Lecture 3: Galaxy Evolution over the Last Half of Cosmic Time

Alexandria Winter School on Galaxy Formation

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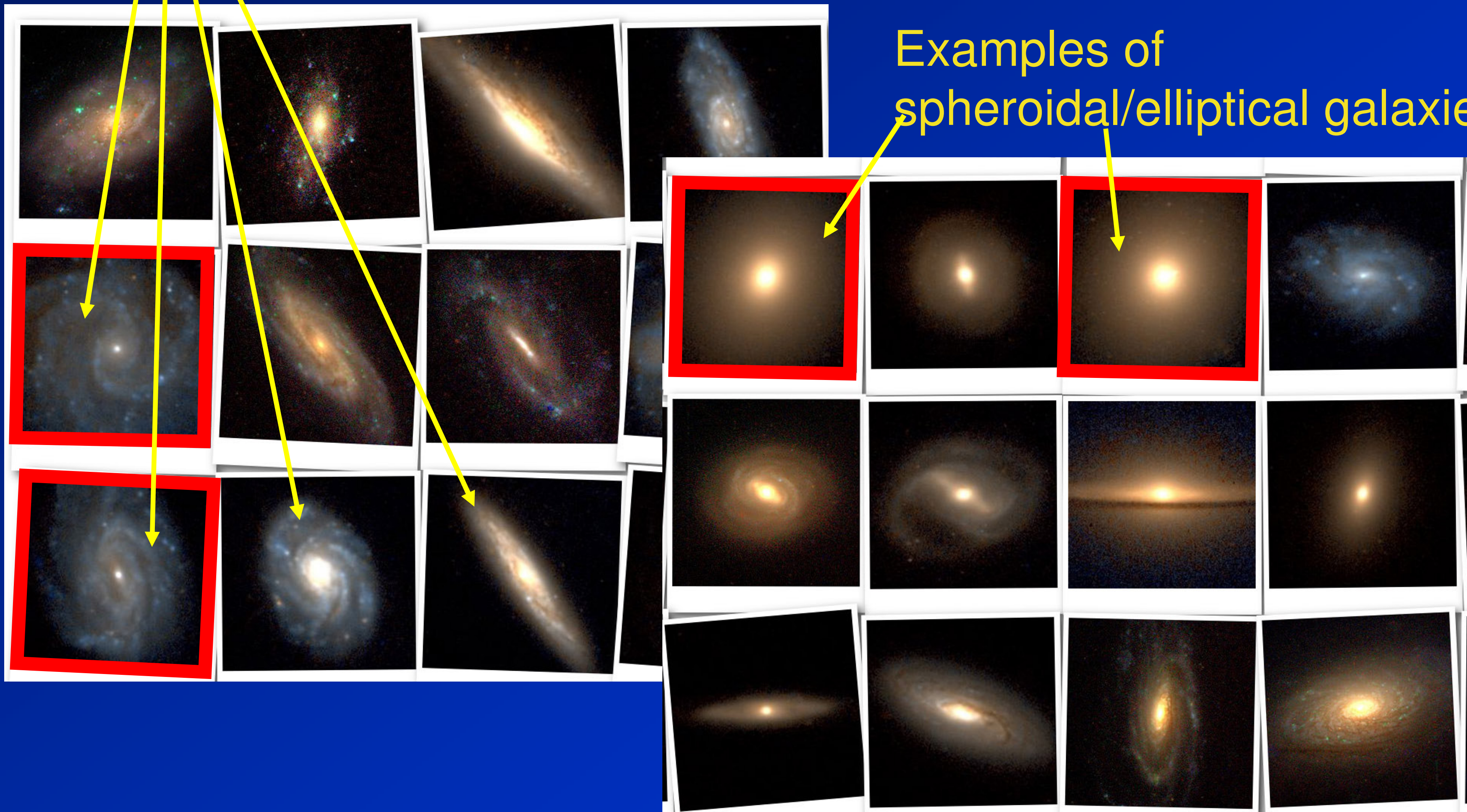
March 22, 2006

A reminder about Hubble types: disky galaxies vs. spheroidal galaxies

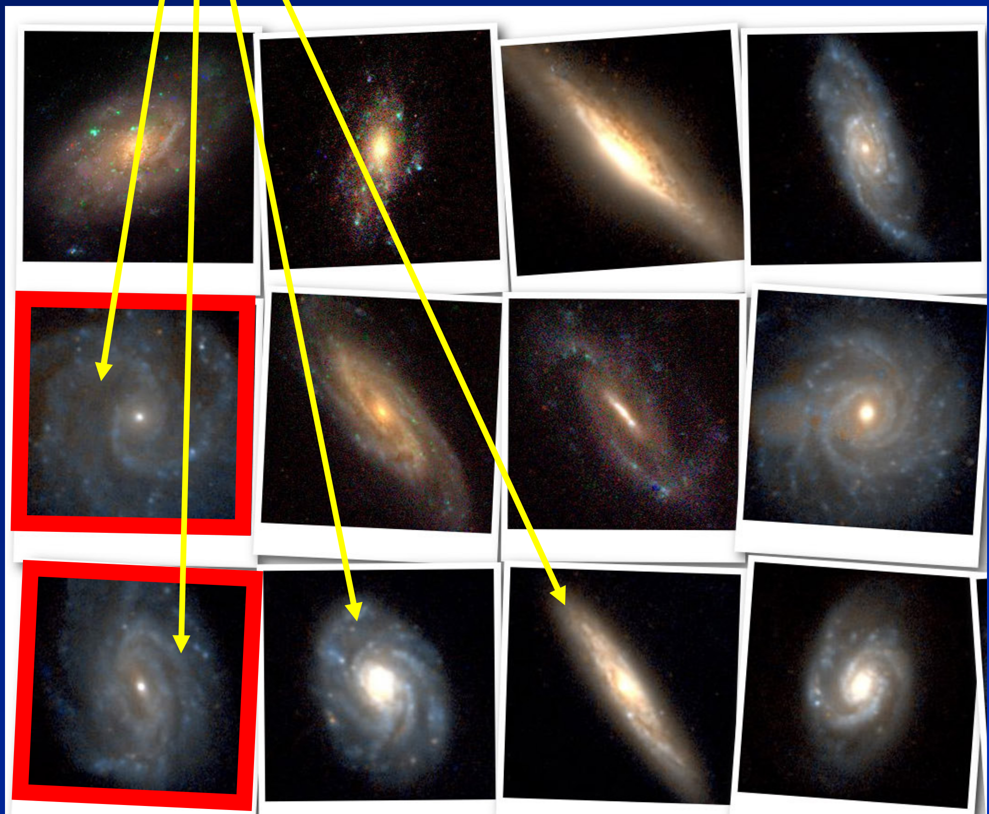
Examples of disky/spiral galaxies

Examples of spheroidal/elliptical galaxies



Properties of disky galaxies

Examples of disky/spiral galaxies



* **"Cold"** means that orbiting objects have small ***velocity dispersion*** relative to one other.

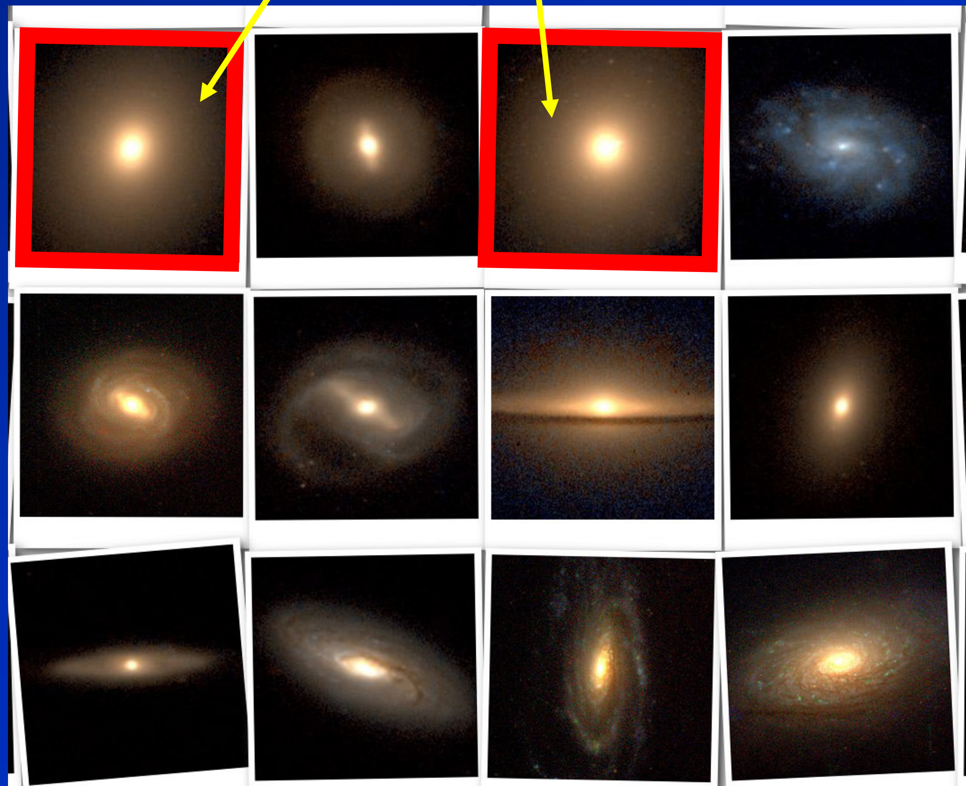
- Flattened, rotating, **"cold"*** systems with stars and gas in NEARLY CIRCULAR orbits.
- Supported by circular motion.
- Spiral arms are caused by spontaneous ***gravitational instability*** in cold disks.
- Have interstellar gas; ***still making stars.***
- Intermediate to small stellar masses: few x 10^{10} $M_\odot$ down to 10^{6-7} $M_\odot$ "dwarfs."

Properties of spheroidal galaxies

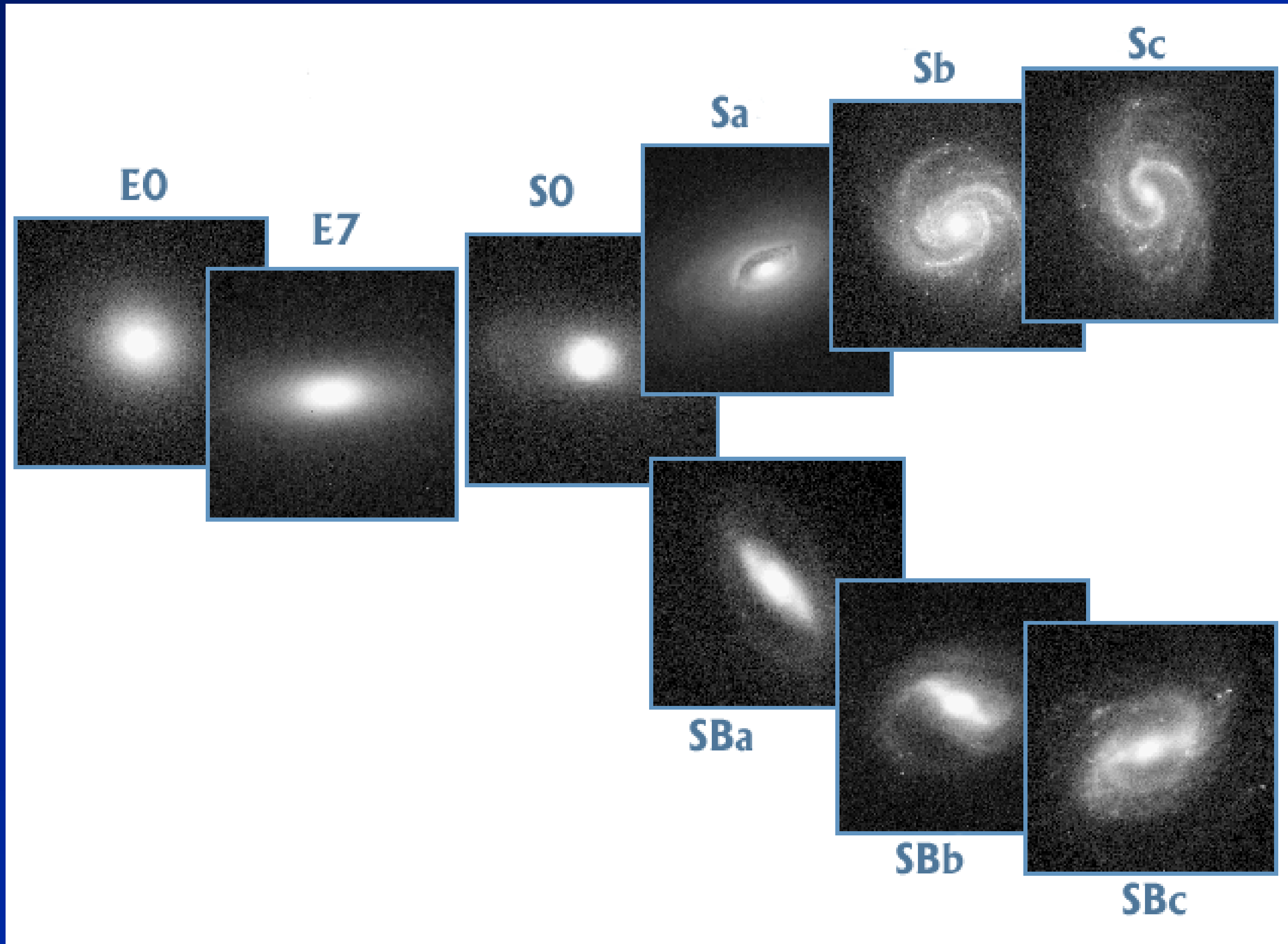
- Roundish, slowly rotating, **"hot"*** stellar systems with stars in RANDOMLY ORIENTED, ELLIPTICAL orbits.
- Supported by random motions ("pressure").
- No spiral arms--too hot. Smooth structure with high central concentration.
- No gas, not forming stars.
- Intermediate to large stellar masses: few x 10^{10} $M_{\odot}$ up to to few x 10^{12} $M_{\odot}$.

* **"Cold"** means that orbiting objects have small ***velocity dispersion*** relative to one other.

Examples of spheroidal/elliptical galaxies



The Hubble Sequence



Trends along the Hubble Sequence

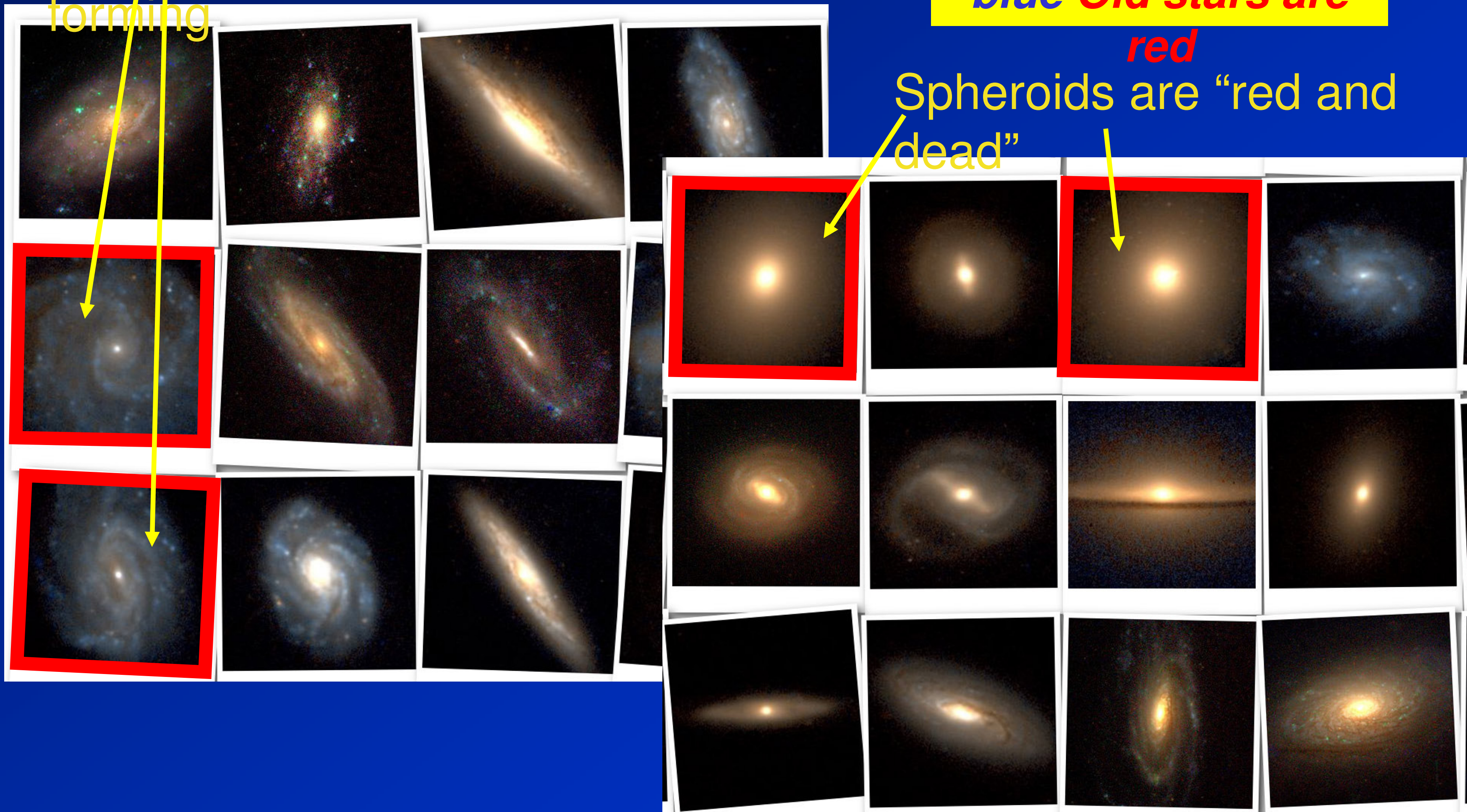
More spheroidal	More disky
Less rotation	More rotation
Less circular orbits	More circular orbits
Less gas	More gas
Less star formation	More star formation
Less prominent spiral arms	More prominent arms
Larger stellar mass mass	Smaller stellar
Bigger central black hole hole	Small or no black

Color indicates different amounts of recent or ongoing *star formation*

Disks are bluish--stars are forming

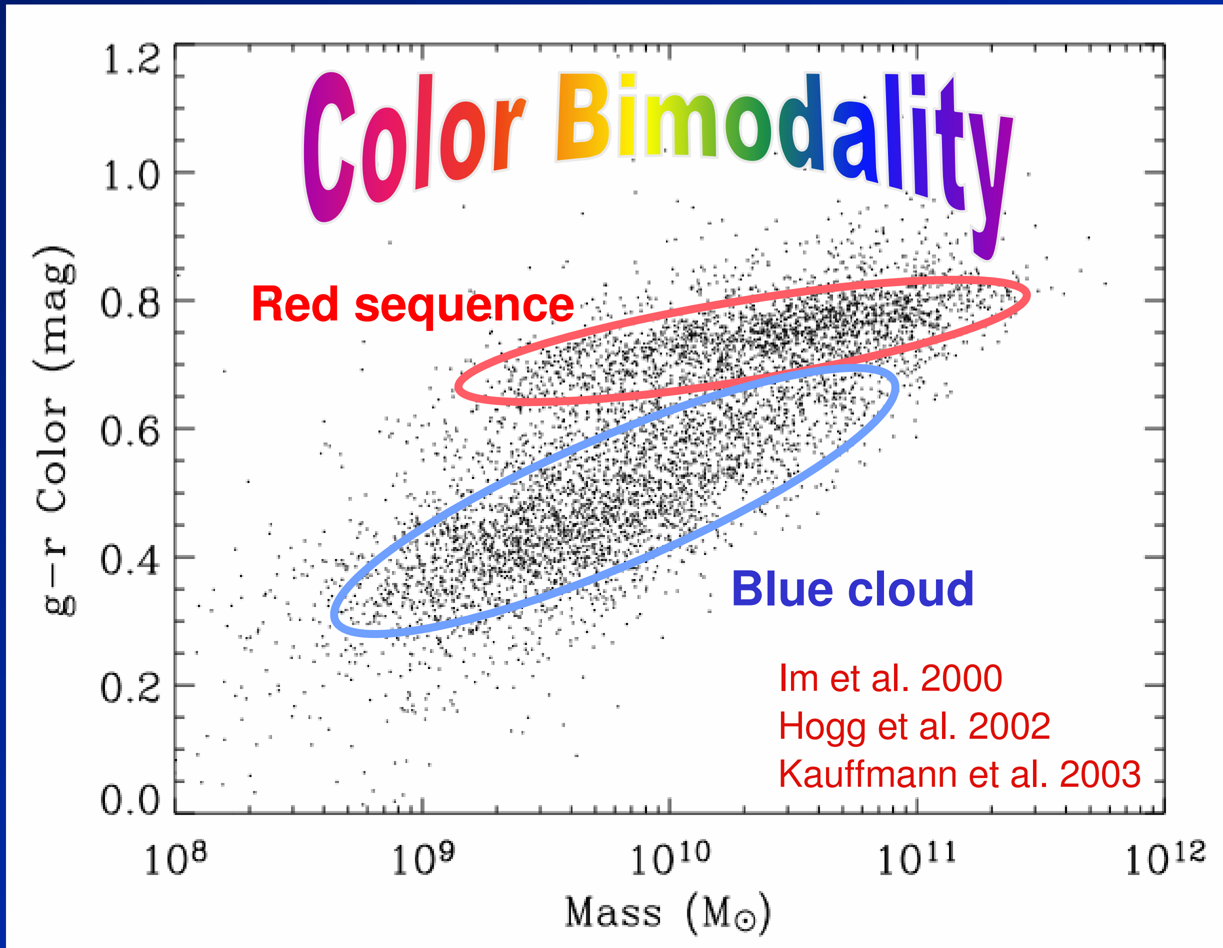
Young stars are blue Old stars are red

Spheroids are “red and dead”



A major recent discovery: *color bimodality*

A color-magnitude diagram for nearby galaxies



Color vs. stellar mass for Sloan Digital Sky Survey galaxies

A major recent discovery: *color bimodality*

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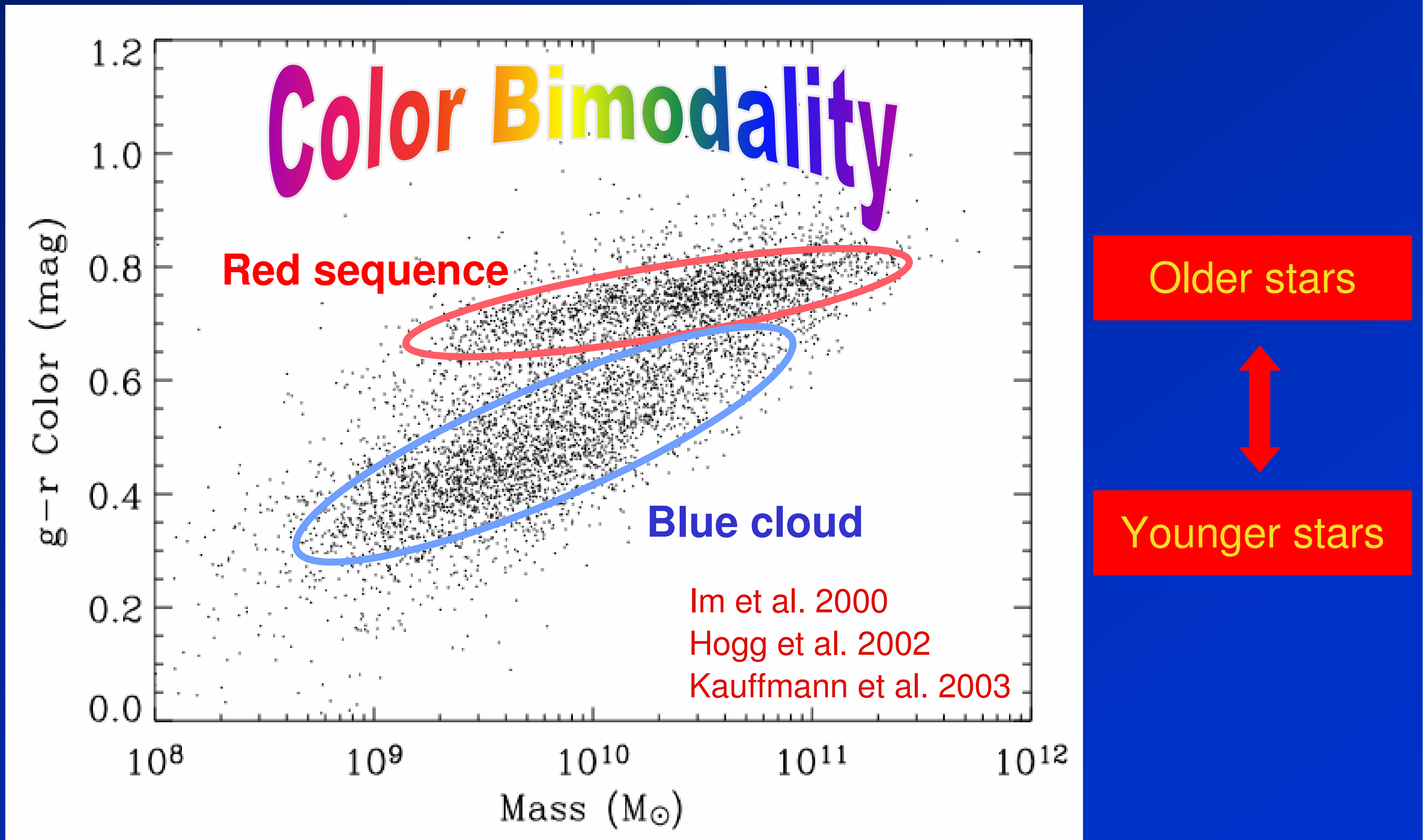

Color vs. stellar mass for Sloan Digital Sky Survey galaxies

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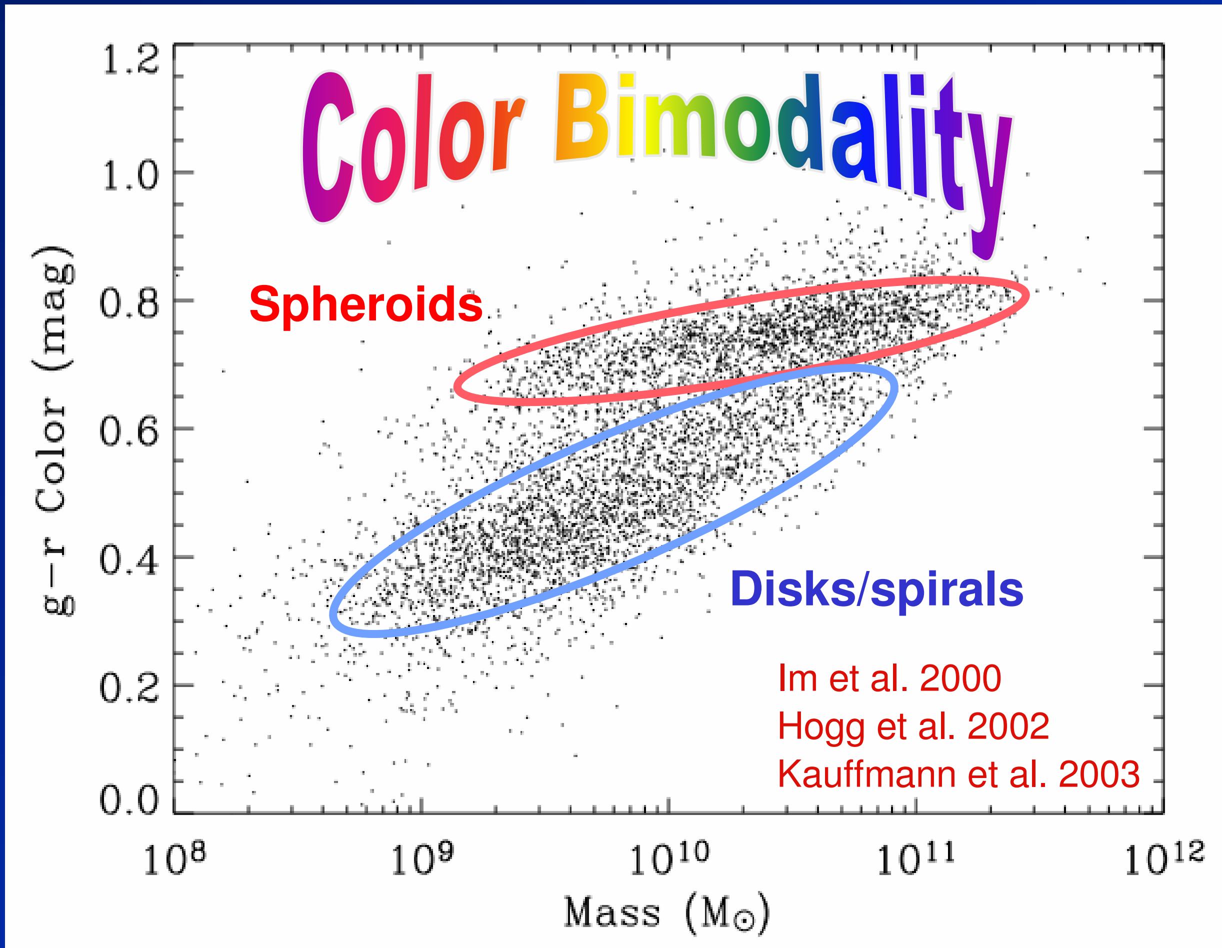


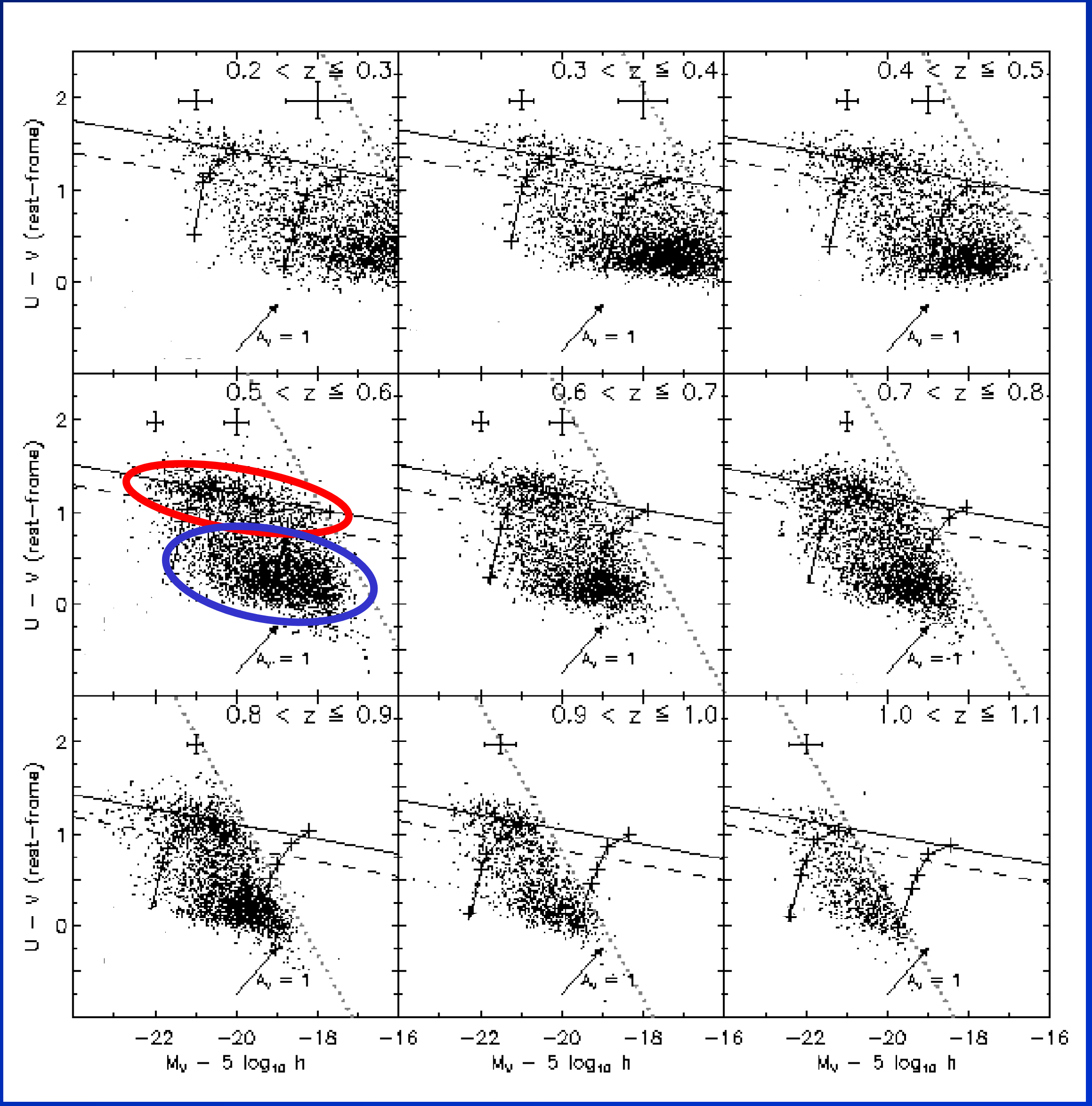
Older stars

Younger stars

Color vs. stellar mass for Sloan Digital Sky Survey galaxies

Color bimodality continues out to at least z ~ 1

Combo-17 survey:
25,000 galaxies



What causes color bimodality? At what epoch did it set in?

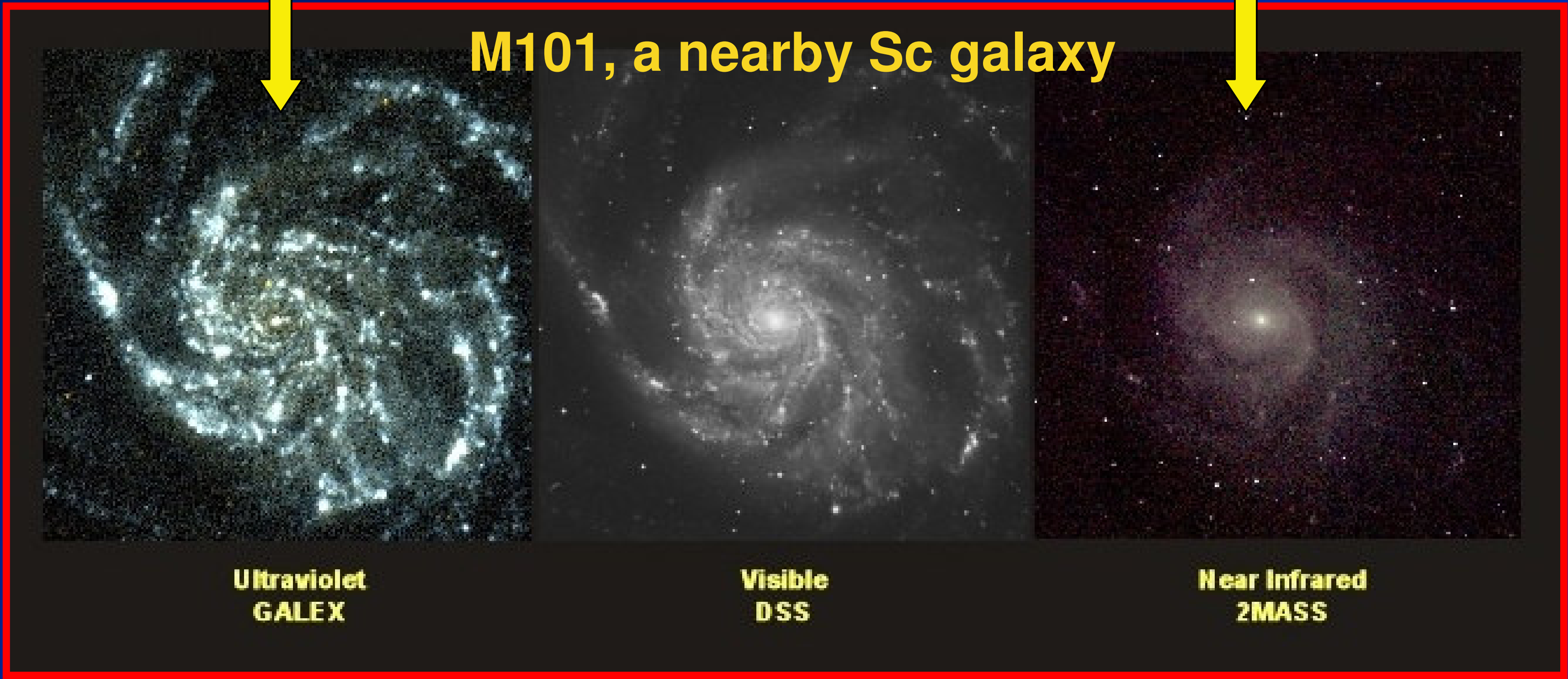
Bell et al. 2003

Star formation in disk galaxies from $z \sim 1$ to the present

Star-forming regions as revealed by GALEX UV satellite

UV shows young, hot stars

IR shows old, cool stars



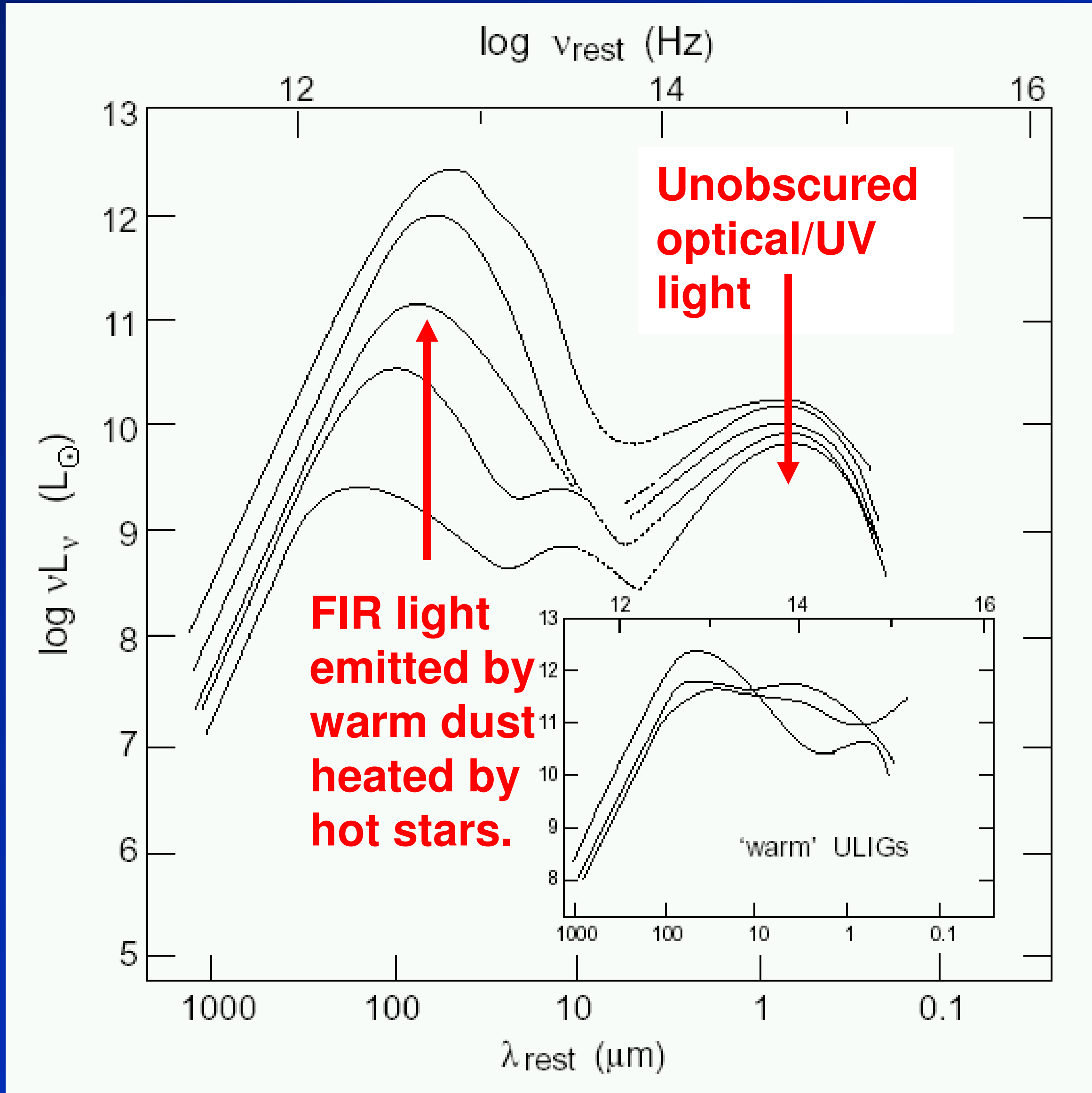
Star formation is triggered by motion of gas through the spiral pattern. Stars form when gas enters arm, gets shocked and compressed. Newly formed, young, hot, blue stars are visible at UV wavelengths; outline spiral structure like "beads on a string."

Much star formation is *obscured by dust,* is visible only in the far IR

Bolometric luminosities can vary by a factor of 1000, yet optical luminosities are constant to x3.

For normal spirals, the fraction or total energy emitted in the FIR is ~50%. For rapidly star-forming galaxies, the FIR component is much larger.

Sanders & Mirabel, Ann Rev, 34, 749, 1996



Ways to measure star formation

Kennicutt, Ann Rev, 36, 189, 1998

I. Ultraviolet continuum intensity (GALEX): direct but obscured by dust

$$\mathrm{SFR}(M_\odot\ \mathrm{year}^{-1}) = 1.4 \times 10^{-28} L_\nu(\mathrm{ergs\ s^{-1}\ Hz^{-1}}).$$

II. Hα emission intensity: most widely used, also obscured by dust

$$\mathrm{SFR}(M_\odot\ \mathrm{year}^{-1}) = 7.9 \times 10^{-42}\ L(\mathrm{H}\alpha)\ (\mathrm{ergs\ s^{-1}})$$

III. [O II] 3727 emission intensity: obscured by dust, intrinsic scatter

$$\mathrm{SFR}(M_\odot\ \mathrm{year}^{-1}) = (1.4 \pm 0.4) \times 10^{-41}\ L[\mathrm{OII}]\ (\mathrm{ergs\ s^{-1}}),$$

IV. Far-IR continuum intensity: good for highly obscured regions

$$\mathrm{SFR}(M_\odot\ \mathrm{year}^{-1}) = 4.5 \times 10^{-44}\ L_{FIR}\ (\mathrm{ergs\ s^{-1}})\ (\mathrm{starbursts}),$$

The "lookback effect": an aid to studying galaxy formation

• The light of distant objects is redshifted owing to the expansion of the Universe. The light of farther objects is redshifted more. The ratio of the observed to emitted wavelength is given by:

$$\lambda_o/\lambda_e = (1 + z),$$

where the quantity **z** is termed the ***redshift.***

•The ***size of the Universe now*** compared to its size when the light was emitted is also ***(1+z)***.

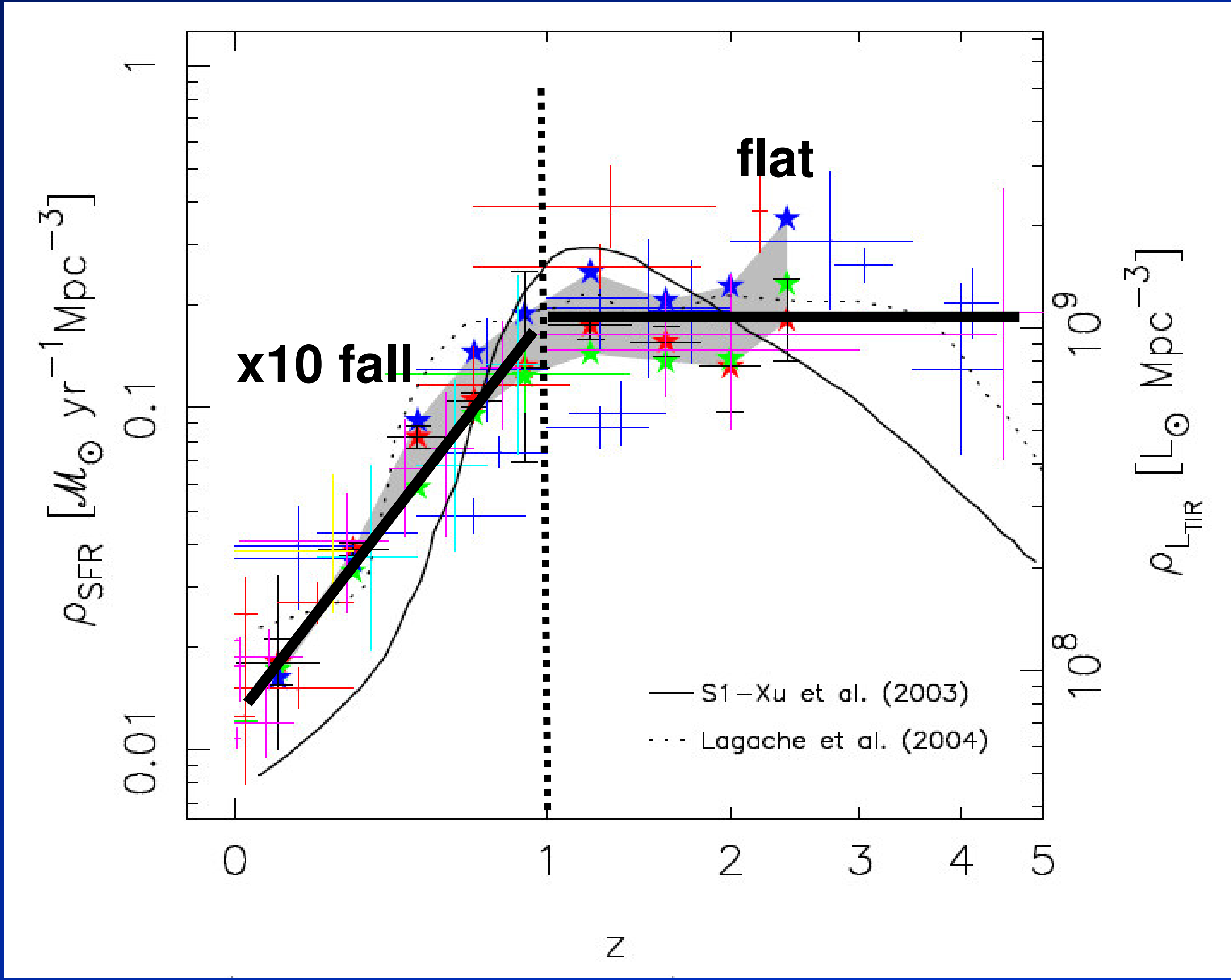
• ***Redshift is a measure of lookback time,*** owing to the finite speed of light. Since the cosmological model is now tightly constrained, the relationship between redshift and epoch is well established (see Ned Wright's website **http://www.astro.ucla/edu/~wright/CosmoCalc.html** for a handy cosmology calculator). Here is a table of representative values, with times in Gyr:

	z	time from Big Bang	lookback time
My talk today	0.5	8.4	5.0
	1.0	5.7	7.7
	2.0	3.2	10.2
	3.0	2.1	11.4
	5.0	1.2	12.3
	10.0	0.5	13.0

Age of Universe now = 13.5 Gyr

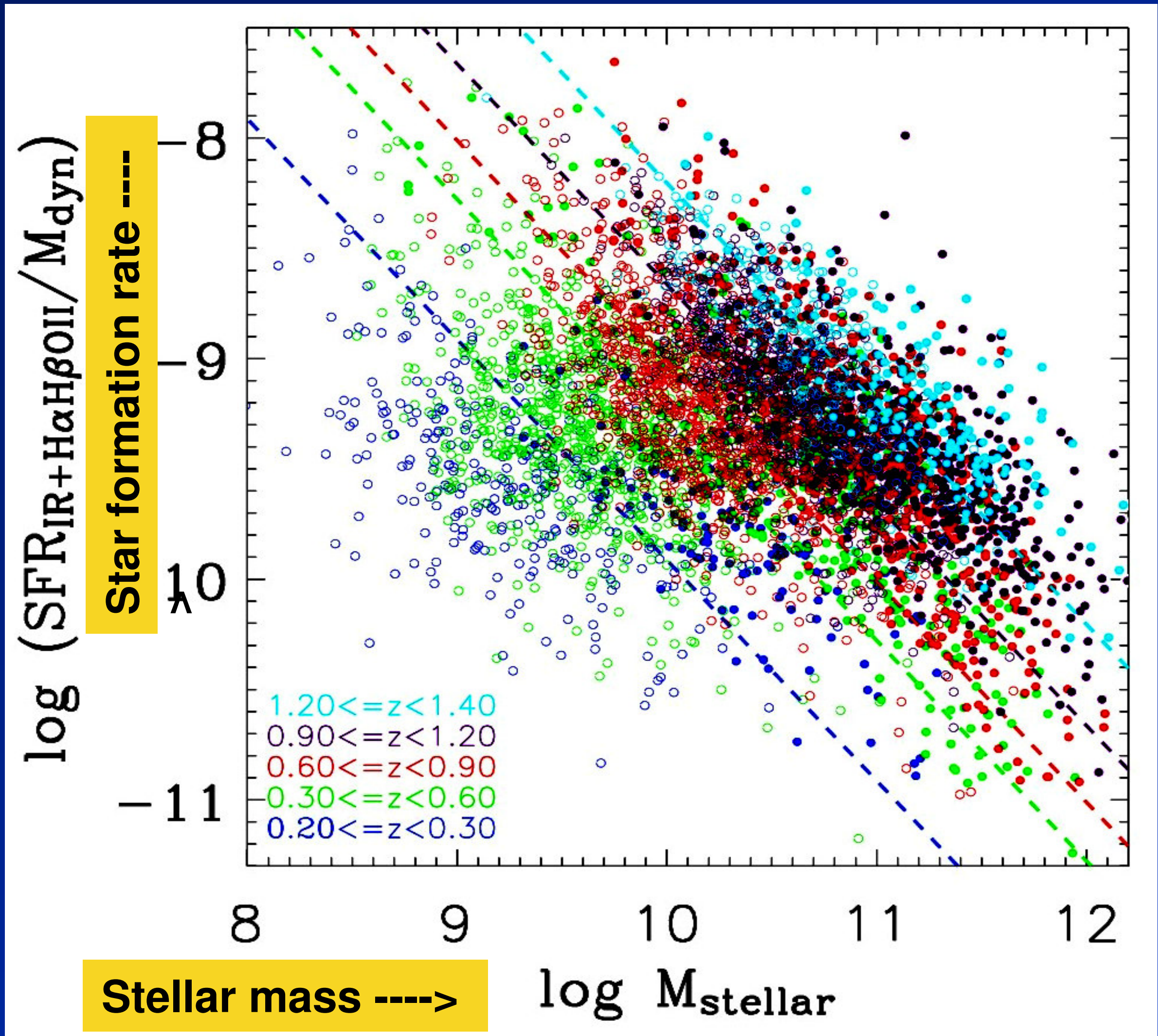
• Observing with large telescopes allows us to look far out in space, and therefore back in time. ***We can make a "cosmic movie" of the formation of structure in the Universe by combining snapshots of galaxies and other data at different epochs.*** When our theory of structure formation is correct, all snapshots will fit properly together. This is the ultimate test of

The star-formation history of the Universe



Current version of the *"Madau diagram"* from Perez-Gonzalez et al. 2005

The *star-formation histories of galaxies* broken down by stellar mass--recent Spitzer IR data



Noeske et al. 2006

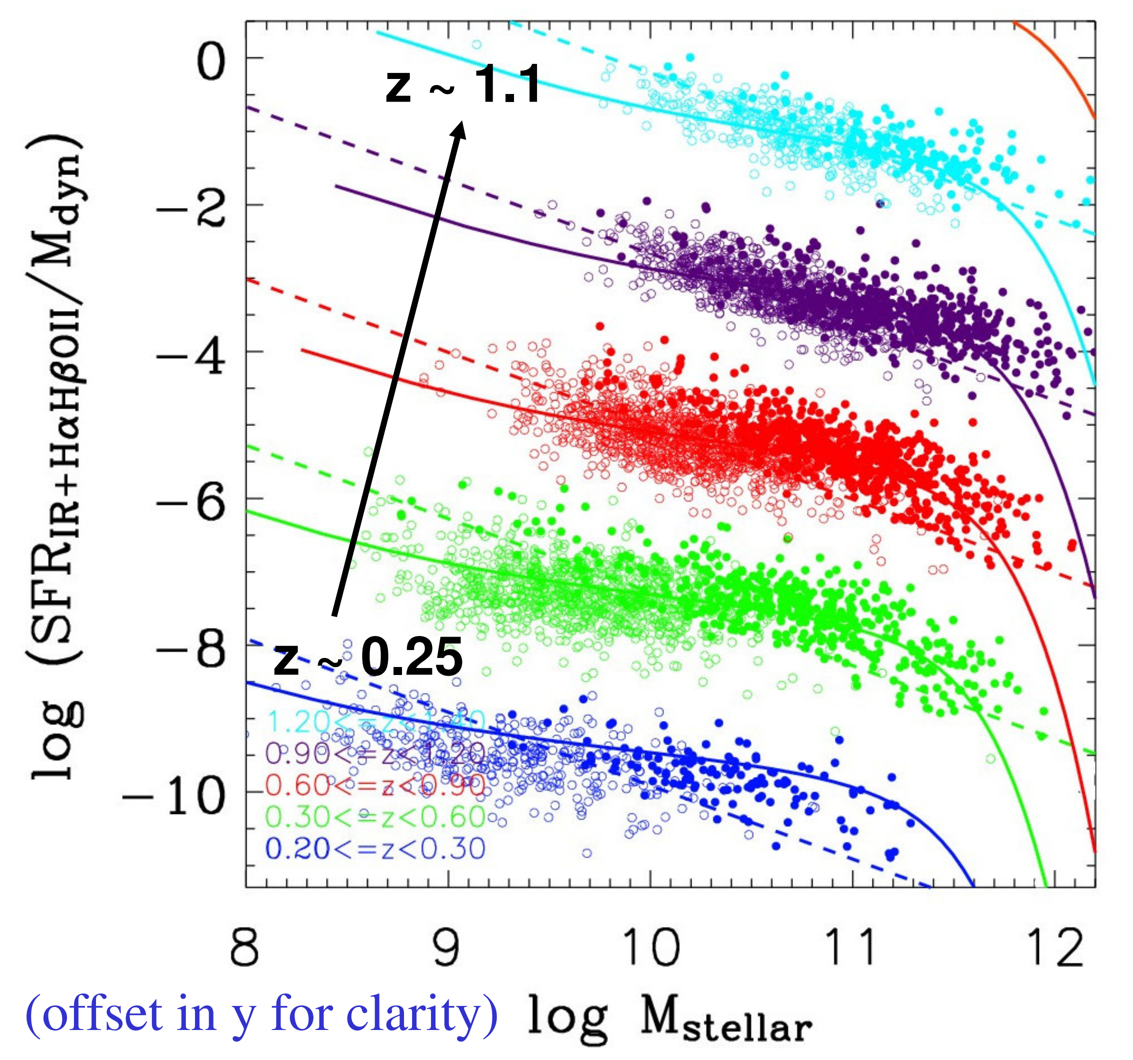
Solid dots: SFR from both MIPS + DEEP2 emission lines

Open circles: SFR from DEEP2 emission lines (extinction-corrected)

Dashed lines: MIPS 24µ 80% completeness limit at center of redshift bin

Note the general rise at fixed stellar mass back in time. ***The overall SFR in the Universe has fallen by x10*** after z = 1.

A smoothly declining *exponential model* fits the star-forming histories of most galaxies



Noeske et al. 2006

The model has

SFR ~ $e^{-t/\tau(M)}$

starting at ***z_f,*** where

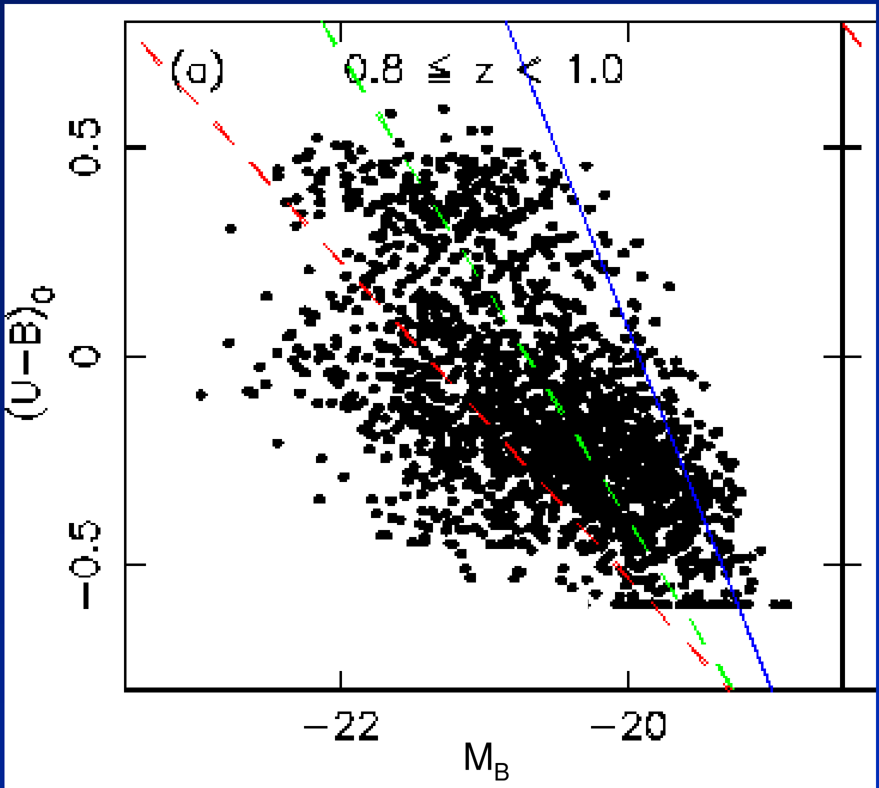
$z_f = 4.5 \times (M_*/10^{12})^{0.33} - 1$

and

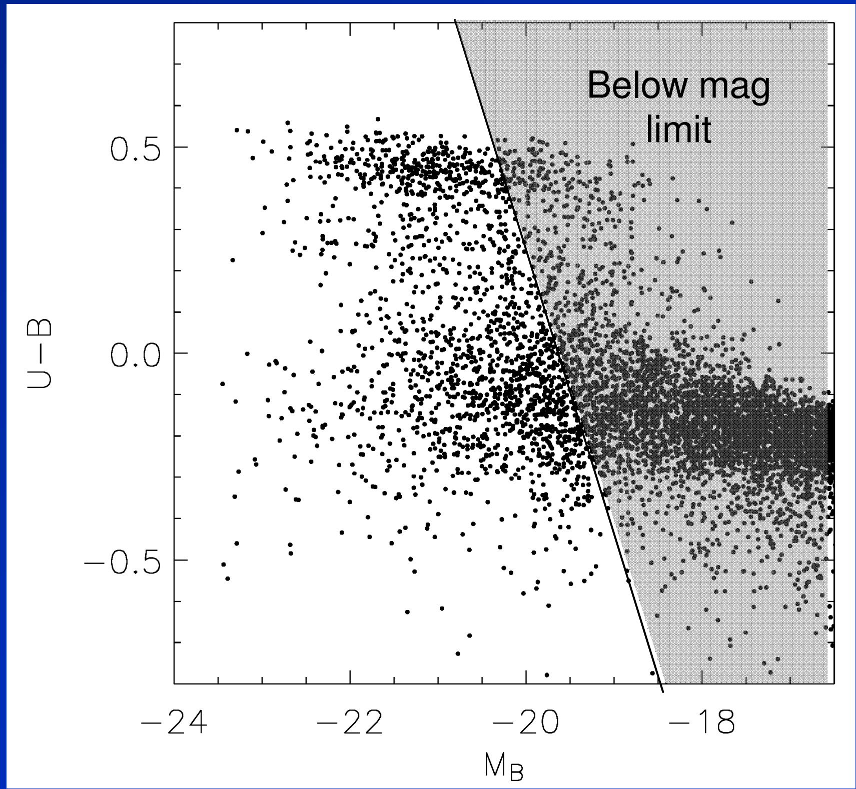
$\tau(M) = 1\ \text{Gyr} \times (M_*/10^{11})^{-1}$.

In the model, ***larger galaxies start forming stars sooner and decline more rapidly*** (***downsizing,*** Cowie et al. 1996). The stellar populations in larger galaxies are older. Most star formation seems to be in "quiescent" mode; the contribution by "starbursts" seems to be relatively small.

The model produces color-magnitude bimodality automatically by ***shutting off SFR in massive galaxies*** at late times. This is probably a clue to how it really happens



Actual CM diagram of distant galaxies from DEEP2 survey (Willmer et al. 2006)



Model CM diagram using SFR model, Noeske et al. 2006

Dark matter halos

Navarro, Frenk & White, ApJ, 462, 563, 1996

NFW dark-matter halo density profile

smooth curves represent fits to the simulation data using a model of the form proposed by Navarro et al. (1995c),

$$\boxed{\frac{\rho(r)}{\rho_{\rm crit}} = \frac{\delta_c}{(r/r_s)(1 + r/r_s)^2}} , \tag{3}$$

where $r_s = r_{200}/c$ is a characteristic radius and $\rho_{\rm crit} = 3H^2/8\pi G$ is the critical density (H is the current value of Hubble's constant); δ_c and c are two dimensionless parameters. Note that r_{200} determines the mass of the halo, $M_{200} = 200\rho_{\rm crit}(4\pi/3)r_{200}^3$, and that δ_c and c are linked by the requirement that the mean density within r_{200} should be $200 \times \rho_{\rm crit}$. That is,

$$\delta_c = \frac{200}{3} \frac{c^3}{[\ln(1 + c) - c/(1 + c)]} . \tag{4}$$

We will refer to δ_c as the characteristic overdensity of the halo, to r_s as its scale radius, and to c as its concentration.

Navarro, Frenk & White, ApJ, 462, 563, 1996

Radial density profiles of sample dark halos

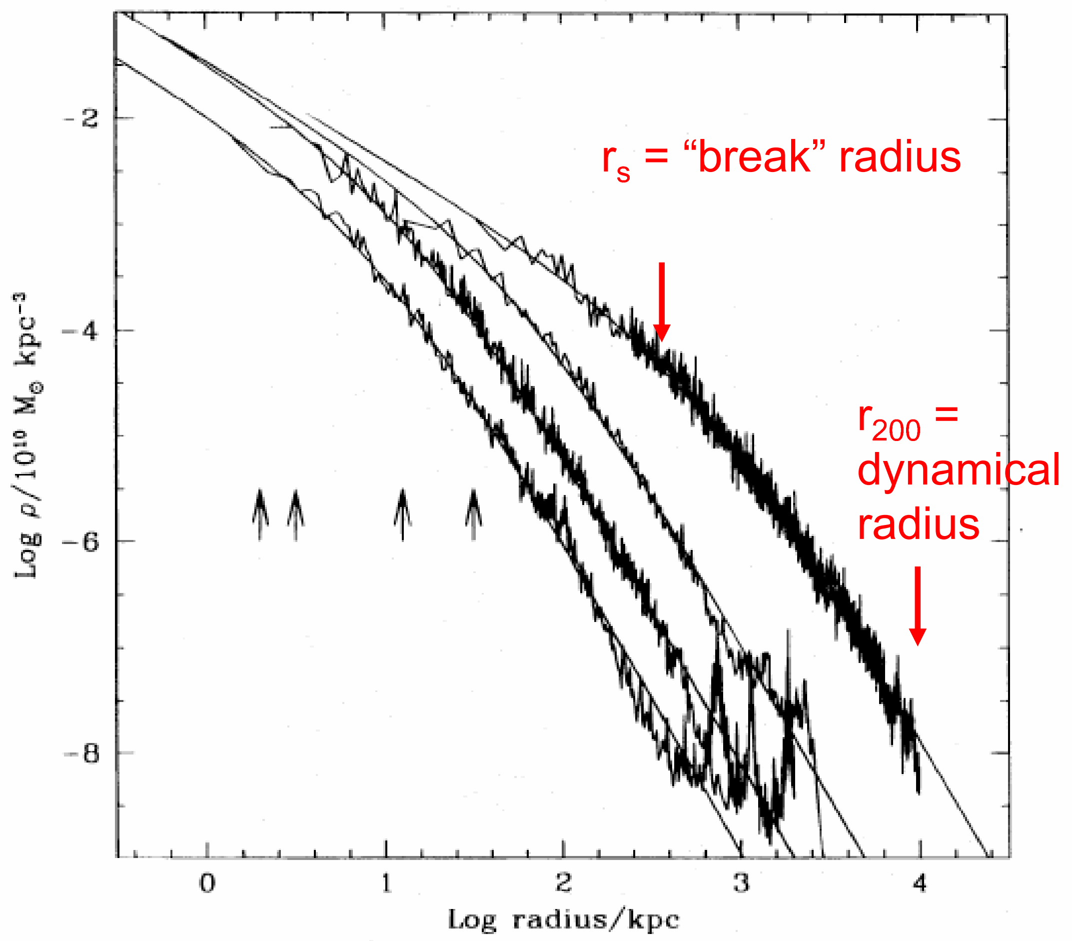


FIG. 3.—Density profiles of four halos spanning 4 orders of magnitude in mass. The arrows indicate the gravitational softening, h_g, of each simulation. Also shown are fits from eq. (3). The fits are good over two decades in radius, approximately from h_g out to the virial radius of each system.

Navarro, Frenk & White, ApJ, 462, 563, 1996

Circular velocity curves of dark halos. Note overall flatness.

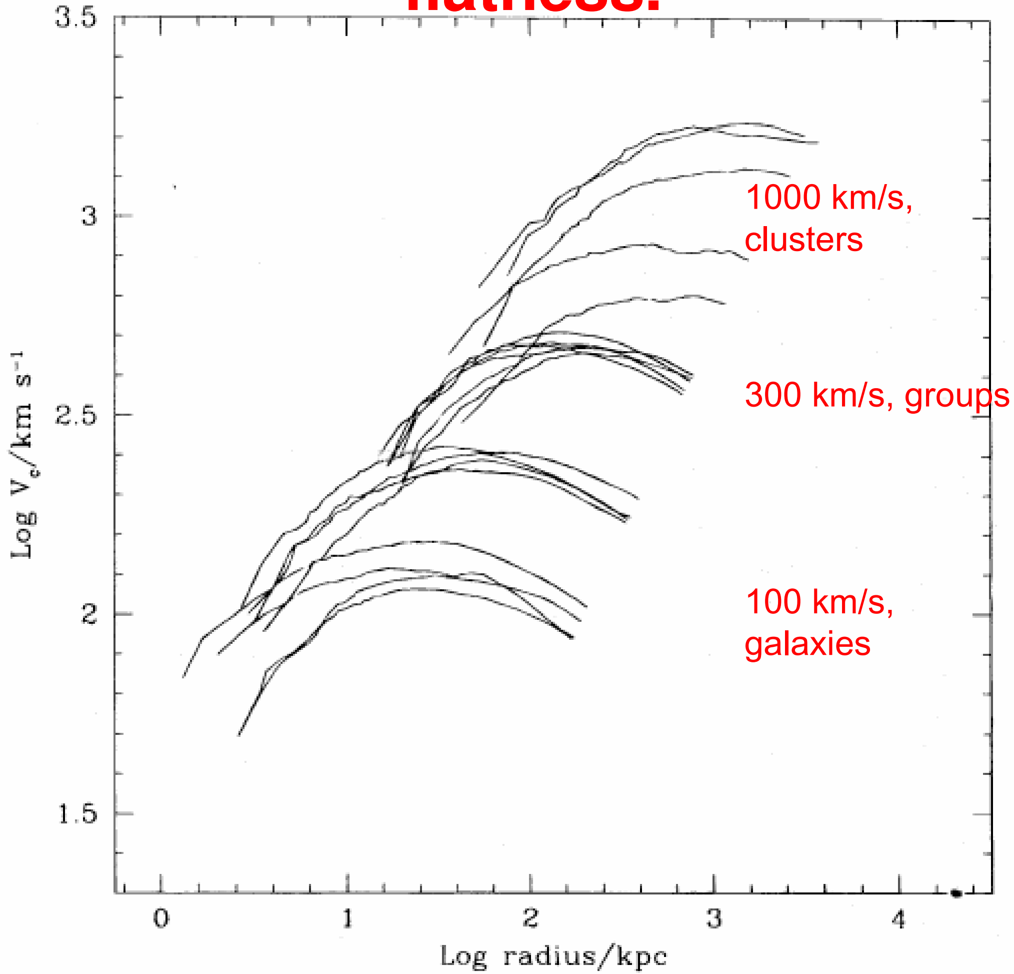
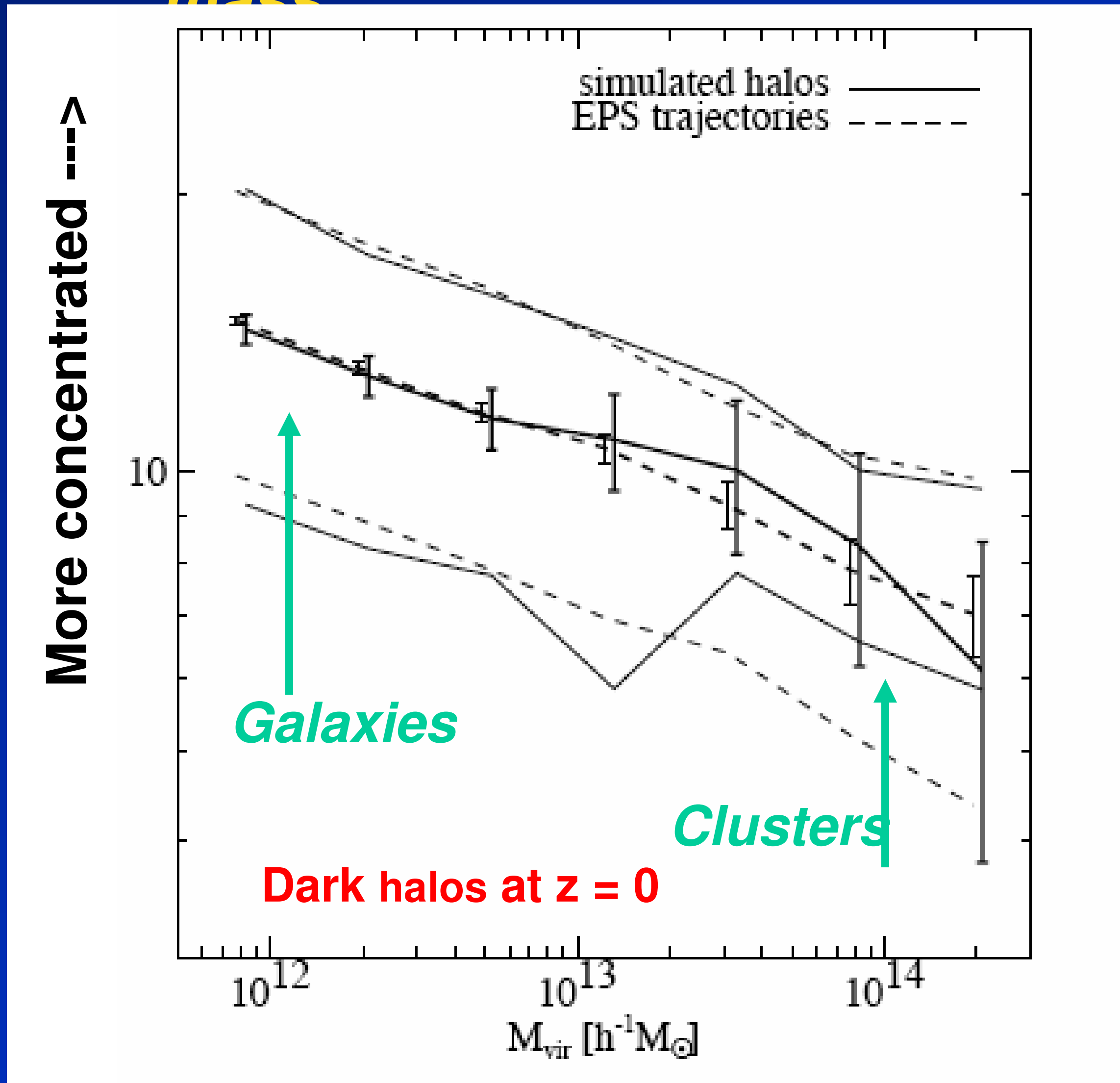


FIG. 5.—Circular velocity profiles of all 19 halos. The profiles are truncated at the virial radius, r_{200}. The gravitational softening is about $10^{-2} \times r_{200}$. Note that all profiles have the same shape.

Wechlser et al., ApJ, 658, 52, 2002

The profile shapes of dark halos *correlate closely with their mass*

Galaxy-sized halos are more concentrated than cluster-sized halos.

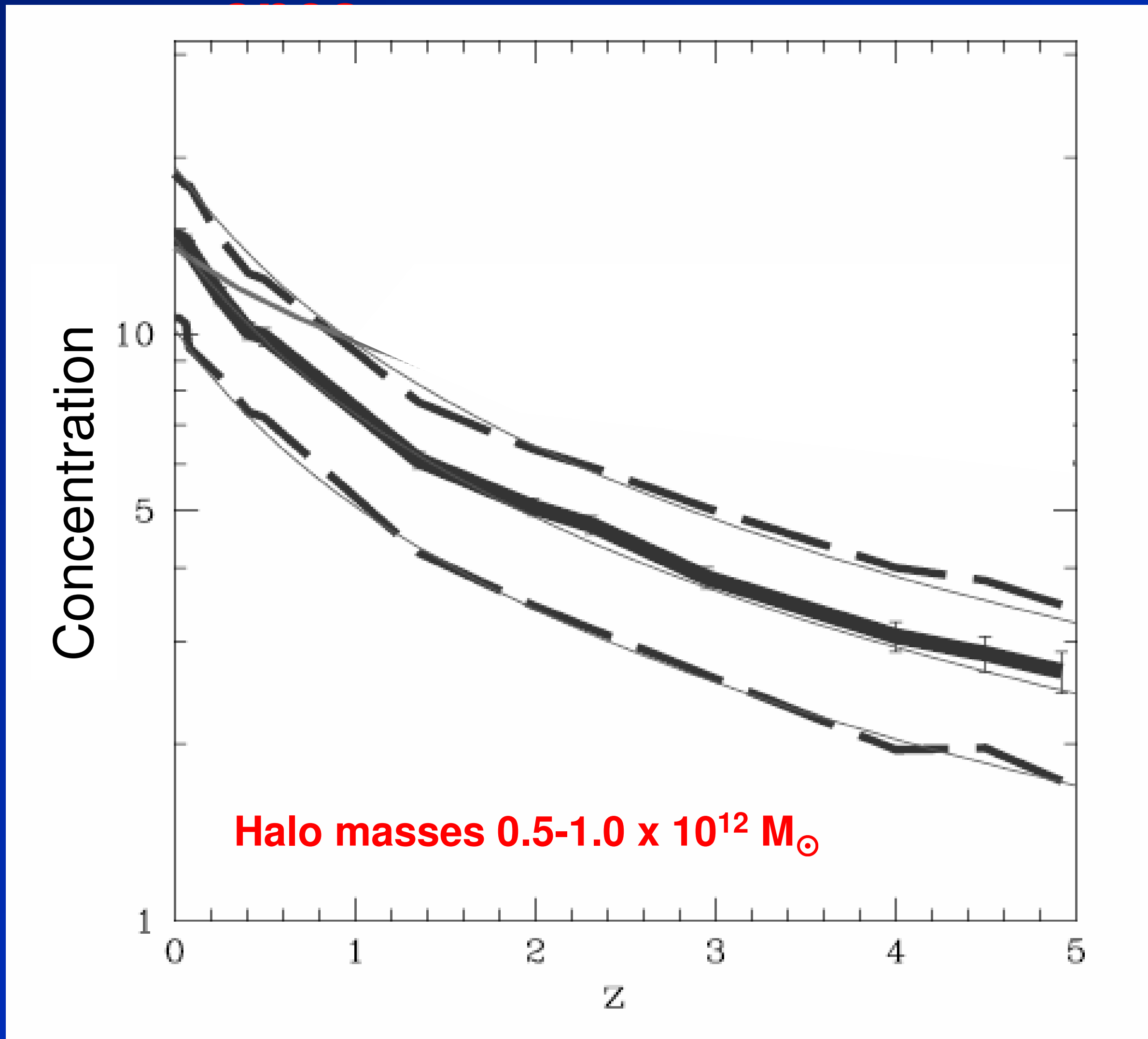


Bullock et al., MN, 321, 559, 2001

Dark halo concentrations also vary smoothly with redshift. High-redshift (early) halos are *less concentrated* than later

Concentration is an example of a ***larger point***---the numbers, masses, sizes, and shapes of dark halos versus redshift are all ***well understood.***

We know how dark matter clusters.

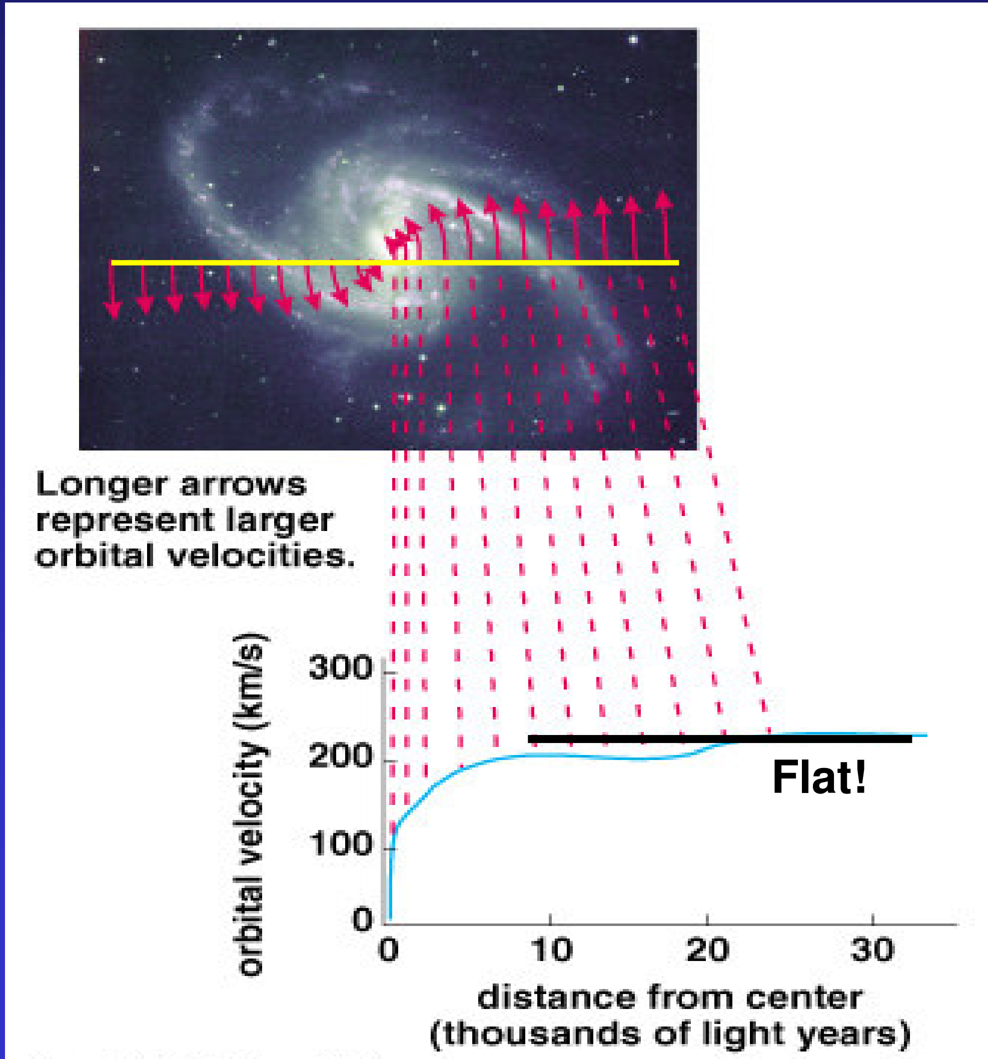


Disk galaxy rotation curves

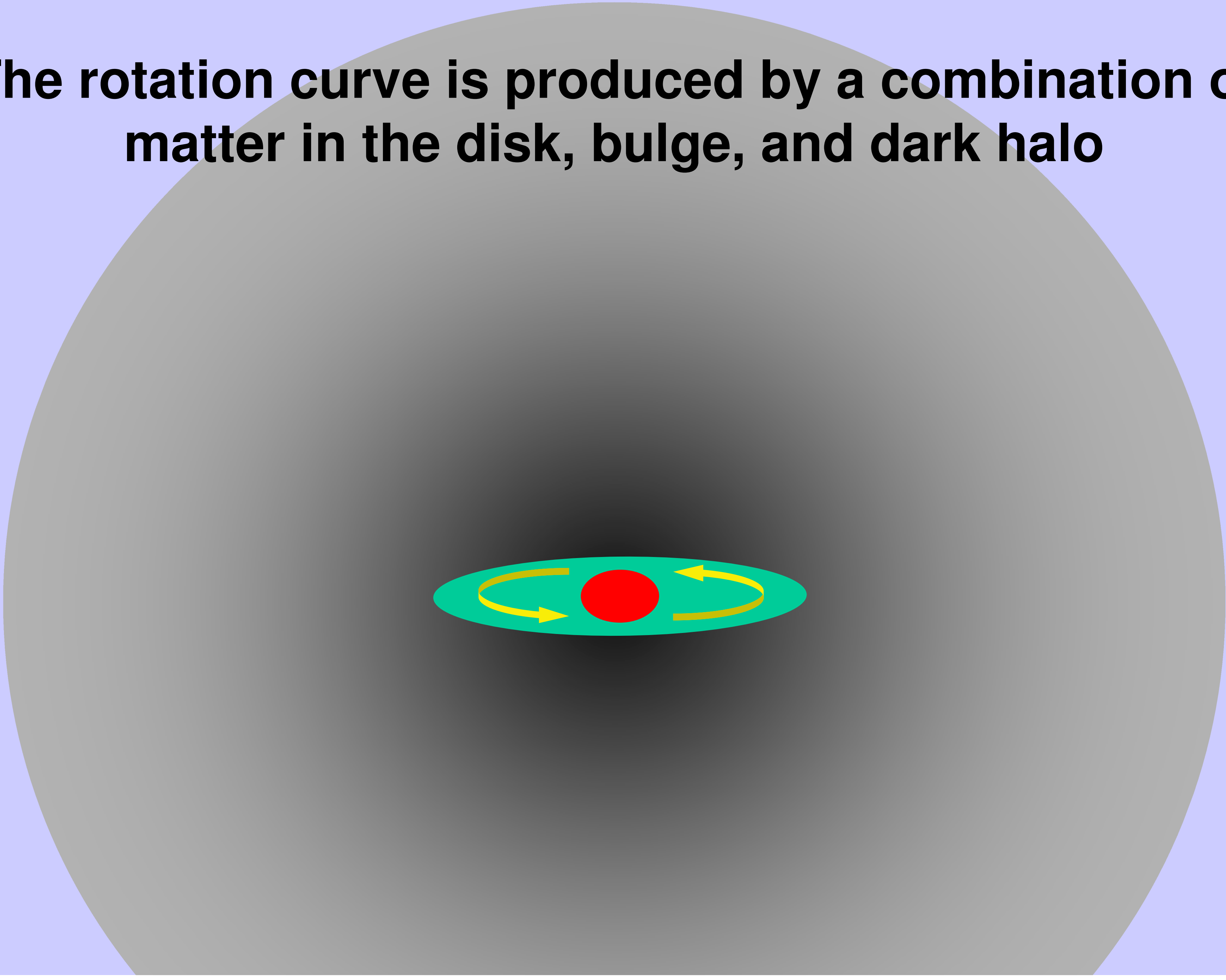
The *rotation curve* shows the speed at which objects rotate around the center of a galaxy.

Interstellar gas clouds tend to be in nearly circular motion, and so the rotation speed of the gas is a good tracer of the ***circular velocity profile*** of the mass distribution.

Rotation curves are measured by setting a spectrograph slit across the image of a galaxy. Emission lines appear in the spectrum from patches of gas that are ionized by the UV light of nearby hot, young stars. The ***Doppler shift*** of the emission frequency gives the average radial velocity of the galaxy, and the rotation speed is given by the difference in the shift between that point and the center.



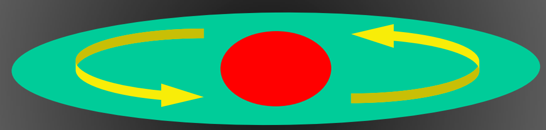
The rotation curve is produced by a combination of matter in the disk, bulge, and dark halo



The enclosed mass is given by the circular speed and radius of the orbit.

$$M(r) = v^2 r/G$$

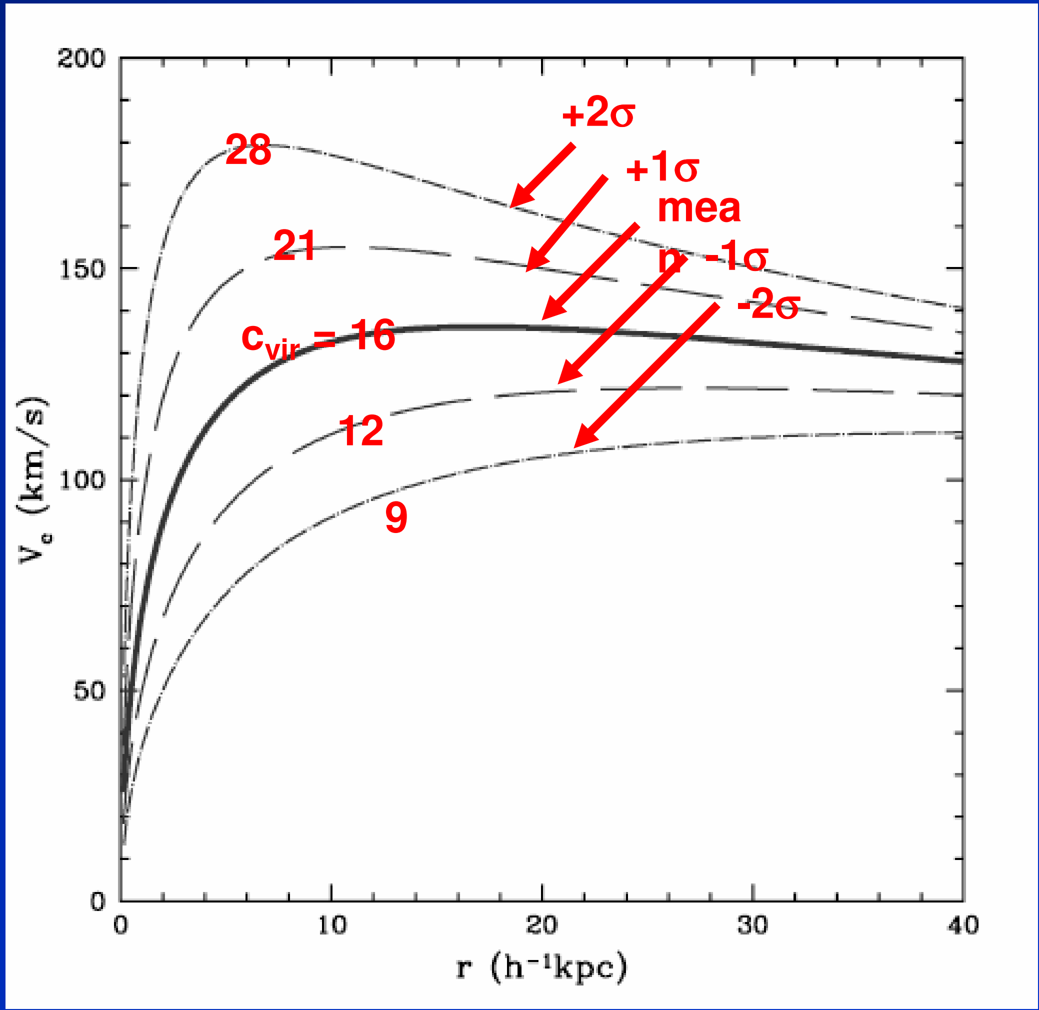
This is strictly valid only for a spherical mass distribution, but the correction for a flattened disk and spheroid is small, ~10%.



Bullock et al., MN, 321, 559, 2001

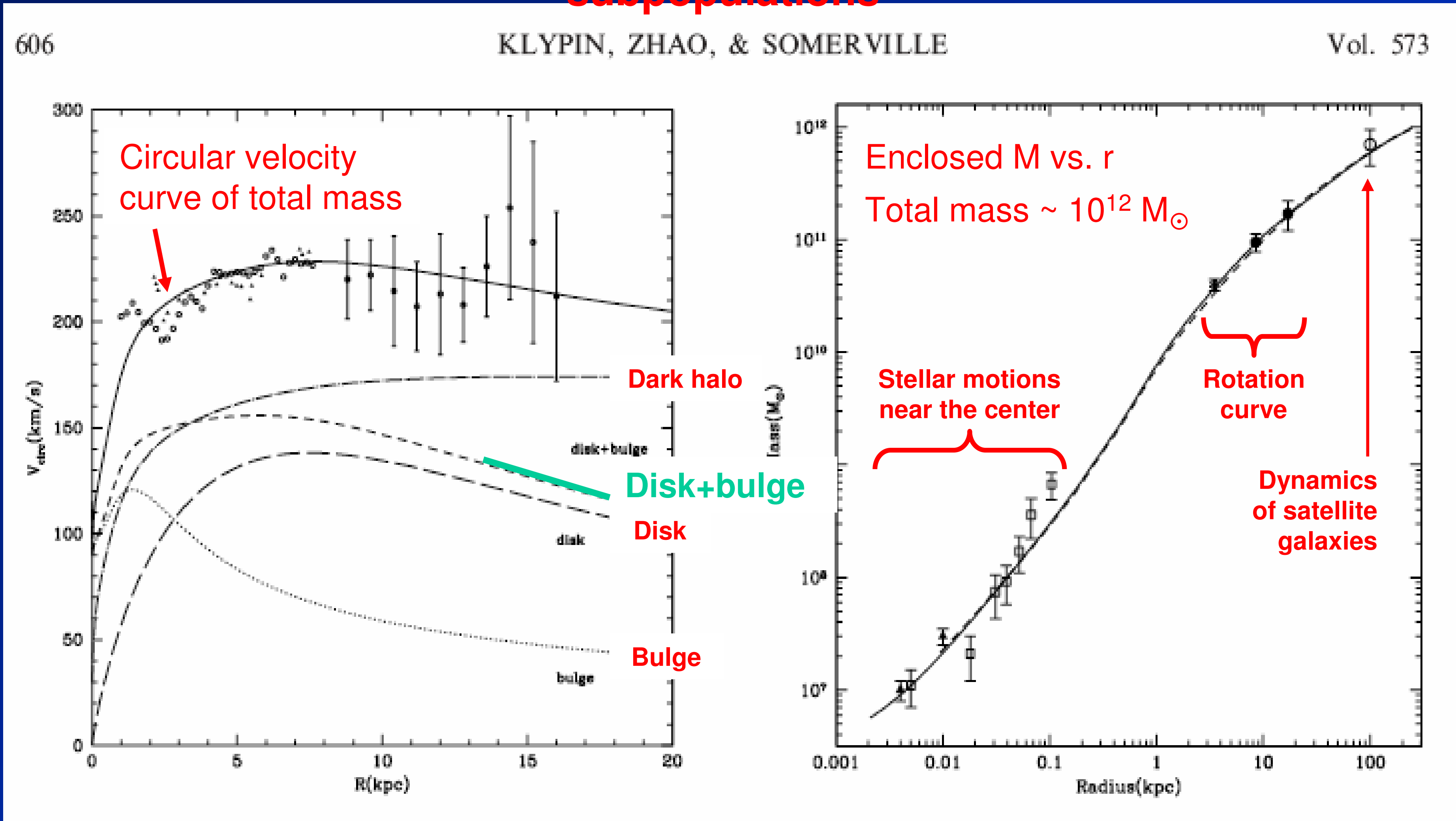
Halo concentration affects the shape of the rotation curve. Here are a selection of rotation curves for halos of the same mass (3 x 10^{11} $M_{\odot}$) but different concentrations.

The circular velocity curves here reflect the dark matter halo only. Rotation curves of real galaxies are affected by baryonic infall and thus possibly **adiabatic contraction.** But the underlying distribution of dark matter by itself clearly has a big effect.



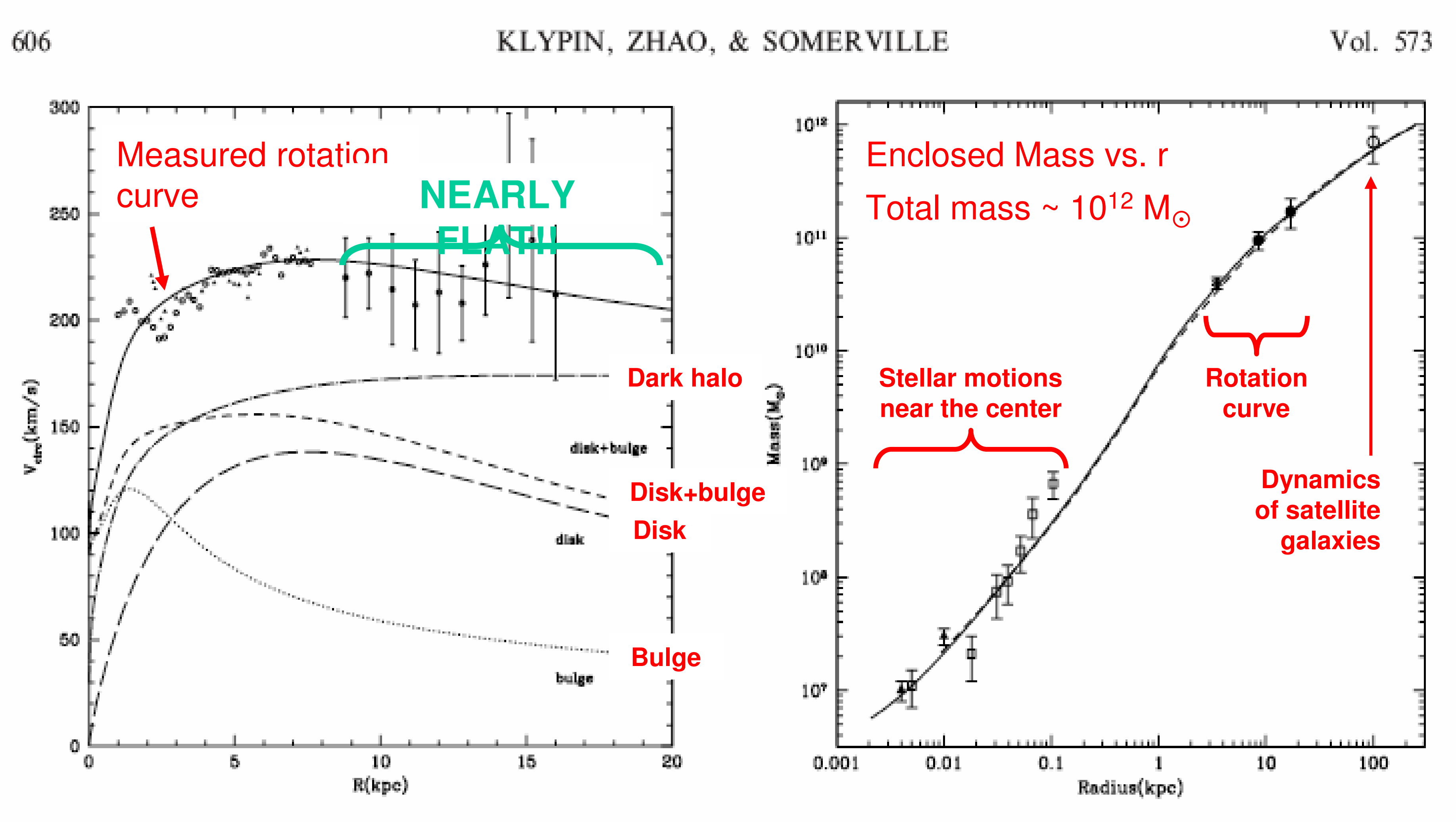
Klypin, Zhao & Somerville, ApJ, 573, 597, 2002

Model Milky Way Galaxy: **decomposed circular velocity curves of dark matter halo, disk, and bulge, based on motions of various subpopulations**

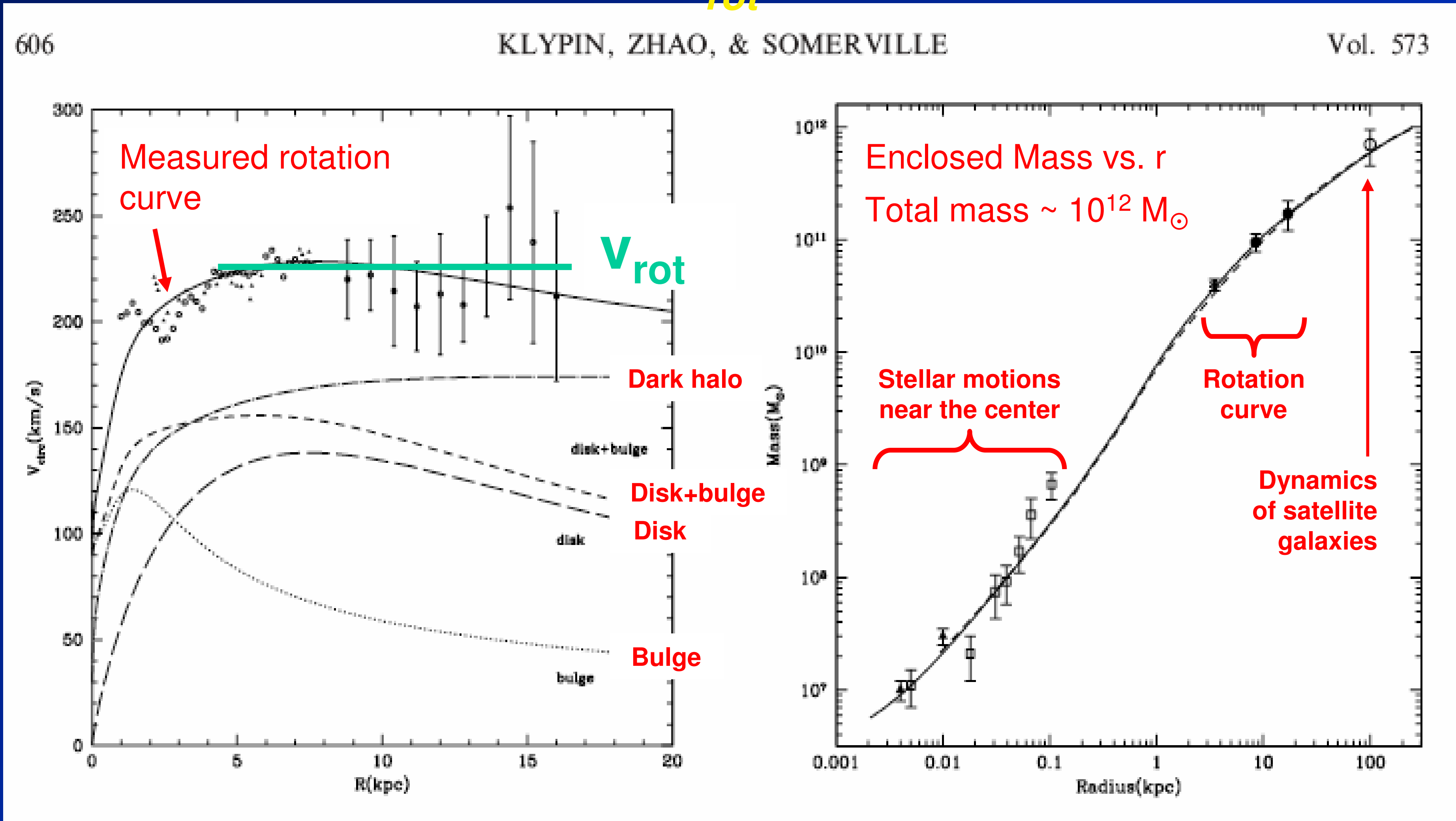


Note how *flat* the outer rotation curve of the Milky Way is. The predicted rotation curve from the disk and bulge is *falling;* the difference is made up by the dark matter. The Milky Way is typical--flat rotation curves are usually seen in the outer parts of disk galaxies.

Flat rotation curves in the outer parts of galaxies are one of the main pieces of evidence for dark halos.



The rotation velocity on the flat part of the rotation curve is the *characteristic orbital speed,* denoted by v_{rot}.



Disk galaxy brightness profiles

The classic disk light profile falls off ***exponentially*** with radius

$$\Sigma_d(r) = \Sigma_e \exp\left[-1.6783\left(\frac{r}{r_e} - 1\right)\right] = \exp(1.6783)\,\Sigma_e \exp\left(-\frac{1.6783}{r_e}r\right)$$
$$= 5.3567\,\Sigma_e \exp\left(-\frac{r}{r_e/1.6783}\right) = \boxed{\Sigma_0 \exp\left(-\frac{r}{r_s}\right)},$$

Σ_d = disk surface brightness profile

r_e = effective radius (encloses half the light)

r_s = radial exponential scale length of the light

Σ_e = surface brightness at effective radius

Σ_0 = central surface brightness

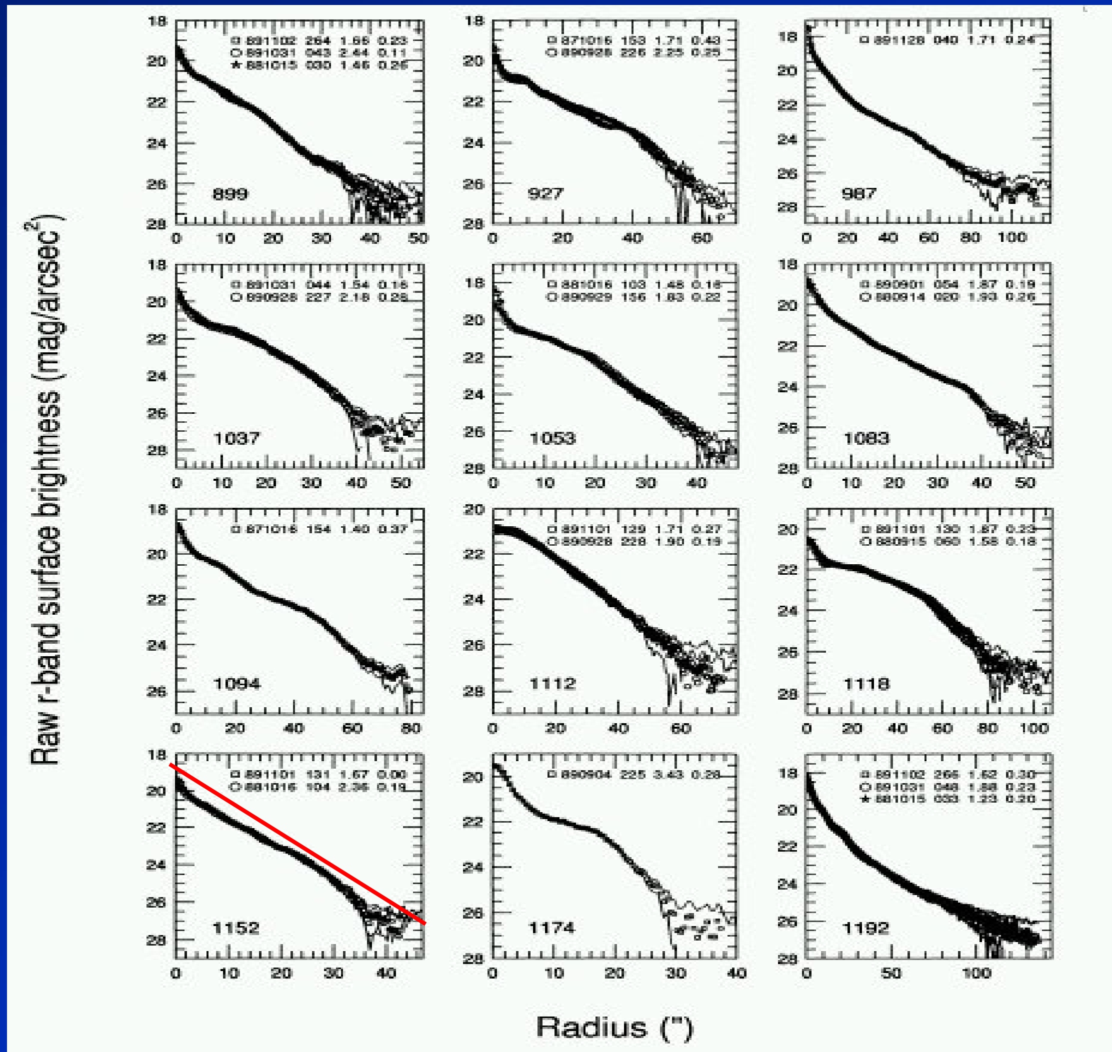
The ***scale length*** $\boldsymbol{r_s}$ and ***half-light radius*** $\boldsymbol{r_e}$ are measures of disk size.

Real disk surface brightness profiles are only approximately exponential.

Pure exponentials would be straight lines.

Typically there is excess brightness in the center and a drop-off at 4-5 scale lengths in the outer parts (not visible here).

But the exponential law is a useful approximation.



Courteau, ApJS, 103, 363, 1996

Disk galaxy scaling laws

We have now accumulated some basic ***structural parameters*** for disk galaxies that compactly sum up their visible ***baryonic*** structure:

* Total luminosity or magnitude: $\mathbf{M_B}$ (luminosity in the blue band)

* Rotation velocity: $\mathbf{v_{rot}}$

* Disk radius: $\mathbf{r_s}$ or $\mathbf{r_e}$

When these quantities are plotted versus one another (in log-log coordinates) one finds power-law correlations called ***scaling laws.***

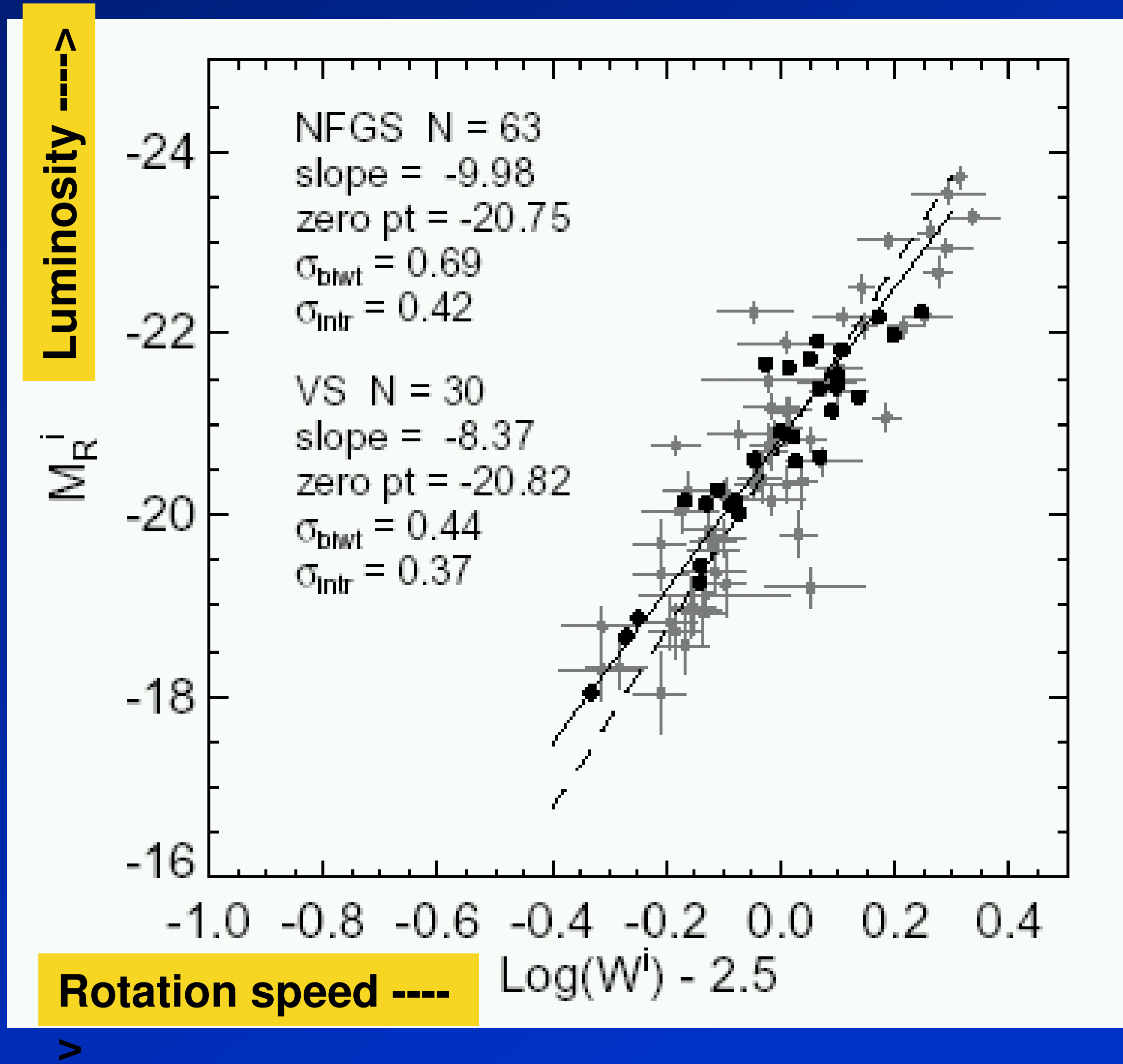
Scaling laws are interesting because they preserve some memory of galaxy formation. Unlike stars, galaxies "remember" how they formed.

The *Tully-Fisher law* relates v_{rot} and luminosity

The TF relation is the correlation between rotation speed and absolute magnitude for disk galaxies.

W is ***total linewidth,*** which is close to but not exactly $2v_{rot}$.

The relation is approximately $\mathbf{L \sim v^3}$.

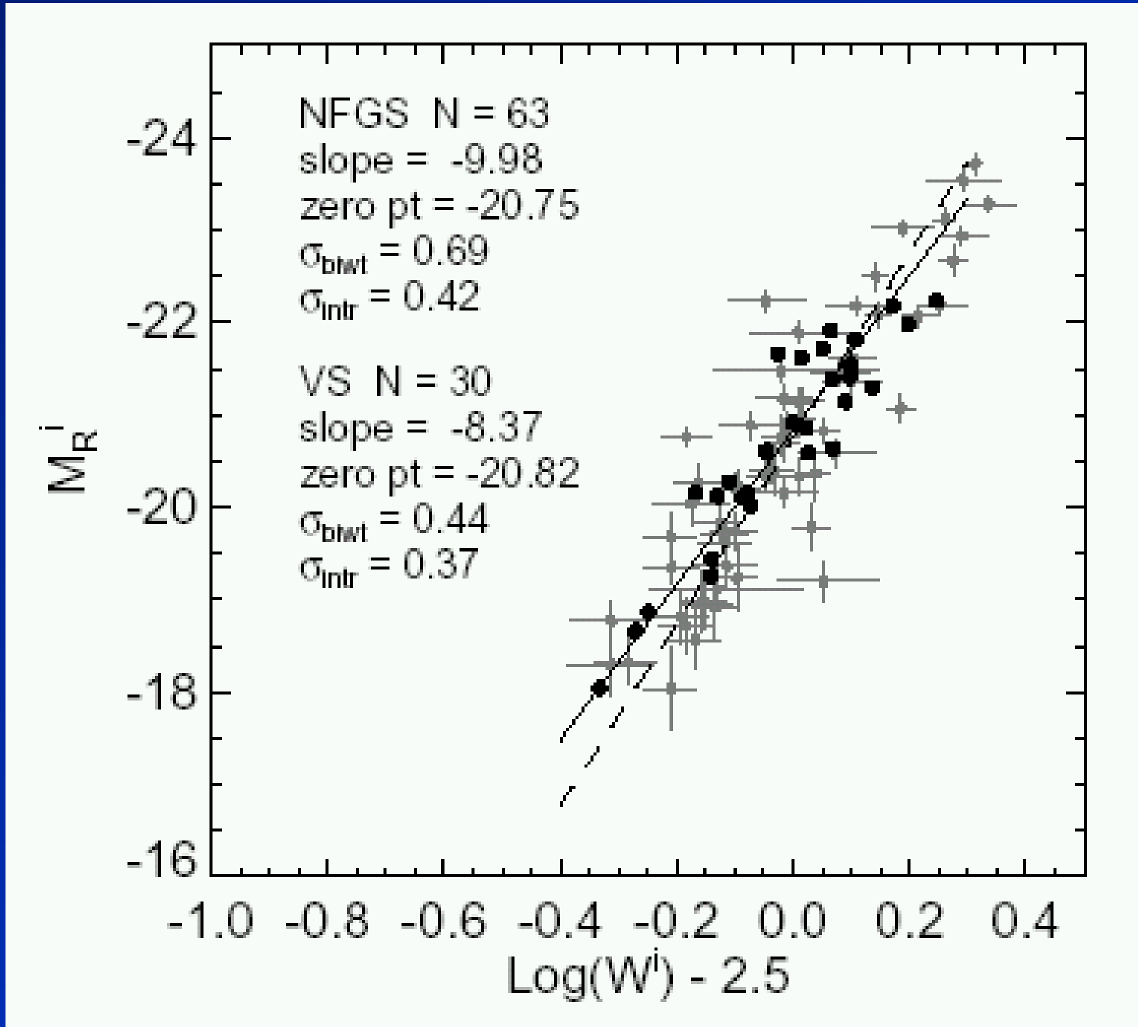


Kannappen et al., ApJ, 123, 2358, 2002

The *Tully-Fisher law* relates v_{rot} and luminosity

The scatter about the TF relation is only about 0.4 mag, and some of this is observational error. This means that ***mass-to-light ratio (M/L)*** scatters by only ~ ±30% at a fixed point on the plane.

The star-formation histories of structurally similar disk galaxies are remarkably similar.



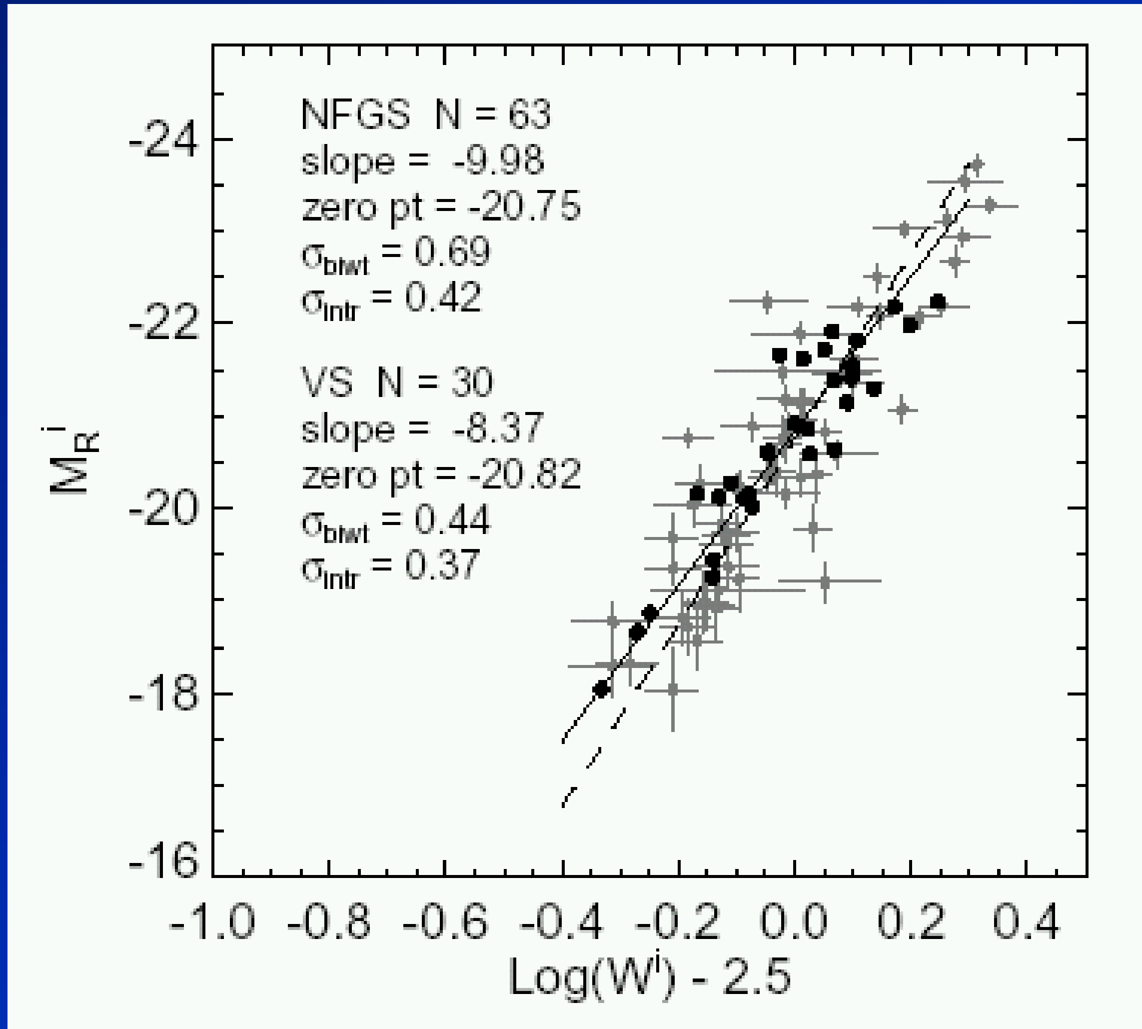
Kannappen et al., ApJ, 123, 2358, 2002

The *Tully-Fisher law* relates v_{rot} and luminosity

The TF relation is the ***virial plane*** of disk galaxies seen edge on. Galaxies in gravitational equilibrium obey

$$M \sim v^2R/G.$$

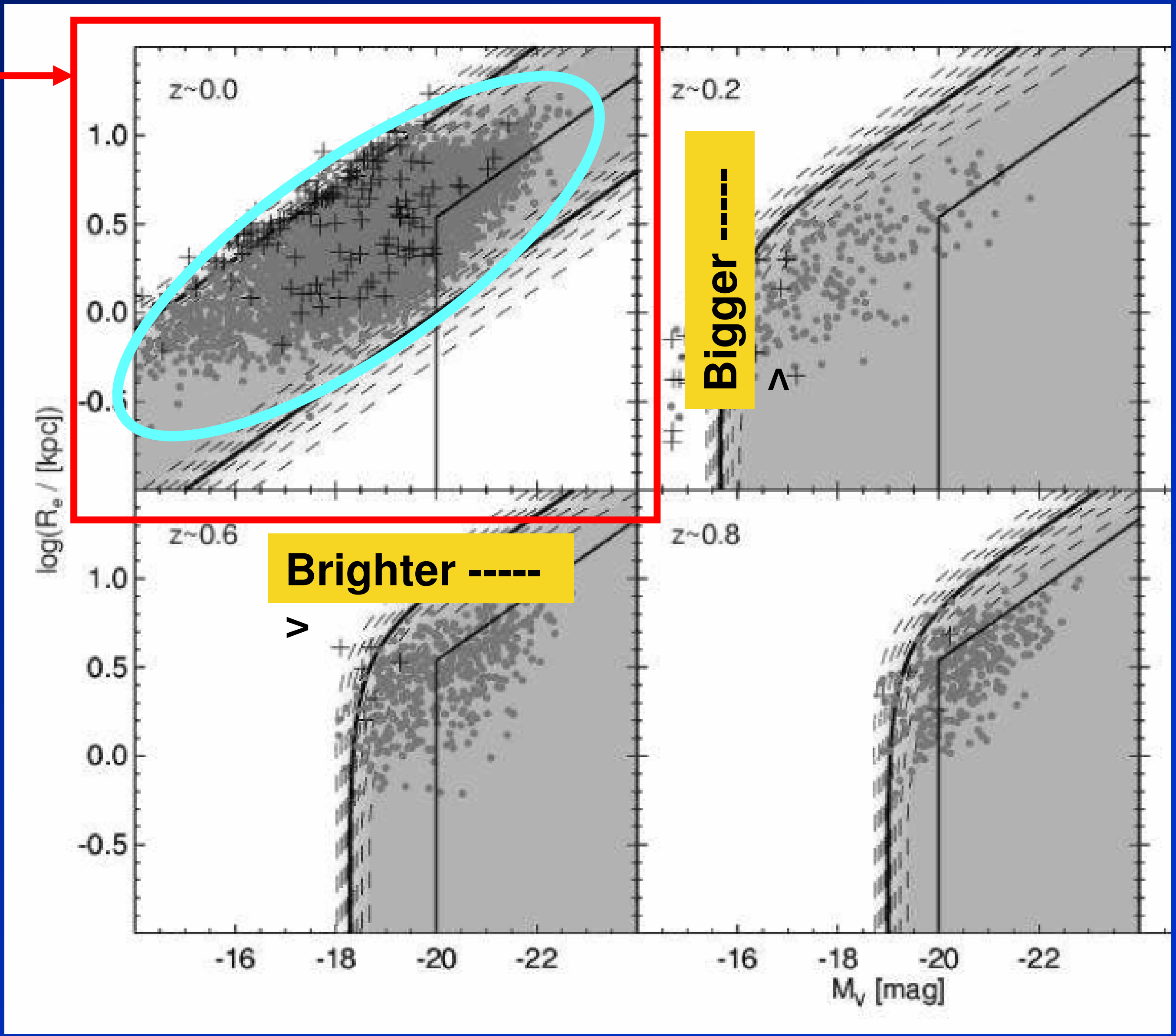
This makes a plane in ***M,v,R-space.*** If L is well-behaved versus M, then we also have a plane in ***L,v,R-space.*** The TF relation for disks views this plane ***edge-on,*** making a tight relation.



Kannappen et al., ApJ, 123, 2358, 2002

Another scaling law is the *magnitude-radius relation*

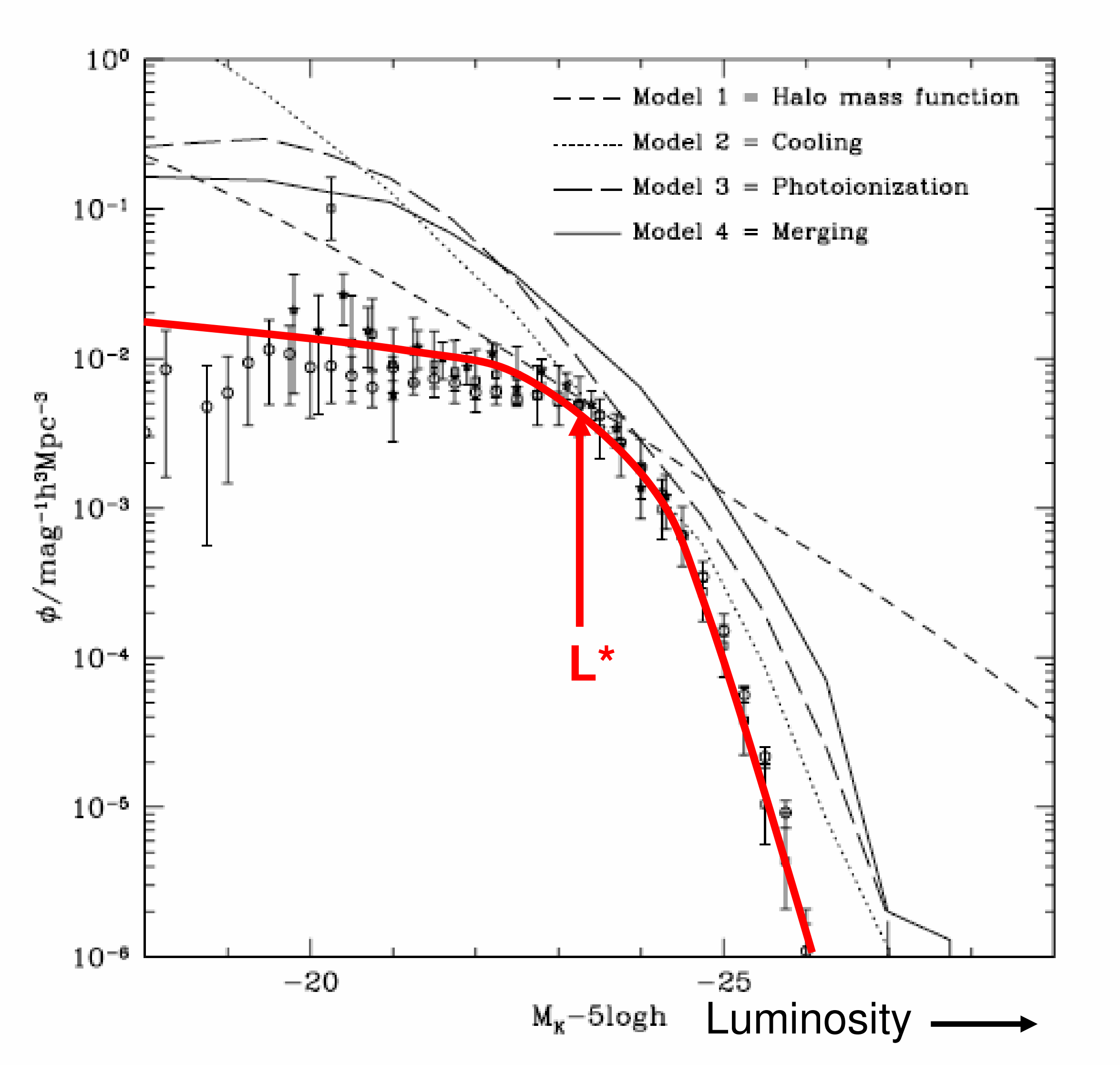
Galaxies at the present epoch



The gray points are from the Sloan Digital Sky Survey (SDSS). The black crosses are nearby galaxies from the GEMS survey.

Barden et al. 2005

The *luminosity function* describes the average number of galaxies per unit magnitude per unit volume.



The location of the "knee" is a characteristic luminosity called ***L*.***

The structural parameters ***M_B, v_{rot}, and radius R*** describe ***individual*** galaxies.

The quantity ***L**** describes the ***population of galaxies***.

Benson et al. 2003

The scaling laws and luminosity function are *major clues* to how galaxies formed.

The structural parameters that describe visible galaxies are ***produced jointly*** by the ***dark matter halos*** plus the behavior of the ***baryons.*** The major factors affecting the appearance of disk galaxies at any epoch are:

* The masses and density distributions of the ***underlying DM halos.***

* The ***timing and amount of baryonic infall*** onto galaxies.

* ***How much angular momentum the baryons received*** as the matter clustered and how much they retained or gained as they fell in---angular momentum determines the radii where the baryons settle, and thus disk radii.

* How fast the baryons turned into stars, i.e., the ***star-formation history.***

* How much gas was driven out by ***feedback.***

Measuring the scaling laws and the luminosity function back in time provides a compact, quantitative record of galaxy

The Virial Plane

Consider a self-gravitating object in dynamical equilibrium:

It obeys the equation:

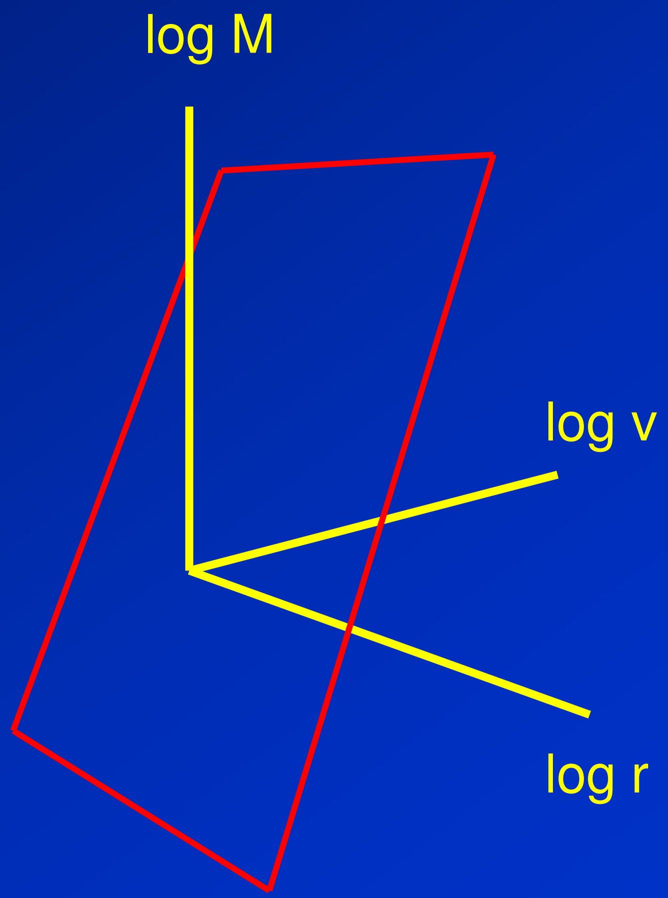
$$M = v^2 r/G$$

where:

M = total mass

r = characteristic radius, e.g. r_e

v = characteristic internal velocity



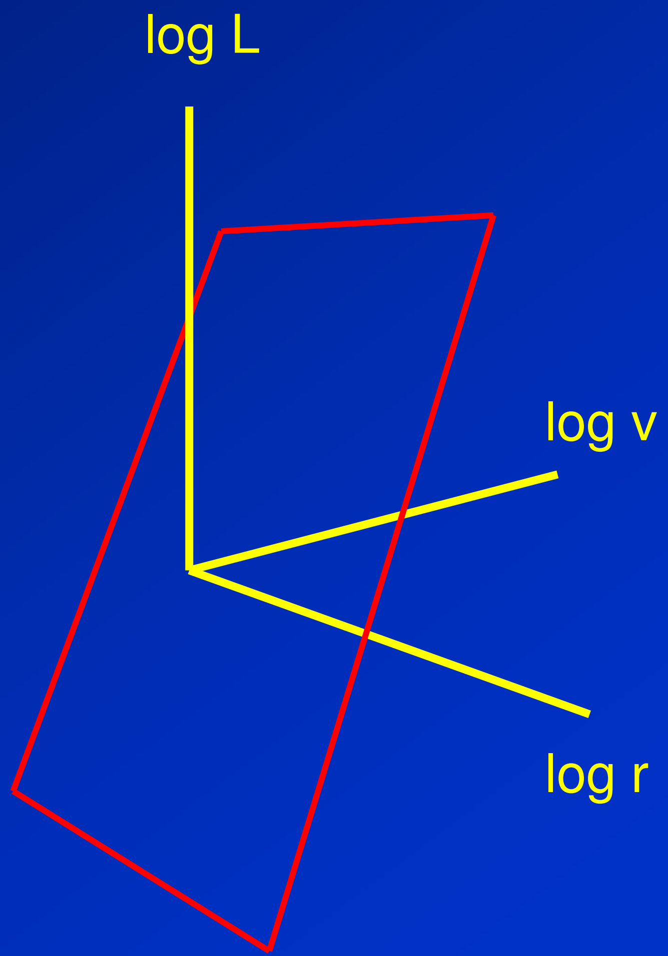
Such objects populate a plane in log-log space called the "Virial Plane"

Transform from Mass to Luminosity

Endow these objects with luminosity and CONSTANT mass-to-light ratio M/L:

Plot the location of these objects in a similar space but with L substituted for M

The objects will populate the SAME PLANE but shifted down or up by the amount -log M/L

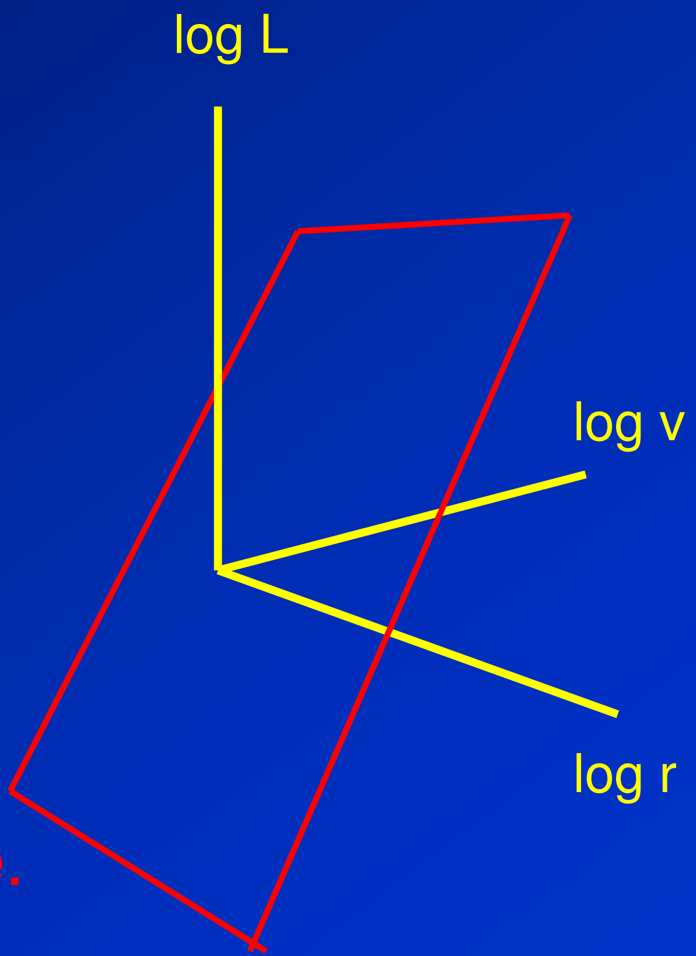


Allow Variable Mass/Light Ratio

Now let M/L vary… but only as a power of r and v:

$$M/L = \text{const}\ \ v^{\alpha}\, r^{\beta}$$

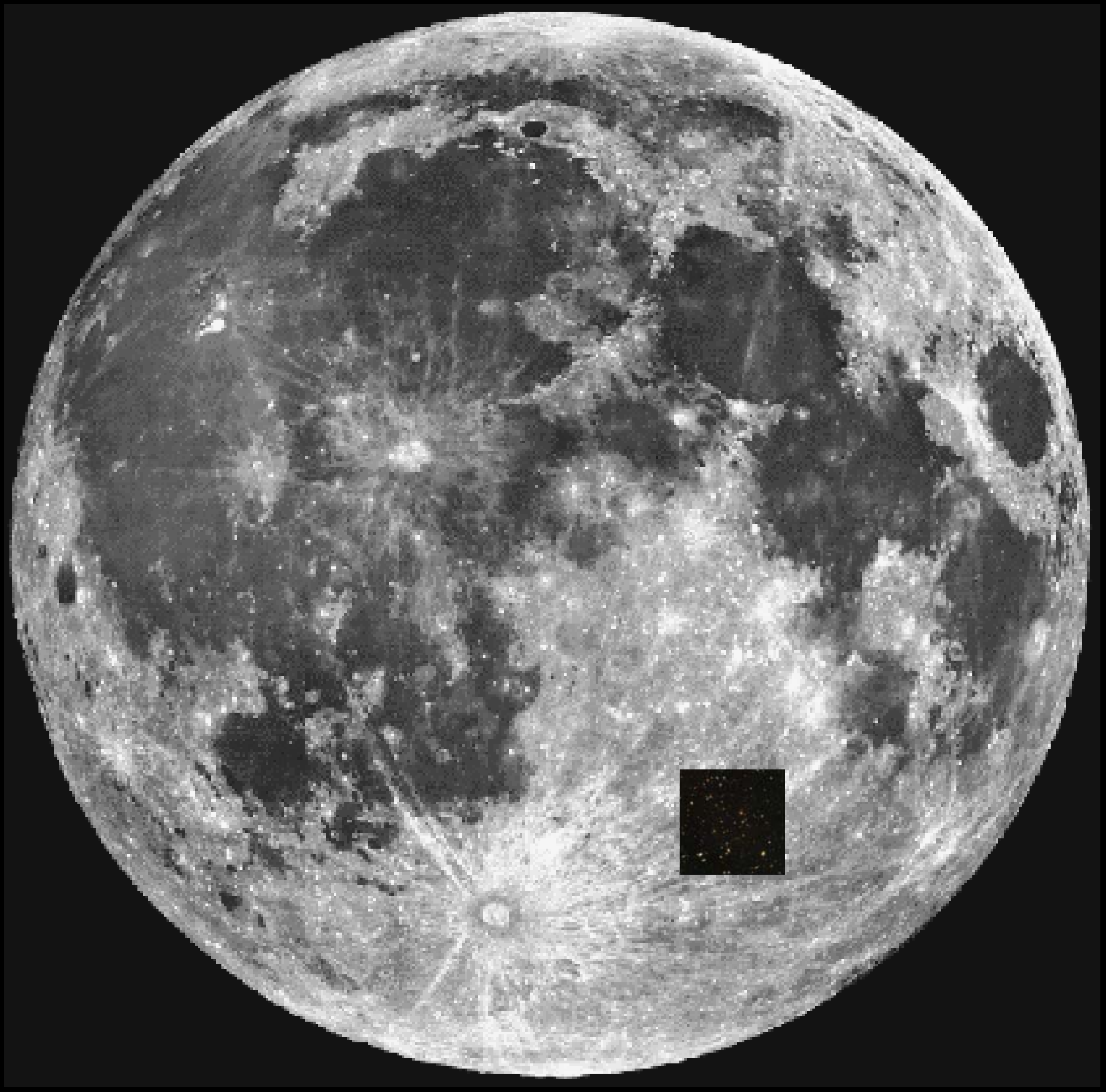
The plane remains a plane but tilts from the virial plane by an amount set by α and β



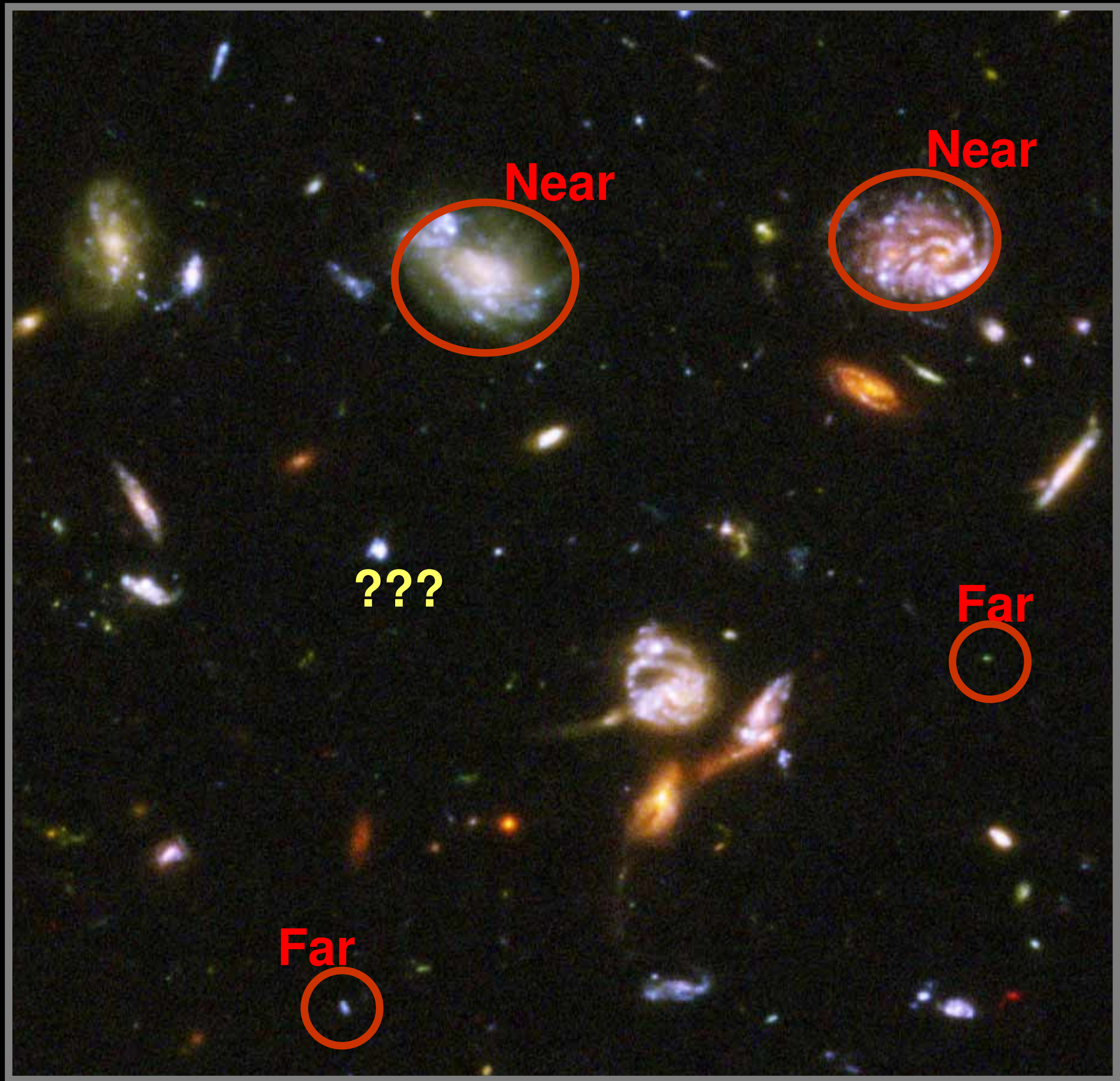
This new plane is called the "Fundamental Plane"

The space has no good name. Usually just called "Fundamental Manifold" space.

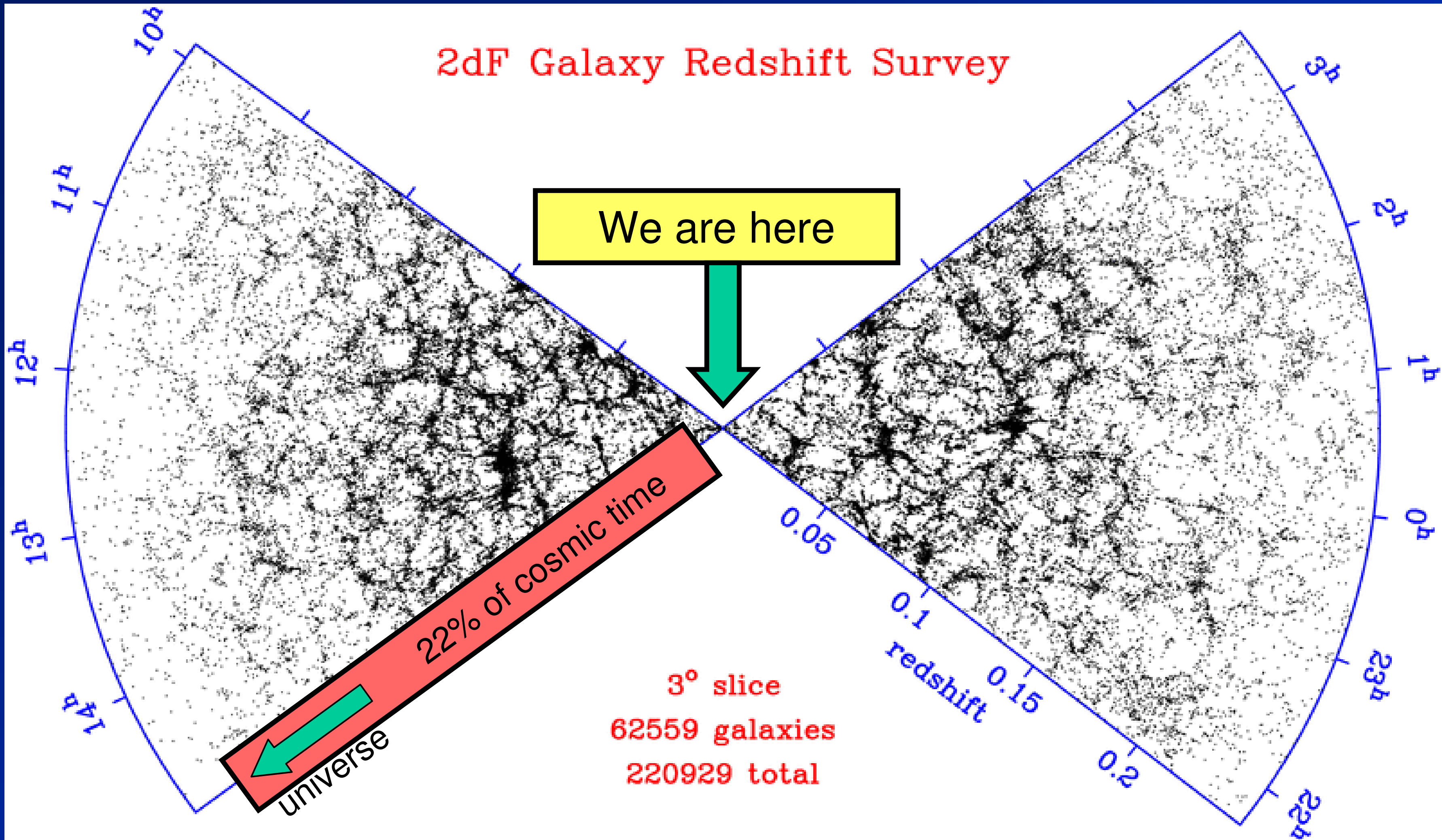
The Hubble Ultradeep Field to scale



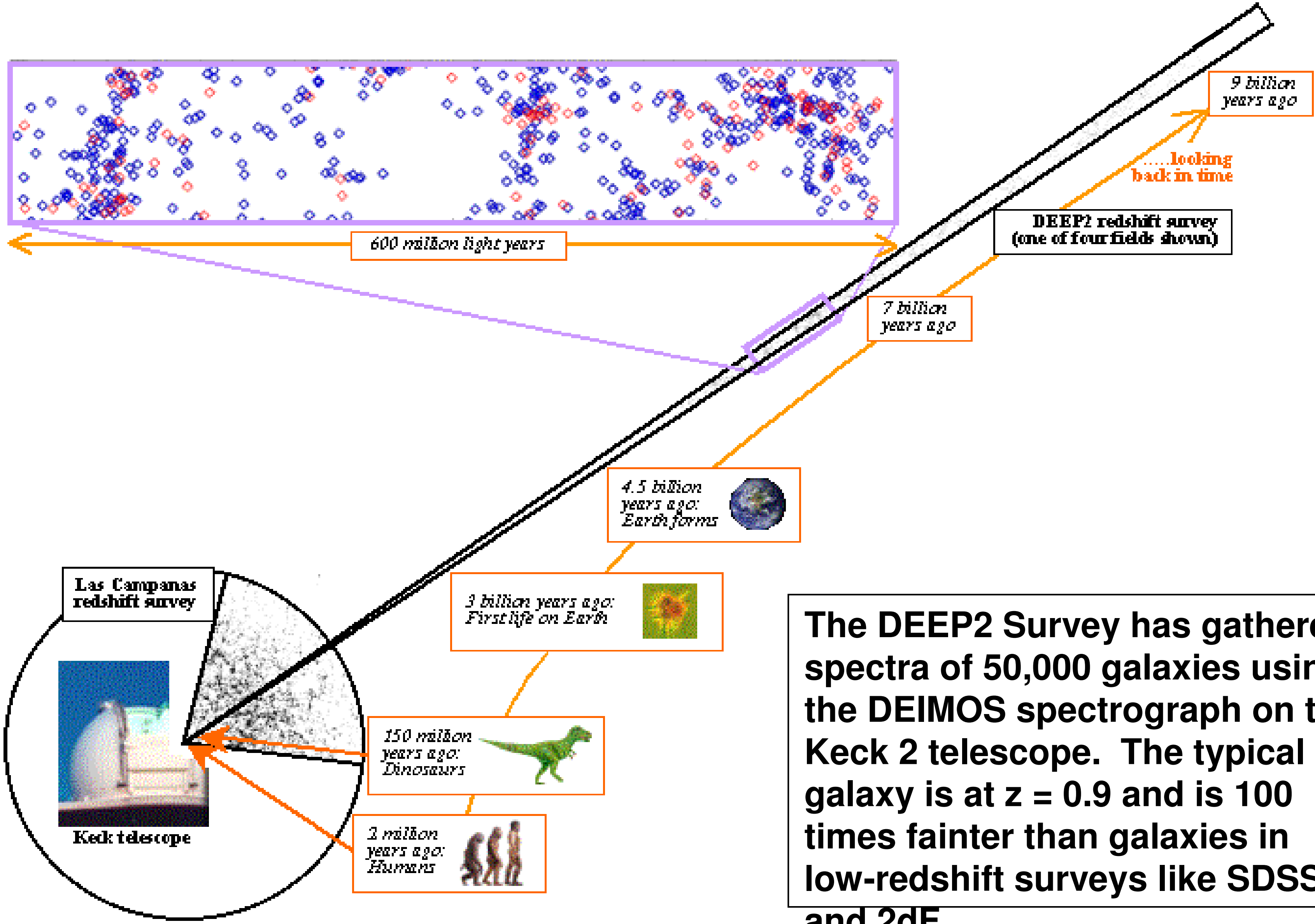
Ultradeep field detail



Looking out in space is looking back in time

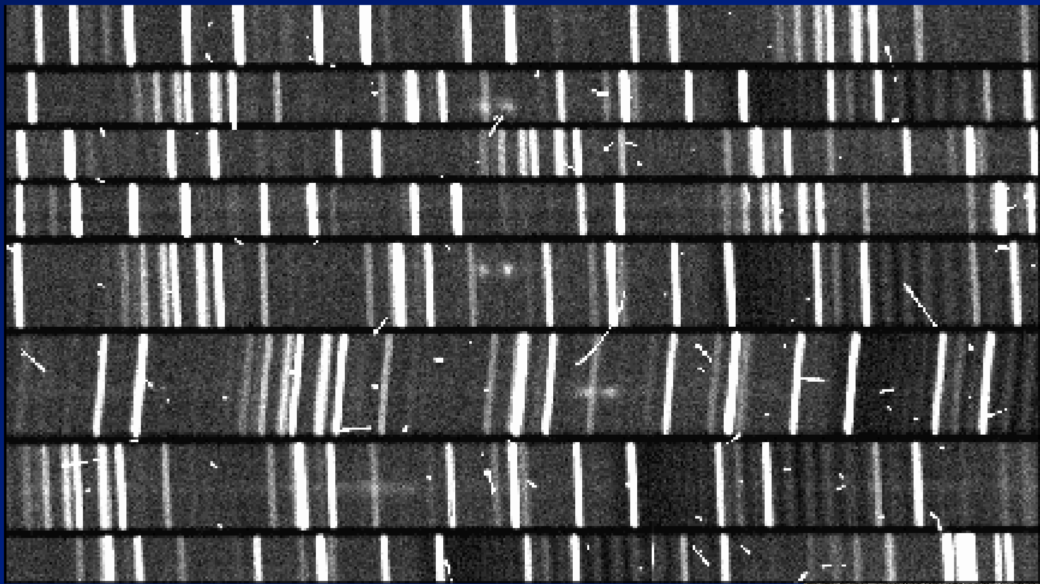


DEEP2 looks 2/3 of the way back to the Big Bang

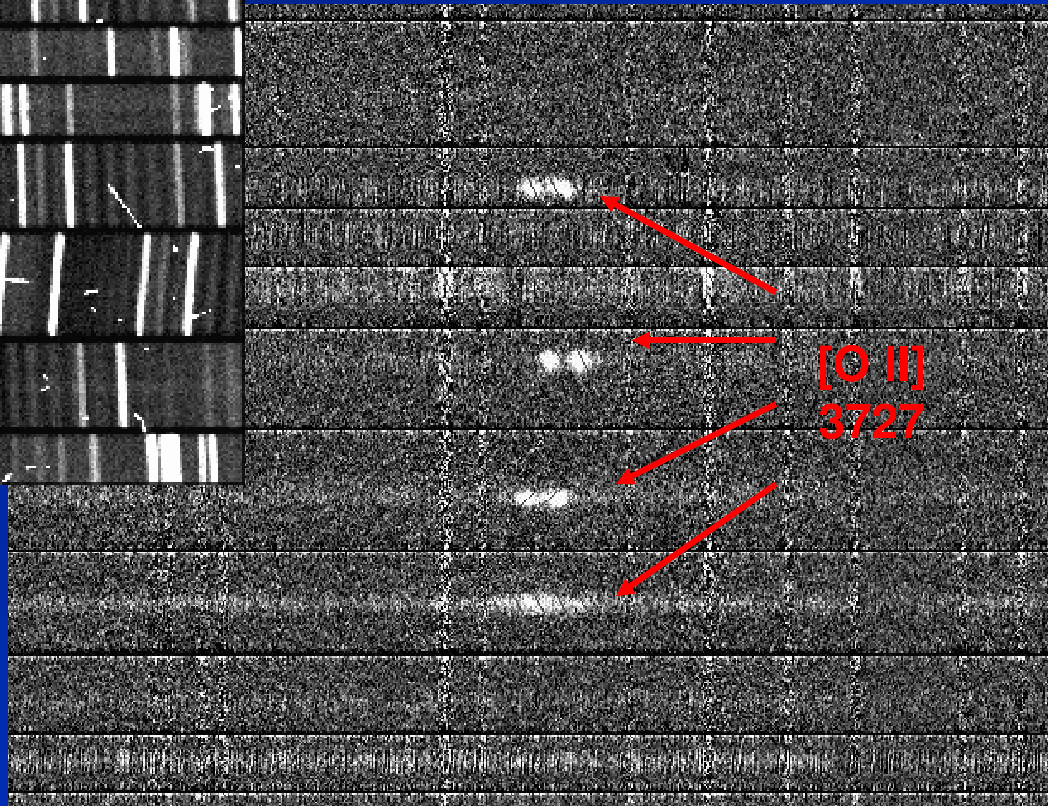


The DEEP2 Survey has gathered spectra of 50,000 galaxies using the DEIMOS spectrograph on the Keck 2 telescope. The typical galaxy is at z = 0.9 and is 100 times fainter than galaxies in low-redshift surveys like SDSS and 2dF.

Multi-object spectrographs **take spectra of up to several hundred galaxies per exposure, several thousand galaxies per night**



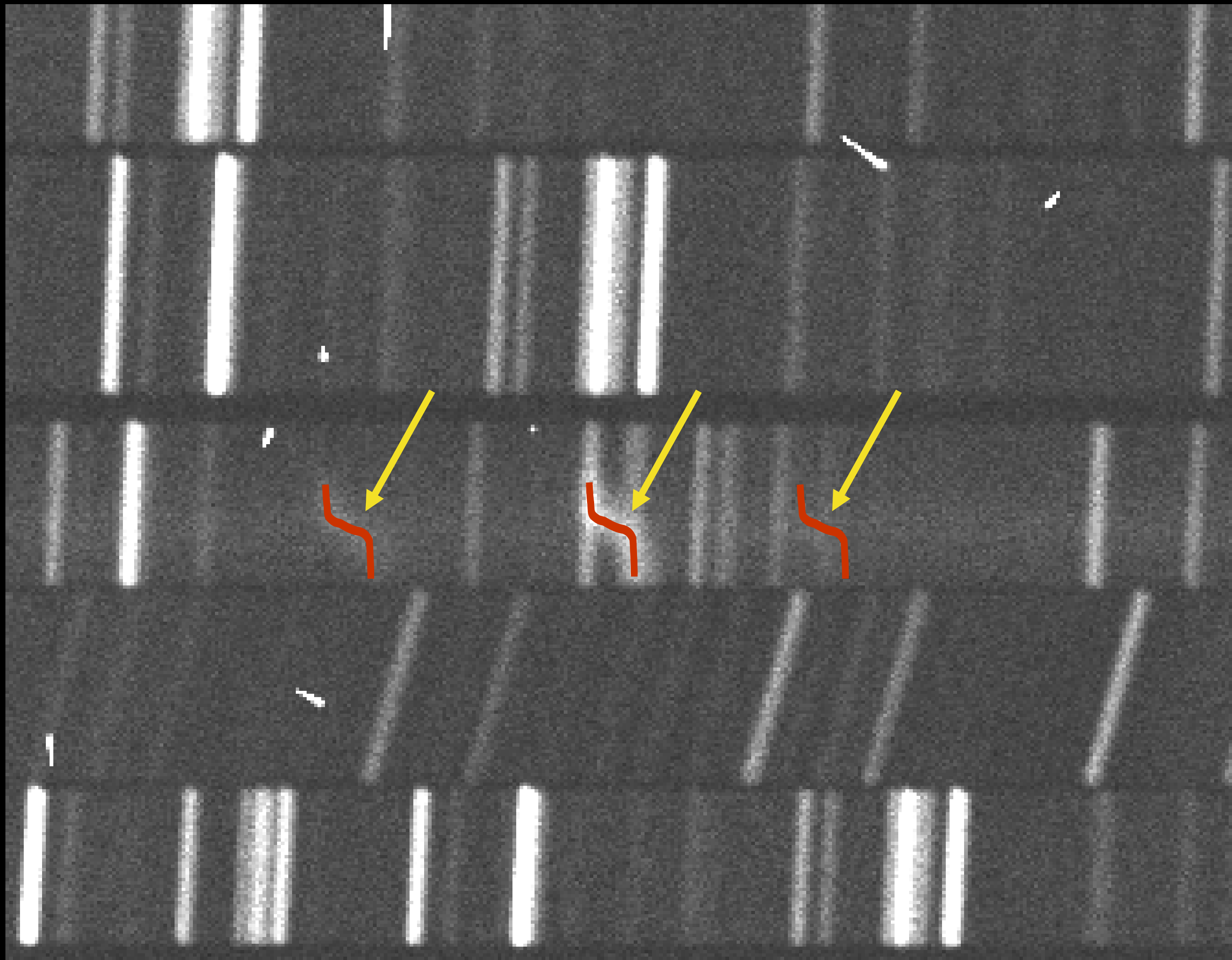
DEIMOS spectra from Keck 2



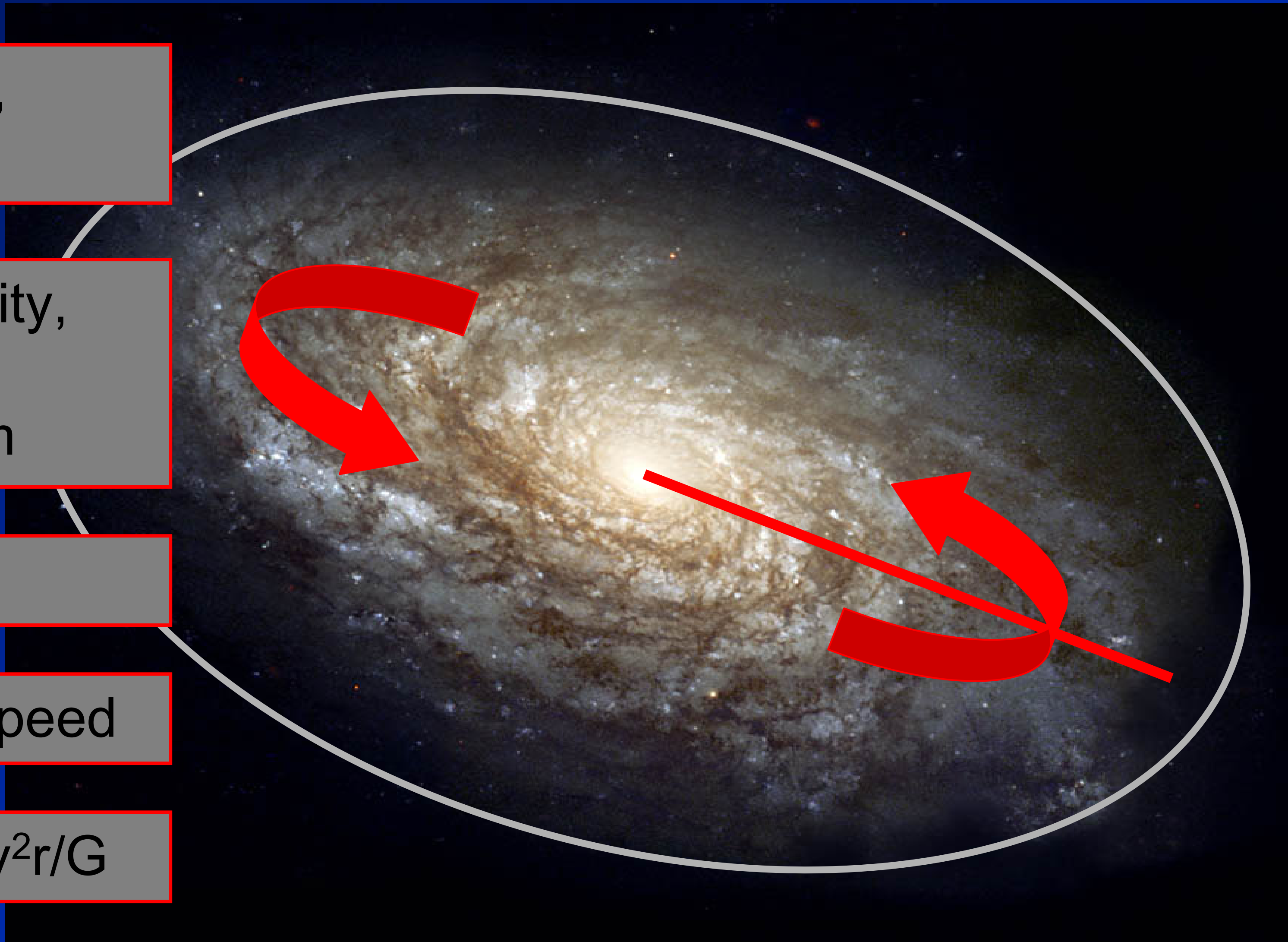
Each stripe is the spectrum of one galaxy. The vertical bright lines are OH atmospheric lines and must be removed along with cosmic rays.

A few percent of one DEEP2 mask, rectified, flat-fielded, CR cleaned, wavelength-rectified, and sky subtracted. Note the resolved ***[OII] doublets.*** Shown is a ***small group of galaxies*** with velocity dispersion σ~250 km/s at z□1.

A rotating galaxy 7 billion years ago



Many data can be measured for each galaxy



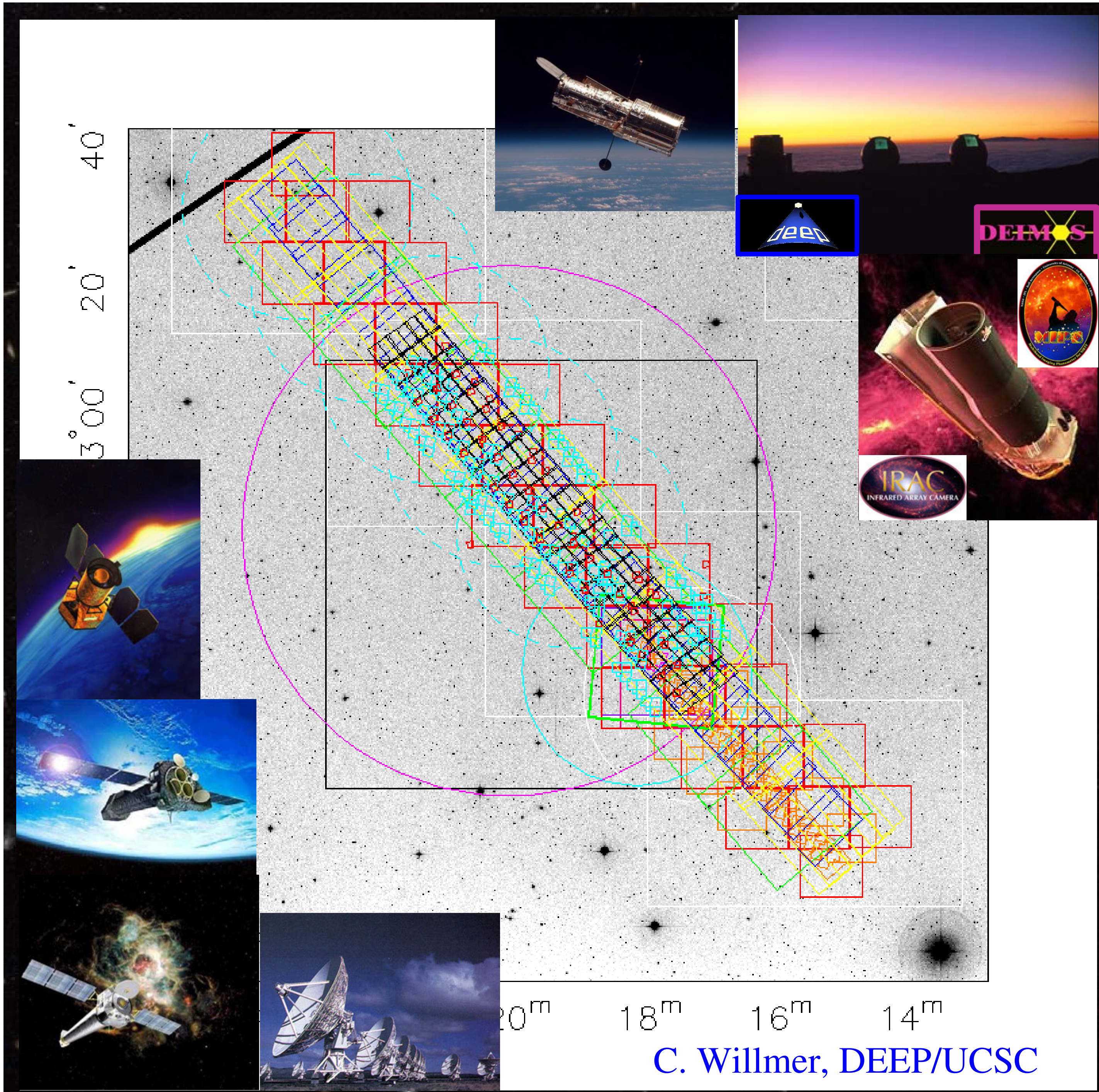
Redshift, distance

Luminosity, color, spectrum

Radius

Orbital speed

Mass ~ v^2r/G



Extended Groth Strip Survey (AEGIS)

A modern panchromatic survey: X-ray to radio

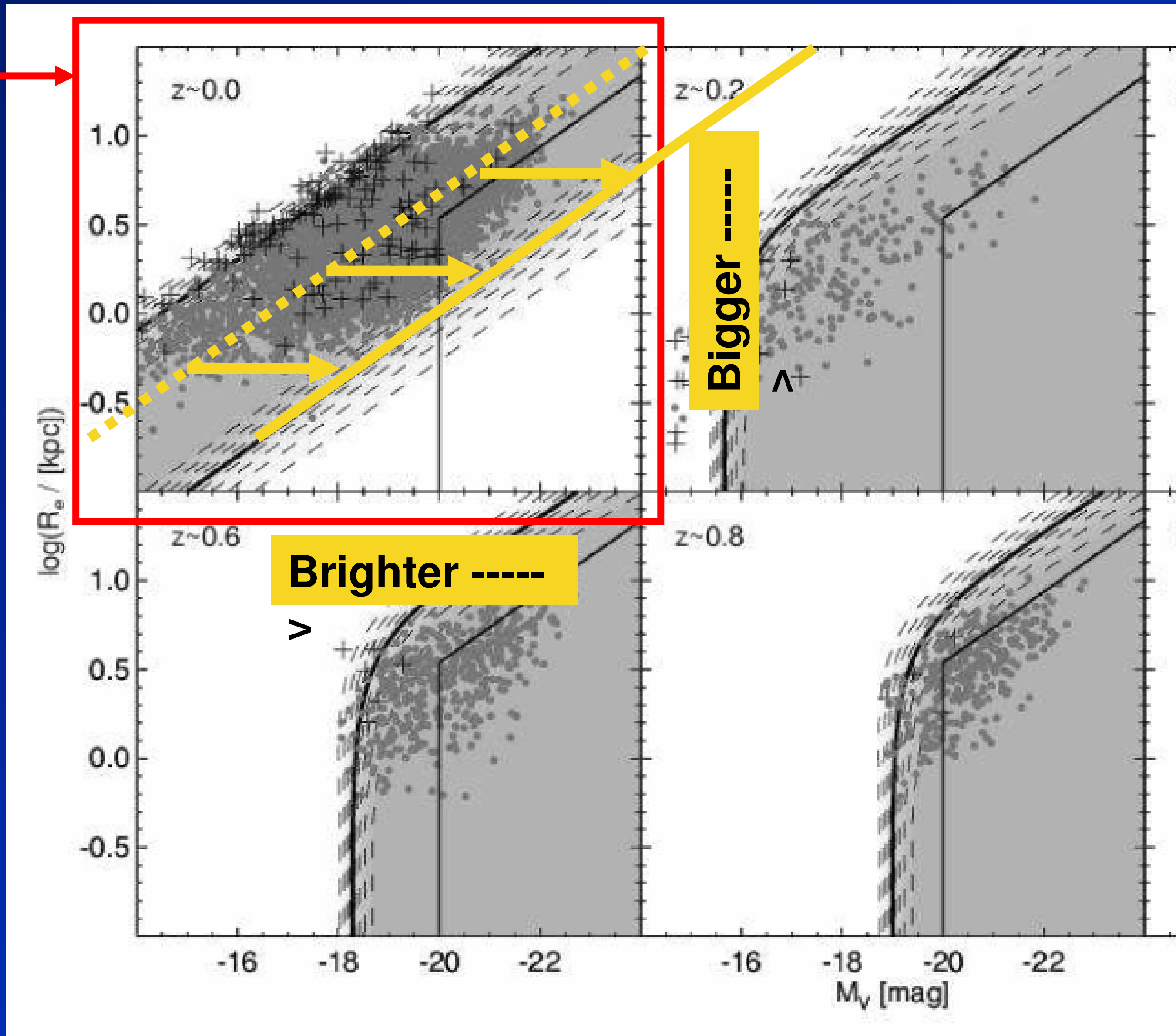
- 12,000 DEEP2 precision redshifts & linewidths
- HST V & I images
- DEEP Spitzer (Near-, Mid-, Far-IR)
- DEEP GALEX UV
- Chandra X-ray
- Deep Palomar and NOAO J,K

Evolution of disk scaling laws since z ~ 1

Recall the *magnitude-radius relation…*

Galaxies at the present epoch

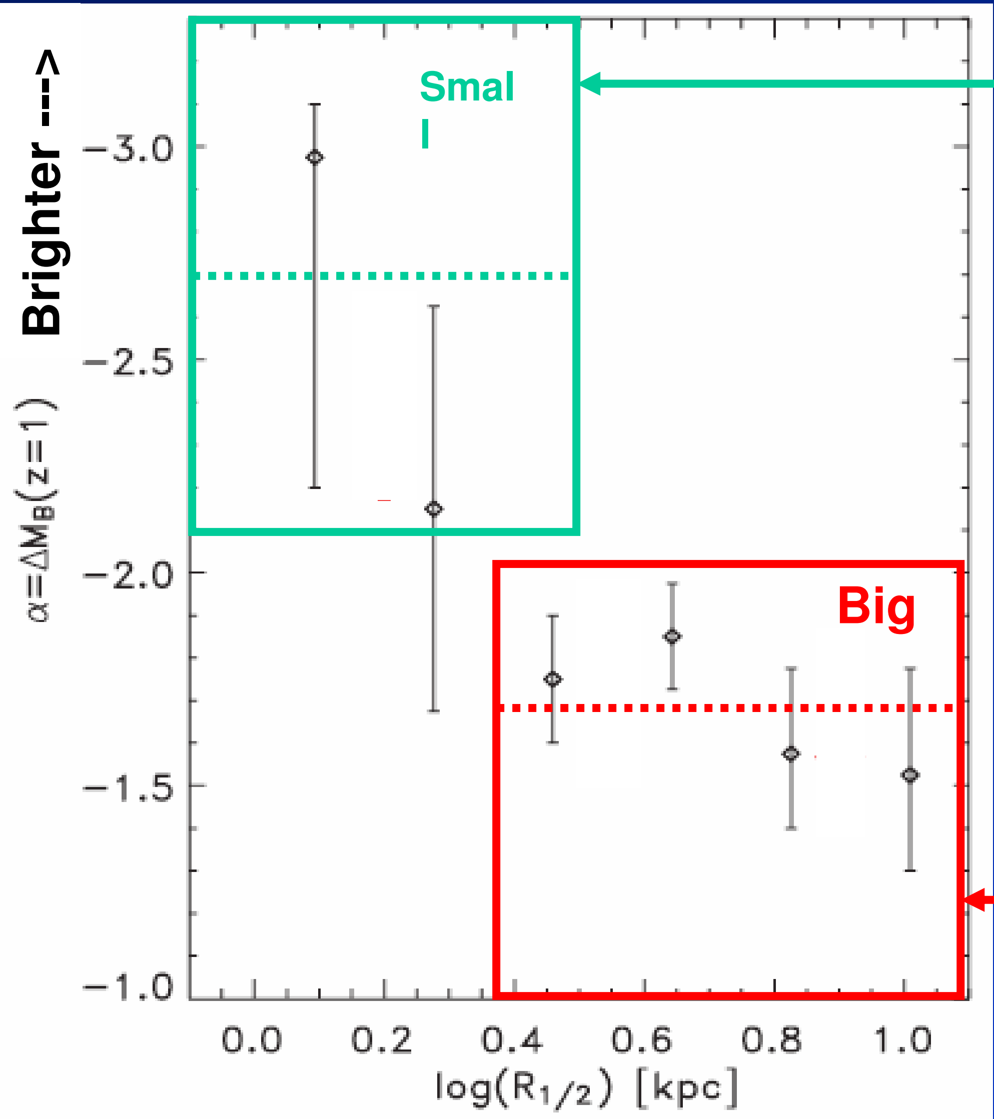
The gray points are from the Sloan Digital Sky Survey (SDSS). The black crosses are nearby galaxies from the GEMS survey.



Barden et al. 2005

Evolution in disk-galaxy mag-radius relation

(ΔM_B at fixed galaxy size from z = 0 back to z = 1)



Small galaxies are ~***2.7 mag brighter*** at z ~ 1. This is impossible…probably due to a trace population of small “bursting” galaxies that later fade and disappear.

Big galaxies are ~***1.7±0.2 mag brighter*** at fixed size at z ~ 1.

DEEP2, Melbourne et al. 2006; also GEMS, Barden et al. 2005

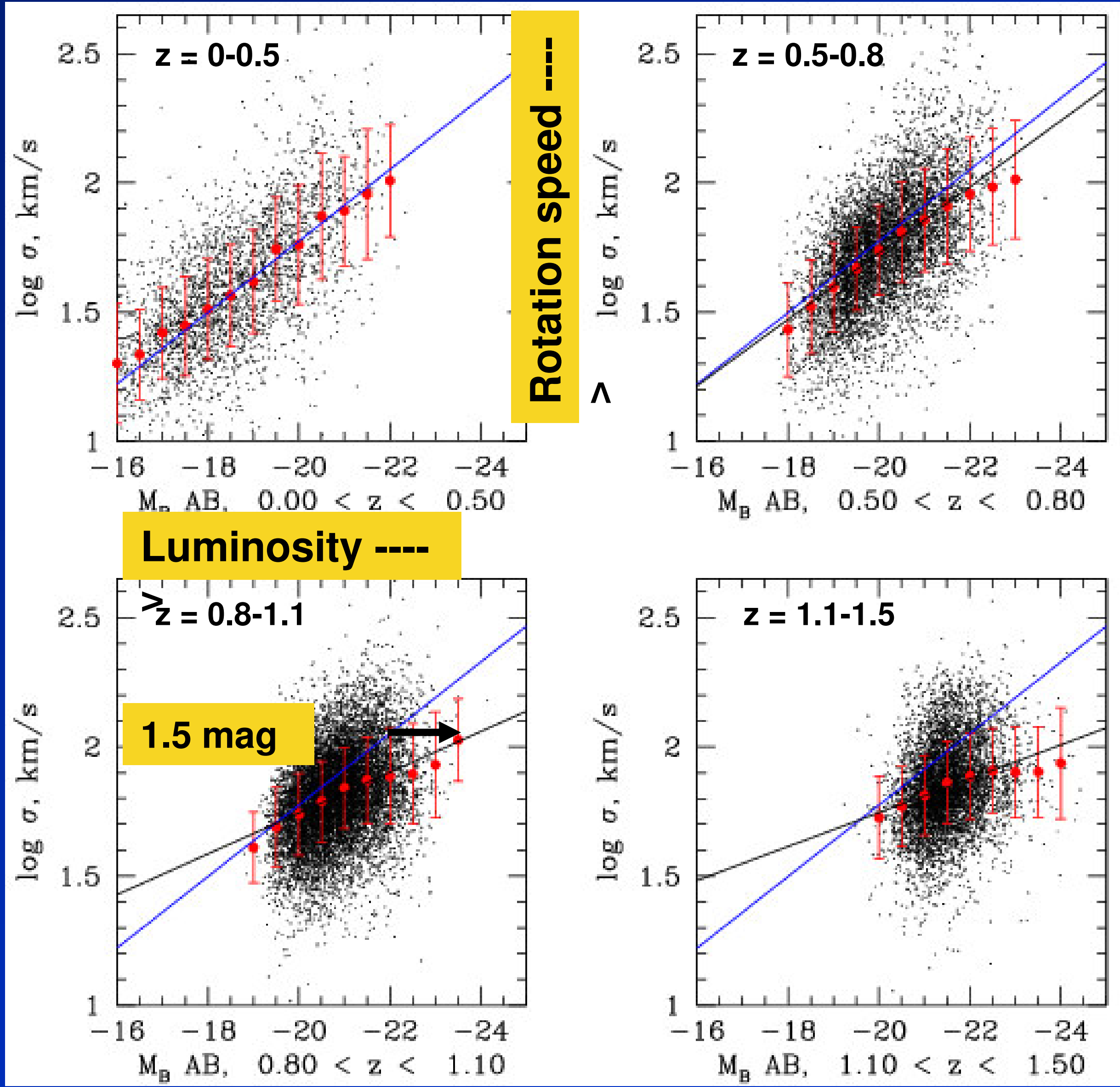
Evolution in disk-galaxy Tully-Fisher relation

(ΔM_B at fixed line-width from z = 0 back to z = 1)

DEEP2, 26,000 galaxies

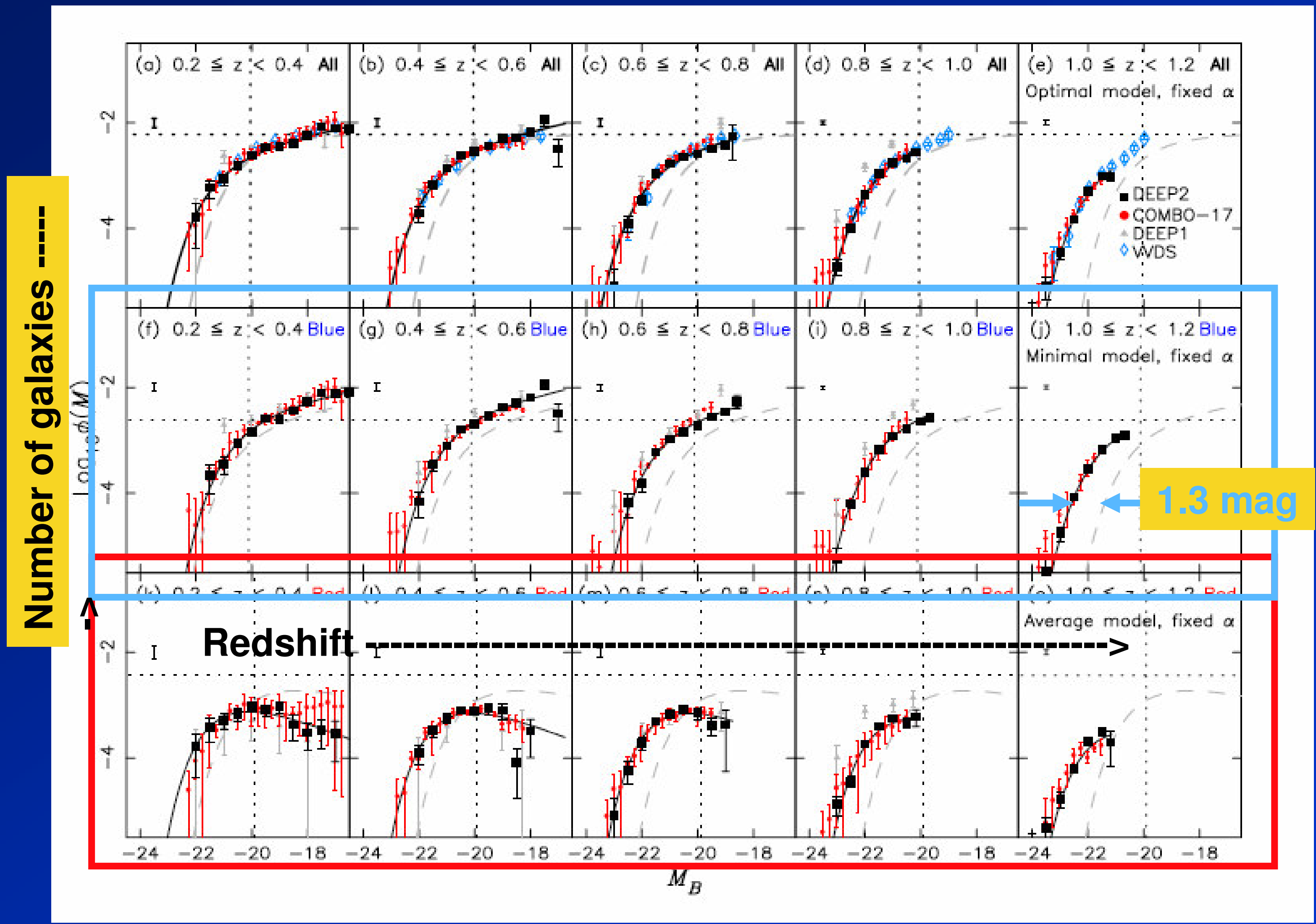
Large galaxies are ***~1.5±0.3 mag brighter*** at fixed rotation speed at z = 1 compared to now.

Again, smaller galaxies seem to differ. This time they ***fade less.***



Weiner et al., 2006

DEEP2 and COMBO-17 *luminosity functions* divided by color back in time



Willmer et al. 2005, Faber et al. 2005

Collected data on the evolution of *bright/large* disk galaxies from z = 1 to z = 0

- Fade in luminosity at fixed radius: $\Delta M_B \sim 1.7 \pm 0.2$ mag
- Fade in luminosity at fixed rotation speed: $\Delta M_B \sim 1.5 \pm 0.3$ mag
- Fade in L* of whole population: $\Delta M_B \sim 1.3 \pm 0.2$ mag
- Predicted aging stellar-pop fade: $\Delta M_B \sim 1.5 \pm 0.3$ mag

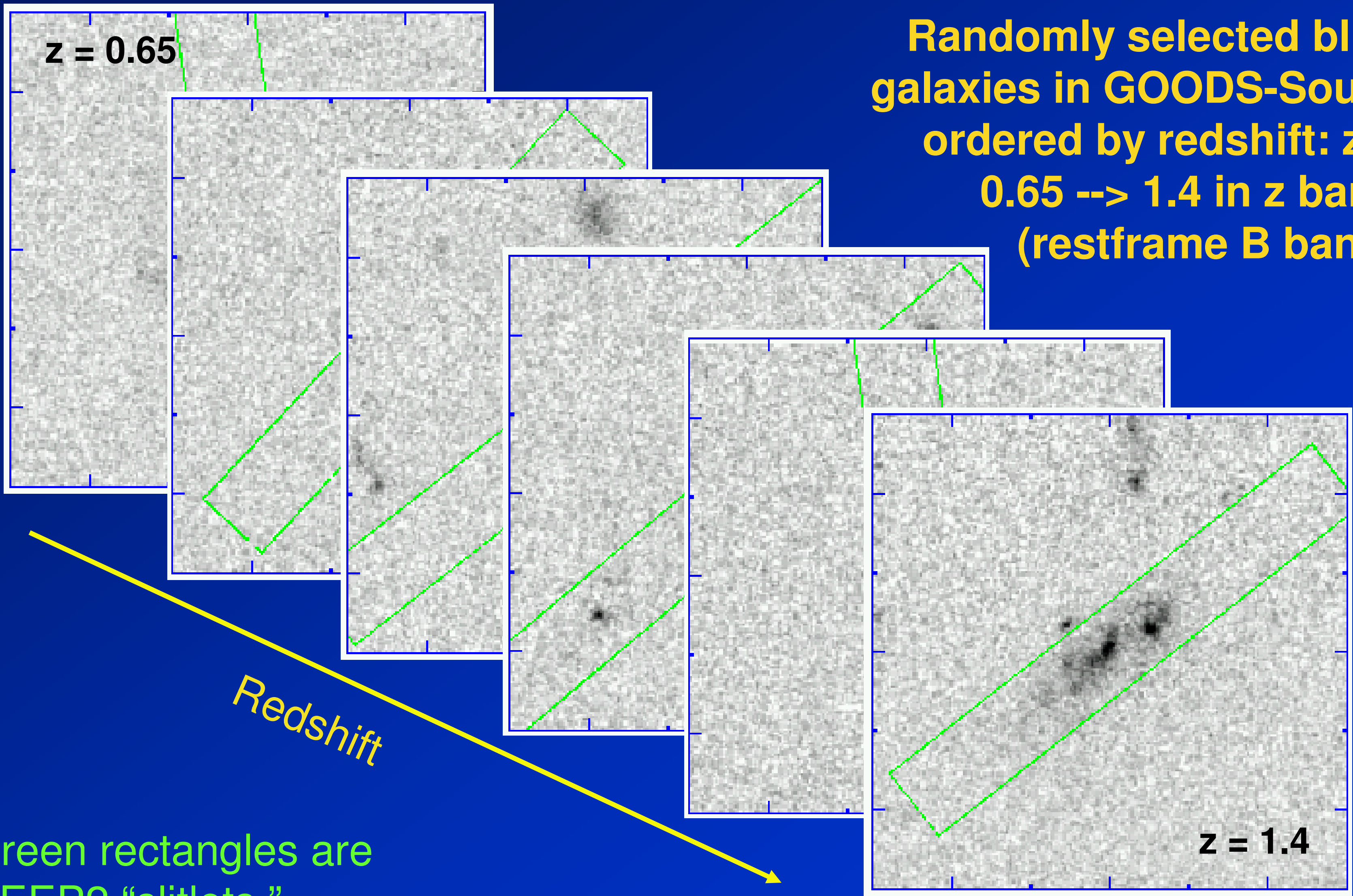
Same!

→ ***This implies little change in average stellar mass!***

- Also…no detectable change in number density (to ± 30%)

These data are consistent with a basically fixed population of large, bright disks that were largely in place by z = 1, after which they don't merge, change number, or change mass by very much---their stars merely fade.

But…disk-galaxy morphologies evolve strongly back in time. *Distant disks look disorganized,* as if just settling.



Randomly selected blue galaxies in GOODS-South ordered by redshift: z = 0.65 --> 1.4 in z band (restframe B band)

Green rectangles are DEEP2 "slitlets."

Spheroidal galaxies :
Brightness profiles
and dark matter

The classic spheroid law is the *de Vaucouleurs law*

$$
\begin{aligned}
I(R) &= \boxed{I(0)\exp(-kR^{0.25})} \\
&= I_e \exp\left\{-7.67\left[\left(\frac{R}{R_e}\right)^{0.25} - 1\right]\right\},
\end{aligned}
$$

I = spheroid surface brightness profile

R_e = effective radius (encloses half the light)

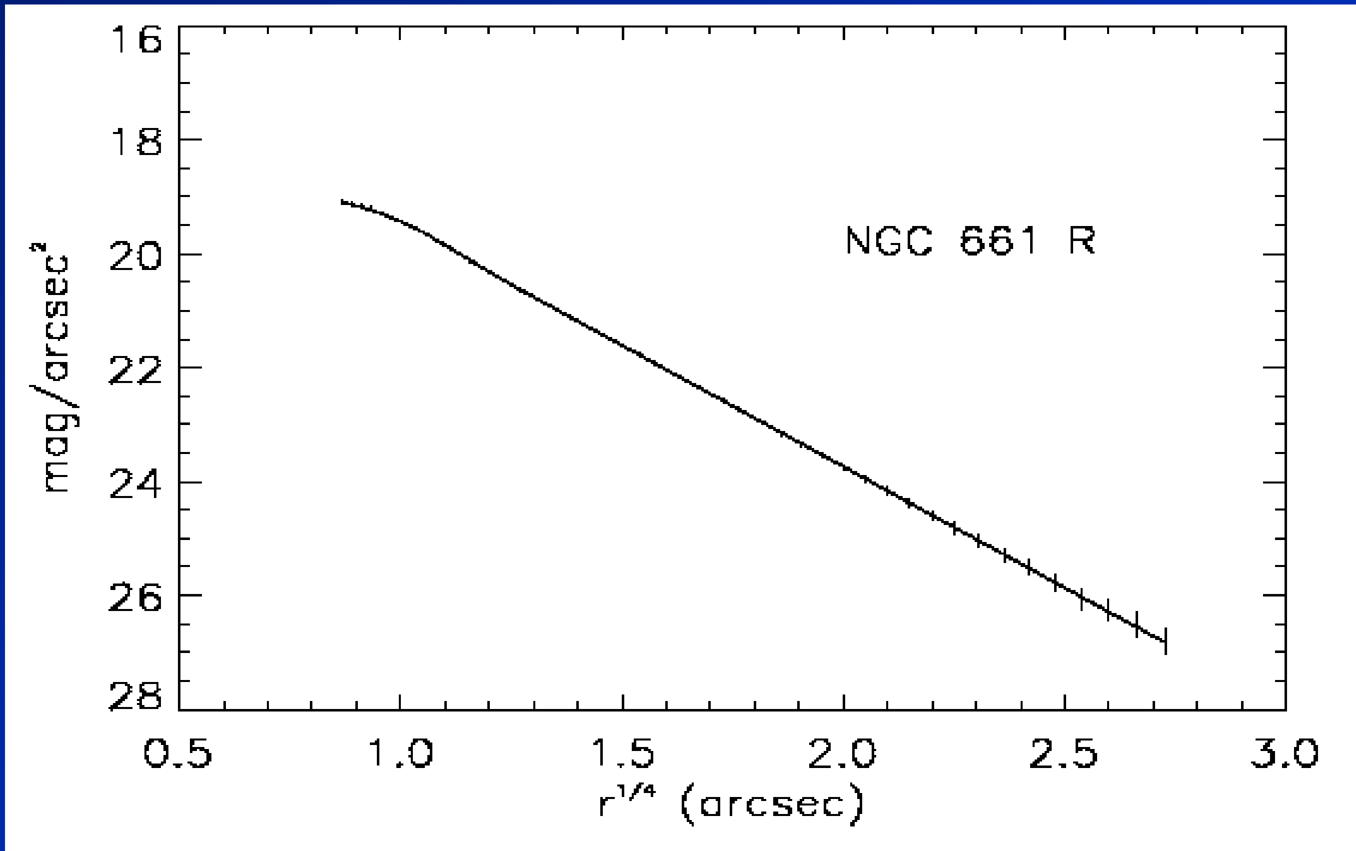
I_e = surface brightness at effective radius

$I(0)$ = central surface brightness

The exponent of R here is 0.25, not 1 as in the disk exponential law. The de Vaucouleurs law is sometimes called the "r-to-the-1/4 law."

A typical spheroid plotted vs. $r^{1/4}$

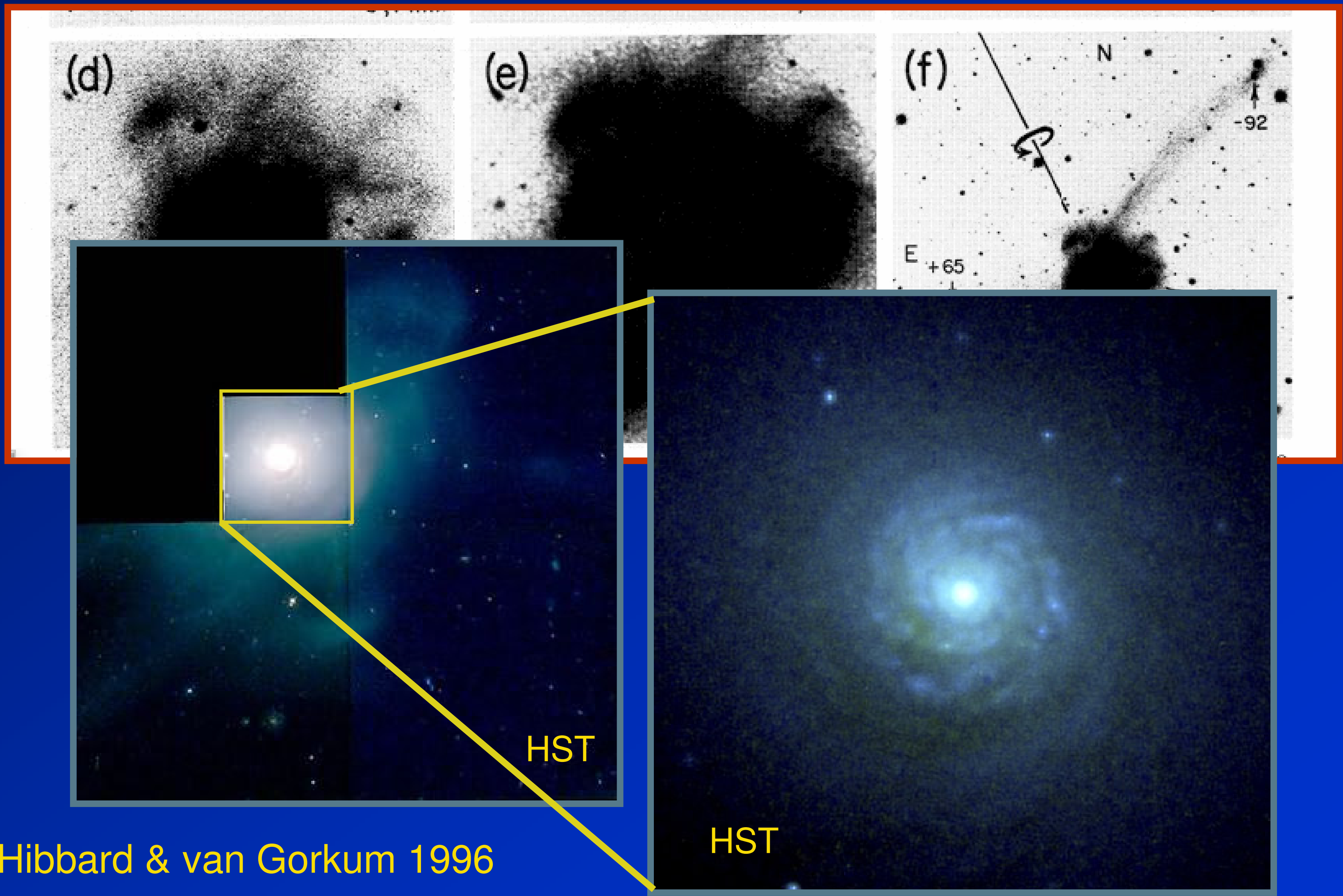
The line is straight except for slight rounding at the center. The ***innermost light profiles*** of spheroids are complicated, not fit by the de Vaucouleurs law, are different from large to small spheroids, and are ***probably affected by black hole formation and black-hole mergers.***



Spheroids: merger evidence

1982: Schweizer -- Merger evidence

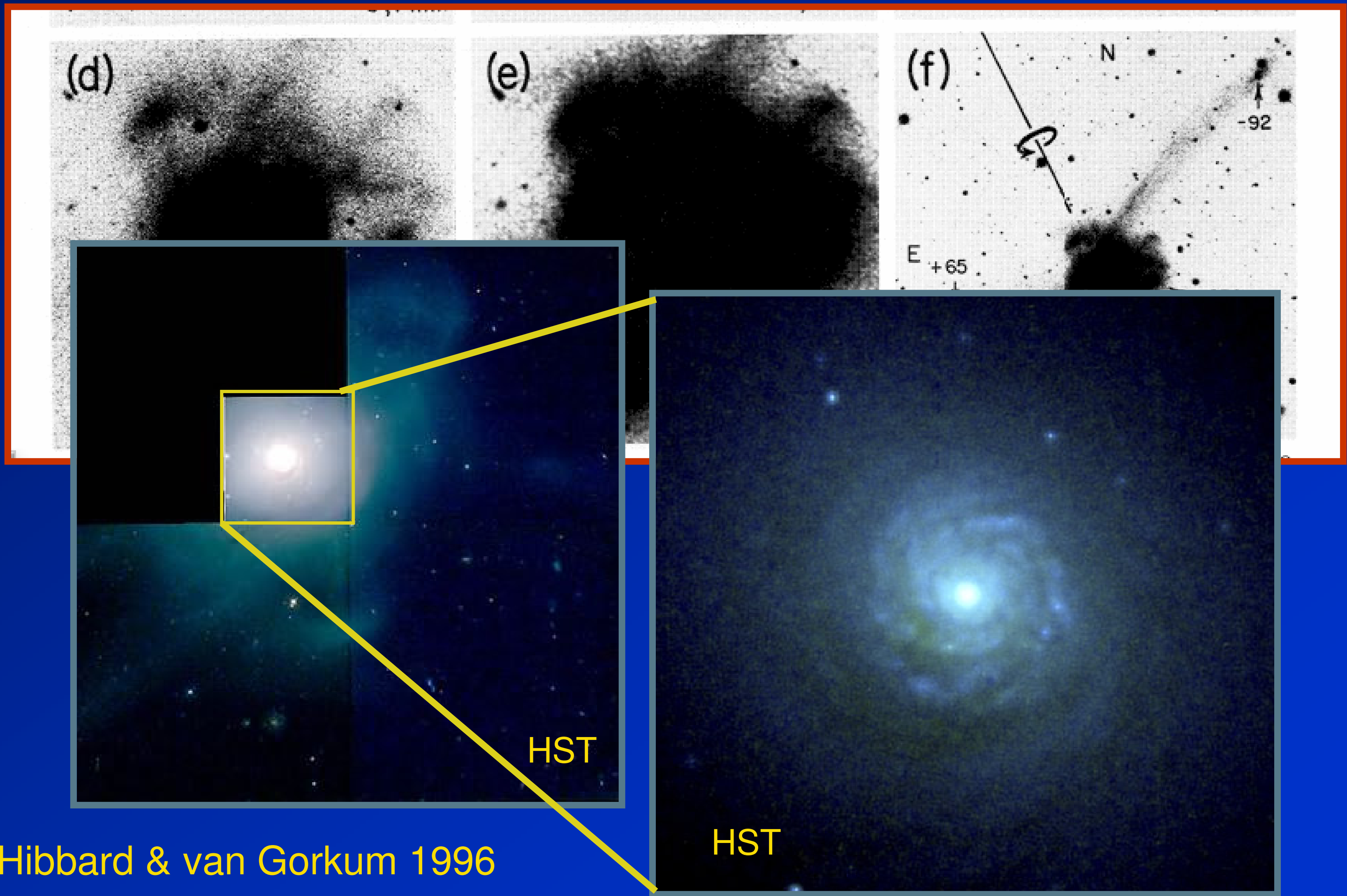
NGC 7252 -- "Atoms for Peace" galaxy



Also Hibbard & van Gorkum 1996

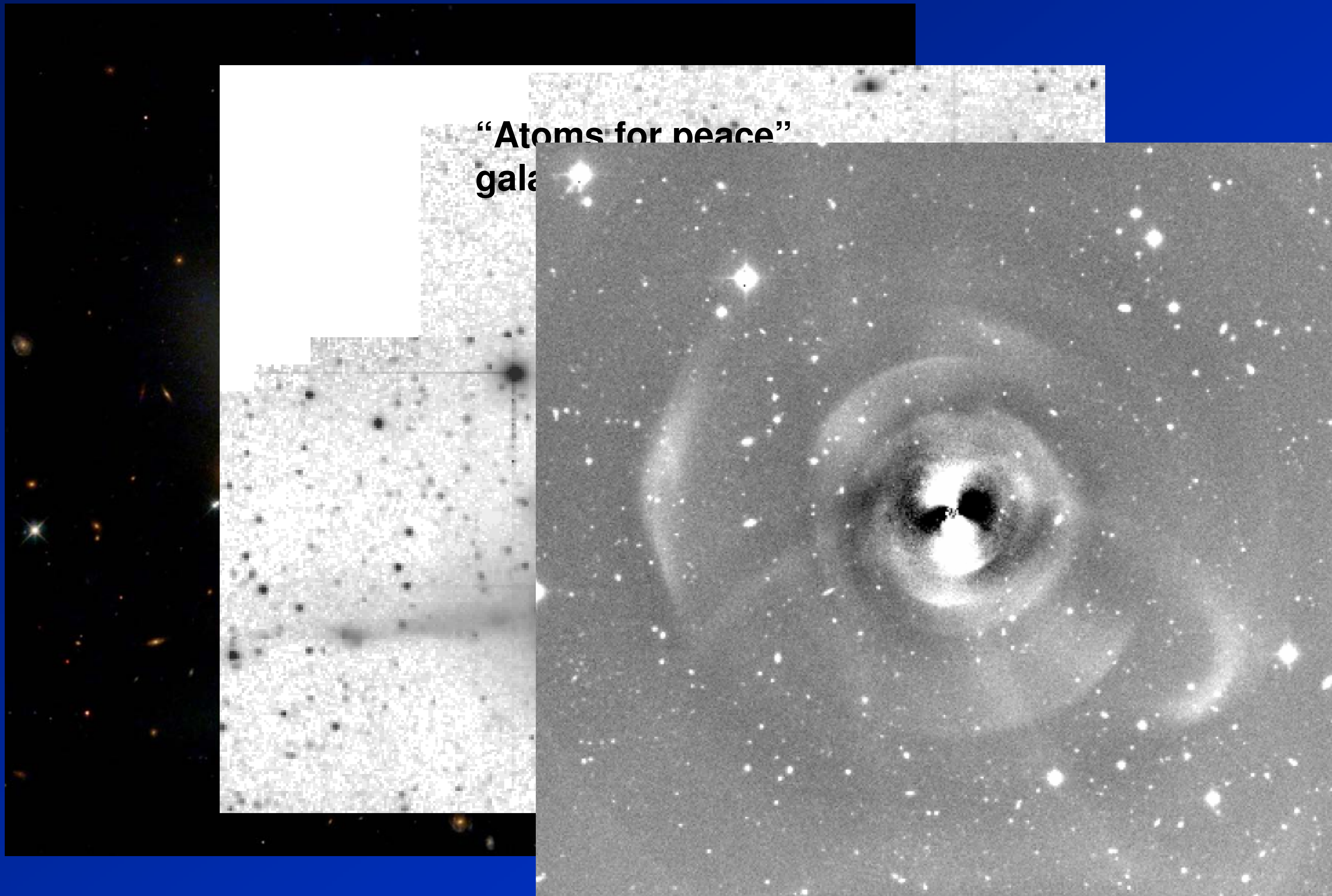
1982: Schweizer -- Merger evidence

Mean light profile is de Vaucouleurs law even though lumpy with tidal tails; wait and these will smooth out



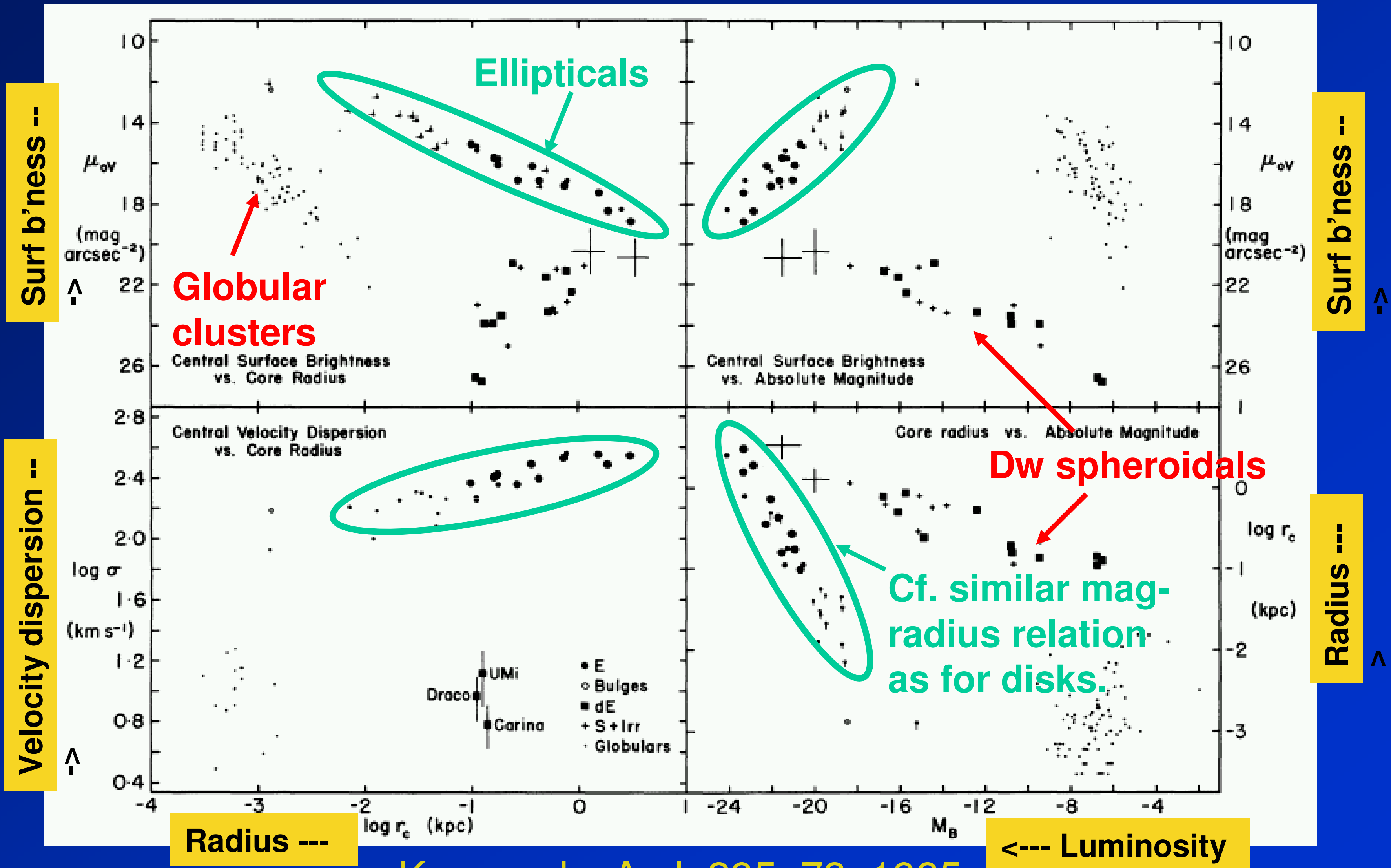
Also Hibbard & van Gorkum 1996

Merging galaxies and *merger remnants* are fairly common now that we know what to look for



Spheroid scaling laws

The *scaling laws* for large spheroidal systems resemble those for disks. (Globular clusters and dwarf galaxies obey different laws, showing that they formed differently.)



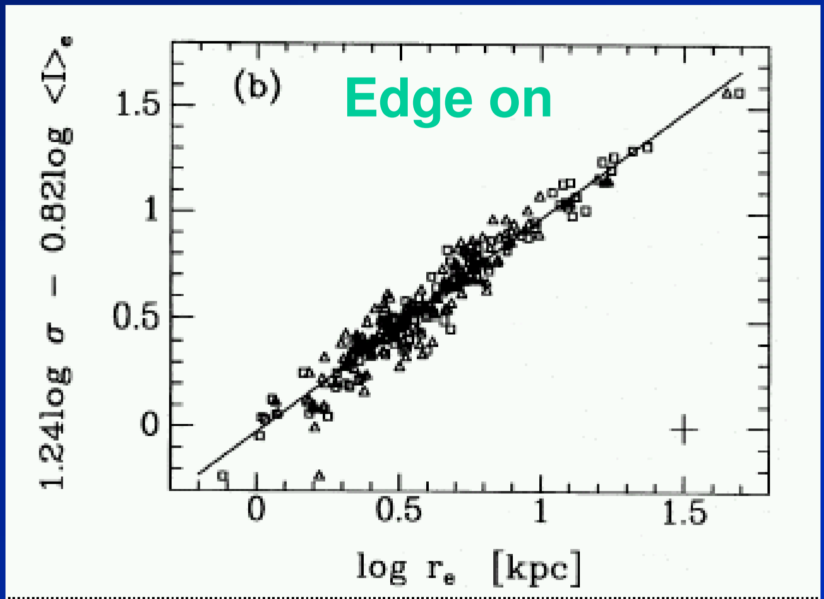
Kormendy, ApJ, 295, 73, 1985

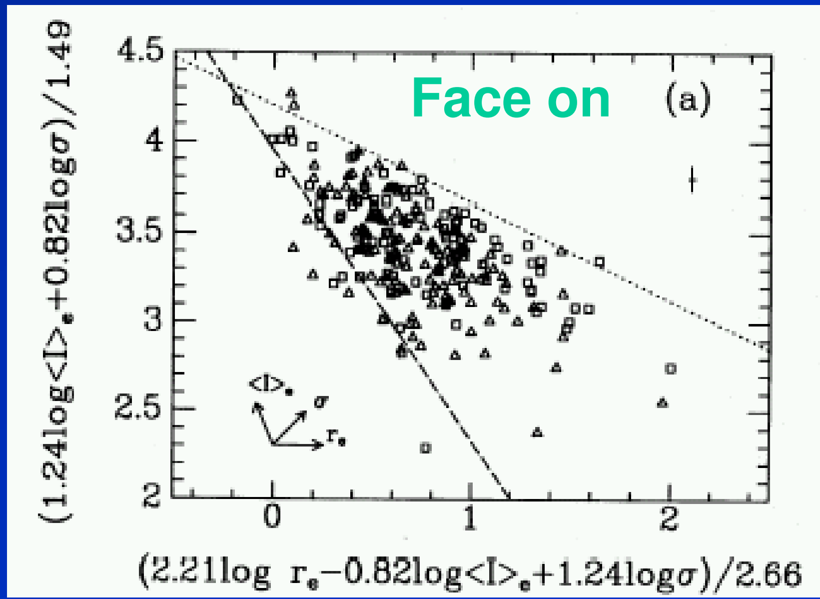
The analog of the TF relation for spheroids is the *Fundamental Plane*

The Fundamental Plane correlates ***R_e, surface brightness, and σ*** for spheroidal galaxies. Since surface brightness $\Sigma \sim L/(R_e)^2$, this is the ***same L,v,R-space*** as for the TF relation.

The thinness of the FP means that the mass-to-light ratios of the stars in spheroidal galaxies are a well-behaved function of their structural parameters. ***Structurally similar spheroidal galaxies have similar star-forming histories.*** This is what we also found for disks.

The FP for spheroidals and the TF plane for disks are two parts of the ***same Virial Plane*** for all galaxies. The two parts are slighly tilted w/r one another and join at a "hinge" where the stellar populations change. This is the same spot that divides the blue cloud from the red sequence.

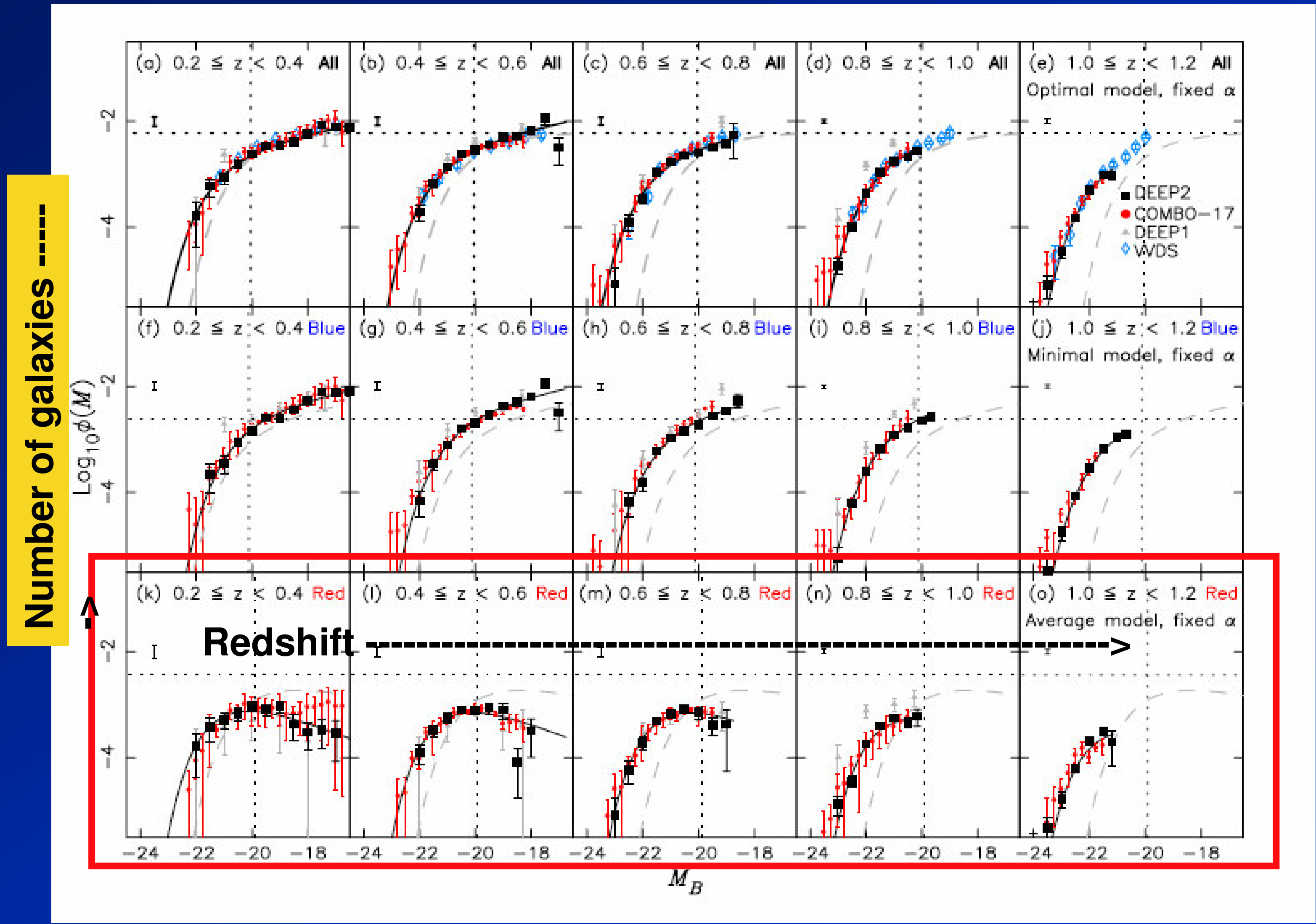




The Fundamental Plane for nearby cluster spheroidals, Jorgensen et al., 1996.

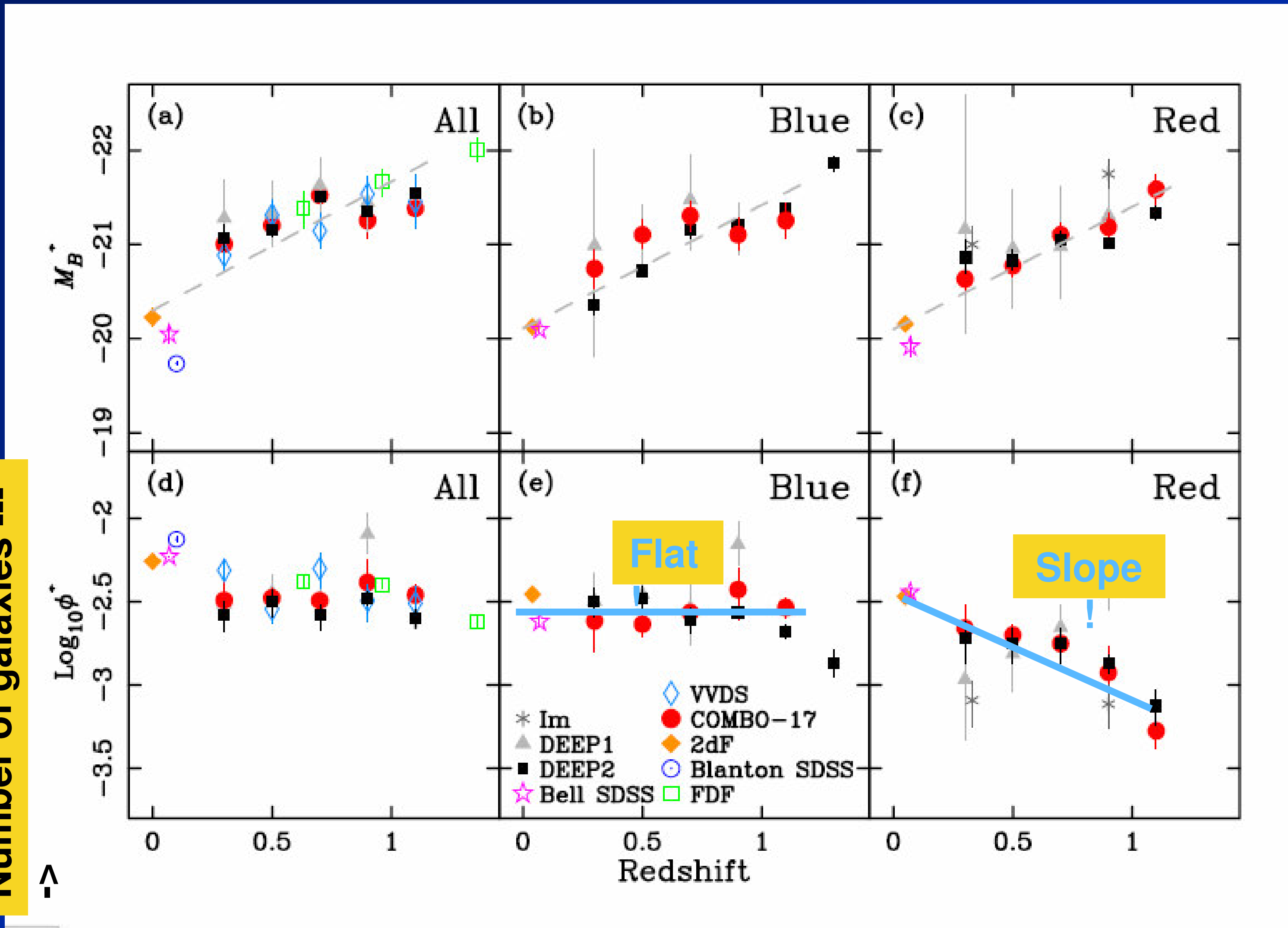
Spheroid number density evolution

DEEP2 and COMBO-17 *luminosity functions* divided by color back in time



Willmer et al. 2005, Faber et al. 2005

DEEP2 and COMBO-17: Most red galaxies *appeared after z = 1*



Number of galaxies --->

Willmer et al. 2005, Faber et al. 2005

Two requirements are needed for making a red spheroid out of blue disks

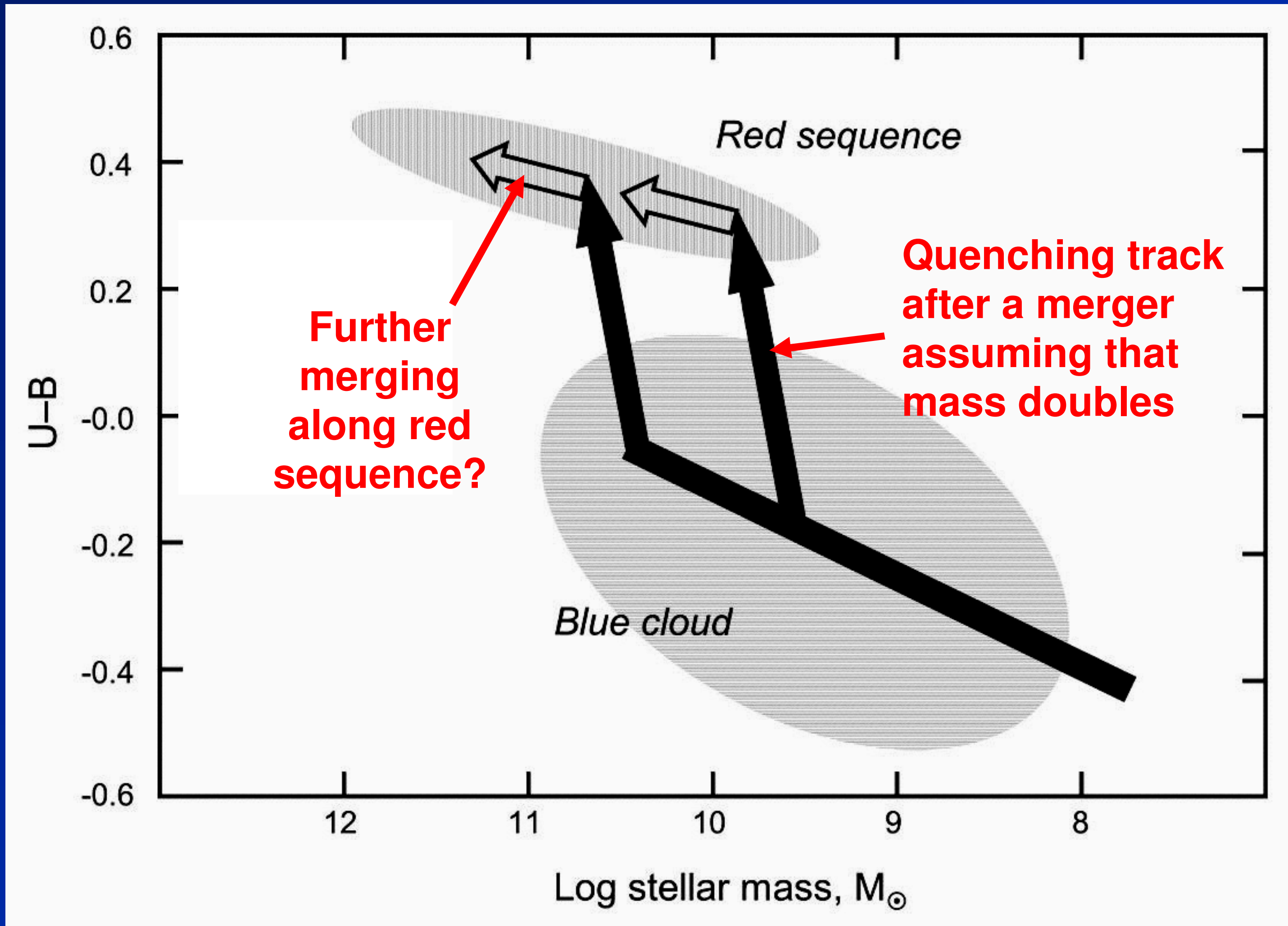
- Dynamical conversion: flat rotating disks need to be "scrambled" into a roundish spheroid:

  ----> Easily done by mergers. No problem.

- Star formation needs to be stopped:

  ----> An idea that partially works: starbursts triggered by mergers, which provide feedback and drive out gas in a "galactic wind."

Motion of galaxies in color-mass diagram if two *equal-mass blue galaxies* merge and quench

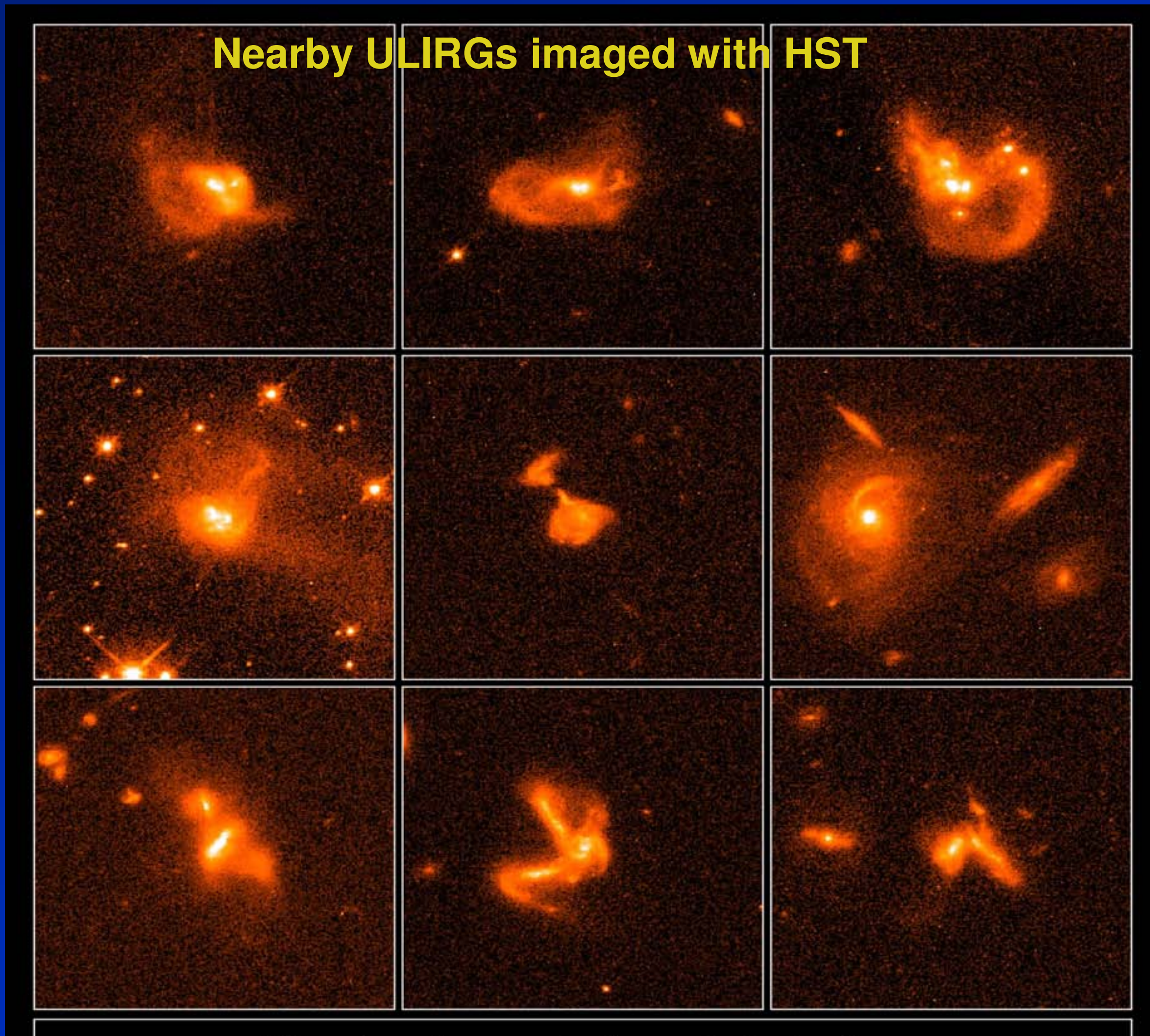


Gas-rich mergers trigger *starbursts,* creating ultraluminous infrared galaxies *(ULIRGs)* that are briefly the most rapidly star-forming galaxies in the Universe

95% of all ULIRGS are seen to be double or interacting. Mean separation of nuclei only 2 Kpc. ***Late-stage mergers.***

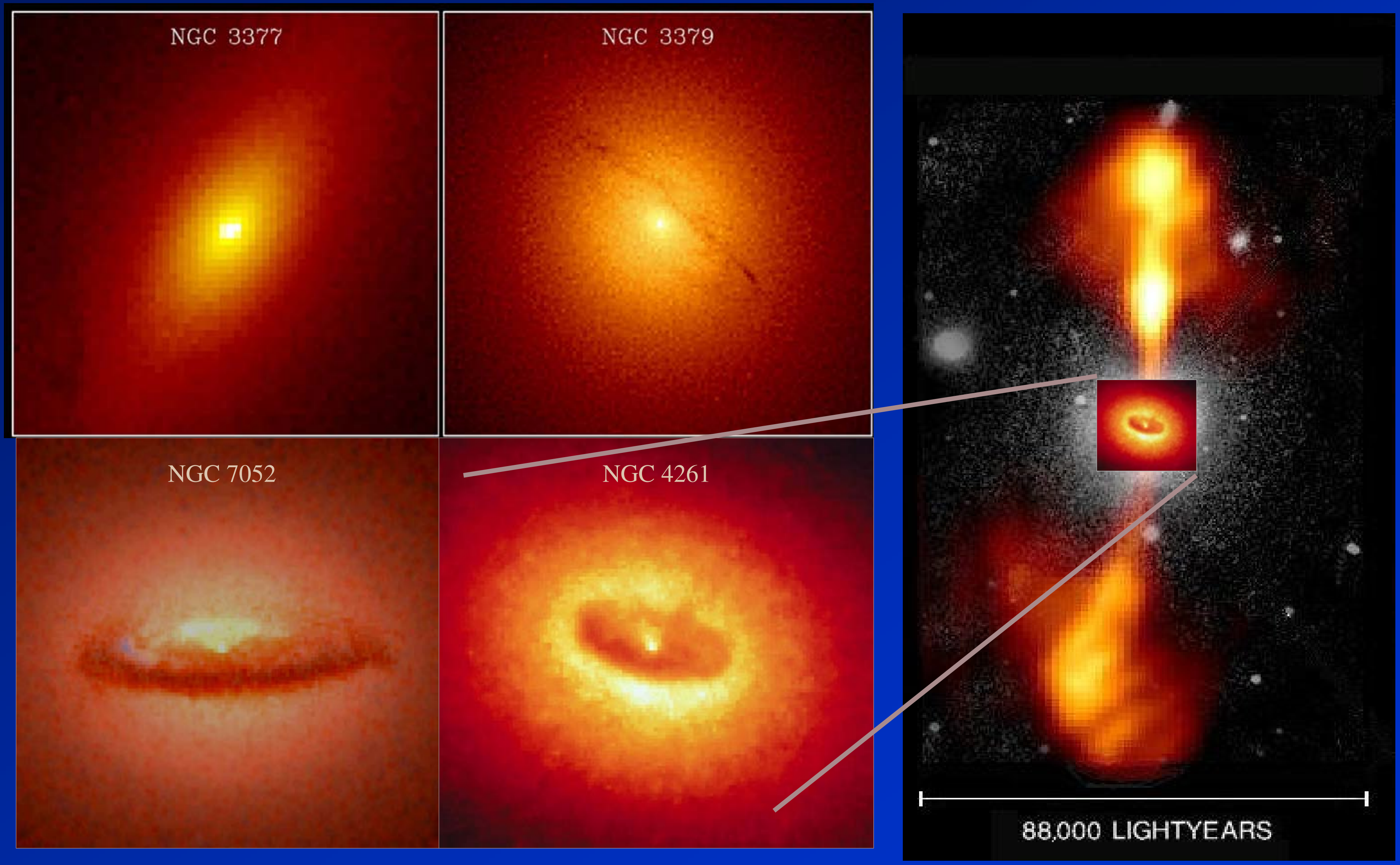
Bright ULIRGs make stars at a rate up to ***100-1000 $M_\odot$/yr.***

Normal disk galaxies make stars at a rate of ~ 1 $M_\odot$/yr.

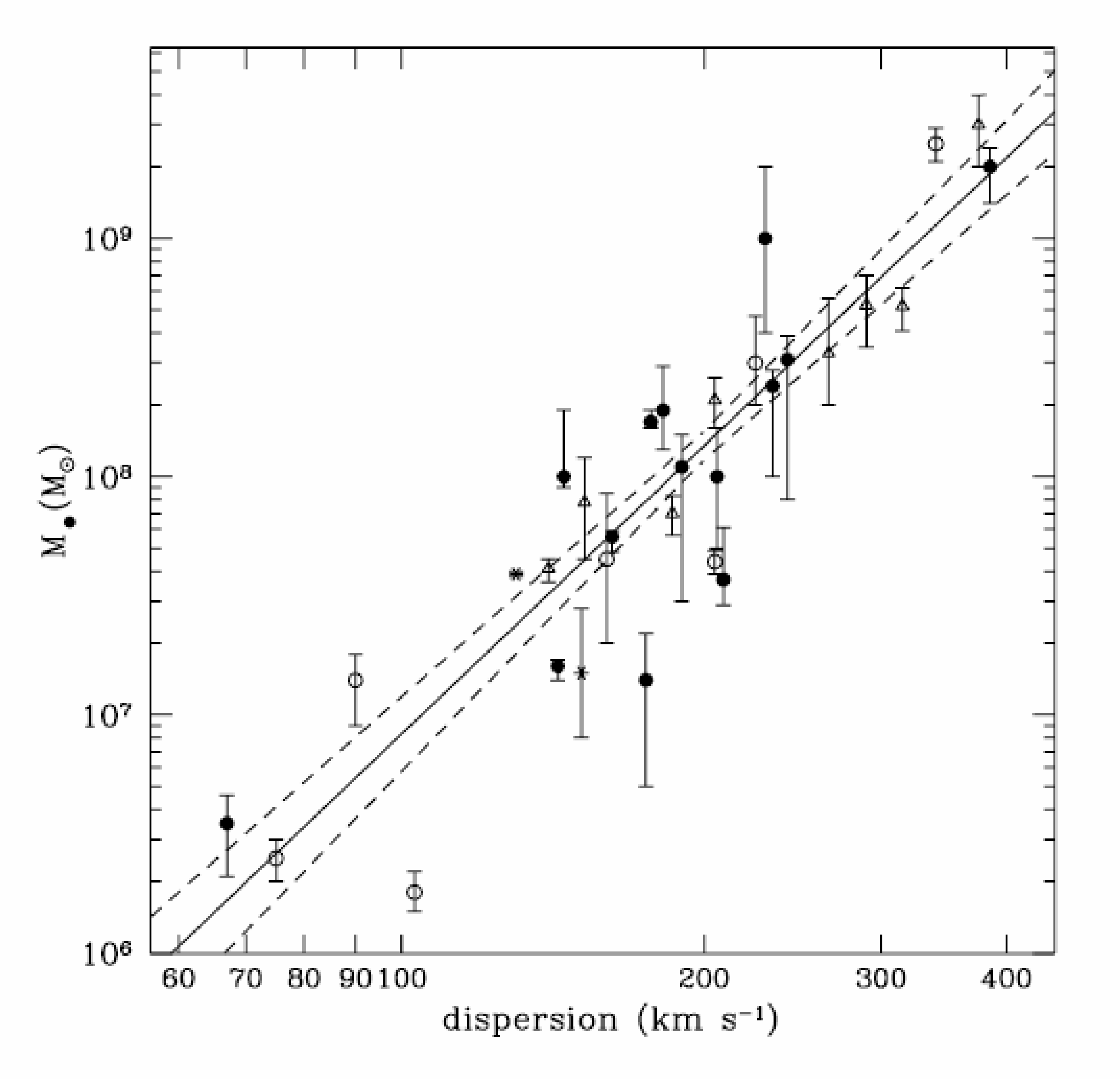


Borne et al., 2000

Spheroids host massive central black holes, which power *quasars* and other kinds of *active galactic nuclei (AGNs)*



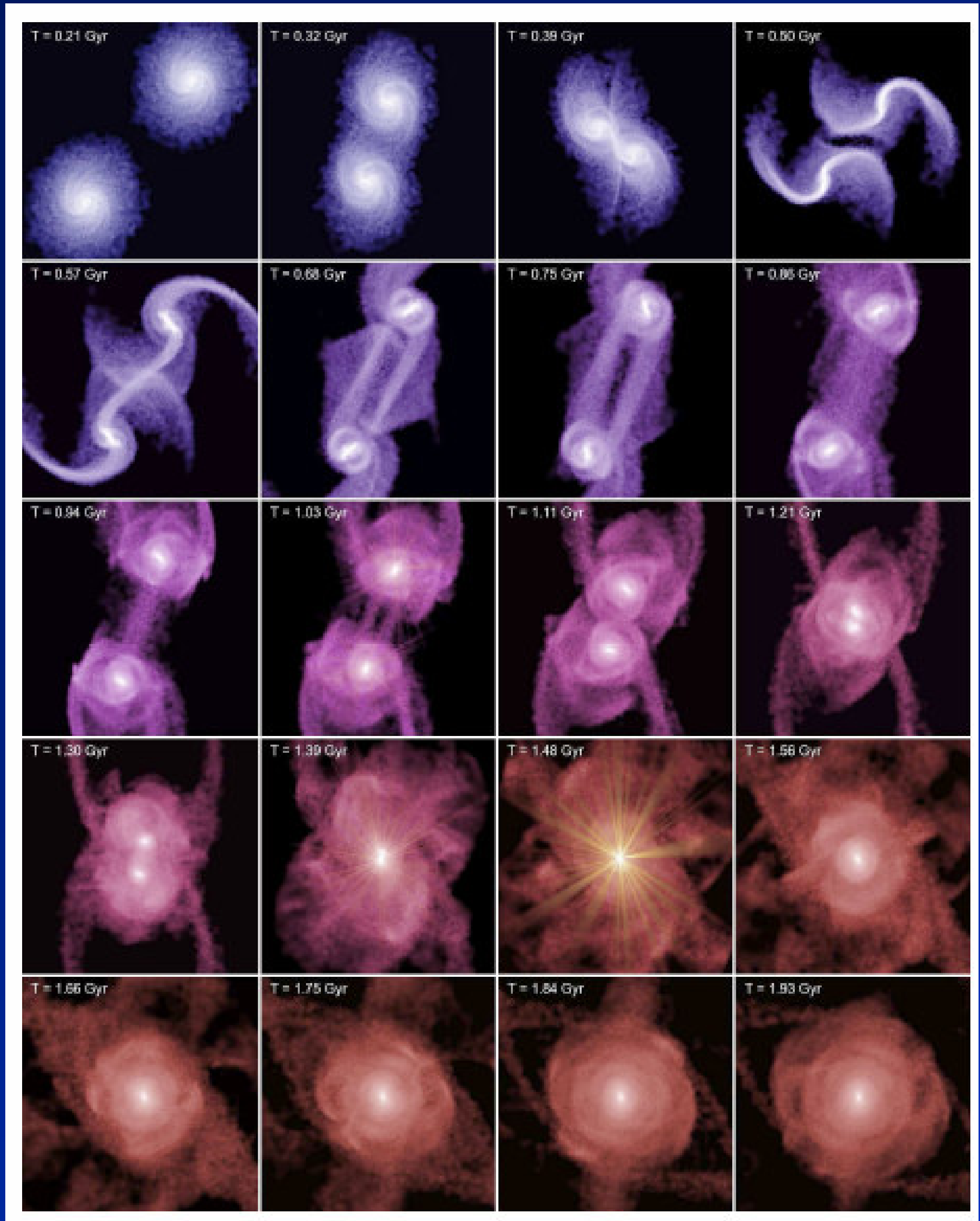
The black hole - σ^4 relation



Virtually all spheroidal galaxies that have been looked at closely with the Hubbel Space Telescope have ***a massive black hole at their centers.***

The mass of the BH scales with the stellar velocity dispersion (σ^4) or with the stellar mass (not clear which).

Tremaine et al. (2002)



Hopkins, Hernquist et al. 2005:

Gas-rich mergers have multiple consequences:

* Stellar disks are scrambled to make spheroids

* Orbital energy shocks gas, drives hot wind

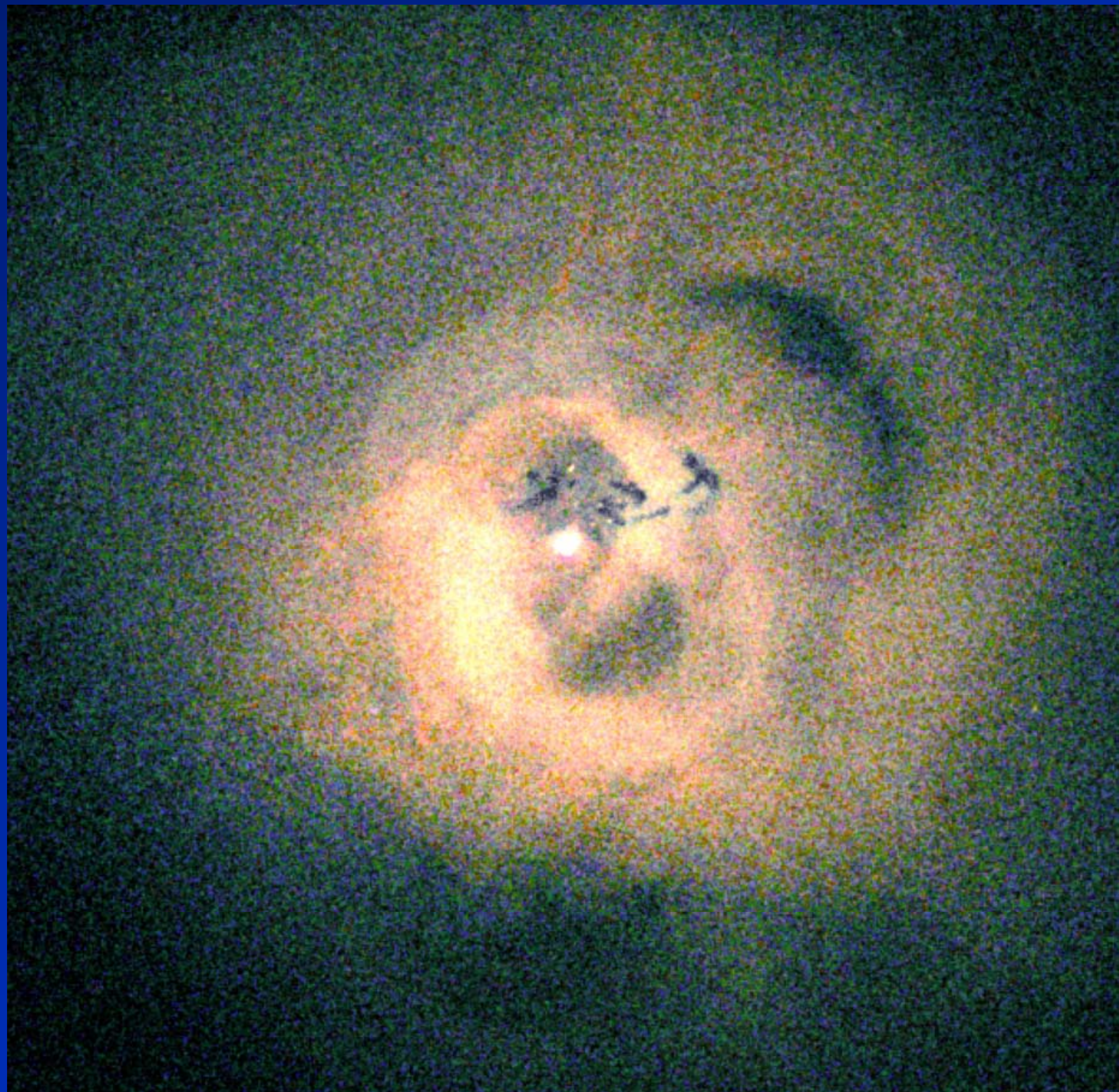
* Fluctuating grav potential drives gas to center, fuels starburst, further driving wind

* Gas accretes onto central BH, fuels AGN, more feedback

* Models match the BH-mass relation with reasonable parameters

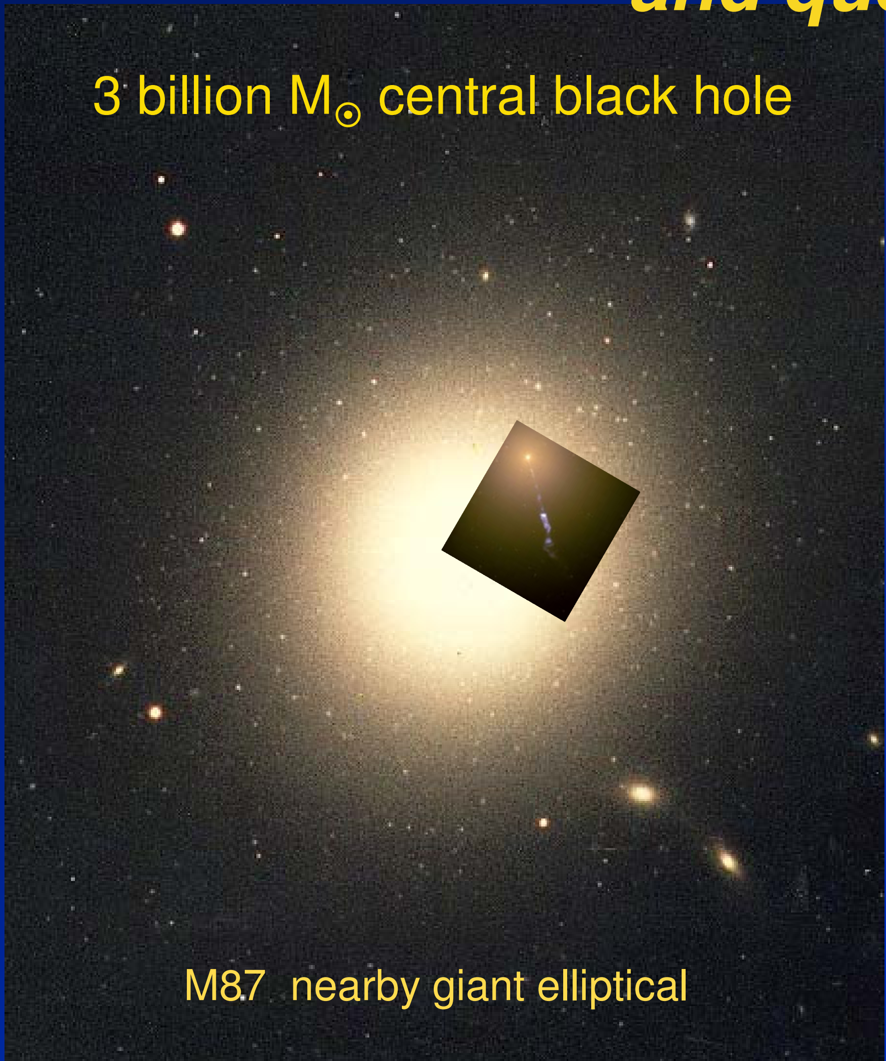
Chandra X-ray map of Perseus Cluster

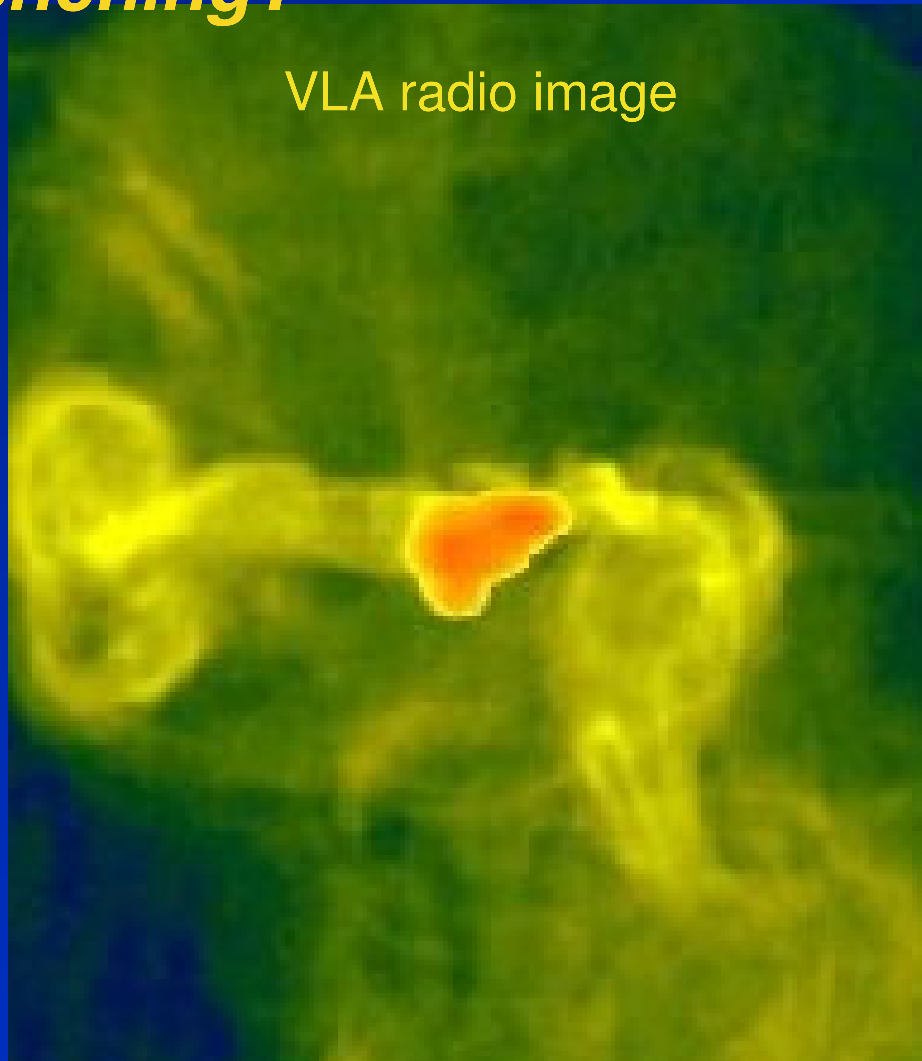
High resolution X-ray imaging shows that the central cluster gas is in fact highly disturbed.



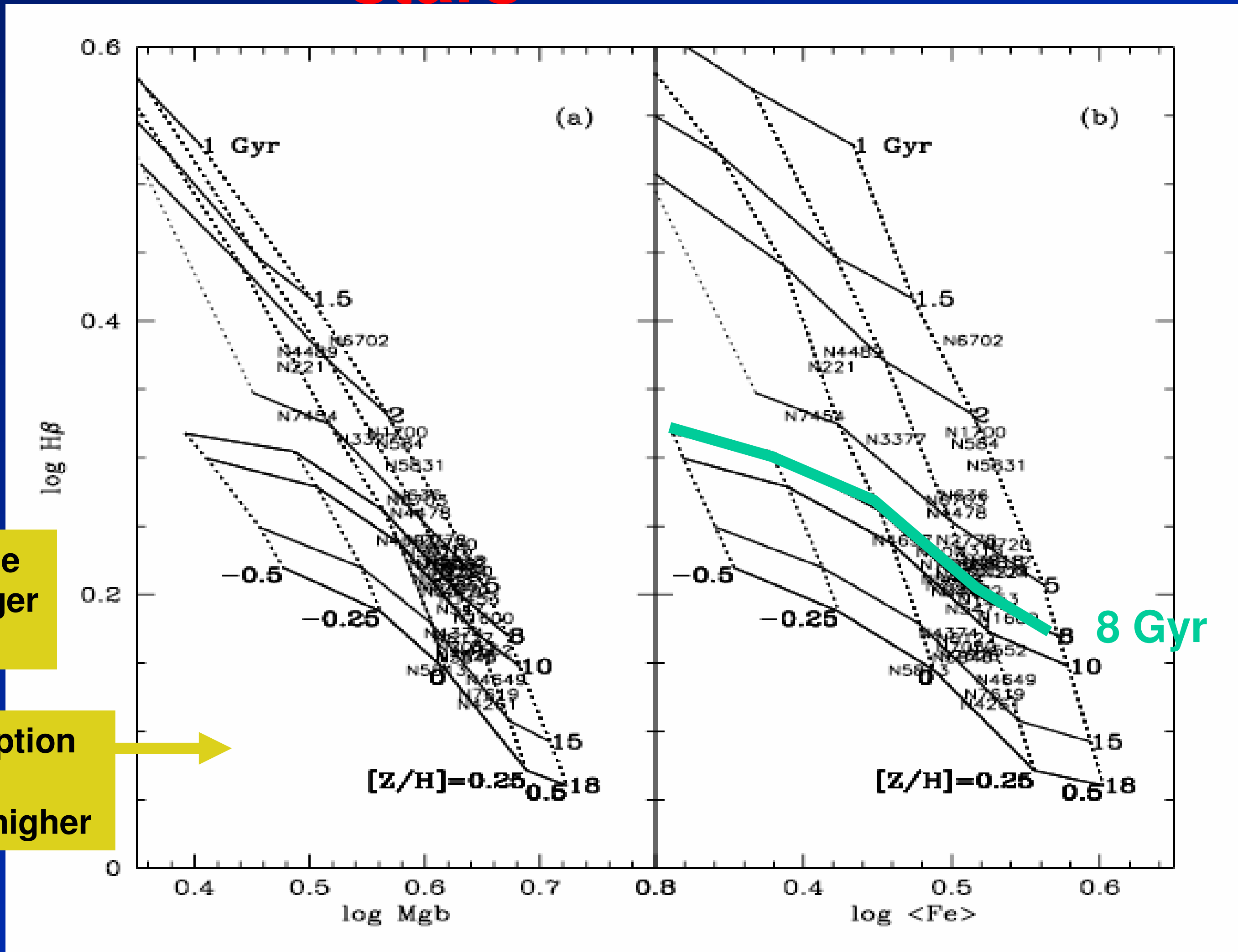
Fabian et al. 2003

AGNs clearly have an "effect" on surrounding gas, but is this really ***feedback and quenching?***





1993-2001: Balmer lines show *young stars;* mean age much less than age of Galactic halo stars

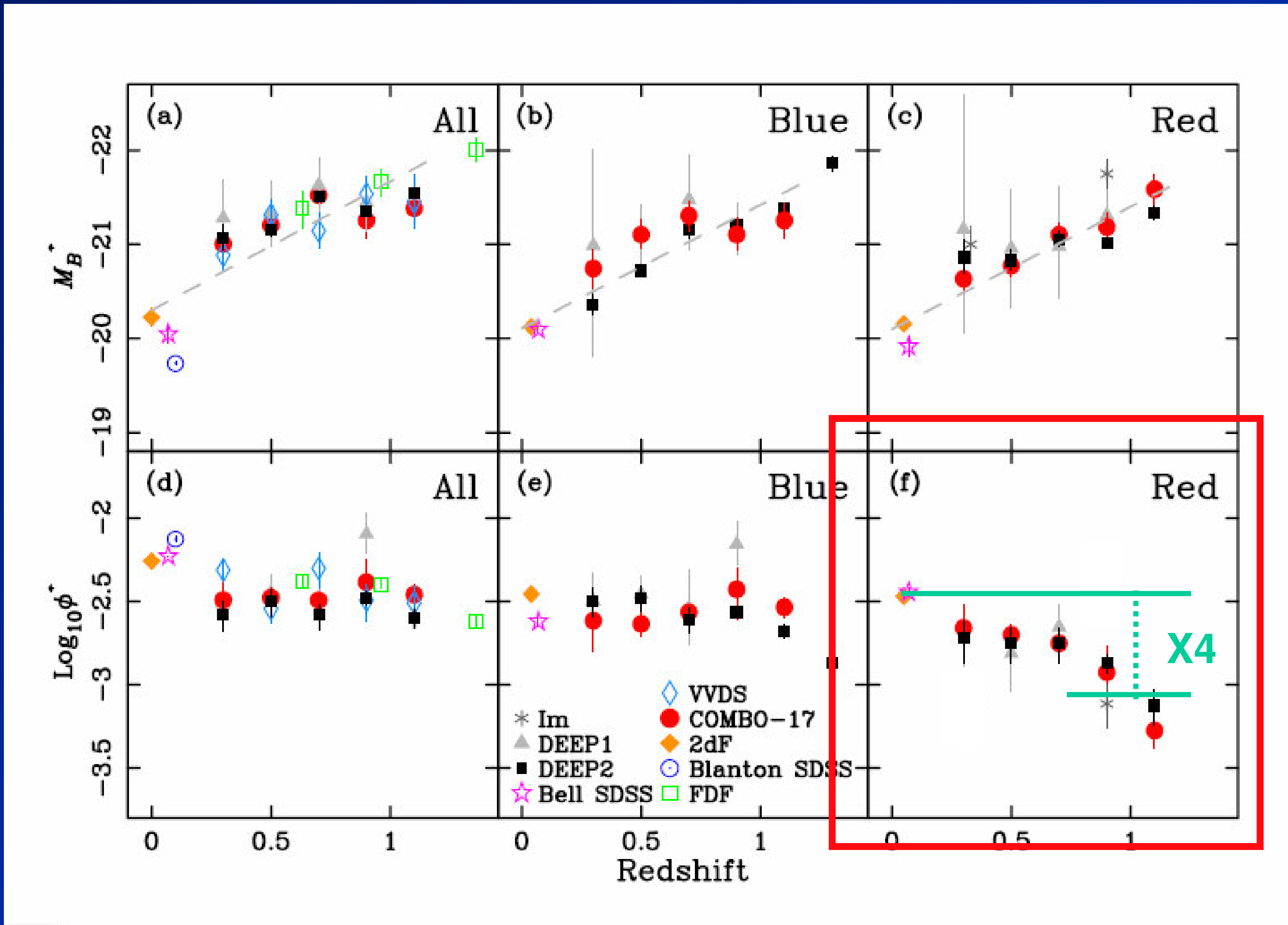


Hβ absorption line strength -- stronger means younger stars

Mg and Fe absorption line strength -- stronger means higher Z

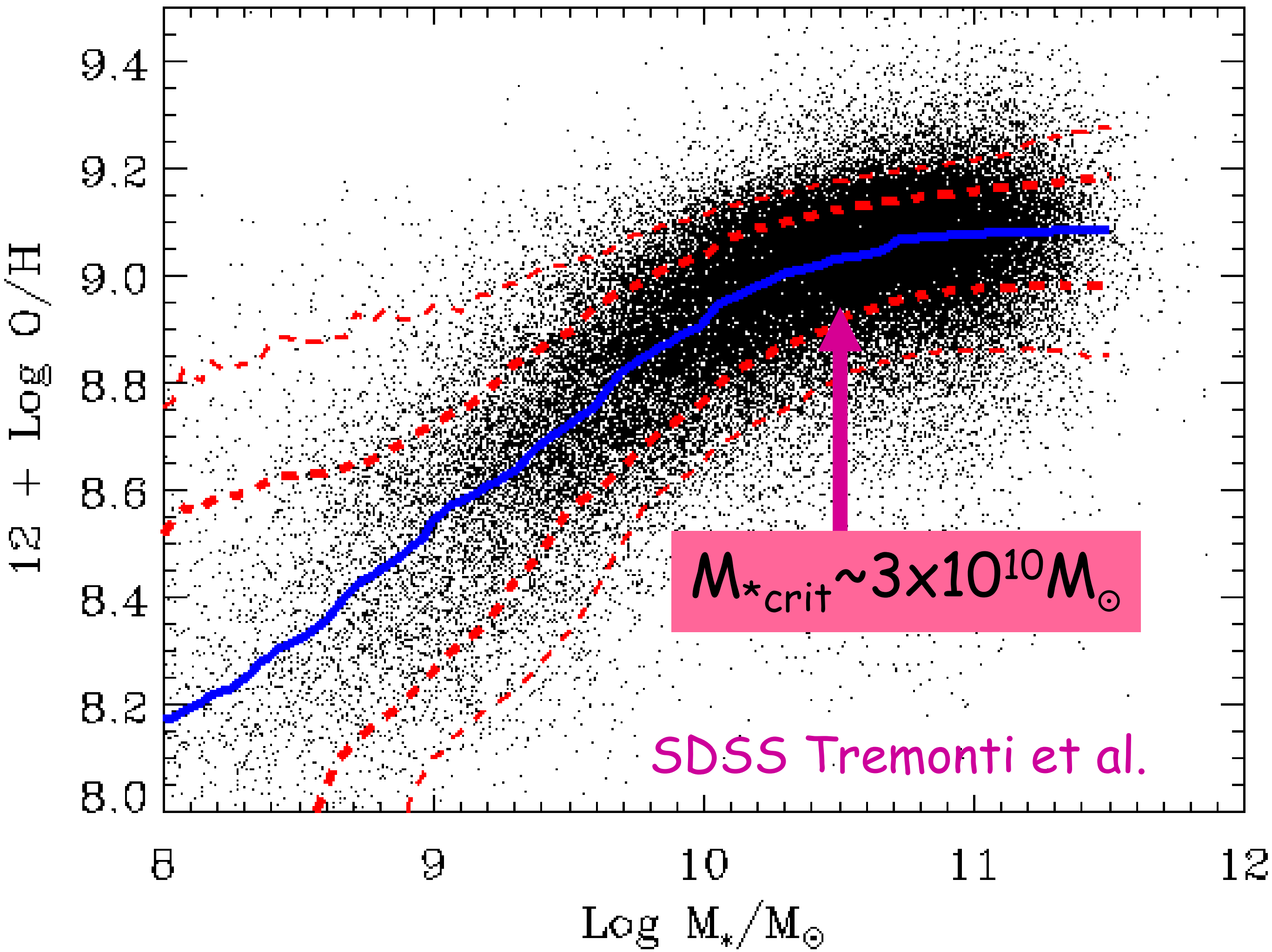
Trager et al. 2001: Ages adjusted for non-solar abundance ratios

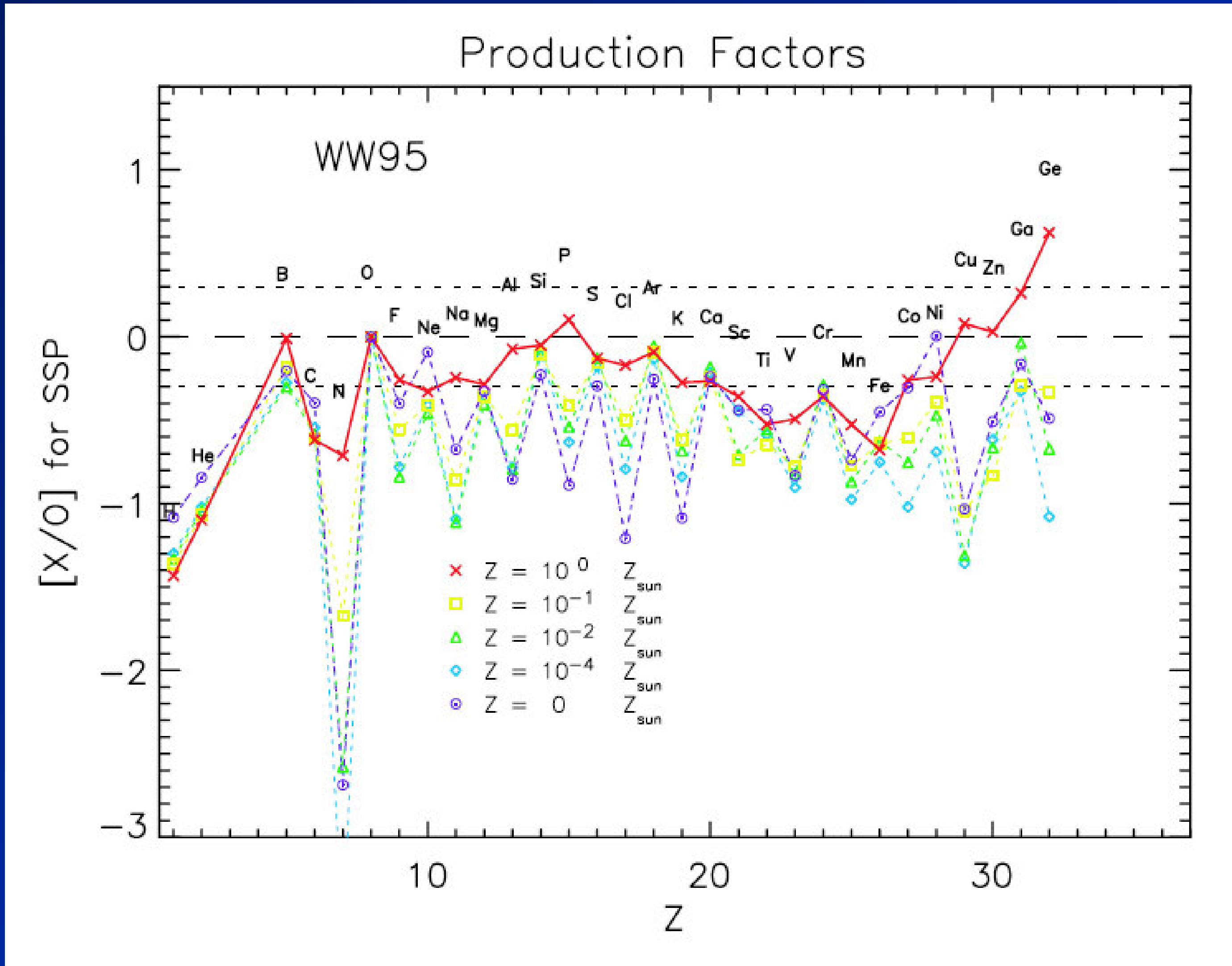
DEEP2 and COMBO-17: Most red galaxies became red after z = 1

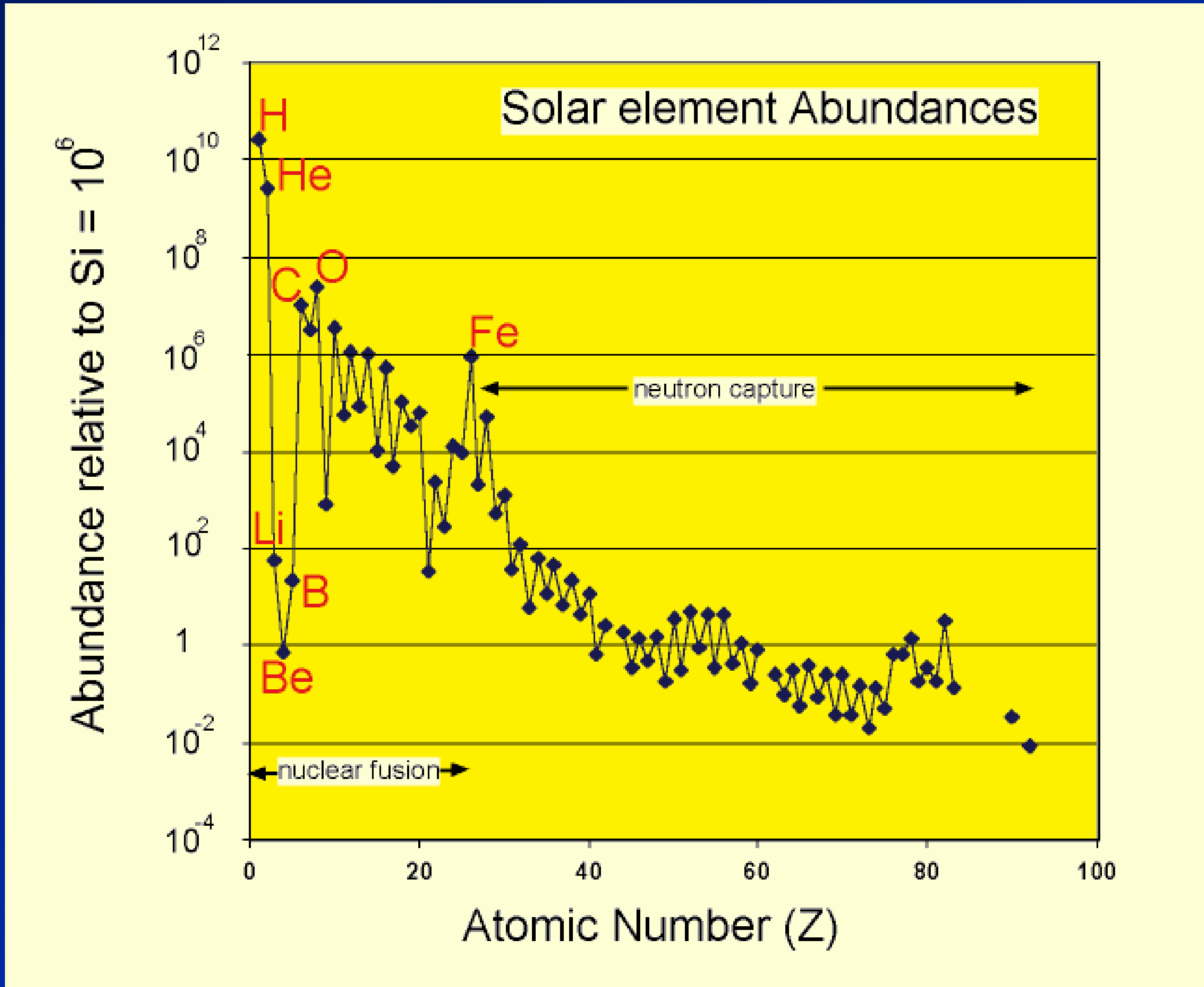


Willmer et al. 2005, Faber et al. 2005

Transition in Metallicity




Production Factors
WW95
[X/O] for SSP
Z
H
He
B
C
N
O
F
Ne
Na
Mg
Al
Si
P
S
Cl
Ar
K
Ca
Sc
Ti
V
Cr
Mn
Fe
Co
Ni
Cu
Zn
Ga
Ge
Z = 10^0 Z_sun
Z = 10^-1 Z_sun
Z = 10^-2 Z_sun
Z = 10^-4 Z_sun
Z = 0 Z_sun


Solar element Abundances
Abundance relative to Si = 10^6
10^{12}
10^{10}
10^8
10^6
10^4
10^2
1
10^{-2}
10^{-4}
0
20
40
60
80
100
Atomic Number (Z)
H
He
C
O
Li
B
Be
Fe
neutron capture
nuclear fusion