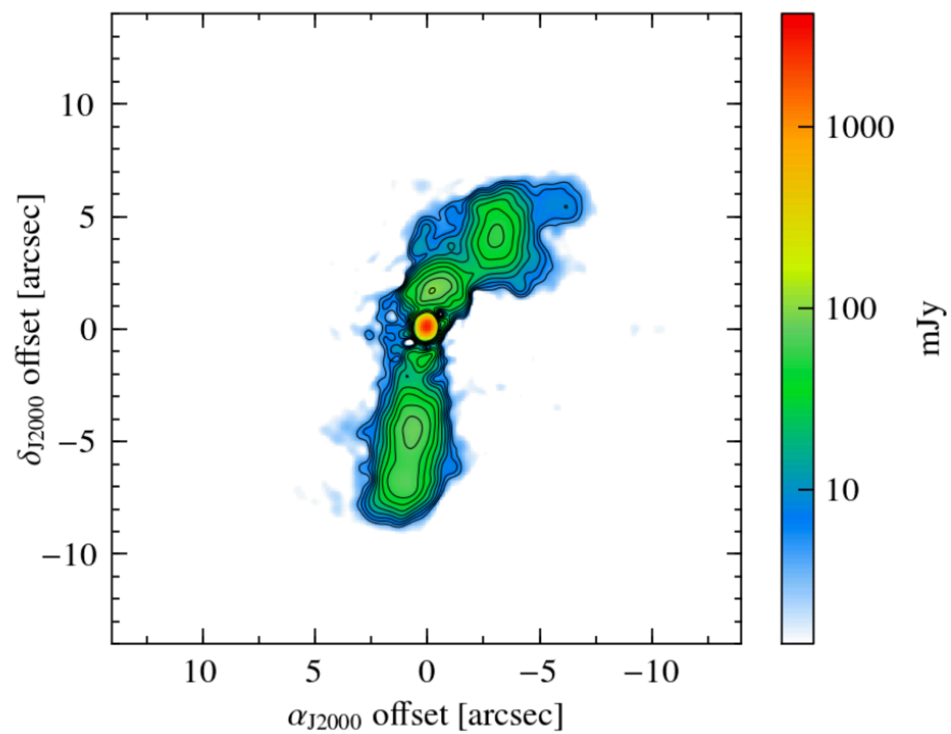
Metre-wavelength VLBI with the International LOFAR Telescope

Adam Deller, Javier Moldon, the LOFAR Long Baseline Working Group & more

ASTRON



4C55.16: Moldon et al., in prep

Why go long at low frequencies?

* Resolution, resolution, resolution
* For even moderately compact structure at low frequency, you **need** long baselines
* 0.7" corresponds to:
  * 3 km baselines @ 45 GHz (VLA C array)
  * 9 km baselines @ 15 GHz (VLA B array)
  * 27 km baselines @ 4.5 GHz (VLA A array)
  * 100 km baselines @ 1.4 GHz (E-MERLIN)
  * 1200 km baselines @ 120 MHz (Intl. LOFAR)

m-wave VLBI: not new!

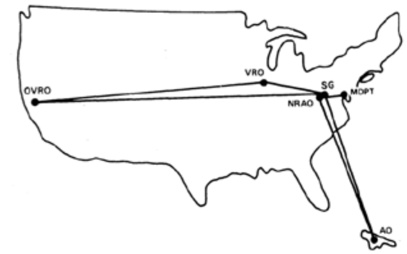


FIG. 1. Map of United States showing stations and baselines used in low-frequency experiments described in Table I.

THE ASTRONOMICAL JOURNAL VOLUME 80, NUMBER 11 NOVEMBER 1975

Meter-wavelength VLBI. II. The observations

T. A. Clark, W. C. Erickson, L. K. Hutton, G. M. Resch,† and N. R. Vandenberg*
Goddard Space Flight Center, Greenbelt, Maryland, University of Maryland, College Park, Maryland

TABLE I. Low-frequency VLBI experiments.

Experiment number	Date	Freq. (MHz)	Telescopes: Name	Telescopes: Symbol[a]	Telescopes: Size (m)	Baseline: Symbol[a]	Baseline: Length (Mλ)	Fringe spacing (arcsec)	
1	10–12 Jan. 1970	121.6	Maryland Point	M	25	MN	0.092	2.2	
			NRAO	N	92				
2	9–14 Mar. 1971	144.3	Sugar Grove	S	46	SV	0.36	0.55	
			Vermilion River	V	36	SO	1.27	0.16	
			Owens Valley	O	40	VO	1.62	0.12	
3	23–24 Nov. 1971					AN	1.7	0.12	
	19–20 Dec. 1971	196.5				AS	1.6	0.12	(196.5)
	23–24 Jan. 1972	and				NS	0.033	6	
	25–27 Feb. 1972	111.5	Arecibo	A	305	AN	0.94	0.20	
	26–28 Mar. 1972		NRAO	N	92	AS	0.93	0.20	(111.5)
			Sugar Grove	S	46	NS	0.019	10	
4	4– 9 Dec. 1973	111.5				AN	0.62	0.30	
	23 Feb. 1973	and				AS	0.62	0.30	(74.0)
	2 Mar. 1973	74.0				NS	0.022	15	

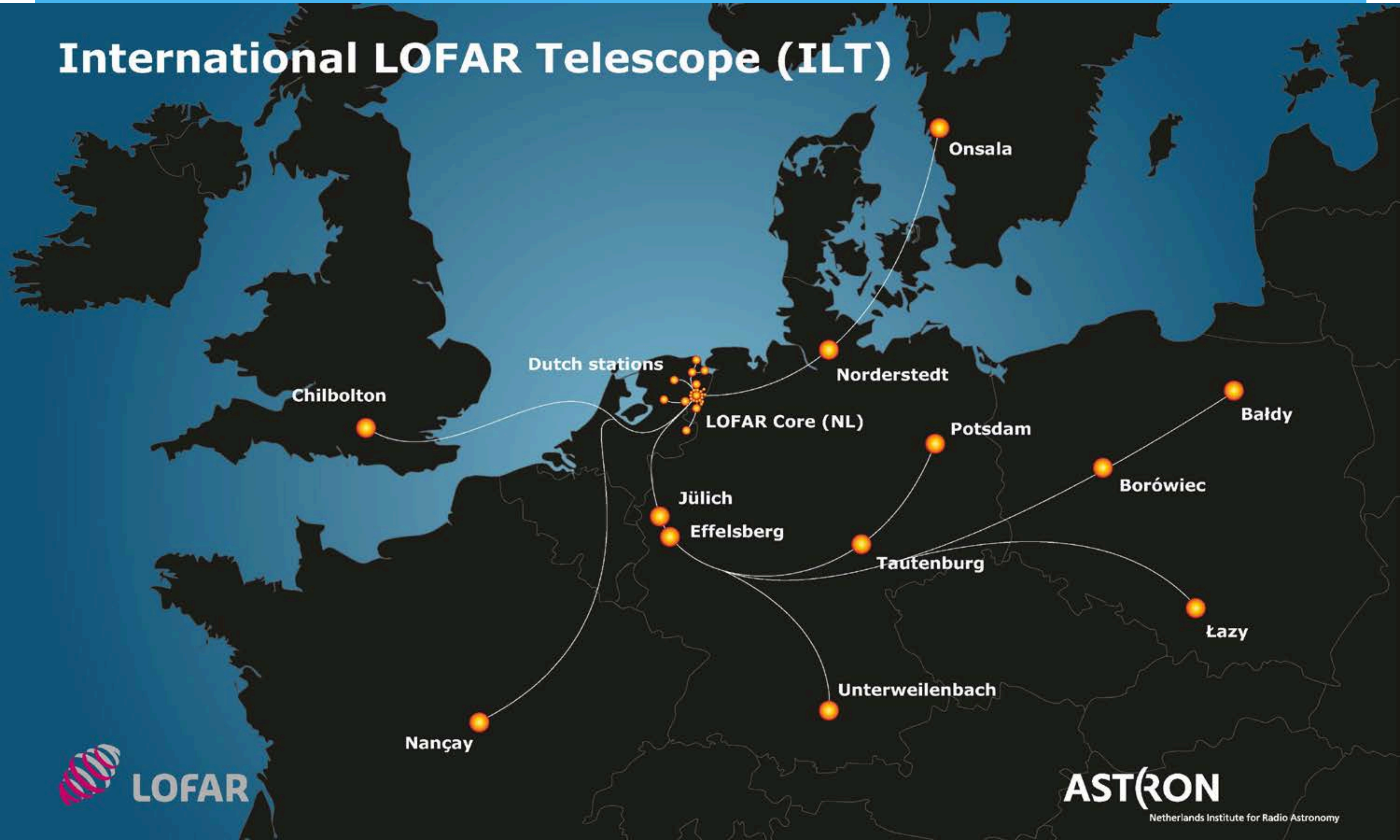
[a] These symbols will be used throughout other tables.

International LOFAR stations

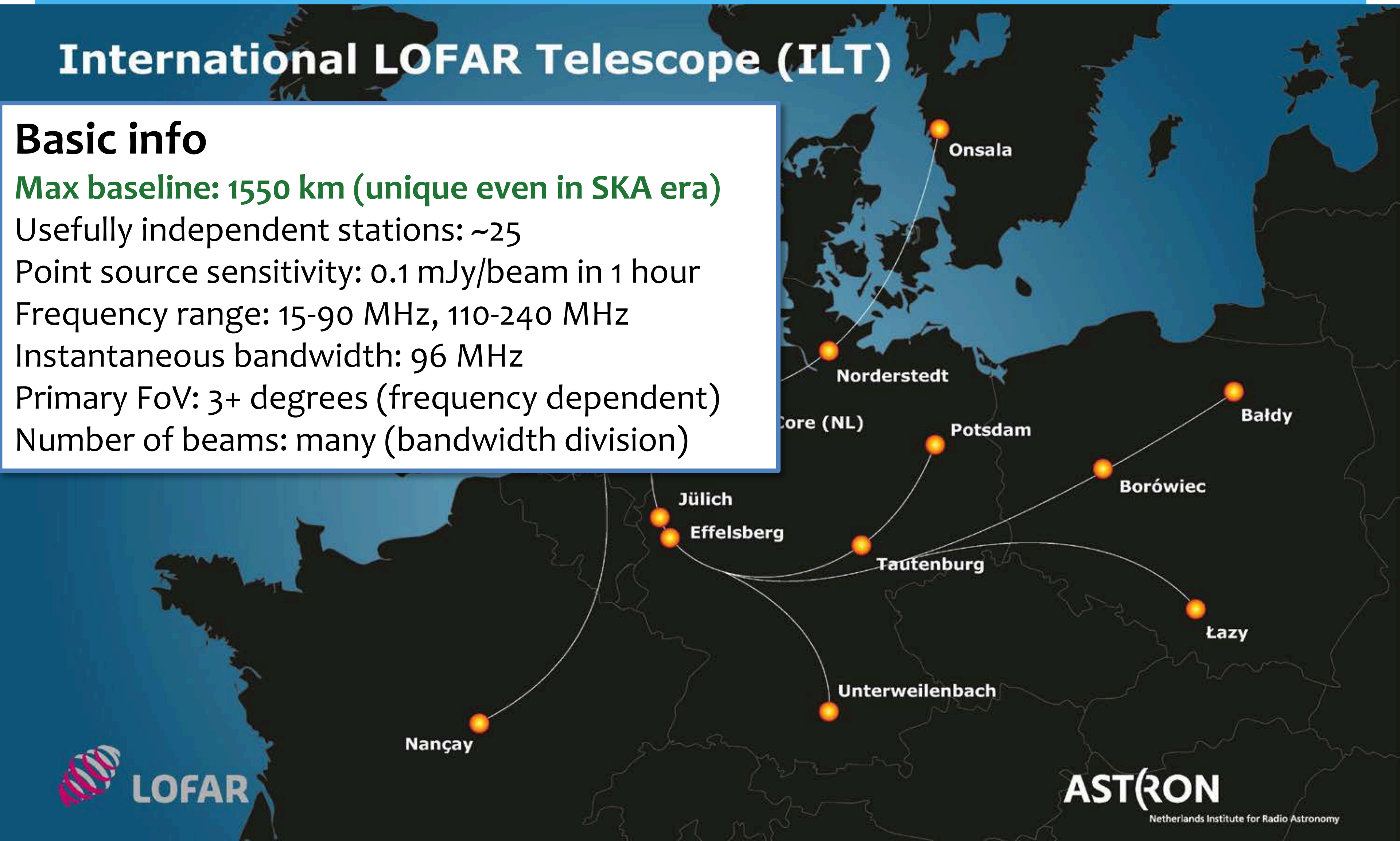
* High band array: 110-240 MHz
* Low band array: 15-90 MHz

ASTRON

The International LOFAR array



The International LOFAR array



Basic info

Max baseline: 1550 km (unique even in SKA era)

Usefully independent stations: ~25

Point source sensitivity: 0.1 mJy/beam in 1 hour

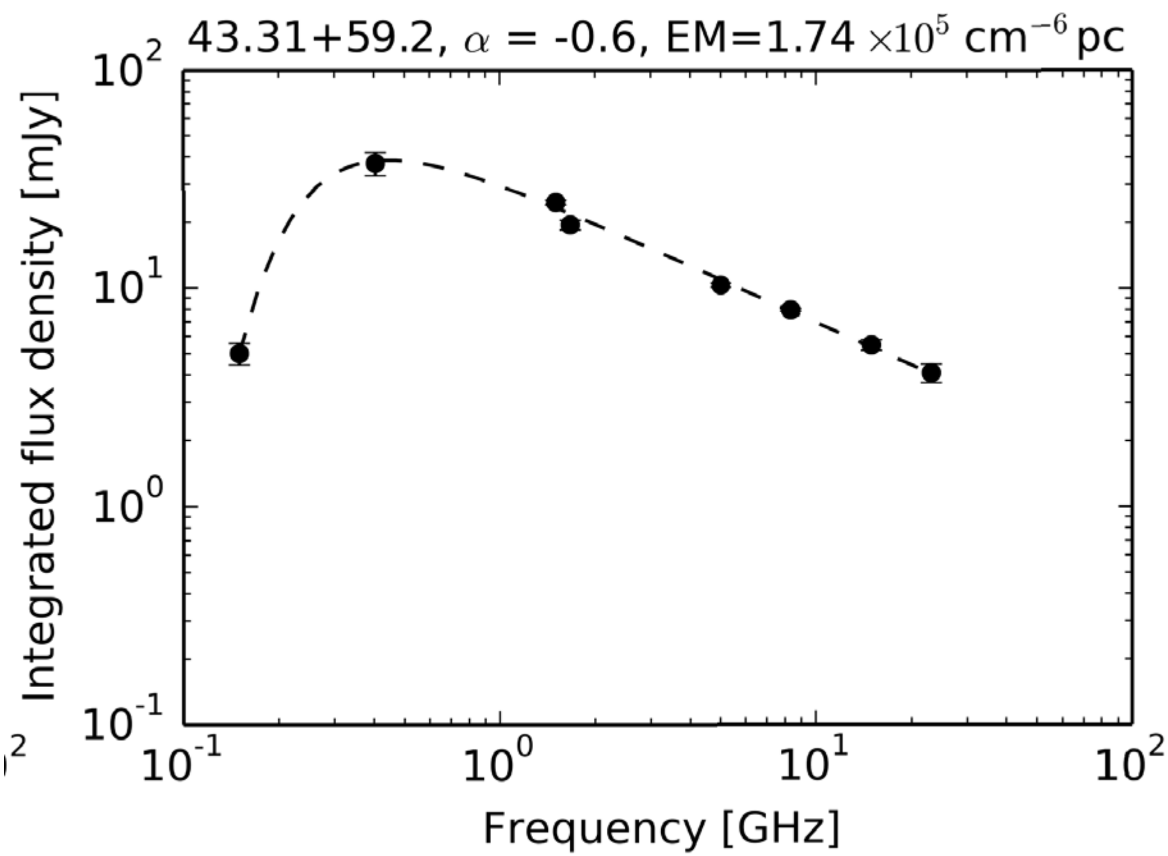
Frequency range: 15-90 MHz, 110-240 MHz

Instantaneous bandwidth: 96 MHz

Primary FoV: 3+ degrees (frequency dependent)

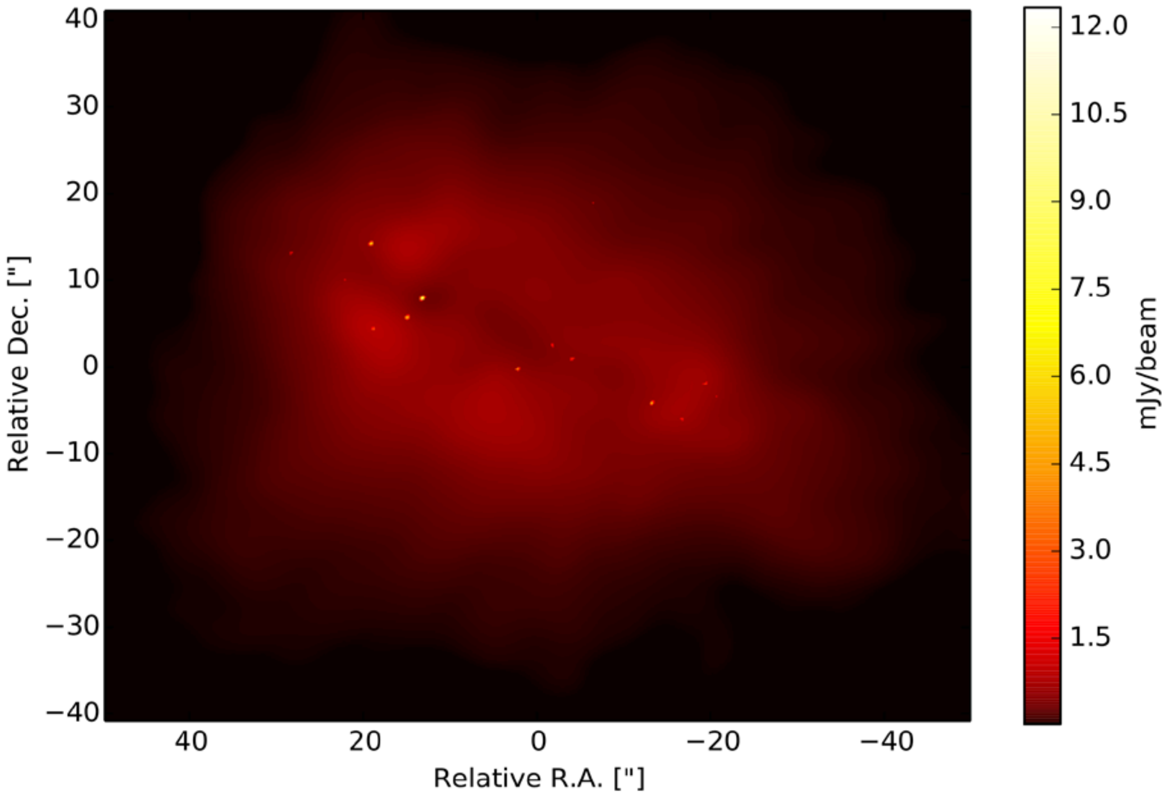
Number of beams: many (bandwidth division)

Science Highlights: M82



M82: starburst galaxy, supernova remnant laboratory

Science Highlights: M82



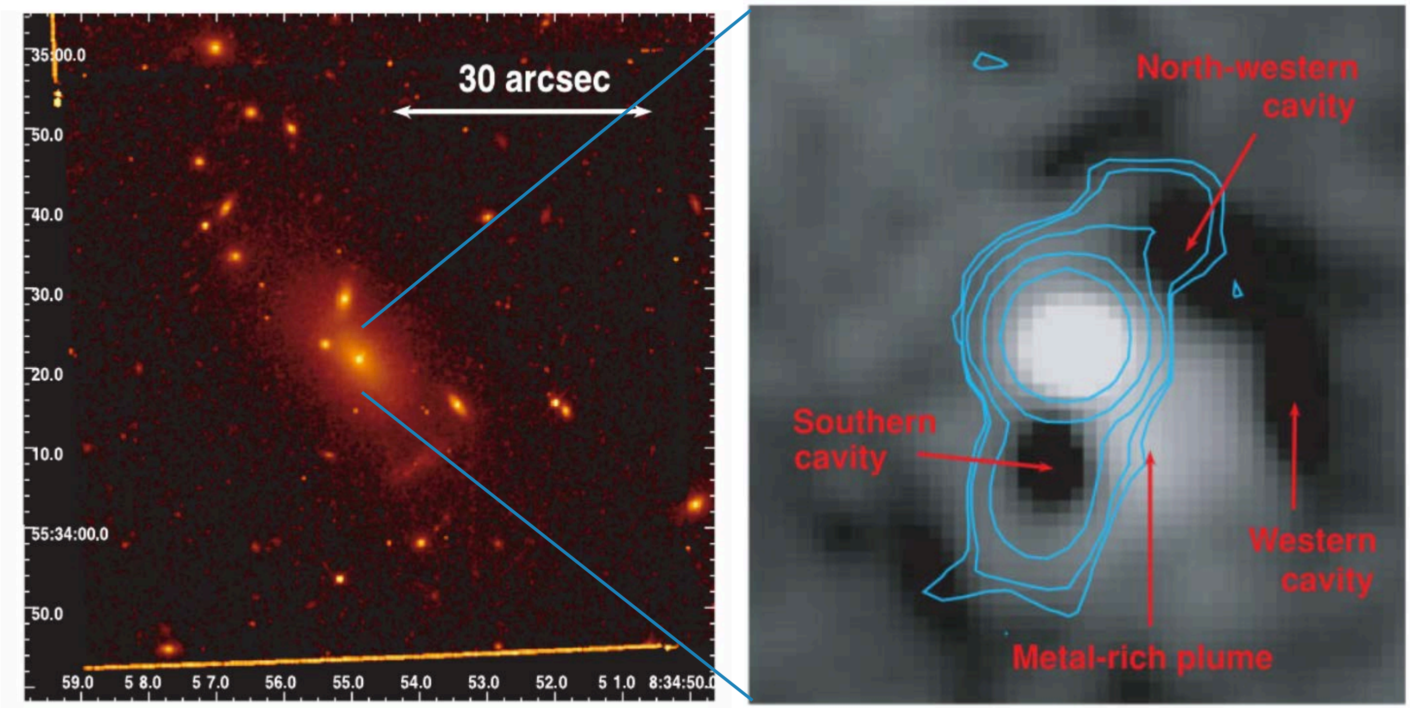
Varenius et. al., 2015, A&A, 574, 114

Early ILT observations (challenging): 0.3” resolution, 150 μJy/beam rms @ 150 MHz

ASTRON

Science Highlights: 4C55.16

* 4C55.16 is a z = 0.24 radio galaxy at the centre of a cool-core galaxy cluster



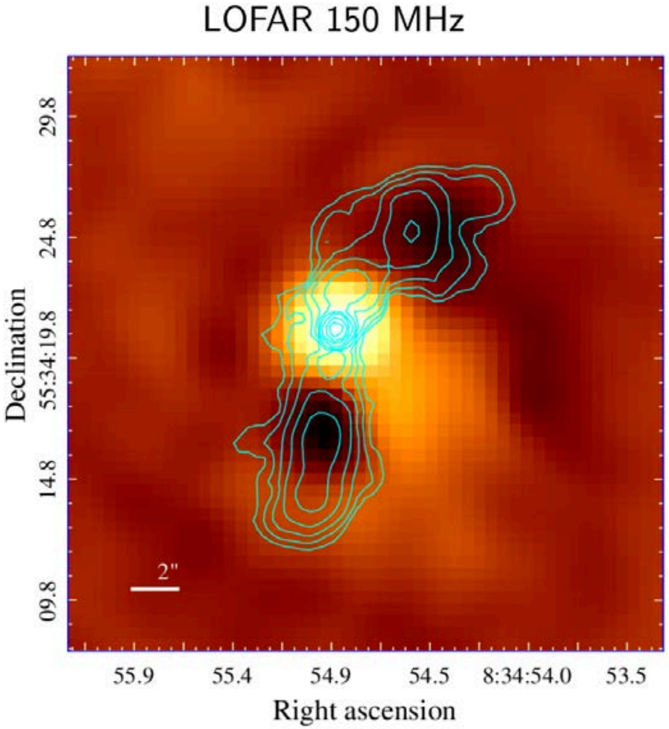
Hlavacek-Larrondo et al. (2011)

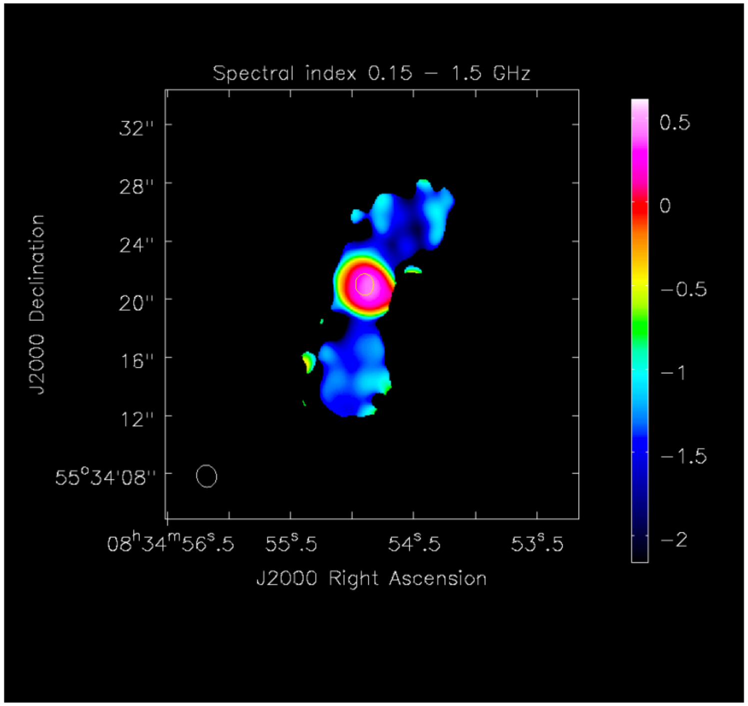
Radio traces excavated X-ray cavities

ASTRON

Science Highlights: 4C55.16

* 10x lower frequency than VLA yet better resolution & 100 μJy rms! Trace steep-spectrum (-1.6, -1.3) lobe emission better



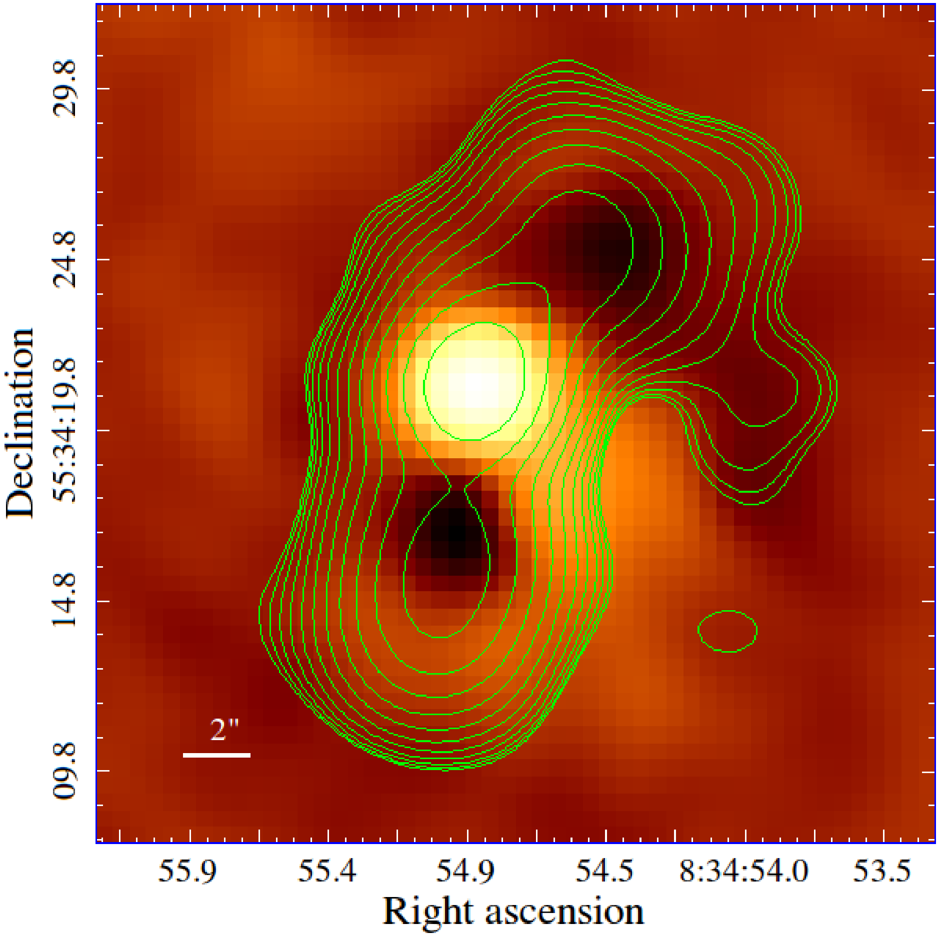


Moldon et al., in prep

ASTRON

Science Highlights: 4C55.16

LOFAR 120 MHz

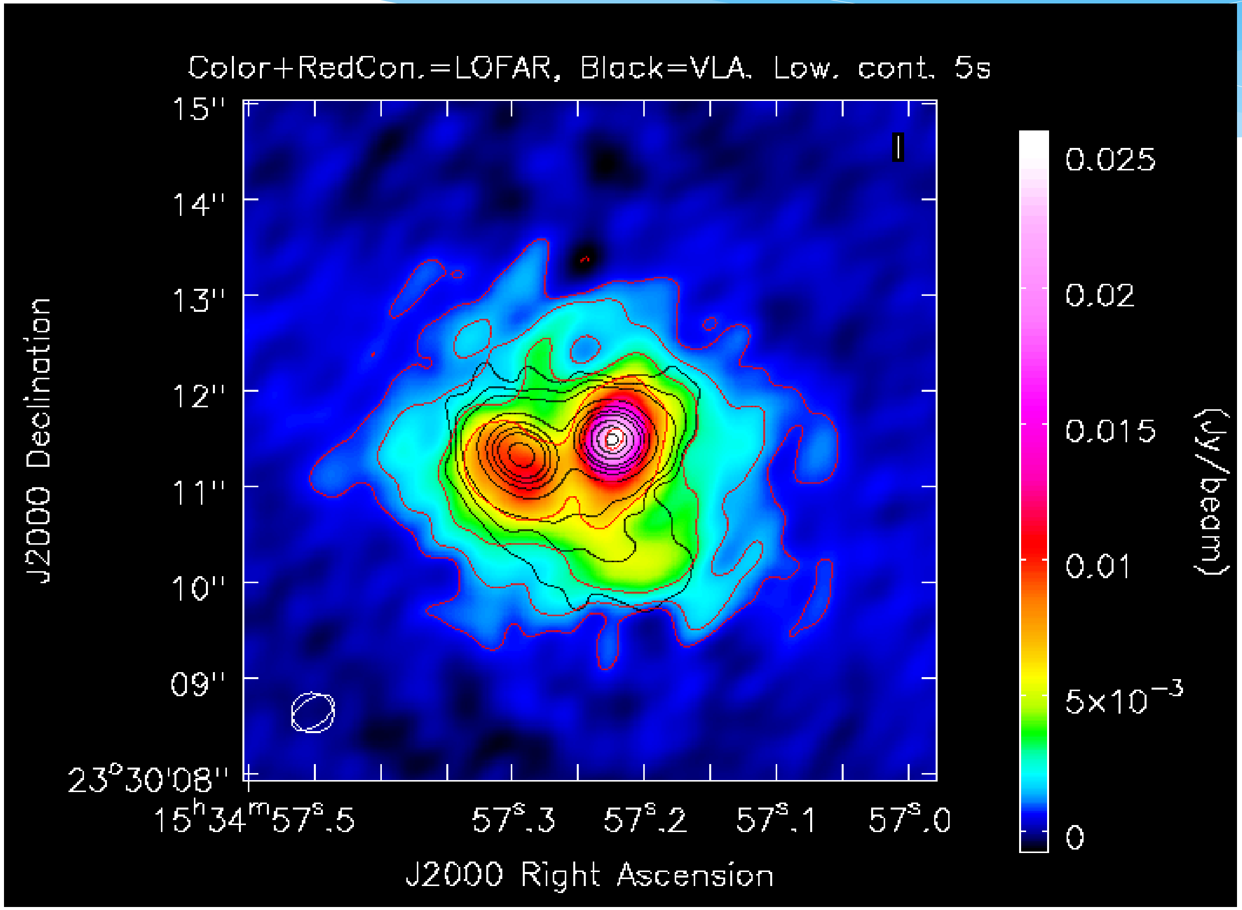


Hot off the press: at the lowest HBA frequencies, "missing" radio emission tracing western cavity discovered!

- Extraordinarily steep spectrum, old electron population

ASTRON

Science Highlights: Arp 220



Varenius, Conway et al. in prep

ASTRON

Differences with traditional VLBI;

or, why making these images was no piece of cake

- Sensitivity is squeezed front and back:
  - Sky noise is higher
  - Calibrator sources are fainter (most compact sources are flat or inverted)
- But we have a lot of collecting area, which helps to compensate:
  - Single international station 2,000 m^2, 800 Jy
  - Combined core stations: 25,000 m^2, 65 Jy

ASTRON

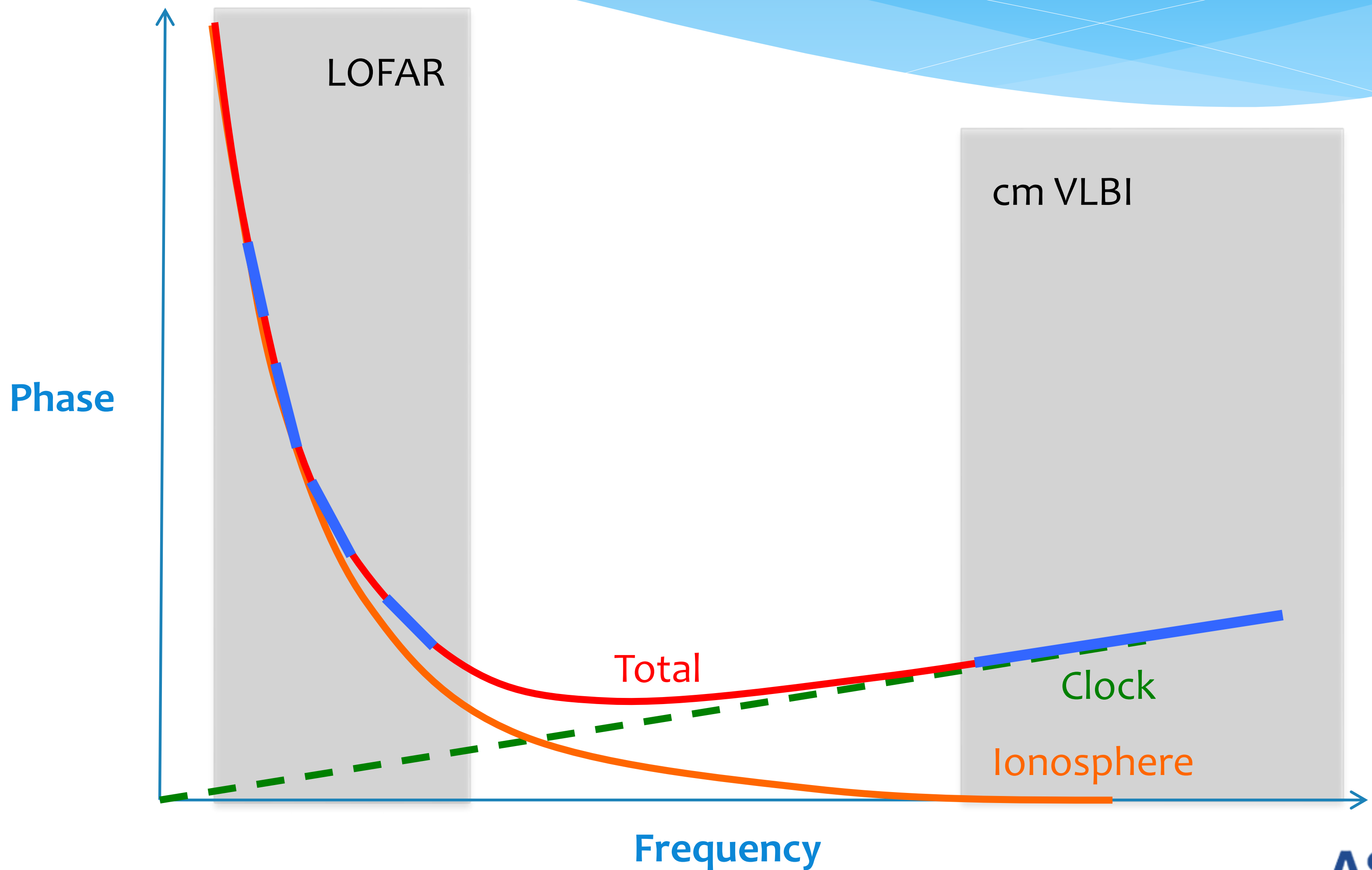
Differences with traditional VLBI;

or, why making these images was no piece of cake

- The real killer is the ionosphere:
  - $\text{delay}_{\text{iono}} \propto \lambda^2$
  - At 1.5 GHz, you get relative delays ~ few ns
  - At 0.15 GHz, that becomes ~ few 100 ns
    - And 2x greater at 120 MHz vs 170 MHz…
    - >1 µs at 60 MHz and below!

ASTRON

Differences with traditional VLBI



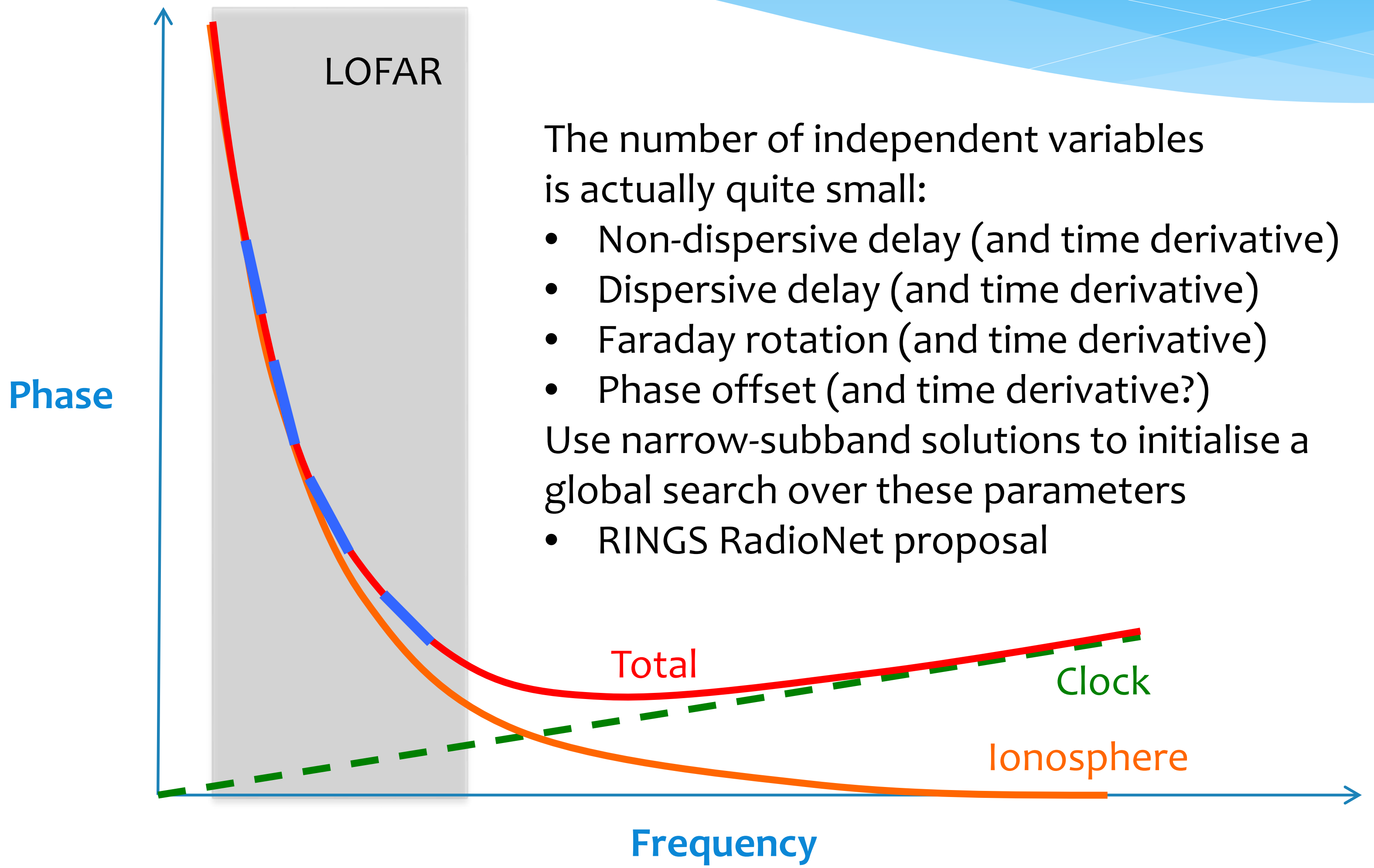
ASTRON

Current Intl. LOFAR calibration

- A series of “non-standard” (compared to short-baseline LOFAR) steps:
  - Calibrate, phase up core stations into “super-station” (visibility summation, offline)
  - Convert to circular polarisation (avoid problems with Faraday rotation)
  - Aggregate bandwidth in relatively narrow subbands (2-3 MHz)
  - Solve with traditional VLBI tools (FRING, CALIB)

ASTRON

Goals for the future



The number of independent variables is actually quite small:

- Non-dispersive delay (and time derivative)
- Dispersive delay (and time derivative)
- Faraday rotation (and time derivative)
- Phase offset (and time derivative?)

Use narrow-subband solutions to initialise a global search over these parameters

- RINGS RadioNet proposal

ASTRON

The link to cm VLBI

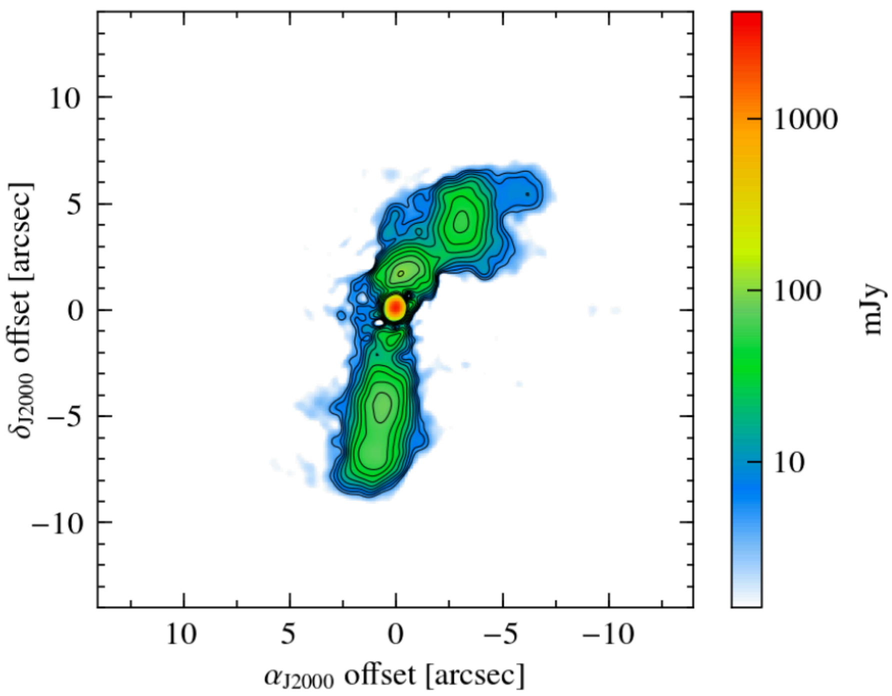
- A dispersive-delay-enabled fringe fitter is useful for wideband observations up to at least a few GHz:
  - Current observations (e.g., 256 MHz bandwidth at 1.5 GHz) are already limited by ionospheric variations
  - Of particular interest to pulsar astrometry (steep spectrum targets bias position errors)
  - Developing this for CASA has multiple benefits: no need for format conversions, insurance against eventual lack of AIPS support

ASTRON

Conclusions

* It's VLBI gone full circle
  - but better! Because…

"At **metre** wavelengths, International LOFAR can resolve the **sub-arcsecond** structure of **sub-mJy** sources"



ASTRON