UNIVERSITY OF Southampton

Radio galaxy physics with LOFAR

LOFAR map by J. McKean

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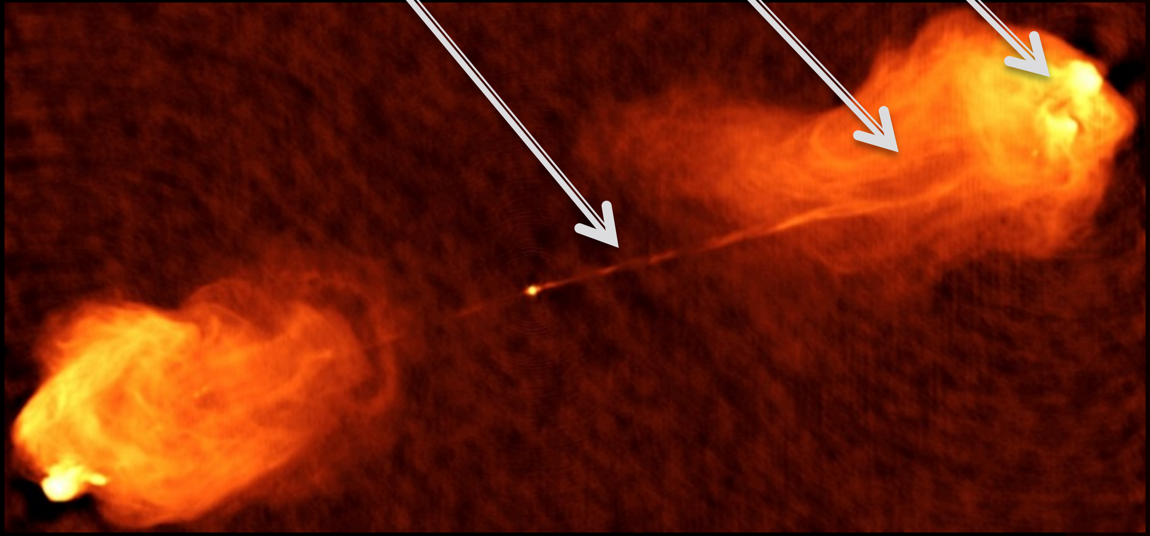
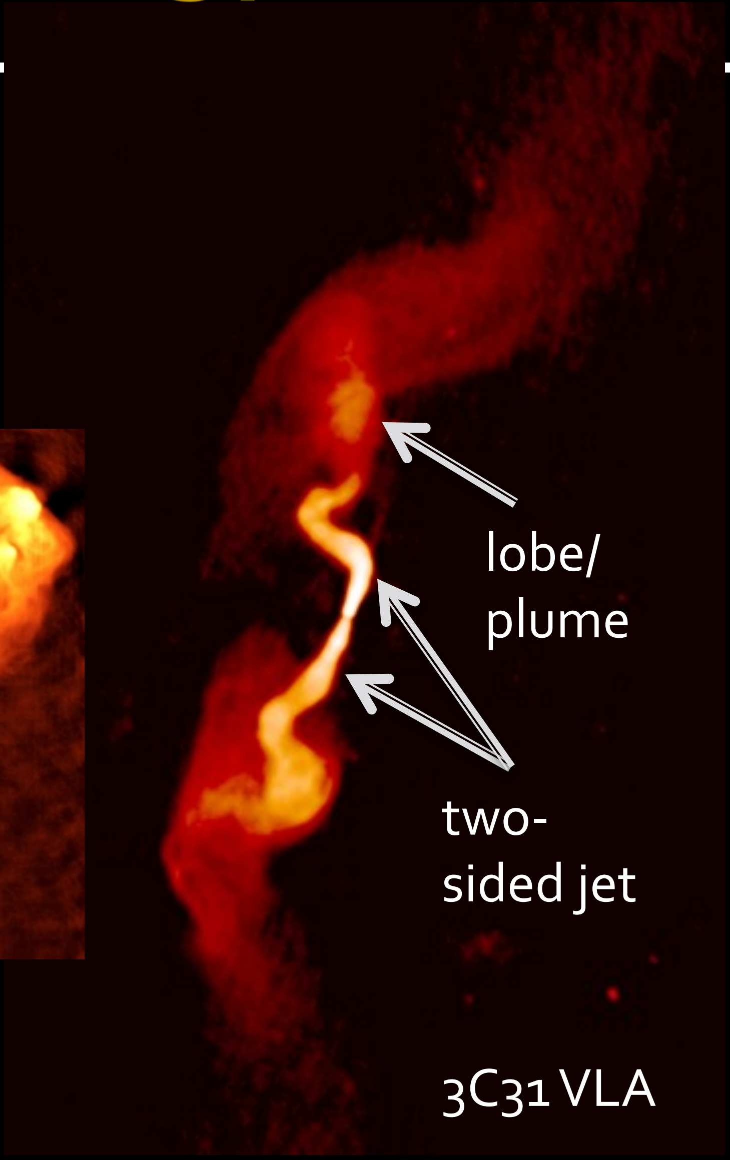
Radio galaxy terminology

FRII



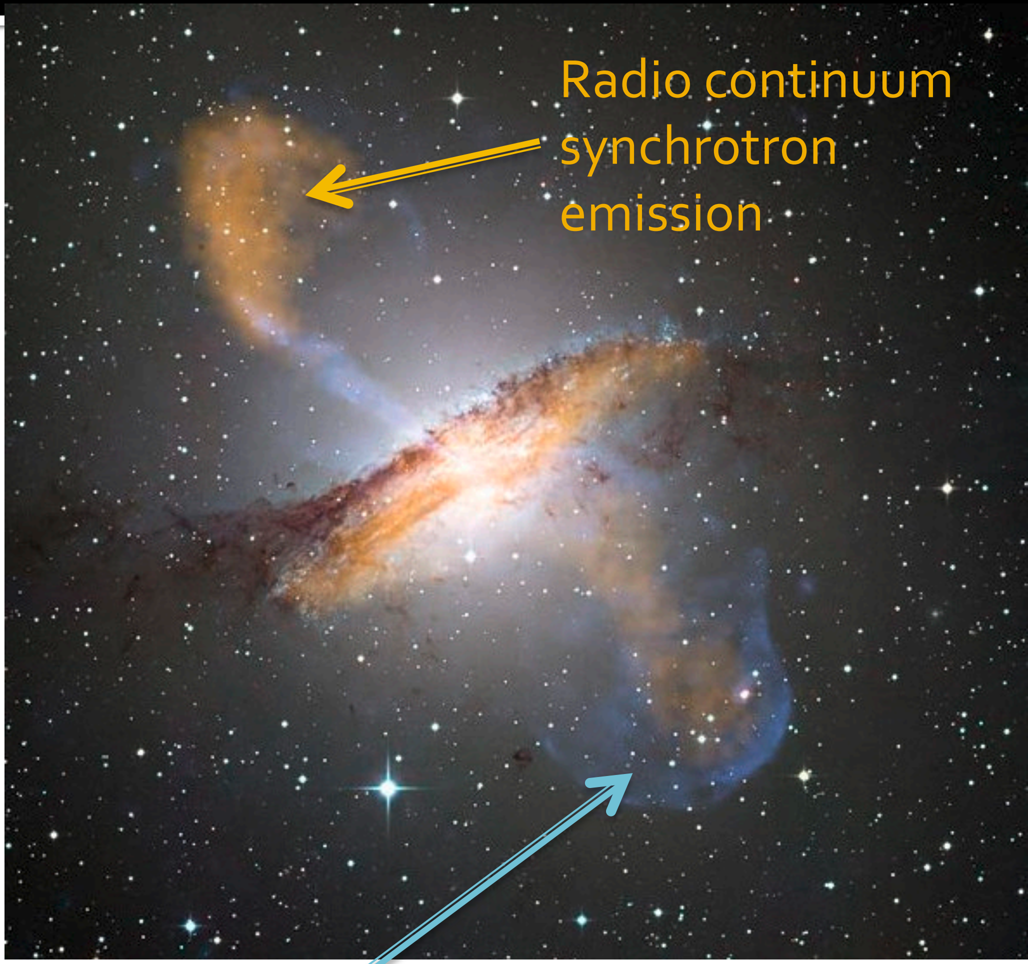
Virgo A VLA

FRI



Influence on the environment

- Bow shocks: most direct method to determine energy input & integrated jet power
- External pressure of hot-gas environment -> PV estimates
- Inverse-Compton emission -> direct measure of lobe energy content (if negligible protons – see later)



X-ray synchrotron emission

Centaurus A

Jet power: what carries the energy in low-power jets?

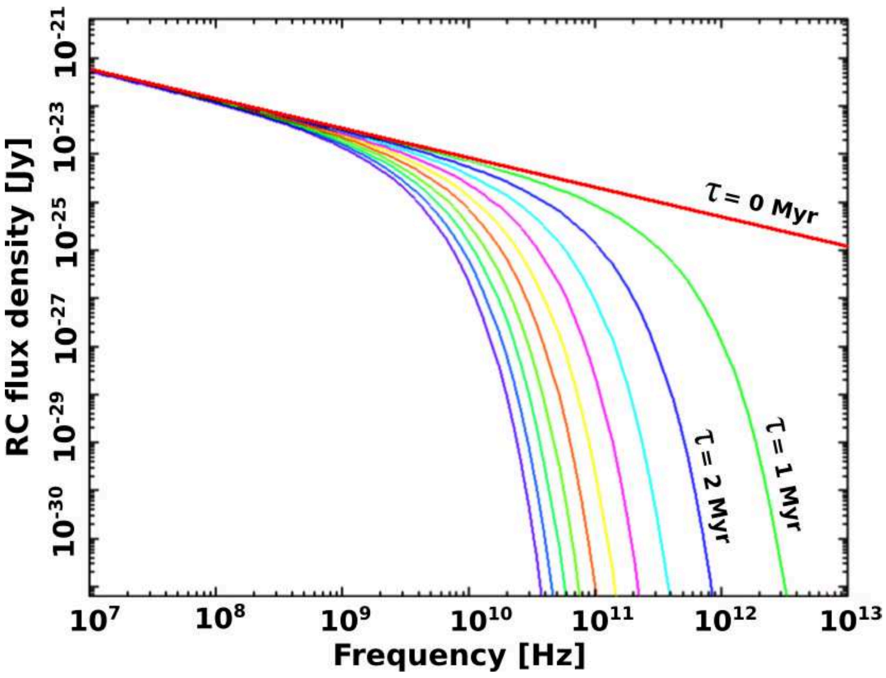
- Departure from equipartition:
  - (1) Lepton dominance
  - (2) Magnetic field dominance
- Protons:
  - (3) Relativistic protons carried up the jet
  - (4) Thermal gas entrained as the jet evolves
- Model 4 -> crucial role for jet/environment interaction

Measuring source ages: radio

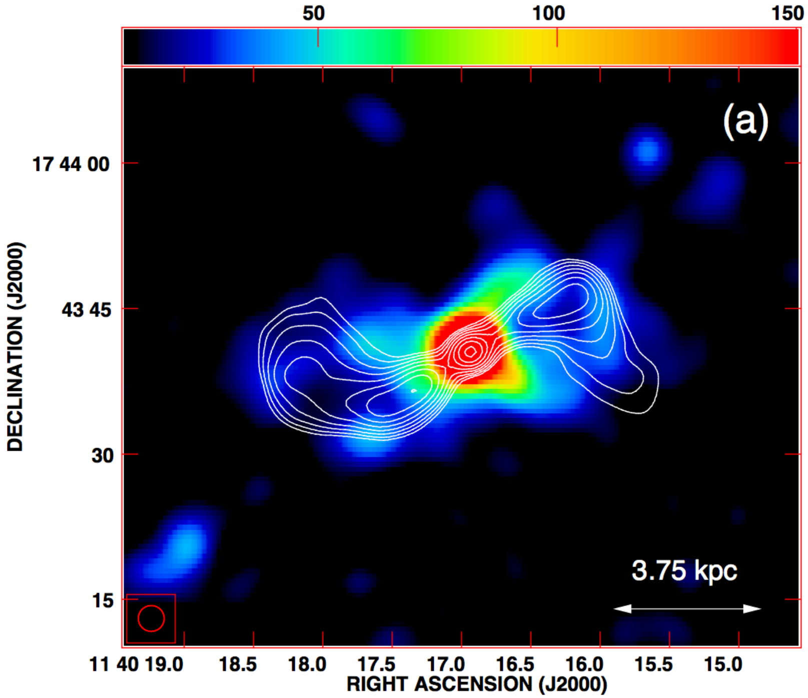
- Power-law "injection" spectrum breaks at $\nu_{brk}(t)$:

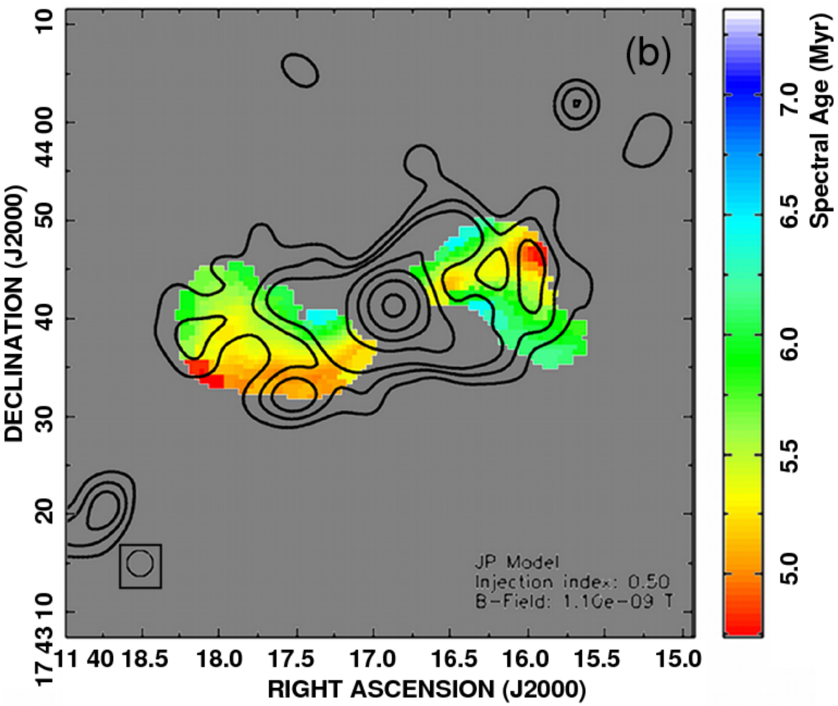
$$\nu_{\rm brk} = 2.52\times10^3 \frac{[B/10\,\mu{\rm G}]}{([B/10\,\mu{\rm G}]^2 + [B_{\rm CMB}/10\,\mu{\rm G}]^2)^2[\tau/{\rm Myr}]^2}\,{\rm GHz}$$

- Above ν_{brk}, spectrum depends on model assumptions (e.g. pitch angle scattering): Jaffe & Perola 1973, Kardashev 1962 & Pacholczyk 1970
- **More complex models exist (e.g. Tribble 1993)**
- **But radio spectral ages have a number of limitations….**



Source age: X-ray + next-generation radio facilities





X-ray:

Density & temperature jump consistent with strong shock: jump conditions => **M** ~ 3 – 4
=> Source age = 4 Myr (age assuming constant expansion speed)

Radio:

Spectral age from fitting electron distribution = 4 - 6 Myr

Croston+ 2007, VH+ 2014

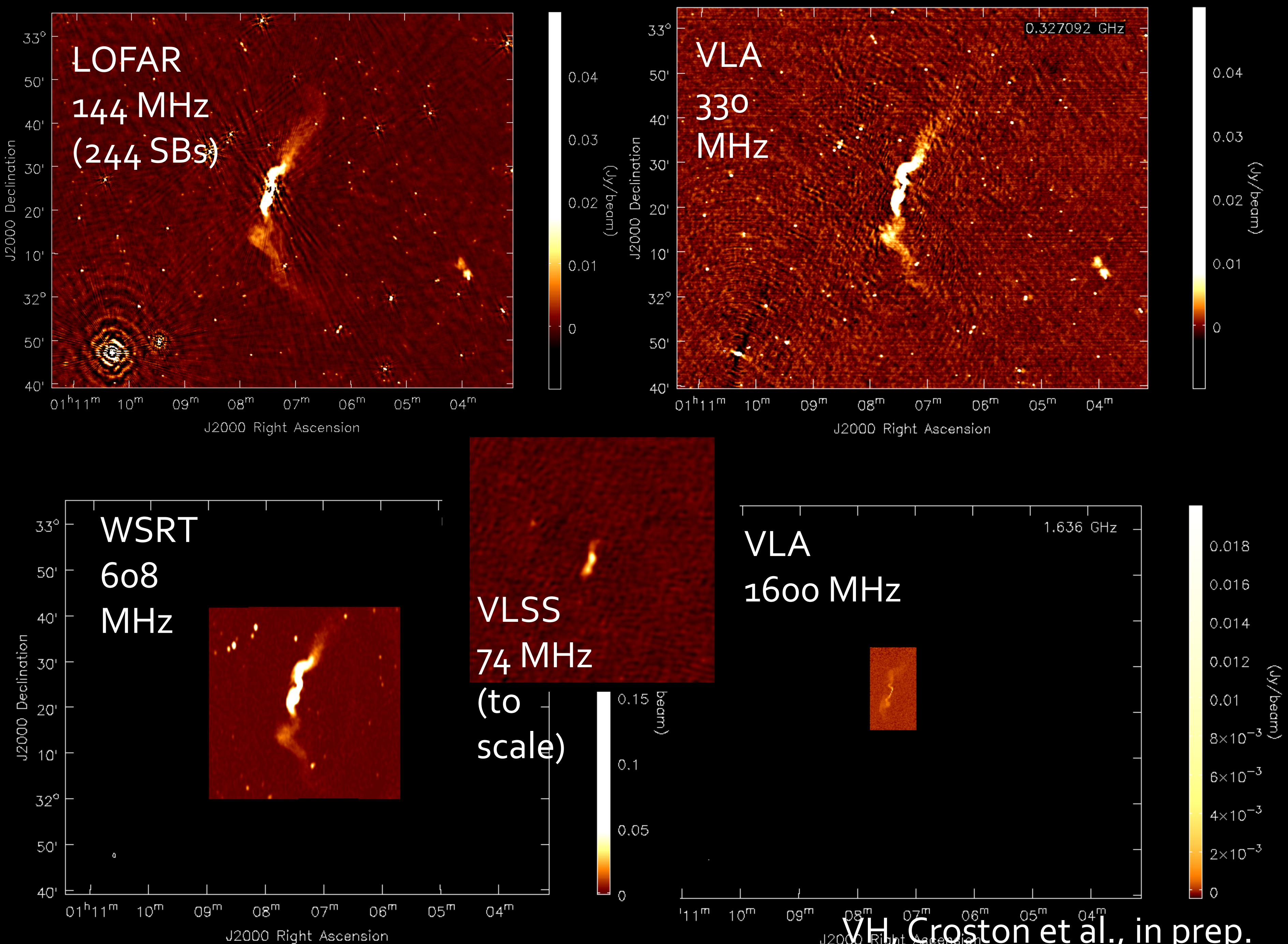
LOFAR AGN Physics

- Deep observations of representative sample of nearby radio galaxies:
  - spans range of morphology and luminosity
  - fully characterized X-ray environments & lobe IC
- Aims to determine how particle content depends on luminosity, morphology & environment -> relation between impact and radio observables
- 7 targets observed to date (20 hrs each, LBA & HBA) as part of Surveys KSP Nearby AGN programme (PI. R. Morganti) – related projects look at radio-galaxy life cycles by detecting multiple epoch outbursts.
- Sample of tens of objects via Surveys KSP

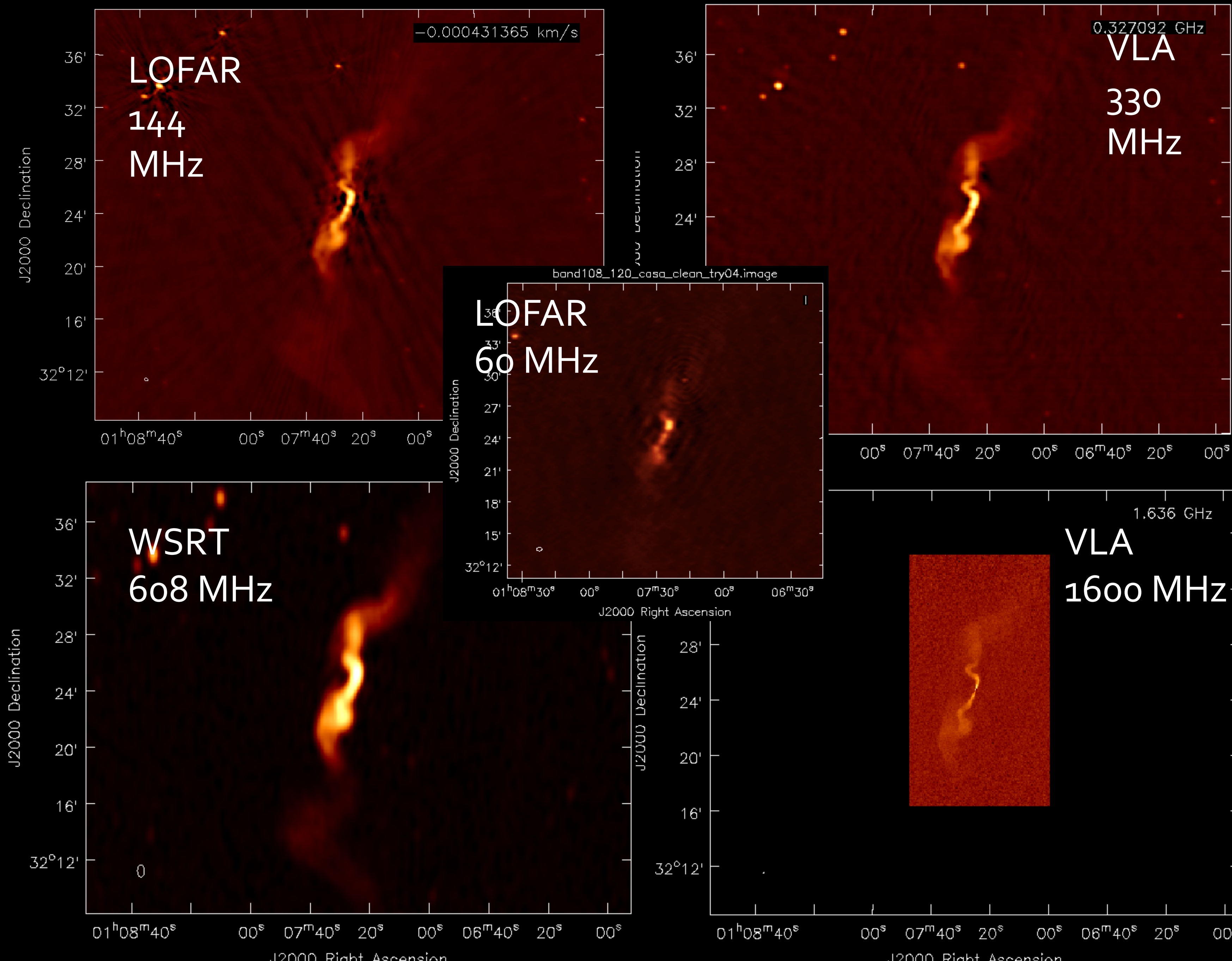
3C31 LOFAR observations

- 10 hrs observing time in HBA
- Interlaced 3C48 and 3C196 as calibrators
- HBA data pre-processed by ASTRON
- Initial NDPPP
- Calibrate calibrator and transfer solutions
- Combine sub-bands
- Phase-only calibration on each band
- Image with CASA or awimager
- Self-calibration in phase
- Directional gains (in progress)

Pipeline in Soton by Adam Stewart

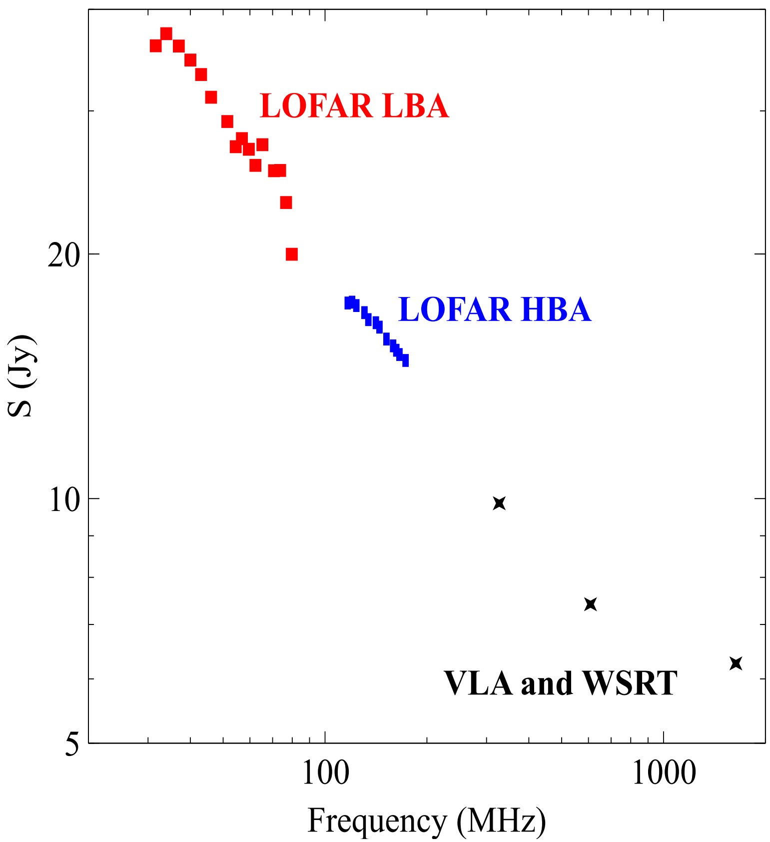


VH, Croston et al., in prep.


LOFAR 144 MHz
−0.000431365 km/s
VLA 330 MHz
0.327092 GHz
LOFAR 60 MHz
band108_120_casa_clean_try04.image
WSRT 608 MHz
VLA 1600 MHz
1.636 GHz
J2000 Declination
J2000 Right Ascension

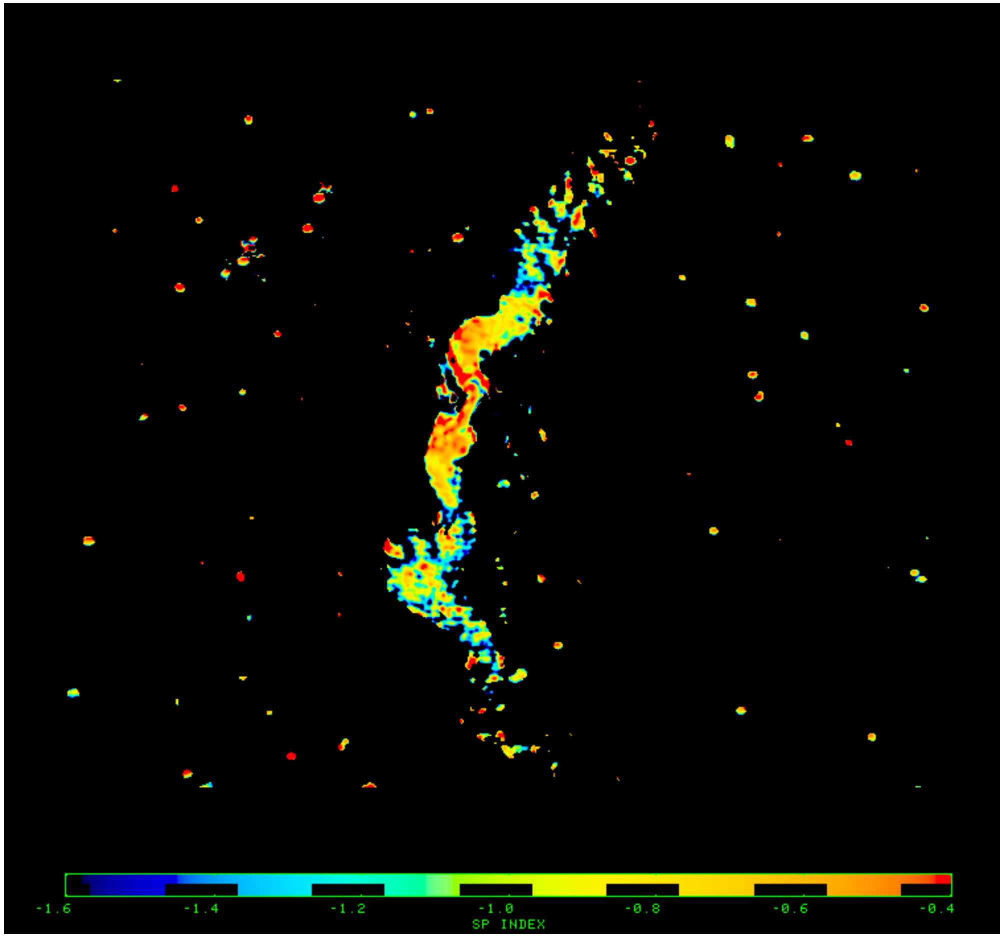
Preliminary spectral mapping

Spectral index constant between 30 MHz and 600 MHz



VH, Croston et al., in prep.

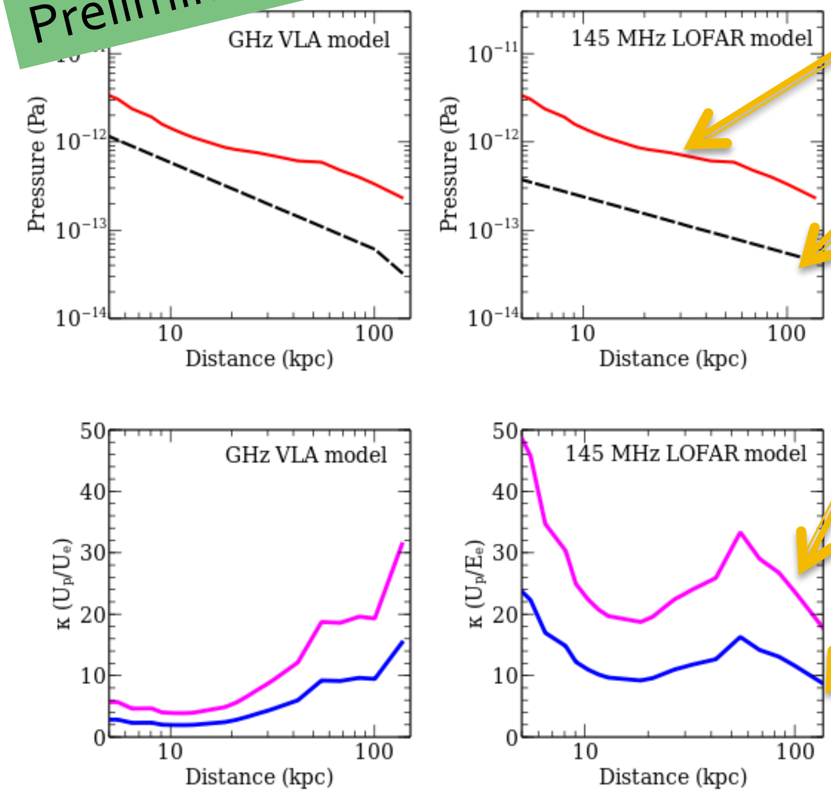
144 / 330 MHz spectral index



-1.6 -0.4

Particle models of 3C31 jet

Preliminary



External pressure (X-ray)

Internal pressure (radio)

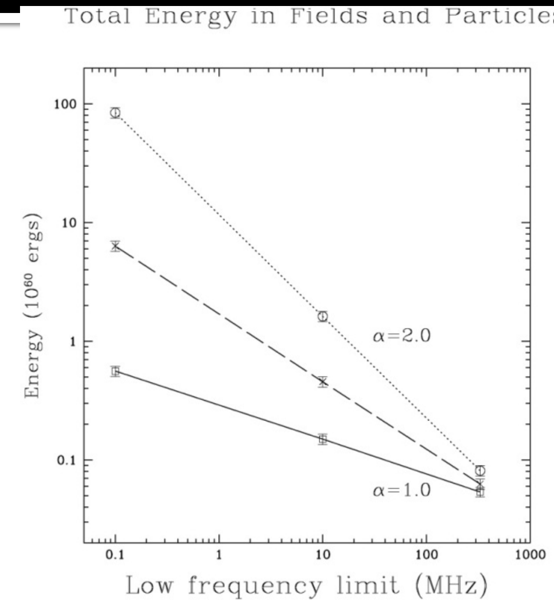
Relativistic protons

Thermal protons

Model with constant SI

Model with SI from LOFAR

Croston, VH, et al., in prep.



Harris (2004)

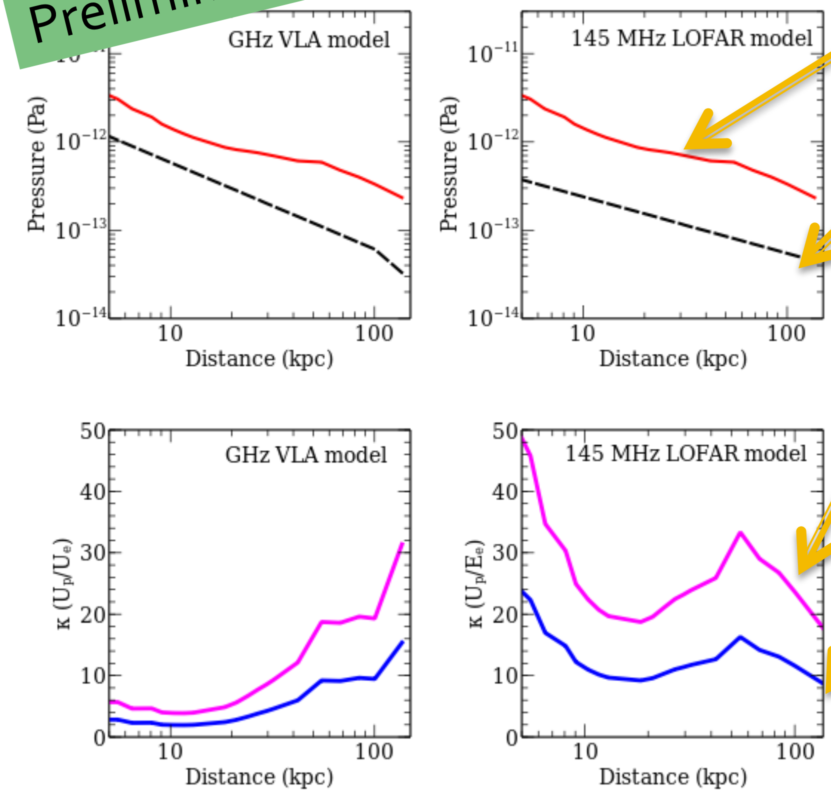
– VLA model: entrainment along jet

– LOFAR model: same rate of entrainment

===> Constant spectral index

Particle models of 3C31 jet

Preliminary



External pressure (X-ray)

Internal pressure (radio)

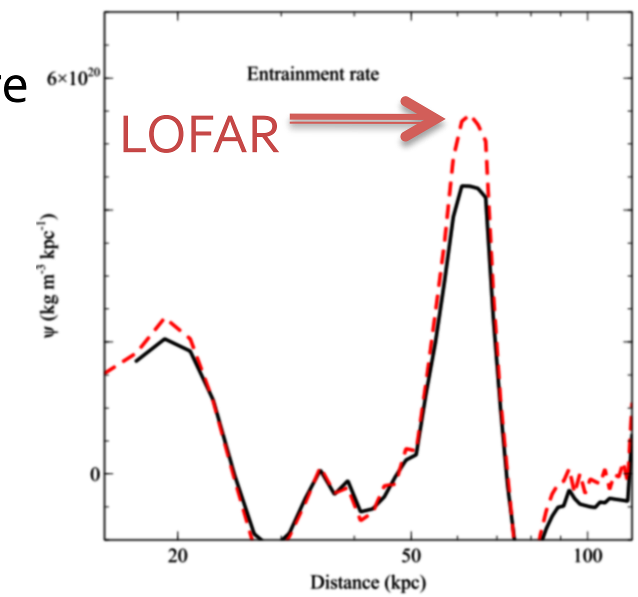
Relativistic protons

Thermal protons

Model with constant SI

Model with SI from LOFAR

Entrainment rate



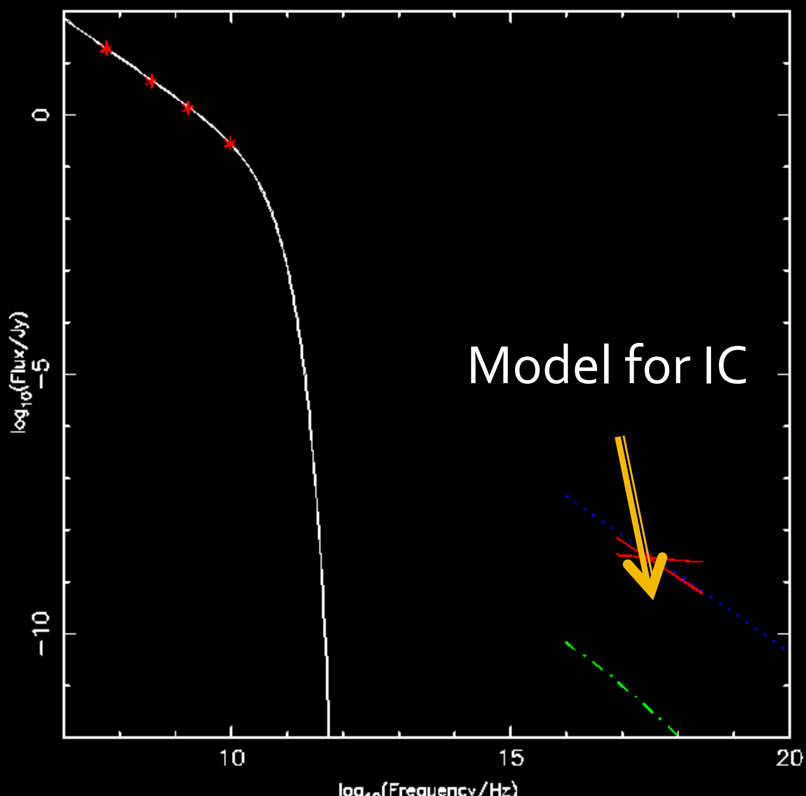
- **VLA model: entrainment along jet**
- **LOFAR model: same rate of entrainment**

===> Constant spectral index

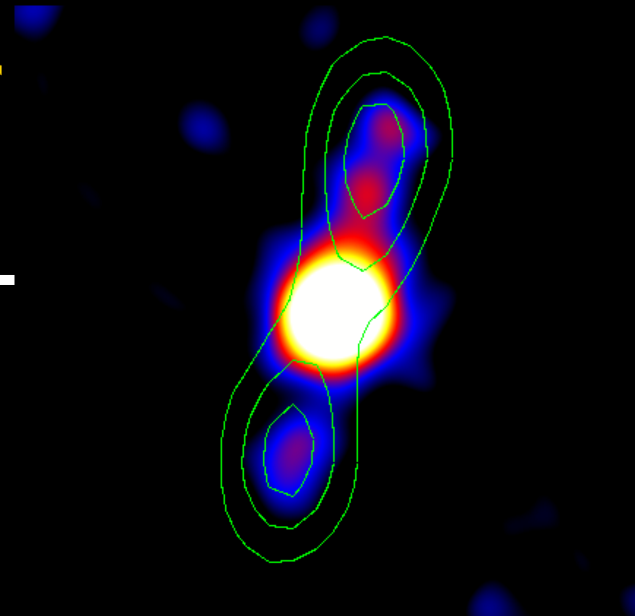
Croston, VH, et al., in prep.

Energy content of FRII with LOFAR

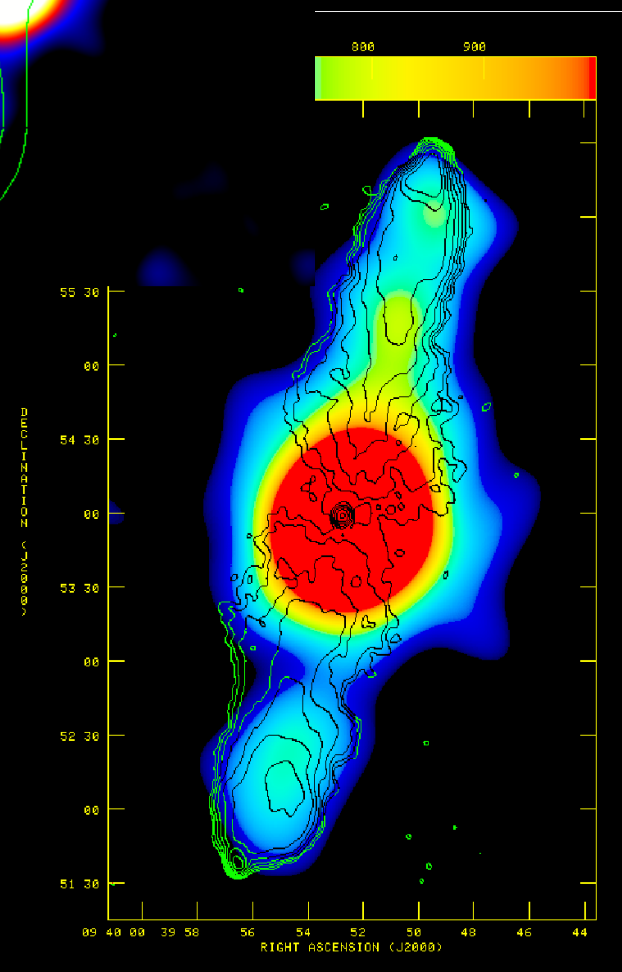
Spectrum does not flatten
-> total energy doubles in northern lobe



Harwood et al., in prep.

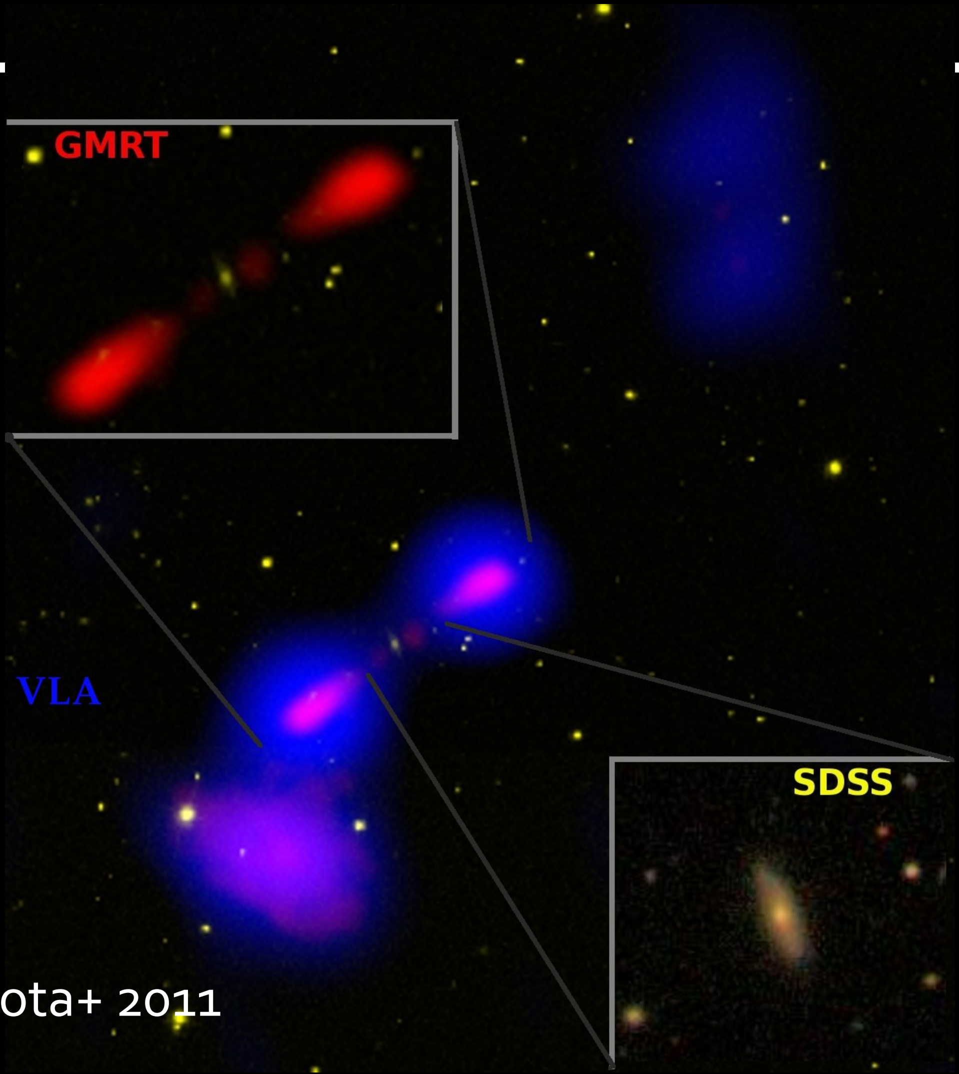


50 MHz
LOFAR +
X-ray

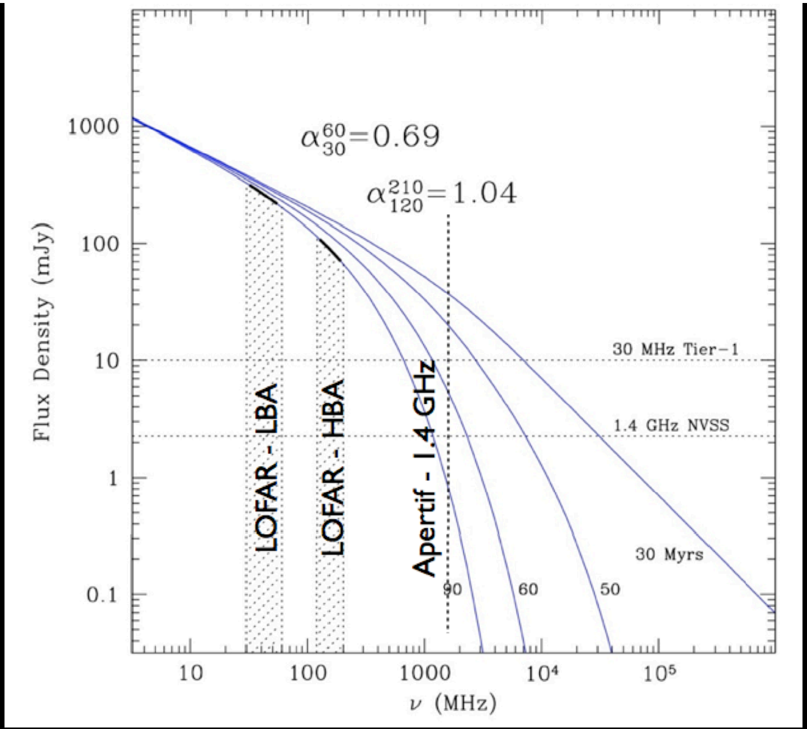


VLA contours + X-ray

Life cycles with LOFAR



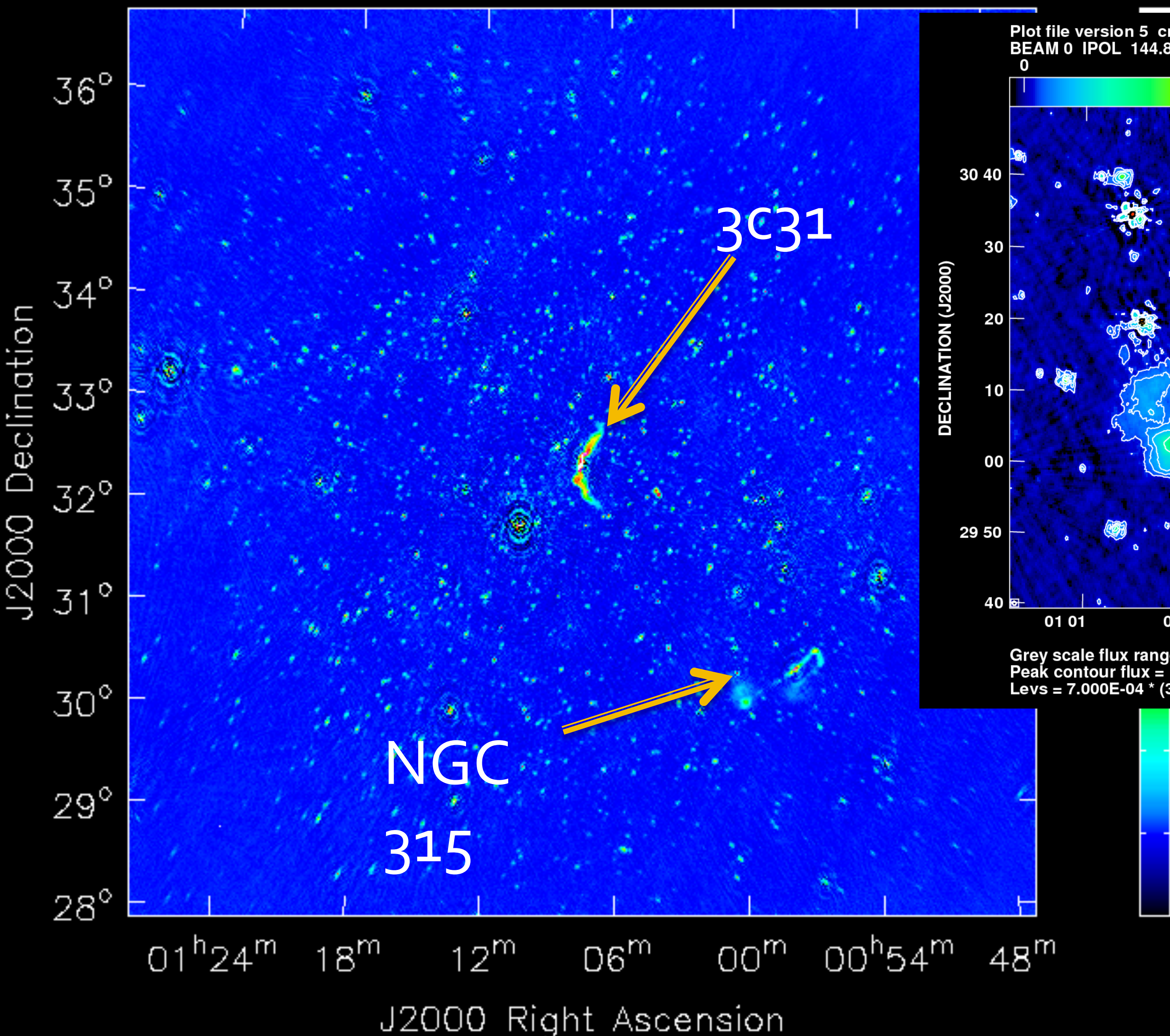
Hota+ 2011

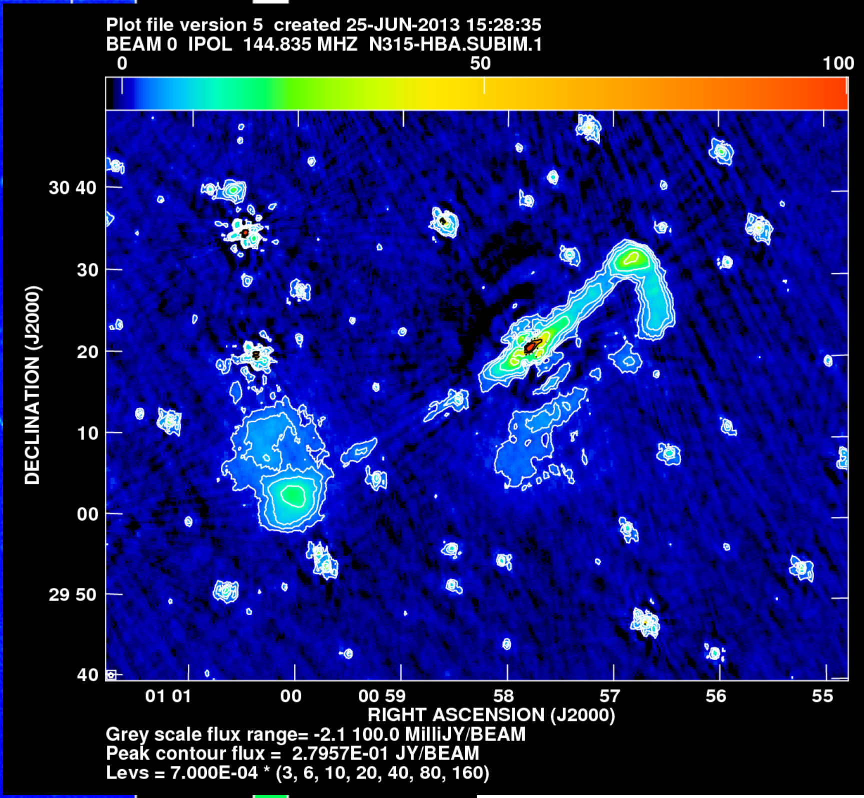


(courtesy M. Murgia)

Wide field of view!

Second radio galaxy for free...





HBA
20 km
baseline
244 SBs

Conclusions

- First promising results
  - Angular extent 15% larger than at 330 MHz
- Flux scale is broadly consistent
  - Spectral indices agree with expected values
- FRI 3C31:
  - LOFAR data support entrainment model
- FRII 3C223:
  - LOFAR data double the energy content

Nearby AGN LOFAR sample

HBA + LBA observations for the entire sample

FRI

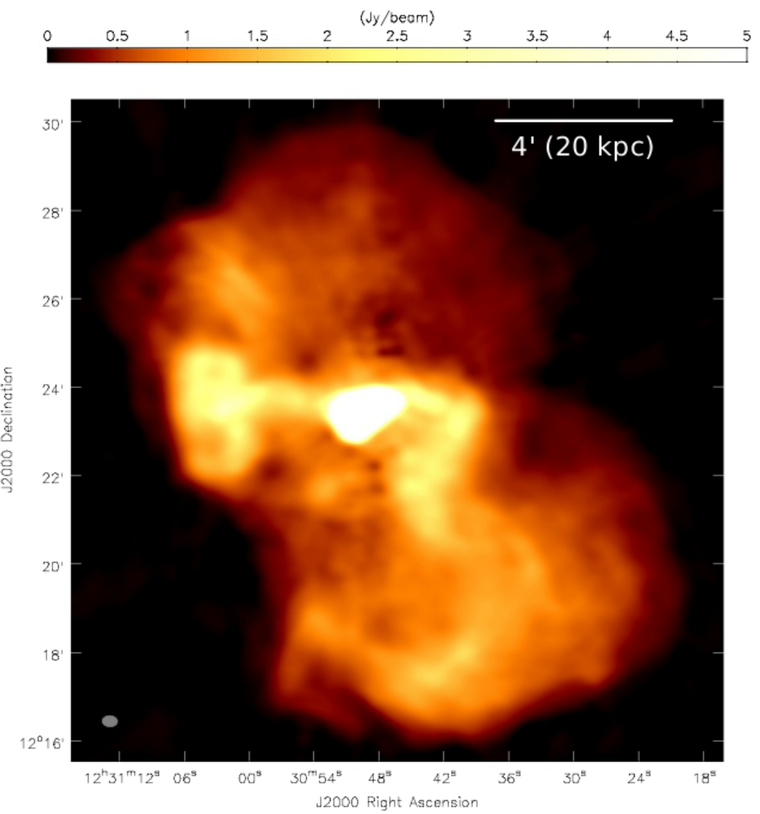
FRII

Targets for LC0_012 Cycle0 LOFAR

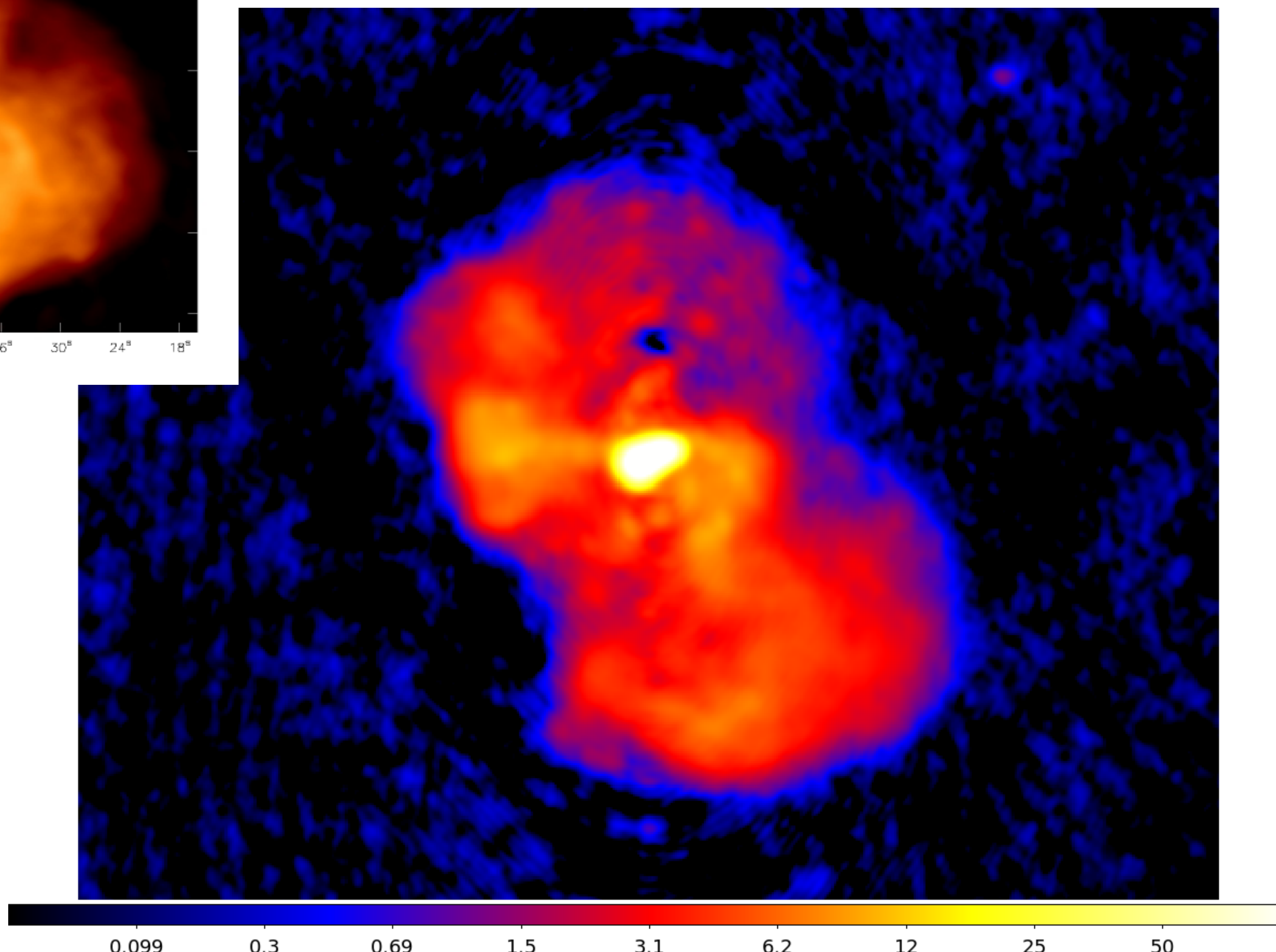
Using LOFAR for detailed studies of AGN, and AGN physics

	HBA obs	HBA comp	LBA obs	LBA comp	Pre-processing	Leading
3C31	10	30	10	15	Southampton?	Nearby 3CR - Croston, Volker Heesen
3C223	10	30	10	15		Orru`+Croston
3C452	10	30	10	15		Croston+Jeremy Harwood
B1834	10	30	10	15	Nijmegen?	DDRG - Orru`+
3C35	10	30	10	15		Orru' (polariz.)+Shulevski
4C33.33	10	30	10	15		Giant RG Jamrozy+
3C237	10	30				LongBaselines group, Hardcastle et al.
3C41	10	30				LongBaselines group, Hardcastle et al.
M87	8	24	8	12		De Gasperin+
3C48			10	15	Amsterdam?	RRL group - Oonk+
Hydra A	6	18	6	9		Cavities - Rafferty, Wise+
Hercules A	6	18				Cavities: Birzan+
VLSS J1431.8+1331	8	24	8	30		Relics - Morganti, Shulevski, Kunert-Bajraszewska
Cygnus A	10	30				McKean+
Total	118	354	92	156		
Total observing	**210**				**Alloc**	**210**
Total computing	**510**					**373**

Virgo A, M87



HBA, published in A&A



LBA, de Gasperin, in prep.

HBA imaging

- Imaged with CASA clean (multi-scale)
- Peak flux density: 5.2 Jy, rms = 0.7 mJy/beam
- Resolution: 17x12 arcsec, S/N = 7400
- First skymodel: VLSS
- Self-calibration in phase, no change!
- Directional dependent gains for 3C34

Directional dependent gains