Phenomenological Properties of Galaxies

(Plus a digression on practical stuff I wish somebody had told me back in grad school)

Particularly useful papers

arXiv:0810.1681

STRUCTURE AND FORMATION OF ELLIPTICAL AND SPHEROIDAL GALAXIES[1,2,3]

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ABSTRACT

New surface photometry of all known elliptical galaxies in the Virgo cluster is combined with published data to derive composite profiles of brightness, ellipticity, position angle, isophote shape, and color over large radius ranges. These provide enough leverage to show that Sérsic $\log I \propto r^{1/n}$ functions fit the brightness profiles $I(r)$ of nearly all ellipticals remarkably well over large dynamic ranges. Therefore we can confidently identify departures from these profiles that are diagnostic of galaxy formation. Two kinds of departures are seen at small radii. All 10 of our ellipticals with total absolute magnitudes $M_{VT} \leq -21.66$ have cuspy cores – "missing light" – at small radii. Cores are well known and naturally scoured by binary black holes formed in dissipationless ("dry") mergers. All 17 ellipticals with $-21.54 \leq M_{VT} \leq -15.53$ do not have cores. We find a new distinct component in these galaxies: All coreless ellipticals in our sample have extra light at the center above the inward extrapolation of the outer Sérsic profile. In large ellipticals, the excess light is spatially resolved and resembles the the central

arXiv:1104.3545

The ATLAS^{3D} project – VII. A new look at the morphology of nearby galaxies: the kinematic morphology-density relation

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The Current Status of Galaxy Formation

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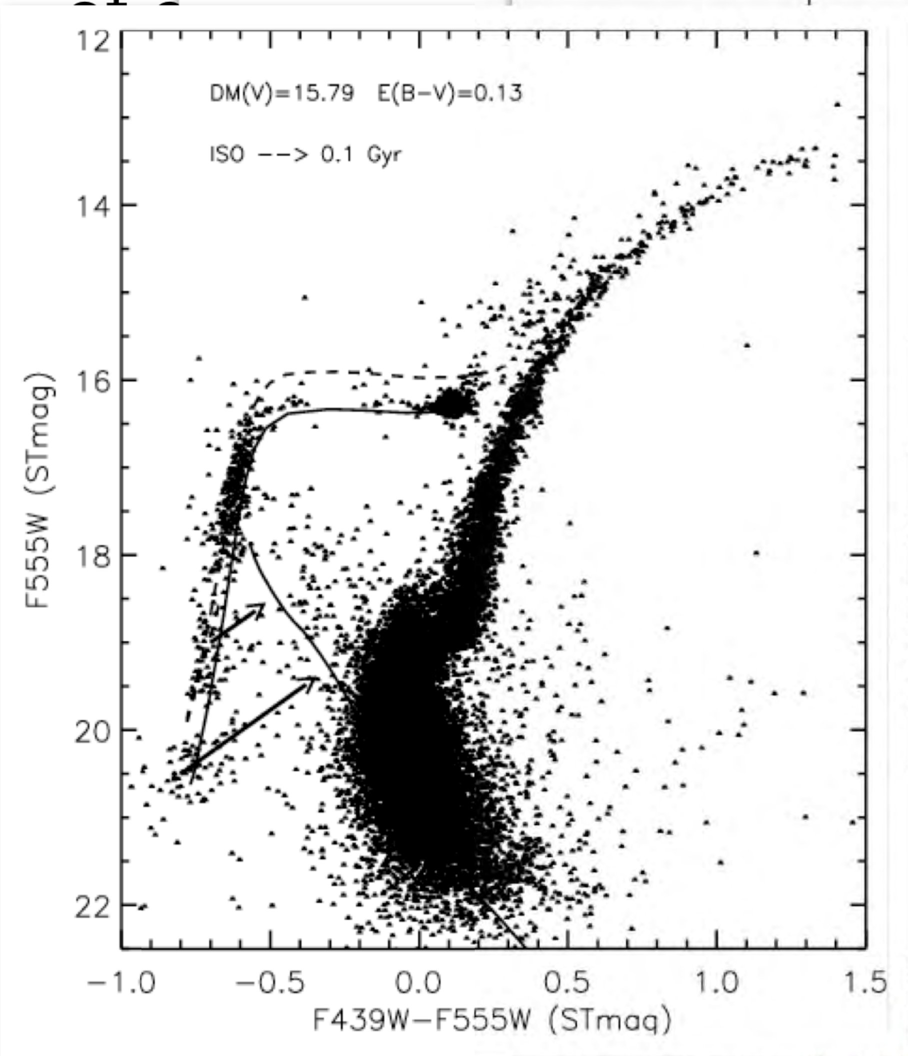
Abstract Understanding galaxy formation is one of the most pressing issues in cosmology. We review the current status of galaxy formation from both an observational and a theoretical perspective, and summarize the prospects for future advances.

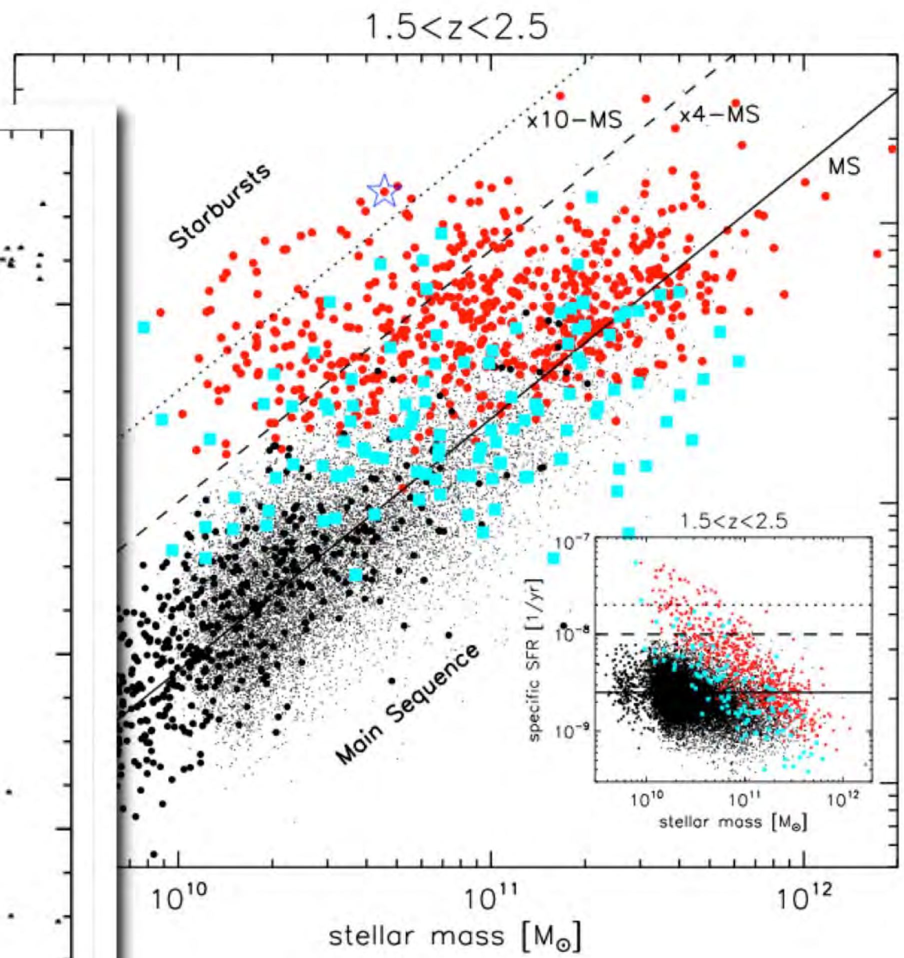
Key words: galaxy: formation — galaxies: evolution — galaxies: star formation — galaxies: active

Do we need to

wo

of a

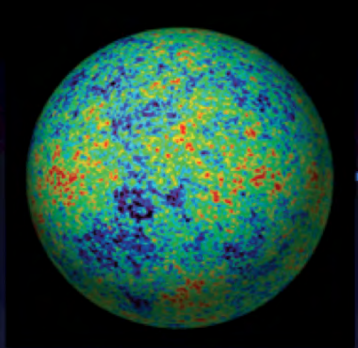


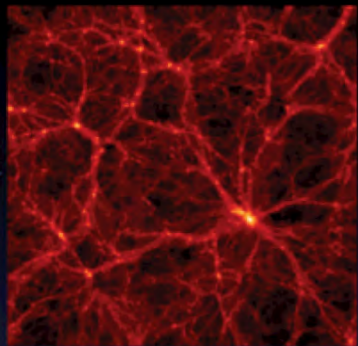


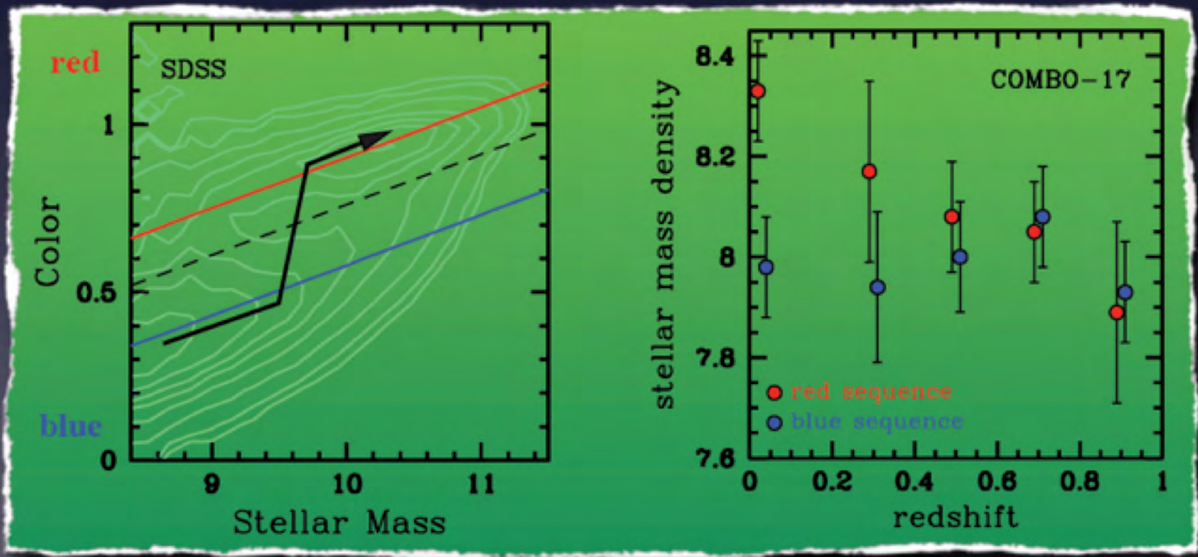
pecific SFR (SSFR) of galaxies of stellar mass $0.2 - 1 \times 10^{10}$ $M_\odot$ *op*); SFR for galaxies from different samples (different color sym- Main Sequence" and a population of starbursts, with SSFR mass-dependence inset (Rodighiero et al., 2011, *bottom*).

The Standard Paradigm

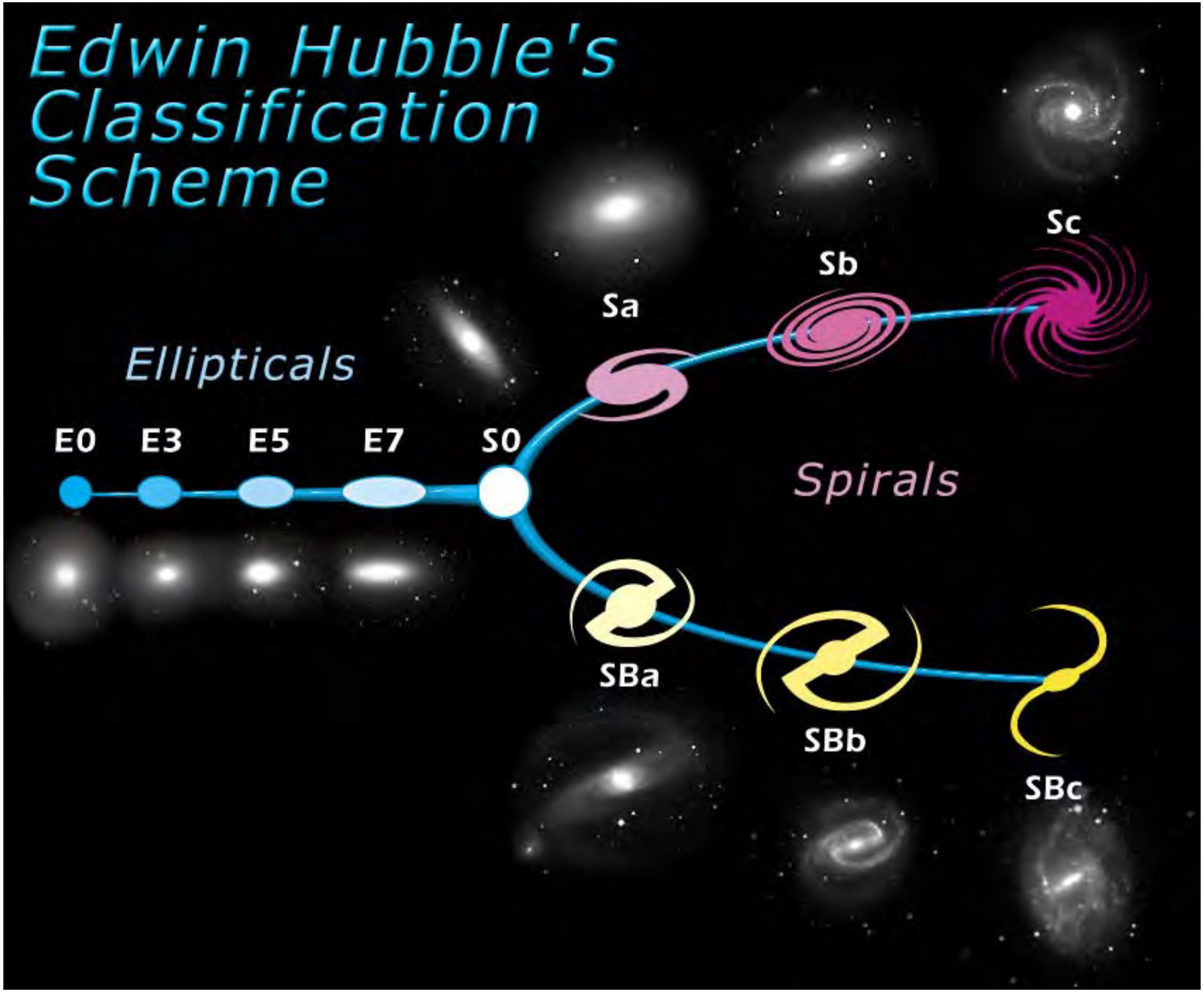
PARADIGM: All Galaxies Originally form as Central Disk Galaxies







Wolf et al. 2003; Bell et al. 2004; Borch et al. 2006


Edwin Hubble's Classification Scheme
Ellipticals
E0
E3
E5
E7
S0
Sa
Sb
Sc
Spirals
SBa
SBb
SBc

Bimodal galaxy populations

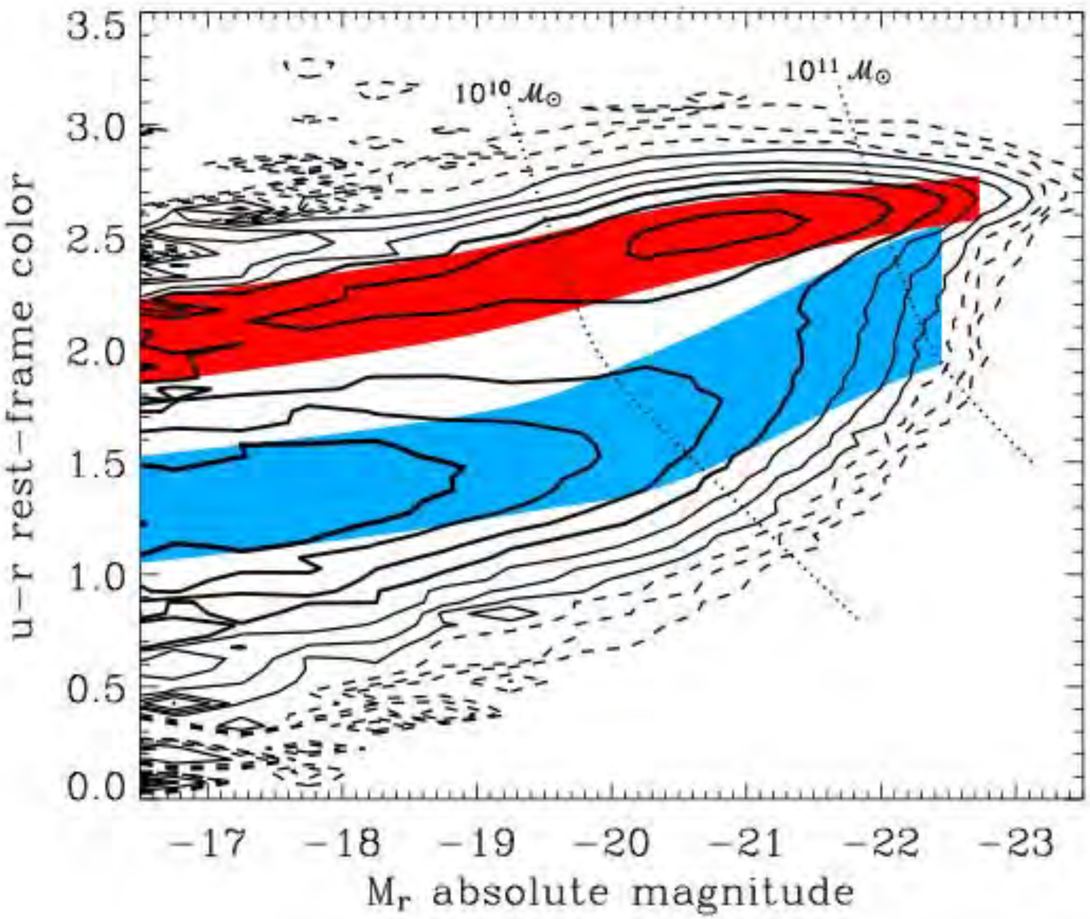
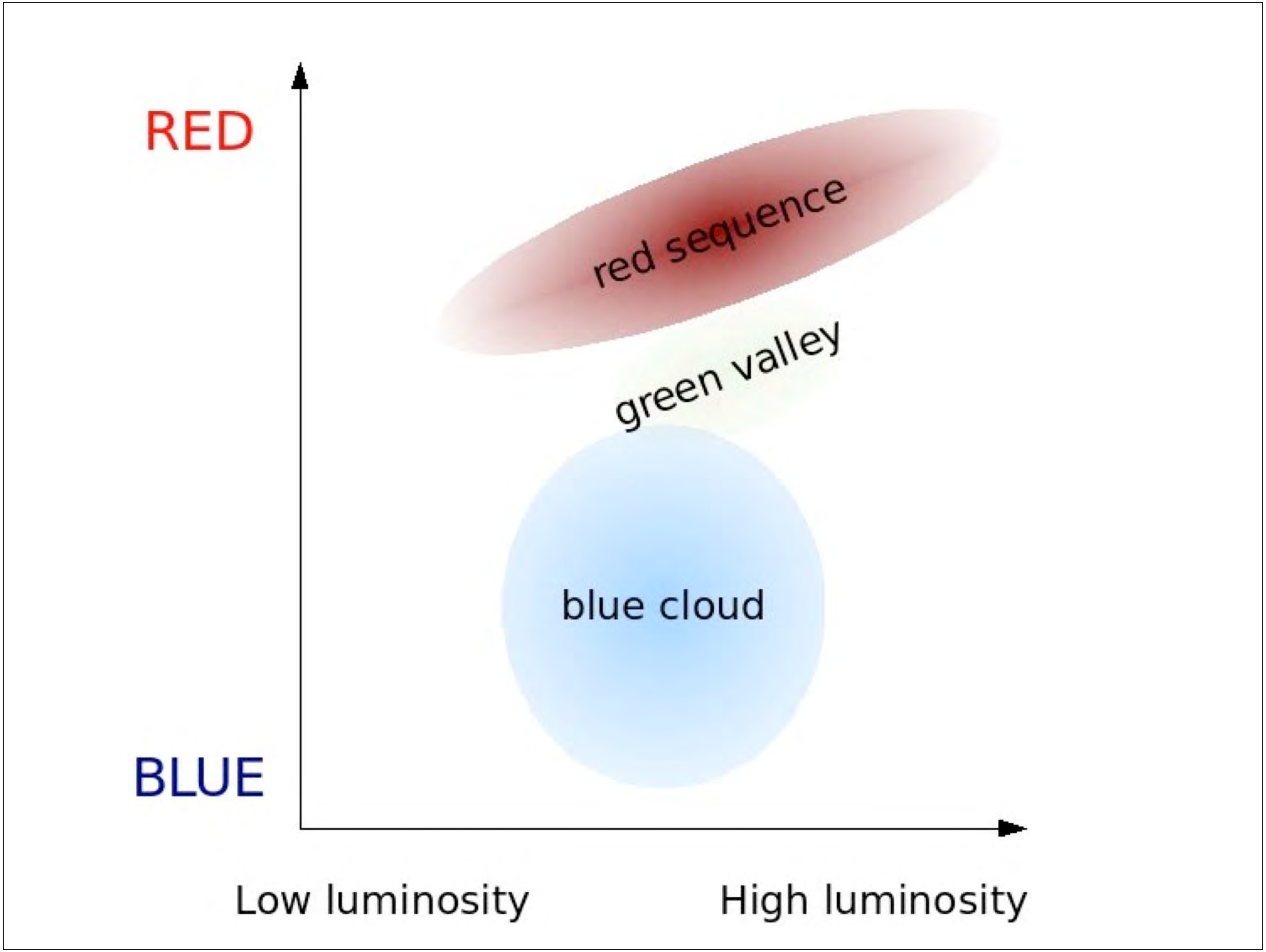


Fig. 3 Illustration of galaxy bimodality. The contours are the density of SDSS galaxies in color-luminosity space, after correction for selection effects (Baldry et al., 2004).

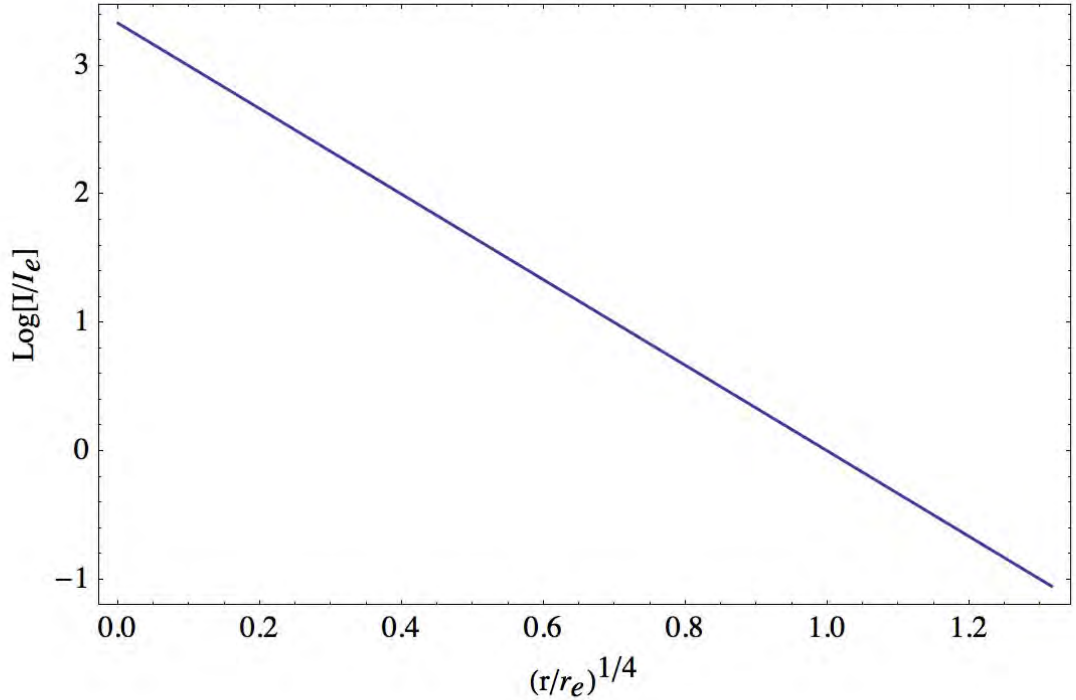

RED
red sequence
green valley
blue cloud
BLUE
Low luminosity
High luminosity

Can we understand the Red Sequence?

Elliptical/S0 galaxies

Old cartoon view: Symmetric, structureless, thermally supported, slowly evolving boring old red galaxies. How much has changed?

Luminosity Profile



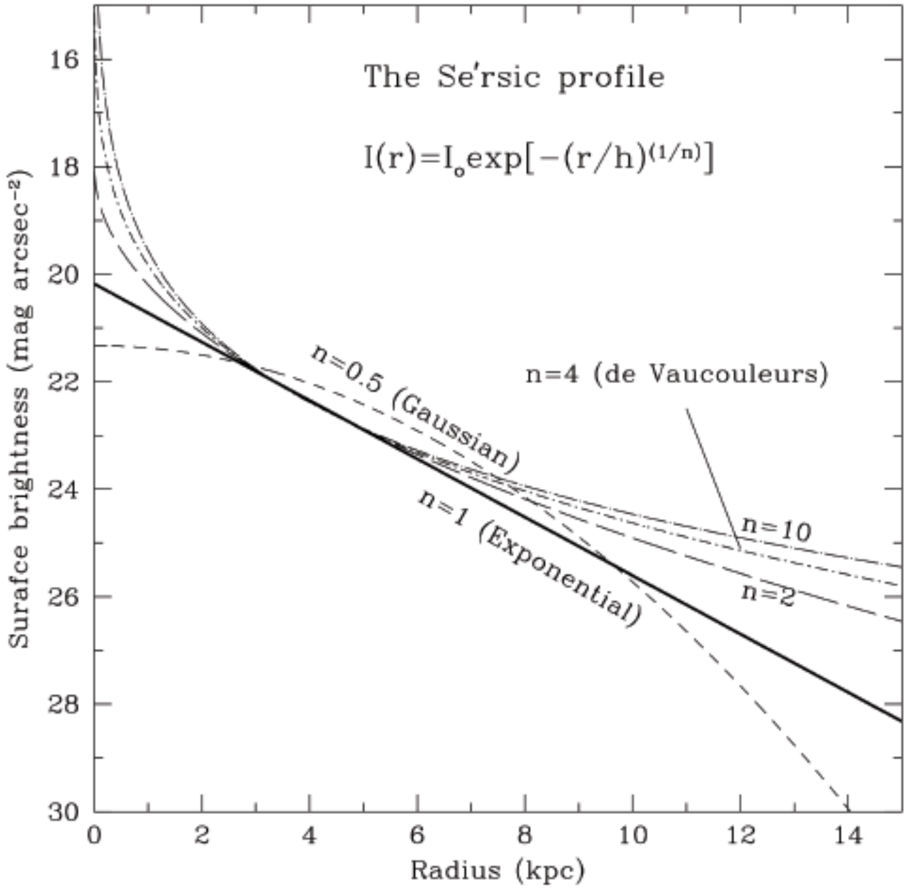
Surface brightness
at the effective radius

$$I(r) = I_e\, e^{-7.67\left[\left(\frac{r}{r_e}\right)^{\frac{1}{4}}-1\right]}$$

"Effective radius"
(contains half the light)

Sersic Profiles


Jose Luis Sersic



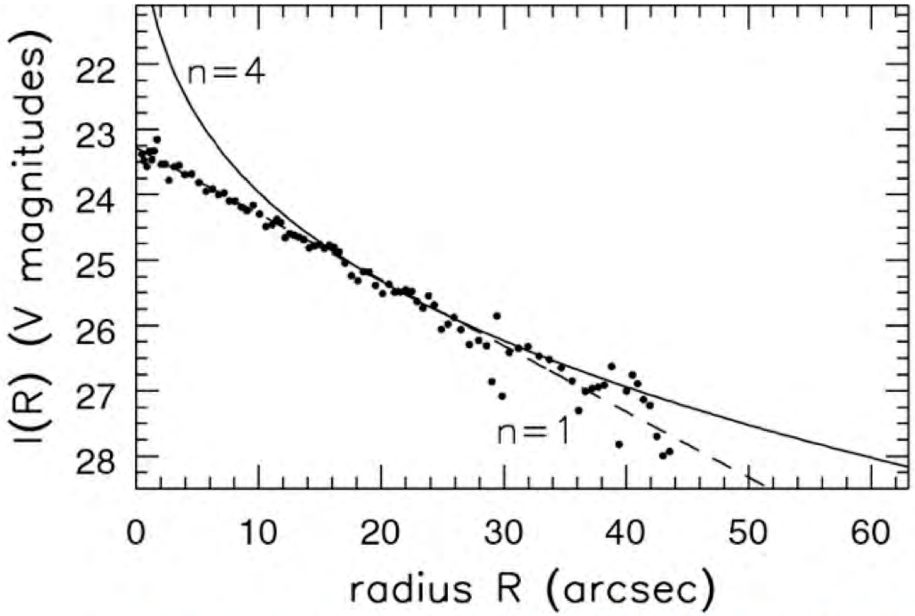


Fig 6.2 (H.Jerjen) 'Galaxies in the Universe' Sparke/Gallagher CUP 2007

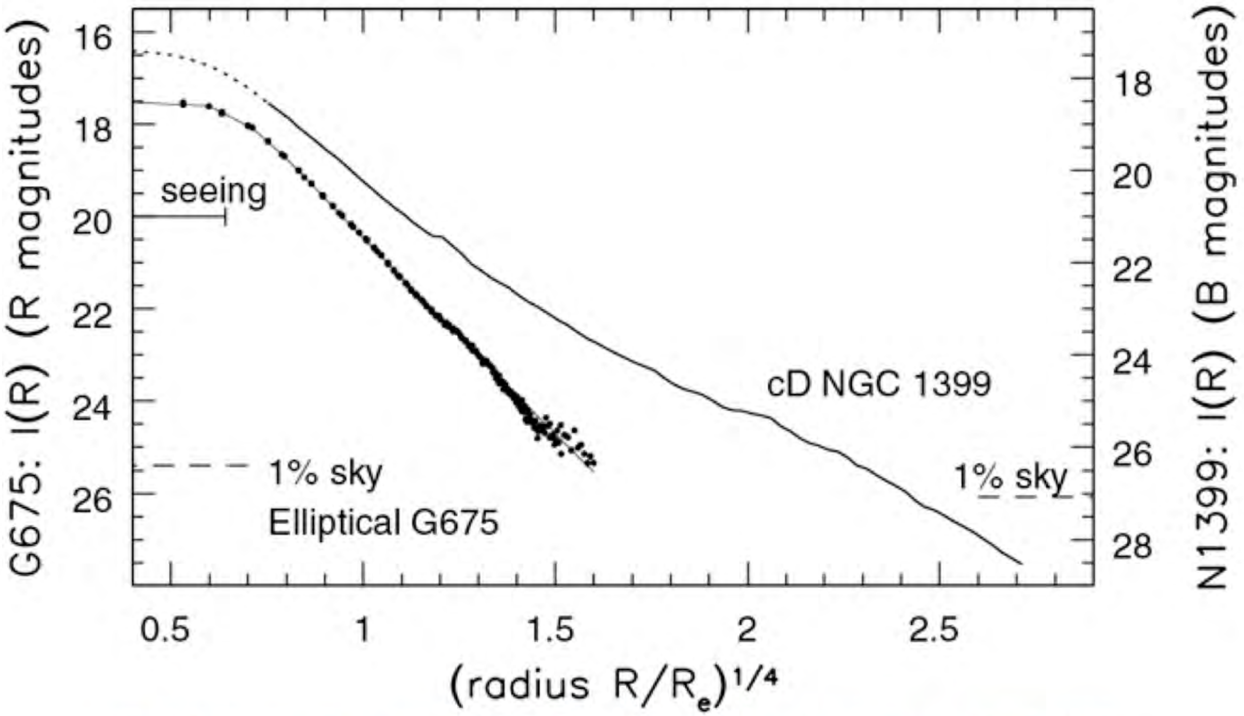


Fig 6.3 (Saglia, Caon) 'Galaxies in the Universe' Sparke/Gallagher CUP 2007

Fig 6.4 (CFHT J.-C. Cuillandre/Coelum) 'Galaxies in the Universe' Sparke/Gallagher CUP 2007

M87

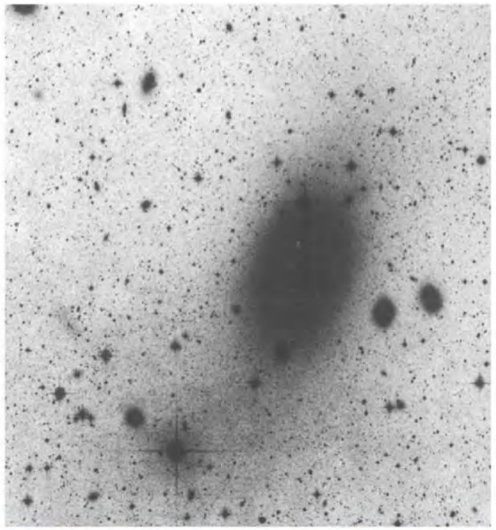


Fig 6.4 (D. Malin) 'Galaxies in the Universe' Sparke/Gallagher CUP 2007

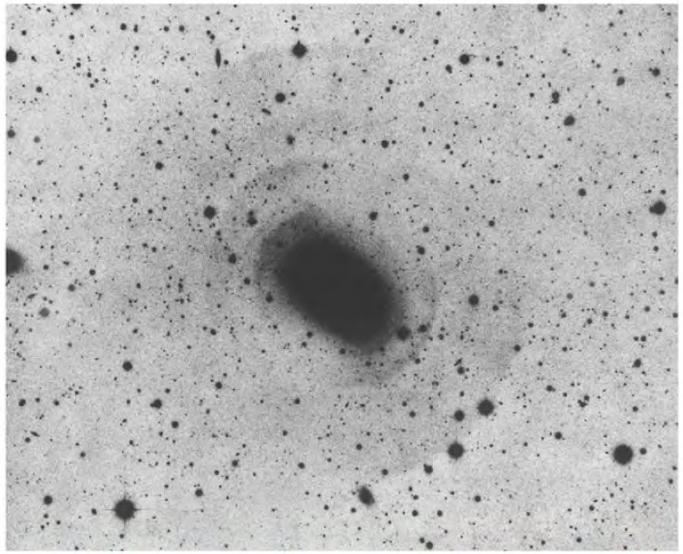
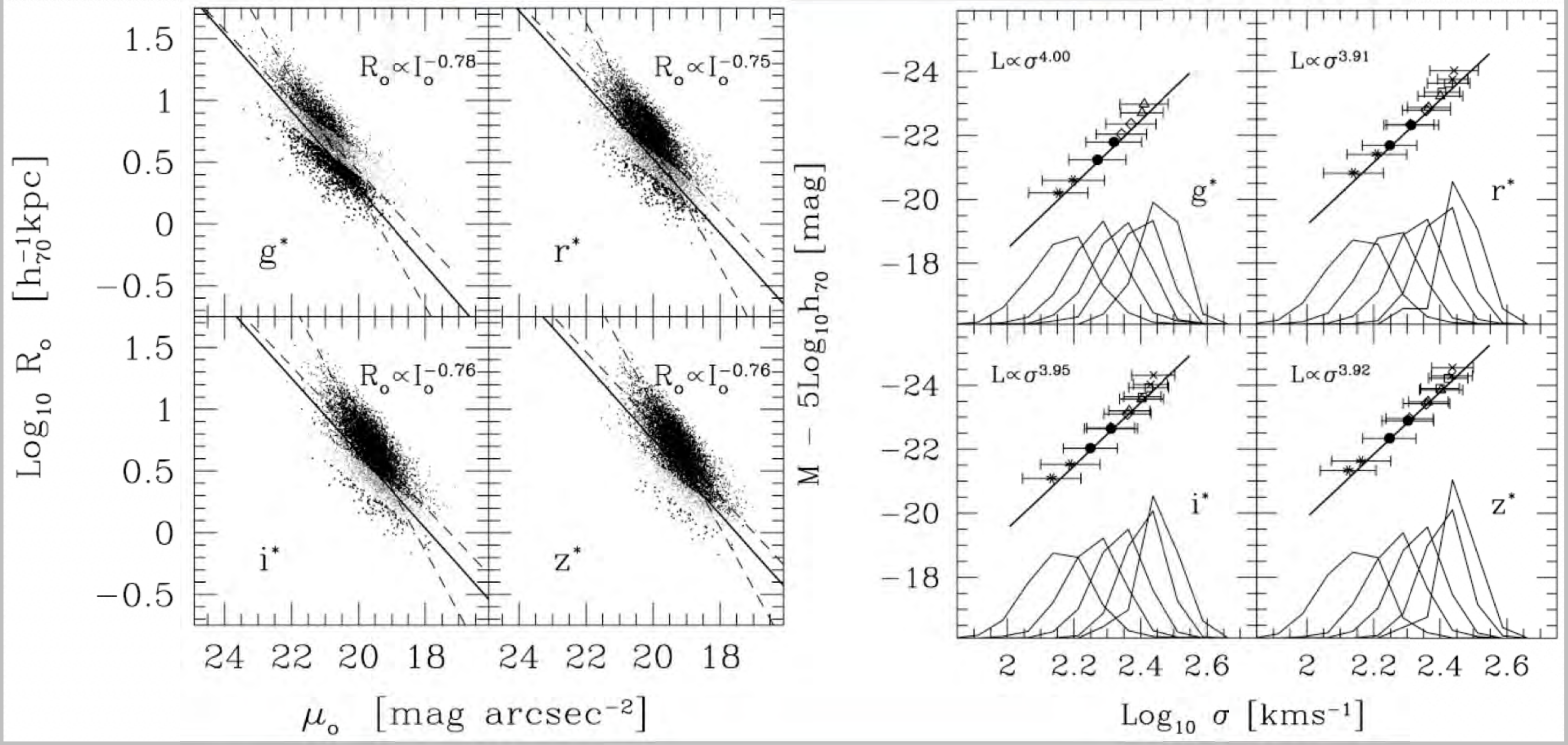


Fig 6.5 (D. Malin) 'Galaxies in the Universe' Sparke/Gallagher CUP 2007

FUNDAMENTAL PLANE

$$R_e \propto \sigma^a I_e^b$$

and its projections

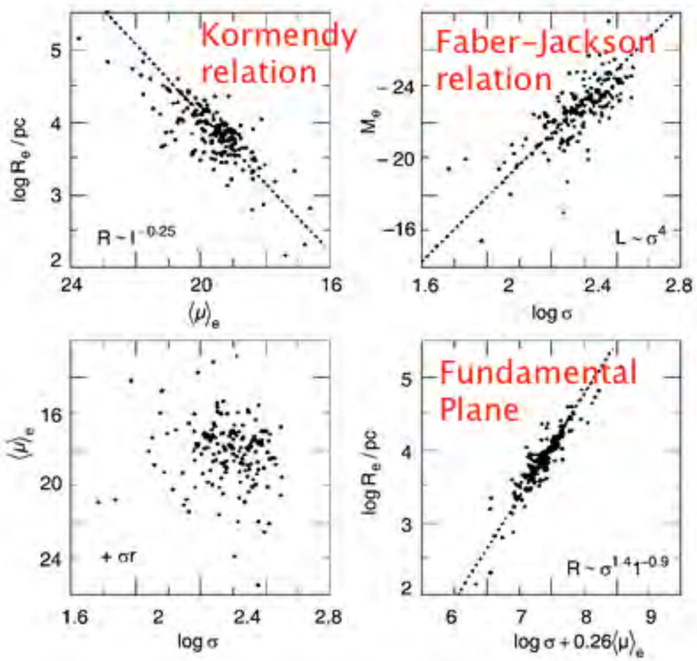


SDSS sample, Bernardi et al. 2003

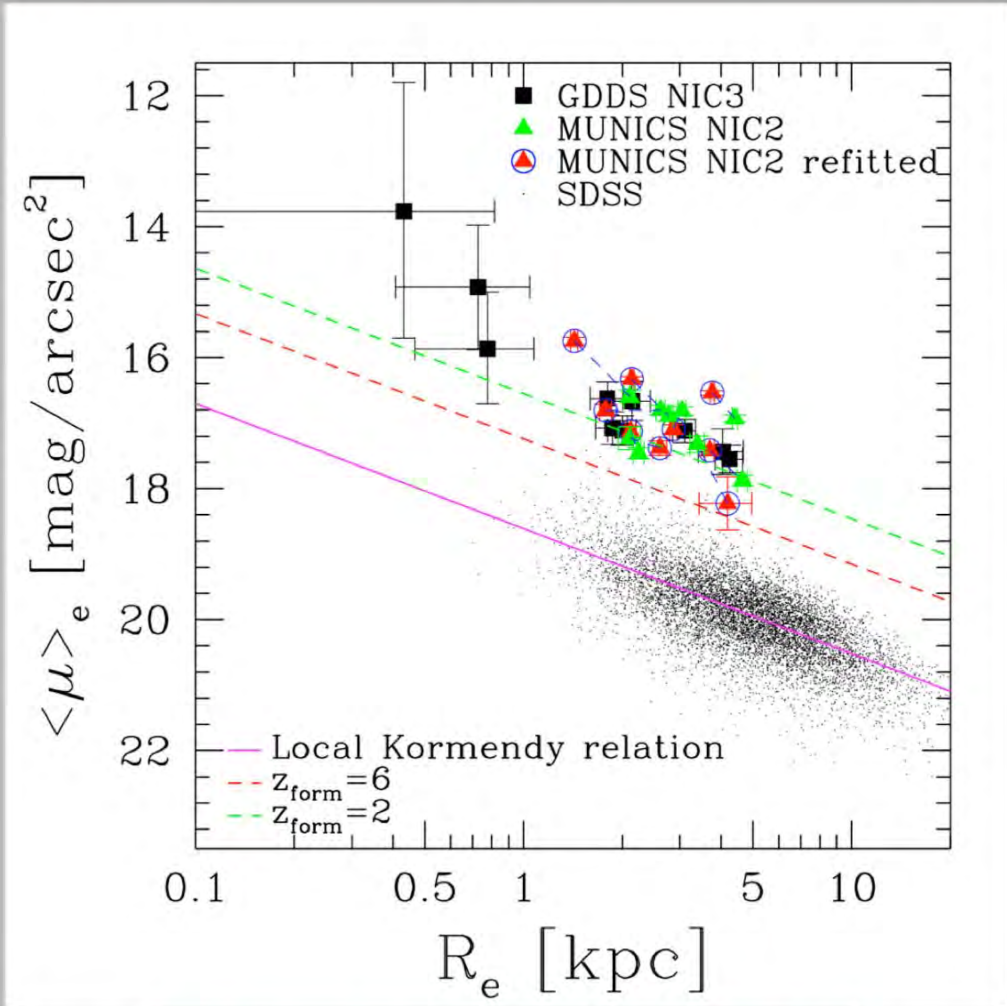
Projection I: Faber-Jackson

- The Faber-Jackson relation, linking luminosity and velocity dispersion σ. $L_B \propto \sigma^{\alpha}$, $3 < \alpha < 4$.
- Faber-Jackson is just a projection of a more fundamental relation, known as the fundamental plane. The fundamental plane relation is $L \propto I_0^{-0.7}\,\sigma^3$. The fundamental plane (σ, r_e, I_0) indicates remarkable homogeneity in the population

(How "fundamental" is the fundamental plane? At some level, it telling you mass-to-light ratio has a weak dependence on mass...
From the virial theorem $\sigma^2 \propto \frac{M}{R_0}$. If $\frac{M}{L} \propto M^a$ and we eliminate R_0 using $L \propto I_0 \cdot R_0^2$ we end up with $L^{1+a} \propto \sigma^{4-4\cdot a}\,I_0^{a-1}$ which is pretty close to the observed relation for $a \sim 0.25$). But deviations from this are telling us some pretty important stuff, though people argue about exactly what (age, homology, etc...)



Projection II: KORMENDY RELATION



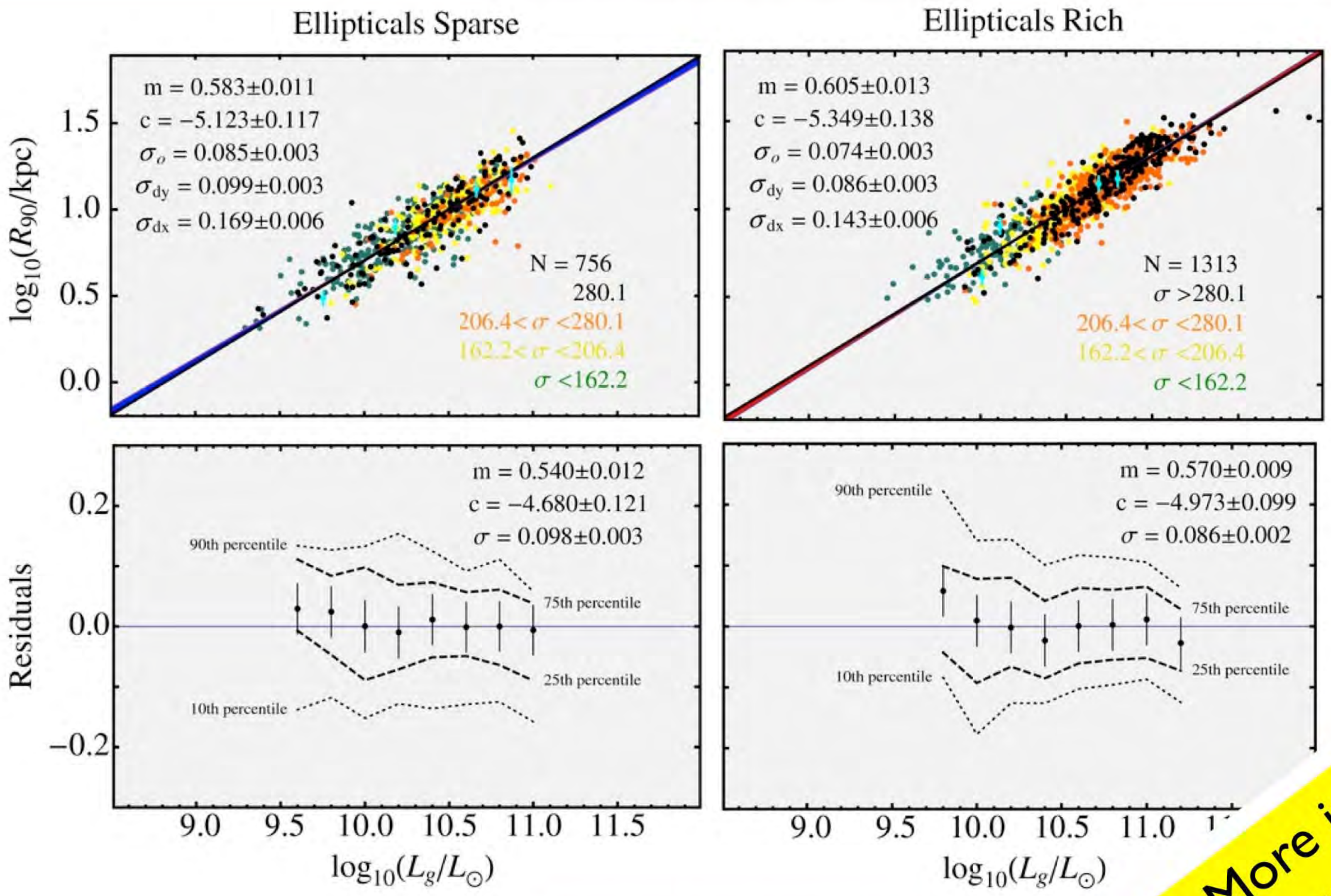
Damjanov et al. 2009

- **Mean rest frame Gunn-r SB within half-light radius as a function of half-light radius**
- **Resulting Kormendy relation at z ~1.5 differs from the one at z ~0, why?**

- **It is not pure luminosity evolution, it's SIZE EVOLUTION**

Much more in lecture 4

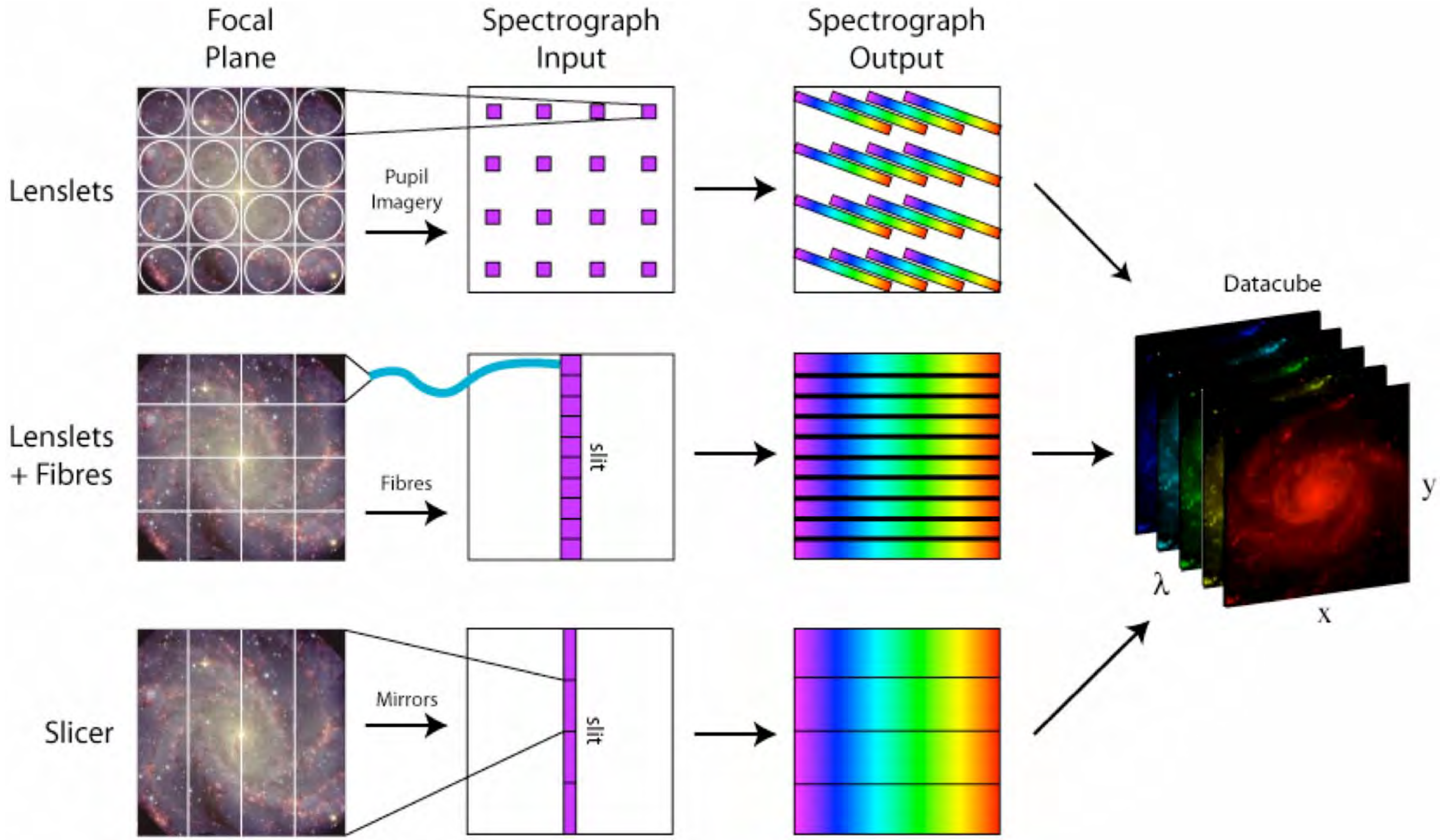
Why are they so organized? And why doesn't environment matter more?

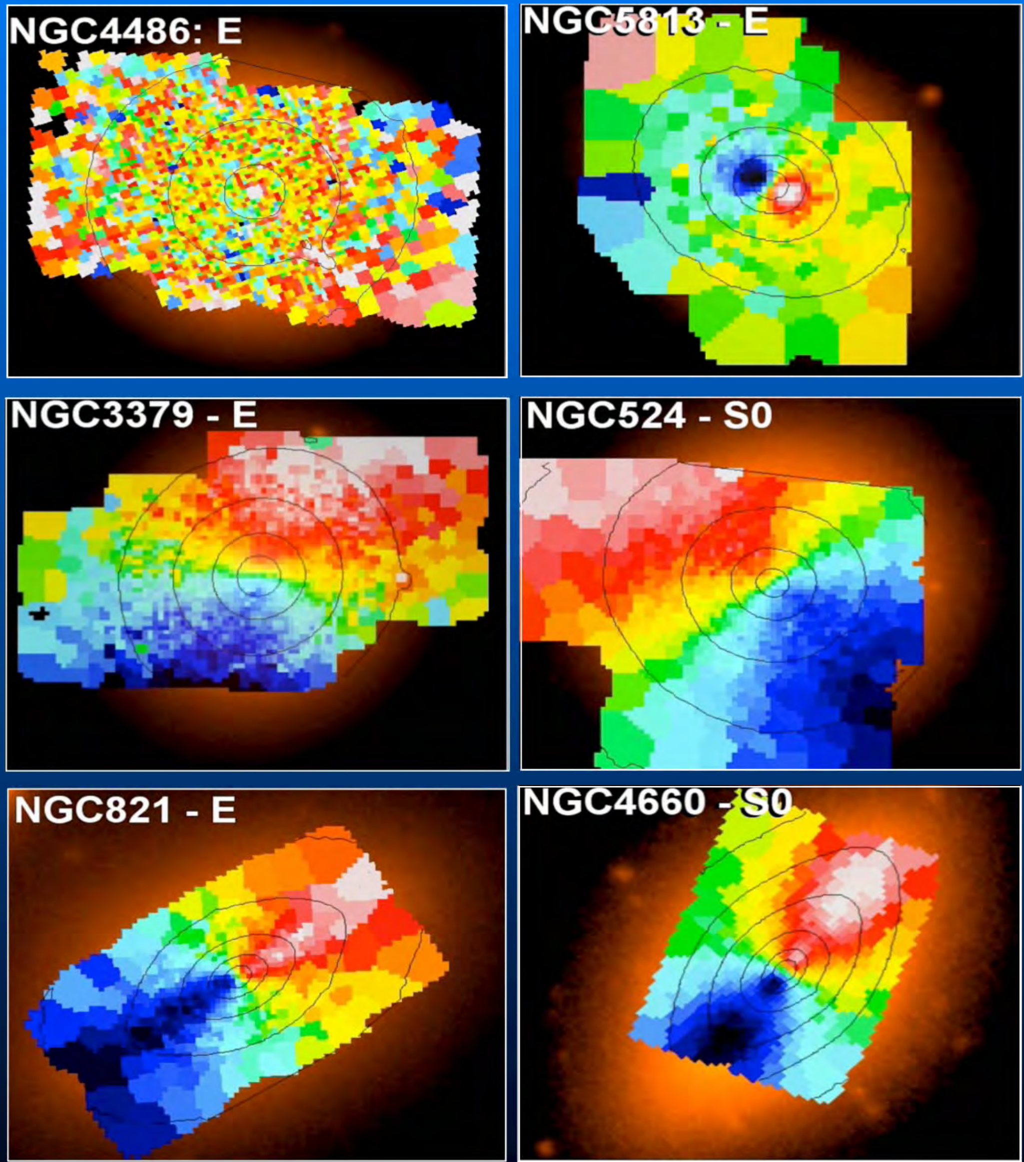


Nair et al. 2010

More in lecture 4

Integral Field Spectrometer Designs





Photometric Classification

- Es are spherical
  - –look similar from all directions
- S0s contain discs
  - –look like Es if face-on
- Some Es have S0 kinematics

New kinematic quantifier: λ_R

- Galaxies show either ordered rotation or no rotation (except for Kinematically Distinct Core KDC)
- Quantify with angular momentum per unit mass:

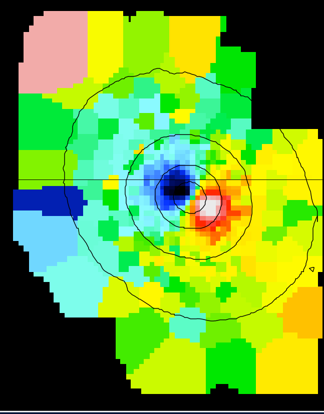
Weighted with Radius

$$\lambda_R \equiv \frac{\langle R\,|V|\rangle}{\langle R\sqrt{V^2+\sigma^2}\rangle}$$

Sky-averaged
→ Need IFU

Normalized by Mass

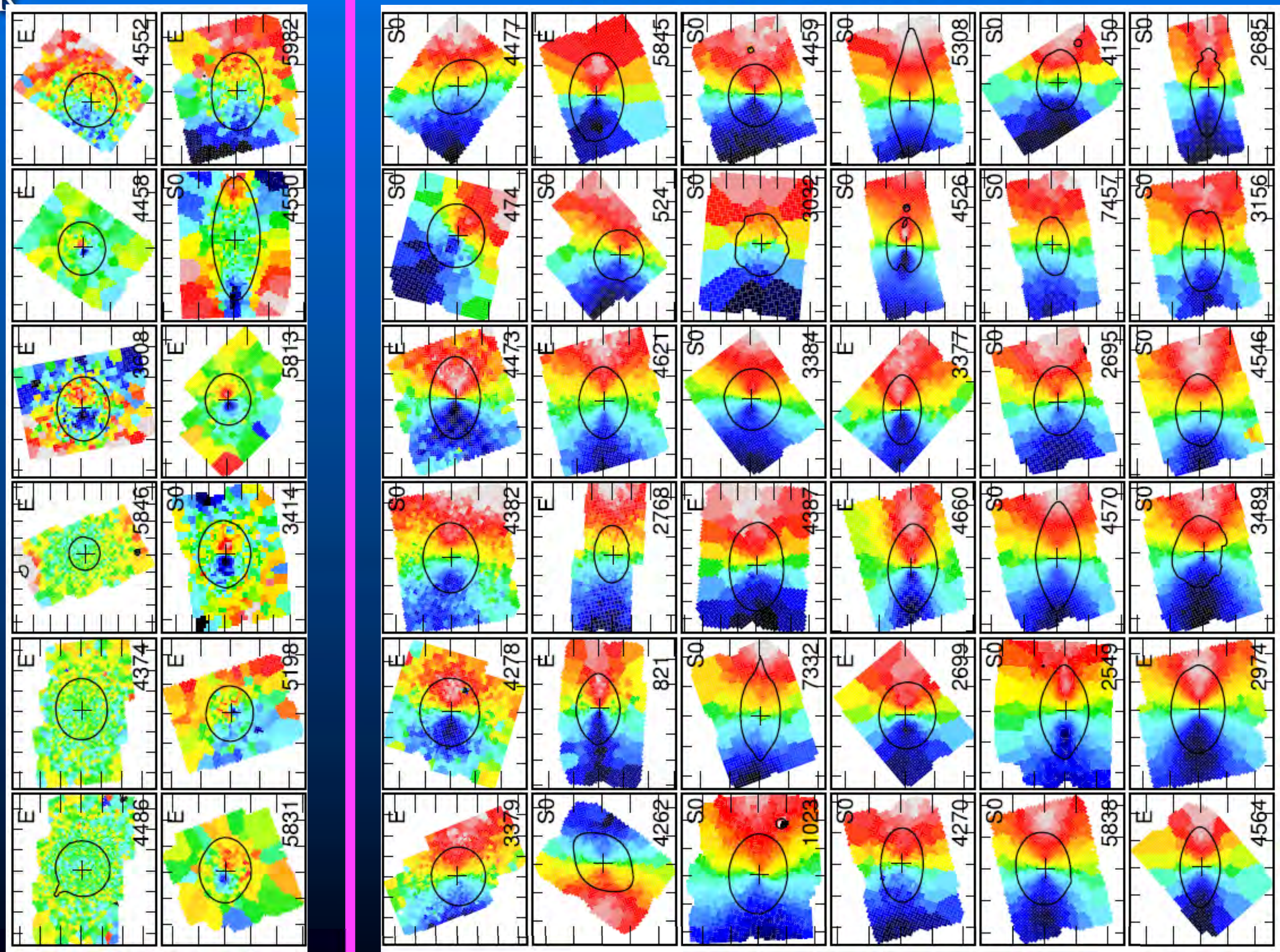
NGC5813



Emsellem et al. 2007

Galaxy classification with λ_R

λ_R → Increasing angular momentum

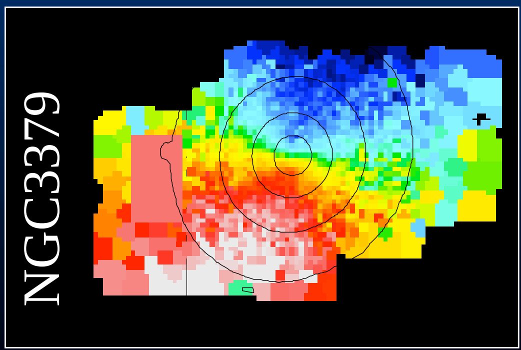


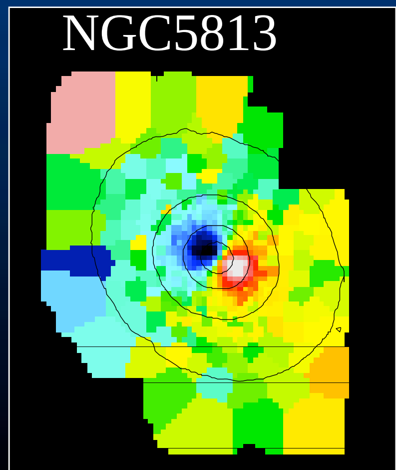
"Slow-rotator" λ_R=0.1 **"Fast-rotator"**

Emsellem et al. 2007

Fast and slow rotators

- Fast rotators: $\lambda_R > 0.1$
  - disc-like rotation
  - kinematically aligned (except for bars)
  - consistent with oblate (axisymmetric) systems
- Slow rotators: $\lambda_R < 0.1$
  - no or little rotation
  - kinematically misaligned
  - often have a KDC
  - mildly triaxial





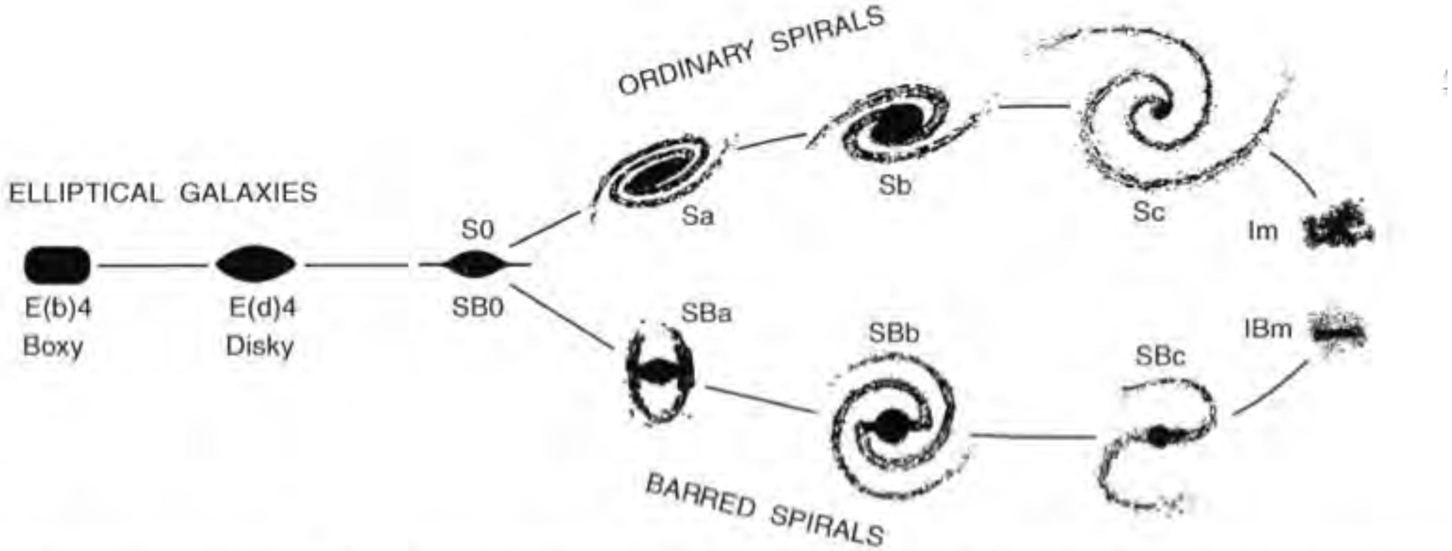


FIG. 2.— Revision of Hubble's (1936) morphological classification scheme proposed by Kormendy & Bender (1996). Here ellipticals are not classified by apparent flattening, which in large part encodes our viewing geometry. Rather, they are classified according to whether they show boxy or disky isophote distortions. This is also the dichotomy between ellipticals that do and do not have cuspy cores (Fig. 1); it is the one summarized in § 2.2. Boxy-core galaxies tend to rotate less and to be more dominated by velosity dispersion anisotropies than are disky-coreless galaxies. Therefore the revised classification orders galaxies along the Hubble sequence by physically fundamental properties, i. e., by the increasing importance from left to right of ordered rotation as compared with random internal velocities.

The ATLAS^{3D} *project – VII. The kinematic morphology-density relation* 5

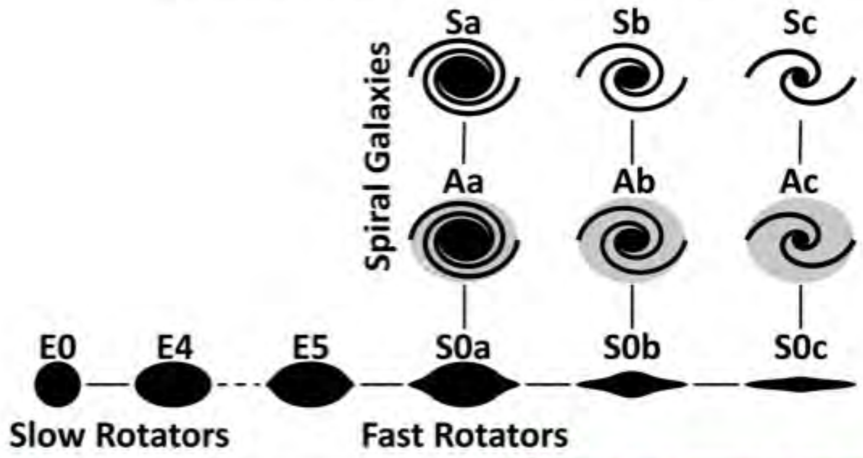


Figure 2. Same as in Fig. 1, but in schematic form. As in previously proposed revisions (van den Bergh 1976; Kormendy & Bender 1996) of Hubble's tuning-fork classification scheme, this diagram represents *intrinsic* galaxy properties. For this reason the slow-rotator (E0–E4) and fast-rotator (E5–S0c) early-type galaxies are visualized as edge-on. Together with the spiral galaxies (Sa–Sc) and the early-type galaxies, here we also explicitly included in the diagram the class of Anemic Spirals (Aa–Ac) by van den Bergh (1976). These represent transition objects between the genuine spirals, with obvious large-scale spiral arms and the fast rotators, with no evidence of spiral structure in optical images.

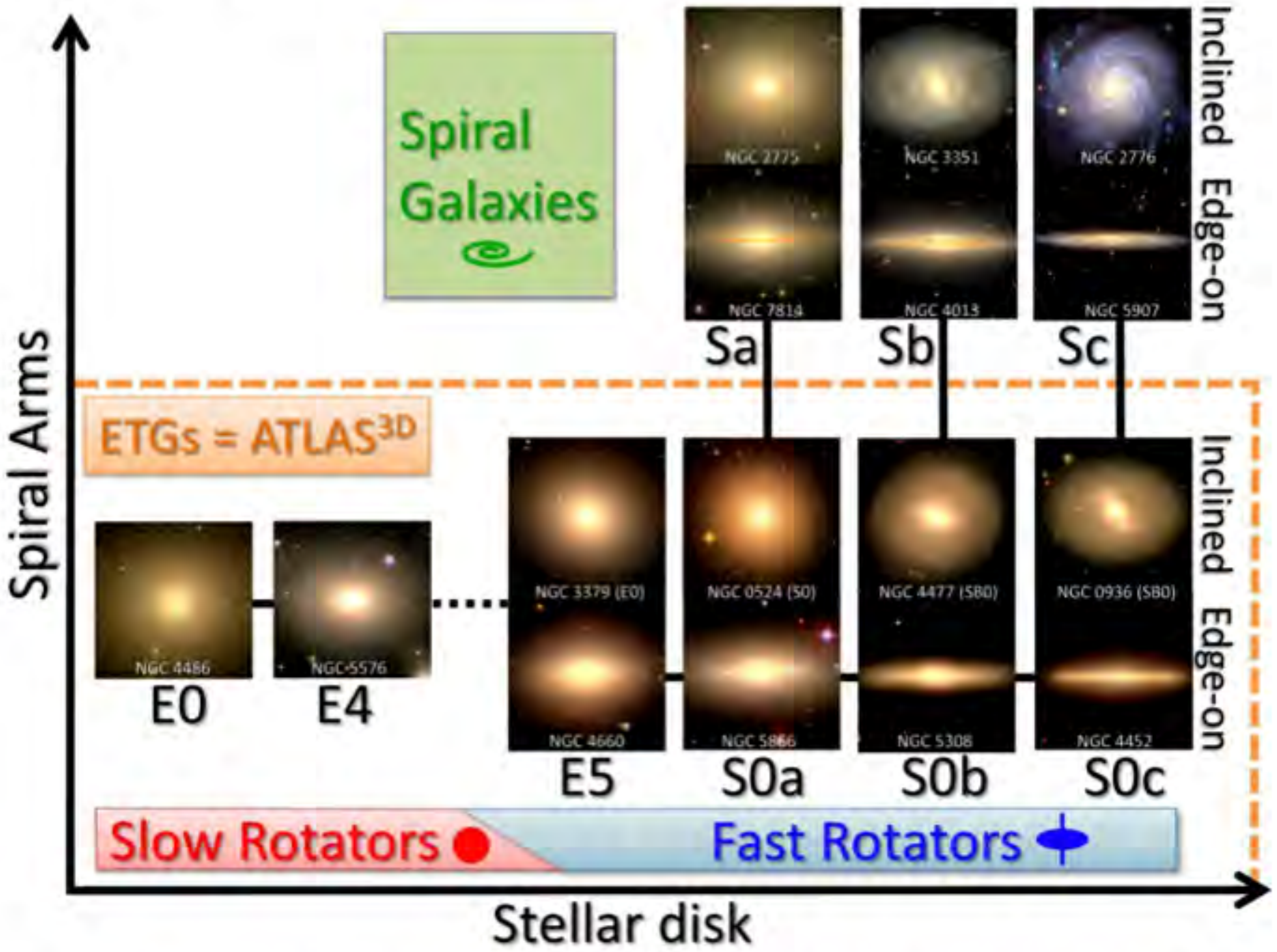


Figure 1. Morphology of nearby galaxies from the ATLAS^{3D} *parent* sample. The volume-limited sample consists of spiral galaxies (70%), fast rotators ETGs (25%) and slow rotators ETGs (5%). The ATLAS^{3D} sample consists of the ETGs only, classified according to the absence of spiral arms or an extended dust lane. The edge-on fast rotators appear morphologically equivalent to S0s, or to flat ellipticals with disky isophotes. Many of the apparently-round fast-rotators display bars or dusty disks, indicating that they are far from edge-on. All the galaxies classified as 'disky' ellipticals E(d) by Bender et al. (1994) belong to the fast-rotators class. However contrary to E(d) and S0 galaxies, the fast-rotators can be robustly recognized from integral-field kinematics even when they are nearly face-on (Emsellem et al. 2007; Cappellari et al. 2007). They form a parallel sequence to spiral galaxies as already emphasized for S0 galaxies by van den Bergh (1976), who proposed the above distinction into S0a–S0c. Fast rotators are intrinsically flatter than $\varepsilon \gtrsim 0.4$ and span the same full range of shapes as spiral galaxies, including very thin disks. However very few Sa have spheroids as large as those of E(d) galaxies. The slow rotators are rounder than $\varepsilon \lesssim 0.4$, with the important exception of the flat S0 galaxy NGC 4550 (not shown), which contains two counter-rotating disks of nearly equal mass. The black solid lines connecting the galaxy images indicate an empirical continuity, while the dashed one suggests a possible dichotomy.

Three Kinds of Ellipticals? (Kormendy et al. 2009)

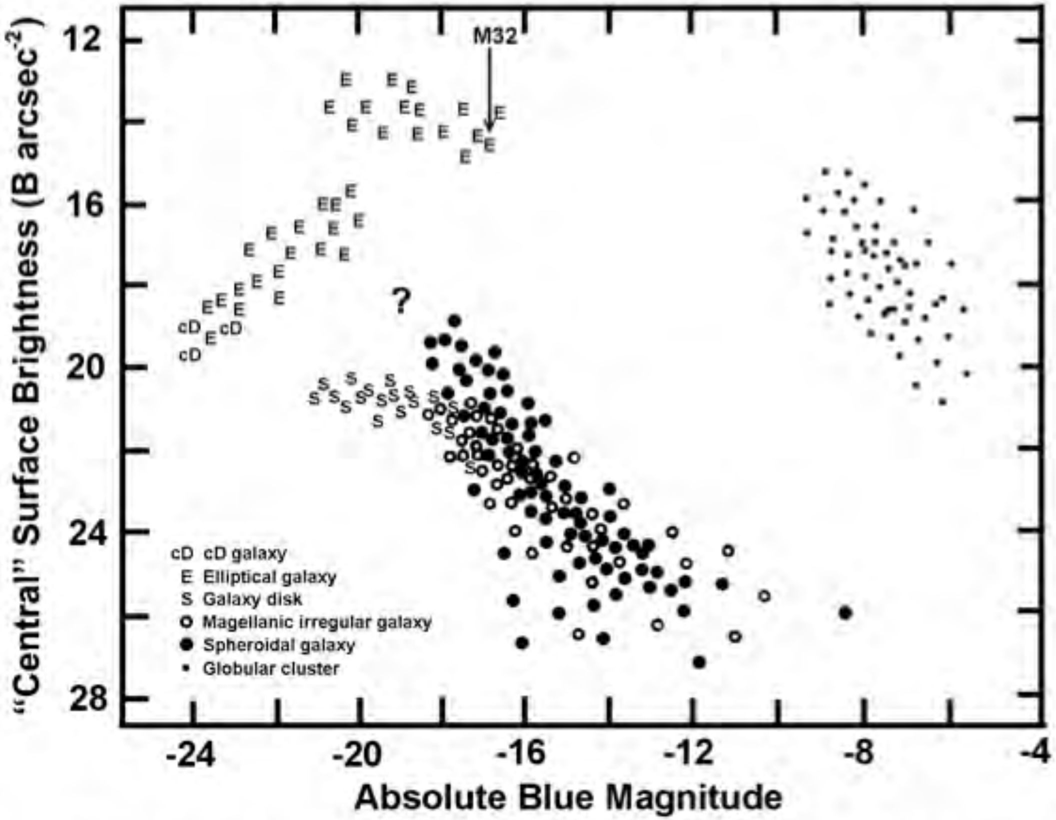
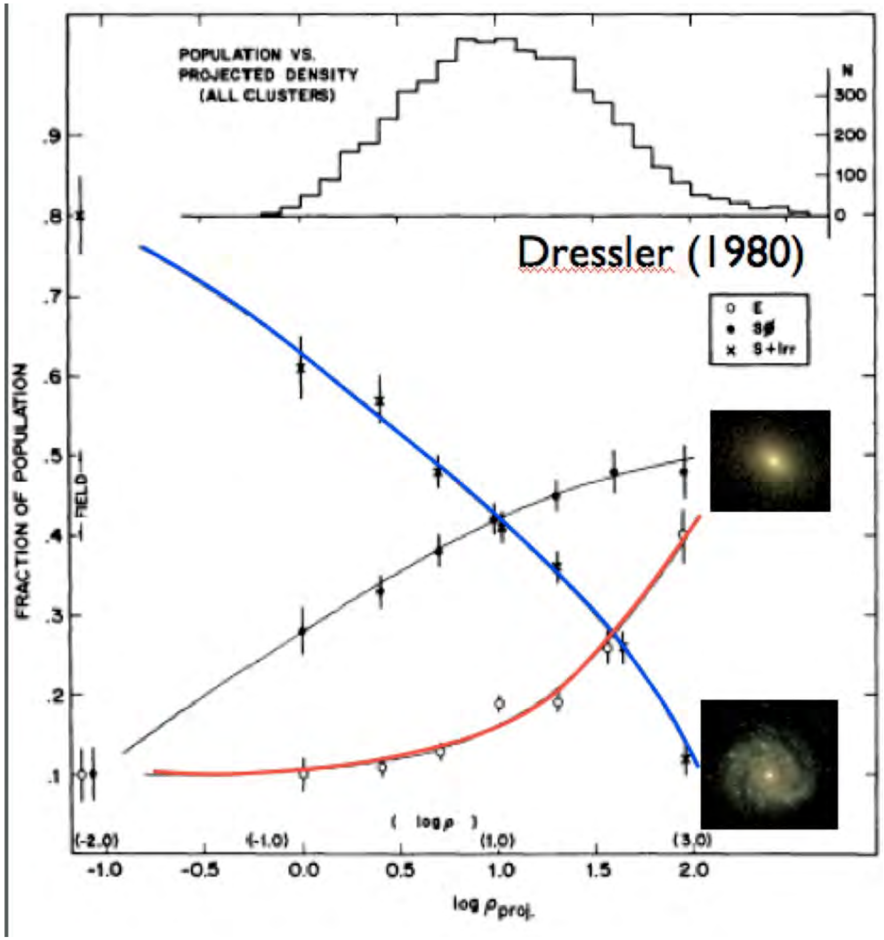


FIG. 1. — Schematic illustration of the dichotomies discussed in this paper. The figure sketches the correlation between total absolute magnitude and central surface brightness (for spheroidal and irregular galaxies, galaxy disks, and globular clusters) or the highest surface brightness resolved by the *Hubble Space Telescope* (for elliptical and cD galaxies). Surface brightnesses apply to the main bodies of the galaxies; that is, nuclear star clusters and active galactic nuclei are omitted. This figure is adapted from Binggeli (1994) but with the dichotomy between "core" and "power law" ellipticals – i.e., the discontinuity in E points at $M_B \sim -20.5$ – added from Faber et al. (1997). M 32 is one of the lowest-luminosity true ellipticals; the arrow points from the maximum surface brightness observed at a distance of 0.8 Mpc to the lower limit that would be observed if the galaxy were moved to the Virgo cluster. M 32 resembles the faintest ellipticals in Virgo. The distribution of Sph and S+Im galaxies is disjoint from that of ellipticals. Sph and S+Im galaxies have similar global parameters at low luminosities, but the most luminous spheroidals "peel off" of the distribution of late-type galaxies toward higher surface brightness. Spheroidals with $M_B \lesssim -18$ are rare, so the degree to which the Sph sequence approaches the E sequence is poorly known (*question mark*). Note: Binggeli (1994) and some other authors call spheroidal galaxies "dwarf ellipticals" (dEs). We do not do this, because correlations like those in this figure and in Figures 34 – 38 and 41, as well as the considerations discussed in § 2.1 and § 8, persuade us that they are not small ellipticals but rather are physically related to late-type galaxies.

Perseus Cluster



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Cappellari et al. 2011

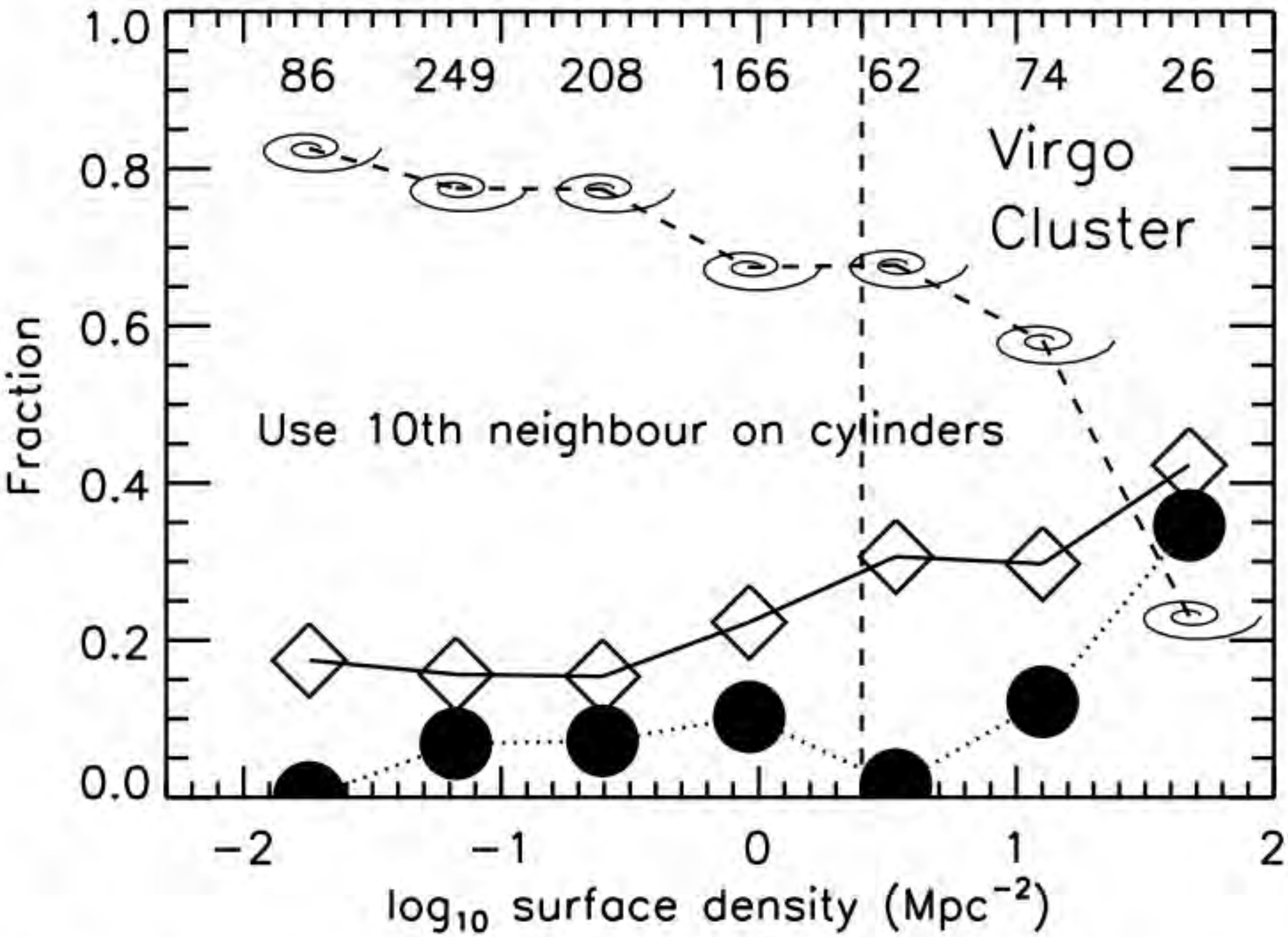


Figure 9. Morphology versus density for elliptical (black filled circles), lenticular (open diamonds) and spiral galaxies (spirals), versus the local surface density Σ_{10}. The numbers above the symbols represent the number of galaxies included in each of the seven density bins.

Seminar 3: “Following the growth of Early-type galaxies since z=1”

Nelson Padilla (PUC, Chile)

Huge Digression to Help Graduate Students

***Doing* Observational Cosmology**

Population Synthesis (today)
Luminosity Functions (if time, tomorrow)

= Stuff I Wish Somebody Had Told Me In Graduate School

How can one model and understand evolving galaxy spectra without tons of specialist knowledge?

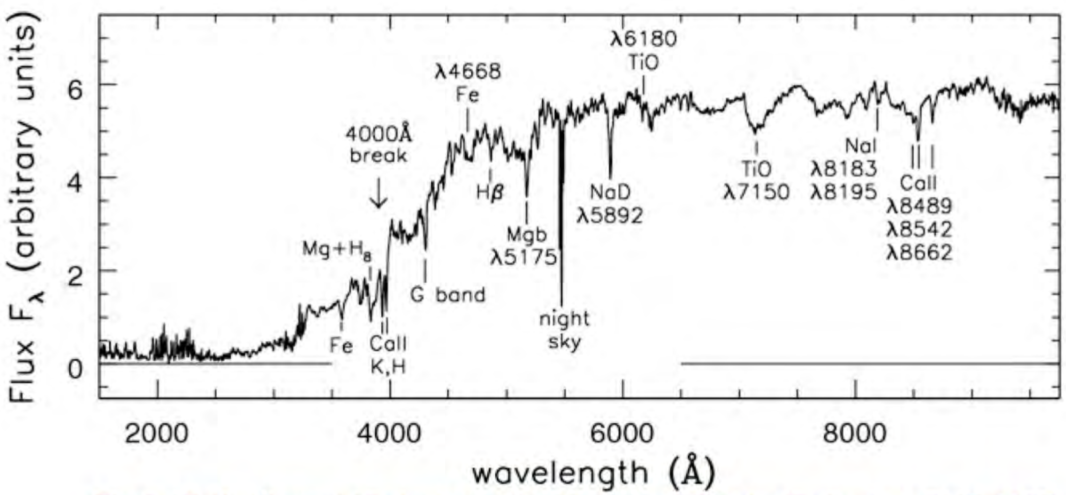


Fig 6.17 (A. Kinney) 'Galaxies in the Universe' Sparke/Gallagher CUP 2007

"What is the age of a galaxy?"

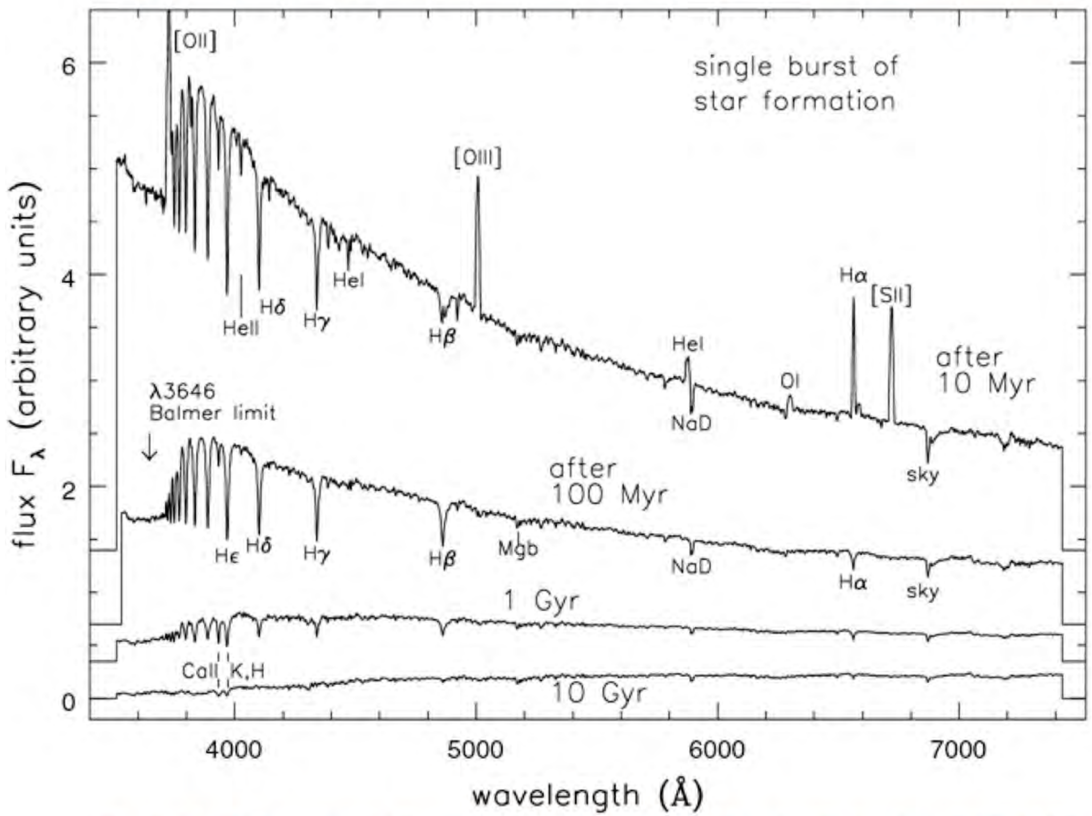
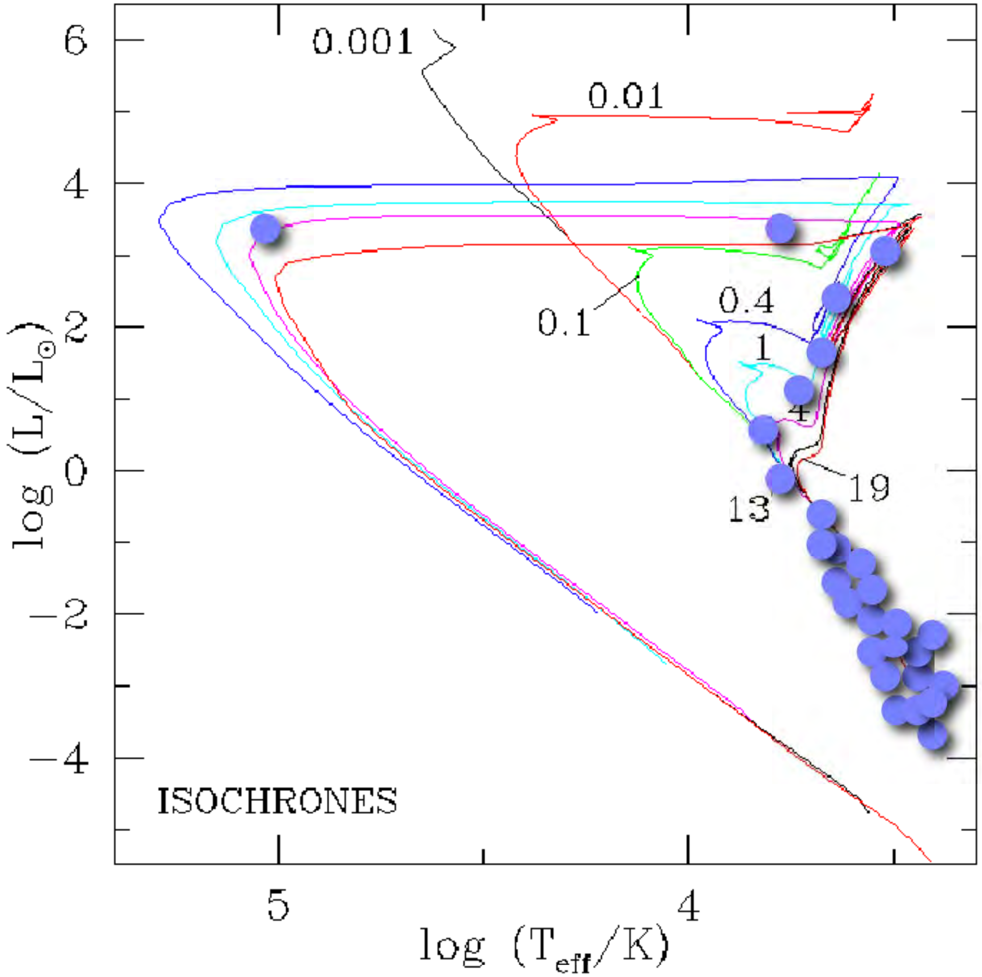


Fig 6.18 (B. Poggianti) 'Galaxies in the Universe' Sparke/Gallagher CUP 2007

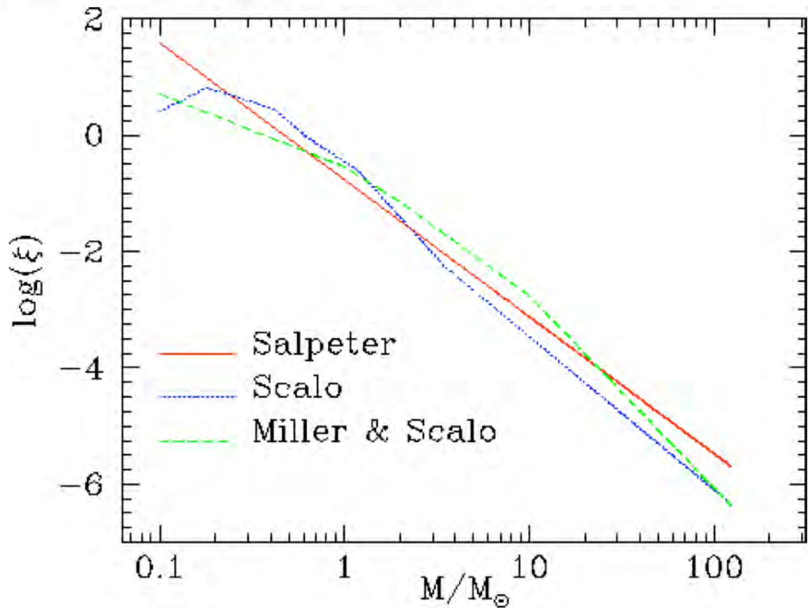
Simple stellar population - note colors!
(this has a well-defined age)


Composite Stellar Population (note colors)
What is the age of this galaxy?

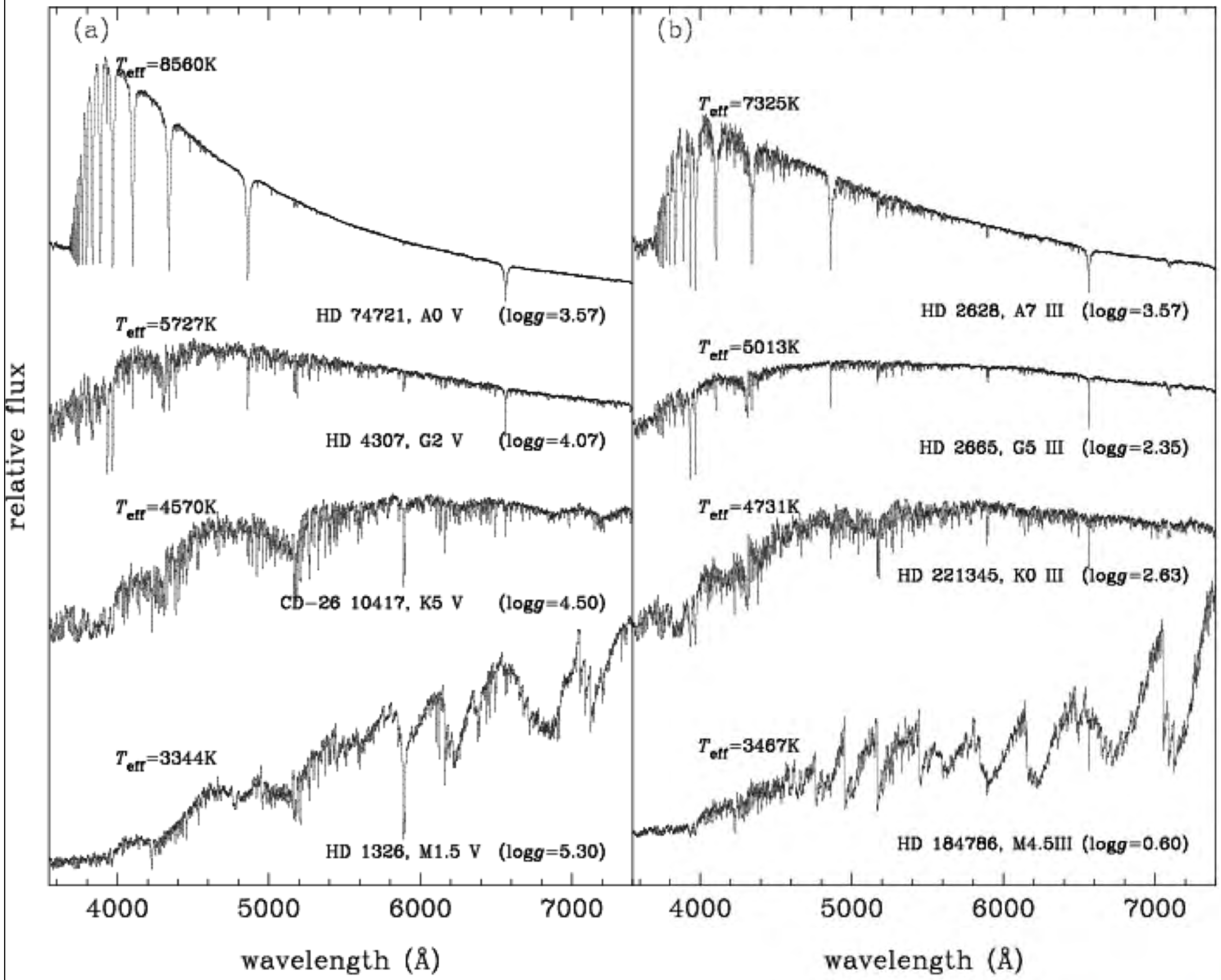
Stellar Isochrones for a simple stellar population + Initial Mass Function



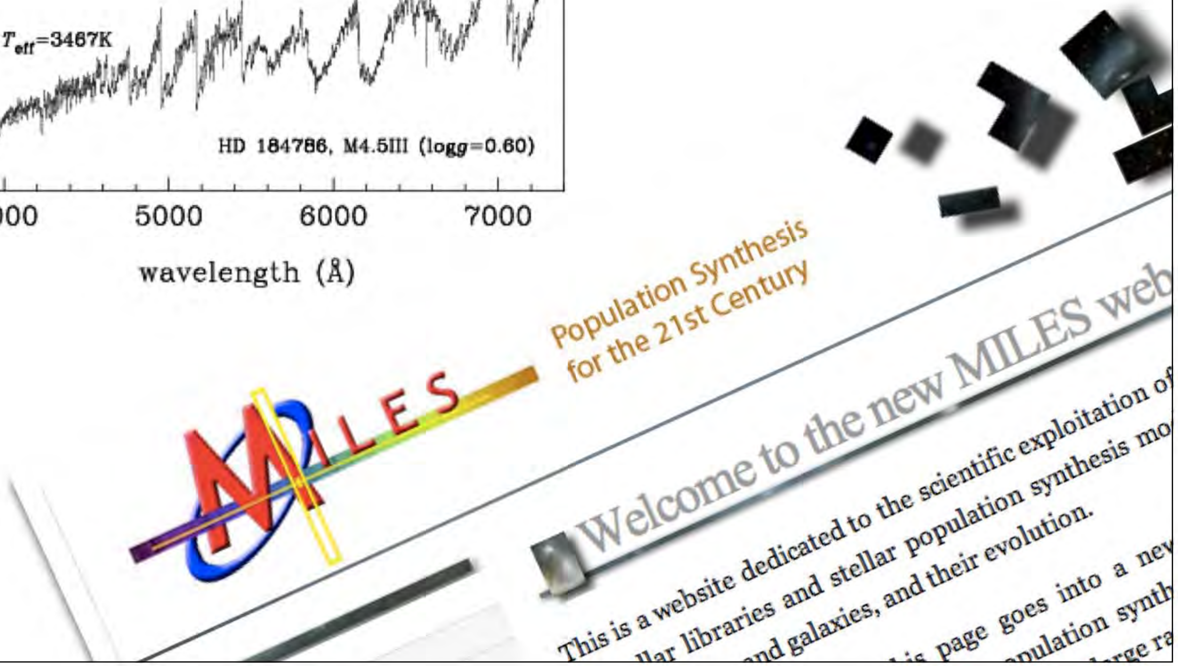
- Snapshots in time for evolution of a "simple stellar population", ie. a population on the Zero Age Main Sequence (ZAMS) at time 0. In other words, the HR diagram for a star cluster will map out an isochrone, with the relative number of stars along the isochrone reflecting the IMF.
- Yale, Padua, and Geneva are the places to go looking for isochrones.
- Imagine adding up the spectra for all the stars along an isochrone (in the proportions dictated by the IMF). What you get is $F^{burst}(t)$, the spectrum for a "simple stellar population" as a function of time.



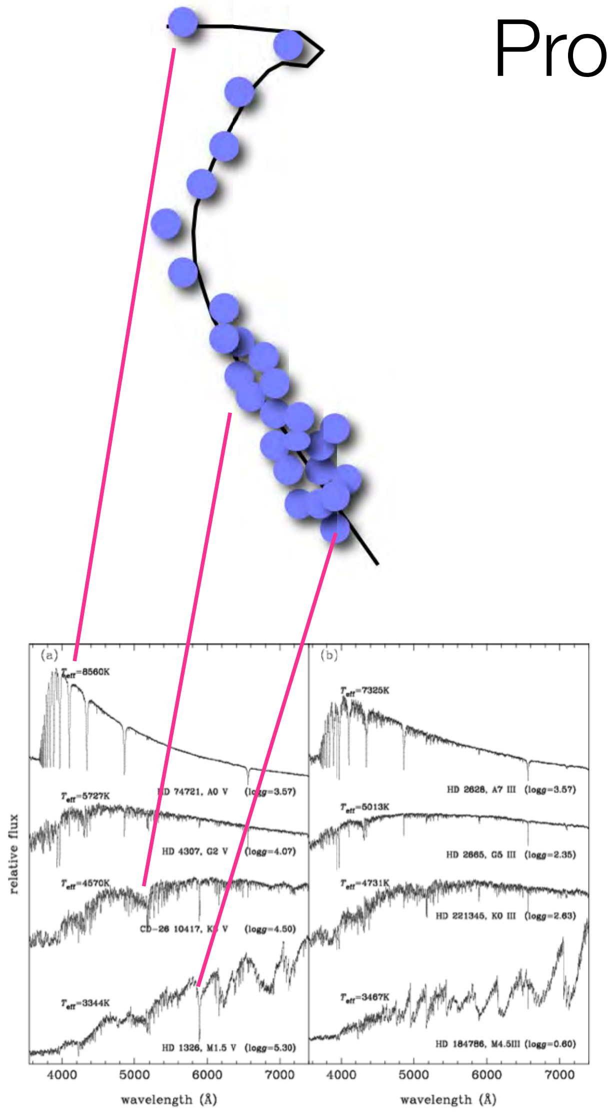
Isochrones + IMF are the product of very hard work done by others.

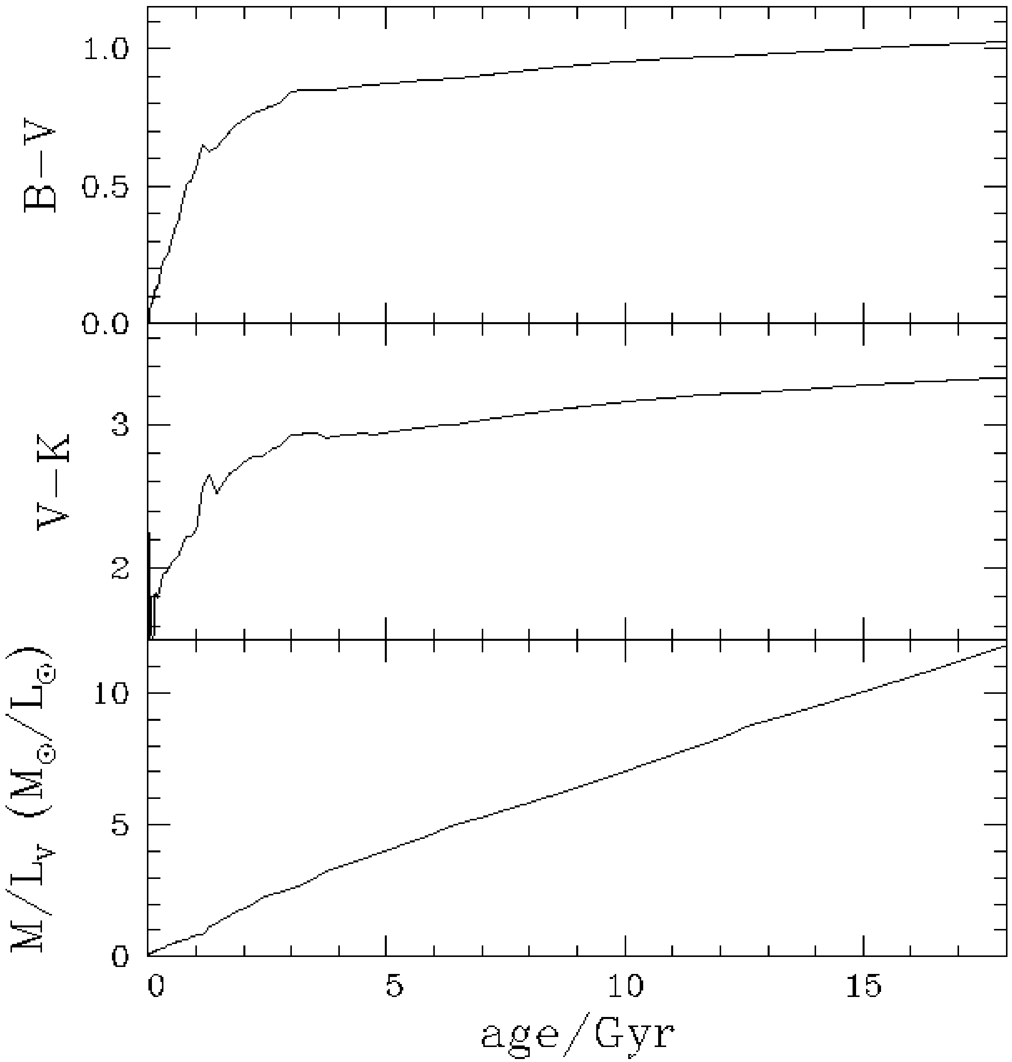


Stellar Library = More Hard Work done by Observers



Properties of Simple Stellar Populations

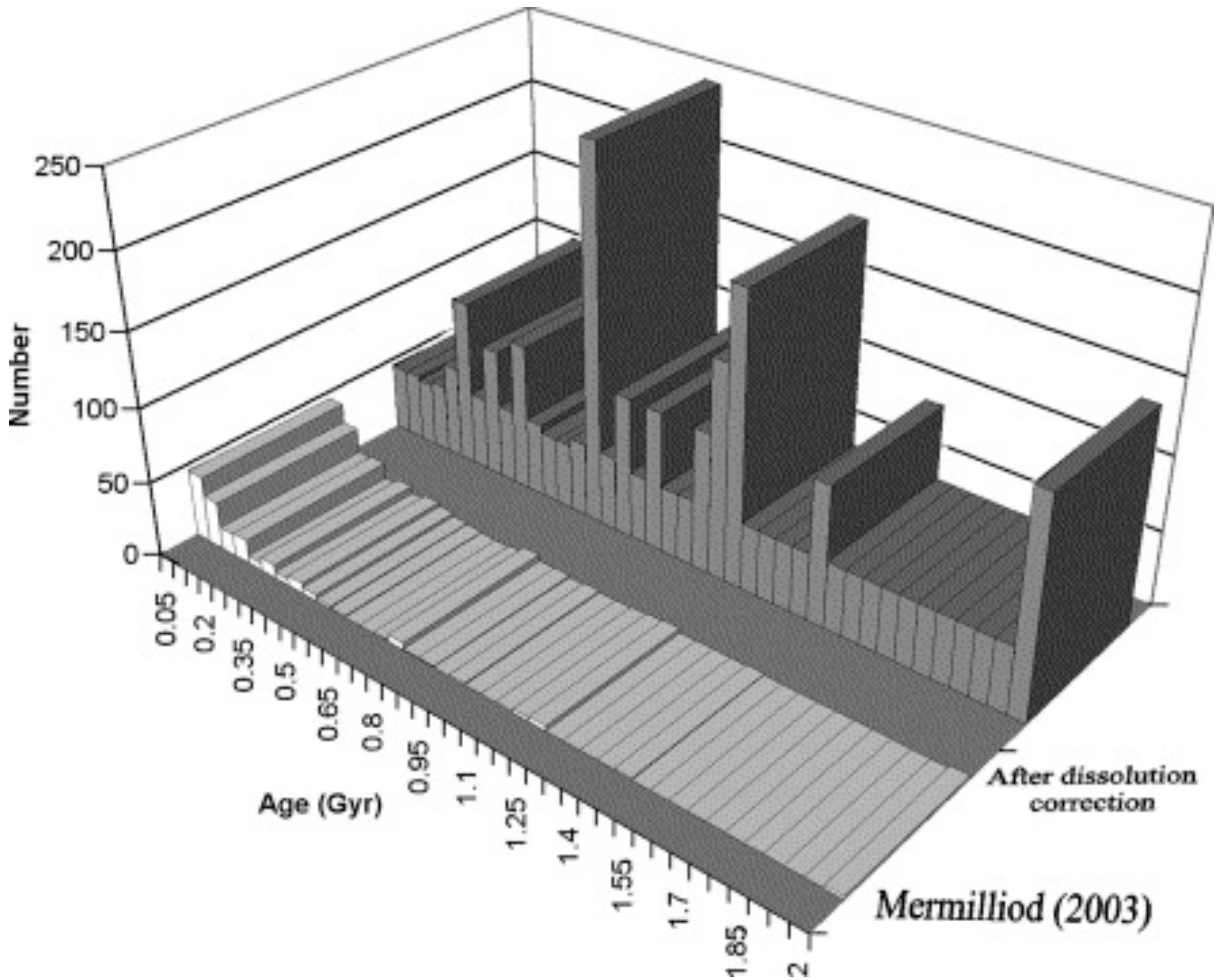




OK!

But what about…

Recent star-formation history of Milky Way (estimated by counting open clusters)

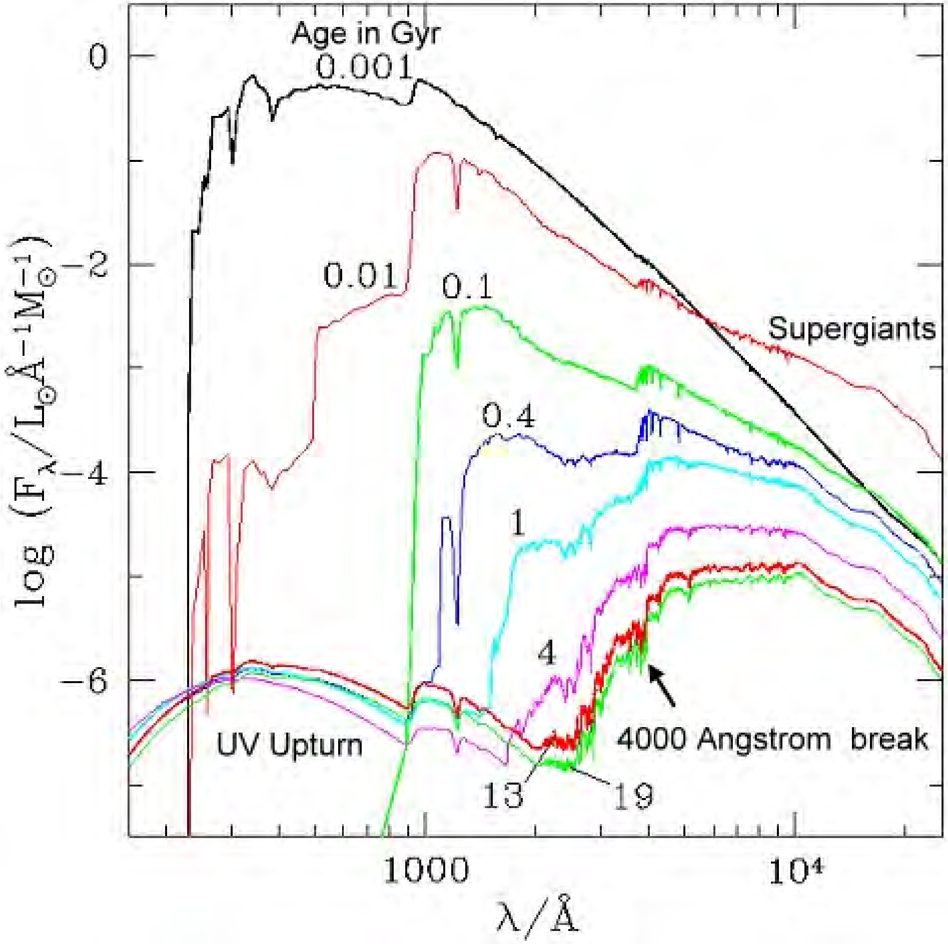


Spectral Synthesis

You pick this

$$F_\lambda(t) = \int_0^t \psi(t-\tau)\, F_{z\,(t-\tau)}^{burst}(\tau)\, d\tau$$

The really hard work is done by other people and is all here



- Evolutionary tracks and construction of isochrones are where theory plays a key role in spectral sythesis models.
- We need a better handle on opacities, heavy element mixtures, helium content, mass diffusion, mass loss, and rotational mixing.
- Cosmologists (like me) tend to treat spectral synthesis codes as a black box... yikes!

YOUR JOB:

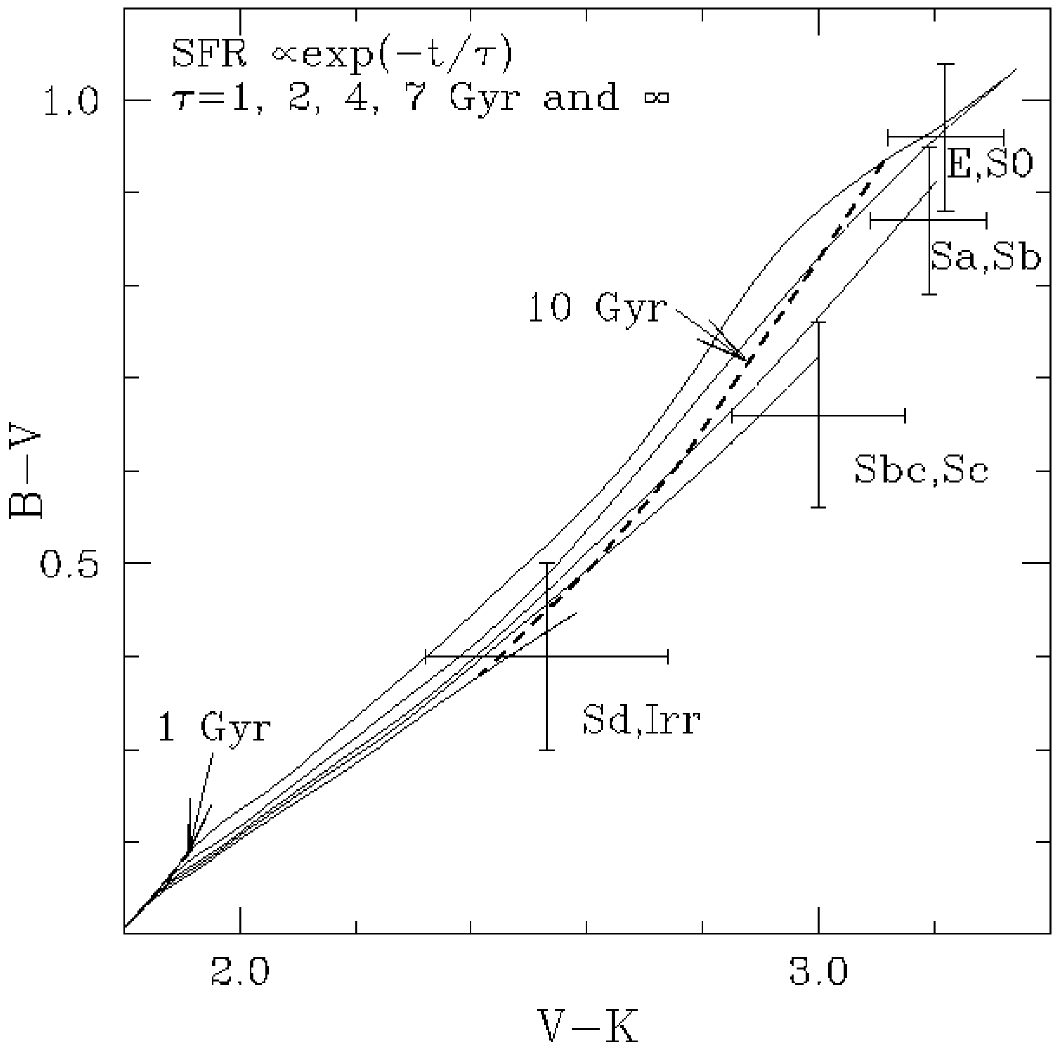
1.) Pick a family of F_z

2.) Pick ψ

Done

Your job is easy *in principle*
but also easy to screw up…

What star-formation history should you use?
Traditional choice = exponential



- Typical assumption is an exponential SFH. Not too bad an assumption?
- Don't be fooled by what this means though... a given bit of a galaxy is a bunch of smoothed starbursts
- Be careful about "ages"... and age means something rather different to a modeller (time from first star-formation) than to an observer (luminosity-weighted, or ideally mass-weighted, age).

Borch et al. 2006 prescription

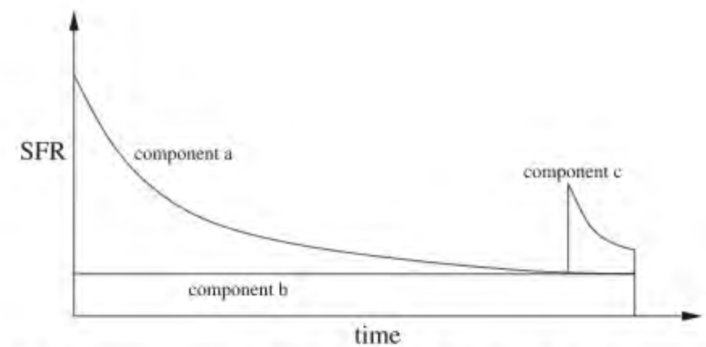
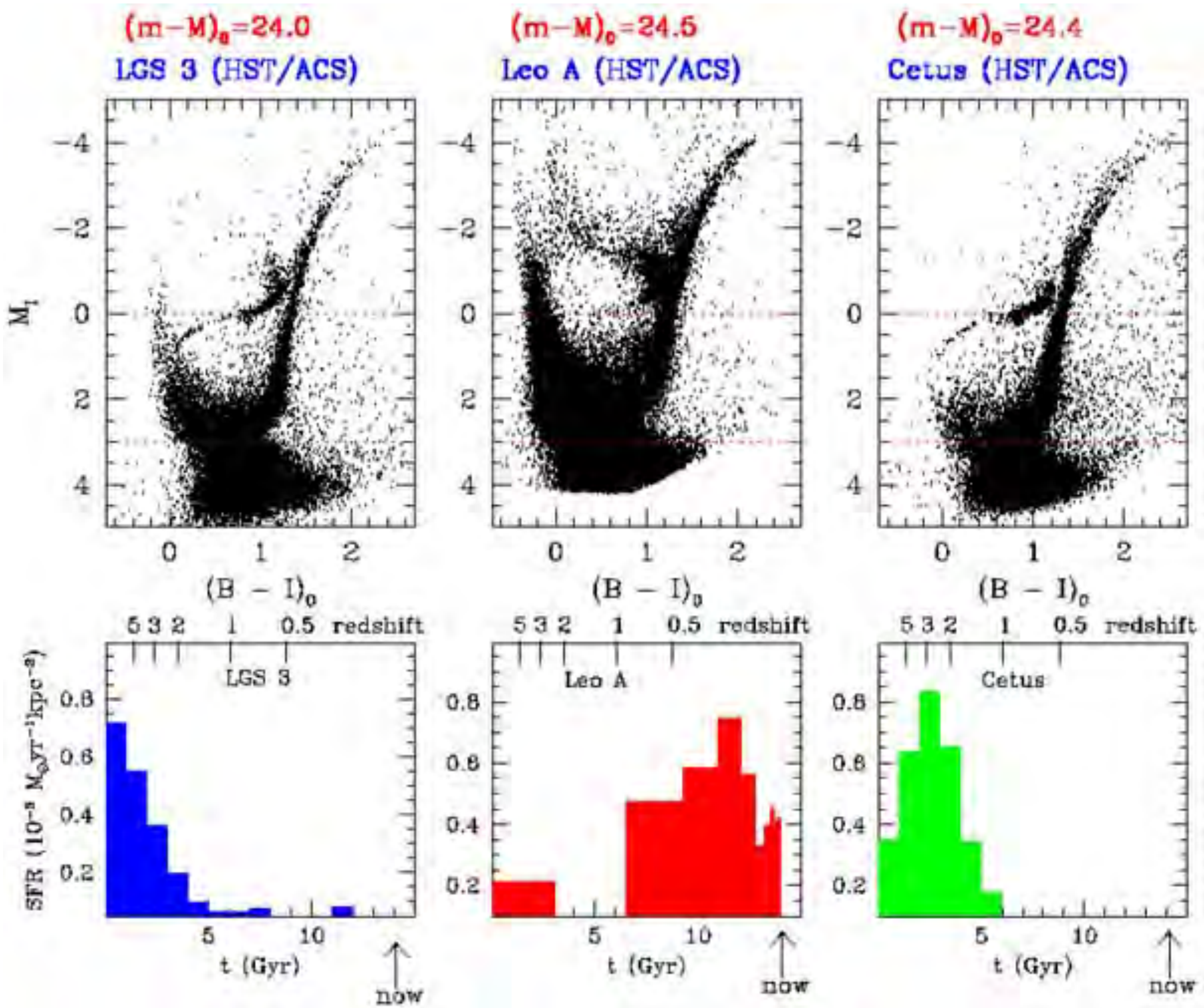
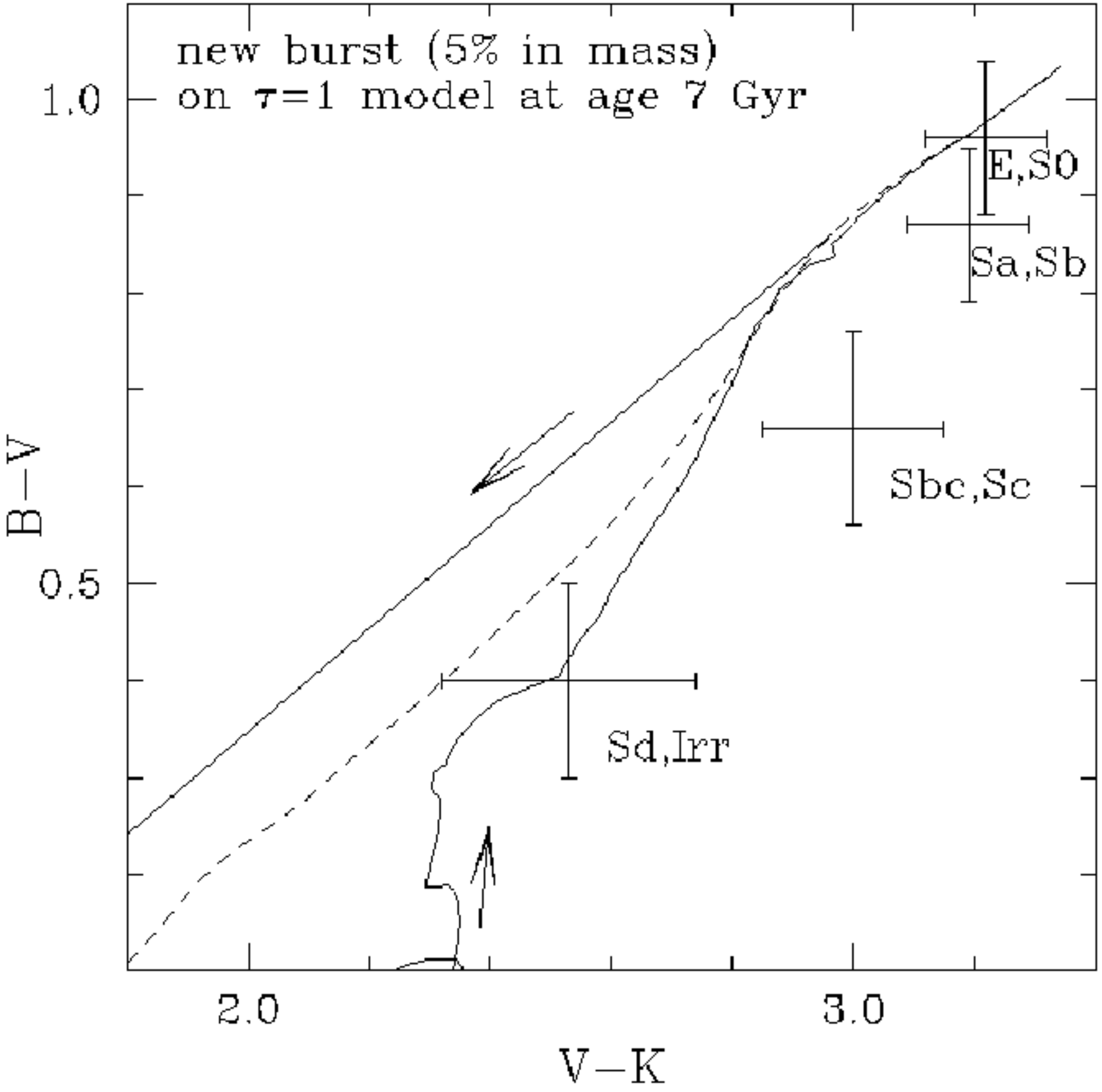


Fig. 1. Parameterization of the star formation history in our templates. An exponentially decaying star formation rate simulates an initial burst (component *a*). A second component *b* provides some constant star formation since the initial burst. For starburst galaxies a second burst in the recent past is assumed (component *c*).

From the beautiful Ann Rev article on star-formation hstories of Dwarf Galaxies by Tolstoy, Hill & Tosi (2009)



Effects of minor starbursts



The plot shows an underlying old stellar population with a 5% (by mass) burst added. The lesson: even tiny bursts screw up visible wavelength colors!

Borch et al. 2006

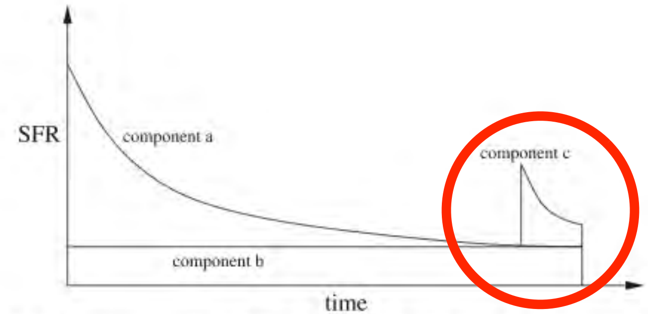


Fig. 1. Parameterization of the star formation history in our templates. An exponentially decaying star formation rate simulates an initial burst (component *a*). A second component *b* provides some constant star formation since the initial burst. For starburst galaxies a second burst in the recent past is assumed (component *c*).

Age-metallicity degeneracy is kinda scary

The Age-Metallicity Degeneracy 285

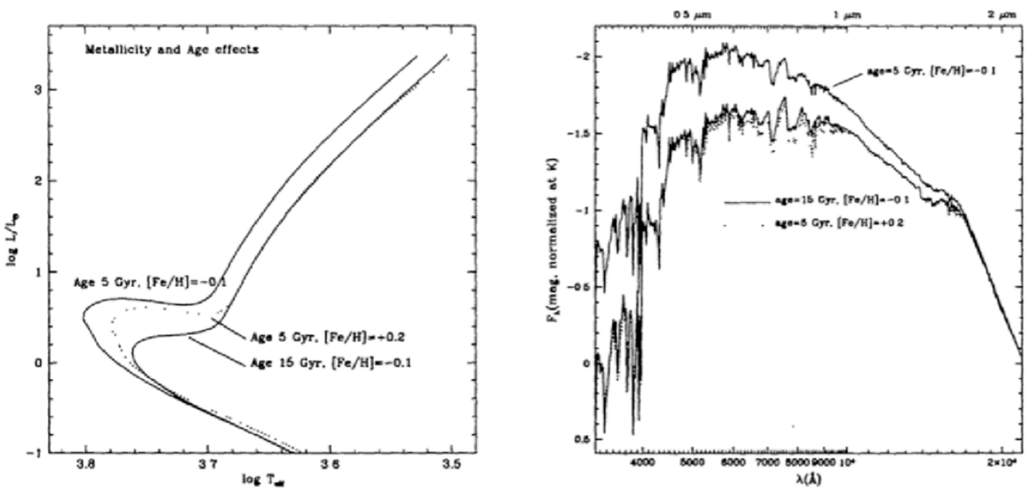


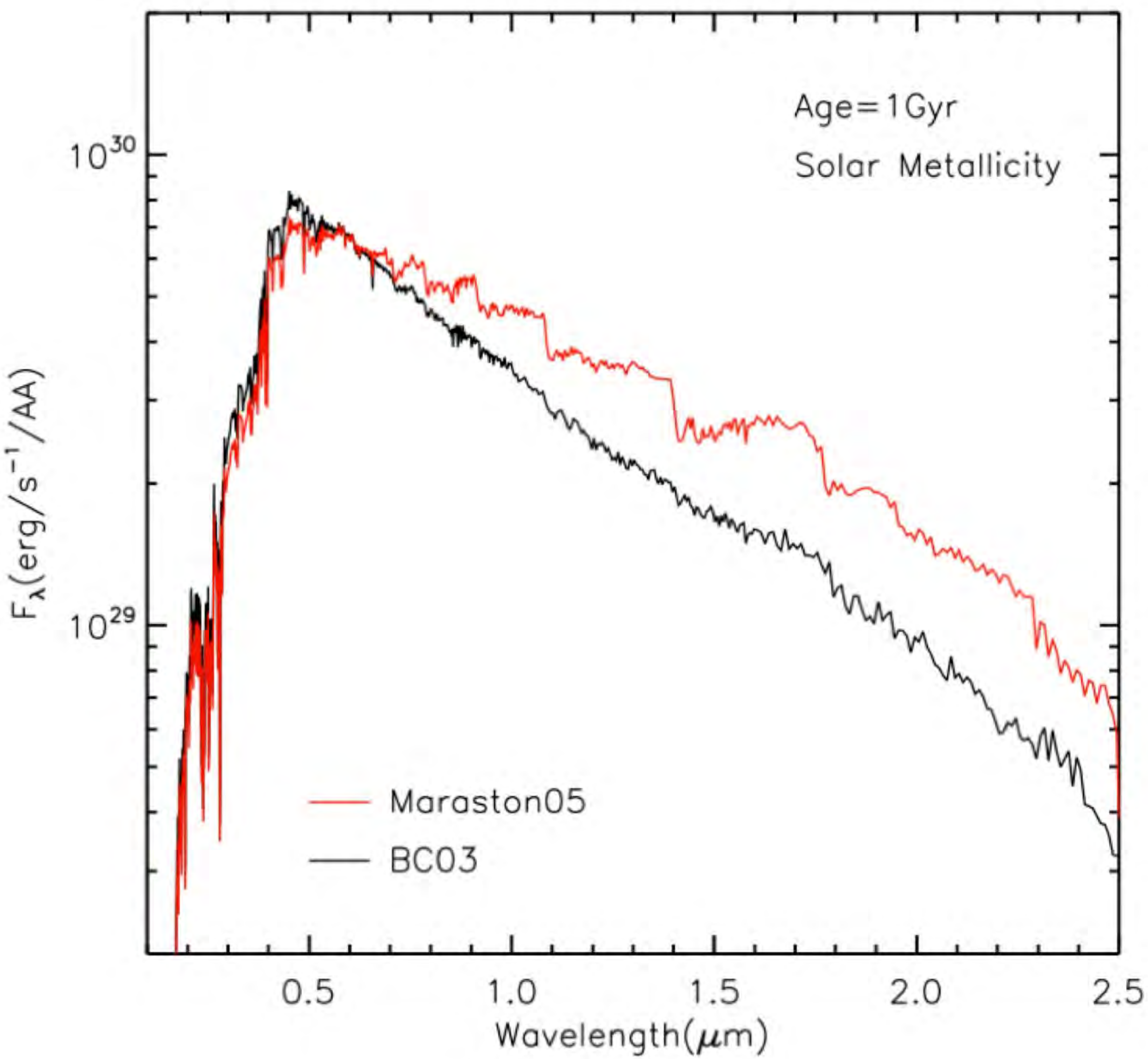
Figure 2. The pan-spectral nature of the 3/2 age-metallicity degeneracy can be illustrated by considering an isochrone of 5 Gyr age, slightly less than solar abundance. Isochrones of 3 times the age or twice the metallicity have nearly identical spectra.

- Worthey (1994) came up with a simple rule valid for old stellar populations with ages determined from colours:

$$\left[\frac{d \ln T}{d \ln Z}\right] \approx -\frac{3}{2}$$

- A 20% increase in metallicity Z can be compensated for by a ~30% decrease in the age
- You can do better with a good spectrum, but it's still fraught with difficulty

Even more scary is if you mess up the input to the models. For example, miss a phase of stellar evolution – effect of the TP-AGB (Thermally Pulsating Asymptotic Giant Branch)



Try it for yourself!

http://deployer.astrogrid.org/2008.2/astrogrid-cea-cec/config/galaxev/GALAXEV.html

http://www.cida.ve/~bruzual/bc2003

http://www2.iap.fr/users/fioc/PEGASE.html

http://astro.wsu.edu/worthy/dial/dial_a_model.html

http://www.icg.port.ac.uk/~maraston/Claudia's_Stellar_Population_Model.html

We will try it NOW

Spiral galaxies

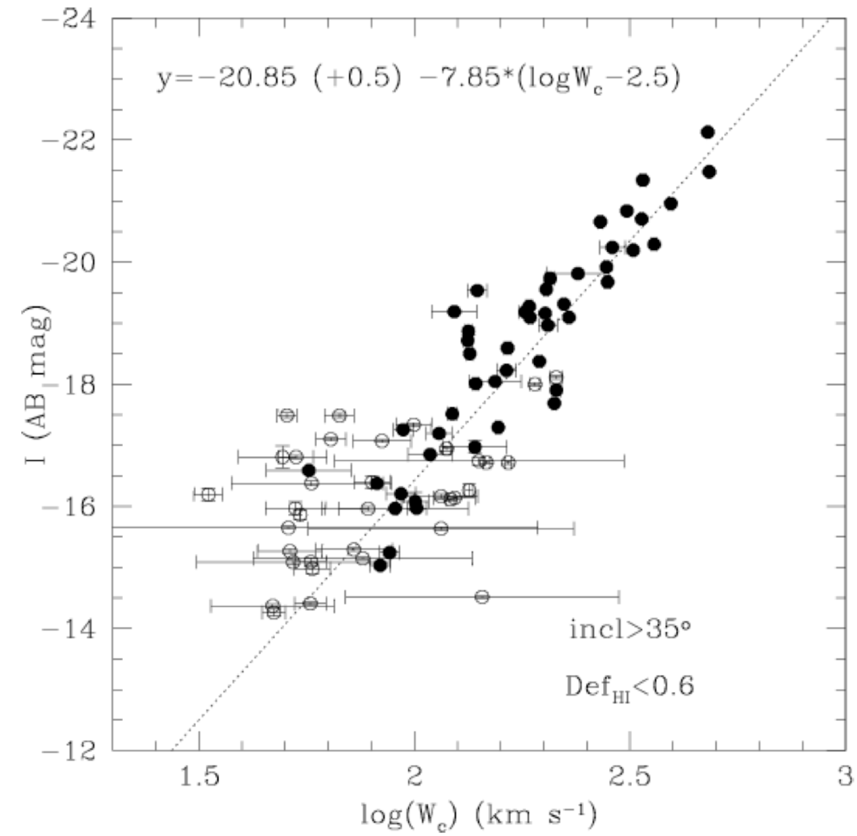
Old cartoon view: Symmetric, structured, rotationally supported, quickly evolving young-ish bluish galaxies. How much has changed?

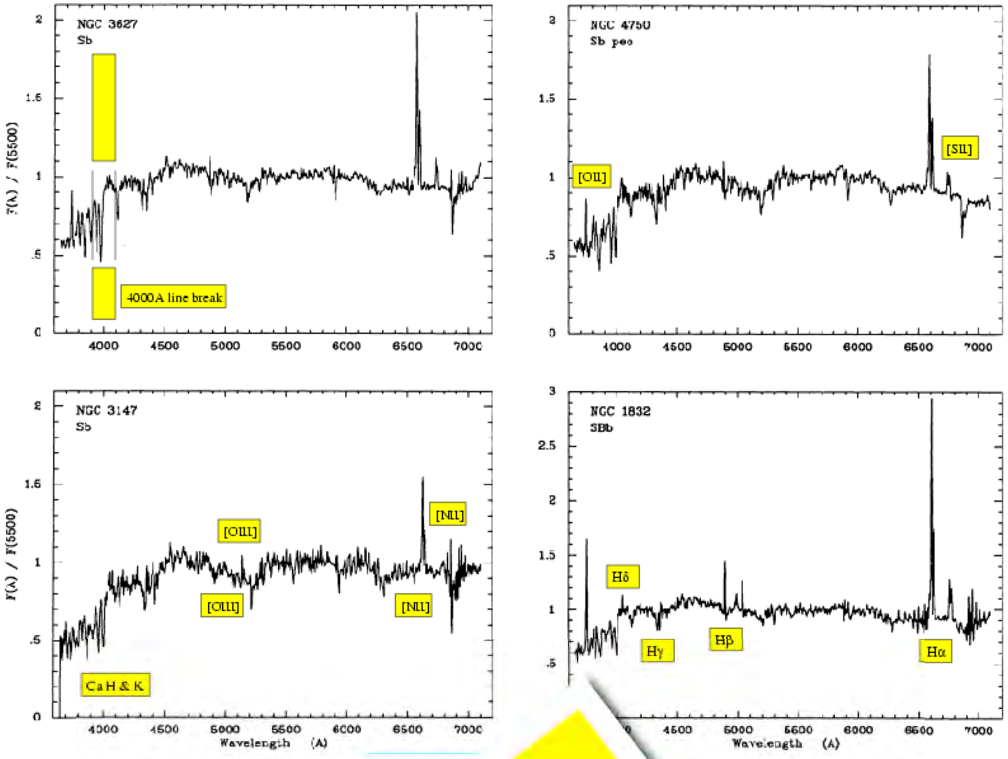
- Exponential radial light profiles for the disk component: $I(r) = I_o\, e^{-(r/h)}$.
- Radial light profile for the bulge component is usually assumed to be an $R^{1/4}$ law, but most recent work shows it to be an exponential for late-type spirals and an $R^{1/4}$ law for early-type spirals. Evidence for different physics in building bulges?
- Bulges were/are usually assumed to be old and to have formed through similar processes to those that formed ellipticals (ie. they are treated as "mini-ellipticals"). But this may not be true and there's increasing evidence that some bulges are built up from disks (secular evolution). We'll have more to say about this when we talk about galaxy evolution later in the course.

- ***Tully-Fisher relation***:

  $L_{IR} \propto \Delta V^4 \Rightarrow M/L \sim$ roughly constant (using IR magnitudes and corrected velocity width of 21cm line... one gets pretty crappy results using optical data). Why does this imply a roughly constant M/L ratio as a function of magnitude? Assume an exponential light distribution and that mass traces light so the mass density is given by $\sigma = \sigma_0 e^{-r/h} dr$. The total mass is given by $M = 2\pi\sigma_0 h^2$ and most of the mass lies within a couple of scale lengths, as can be trivially verified...

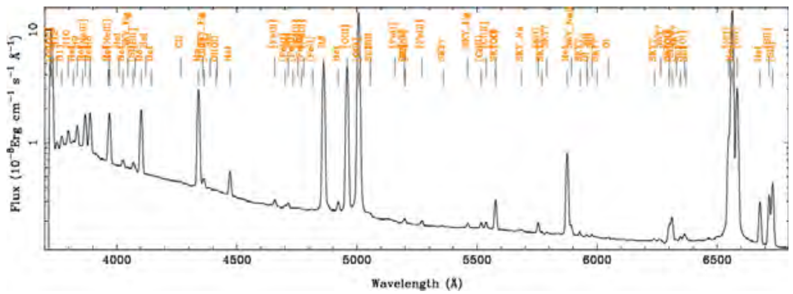
Gavazzi et al. 2008, A&A, 482, 42





Much more in Lecture 3. But note these lines are absent from most models!

Here is a spectrum of the Orion nebula, taken from Sanchez et al. 2007, A&A, 465(1), 207.



- Flat rotation curves ⇒ presence of a dark matter halo. The absence of a keplerian drop-off to the rotation curves of spirals was first discoverred by Vera Rubin in the early '80s. The figure below from Persic, Salucci, & Stel 1996 shows this most clearly for a large sample.Each panel isolates those spirals within a limited magnitude range. Note the correlation between the slope of the rotation curve and galaxy luminosity. *Faint spirals are relatively speaking much more dominated by the dark matter component than are luminous spirals. And the inner parts of spiral galaxies are often dominated by the baryons… the dark matter is more important the further out you go!*

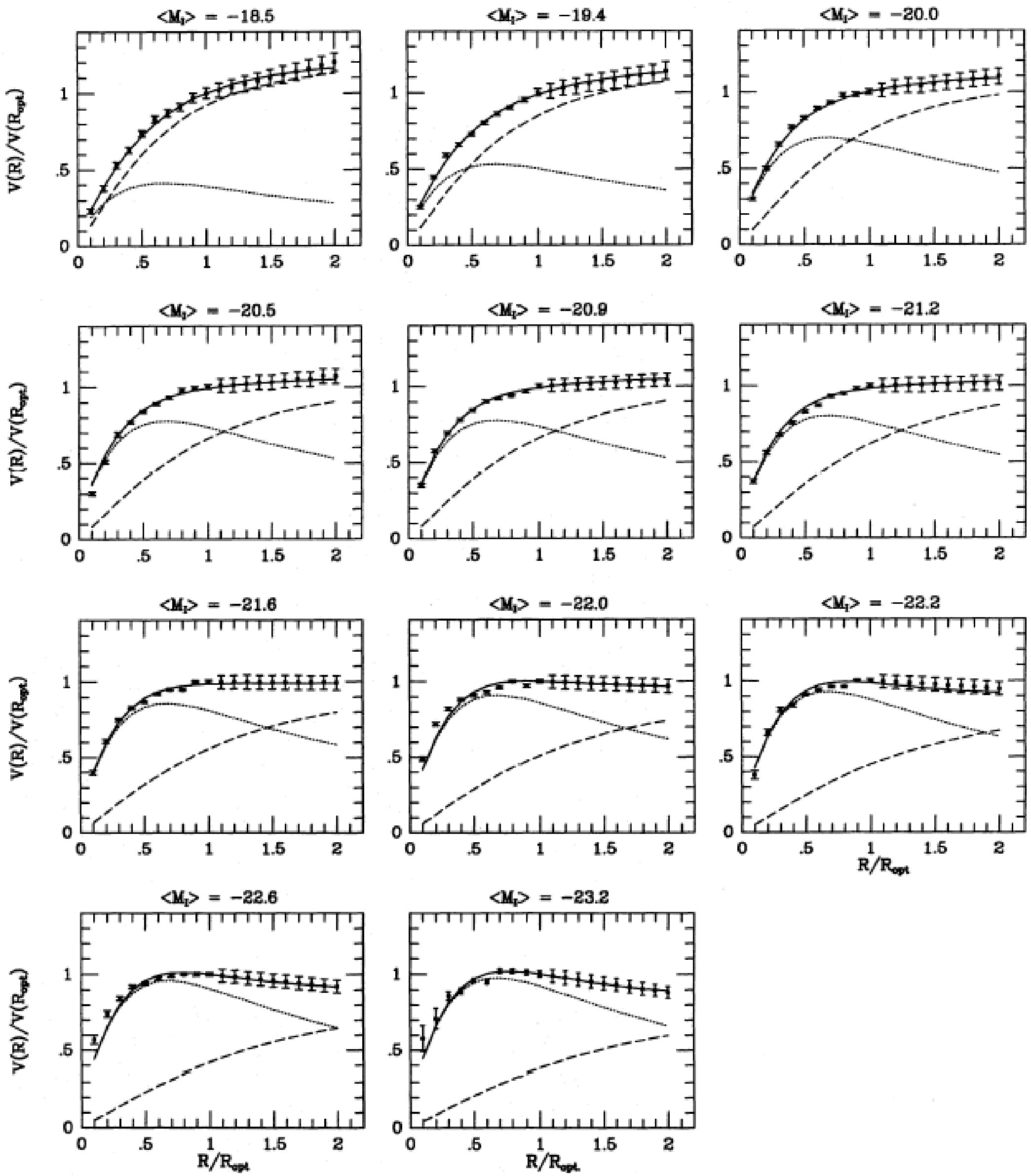


Figure 6. Best two-component fits to the universal rotation curve (dotted line: disc; dashed line: halo). The URC beyond R_{opt} is built by linear extrapolation according to equation (6). Notice that the extent of the RCs and the smallness of their rms errors limit the uncertainties on the parameters β and a to about 10 and 5 per cent, respectively.

Evolutionary Properties

Bar fraction

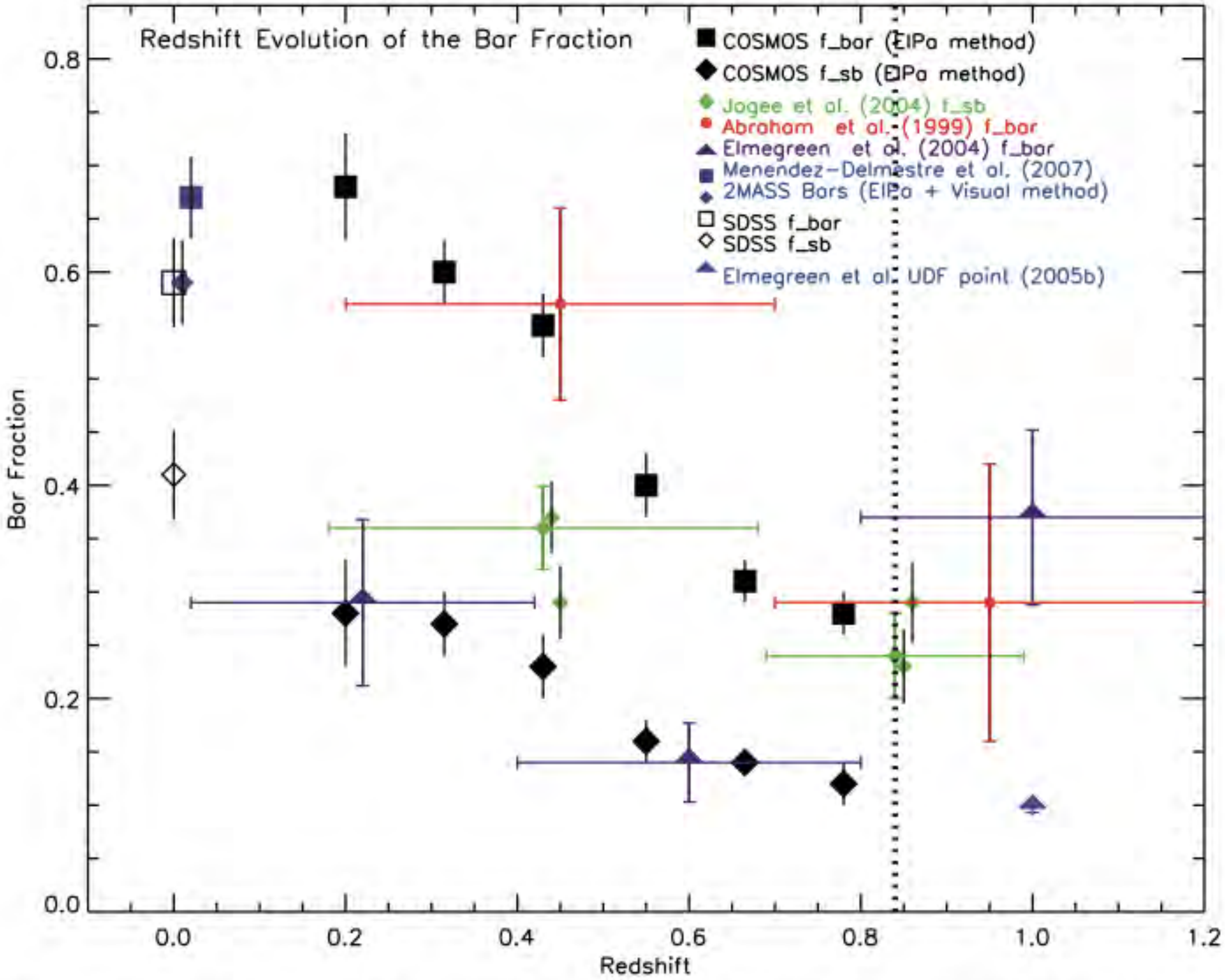
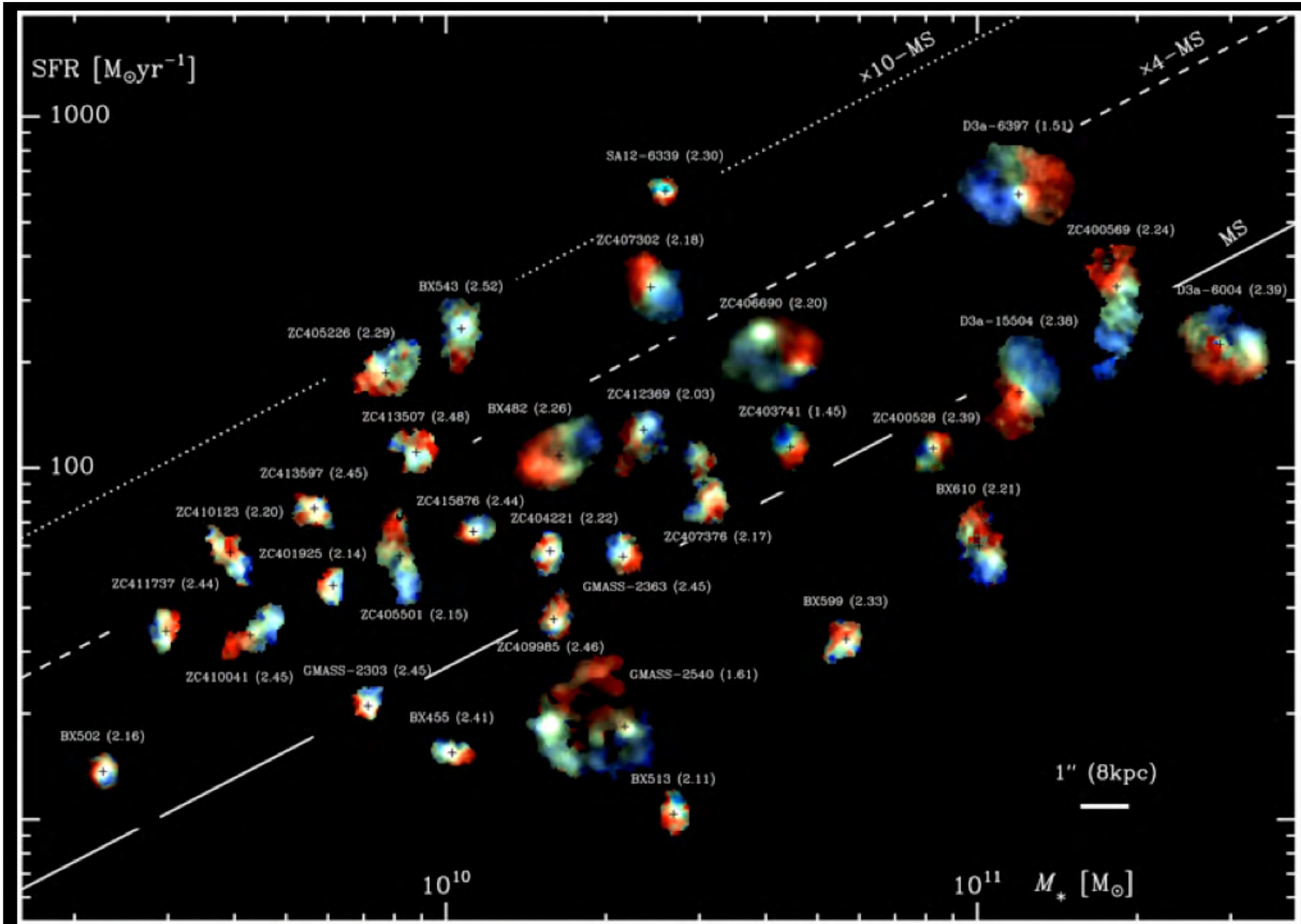
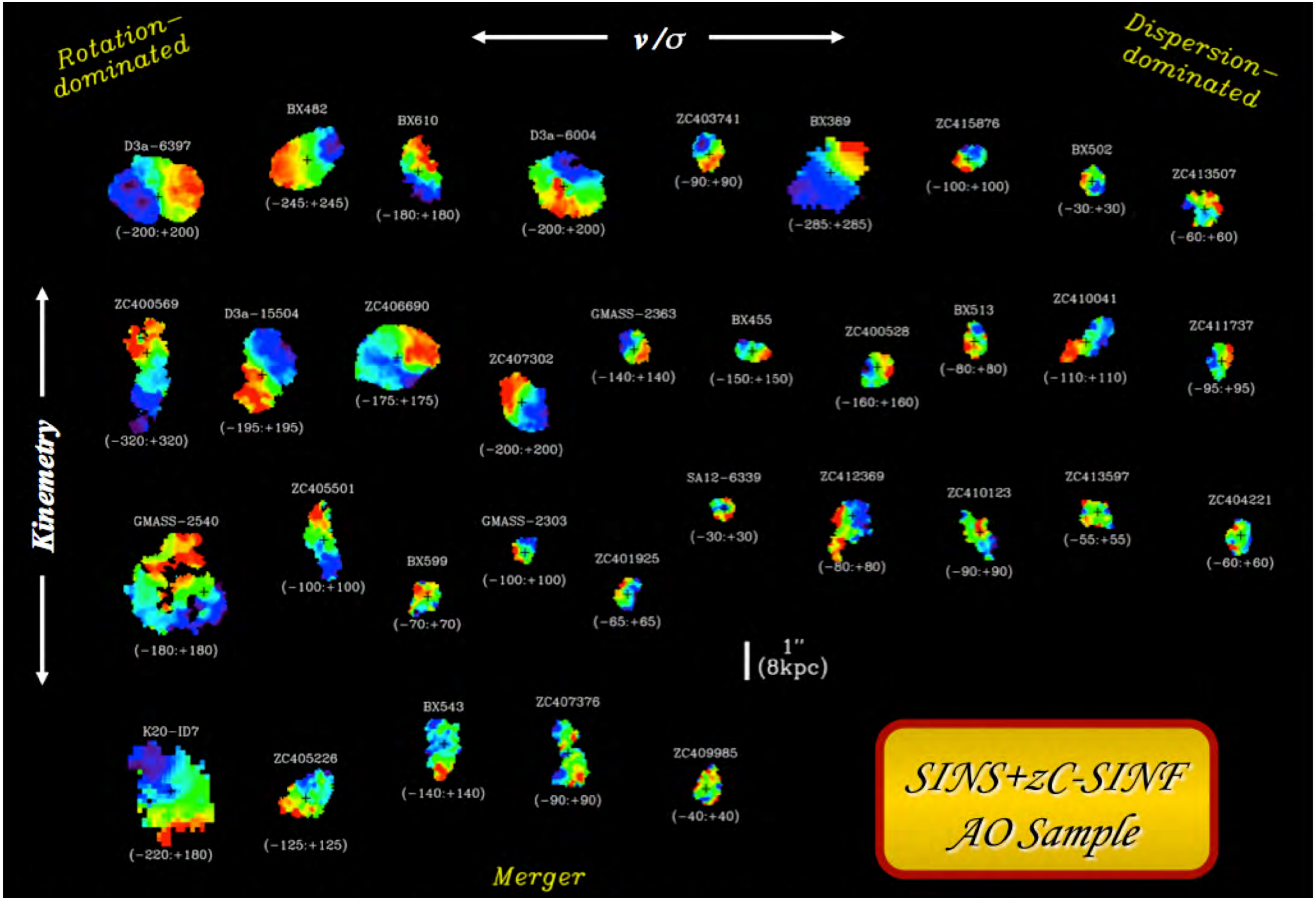


FIG. 6.—Comparison of measurements of our bar fraction with previous studies. f_{bar} and f_{SB} measured using the ElPa method for the COSMOS data are shown with the black filled squares and diamonds respectively. The red data circles (13/30 bars in low z bin, 4/14 in the high-z bin) are from Abraham et al. (1999); these do not distinguish between weak and strong bars. Purple triangles are bars and twists from Elmegreen et al. (2004) (10/34, 13/90, 13/35 bars, respectively); we summed adjacent bins from their data; they suggested inclination and resolution effects should increase the fractions by about a factor of 2. The green points from Jogee et al. (2004) are the strong bar fractions from GEMS; the three points in the two redshift bins are not independent of each other—they are measured for ~110–175 galaxies, chosen in different ways from the same sample. The horizontal bars show the redshift range over which these data are averaged. Also shown are data from our analysis of a SDSS control sample (square—f_{bar}, diamond—f_{SB}), and from the 2MASS survey by Menéndez-Delmestre et al. (2007) (blue diamond is when both ellipticity and position angle signatures are present, whereas the square also includes candidate bars. The vertical dotted line is the limiting redshift for our survey. Within the error bars all the data seem to be in agreement. Contrary to earlier interpretations, it seems that all studies show a general decline in the bar fraction with redshift. It is only with the COSMOS data that we are able to analyze this decline in detail.



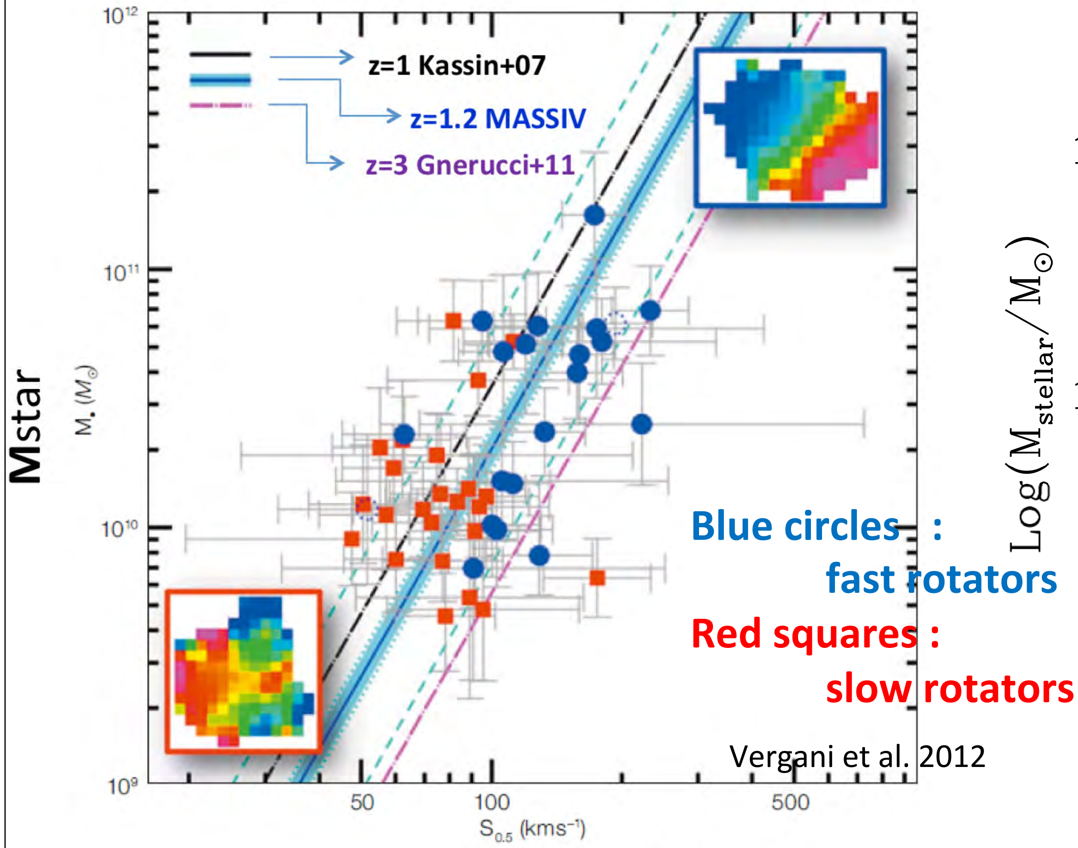
Förster Schreiber et al. (2009, in prep); Mancini et al. (2011)



NMFS et al. (2009); Mancini et al. (2011); and SINS+zCOSMOS (in prep.)
Kinemetry: Shapiro et al. (2008); Kinematic modeling: Genzel et al. (2008,2011); Cresci et al. (2009)

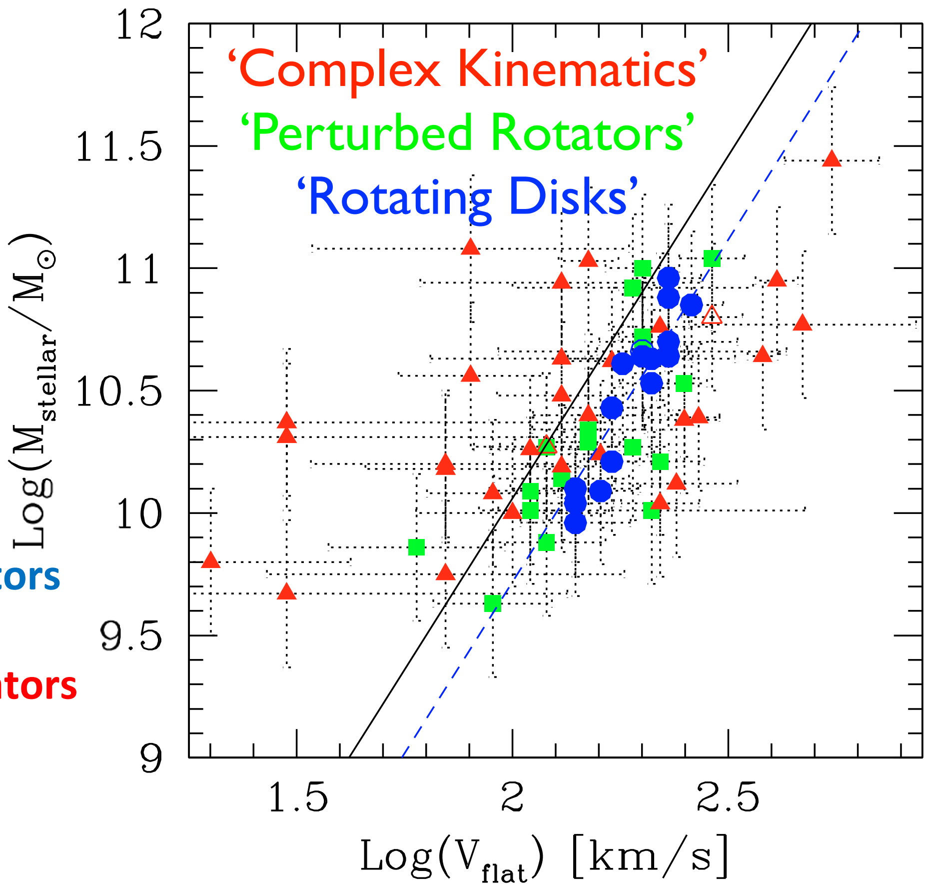
Hi-z Tully-Fisher relation

MASSIV: z~1.2



$$S_{05} = \sqrt{(0.5 \times v_{rot}^2 + \sigma_0^2)}$$

SINS: z~0.6



Amram

Puech et al. (2010)

What is the merger rate?

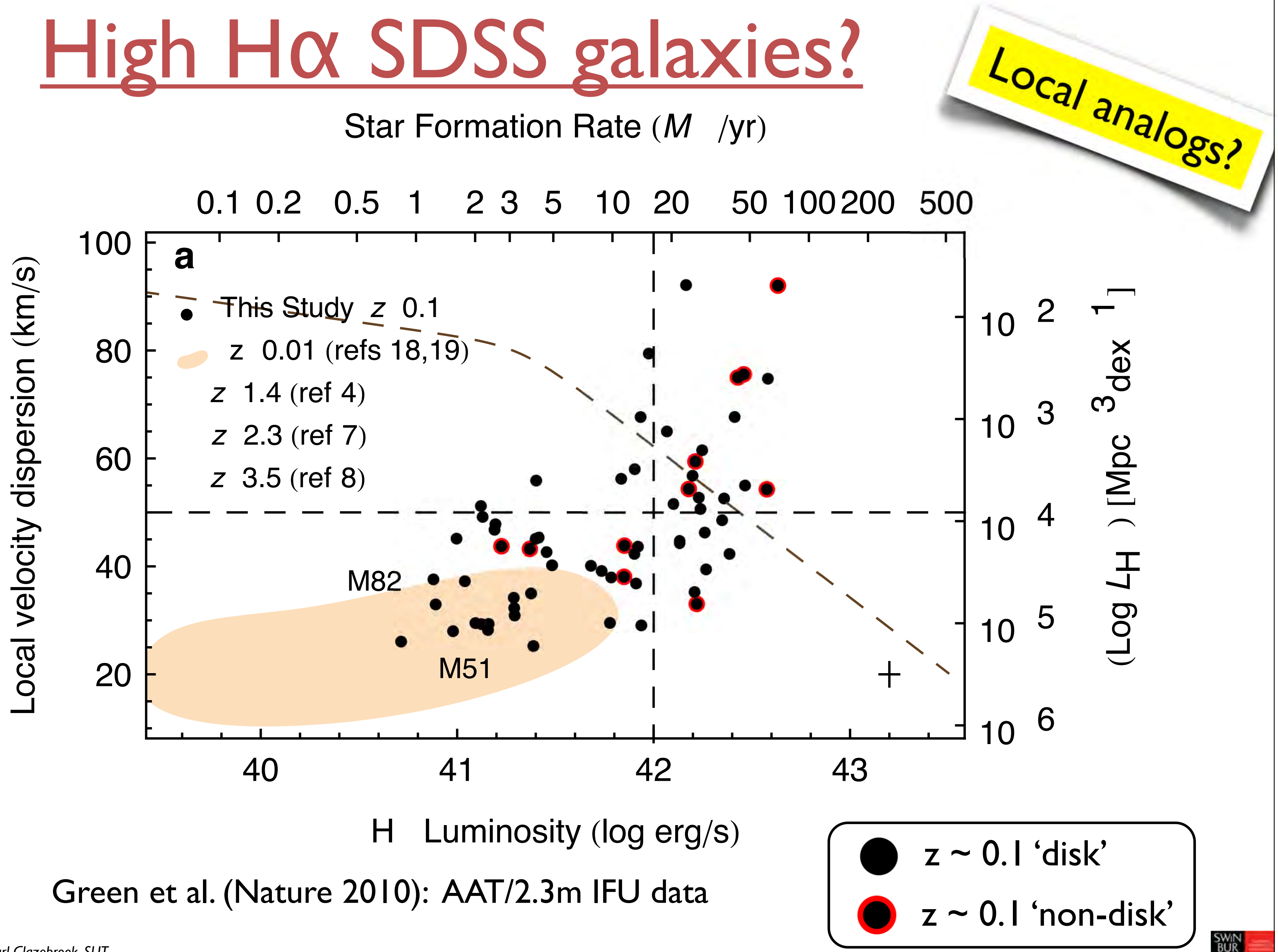
Fractions defined by anomalous kinematics in SFGs:

- Förster-Schreiber et al. 2009 (SINS), ~33% at z~2
- Lopez-Sanjuan et al. 2012 (MASSIV), 21% at z~1
- Yang et al. 2008, (IMAGES), ~26% at z~0.6

T(merg) ~ 1–2 Gyr ⇒ 0.1–0.2 per Gyr or ~ 1–2 since z~2

If these are MAJOR MERGERS is this consistent with in-situ formation being dominant?

High Hα SDSS galaxies?



Green et al. (Nature 2010): AAT/2.3m IFU data

Karl Glazebrook, SUT

The Luminosity Function - The fundamental thing that enters into almost every calculation

The distribution of galaxy luminosities is quantified by the *luminosity function*, ϕ(L). The number of galaxies *d*N located in a volume *d*V with luminosity in the range (L,L+*d*L) is:

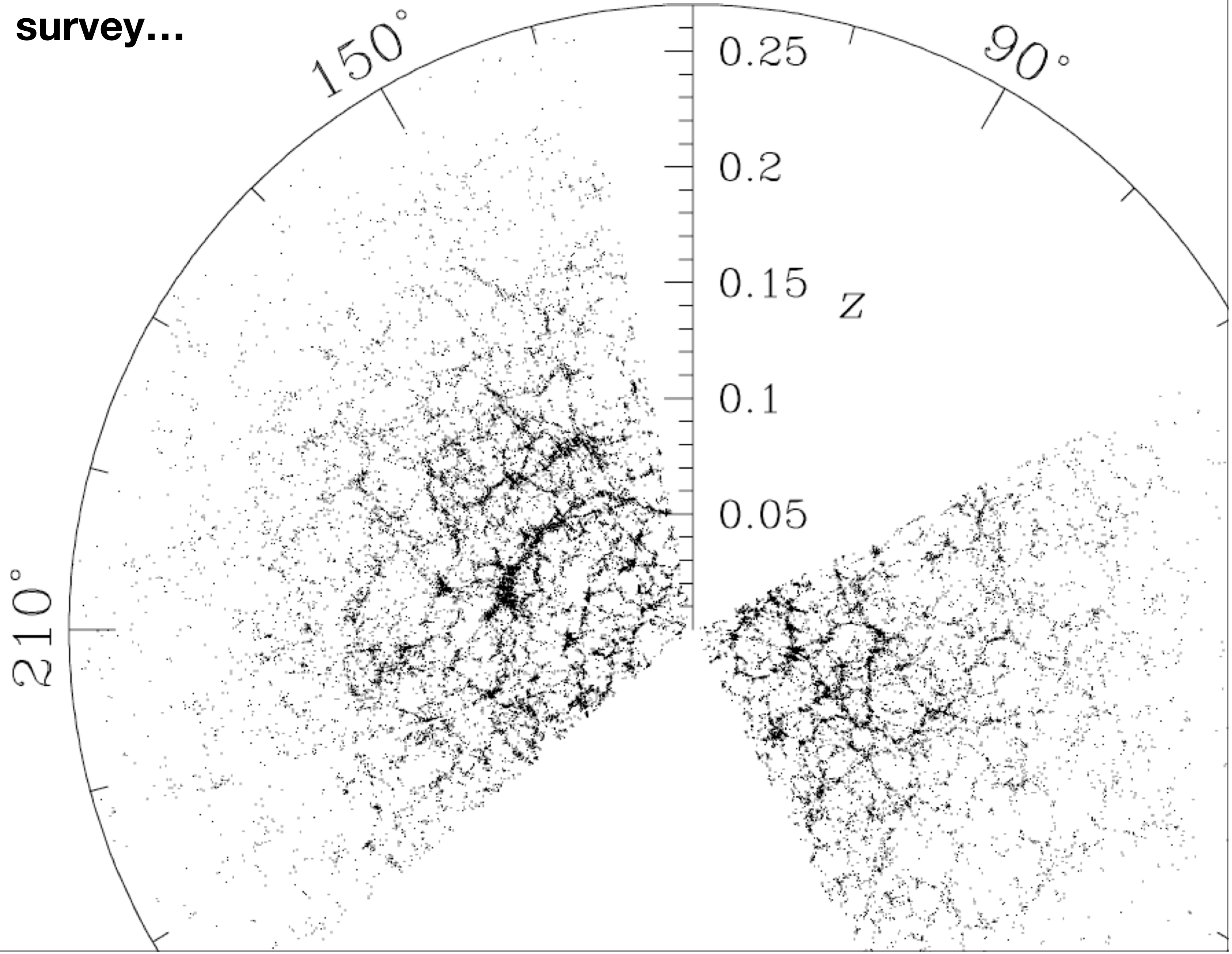
$$dN = \phi(L)\, dL\, dV \tag{1}$$

Note that what we're talking about here is a *universal* luminosity function, that is independent of position! How realistic do you think this is? In principle we should have a luminosity function that depends on position, but we are making two approximations. Firstly, we're assuming the luminosity function is separable from the density function, $D(\vec{r})$, which gives the number of galaxies as a function of position. So, in principle: $\phi(L, \vec{r}) \sim \phi(L) \cdot D(\vec{r})$. Secondly we're assuming $D(\vec{r}) \sim$ constant. But though we're making these assumptions be aware that in reality the luminosity function depends on morphology, environment, bandpass etc, and furthermore the luminosity function evolves with cosmic epoch.

We need to know the luminosity function to interpret *all* of these:

- Galaxy number counts as a function of apparent magnitude and redshift
- Statistics of quasar absorption line systems
- Spatial distributions of galaxies and all things that spring therefrom (eg. gravitational lenses)

You compute a Luminosity Function from a galaxy survey…



SDSS has nailed this!

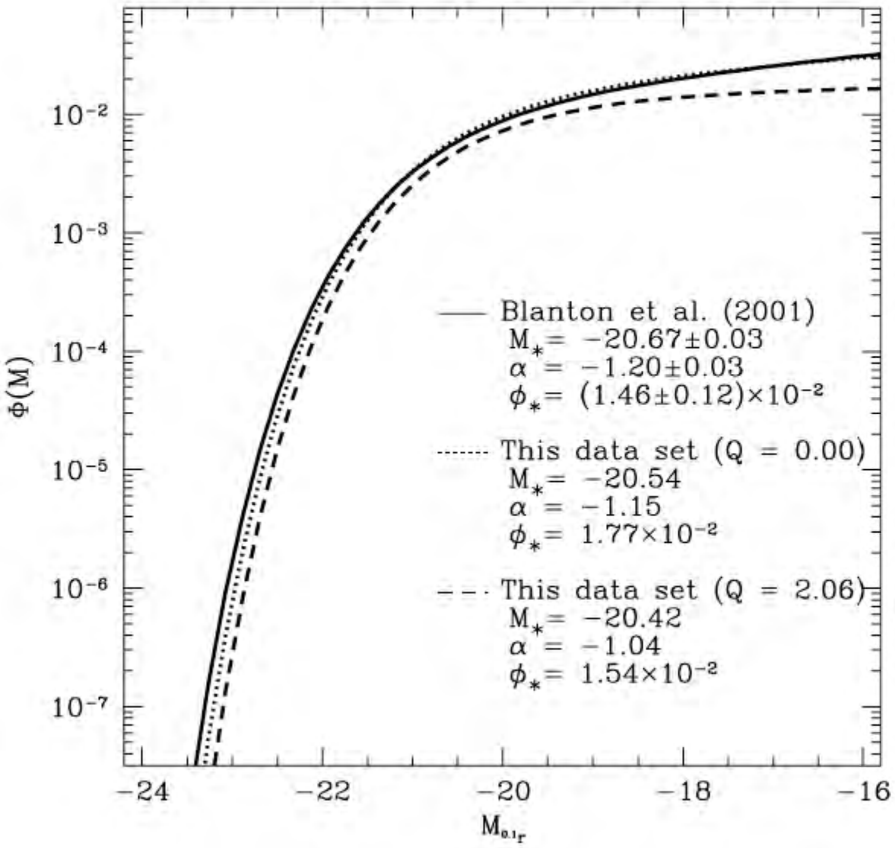
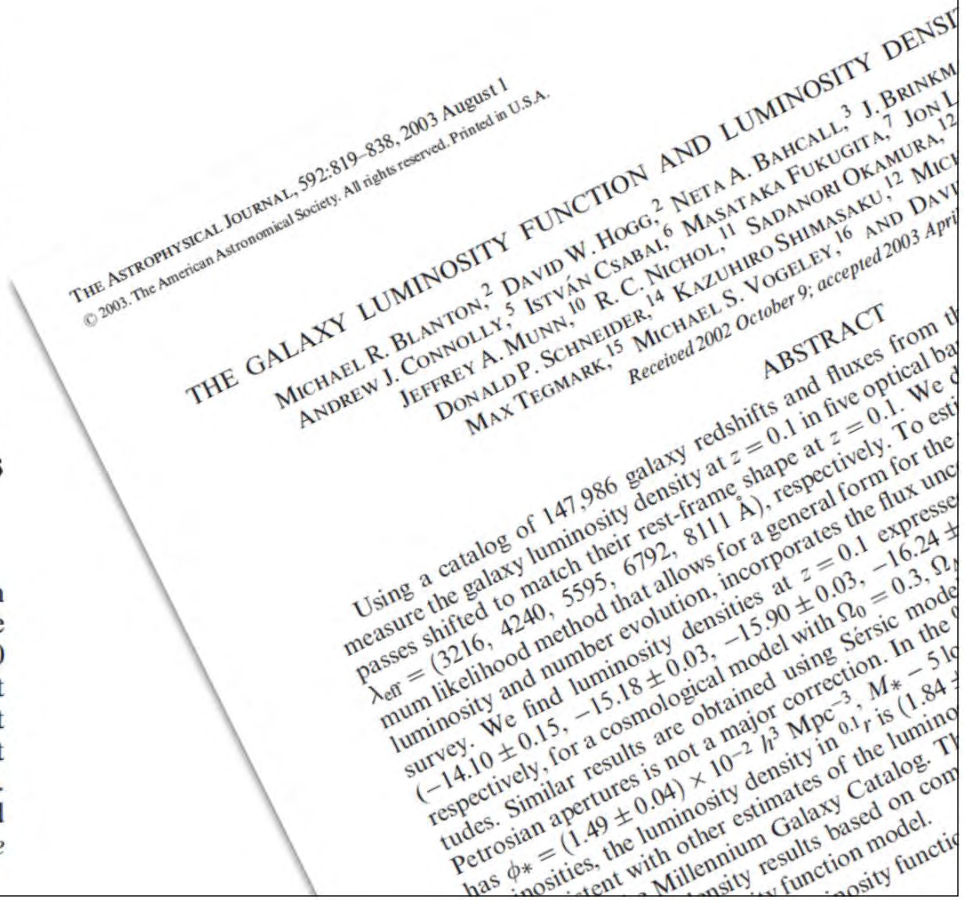


FIG. 15.—Best-fit Schechter function of Blanton et al. (2001), based on the sample of ~10,000 galaxies in sample5 (*solid line*), and a fit using the same method to the current sample of ~150,000 galaxies in sample10 (*dotted line*). These two results are in remarkable agreement, showing that the differences between our results and those of Blanton et al. (2001) are not due to cosmic variance. The dashed line shows a Schechter fit to the current sample allowing for luminosity evolution (finding a best fit of $Q = 2.06$). When evolution is allowed for, the faint-end slope becomes shallower and the overall luminosity density decreases. [*See the electronic edition of the Journal for a color version of this figure.*]



THE ASTROPHYSICAL JOURNAL, 592:819–838, 2003 August 1

THE GALAXY LUMINOSITY FUNCTION AND LUMINOSITY DENSI

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Received 2002 October 9; accepted 2003 April

ABSTRACT

Using a catalog of 147,986 galaxy redshifts and fluxes from th
measure the galaxy luminosity density at $z = 0.1$ in five optical ba
passes shifted to match their rest-frame shape at $z = 0.1$. We d
$\lambda_{\rm eff}$ = (3216, 4240, 5595, 6792, 8111 Å), respectively. To esti
mum likelihood method that allows for a general form for the
luminosity and number evolution, incorporates the flux unc
survey. We find luminosity densities at $z = 0.1$ expresse
(-14.10 ± 0.15, -15.18 ± 0.03, -15.90 ± 0.03, $-16.24 \pm$
respectively, for a cosmological model with $\Omega_0 = 0.3$, Ω
tudes. Similar results are obtained using Sérsic mode
Petrosian apertures is not a major correction. In the
has $\phi_* = (1.49 \pm 0.04) \times 10^{-2}\ h^3$ Mpc^{-3}, $M_* - 5$ lo
nosities, the luminosity density in $^{0.1}r$ is (1.84 ±

The Schechter Function

The most common modern parameterization of the luminosity function is the Schechter function (Schechter 1976, ApJ, 203, 297). This is basically a power law truncated by an exponential (when expressed using linear flux units):

$$n(x)\,dx = \phi_* \, x^{\alpha} \, e^{-x} \, dx \tag{2}$$

where $x = L / L_*$. Note that ϕ_* gives the number density over e at L_*, and α gives the faint-end slope. Remember that L_* does not give precisely the number density at L_*, but rather a number fairly close to this!

This is the Schechter function in units of number per magnitude interval:

$$n(M)\,dM = \frac{2}{5}\,\phi_*\,\ln(10)\left[10^{0.4\,(M_*-M)}\right]^{\alpha+1}\exp\left[-10^{0.4\,(M_*-M)}\right] \tag{3}$$

The Schechter function is characterized by:

- a knee at M_*
- a faint-end slope of $0.4 \cdot (1+\alpha)$
- a normalization ϕ_*

The total number of galaxies per unit volume by a Schechter function is:

$$N = \int_0^\infty \phi(L)\, dL = \phi_* \Gamma(\alpha + 1) \tag{4}$$

where Γ is the incomplete gamma function. For $\alpha = -1.5$ about half the galaxies are brighter than $0.7\, L_*$. The mean luminosity density in galaxies is:

$$< L > = \int_0^\infty L\, \phi(L)\, dL = \phi_* L_* \Gamma(\alpha + 2) \tag{5}$$

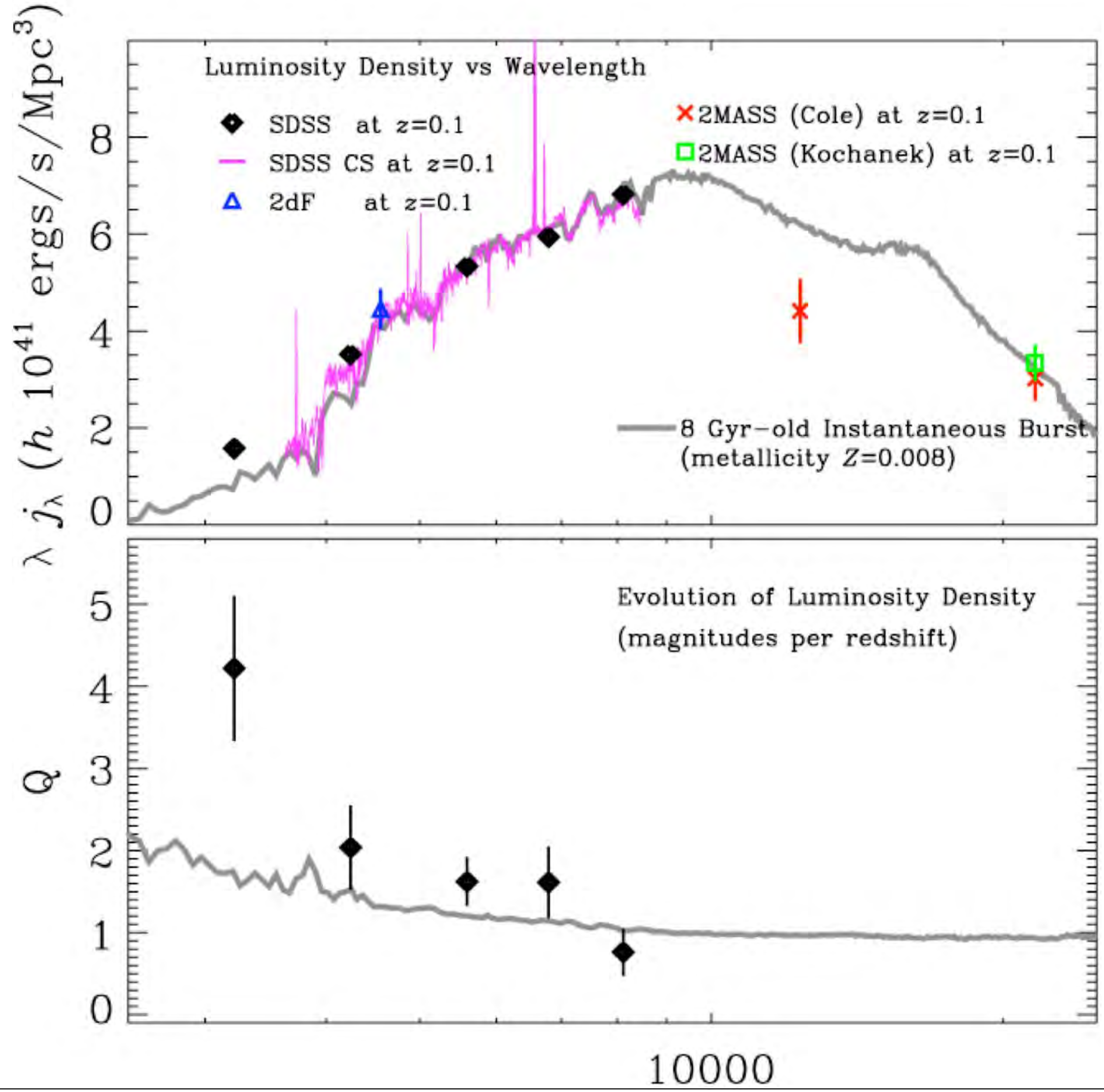
For $\alpha = -1.5$ we find $L_{tot} \sim 1.77\, \phi_*\, L_*$. Note that the mean number density diverges if $\alpha < -1$, but the mean luminosity density diverges only if $\alpha < -2$. Of course in the real universe the integrals should not be taken over the range $(0,\infty)$!

TABLE 2

SCHECHTER FUNCTION FITS

Ω_0	Ω_Λ	Band	ϕ_* ($\times 10^{-2} h^3$ Mpc^{-3})	$M_* - 5 \log_{10} h$	α
0.3..............	0.7	$^{0.1}u$	3.05 ± 0.33	-17.93 ± 0.03	-0.92 ± 0.07
		$^{0.1}g$	2.18 ± 0.08	-19.39 ± 0.02	-0.89 ± 0.03
		$^{0.1}r$	1.49 ± 0.04	-20.44 ± 0.01	-1.05 ± 0.01
		$^{0.1}i$	1.47 ± 0.04	-20.82 ± 0.02	-1.00 ± 0.02
		$^{0.1}z$	1.35 ± 0.04	-21.18 ± 0.02	-1.08 ± 0.02

Blanton et al. (2003) (astro-ph/0210215)



Not all types of galaxy are the same luminosity

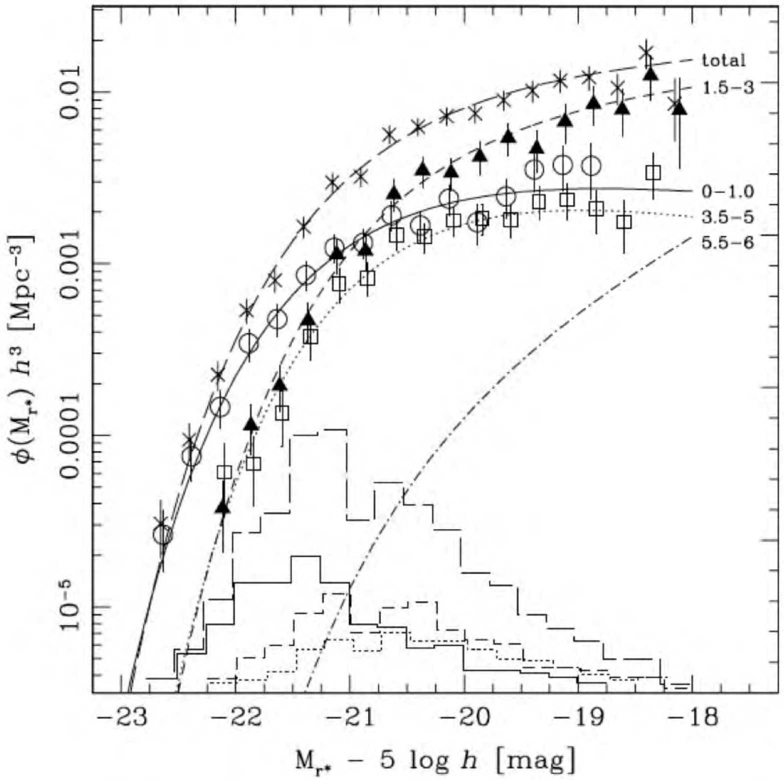
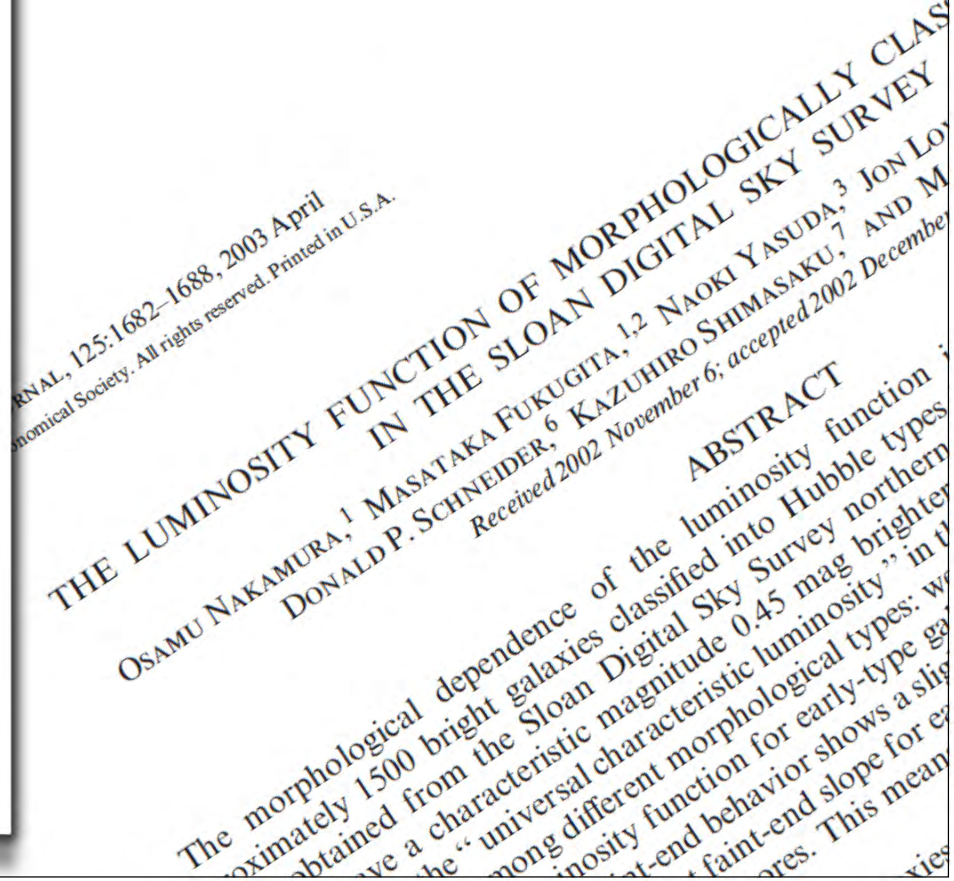
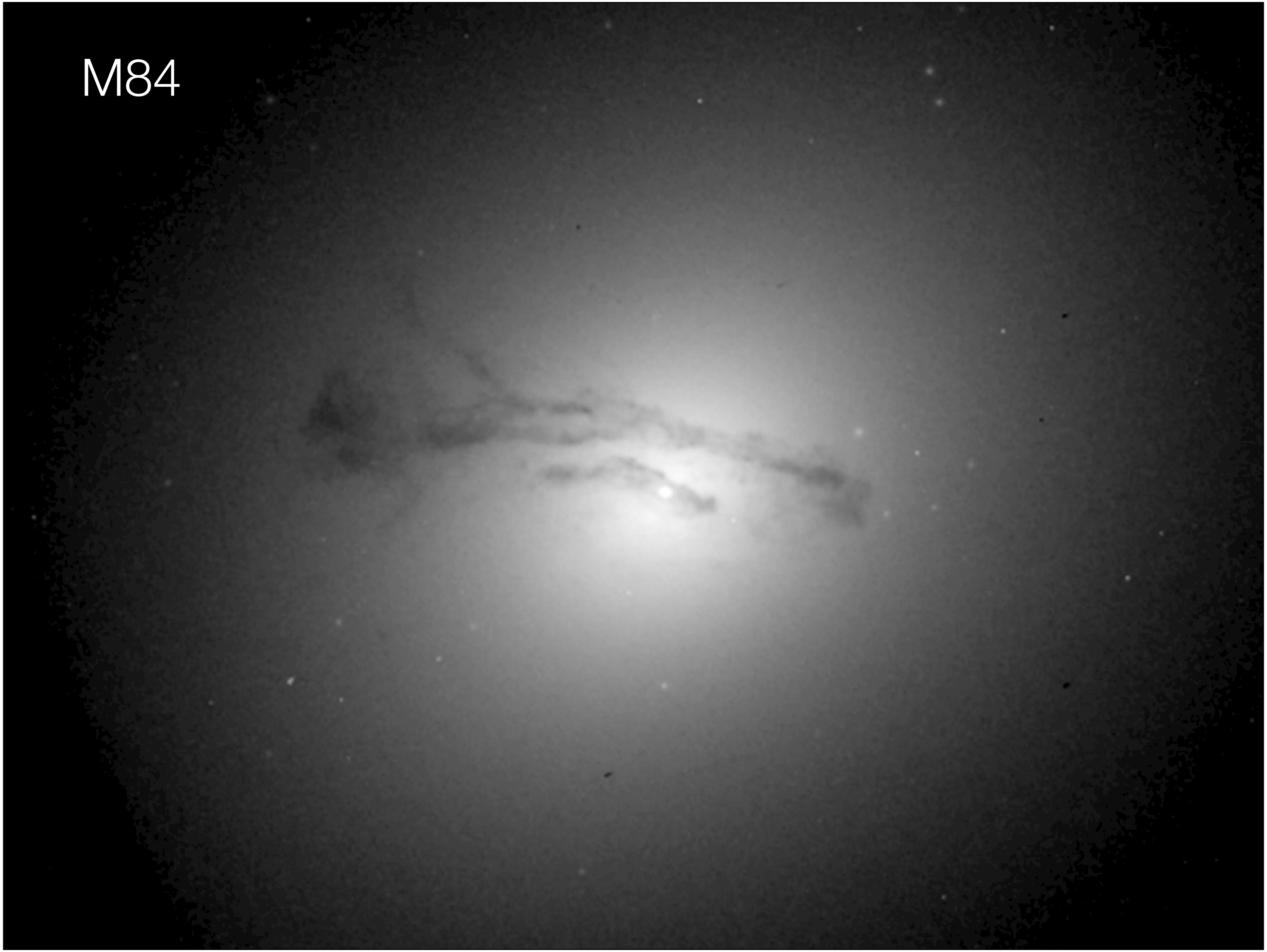


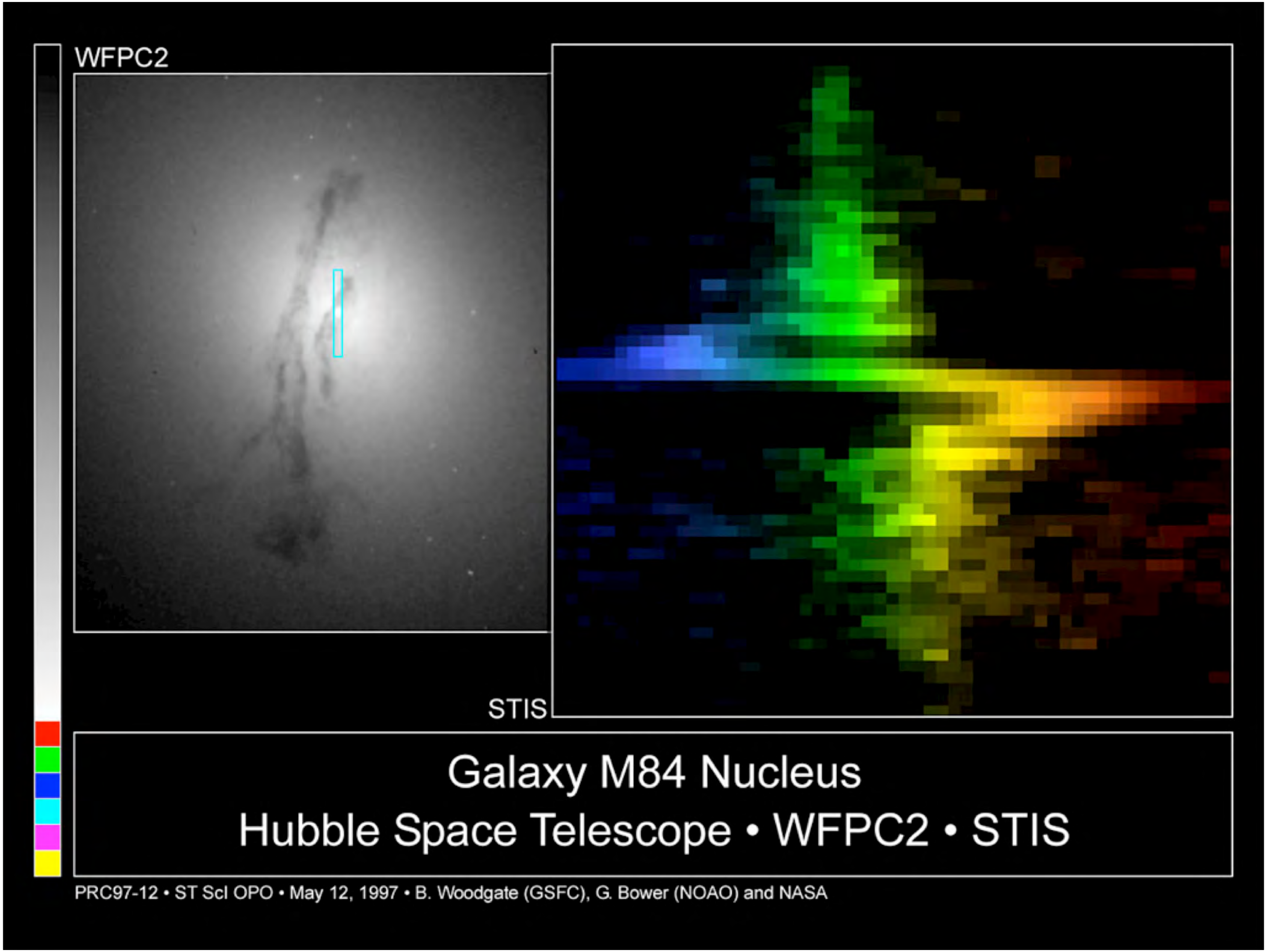
FIG. 3.—MDLF in the r^* band for three types, E–S0, S0a–Sb, and Sbc–Sd, from visual classifications. The SWML results are represented by data points (*circles*, E–S0; *triangles*, early spiral galaxies; *squares*, late-type spiral galaxies), and the ML fits are shown by solid, short-dashed, and dotted curves, respectively. The ML estimate for Im galaxies is represented by the dot-dashed curve. The luminosity function for the total sample is also plotted for comparison, represented by crosses and the long-dashed curve. The histograms are the actual numbers of galaxies for the three types and the total sample used in this analysis.



End of Huge Digression

How could we forget the central black holes?


M84


WFPC2
STIS
Galaxy M84 Nucleus
Hubble Space Telescope • WFPC2 • STIS
PRC97-12 • ST ScI OPO • May 12, 1997 • B. Woodgate (GSFC), G. Bower (NOAO) and NASA

Bower et al. 1998 - an early example

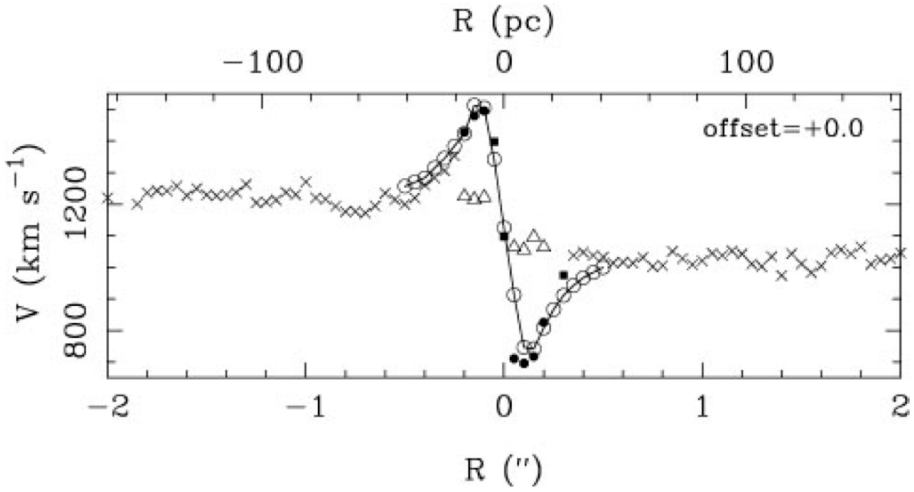


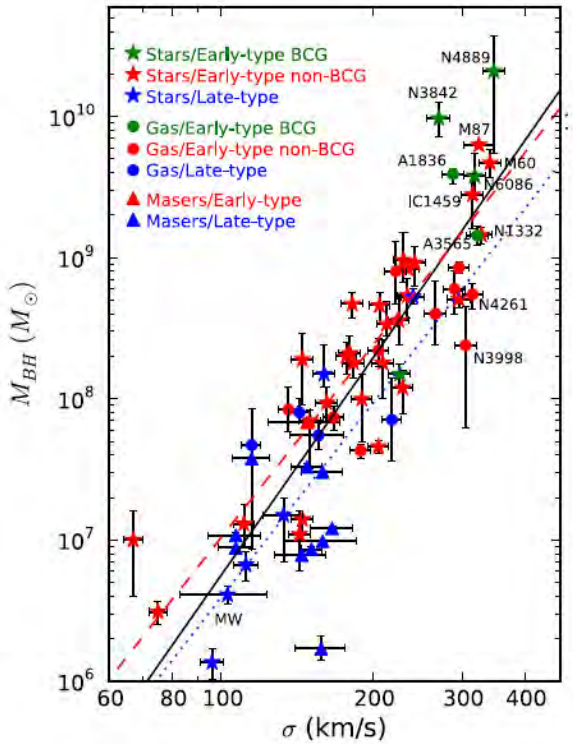
TABLE 1

KEPLERIAN DISK MODEL PARAMETERS

Parameter	Best Fit	Uncertainty Range
Black hole mass ($M_\odot$)	1.5×10^9	$(0.9\text{–}2.6) \times 10^9$
Disk inclination (deg)	80	75–85[a]
Disk P.A. (deg)	83	80–85
Gas systemic velocity (km s^{-1})	1125	1100–1150
Intensity law	$I(r) \propto r^{-1}$	...
$I(r)$ inner radius (pc)	1	0.3–3
$V(r)$ inner radius (pc)	0.03	0.01–0.1
PSF σ (arcsec)	0.05	0.04–0.06

[a] Lower mass requires lower inclination.

McConnell et al. 2011 – Recent synthesis



The M-sigma relation

$$\frac{M}{10^8 M_\odot} \approx 1.9 \left(\frac{\sigma}{200 \text{ km s}^{-1}} \right)^{5.1} .$$

Looks probable that every bulge contains a supermassive black hole