Dynamical Distance Indicators

Spiral Galaxies: $L \sim v^{\alpha}$

"Tully-Fisher Relation"

Elliptical Galaxies: $D_n \sim \sigma^{1.4}$

"$D_n - \sigma$" or "Fundamental Plane"

- why would distances to spirals help us?

- where would good distances to ellipticals be useful?

The "Physics" of Tully-Fisher

gravity: $V^2 = \frac{GM}{R} \Rightarrow M \sim RV^2$

mass-to-light ratio: $M = L\left(\frac{M}{L}\right)$

surface brightness: $\overset{\Sigma}{SB} = \frac{L}{\text{area}} \sim \frac{L}{R^2} \Rightarrow L \sim R^2\Sigma$

so

$$M \sim M$$

$$RV^2 \sim L\left(\frac{M}{L}\right)$$

$$\sqrt{\frac{L}{\Sigma}}\,V^2 \sim L\left(\frac{M}{L}\right)$$

$$\Downarrow$$

$$L \approx \frac{V^4}{\Sigma (M/L)^2}$$

$$L \sim \frac{v^4}{\Sigma (M/L)^2}$$

if: $\Sigma (M/L)^2 = \text{constant}$

$$L \sim v^4$$

since $M \sim -2.5 \log L$

$$M \sim -10 \log v$$

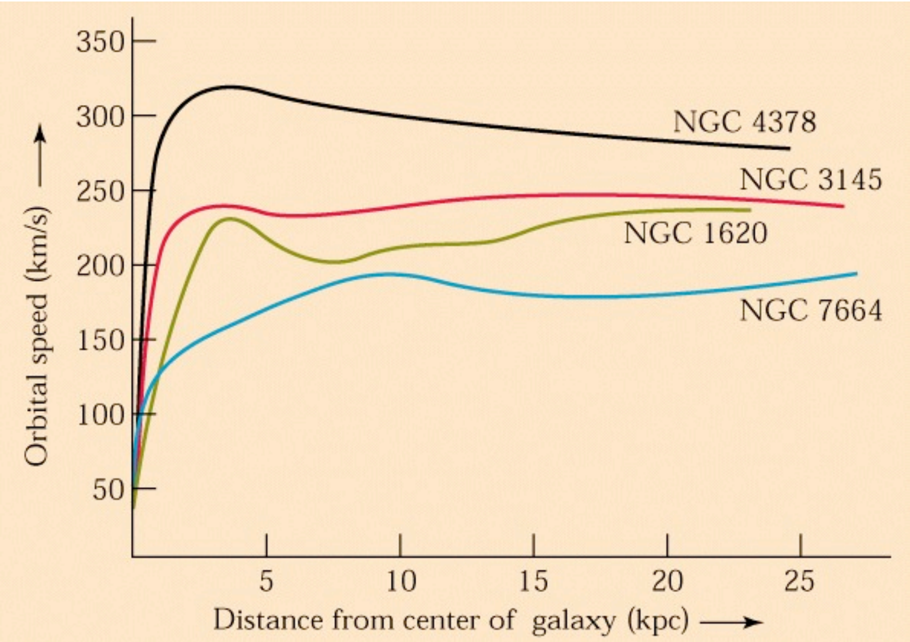
↑ mag, not mass

- is it reasonable that $\Sigma \sim$ constant?

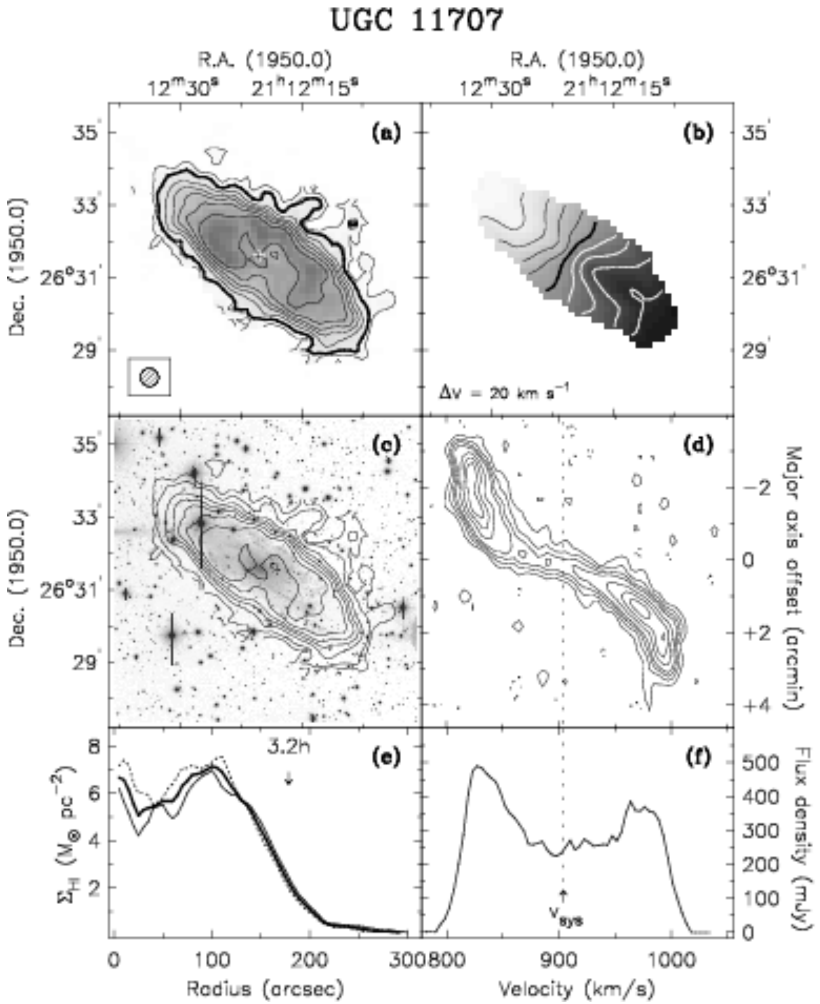
- is it reasonable that $(M/L) \sim$ constant?

- is it reasonable that $\Sigma (M/L)^2 \sim$ const?

Defining Rotation Speed



Measure from Rotation Curve



Measure from HI line width

Effect of Inclination

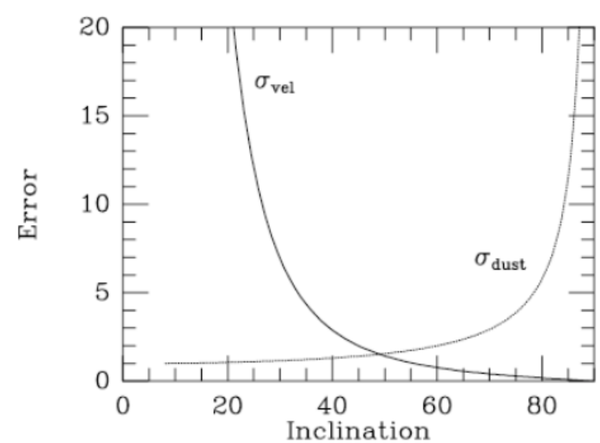
Inclination: i=0 is face-on, i=90 is edge-on. Then $V_{obs}=V_c\sin(i)$

We want to measure both an accurate magnitude and an accurate rotation speed.

What kind of inclinations do we want if we want:

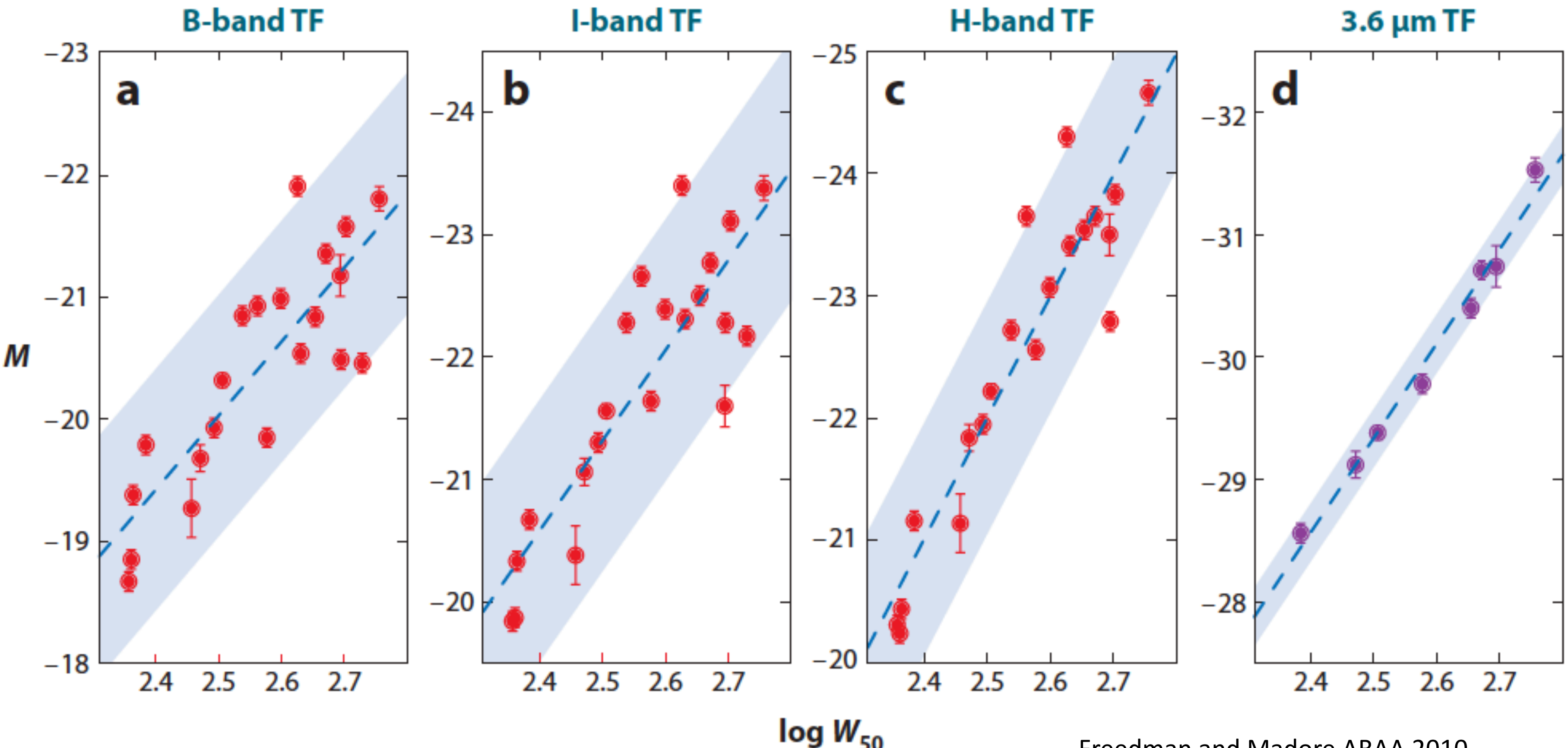
- accurate velocities?
- accurate magnitudes?

How do we measure inclinations?



Tully-Fisher at Different Wavelengths

Tully-Fisher relationship for galaxies with accurate Cepheid distances

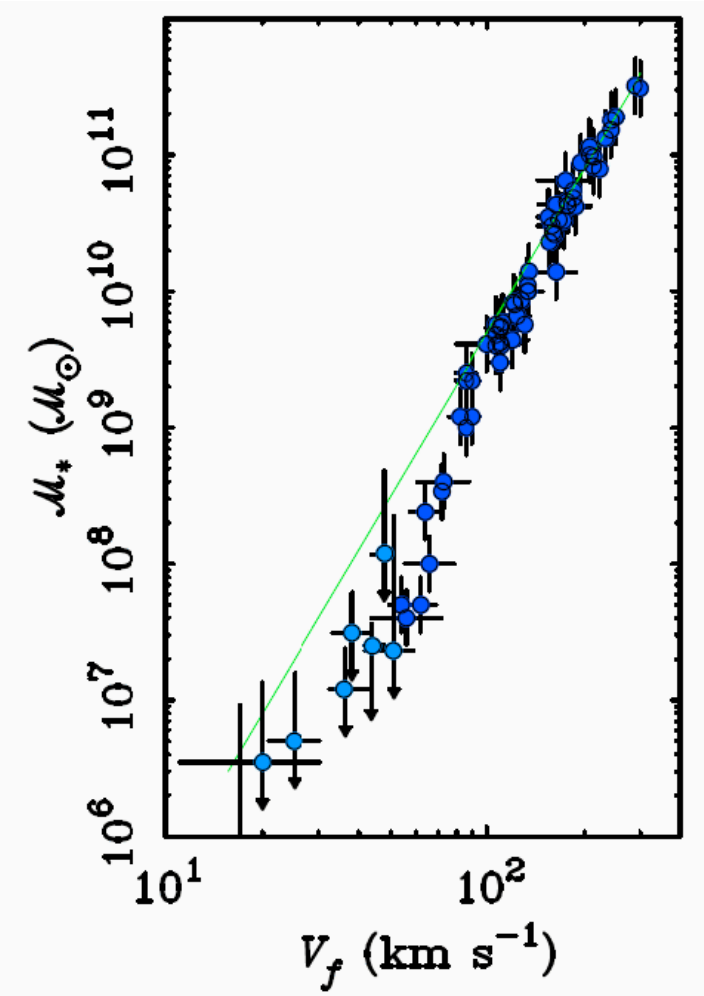


Freedman and Madore ARAA 2010

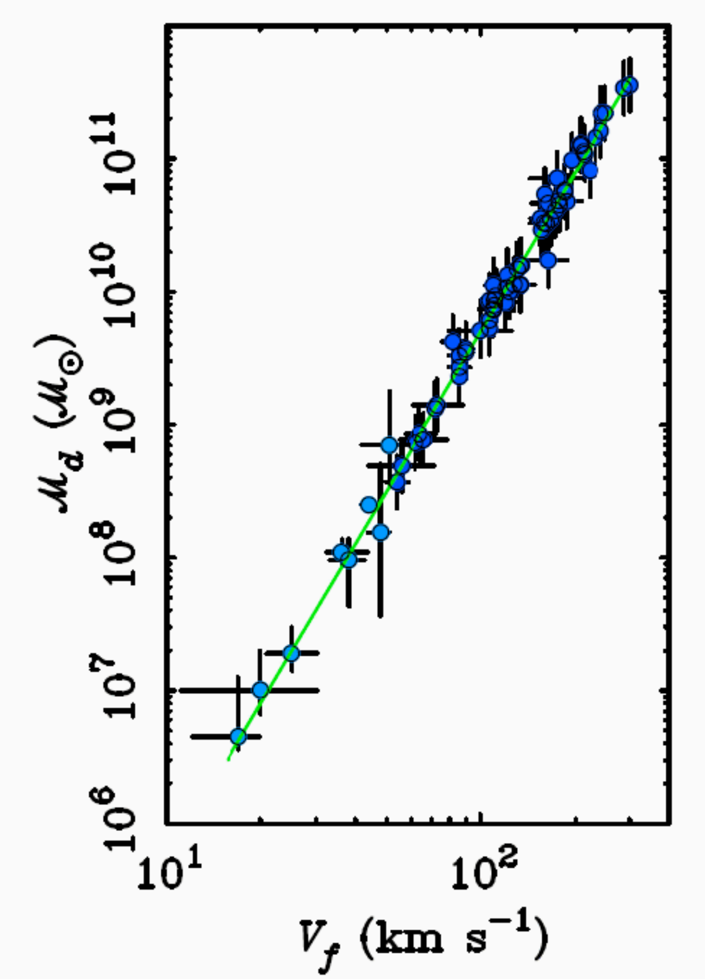
At longer wavelengths, scatter becomes less and slope becomes steeper. Why?

Underlying Relationship: the Baryonic Tully Fisher Relationship (McGaugh 2005)

Stellar Mass vs Rotation Speed



Stellar + Gas Mass vs Rotation Speed



line: $log(M_b) = 4log(V)+1.7$

Important Aside: The difference between scatter and zeropoint

For a sample of objects that obeys some relationship (like Tully-Fisher) with a given amount of scatter:

- With a large sample of points, you can beat down the uncertainty in the fit parameters (slope and zeropoint). So you can make good statistical statements about the population if you know your uncertainties.

- However, even if the fit parameters are very accurately known, any individual galaxy only obeys the relationship within the scatter.

I-band Tully-Fisher, scatter of σ≈0.36 mags:

$$I_T^c = -(9.24 \pm 0.75)(\log W_{20}^c - 2.5) - (21.12 \pm 0.12)$$

- Measuring TF distances for a population of 30 spirals in a cluster would give you a distance estimate to the cluster that's good to 0.12 mags (~ 6% in distance).

- But measuring a TF distance to a single galaxy elsewhere in the universe only gives you a distance estimate that's good to 0.36 mags (~ 20% in distance).

Plotting Tully-Fisher

I measure apparent magnitude (m) and velocity width (W).

1) If I know distance, I can calculate absolute magnitude ($m-M=5\log D-5$) and plot that, I should get a nice TF plot with a calibrated **absolute magnitude zeropoint**.

2) If all galaxies are in a cluster, I can assume they are at a common cluster distance and plot an apparent magnitude TF plot. Should have same slope, but an **apparent magnitude zeropoint.**

3) If I am looking at galaxies in the field with different distances, I can use Hubble's law to plot a Hubble dependent plot. Hubble's law says D=v/H0, so D scales as h^{-1} where h=H0/100.

> Hubble's law: $D=v/H_0$
> So D scales as h^{-1} where $h=H_0/(100\text{km/s/Mpc})$
> So M shifts as $M-5\log(h)$ if the Hubble Constant is different

So use your Hubble distance to calculate absolute magnitude, understanding that different Hubble Constants will shift your plots up and down.

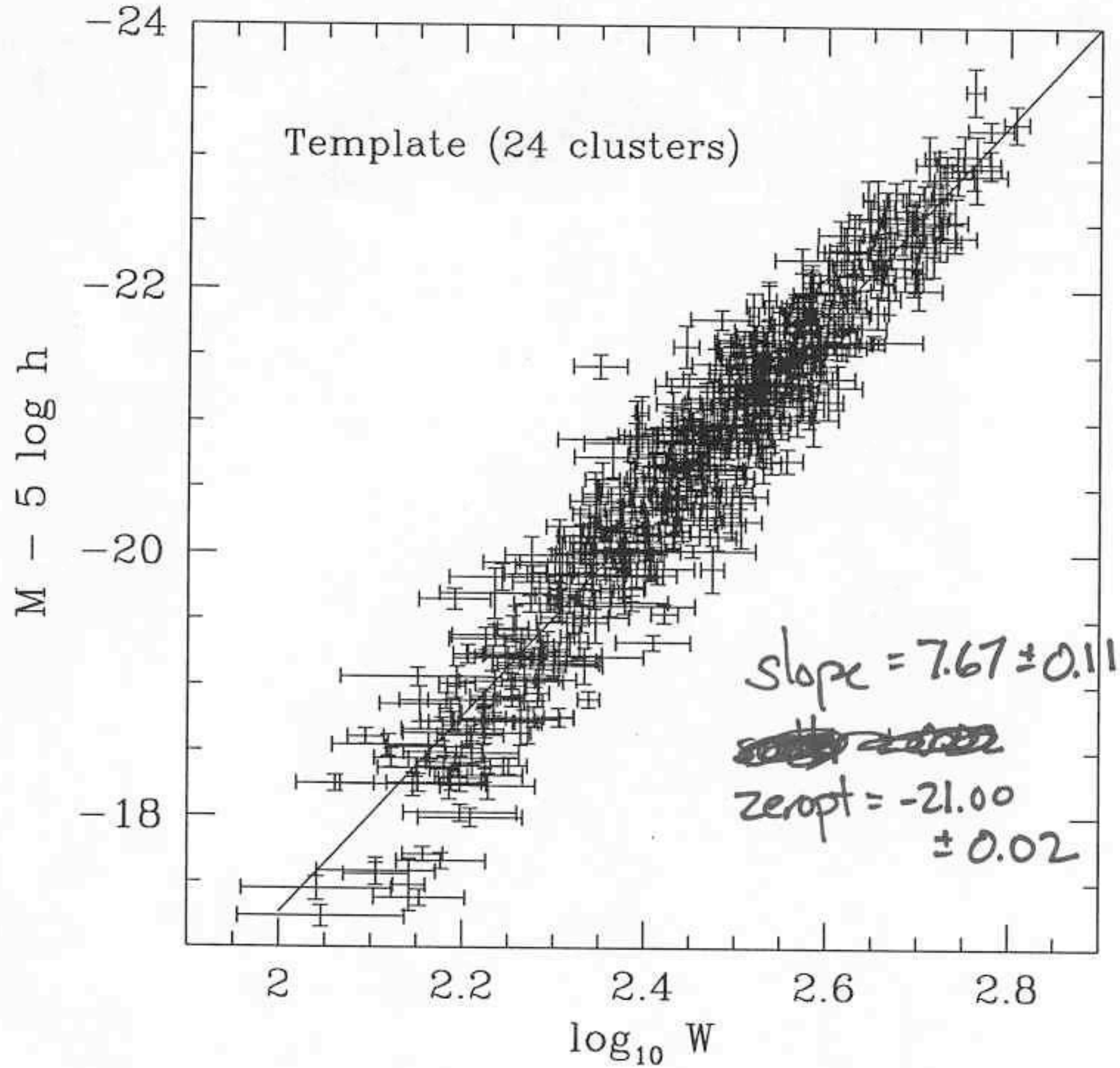
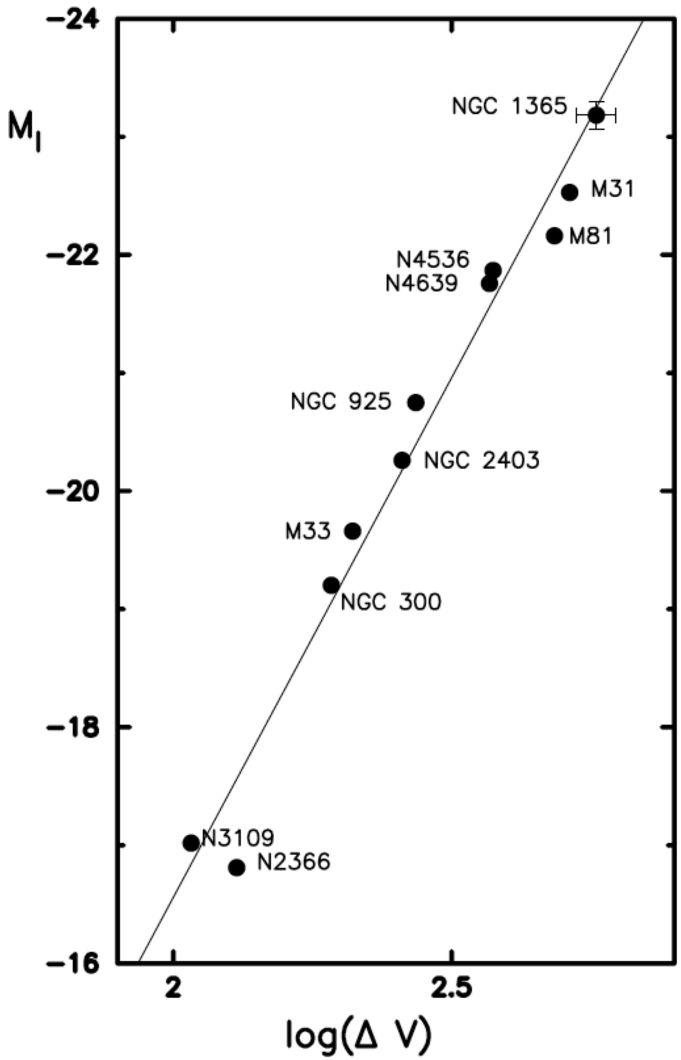


FIGURE 4. Template relation based on 555 galaxies in 24 clusters.

Cepheid Calibration



Madore+ 1999

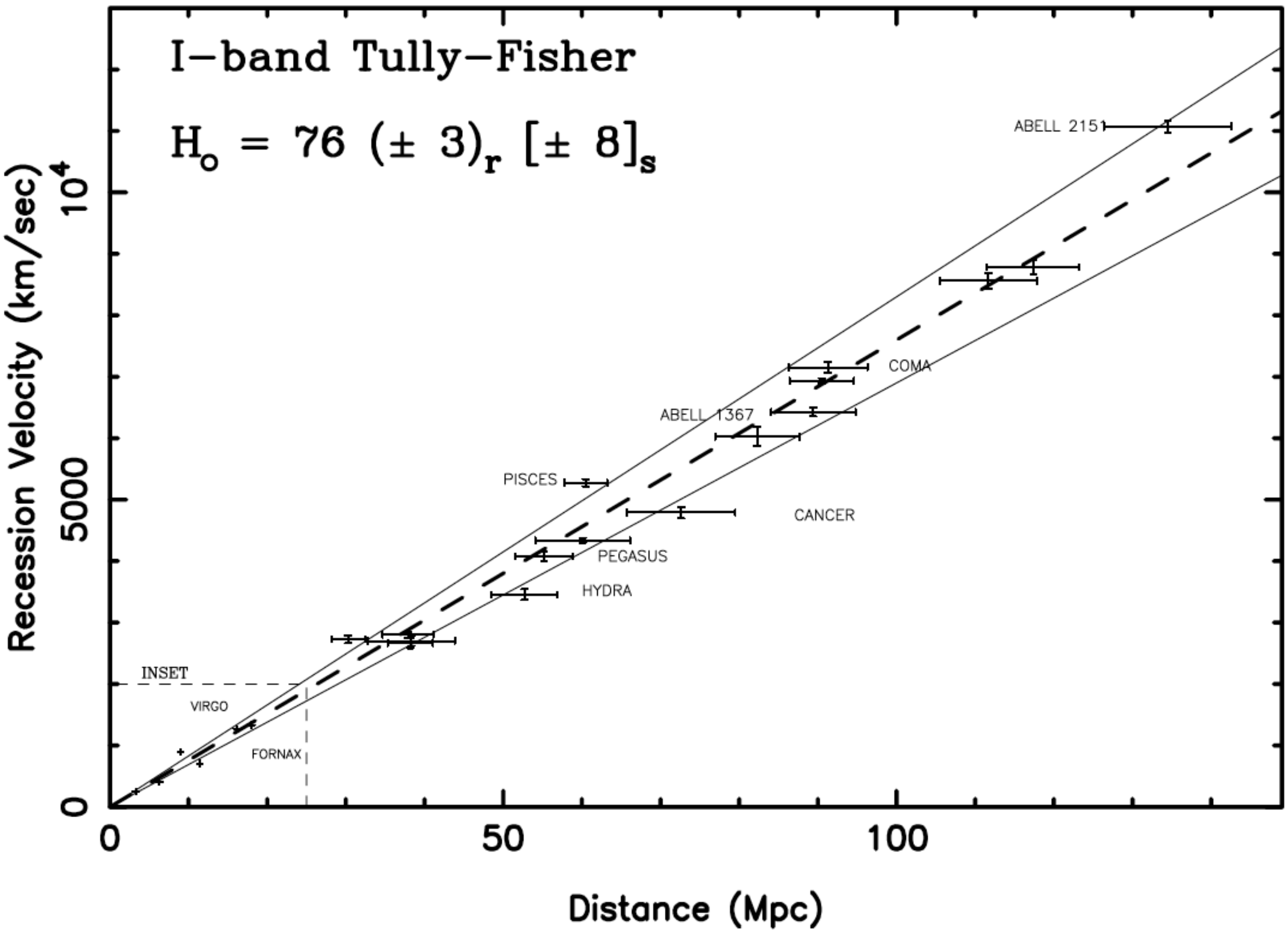
$$B_T^c = -(7.97 \pm 0.72)(\log W_{20}^c - 2.5) - (19.80 \pm 0.11)$$
$$V_T^c = -(8.87 \pm 0.83)(\log W_{20}^c - 2.5) - (20.34 \pm 0.12)$$
$$R_T^c = -(8.78 \pm 0.72)(\log W_{20}^c - 2.5) - (20.65 \pm 0.11)$$
$$I_T^c = -(9.24 \pm 0.75)(\log W_{20}^c - 2.5) - (21.12 \pm 0.12)$$
$$H_{-0.5}^c = -(11.03 \pm 0.86)(\log W_{20}^c - 2.5) - (21.74 \pm 0.14)$$

Sakai+ 2000

Cepheid calibrators…

Cepheid Calibrated Distance Scale

Madore+ 1999



Bias in Tully-Fisher

- imagine a TF relation with intrinsic scatter σ

$$M = \alpha \log V_c + b \pm \sigma$$

- at any given V_c, galaxies will have a range in absolute magnitude of $M \pm \sigma$

- in a magnitude-limited sample, the things you detect at the faintest level are systematically overluminous for their V_c

- since they are more luminous than you think (based on their V_c), you will get an erroneously low ~~high~~ distance.

- since $H_0 = V/d$, low distance → high H_0

→ problem for both field & cluster surveys

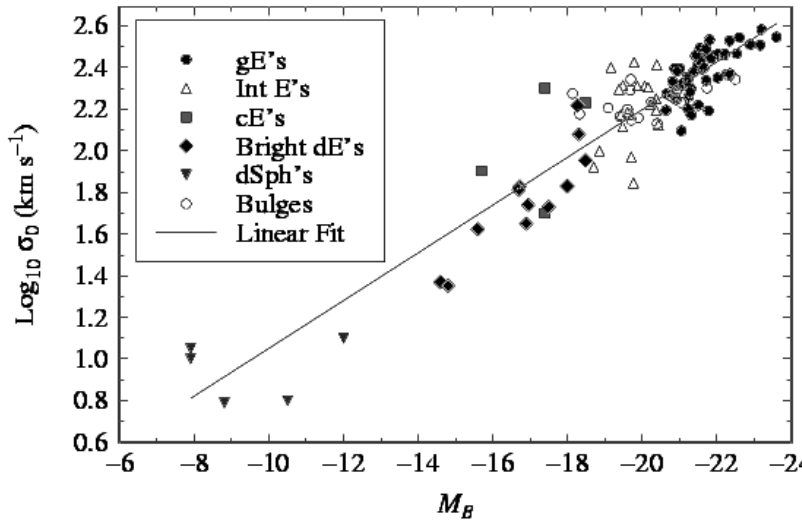
→ motivates need for low σ distance indicators

Elliptical Galaxies: Fundamental Plane

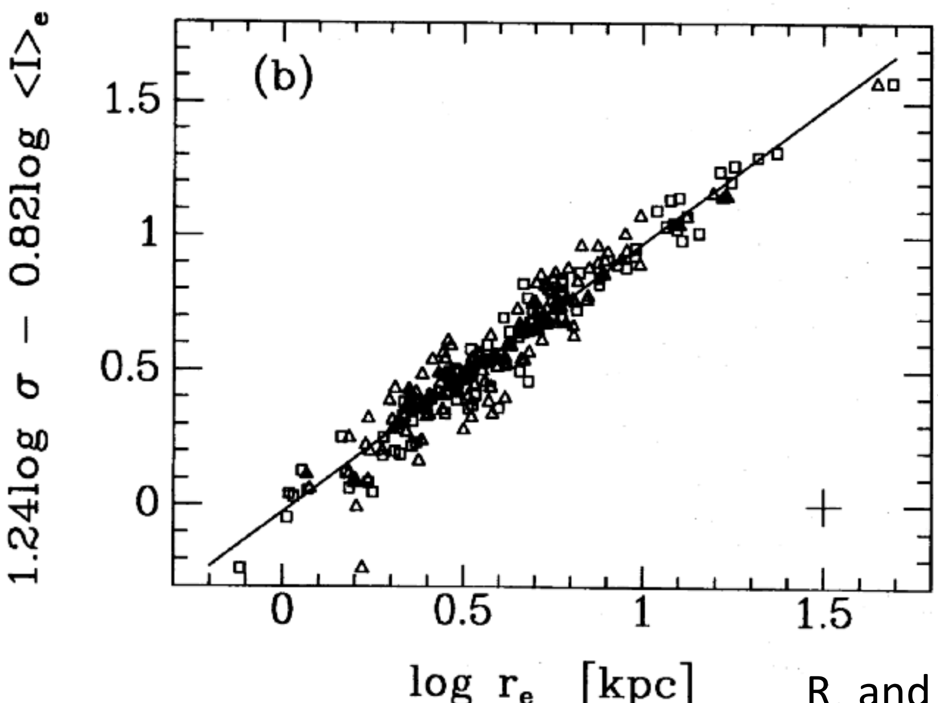
Define structural parameters for elliptical galaxies:
- R_e: effective ("half-light") radius
- L (or M): total luminosity
- μ_e (or $\log\langle I_e\rangle$) : surface brightness within R_e

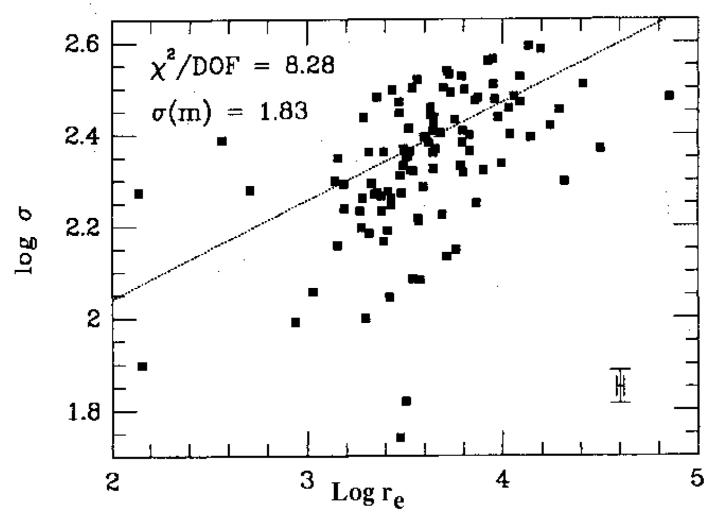
And also measure velocity dispersion: σ

How do they scale?



σ and M: lots of scatter





σ and R_e: even more scatter

R_e and a *combination* of σ and μ: Fundamental Plane!

Elliptical Galaxies: Fundamental Plane

Define structural parameters for elliptical galaxies:

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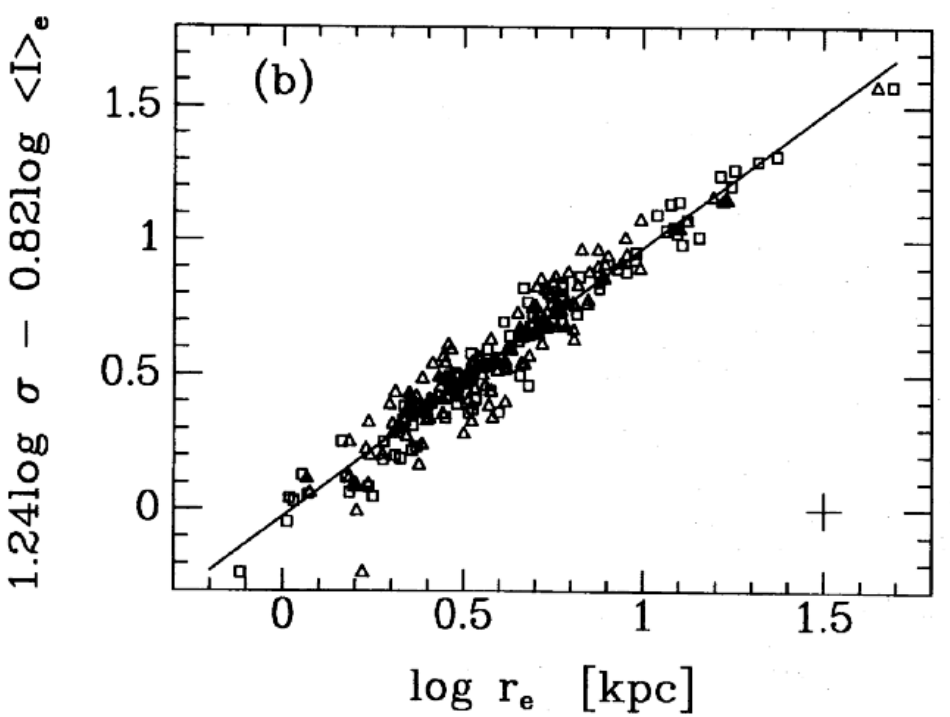

Important Notes:

- R_e, L, and μ_e are **not** independent parameters! (if you know 2, you can calculate the 3rd)
- μ_e and σ are **distant independent** parameters!
- If we calibrate it with galaxies of known distance, R_e can be expressed in **physical units** (kpc).

D_n-sigma:

Define D_n to be an isophotal diameter – the diameter in which the mean B-band surface brightness is 20.75 mags/arcsec^2.

If the elliptical galaxy light profile follows a Sersic profile with n=4 (i.e., an $r^{1/4}$ or de Vaucouleurs profile), you can work out that $\log(D_n) = \log(R_e) - 0.4\mu_e$.

That makes D_n a linear combination of two of the parameters (R_e and μ_e), and so it will correlate with the third parameter of the fundamental plane (σ)

Combine the definition of D_n with the Fundamental Plane equation to get the relationship $\log(D_n) \approx 1.4\log(\sigma)$ + constants, *(where exact details depend on FP fit and assumed galaxy profile….)*

So both the Fundamental Plane and the Dn-sigma relationship trace the same underlying properties of the ellipticals, and either can be used (although FP has less scatter).

Using Fundamental Plane or D_n-sigma:

- Measure velocity dispersion (in km/s, distance-independent)
- Measure light profile to get :
    - R_e (arcsec) and μ_e (mag/arcsec^2), or
    - D_n (arcsec)
- Make an *observed* FP or D_n-sigma plot using R_e or D_n in arcsec.

Then either:

- Use a **calibrated relation** to tell you what R_e or D_n is in parsecs, or
- Use the **relative shift** of the *observed* FP or D_n-sigma plot between your cluster and a cluster of known distance to get the distance to your cluster.

Calibration is tricky: Need Cepheid distances to clusters (ie, Virgo or Fornax)

Also, possible systematic FP variations:

- cluster-to-cluster
- as a function of redshift (evolution?)

D_n-sigma in Virgo, Fornax and Coma:

D'Onofrio+ 97

Scatter in FP size/distance estimates (Kelson+ 00):

- Virgo: 10%
- Coma: 14%
- Fornax: 21%

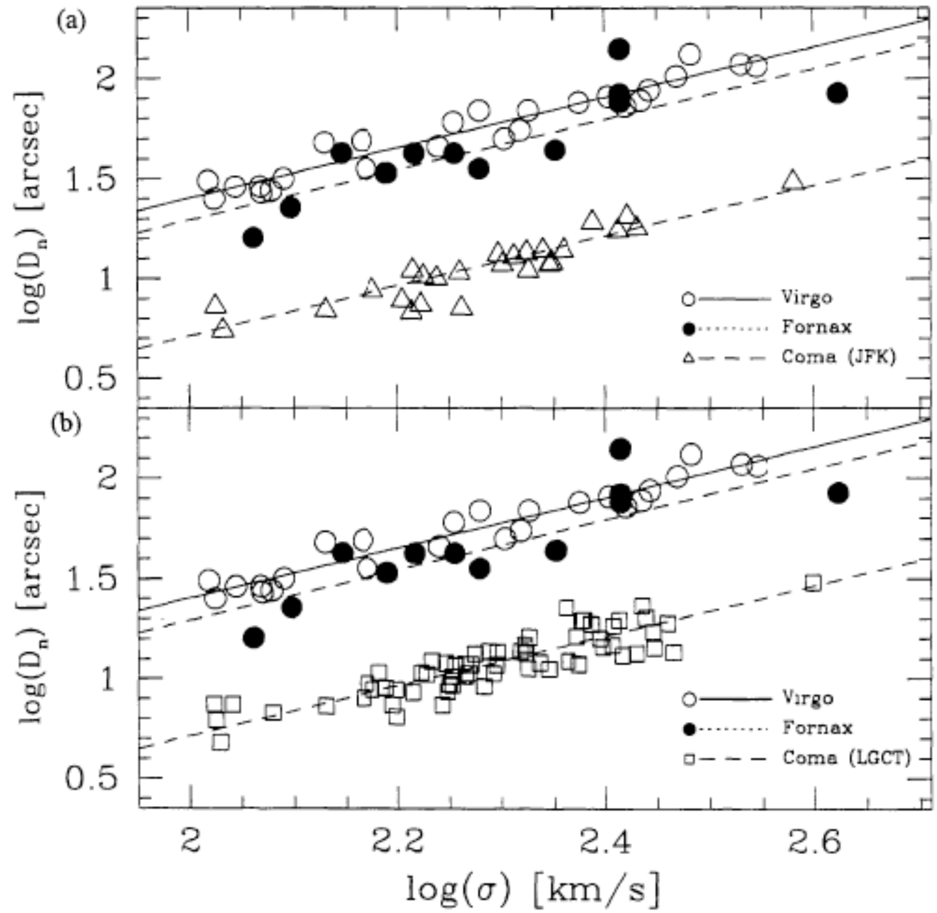

Figure 3. (a) The $\log D_n - \log \sigma$ relation for the Virgo, Fornax and Coma samples using the data from LGCT for the latter cluster. (b) same as panel (a) with the data of JFK. The solid, dotted and dashed lines give the fits to the Virgo, Fornax and Coma data points respectively.