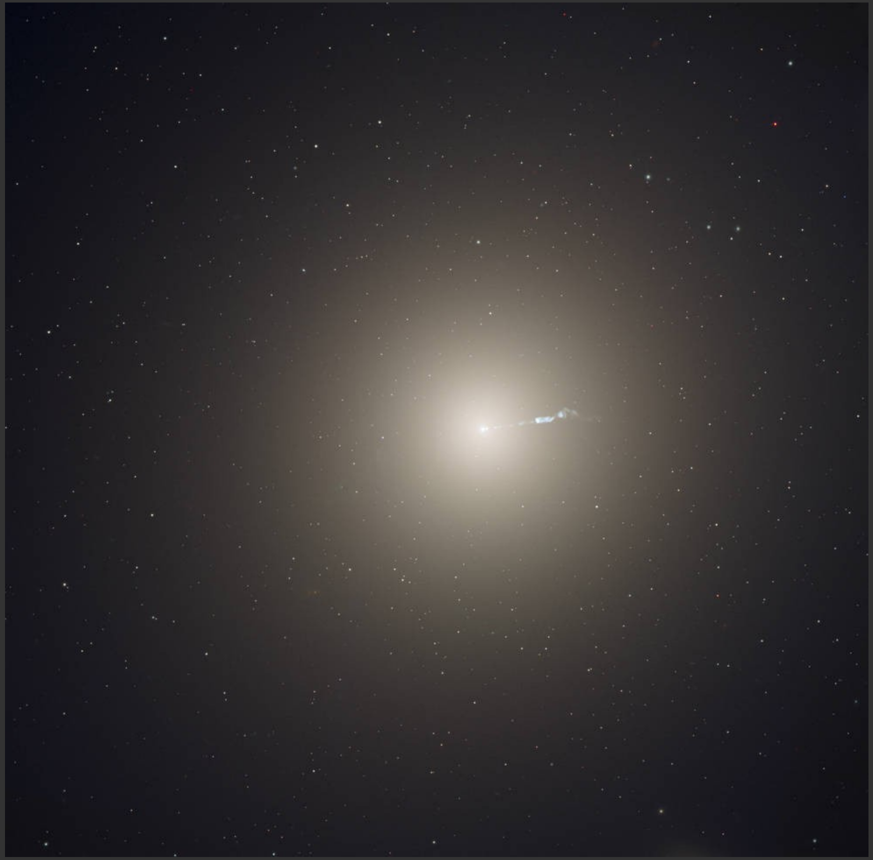
What goes into the images made by the Event Horizon Telescope?

Rajaram Nityananda
ICTS+.......

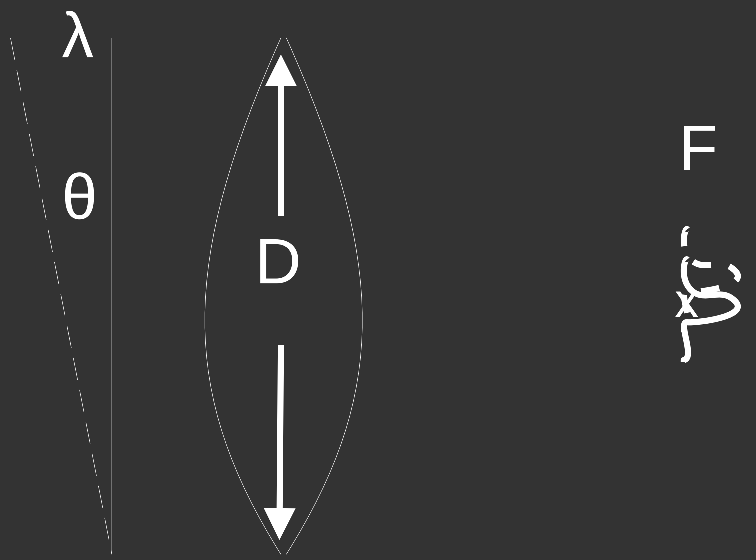
The Elliptical galaxy M87



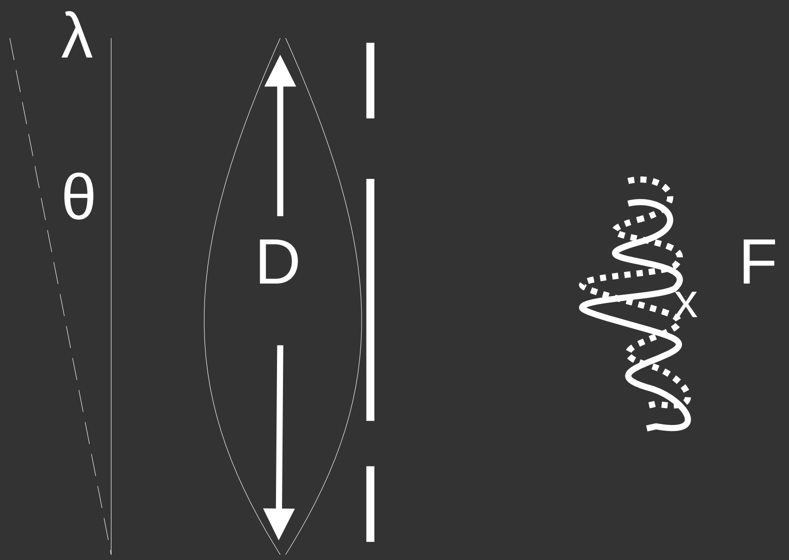
EHT target: long suspected BH at the centre of M87

- Galaxy known to have an optical ‘jet’ since 1918, large scale radio emission and radio jet observed by the 70’s
- Gas disk (1994, HST) evidence points to a central mass of several billion solar masses within 3” (≈ 800 ly at 55e6 ly)
- 3e9 M_{sun} implies $r_{schwarzsdhild}$ ≈ 3e4 ls
- Strong energy release around ~10 r_s ~ 3 ld
- 1 ld / 55 e6 ly ≈ 5e-11 (radians) or 1e -5 “ or 10 µas
- λ/D ~ 1mm/ 1e4 km ~ 1e-10 or 20 µas

Resolving a binary star



$\theta = \lambda / D$



$at\, \theta = \lambda / 2D$ the fringes disappear

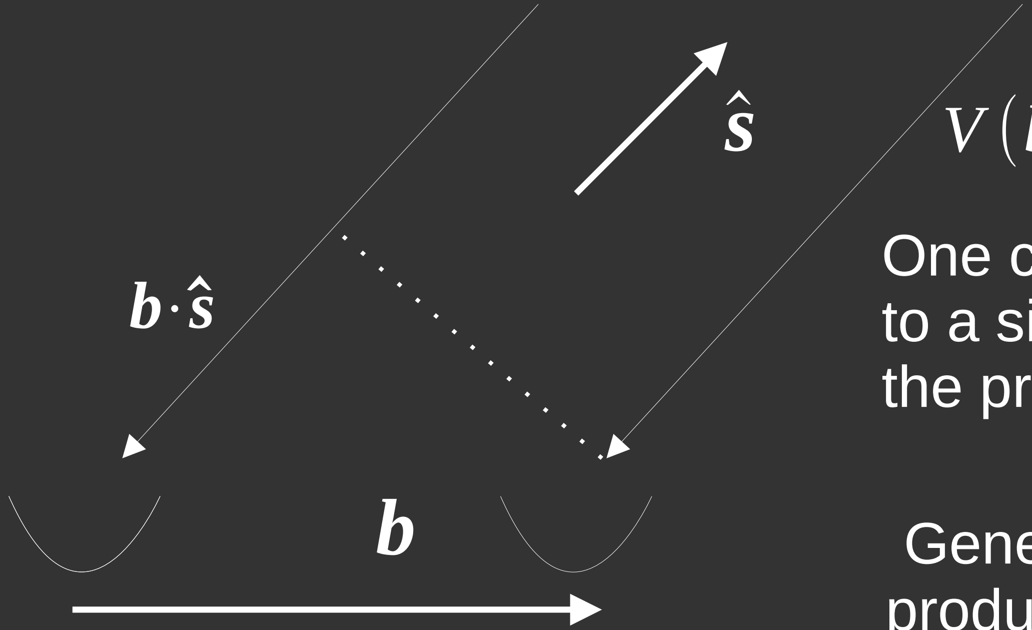
Interferometry

- Fizeau – Disappearance of fringes from two apertures can give the separation of a binary star
- Michelson and Pease 1930’s: a pair of mirrors of variable separation (upto 6m) to find the angular diameter of Betelguse as 47 mas at optical wavelengths
- Extended to radio wavelengths post WW2 in Austraila, UK
- An interferometer measures the Fourier transform of the sky brightness distribution - credited very belatedly to Ruby Payne-Scott , a pioneering woman radio astronomer in Australia

Radio ‘signals’

- Classical regime so occupation number >>1   i.e $h\nu \ll k_B T$ Rayleigh and Jeans are alive and well in radio astronomy
- We measure random electric fields which can be modeled as a sum of waves at multiple frequencies ω arriving from multiple directions $\hat{\mathbf{s}}$ with random phases.
- Gaussian statistics stationary in space and time
- Power spectrum in frequency and angle $dE = I\left(\omega, \frac{\omega}{c}\hat{\mathbf{s}}\right)\ d\hat{\mathbf{s}}\, d\omega\, dA\, dt$
- ‘Band’ is split into narrow frequency ‘channels’– nowadays by direct sampling in the time domain and real time Fourier transformation
- At each frequency, transverse correlation functions are related by Fourier transformation to the angular content (i.e map)

A tale of two telescopes



$$I_{12} = \langle (\boldsymbol{E_1} + \boldsymbol{E_2})(\bar{\boldsymbol{E}}_1 + \bar{\boldsymbol{E}}_2) \rangle$$

$$I_{12} = I_1 + I_2 + \langle \boldsymbol{E_1} \bar{\boldsymbol{E}}_2 + \bar{\boldsymbol{E}}_1 \boldsymbol{E_2} \rangle$$

$$V(\boldsymbol{b}) = \langle \boldsymbol{E_1} \bar{\boldsymbol{E}}_2 \rangle \propto I(\hat{\boldsymbol{s}}) \exp(2\pi i (\boldsymbol{b} \cdot \boldsymbol{s}) / \lambda)$$

One can consider *E*, *I* , and *V* as referring to a single polarisation – say *x*- or *y*, and the products as dot products.

Generalisation: *E* is 2x1, *V* is the outer product, *V* and *I* are 2x2, (like density matrices for a two state system)

A source-eye view

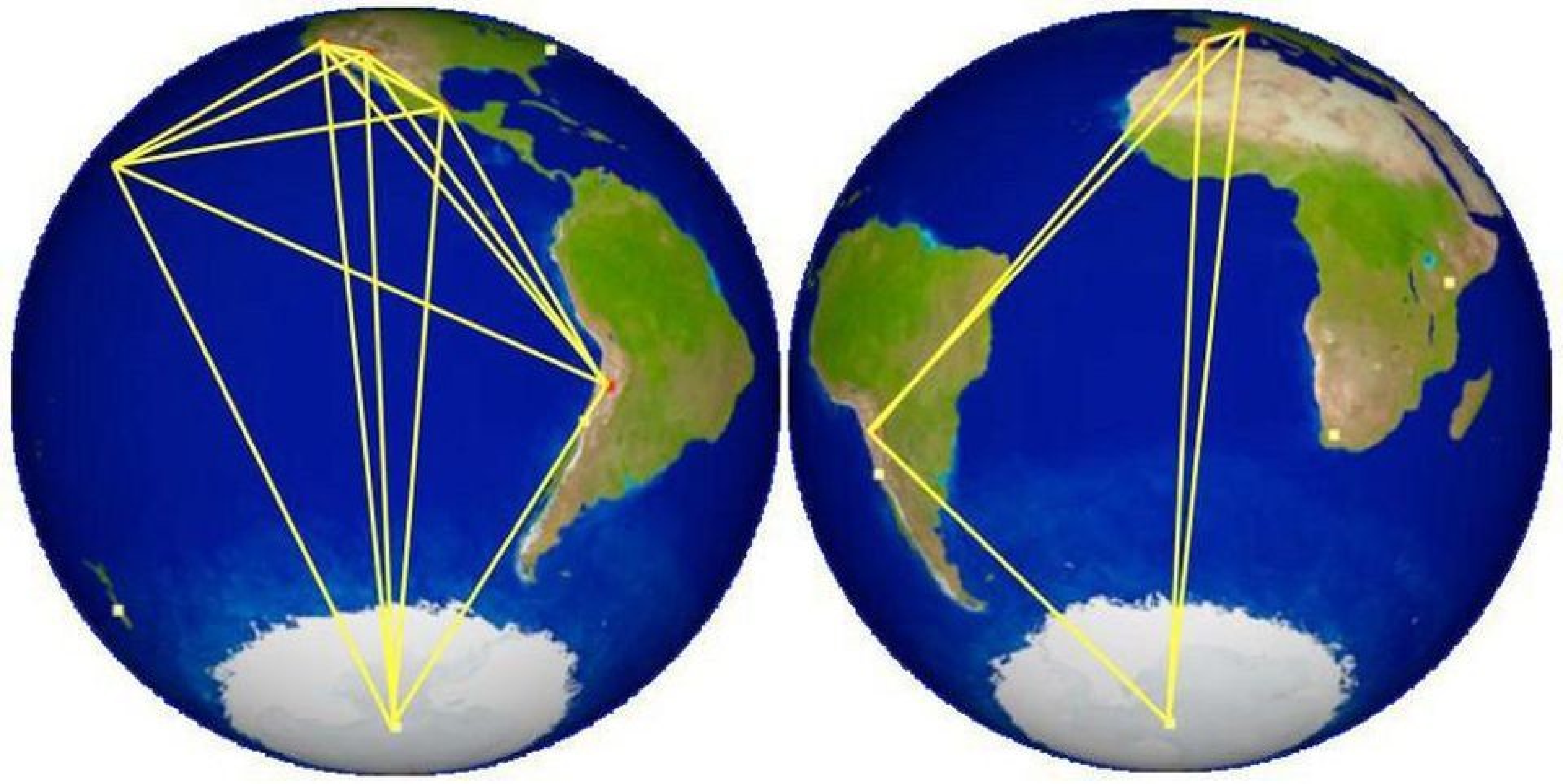
$$V(\boldsymbol{b}) = \int I(\hat{\boldsymbol{s}}) \exp(2\pi i\, \boldsymbol{b}\cdot\boldsymbol{s}/\lambda)\, d\boldsymbol{s} + n(\boldsymbol{b})$$

$\boldsymbol{b}$ filled in by earth rotation, multiple telescopes

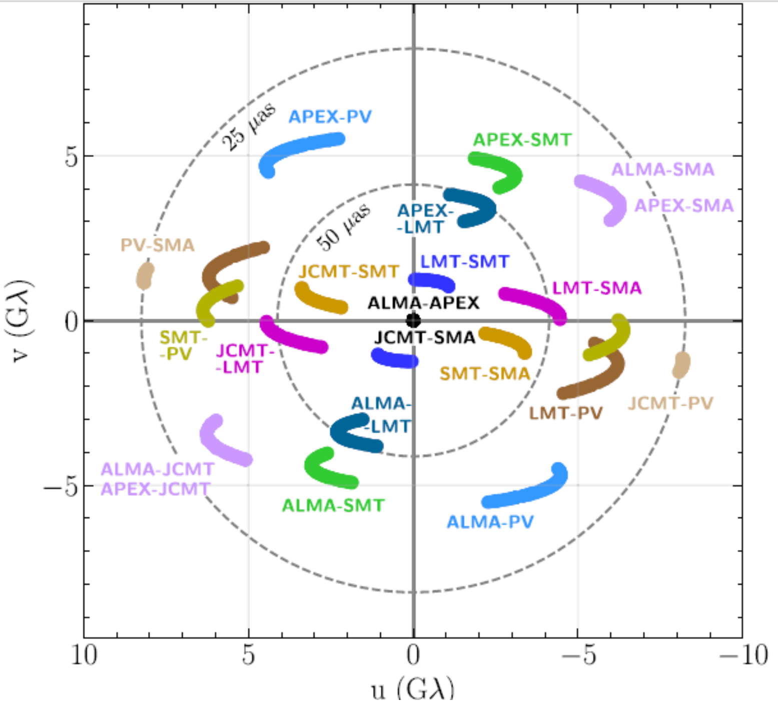
In a common limiting case we get a Fourier transform relationship

Flat sky $\boldsymbol{b}\cdot\boldsymbol{s} = b_{par}\, s_{par} + \boldsymbol{b}_{\boldsymbol{perp}}\cdot\boldsymbol{s}_{\boldsymbol{perp}}$

$$V(\boldsymbol{b}) = \exp(2\pi i\, b_{par}/\lambda) \int I(\hat{\boldsymbol{s}}) \exp(2\pi i\, \boldsymbol{b}_{\boldsymbol{perp}}\cdot\boldsymbol{s}_{\boldsymbol{perp}}/\lambda)\, d\boldsymbol{s} + n(\boldsymbol{b})$$



Locations of the EHT antennas. Note that correlations are measured only when all the antennas are visible from the source



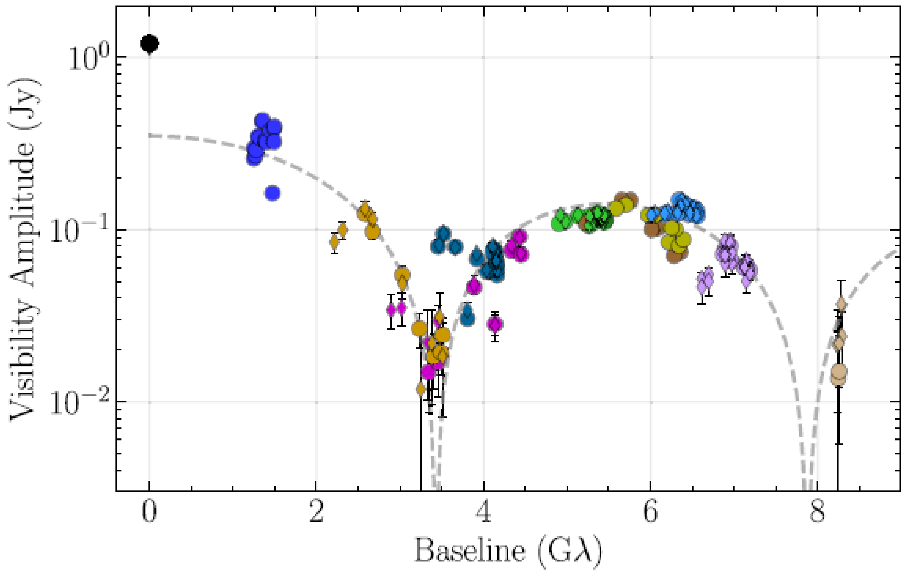


Figure 2. Top: (*u*, *v*) coverage for M87*, aggregated over all four days of the observations. (*u*, *v*) coordinates for each antenna pair are the source-projected baseline length in units of the observing wavelength λ and are given for

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First M87 Event Horizon Telescope Results. I. The Shadow of the Supermassive Black Hole

The Event Horizon Telescope Collaboration
(See the end matter for the full list of authors.)

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Abstract

The devil in the details I : getting the correlations from the data

- EHT does not have the luxury of a common ‘local oscillator” at the different telescopes
- But it is is affected by atmospheric water vapour, baseline calibration, clock differences and drifts....
- Even the amplitudes fluctuate – differently at different sites
- Acheiving an equal time correlation function requires a major computational search
- The $b_{par} s_{par}$ term carries information both about source postion and antenna separation. - astrometry and geodesy
- VLBI routinely measures points on earth to few mm accuracy and positions on the sky to milliarcseconds (nanoradians)

The devil in the details II : Making an image from the correlations

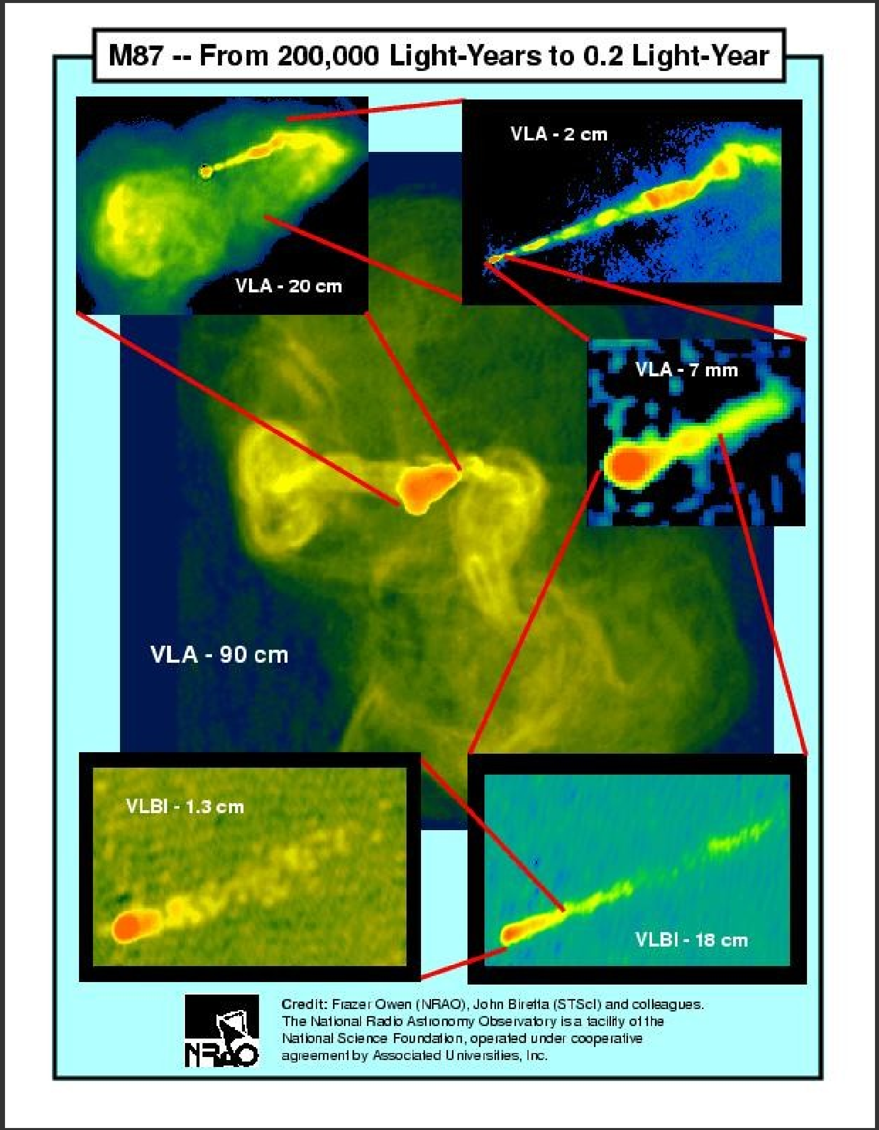
- The coverage of the Fourier plane is incomplete so the sky brightness is convolved with a ‘point spread function’. Deconvolution is ‘ill posed’
- Traditionally, phases and amplitudes are corrected by going to a point source ‘calibrator’ – works very well at mid frequencies (1-10 GHz)
- At very high frequencies, and in VLBI, the phases could be inaccurate or unavailable – but there are schemes for cancelling antenna based errors
- These are based on ‘invariants’ which cancel the errors in amplitude, phase, at the price of reducing the number of measurements

Devil in the details III: Deconvolution by regularisation

- ME says: maximise $\int -I(\hat{s}) \ln I(\hat{s}) \; d\hat{s}$ subject to the measurements as constraints
- In favourable cases, gets rid of the artefacts coming from missing Fourier components, and can even enhance resolution
- But there are unfavourable cases as well
- 1970’s work at Ooty, RRI
- CLEAN, “compressed sensing”
- Part of ‘self calibration’ – a bootstrap invented in 1980’s

Superresolution extract (paper 2)

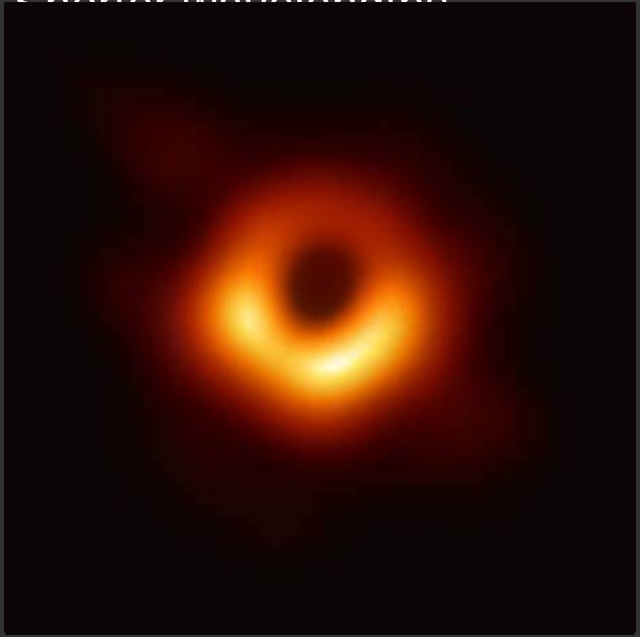
the feature. The longest baselines of the EHT (e.g., South Pole to Arizona, Hawaii, or Spain) provide nominal angular resolutions of $\lambda/D \simeq 25\ \mu$as in the 1.3 mm wavelength band. Regularized maximum likelihood (RML) imaging methods (see Paper IV) typically achieve angular resolutions that are better than the nominal figure by factors of 2–3 (Narayan & Nityananda 1986). For the EHT case in particular, RML methods have been extensively tested using realistic and synthetic interferometric data to set the optimal resolution of the array (Honma et al. 2014; Bouman et al. 2016; Chael et al.



Zooming in to the nucleus of M87

VLA has baselines upto 30km and pre EHT cm wavelength VLBI upto a few thousand km

Shorter wavelengths



Not talked about

- Polarisation measurements , sensing magnetic fields (2019)
- Our own galactic centre (2022) – 2000 times closer 1500 times smaller mass, hence similar angular size, BUT variability timescale of minutes rather than days
- mm VLBI in India, in Ladakh? SMA, ISRO discussions
- Astrophysics / relativity