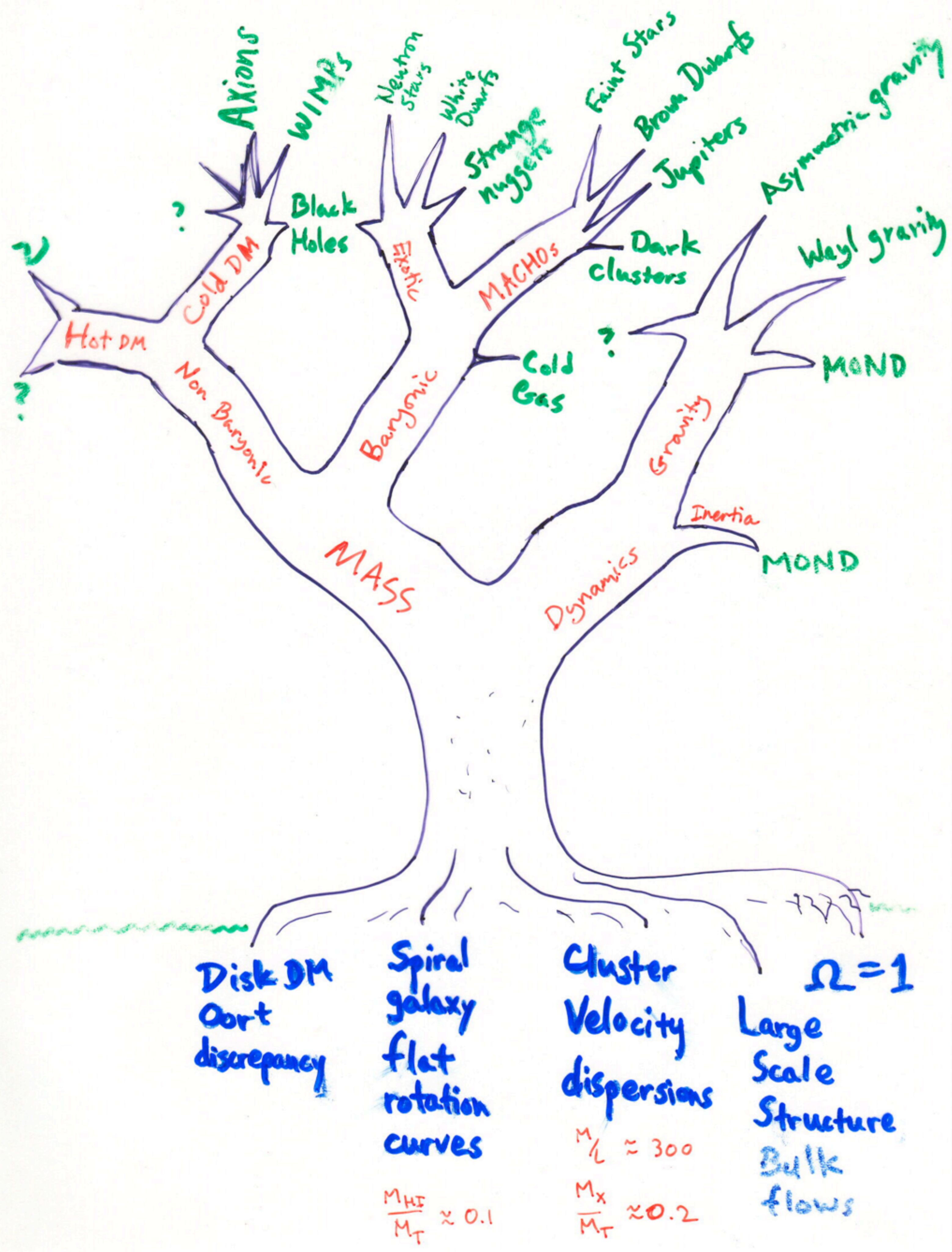
Dark Matter

ASTR 333/433

TODAY

Range of Galaxy Properties
The Interstellar Medium



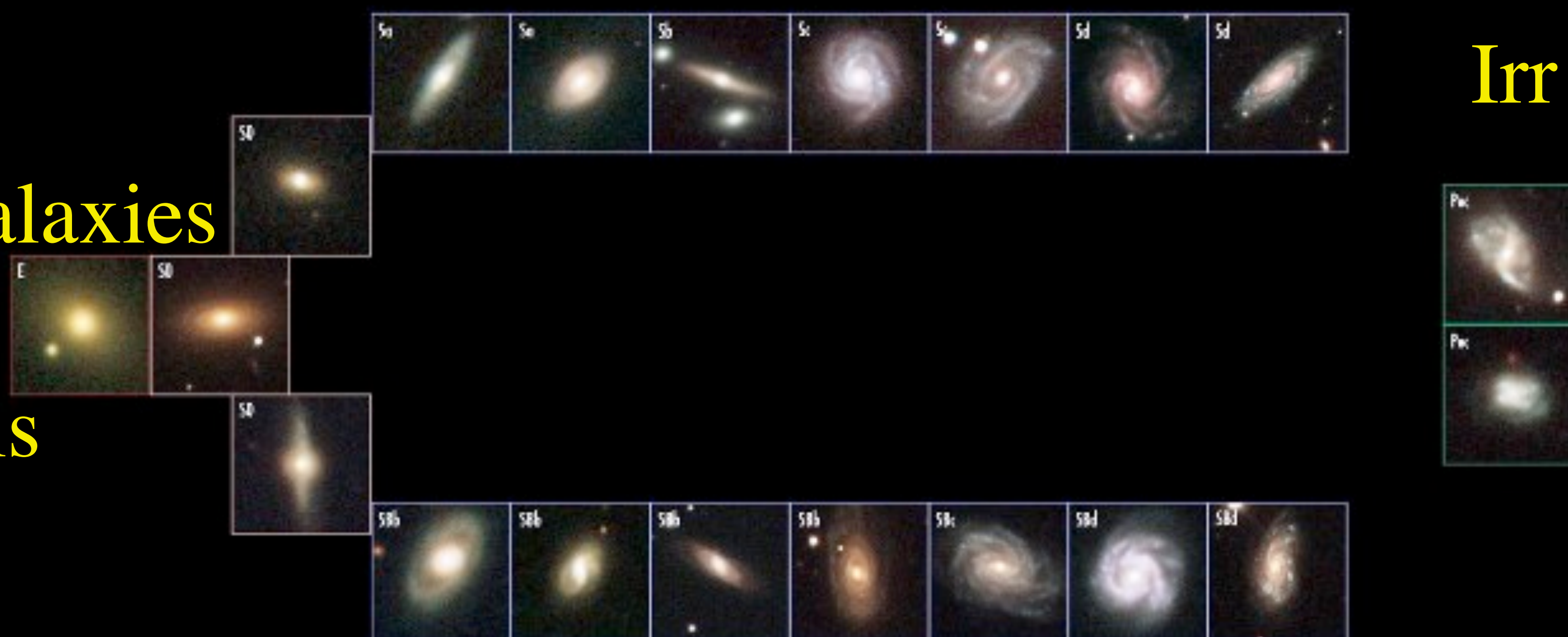
The original Hubble sequence stopped at Sc; subsequently extended to later types

Late Type Galaxies
LTGs

Sa Sb Sc Sd Sm

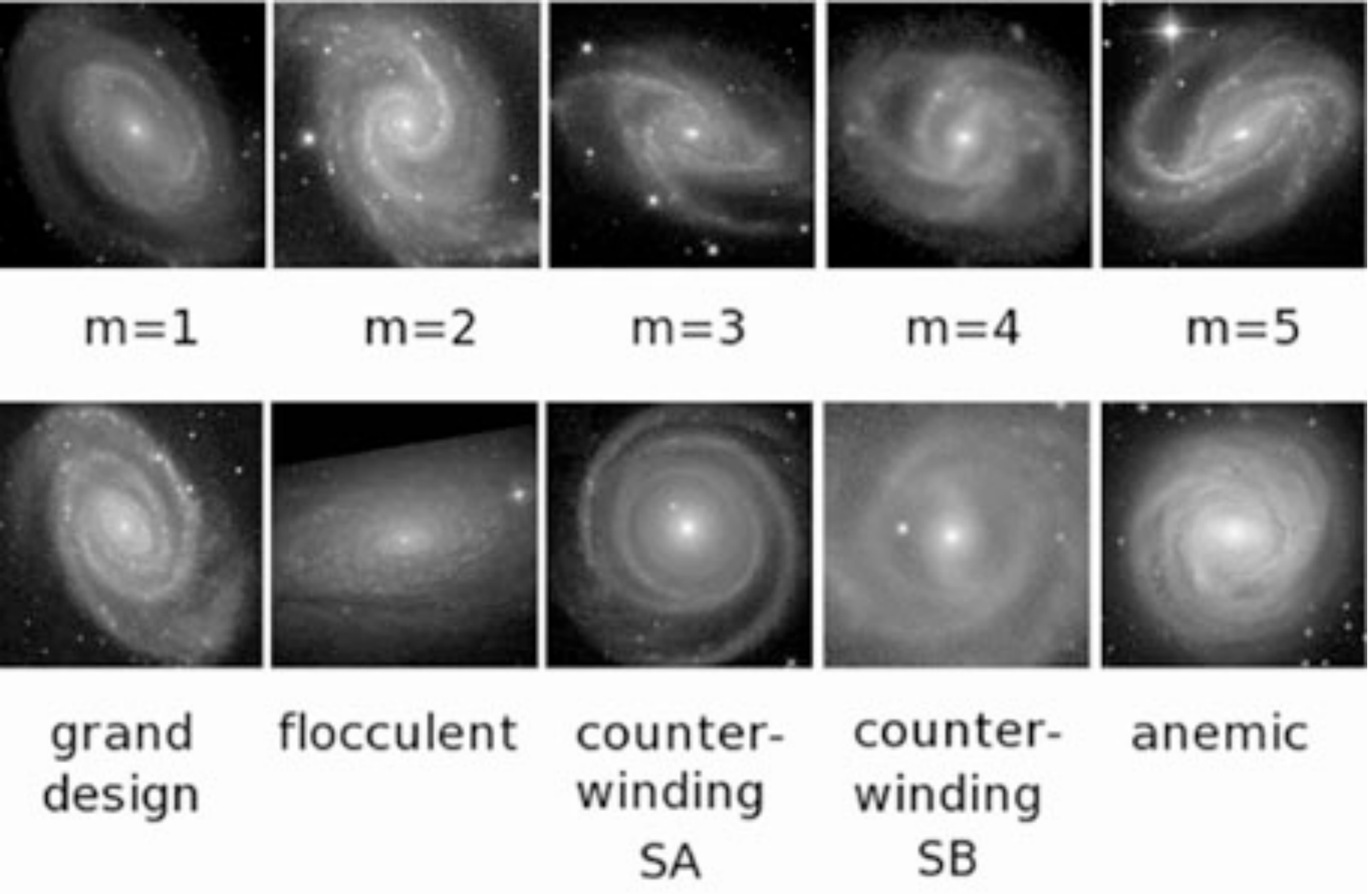
Irr

Early Type Galaxies
ETGs
Ellipticals

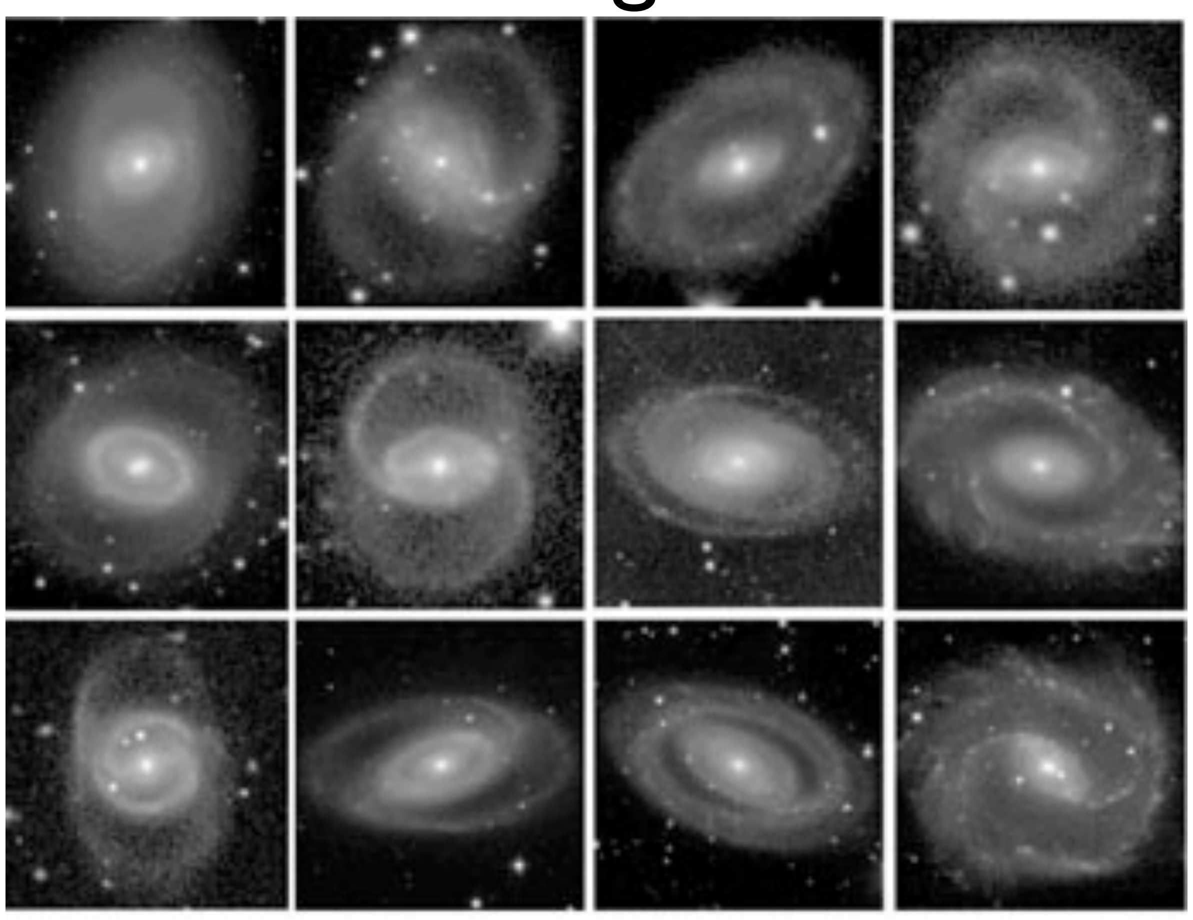


early type spirals late type spirals & irregulars

Spiral arm type & multiplicity



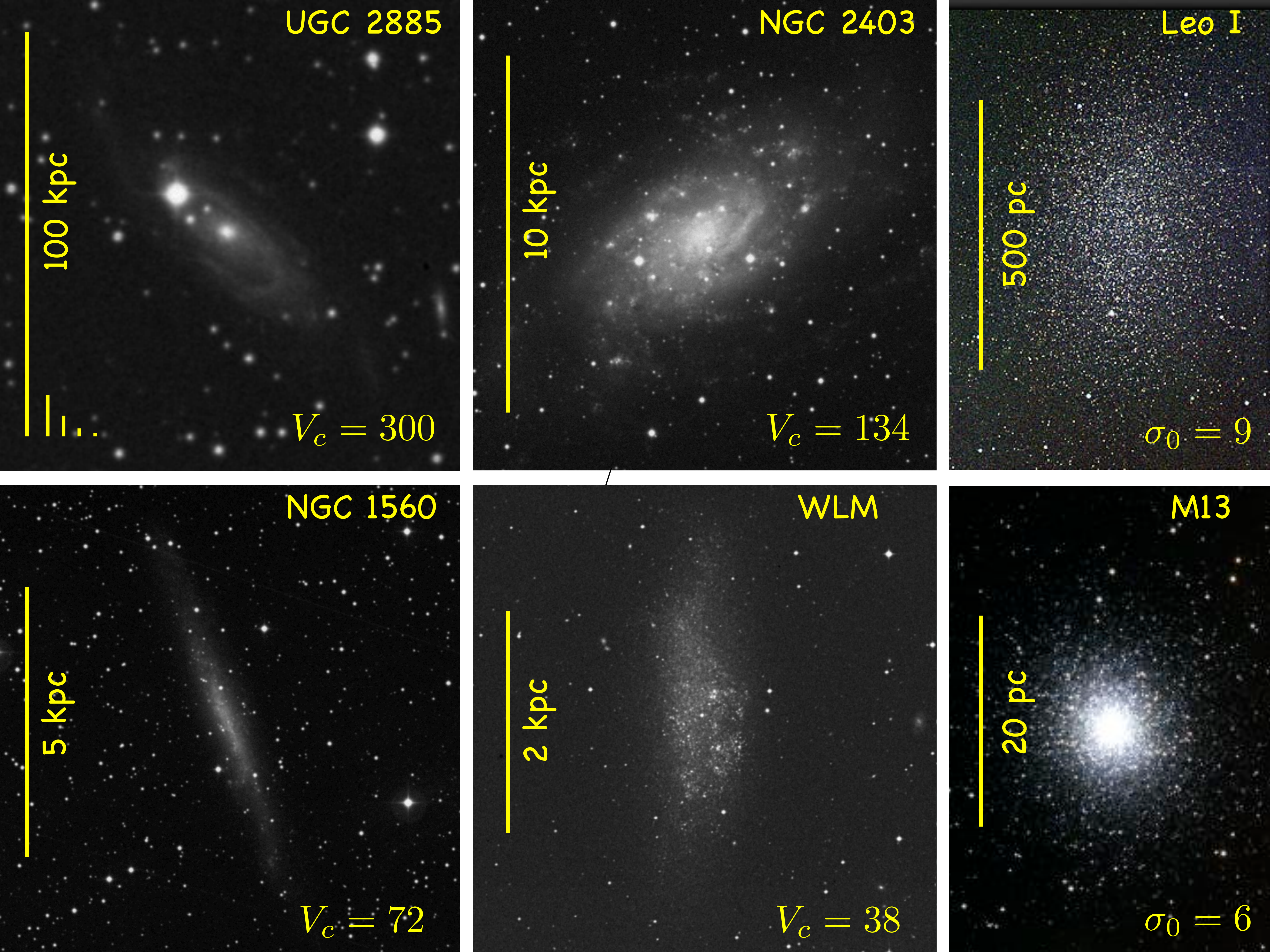
rings



Disk self-gravity drives bars and also spiral structure. Need a dark matter halo to suppress the rate of growth of these modes (but see Sellwood 2016 on live halos). But need some disk self-gravity to drive the observed features -

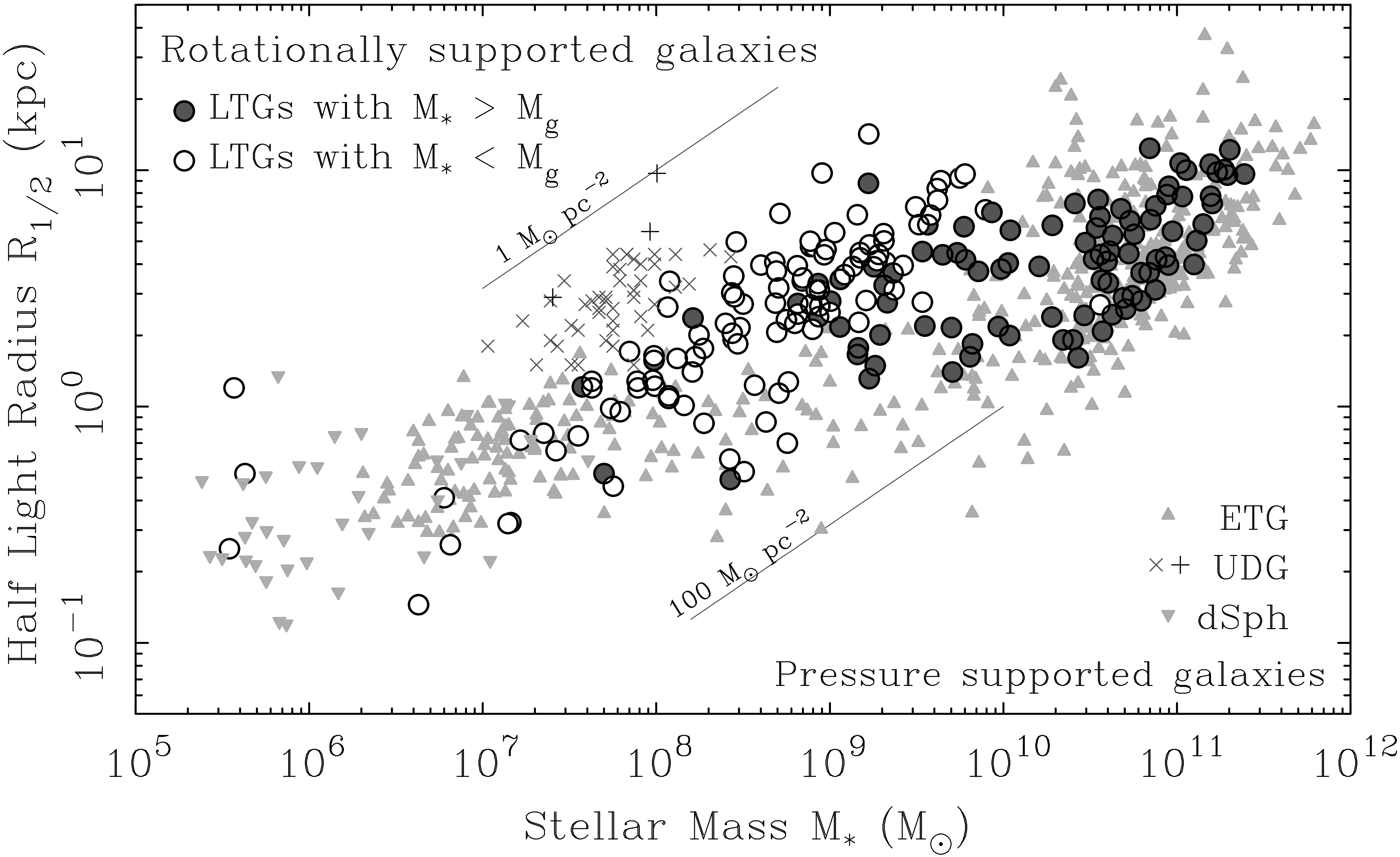
Athanassoula et al. (1987, A&A, 179, 23) find the disk mass has to be within a factor of 2 of maximum disk.

Fuchs (2003, Ap&SS, 284, 719) finds LSB disks need to be heavier than expected by stellar population models in order to drive the observed structure.

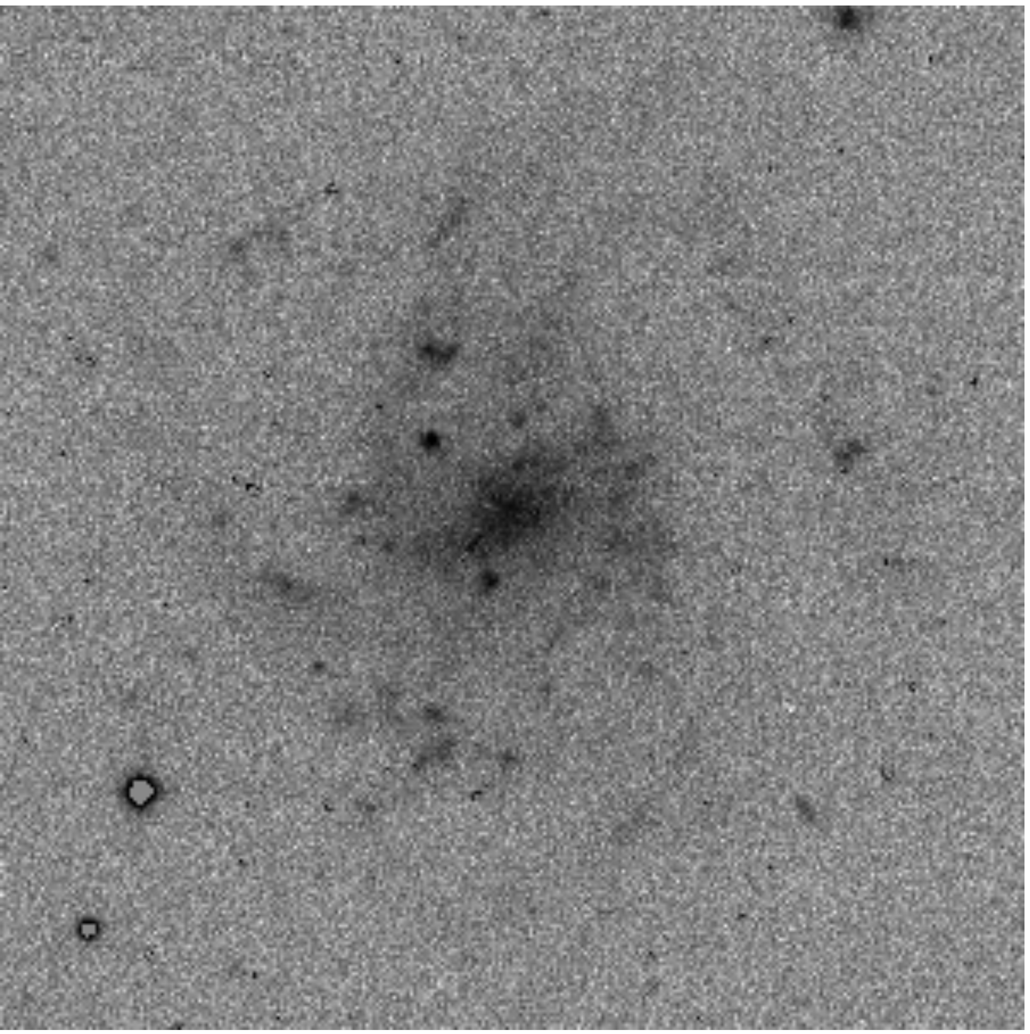


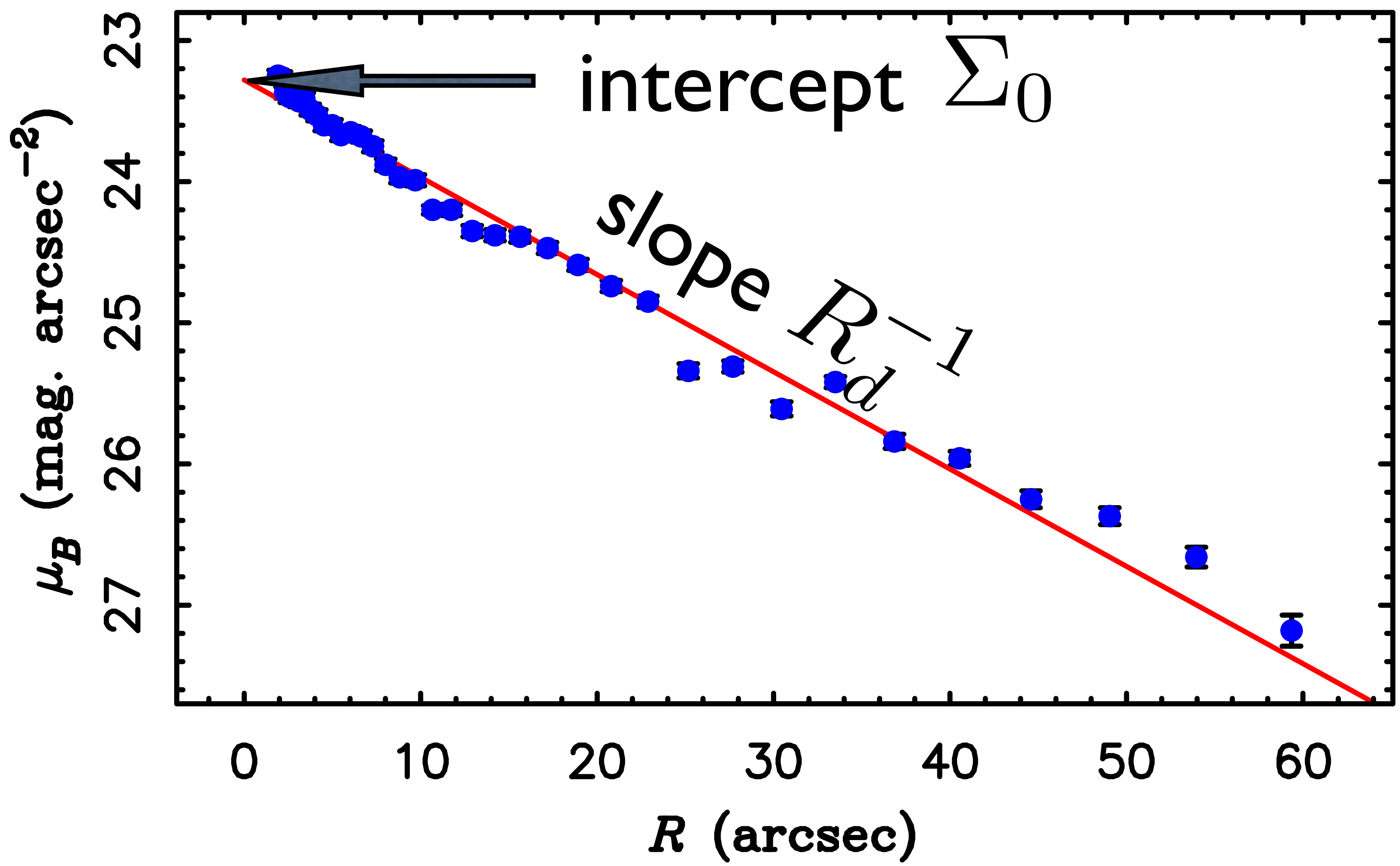
UGC 2885
100 kpc
$V_c = 300$
NGC 2403
10 kpc
$V_c = 134$
Leo I
500 pc
$\sigma_0 = 9$
NGC 1560
5 kpc
$V_c = 72$
WLM
2 kpc
$V_c = 38$
M13
20 pc
$\sigma_0 = 6$

Sizes and masses of galaxies



LTG: Exponential disk

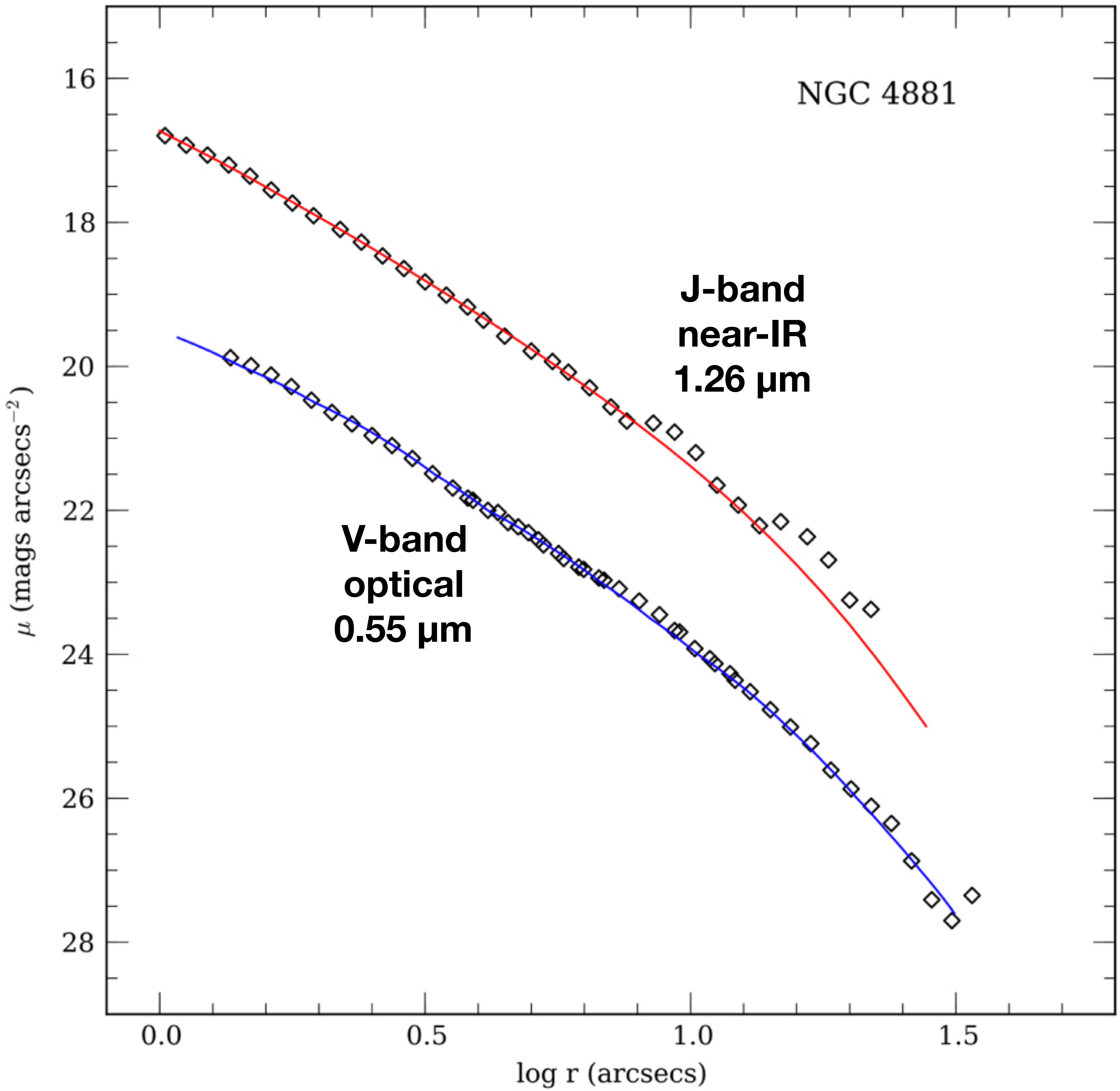




$$\Sigma(R) = \Sigma_0 e^{-R/R_d}$$

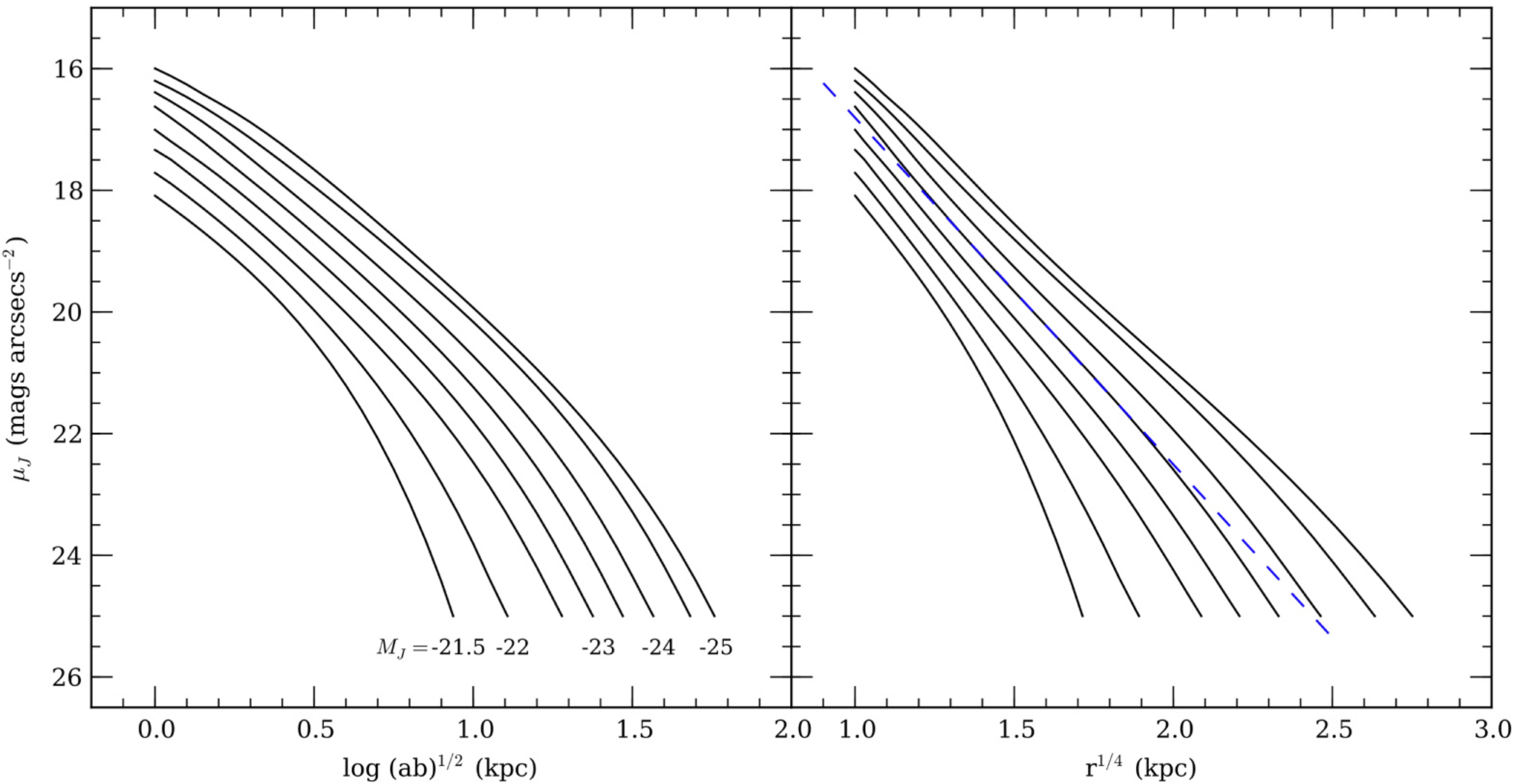
Azimuthally averaged light distribution approximately exponential for spiral disks.

ETG: de Vaucouleurs or generalized Sersic profile



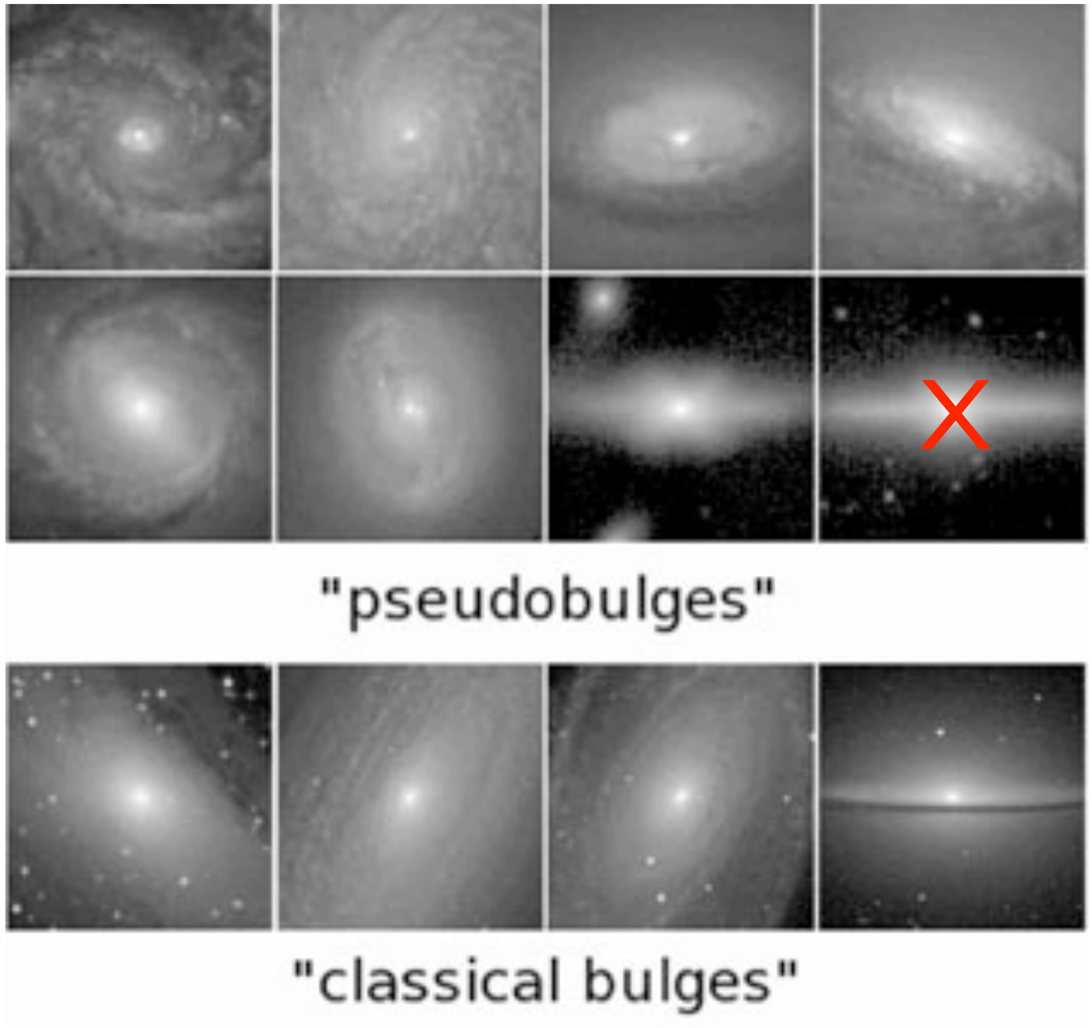
ETG profiles vary systematically with luminosity

Schombert (2015) AJ, 150, 162



Profiles would be straight lines here if the de Vaucouleurs profile were a perfect representation of ETGs

Classical bulges tend to have Sersic indices close to n=4 (de Voucoulers profile)



X/peanut shape characteristic of bars seen edge-on

Pseudo-bulges have various Sersic indices, often closer to n=1 (exponential) than to n=4 (de Voucoulers profile)

"Galaxies are made of stars" - D. Silva (1990) private communication

- **Stars**
  - Majority of baryonic mass in elliptical and early type spiral galaxies
- **Gas**
  - *Atomic HI*
    - Majority of baryonic mass in Irregular and some late type spiral galaxies
  - *Molecular H_2*
    - traced by CO
  - *Ionized H^+*
    - traced by $H\alpha$ Little mass at small radii.
- **Dust**
  - little mass, but does get in the way.

Multi-wavelength Milky Way

radio (21 cm)
HI gas

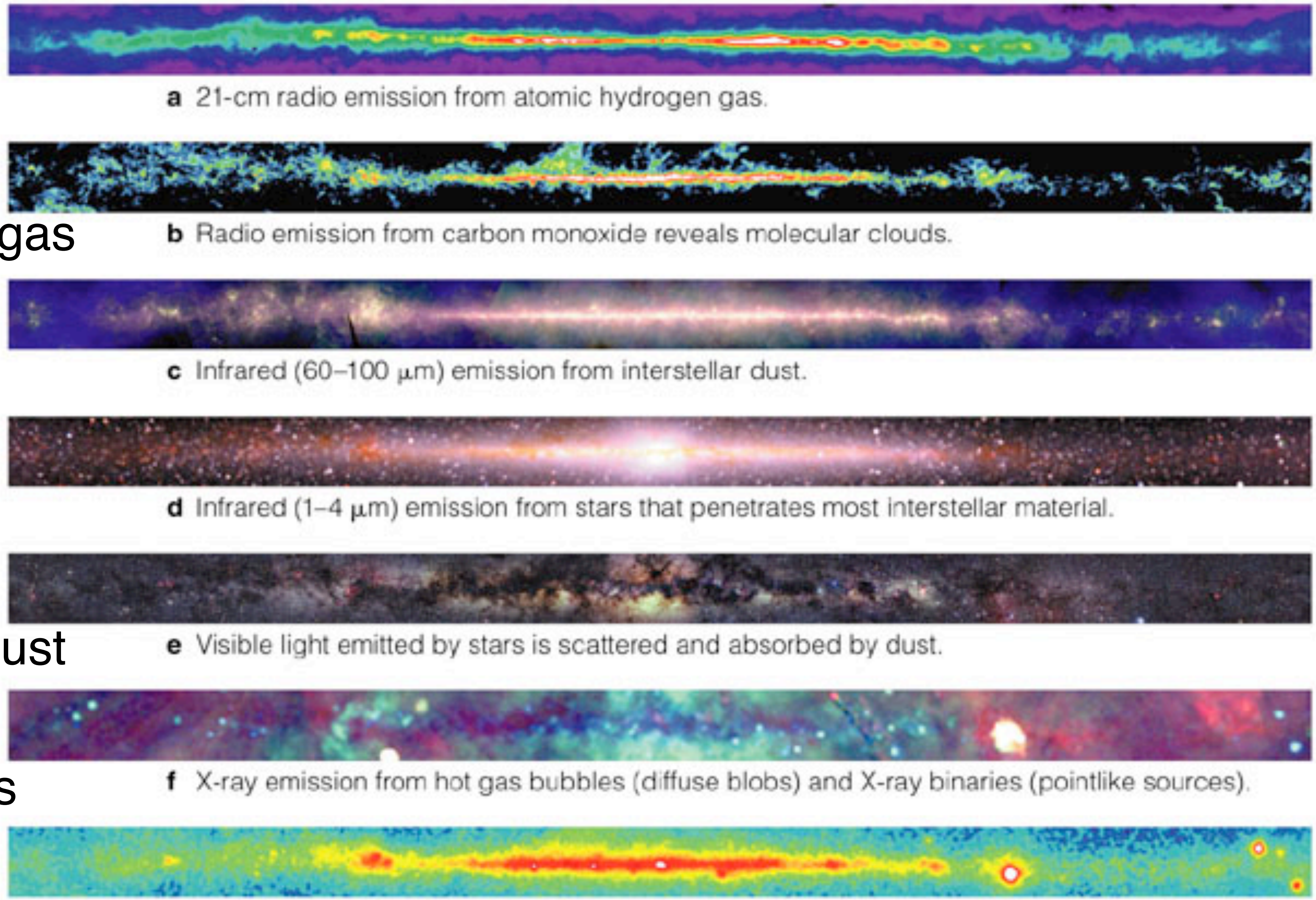
radio (CO)
molecular gas

far-IR
dust

near-IR
stars

Optical
stars & dust

X-ray
hot gas



a 21-cm radio emission from atomic hydrogen gas.

b Radio emission from carbon monoxide reveals molecular clouds.

c Infrared (60–100 μm) emission from interstellar dust.

d Infrared (1–4 μm) emission from stars that penetrates most interstellar material.

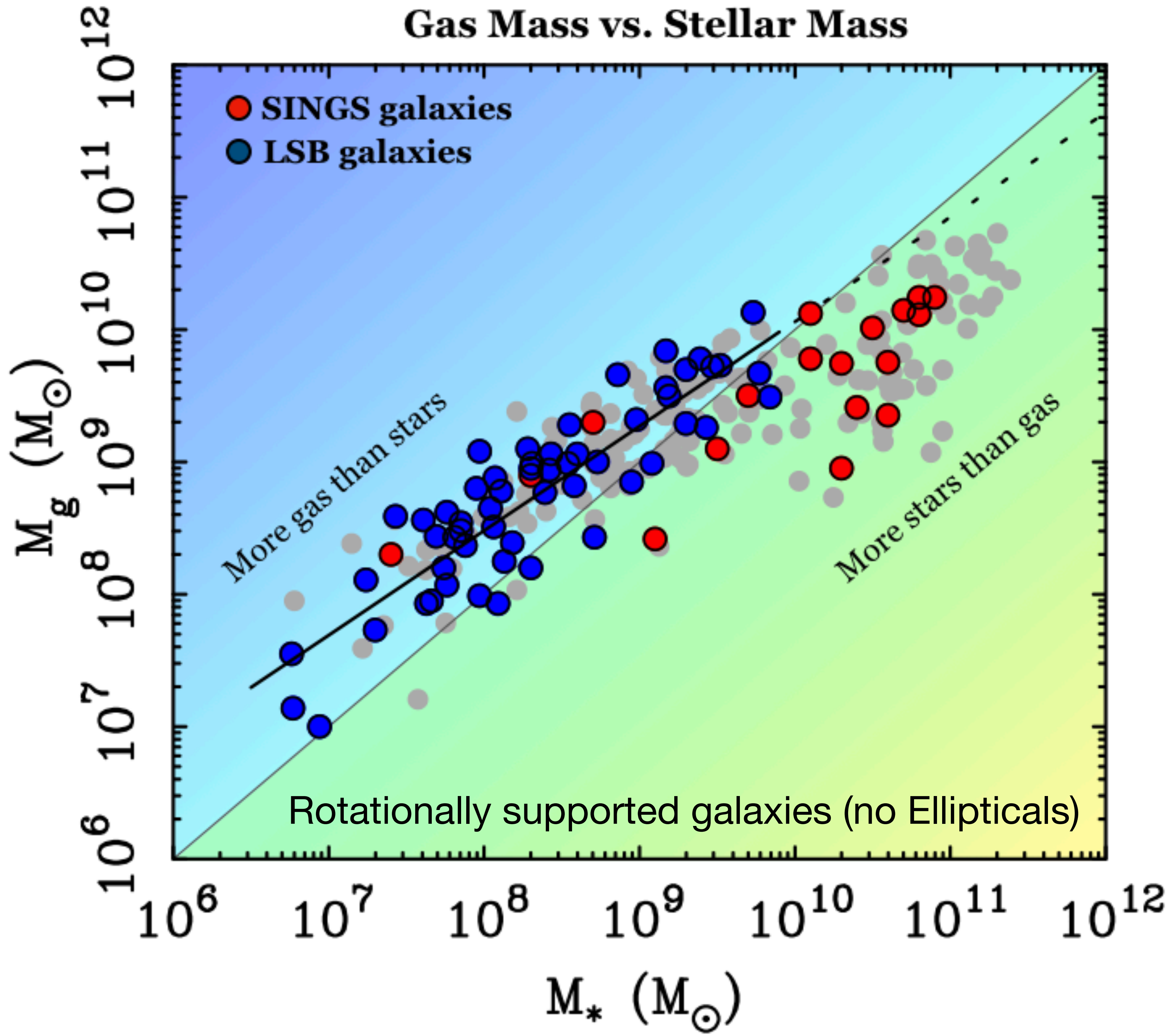
e Visible light emitted by stars is scattered and absorbed by dust.

f X-ray emission from hot gas bubbles (diffuse blobs) and X-ray binaries (pointlike sources).

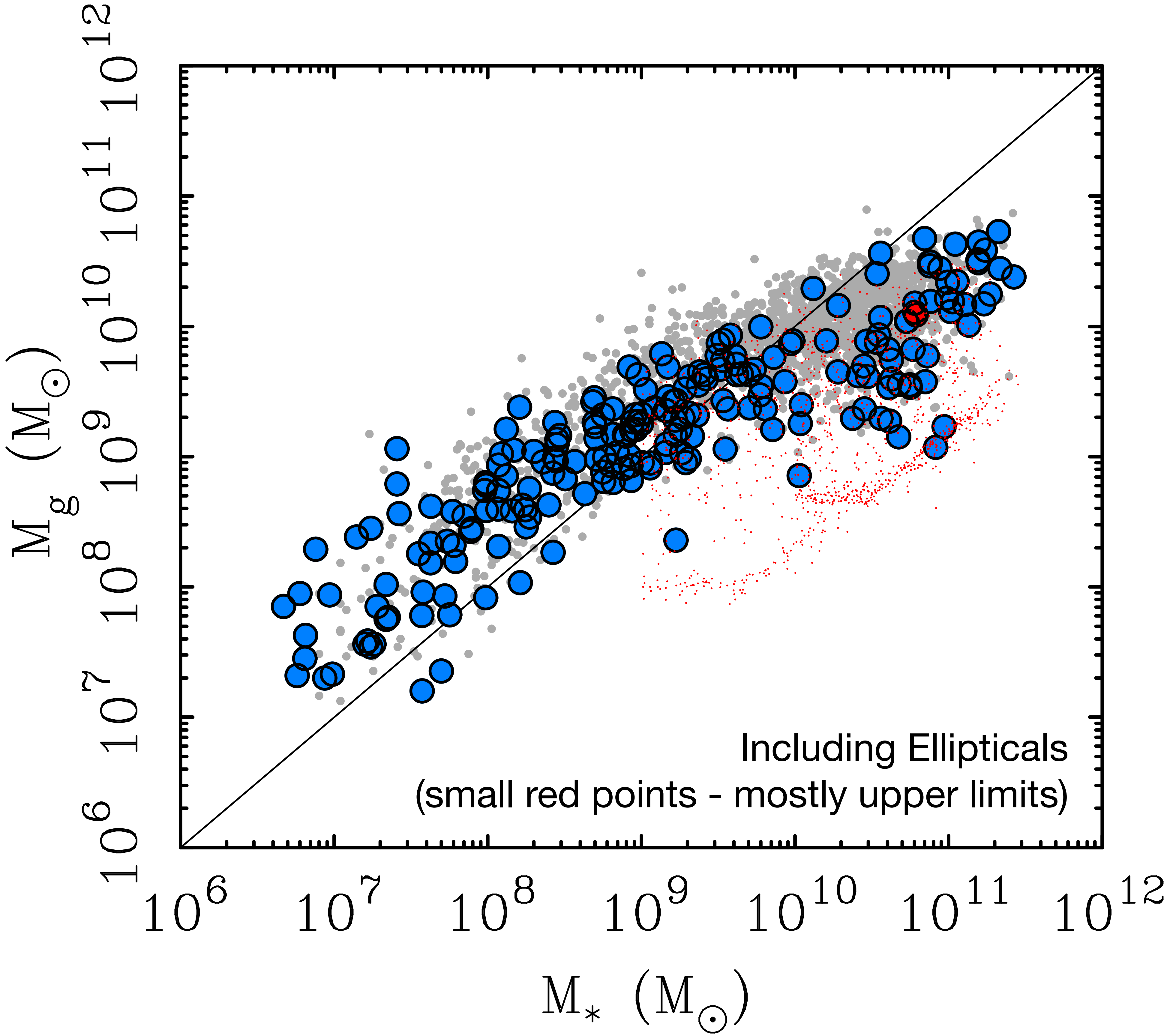
g Gamma-ray emission from collisions of cosmic rays with atomic nuclei in interstellar clouds.

Galaxies span a large dynamic range in mass - both stellar and gas mass

gas mass - mostly atomic

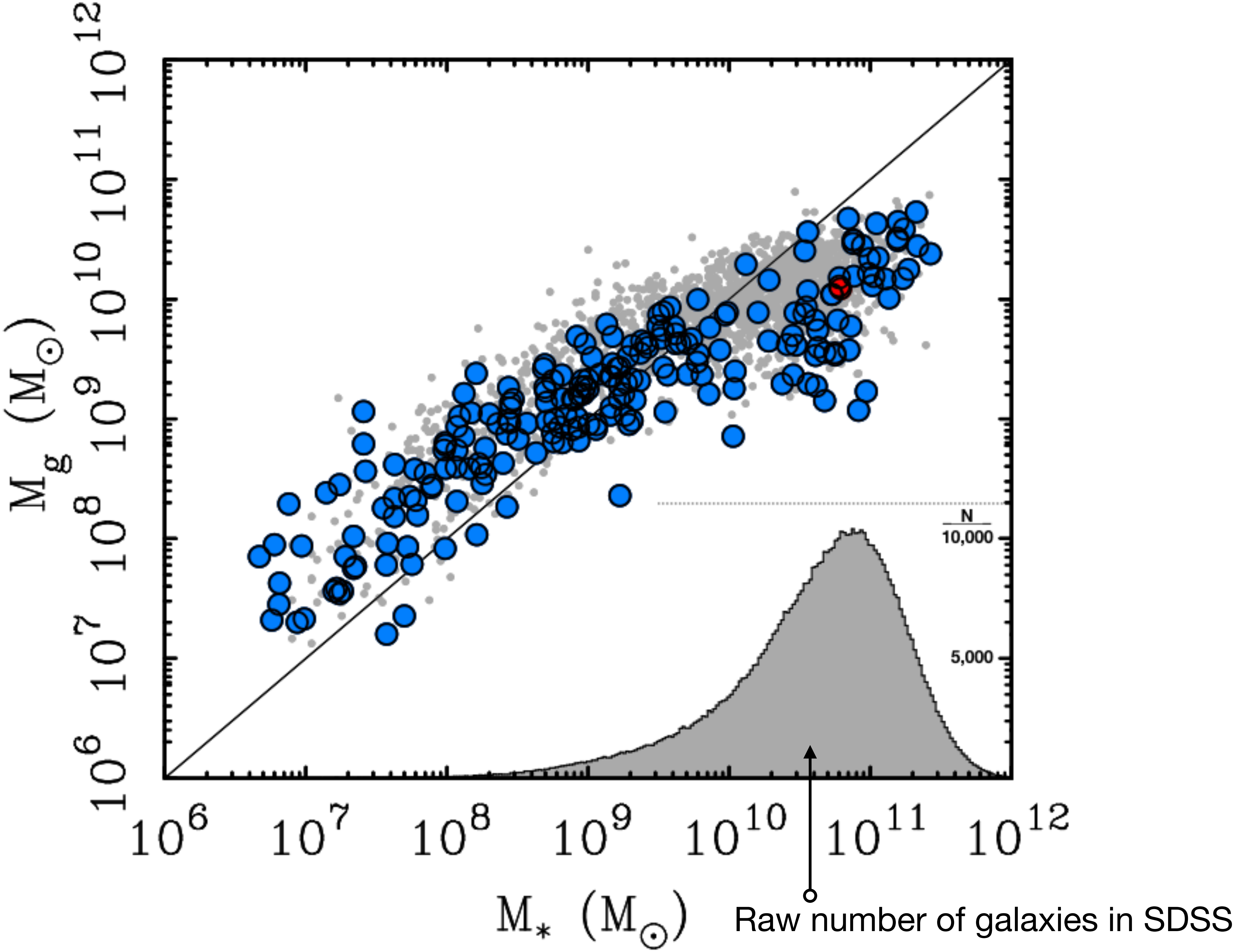


stellar mass



Including Ellipticals
(small red points - mostly upper limits)
M_g ($M_\odot$)
M_* ($M_\odot$)
10^6
10^7
10^8
10^9
10^{10}
10^{11}
10^{12}

Beware selection effects! Catalogs are always dominated by brightest objects



ISM

The stuff between the stars

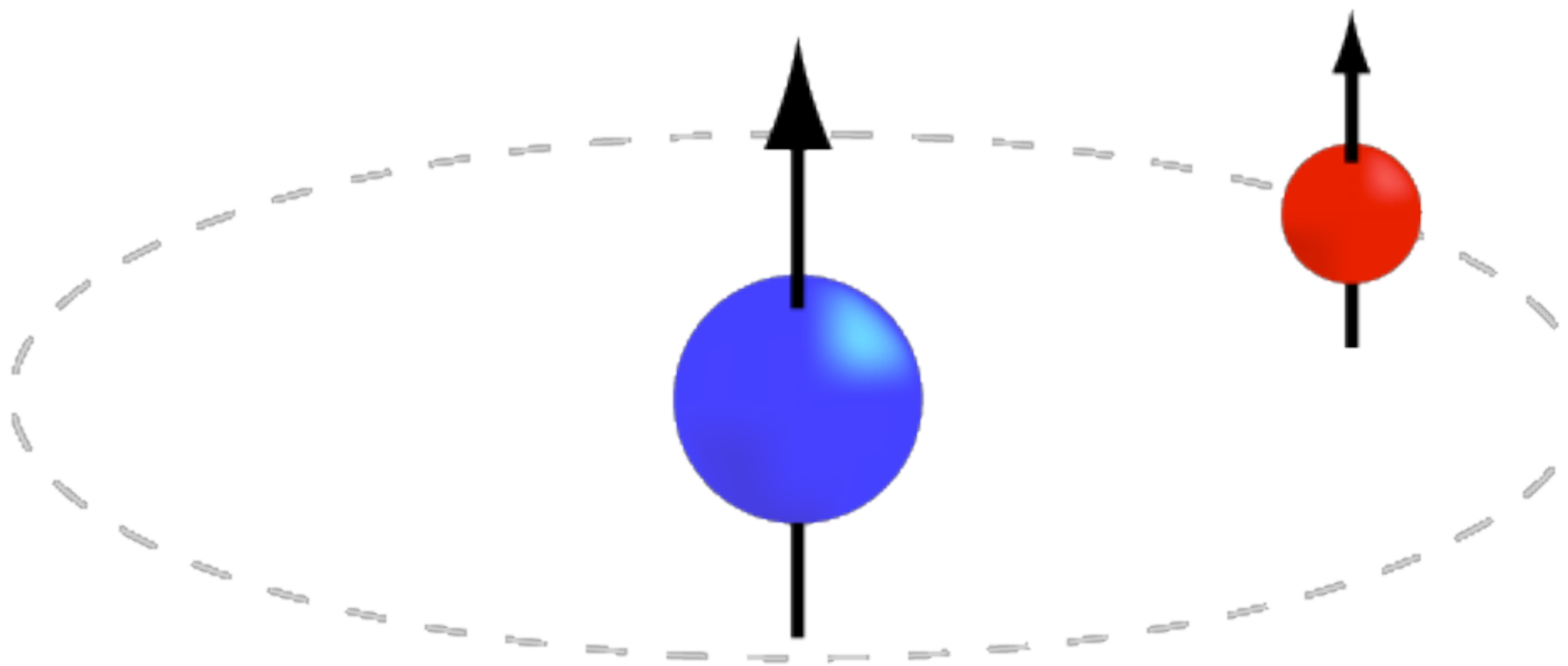
Atomic gas (H I)
Molecular gas (H_2)
Ionized gas (H II)
Dust

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



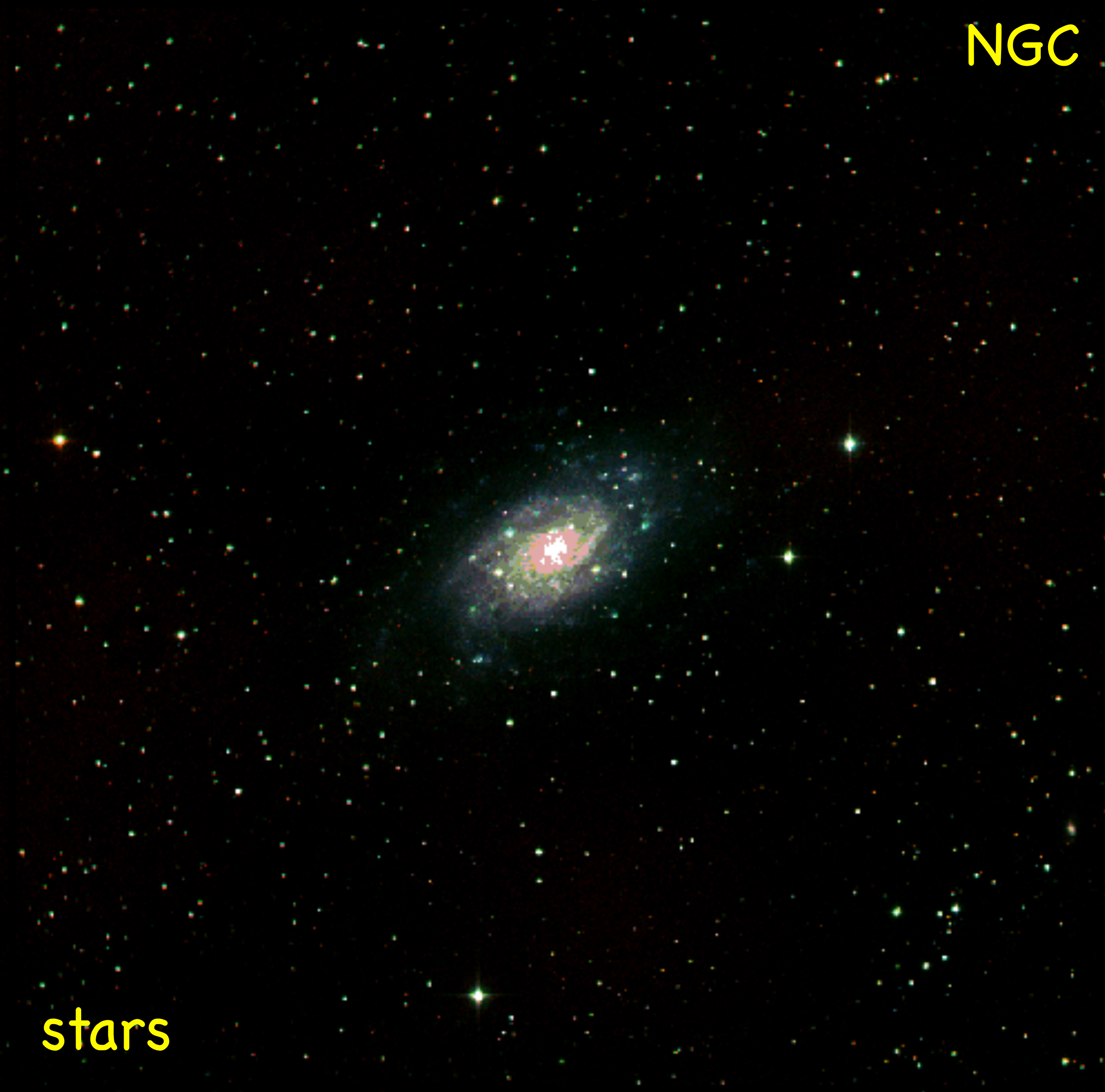
21 cm emission from hyperfine transition: parallel to anti-parallel spins

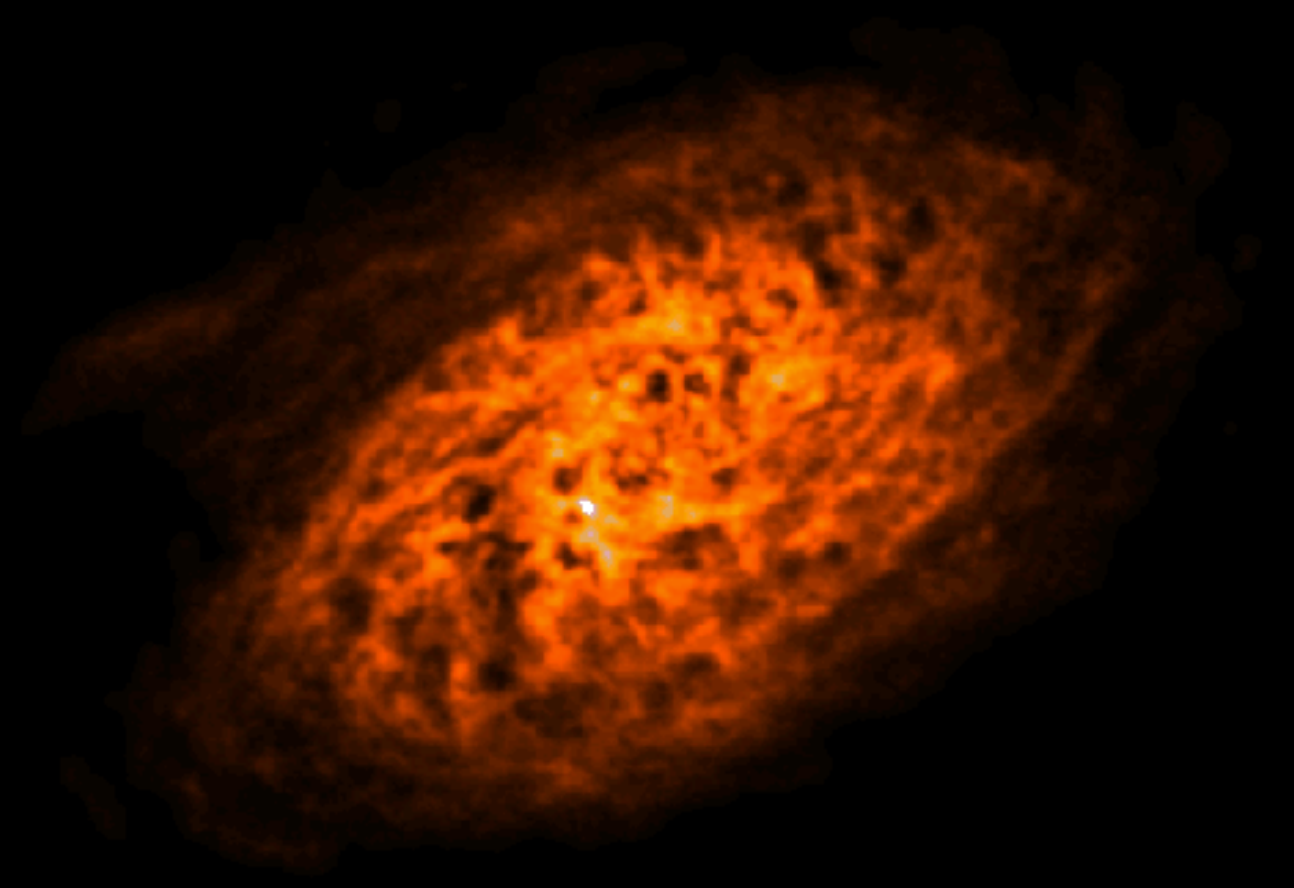
$$\nu = \frac{8}{3} g_I \frac{m_e}{m_p} \alpha^2 R_m c = 1420.405751 \text{ MHz}$$

The 21 cm line is in the radio at 1420 MHz

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

NGC 2403

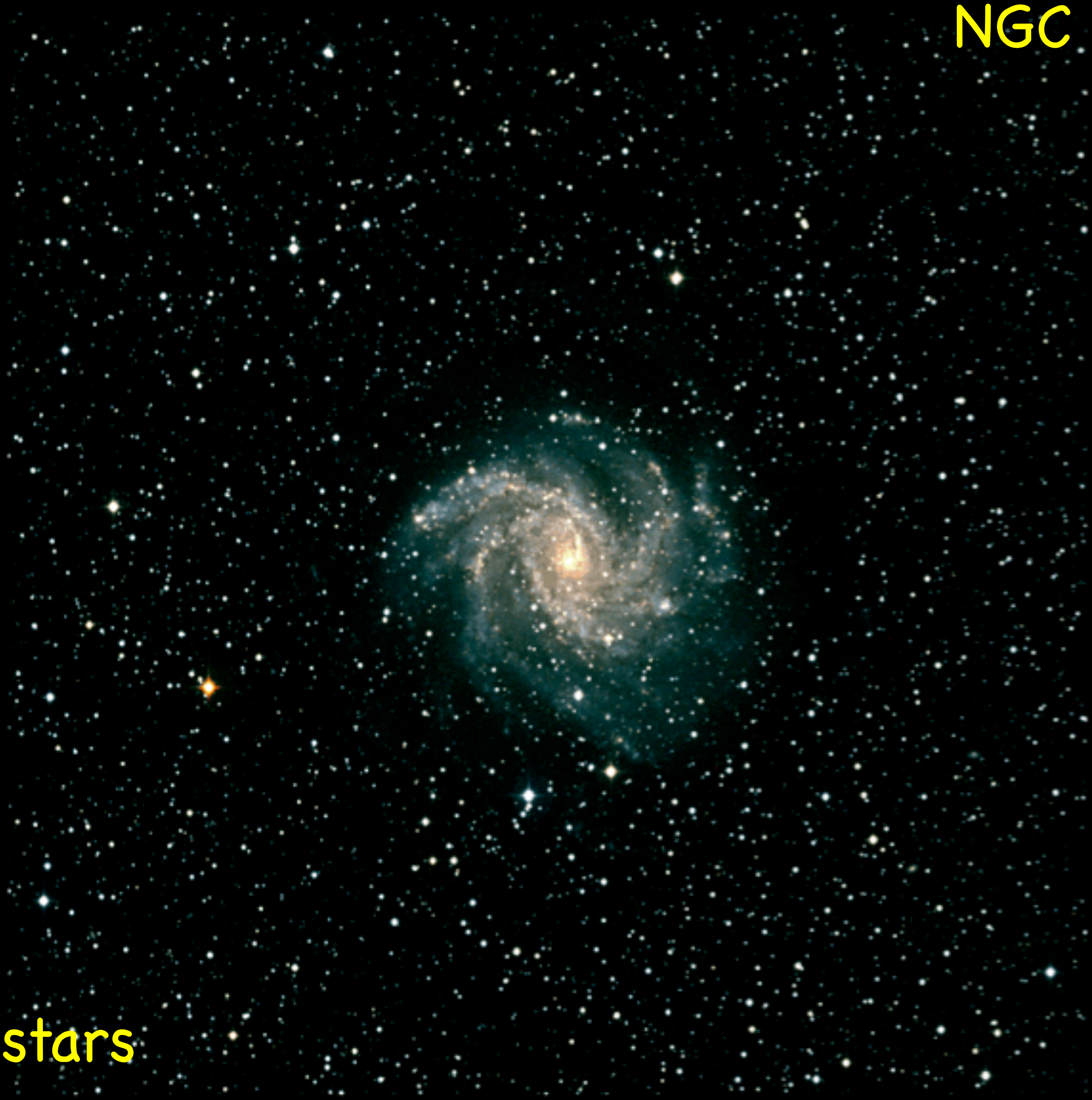


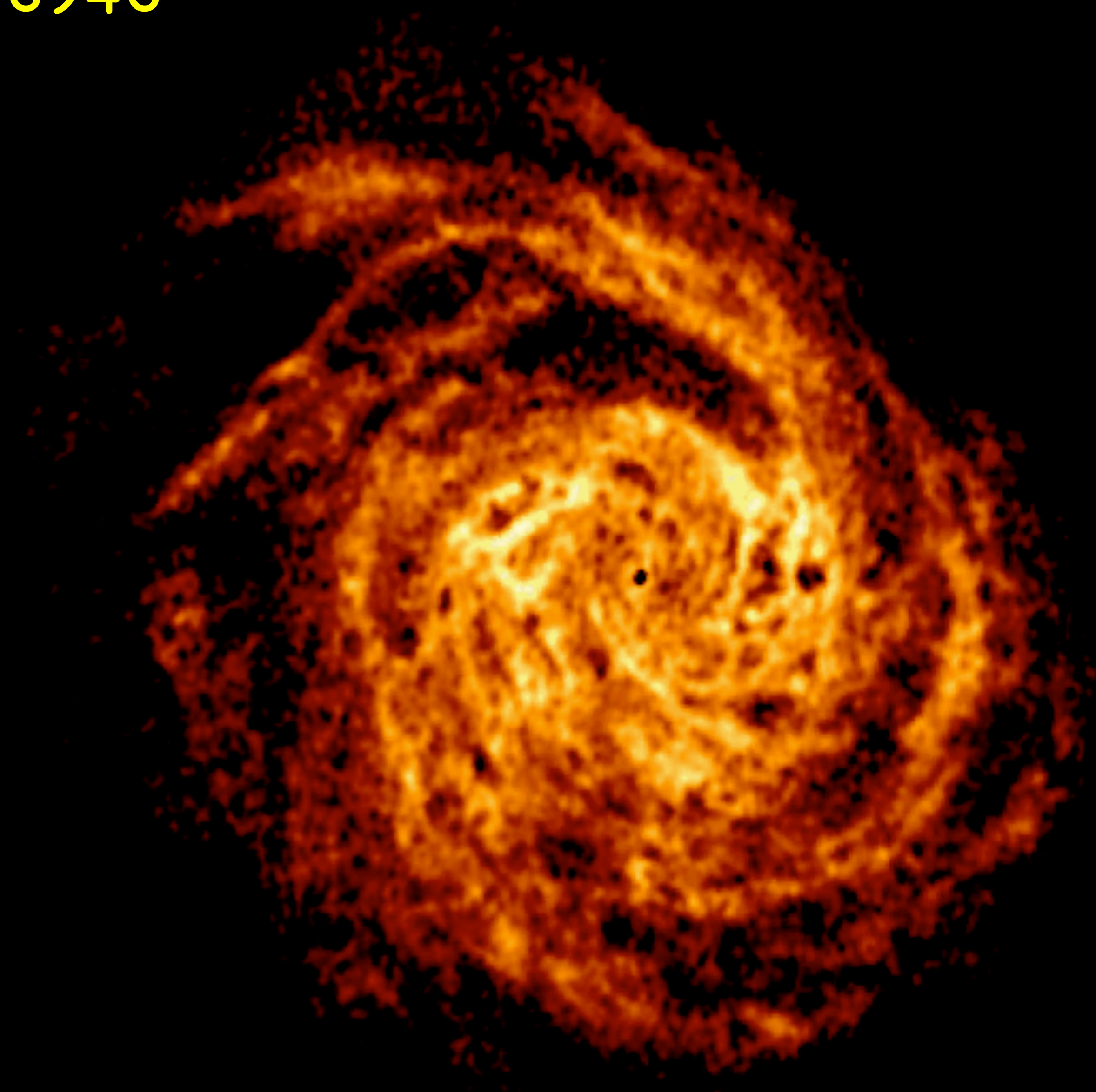


Fraternali, F., Oosterloo, T., Sancisi, R., van Moorsel, G.A. 2001, ApJ, 562, L47

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

NGC 6946



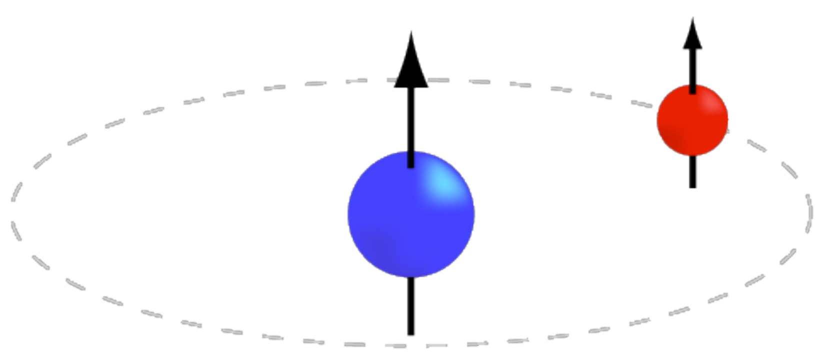


Boomsma 2005

emission coefficient

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

Bohr magneton



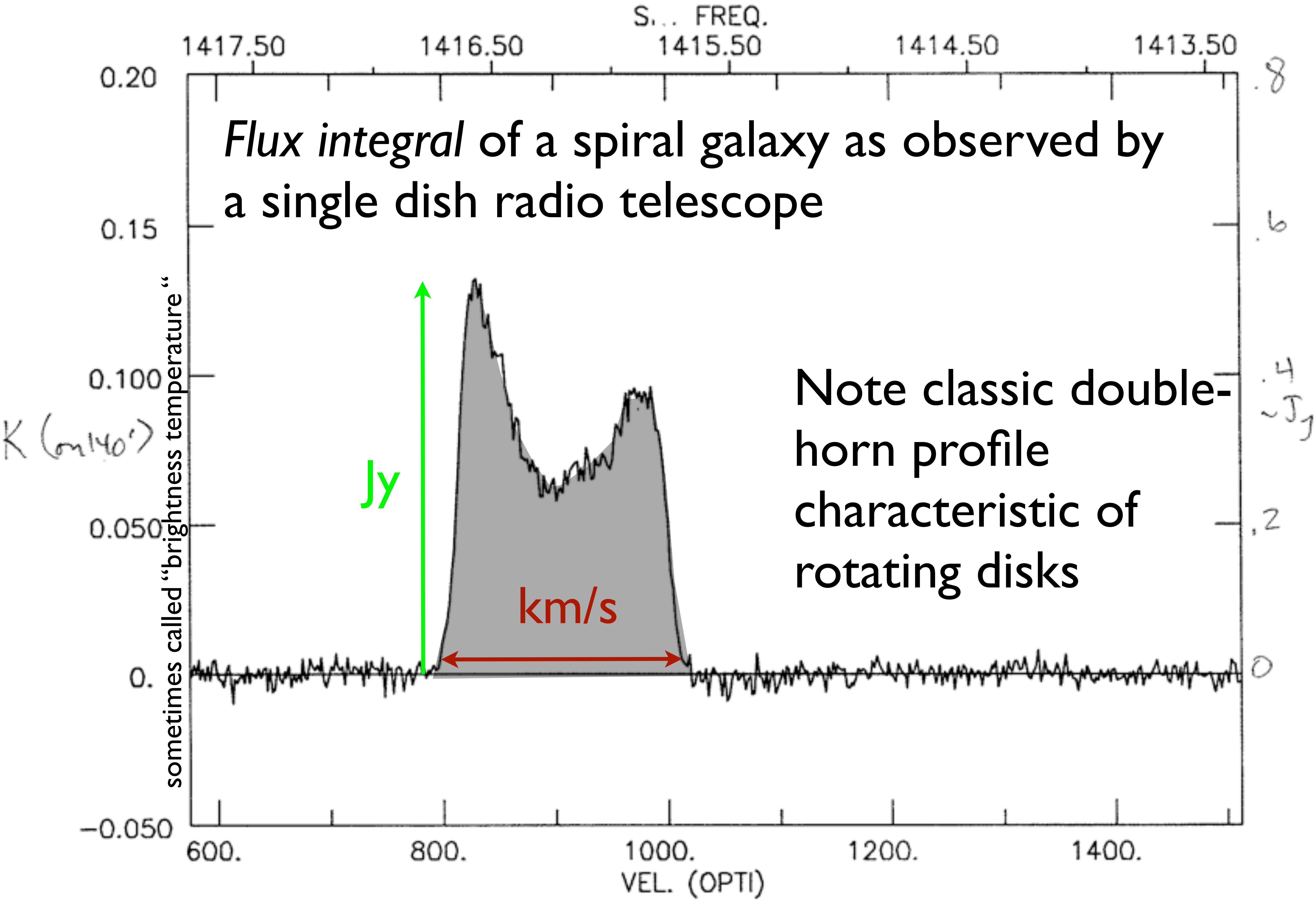
The radiative half-life of this transition is 11 Myr. This is readily maintained in equilibrium even in a cool (~100 K), diffuse ISM (< 1 atom/cc)

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 F_{HI}, the flux integral in Jy-km/s

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

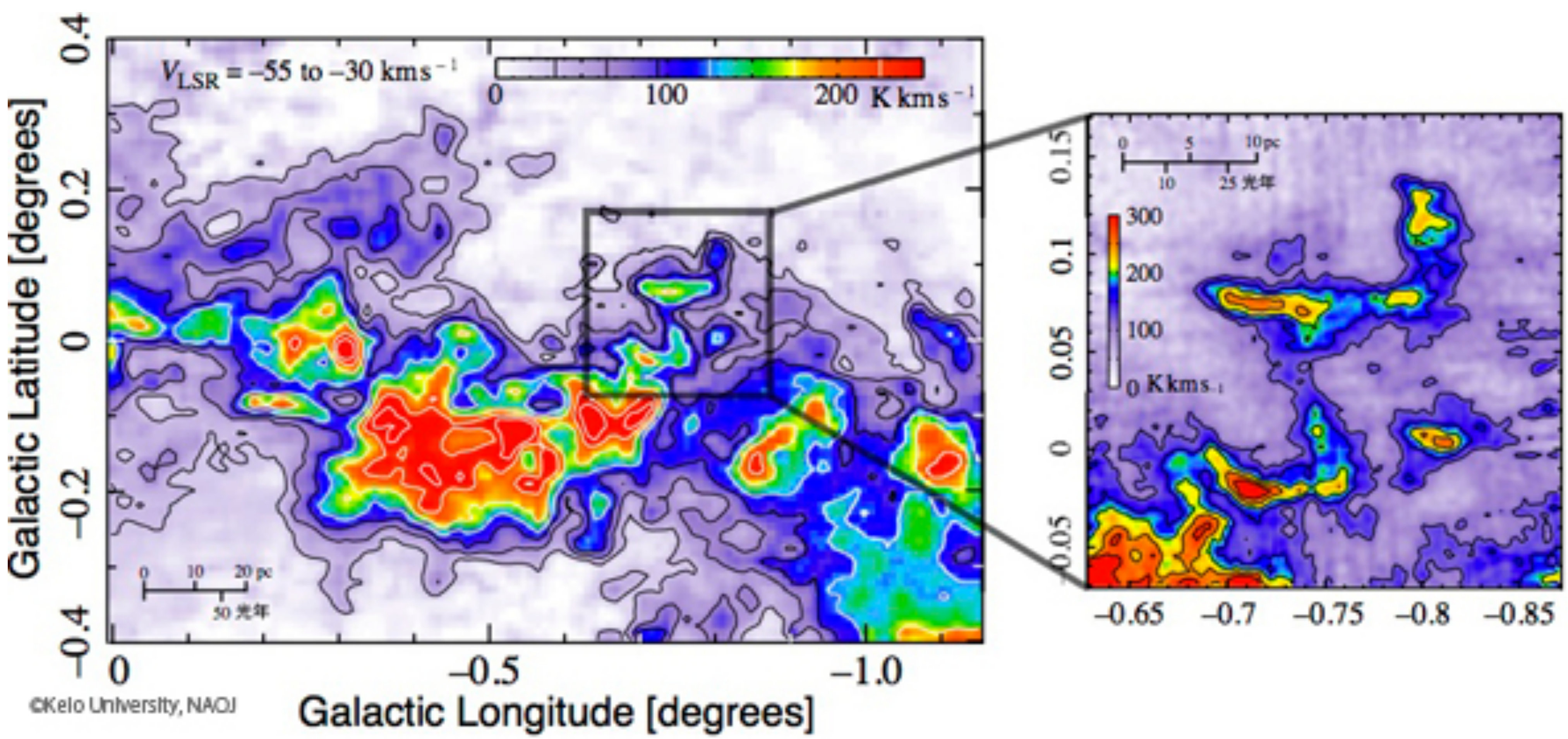


Flux integral of a spiral galaxy as observed by a single dish radio telescope
Note classic double-horn profile characteristic of rotating disks
Jy
km/s
sometimes called "brightness temperature"
S... FREQ.
1417.50
1416.50
1415.50
1414.50
1413.50
0.20
0.15
0.100
0.050
0.
−0.050
600.
800.
1000.
1200.
1400.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

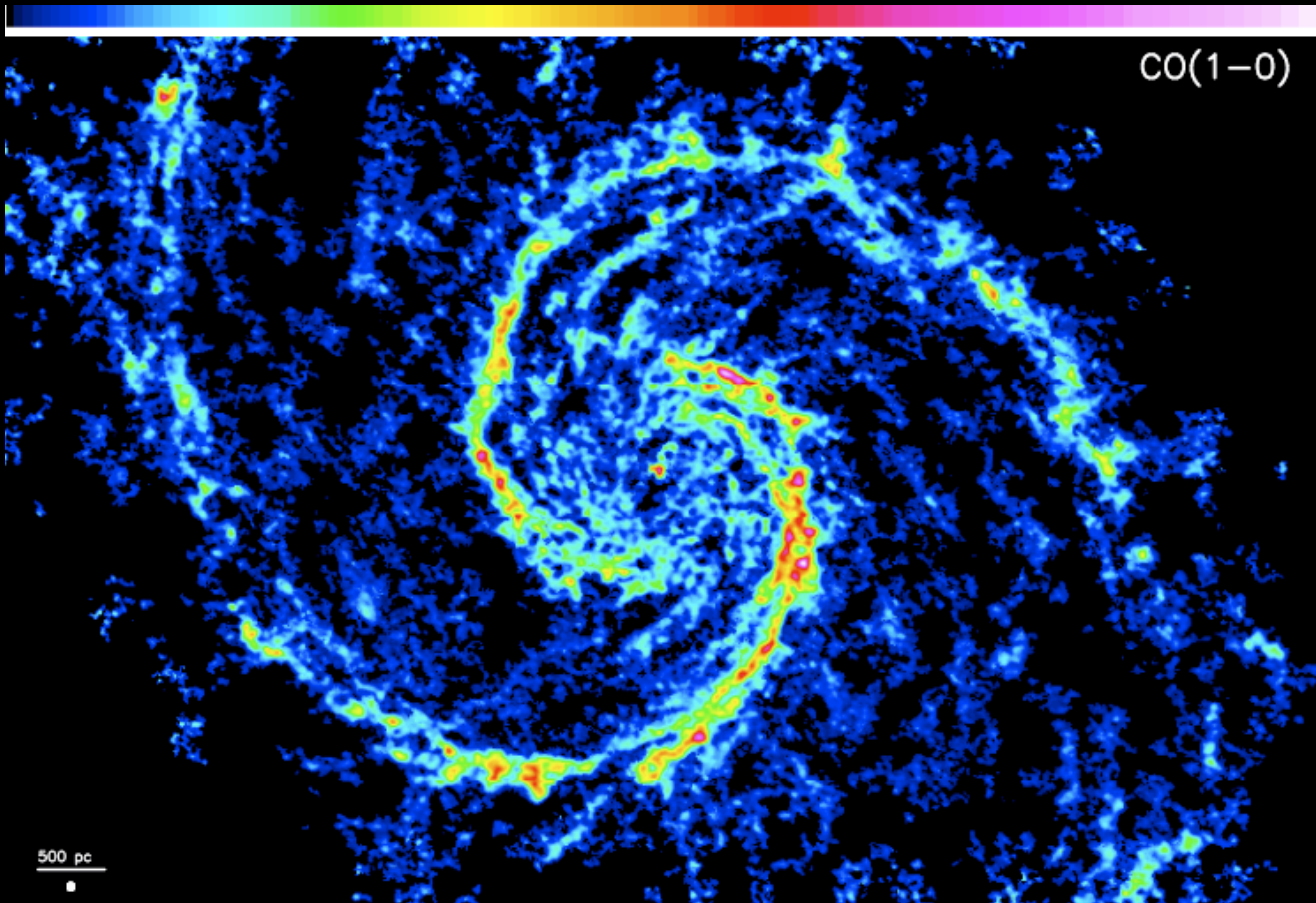
Molecular ISM

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

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 in CO



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

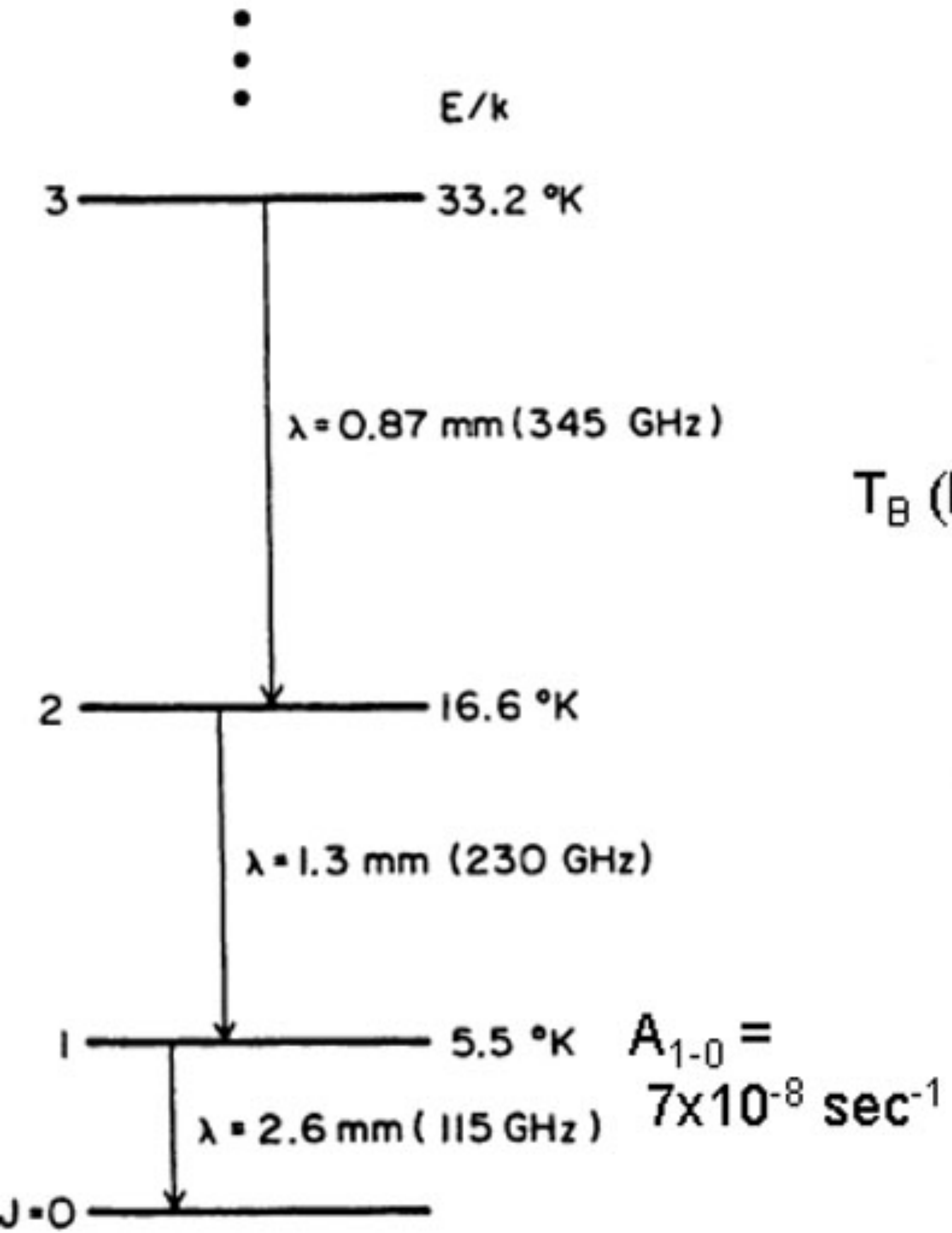
Polar molecules (esp. CO) have a permanent dipole moment thanks to asymmetry so have a rich rotational spectrum (typically in the mm or cm wavelengths).

$$E_{rot} = \frac{J(J+1)\hbar^2}{2I}$$

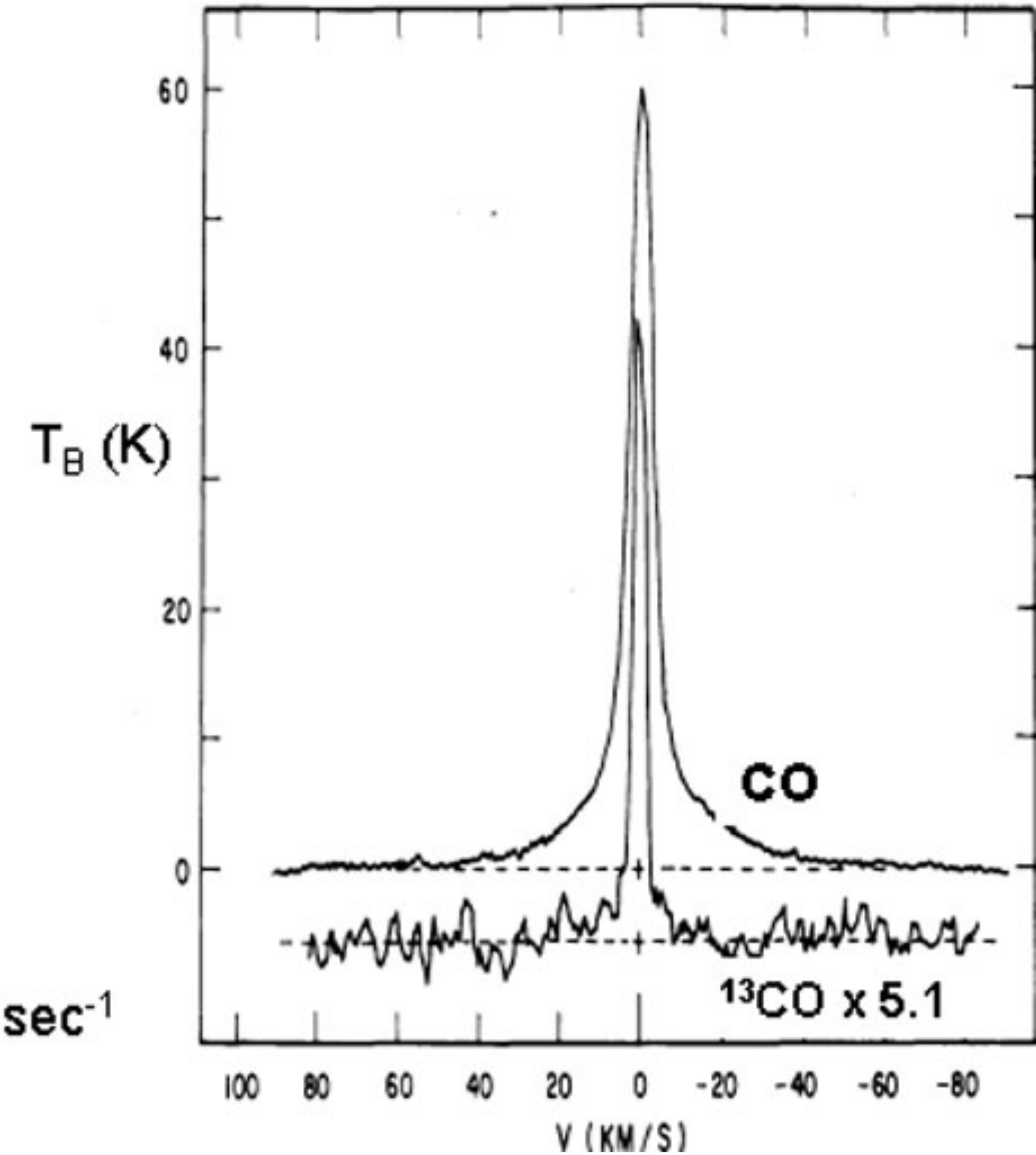
$$M_{H_2} = 1.1 \times 10^4 D^2 F_{CO}$$

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

CO Rotational Levels

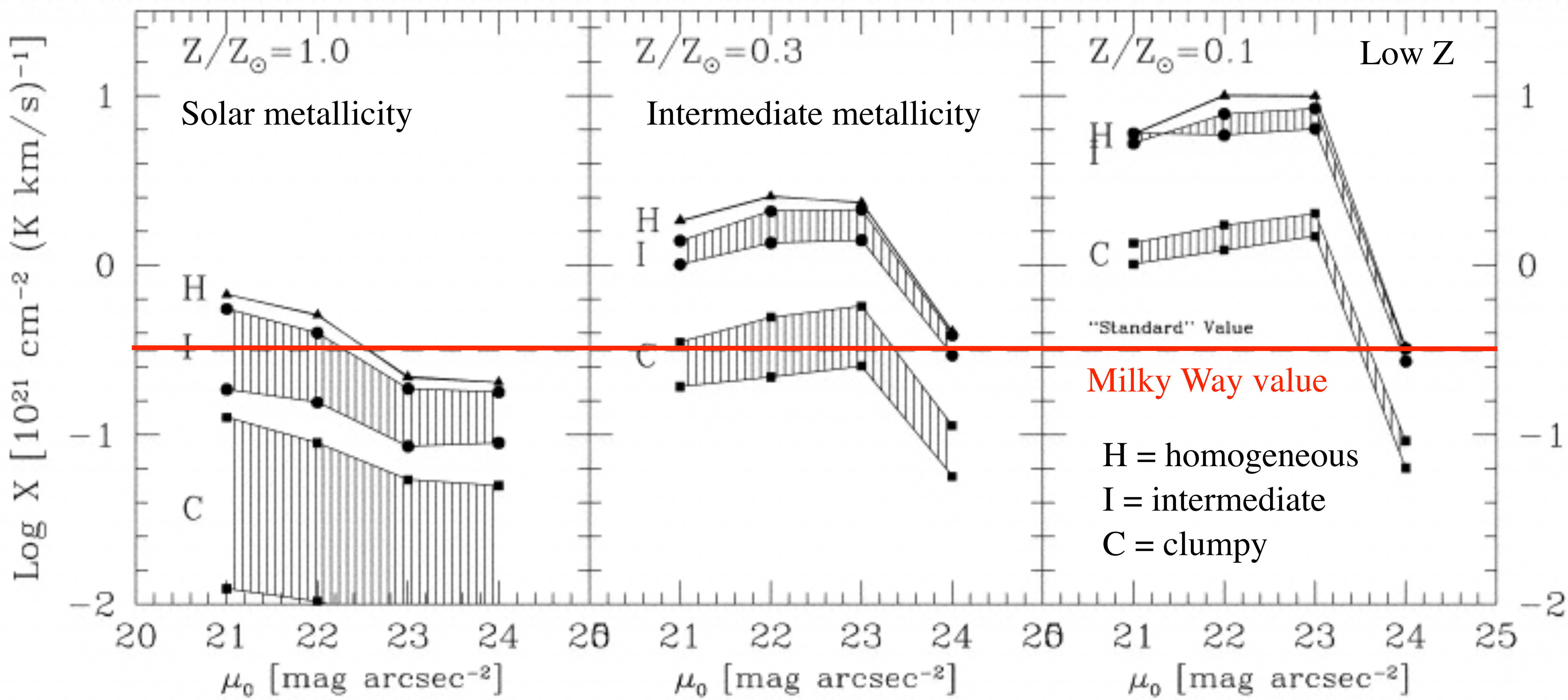


CO (J=1-0) in Orion KL Nebula



X: CO-to-H_2 conversion factor

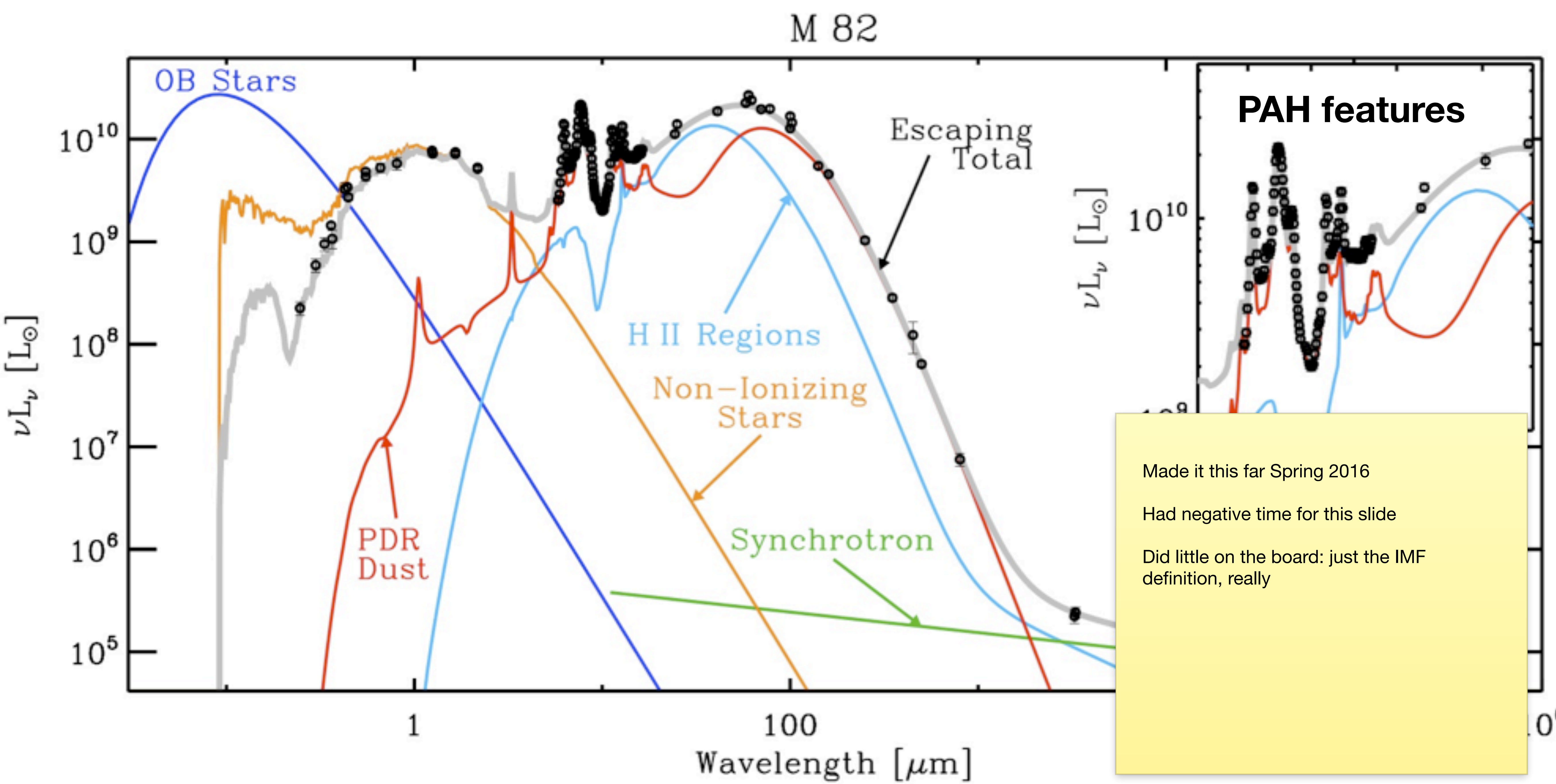
(Mihos, Spaans, & McGaugh 1998)



X should depend on the metallicity, the radiation field, the density of the gas, and how dusty and clumpy it is. So we usually just assume it is constant.

Dust

Scatters optical light
Absorbs UV; reradiates in IR
typically 60 - 100 microns



Made it this far Spring 2016

Had negative time for this slide

Did little on the board: just the IMF definition, really

Dust

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Absorbs UV; reradiates in IR

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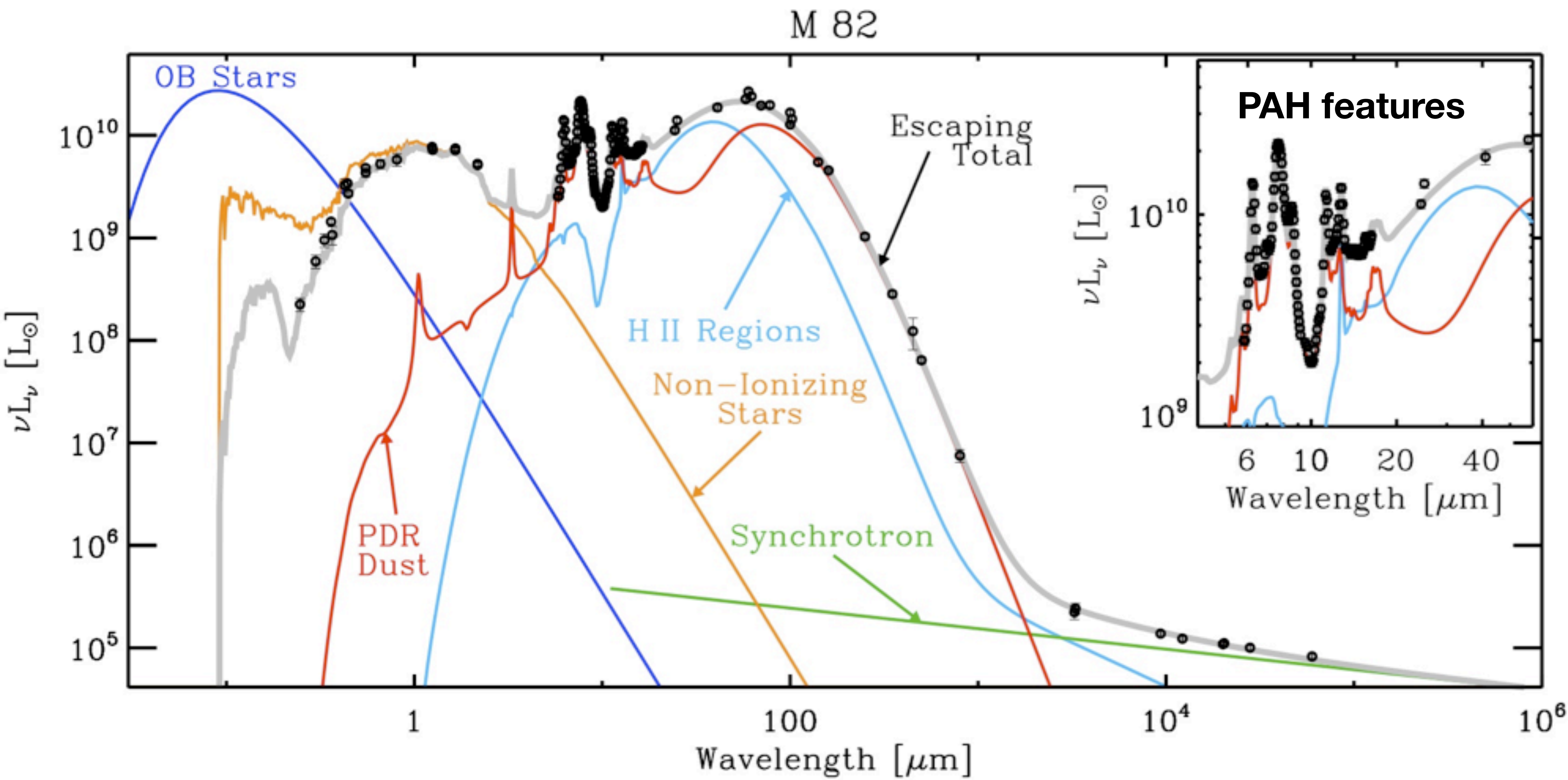
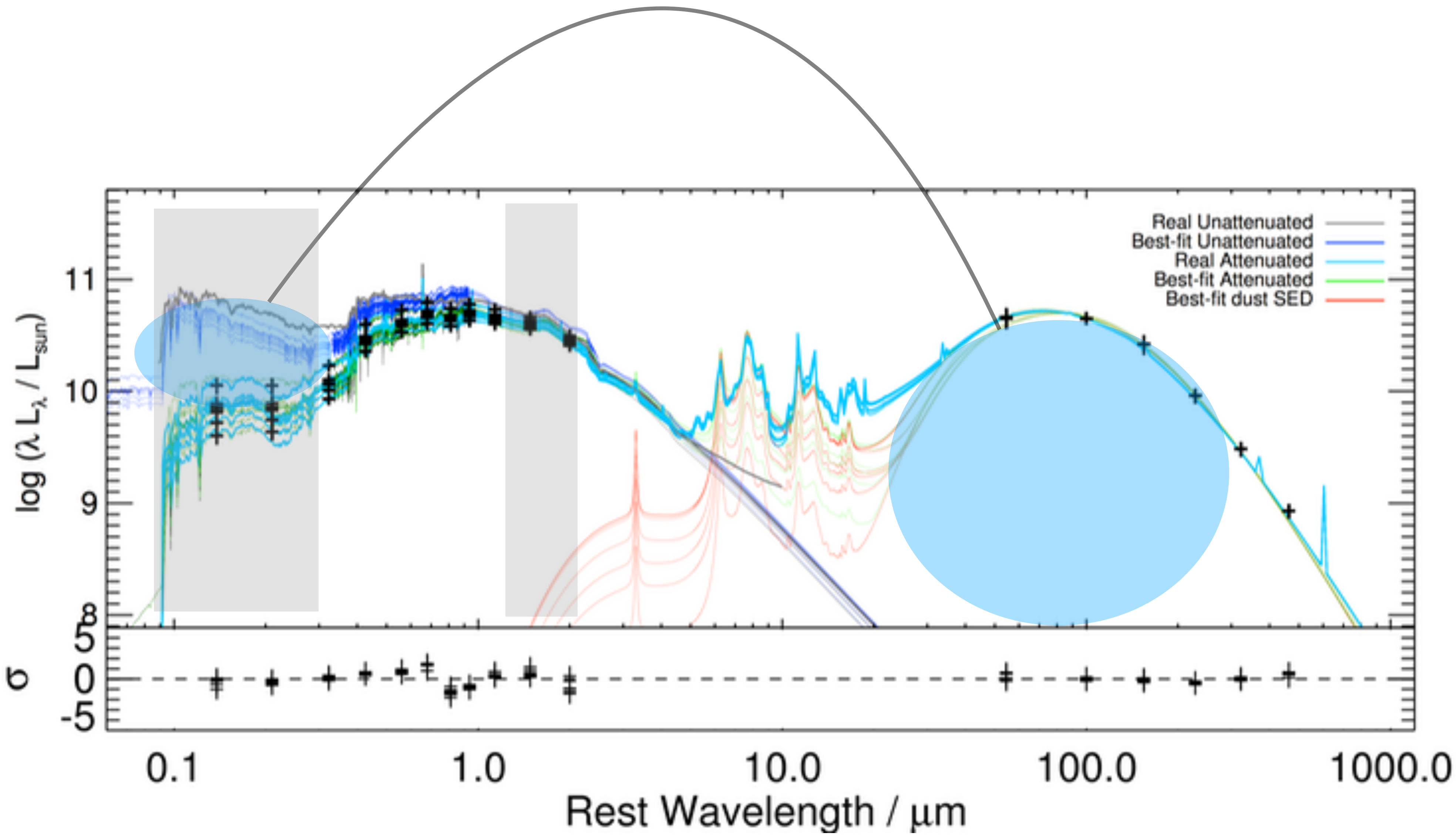


Dust-absorbed UV & optical radiation re-emitted in the IR



Lousy spot for measuring stellar mass - blue & UV wavelengths

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

Some galaxies are "ultraluminous" in the IR (ULIRGs)
Most are not

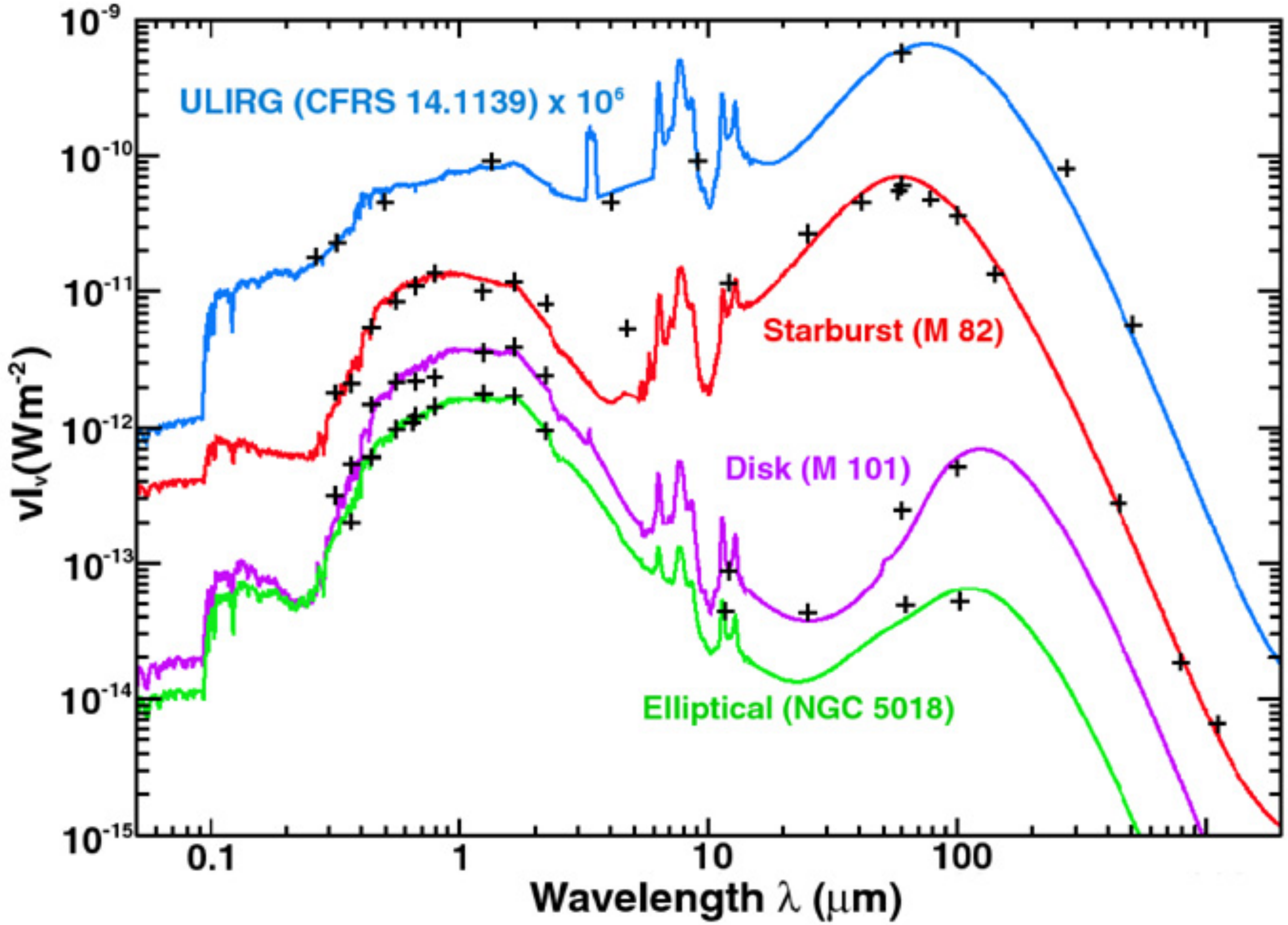


Fig 7.7 (P. Chanial, G. Lagache) 'Galaxies in the Universe' Sparke/Gallagher CUP 2007