

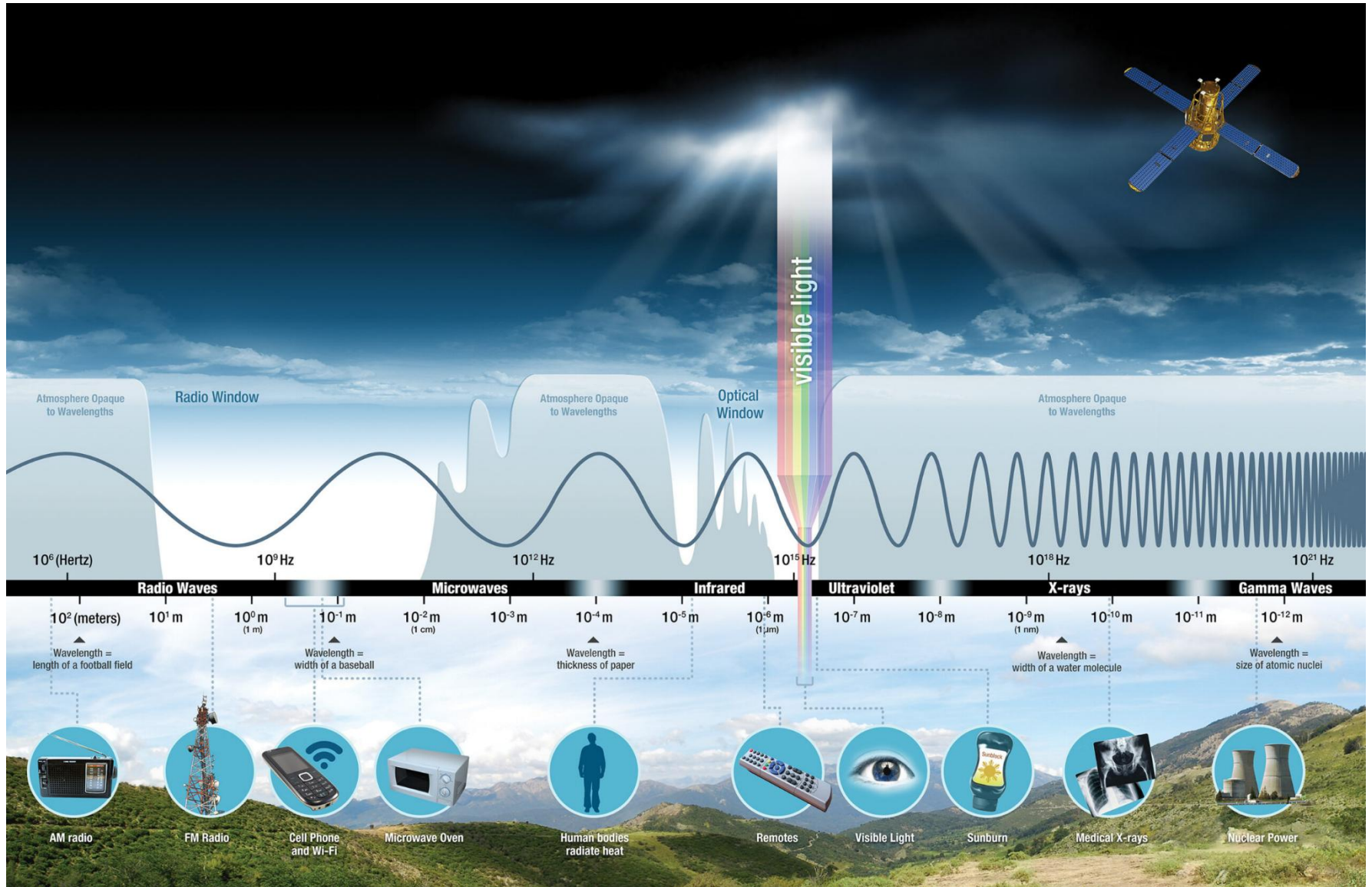
# LOFAR AND THE GIGANTIC LEAP FORWARD IN LOW-FREQUENCY RADIOASTRONOMY



**Gianfranco Brunetti**



# THE RADIO WINDOW



Multimessenger astronomy : photons + CR + neutrino + GW

# INTERFEROMETRY



$$\theta \sim \frac{\lambda}{D}$$



Due to the (long) wavelengths of radio waves, the largest traditional radio telescopes we can build have an angular resolution comparable to that of the human eye... this clashes with the enormous signal collection capacity that radio telescopes have (Confusion Noise)



# INTERFEROMETRY



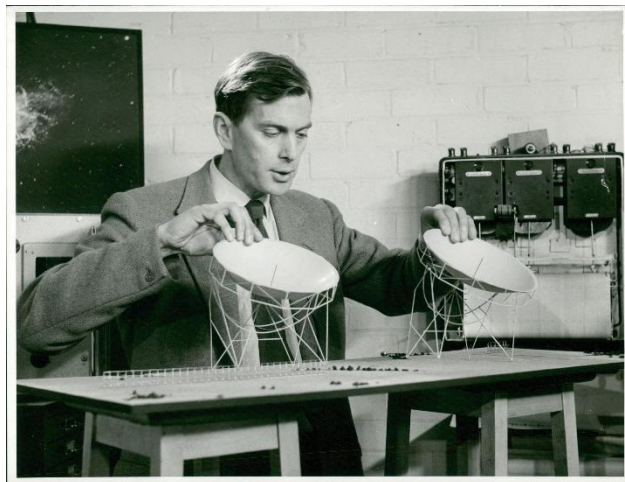
$$\theta \sim \frac{\lambda}{D}$$



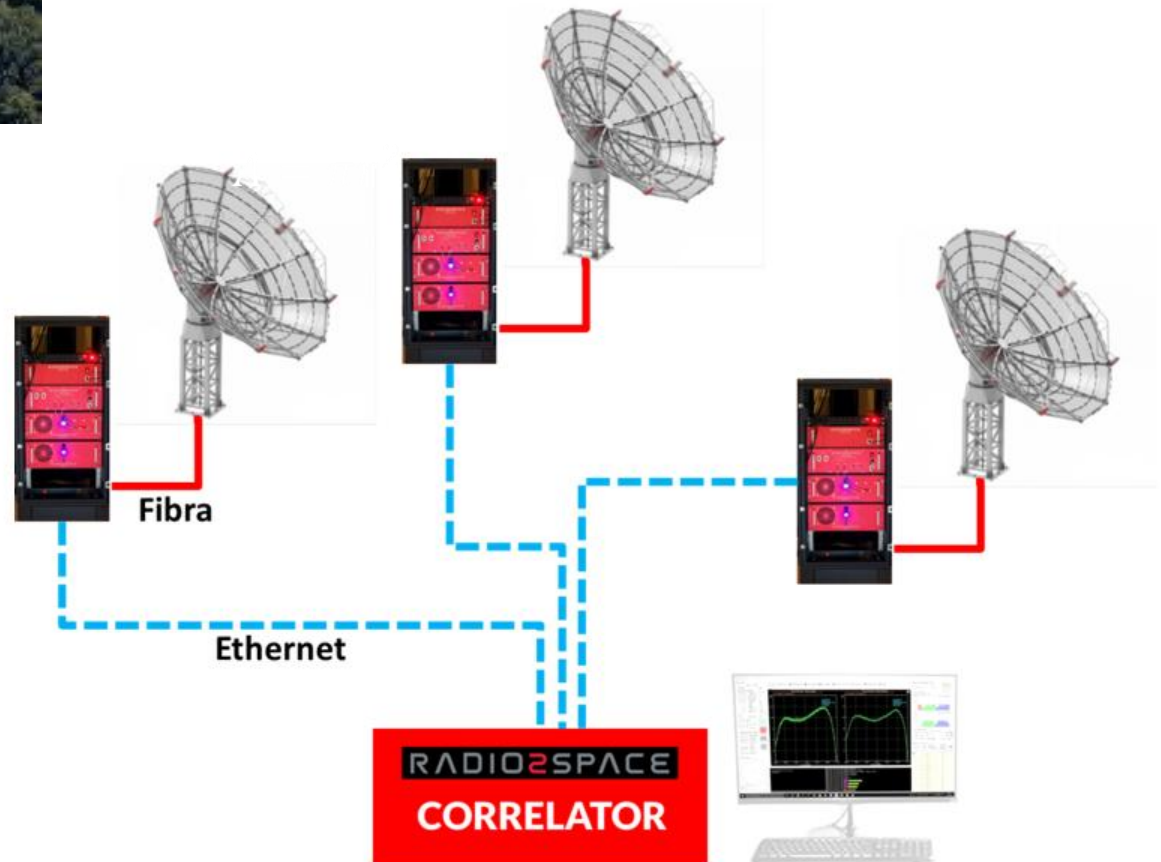
$$N = \binom{n}{2} \sim n^2$$

$$\text{FoV} \sim \frac{\lambda}{D}$$

$$\theta \sim \frac{\lambda}{d}$$



M. Ryle ..Nobel prize 1974



# INTERFEROMETRY



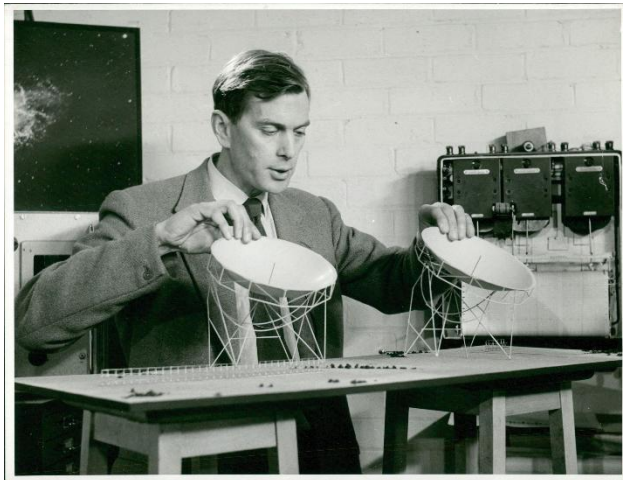
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# INTERFEROMETRY



$$\theta \sim \frac{\lambda}{D}$$



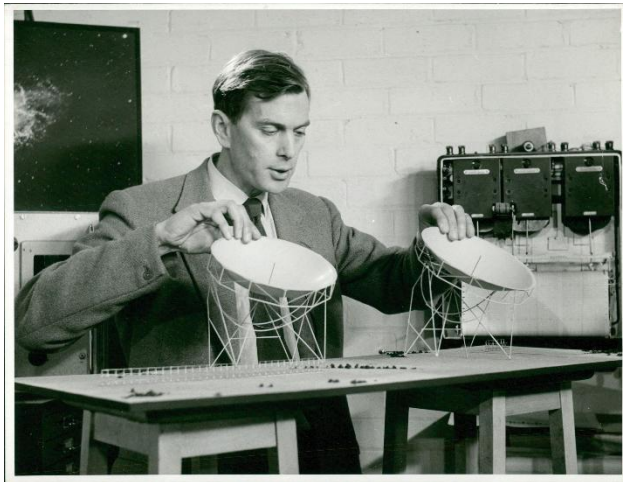
$$N = \binom{n}{2} \sim n^2$$

$$\text{FoV} \sim \frac{\lambda}{D}$$

$$\theta \sim \frac{\lambda}{d}$$

$$A = \pi r^2$$

L'Event Horizon Telescope (EHT)



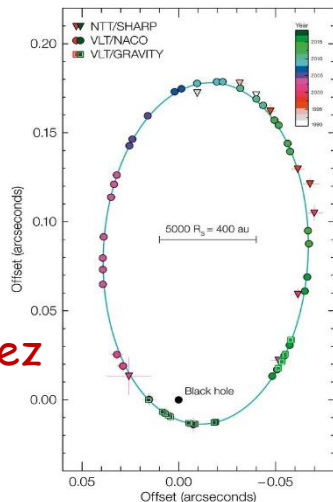
M. Ryle ..Nobel prize 1974



# THE BLACK HOLE AT THE CENTER OF OUR GALAXY

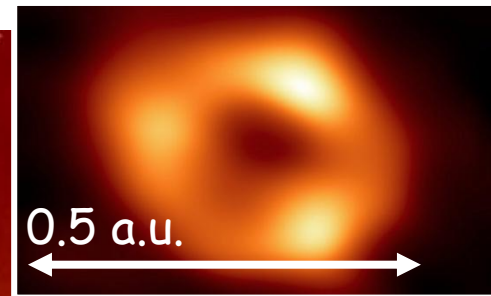
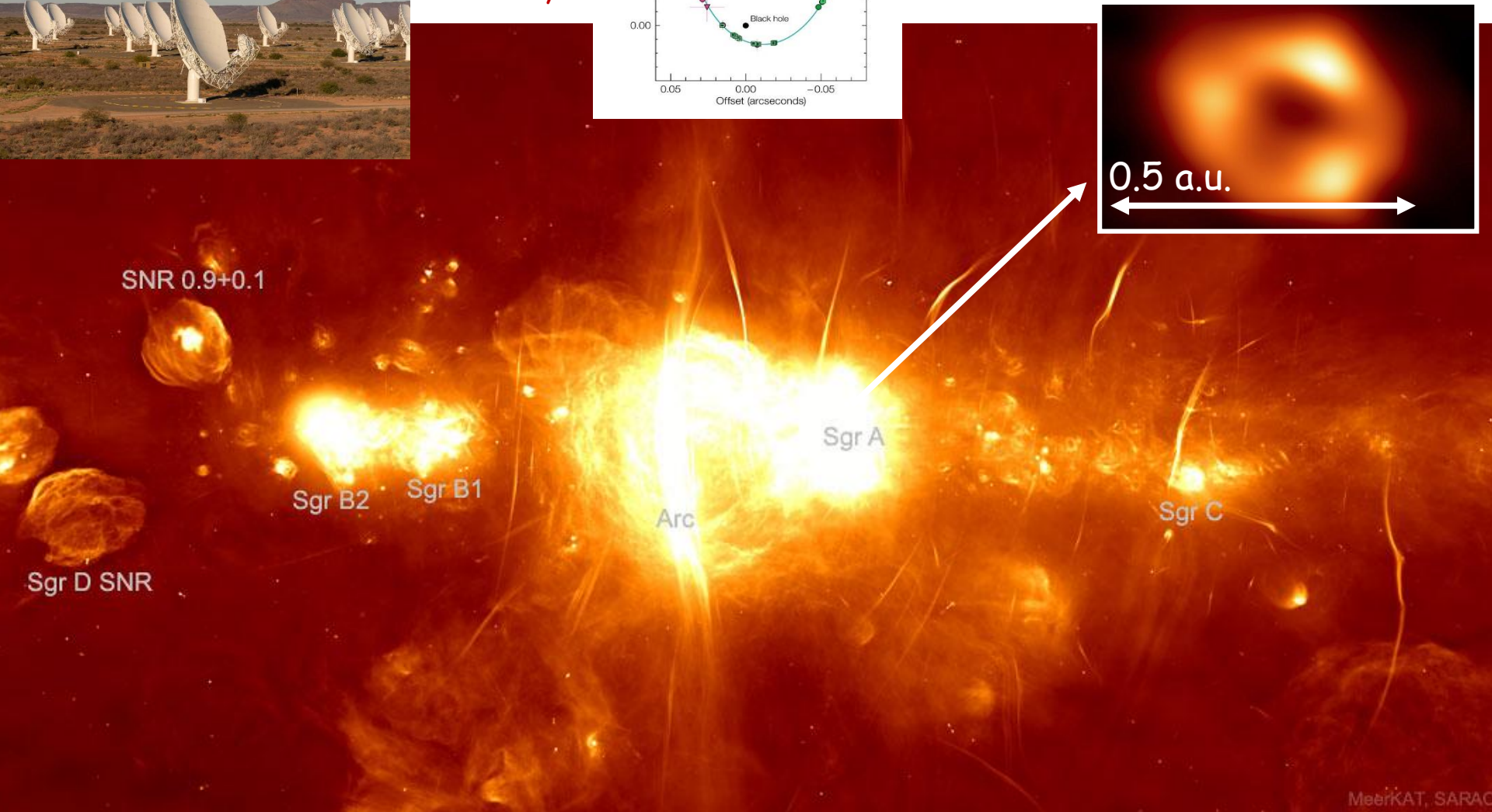


Genzel, Ghez



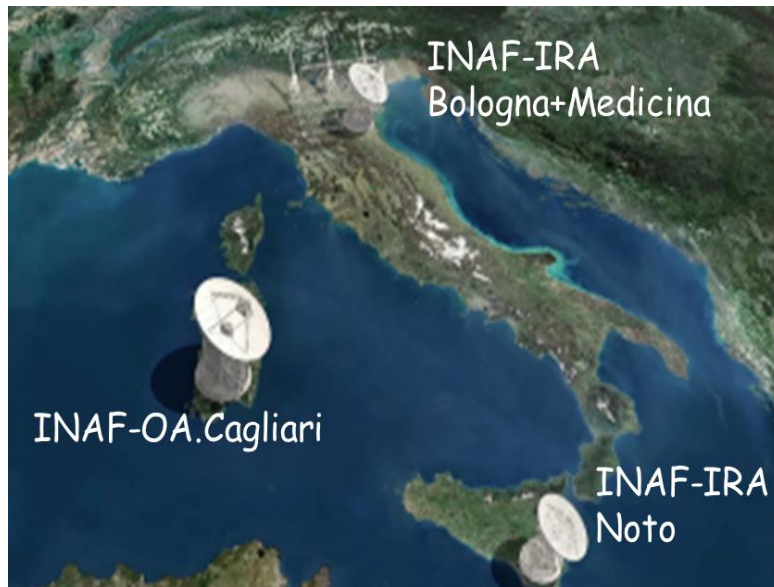
$$\theta \sim \frac{\lambda}{d}$$

EHT reaches an angular resolution of 20 micro-arcsec



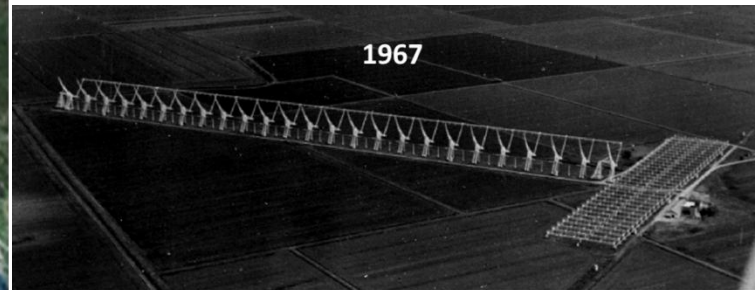


# ITALIAN RADIOTELESCOPES

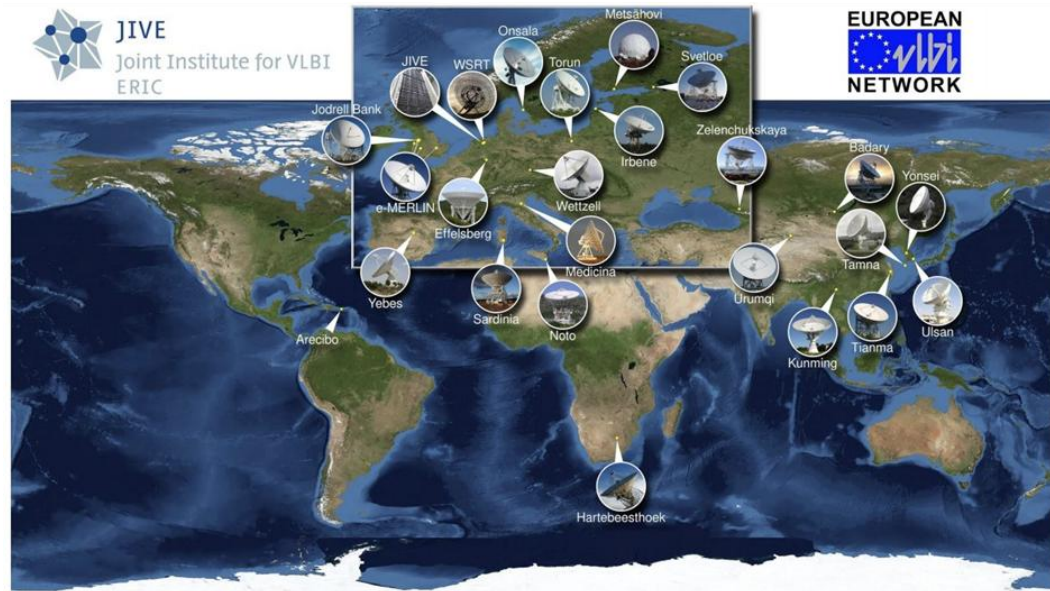


Long tradition..  
Italian radio astronomy  
participates in all the  
major international  
projects, from EVN  
(long-baseline  
interferometry), ALMA,  
EHT, ... **LOFAR**,  
MeerKAT, **SKA**

Croce del Nord

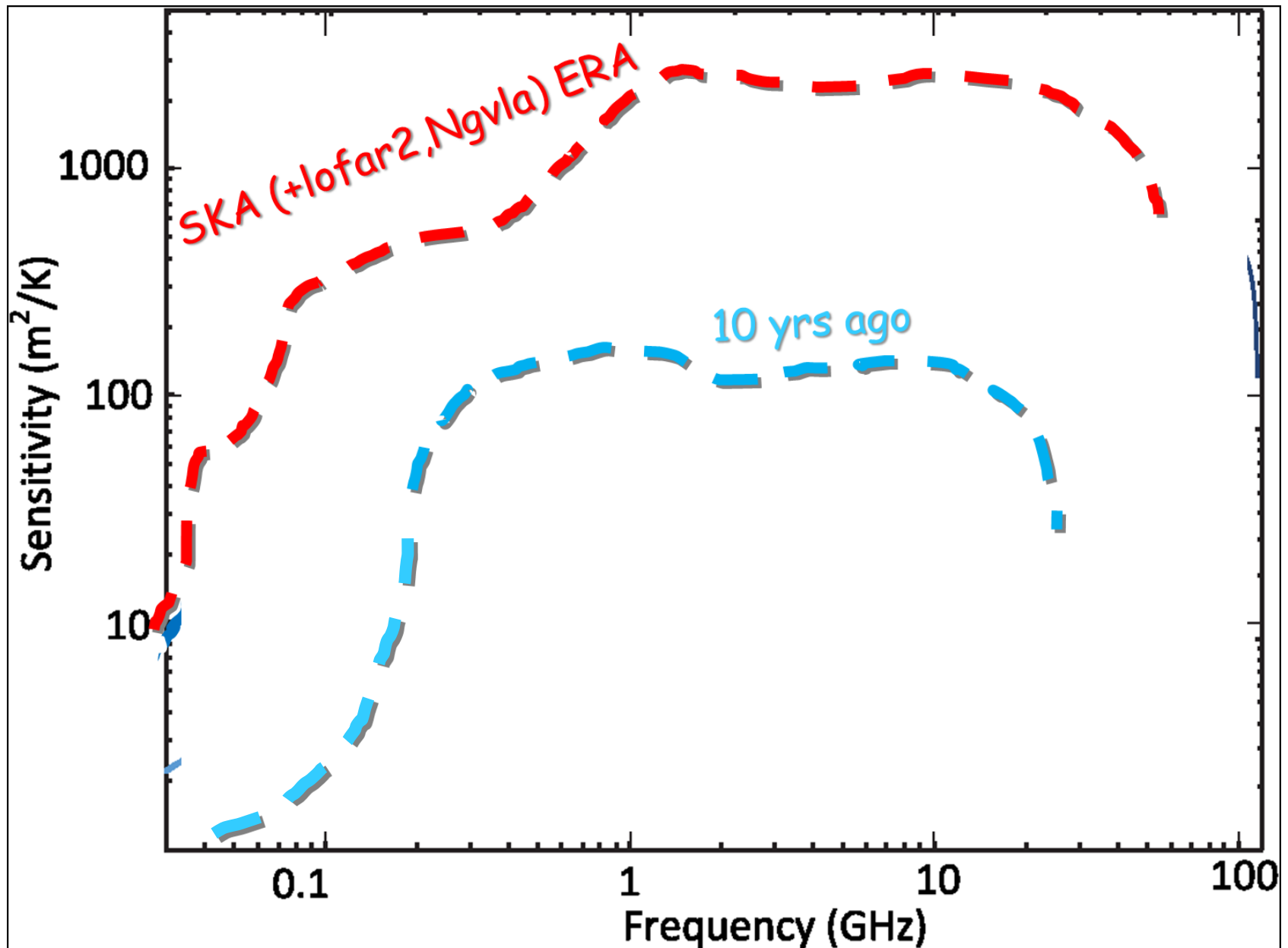


EVN 1980+  
JIV-ERIC 2015

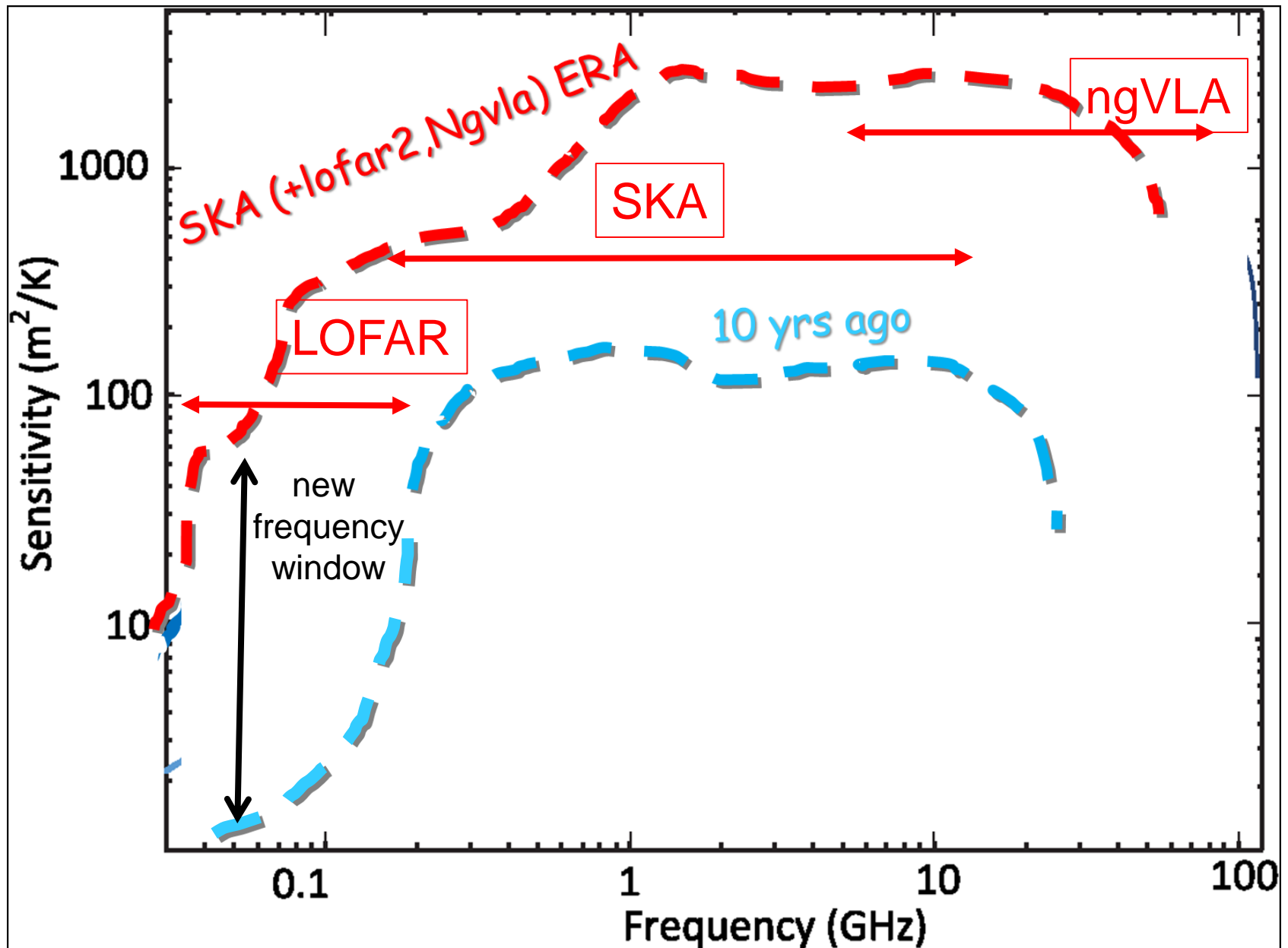




# GOLDEN AGE FOR RADIOASTRONOMY

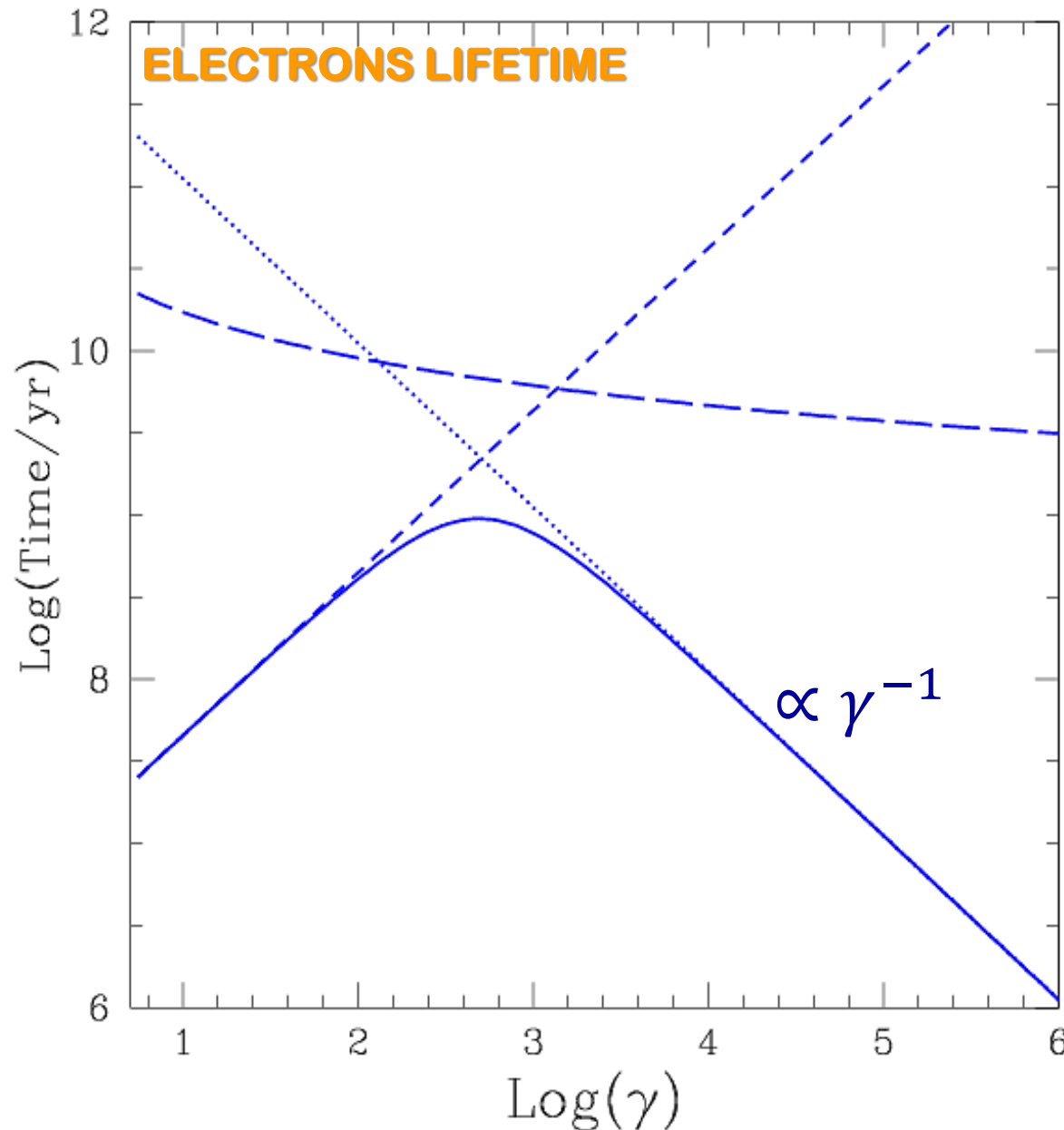


# GOLDEN AGE FOR RADIOASTRONOMY





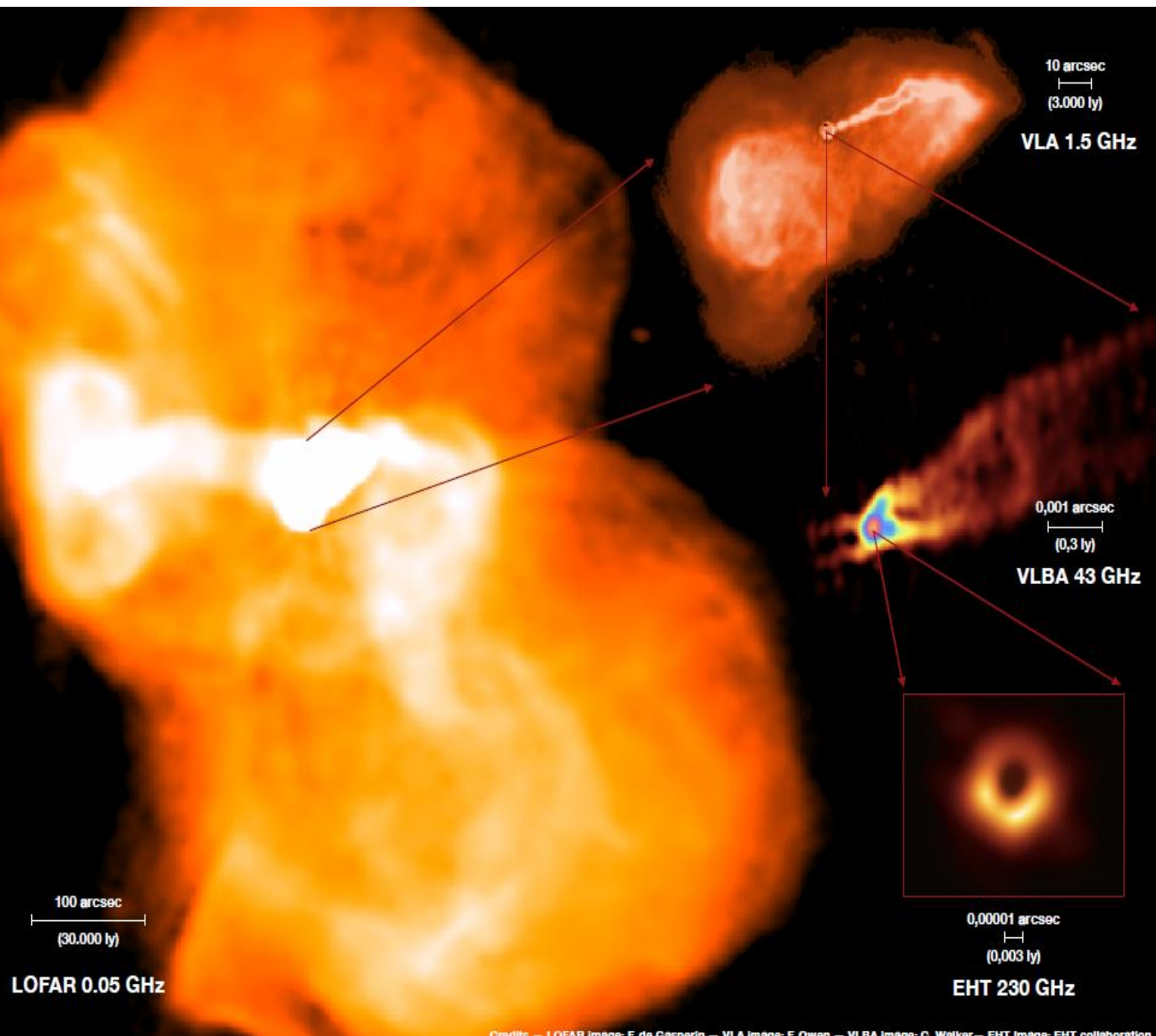
# WHY LOW FREQUENCIES ??



Synchrotron frequency

$$\nu \propto B\gamma^2$$

- ☐ Long living particles  
(longer look-back times)
- ☐ Lower energy electrons  
(new mechanisms)
- ☐ Lower B  
(magnetogenesis)



Credits — LOFAR image: F. de Gasparis — VLA image: F. Owen — VLBA image: C. Walker — EHT image: EHT collaboration

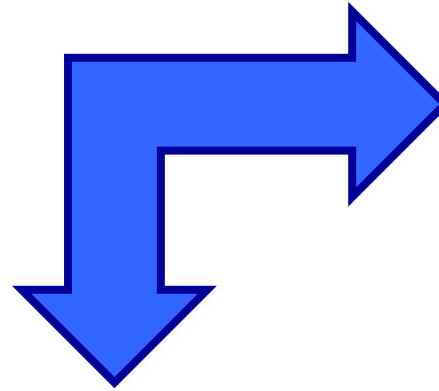


# CHALLENGES AT LOW FREQUENCIES

$$N = \binom{n}{2} \sim n^2$$

$$\text{FoV} \sim \frac{\lambda}{D}$$

$$\theta \sim \frac{\lambda}{d}$$



BIG DATA

- ☐ BIG TO REACH HIGH RESOLUTION
- ☐ MANY BASELINES
- ☐ LARGE FoV
- ☐ DISTORSION OF PHASES

NEW TECH

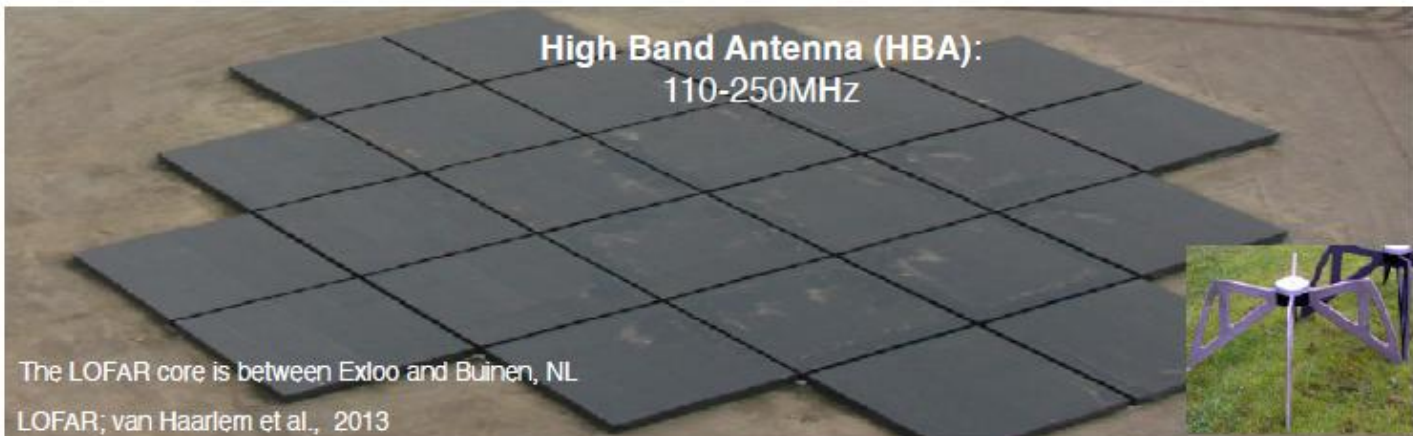
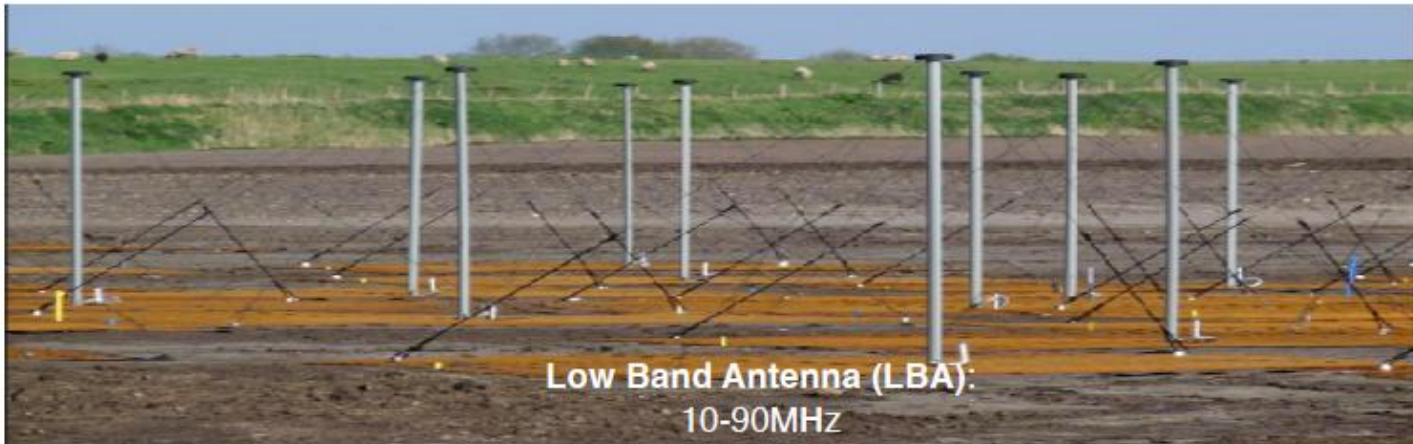
LIMITED BY CALIBRATION, COMPUTING, DATA TRANSPORT

# THE LOW FREQUENCY ARray

**Giant digital aperture array radio telescope opening up a new window in the electromagnetic spectrum at low radio frequencies**

(van Haarlem + 2013)

**Low and High band antennas : 10-250 MHz**



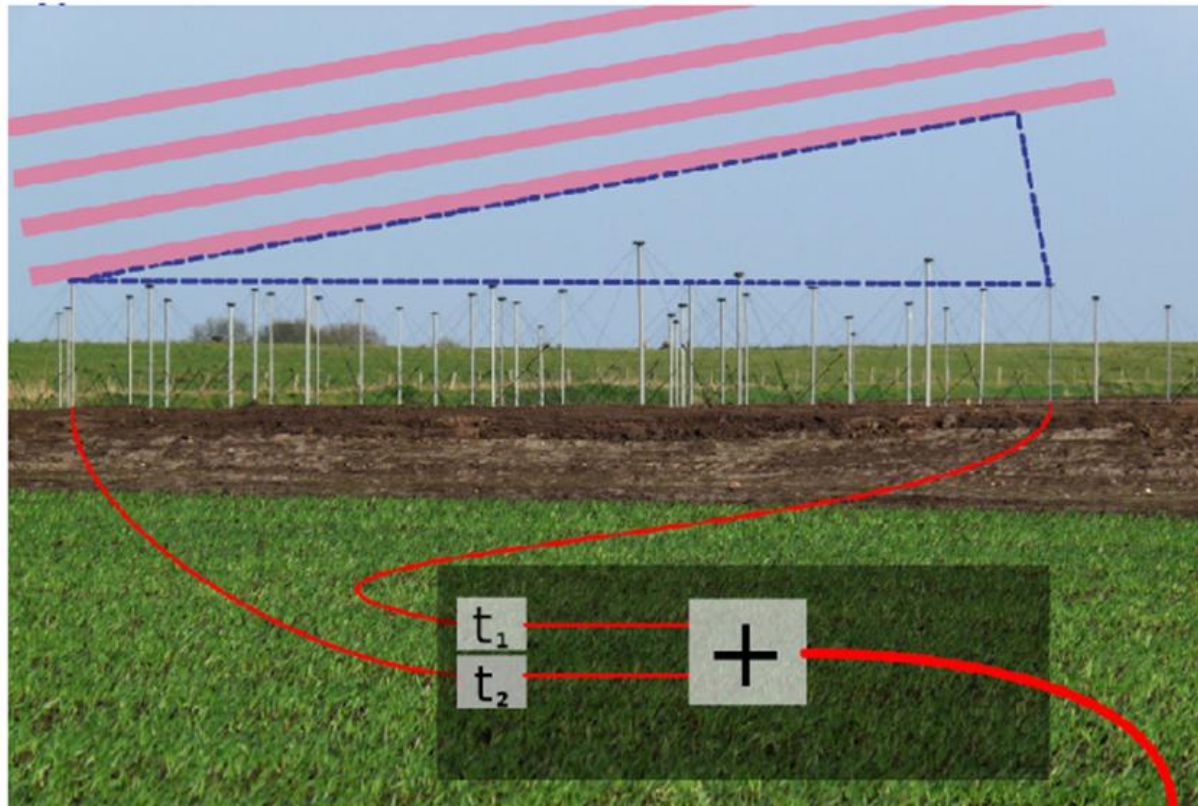


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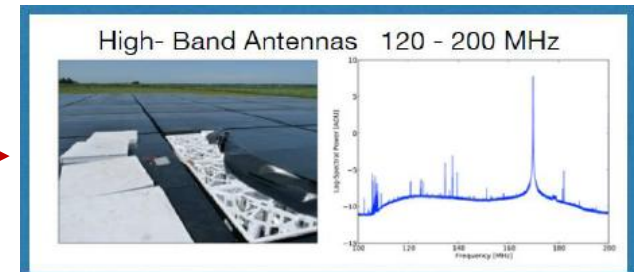
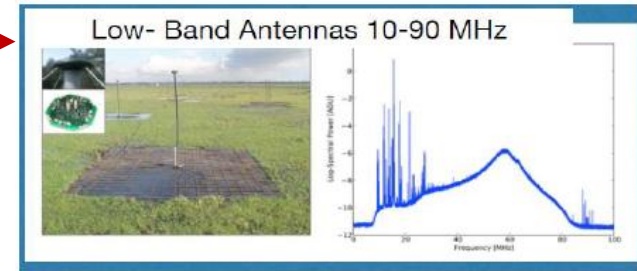
## Beam forming



# THE LOW FREQUENCY ARray

**Giant digital aperture array radio telescope opening up a new window in the electromagnetic spectrum at low radio frequencies**

(van Haarlem + 2013)



10 Countries  
24+14+14(16) stations



# THE LOW FREQUENCY ARray





# THE LOW FREQUENCY ARray



# THE LOW FREQUENCY ARray

**Giant digital aperture array radio telescope opening up a new window in the electromagnetic spectrum at low radio frequencies**  
**- The largest (area & dataflow) pathfinder toward the SKA(low) -**

(van Haarlem + 2013)

✓ 250 Gb/s across the entire network



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x100 VLA



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**Giant digital aperture array radio telescope opening up a new window in the electromagnetic spectrum at low radio frequencies**  
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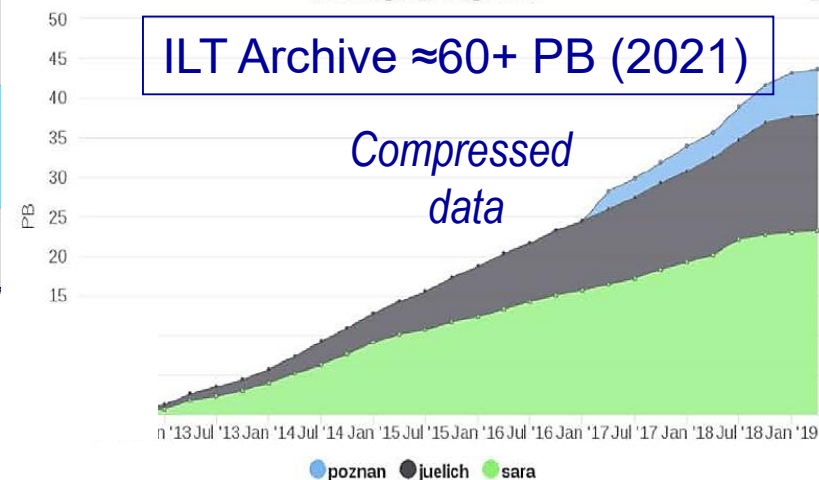
(van Haarlem + 2013)

- ✓ 250 Gb/s across the entire network
- ✓ Large FoV, n baselines, n channels, produce typical **TB-size datasets**
- ✓ Archiving problem and managing Big Data



LTA Storage Site Usage Trend

ILT Archive  $\approx 60+$  PB (2021)

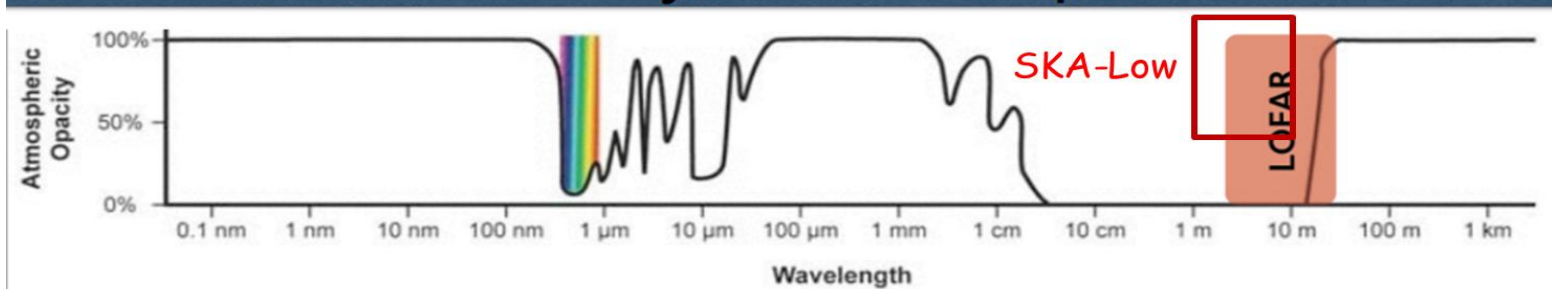


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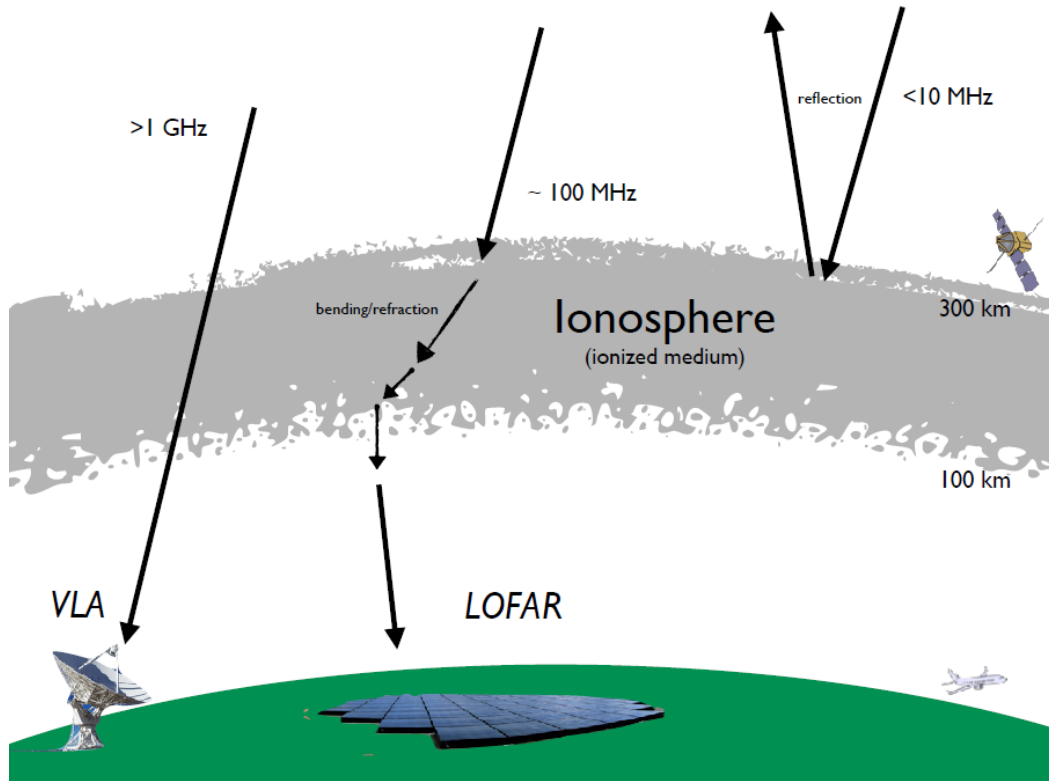
**BIG Challenges with data calibration and analysis**

Our enemy: the ionosphere



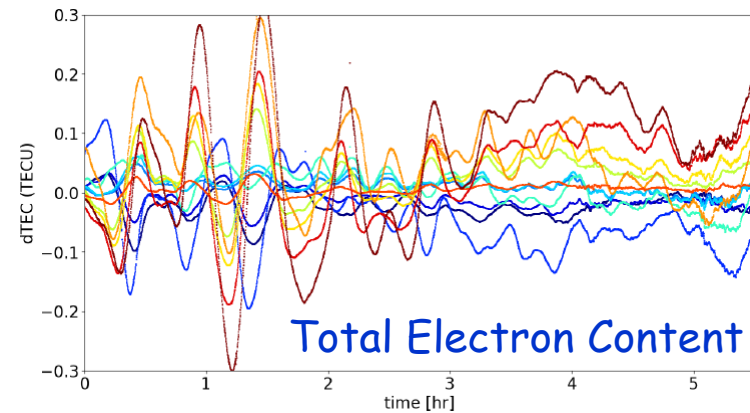


# LOFAR & THE IONOSPHERE

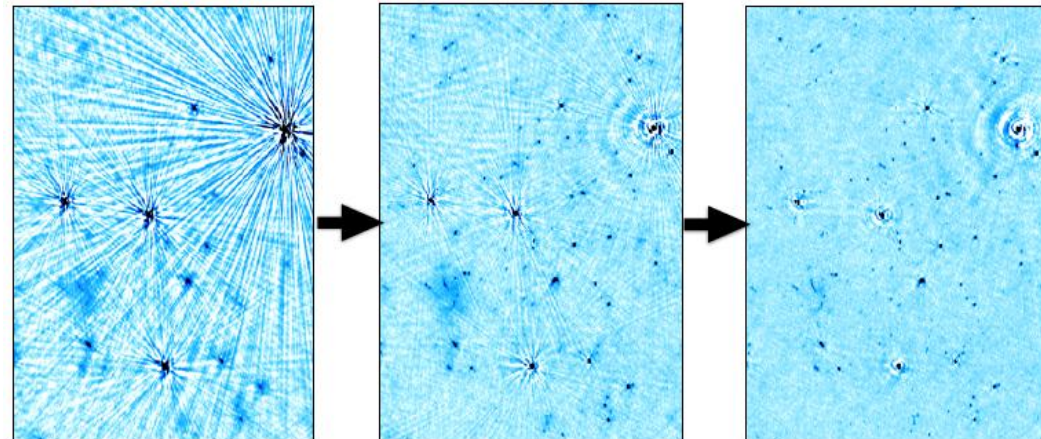


$$\Phi_{\text{ion}} = -\frac{2\pi\nu}{c} \int_{\text{LoS}} (n - 1) dl.$$

$$n \approx 1 - \frac{q^2}{8\pi^2 m_e \epsilon_0} \cdot \frac{n_e}{\nu^2} \pm \frac{q^3}{16\pi^3 m_e^2 \epsilon_0} \cdot \frac{n_e B \cos \theta}{\nu^3} - \frac{q^4}{128\pi^4 m_e^2 \epsilon_0^2} \cdot \frac{n_e^2}{\nu^4} - \frac{q^4}{64\pi^4 m_e^3 \epsilon_0} \cdot \frac{n_e B^2 (1 + \cos^2 \theta)}{\nu^4}$$

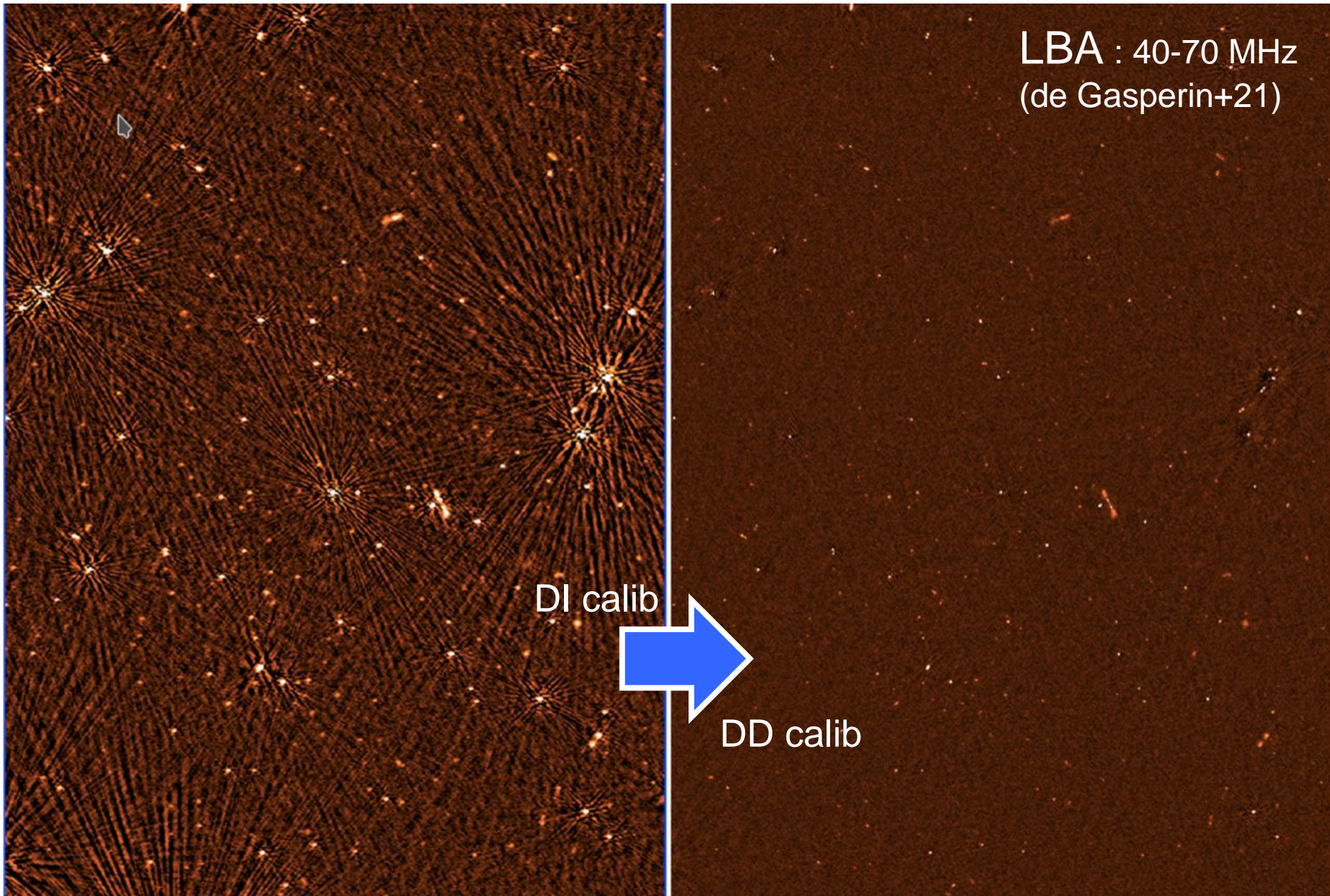


To correct ionospheric effects it is necessary to implement new strategies for data calibration that in recent years have given very important results

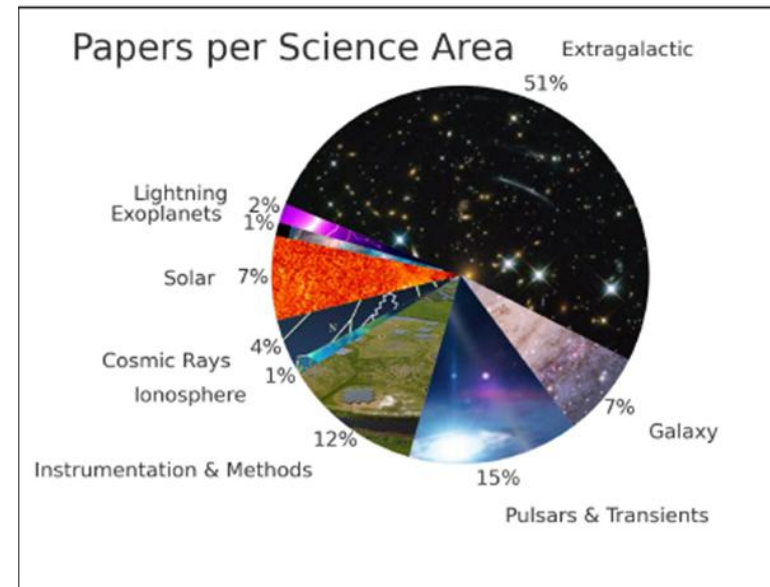
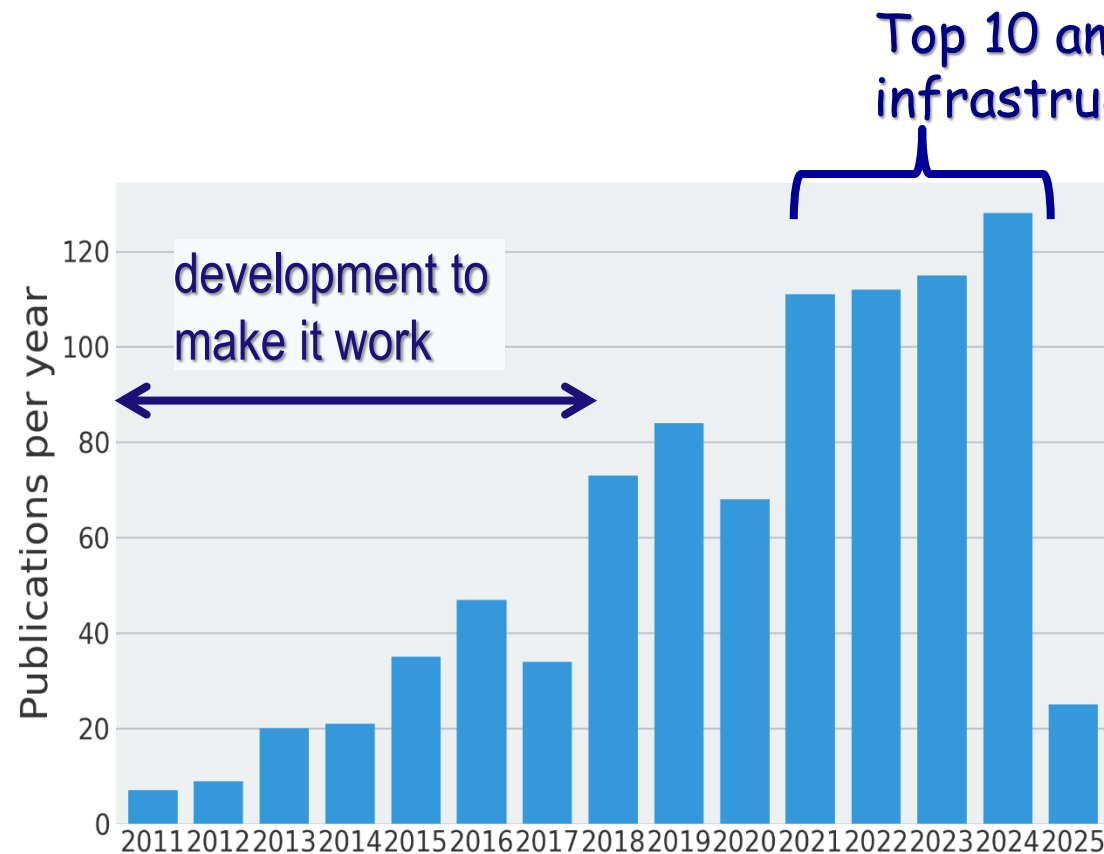




# THE LOW FREQUENCY ARray



# SCIENCE WITH LOFAR



*Credits: ASTRON*

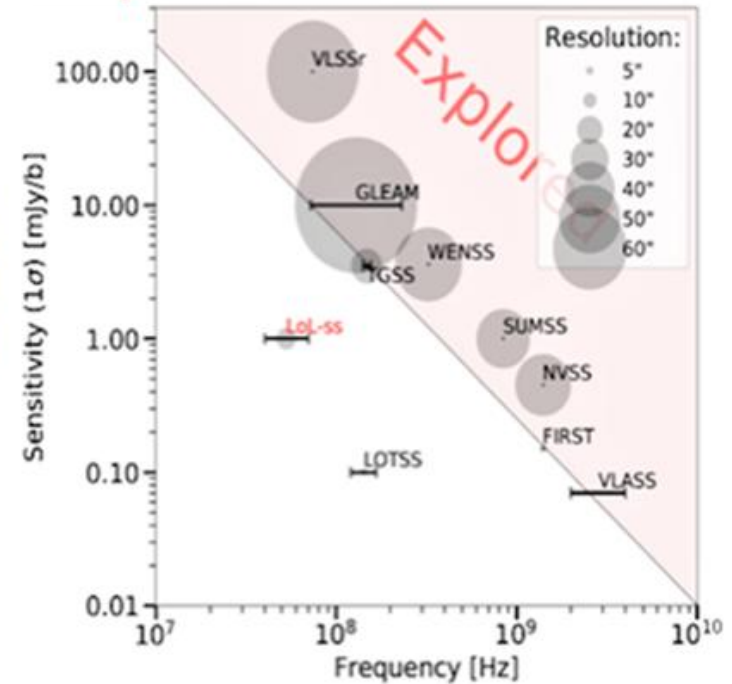
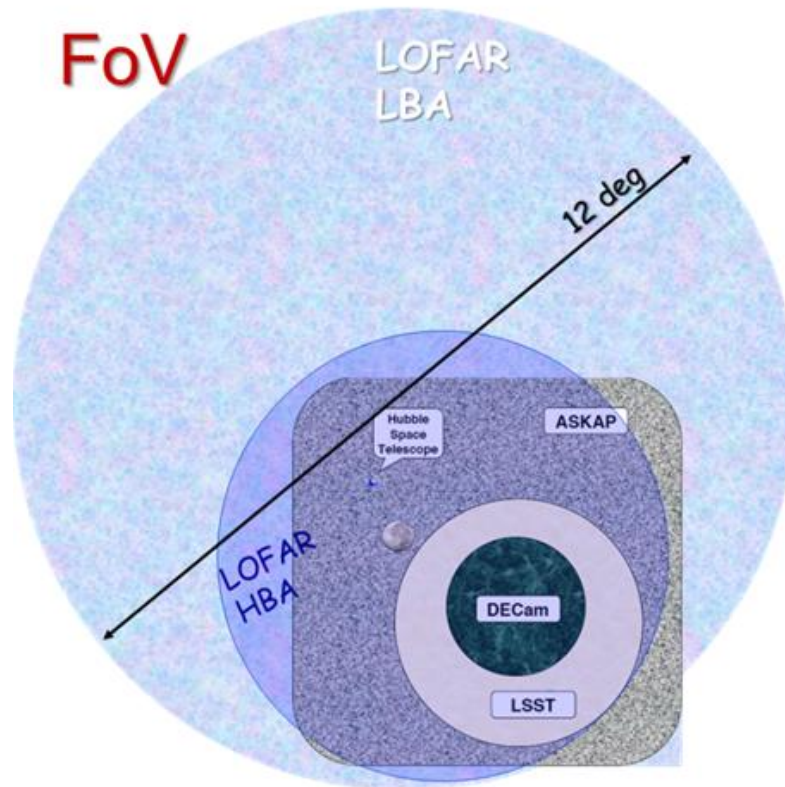
IT joins ILT

LOFAR-ERIC

IT funding member



# THE LOFAR SURVEYS

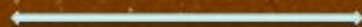


LOFAR Surveys of the entire northern sky are opening a new observational window of the Universe

- 10-100x better sensitivity
- 10x better spatial resolution (100x using international baselines)

# LoTSS-deep

Several ksources



1 degree

ELAIS-N1 ( $< 20 \mu\text{Jy}/\text{beam}$ )  
(Sabater+ 2021; Tasse+ 2021)



# LoTSS-deep



1 degree

ELAIS-N1 ( $< 20 \mu\text{Jy}/\text{beam}$ )  
(Sabater+ 2021; Tasse+ 2021)



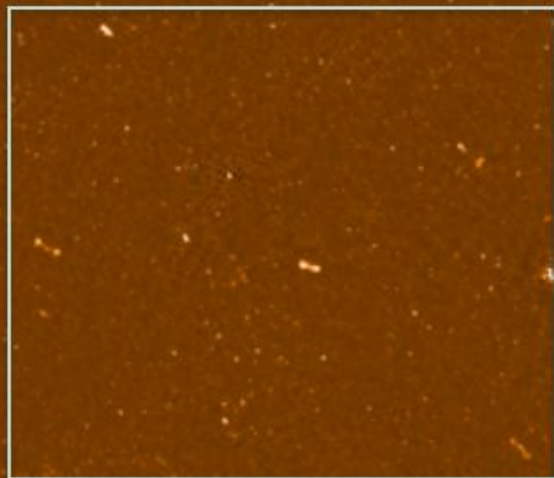
# LoTSS-deep



15 arcmin

ELAIS-N1 ( $< 20 \mu\text{Jy}/\text{beam}$ )  
(Sabater+ 2021; Tasse+ 2021)

# LoTSS-deep

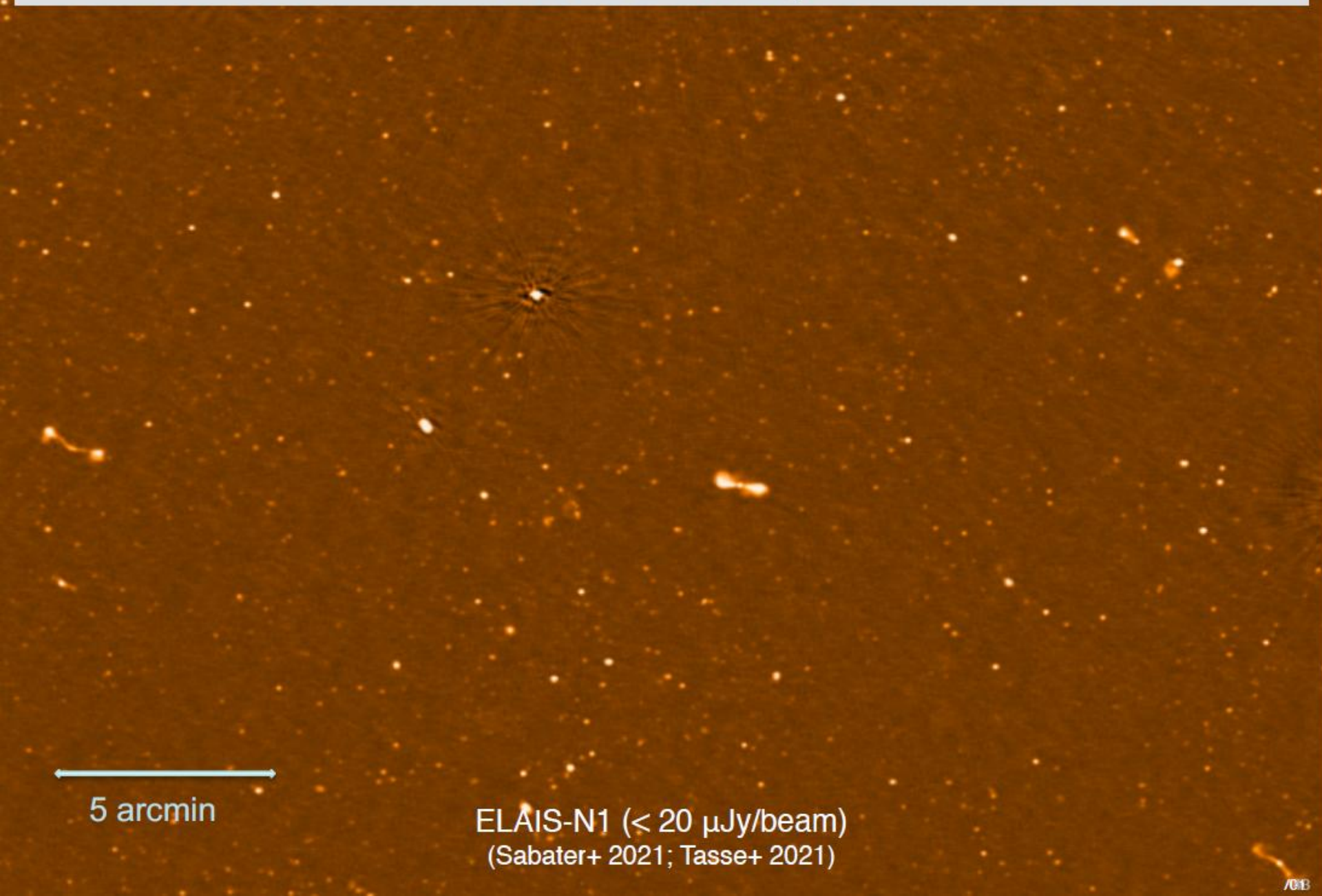


15 arcmin

ELAIS-N1 ( $< 20 \mu\text{Jy/beam}$ )  
(Sabater+ 2021; Tasse+ 2021)



# LoTSS-deep

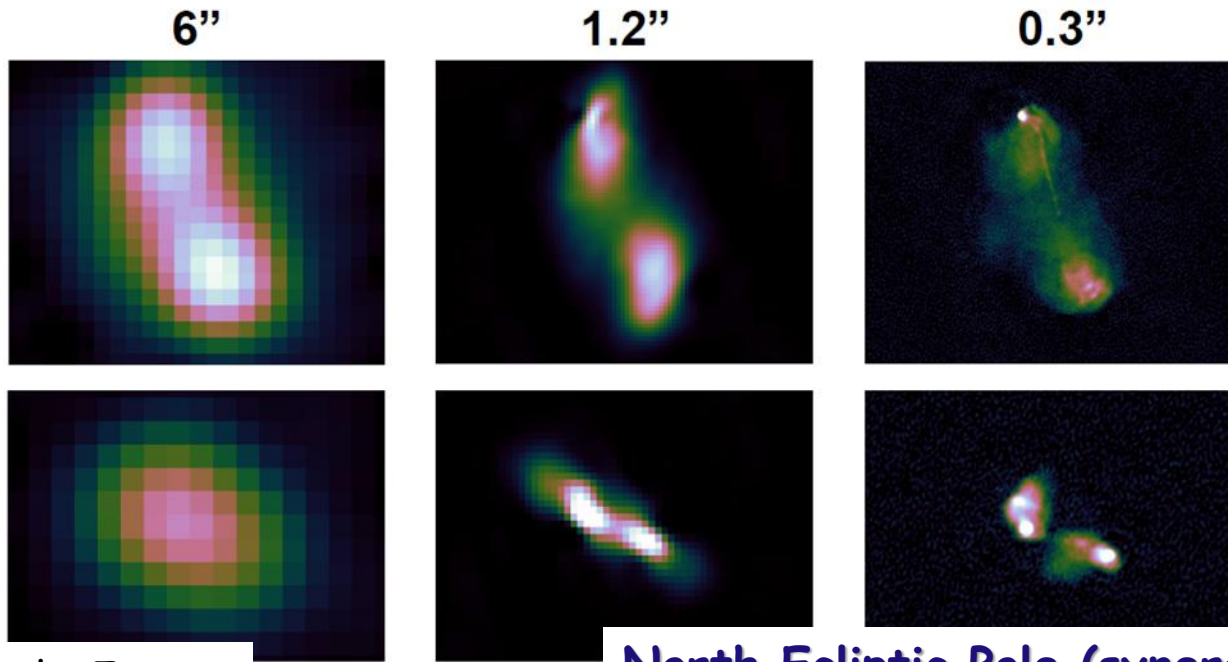


5 arcmin

ELAIS-N1 ( $< 20 \mu\text{Jy/beam}$ )  
(Sabater+ 2021; Tasse+ 2021)



## LONG-EU Baselines



de Jong+

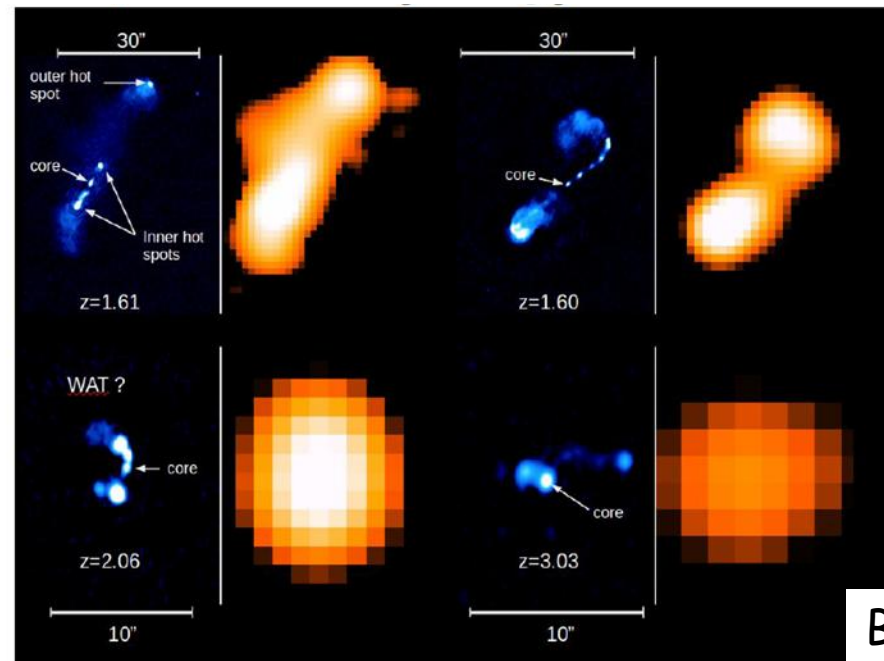
North Ecliptic Pole (synergy with EUCLID+JWST)



Computationally expensive !!

300,000 core hours necessary to  
image  $\sim 5 \text{ deg}^2$  field observed with  
8 hrs at **0.3 arcsec resolution**  
(eg Sweijen+ 2022, Nat Astr)

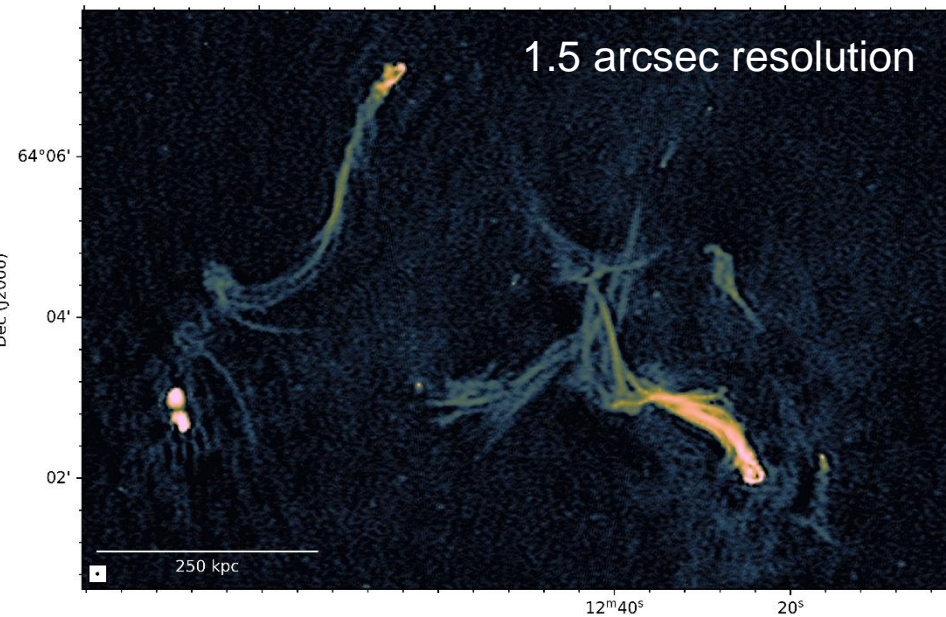
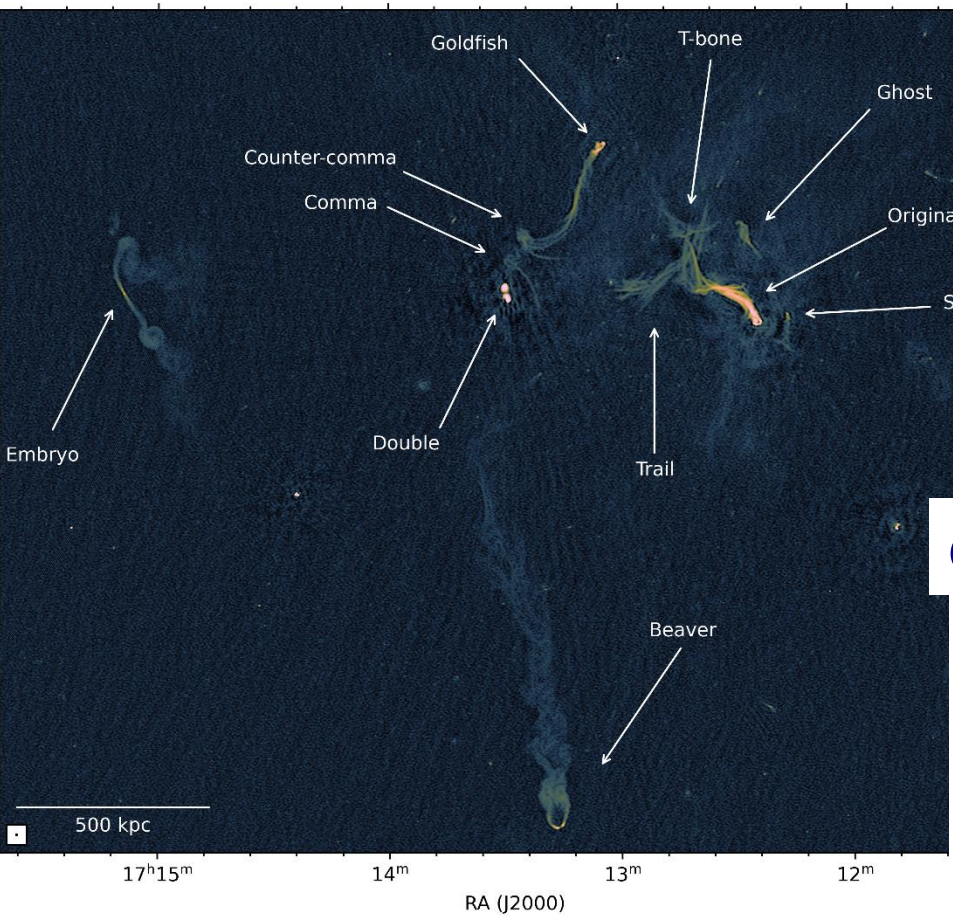
Imaging large regions with deep  
observations at sub-arcsec  
resolution is a **major  
computational challenge**



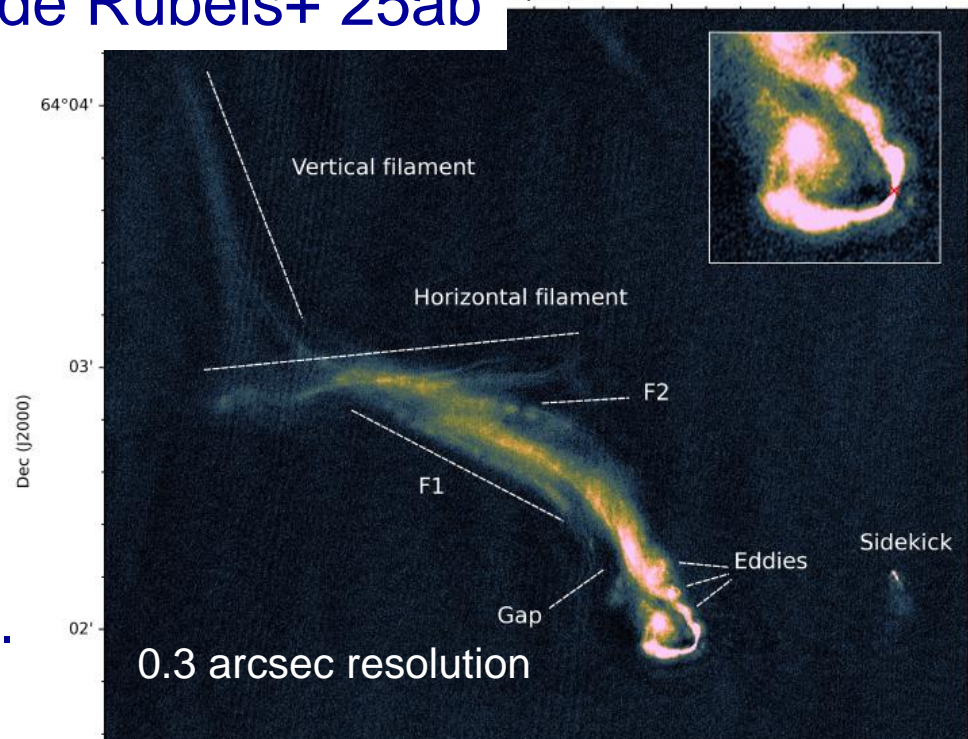
Bondi+



# BH activity & their impact



de Rubeis+ 25ab



generation & growth of instabilities,  
extraction and advection of magnetic  
filaments, mixing in the turbulent ICM....



# EXPLORING LSS

SCIENCE ADVANCES | RESEARCH ARTICLE

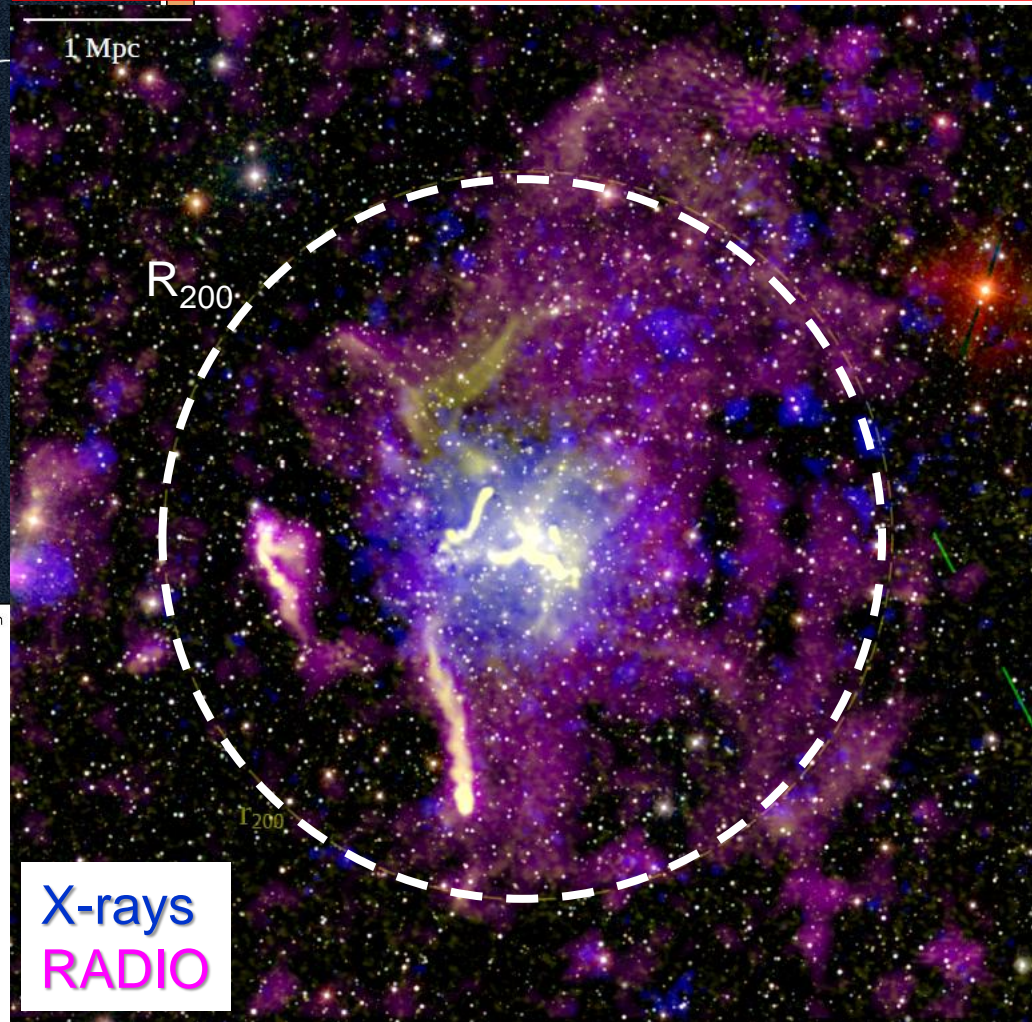
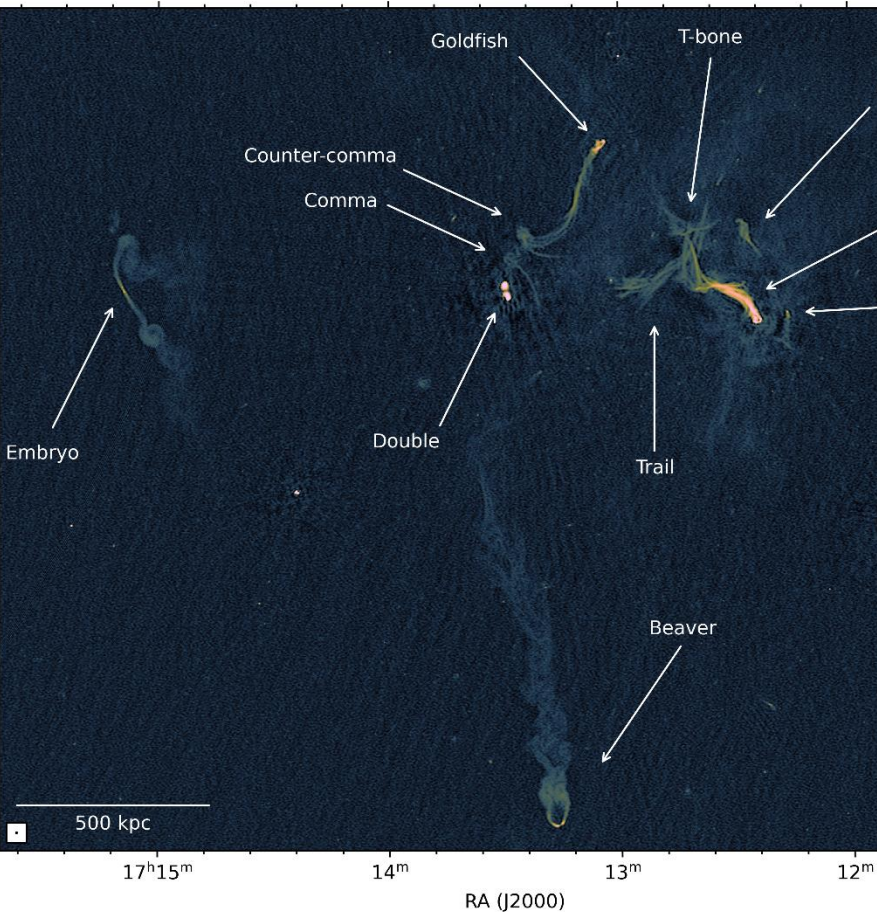
Science  
Advances

AAAS

ASTRONOMY

## Magnetic fields and relativistic electrons fill entire galaxy cluster

Andrea Botteon<sup>1,2,3\*</sup>, Reinout J. van Weeren<sup>1</sup>, Gianfranco Brunetti<sup>3</sup>, Franco Vazza<sup>2,3</sup>, Timothy W. Shimwell<sup>1,4</sup>, Marcus Brüggen<sup>5</sup>, Huub J. A. Röttgering<sup>1</sup>, Francesco de Gasperin<sup>3,5</sup>, Hiroki Akamatsu<sup>6</sup>, Annalisa Bonafede<sup>2,3</sup>, Rossella Cassano<sup>3</sup>, Virginia Cuciti<sup>3,5</sup>, Daniele Dallacasa<sup>2,3</sup>, Gabriella Di Gennaro<sup>5</sup>, Fabio Gastaldello<sup>7</sup>

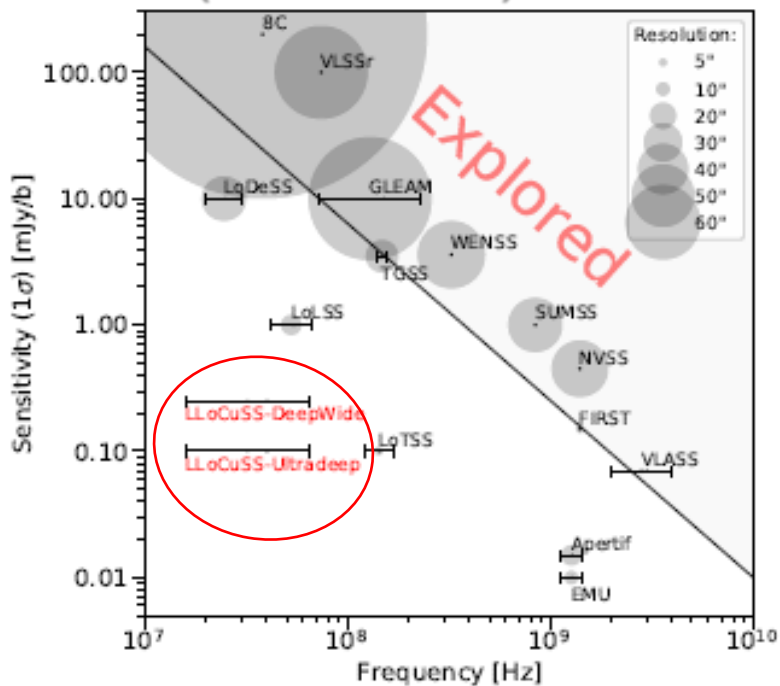


generation & growth of instabilities,  
extraction and advection of magnetic  
filaments, mixing in the turbulent ICM....

Magnetogenesis & particle acceleration  
by turbulence & shocks



# LOFAR 2.0 upgrade (2026+...)



## Upgrade :

- Electronics
- Correlator
- Dual beam (es Medicina)

will bring LOFAR into a new regime entering an uncharted territory at the very low frequencies (10-60 MHz)

## NEW ELECTRONICS

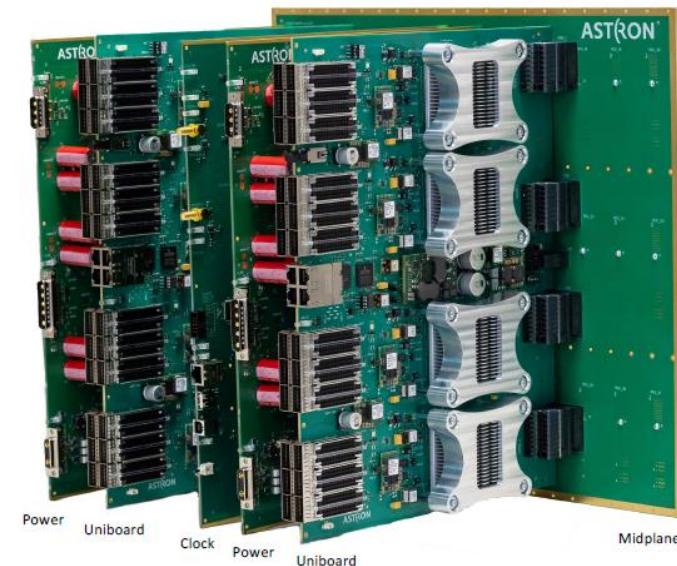
(ASTRON+INAF)



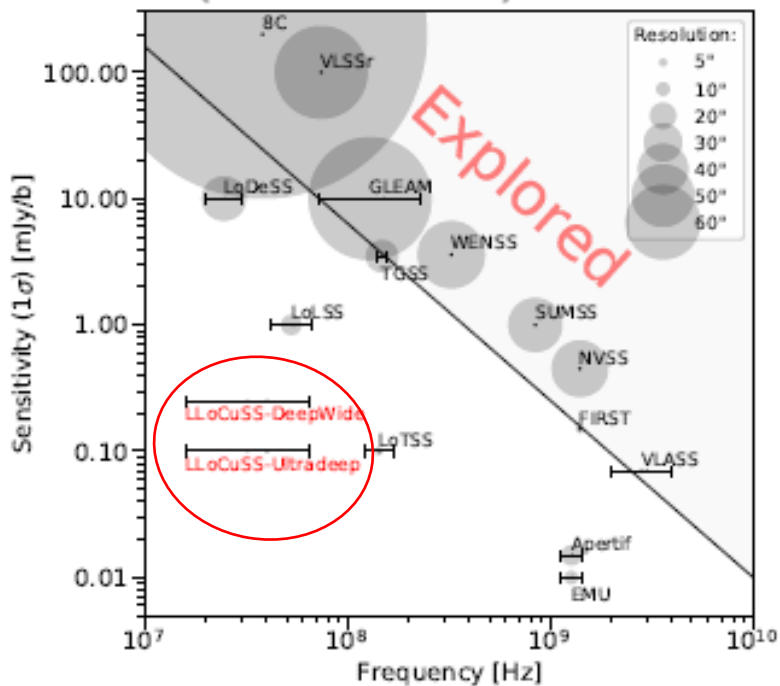
RCU



Subrack



# LOFAR 2.0 upgrade (2026+...)



**LOFAR 2 data rate  $\sim 4 \times$  LOFAR**

*Large Programs:*

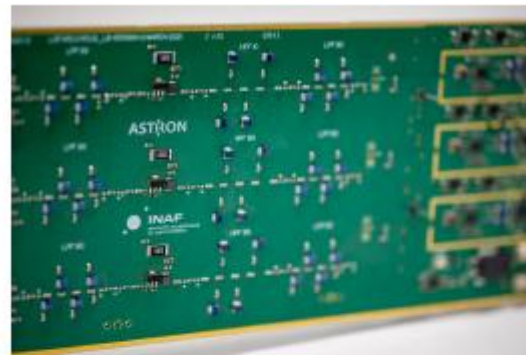
**12-20 PB/yr**

**120 PB total**

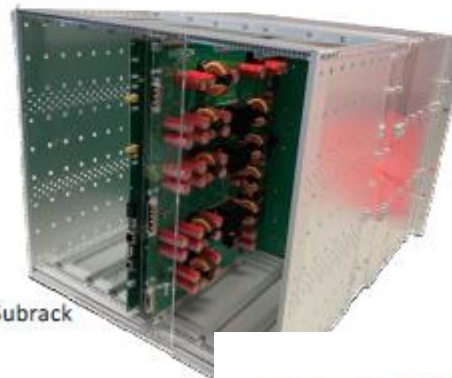


## NEW ELECTRONICS

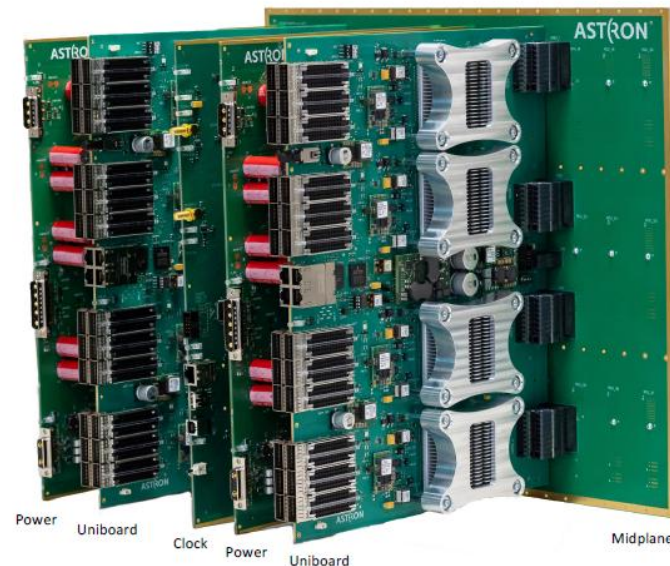
(ASTRON+INAF)



RCU

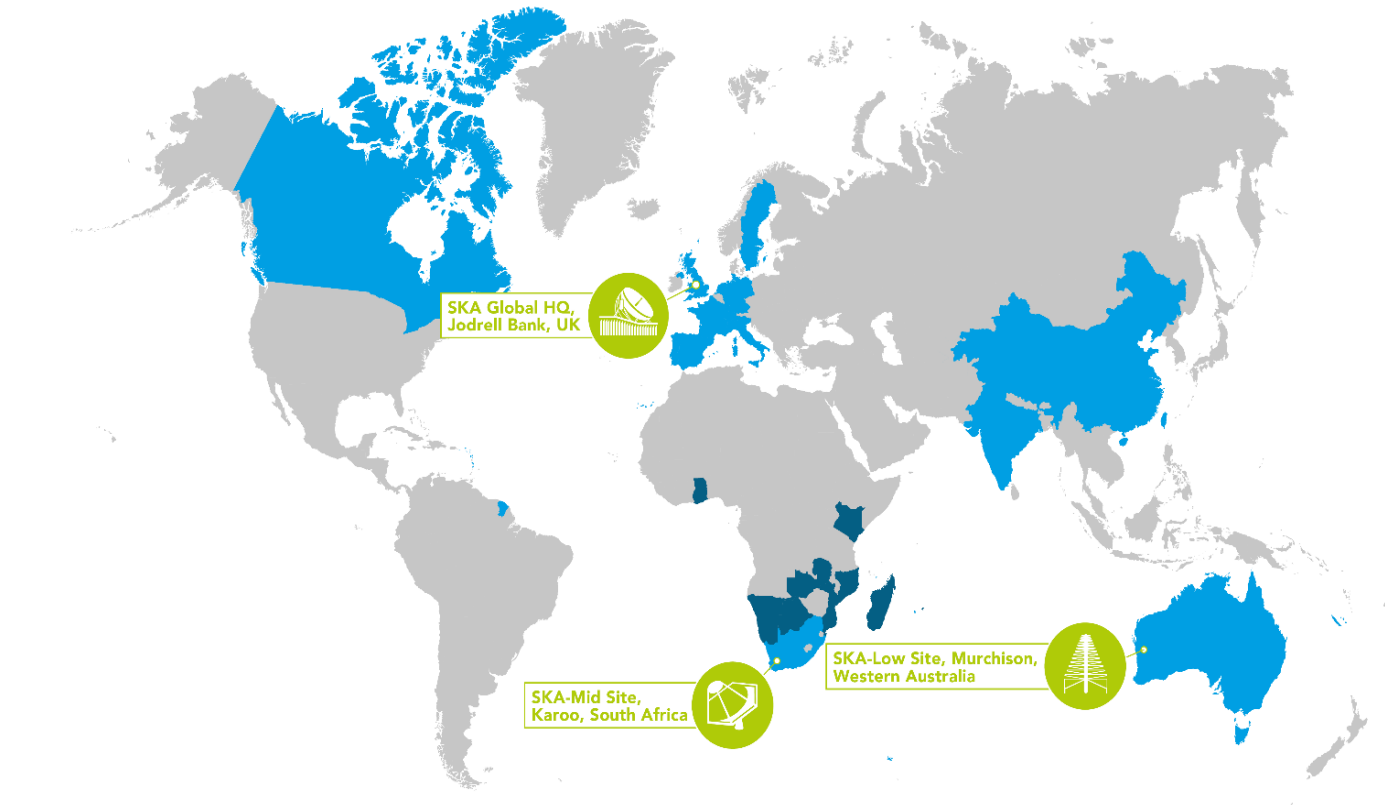


Subrack



# THE SKA OBSERVATORY

- ✓ Unprecedented Scale : 10x largest radio telescope
- ✓ A global effort : 100 organisations across about 20 countries
- ✓ Gigantic leap : Technology & Big Data



SKA Partners – includes Members of the SKA Organisation, precursor to the SKAO –, current SKAO Member States\*, and SKAO Observers (as of January 2022)



African Partner Countries



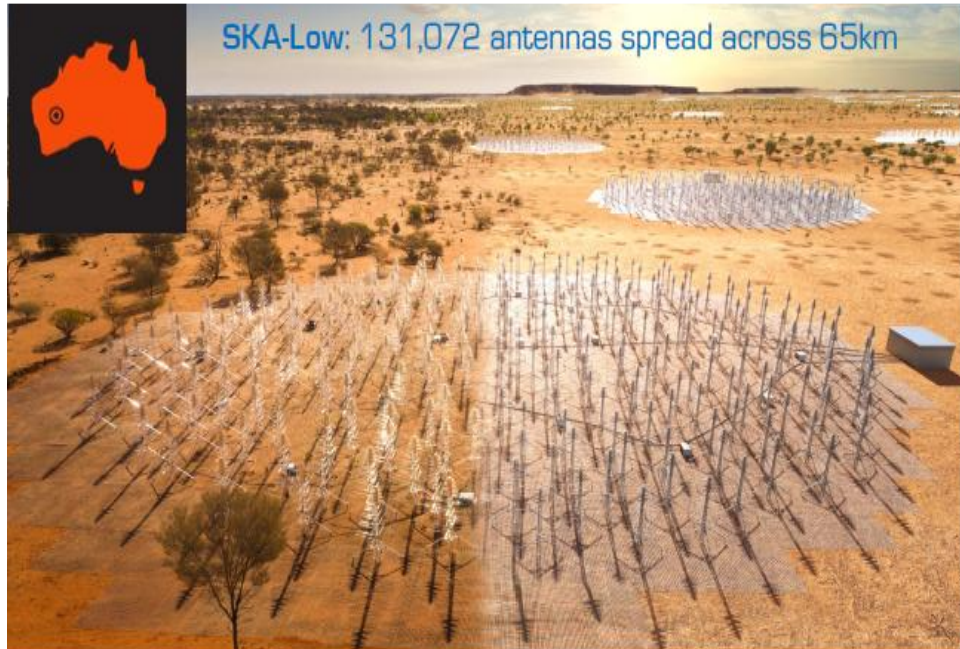


# TWO GIGANTIC INTERFEROMETERS

## SKAO

- A global collaboration of 16 countries which is building and will operate the next-generation radio astronomy observatory
- SKA Observatory (SKAO), a new Inter-Governmental Organisation governed by a treaty, was born on 4 February 2021.

SKA-Low: 131,072 antennas spread across 65km



SKA-Mid: 197 15m dishes spread across 150km.  
Incorporates South Africa's MeerKAT



# SKA Observatory Data Flow



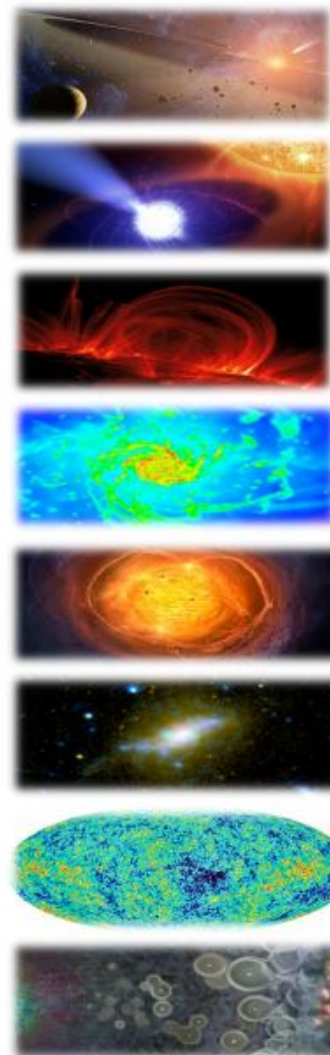
SKA output Data rates are vast – about 100x the output of other major astronomical facilities.  
In line with 'High Luminosity' LHC at CERN



# SKA Big Questions



- **The Cradle of Life & Astrobiology**
  - *How do planets form? Are we alone?*
- **Strong-field Tests of Gravity with Pulsars and Black Holes**
  - *Was Einstein right with General Relativity?*
- **The Origin and Evolution of Cosmic Magnetism**
  - *What is the role of magnetism in galaxy evolution and the structure of the cosmic web?*
- **Galaxy Evolution probed by Neutral Hydrogen**
  - *How do normal galaxies form and grow?*
- **The Transient Radio Sky**
  - *What are Fast Radio Bursts? What haven't we discovered?*
- **Galaxy Evolution probed in the Radio Continuum**
  - *What is the star-formation history of normal galaxies?*
- **Cosmology & Dark Energy**
  - *What is dark matter? What is the large-scale structure of the Universe?*
- **Cosmic Dawn and the Epoch of Reionization**
  - *How and when did the first stars and galaxies form?*



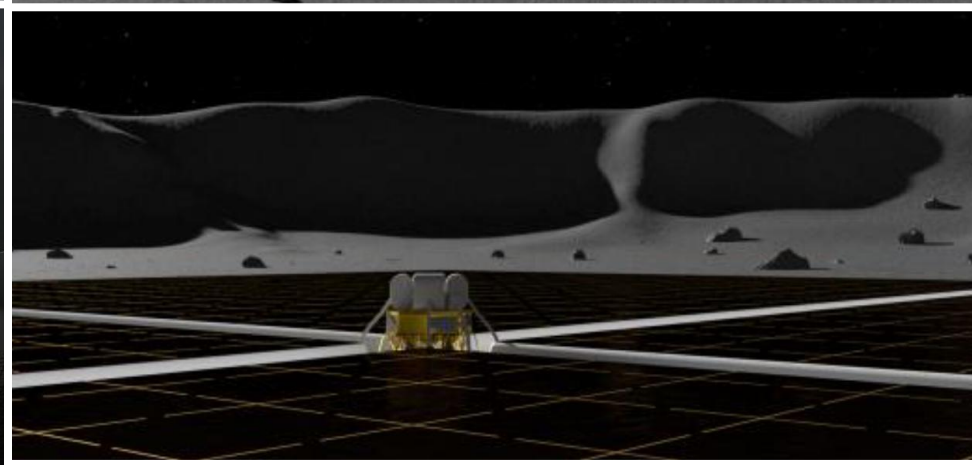
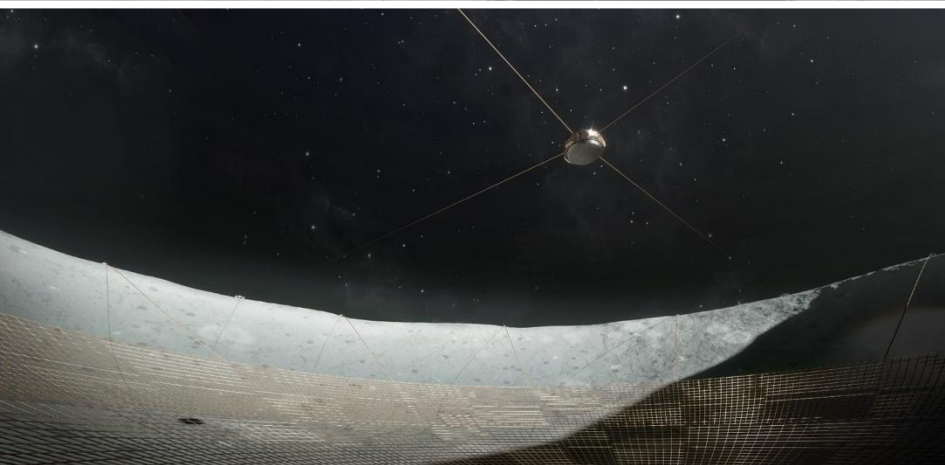
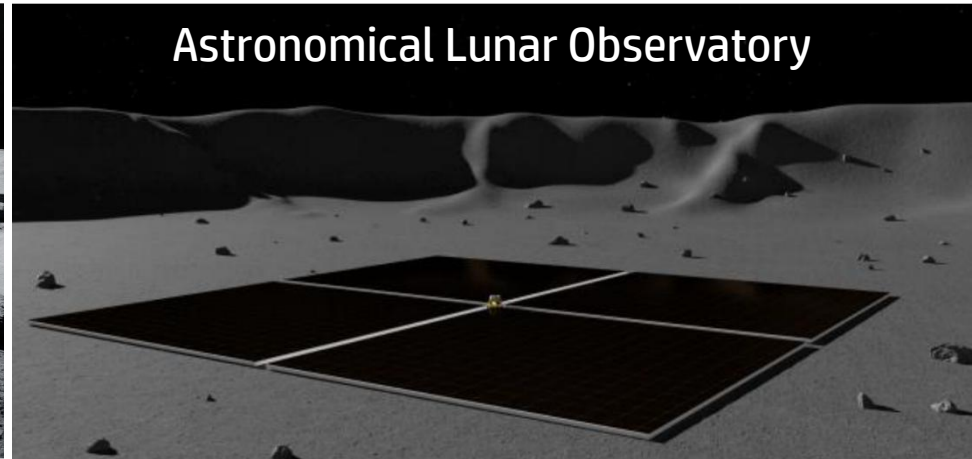


# The Moon?

Lunar Crater Telescope



Astronomical Lunar Observatory



# TAKE HOME

- ❑ Radioastronomy is living in a golden age
- ❑ Advances in computer science & calibration have allowed a leap forward in low frequency radio astronomy
- ❑ LOFAR is opening a new windows in the observation of the universe with important discoveries



LOFAR is @  
top priorities in  
PNIR 2021-27

- ❑ In the next few years LOFAR 2.0 will enter a new discovery space
- ❑ Next step (2030-35) is the SKA
- ❑ Next(?) step... is a radio interferometer on the Moon to observe at ultra-low frequencies ( $< \text{MHz}$ )