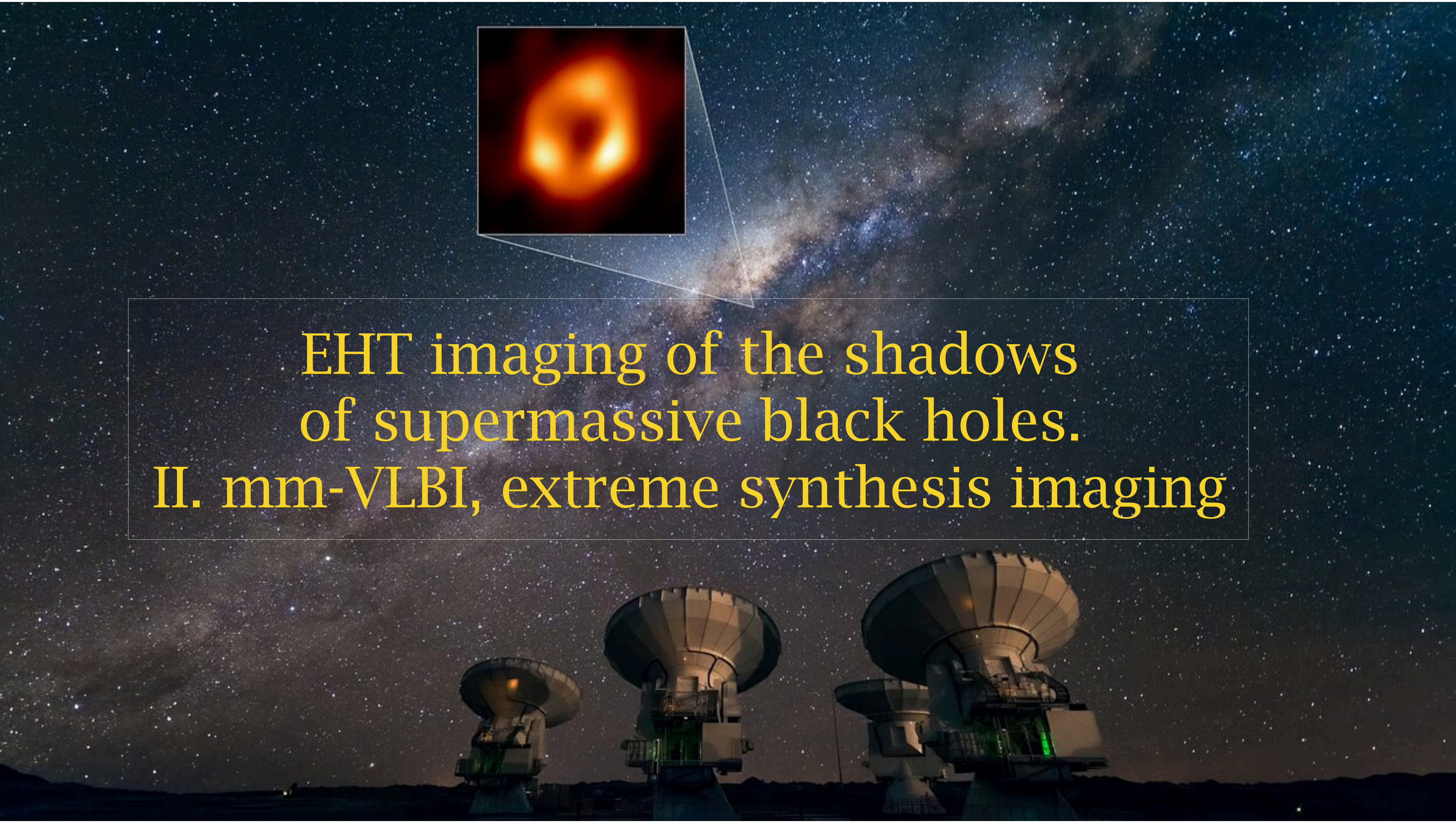


EHT imaging of the shadows of supermassive black holes. II. mm-VLBI, extreme synthesis imaging

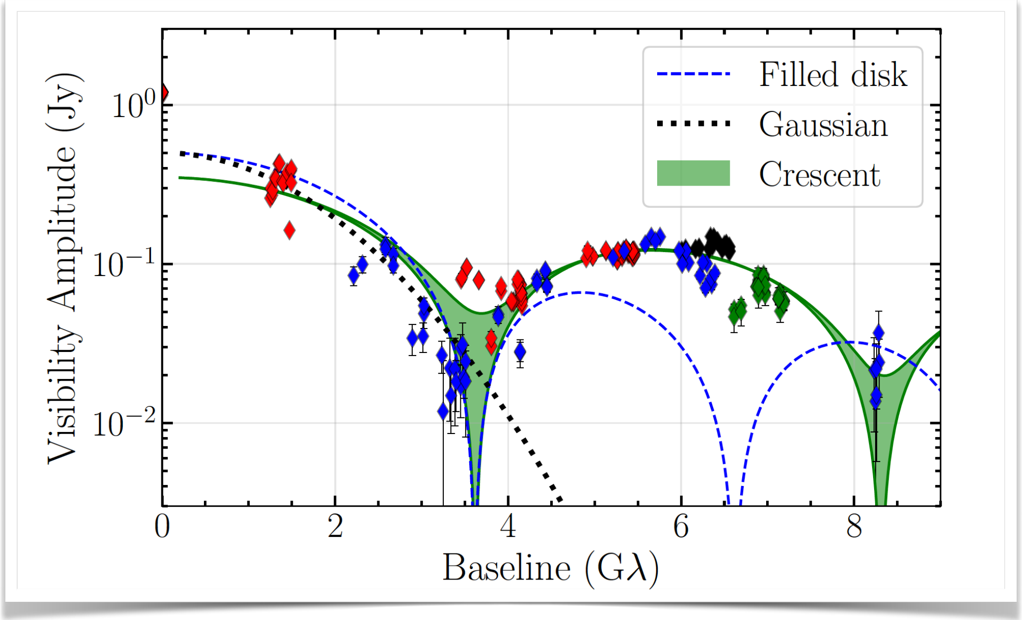
Today

- Overall Objective
  - Introduce the practices of our trade: what it takes to measure the shadow of supermassive black holes

- Understanding synthesis imaging
  - Fourier relation
  - uv-plane sampling
  - imaging and deconvolution
  - Clean and RML approaches
  - imaging artefacts
  - Robust approaches
  - Variability/movie making
  - Model fitting, super-resolution

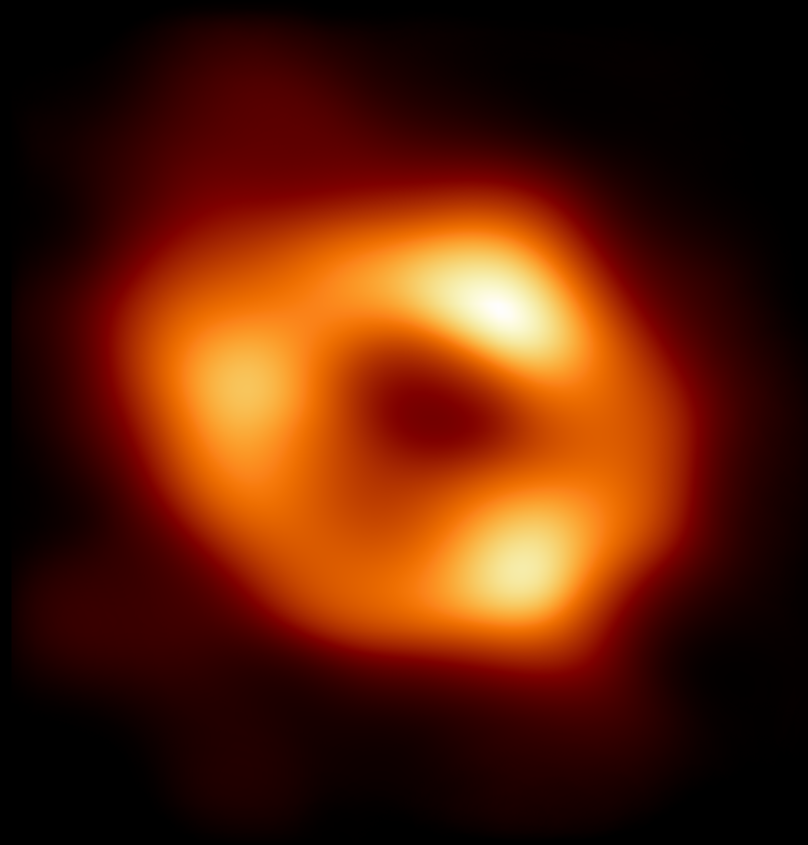
Starting the story in the middle....

telescopes - digitisation - correlation - calibration - imaging - analysis



- Later lectures
  - Techical implementation, calibration
  - Interpretation, calibrating gravity

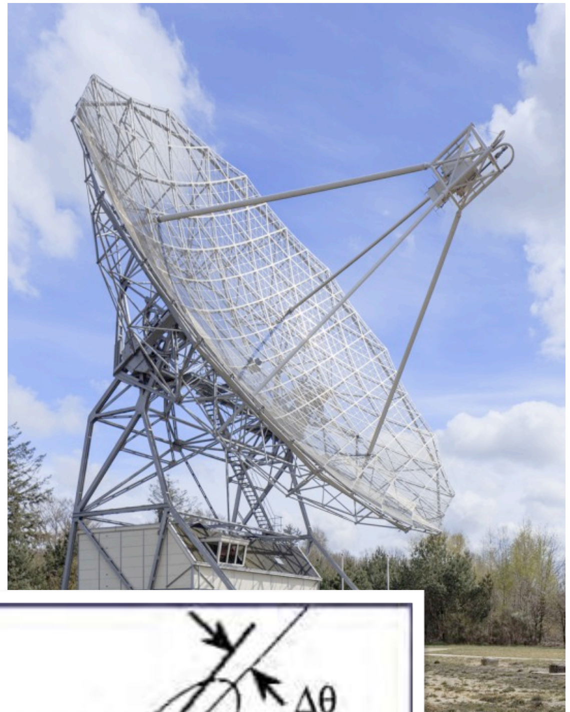
Which features can I trust in these images?
What magic processing went in?
What are the assumptions?
Are these really rings?

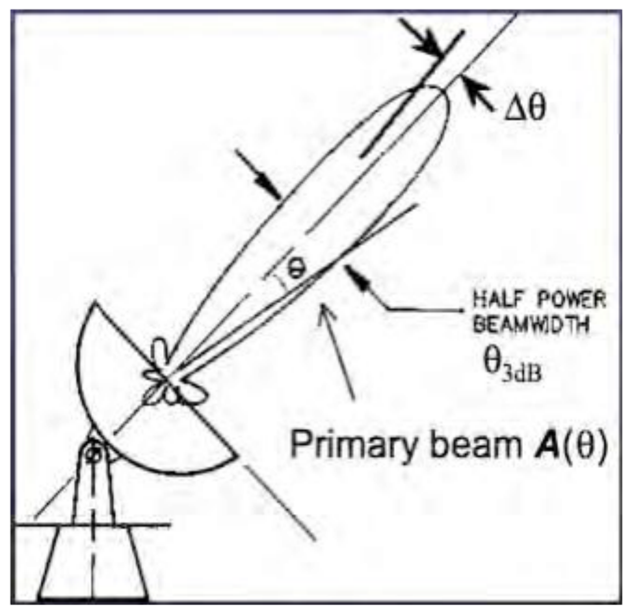


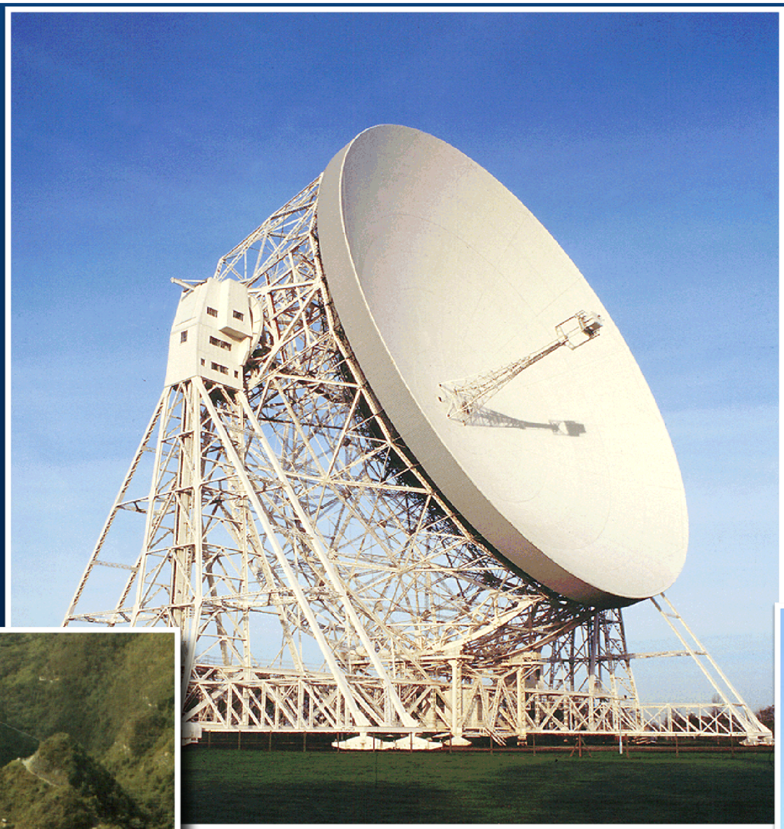
Angular resolution

- Example: parabolic dish
  - Focus incoming radiation on antenna in primary focus
  - Amplify, measure, digitise
  - Must use some differential method against strong background
- Diameter determines sensitivity and resolution
  - Must have surface accuracy better than < λ
    - And receiver (bandwidth) also matters
  - From simple (Fourier optics)
- Compare t human eye
  - 1.22 * 580nm/2mm = 0.00035 rad = 1.2’
  - Eye comes with optimised detector…
- 25 meter parabolic dish at 1.4 GHz
  - 1.22 * 21cm/25m = 0.010 rad = 35’
  - Traditionally radio telescopes only have single pixel…

$$\theta = 1.22\frac{\lambda}{D}$$

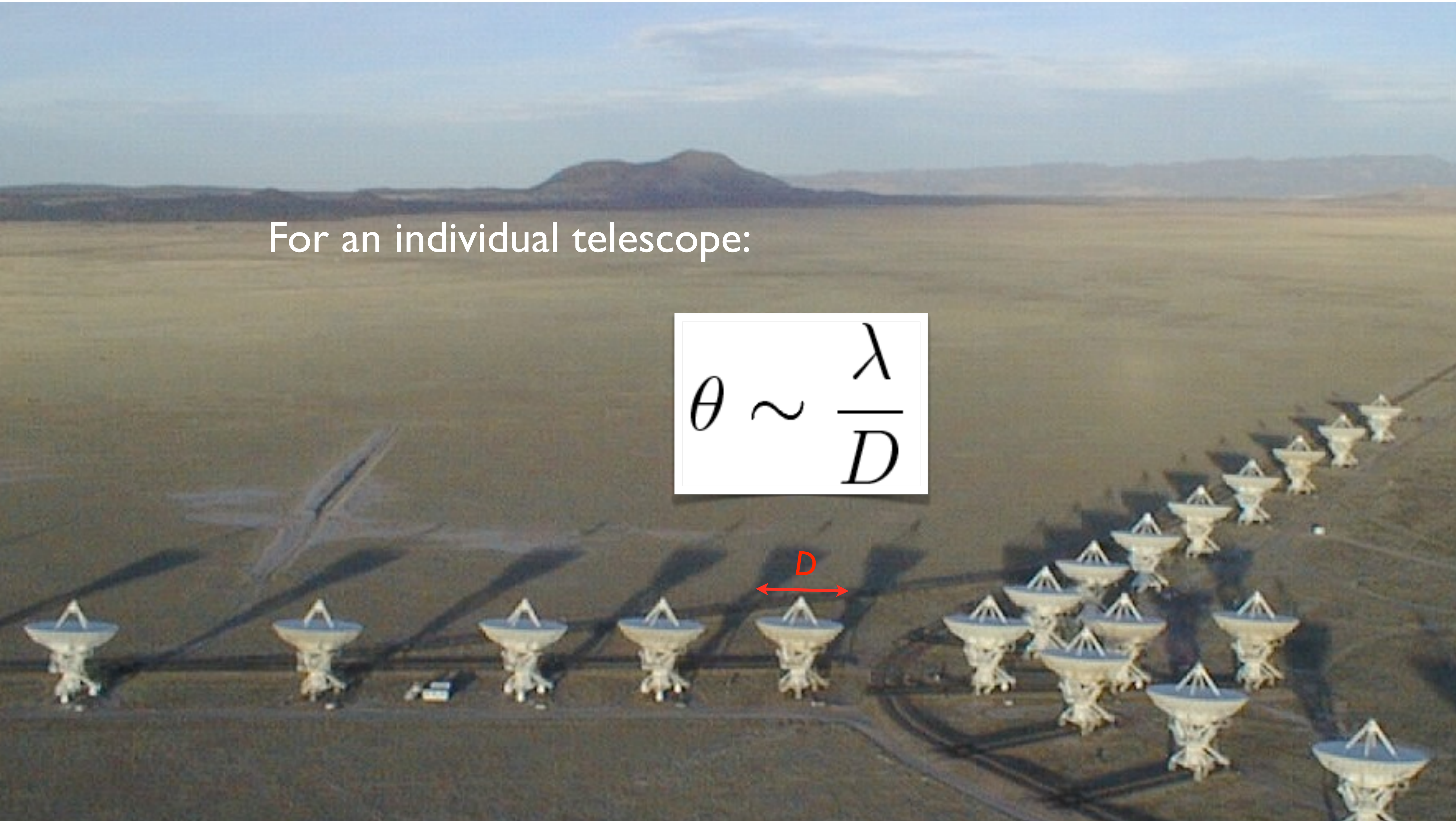






For an individual telescope:

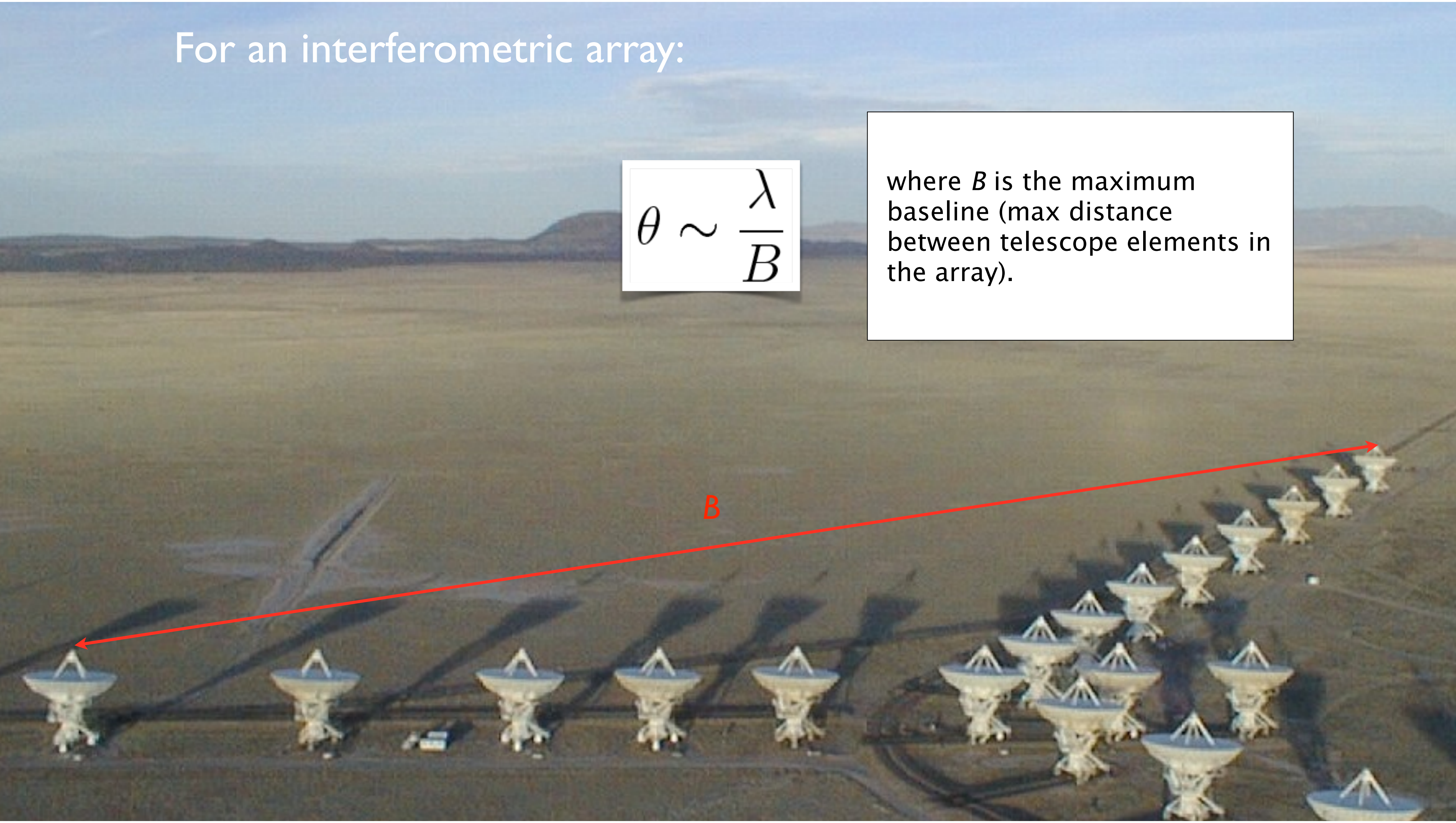
$$\theta \sim \frac{\lambda}{D}$$

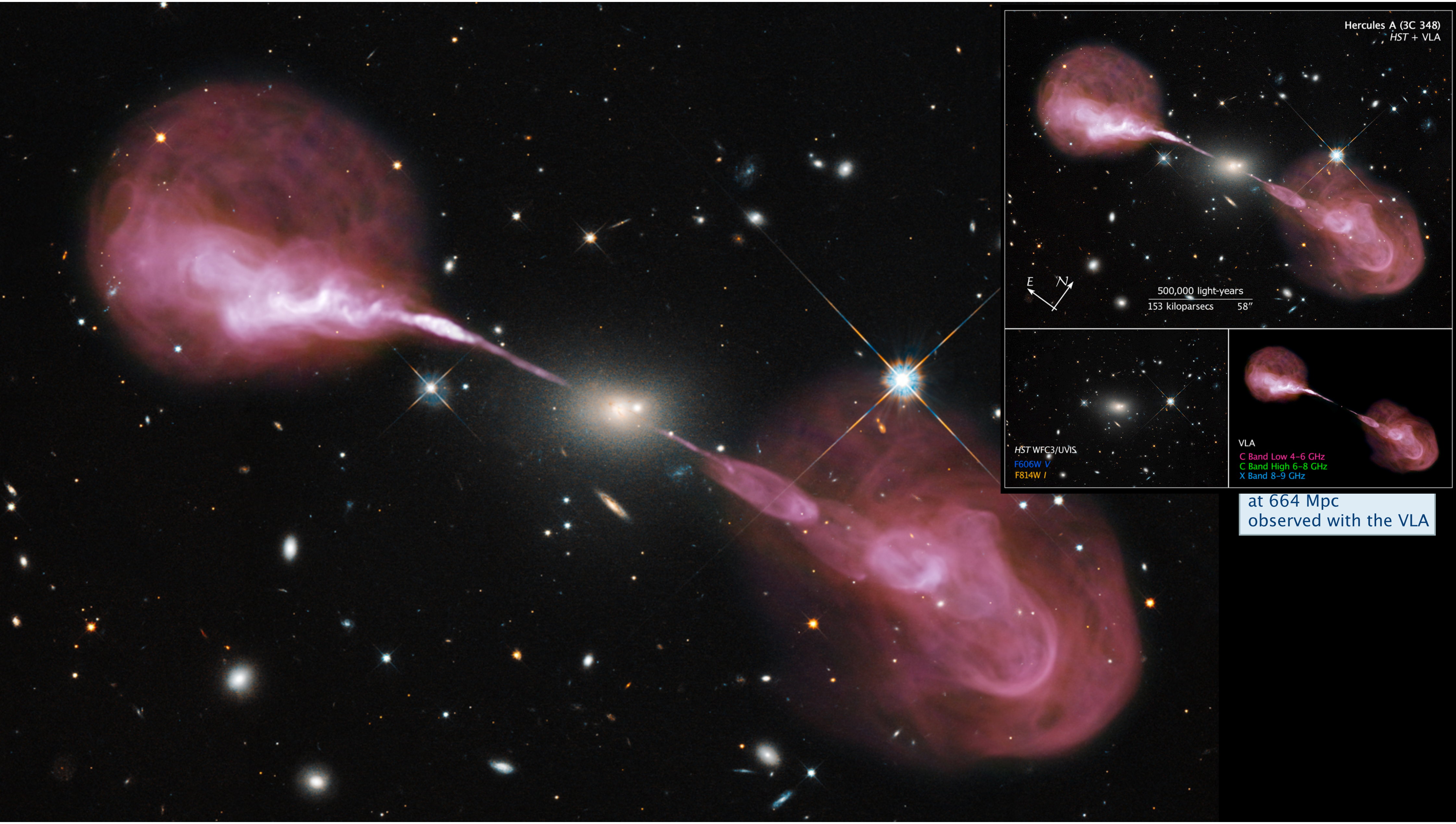


For an interferometric array:

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

where *B* is the maximum baseline (max distance between telescope elements in the array).

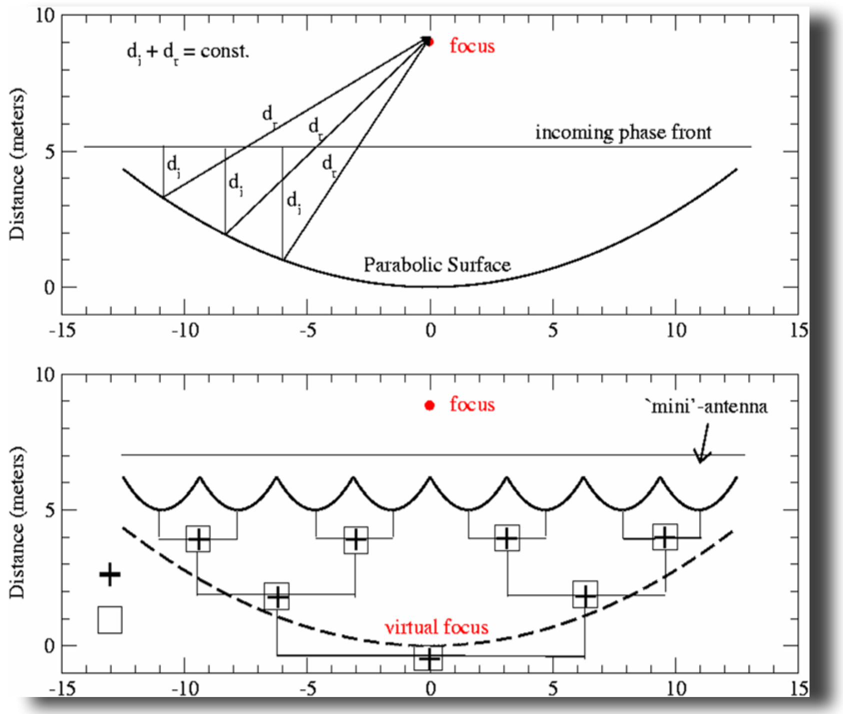




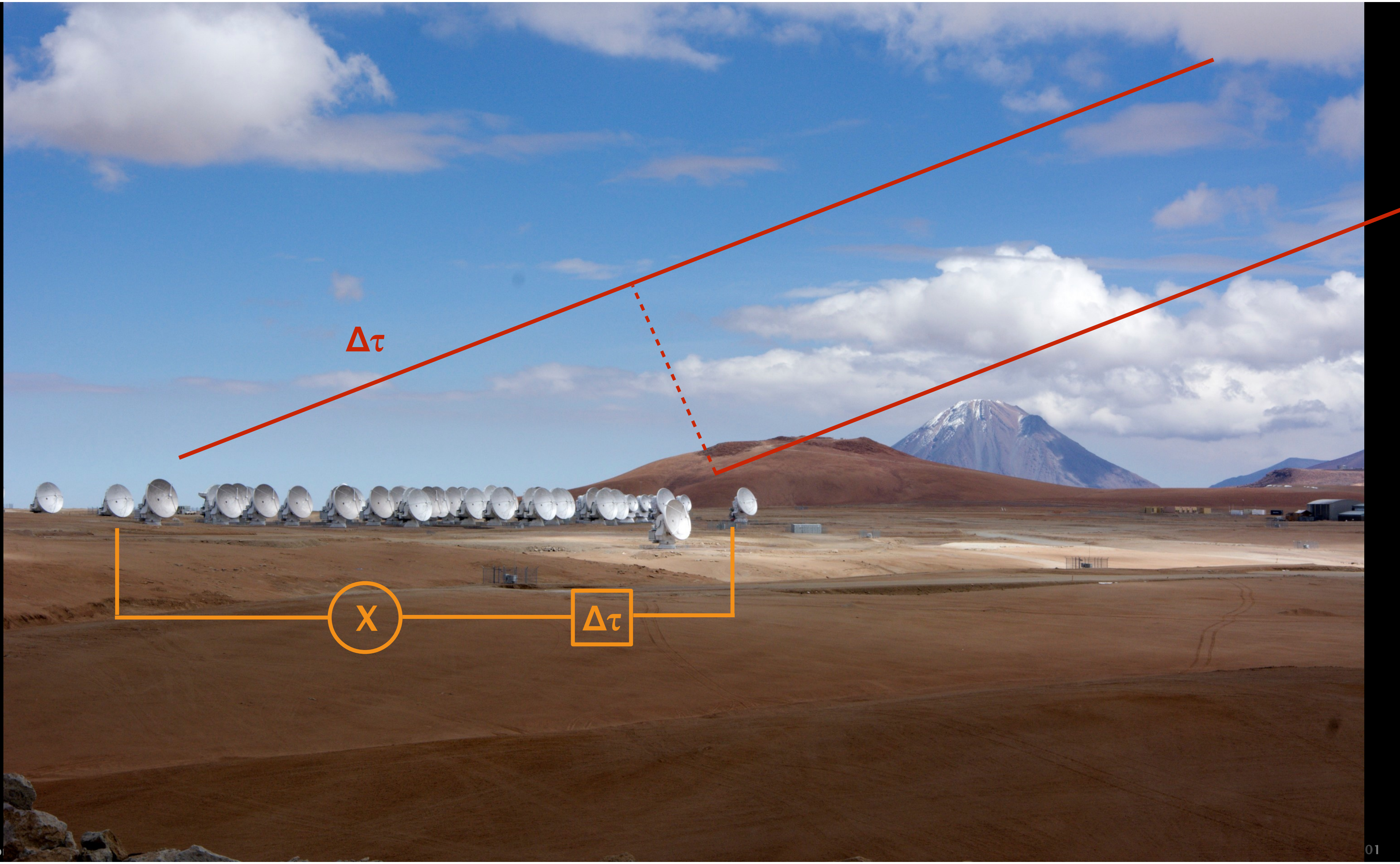
at 664 Mpc
observed with the VLA

How to understand interferometry…

- Parabolic antenna combines incoming waves
  - Exactly phase up in (primary) focus
- Can also be achieved electronically
  - Low freq signal can be processed, amplified even
  - Compensate the delay due to geometry
  - Achieve a "phased-up" beam on the sky
- Can be improved by correlating all pairs
  - Each pair sensitive to different spatial frequency
  - In different direction as earth turns
- Combine many interference patterns into image
  - Requires a ½N(N-1) complex correlator



$$\theta = 1.22\frac{\lambda}{B}$$



Δτ
X
Δτ

Two element interferometer

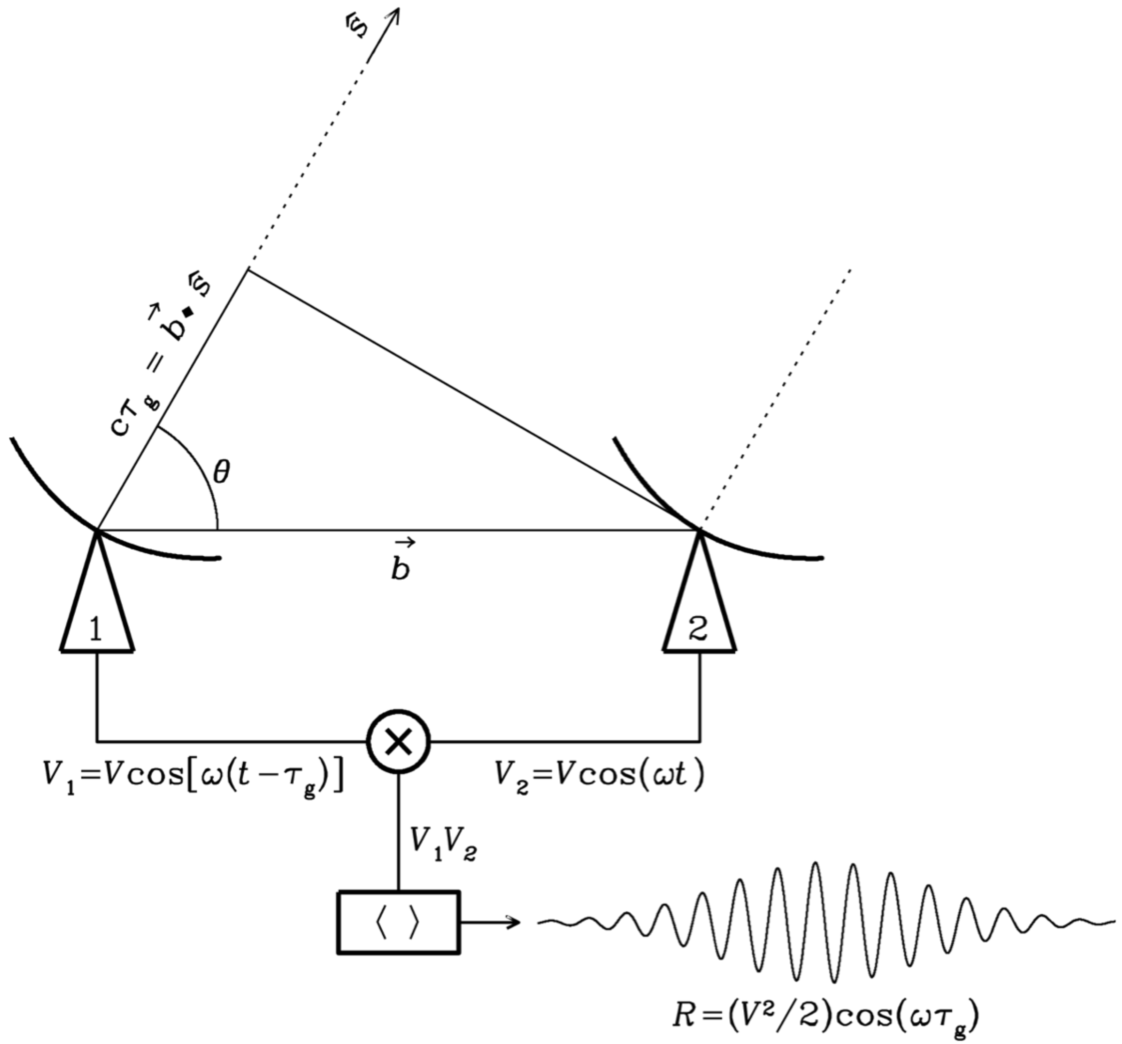
A radio interferometer measures the coherence of the electric field between the 2 receiving elements.

$$C_{ij} = \left\langle \mathrm{v}_i(t)\, \mathrm{v}_j(t+\tau) \right\rangle_T$$

Many complicating factors, need to track the source, project to the baseline plane, compensating τ

Assuming a monochromatic source, we can show that a quasi sinusoidal fringe occurs at the output, as the source moves through the beam of the telescopes.

The sky sensitivity pattern depends beams of the telescopes.



Heart of the matter:

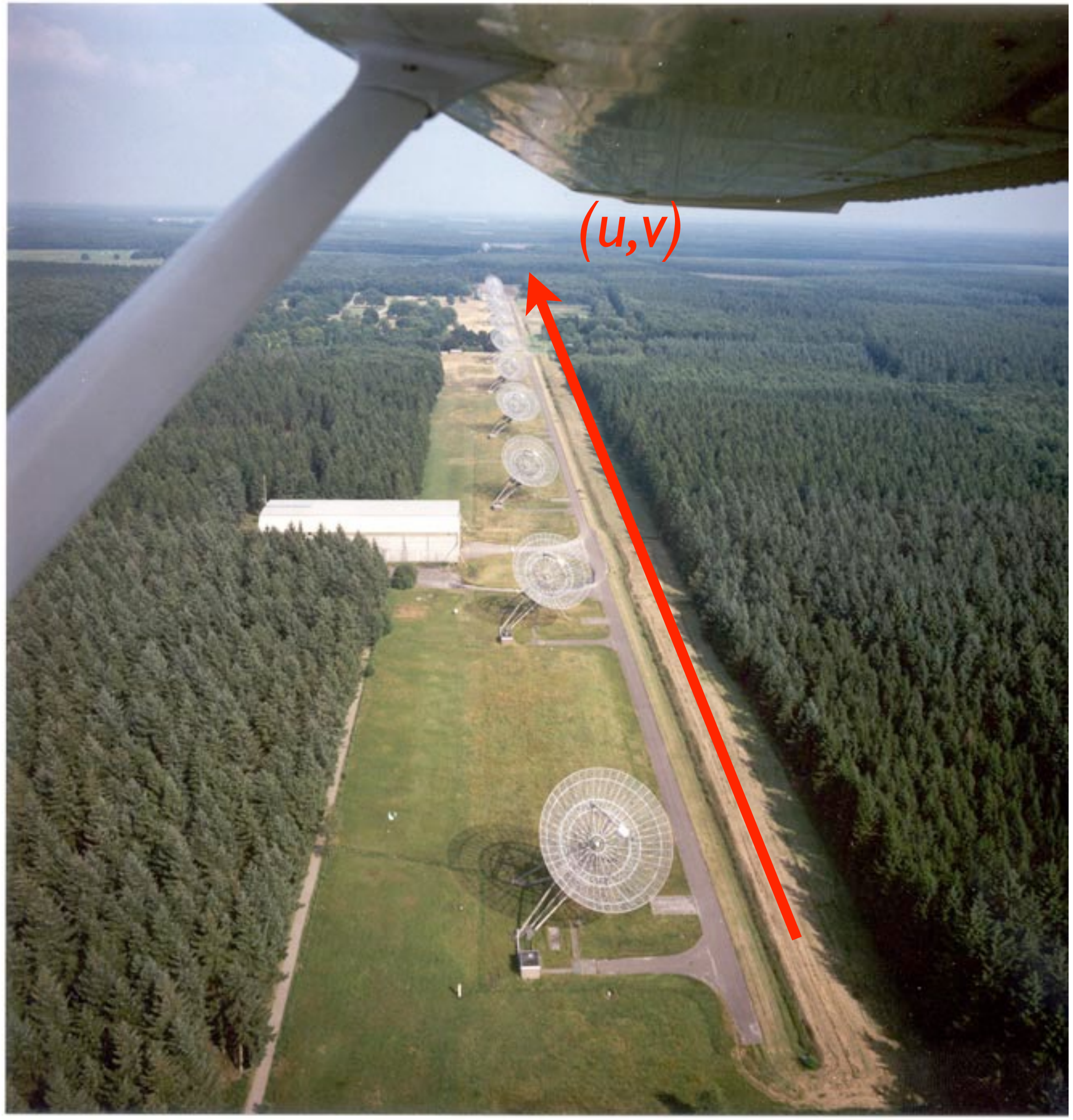
- In reality there will be a superposition of all sources in the beam:
- And each Interferometer can measure complex visibility
  - Result: Fourier relation with sky brightness:

$$V(\mathbf{b}) = \iint I_\nu(\mathbf{s})\, e^{-2\pi i \nu \mathbf{b}\cdot\mathbf{s}} d\Omega$$

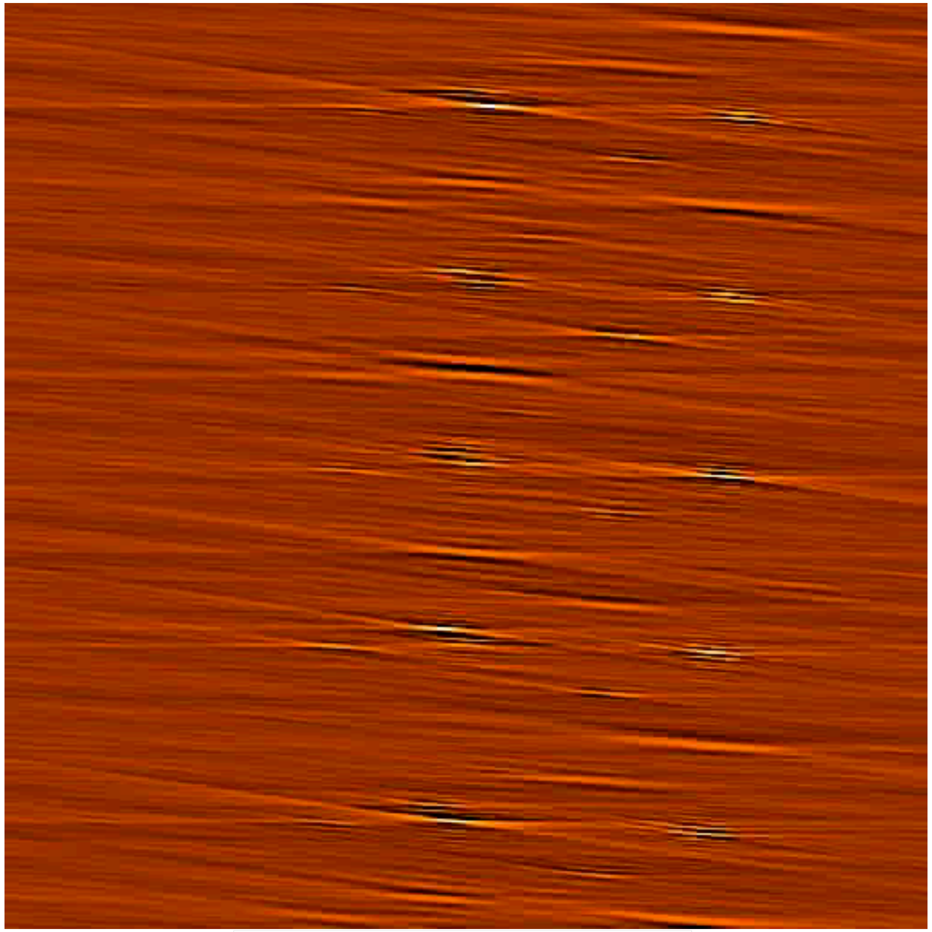
- Ignoring (for now) many complicating aspects
  - Such as finite bandwidth, integration times, 3-D, polarisation, digitisation
- Arrays of telescope sample aperture (u,v domain)
  - Helped by the rotation of the earth
  - Visibilities can be inverted to form dirty image
  - Needs to be de-convolved to image source

The visibilities are registered as a function of baseline. For an east-west array this can be a 2D plane on which the baselines project as seen from the source.

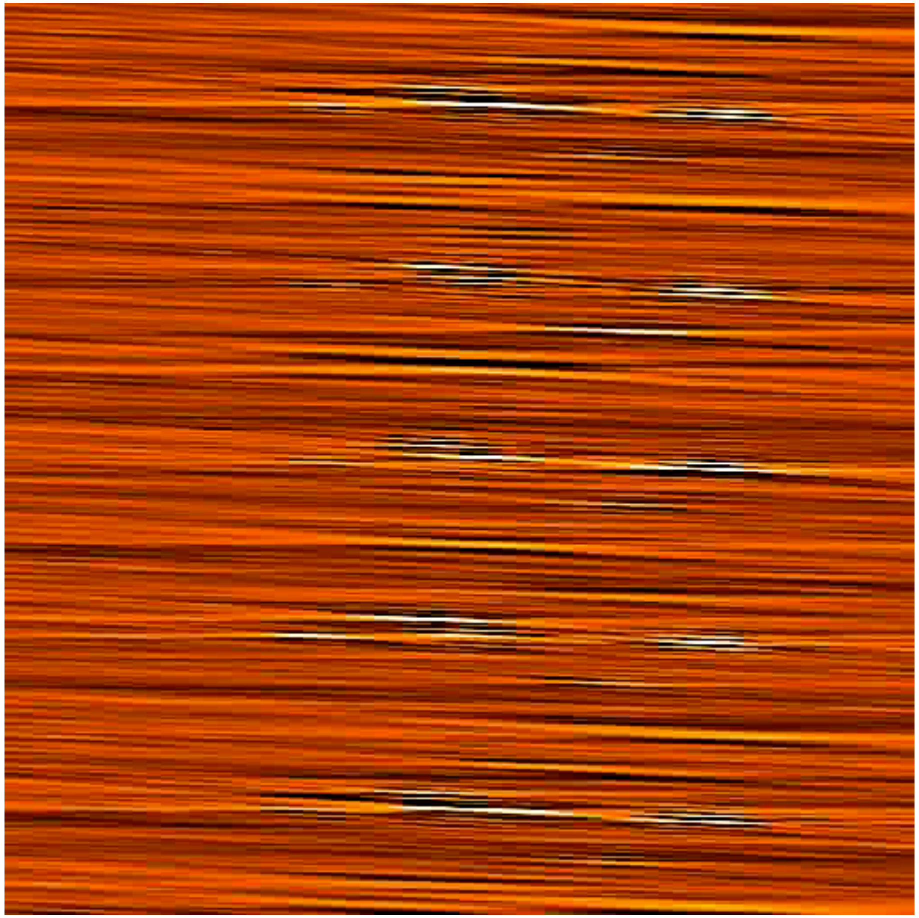
Westerbork was built this way, because it simplified the computational burden considerably



How an E-W array sees the sky

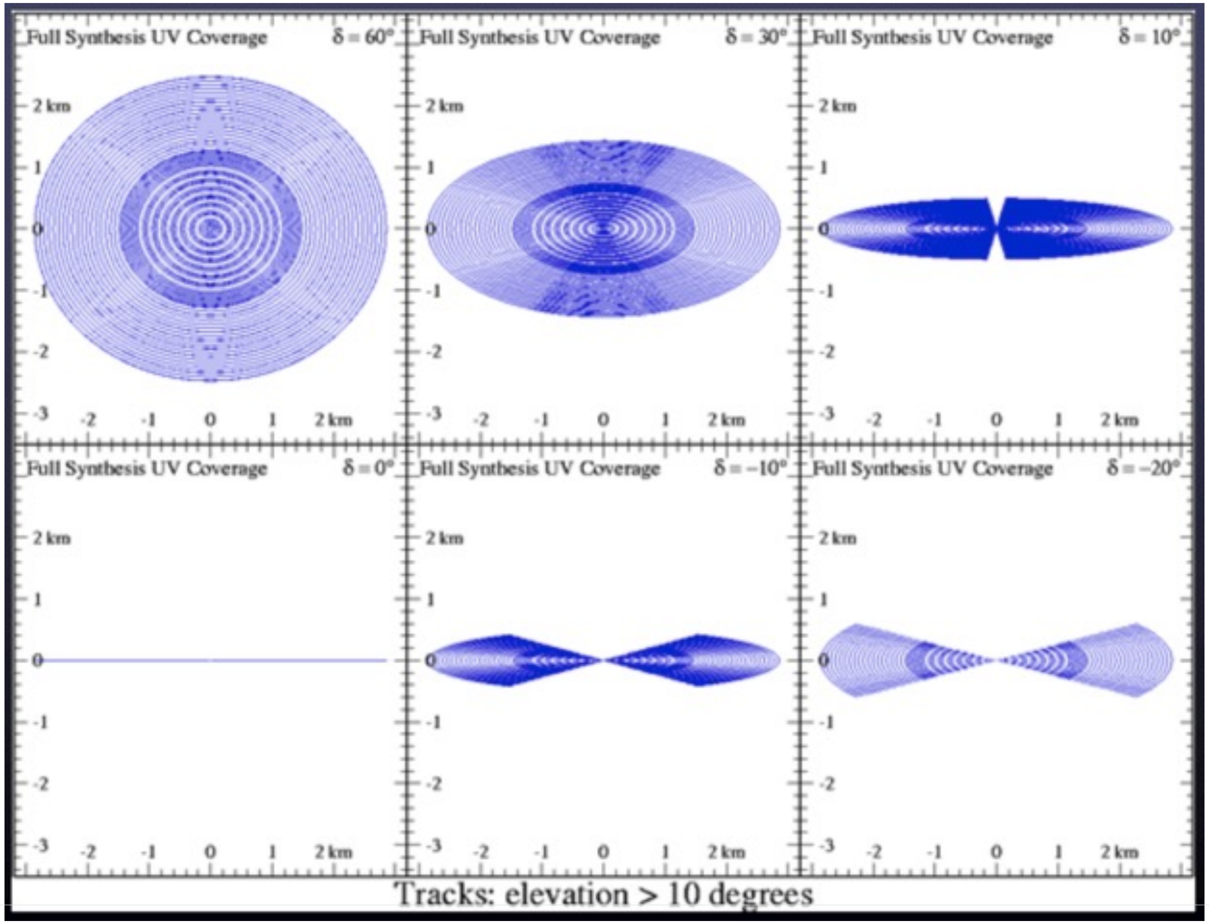


Instantaneous view



Cumulative view

WSRT uv coverage

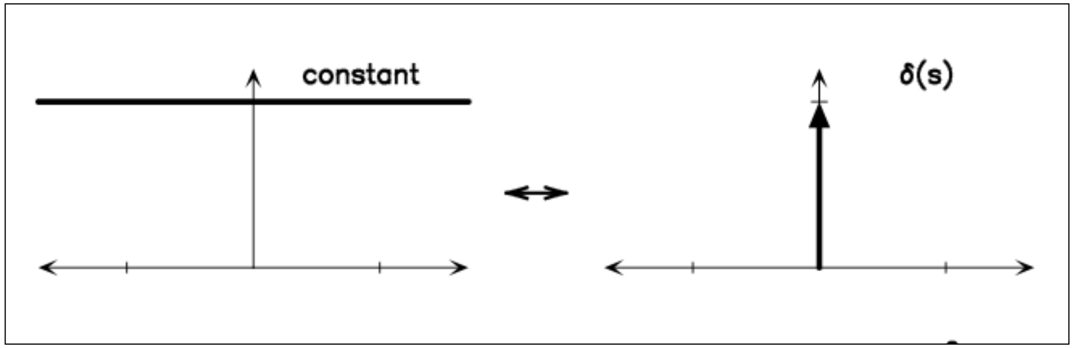


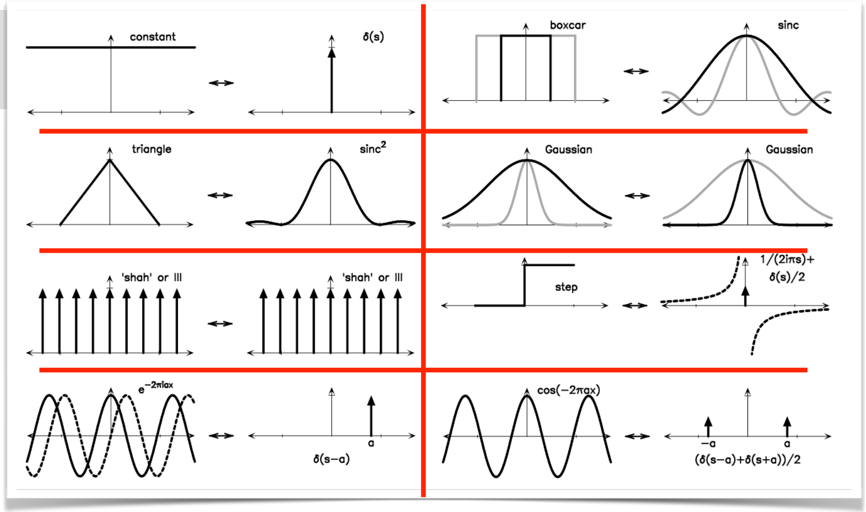
uv-coverage of the WSRT for various source declinations.

The uv-tracks are only plotted when the source is 10 degrees above the local horizon. Below 10 degrees the data are often discarded because they are partially corrupted by the atmosphere a low elevations.

Note that the uv-coverage becomes poorer for low-declination sources and becomes 1-dimensional for source located at zero declination.

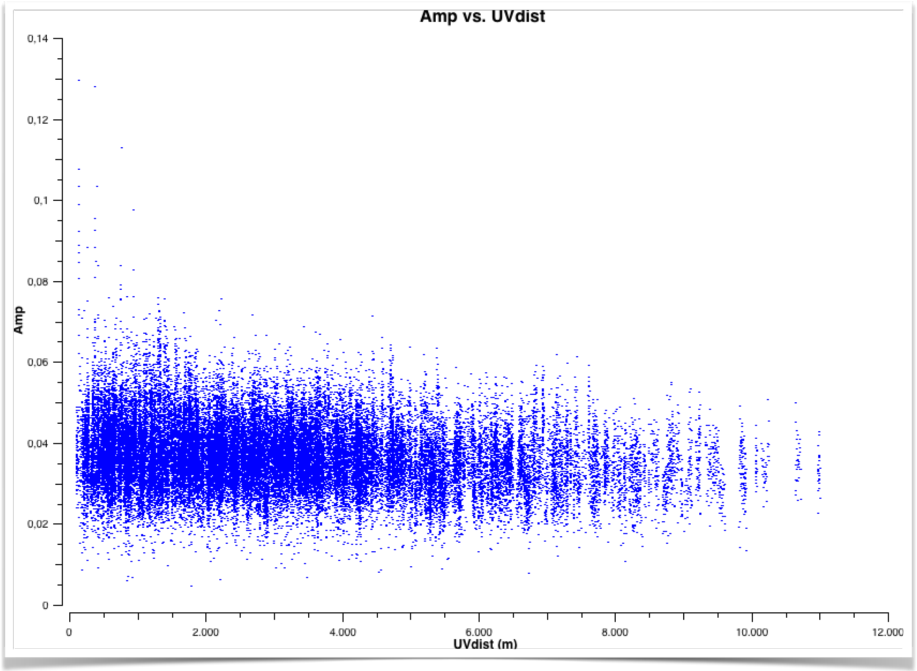
Point source response





Expected respons from point source is very simple:
A = S
$\phi = 0$
on all baselines.

This allows us to calibrate all individual antenna responses as a function of time



Making Dirty Images

- Complication: discrete sampling
- In practise, visibilities are observed only at discrete locations (u_k, v_k) in uv plane:

$$S(u,v) = \sum_{k=1}^{M} \delta(u-u_k, v-v_k)$$

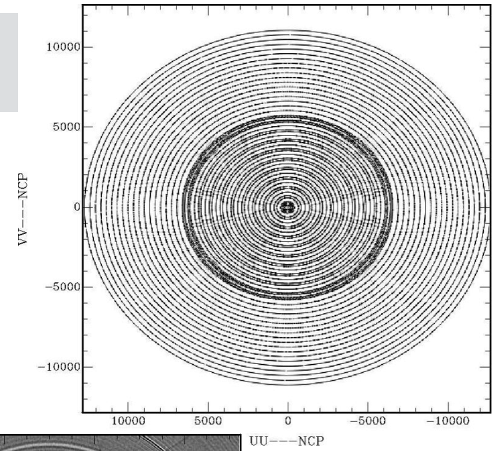
= Sampling function

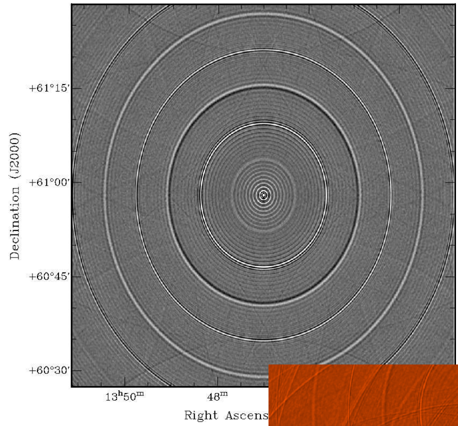
$$I(l,m) = \iint S(u,v) V(u,v) e^{2\pi i(ul+vm)} du dv$$

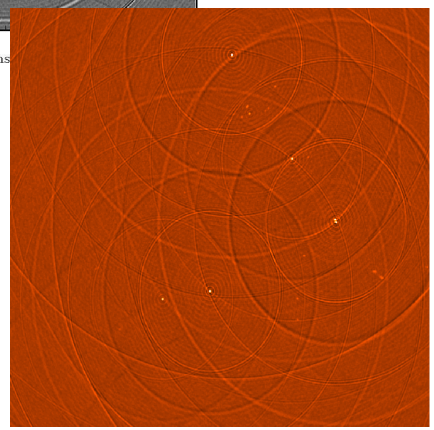
- Image is convolution of sky with "dirty beam" B

$$I^D = I * B$$

$$B(l,m) = \iint S(u,v) e^{2\pi i(ul+vm)} du dv$$







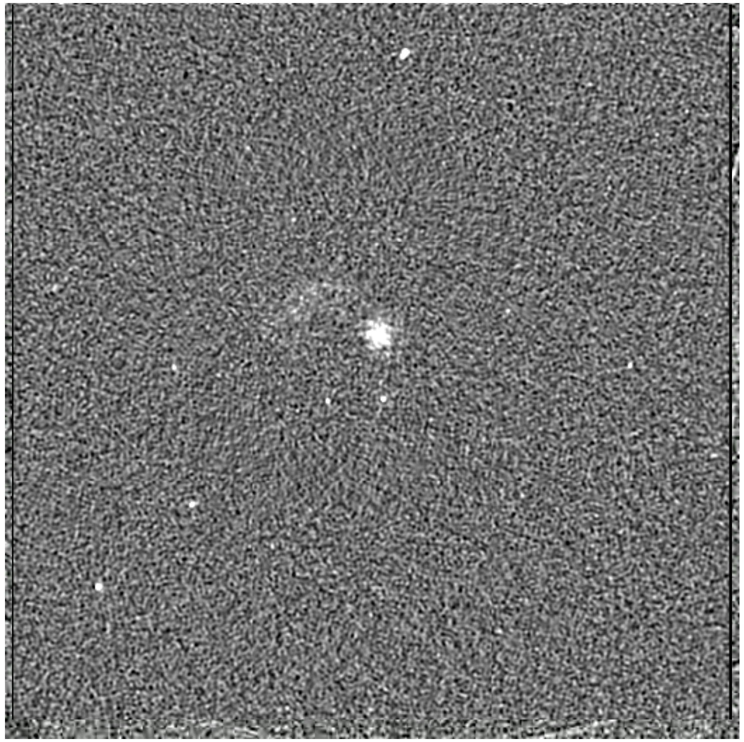
The classic Clean algorithm

Högbom, 1974

- Start with calculating the Beam
  - Fourier transform of the u,v sampling
  - Start an ImageModel
    - Which will be made of set of delta functions
- Algorithm:
  - 1. Search for the peak in the dirty image.
  - 2. Add a fraction g (loop gain) of the peak value to ImageModel
    - (add delta-function to model).
  - 3. Subtract a scaled version of the PSF from the position of the peak.

$$I_{i+1}^{R} = I_{i}^{R} - g \cdot B \cdot \max(I_{i}^{R})$$

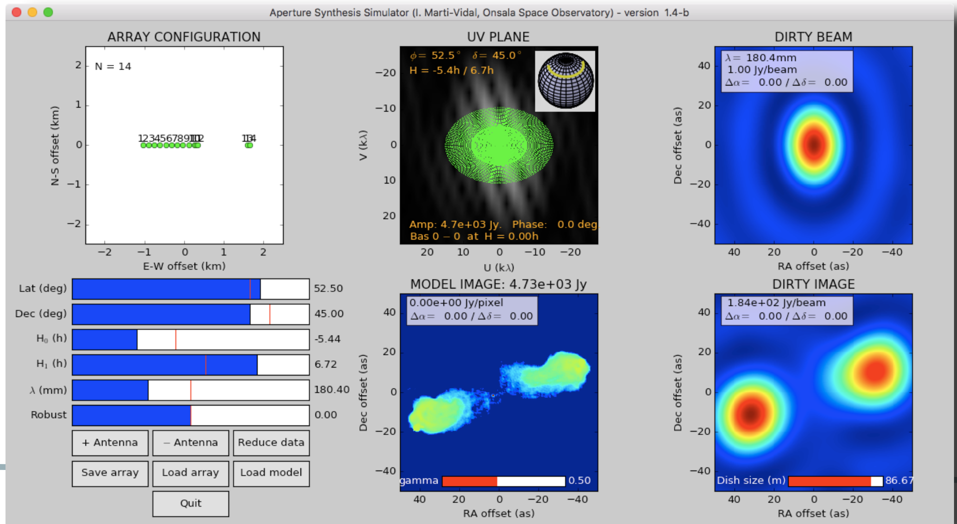
  - 4. If residuals are *not* “noise like”, goto 1, else:
  - 5. Smooth IM by an estimate of the main lobe (the “clean beam”) residuals to make the “restored image”2
- Many variations exist:
  - Clark clean: go back to discrete Visibilities in major cycles
  - Multi-resolution: not just delta-functions

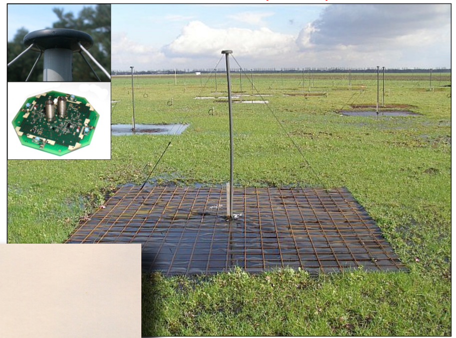


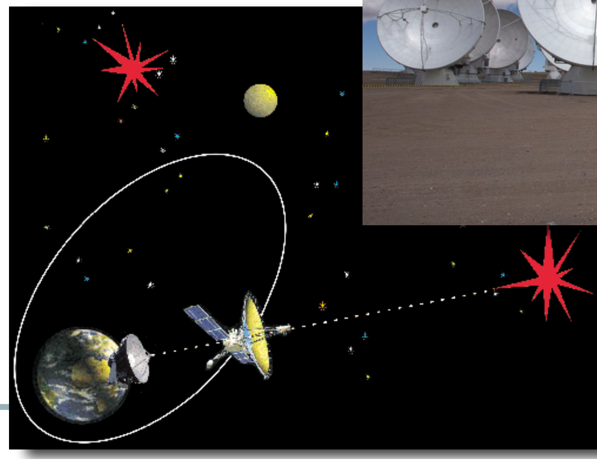
- And many subtleties:
  - Implemented by gridding and FFT
  - weighting functions can be important
  - prior information about source (aka clean boxes)

Earth rotation synthesis

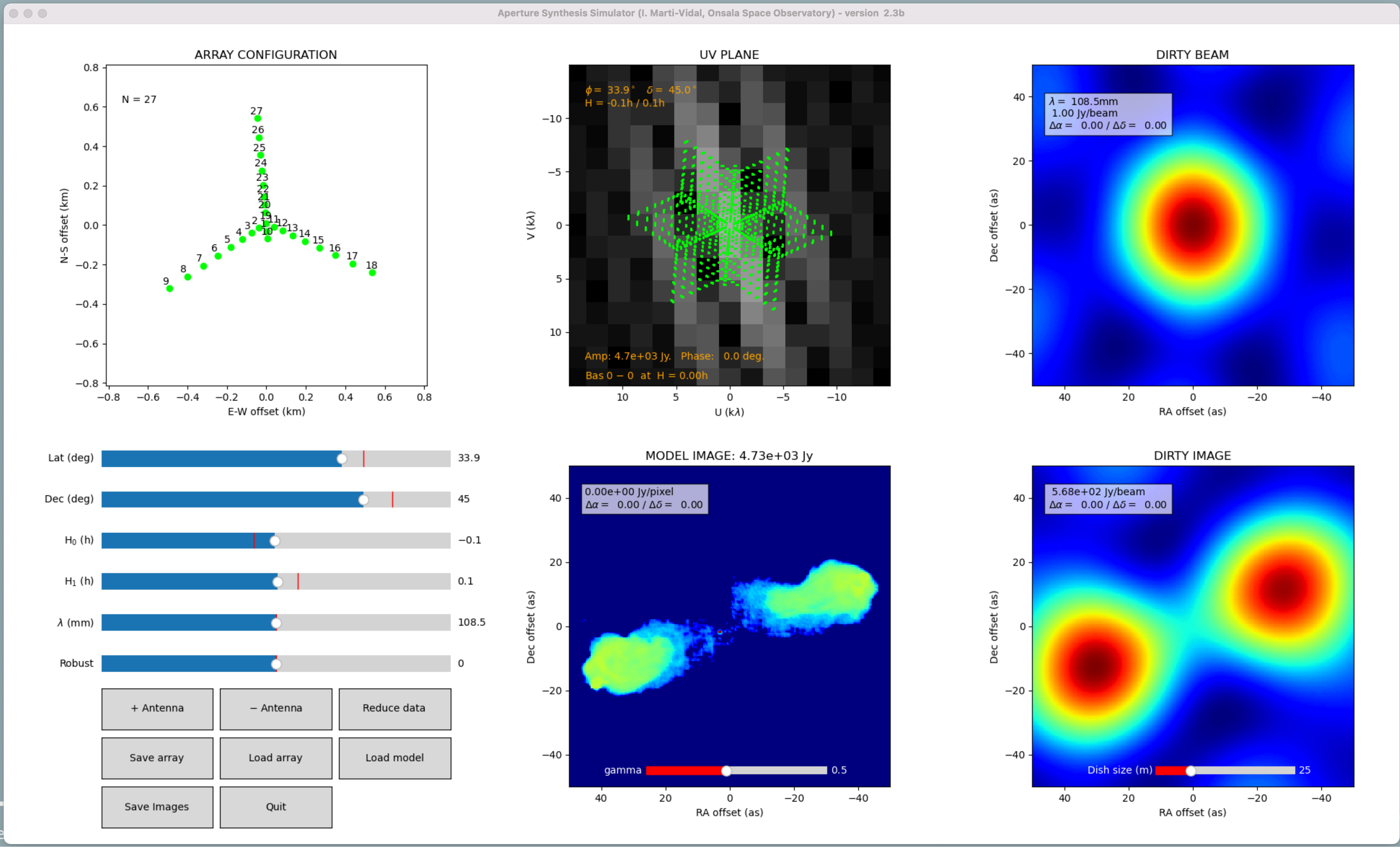
- Applied in many radio arrays
  - From meter to sub-millimeter
  - Baselines in meters to Earth diameter
- Many different regimes for imaging and calibration
  - Various algorithms, all compute intensive
- We can play with
  - Ivan Marti-Vidal's APSYNSIM, APSYNTRUE
  - https://github.com/marti-vidal-i/APSYNSIM



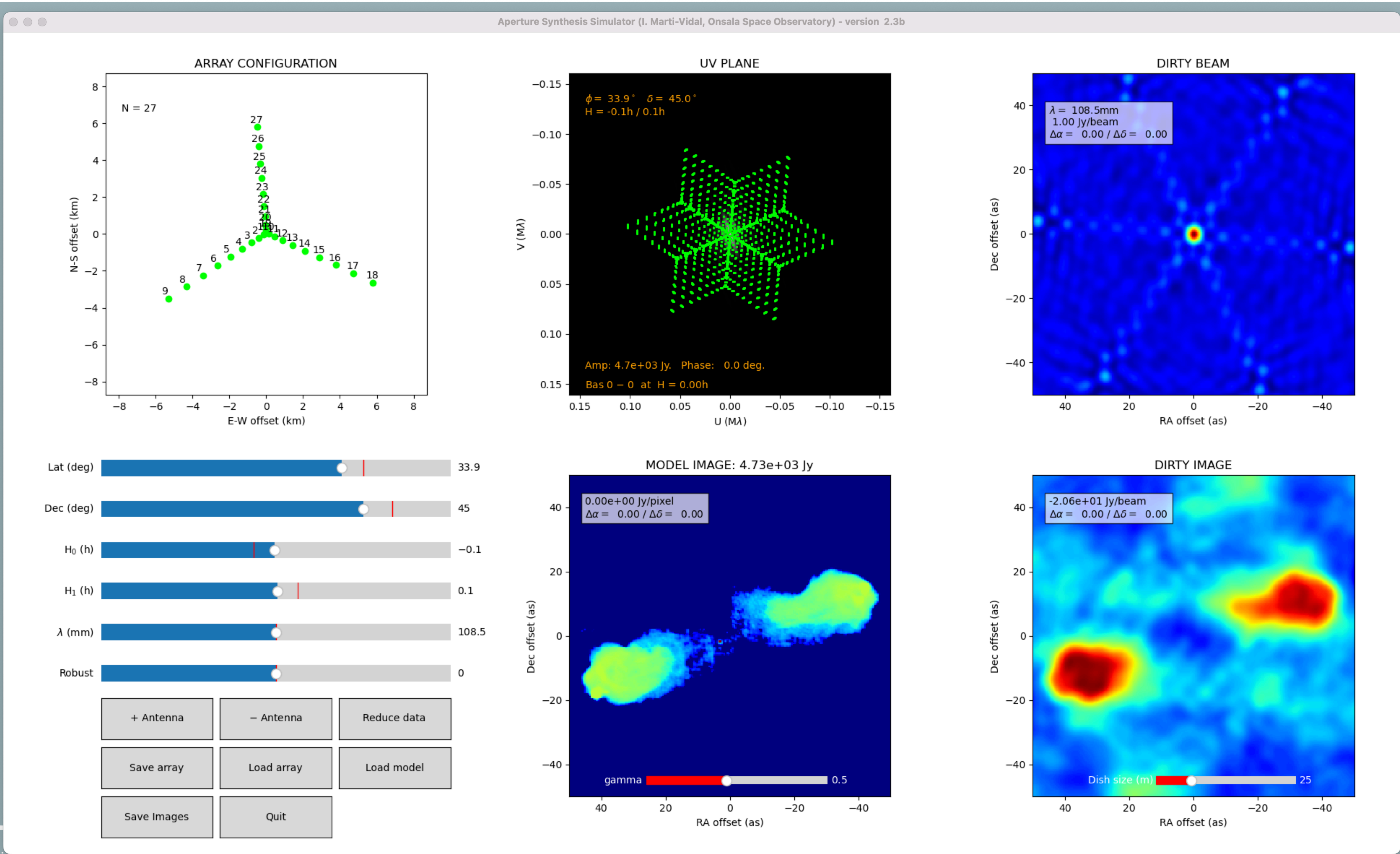


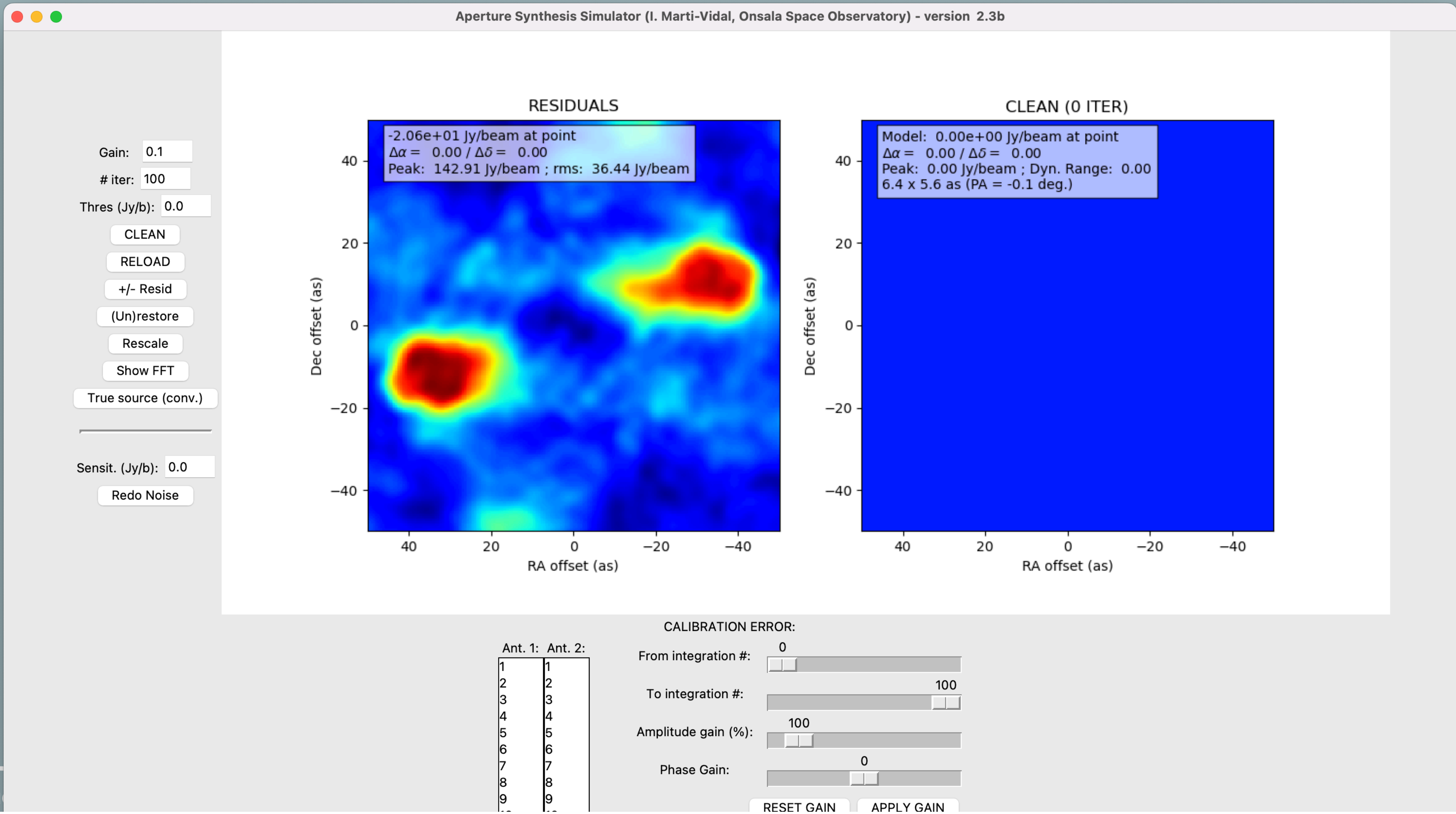


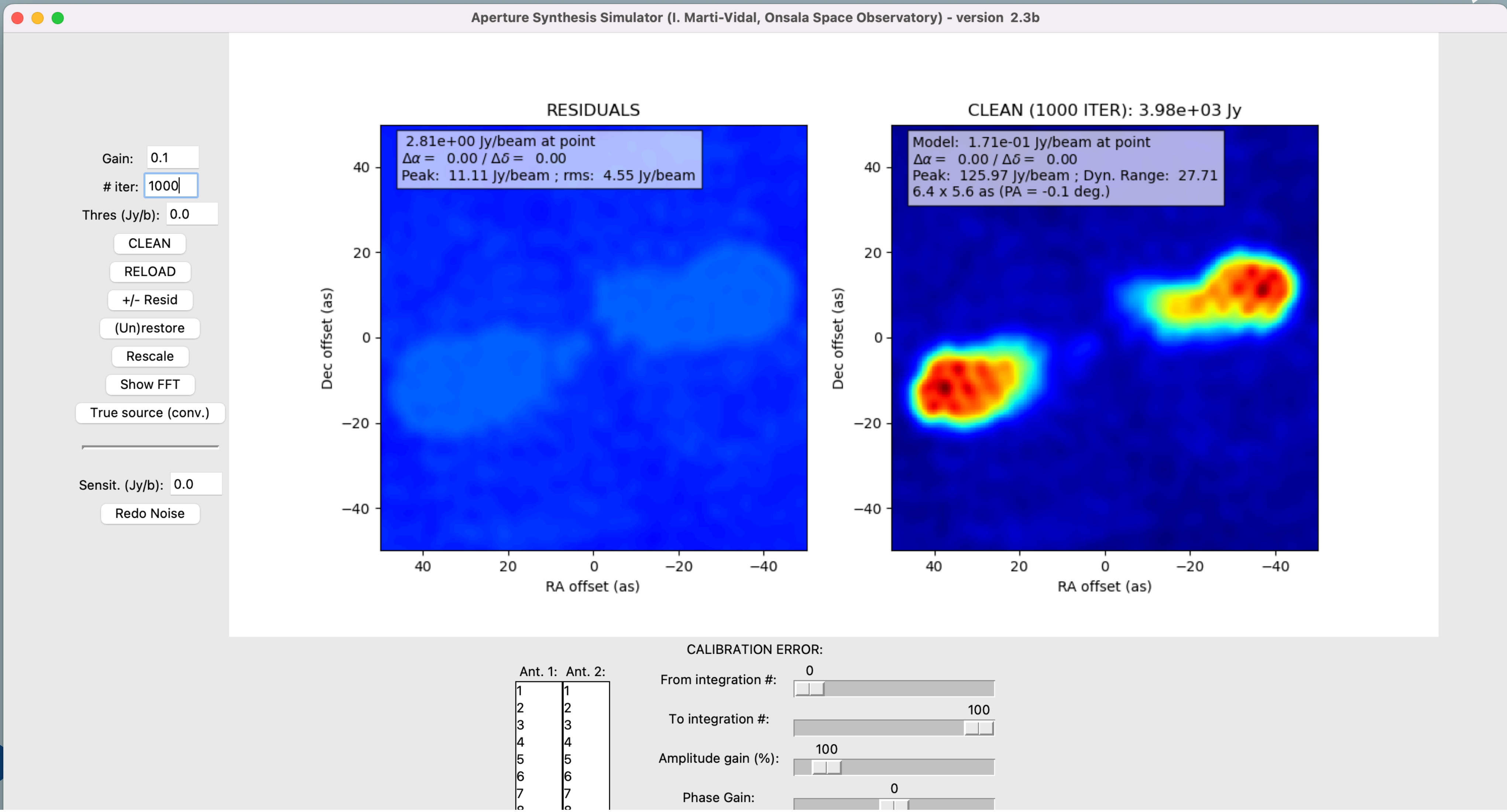
VLA D array with 10cm wavelength



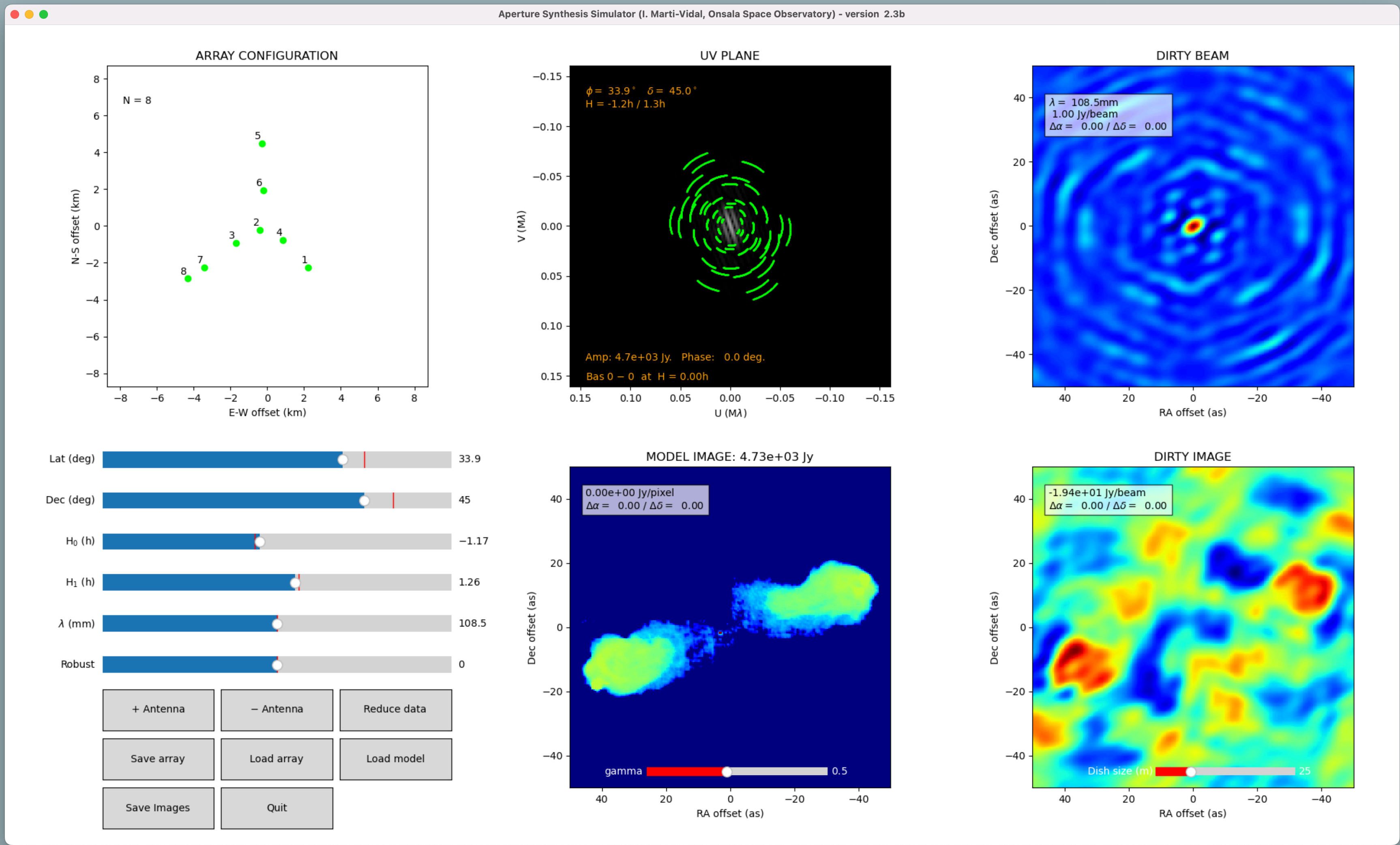
VLA B-array 10km baselines



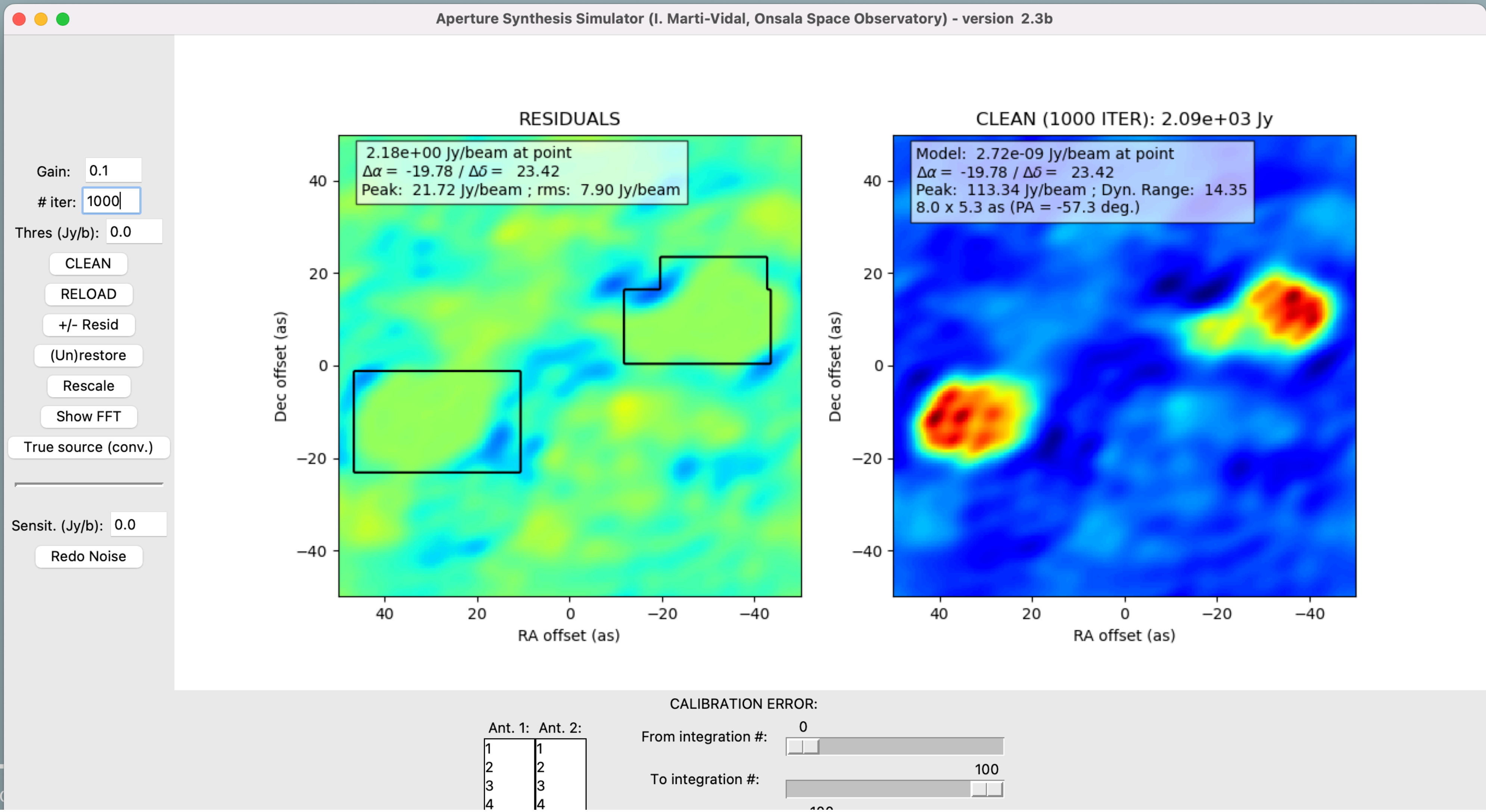

Aperture Synthesis Simulator (I. Marti-Vidal, Onsala Space Observatory) - version 2.3b
Gain: 0.1
iter: 100
Thres (Jy/b): 0.0
CLEAN
RELOAD
+/- Resid
(Un)restore
Rescale
Show FFT
True source (conv.)
Sensit. (Jy/b): 0.0
Redo Noise
RESIDUALS
-2.06e+01 Jy/beam at point
Δα = 0.00 / Δδ = 0.00
Peak: 142.91 Jy/beam ; rms: 36.44 Jy/beam
Dec offset (as)
RA offset (as)
CLEAN (0 ITER)
Model: 0.00e+00 Jy/beam at point
Δα = 0.00 / Δδ = 0.00
Peak: 0.00 Jy/beam ; Dyn. Range: 0.00
6.4 x 5.6 as (PA = -0.1 deg.)
CALIBRATION ERROR:
Ant. 1: Ant. 2:
From integration #:
To integration #:
Amplitude gain (%):
Phase Gain:
RESET GAIN
APPLY GAIN


Aperture Synthesis Simulator (I. Marti-Vidal, Onsala Space Observatory) - version 2.3b
Gain: 0.1
iter: 1000
Thres (Jy/b): 0.0
CLEAN
RELOAD
+/- Resid
(Un)restore
Rescale
Show FFT
True source (conv.)
Sensit. (Jy/b): 0.0
Redo Noise
RESIDUALS
2.81e+00 Jy/beam at point
Δα = 0.00 / Δδ = 0.00
Peak: 11.11 Jy/beam ; rms: 4.55 Jy/beam
CLEAN (1000 ITER): 3.98e+03 Jy
Model: 1.71e-01 Jy/beam at point
Δα = 0.00 / Δδ = 0.00
Peak: 125.97 Jy/beam ; Dyn. Range: 27.71
6.4 x 5.6 as (PA = -0.1 deg.)
Dec offset (as)
RA offset (as)
40
20
0
−20
−40
CALIBRATION ERROR:
Ant. 1: Ant. 2:
1
2
3
4
5
6
7
From integration #: 0
To integration #: 100
Amplitude gain (%): 100
Phase Gain: 0

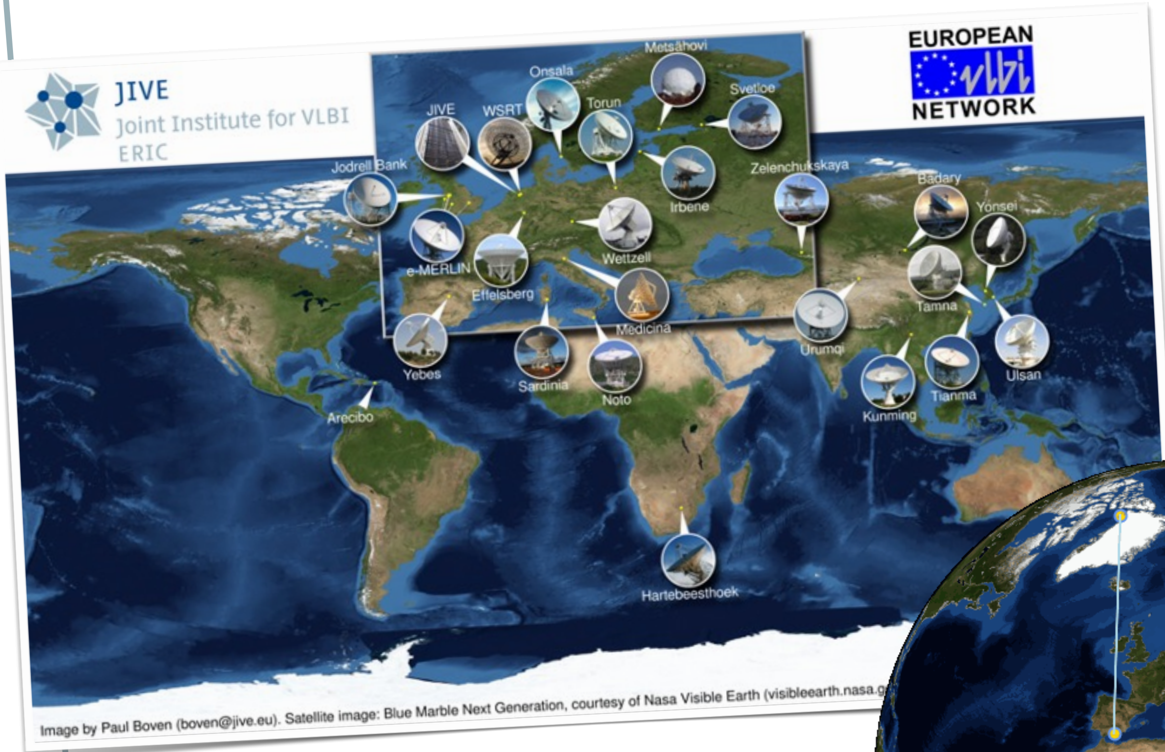
Make an 8 station array

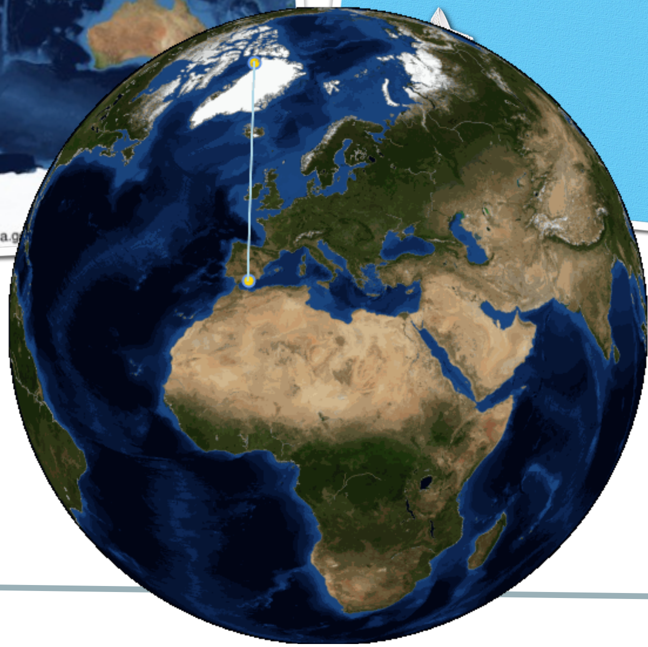


Can still image if careful



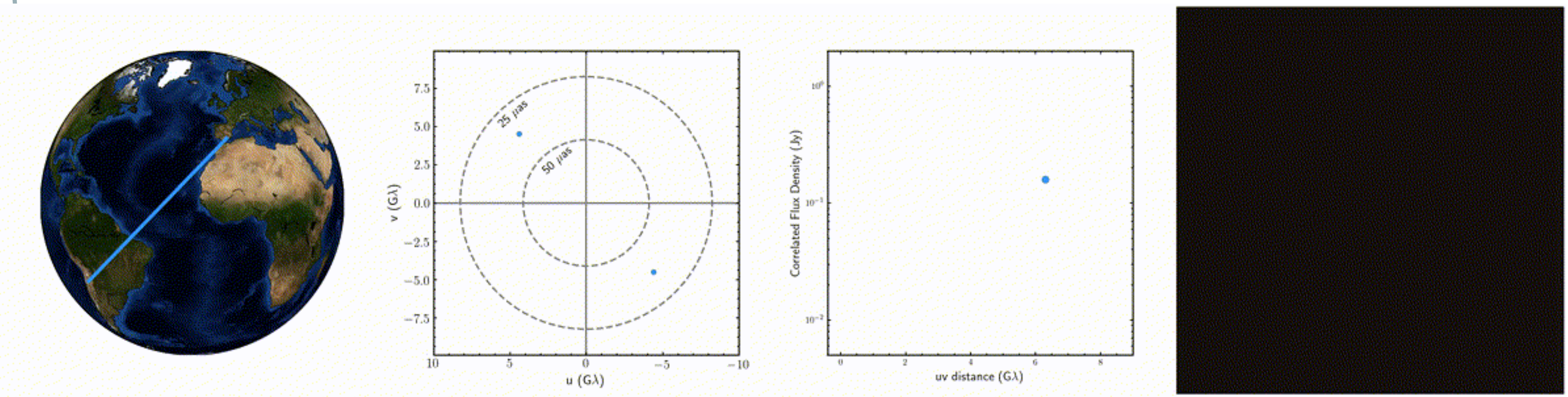
Now: Very Long Baseline





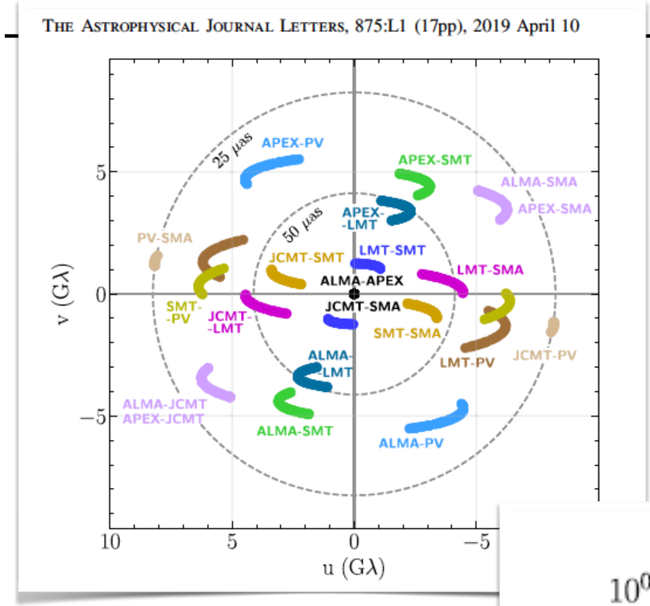
Earth Rotation Synthesis

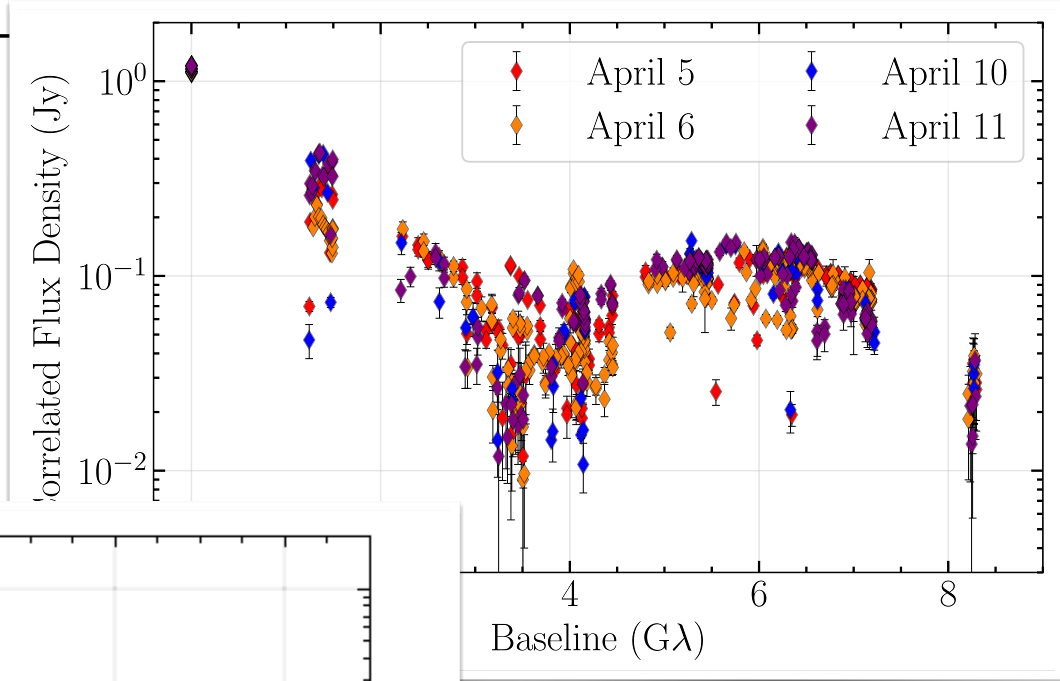
- The EHT on M87...

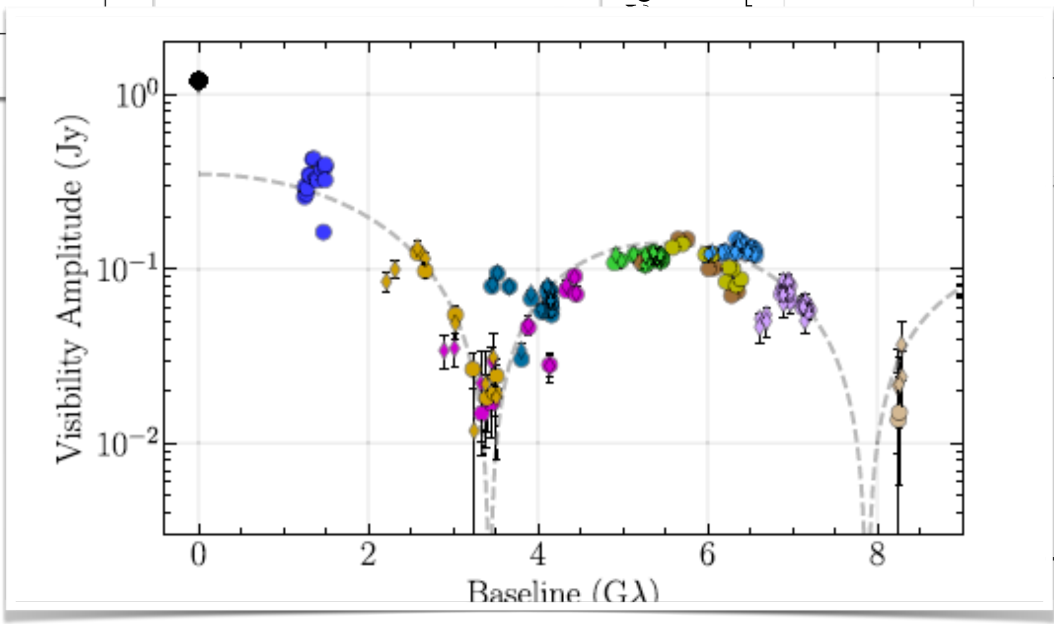


Video Credit: Daniel Palumbo and Maciek Wielgus

First M87 results

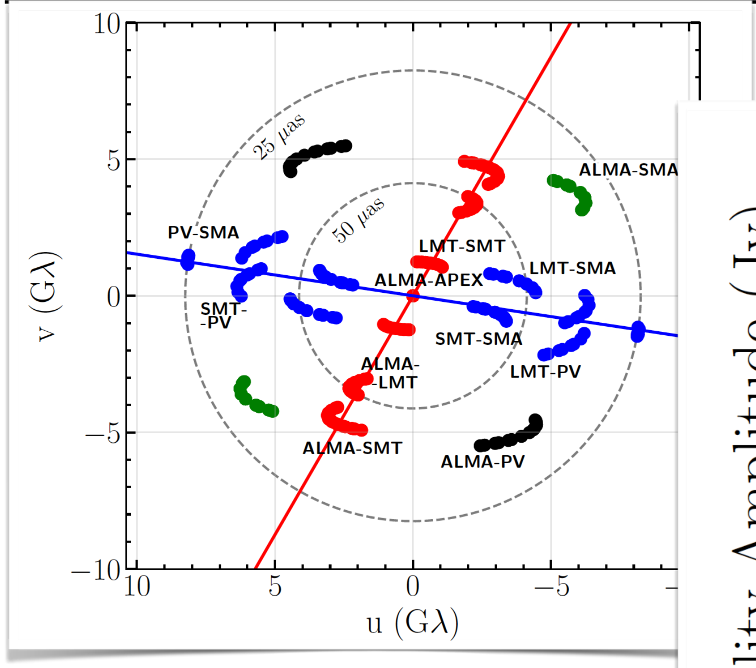


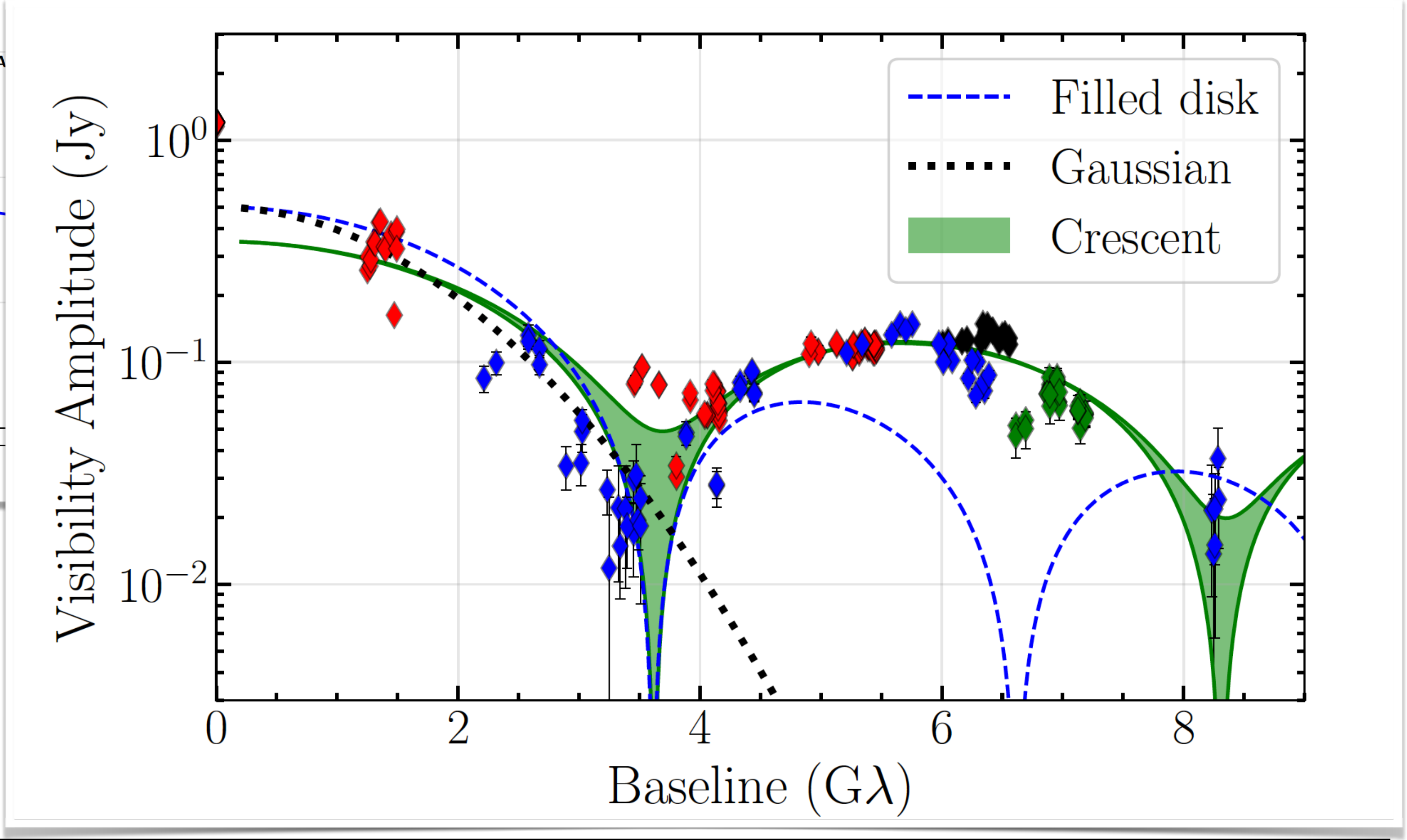




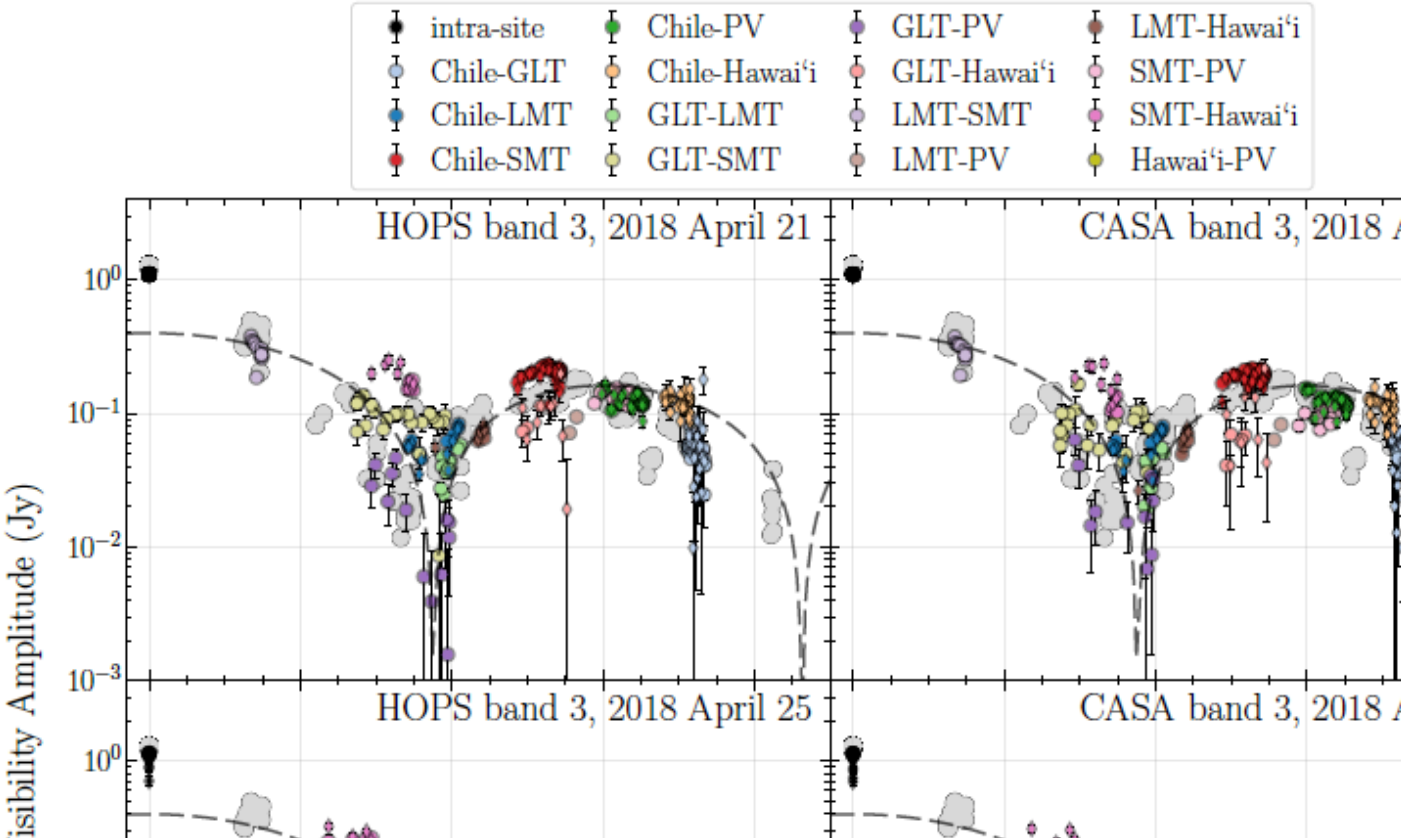
Event Horizon Telescope

April 11 2017 data in detail



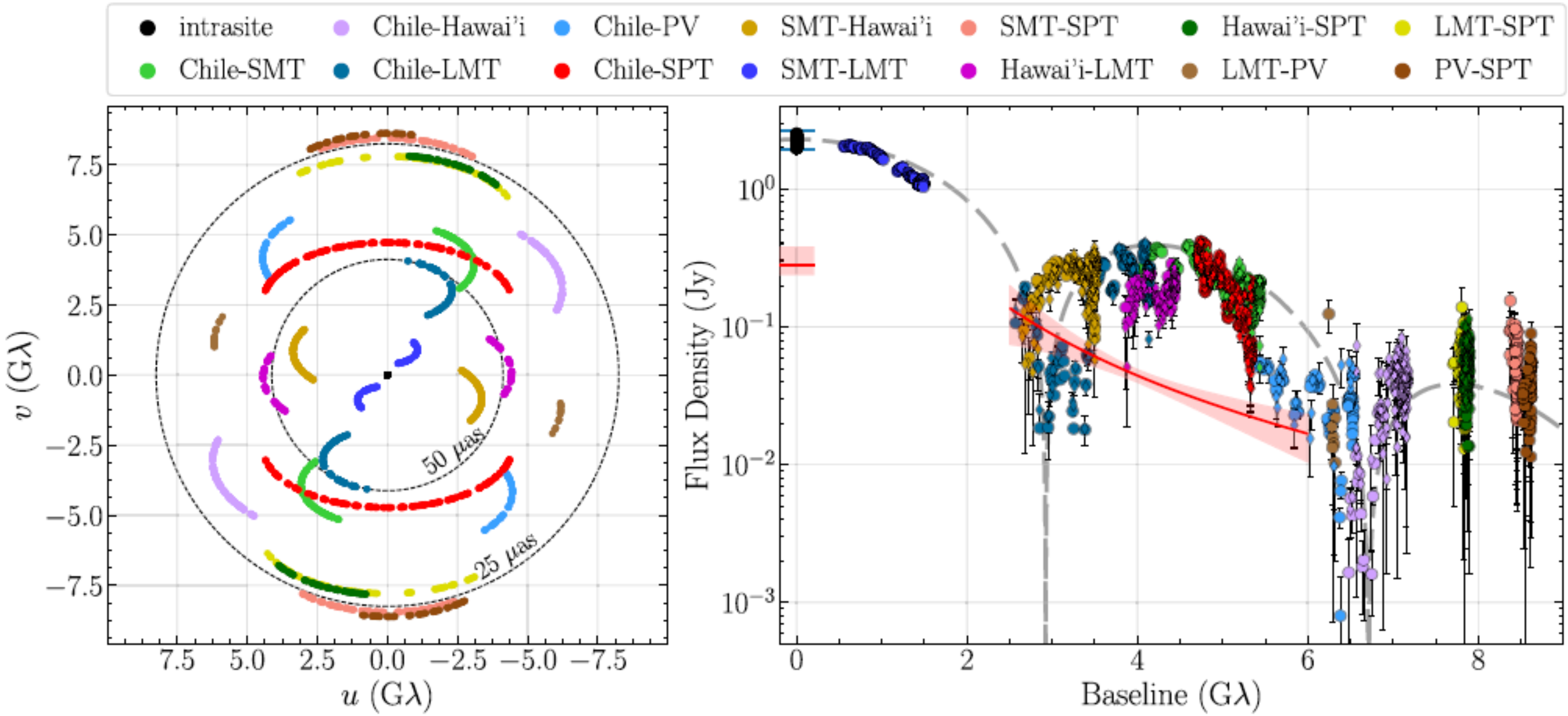


Event Horizon Telescope


intra-site
Chile-GLT
Chile-LMT
Chile-SMT
Chile-PV
Chile-Hawai‘i
GLT-LMT
GLT-SMT
GLT-PV
GLT-Hawai‘i
LMT-SMT
LMT-PV
LMT-Hawai‘i
SMT-PV
SMT-Hawai‘i
Hawai‘i-PV
HOPS band 3, 2018 April 21
CASA band 3, 2018 A
HOPS band 3, 2018 April 25
CASA band 3, 2018 A
isibility Amplitude (Jy)
10^0
10^{-1}
10^{-2}
10^{-3}

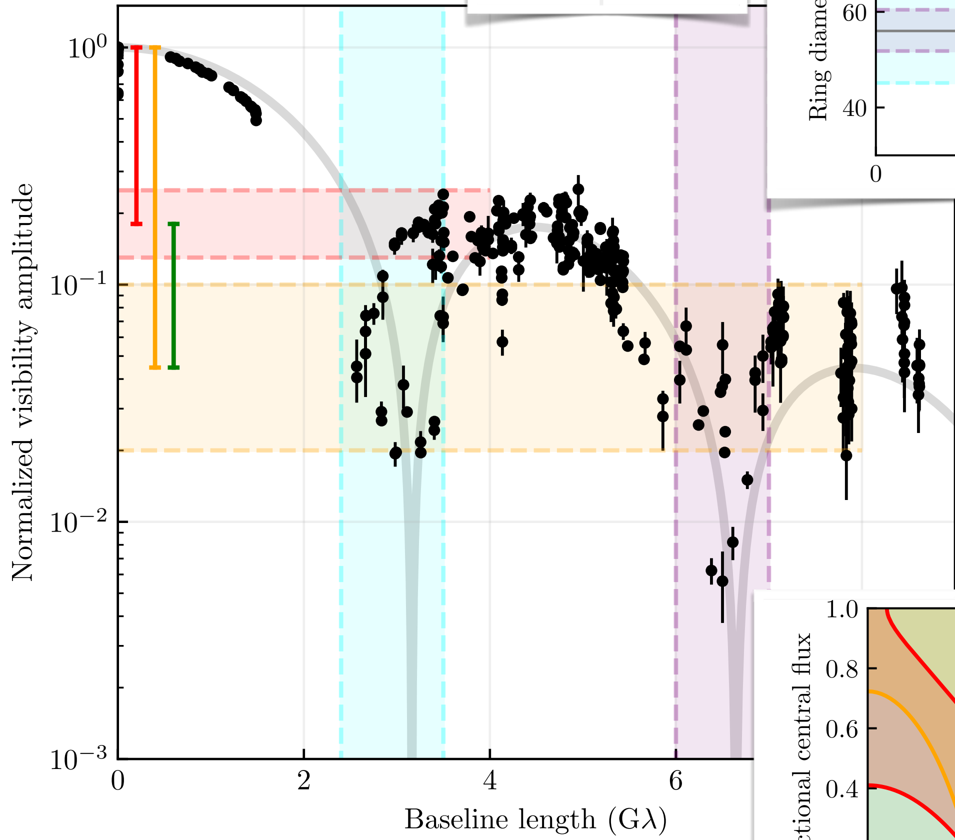
And for SgrA* in 2017, April 7

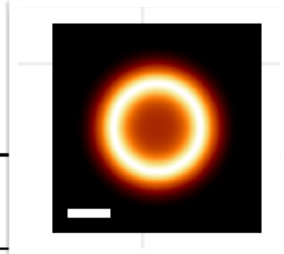
The Astrophysical Journal Letters, 930:L12 (21pp), 2022 May 10 Event Horizon Telescope Collaboration et al.

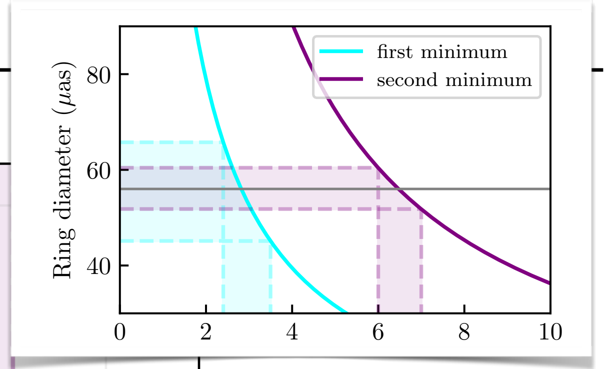


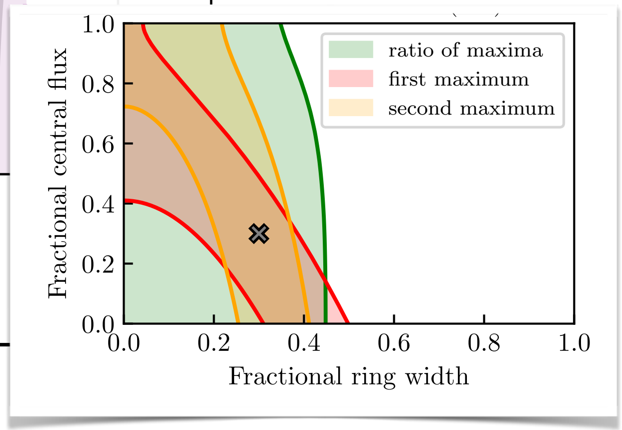
SgrA* April 7

- After a-priori calibration
  - Corrected for scattering
- Clearly 2 minima
  - Noise structure attributed to variability
  - Asymmetry visible in first minimum
  - Ring diameter from locations of minima
  - Fractional width from maxima



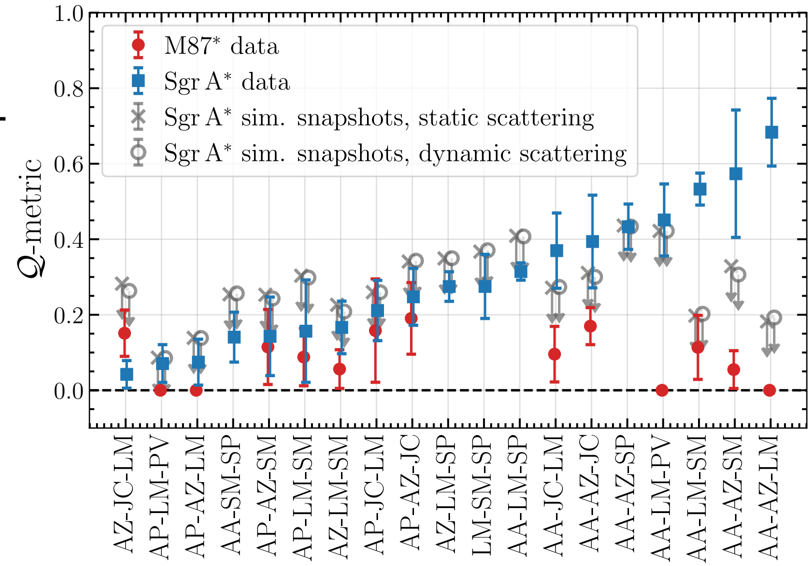






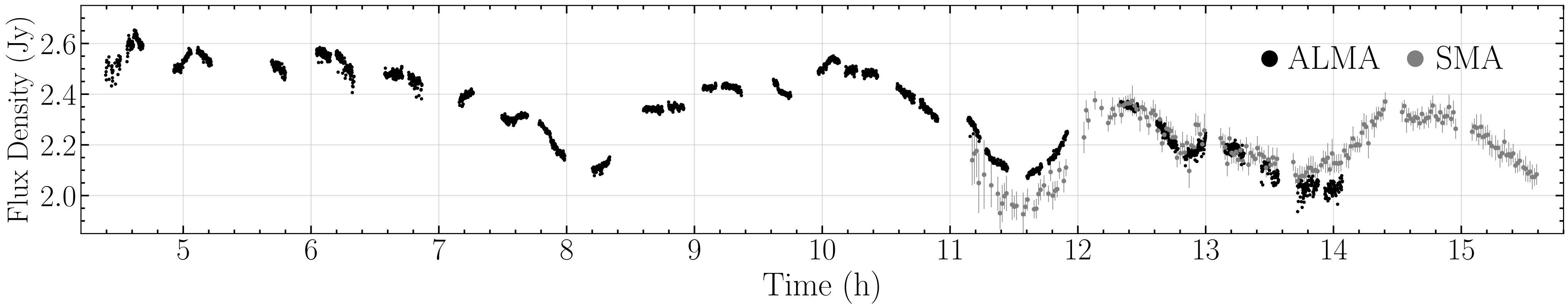
SgrA* Variability

Q-metric measures closure phase statistics (Roelofs et al., 2017), shows SgrA* variability on long baselines



- Total flux variability
  - Can be estimated robustly from interferometers
- Structural variability
  - Must be estimated from redundant visibilities
    - Between days
    - Baseline crossings
  - Or from modelling
    - Using closure properties

Interferometrically measured total flux variations, Wielgus et al., 2022



Imaging, first M87 as it is static…

The Astrophysical Journal Letters, 875:L4 (52pp), 2019 April 10 The EHT Collaboration et al.

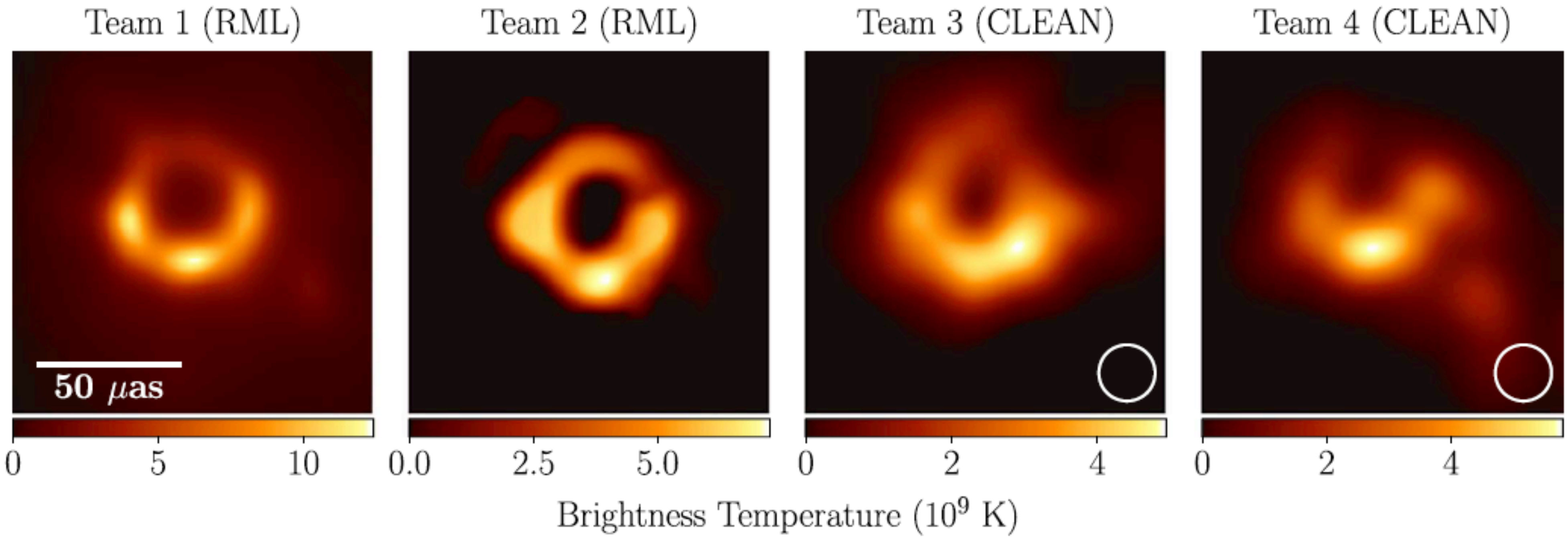


Figure 4. The first EHT images of M87, blindly reconstructed by four independent imaging teams using an early, engineering release of data from the April 11 observations. These images all used a single polarization (LCP) rather than Stokes *I*, which is used in the remainder of this Letter. Images from Teams 1 and 2 used RML methods (no restoring beam); images from Teams 3 and 4 used CLEAN (restored with a circular 20 μas beam, shown in the lower right). The images all show similar morphology, although the reconstructions show significant differences in brightness temperature because of different assumptions regarding the total compact flux density (see Table 2) and because restoring beams are applied only to CLEAN images.

Inverse vs Forward modelling

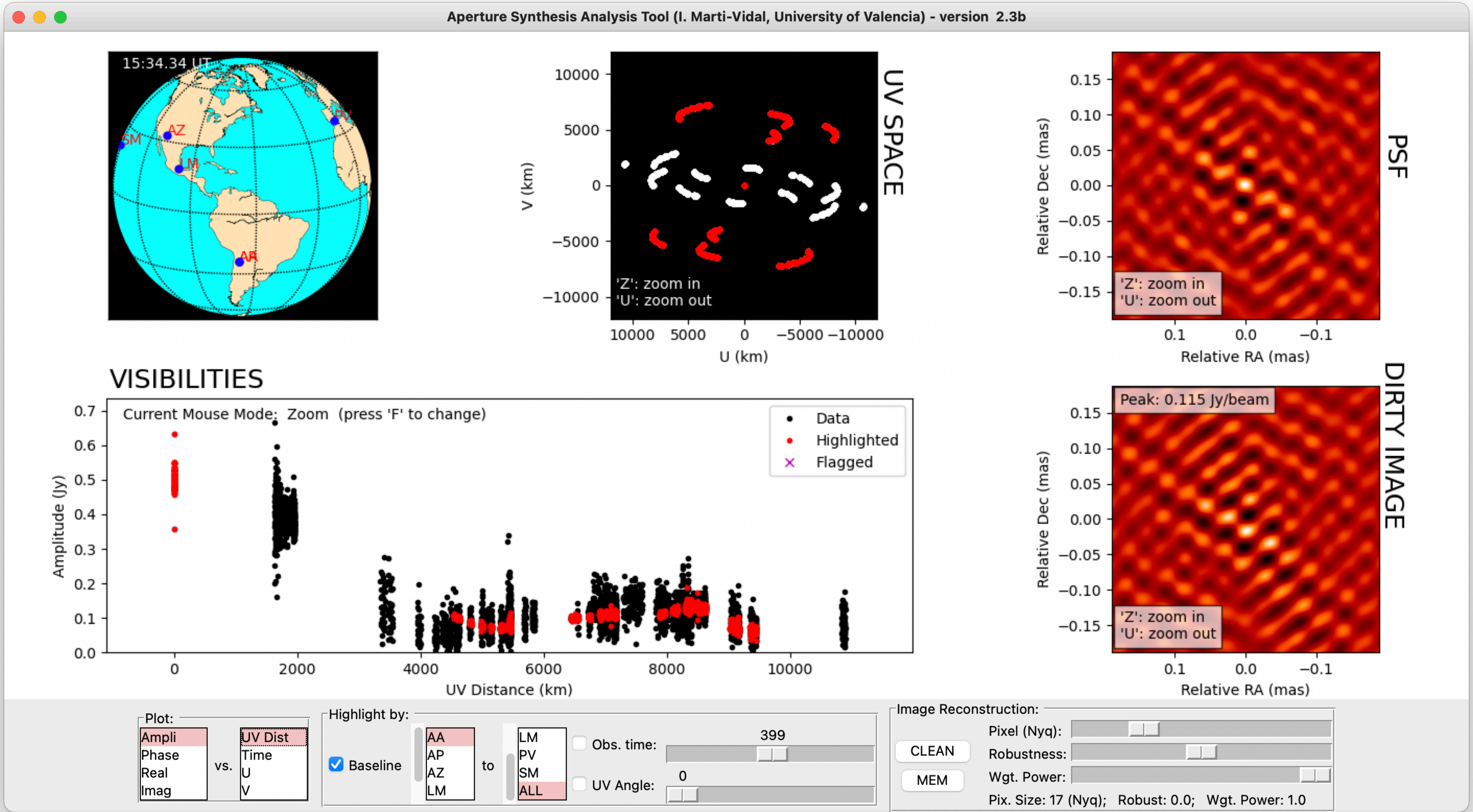
- Deconvolution, or finding a way to interpolate the missing uv-samples
- CLEAN is a procedural approach
  - Start with Fourier inversion
- Also Regularised Maximum Likelihood (RML) methods
  - Find best fit to data with specified image property

$$J(I) = \sum_{\text{data terms}} \alpha_D \chi^2_D(I) - \sum_{\text{regularizers}} \beta_R S_R(I).$$

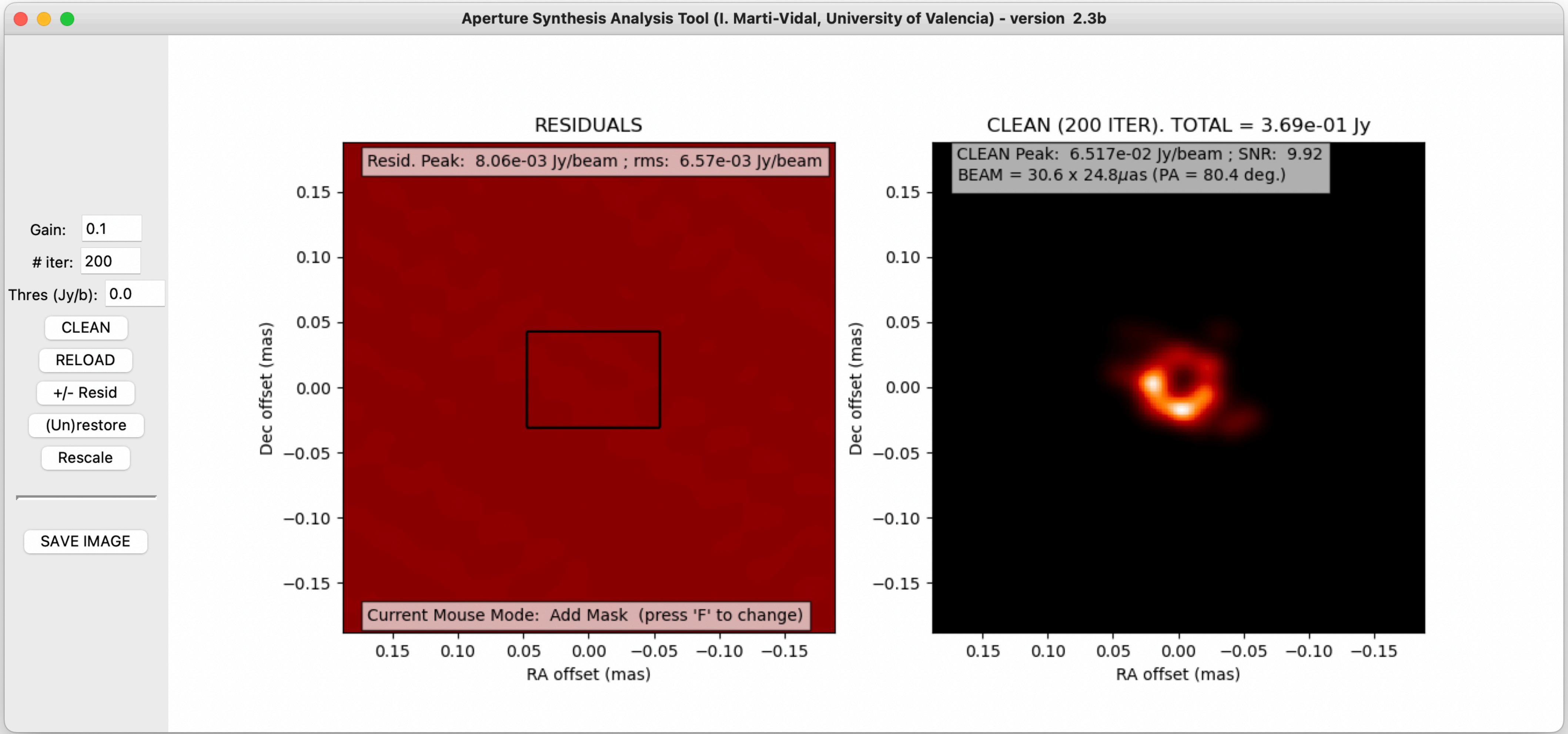
  - Traditionally "MEM", maximises entropy in data pixels: positive and compressed
  - Need constraints like
    - Total Field of View (FoV)
    - And total flux

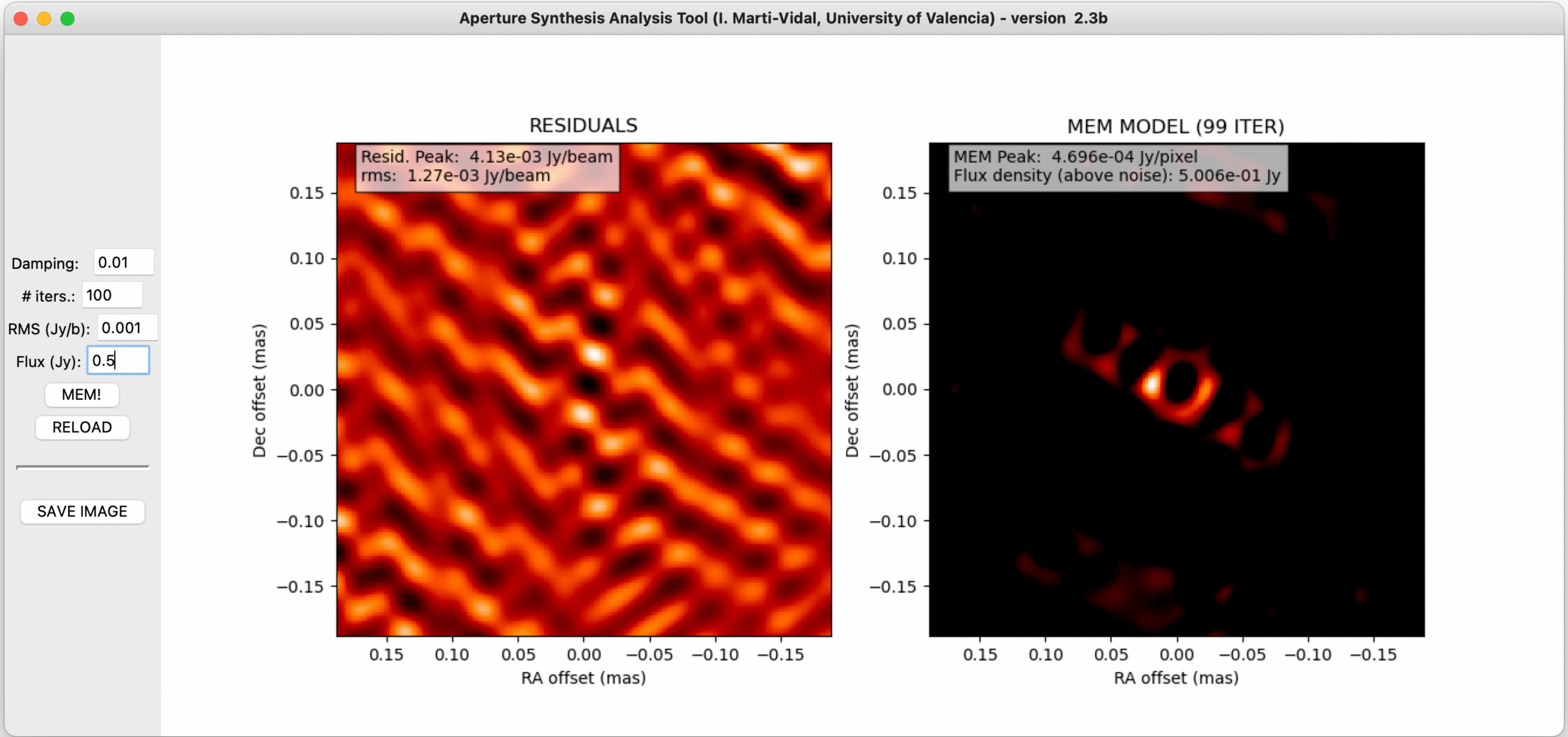
$$S_{\mathrm{MEM}} = -\frac{1}{\zeta} \sum_i I_i \log\left(\frac{I_i}{P_i}\right).$$

  - Iterate from start image



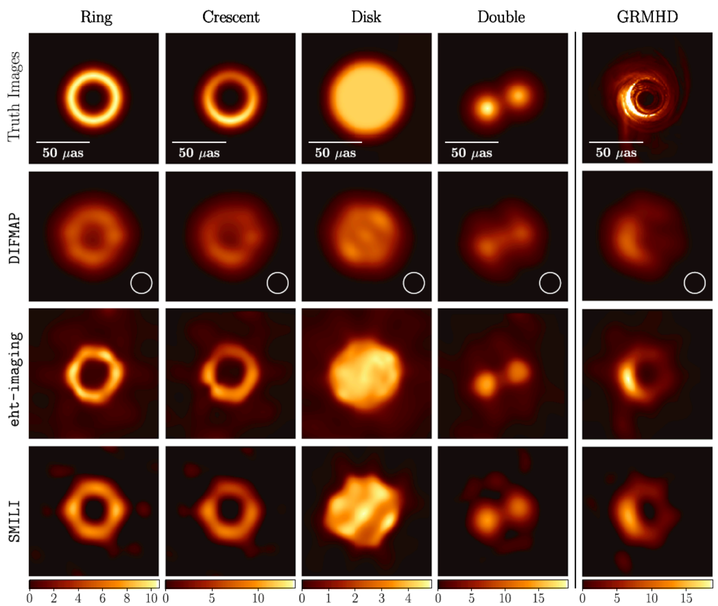
Aperture Synthesis Analysis Tool (I. Marti-Vidal, University of Valencia) - version 2.3b
15:34.34 UT
SM
AZ
LM
PV
AR
UV SPACE
V (km)
U (km)
'Z': zoom in
'U': zoom out
PSF
Relative Dec (mas)
Relative RA (mas)
VISIBILITIES
Current Mouse Mode: Zoom (press 'F' to change)
Data
Highlighted
Flagged
Amplitude (Jy)
UV Distance (km)
DIRTY IMAGE
Peak: 0.115 Jy/beam
Plot:
Ampli
Phase
Real
Imag
vs.
UV Dist
Time
U
V
Highlight by:
Baseline
AA
AP
AZ
LM
to
LM
PV
SM
ALL
Obs. time:
399
UV Angle:
0
Image Reconstruction:
CLEAN
MEM
Pixel (Nyq):
Robustness:
Wgt. Power:
Pix. Size: 17 (Nyq); Robust: 0.0; Wgt. Power: 1.0

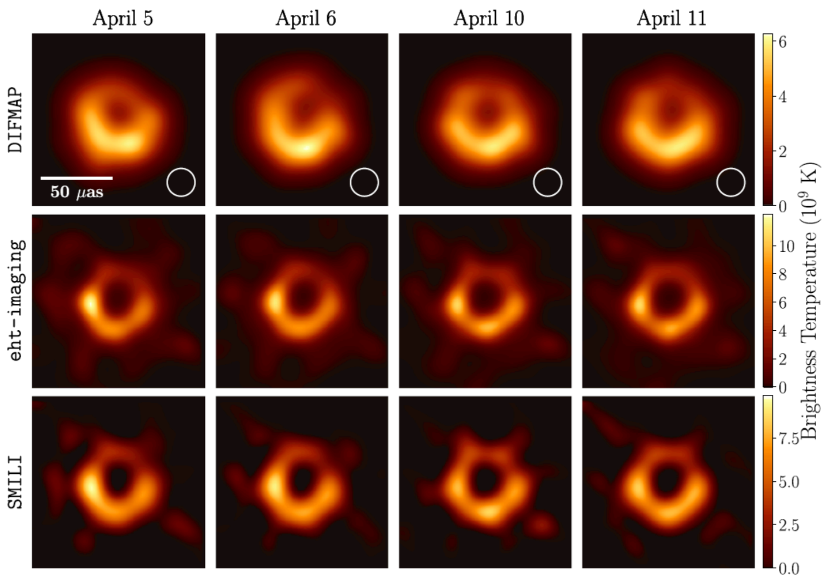

Aperture Synthesis Analysis Tool (I. Marti-Vidal, University of Valencia) - version 2.3b
Gain: 0.1
iter: 200
Thres (Jy/b): 0.0
CLEAN
RELOAD
+/- Resid
(Un)restore
Rescale
SAVE IMAGE
RESIDUALS
Resid. Peak: 8.06e-03 Jy/beam ; rms: 6.57e-03 Jy/beam
Current Mouse Mode: Add Mask (press 'F' to change)
CLEAN (200 ITER). TOTAL = 3.69e-01 Jy
CLEAN Peak: 6.517e-02 Jy/beam ; SNR: 9.92
BEAM = 30.6 x 24.8μas (PA = 80.4 deg.)
Dec offset (mas)
RA offset (mas)


Aperture Synthesis Analysis Tool (I. Marti-Vidal, University of Valencia) - version 2.3b
Damping: 0.01
iters.: 100
RMS (Jy/b): 0.001
Flux (Jy): 0.5
MEM!
RELOAD
SAVE IMAGE
RESIDUALS
Resid. Peak: 4.13e-03 Jy/beam
rms: 1.27e-03 Jy/beam
MEM MODEL (99 ITER)
MEM Peak: 4.696e-04 Jy/pixel
Flux density (above noise): 5.006e-01 Jy
Dec offset (mas)
RA offset (mas)
0.15
0.10
0.05
0.00
−0.05
−0.10
−0.15

How to do this robustly?

- The EHT developed parameter top sets
  - Making artificial data with same uv-coverage and noise properties
  - Establishing settings that produce consistent results





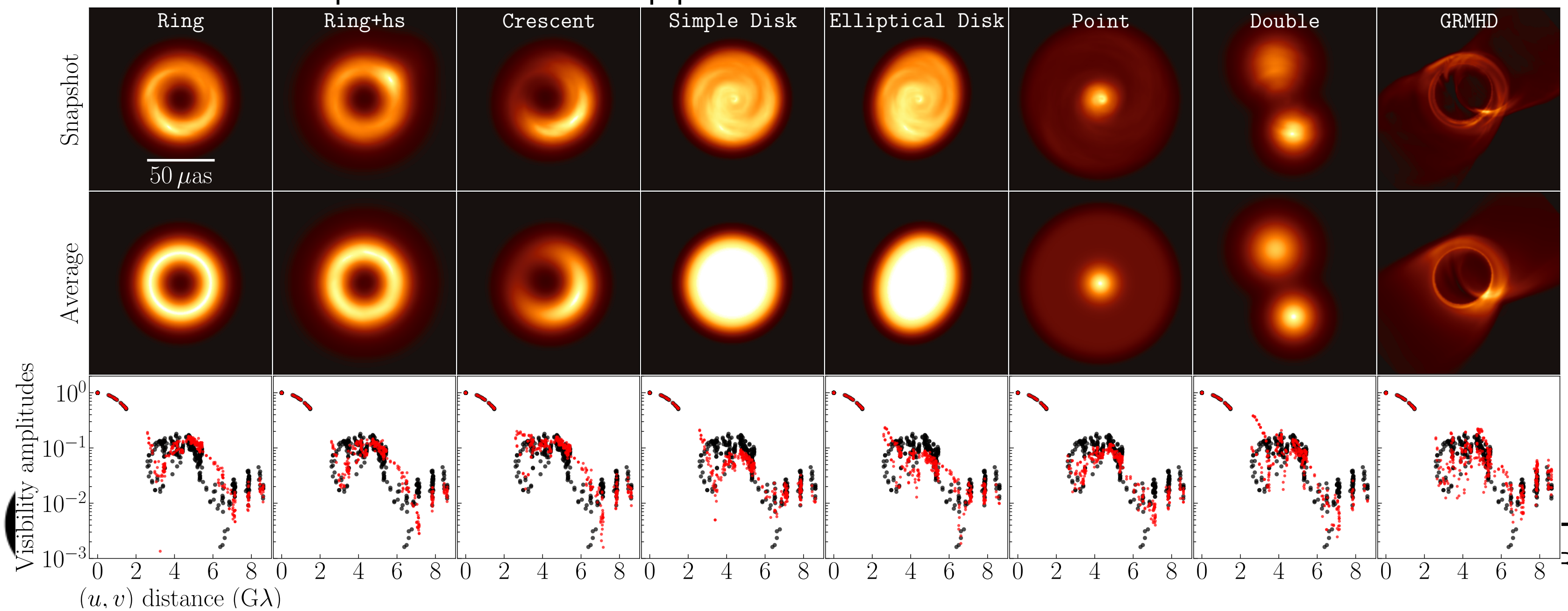
- And average over different methods

Even more complex for variable SgrA*

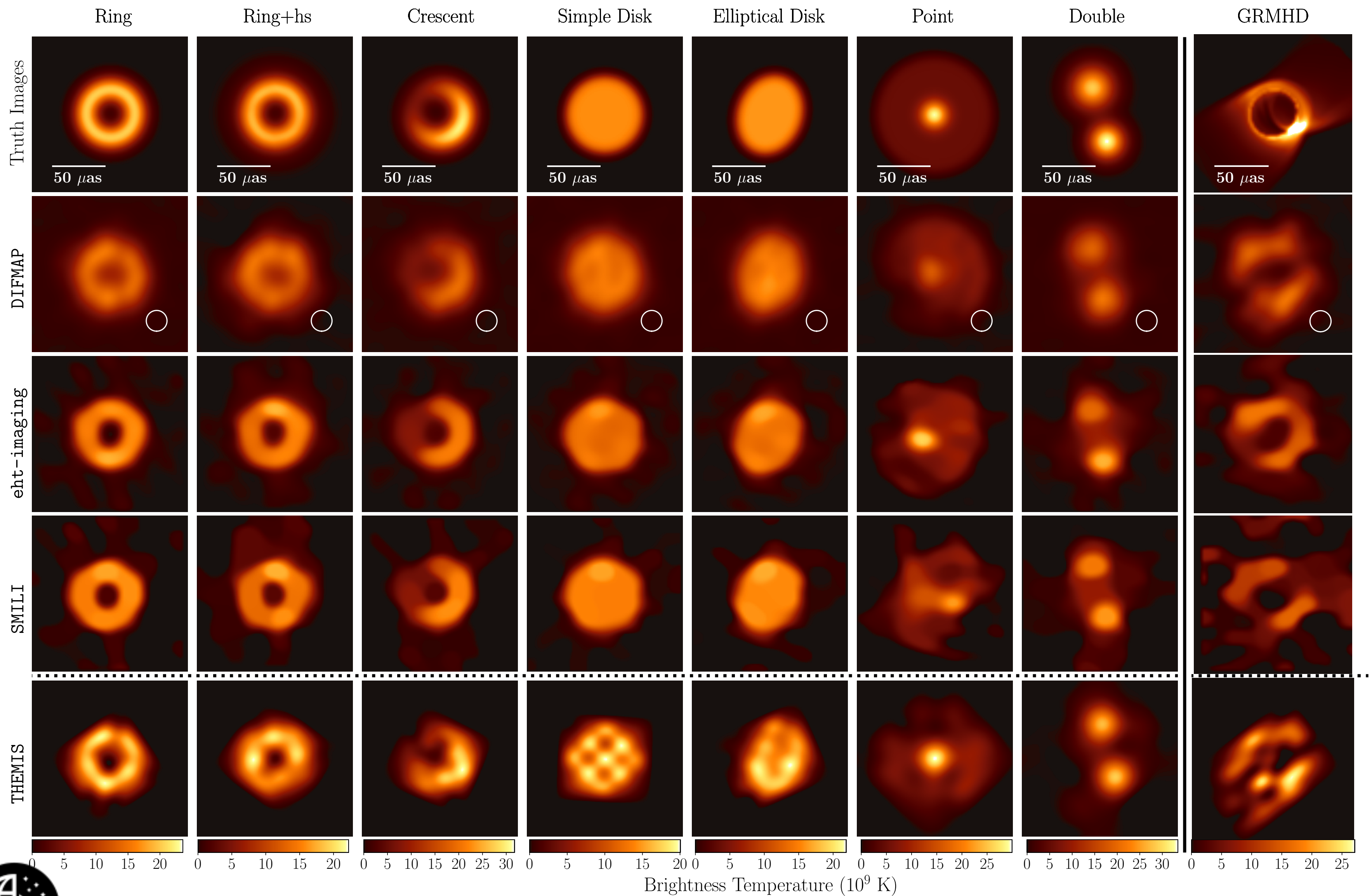
- Sliding scale between:

independent frames ← temporal constraints → average images

- Imaging can be a black-belt art
  - Unacceptable for our application

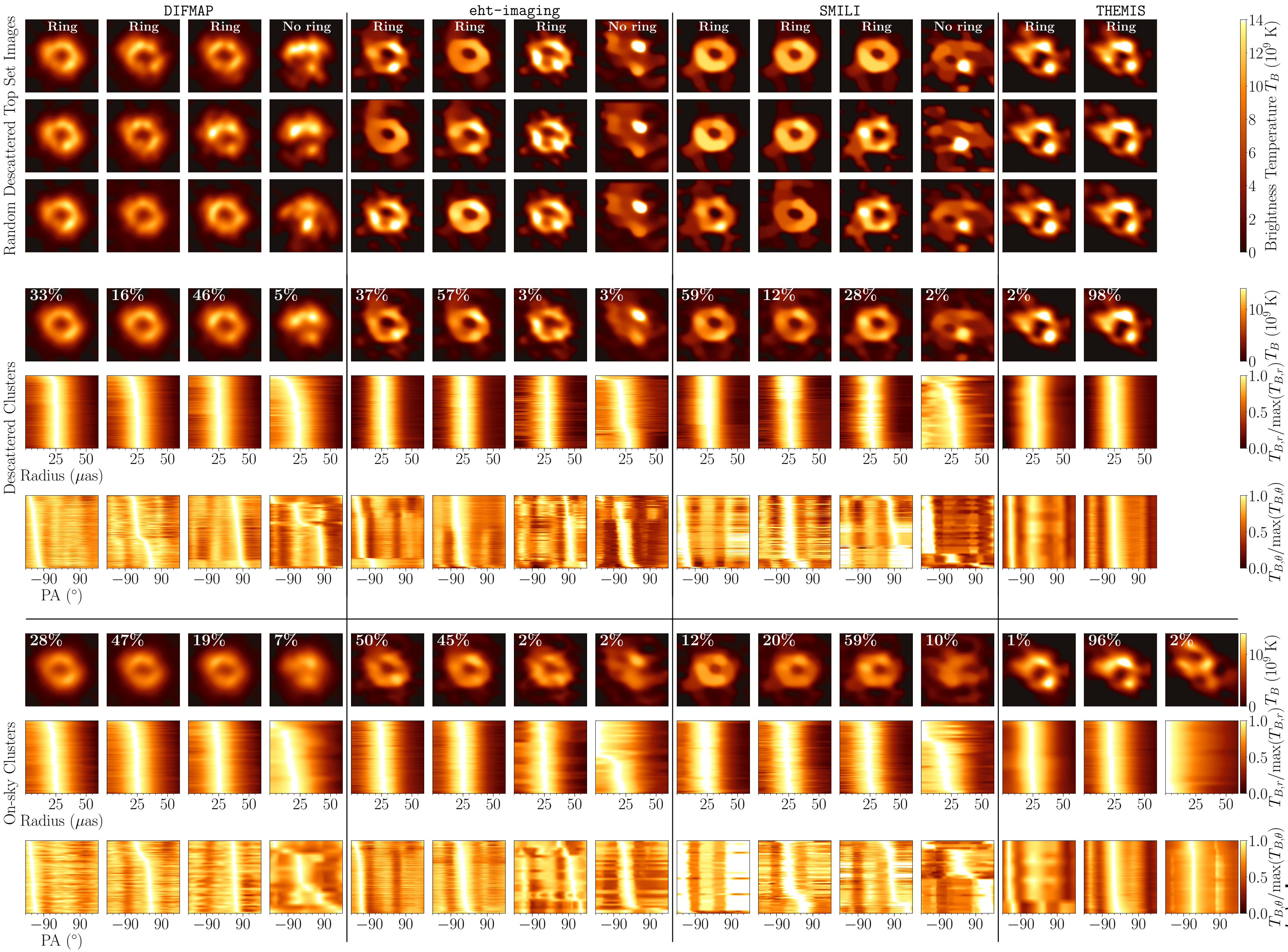


- Test 4 pipelines on artificial, time variable, scattered data
  - Using the same uv-coverage and telescope characteristics
  - Derive parameter 'top sets' that match truth images
  - Use same 'top sets' to process SgrA*



Fitting the average image

- Simulate data with test images
- Inflate error budgets with estimates of variability
- Recovering the test images with top set parameters

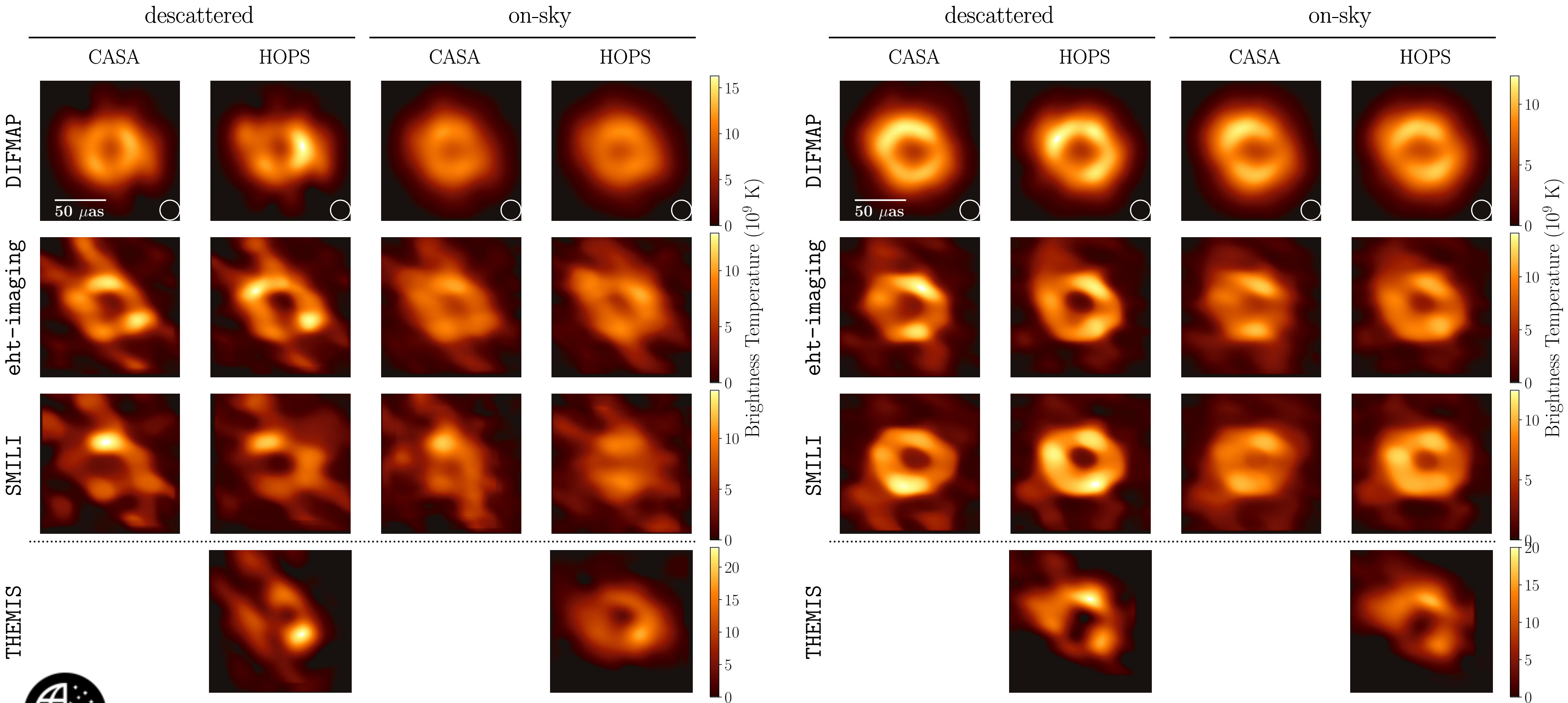


Then repeat for real data!

Results in families of solutions

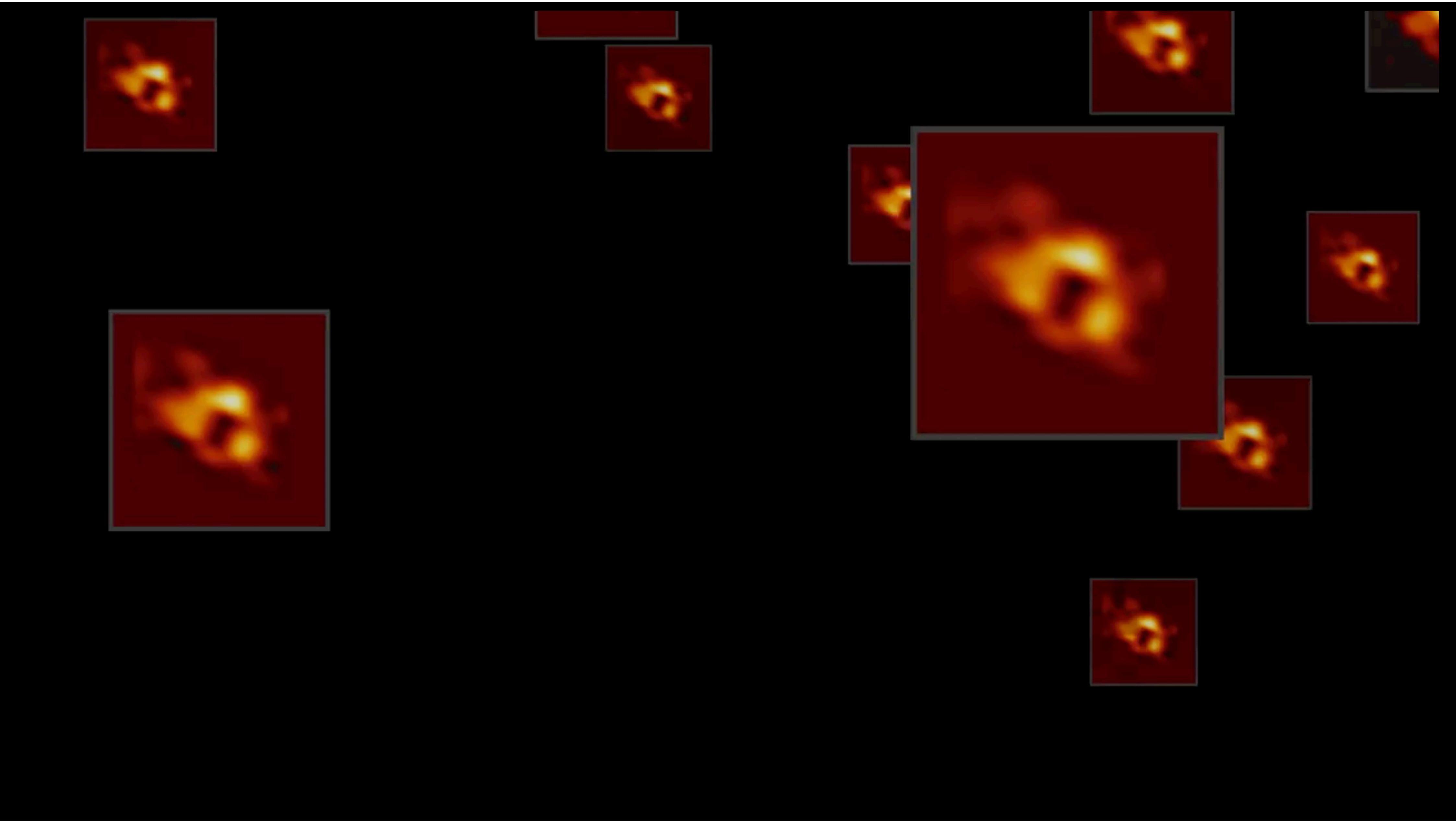
- Many rings
- Constant diameter
- Shaky azimuthal structure

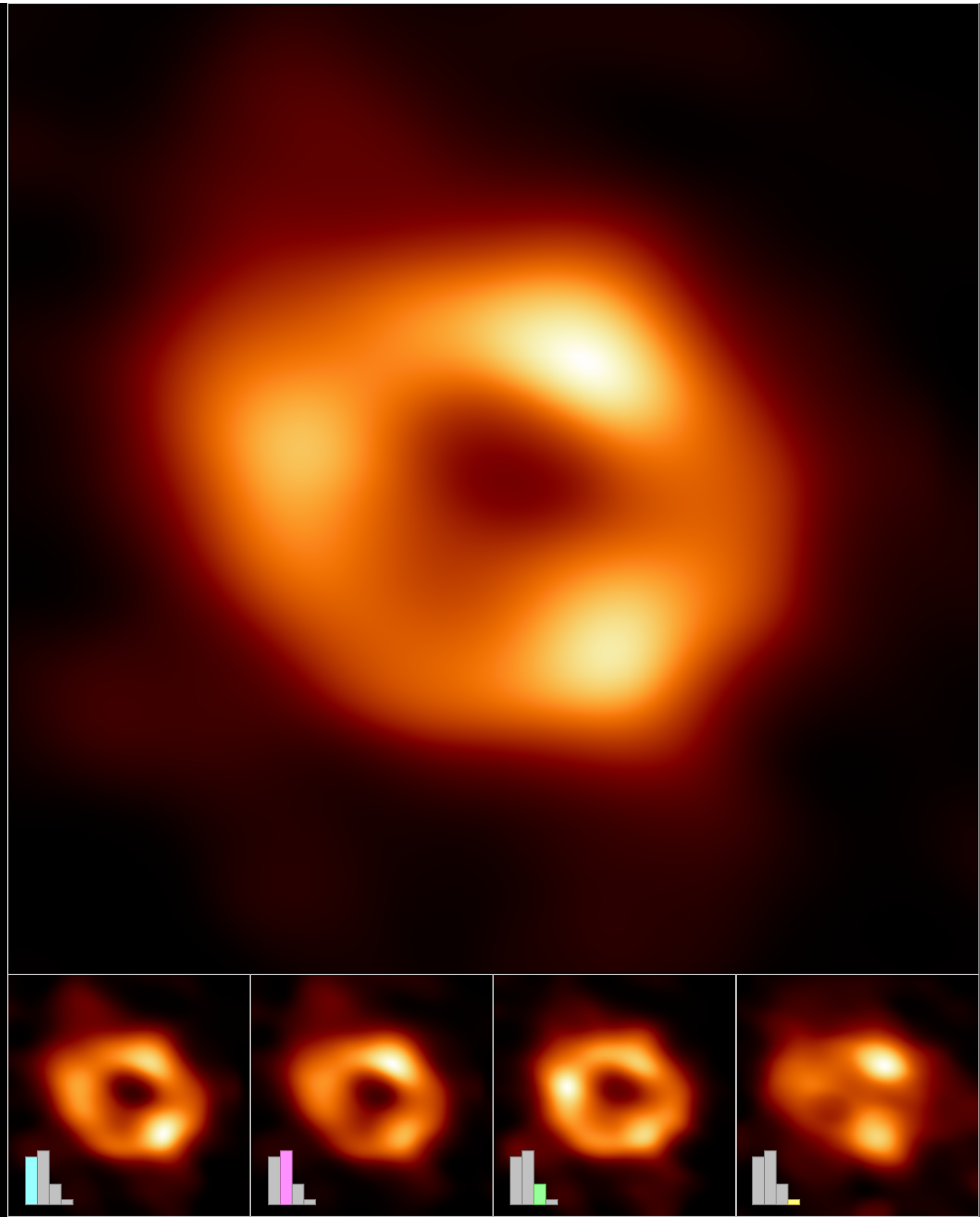
Average in morphology families



April 6

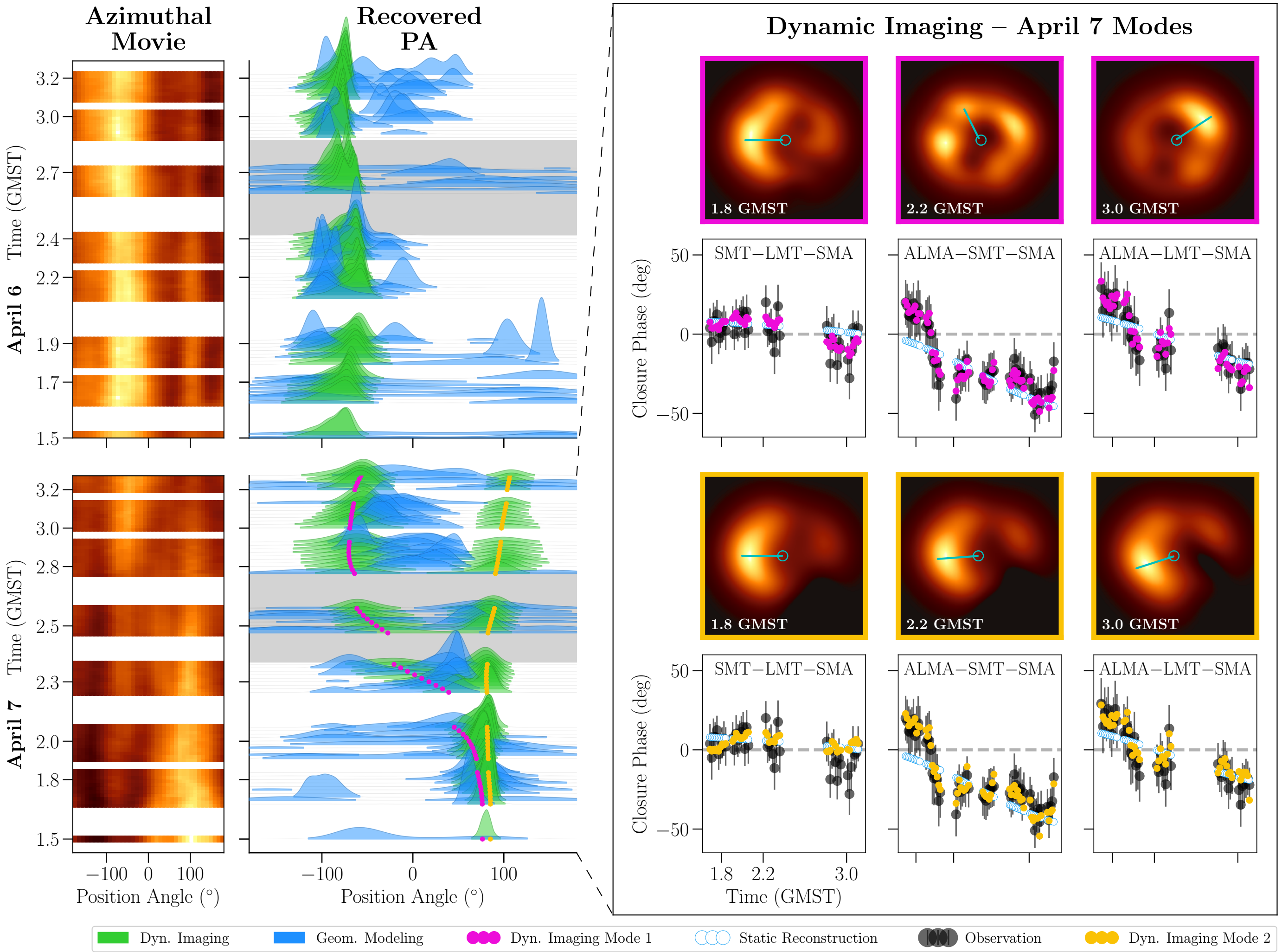
April 7



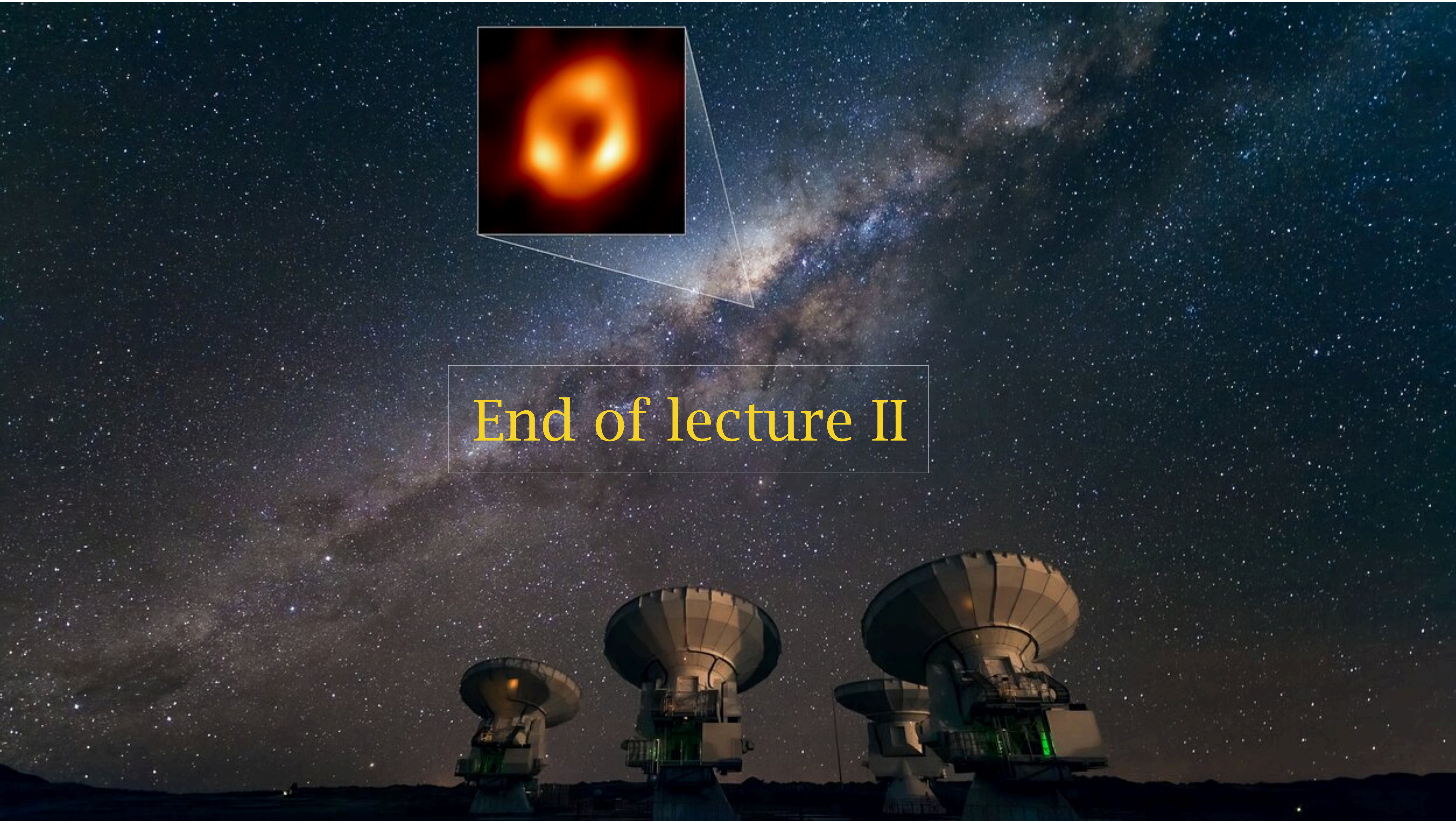


Dynamic imaging

- Promising but not conclus
  - Focusing on 100 minutes wit
  - Stable results on April 6
  - Azimuthal evolution on April
  - Still not very consistent resul
  - But hopeful for future



Event Horizon Telescope


End of lecture II