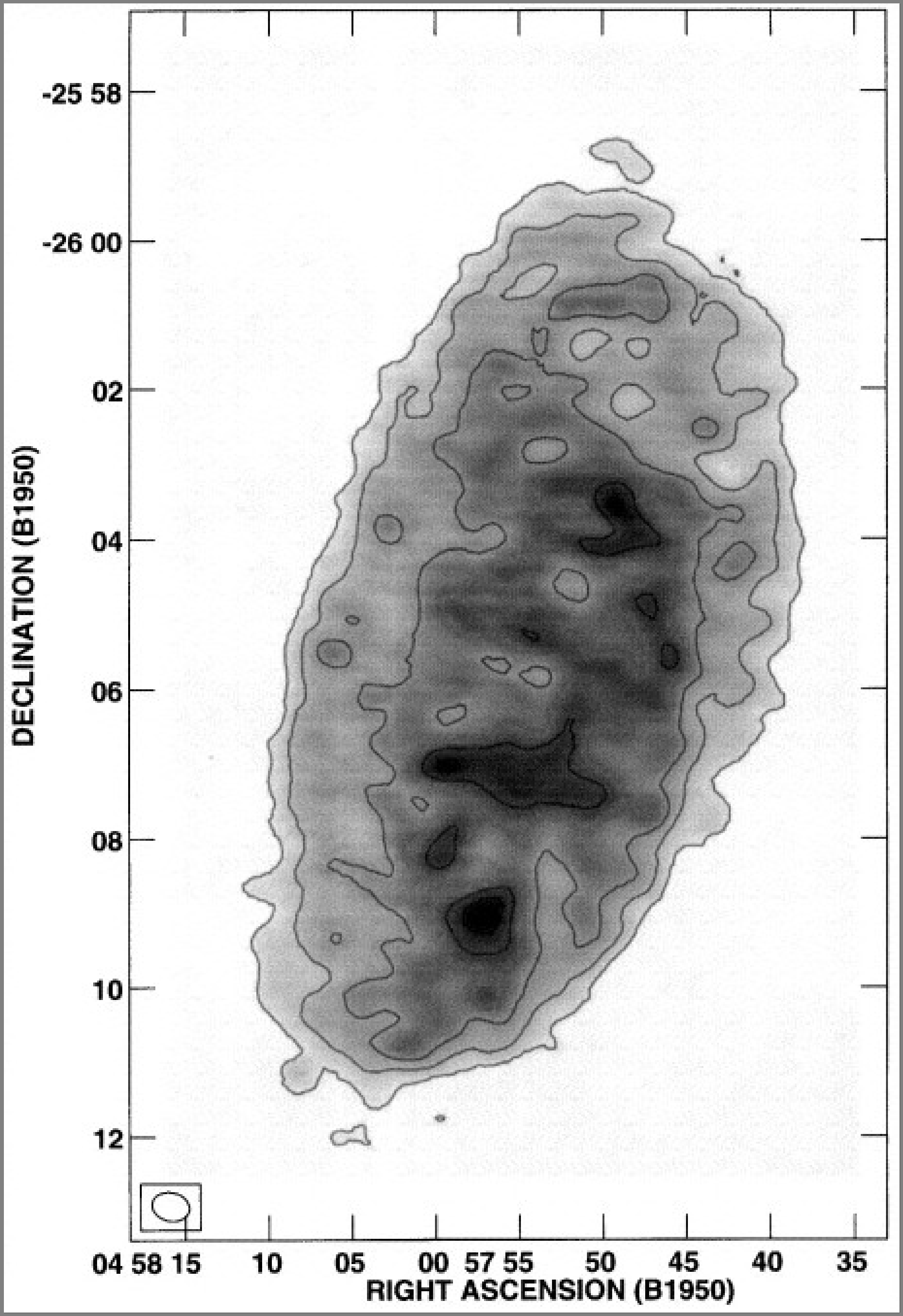
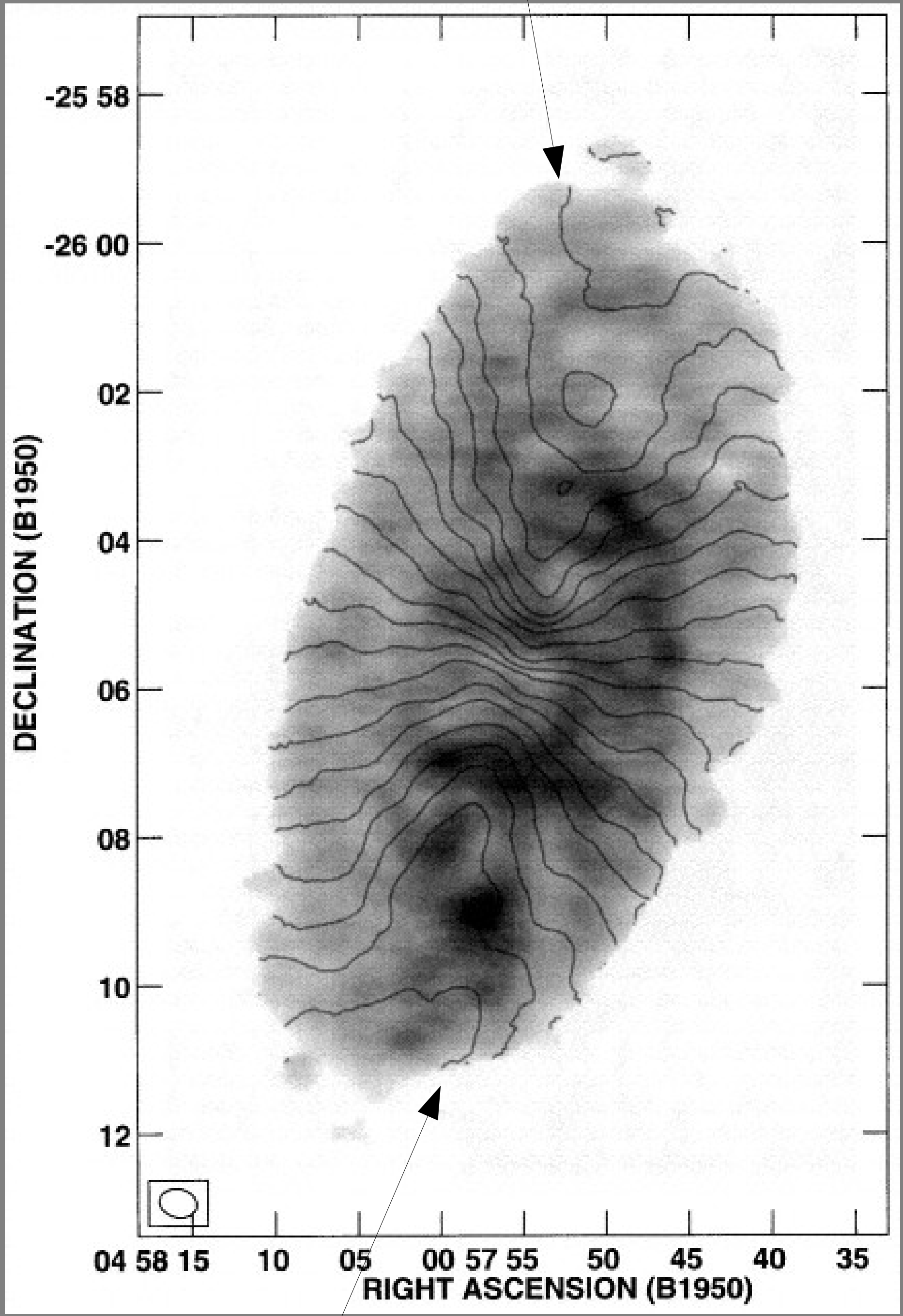
Gas in Spirals

- Spirals have large HI disks
  - This gas is optically thin
    - This means that we see all the gas and can measure the amount directly from the line intensity
  - HI gas is much more extended than the optical light, $r > 2.5\ R_{25}$
  - Gives a unique tracer for the velocity in spiral galaxies

NGC 1744 Pisano et al. 1998



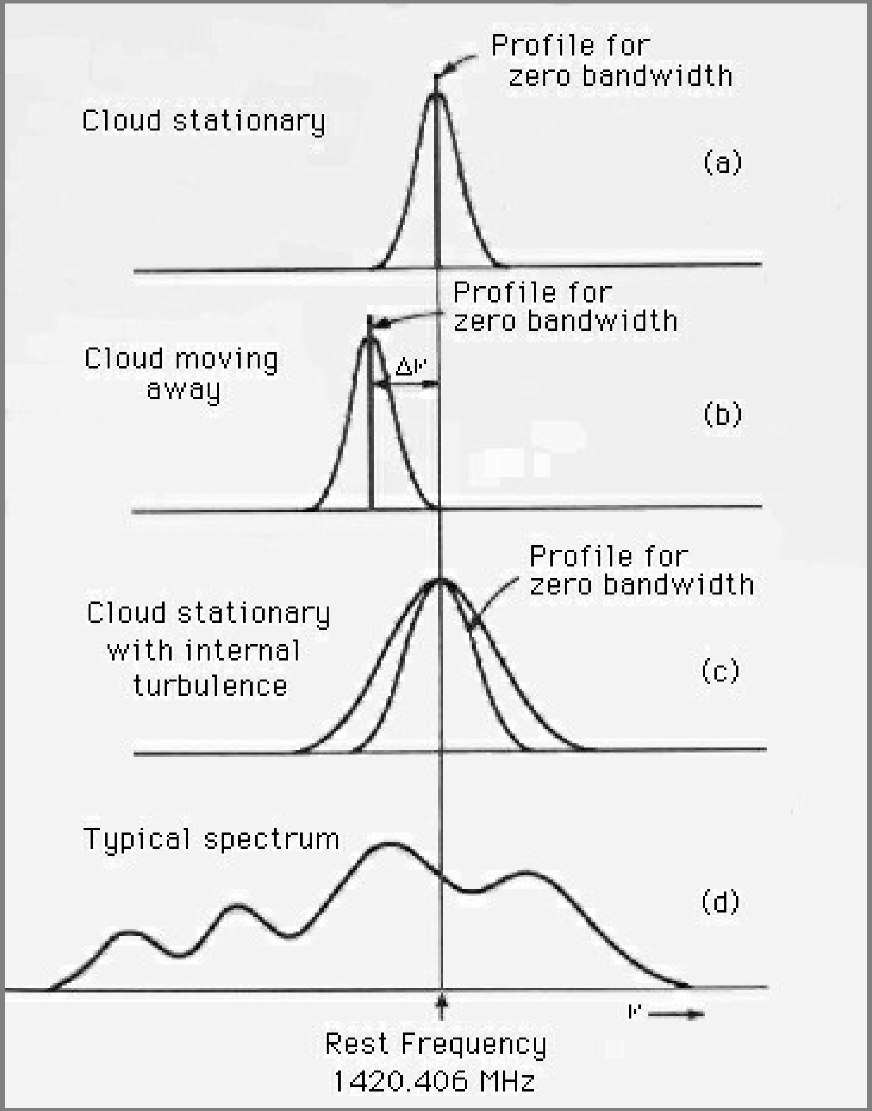
620 km/s

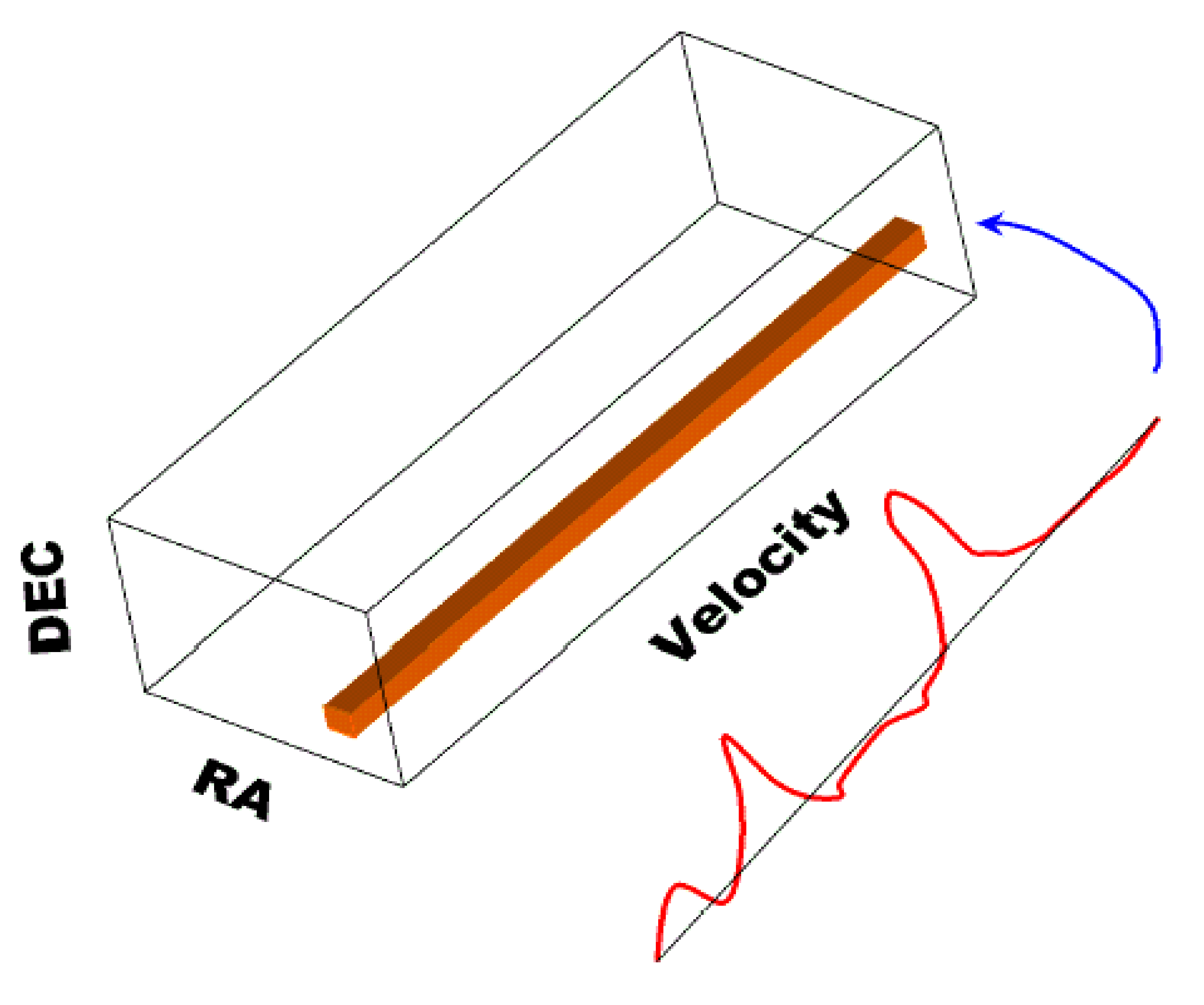


830 km/s

Radio spectral observations

- Radio telescopes can also act like a spectrometer by isolating a single spectral line, e.g. HI line emission
- By measuring the line shift we can determine the radial velocity of a patch of gas
- By measuring the width of the line we can determine the internal velocities (turbulent velocity)



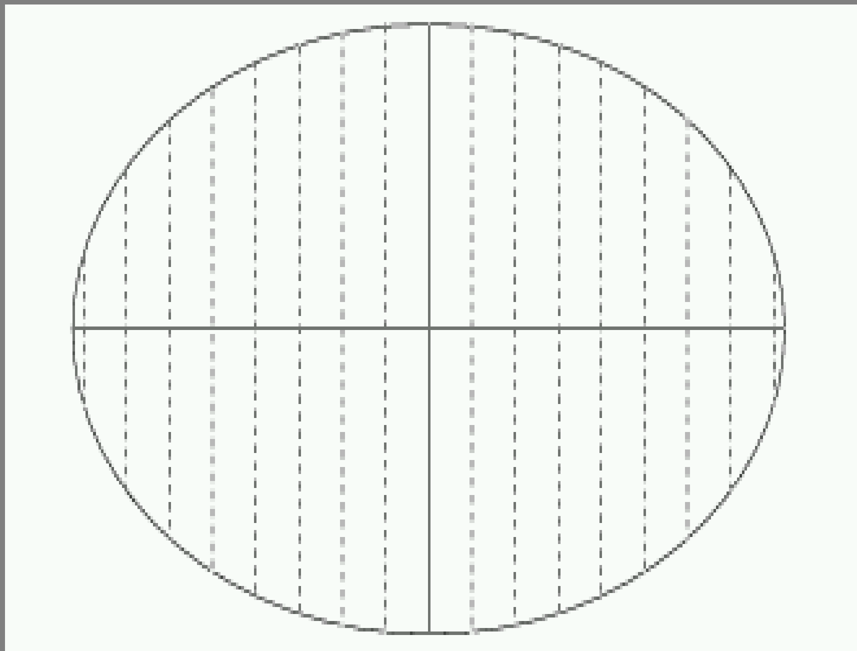

DEC
RA
Velocity

HI Kinematics

- Interferometric observations yield a 3-D map of the of HI gas
  - distribution (x,y)
  - Kinematics (velocity)
- This can be described by the moments
  - 0^{th} moment = total intensity (integrate over velocity)
  - 1^{st} moment = velocity field (mean velocity as a function of position)
  - 2^{nd} moment = velocity dispersion

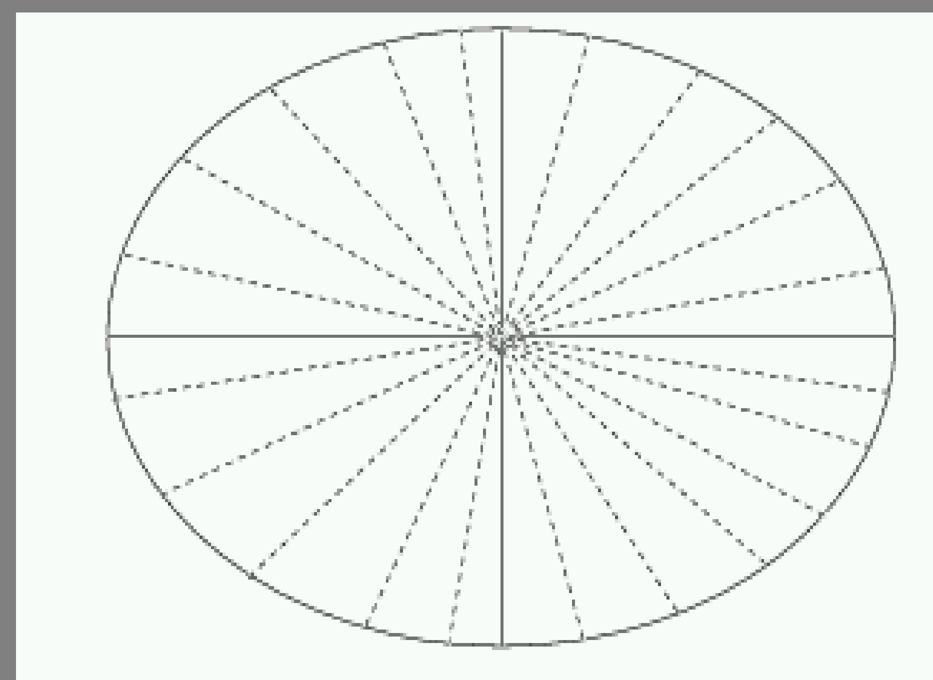
How do we turn this into a rotation curve?

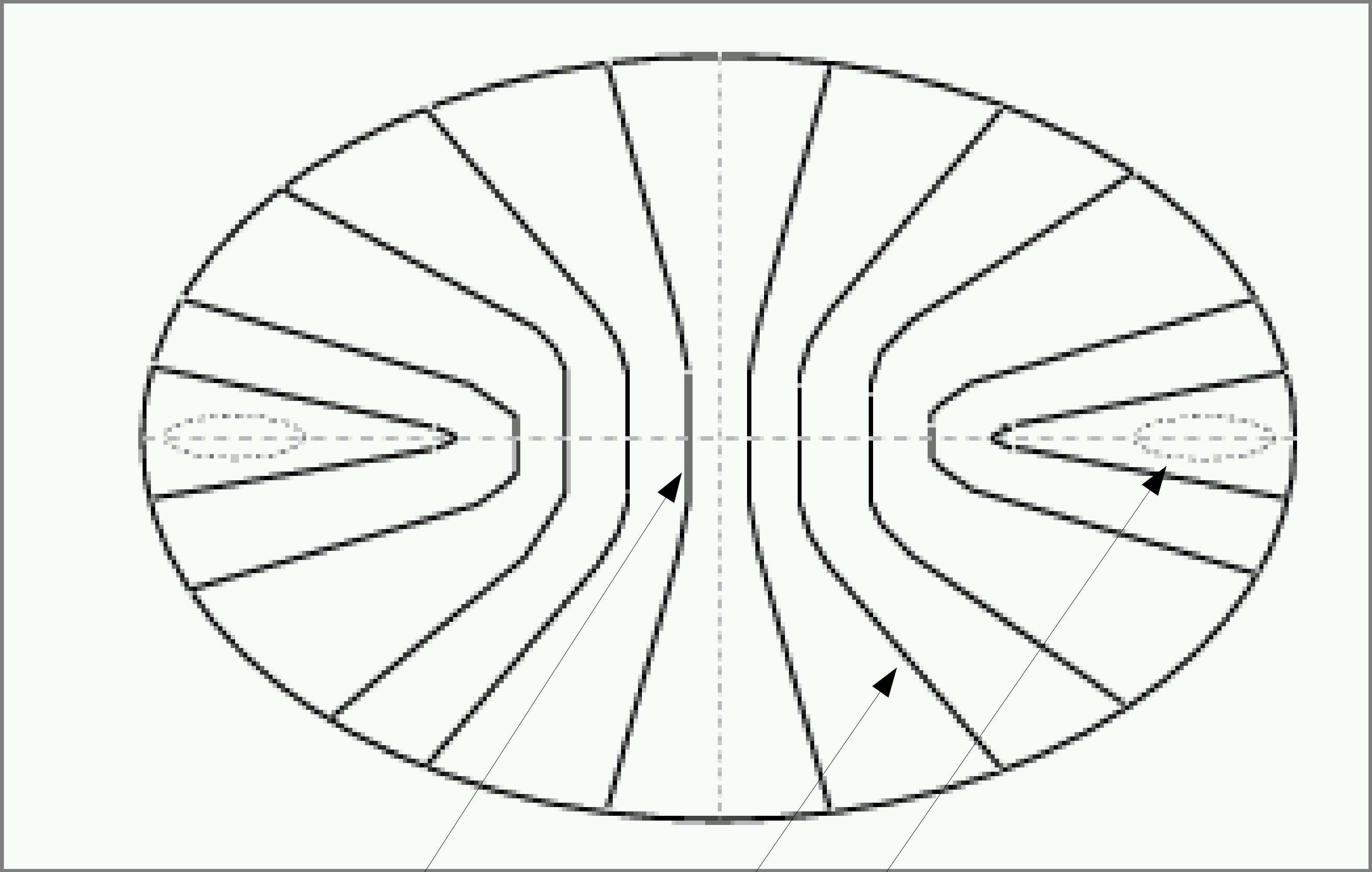
- We only have the radial velocity!
- We need
  - Systemic velocity (Hubble flow)
  - Inclination (if a galaxy is face on we see no doppler shifted velocities)
  - Angle of the major axis of the galaxy, ϕ
  - $V_r = V_{sys} + V(r)\sin(i)\sin(\phi)$



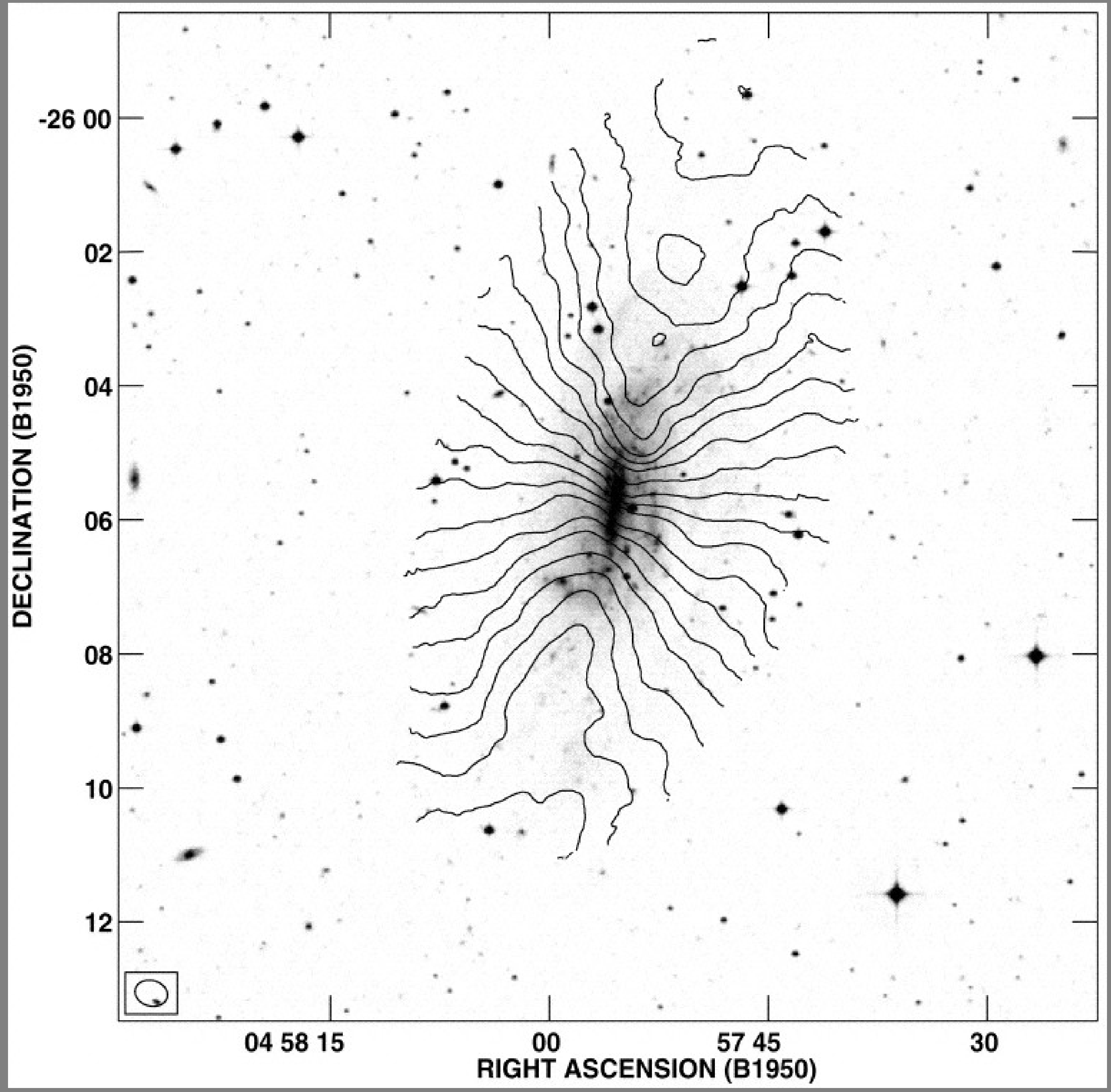
Solid Body rotation v(r) ~ dr

Flat rotation curve v(r) ~ d



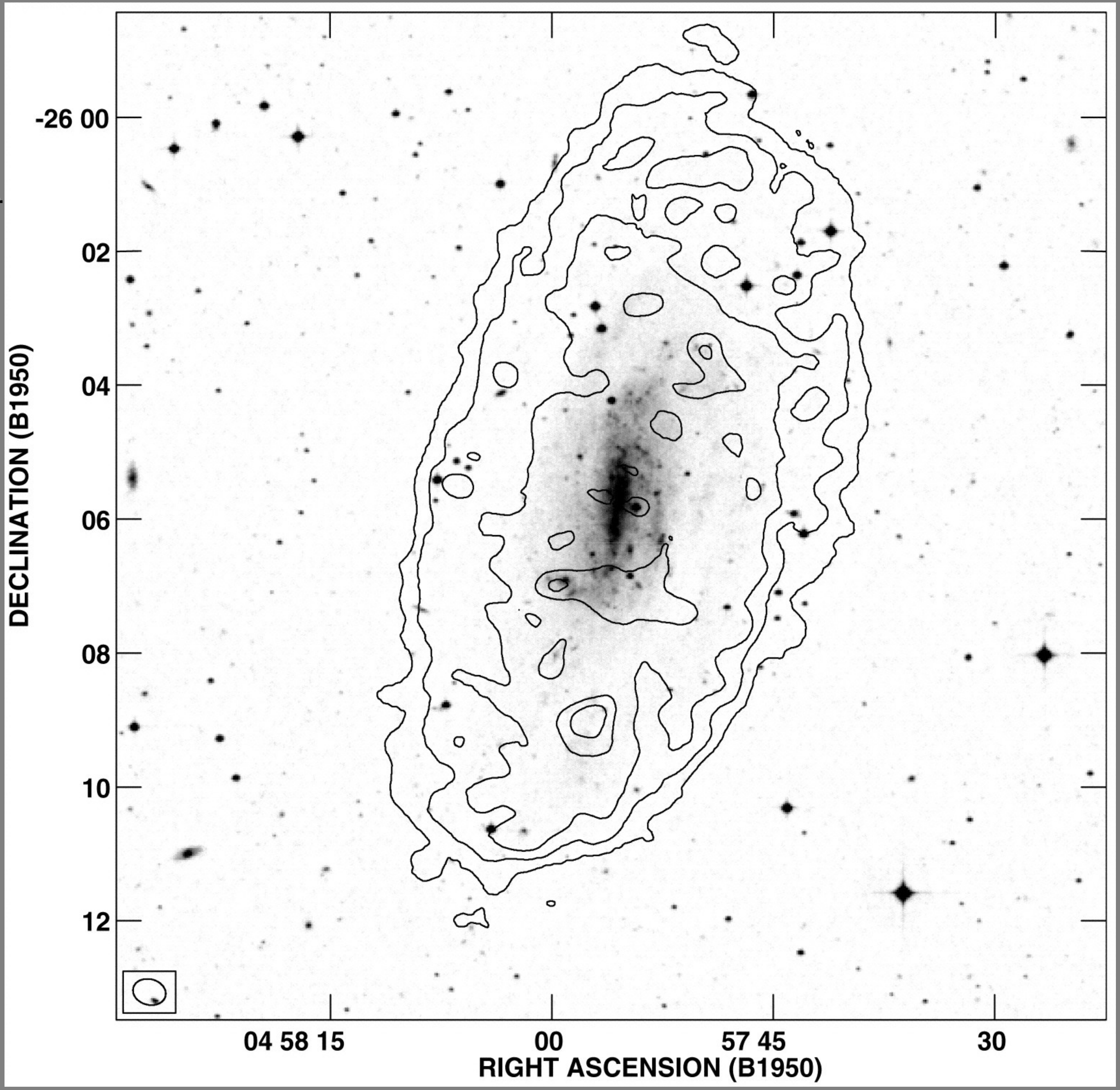


Solid Body rotation
Flat Rotation curve
Falling Rotation curve



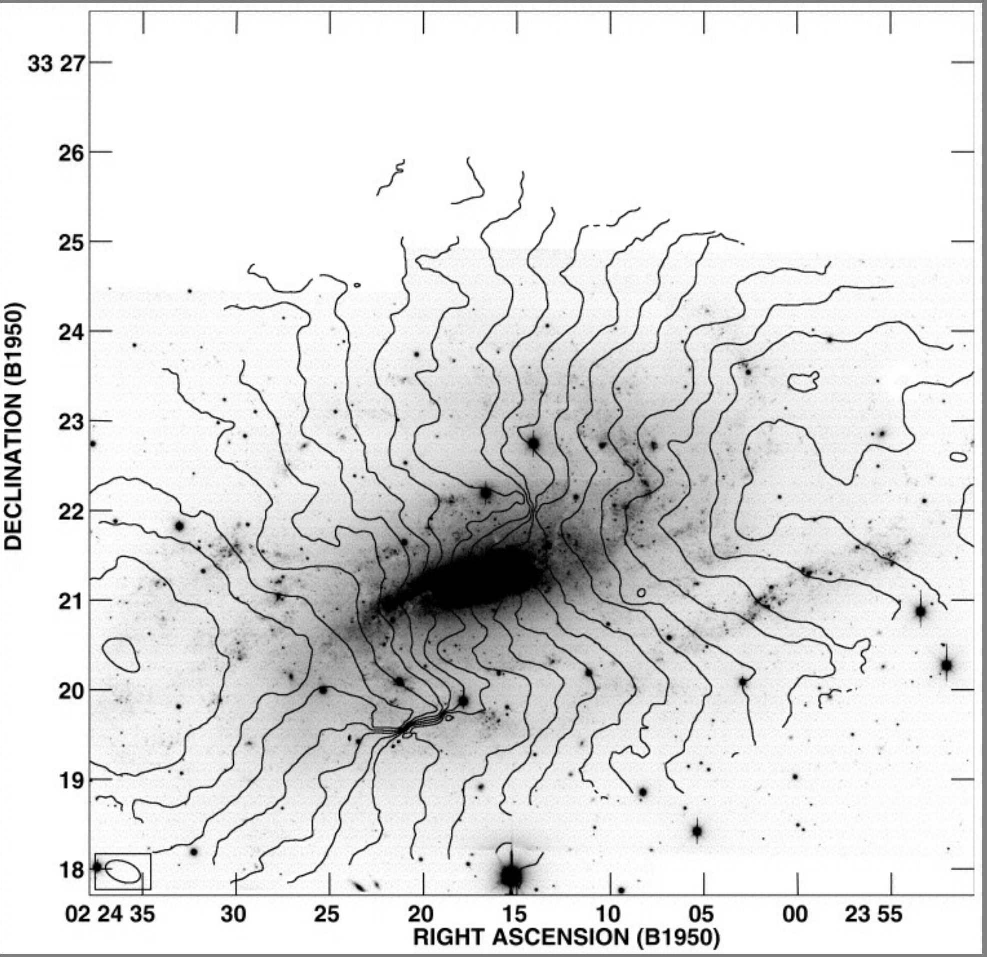
-26 00
02
04
06
08
10
12
DECLINATION (B1950)
04 58 15
00
57 45
30
RIGHT ASCENSION (B1950)

NGC 1744 in HI
(the contours)
and in the B band
image.

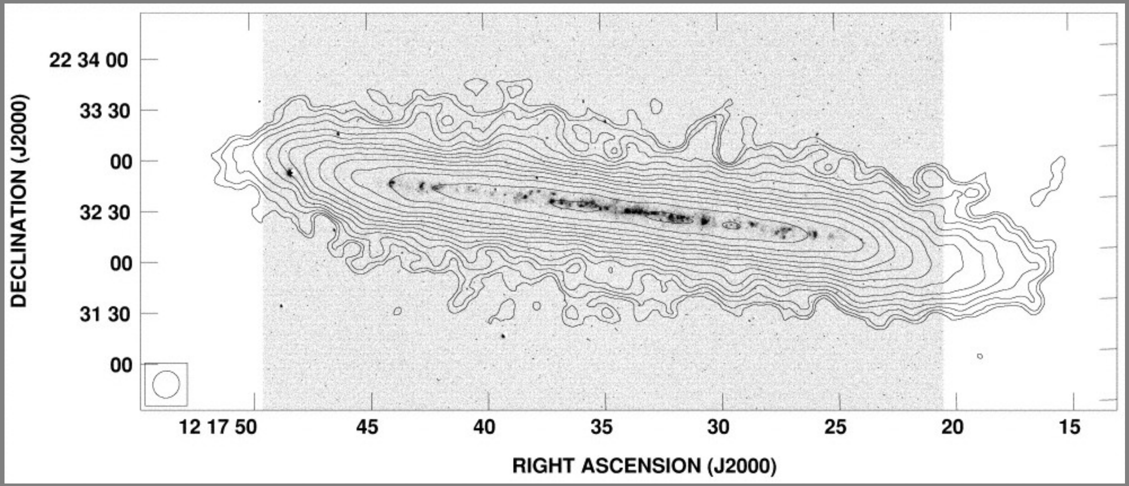


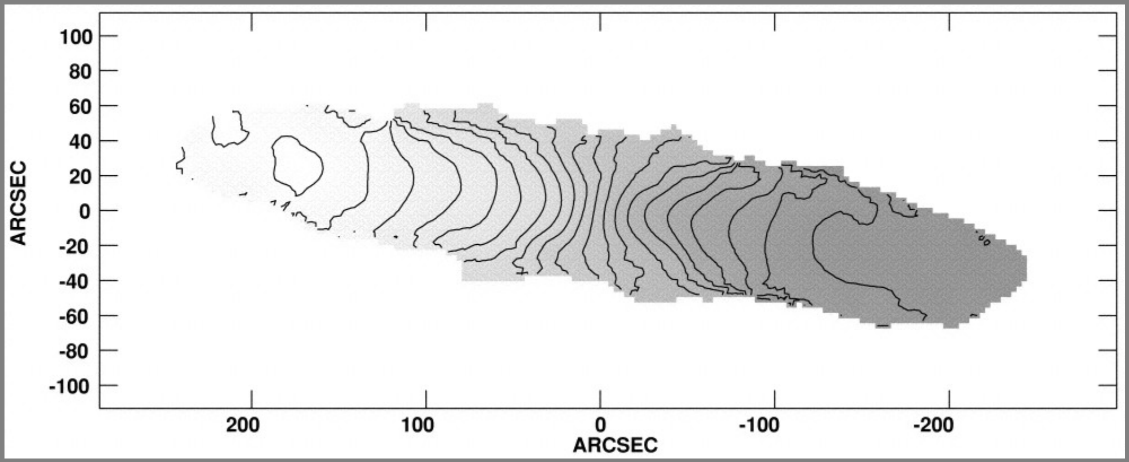
Spider Diagram – NGC 925

Note that this is a much more messy system.



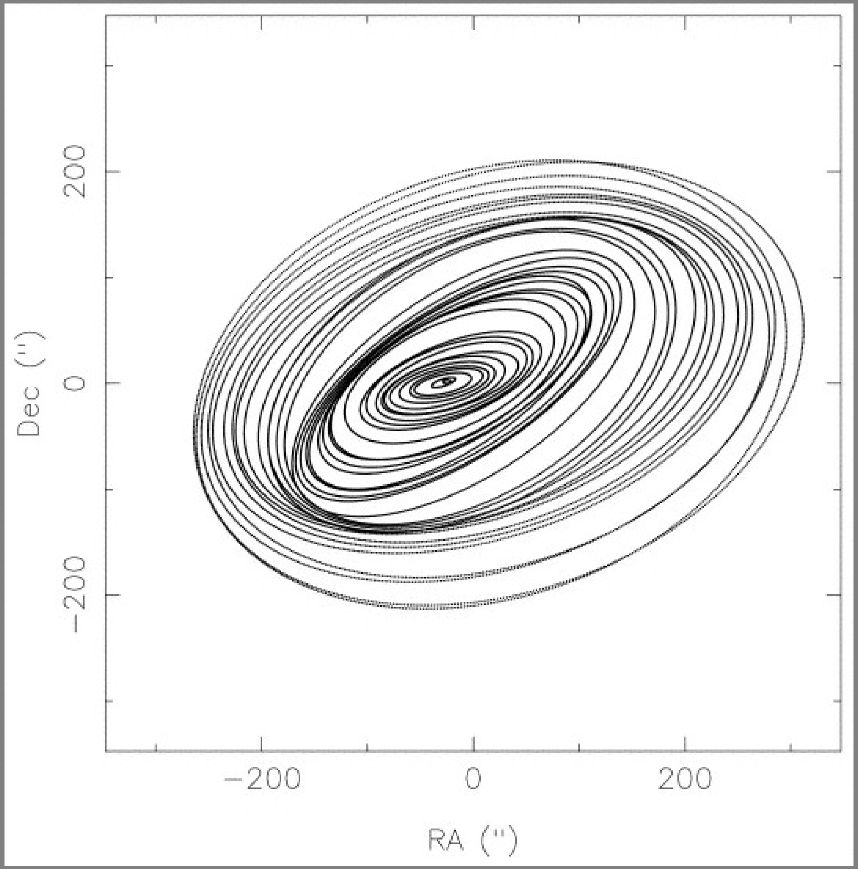
Spider Diagram – Edge-on Galaxy



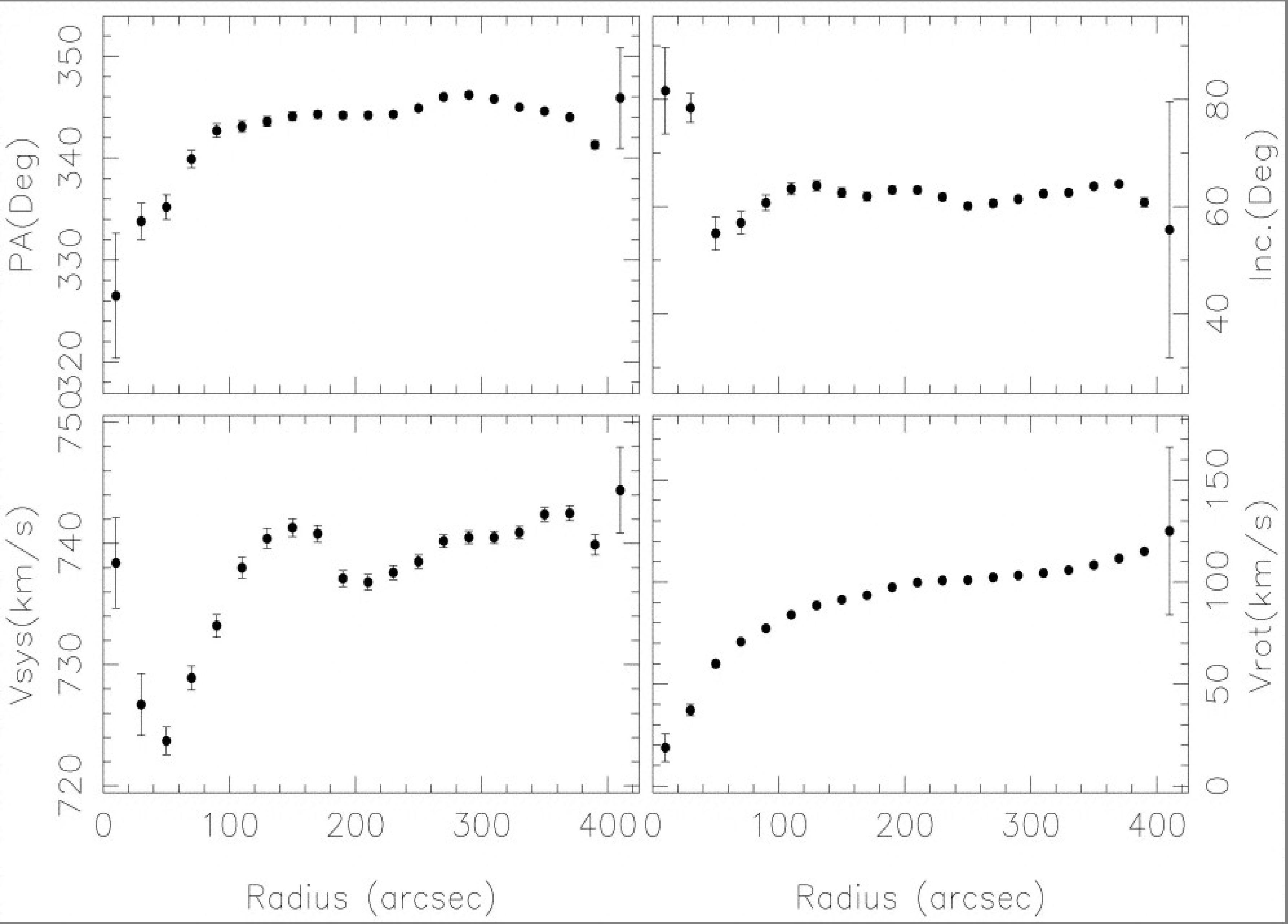


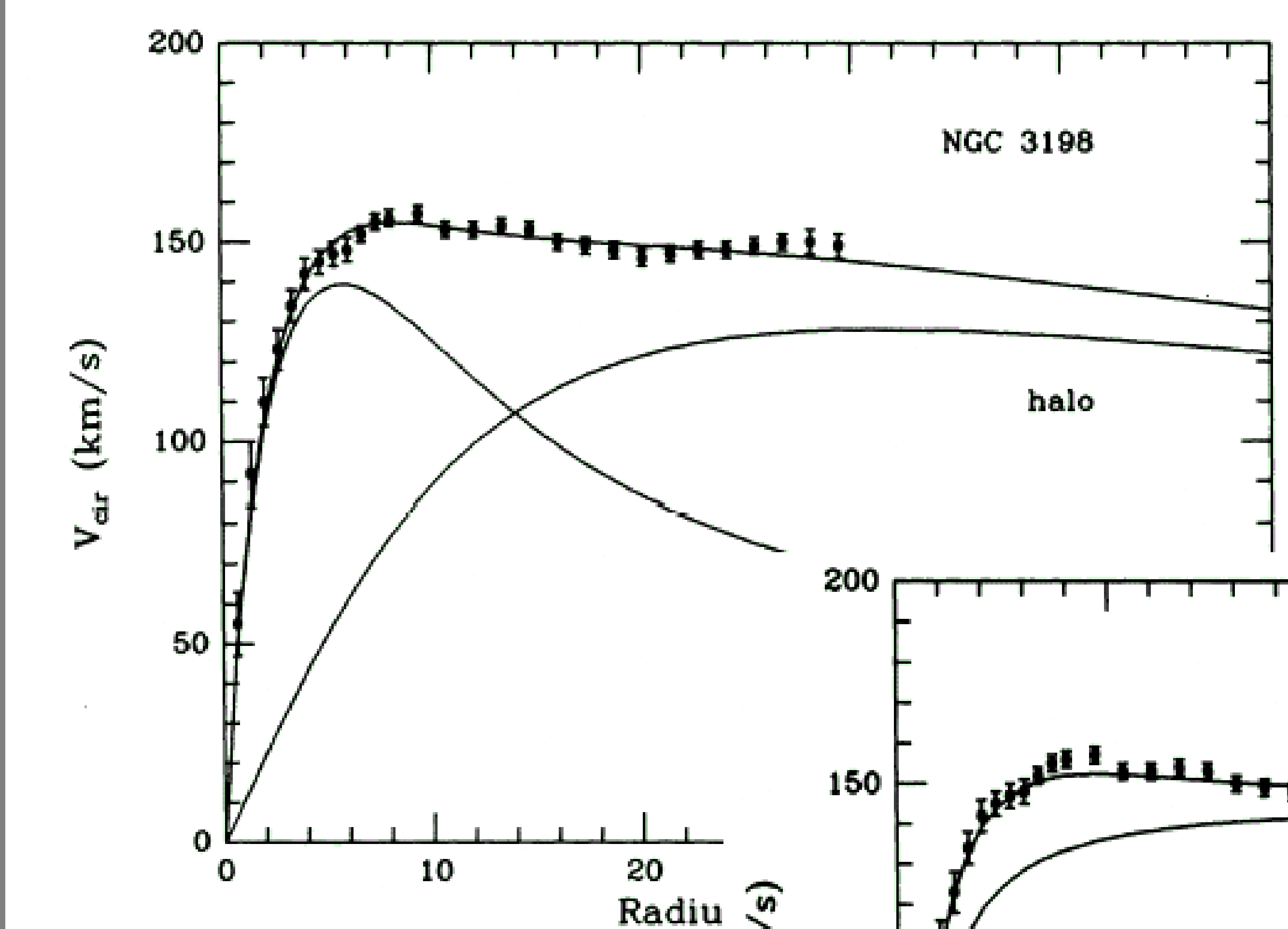
Deriving a Rotation Curve

- Tilted ring models allow you to fit the circular velocity, inclination, position angle as a function of radius.



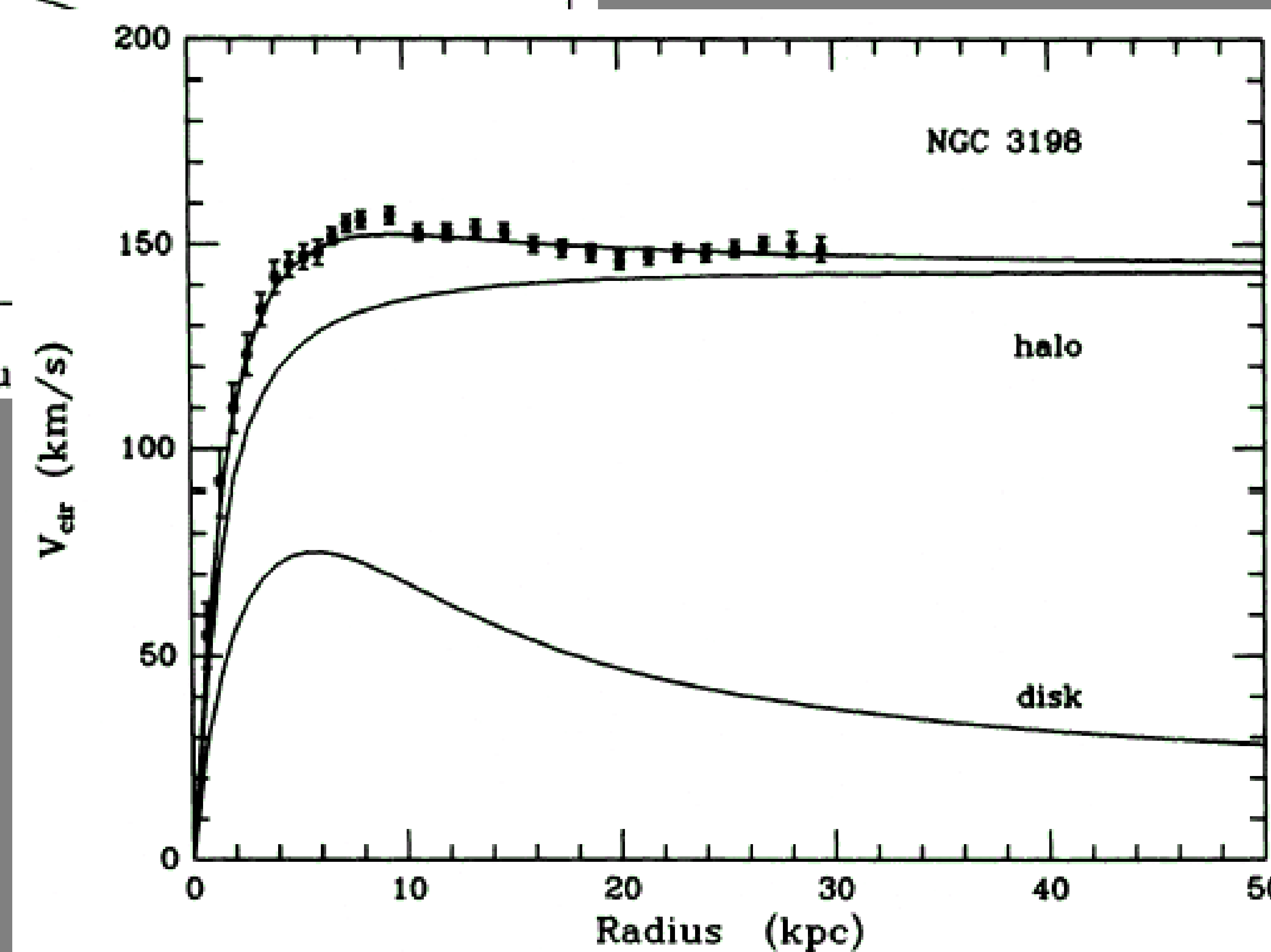
Data fitted with a tilted ring model – NGC 1744, Pisano et al. 1998





Maximum disk model

Minimum disk model

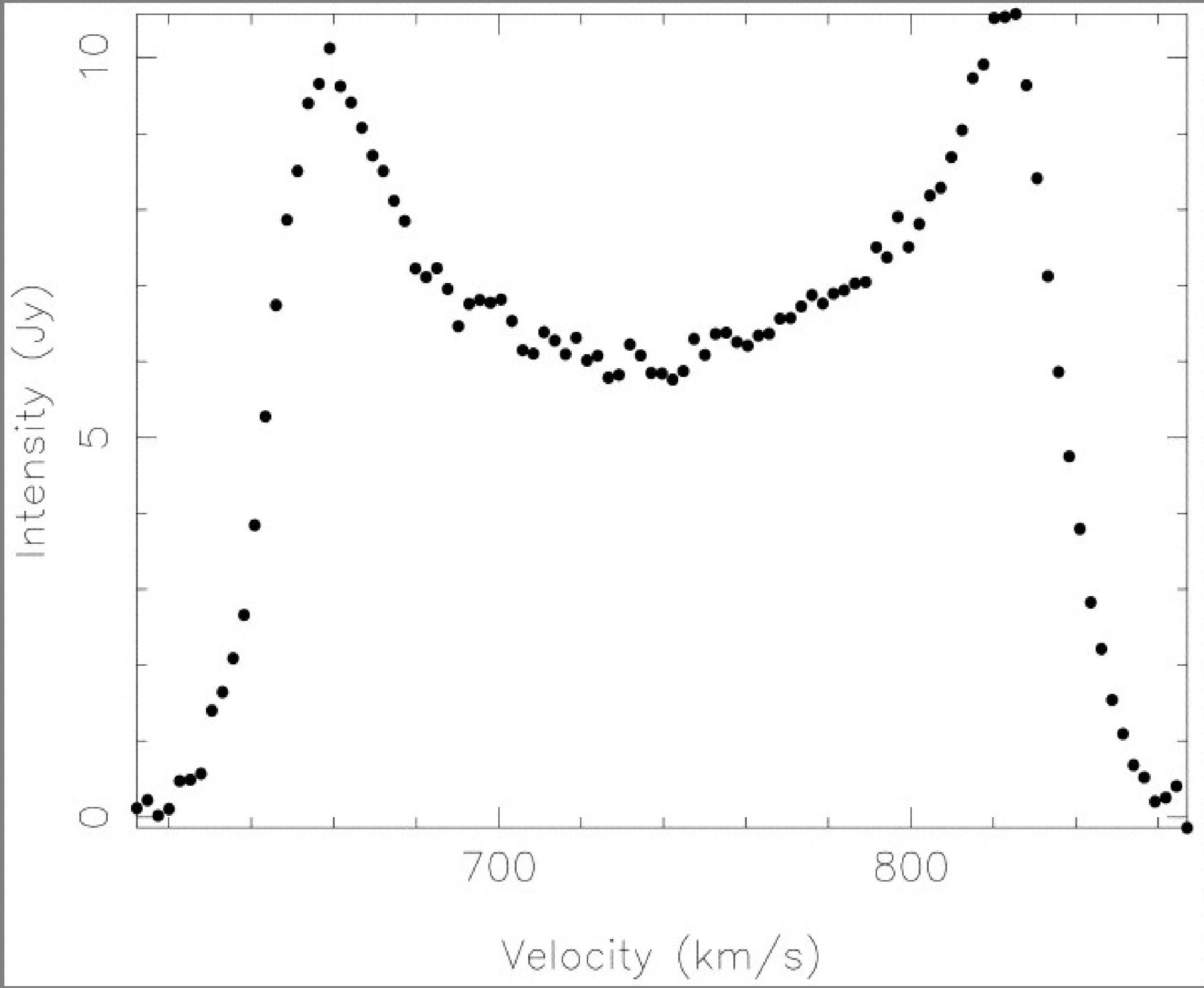


Van Albana et al. (1985)

Another way to measure the mass is to look at the integrated velocity profile. The width of this profile gives the velocity range and you can derive a mass from that.

For circular motion

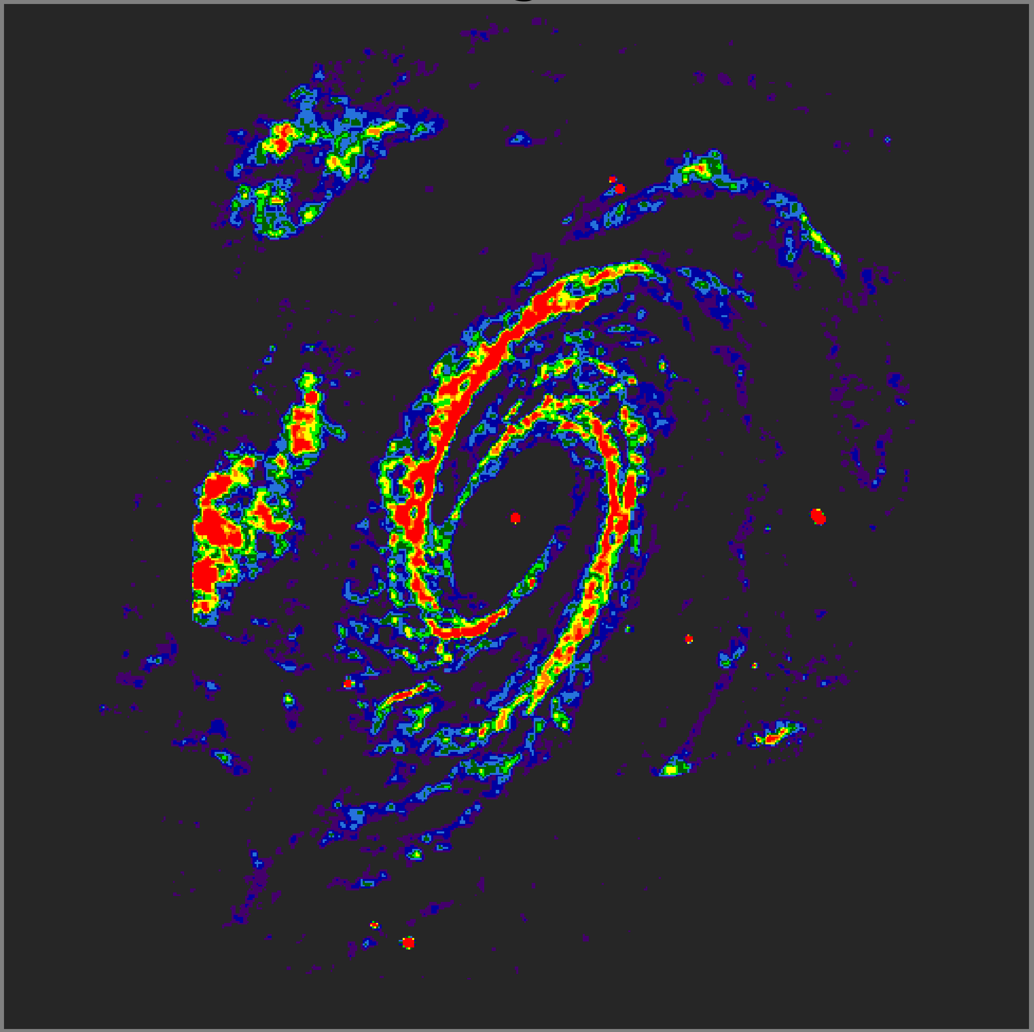
$M(<r) = v^2r/G$



M81 optical

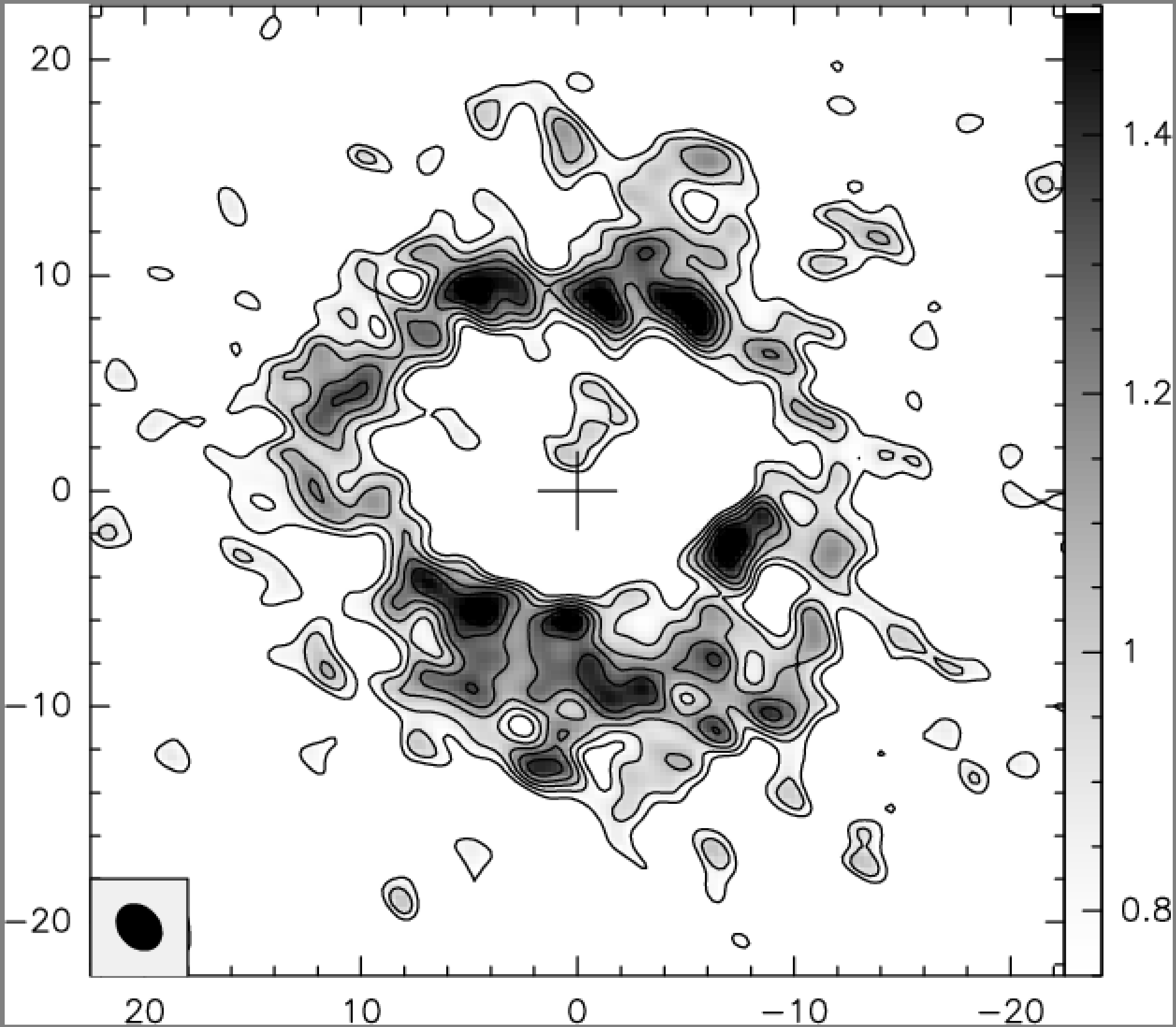
Bright in the center, faint in the outer parts where most of the mass is

HI gas

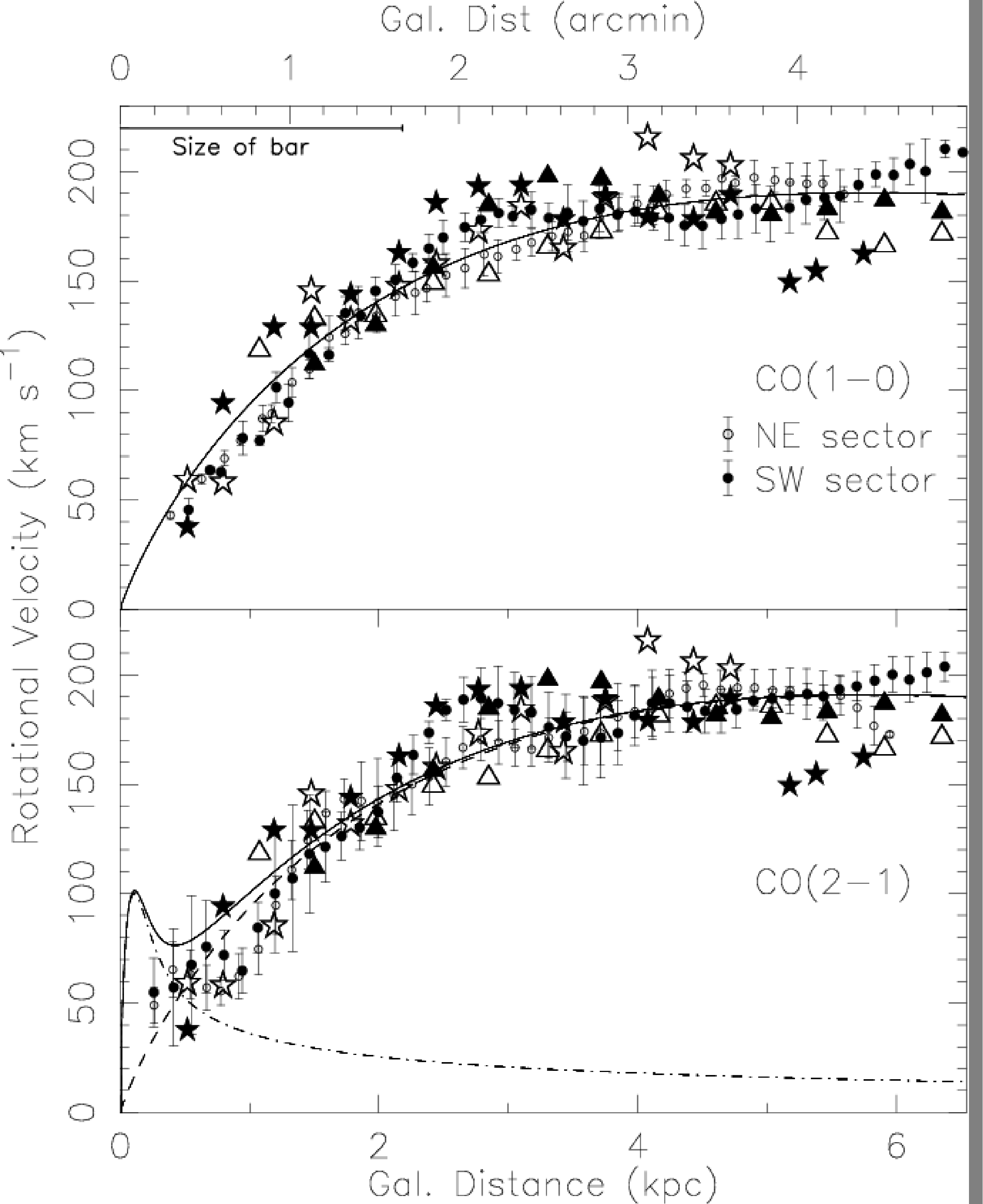


Dim in the center, brighter in the outer parts where most of the mass is

Using CO to derive a rotation curve



CO gas is much more common in the inner parts of spiral galaxies and can also be used to derive a rotation curve
Lundgen et al. 2004



Hα rotation curves

Using long slit spectroscopy we can derive a velocity “slice” across the galaxy.

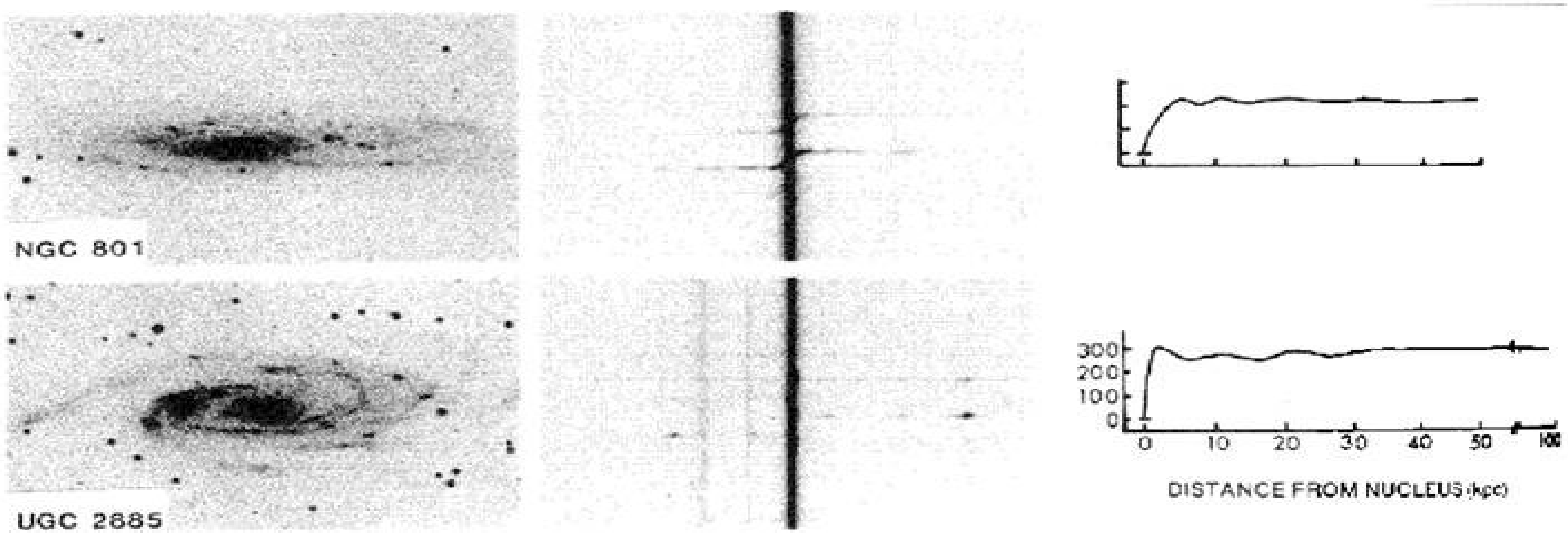
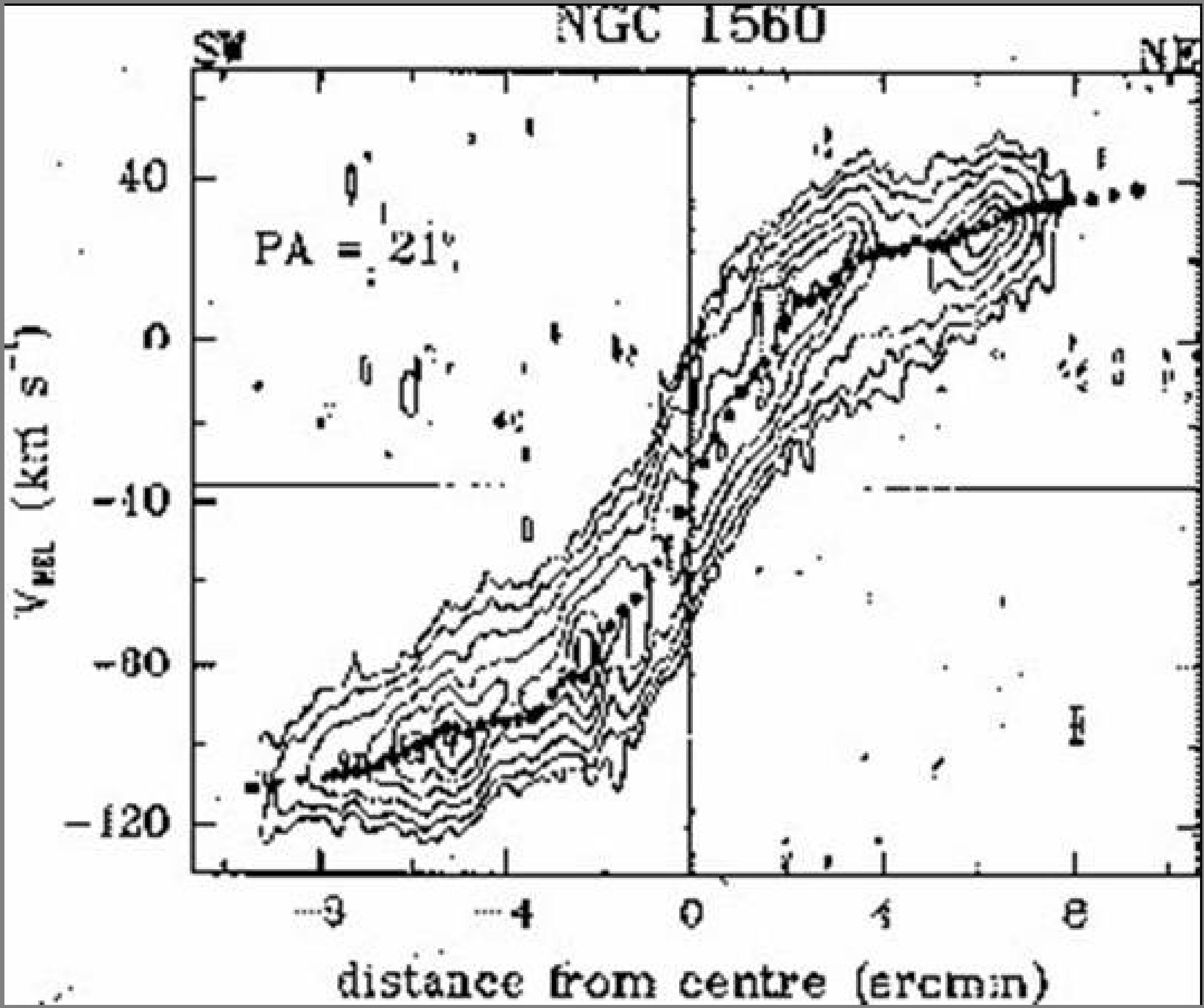
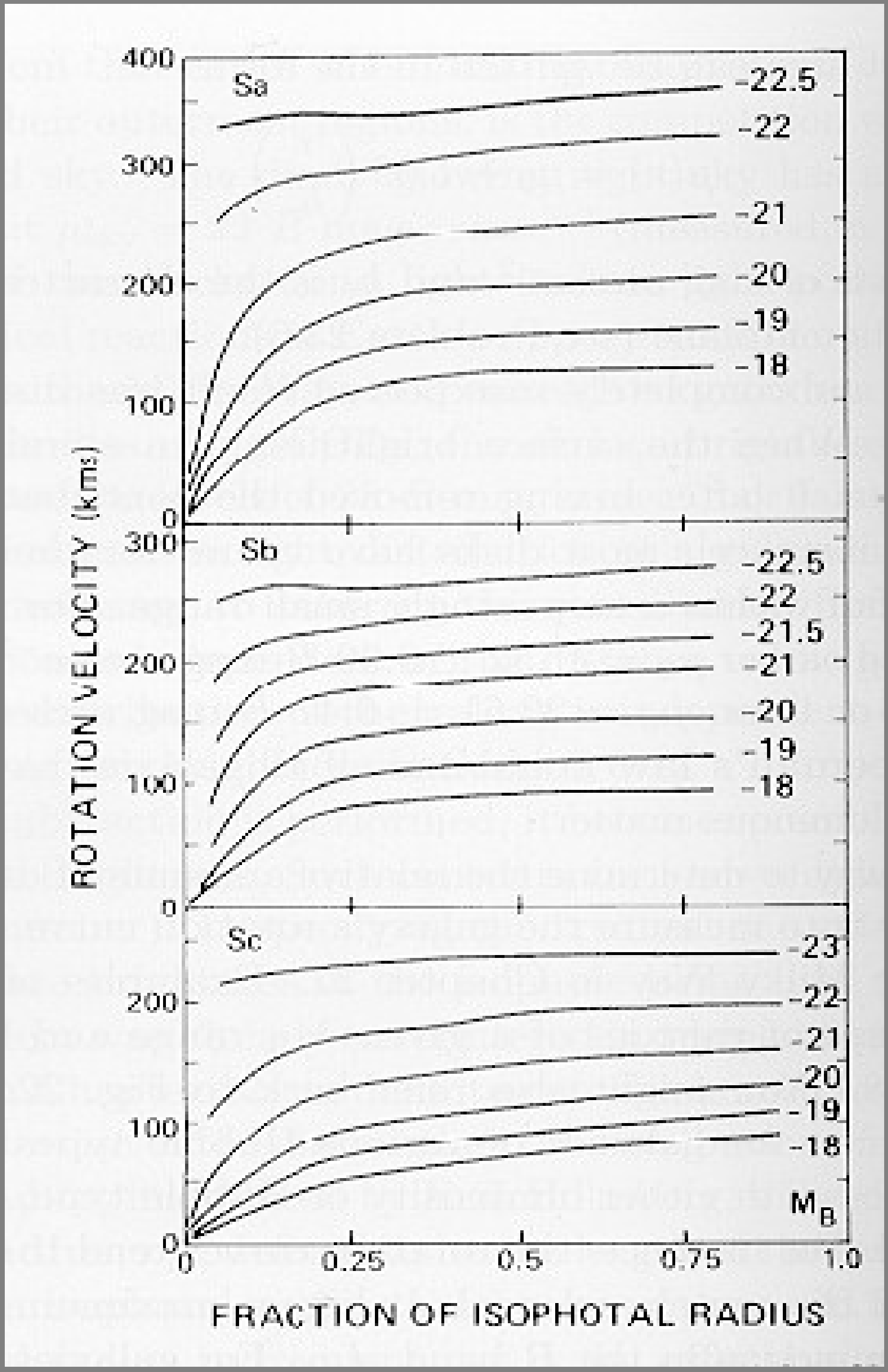


Figure 10-1. Photographs, spectra, and rotation curves for five Sc galaxies, arranged in order of increasing luminosity from top to bottom. The top three images are television pictures, in which the spectrograph slit appears as a dark line crossing the center of the galaxy. The vertical line in each spectrum is continuum emission from the nucleus. The distance scales are based on a Hubble constant $h = 0.5$. Reproduced from Rubin (1983), by permission of *Science*.

see: Binney, Tremaine (1994) *Galactic Dynamics* p.600


NGC 1560
SW
NE
PA = 21°
V_{HEL} (km s^{-1})
40
0
-80
-120
-4
0
4
8
distance from centre (arcmin)



- Hα rotation curves for galaxies of various Hubble types
- Galaxies with higher luminosity generally have higher rotation velocities
- Later types generally show a slower rise of the rotation curve
- Typical spirals have peak v_{rot} 150-300 km/s

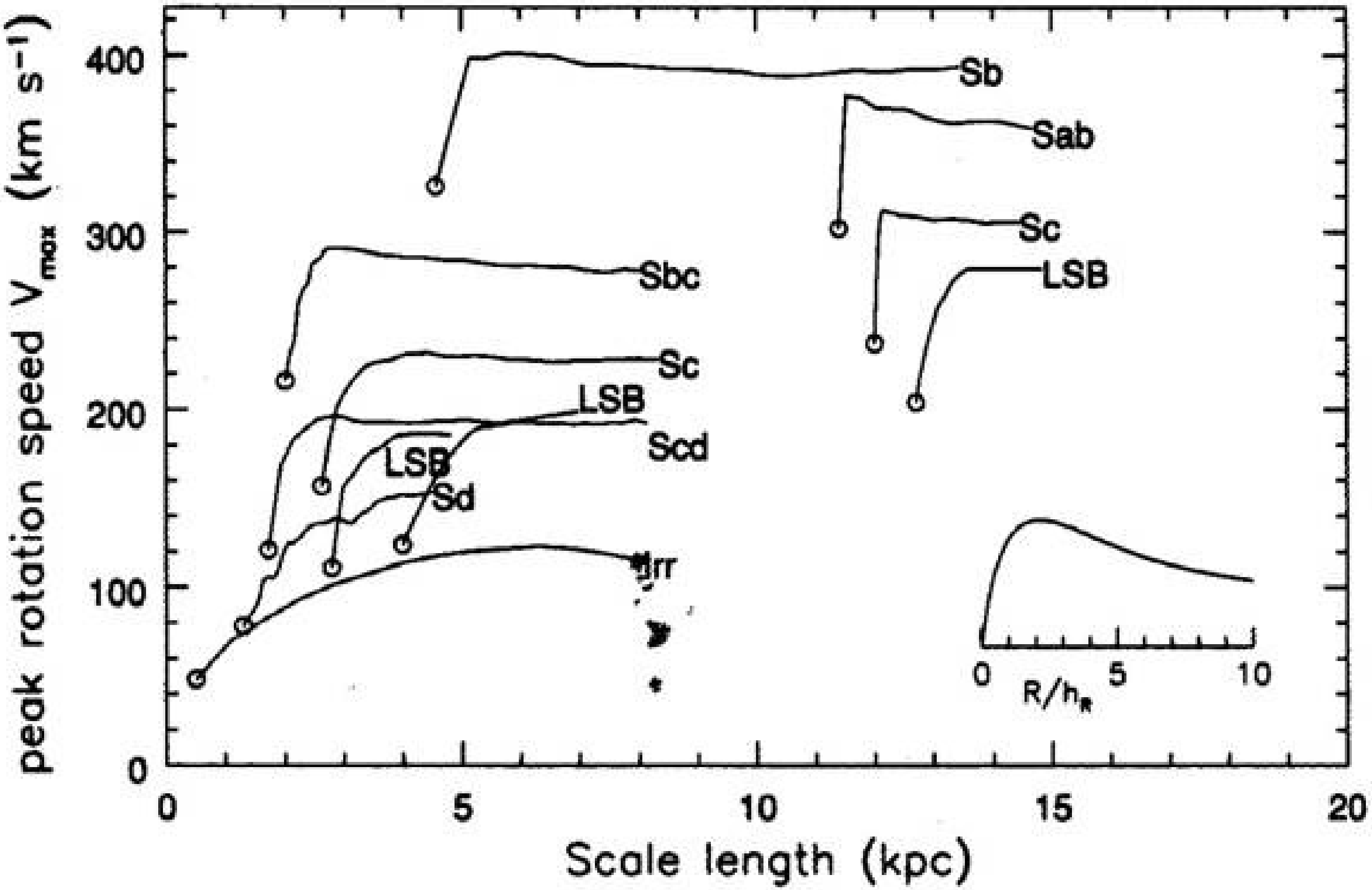
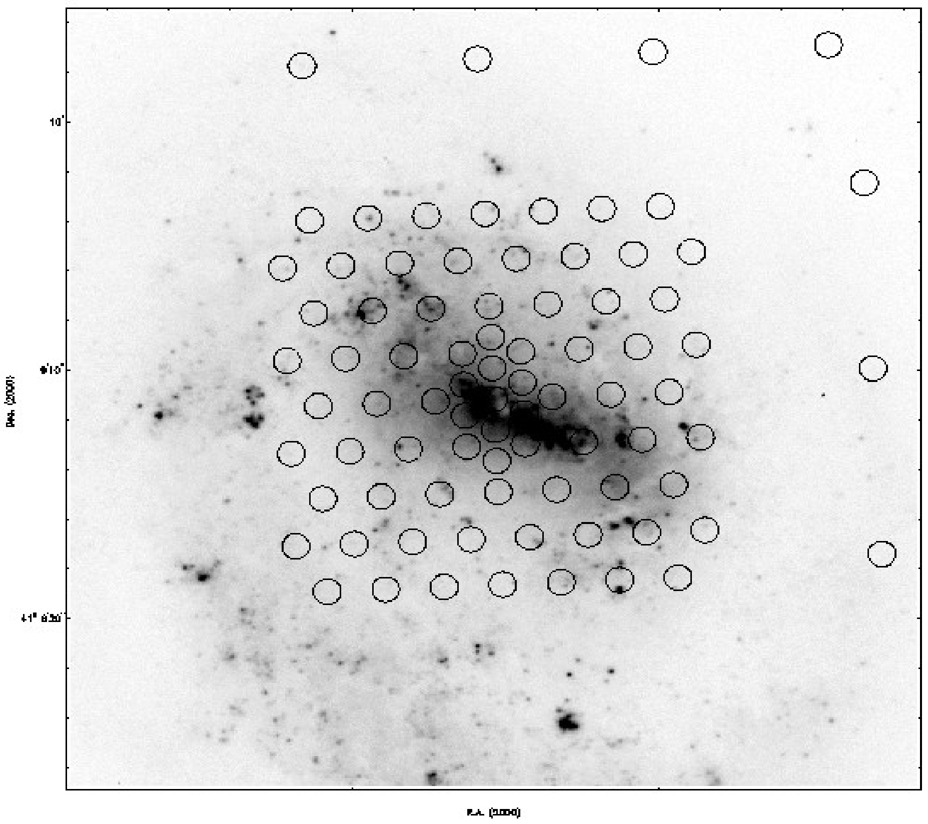


Figure 5.21 Rotation curves for disk galaxies of various types. Open circles show scale length h_R of the stellar disk, and peak rotation speed V_{max} for each galaxy. Curves are plotted in units of R/h_R, to the same horizontal scale as the inset, showing $V(R)$ for the exponential disk (Equation 5.1). LSB denotes a low-surface-brightness galaxy. The measured rotation does not fall as it should if the stellar disk contained most of the mass – A. Broeils, E. de Blok.

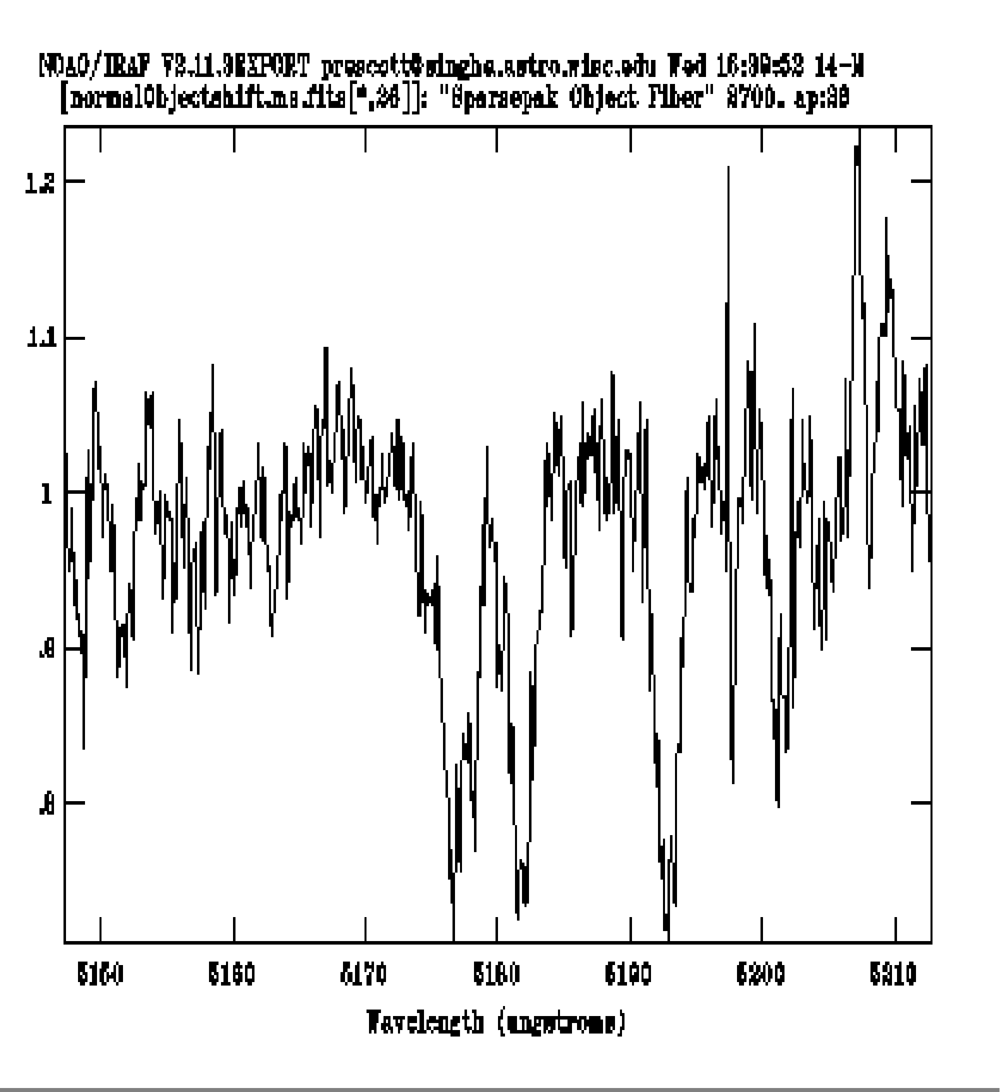
Stellar Kinematics

- restricted to high surface brightness systems
- cross-correlation between observed spectrum and template spectrum broadened with a known gaussian



NGC 4618

- Mg I and Fe lines yield stellar velocities and velocity dispersion
- Method
  - Choose a template K0.5III star in this case
  - Broaden template with a Gaussian and fit to the spectra
  - σ is between 18 and 31 km/s



NGC 4618 Results

- Stellar velocities and HI velocities are offset by ~15km/s
- If we assume a stellar density profile (based on the amount of light)
  - We find the stellar density of ~$79 M_\odot\ pc^{-2}$
- So stars make up about 40% of the total (dynamical) mass of the disk

Rotation Curves

- In the absence of dark matter, we expect:
  - $mv^2 / r = GM_r\, m/r^2$ for a "particle" of mass m at radius r, where M_r is the mass within a radius r
  - $M_r = v^2 r/G$
  - If all mass was contained within a radius R, then M=constant for r>R, $v^2 \propto r^{-1/2}$ (Keplerian!)
  - Instead, rotational velocity is constant, so that means $M_r \propto r$ at distances larger than stellar disks, the light shows an exponential drop off and thus the stellar mass is also dropping rapidly

Rotation Curves cont.

- For rotational velocity to remain constant with radius we need
  - $M_r \propto r$
  - There must be extra “dark” mass around spiral galaxies, extending far beyond the optical disk.
  - So how do you measure the total mass of a spiral? Where can you stop?

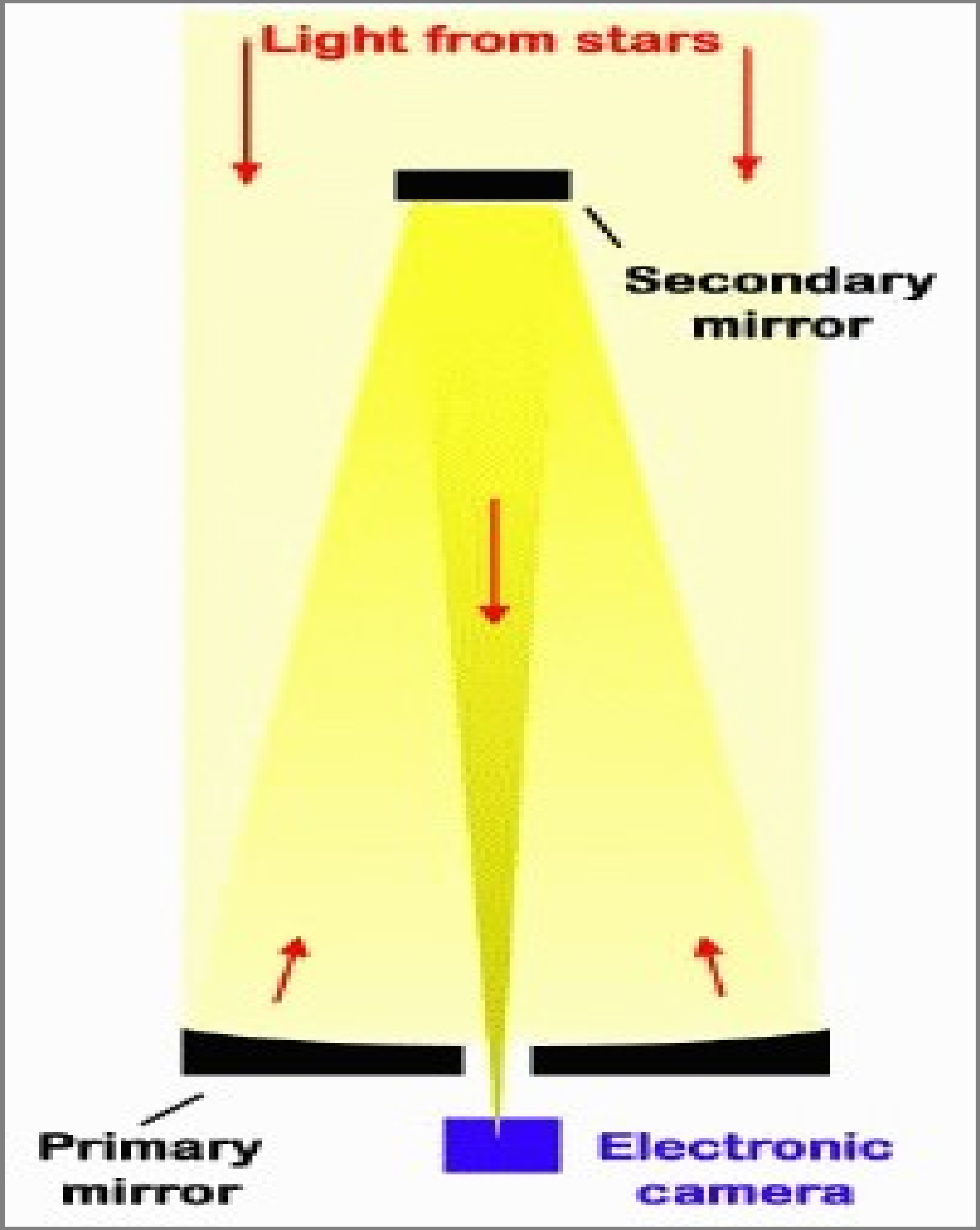
What do we now know about the density profile of dark matter?

- What does this mean for the density profile of the dark halo?
- If the DM halo is spherical then
  - $dM = 4\ r^2\ (r)\ dr$
  - We know that $m = v^2\ r/(2G)$ eqn 3.46
  - Take the derivative wrt r and we get $dM/dr=V^2/2G$, so $V^2/2G= 4\ r^2\ \ (r)$
  - Thus, $\ (r) = V^2\ /8\ Gr^2$

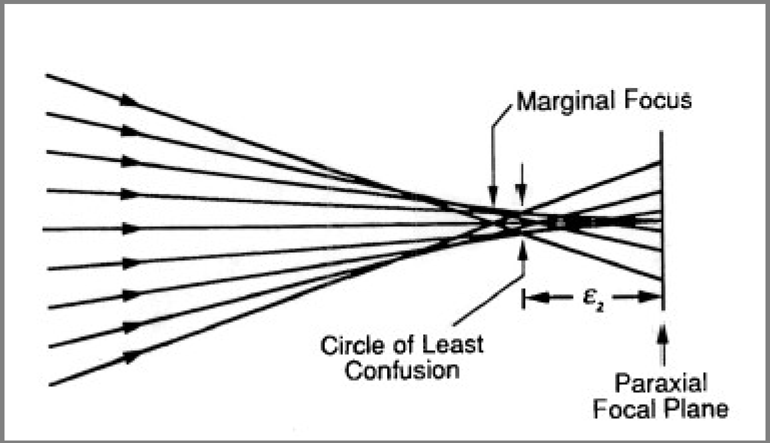
Aside: Imaging

Question: How does astronomical imaging work?

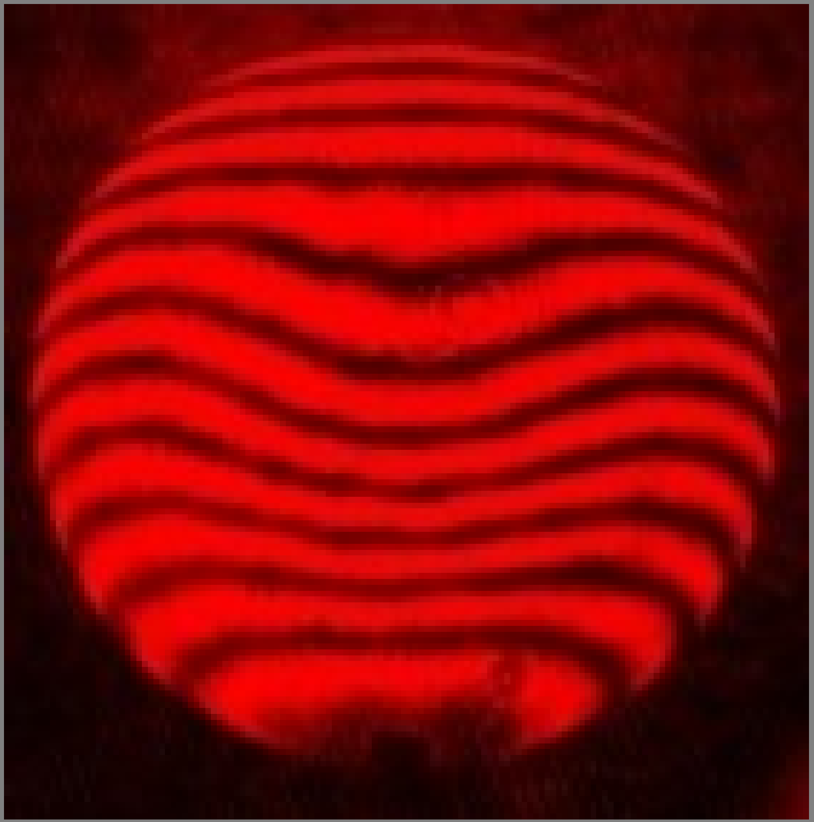
Lets first look at optical images and then we'll examine how radio images are made



To focus light and form an image you need a well designed optical system. The margin of error for forming the reflective surfaces is only about 1/10 the wavelength of the light you want to focus.

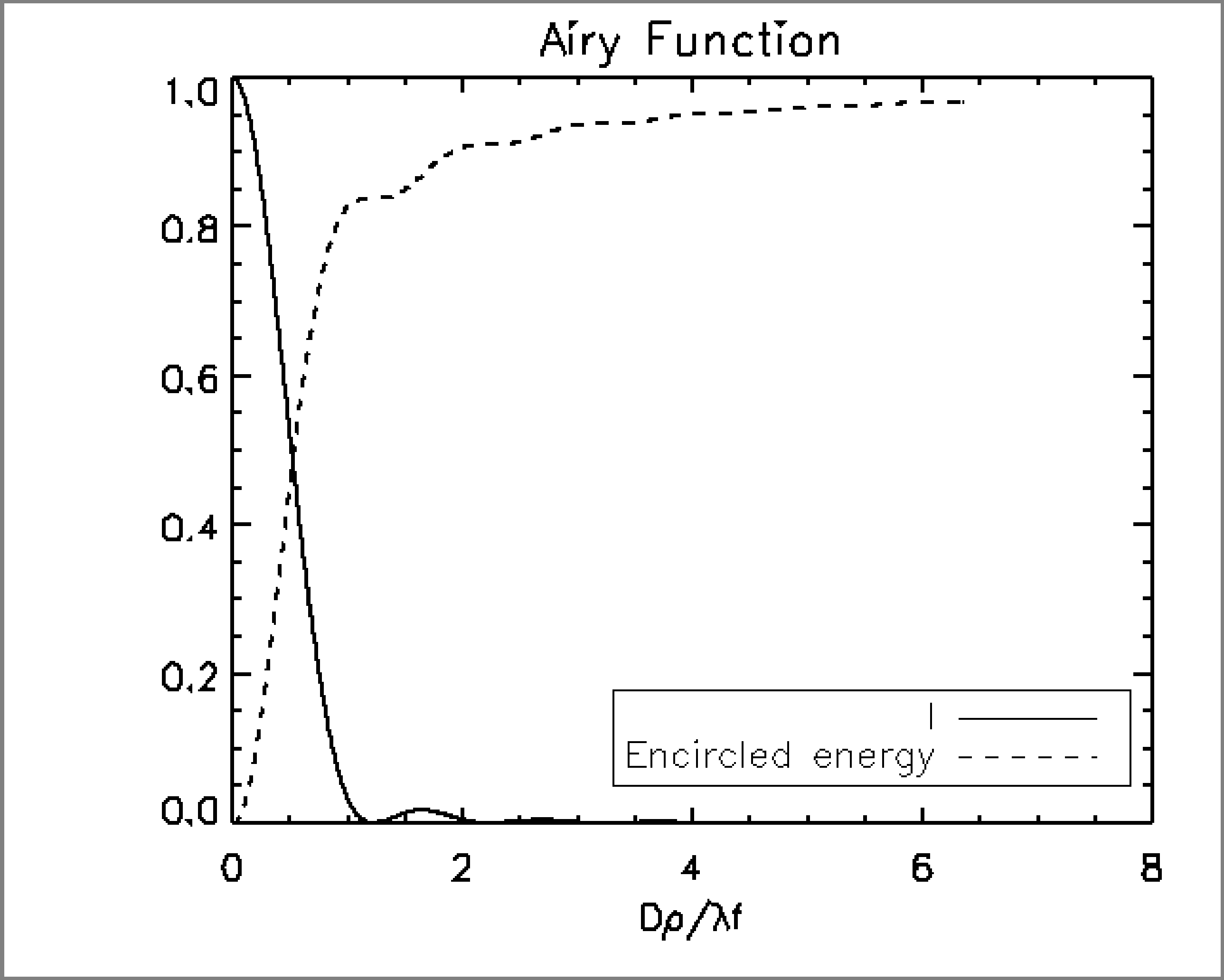


So in designing these systems you need a method to determine the shape of the mirror very accurately. This means measuring distances with an accuracy of about 55nm! One of the methods used is with interferometry. Below shows the interference fringes from a mirror that still needs work. The curvature of the fringes shows that spherical aberation is present.



Airy function
(1^{st} order Bessel function)

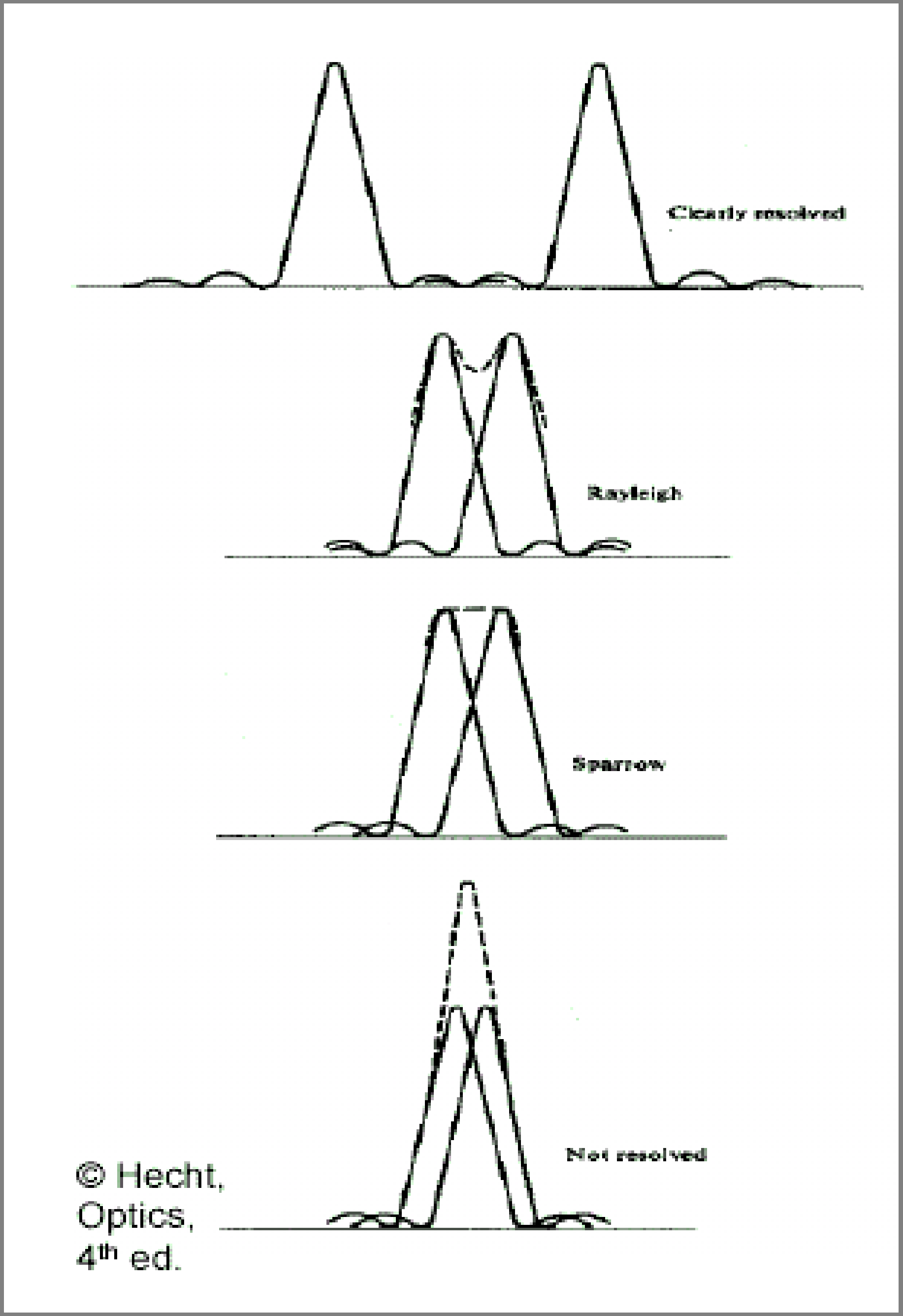
$$I(\rho) = I_0 \left[\frac{J_1(\pi D\rho/\lambda R)}{\pi D\rho/\lambda R} \right]^2$$



According to the Rayleigh criteria the resolution of a lens or mirror of diameter D is given by

$$\theta_{\text{Rayleigh}} = 1.22\lambda/D$$

where λ is the wavelength of the radiation. It follows from Fraunhofer diffraction around a circular aperture, and the value 1.22 is given by x/π, where $x \approx 3.832$ is the first zero of the Bessel function mathematical expression for the Airy Disk.



Lets look at some of the consequences of this. Suppose we have a telescope with a 10” mirror and we are observing in blue light (500nm) what is our resolution?

λ=500nm = 5x10^{-6} m

D=10” = 25.4cm = 0.254m

$$\theta_R = 1.22*5\times10^{-6}\ \mathrm{m}/0.254\mathrm{m}$$

$$\theta_R = 2.64\times10^{-6}\ \mathrm{rad} = 0.6\ \mathrm{arcsec}$$

Now lets look at what size mirror we need at 21cm to get the same resolution?

λ=21cm = 0.21 m

θ_R=2.64x10^{-6} rad

D=?

$$D=1.22\lambda /\theta_R$$

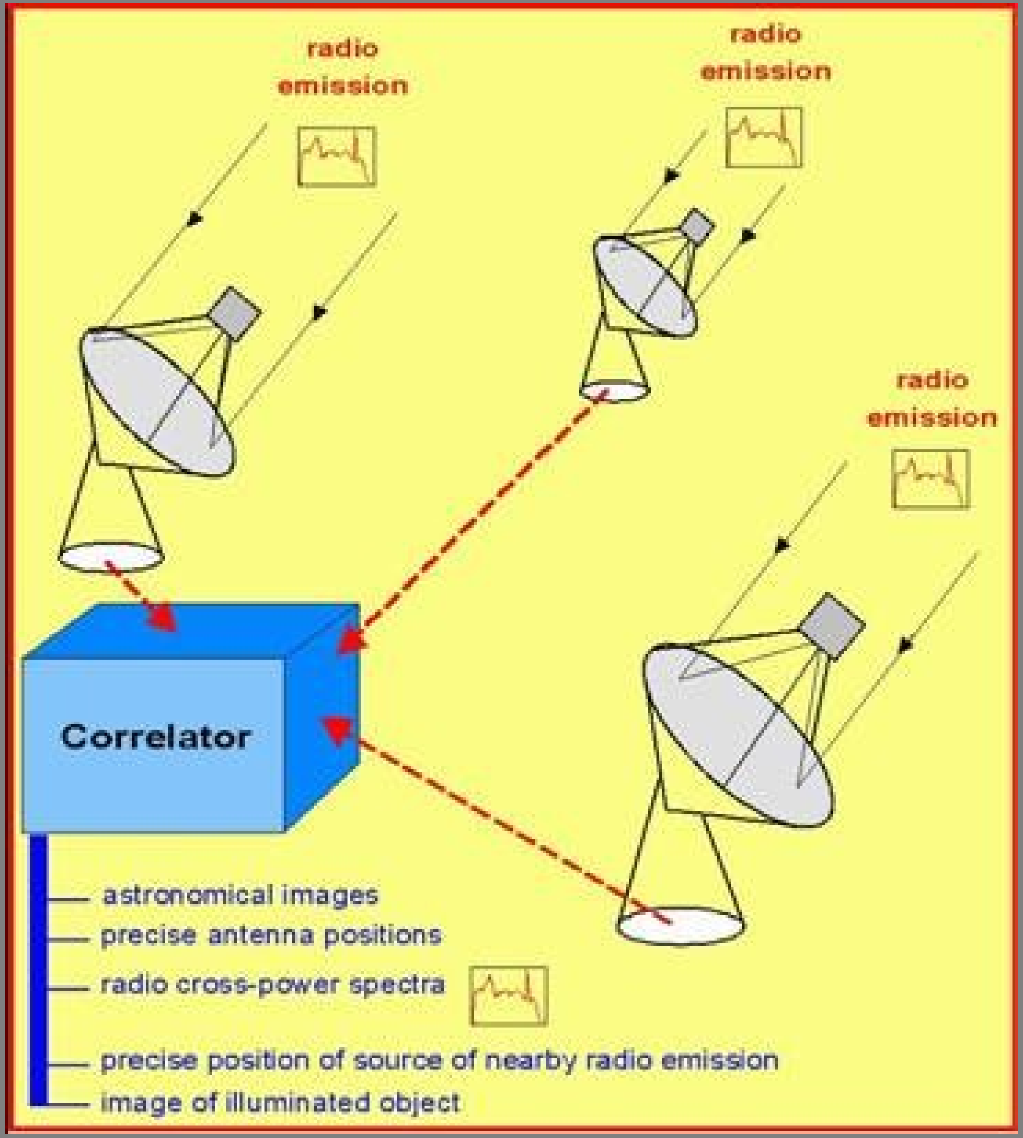
$$D= 1.22*0.21m/2.64x10^{-6} \text{ rad}$$

$$D = 9.7x10^{4} \text{ m}$$

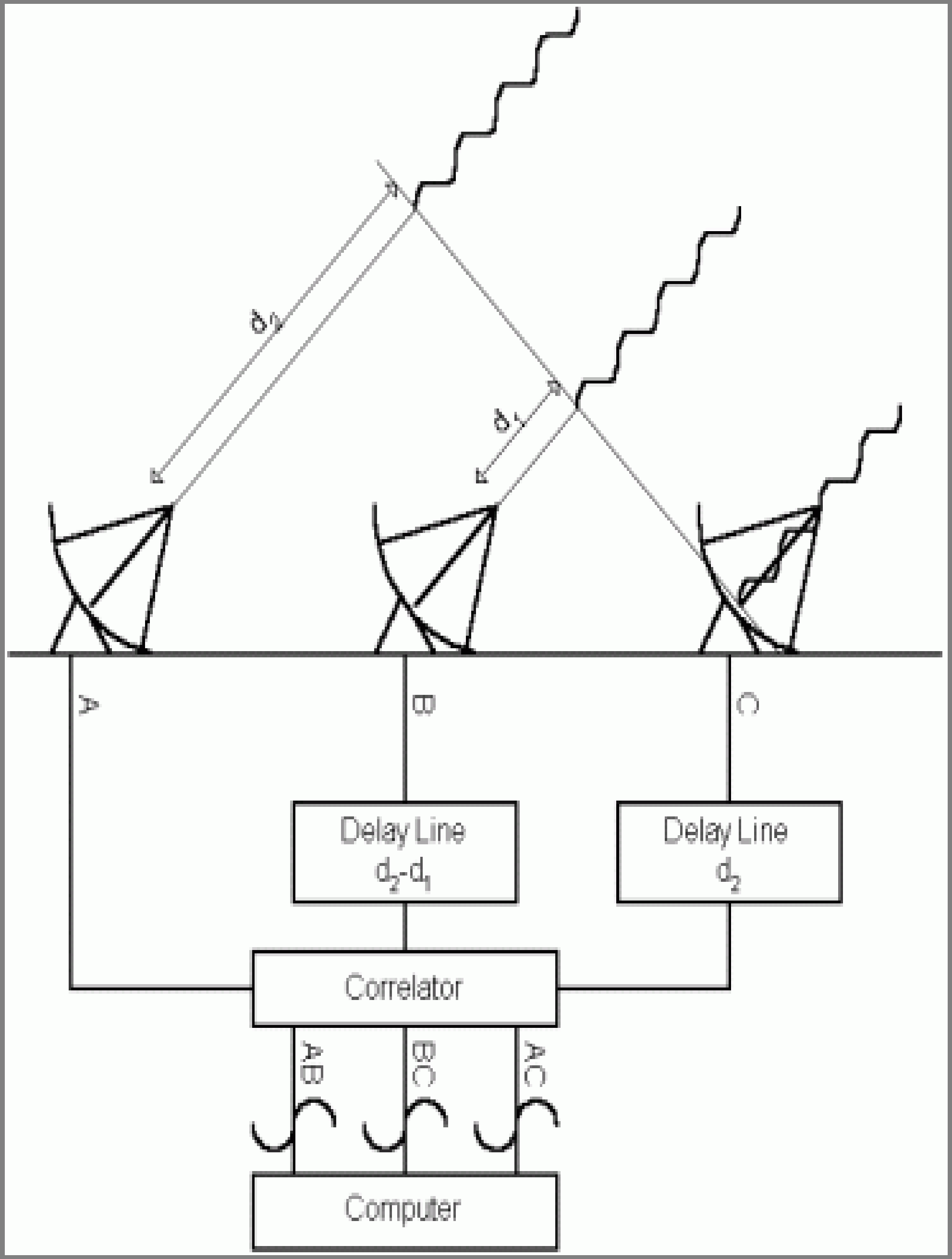
$$D = 97km$$

Radio Astronomy

- Use many small antennas
- Each antenna can be thought of as a part of a large dish



- We can add a “extra” length in the electronics to simulate a physical offset of the radio telescopes
- This delay serves the same purpose as a curved mirror and the radio waves “focus” like the optical light.

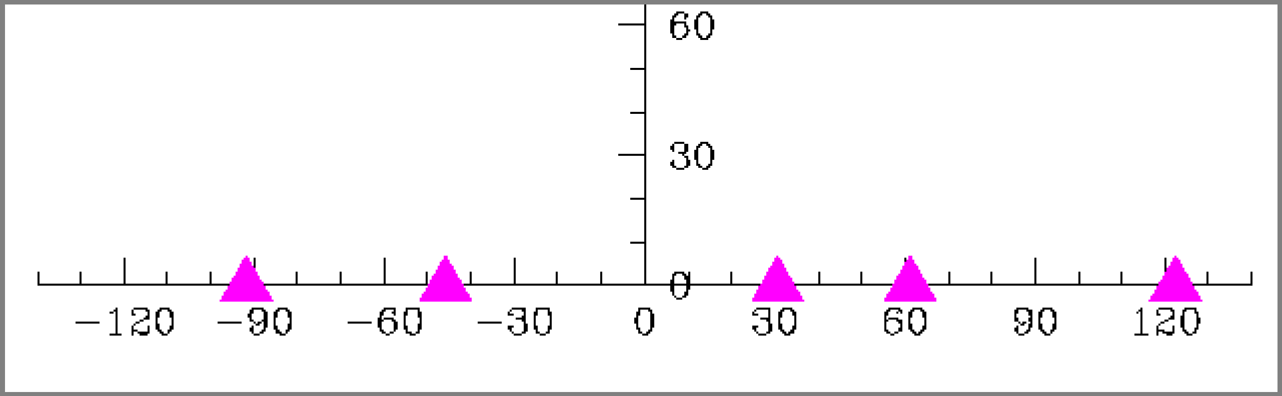


- Fully steerable array of 14 antennas 10 fixed and two pair on rails
- Can observe multiple frequencies at the same time

Aperture Synthesis

As an example lets look at an East – West array

West



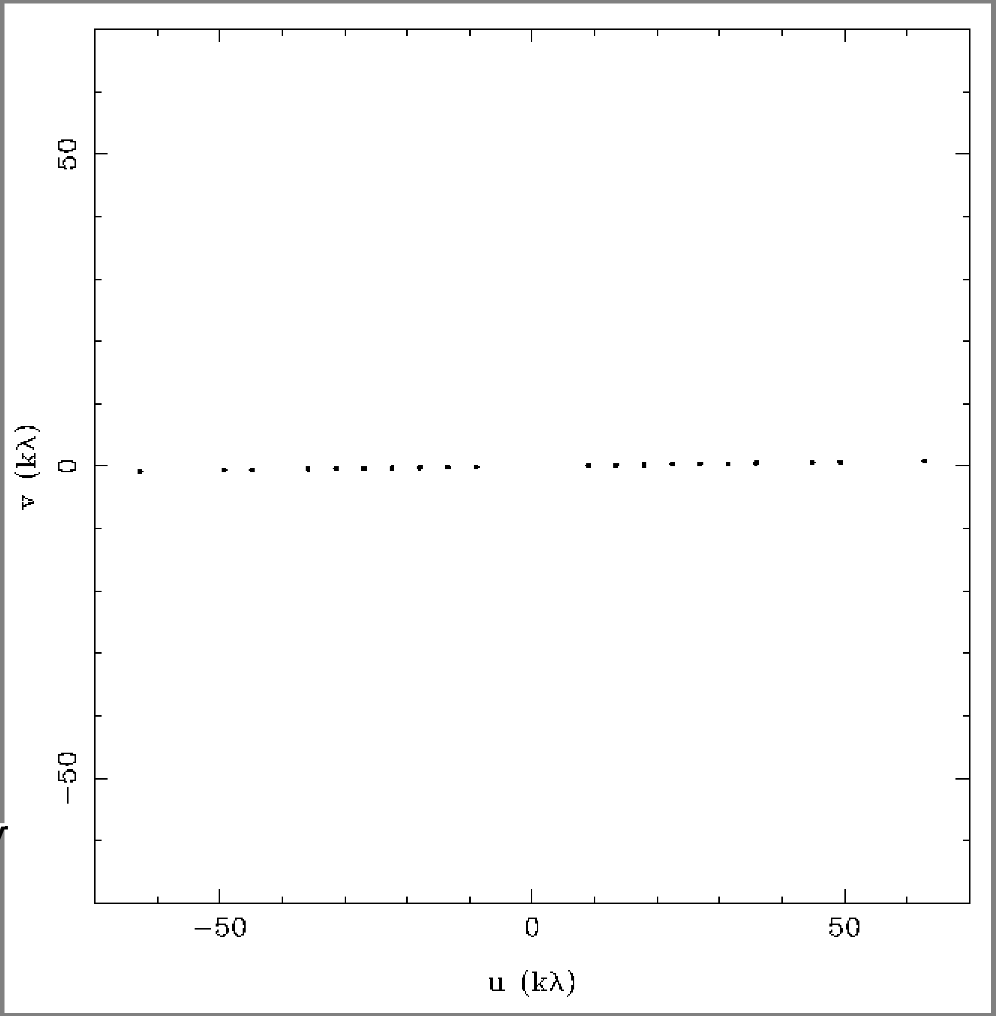
East

If we look in the U-V plane (this is just a coordinate system defined by the antennas) then at one time we get information for these points.

For our 5 antennas we have 20 distances between pairs of antennas.

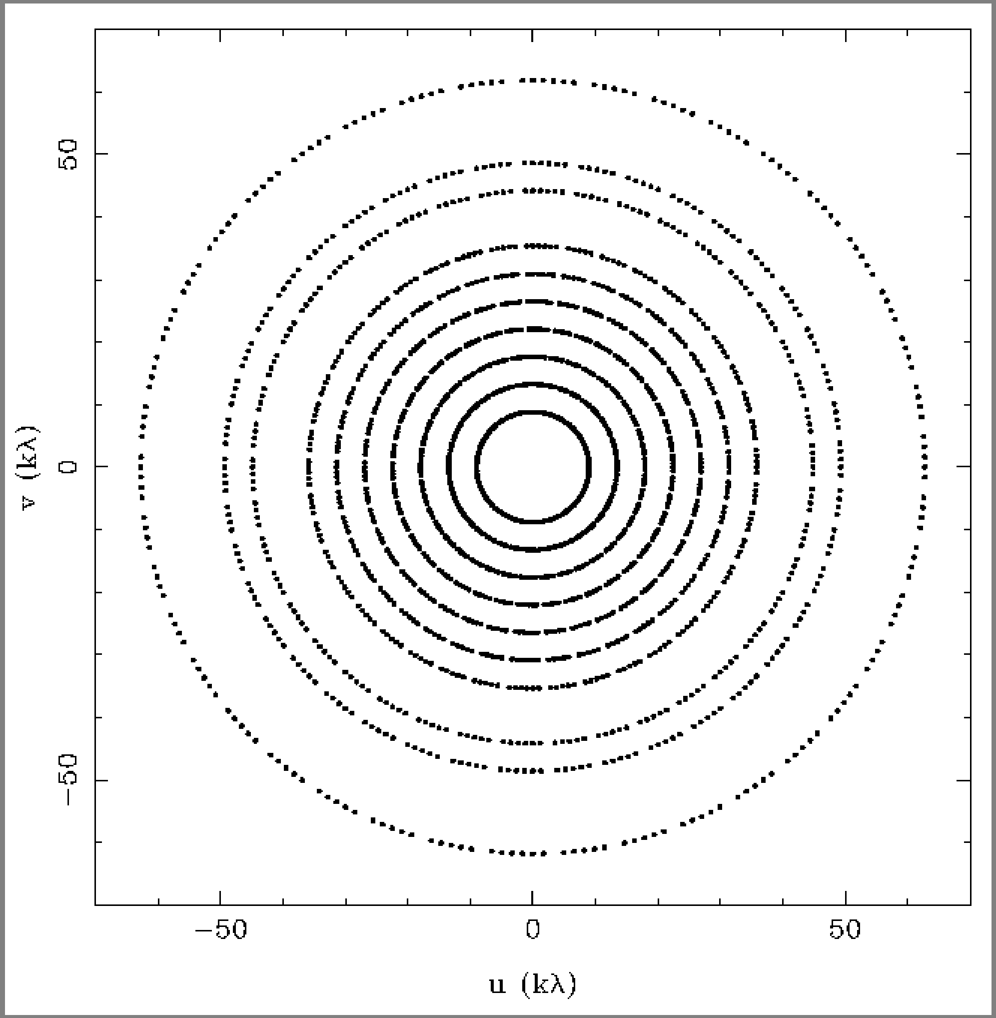
Since we can mathematically "swap" any pair on antennas we can also fill in the -U,-V plane at the same time.

What happens over time?



Over time (12 hrs) we make a complete rotation and fill part of the U-V plane.

After 12 hrs we can move the antennas around and observe for another 12 hrs to fill more of the plane

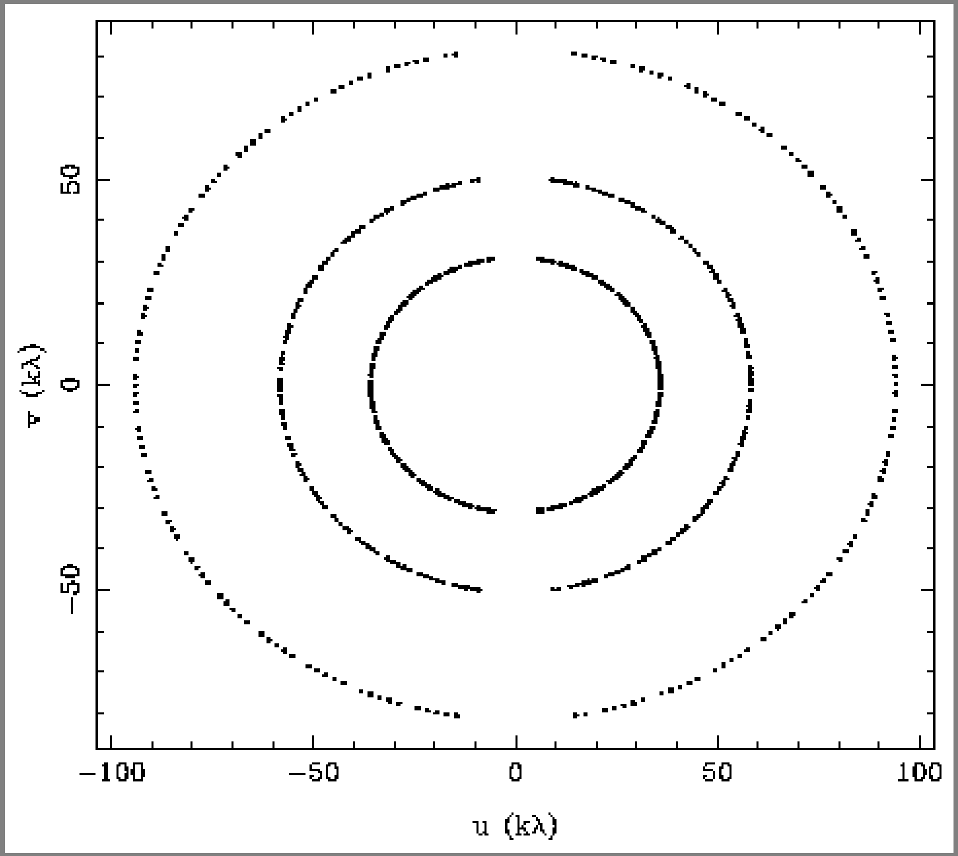


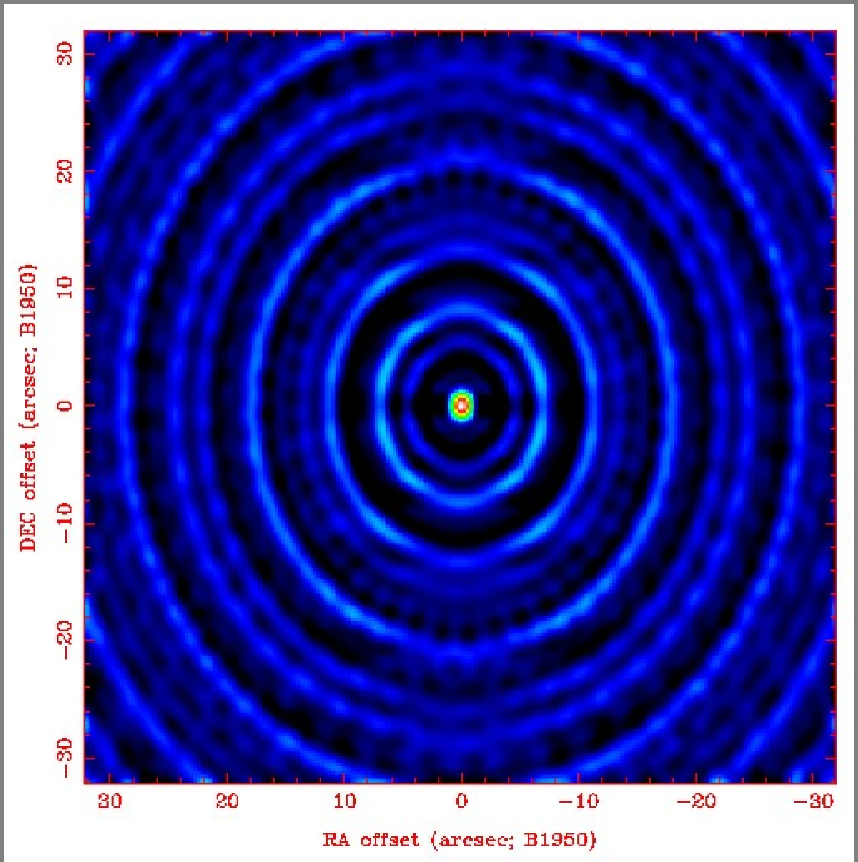
Very Large Array (VLA)

Note that the array is flat not curved like a mirror!

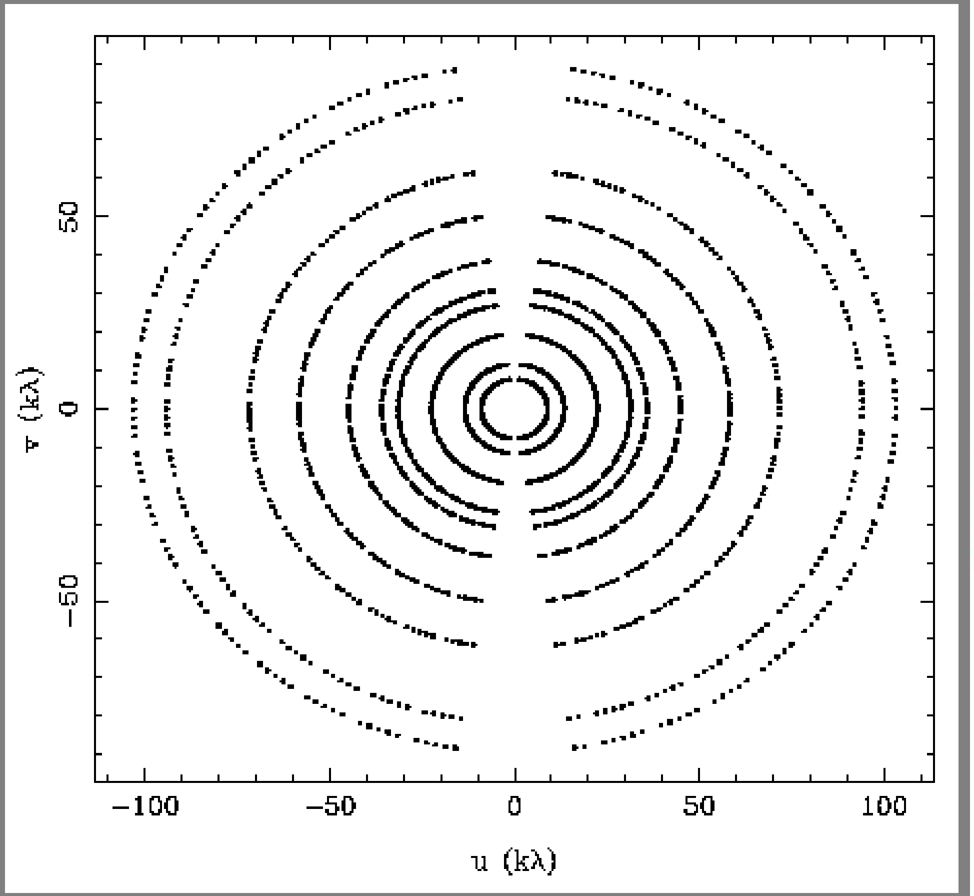
If there are gaps in the UV plane then the reconstructed image has artifacts

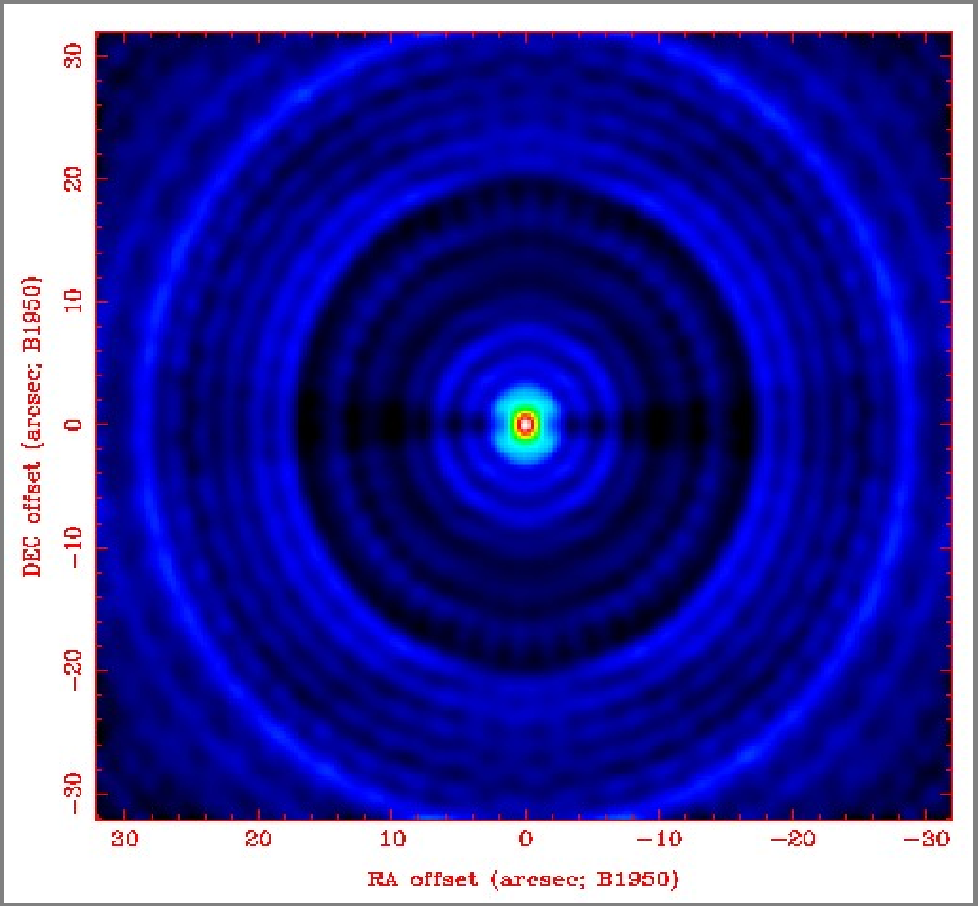
FT





Adding antennas can dramatically reduce the artifacts, adding 1 antenna adds N-1 new baselines!





- VLA observation of a point source
- Note the artifacts due to the finite number of antennas