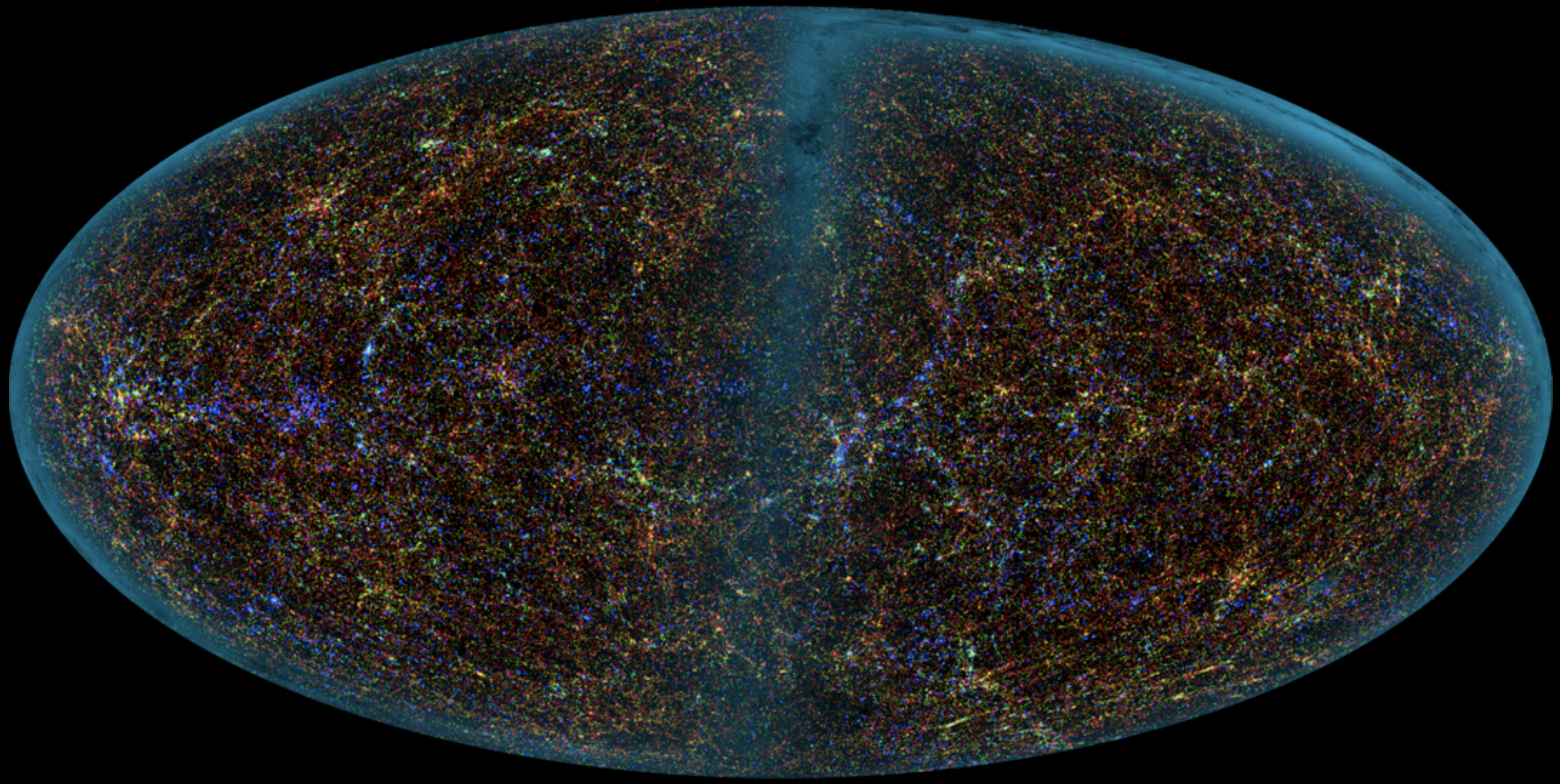
Cosmology

and Large Scale Structure



Today

Observational Tests

Number Counts

e.g., Galaxy N(m), N(z)

Galaxy selection

26 September 2024

http://astroweb.case.edu/ssm/ASTR328/

Observational Tests

Five Classic Tests

• Luminosity-redshift relation	$D_L - z$	Standard Candle
• Angular size-redshift relation	$D_A - z$	Standard Rod
• Number-redshift relation	$N(z)$	Source counts with redshift
• Number-magnitude relation	$N(m)$	Source counts with magnitude
• Tolman test	$\Sigma(z)$	Surface brightness not distance independent in Robertson-Walker geometry

"Galaxies are the building blocks of the universe"
- Jim Peebles

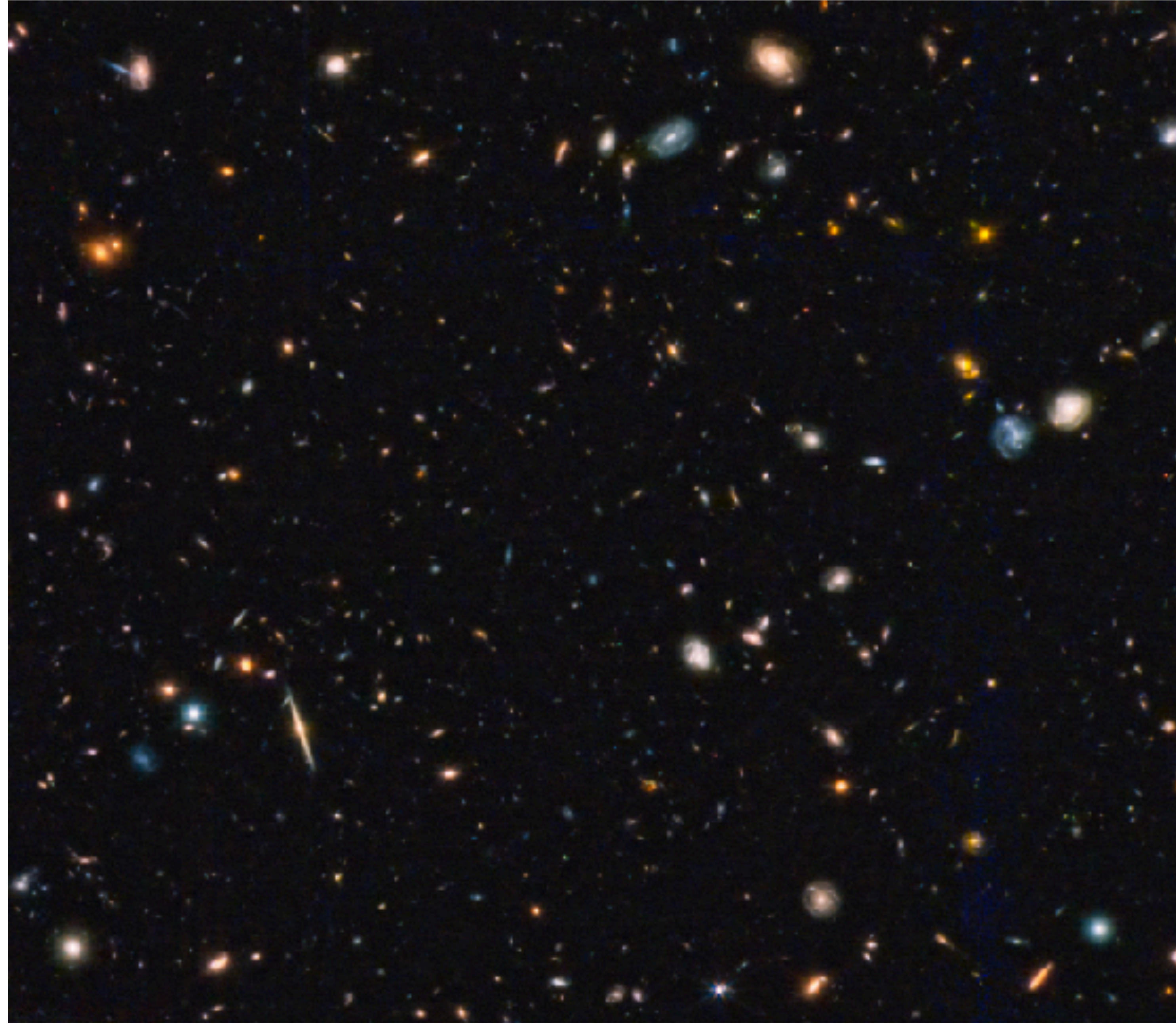
It is easier for a camel to go through the eye of a needle than to understand cosmology without understanding galaxies
- Matthew 19:23

- Number-redshift and Number-magnitude relations

Since the volume depends on curvature, source counts N(m) provide a test

For sources of luminosities L and constant comoving number density $\Phi(L)$,

homogeneity, no evolution



Number-redshift:

$$N(<z) = \frac{4\pi}{3H_0^2} z^3 \int_0^\infty \Phi(L) \left[1 + \frac{3}{2} z(1+q_0)\right] dL$$

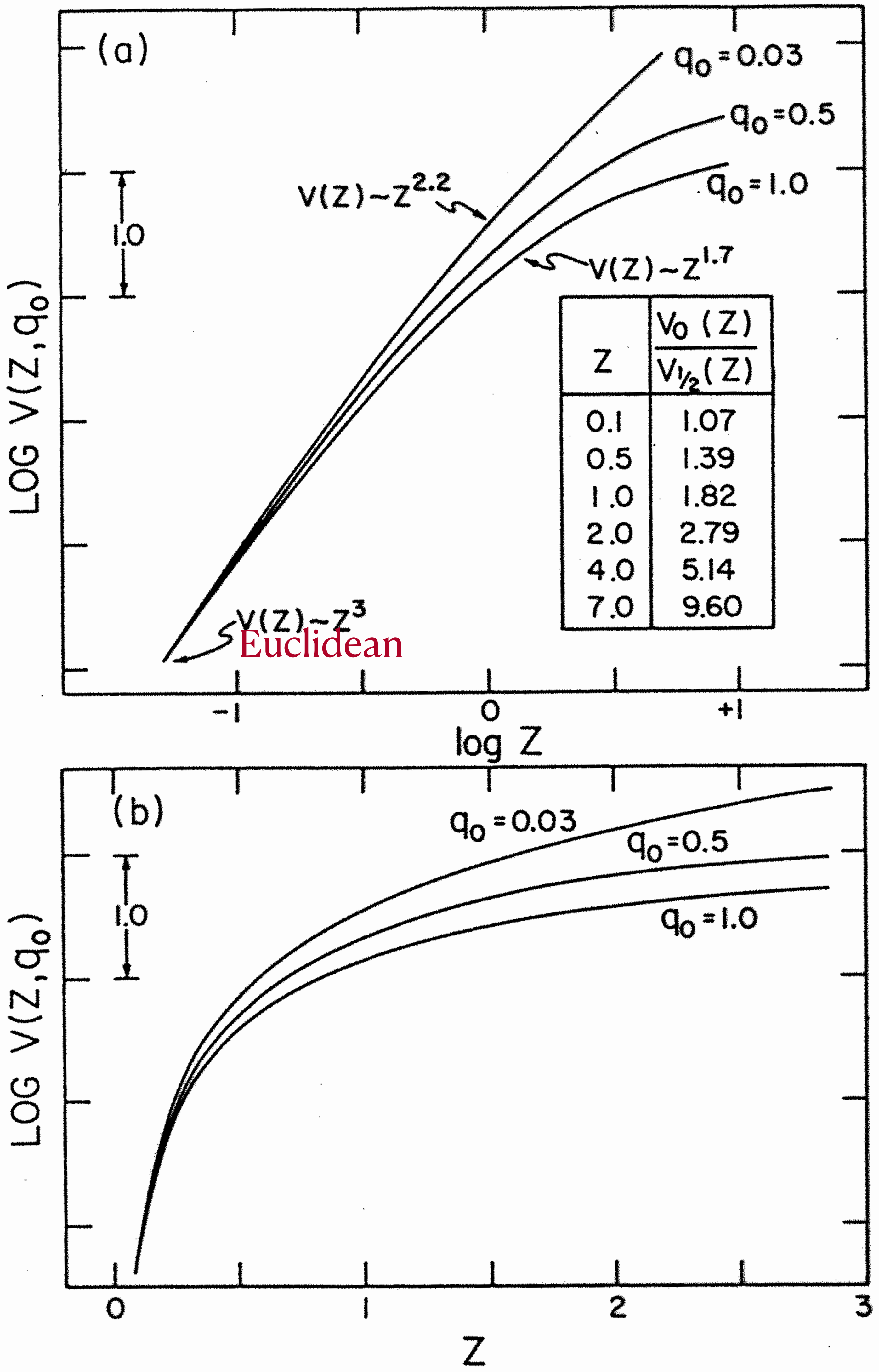
Number-magnitude:

$$N(<f) = \frac{4\pi}{3}(4\pi f)^{-3/2} \int_0^\infty \Phi(L) \left[1 - 3H_0 \left(\frac{L}{4\pi f}\right)^{1/2}\right] L^{3/2} dL$$

Historically, radio source counts in the 1960s played an important role in excluding the Steady State cosmology.

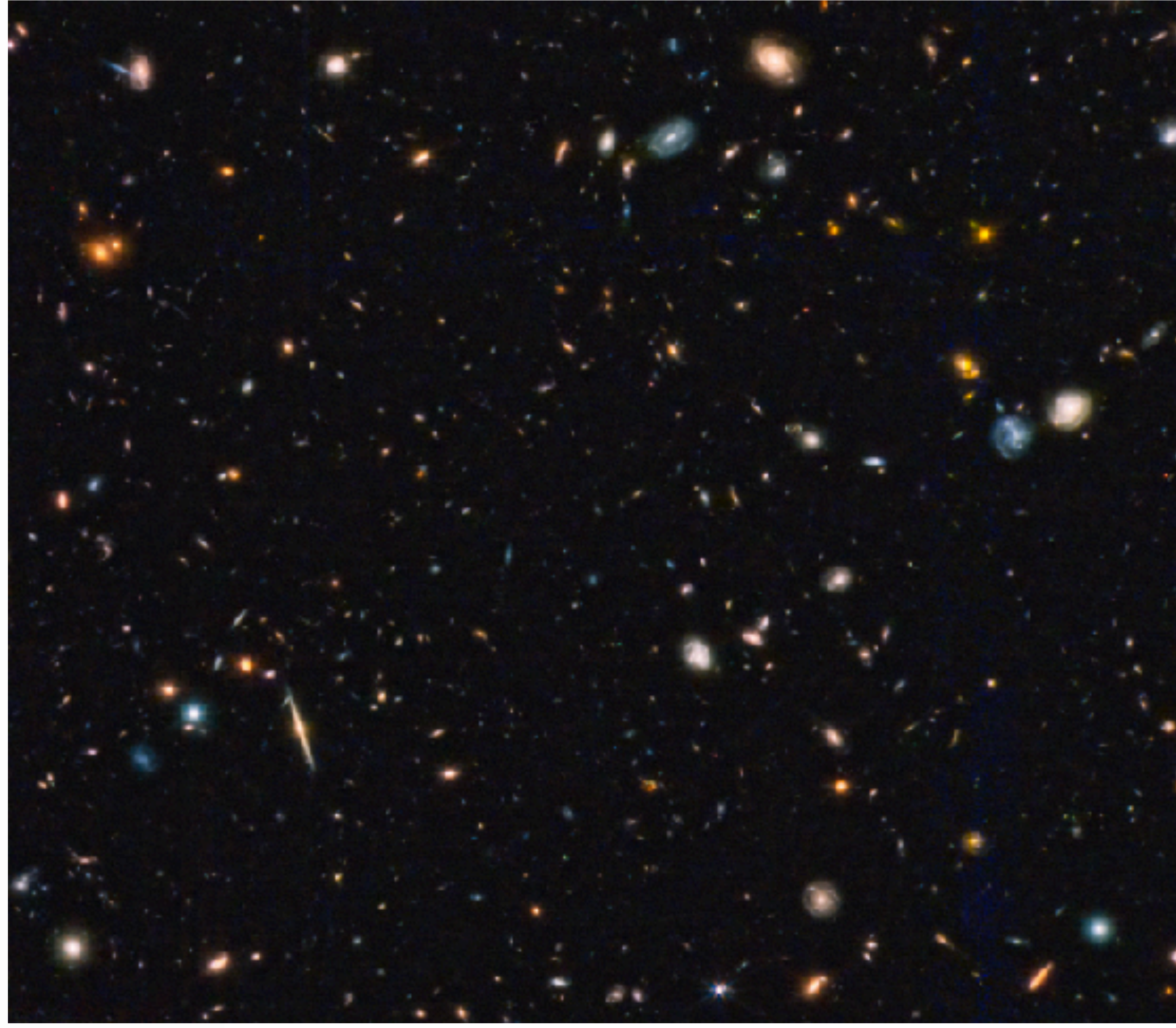
Sandage 1988, ARAA, 26, 561

predicted N(< z)



Z	$V_0(Z) / V_{1/2}(Z)$
0.1	1.07
0.5	1.39
1.0	1.82
2.0	2.79
4.0	5.14
7.0	9.60

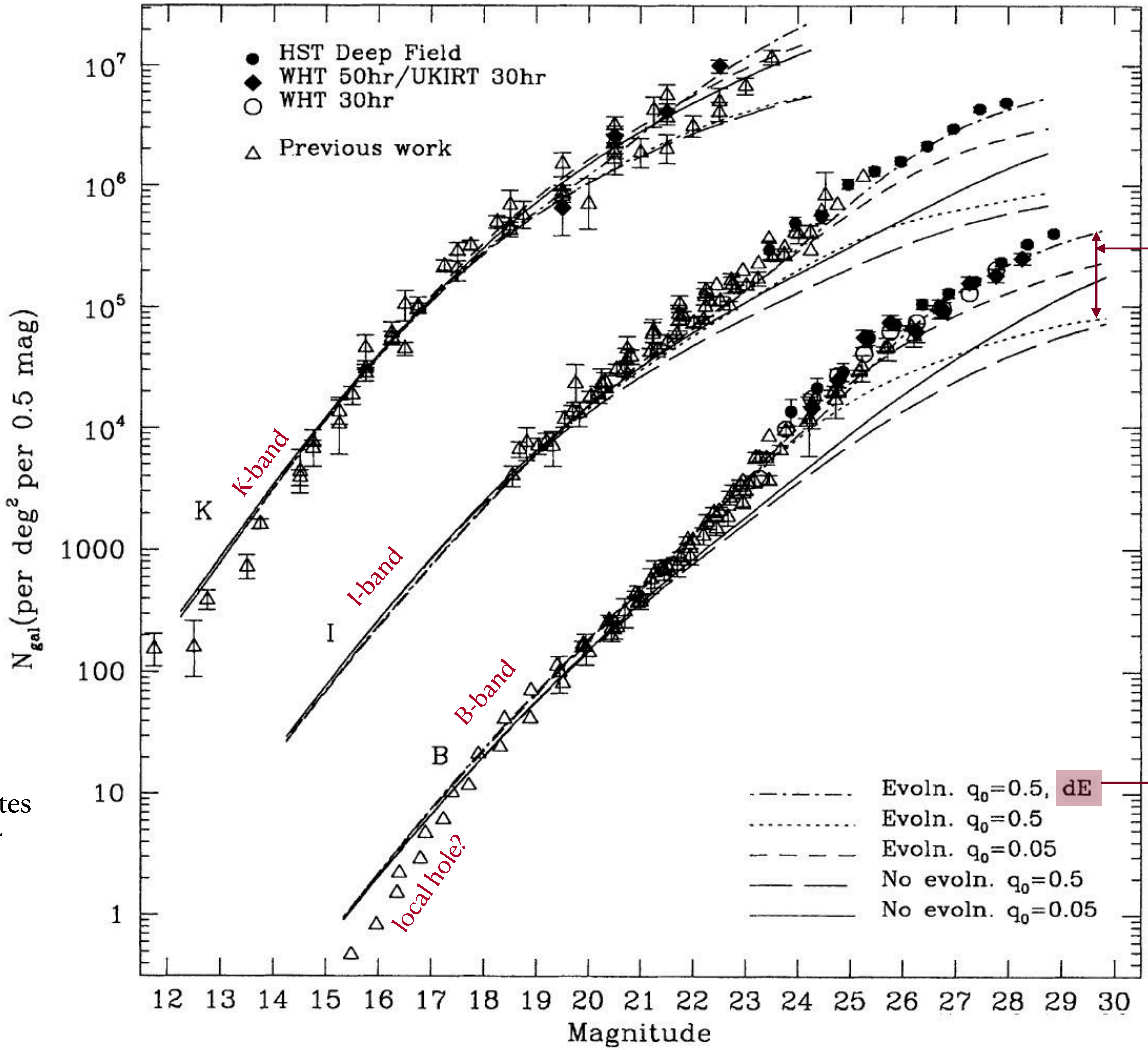
Figure 1 Theoretical $N(z, q_0)$ relations for three values of q_0. Plotted is the integral count, i.e. the total number of galaxies in a complete (volume-limited) sample that have redshifts smaller than z. Parts (*a*) and (*b*) are the same function but plotted as log z (*a*) and z (*b*).



as $q_0 \downarrow$, $V \uparrow$

Number-magnitude:

Metcalfe et al. (1996)



Faint blue galaxy excess

"The fit of the $q_0 = 0.5$ model is improved when an extra high redshift galaxy population (dE) with constant star formation rate (SFR) at z > 1 and rapidly fading at z < 1 is invoked."

A "no evolution" model extrapolates the locally measured Schechter function to high redshift.

Number-magnitude:

Metcalfe et al. (1996)

Only test that does not explicitly require redshift information.
Basically integrate over all the relevant distributions.

Integrate over volume (metric-dependent)

$$A(m, T) = A_0 \int_0^z D(z, T)\Phi(M, T)dV(z, q_0)$$

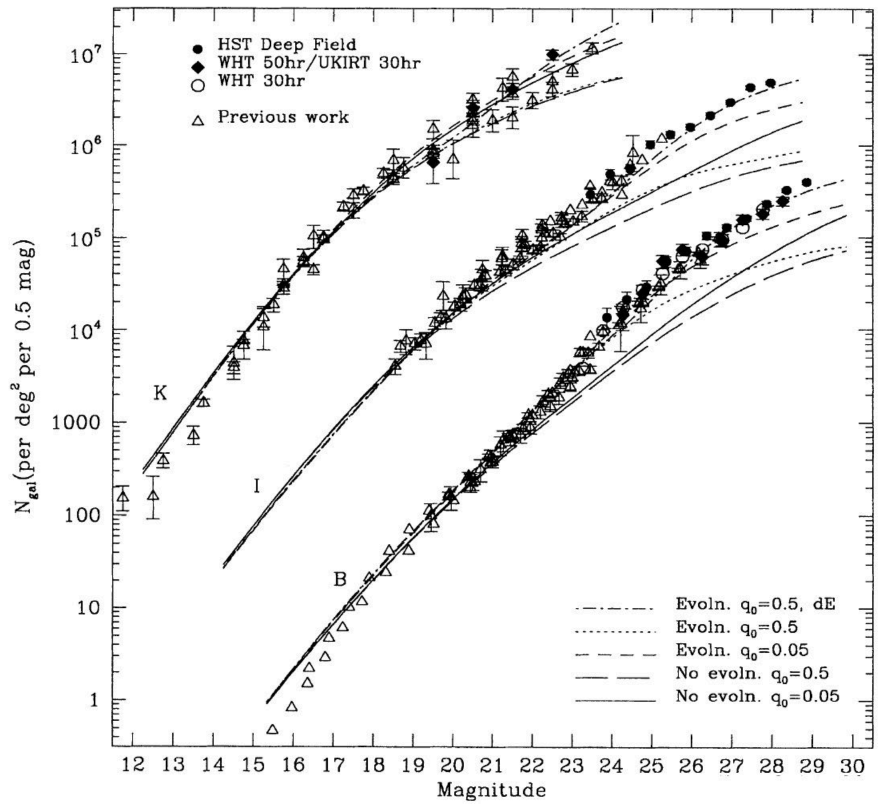
Density distribution (e.g., non-uniform large scale structure)

Luminosity function n(L)↔Φ(M)

Volume element (cosmological)

Surface density of galaxies on the sky

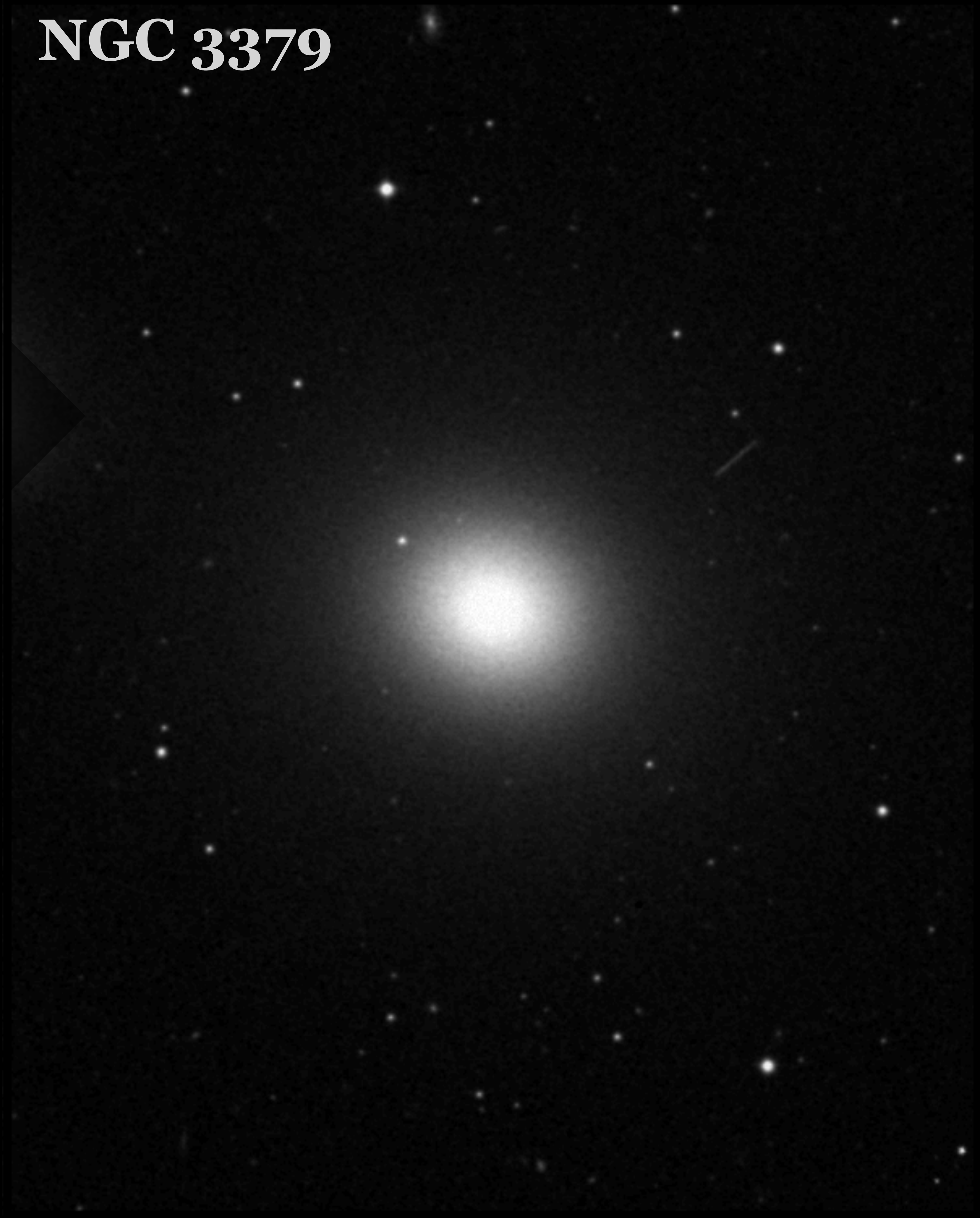
$$N(m, T) = \int_T \int_0^m A(m, T)dTdm$$

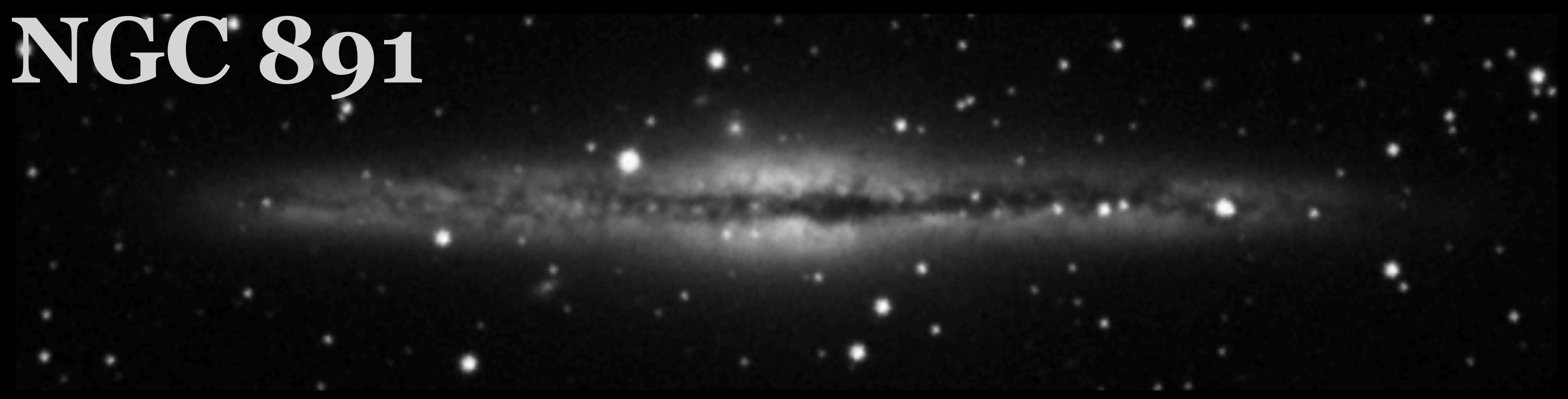


For sources of type *T* and magnitude *m*.

We can only get at the volume element if we understand the other terms and their redshift evolution.

Galaxy Morphology





Early Types
(Ellipticals)

Late Types
(Spirals & Irregulars)

Ellipticals
3D ellipsoids
pressure supported,
dynamically hot: V/σ small

Spirals
2D disks
rotationally supported,
dynamically cold: V/σ large

Schechter function

$$\Phi(L) = \Phi^* \left(\frac{L}{L^*}\right)^{-\alpha} e^{-L/L^*}$$

L^* Characteristic luminosity

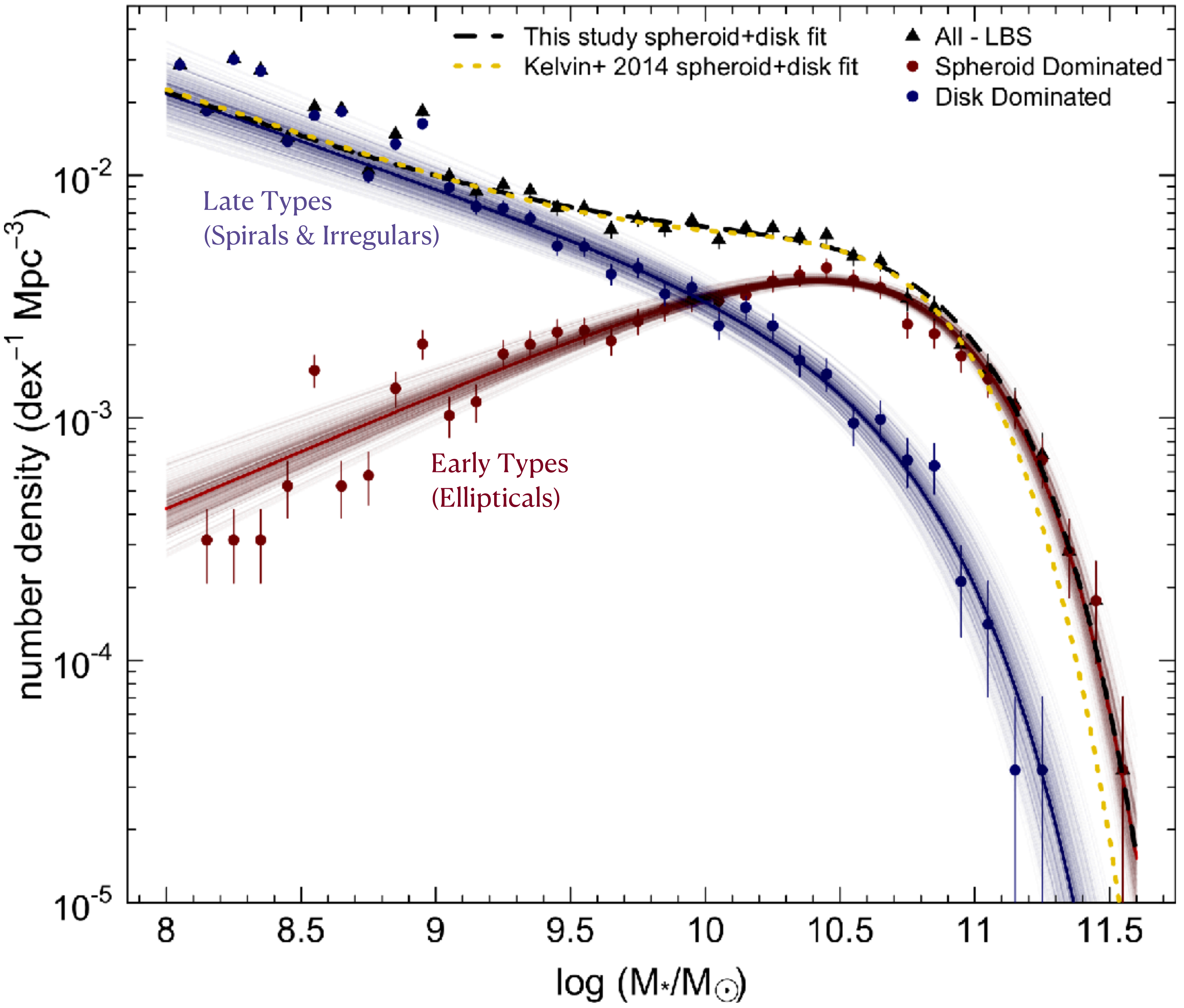
Φ^* Characteristic number density

α Faint end slope

Population	$\log(M^*\ h_{0.72}/M_\odot)$	α	$\phi^*/10^{-3}$ ($dex^{-1}\ Mpc^{-3}\ h_{0.7}^3$)
Early Type	10.74 ± 0.026	0.525 ± 0.029	3.67 +0.20
Late Type	10.70 ± 0.049	1.39 ± 0.021	0.855 +0.10

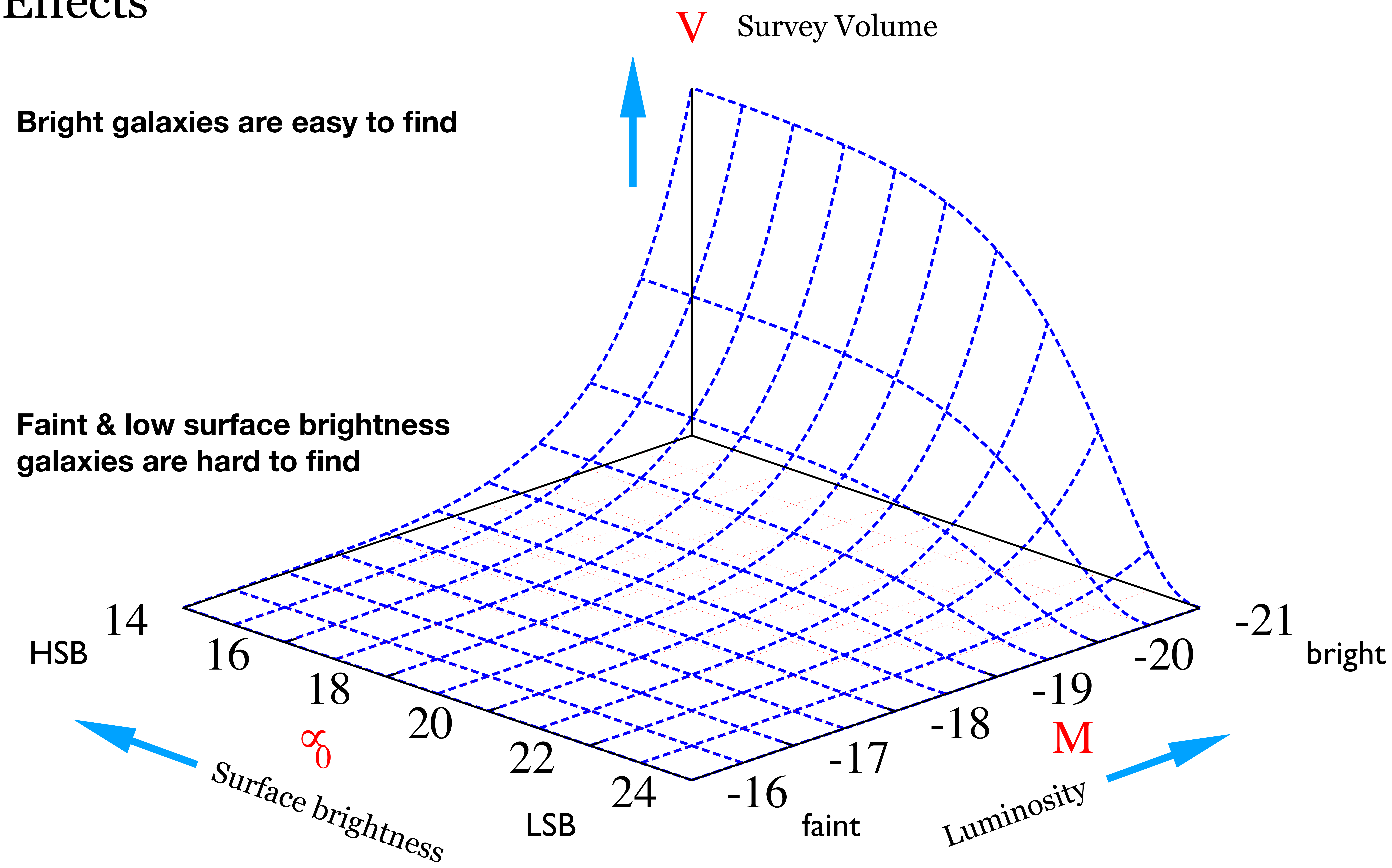
updated Early Type: $\log M_*^* = 10.95$

Galaxy mass function from the GAMA survey



Moffett et al. 2016, MNRAS, 457, 1308

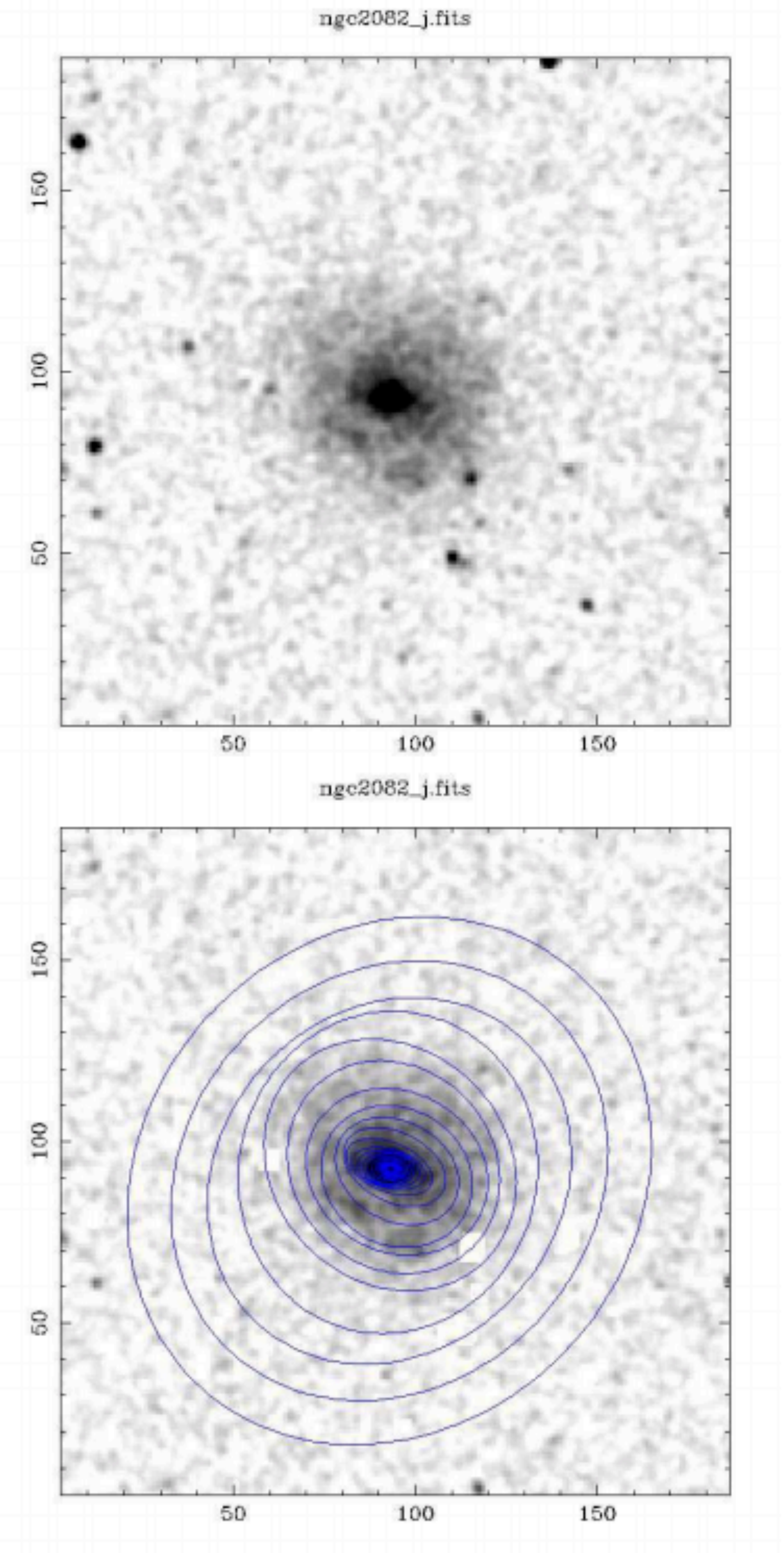
Selection Effects



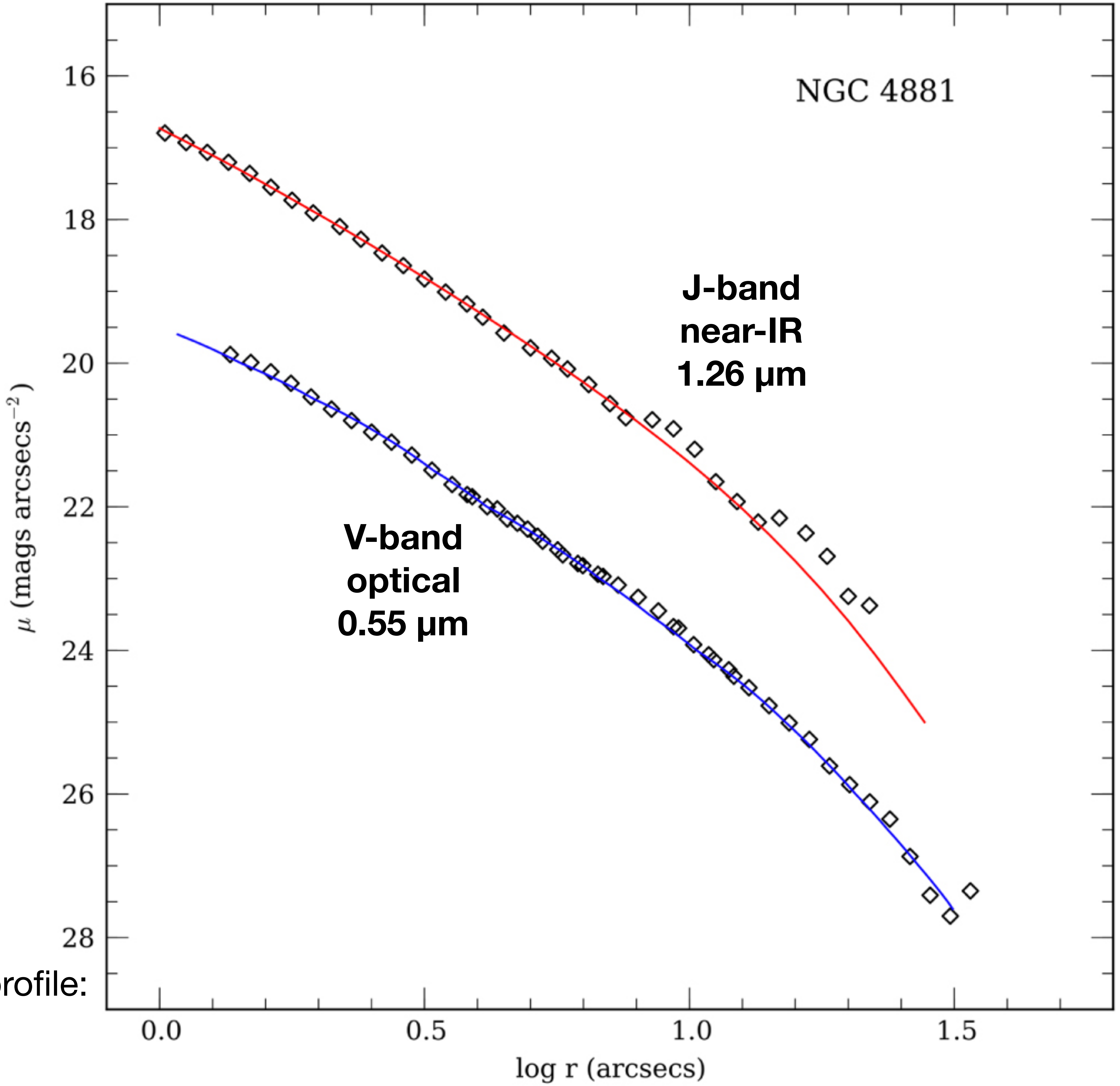
Quantitative Surface photometry

Elliptical galaxies typically fit with de Vaucouleurs profiles.
Spiral galaxies typically fit with exponential profiles.

Schombert (2007) arXiv:astro-ph/0703646



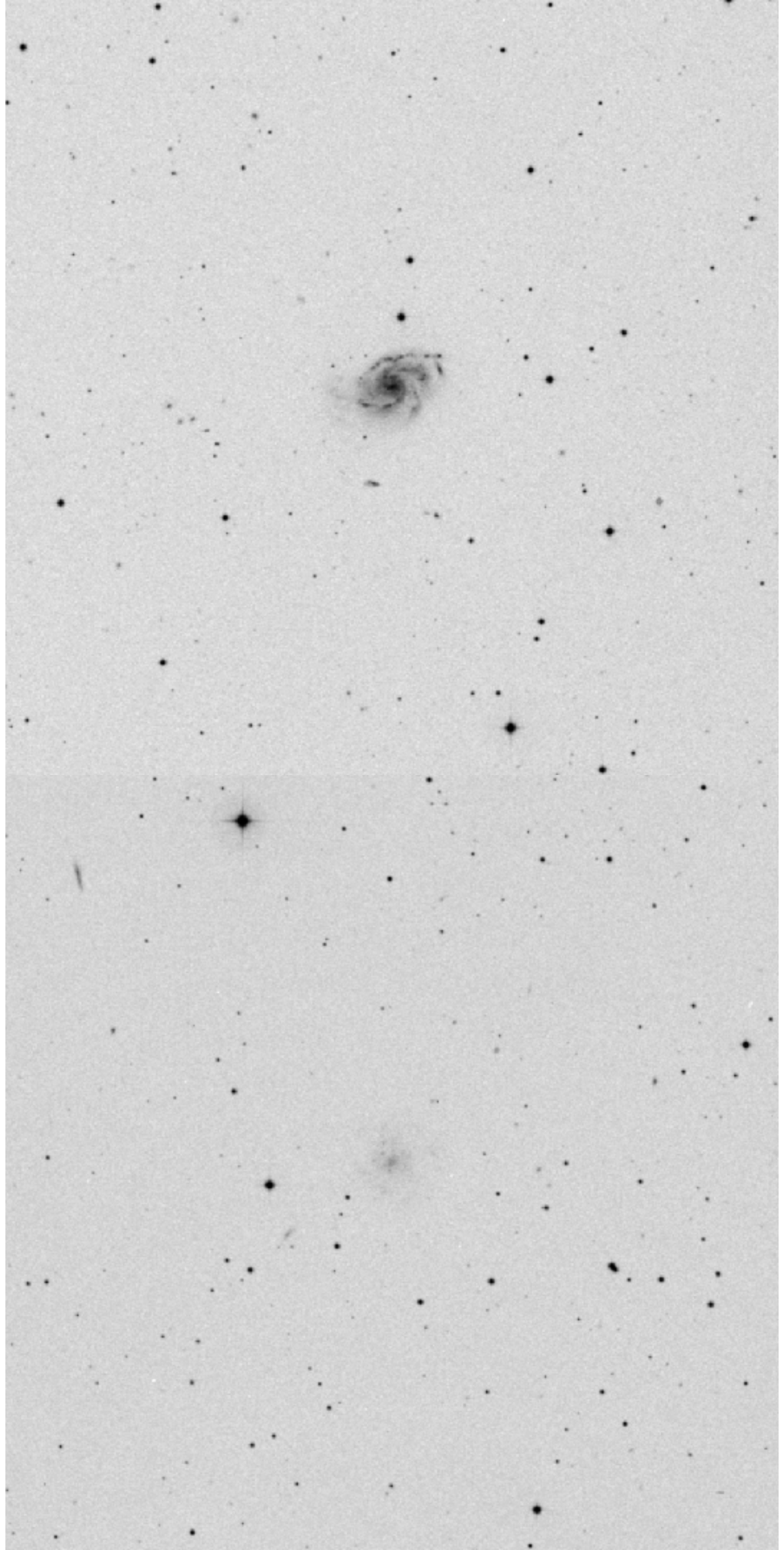
Fit ellipses, derive surface brightness profile:



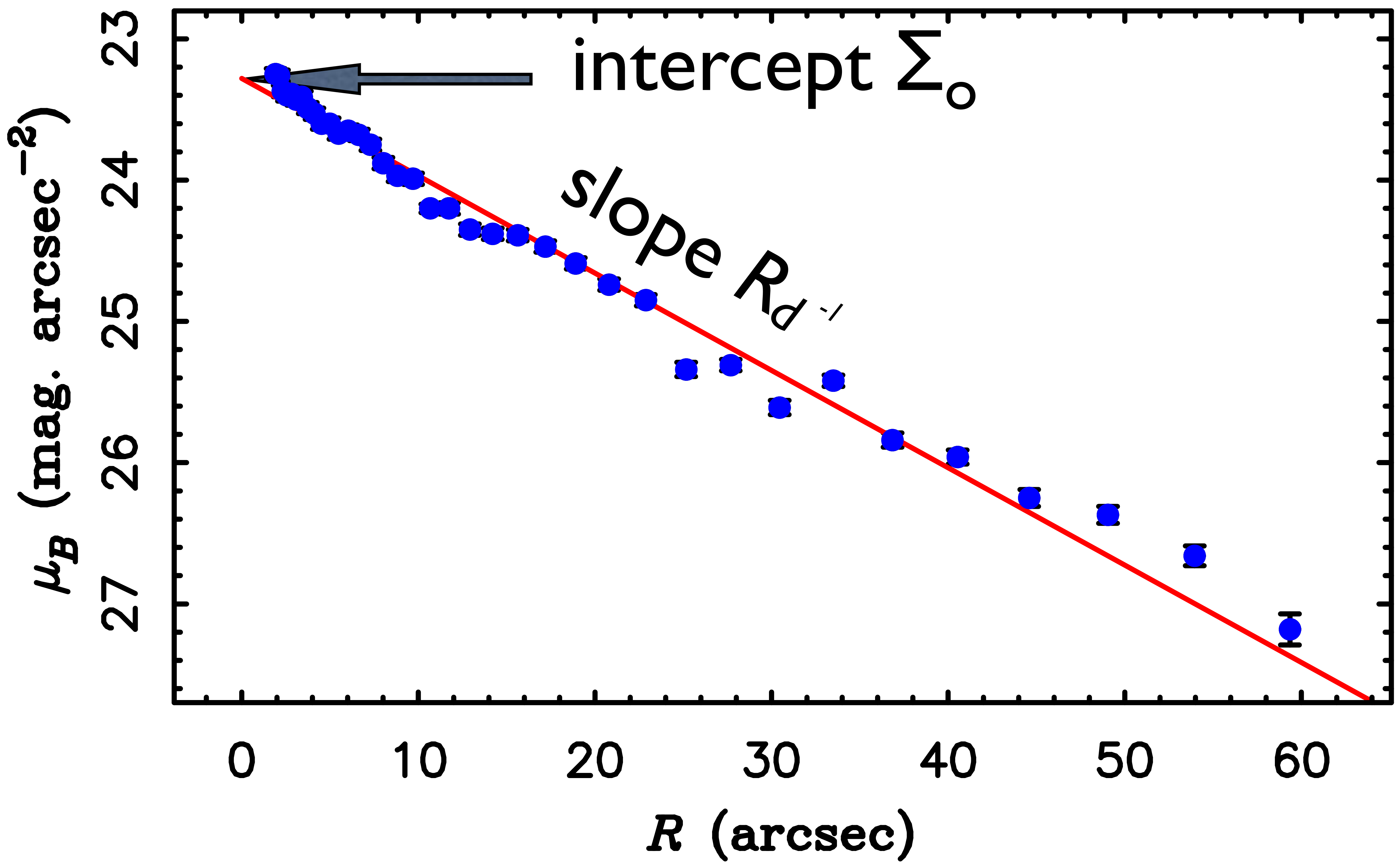
Disk galaxies (Spirals+Irrs)

HSB

LSB



High Surface Brightness Galaxy

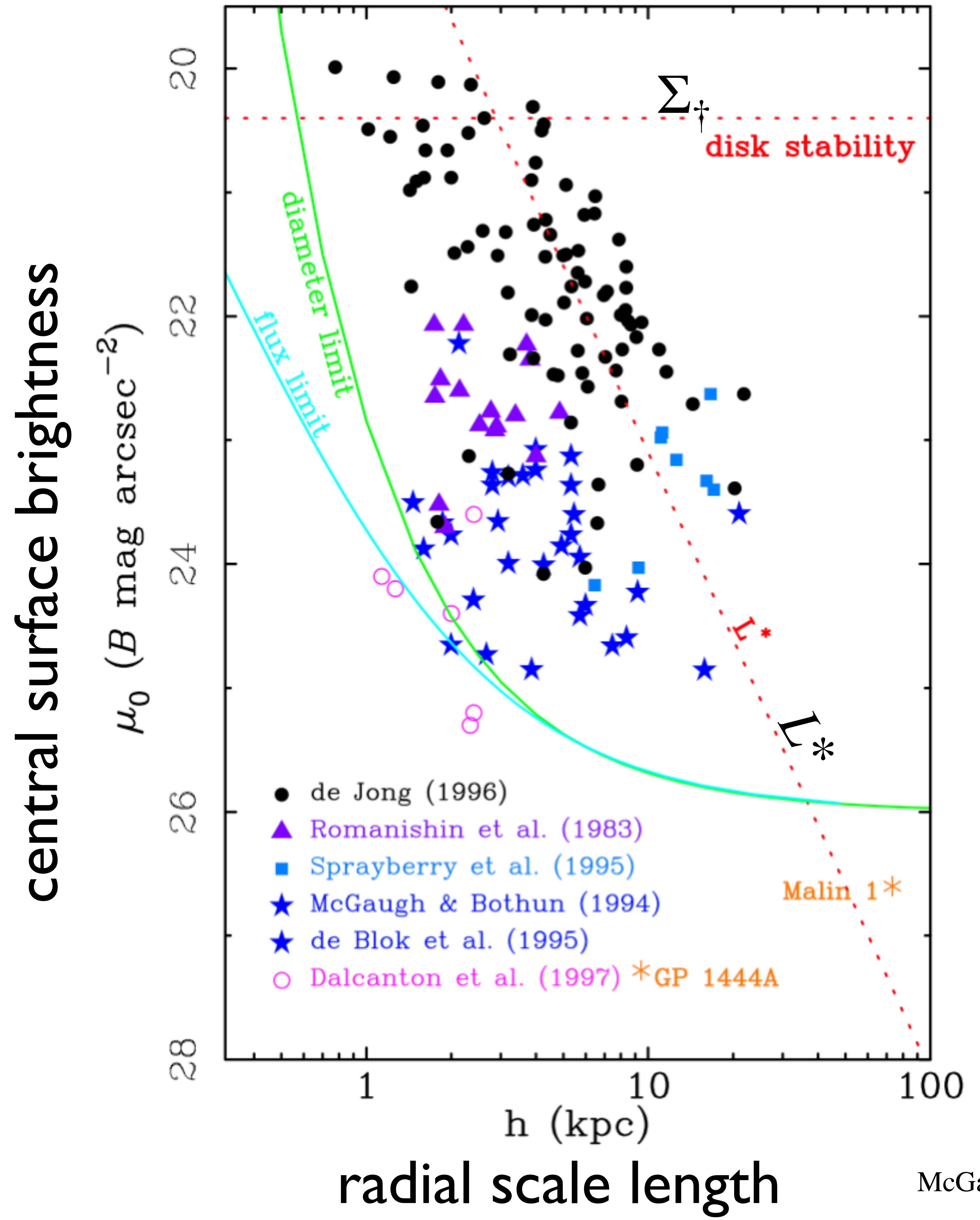


$$\Sigma(R) = \Sigma_o\, e^{-R/R_d}$$

Azimuthally averaged light distribution approximately exponential for spiral disks.

Low Surface Brightness Galaxy

Disk galaxies (Spirals+Irrs)



Galaxies exist all over the size-surface brightness plane up to maximums in luminosity $L*$ and surface brightness $\Sigma_\dagger$

No minimums known - lower boundaries set by selection effects.

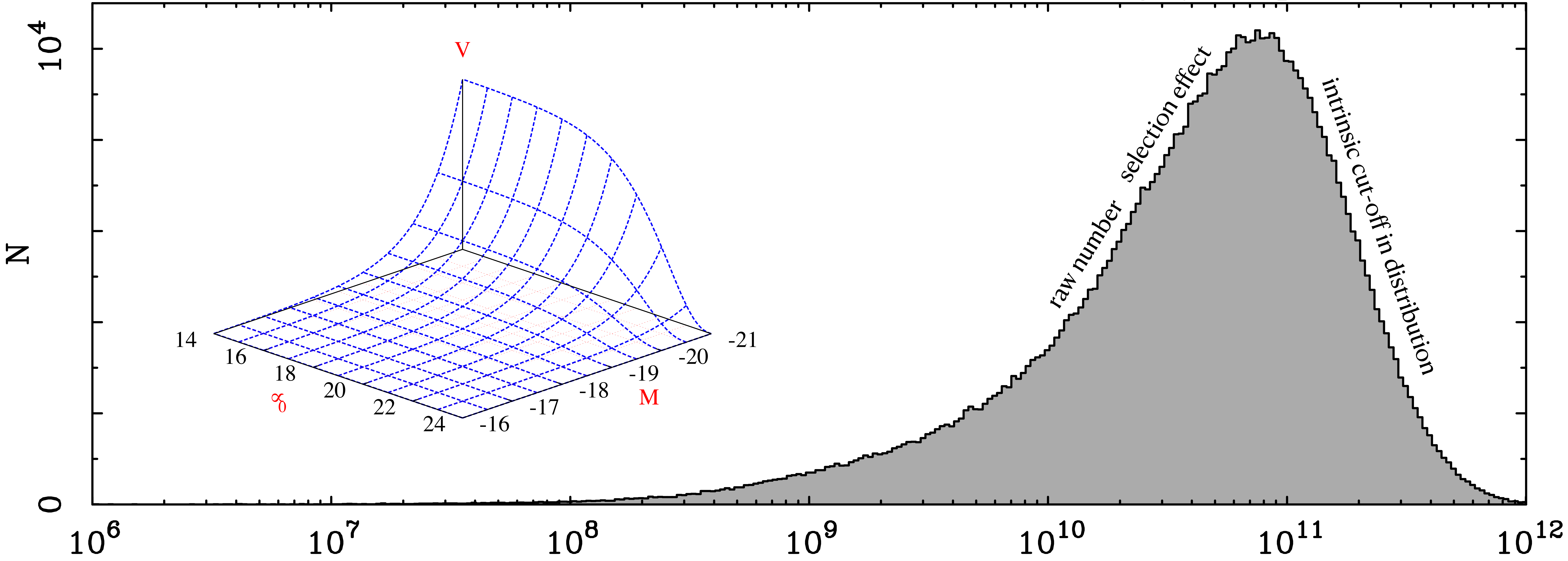
Note that galaxies of a given luminosity exist over a wide range of size and surface brightness. Galaxies are **not** a single parameter sequence in mass.

McGaugh (1999) IAU 171: ASP 170, 19 (arXiv:astro-ph/9810363)

Selection effects in galaxy surveys -
the number of galaxies in the Sloan survey as a function of mass

Faint and low surface brightness galaxies are hard to see. Only detected over a small volume.

Bright galaxies are easy to see. Are detected over a large volume. This is highly unrepresentative.



raw number peaks around $\sim 0.7L^*$

The intrinsic *numbers* of galaxies increase with decreasing mass after volume correction.

Most *mass* is in the most massive galaxies.

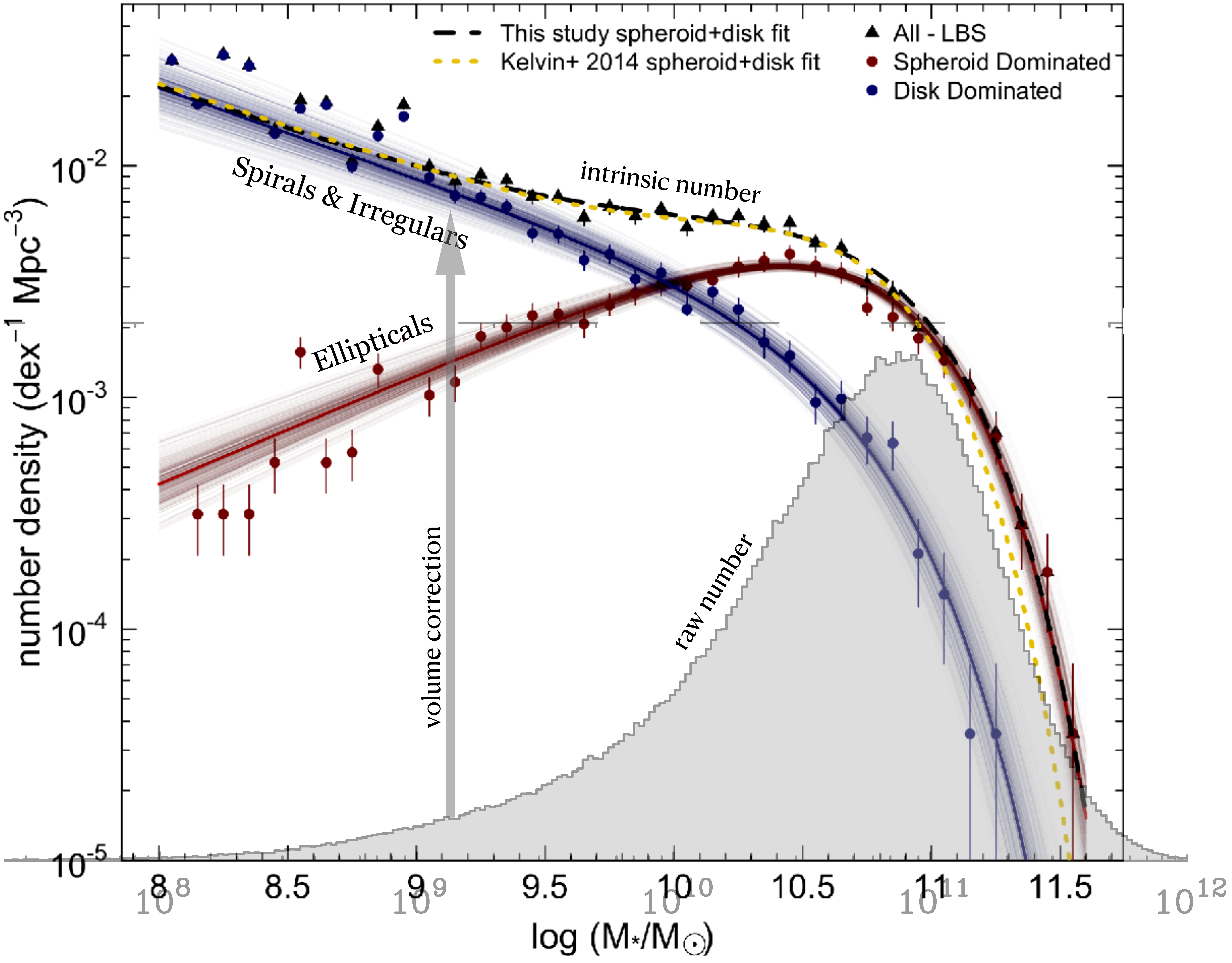
Luminosity density

$$j = \int_0^\infty L\,\Phi(L)\,dL = \Phi^* L^* \Gamma(2-\alpha)$$

Incomplete Γ function of order unity for $\alpha < 1.5$; diverges for $\alpha = 2$.

$$j = \Phi^* L^* \Gamma(2-\alpha) \approx \Phi^* L^*$$

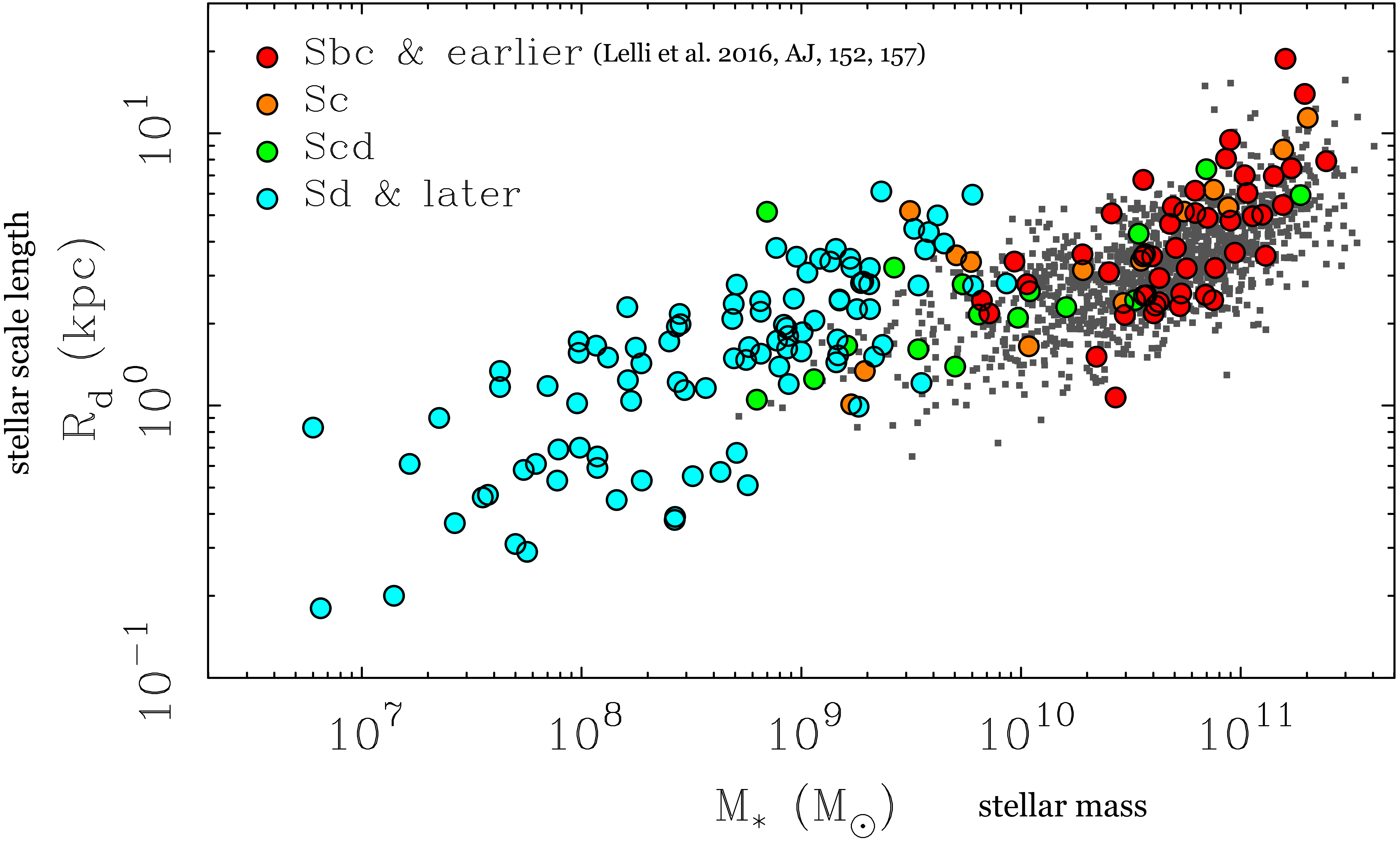
Galaxy mass function from the GAMA survey



Moffett et al. 2016, MNRAS, 457, 1308

Magnitude selected samples are biased towards bright galaxies.

They underrepresent dwarf and LSB galaxies.

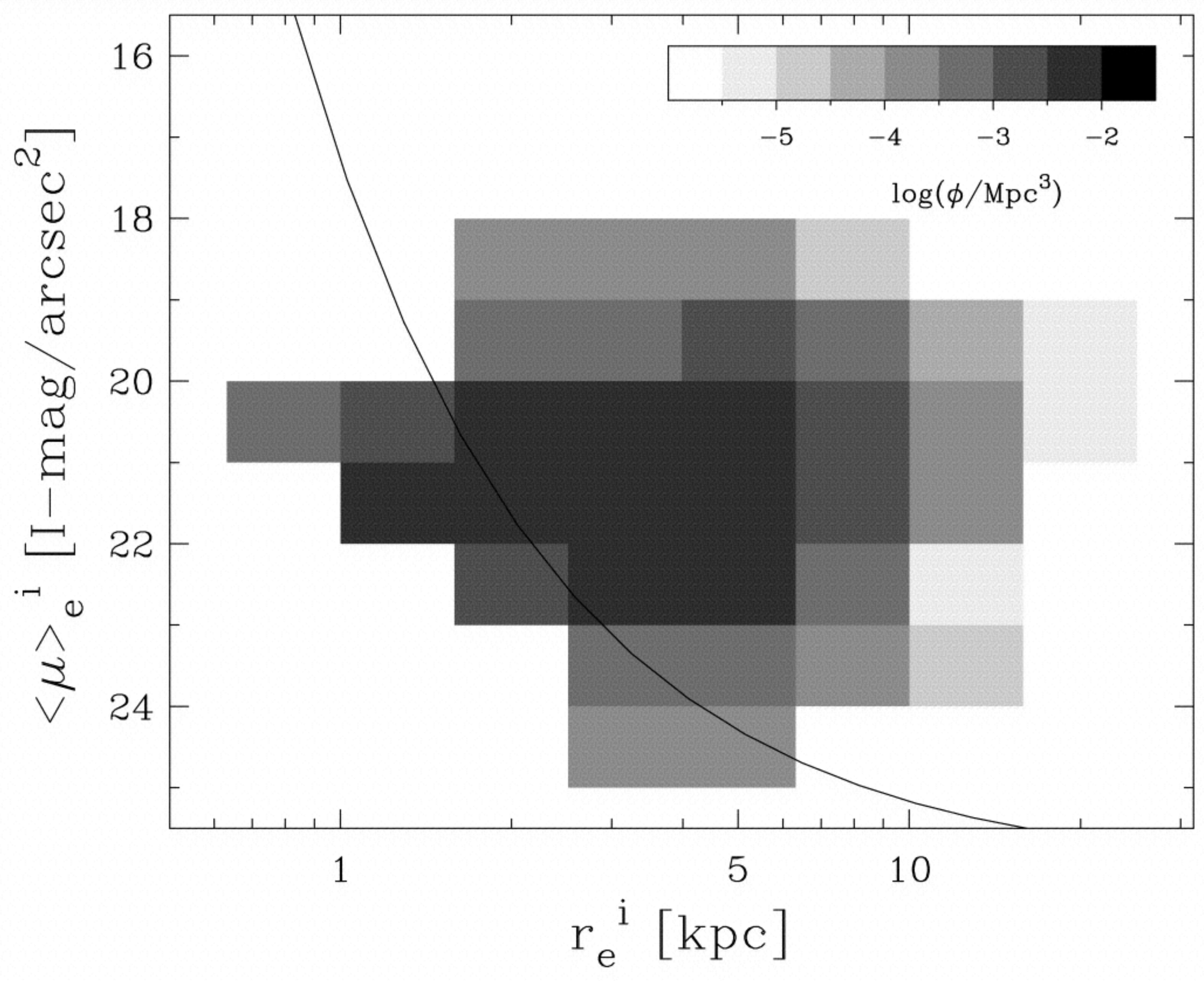


In general, one would like to know the bivariate distribution of size and surface brightness.

This is the 2D projection of a 3D plot with number density illustrated by the shading.

The luminosity function is an integral over the bivariate distribution: $L \propto \Sigma_e R_e^2$.

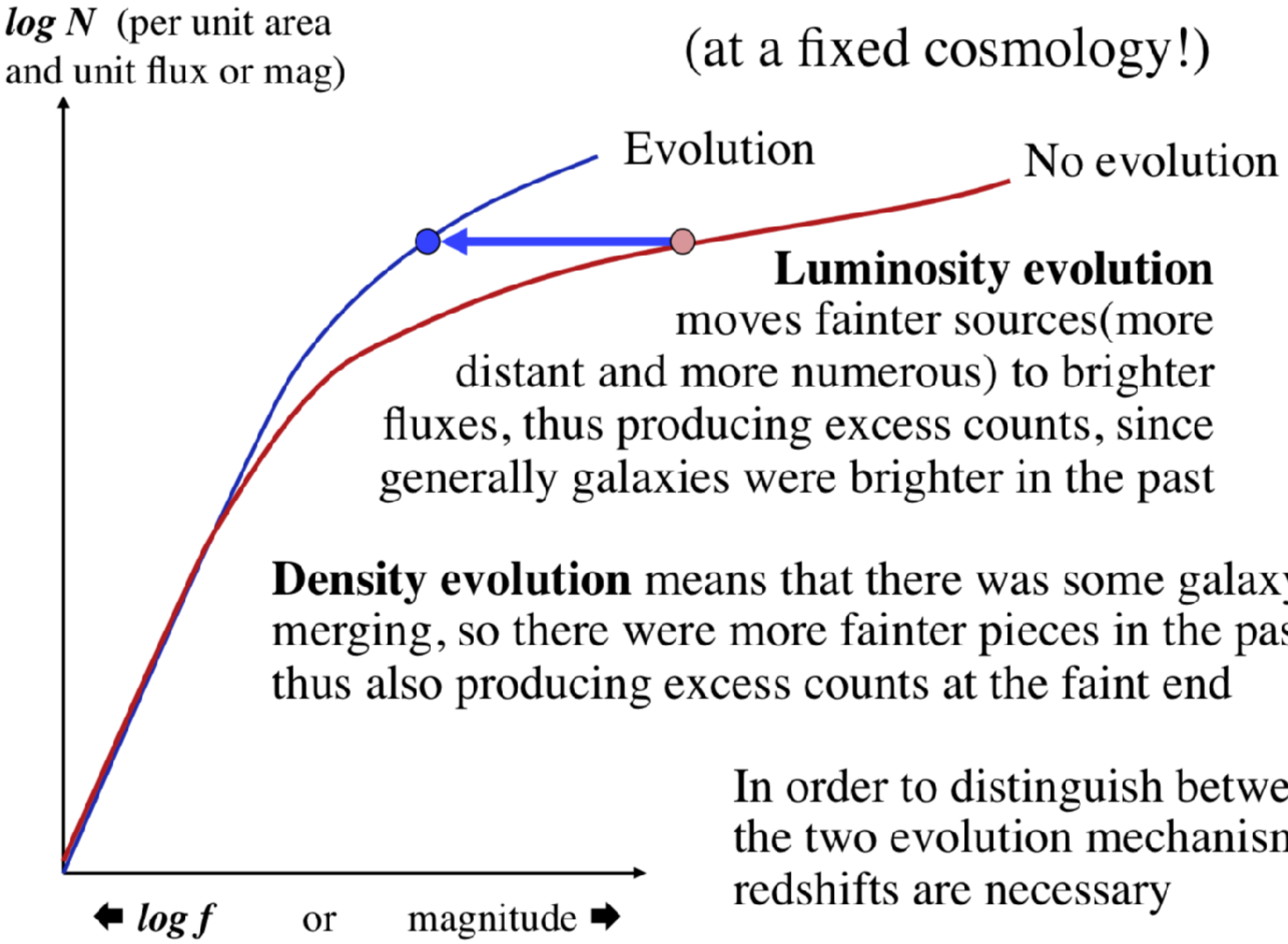
Can employ more parameters to more fully describe galaxies. E.g., this plot is restricted to morphological types Sb - Sdm.



Bivariate space density distribution of Sb-Sdm galaxies as a function of effective surface brightness and effective radius from de Jong & Lacey (2000, ApJ, 545, 781).
The line indicates the 20 Mpc sample selection limit for face-on exponential disks. To the left of the line we are limited by small number statistics and local density fluctuations.

Source Counts: The Effect of Evolution

(at a fixed cosmology!)



Luminosity evolution moves fainter sources(more distant and more numerous) to brighter fluxes, thus producing excess counts, since generally galaxies were brighter in the past

Density evolution means that there was some galaxy merging, so there were more fainter pieces in the past, thus also producing excess counts at the faint end

In order to distinguish between the two evolution mechanisms, redshifts are necessary

Djorgovski (2017)

What We Need

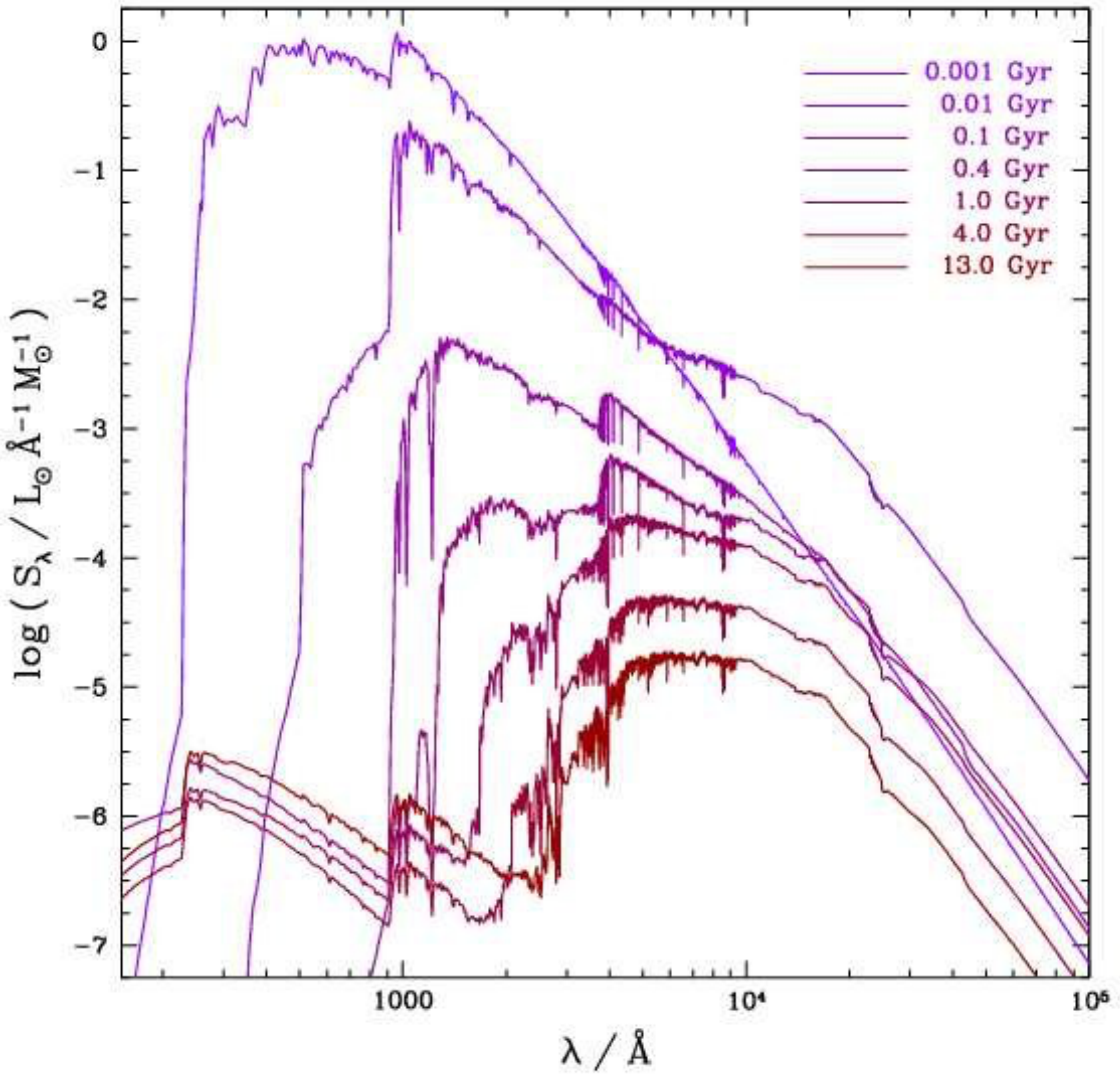
- Stellar theory predicts the evolution or (***stellar tracks***) or stars of a given mass. There is some variation among different theoretical models
- Observations give us ***libraries of stellar spectra*** as a function of age, mass, metallicity, etc.
- We need the ***initial mass function (IMF)*** of stars
- All of these are uncertain at very low metallicities and high stellar masses
- We have to assume some ***star formation rate (SFR)*** as a function of time. Popular choices include a sharp burst, a constant SFR, or an exponentially declining one:

$$\frac{\partial M}{\partial t} \propto \exp\left(-\frac{t}{\tau}\right)$$

Djorgovski (2017)

Galaxy Evolution

SSP: evolution of simple stellar population in which all stars are born at the same time.

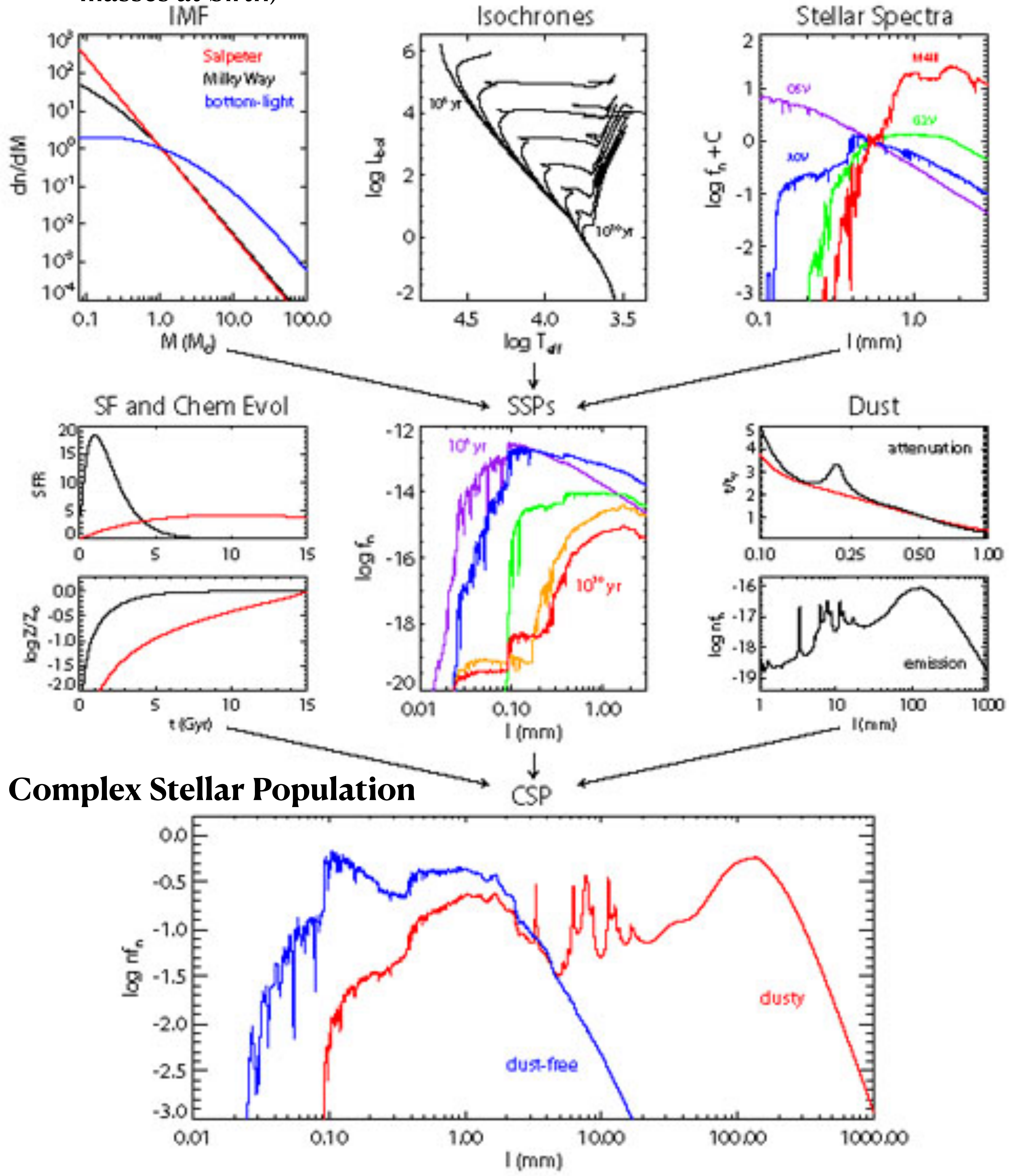


IMF
(distribution of stellar masses at birth)

Stellar Evolution

Stellar Spectra

Complex Stellar Population

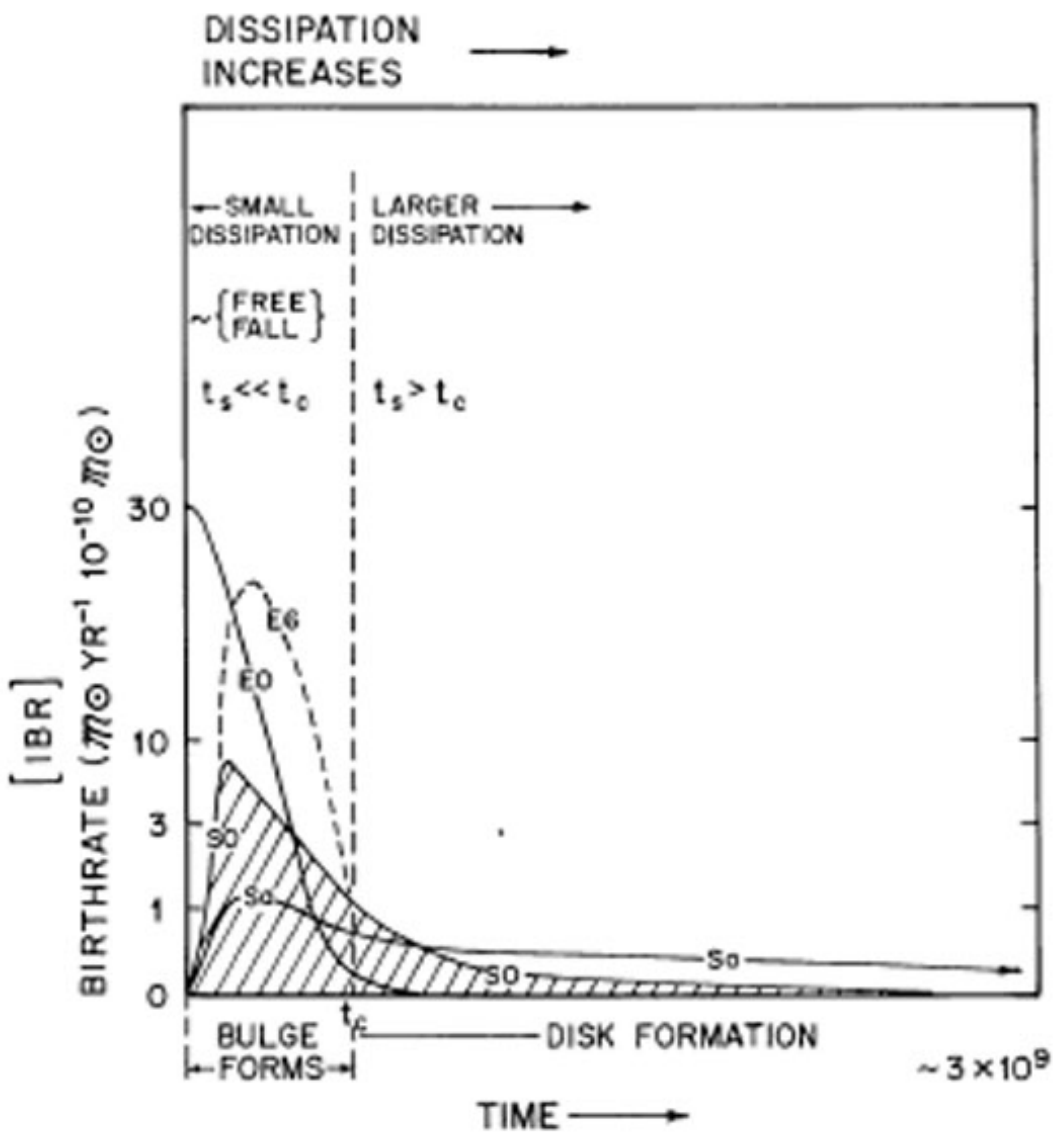


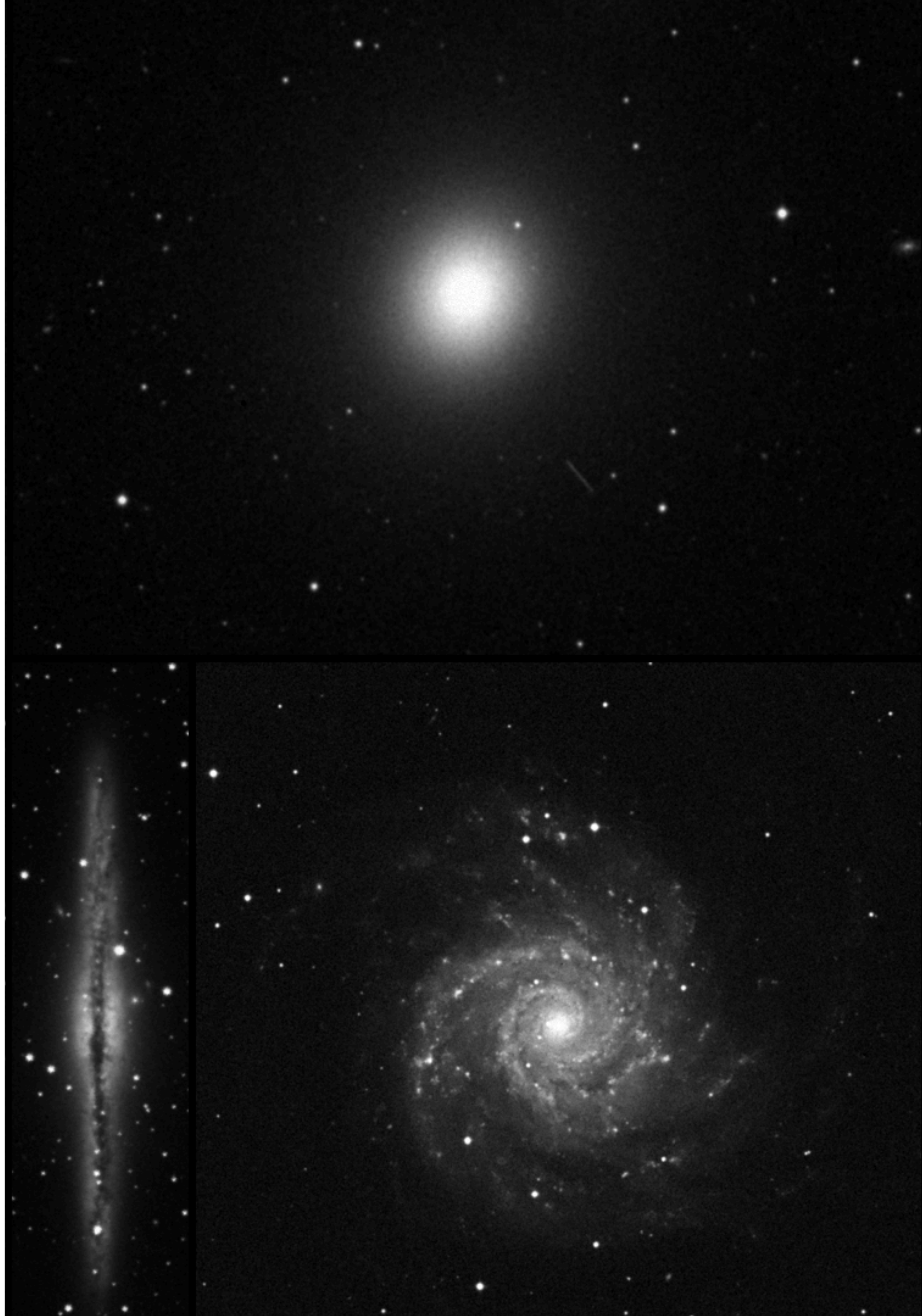
Galaxy Evolution

Early Types
(Ellipticals)

Star formation rate

Sandage (1986)





Late Types
(Spirals & Irregulars)

Galaxy Evolution

Early Type Galaxies (aka ETGs: Elliptical galaxies) generally formed most their stars early, in the first few billion years or so.

Late Types (aka LTGs: Spirals & Irregular galaxies) have a more continuous star formation history, and continue to form stars today.

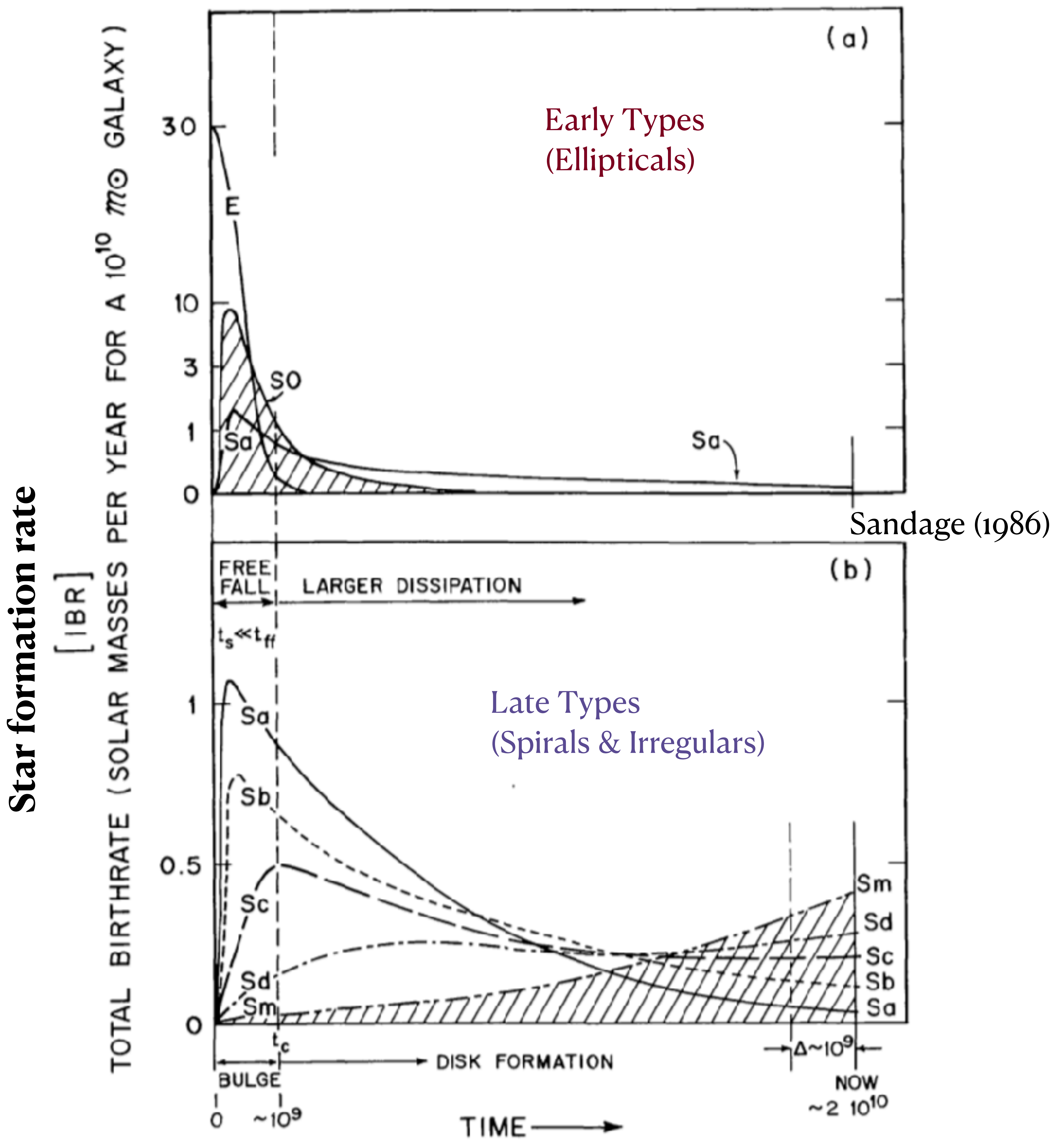


Fig. 10. Same as Fig. 9 with later Hubble types shown in the lower panel. The integral under the Sm curve is shaded for illustration. The curves are only schematic showing the trends that have been established by Gallagher et al. (1984)

Galaxy Evolution

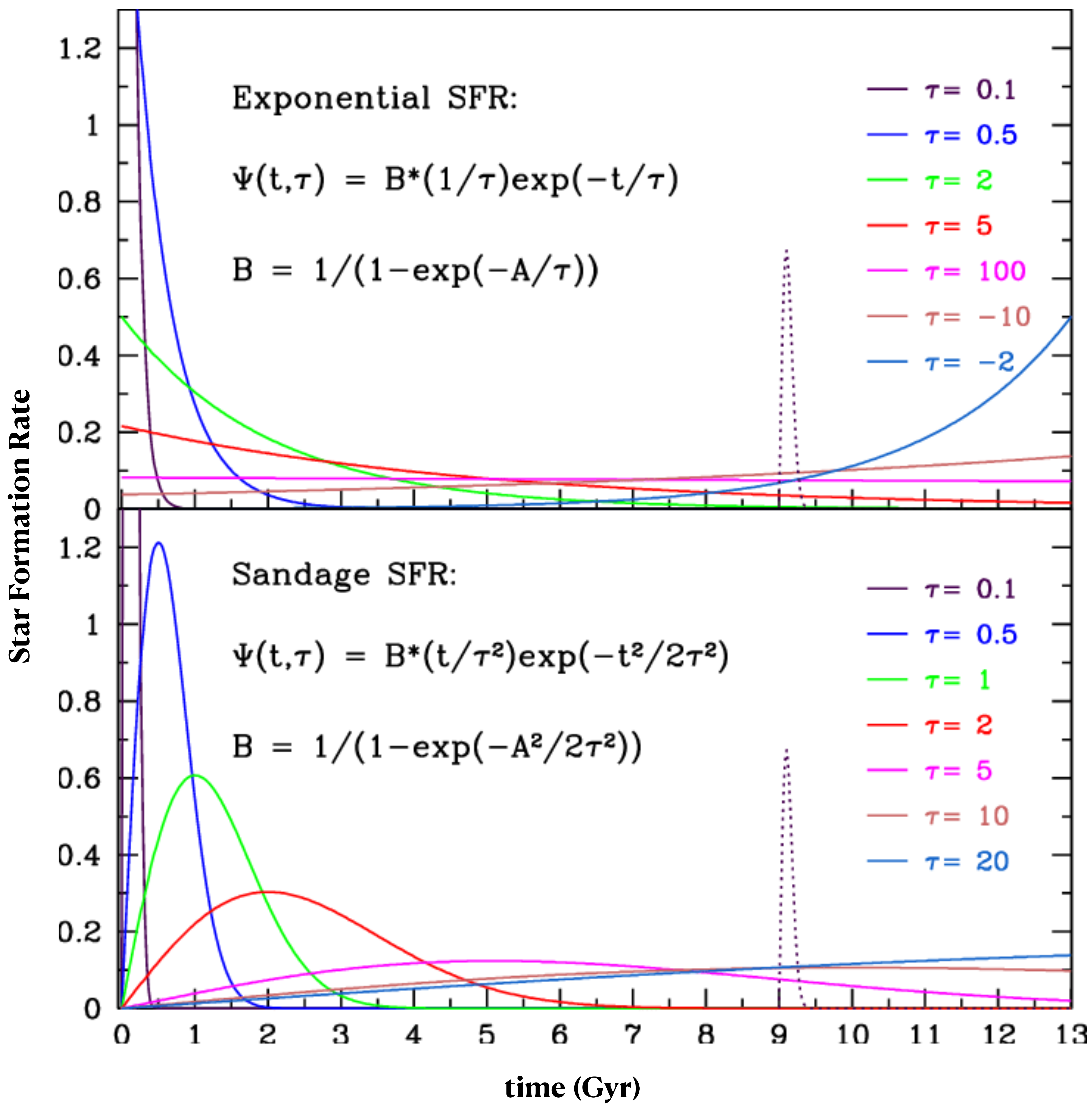
Common model star formation history

Exponential:

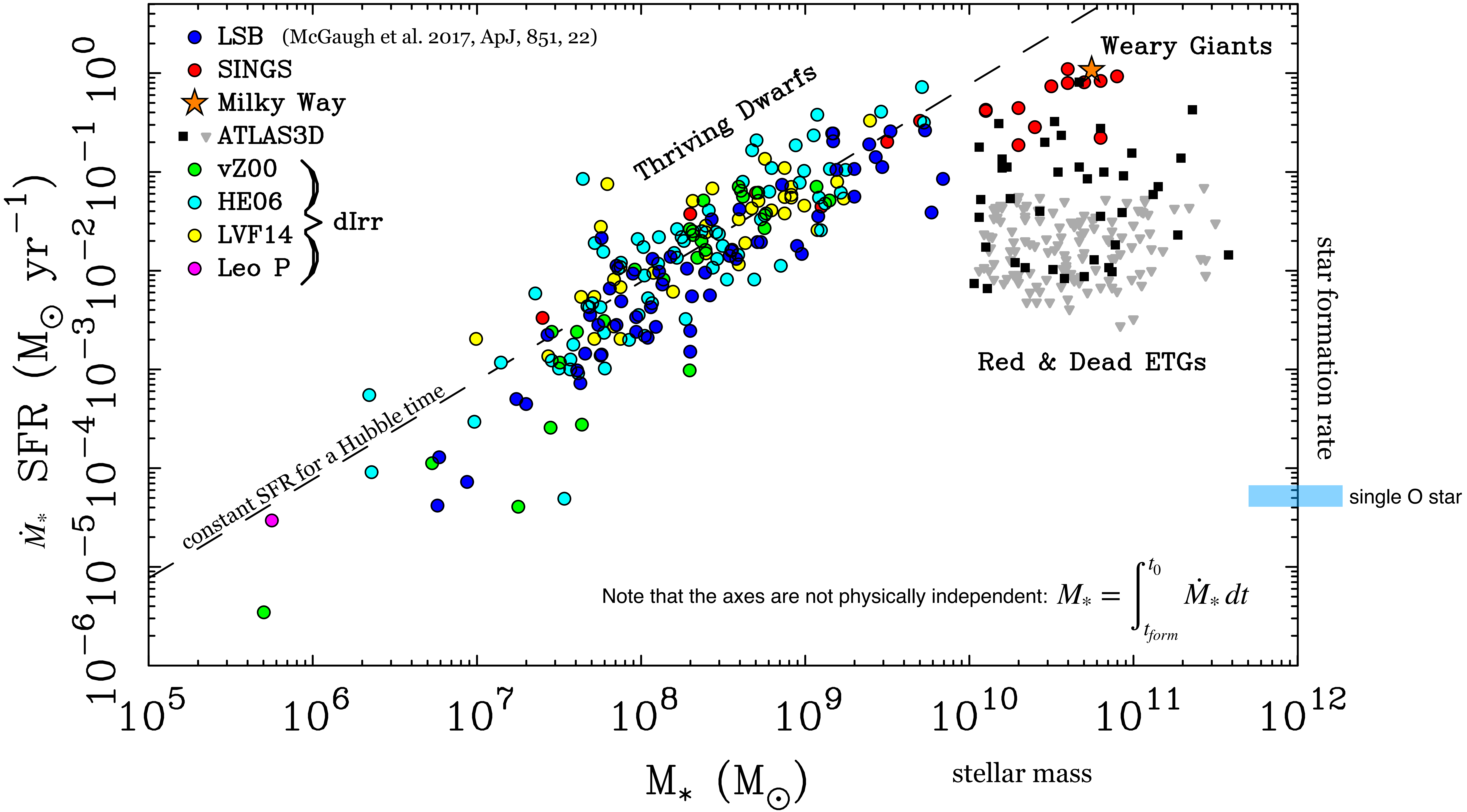
$$\mathrm{SFR} = \dot{M}_* = \Psi(t, T) \propto e^{-t/\tau}$$

with different e-folding timescales characteristic of different morphological types T.

ETGs typically have small $\tau \approx 1$ Gyr;
LTGs typically have longer timescales, sometimes of order a Hubble time.
Individual galaxies vary substantially.

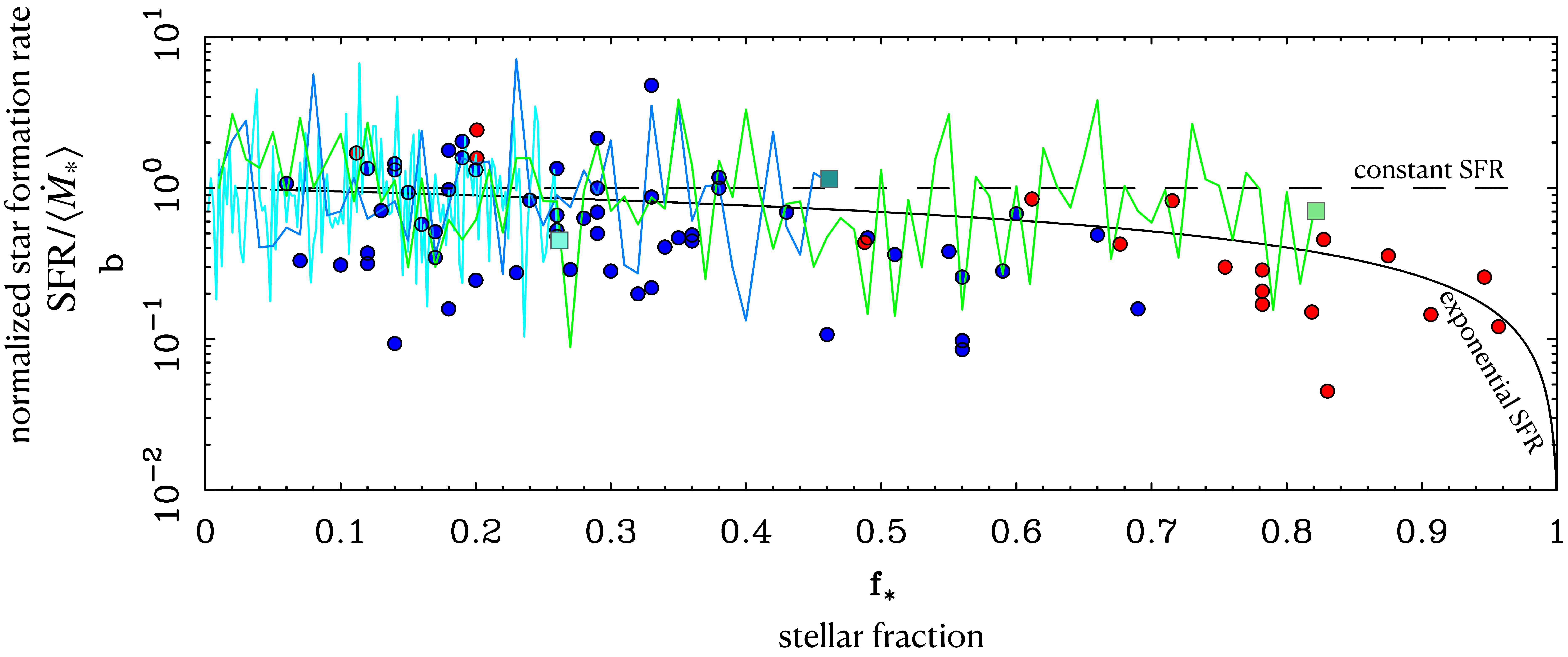


Star formation and Stellar mass - the “star forming main sequence”



Note that the axes are not physically independent: $M_* = \int_{t_{form}}^{t_0} \dot{M}_* \, dt$

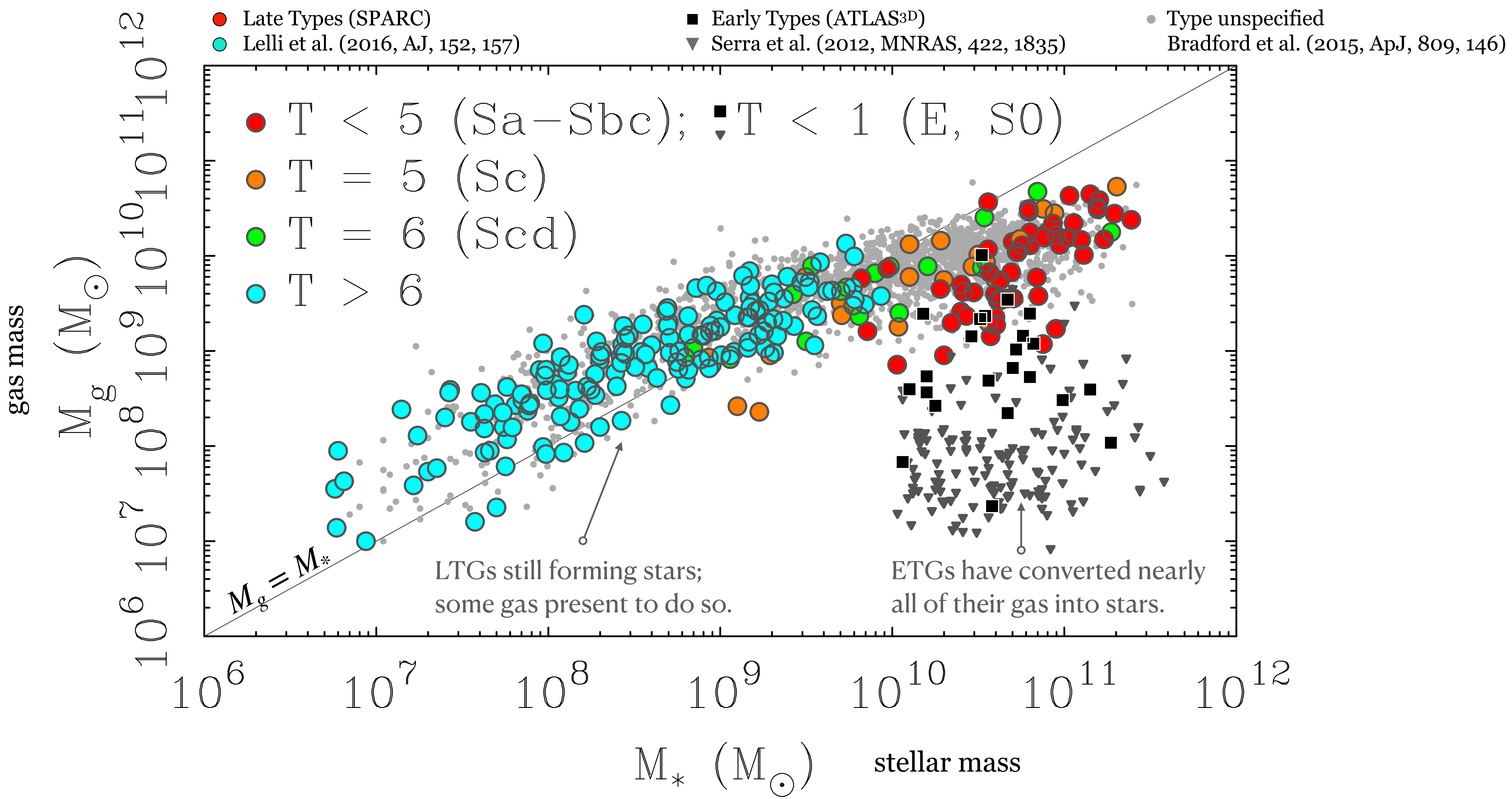
ETGs typically have small $\tau \approx 1$ Gyr;
LTGs typically have longer timescales,
often roughly constant but usually with
substantial short-term variations.



$$b = \frac{\dot{M}_*}{\int_0^t \dot{M}_*\, dt} = \frac{\dot{M}_*}{\langle \dot{M}_* \rangle} \approx \frac{\mathrm{SFR}}{M_*/t}$$

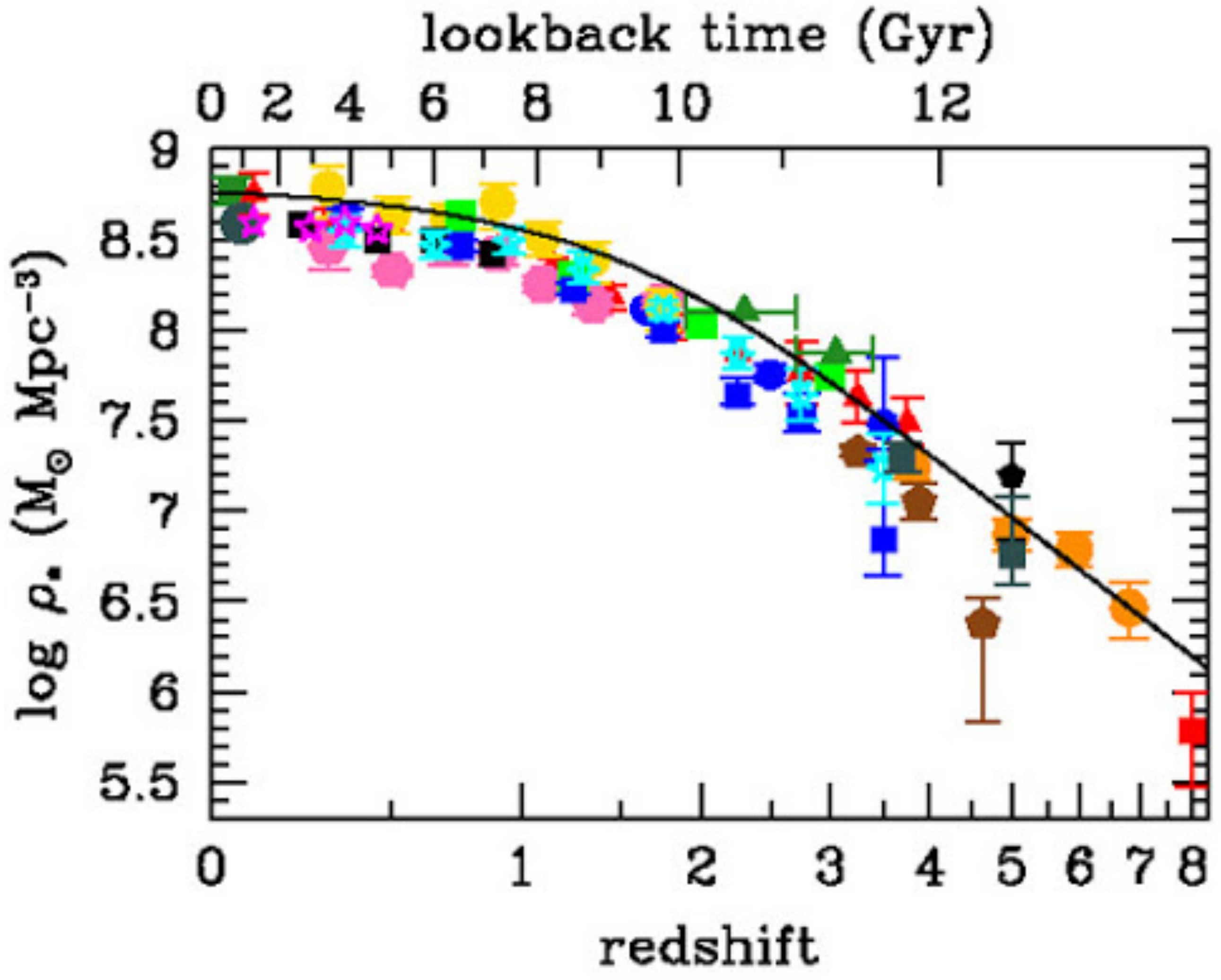
$$f_* = \frac{M_*}{M_* + M_g}$$

Gas mass and Stellar mass

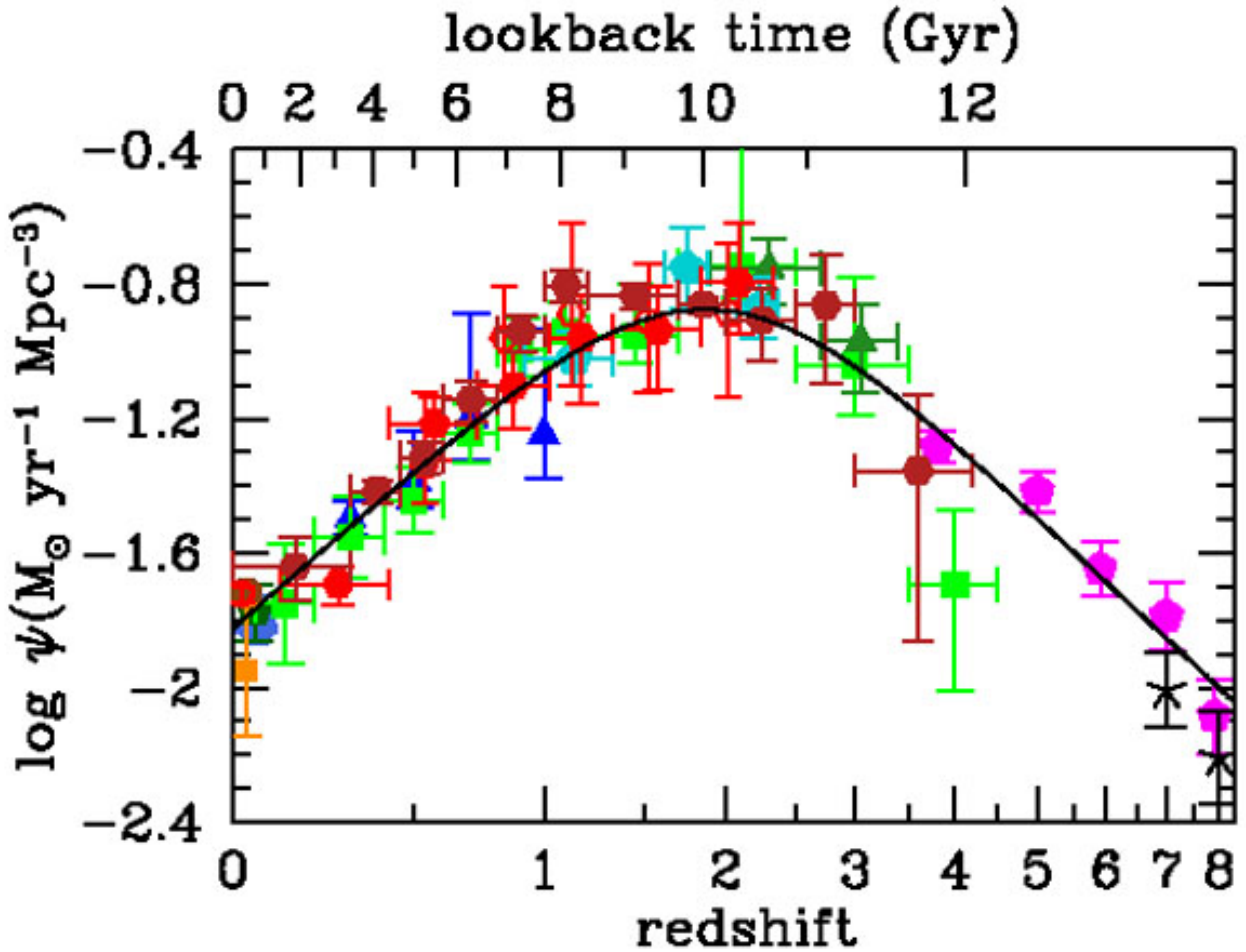


Integrated stellar mass and star formation rate

stellar mass density



star formation rate



The mass density in stars is small: about 7% of the BBN baryon density

$$\Omega_{*_0} \approx 0.0035$$

$$\Omega_{*_0} = \Upsilon_* [\Phi_0^* L_0^* \Gamma(\alpha)]/\rho_c$$

Stellar mass-to-light ratio

Schechter function at $z = 0$

critical density

The cosmic star formation rate peaked early, around $z \approx 2$ (“cosmic noon”).

The star formation rate at high redshift is highly uncertain due to extinction corrections.