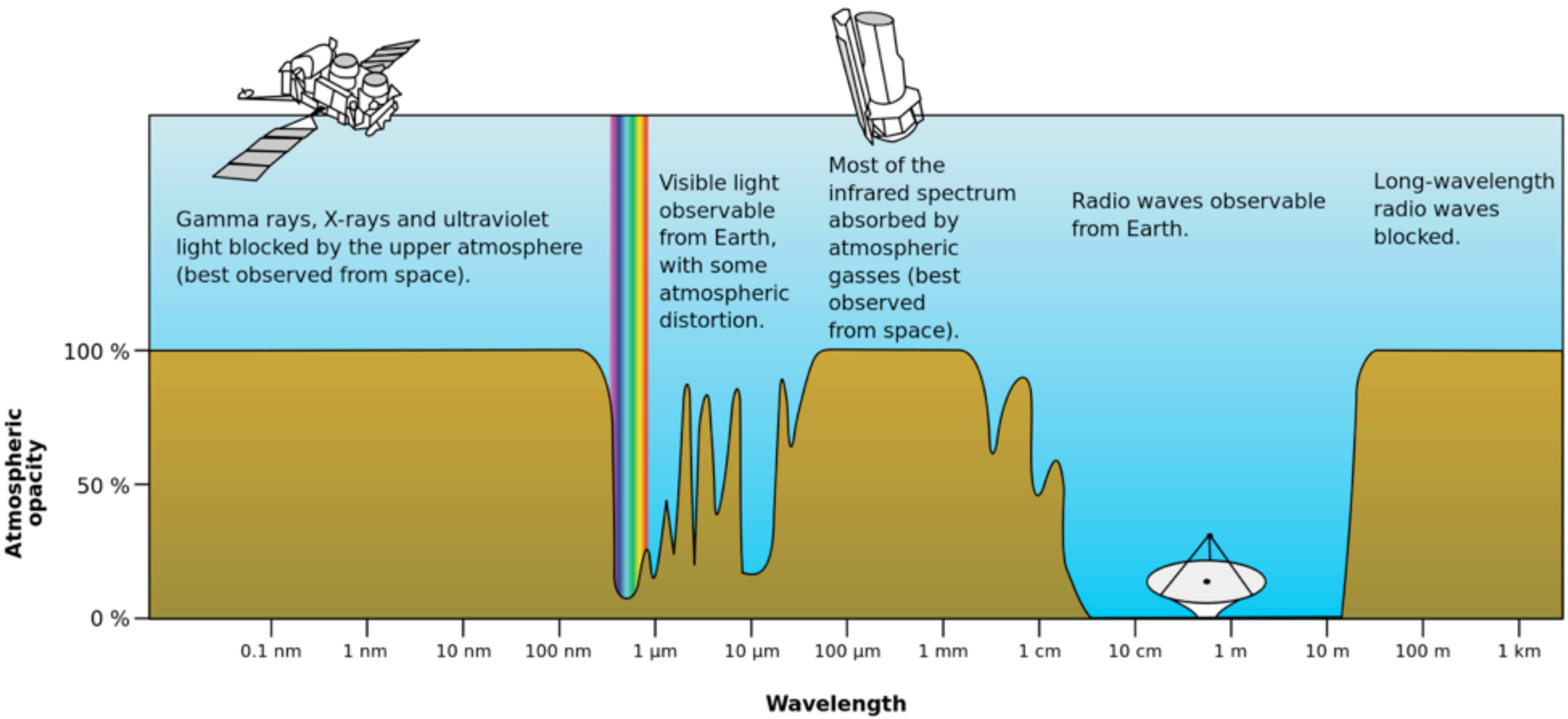
PHY 517 / AST 443:
Observational Techniques in Astronomy

Lecture 5:
Radio Astronomy

Earth's atmosphere

radio waves: second large atmospheric window - accessible for ground-based astronomy



Units

- optical astronomy:
  - photon energy expressed as wavelength (Angstrom or nm)

- radio astronomy:
  - photon energy usually expressed as frequency (MHz or GHz)
  - 1cm = 30 MHz
  - boundary radio / far-infrared: ~1 THz = 0.3mm
  - low-frequency limit: ~10 MHz = 30m

Units

- optical astronomy:
  - flux measured in ergs s^{-1} cm $^{-2}$ Hz $^{-1}$ (and usually expressed as magnitudes)

- radio astronomy:
  - flux measured in Jansky = 10^{-26} ergs s^{-1} cm $^{-2}$ Hz $^{-1}$

Reminder

- intensity: energy per unit time, per unit area, per bandwidth, and per unit solid angle
- flux: energy per unit time, per unit area, per bandwidth

- flux depends on distance between source and observer
- intensity does not depend on distance to observer, if source is resolved
- (energy per unit area drops as d^{-2}; surface observed under same solid angle increases with d^2 -> cancel out)

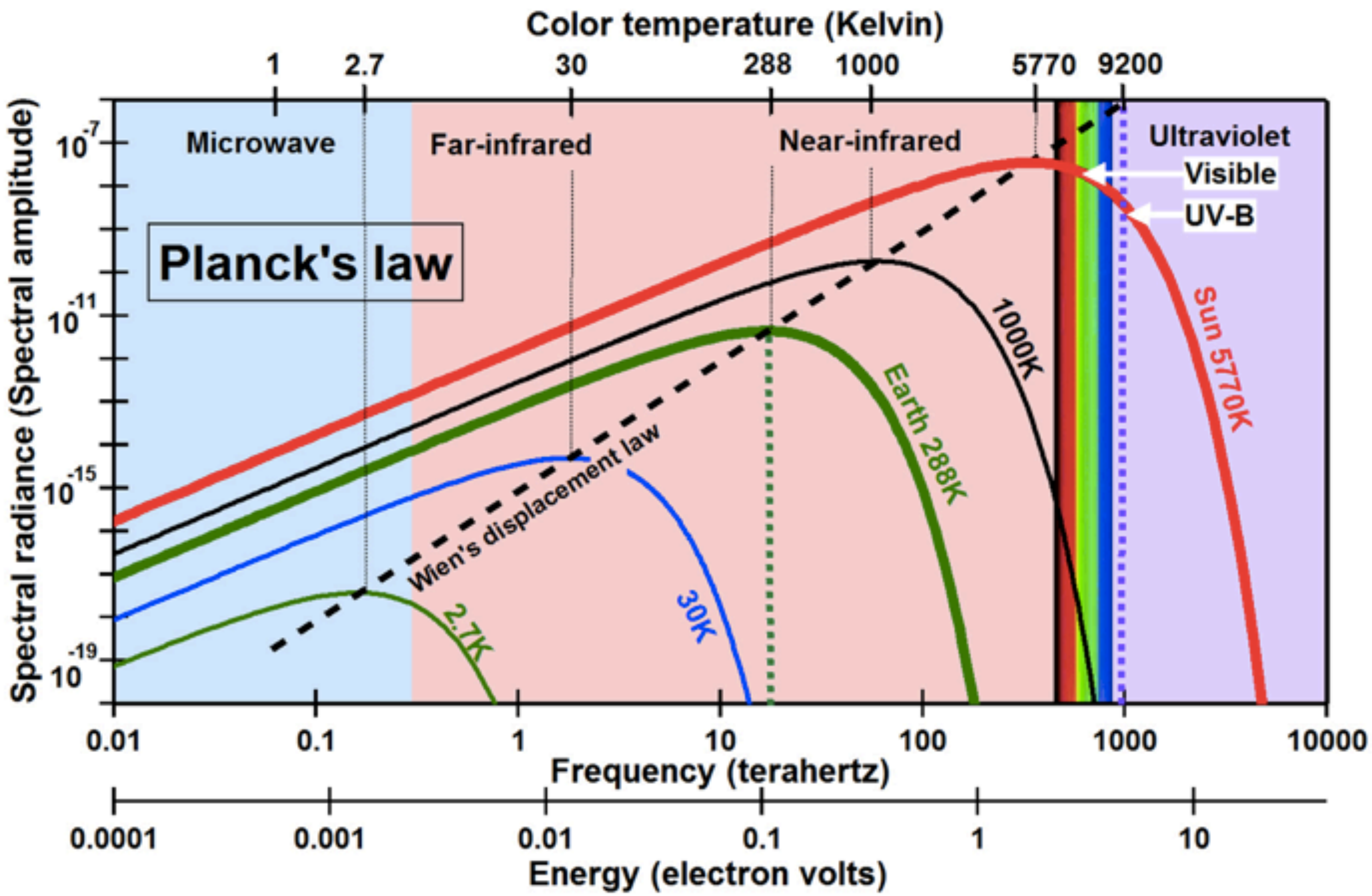
What emits radio waves?

Thermal emission

thermal emission: described by black-body radiation

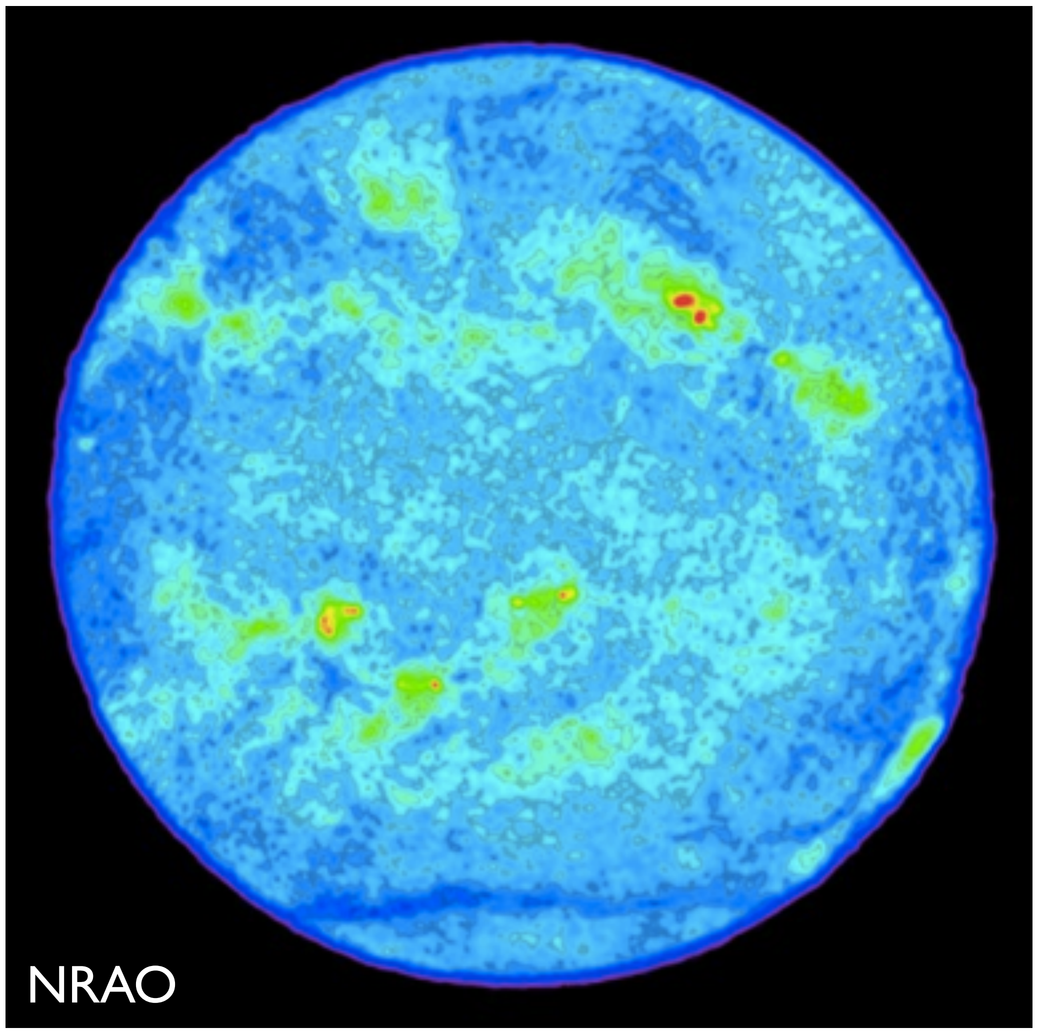
every thermal source emits in the radio, too

can almost always use Rayleigh-Jeans approximation

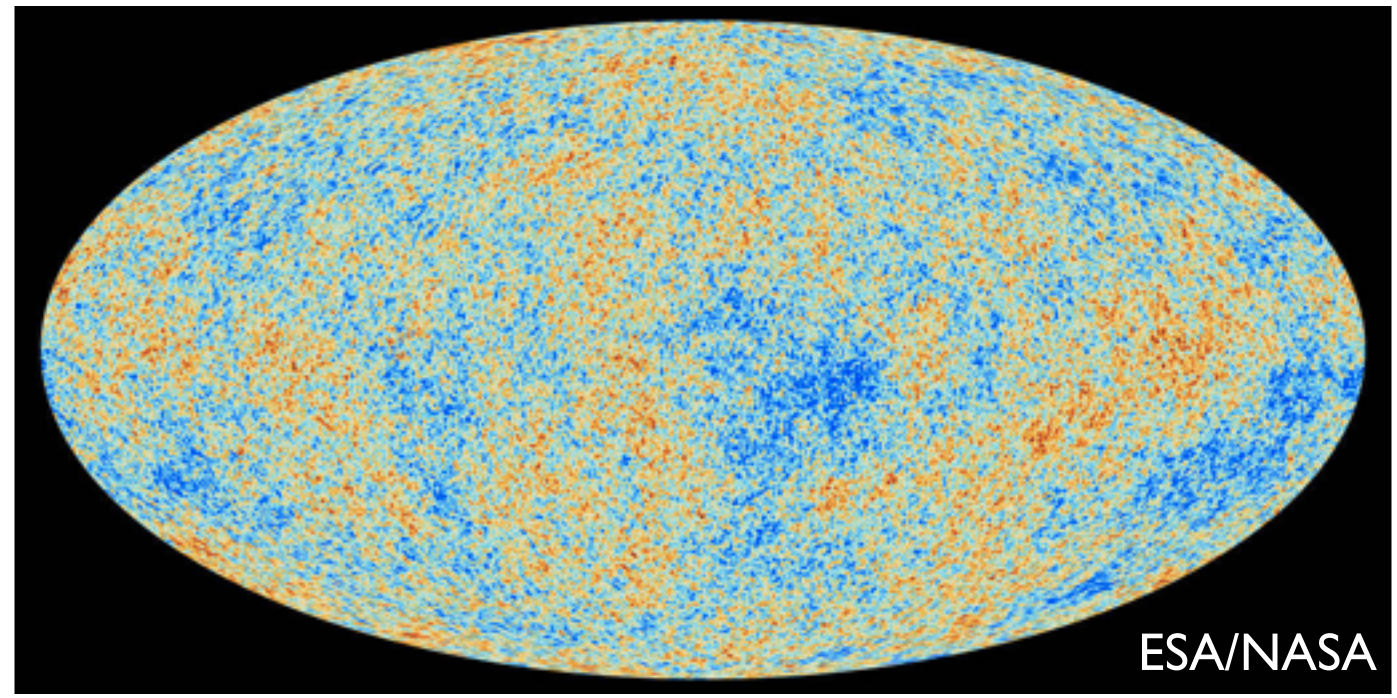


Thermal emission

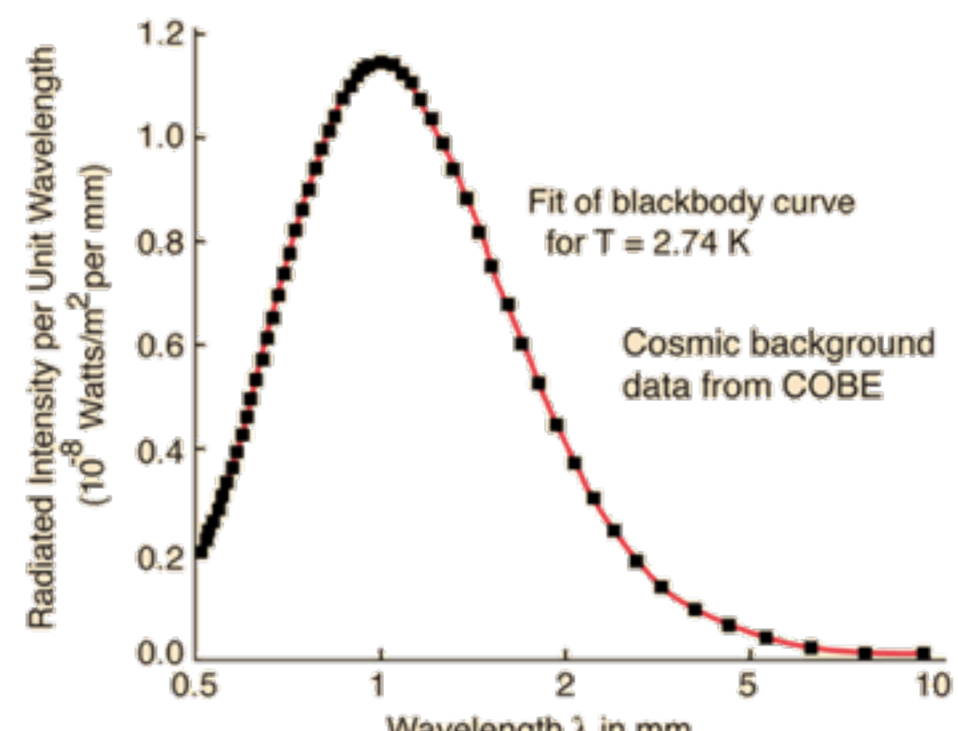
examples of thermal emission:



The Sun!
(your target in Lab 3)



The CMB



Thermal emission

Rayleigh-Jeans approximation: describes the low-energy tail of Planck's law

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

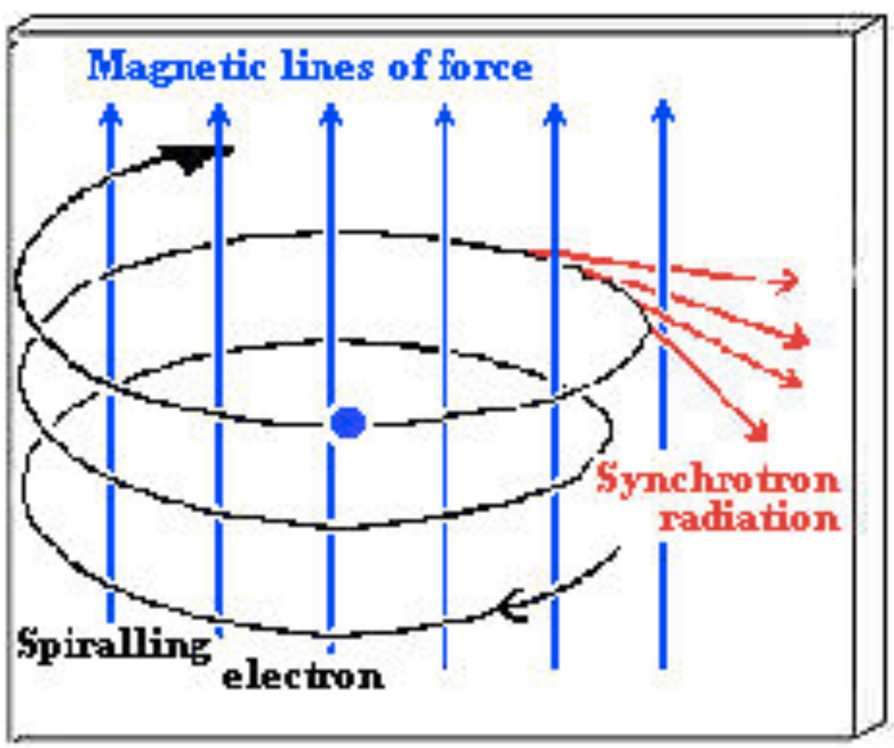
note: B_ν is an intensity, measured in Jansky sterad^{-1}

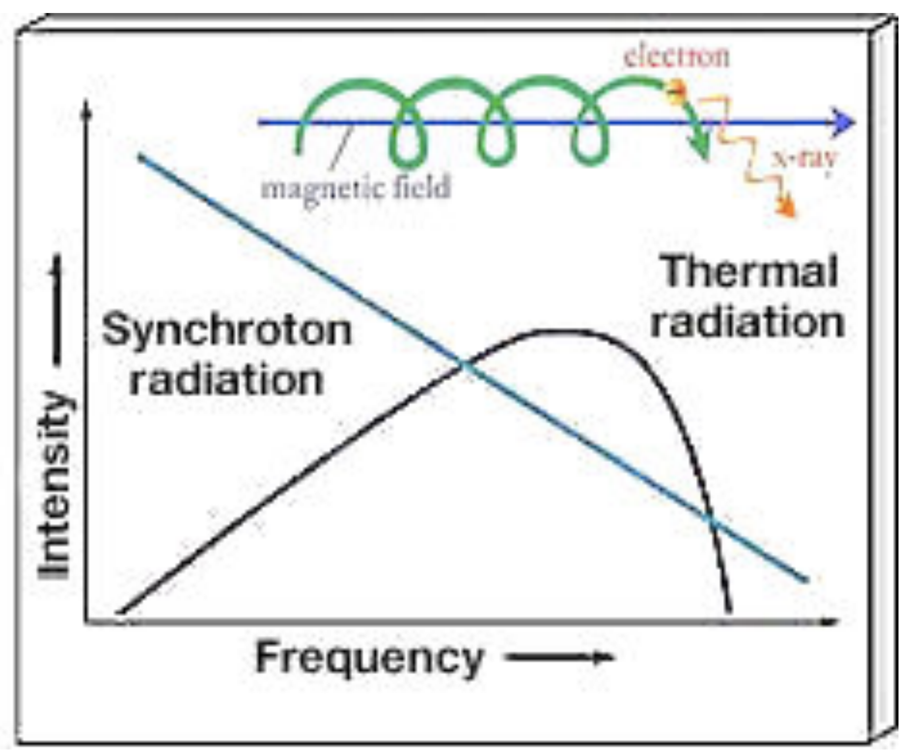
radio astronomers often use brightness temperature to express intensity:

$$T_{\rm b} = \frac{B_\nu c^2}{2k\nu^2}$$

Non-thermal continuum emission

- e.g. synchrotron radiation: acceleration of charged particles in magnetic fields

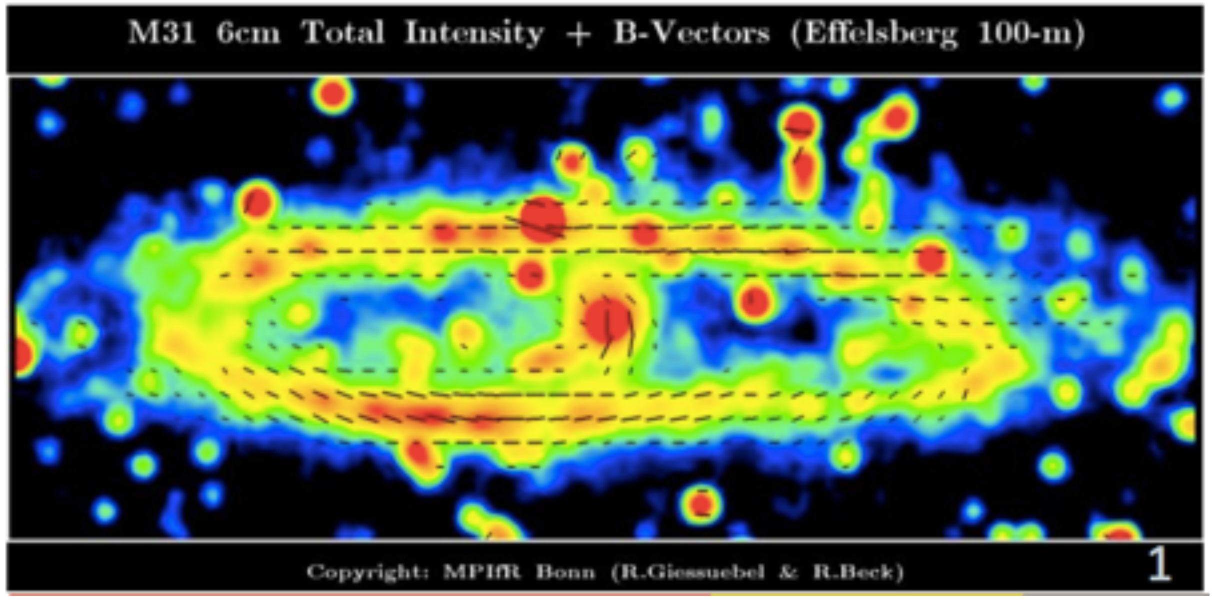




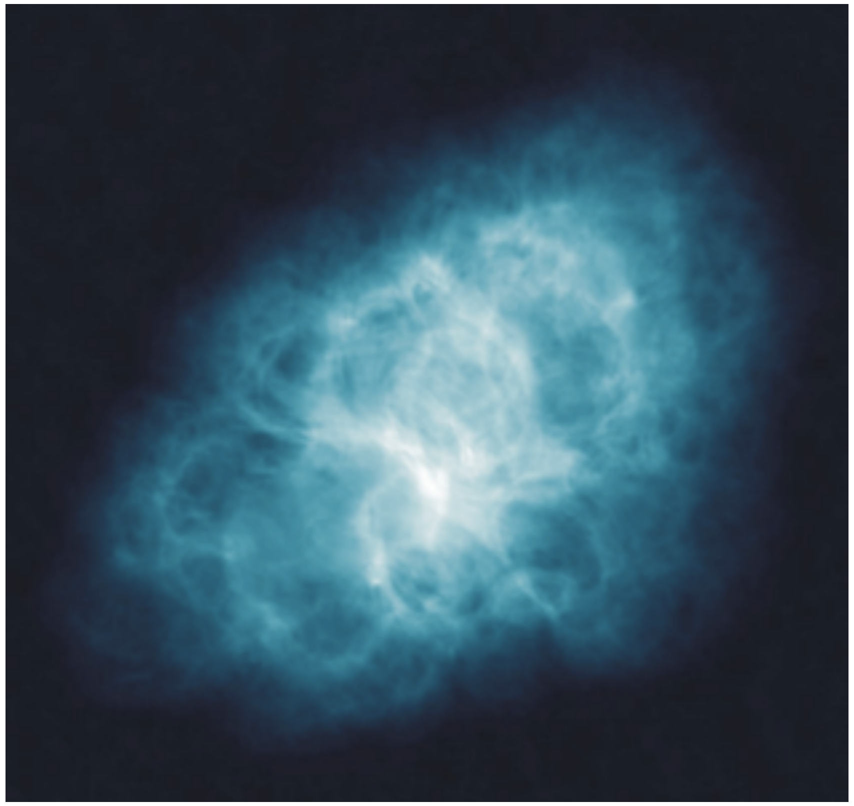
Non-thermal continuum emission

- examples:

radio galaxies



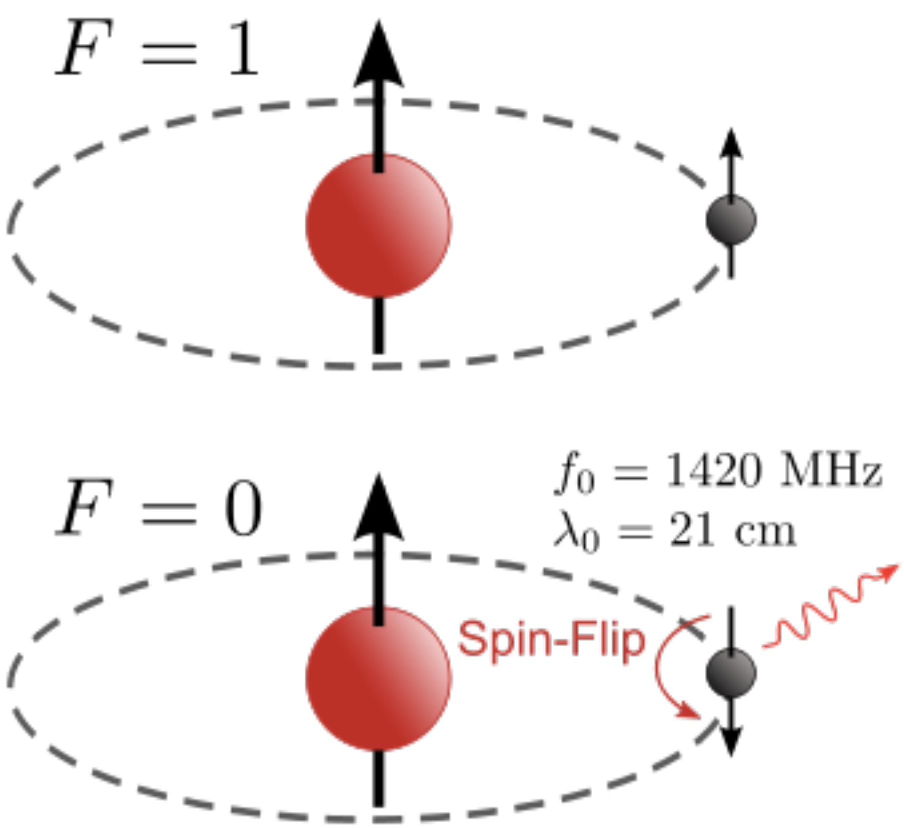
star forming regions



supernova remnants

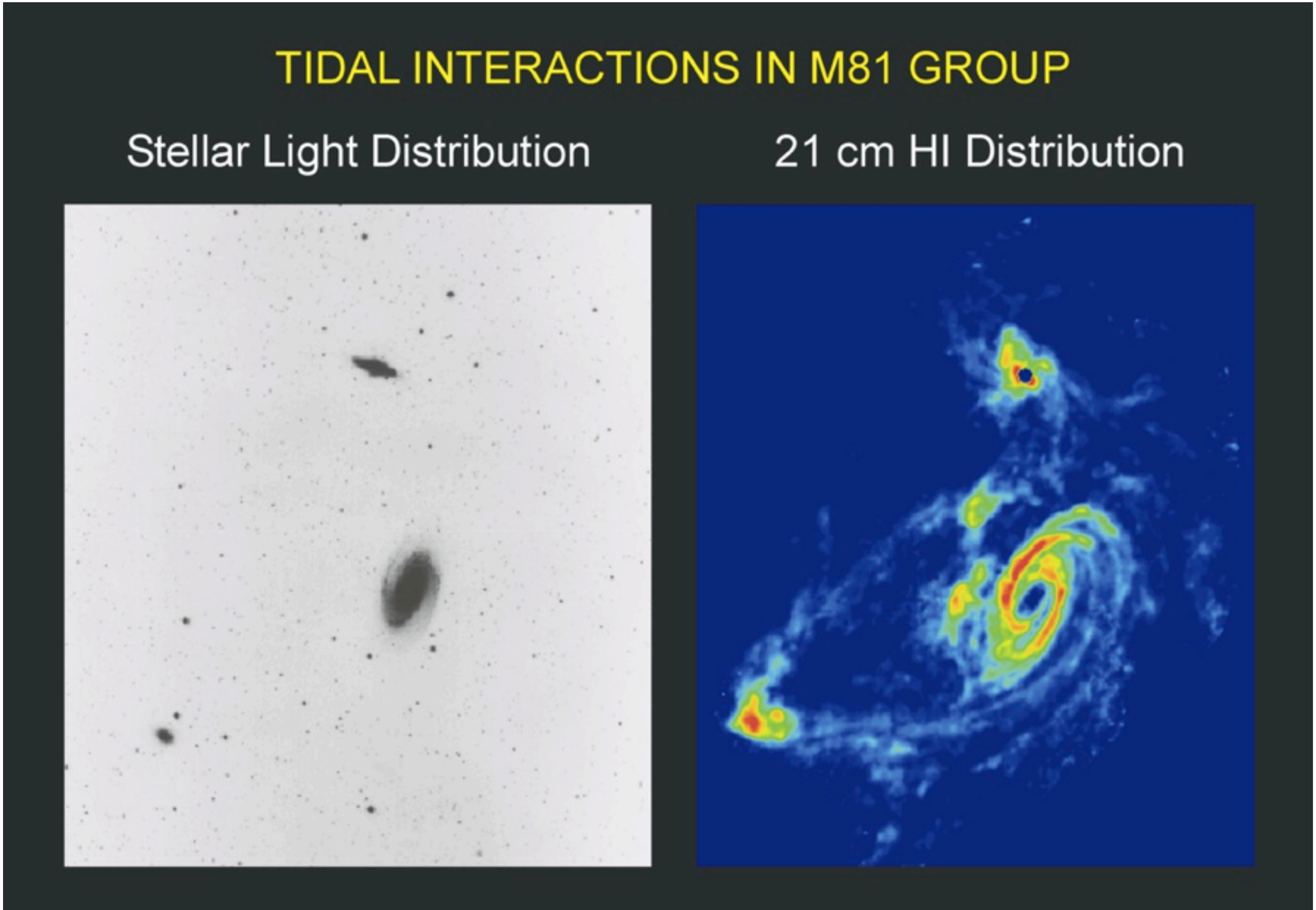
Line emission

- e.g. 21-cm line: spin-flip transition between two hyperfine levels in atomic hydrogen



- hydrogen makes up most of the normal matter in the Universe
- in galaxies, most of hydrogen gas is cool (atomic)
- atomic hydrogen has no transitions in the optical
- 21-cm is our tracer of much of the gas in galaxies

Line emission

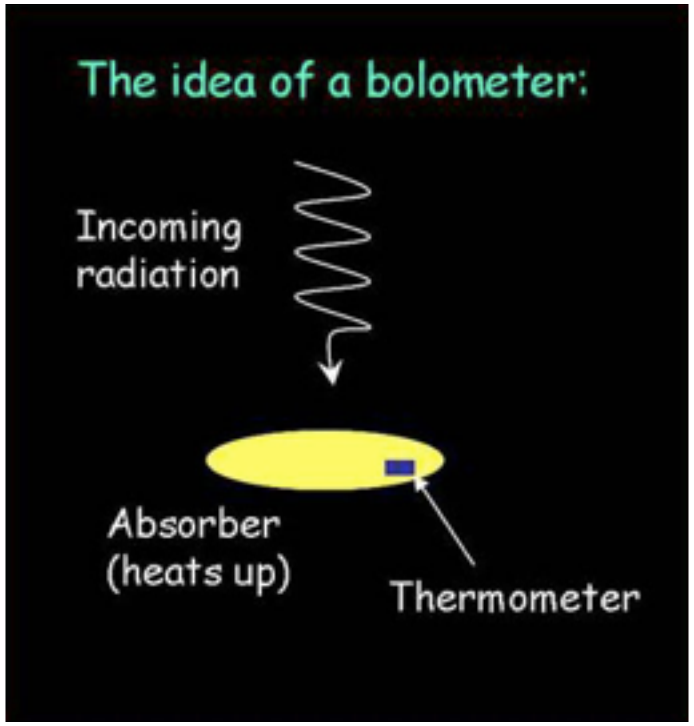


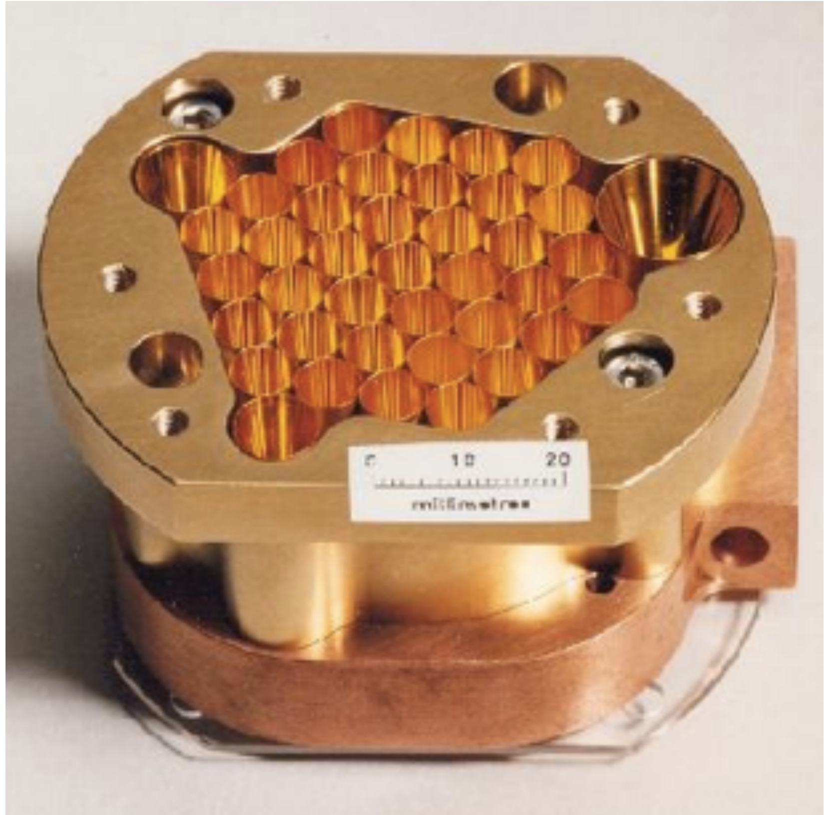
Radio detectors (receivers)

Bolometers

Bolometers: based on thermo-electric effect

- photon is absorbed -> generates heat -> change in voltage
- sensitive to incoming intensity
- EM radiation is treated as a particle
- used primarily in the sub-mm
- can record over broad range in wavelength
- need to be cooled (milli-Kelvin level); otherwise dominated by thermal noise





SCUBA bolometer

Heterodyne receivers

Heterodyne receivers:

- sensitive to the incoming electric field (amplitude + phase)
- incoming signal is mixed with a reference signal to convert to a lower frequency (better manageable)
- EM radiation is treated as a wave
- used from meter to sub-mm wavelengths

The SBU radio interferometer uses a heterodyne receiver.

Radio telescopes

Single-dish telescopes

Mirror surface needs to be precise to ~$\lambda/16$ -> do not need high-recision glass mirrors as in optical astronomy -> easier to build large telescopes

Effelsberg 100-m

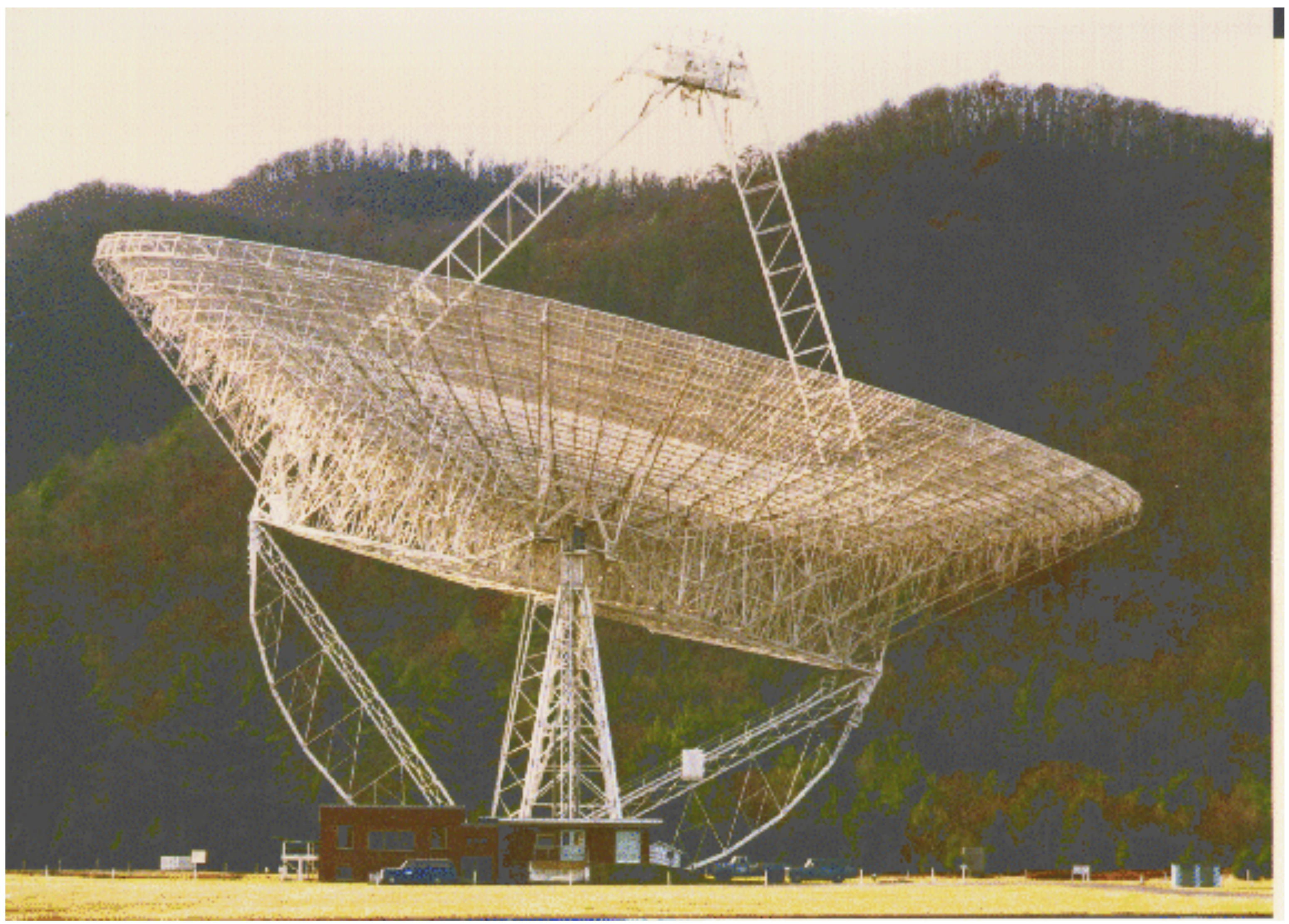
Green Bank 100-m

Arecibo 300-m

FAST 500-m

Single-dish telescopes

... but there's a limit.



original Green Bank telescope, Nov. 15, 1988

Single-dish telescopes

... but there's a limit.

original Green Bank telescope, Nov. 16, 1988

Single-dish telescopes

Recall: diffraction-limited spatial resolution

$$\theta_{\min} = 1.22\,\frac{\lambda}{D}$$

D: telescope aperture (diameter)

What's the angular resolution of GBT at 10mm? At ~1m?

$$\begin{aligned}\theta(10\mathrm{mm}) &= 1.22 \times \frac{10^{-2}\,\mathrm{m}}{100\,\mathrm{m}} \\ &= 0.007\,\mathrm{rad} = 25'' \\ \theta(1\mathrm{m}) &= 42'\end{aligned}$$

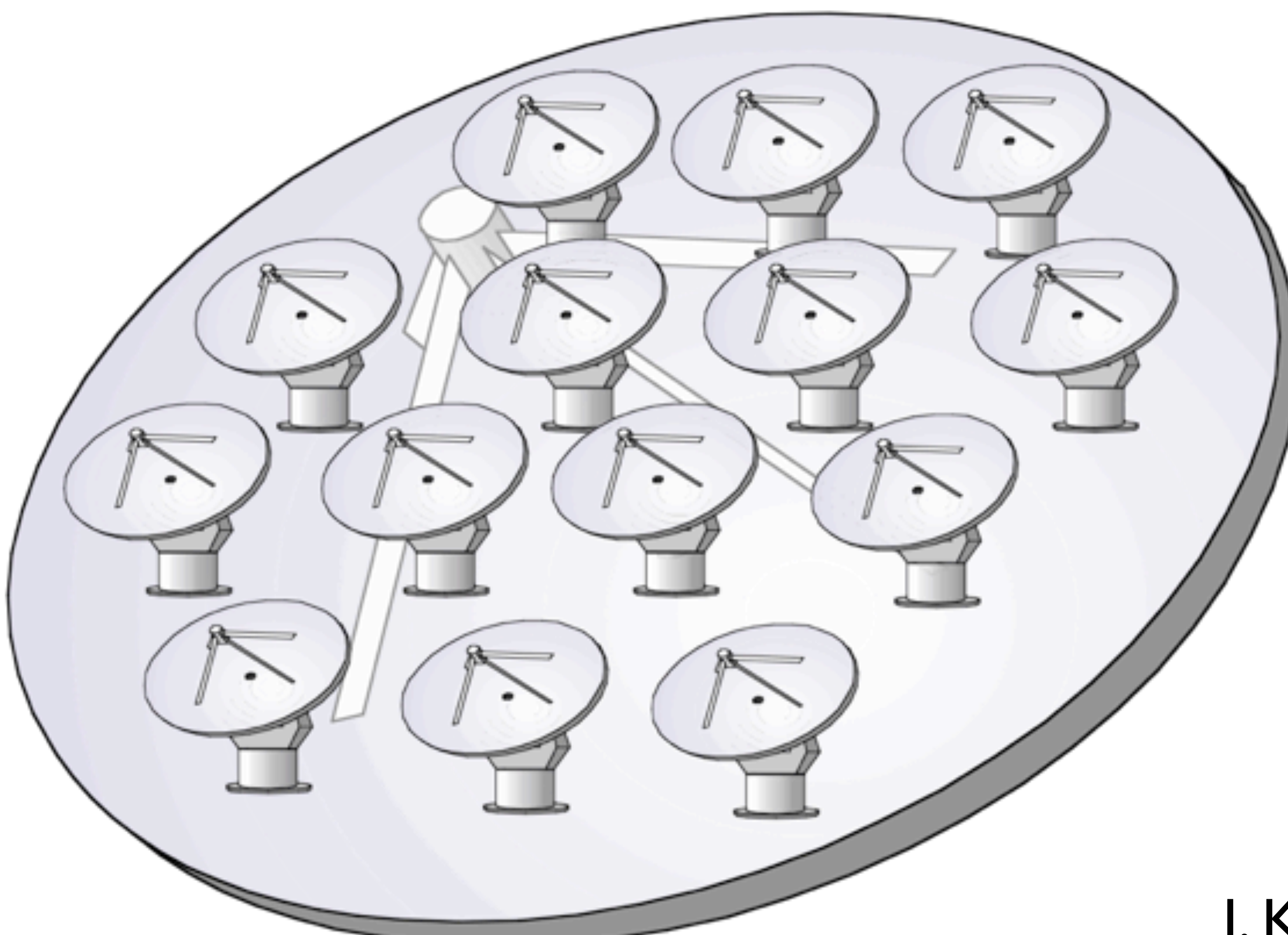
In comparison, the resolution of our 14" telescope is ~2" (seeing-limited)

Interferometers

Interferometers

Idea: instead of one large dish, build many smaller dishes

→ maximum resolution determined by largest distance between two dishes



J. Koda

Interferometers

Very Large Array
(27 dishes)

CARMA
(15 dishes)

ALMA (66 dishes)

Interferometers

van Cittert - Zernicke theorem: the degree of similarity of the electric field at observed at two locations is a measure of the Fourier transform of the sky brightness distribution.

- observe the same source from two telescopes, correct for time travel distance, take correlation function (how similar is the signal) → non-zero signal

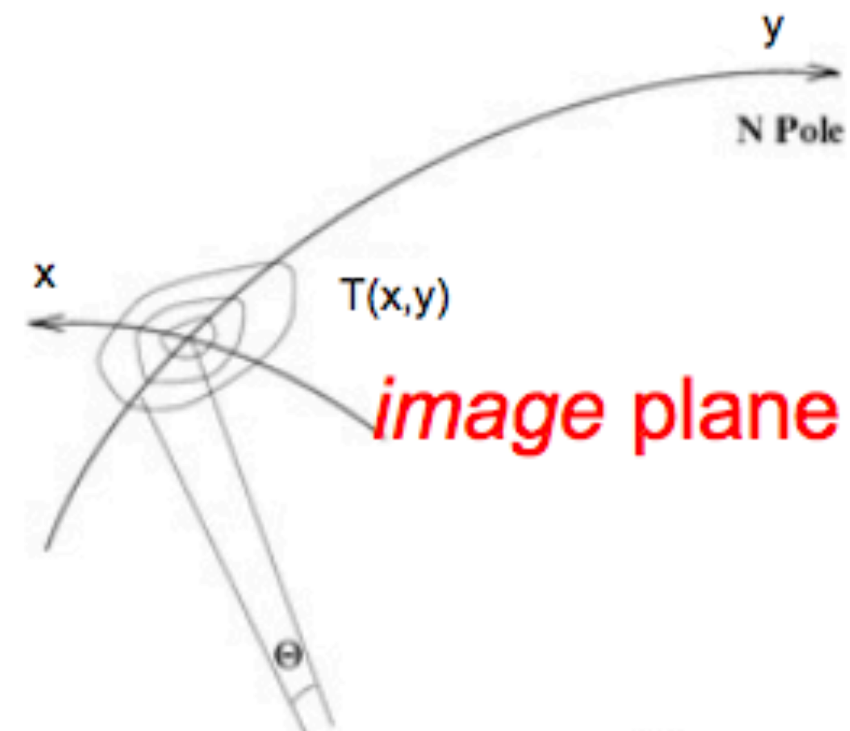
- observe two random locations, take correlation function → zero signal on average

Takeaway: in interferometry, our measurements are related to the Fourier transform of the image. Sample enough Fourier frequencies to reconstruct the image.

For small fields of view: the complex visibility, V(u,v), is the 2D Fourier transform of the brightness on the sky, T(x,y)

$$V(u,v) = \int \int T(x,y) e^{2\pi i(ux+vy)} dxdy$$

$$T(x,y) = \int \int V(u,v) e^{-2\pi i(ux+vy)} dudv$$



- u,v (wavelengths) are spatial frequencies in E-W and N-S directions, i.e. the baseline lengths
- x,y (rad) are angles in tangent plane relative to a reference position in the E-W and N-S directions

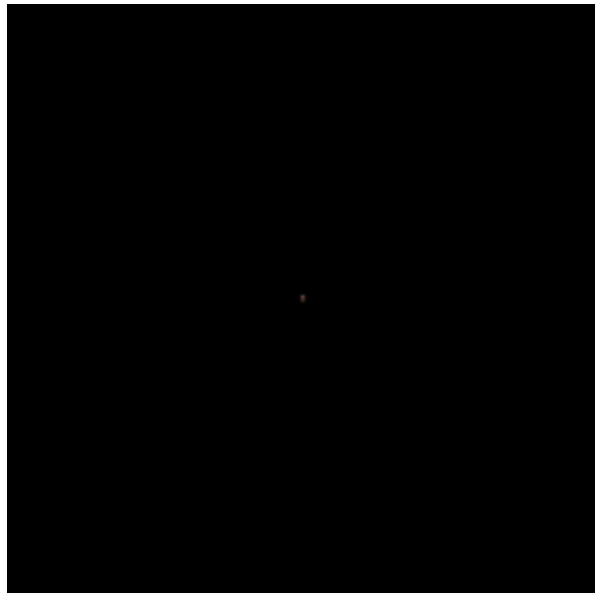
$$V(u,v) \rightleftharpoons T(x,y)$$

Some 2D Fourier Transform Pairs

T(x,y)

Amp{V(u,v)}

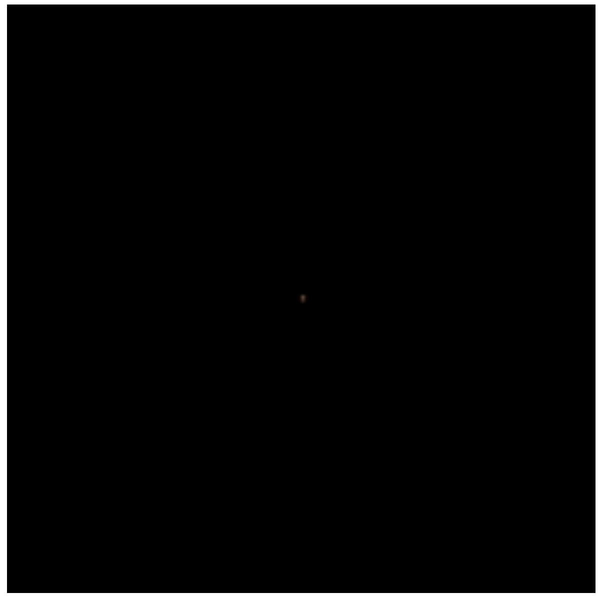
δ Function



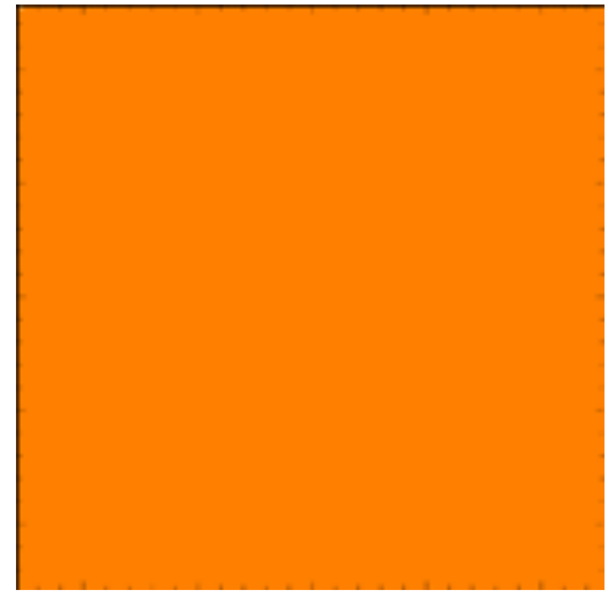
Some 2D Fourier Transform Pairs

T(x,y)

δ Function



⇌



Amp{V(u,v)}

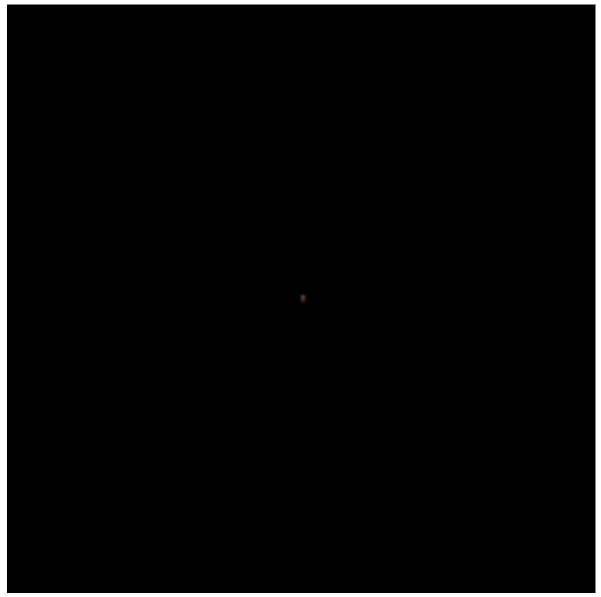
Constant

Some 2D Fourier Transform Pairs

T(x,y)

Amp{V(u,v)}

δ Function



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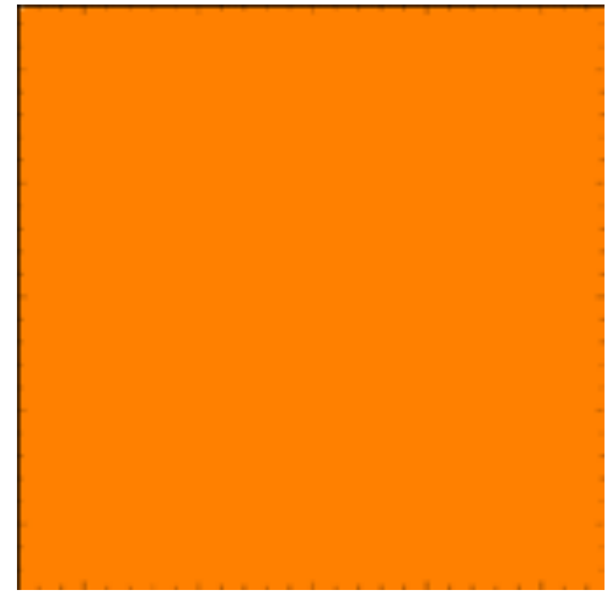
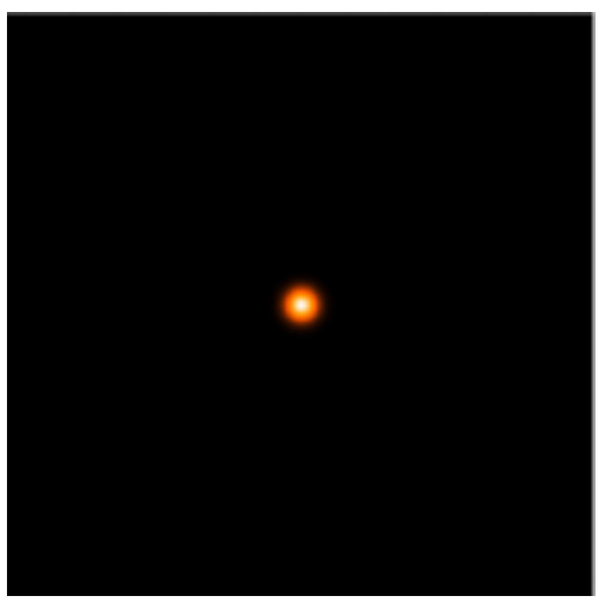


Constant

Gaussian

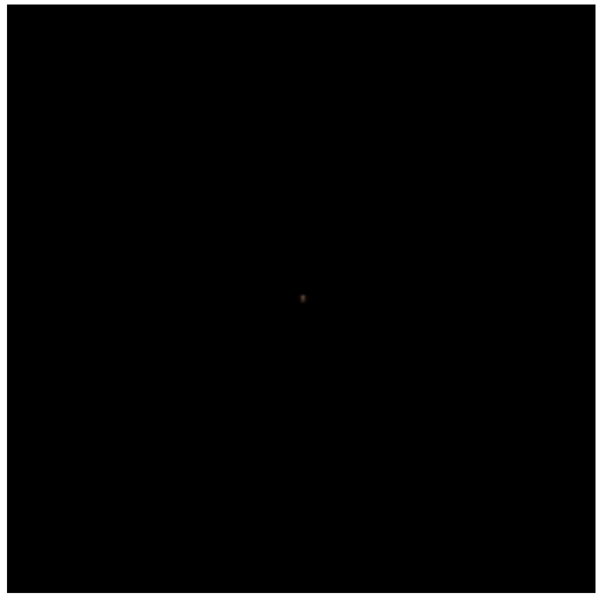


L. Ricci

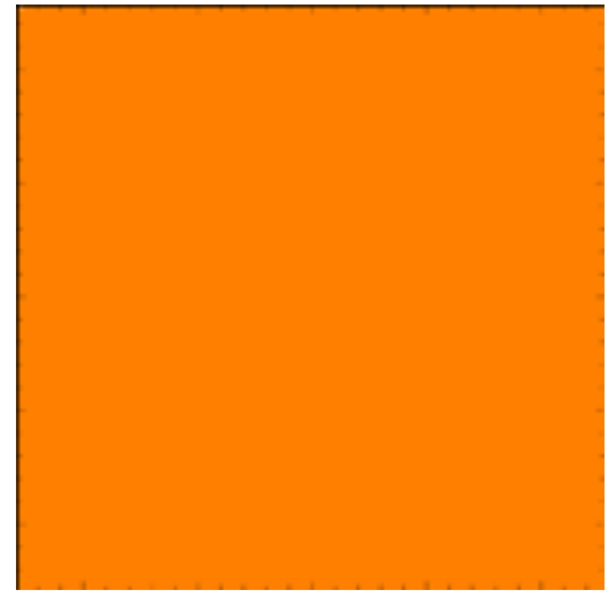
Some 2D Fourier Transform Pairs

$T(x,y)$ $\quad$ $\mathrm{Amp}\{V(u,v)\}$

δ Function

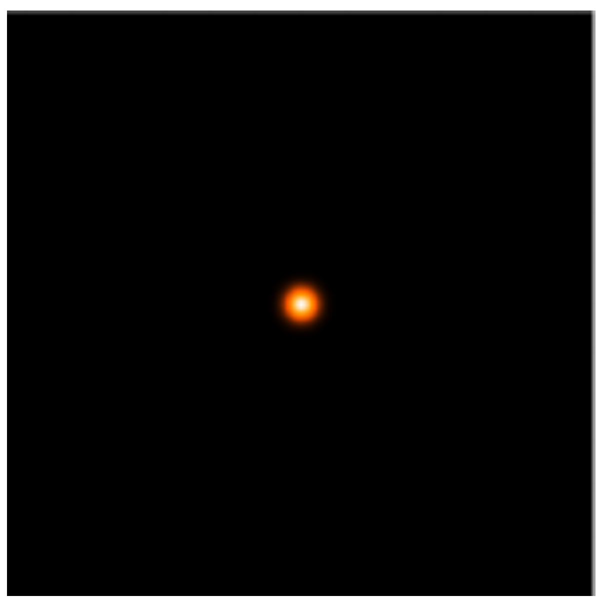


$\rightleftharpoons$



Constant

Gaussian



$\rightleftharpoons$

Gaussian

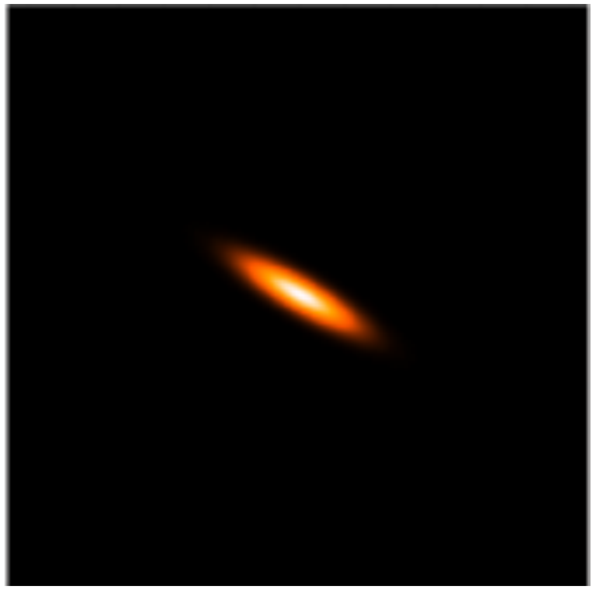
narrow features transform to wide features (and vice-versa)

L. Ricci

2D Fourier Transform Pairs

T(x,y)

elliptical
Gaussian



$\rightleftharpoons$

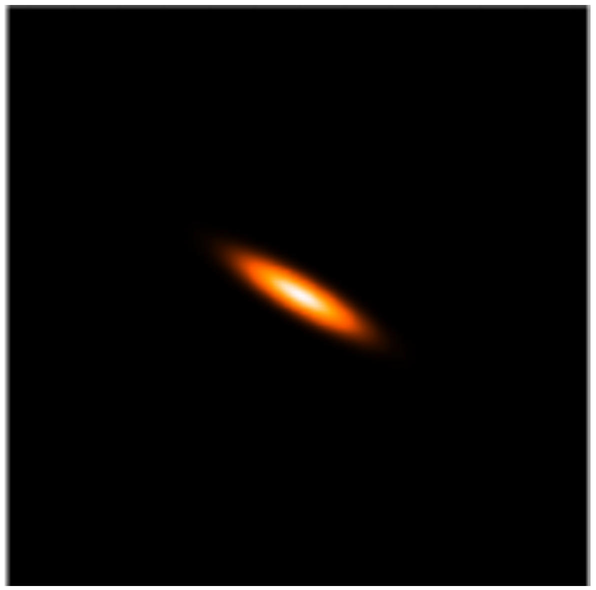
Amp{V(u,v)}

elliptical
Gaussian

2D Fourier Transform Pairs

T(x,y) | Amp{V(u,v)}

elliptical Gaussian

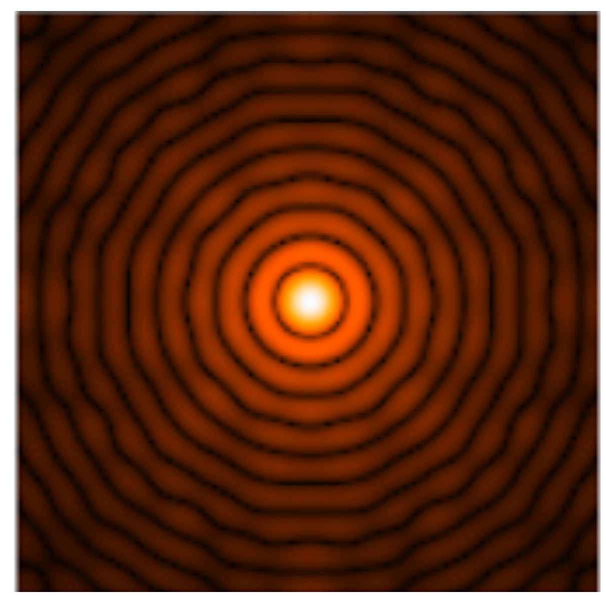


$\rightleftharpoons$

elliptical Gaussian

Disk

$\rightleftharpoons$



Bessel

sharp edges result in many high spatial frequencies

NRAO

L. Ricci

Interferometry

Each baseline vector between 2 telescopes probes one combination of (u,v), i.e. one spot in the (u,v)-plane.

The larger the baseline distance B, the higher the resolution, and the higher the spatial frequency.

$$(u, v) = \frac{\vec{B}}{\lambda}$$

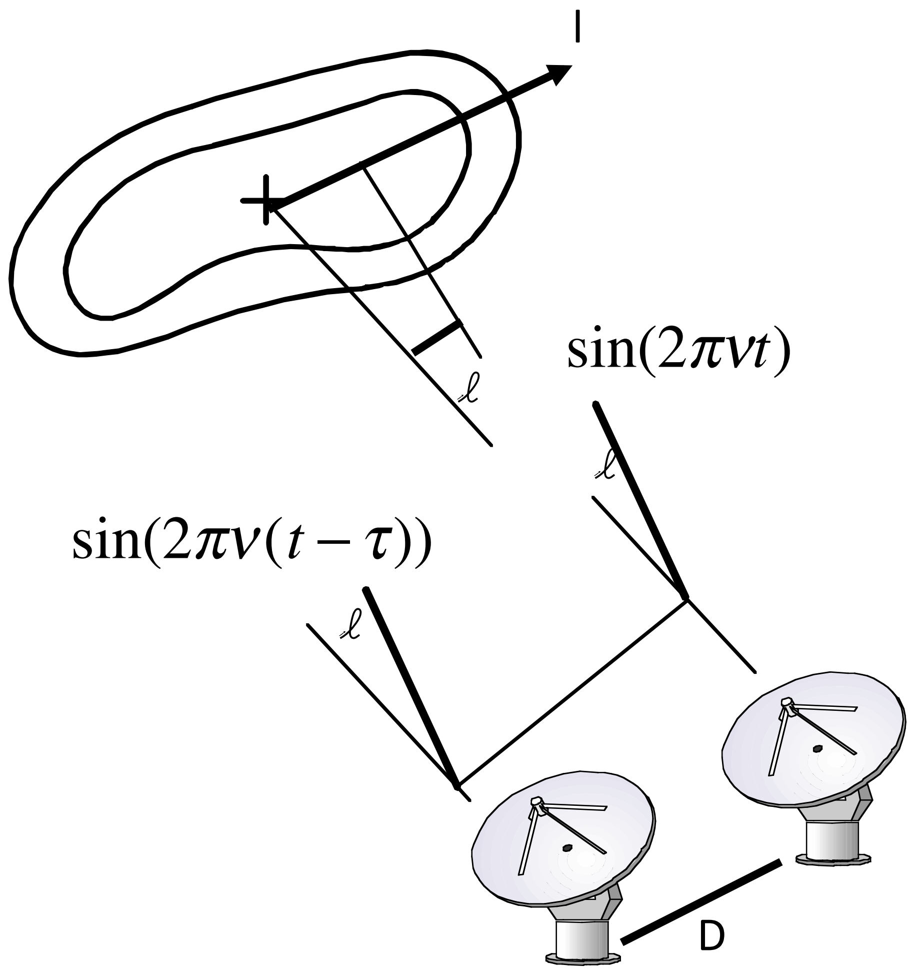
To reconstruct the image T(x,y), we need measurements at many (u,v) pairs. From each measurement, we can deduce the visibility V(u,v) - the Fourier coefficient.

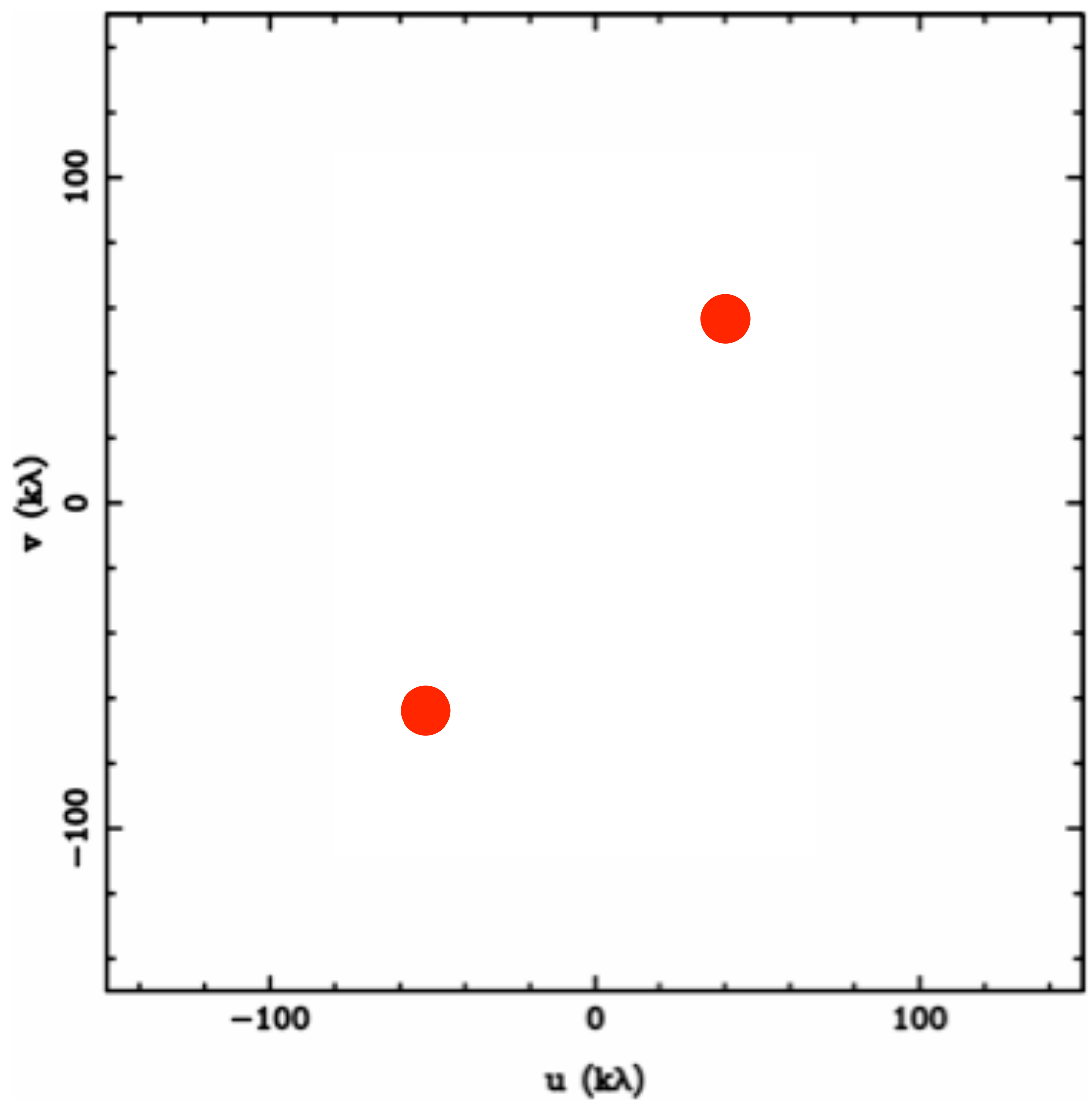
$$T(x, y) = \int\int V(u, v) e^{-2\pi i(ux+vy)} \mathrm{d}u \mathrm{d}v$$

In reality, only a finite sum. Reconstruction is never perfect.

Synthesis Imaging

2 telescopes:

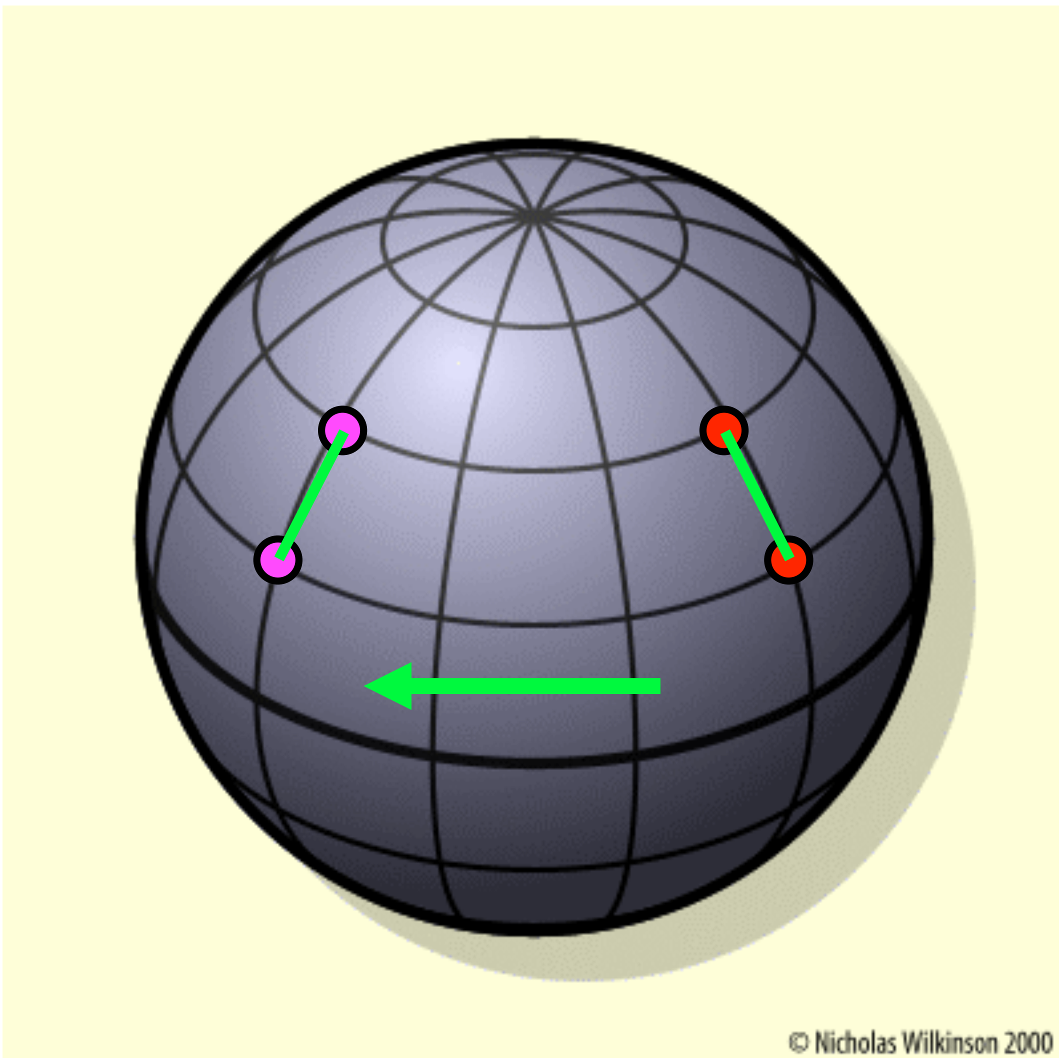




Note: 2 pairs of (u,v) because 2 baseline vectors.

Synthesis Imaging

With Earth's rotation:



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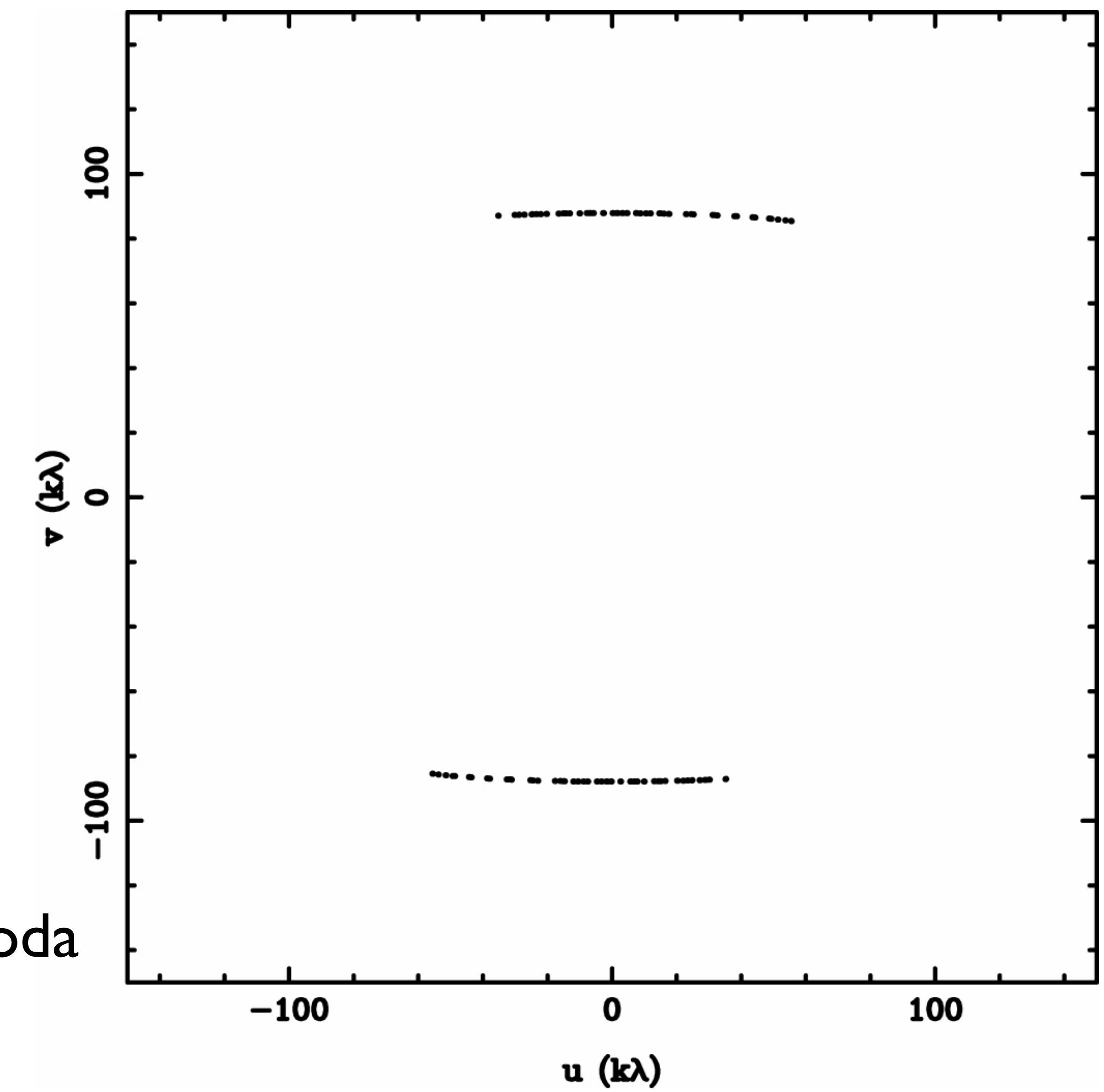
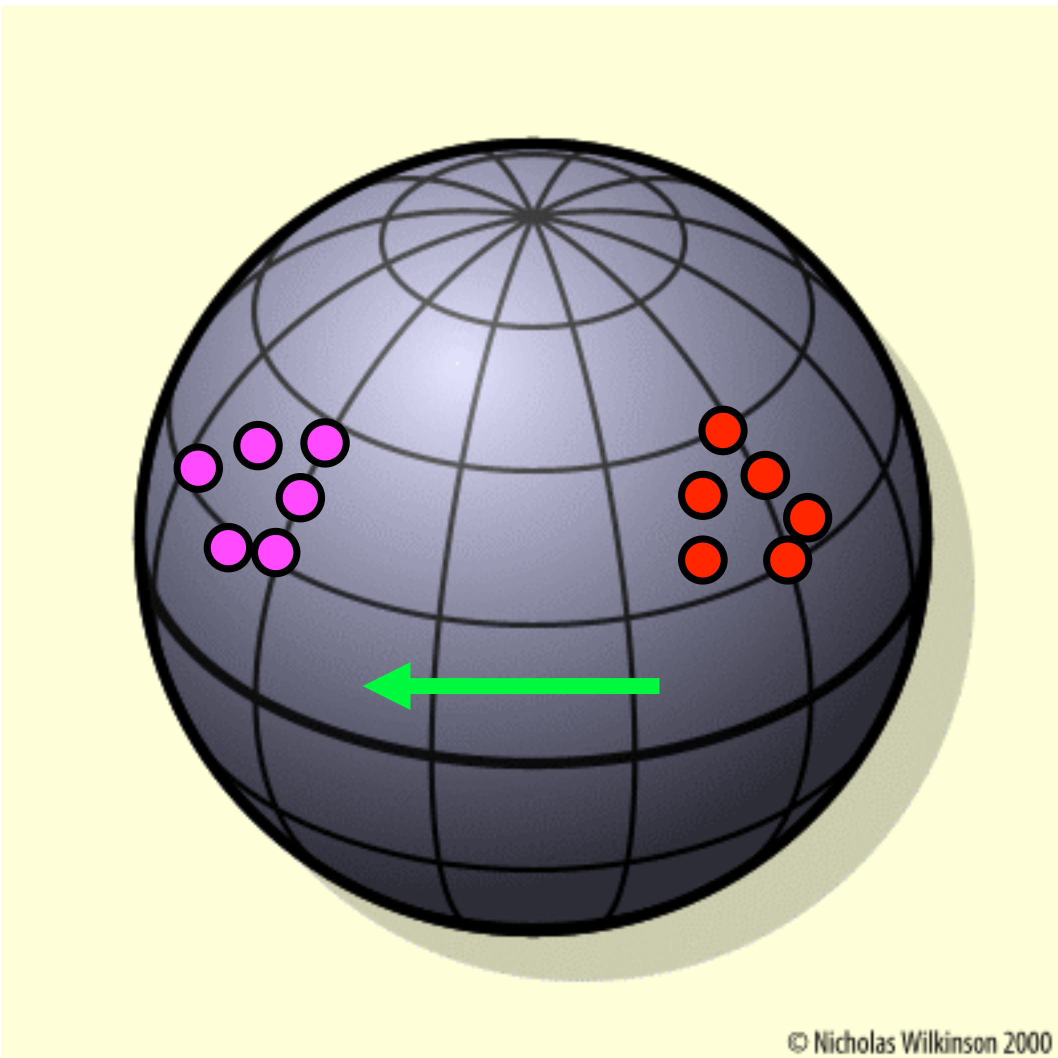


Effective baseline vector B changes -> (u,v) change

Synthesis Imaging

With six antennas:



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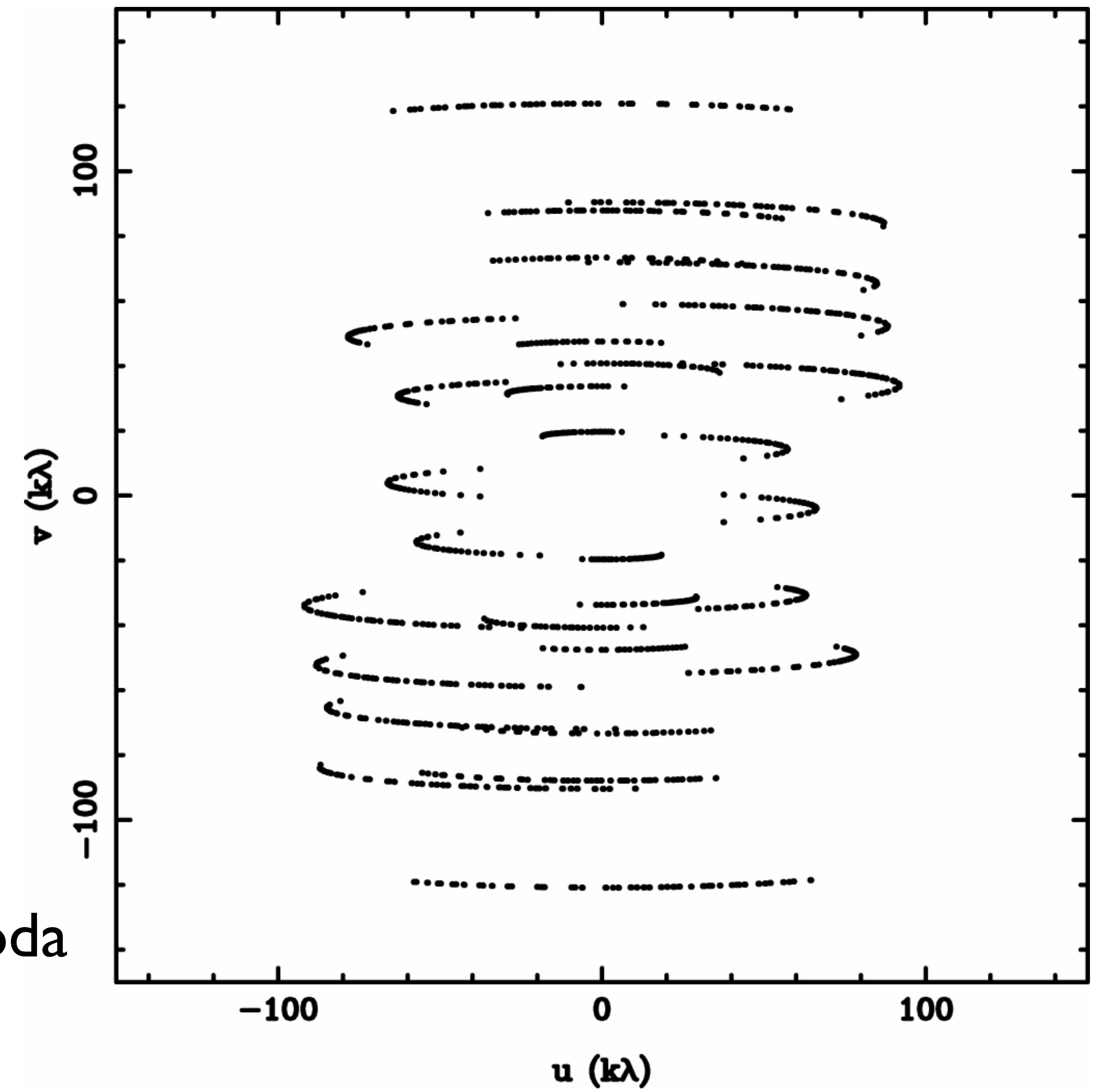
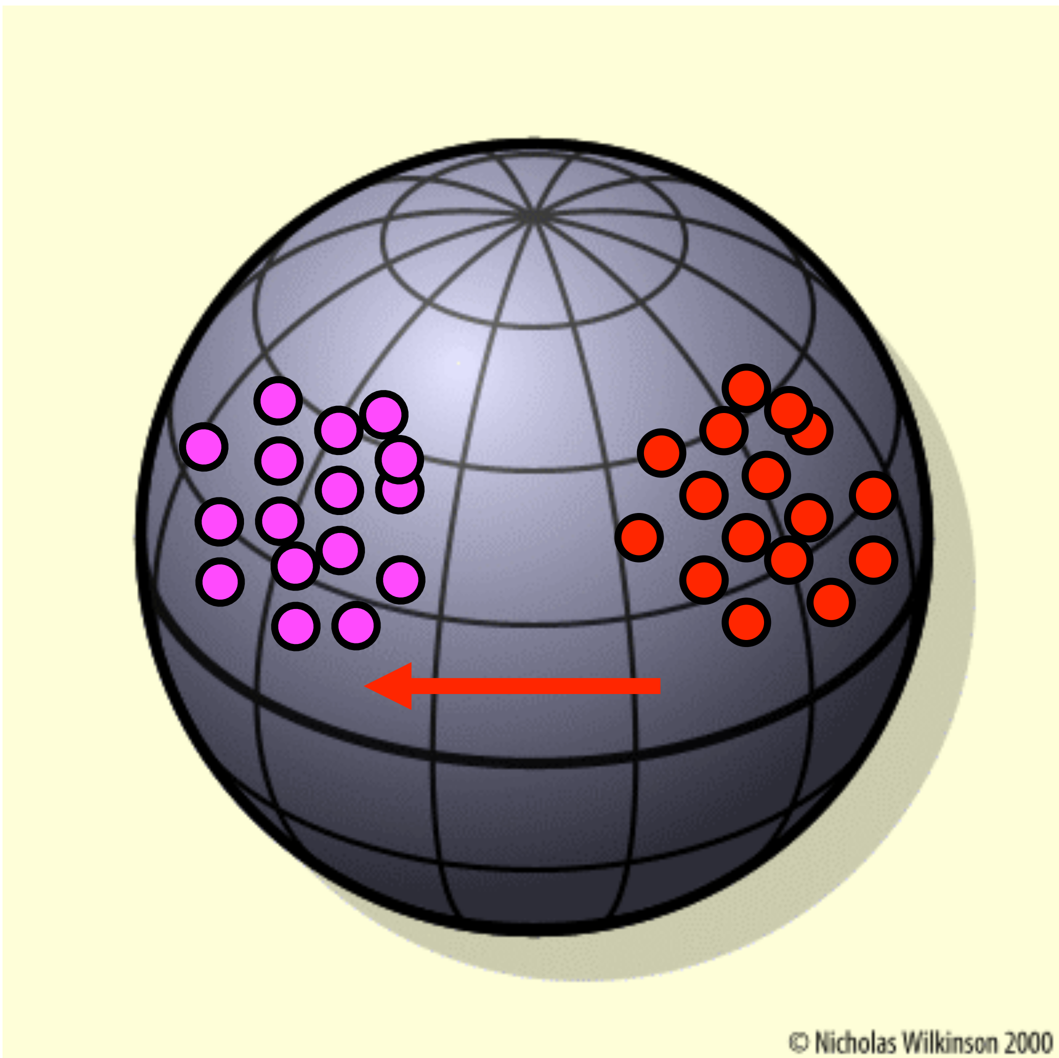


Number of pairs: N(N+1)/2 → 15 pairs

Synthesis Imaging

With 15 antennas (CARMA array):



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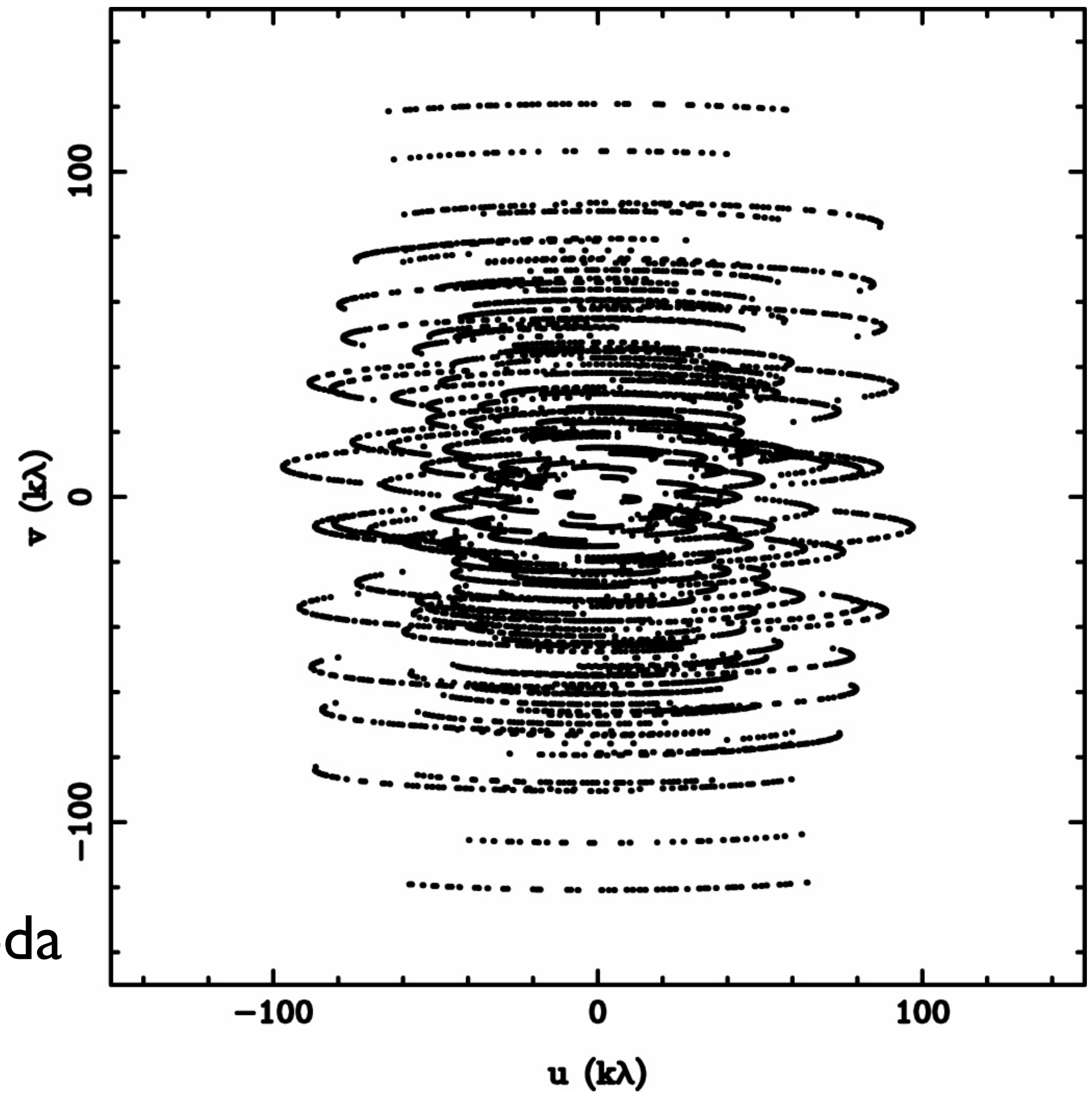


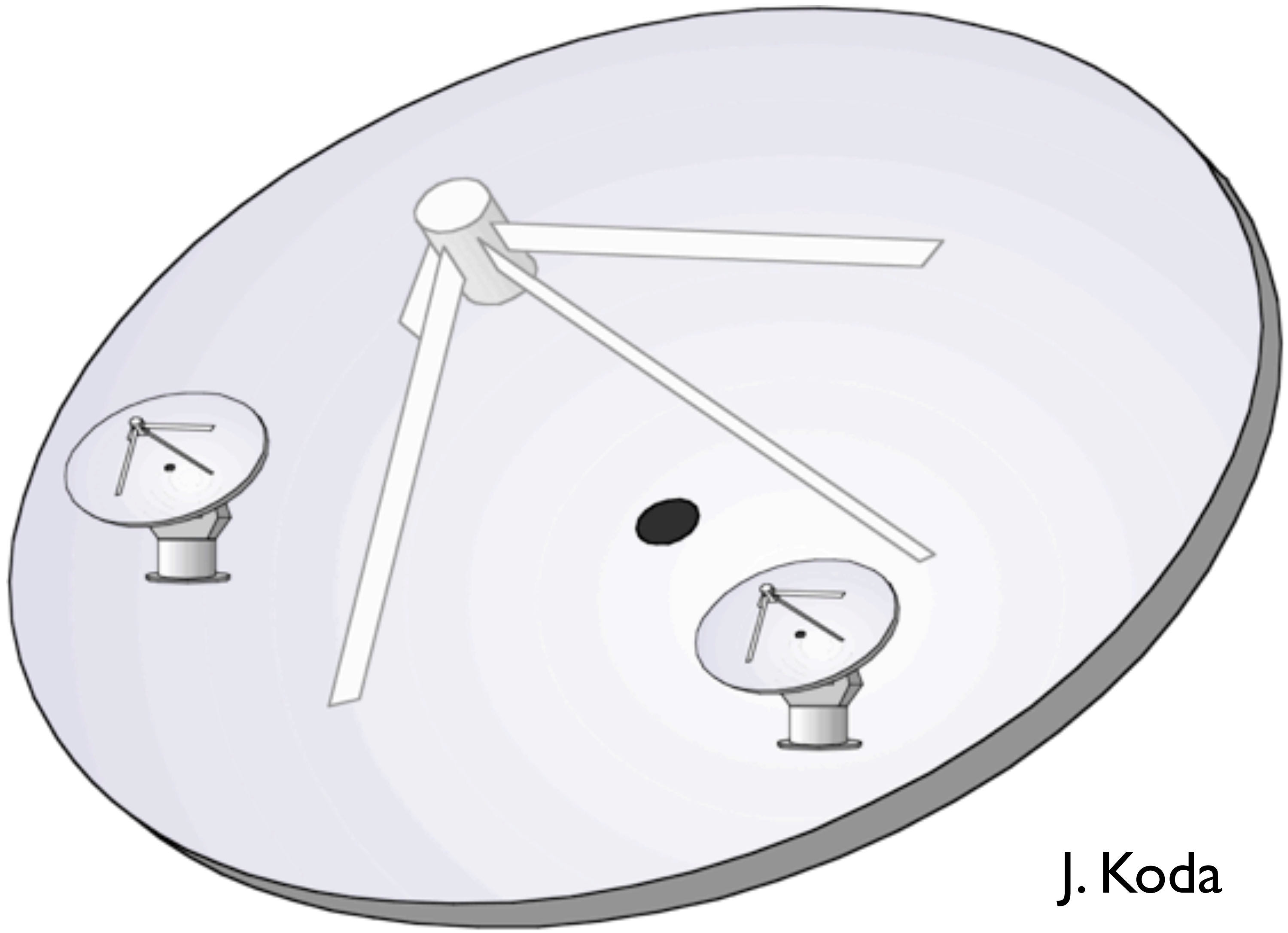
105 pairs

The Stony Brook Radio Interferometer

Koda et al., 2016,
AmJPh, 84, 249

SBU radio interferometer

2 “antennas”



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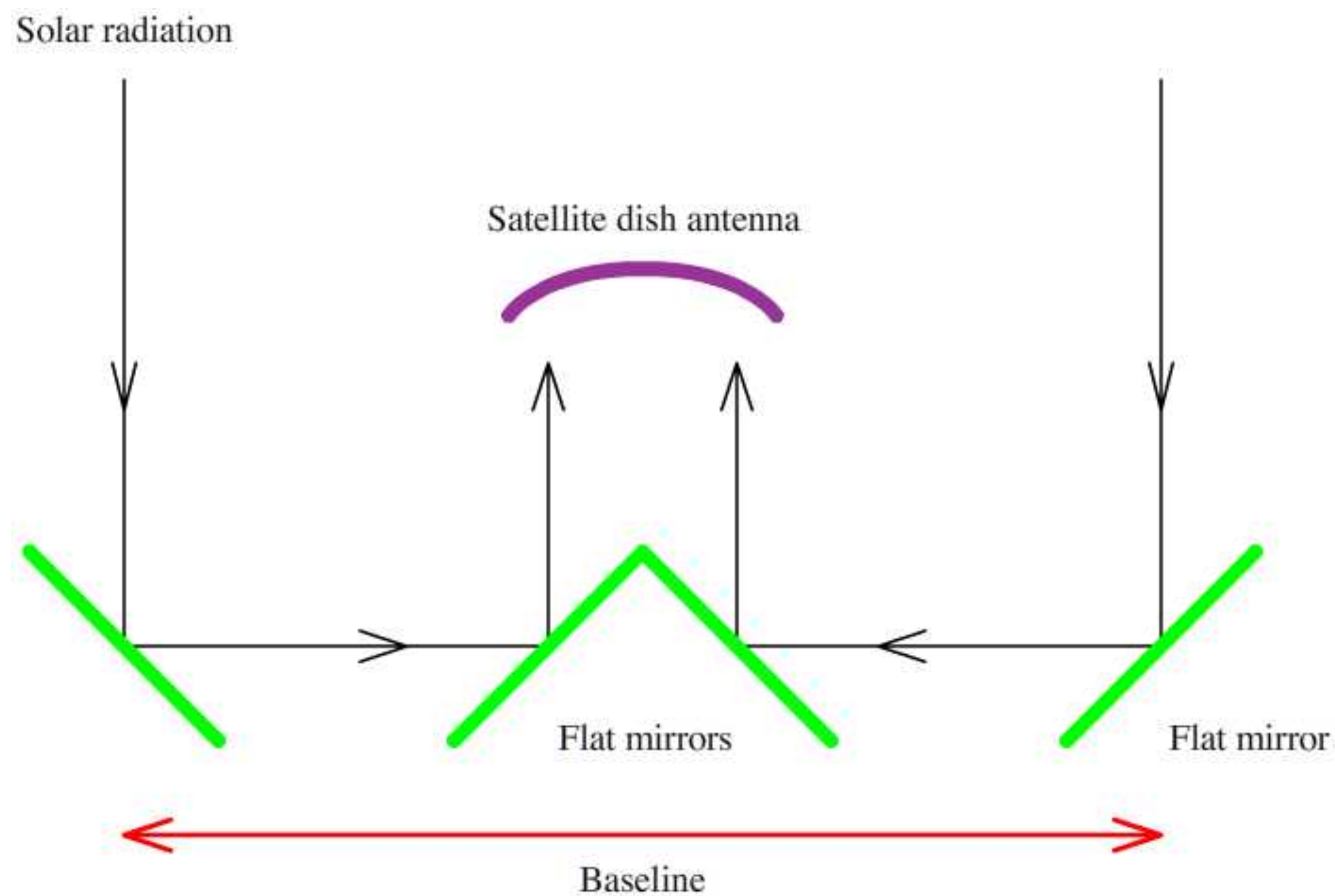
SBU radio interferometer

2 “antennas”

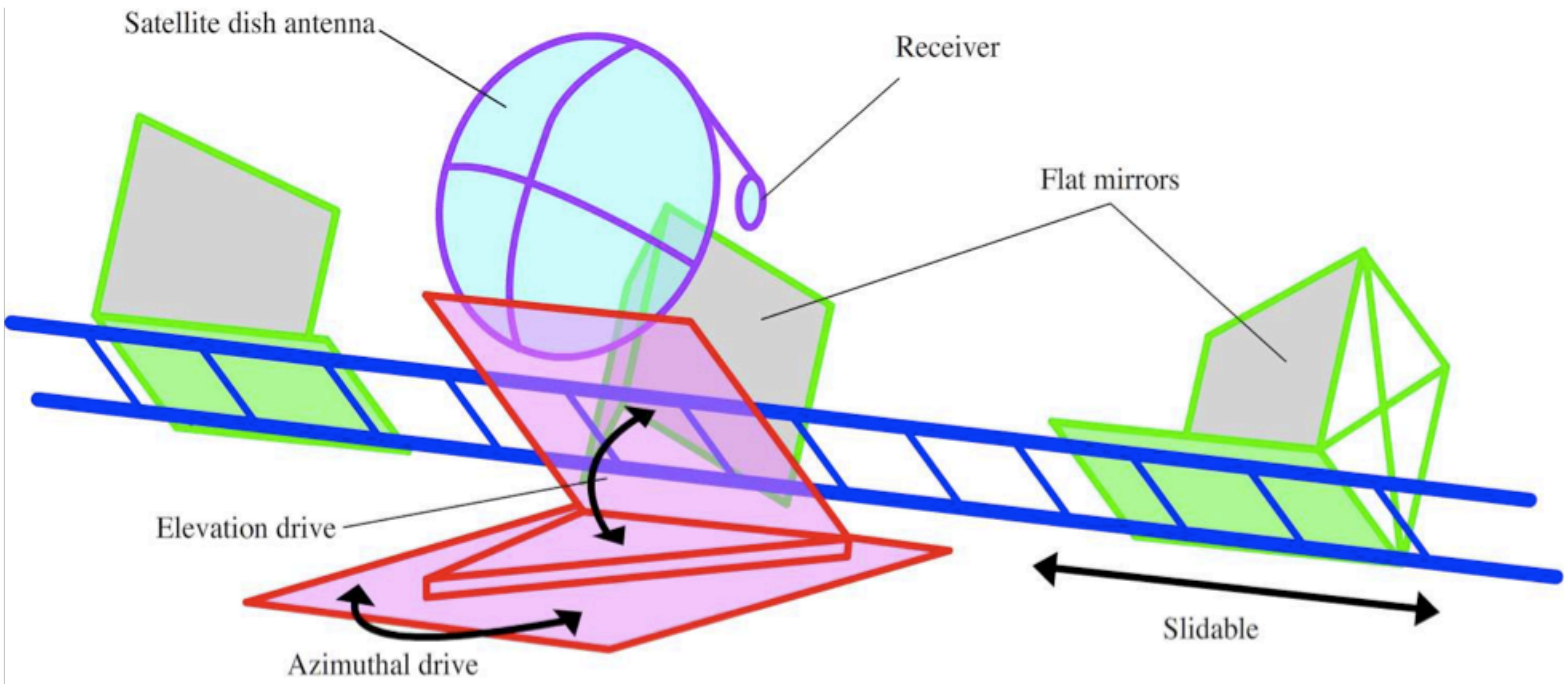
SBU radio interferometer

2 “antennas”



SBU radio interferometer

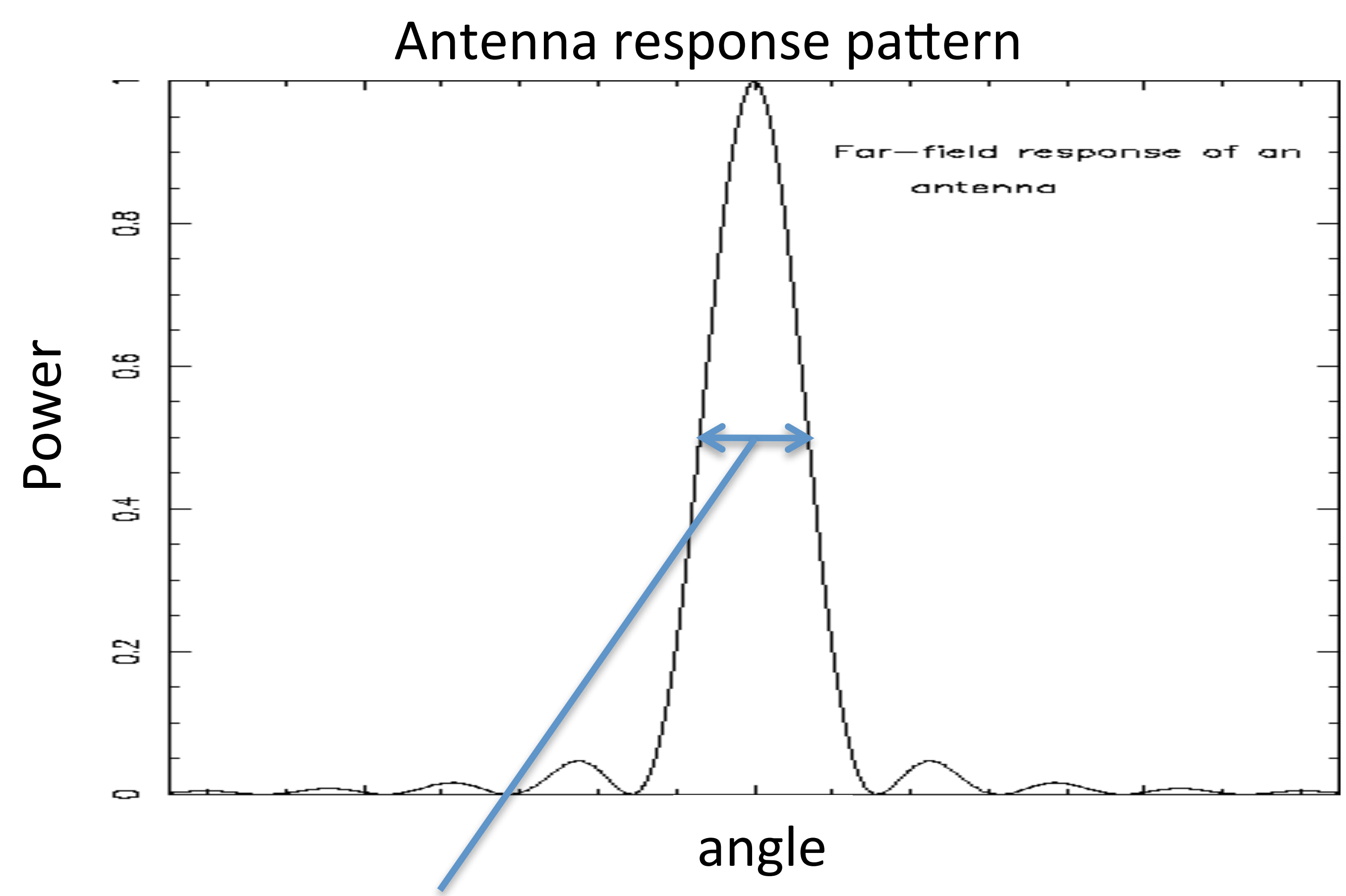
2 “antennas”



Antenna

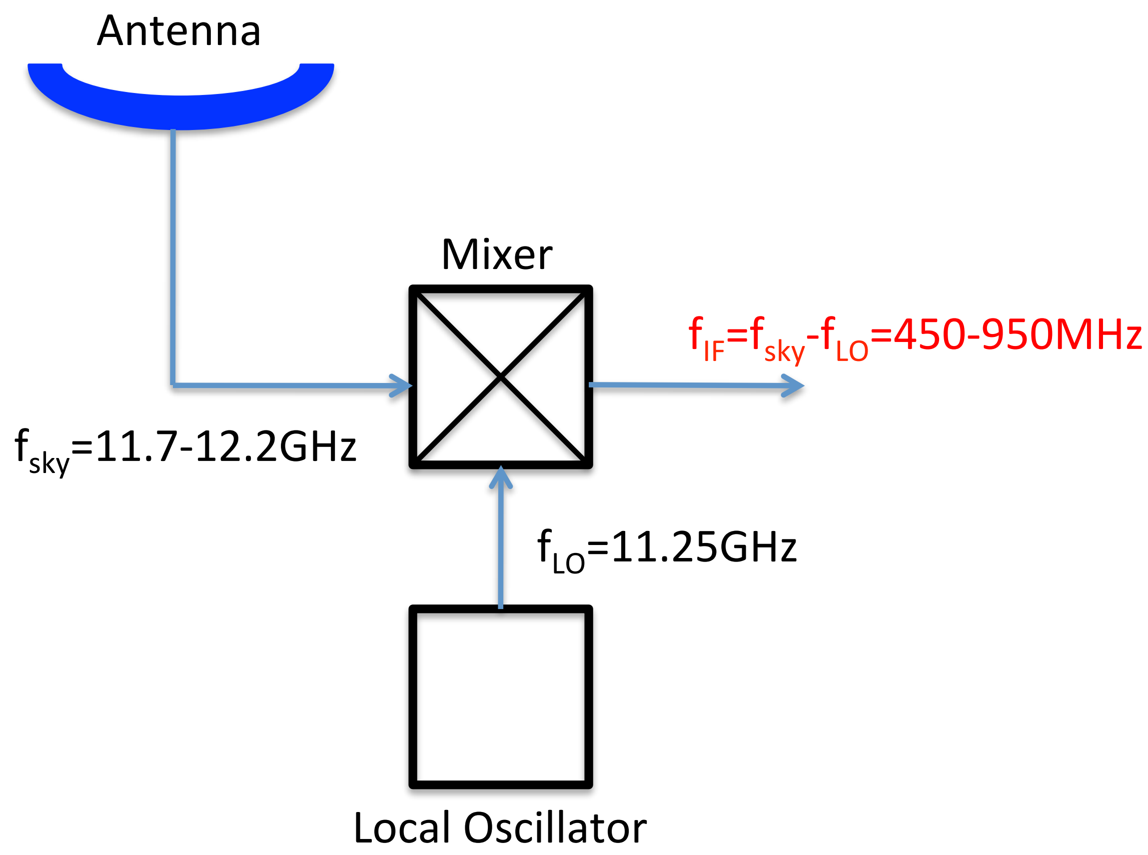
off-the-shelf dish
for satellite TV

diameter: 1m
wavelength: 2.6 cm



beam width →angular resolution

Heterodyne Receiver

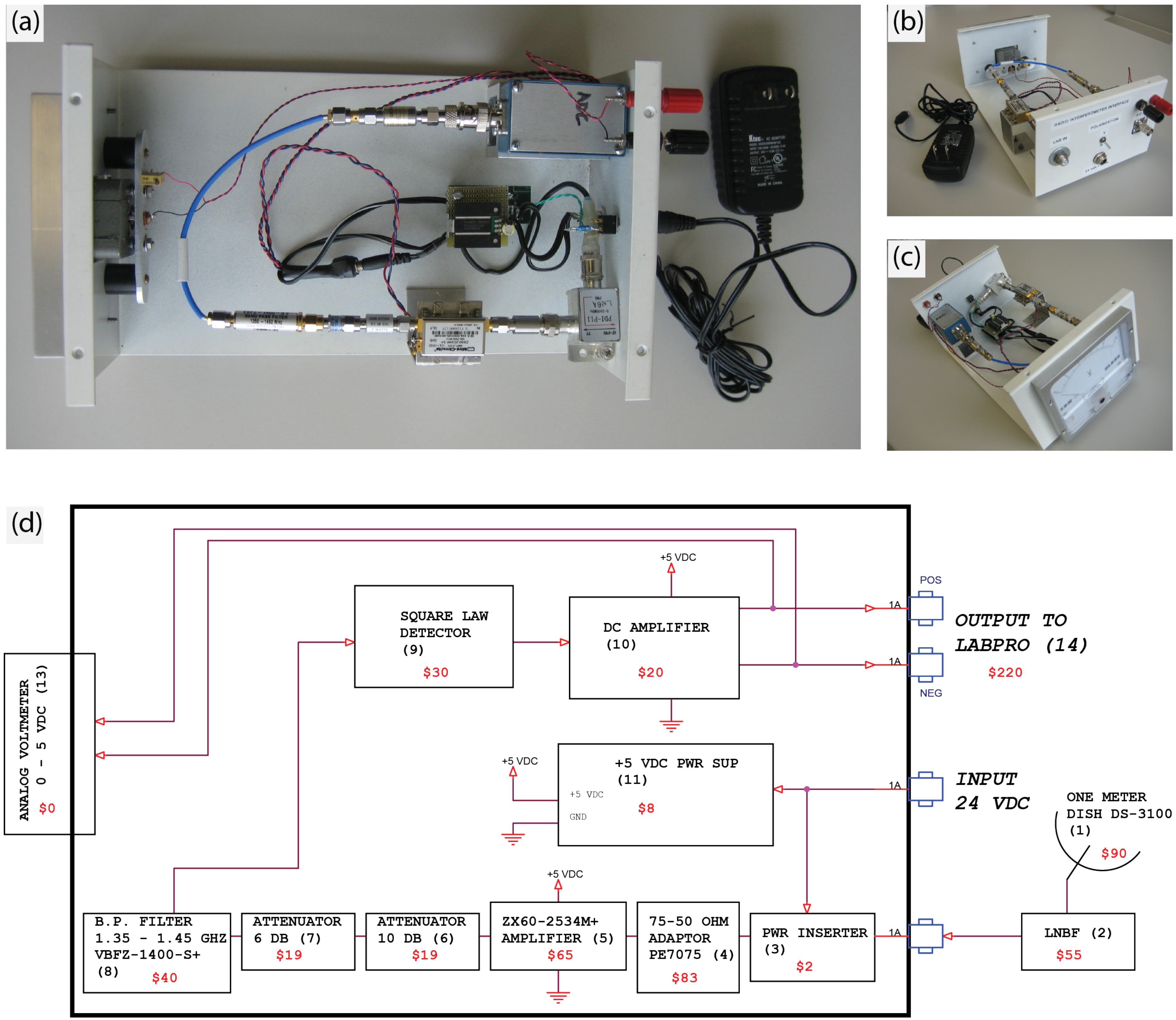


mixing the sky signal with the signal from the local oscillator results in:

$$\sin(2\pi f_1 t)\sin(2\pi f_2 t) = \frac{1}{2}\cos[2\pi(\underline{f_1 - f_2})t] - \frac{1}{2}\cos[2\pi(f_1+f_2)t]$$

lower frequency easier to use

Heterodyne Receiver



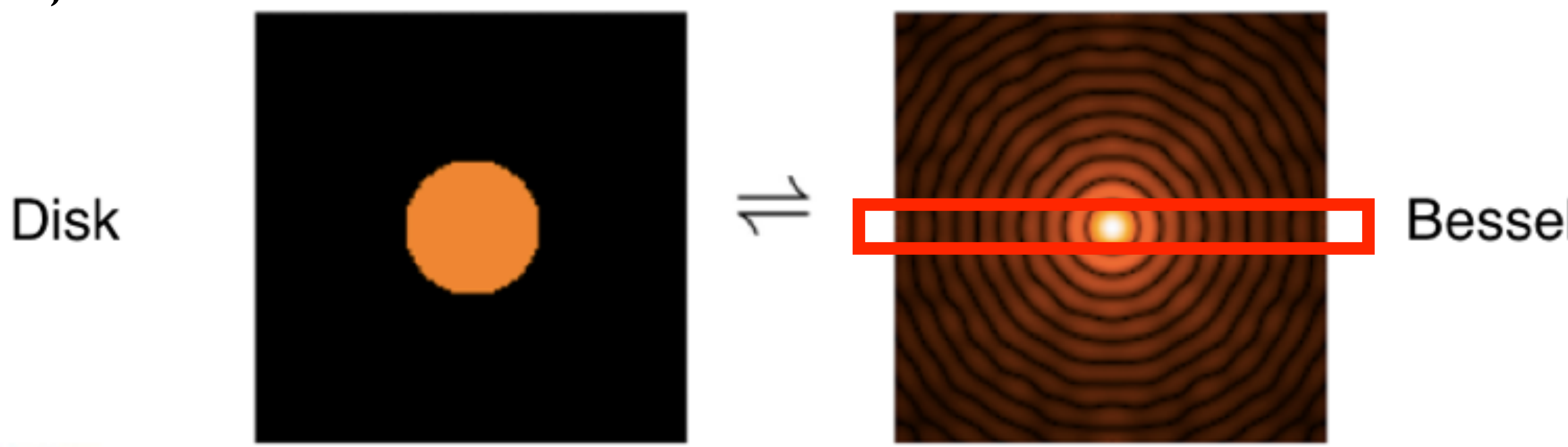
Analog-Digital Converter

analog signal (voltage) → digital signal → computer

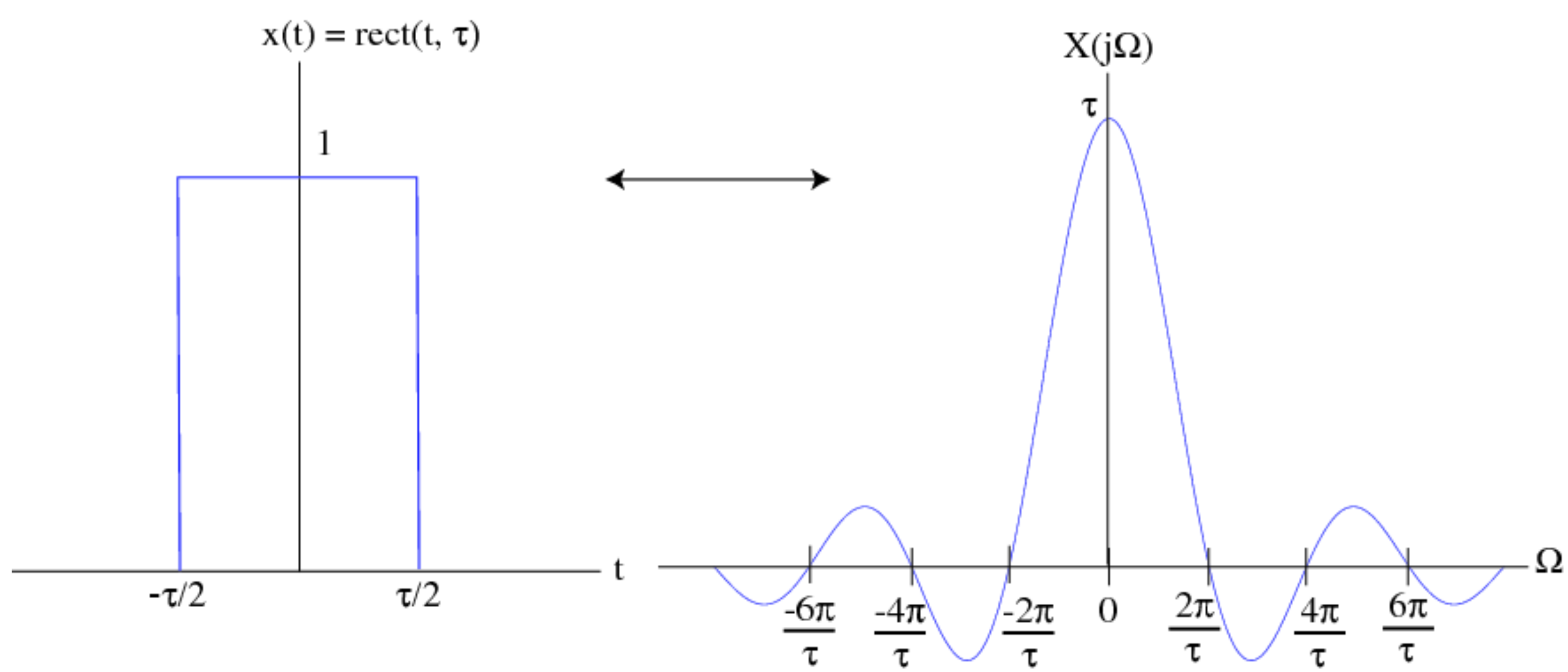
Lab 3

measure the diameter of the Sun

in 2-dimensions,
this would be:



we will do this
in 1-d:

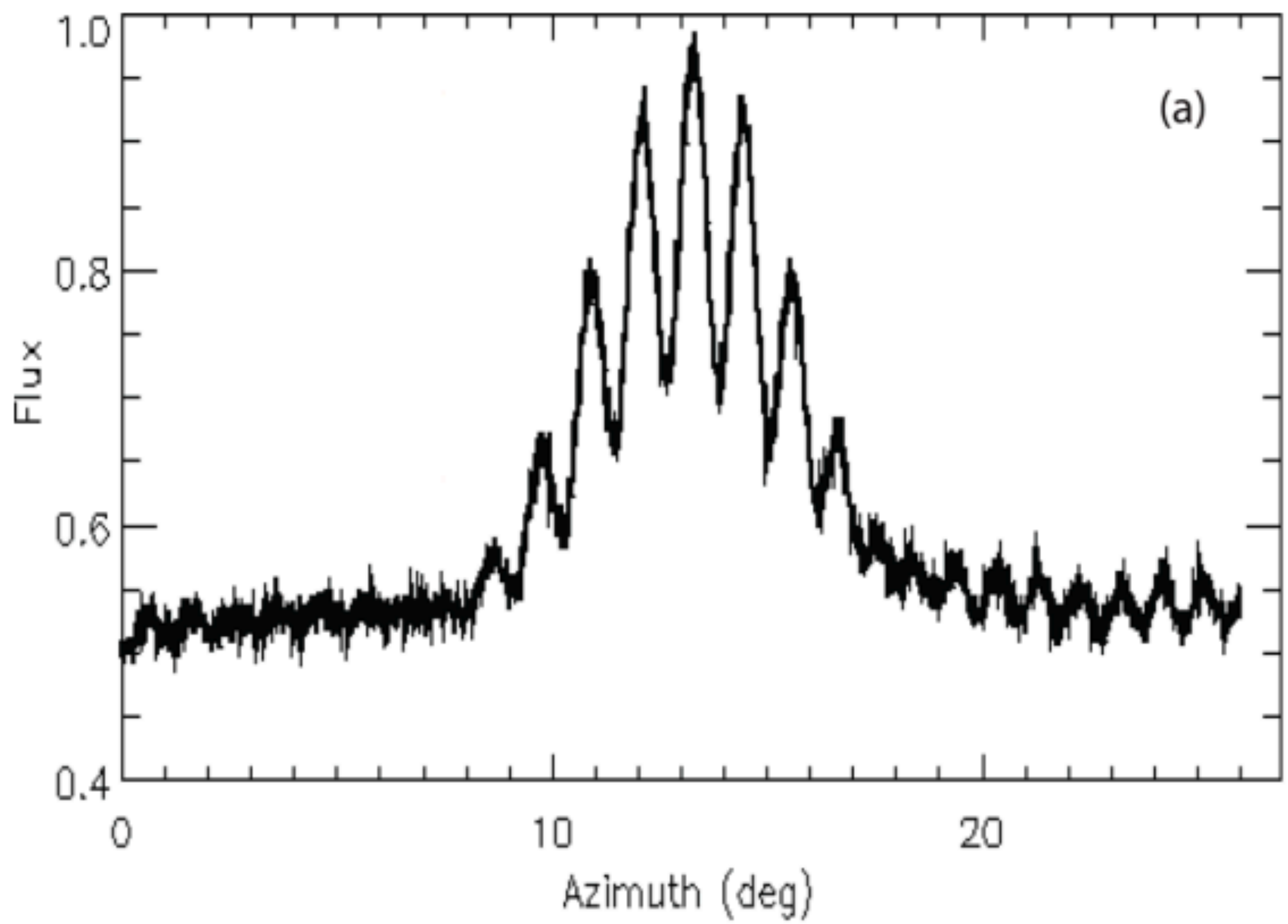


Lab 3

for several baseline distances B, slew across the Sun to measure P(θ) and determine the visibility V(B)

Lab 3

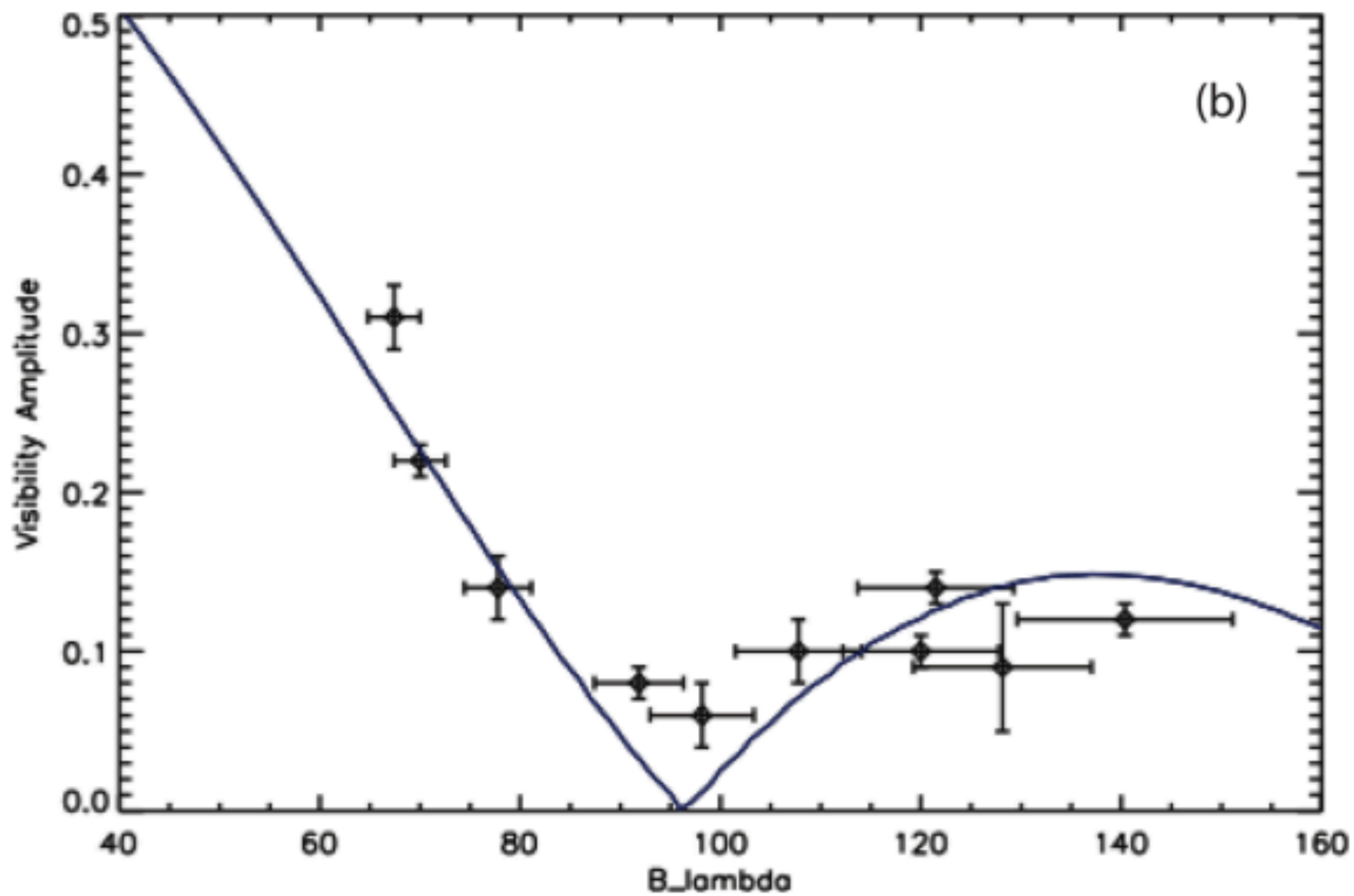
a scan across the Sun:



the visibility can be determined from the relative height of maxima and minima (homework)

Lab 3

visibility as function of baseline:



the diameter of the Sun can be determined from the data by fitting a sinc-function to the data

Lab 3

scheduling: the Sun needs to be far enough from satellites on the equator → can observe after Oct. 9

data needs to be taken during the day, on a week-day

request 3 observing days (weather contingency)