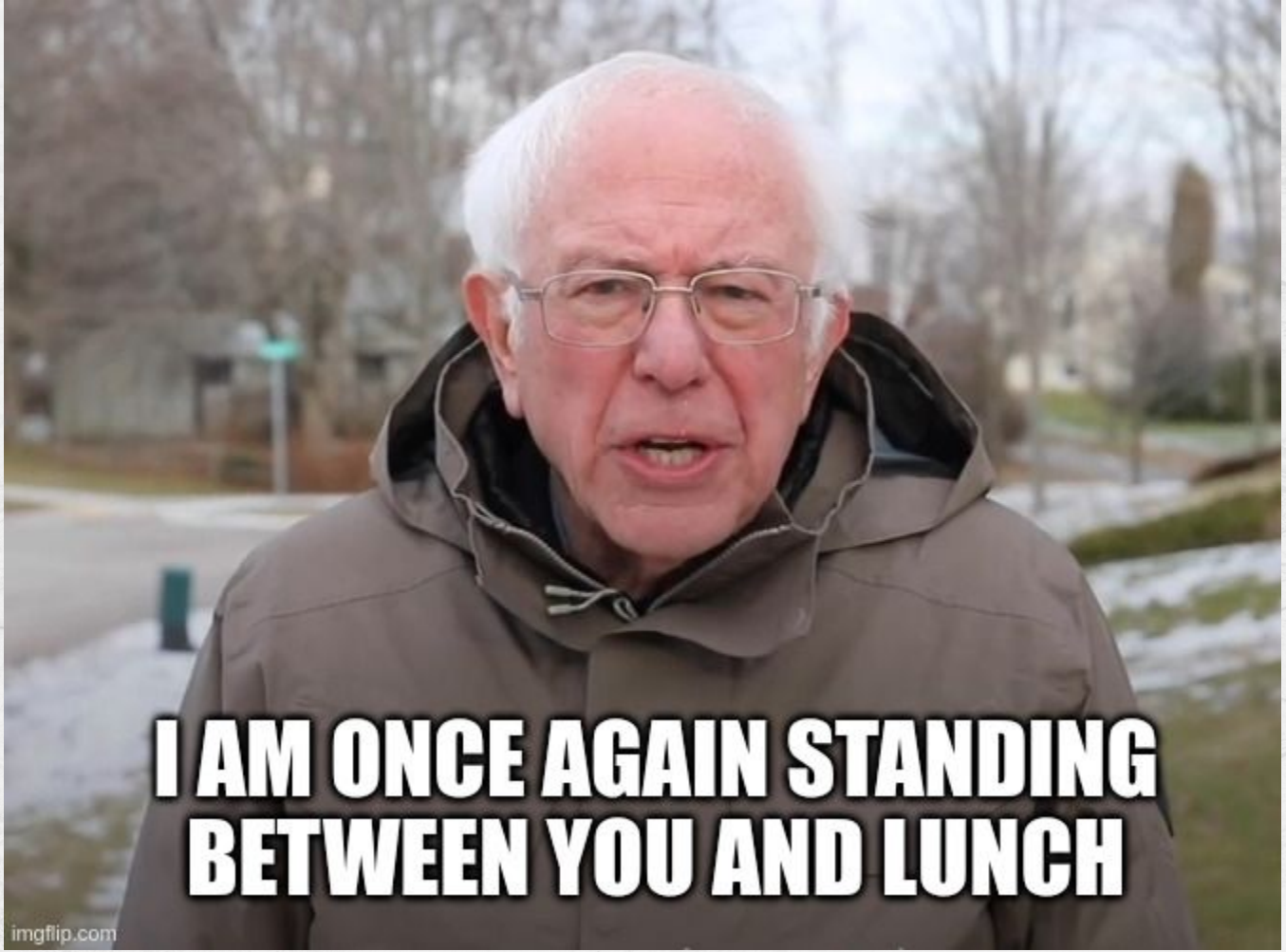
Pushing the fringe

Low-frequency VLBI with the ILT

Frits Sweijen // LOFAR Data School 2026, Dwingeloo


I AM ONCE AGAIN STANDING
BETWEEN YOU AND LUNCH
imgflip.com

Someday when LOFAR is all grown up, you'll be amazed to think back and remember how small and cute it once was.

George Heald; ASTRON/JIVE Daily Image 12/12/2009

Outline

What sets the ILT apart from other VLBI instruments

Science with the ILT

LBWG & Pipeline for International LOFAR Telescope (PILOT)

Future ILT prospects

Introduction

What sets the ILT apart from the competition?

Very long baseline interferometry

What constitutes “very long”?

Telescopes “very far apart”, whatever that is

Independent clocks without direct synchronisation

Data recording and correlation separately; “offline”

Sufficiently different line-of-sight effects per antenna?

Fringe fitting?

Long Base Line Interferometry: A New Technique

Abstract. *The technique of using magnetic-tape recorders and atomic frequency standards to operate two widely separated radio telescopes as a phase-coherent interferometer when the stations have no radio-frequency connecting link has been successfully tested at the National Research Council of Canada's Algonquin Radio Observatory.*

The first test was performed at a center frequency of 448 Mhz. The antenna system consisted of the 46-m radio telescope and a 10-m instrument located 200 m away. The two local oscillators were *not synchronized*, each being controlled by its own atomic frequency standard. There was no noticeable evidence of any short-term phase drift in the local oscillators.

Broten+1967

When is interferometry “very long baseline”?

VLA	EVN	LOFAR
Max. baseline: 36 km	**Max. baseline:** ~12,000 km	**Max. baseline:** ~2,000 km
Correlation: online	**Correlation:** online or offline	**Correlation:** online
Independent clocks: no	**Independent clocks:** yes	**Independent clocks:** Sort of
Connected elements: yes	**Connected elements:** no	**Connected elements:** yes

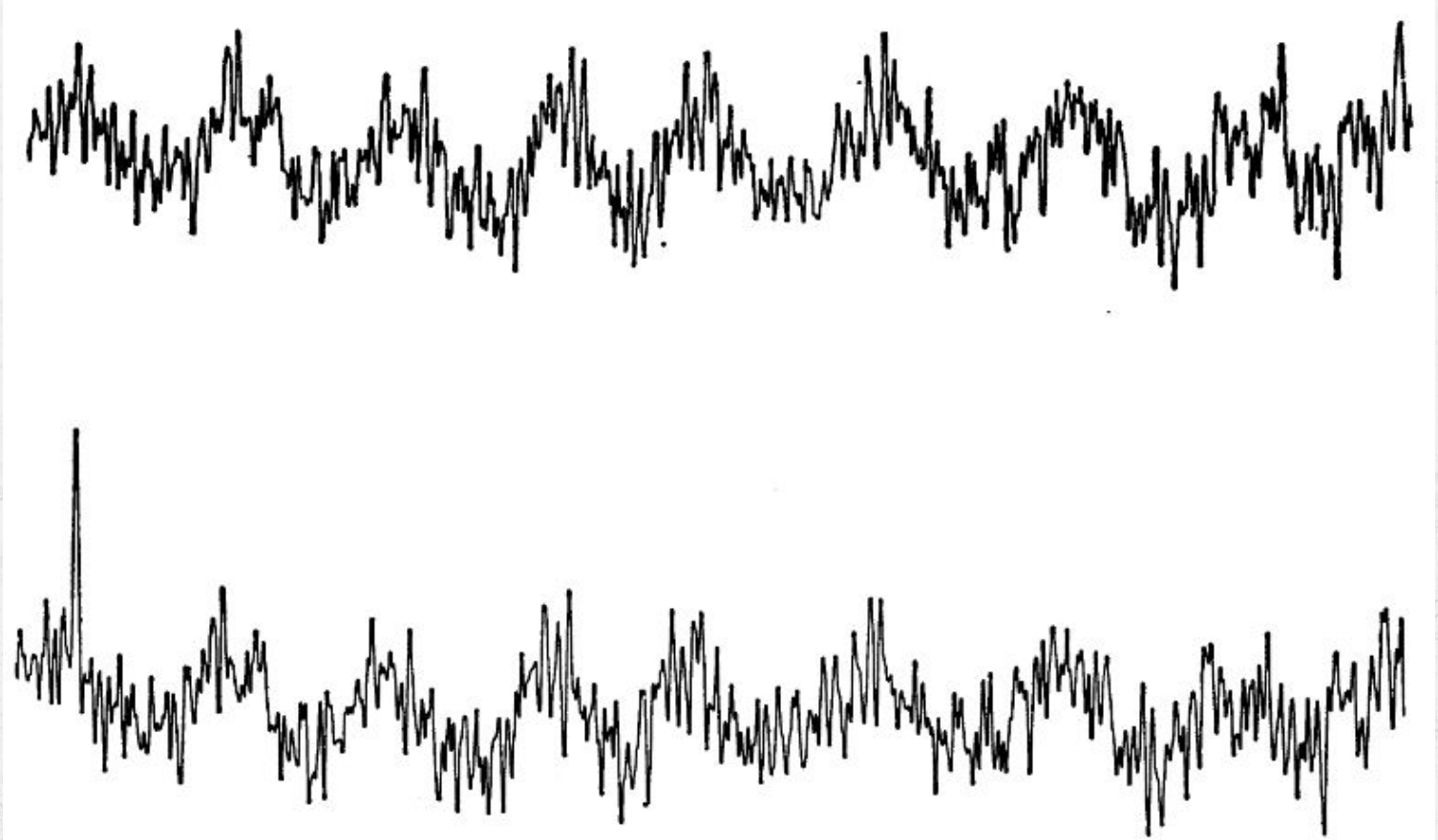
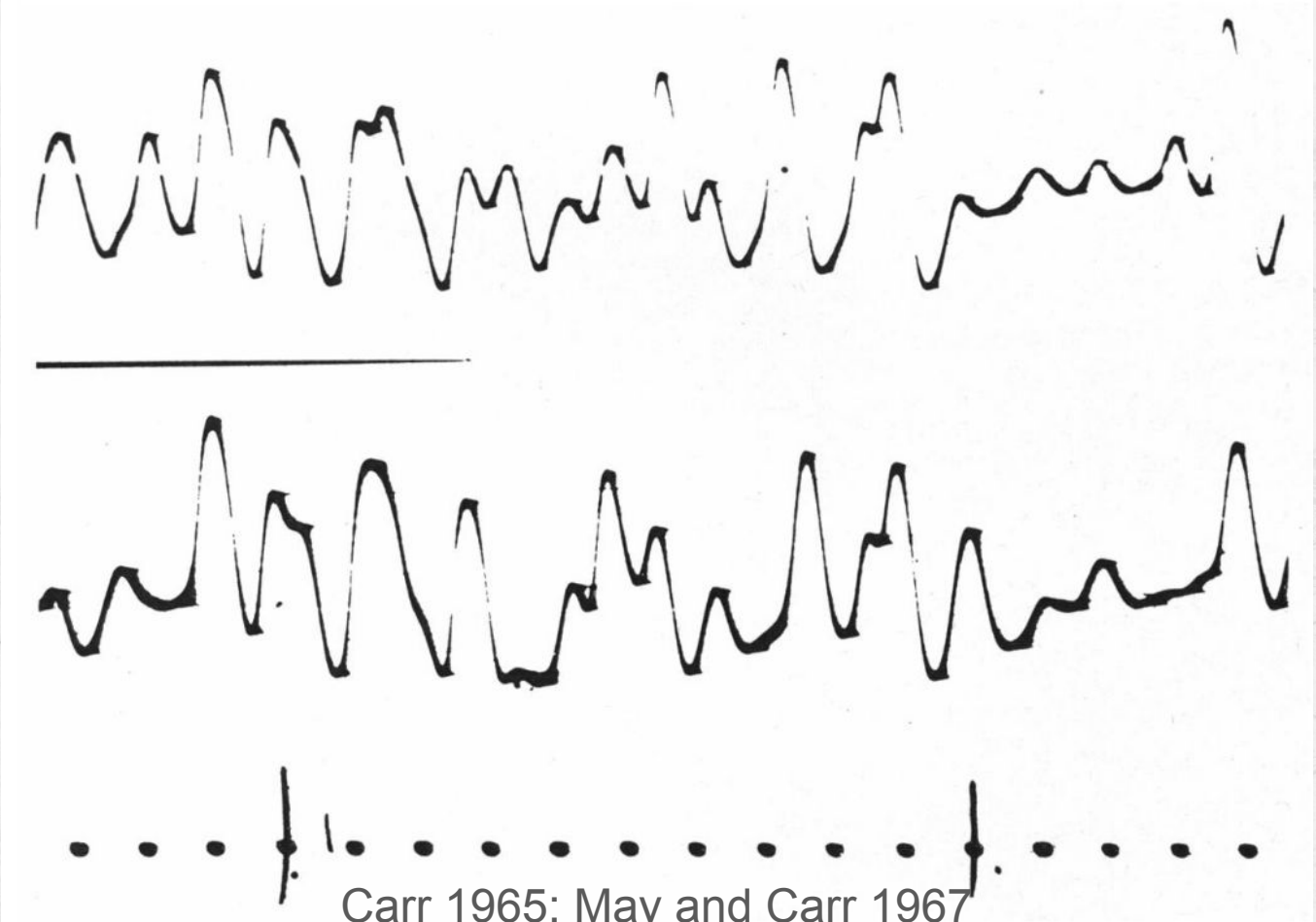


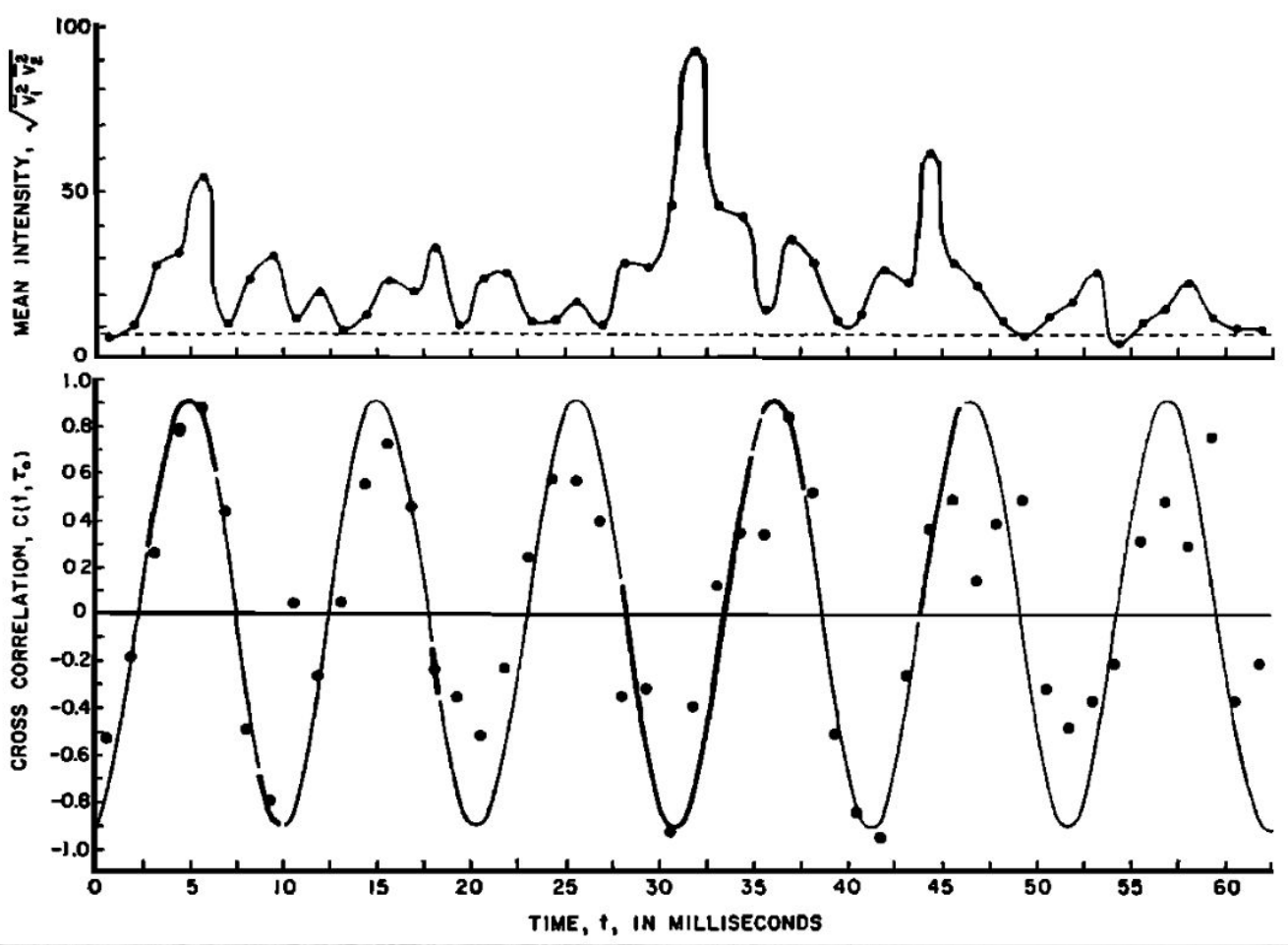
Fig. 1. (Top) An interferometer pattern from the source 3C-294 obtained directly while a recording was being made. (Bottom) An interferometer pattern from the source 3C-294 obtained on playback. The recorded signals were those correlated directly to produce the pattern in the top part of the figure.



Carr 1965; May and Carr 1967

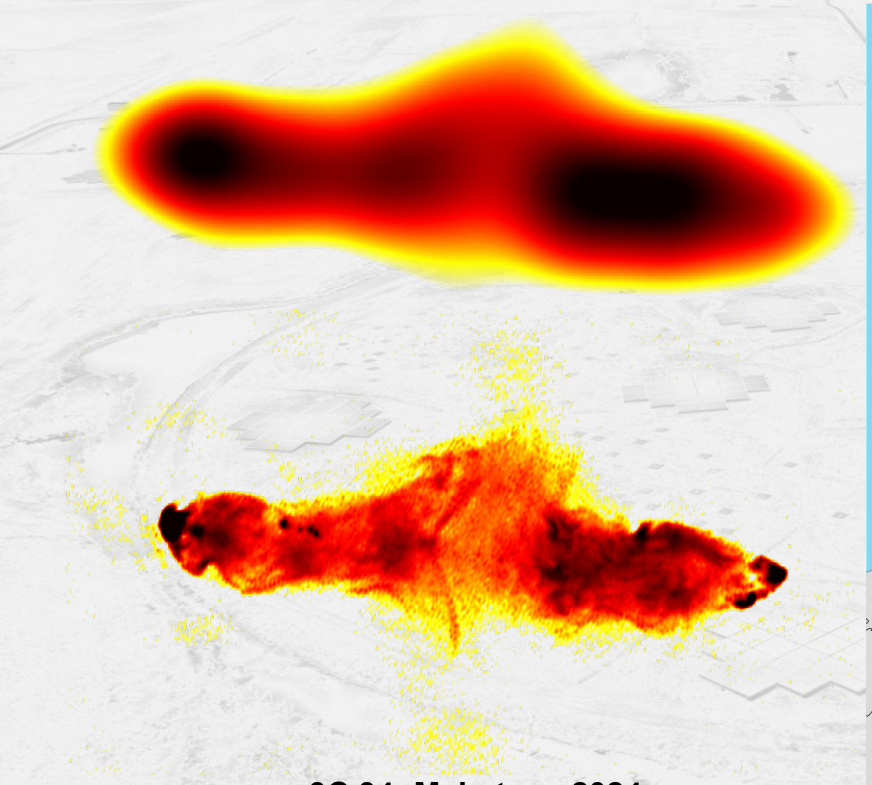
Fig. 3. Audio-frequency noise from Jupiter obtained with receivers 55.3 km apart during the 1964-65 apparition. Time marks are milliseconds.



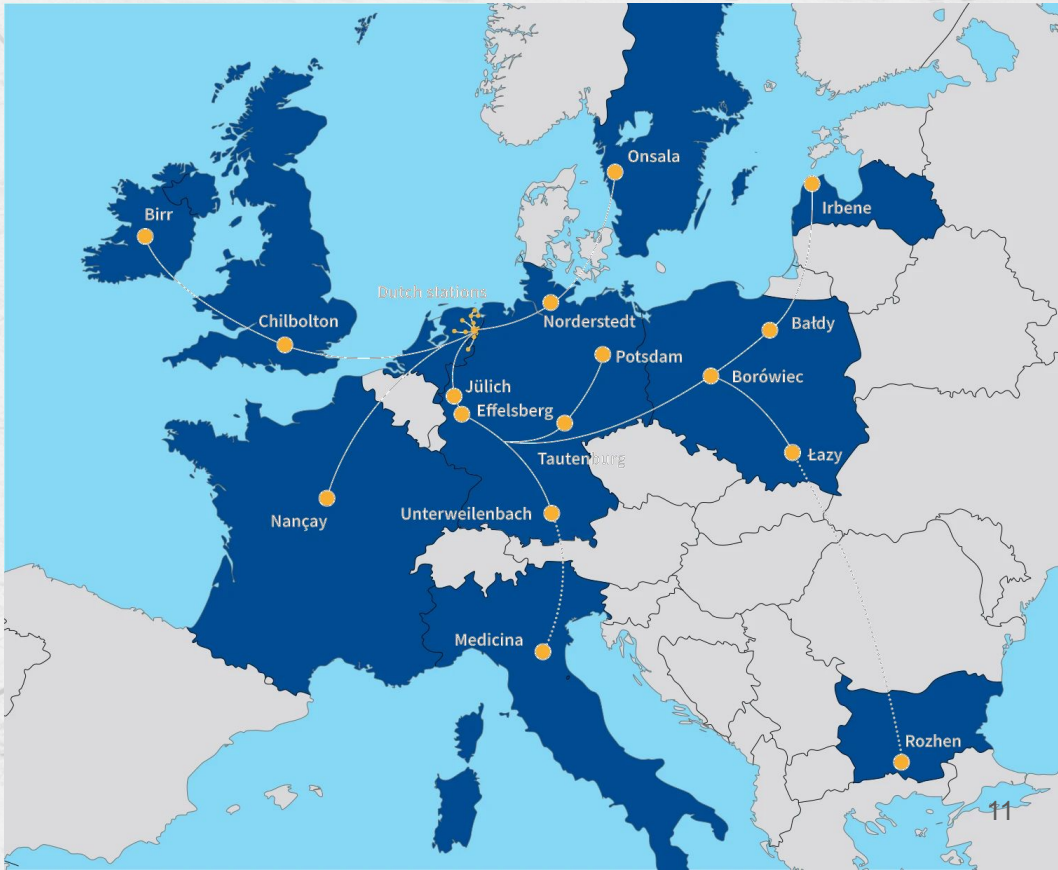


18 MHz VLBI of Jupiter on 7900 km baseline; Carr 1970

International LOFAR Telescope



3C 34; Mahatma+2024



What sets the ILT apart – angular scales

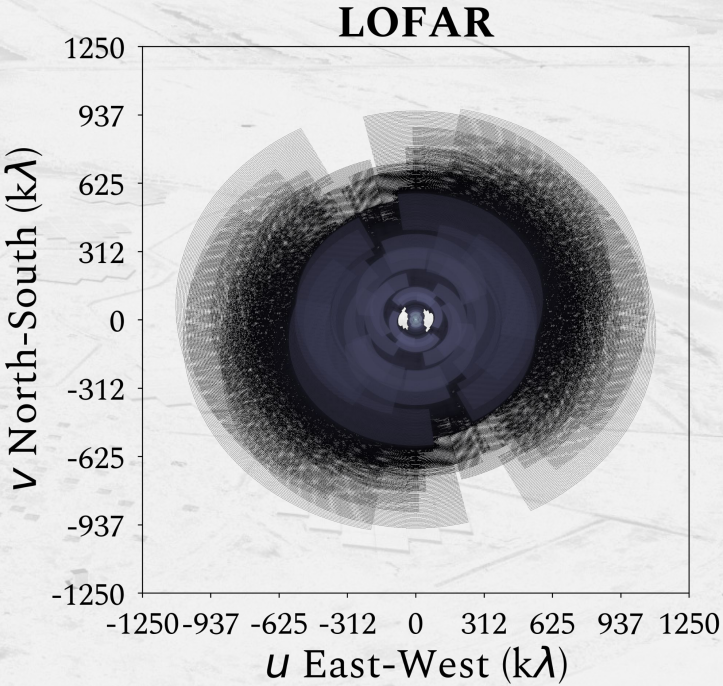
8 hour synthesis + 48 MHz bandwidth

Nearly fully sampled uv plane

Shortest baseline: ~100 m // ~1 deg

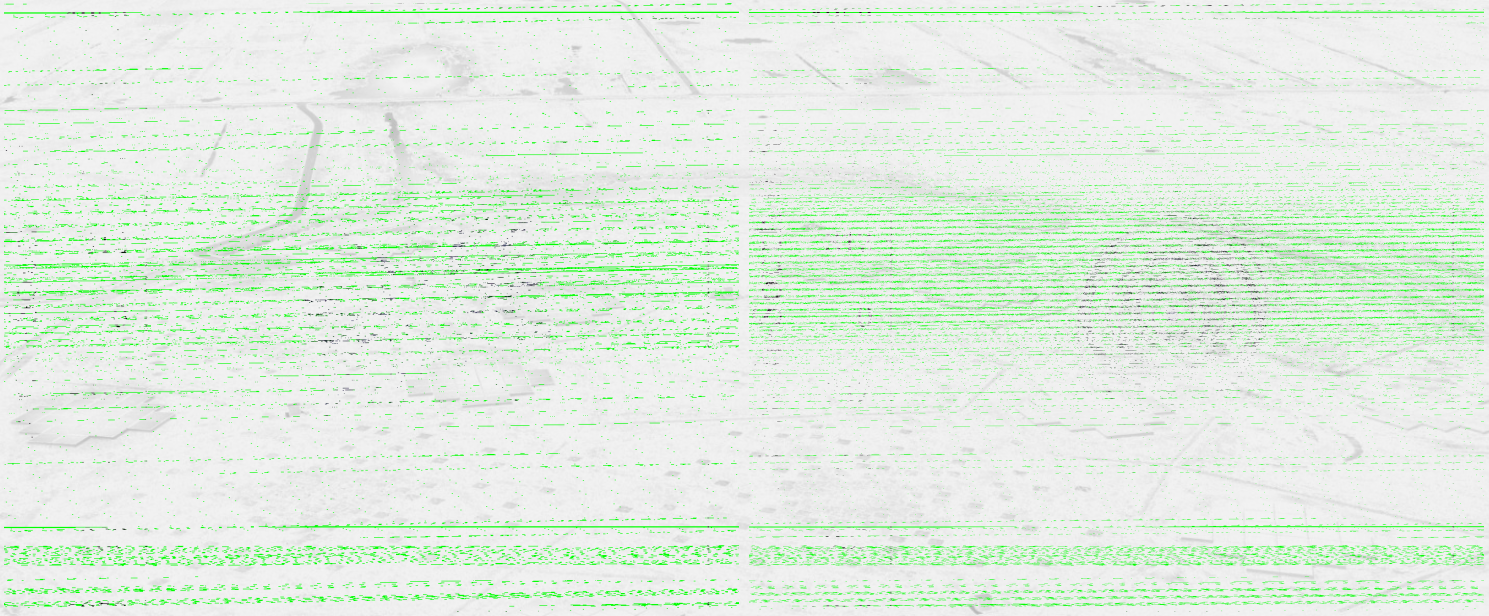
Longest baseline: ~1980 km // 0.2” @ 144 MHz

Missing baselines: 100-300 km east-west :)



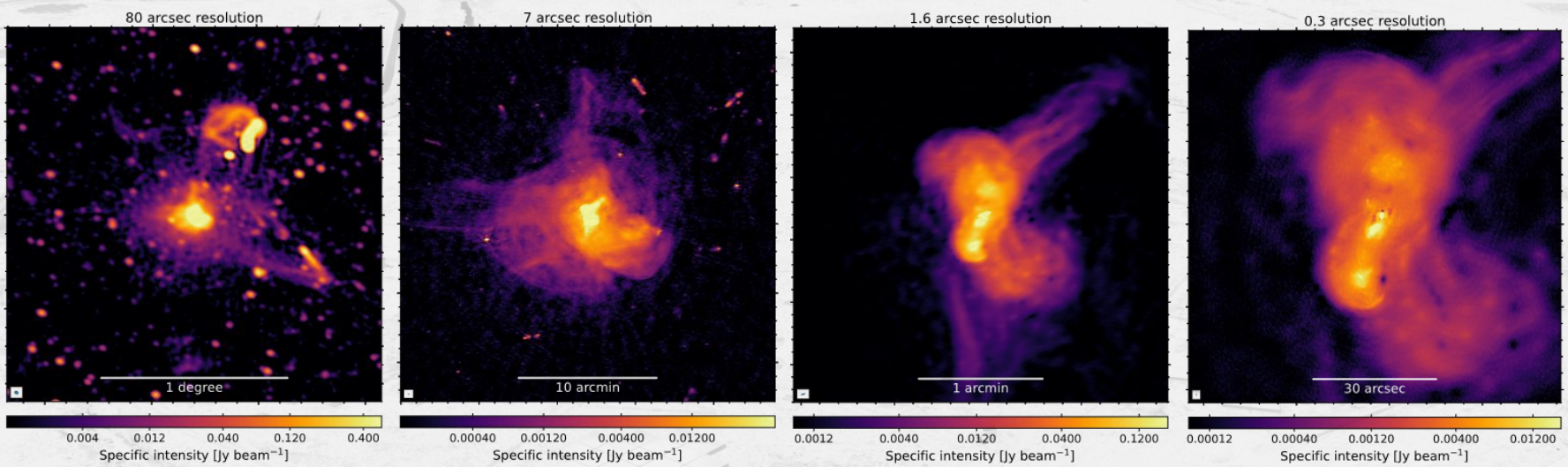
See https://tikk3r.github.io/wati/ for an interactive version

What sets the ILT apart – angular scales



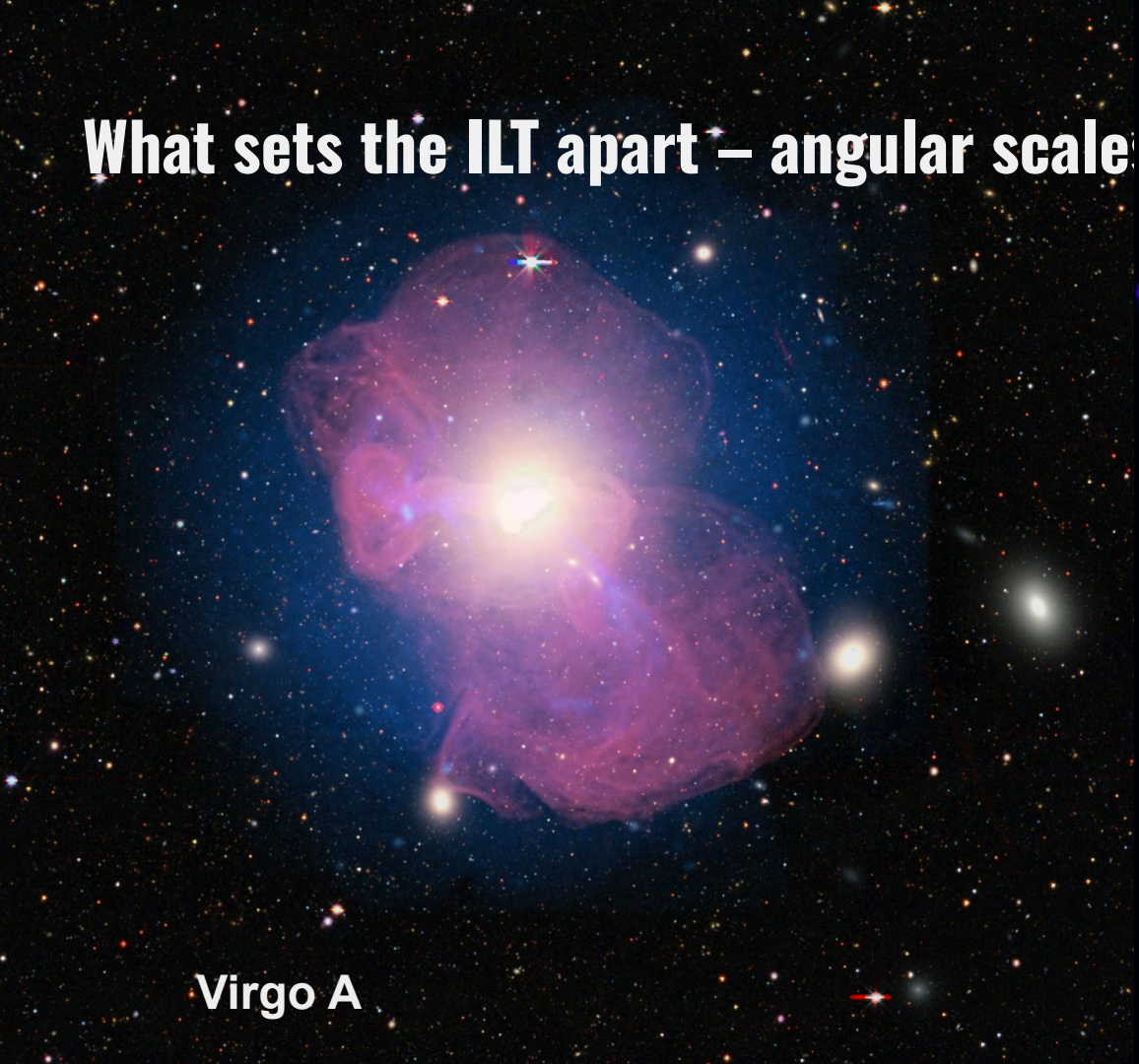
See https://tikk3r.github.io/wati/ for an interactive version

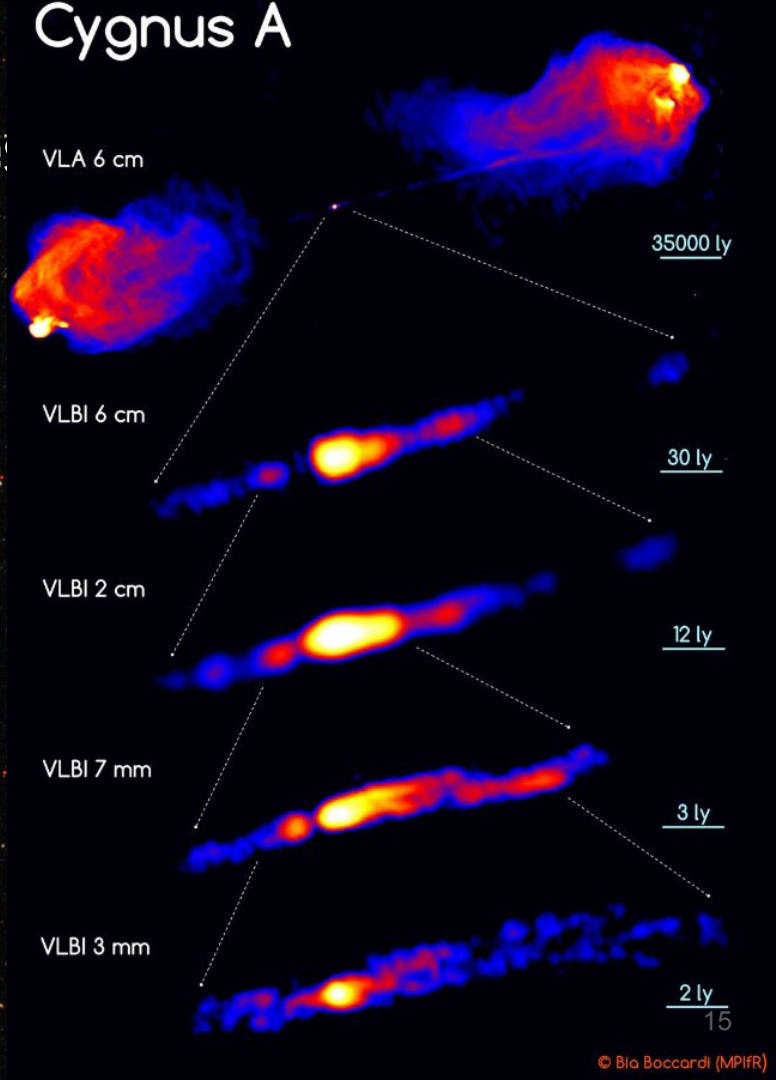
What sets the ILT apart – angular scales



van Weeren+2024

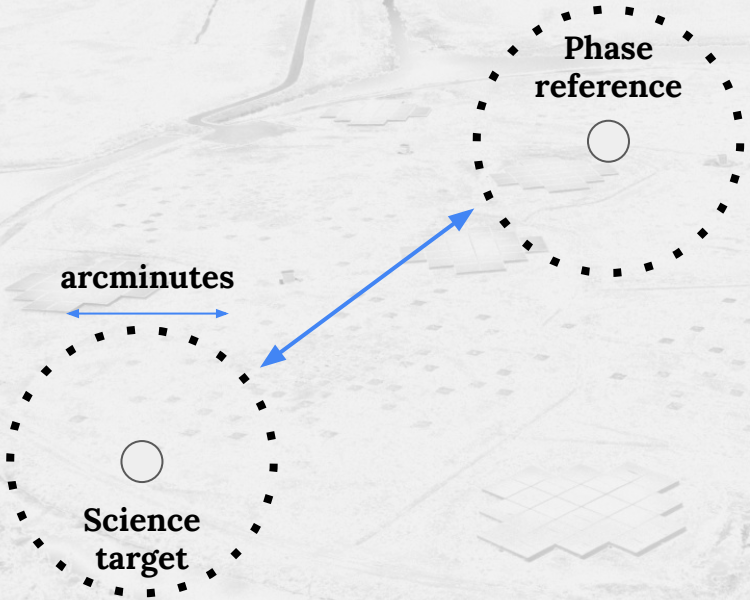
What sets the ILT apart – angular scale



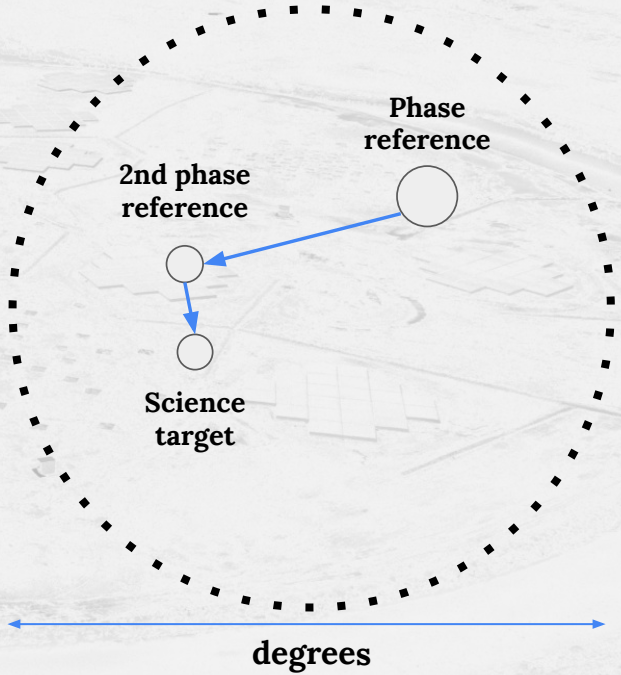


What sets the ILT apart – efficiency

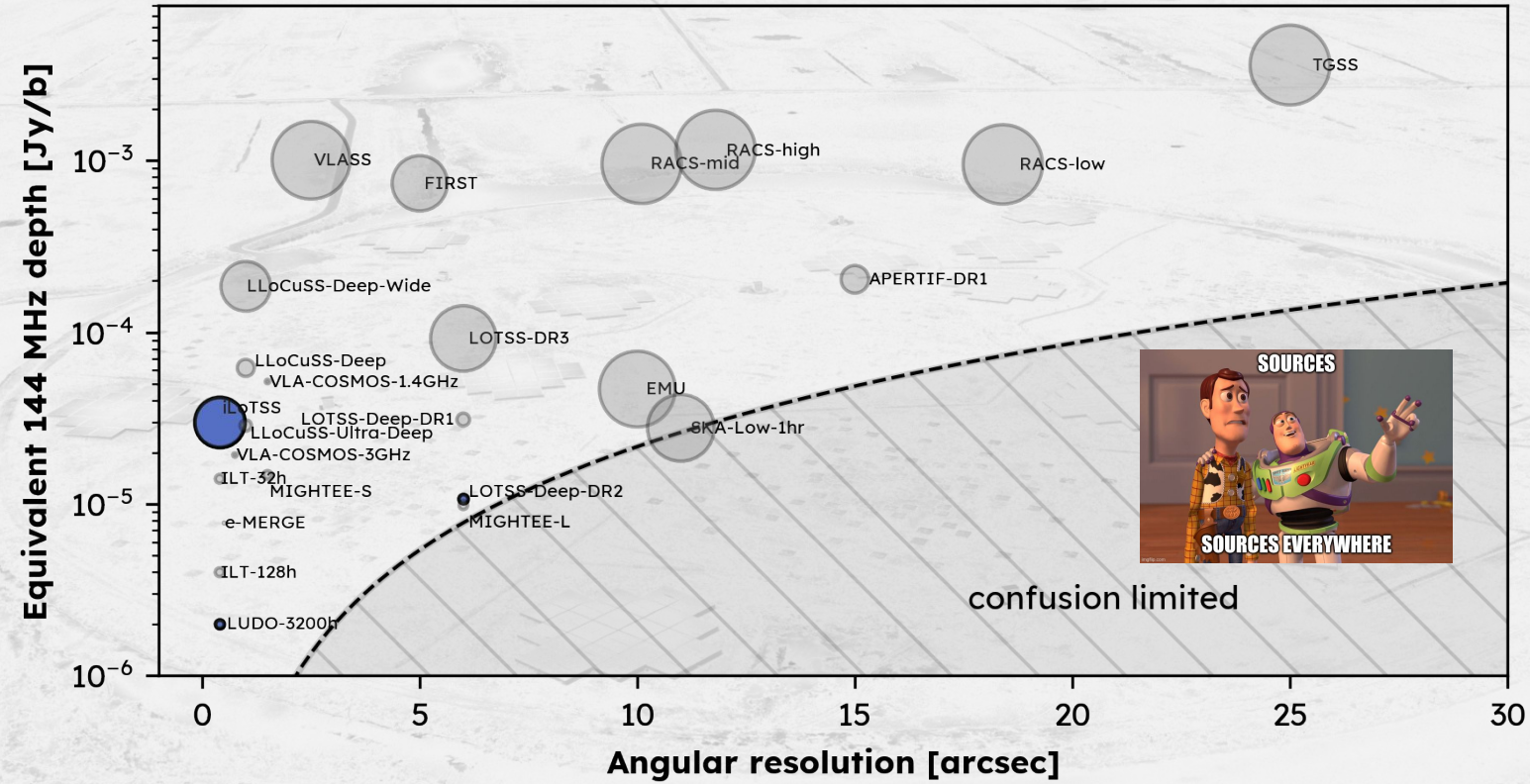
“Traditional” VLBI



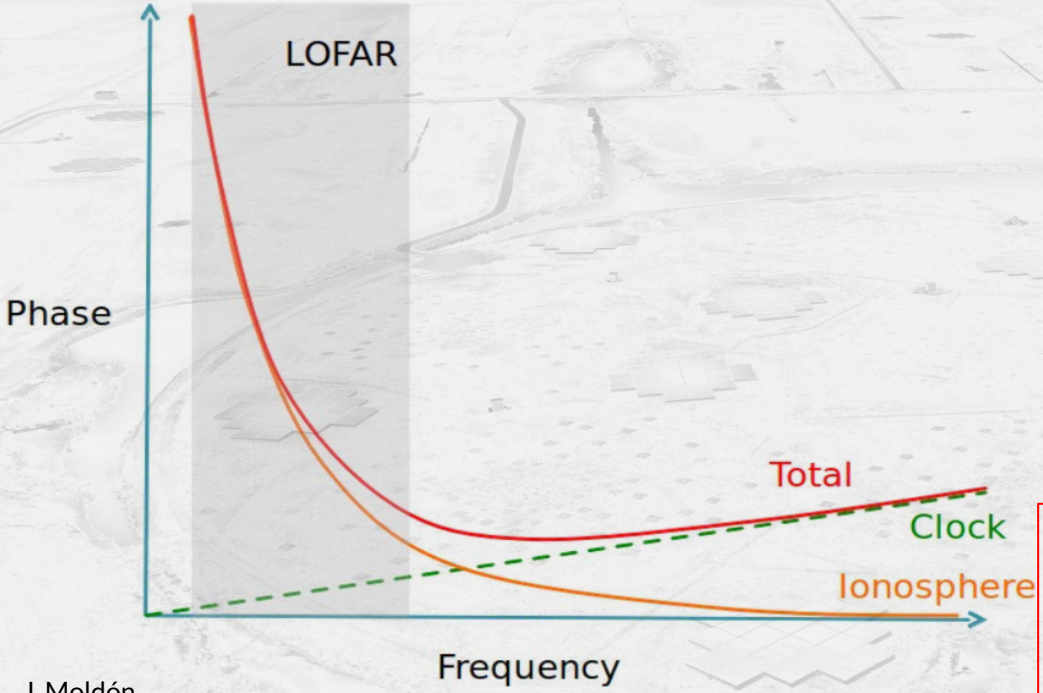
ILT



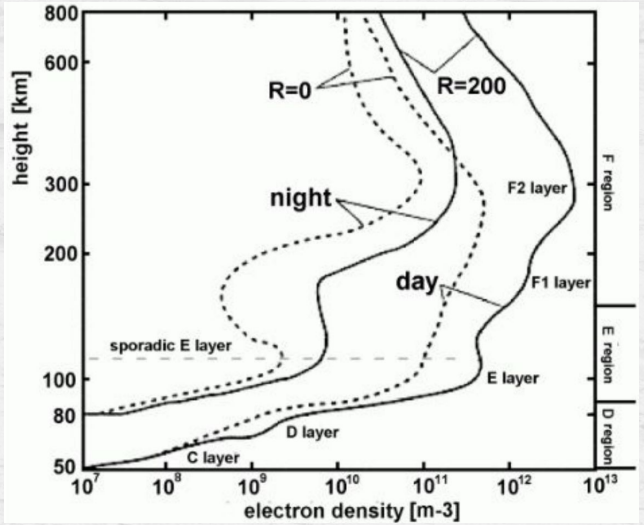
What sets the ILT apart – confusion



Low radio frequencies

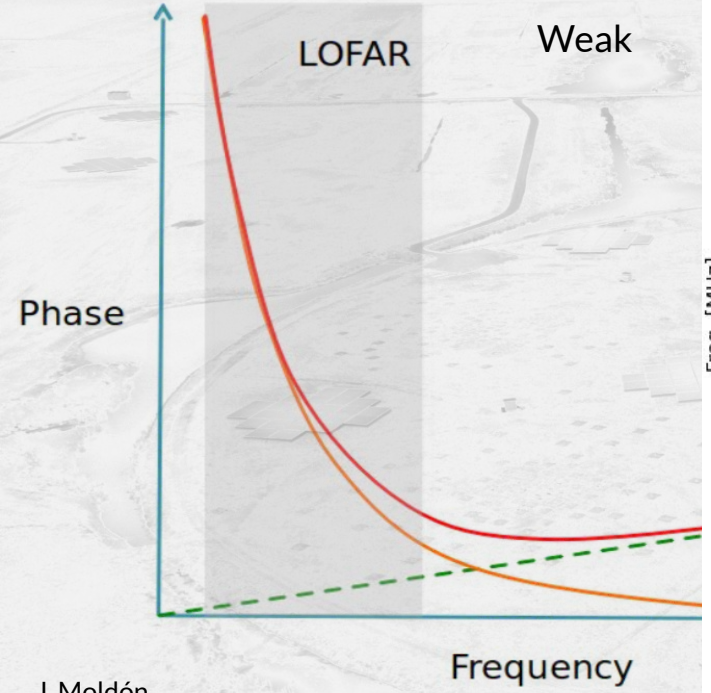


J. Moldón

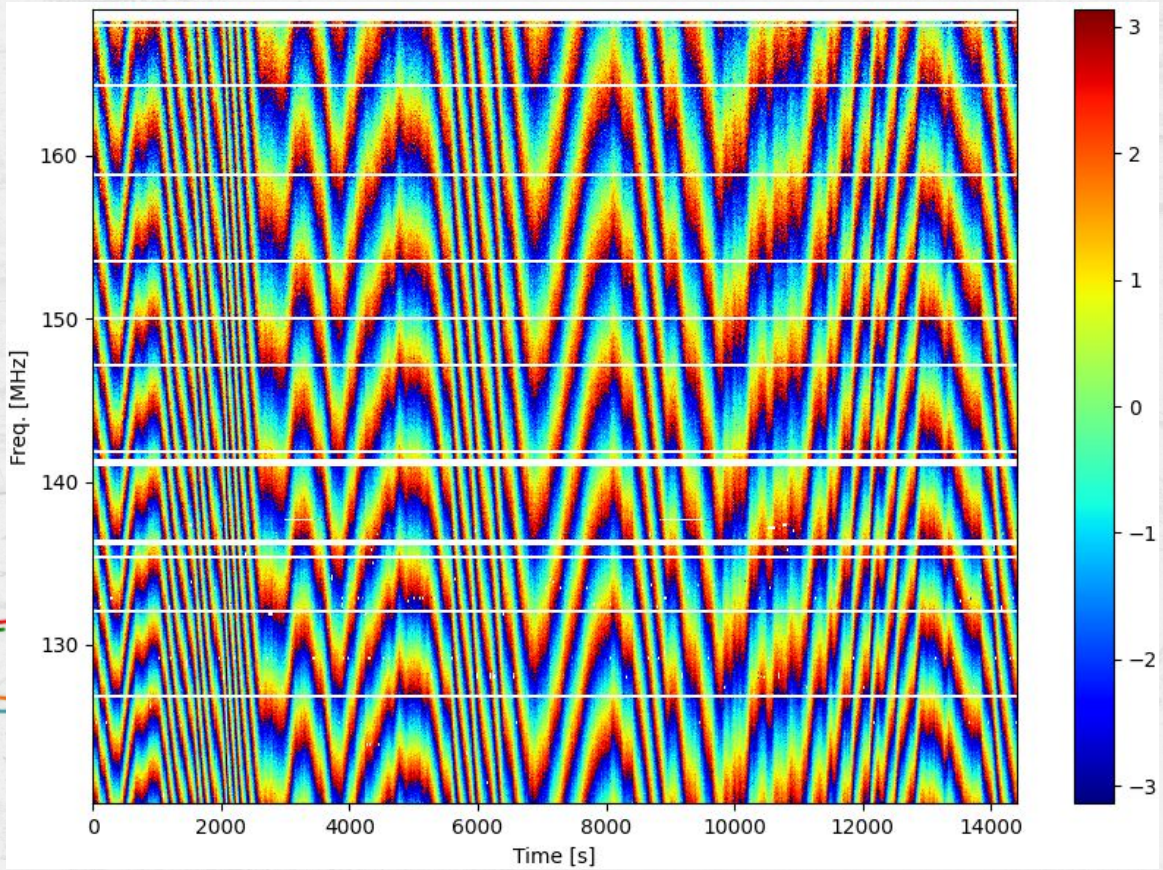


LOFAR is dominated by **dispersive delays** caused by the ionosphere, which scale as $\varphi \propto \nu^{-1}$

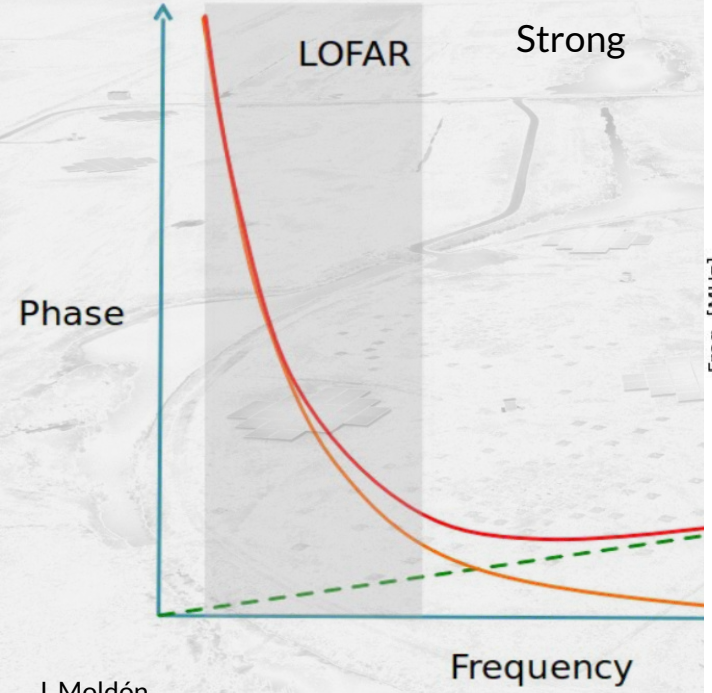
Low radio frequencies



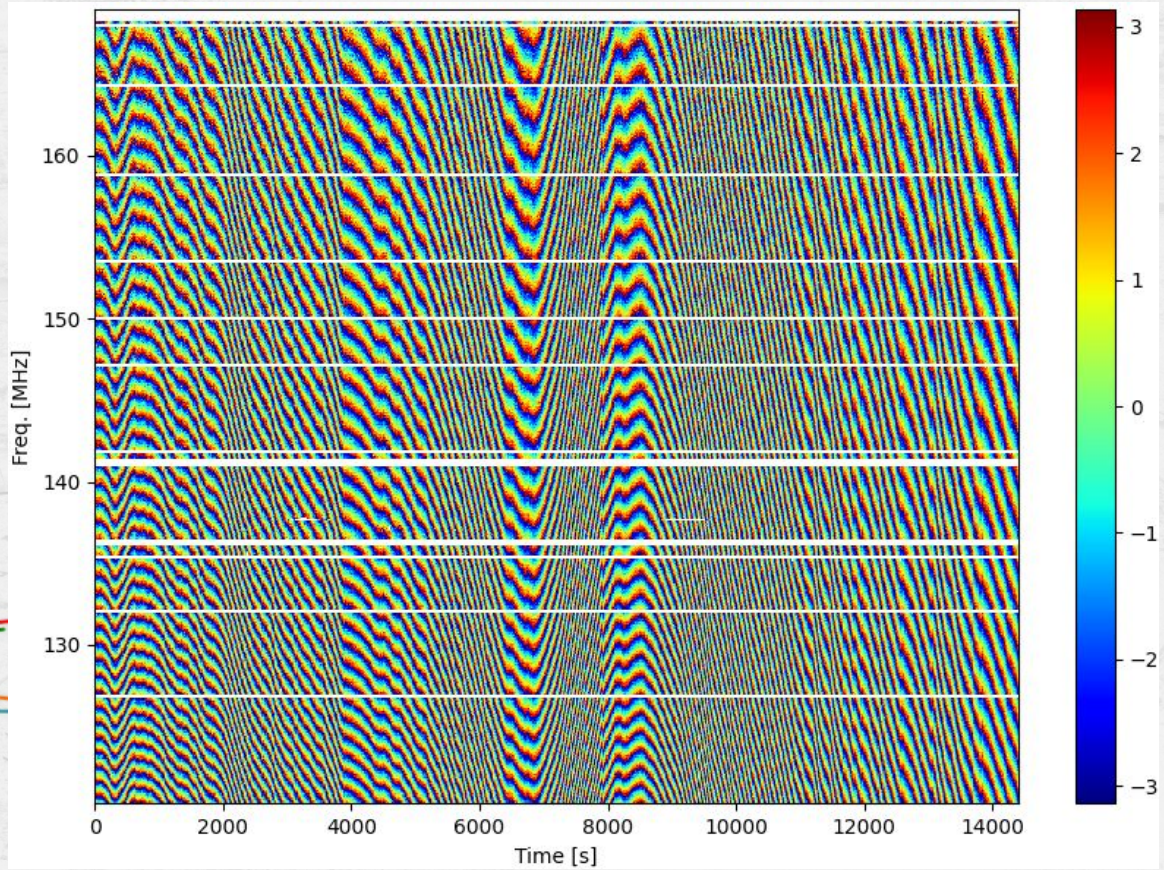
J. Moldón



Low radio frequencies

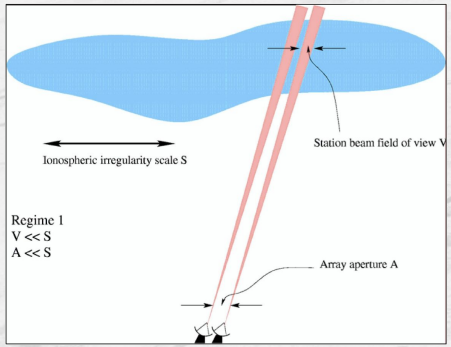


J. Moldón

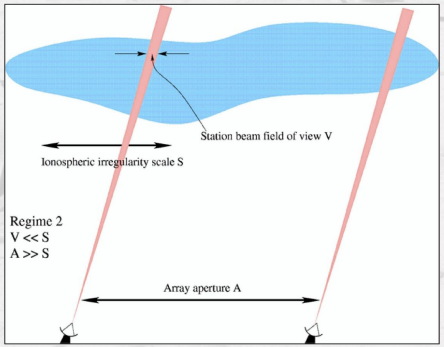


Very long baseline interferometry challenges

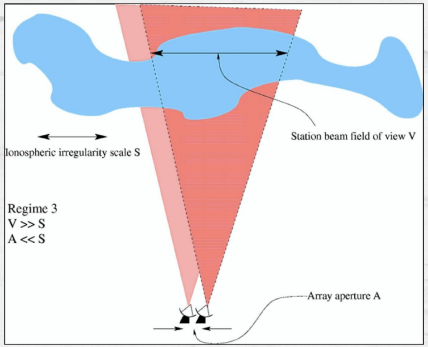
Wijnholds et al. 2010



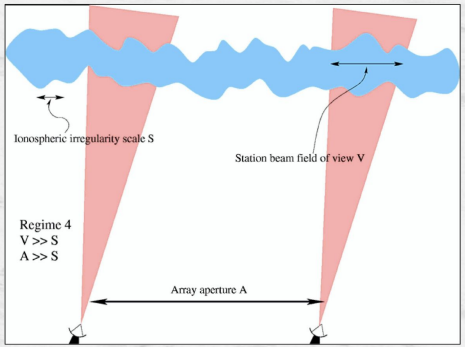
Antennas see the same ionosphere



One ionosphere per antenna

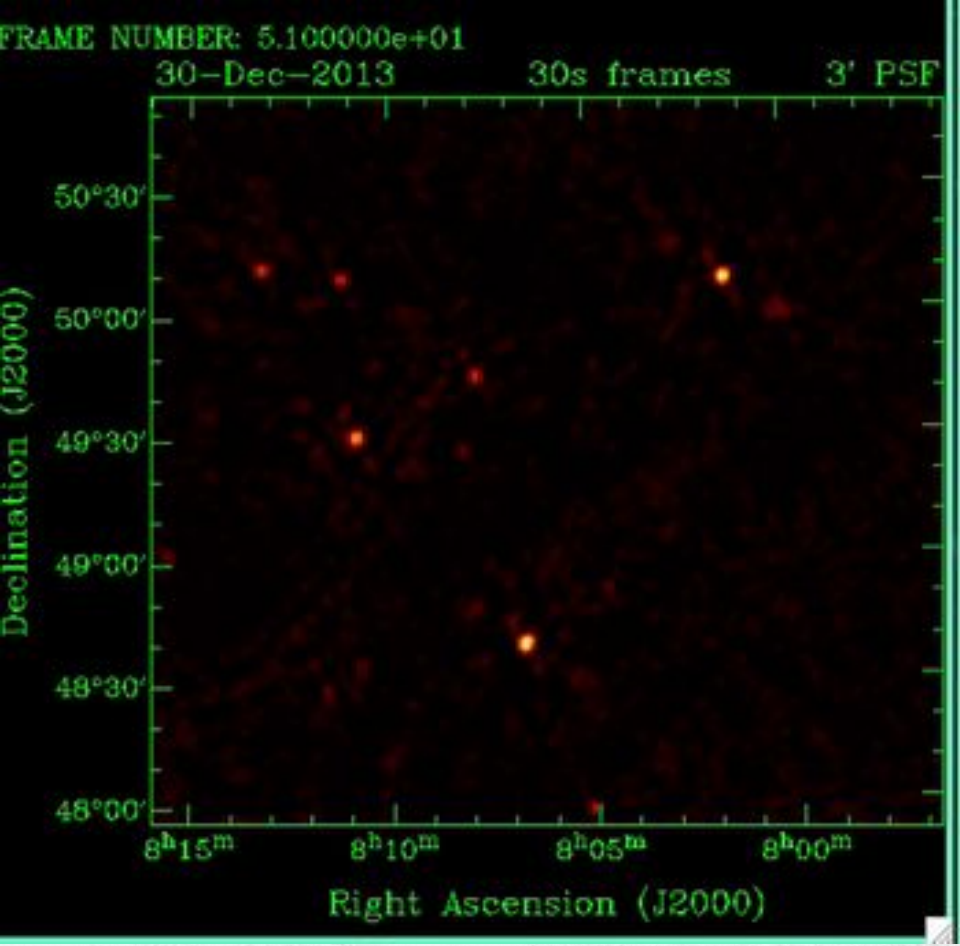


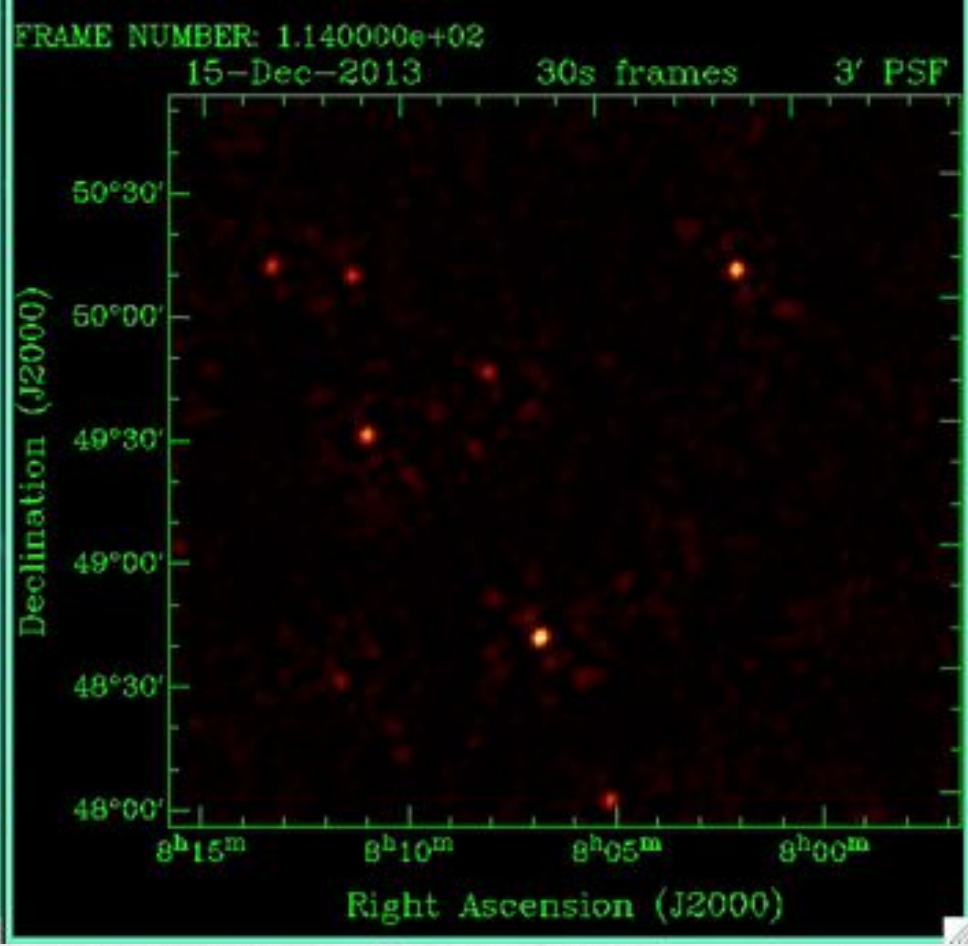
Multiple, but similar ionospheres per antenna



Multiple different ionospheres per antenna

Short baselines see similar ionospheres, long baselines see different independent ionospheres: a direction-, time-, frequency-dependent problem


FRAME NUMBER: 5.100000e+01
30-Dec-2013
30s frames
3' PSF
50°30'
50°00'
49°30'
49°00'
48°30'
48°00'
Declination (J2000)
8h15m
8h10m
8h05m
8h00m
Right Ascension (J2000)


FRAME NUMBER: 1.140000e+02
15-Dec-2013
30s frames
3' PSF
50°30'
50°00'
49°30'
49°00'
48°30'
48°00'
Declination (J2000)
8h15m
8h10m
8h05m
8h00m
Right Ascension (J2000)

Low radio frequencies

$$\Delta\phi_{\nu,f} = \phi_0 + \left(\frac{\delta\phi}{\delta\nu}\Delta\nu + \frac{\delta\phi}{\delta t}\Delta t\right)$$

$\phi_0 \equiv$ the **phase** error at t_0, ν_0

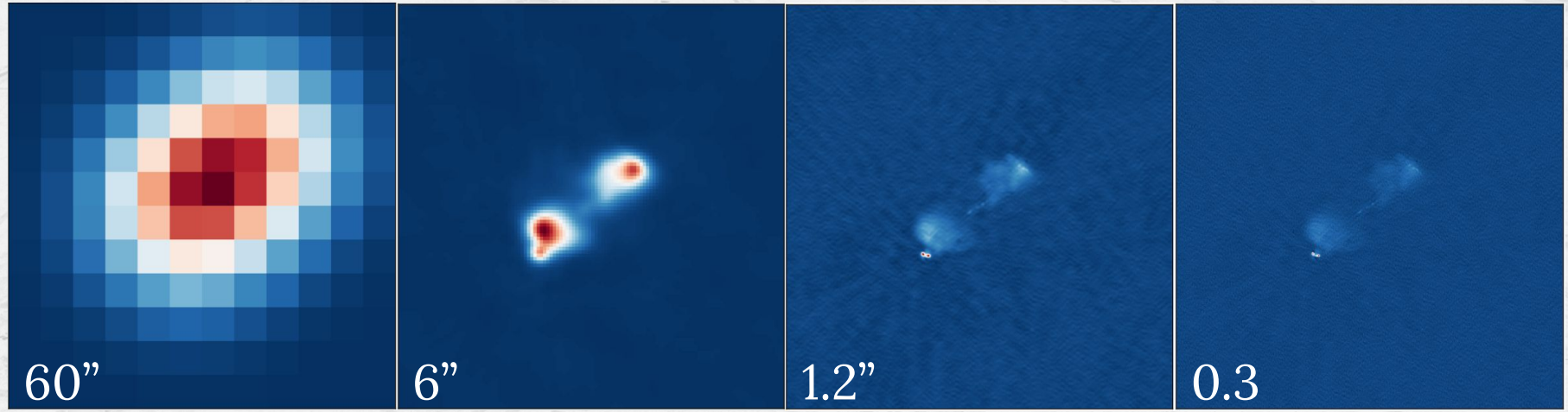
$\frac{\delta\phi}{\delta\nu} \equiv$ **delay** or delay residual

$\frac{\delta\phi}{\delta t} \equiv$ **rate**, delay rate, or delay residual

Dispersive (e.g. ionosphere)

non-dispersive (e.g. clock)

Very long baseline interferometry challenges



Higher resolution gives more detail, but generally at the cost of SNR

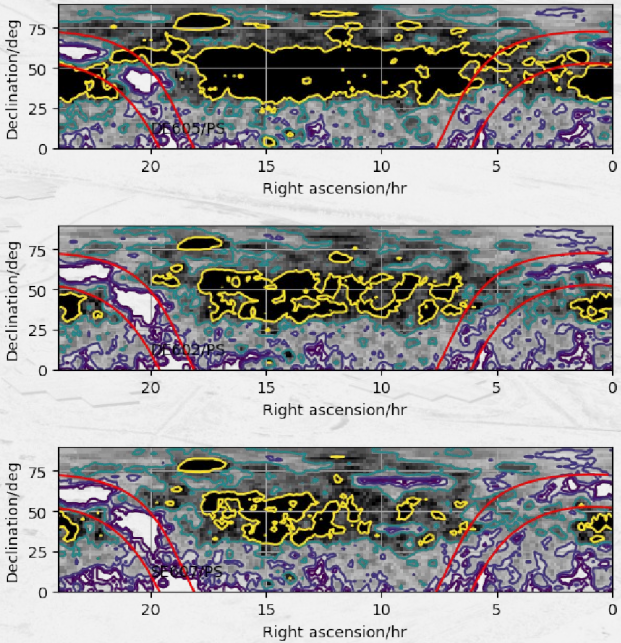
Long baseline calibrator survey (LBCS)

Catalogue of delay calibrator sources with strong compact signal

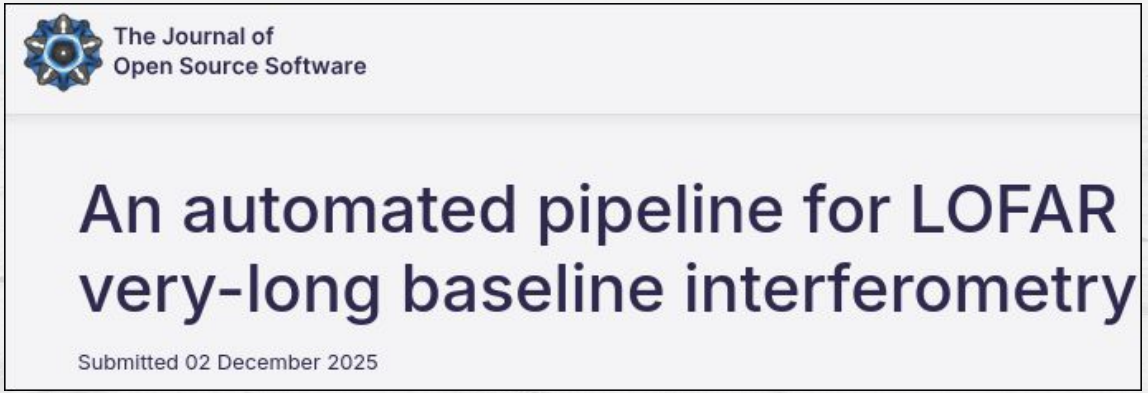
Predominantly dec > 30

Approx. 1 per square degree

https://lofar-surveys.org/lbcs.html



Jackson+2022



van der Wild+subm.

PILOT

Pipeline for the International LOFAR Telescope

https://github.com/LOFAR-VLBI/pilot

PILOT

One stop shop end-to-end pipeline

Single or multi-target

Full FoV imaging

Polarisation calibration/imaging (freshly merged)

Scalable and user-friendly

Single machine or Slurm through CWL + flocs

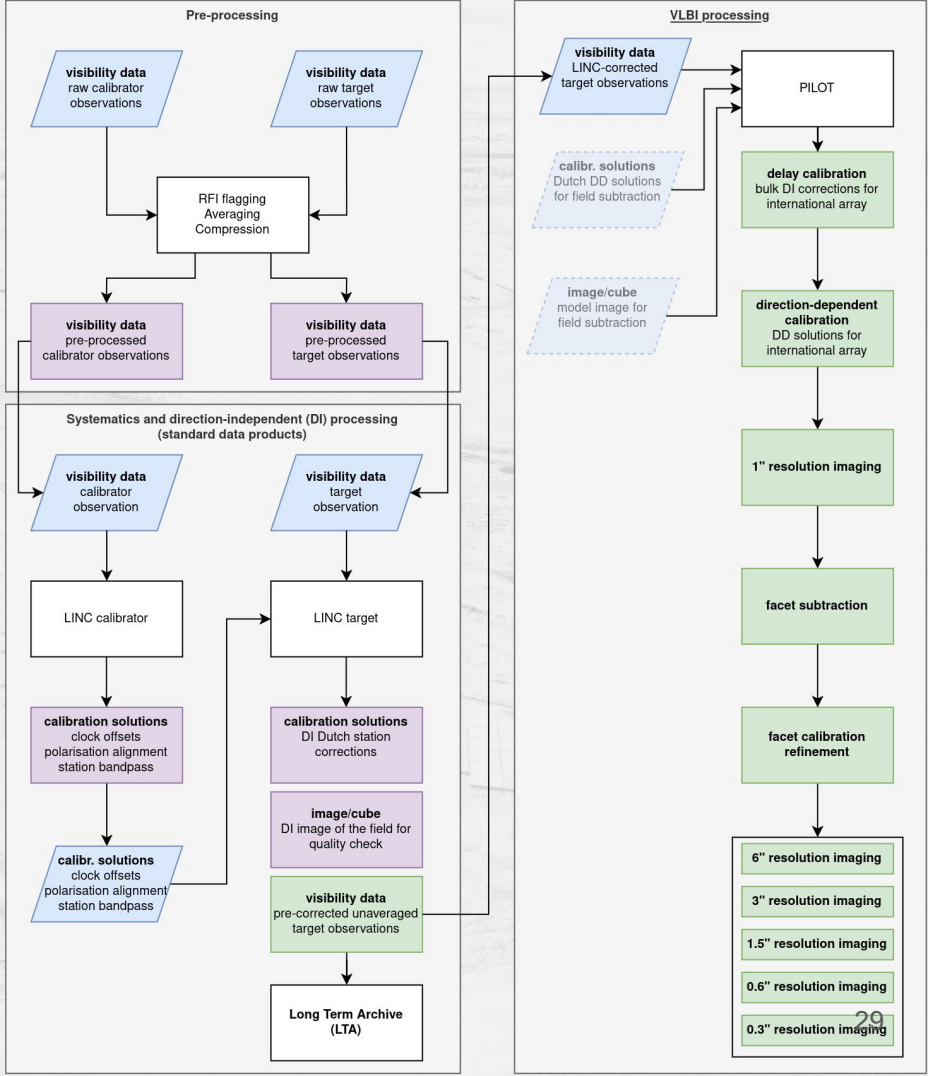
PILOT

Scalable and user-friendly

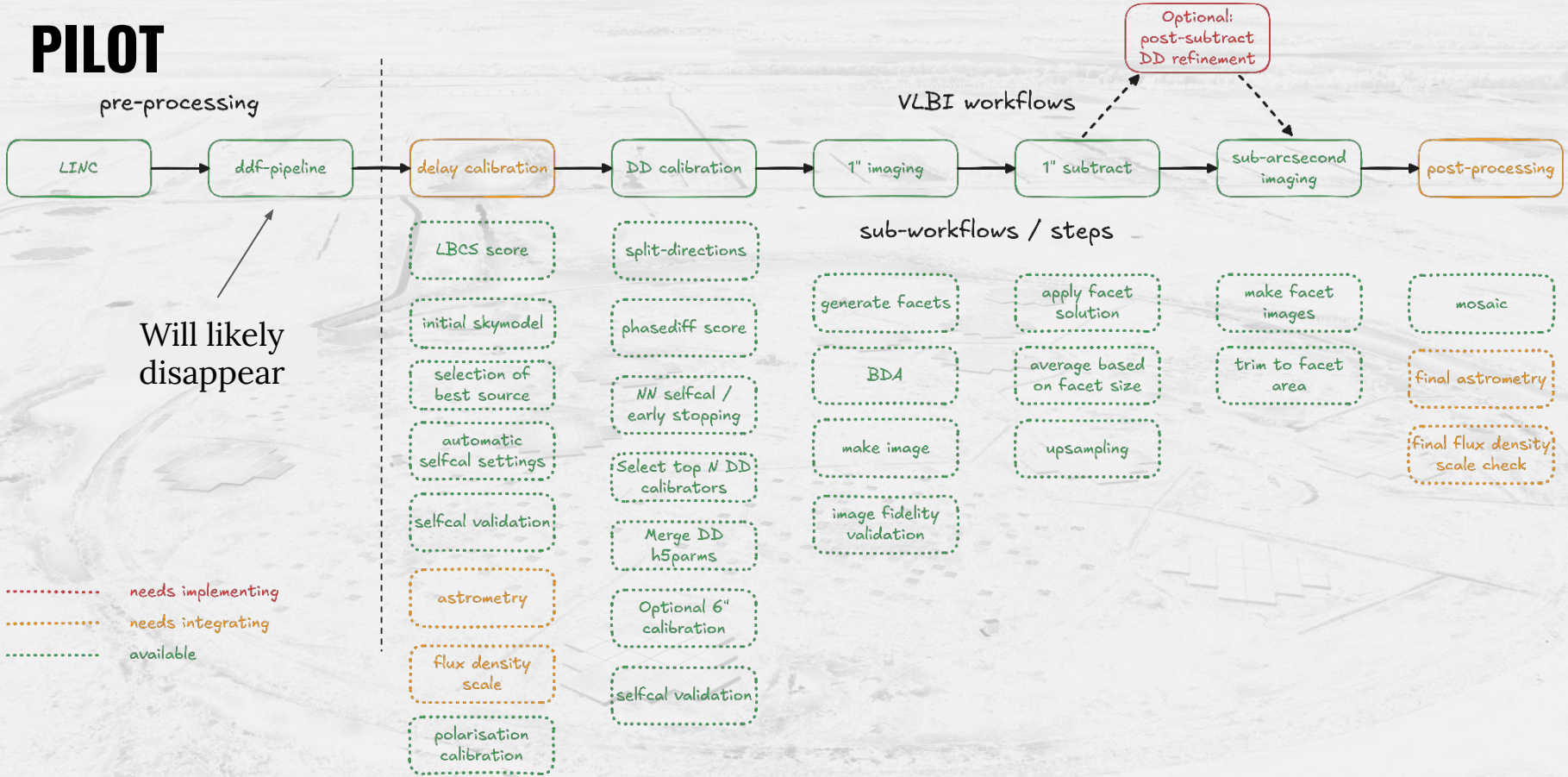
Single machine or Slurm through CWL + flocs

Automated
- selection of calibrators
- calibration settings
- validation of image and solution quality

PILOT


Pre-processing
visibility data
raw calibrator observations
visibility data
raw target observations
RFI flagging
Averaging
Compression
visibility data
pre-processed calibrator observations
visibility data
pre-processed target observations
Systematics and direction-independent (DI) processing (standard data products)
visibility data
calibrator observation
visibility data
target observation
LINC calibrator
LINC target
calibration solutions
clock offsets
polarisation alignment
station bandpass
calibration solutions
DI Dutch station corrections
calibr. solutions
clock offsets
polarisation alignment
station bandpass
image/cube
DI image of the field for quality check
visibility data
pre-corrected unaveraged target observations
Long Term Archive (LTA)
VLBI processing
visibility data
LINC-corrected target observations
PILOT
calibr. solutions
Dutch DD solutions for field subtraction
delay calibration
bulk DI corrections for international array
image/cube
model image for field subtraction
direction-dependent calibration
DD solutions for international array
1" resolution imaging
facet subtraction
facet calibration refinement
6" resolution imaging
3" resolution imaging
1.5" resolution imaging
0.6" resolution imaging
0.3" resolution imaging

PILOT

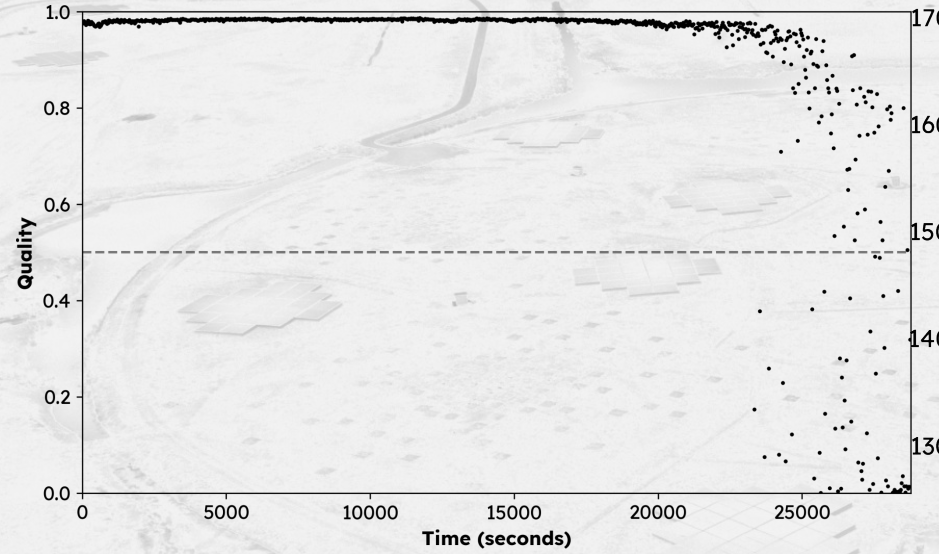

pre-processing
VLBI workflows
Optional: post-subtract DD refinement
LINC
ddf-pipeline
delay calibration
DD calibration
1" imaging
1" subtract
sub-arcsecond imaging
post-processing
Will likely disappear
sub-workflows / steps
LBCS score
initial skymodel
selection of best source
automatic selfcal settings
selfcal validation
astrometry
flux density scale
polarisation calibration
split-directions
phasediff score
NN selfcal / early stopping
Select top N DD calibrators
Merge DD h5parms
Optional 6" calibration
selfcal validation
generate facets
BDA
make image
image fidelity validation
apply facet solution
average based on facet size
upsampling
make facet images
trim to facet area
mosaic
final astrometry
final flux density scale check
needs implementing
needs integrating
available

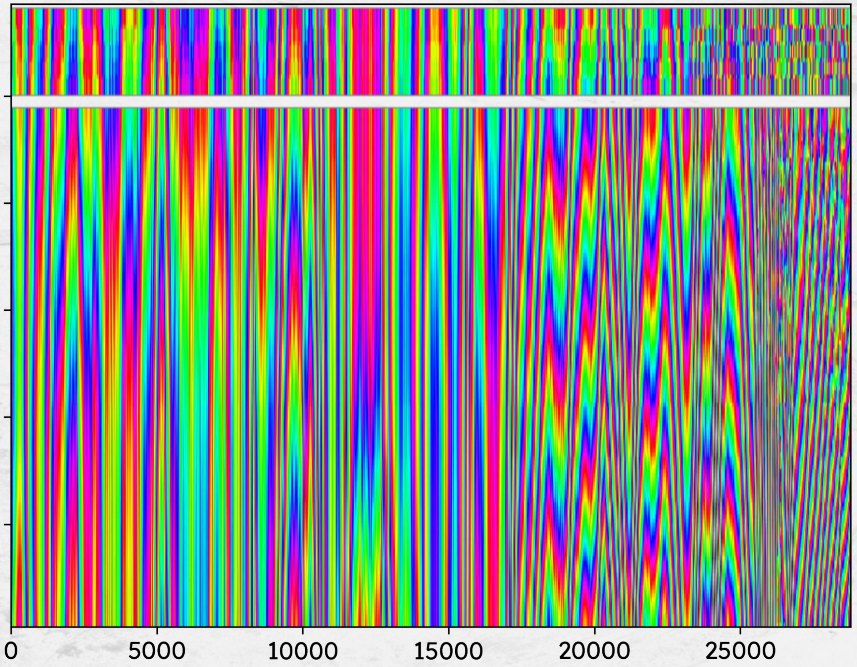
Delay calibration is the absolute critical point-of-no-return!

PILOT - automatic calibration settings

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imsize                          = 1024
pixelscale                      = 0.075
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maskthreshold                   = [7.0]
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soltype_list                    = ['scalarphasediff','scalarphase','scalarcomplexgain','fulljones']
solint_list                     = ['4min','33s','20min','20min']
nchan_list                      = [1,1,1,1]
smoothnessconstraint_list       = [15.0,1.5,5.0,5.0]
smoothnessreffrequency_list     = [120.0,120.0,0.0,0.0]
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forwidefield                    = "True"
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parallelgridding                = 6
channelsout                     = 12
fitspectralpol                  = 5
update_multiscale               = "True"
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antenna_smoothness_factors_list =
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robust                          = -1.4
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PILOT - automatic solution quality validation



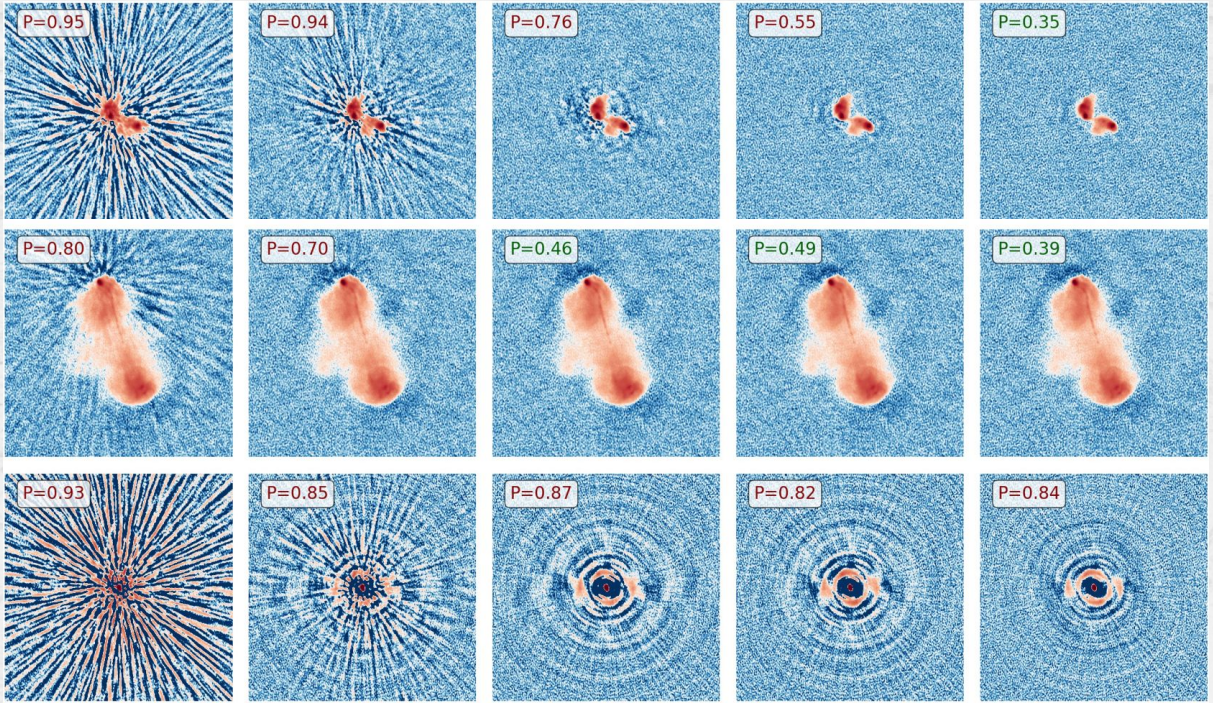


PILOT - automatic image quality validation

Neural network for assessing convergence

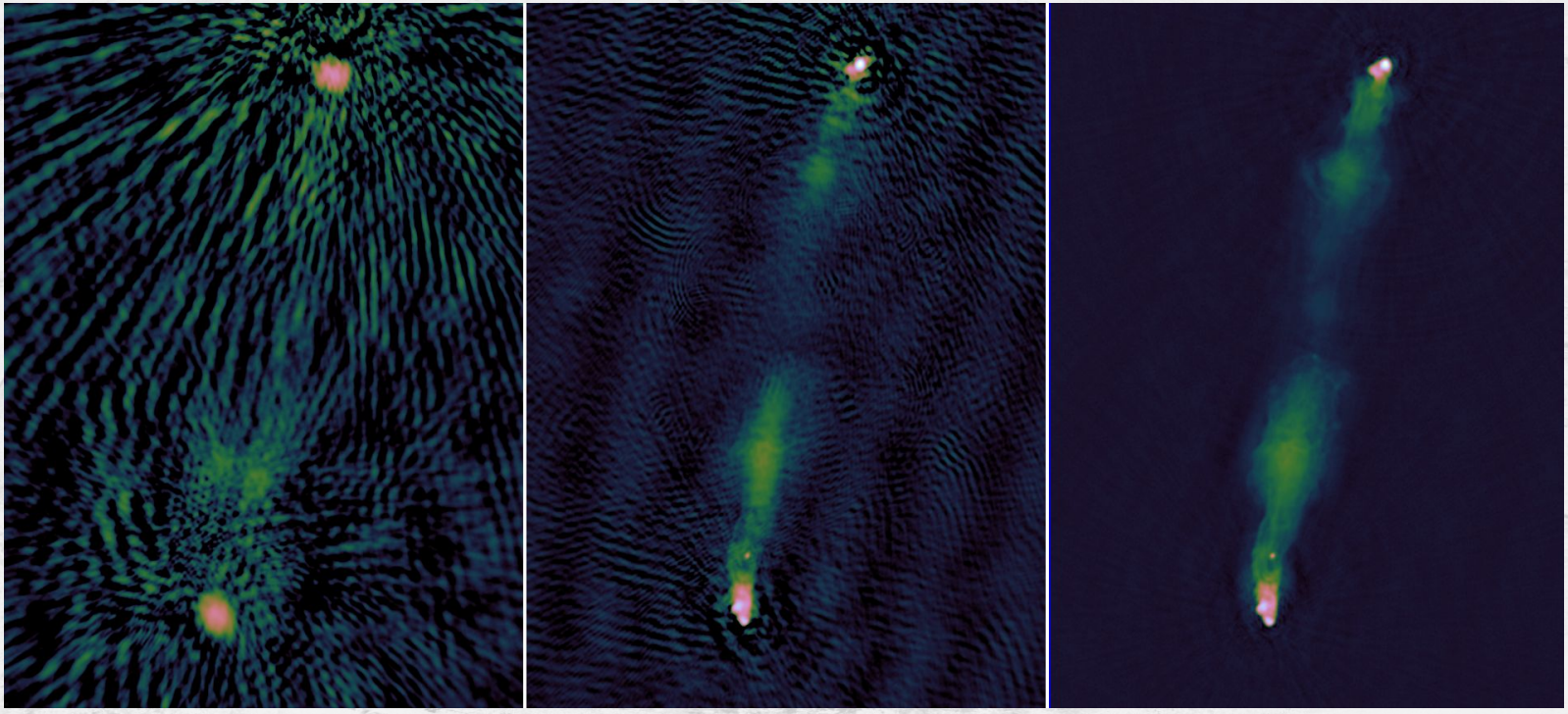
Refined from DINOv2

Trained on many selfcal images from widefield and LoTSS-HR with manual “stop/continue” labelling



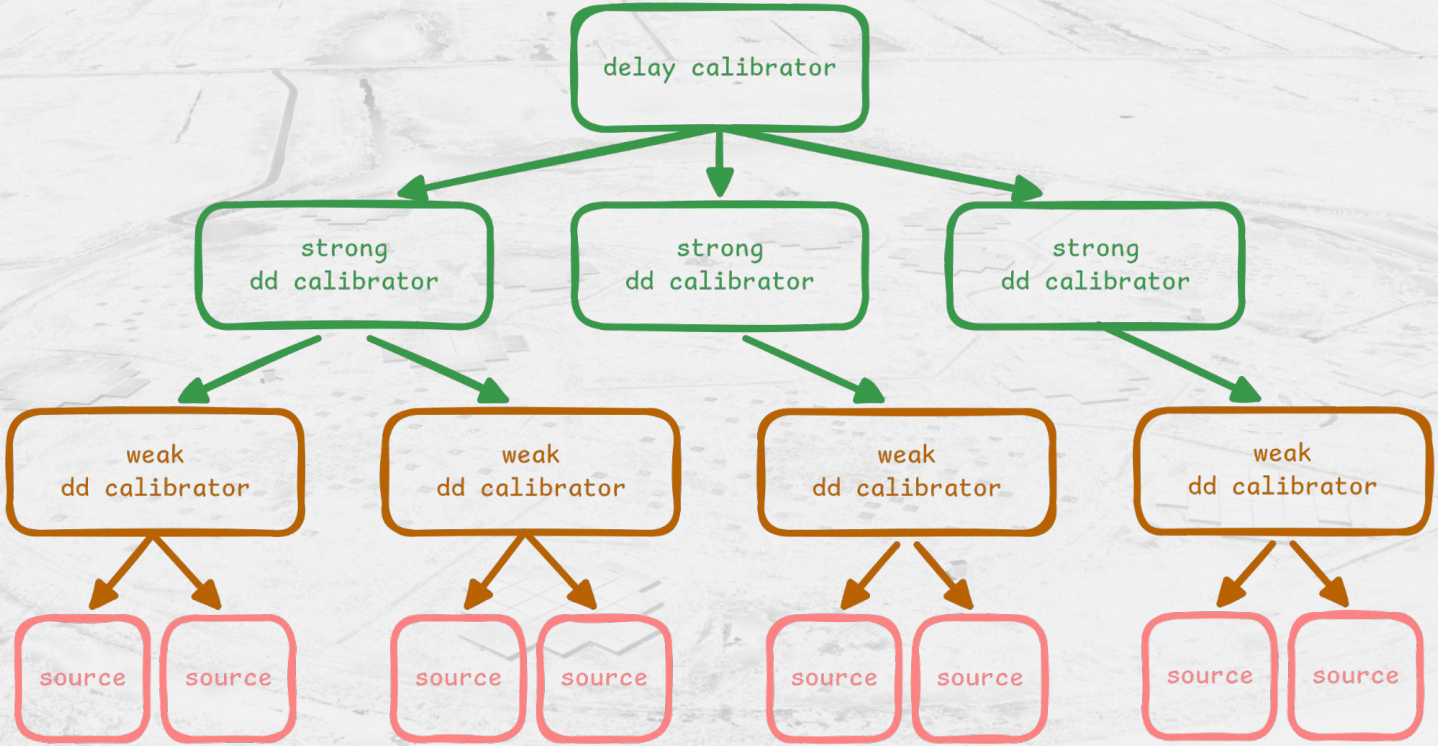
Detecting selfcal convergence (de Jong+2025)

PILOT - delay calibration



systematics + NL DI | VLASS starting model | Full dd calibration

PILOT - direction-dependent calibration



PILOT

Active working group with a strong feedback loop

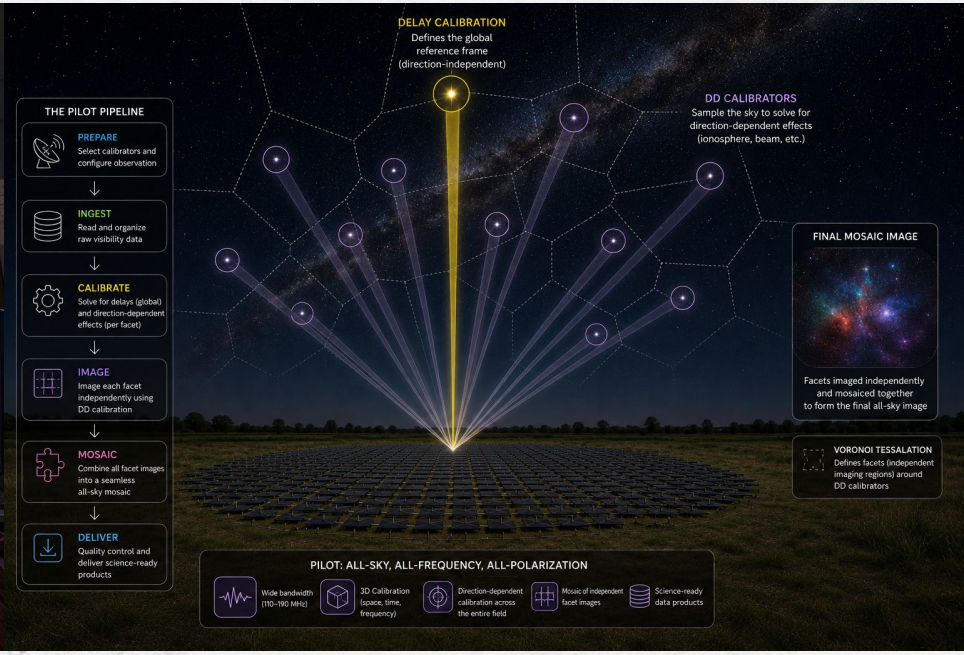
Regular “busy weeks” to develop the pipeline, help with data reduction etc.

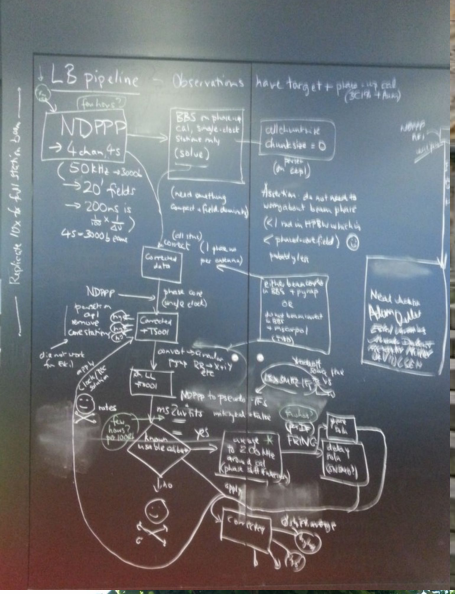
Tri-weekly telecons

Active Slack workspace

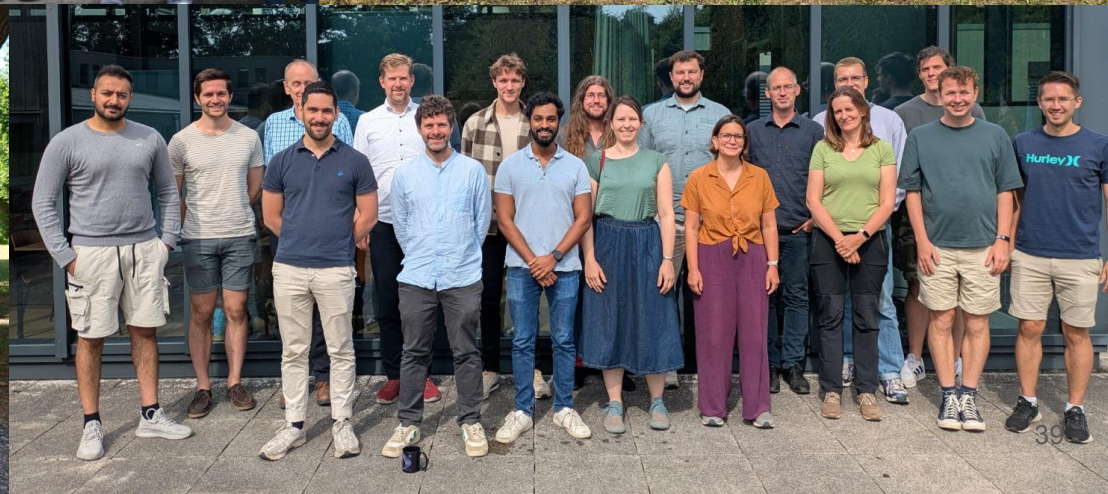
GPT Image 2.0's idea of a busy week and the pipeline





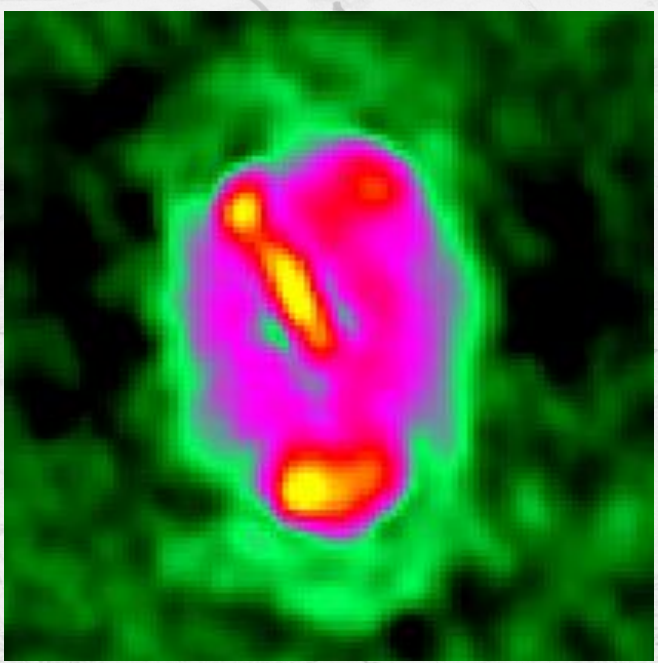

LB pipeline
NDPPP
Compress
Compress
Compress
FRING



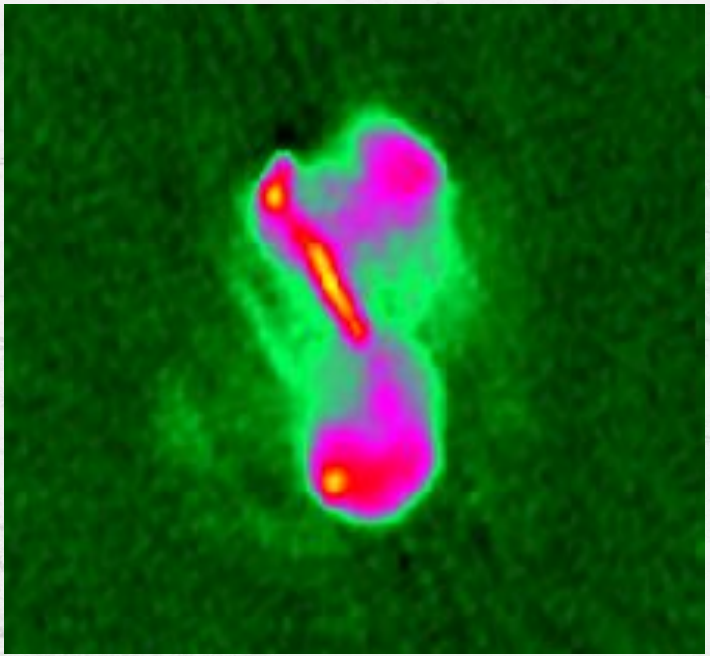

Hurley

PILOT

Then (Sweijen+2022)



Now



PILOT

Affordable processing

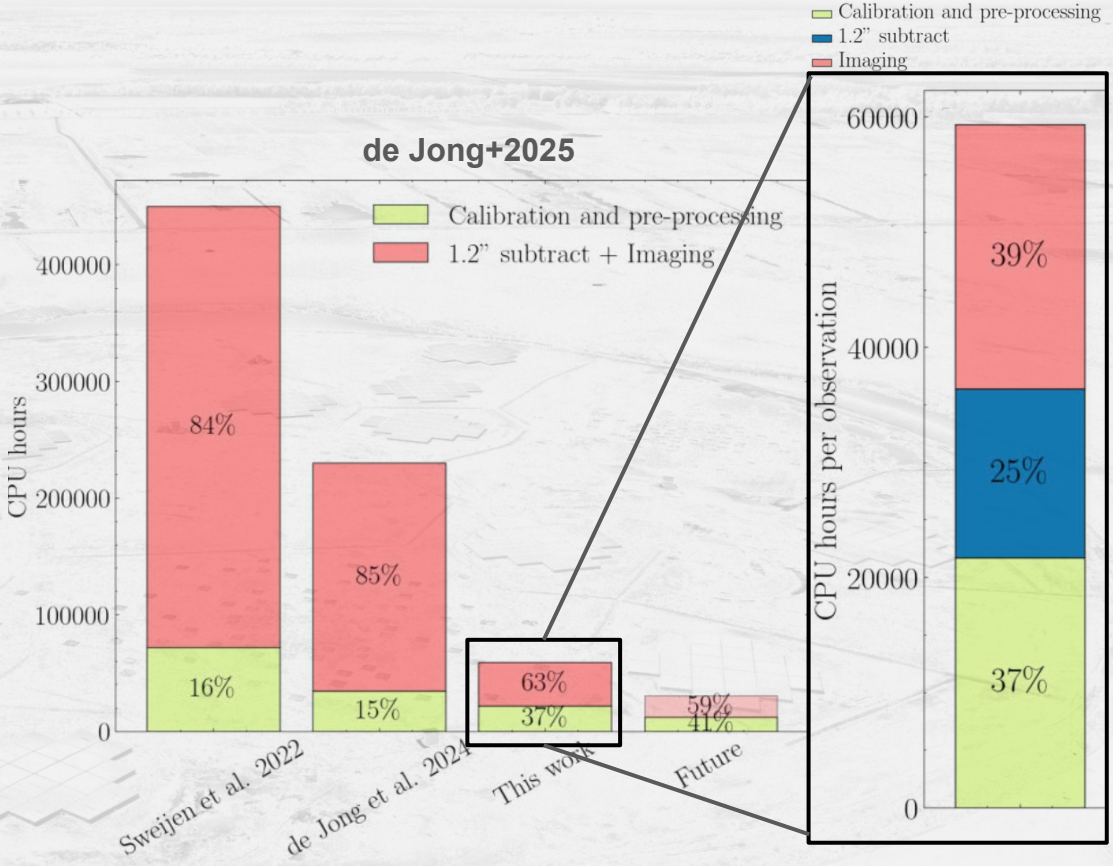
~3,000 ch single target

~10,000 ch 100 targets

~60,000 ch full FoV

LoTSS DR2 ≈ 5M ch

iLoTSS ≈ 273M ch
841 DR2 ponitings
+ 3,714 new pointings



Science with the ILT

Science with the ILT

Matched-resolution multi-wavelength

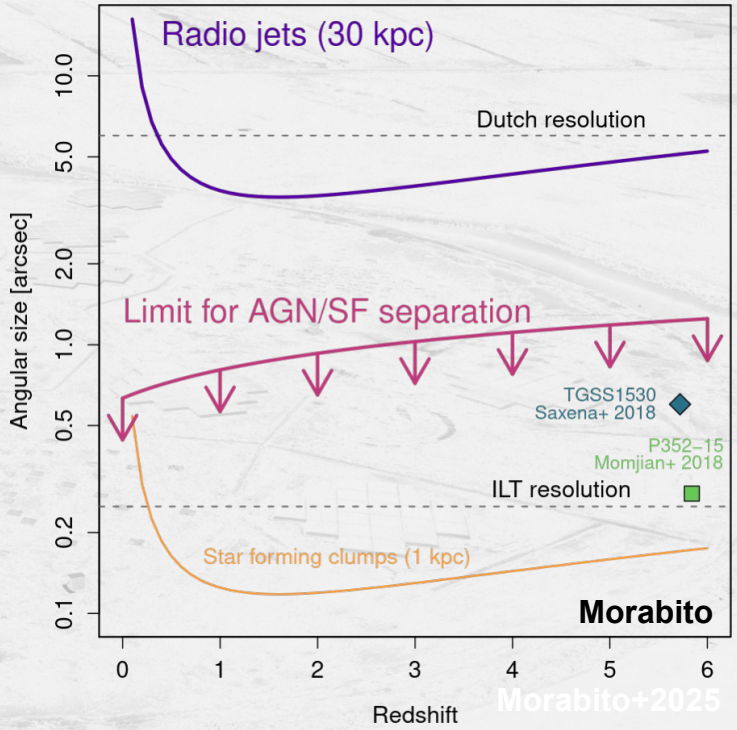
Same spatial scales between optical, x-ray, IR etc.

Statistical studies

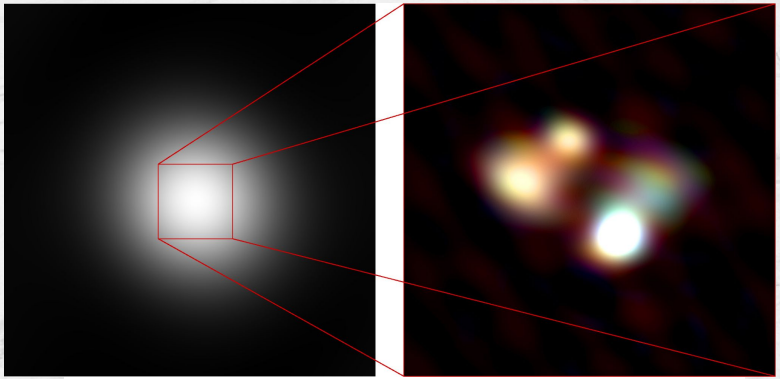
Blind sample follow-up, luminosity functions (see Leah's talk S9 Wed)

Rare/serendipitous object discovery space

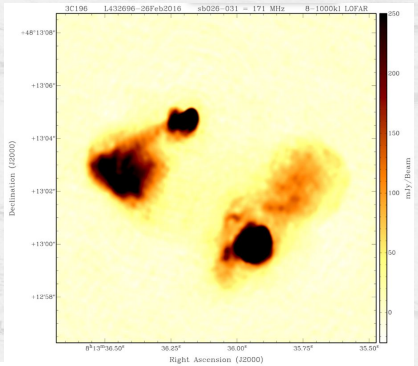
Lenses, high-z AGNs, strange objects



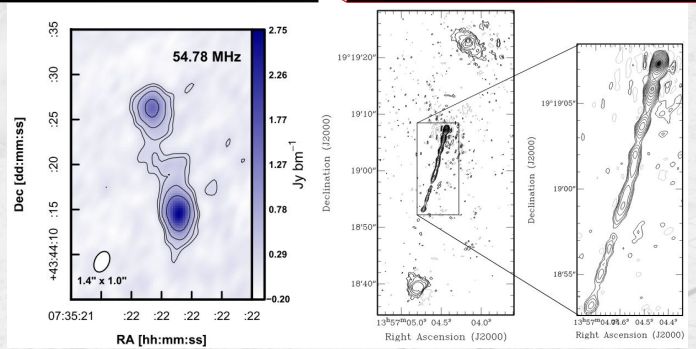
Science with the ILT



Wucknitz 2010

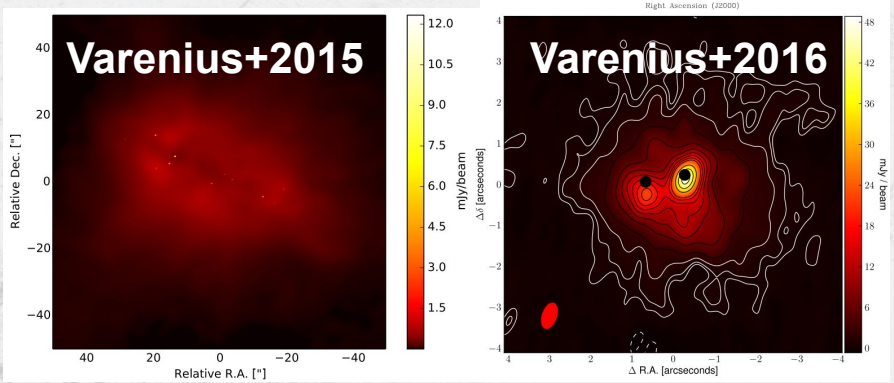


De Bruyn 2016

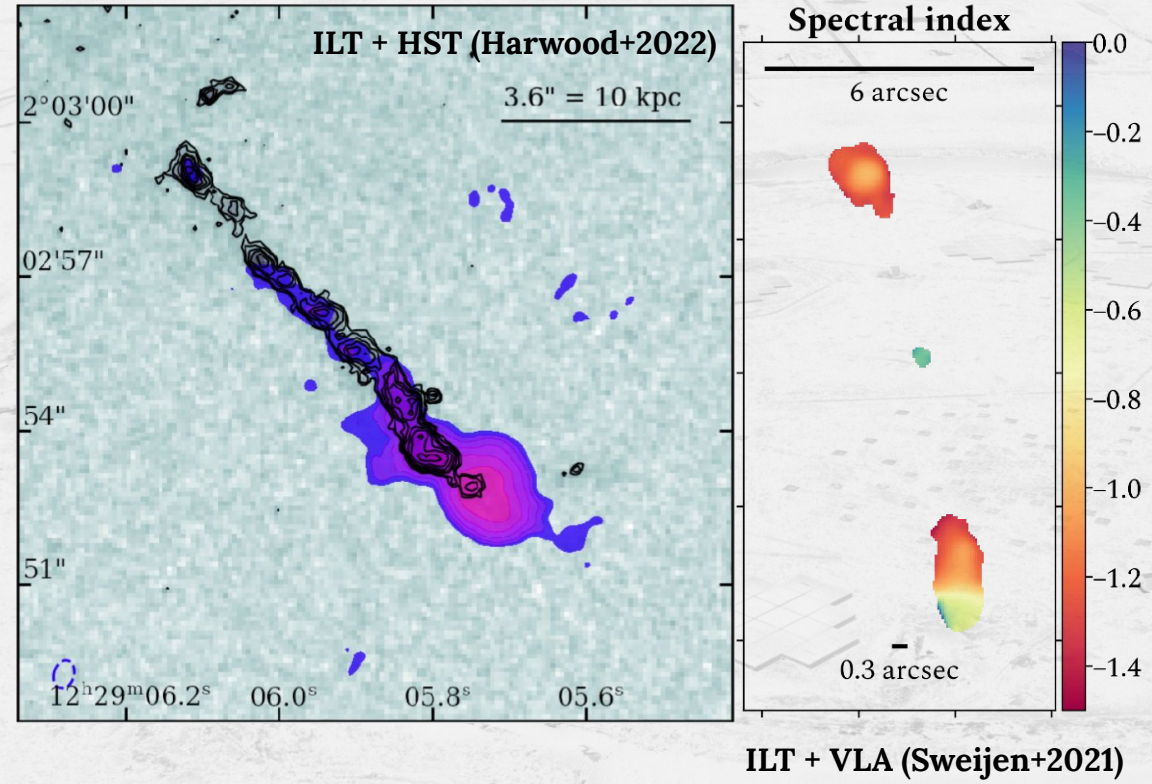


Morabito+2016

Harris+2019



Science with the ILT



ILT + VLA (Sweijen+2021)

Science with the ILT

2022: A&A special issue

11 diverse papers jointly published

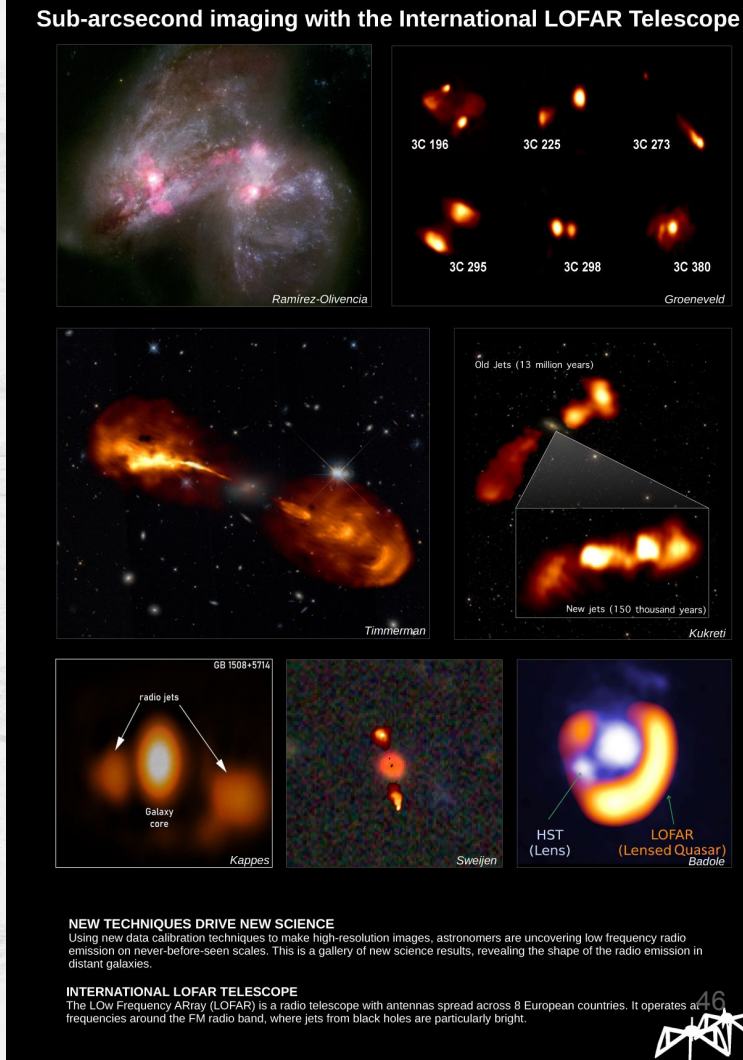
Foundational strategies

Nearby AGNs

High-z AGNs

Gravitational lens

LBA 50 MHz



Science with the ILT

2022: A&A special issue

11 papers jointly published

2025: review of 10 years ILT

Reflection on past efforts, current science and future prospects

Astrophysics and Space Science (2025) 370:19
https://doi.org/10.1007/s10509-025-04406-x

REVIEW

A decade of sub-arcsecond imaging with the International LOFAR Telescope

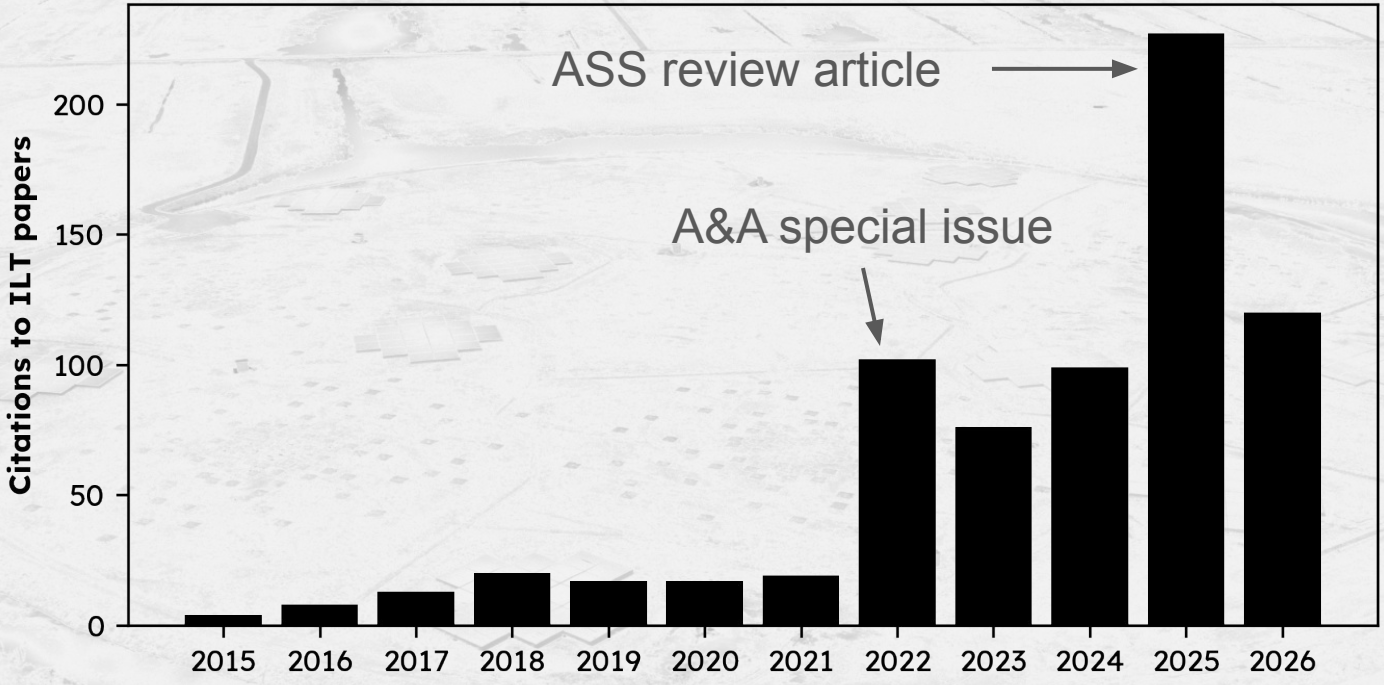
Leah K. Morabito[1,2] · Neal Jackson[3] · Jurjen de Jong[4] · Emmy Escott[1] · Christian Groeneveld[4,5] · Vijay Mahatma[6,7] · James Petley[1,4] · Frits Sweijen[1] · Roland Timmerman[1,2] · Reinout J. van Weeren[4]

Received: 6 December 2024 / Accepted: 7 February 2025 / Published online: 24 February 2025
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Abstract
The International LOFAR Telescope (ILT) is a pan-European radio interferometer with baselines up to 2000 km. This provides sub-arcsecond resolution at frequencies of <200 MHz. Since starting science operations in 2012, the ILT has carried out observations for the state-of-the-art LOFAR Two-metre Sky Survey, which has 6 arcsec resolution at 144 MHz. Wide-area surveys at low frequencies, while scientifically productive, have to compromise on resolution. Sub-arcsecond imaging with the ILT has become more accessible over the last decade, thanks to efforts to build a publicly available pipeline using LOFAR-specific tools, which has resulted in a dramatic increase in the number of publications. The ILT's combination of resolution, field of view, and low observing frequency make it a unique instrument for a wide range of scientific applications, and it will remain unparalleled even in the era of the Square Kilometre Array Observatory. Here we provide an overview of the technical considerations and calibration methods sub-arcsecond imaging with the ILT. This is followed by a review of the unique capabilities unlocked by sub-arcsecond imaging with the ILT, using examples from the literature for demonstration. Finally we describe ongoing work including: surveying large areas of the sky at high resolution, going deeper in fields with excellent ancillary information, producing images of polarisation, and extending to lower frequencies (<100 MHz).

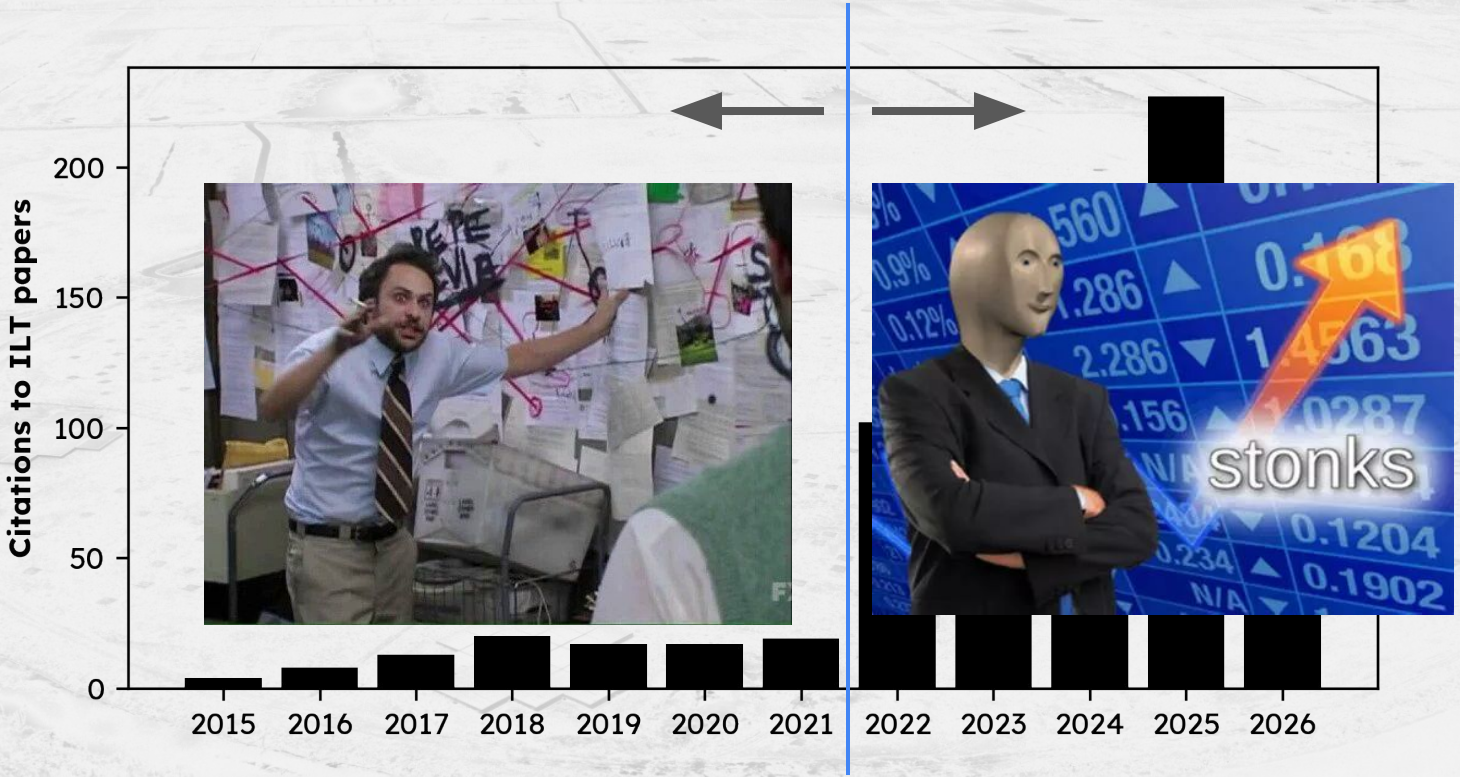
Keywords Radio astronomy · Extragalactic · High-resolution imaging · Radio surveys

Science with the ILT

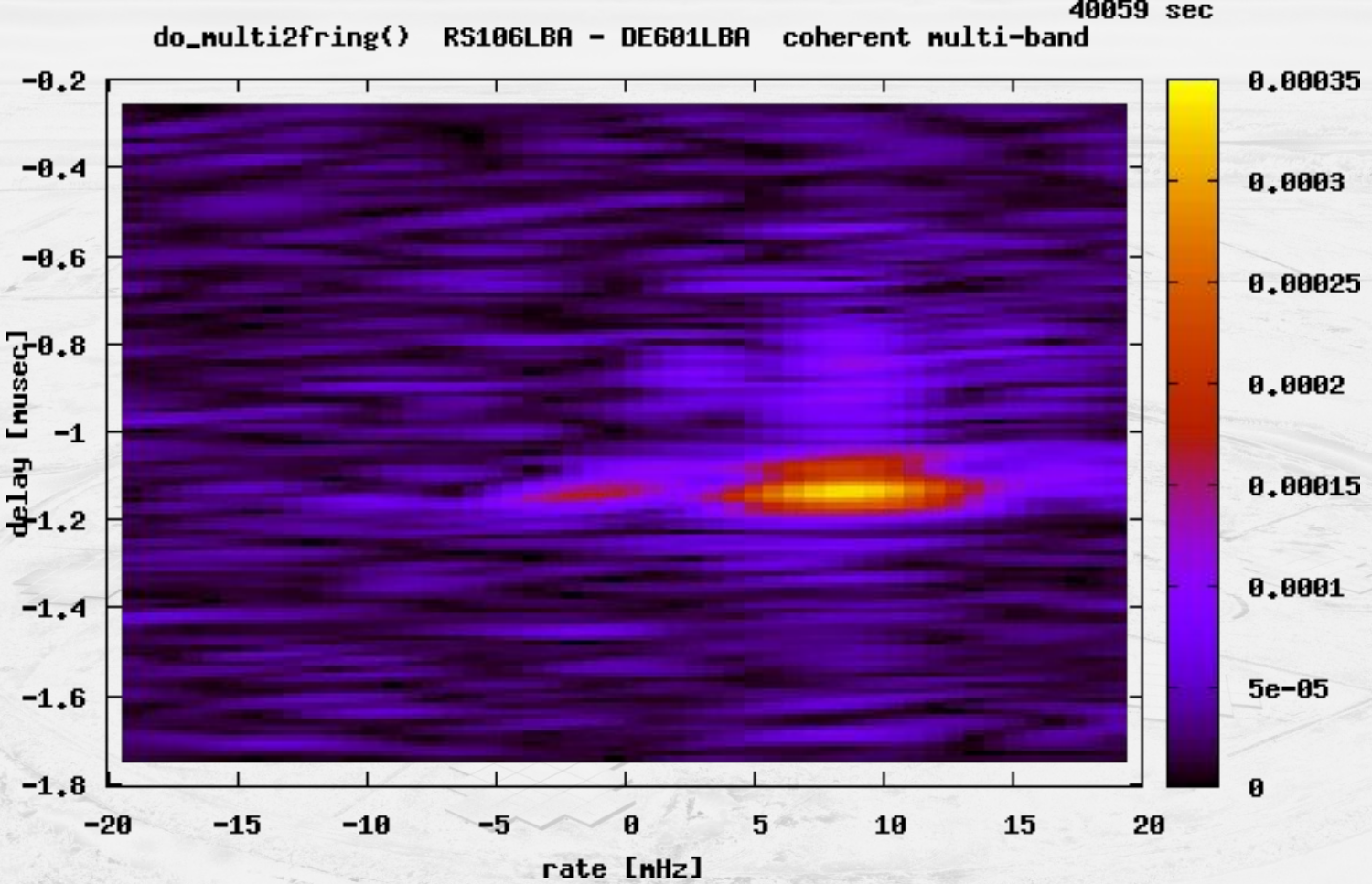


https://ui.adsabs.harvard.edu/public-libraries/fy3hB2dNToiiWGJSqMMcVg

Science with the ILT



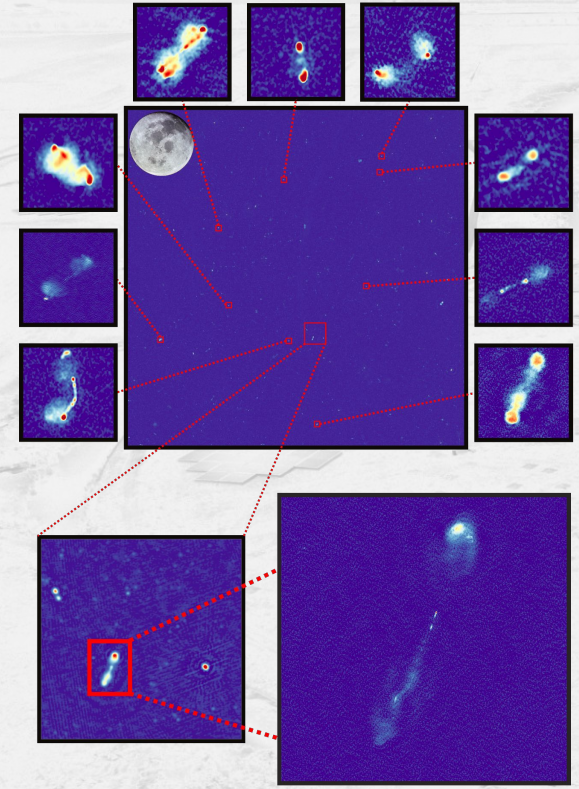
https://ui.adsabs.harvard.edu/public-libraries/fy3hB2dNToiiWGJSqMMcVg



First international baseline fringes (O. Wucknitz, ASTRON/JIVE Daily Image 2/10/2009

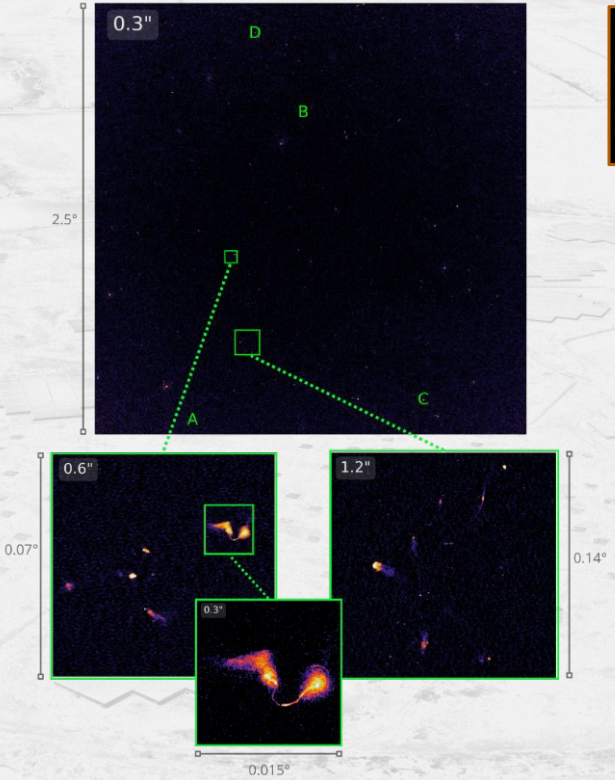
Some 24 deg^2 at 0.3” resolution between Lockman Hole, ELAIS-N1, Boötes and EDF-N!

Lockman Hole



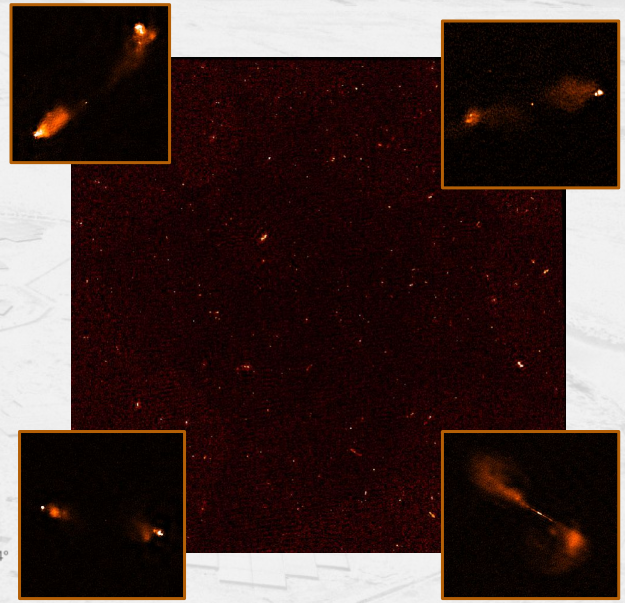
Sweijen et al. 2022

ELAIS-N1



de Jong et al. 2024

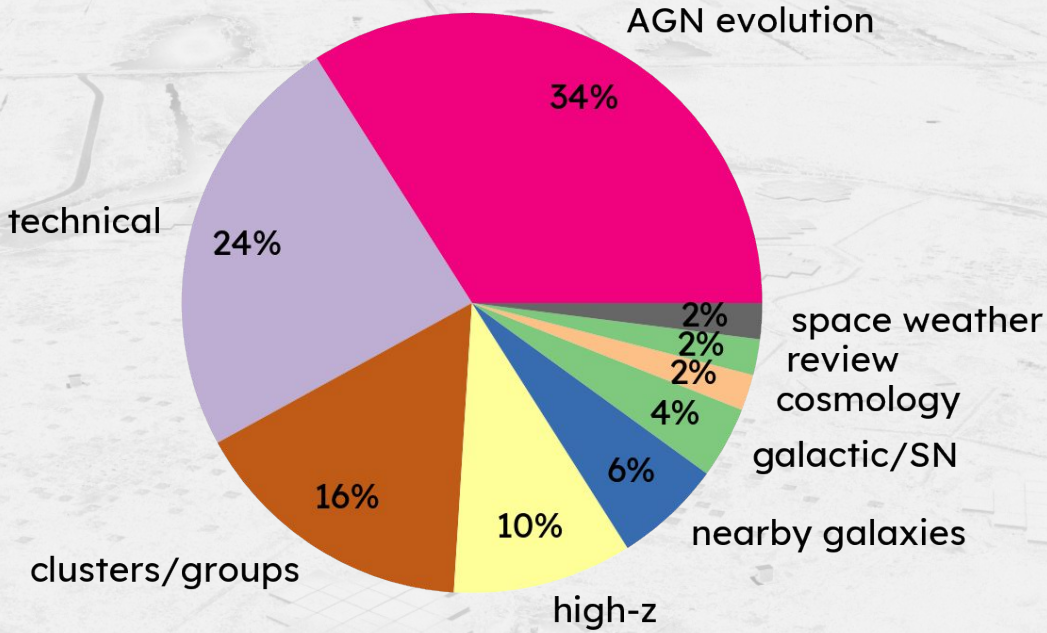
Boötes



Escott et al. 2026

Also EDF-N (de Jong+in prep.)

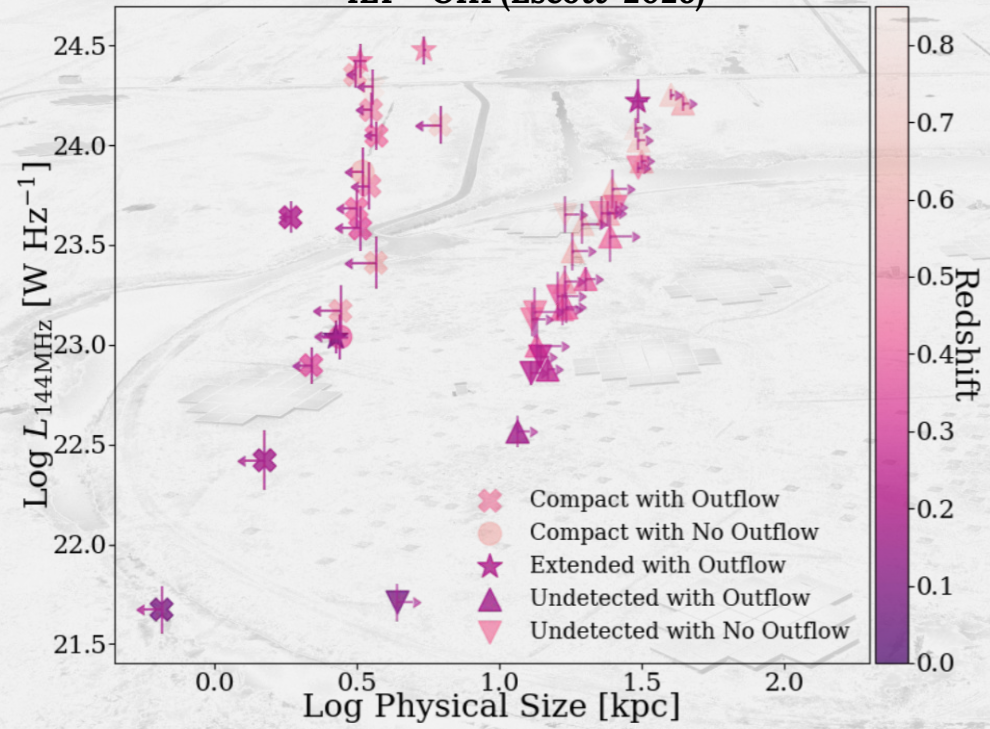
Science with the ILT



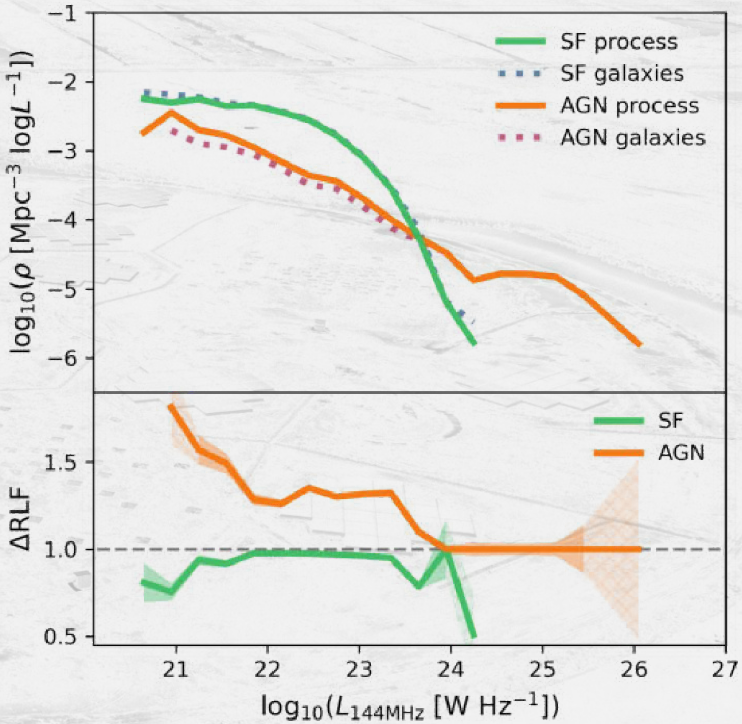
*Disclaimer: based on my totally unbiased classification of my ADS library that may or may not be complete

Sample studies

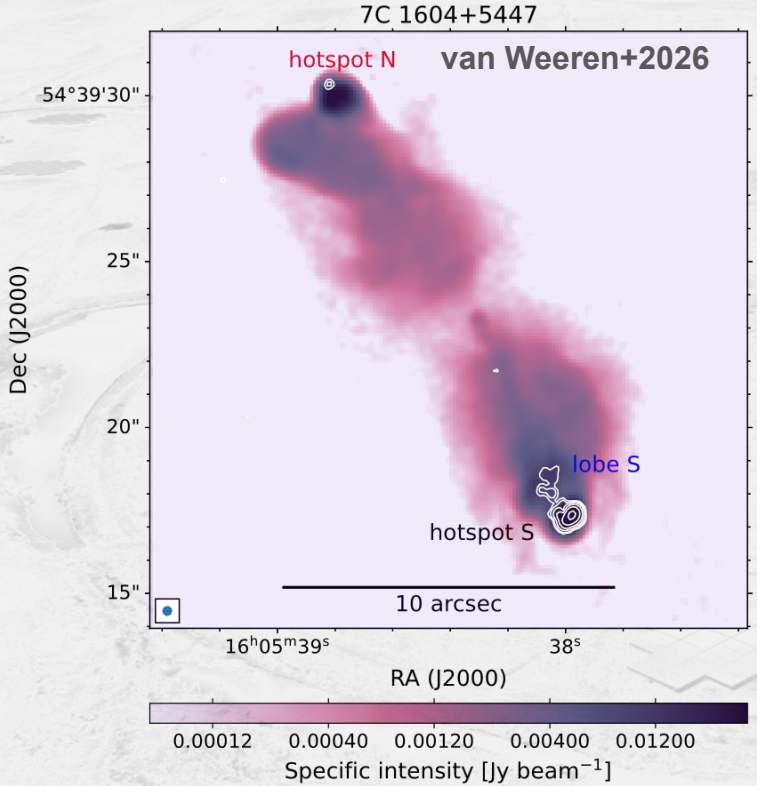
ILT + OIII (Escott+2026)

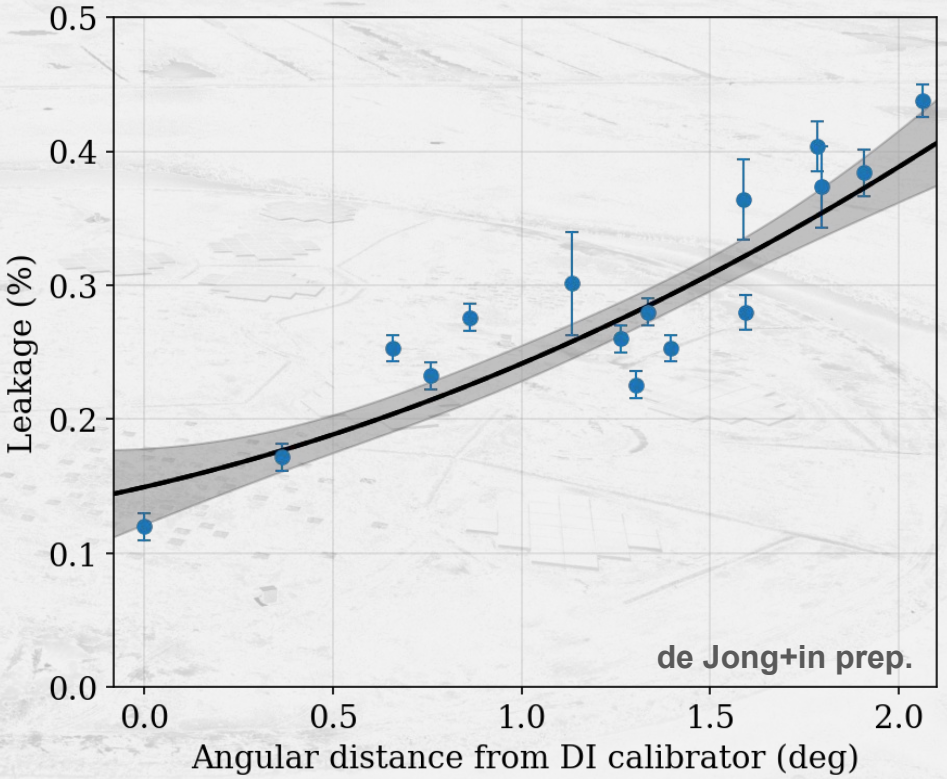


AGN-SF separation(Morabito+2026)

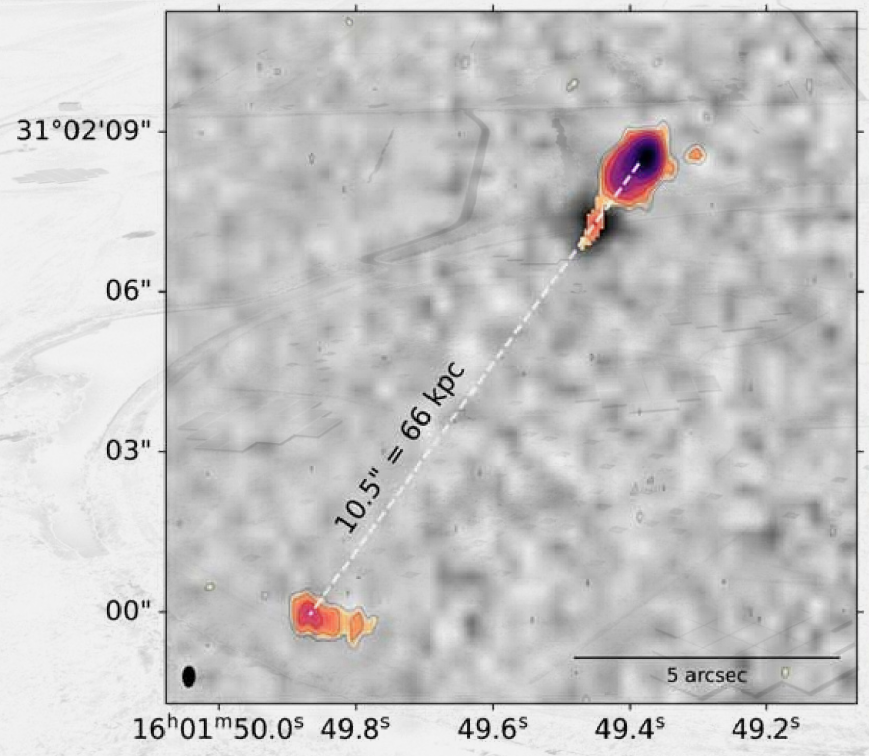


Sub-arcsecond resolution polarisation

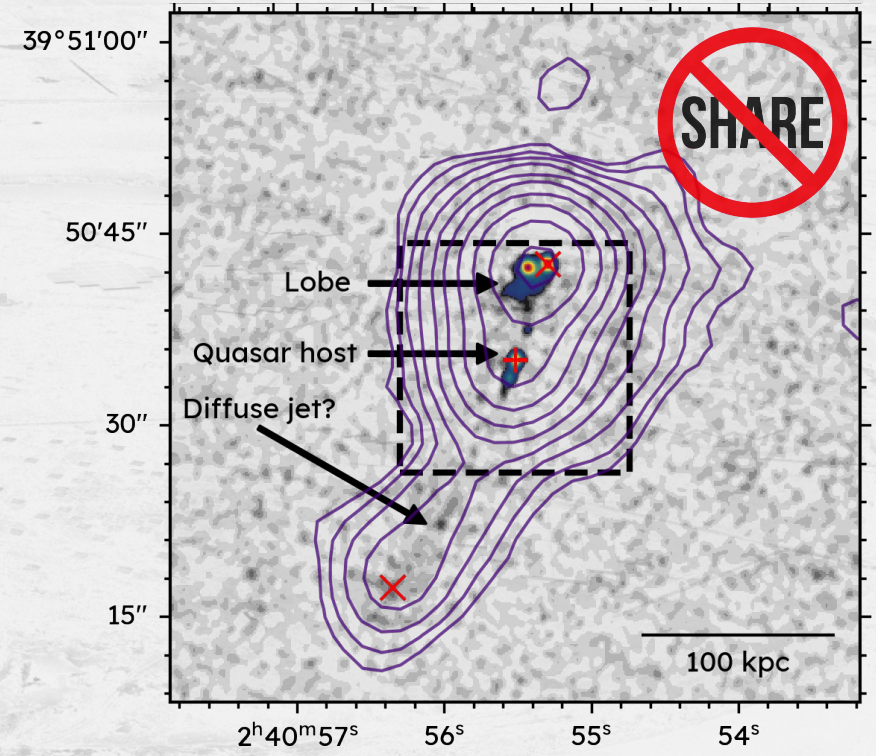




High-redshift



Gloudemans+2026



Sweijen in prep.

Future prospects – LOFAR2 era

LoTSS-HR

High-resolution follow-up of >10 mJy sources

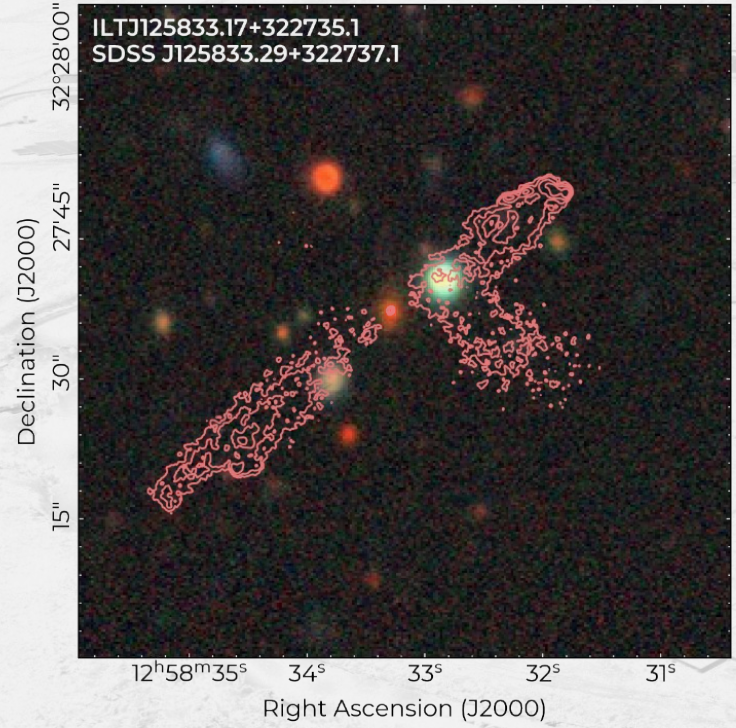
iLoTSS (https://lofar-surveys.org/ilotss.html)

Archival reprocessing and new observations to fill gaps in the LoTSS grid
Full FoV imaging across ~7,600 deg^2 targeting ~30 μJy $beam^{-1}$

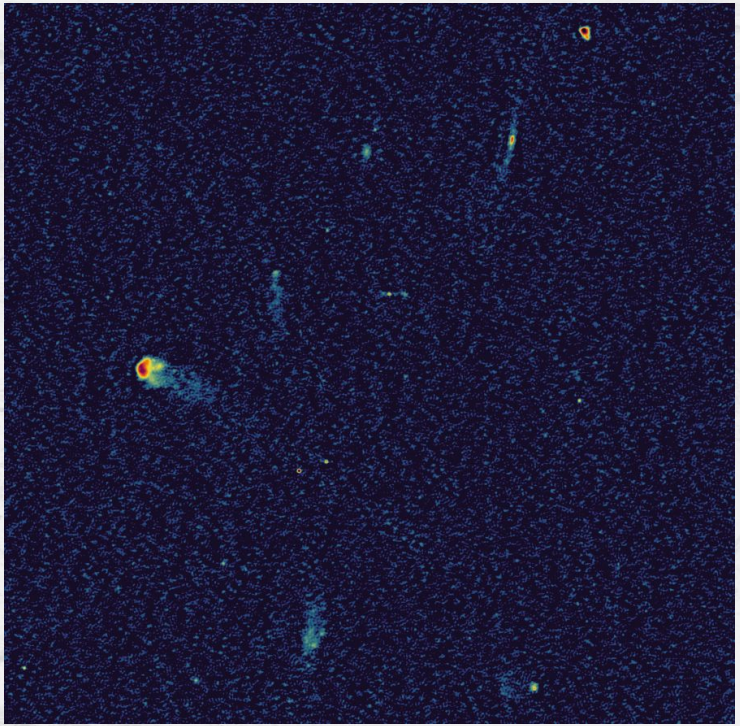
LUDO (https://sites.google.com/view/lofarultradeep/eoi)

Ultra deep observations of EDF-N – ~3,200 h targeting ~2 μJy $beam^{-1}$

Future prospects



Timmerman+subm.



de Jong in prep.

Future prospects – technical frontiers

Quality assurance

Need robust quality control all the way back to LINC

Polarisation

Need to know (un)polarised calibrator sources

Galactic plane

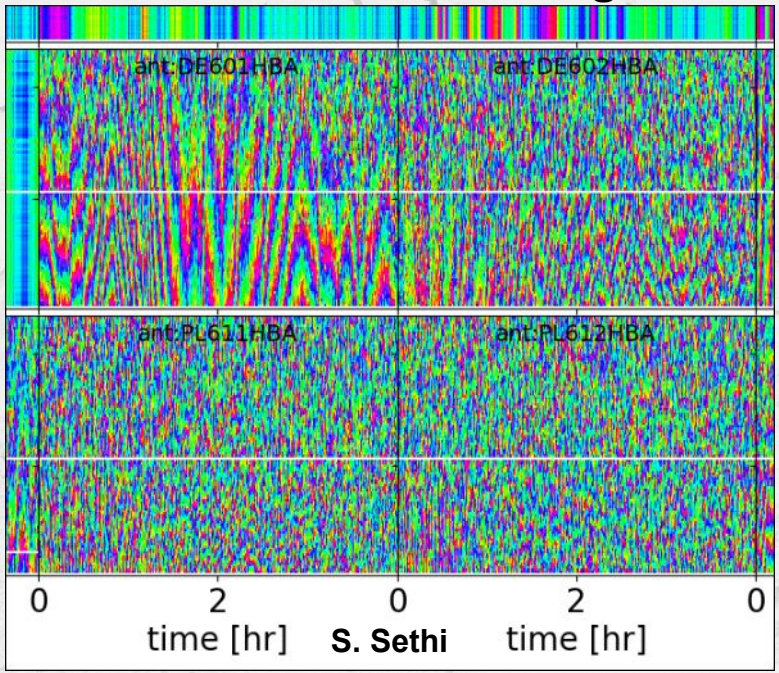
Interstellar scattering washes out usable signal; not properly characterised yet

LBA

ionosphere $\propto \lambda$; FR $\propto \lambda^2$, so everything at least 3x worse ¯_(ツ)_/¯

Future prospects

Interstellar scattering?

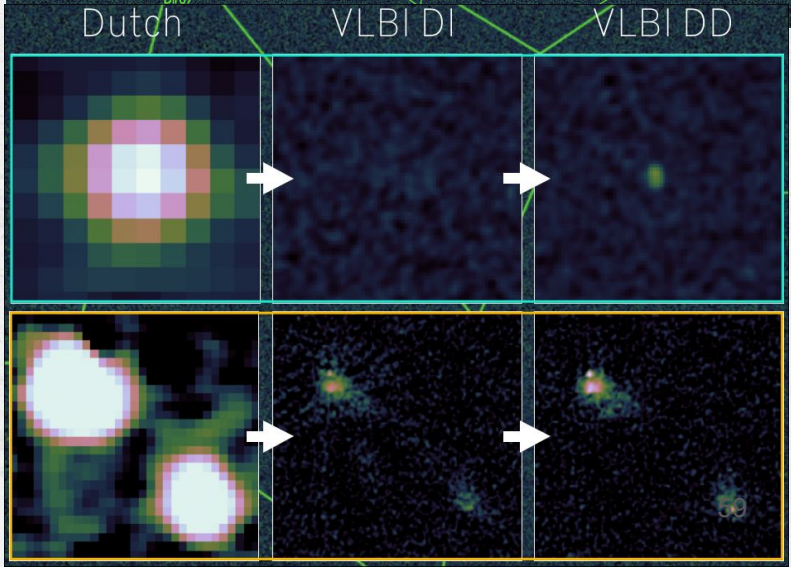


S. Sethi



First LBA widefield 0.7”

H. Edler



But no, we are not planning to disconnect the German stations from the rest of the array to produce our own maps. An interferometer is more valuable than the sum of its parts, and the same is true for the combination of the Dutch and German subarrays.

Olaf Wucknitz; ASTRON/JIVE Daily Image 03/03/2010

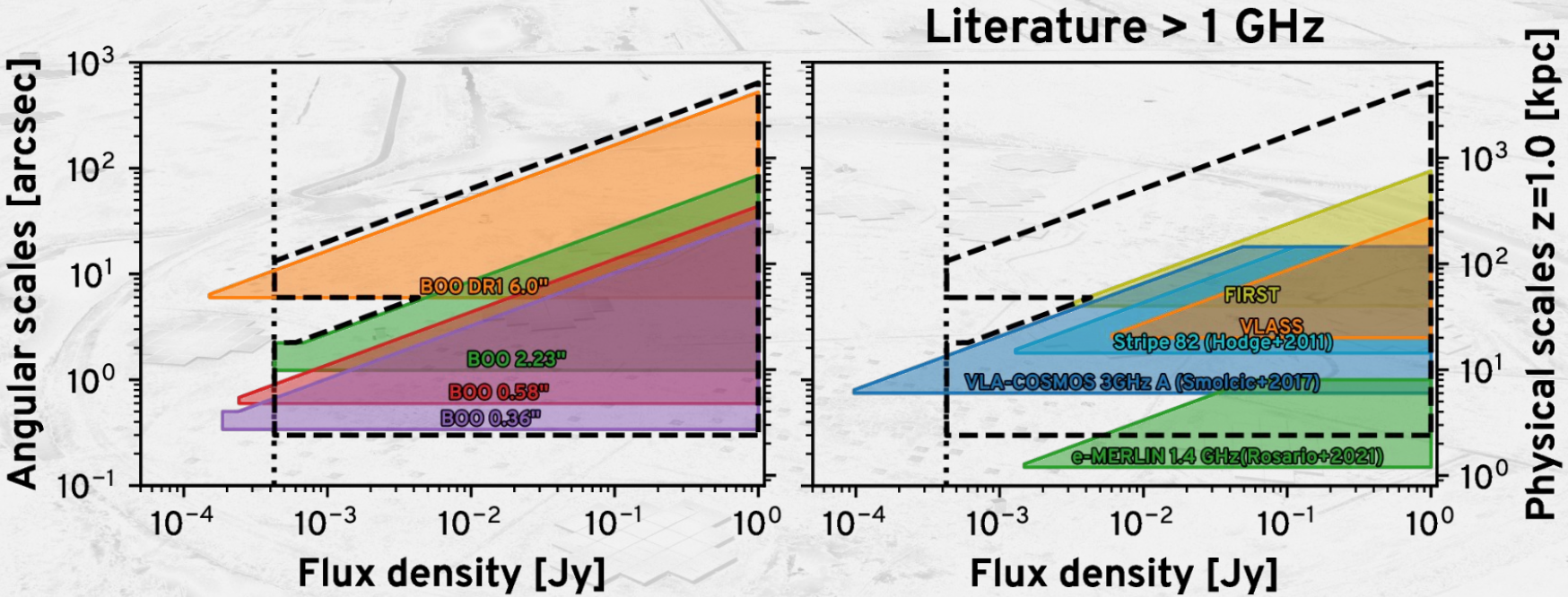
Conclusions

ILT facilitates a diverse palette of science
Statistical studies, matched-resolution multi-wavelength, serendipity
Wide-field images available for Lockman Hole, EN1, Bootes (and EDF-N soon)
LoTSS-HR DR1 4,286 postage stamps across H-ATLAS close to public release

HBA long baseline processing is now accessible
PILOT provides end-to-end data reduction
Scalable from single machine to clusters

Active working group chipping away at the next challenges
Regular “busy weeks”
Issues or pull requests welcome

What sets the ILT apart – angular scales



Sweijen+in prep.