

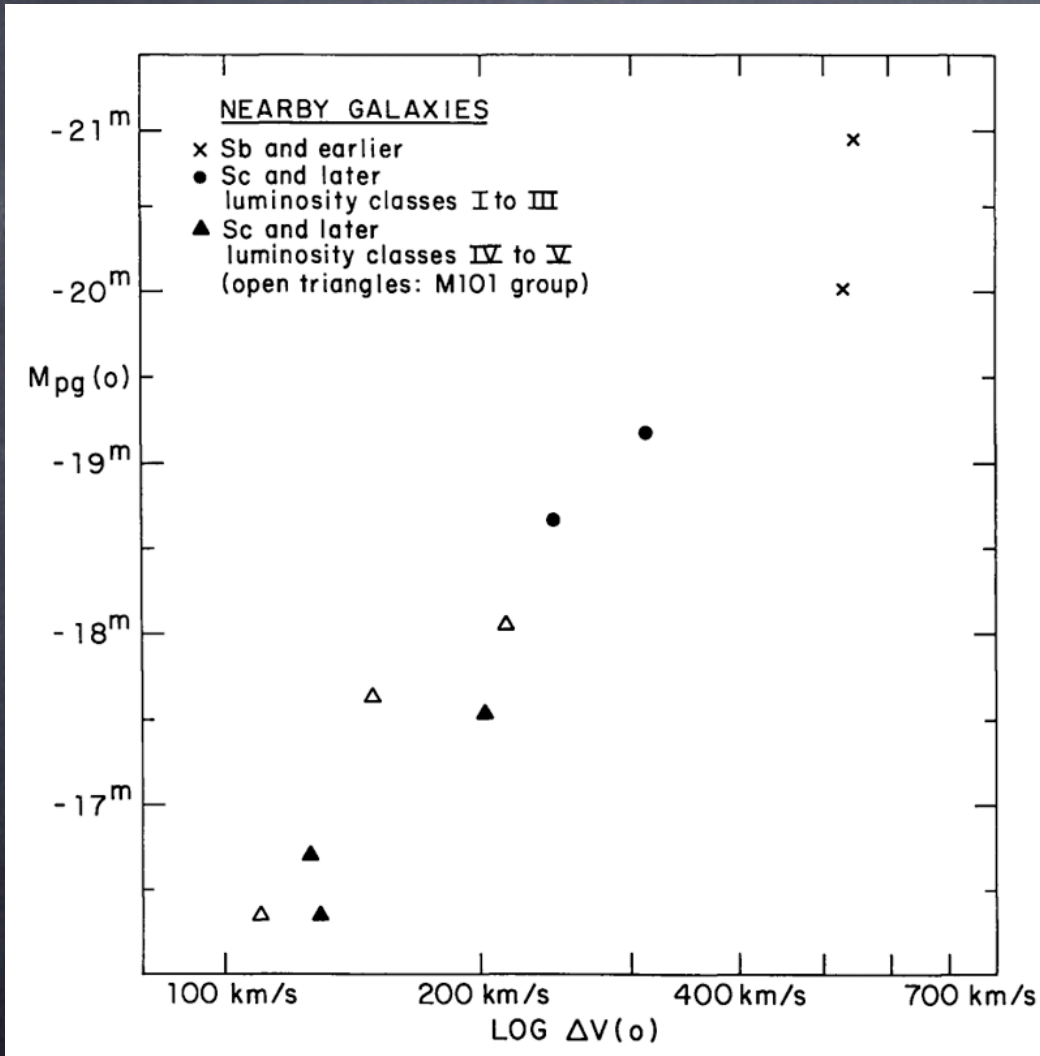
# Scaling Relations of late-type galaxies

- an observational perspective -

- Lecture I Trends along the Hubble sequence
- Lecture II Galaxy rotation curves
- Lecture III Tully-Fisher relations

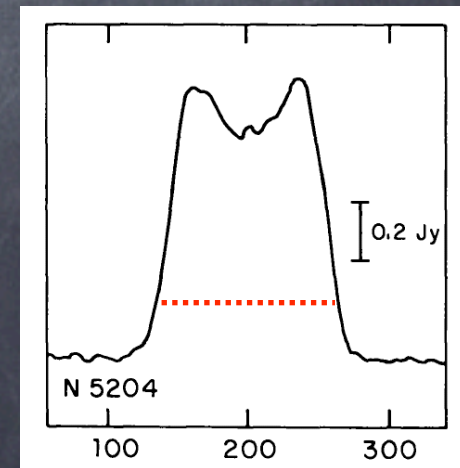
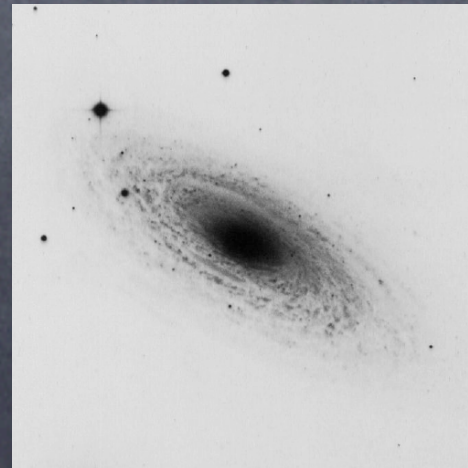


# III. Tully-Fisher Relations



Tully & Fisher, 1977

- Photographic magnitudes Holmberg (1958)
- Width of global 21cm HI emission line (independent of distance)



# Tully-Fisher Relations

- Useful tool for measuring distances  
 $\Delta V$  predicts absolute magnitude,  $m-M \rightarrow$  distance
- Constraint for galaxy formation models  
scatter, slope, zero point
- Powerful probe of galaxy evolution  
galaxies brighter, bluer, more massive in the past?

Results of T-F studies depend critically on understanding sample selection and biases!

# Corrections of observables

- Correct HI line width for:

- spectral resolution
- turbulent motion of the gas
- inclination of the disk



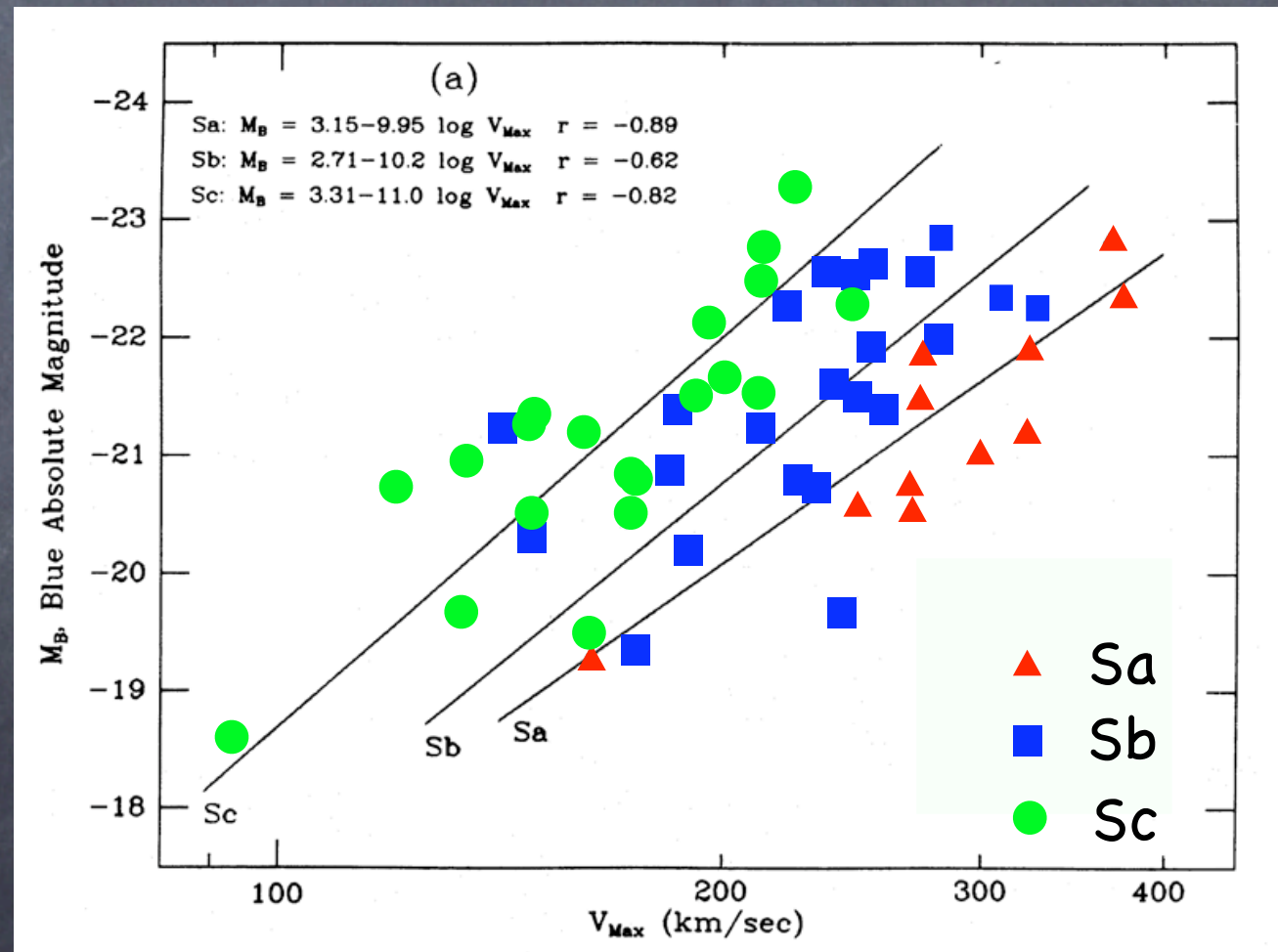
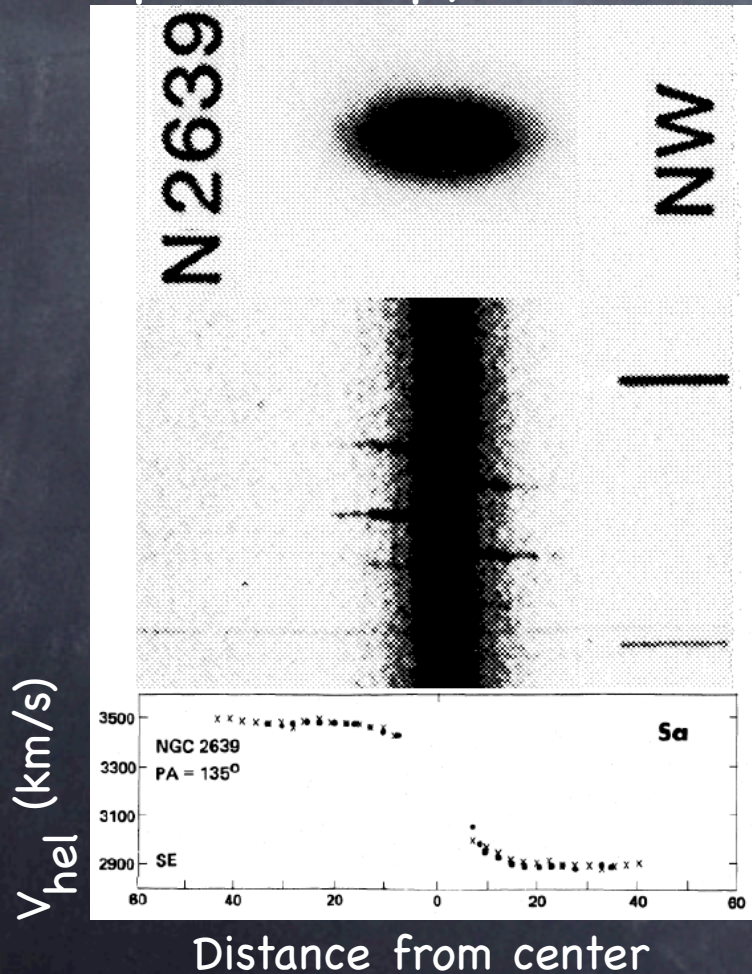
- Correct luminosity for:

- flux outside aperture or isophote
- Galactic foreground extinction
- internal extinction

# a morphological dependence?

- photographic blue magnitudes
- $V_{\max}$  from H $\alpha$  rotation curves

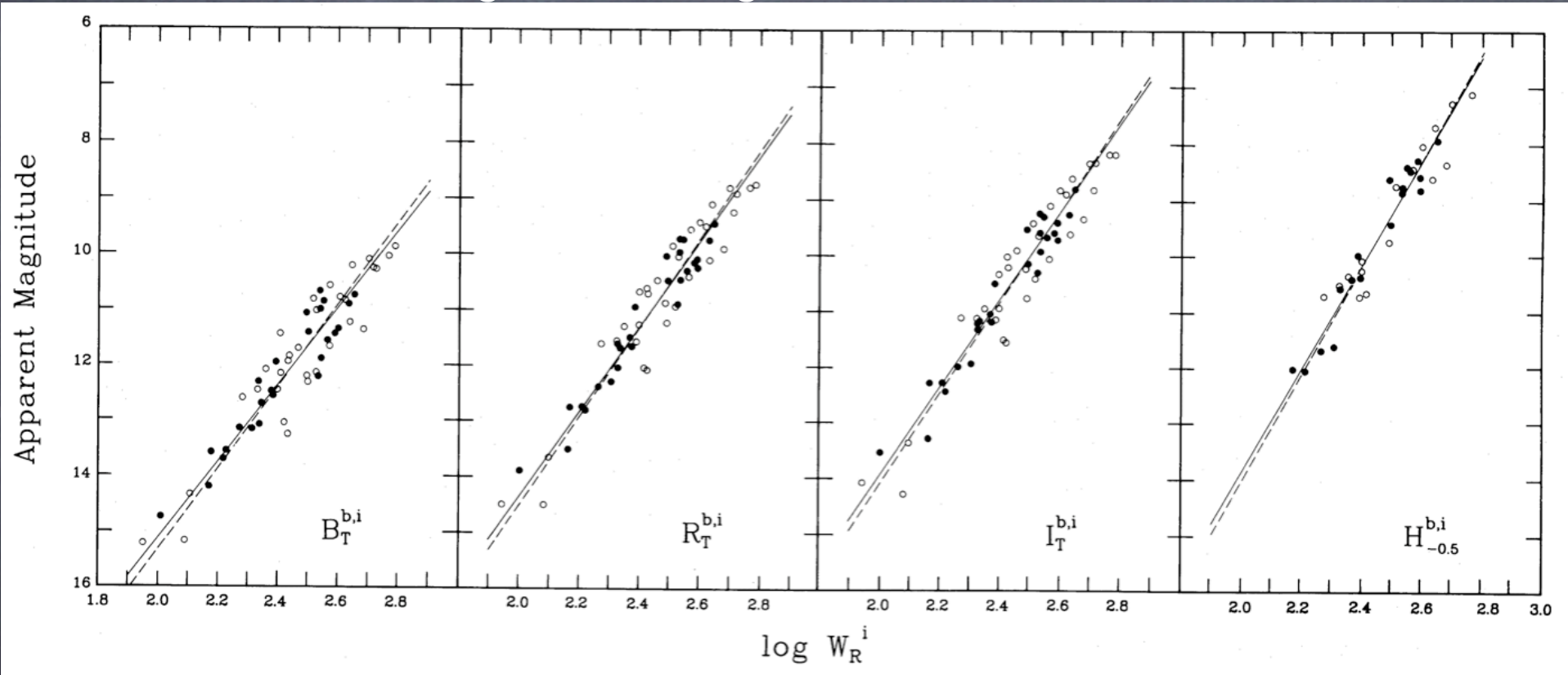
H $\alpha$  long-slit spectroscopy



# advances in photometry

- Linear CCD detectors at optical wavelengths
- Photo-electric aperture photometry at 1.6  $\mu\text{m}$

Ursa Major and Virgo cluster galaxies



Pierce & Tully, 1988

➤ mild or no type-dependence  
when using HI line widths

# Multi-band Tully-Fisher relations

## Ursa Major cluster galaxies

$$\alpha = -6.8$$

$$\sigma = 0.61$$

$$\alpha = -7.1$$

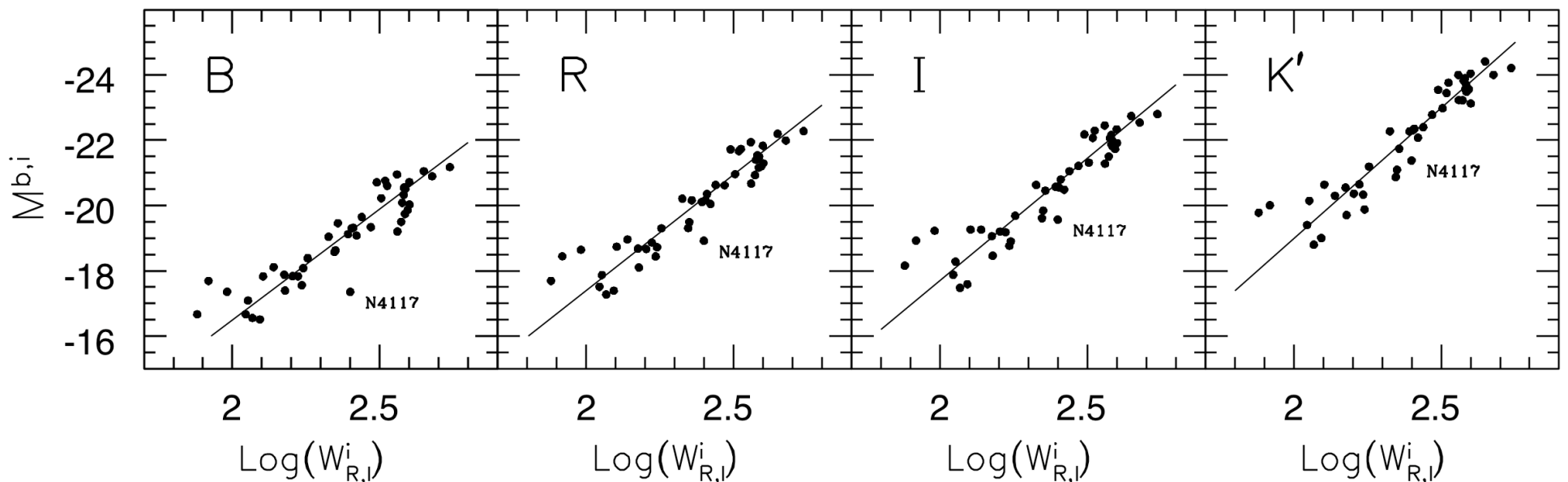
$$\sigma = 0.56$$

$$\alpha = -7.5$$

$$\sigma = 0.61$$

$$\alpha = -8.0$$

$$\sigma = 0.59$$



Verheijen, 2001

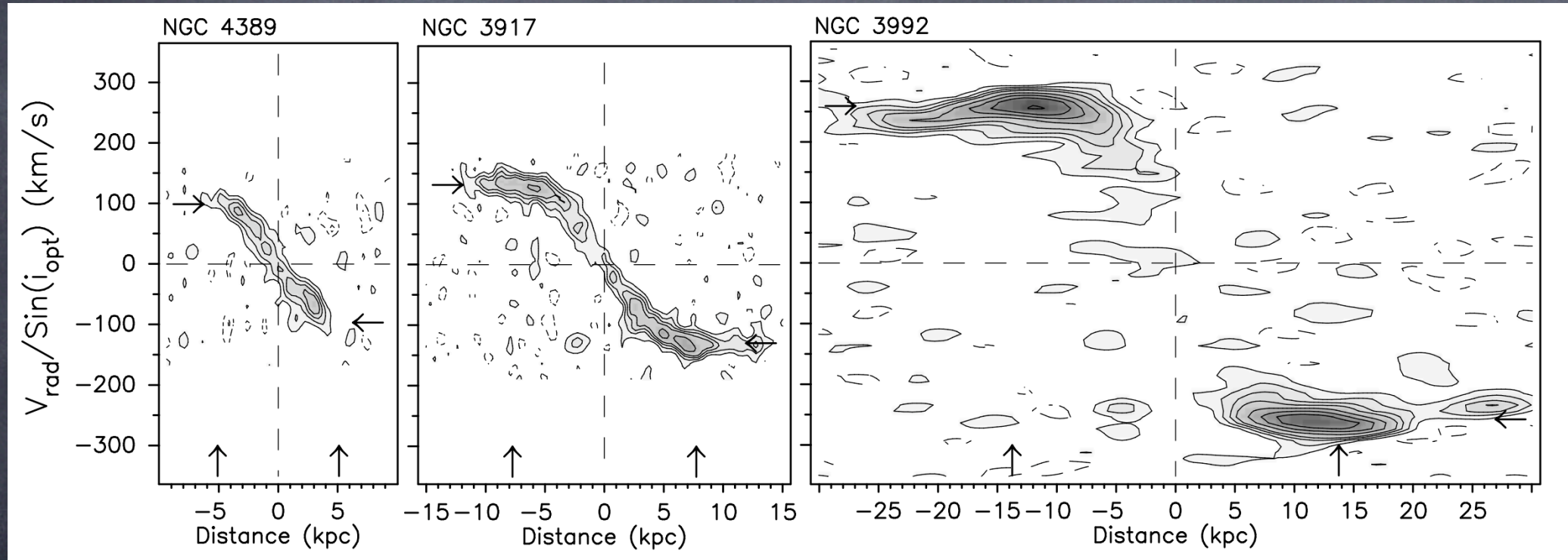
- Clear steepening towards the near-infrared
- Significant scatter

# Three kinds of Rotation Curves

Rising 

Flat 

Declining 



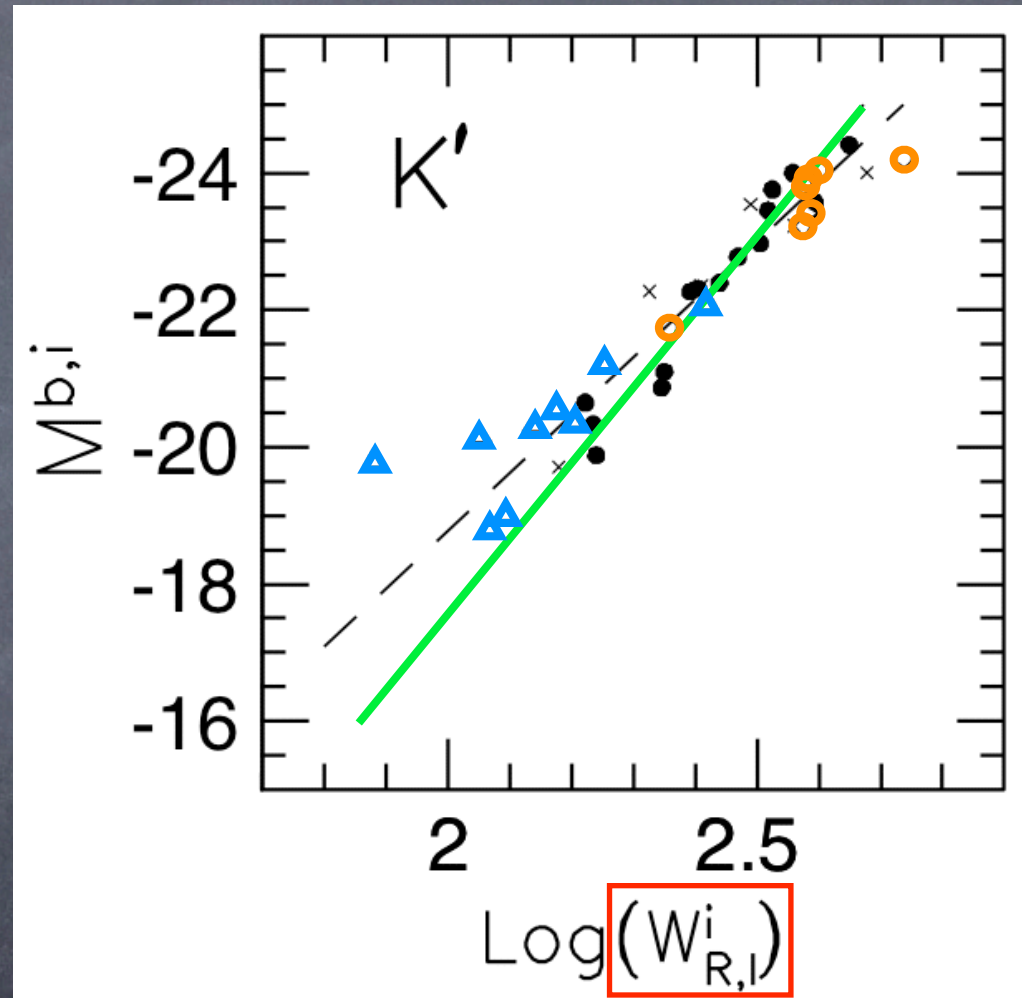
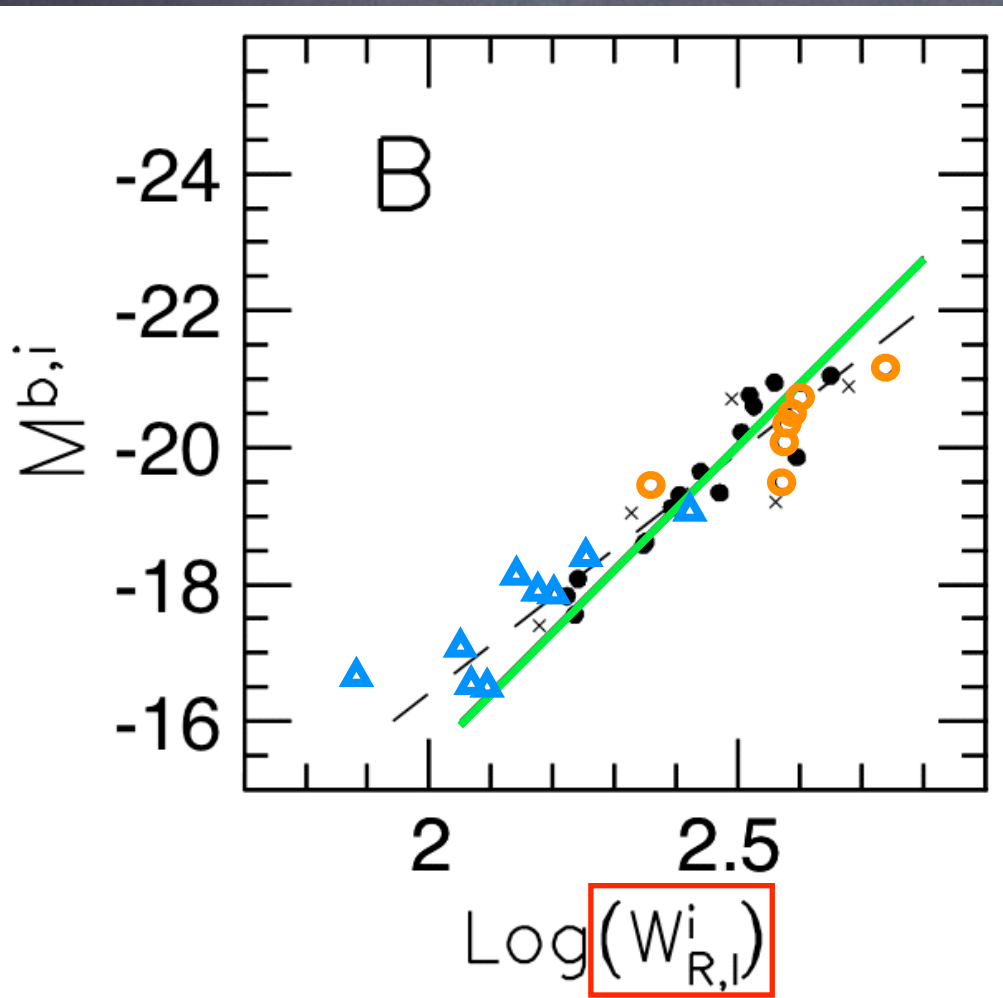
$$V_{\text{max}}$$

$$V_{\text{flat}} = V_{\text{max}}$$

$$V_{\text{flat}} < V_{\text{max}}$$

no  $V_{\text{flat}}$  !

# TF-relations encoded with RC shapes



→ Still using global HI line widths...

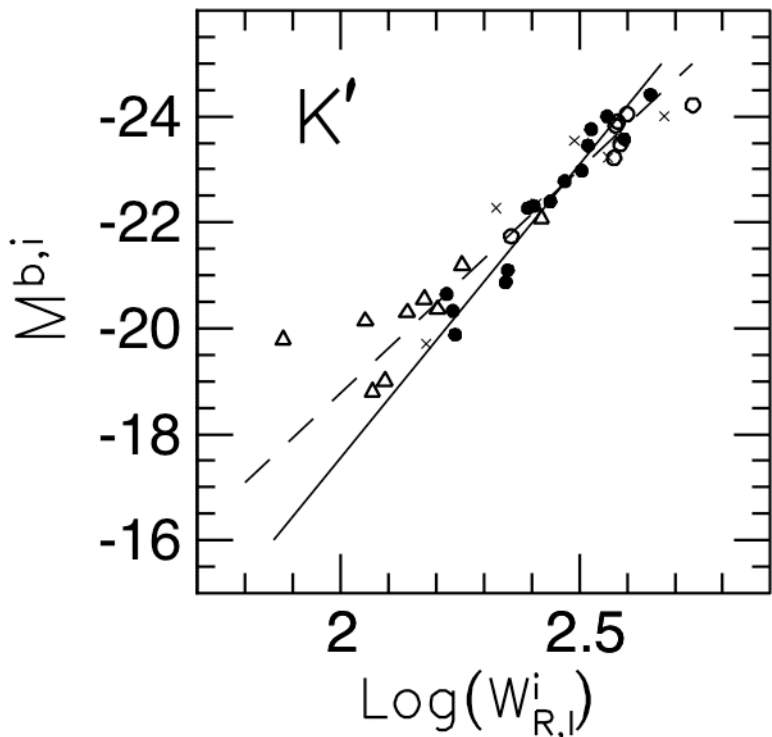
# Using different kinematic measures

Excluding rising RCs:

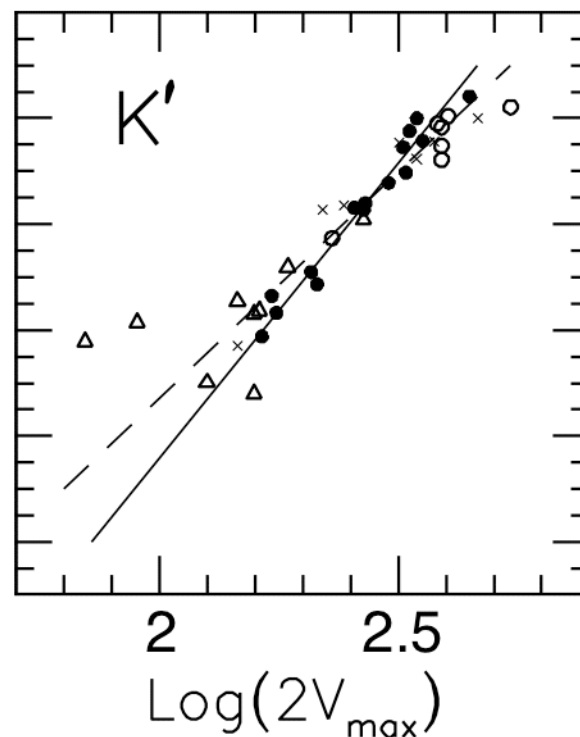
$$\alpha = -10.6$$
$$\sigma = 0.34$$

$$\alpha = -10.5$$
$$\sigma = 0.31$$

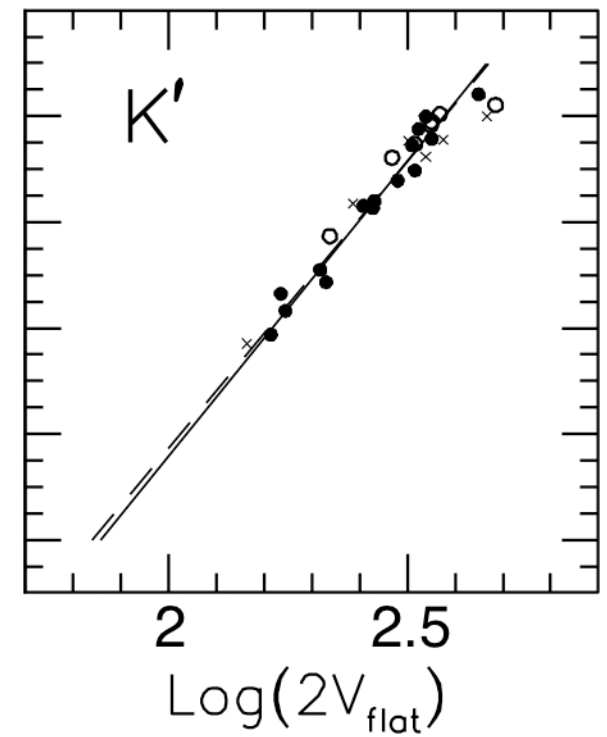
$$\alpha = -11.3$$
$$\sigma = 0.26$$



$W_{R,I}^i$



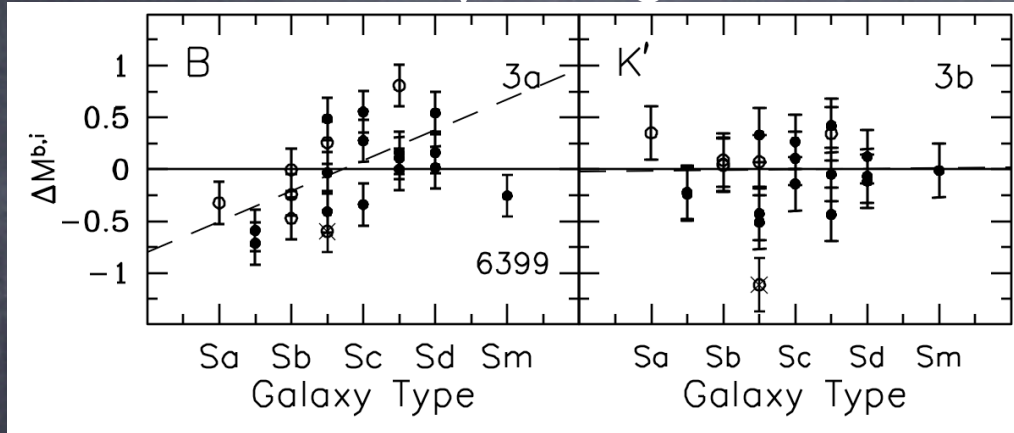
$V_{\max}$



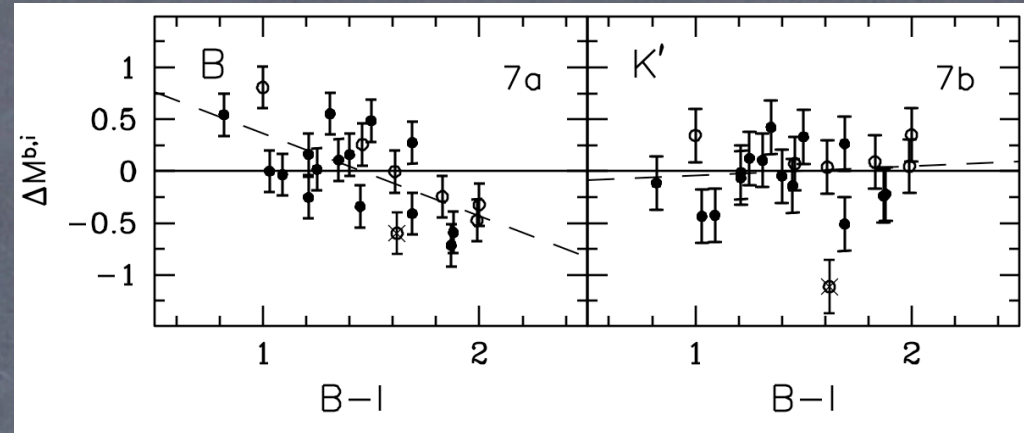
$V_{\text{flat}}$

# Residuals in the $M^{b,i} - \text{Log}(2V_{\text{flat}})$ relations

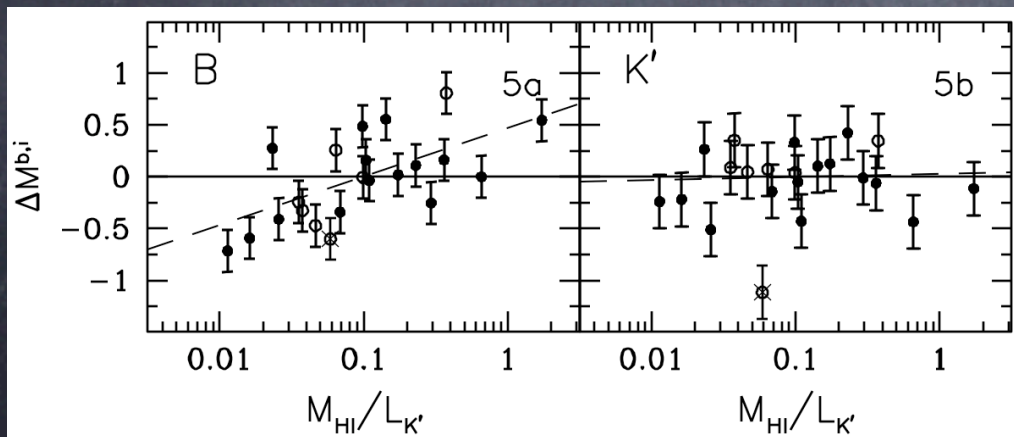
## Morphology



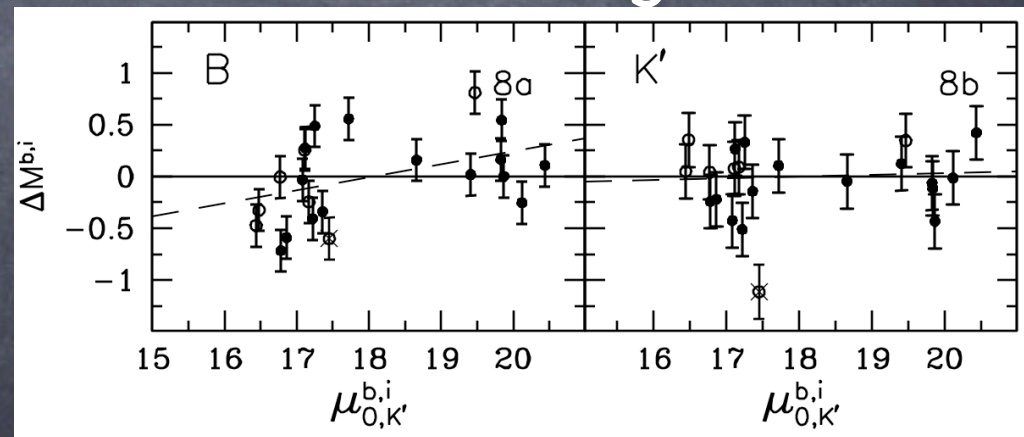
## Colour



## Gas content



## Surface brightness



a consistent trend along the Hubble sequence

# naïve expectation for T-F slope

Assume:

- pure exponential disk with  
h = disk scale length  
 $\mu_0$  = central surface brightness
- no other mass components like a dark matter halo

absolute magnitude  $M \propto \mu_0 - 2.5 \text{Log}(2\pi h^2)$

$$\mathcal{L} \propto 10^{-0.4M} \propto 2\pi h^2 10^{-0.4\mu_0} \propto I_0 h^2$$

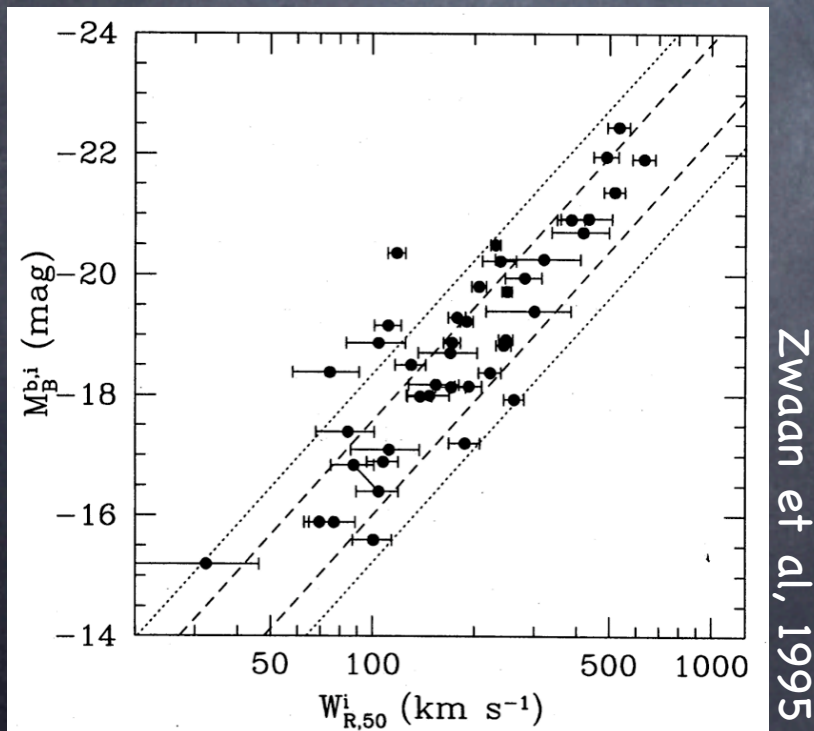
$$V_{\max}^2 \propto \frac{GM}{h} \propto \frac{\mathcal{M}}{\mathcal{L}} \frac{\mathcal{L}}{h} \xrightarrow{\downarrow} \mathcal{L} \propto \frac{V_{\max}^4}{I_0 (\mathcal{M}/\mathcal{L})^2}$$

or:  $M \propto -10 \text{Log} V_{\max} + \mu_0 + 5 \text{Log}(\mathcal{M}/\mathcal{L})$

$$M \propto -10 \log V_{\max} + \mu_0 + 5 \log (\mathcal{M}/L)$$

- Low Surface Brightness galaxies (large  $\mu_0$ ) with the same  $M$  and  $(\mathcal{M}/L)$  should rotate slower!

However:



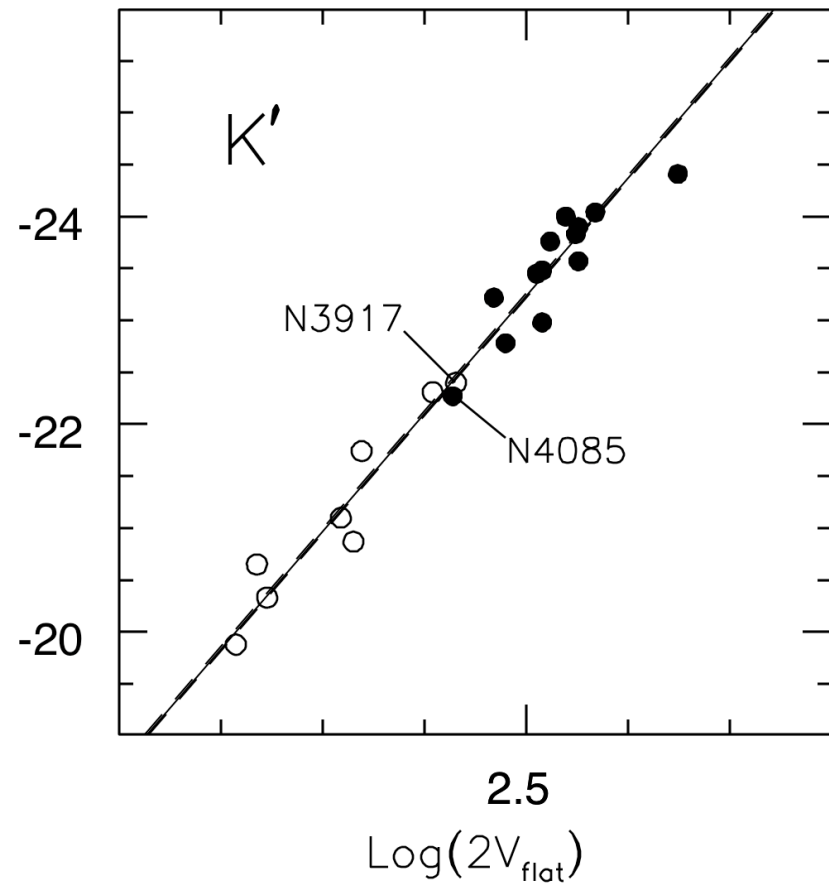
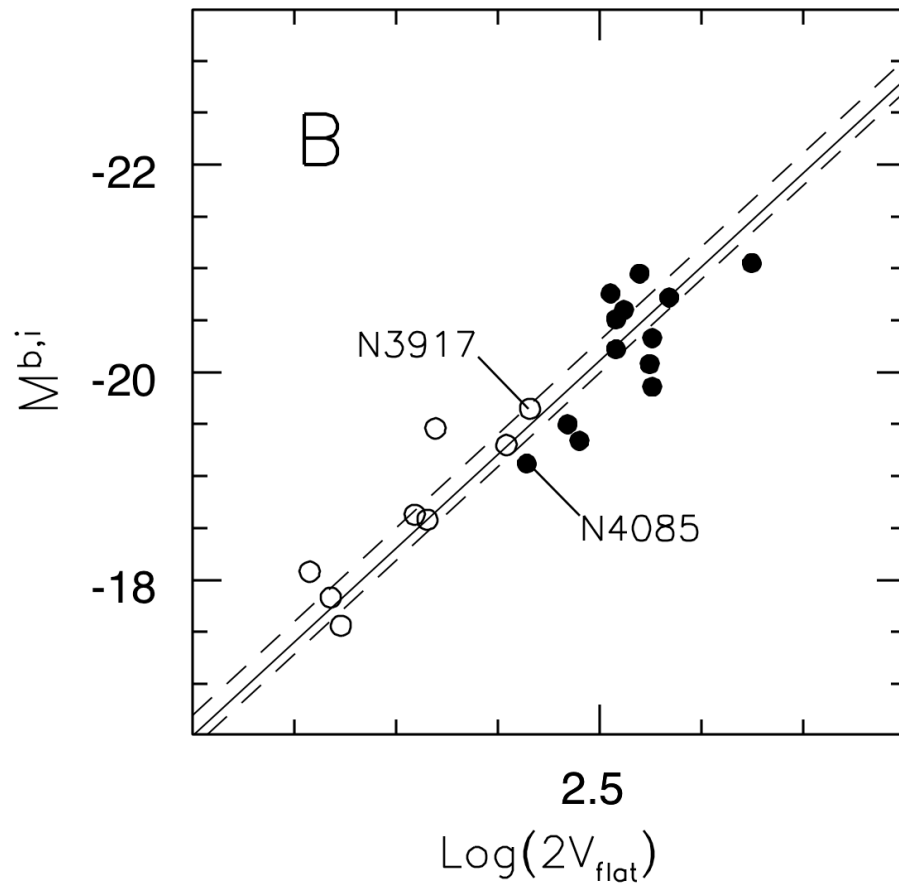
LSB and HSB galaxies follow the same TF relation!

- LSBs have higher  $(\mathcal{M}/L)$  and/or are dark matter dominated.

a subtle difference:

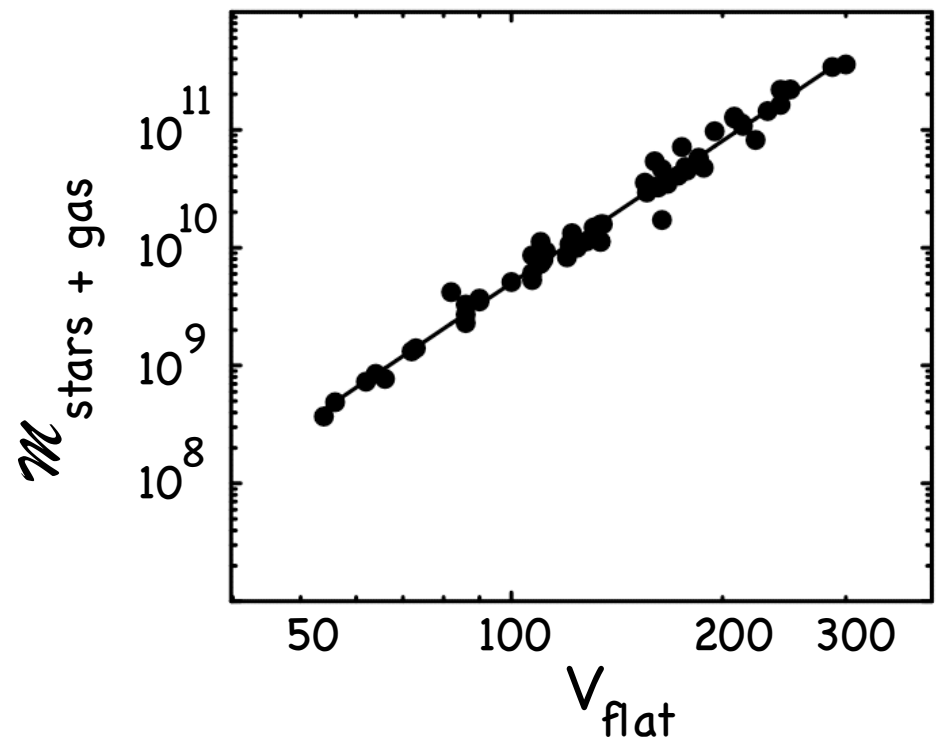
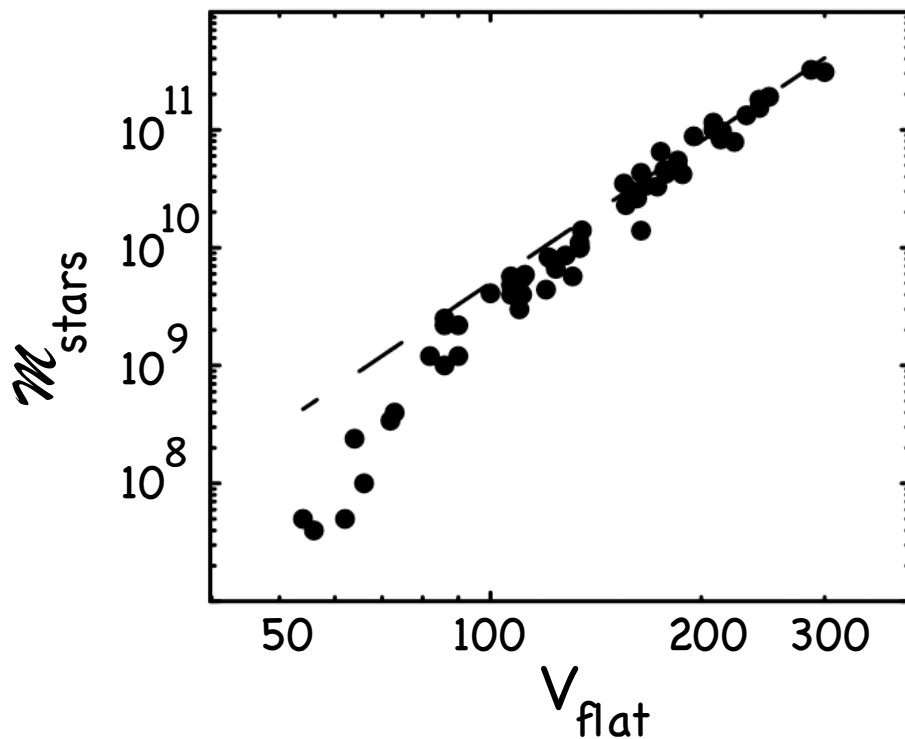
LSBs are on average bluer than HSB galaxies

○ : LSB    ● : HSB



# The baryonic TF-relation

- K-band luminosities give smallest scatter
  - mass likely more relevant than luminosity
- downward curvature at lowest luminosities
  - galaxies with the highest  $M_{\text{HI}}/L_K$  are too faint



# Evolution of the TF relation

Galaxy formation models predict:

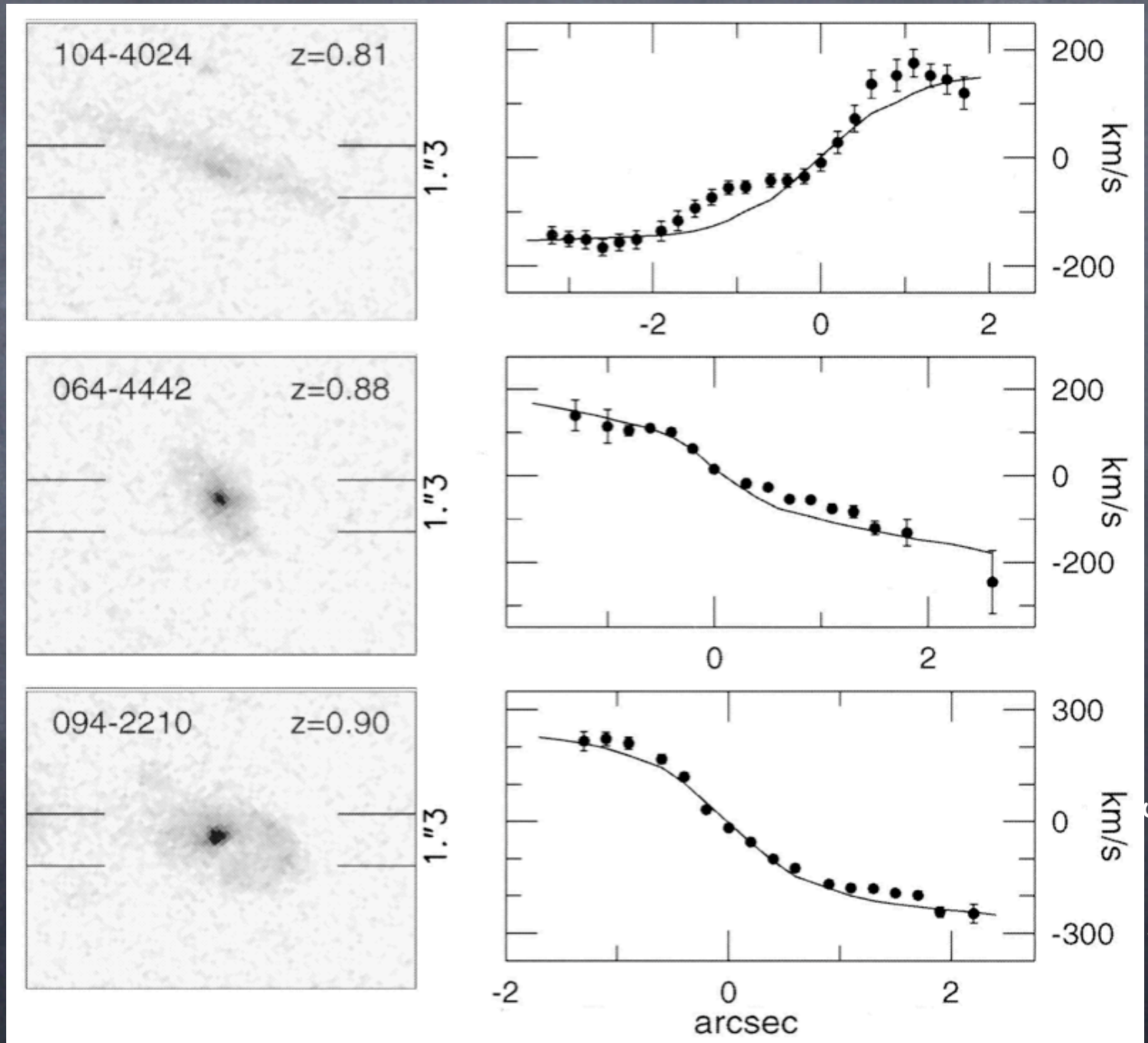
- evolving stellar populations
- mass accretion by merging
- asymmetries

Crucial to understand selection criteria  
for high redshift samples

Careful comparison to local samples  
(restframe luminosities, different kinematic measures)

# long-slit spectroscopy of high- $z$ galaxies

Is  $V_{\text{flat}}$   
measured?



their conclusion:

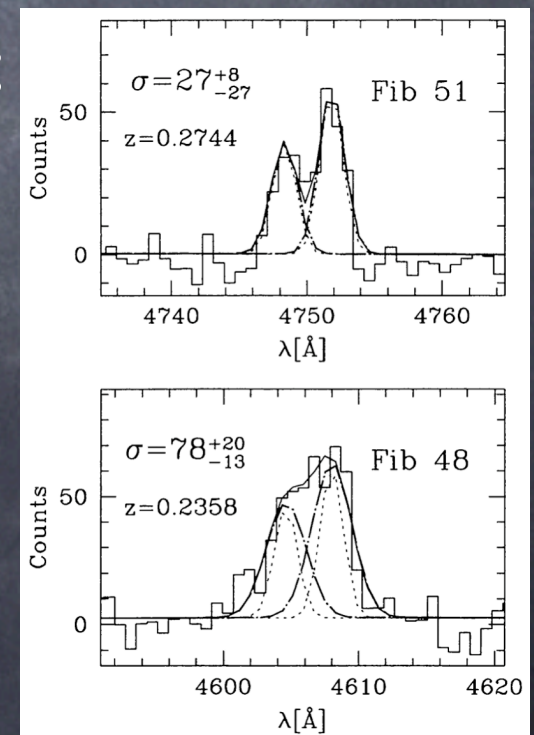
→ modest increase  
in luminosity:

$$\Delta M_B \leq 0.6 \text{ mag}$$

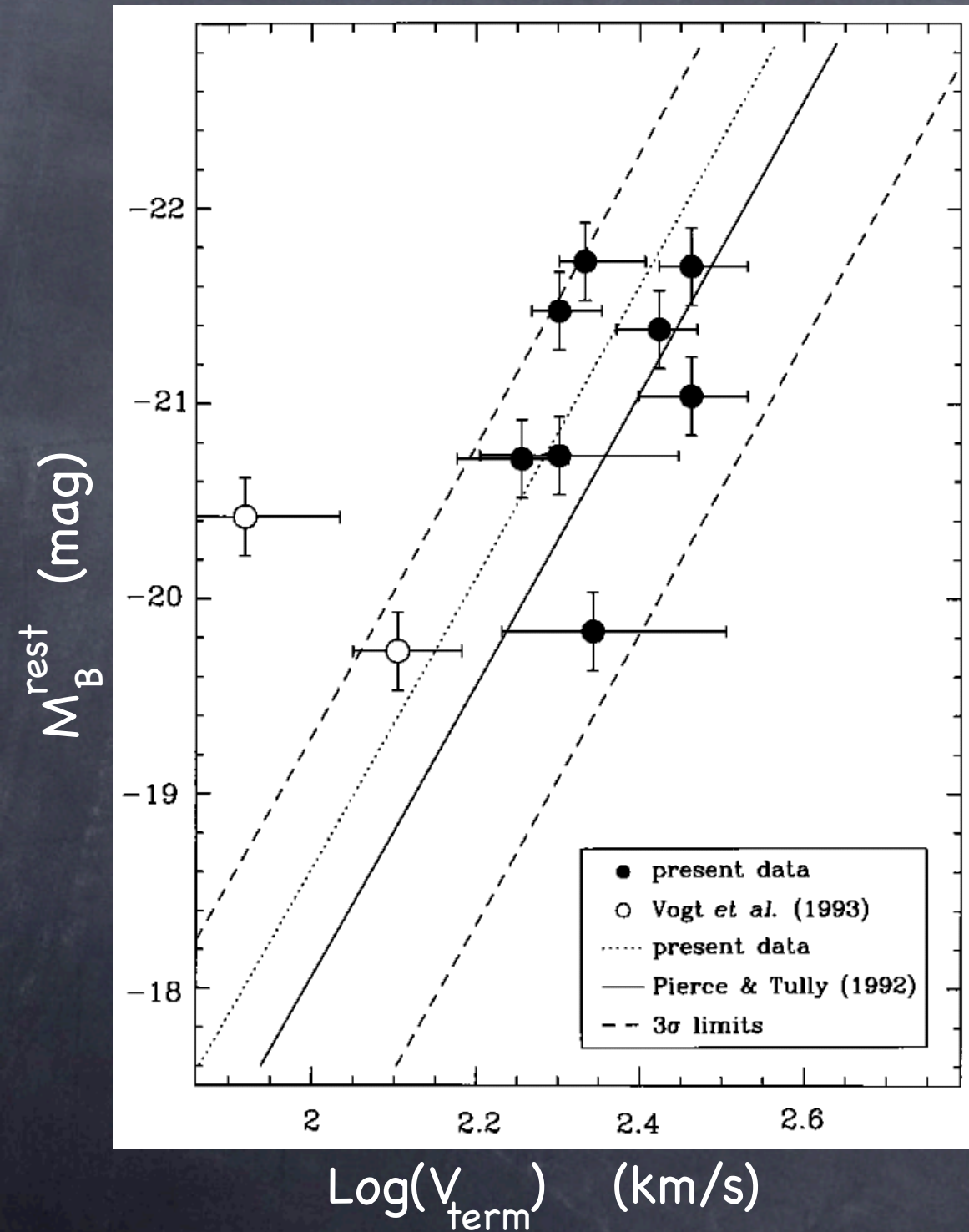
But Rix et al (1997):

$$\Delta M_B \approx 1.5 \text{ mag}$$

using:



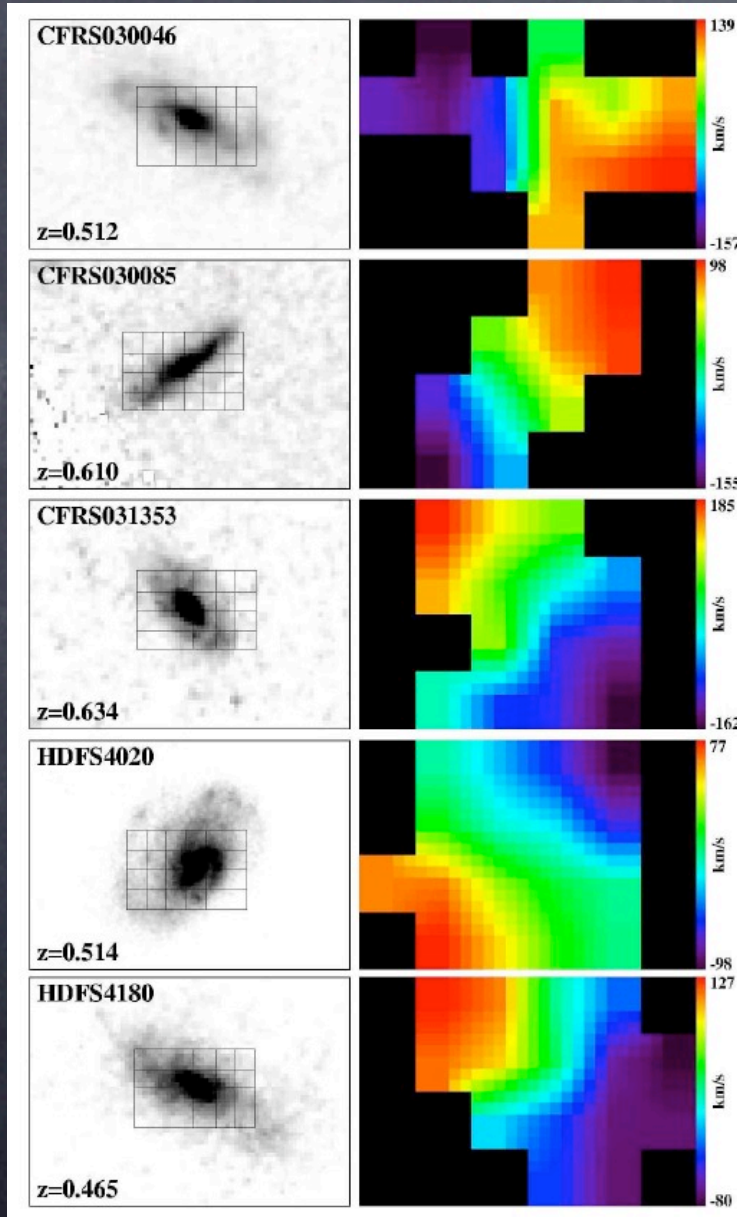
Vogt et al, 1996



# TF relations

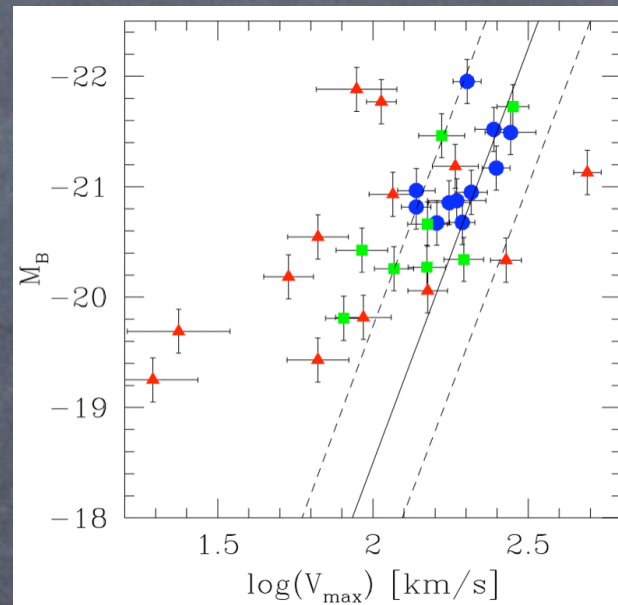
based on optical velocity fields

[OII] velocity fields

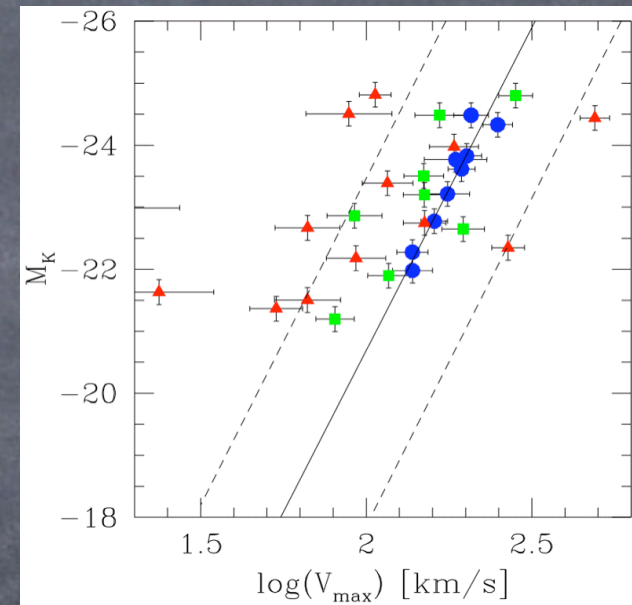


Flores et al, 2006

B-band



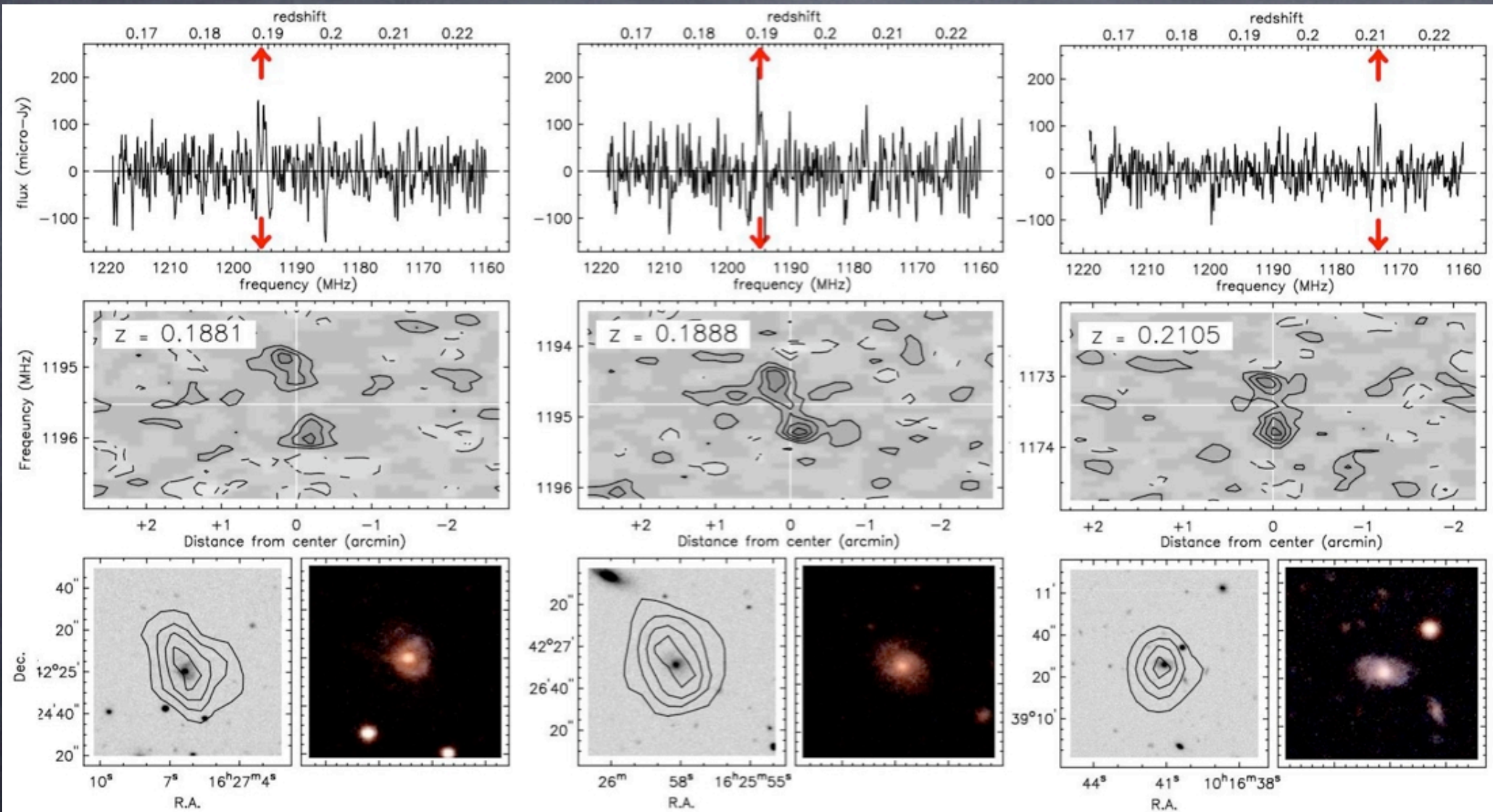
K-band



rotating disks  
perturbed disk  
'complex' kinematics

# First step to HI kinematics at intermediate redshifts

## Westerbork HI observations at $z=0.2$



Need the Square Kilometre Array SKA to do better.

# Summary

## Tully-Fisher relations

- Understanding TF-relation can be improved by using extended HI rotation curves
- Morphological dependence disappears when using  $V_{\text{flat}}$  of declining rotation curves
- Baryonic TF-relation removes curvature at low mass end, yields a slope of -10.
- A fundamental relation between halo mass and baryonic mass, regardless of how baryons are distributed in the halo