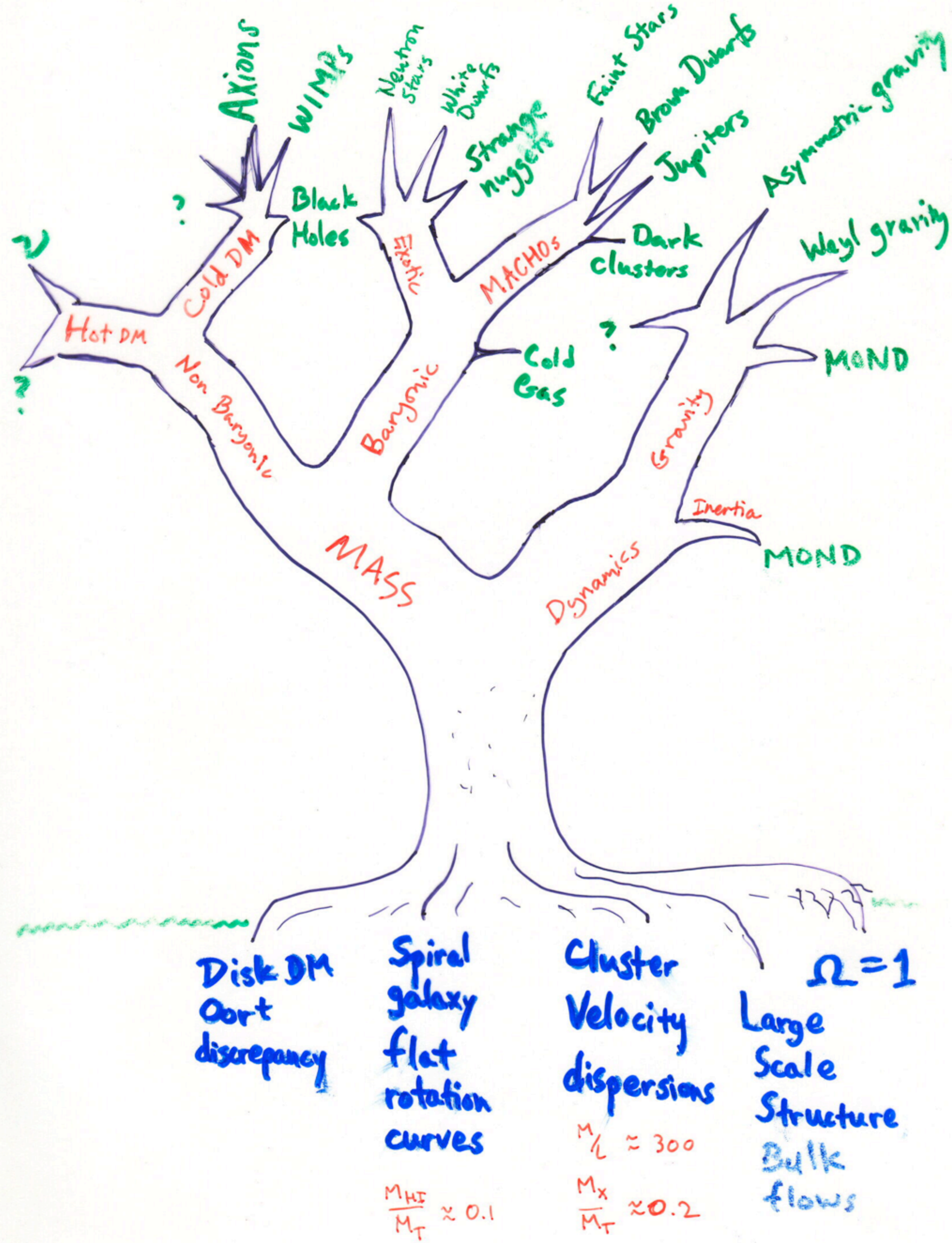
Dark Matter

ASTR 333/433

TODAY

Range of Galaxy Properties
The Interstellar Medium
Baryonic Mass Estimators



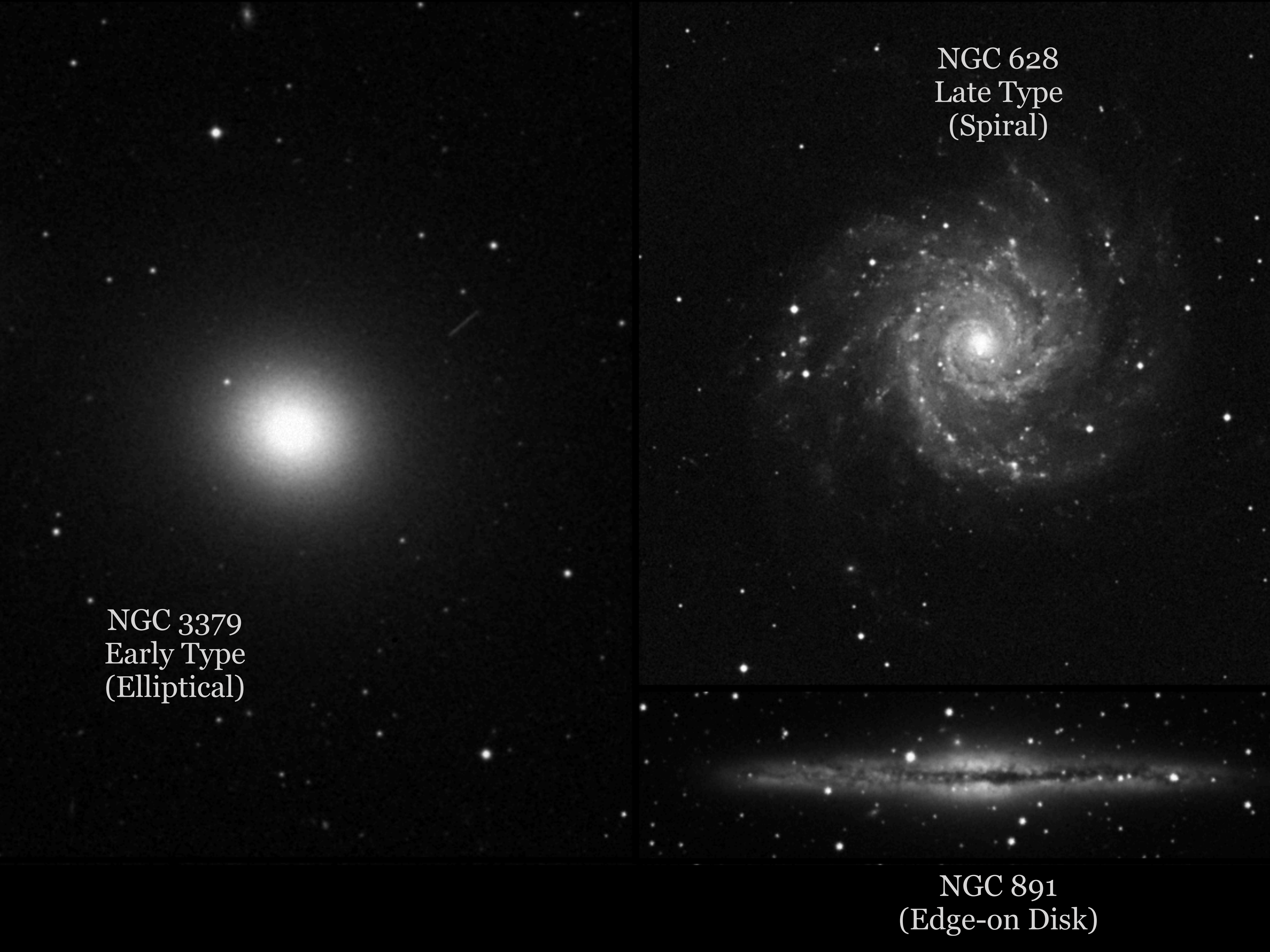
Baryonic Mass of Galaxies

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

$X \approx 0.73$ (hydrogen fraction)

- **Stars** $M_* = \Upsilon_*^i L_i$ $L_i = 4\pi D^2 F_i$
  - Υ_*^i is the stellar mass-to-light ratio in photometric band i
- **Gas**
  - *Atomic gas* - H I
    - $M_{HI} = 2.36 \times 10^5 D^2 F_{HI}$
  - *Molecular gas* - H_2
    - $M_{H_2} = 1.1 \times 10^4 D^2 F_{CO}$

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


NGC 3379
Early Type
(Elliptical)
NGC 628
Late Type
(Spiral)
NGC 891
(Edge-on Disk)

Galaxies exist over a huge dynamic range in

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

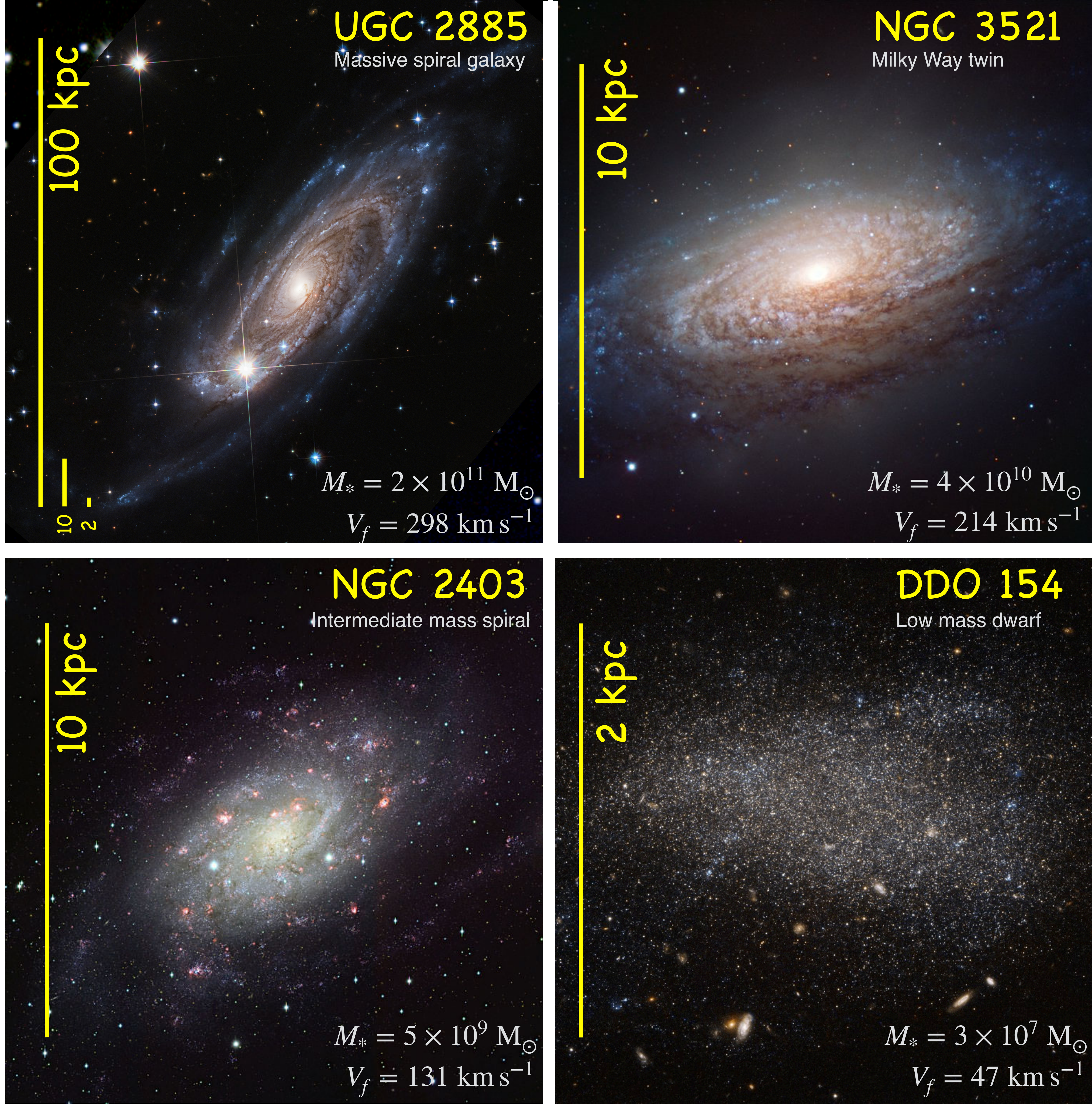
Gas mass
$1 \times 10^{7} < M^{*} < 5 \times 10^{10}\ M_{\odot}$

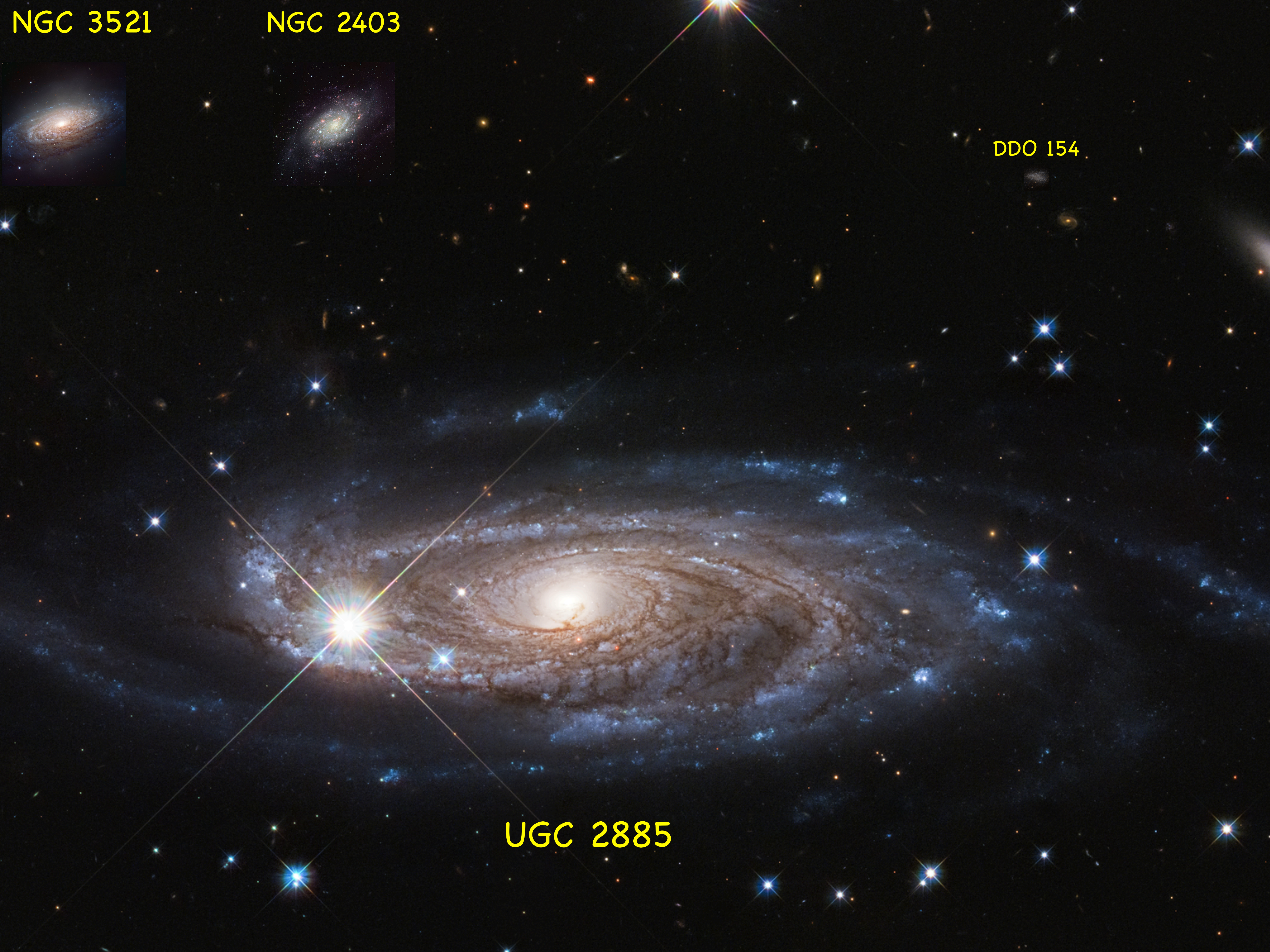
Surface brightness
$5 < \mu_{e} < 3 \times 10^{3}\ L_{\odot}\,pc^{-2}$

Gas fraction
$0.03 < f_{g} < 0.97$

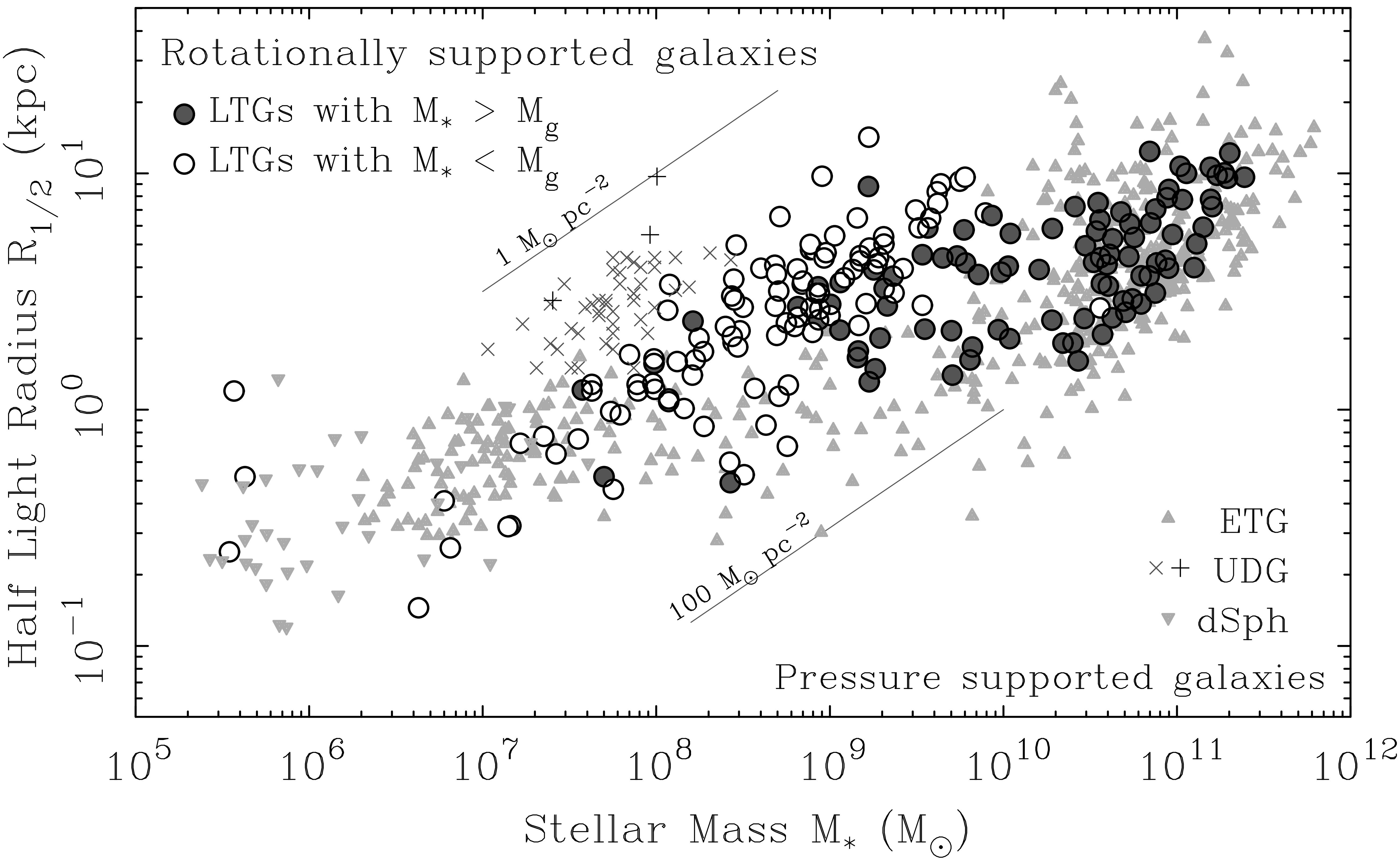
Rotation velocity
$15 < V_{f} < 300$ km/s

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

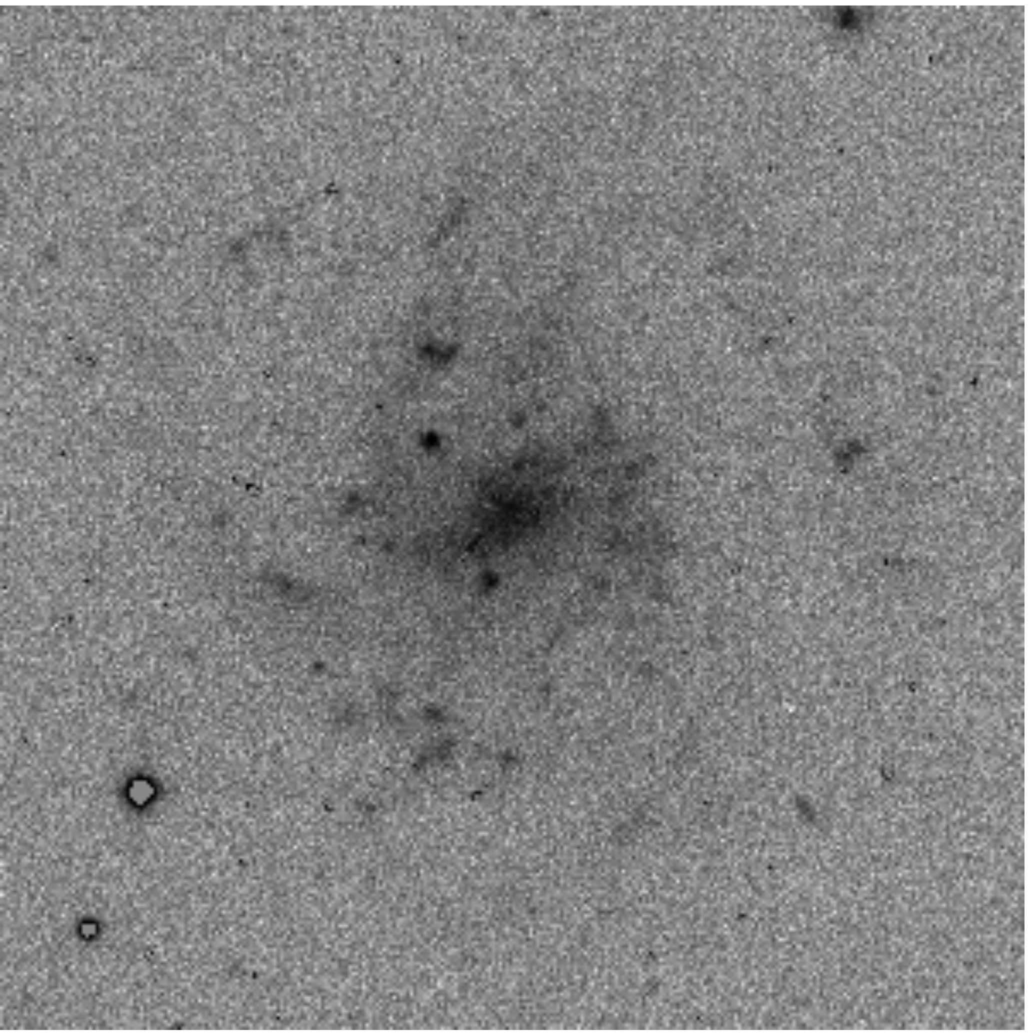


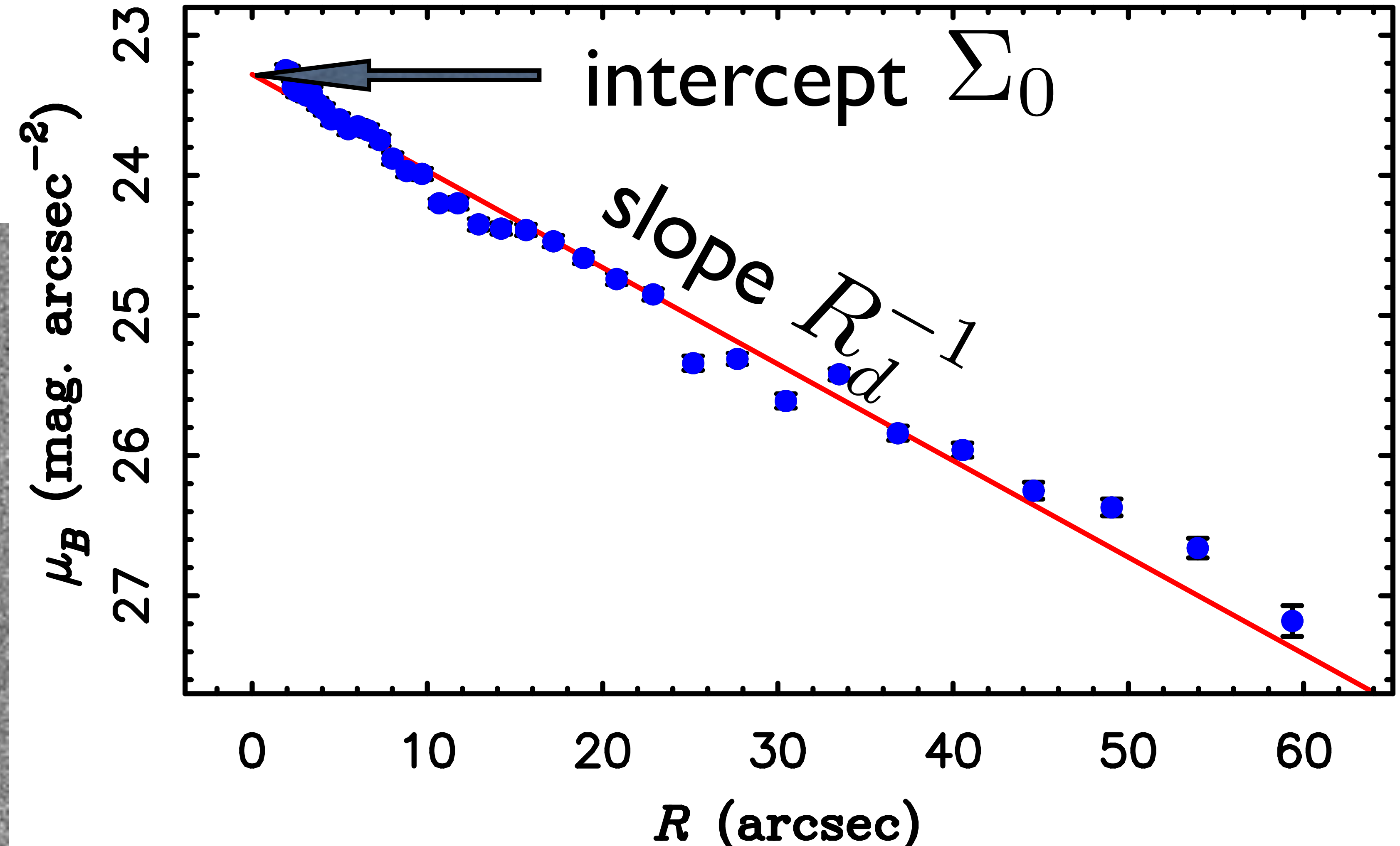

NGC 3521
NGC 2403
DDO 154
UGC 2885

Sizes and masses of galaxies



Late Type Galaxies are typically Exponential disks





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

Azimuthally averaged light distribution approximately exponential for spiral disks.

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

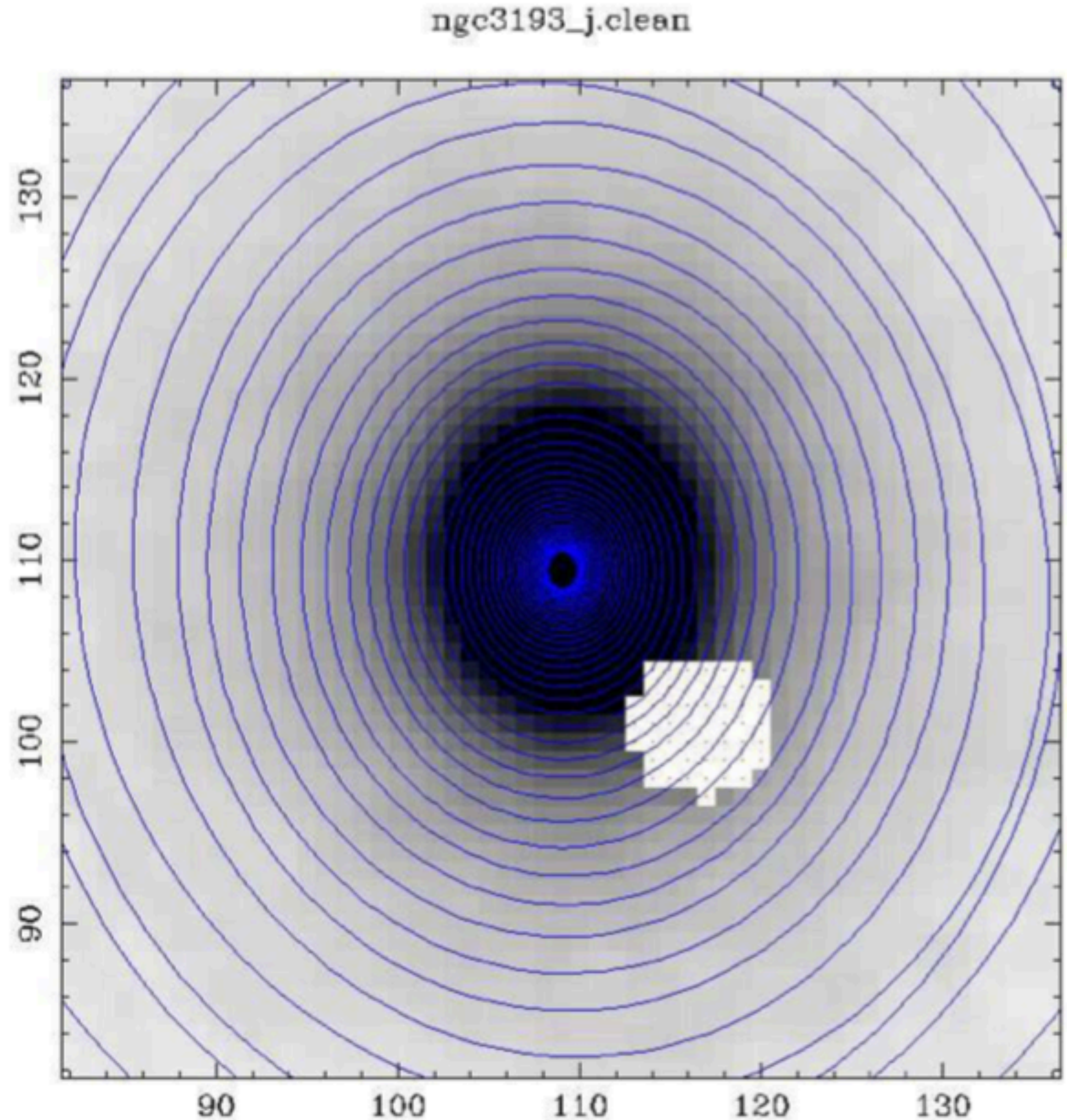
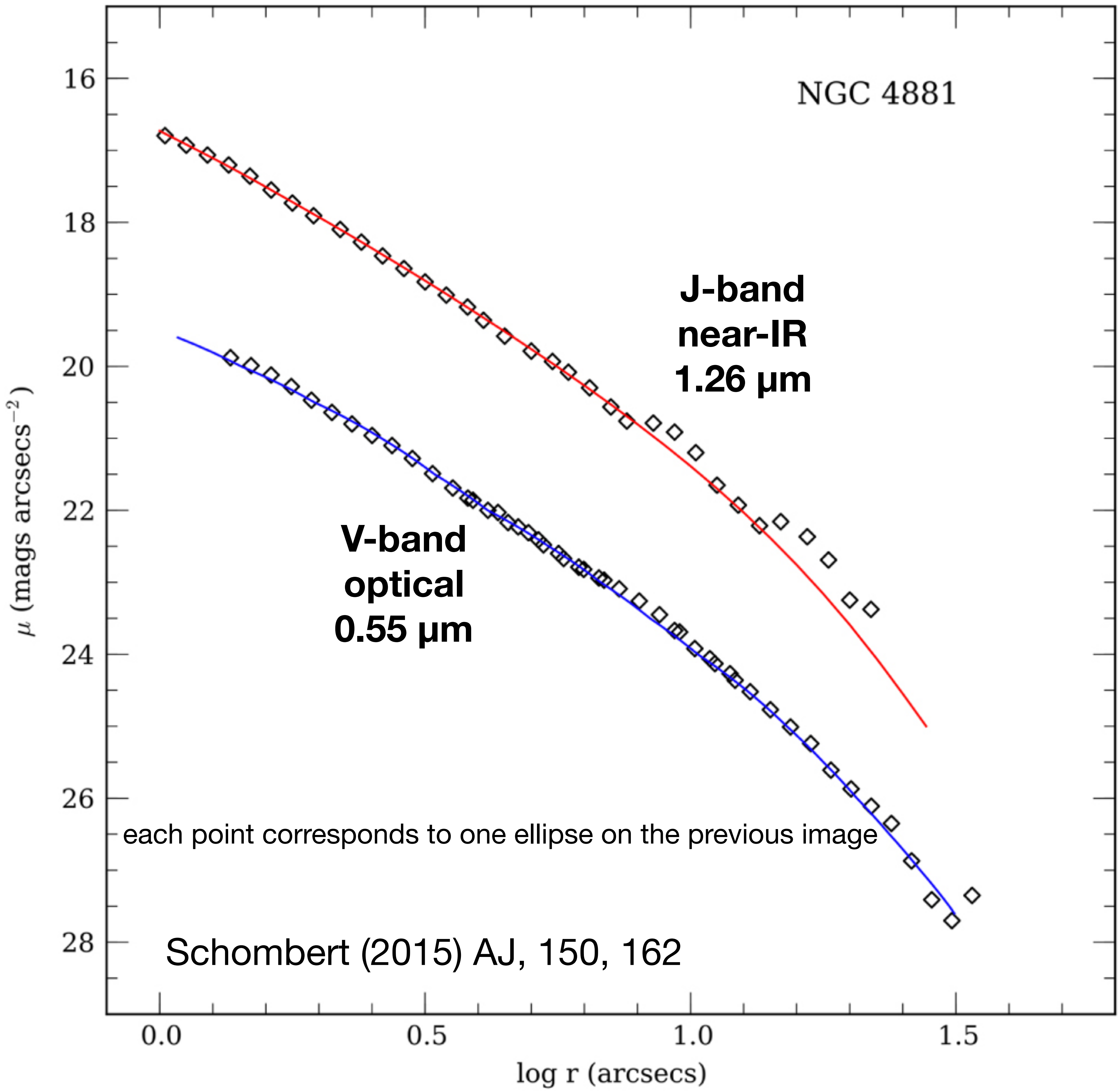


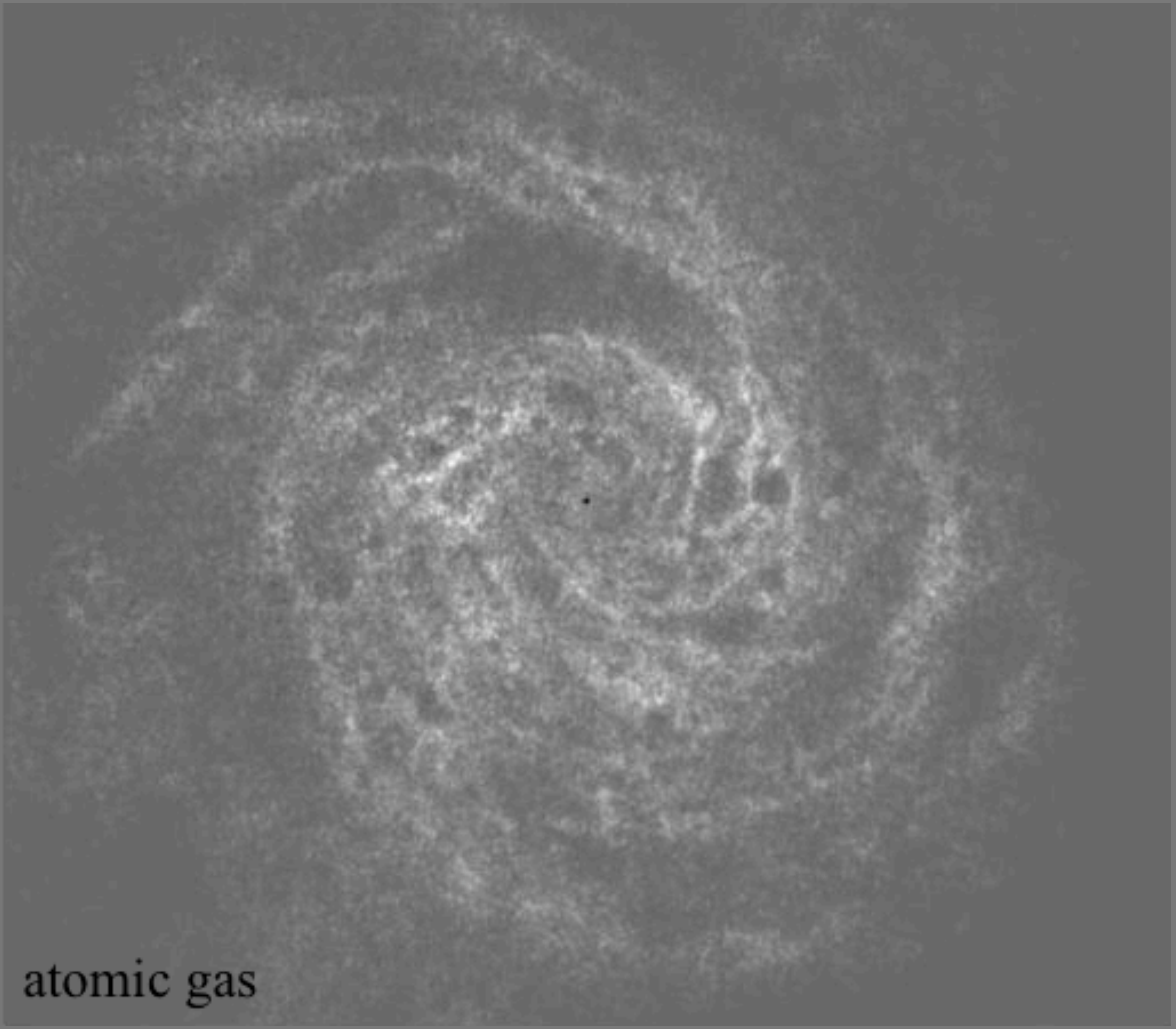
Fig. 2.— The resulting ellipse fits to NGC 3193's core region. While the automatic masking of the contaminating star is not perfect, it is sufficient to maintain a high quality fit.

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



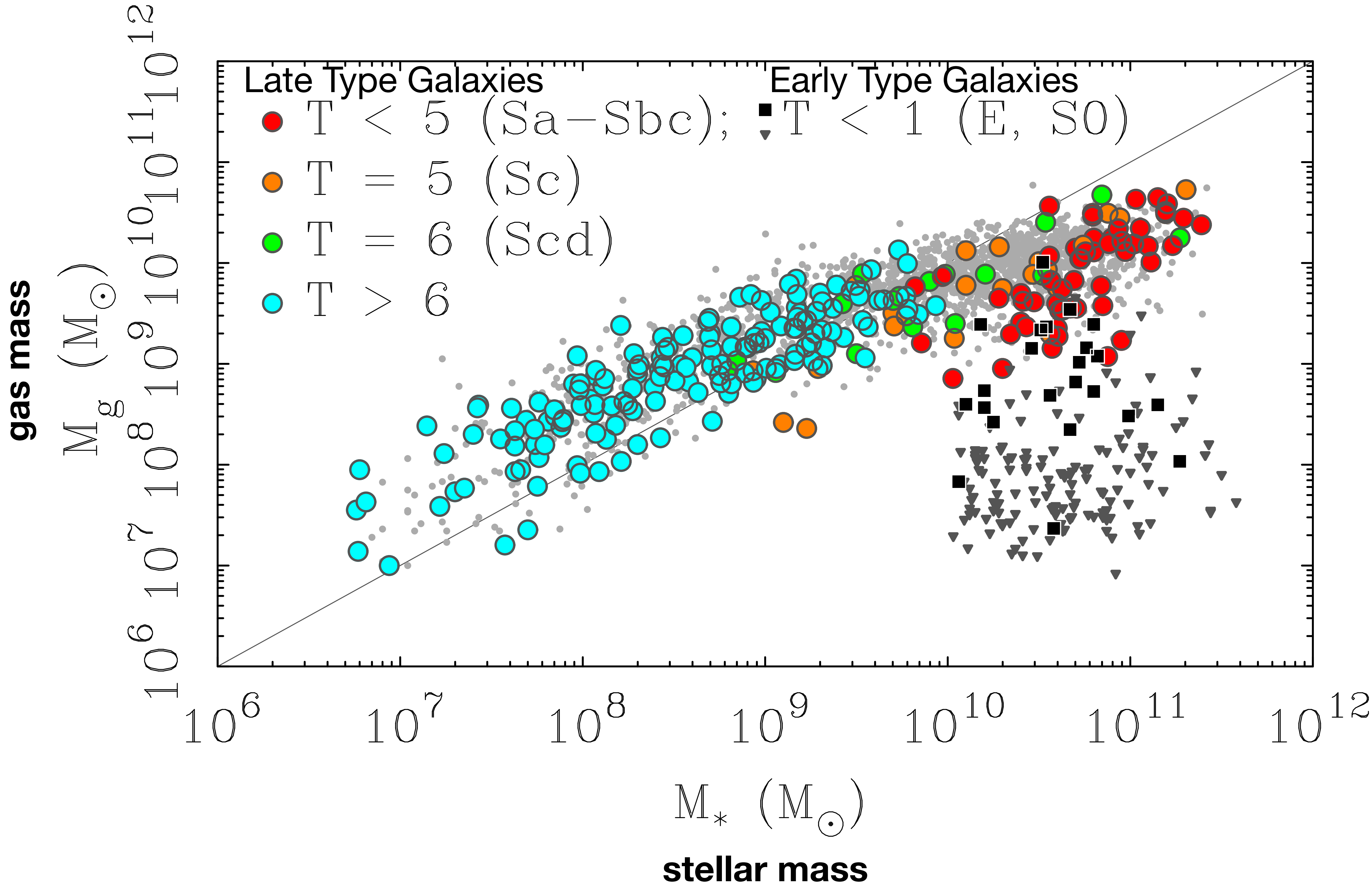
Galaxies are made of gas as well as stars

near infrared

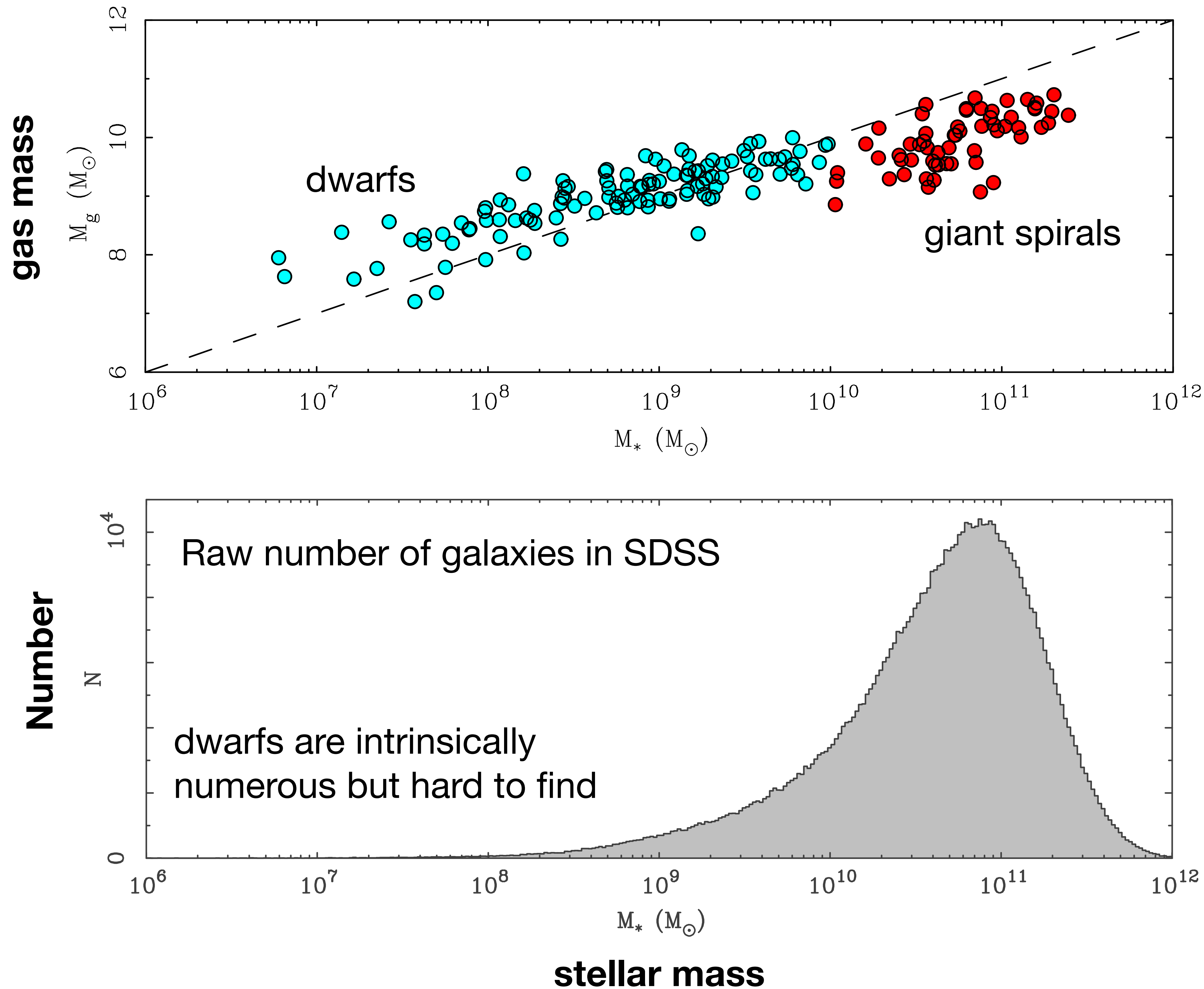


NGC 6946 stars & gas

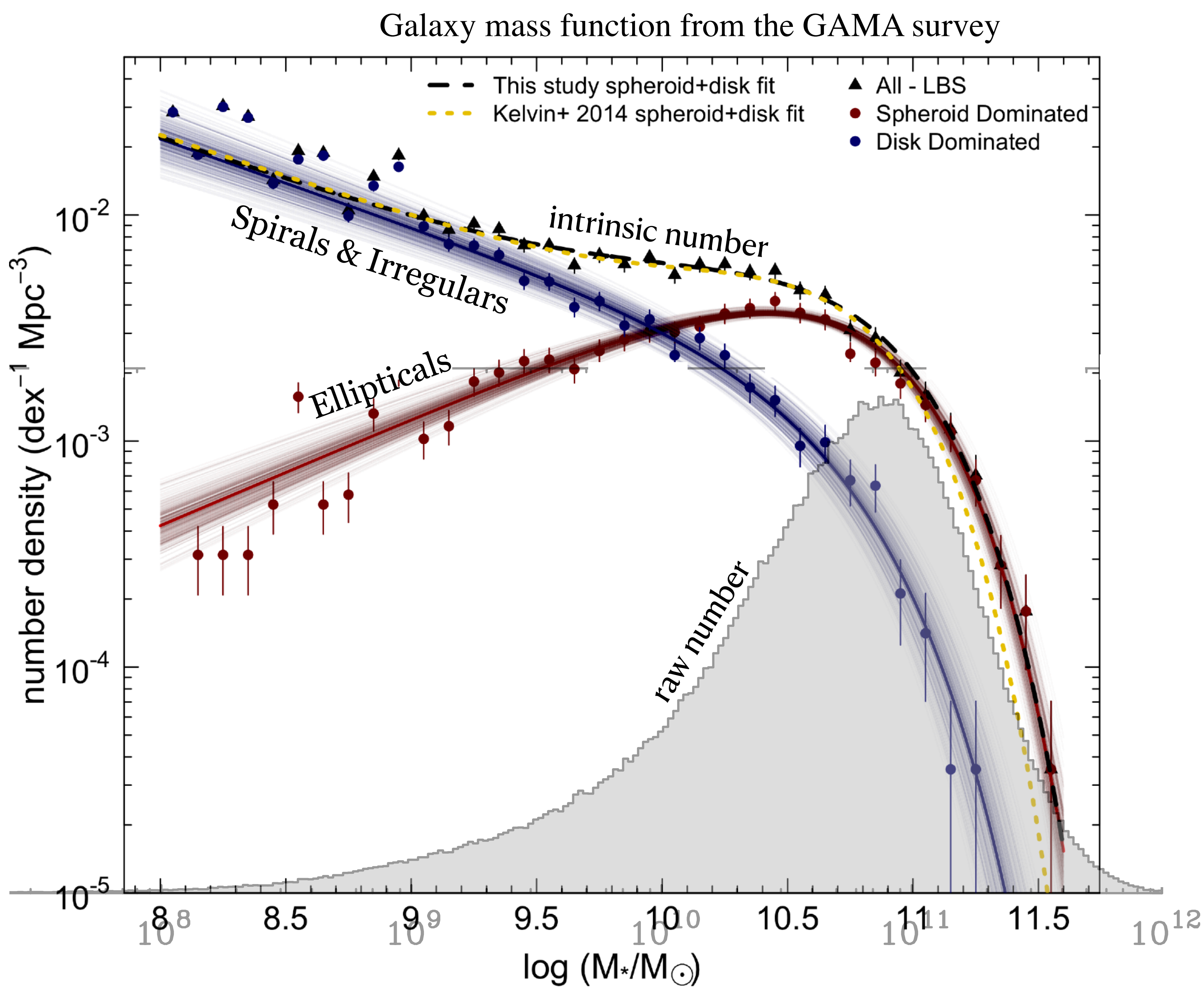
Gas and Stars in Galaxies



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.



Moffett et al. 2016, MNRAS, 457, 1308

ISM

The stuff between the stars

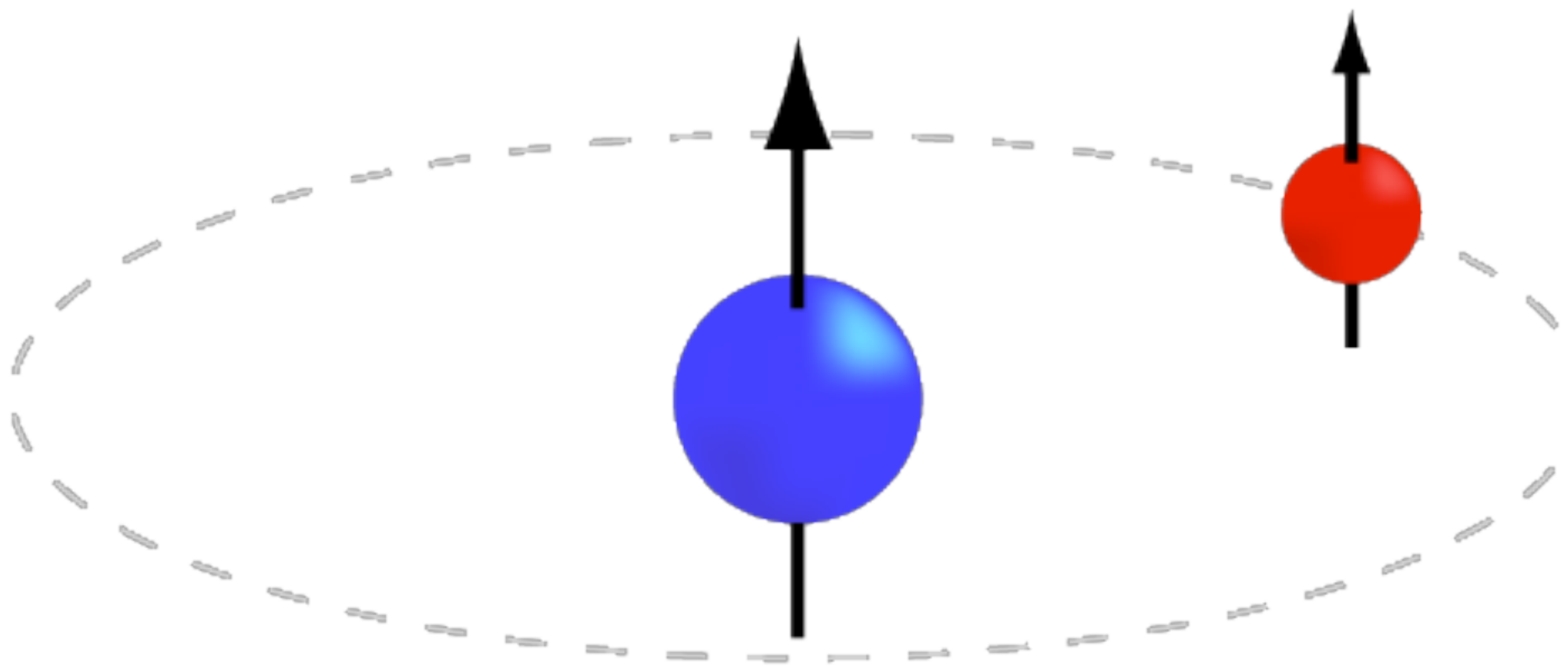
Atomic gas (H I)
Molecular gas (H_2)
Ionized gas (H II)
Dust

Explanatory links at NRAO

H I: http://www.cv.nrao.edu/course/astr534/HILine.html

H_2: http://www.cv.nrao.edu/course/astr534/MolecularSpectra.html

HI: atomic hydrogen in the interstellar medium

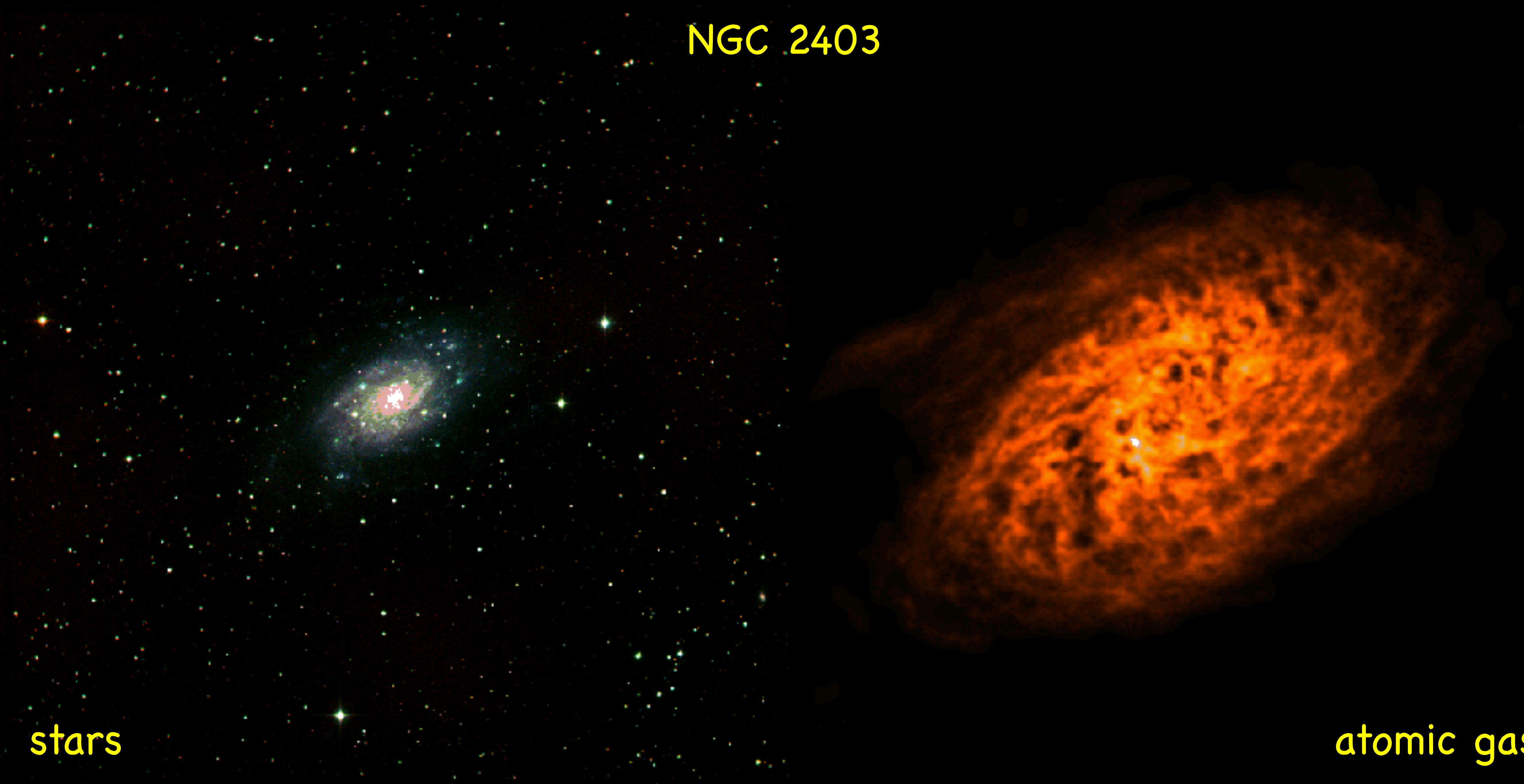


21 cm emission from hyperfine transition: parallel to anti-parallel spins

$$\nu = \frac{8}{3} g_I \frac{m_e}{m_p} \alpha^2 R_m c = 1420.405751 \text{ MHz}$$

The 21 cm line is in the radio at 1420 MHz

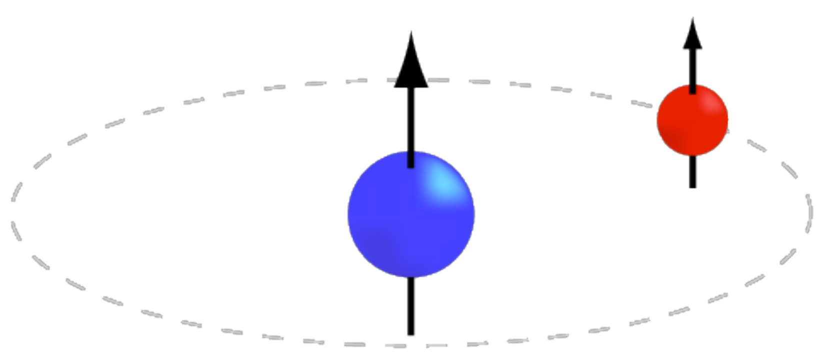
The atomic gas of the ISM is often more extended than the stars



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

$$A_{UL} = \frac{64\pi^4}{3hc^3}\nu^3|\mu^*|^2$$

Bohr magneton



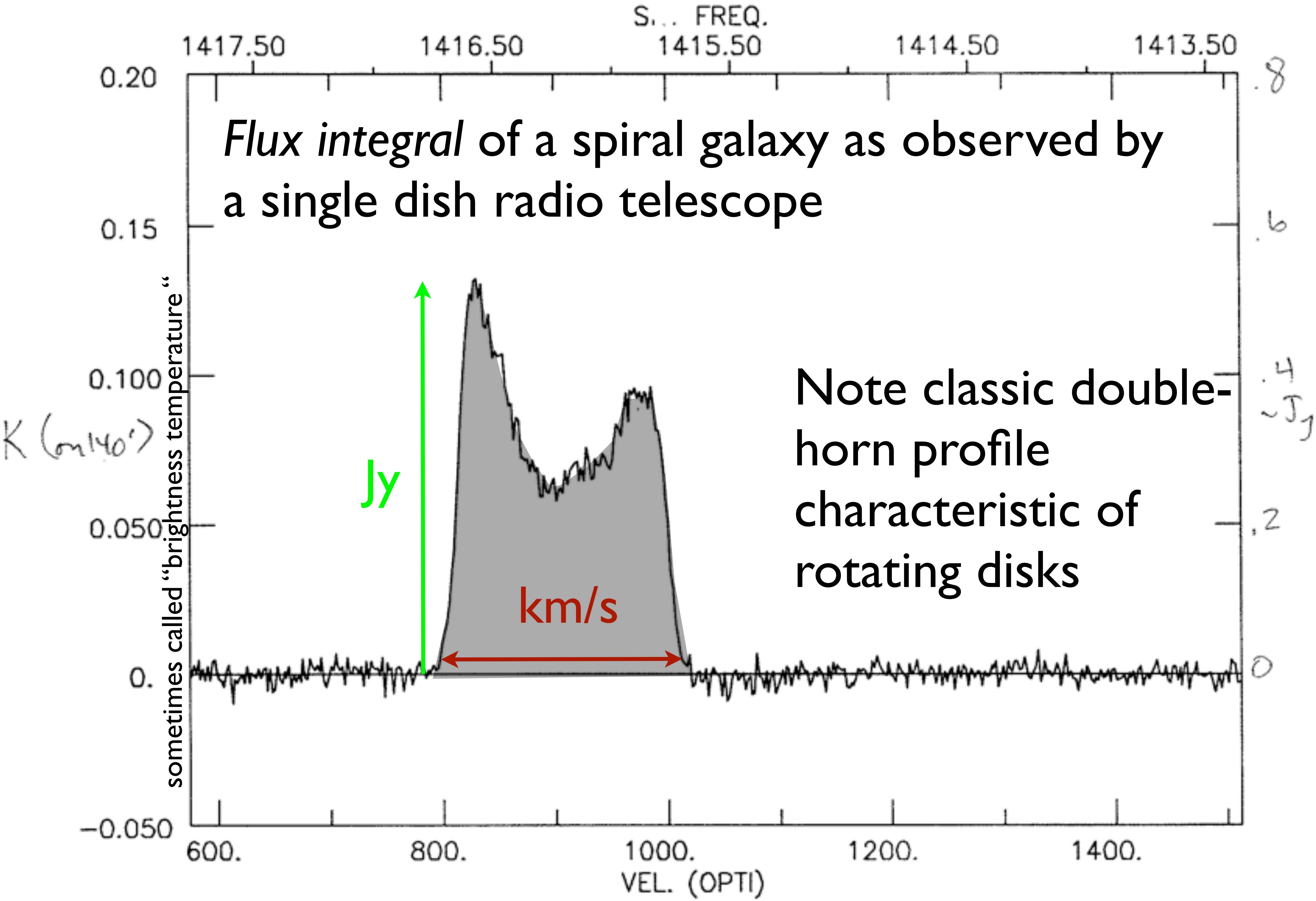
The radiative half-life of this transition is 11 Myr. This is readily maintained in equilibrium even in a cool (~100 K), diffuse ISM (< 1 atom/cc)

Counting 21 cm photons is equivalent to counting hydrogen atoms - a direct relation to mass!

$$M_{HI} = 2.36 \times 10^5 D^2 F_{HI}$$

Gives mass in solar masses for *D* in Mpc and measured flux F_{HI}, the flux integral in Jy-km/s

$1\ \mathrm{Jy} = 10^{-26}\ \mathrm{W\,m^{-2}\,Hz^{-1}}$

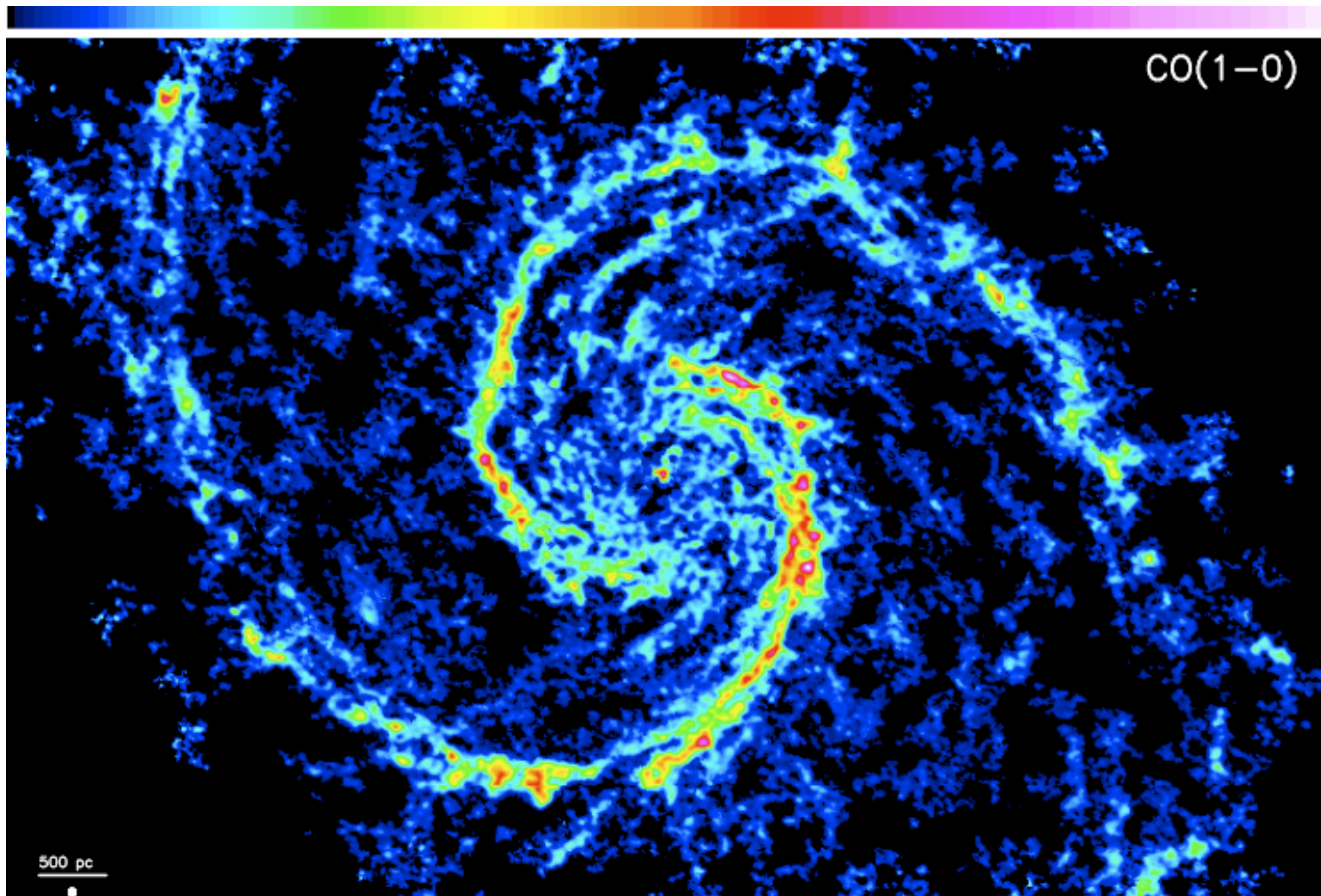

Flux integral of a spiral galaxy as observed by a single dish radio telescope
Note classic double-horn profile characteristic of rotating disks
Jy
km/s
sometimes called "brightness temperature"
S... FREQ.
1417.50
1416.50
1415.50
1414.50
1413.50
0.20
0.15
0.100
0.050
0.
−0.050
600.
800.
1000.
1200.
1400.
VEL. (OPTI)

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.

M51 seen in CO



Diatomic molecules (H_2, N_2, O_2) boring - or at least hard to excite, as they have no dipole moment.

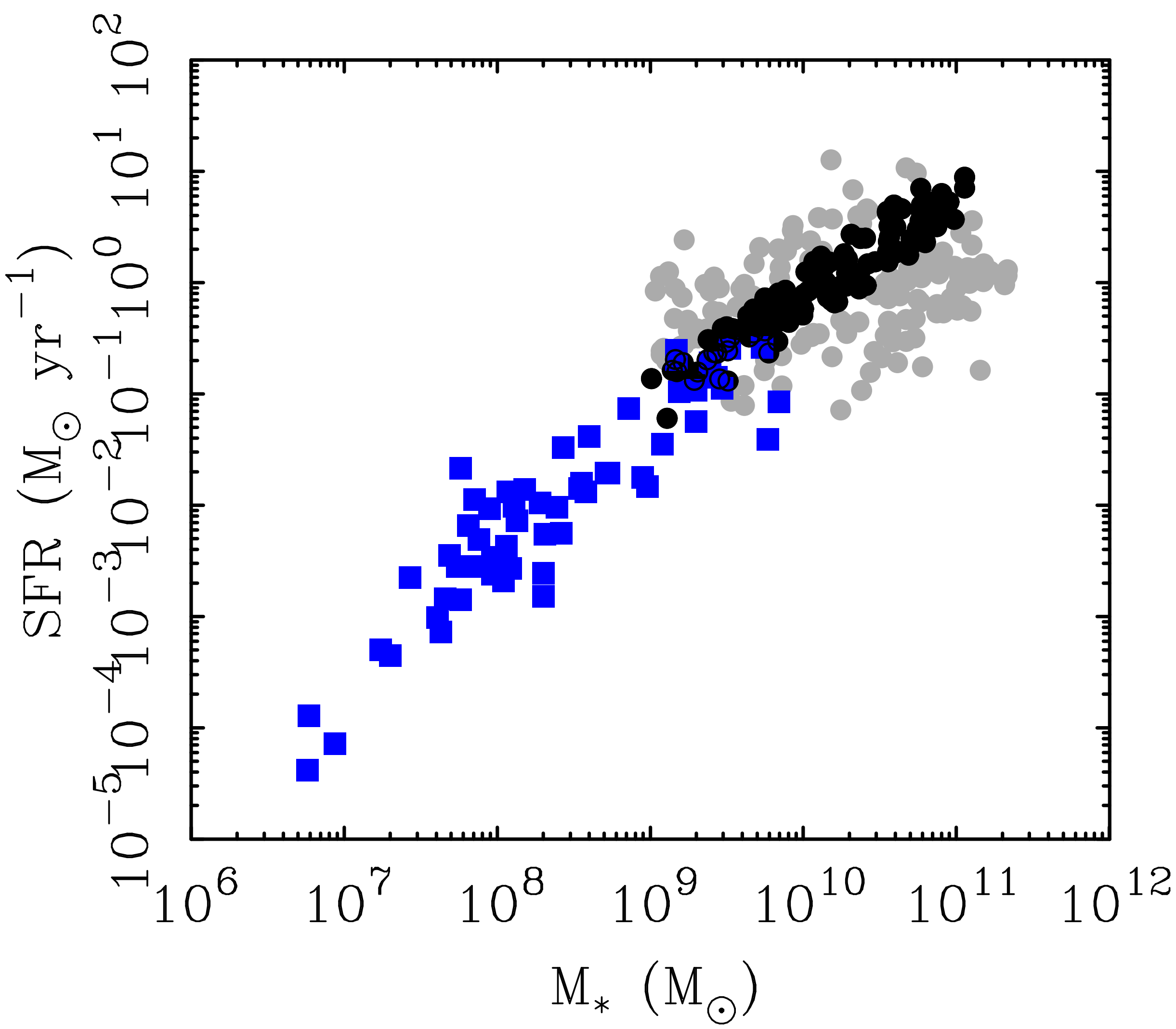
Polar molecules (esp. CO) have a permanent dipole moment thanks to asymmetry so have a rich rotational spectrum (typically in the mm or cm wavelengths).

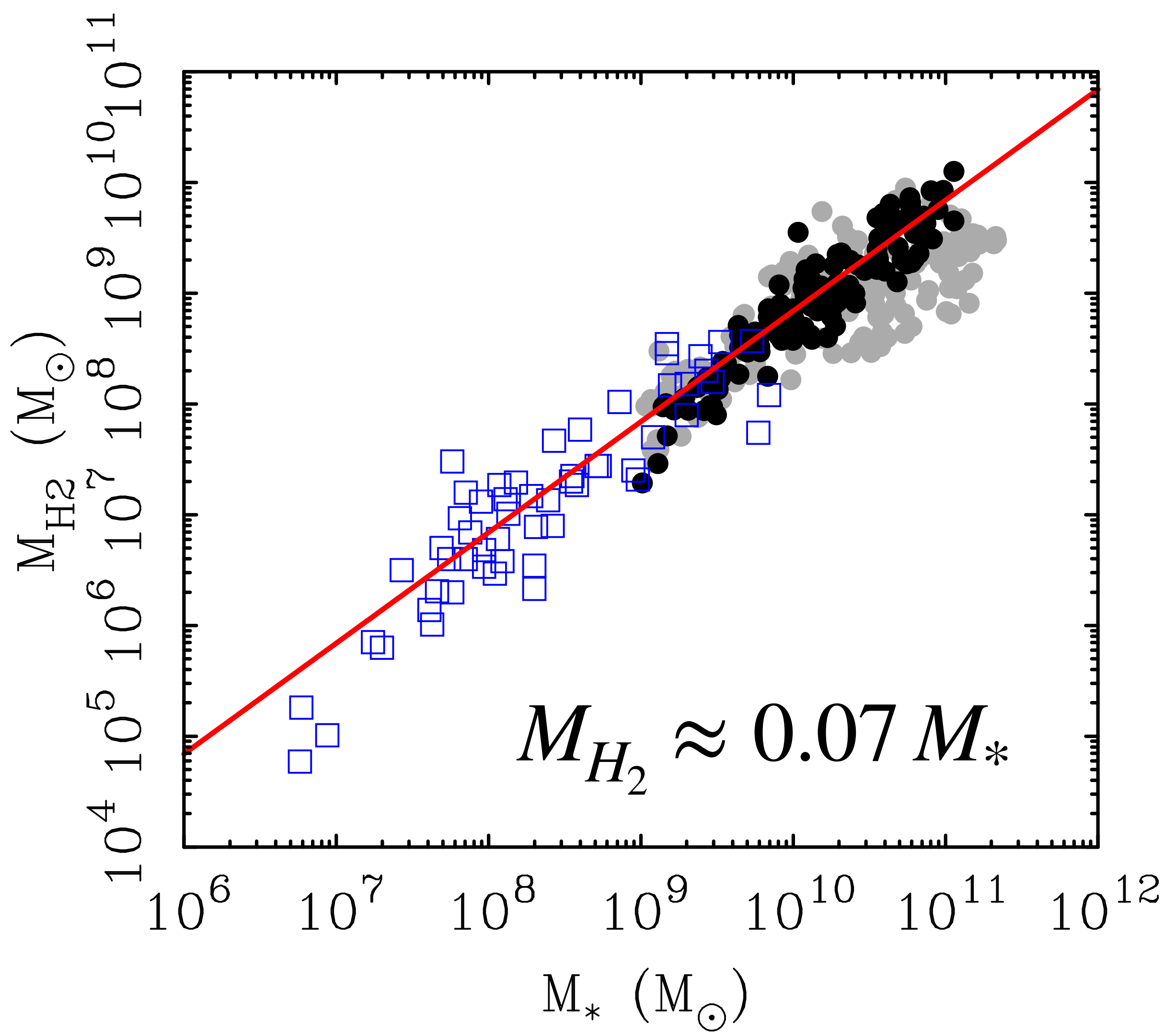
$$M_{H_2} = 1.1 \times 10^4 D^2 F_{CO}$$

assuming the conversion factor $X_{CO} = 2.8 \times 10^{20} \mathrm{cm}^{-2} (\mathrm{K\ km/s})^{-1}$

which is calibrated by estimating the virial mass of nearby molecular clouds

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.





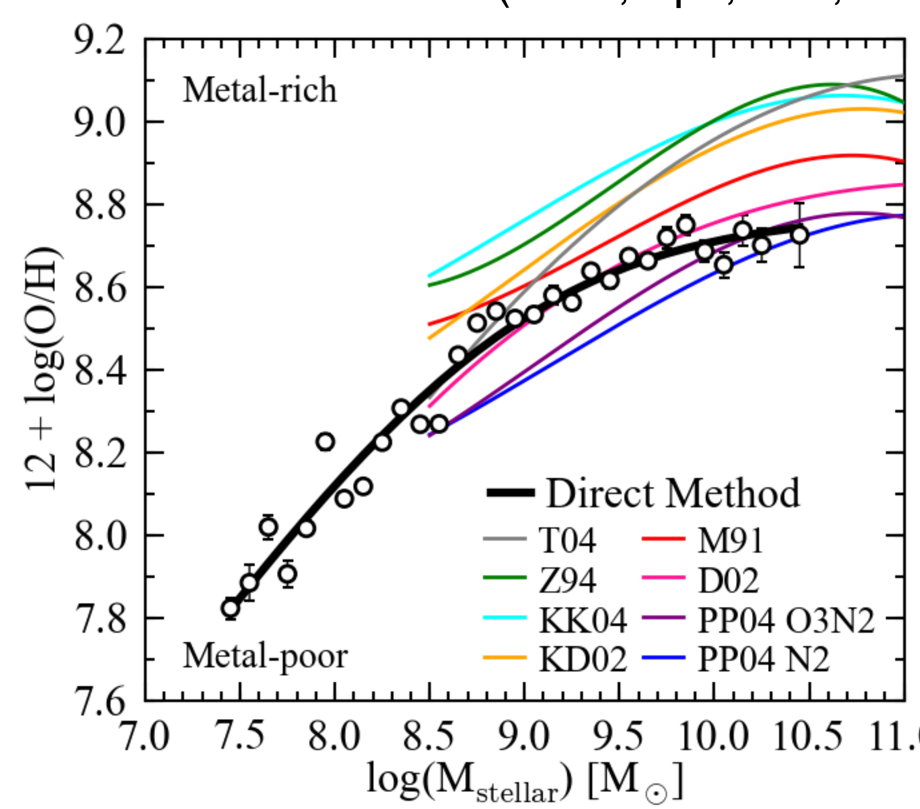
McGaugh et al. (2020, RNAAS, 4, 45)

Metallicity Dependence of the Hydrogen Fraction

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

Andrews & Martini (2013, ApJ, 765, 140)



As galaxies evolve, they form stars which make metals. Consequently, the metallicity correlates with stellar mass

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

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

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 of Galaxies

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

$$X^{-1} \approx 1.33 \; - \; 1.42$$

- **Stars** $\quad M_* = \Upsilon_*^i L_i \qquad L_i = 4\pi D^2 F_i$
  - Υ_*^i is the stellar mass-to-light ratio in photometric band i
- **Gas**
  - *Atomic gas* - H I
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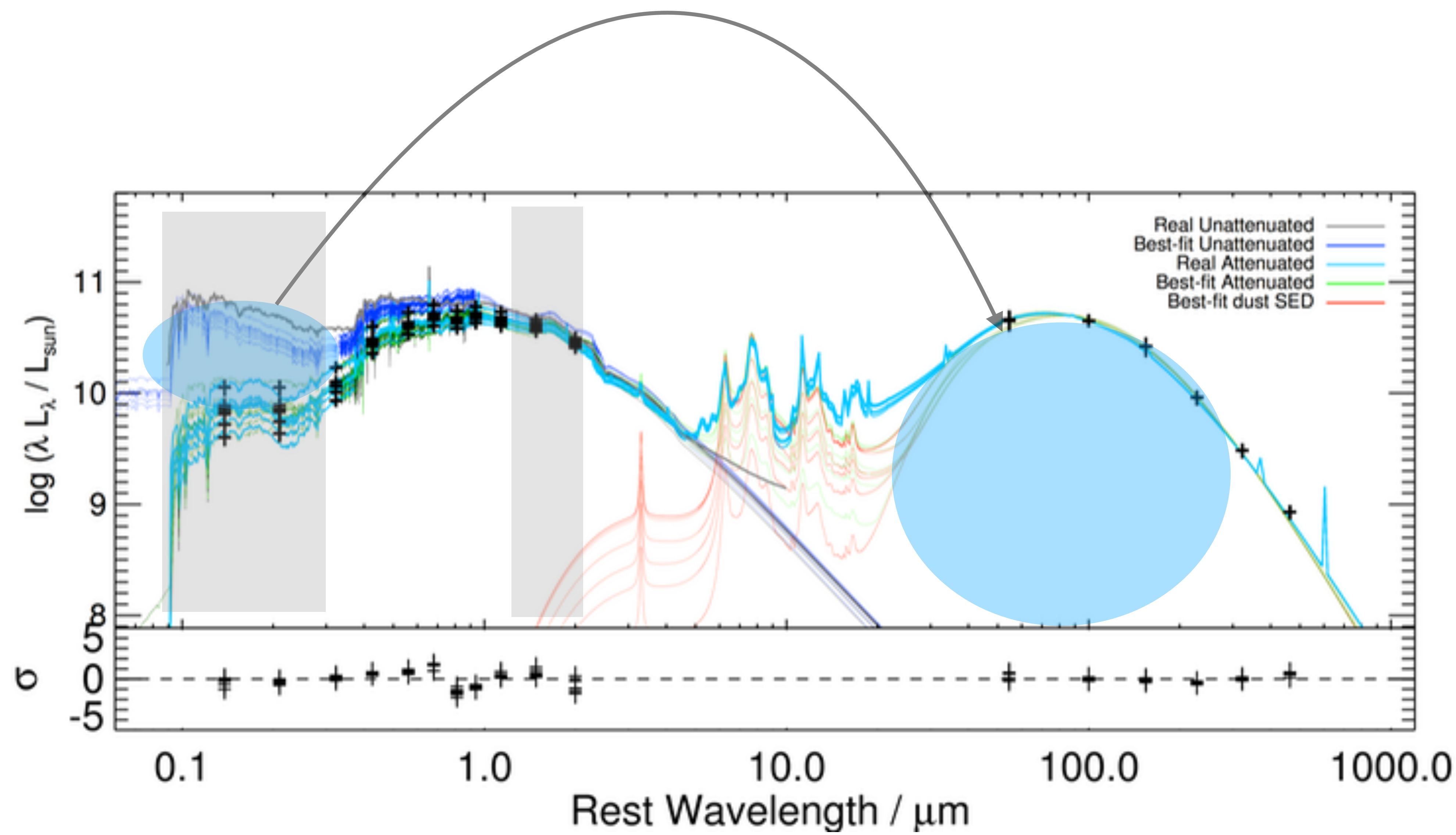
also scales with stellar mass $\quad M_{H_2} \approx 0.07 \, M_*$

Dust: the dust itself has negligible mass, but it can affect mass-to-light ratio estimates for stars

Dust-absorbs UV & optical radiation; re-emits in the IR



Lousy spot for measuring stellar mass - blue & UV wavelengths

Sweet spot for measuring stellar mass near-IR: 2-4 microns