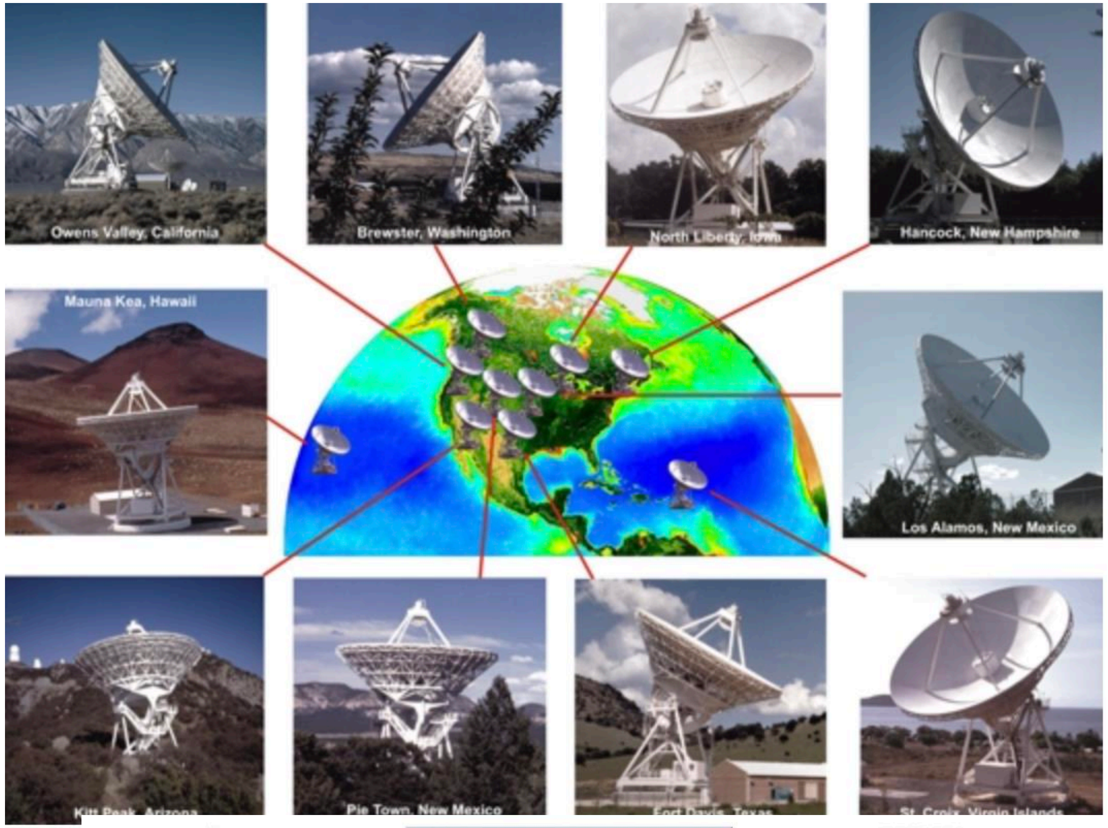
ALMA - VLBI

VIOLETTE IMPELLIZZERI

WHAT IS VLBI?

And how is it different from ALMA?

VLBI VS ALMA



Owens Valley, California
Brewster, Washington
North Liberty, Iowa
Hancock, New Hampshire
Mauna Kea, Hawaii
Los Alamos, New Mexico
Pie Town, New Mexico

JIVE
EUROPEAN
vlbi
NETWORK
Metsähovi
Onsala
JIVE
WSRT
Torun
Irbene
e-MERLIN
Effelsberg
Wettzell
Medicina
Yebes
Arecibo
Sardinia
Noto
Hartebeesthoek
Yonsei
Tamna
Urumqi
Ulsan
Tianma
Kunming

VLBI VS ALMA

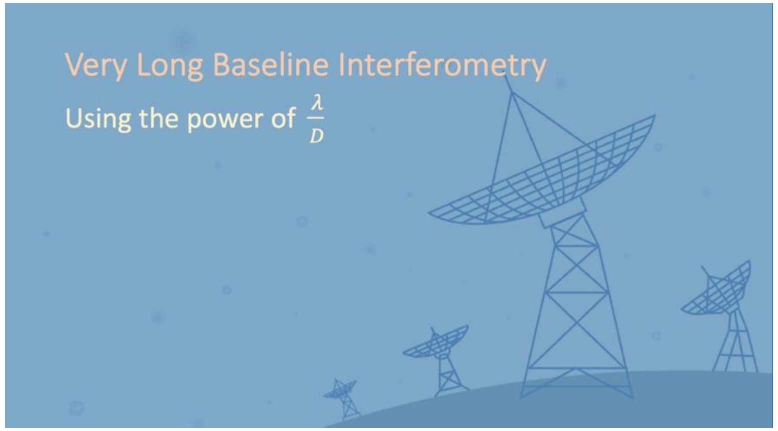
WHY VLBI?

Very Long Baseline Interferometry

Using the power of $\frac{\lambda}{D}$

WHY VLBI?

IN A NUTSHELL



VLBI stands for "Very Long Baseline Interferometry"

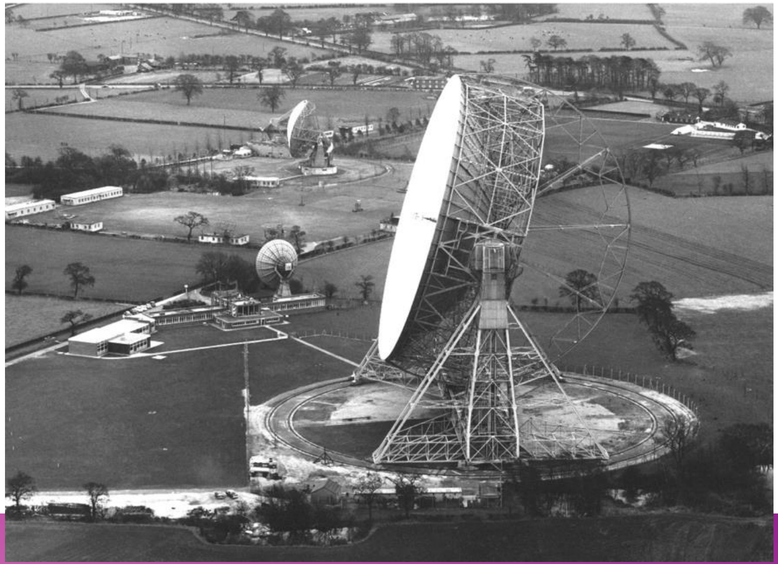
--- It is a technique!

In the 1950s radio interferometers and arrays of antennas were connected by cable, waveguide, or radio links separated by up to a hundred kilometers or more!

….starting in 1967, radio astronomers began to experiment with independent local oscillators and broad band tape recorders to record data collected by widely separated antennas

VLBI baselines were increased to thousands of kilometers, even ultimately to space, with baselines ranging out to hundreds of thousands of kilometers.

Mark II VLBI correlator at NRAO offices in Charlottesville.

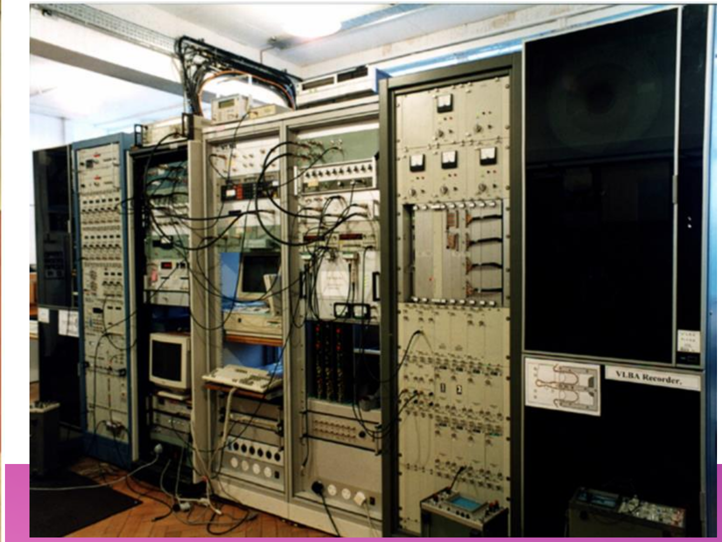


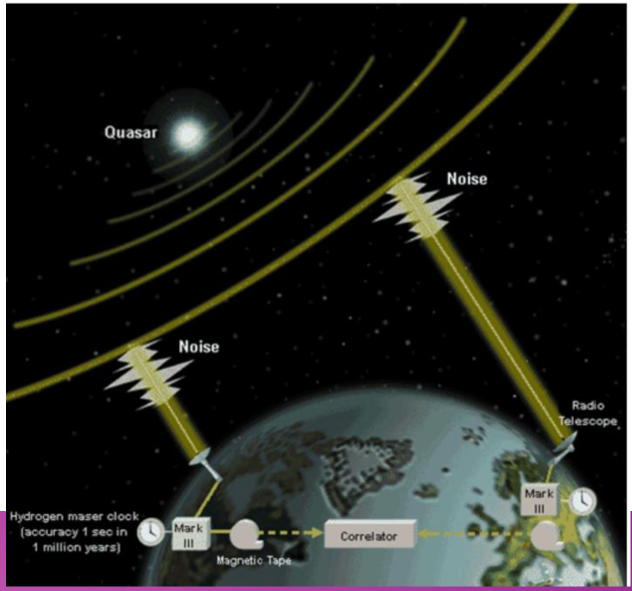
WHAT MADE VLBI POSSIBLE?

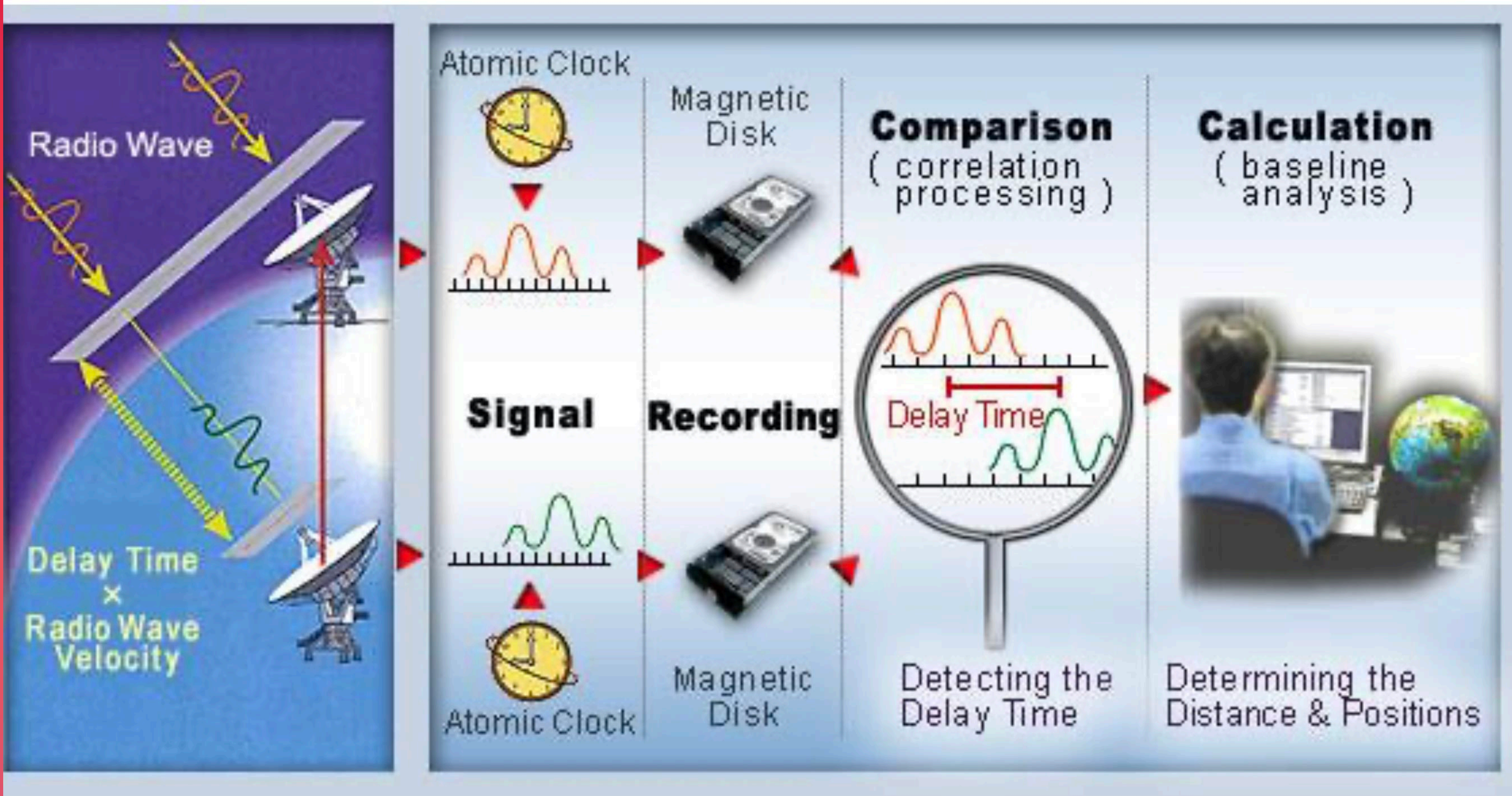
VLBI became a result of three key technological advances:

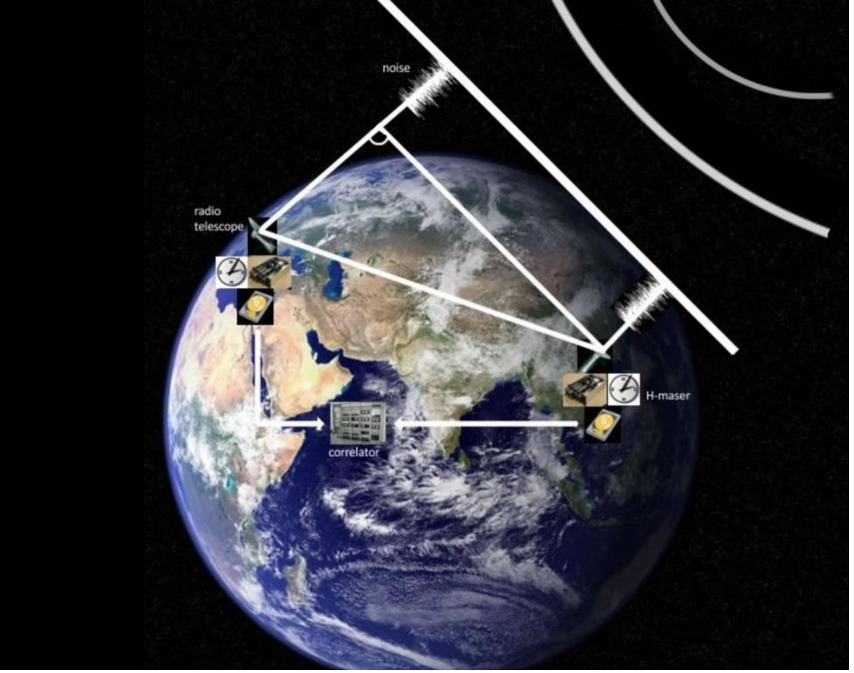
- precision atomic clocks to provide precise time and frequency,
- high speed tape recorders capable of recording the broad bandwidths needed to obtain adequate interferometer sensitivity
- and fast digital computers to correlate the data, all of which became commercially available in the mid-1960s.

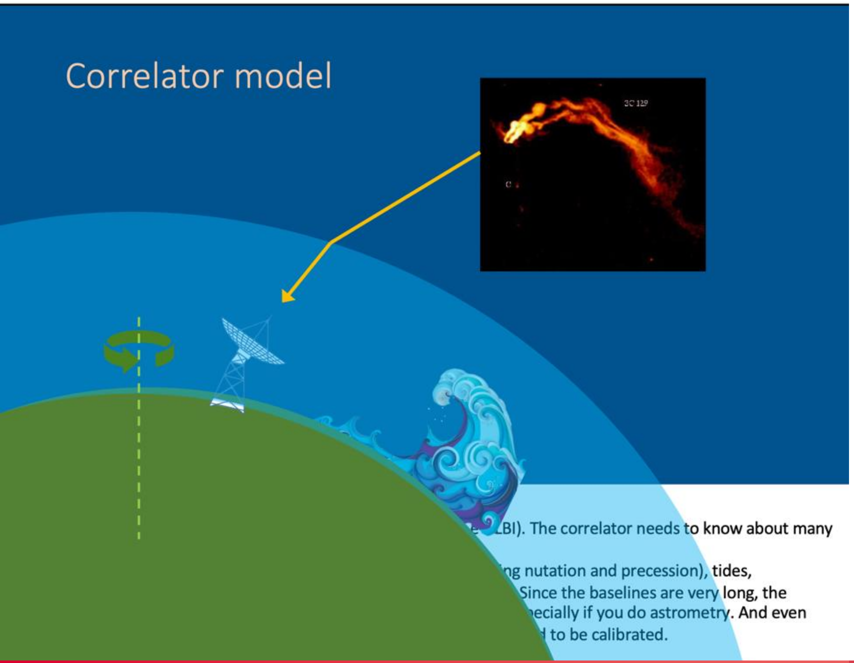
The Mark5A recorder supports data rates of up to 1024 Mbps and records to an array of 8 removable IDE disks.






Radio Wave
Delay Time
×
Radio Wave
Velocity
Atomic Clock
Signal
Atomic Clock
Magnetic
Disk
Recording
Magnetic
Disk
Comparison
(correlation
processing)
Delay Time
Detecting the
Delay Time
Calculation
(baseline
analysis)
Determining the
Distance & Positions





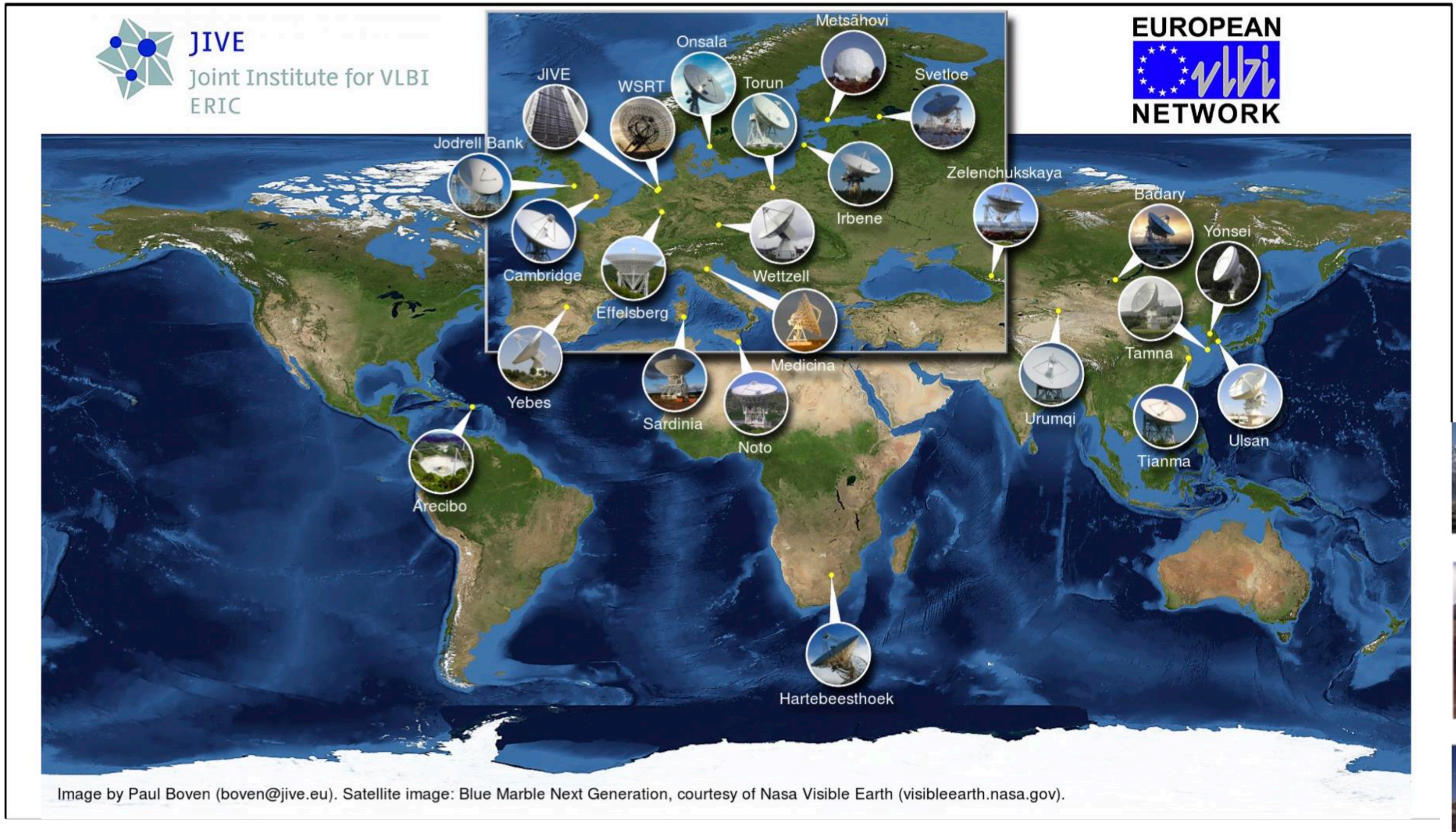
CORRELATOR MODEL

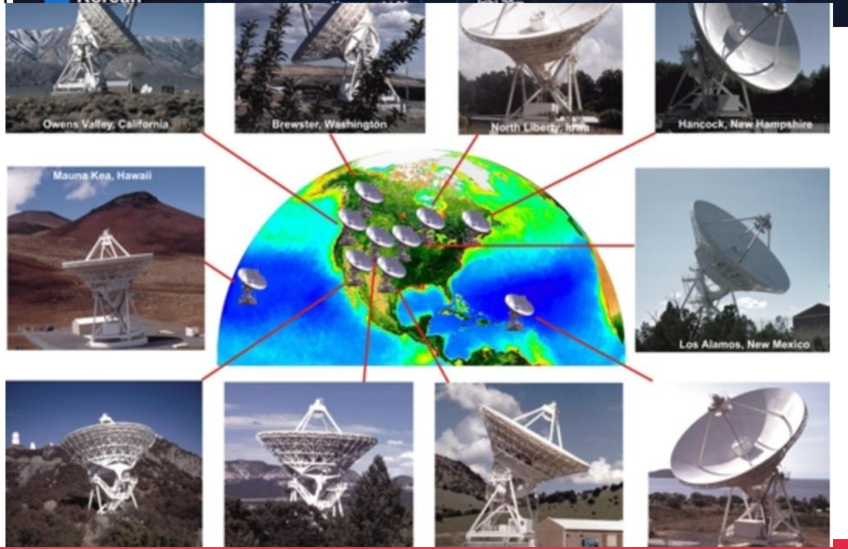
1. Geometric delay model

- Precise **station positions** / **Source direction,** proper motion & parallax if needed
- **Earth rotation** / Full 3-D **baseline geometry**

- **2. Earth orientation & reference frames/** Polar motion / **Precession & nutation models**
- **3. Clock model /** Clock **offset/** Clock **rate**
- **4. Propagation effects/ Troposphere (non-dispersive)/** Zenith delay (dry + wet)/ **Ionosphere (dispersive)**
- **5. Relativistic corrections/** Small, but mandatory at VLBI precision / **Gravitational delay** (Sun, major planets)/ Time dilation terms/ Shapiro delay for sources near massive bodies

- ETC etc etc





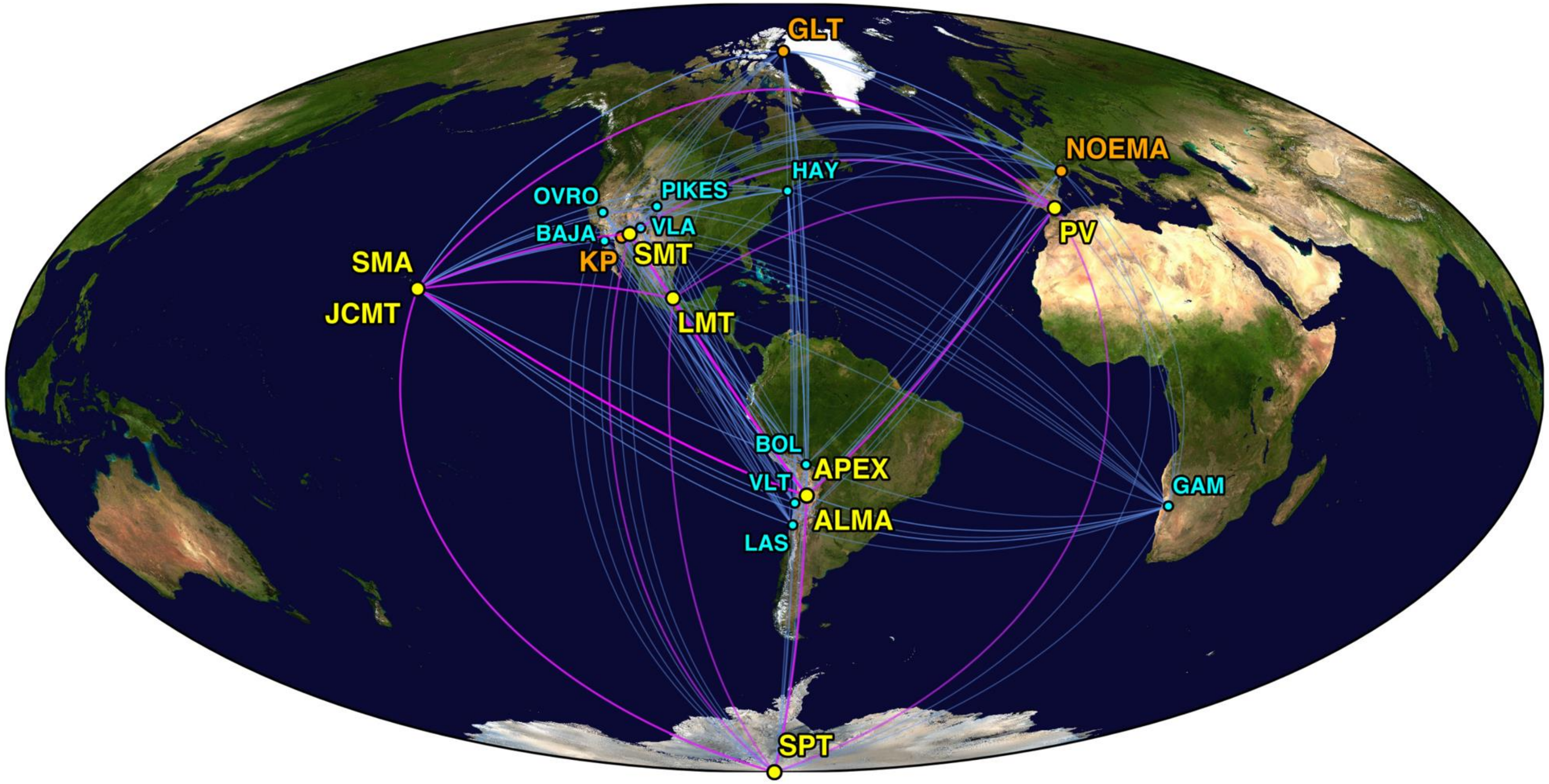
VLBI ARRAYS IN THE WORLD

MOSTLY CM-M WAVE FACILITIES

LOFAR2.0

Onsala
Irbene
Birr
Dutch stations
Chilbolton
Norderstedt
Bałdy
Potsdam
Borówiec
Jülich
Effelsberg
Tautenburg
Łazy
Nançay
Unterweilenbach
Medicina
Rozhen

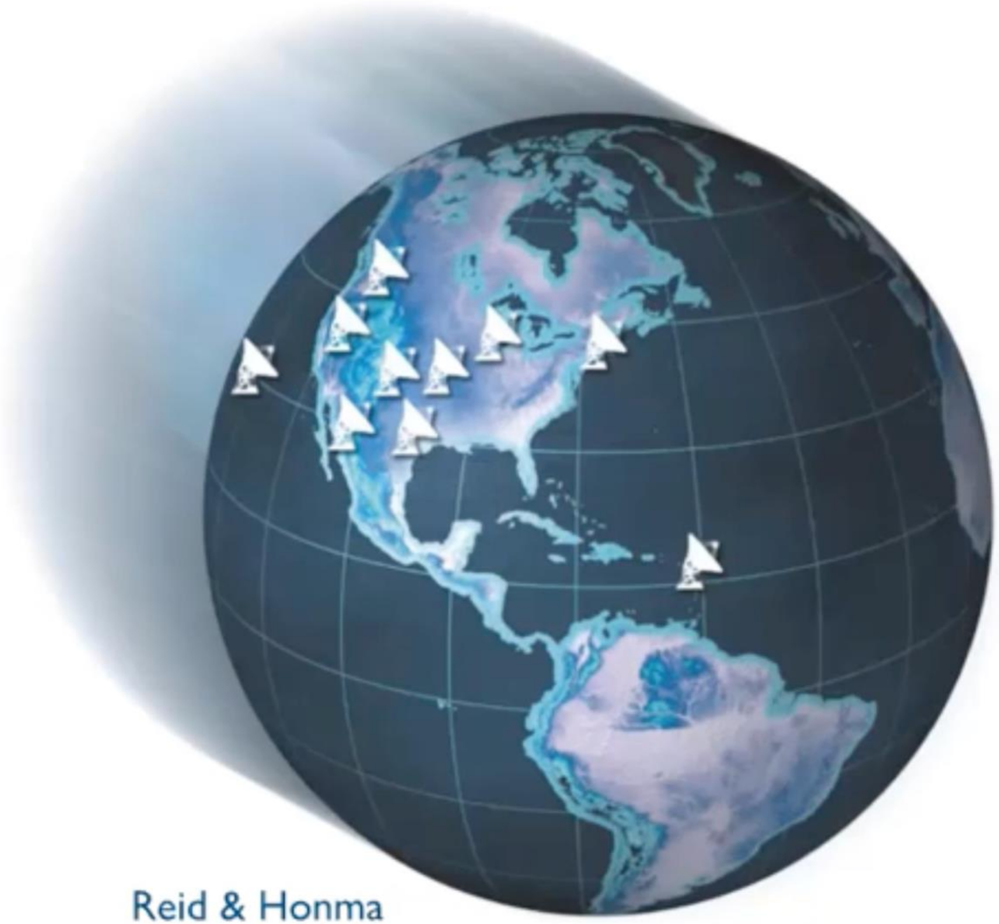
THE GLOBAL MILLIMETER VLBI ARRAY (GMVA)



THE EVENT HORIZON TELESCOPE

AT EVEN HIGHER FREQUENCIES

DISTRIBUTED ELEMENTS ACROSS THE WORLD! Why is it hard?


Reid & Honma

We just need to measure E_1 and E_2 at various locations in the plane of propagation, but..

1. Earth is round & moving
2. Irregular delays from troposphere/ionosphere
3. Different atmospheric and receiver noise
4. Various electronics and path delays
5. Independent and imperfect clocks at all stations
6. Post-digitization artifacts
7. Unexpected data issues

In data reduction, we are asked to "hide" as many of these effects as possible (without ruining the data)

DISTRIBUTED ELEMENTS ACROSS THE WORLD! Why is it hard?

It is a unique technique:

Large (>1,000km) baselines
Different types of telescopes (mount, size)
Individual clocks and back-end
Sparse uv-coverage
Specific needs for correlation and calibration
Never a true point-source…

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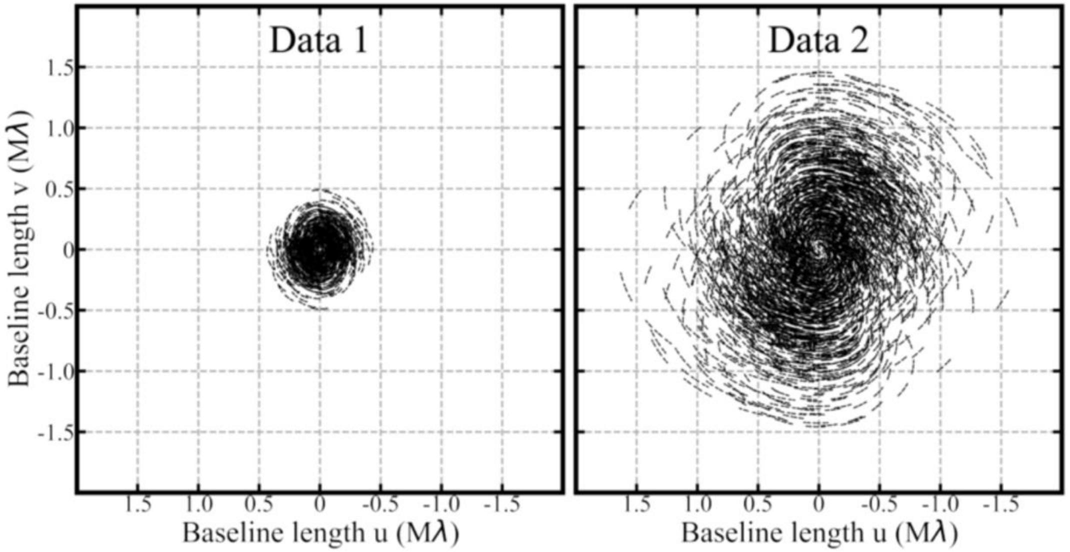
ALMA uv coverage



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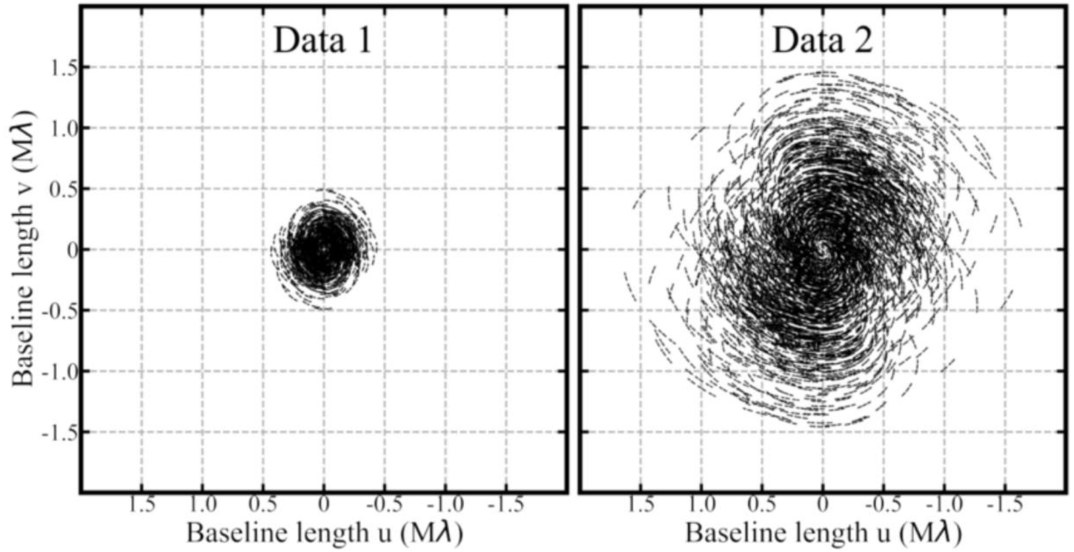
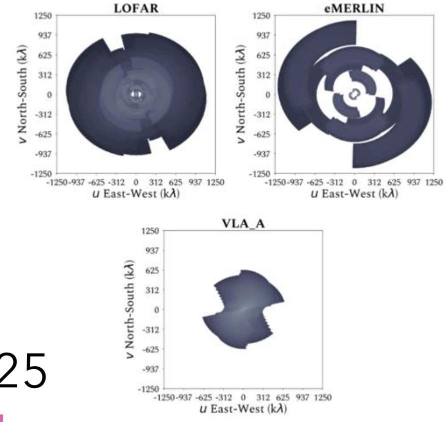
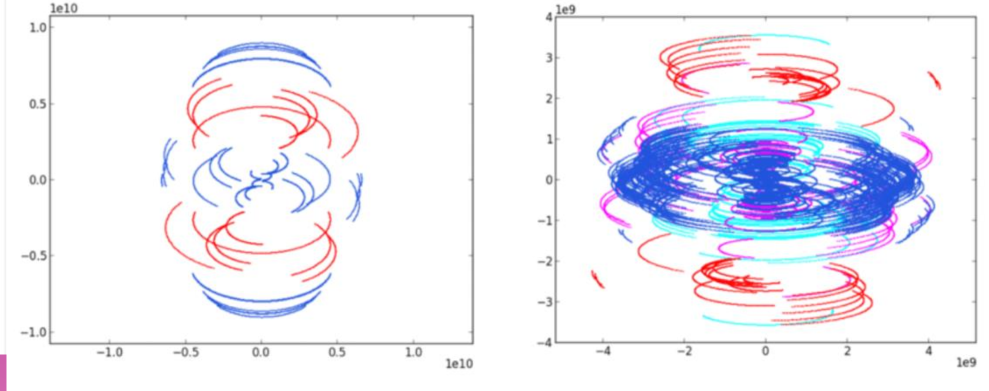




Morabito 2025

EHT and GMVA uv coverage



Calibration

Amplitude

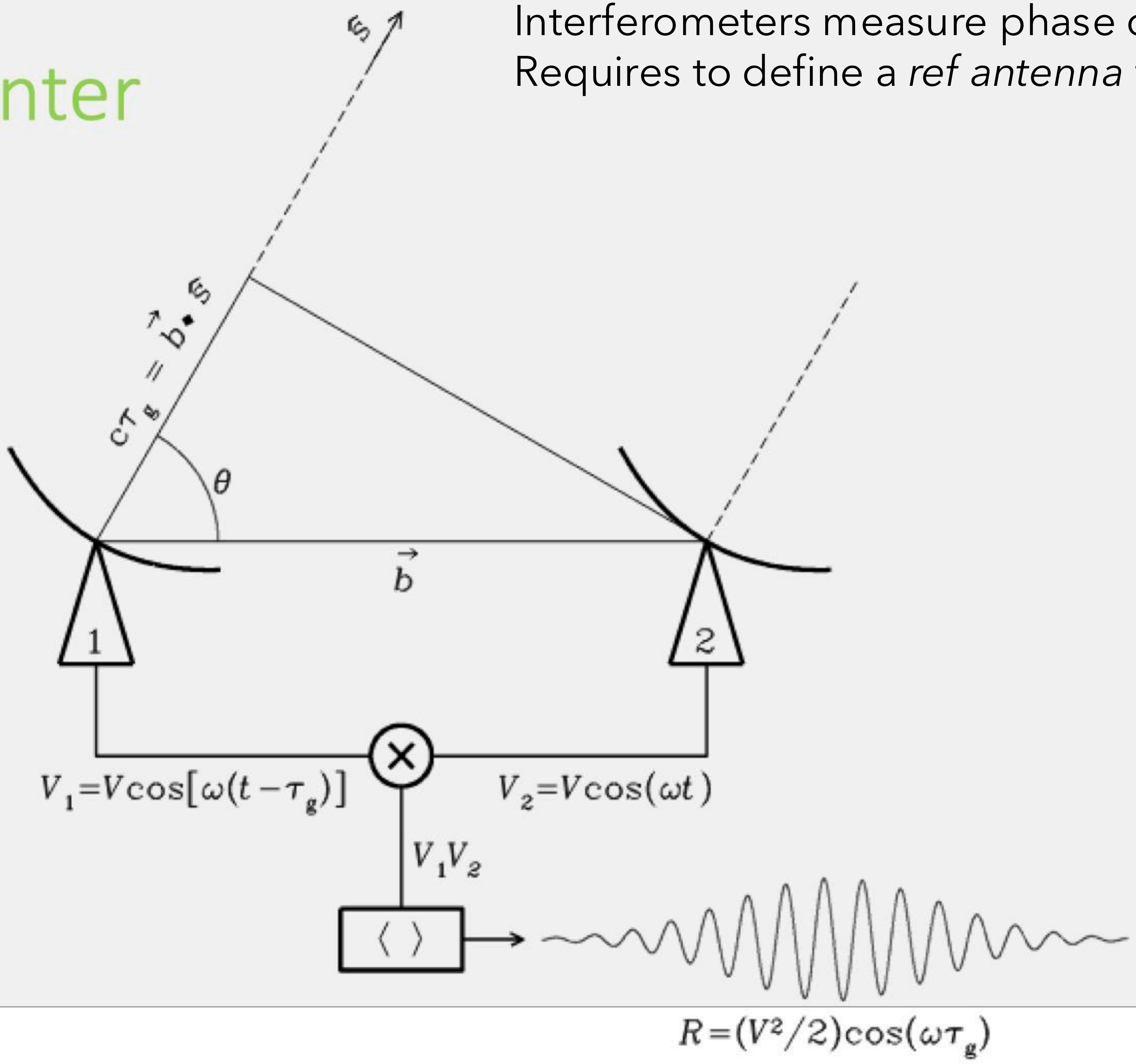
- System temperature (Tsys)
- Gain curve

Residual phase errors after correlation

- Clock
- Earth model and telescope positions
- Atmosphere

Phase center

Interferometers measure phase difference:
Requires to define a *ref antenna* that has zero phase.



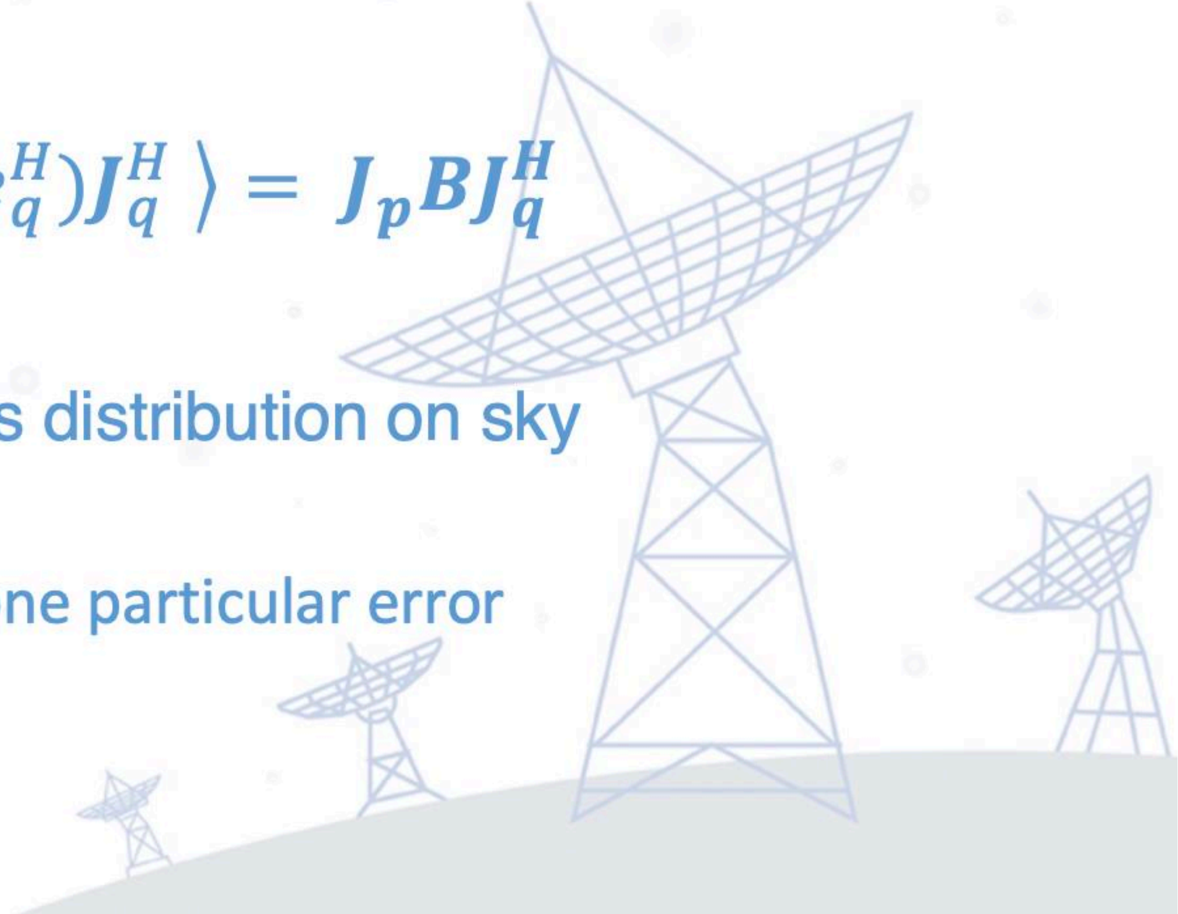
CASA calibration framework

provides a mathematical description of how the **true sky signal** is transformed into the observed interferometric **visibilities**.

Based on the Measurement Equation (Hamaker+ ,1996; Smirnov 2011)

$$V_{pq} = 2\langle J_p(e_p e_q^H)J_q^H \rangle = \boldsymbol{J_p B J_q^H}$$

- $\boldsymbol{B} = \begin{pmatrix} I+Q & U+iV \\ U-iV & I-Q \end{pmatrix}$ is the brightness distribution on sky
- J is a 2x2 Jones matrix describing one particular error



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Visibilities are modeled as a sequence of Jones matrices, each representing a specific instrumental or propagation effect acting on the electric field.

The Jones matrices

Calibration: determine J_p for all antennas p

- K_p: delay
- B_p : bandpass
- G_p : electronic gain response
- D_p : instrumental polarization (leakage)
- E_p : telescope based effects (e.g. Tsys, gain curve)
- P_p : parallactic angle
- T_p : tropospheric opacity and path-length variation
- F_p : Faraday rotation
- *(Z_p, beam)*

CASA handles this always in the same and physcially correct order

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- *(Z_p, beam)*

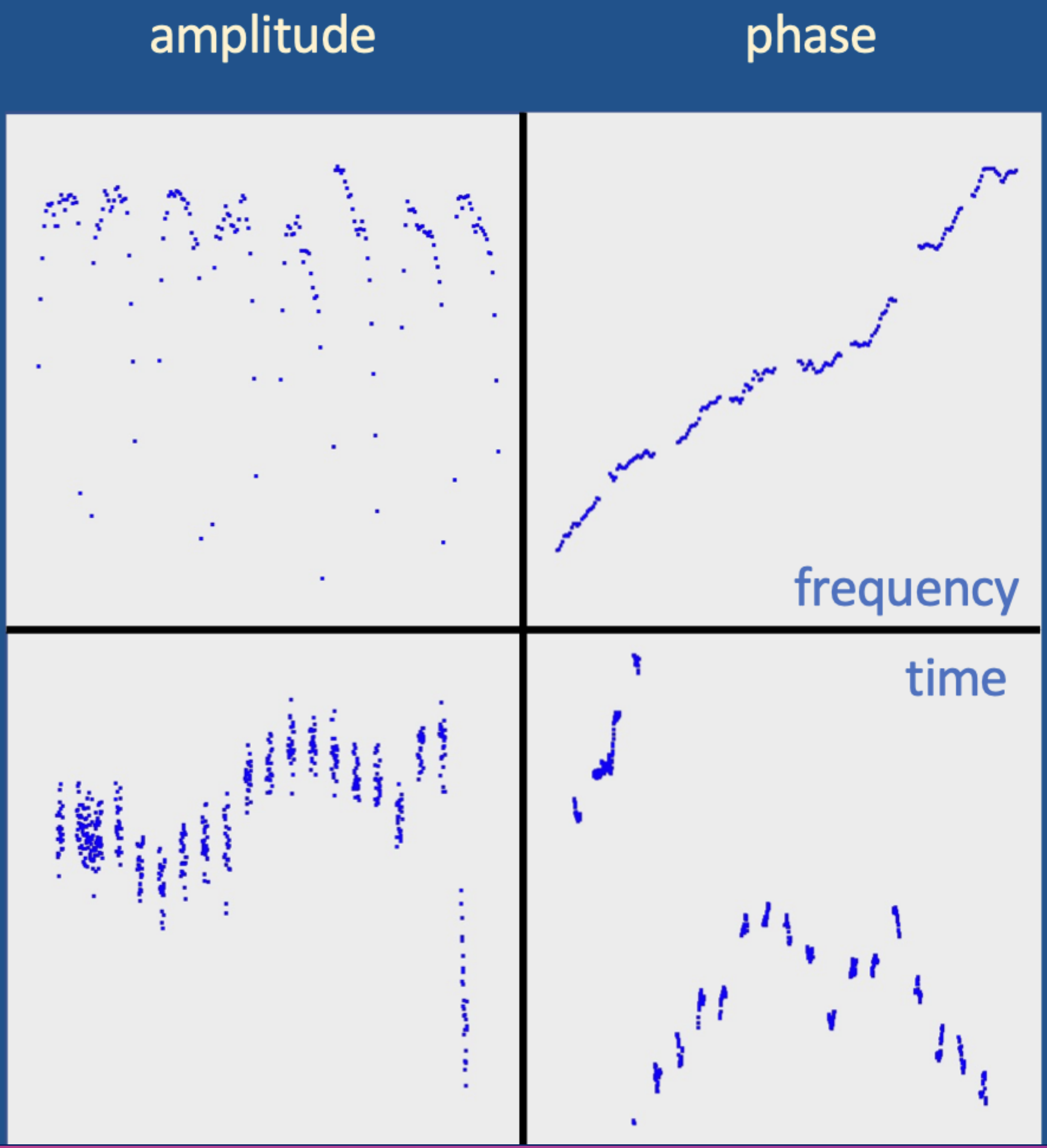
Each **calibration table** is a Jones term, stored per antenna.

Applycal applies the inverse of the corresponding Jones chain to the data.

CASA handles this always in the same and physcially correct order

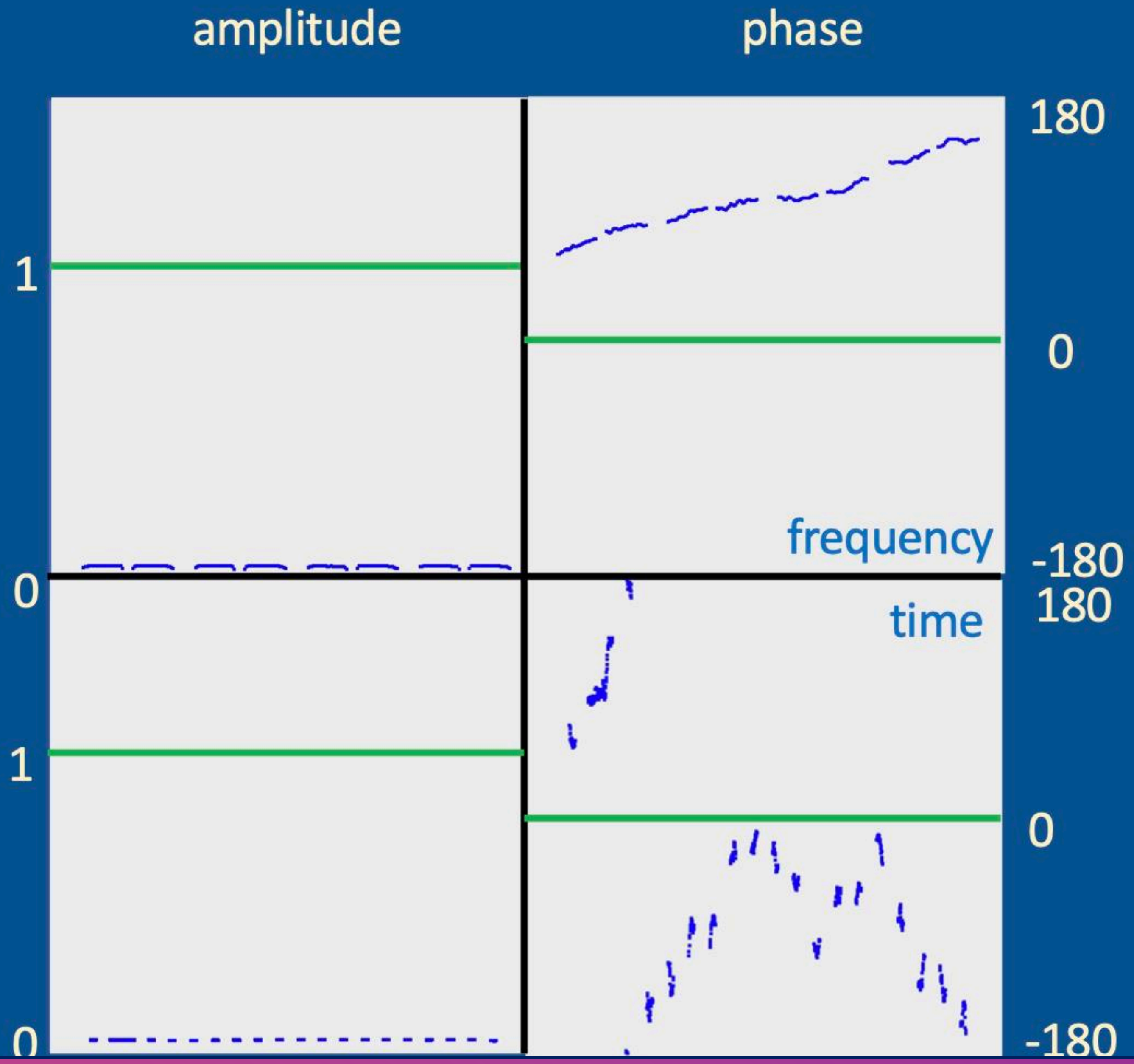
Calibration

VISIBILITIES!



One baseline,
one polarization

Calibration



System temperature

Convert correlator units to flux scale:

System Equivalent Flux Density

$$\mathrm{SEFD}\ [\mathrm{Jy}] = \frac{2 k_B T_{\mathrm{sys}} [K]}{\eta_{\mathrm{A}}\, A_{\mathrm{eff}}}$$

η_A : efficiency

A_{eff}: effective antenna area

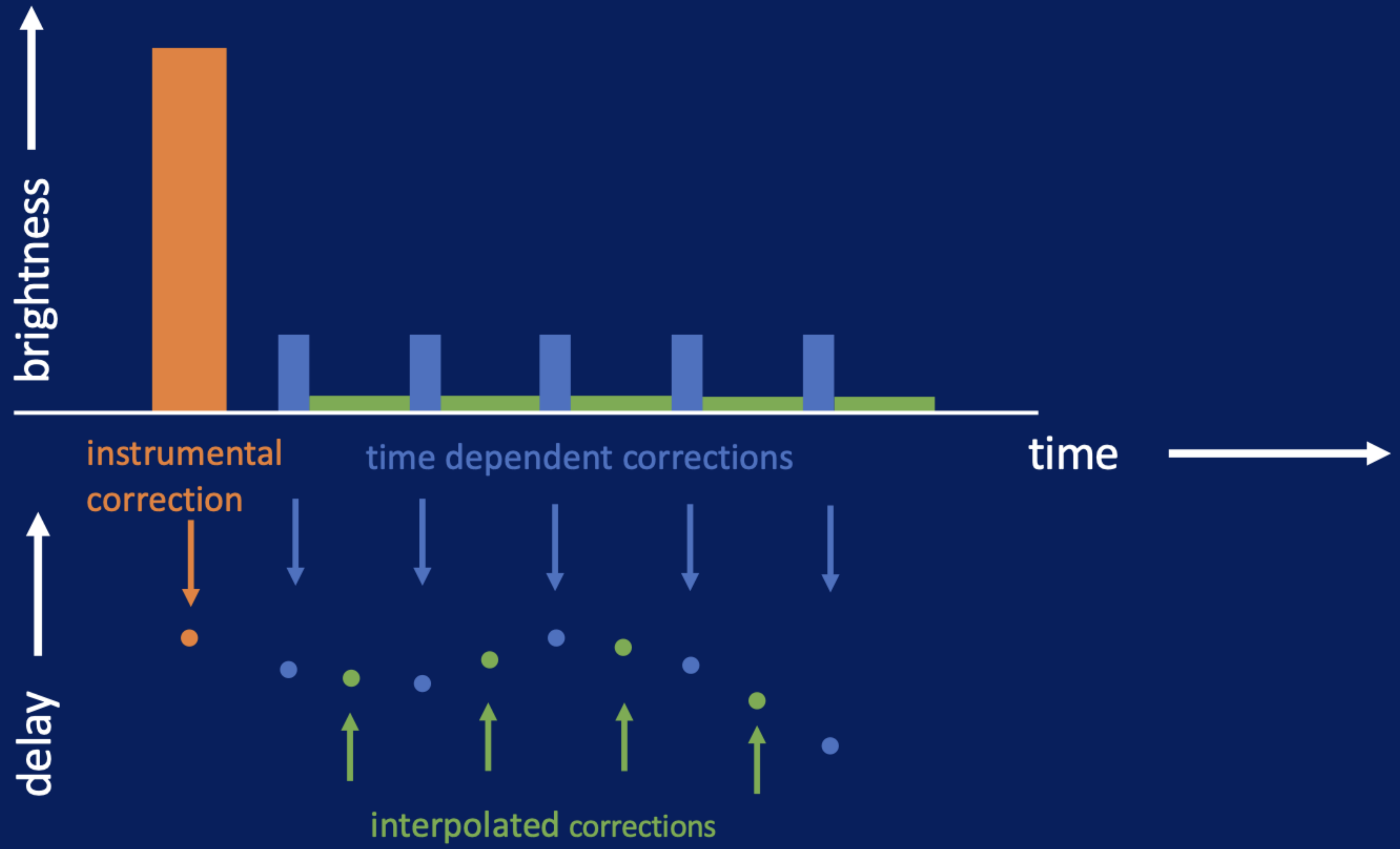
Calibration

- Amplitude: Tsys and gain curve
- Phase
- Delay
- Rate

$$\phi_{t,\nu} \approx \phi_0 + \frac{\partial \phi}{\partial \nu} \Delta \nu + \frac{\partial \phi}{\partial t} \Delta t$$

- Higher order terms: dispersive delay, acceleration

Phase referencing

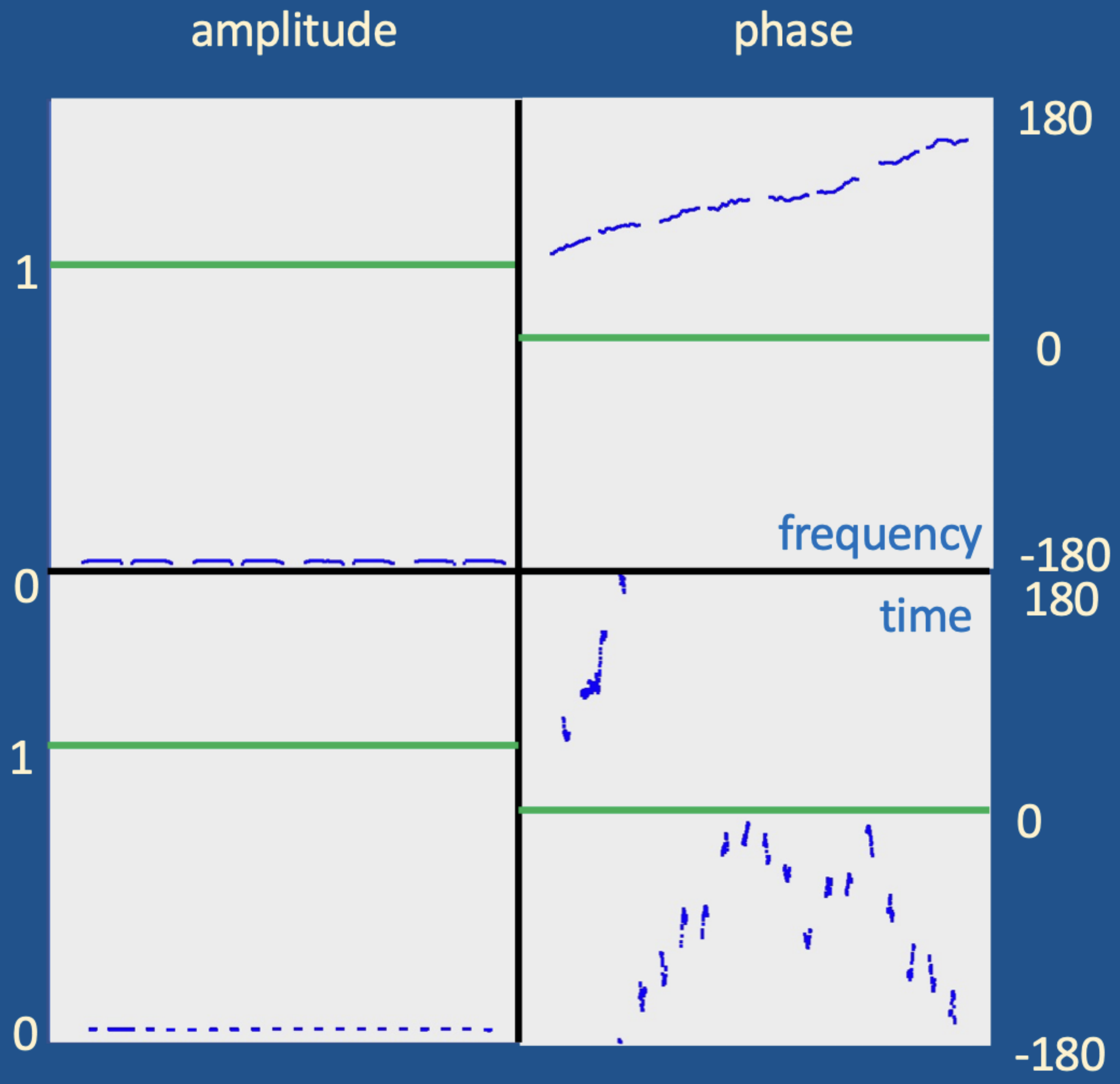


Fringe fit

Fringe fitting solves for:

residual **delay**,
residual **delay rate**,
and a constant **phase offset**

per antenna, relative to a reference antenna.



Fringe fit

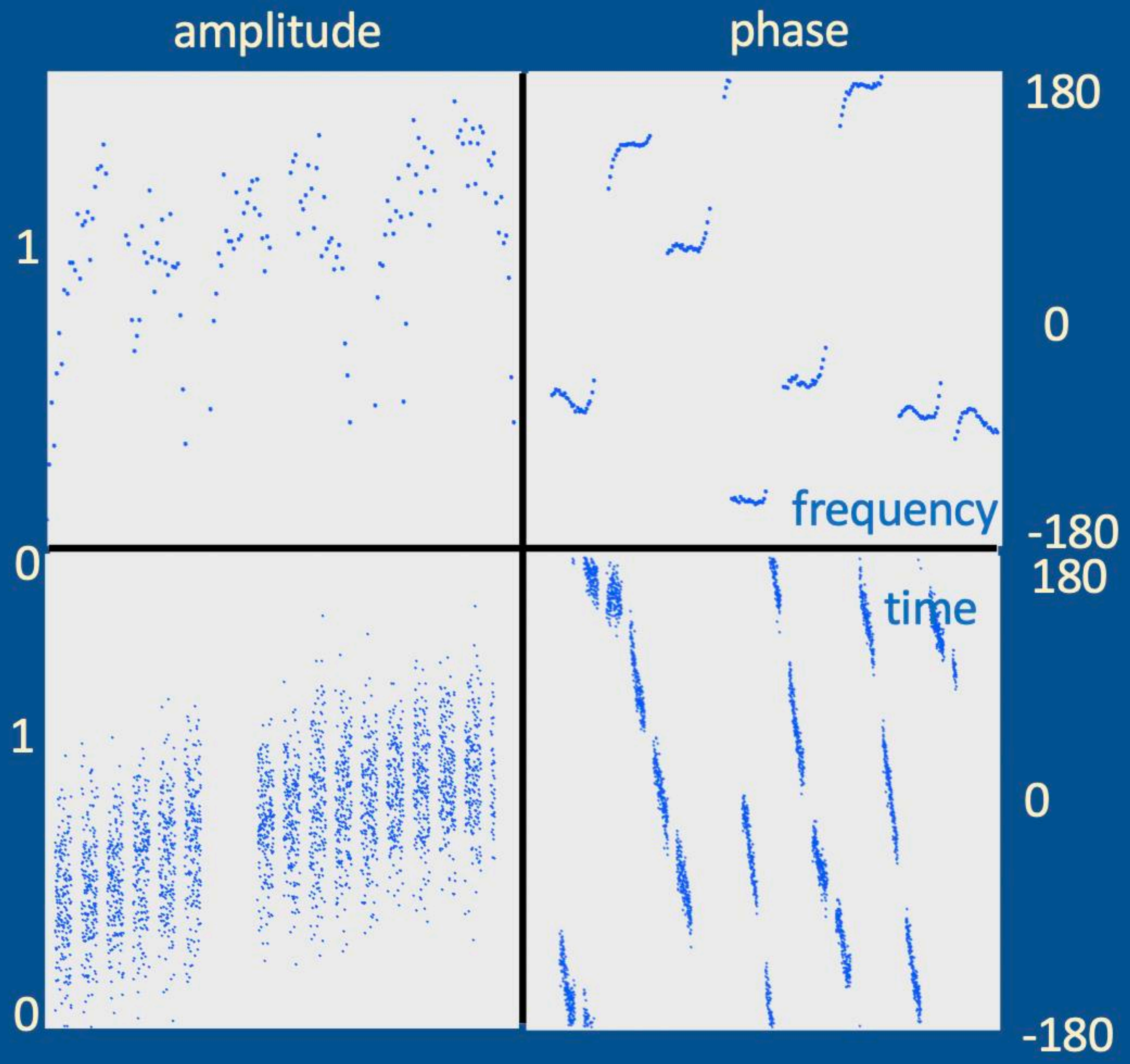
Practically:

You search for fringes in delay-rate space

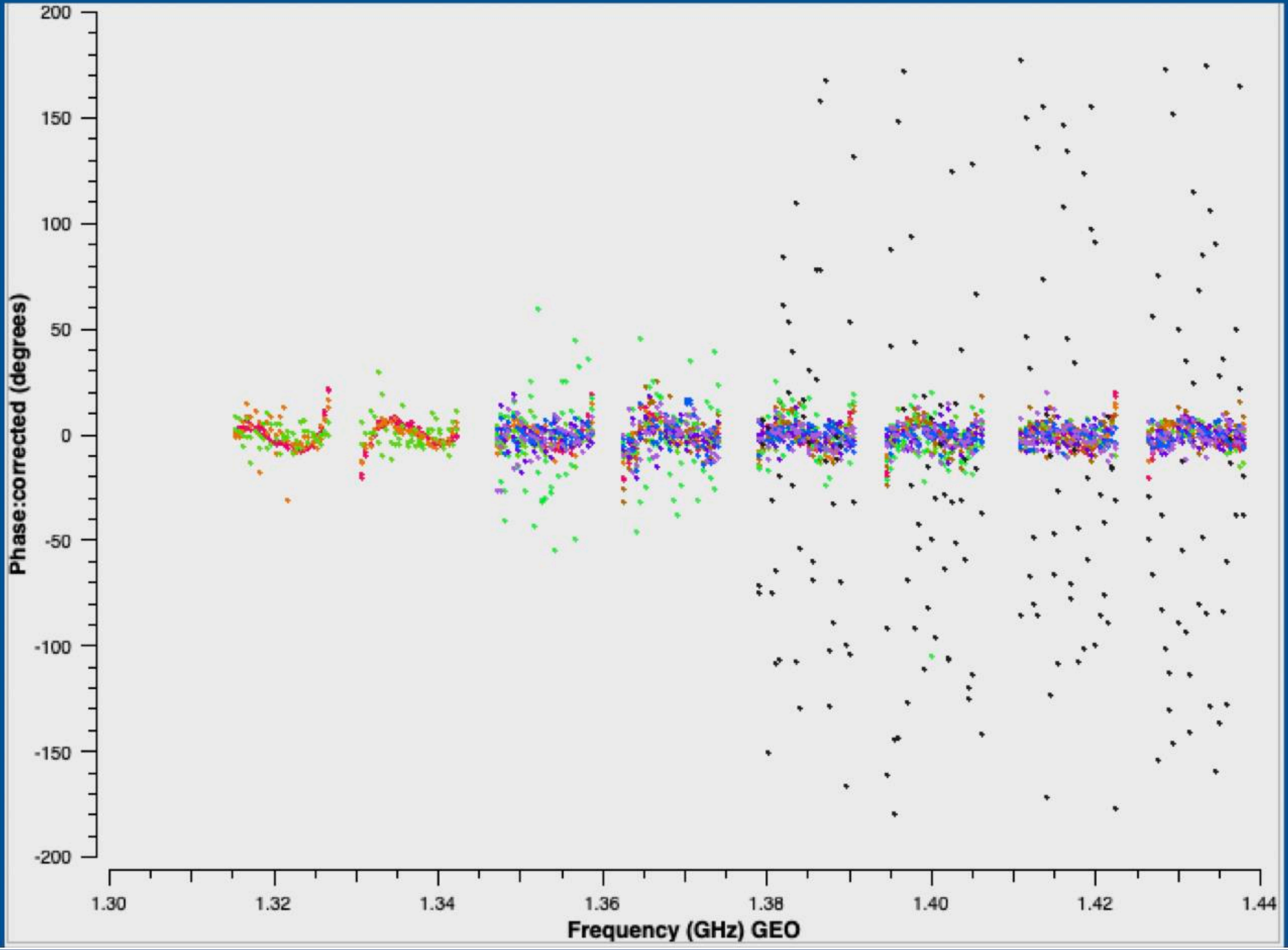
maximize coherence over frequency and time

then apply the solutions to align phases across the array.

Without successful fringe fitting, you simply don't have coherent VLBI data!

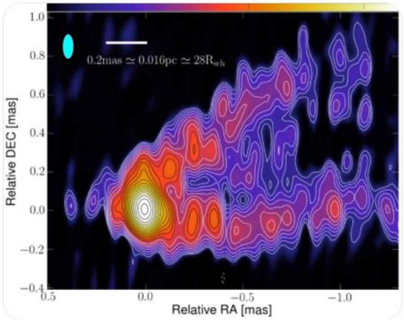


Fringe fit



Phase:corrected (degrees)
200
150
100
50
0
-50
-100
-150
-200
1.30
1.32
1.34
1.36
1.38
1.40
1.42
1.44
Frequency (GHz) GEO

IMAGING IS NEXT!



- Most likely, this is where you will start!
- Imaging tools, tclean widely used: **look out on Friday for more imaging tools by Fabrizia 9:00**

Some popular EHT/GMVA imaging algorithms include:

CLEAN, Multiscale Clean Assumes the sky can be represented as a collection of point sources (iterative)/ Works well on cm VLBI, but struggles with disperse uv-coverage. (includes selfcal loops)

Maximum Entropy Methods (**MEM**), Image is found by maximizing entropy, subject to fitting the data Works well for extended emission, sensitive to a-priori assumptions

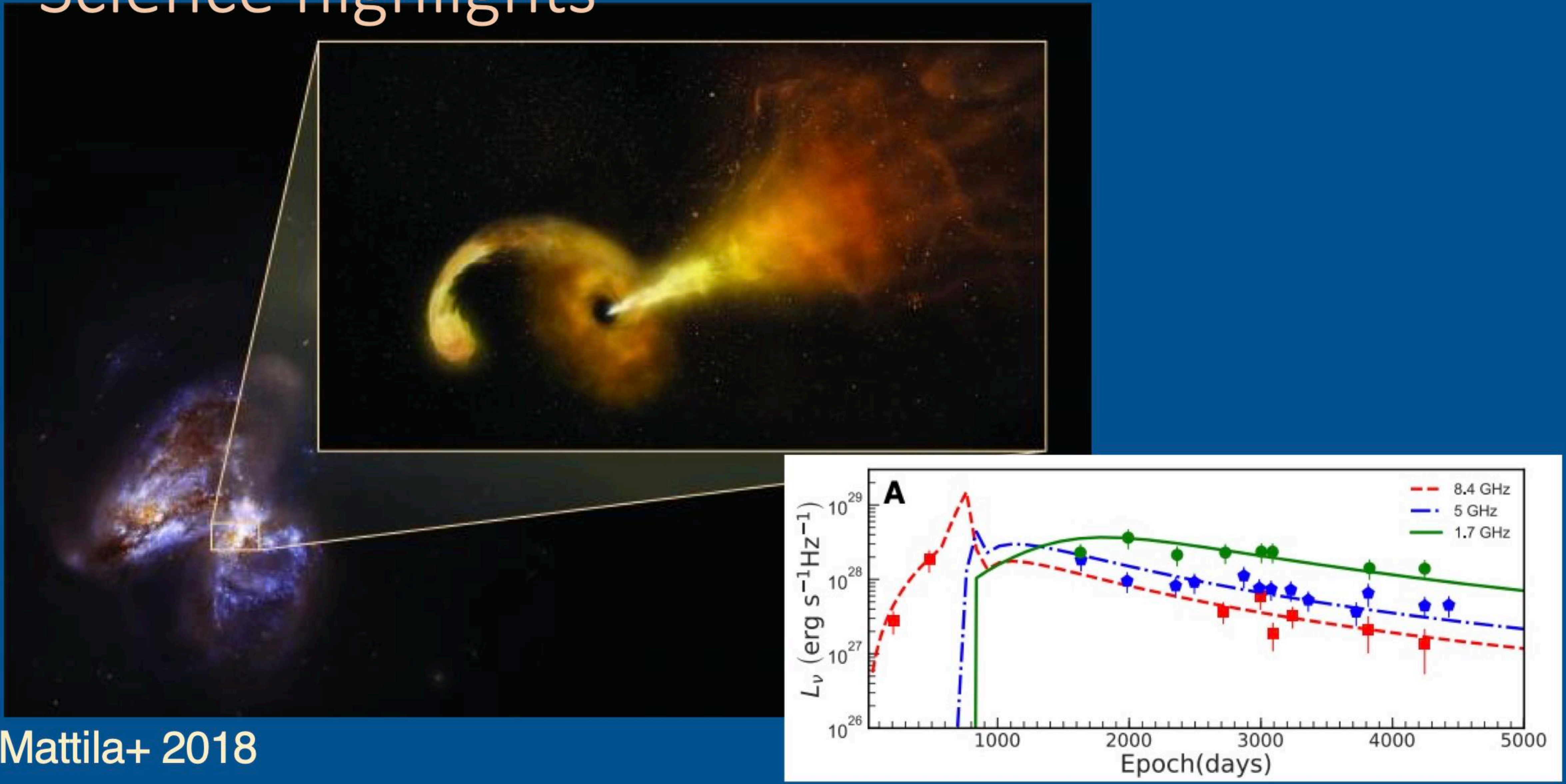
Closure-quantity imaging: Closure phases remove antenna-based phase errors, Closure amplitudes reduce gain uncertainties; ideal for mm- unstable atmospheric conditions

Regularized Maximum Likelihood (**RML**) : reconstructs an image by directly fitting visibilities or closure quantities while imposing physically motivated priors.
Handles poor uv-coverage well. Separates calibration from imaging. Popular tools: eht-imaging, SMILI…

Science cases

Compact and bright objects

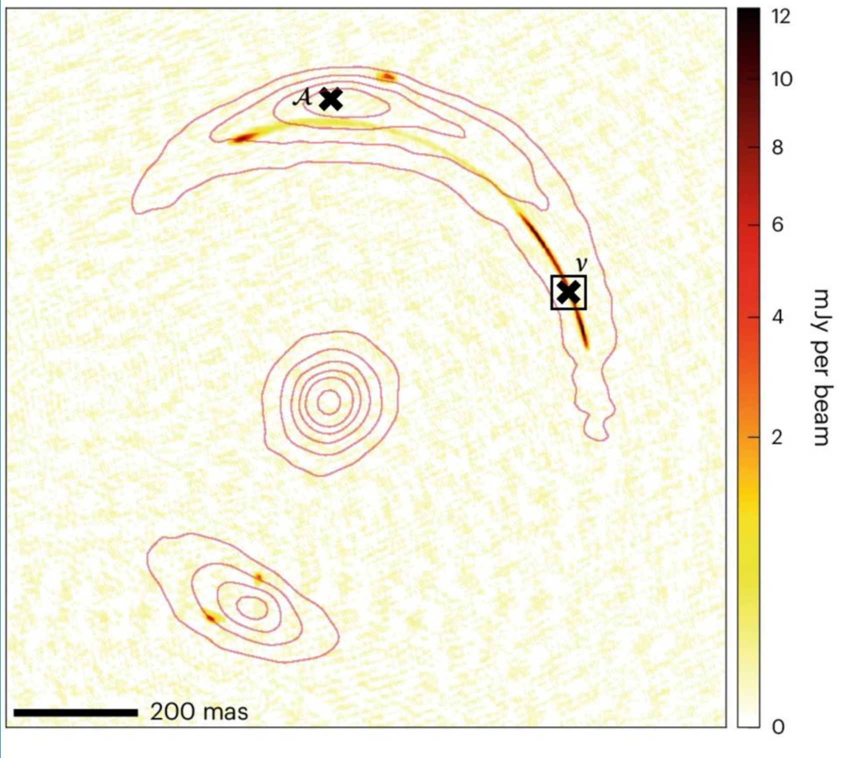
Science highlights

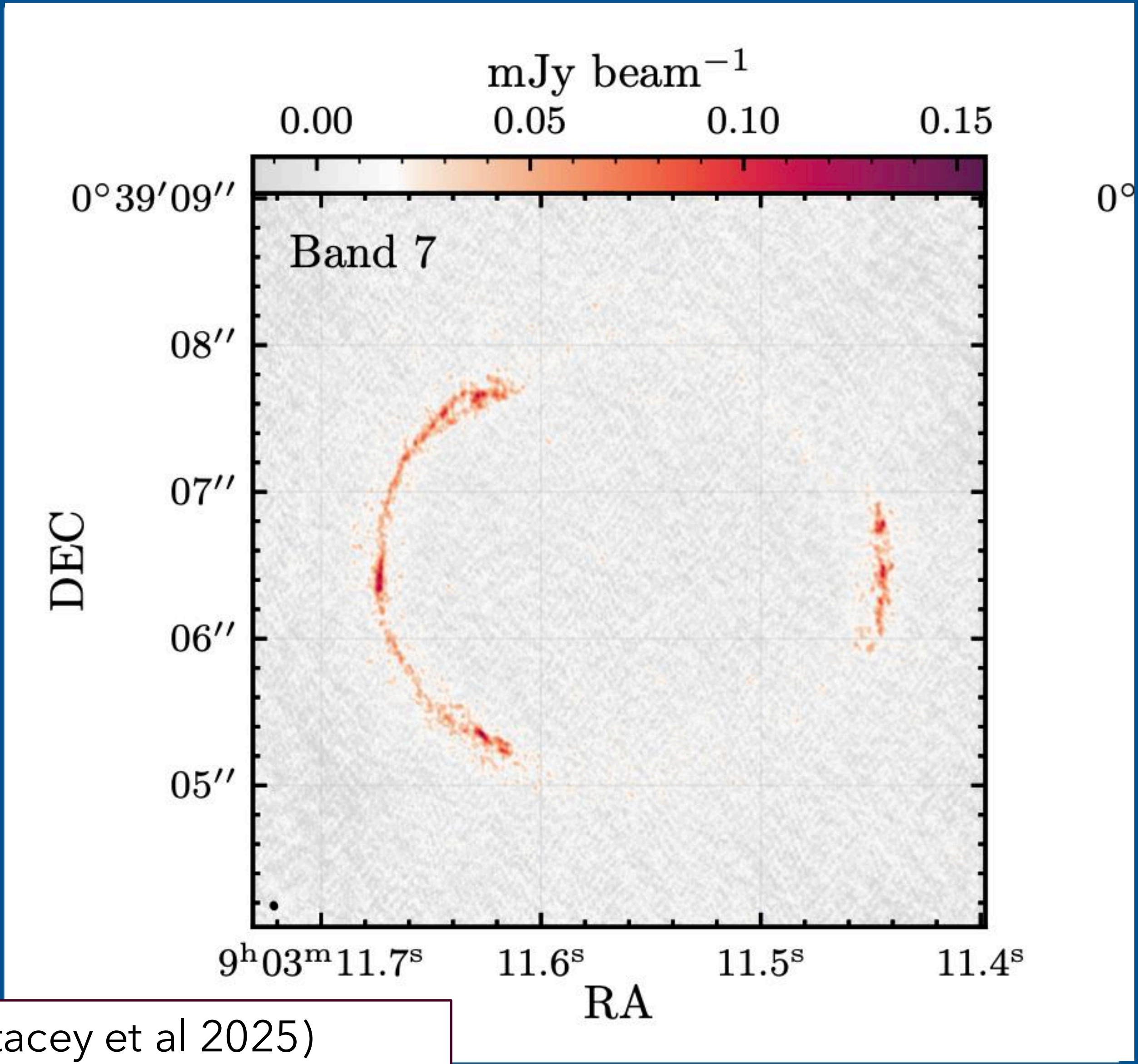


Mattila+ 2018

Science highlights

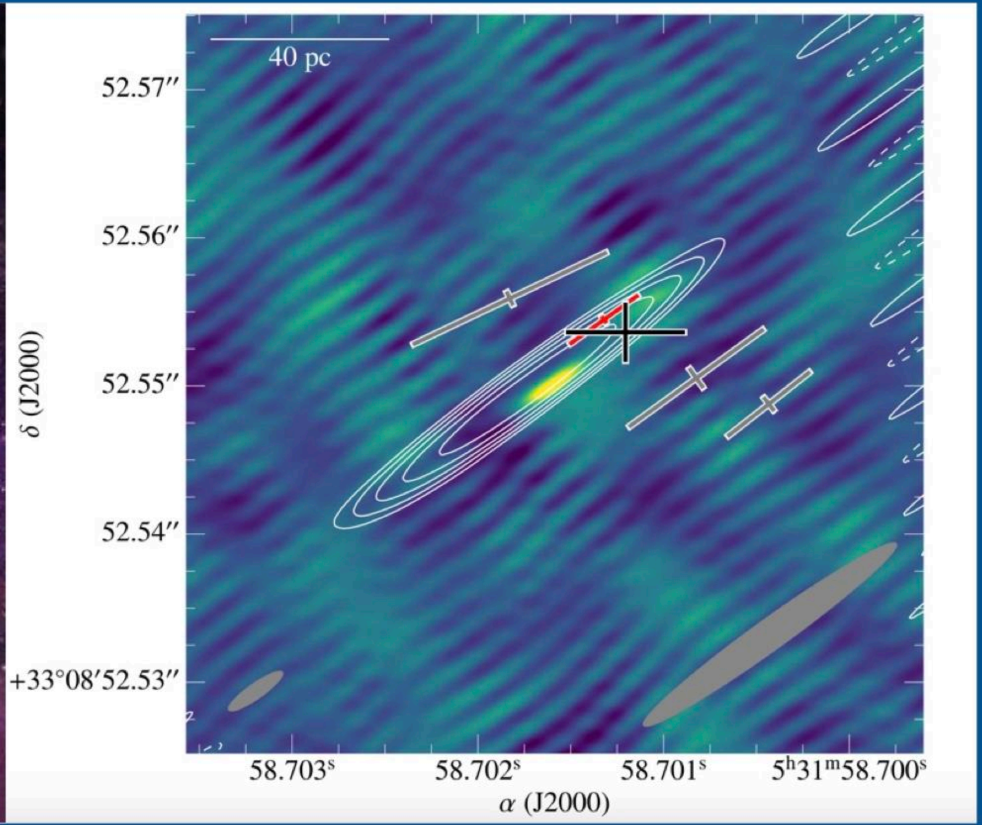
Dark Matter candidate at z= 2
1.7-GHz global VLBI (Powell et al. 2025)





Searching for substructure in SDP81 (Stacey et al 2025)

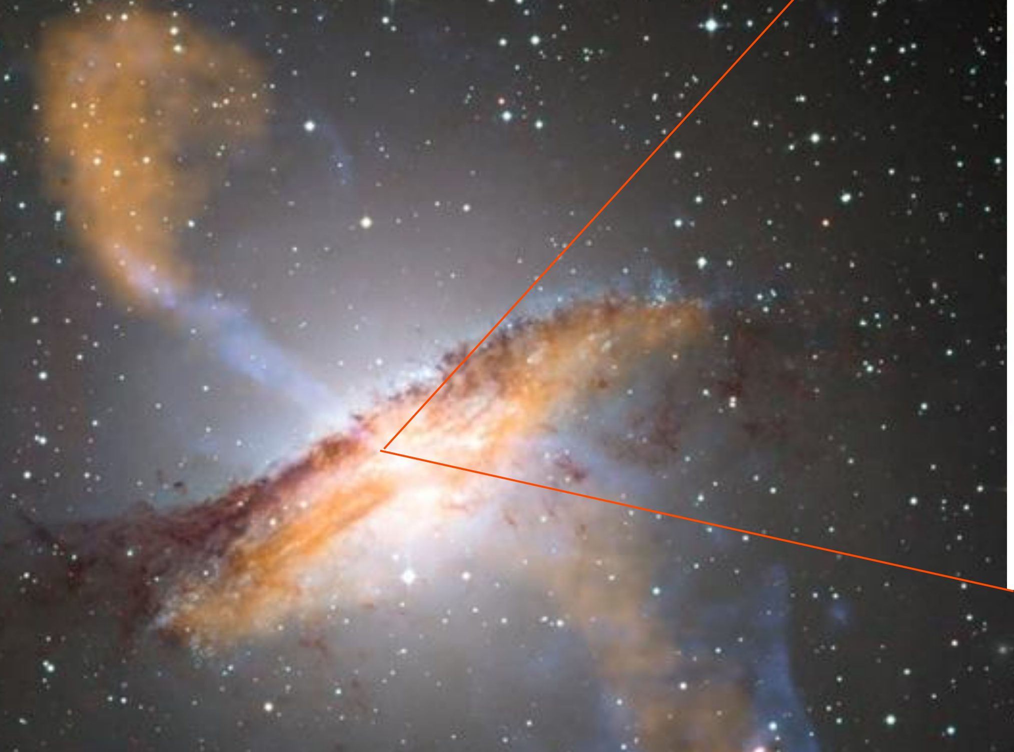
Science highlights



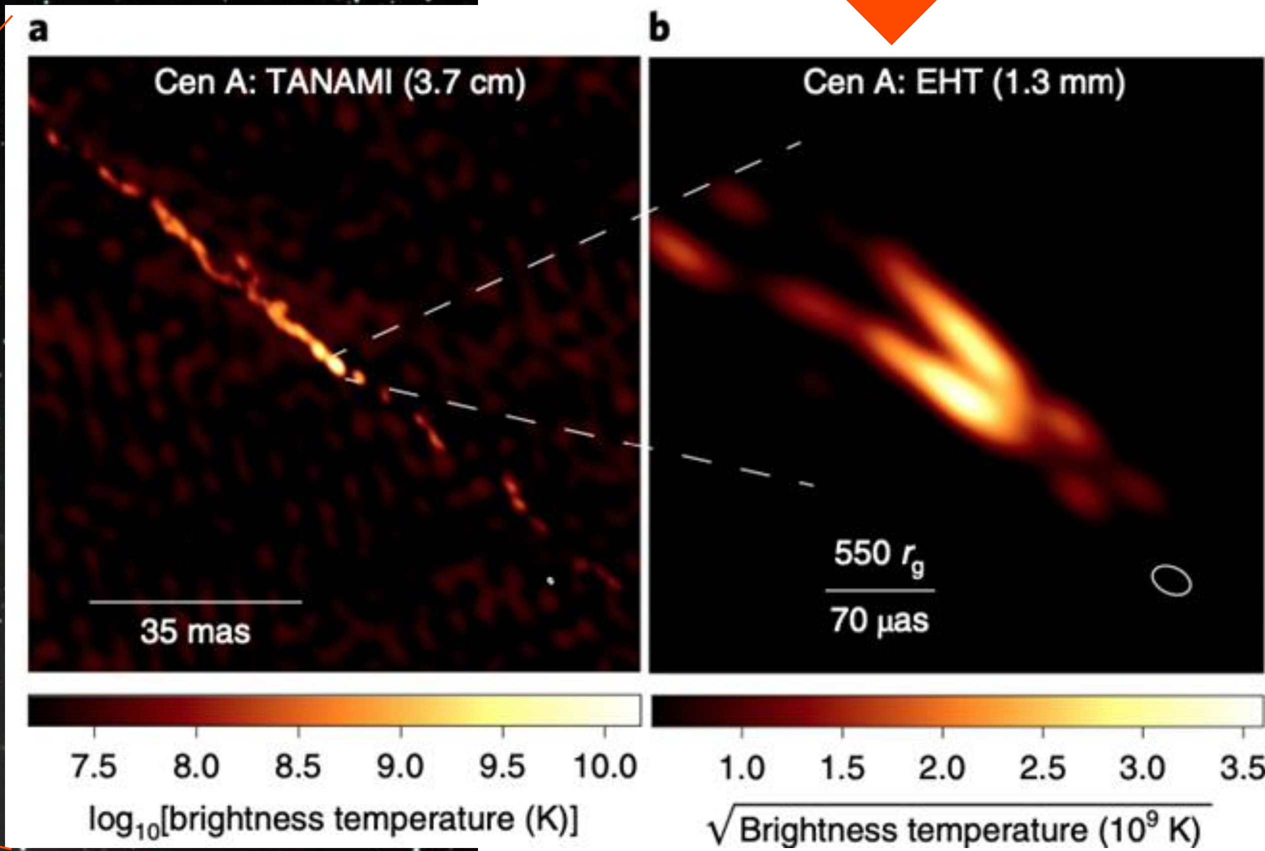
Chatterjee+ 2017, Marcote+ 2017

JET STRUCTURE AND JET LAUNCHING

Highly collimated edge-brightened jet structure with same orientation as large scale jet in mm emission.



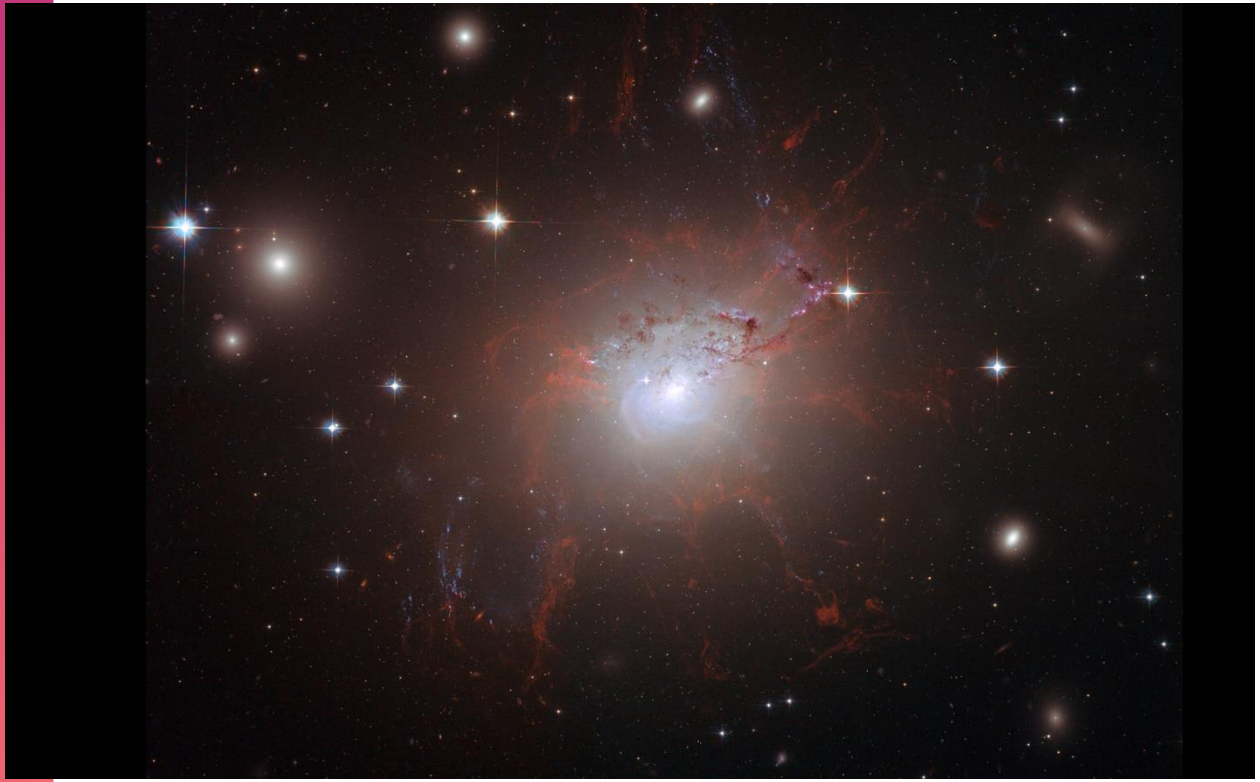
zoom by 1.5 million times!



Janssen et al. 2021

ESO/WFI (Optical); MPIfR/ESO/APEX/A.Weiss et al. (Submm); NASA/CXC/CfA/R.Kraft et al. (X-ray)

3C84, PERSEUS A



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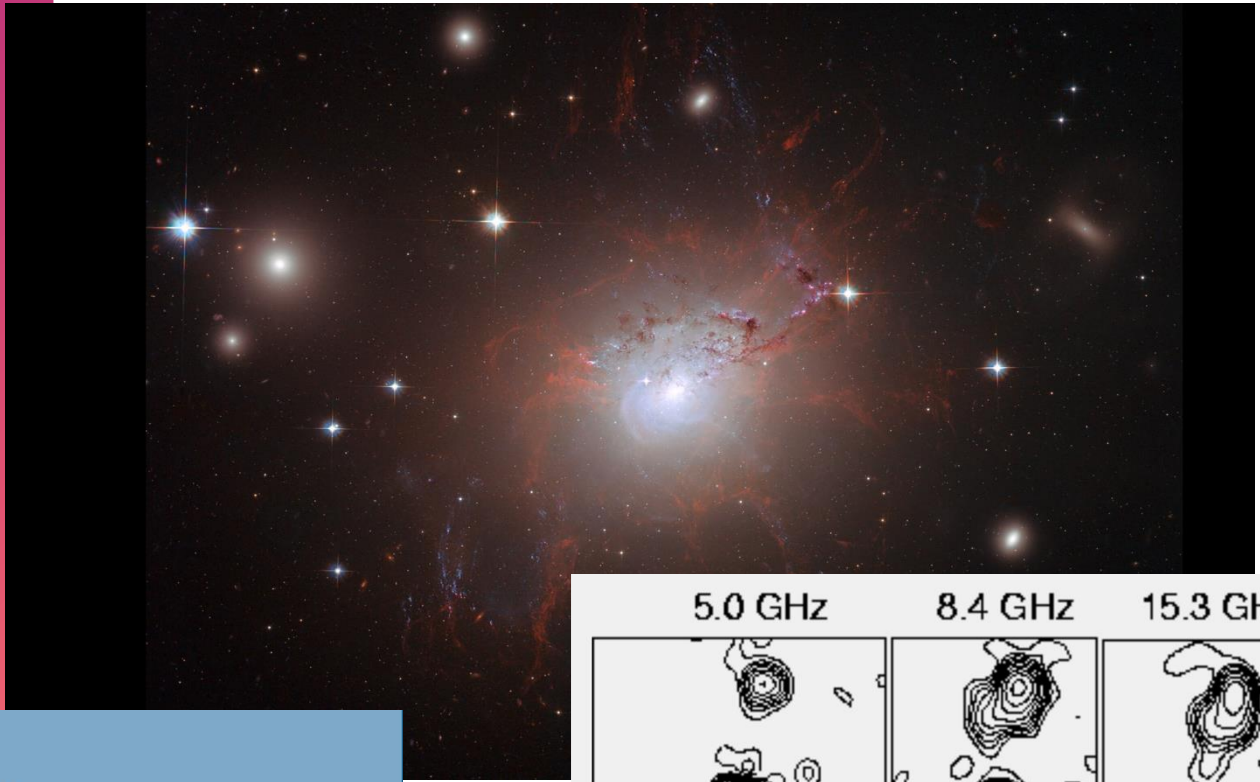
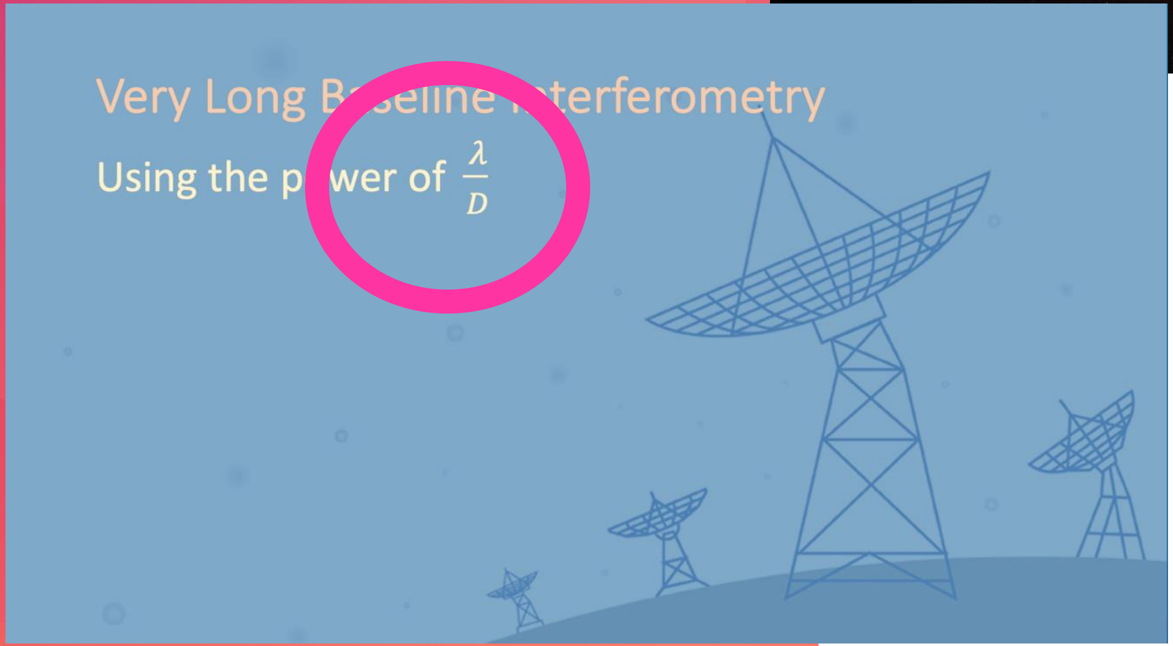
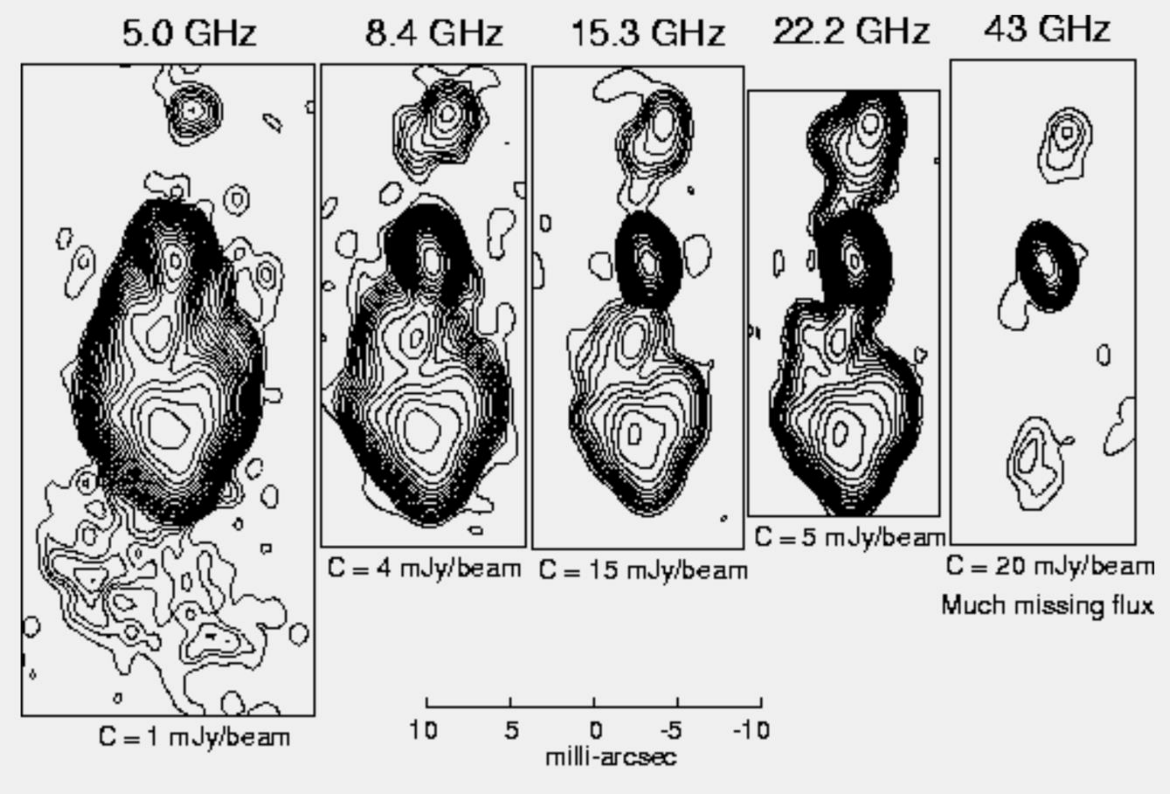
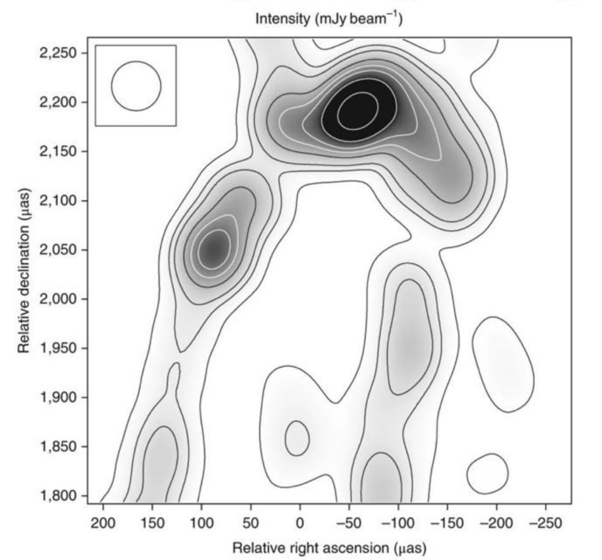
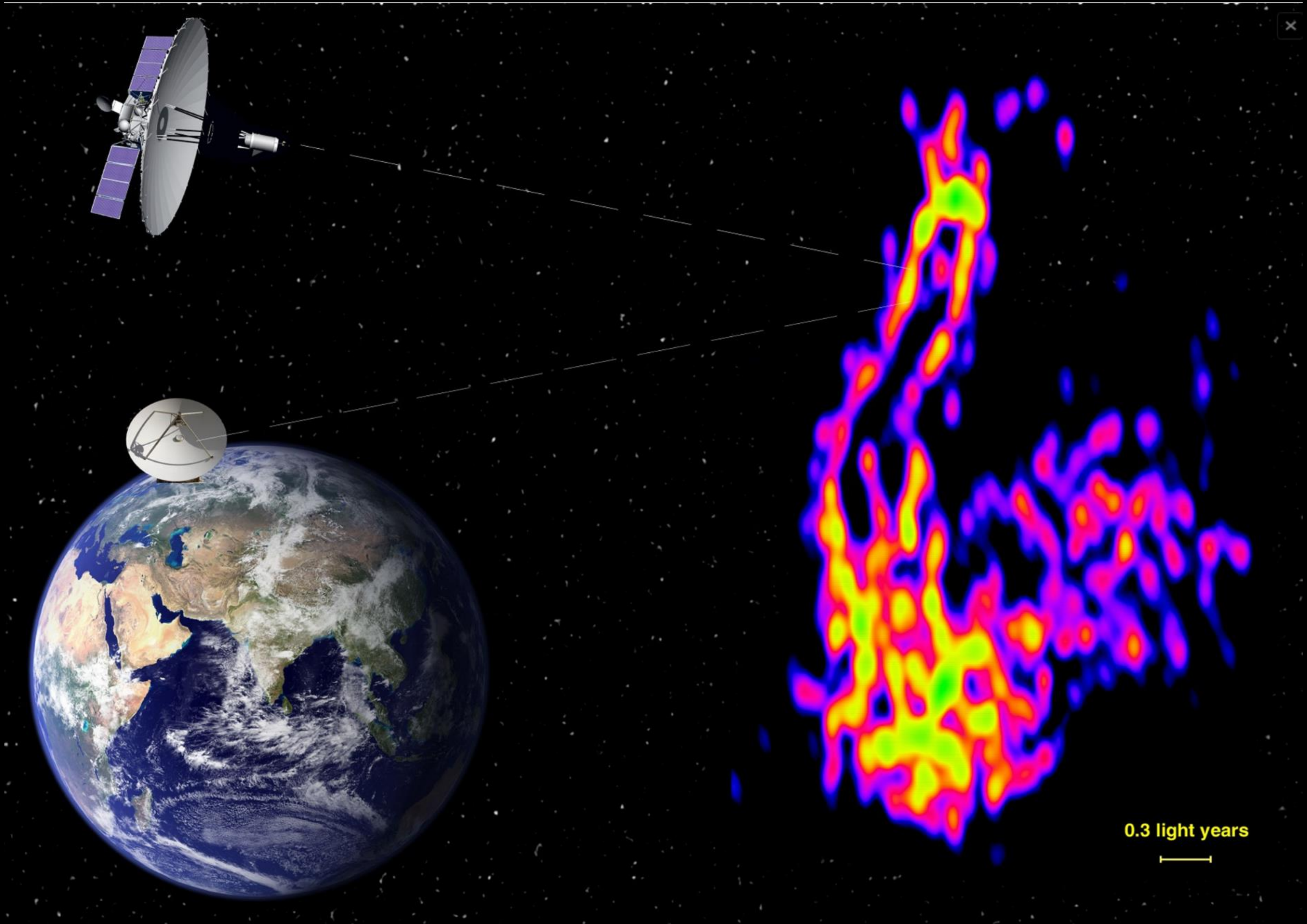






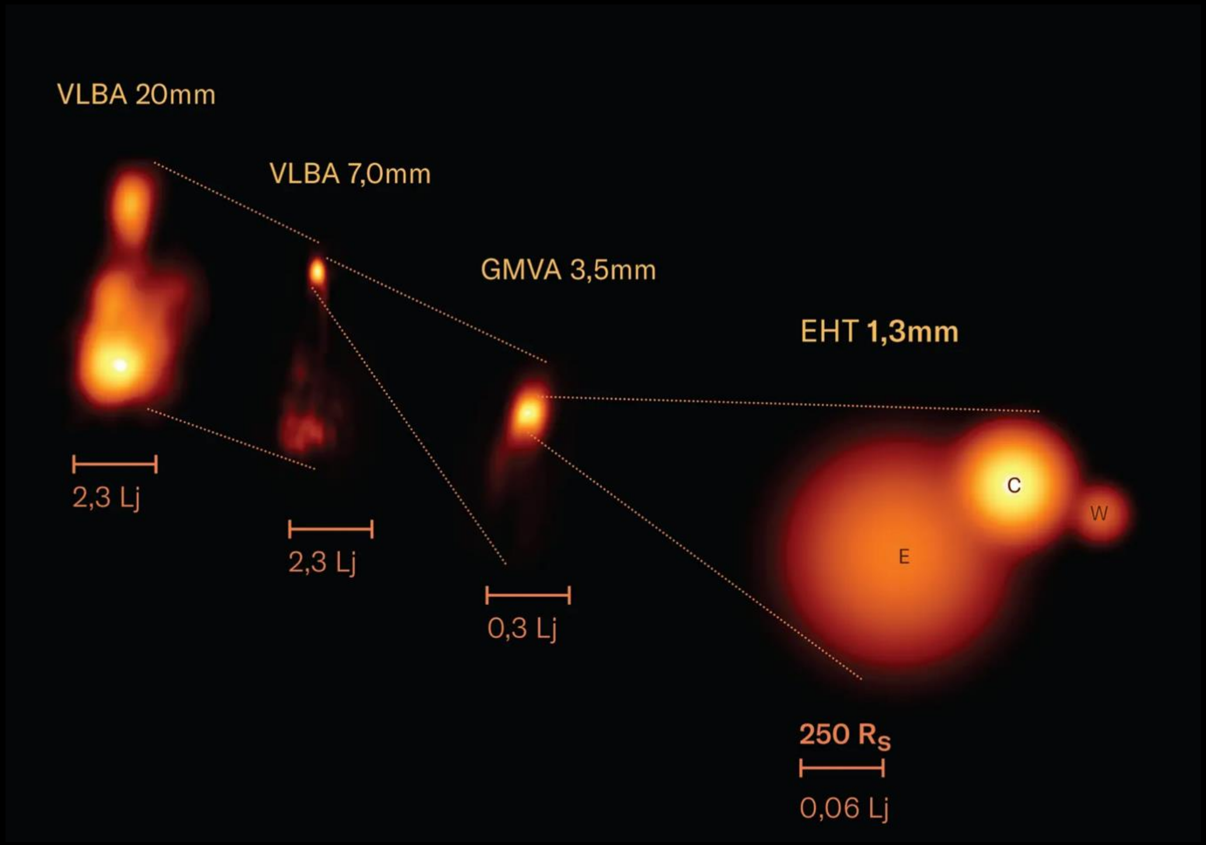
3C 84



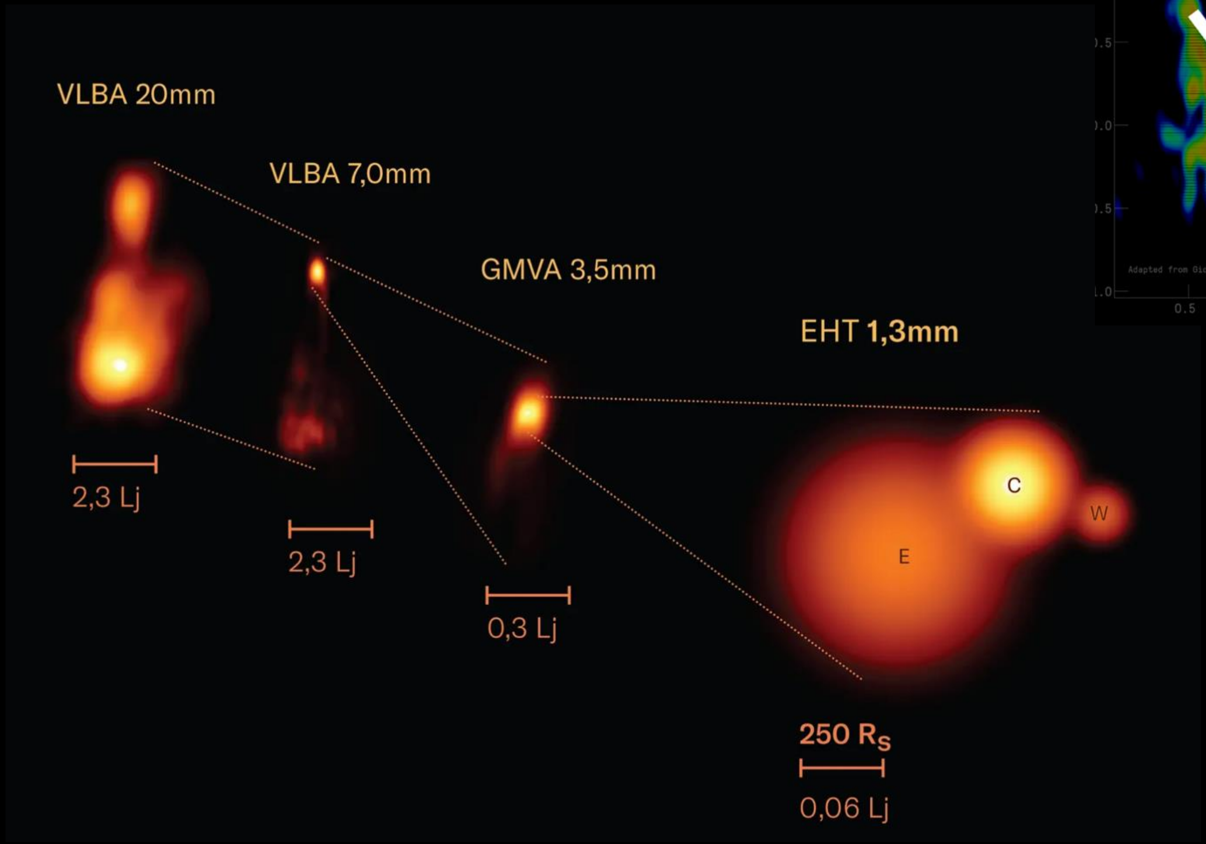


Giovannini et al. 2018

Crediti: Pier Raffaele Platania Inaf/Ira; Asc Lebedev I



Paraschos et al. 2024



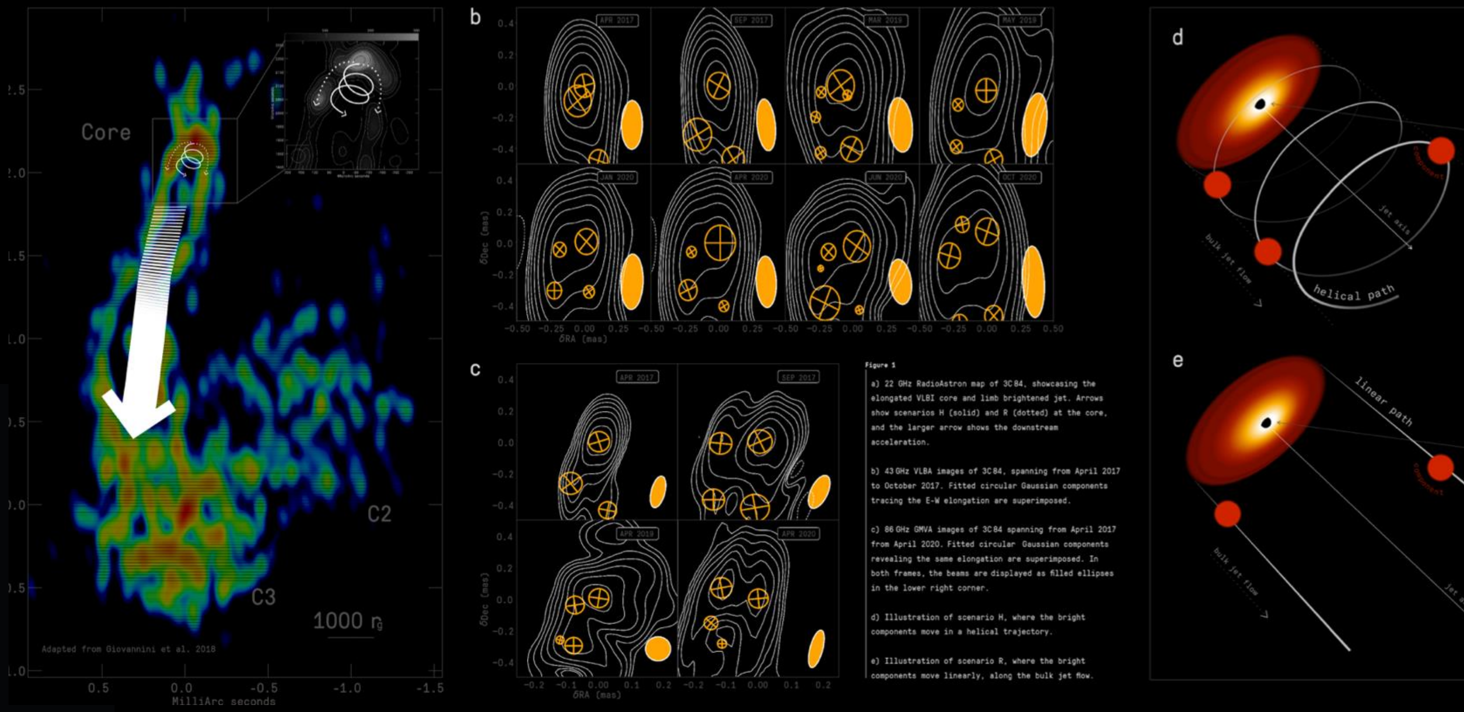


Figure 1

a) 22 GHz RadioAstron map of 3C84, showcasing the elongated VLBI core and limb brightened jet. Arrows show scenarios H (solid) and R (dotted) at the core, and the larger arrow shows the downstream acceleration.

b) 43 GHz VLBA images of 3C84, spanning from April 2017 to October 2017. Fitted circular Gaussian components tracing the E-W elongation are superimposed.

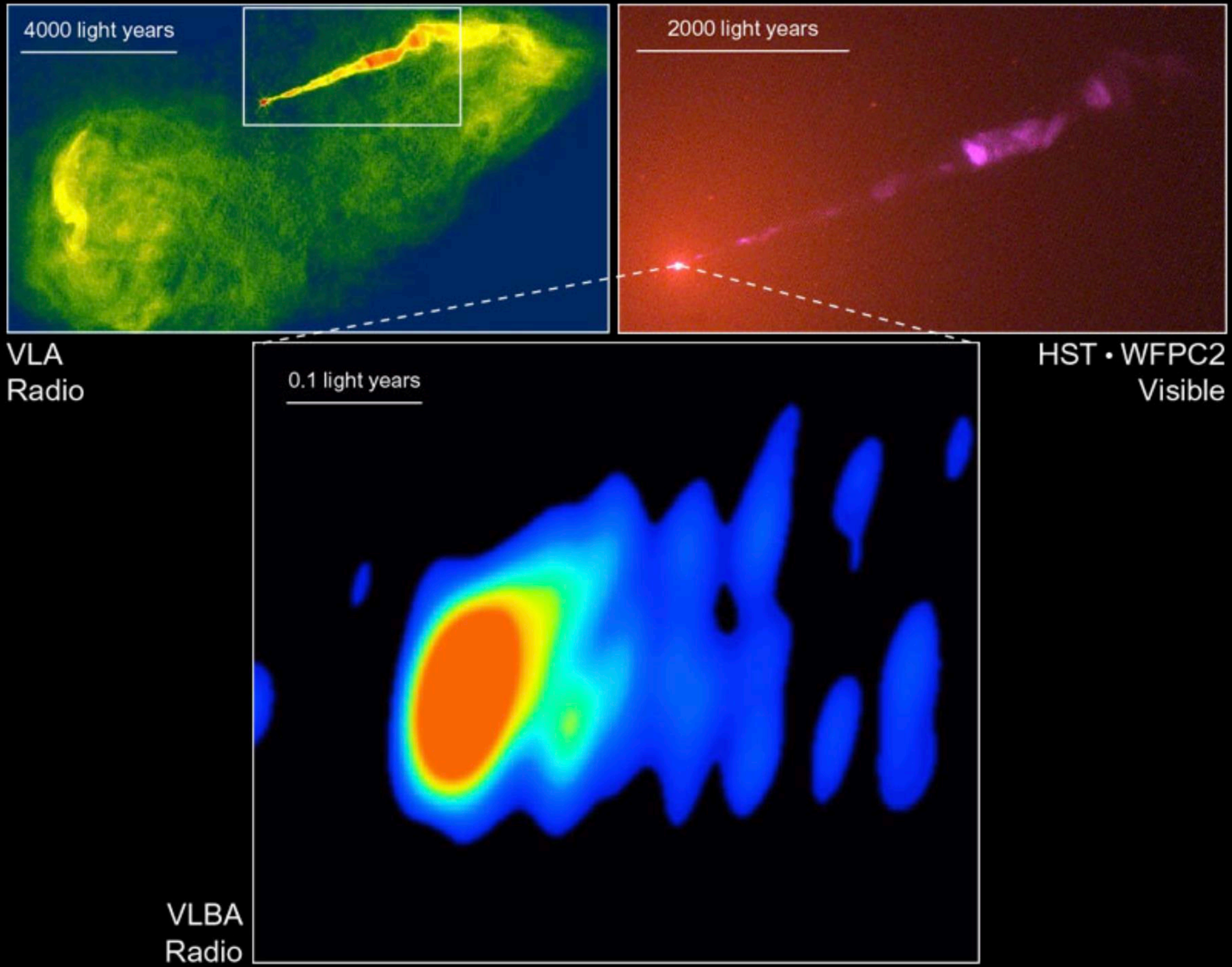
c) 86 GHz GMVA images of 3C84 spanning from April 2017 from April 2020. Fitted circular Gaussian components revealing the same elongation are superimposed. In both frames, the beams are displayed as filled ellipses in the lower right corner.

d) Illustration of scenario H, where the bright components move in a helical trajectory.

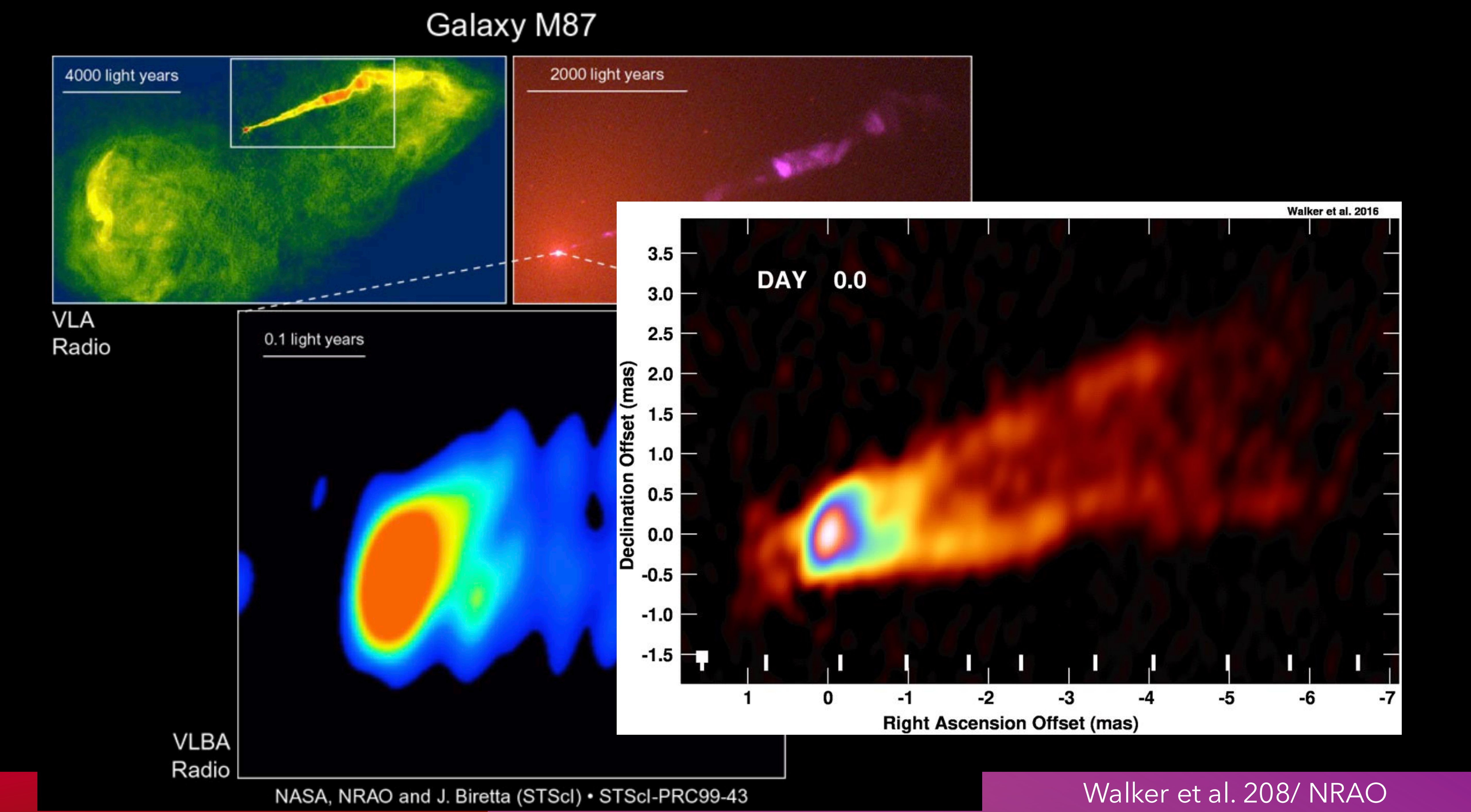
e) Illustration of scenario R, where the bright components move linearly, along the bulk jet flow.

Paraschos et al. 2024

Galaxy M87



NASA, NRAO and J. Biretta (STScI) • STScI-PRC99-43



Walker et al. 208/ NRAO

MM VLBI SCIENCE: FIRST BLACK HOLE IMAGES

M87*

EHTC et al.
2019a,b,c,d,e,f

Black hole imaging at event horizon scales

Magnetic fields near event horizon

Study accretion disk physics

Gravitational physics

Sgr A*

EHTC et al.
2022a,b,c,d,e,f

MM VLBI SCIENCE: FIRST BLACK HOLE IMAGES

M87*

EHTC et al.
2021a,b

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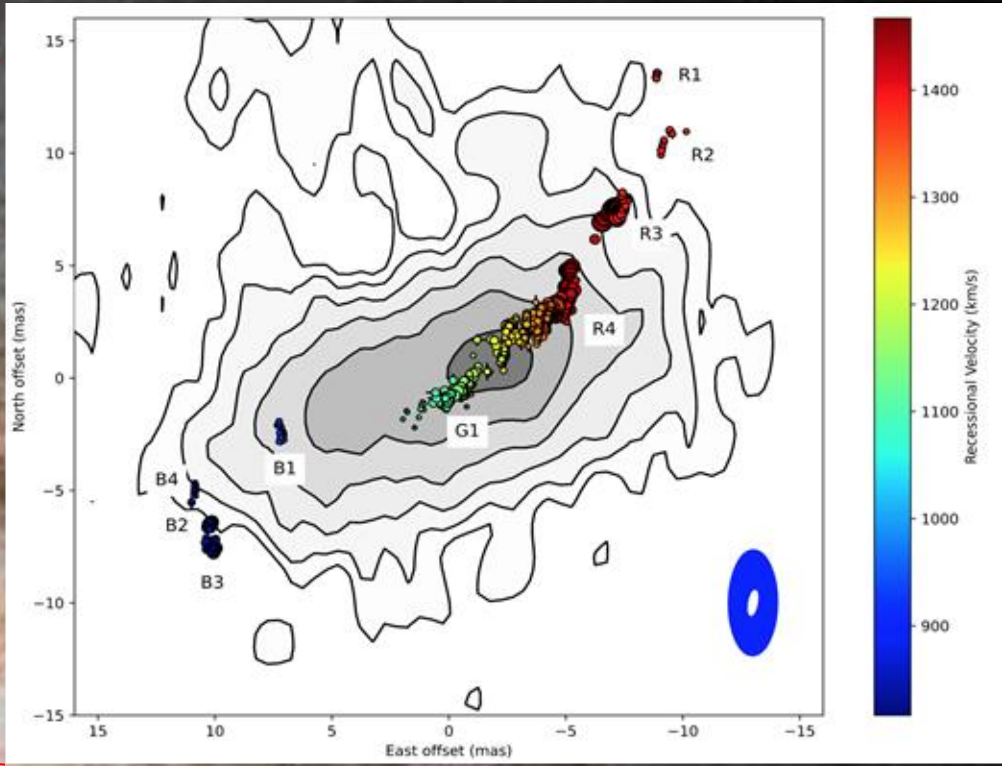
Sgr A*

EHTC et al.
2022a,b,c,d,e,f

MASERS STUDIES OF GALAXY DISKS AND TORI

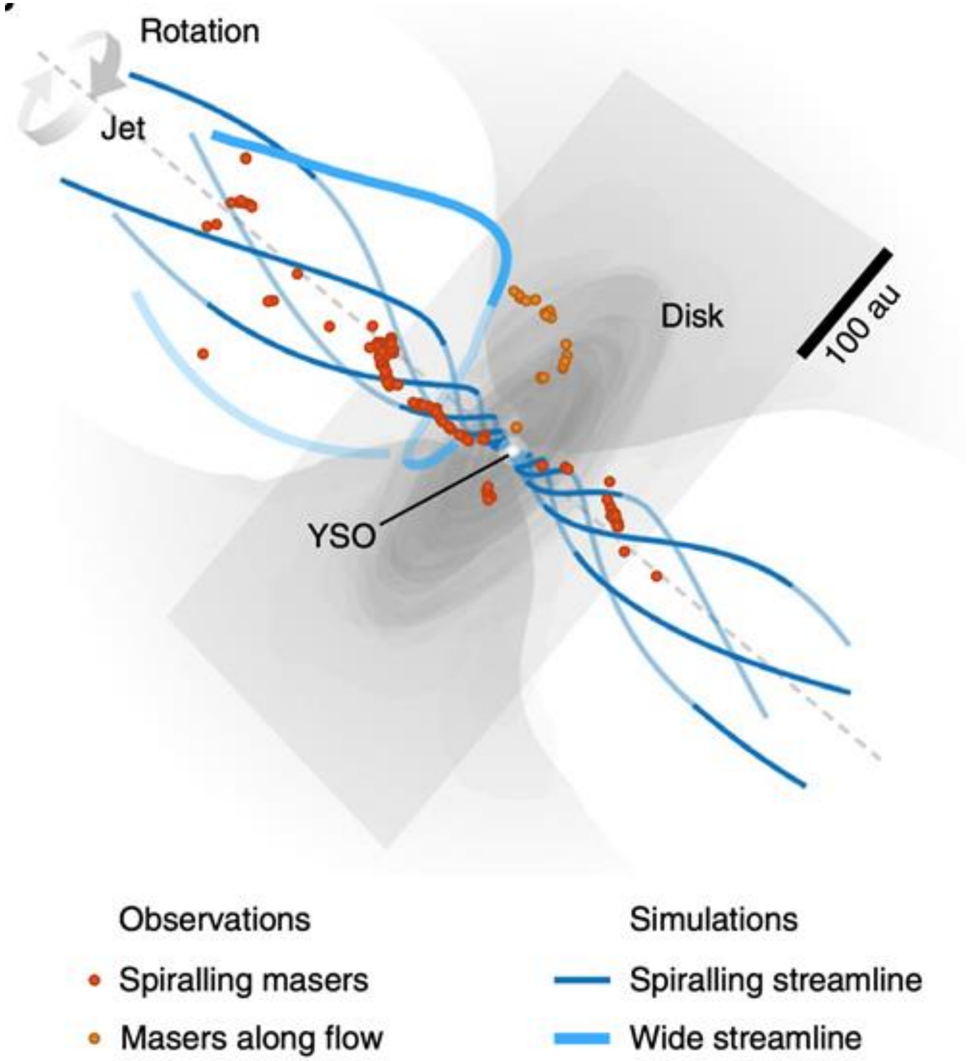
22 GHz water masers to study gas kinematics of the inner parsec in NGC 1068's disk using the High Sensitivity Array



Gallimore & Impellizzeri 2023

HST image

MASERS AROUND FORMING STARS



First observation of disk wind revealed by 22 GHz water masers (global VLBI)

Maser imaging on 1-100 au resolution traces individual streamlines launched from the disk.

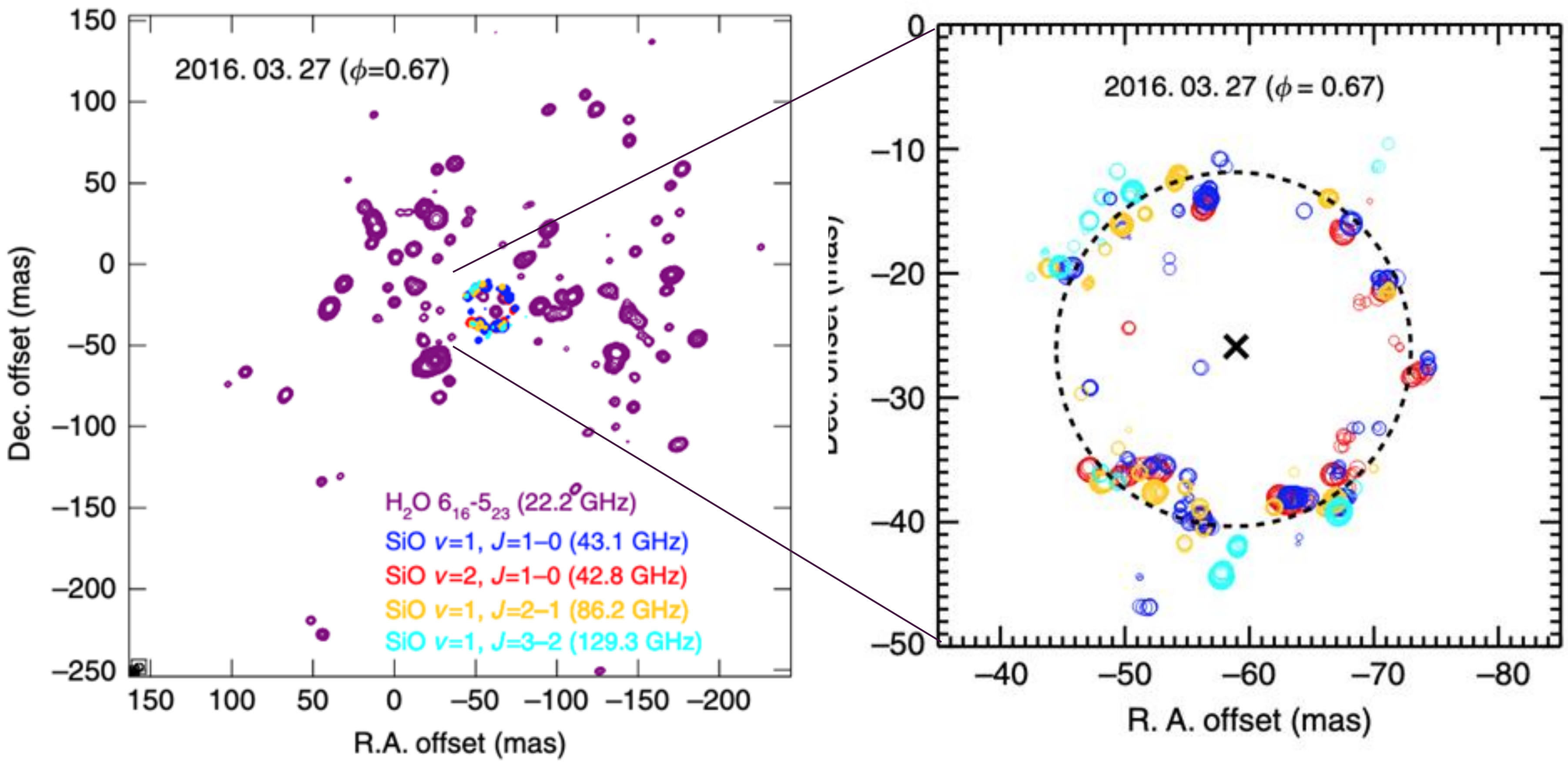
Moscadelli et al. 2022

MASERS AROUND EVOLVED STARS

Study mass transfer in stellar envelope of RSGs

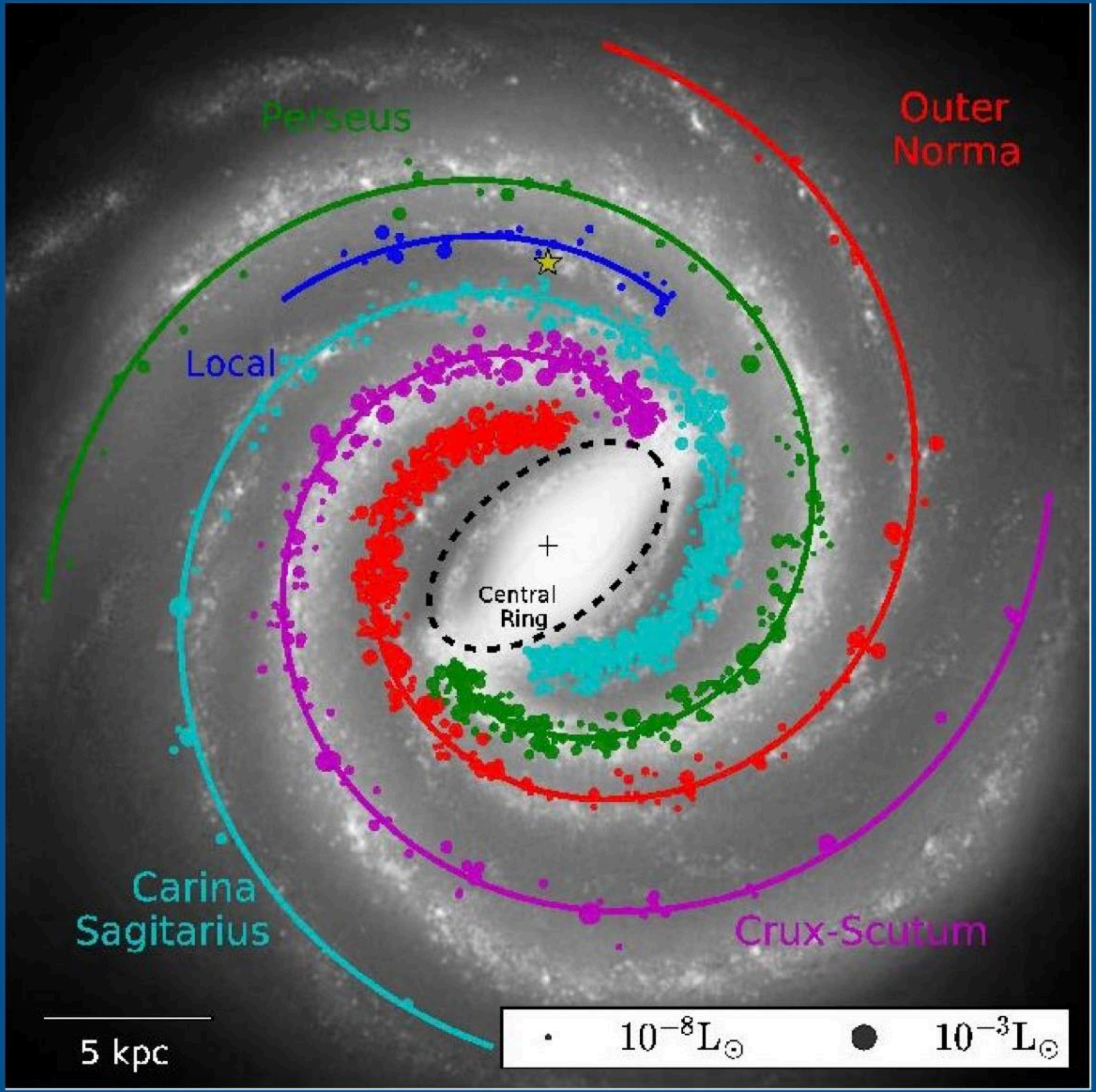
Korean VLBI Network

K/Q/W band



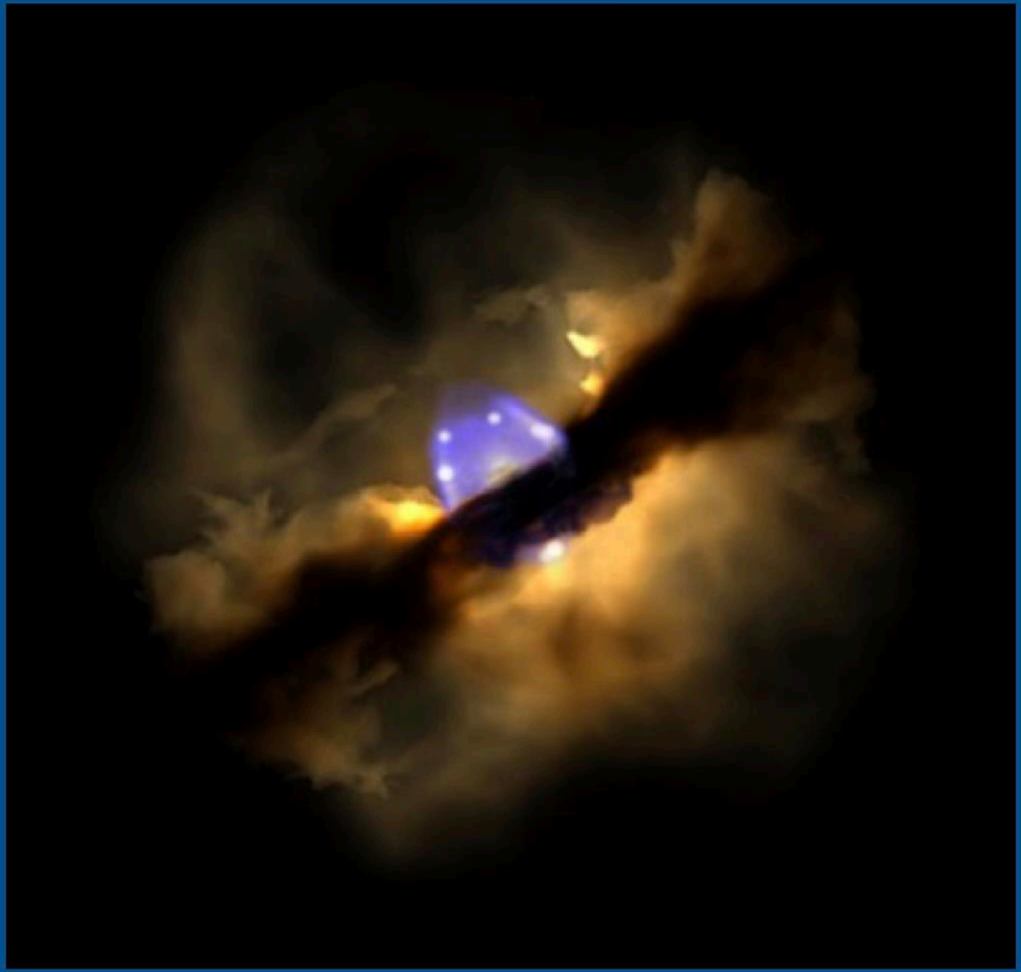
Yoon et al. 2018

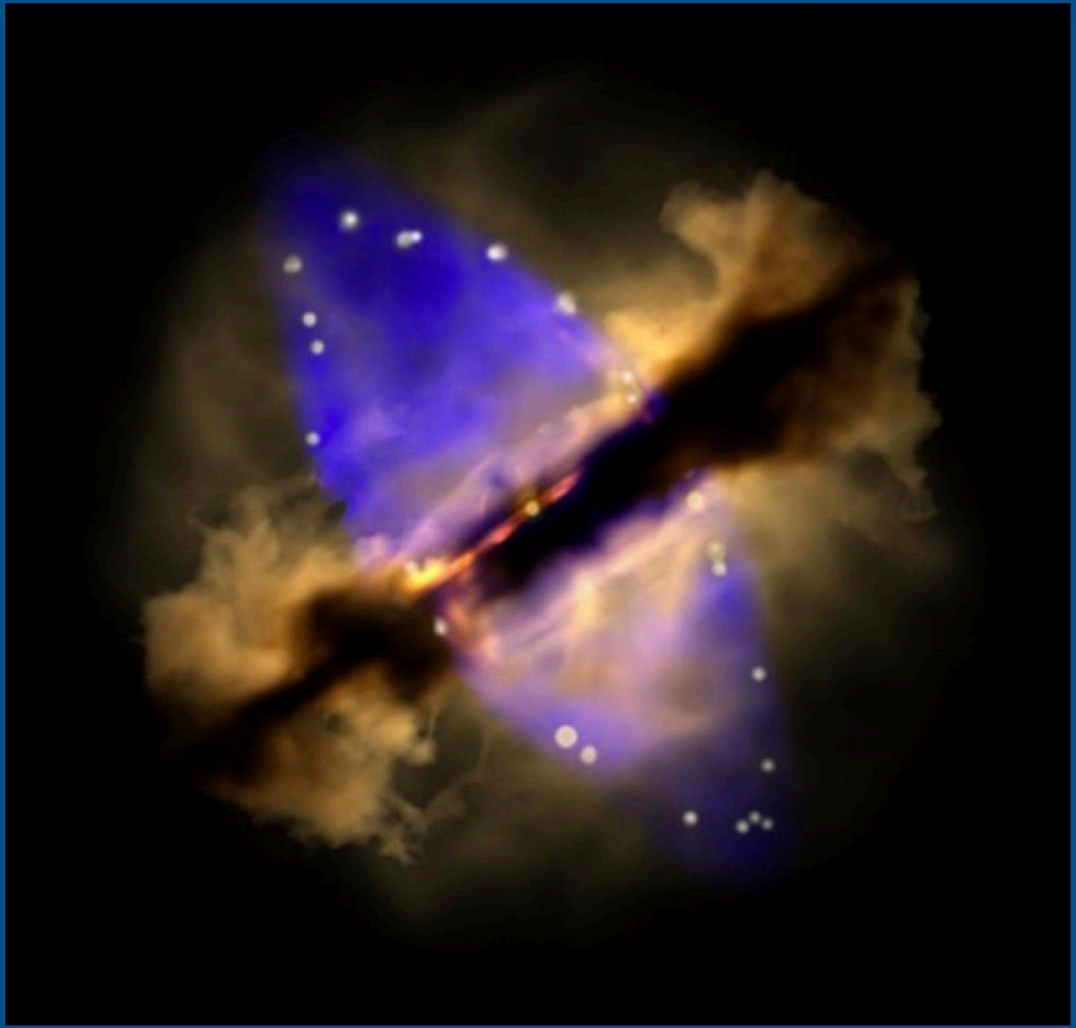
Science highlights



Quiroga+ 2017

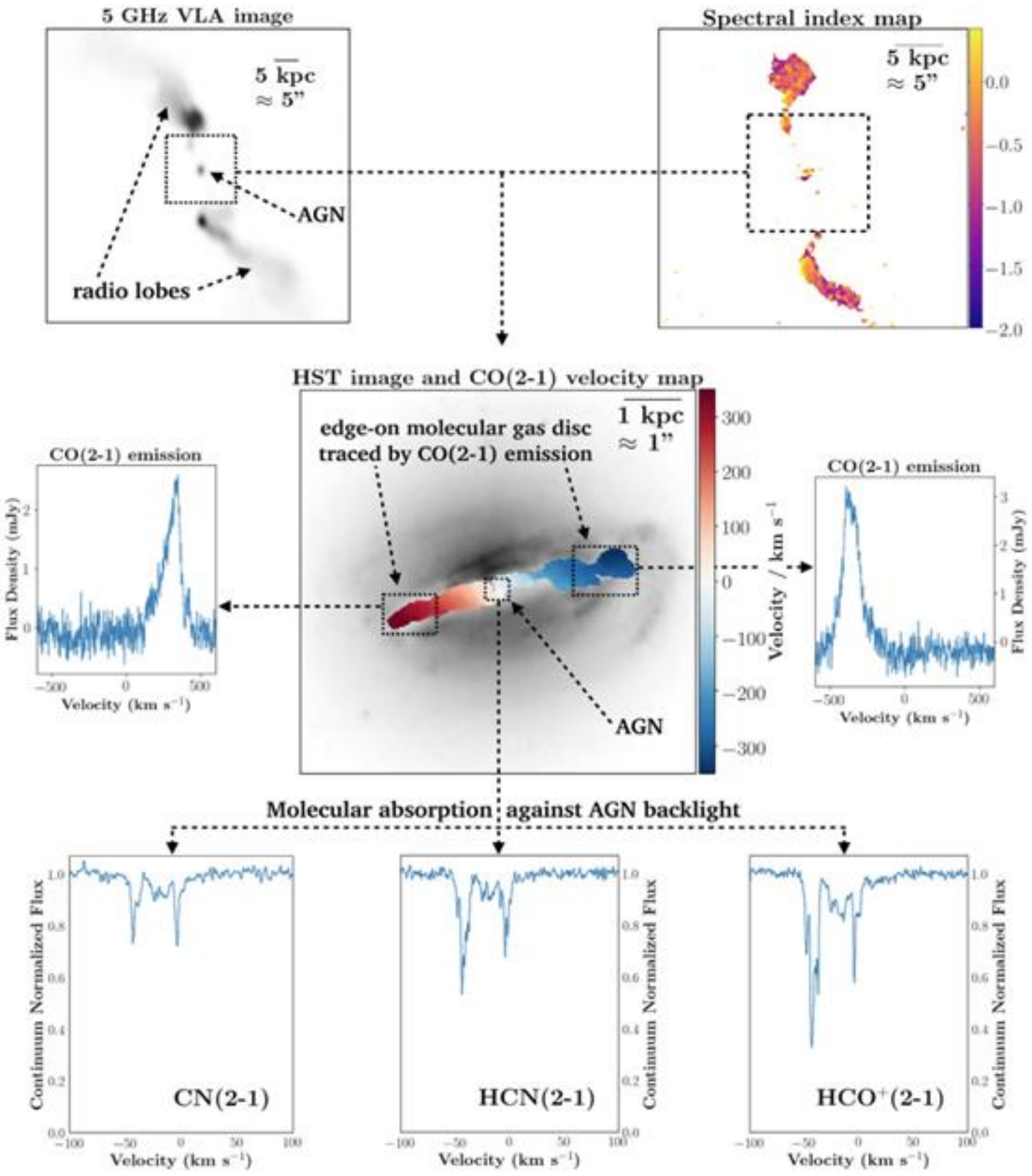
Science highlights





Carrasco-González+ 2015

MOLECULAR ABSORPTION LINES



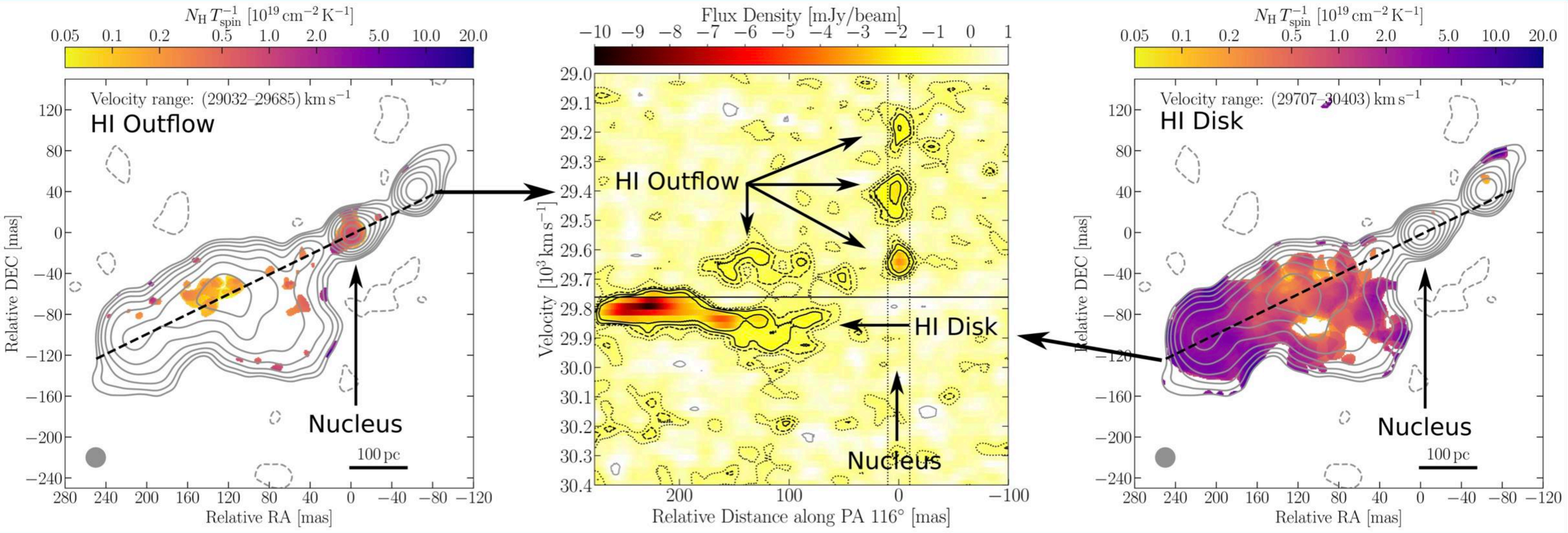
Observable against bright mm continuum of the AGN core.

Reveal molecular cloud dynamics in the inner part of the disk.

Studies of AGN gas accretion and feedback.

ALMA B6 data (no VLBI), Rose et al. 2020

Science highlights

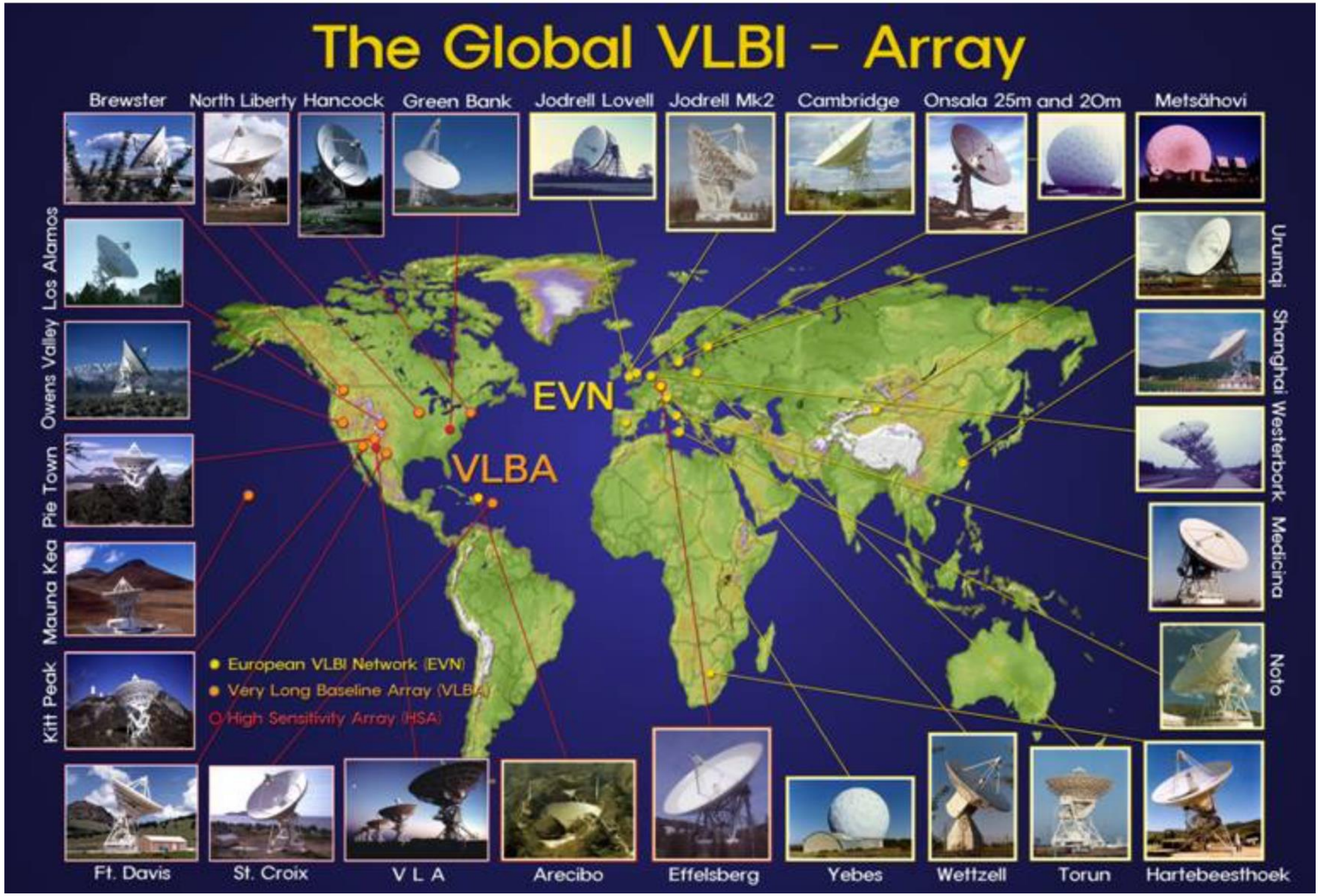


Schulz+ 2018, Morganti+ 2018

SUMMARY OF SCIENCE CASES

Examples of science case for phased ALMA are described in detail by Fish et al. (2013) and Tilanus et al. (2014).

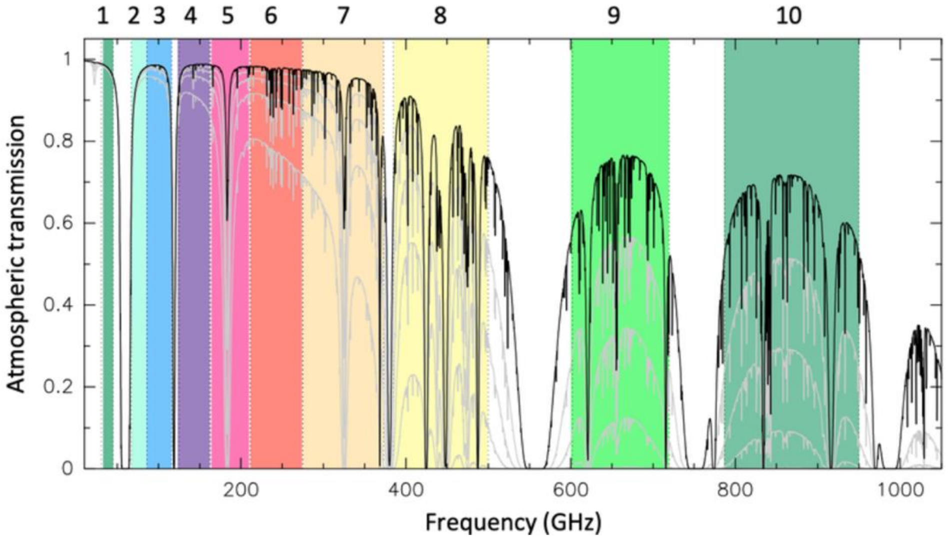
WHAT ARRAYS EXIST?



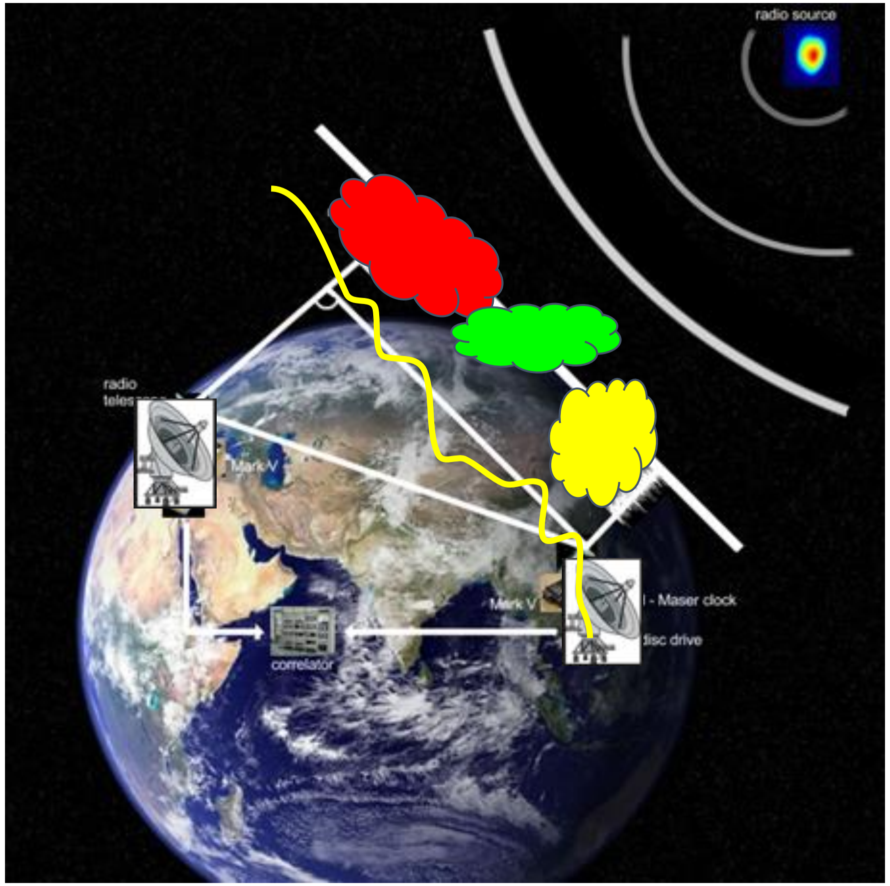
AND HOW DOES ALMA PARTICIPATE TO VLBI?

WHY IS MM-VLBI "DIFFERENT"?

- Atmosphere blocks millimeter waves
- Mostly pressure broadened water and ozone lines
- Observing conditions characterised by water vapour column
- Dishes need to be very precise
- Receivers very small and delicate
- Accurate (and expensive) maser clocks
- We must observe close to horizon very regularly
- Requires good weather across the globe
- Some of our telescopes are interferometers



VLBI in the mm - challenges



At <3mm VLBI is still **challenging**:

- ***weaker*** astronomical signal
- distortion effect by the ***troposphere*** → *dependence on weather, short time coherence*
- Worse receiver performances
- typically *small dishes* (10-15 m)
- *small number* of telescopes

  → **lower sensitivity**

For an interferometer :

$$\sigma_S \approx \frac{2\,k\,T_{sys}}{A_{eff}\,\sqrt{n(n-1)\times\Delta\nu\times\eta_{pol}\times t_{int}}}\ [\mathrm{Jy}]$$

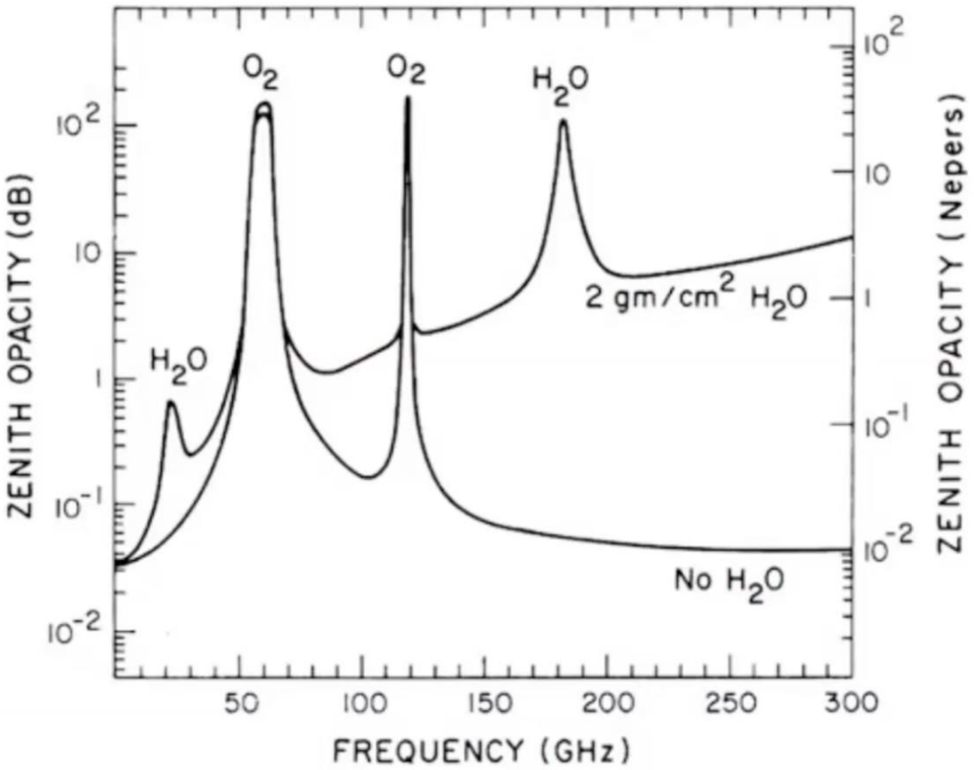
mm VLBI challenges

1. Reflective telescope dishes with excellent surface accuracies needed → Small collecting areas

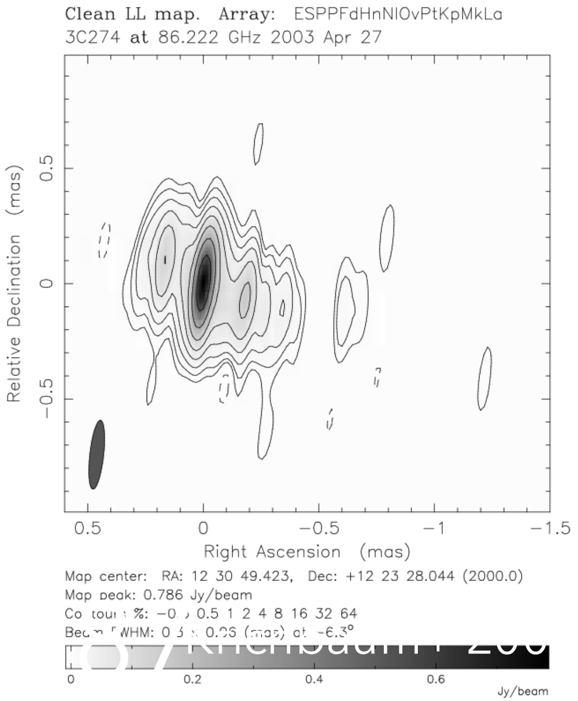
2. Troposphere: The water vapor problem
   a. Short (~seconds) coherence times due to atmospheric turbulence
   b. Emission → larger SEFDs (+ large receiver noise)
   c. Absorption → source signal attenuated

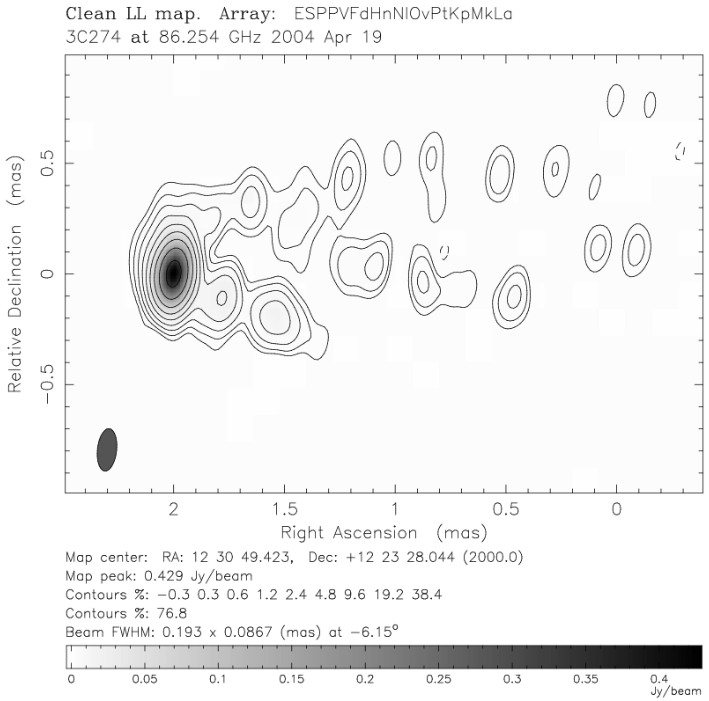
3. To (partially) counter atmosphere: Must be on high and dry site & have good weather → sparse arrays!

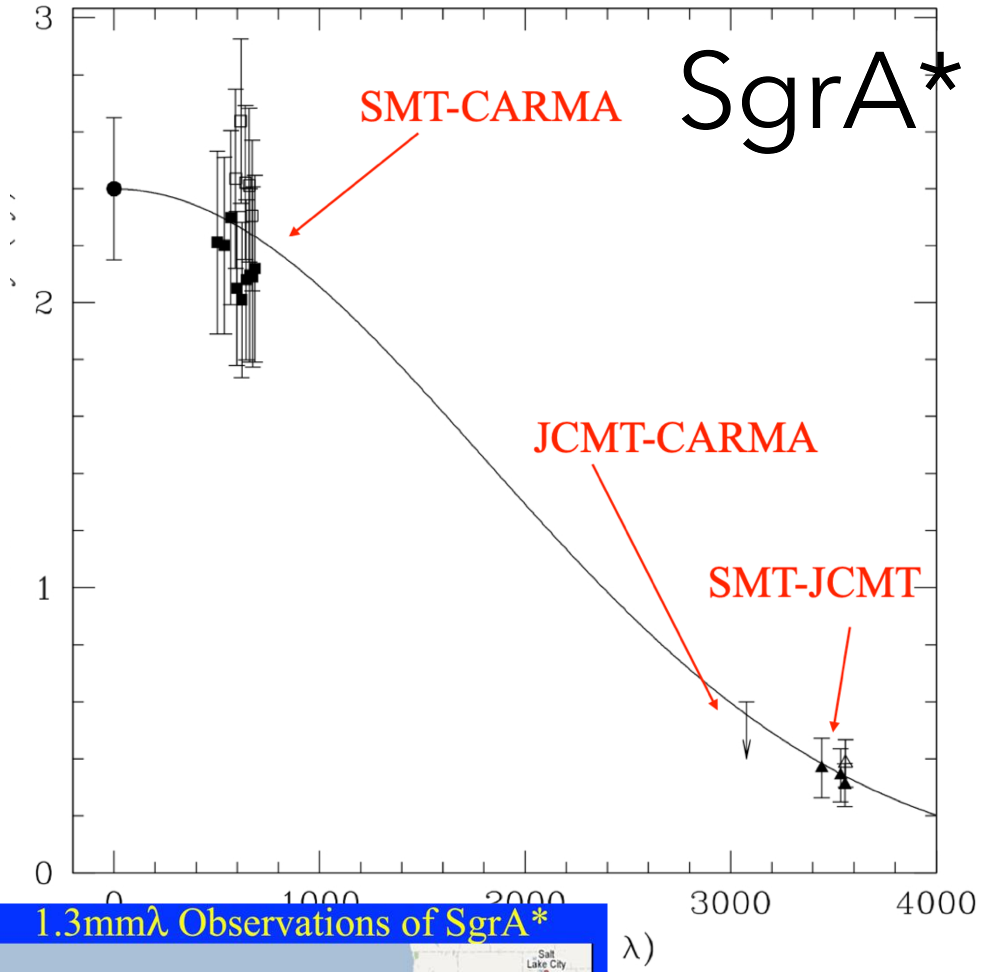
Taken from TMS III

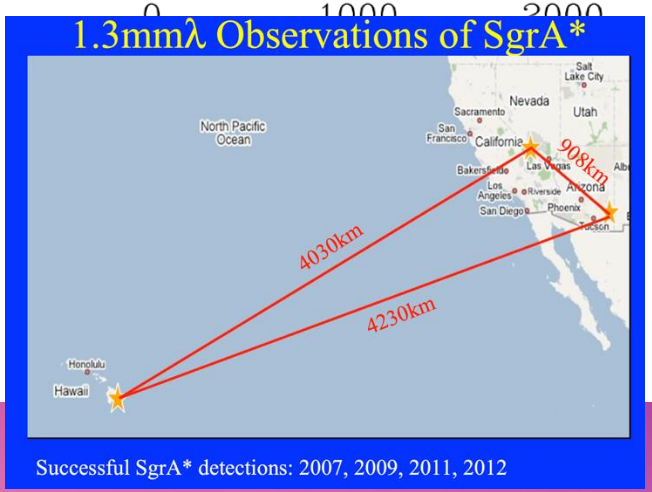


First attempts… on mmVLBI









86 GHz with Effelsberg 100m, Pico Veleta 30m, the phased Plateau de Bure interferometer 6x15m, Onsala 20m, Metsahovi 14

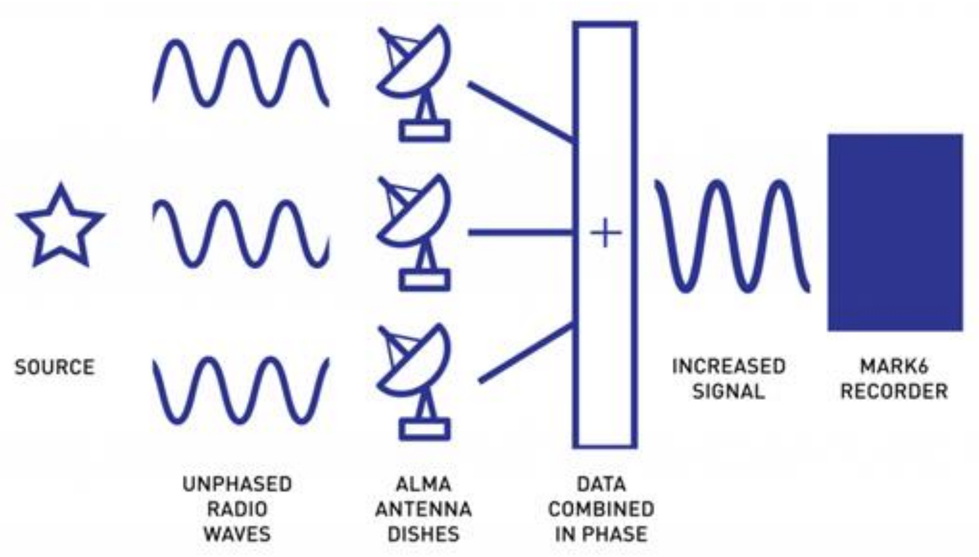
THE ALMA PHASING PROJECT (APP)

The APP was conceived to take advantage of the extraordinary sensitivity of ALMA.

ALMA can be used as a single VLBI antenna if the data from its individual antennas are phase-corrected and coherently added together.

A phased array provides a collecting area equivalent to the combined effective area of the individual antennas
→ add an order of magnitude boost in sensitivity to the array ! e.g. **37 x 12m phased ALMA antennas = 73m** dish !

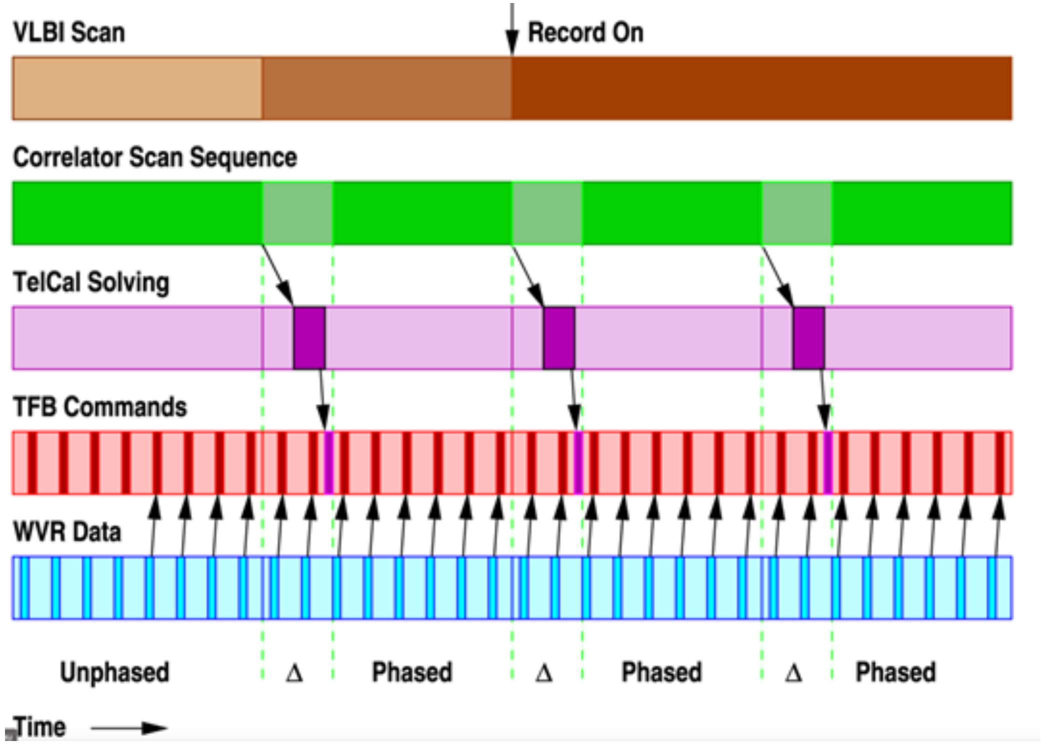
Also: a privileged location in the Chajnantor desert! (pwv conditions unparalleled)

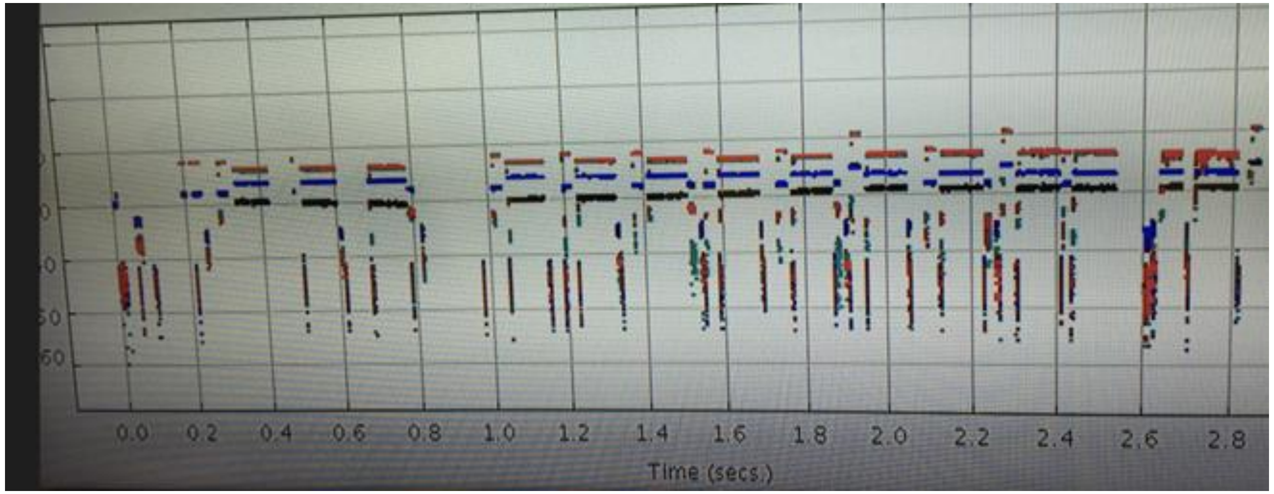


PHASING: ALMA 12-M ARRAY AS A LARGE SINGLE DISH

Phasing requires to remove (in real time) instrumental and atmospheric phases from the observed baseline phases (by selecting one **ref antenna**) in order to add all antenna phases coherently → this will result in a boost in the signal!

The phasing process requires a "phasor" - which can be 'active' (the target itself) or 'passive' (a nearby calibrator)





ALMA console (2019)

See Matthews et al. 2018 for more details

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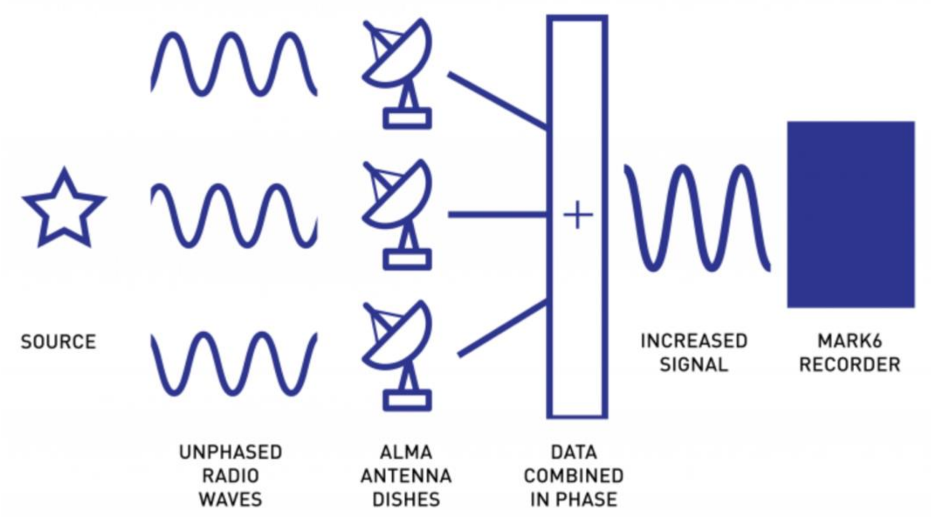
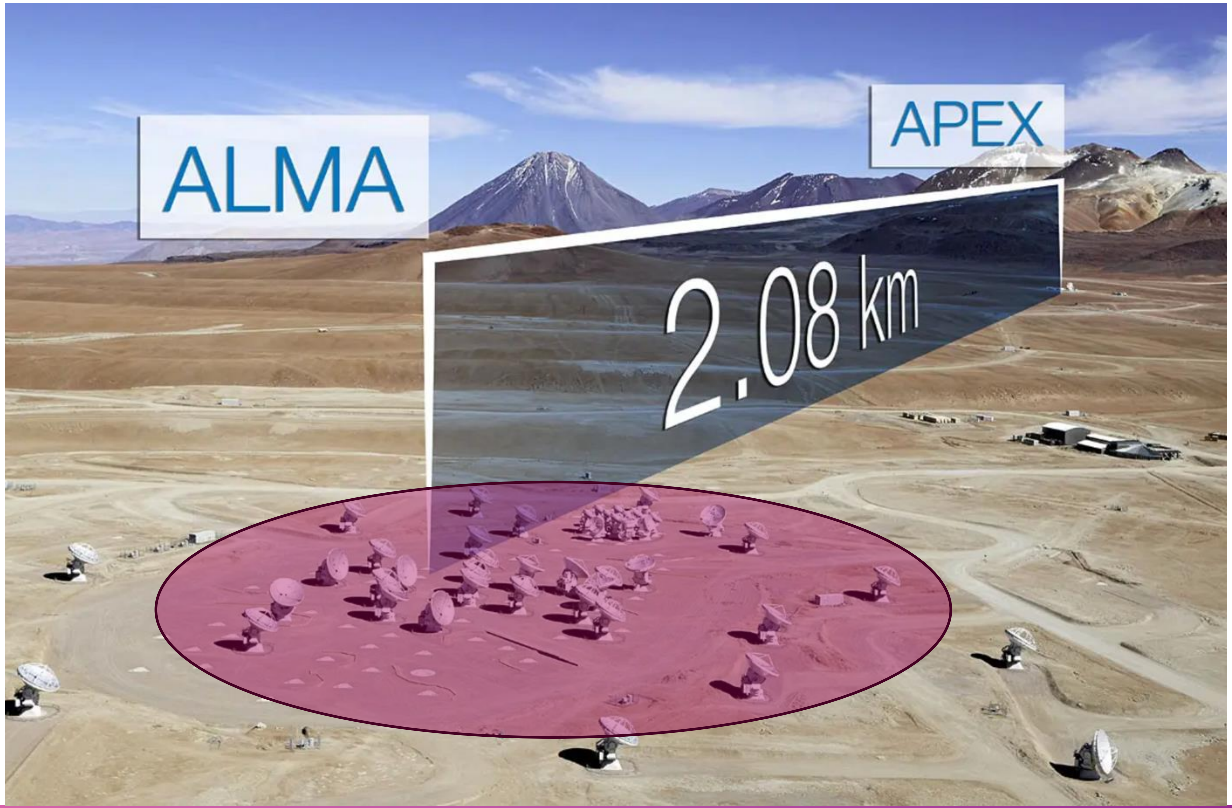




See Matthews et al. 2018 for more details

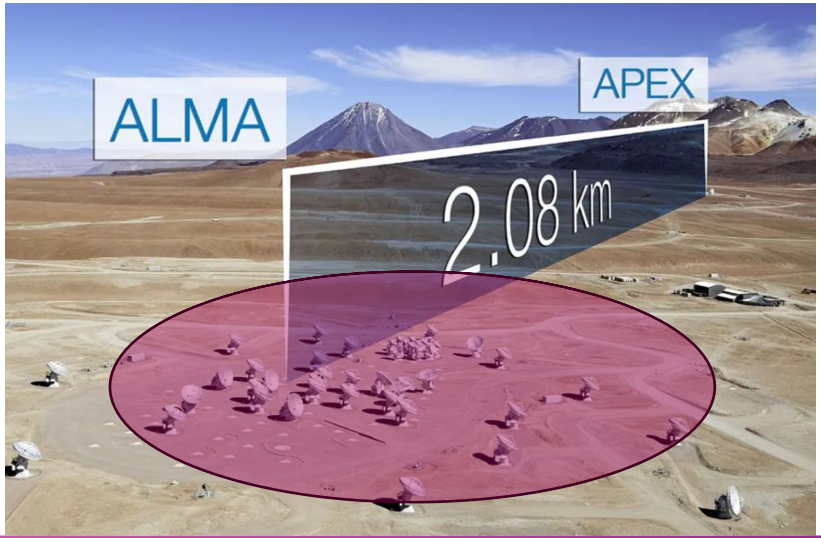
WHY ADDING ALMA WAS IMPORTANT: SENSITIVITY

Telescope	SEFD / Jy (1.4mm)
ALMA (phased)	94*
APEX	4700
JCMT	4500
SMA (phased)	6200*
LMT	1000**
IRAM 30m	1900
SMT	17100
SPT	19300**
GLT	12000**
NOEMA (phased)	700*
KP	13000

System Equivalent Flux Density = Tsys/ Gain

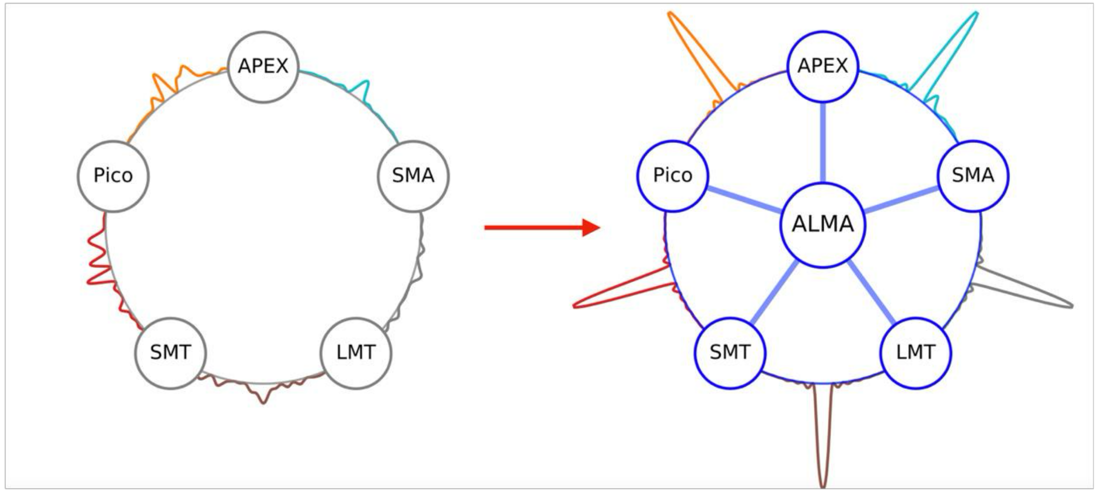
Phased ALMA (*=37 antennas) is the most sensitive element in the array!

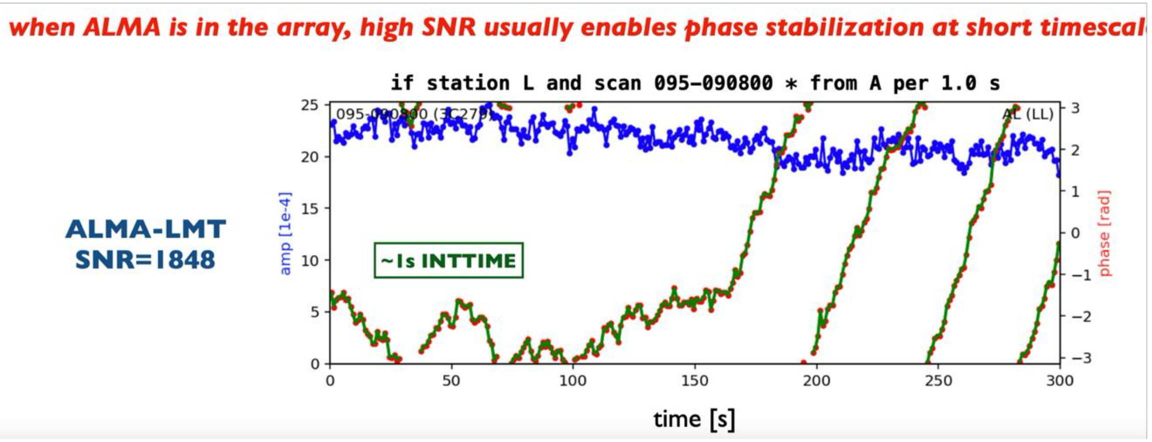
Reference antenna for calibration

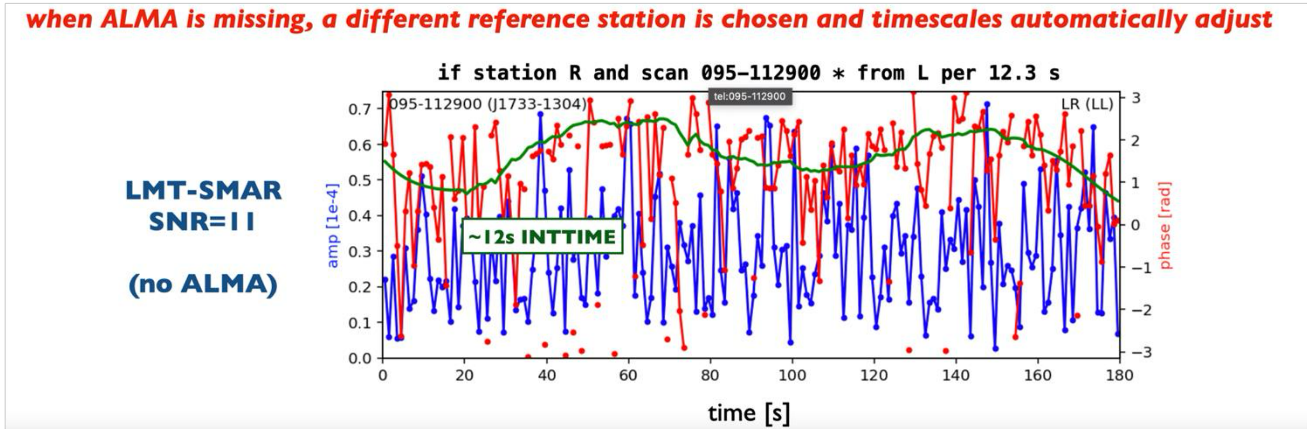


Source: EHT website

ALMA as part of the the EHT array







SPECTRAL LINE MM VLBI: A NEW ALMA CAPABILITY!

MASER TRANSITIONS WITHIN ALMA BANDS FOR VLBI (1,3,6,7)

H_2O masers include: 96, 268, 321, 325 GHz

SiO masers include: 43, 86, 215, 258, 301, 344 GHz

HCN masers include: 89 GHz

CH_3OH masers include: 44, 95, 217, 230, 349 GHz

→ But do check the tuning compatibility of the other antennas in the array

SPECTRAL-LINE VLBI

- Any ALMA basebands to be recorded for VLBI must utilize the widest bandwidth FDM correlator mode (1.875GHztotalbandwidth) and full polarization (1920 channels per polarization); this is the only baseline.
- The PI is responsible for ensuring that tuning choices are compatible with all VLBI partner sites, which may have very different tuning restrictions from ALMA; see the GMVA and EHT web sites (referenced above) for details

Phasing:

- For targets with sufficient strong emission lines (i.e., bright maser emission), it is possible to perform active phasing of the array using a narrow spectral window centered online emission from the science target.
- As a guideline, the flux density threshold Flim,line(ν) for utilization of active phasing for spectral line VLBI at ALMA may be expressed as:

$$F_{\mathrm{lim,line}}(\nu) \geq F_{\mathrm{lim,c}}(\nu)\sqrt{(234.4\ \mathrm{MHz})/(W_l)}\quad (\mathrm{Jy})$$

- For weaker or very broad spectral lines, absorption lines, use active or passive phasing.

EHT BAND 6 MONITORING

- Aka “movie campaign”
- Each monitoring epoch will last 4–5 hours and epochs will be separated by a minimum of three days. Monitoring observations may occur in March–April 2026, with a potential extension to May.!
- Joint proposals

WHAT IF MY PROPOSAL IS ACCEPTED?

Successful VLBI proposals will be passed to a network Scheduler who builds the common VLBI schedules.

In these schedules, some number of contiguous hours will be devoted to each set of science targets and necessary VLBI calibrators.

The observatory and schedulers will get in touch with the PIs well in advance to make sure their program is fully integrated into the final program that is run during the campaign!

DOCUMENTATION & HELP

ARC nodes are available for any help and support!

Documentation:

- GMVA: https://www3.mpifr-bonn.mpg.de/div/vlbi/globalmm/
- EHT: https://eventhorizontelescope.org/
- ALMA Technical handbook (particularly Ch 11)
- https://astro.uni-bonn.de/ARC/development/mmvlbi/guidelines.shtml

Source Catalogs:

- https://asa.alma.cl/sc/,
- http://sma1.sma.hawaii.edu/callist/callist.html
- https://github.com/kamenoseiji/AMAPOLA

GOOD LUCK PROPOSING VLBI!