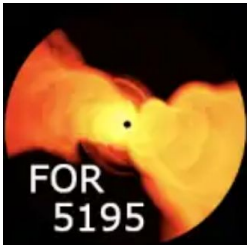


Plasma and magnetic field properties in the kpc jet of OJ287 with LOFAR-VLBI



LOFAR



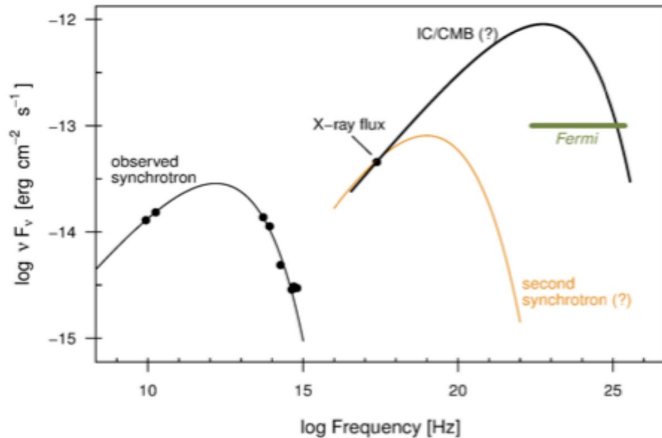
16th EVN Symposium

Etienne Bonnassieux, JMU Würzburg

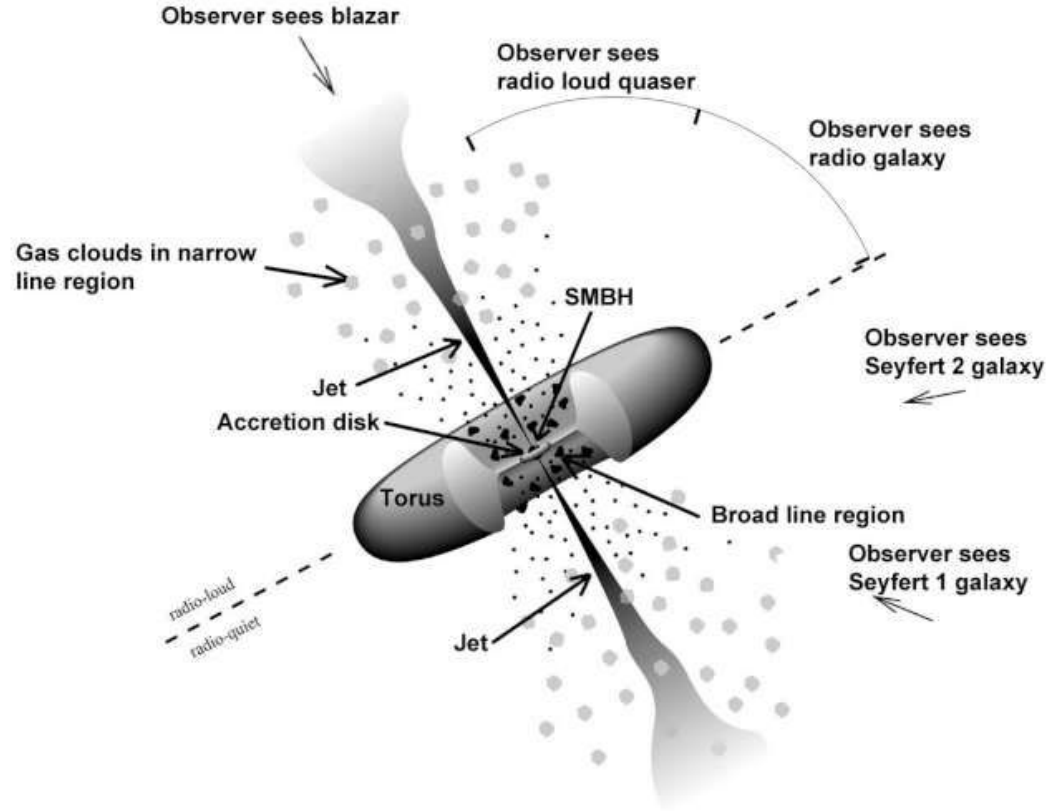
in collaboration with Hrishikesh Shetgaonkar, Matthias Kadler, ++₁

Blazars

- AGN pointed towards us
- Usually quite compact
- Significant relativistic boosting
- Emission from radio to gamma



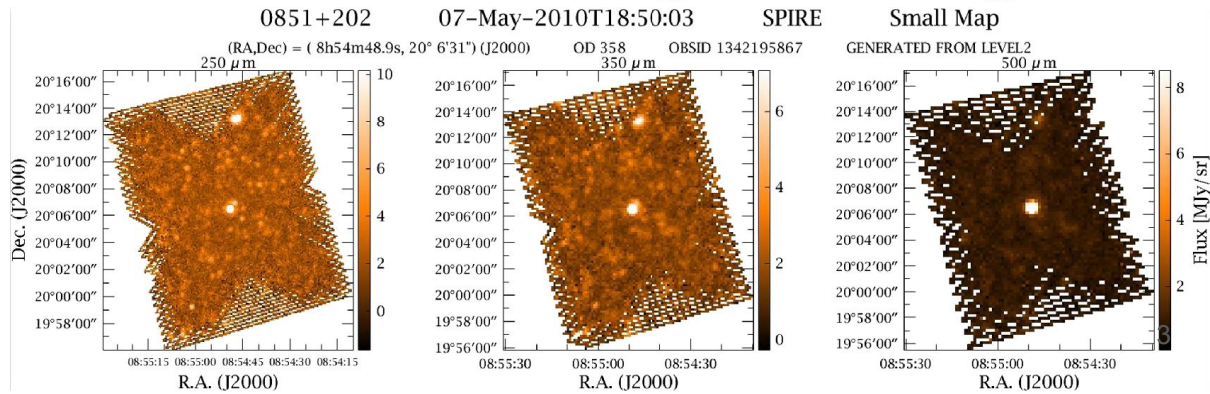
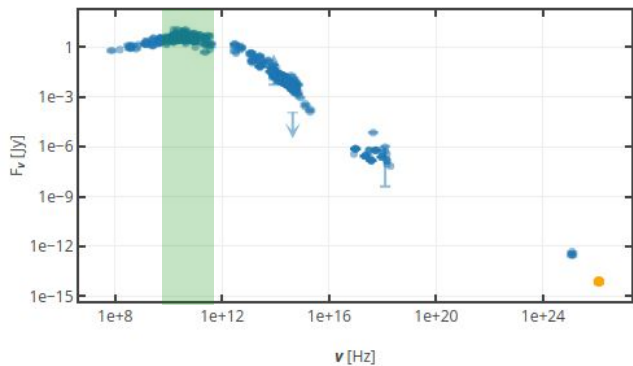
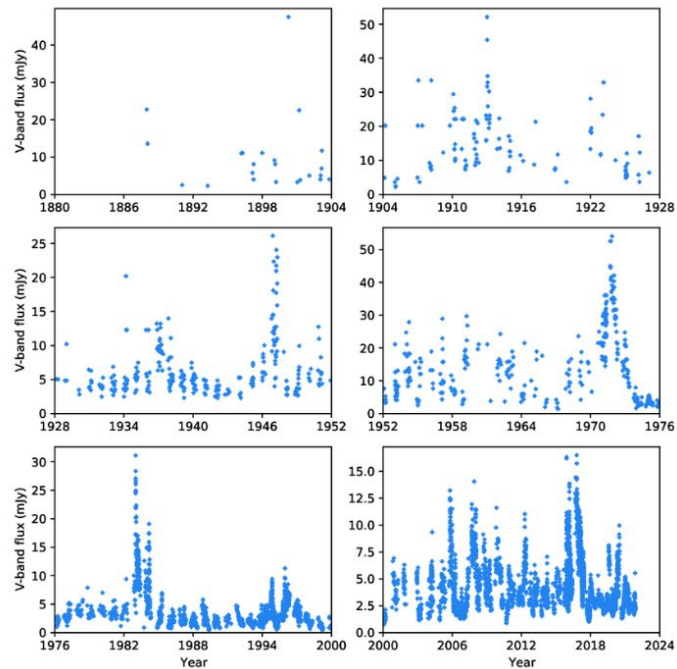
SED for PKS 0637-752 *Perlman et al. (2019)*



<https://fermi.gsfc.nasa.gov/science/eteu/agn/>

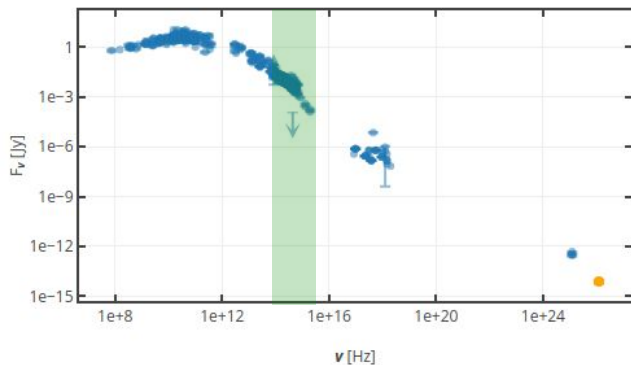
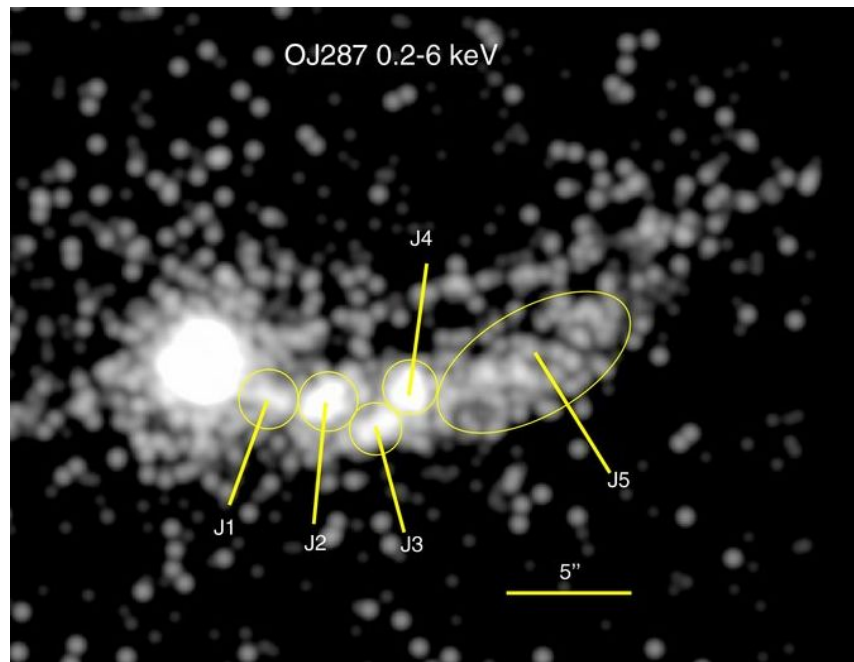
OJ287 in optical

- Persistent V-band variability (cf M. Valtonen et al, right)
- Observed with Herschel at 250, 350, 500 micrometers (cf M. Kidger et al, bottom)
- Monitoring ongoing - optical variability key driver for continuing observations!



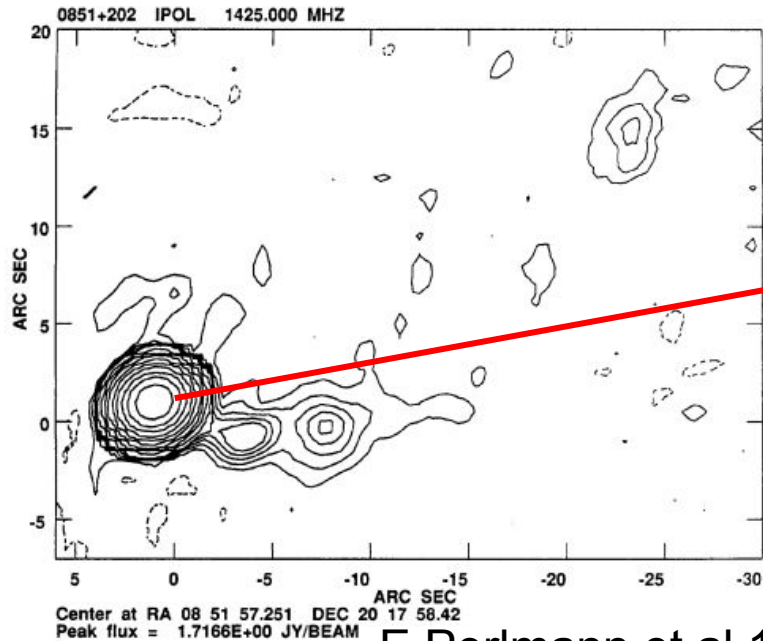
OJ287 in X-rays

- X-ray emission from core consistent with FR-I AGN (A. Marscher 2011)
- Unusual: Mpc-scale X-ray jet!
- Multiple knot features detected
- Question: synchrotron or IC/CMB?

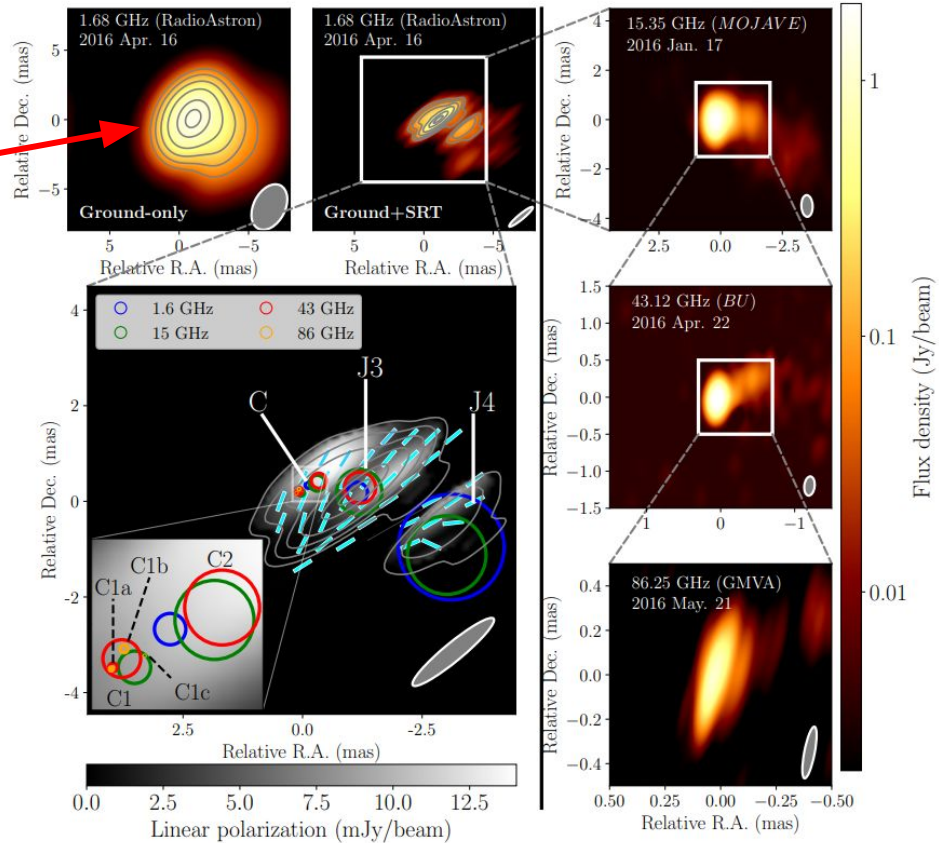
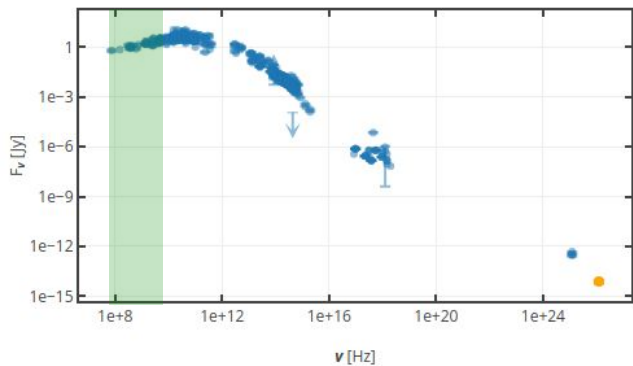


- Estimate of B-field ~ 5 microG, minimum e^- energy 7-40 $m_e c^2$, doppler factor ~ 8 at J2
- Jet bent consistent with standing shocks inclined by ~ 7 deg to jet axis

OJ287 in radio



E Perlmann et al 1994

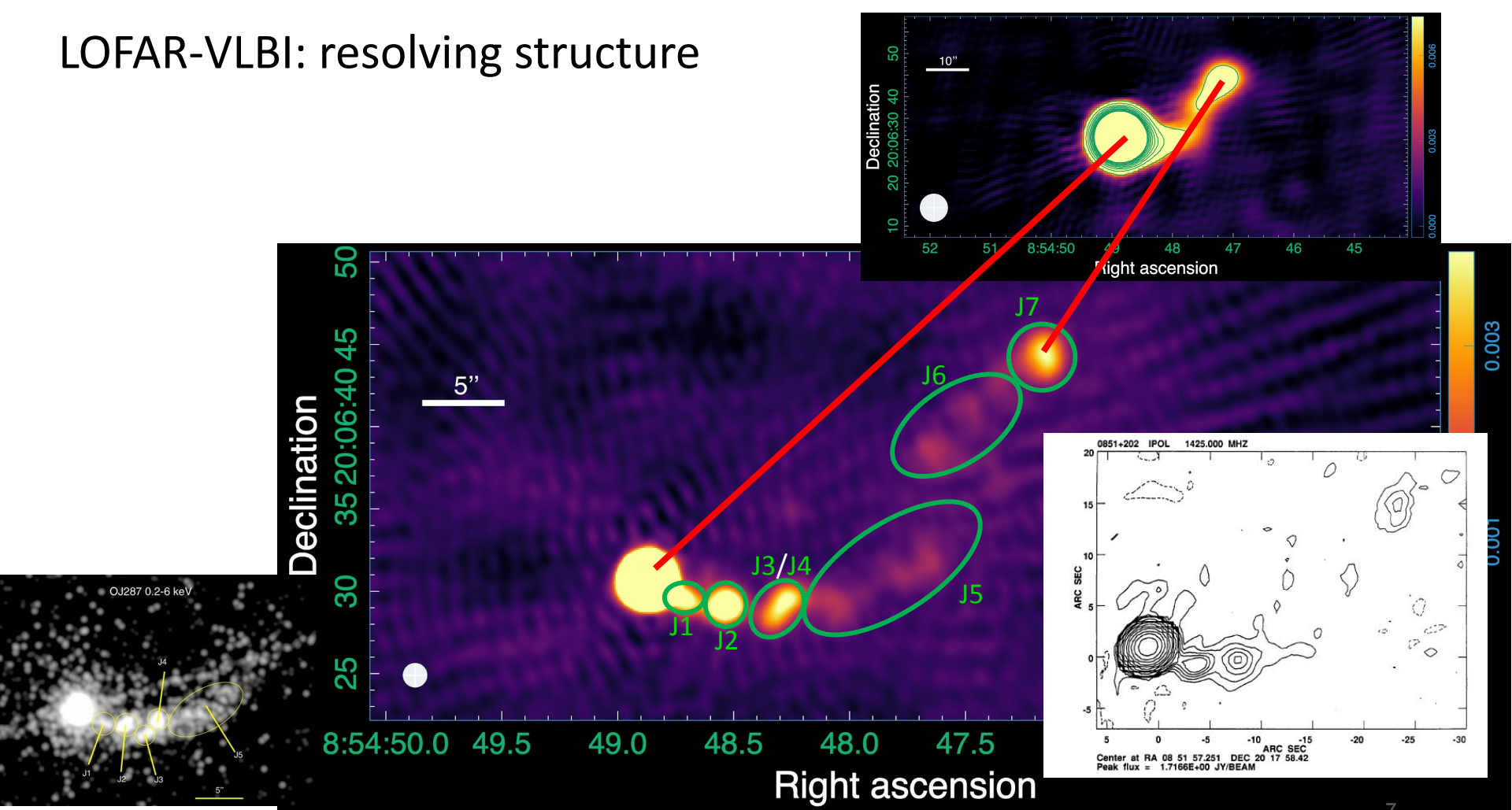


Ilje Cho et al 2024

Stations:
24 core
14 remote
14 international
+2 in construction

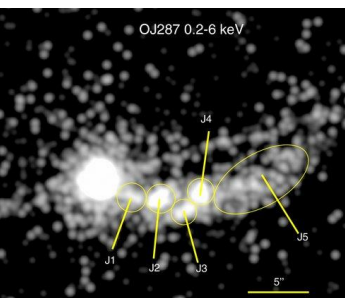
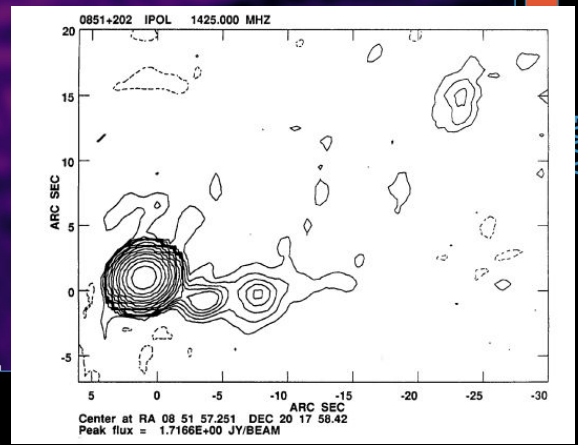
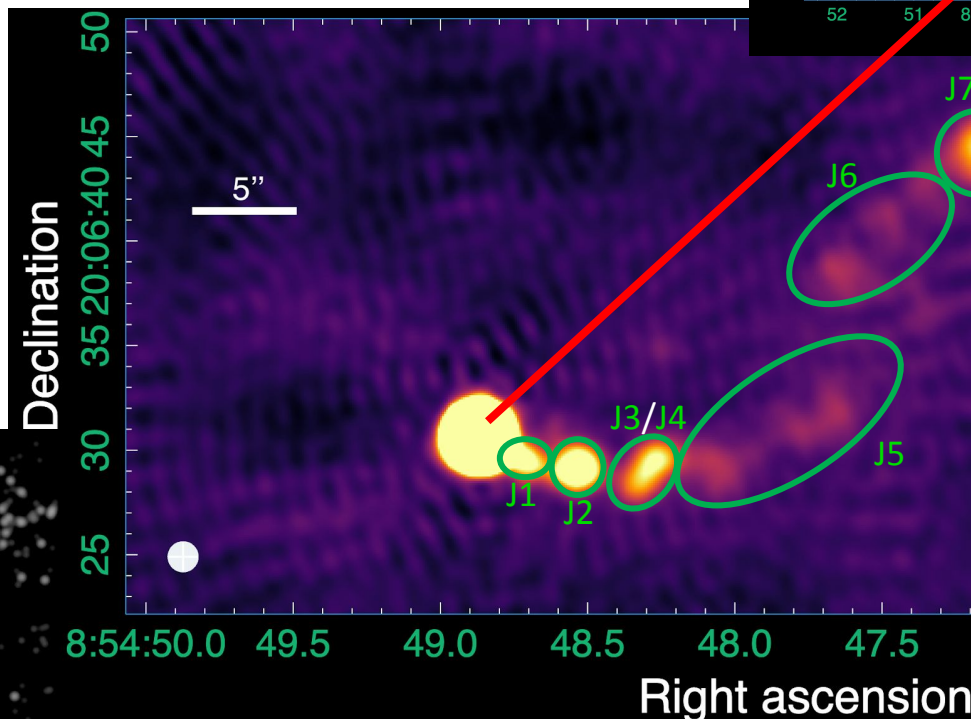
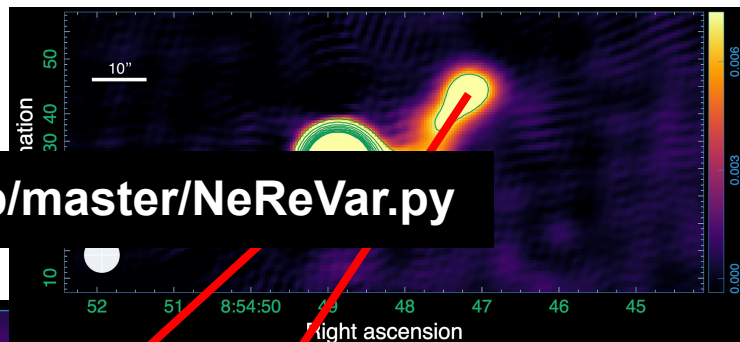


LOFAR-VLBI: resolving structure



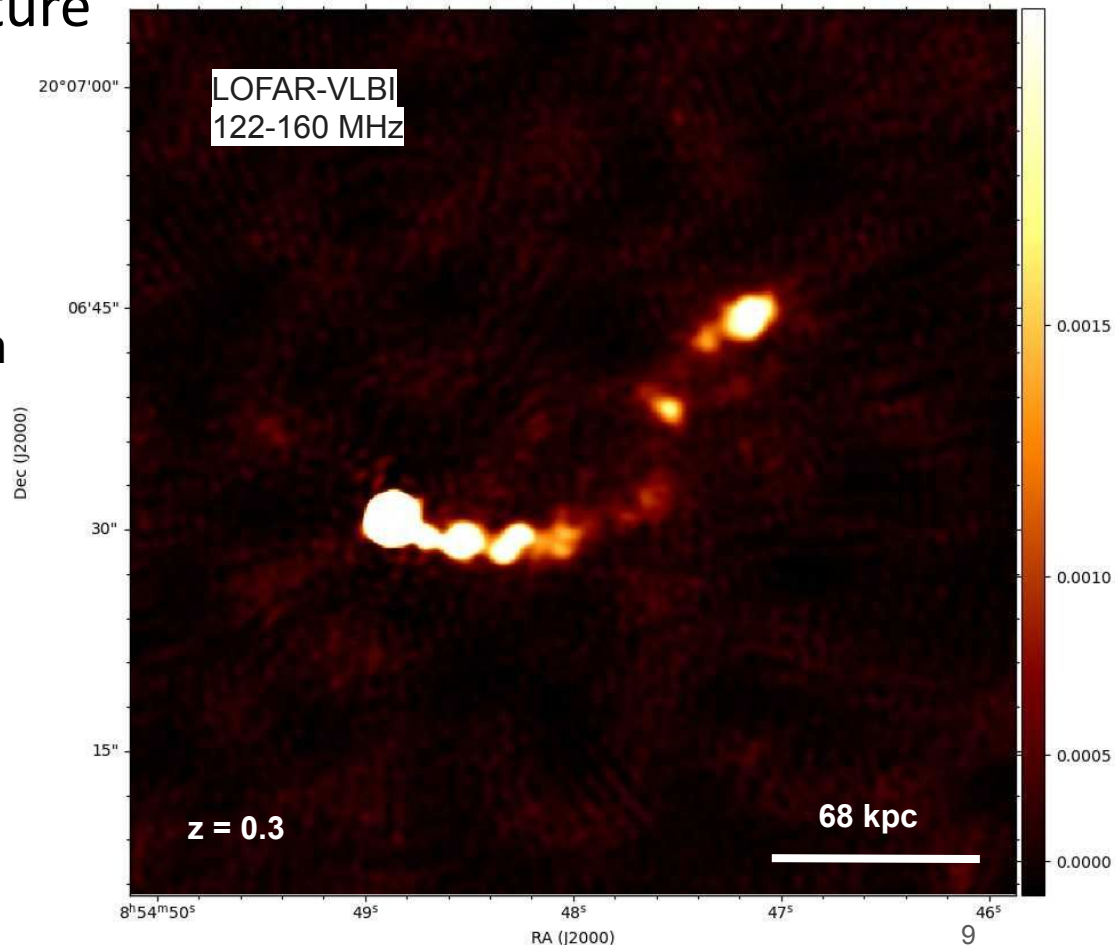
LOFAR-VLBI: resolving structure

<https://github.com/ebonnassieux/Scripts/blob/master/NeReVar.py>



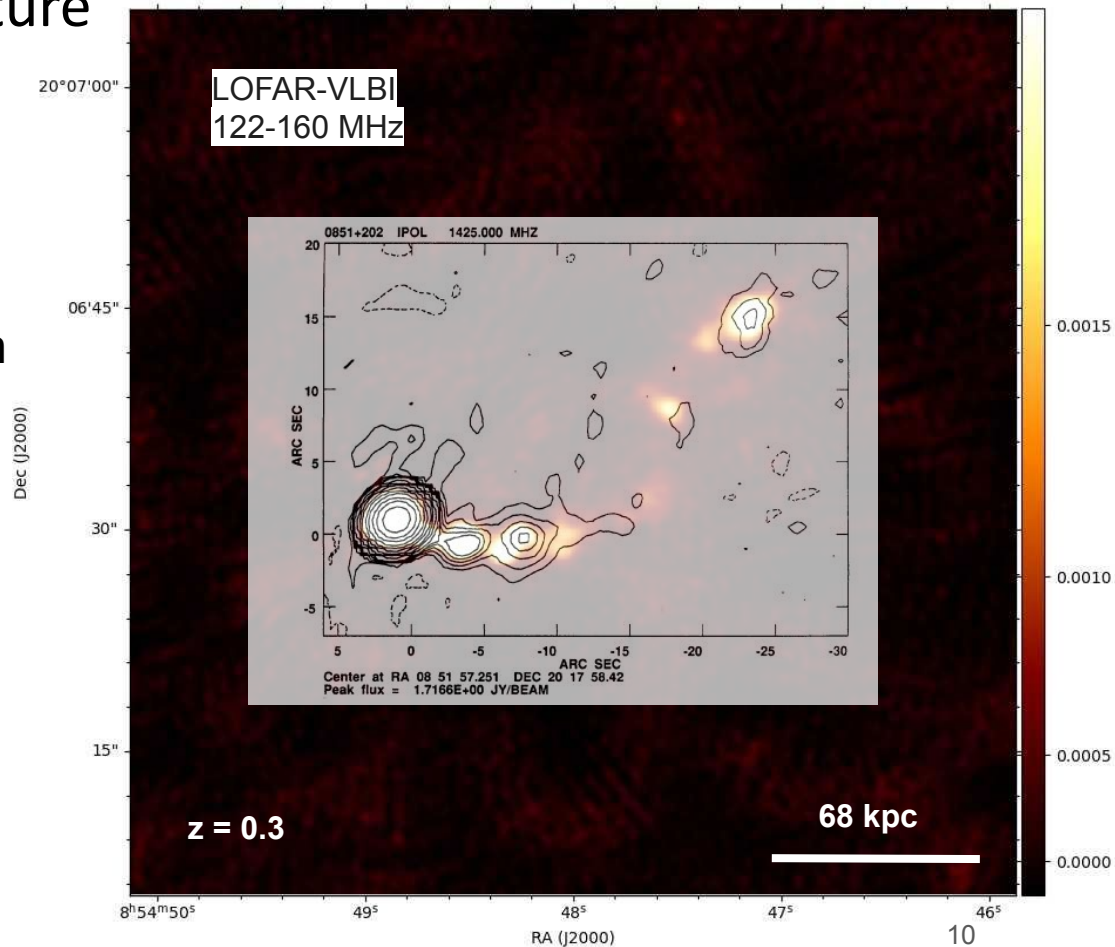
LOFAR-VLBI: resolving structure

- Spectral index analysis a powerful tool to probe plasma properties
- Core behaviour consistent with higher-freq constraints
- Knot behaviour consistent with local re-acceleration
- Terminus spectrum consistent with AGN “hotspot” plasma!
- **Preliminary** - flux scale validation ongoing



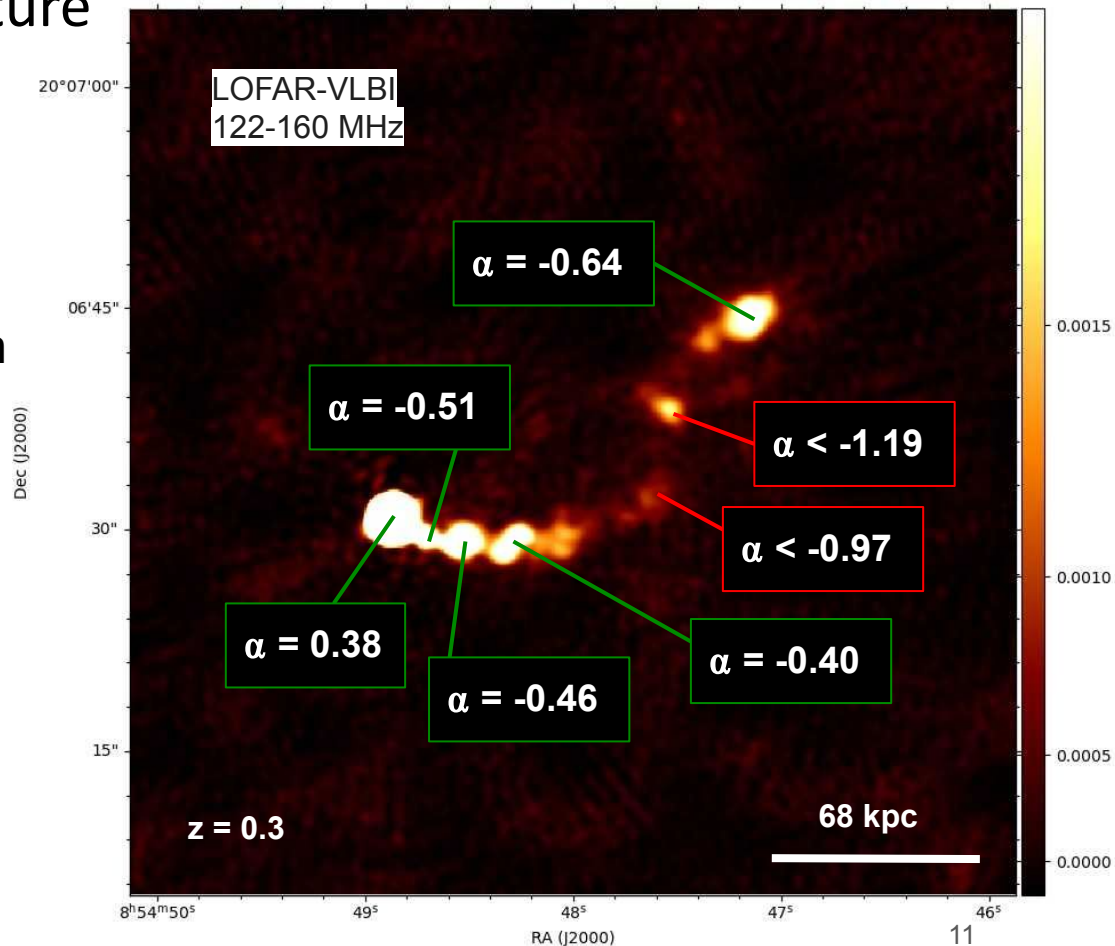
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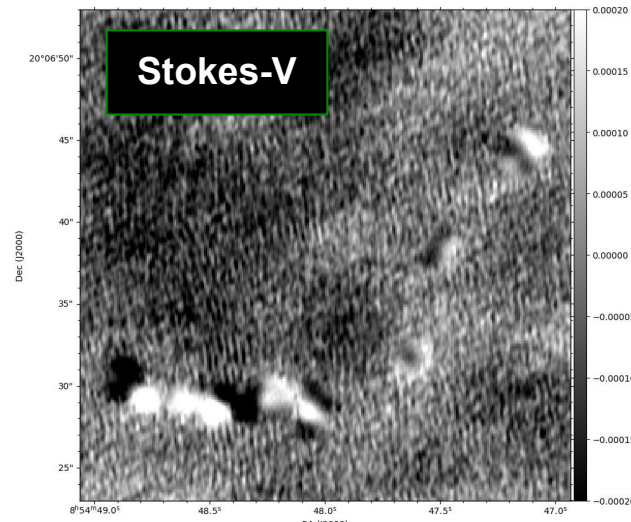
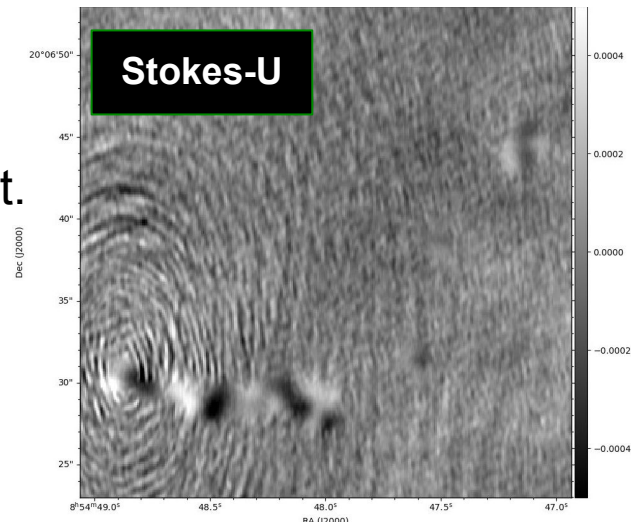
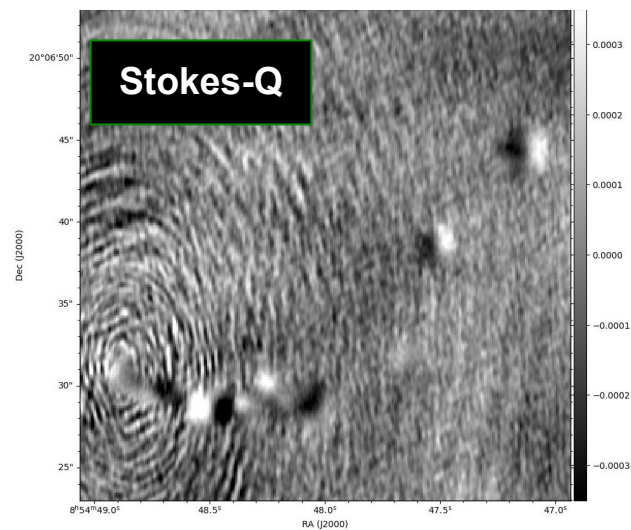
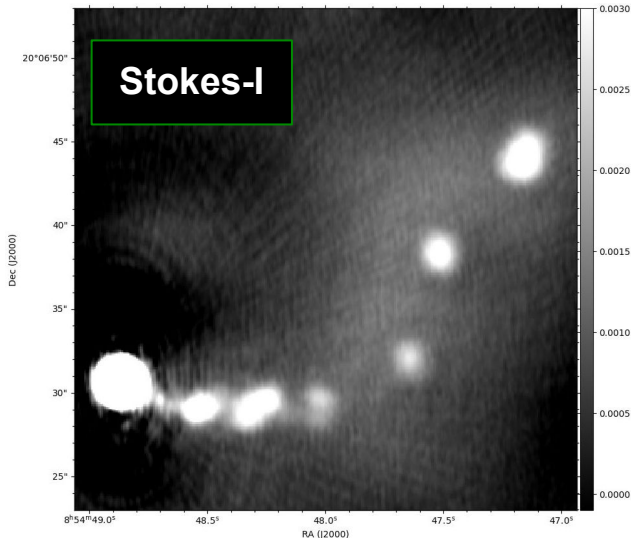
LOFAR-VLBI: resolving structure

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- **Preliminary** - flux scale validation ongoing



LOFAR-VLBI: 4-Stokes

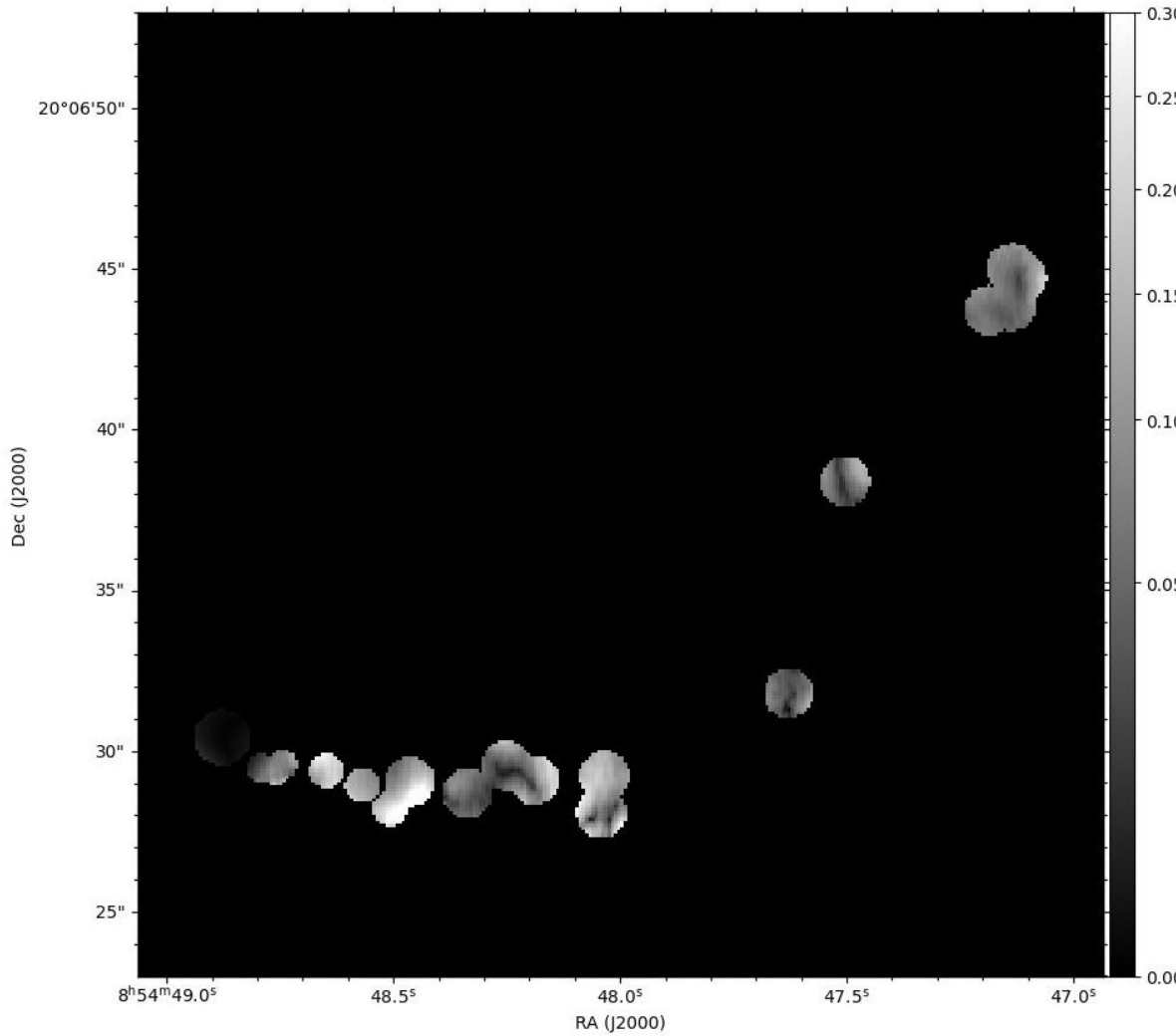
- **Preliminary** work: calibration errors remain
- This due to calib. strategy
- Structure shown here **driven by data**
- Showing **intermediate** data, to maximise contrast.
- Instrument sensitive from 0.2-20arcsec scales.



LOFAR-VLBI: Frac. pol.

- Fractional polarisation generally between 0 - 0.4
- Suggestion of depolarised spine in the jet; more likely tracer of signal-to-noise
- Larger mask degrades reconstruction (MSMF)

$$p = \frac{I}{\sqrt{Q^2 + U^2}}$$

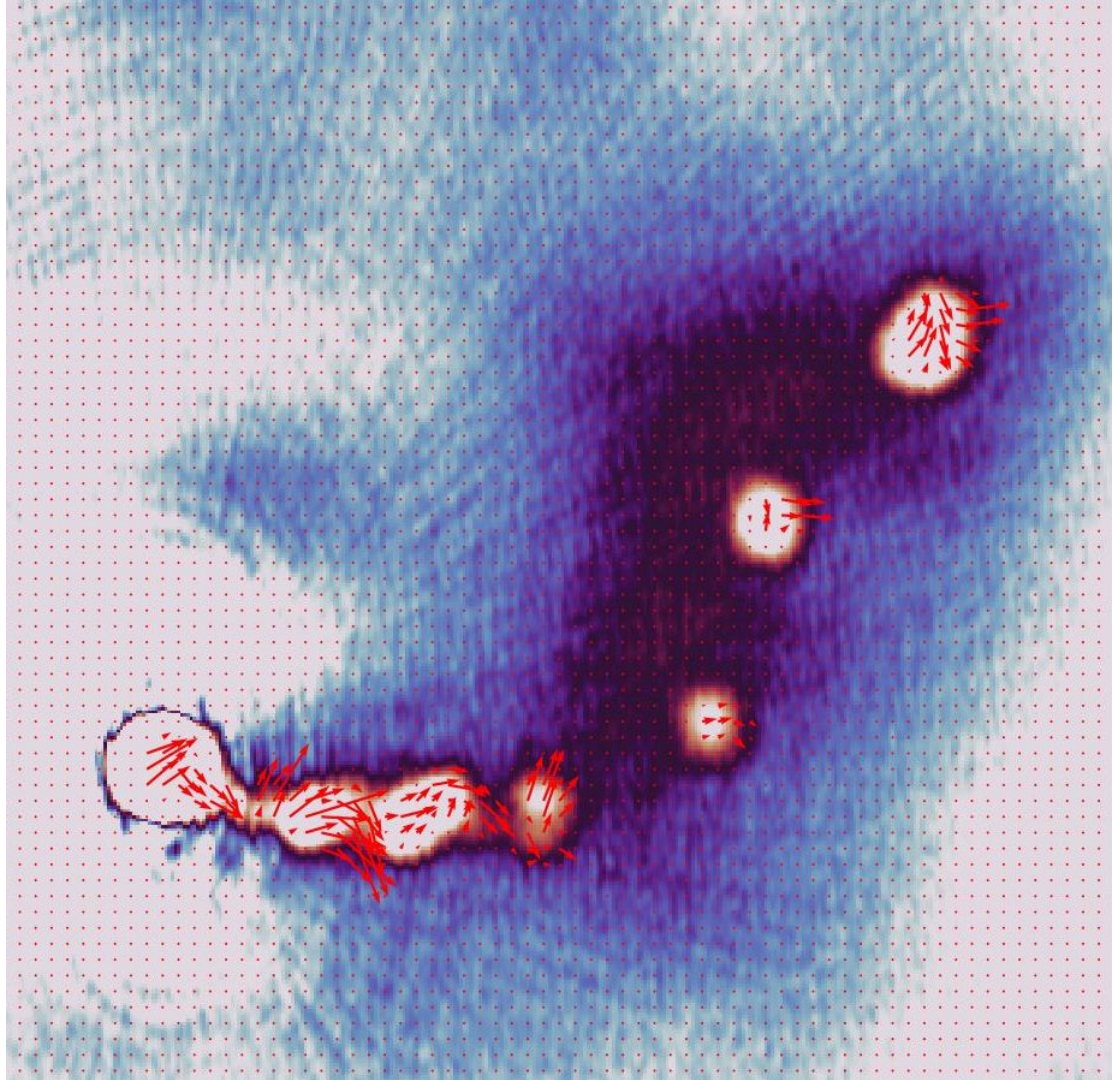


LOFAR-VLBI: EVPA

- 4 / 8h ILT reduced.
- **Polcal converged:** LOFAR Pipelines + facet_self_cal + kMS/DDF
- Preliminary results: EVPA of fossil plasma acquired along jet.

$$P = \sqrt{Q^2 + U^2}$$

$$\chi = \frac{1}{2} \arctan \left(\frac{U}{Q} \right)$$

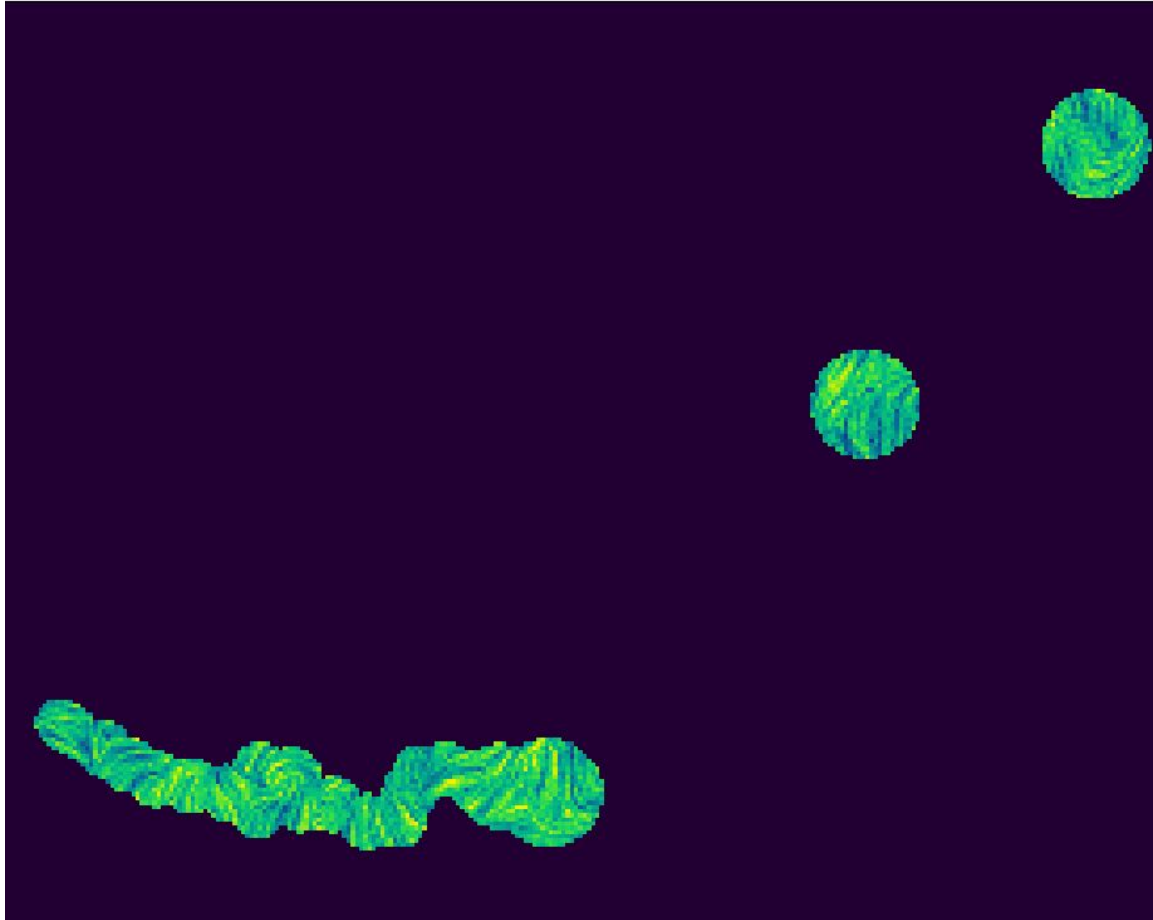


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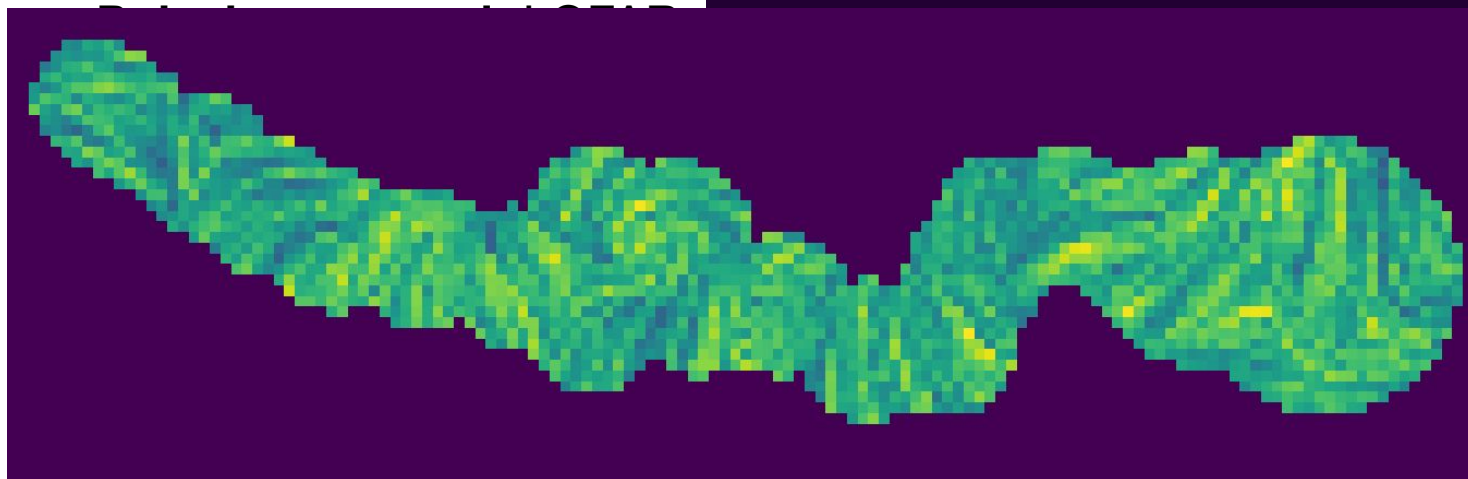
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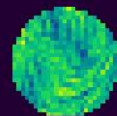
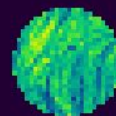
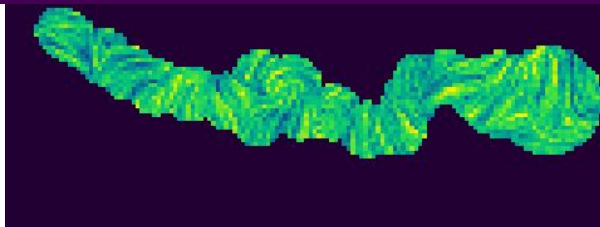
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- 4 / 8h ILT reduced.



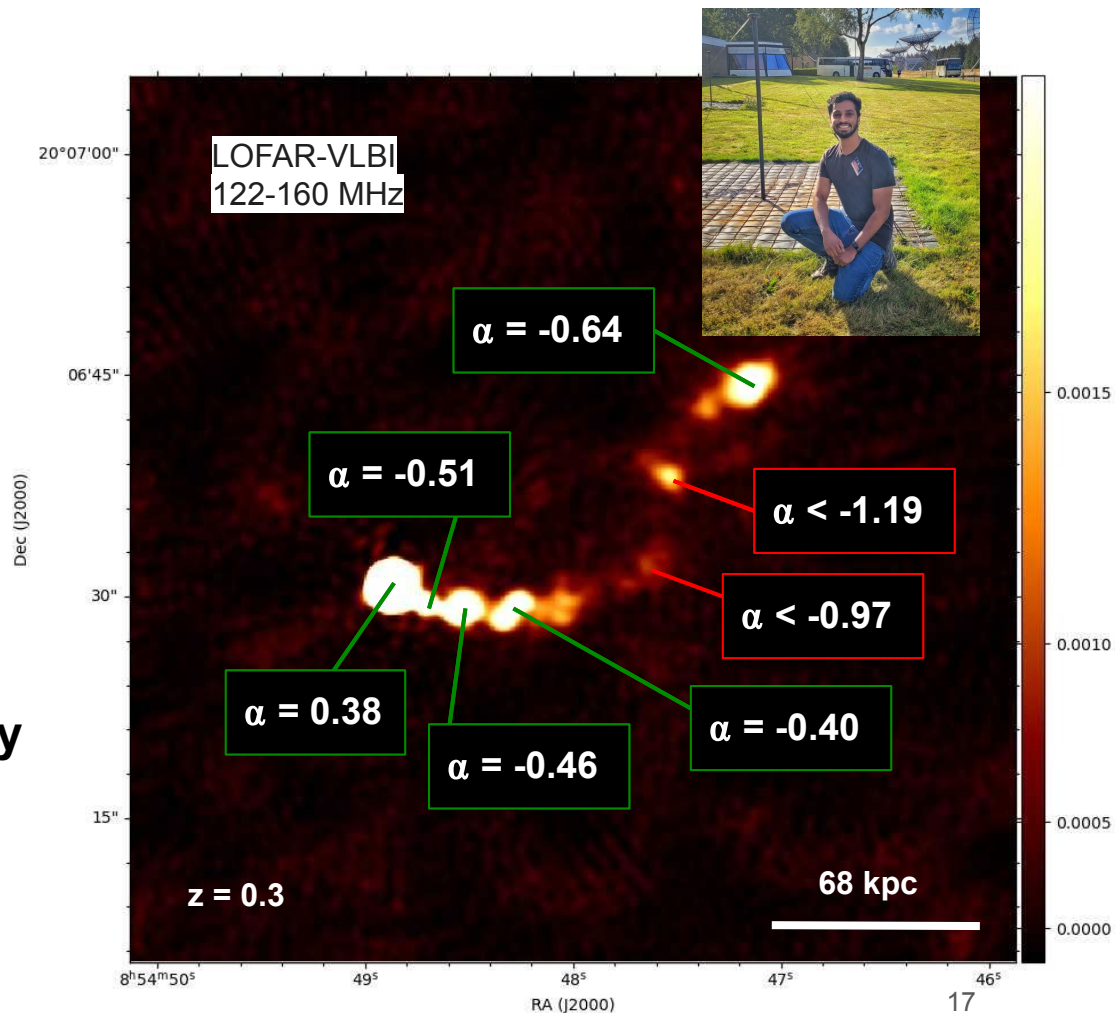
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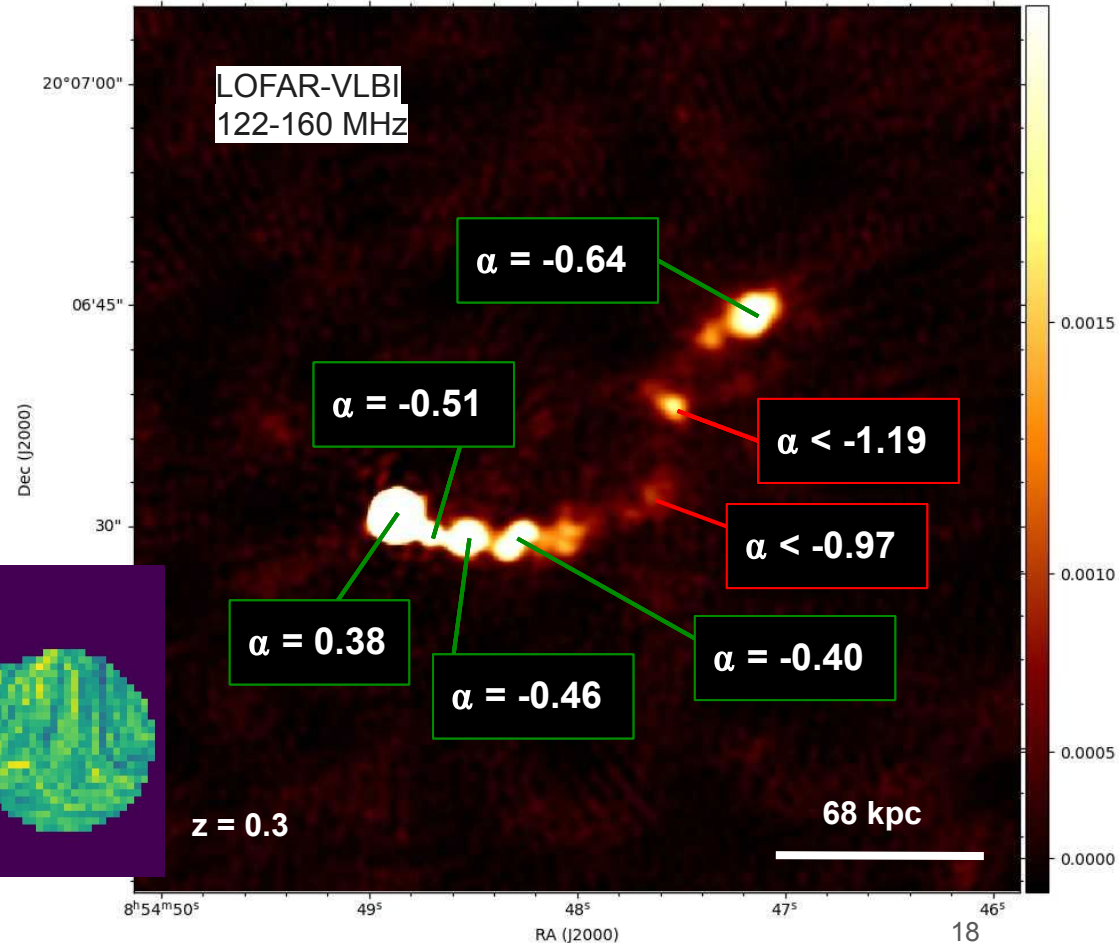
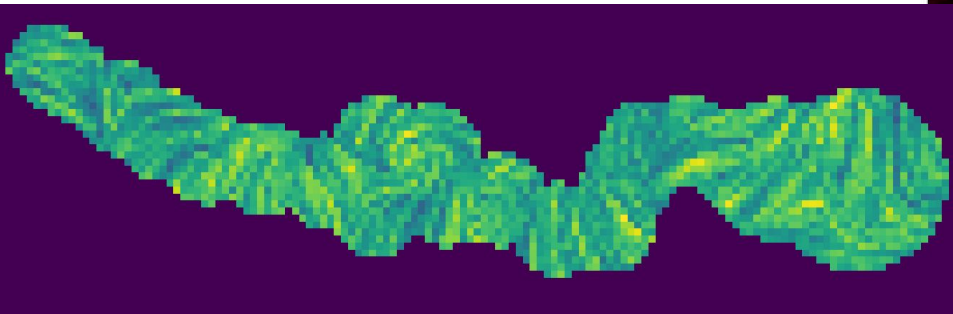
Future Work

- **Publish** current results - **first** ILT pol. map
- **Complement** with uGMRT
- **RM-Synthesis** 144-850 MHz
- EVN, e-MERLIN L-band
- **Full spectral curvature study**
- **SED modeling** along jet



Conclusion

- First ILT polarisation map
- New jet components detected
- Counterjet still not detected
- Multi-scale coverage critical



OJ287

- BL Lacerta object, **discovered in 1967**, monitoring since 1890, $z = 0.306$
- Major outburst fluctuations of ~ 12 years
- Candidate for **binary black hole** (Sillanpaa 1988):
 - major flare predicted for 1994 in 1988; measured and confirmed then.
- Binary orbit parameters (H. Lehto & M. Valtonen):
 - Eccentricity 0.68, (redshifted) period 12.07yr, (relativistic) precession 130yr, inclination of accretion disk in sky 4deg
 - Secondary black hole mass $1e8 M_{\text{sun}}$
 - Current semimajor axis of orbit, 0.056pc



(NenuFAR)

HBA

LBA

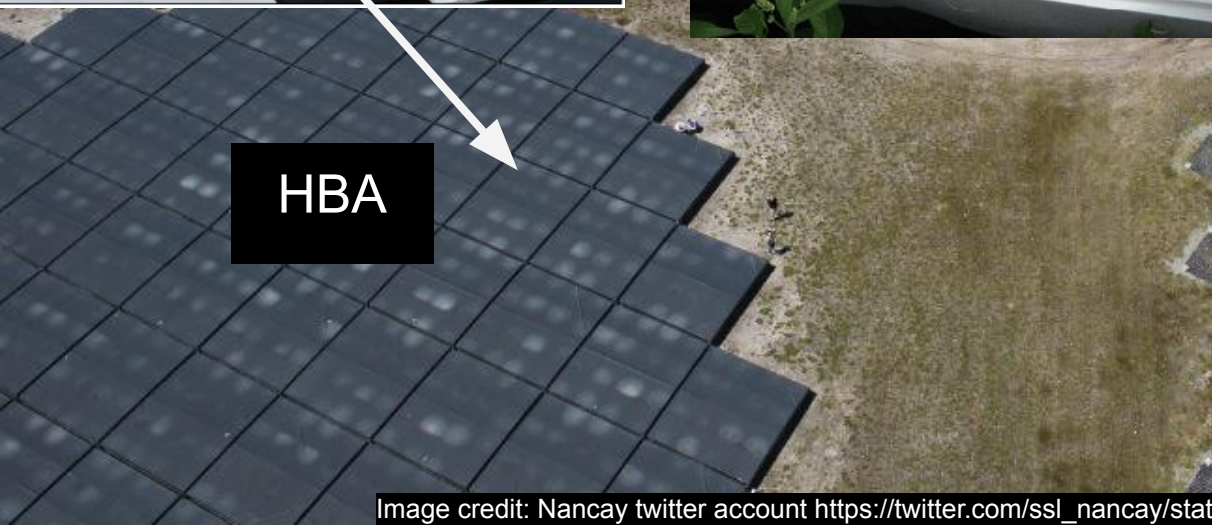
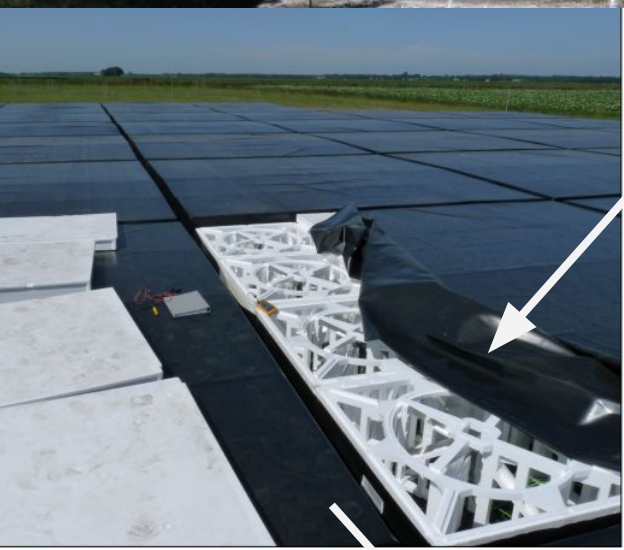
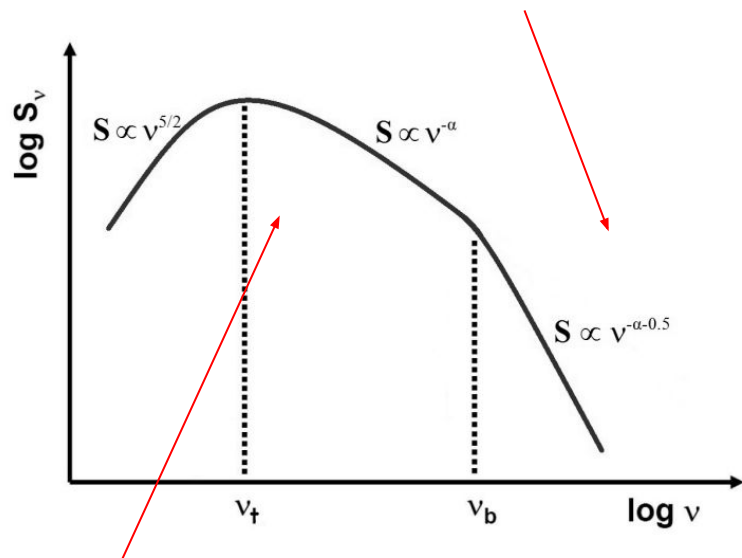


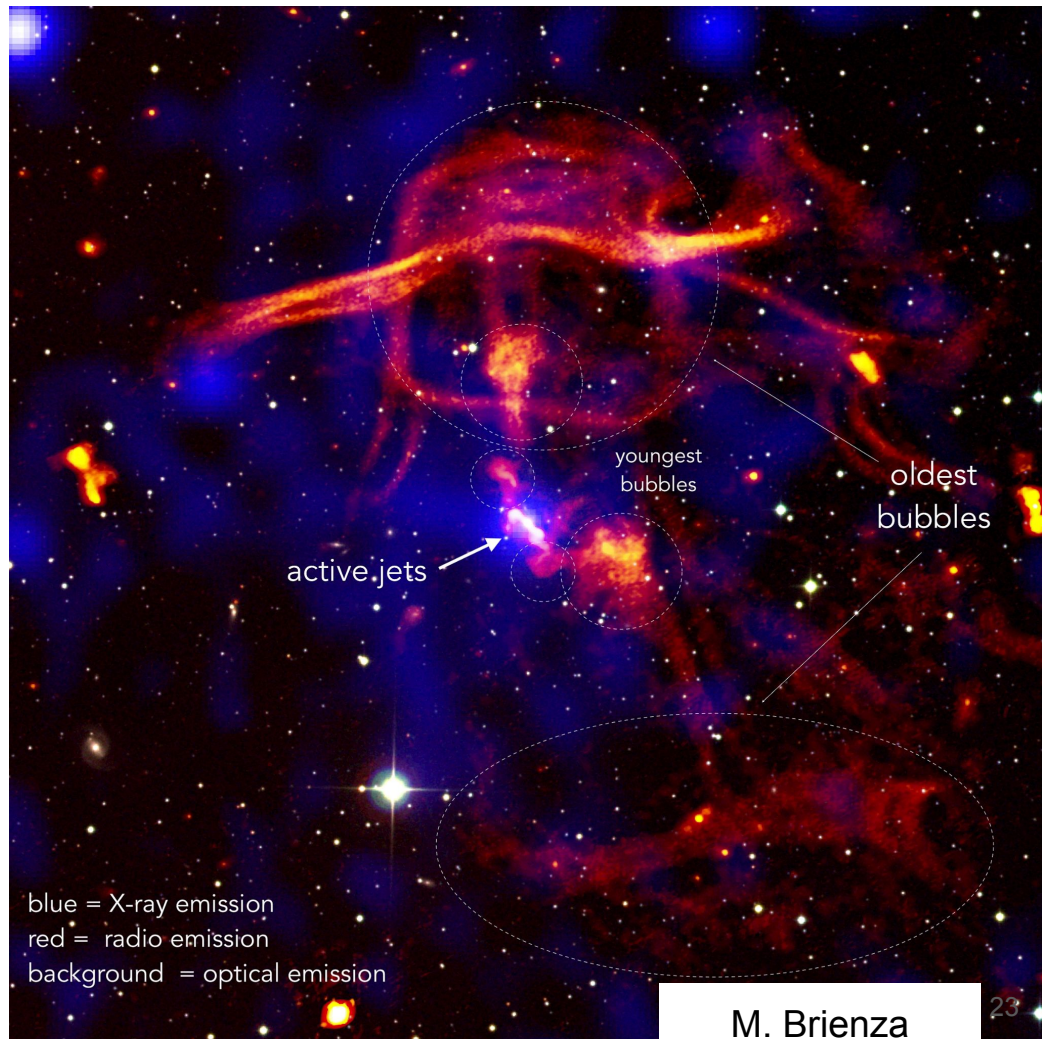
Image credit: Nancay twitter account https://twitter.com/ssl_nancay/statu

Archeology

At a given age of an astrophysical plasma, it will emit synchrotron - but emission falls precipitously above a break frequency



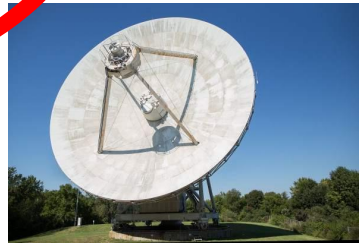
By going to lower frequencies, it becomes possible to see the plasma still emitting at these lower energies - “fossil” emission.



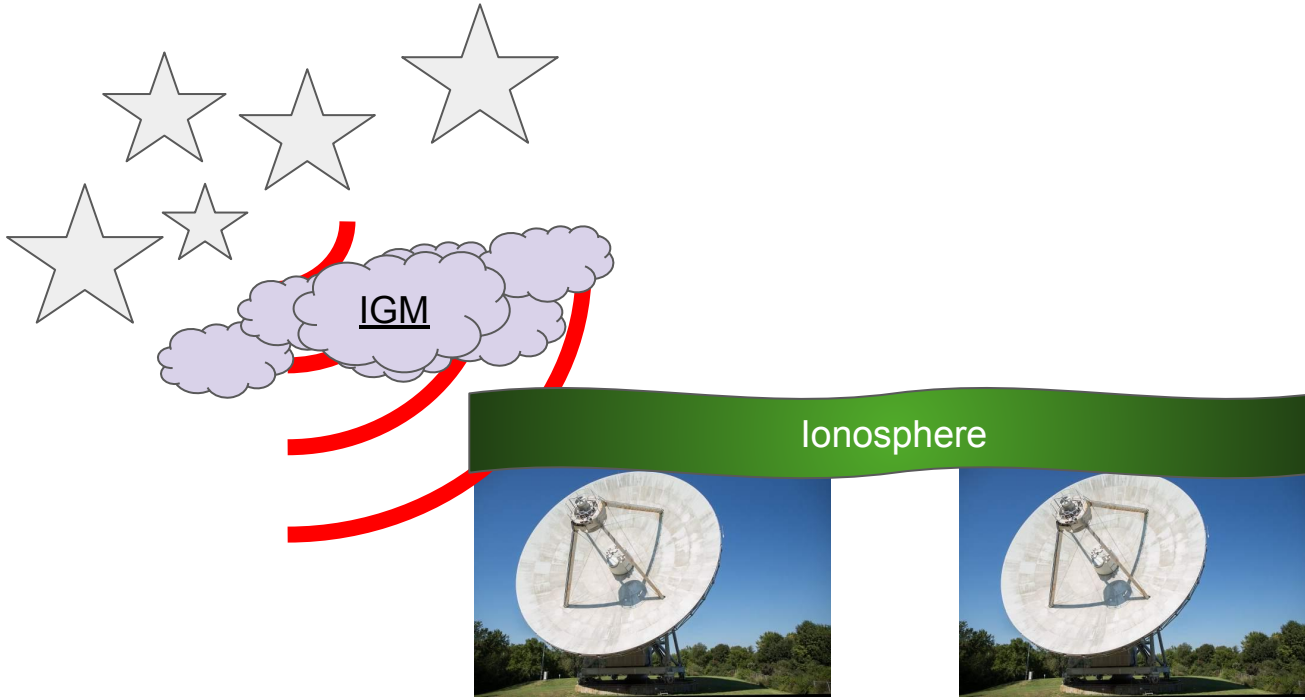
The inverse problem of interferometry: the "truth"

Signal from entire sky is measured

...affected by IGM...



The inverse problem of interferometry: the "truth"

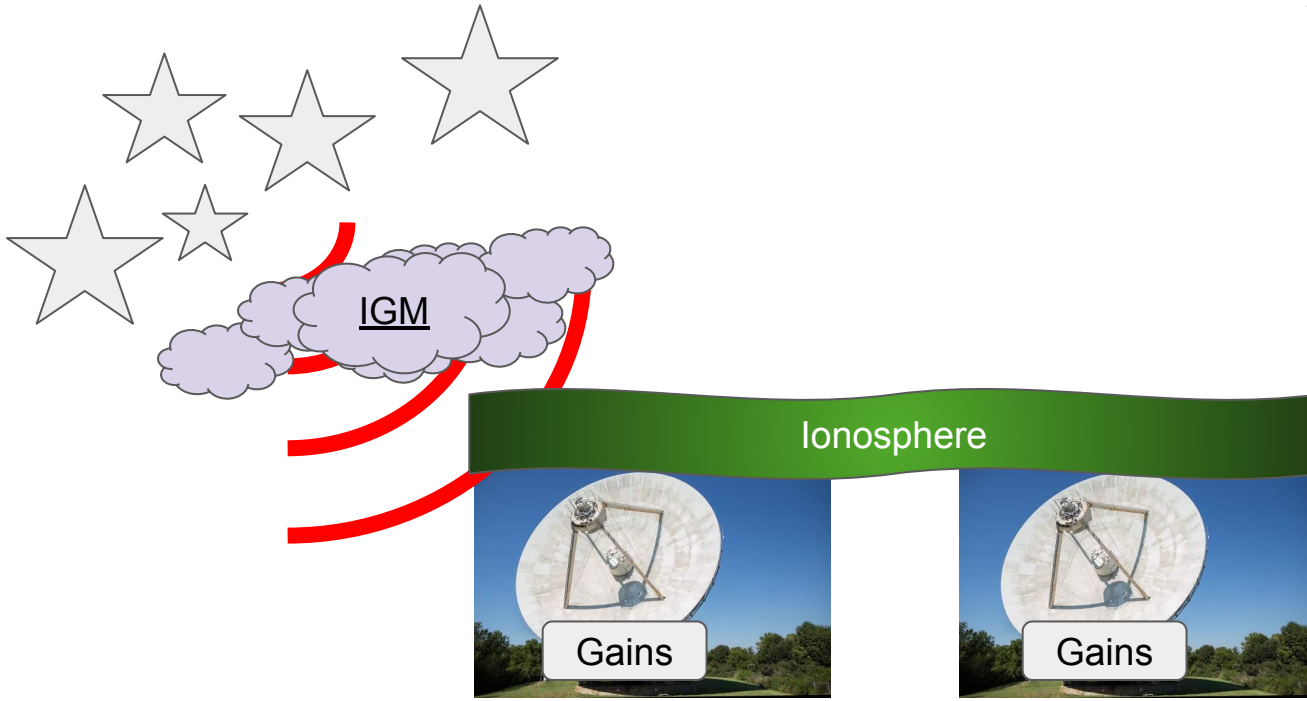


Signal from entire sky is measured

...affected by IGM...

...the impact of the Ionosphere...

The inverse problem of interferometry: the "truth"



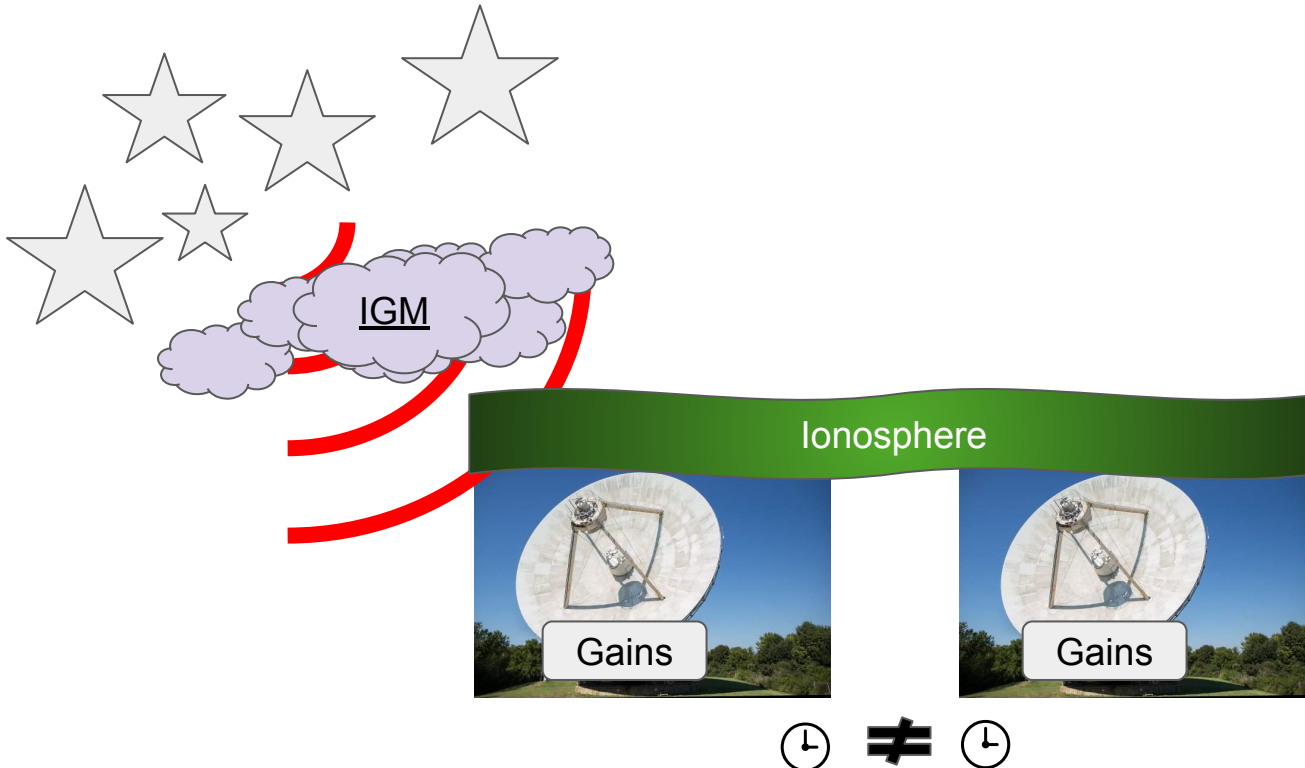
Signal from entire sky is measured

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...the antenna gains...

The inverse problem of interferometry: the "truth"



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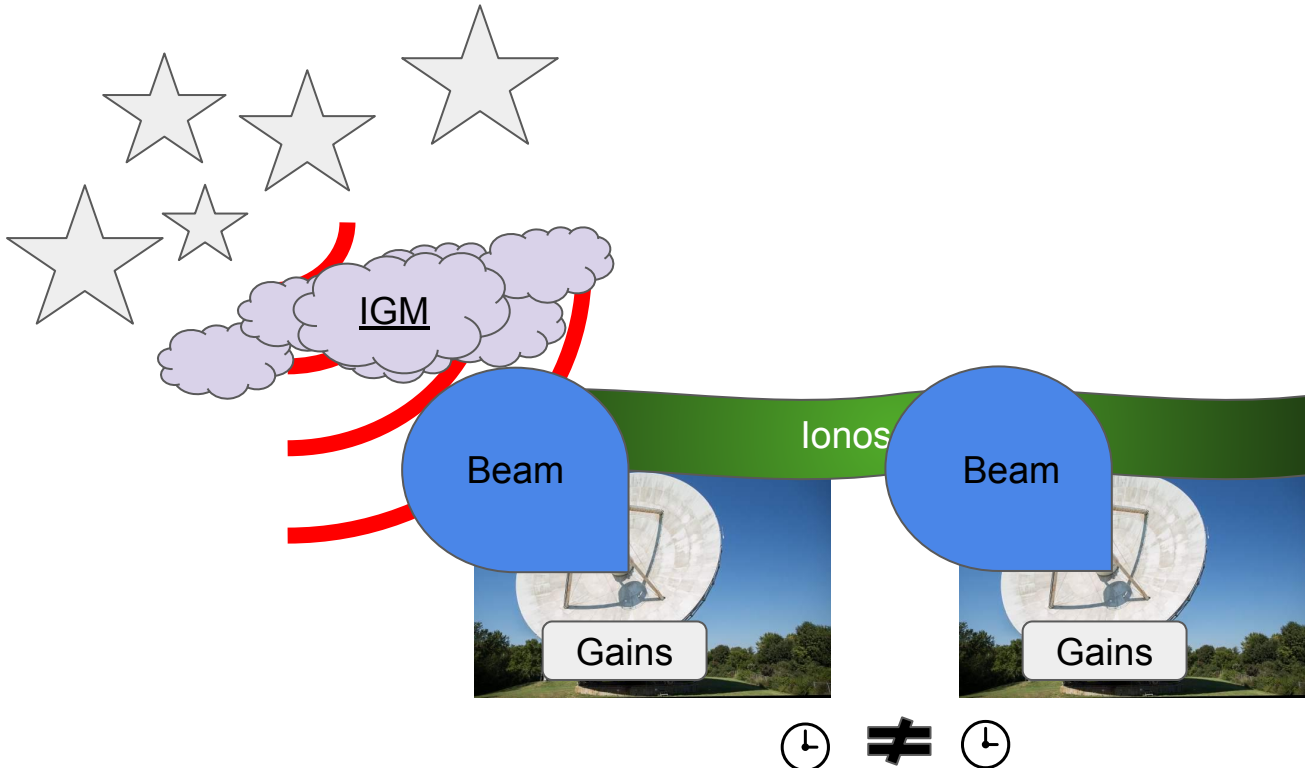
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...clock errors between stations...

The inverse problem of interferometry: the "truth"



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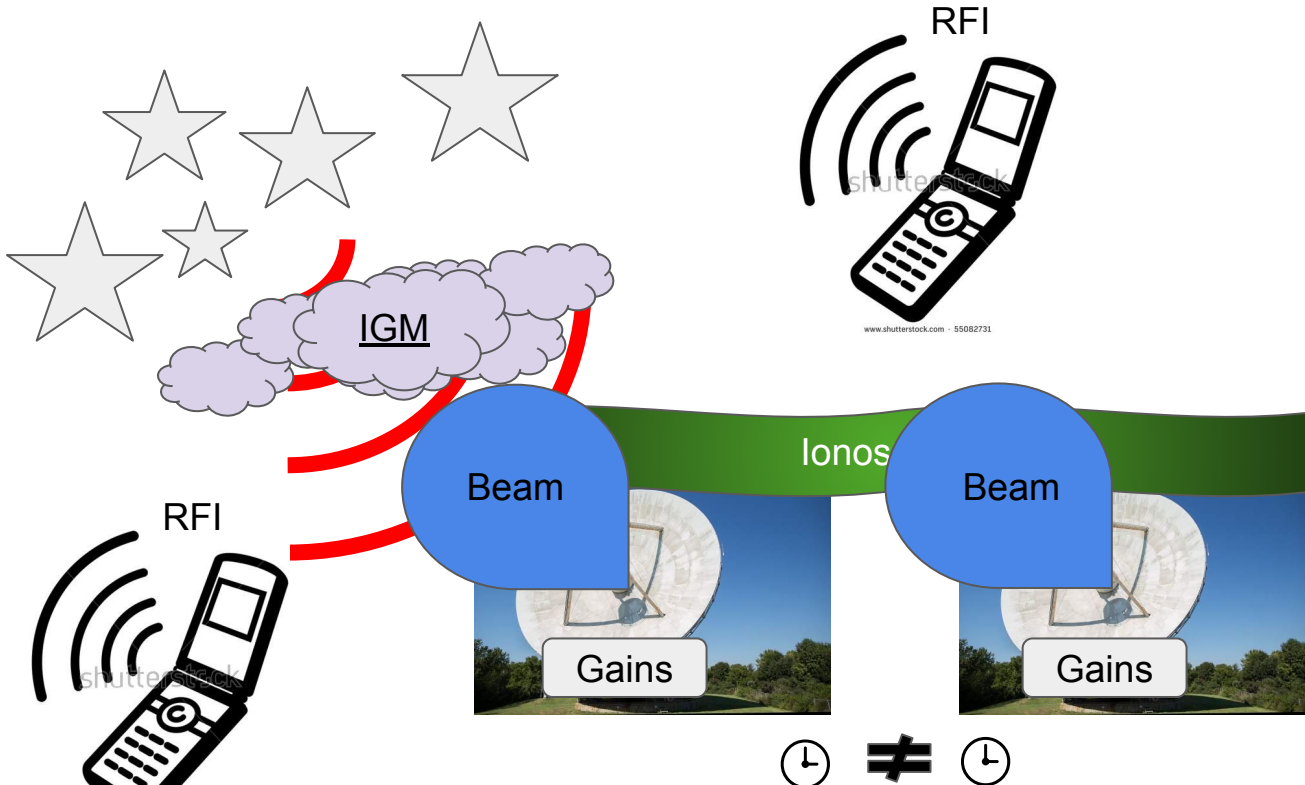
...the impact of the Ionosphere...

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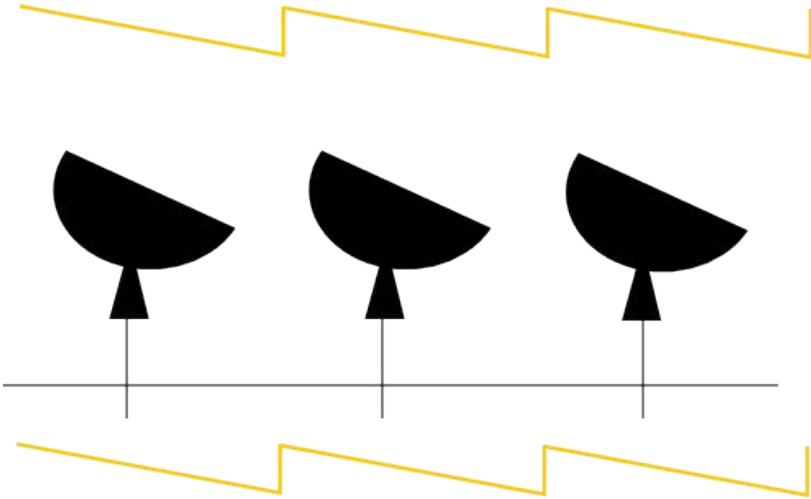
...antenna beam...

The inverse problem of interferometry: the "truth"

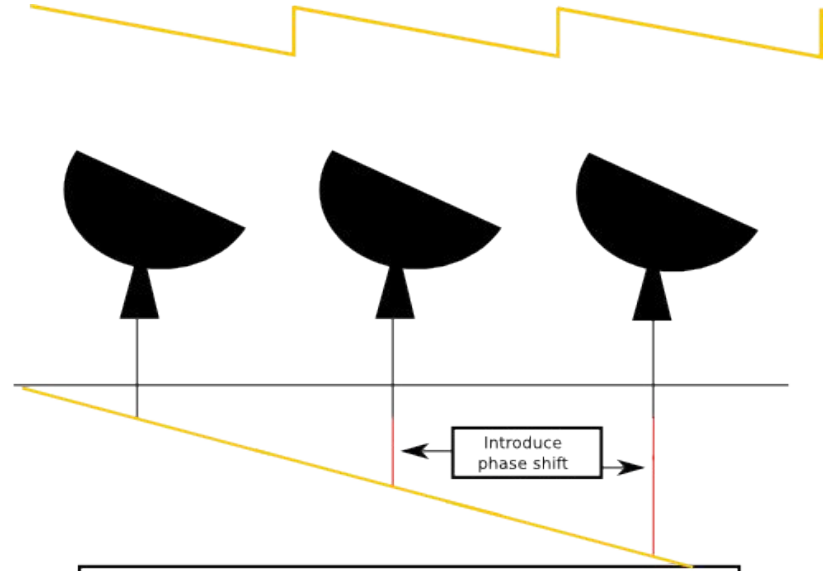


- Signal from entire sky is measured
- ...affected by IGM...
- ...the impact of the Ionosphere...
- ...the antenna gains...
- ...clock errors between stations...
- ...antenna beam...
- ...radio frequency interference...
- ...and more besides.....

Self-calibration as Adaptive Optics

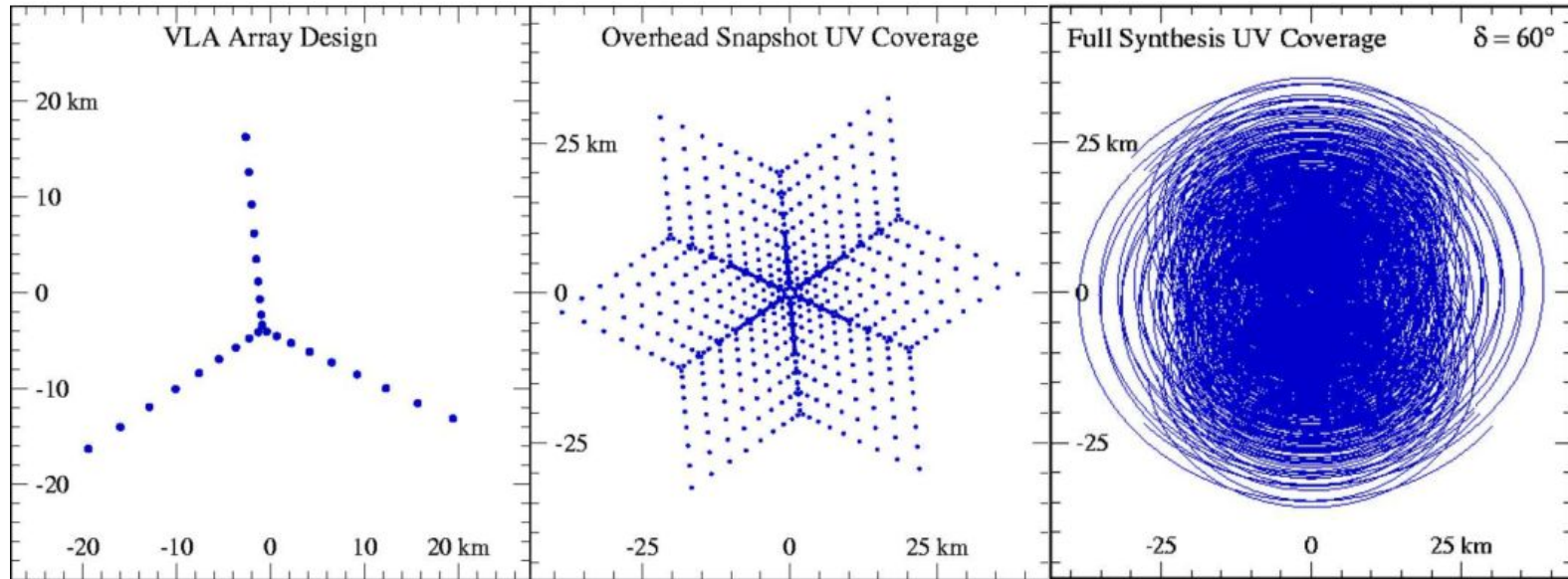


Phase Errors Remain



Signal hits all antennas
simultaneously

Interferometry inverse problem



Pros:

- Homogeneous arrays (usually)
- Large number of array elements
- Supersynthesis + large bandwidth
- Shared clocks for signal correlation

Cons:

- Much larger data for each new element
- Combination of short and long baselines
- Larger FoVs - \rightarrow more complex fields
- Better sensitivity - \rightarrow more complex fields

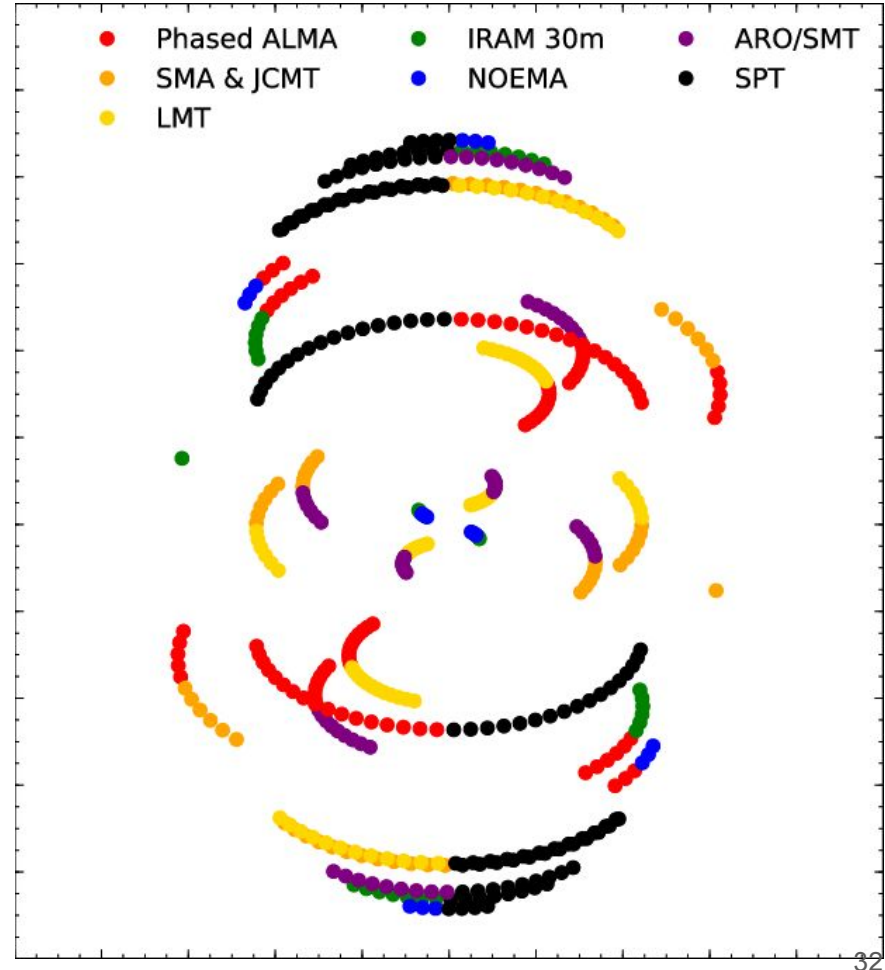
VLBI inverse problem

Pros:

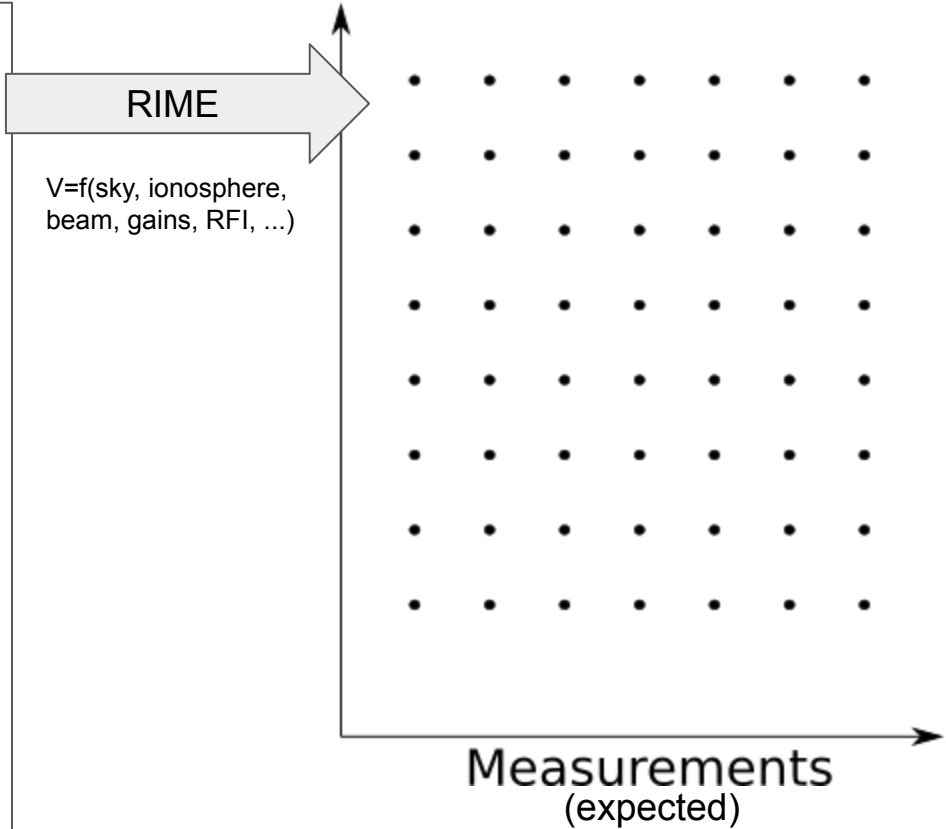
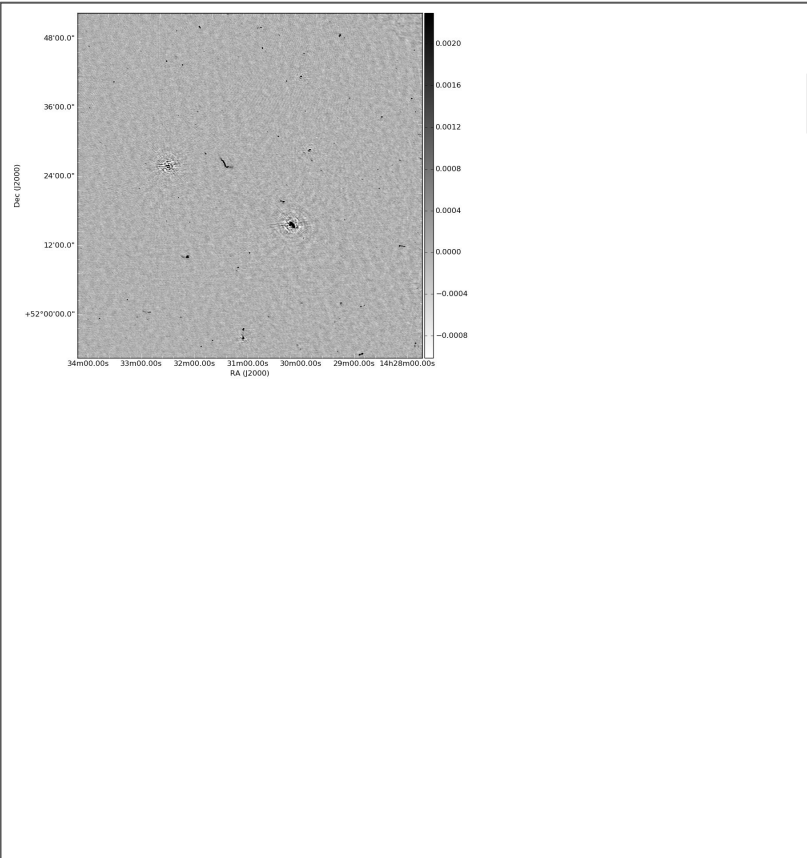
- Small field of view
- All baselines of comparable lengths
- No short baselines -> no pollution from Galactic emission
- Small data size (post-correlation...)
- Robust, reliable, expert tools available (difmap, ehtim)

Cons:

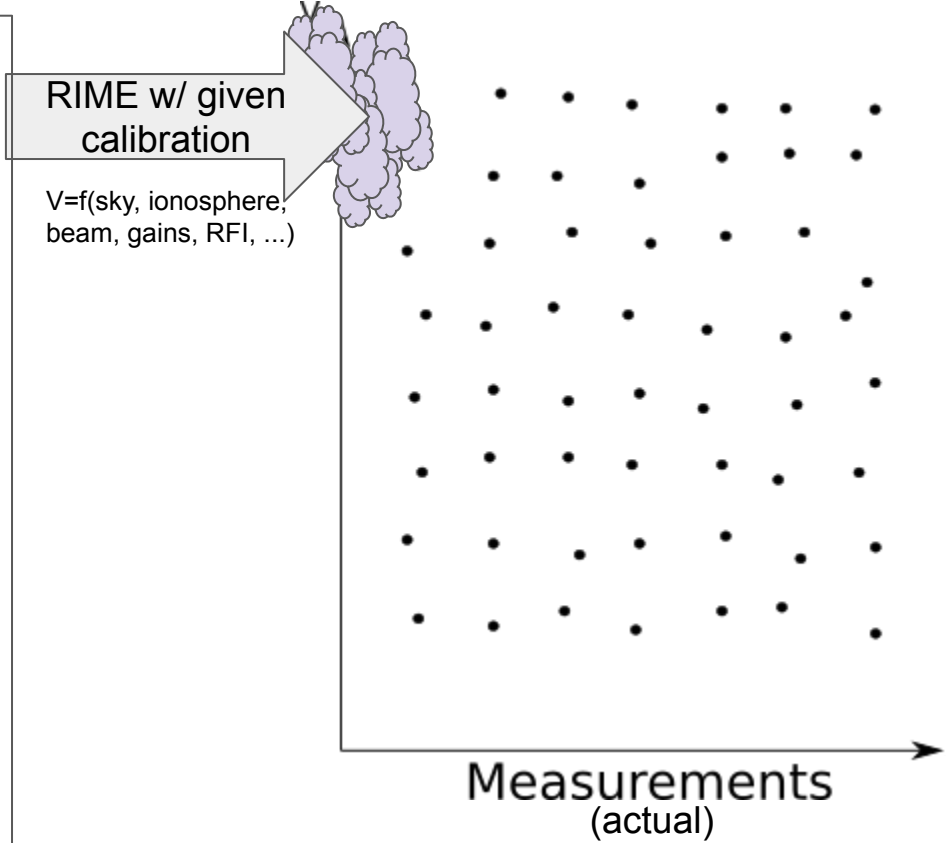
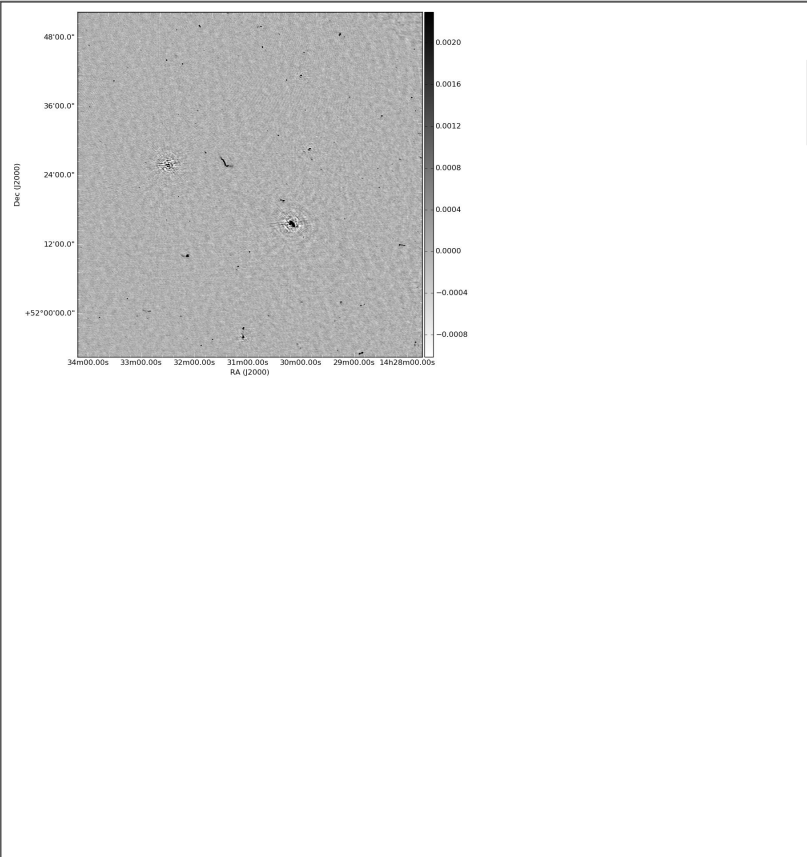
- Very few array elements
- Heterogeneous arrays
- Few baselines -> bad conditioning
- True for both calibration and imaging
- Bursts of short integration times



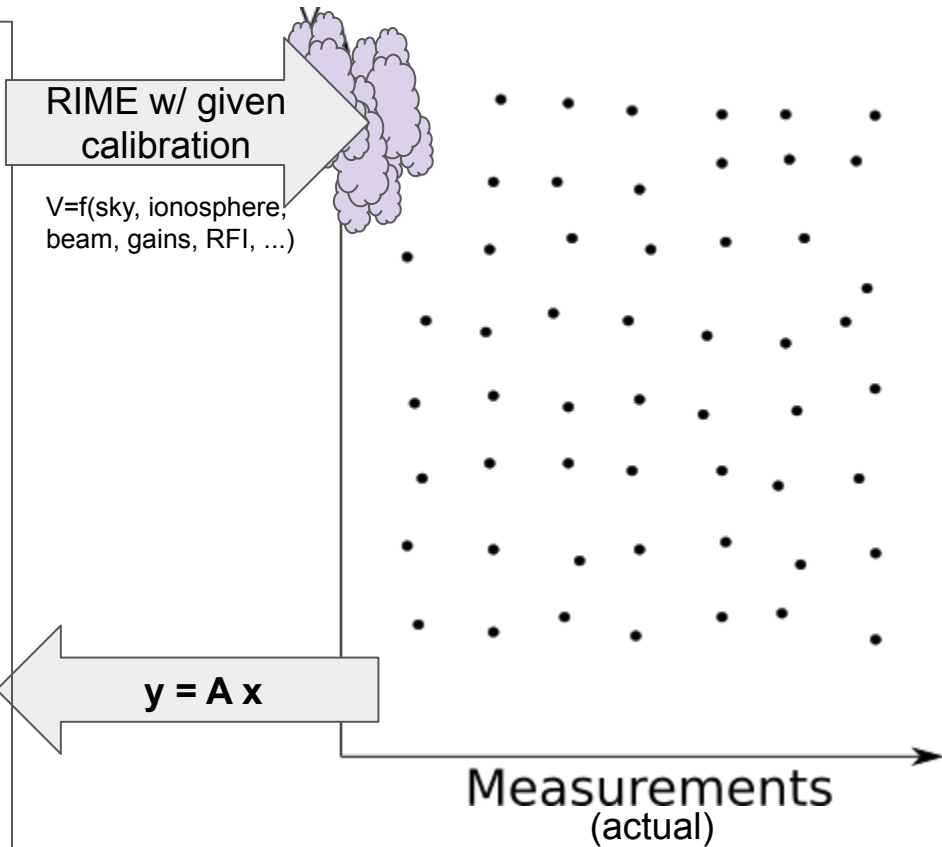
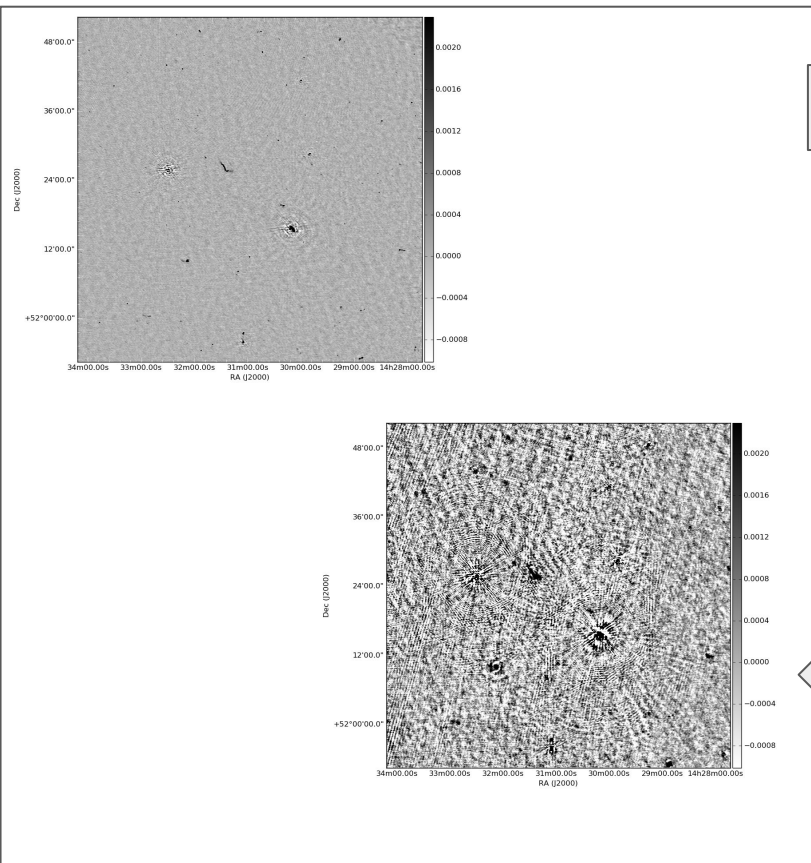
The inverse problem of interferometry: the observation



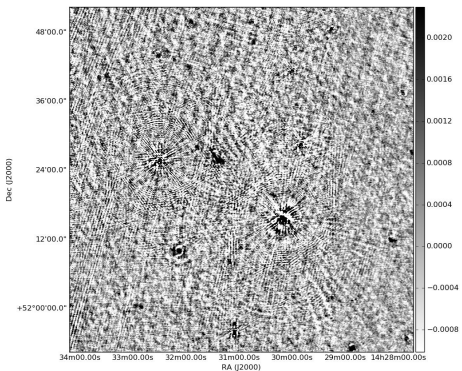
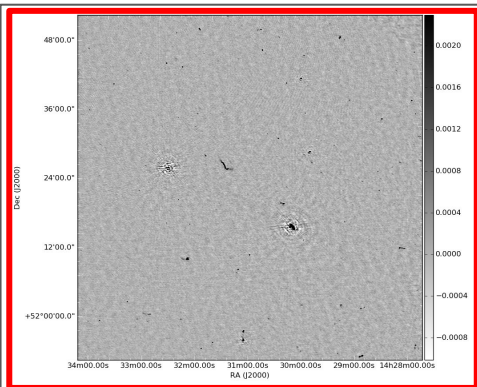
The inverse problem of interferometry: the observation



The inverse problem of interferometry: the observation



The inverse problem of interferometry: the observation



RIME w/ given calibration

$V=f(\text{sky, ionosphere, beam, gains, RFI, ...})$

$$y = Ax$$

Measurements
(actual)