Making the Deepest Radio Image

By: Jurjen de Jong

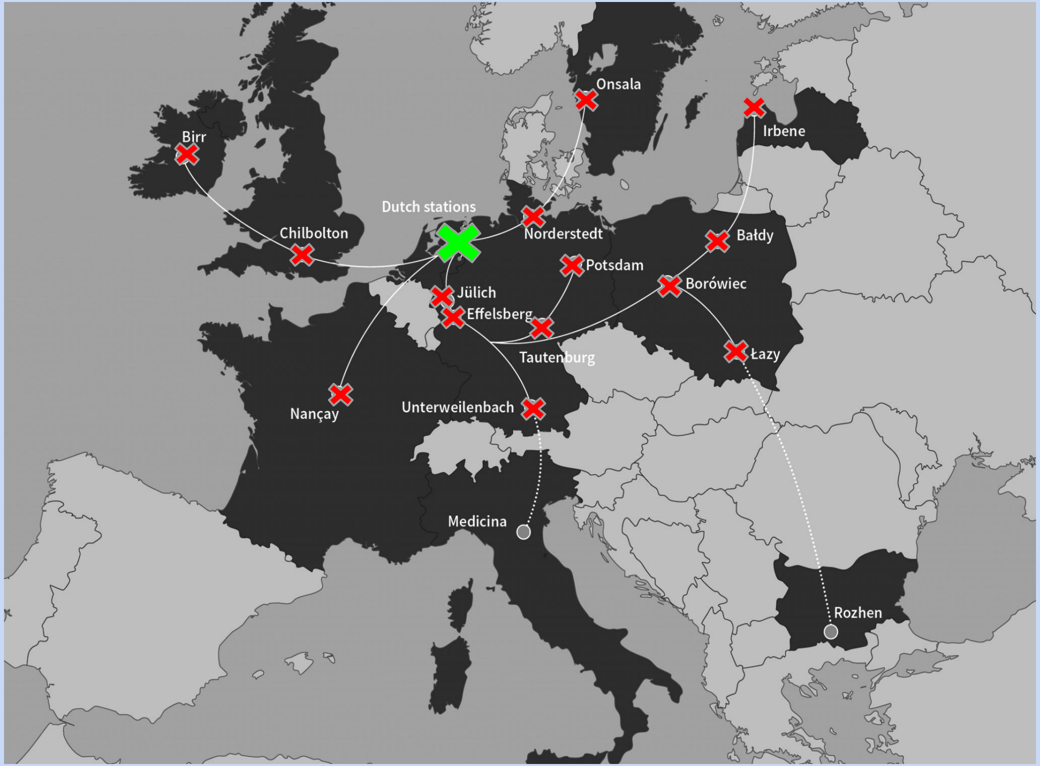
Universiteit Leiden
The Netherlands

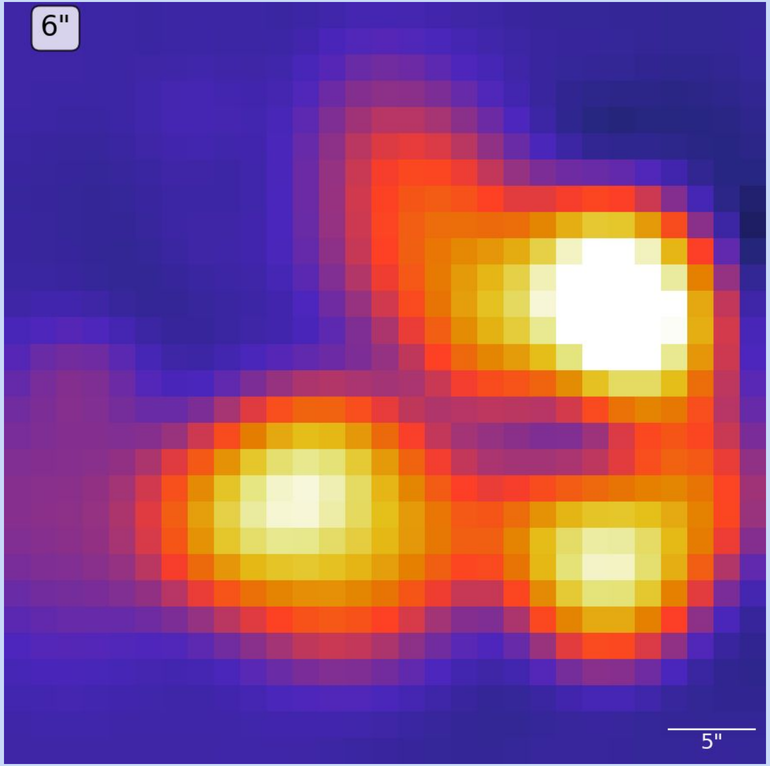
Sterrewacht Leiden

SURF

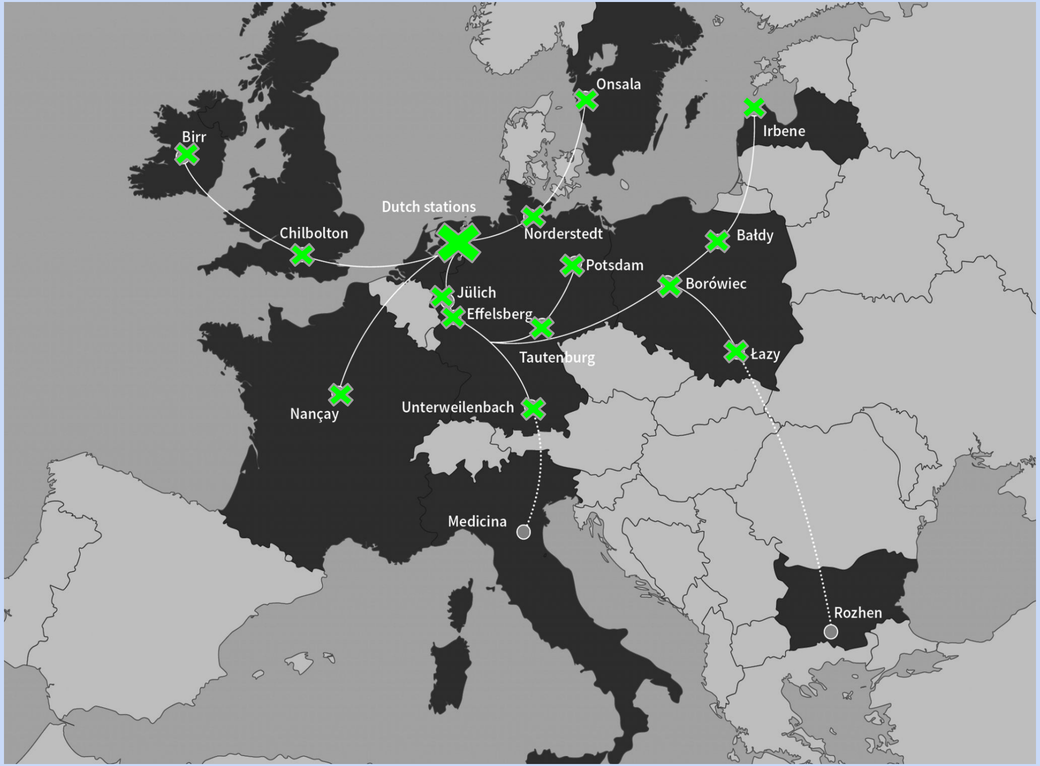
OSCARS
Open Science Clusters' Action for Research & Society

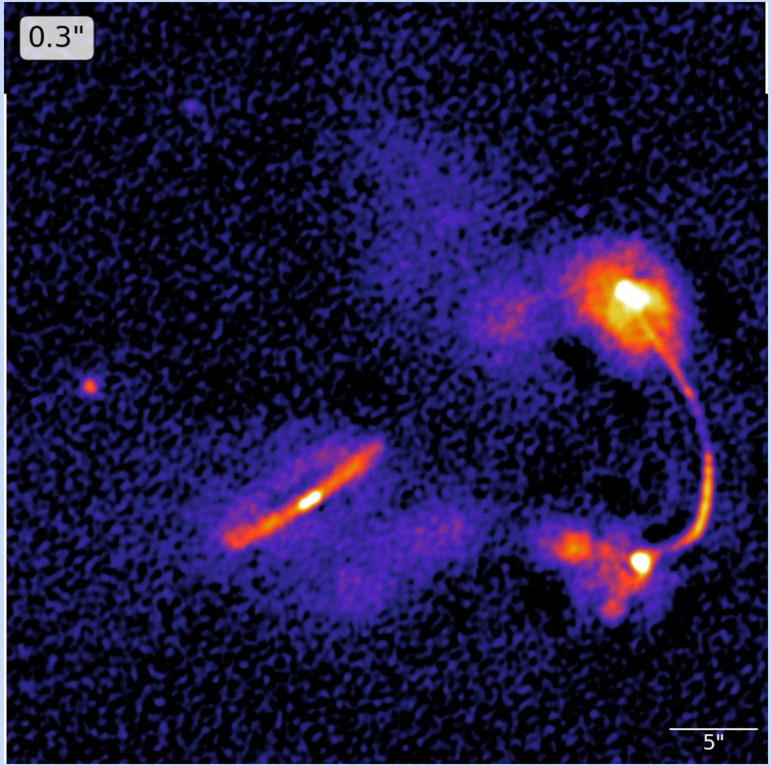
European LOFAR: 6” → 0.3”





European LOFAR: 6” → 0.3”

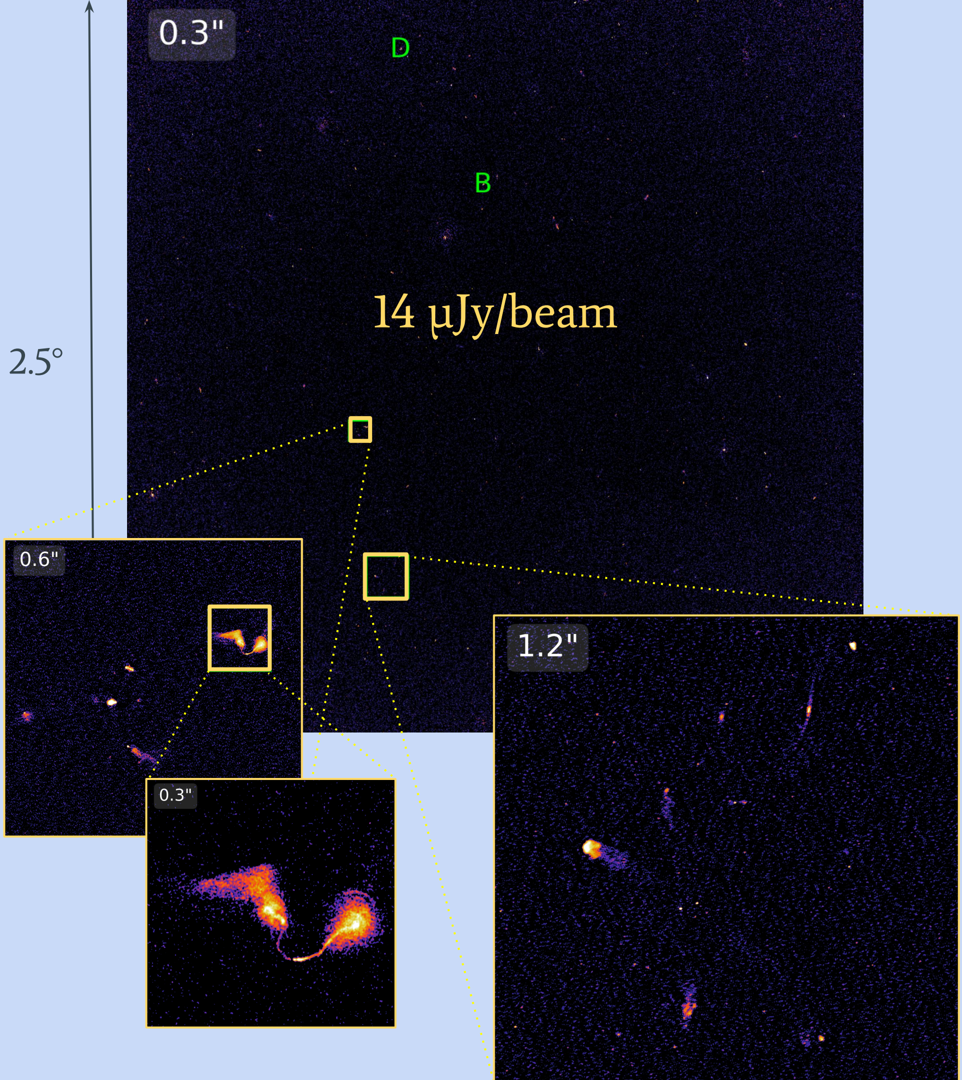




ELAIS-N1 with 32 hours HBA

- ★ 4 observations
  - 26-11-2018
  - 24-05-2020
  - 14-11-2020
  - 13-5-2021
- ★ 2 times deeper than 1 observation
- ★ ~13,000 sources

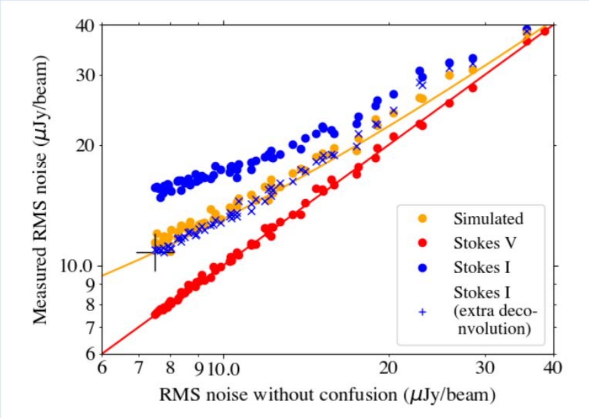
(See de Jong et al. 2024)

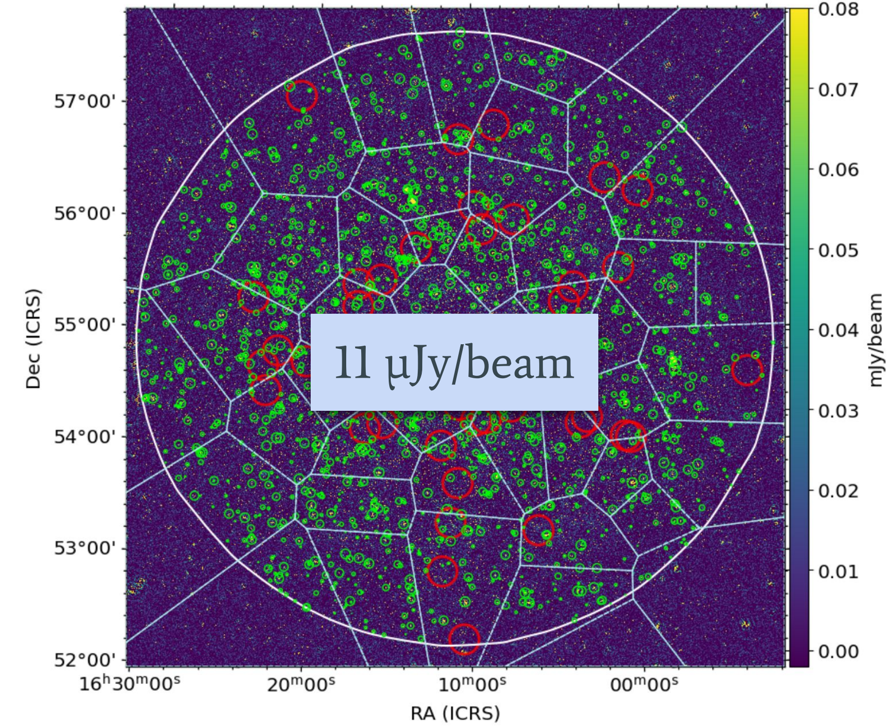


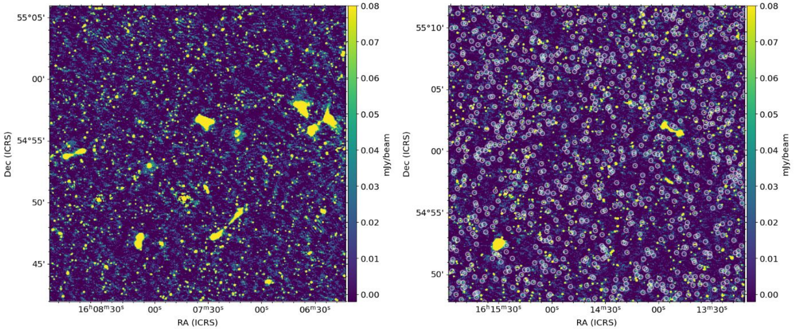
LoTSS Deep Fields → ELAIS-N1

- ★ **505 hrs of HBA data**
- ★ 6” angular resolution
- ★ **11 μJy/beam sensitivity**
- ★ Confusion noise!

(Shimwell et al. 2025)







Deeper with LOFAR longest baselines?

★ International stations -> more collecting area

★ Confusion noise negligible at sub-arcsecond resolution

Computational challenges:

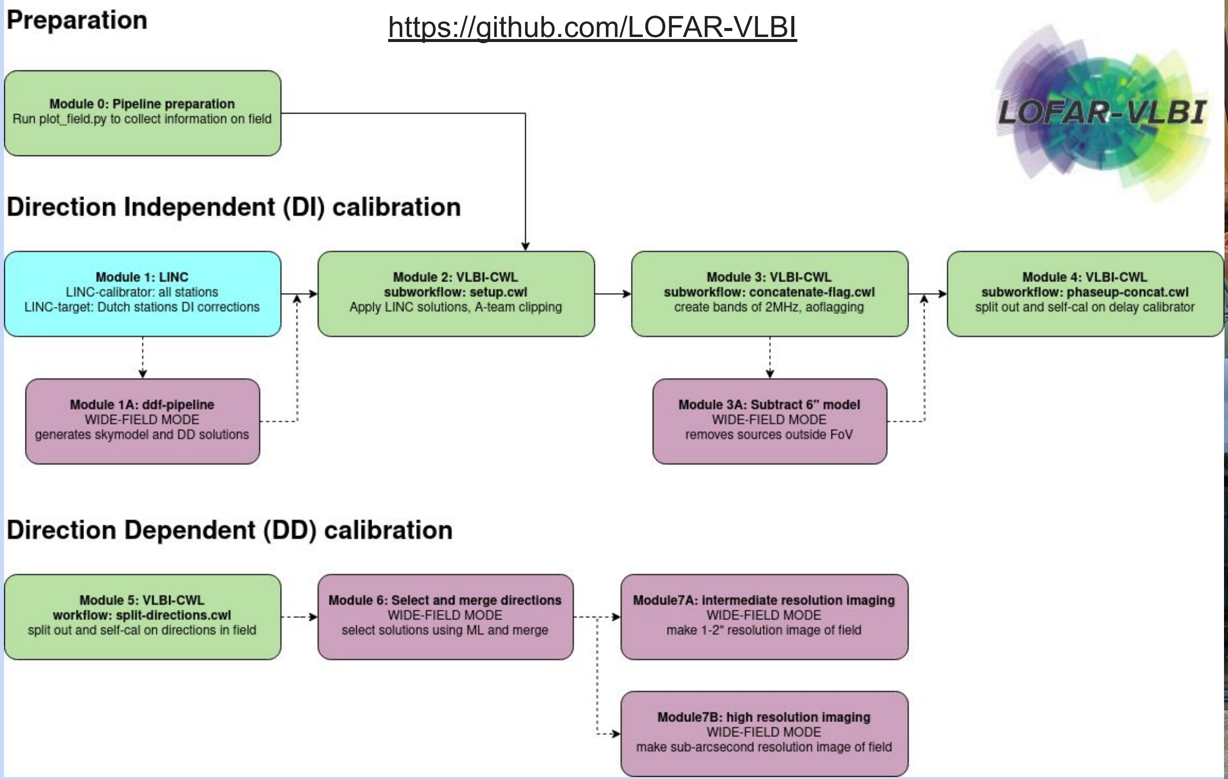
- 25 observations -> 400 TB (100 TB compressed)
- 8 billion pixels

Table 1: Metadata from the four ELAIS-N1 observations used in this paper.

Observ. ID	Project	Calibrator ID	Observ. date	Stations (int)	Frequencies
L686892	LT10_012	686888	06-12-2018	70 (12)	120-165 MHz
L686906	LT10_012	L686902	08-12-2018	75 (13)	120-165 MHz
L686920	LT10_012	L686916	03-12-2018	74 (12)	120-165 MHz
L686934	LT10_012	L686940	02-12-2018	74 (12)	120-165 MHz
L686948	LT10_012	L686944	30-11-2018	73 (11)	120-167 MHz
L686962	LT10_012	L686958	26-11-2018	73 (11)	120-165 MHz
L686976	LT10_012	L686972	25-11-2018	73 (11)	128-167 MHz
L687004	LT10_012	L687000	22-11-2018	70 (9)	128-167 MHz
L686990	LT10_012	L686986	24-11-2018	73 (11)	126-167 MHz
L760853	LT10_012	L769403	02-12-2019	67 (12)	120-166 MHz
L769393	LT10_012	L769389	24-05-2020	75 (13)	120-165 MHz
L769407	LT10_012	L769403	08-05-2020	71 (12)	120-165 MHz
L769421	LT10_012	L769417	11-05-2020	73 (13)	120-167 MHz
L769435	LT10_012	L769431	14-03-2020	72 (11)	120-166 MHz
L798022	LT14_003	L798030	12-11-2020	72 (11)	117-166 MHz
L798074	LT14_003	L798082	14-11-2020	74 (11)	115-164 MHz
L798092	LT14_003	L798100	20-11-2020	68 (11)	115-164 MHz
L798128	LT14_003	L798136	26-11-2020	69 (9)	115-166 MHz
L811718	LT14_003	L811726	18-03-2021	72 (11)	117-165 MHz
L811736	LT14_003	L811744	19-03-2021	75 (13)	115-164 MHz
L816272	LT14_003	L816280	13-05-2021	75 (14)	115-164 MHz
L816308	LT14_003	L816316	22-05-2021	75 (13)	116-162 MHz
L816344	LT14_003	L816352	26-05-2021	73 (14)	115-166 MHz
L818954	LT14_003	L818962	21-06-2021	72 (10)	115-156 MHz
L833466	LT14_003	L833474	09-10-2021	73 (13)	119-165 MHz

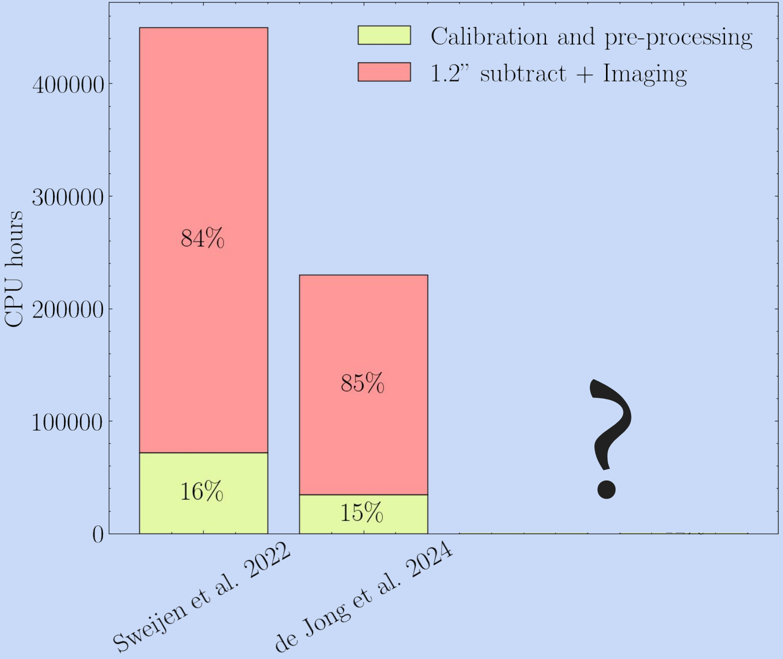
LOFAR VLBI pipeline

https://github.com/LOFAR-VLBI

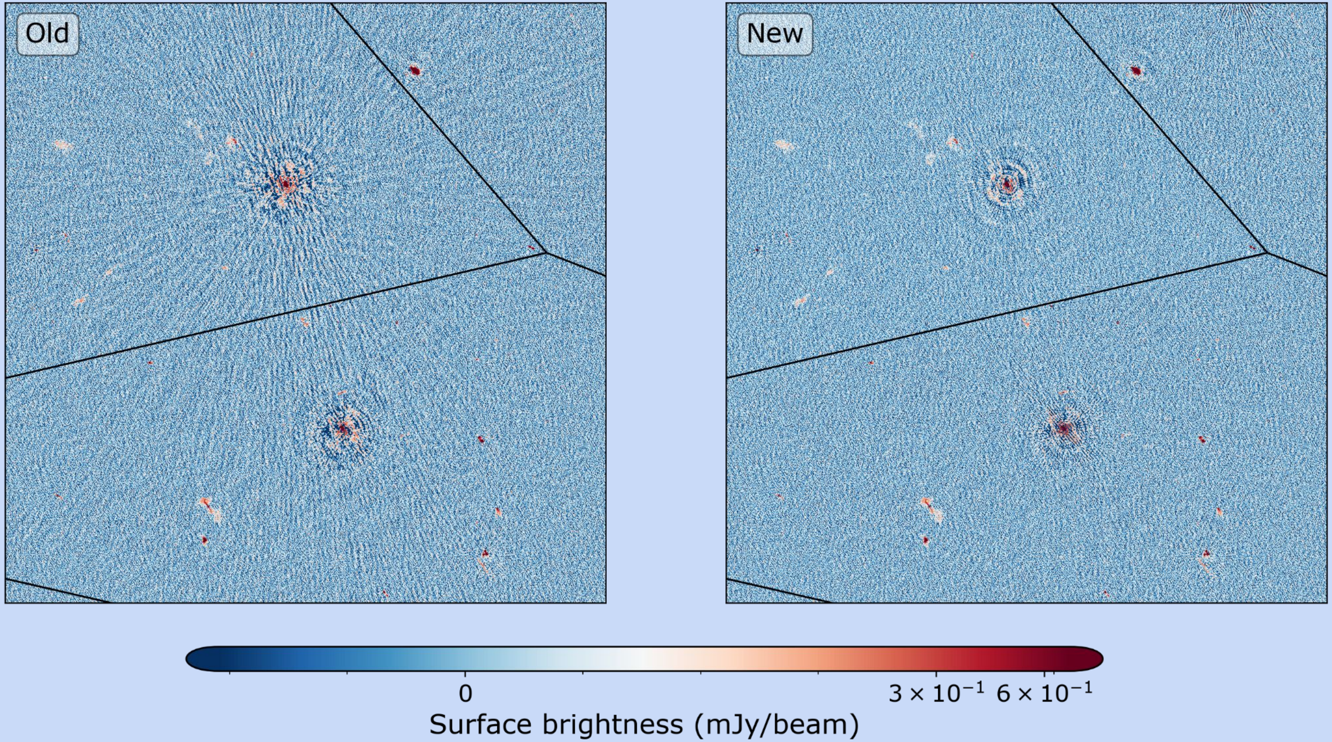


Remaining challenges (de Jong et al. 2024)

- ★ Calibration artefacts (high S/N calibrators)
- ★ Human ‘labour’ (-> automation!)
- ★ Imaging cost (85% total compute)

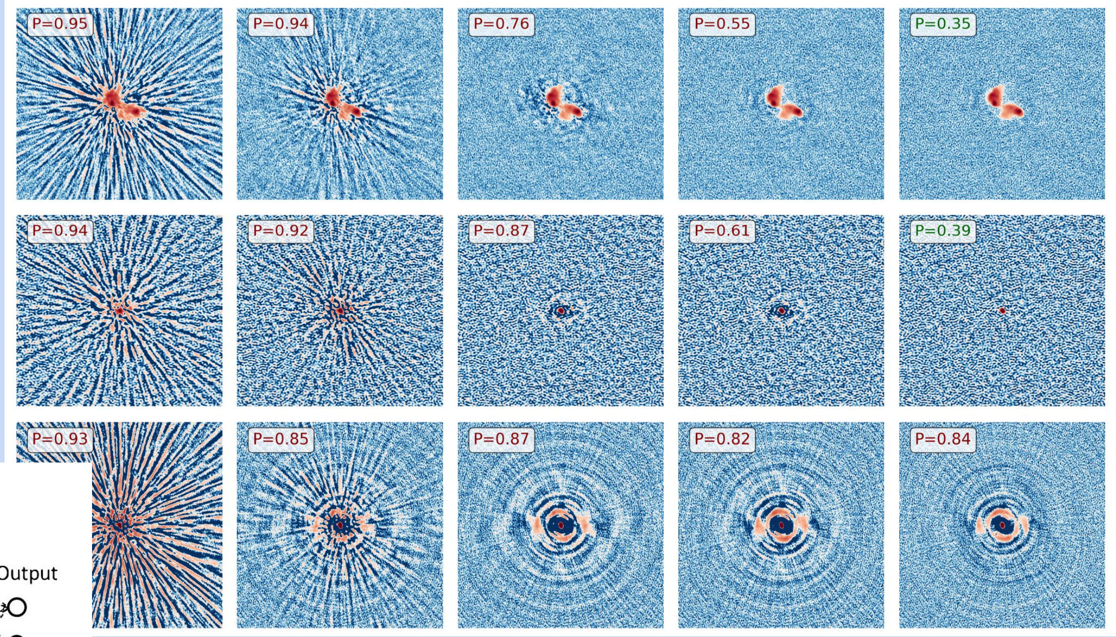


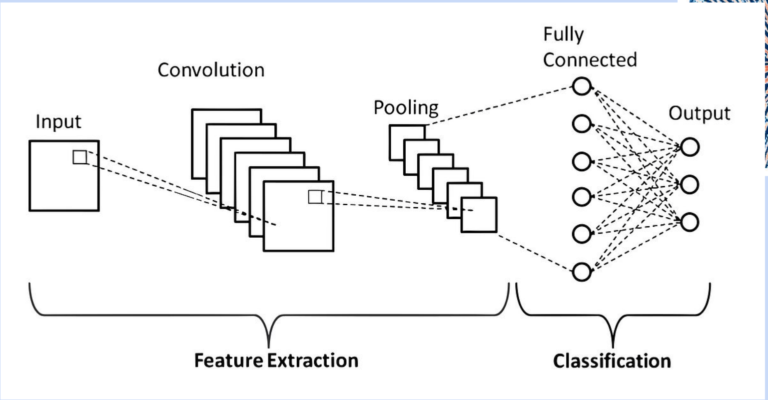
Calibration improvements (challenging ionosphere)



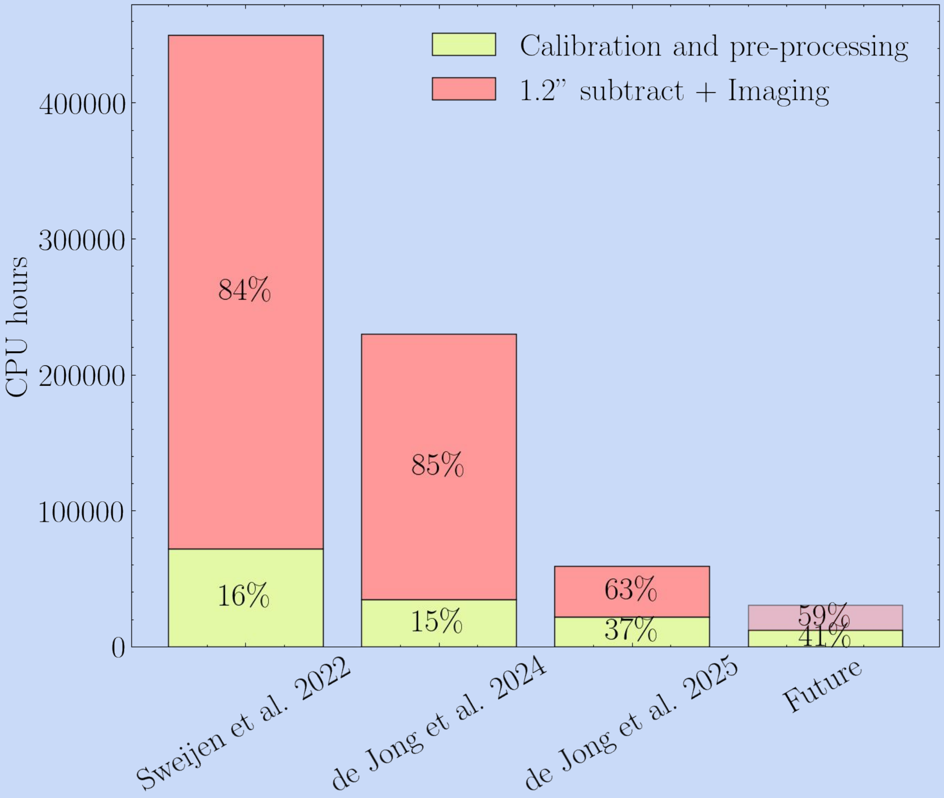
Validation with AI

- ★ Neural network
- ★ DinoV2 model
- ★ Pre-trained
- ★ 3,000 images

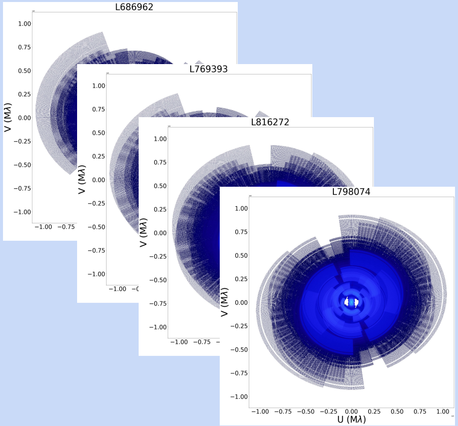


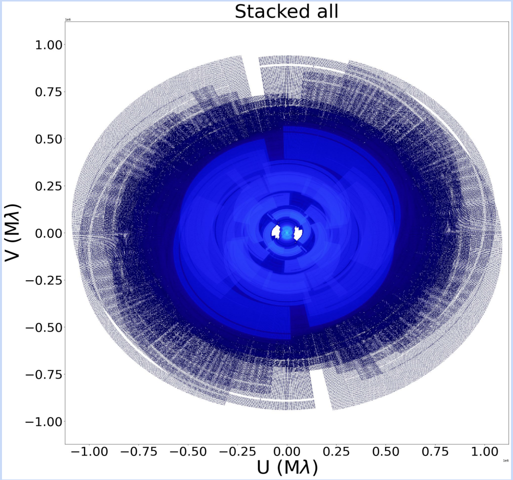


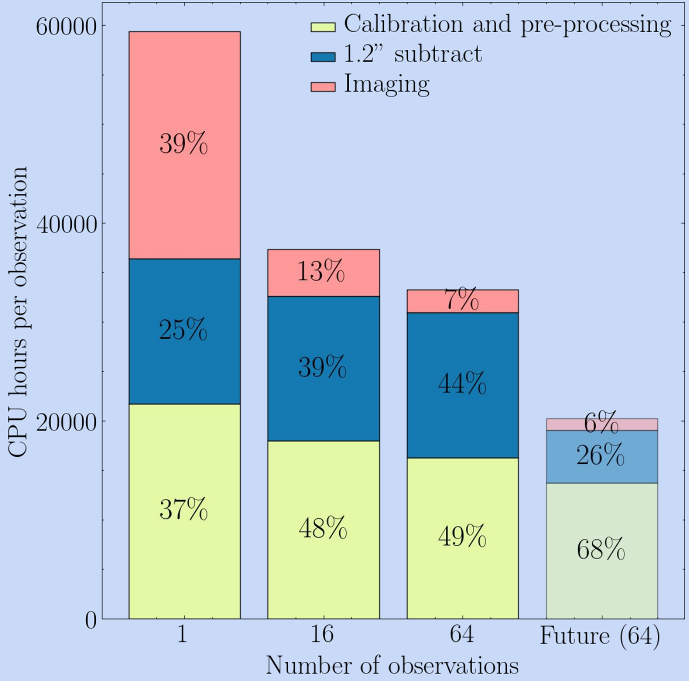
Computational cost (1 observation)



Sidereal visibility averaging (see de Jong et al. 2025a)







Back to ELAIS-N1

★ Processing 200 hrs of HBA data
- 400 TB
- 8 billion pixels

★ Applying and testing automation

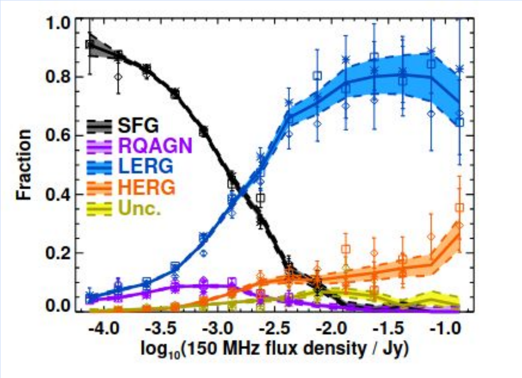
Table 1: Metadata from the four ELAIS-N1 observations used in this paper.

Observ. ID	**Project**	**Calibrator ID**	**Observ. date**	**Stations (int)**	**Frequencies**
L686892	LT10_012	686888	06-12-2018	70 (12)	120-165 MHz
L686906	LT10_012	L686902	08-12-2018	75 (13)	120-165 MHz
L686920	LT10_012	L686916	03-12-2018	74 (12)	120-165 MHz
L686934	LT10_012	L686940	02-12-2018	74 (12)	120-165 MHz
L686948	LT10_012	L686944	30-11-2018	73 (11)	120-167 MHz
L686962	LT10_012	L686958	26-11-2018	73 (11)	120-165 MHz
L686976	LT10_012	L686972	25-11-2018	73 (11)	128-167 MHz
L687004	LT10_012	L687000	22-11-2018	70 (9)	128-167 MHz
L686990	LT10_012	L686986	24-11-2018	73 (11)	126-167 MHz
L760853	LT10_012	L769403	02-12-2019	67 (12)	120-166 MHz
L769393	LT10_012	L769389	24-05-2020	75 (13)	120-165 MHz
L769407	LT10_012	L769403	08-05-2020	71 (12)	120-165 MHz
L769421	LT10_012	L769417	11-05-2020	73 (13)	120-167 MHz
L769435	LT10_012	L769431	14-03-2020	72 (11)	120-166 MHz
L798022	LT14_003	L798030	12-11-2020	72 (11)	117-166 MHz
L798074	LT14_003	L798082	14-11-2020	74 (11)	115-164 MHz
L798092	LT14_003	L798100	20-11-2020	68 (11)	115-164 MHz
L798128	LT14_003	L798136	26-11-2020	69 (9)	115-166 MHz
L811718	LT14_003	L811726	18-03-2021	72 (11)	117-165 MHz
L811736	LT14_003	L811744	19-03-2021	75 (13)	115-164 MHz
L816272	LT14_003	L816280	13-05-2021	75 (14)	115-164 MHz
L816308	LT14_003	L816316	22-05-2021	75 (13)	116-162 MHz
L816344	LT14_003	L816352	26-05-2021	73 (14)	115-166 MHz
L818954	LT14_003	L818962	21-06-2021	72 (10)	115-156 MHz
L833466	LT14_003	L833474	09-10-2021	73 (13)	119-165 MHz

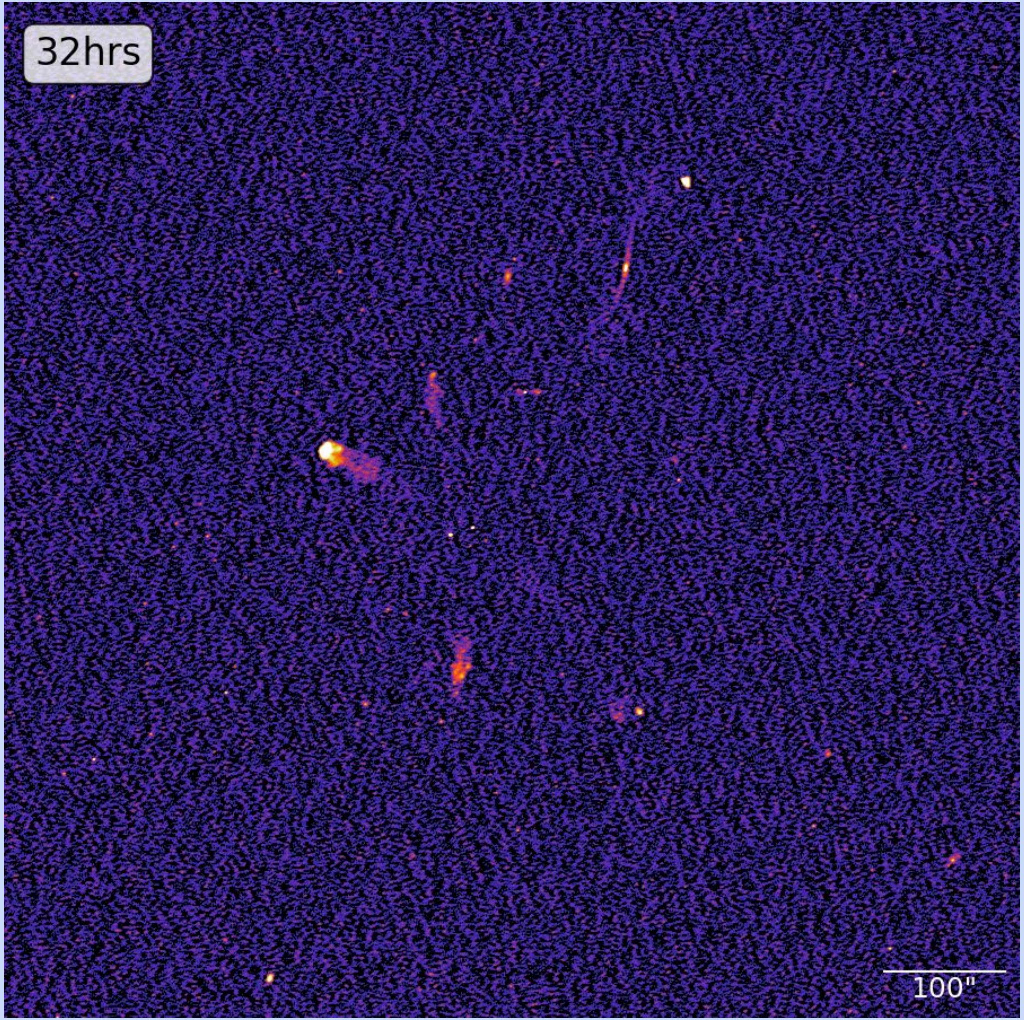
ELAIS-N1: 32hrs vs. 200hrs

★ **2.5x** times deeper
(up to **6 µJy/beam** !)

★ Processing **6 times faster**

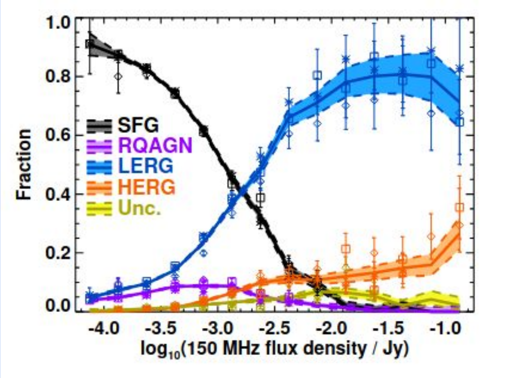


Best et al. (2023)

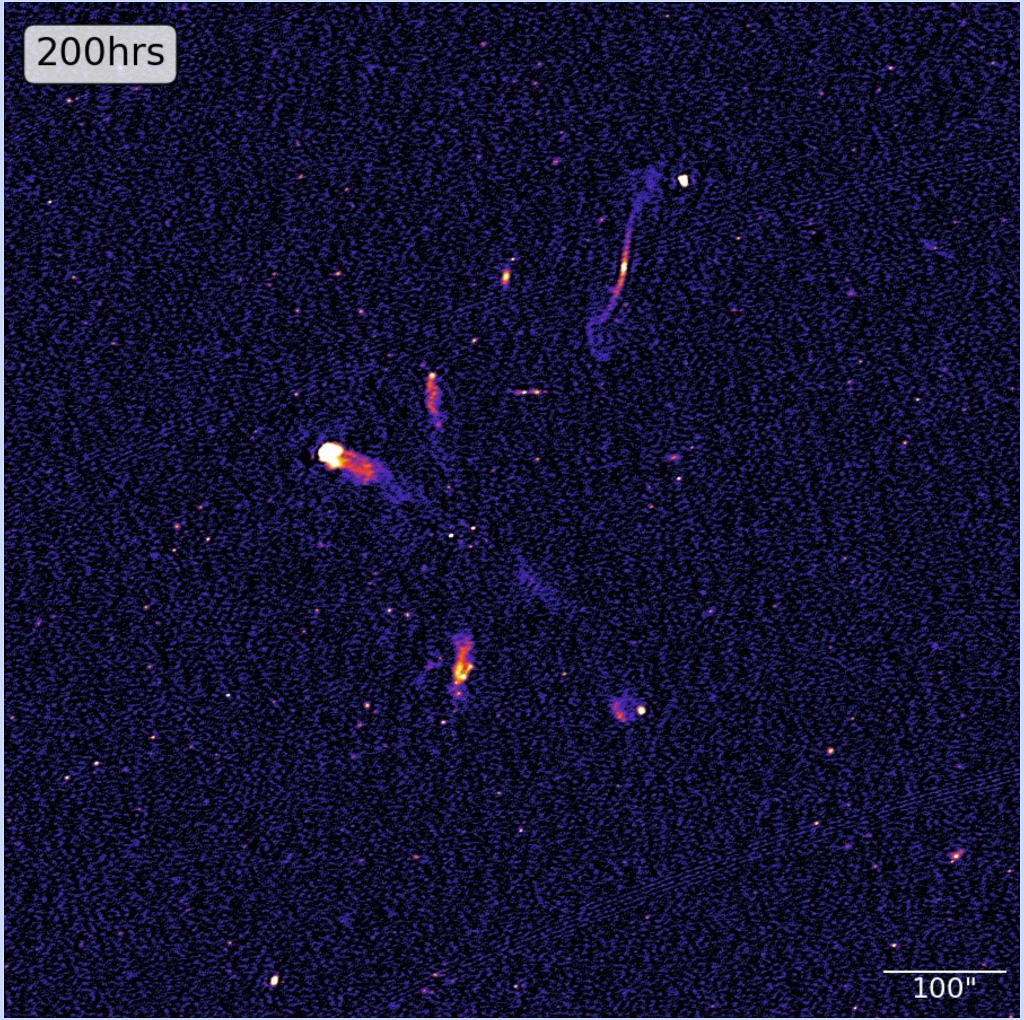


ELAIS-N1: 32hrs vs. 200hrs

- ★ **2.5x** times deeper (up to **6 μJy/beam** !)
- ★ Processing **6 times faster**



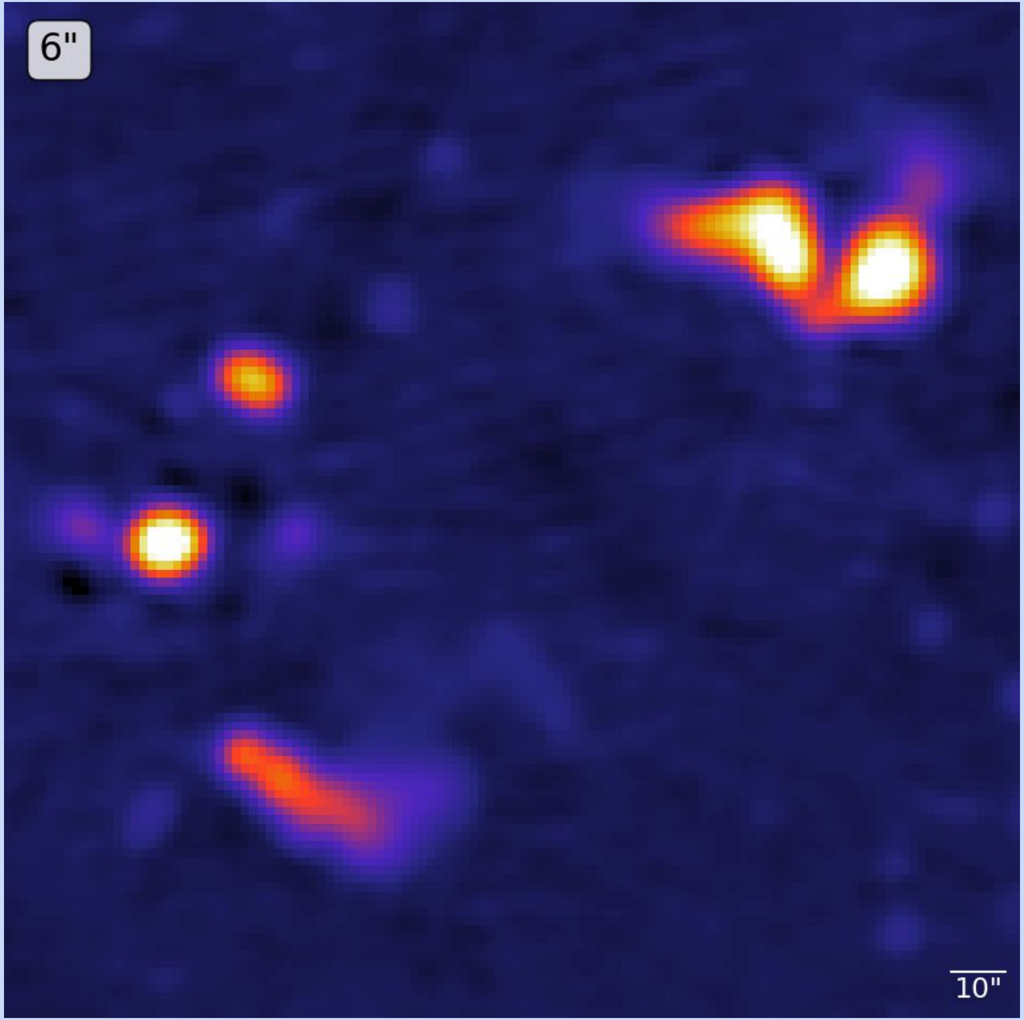
Best et al. (2023)



Comparison with deep ELAIS-N1 6”

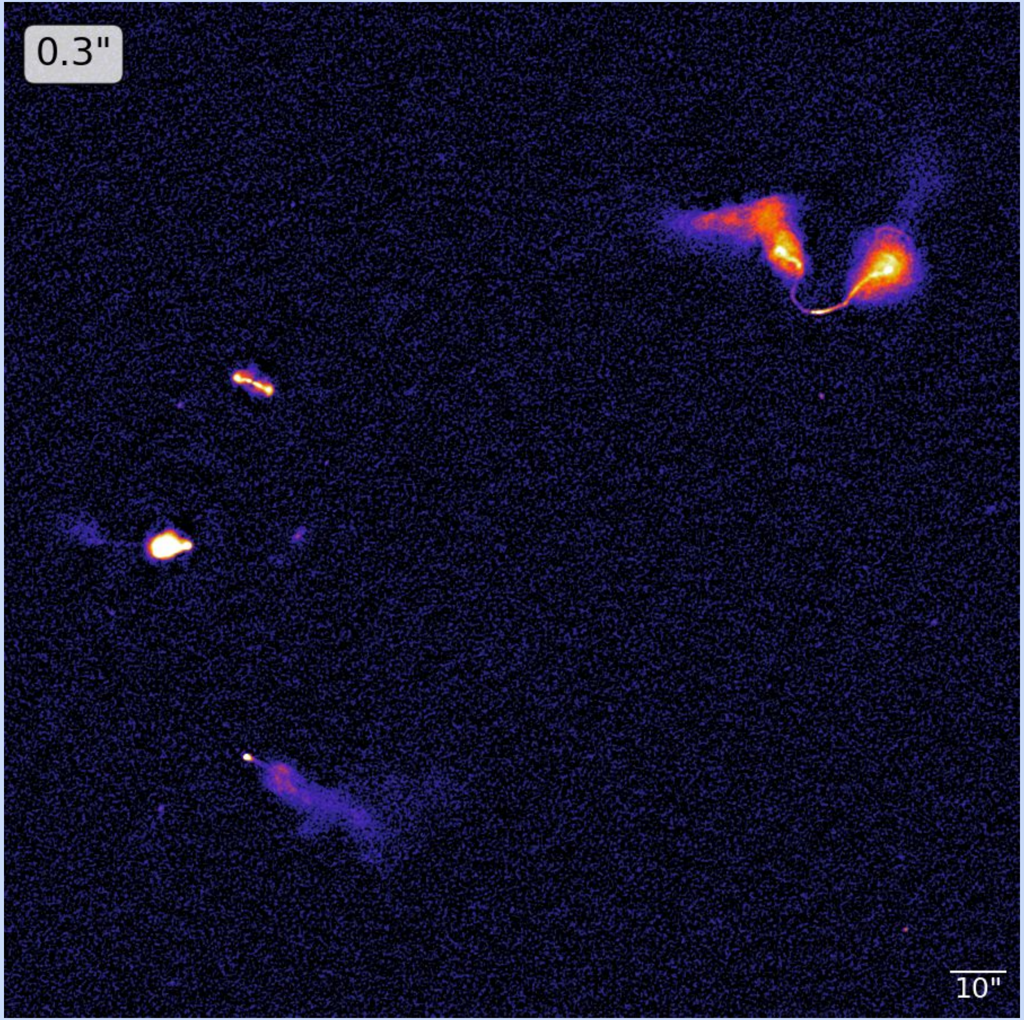
(Shimwell et al. 2025)

- ★ **1.8x** times deeper
  (6 μJy/beam !)
- ★ **20 times** better resolution

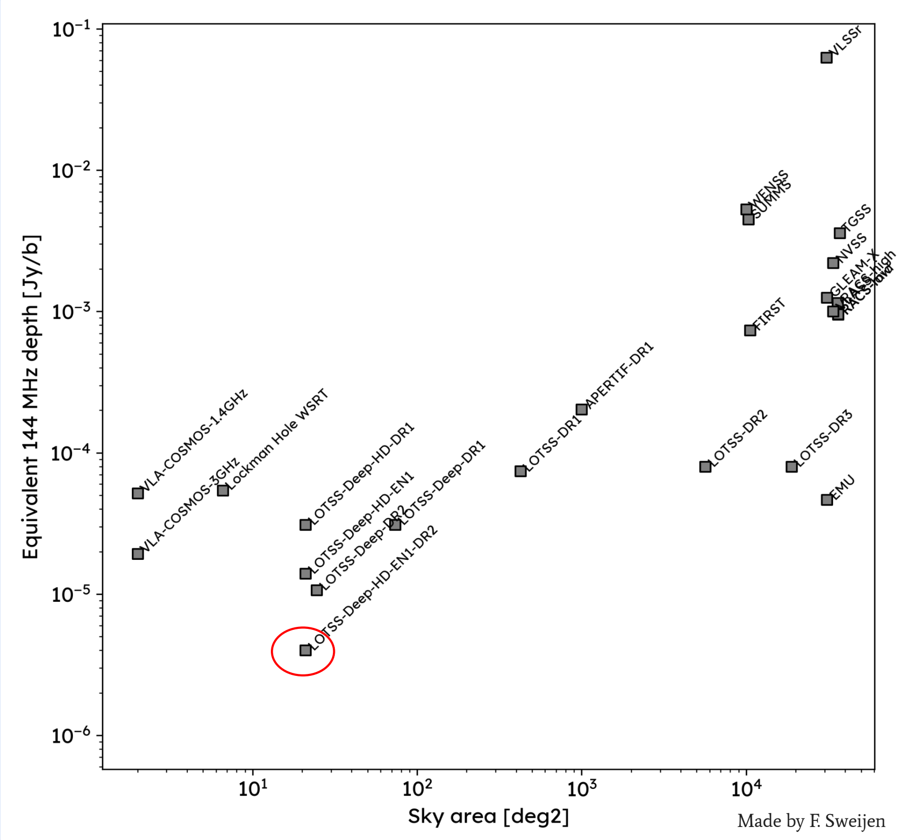


Comparison with deep ELAIS-N1 6”
(Shimwell et al. 2025)

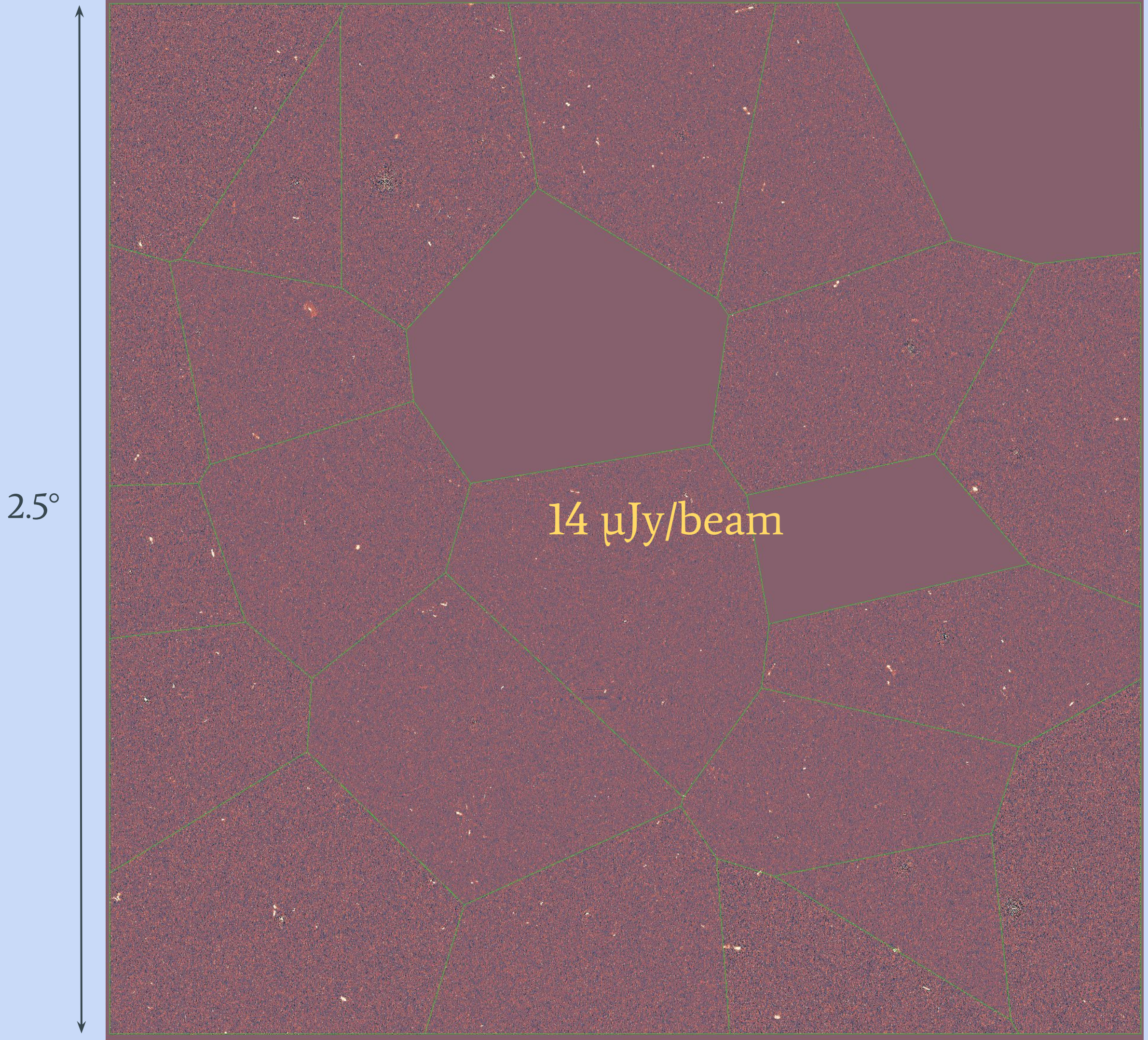
- ★ **1.8x** times deeper
  (**6 µJy/beam** !)
- ★ **20 times** better resolution



The deepest image!



- ★ **Finishing imaging**
- ★ **Cataloguing**
  - ○ Radio
  - ○ Multiwavelength(?)



Conclusion

Data processing improvements

- ★ Long-baseline calibration improved
- ★ Computational costs reduced (~10x in 3 years)
- ★ Almost fully automated pipeline
- ★ Deepest ever radio image upcoming!
  (Reach out if you want to get early access to the data)

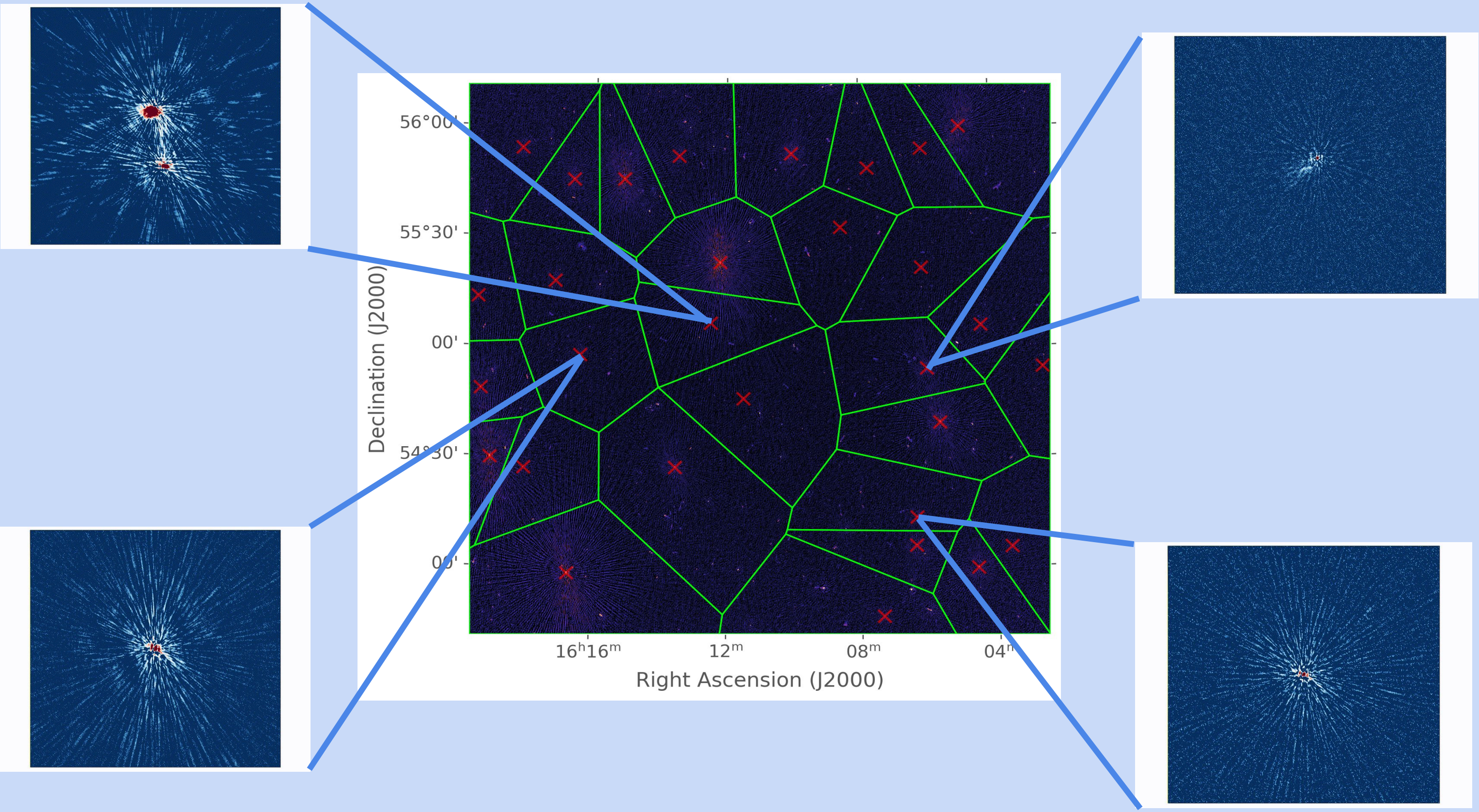
Acknowledgement

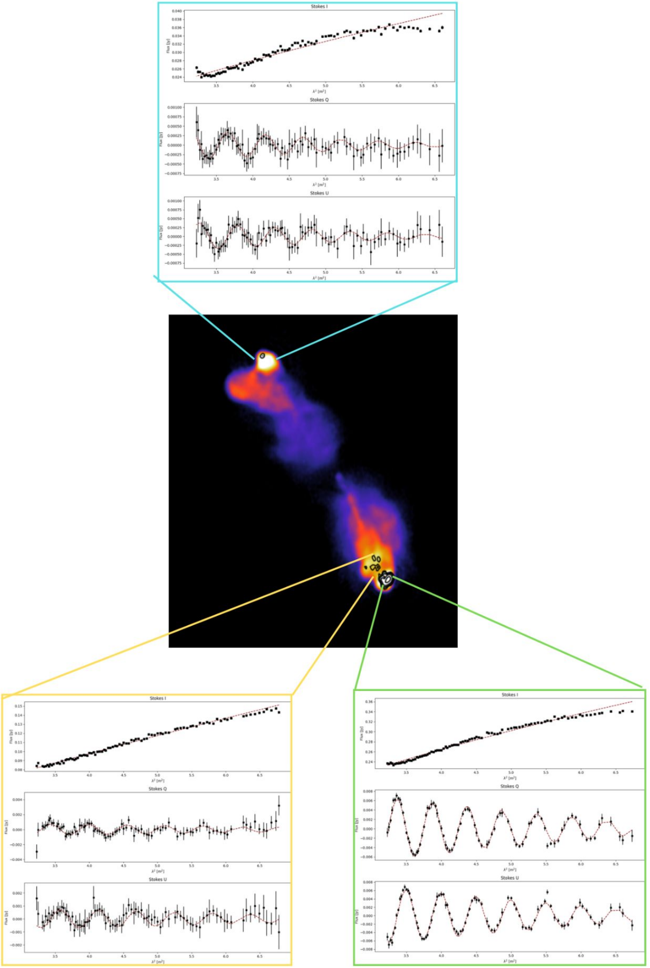
This presentation is part of the project CORTEX (NWA.1160.18.316) of the research programme NWA-ORC which is (partly) financed by the Dutch Research Council (NWO). This work made use of the Dutch national e-infrastructure with the support of the SURF Cooperative using grant no. EINF-6218. This work is co-funded by the EGI-ACE project (Horizon 2020) under Grant number 101017567.

This work was sponsored by NWO Domain Science for the use of the national computer facilities.

The authors acknowledge the OSCARS project, which has received funding from the European Commission's Horizon Europe Research and Innovation programme under grant agreement No. 101129751

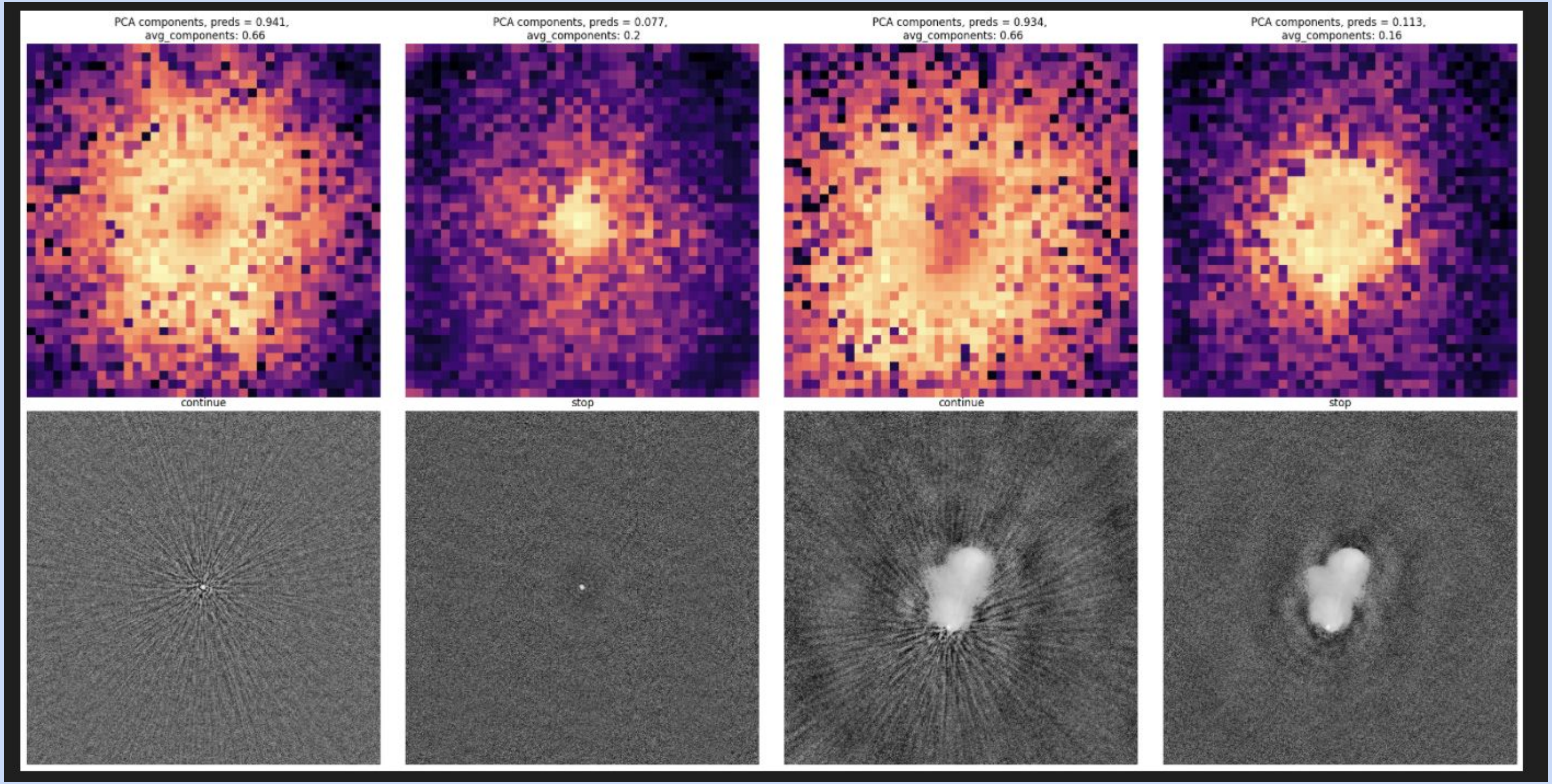
Facet-calibration



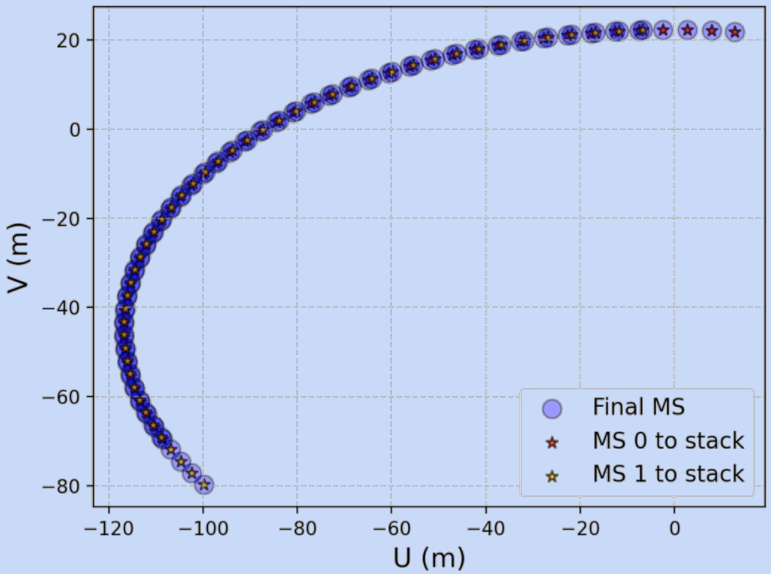


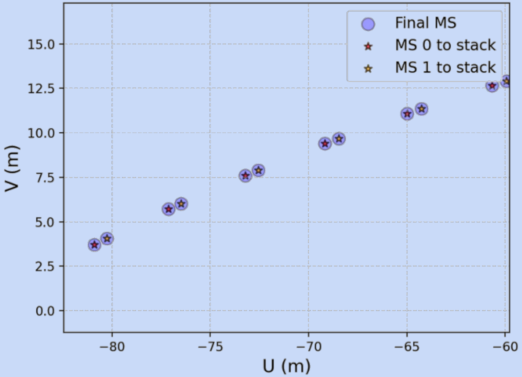
Stokes I
Stokes Q
Stokes U
Stokes I
Stokes Q
Stokes U
Stokes I
Stokes Q
Stokes U

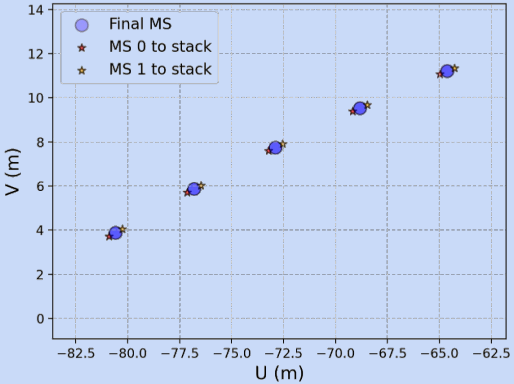
Diving into the “black box”



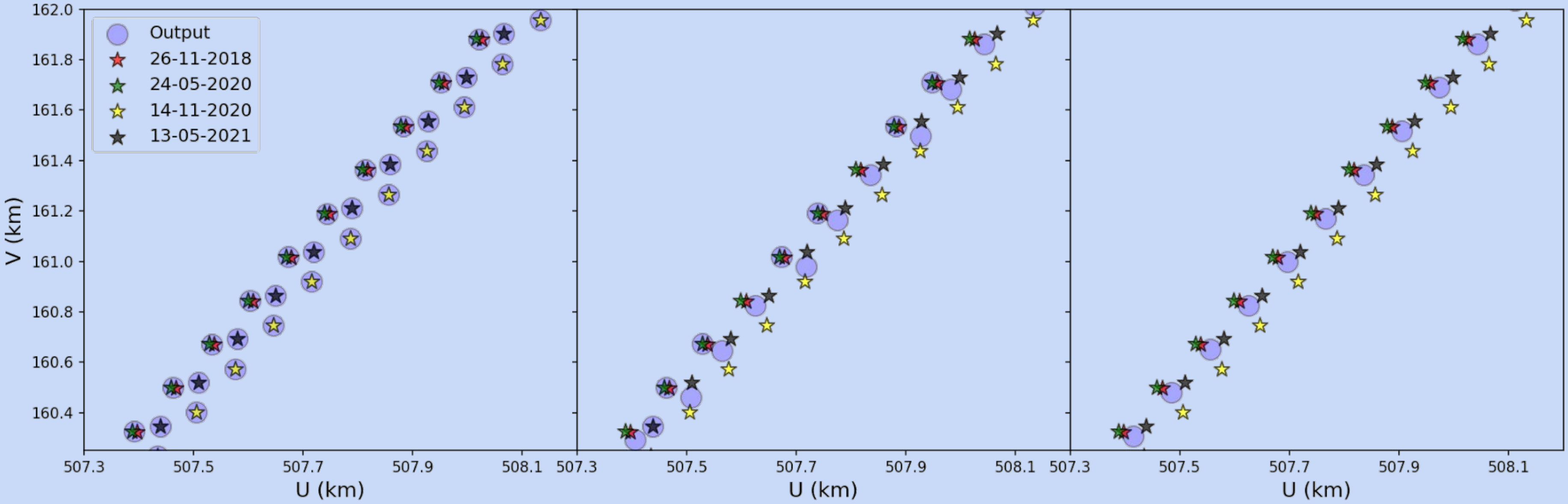
Baseline tracks



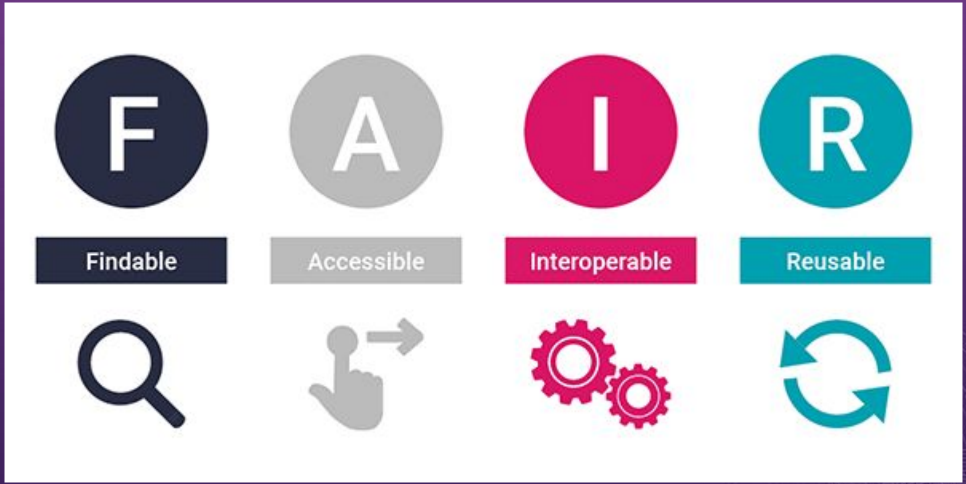




Nutation, precession, aberration



OSCARS
Open Science Clusters’ Action
for Research & Society



Funded by
the European Union