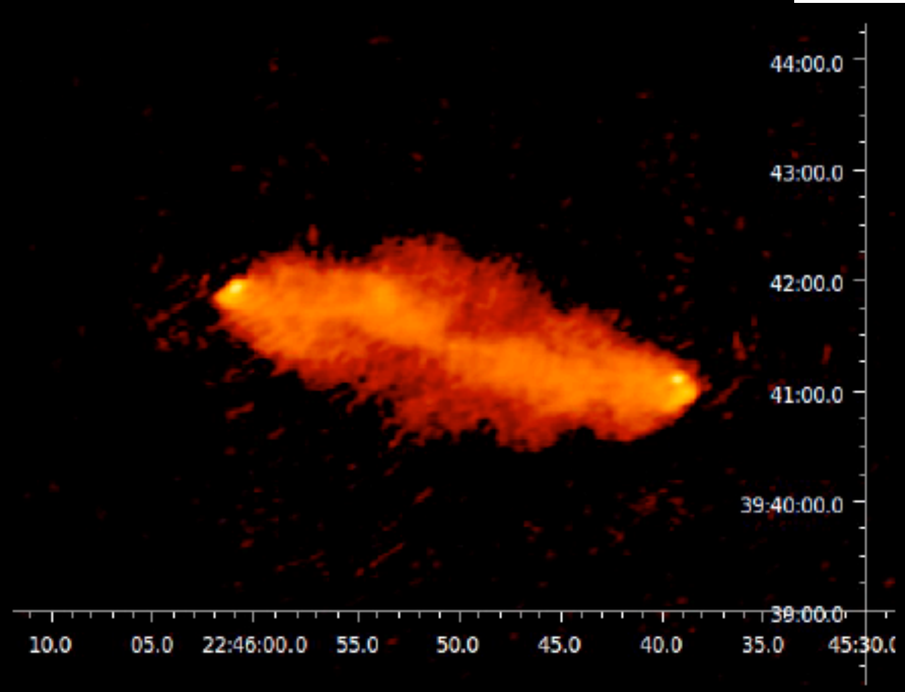
VLA 1400 MHz

Selfcal pipeline + CASA multiscale clean

RMS 3 mJy/beam
Beam 6”x4”
SB 20

3C452 Marisa Brienza & Leith Godfrey (Cycle 0)

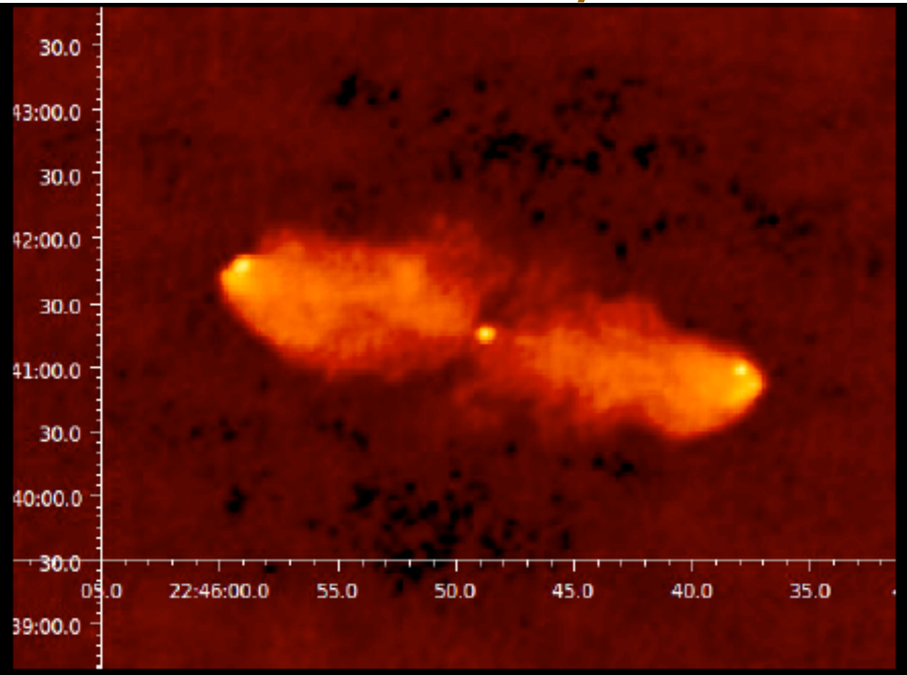
Planned a similar study as 3C223 (with J. Harwood)



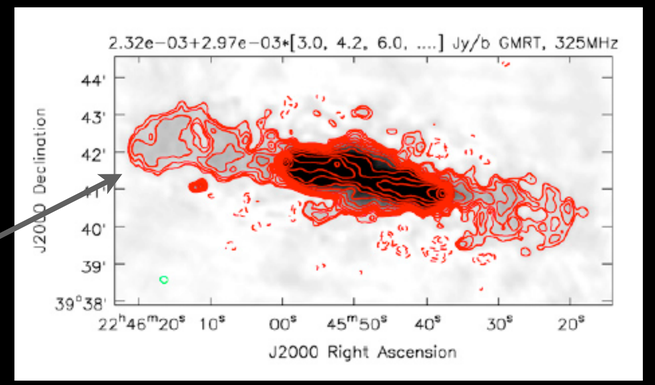
LOFAR 150 MHz

Selfcal pipeline + CASA multiscale clean

RMS 3 mJy/beam
Beam 6”x4”
SB 20

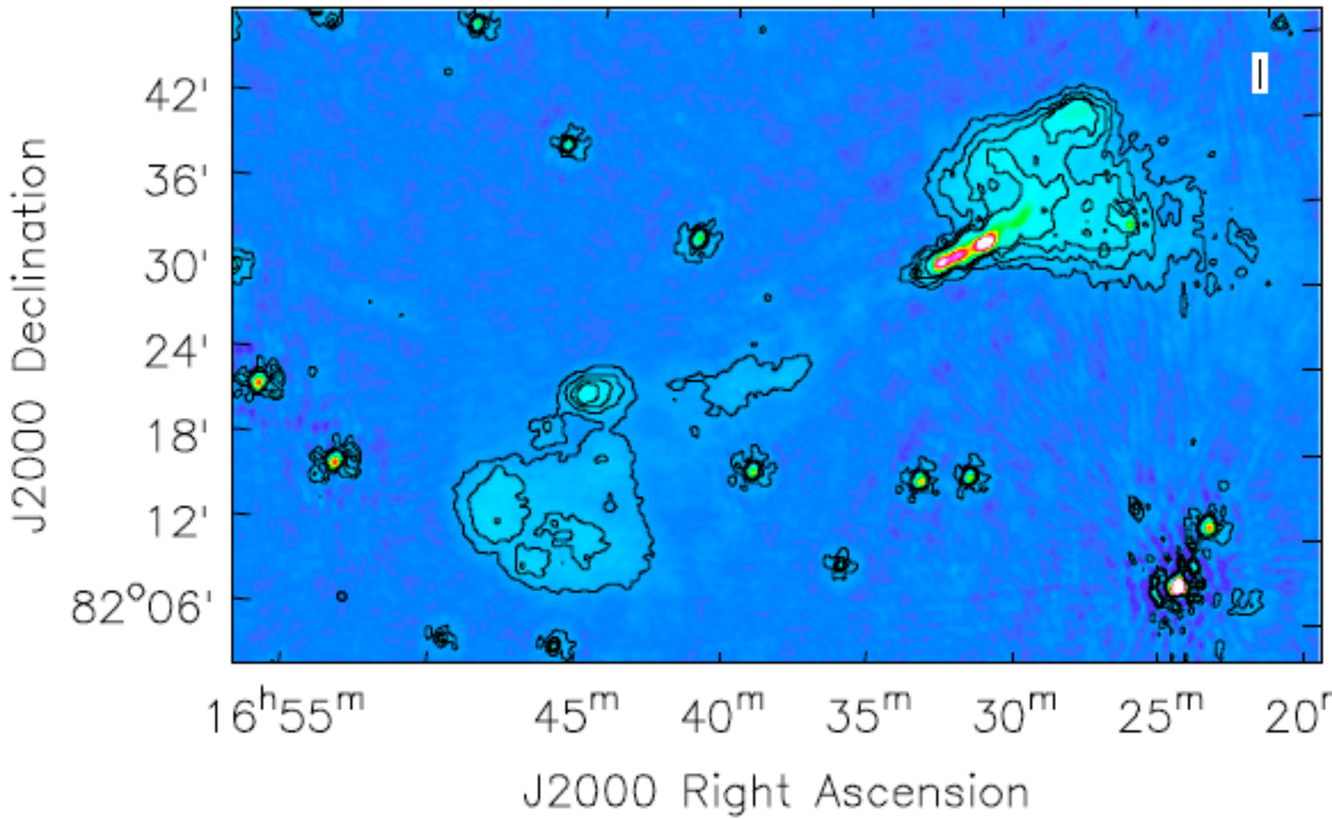


VLA 1400 MHz



No relic lobes found!!!! (see GMRT Sirothia et al.)

NGC 6251: HBA Image



- $\nu_{\text{centre}} = 140$ MHz
- Bandwidth 24 MHz
- UVrange < 11.5 klambda
- Rms ~ 3 mJY

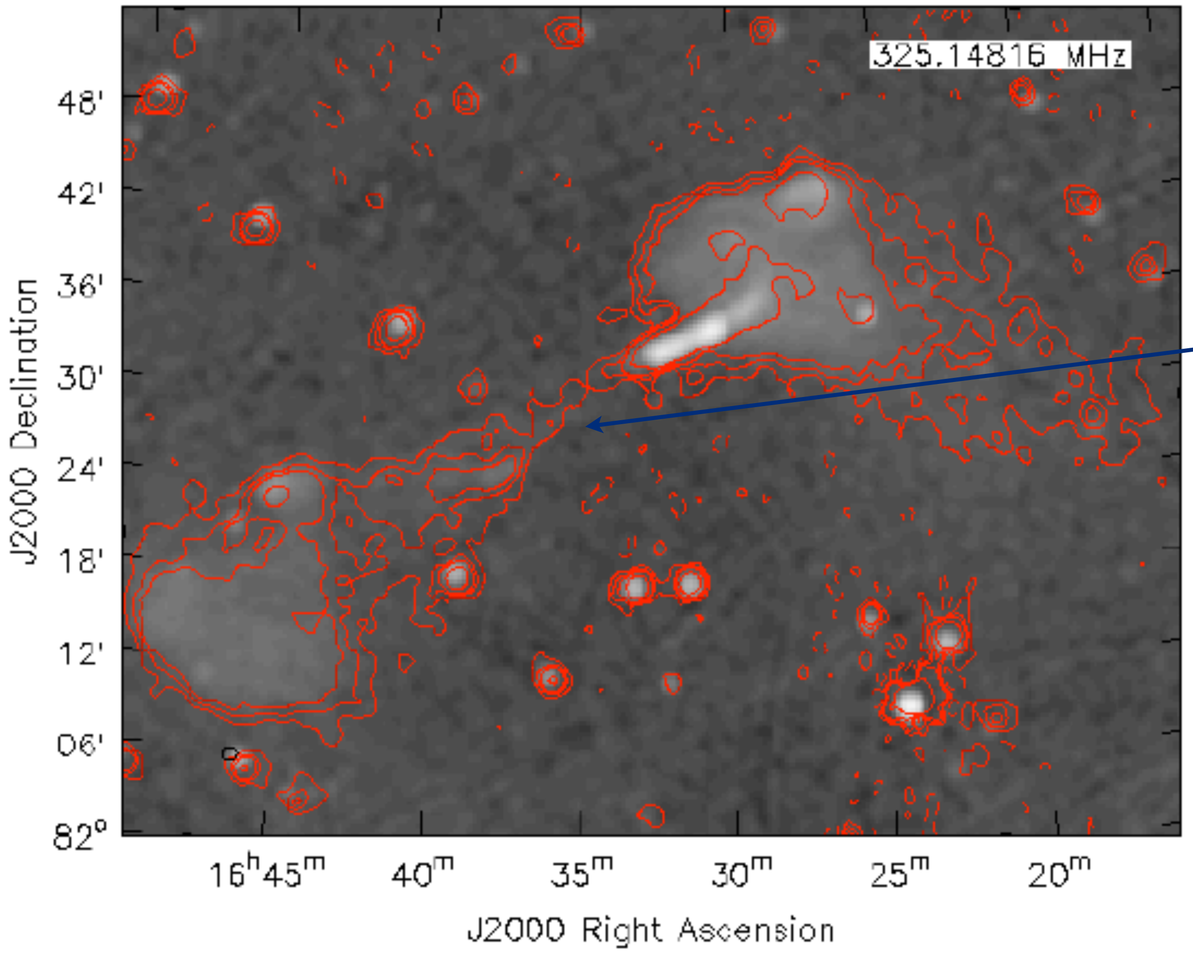
Therese Cantwell & Judith Croston (Cycle 1)

Highlights:

NGC 6251

- Counterjet cocoon detected by LOFAR.

rms ~ 4 mJy/b

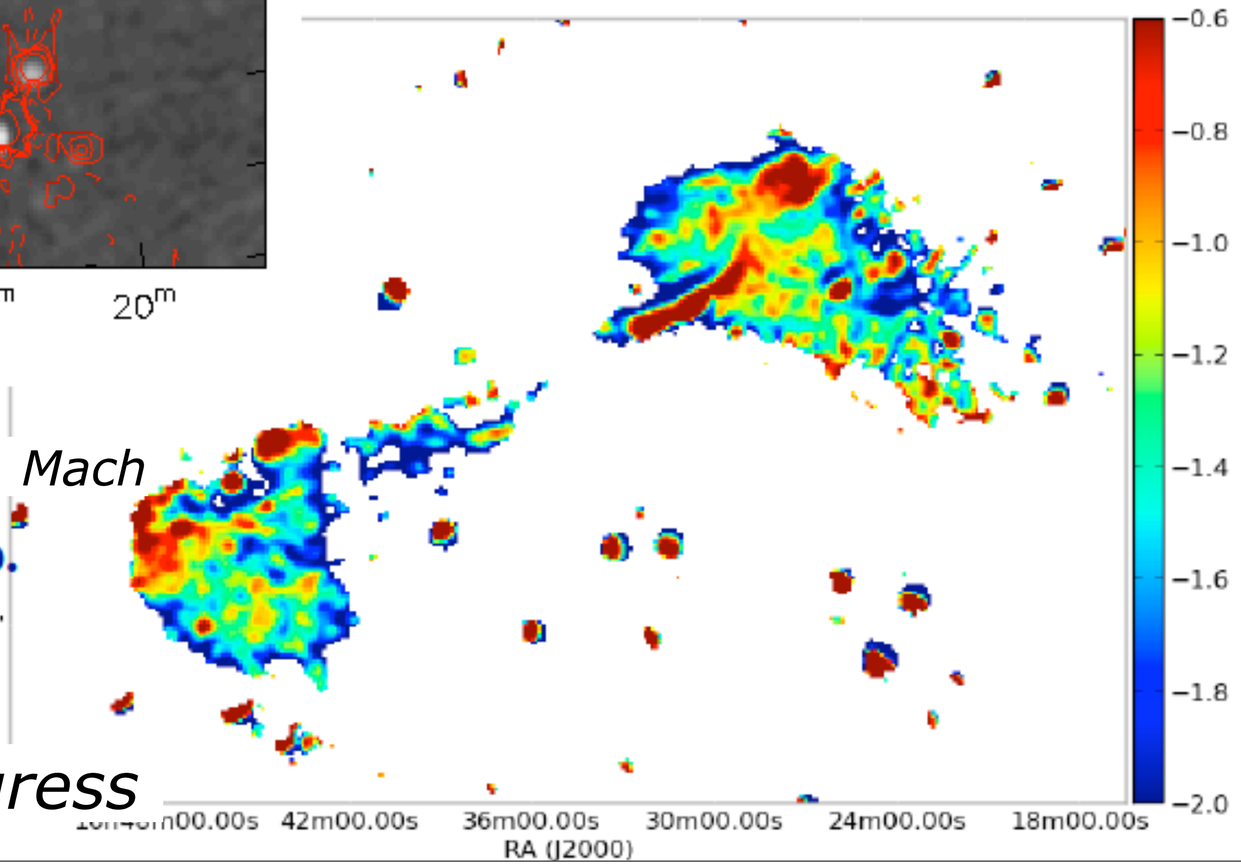


Combined with WSRT images from K. Mach

- Highest resolution spectral index map.

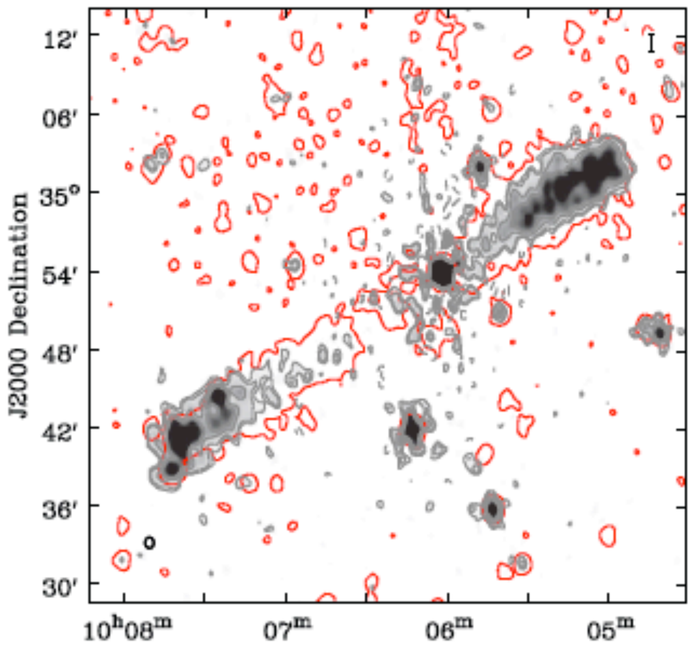
140 – 325 MHz

Shulevski et al. work in progress



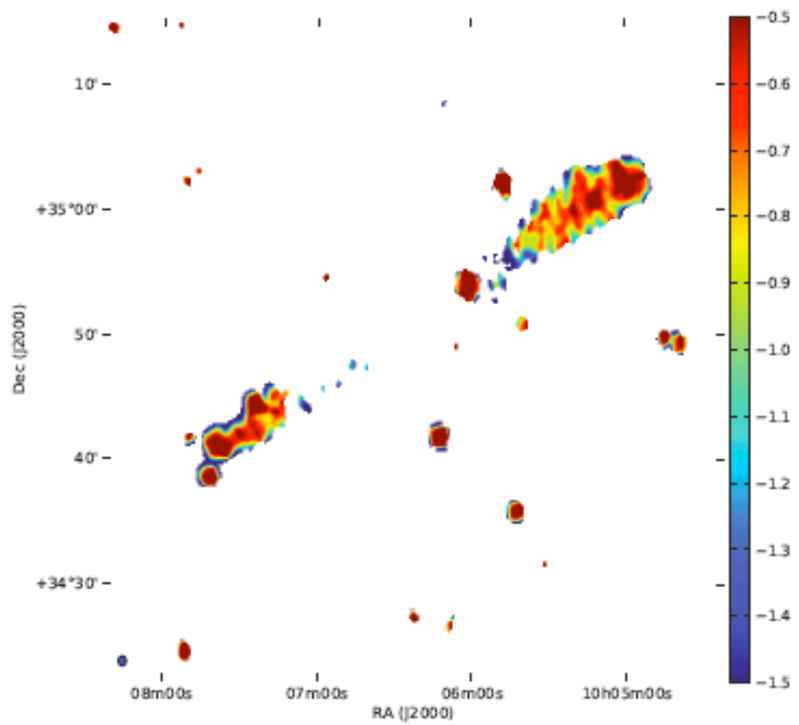
014

Double-double, giant 3C236 (Cycle 1)



rms ~ 7 mJy/b

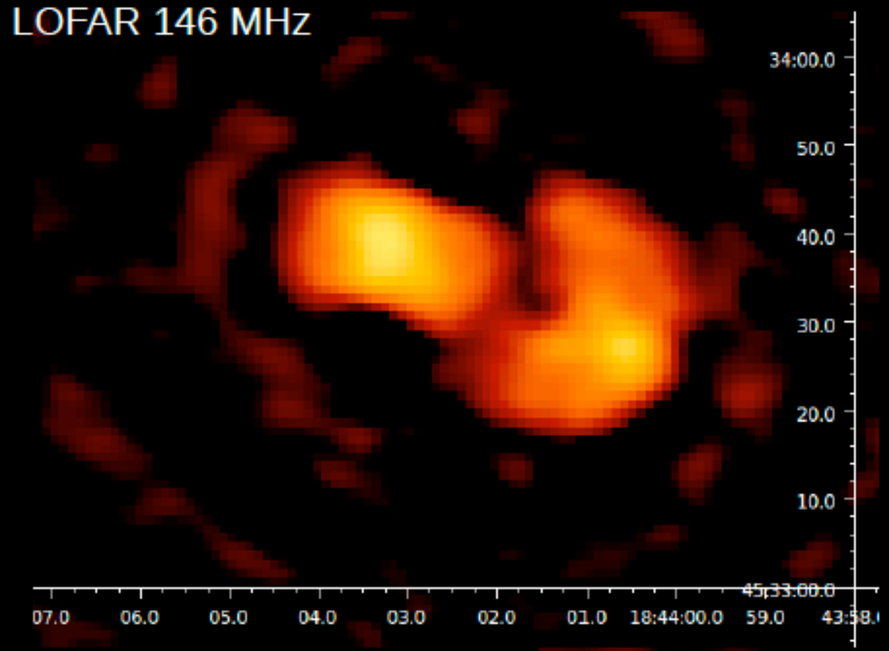
(a) Grayscale LOFAR map of 3C 236. Grey contours: $(-3, 2, 3, 6, 9)\sigma$. Shown in red is the 2σ contour level of the WSRT 609 MHz map.

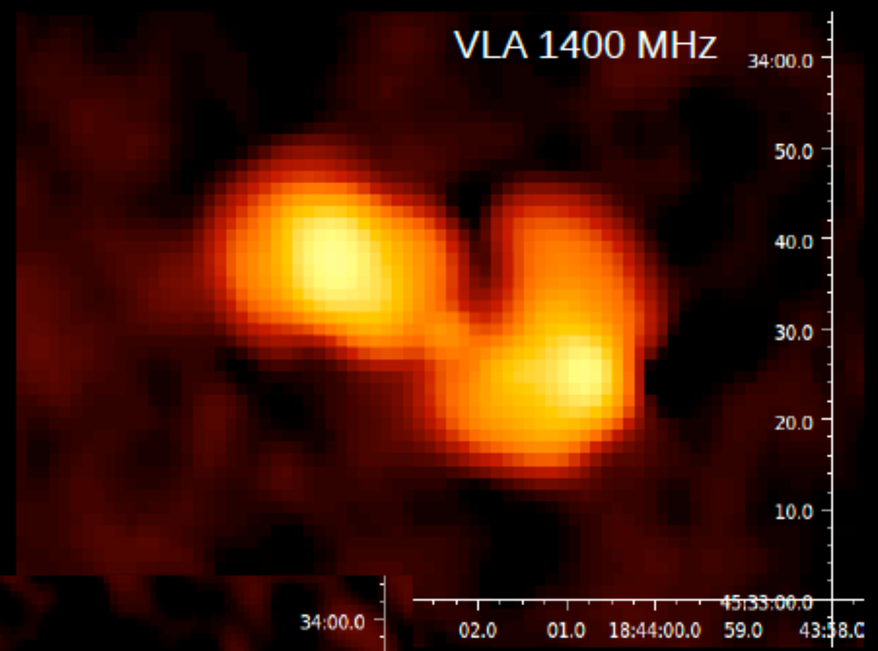


(b) α_{144}^{609} spectral index map.

Shulevski in prep - sign of intermettent activity from the spectral index? consistent with what found from stellar population?

3C388 => Leith Godfrey & Marisa Brienza (Cycle 1)





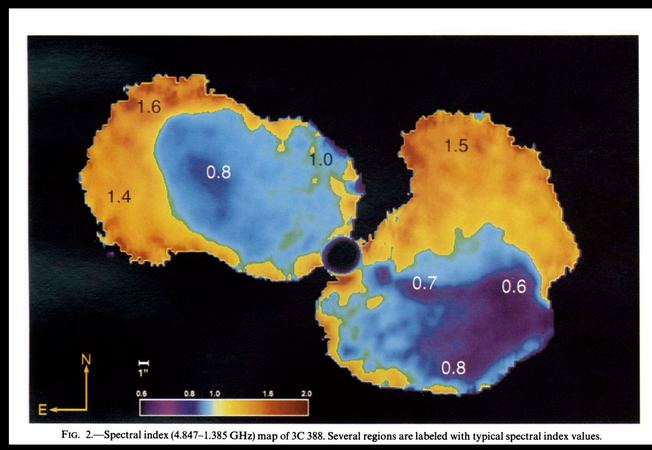


FIG. 2.—Spectral index (4.847–1.385 GHz) map of 3C 388. Several regions are labeled with typical spectral index values.

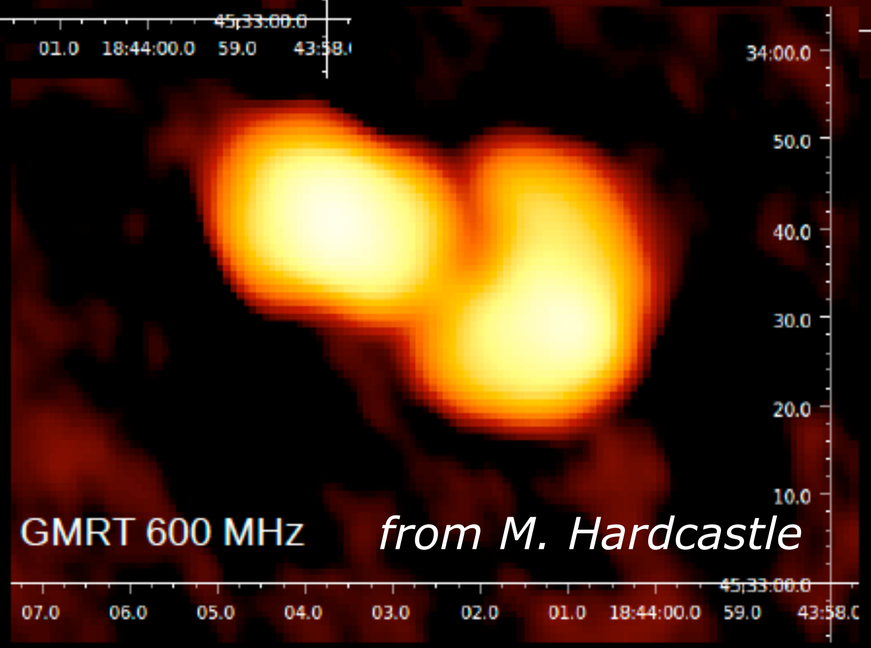
3C388
Roettiger et al.

Selfcal pipeline with annulus subtraction + manual self-calibration

Beam 4”x5”

RMS 10mJy/beam

9 SB

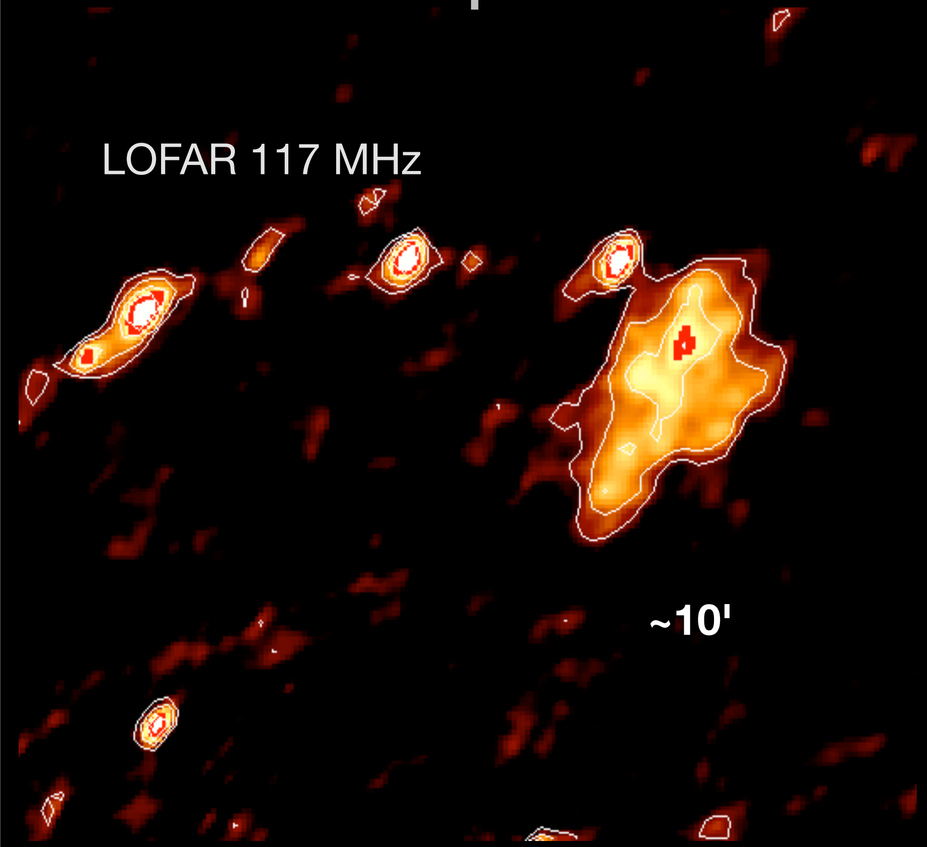


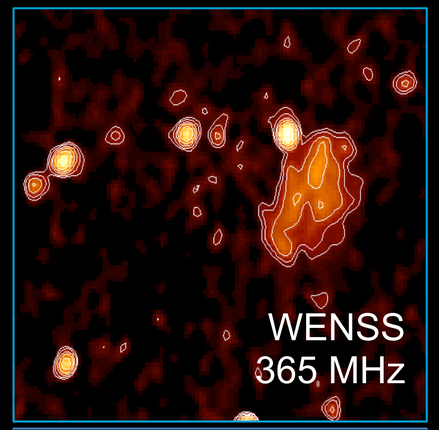
from M. Hardcastle

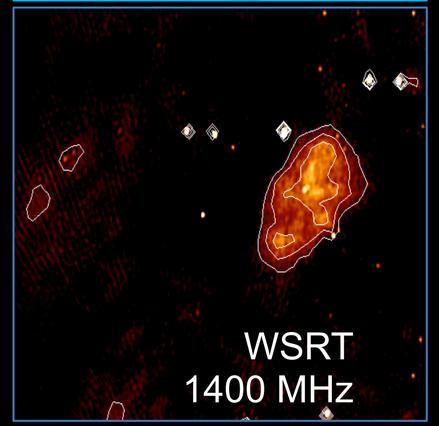
data reduction and analysis of the spectral index in progress:

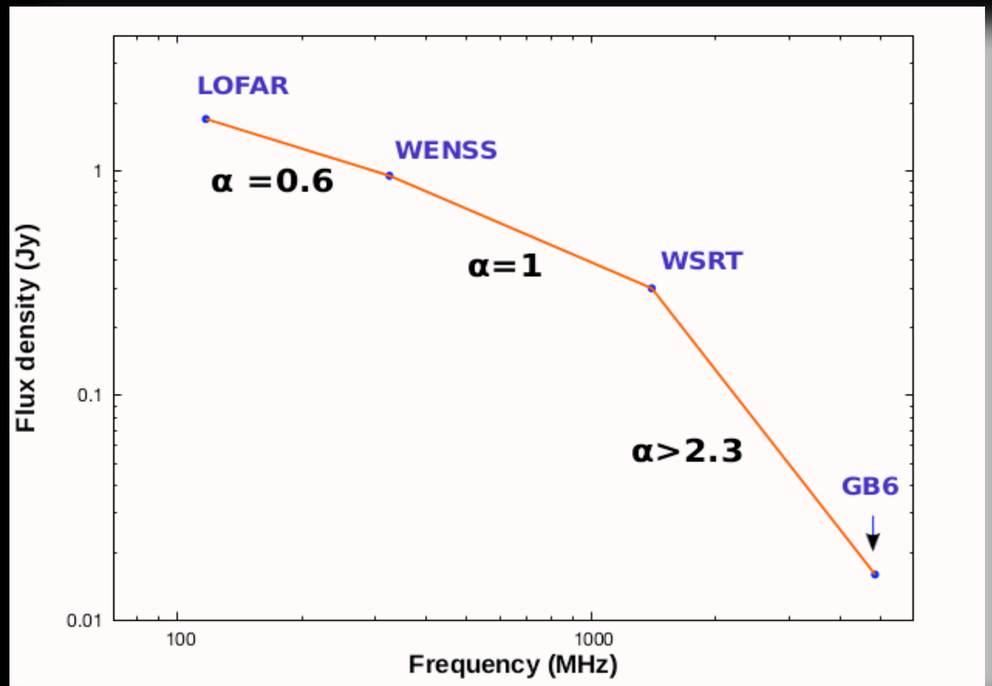
do we confirm the two spectral index regions also at low frequencies?

AGN remnants in LOFAR field
serendipitous relic in the field of 3C380







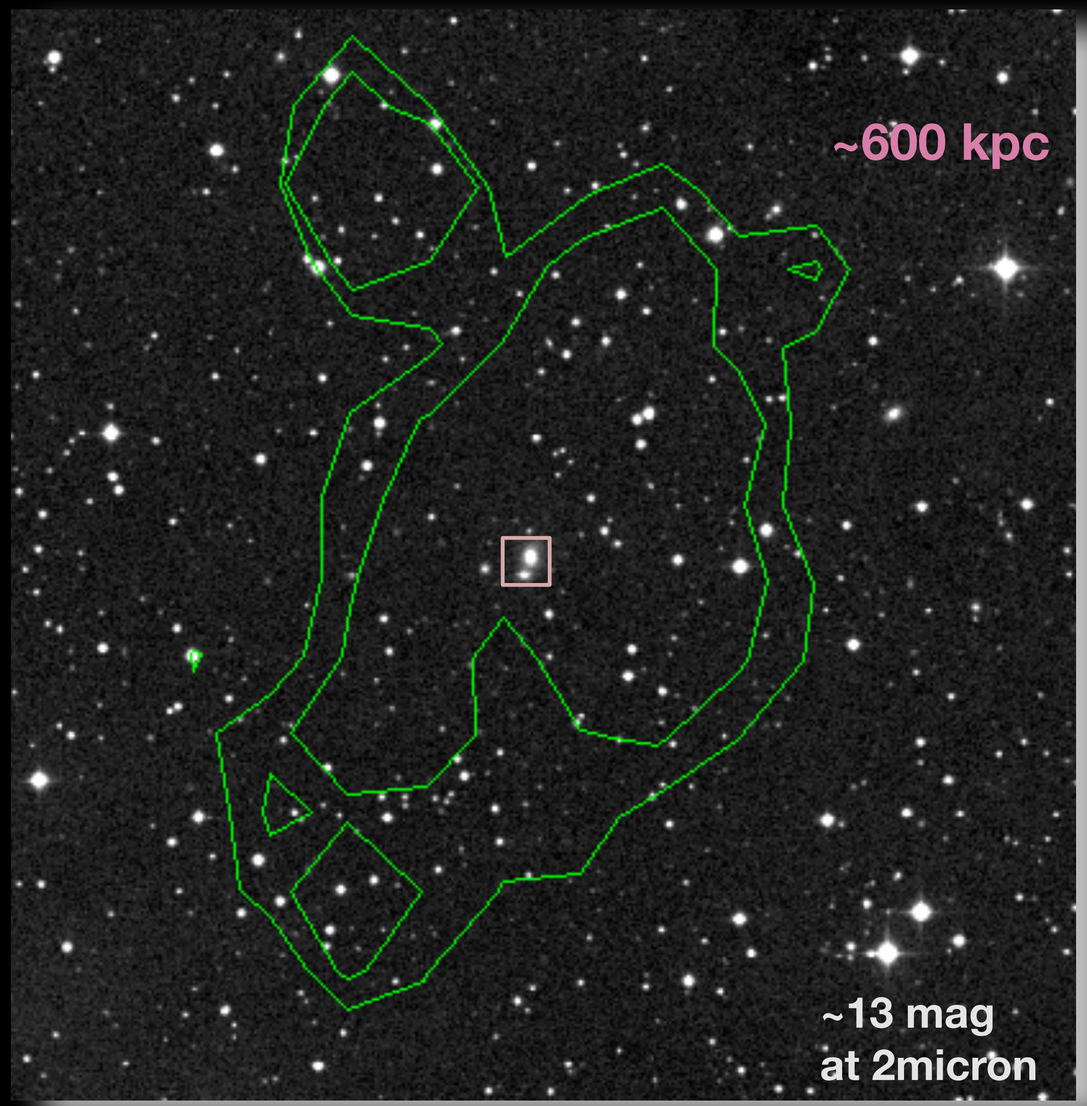


90”x60” beam
20 SB - RMS = ~ 7mJy/beam
(selfcal pipeline)

Brienza et al. in prep.

Radio source switched off in the recent past (low freq spectral index not so steep) similar to relic in Bootes field (de Gasperin et al. 2014)

Optical counterparts?



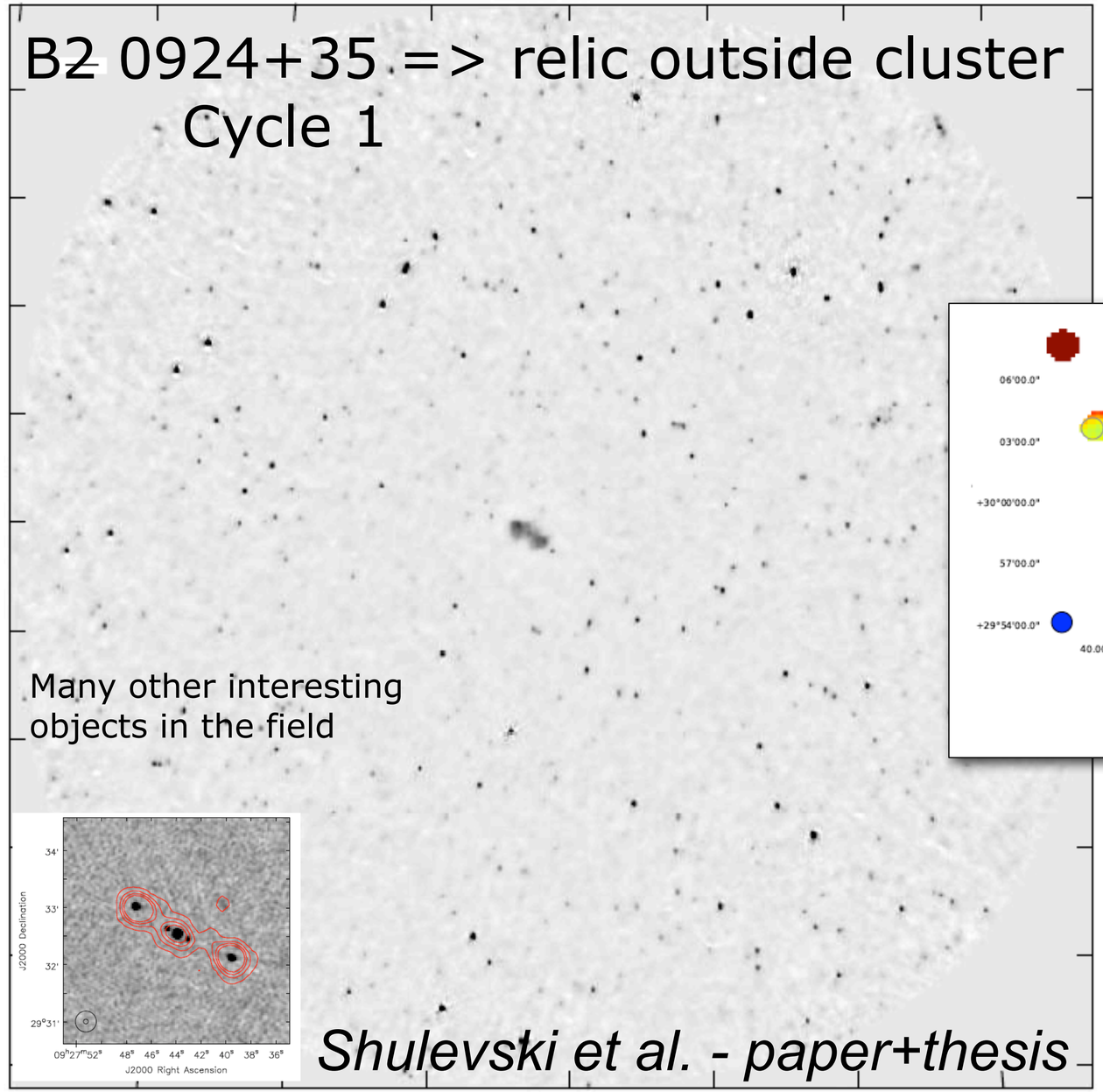
POSS-II image + WENSS contours

No spectral information
but PHOTOMETRIC
REDSHIFT available
z = 0.05
for both galaxies
(2MASX photometric catalogue)

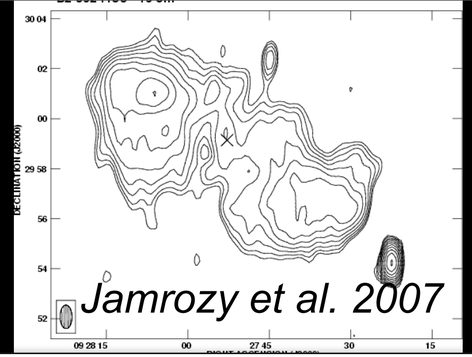
Interacting galaxies?

B2 0924+35 => relic outside cluster

Cycle 1



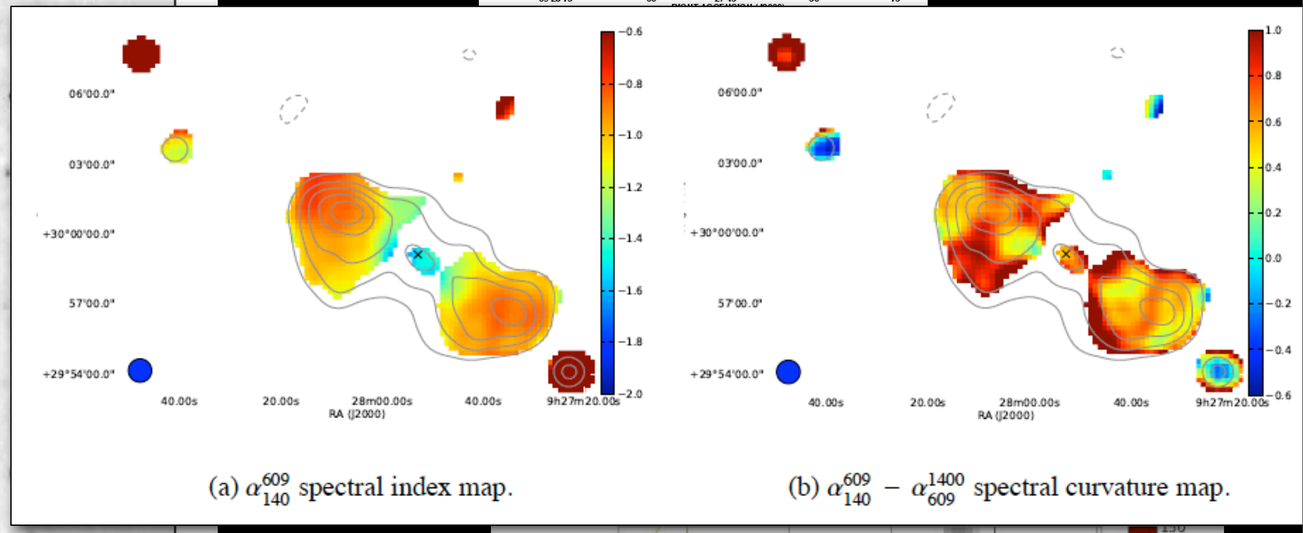
Shulevski et al. - paper+thesis



Jamrozy et al. 2007

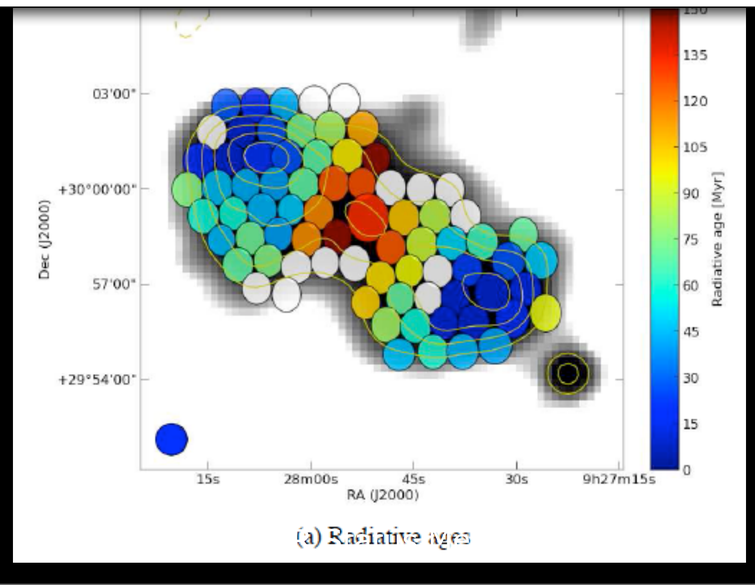
0924+30

Cordey, 1987



(a) α_{140}^{609} spectral index map.

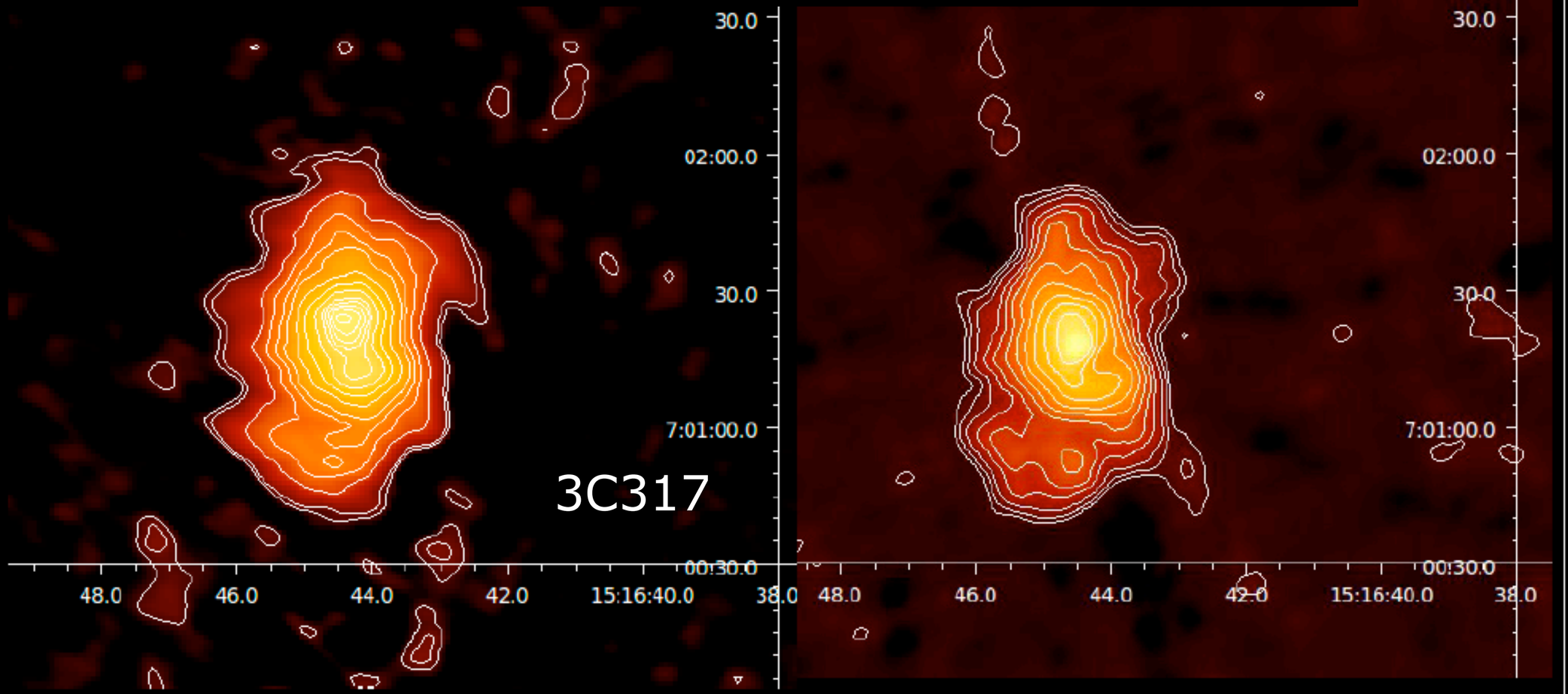
(b) $\alpha_{140}^{609} - \alpha_{609}^{1400}$ spectral curvature map.



(a) Radiative ages

Cycle 2 => Brienza et al.

Exploring radio-loud AGN recurrent activity with LOFAR



LOFAR 150 MHz

VLA 1400 MHz

Selfcal pipeline
RMS 5 mJy/beam
Beam 6”x4”
SB 20

t 2014

Field B2 0258+35 - Brienza et al.

HBA - 20 SB, rms~1mJy

BEAM 58”x53”
RMS = 4.2 mJy/beam

4C35.06
150MHz - 20SB

BEA
RMS = 2 r

BEAM 6.5”x6”
RMS = 1.3 mJy/beam

LOFAR, VLA data
Schulevski et al. submitted

WSRT - HI

<= from LBA commissioning data

VLA

What did we learn?

- major improvements thanks to the imaging pipeline: effort of the group in testing
- if the data are good, the pipeline seems to provide nice images...cases of datasets not so good. Quality requirements could be higher?
- still problems with high resolution: need to improve the construction of the model ?
- careful with flux for very diffuse, low surface brightness sources (e.g. relic)
- many images made with e.g. 20SB but not always with the full band
- **at least 5 papers in relatively advanced stage.....but the "last mile" is tough!**
- very little done with LBA, we need to catch up on this!
- FLITS just manages to cope with the data (disks already full!) - tough control from Nicolas: sloppy users or facilities for data reduction not adequate???!!!