Low radio frequencies and high resolution: impact of SKA pathfinders on blazar science

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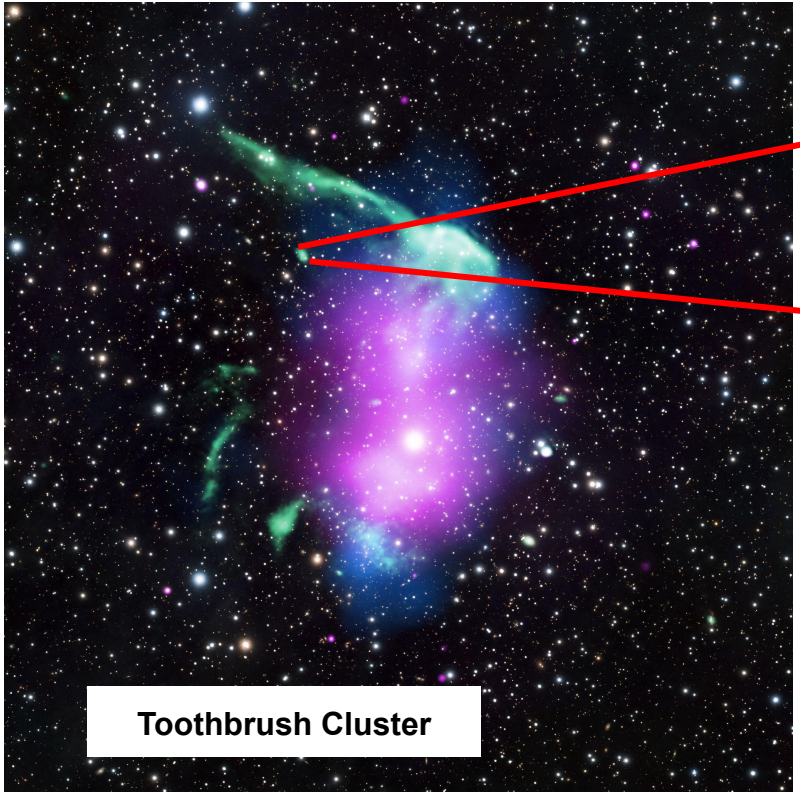
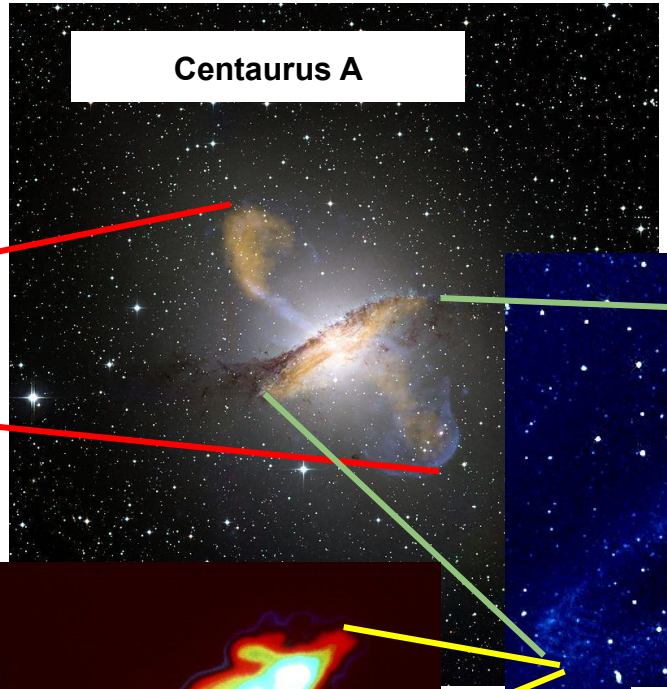
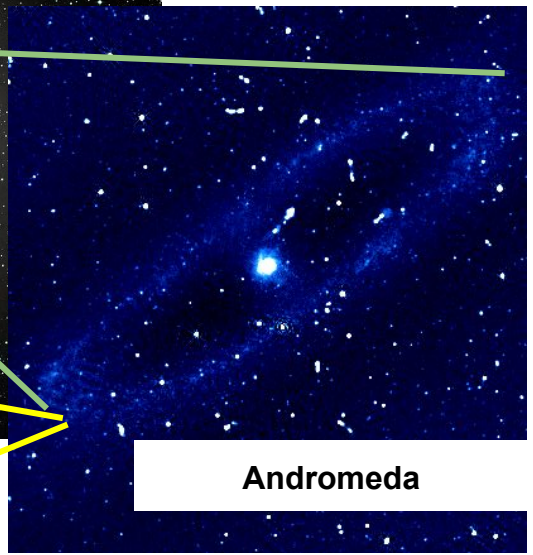
ECLAT workshop 2024

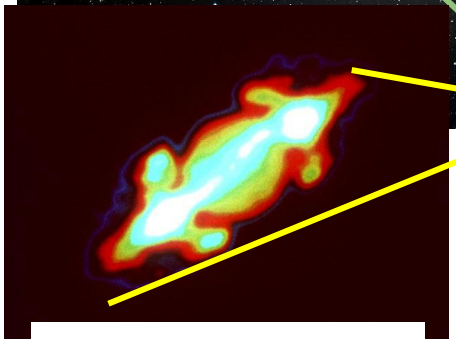
Etienne Bonnassieux, IAA-CSIC
with Hrishikesh Shetgaonkar, Matthias Kadler, +++ at JMU Wurzburg

Non-Thermal Universe







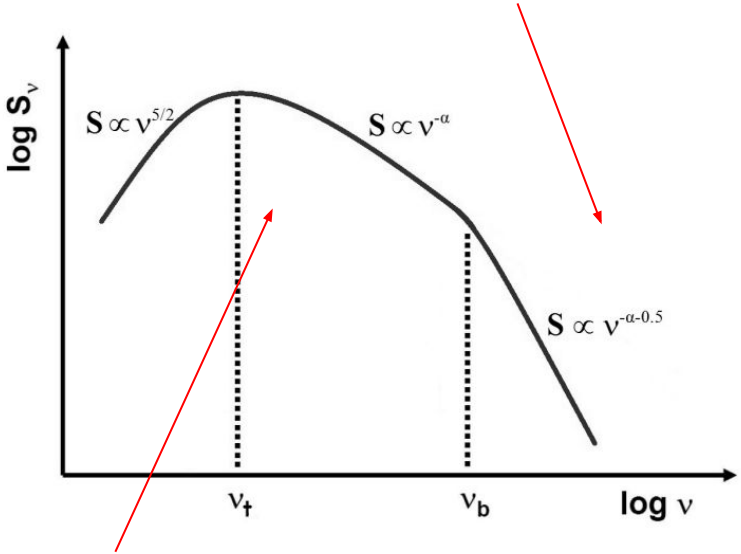


Jupiter

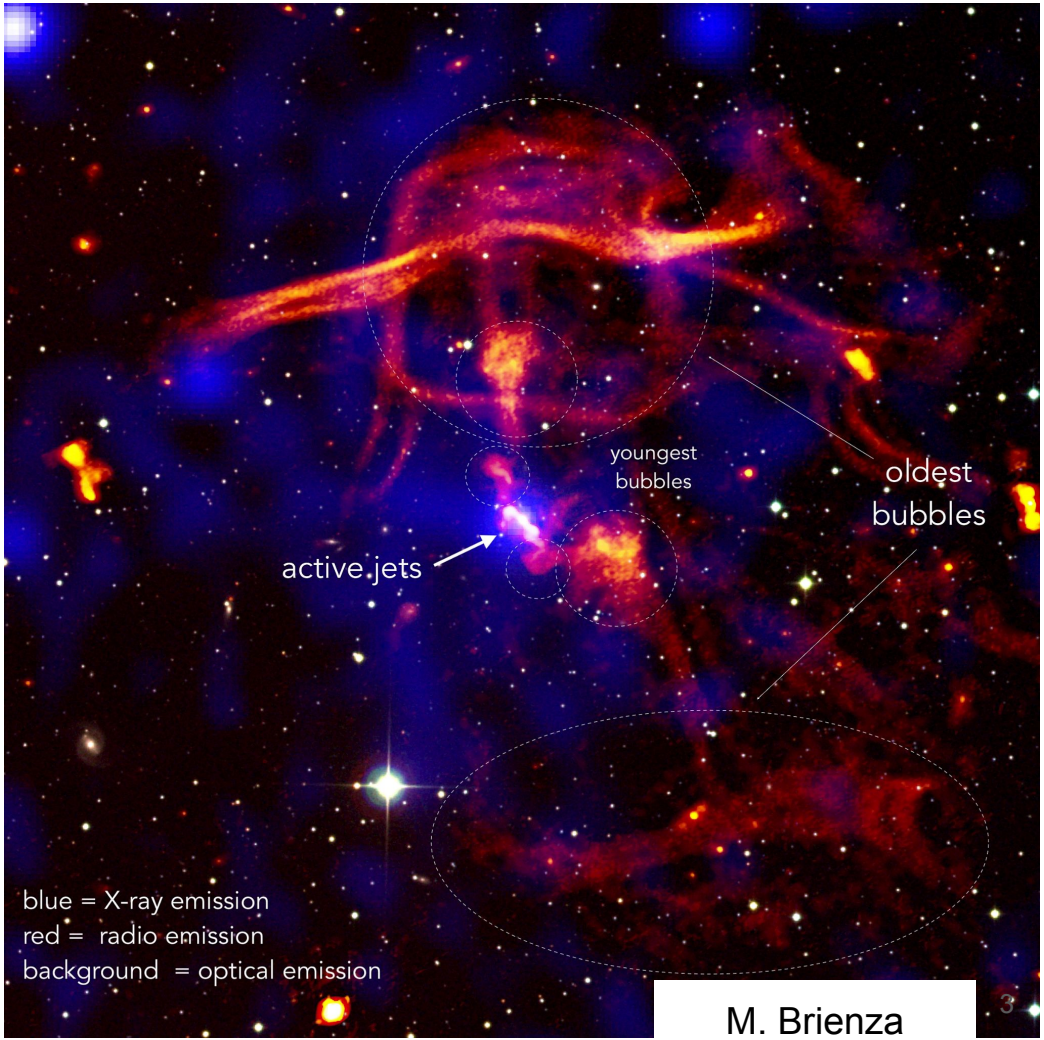
Image credits:
Toothbrush: https://www.nasa.gov/mission_pages/chandra/toothbrush-cluster-rx-j060334214.html
Centaurus A: https://www.eso.org/public/images/eso0903a/
Jupiter: https://www.windows2universe.org/jupiter/magnetosphere/J_radio_emissions.html

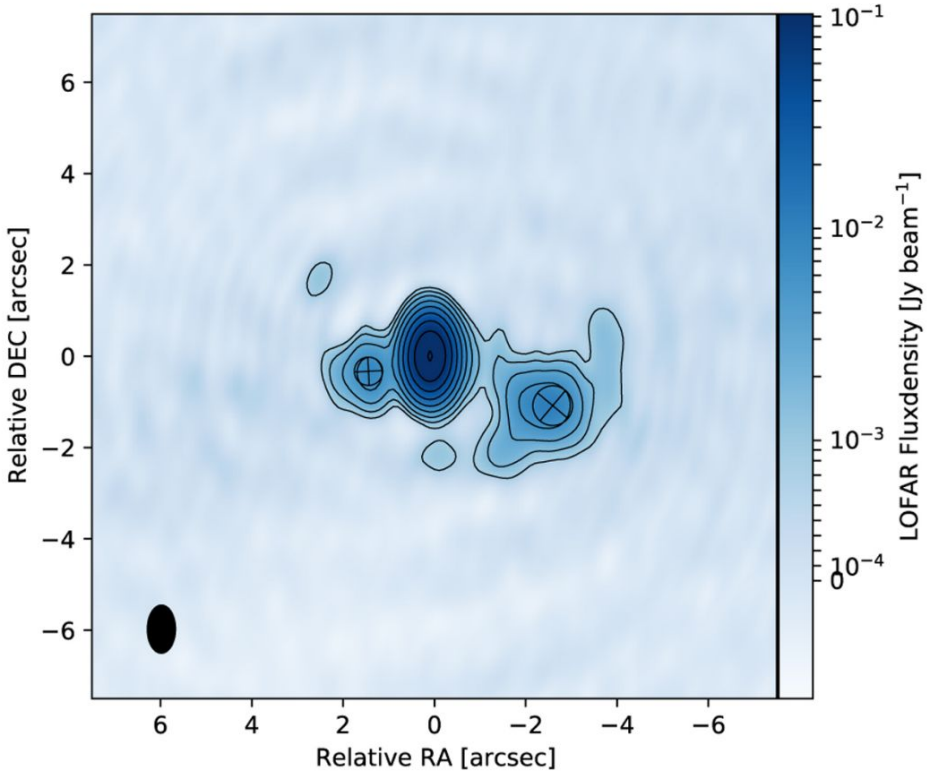
Archeology

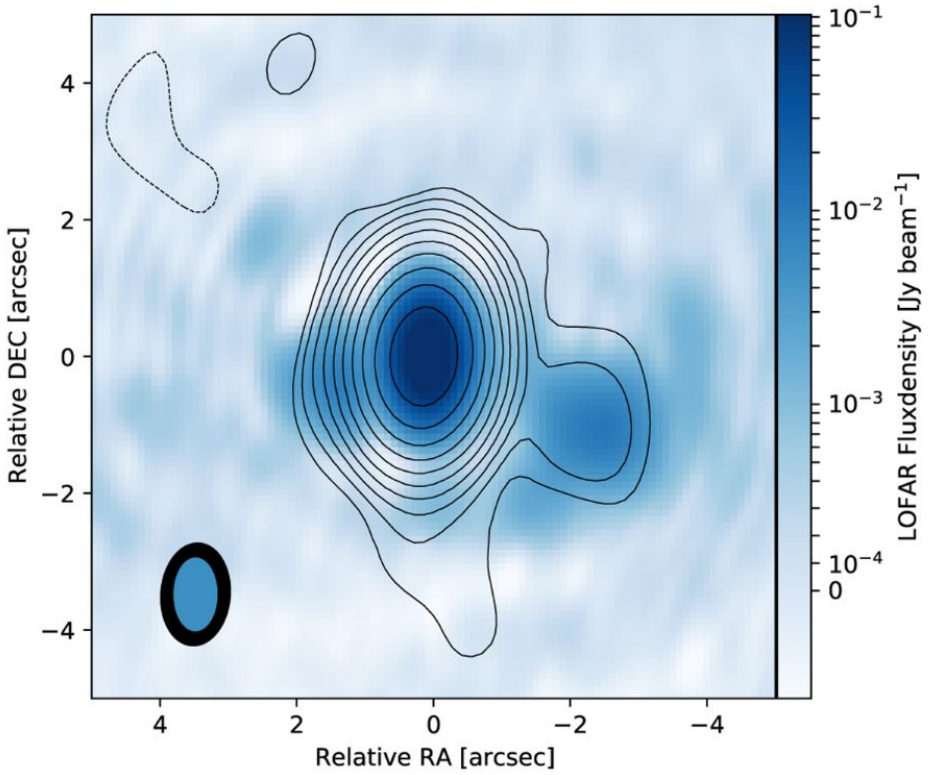
At a given age of an astrophysical plasma, it will emit synchrotron - but emission falls precipitously above a break frequency



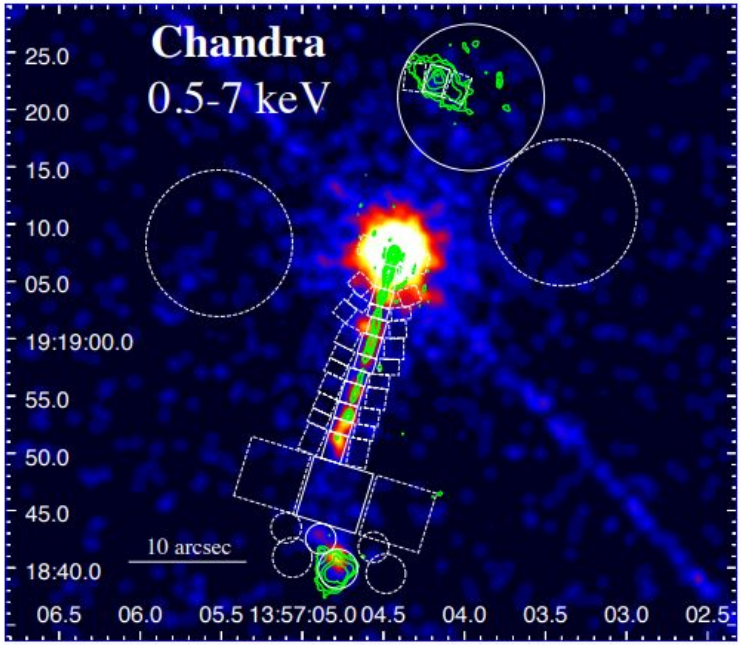
By going to lower frequencies, it becomes possible to see the plasma still emitting at these lower energies - “fossil” emission.

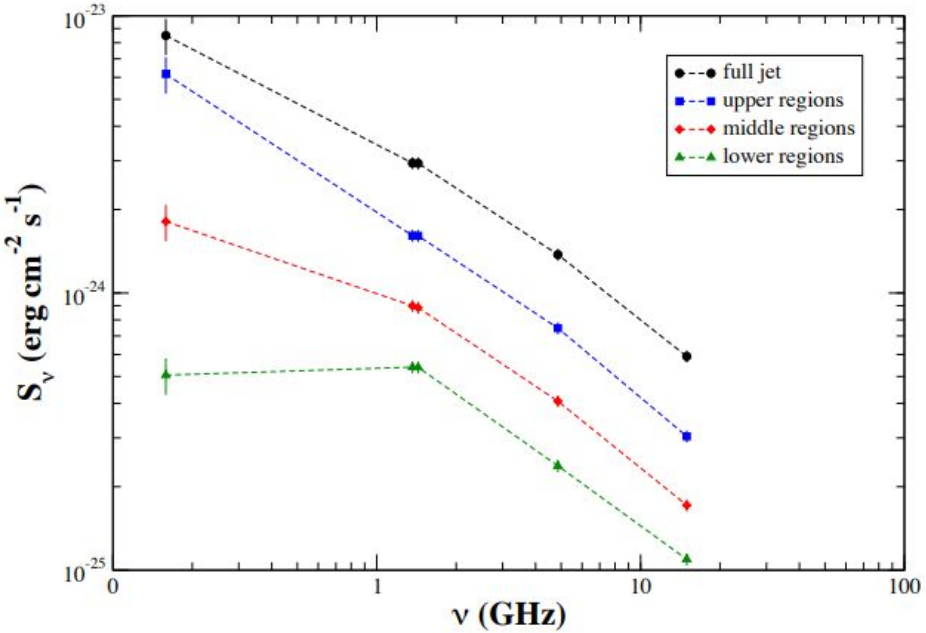






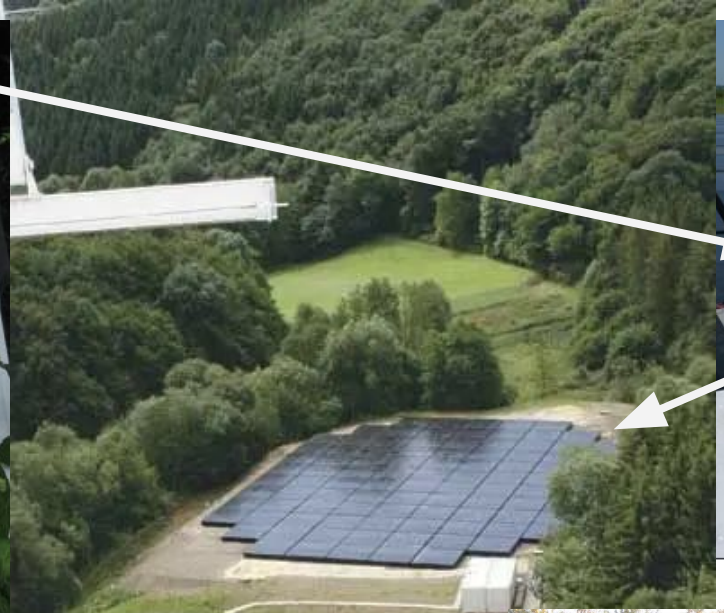
Kappes et al. : Subarcsecond view on the high-redshift blazar GB 1508+5714 by the International LOFAR Telescope
https://arxiv.org/abs/2205.11288

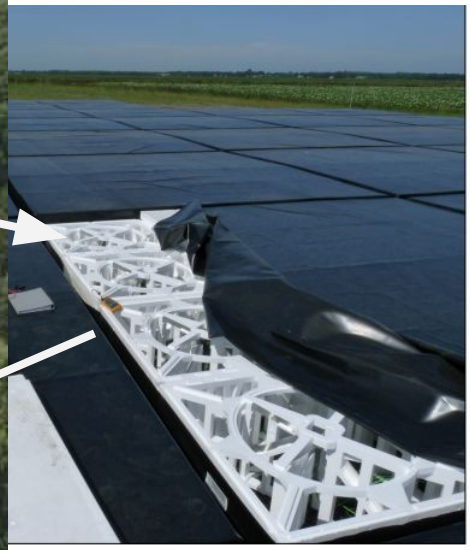




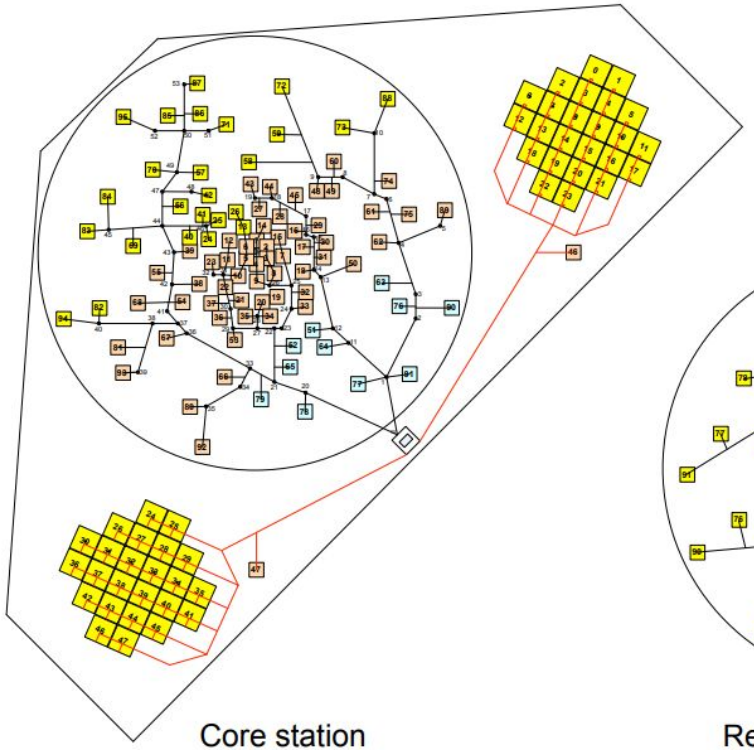
Harris et al. : LOFAR Observations of 4C+19.44: On the Discovery of Low-frequency Spectral Curvature in Relativistic Jet Knots
https://ui.adsabs.harvard.edu/abs/2019ApJ...873...21H/abstract

Image credit: Nancay twitter account https://twitter.com/ssl_nancay/status/611901153635381248

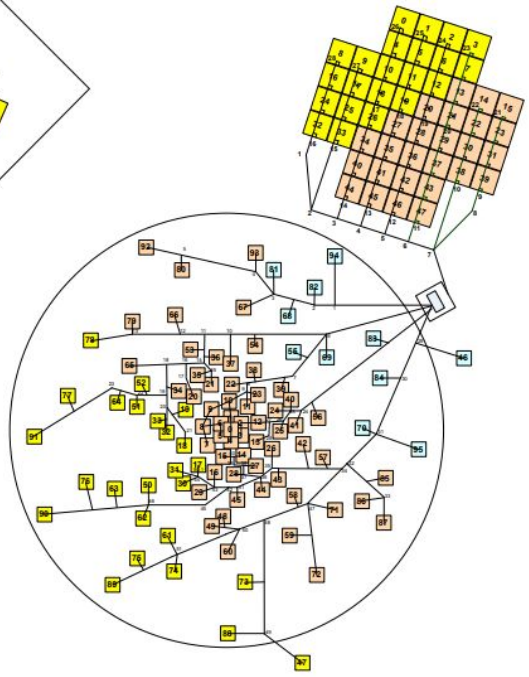




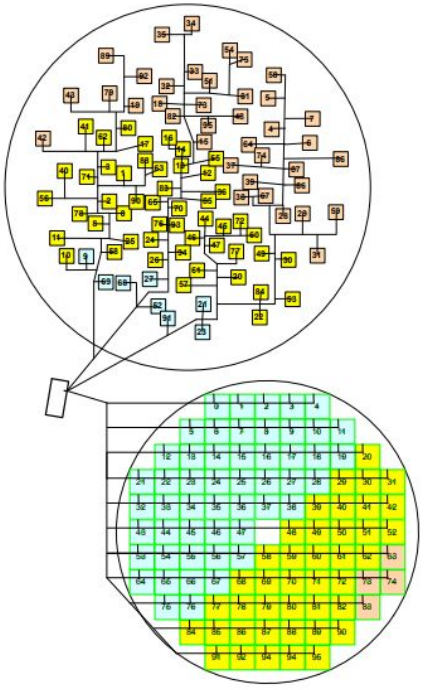
https://arxiv.org/pdf/1305.3550



Core station



Remote station

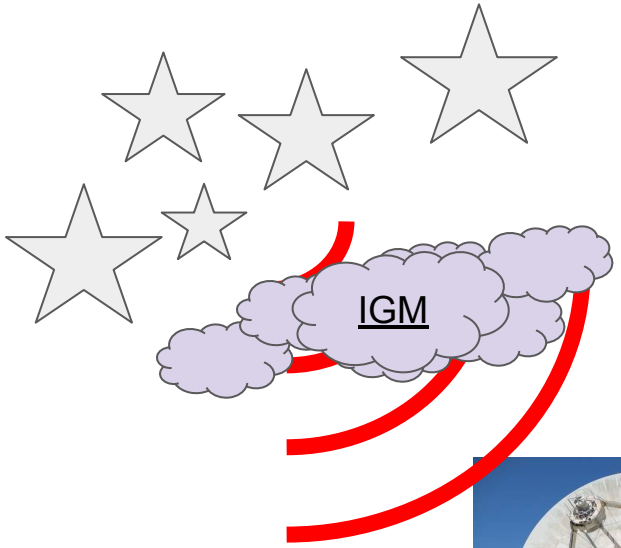


International station

Station configurations	Number of stations	LBA dipoles	HBA tiles	Signal paths	Min. baseline (m)	Max. baseline (km)
Superterp	6	2 × 48	2 × 24	96	68	0.24
NL Core Stations	24	2 × 48	2 × 24	96	68	3.5
NL Remote Stations	16	2 × 48	48	96	68	121.0
International Stations	8	96	96	192	68	1158.0

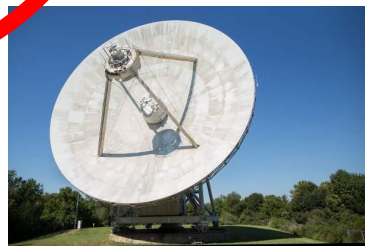
Stations:
24 core
14 remote
14 international
+2 in construction

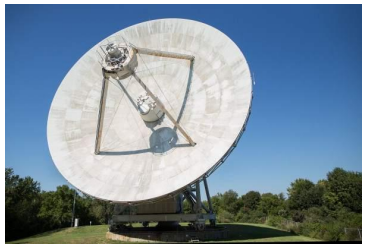
The inverse problem of interferometry: the "truth"



Signal from entire sky is measured

...affected by IGM…





North Liberty telescope image source: https://www.thegazette.com/2013/10/08/north-liberty-telescope-peers-into-deep-space

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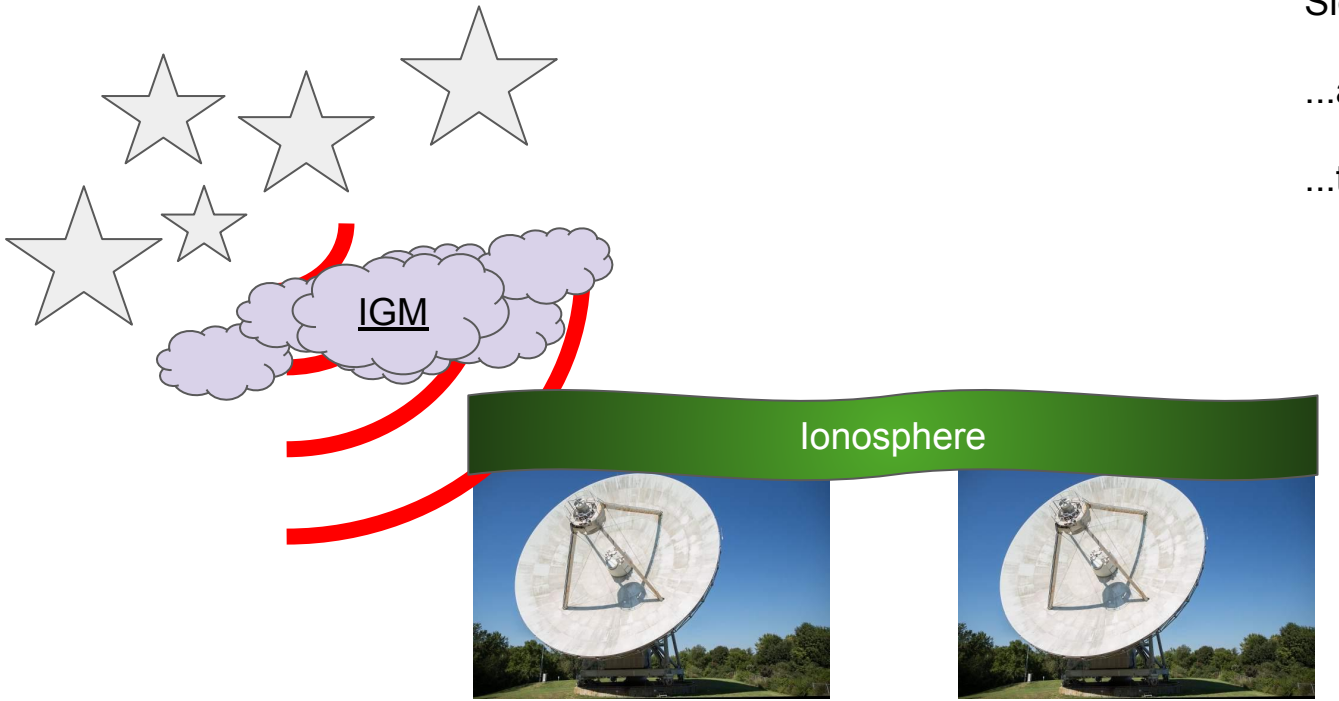

Signal from entire sky is measured

...affected by IGM…

...the impact of the Ionosphere…

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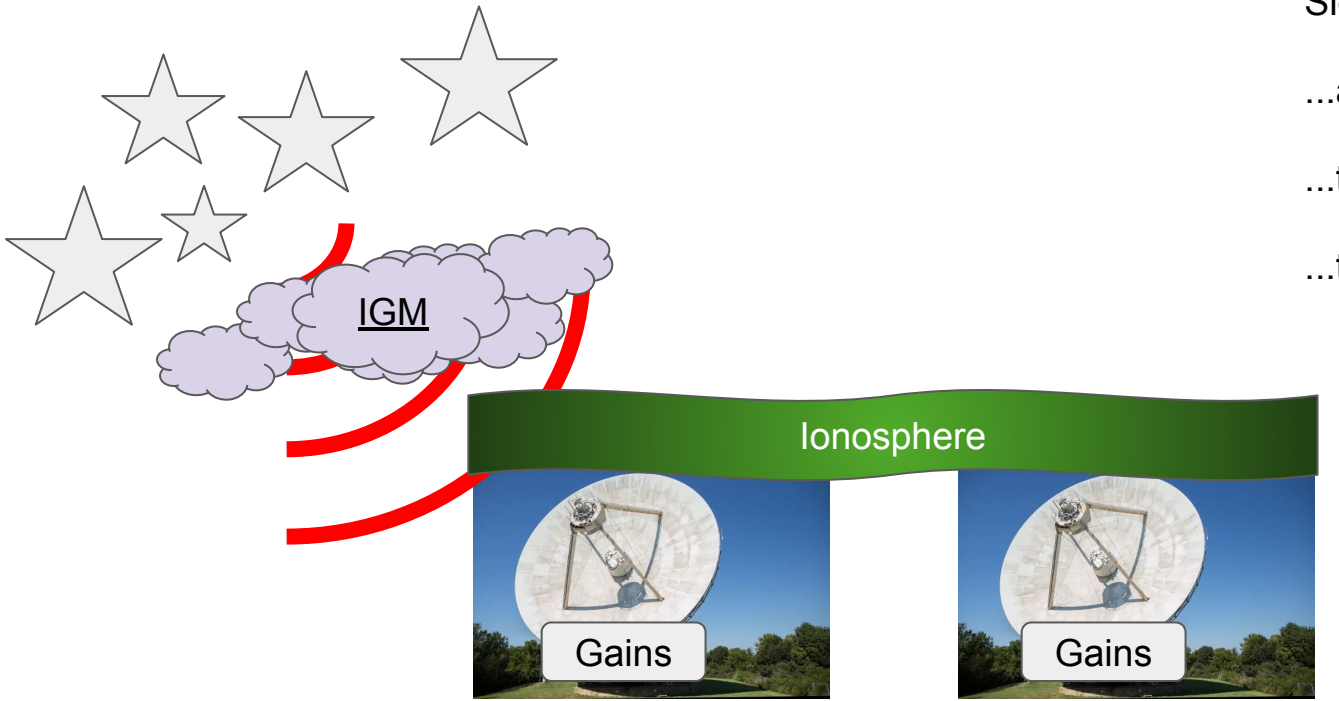

Signal from entire sky is measured

...affected by IGM…

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...the antenna gains…

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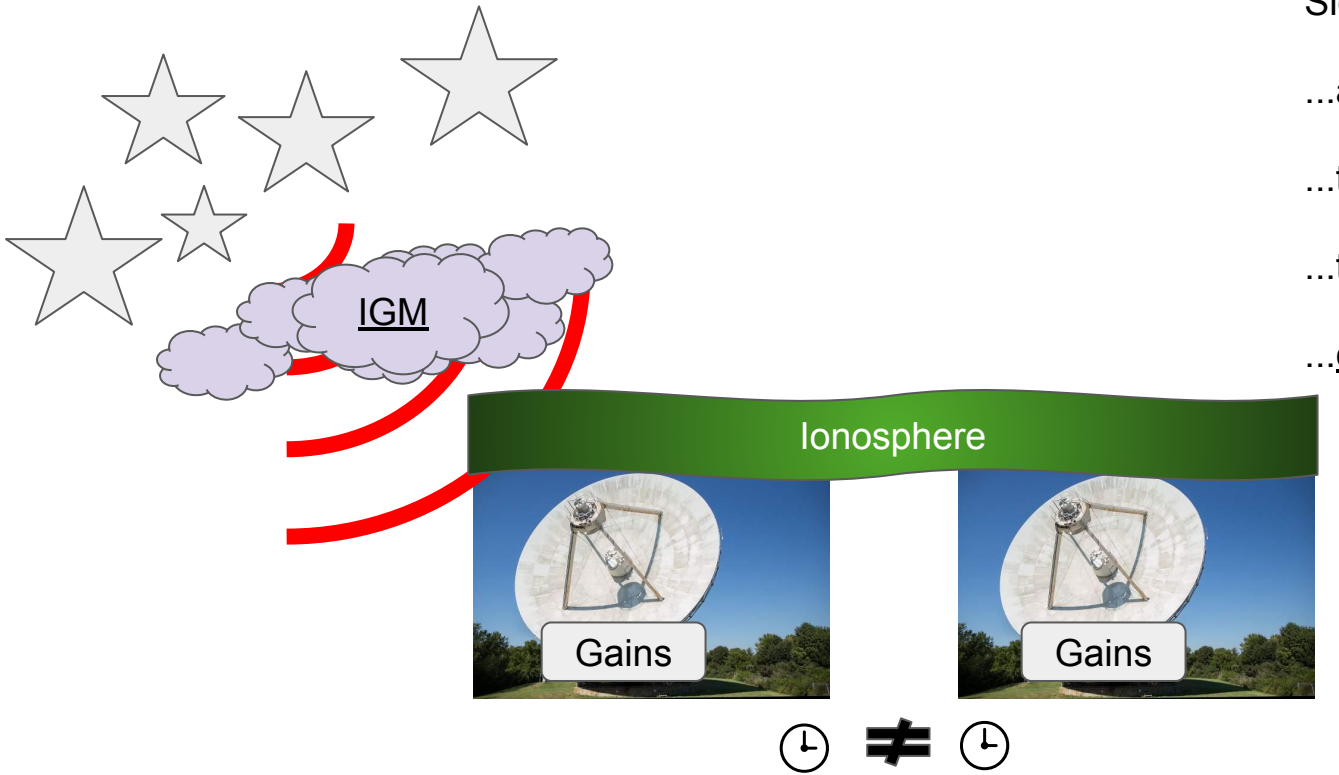


Signal from entire sky is measured

...affected by IGM…

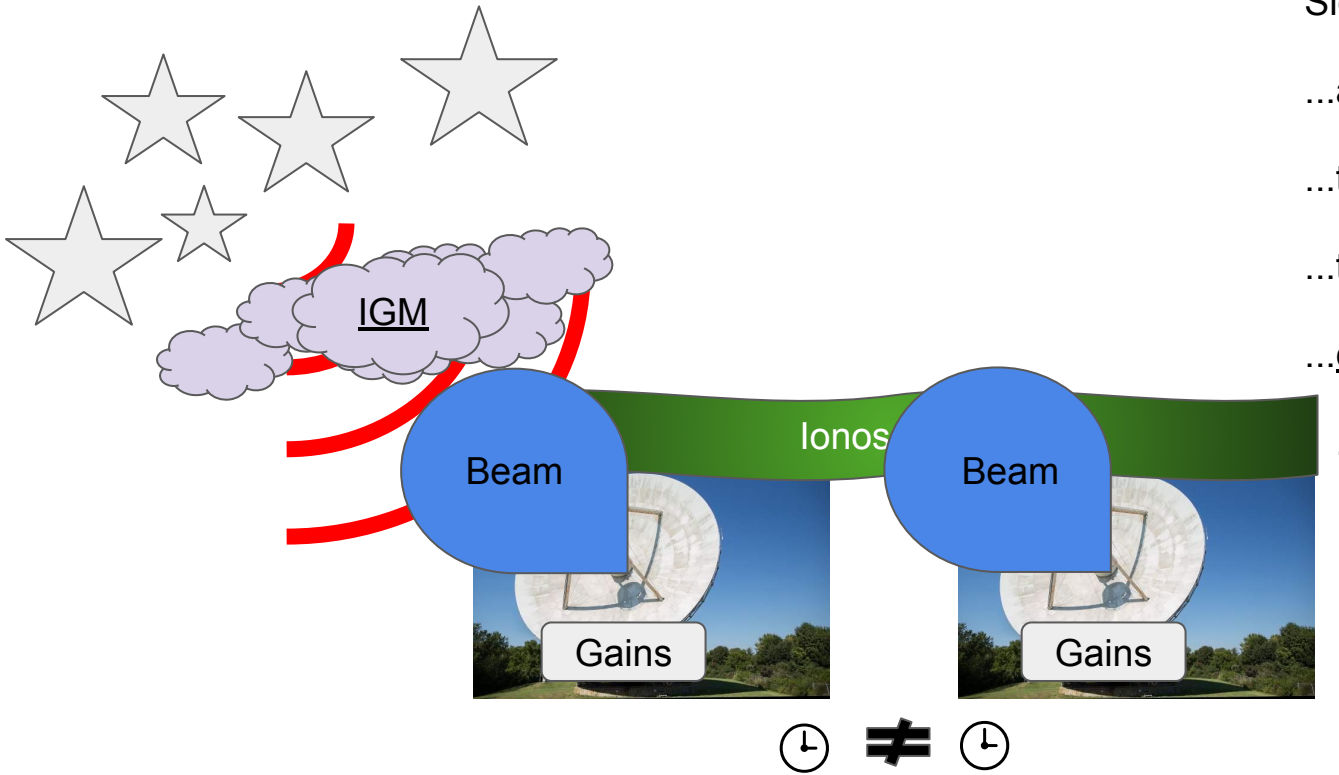
...the impact of the Ionosphere…

...the antenna gains…

...clock errors between stations...

North Liberty telescope image source: https://www.thegazette.com/2013/10/08/north-liberty-telescope-peers-into-deep-space

The inverse problem of interferometry: the "truth"



Signal from entire sky is measured

...affected by IGM…

...the impact of the Ionosphere…

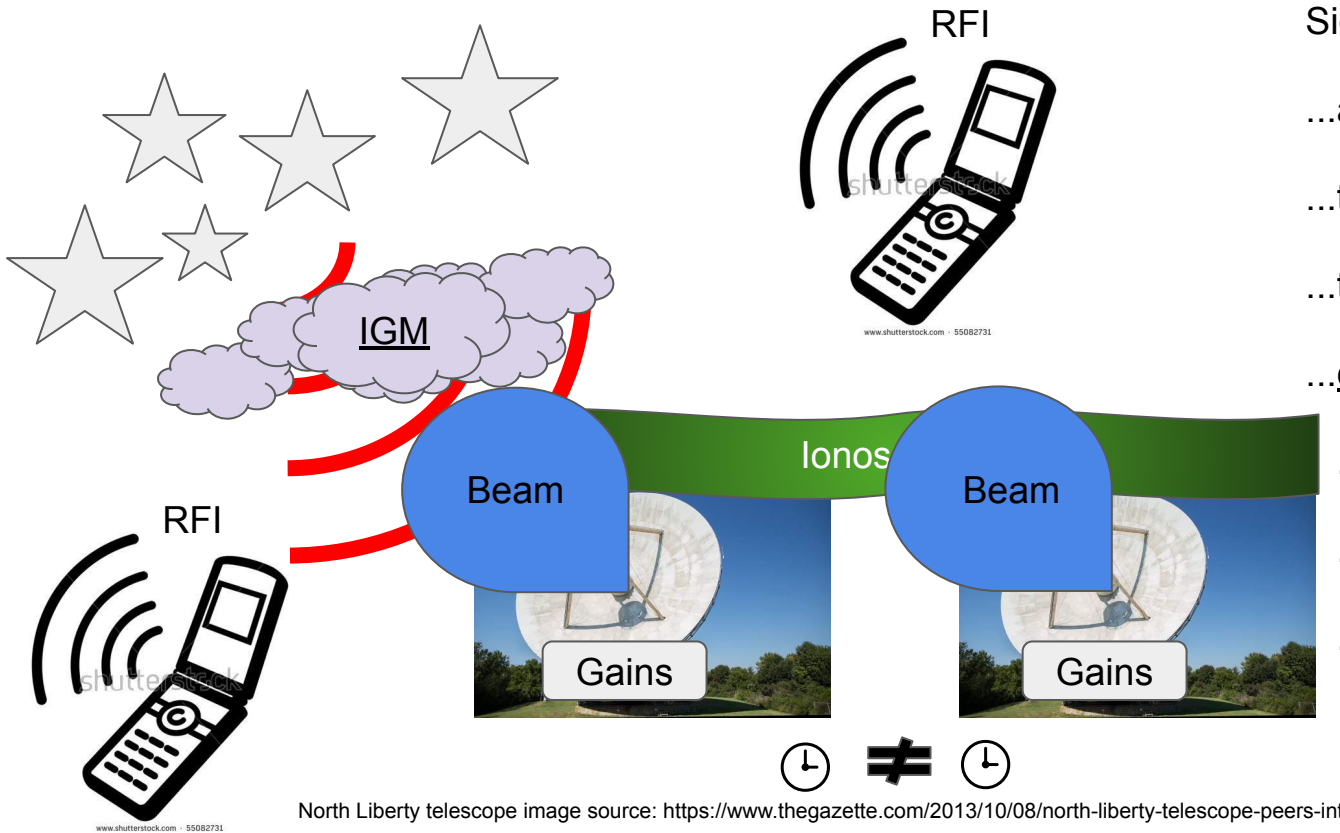
...the antenna gains…

...clock errors between stations…

...antenna beam…

North Liberty telescope image source: https://www.thegazette.com/2013/10/08/north-liberty-telescope-peers-into-deep-space

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……..

North Liberty telescope image source: https://www.thegazette.com/2013/10/08/north-liberty-telescope-peers-into-deep-space

Calibration

Measurements are voltages - not physical flux!

To correct, modern approach is Radio Interferometer's Measurement Equation:

$$\mathbf{V}_{pq} = \mathbf{G}_p \left(\sum_s \mathbf{E}_{sp} \mathbf{K}_{sp} \mathbf{B}_s \mathbf{K}_{sq}^H \mathbf{E}_{sq}^H \right) \mathbf{G}_q^H + \mathbf{N}$$

$$= \sum_s \mathbf{J}_{sp} \mathbf{B}_s \mathbf{J}_{sq}^H + \mathbf{N}$$

(cf. Smirnov 2011 and associated papers)

which implies assuming that measured voltage is linear function of sky signal. All above are 2x2 complex-valued matrices: calibration consists of **solving for $\mathbf{J}_{sp}$**.

Calibration

Fourier sampling with baseline *pq*, direction s

Noise

Measurements are voltages - not physica ux!

To correct, modern approach is Radio Inte erome r's Measuremen quation:

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Brightness in direction *s*

which implies assuming that measured voltage ction of sky signal. All above are 2x2 complex-valued matrices: calib s of **solving for $\mathbf{J}_{sp}$**.

Calibration

Measurements are voltages - no

To correct, modern approach is Radic nterferometer's easuremen quation:

Direction-dependent effects acting on antennas *p* and *q*

Noise

$$\mathbf{V}_{pq} = \mathbf{G}_p \left(\sum_s \mathbf{E}_{sp} \mathbf{K}_{sp} \mathbf{B}_s \mathbf{K}_{sq}^H \mathbf{E}_{sq}^H \right) \mathbf{G}_q^H + \mathbf{N}$$

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Brightness in direction *s*

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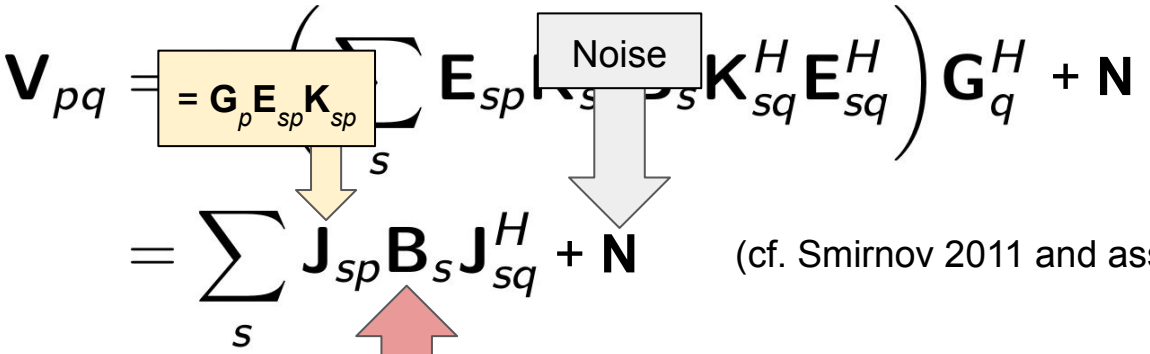


(cf. Smirnov 2011 and associated papers)

which implies assuming that measured voltage is linear function of sky signal. All above are 2x2 complex-valued. Calibration consists of **solving for $\mathbf{J}_{sp}$**.

Generational Calibration

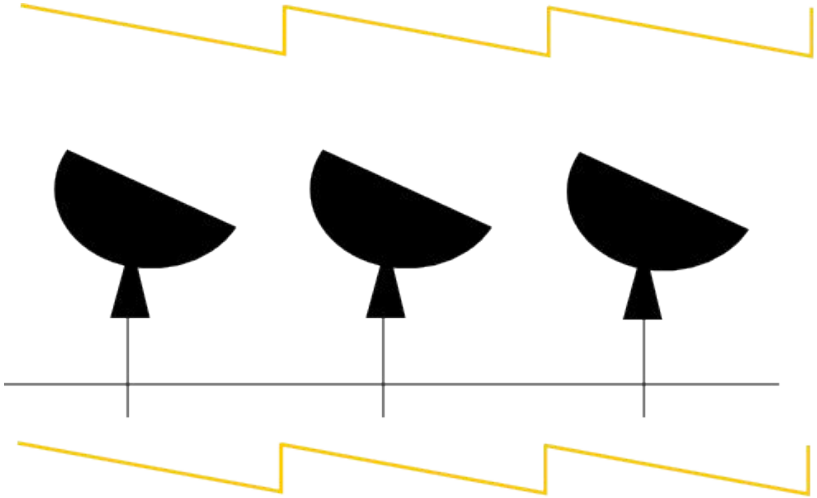
Very(!) roughly:

- 1GC, in the words of Jan Noordam, is comparing the signal of each baseline to the signal from a known source (the calibrator).

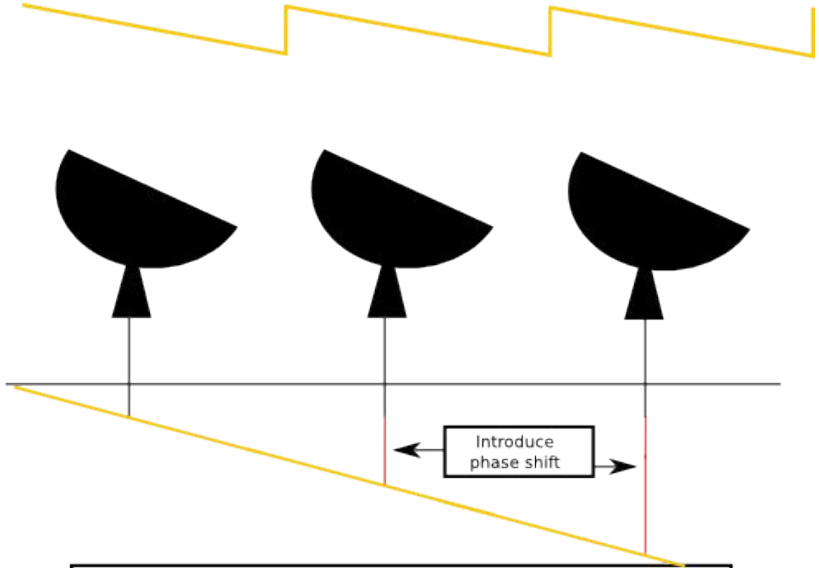
- 2GC is self-calibration: post-processing adaptive optics.

- 3GC is the above with direction-dependent effects taken into account.

Self-calibration as Adaptive Optics

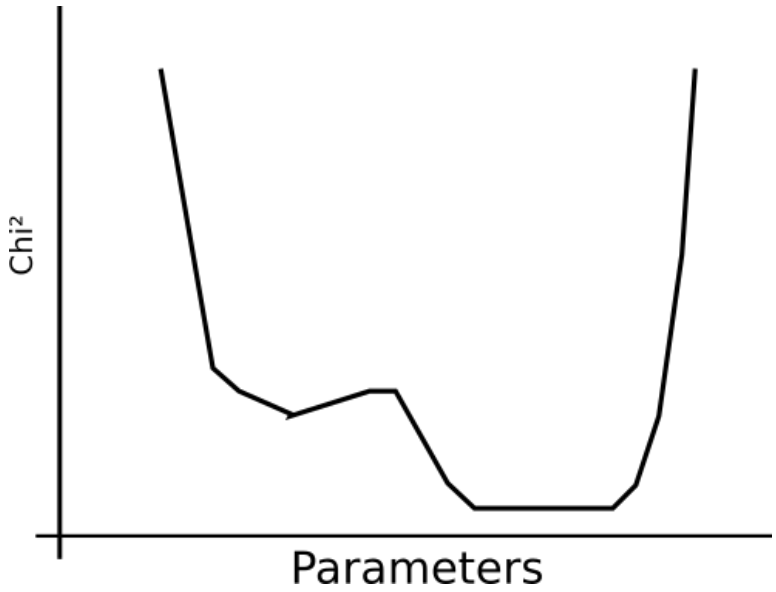


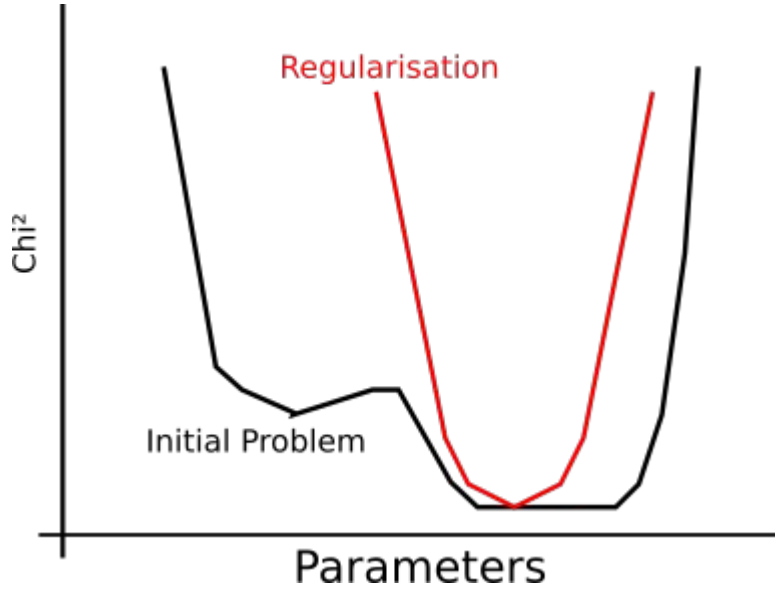
Phase Errors Remain



Signal hits all antennas simultaneously

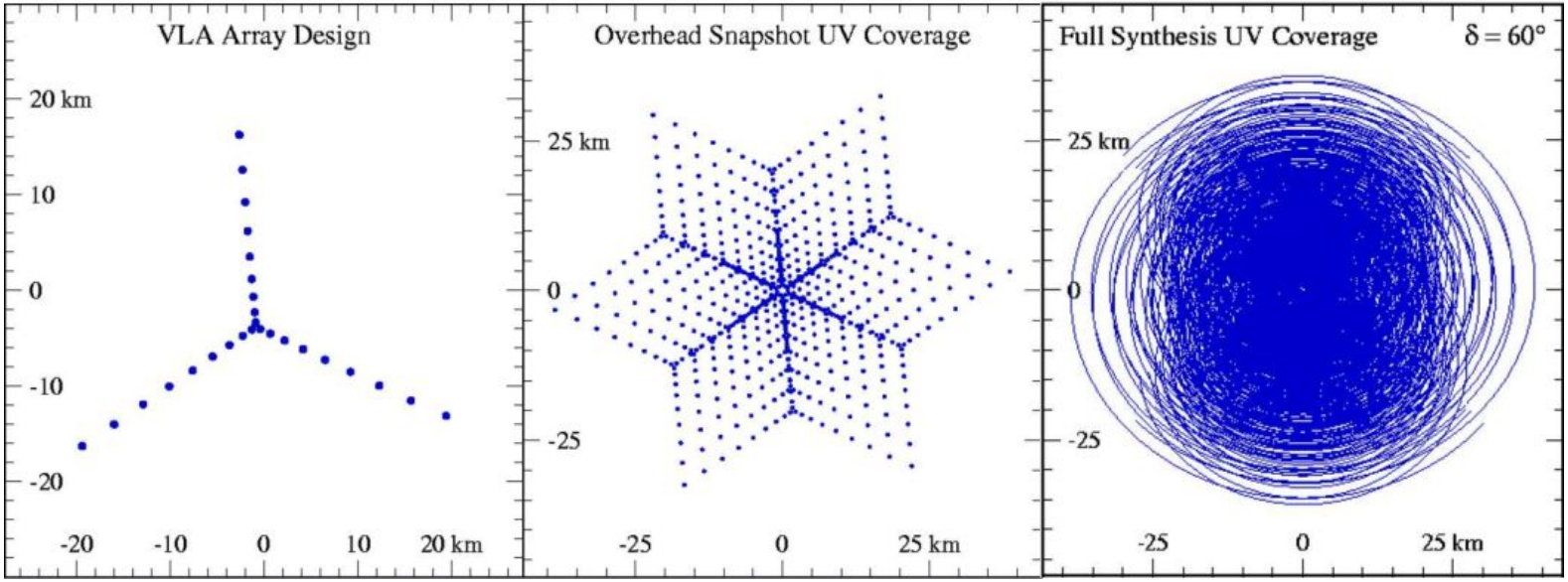
Conditioning & Regularisation





Inverse problem: not convex, poorly-conditioned → **regularise**

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 - > more complex fields
- Better sensitivity -> more complex fields

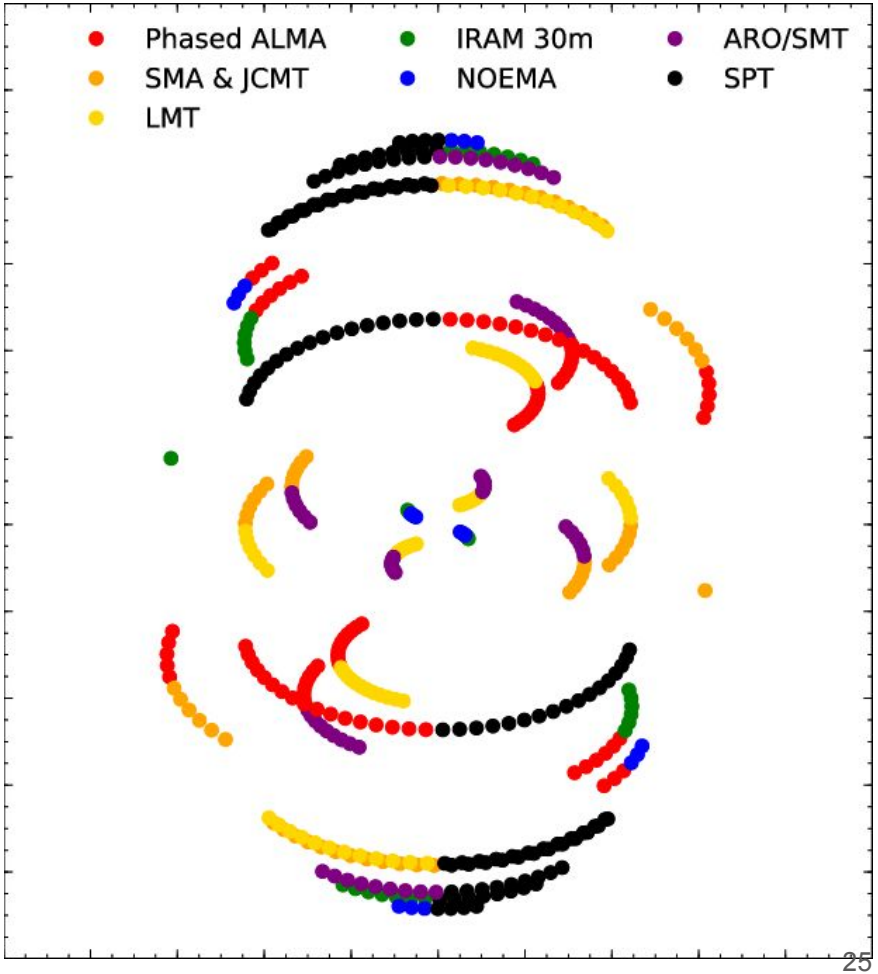
VLBI inverse problem

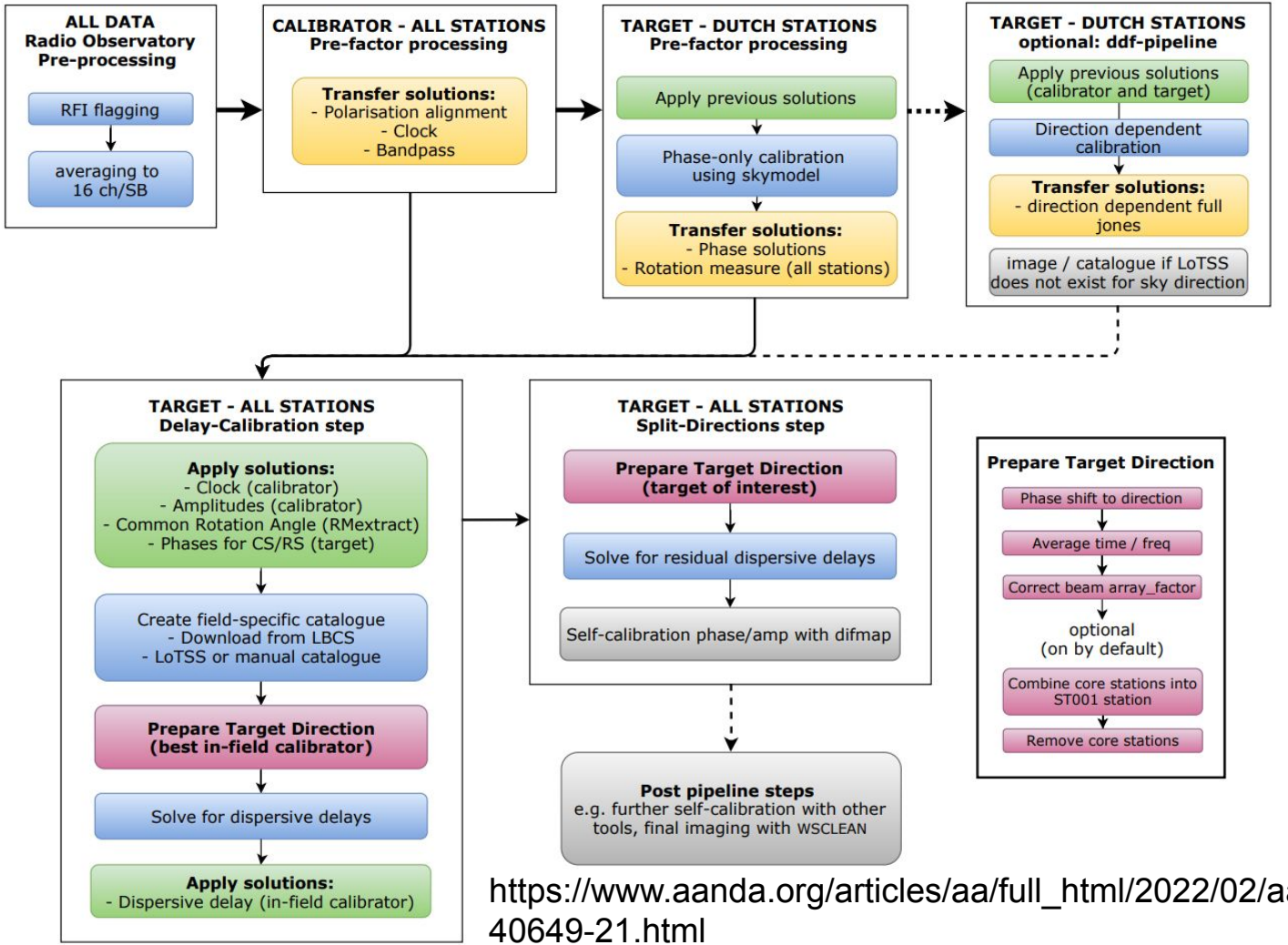
Pros:

- 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)

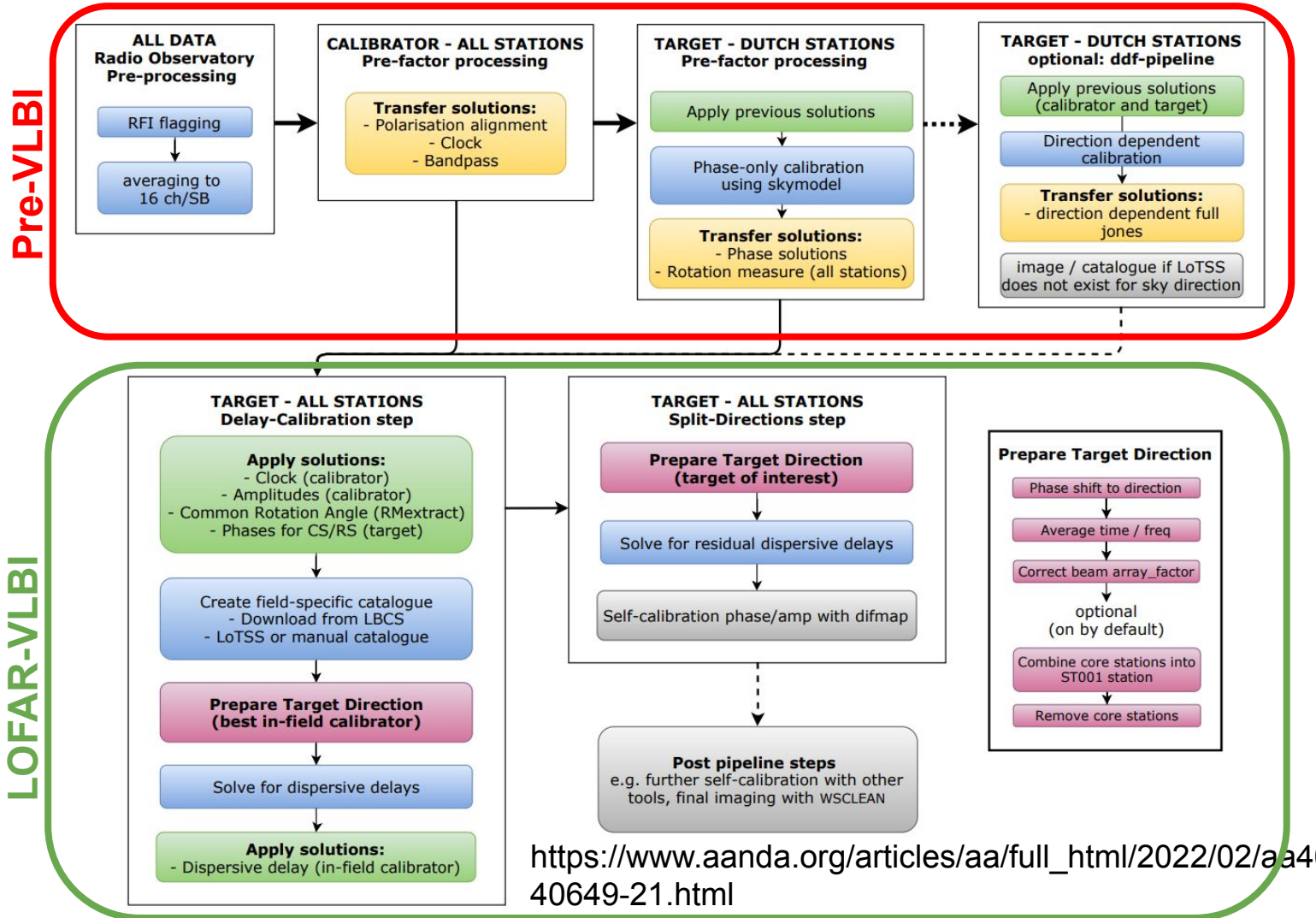
Cons:

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





https://www.aanda.org/articles/aa/full_html/2022/02/aa40649-21/aa40649-21.html



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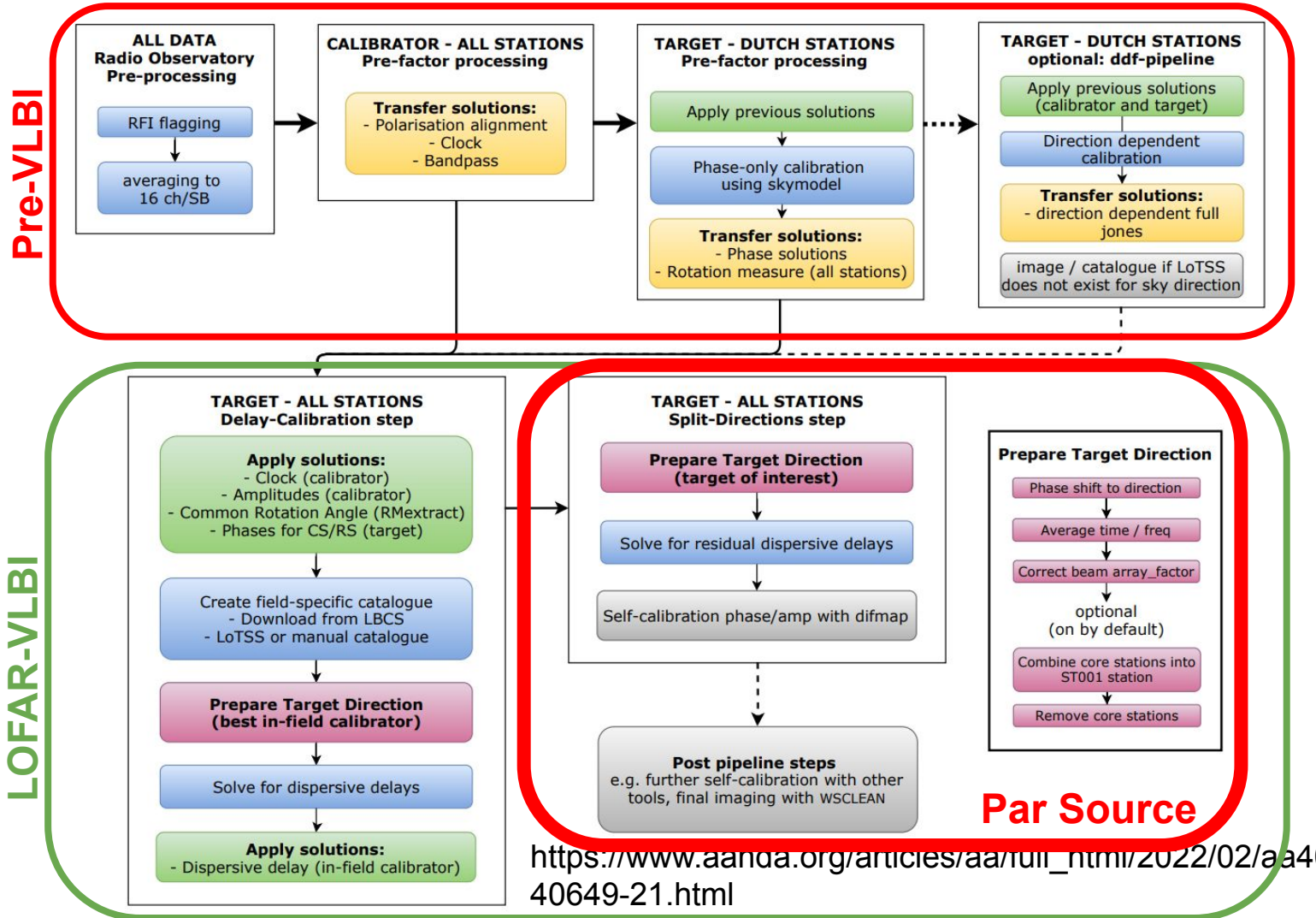
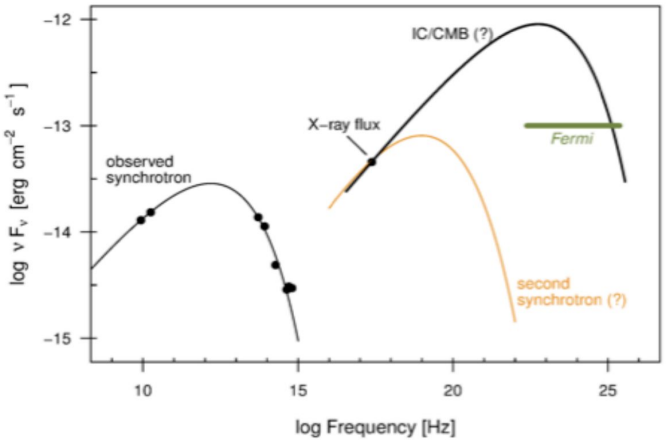


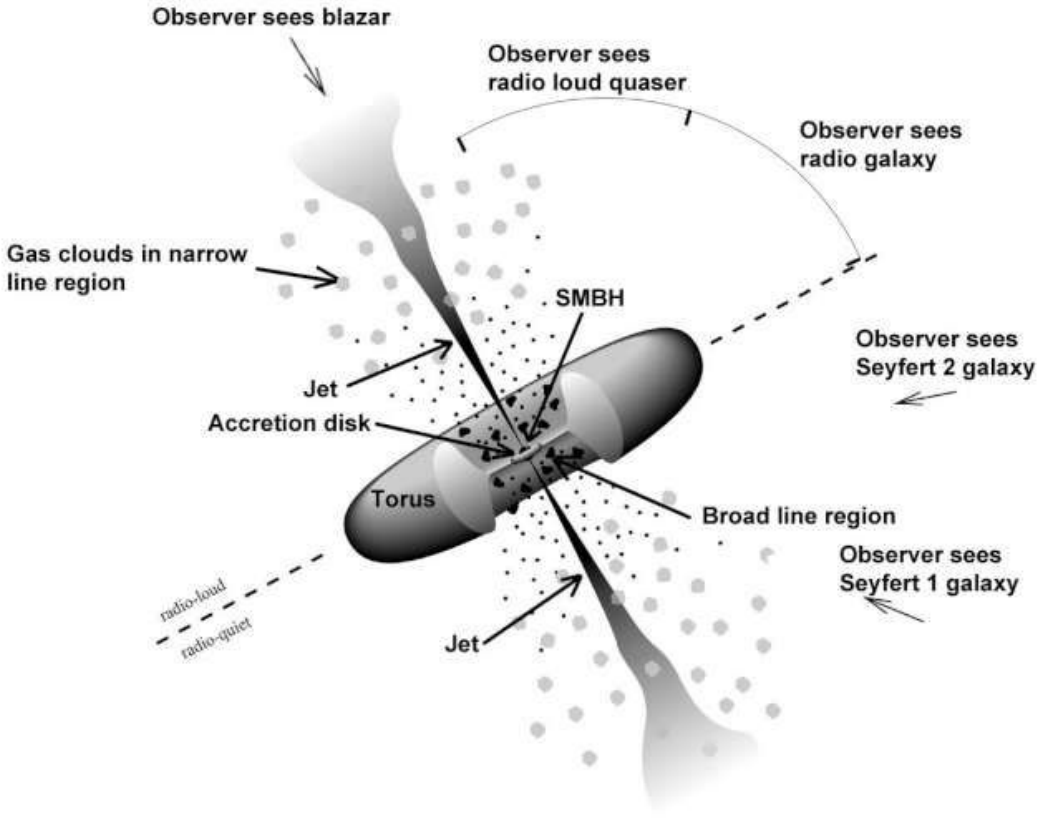
https://www.aanda.org/articles/aa/full_html/2022/02/aa40649-21/aa40649-21.html

Blazars

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



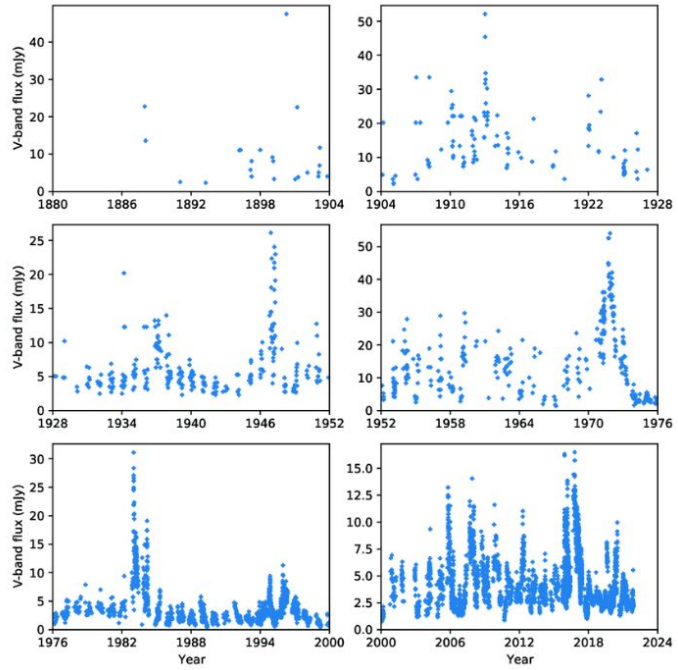
SED for PKS 0637-752 *Perlman et al. (2019)*

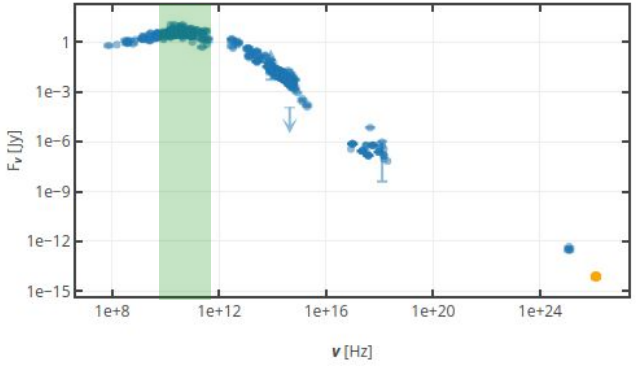


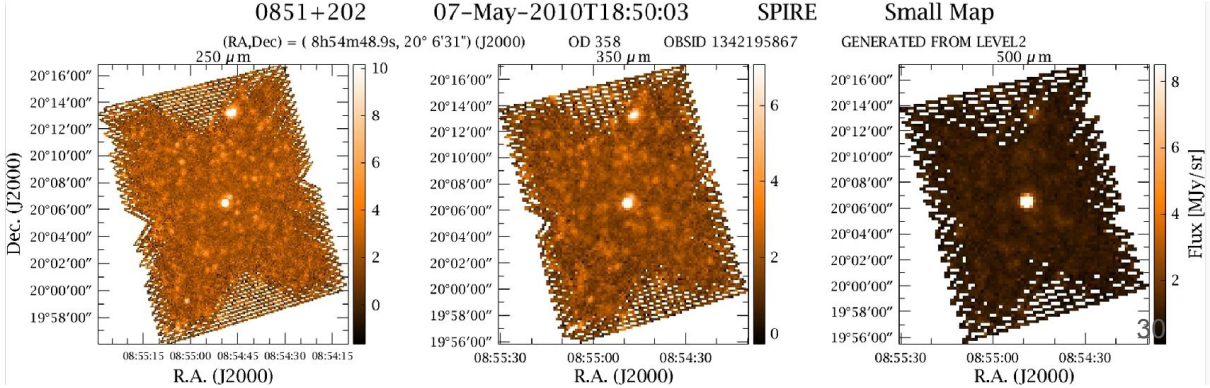
https://fermi.gsfc.nasa.gov/science/eteu/agn/

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!

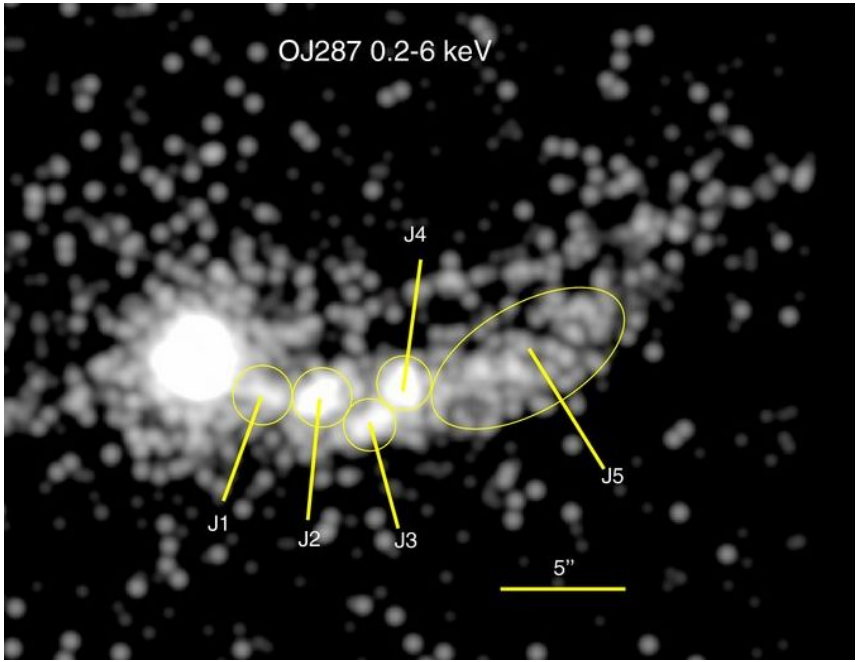


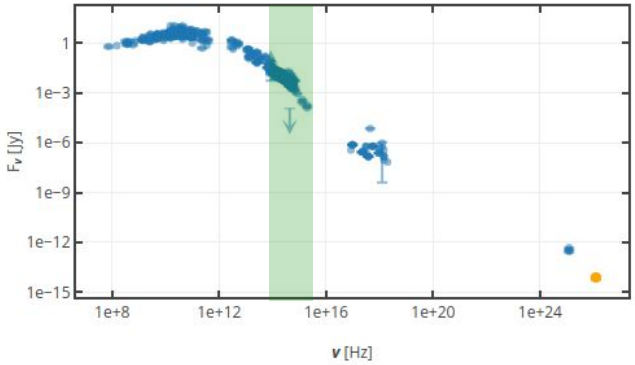




OJ287 in X-rays

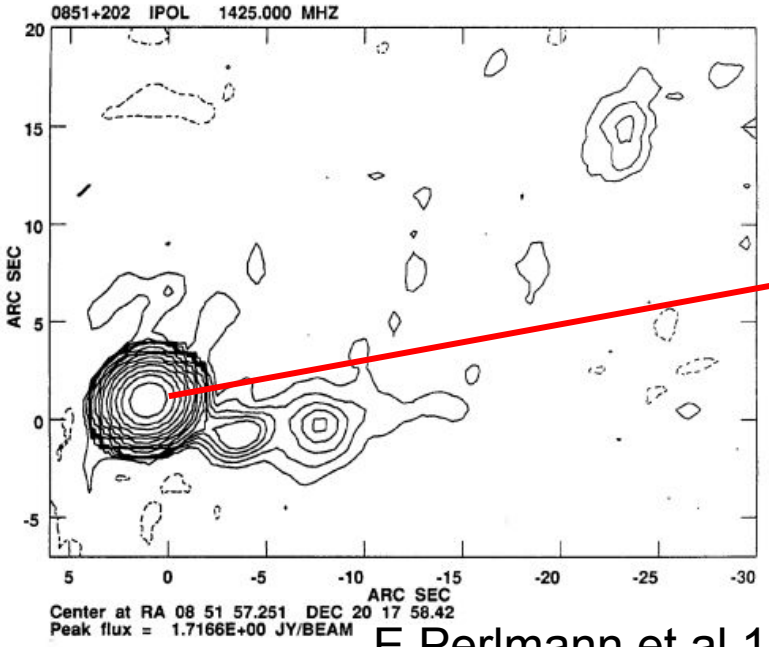
- X-ray emission from core consistent with FR-I AGN (A. Marscher 2011)
- Unusual: Mpc-scale X-ray jet!
- Multiple knot features detected
- Question: synchrotron or IC/CMB?



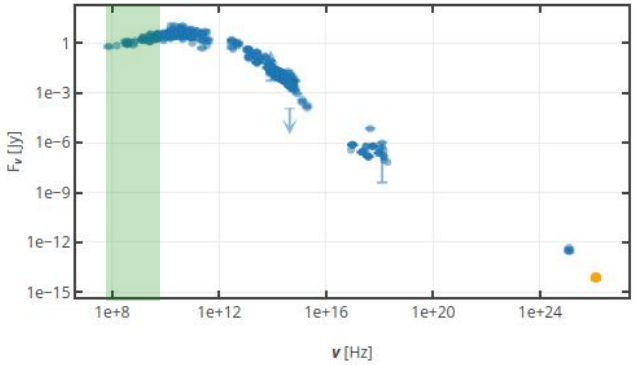


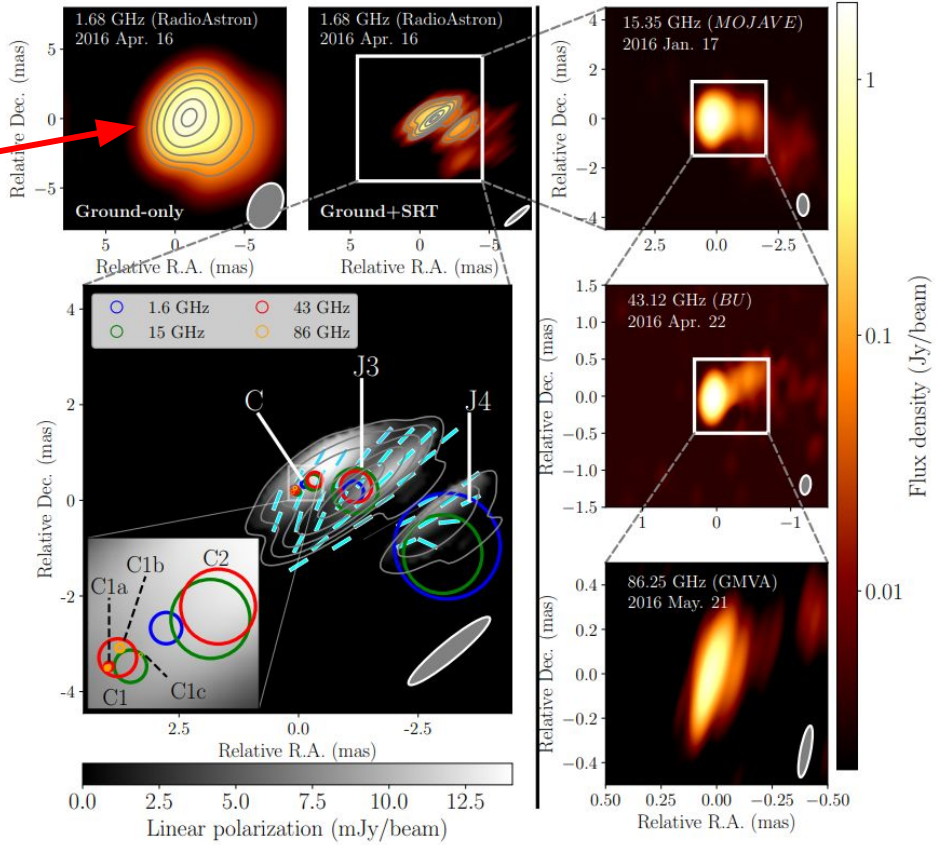
- Estimate of B-field ~ 5 microG, minimum e^- energy 7-40 $m_e c^2$, doppler factor ~8 at J2
- Jet bent consistent with standing shocks inclined by ~7deg to jet axis

OJ287 in radio



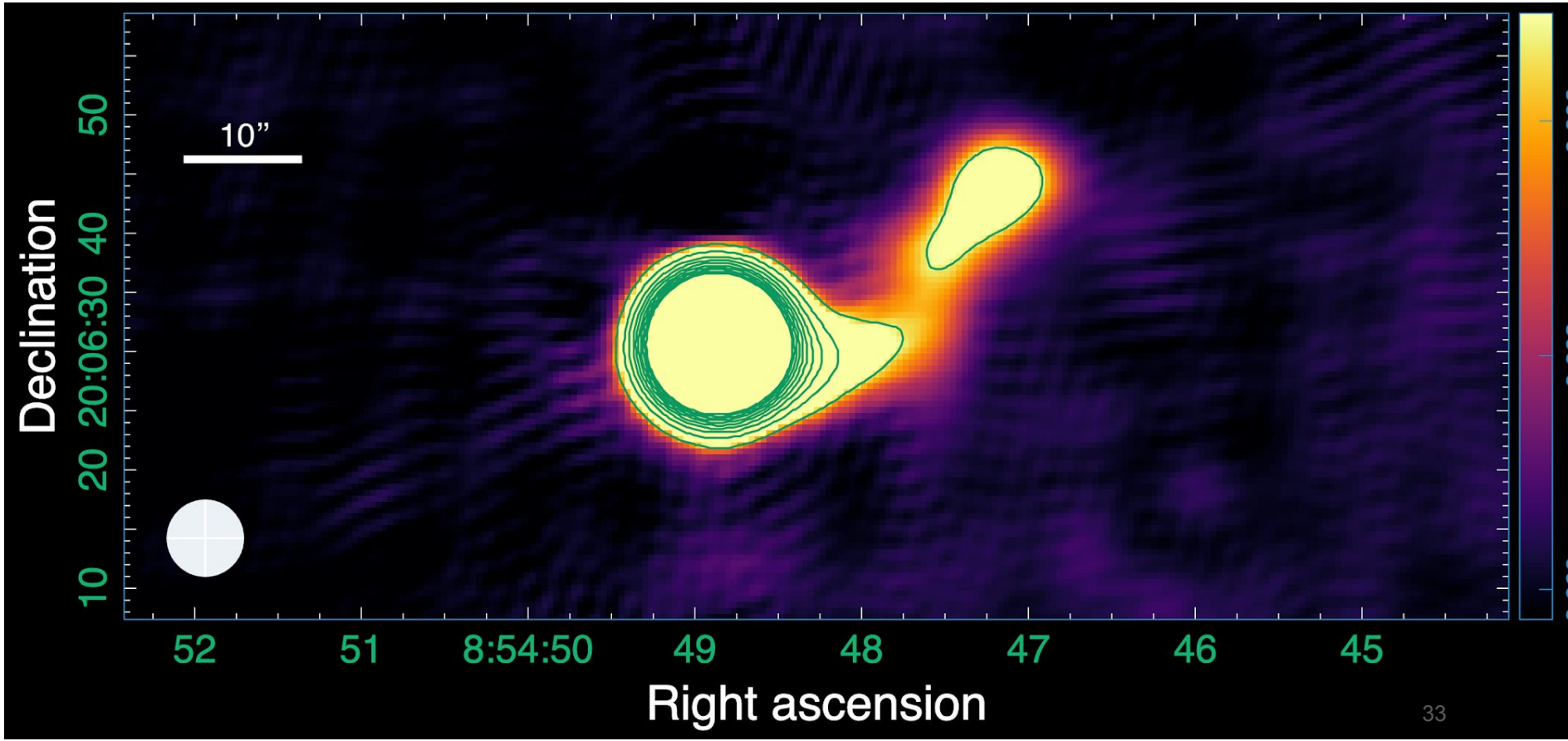
E Perlmann et al 1994





Ilje Cho et al 2024

LOFAR-VLBI: resolving structure



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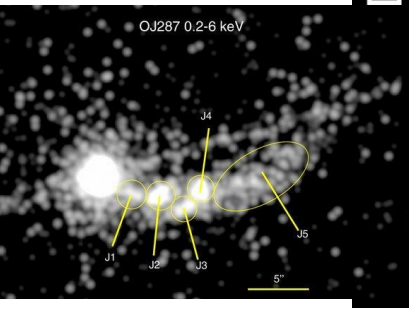
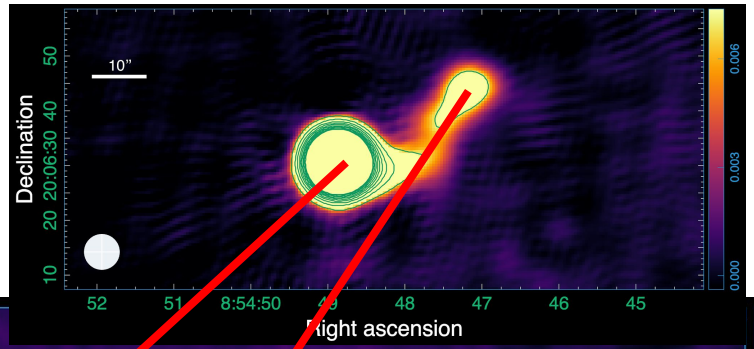
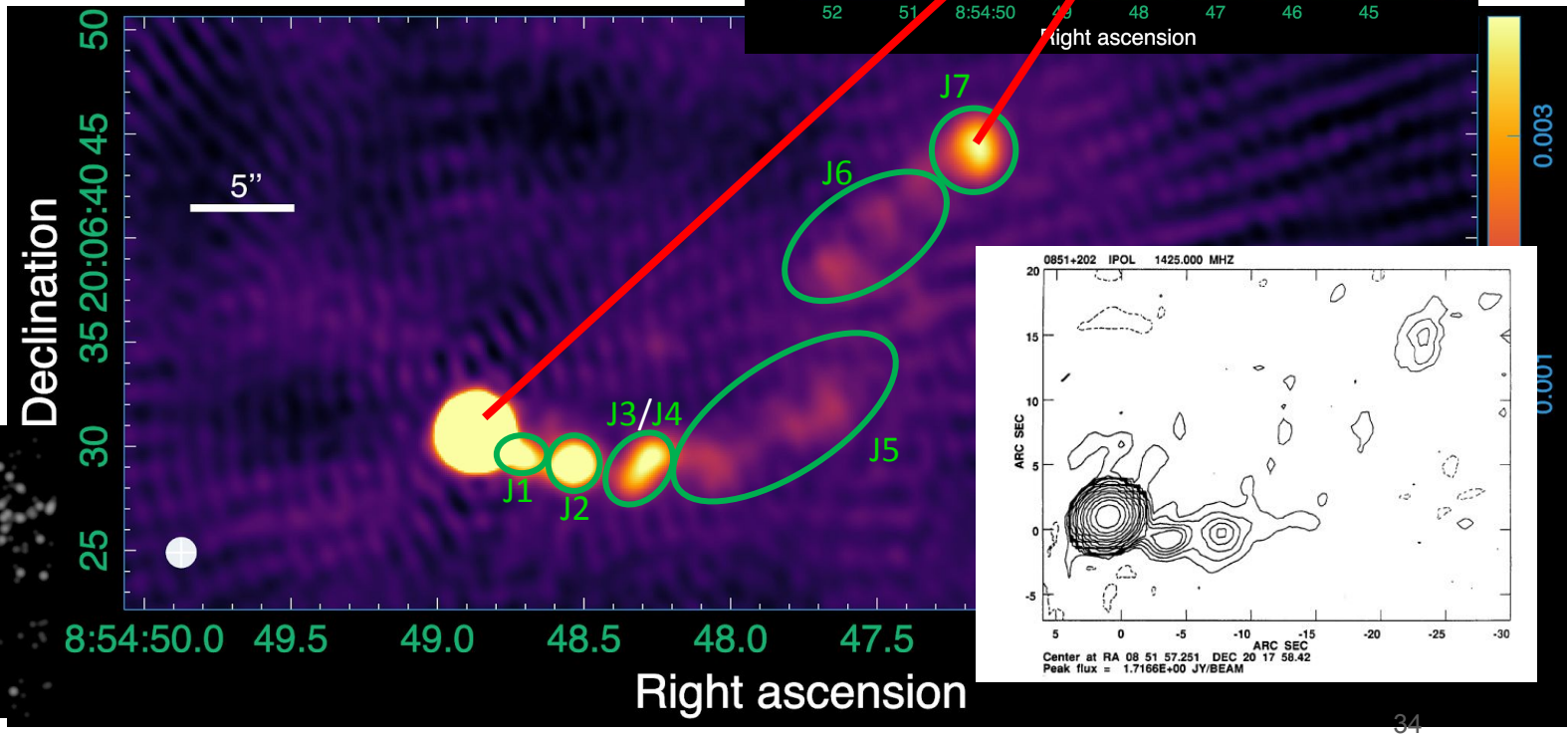
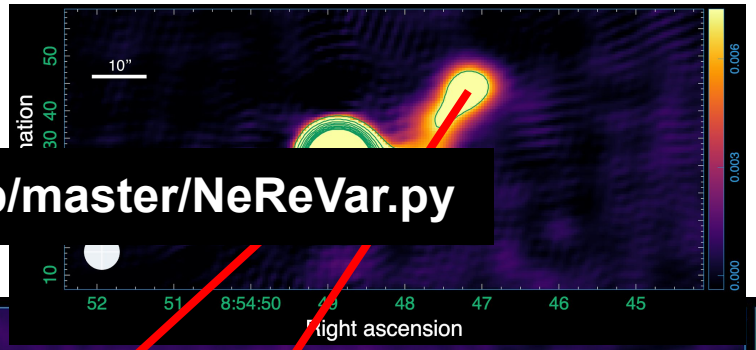


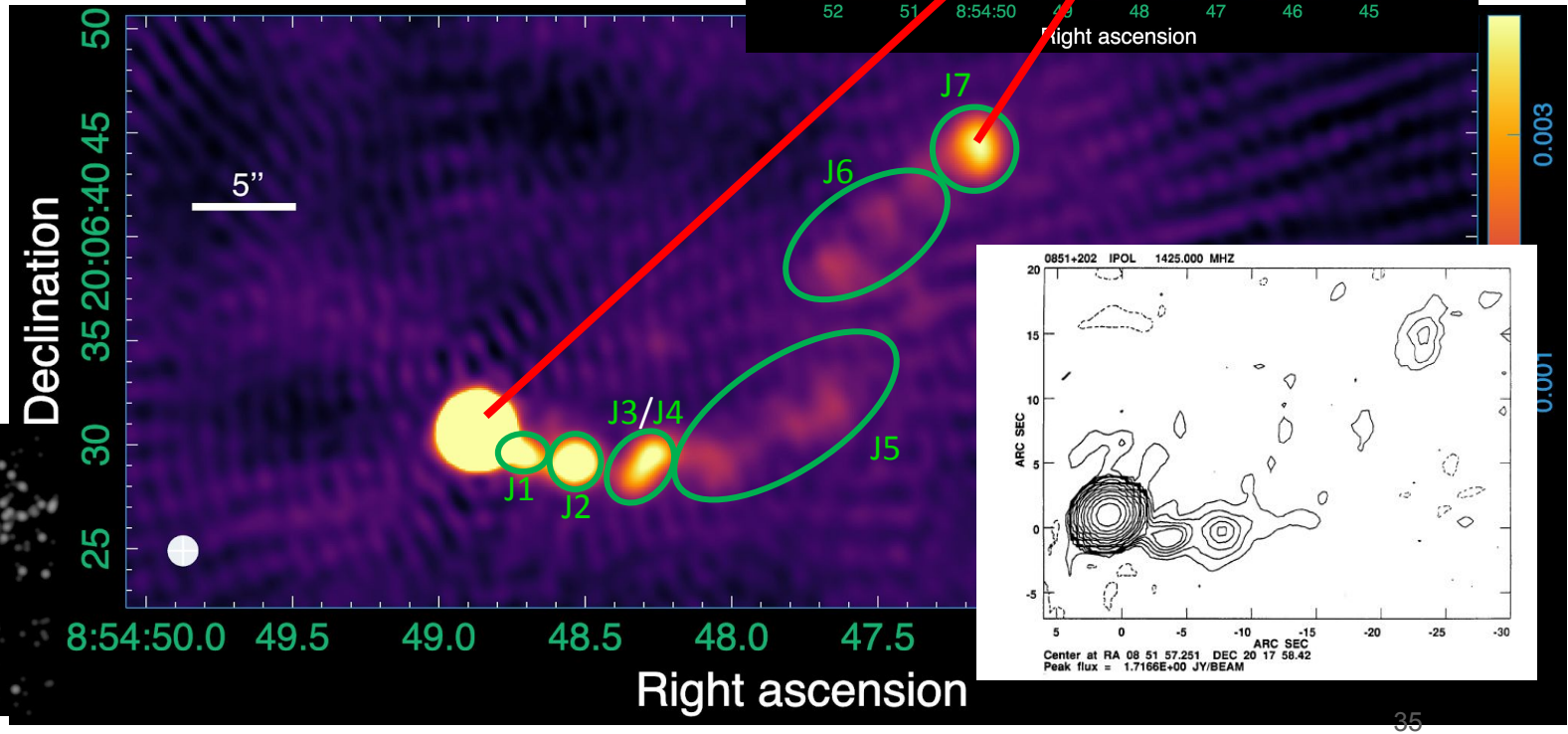


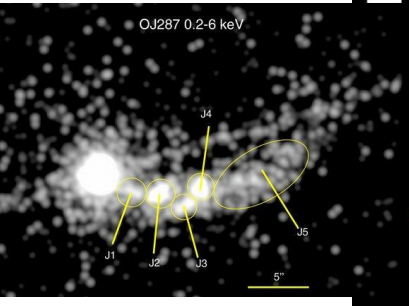


LOFAR-VLBI: resolving structure

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

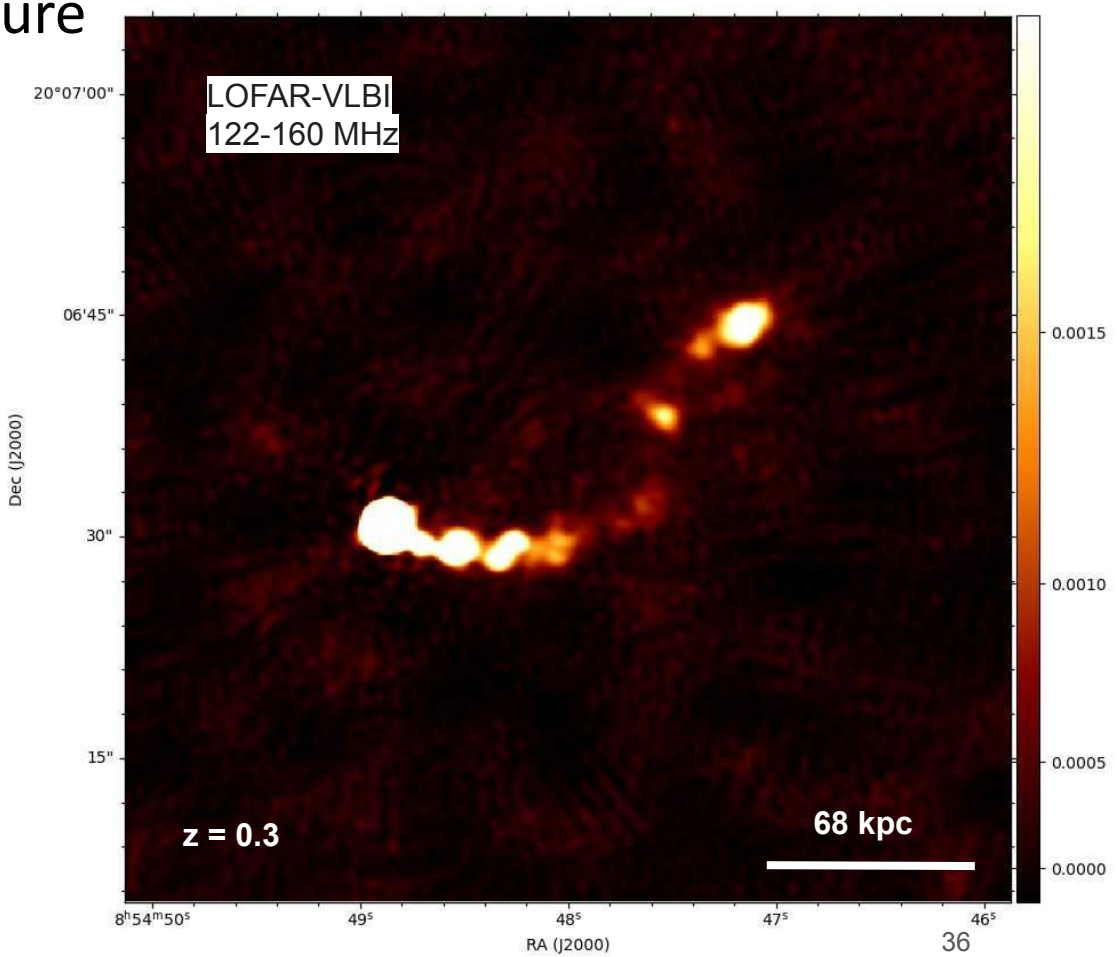






LOFAR-VLBI: resolving structure

- 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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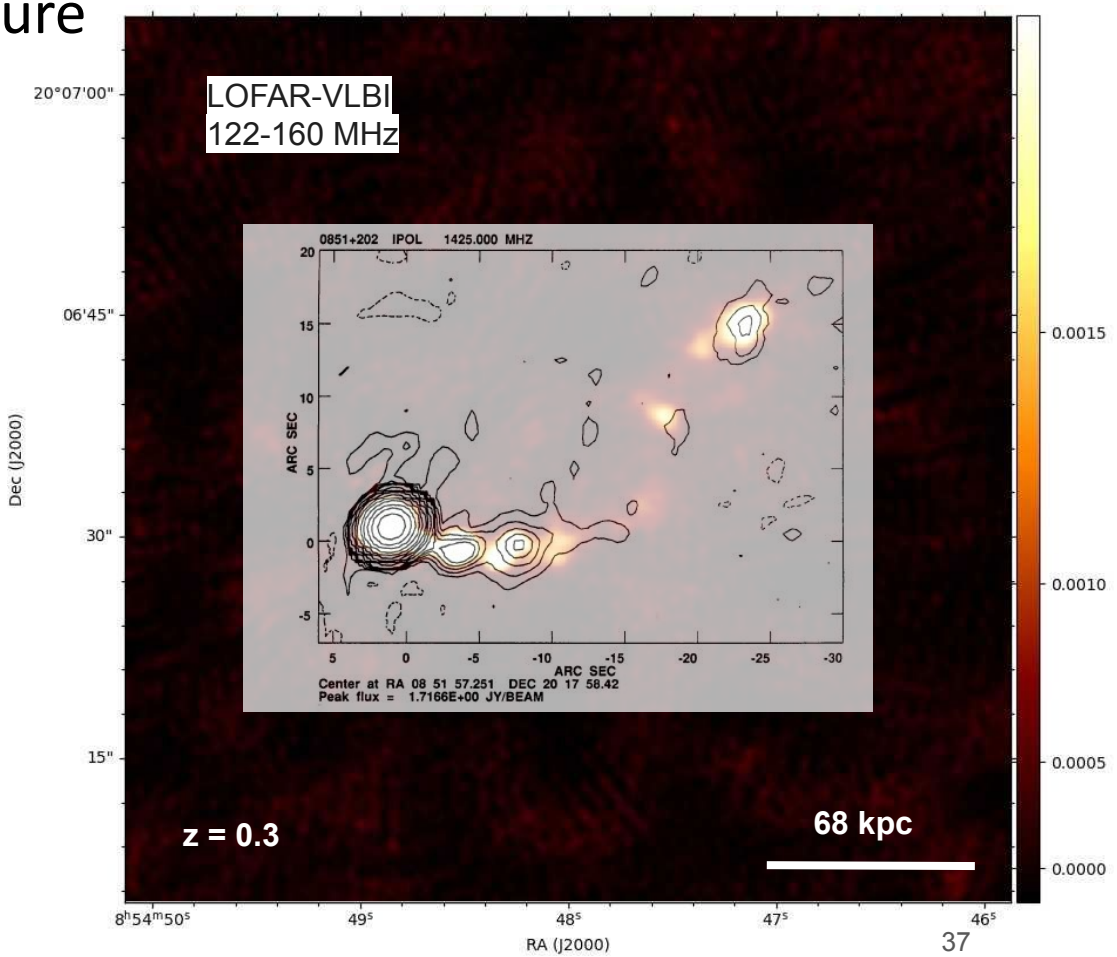

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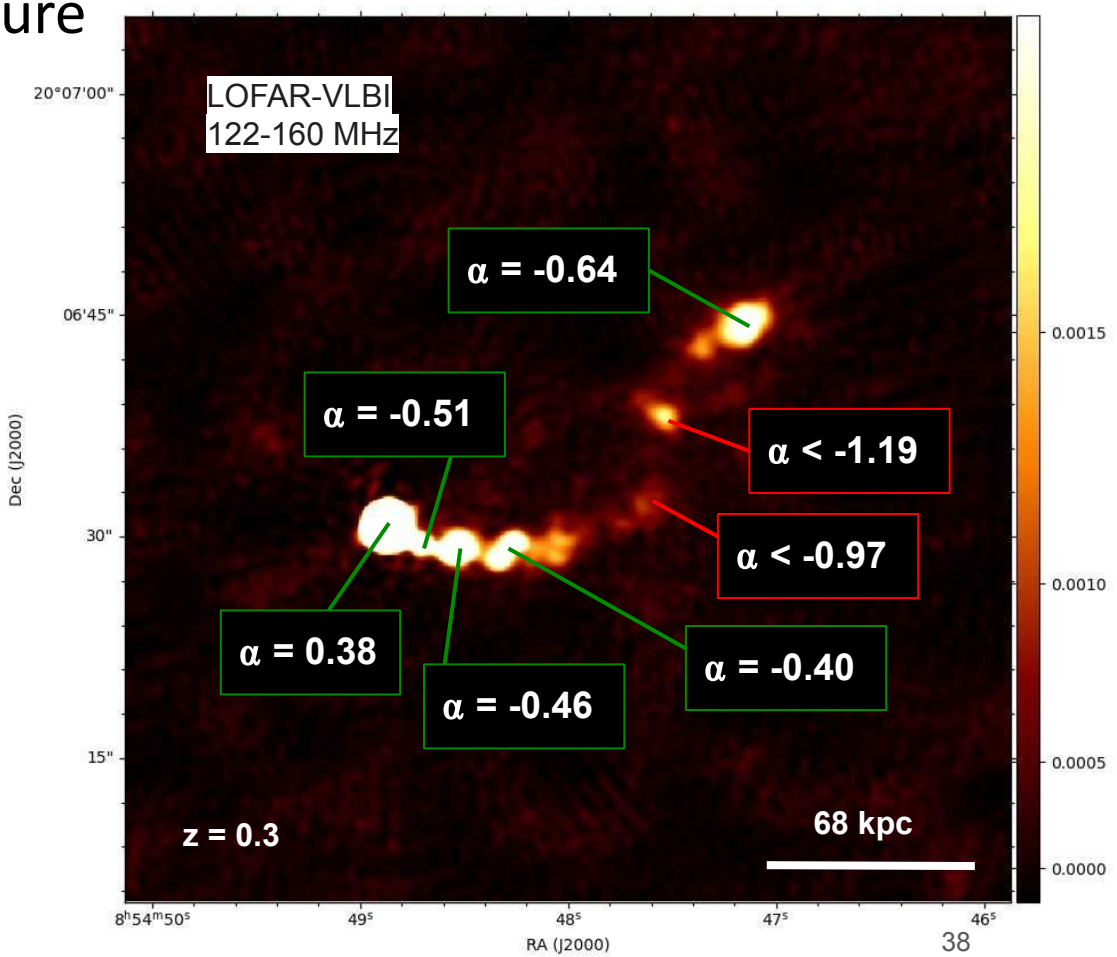
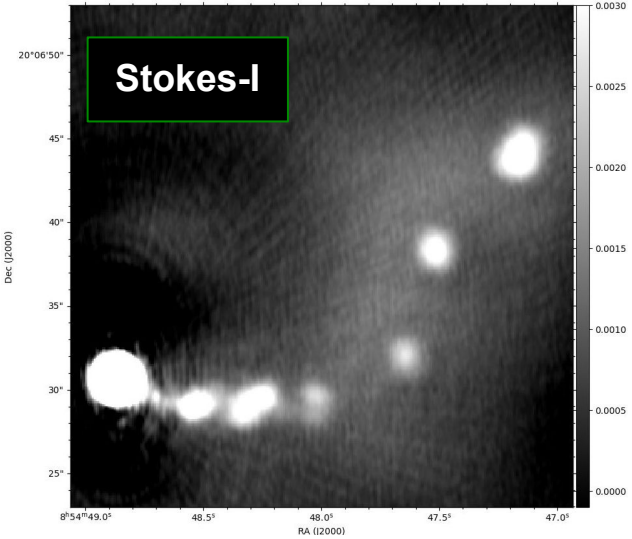
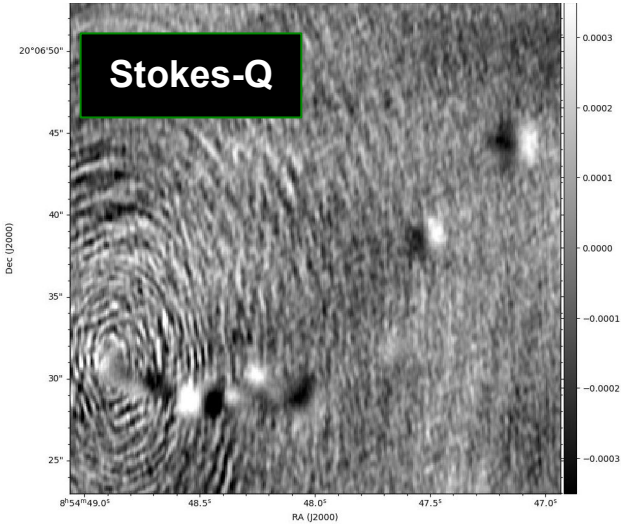
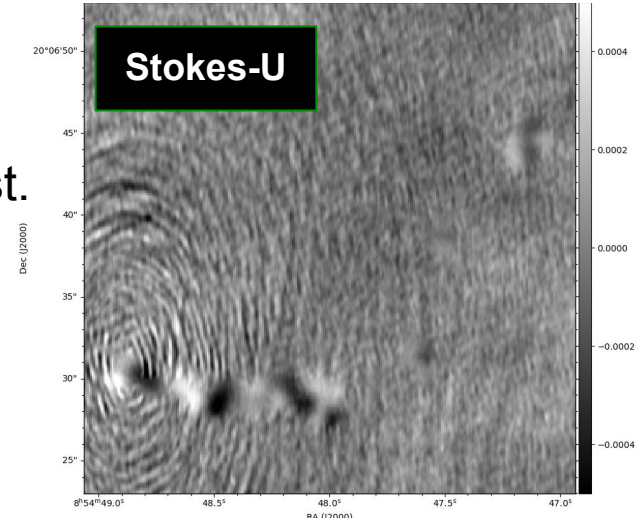


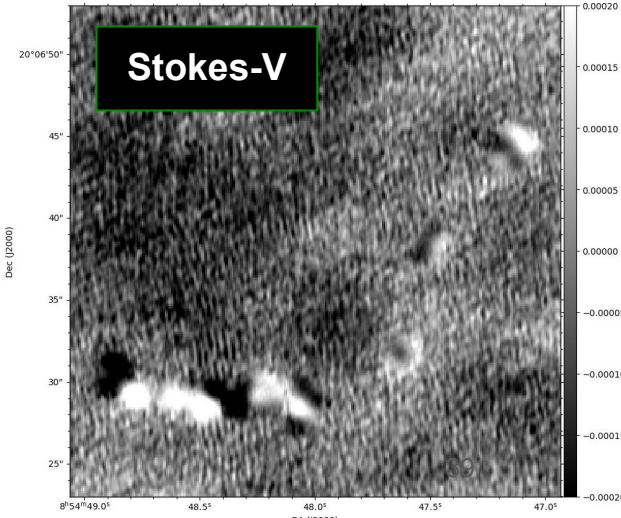
LOFAR-VLBI: 4-Stokes

- **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.





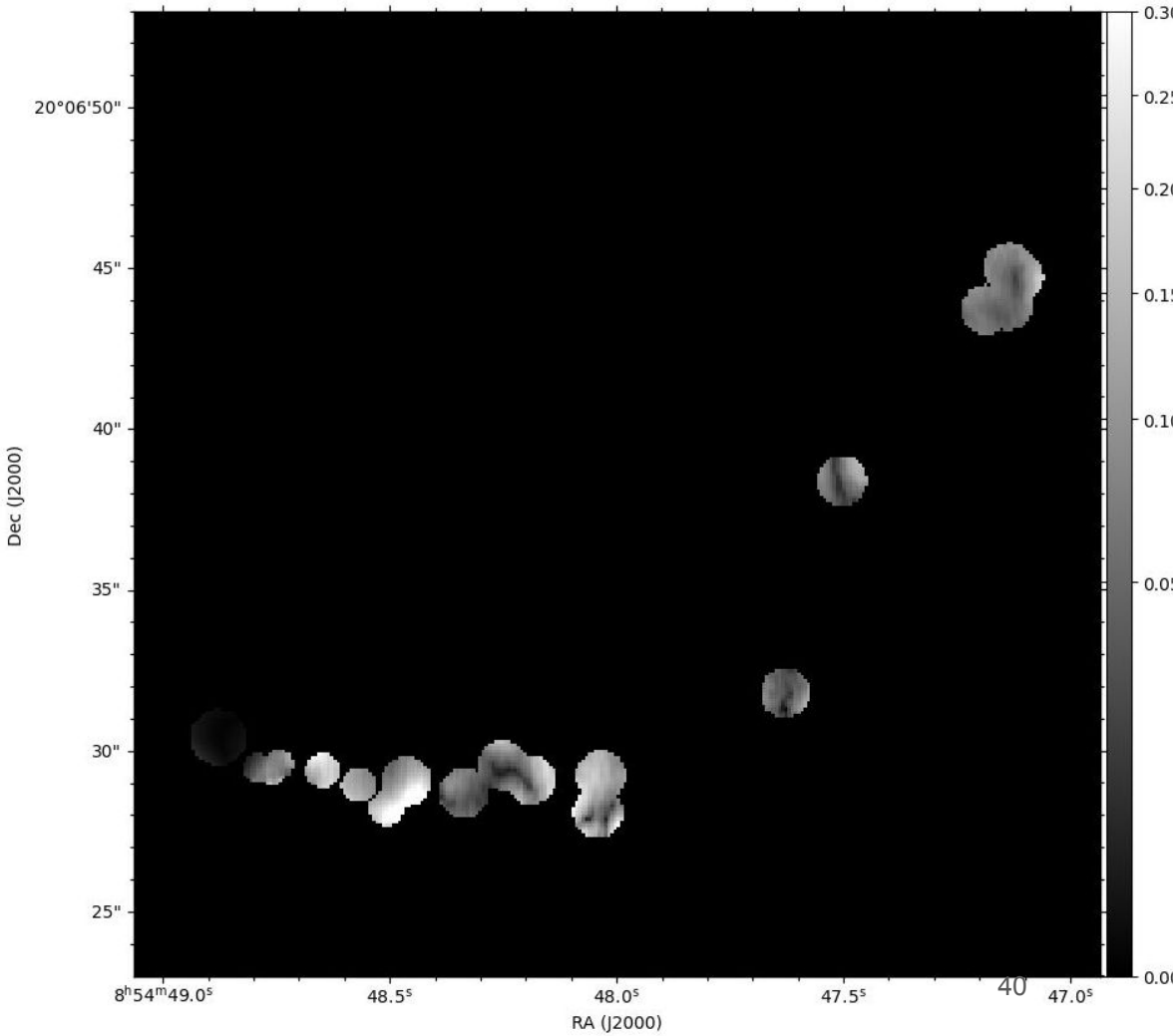




LOFAR-VLBI: Frac. pol.

- 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)

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

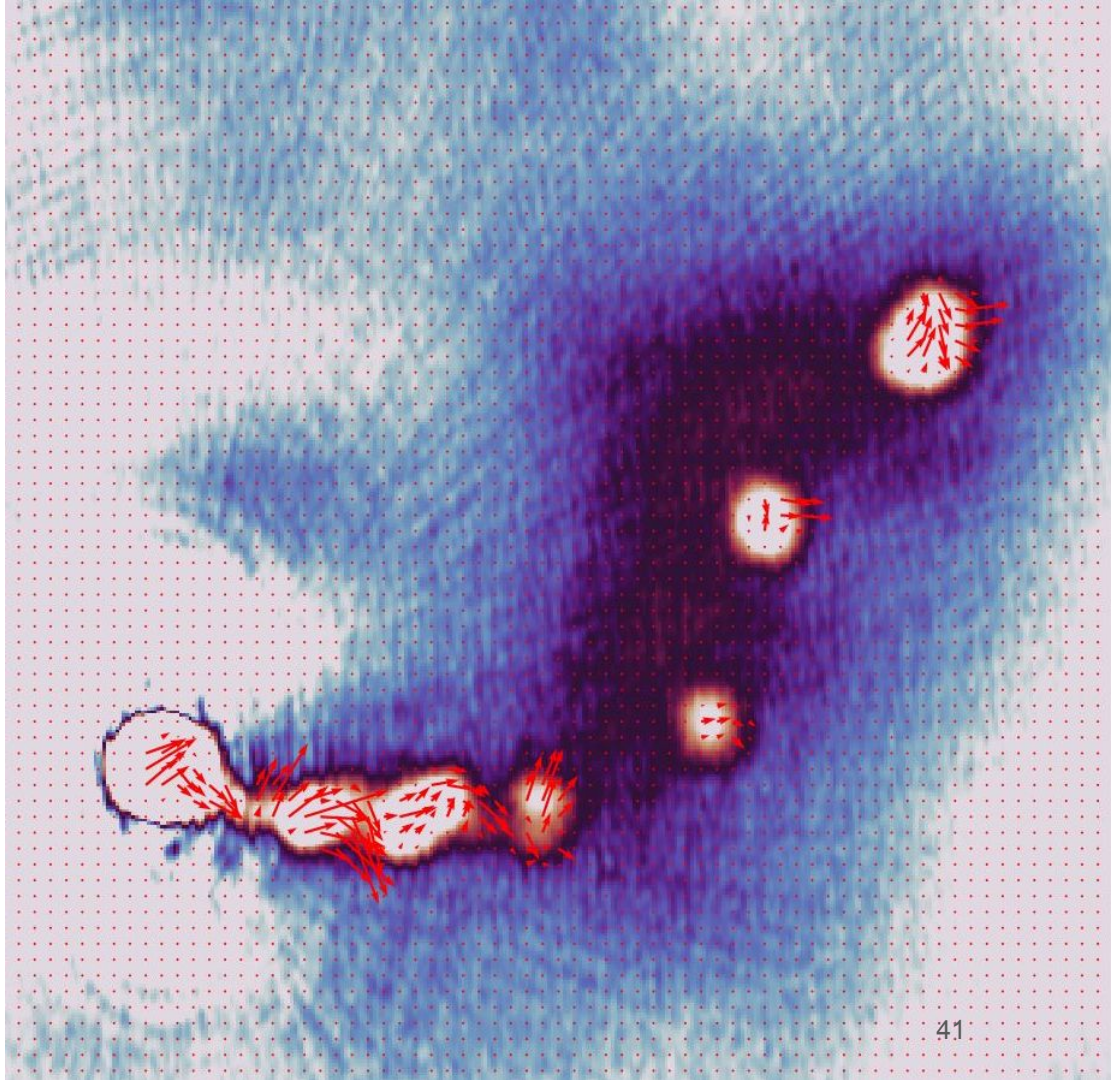


LOFAR-VLBI: EVPA

- 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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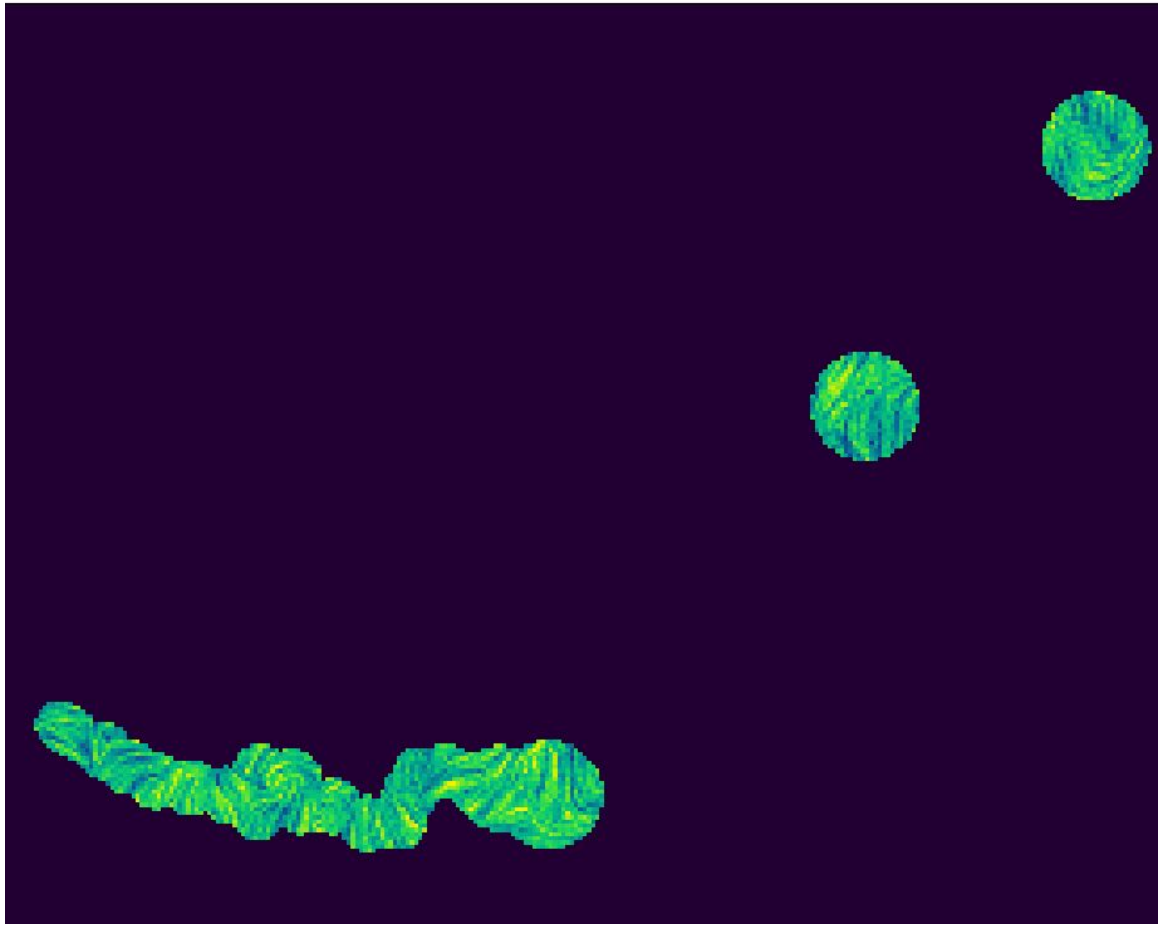

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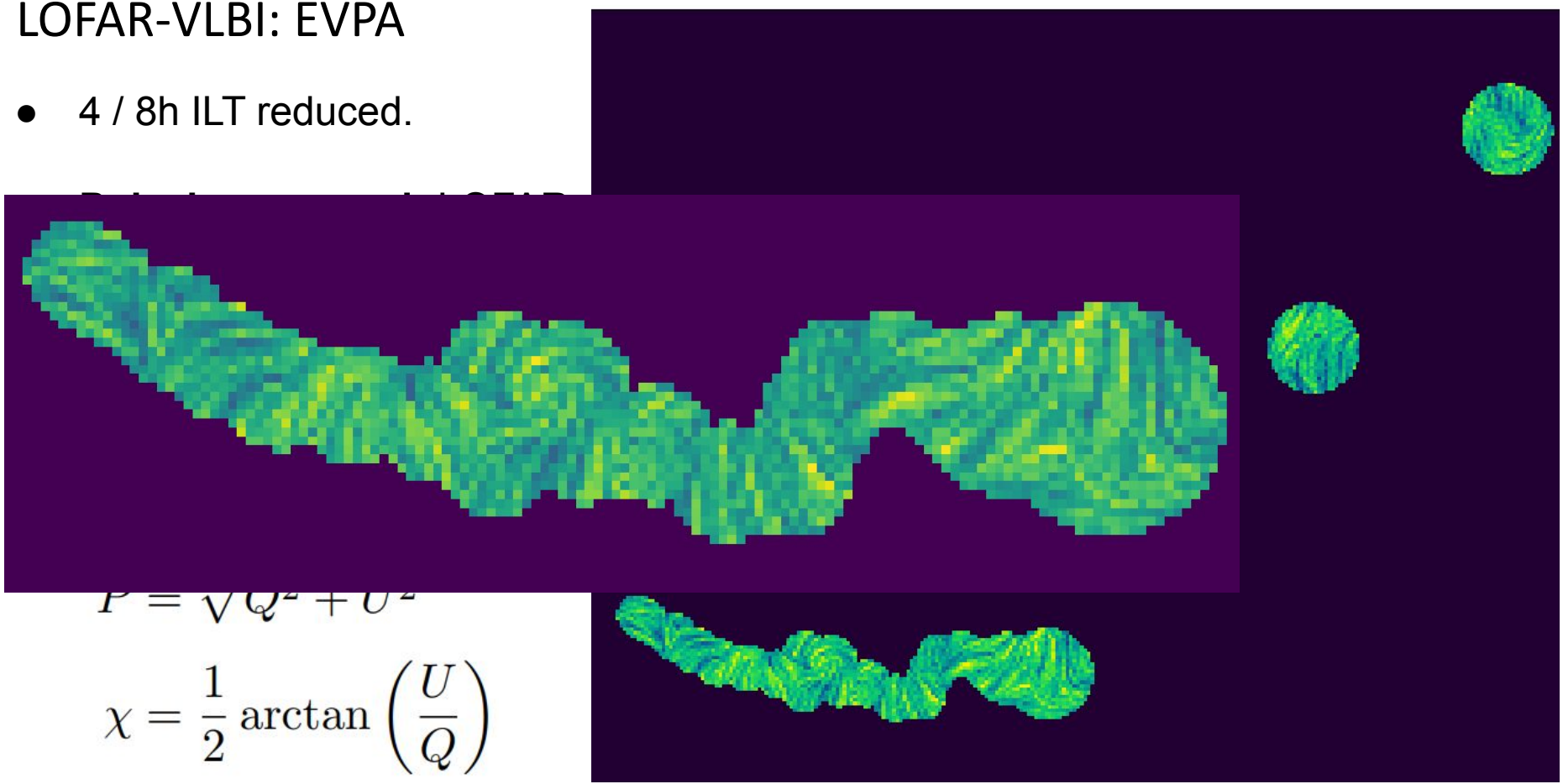

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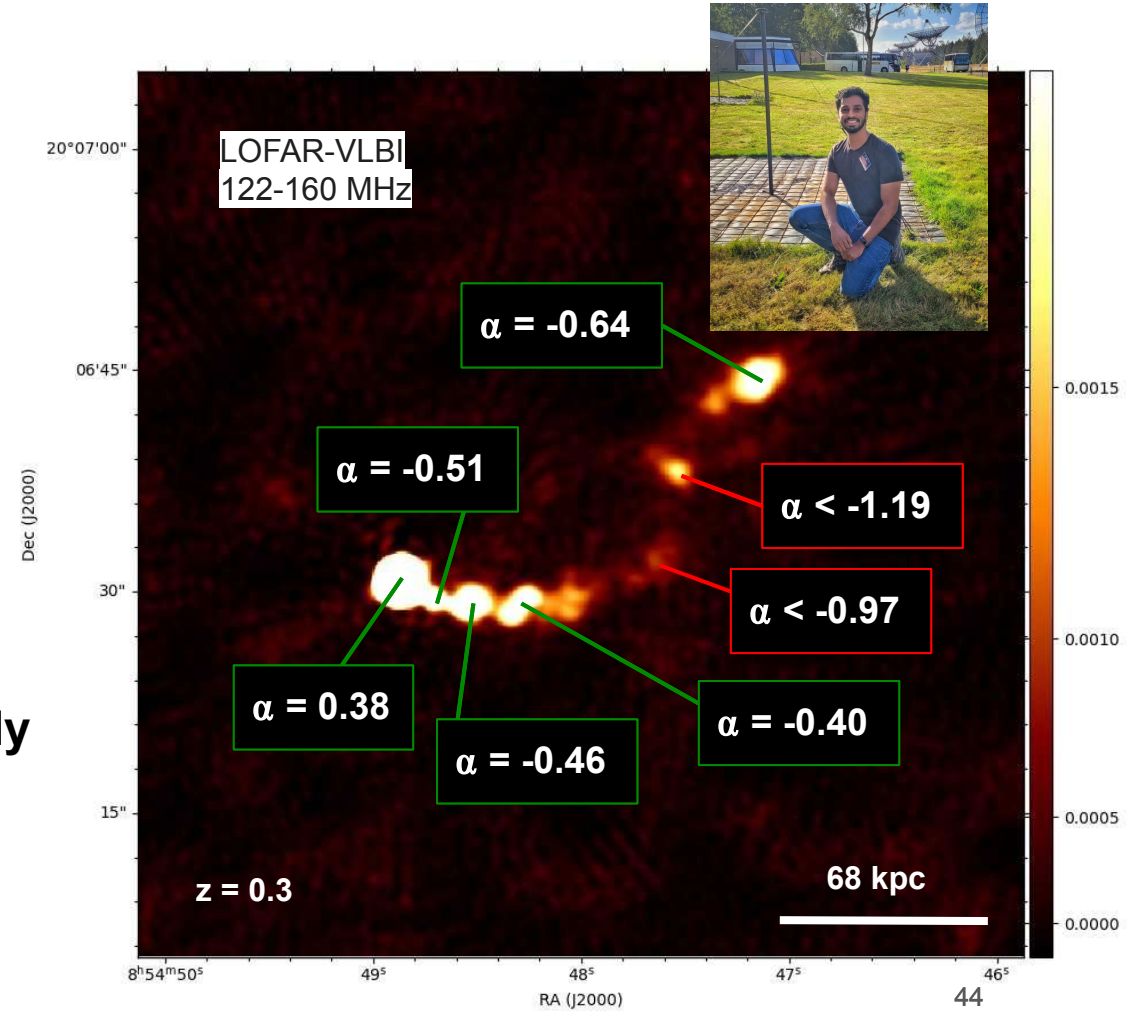
Future Work

- **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



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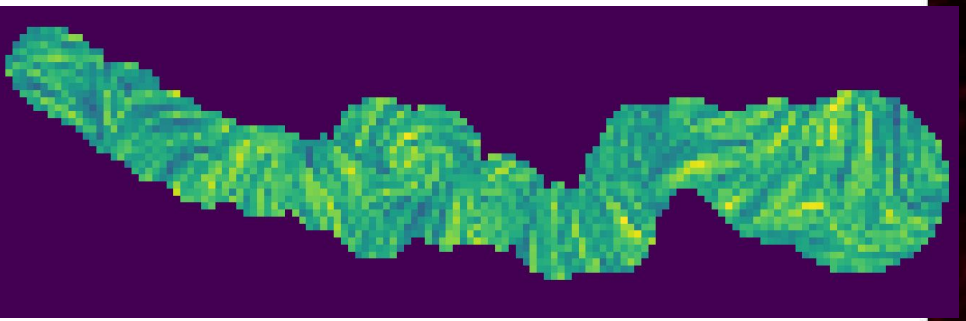
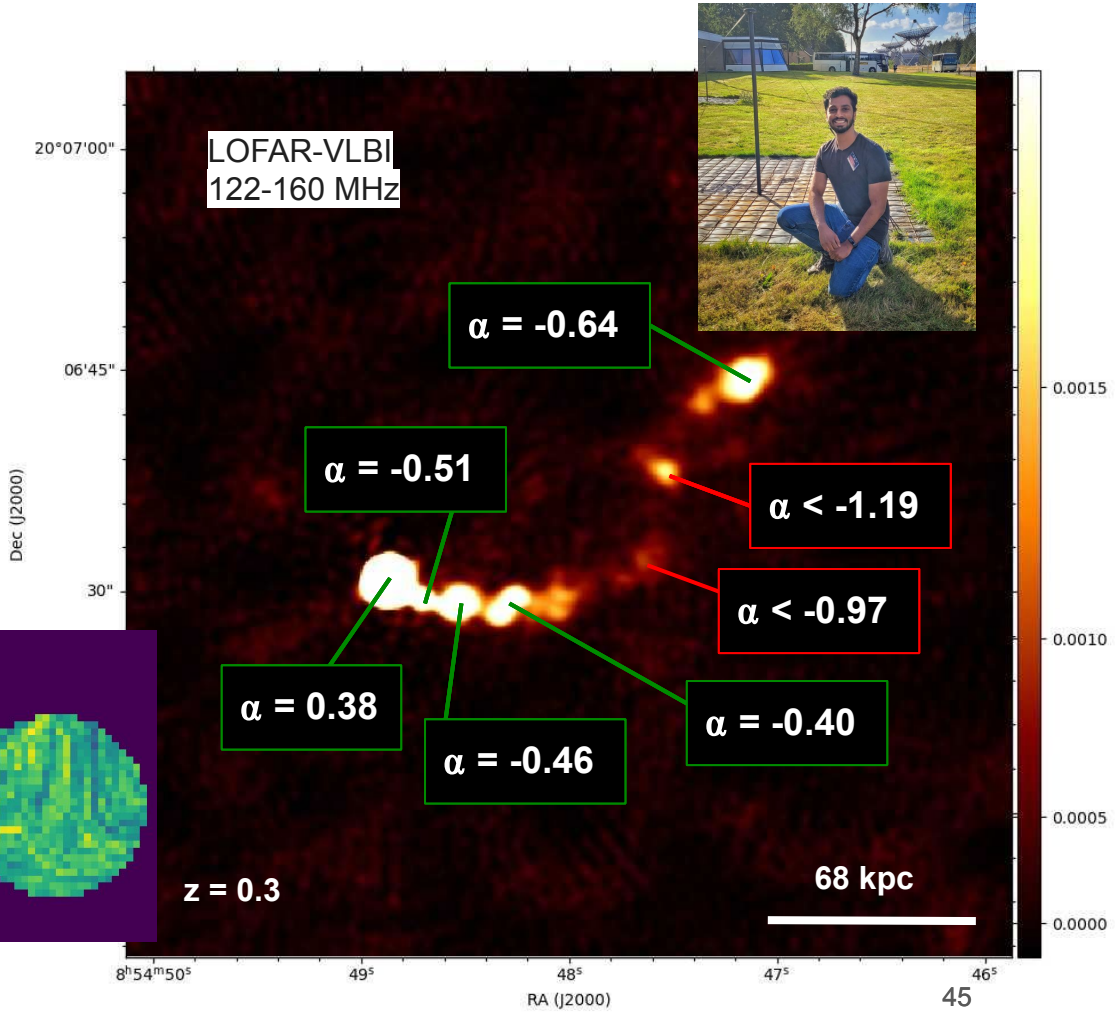
Conclusion

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





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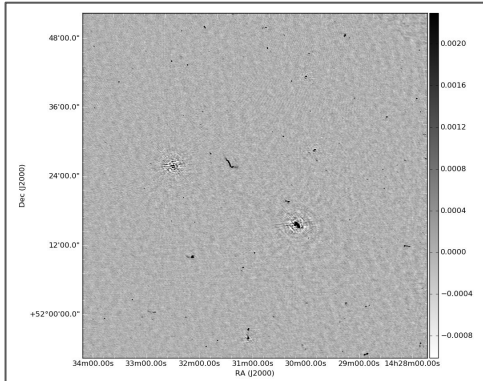
OJ287

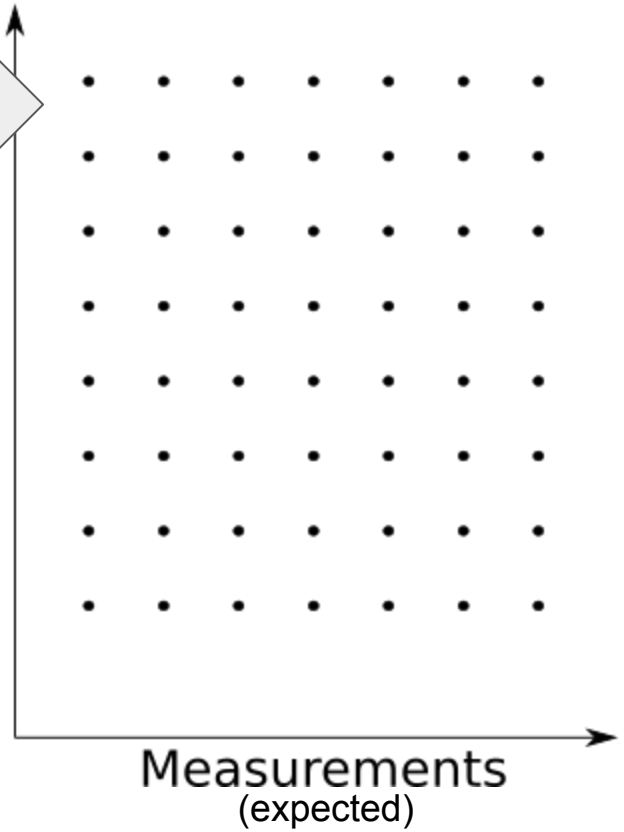
- BL Lacerta object, **discovered in 1967**, monitoring since 1890, z = 0.306
- Major outburst fluctuations of ~ 12 years
- Candidate for **binary black hole** (Sillanpaa 1988):
  - major flare predicted for 1994 in 1988; measured and confirmed then.
- Binary orbit parameters (H. Lehto & M. Valtonen):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

The inverse problem of interferometry: the observation



RIME

V=f(sky, ionosphere, beam, gains, RFI, ...)



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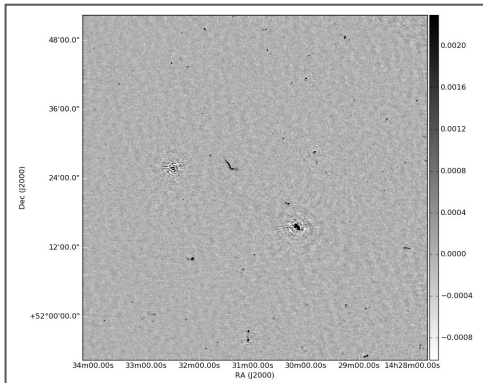

RIME w/ given calibration

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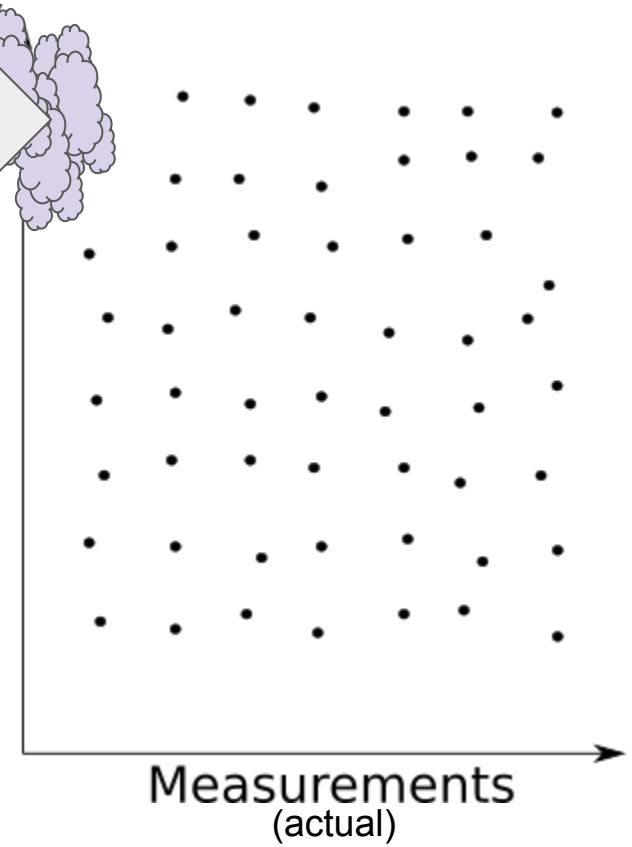

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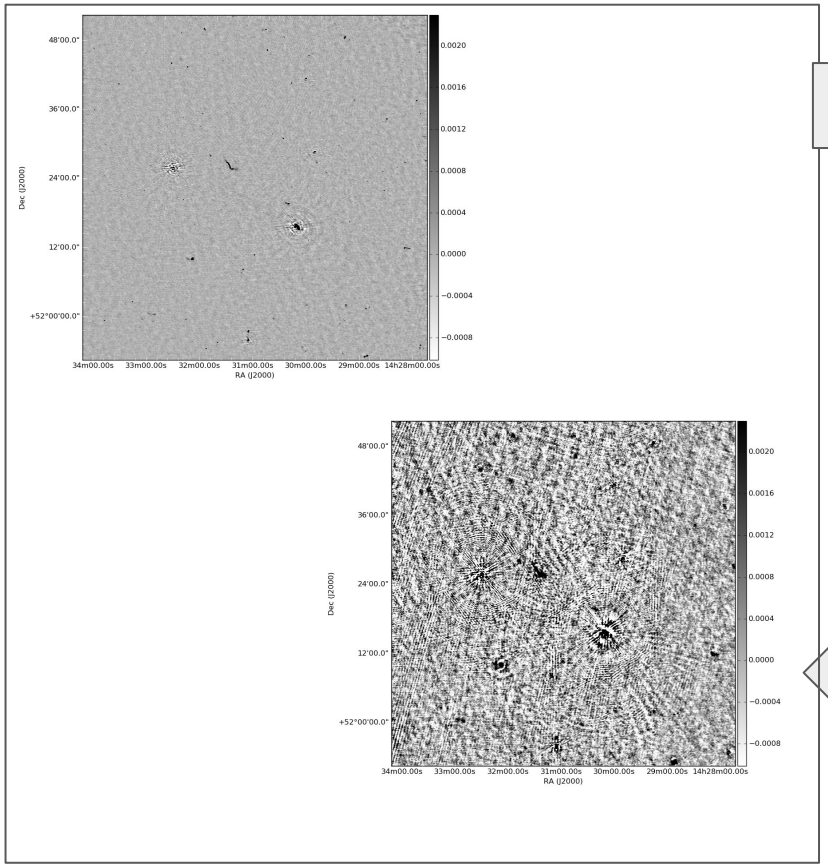


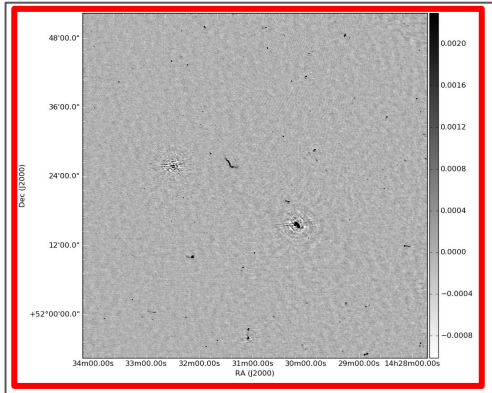
RIME w/ given calibration

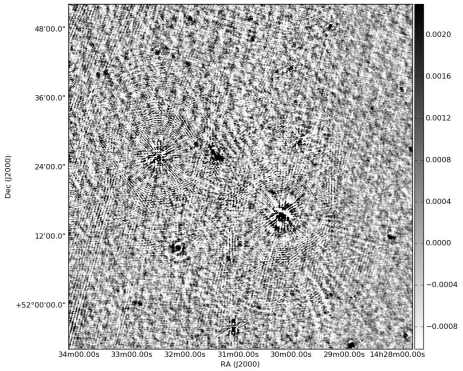
V=f(sky, ionosphere, beam, gains, RFI, ...)

y = A x

Measurements
(actual)

The inverse problem of interferometry: the observation





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