Astronomy 330

Lecture 11

08 Oct 2010

Outline

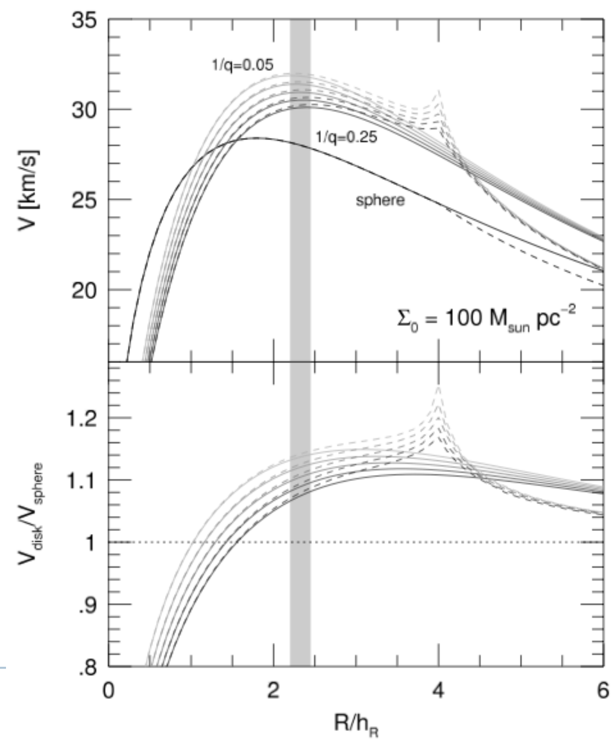
- Review: disk potentials & rotation curves
  - Disk-halo degeneracy
- Characteristics of dynamical systems
- Disk Galaxies
  - Structural properties
  - Kinematics

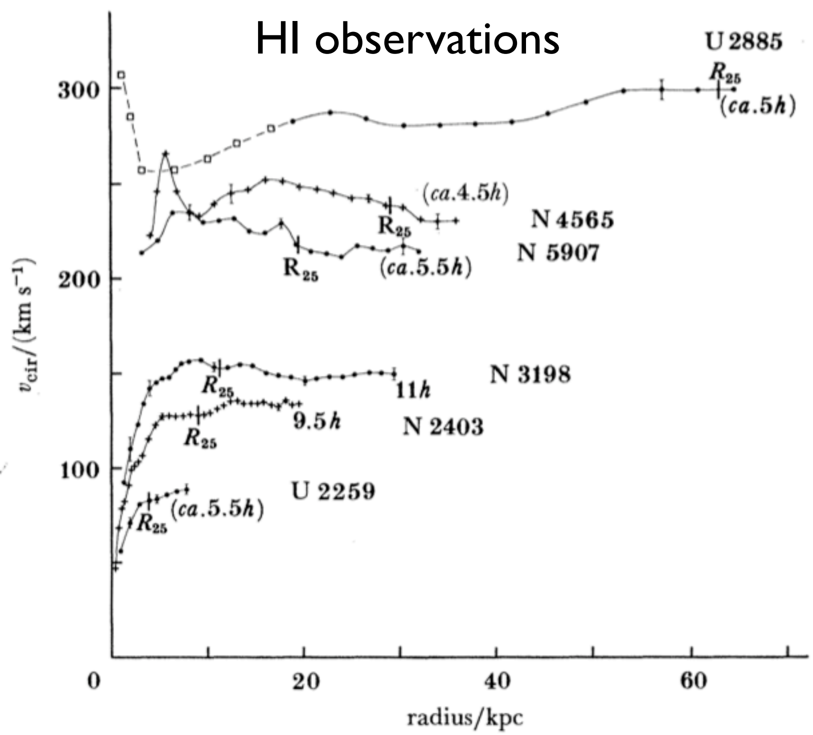
Review: rotation curves

- Recall: flattened potential of double exponential disk does *not* give flat rotation curve
- spiral galaxies *have* flat rotation curves ➔ dark halo
  - $\rho_{halo}(r)$: pseudo-isothermal or NFW, go as $1/r^2$ for large r

Disk density:
$\rho(r,z) = \rho_0 \exp(-r/h_R) \times \exp(-z/h_z)$

Disk oblateness:
$q \equiv h_z/h_r$



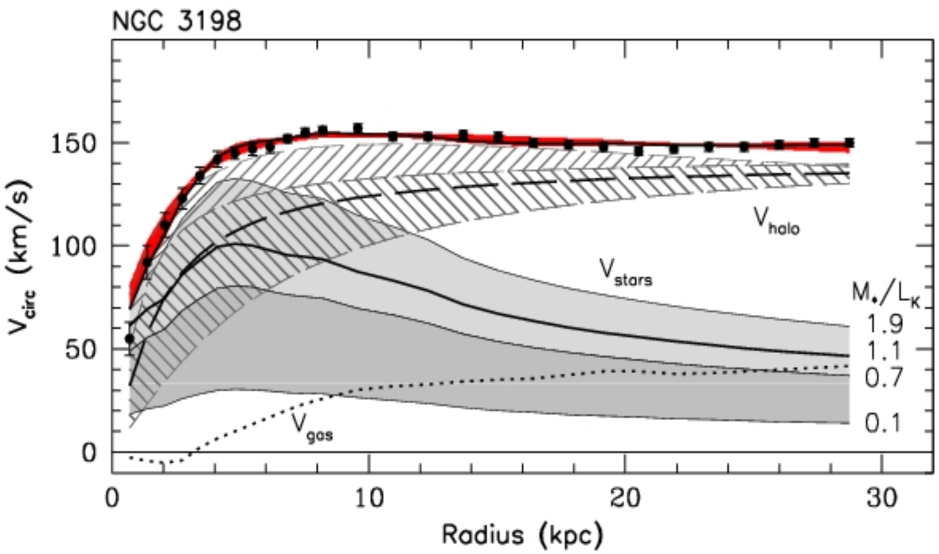


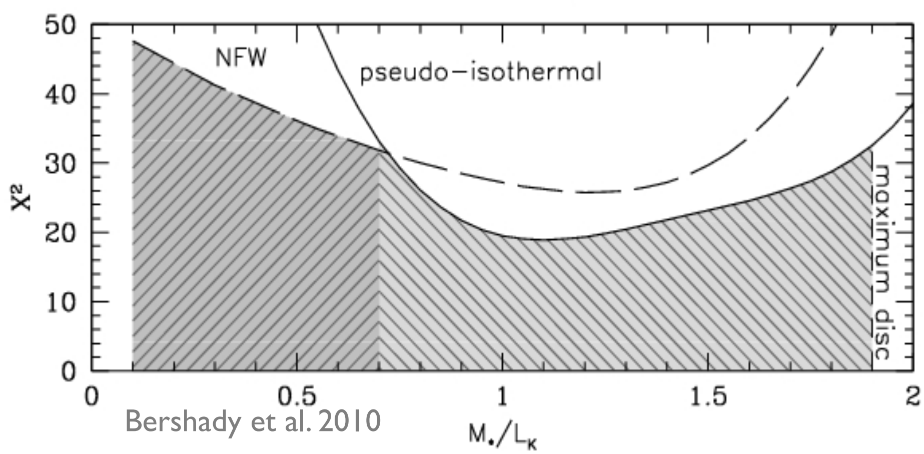
The Disk-Halo Degeneracy

- **Q:** Is it possible to decompose the rotation curve of a spiral galaxy into disk, bulge, and halo components?
  - Estimate individual components $v_{c,i}^2$ constrained by $v_c^2 = \Sigma_i v_{c,i}^2$
- **A:** *No; Solutions are degenerate*
- Degeneracies:
  - Unconstrained fitting functions for halo:
    - e.g., pseudo-isotherm. vs NFW
  - Disk M/L (Υ_{disk}) uncertain
    - Stellar populations Υ_*: depends on SFH, IMF, and detailed knowledge of all phases of stellar evolution.
    - ISM
      - Gas
        - Atomic: straightforward to measure
        - Molecular: harder to measure
      - Dust: probably insignificant
    - Dark matter?
  - Non-circular motions
- However, it is possible to set upper-limits on the disk (so-called maximum disks)

The Disk-Halo Degeneracy: best case

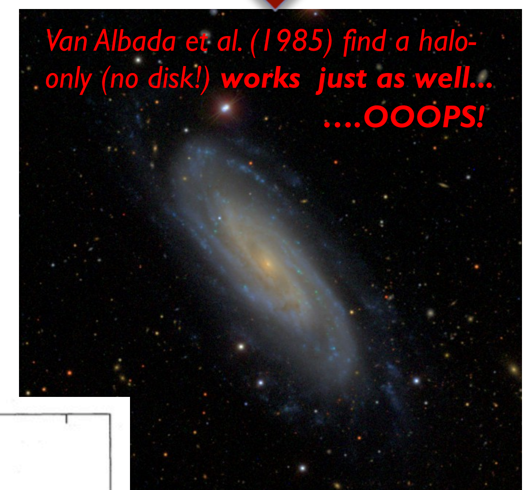
- Rotation curve decomposition constraints:
  - Maximum disk - *yes*   Minimum disk - ***NO***



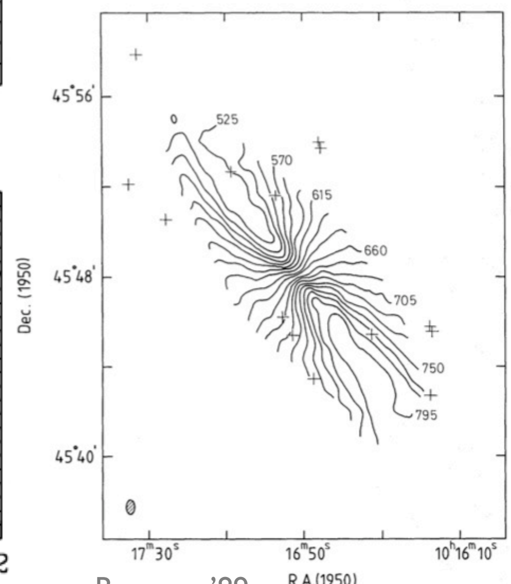


Bershady et al. 2010

← *Degenerate solutions…*



SDSS gri



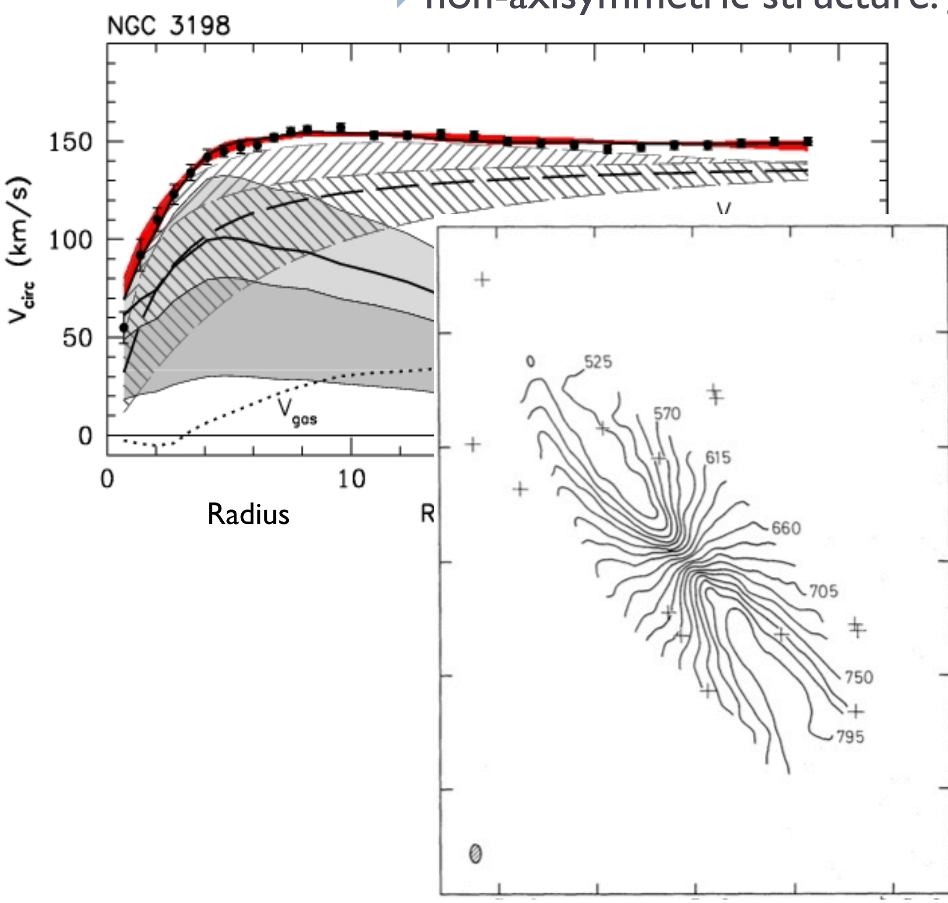
Begeman'89

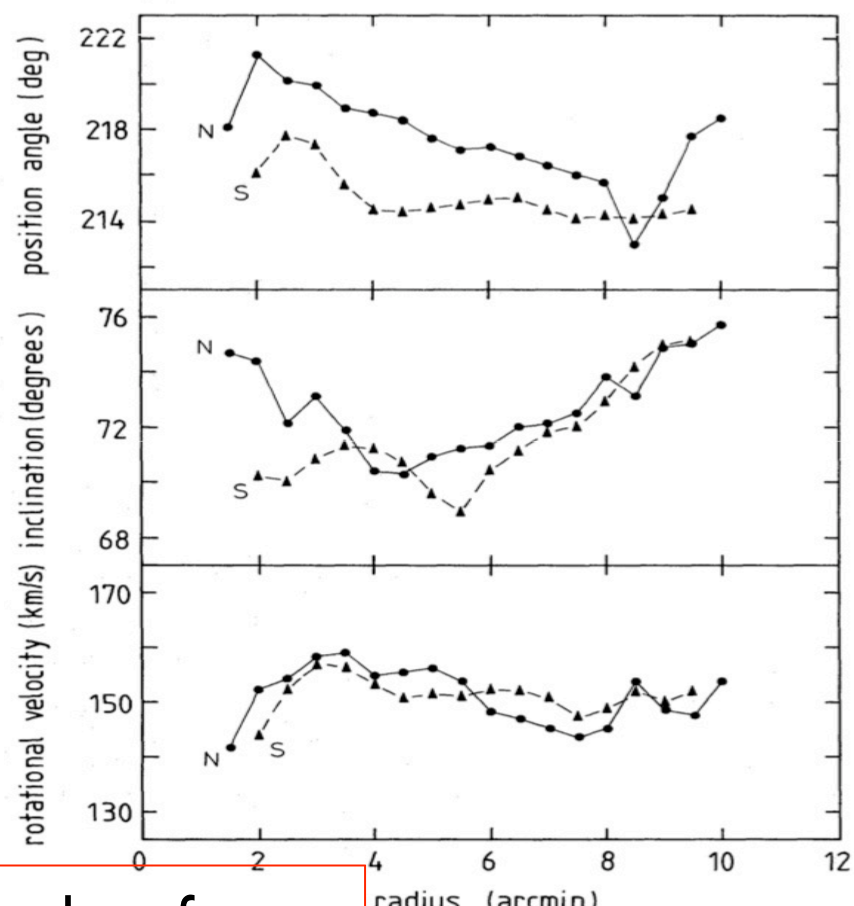
…it doesn't get better than this

←HI velocity field

The Disk-Halo Degeneracy: Best case

- Formal χ^2 not meaningful at level of ΔV_{circ}<5 km/s
  - non-axisymmetric structure: gas-flows, arms, winds, etc.





Begeman'89

➔ So we need another dynamical probe of mass

Characteristics of dynamical systems - 1

- Summary:
  - $v_c \equiv \sqrt{(r\, d\Phi/dr)} = \sqrt{(GM(r)/r)}$, circular velocity
  - $v_e \equiv (2|\Phi|)^{1/2}$, escape velocity
  - $t_{dyn} \equiv \sqrt{(3\pi/16G\rho)}$
  - $t_{ff} \equiv \sqrt{(1/G\rho)}$, free-fall time $\sim t_{dyn}$
  - $t_{cross} \equiv R/v$, use characteristic radius and velocity

Characteristics of dynamical systems - 2

- Relaxation from N-body encounters of *stars*:
  - $t_s \equiv v^3 / (4\pi G^2 m_*^2 n)$, …time-scale for strong encounters
    - $\sim 4\times10^{12}$ yr $(v/10 \text{ km s}^{-1})^3 (m_*/M_\odot)^{-2} (n/1 \text{pc}^{-3})^{-1}$
    - ➔ unimportant except in very dense star systems
  - However, many weak encounters cumulate such that after a time t_{relax}, the amplitude of the perturbed motion of the star is comparable to its initial motion:
  - $t_{relax} \equiv t_s / 2 \ln \Lambda$
    - $\sim 2\times10^{12}$ yr $(v/10 \text{ km s}^{-1})^3 (m_*/M_\odot)^{-2} (n/1 \text{ pc}^{-3})^{-1} (\ln \Lambda)^{-1}$
    - where $\Lambda = b_{max}/b_{min} \sim R/r_s = N/2$ for isolated system of N stars
      - when $\frac{1}{2} N m_* v^2 \sim G(N m_*)^2/2R$ and $r_s = 2Gm_*/V^2$
    - $t_{relax}/t_{cross} \sim N / 6 \ln N/2$
    - Still very large for realistic N (10^{10} to 10^{11} for galaxies)

Characteristics of dynamical systems - 3

- Instabilities to collapse: the Jean's length
  - $c_s \equiv \sqrt{(k_B T / \mu m_H)}$
    - sound-speed for temperature T and mol. mass μm_H
  - $\lambda_J \equiv c_s\sqrt{(\pi/G\rho)} \sim c_s t_{ff}$
  - $M_J \equiv (\pi/6) \lambda_J^3 \rho = 20 M_\odot(T/10K)^{3/2}(100cm^{-3}/n)^{1/2}$

  - What this basically says is that regions smaller than the sound-crossing time have time to re-arrange their density structure in response to gravity, and hence are stable *against* gravitational collapse; larger structures are unstable to collapse.
  - It is relevant for setting the mass-scales for star-formation and galaxy formation.

Disk Galaxies

Disk Galaxies: distribution of starlight

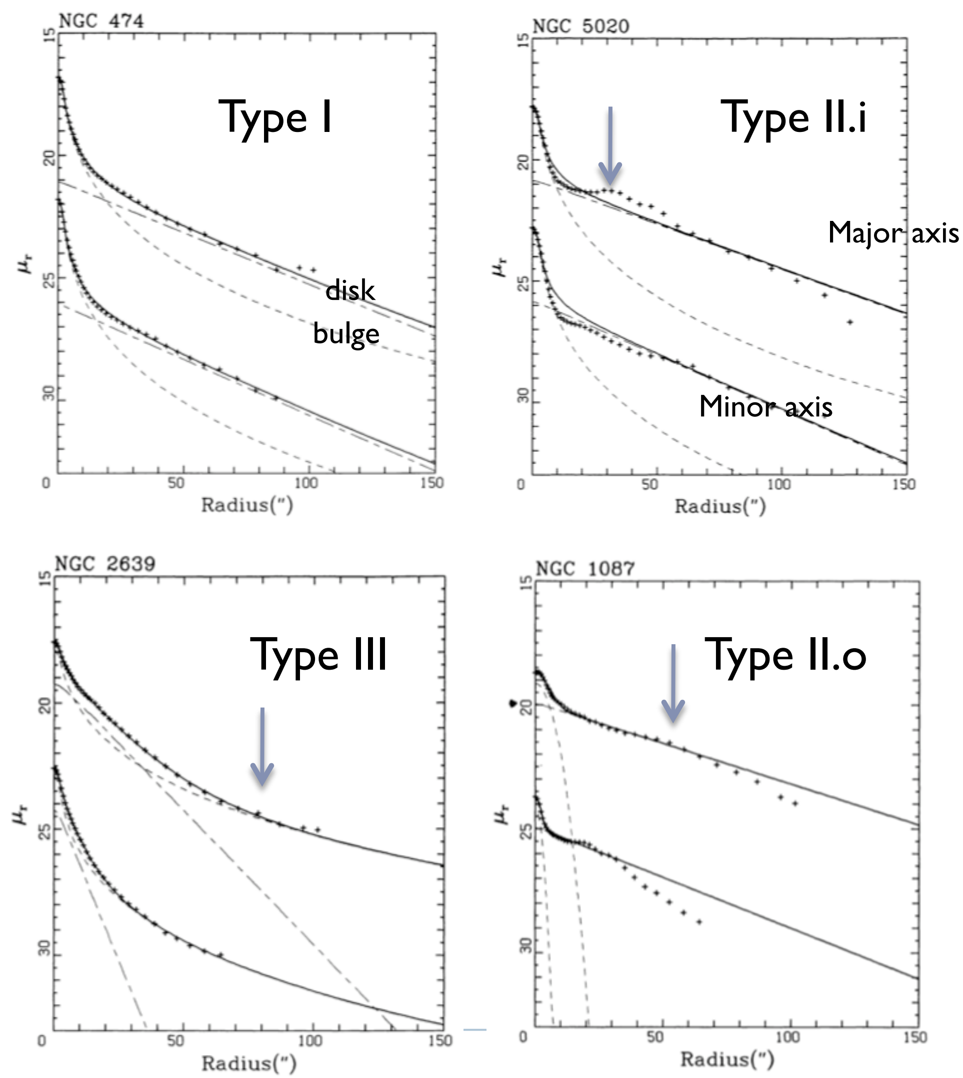
- De-composition of the light profile
  - Disk – generally fit with an exponential or two
    - $I(r) = I_0 e^{-r/hR}$
    - I_0= central surface brightness
    - h_R = scale length of the exponential
  - Bulge – generic function that goes as $r^{1/n}$
    - $I(r)=I_e e^{-k}$ where $k = b_n[(r/r_e)^{1/n} - 1]$
      - Sersic profile: n=4 fits many ellipticals; n=1 is exponential; n=1/2 is Gaussian
    - I_e= effective surface brightness, r_e= effective radius :
      - where half the total light is enclosed
    - $b_n \sim 2n - 0.33$ for $1<n<10$.
    - $n = 1.7 \pm 0.7$ (Balcells et al. 2003)
  - Halo
    - Doesn't contribute much light, treat as extension of bulge

Disk Galaxies: distribution of starlight

- Central surface brightness
  - Usually measured in mag arcsec^{-2} ($\mu = -2.5\log I + \text{const.}$)
  - *It is independent of distance!* (ignoring cosmological dimming)
- Freeman's law (1970): luminous spirals have nearly constant disk central surface-brightness:
  - μ_0 = 21.65 (*B*-band), 21(*R*-band), 20.65 (*I*-band) ± 0.65 mag arcsec^{-2}
    - Turns out to be a Malmquist-like bias; lower-luminosity systems have lower μ_0
- Central surface-brightness for bulges:
  - typically 10-100 times higher.
  - *Easy to see!*
- Bulge-to-disk (B/D) luminosity ratio a key parameter in describing disk-galaxies

Bulge/Disk decomposition

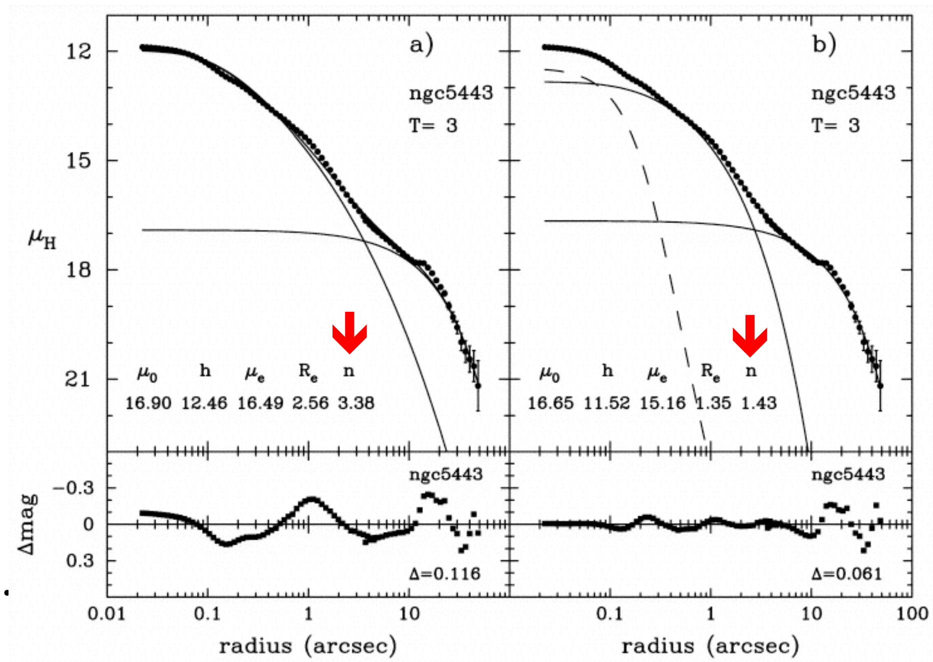
- Traditionally these have been done as 1D fits in radius (Kent 1985, ApJS, 59, 115) ➔
- Several distinct *disk* profile types:
  - Inner breaks (Freeman 1970)
    - Type I, II(.i)
  - Outer breaks (Erwin et al. 2006, Pohlen & Truillo 2006, A&A, 454, 759)
    - Type II.o, III
- Most disks show smooth exponential behavior between $1<R/h_R<4$
- Few extend far beyond $R/h_R=4$ *in starlight*



Bulge/Disk decomposition

- Recent work has focused on high-resolution in the NIR to probe bulge structure
  - HST H-band SB profile: NGC 5443 (Sb).
    - (a) Solid lines = Sersic bulge + exponential disk
    - (b) Adding central point source in leads to a better fit
    - ➔ n = 1.7±0.7
    - w/o central source, overestimate n.
    - *What is the cusp?*
- Bulges have near-exponential radial light-profiles, likes disks, but not highly flattened.
  - *Heated inner disks?*

Balcells et al. 2003



↓ core

$$\rho_{\text{pseudo-isothermal}}(r) = \rho_0[1 + (r/r_c)^2]^{-1}$$

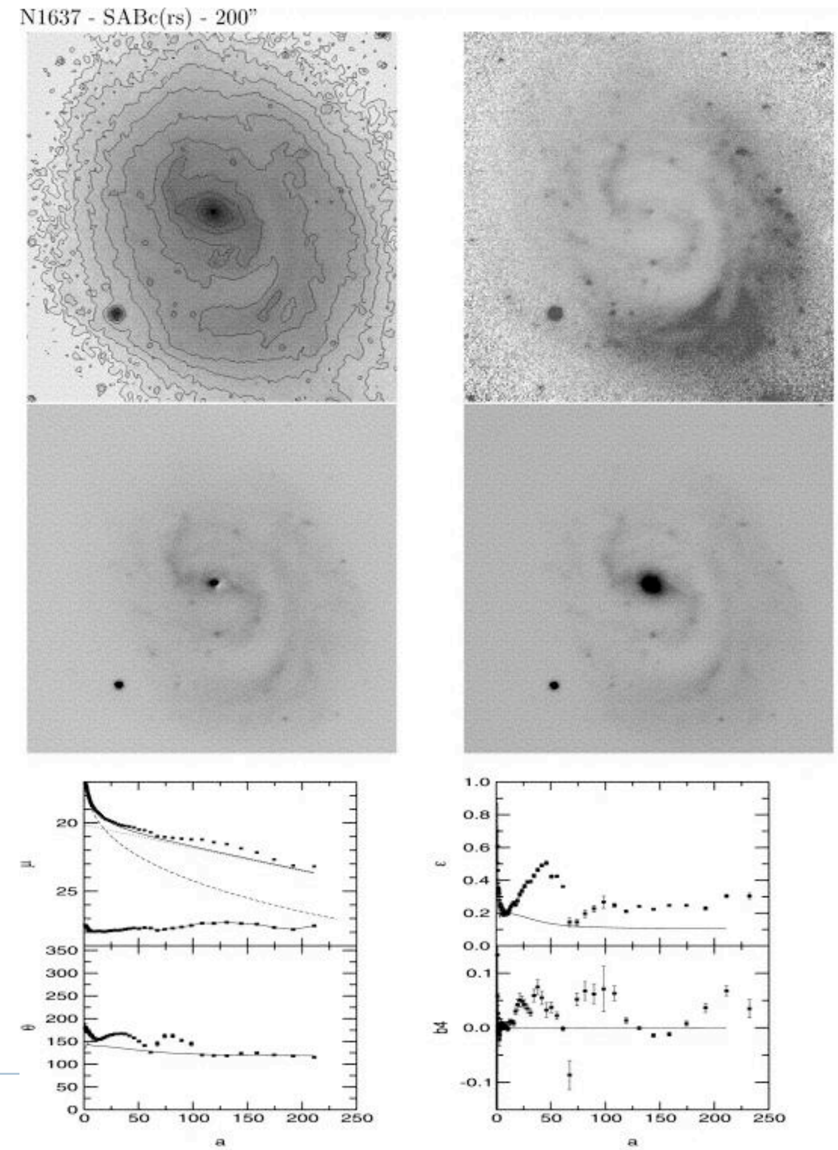
$$\rho_{\text{NFW}}(r) = \rho_n(r/a_n)^{-1}[1 + (r/a_n)]^{-2}$$

↑ cusp

Bulge/Disk decomposition

- Best modern methods do simultaneous fits of both *inclined* exponential disk and a Sersic-profile bulge in 2D
  - e.g., De Souza et al. 2004, ApJS, 153, 411
- Reveals wealth of residual structure:
  - Lopsidedness (m=1)
  - Bars, oval distortions (m=2)
  - spiral arms (m=2,3,…)

Fourier modes ↑



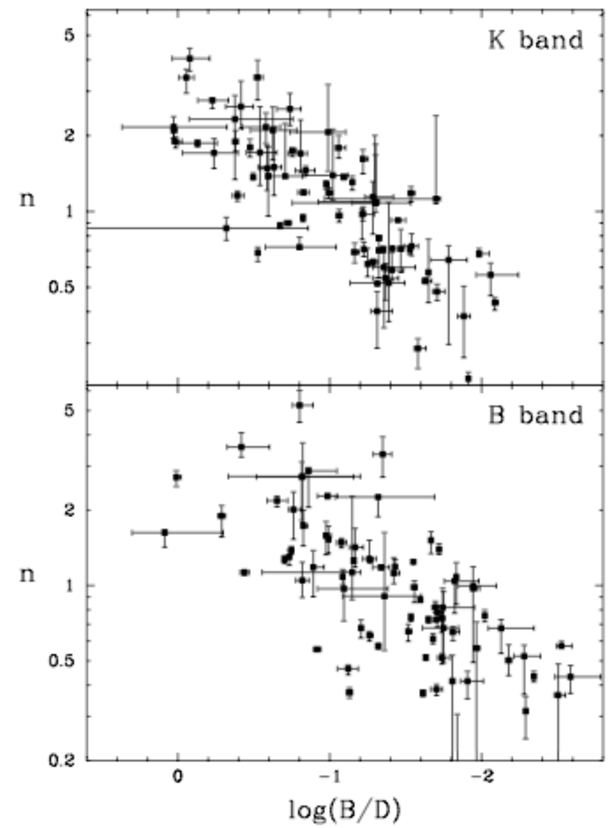
Oval distortions

- 50% of disk galaxies have some sort of oval distortion
  - (bar, linear structure, m=1 Fourier mode at center of galaxy):
    - stars and gas in largely radial orbits, precessing in phase.
  - More easily seen in red light (old stars), but often gas
- Outstanding questions:
  - *Are bars long-lived or short-lived phenomenon?*
    - Investigations of distant samples inconclusive.
      - e.g, Abraham et al. 1999, MNRAS, 308, 569
  - Do bars give rise to bulges?
    - e.g., pseudo-bulges (Kormendy & Freeman 2004)

NGC 1300

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

Trends along Hubble sequence

- Kent (1985) showed that light-concentration (C) and mean surface-brightness (μ_e) correlated with each other, B/D, and the Morgan spectral type.
  - ➔ Requires no B/D decomposition to characterize disk systems

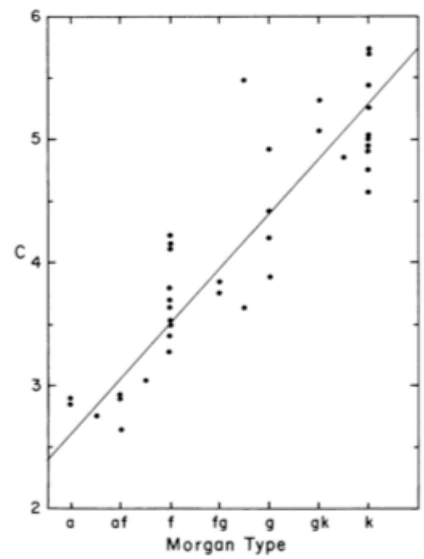


FIG. 9.—Correlation between concentration parameter c and Morgan type. The line drawn is an eyeball fit to the points.

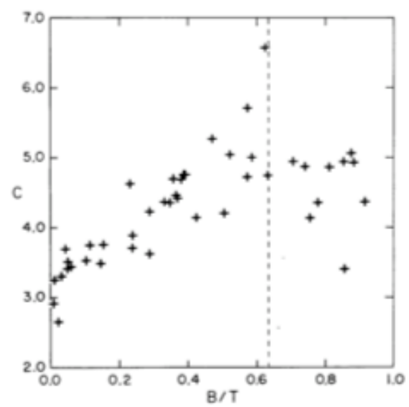


FIG. 10.—Correlation between concentration parameter c and B/T. Dashed line at $B/T = 0.63$ marks the point where bulge/disk decompositions become unreliable.

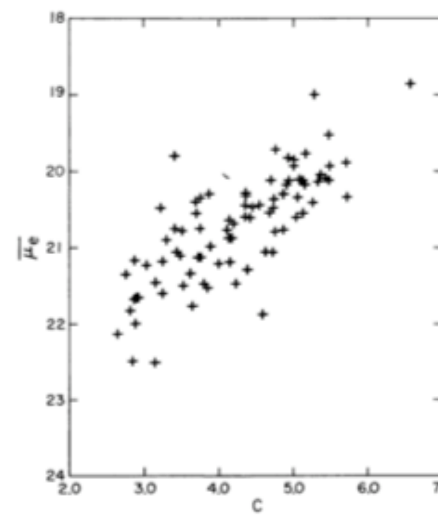
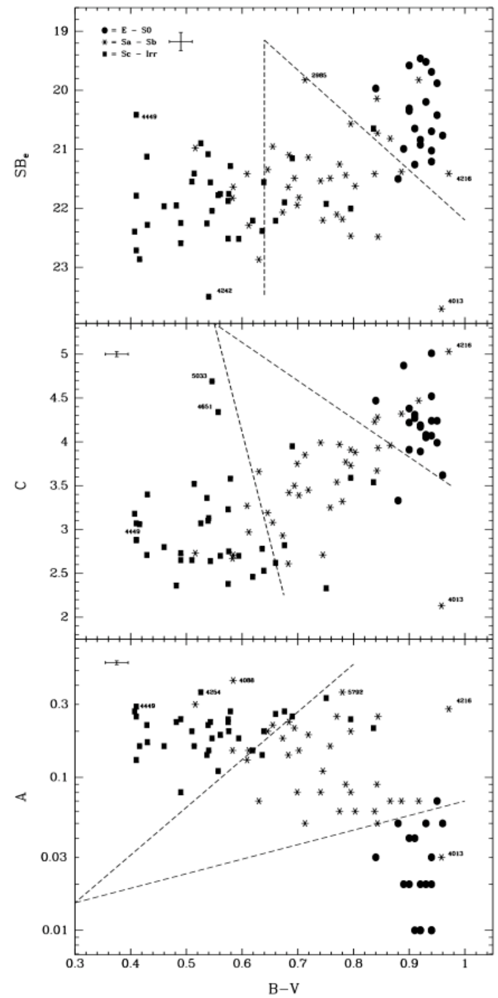
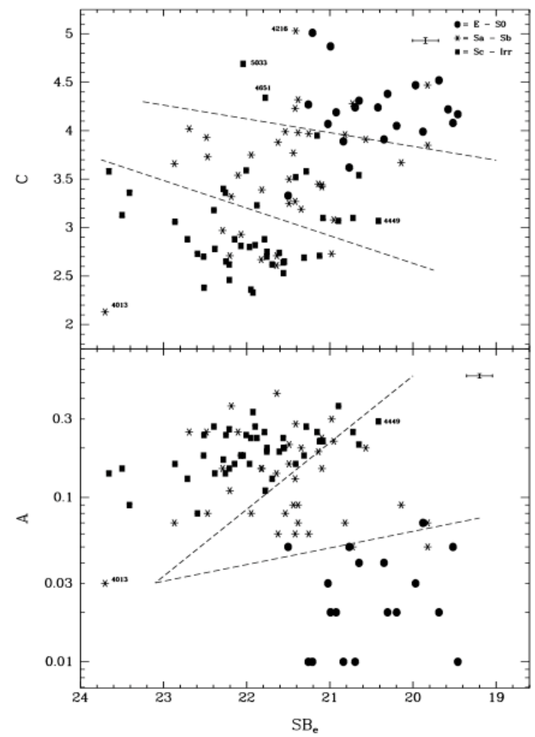


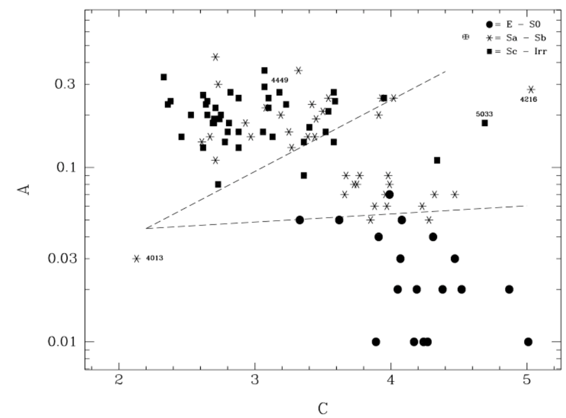
FIG. 12.—Correlation between mean surface brightness $\bar{\mu}_e$ inside effective radius r_e as a function of concentration parameter c.

Alternative classifications

Bershady et al. 2001
Conselice et al. 2001



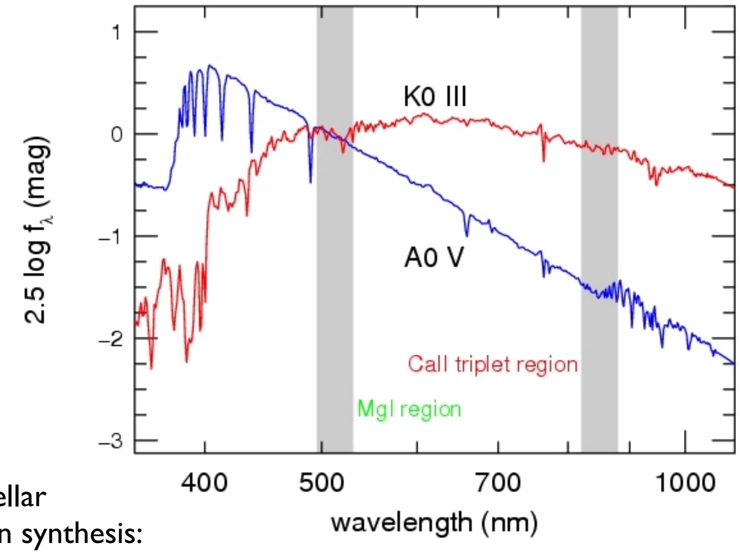




Mean surface-brightness (Sb$_e$= μ_e), image concentration (C) and asymmetry (A) correlate with color (stellar populations)

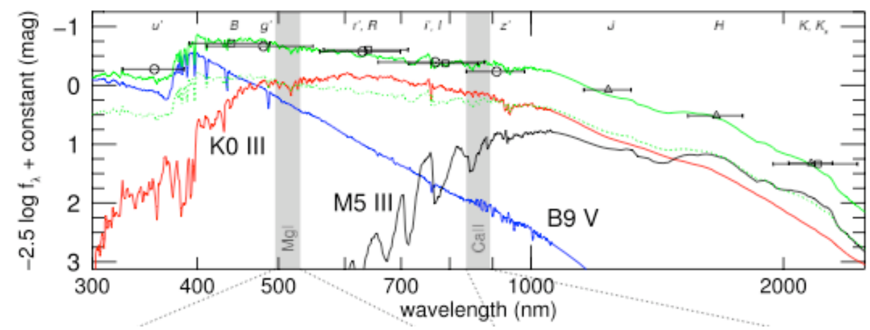
Optical vs NIR view

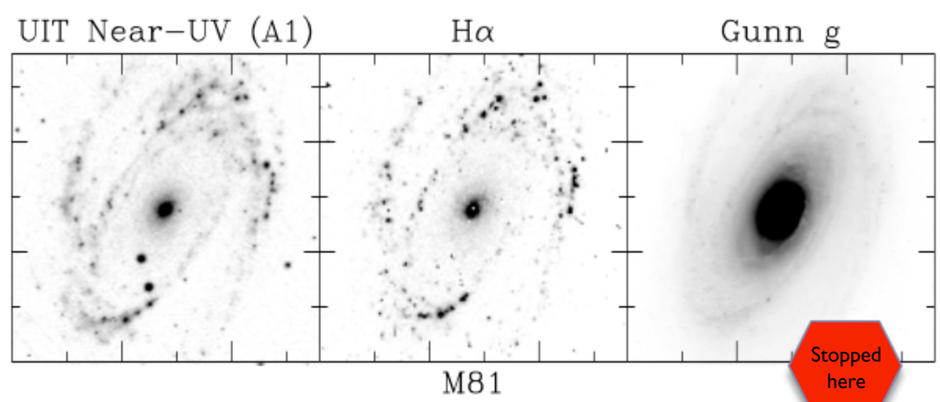
- Modern measurements
  - Digital detectors: CCDs or IR arrays
- Hot stars emit relatively little in the near-IR compared to cool stars of comparable total (bolometric) luminosity.
- Giant stars emit much of their radiation in near-IR
  - ➔ Galaxies appear less "splotchy" in the red and NIR because you see mostly the cool, older stars that are relaxed.
  - Effects of extinction mitigated:
    - $A \equiv -2.5\log(I_{obs}/I_{em}) = 1.065\ \tau$, where τ is optical depth, and goes as $\sim \lambda^{-1}$
    - more accurate view of the stellar distribution.



Simple stellar population synthesis: 2 and 3 star models

Aaronson 1980; Bershady 1995, 2010



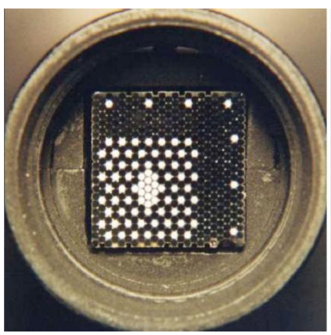


Disk Galaxy Kinematics: 3D

- From easy to hard:
  - Ionized gas kinematics based on centroids of the optical emission lines ([OII], [OIII], H α).
  - 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.

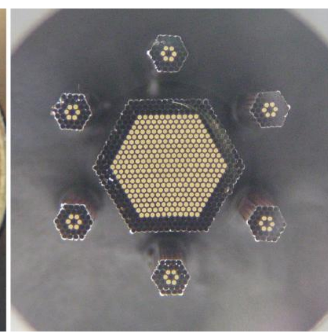
Disk Galaxy Kinematics: 3D

- Optical fibers and image slicers…
  - ….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

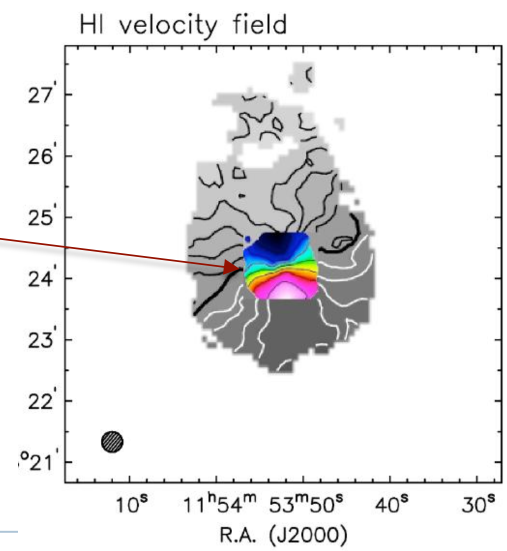
(Bershady et al.'04,'05)



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

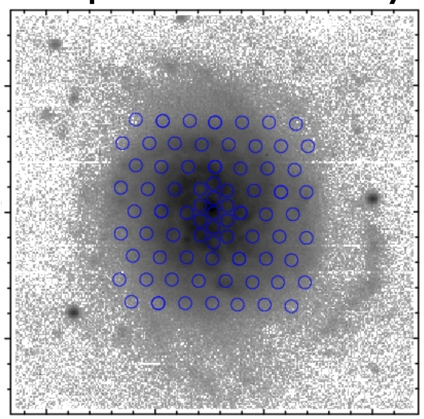
(Verheijen et al.'05)

Hα

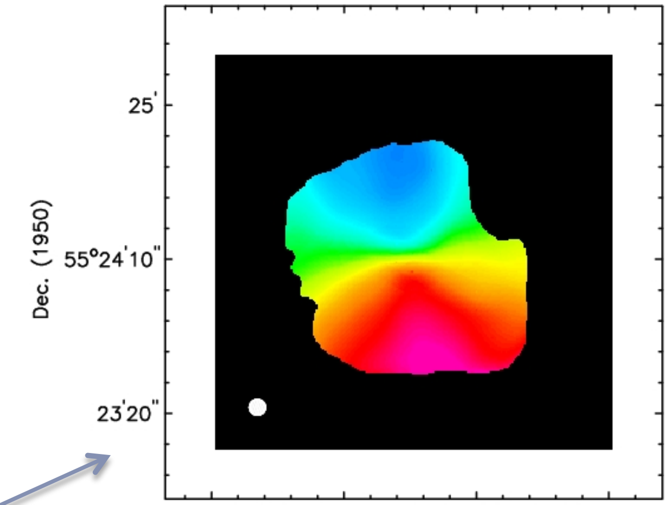


Disk kinematics: UGC 6918 = NGC 3982

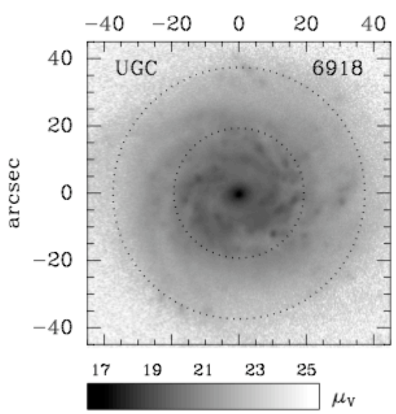
SparsePak overlay

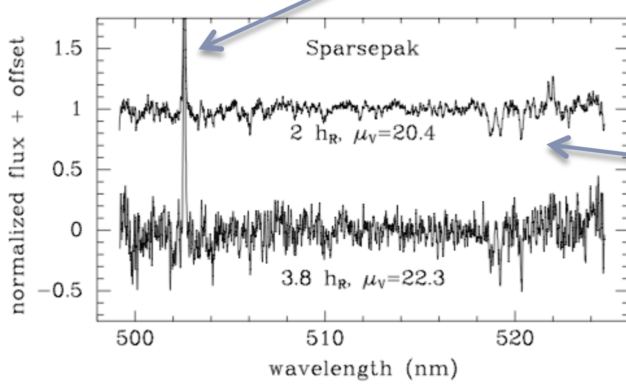


i=26 ± 2°
B-R=1.0
B-K=3.25
h_R=0.94 kpc
$\mu_B(0)$=19.3
M_B=-19.3



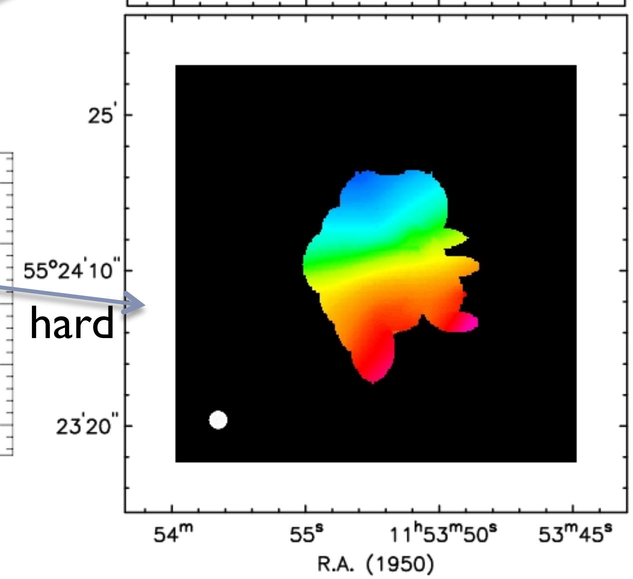
gas





easy

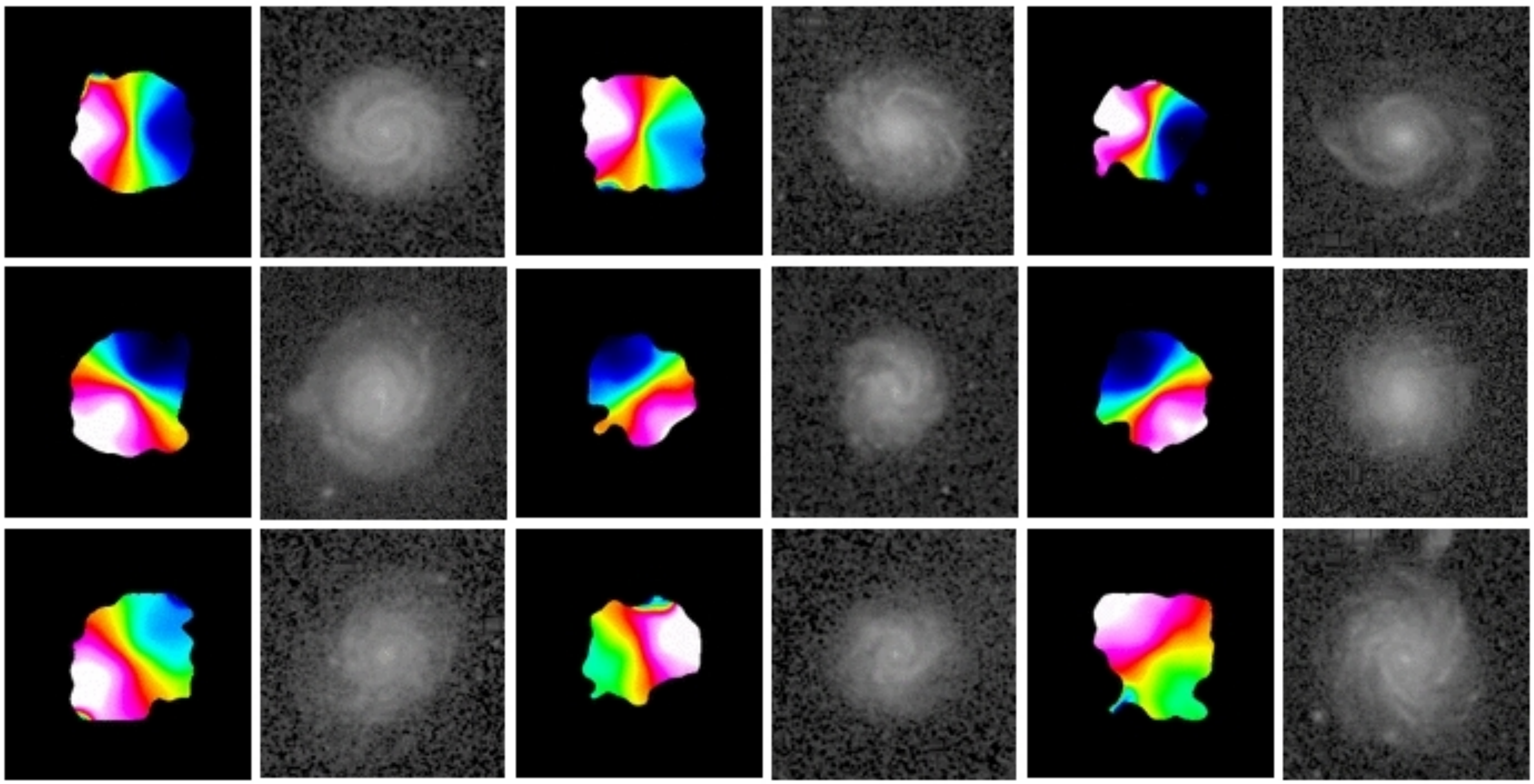
hard



stars

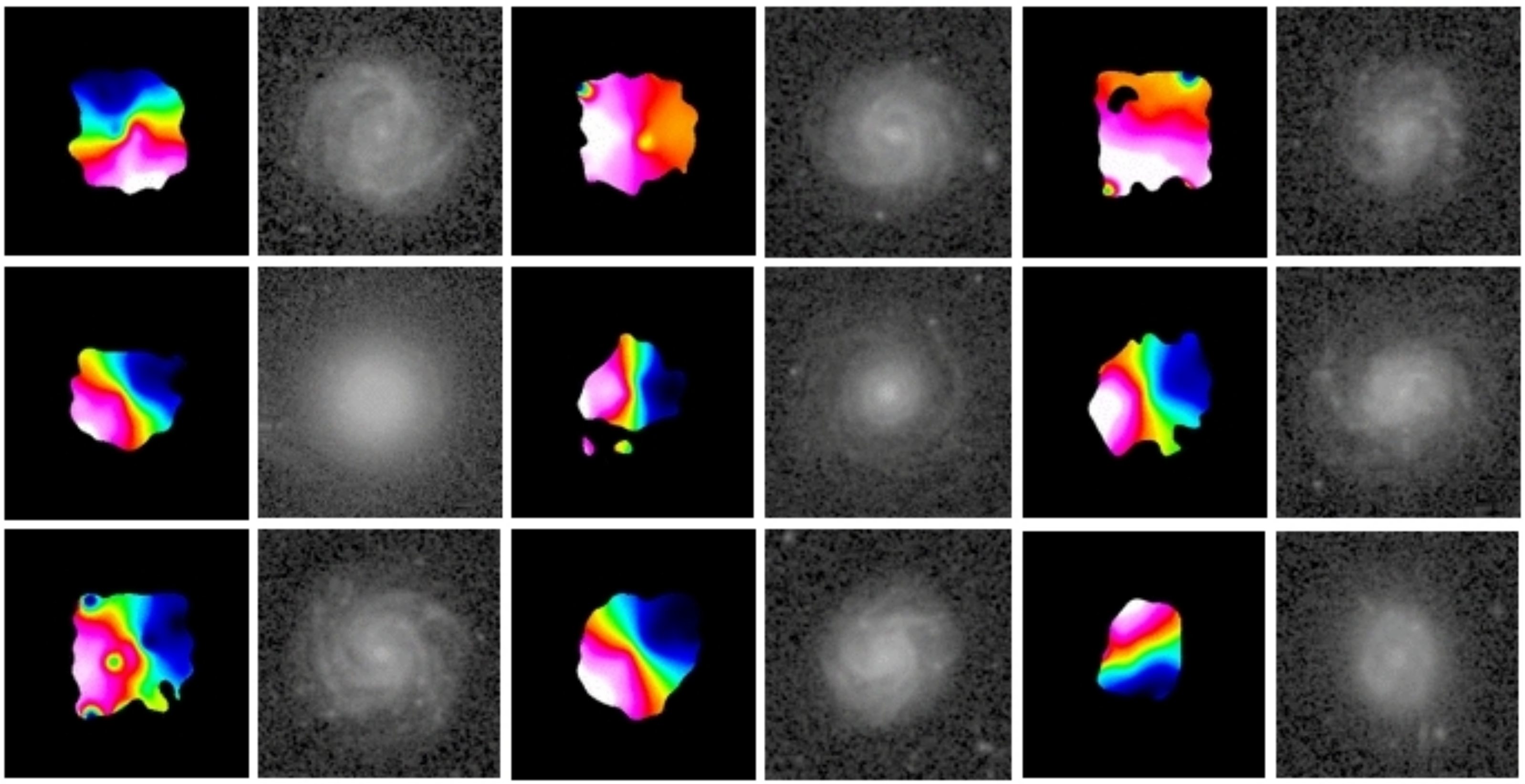
Symmetric, normal galaxies

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)

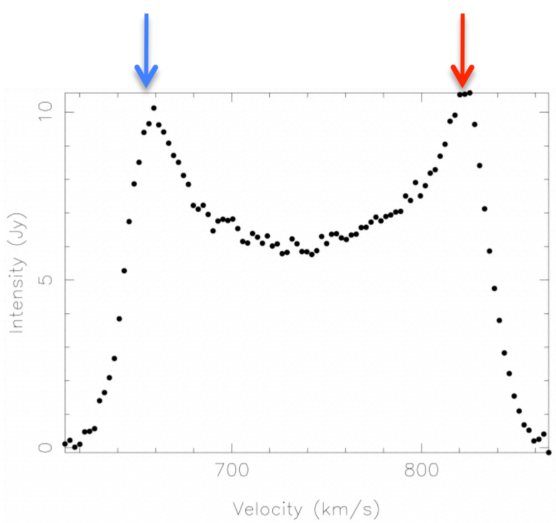
  - These concepts are generic and apply to all line data, e.g., optical emission lines, stellar absorption lines.
  - HI data cubes take 10's of hours to collect on the world's biggest interferometers.

Single-dish vs Inteferometer

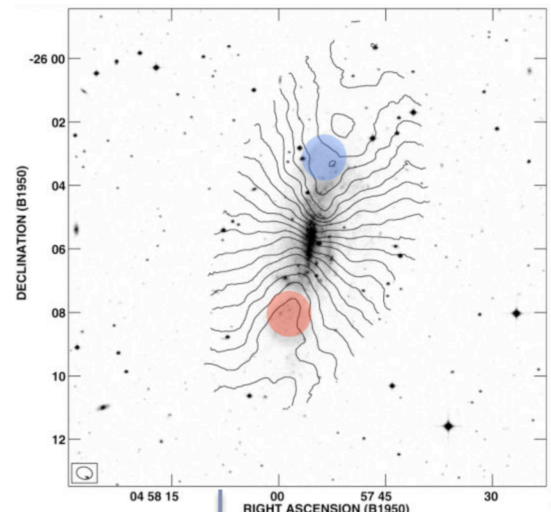
- Sensitivity vs spatial information
- Analogous to single-fiber vs IFU

Inteferomter:

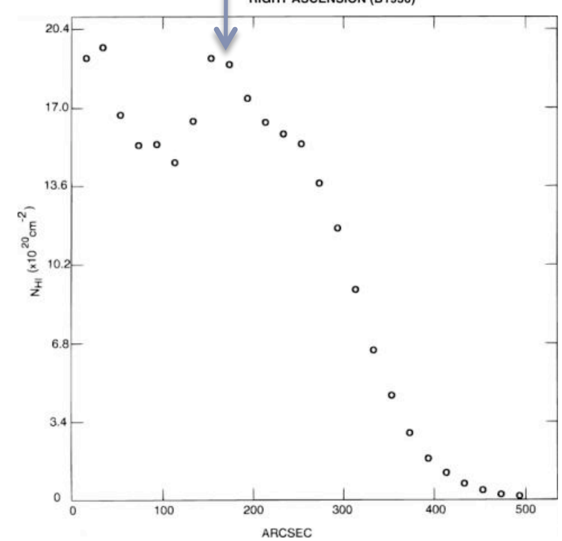
Single dish:



Velocity field:



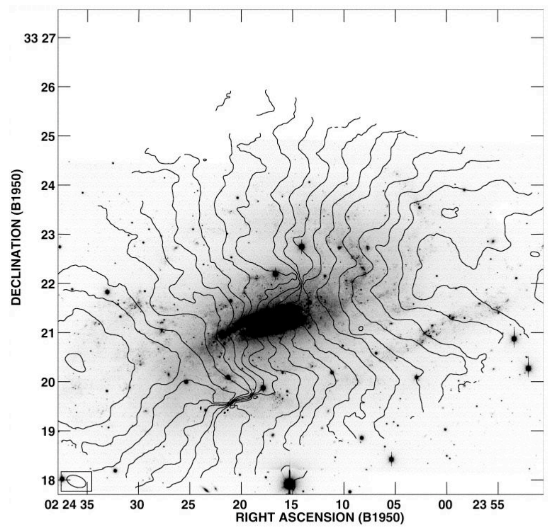
Radial profile:

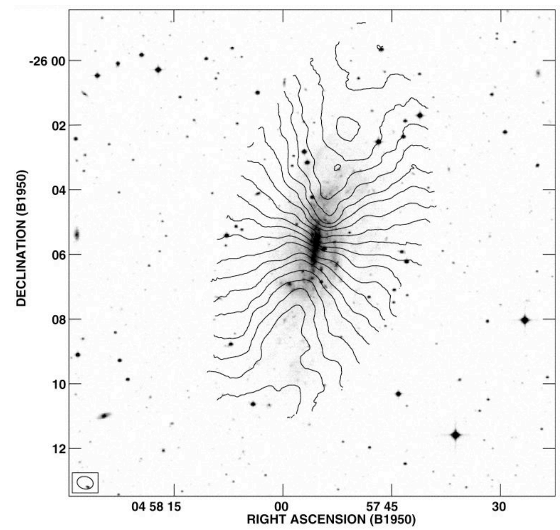


HI spider diagrams

Moderate inclination:

Note beam size relative to optical structure.





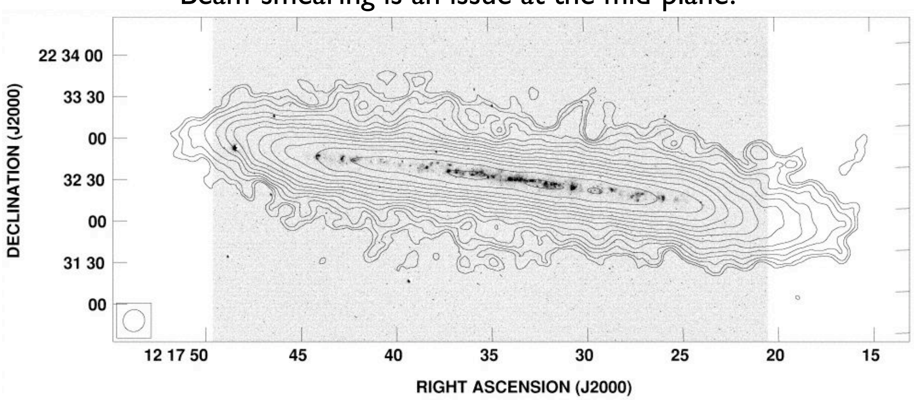
NGC 925

NGC 1744

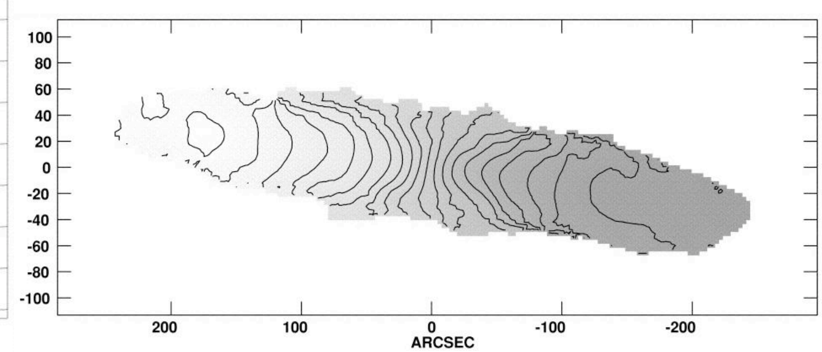
1st moment maps = velocity field

Highly inclined:

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



1st moment map = Velocity field

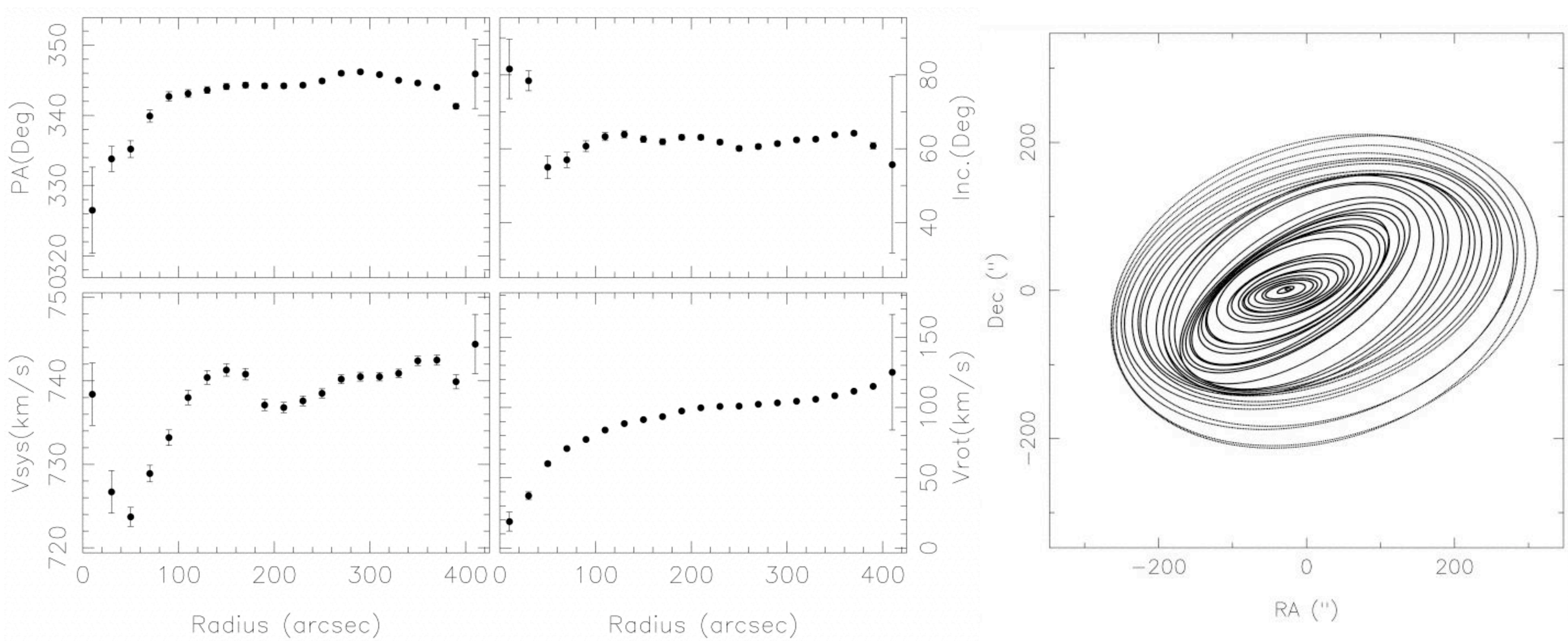


Deriving the rotation curve

- 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 (of 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.