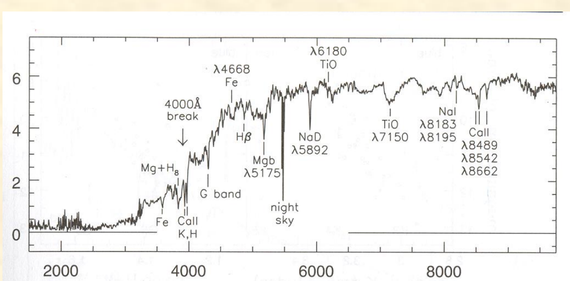
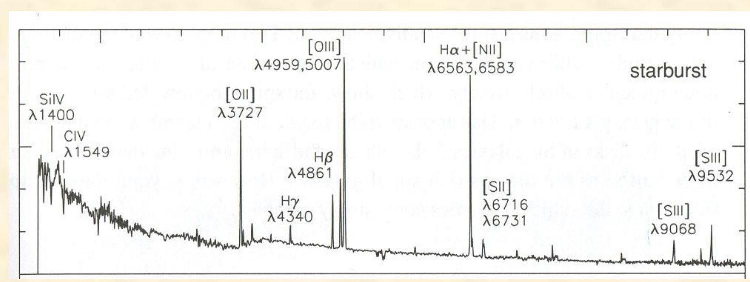
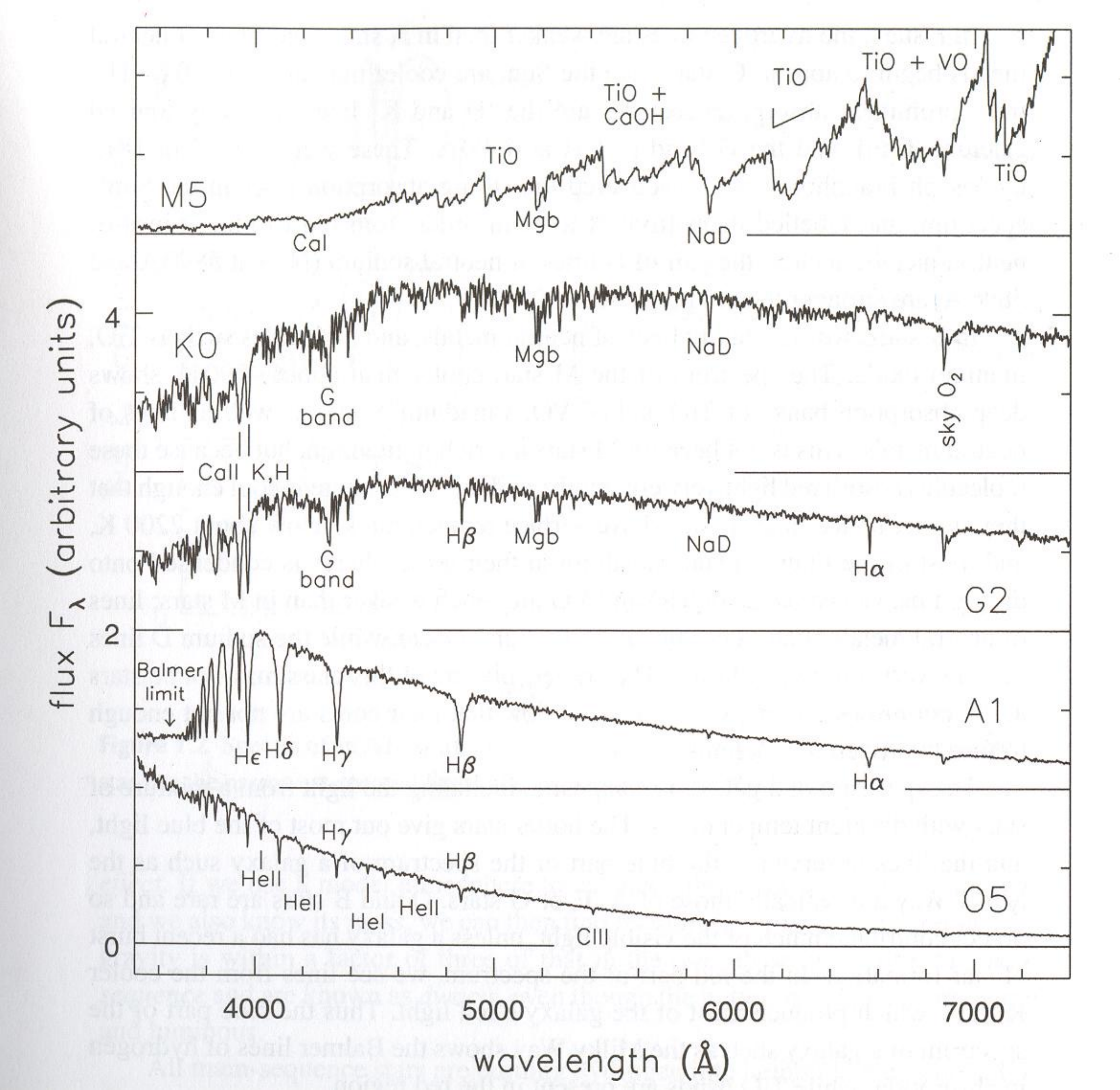
Kinematics of Galaxies

- Spectral Features of Galaxies
- Basics of Spectroscopy
- Elliptical Kinematics
- Faber-Jackson and the Fundamental Plane
- Disk Kinematics (Stellar and H I)
- 2D Velocity Fields
- Rotation Curves and Masses
- Tully-Fisher
- Detection of Supermassive Black Holes



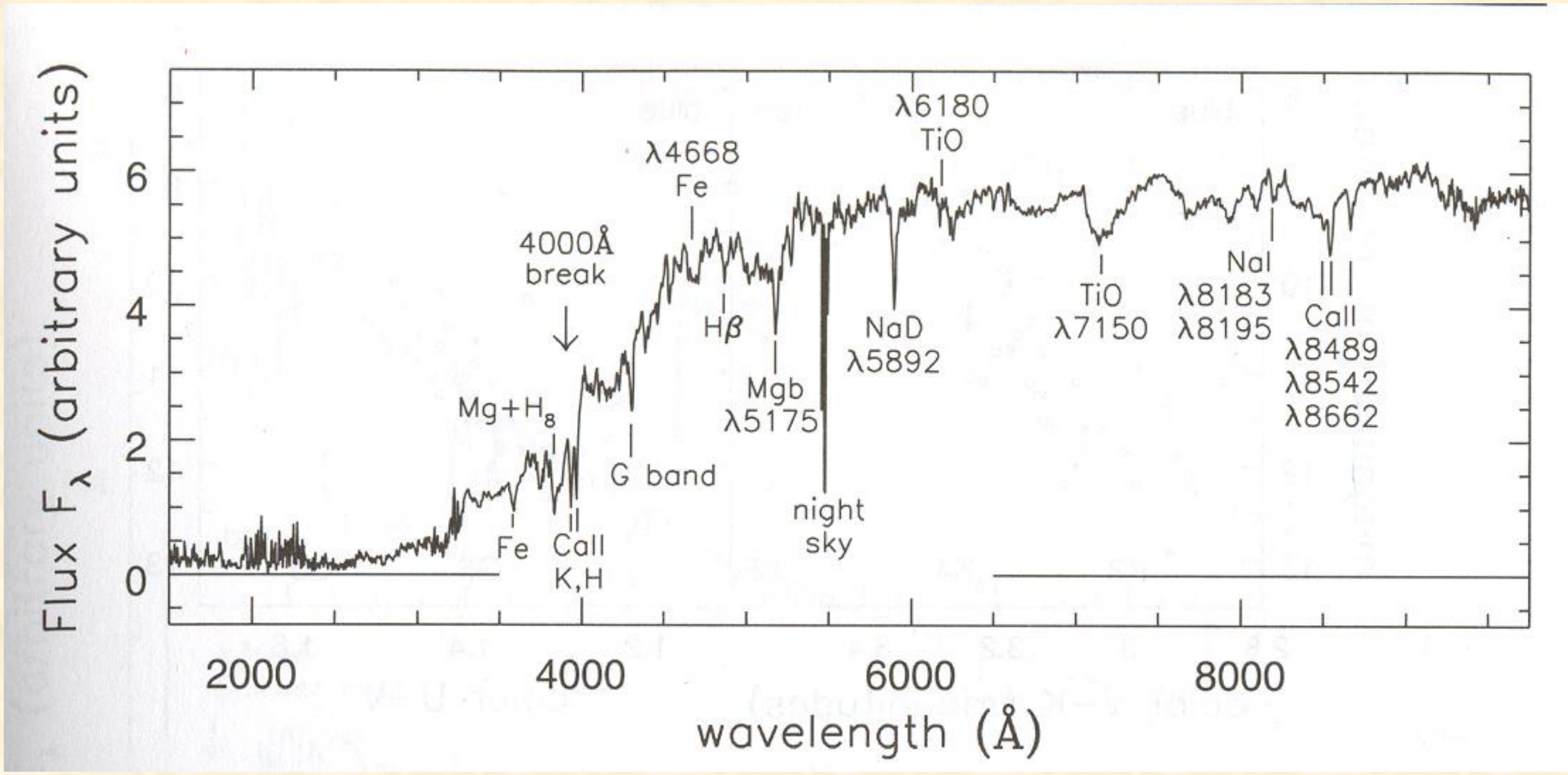


Stellar Spectra



(Sparke and Gallagher, p. 5)

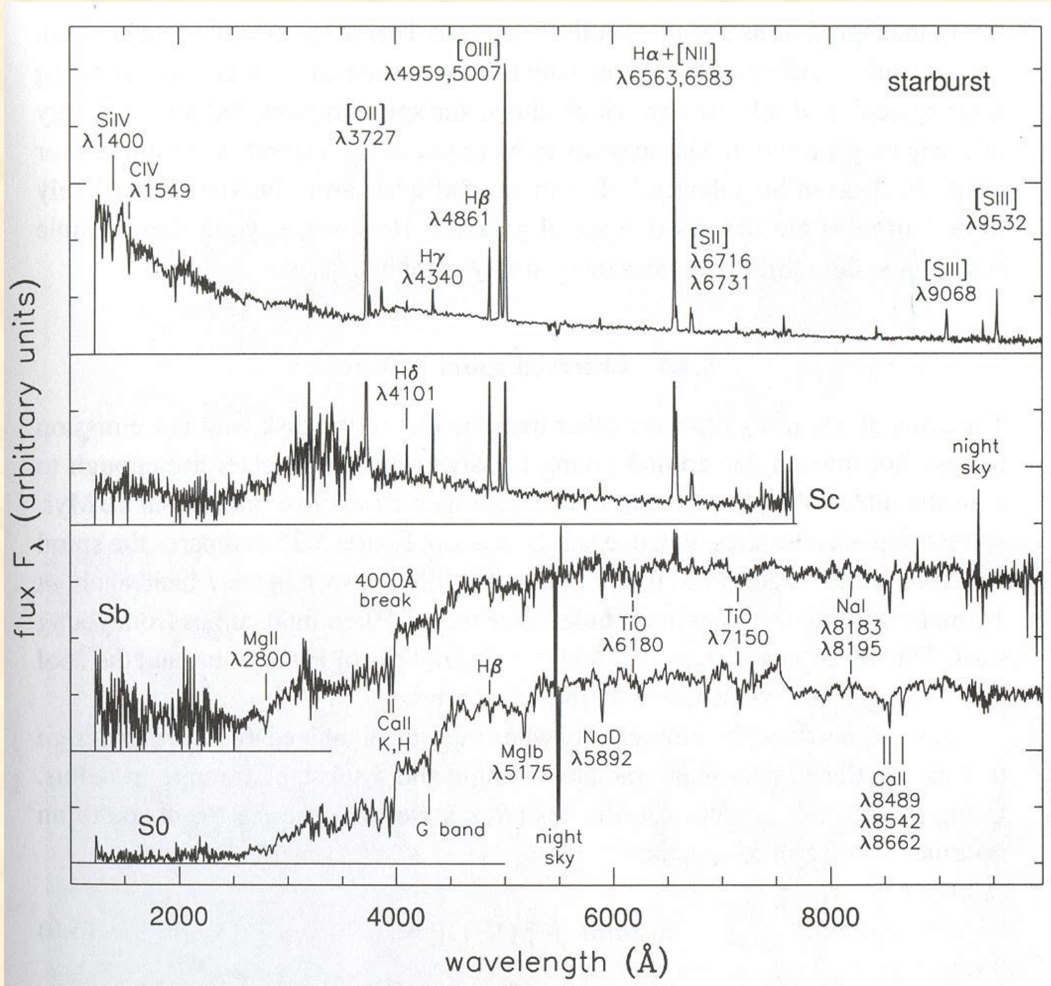
Galaxy Spectra - Ellipticals



(Sparke and Gallagher, p. 267)

- Most features from giant G and K stars (e.g., G band is from CH)
- In the optical, most absorption is stellar. Ca II H, K and Na I D can come from ISM as well (but not much in Ellipticals)
- Lines are broadened from stellar motions
- Ca II triplet lines at ~8500 Å are good for kinematics (well separated, uncontaminated)

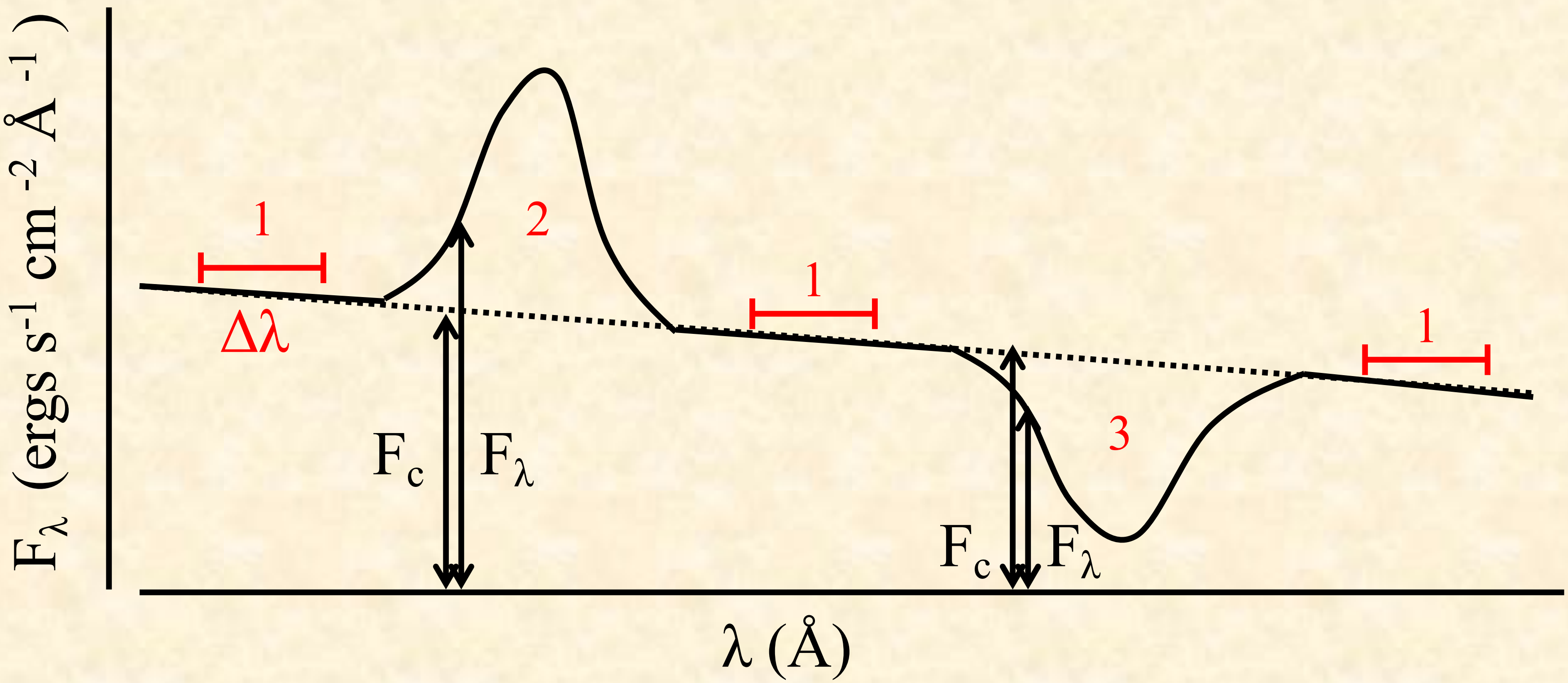
Disk Galaxies



(Sparke and Gallagher, p. 224)

- SO similar to E' s → old stellar populations
- Sa/Sb have stronger Balmer lines (A, F stars) and bluer continua
- Sc have emission lines from H II regions (young hot stars)
- Starburst galaxies have very strong emission lines and blue continua

Basics of Spectroscopy

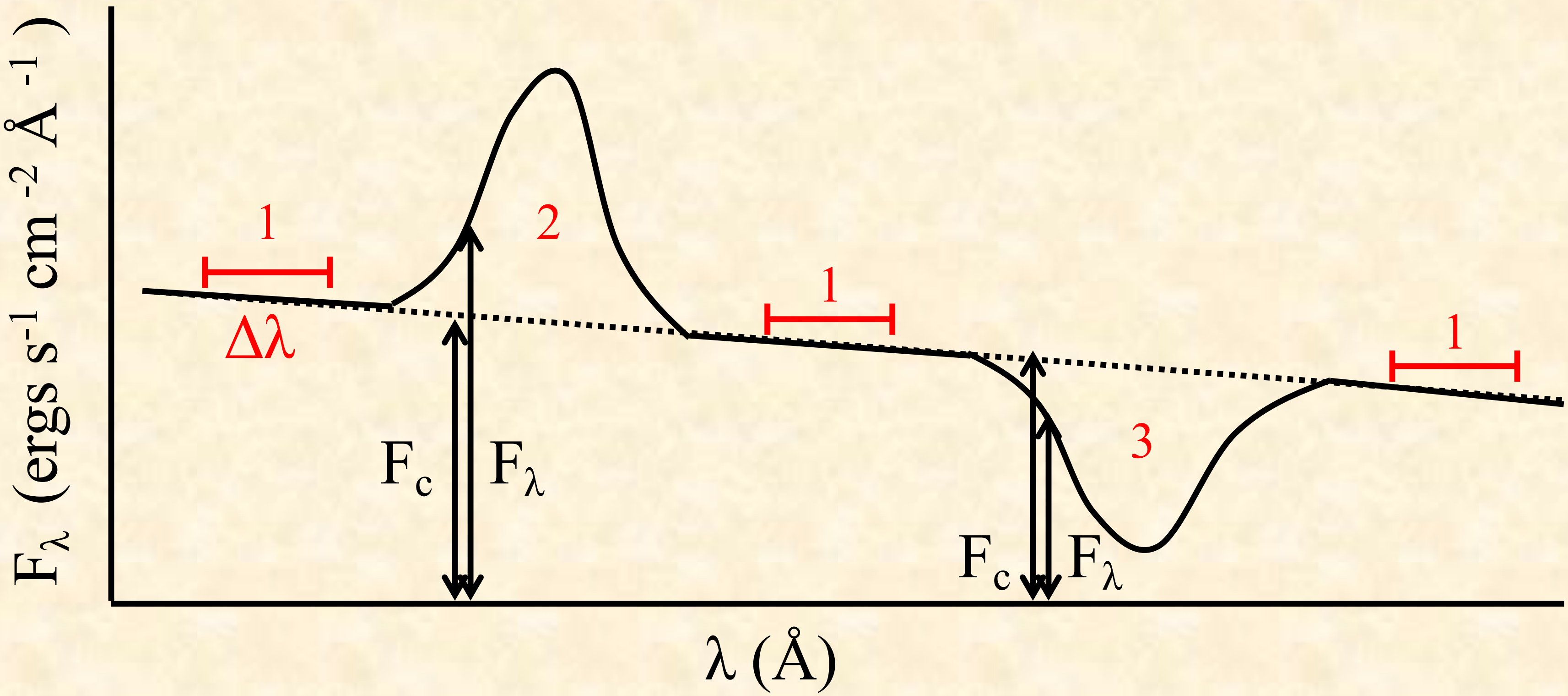


Units:

1. Continuum Flux: $F_c = \dfrac{\int F_\lambda \, d\lambda}{\Delta\lambda} = \langle F_\lambda \rangle$ (ergs s^{-1} cm^{-2} Å^{-1})

2. Emission Line Flux: $F = \int (F_\lambda - F_c)\, d\lambda$ (ergs s^{-1} cm^{-2})

3a. Absorption Equivalent Width: $W_\lambda = \int (1 - F_\lambda / F_c)\, d\lambda$ (Å)



3b. Absorption-Line Centroid:

$$\lambda_c = \frac{\int \lambda (F_c - F_\lambda) d\lambda}{\int (F_c - F_\lambda) d\lambda} \quad \text{(Å)}$$

3c. Radial Velocity Centroid:
(nonrelativistic)

$$v_r = \frac{\lambda_c - \lambda_{lab}}{\lambda_{lab}} c \quad \text{(km s}^{-1}\text{)}$$

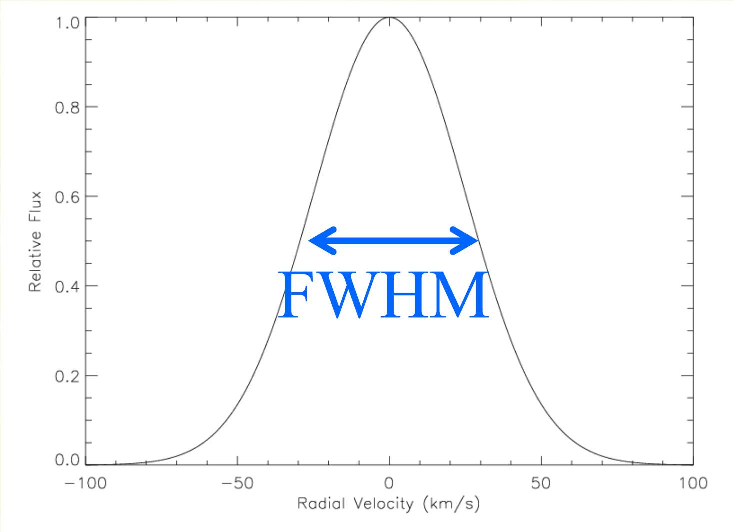
- For Galactic kinematics, v_r and σ are used
- A **Gaussian** profile is often assumed for the LOSVD (line of sight velocity distribution):

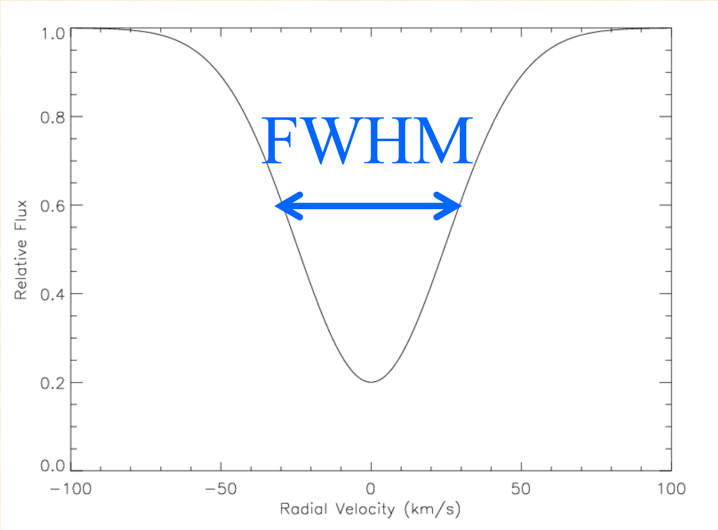
$$P(v_r) = \frac{1}{\sqrt{2\pi}\sigma} e^{-\frac{1}{2}(v_r/\sigma)^2}$$

where v_r = centroid = peak, σ = velocity dispersion

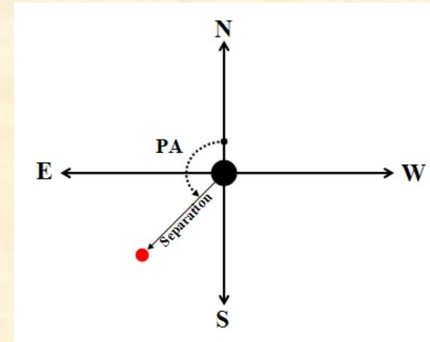
- Note the full-width at half-maximum for a Gaussian is:

$$\text{FWHM} = 2.355\,\sigma$$





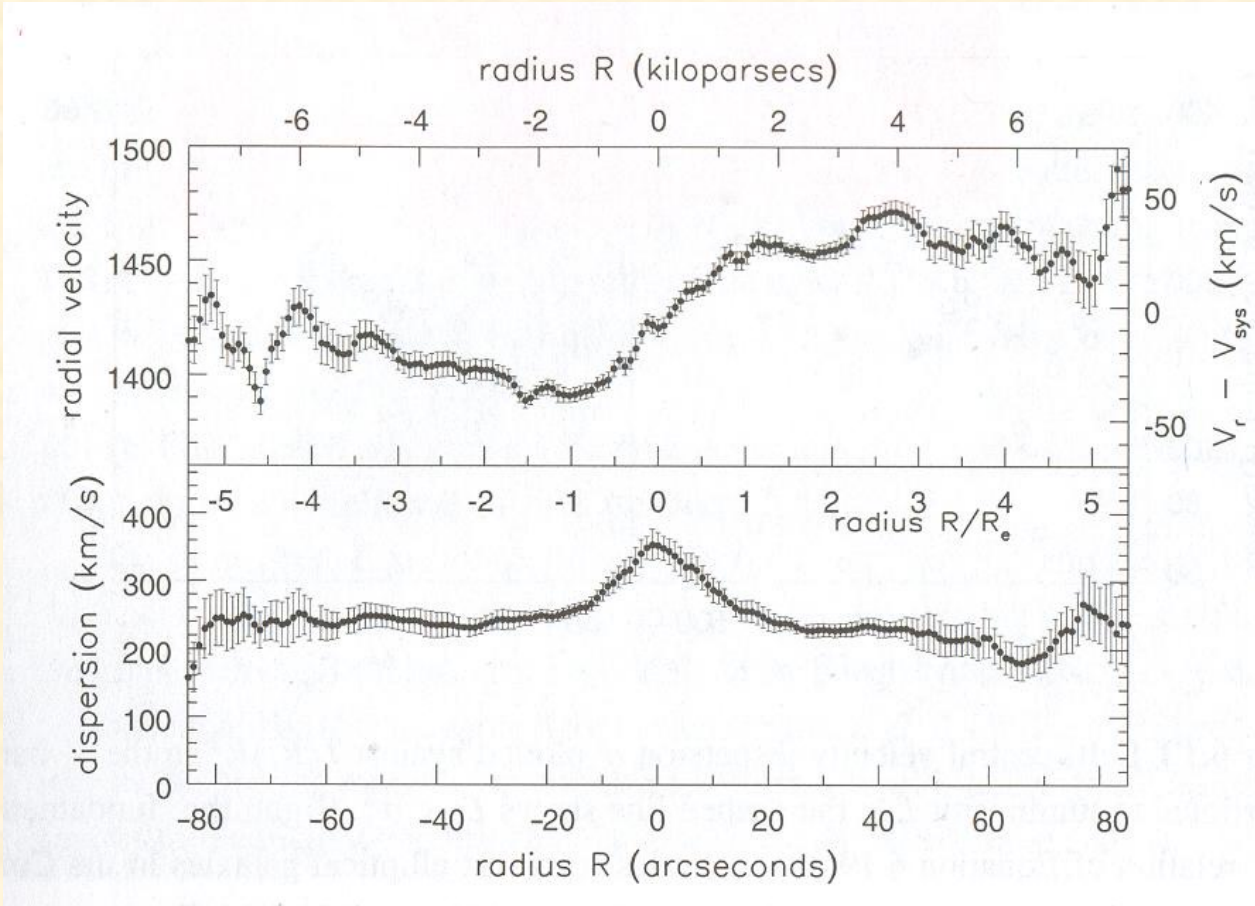
Spatially-Resolved Spectra



- Long-slit spectroscopy: spectra at each position along slit
- Resolving power needed: $R = \lambda/\Delta\lambda \approx 5000$
  (where $\Delta\lambda$ is the FWHM of the line-spread function (LSF)
- Measure v_r and σ at each position.
- Subtract systemic velocity (due to Hubble flow, etc.) from v_r
- Net v_r at each position is a measure of rotation: $v_r = v \sin(\mathrm{incl})$
- σ gives component of random motion in the line of sight

Ellipticals: Kinematics

Ex) cD galaxy NGC 1399



(Sparke and Gallagher, p. 257)

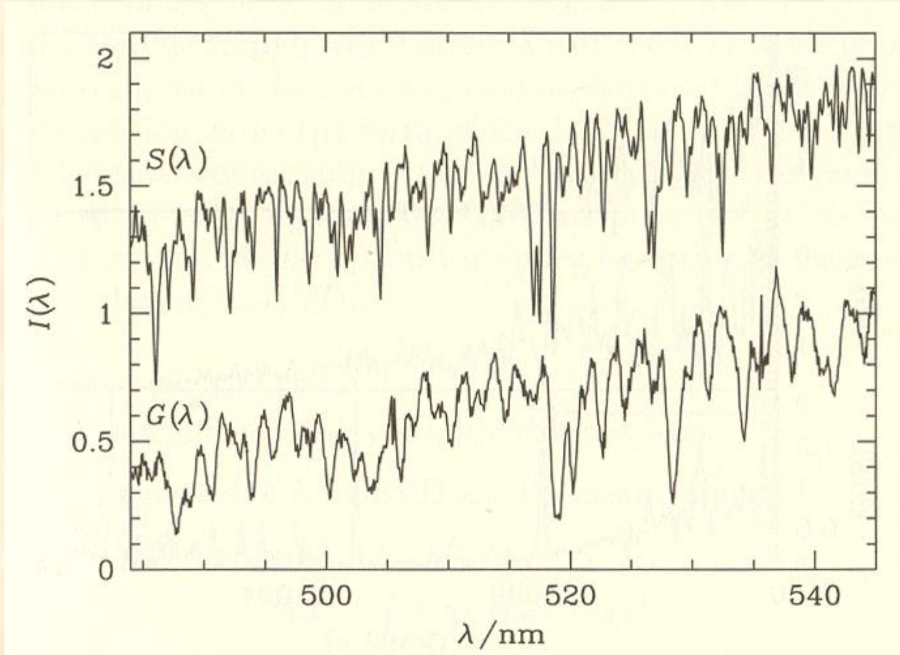
- For most E's: v_r (max) << σ (central velocity dispersion)

Determination of v_r and σ

- One method: use cross-correlation function (CCF)
- Cross-correlate the galaxy spectrum with that of a star (like a K giant) or a synthetic galaxy
  - At each λ, you have F_λ(star) and F_λ(galaxy)
  - Do a linear fit of F_λ(galaxy) vs. F_λ(star) to get "r" (linear-correlation coefficient) (Bevington, p. 121)
  - Shift one spectrum in λ, and calculate r again

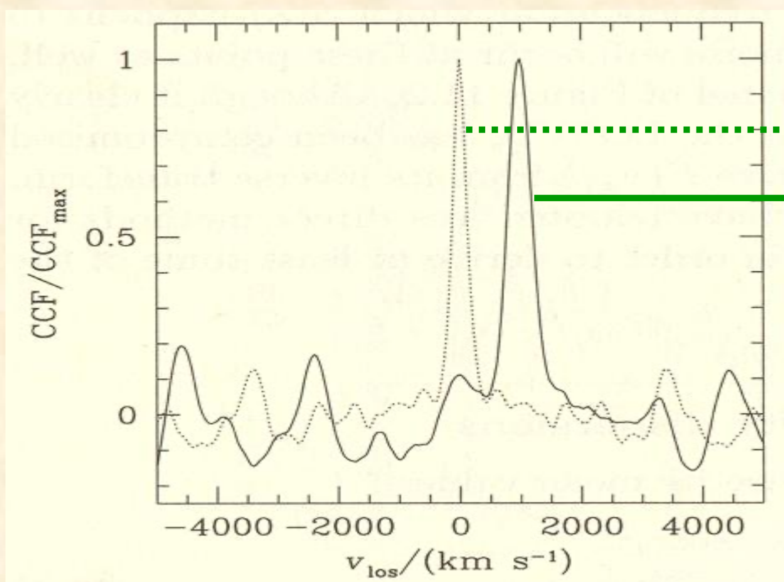
    ($r = 1 \rightarrow$ perfect correlation; $r = 0 \rightarrow$ no correlation)
  - The CCF is just r as a function of shift
- The CCF peak give the velocity centroid v_r; the CCF width gives σ
- The auto-correlation function (ACF) is a function cross-correlated with itself.

CCF Example



→ K0 giant

→ NGC 2549



ACF

CCF

(Binney & Merrifield p.695, 698)

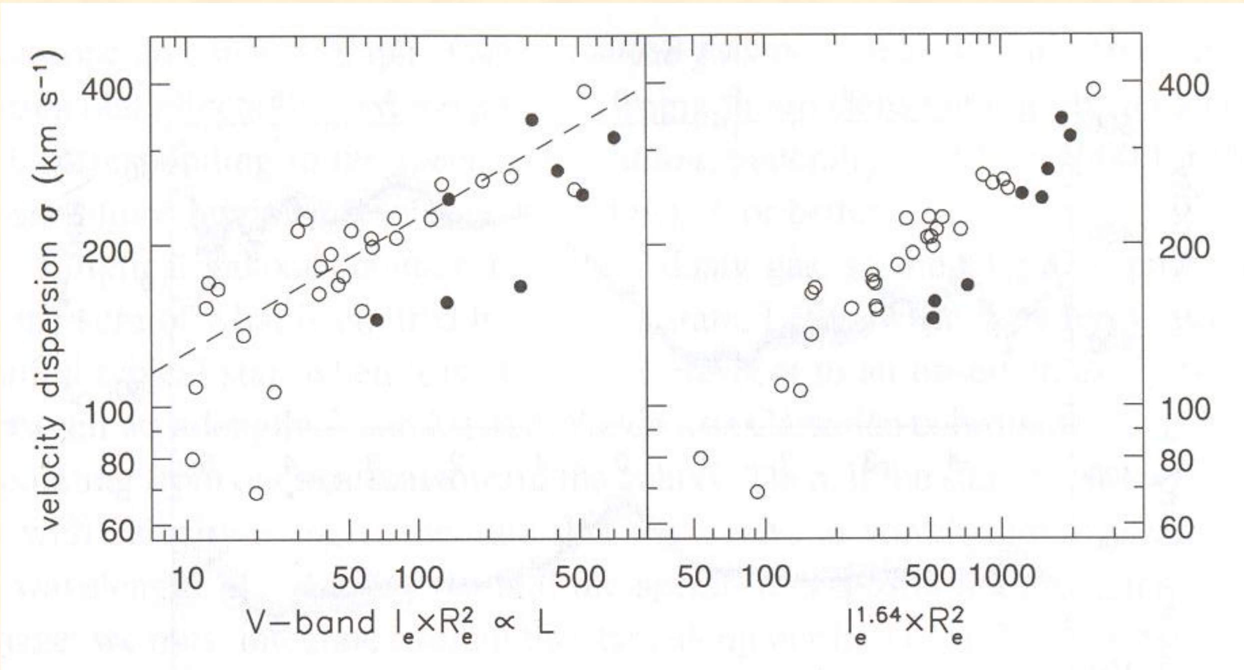
Results for Ellipticals: Kinematic Correlations

- Faber-Jackson relation: $L \sim \sigma^4$ (σ: central velocity disp.)

$$\frac{L_V}{2\mathrm{x}10^{10} L_\odot} = \left(\frac{\sigma}{200 \text{ km s}^{-1}} \right)^4$$

- Note $L \sim I_e R_e^2$ → Is there a tighter relationship for σ, I_e, R_e?

Faber-Jackson　　Fundamental Plane



(Sparke and Gallagher, p. 258)

→ projection:

$$I_e^{1.64} R_e^2 \propto \sigma^{2.48}$$

Note: These relations do *not* apply to diffuse E's and dwarf spheroidals

Rotation of Elliptical Galaxies

- Is the oblateness of ellipticals due to rotation?

  → no, E's tend to rotate more slowly than they should
- How fast should they rotate?
- Virial Theorem – if the galaxy is dynamically relaxed, velocity dispersions are equal in all directions and:

  $$2\langle KE_i \rangle + \langle PE_i \rangle = 0 \quad \text{for i = x, y, z (axes of symmetry)}$$

  where $\langle PE_i \rangle$ is the average gravitational potential.

  For an oblate galaxy rotating around the z axis:

  $$\frac{\langle PE_z \rangle}{\langle PE_x \rangle} = \frac{\langle KE_z \rangle}{\langle KE_x \rangle} = \frac{\sigma_z^{\;2}}{\frac{1}{2} v^2 + \sigma_x^{\;2}}$$

  $$\frac{\langle PE_z \rangle}{\langle PE_x \rangle} \approx (B / A)^{0.9} = (1 - e)^{0.9} \quad \text{(Sparke \& Gallagher, 260)}$$

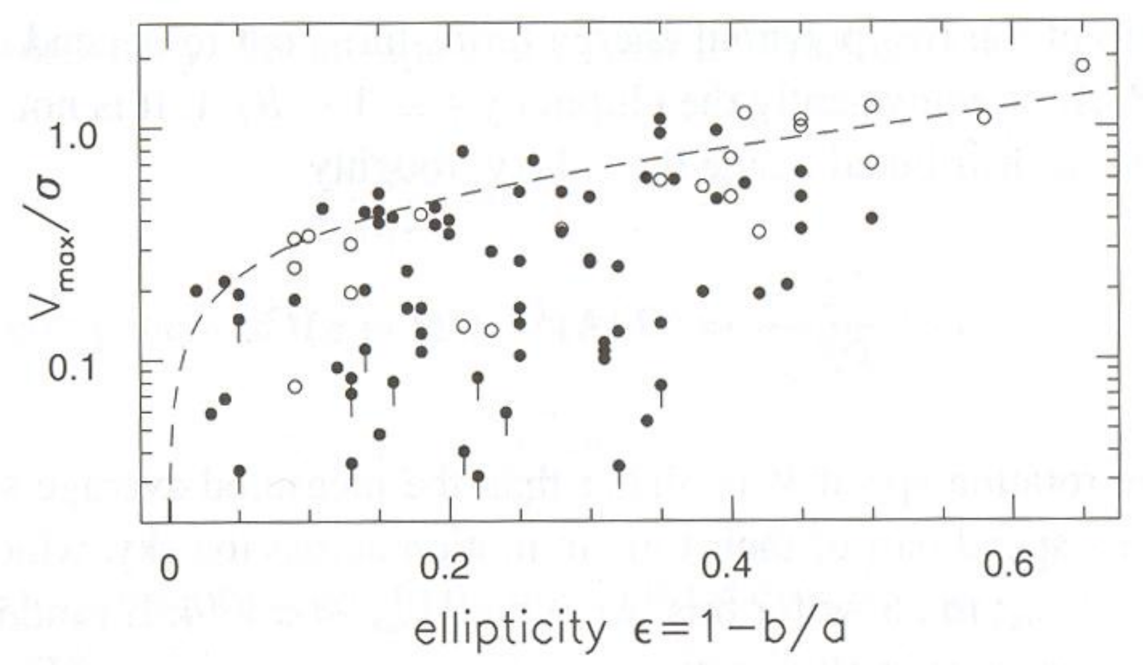
  where A, B, and e are the actual axes and ellipticity

If the virial theorem applies, $\sigma = \sigma_x = \sigma_y = \sigma_z$

Note that the maximum radial velocity at σ $(= \sigma_0)$ is:

$$v(\max) \approx \frac{\pi}{4} v \quad \text{(Sparke \& Gallagher, p. 260)}$$

$$\text{Thus } \frac{v(\max)}{\sigma} = \frac{\pi}{4}\sqrt{2\left[\left(1-e\right)^{-0.9} - 1\right]}$$

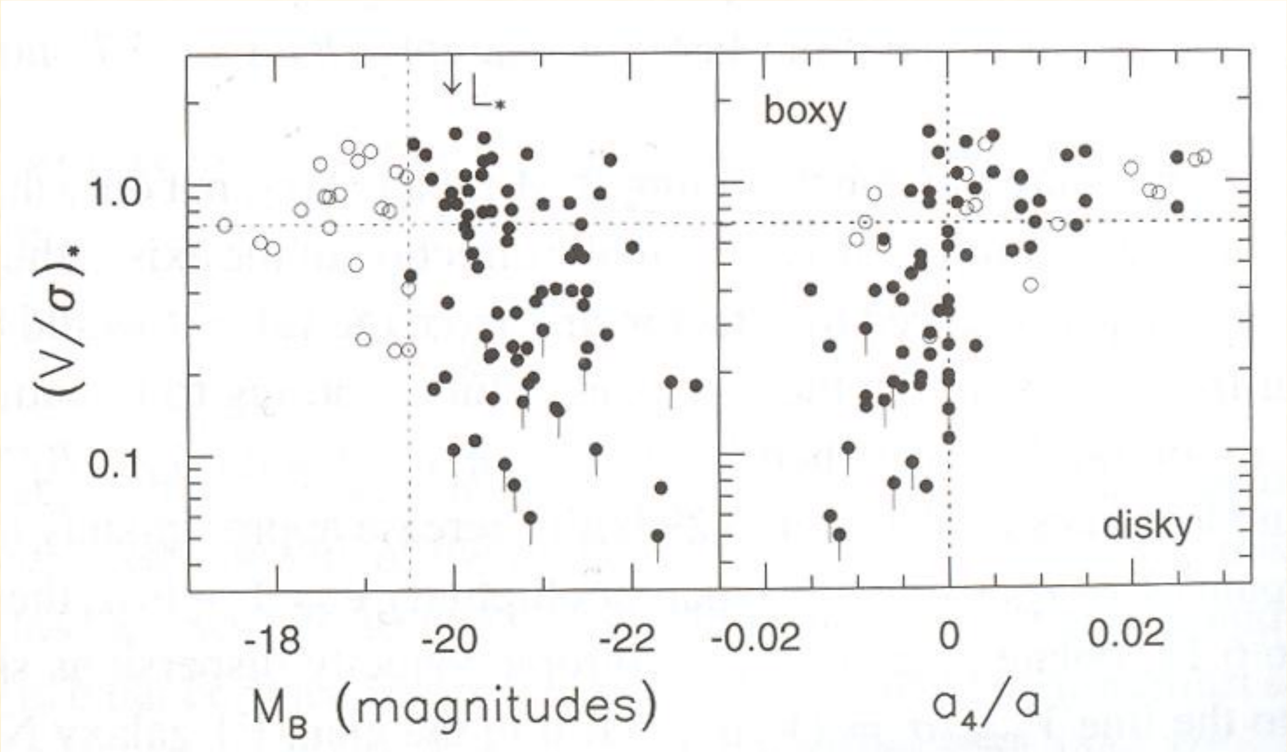


(Sparke & Gallagher, p. 262)

→ observed v(max) much lower than expected from relaxed systems

- So most ellipticals are not supported by rotation, but by anisotropic velocity dispersions: $\sigma_x \neq \sigma_y \neq \sigma_z.$

Observations: Let $(v/\sigma)_* = \dfrac{(v_{max}/\sigma_0)_{obs}}{(v_{max}/\sigma_0)_{eqn}}$

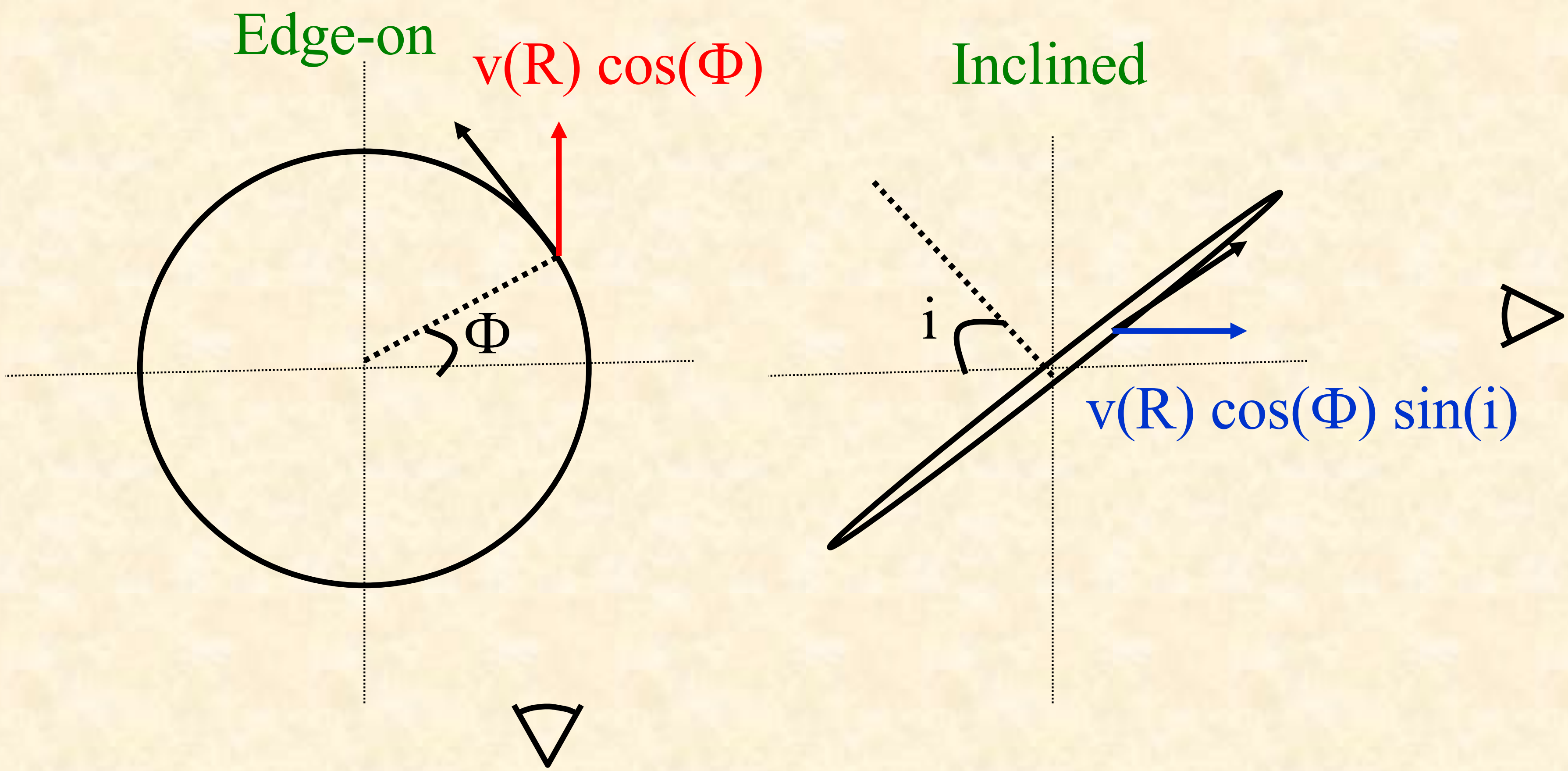


(Sparke & Gallagher, p. 261)

- Luminous and boxy ellipticals rotate much slower than expected.
- Disky E's may be composite: rotating disk embedded in normal elliptical

Kinematics of Rotating Disks (Spirals)

- Spiral galaxies are dominated by rotation ($v_r \geq 10\sigma$)
- Can determine true velocity v(R), since we know inclination



- Observed radial velocity: $v_r = v_{sys} + v(R)\cos(\Phi)\sin(i)$

Axisymmetric Disk:

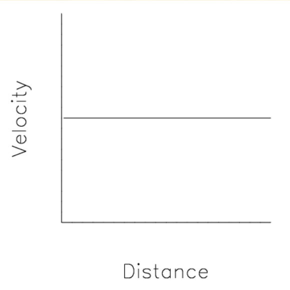
$$v^2(R) = \frac{GM(r<R)}{R}$$

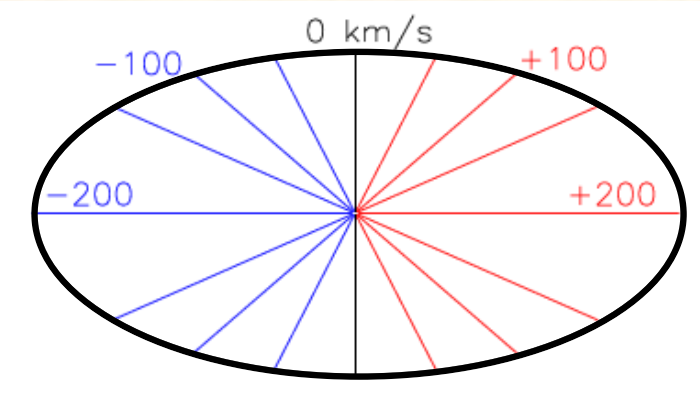
Velocity law

Spider Diagrams for i = 60°
(isovelocity contours in equal steps)

1) If $M \sim R$: $v = \text{const.}$

$v_r - v_{sys} \sim \cos(\Phi)\sin(i)$

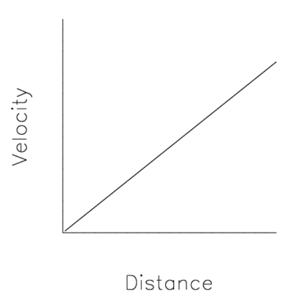


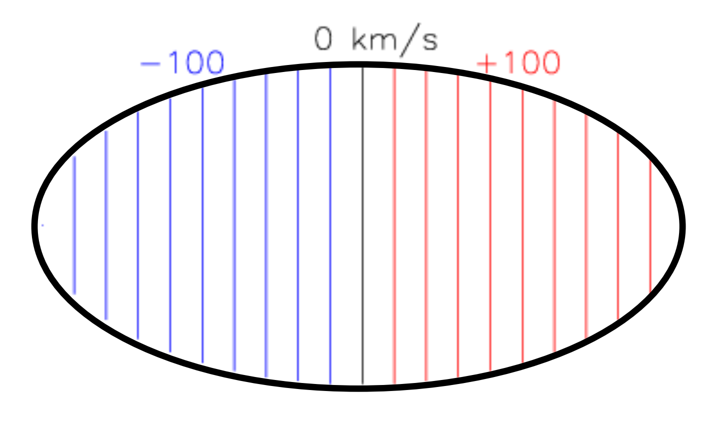


2) If $M \sim R^3$: $v \sim R$

$v_r - v_{sys} \sim R\cos(\Phi)\sin(i)$

(constant density)

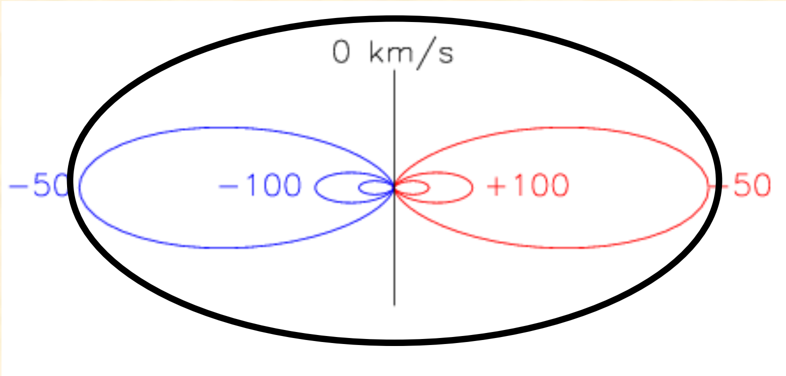




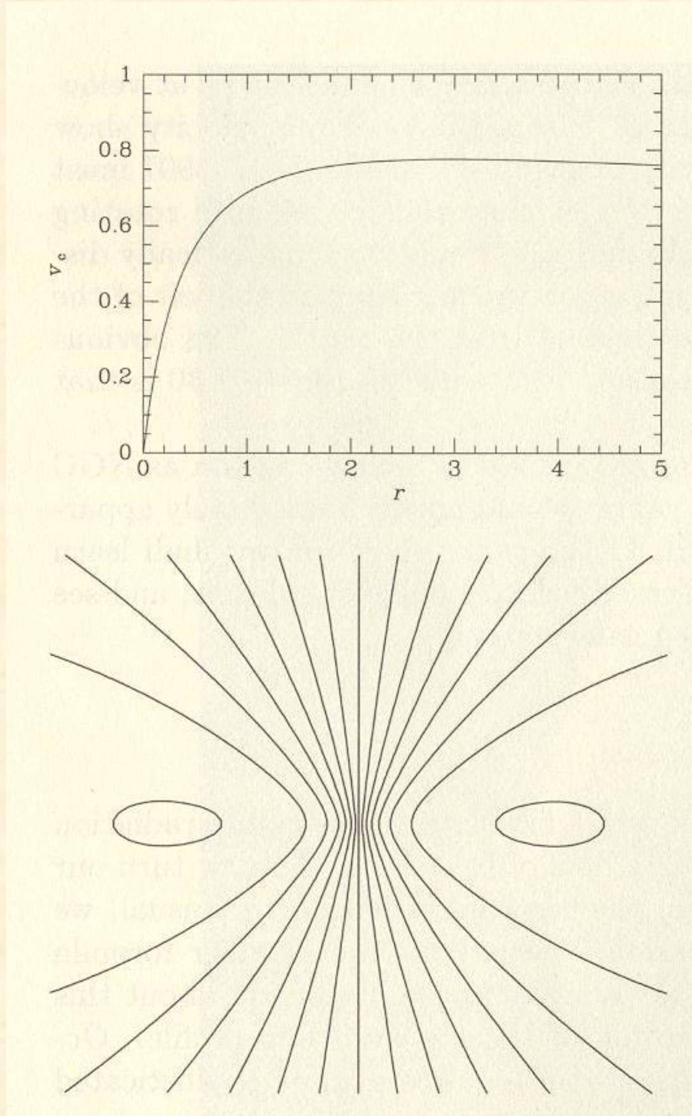
3) If $M = \text{constant}$: $v \sim R^{-1/2}$

$v_r - v_{sys} \sim R^{-1/2}\cos(\Phi)\sin(i)$

(point-source mass)



More realistic example

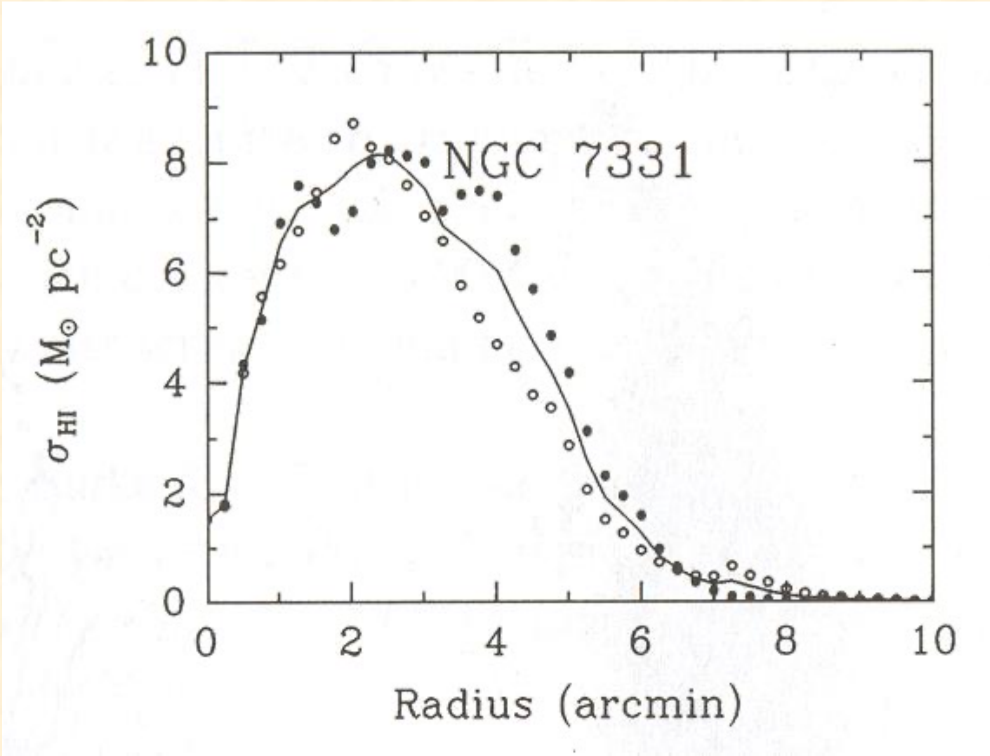


Binney & Merrifield, 506

Radial Velocities from H I 21-cm Emission

- H I gas is better tracer of kinematics than stars:
  - More uniformly distributed and more extensive

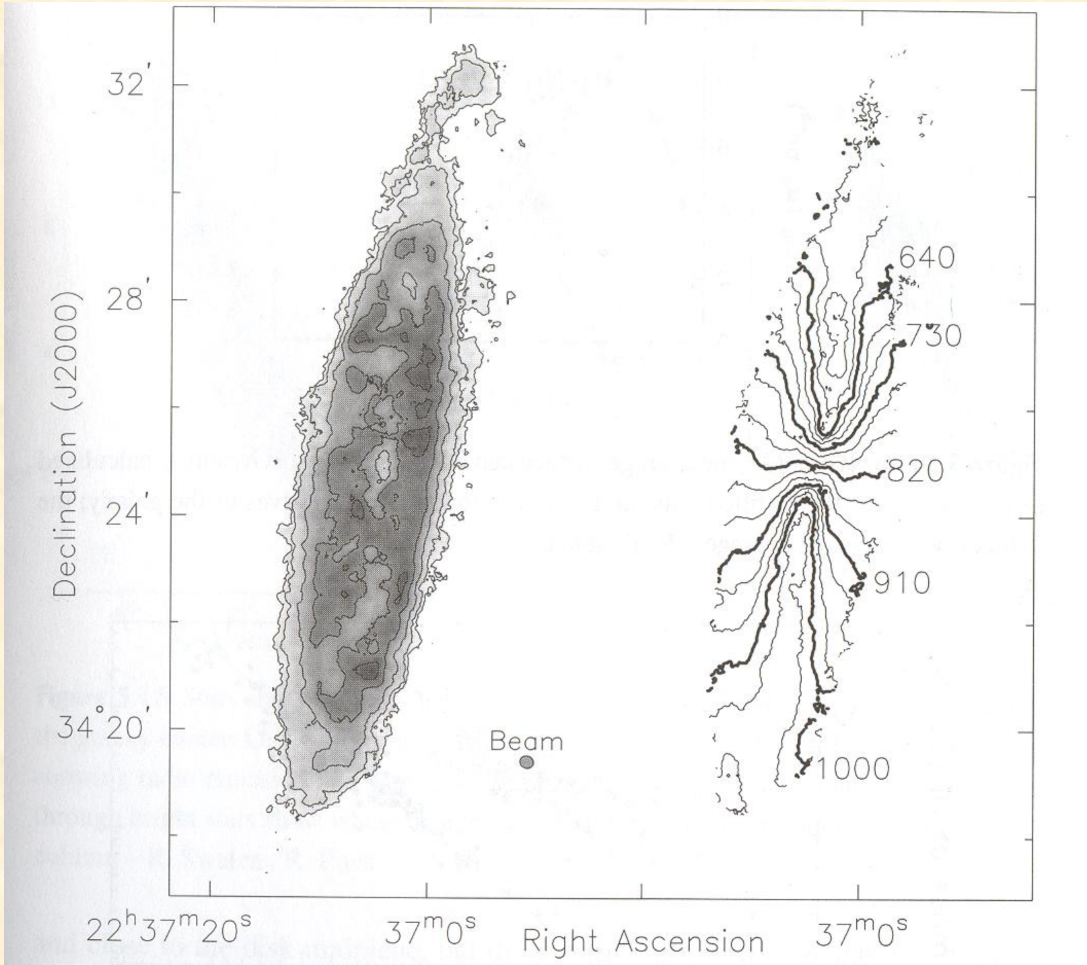
Surface Density



(Sparke & Gallagher, p. 211)

- H I typically detected out to $2R_{25}$ to $4R_{25}$ (R_{25} of MW ≈10 kpc)
- Mass (H I) ≈ 1 to 10% Mass (stellar disk)
  (Sa →Sd)

NGC 7331 - HI Intensity and Spider Diagram

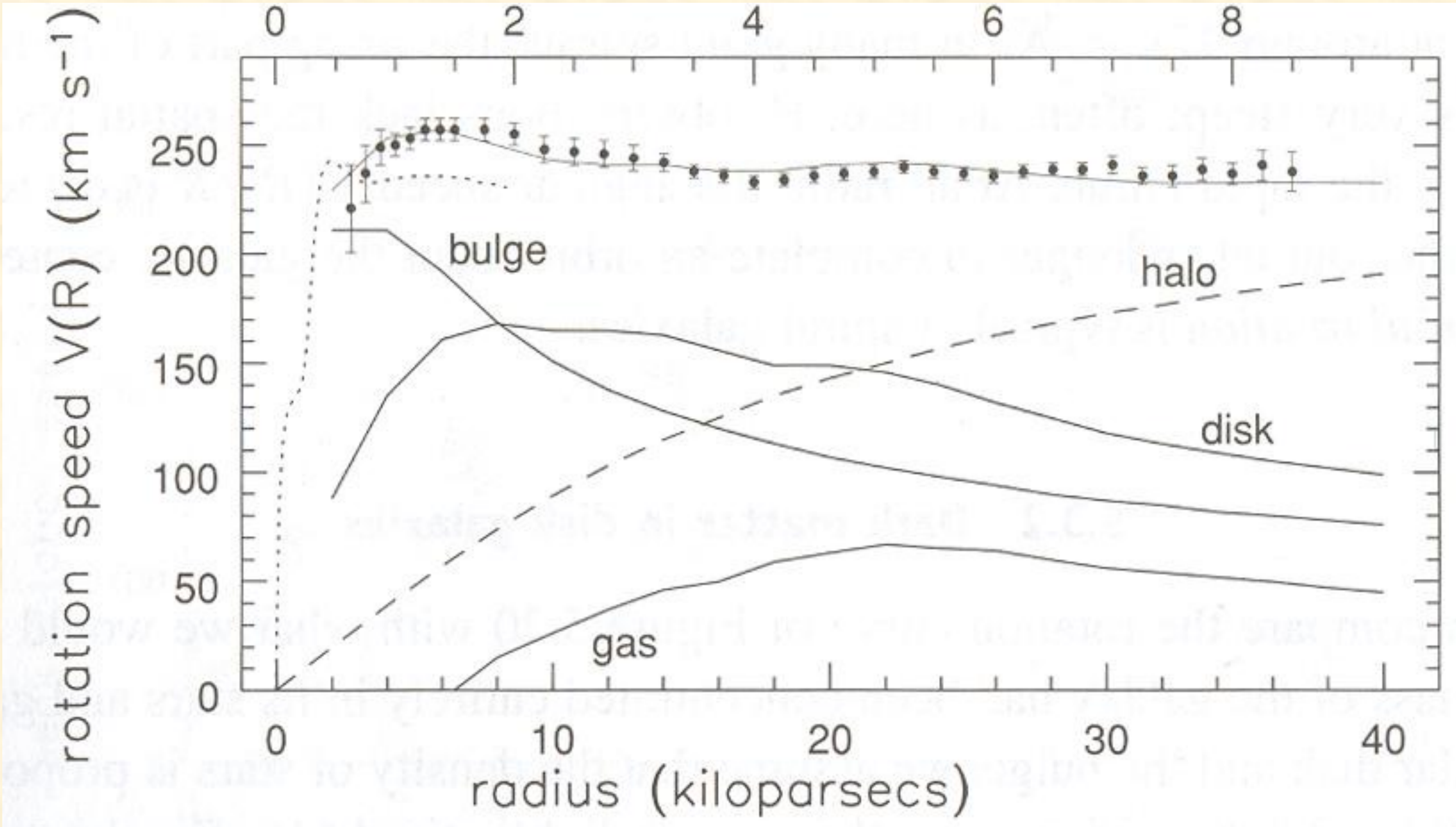


linear increase in v_r
followed by constant v_r

(Sparke & Gallagher, p. 210)

Complications: Isophotes twisted in same direction: warped disk
Gradient along minor axis – radial motion
Kinks in isophotes – random motions

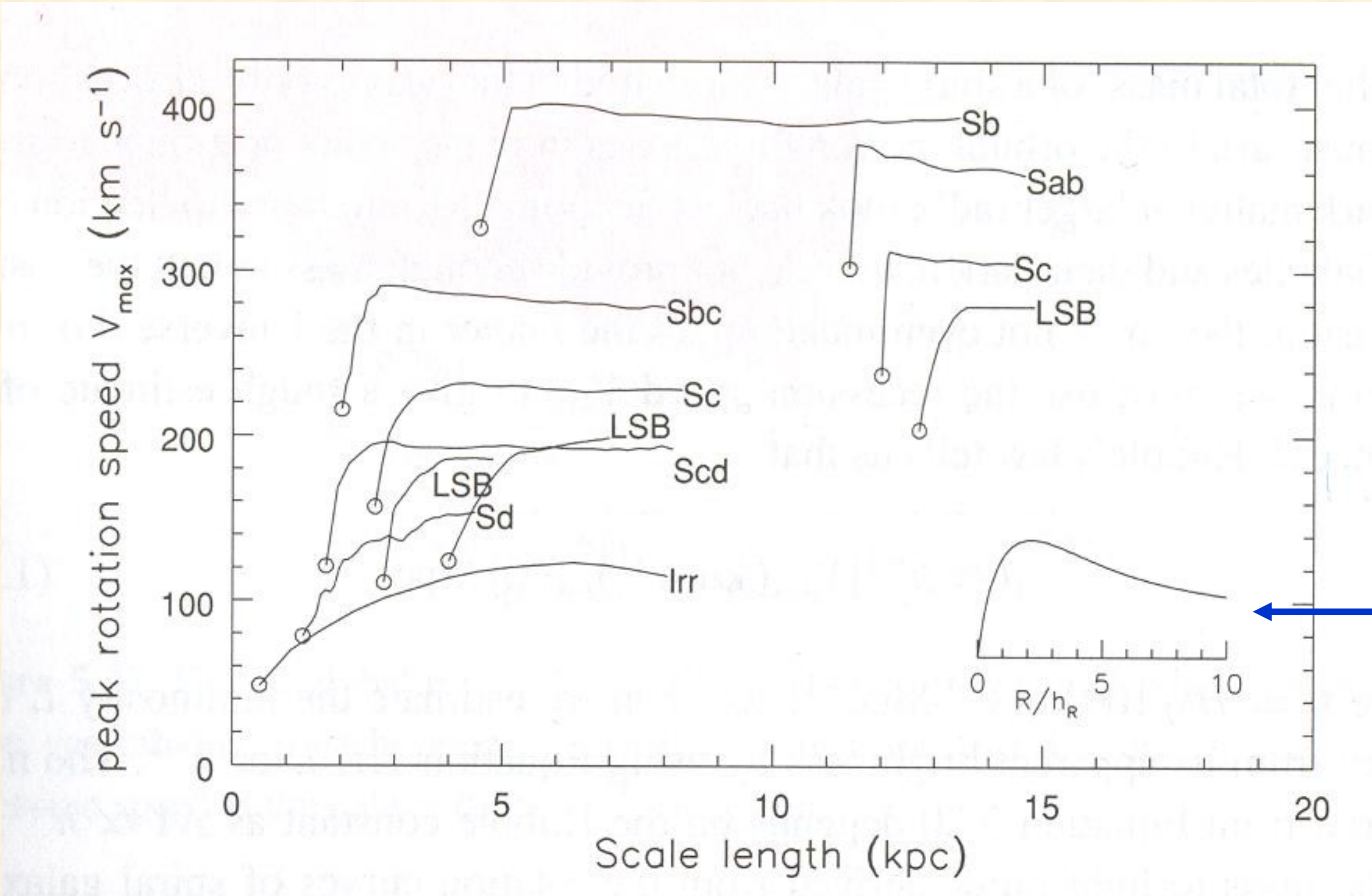
Rotation Curve (along major axis) for NGC 7331



(Sparke & Gallagher, p. 197)

- Dotted line: CO observations (traces colder molecular gas)
- Points and solid line: H I 21-cm measurements
- Bulge, disk, and gas: deduced from surface-brightness profiles
- Inferred dark halo mass: 2 to 4 times visible mass (in general)

Rotation Curves for Other Galaxies



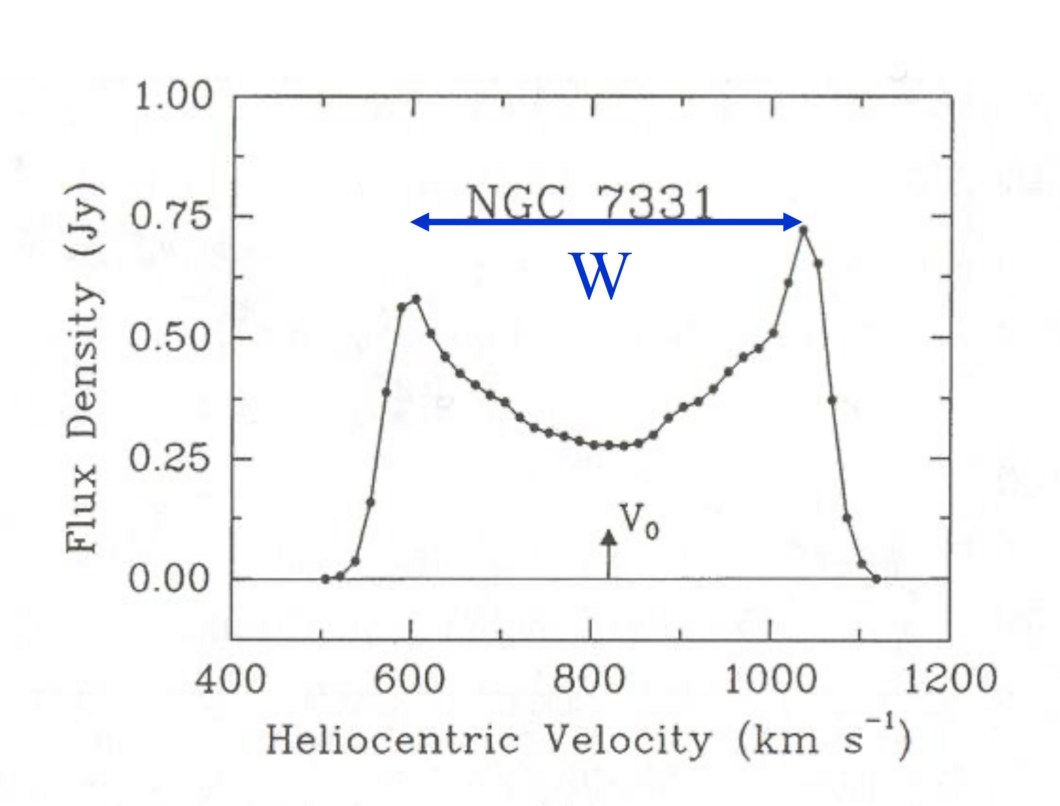
expected from disk + bulge

(Sparke & Gallagher, p. 218)

- Larger disk galaxies rotate faster
- Early types tend to rise more steeply
- Flat rotation curves: evidence for dark halos in disk galaxies

Tully-Fisher Relation

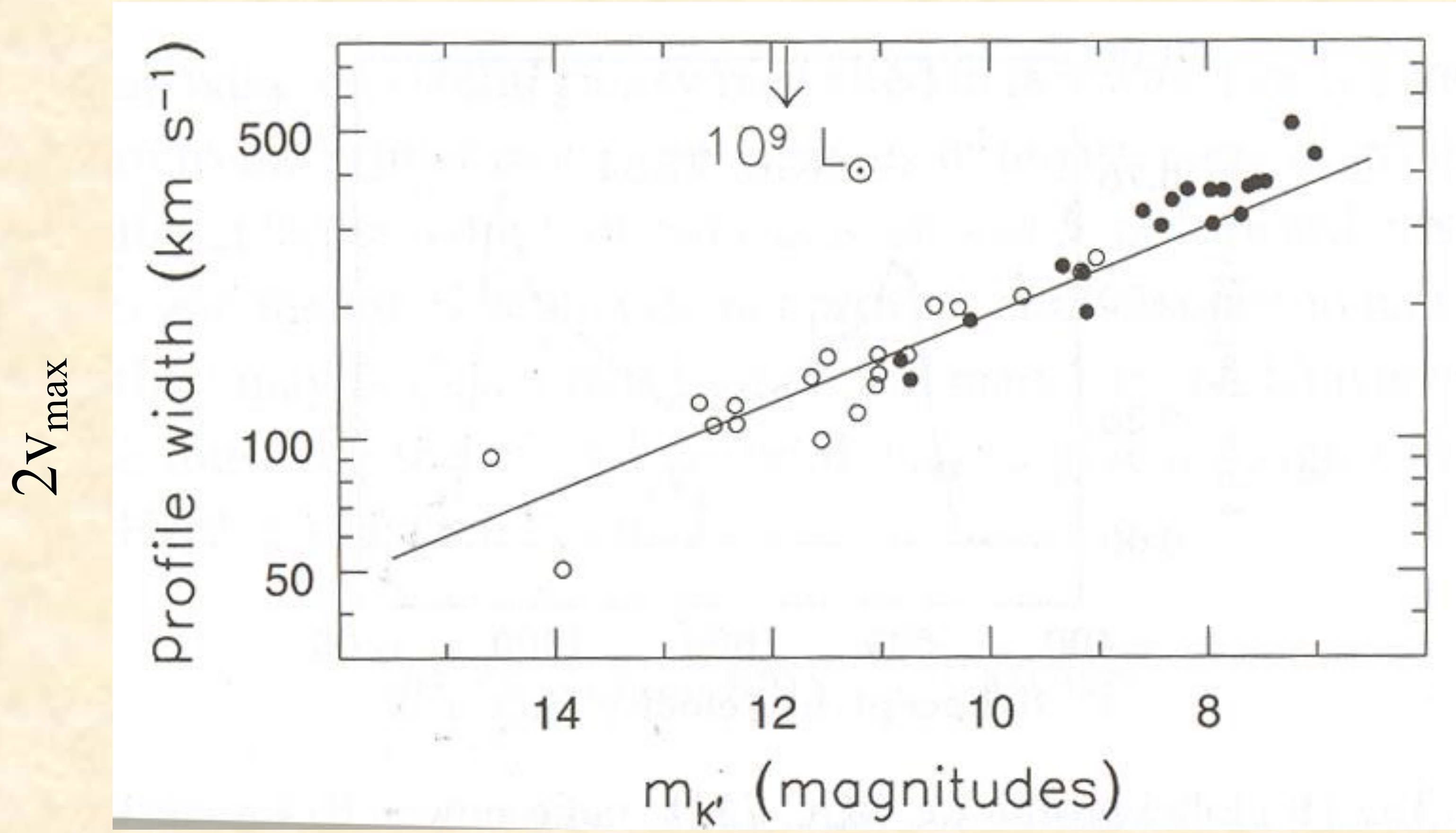
- Rotation curves not possible for more distant spirals
- Use "integrated" H I profile: double-horned common



(Sparke & Gallagher, p. 220)

$$V_{max} = \tfrac{1}{2}W/\sin(i)$$

Ex) Ursa Major Group



(Sparke & Gallagher, p. 221)

$$\text{Tully – Fisher}: L_{IR} \propto v_{max}^4$$

Recent calibration: $$\frac{L_I}{4 \times 10^{10}\ L_{I,\odot}} = \left(\frac{v_{max}}{200 \text{ km s}^{-1}}\right)^4$$

Hand-waving Justification for Tully-Fisher:

$$M(R_d) \propto R_d V_{max}^2$$

If M/L ratio is constant:

$$L \propto R_d V_{max}^2$$

$$\text{Also: } L \propto I_0 R_d^2 \propto I_0 \frac{L^2}{V_{max}^4}$$

If I_0 is constant: $L \propto V_{max}^4$

This probably shouldn't work:

- I_0 and M/L are not constant with type or luminosity
- Velocities are affected by dark halo, luminosity is not

Spirals

- Even for constant v(R), the angular velocity (v/R) drops with increasing distance
  - differential rotation should wind spirals up
- Theories:

  1) Starburst is stretched out by differential rotation:

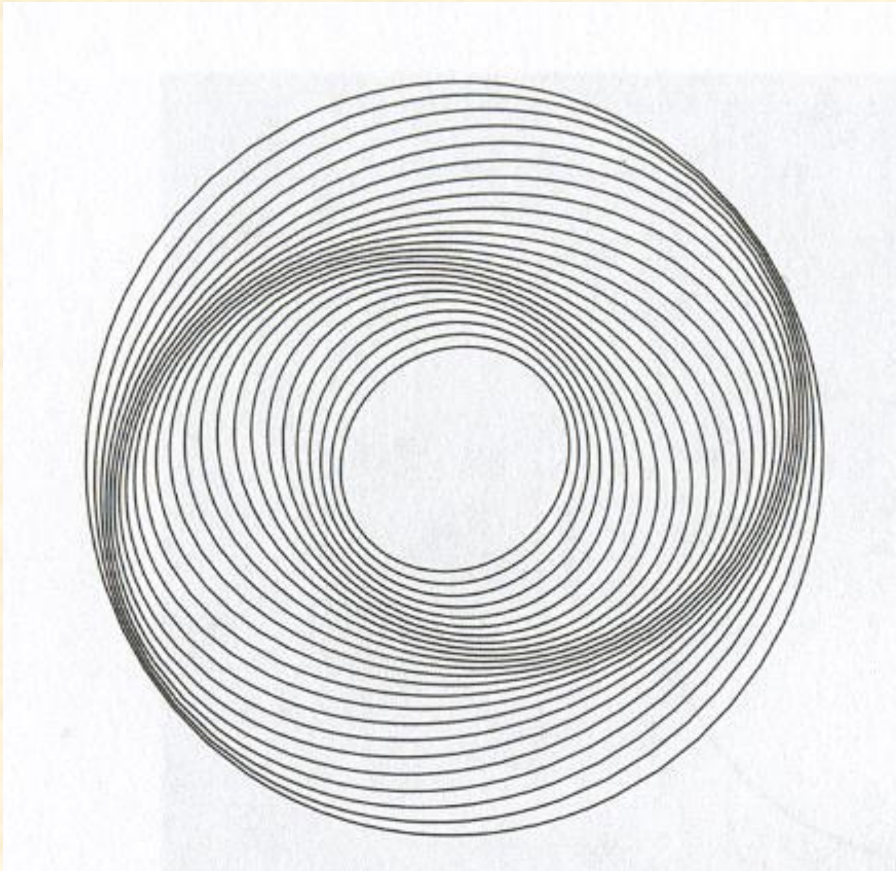
  → works for fragmentary (flocculent) arms

  2) Density wave

  → continuous (including grand design) arms

  → pattern speed tends to be much slower than rotation

  → pattern is maintained by self gravity

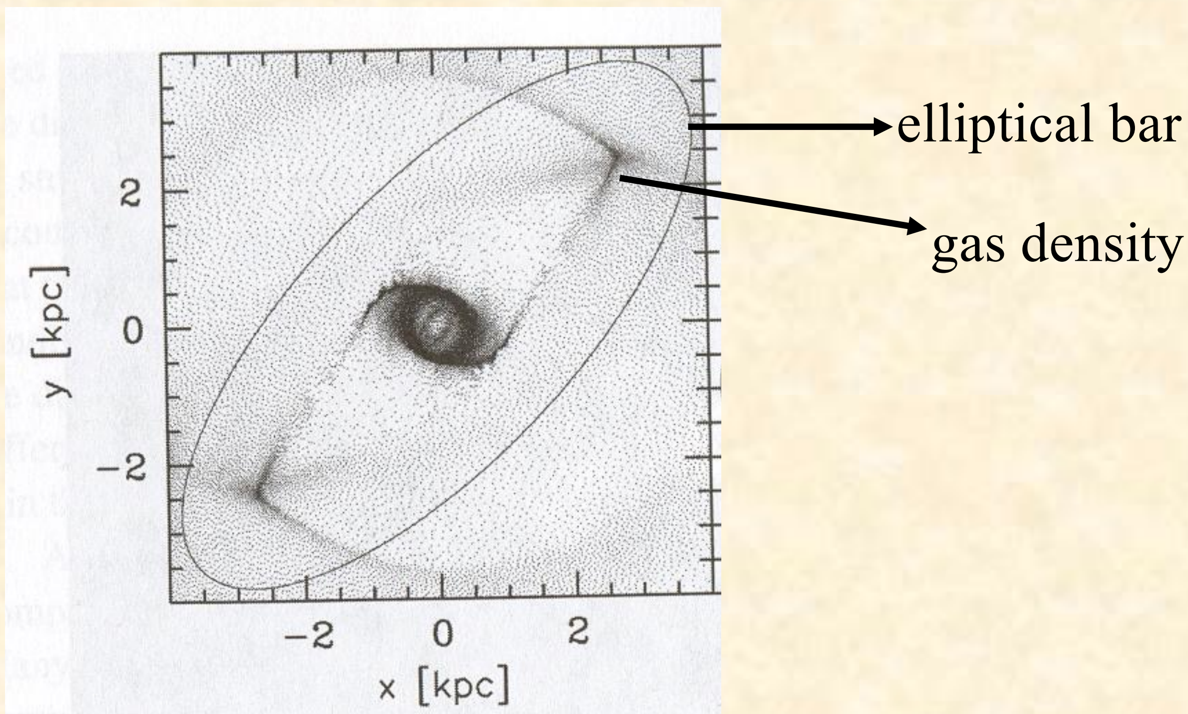


(Sparke & Gallagher, p. 219)

- Two-armed spiral: nested ovals with rotating position angles
- Originates from external (another galaxy) or internal (bar) perturbations

Bars

- Not a density wave - “stars remain in bars”
- As with spirals, pattern speed is slower than rotation (up to the co-rotation radius, where bar ends)
- Gas builds up and is shocked on leading edge → infall



(Sparke & Gallagher, p. 235)

Supermassive Black Holes (SMBHs)

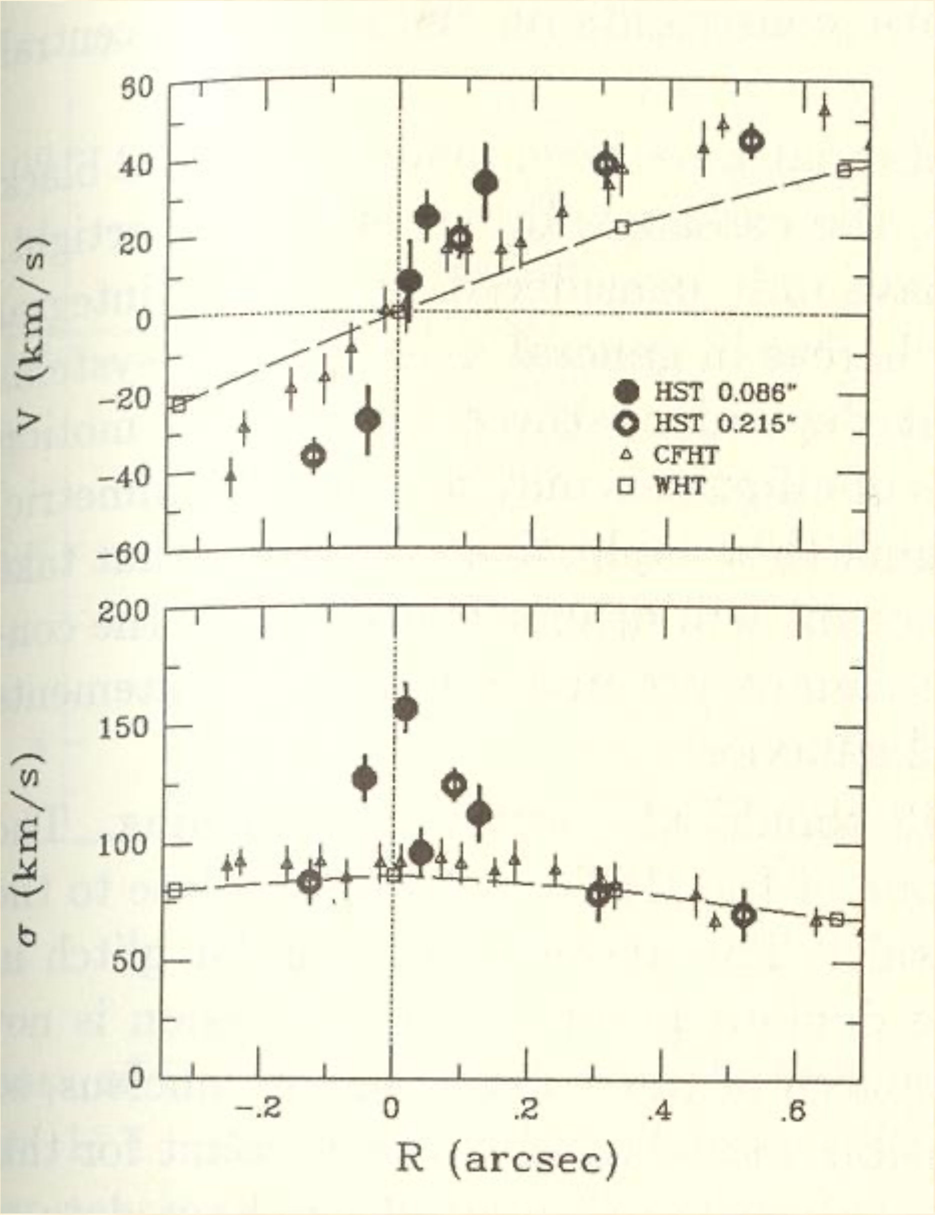
- SMBHs have been detected in the gravitational centers of most nearby galaxies.
- Direct methods to detect and measure masses of *quiescent* SMBHs are based on **resolved** spectroscopy:

1) Stellar kinematics:
   - Should show rapid rise in v_r and/or σ near center.
   - Need high angular resolution (HST or Ground-based AO)
   - Use dynamical models (dominated by ellipticals and bulges).
   - What range of stellar orbits and mass density distributions $\rho(\mathbf{r})$ give the observed v_r, σ, and μ (2D) distributions?
   - Add a point-source mass (if necessary) to match the core.
2) Measurement of positions, proper motions and radial velocities of individual stars

   - only the Milky Way → $M_\bullet = 4.3 \times 10^6\ M_\odot$

1) Stellar Kinematics from HST

Ex) M32 (compact dE)



- HST detected high v_r and σ in core.
- trends smeared out in ground-based telescopes
- SMBH Mass: $M_\bullet = 3 \times 10^6\ M_\odot$

"Clincher": STIS LOSVD in core shows high-velocity wings (Joseph, et al. 2001, ApJ, 550, 668)

Why do we need high angular resolution?

- What is the radius of influence for the SMBH in M32?

$$r = \frac{GM_\bullet}{\sigma_*^2}, \quad \text{where } \sigma_* = \text{typical stellar velocity dispersion}$$

For M32, $r \approx 1$ pc $\rightarrow 0.3''$ at a distance of 725 kpc.

- SMBH "machine": HST's Space Telescope Imaging Spectrograph (STIS) – long slit, high resolution spectra
  - angular resolution ~ 0.1", velocity resolution ~ 30 km/s
  - measured SMBH masses in many nearby galaxies
- Note these observations do not **prove** existence of SMBHs

  Ex) M32 mass concentrated within ~0.3 pc:

  → $\rho \approx 10^{-15}$ g cm^{-3} ! (pretty good vacuum)

  → previously: must rely on arguments that stars inside this volume would collide and eventually form a SMBH

What would prove the existence of a SMBH?

- Gravitationally redshifted emission from gas within a few times the Schwarzschild radius (R_s)

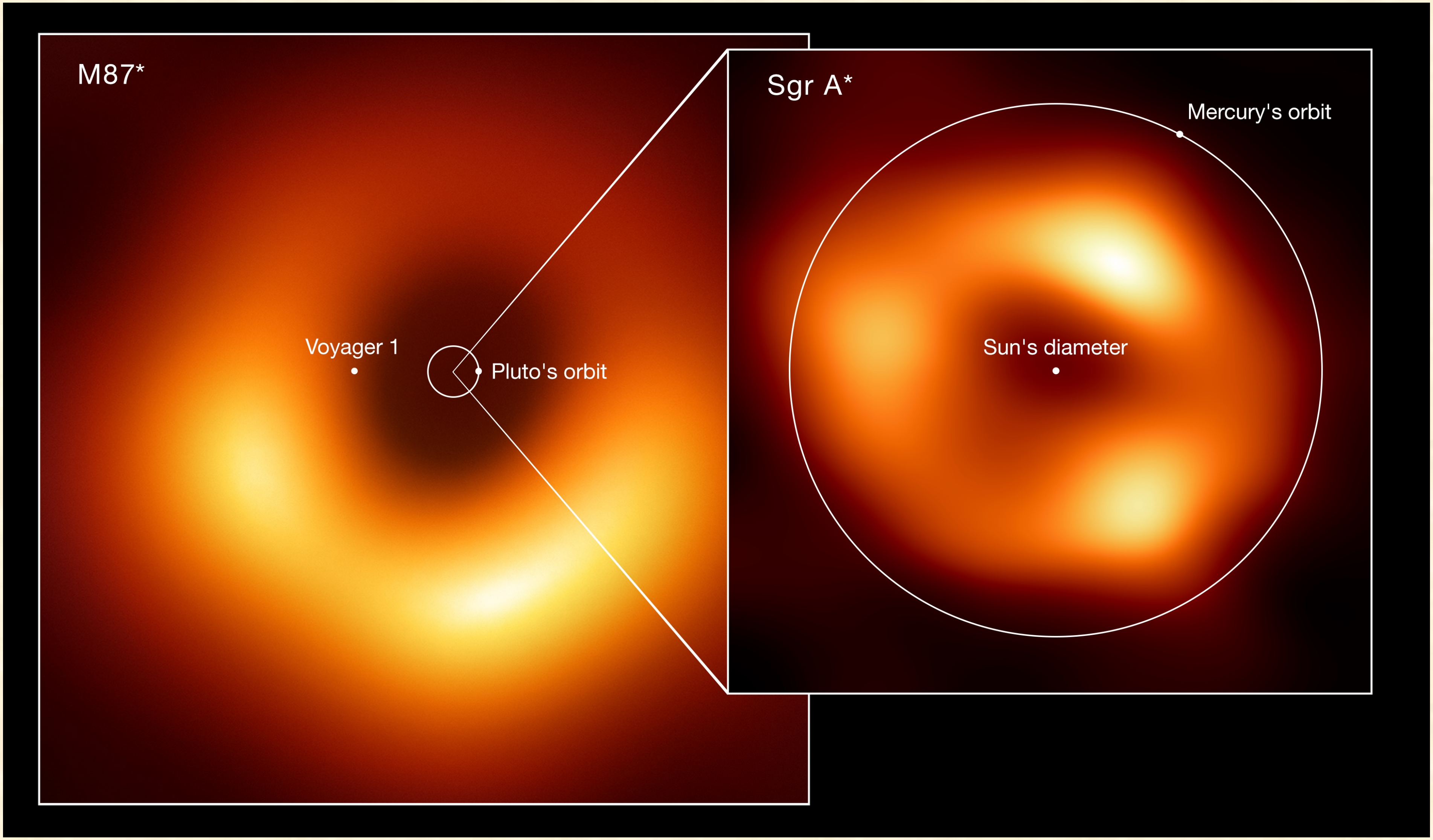
$$v_{esc}^2 = c^2 = \frac{2GM_\bullet}{R_s} \quad \rightarrow \quad R_s = \frac{2GM_\bullet}{c^2}$$

For M32: $R_s = 9 \text{ x } 10^{11}\text{cm} \approx 13 R_\odot$

$\rightarrow$ projected angular size: $\theta \approx 10^{-7}$ arcsec

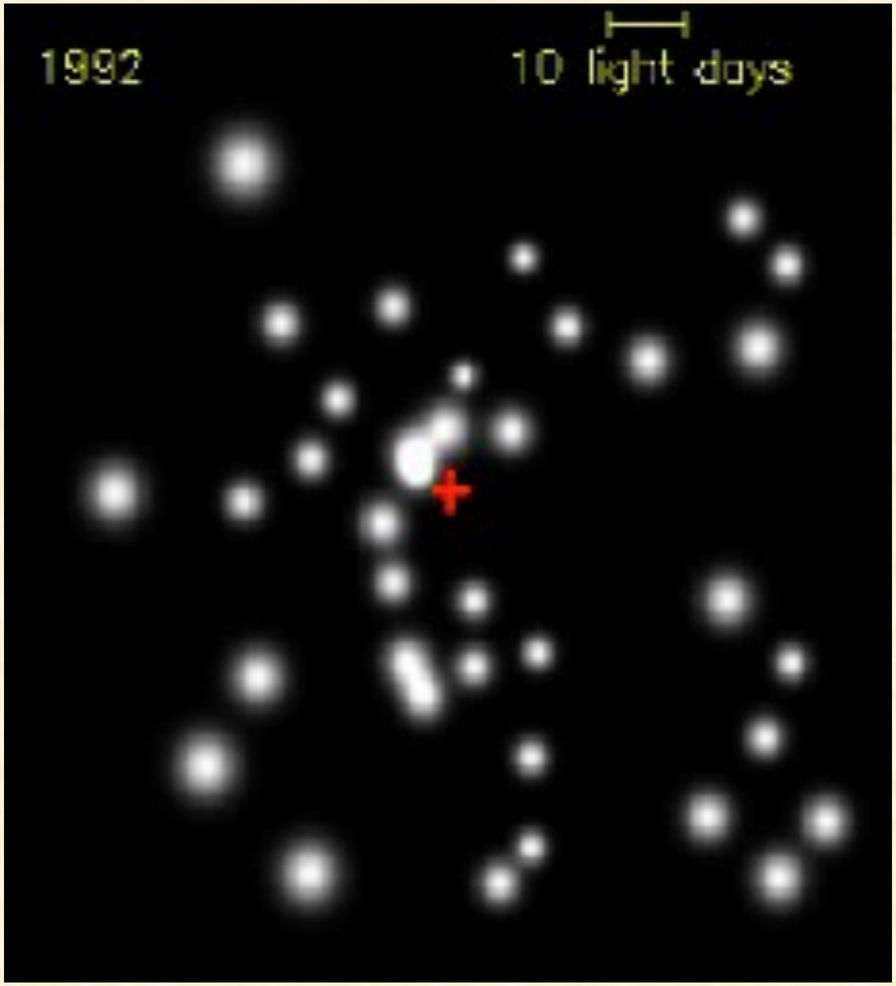
- No hope of resolving directly (can't get rotation curve)
- X-ray observations of AGN have detected gravitationally-redshifted Fe Kα emission (presumably from accretion disk)
- Now we have proof from Event Horizon Telescope observations of M87 and Sgr A*.

EHT



$M_\bullet = 6.5 \times 10^9 \, M_\odot$ $M_\bullet = 4.3 \times 10^6 \, M_\odot$

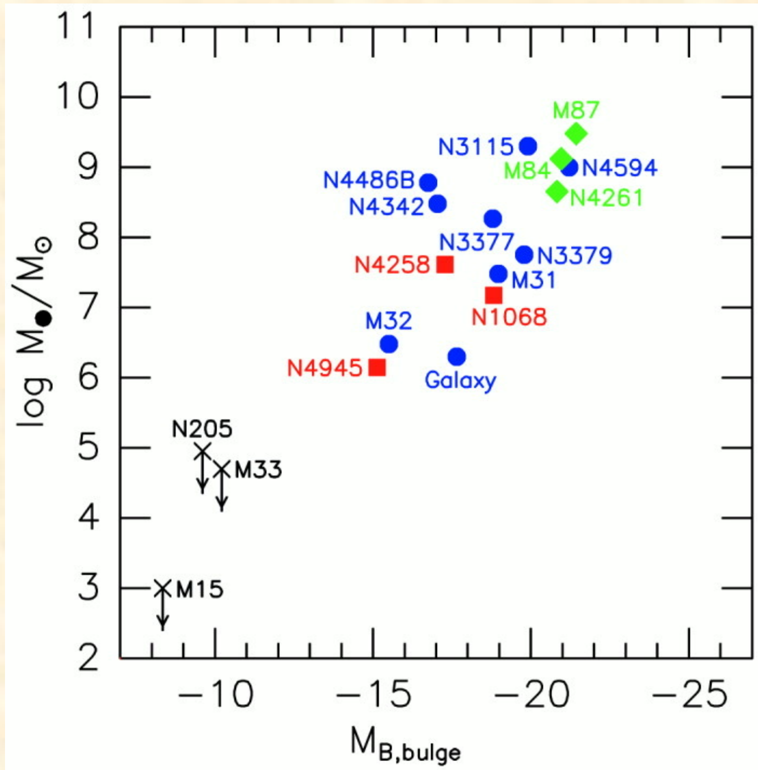
2) Individual Stars - Milky Way



- K band observations with NTT, VLT (mostly O and B supergiants)
- Proper motions plus radial velocities give $M_\bullet = 4.3 \times 10^6\ M_\odot$

SMBH Mass/Bulge Correlations

- Kormendy et al. found a correlation between SMBH mass ($M_\bullet$) and absolute blue magnitude of the bulge/elliptical

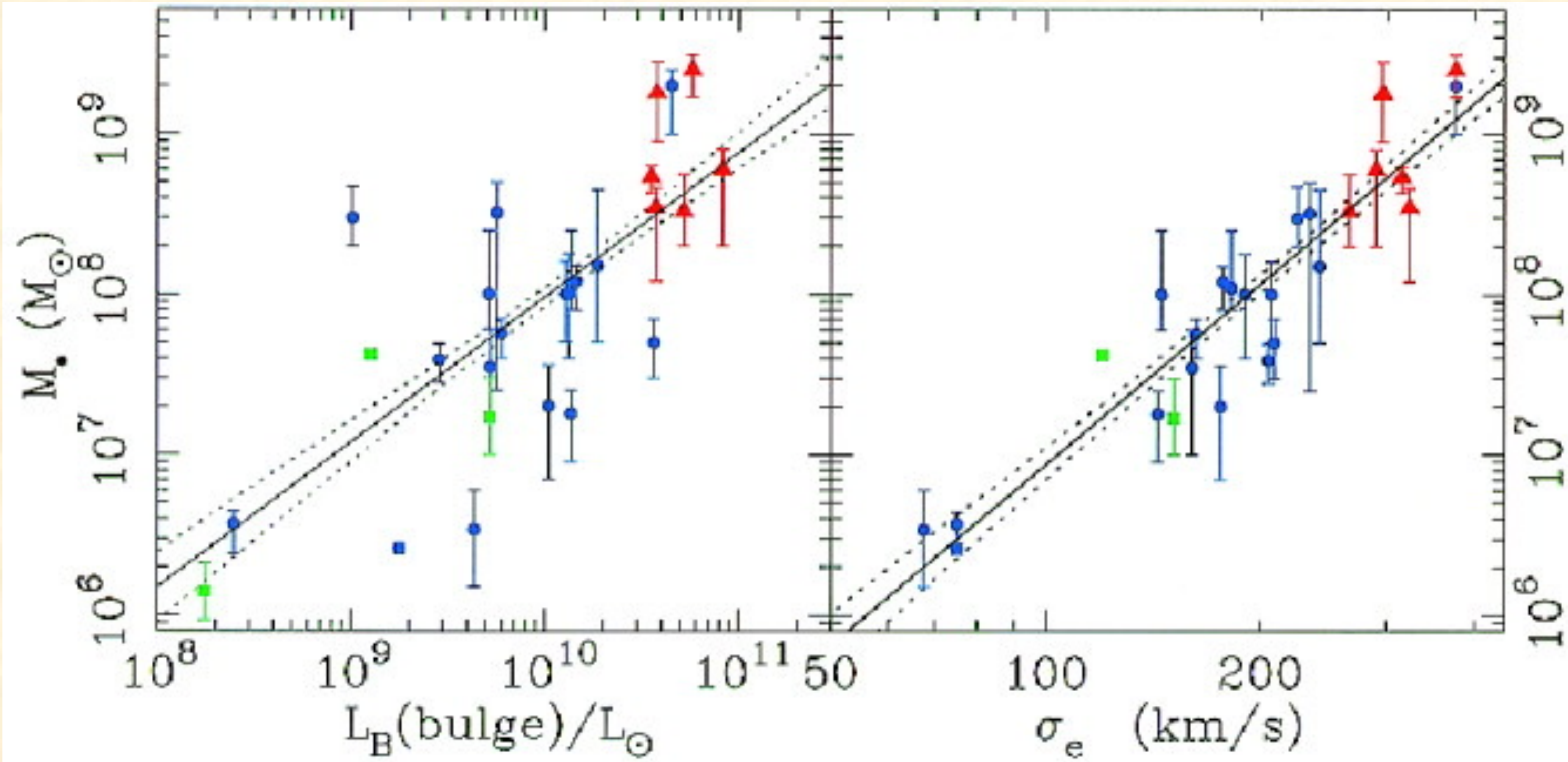


green – gas kinematics
blue – stellar kinematics
red – H_2O maser

(Kormendy, et al. 1998, AJ, 115, 1823)

- recent studies confirm: $L_{bulge} \sim M_\bullet$
- given a constant M/L ratio: $M_\bullet \approx 0.002\ M_{bulge}$

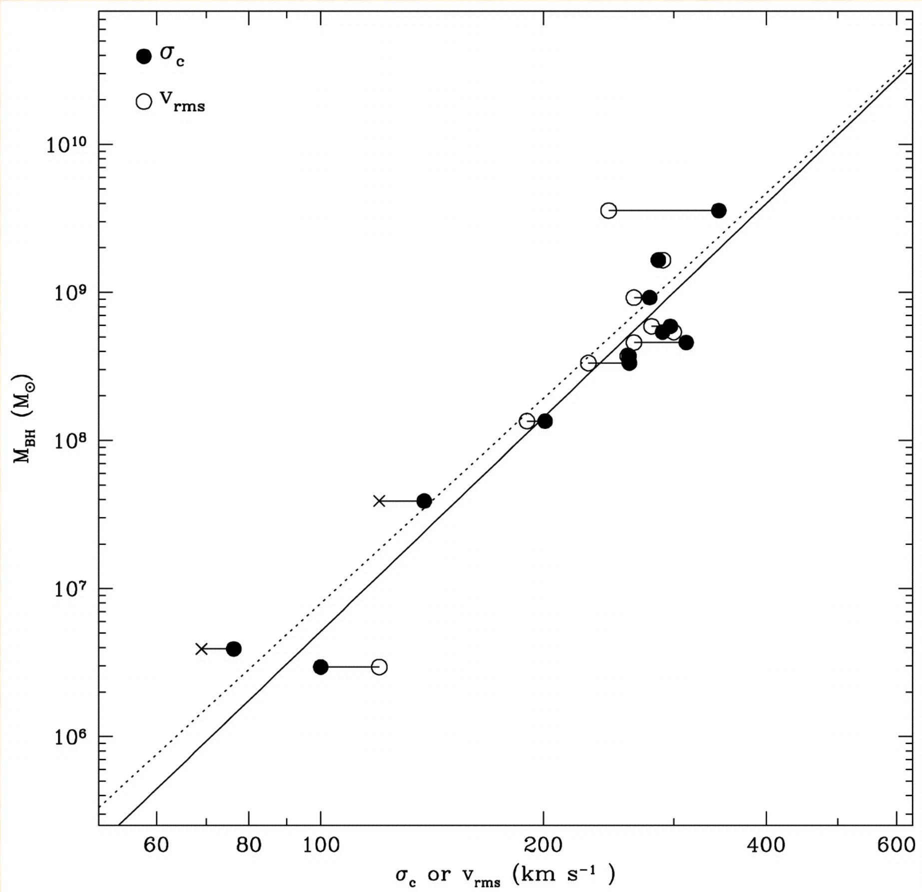
- Tighter correlations have been found with σ (bulge):
  1) $M_{\bullet} \sim \sigma^{3.75}$



(Gebhardt et al. 2000, ApJ, 539, L13)

- from stellar, gas kinematics, and masers
-σ_e: velocity dispersion of bulge within half-light radius

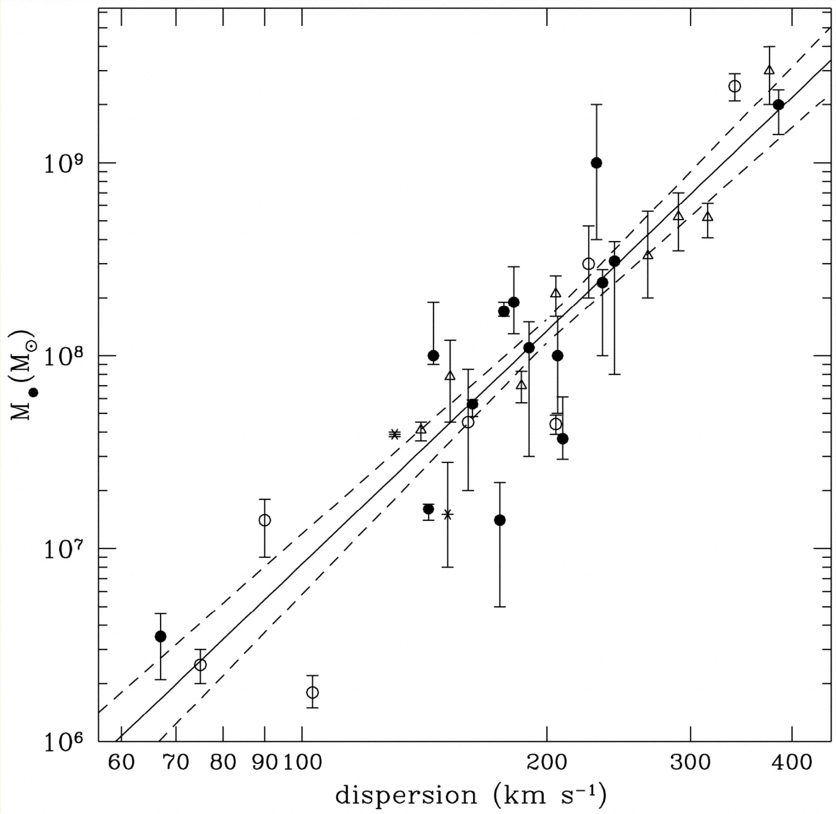
2) $M_\bullet \sim \sigma^{4.80}$



(Ferrarese & Merritt 2000, ApJ, 539, L9)

σ_c – velocity dispersion within 1/8 the effective radius of bulge

3) Subsequent Calibration: $M_\bullet \sim \sigma^4$



(Tremaine, et al. 2002, ApJ, 574, 740)

- based on stellar (circles), gas kinematics (triangles), masers (asterisks)
- previous disagreements probably due to different ways to measure σ(bulge)

$$\log\left(\frac{M_\bullet}{M_\oplus}\right) = (4.02 \pm 0.32)\log\left(\frac{\sigma}{200\ \mathrm{km\ s^{-1}}}\right) + \left(8.19 \pm 0.06\right)$$

Implications

- SMBHs present in all galaxies with a spheroidal component
- For distant galaxies, $M_\bullet$ can be inferred from σ_0 or L_{bulge}
- SMBHs in AGN have the same mass as quiescent SMBHs for a given spheroidal (bulge) mass ($M_\bullet \approx 0.002\ M_{bulge}$)
  - AGN were much more common in the past. Many quiescent SMBHs are dead remnants of AGN/QSOs.
- How do SMBHs know about their bulges? – linked by evolution?
- SMBHs formed by
  1) Overdensities in the early Universe?
  2) Massive Pop III stars?
  3) BHs from evolution of nuclear star cluster?

→ Perhaps linked by AGN feedback: radiation and mass outflows determine size of SMBH and bulge