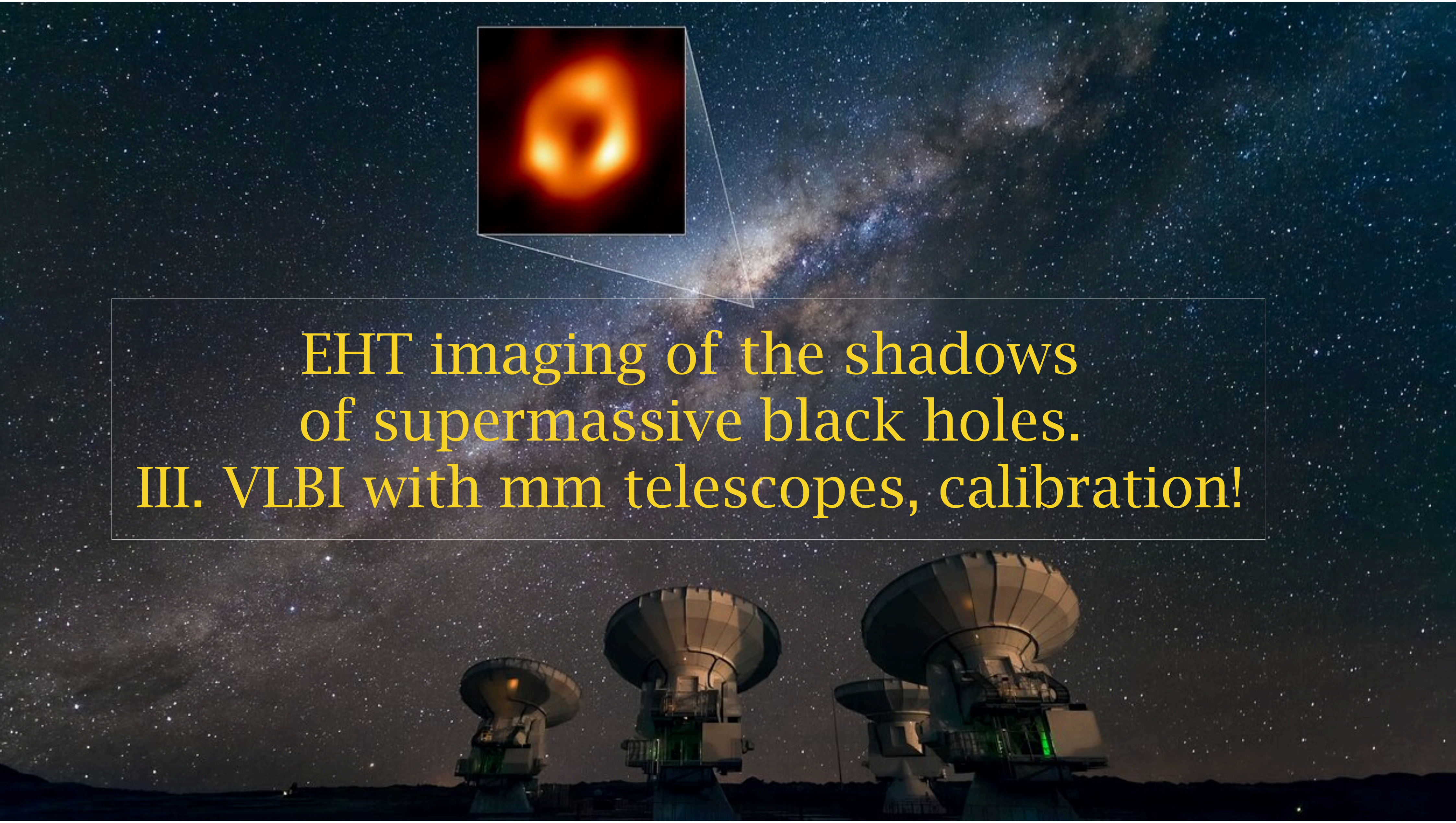
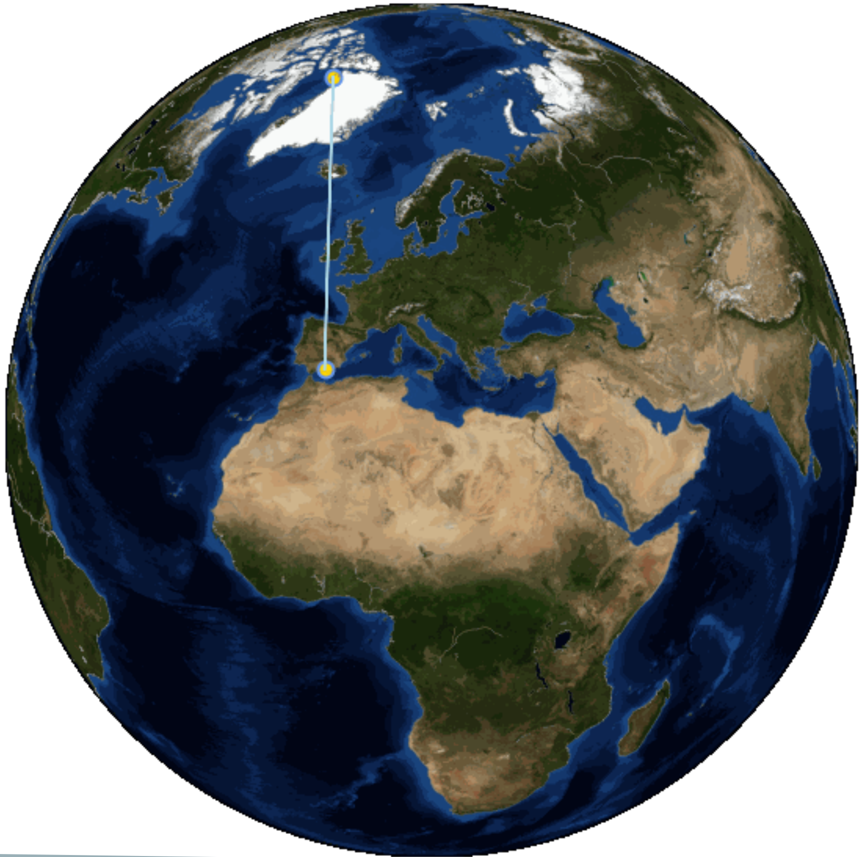
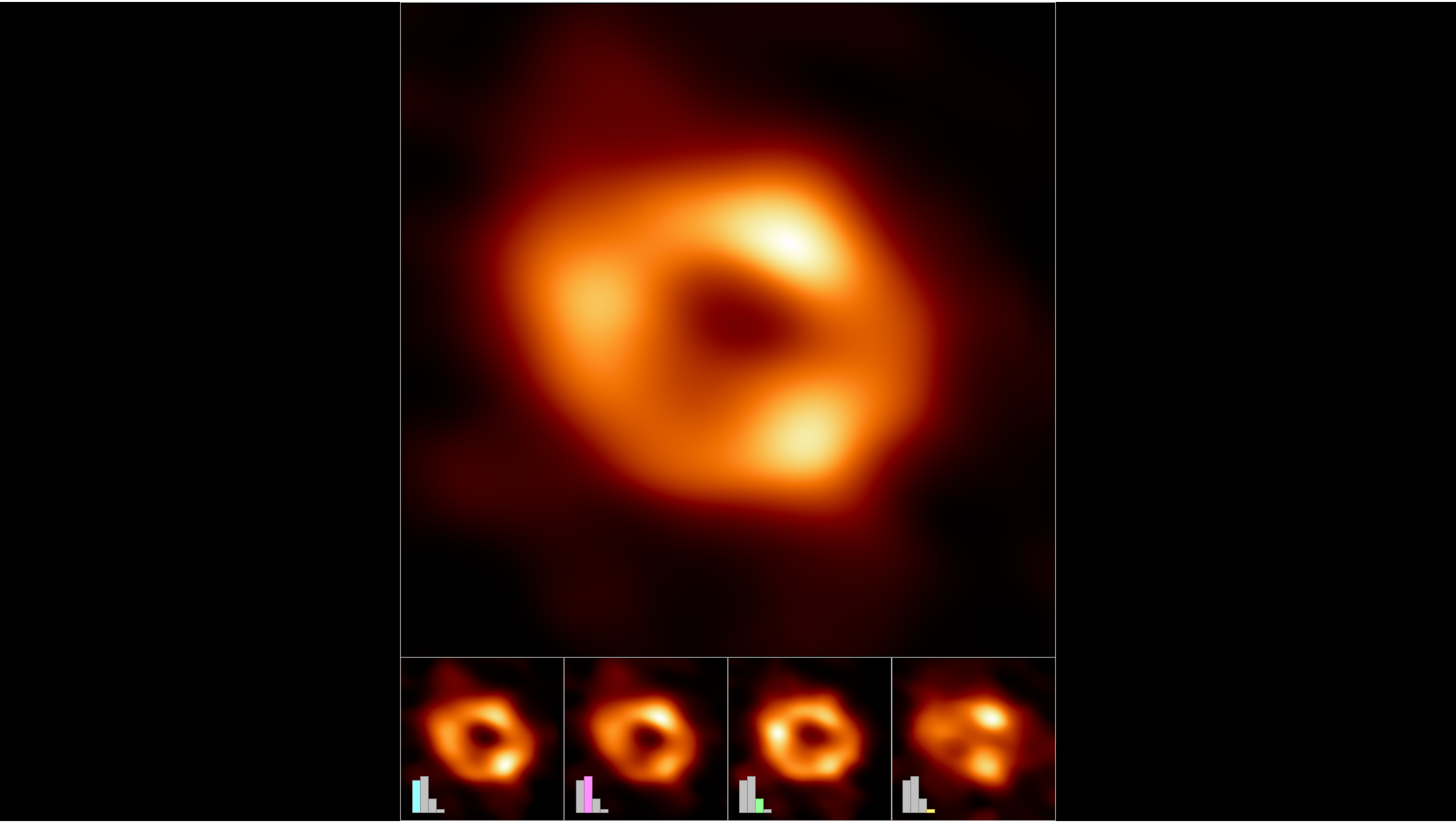


EHT imaging of the shadows of supermassive black holes.
III. VLBI with mm telescopes, calibration!

Today

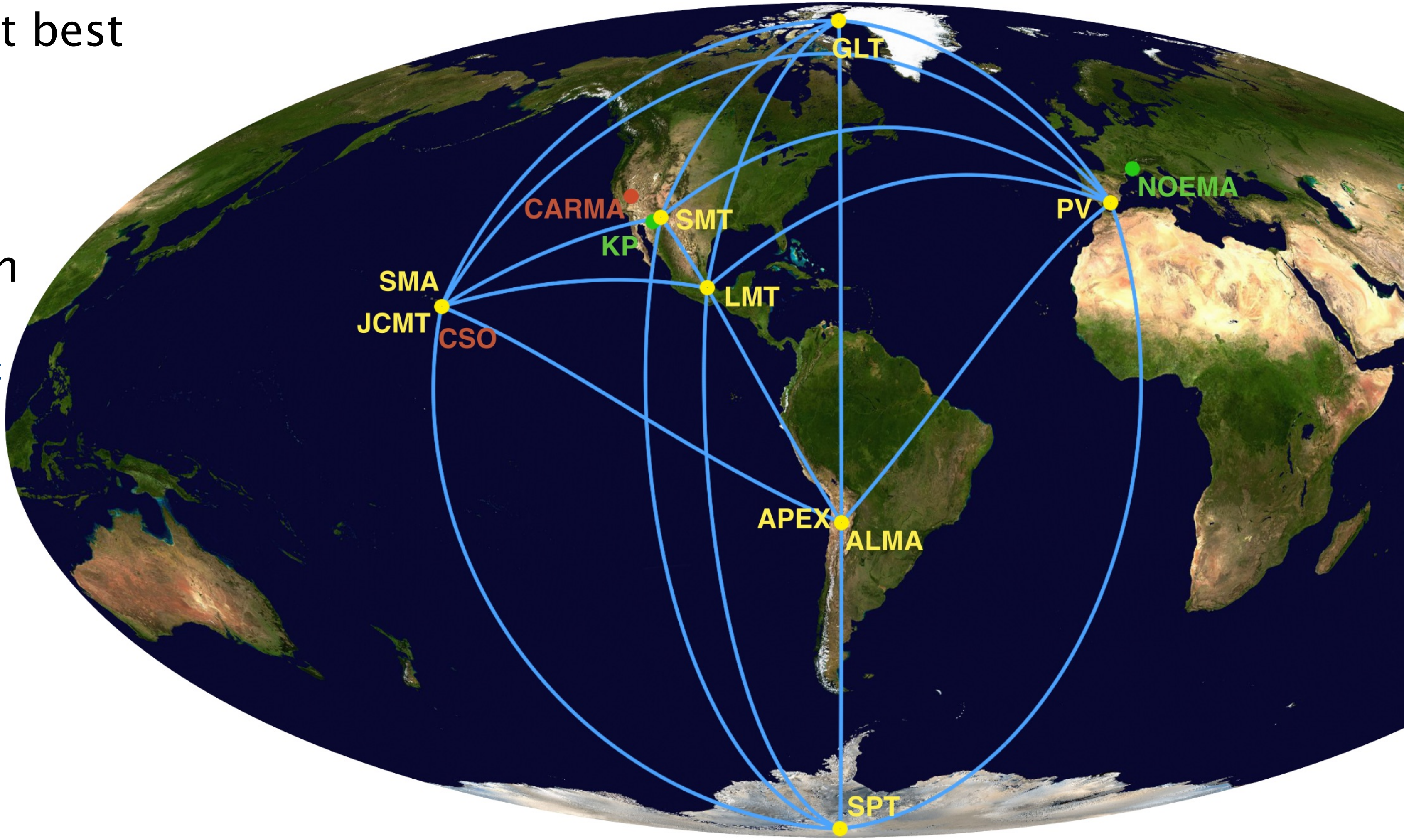
- Overall Objective
  - Introduce the practices of our trade: what it takes to measure the shadow of supermassive black holes
- Understanding your telescope
  - Locations
  - Dishes
  - Receivers
  - Digitisation
  - Transport
  - Correlation
  - Data products
  - Instrument calibration
  - On sky calibrators
  - Self calibration
  - Closure properties
  - Polarisation
- Last lecture:
  - Interpretation, calibrating gravity

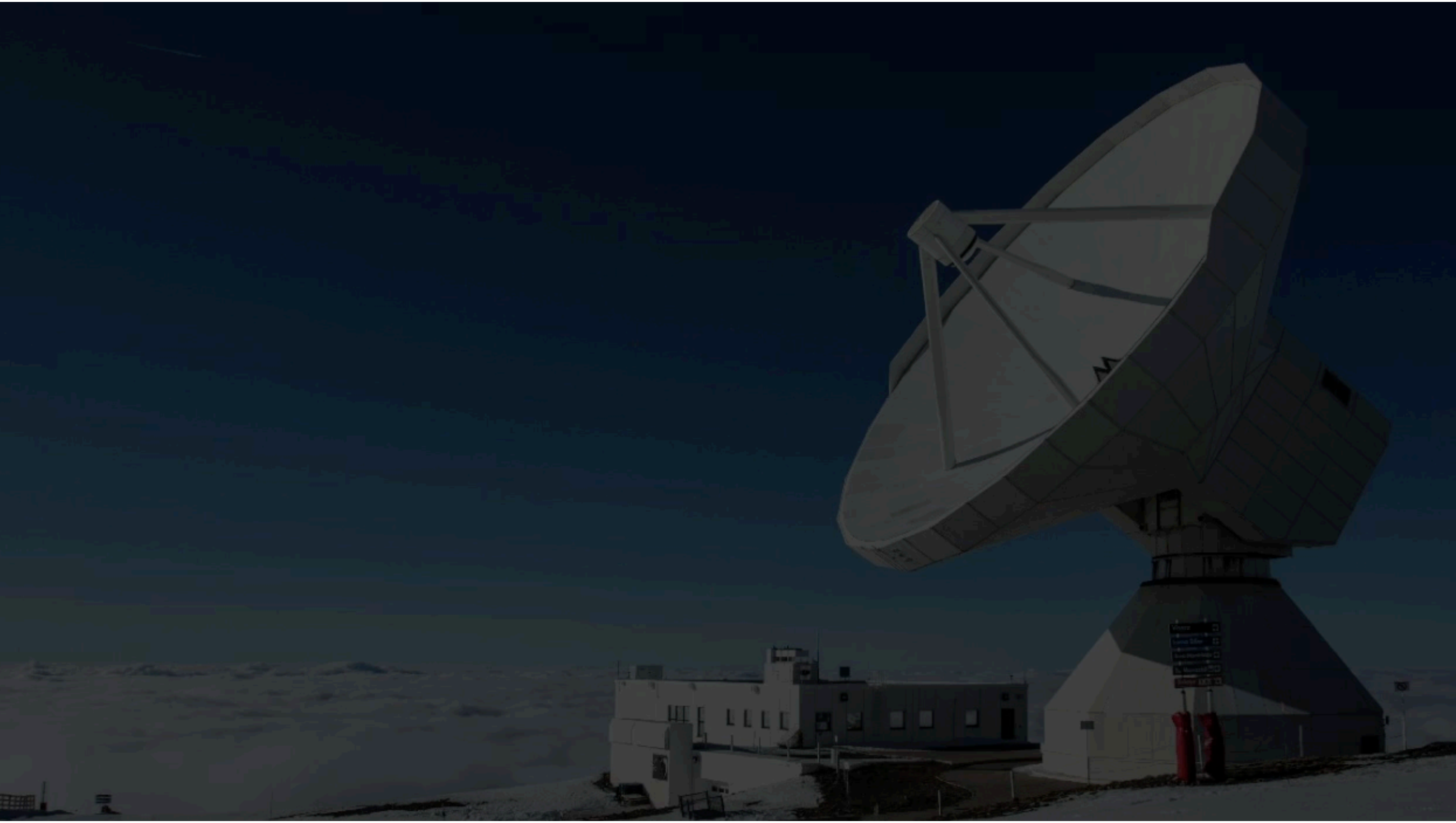




Event Horizon Telescope

- 8 telescopes at best sites
  - working together
  - Not positioned for this purpose
- Recording high bandwidth
  - 32 Giga bit per sec
  - 64 Gbps later
- Good weather
  - around the world

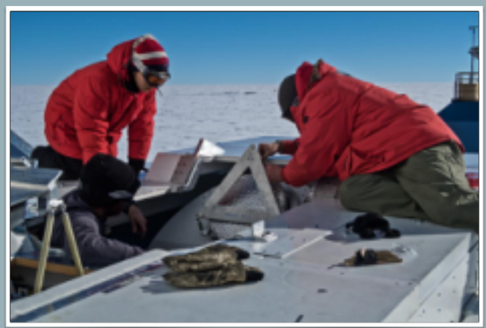




EHT members at telescopes



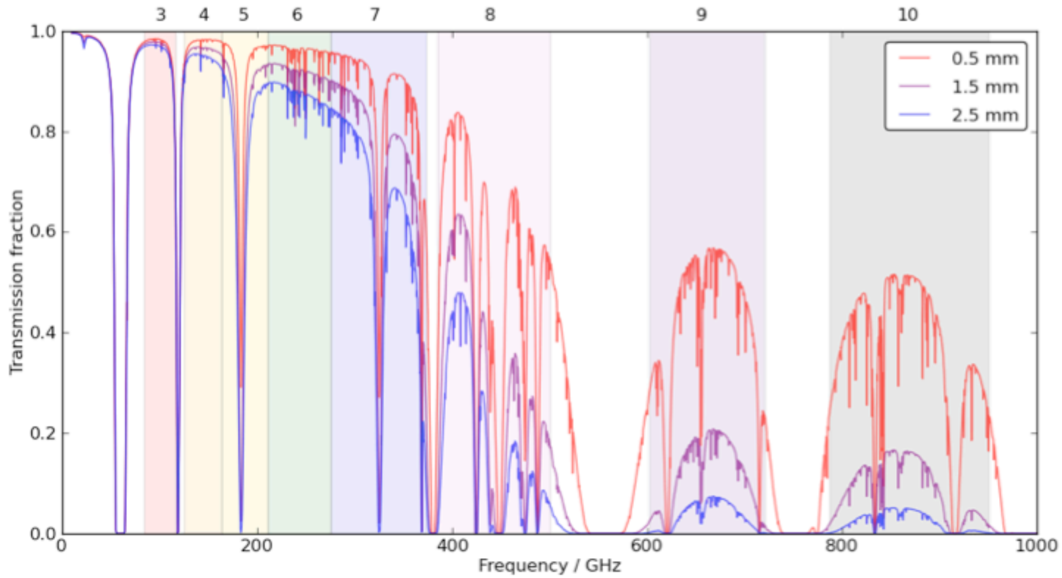




High sites, small dishes

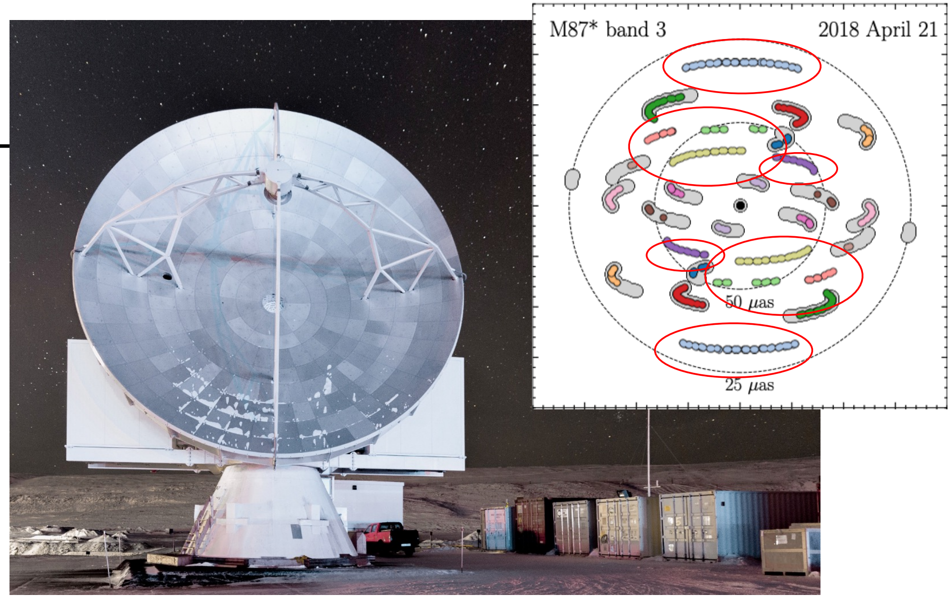
- Atmosphere blocks millimeter waves
  - Mostly pressure broadened water and ozone lines
  - Observing conditions characterised by water vapour column
    - halfway space…
- Other requirements:
  - Dishes need to be very precise
  - Receivers very small and delicate

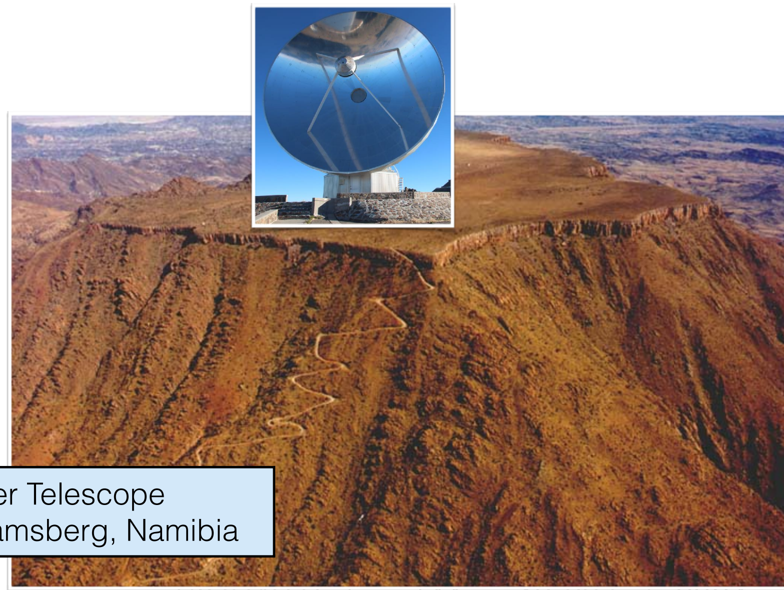
- In addition for EHT
  - Accurate (and expensive) maser clocks
  - We must observe close to horizon very regularly
  - Requires good weather
    - across the globe
  - Some of our telescopes are interferometers



More telescopes

- GLT added to 2018 campaign
  - NOEMA, Kitt Peak in 2021, 2022
  - 2025+ possibly more observatories:
    - Owens Valley, Haystack, South-Korea, Africa Millimeter Telescope (Dutch project!), Llama (Argentina)
  - ngEHT project to build dedicated telescopes
- Option to use higher frequency in 2024
  - 345 GHz: 1.5x better resolution
  - Time sampled images
- To space for more targets and photon rings

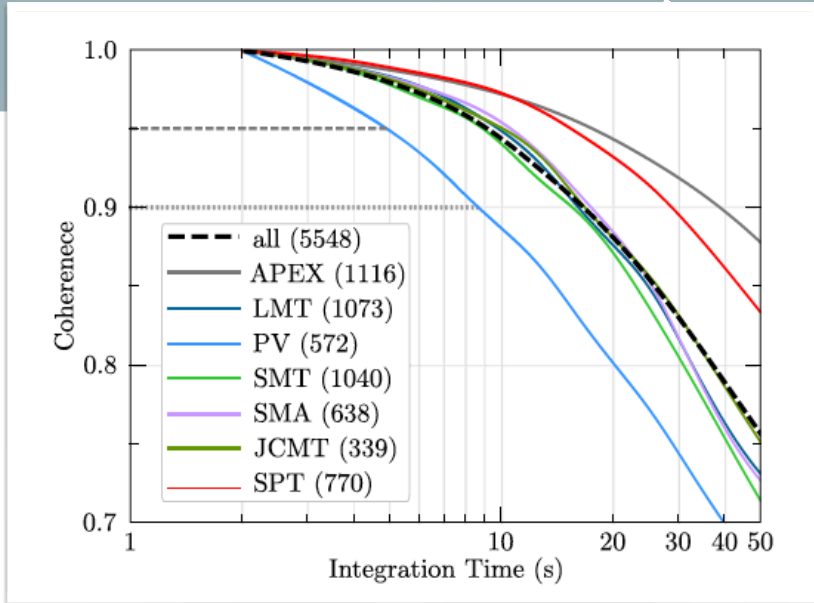




African Millimeter Telescope projected on Gamsberg, Namibia

Lucky in 2017

- Observe strategy
  - Central go/no-go decisions based on local weather
- Interleave BH target with other source
  - For calibration purposes (and science)
- Good weather
  - Still results in 10s coherence times
  - Every 10s the phases fluctuate to destroy signal



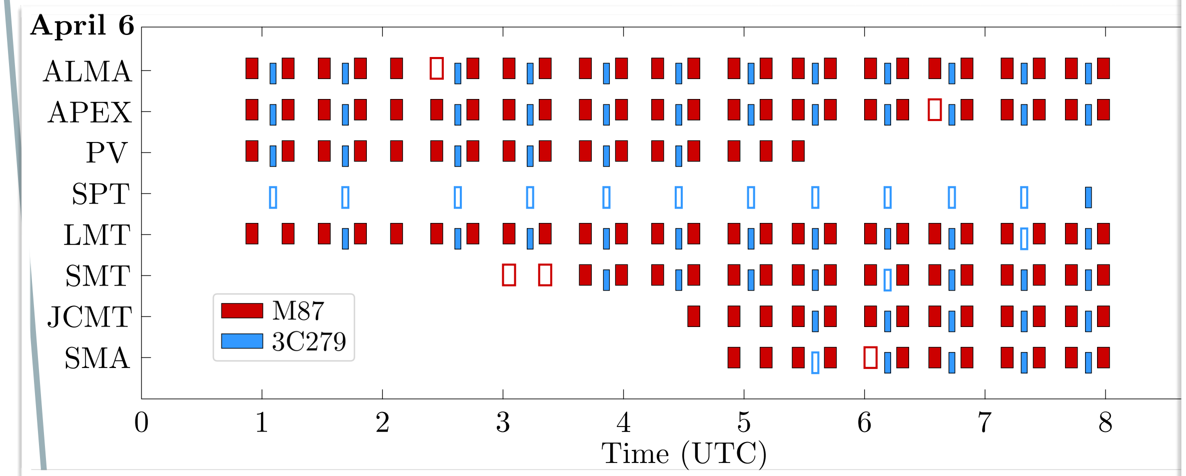
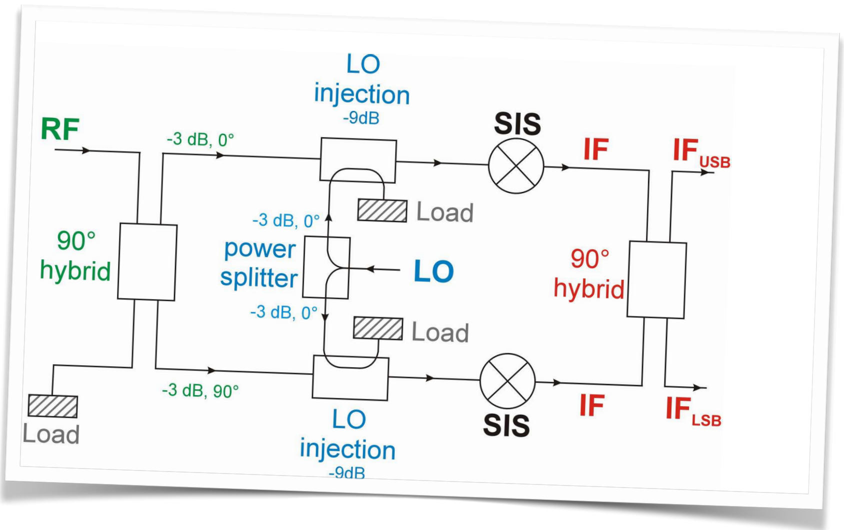


Table 1
Median Zenith Sky Opacities (1.3 mm) at EHT Sites during the 2017 April Observations

Station	Median Zenith $\tau_{1.3\ \mathrm{mm}}$				
	Apr 5	Apr 6	Apr 7	Apr 10	Apr 11
ALMA/APEX	0.06	0.04	0.05	0.03	0.06
SMA/JCMT	0.10	0.07	0.09	0.05	0.08
PV	0.18	0.13	0.14	0.10	0.15
LMT	0.13	0.16	0.21	0.26	0.24
SMT	0.21	0.28	0.23	0.19	0.16
SPT	0.04	0.05	0.07	0.08	0.07

All telescopes require same receiver bands

- Millimeter bands require mixing before amplification
  - Receivers and LO generation very delicate
  - Mixes down to frequency for digitiser
  - 4 x 4GHz output for each receiver



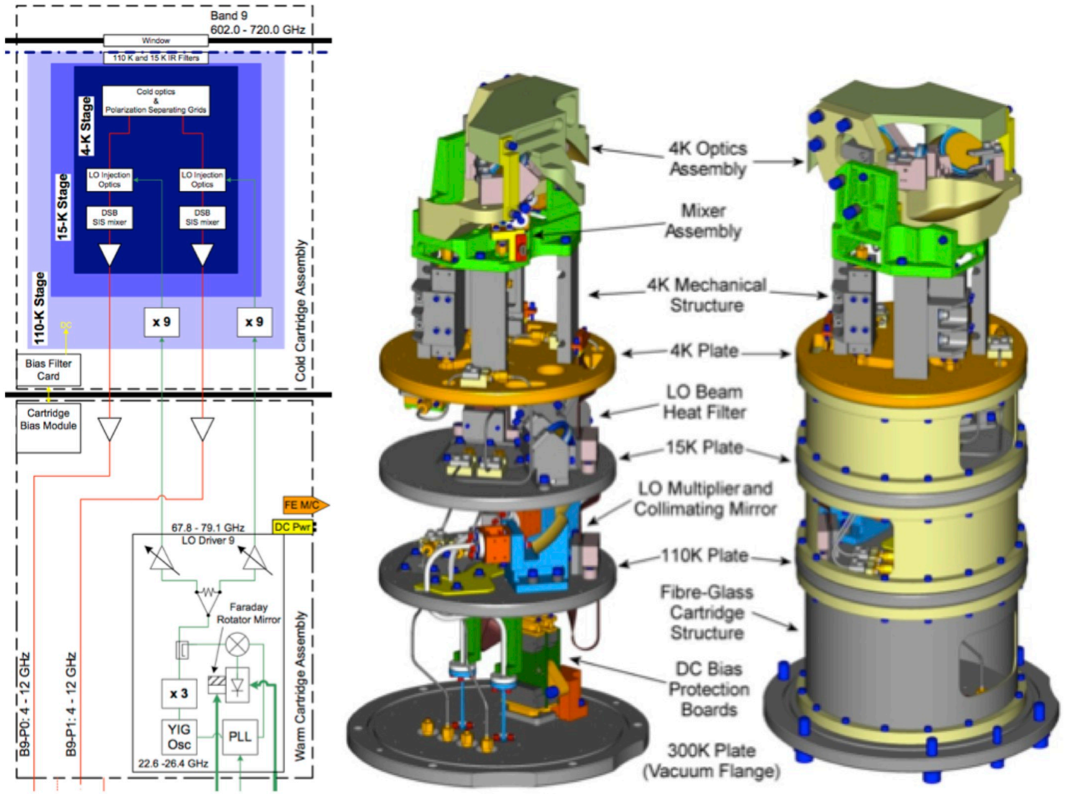
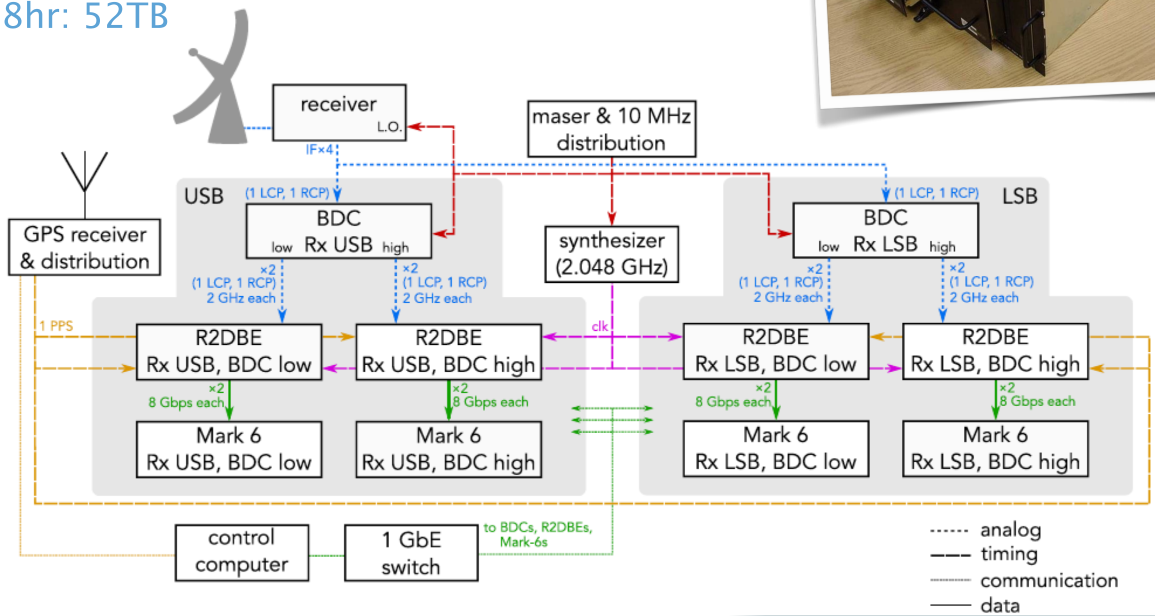


Figure 2.15: Block diagram of Band 9 cartridge (left) and a schematic image (right). Note that there are only two IF outputs, one from each polarization in this DSB receiver. The Band 9 receiver was built at SRON in the Netherlands.

- Often double for 2 circulair polarisations
- but linear at ALMA…

Then digitise…

- Must capture large BW for sensitivity
  - But only useful when same bandwidth at all telescopes
- Digitise before transport
  - Example:
    - 4GHz (at IF band)
    - Requires 8 GHz sampling (Nyquist)
    - Requires 16 Gbps (2 bit sampling!)
    - In 8hr: 52TB



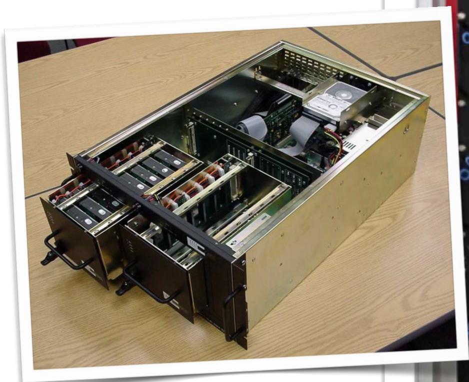
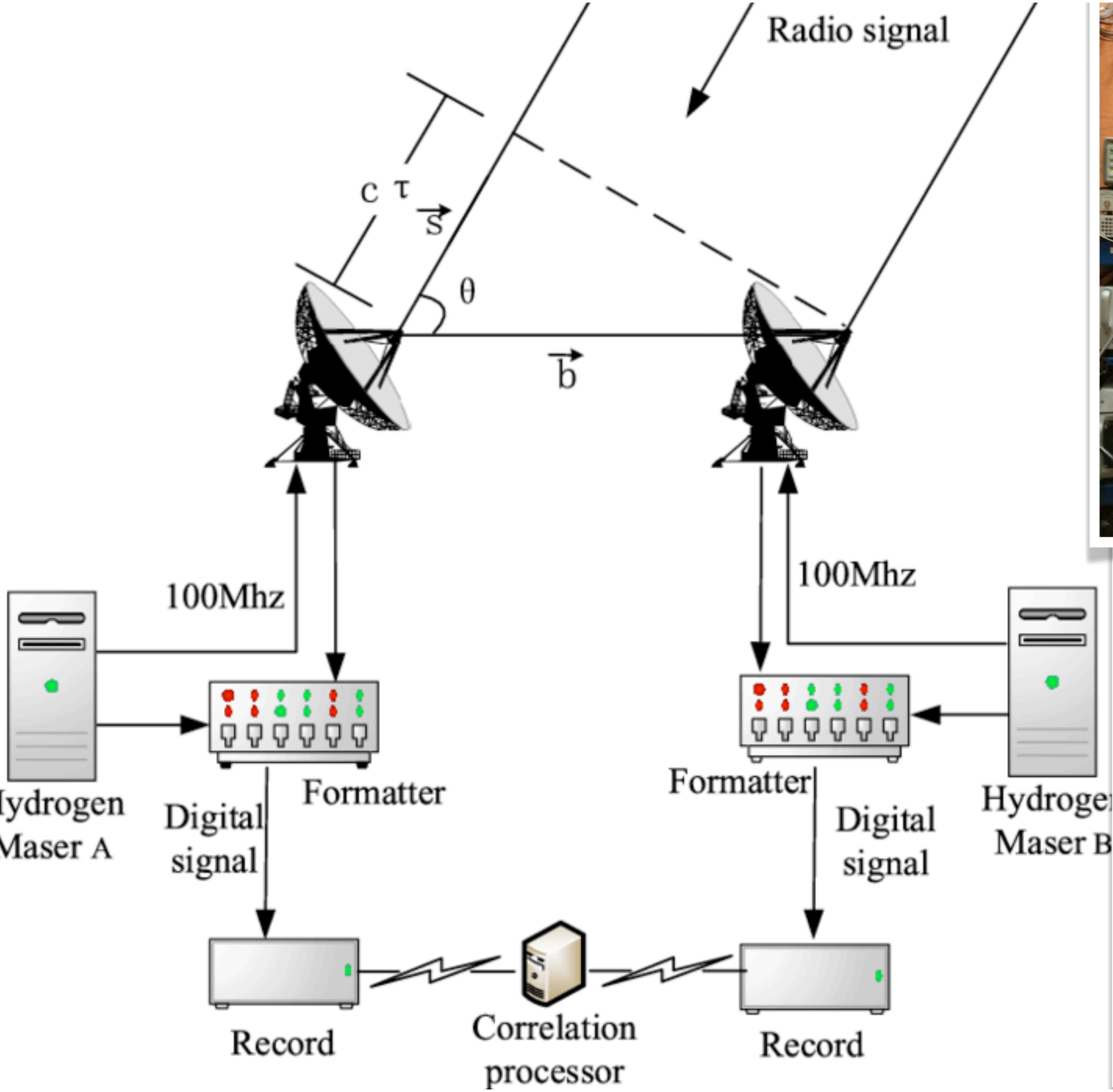


Figure 8. EHT digital VLBI backend as installed at the Institut de Radioastronomie Millimétrique (IRAM) PV 30 m telescope in Spain. The


Radio signal
c τ
$\vec{s}$
θ
$\vec{b}$
100Mhz
100Mhz
ydrogen
aser A
Digital
signal
Formatter
Formatter
Digital
signal
Hydroge
Maser B
Record
Correlation
processor
Record


acer

Correlator

- Correlators must deal with data from telescopes
  - Must keep up with data rate
- Deliver user product
  - May determine sensitivity of interferometer
  - Spectral resolution
  - Time resolution
  - And resulting Field of view

telescope streams

N telescopes
N beams
N subbands
1-2 polarisations
2xBW sample
X bits/sample

correlator

$\otimes$

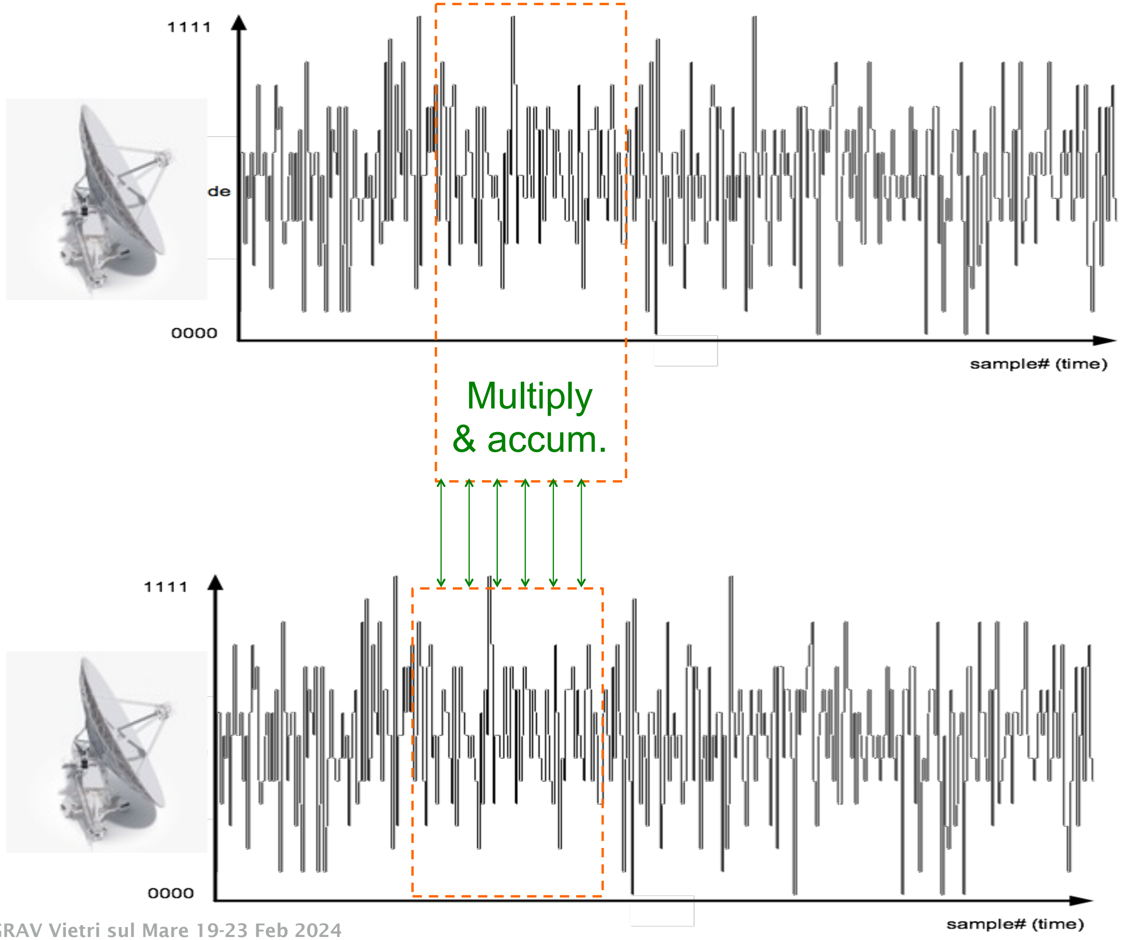
astronomical product

N fields
T/dt integrations
N(N-1) baselines
N subbands/filters
N frequency points
1-4 polarisations
pulsar bins
Complex visibilities (+weight)
Float representation

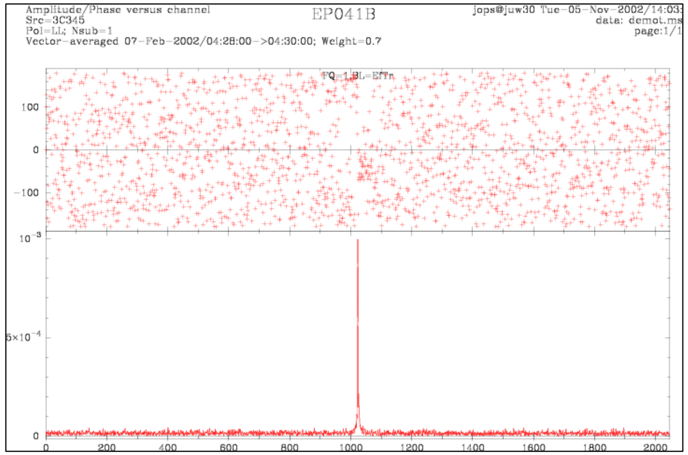
Correlator principle

Continuum source

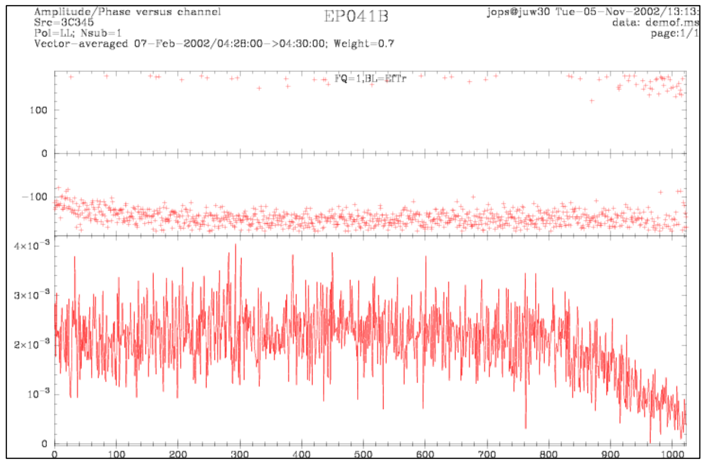
- Put in range of ‘test’ delays, correlate, accumulate
- Results in delay spectrum, or FT to frequency



Lag domain



Frequency



Stringent constrains on geometry

- Same errors affect phase rate and delay
  - 1° of phase over 16 MHz = 173ps (ps = 10^{-12}s)
  - To keep both clocks stable over 10min and 500 MHz ≈ 1:10^{15}
    - Expensive maser clocks to make atmosphere limiting factor
  - And 16ps ≈ 5mm required accuracy over 1000km
- The natural fringe rate is high for long baselines

$$\phi_{LO} = \omega_{LO}\hat{\tau}_g = \omega_{LO}\frac{d\tau_g}{dt}t = \omega_{LO}\frac{d\vec{B}\cdot\vec{s}/c}{dt}t$$

  - This comes out at 100 kHz for VLBI
  - Small errors in model leave mHz fringe rate
    - And more at high frequency
    - Example small few mas position error

Item	Approx Max.	Time scale
Zero order geometry.	6000 km	1 day
Nutation	~ 20"	< 18.6 yr
Precession	~ 0.5 arcmin/yr	years
Annual aberration.	20"	1 year
Retarded baseline.	20 m	1 day
Gravitational delay.	4 mas @ 90° from sun	1 year
Tectonic motion.	10 cm/yr	years
Solid Earth Tide	50 cm	12 hr
Pole Tide	2 cm	~1 yr
Ocean Loading	2 cm	12 hr
Atmospheric Loading	2 cm	weeks
Post-glacial Rebound	several mm/yr	years
Polar motion	0.5 arcsec	~ 1.2 years
UT1 (Earth rotation)	Several mas	Various
Ionosphere	~ 2 m at 2 GHz	All
Dry Troposphere	2.3 m at zenith	hours to days
Wet Troposphere	0 – 30 cm at zenith	All
Antenna structure	<10 m. 1cm thermal	—
Parallactic angle	0.5 turn	hours
Station clocks	few microsec	hours
Source structure	5 cm	years

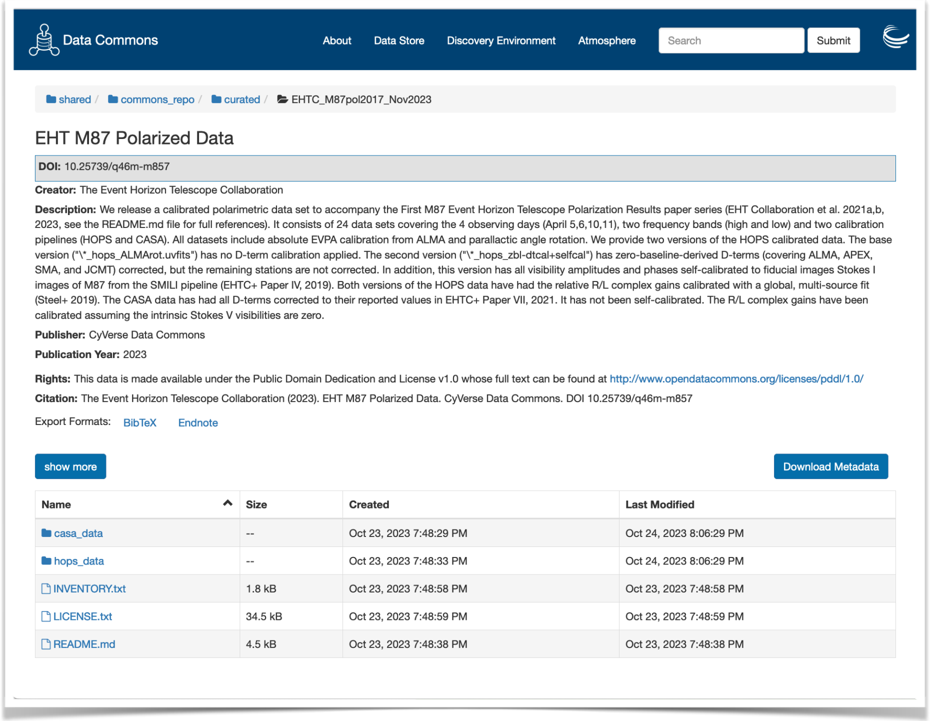
Adapted from Sovers, Fanselow, and Jacobs Reviews of Modern Physics, Oct 1998

Output data

- Usually presented to astronomer as $V_{ij}(\nu,t)$
  - Cross (and auto) correlation spectra
  - Sampled at visibility dump time, integration time
    - Can be quite long 10 - 30s for short baselines

- Need a lot of overhead information to be used for calibration and processing
  - IF labels, and polarizations
  - Time tags
  - frequency information, edge and increment
  - Antenna indexes
  - u,v,w coordinates
  - Telescope pointing and source labeling
  - Maybe other details of correlator model

- Format for transport: FITS
  - But calibration software depends critically on content…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EHT M87 Polarized Data

DOI: 10.25739/q46m-m857

Creator: The Event Horizon Telescope Collaboration

Description: We release a calibrated polarimetric data set to accompany the First M87 Event Horizon Telescope Polarization Results paper series (EHT Collaboration et al. 2021a,b, 2023, see the README.md file for full references). It consists of 24 data sets covering the 4 observing days (April 5,6,10,11), two frequency bands (high and low) and two calibration pipelines (HOPS and CASA). All datasets include absolute EVPA calibration from ALMA and parallactic angle rotation. We provide two versions of the HOPS calibrated data. The base version ("*_hops_ALMArot.uvfits") has no D-term calibration applied. The second version ("*_hops_zbl-dtcal+selfcal") has zero-baseline-derived D-terms (covering ALMA, APEX, SMA, and JCMT) corrected, but the remaining stations are not corrected. In addition, this version has all visibility amplitudes and phases self-calibrated to fiducial images Stokes I images of M87 from the SMILI pipeline (EHTC+ Paper IV, 2019). Both versions of the HOPS data have had the relative R/L complex gains calibrated with a global, multi-source fit (Steel+ 2019). The CASA data has had all D-terms corrected to their reported values in EHTC+ Paper VII, 2021. It has not been self-calibrated. The R/L complex gains have been calibrated assuming the intrinsic Stokes V visibilities are zero.

Publisher: CyVerse Data Commons

Publication Year: 2023

Rights: This data is made available under the Public Domain Dedication and License v1.0 whose full text can be found at http://www.opendatacommons.org/licenses/pddl/1.0/

Citation: The Event Horizon Telescope Collaboration (2023). EHT M87 Polarized Data. CyVerse Data Commons. DOI 10.25739/q46m-m857

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Name	Size	Created	Last Modified
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hops_data	--	Oct 23, 2023 7:48:33 PM	Oct 24, 2023 8:06:29 PM
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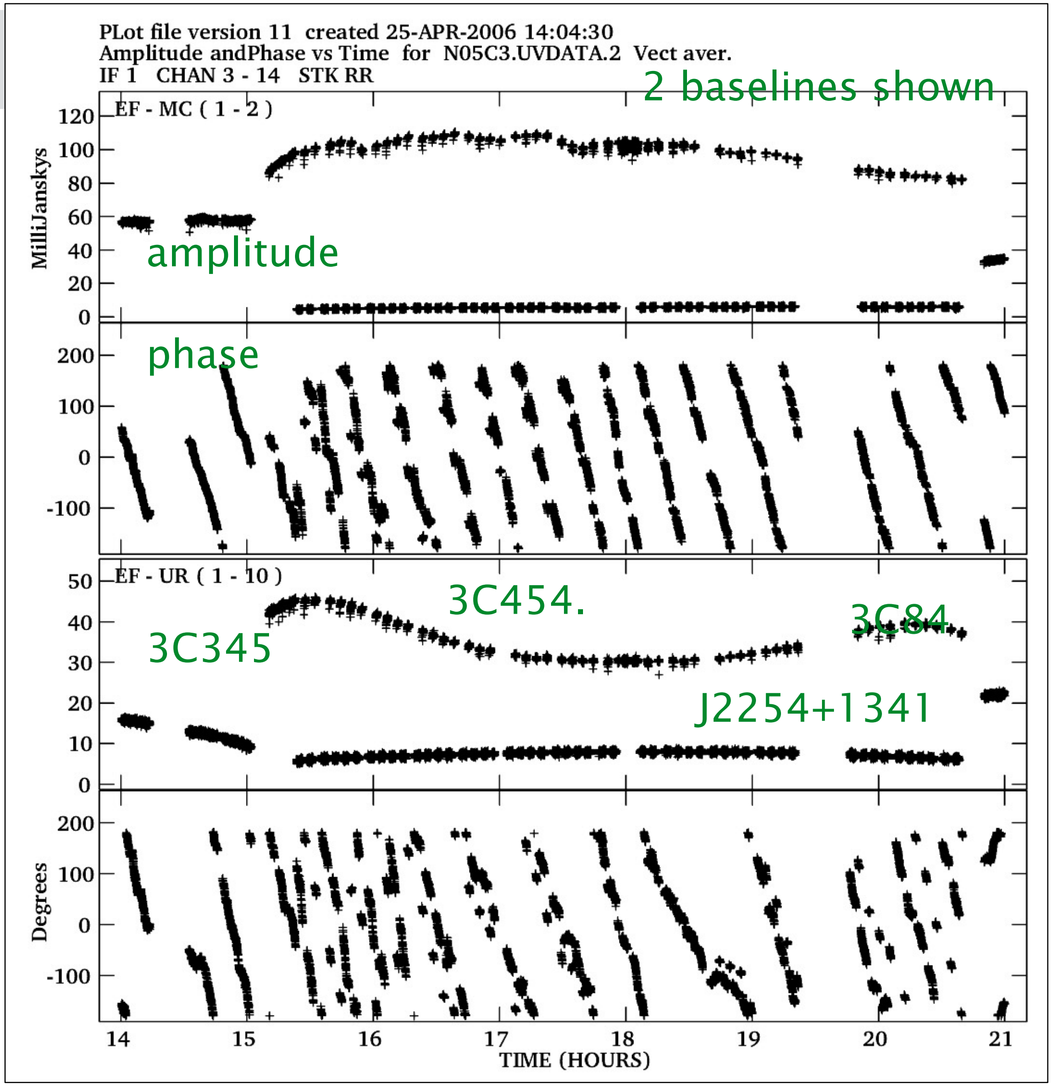
LICENSE.txt	34.5 kB	Oct 23, 2023 7:48:59 PM	Oct 23, 2023 7:48:59 PM
README.md	4.5 kB	Oct 23, 2023 7:48:38 PM	Oct 23, 2023 7:48:38 PM

Calibration

- Three levels of calibration, and editing also important

- A priori and built in:
  - Pointing, antenna gain, system temperatures
  - Antenna positions, time, frequency
  - Geometrical model, delay, uv coordinates
- Cross calibration
  - Known sources, bright, simple structure, accurate position
  - Often making assumptions on stability instrument, sky
  - Sometimes done by observatory, sometimes astronomer
    - Can be critical for the succes of the experiment
- Self-calibration
  - Iterative process done by astronomer
  - Let's say it is 'heuristic'…



Antenna based calibration

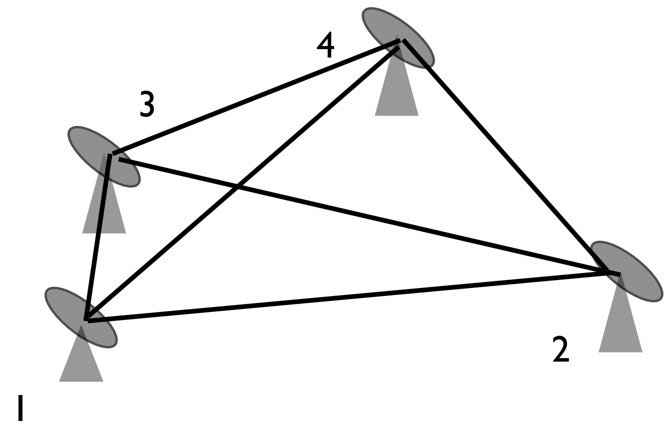
- Want to measure the visibility produced by the sky intensity
- Practice is signals corrupted by instrumental and propagation effects

$$\tilde{V}_{ij}(t) = G_{ij}V_{ij}(t) + \varepsilon_{ij} + \eta_{ij}$$

- Assume G being dominated by antenna based effects:

$$G_{ij} = g_i(t)\, g_j^*(t) = a_i(t) a_j(t)\, e^{i(\theta_i(t) - \theta_j(t))}$$

  - There should be no baseline-based error for robust correlators
- Use known source to solve for complex antenna gains
    - Intuitive to talk about antenna amplitude and phase
  - Point source (unresolved) with known (or constant) flux
  - With N antennas need to solve for 2N-1 unknowns
    - And we have N(N-1) measurements (complex)
    - S/N considerations and coherence time



For N=4, 6 baselines responses are measured: r_{12}, r_{13}, r_{14}, r_{23}, r_{24}, r_{34}

Normal practices include iterative self-calibration

Closure quantities

- Important property when effects are antenna based $V_{ij} = g_i \cdot g_j^* \; \hat{V}_{ij}$
  - Both instrumental and atmospheric phases:

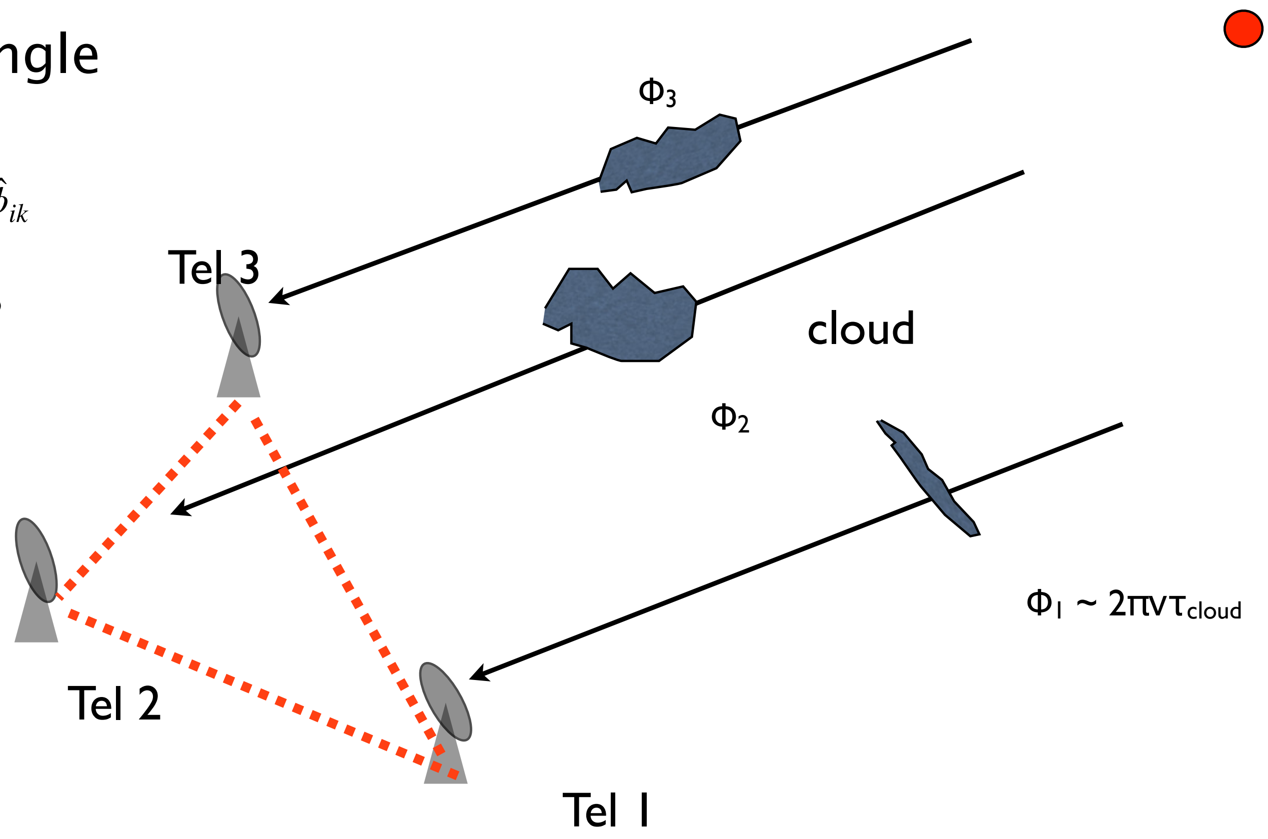
$$\phi_{ij} = \hat{\phi}_{ij} + \eta_i - \eta_j$$

- Can form closure phase on triangle
  - All antenna-based errors drop out

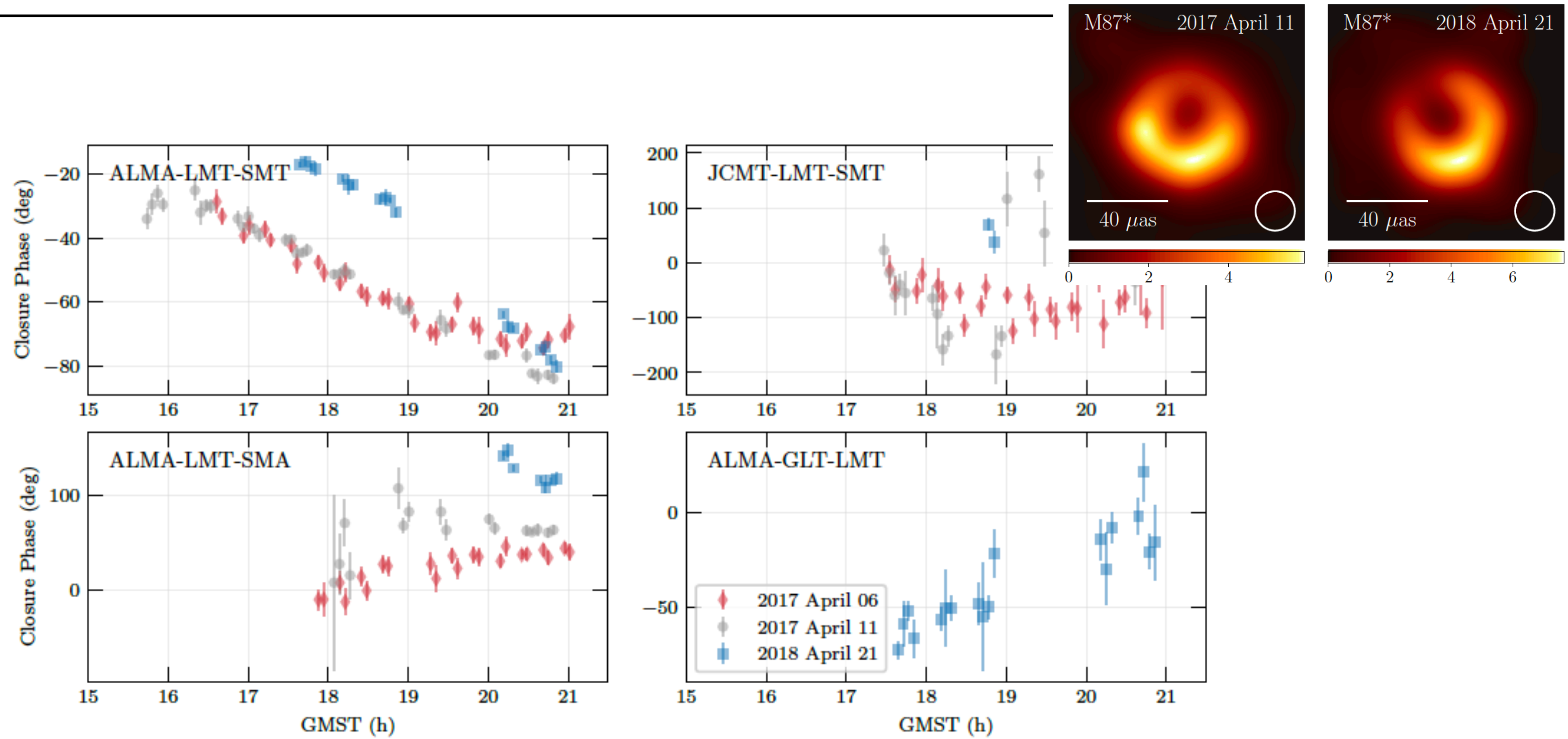
$$C_{ijk} = \phi_{ij} + \phi_{jk} + \phi_{ik} = \hat{\phi}_{ij} + \hat{\phi}_{jk} + \hat{\phi}_{ik}$$

- Similar for amplitude and 4 tels

- Important constraint for
  - self-calibration
  - hybrid mapping
  - RML methods can work directly with this
    - But require pos and total flux to be fixed
  - Data quality control

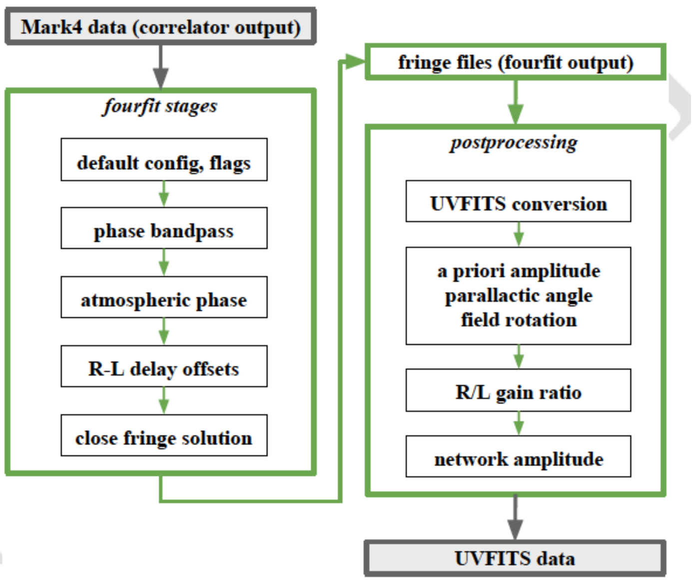


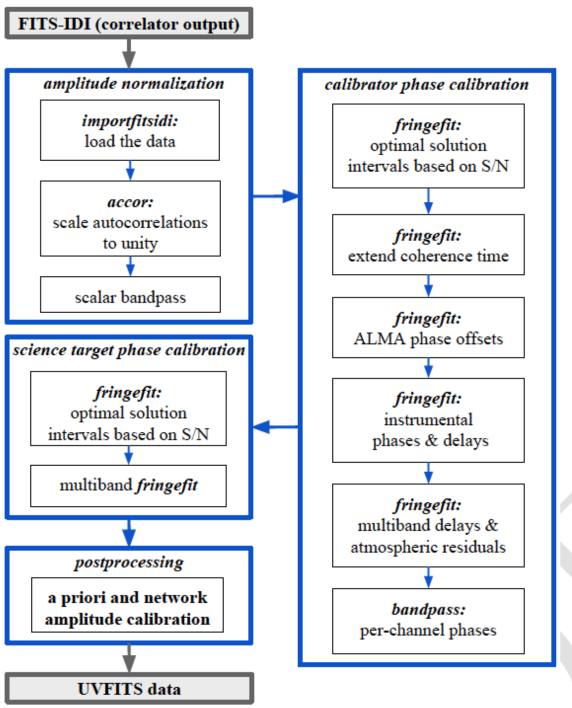
Example comparison 2017 vs 2018

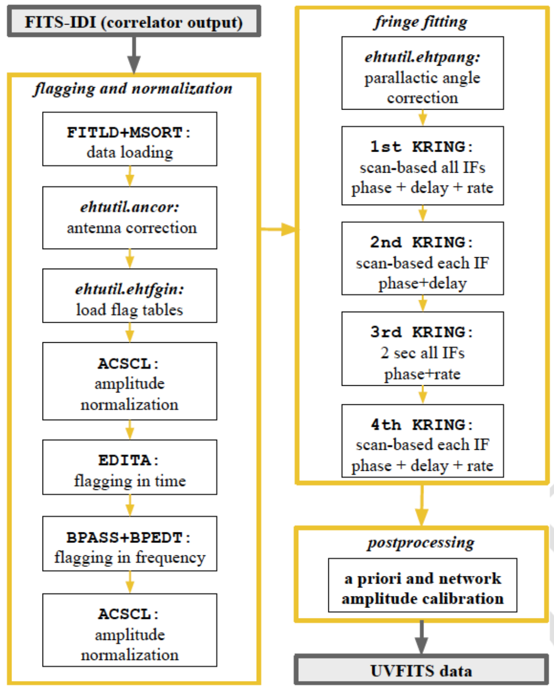


Robust calibration

- Comparing old an new software
  - Some non-standard processing
  - Amplitudes from overlapping uv-tracks
  - Constrained estimates of zero-spacing
- Several engineering releases

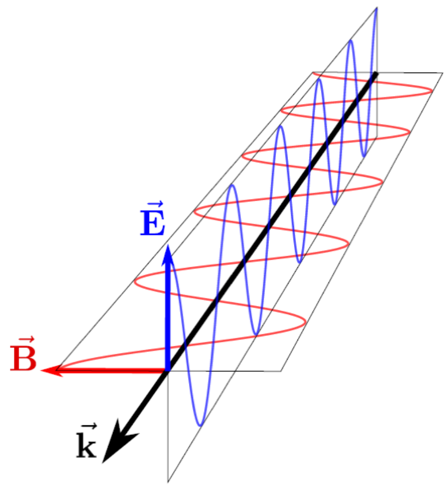






- Flagging bad data is a major effort in this process
- *"Bad data is worse than no data"*

Polarization



- EM waves (including radio) have E- and B components
- In radio interferometry measure two orthogonal E-field components
  - circular (RL) or linear (XY)
  - Linear polarization: E_x and E_y are unequal
  - Circular polarization: $\vec{E}$ rotates
  - Combined: $\vec{E}$ traces an ellipse
- Form Stokes I,Q,U,V from cross hands
- For example in circular basis:

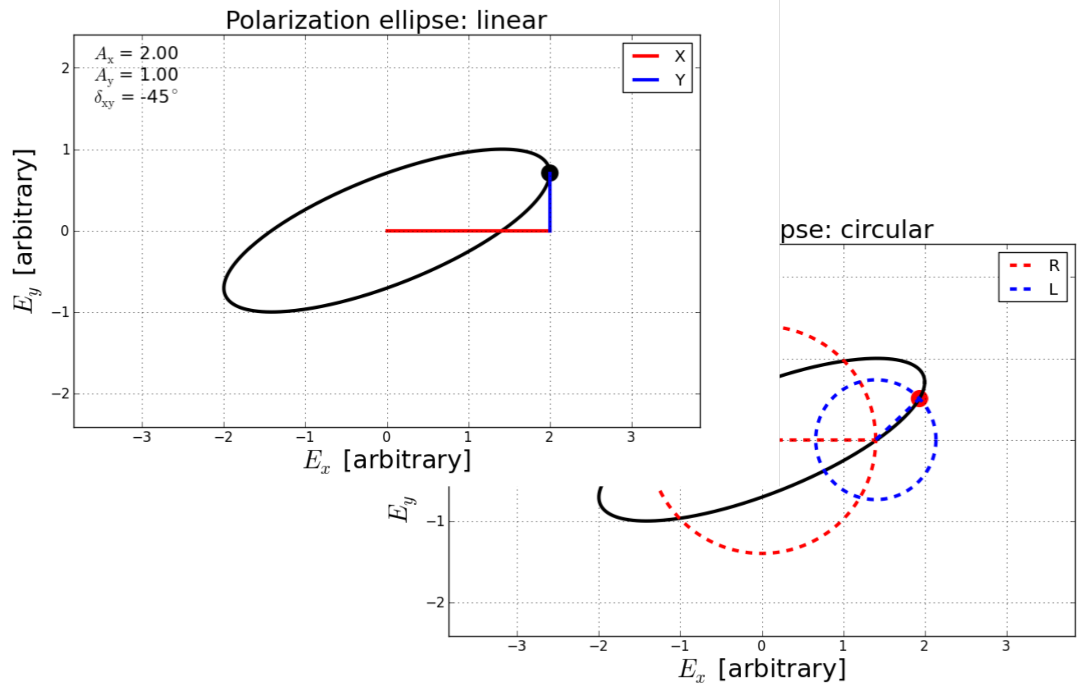
$$I = \langle E_r E_r^* \rangle + \langle E_l E_l^* \rangle = \langle A_r^2 \rangle + \langle A_l^2 \rangle$$

$$Q = \langle E_r E_l^* \rangle - \langle E_l E_r^* \rangle = \left\langle 2A_r A_l \cos(\delta_{rl}) \right\rangle$$

$$U = -i\langle E_r E_l^* \rangle + i\langle E_l E_r^* \rangle = \langle -2A_r A_l \sin(\delta_{rl}) \rangle$$

$$V = \langle E_r E_r^* \rangle - \langle E_l E_l^* \rangle = \langle A_r^2 \rangle - \langle A_l^2 \rangle$$

-



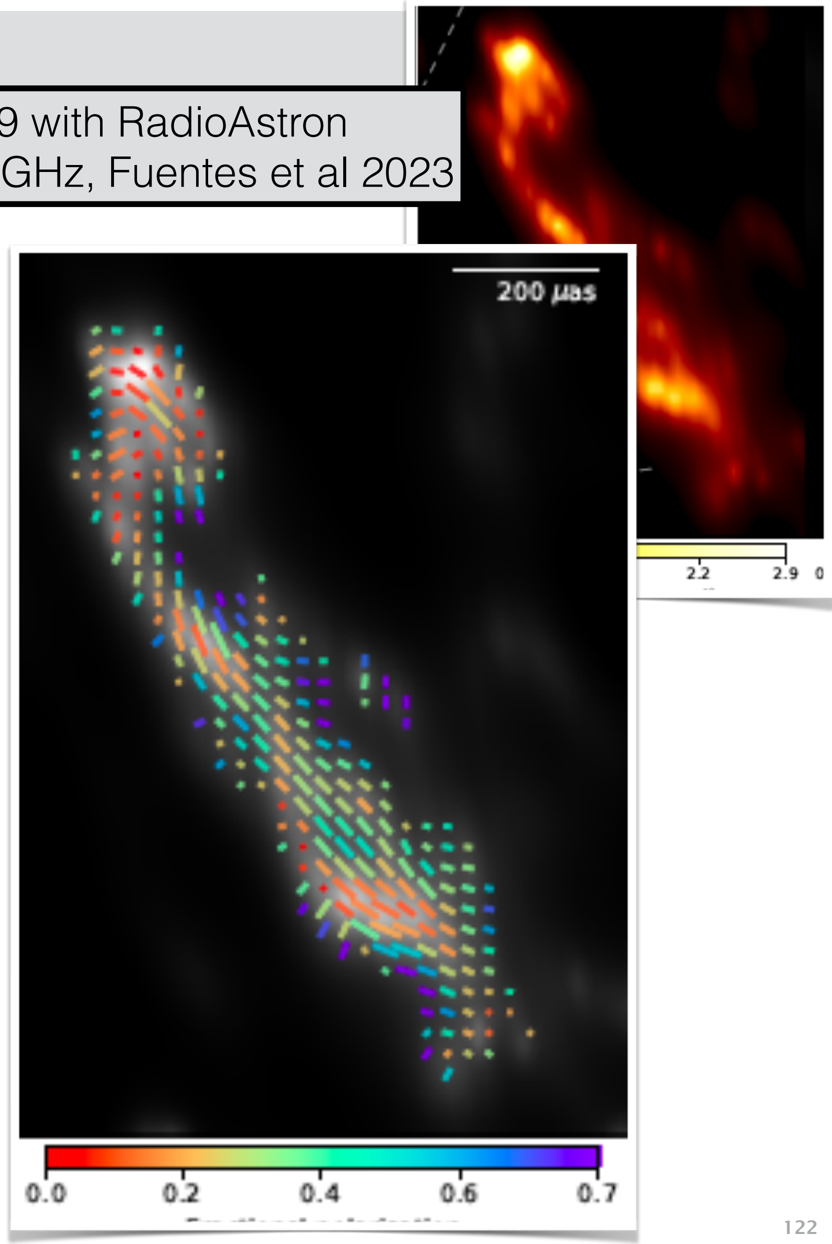
More Stokes

- Stokes I measures total intensity
- Stokes Q and U measure linear polarization
    - Fractional linear polarization: $p = \sqrt{Q^2 + U^2}/I \leq 1$
- Stokes V measures circular polarization
    - Fractional circular polarization: $v = \|V\|/I \leq 1$
- Degree of polarization:

$$P = \sqrt{Q^2 + U^2 + V^2}/I$$

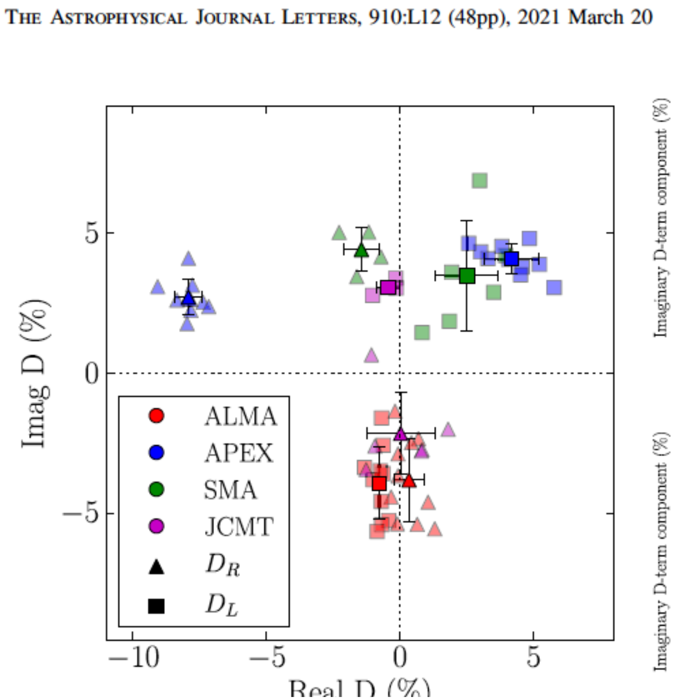
- Very relevant for AGN studies
    - Synchrotron intrinsically polarised
    - Jet collimination
    - Jet launching

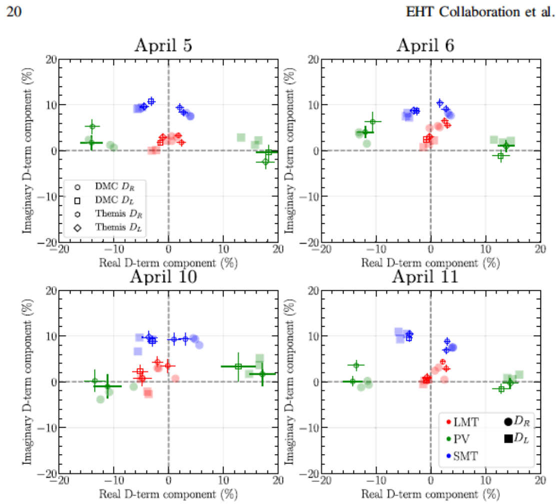
3C279 with RadioAstron at 22 GHz, Fuentes et al 2023



Polarisation in the EHT

- Particularly challenging
- ALMA has linear feeds, most other telescopes circular
  - Current solution: calculate from correlator output
  - Using ALMA internal calibration
- Other antennas have various mount configurations
  - Rotating their polarised beams differently on the sky
  - Occasionally even one channel may be missing





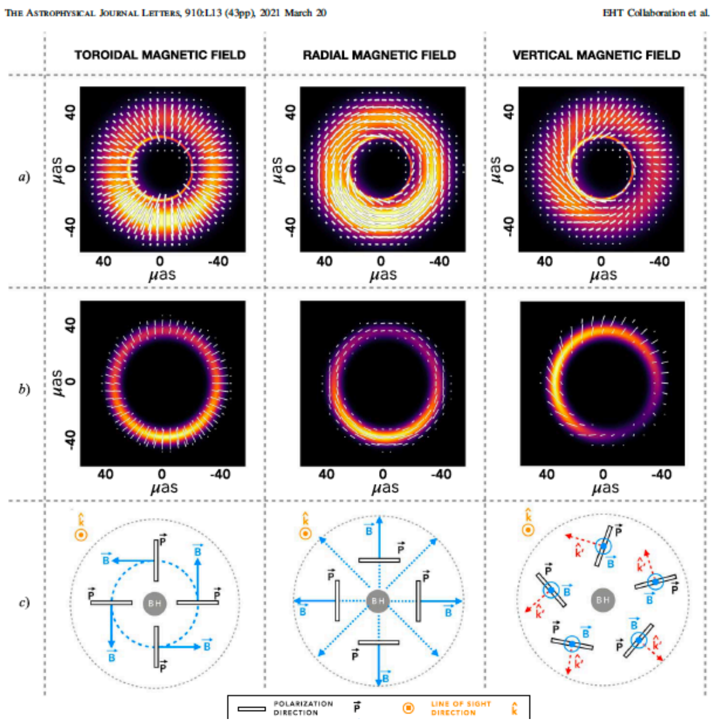
- Polarisation calibration
  - Requires unpolarised sources
  - and/or source of known polarisation
  - Developed method of self-polarisation calibration
    - Using polarimetric closure properties

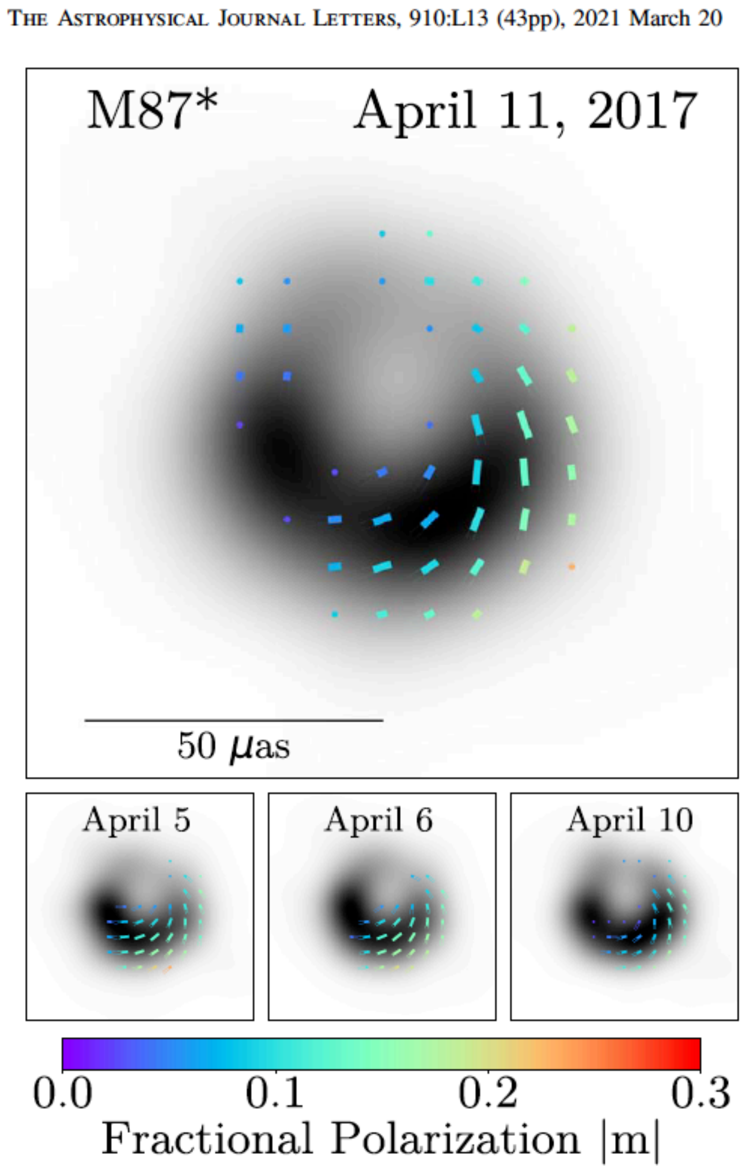
EHT results

- Published 2y after Stokes I…
- Significantly polarised
  - Mostly azimuthal
  - With some significant evolution

- A simple model has:
  - $n_e \sim 10^{4-7}$ cm^{-3}
  - B = 1 - 30 G
  - $T_e = 10^{10-11}$ K

- Polodial/Vertical organised
- MAD models favoured





Event Horizon Telescope

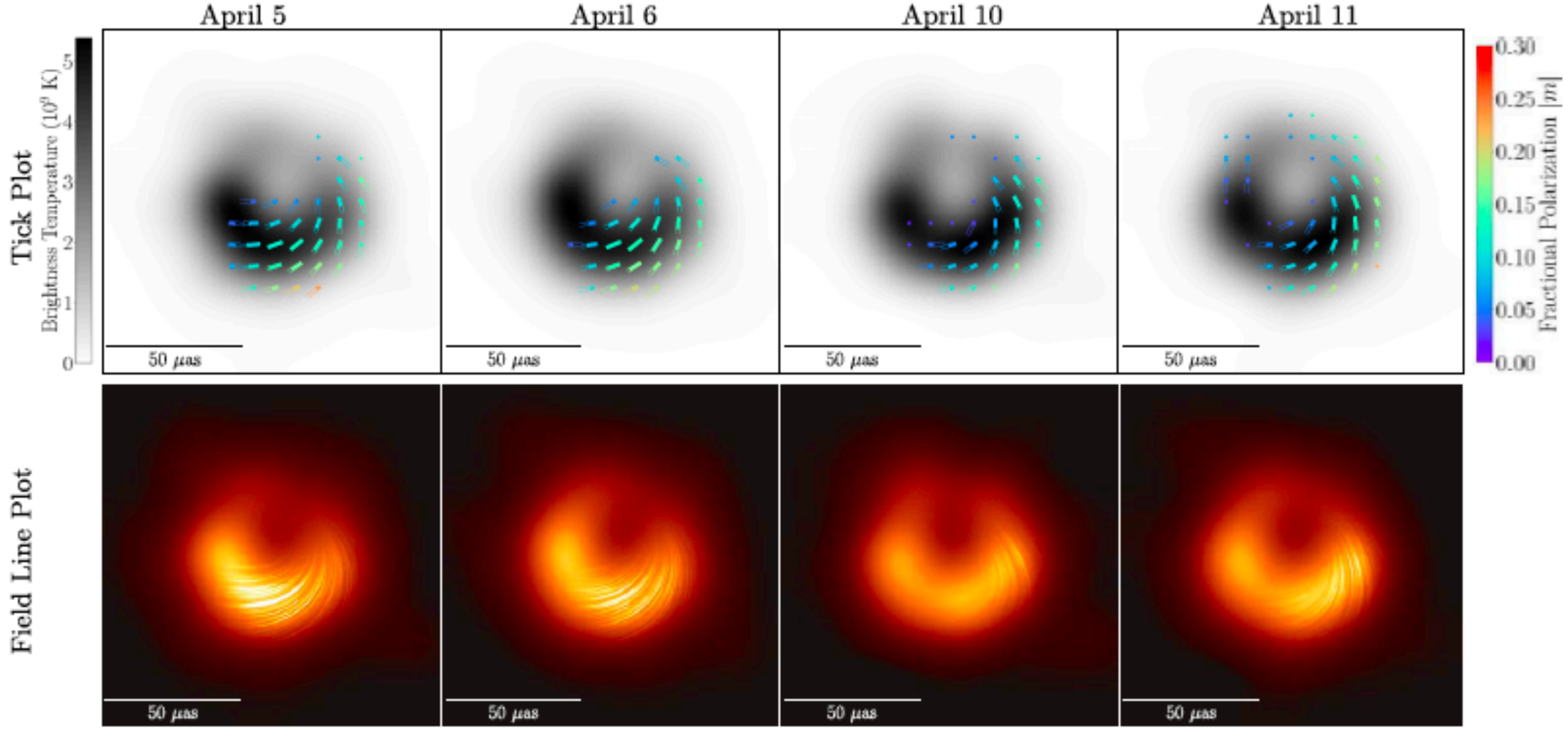
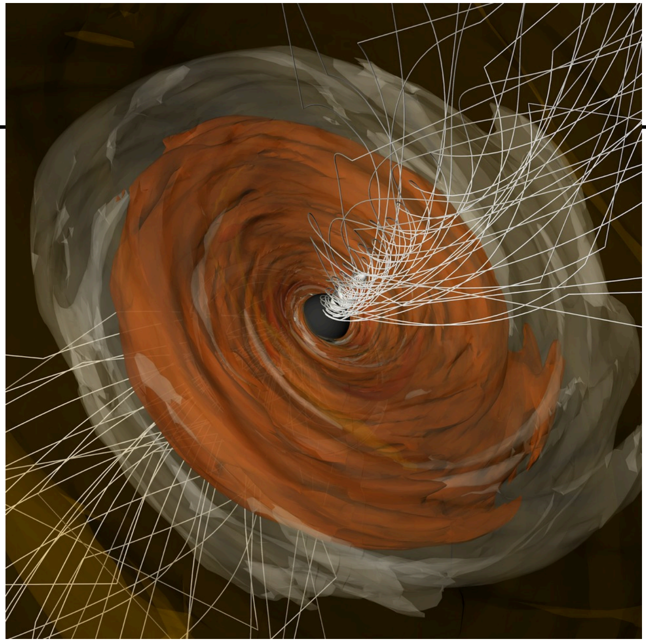


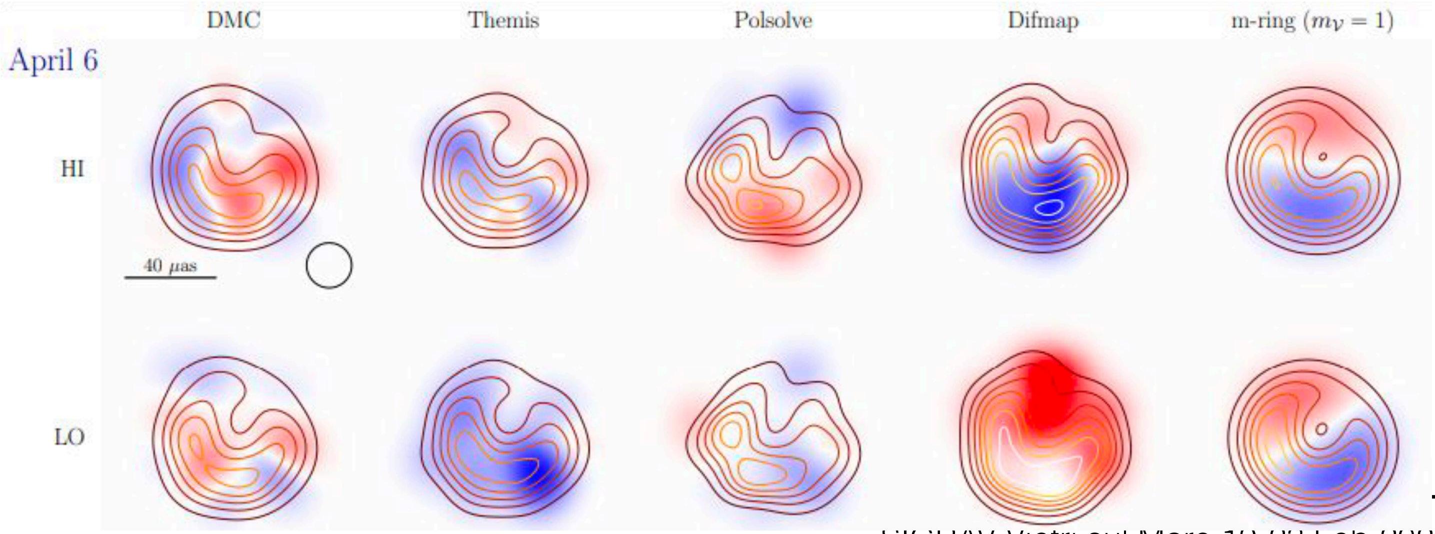
Figure 7. Fiducial M87 average images produced by averaging results from our five reconstruction methods (see Figure 6). Method-average images for all four M87 observation days are shown, from left to right. These images show the low-band results; for a comparison between these images and the high-band results, see Figure 28 in Appendix I. We employ here two visualization schemes (top and bottom rows) to display our four method-average images. The images are all displayed with a field of view of 120 μas. Top row: total intensity, polarization fraction, and EVPA are plotted in the same manner as in Figure 6. Bottom row: polarization "field lines" plotted atop an underlying total intensity image. Treating the linear polarization as a vector field, the sweeping lines in the images represent streamlines of this

Even did stokes V



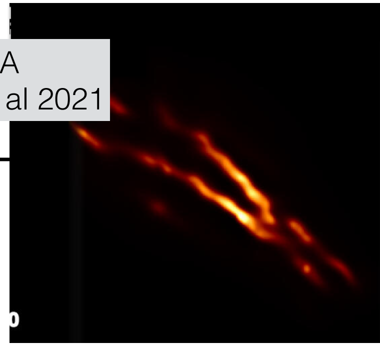
- Some low level circular pol detected
  - But not really imaged at 5%
- Faraday rotation of linear pol
  - Probably not a good measure of physical conditions

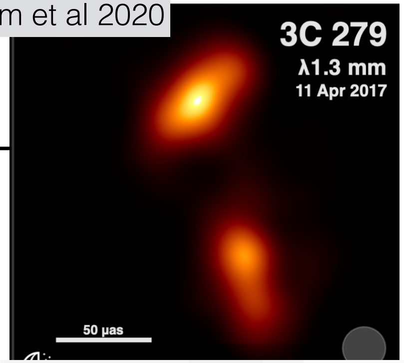
- And we still owe you..
  - Polarisation of SgrA*



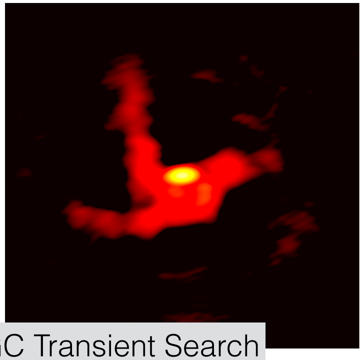
Many ‘official’ results

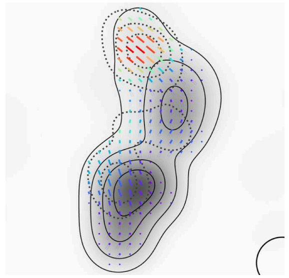
- 187 Papers in 6 years
  - >100 individual first authors
  - Theory, simulation, i
  - maging,
  - methodology,
  - data analysis,
  - technical development
  - other targets
  - pulsar search
  - ALMA polarisation properties

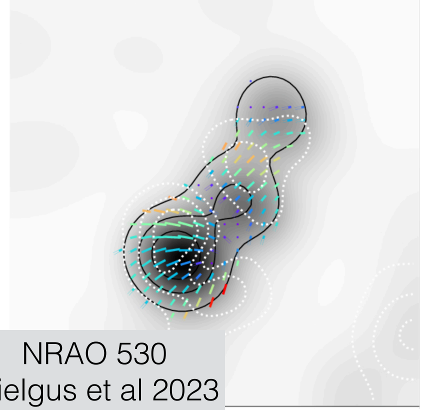

Cen A
Janssen et al 2021

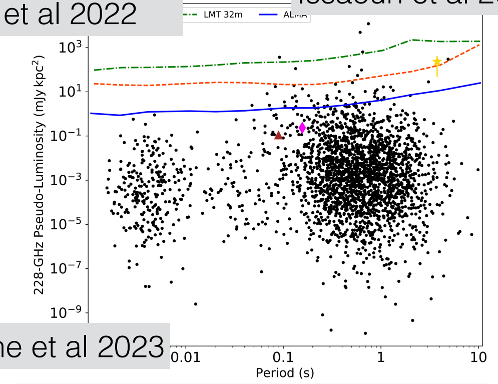


Kim et al 2020

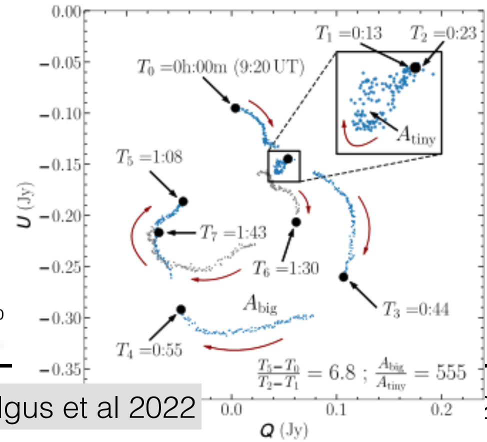

GC Transient Search
Mus et al 2022


J1924-2912
Issaoun et al 2022

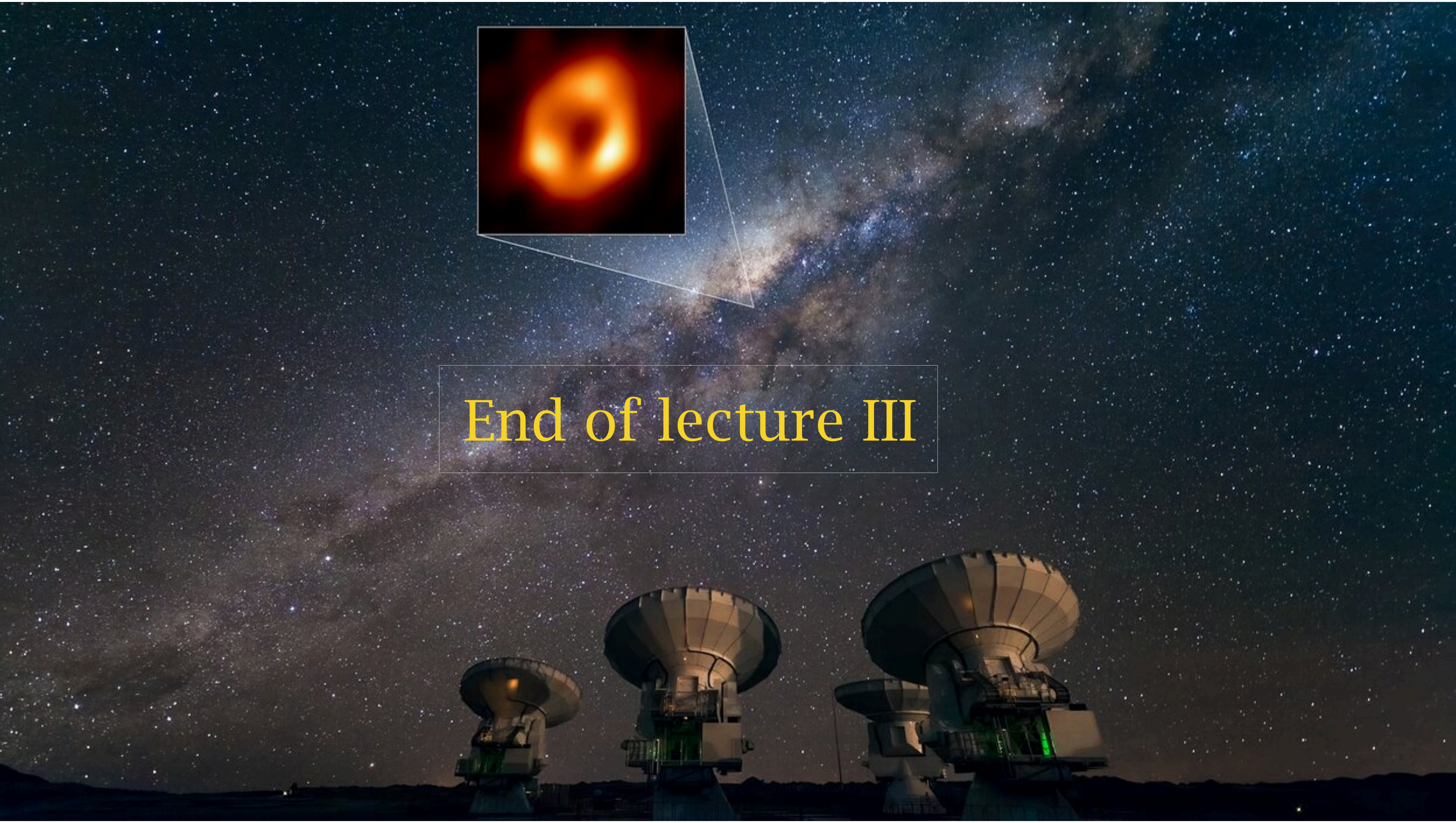

NRAO 530
Wielgus et al 2023



GC Pulsars, Torne et al 2023



Rotation from Polarimetry, Wielgus et al 2022


End of lecture III