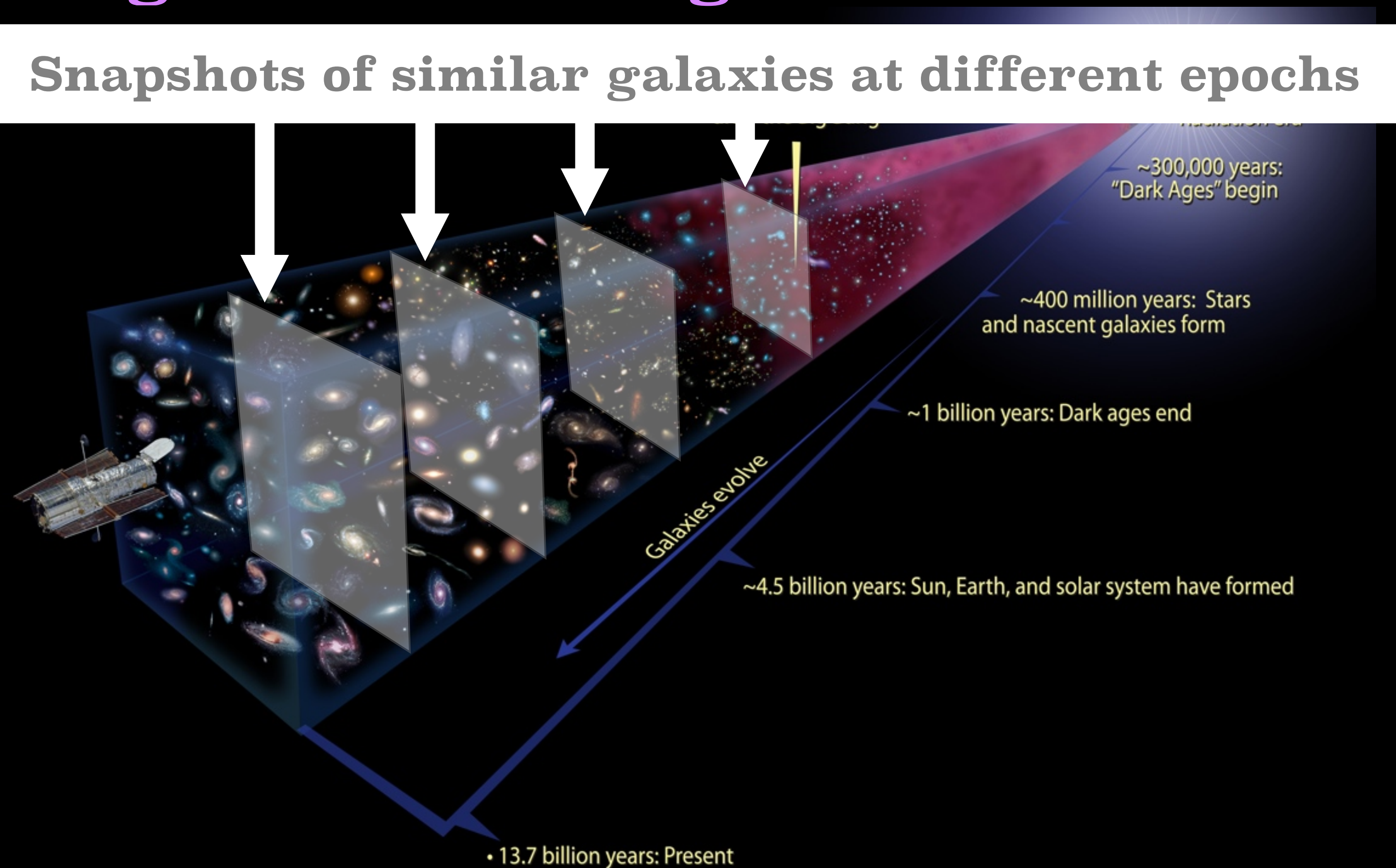
Galaxy Evolution:

identify, *examine*, and *connect* galaxies through cosmic time

Snapshots of similar galaxies at different epochs



NASA, ESA, and A. Feild (STScI)

Rachel Bezanson

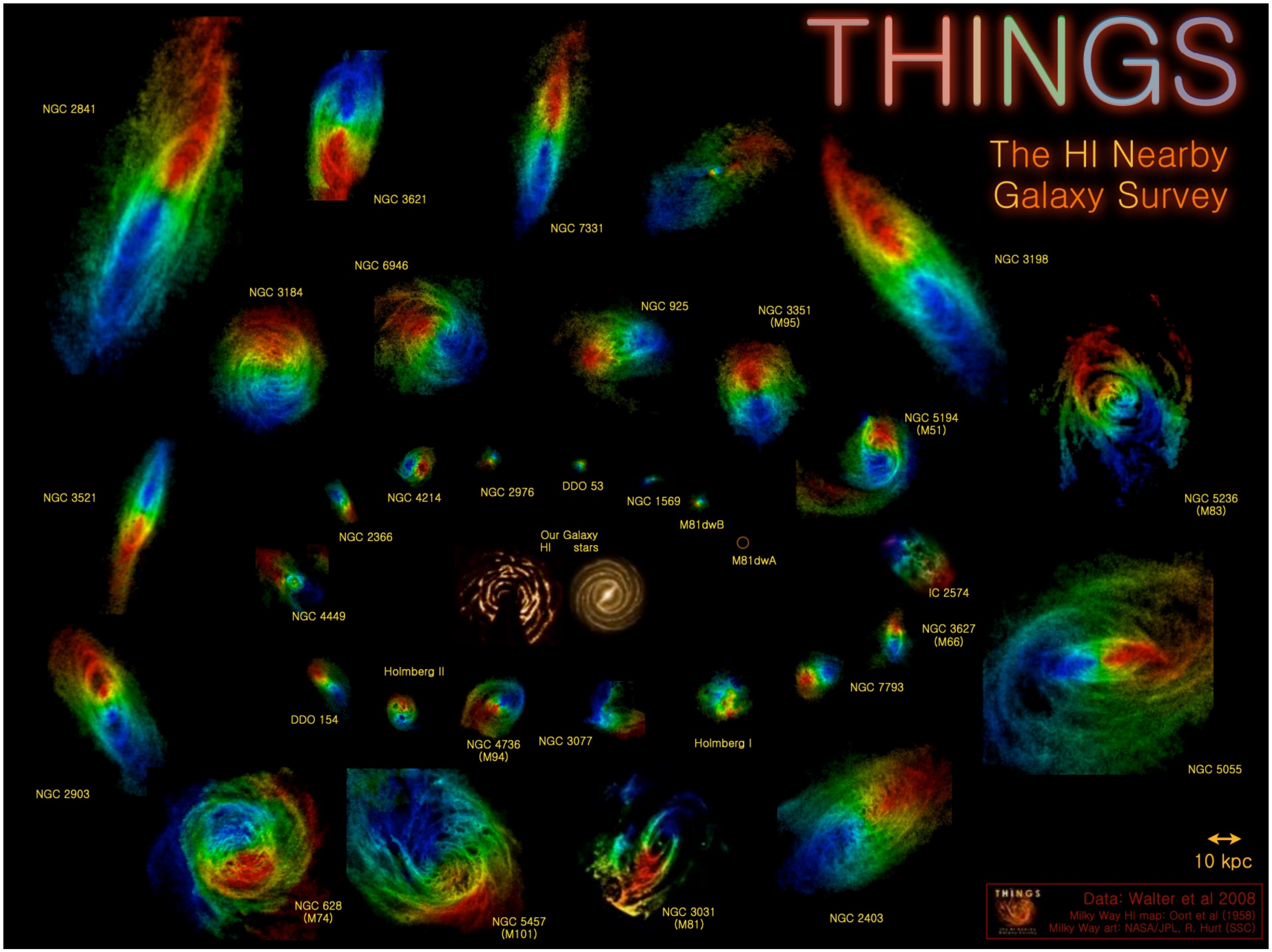
Galaxy Kinematics & Scaling Relations

- Spirals: Rotation Supported
  - Tully Fisher Relation
- Ellipticals: Dispersion Supported
  - Faber-Jackson Relations
  - Fundamental Plane

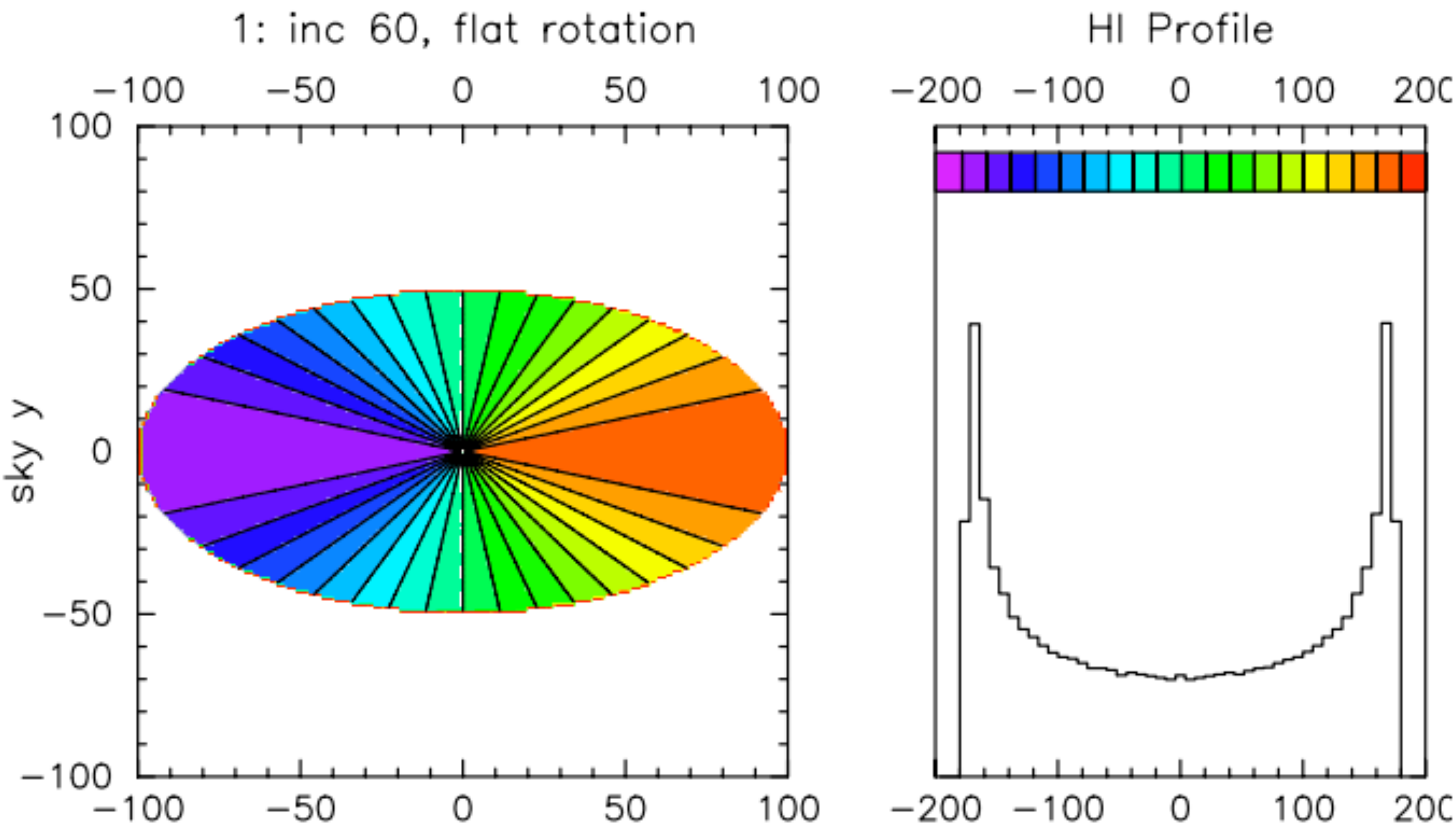
Scaling Relations

- Galaxy morphological properties (Luminosity, Size) are easier to measure than internal kinematics.
- Scaling Relations relate galaxy properties (Luminosity, Size) to their internal kinematics.
- Kinematics is dictated by total mass
- So, scaling relations tell us about the relationship between galaxy properties and dark matter.
- Evolution of these scaling relationships over time can then tell us how galaxies assemble.

Spiral Galaxies are star forming, gas rich, rotationally supported disks



Galaxy Kinematics: Spirals



The Integrated HI Spectrum of Spiral Galaxies

Double peaked profile is characteristic of galaxies with the flat rotation curve and rising part in the center.

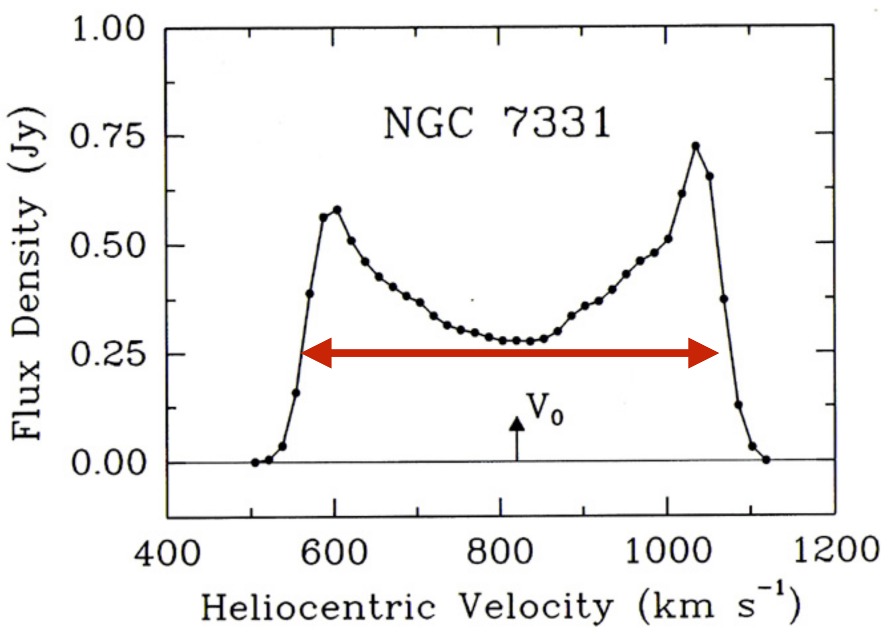


Fig5.22 (K. Begeman) 'Galaxies in the Universe' Sparke/Gallagher CUP 2007

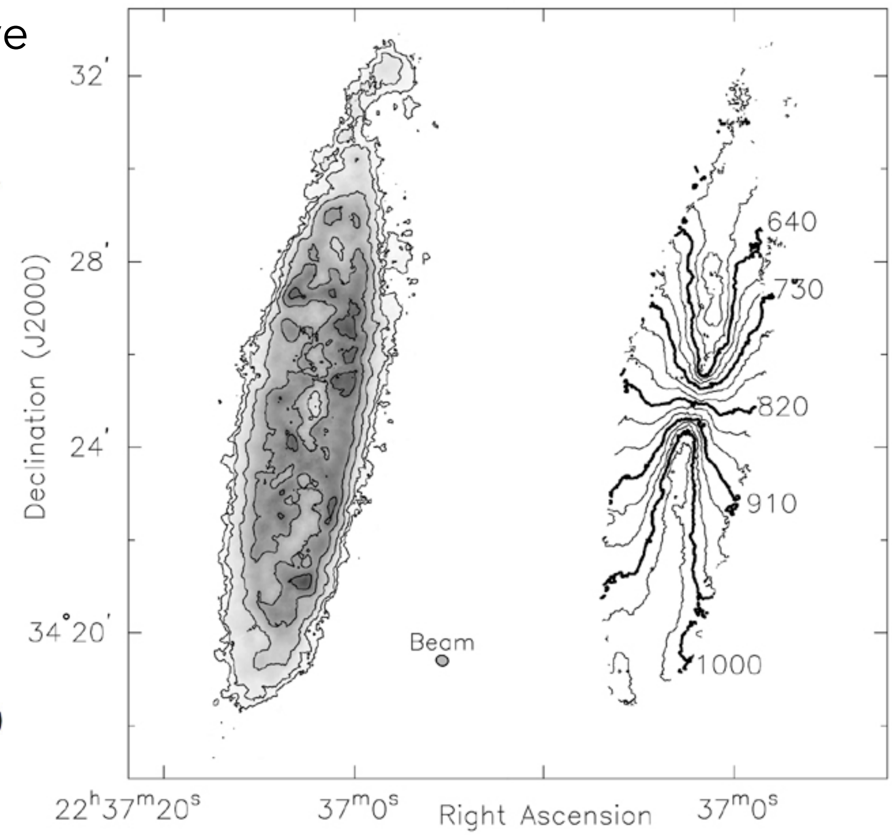


Fig 5.13 (Thornley & Bambic) 'Galaxies in the Universe' Sparke/Gallagher CUP 2007

Width of line ~ $2V_{max}\sin(i)$

Caveat: Inclination

$V = V_{sys}$

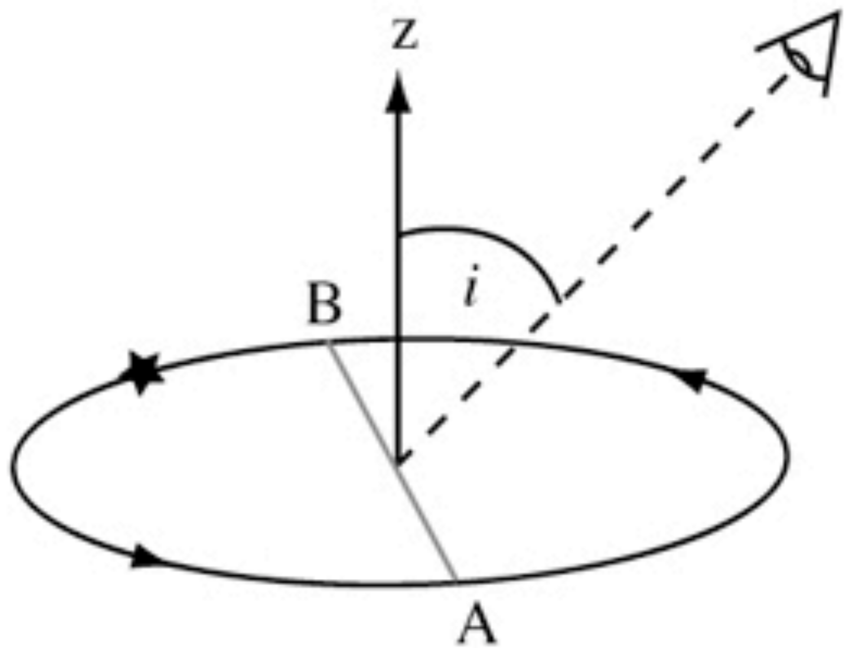
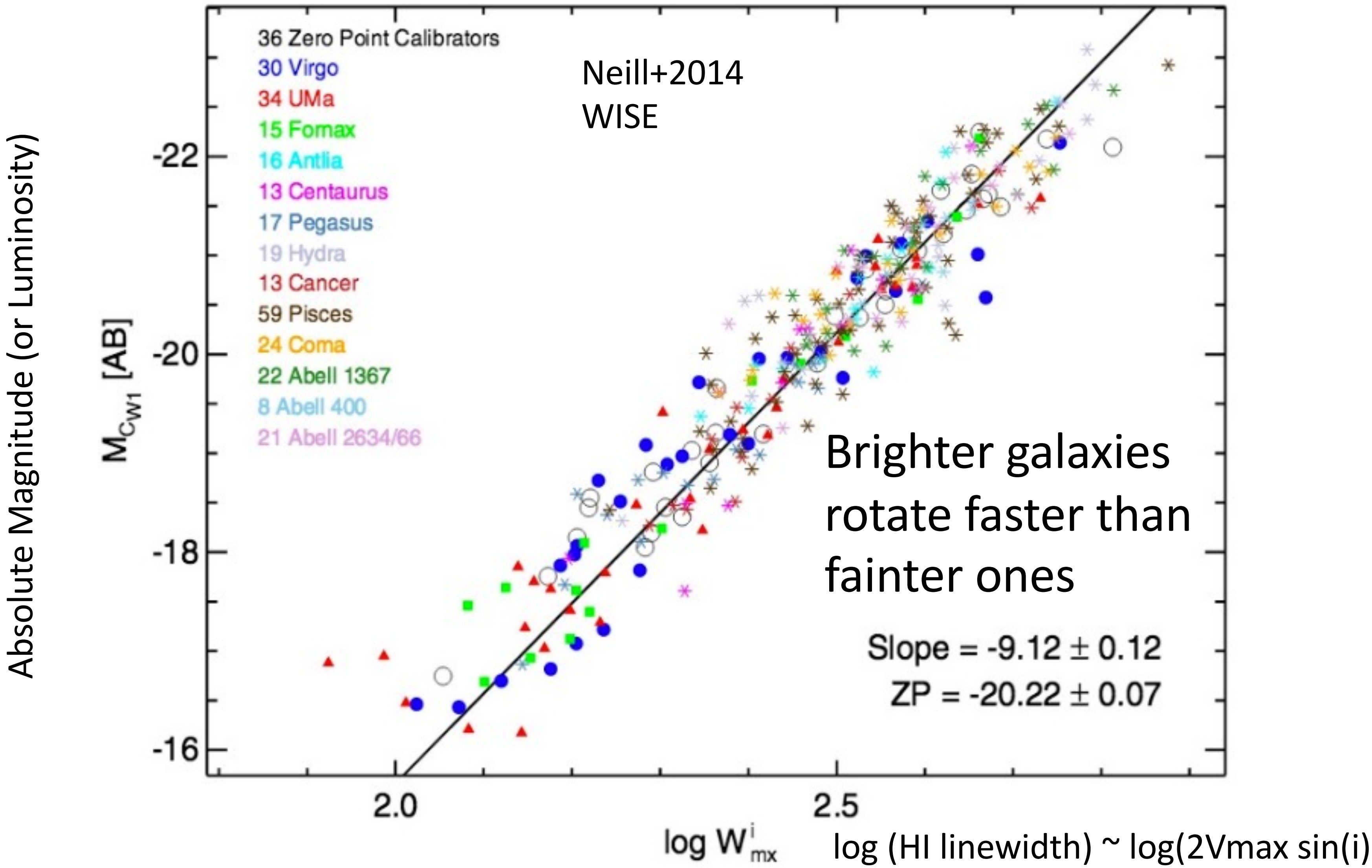


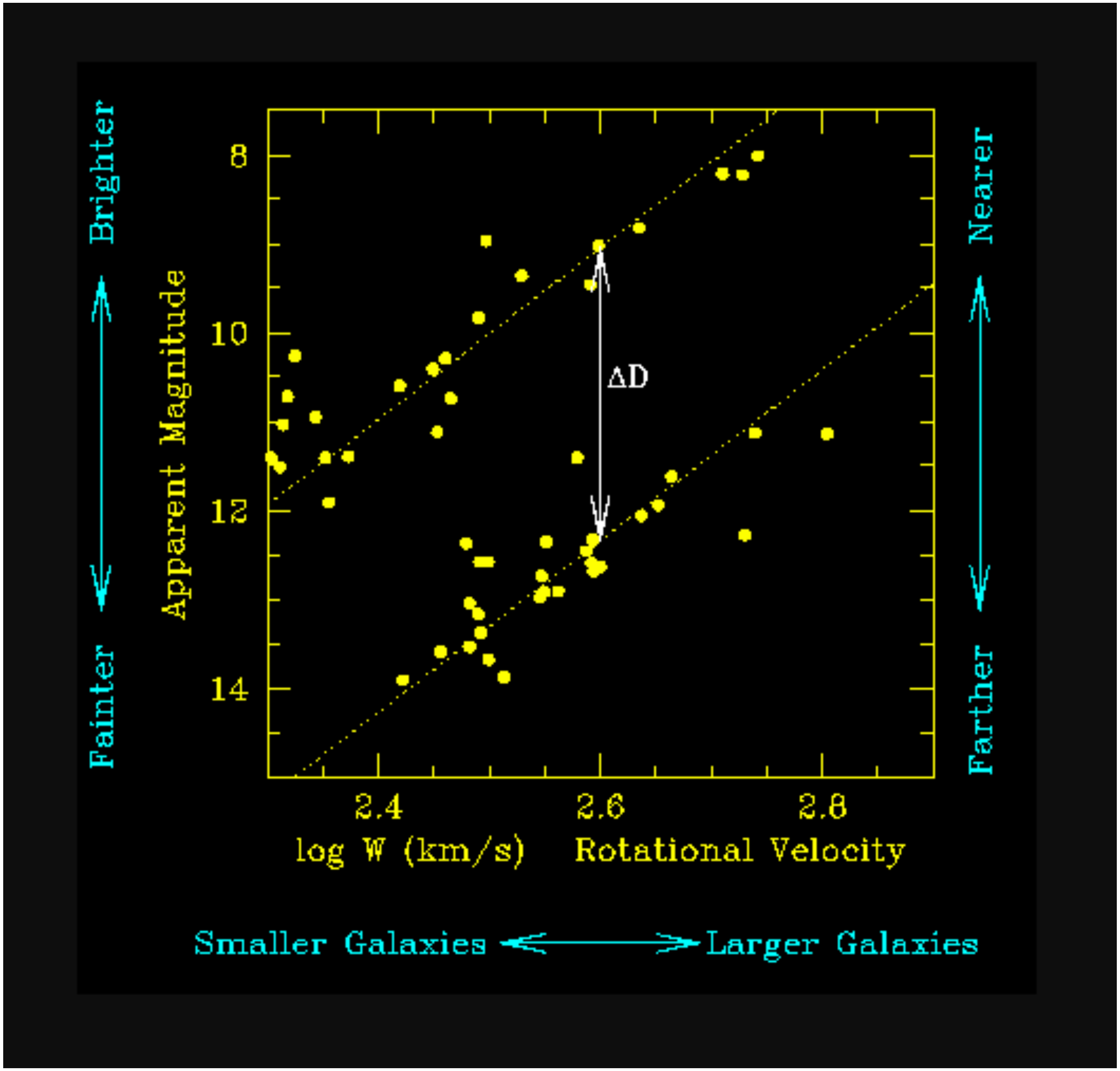
Fig 5.18 'Galaxies in the Universe' Sparke/Gallagher CUP 2007

The observer's line of sight makes angle i with the disk's rotation axis z. We observe Vsys = Vmax sin(i)

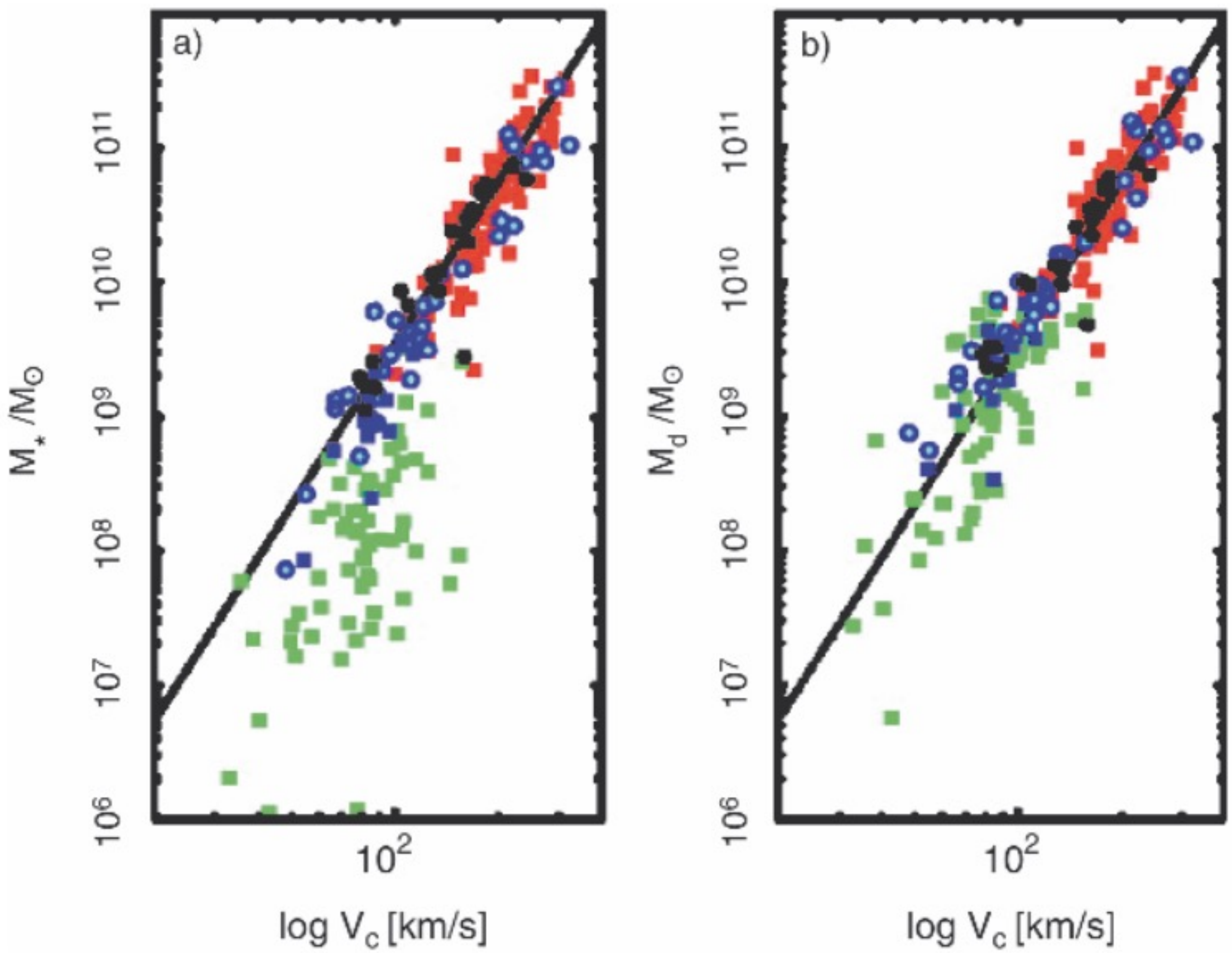
Tully Fisher Relation



- In spirals, luminosity $L \sim v_{max}^{\alpha}$ with $\alpha \sim 4$.


Brighter
Fainter
Apparent Magnitude
8
10
12
14
ΔD
Nearer
Farther
2.4
2.6
2.8
log W (km/s) Rotational Velocity
Smaller Galaxies
Larger Galaxies

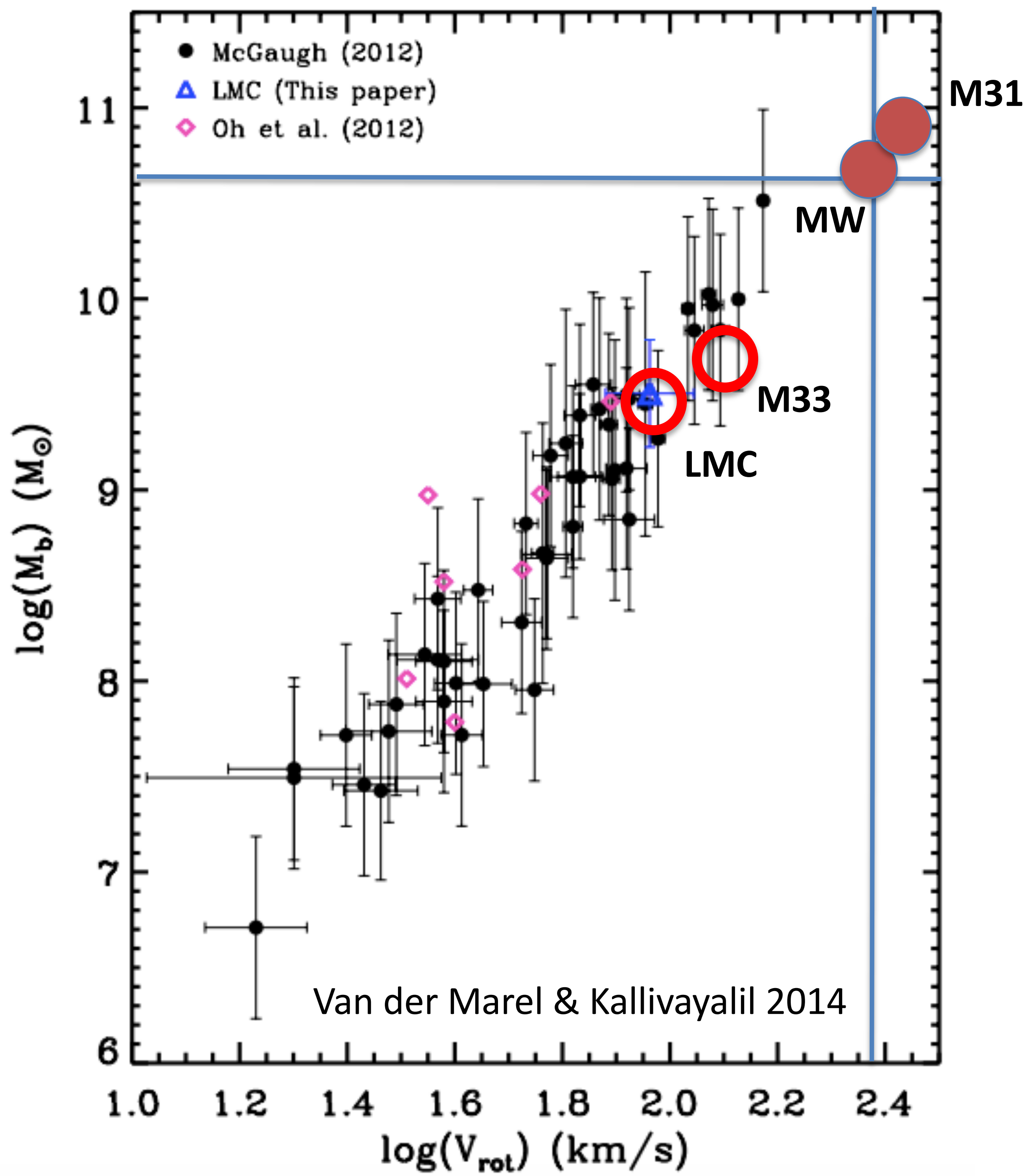
Baryonic Tully Fisher Relation

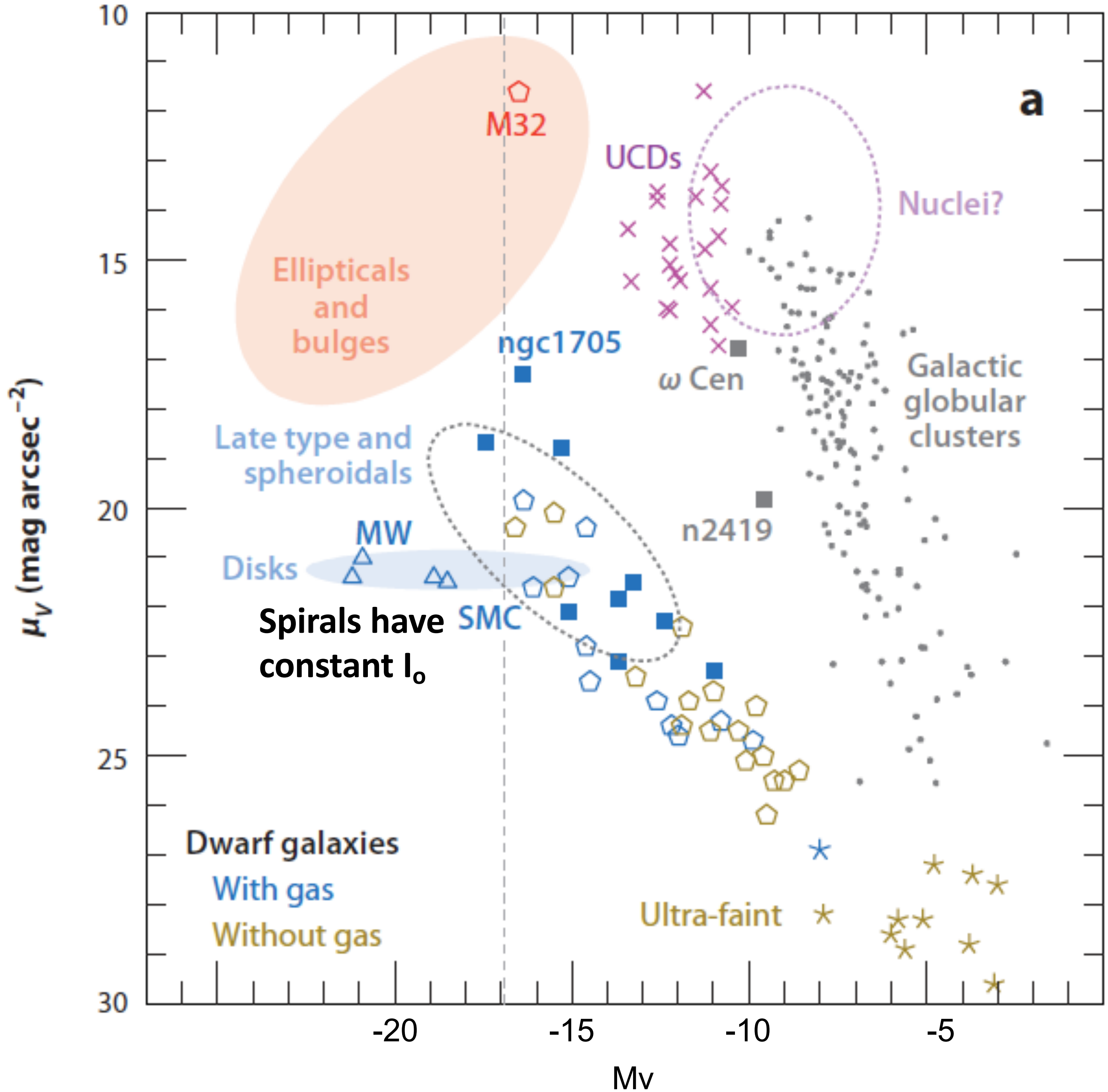


McGaugh 2011

Deviations from the Tully Fisher relation at the low mass end largely disappear if you include the gas mass in addition to the stellar mass (i.e. total disk mass).

Local Group & TF





a
Ellipticals and bulges
M32
UCDs
Nuclei?
ngc1705
ω Cen
Galactic globular clusters
Late type and spheroidals
MW
Disks
n2419
Spirals have constant I_o
SMC
Dwarf galaxies
With gas
Without gas
Ultra-faint
μ_V (mag arcsec^{-2})
Mv
10
15
20
25
30
-20
-15
-10
-5

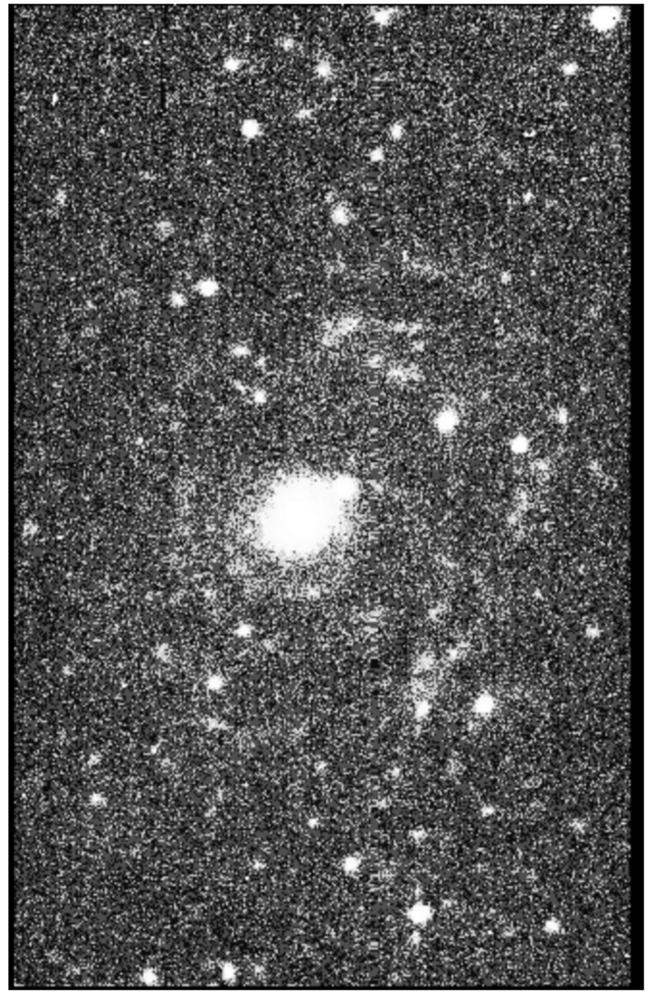
The central surface brightness of many spirals is ~ constant, irrespective of the absolute magnitude of the galaxy!

$$I_B(0) \approx 21.65 \text{ mag arcsec}^{-2}$$ ~100 Lsun/pc^2

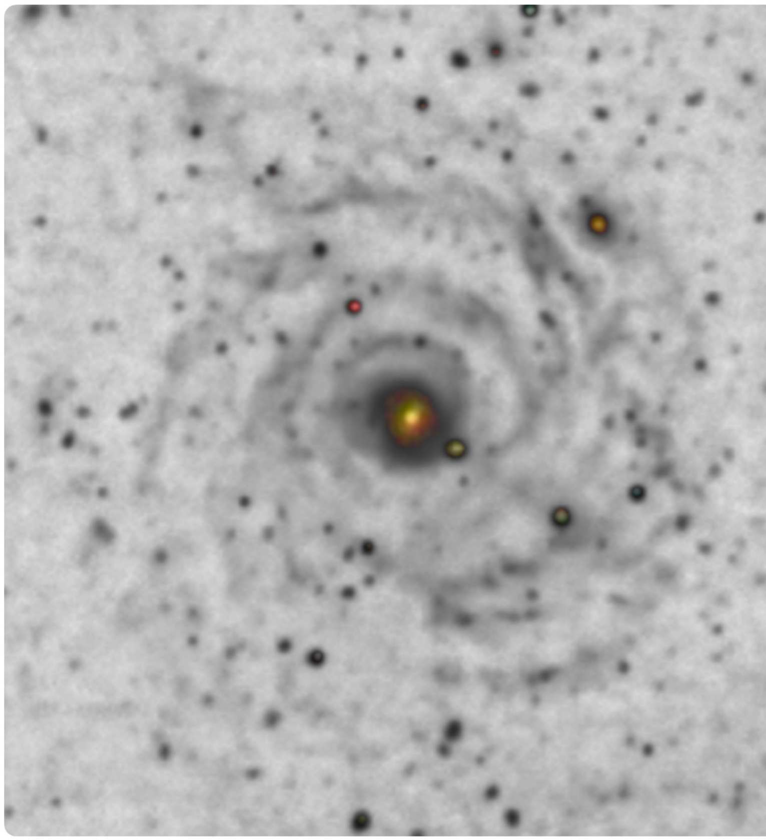
BUT: Low Surface Brightness Galaxies

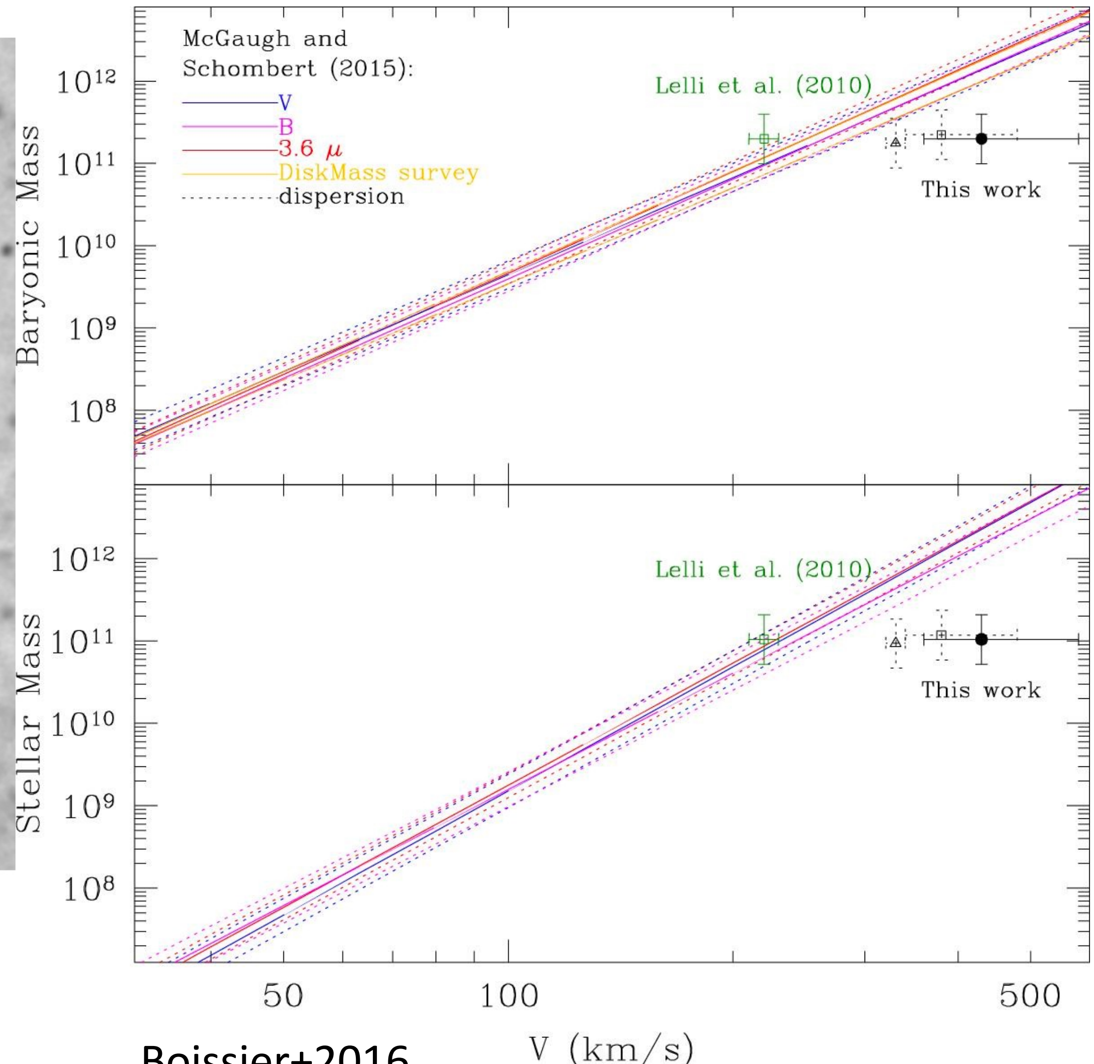
M101

Malin 1



Malin I – Vrot ~ 350 km/s





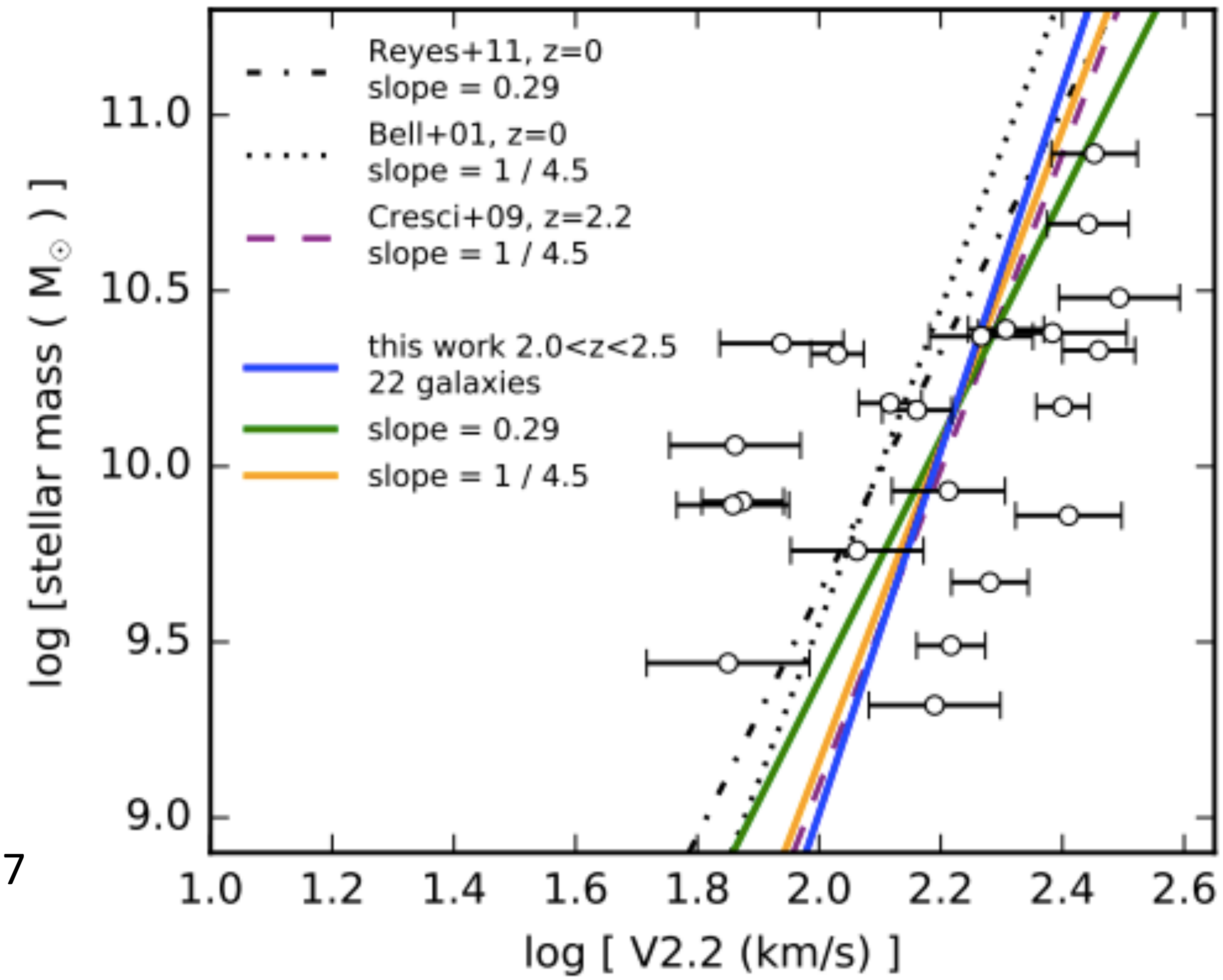
For Tully Fisher to hold true at low surface brightness:

$$M/L \propto 1/\sqrt{(I_o)}$$

Boissier+2016
Junais+2020

Evolution of Tully Fisher?

- Lots of debate! Slope? Zero Point?

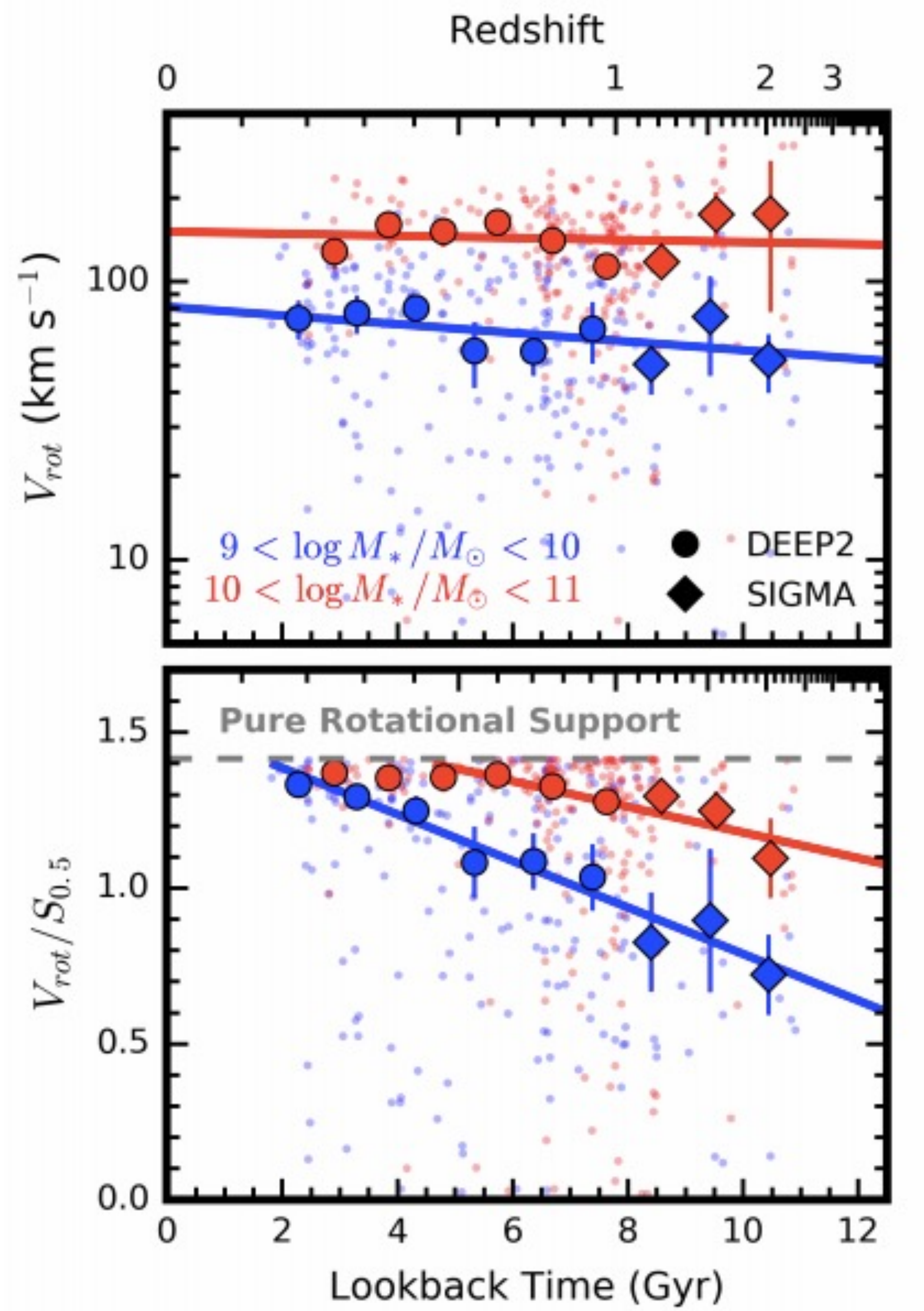


Straatman+17

Evolution of Tully Fisher?

Evolution at low masses?

Simons+2017

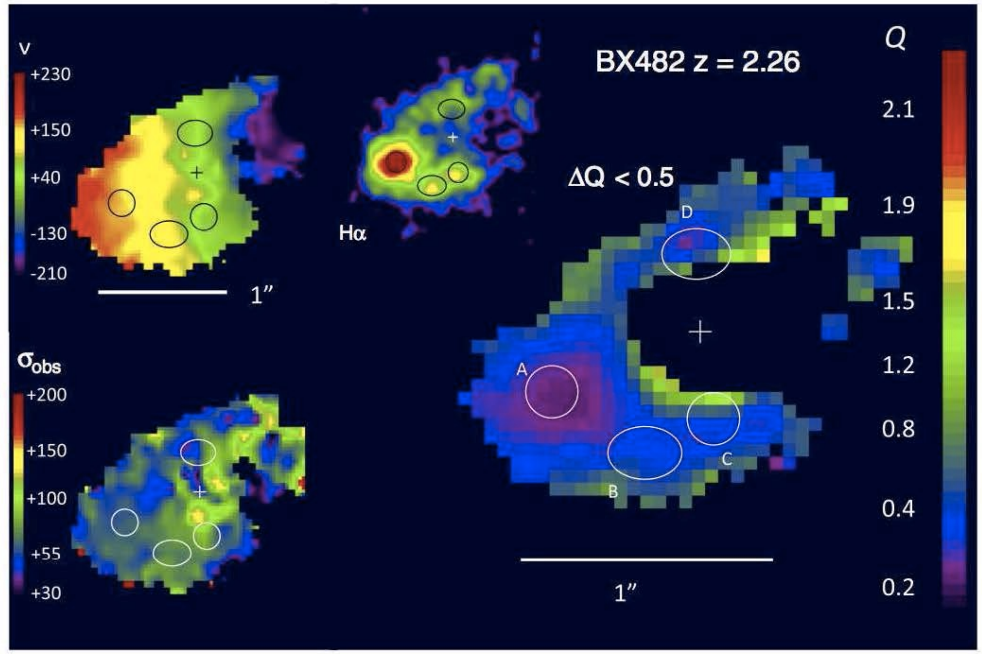


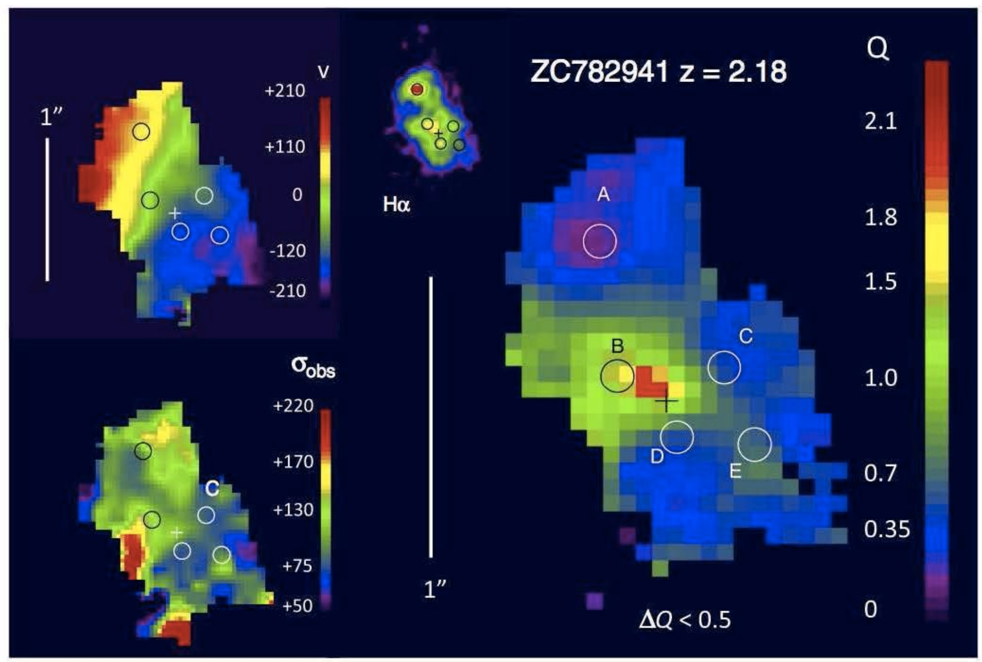
Morphology of high z galaxies

$$\sigma^2 = \frac{1}{N}\sum_{i=1}^{N}(v - \langle v \rangle)^2$$

$$\langle v \rangle = \frac{1}{N}\sum_{j=1}^{N} v_j$$

Genzel+2011



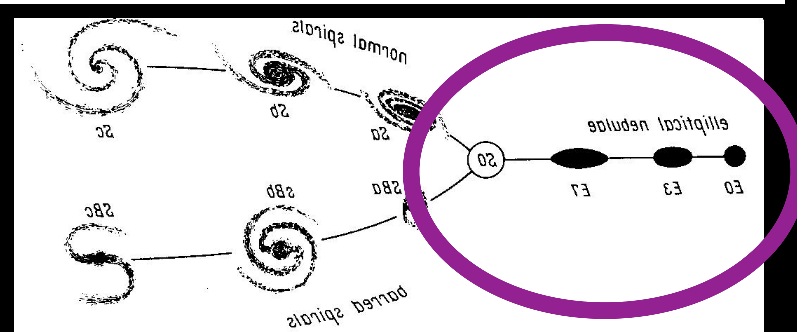


Massive Galaxies Today

local **massive galaxies are OLD:**

large effective radii (r_e~5 kpc)
red, quiescent stellar populations
spheroidals with de Vaucouleurs profiles
dispersion dominated dynamics

Star-Forming ***Quiescent***

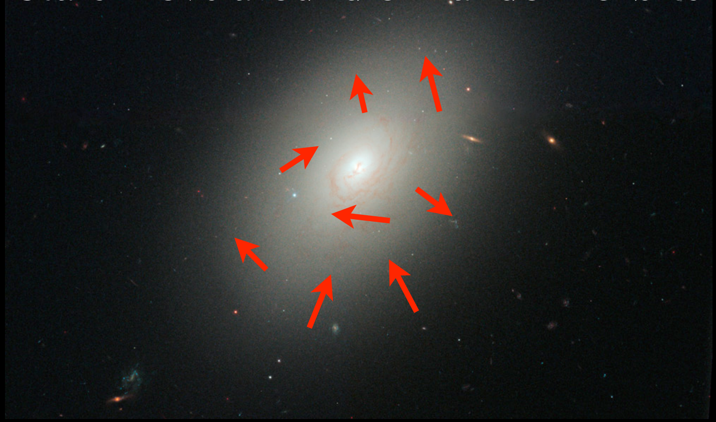


Hubble, 1936

Velocity Dispersion

average motion of stars in a galaxy

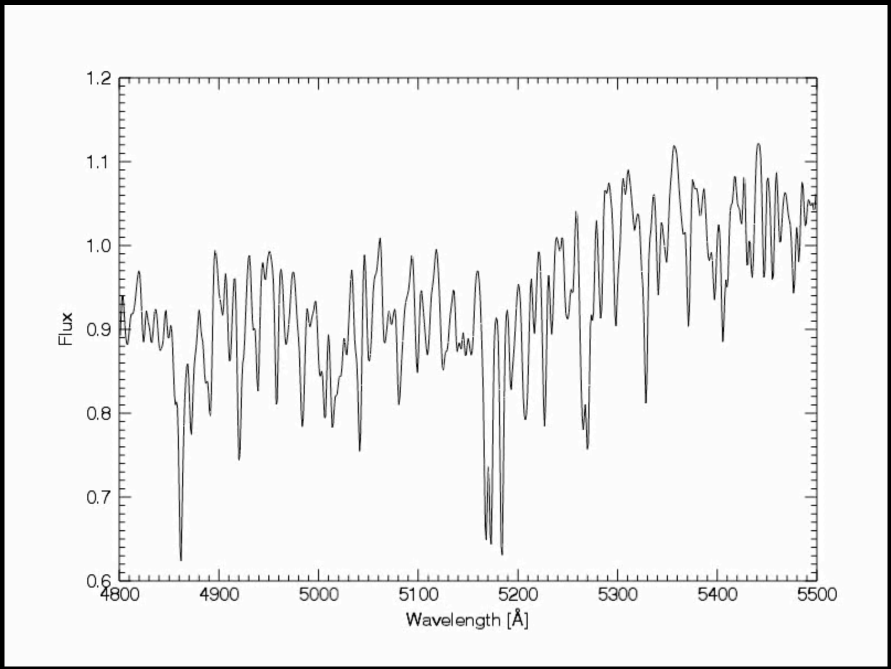
Stars move around on random orbits



(like bees in a swarm)

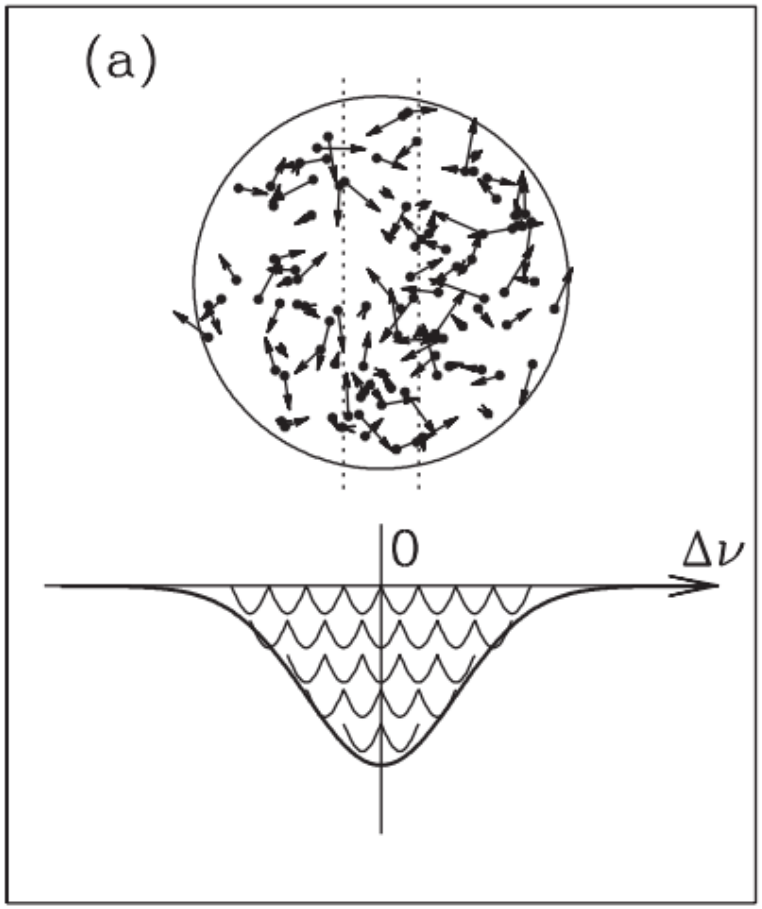
photo credit: http://www.dailymail.co.uk/sciencetech/article-457344/Tourists-shocked-swarm-bees-descend-Bournemouth.html

Measured from doppler broadening of spectral features



Rachel Bezanson

Measuring Velocity Dispersion from the spectrum of many stars simultaneously

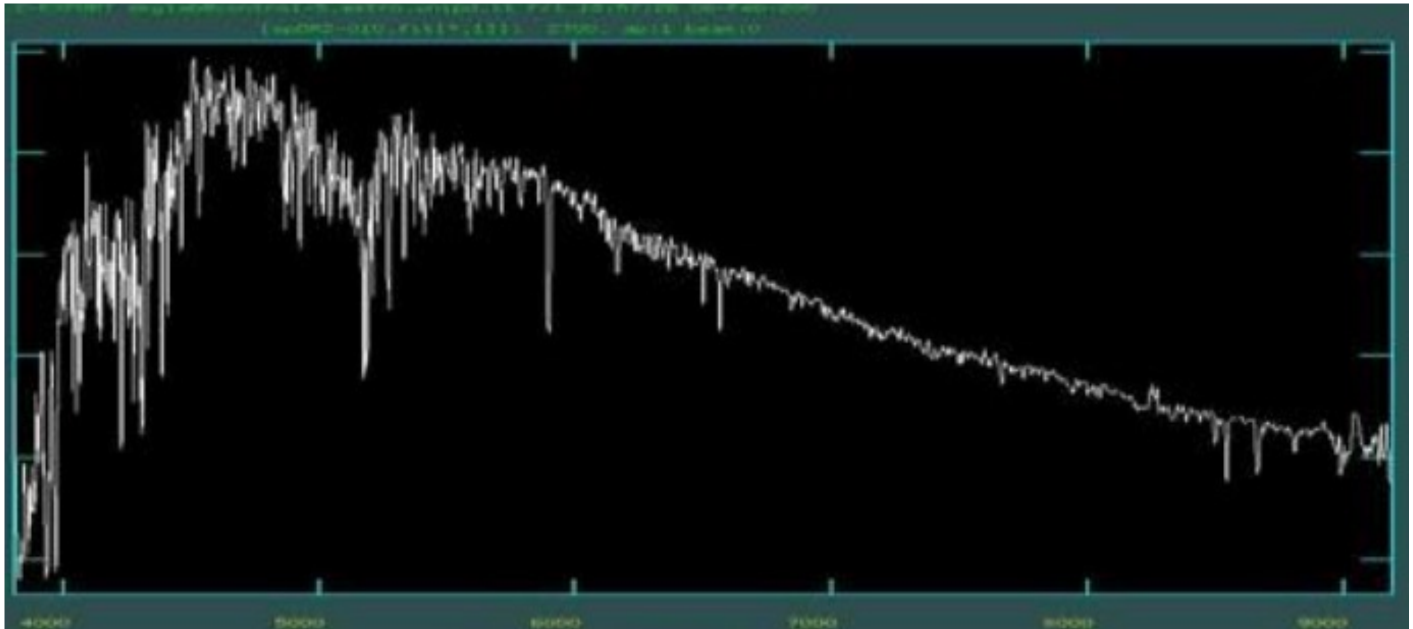


For nearby galaxies, can measure individual Vr for stars we see and measure σ

In distant galaxies, light from all stars is blended together.

Take an optical spectrum of an elliptical and a template star (usually a K-giant). Convolve the template with a gaussian of width σ until it matches the galaxy.

Template K star



Elliptical

Galaxy Kinematics: Ellipticals

Faber-Jackson relation

- Stars move (dispersion) faster in more luminous galaxies. Similar to Tully-Fisher relation for spirals, ellipticals obey so called Faber-Jackson relation:

$$\frac{L_V}{2 \times 10^{10} L_\odot} \approx \left(\frac{\sigma}{200\,\mathrm{km\,s^{-1}}} \right)^4$$

- Can be used to determine distances: less precise than T-F. harder to measure total light from an elliptical.

Dr Sandy Faber

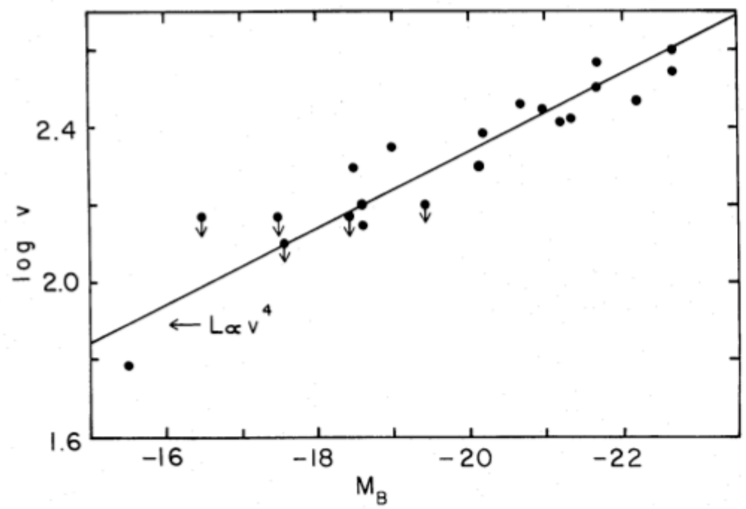
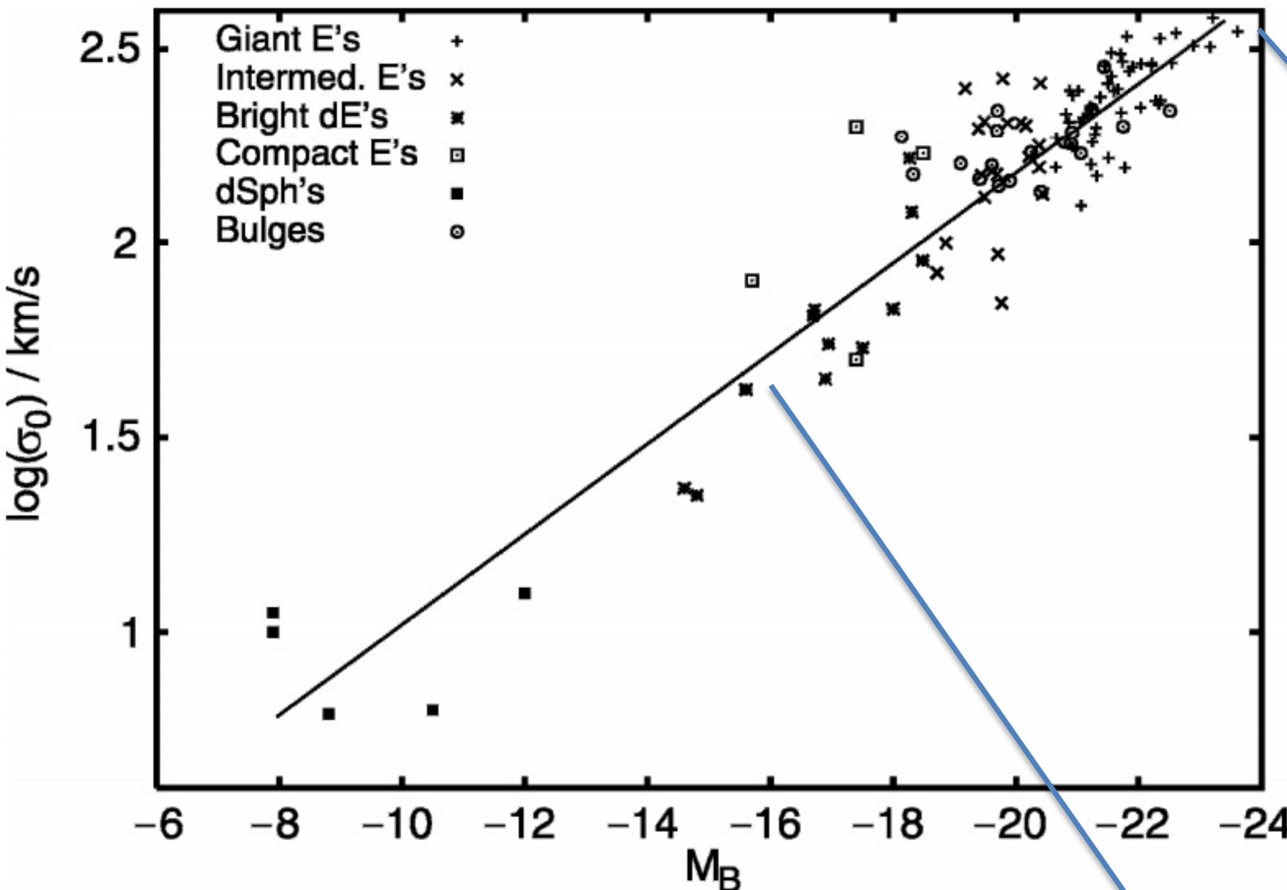
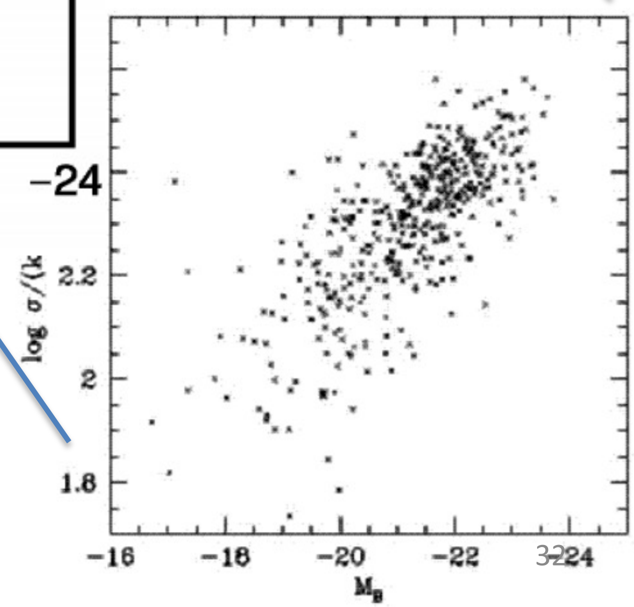


FIG. 16.—Line-of-sight velocity dispersions versus absolute magnitude from Table 1. The point with smallest velocity corresponds to M32, for which the velocity dispersion (60 km s^{-1}) was taken from Richstone and Sargent (1972).

From
Faber and Jackson 1976

Faber-Jackson Relation





$L \ \alpha \ \sigma^4$

Recall …

$$L = 7.2\pi I_e R_e^2$$

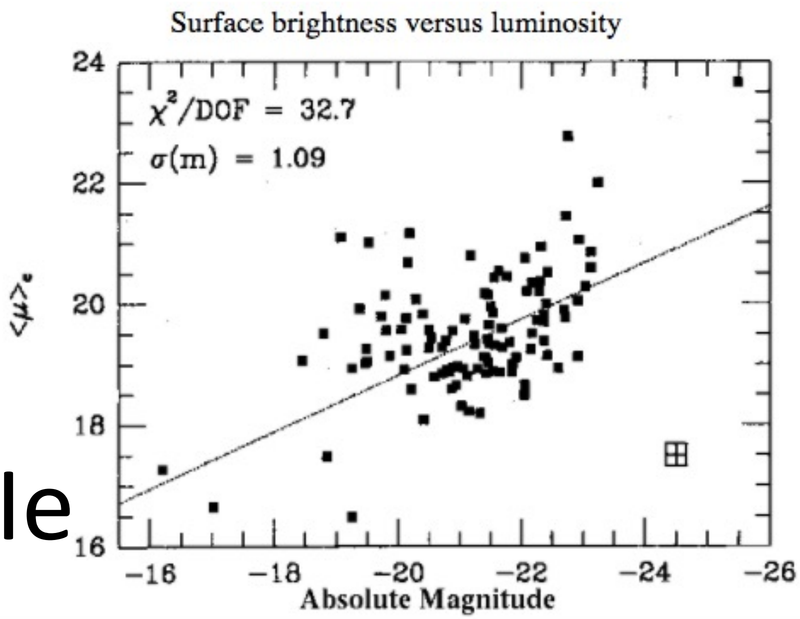
$$I(r) = I_e \exp(-7.67[(\mathrm{r}/\mathrm{R_e})^{1/\mathrm{n}} - 1])$$

And …

$$L \;\alpha\; \sigma^4$$

There are 4 quantities: L, Ie, Re, σ

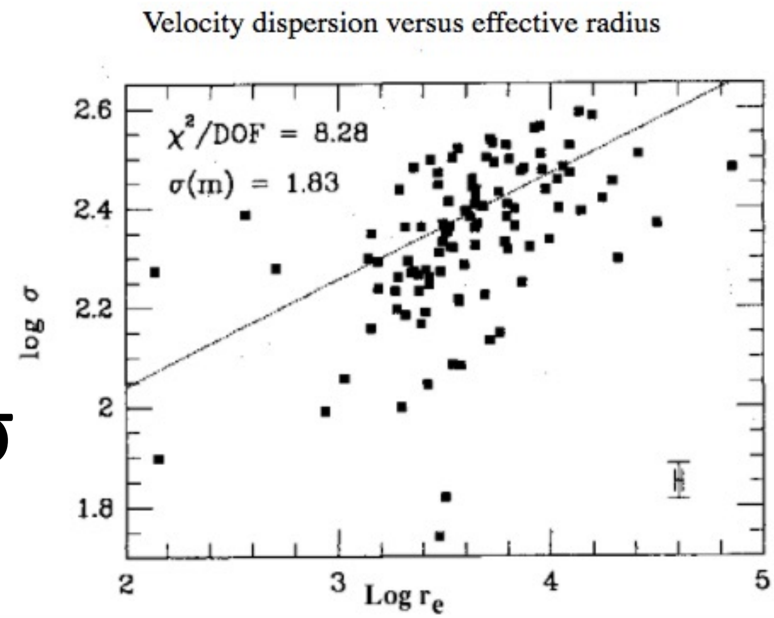
2 quantities .. Get scatter



Ie

L

σ

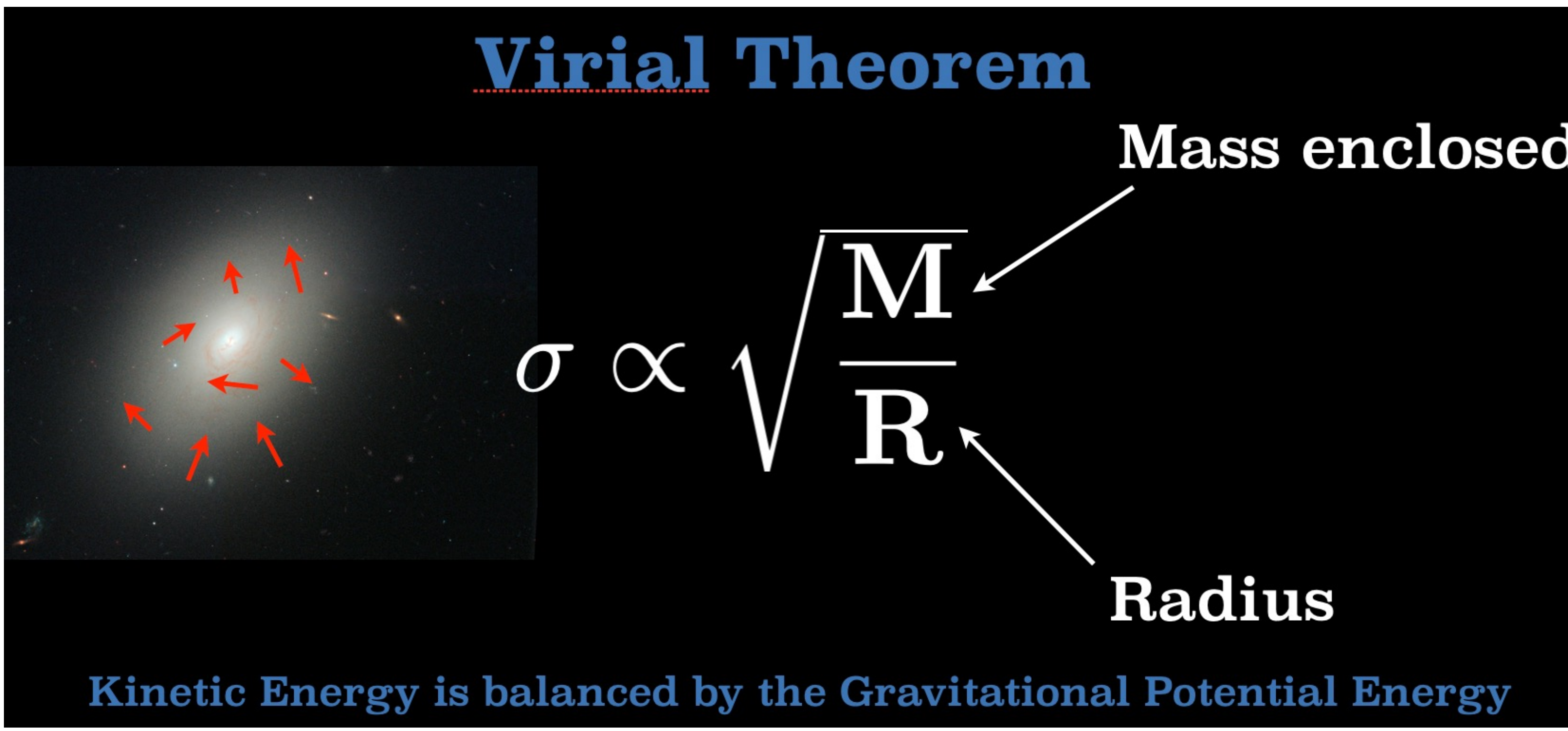


Re

Recall ...

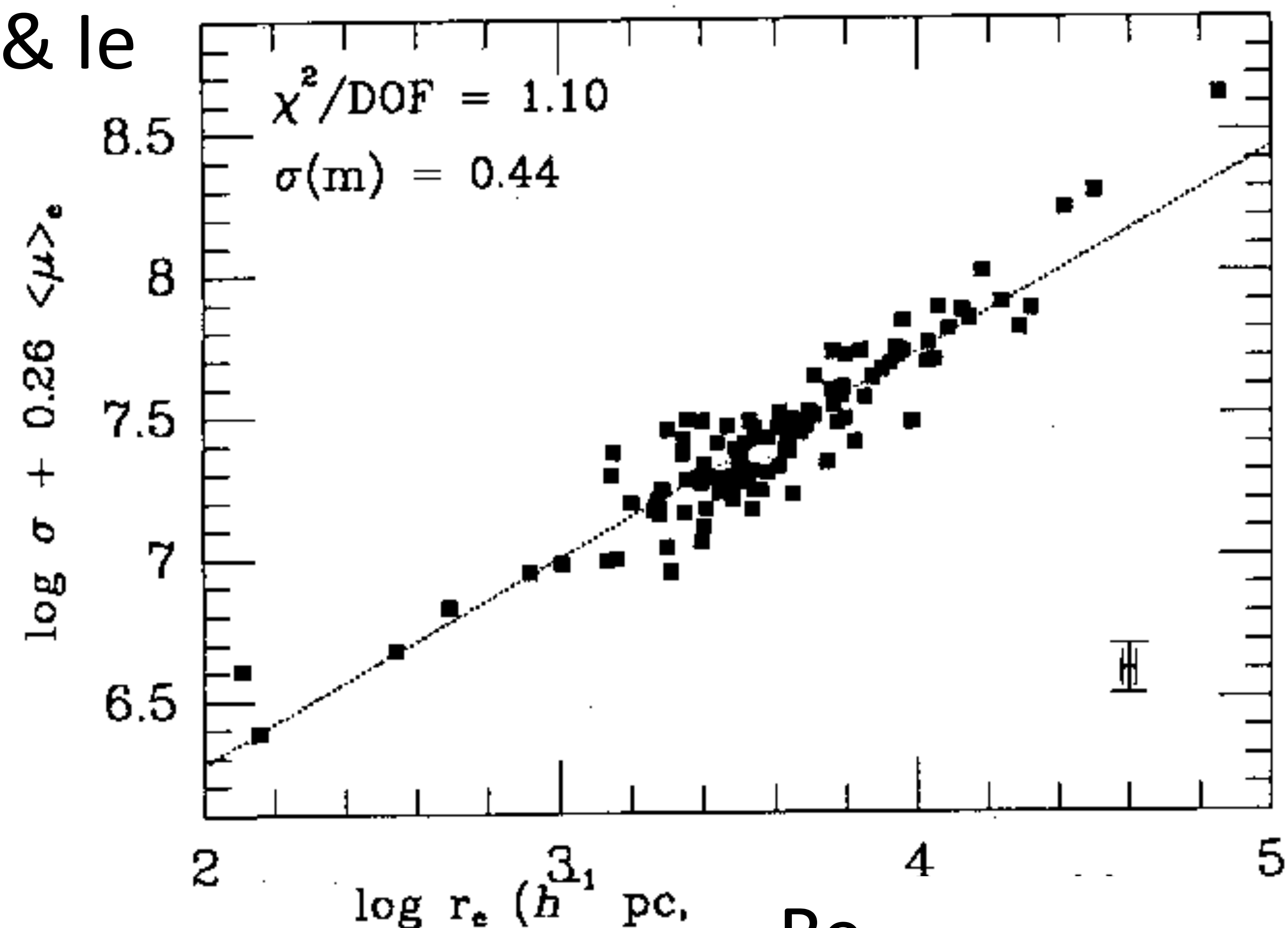
$$L = 7.2\pi I_e R_e^2$$

$$I(r) = I_e \exp(-7.67[(\mathrm{r}/\mathrm{R_e})^{1/\mathrm{n}} - 1])$$



2 quantities vs a 3rd

σ & Ie

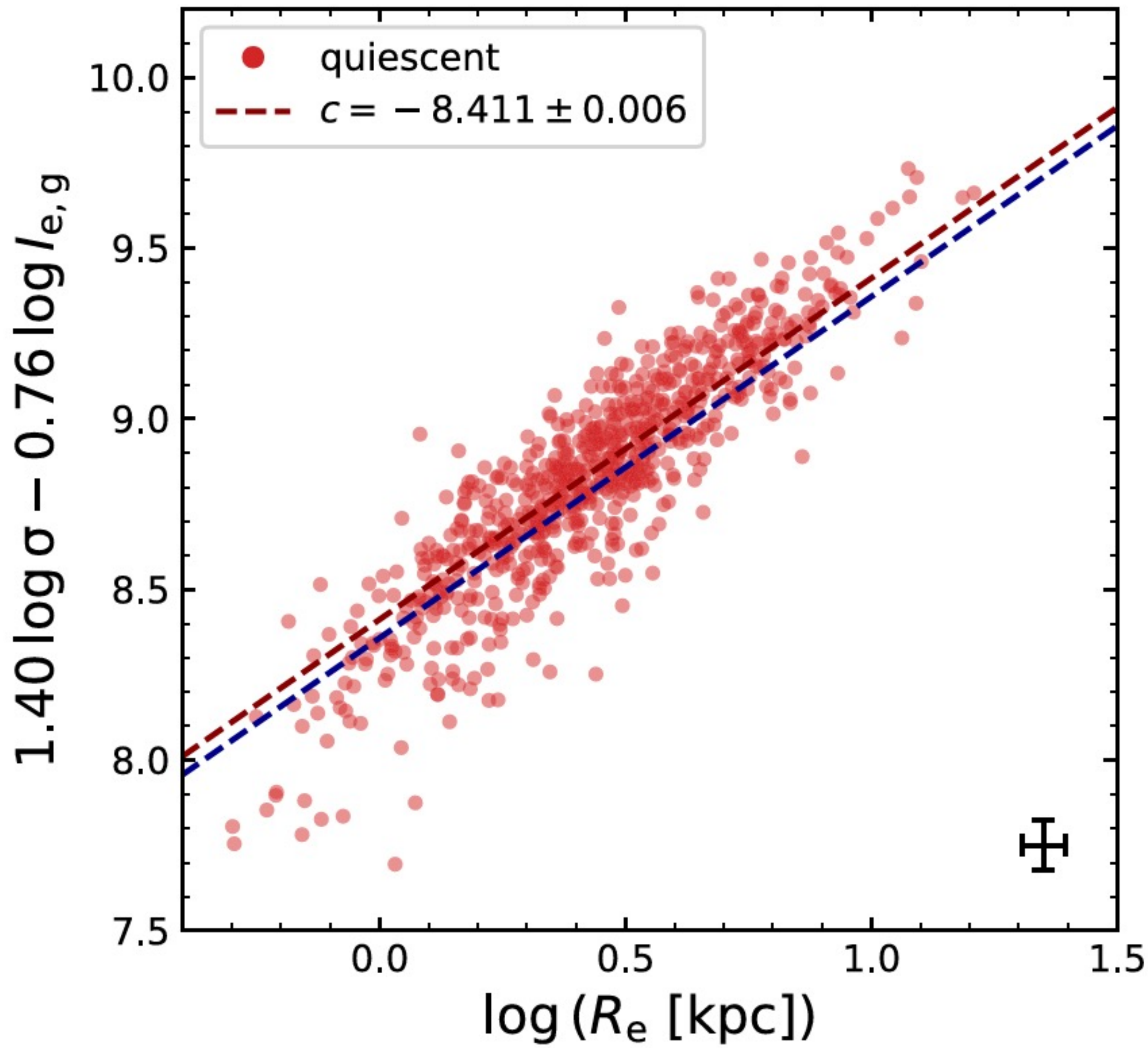


Re

de Graaf + 2021, ApJ, 913

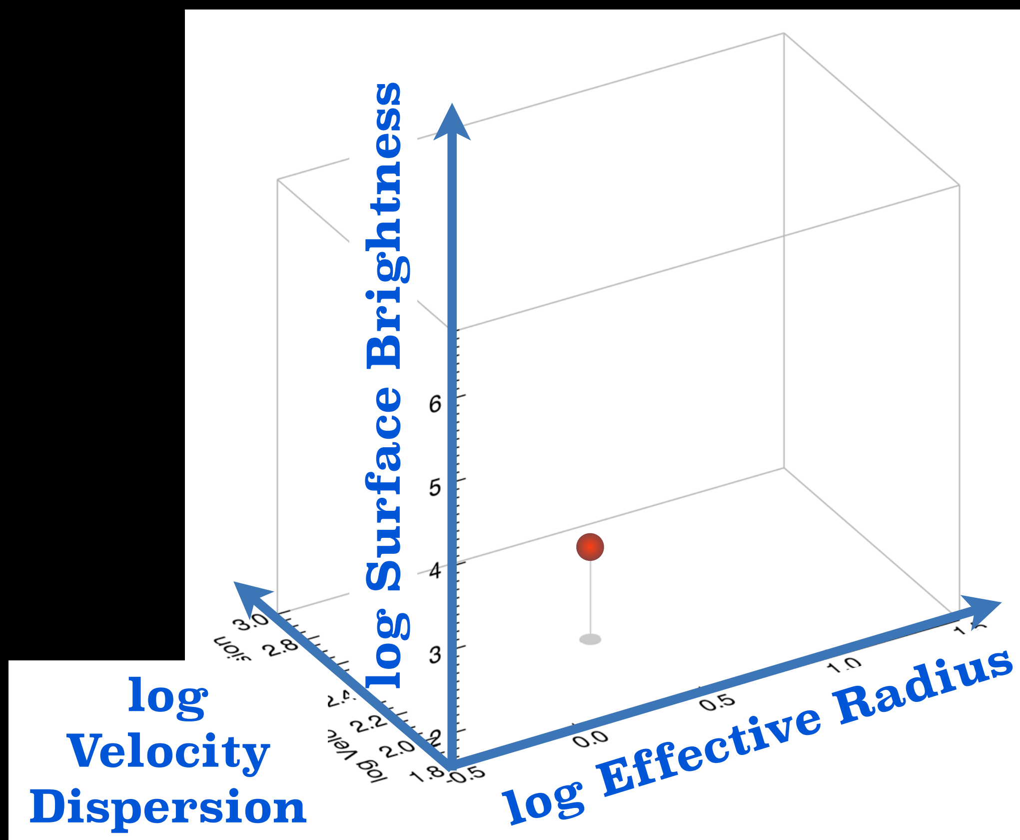
LEGA-C
Survey (HST)

Z~0.8



The Fundamental Plane

scaling relations reveal simplicity in galaxy evolution



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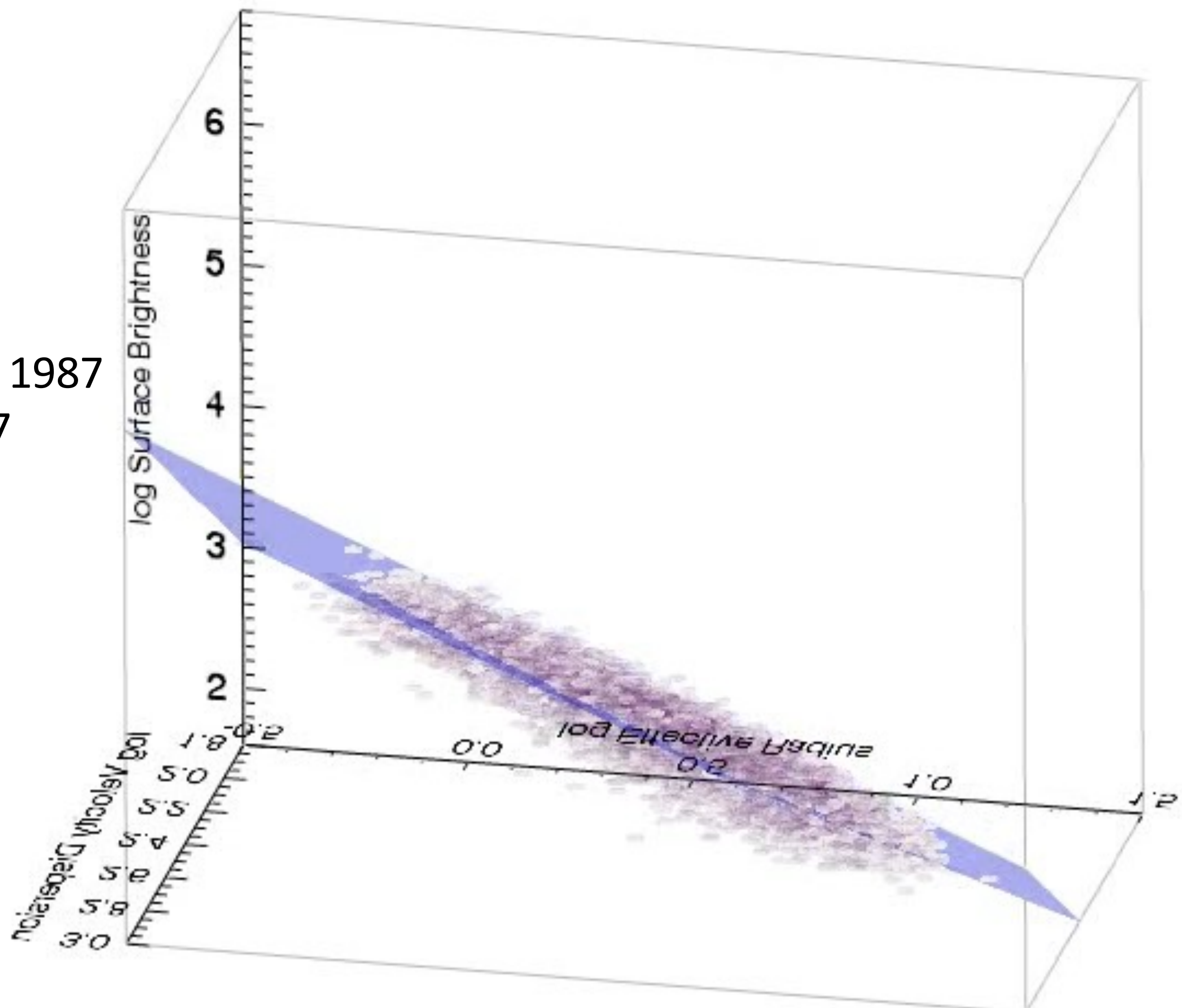
The Fundamental Plane

Quenched
SDSS galaxies
0.05 < z < 0.07

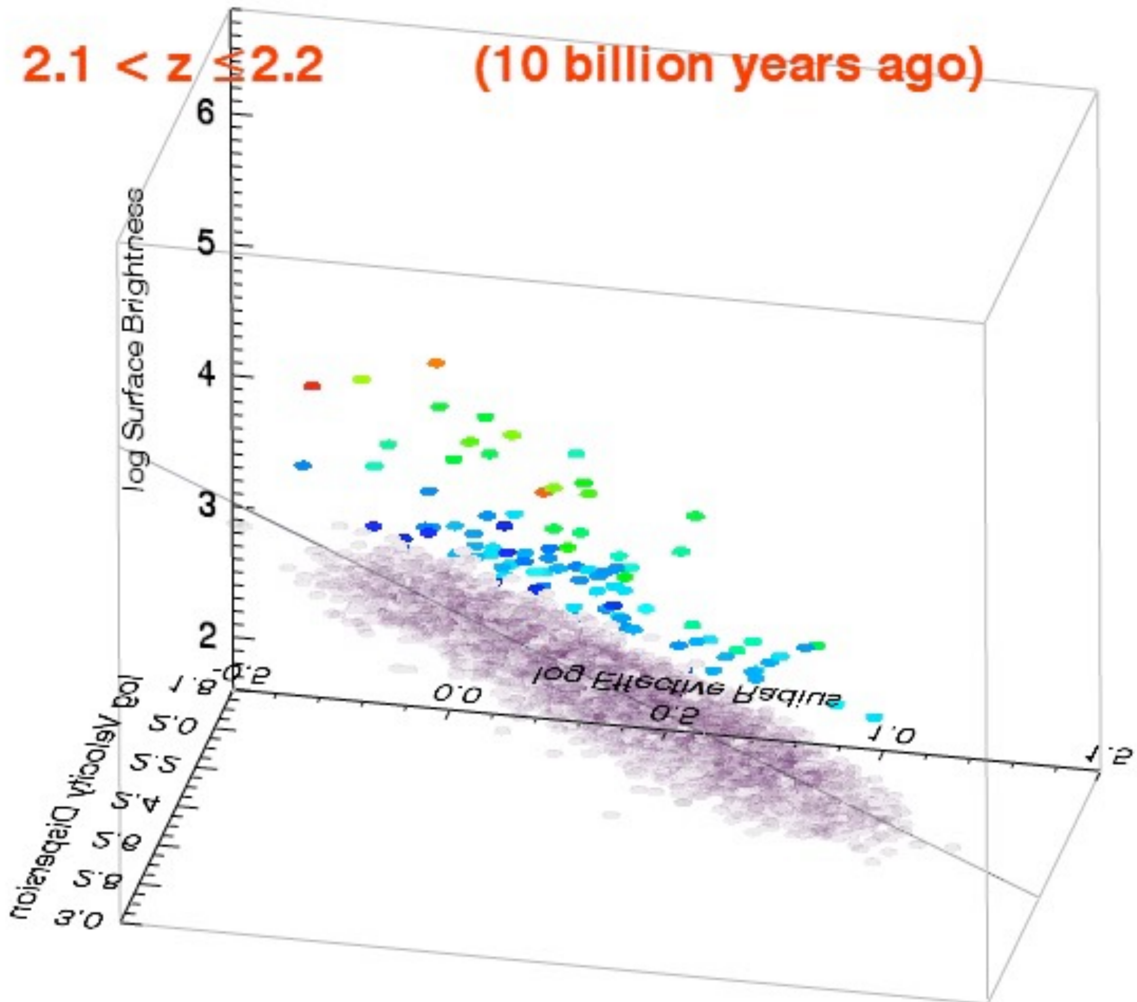
Djorgovski & Davis 1987
Dressler et al. 1987



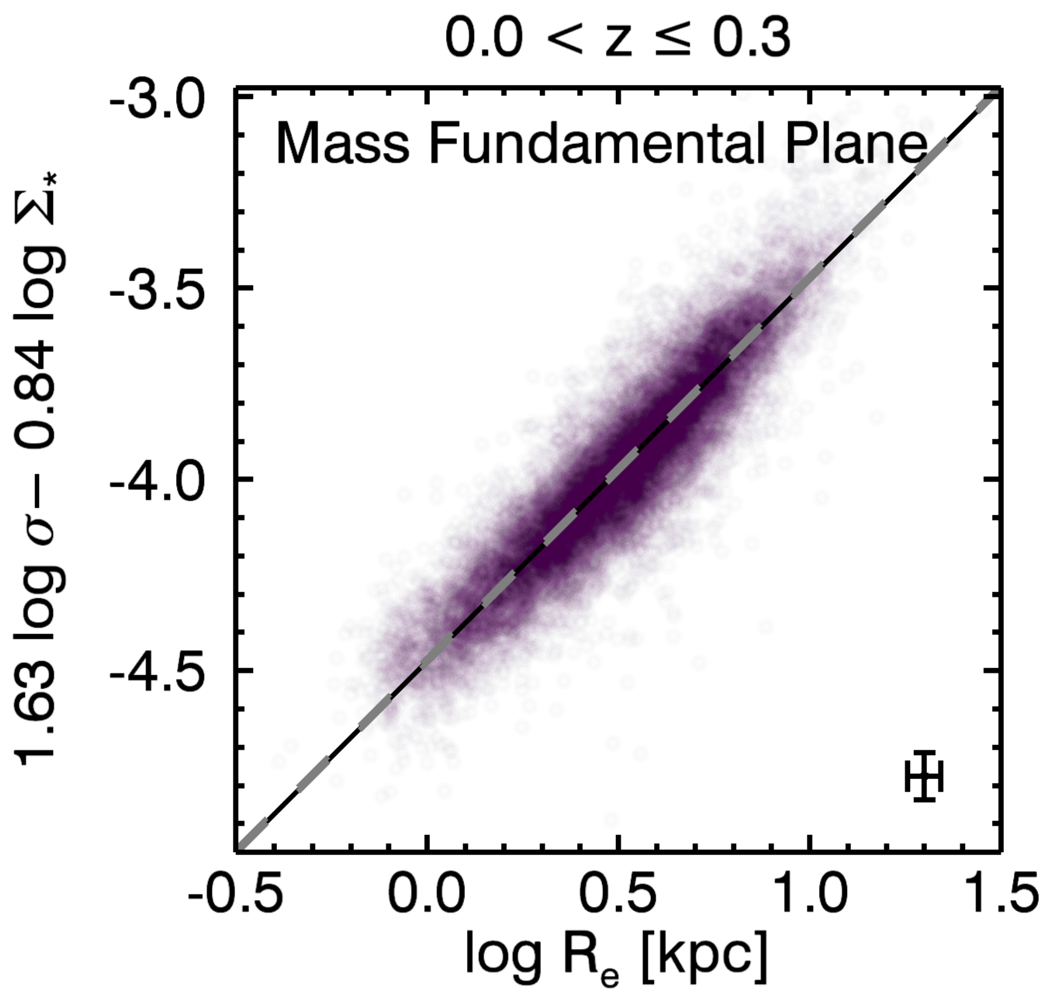
Courtesy: Rachel Bezanson

Courtesy: Dr. Rachel Bezanson

Redshift Evolution of the Fundamental Plane



Mass Fundamental Plane
Bezanson+2015, 2013



0.1 < z ≤0.2 (1 billion years ago)