Interferometry

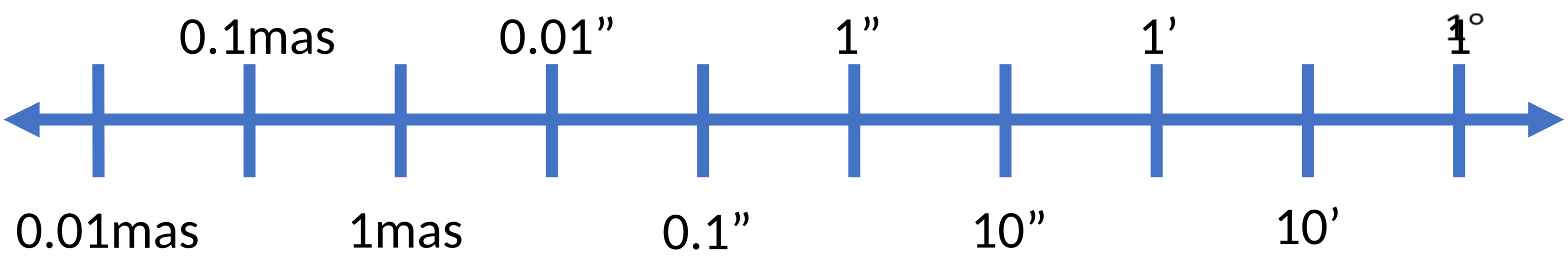
The basics

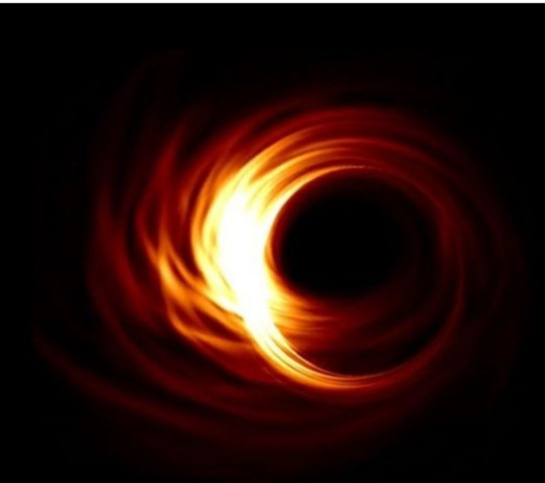
Slides originally by Jack Radcliffe

Based upon N. Jackson’s ERIS 2015 lecture

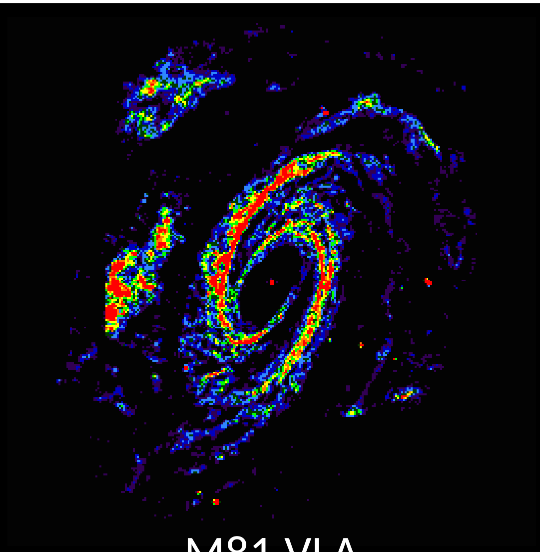
Why interferometry?

- Single dish vs. interferometers – resolution is key!

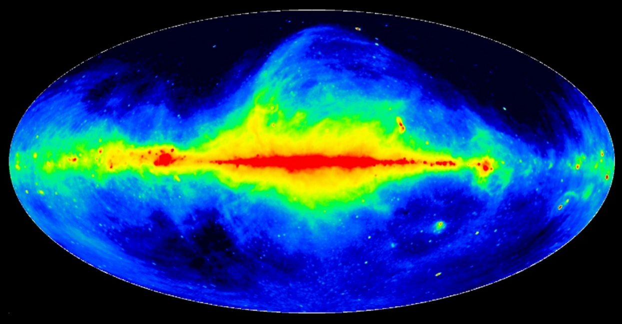




Event Horizon Telescope

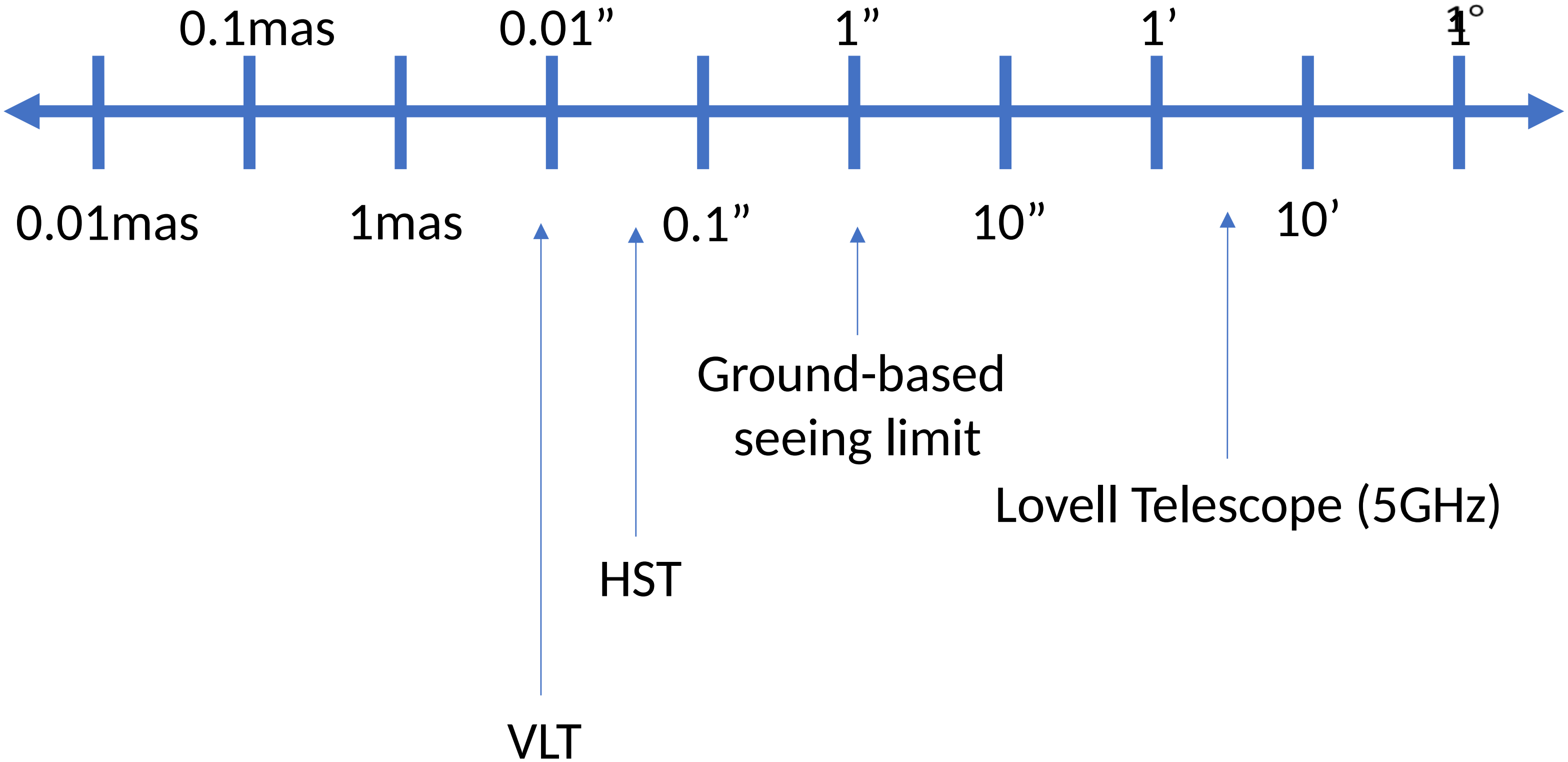


M81 VLA



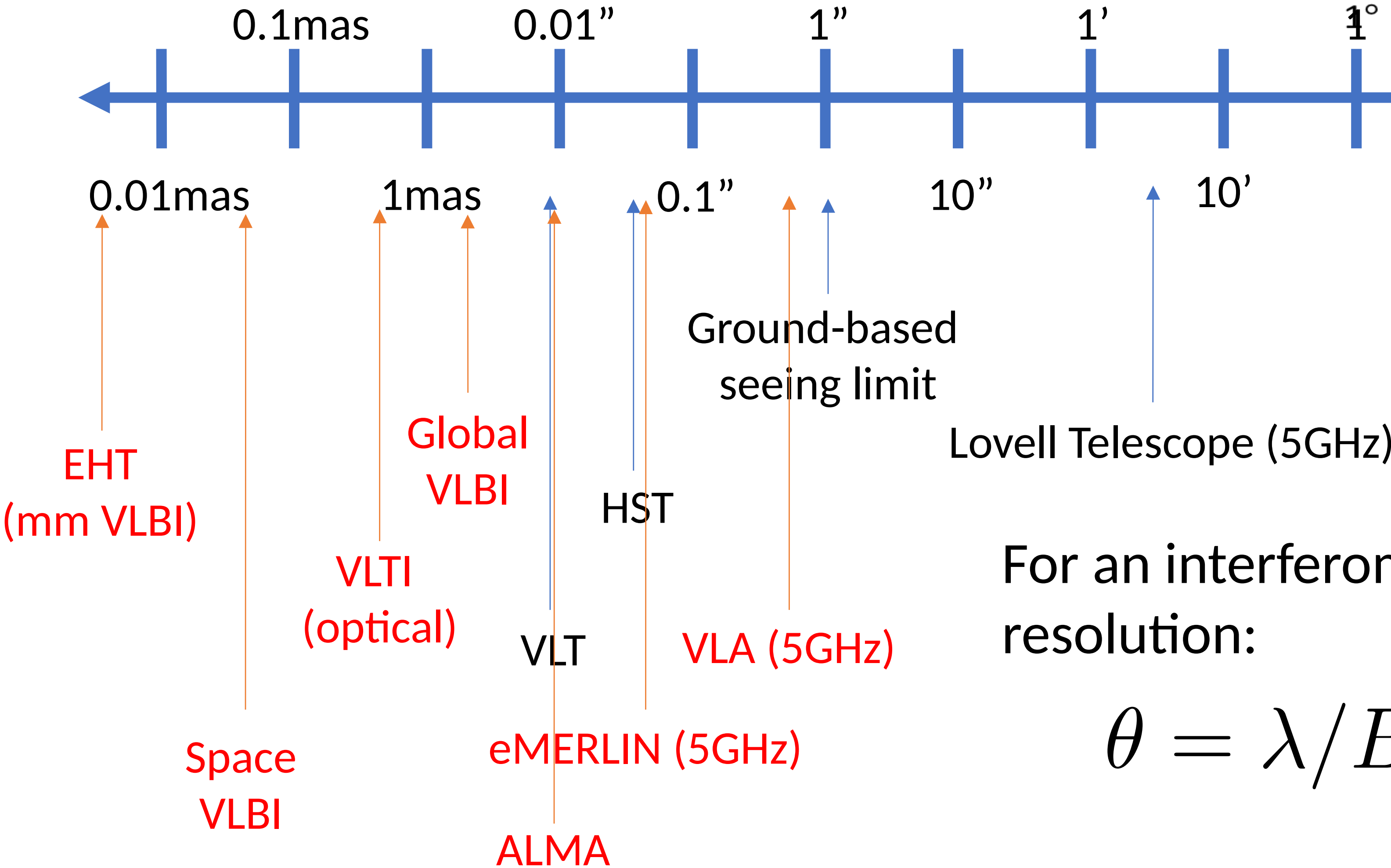
Bonn Single Dish 21cm survey

Resolution: Single Dish



For a single dish, resolution: $\theta = \lambda / D$

Resolution: Interferometers

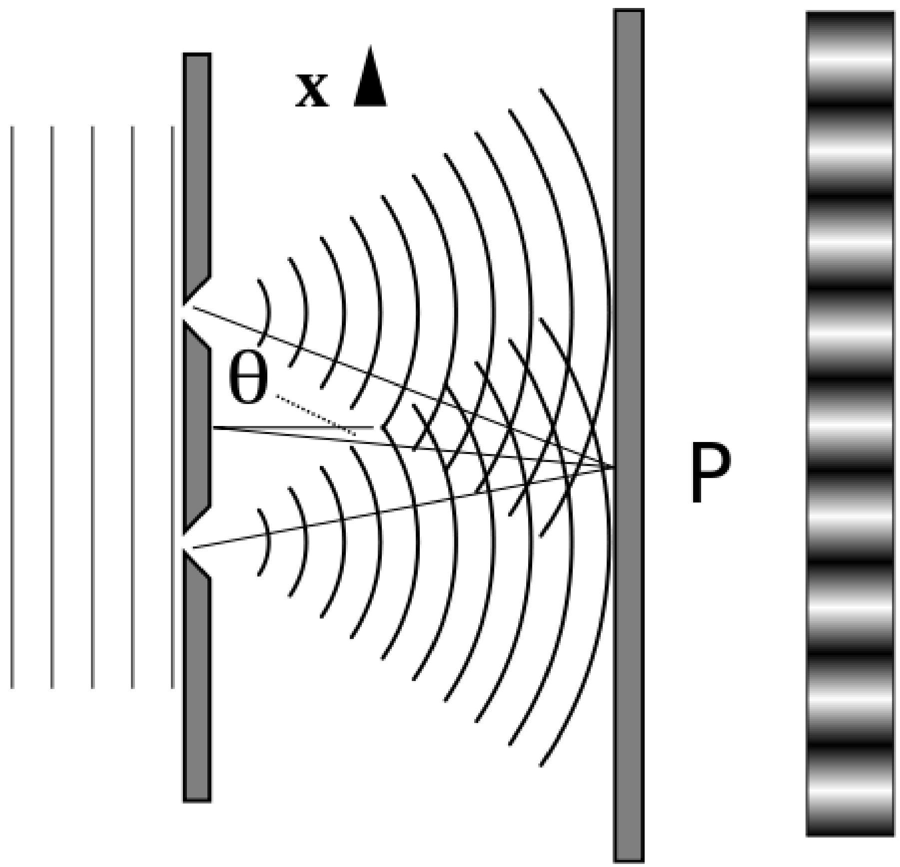


For an interferometer, resolution:

$$\theta = \lambda / B$$

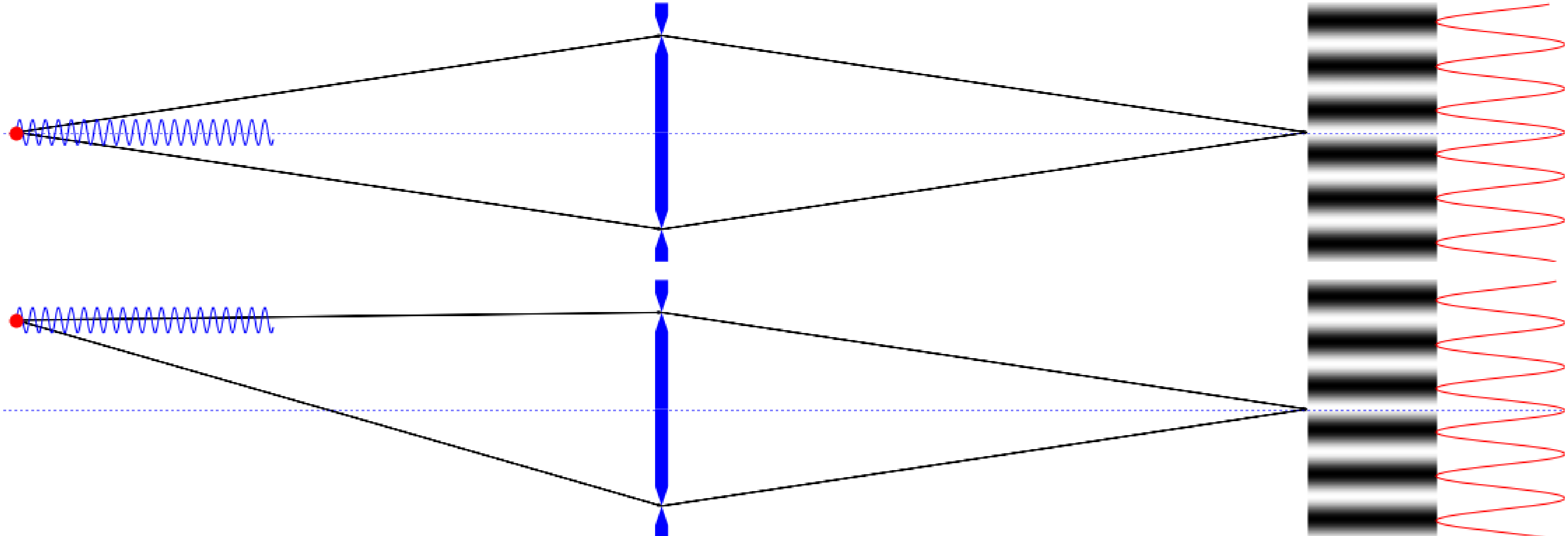
A Simple Interferometer

- Young's slits … see interactive demo



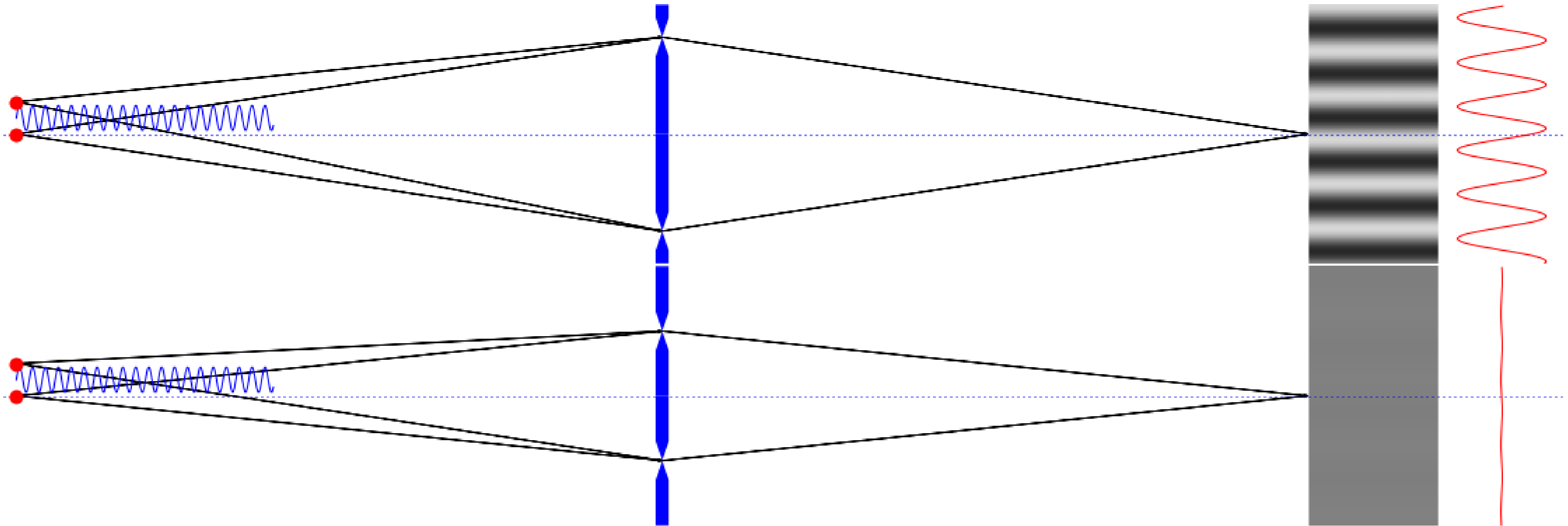
A Simple Interferometer

- Single source, two slits
- Increasing the baseline increases the frequency of the fringes
- Increasing the wavelength decreases the frequency of the fringes
- Fringe *phase* depends on source position
- But with just one baseline/wavelength this is ambiguous – several source positions can give the same result
- Use more than one baseline!



A Simple Interferometer

- Two sources
- Now destructive interference is possible – waves from the two sources can cancel out
- Again with only one baseline various source positions can give the same fringes
- With many baselines we could work out the source separation



A Simple Interferometer

- An extended source
- As the source extends the fringes get more blurred
- Amplitude of the fringes encodes source structure (size)
- Phase encodes position (so is constant for this example).
- As the baseline changes the amplitude of the fringes changes – the longer the baseline, the weaker the extended source becomes

Visibilities

- What we are measuring is called the *visibility* of the source seen through the double slit
- Amplitude encodes structural information; phase encodes positional information
- Can denote this by one complex number, the complex visibility $Ae^{i\theta}$
- Historically the first use of interferometers in astronomy was of this type – a *Michelson interferometer* was used to measure the size of stars

The ‘visibility’ is a Fourier transform!

- The fringe visibility of an interferometer gives information about the Fourier transform of the sky brightness distribution.

- Long baselines record information about the small-scale structure of the source but are INSENSITIVE to large-scale structure (fringes wash out)

- Short baselines record information about large-scale structure of the source but are INSENSITIVE to small-scale structure (resolution limit)

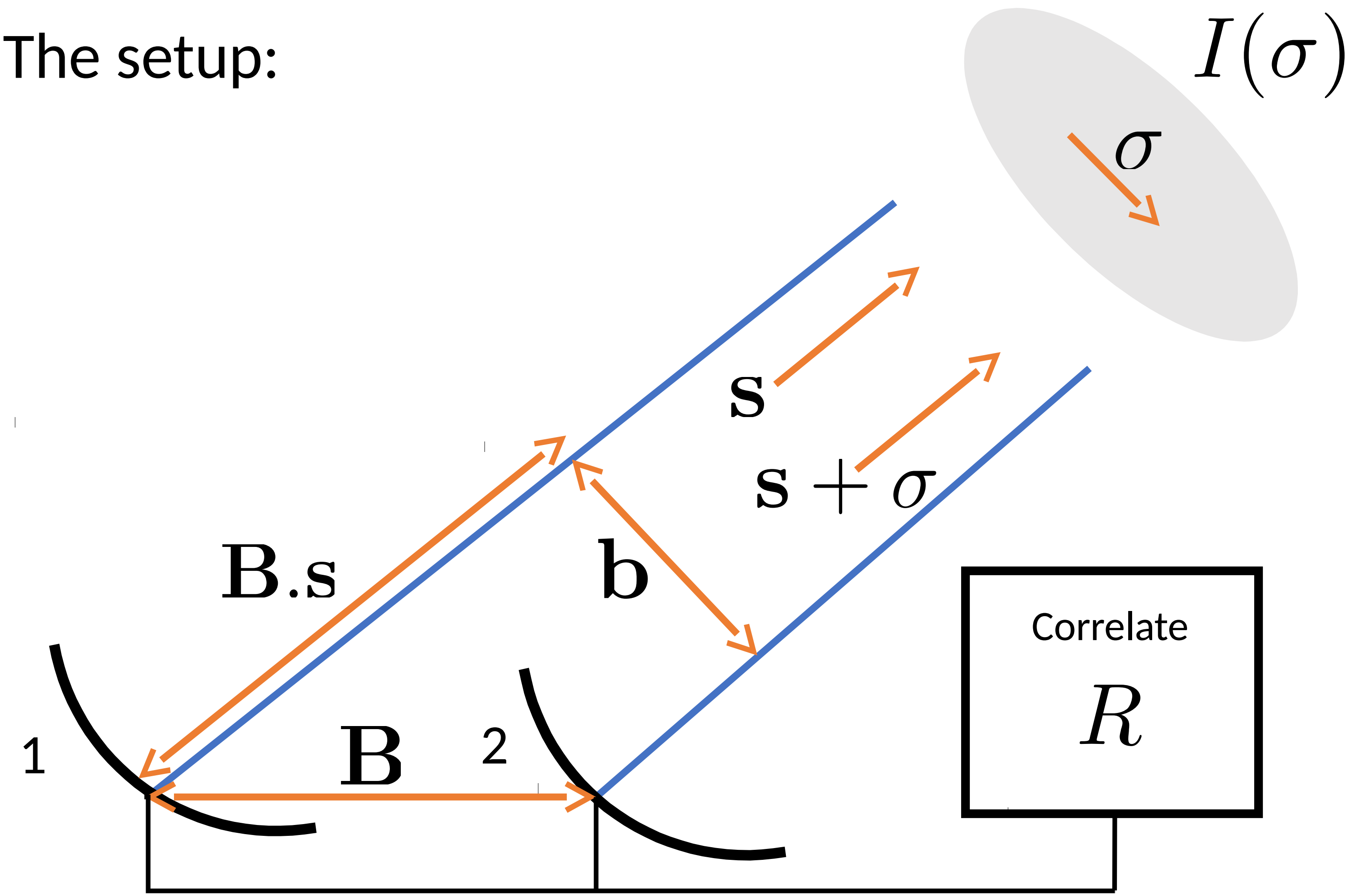
How to combine signals

- **Non photon limited (e.g. radio)**:
  - Electronic, relatively straightforward: can clone and combine signals
  - ‘Correlation’ (multiplication+delay)
  - Can record signals and combine later

- **Photon limited case**:
  - Use classical Michelson/Fizeau arrangements
  - Delay lines for manipulation cannot clone photons !

Two element interferometer

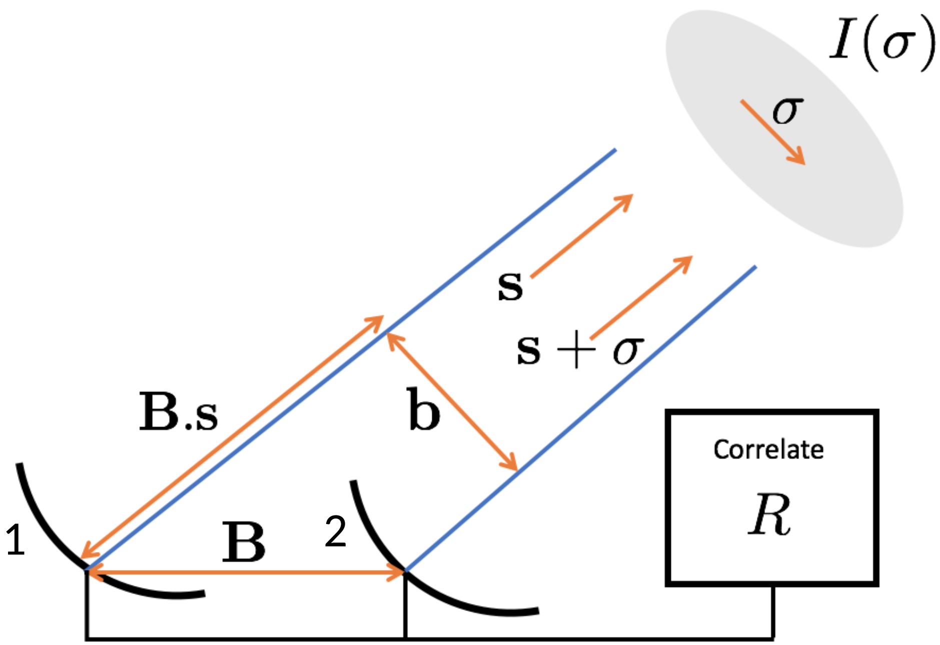
- The setup:



Two element interferometer

- The maths:

- A multiplying interferometer:



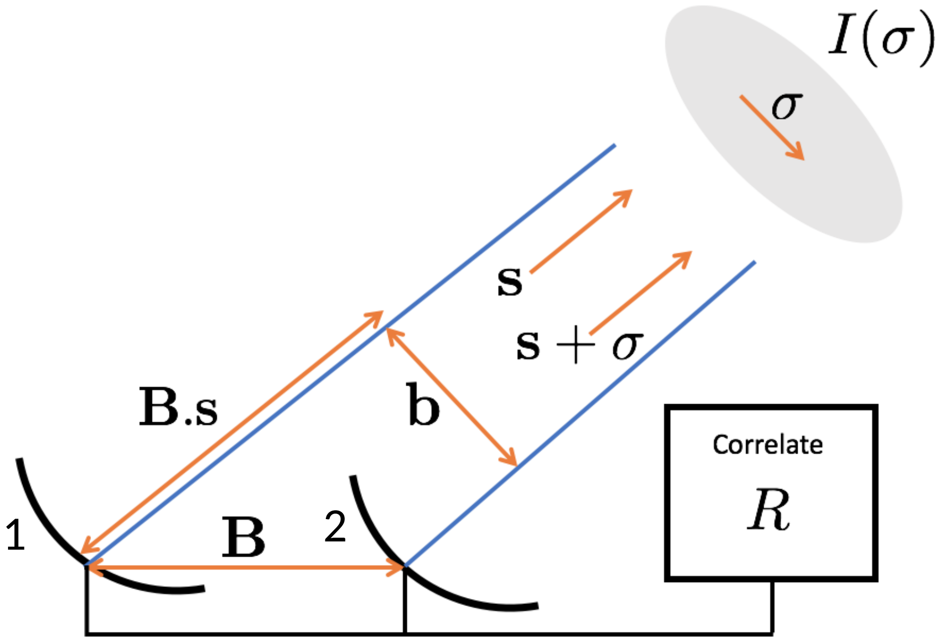
$$R = \langle E_1^* E_2 \rangle = E_1 E_2 e^{ikx}$$

$$dR = dI(\sigma)e^{ik\mathbf{B}.(\mathbf{s}+\theta)}$$

Two element interferometer

- Now:

$$\mathbf{B}.\sigma = \mathbf{b}.\sigma$$



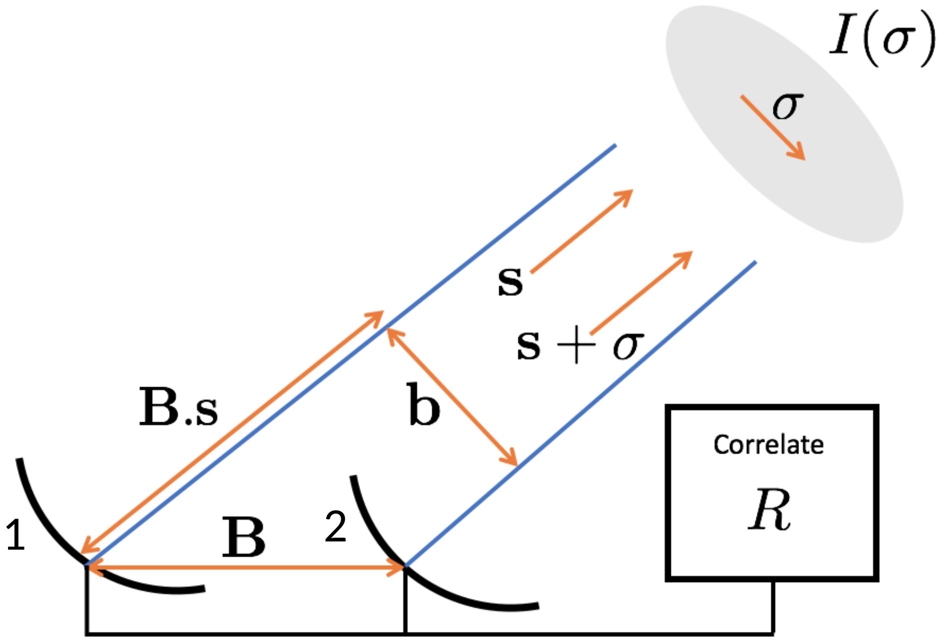
- Split & integrate:

$$R = e^{ik\mathbf{B.s}} \int I(\sigma) e^{ik\mathbf{b}.\theta} d\sigma$$

Two element interferometer

- Now in 2D assume:

$$\sigma = \sigma(x, y)$$
$$\mathbf{b} = \mathbf{b}(u, v)$$



- Therefore:

$$R(u, v) = e^{ik\mathbf{B.s}} \int I(x, y) e^{2\pi i(ux+vy)} dx dy$$

Fringes

$$R(u,v) = e^{ik\mathbf{B}.\mathbf{s}} \int I(x,y) e^{2\pi i(ux+vy)} dxdy$$

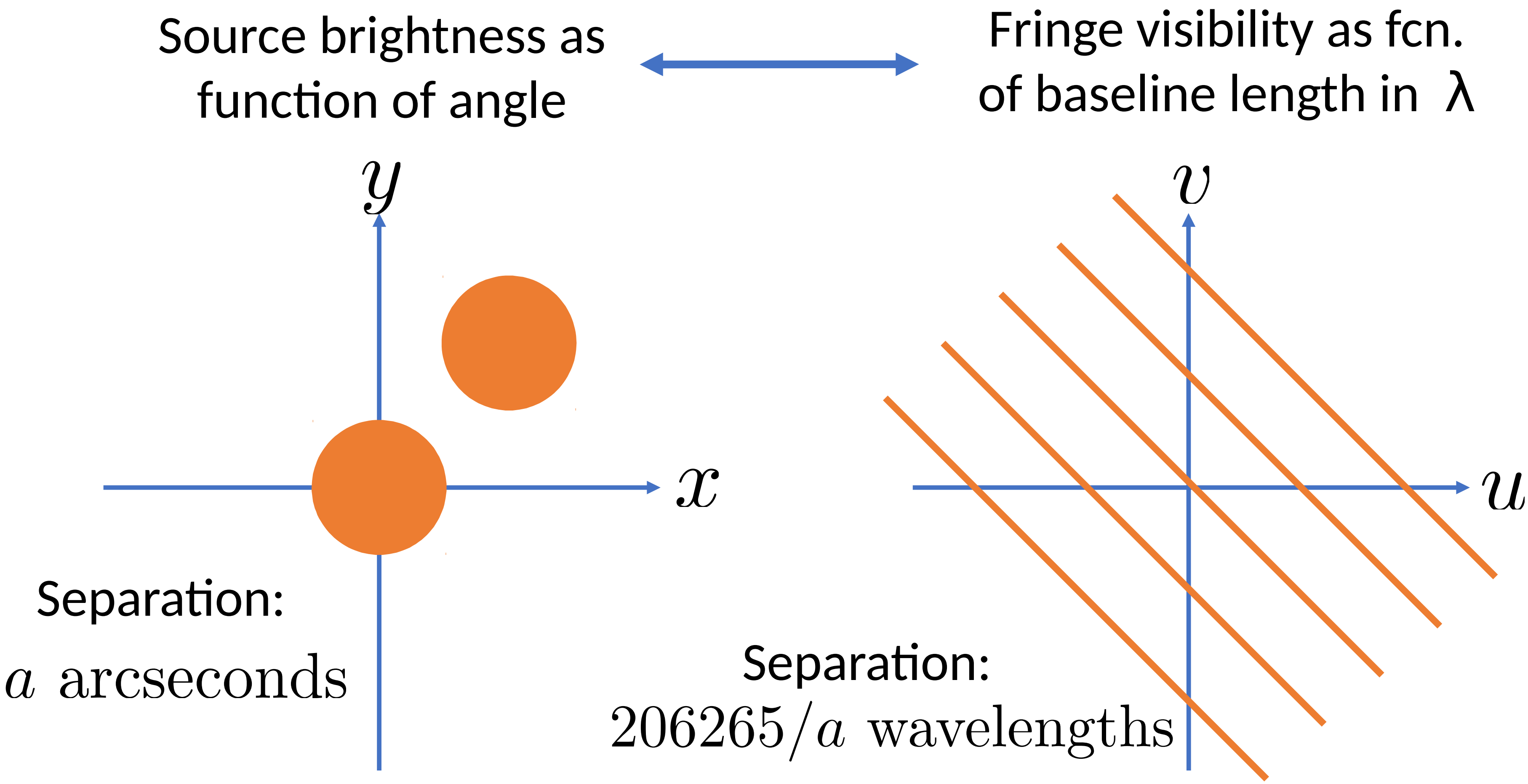
- First term just depends on baseline separation and can be dropped

- Otherwise this relation describes the visibility of a series of fringes and is the 2D Fourier transform of the source brightness distribution.

- $R(u,v)$ has amplitude and phase; both are interesting!

uv plane

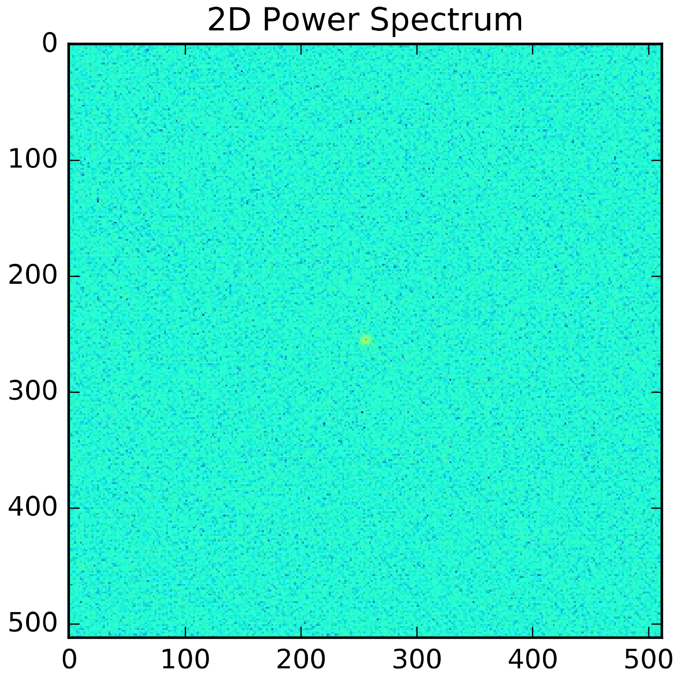
- Direct relationship between x,y and u,v



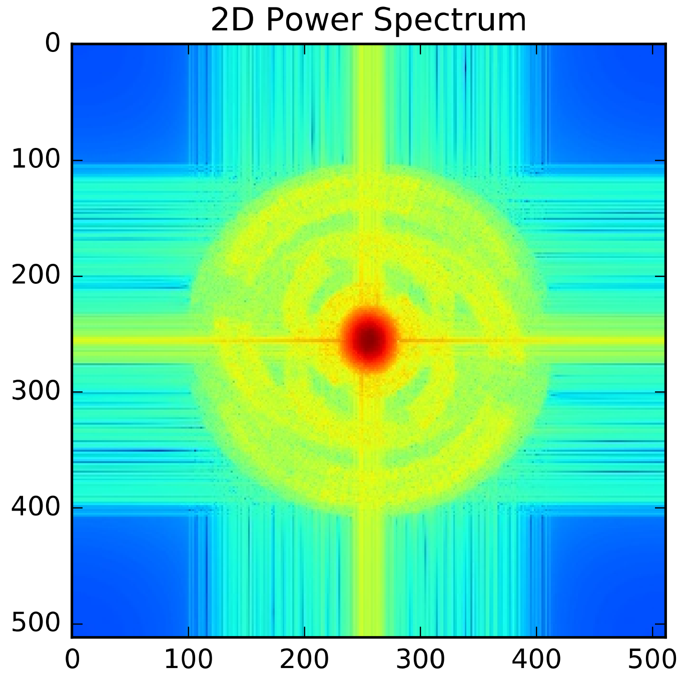
Imaging

- If we could measure R(u,v) for all u,v, transform -> image
- But we don’t! We can only put elements at fixed positions

Optical

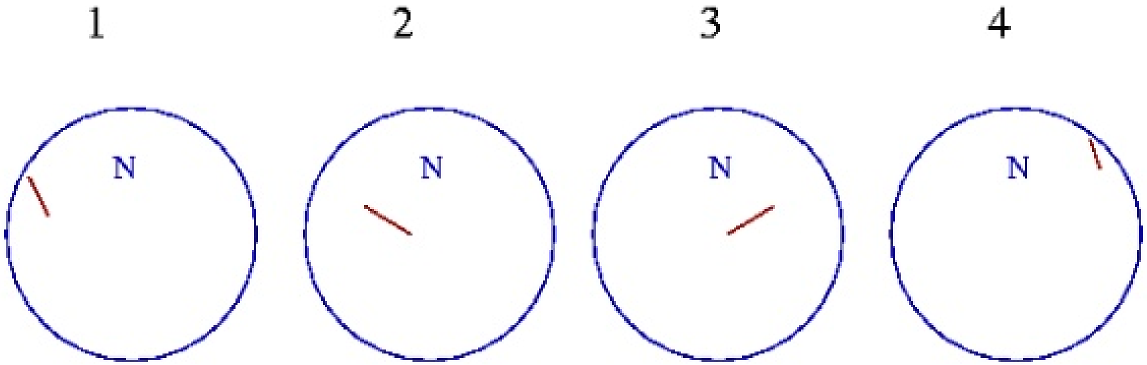


Radio Interferometer



Earth Rotation Aperture Synthesis

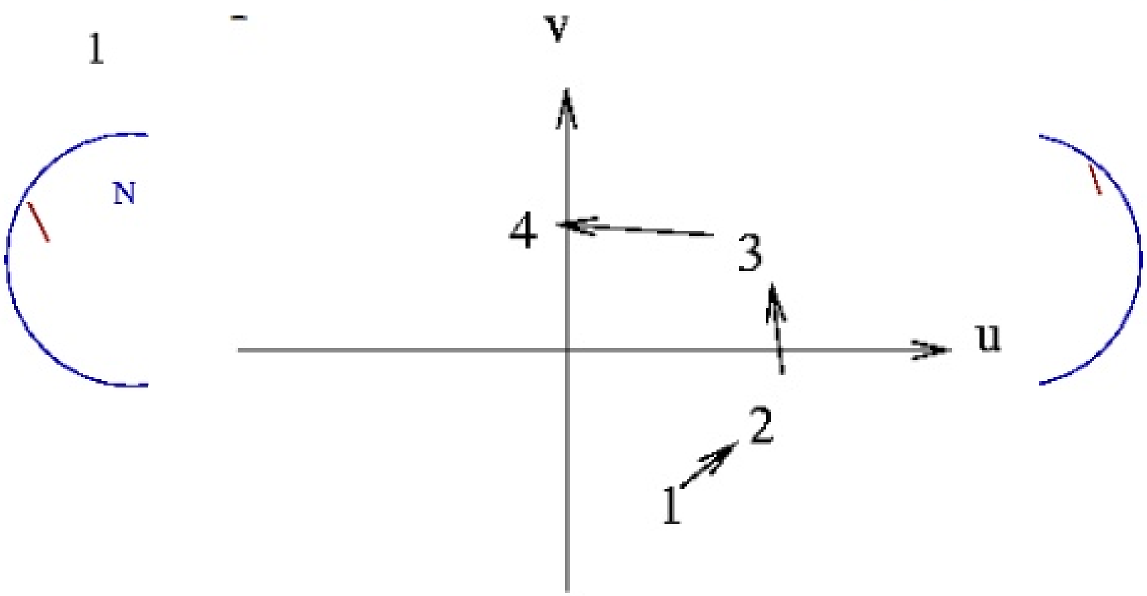
Let’s get some help by using the rotation of the Earth



- Can measure many points in uv plane with a single baseline
- Locus is an ellipse; the longer the baseline, the larger the uv distance (higher resolution)

Earth Rotation Aperture Synthesis

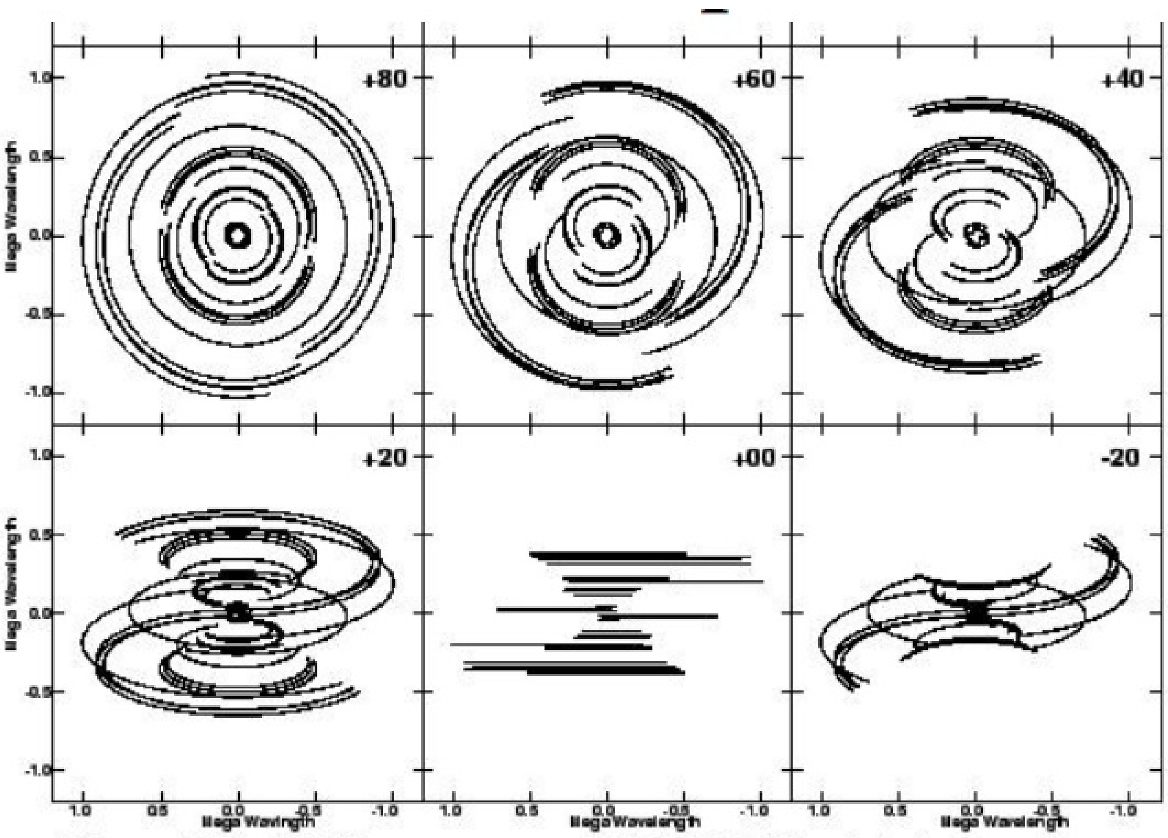
Let’s get some help by using the rotation of the Earth



- Can measure many points in uv plane with a single baseline
- Locus is an ellipse;
  the longer the baseline, the larger the uv distance (higher resolution)

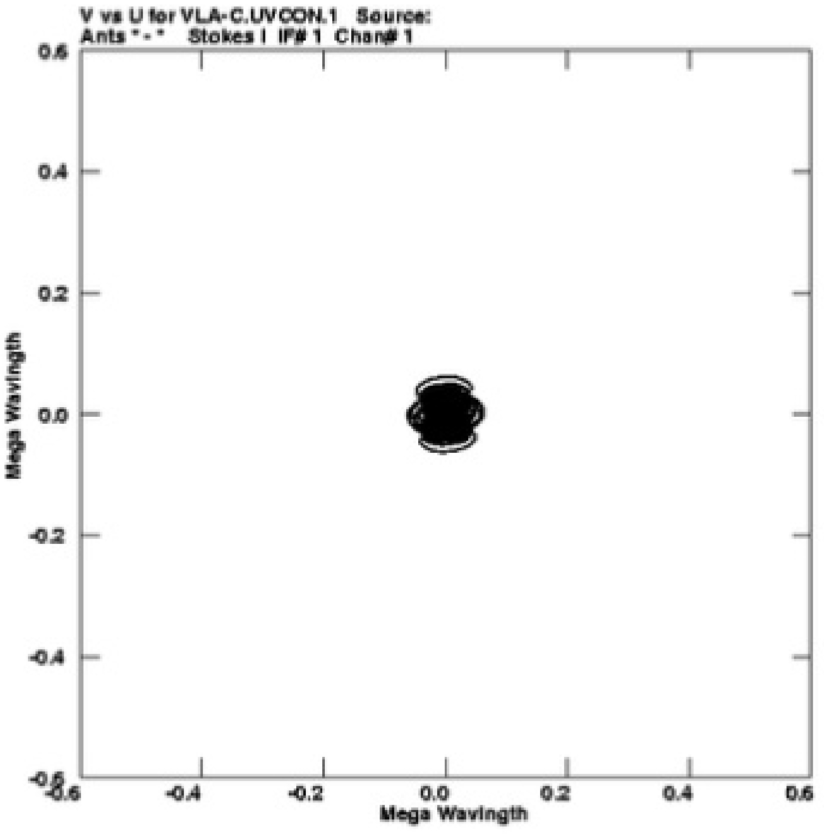
uv tracks

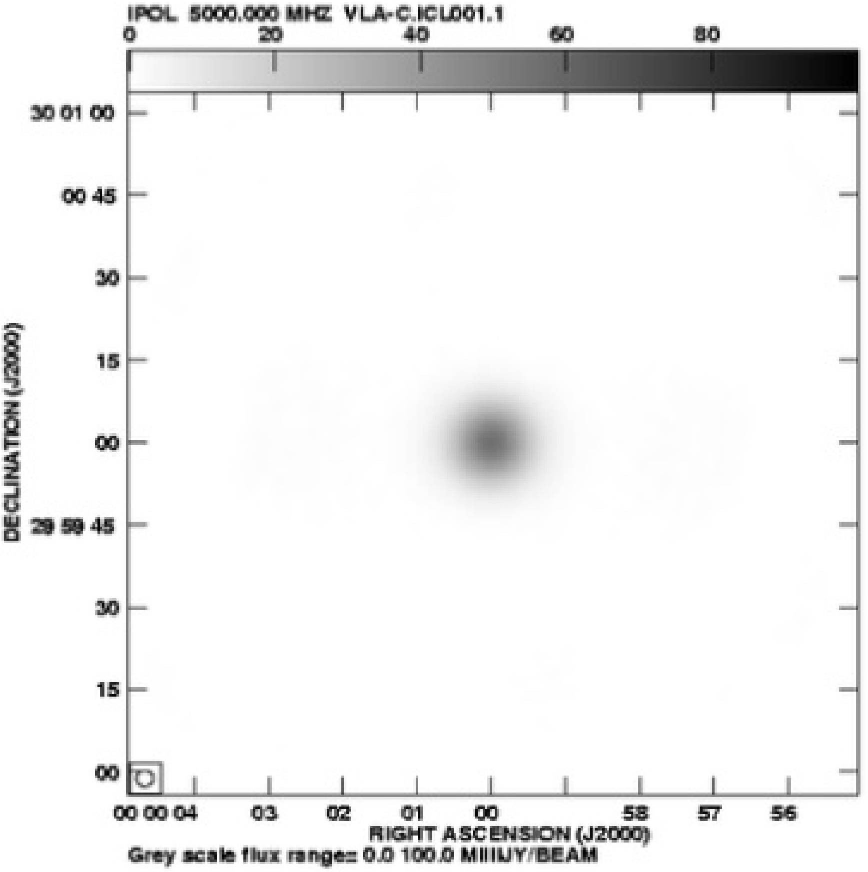
- E.g. MERLIN



- MERLIN in Northern hemisphere
- Elongated at low declination

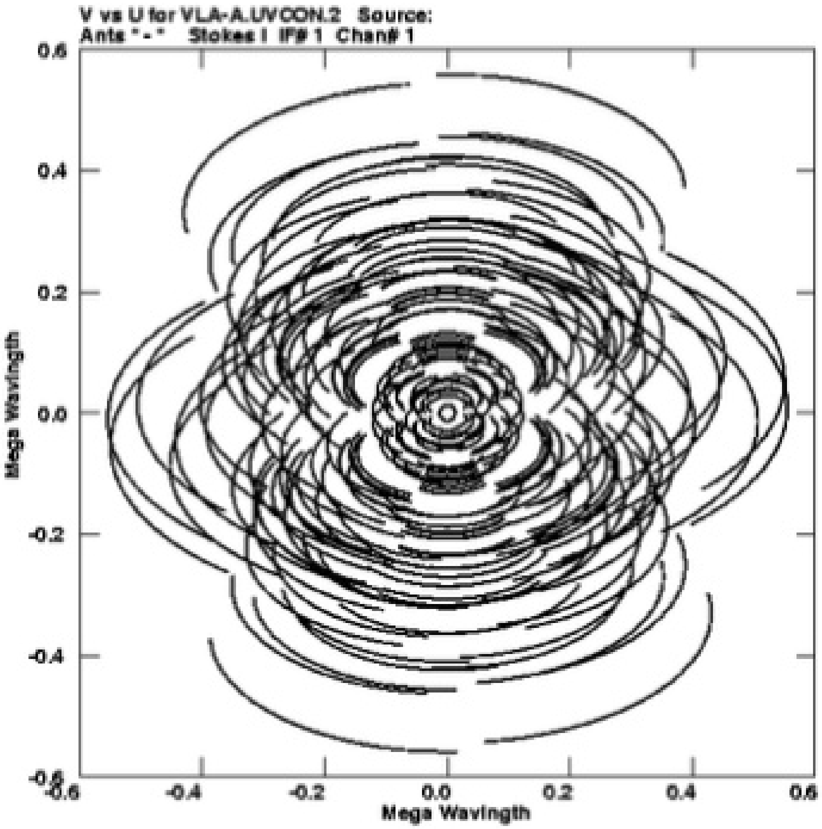
FT imaging is not like direct imaging!

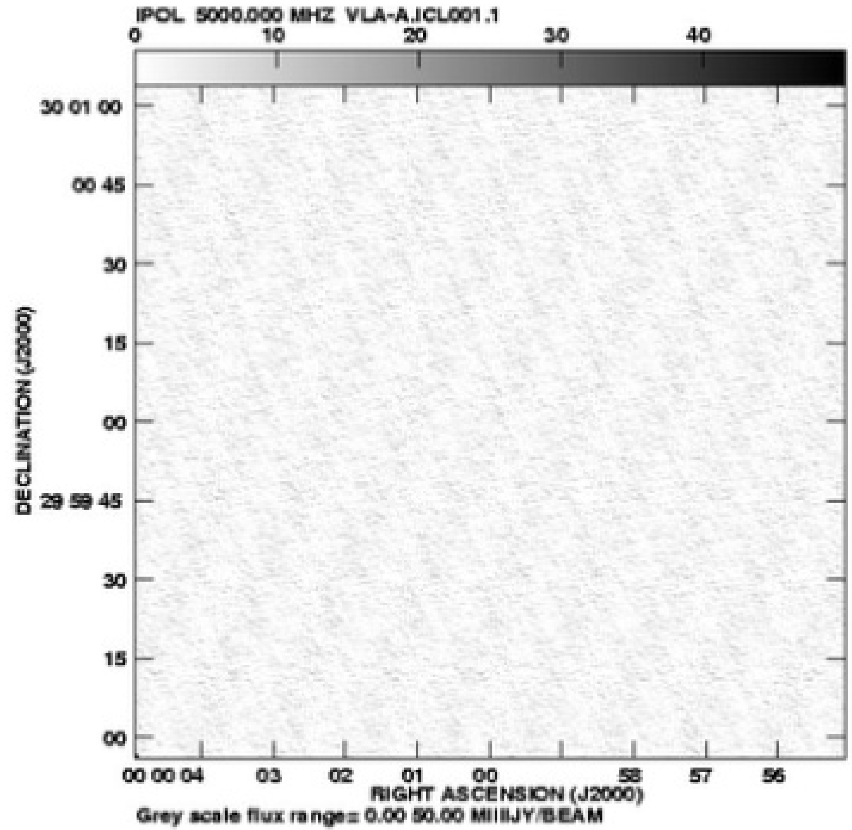




12 arcsec source mapped with uv coverage giving 3 arcsec resolution

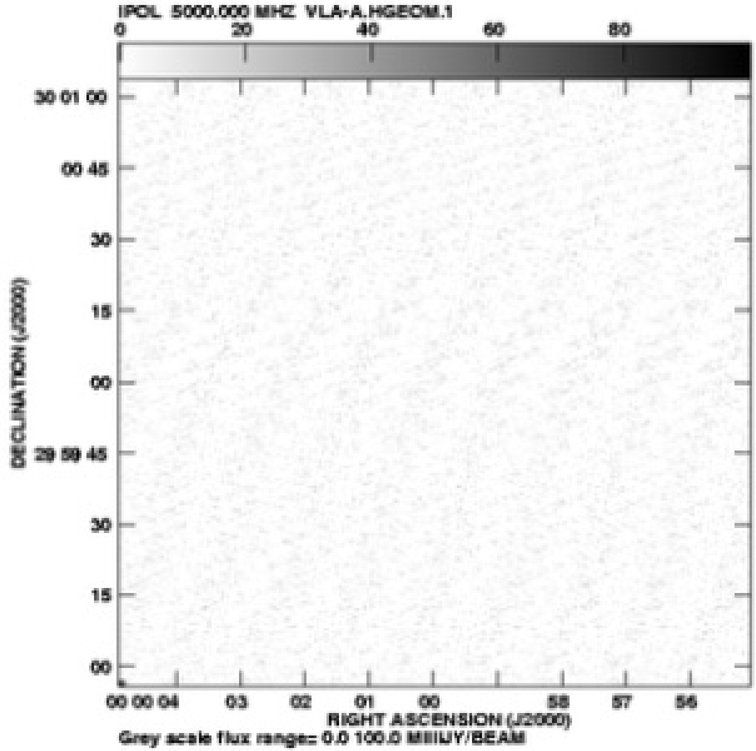
FT imaging is not like direct imaging!





Multiply all baseline lengths by 10 = higher resolution (0.3 arcsec).
No image! But **you can get it back by smoothing, right**?

FT imaging is not like direct imaging!

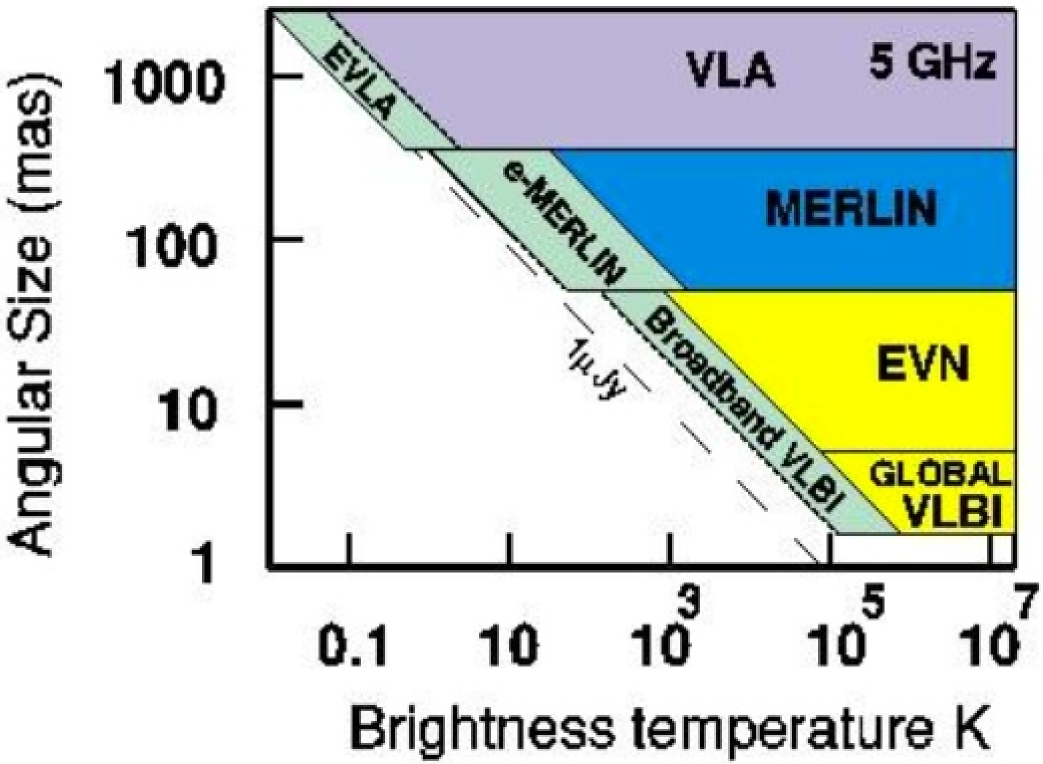


Wrong! Smoothed image to 3” shows no source.

Moral: ***longer baselines are INSENSITIVE to the large-scale structure – unlike direct imaging you lose it IRRETRIEVABLY.***
Use the range of baselines appropriate to the problem.

This is why you need interferometers….

- … and more than one of them!



- JVLA 30m36km
- eMERLIN 6km-250km
- EVN 250km-2300km
- VLBA 250km-9000km
- Global VLBI 12000km
- Space VLBI 32000km