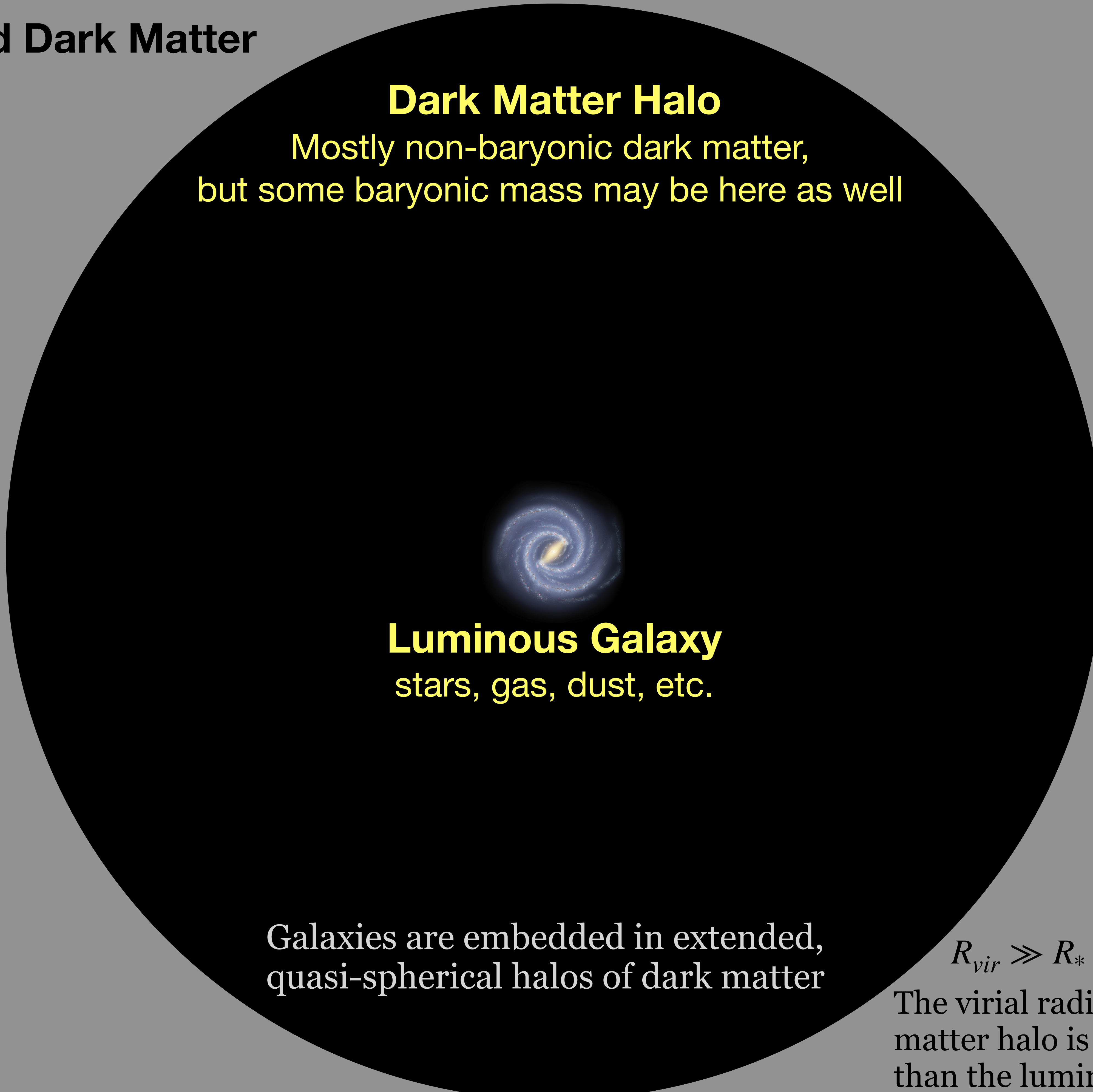
Standard Dark Matter Picture:

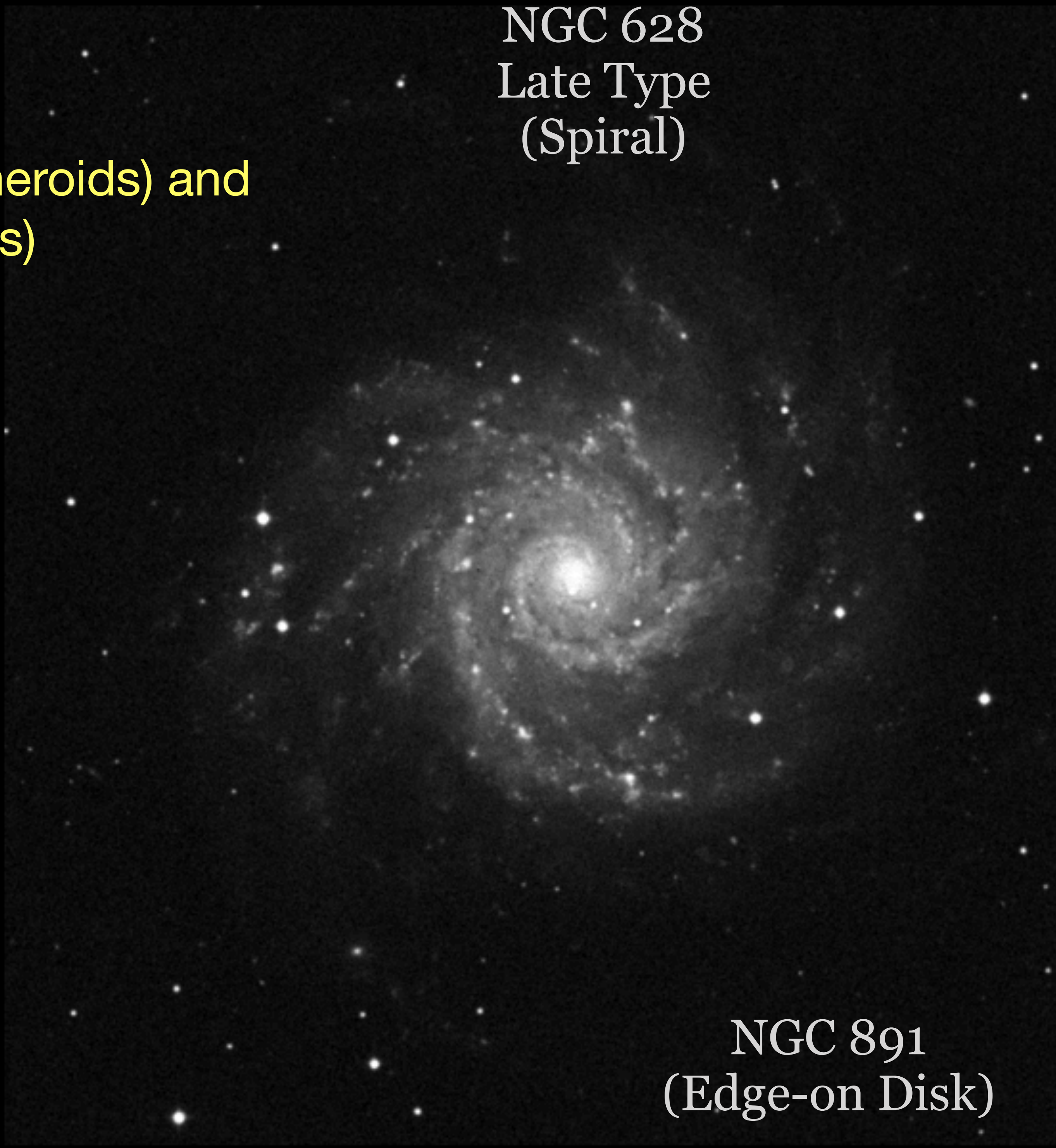


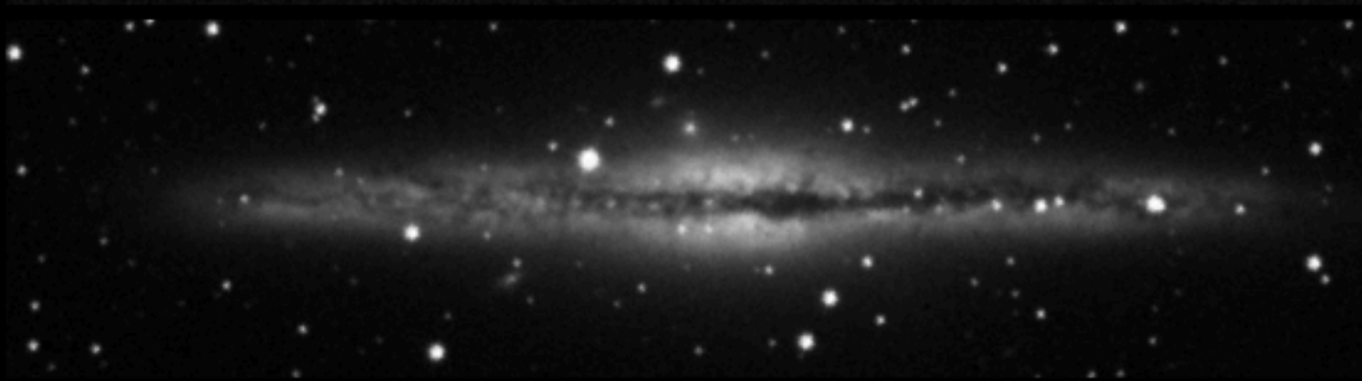
$R_{vir} \gg R_*$

The virial radius of the dark matter halo is much larger than the luminous galaxy

In MOND, what you see is what you get.

Galaxies come in two basic flavors:
Early Types (Ellipticals; pressure supported spheroids) and
Late Types (Spirals and Irregulars; rotating disks)





Galaxies exist over a huge dynamic range in

Luminosity
$1\text{x}10^7 < L_{[3.6]} < 5\text{x}10^{11}\ L_\odot$

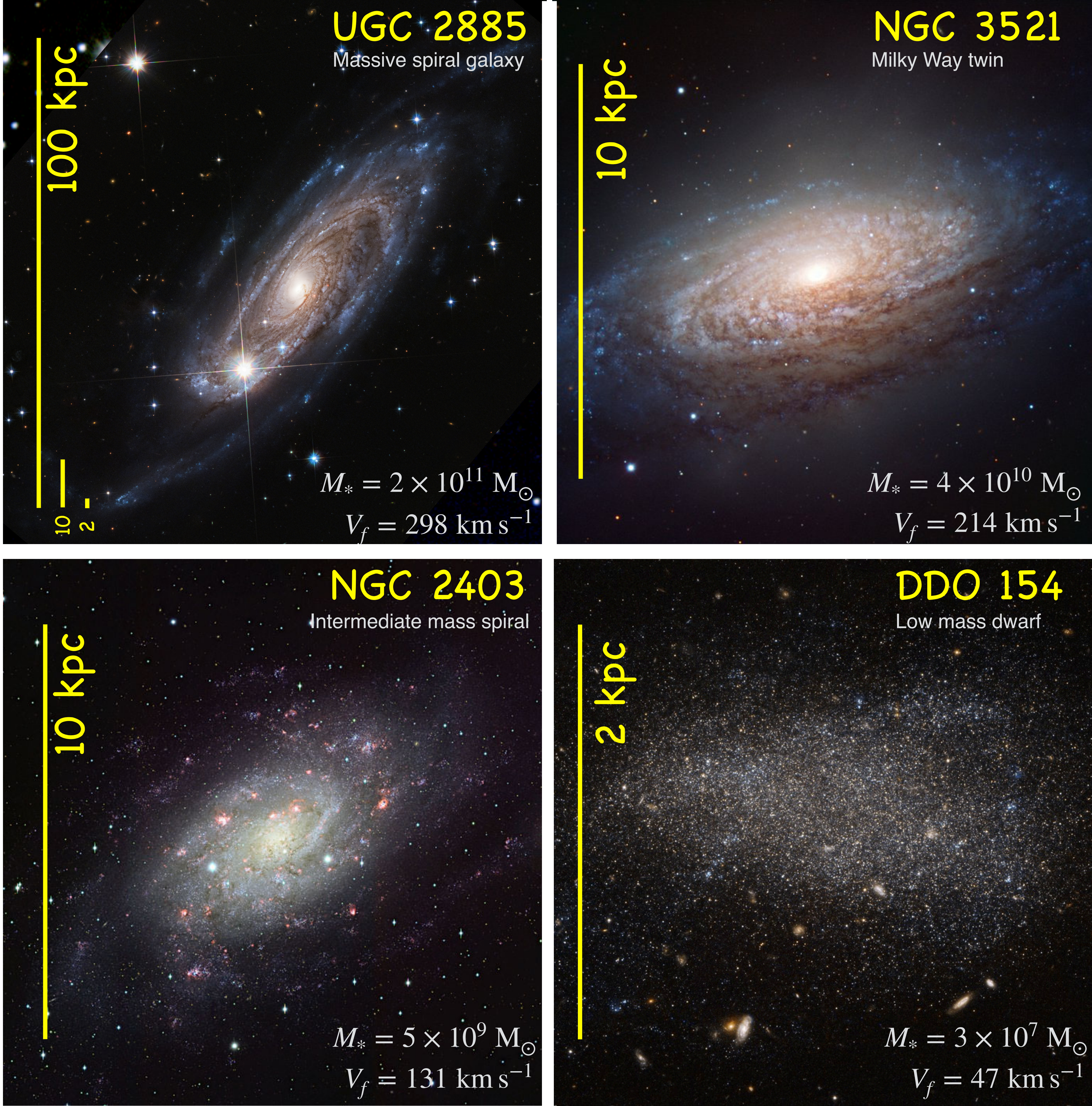
Gas mass
$1\text{x}10^7 < M^* < 5\text{x}10^{10}\ M_\odot$

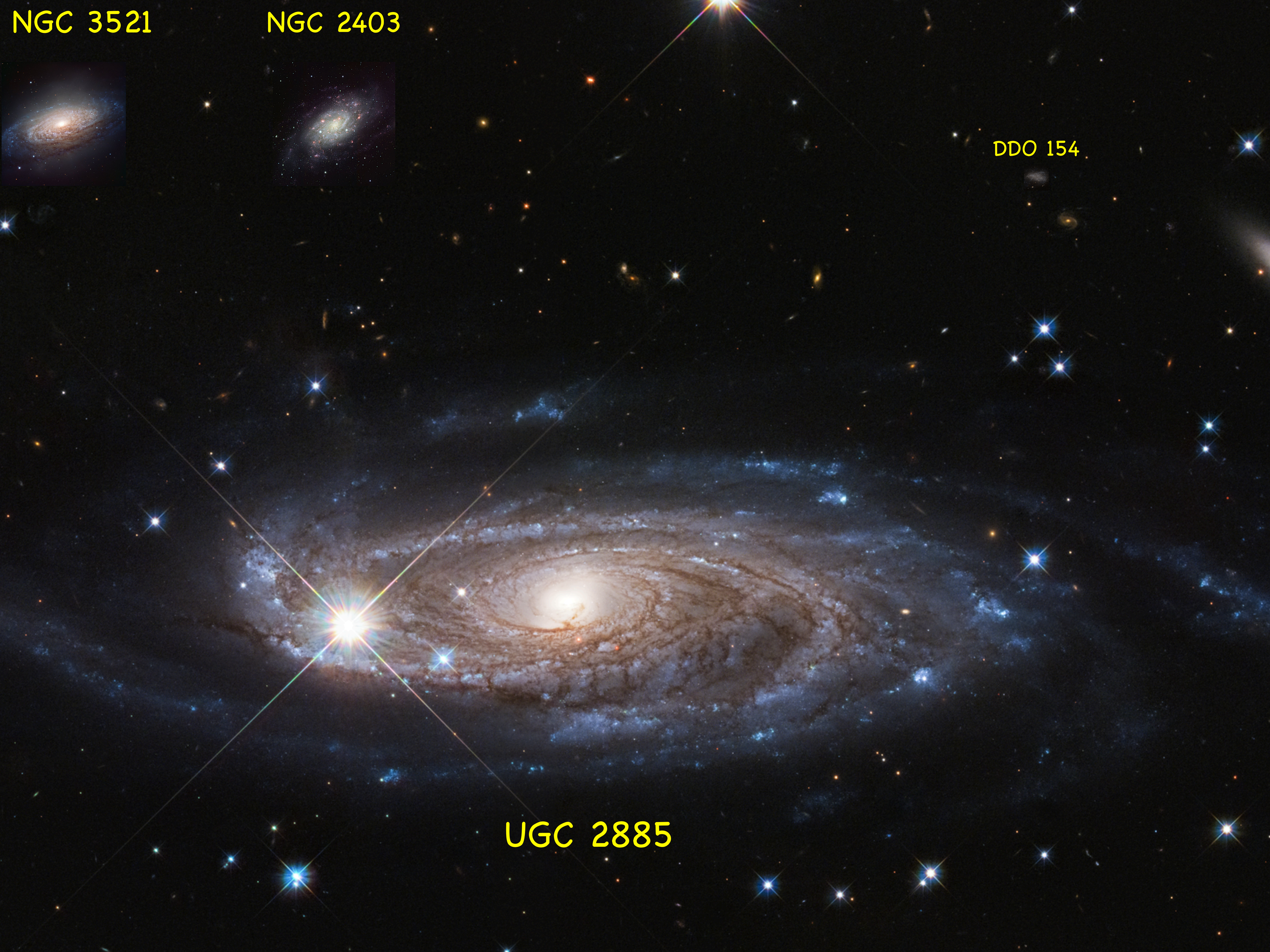
Surface brightness
$5 < \mu_e < 3\text{x}10^3\ L_\odot\,\text{pc}^{-2}$

Gas fraction
$0.03 < f_g < 0.97$

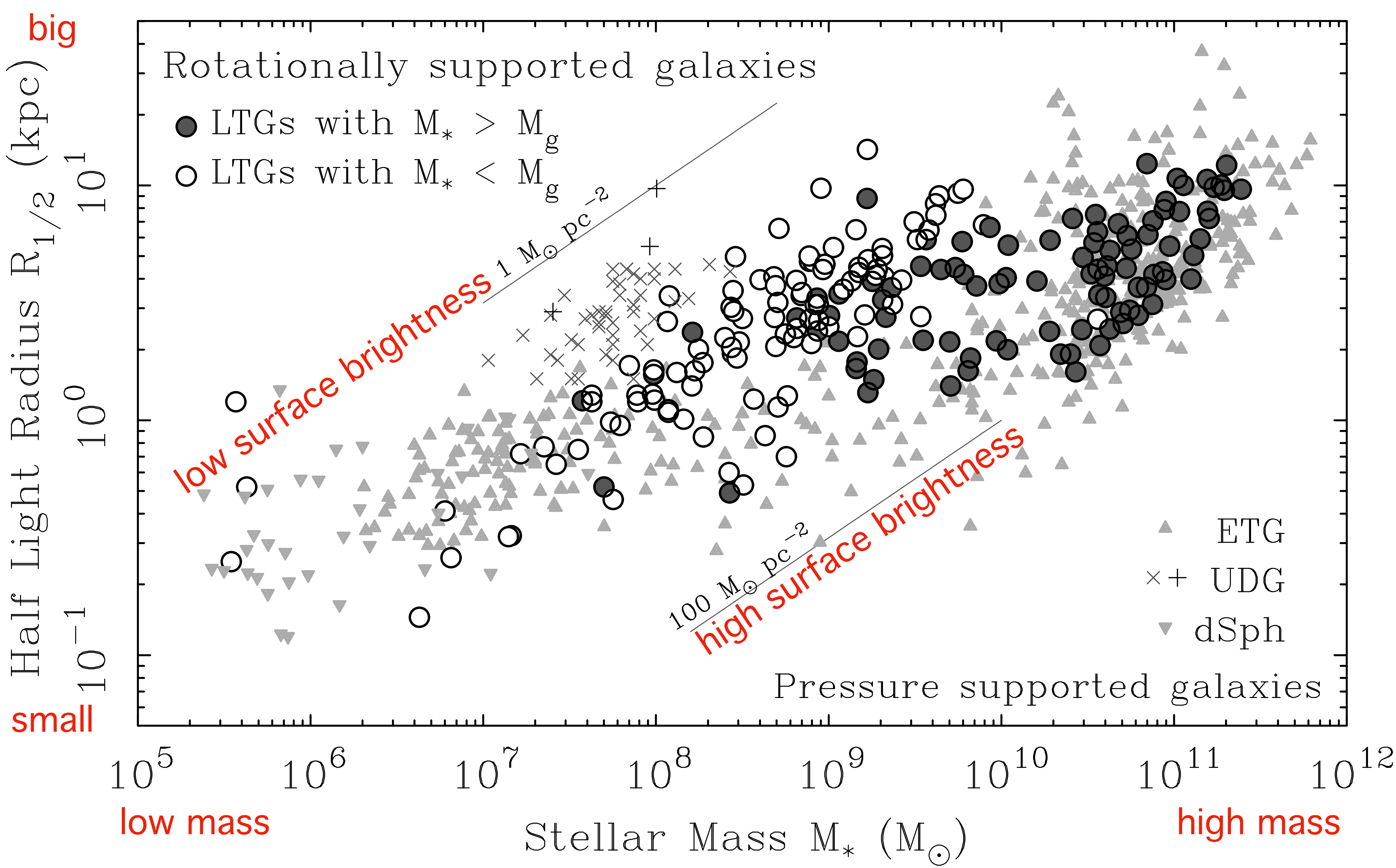
Rotation velocity
$15 < V_f < 300$ km/s

and probably more - the faint/dim end is always limited by selection effects.




NGC 3521
NGC 2403
DDO 154
UGC 2885

Sizes and masses of galaxies



Measuring the properties of a galaxy

The surface brightness profile is obtained by fitting ellipses to galaxy images, as in this example from Schombert (2007) using ARCHANGEL.

Each ellipse corresponds to an *isophote* - a ring of constant surface brightness.

Surface brightness is conventionally expressed in magnitudes per square arcsecond, with a corresponding physical unit of solar luminosities per square parsec.

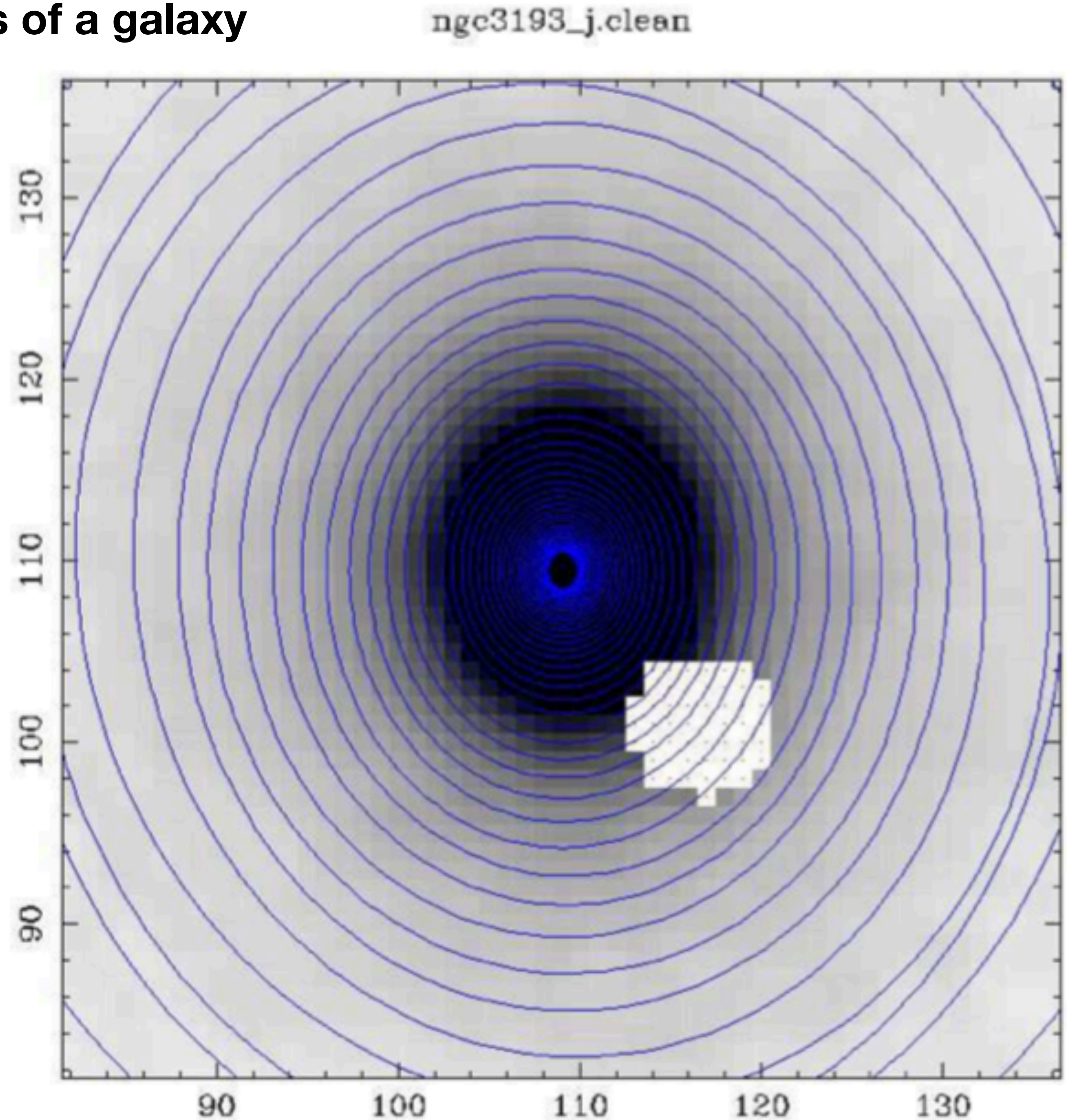
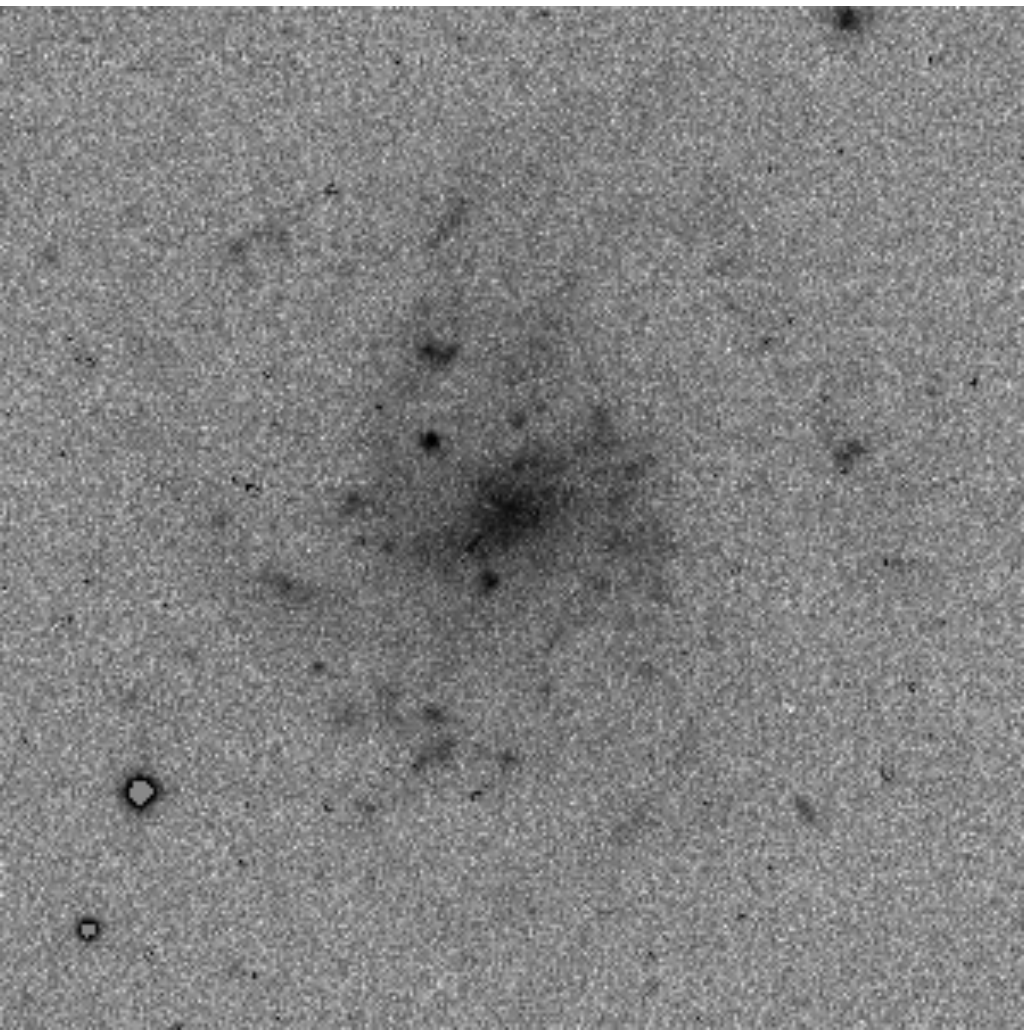
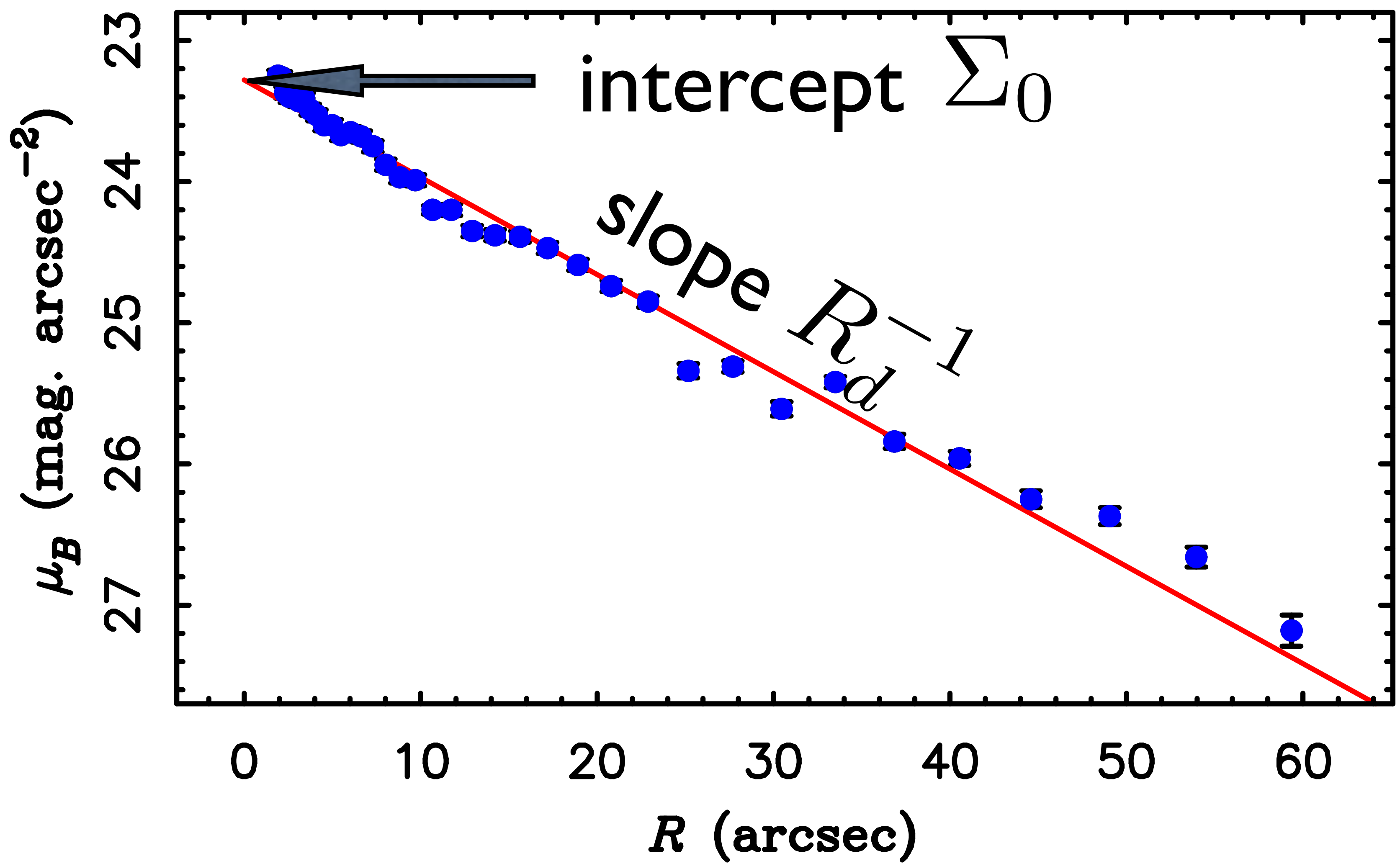


Fig. 2.— The resulting ellipse fits to NGC 3193's core region. While the automatic masking of the contaminating star is not perfect, it is sufficient to maintain a high quality fit.

Late Type Galaxies are typically approximated as Exponential disks

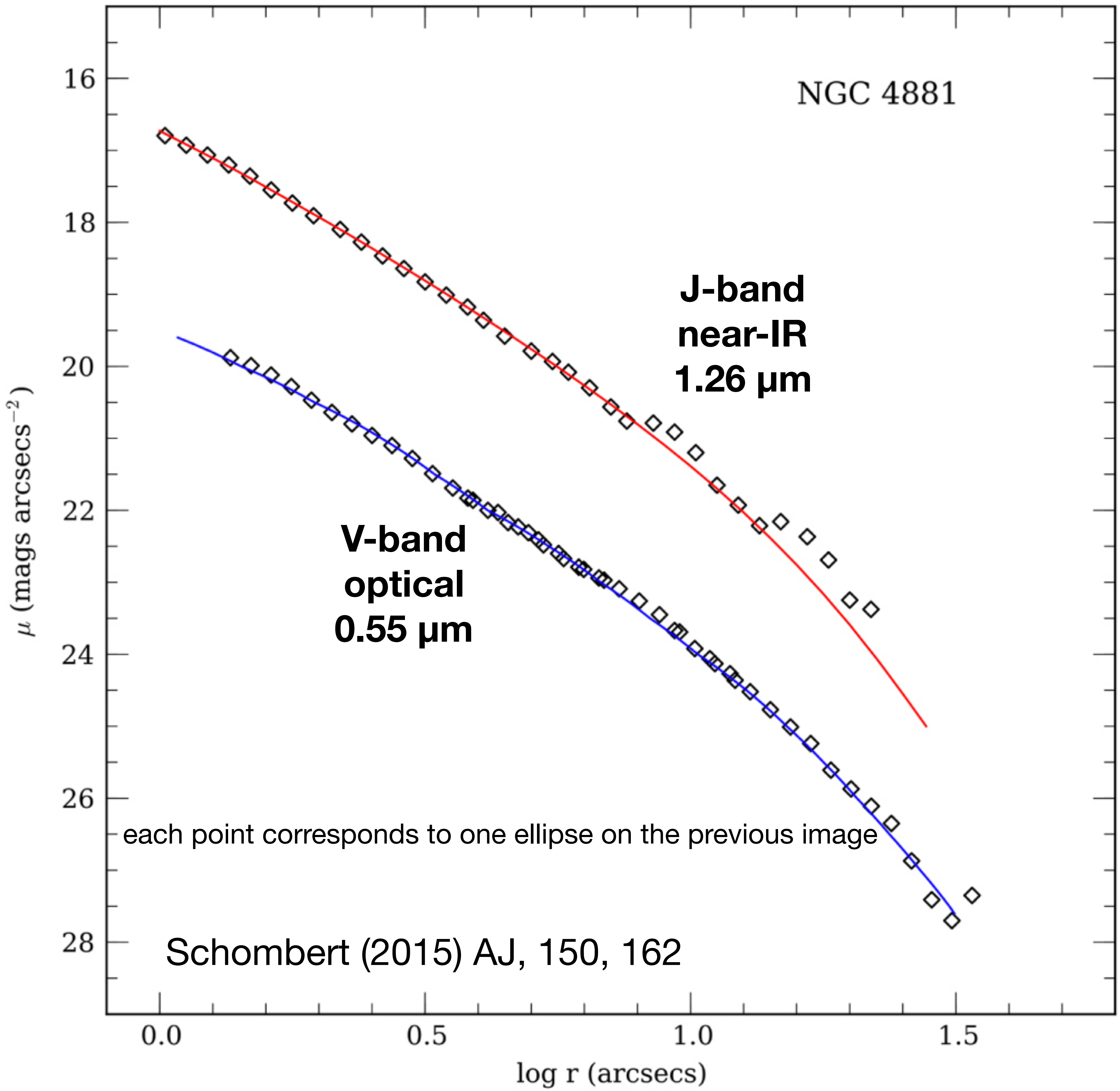




$$\Sigma(R) = \Sigma_0 e^{-R/R_d}$$

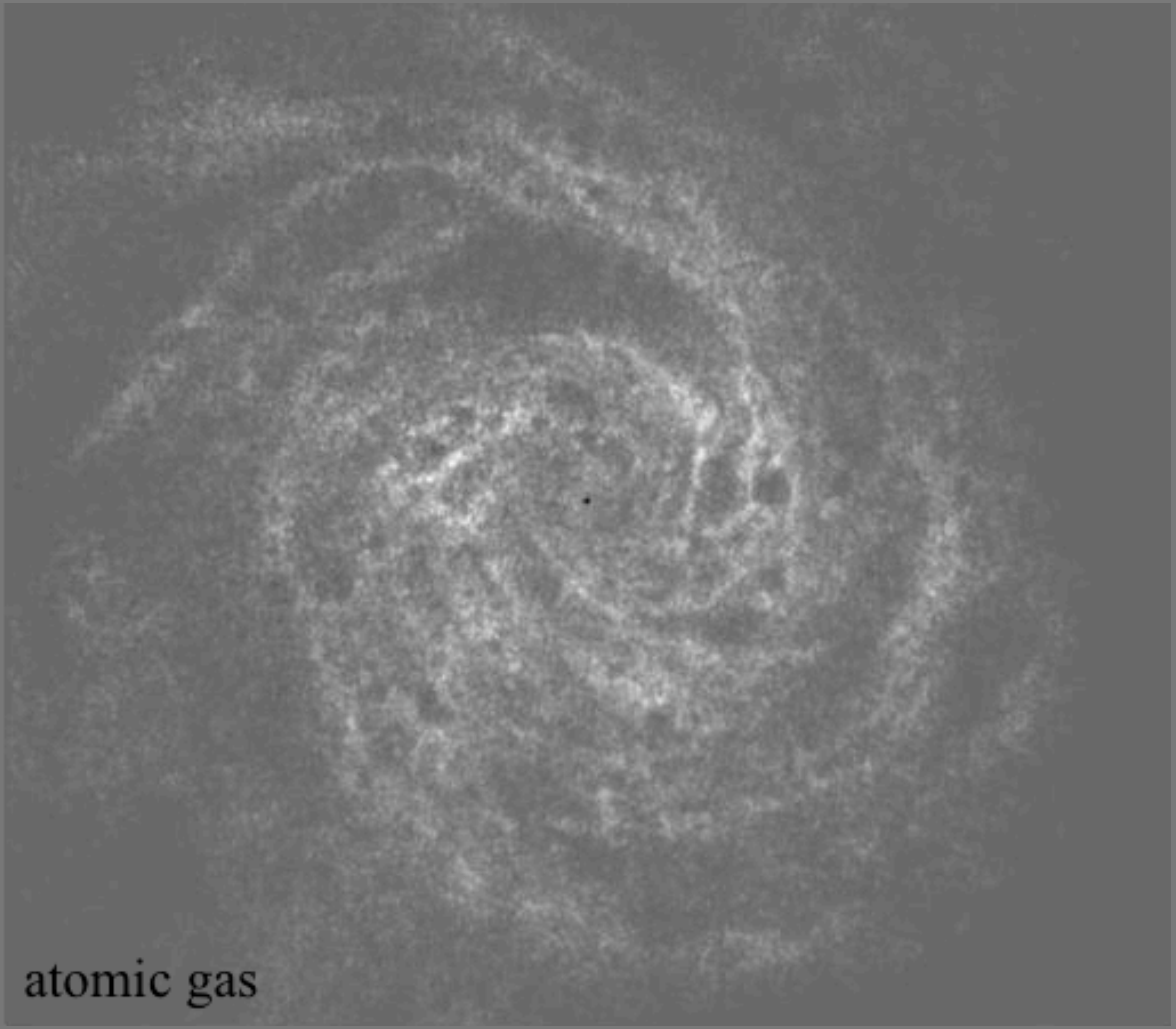
Azimuthally averaged light distribution approximately exponential for spiral disks.

Early Type Galaxies typically have approximately de Vaucouleurs $r^{1/4}$ profiles



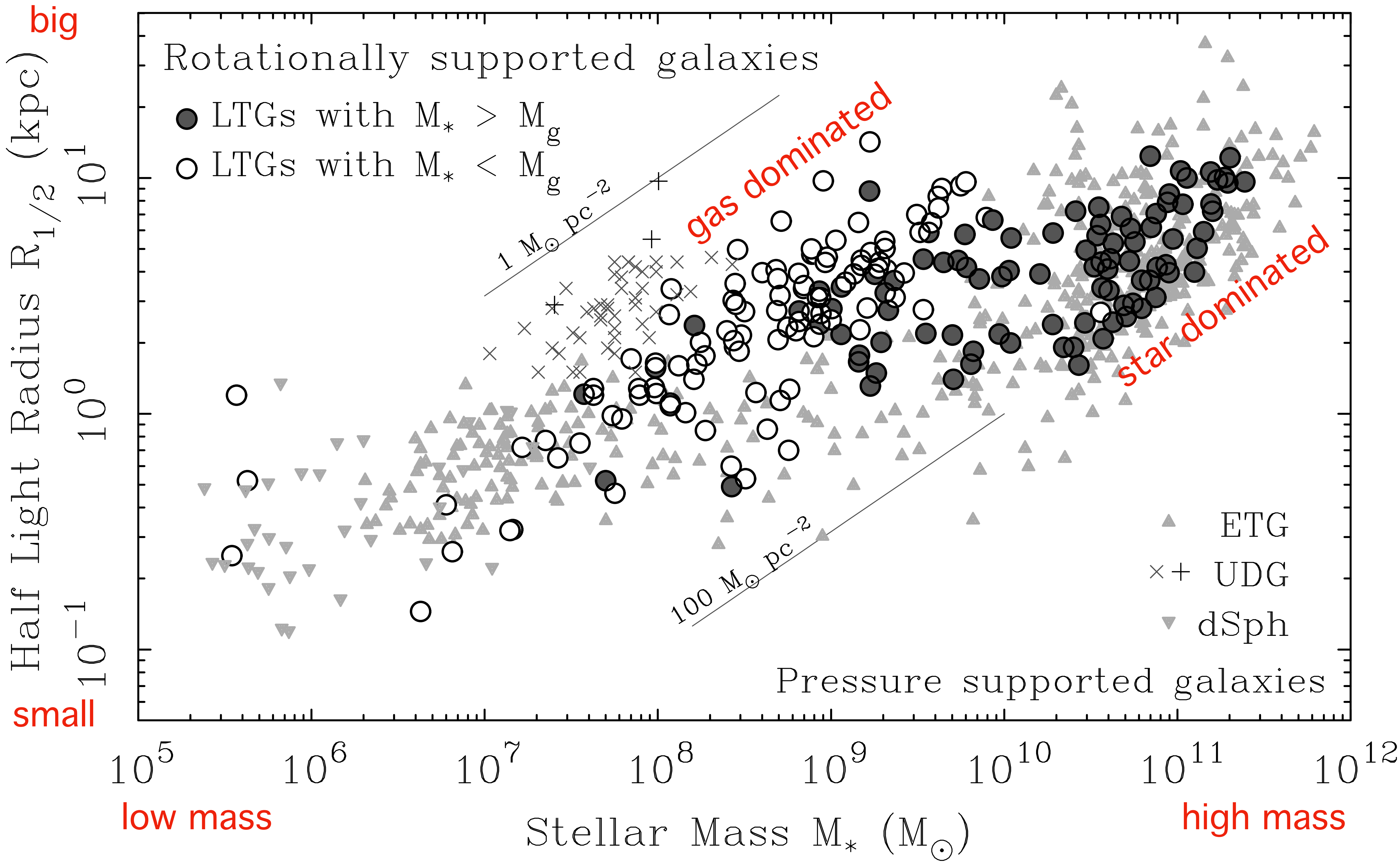
Galaxies are made of gas as well as stars

near infrared

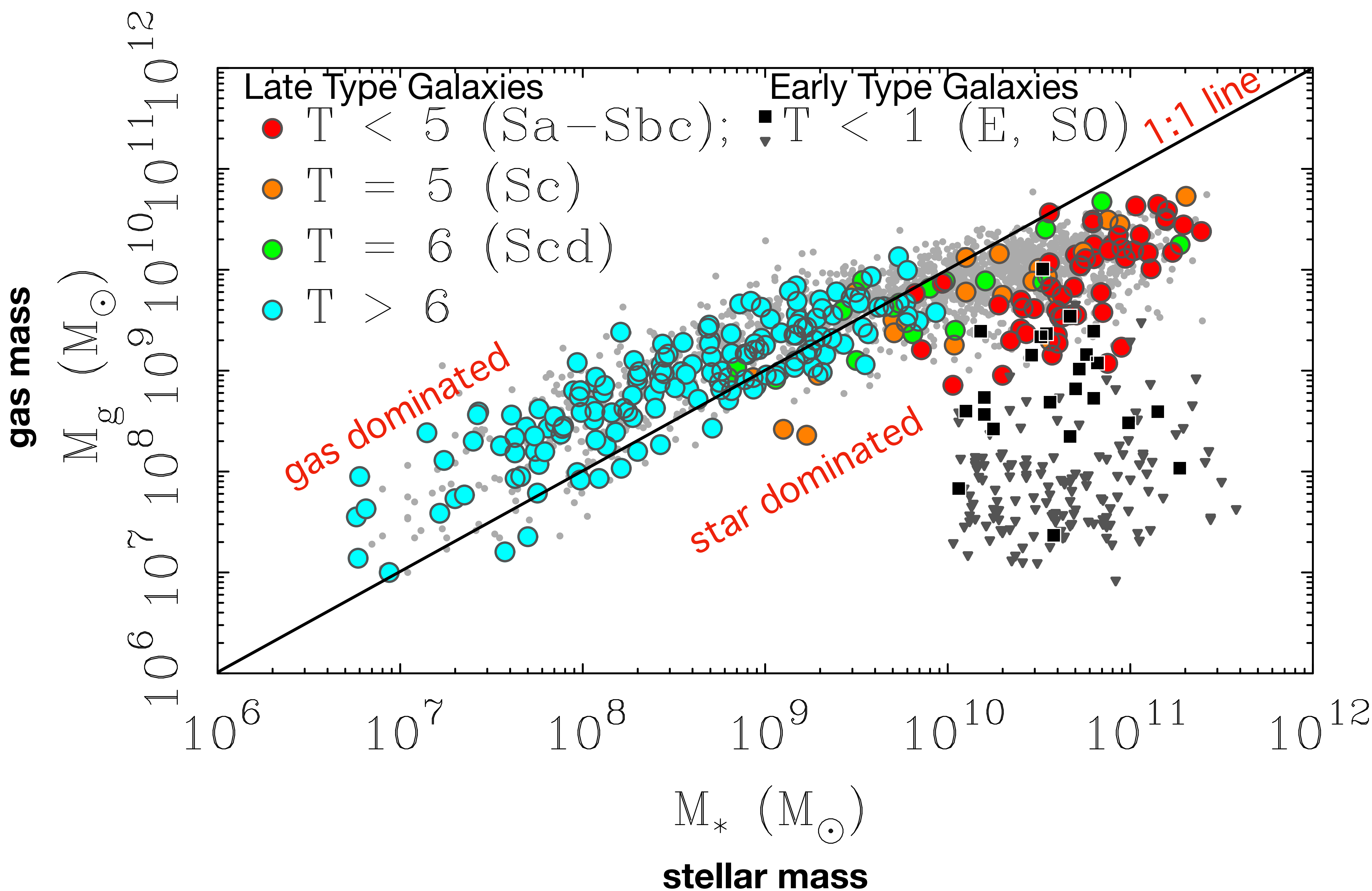


NGC 6946 stars & gas

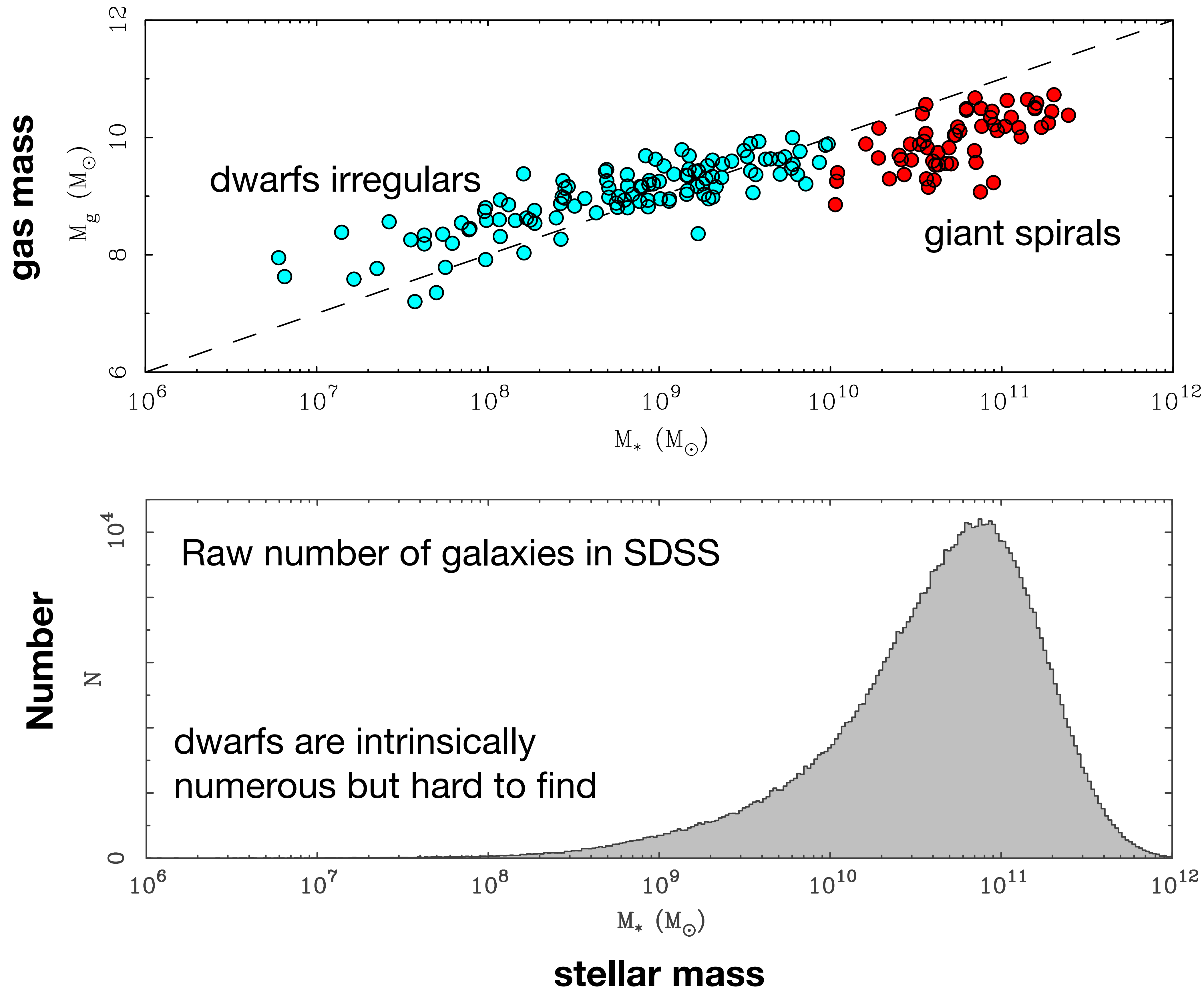
Analytic approximations are useful for defining metrics for size. Here, a non-parametric radius that contains half the light is used. The stellar mass is estimated from the integrated light and some estimate of the stellar mass-to-light ratio.



Gas and Stars in Galaxies

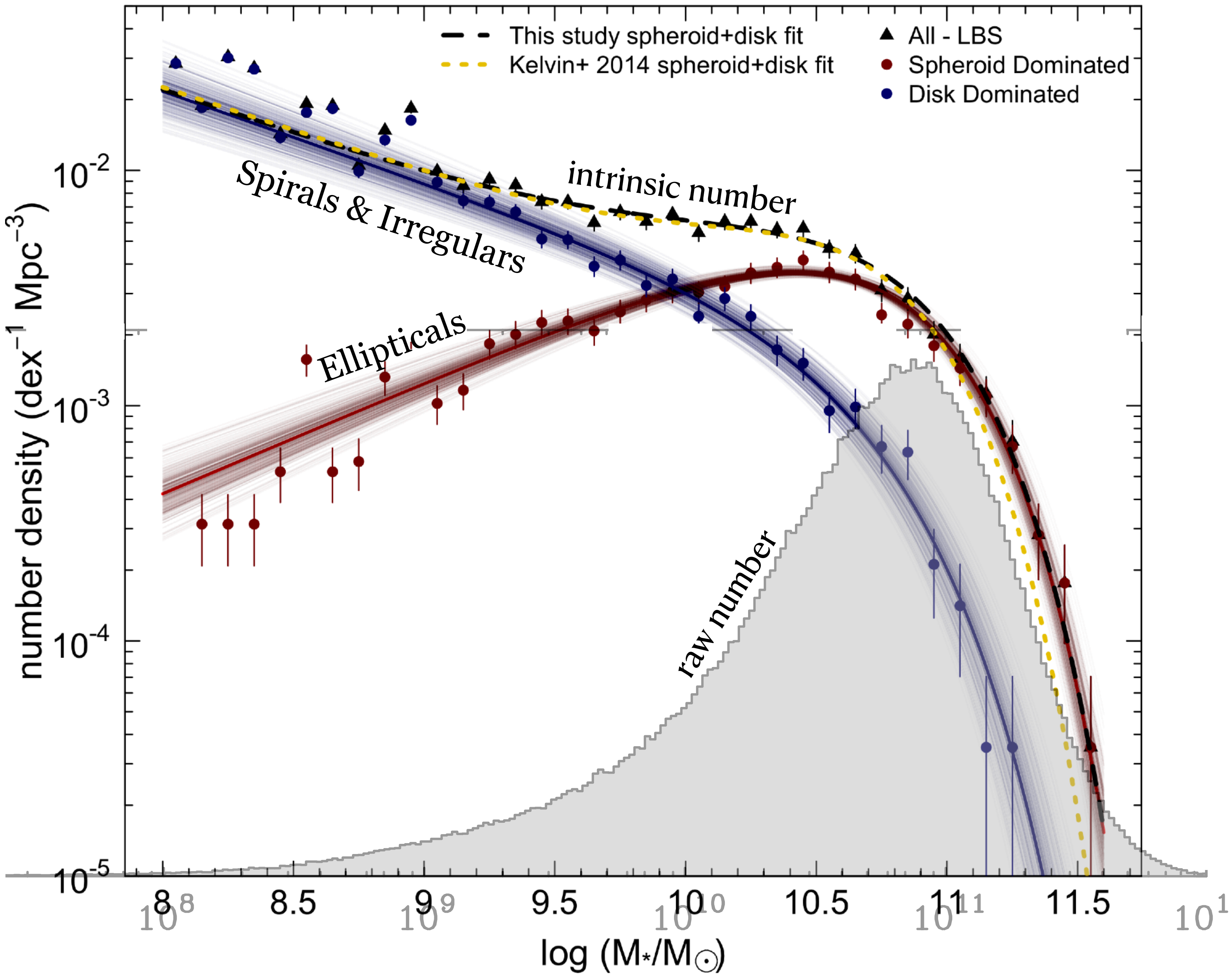


Beware selection effects! Catalogs are always dominated by brightest objects



The apparent numbers of galaxies in magnitude-limited samples decreases with decreasing mass, while their intrinsic numbers increase.

Galaxy mass function from the GAMA survey



Moffett et al. 2016, MNRAS, 457, 1308

Baryonic Mass Components of Galaxies

$$M_b = M_* + M_g = \Upsilon_* L + \frac{1}{X}\left(M_{HI} + M_{H_2}\right)$$

$X \approx 0.73$ (hydrogen fraction)

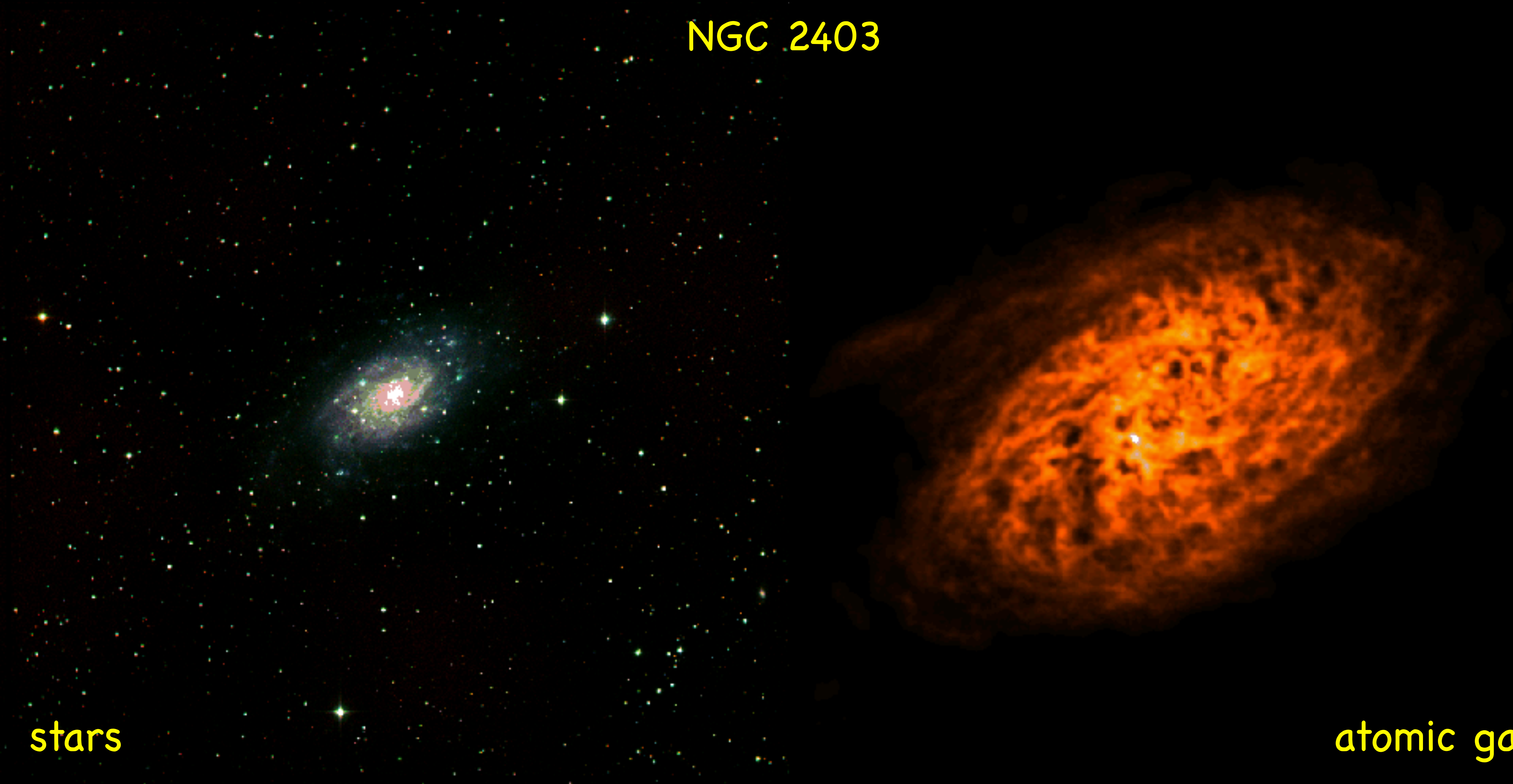
- **Stars** $M_* = \Upsilon_*^i L_i \qquad L_i = 4\pi D^2 F_i$
  - Υ_*^i is the stellar mass-to-light ratio in photometric band i
- **Cold Gas**

dust and hot ionized gas are typically negligible within the optical radius

  - *Atomic gas* - H I
    - $M_{HI} = 2.36 \times 10^5 \, D^2 \, F_{HI}$ counting hydrogen atoms
  - *Molecular gas* - H_2
    - $M_{H_2} = 1.1 \times 10^4 \, D^2 \, F_{CO}$ using carbon monoxide as a proxy

also scales with stellar mass at least for late type galaxies $M_{H_2} \approx 0.07 \, M_*$

The atomic gas of the ISM is often more extended than the stars



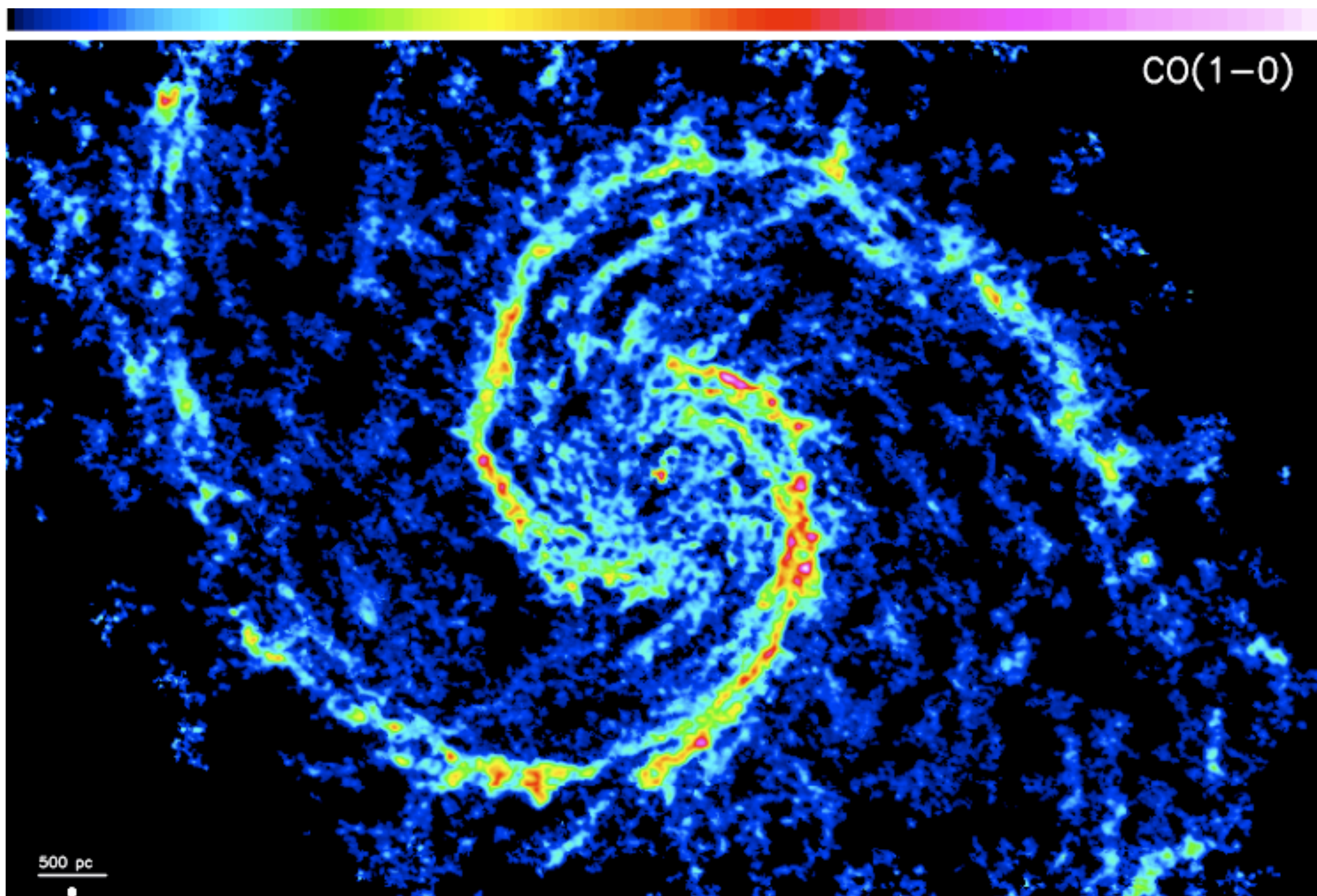
Fraternali, F., Oosterloo, T., Sancisi, R., van Moorsel, G.A. 2001, ApJ, 562, L47

Molecular ISM

Cold (~ 30 K), "dense" (> 100 molecules/cc) phase of the ISM

Very clumpy, with low filling factor - much of the
H_2 mass is in Giant Molecular Clouds (~10^6 $M_{\odot}$). This is where stars form.
The distribution of molecular gas typically follows that of the stars.

M51 seen in CO



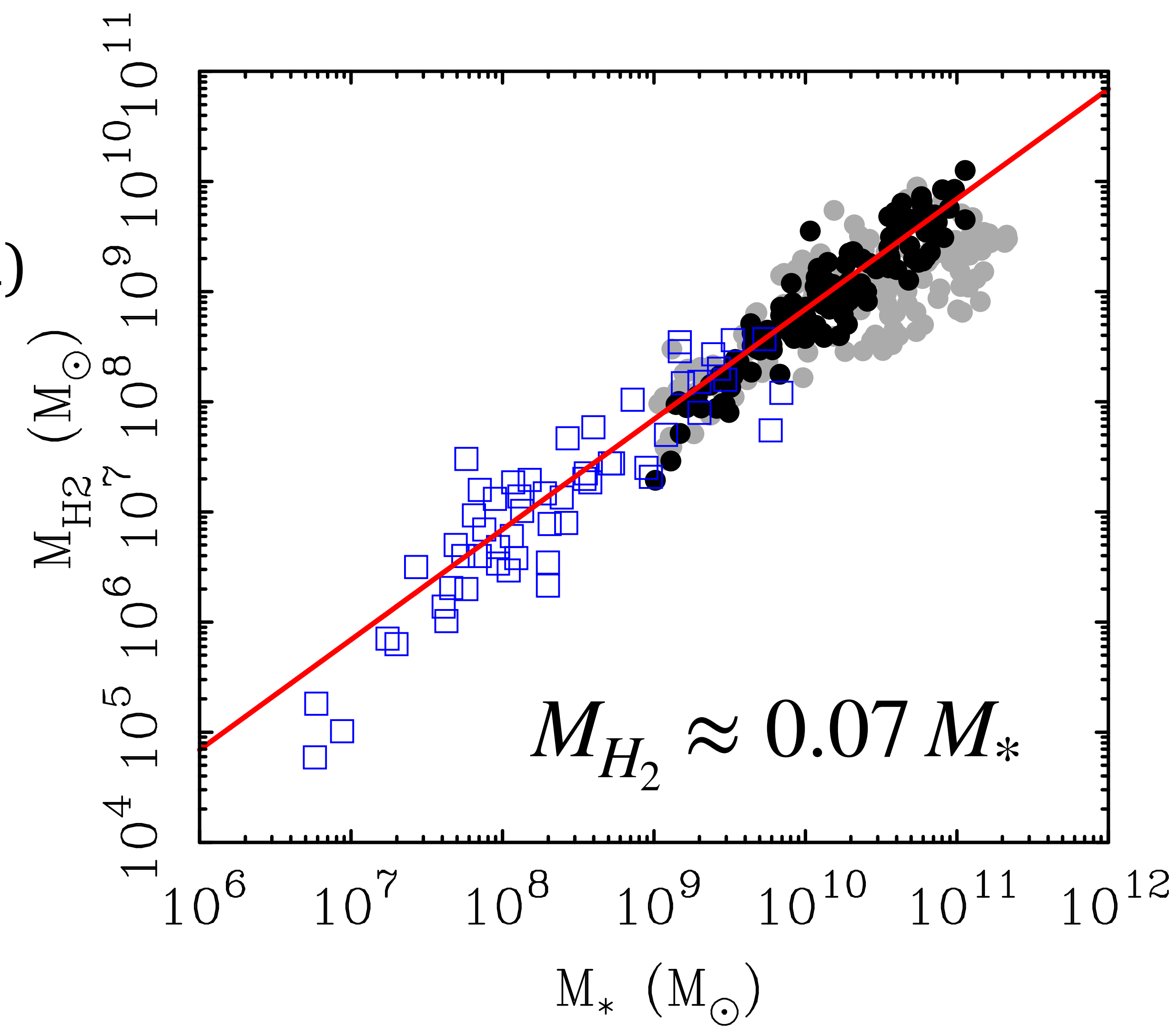
Often CO observations are not available, in which case one approach is to use scaling relations: the amount of molecular gas is proportional to the star formation rate and the stellar mass.

Typically we measure the mass of hydrogen gas (e.g., M_{HI}). This needs to be corrected to account for the presence of helium and metals.

X = hydrogen fraction (primordial fraction 3/4)
Y = helium fraction (primordial fraction 1/4)
Z = everything else

$$X = 0.75 - 38.2\left(\frac{M_*}{M_0}\right)^{\alpha}$$

with $\alpha = 0.22$ and $M_0 = 1.5 \times 10^{24}\ M_\odot$



For a low mass dwarf galaxy, $X^{-1} = 1.34$, while for a Milky Way mass galaxy, $X^{-1} = 1.41$.

McGaugh et al. (2020, RNAAS, 4, 45)

Baryonic Mass Components of Galaxies

$$M_b = M_* + M_g = \Upsilon_* L + \frac{1}{X}\left(M_{HI} + M_{H_2}\right)$$

$X \approx 0.73$ (hydrogen fraction)

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