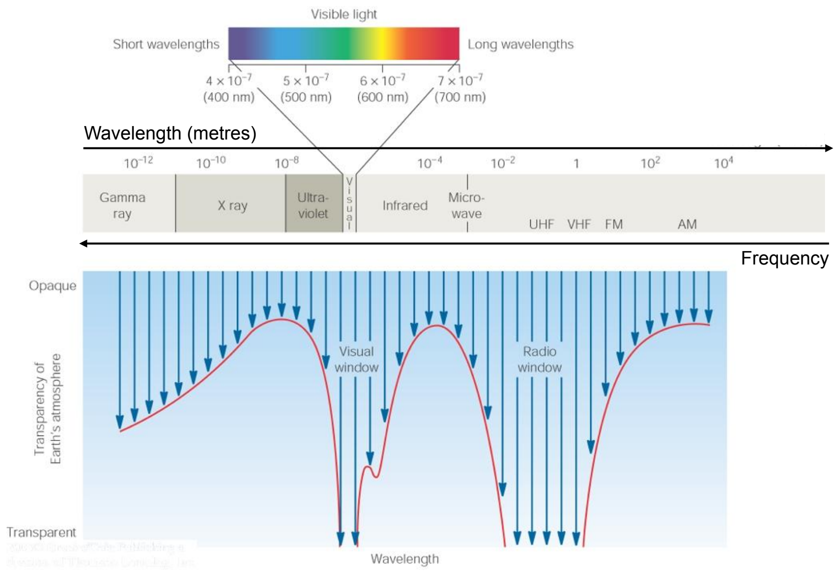
Radio Astronomy

Thermal and non-thermal production of radio waves
Cosmic sources of radio waves
Key differences between radio and optical observations
Interferometry and aperture synthesis

The Electromagnetic Spectrum



Thermal and Non-thermal Emission

- Electromagnetic radiation is emitted by charged particles when they accelerate
- **Thermal** emission caused by acceleration of charged particles **due to the temperature** of the emitting body
  - black body radiation
  - free-free emission
  - line emission
- **Non-thermal** emission caused by acceleration of charged particles **not due to the temperature** of the emitting body
  - synchrotron emission
  - masers

Thermal Emission: Black bodies

- Black bodies …
  - are a useful idealized objects
  - they can be used as an approximation to real stars and galaxies
  - are in thermal equilibrium with their surroundings
  - are perfect absorbers and emitters of radiation at all wavelengths
- Radiation from a black body therefore …
  - is independent of its composition, size and shape
  - depends only on its temperature
- Flux (formally specific intensity) from a black body of temperature T is described by the Planck functions:

$$B_\nu(T) = \frac{2h\nu^3}{c^2} \frac{1}{e^{h\nu/(kT)} - 1}$$

$$B_\lambda(T) = \frac{2hc^2}{\lambda^5} \frac{1}{e^{hc/(\lambda kT)} - 1}$$

Thermal Emission: Black bodies

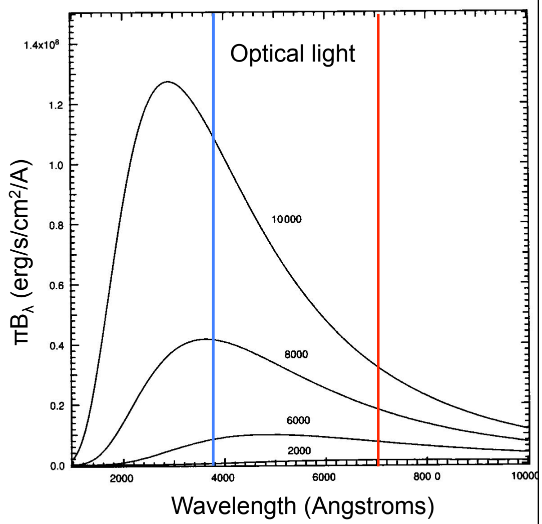
- Hotter black bodies emit more energy
- For a spherical blackbody of temperature T and radius R:

$$L = \int_{\pi} d\Omega \int_{4\pi R^2} dA \int_0^{\infty} B_\lambda(T) d\lambda = 4\pi R^2 \sigma T^4$$

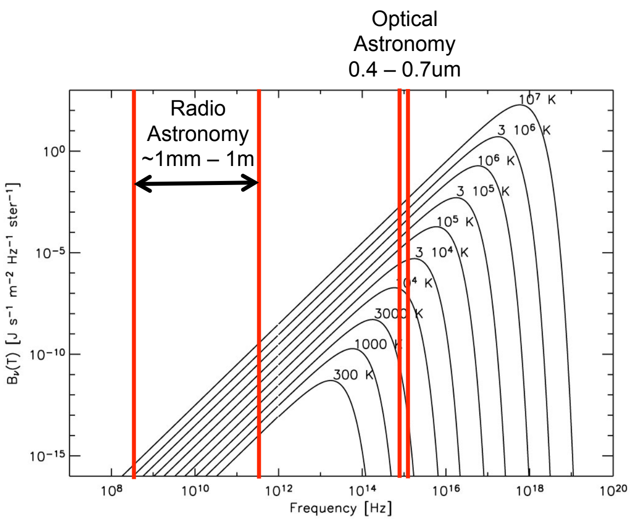
$\sigma = 5.67 \times 10^{-8}$ W m^{-2} K^{-4}
(Stefan-Boltzmann constant)

- Radiation from hotter black bodies peaks at shorter wavelengths

$\lambda_{max}(m) = 2.8983 \times 10^{-3} / T(K)$
(Wien displacement law)



Thermal Emission: Black bodies



$$B_\nu(T) = \frac{2h\nu^3/c^2}{e^{h\nu/kT} - 1}$$

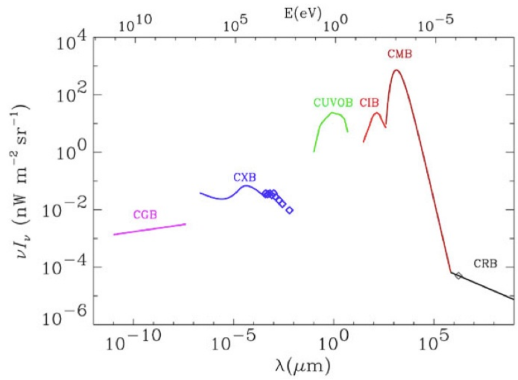
Radio observations are in the Rayleigh-Jeans limit:

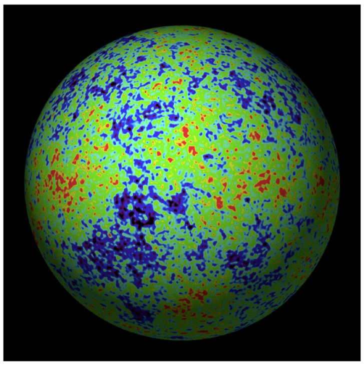
$$h\nu << kT$$

$$e^{h\nu/kT} \approx \frac{h\nu}{kT} + 1$$

$$B_\nu(T) = \frac{2\nu^2 kT}{c^2}$$

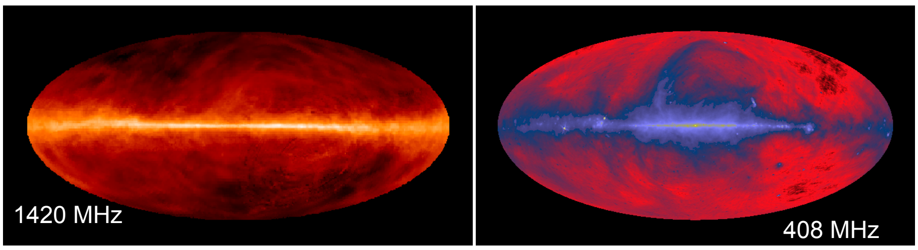
Cosmic Spectrum and the CMB

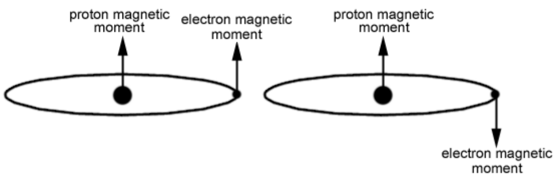




The big picture: the electromagnetic spectrum of the universe (Dwek, E., & Barker, M. K. 2002, ApJ, 575, 7). The brightness νI_ν per logarithmic frequency (or wavelength) interval is shown as a function of the logarithm of the wavelength, so the highest peaks correspond to the most energetic spectral ranges.

Thermal Emission: Line emission

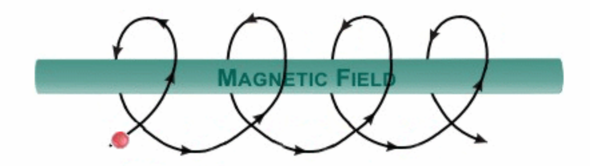


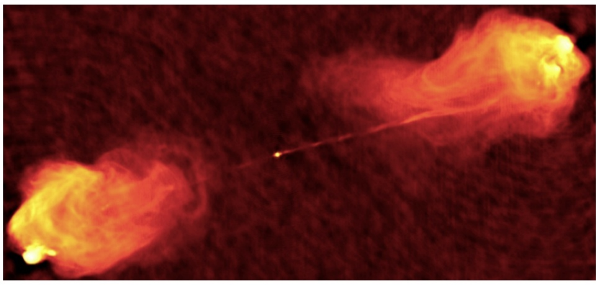


Hydrogen is the most common element in the Universe

The spin-flip transition causes a forbidden line at 1420 MHz (21 cm)

Non-thermal emission: synchrotron





A high-resolution VLA image of the radio source Cygnus A. The bright central component is thought to coincide with a supermassive black hole that accelerates the relativistic electrons along two jets terminating in lobes well outside the host galaxy. [Image credit]

Energy of "photons"

For an optical photon λ = 500 nm:

$$E = h\nu = h\frac{c}{\lambda} = 6.6\times10^{-34} J.s \times \frac{3\times10^{8}\ ms^{-1}}{500\times10^{-9}\ m} = 4\times10^{-19} J \simeq 2.5\ eV$$

For a radio photon λ = 21 cm:

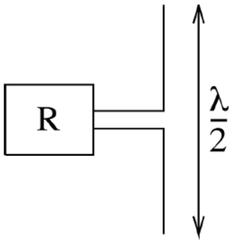
$$E = h\nu = h\frac{c}{\lambda} = 6.6\times10^{-34} J.s \times \frac{3\times10^{8}\ ms^{-1}}{21\times10^{-2}\ m} = 3.8\times10^{-25} J \simeq 2.4\times10^{-6}\ eV$$

Therefore radio waves are too low energy to be detected with CCDs, PMTs, Photography.

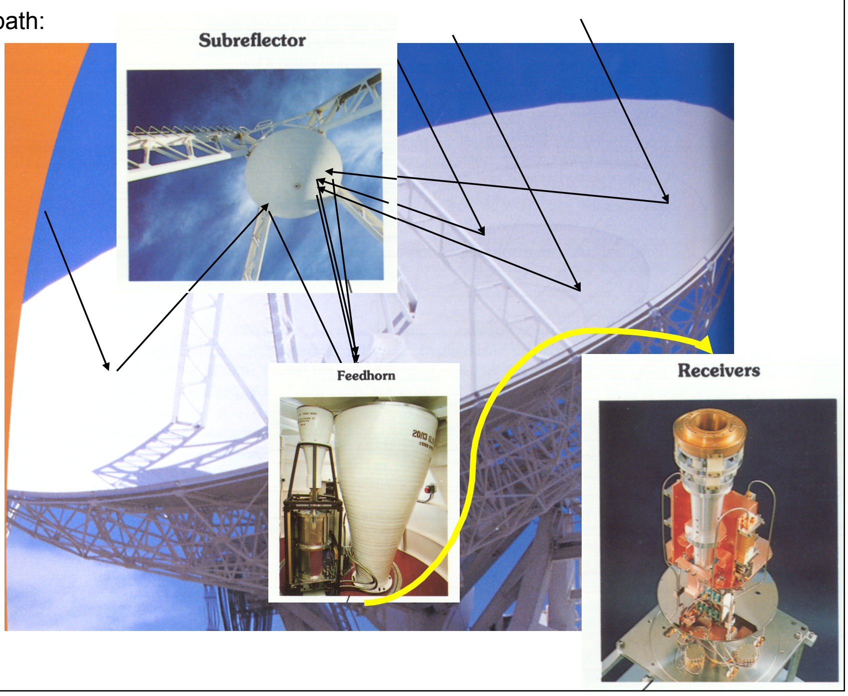
Radio waves are detected by the oscillating current that their electric field induces in an antenna.

Radio detectors

- Simplest detector for radio telescope is half-wave dipole aerial
- Consists of two wires length λ/4
- Electric field of EM waves induce oscillating current in wires
- Detect and analyse to measure radio power



Signal path:



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

Diffraction versus Seeing

Keck telescope

- D=10m, FWHM>~0.5arcsec (seeing), λ=500nm
- Δθ = 1.22x500nm/10m = 0.51x10^{-7} radians
  = 0.01arcsec
- Keck is seeing limited

Hubble Space Telescope

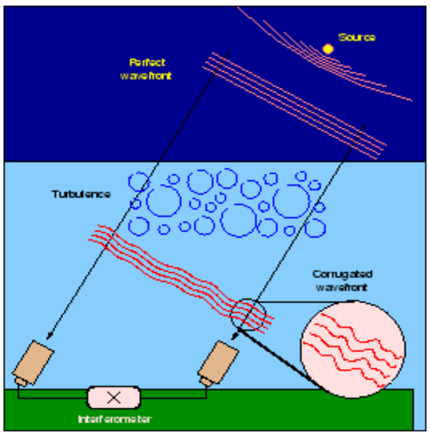
- D=2.4m, FWHM~0.1arcsec (seeing), λ=500nm
- Δθ = 1.22x500nm/2.4m
  = 2.54x10^{-7} radians = 0.05arcsec
- Hubble is seeing limited – but only just!

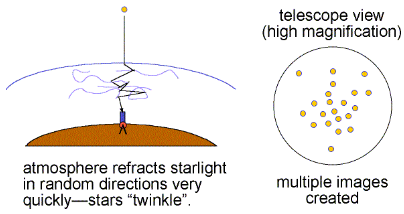
Arecibo

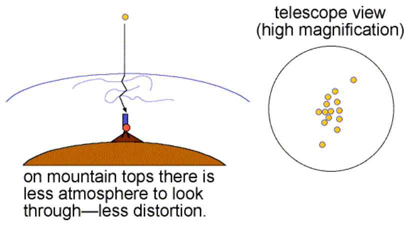
- D=305m, FWHM~10arcsec (seeing), λ=21cm
- Δθ = 1.22 x 21cm / 305m
  = 8.4x10^{-4} radians
  = 173arcsec
- Arecibo is diffraction limited

Atmospheric Turbulence

- Turbulence causes the refractive index of the atmosphere to change randomly and rapidly – this blurs our view of stars and galaxies

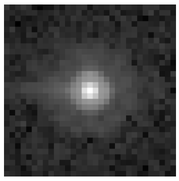


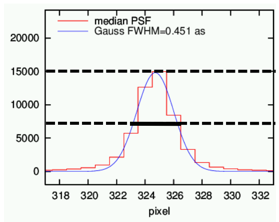




"Seeing"

- In practice seeing blurs our view of stars and galaxies
- A star is blurred from a point to a smooth light distribution
- Astronomers measure seeing by fitting (e.g.) a Gaussian to the measured light distribution
- Seeing is defined as the full width at half maximum
- Typically FWHM = 1arcsec at 550nm

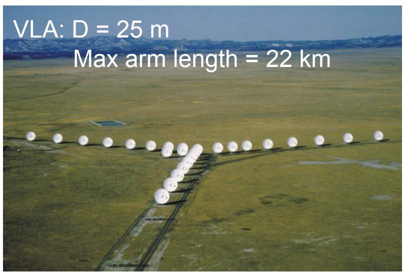


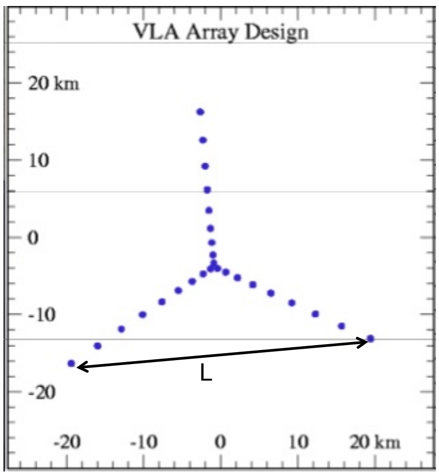


- It can be shown from Kolmogorov theory of turbulence that seeing has a gentle wavelength dependence: FWHM propto $\lambda^{-0.2}$

Very Large Array

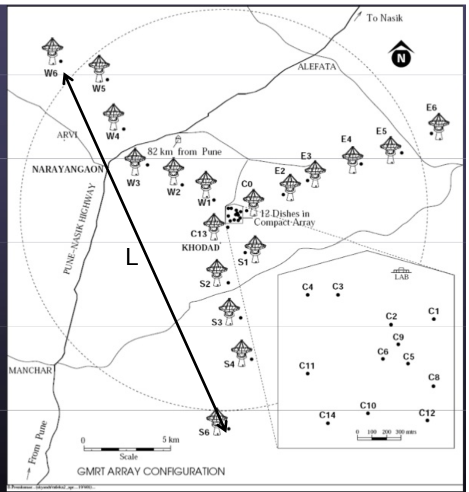
$$\Delta\theta = \frac{\lambda}{L}$$





$$\Delta\theta = \frac{\lambda}{L}$$

Giant Metre-wave Radio Telescope (GMRT)



- Located near Khodad, India
- Contains 30 antennas each with 45m diameter

$$\Delta\theta = \frac{\lambda}{L}$$

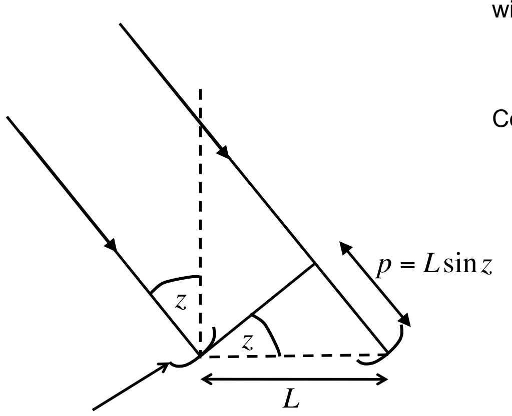
Very Long Baseline Array (VLBA)

- Built in 1995
- 10 VLA-type antennas
- Spread throughout continental US plus Hawaii and St. Croix
- Maximum baseline over 8,000 km
- Elements not electronically connected
  - must bring recorded data to central correlator

What is the best angular resolution achievable with VLBA at λ=21cm?

Two Element Interferometer

Observe an object at a zenith angle of z with a two element interferometer:



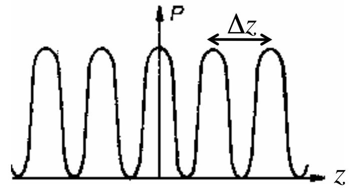
Reflector of diameter D

Phase difference between signals collected by each reflector will vary with zenith angle:

$$\phi = \frac{2\pi p}{\lambda} = \frac{2\pi L\sin z}{\lambda}$$

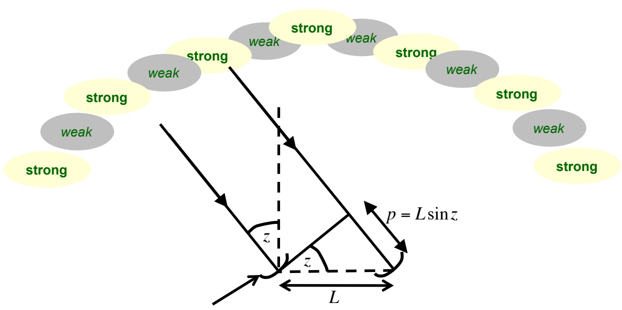
Constructive interference when:

$$\phi = 2n\pi \Leftrightarrow n\lambda = L\sin z$$



At small zenith angle maxima separated by: $\Delta z = \frac{\lambda}{L}$

Two Element Interferometer



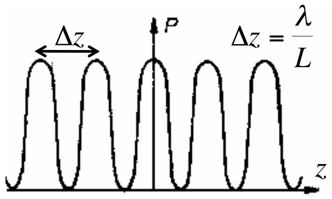
Reflector of diameter D

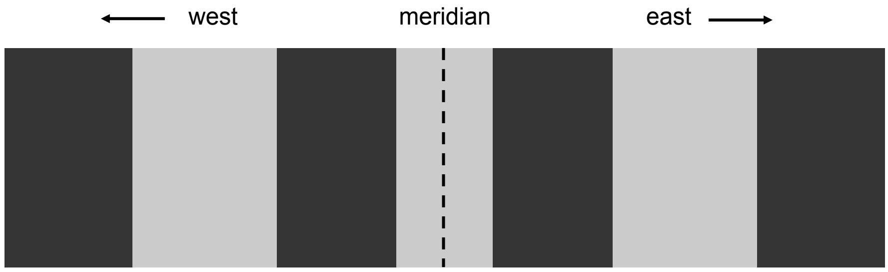
- As the Earth rotates, the zenith angle of the target will change
- The path and phase differences at the two antennae will therefore also change
- The intensity of the measured signal from a point source therefore varies sinusoidally
- Fringe separation is a measure of the angular resolution of the interferometer

$$\Delta z = \frac{\lambda}{L}$$

Two Element Interferometer

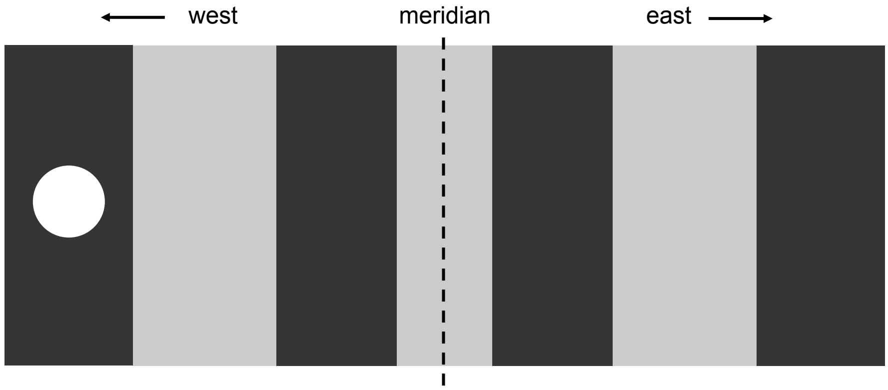
- Consider a 2-element east-west interferometer
- Regions of constructive and destructive interference can be considered “stripes” in the sky





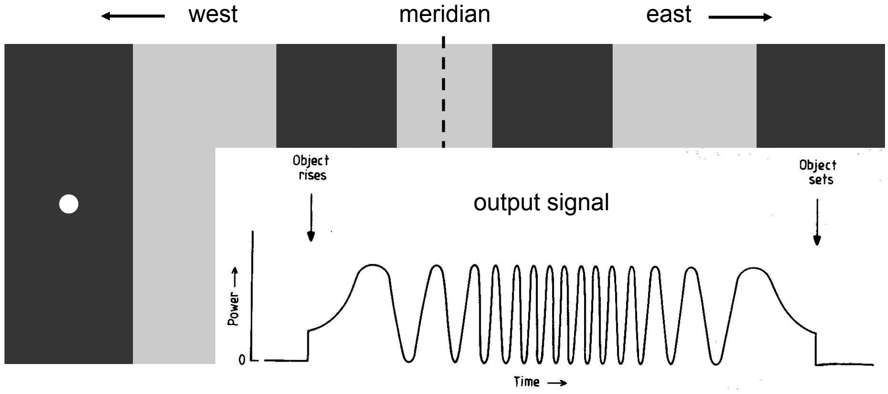
Two Element Interferometer

As a target moves through the fringe pattern, it produces an oscillating output signal from the interferometer



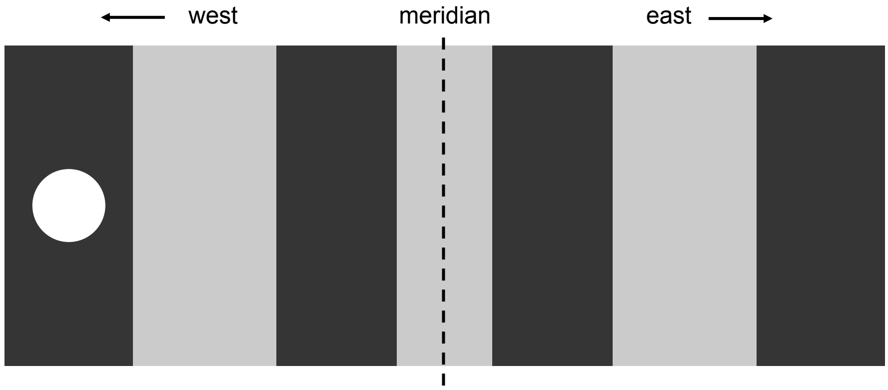
Two Element Interferometer

If the target is very small compared to the fringe half-spacing λ/2L, it is unresolved. The output signal is just the fringe pattern, and the source structure cannot be determined.



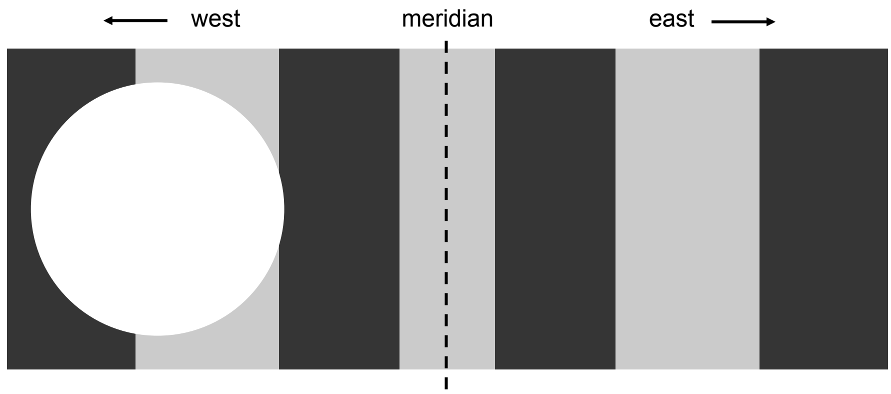
Two Element Interferometer

If the source is comparable to the fringe half-spacing λ/(2B), then the output signal is the fringe pattern smoothed by the finite size of the source.



Two Element Interferometer

If source spans both a peak and a trough, the output signal is nearly constant.
The source is over-resolved or "resolved out", and its structure poorly determined



Two Element Interferometer

If you are interested in source structure that is being resolved out, then observe with a *shorter* baseline B to make the fringe spacing λ/B larger.