Radio Observations
4th graduate school on Plasma-Astroparticle physics

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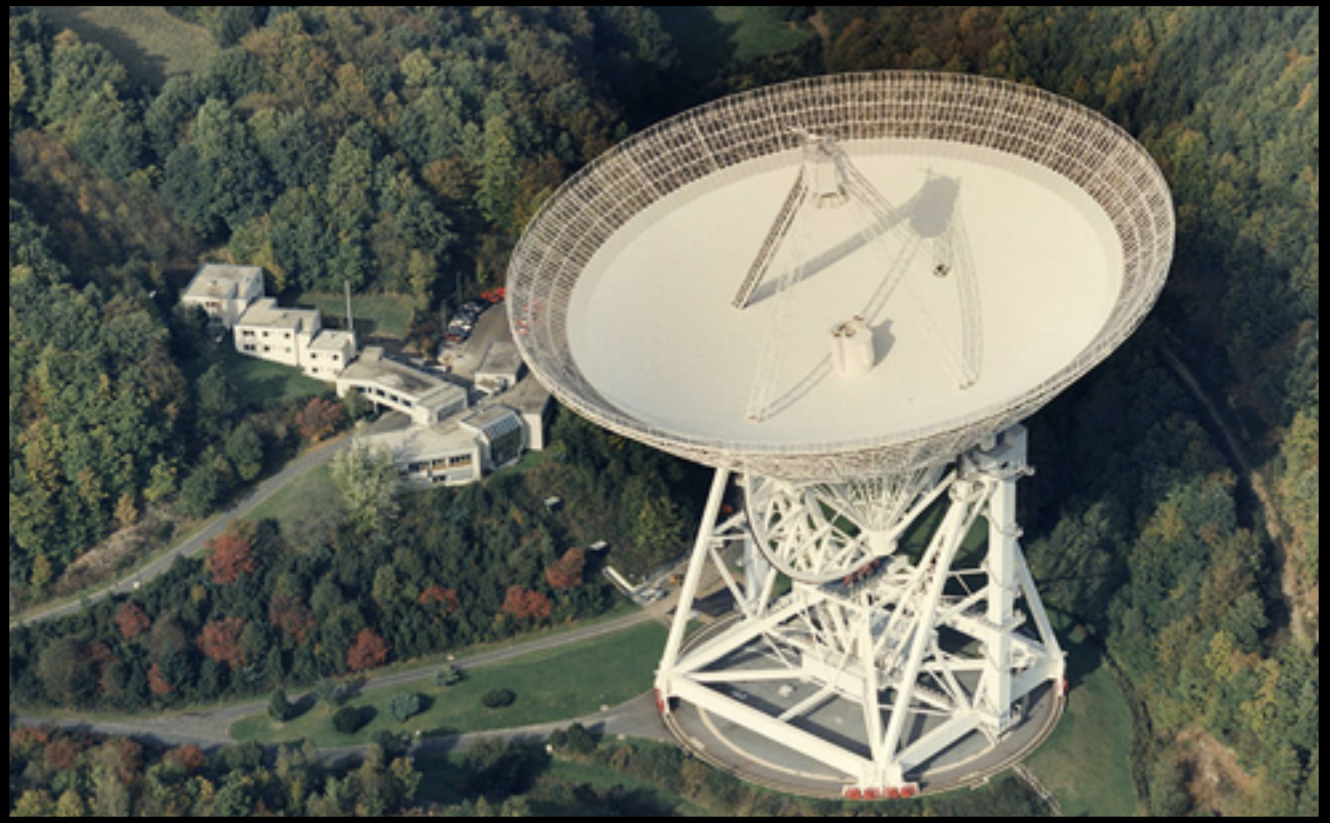
Single dishes have limitations

- low angular resolution ($\theta \approx \lambda/D$)
- low pointing accuracy (arcmin)
- limited sensitivity and/or limited mobility
- Interferences

Effelsberg



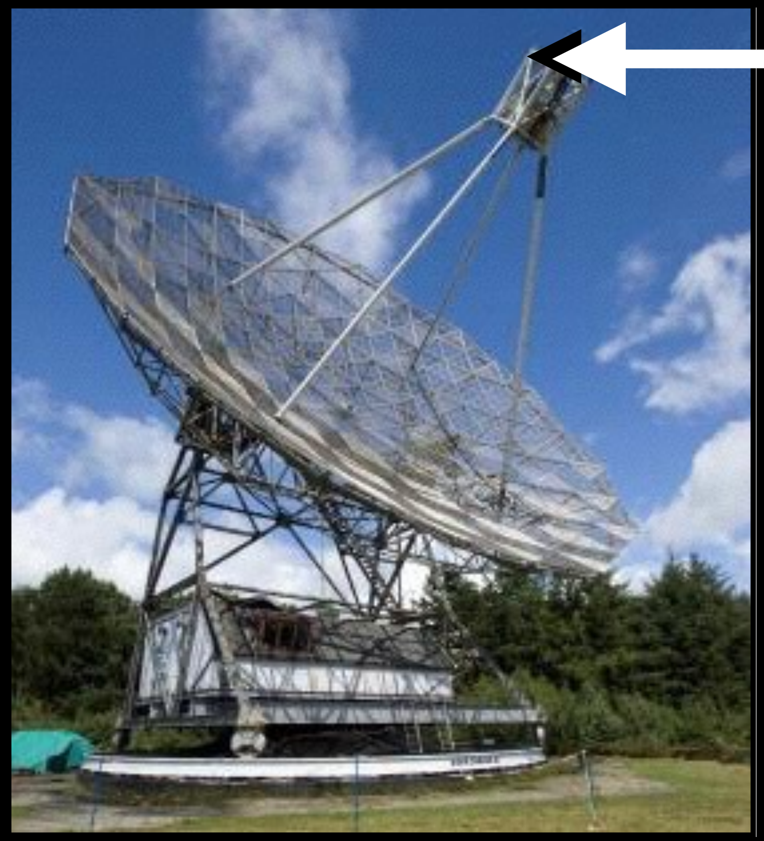
FAST

The quest for angular resolution

- We want sub-arcsecond resolution (cf. optical, X-ray)
- Θrad $\propto \lambda/D$
- Unlike large, ground-based optical telescopes (atm. limits!), radio telescopes are always diffraction limited.
- $\Theta_{\mathrm{arcsec}} \approx 2\frac{\lambda_{\mathrm{cm}}}{D_{\mathrm{km}}}$
- So to get 1 arcsec resolution at 21 cm requires a 42 km diameter!

Resolution of an interferometer

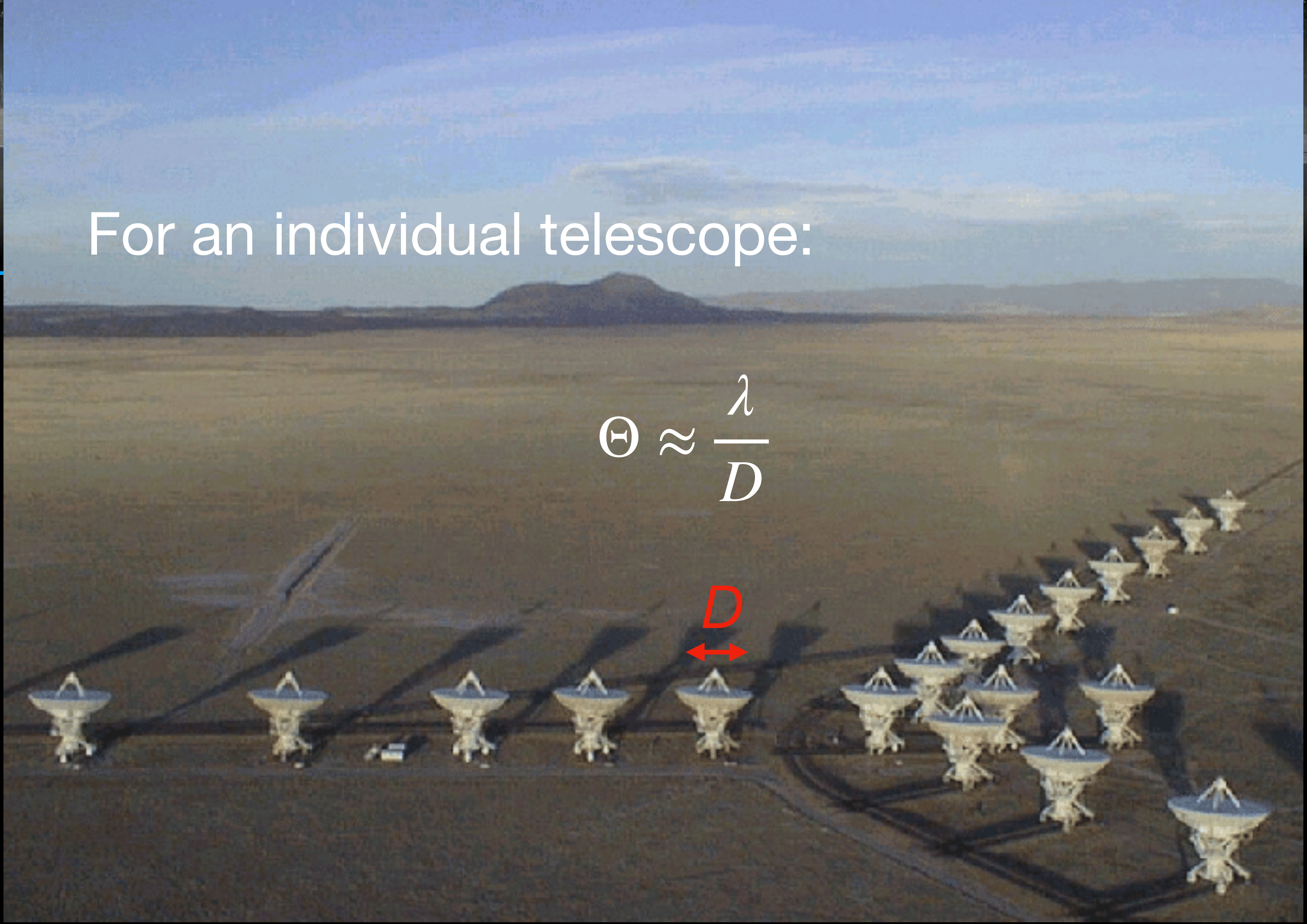
- Fortunately, we don't have to build a single 42-km-wide radio dish Aperture synthesis
- $\Theta \propto \frac{\lambda}{D} \propto \frac{\lambda}{B}$; B = Baseline (i.e. distance between telescopes/elements)



B

For an individual telescope:

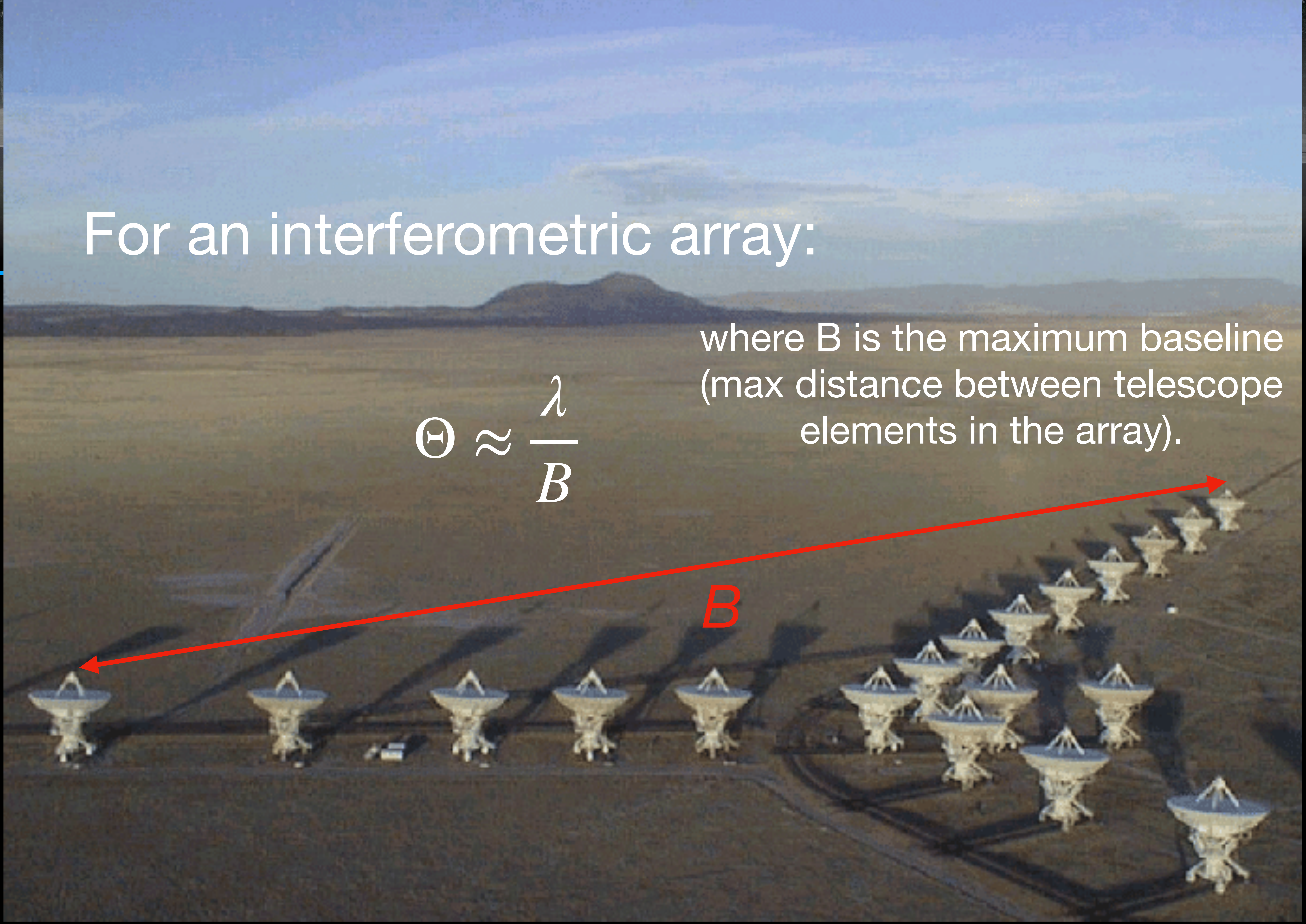
$$\Theta \approx \frac{\lambda}{D}$$



For an interferometric array:

$$\Theta \approx \frac{\lambda}{B}$$

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



ATCA

LOFAR

VLA

AMI

WSRT

GMRT

Some examples for resolution

- Lets take λ = 20cm (1.5 GHz)
  - Lets take D = 3km (VLA or WSRT)

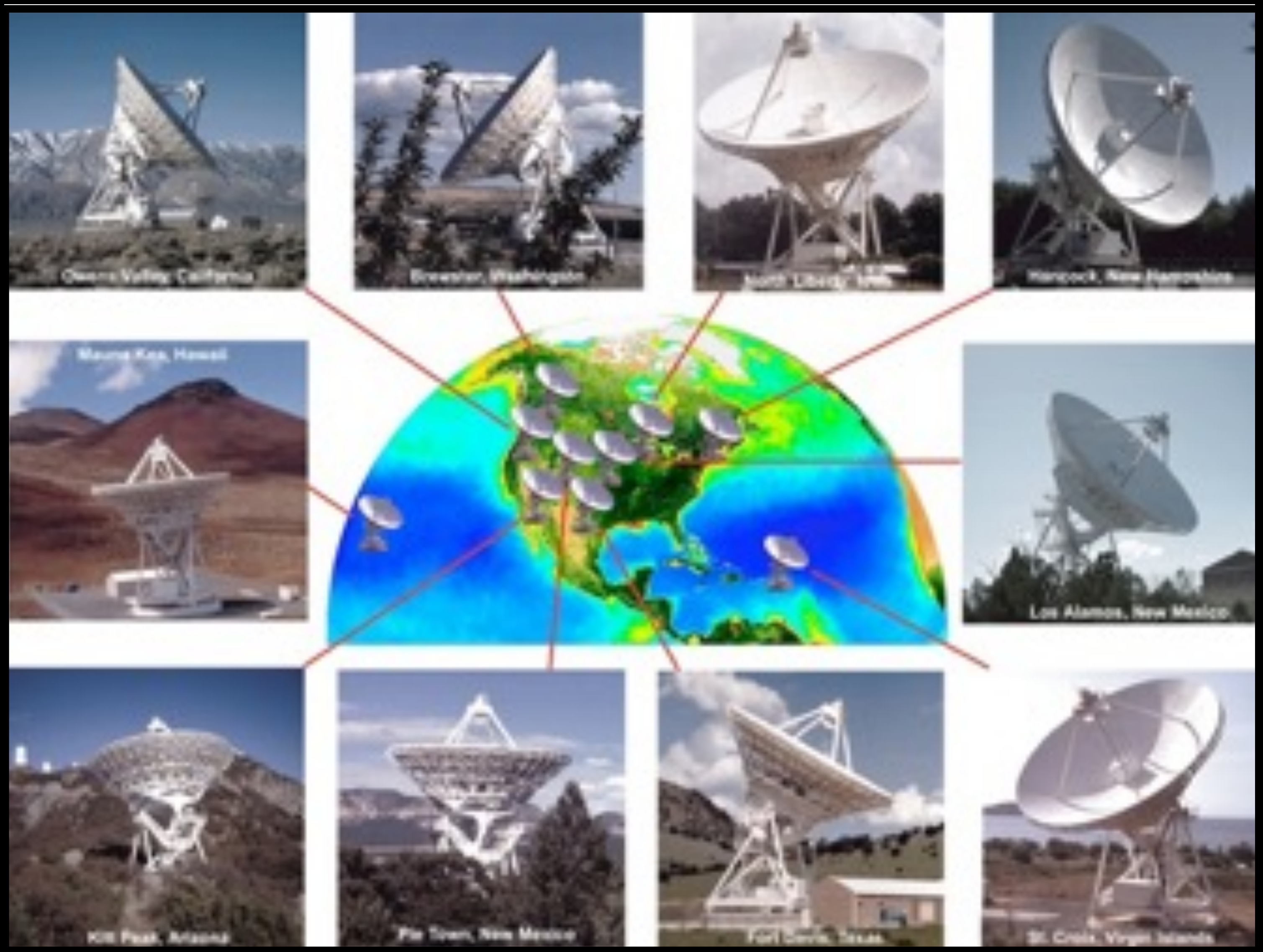
- B = 15 kλ
  θ = 6.7 10-5 rad = 14”

Array	B [km]	ν [GHz]	θ [mas]
WSRT	3	1,5	14”
VLA A	10	22	0.28”
ALMA	1	300	0.21”
EVN	1000	5	12 mas
mm VLBI	10.000	300	21 µas

1000-km baselines

Data traditionally recorded locally and shipped to correlator

VLBA, USA



EVN, Europe

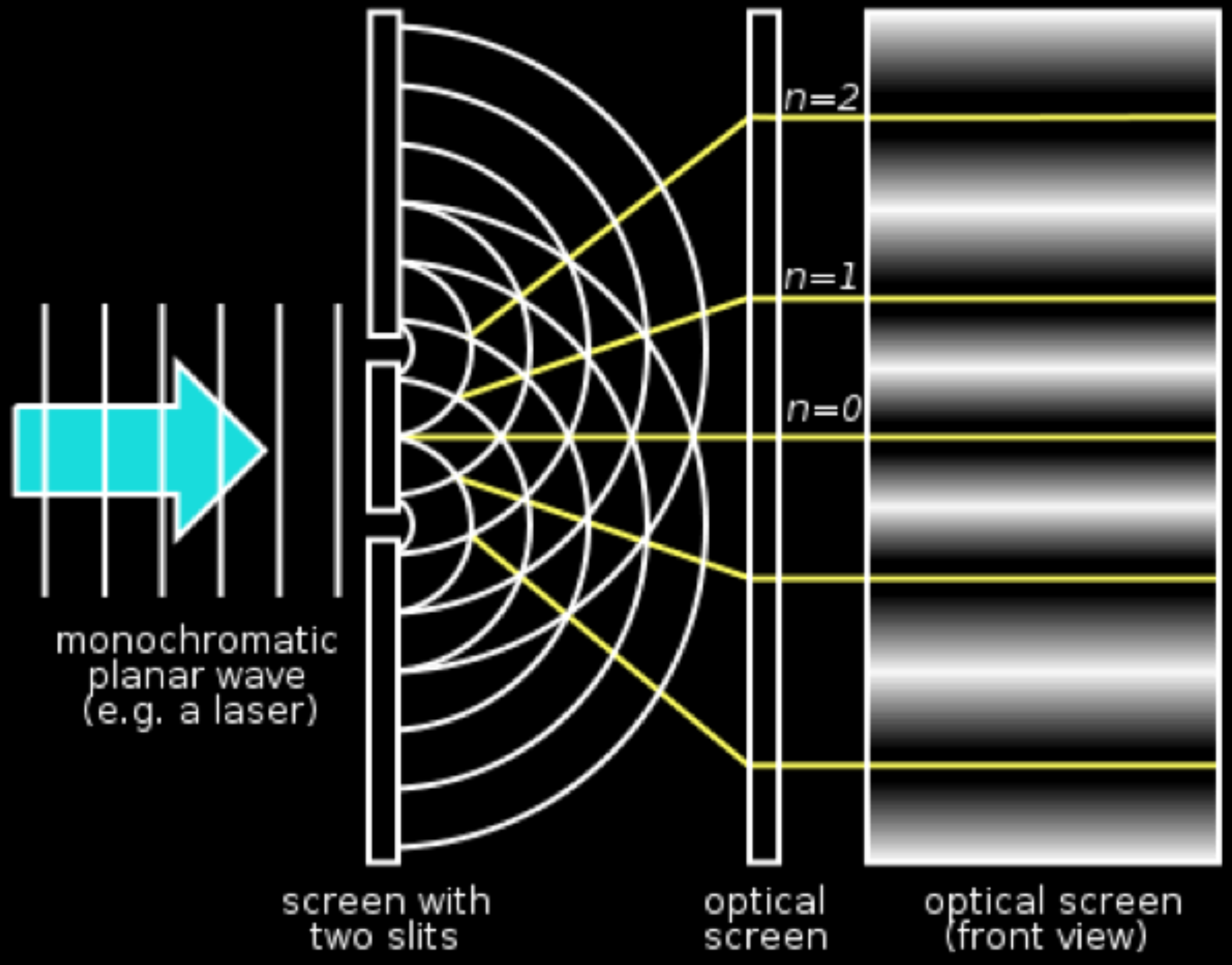
Global VLBI


Size of the Milky Way (100.000 ly)
10 arcsec
(3.000 ly)
VLA 1.5 GHz
0,001 arcsec
(0,3 ly)
VLBA 43 GHz
100 arcsec
(30.000 ly)
LOFAR 0.05 GHz
0,00001 arcsec
(0,003 ly)
EHT 230 GHz
Credits — LOFAR image: F. de Gasperin — VLA image: F. Owen — VLBA image: C. Walker— EHT Image: EHT collaboration

What an interferometer measures

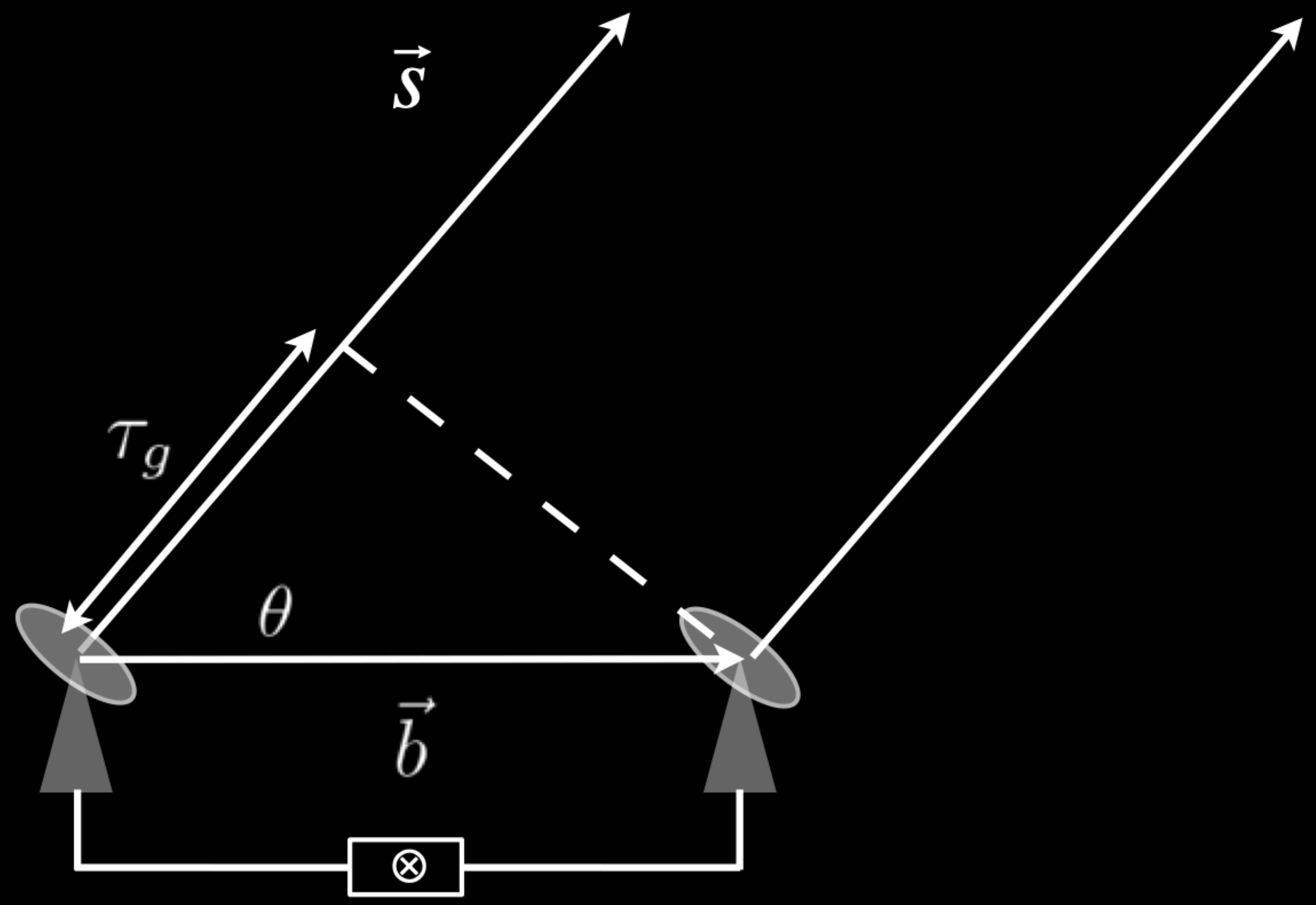
- An interferometer measures the interference pattern produced by multiple apertures, much like a 2-slit experiment

- However, the interference patterns measured by radio telescopes are produced by multiplying - not adding - the wave signals measured at the different telescopes (i.e. apertures)



Geometric delay

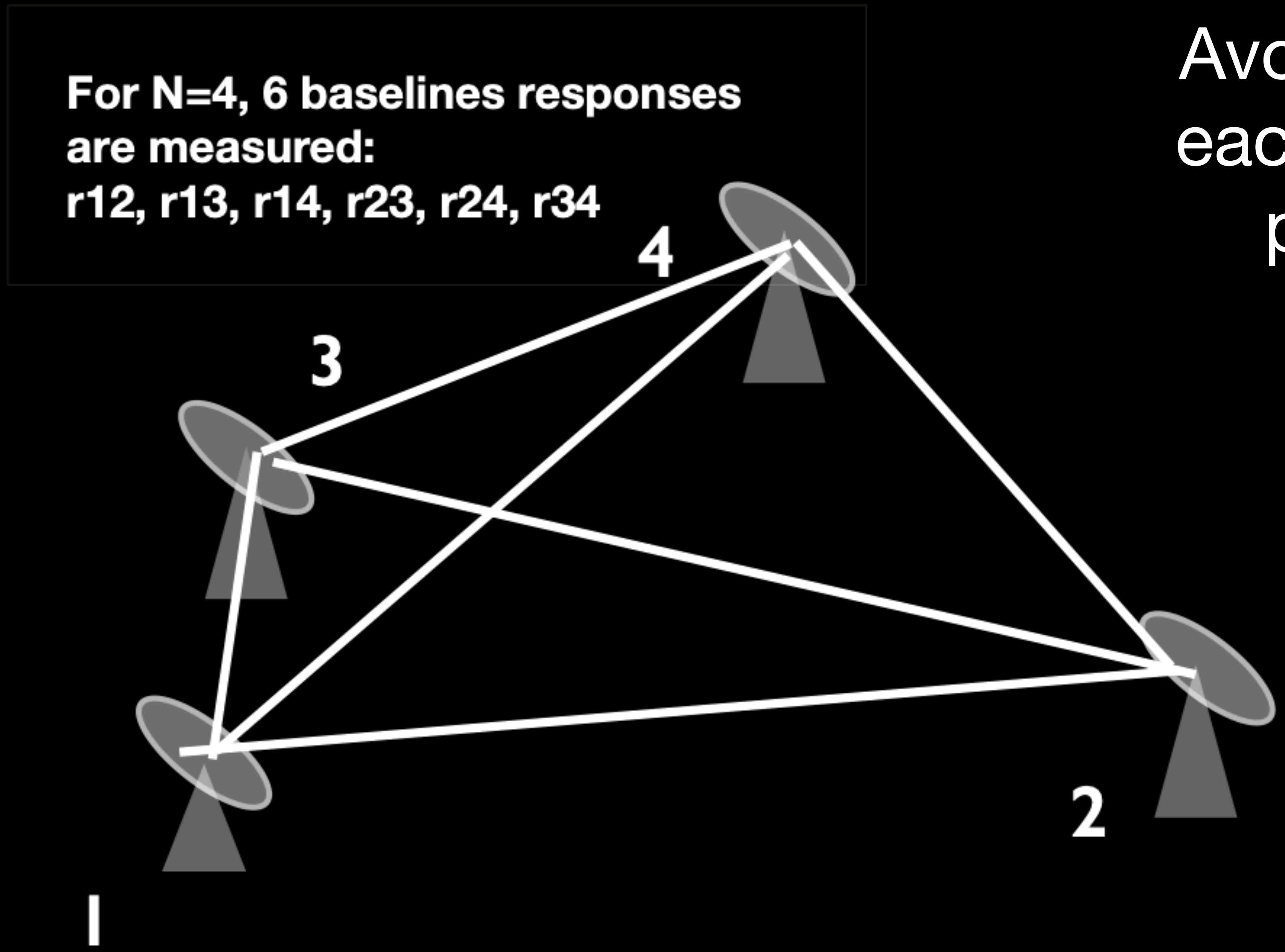
- The geometrical delay: $\tau_g = b\,s/c$
- where s is a unit vector in the direction of the source, and b is the baseline vector.
- Example: a geometrical delay of about 1 millisecond is expected for B ~ 300 km.



Multi-element interferometer
N antennas

- $N_{baselines} = N_{elements}(N_{elements} - 1)/2$

Avoid counting each telescope pair twice

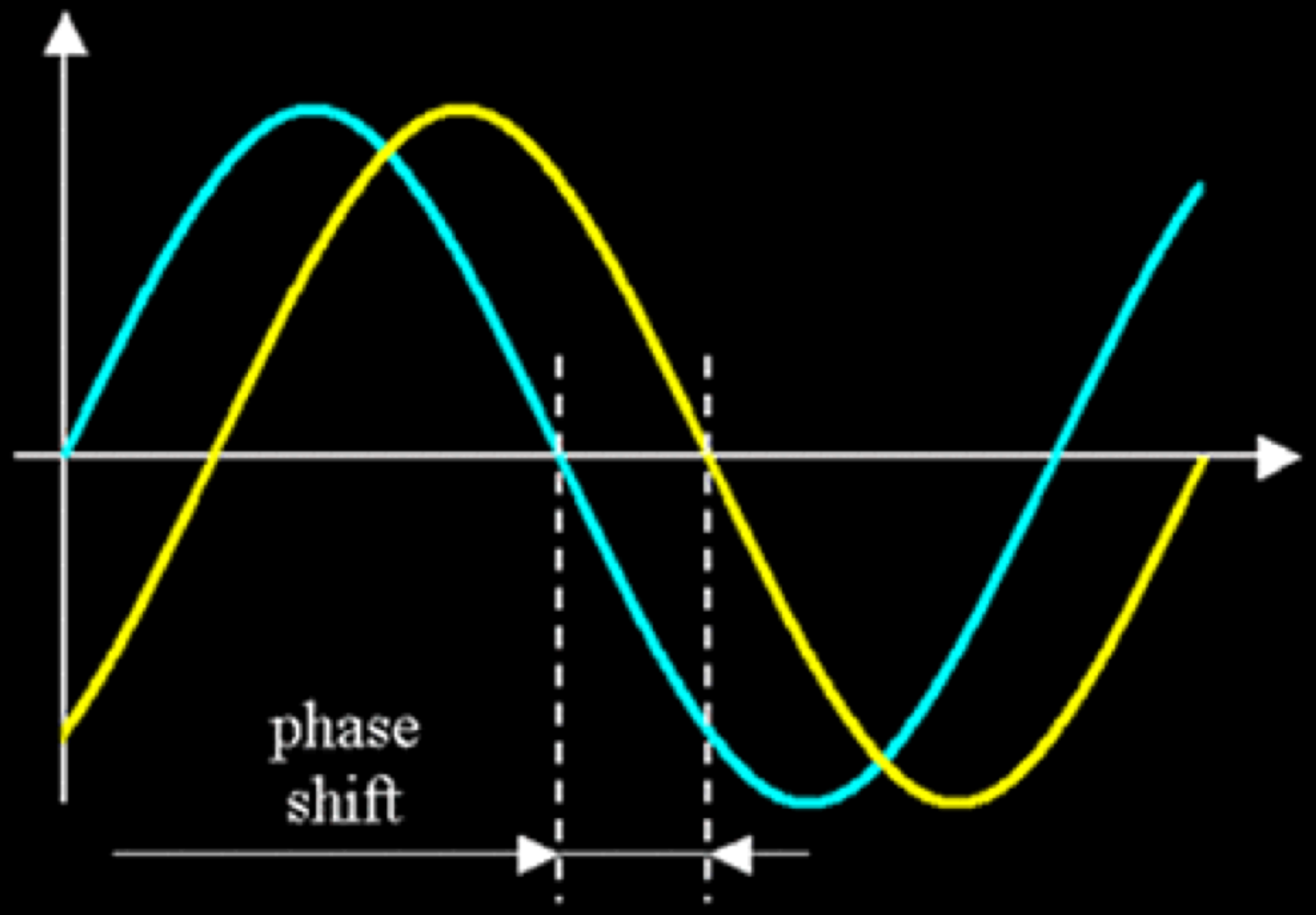


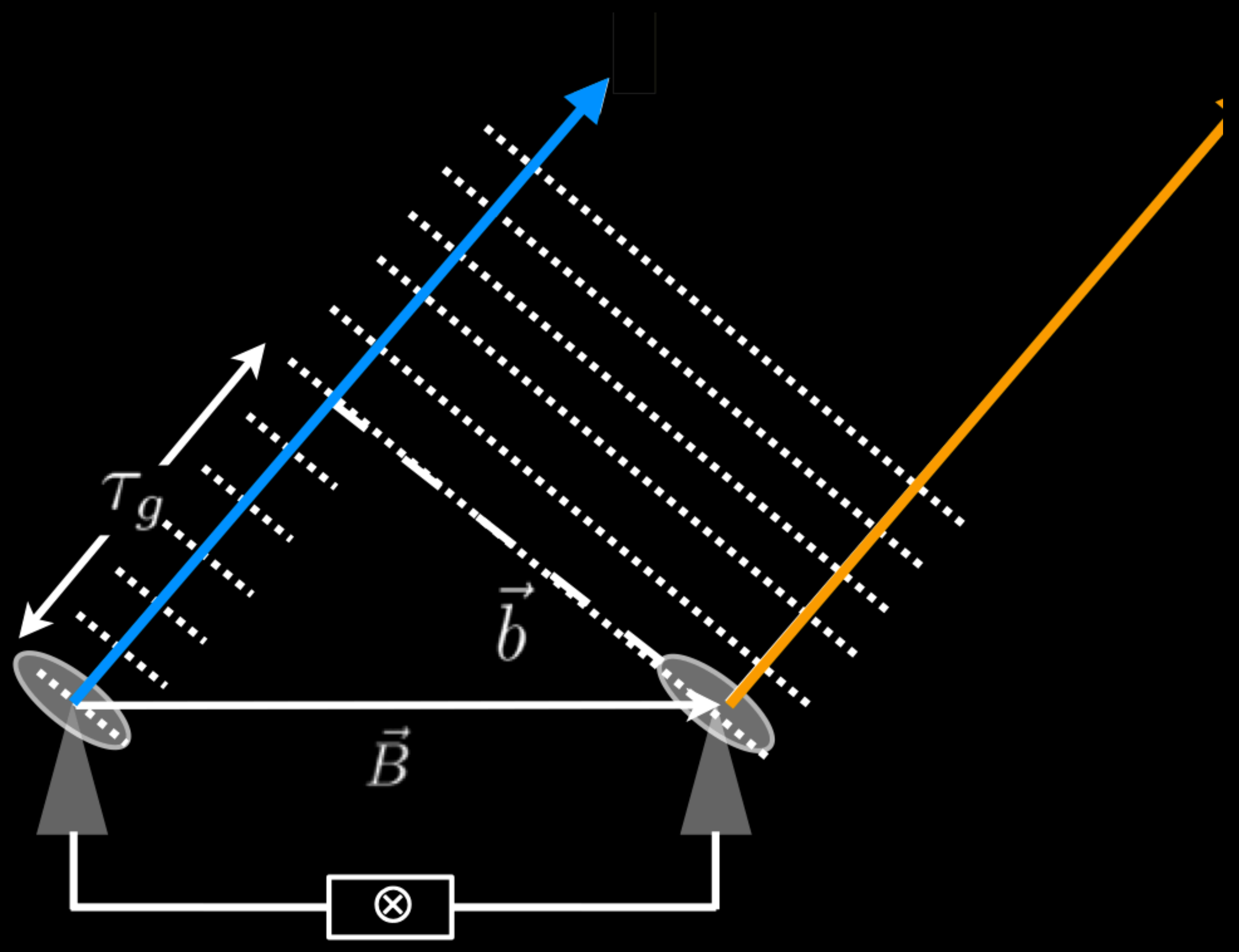
VLA
27 antennas
351 baselines

WSRT
14 antennas
91 baselines

Definition of phase

- $E(\nu,t) = E\cos(2\pi\nu t + \phi)$
- E = amplitude; ϕ = phase





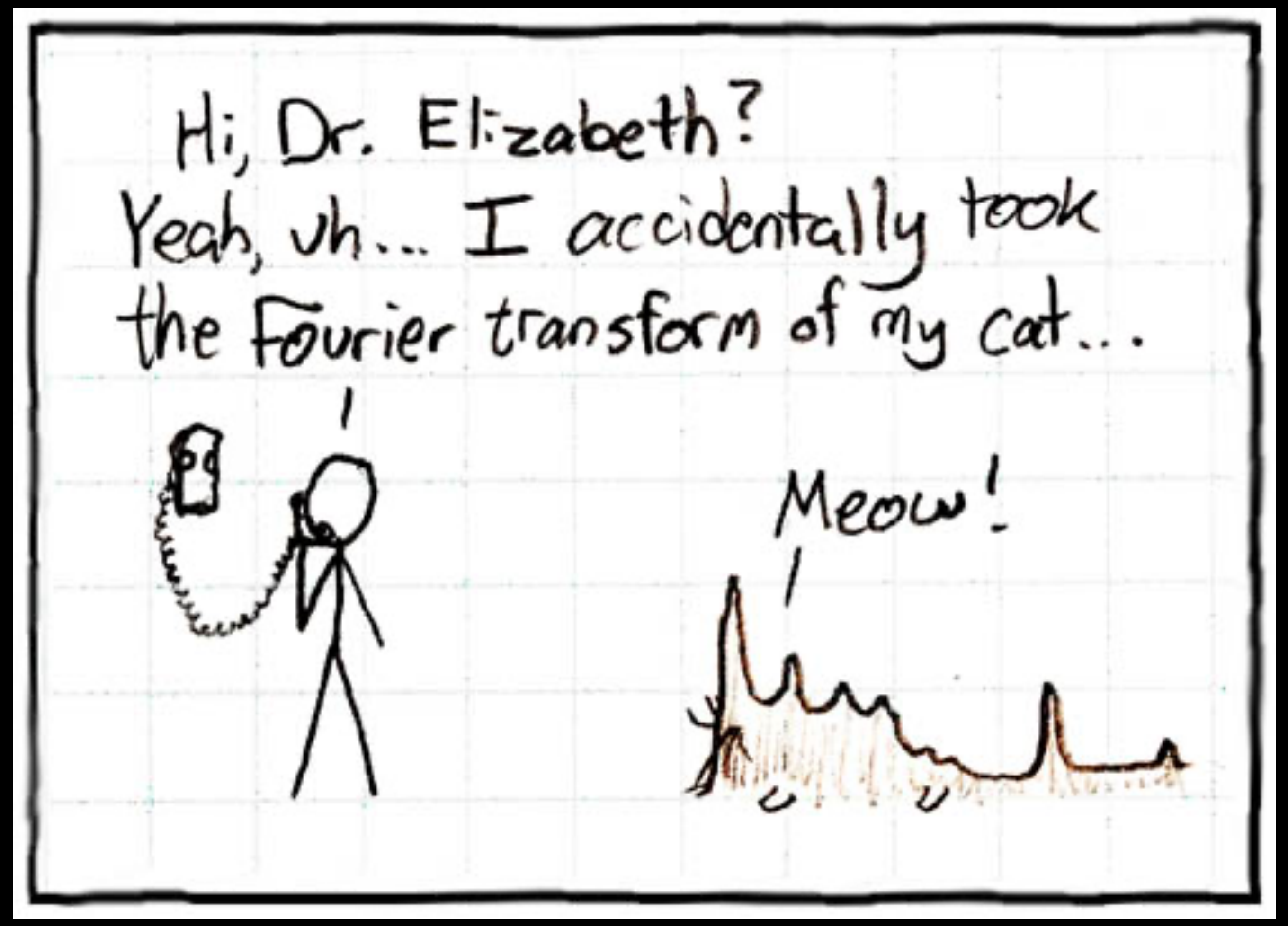
Visibility and Sky Brightness

Van Cittert- Zernike theorem

- Visibility as a function of baseline coordinates (u,v) is the Fourier transform of the sky brightness distribution as a function of the sky coordinates (l,m)

$$V(u,v) \xrightarrow{\text{FT}} T(l,m)$$

- V(u,v) = the complex visibility function
- T(l,m)=the skybrightness distribution



xkcd

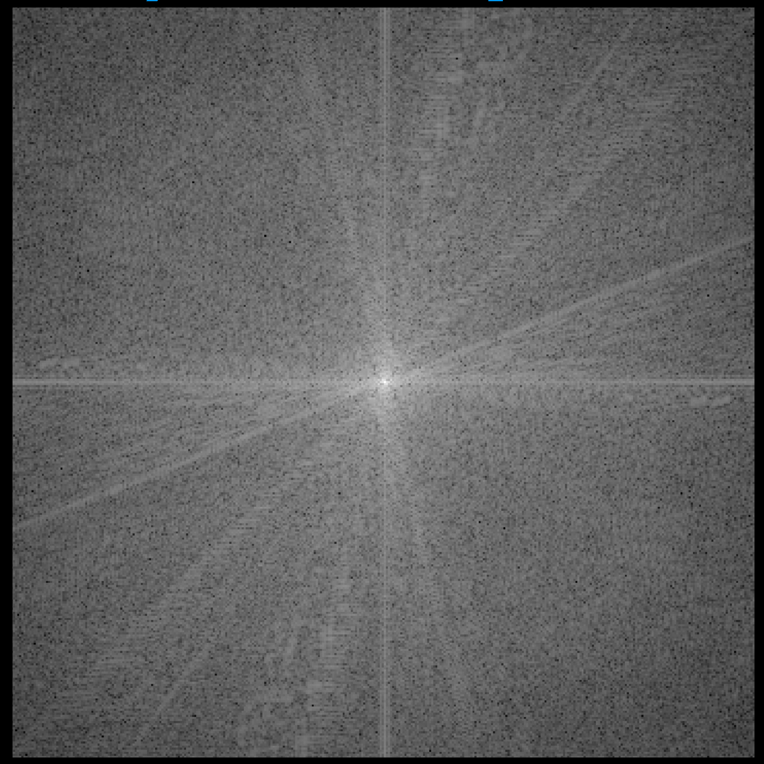
What Are Visibilities?

- Each V(u,v) contains information on T(l,m) everywhere
- Each V(u,v) is a complex quantity
- Expressed as (real, imaginary) or (amplitude, phase)

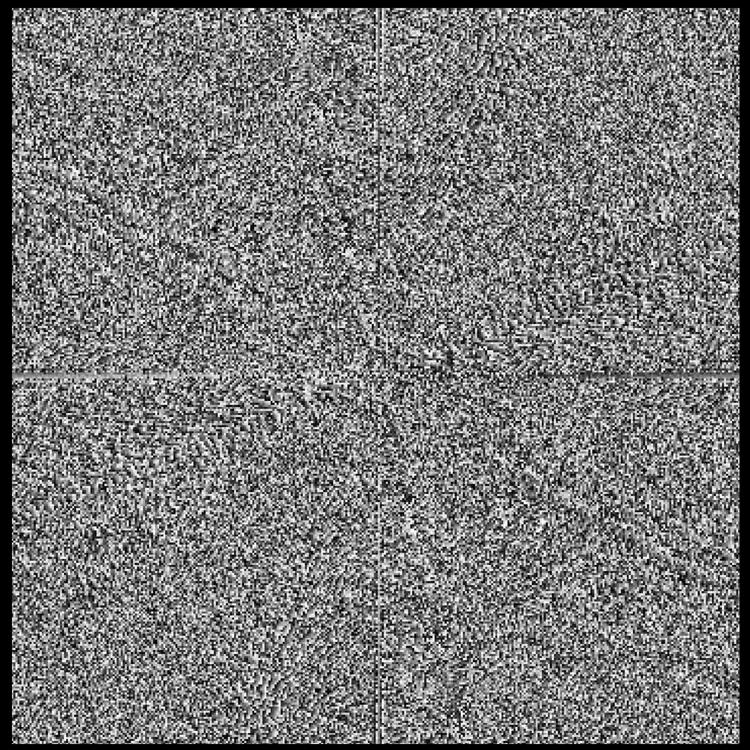
T(l,m)

FT →

V(u,v) amplitude



V(u,v) phase



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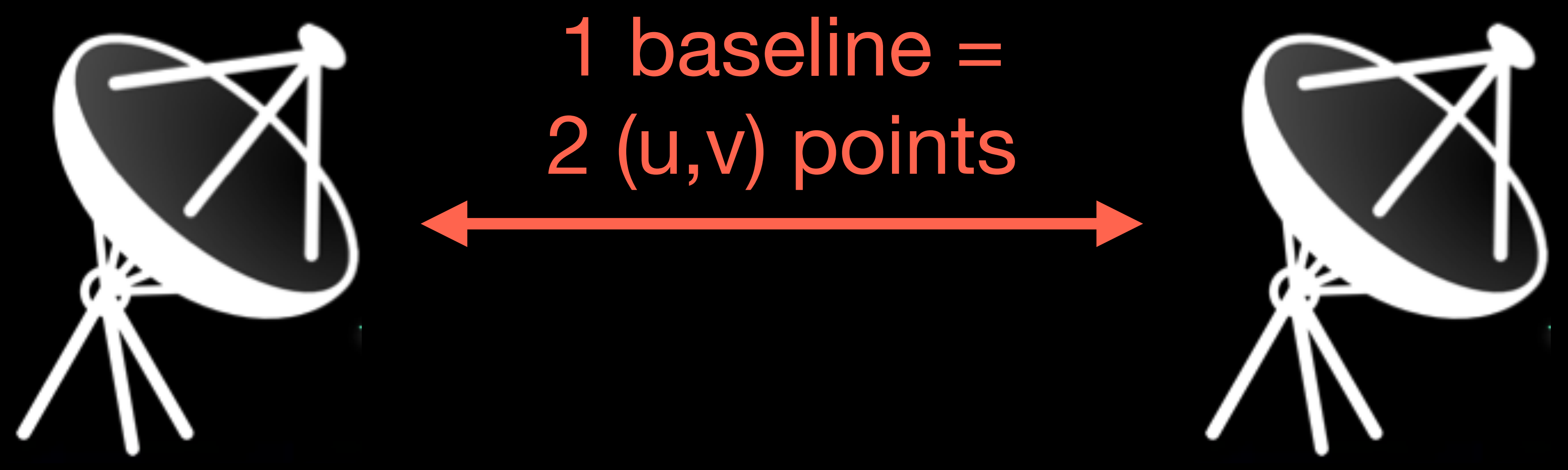
Aperture Synthesis

- **Idea:** Sample V(u,v) at a enough (u,v) points using distributed small aperture antennas to synthesize a large aperture antenna of size (umax,vmax)
- One pair of antennas = one baseline
  For N antennas, we get N(N-1) samples at a time
- How do we fill in the rest of the (u,v) plane?
- 1. Earth's rotation
  2. Reconfigure physical layout of N antennas

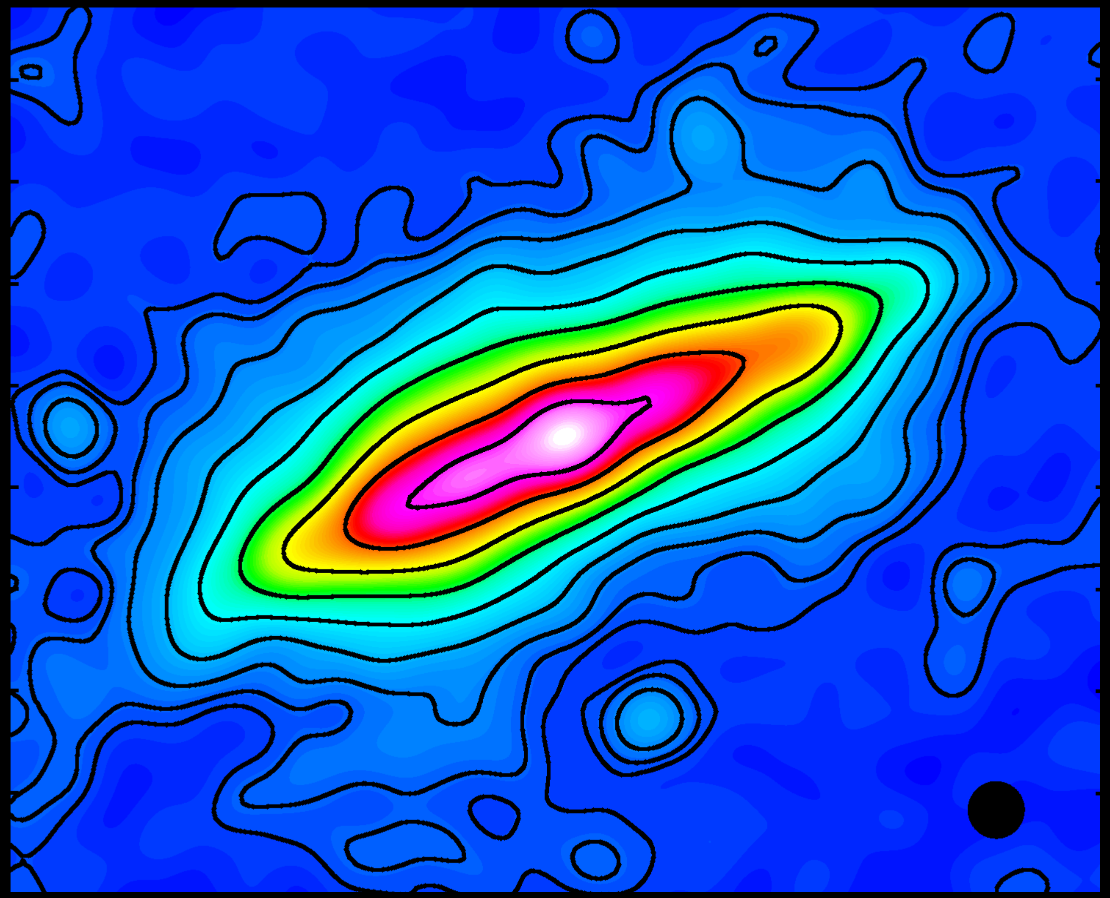


Merging of VLA configurations

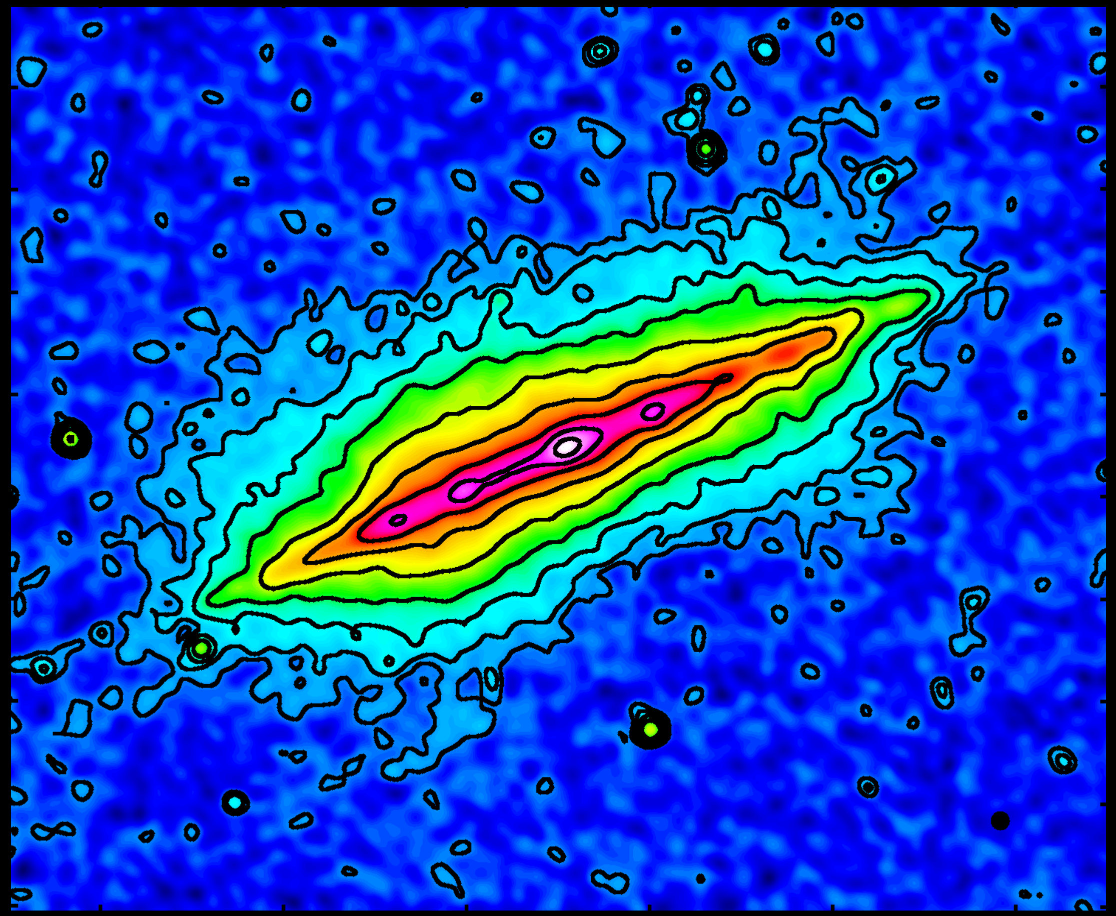
as an example for aperture synthesis

- VLA C-configuration shows smaller spatial scales (denser, clumpier emission)
- VLA D-configuarion data shows larger spatial scales (diffuse, extended emission)
- To get both — you need a combined image!

D-configuration



B+C+D-configuration



Schmidt et al. (2019)

Making an Image with CLEAN algorithm

Assumption: Image T(l,m) is a collection of point sources

- Start by identifying the highest peak in the residual map as a point source
- Subtract a fraction of this peak from the residual map using a scaled dirty beam: s(l,m) x gain
- Add this point source location and amplitude to the “clean component list”
- Go back to step 1 (complete an iteration) unless stopping criterion reached
- Stopping Criteria? Usually max(residual map) < multiple of rms noise

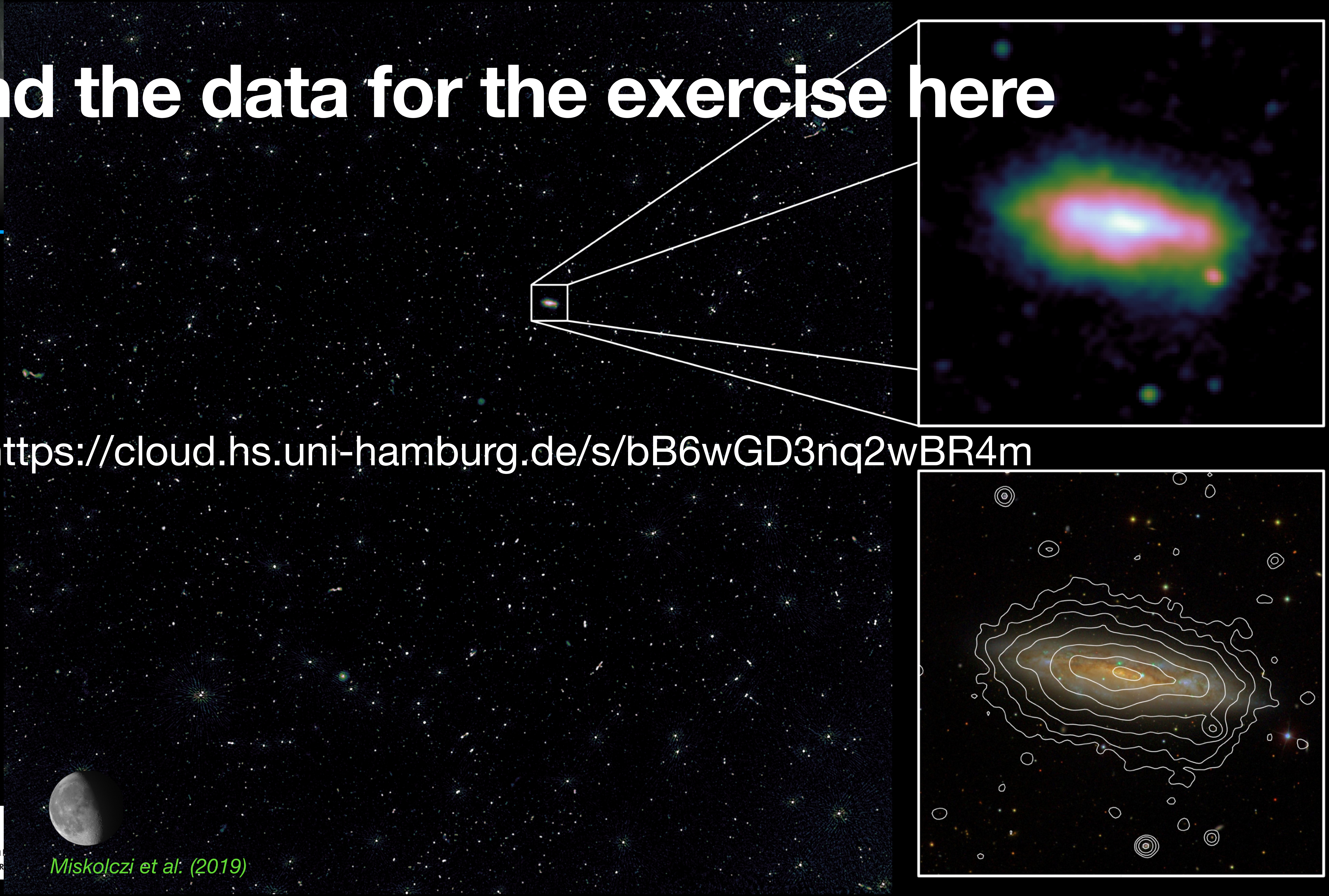
Creating the CLEANed image

Restore with the CLEAN Gaussian beam

- Make a model image with all point sources from the “clean component list”
- Convolve point sources with an elliptical Gaussian, fit to the main lobe of the dirty beam (“clean beam”)
- Add residual map of noise and source structure below the set threshold
- Result: A final “restored image” that is an estimate of the true sky brightness T(l,m)
- Units of the restored image are (mostly) Jy per clean beam area = intensity

Find the data for the exercise here

- https://cloud.hs.uni-hamburg.de/s/bB6wGD3nq2wBR4m



Miskolczi et al. (2019)