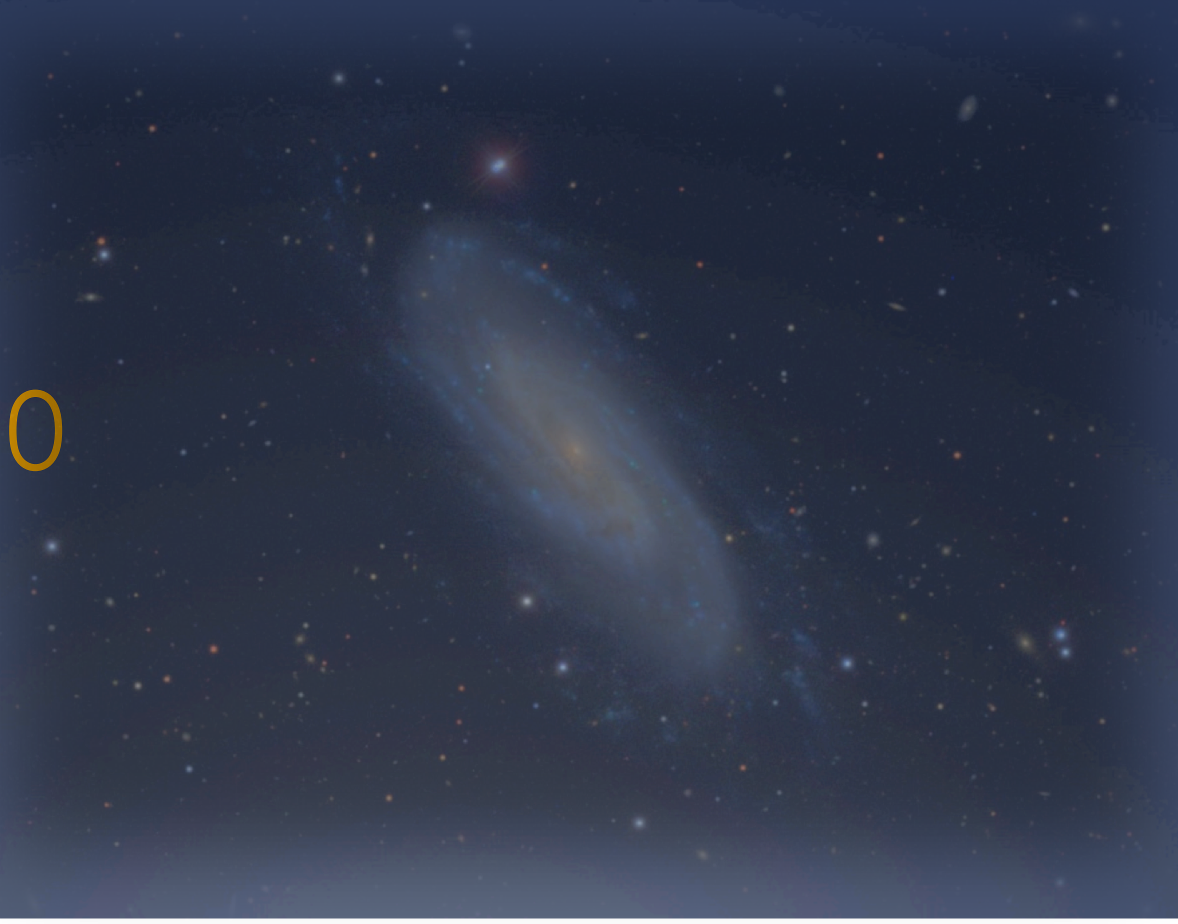
Astronomy 330

Lecture 12

13 Oct 2010

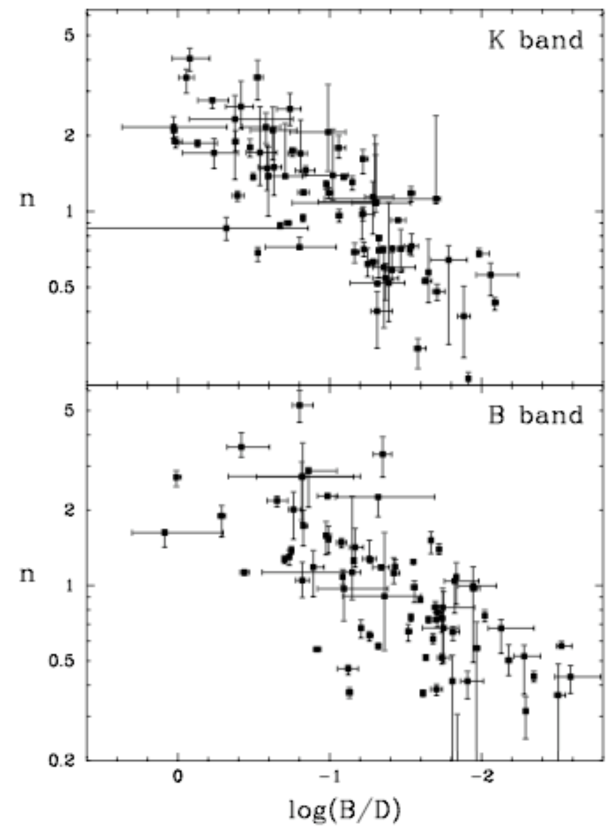


Outline

- Review: light profiles
  - Disk + bulge
  - Trends along the Hubble sequence
- Disk Kinematics in 3D
- Spiral arms and star-formation

Review: trends along Hubble Sequence

- Important structural parameters:
  - μ_0, h_R, n, B/D ratio
- Also gas and stellar content
- Early ➔ Late
  - Decreasing:
    - disk size (h_R), disk surface-brightness μ_0
    - B/D and bulge Sersic index n
    - Overall luminosity, rotation speed
    - metallicity, mean stellar age
  - Increasing:
    - gas content
    - star-formation (per unit mass)
    - disk thickness
    - Lopsidedness, asymmetry (*i.e., irregularity!*)



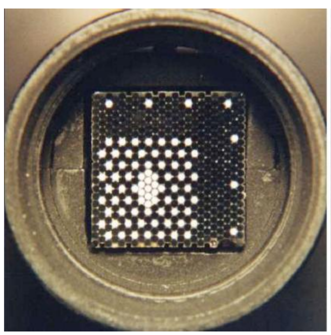
Graham 2001, AJ 121, 820

Disk Galaxy Kinematics: 3D

- From easy to hard:
  - Ionized gas kinematics based on centroids of the optical emission lines ([OII], [OIII], Hα).
  - HI kinematics based on radio interferometric studies.
  - Stellar velocity fields and dispersions largely based on centroids and widths of stellar absorption lines.
    - We'll come back to this.

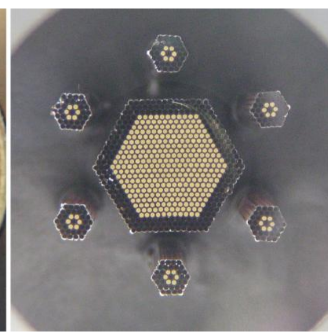
Disk Galaxy Kinematics: 3D

- Optical fibers and image slicers… integral field units (IFU)
  - ….feeding conventional long-slit spectrographs…
  - ….have opened up 2D mapping of disk velocities (3D data = data cube).
- Data cubes:
  - Once only the domain of radio astronomy, where we could probe only neutral or molecular gas
  - We can now probe ionized gas and stars, much more quickly.
- *Why bother with radio ??* Here's just one of several critical reasons:



- WIYN 3.5m/ SparsePak FFU
- 82 fibers, 4.”7 diameter
- 72” FOV
- $\lambda/\Delta\lambda$ = 11,000

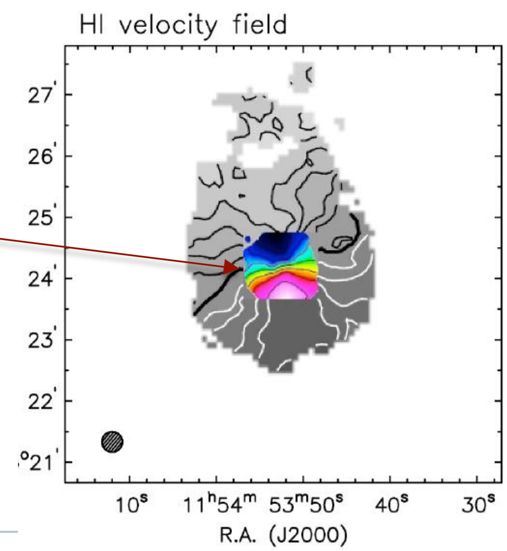
(Bershady et al.'04,'05)



- Calar Alto 3.5m / PPak IFU
- 331 fibers, 2.”7 diameter
- 75” FOV
- $\lambda/\Delta\lambda$ = 8000

(Verheijen et al.'05)

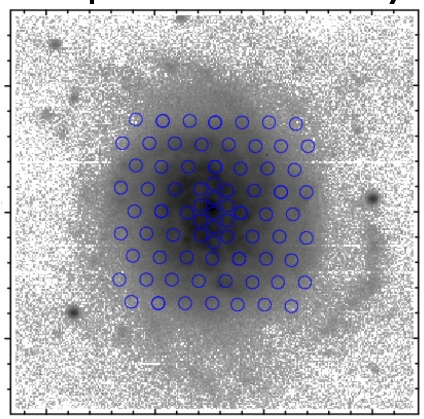
Hα

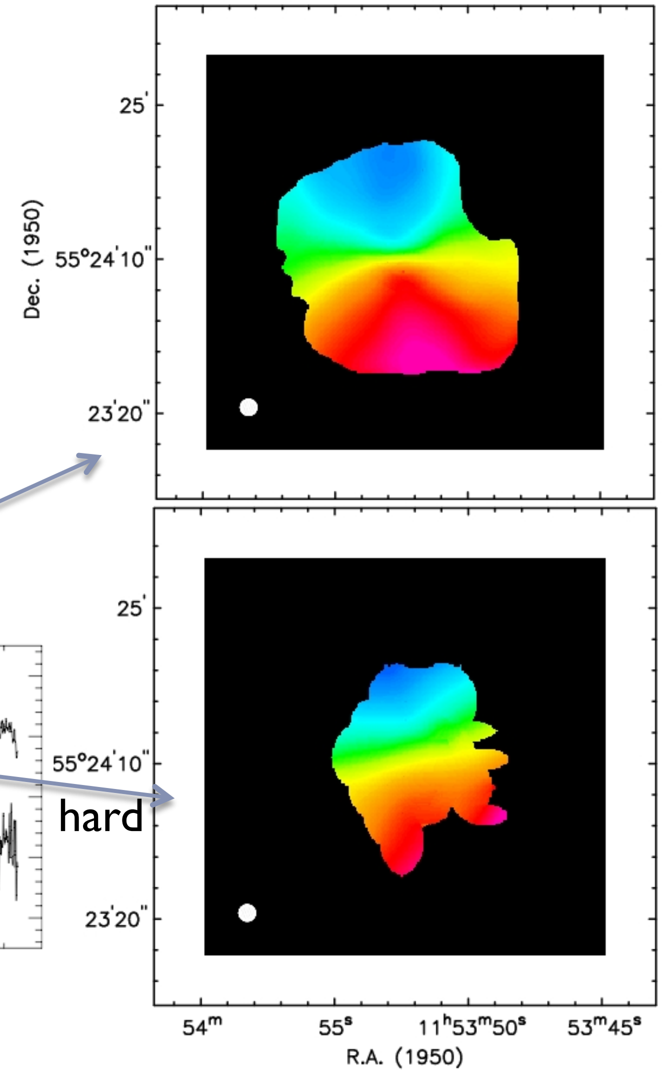


Disk kinematics: UGC 6918 = NGC 3982

i=26 ± 2°
B-R=1.0
B-K=3.25
h_R=0.94 kpc
$\mu_B(0)$=19.3
M_B=-19.3

SparsePak overlay



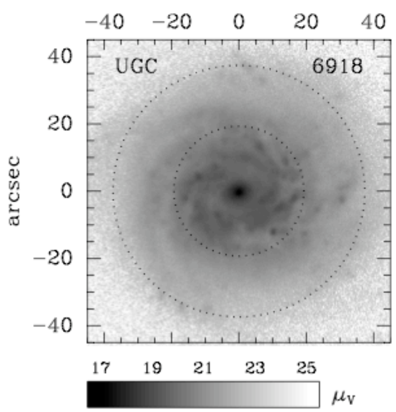


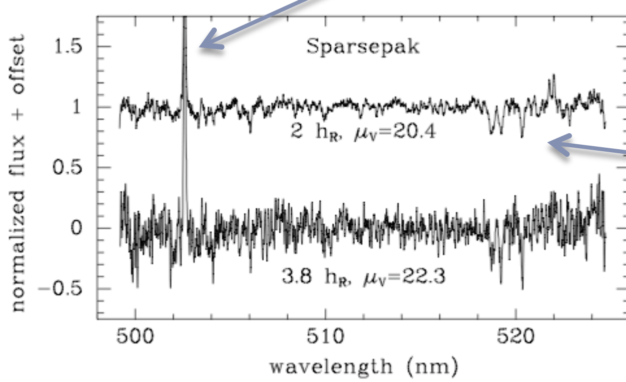
gas

stars

easy

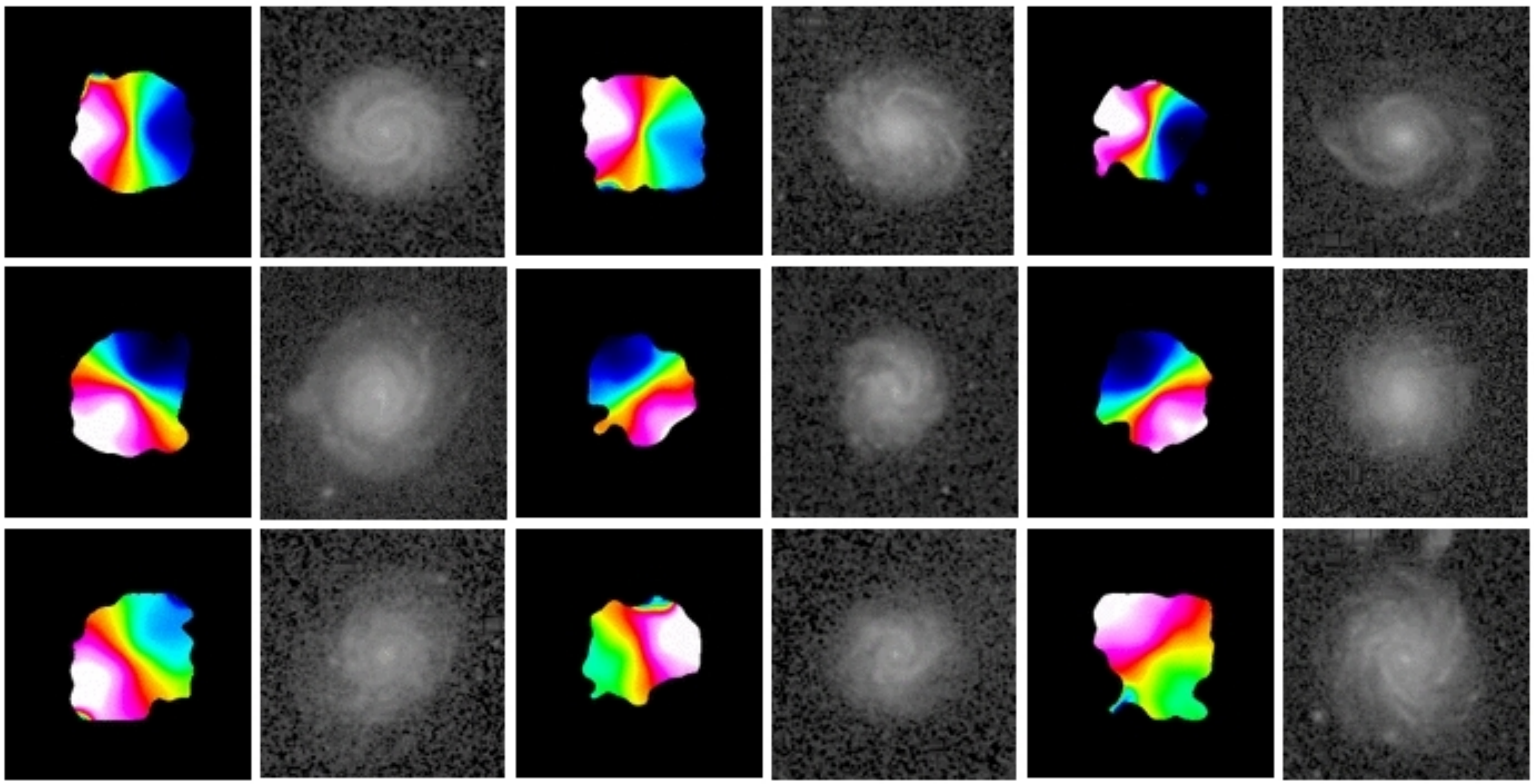
hard





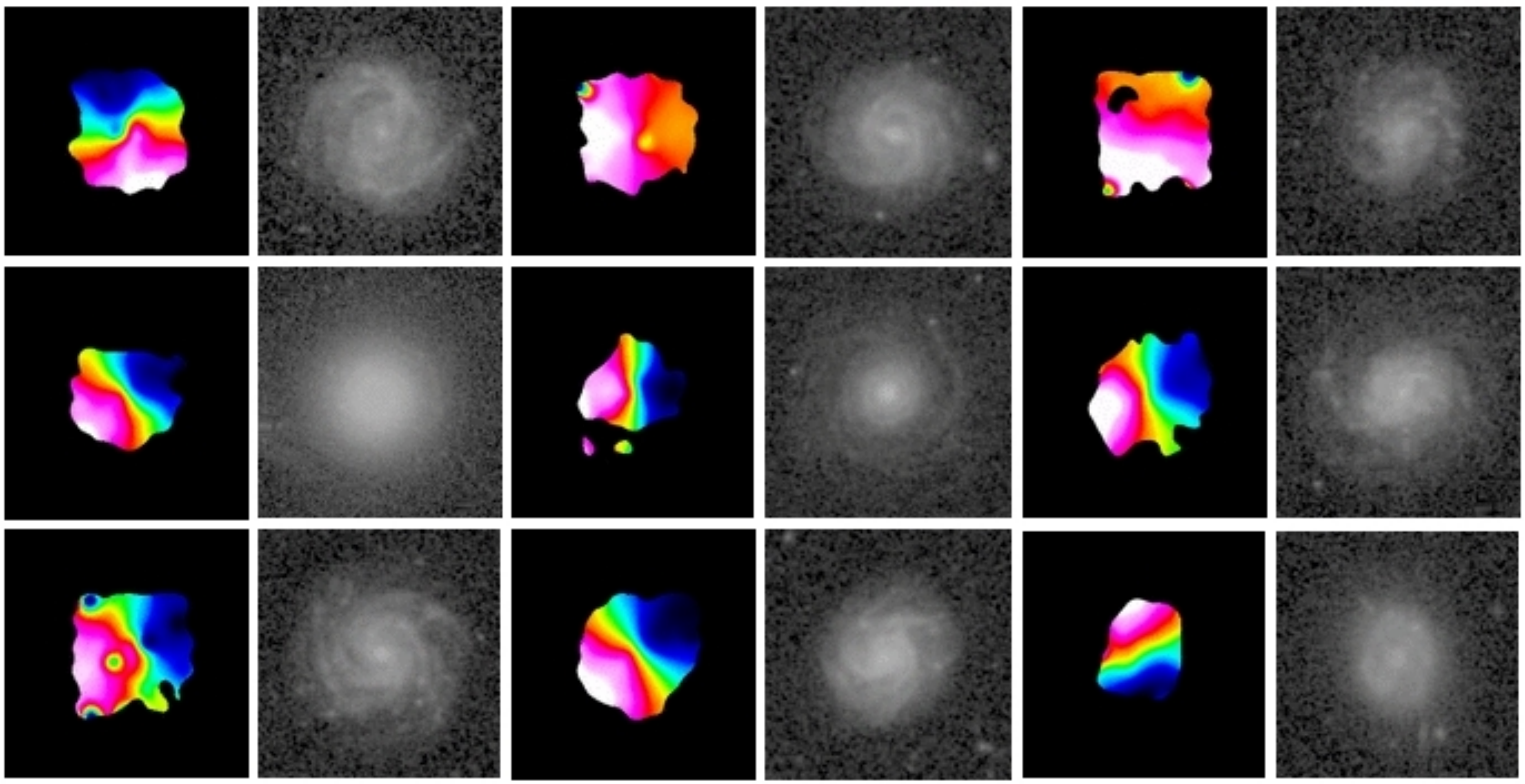
Symmetric, normal galaxies

WIYN/SparsePak Hα velocity fields



Bi-symmetries and Asymmetries

WIYN/SparsePak Hα velocity fields



This is easy: 1hr in bright-time on a 3.5m telescope

Radio Telescopes

Single dish: Green Bank

Interferometers: VLA

HI Kinematics of Disk Galaxies

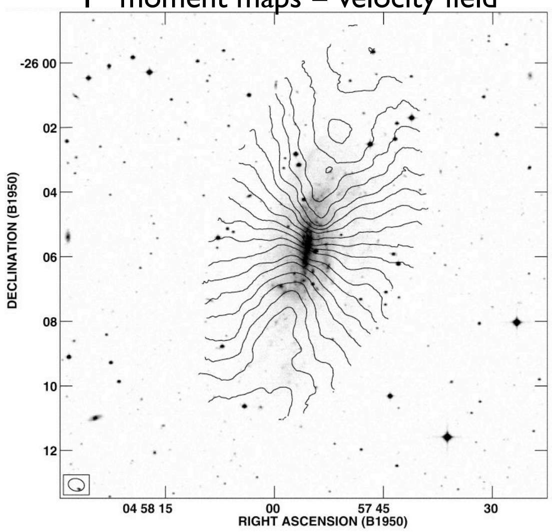
- Until the last decade, this has been the only source of bi-dimensional kinematics of external galaxies.
- Interferometric observations yield a 3-dimensional map (a data cube) of the distribution and kinematics of HI
  - ➔ x,y,z (RA, DEC, velocity).
    - Moment 0 = total intensity (integrate over v)
    - Moment 1 = velocity field (mean velocity as function of position)
    - Moment 2 = velocity dispersion
    - etc. (skew, kurtosis)

  - These concepts are generic and apply to all line data, e.g., optical emission lines, stellar absorption lines.
  - HI data cubes take 10's of hours to collect on the world's biggest interferometers.

HI spider diagrams

Moderate inclination:

1^{st} moment maps = velocity field

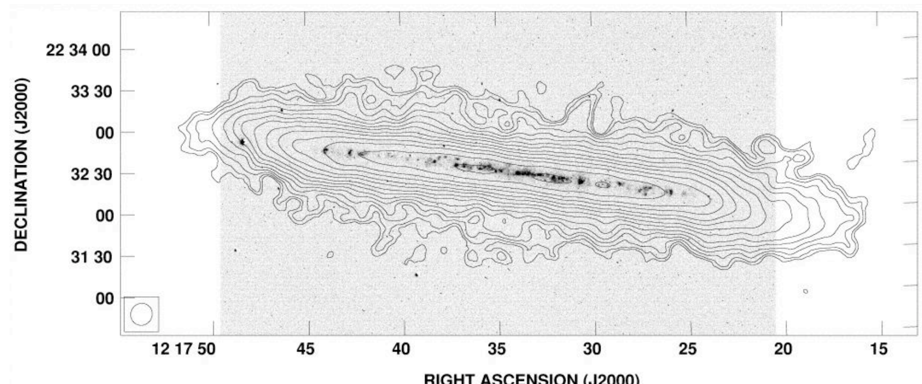


NGC 1744

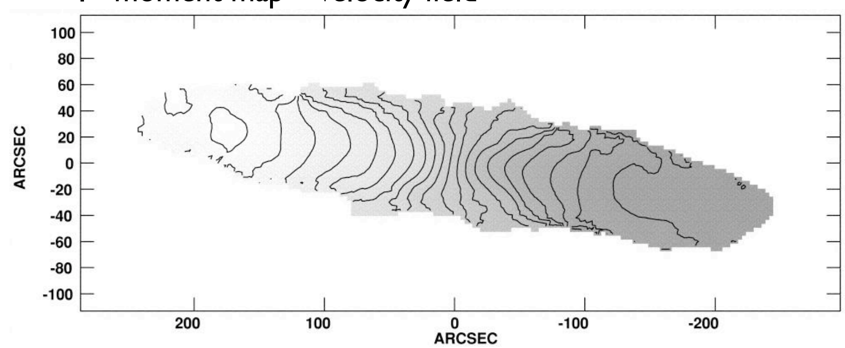
Highly inclined:

Note beam size relative to optical structure.

0^{th} moment map superimposed on optical image.
Beam-smearing is an issue at the mid-plane.



1^{st} moment map = Velocity field

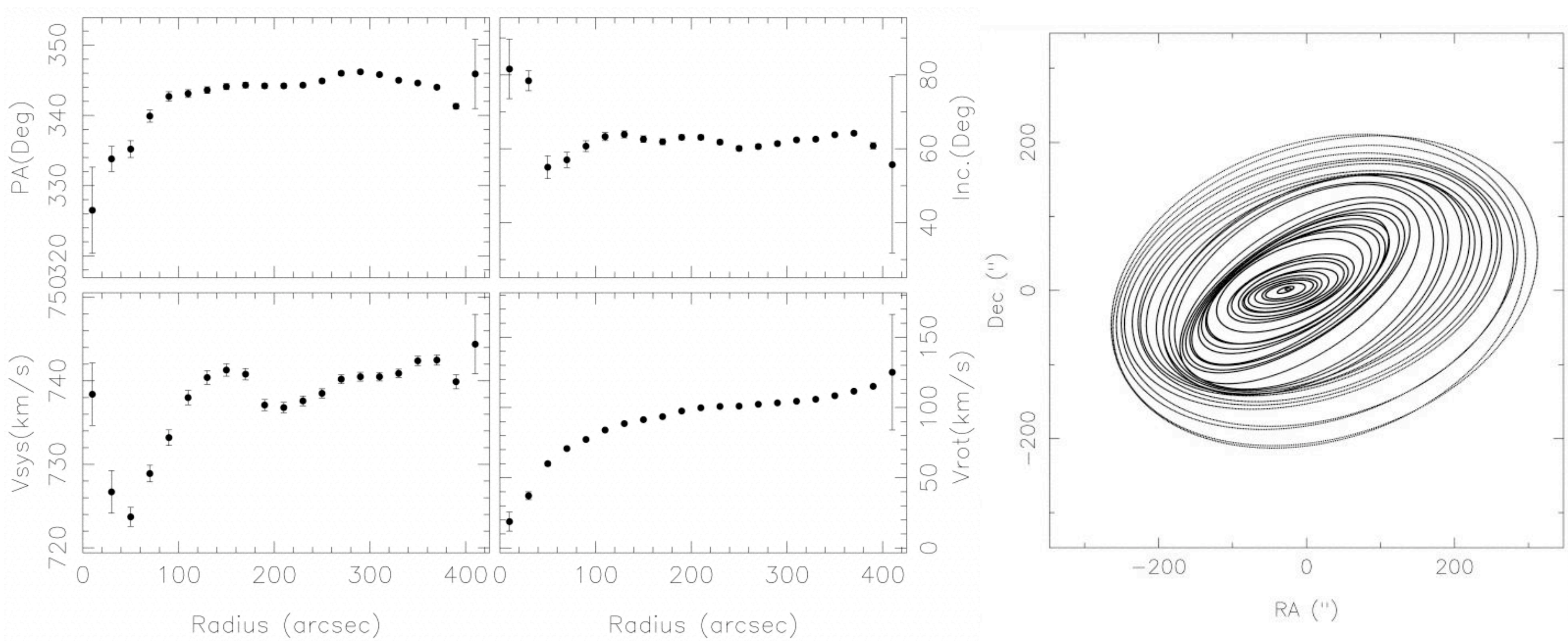


Deriving the rotation curve

- We only measure the radial velocity (i.e. velocity along the line of sight). How do we translate this into a velocity field?
- Components
  - Systemic velocity (e.g. Hubble flow)
  - Inclination, *i*, (i.e. if its face-on we see no rotation)
  - Azimuthal angle ϕ (from the major axis)
  - $V_c = V_{SYS} + V(R) / (\sin i) (\cos \phi)$

Deriving the rotation curve

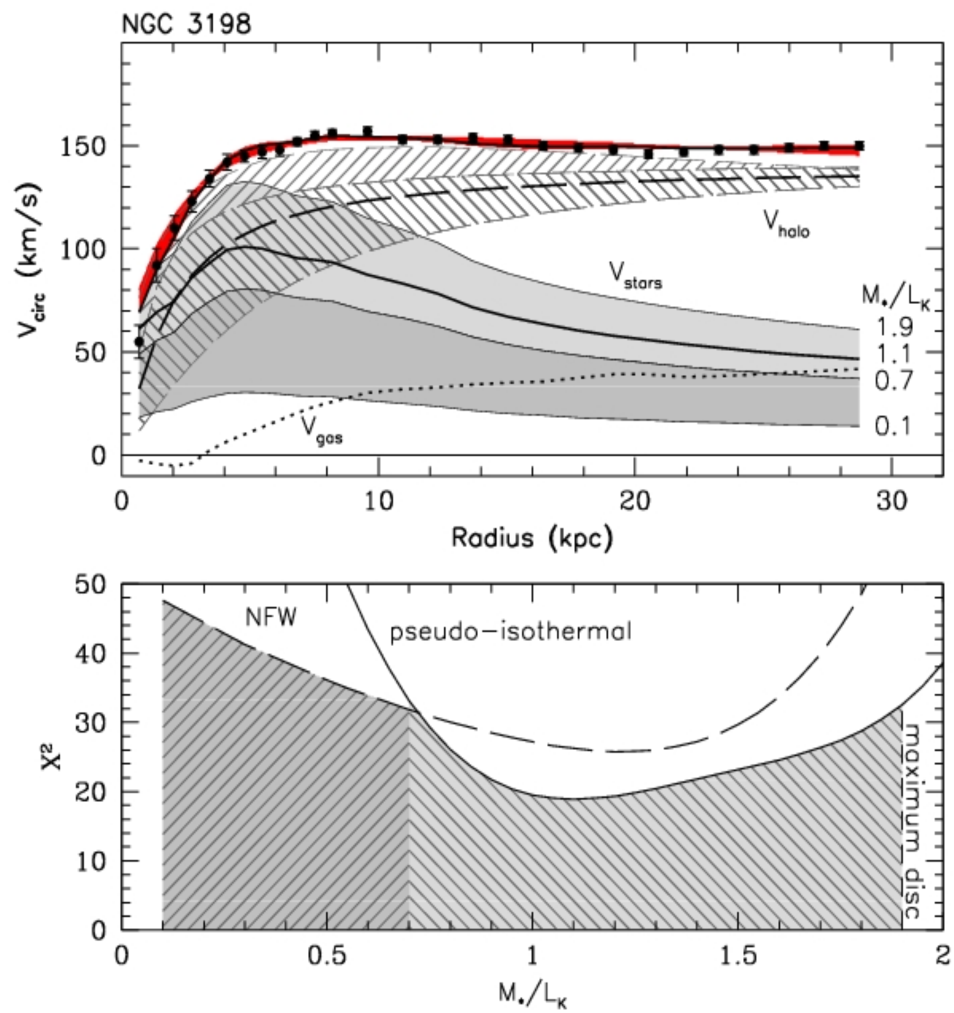
- Tilted ring models allow you to fit the circular velocity, inclination, position angle as a function of radius.



NGC 1744

Deriving the rotation curve

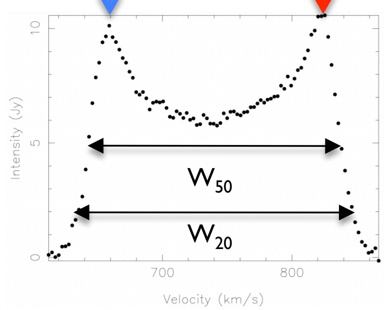
- But it's still just a rotation curve, degenerate to disk+halo, good for estimating total mass only.



Surrogates measures of rotation

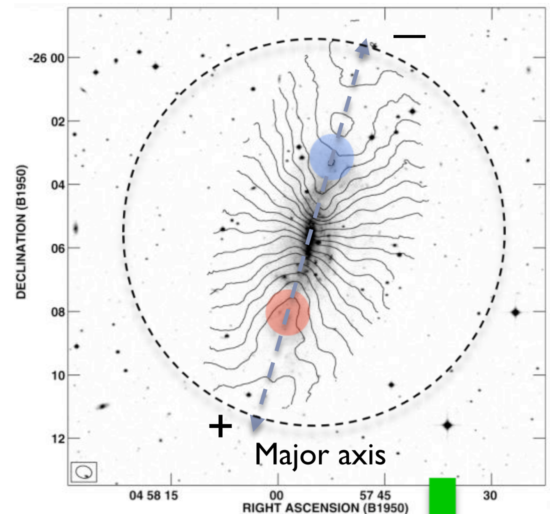
- Spatial information vs sensitivity:

4. Single dish (fiber):
Line width W ~ 2 V_c



1. Interferometer/IFU:

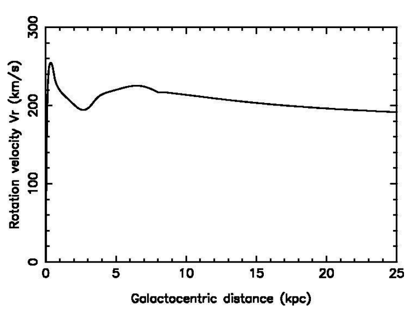
→ Velocity field
2D map of velocities,
or data cube

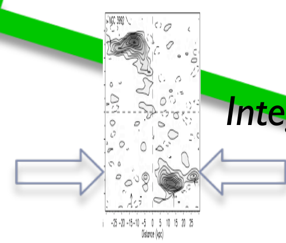


2. Position-velocity diagram (PVD):
Equivalent to long-slit spectrum

Slice down the major axis

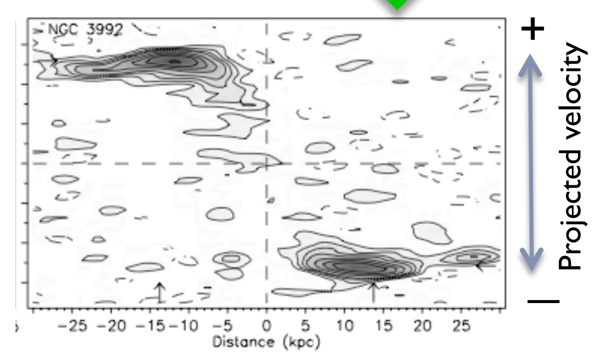
3. Rotation curve





Integrate in x (and y)

Flip (in V) and fold (in x)



Major axis

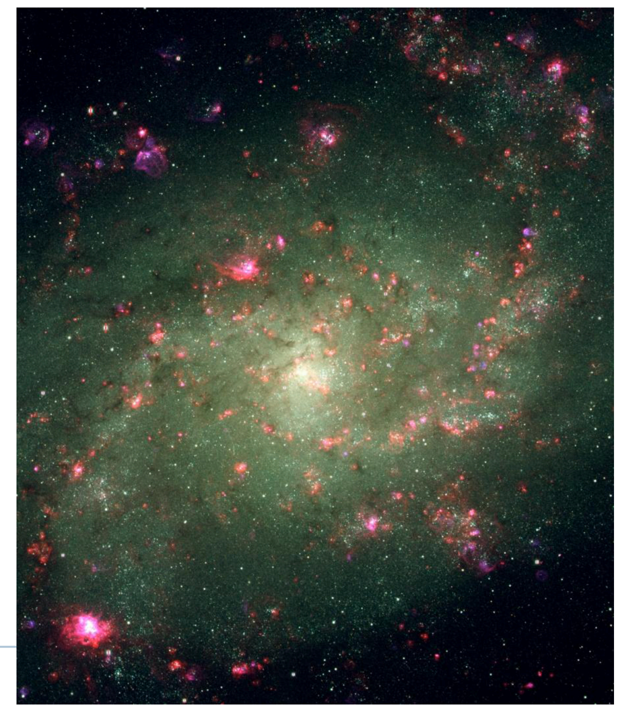
Spiral arms

- Recall Hubble's classification criteria
  - Openess of arms
  - Resolution of arms into "stars"
  - Bulge/disk ratio
    - **Sa** - tightly wound, large b/d ratio, some gas, steeply rising rotation curves
    - **Sb** - intermediate
    - **Sc** - open spiral arms, lots of substructure, small bulge, lots of gas, slowly rising rotation curves, lots of HII regions
    - **Sd** - no bulge, open arms, lots of HII regions
    - **Sm** - lopsided (like LMC)

Spiral sequence

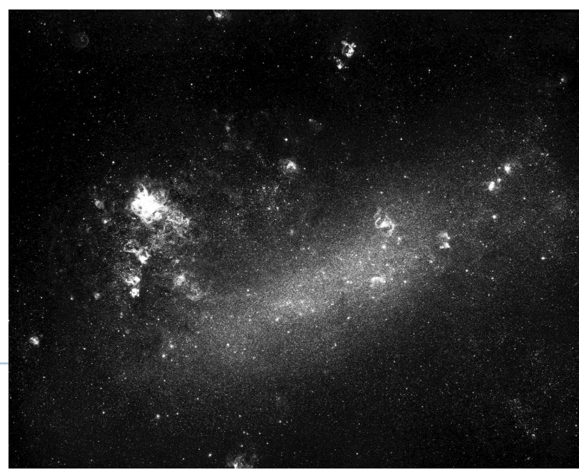
Sc
M101

Sb
M31



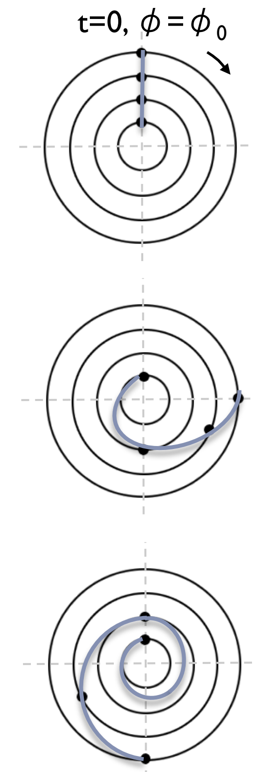
Sd
M33

Sm
LMC



Spiral arms: winding problem?

- Assumptions:
  - Start with an arm as a straight radial strip at $t = 0$ and $\phi = \phi_0$.
  - Pattern speed of arm is locked to the rotation of the disk: $\omega_p = \omega(R)$.
  - Disk rotates with $\omega(R) = V(R)/R \neq$ constant
  - In general $V(R) \sim$ constant over most of the disk.
  - ➔Within a few $\langle t_{dyn} \rangle$, arms wrap up
    - Recall $t_{dyn} \sim T/4$
    - For $V = 220$ km/s, $R = 8.5$ kpc… $T = 2.4\text{x}10^5$ yr



Winding problem resolutions

- There is likely no one solution, so the situation is complicated:
  - Arms are constantly regenerated.
    - Transient phenomenon (interactions?)
    - Star-formation generated/stochastic wave
      - Might be a suitable explanation for flocculent spirals
  - Kinematic wave:
    - Nesting of oval orbits (see S&G Figure 5.29)
    - Still a winding problem, but twice as slow as for case where $\omega_p = \omega(R\ \omega(r)$.
      - Might be suitable for spirals in gas-free disks
  - "Density wave" arising in the gravitational potential
    - Stars and gas gravitational attraction offset kinematic wave from winding up by making $\omega_p(R)$ = constant.
    - Disk stability must be low:
      - $Q = (\sigma_R \kappa)/3.36\pi G \Sigma \sim 1$ ratio of kinetic : potential energy

Random motions Epicyclic frequency Disk mass surface-density

Density waves

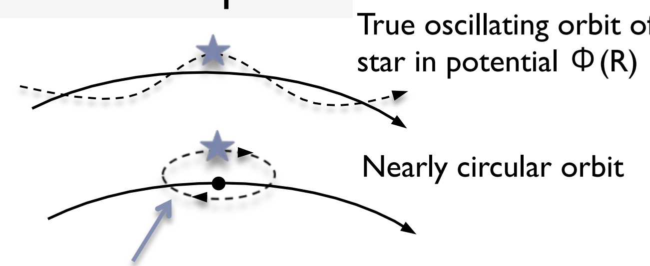
- Epicycles: stars oscillations (random motions) about circular orbit described as elliptical epicycles with frequency κ .
  - $\kappa^2(R) = -4B(R)\,\omega(R)$
  - B = (Oort's constant)

- Spiral is strengthened when
  - $m|\omega_p - \omega(R)| < \kappa(R)$
  - m = number of arms

- Continuous wave propagates only between inner and outer Linblad resonances:
  - $\omega_p = \omega(R) - \kappa/m$ (ILR)
  - $\omega_p = \omega(R) + \kappa/m$ (OLR)

- Co-rotation (CR): $\omega_p = \omega(R)$

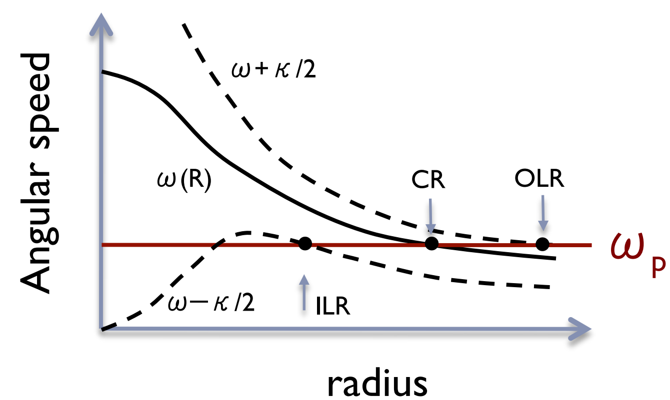
In the disk plane:



Epicycle describing apparent stellar motion from the frame of the LSR – circular orbit with angular speed $\omega(R)$.

There's also a component out of the disk plane (z) -- not relevant here.

Schematic for m=2:



Beginning and end of spirals arms indicate location of resonances

Star formation

- Basic raw materials:
  - Molecular mass at some critical density
    - recall instabilities to gravitational collapse: the Jean's length
  - Spiral arms collect gas into shocks, accelerating collapse
- On a large enough scale, clouds should make stars according to the initial mass function (IMF) and do so largely in clusters
  - there are interesting deviations from this

- Whatever factors give rise to spiral structure, this is where most of the star-formation occurs.
- What we do see: Massive stars and the effect of their radiation
- What we don't see (directly): low-mass stars
  - How can we detect them?

Stopped here

Tracers of massive stars: UV to Mid-IR

- UV luminosity
  - Directly traces the massive stars and their supply of ionizing photons
  - Susceptible to extinction!
  - Requires UV telescope (GALEX)
- Emission lines arising from ionized gas
  - Not as susceptible to extinction (at least Hα)
  - Measures the number of recombinations = number of ionizing photons = number of massive stars
- Warm Dust
  - Photons warm surrounding dust ➔dust reradiates in sub-mm and far-IR (based on properties of dust: T and composition)
  - Unaffected by extinction (it *is* the extincting material!)

Tracers of massive stars: radio continuum

- Continuous radiation from free electrons (free-free emission)
  - Depends on electron density ρ_e
  - ρ_e depends on number of ionizing photons and number of massive stars
    - Unaffected by extinction
- Radio synchrotron emission
  - Massive stars explode ➔ expanding shocks accelerate particles to relativistic velocities ➔ combine with magnetic field ➔ synchrotron emission
    - Indirect measure of number of Sne
- The Far-IR/Radio continuum correlation:
  - Massive stars warm dust ➔ Far-IR
  - SNe accelerate cosmic rays ➔ radio continuum
    - But this hasn't really been demonstrated and
    - Implies a fixed fraction of SNe energy is converted into cosmic rays

Tracers of star formation

- Is any one better than the others?
  - Depends on redshift
  - UV hard to measure at low redshift
    - not visible from ground
  - H α hard to measure at high redshift
    - moves into NIR where sky is bright
  - Sub-mm sensitivity and radio continuum sensitivity isn't what it needs to be for high-redshift measurements

- Primary limitations are two-fold:
  - Only measures the number of massive stars (those massive enough to emit lots of ionizing photons)
  - No single tracer can be used well over broad range in redshift