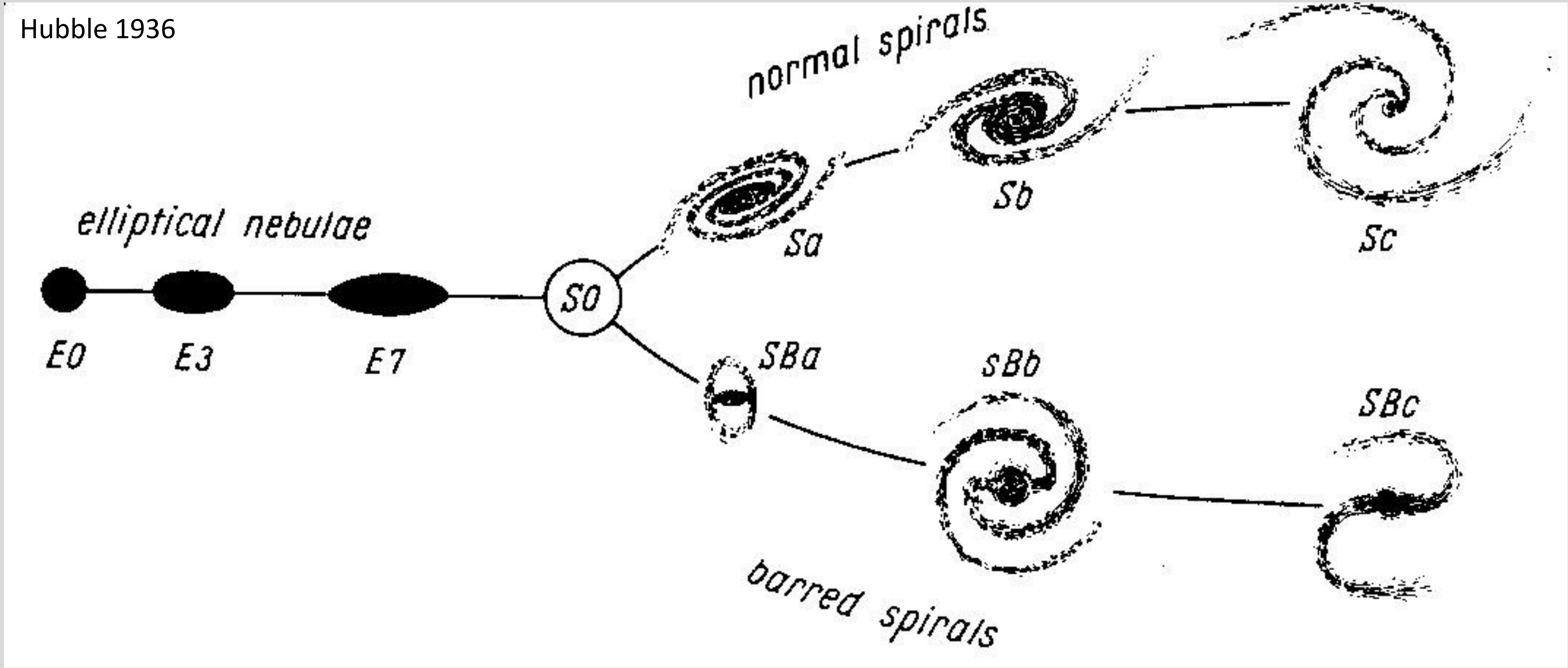
Galaxies: Types and Properties

Hubble Sequence ("The Tuning Fork"): The most basic of classification schemes: visual morphology.



Ellipticals: EN

$$N = 10\left(1 - \frac{b}{a}\right)$$

S0 ("Lenticulars")
intermediate type,
disky but smooth

Spirals: Sa,Sb,Sc
tightness of spiral
prominence of bulge

Barred Spirals: SBa, SBb, SBc
presence of central bar
otherwise like Spiral

Galaxies: Types and Properties

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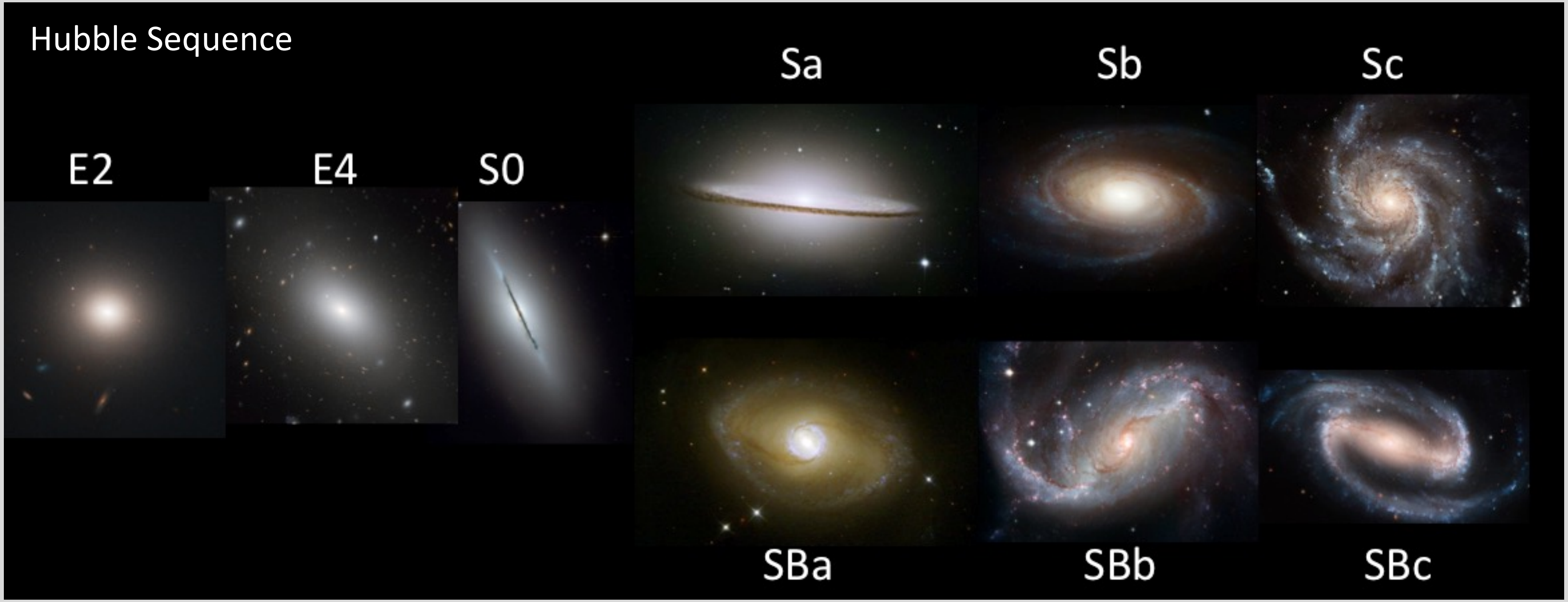

Extensions
(de Vaucouleur)

Sd
(diffuse spiral)

Sm
(irregular spiral)

Irr
(very irregular)

Ellipticals: EN

$$N = 10\left(1 - \frac{b}{a}\right)$$

S0 (“Lenticulars”)
transitional type
disky but smooth

Spirals: Sa,Sb,Sc
tightness of spiral
prominence of bulge

Barred Spirals: SBa, SBb, SBc
presence of central bar
otherwise like Spiral

Galaxies: Types and Properties

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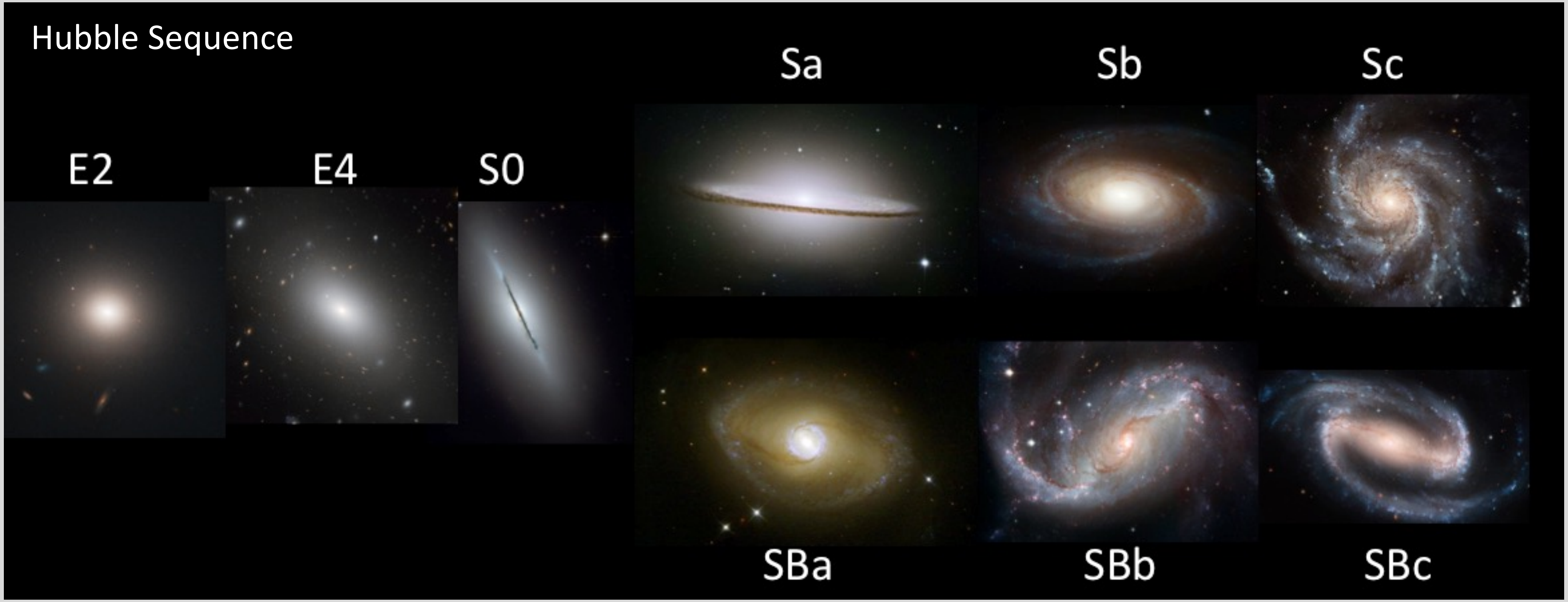


Extensions
(de Vaucouleur)

Sd
(diffuse spiral)

Sm
(irregular spiral)

Irr
(very irregular)

"Early" → "Late"

"T-type":

-5	-2	0	2	3	5	8-10

Galaxies: Types and Properties

Many, many other classification schemes exist:

Morphology, colors, bulge:disk ratio, spectral properties, structural properties, star forming properties, luminosity classes, kinematic properties, etc, etc.

Classifications for MESSIER 101

1 of 2 (1 - 100 of 132)

Domain	Published Classification	Refcode	NED Homogenized Classificati
Luminosity Class	Sc(s) I	1981RSA...C...0000S	LC I
Galaxy Morphology	SAB(rs)cd	1991RC3.9.C...0000d	SAB(rs)cd
Galaxy Morphology	Sc(s)	1981RSA...C...0000S	S(s)c
Galaxy Morphology	WR	1999A&AS..136...35S	Wolf-Rayet Galaxy
Galaxy Morphology	Sc	1973UGC...C...0000N	Sc
Galaxy Morphology	spiral with one heavy arm	1966ApJS...14....1A	spiral with one heavy arm
Galaxy Morphology	AC 09	1987ApJ...314....3E	Arm Class 09
Galaxy Morphology	2	1975SoByu..47...43A	flat central luminosity profile
Galaxy Morphology	multi-armed spiral	1994CAG1..B...0000S	multi-armed spiral
Galaxy Morphology	arms branch into multiple	1994CAG1..B...0000S	arms branch into multiple fragmer
Galaxy Morphology	Type 1 XUV disk	2007ApJS..173..538T	Type 1 XUV disk
Galaxy Morphology	lopsided galaxy	1980MNRAS.193..313B	lopsided galaxy

Galaxies: Types and Properties

Many, many other classification schemes exist:

Morphology, colors, bulge:disk ratio, spectral properties, structural properties, star forming properties, luminosity classes, kinematic properties, etc, etc.

Classifications for MESSIER 087

1 of 1 (1 - 96 of 96)

Domain	Published Classification	Refcode	NED Homogenized Classificati
Hierarchy	GM	1975SSS.....9..557d	Group member
Galaxy Morphology	cD pec	1991RC3.9.C...0000d	cD0-1 pec
Galaxy Morphology	E0	1981RSA...C...0000S	E0
Galaxy Morphology	E	1973UGC...C...0000N	E
Galaxy Morphology	galaxy with jet	1966ApJS...14....1A	jet
Galaxy Morphology	E	2002MNRAS.333..423T	E
Galaxy Morphology	3	1975SoByu..47...43A	no nucleus
Galaxy Morphology	3	1975SoByu..47...43A	continuous brightening towards c
Galaxy Morphology	jet	1994CAG1..B...0000S	jet
Galaxy Morphology	Jet	1988AJ.....95..422E	jet
Galaxy Morphology	smooth nebulosity	1964RC1...C...0000d	smooth nebulosity
Galaxy Morphology	extremely bright center	1964RC1...C...0000d	extremely bright center
Galaxy Morphology	blue jet	1964RC1...C...0000d	blue jet

Galaxies: Types and Properties

Many, many other classification schemes exist:

Morphology, colors, bulge:disk ratio, spectral properties, structural properties, star forming properties, luminosity classes, kinematic properties, etc, etc.

Classifications for MESSIER 082

1 of 1 (1 - 40 of 40)

Domain	Published Classification	Refcode	NED Homogenized Classificati
Kinematics	HI line width	1961BAN....15..307V	HI line width
Galaxy Morphology	I0 edge-on	1991RC3.9.C...0000d	I0 edge-on
Galaxy Morphology	Amorphous	1981RSA...C...0000S	Amorphous
Galaxy Morphology	IRR	1973UGC...C...0000N	Irr
Galaxy Morphology	2s	1975SoByu..47...43A	structured nuclear region
Galaxy Morphology	high-surface-brightness d	1994CAG1..B...0000S	high-surface-brightness disk
Galaxy Morphology	dusty	1994CAG1..B...0000S	dusty
Galaxy Morphology	amorphous	1994CAG1..B...0000S	amorphous
Galaxy Morphology	Sm	1979AISAO..11....3K	Sm
Galaxy Morphology	nb/d	2011ApJ...733L..47F	no bulge
Radio Morphology	I	1983MNRAS.204..151L	FR I
Radio Morphology	C I	1974MNRAS.167P..31F	FR I C

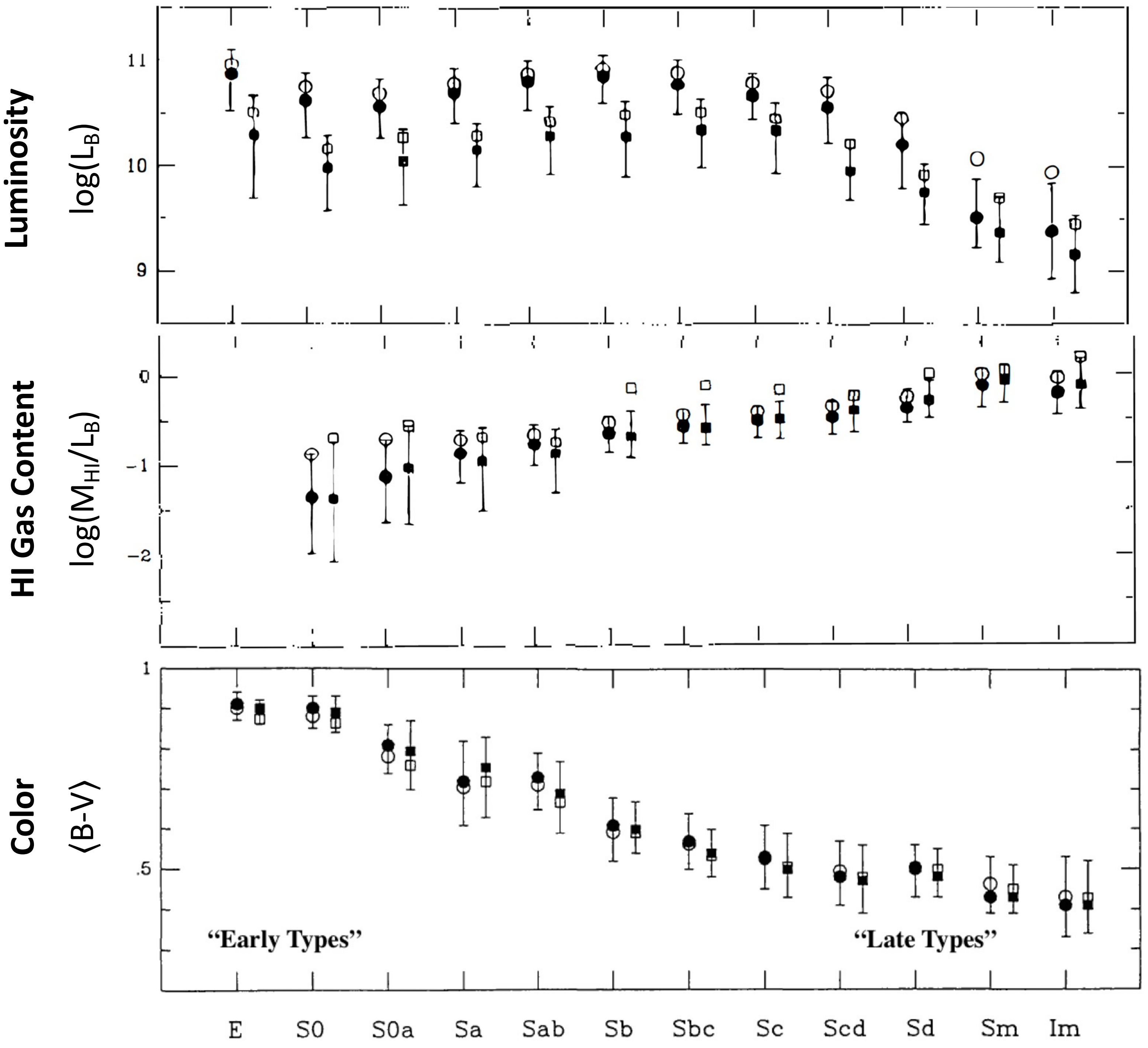
Trends along the Hubble Sequence

Later-type galaxies *tend to be*

- lower in luminosity
- more gas rich
- bluer in color

than early-type galaxies.

(caveat: this is for bright galaxies; dwarf galaxies behave differently...)



data catalogs: RC3, UGC

open symbols ⇒ mean
filled symbols ⇒ median
errorbars ⇒ 25-75% range

Roberts & Haynes 94 ARAA

Galaxies: Luminosities

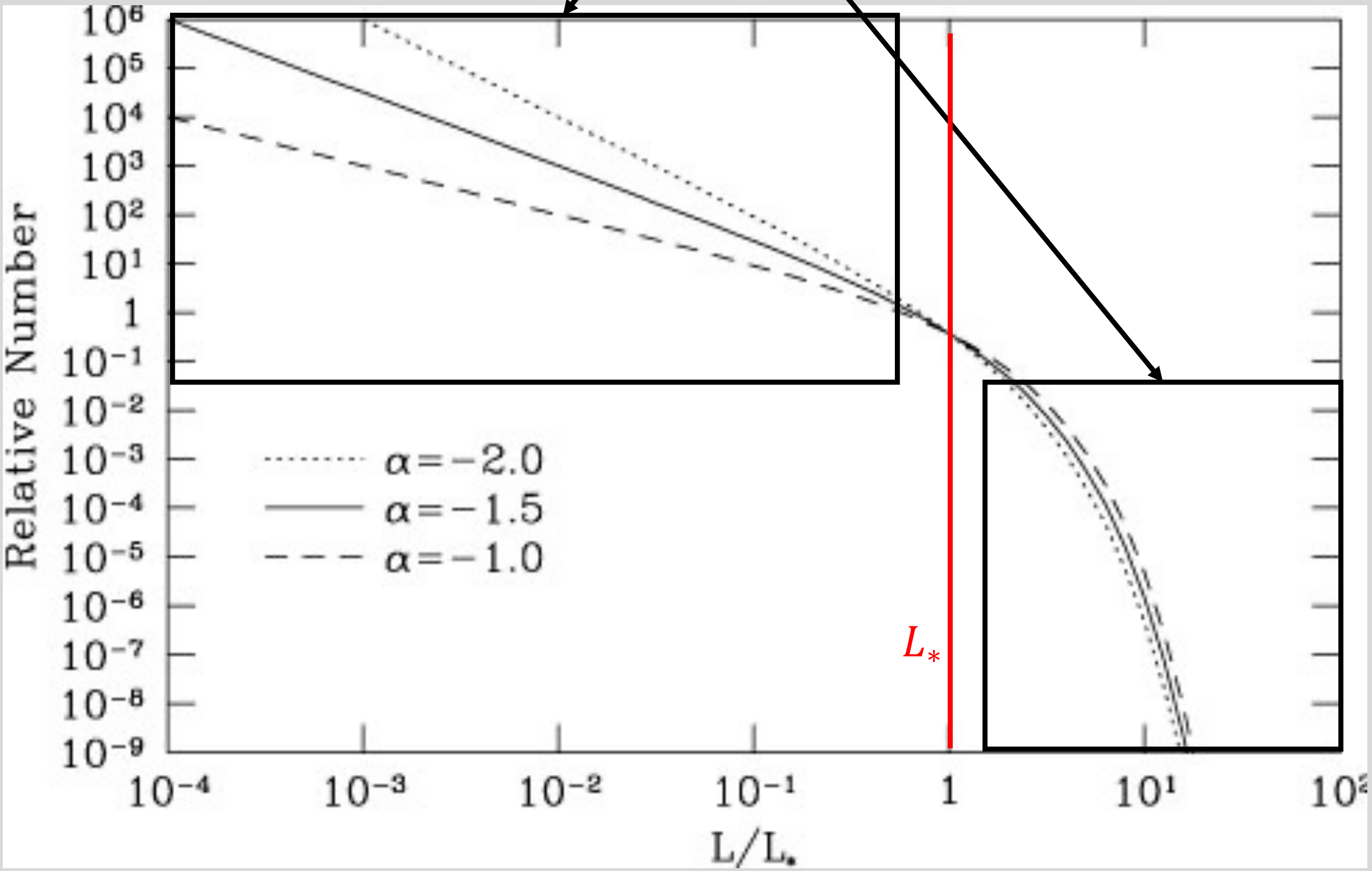
Luminosity function: number of galaxies (per unit volume) in a luminosity range L ⇒ L + dL

Common parameterization is the **Schechter Function**: $\Phi(L)dL = \Phi_* \boxed{\left(\frac{L}{L_*}\right)^\alpha} \boxed{e^{(-L/L_*)}} dL$

$\mathbf{\Phi}_*$: overall density (units = #/Mpc^3)

L_*: characteristic luminosity, the “knee” of the luminosity function

α: faint end power law slope



Galaxies: Luminosities

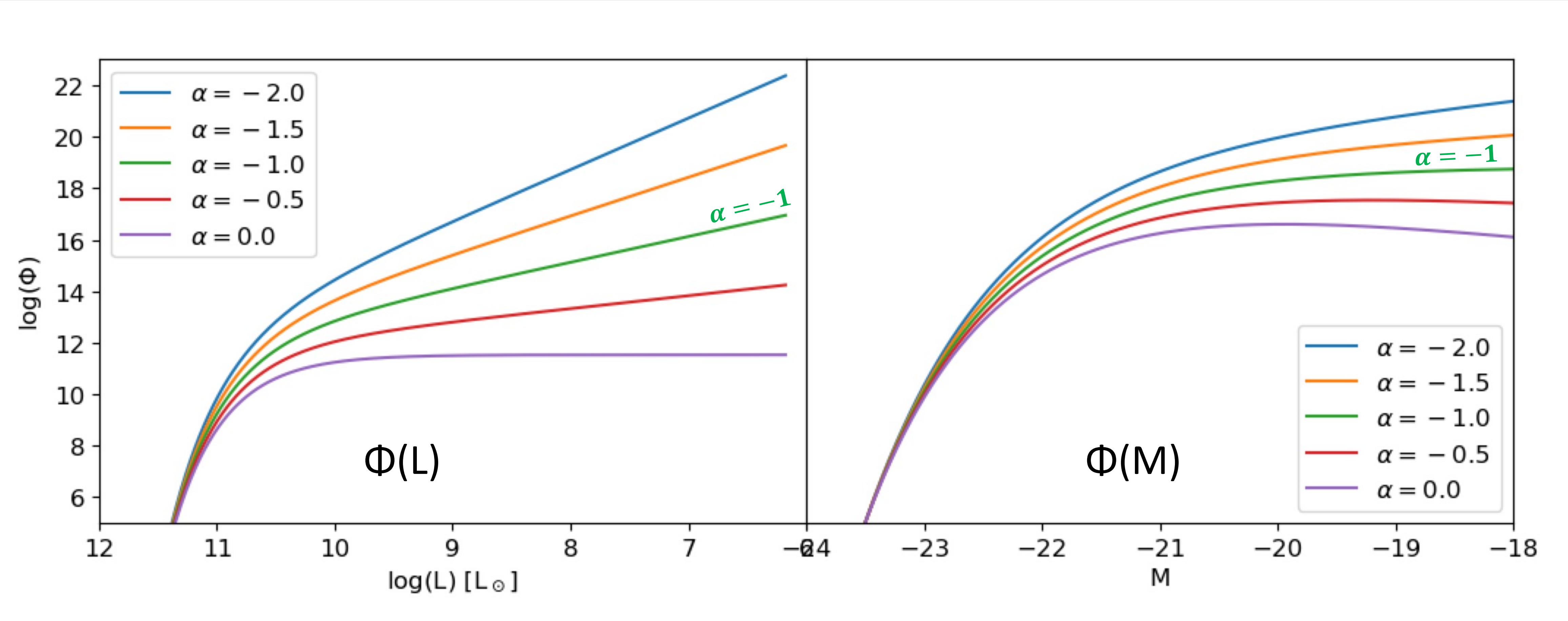
We usually work in magnitudes, looking at the number in an absolute magnitude bin M ⇒ M + dM

The Schechter LF looks different expressed in magnitudes (Φ(M) dM) rather than luminosity (Φ(L) dL)

since $M = -2.5\, log\, L + C$, *this means*

$$dM \sim \frac{dL}{L}$$

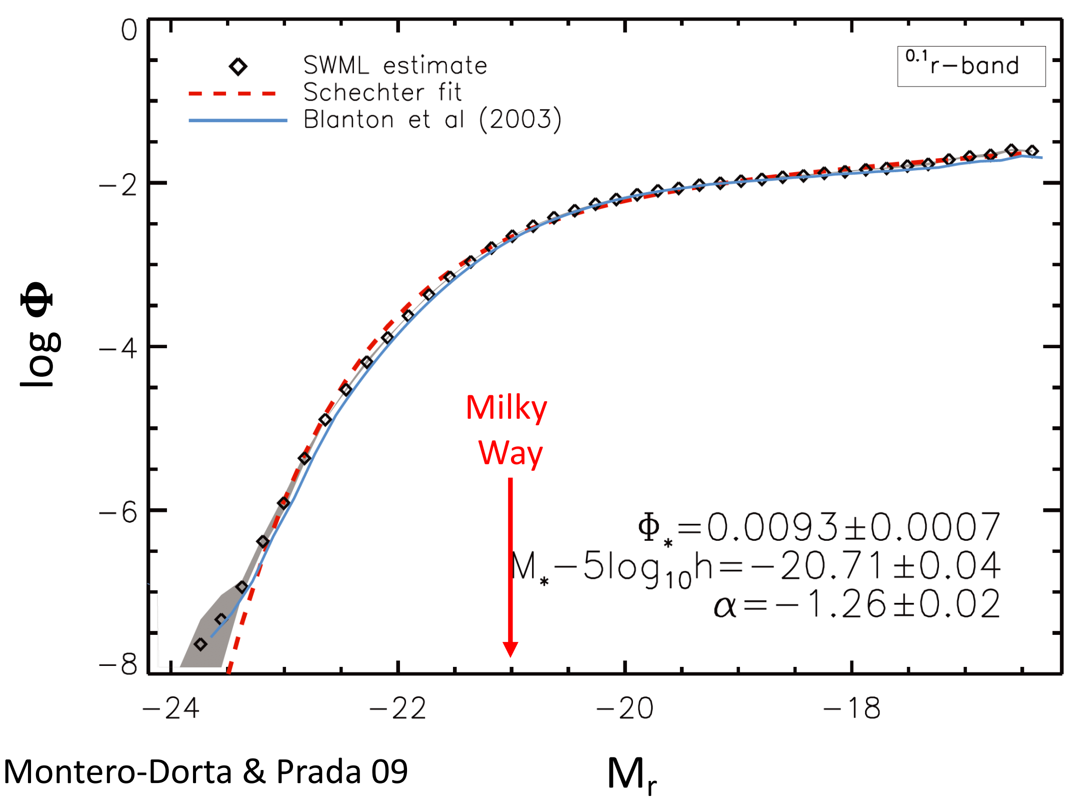
so a magnitude bin is a fractional luminosity bin.



Note: α=−1 is referred to as “flat” because of its shape in magnitude plots, not luminosity plots.

Galaxies: Luminosities

Luminosity function depends on many things, including filter choice and galaxy color….



Montero-Dorta & Prada 09

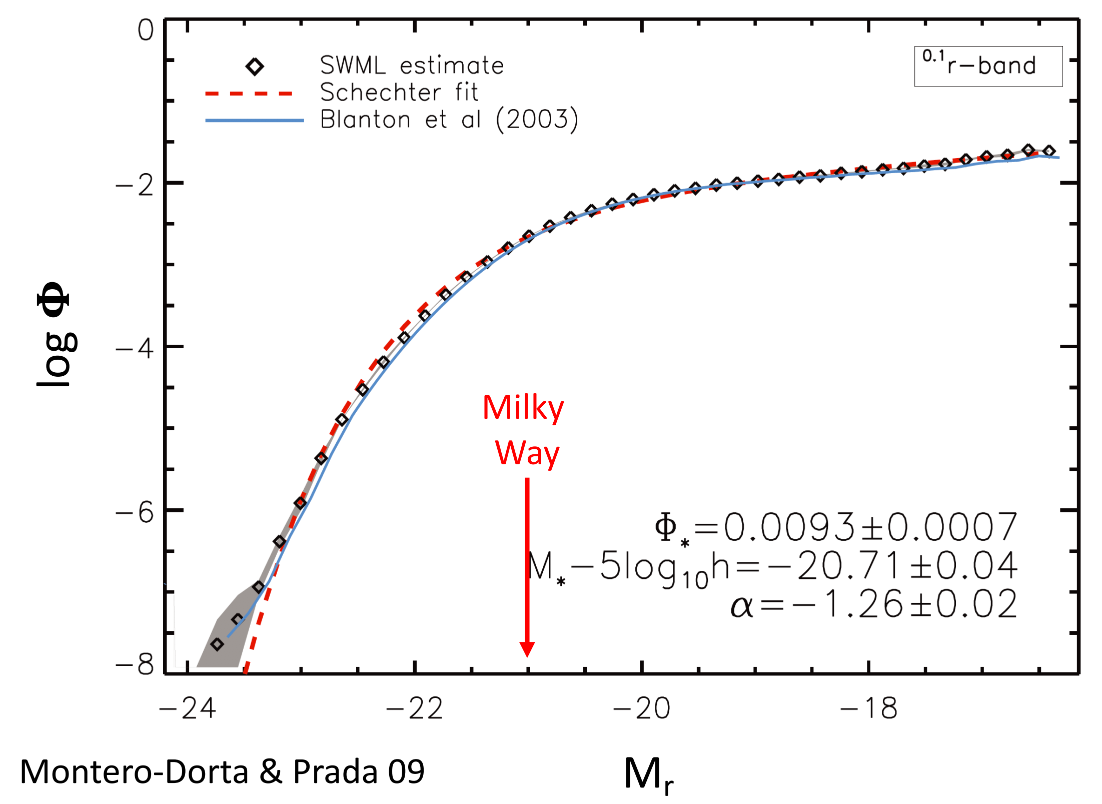
All Galaxies

What's this $M_* - 5\,log\,h$ stuff?

Distances have been derived from the Hubble relation: $v = H_0 d$. So their distances and absolute magnitudes depend on the assumed Hubble constant. We define $h = H_0/100$, and can then scale the magnitude to any Hubble constant we want.....

Galaxies: Luminosities

Luminosity function depends on many things, including filter choice and galaxy color….



All Galaxies

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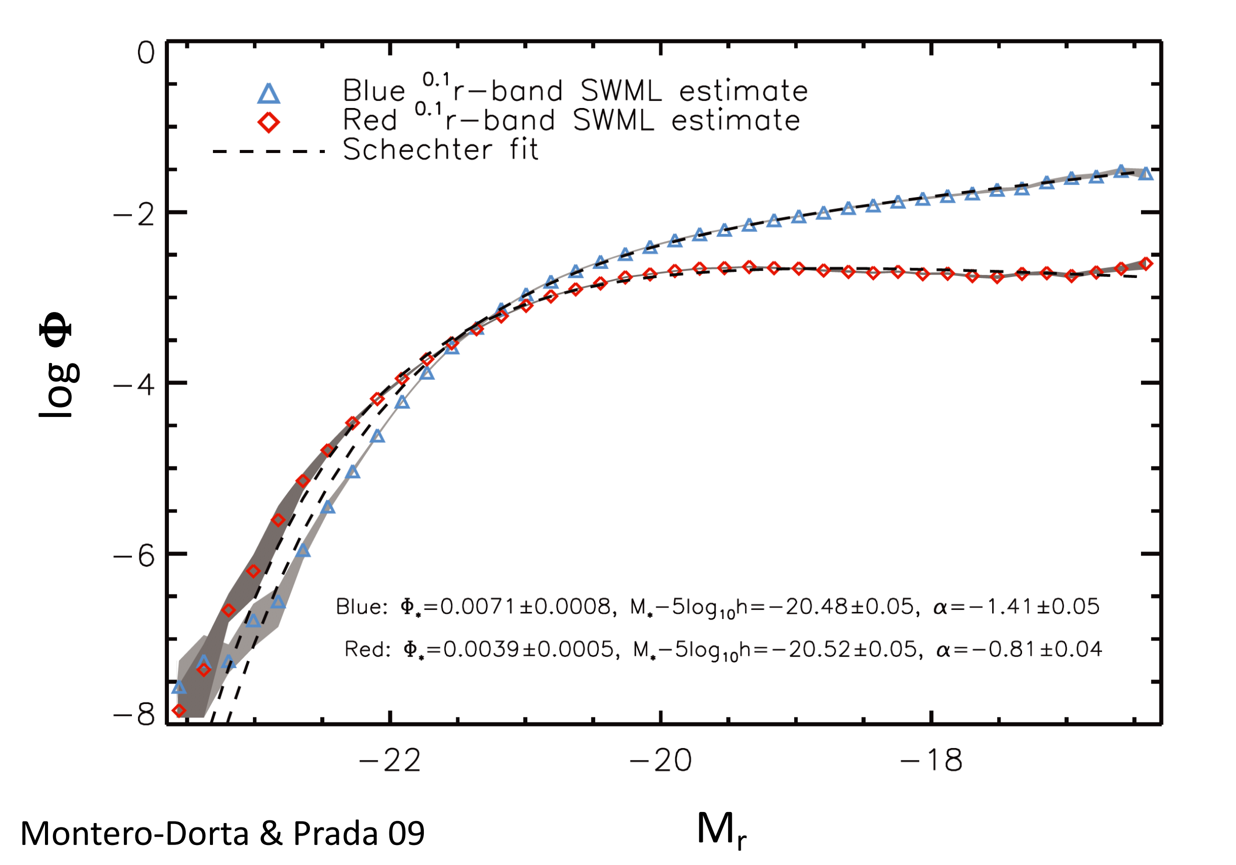


By Color

Brightest galaxies tend to be red
Blue galaxies dominate the counts at fainter magnitudes

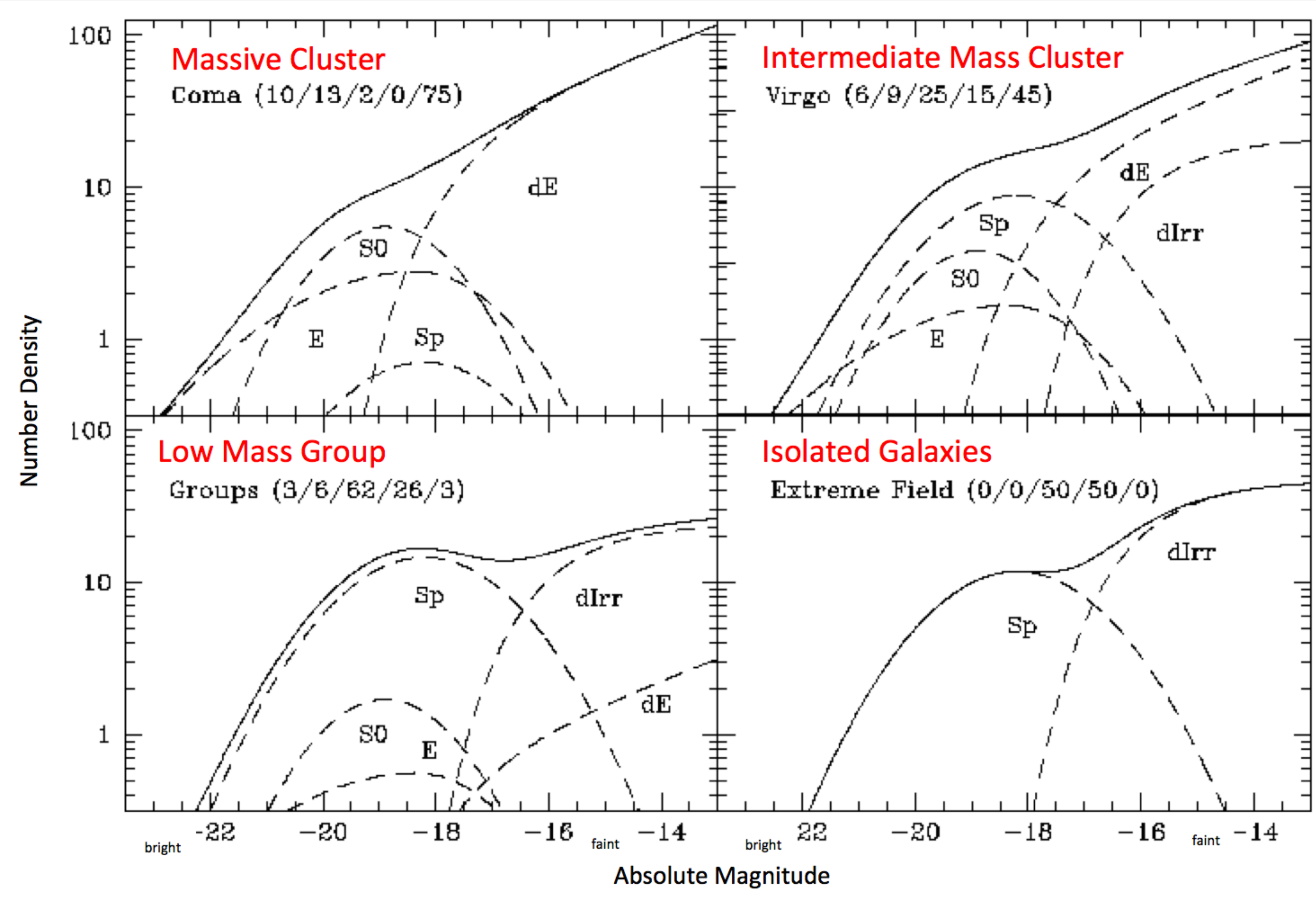
Galaxies: Luminosities

…and a very strong dependence on galaxy type and environment

These are schematic LFs, not real

Inside big galaxy clusters:
- E/S0 dominate
- faint end mostly red things

In groups and field:
- Spirals dominate
- faint end mostly blue things



E = Elliptical dE = dwarf elliptical
S0 = S0 dIrr = dwarf irregular
Sp = Spiral

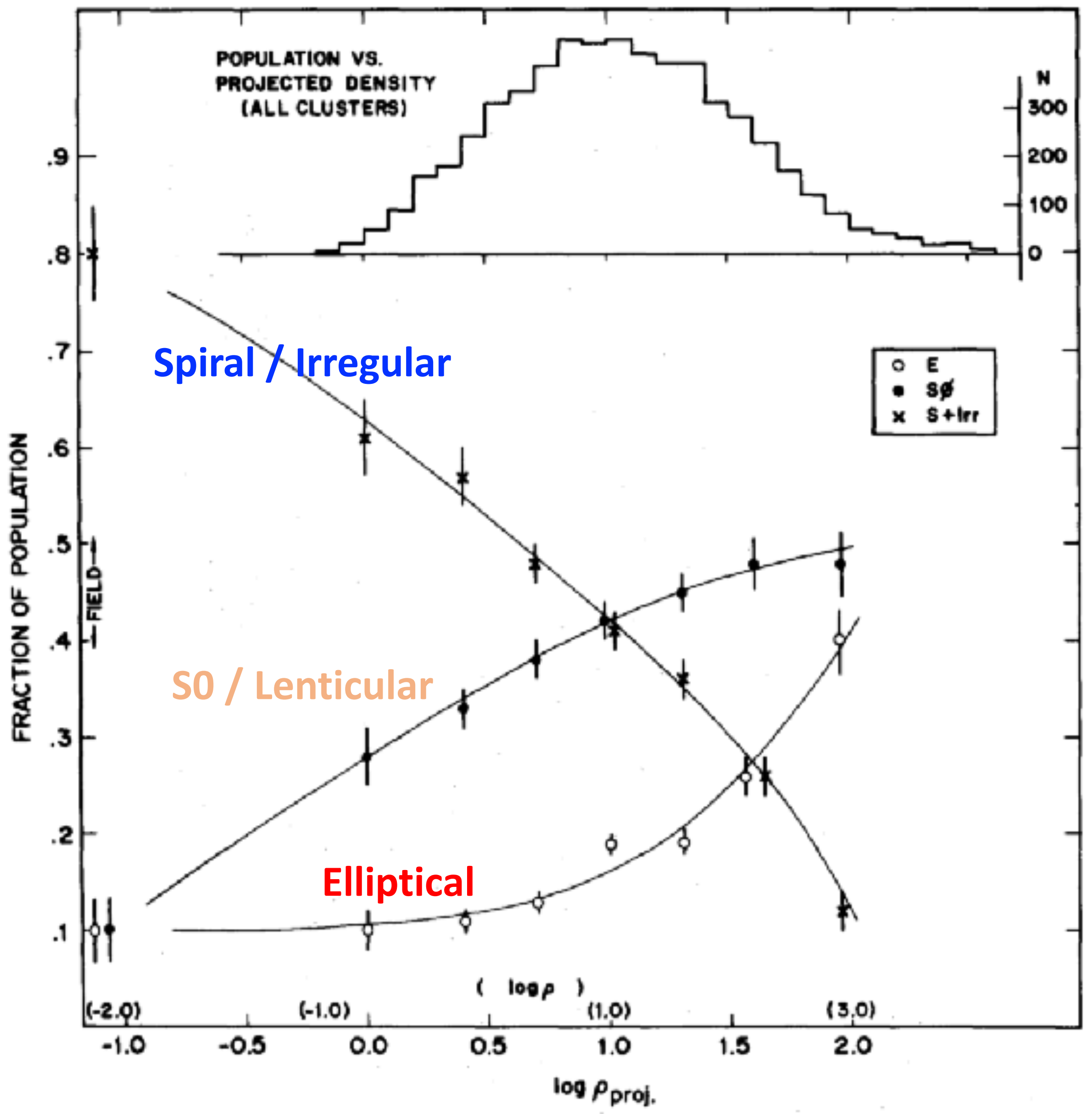
Galaxies: Morphology-Density Relationship

In the local universe, the fraction of galaxy types is a strong function of local environment.

Spirals/Irregulars dominate the in the field environment.

S0's and E's dominate in galaxy clusters.

Galaxy Population Fraction



Dressler 1980

Projected Number Density of Galaxies log(# per Mpc^2)

Galaxy Structure: Surface Brightness Profiles

Remember, surface brightness is intrinsic, does not depend on distance:

Surface Brightness [μ in mags/arcsec²] ⇒
Flux Density on Sky [I in erg/s/cm²/arcsec²] ⇒
Luminosity Density in Galaxy [Σ in L⊙/pc²]

Galaxy Disks: roughly exponential with radius:

$$I(r) = I_0 e^{-r/h}$$

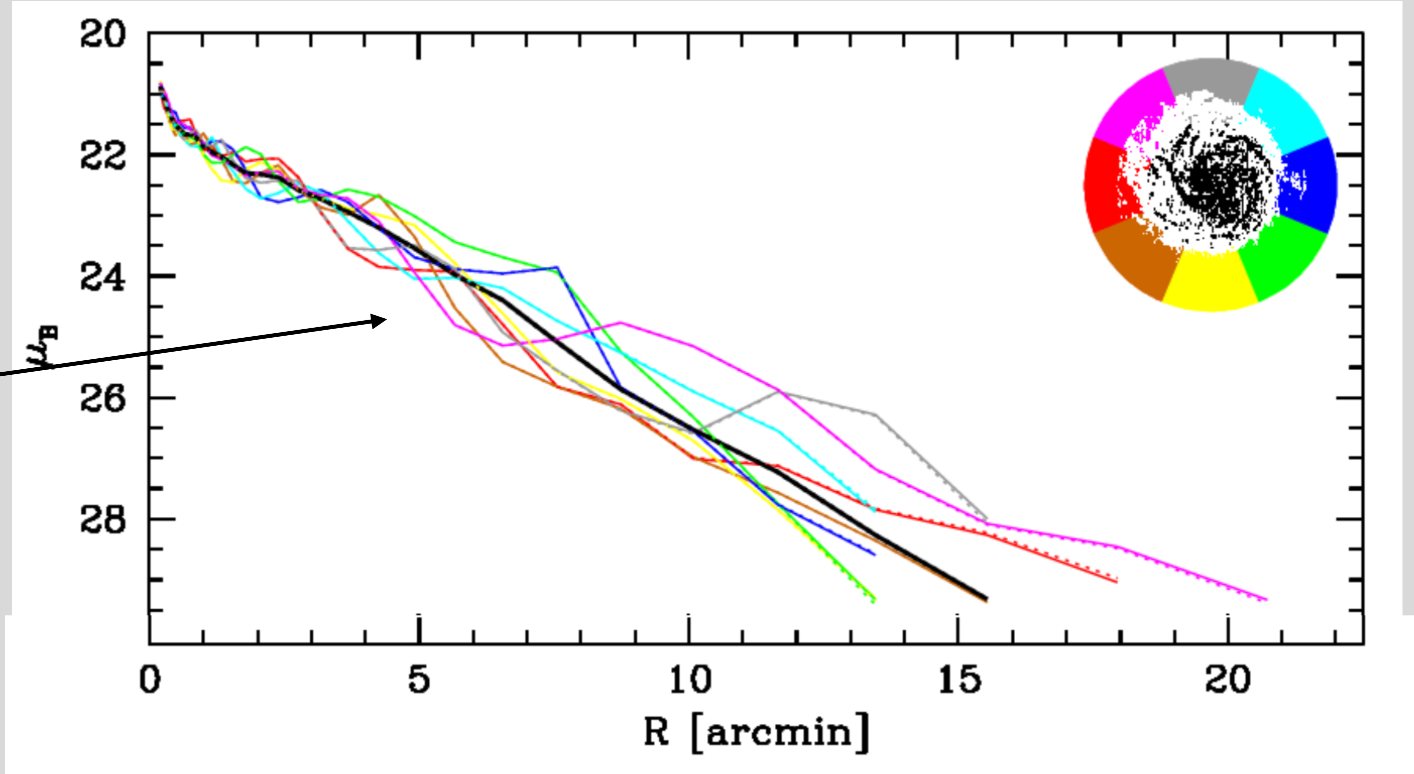
or, expressed in mag/arcsec²:

$$\mu(r) = \mu_0 + \frac{2.5}{h \ln(10)} r$$

this is the equation for a line

so surface brightness falls linearly with radius.

where
- h : exponential scale length
- μ_0 : central surface brightness

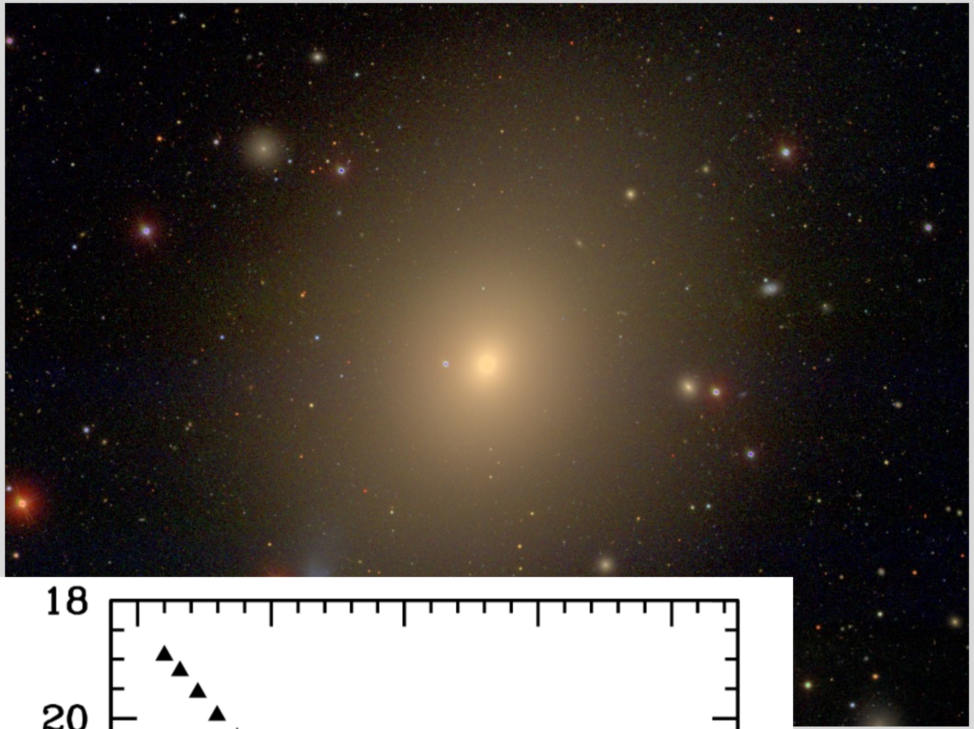


then total mag is: $m_{tot} = \mu_0 - 2.5 \log(2\pi h^2)$

Galaxy Structure: Surface Brightness Profiles

Remember, surface brightness is intrinsic, does not depend on distance:

Surface Brightness [μ in mags/arcsec²] ⇒
Flux Density on Sky [I in erg/s/cm²/arcsec²] ⇒
Luminosity Density in Galaxy [Σ in L⊙/pc²]



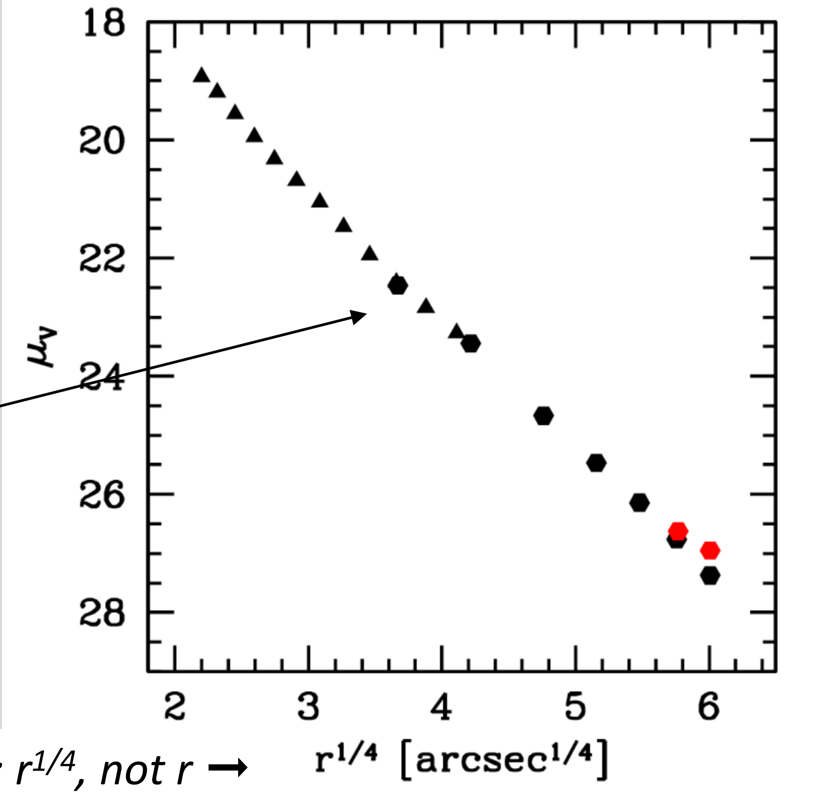
Ellipticals and Spiral Bulges:
classically, a de Vaucouleur "r-to-the-quarter" law:

$$I(r) = I_e e^{-7.669\left[(r/r_e)^{1/4}-1\right]}$$

or in mag/arcsec²:

$$\mu(r) = \mu_e + 8.3265\left[(r/r_e)^{1/4} - 1\right]$$

this will be a straight line when plotted against $r^{1/4}$.



note: $r^{1/4}$, not r ➞

Where
r_e : effective or "half-light" radius, contains half the total light
μ_e : surface brightness ***at*** the effective radius

Galaxy Structure: Surface Brightness Profiles

Most spiral galaxies are some **combination** of disk and bulge. Can fit the components separately and arrive at a bulge:disk or bulge:total luminosity ratio ("B/D" or "B/T"):

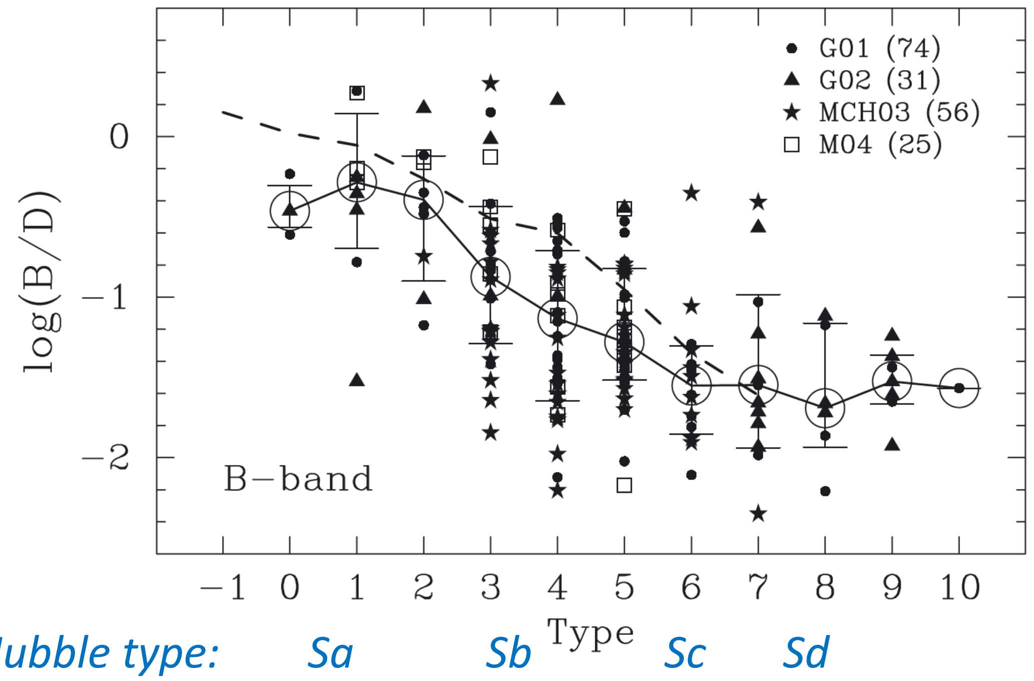


Figure 6. Logarithm of the *B*-band, bulge-to-disc flux ratio as a function of galaxy type (see Table 5, column 7). The dashed line traces the *B*-band values from Simien & de Vaucouleurs (1986).

Graham & Worley 08

μ(R) vs R

Boroson 81

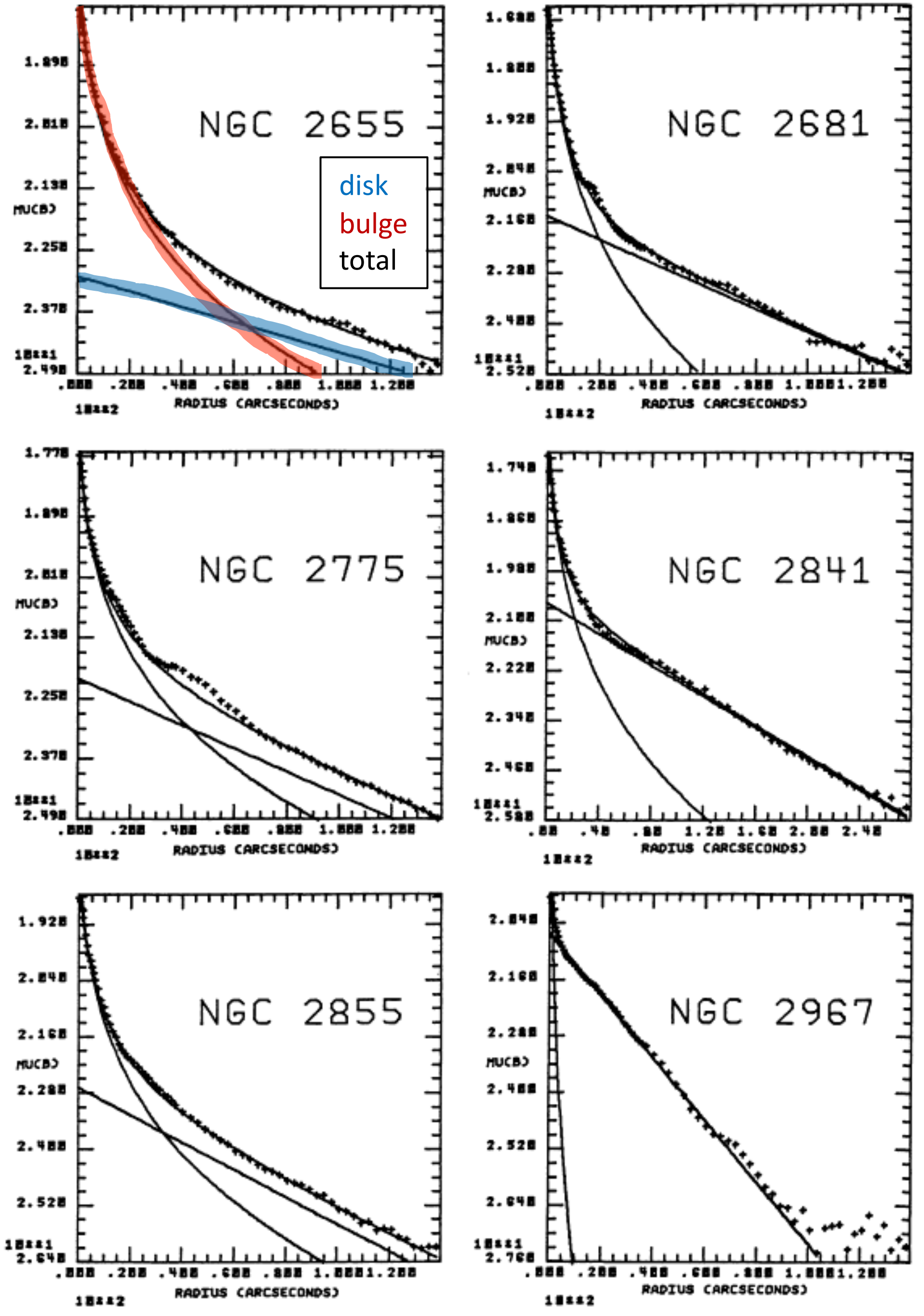


FIG. 6.—*Continued*

Galaxy Structure: The Sérsic Profile

Instead of using exponential or $r^{1/4}$ fits, use a generalized fitting function called a **Sérsic profile**:

$$I(R) = I_e \exp\left(-b_n \left[\left(\frac{R}{R_e}\right)^{1/n} - 1\right]\right)$$

or, in $\mathrm{mag/arcsec^2}$

$$\mu(R) = \mu_e + \frac{2.5 b_n}{\ln(10)}\left[\left(\frac{R}{R_e}\right)^{1/n} - 1\right]$$

Three parameter fits:

n : Sérsic index ($b_n \approx 2n - 0.333$)

R_e : effective radius (radius containing half the total light)

μ_e : surface brightness at R_e

Note:

n can be anything, but galaxies generally span n ≈ 0.5 − 10.

n=1: exponential profile

n=4: de Vaucouleurs $r^{1/4}$ law.

Galaxy Structure: The Sérsic Profile

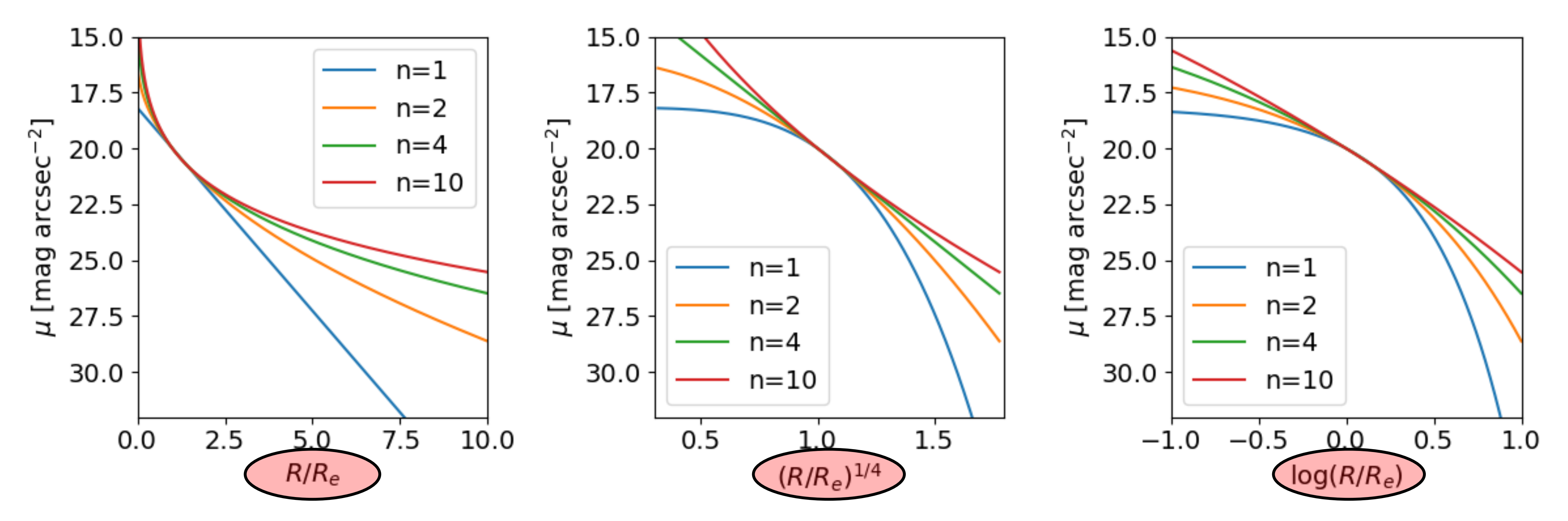
$$\mu(R) = \mu_e + \frac{2.5 b_n}{\ln(10)}\left[\left(\frac{R}{R_e}\right)^{1/n} - 1\right]$$

Remember:
n=1: exponential
n=4: de Vaucouleur

Three parameter fits:
- n : Sérsic index
- R_e : effective radius (half light)
- μ_e : surface brightness at R_e

also can work out:
- $\langle\mu\rangle_e$: average surface brightness within R_e.
- m_{tot}: total (apparent) magnitude

Three projections of the Sérsic profile



Higher n: more light at both small and large radius compared to exponential.

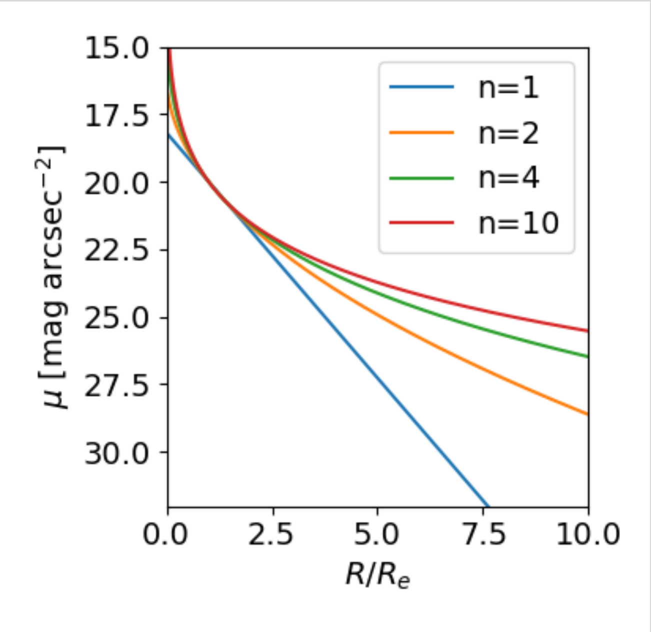
Galaxy Structure: The Sérsic Profile

µ(R) vs R
disk+bulge
Boroson 81

$$\mu(R) = \mu_e + \frac{2.5 b_n}{\ln(10)} \left[\left(\frac{R}{R_e} \right)^{1/n} - 1 \right]$$

Disk galaxies are generally a combination of bulge (n≈4) and disk (n≈1). As bulge-to-disk ratio increases, the **total profile** can often be described by intermediate values for n.

Thus the Sérsic index (n) can be used as a tracer of B:D, and thus, crudely, Hubble type.



But remember, a composite profile represented by a given value of Sérsic-n is not conceptually the same as a single component Sérsic profile!

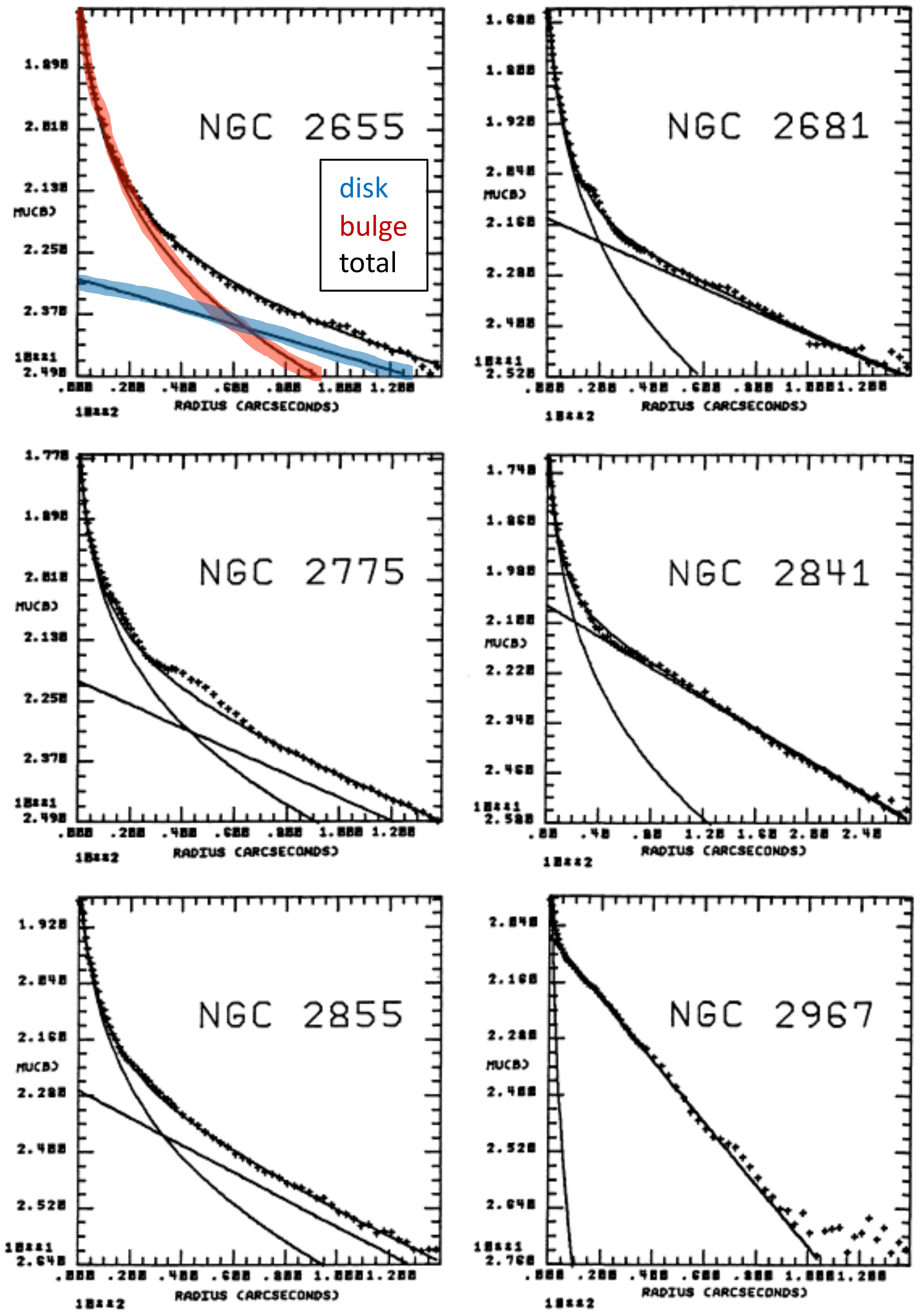


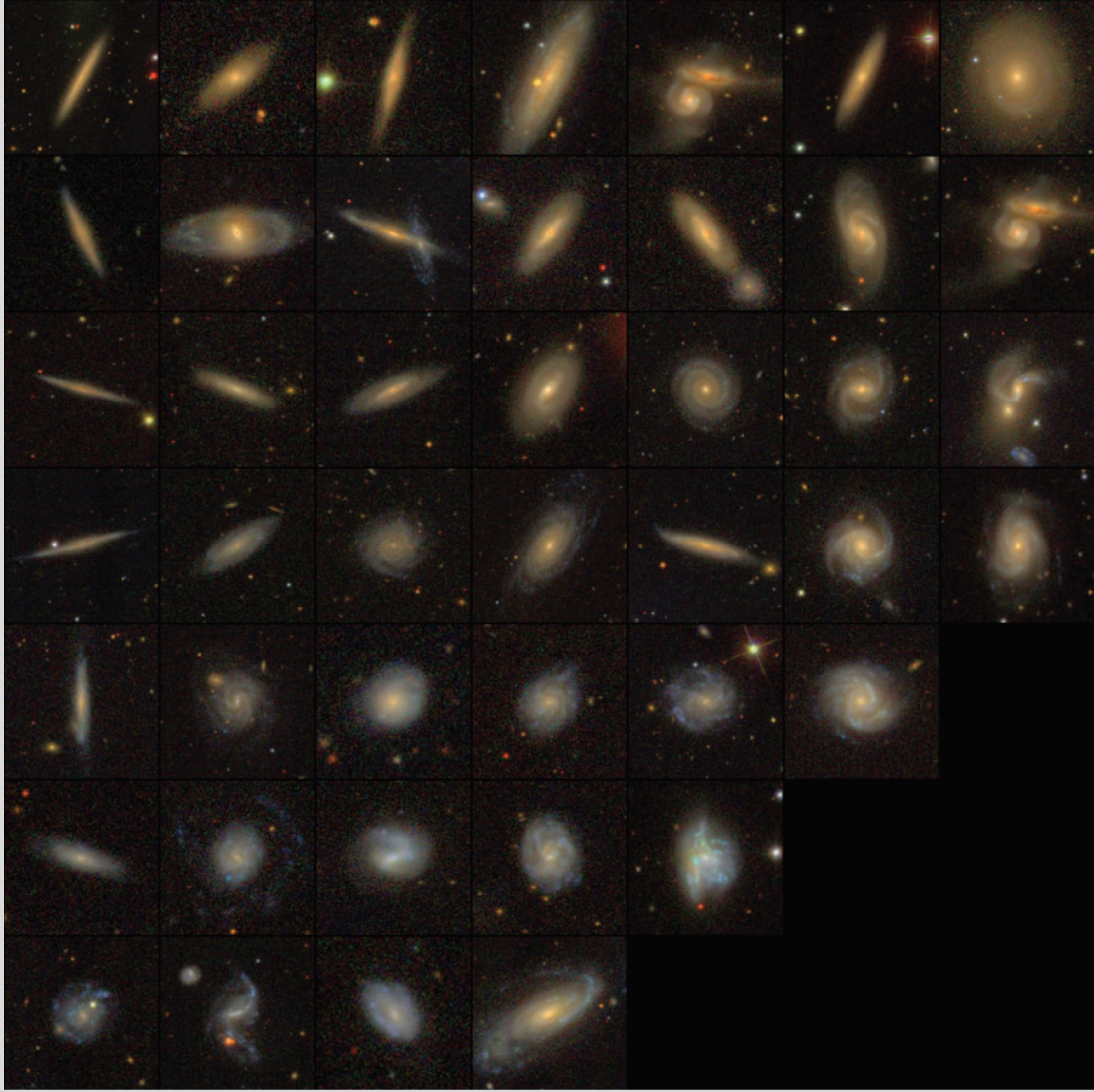
FIG. 6.—*Continued*

Galaxy Structure: SDSS and the Deluge of Data

SDSS: Sloan Digital Sky Survey

Over the early 2000s, SDSS began releasing data for millions of galaxies.

redder



bluer

low luminosity

high luminosity

Spirals (Sa−Sd)

Blanton & Moustakas 2009

ARAA

Galaxy Structure: SDSS and the Deluge of Data

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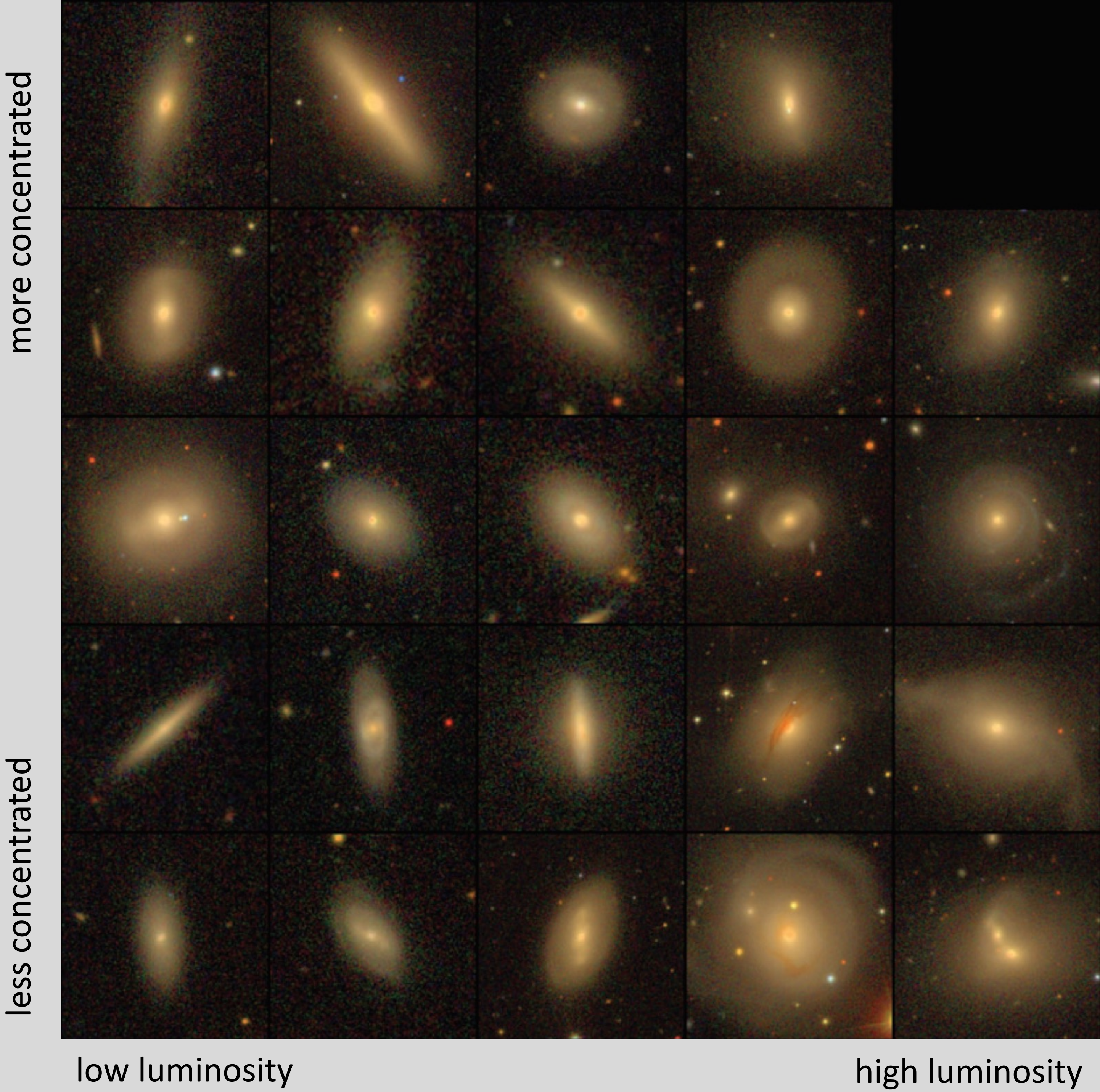

S0 / Lenticular Galaxies

Blanton & Moustakas 2009

ARAA

Galaxy Structure: SDSS and the Deluge of Data

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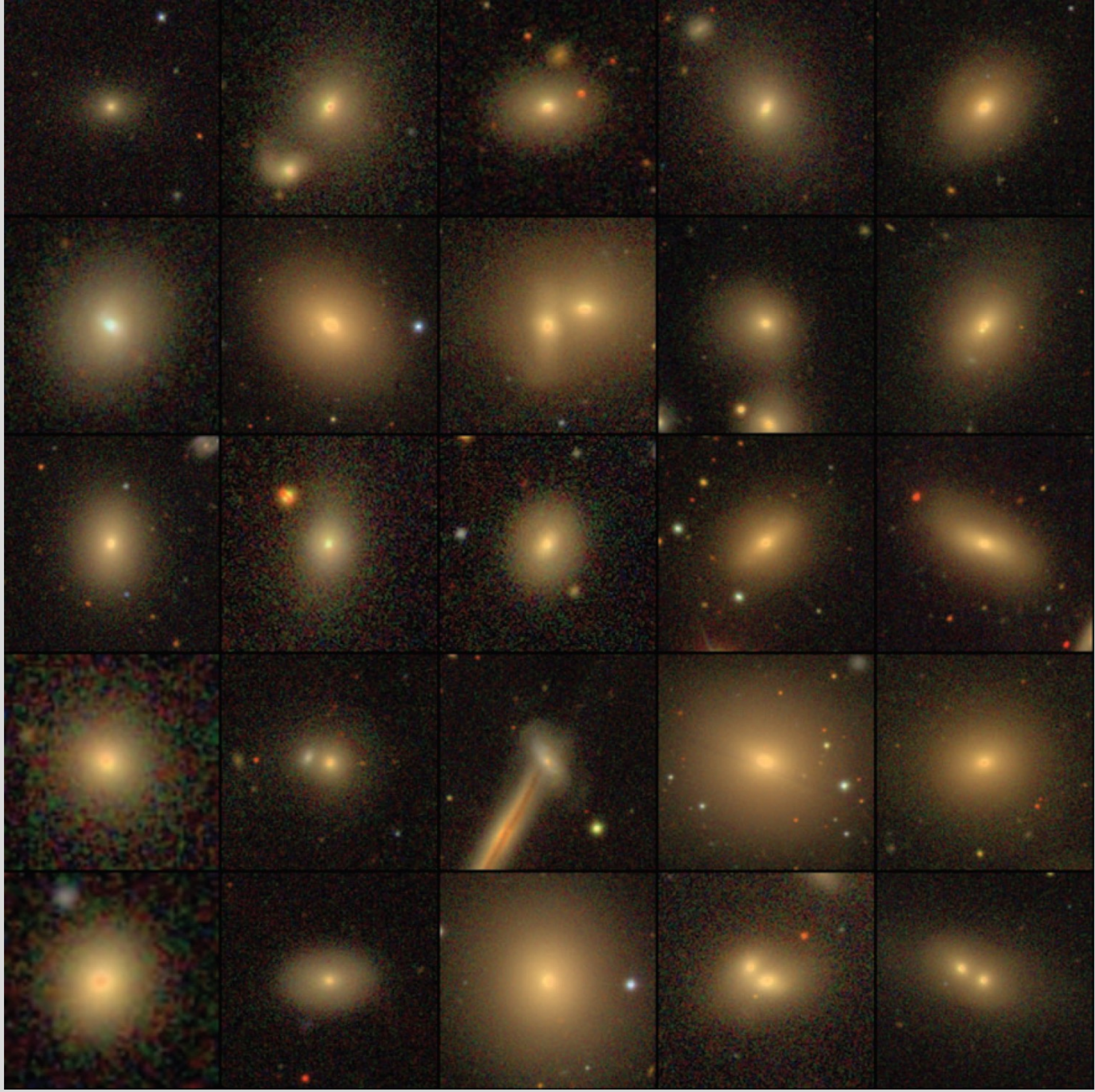


Elliptical Galaxies
Blanton & Moustakas 2009
ARAA

Galaxy Structure: SDSS and the Deluge of Data

Careful multicomponent fitting is time intensive, easier just to autofit a single Sérsic profile to each galaxy.

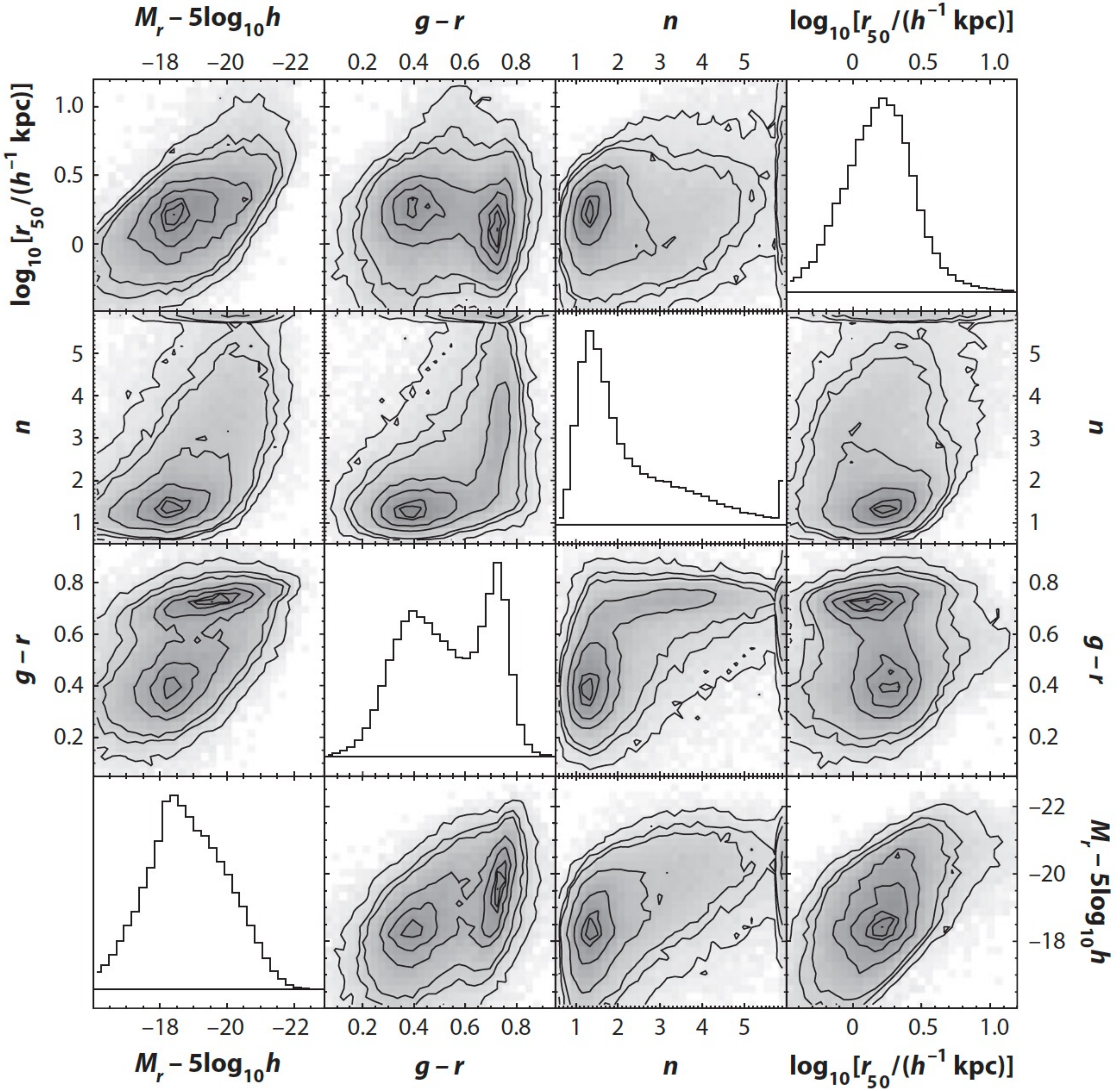
This gives you:

- Sérsic index (n)
- effective radius (r_e, also called r_{50})
- total magnitude (m)

Multiband data, so also color (g-r)

Sérsic n becomes a proxy for galaxy type

Spectroscopy gives you a Hubble distance, can work out absolute magnitude (M) and physical size. Distance-dependent values have an h ($\equiv H_0/100$) term.



77, 153 galaxies
Blanton & Moustakas 2009
ARAA

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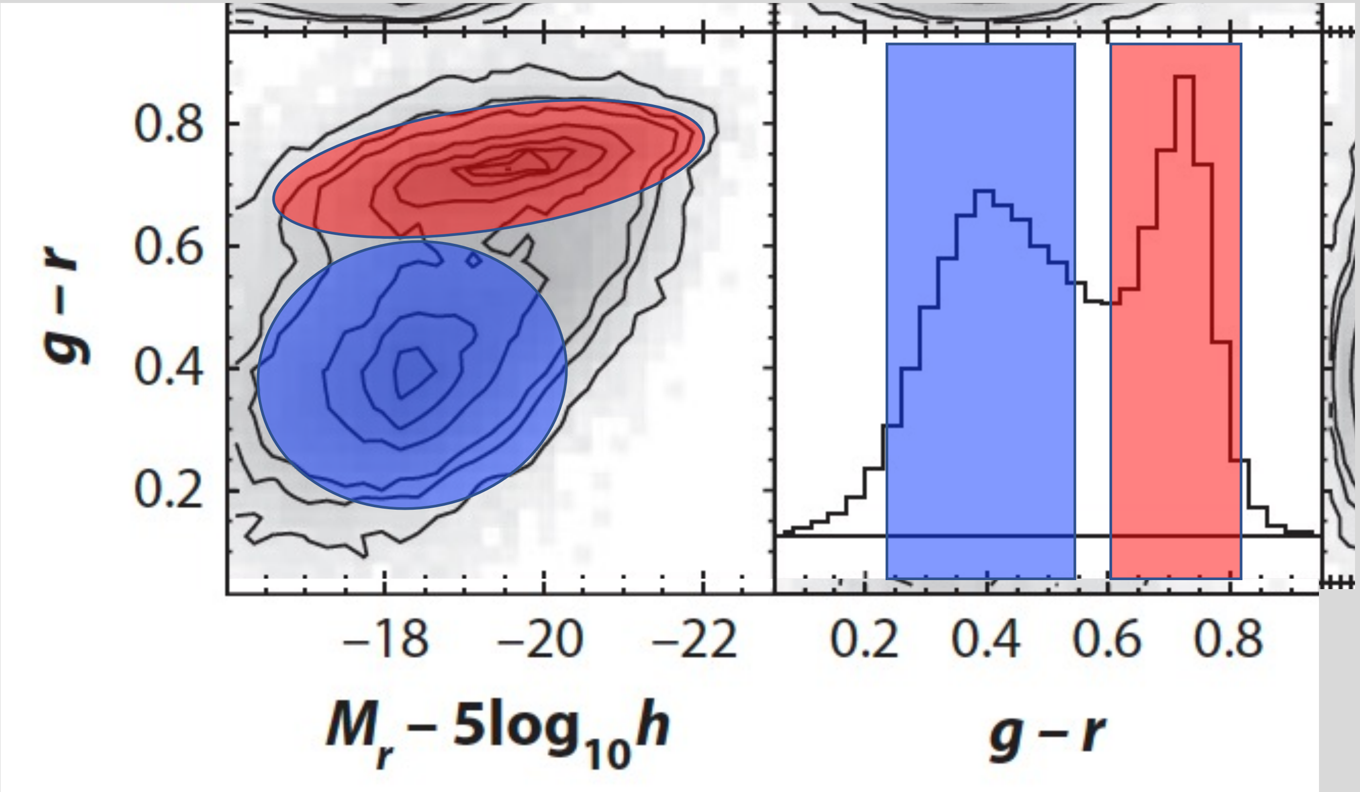

Color vs Luminosity:
galaxies segregate into “red sequence” and “blue cloud”.

77, 153 galaxies
Blanton & Moustakas 2009
ARAA

Galaxy Structure: SDSS and the Deluge of Data

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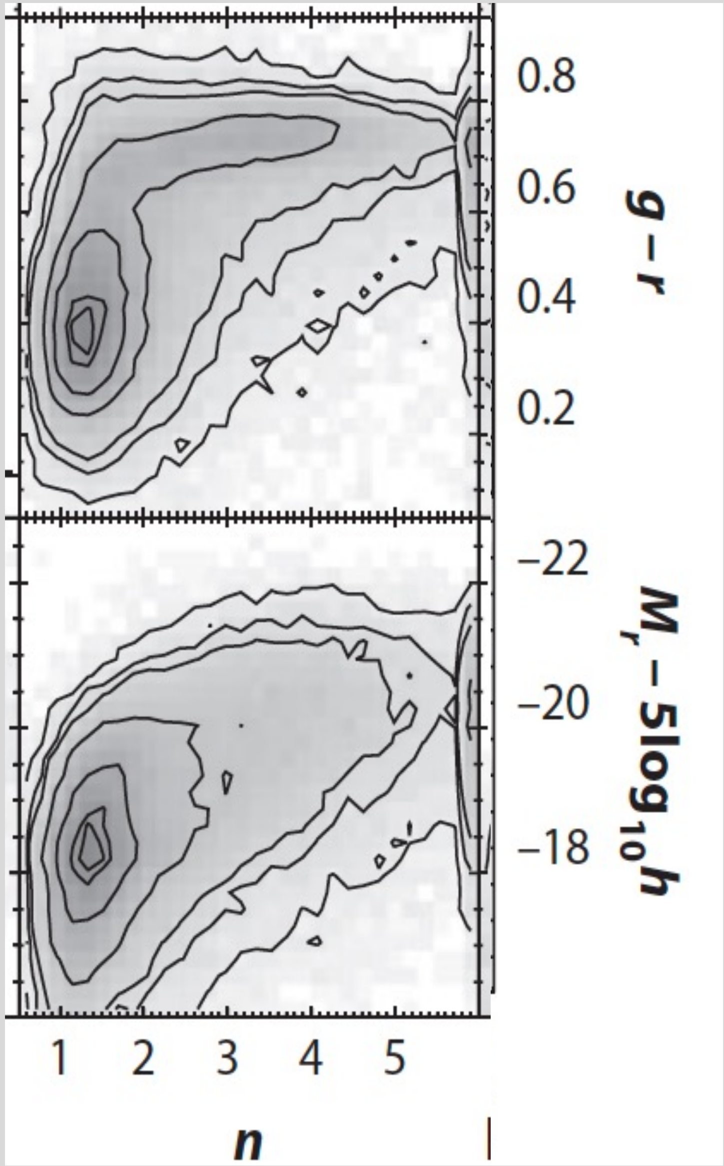
77, 153 galaxies
Blanton & Moustakas 2009
ARAA

Color and Luminosity vs Sérsic n :

- Red galaxies span a range of Sérsic n.
- Blue galaxies tend to have lower n.
- Luminous galaxies tend to be high n and red.



Blanton & Moustakas 2009
ARAA

Galaxy Structure: SDSS and the Deluge of Data

Can derive **stellar mass** from colors and luminosities

Also have spectroscopic information which tells us

Metallicity: 12+log(O/H) (Solar ≈ 8.75)

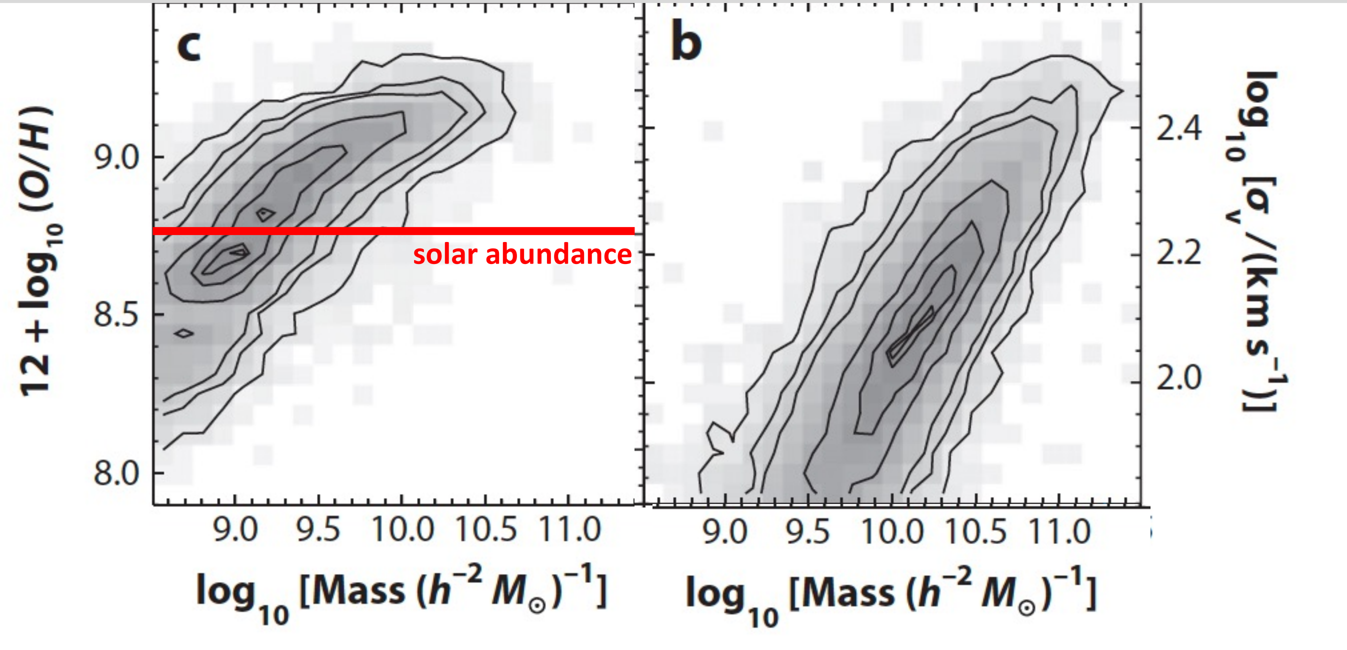
> Galaxies follow a **mass-metallicity relation**: more massive galaxies are more metal-rich

Velocity dispersion: σ, in km/s. the characteristic random speeds of stars, a tracer of total mass.

> Galaxies with higher stellar mass have higher velocity dispersion.

mass - metallicity

mass – velocity dispersion



stellar mass

Important Caveats: Observational Bias

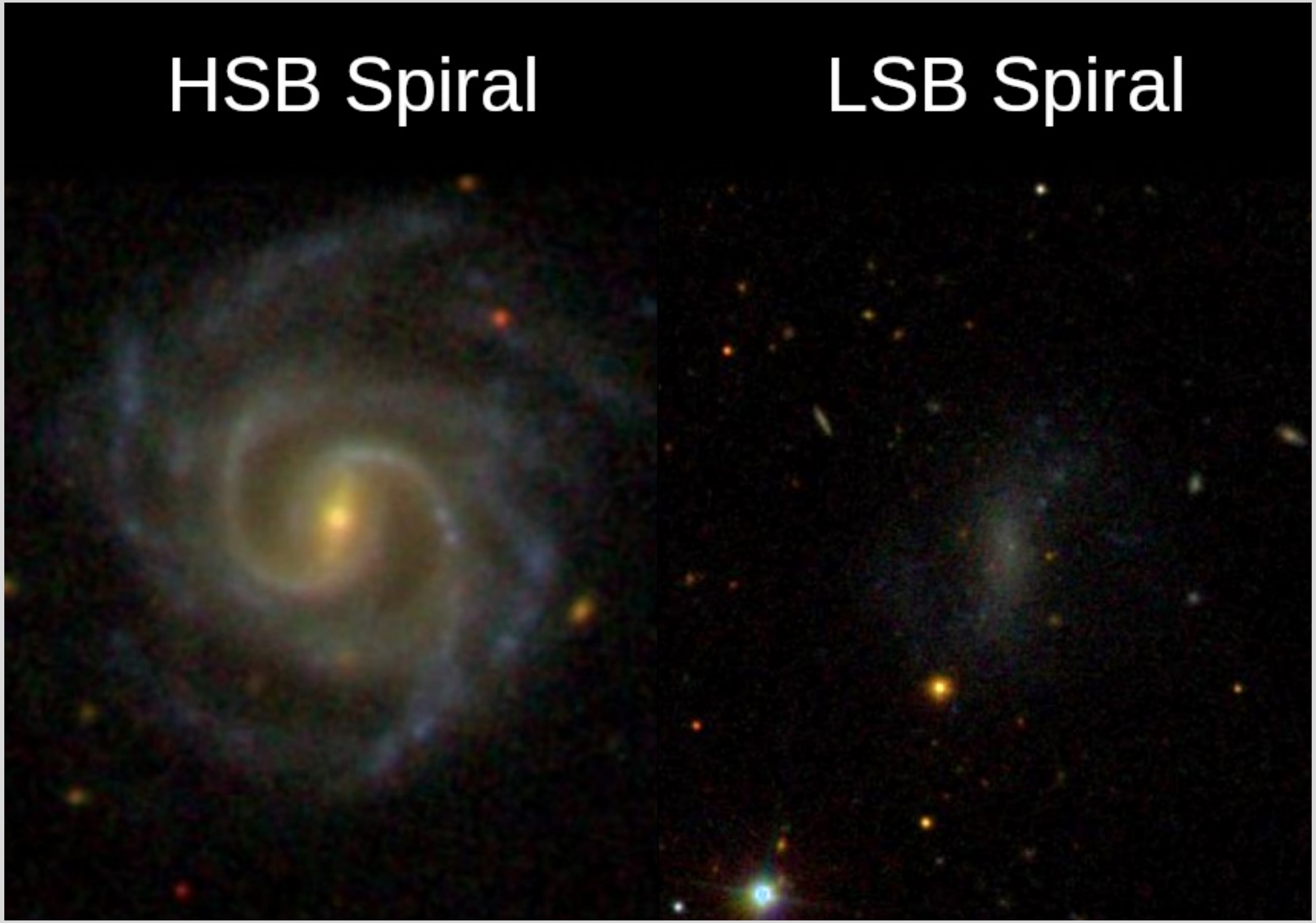
SDSS is both **flux limited** and **surface brightness limited**. This means it it is likely to miss galaxies that are faint, small, and low in surface brightness.

Night Sky Surface Brightness:

- Full Moon: $\mu_{B,sky} \approx 19.5$ mag/arcsec^2
- New Moon: $\mu_{B,sky} \approx 22.7$ mag/arcsec^2

It quickly become hard to detect objects (or measure profiles) when their surface brightness is significantly "below sky."

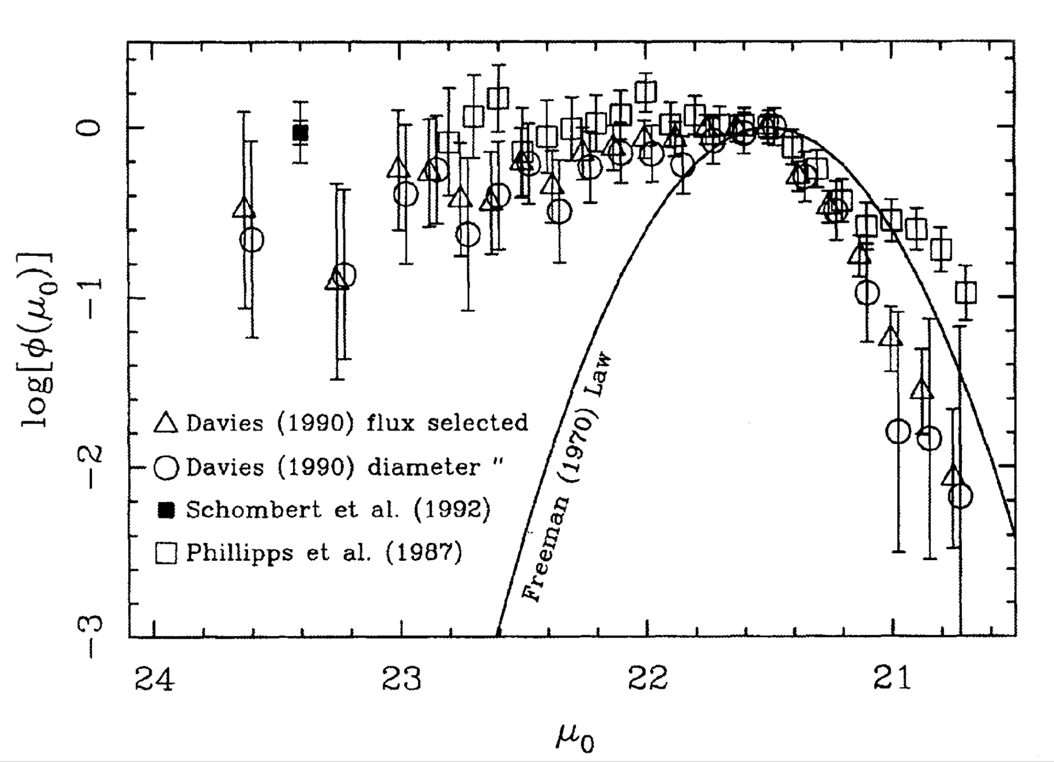
Particularly problematic for low luminosity galaxies (which are typically low surface brightness: "LSB").



Low surface brightness (LSB) galaxies

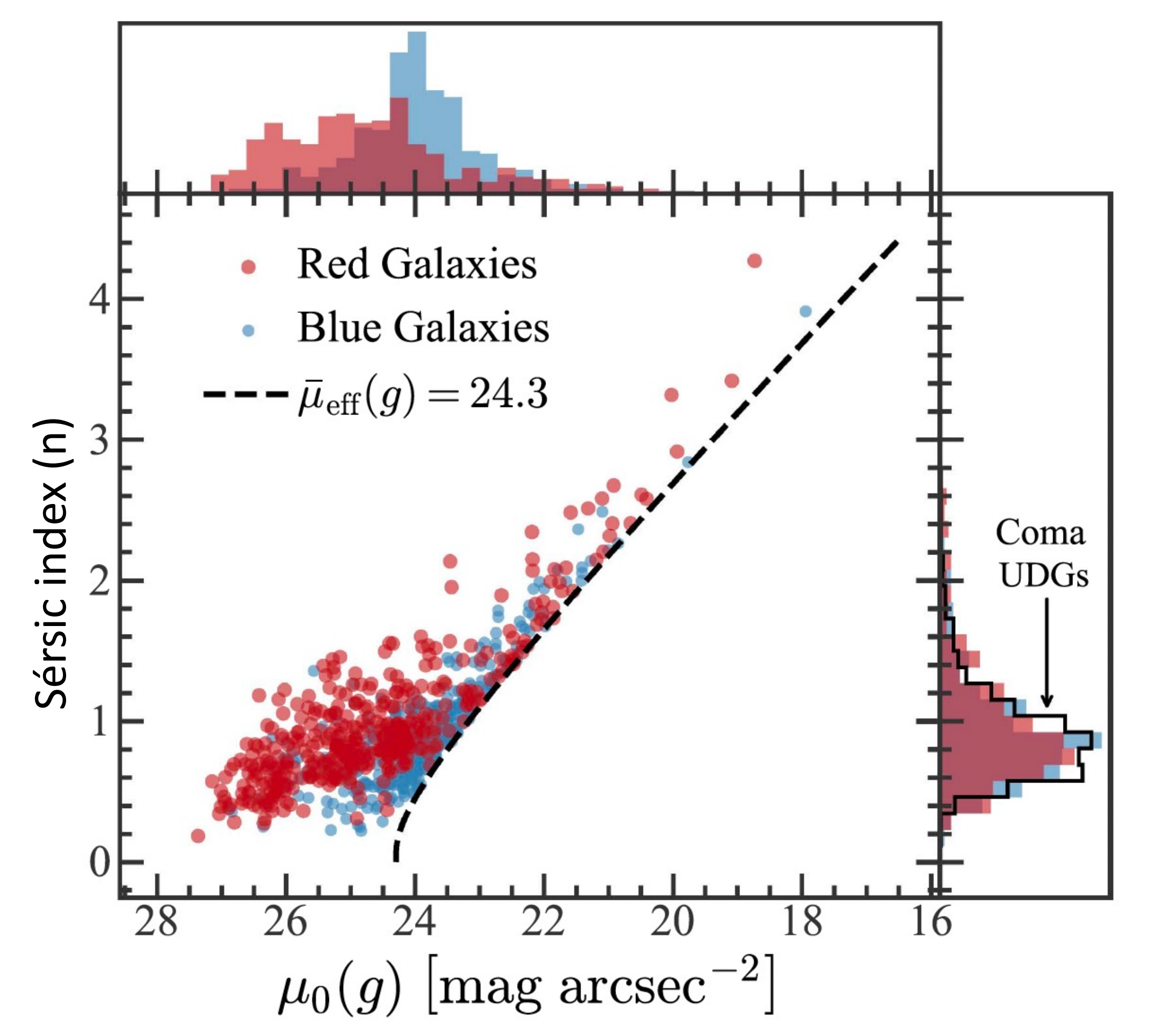
There are lots of them out there!

Number of galaxies per Mpc^3 as a function of surface brightness (McGaugh 95)



LSB HSB

Recent surveys show lots of galaxies exist at really low surface brightness! (Greco+18).



VLSB VHSB