Part 4: Structural & scaling laws for galaxies

Structure of galaxies

Surface brightness distributions

- Elliptical galaxies
  - King models
    - fit some elliptical galaxies well
      - ex. NGC 4472 ->

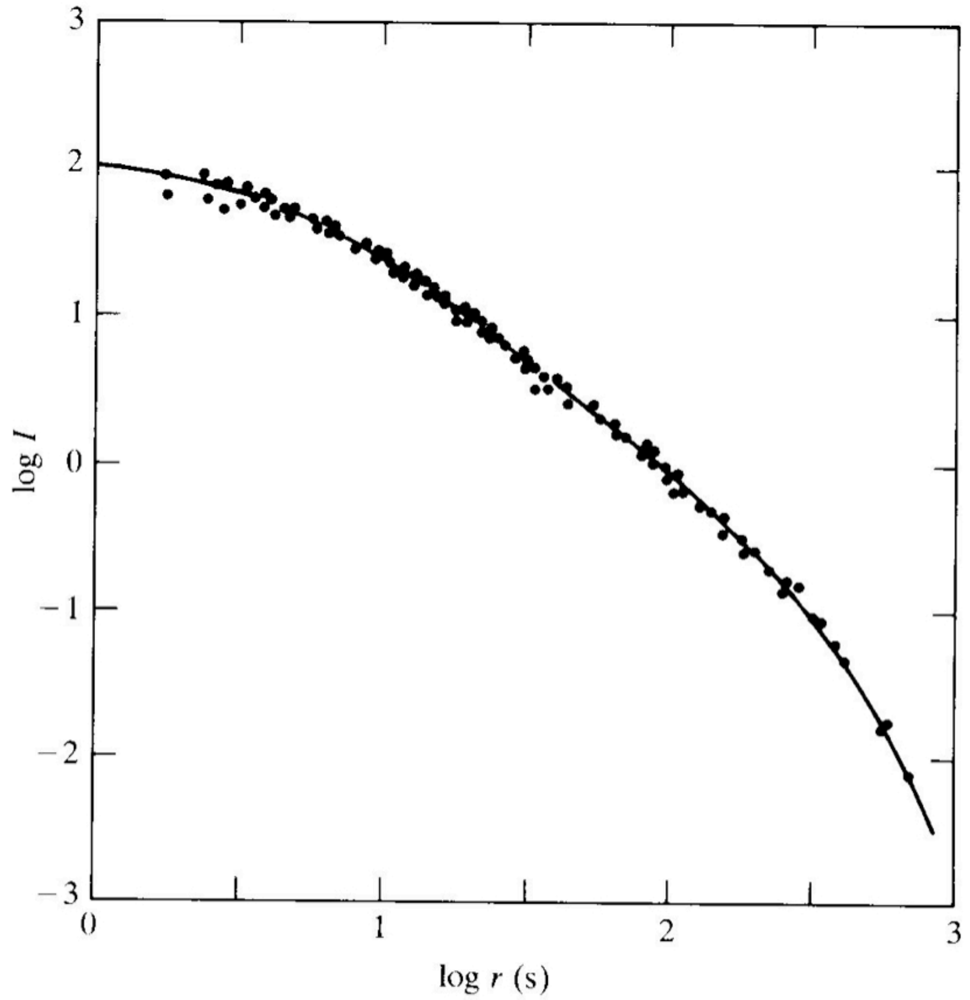
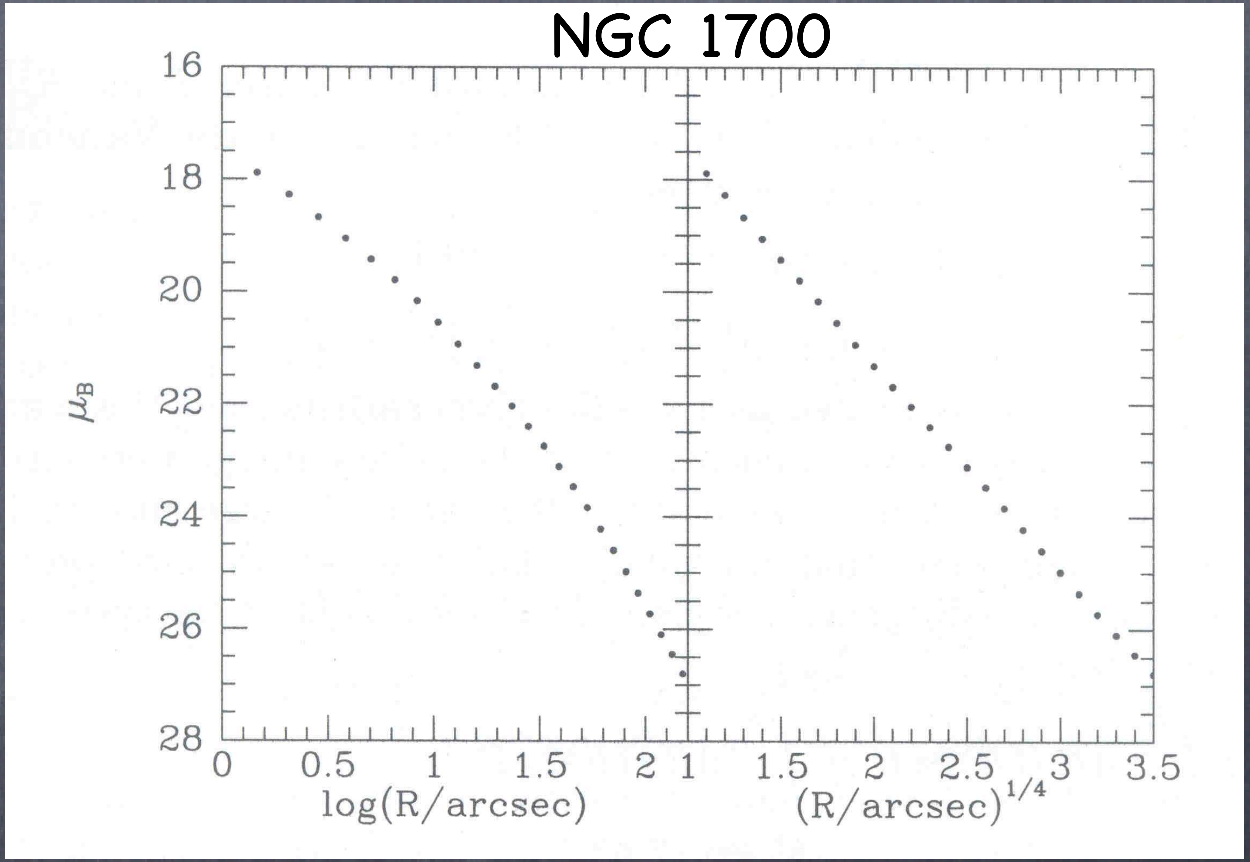


Figure 5-11. The brightness profile of NGC 4472 (data points) is well fitted by the $c = 2.35$ King profile (curve). It follows from this and Figure 5-13 that these observations of NGC 4472 cannot be so well fitted with the de Vaucouleurs law. [From (**K2**), by permission. Copyright © 1978 by the American Astronomical Society.]

- de Vaucouleurs “law”
  - better fit, empirical:

$$I = I_0 10^{-3.33[(r/r_e)^{1/4}-1]} = I_0 \exp\{-7.67[(r/r_e)^{1/4} - 1]\}$$

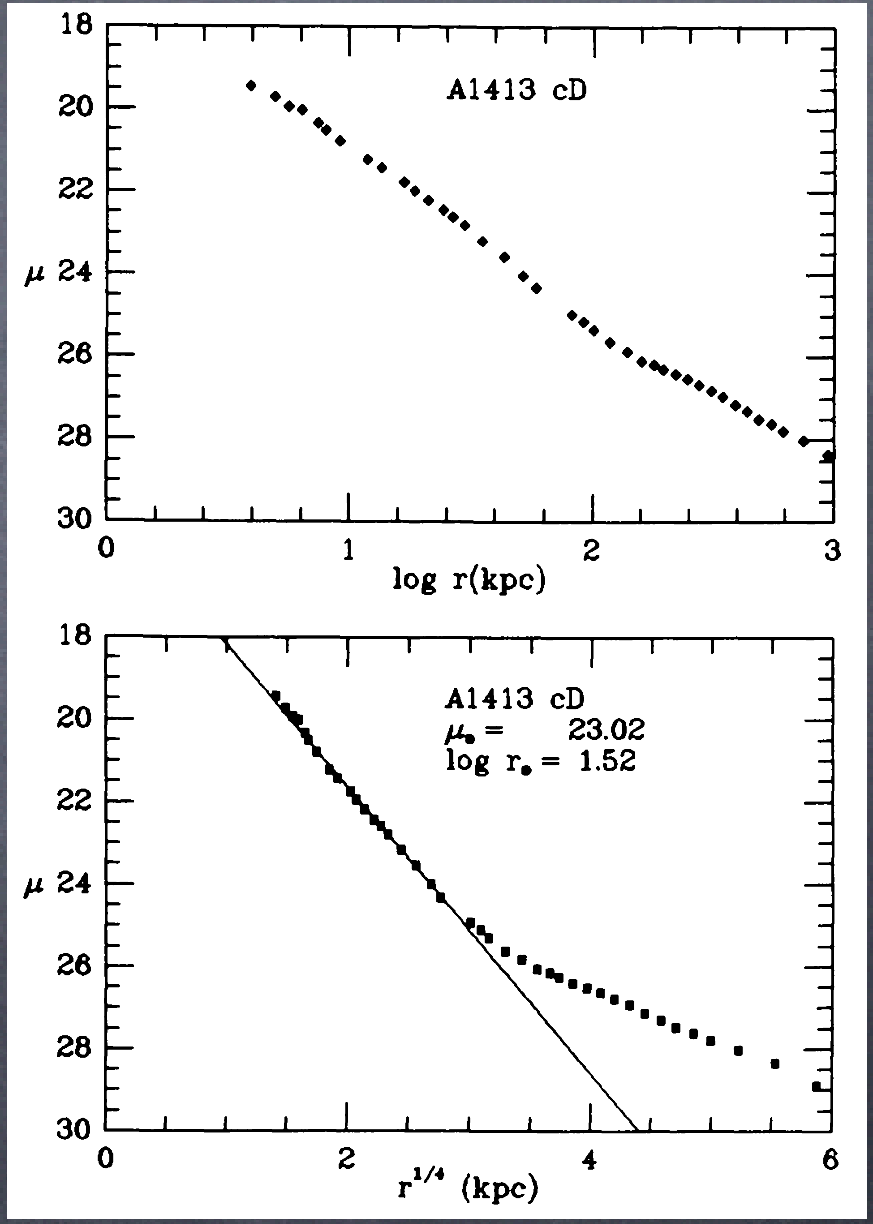
  - r_e is half-light radius (i.e., half of total light is contained within r_e)
  - I_0 is surface brightness at r_e
  - Binney suggest that dV law is close to the profile given by $f(\epsilon) \sim exp[-\frac{E}{\beta}]$
    - but no perfect DF for dV law...



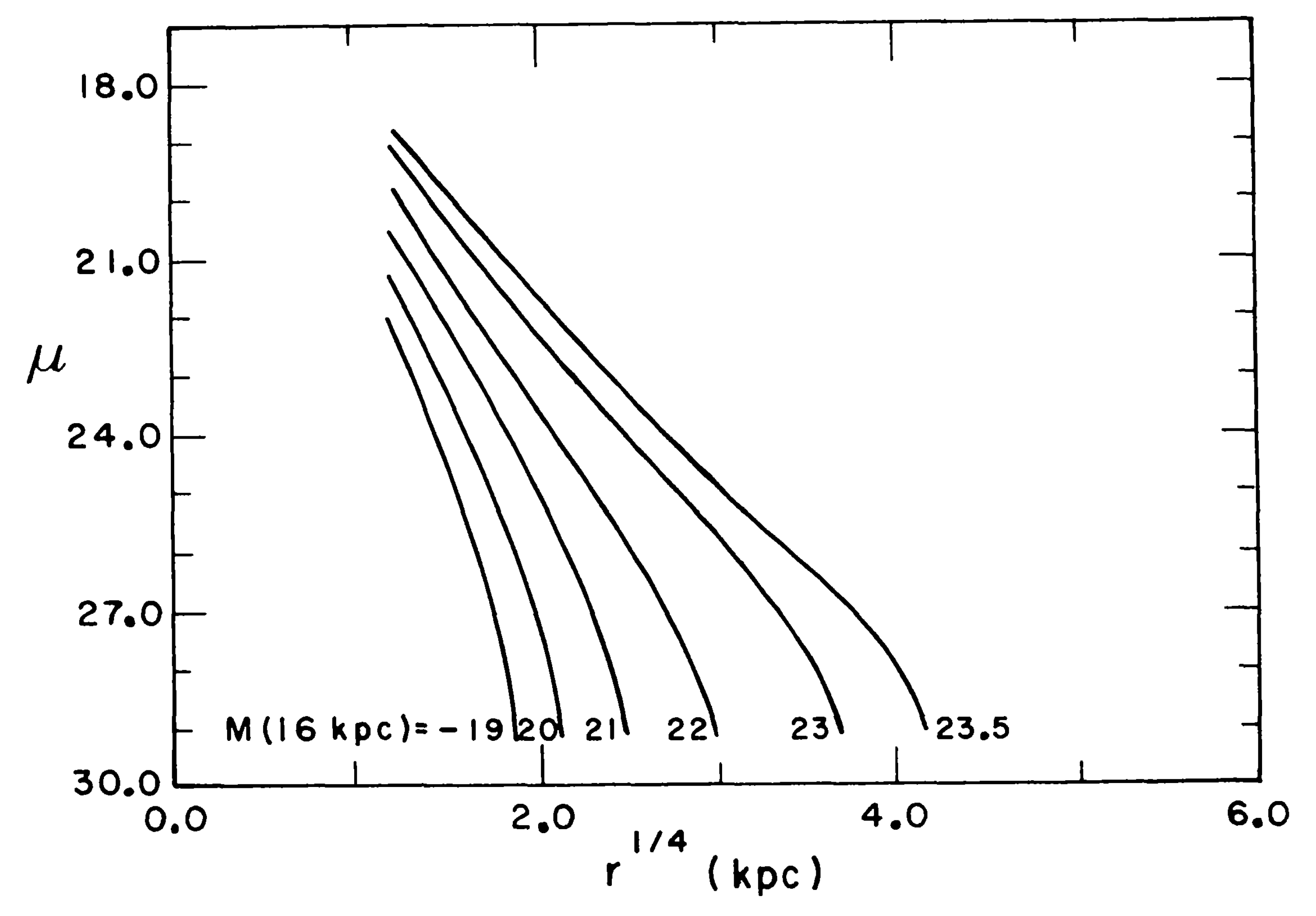
- Comparing distributions, find that
  - Core: King models have a core at center; dV doesn't
  - Envelope: King models have finite boundary; dV has infinite extent
- Goodness of fit:
  - Envelope: dV fits better
  - Core: dV a bit better for big E's, King a bit better for small E's
    - but note that the true inner regions are better fit by other profiles: Sérsic or Nukers

Deviations from deVaucouleurs law

- cD galaxies are elliptical galaxies with extended envelopes that sit at (or near) the center of clusters (or rich groups)
  - cD galaxies are always the brightest cluster members
  - note that not <u>all</u> clusters have a cD
  - and that not <u>all</u> "cD" galaxies have extended envelopes
- Where does the envelope come from?

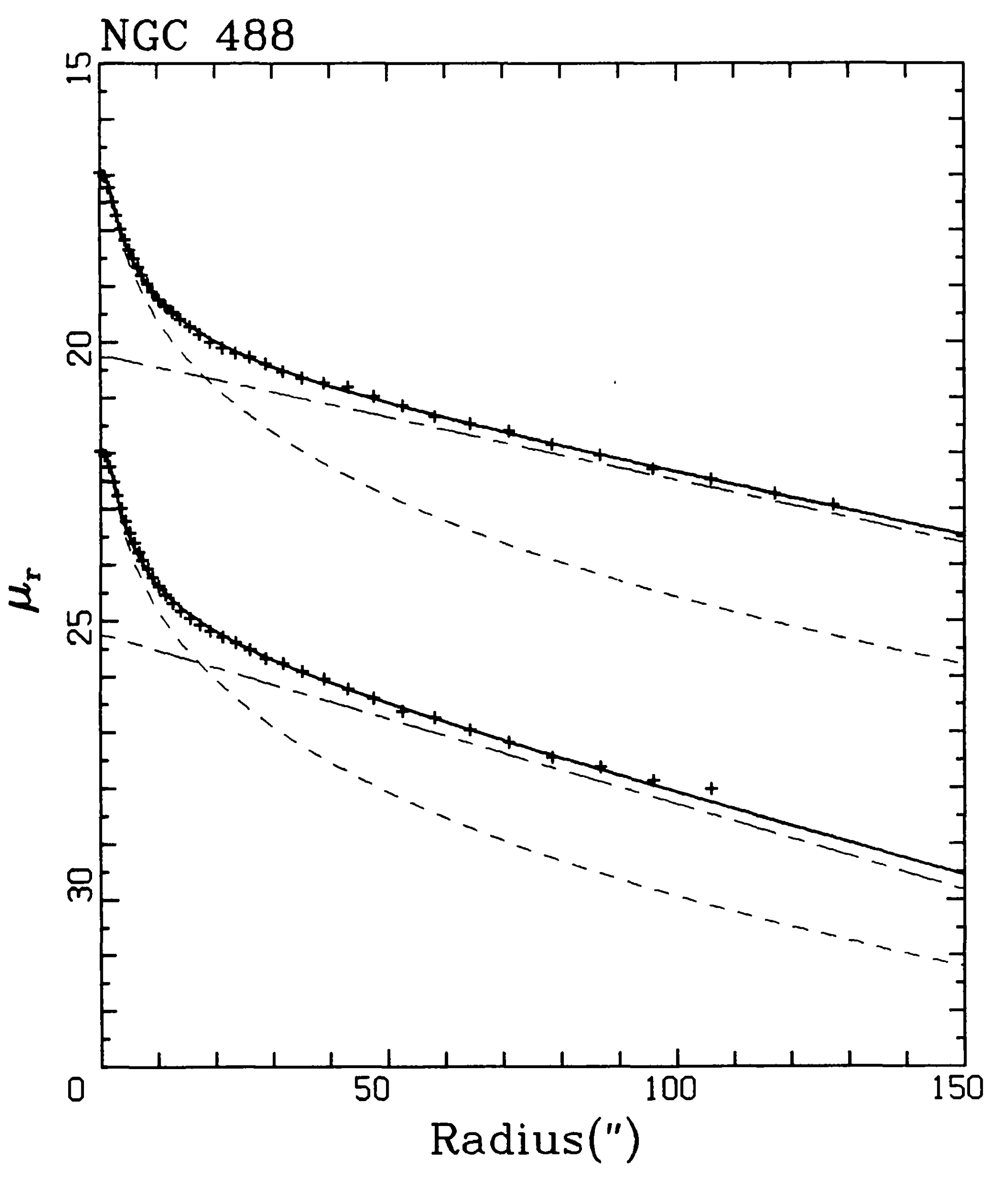


- Surface brightness profile shape also seems to correlate with luminosity (Schombert 1986)



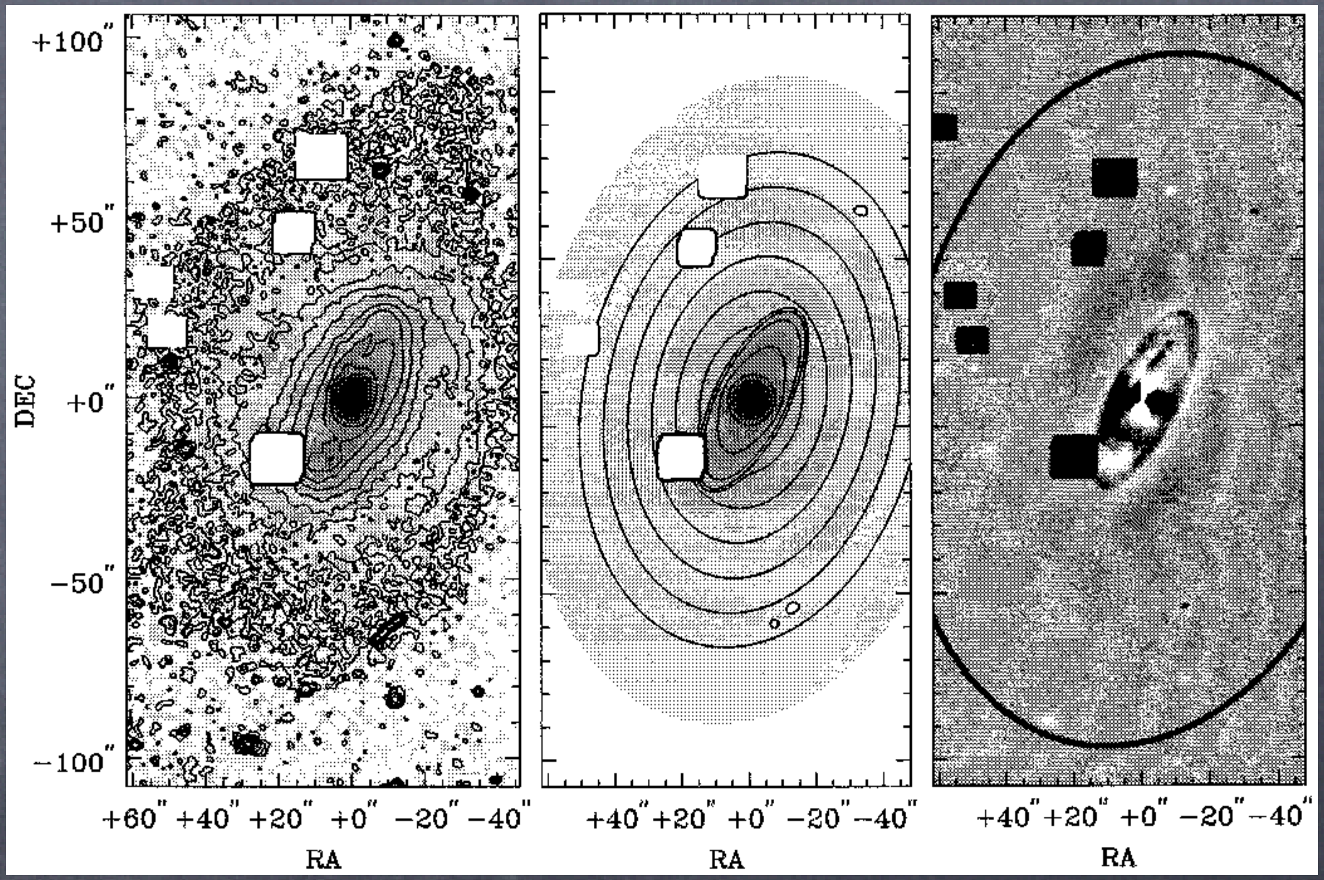
Disk galaxies

- Basic law: exponential disk, $I = I_0 e^{-r/a}$
  - a is the disk scale length; roughly 1-10 kpc
- Freeman (1970) showed that big spirals had I_0 strongly clustered around $I_0^B = 21.5\,\mathrm{mag}/\square''$
  - I_0 fainter for dwarfs and LSB galaxies



Bulge-disk decomposition

- In the bad old days, bulges and disk were "decomposed" from 1D surface brightness profiles
- Now, we do something a bit more sensible: we use the full 2D information
  - allows for cleaner separation between components



- Some issues with bulge-disk decompositions
  - Not all “bulges” are deVaucouleurs: many are exponential and may be “pseudobulges” formed from some internal secular evolution process (Kormendy & Kennicutt 2004, ARAA)
    - e.g. M33 has a significant SB excess in center, but has no bulge: spiral arms go right into center
  - Not all disks are perfect exponentials: spiral arms, dust, “peculiarities”

A generalized surface brightness “law”

- The Sérsic profile: $I = I_0 10^{-b_n[(r/r_e)^{1/n}-1]}$
  - when n=1, this is an exponential profile
  - when n=4, this is a deVaucouleurs profile
- Early-type galaxies range in n from 2.5 to 6
- Disk-dominated galaxies generally range from 0.5 to 2
- Does n tell us something physical about the galaxy, or just the amount of light in a disk component?

Scaling laws for galaxies

The Virial Plane

- Using dimensional analysis, let's examine the mass of galaxies using global variables from SB profile
  - length scale (R), surface brightness zeropoint
- and characteristic velocity (V)
- Then we can write from the scalar Virial Theorem:

$$\begin{aligned} K &= -W/2 \\ \frac{MV^2}{2} &= \frac{GM^2}{2} \\ \boxed{M = \frac{V^2R}{G}} \end{aligned}$$

- This can be rewritten in terms of mass surface density:

$$\eta \approx \frac{M}{R^2} \approx \frac{V^2}{GR}$$

- Introduce the (observable) surface brightness:

$$I \approx \eta \left(\frac{L}{M} \right)$$

- or

$$\boxed{I \approx \frac{V^2}{GR(M/L)}}$$

- This is the basic <u>virial plane equation</u>
  - Expresses mass in terms of
    - <u>observables:</u> V, R, I
    - and <u>unobservable:</u> mass-to-light ratio (M/L)

- Important result!
- We have three-space of V, I, R (observables!) and impose <u>one</u> constraint: hydrostatic equilibrium
- Result: expect a <u>surface</u> in V, R, I space
  - <u>provided (M/L) is well-behaved</u>

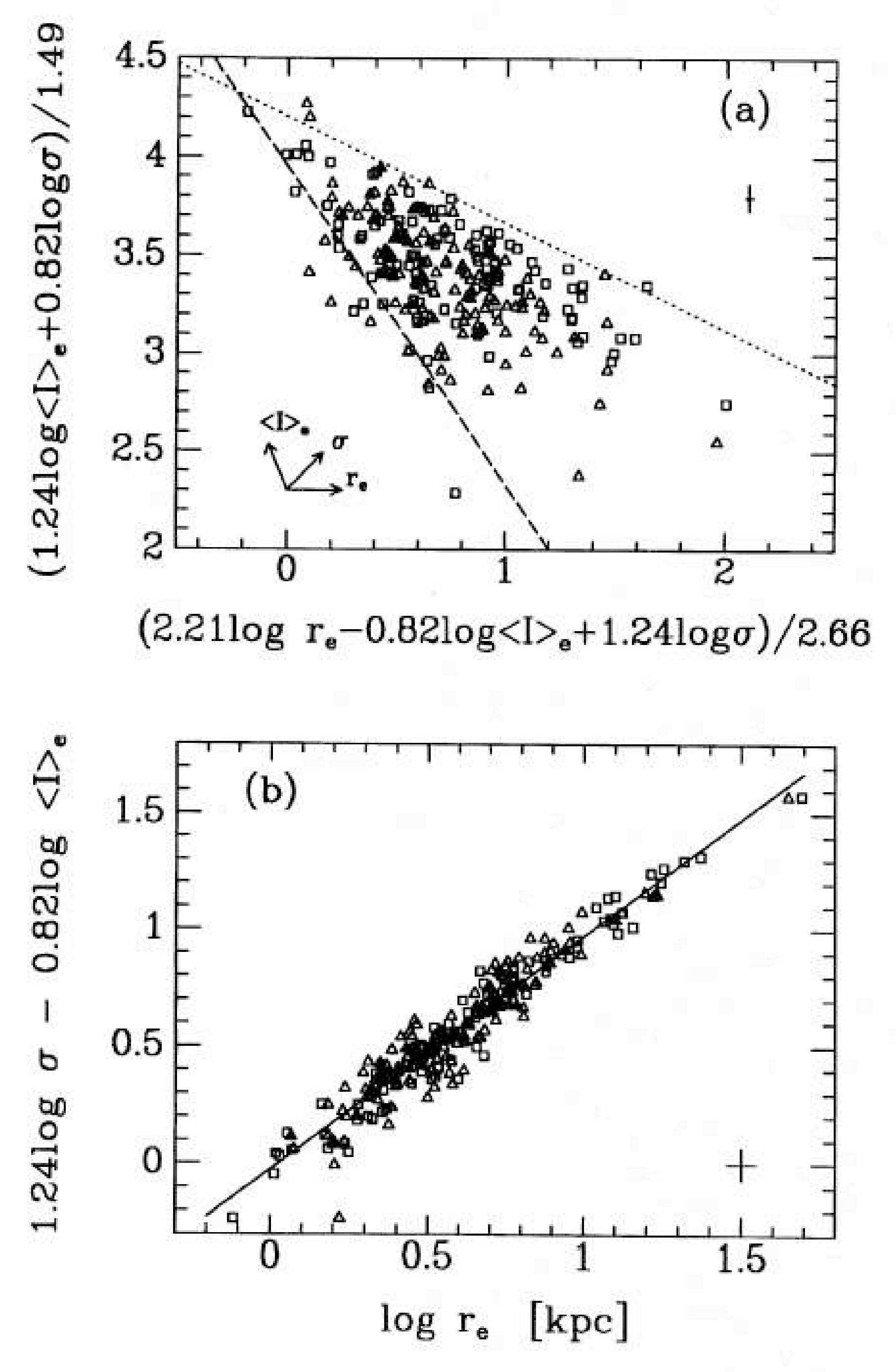
The Fundamental Plane of Early-type Galaxies

- The FP was discovered simultaneously by Dressler et al. (1987) and Djorgovski & Davies (1987)
  - earlier for E-gal cores by Lauer (1985)
- Current "canonical" parameters from Jørgensen et al. (1996):

$$r_e \propto \sigma^{1.24} \langle I_e \rangle^{-0.82}$$

- and

$$M/L_r \propto L_r^{0.31} \langle I_e \rangle^{0.02}$$



- Physical content: we expected $r_e \propto \sigma^2 I^{-1}$ from the Virial Plane if M/L is constant for all galaxies (see Bender, Burstein & Faber 1992/3)
  - Variable M/L "tilts" plane, so we actually get the observed parameters
  - Interesting result is how M/L affects plane:

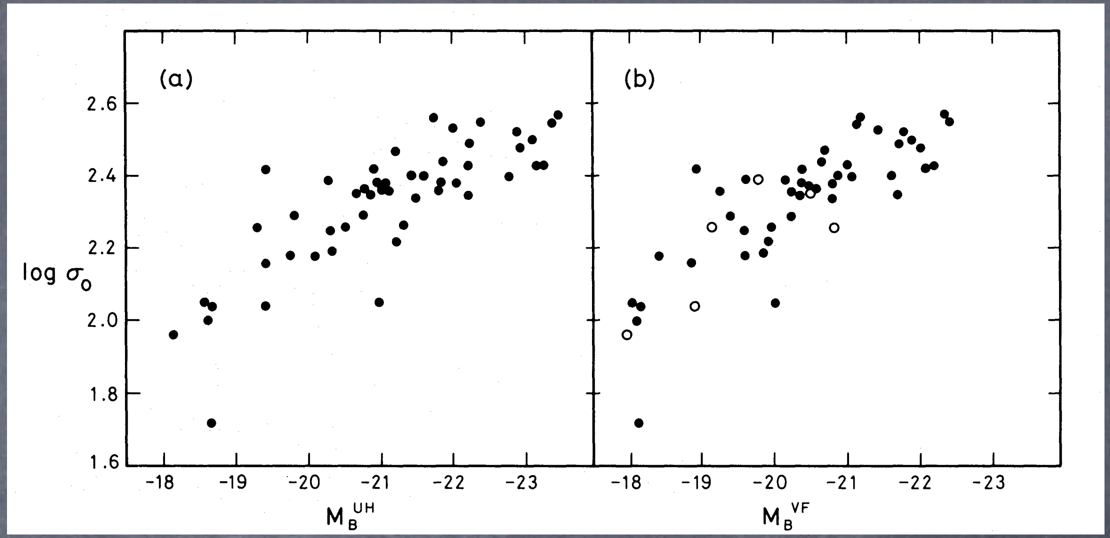
$$M/L_B \propto L_B^{1/4}$$

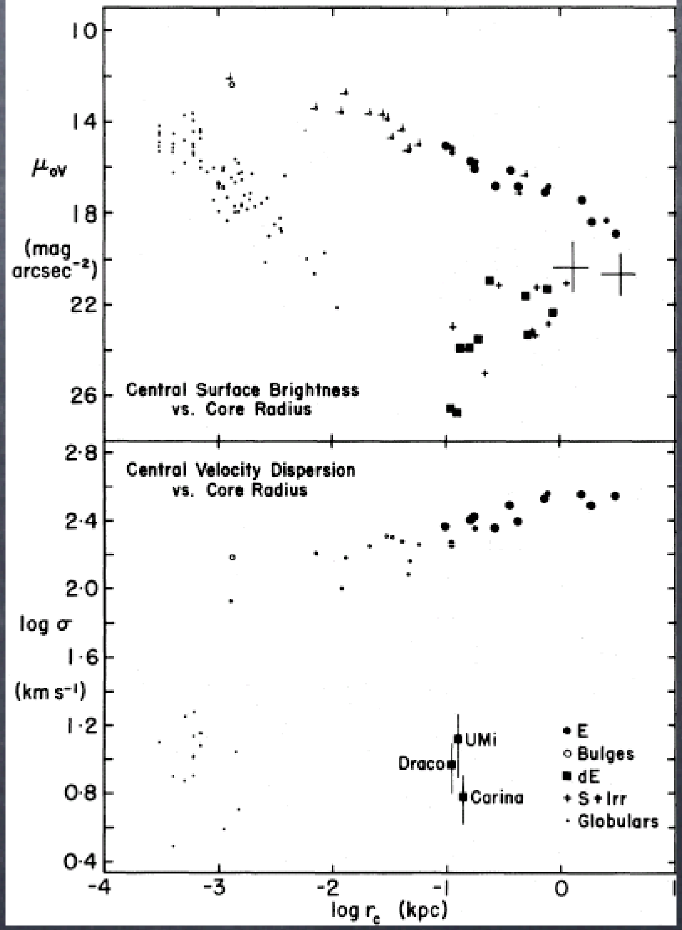
- Note:
  - same M/L for core parameters (Lauer) and global parameters: M/L constant throughout visible region of early-type galaxies
    - little DM in luminous regions of E's, unlike spirals
    - are baryons in E's more concentrated in dark halos?

- Notes, continued:
  - Orientation effects move galaxies parallel to plane, not off of it
  - But! We've assumed a homology relation here: small and large ellipticals have same shape
    - does this cause tilt? (long literature!)
  - FP provides a distance indicator: σ and I are distance independent; r_e depends on $D\theta_e$
    - accuracy as a distance indicator is ~14%
    - scatter in M/L roughly 23%
      - important question: why do early-type galaxies have such similar stellar populations? (or does M/L lie?)

Projections of the FP

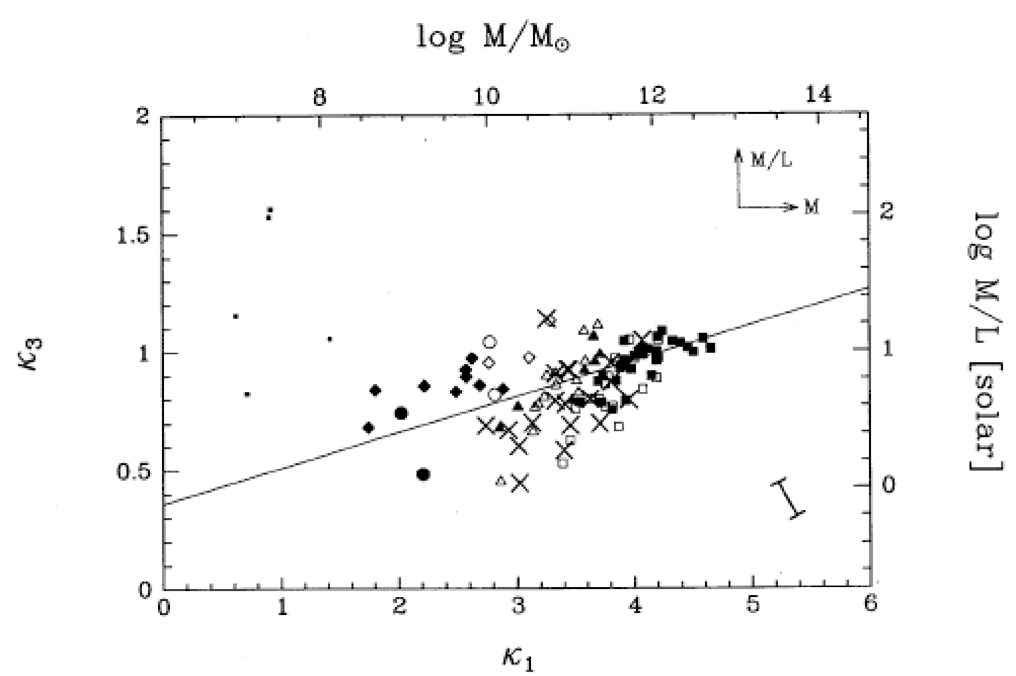
- Rotate plane:
  - face-on: σ vs I
  - edge-on: σ vs L:
    - the Faber-Jackson (1976) relation, $L \propto \sigma^4$
    - also I vs R: the Kormendy relation
      - a useful distance indicator from photometry alone!

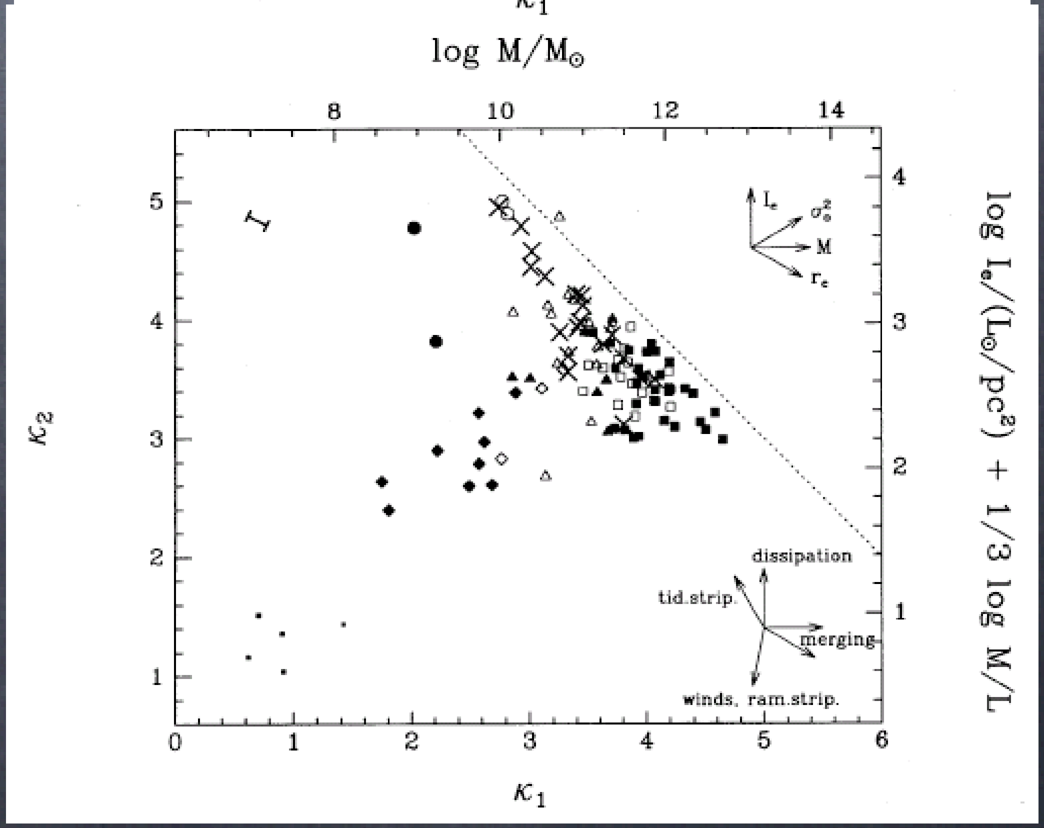




The Virial Plane and Galaxy Formation

- The existence and tilt of the FP has only a slight relation to galaxy formation and evolution, through M/L vs. (I, R, σ)
  - but zeropoint evolution important!
- Essence of galaxy formation is where galaxies stop in FP





- Consider a collapsing galaxy inside its dark halo, so that $M \sim M_{\rm baryon}$
  - as it collapses, $M_{\rm baryon}$ is roughly constant, so $v_{\rm orb}^2 \sim GM/R$
  - But what stops the collapse? How do galaxies know to have the right radii?
- Observations tell us that final R is controlled by M to about a factor of 2, but total M range is about 100x
  - volume of possible VP space occupied by ellipticals is thin cigar