Dark Matter

ASTR 333/433
Spring 2024
TR 11:30am-12:45pm
Sears 552

http://astroweb.case.edu/ssm/ASTR333/

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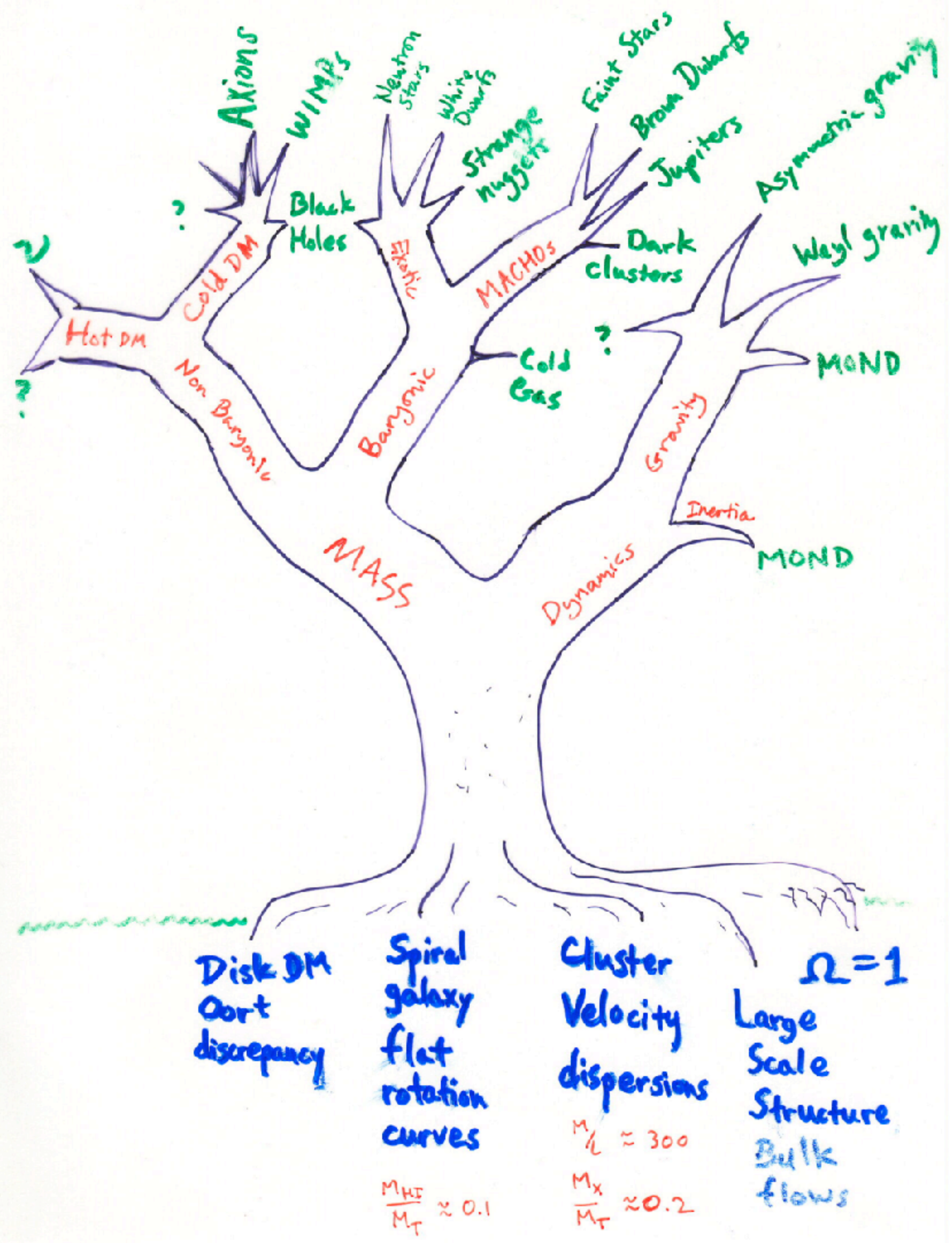

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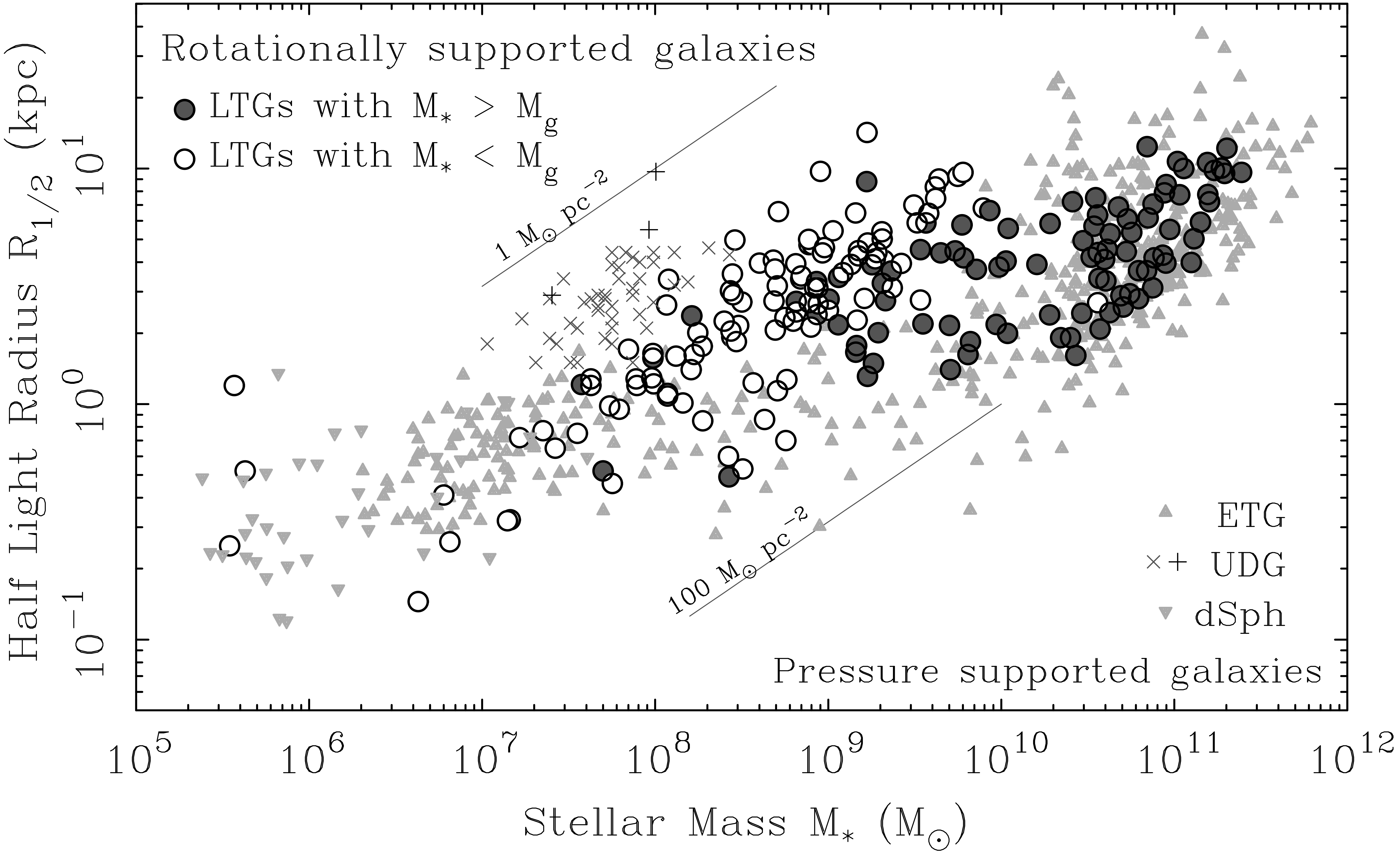
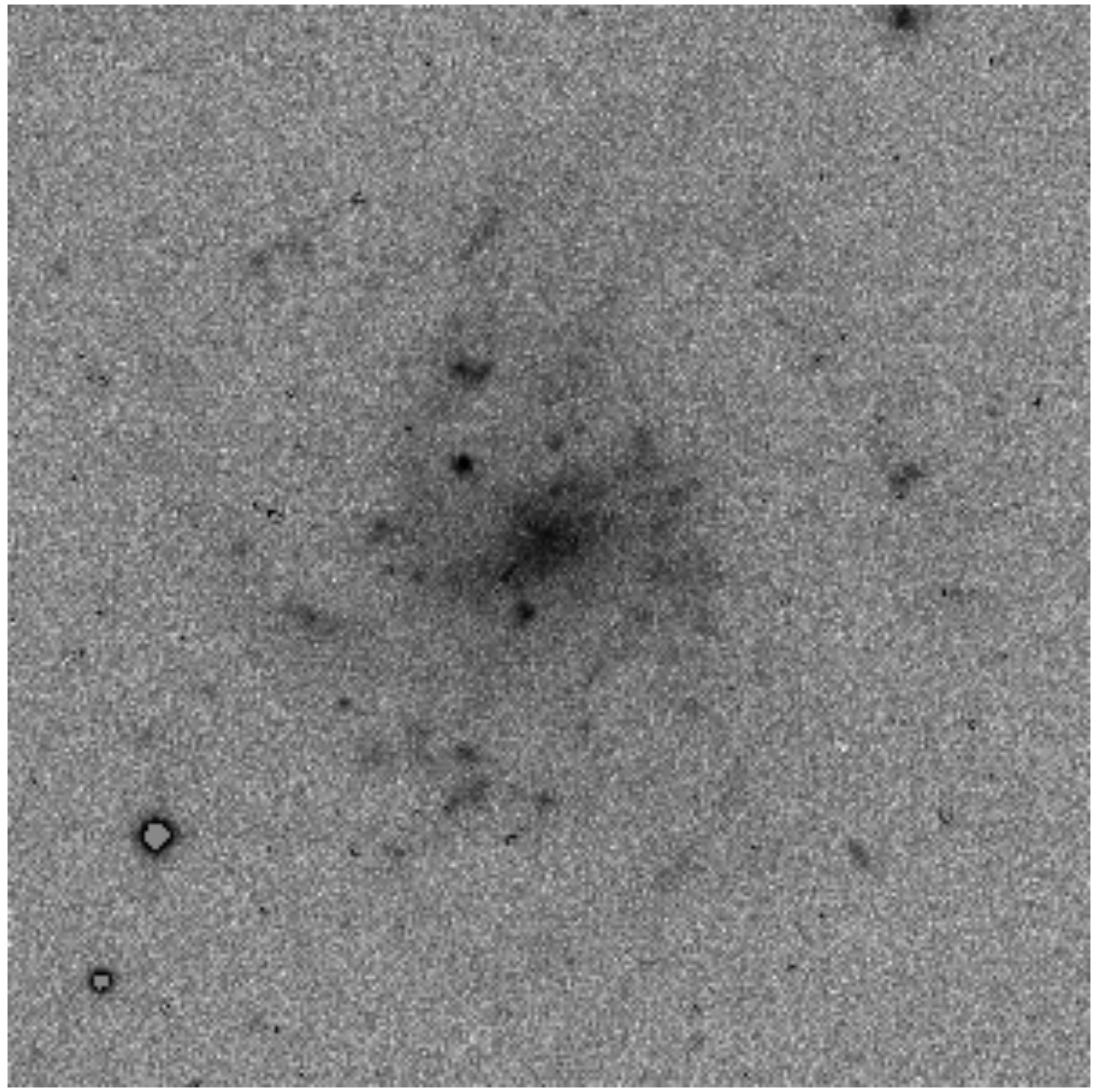
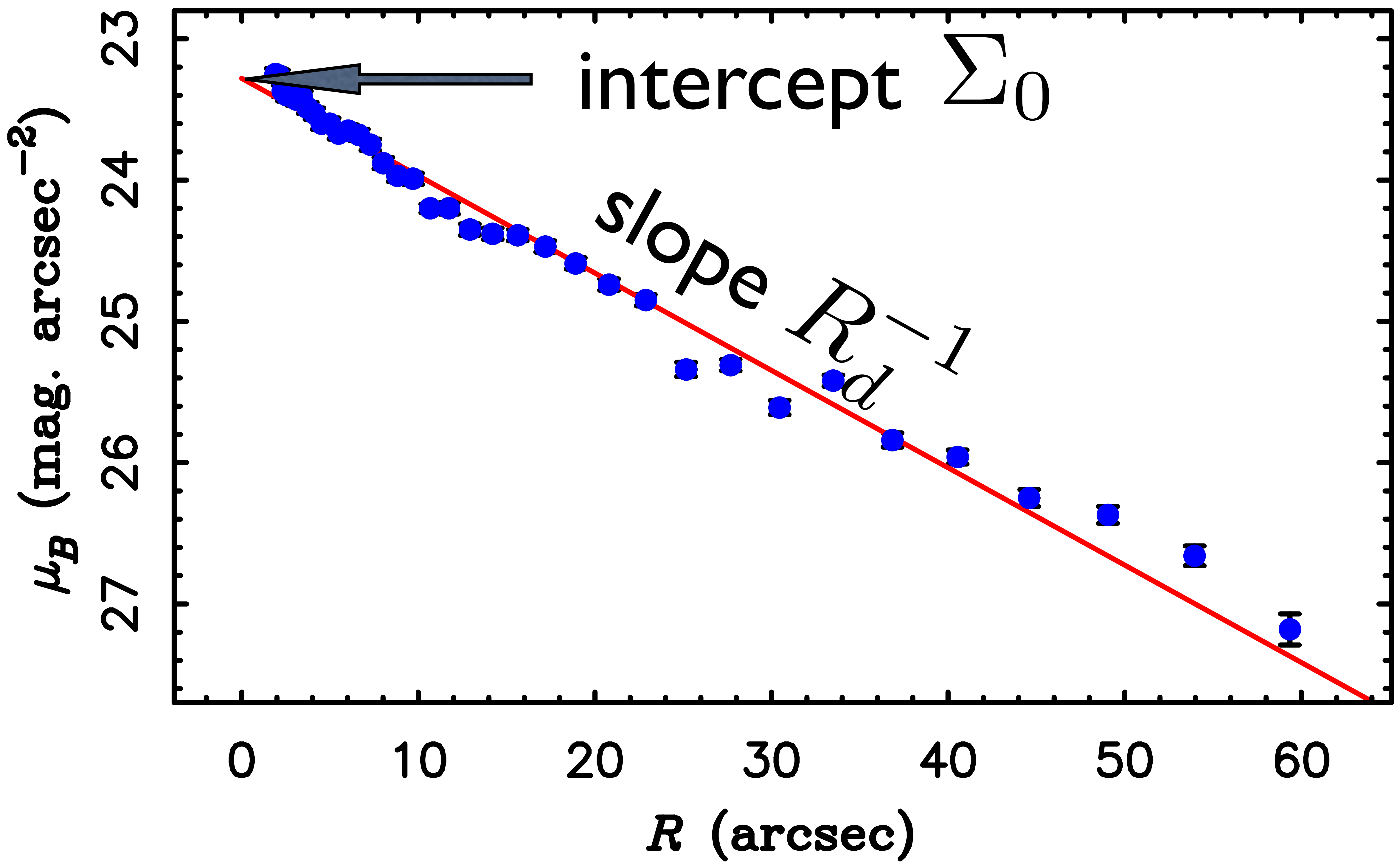
Sizes and masses of galaxies



Late Type Galaxies are typically Exponential disks





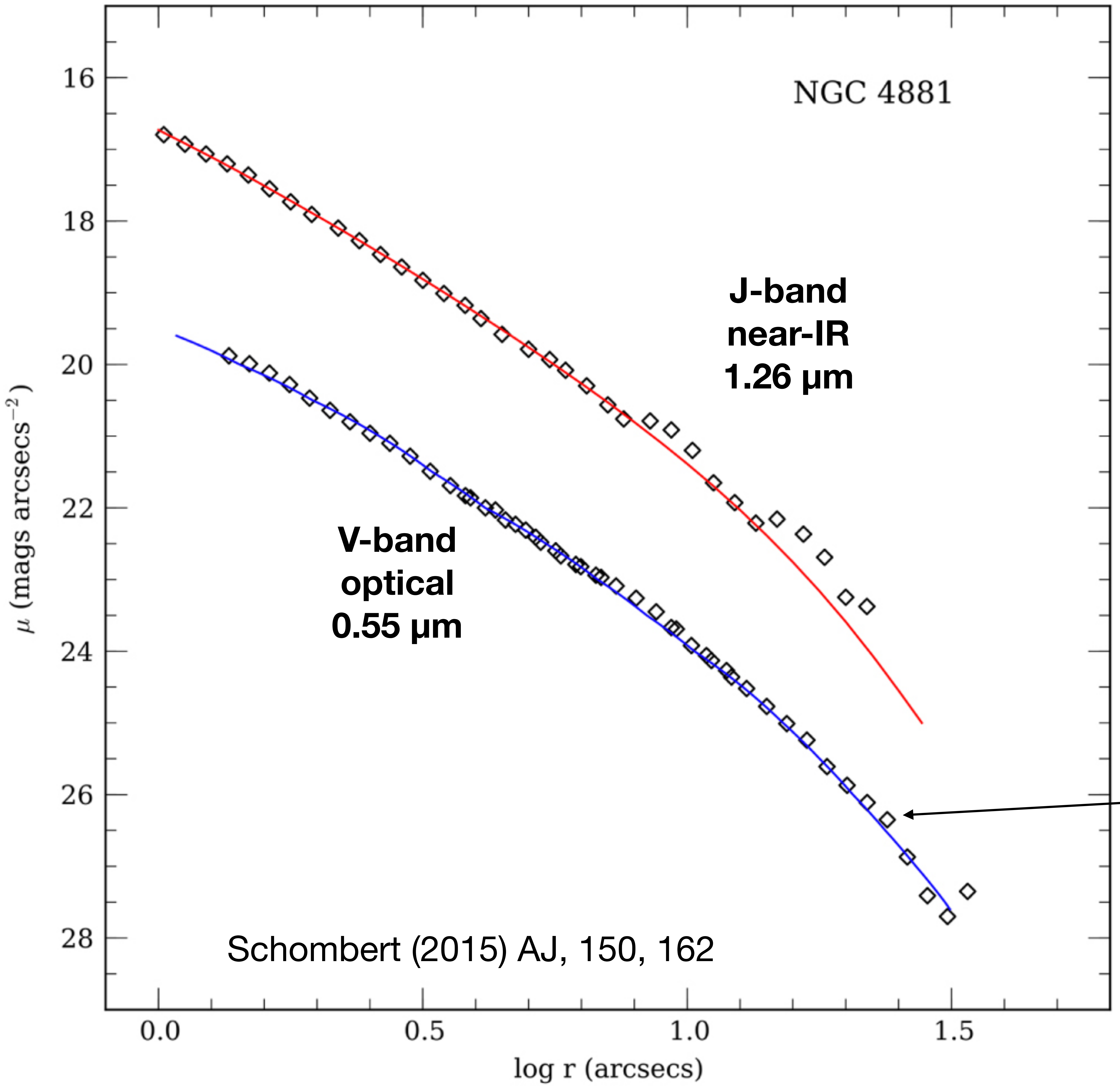
$$\Sigma(R) = \Sigma_0 e^{-R/R_d}$$

Azimuthally averaged light distribution approximately exponential for spiral disks.

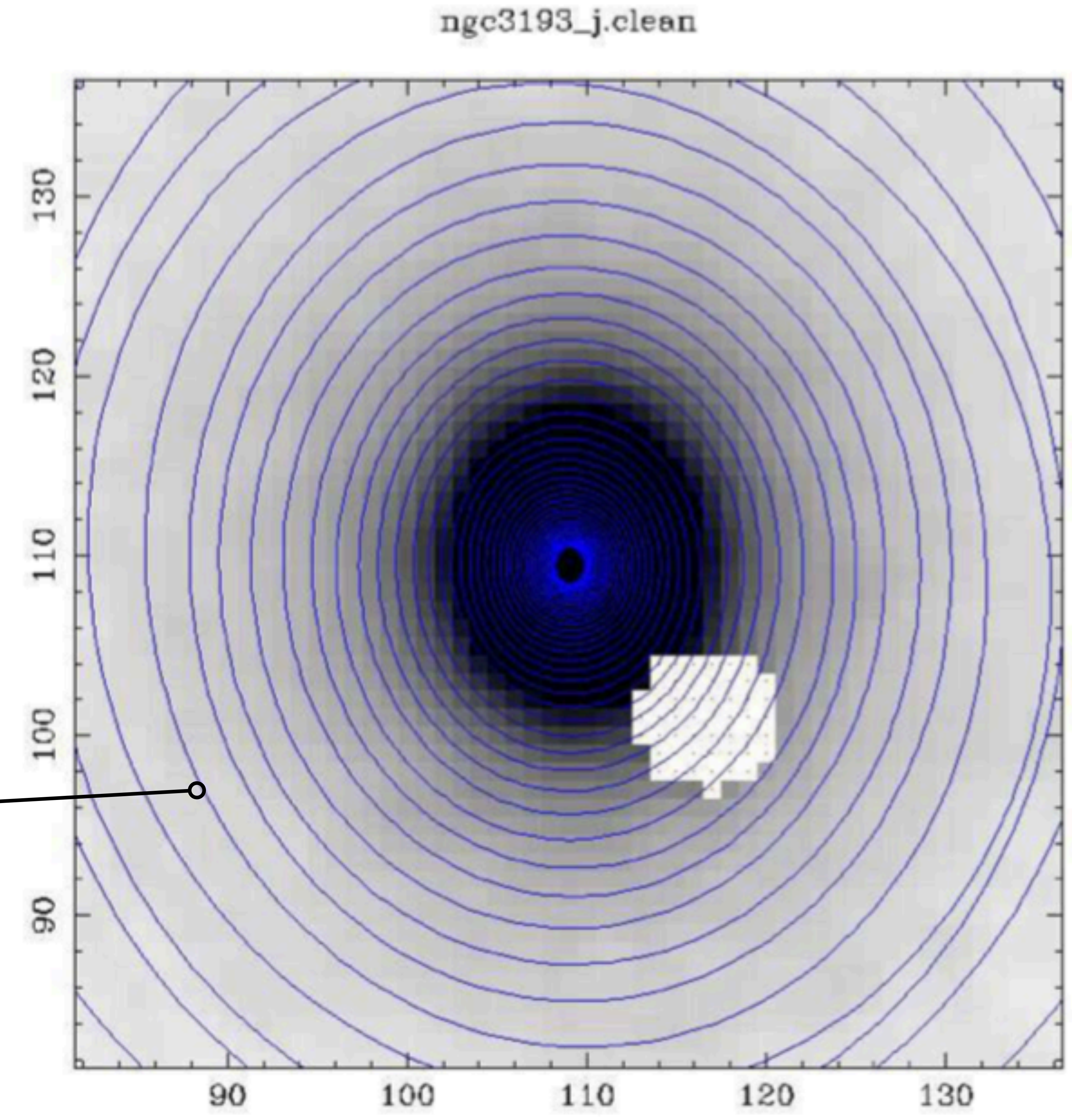
Surface brightness: conversion between linear Σ in $L_\odot$ pc^{-2} and logarithmic μ in magnitudes arcsecond^{-2}: $\mu = 21.57 + M_\odot - 2.5\log\Sigma$ where the absolute magnitude of the sun $M_\odot$ is bandpass-specific. See useful numbers page and astronomical magnitude systems.

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

see Schombert (2015) AJ, 150, 162

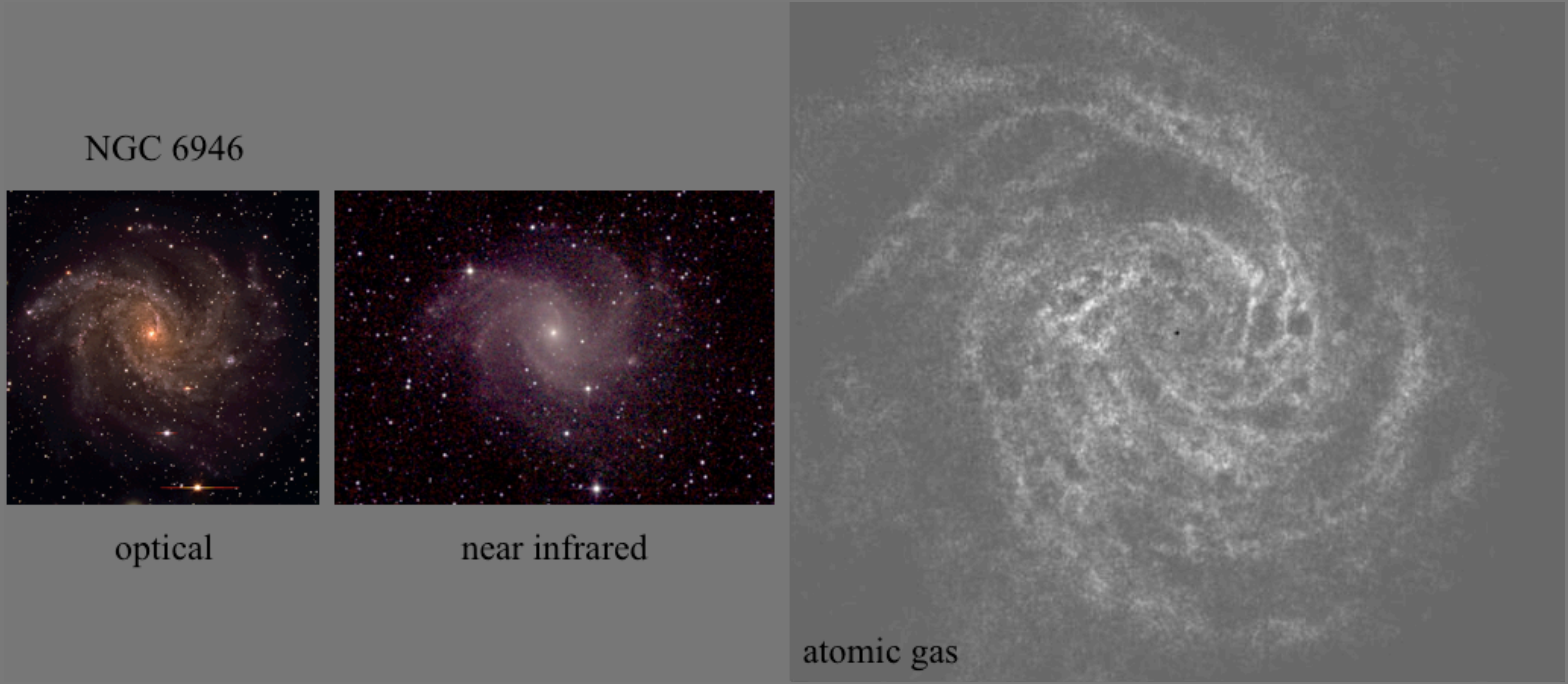


The surface brightness profile is obtained by fitting ellipses to galaxy images, as in this example from Schombert (2007) using ARCHANGEL.

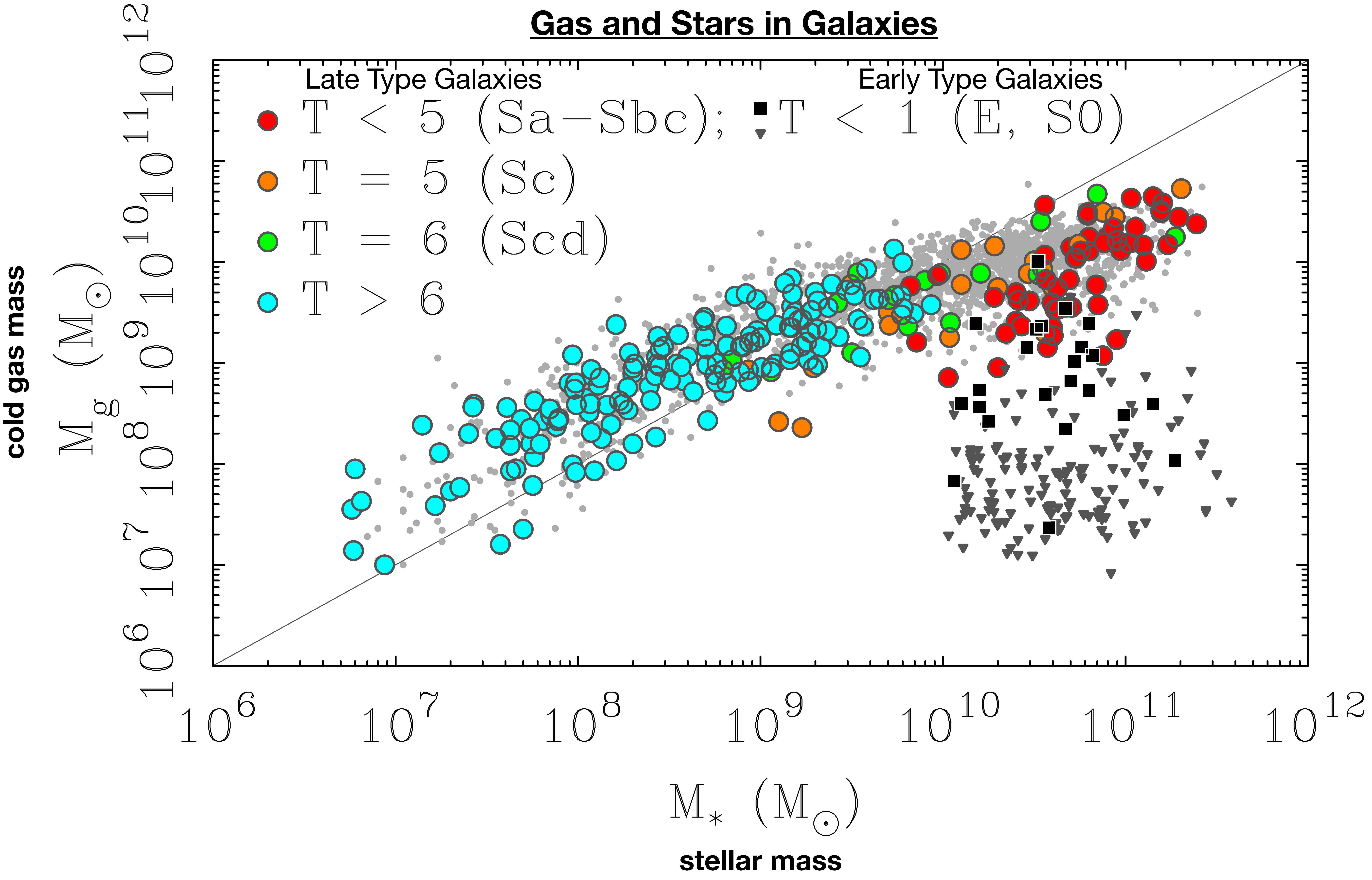


each point corresponds to one ellipse on the image

Galaxies are made of gas as well as stars

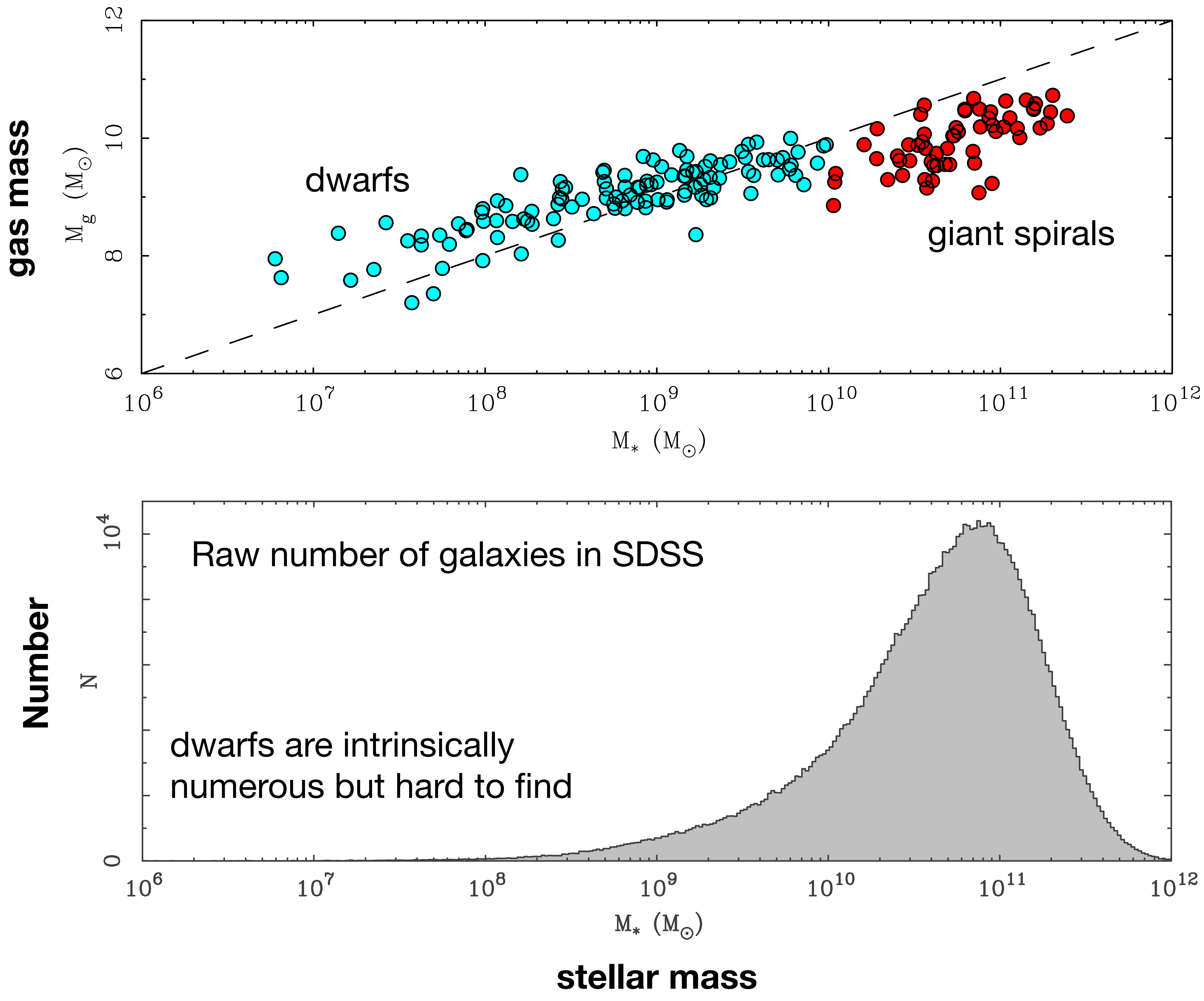


NGC 6946 stars & gas



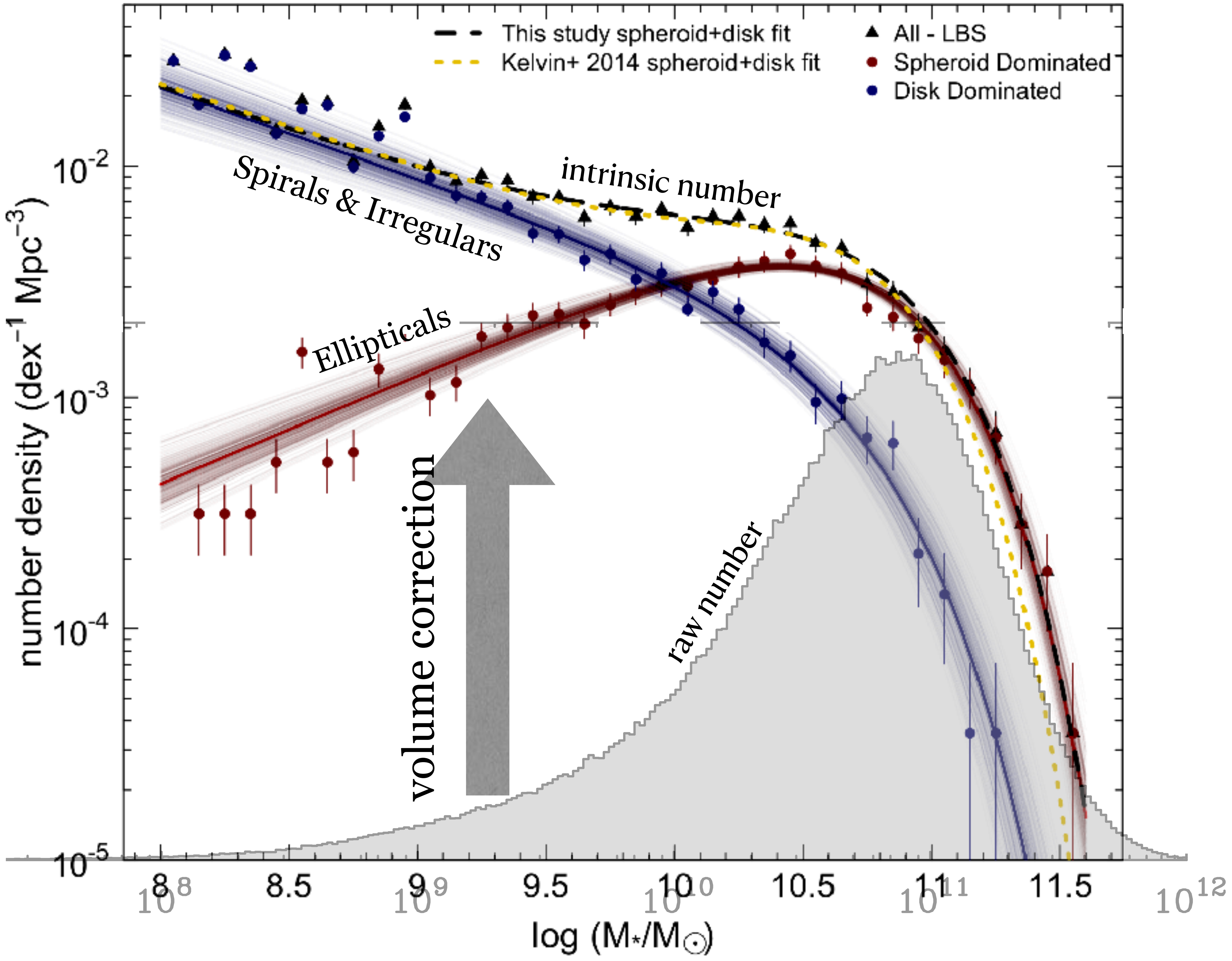
Gas and Stars in Galaxies
Late Type Galaxies
Early Type Galaxies
T < 5 (Sa−Sbc); T < 1 (E, S0)
T = 5 (Sc)
T = 6 (Scd)
T > 6
cold gas mass
M_g $(M_\odot)$
M_* $(M_\odot)$
stellar mass
10^6
10^7
10^8
10^9
10^{10}
10^{11}
10^{12}

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

ISM

The stuff between the stars

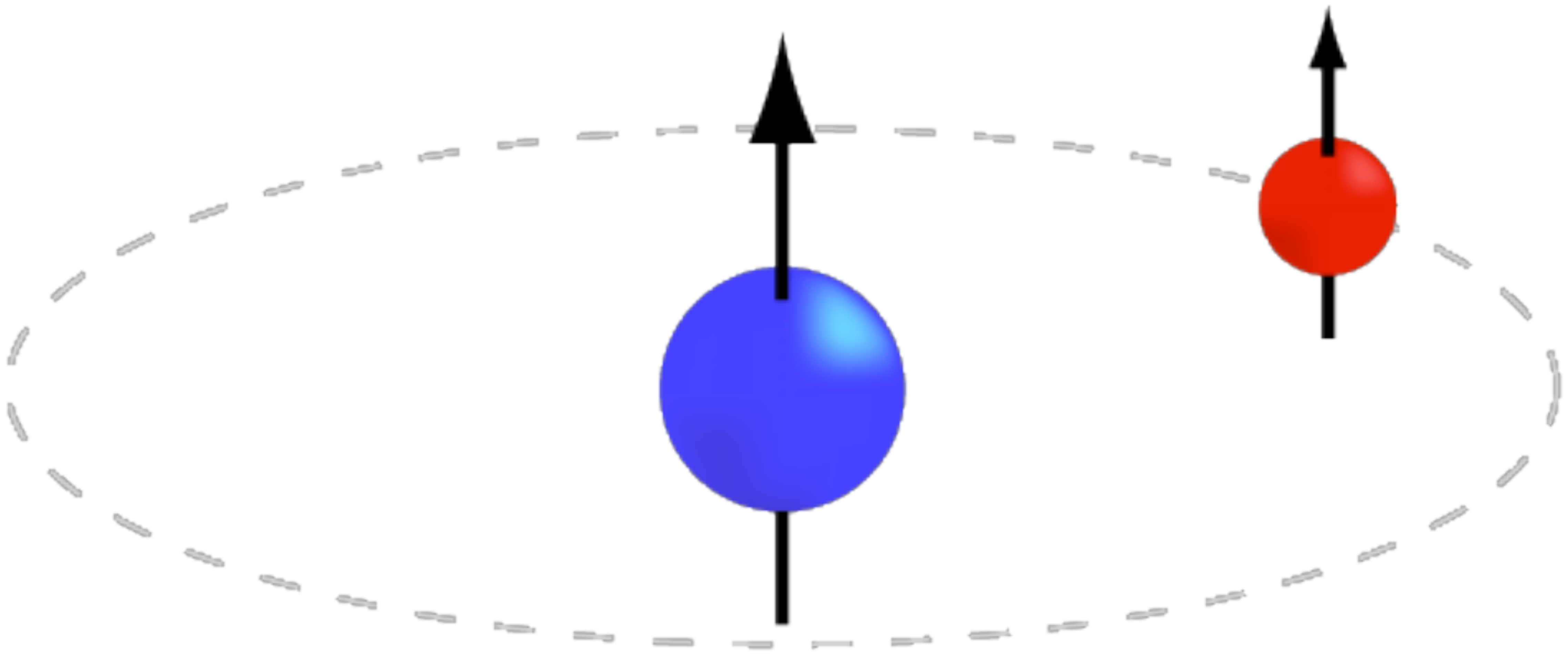
Atomic gas (H I)
Molecular gas (H_2)
Ionized gas (H II)
Dust

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



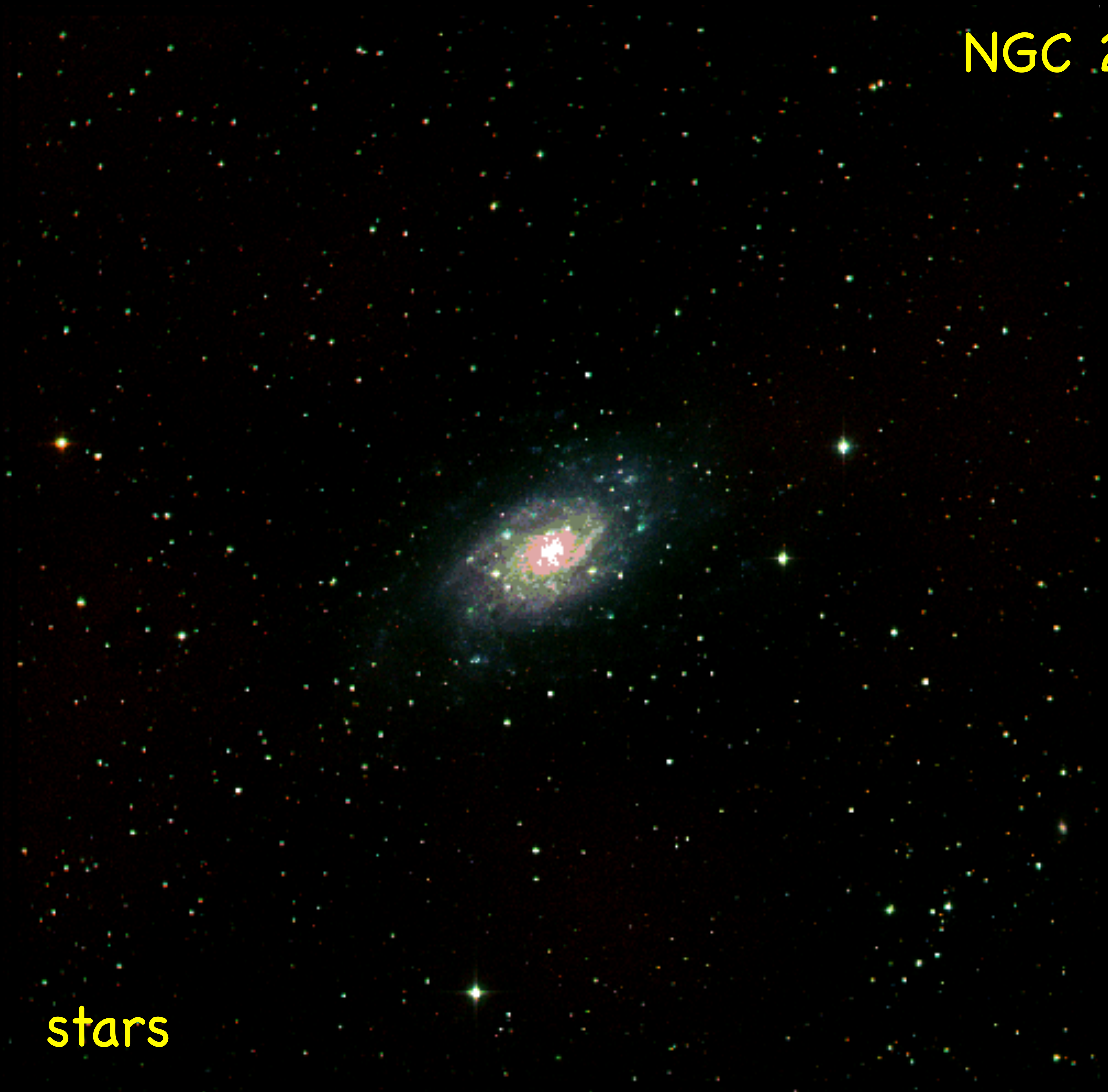
21 cm emission from hyperfine transition: parallel to anti-parallel spins

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

The 21 cm line is in the radio at 1420 MHz

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

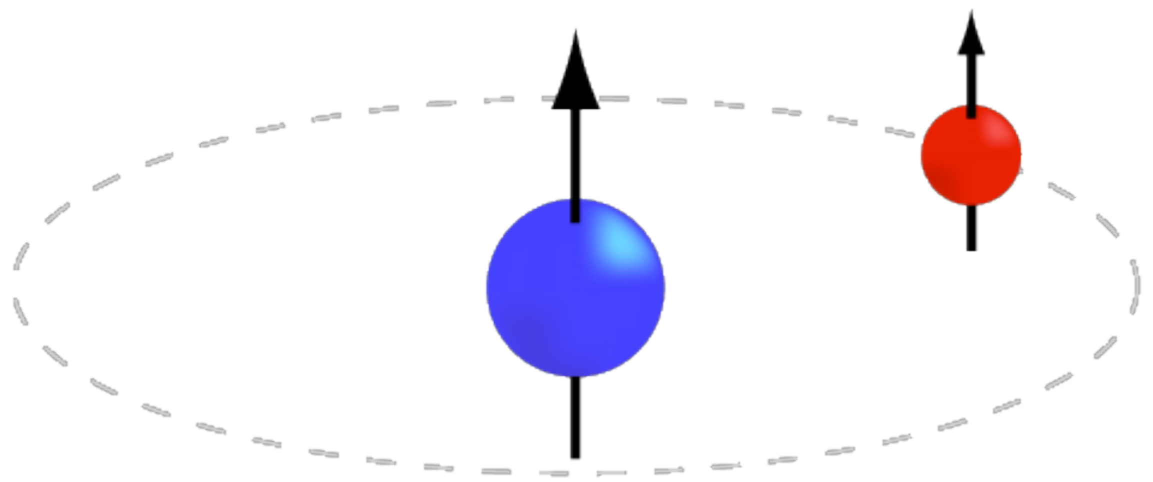
NGC 2403



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

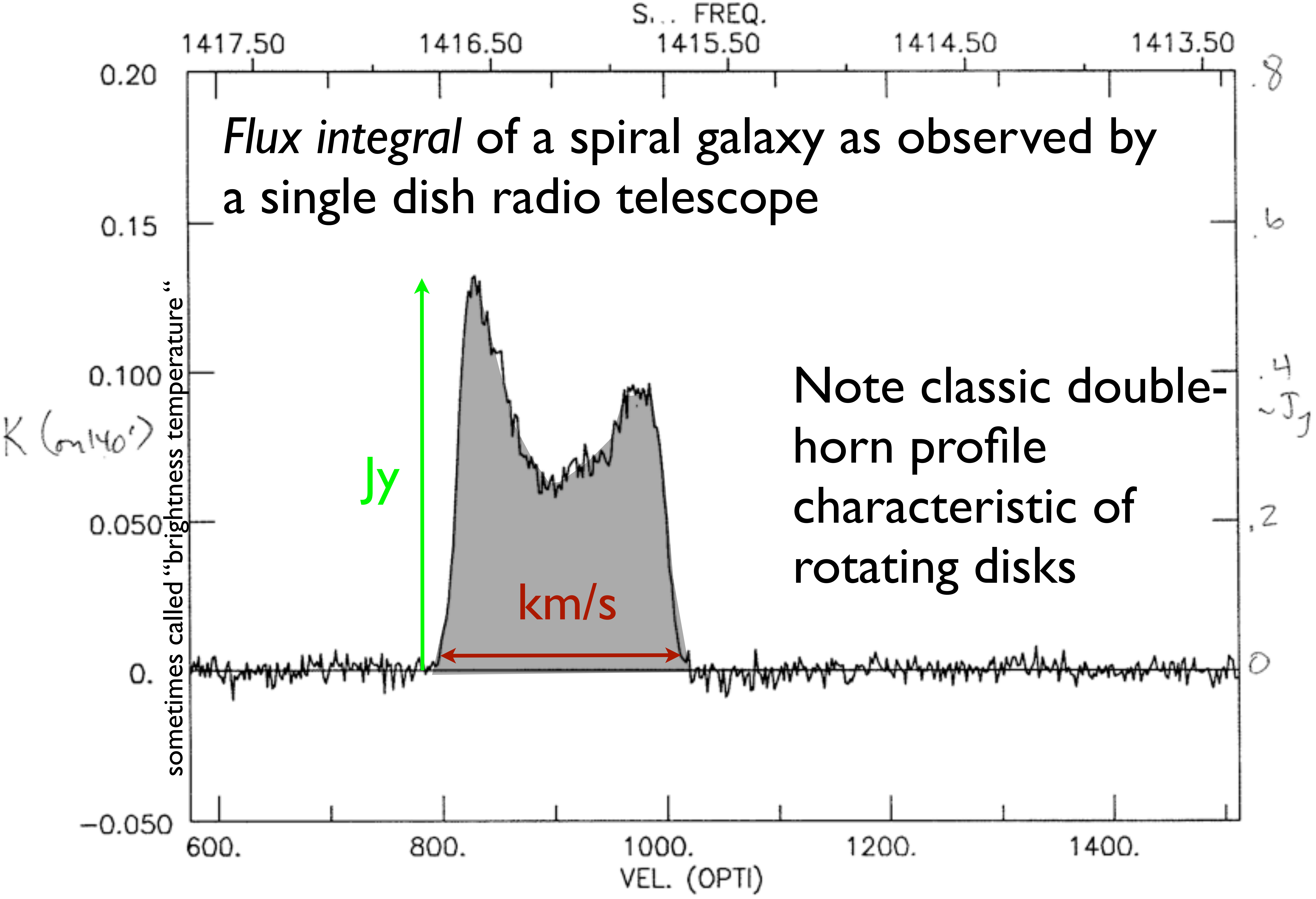
Counting 21 cm photons is equivalent to counting hydrogen atoms - a direct relation to mass!

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

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



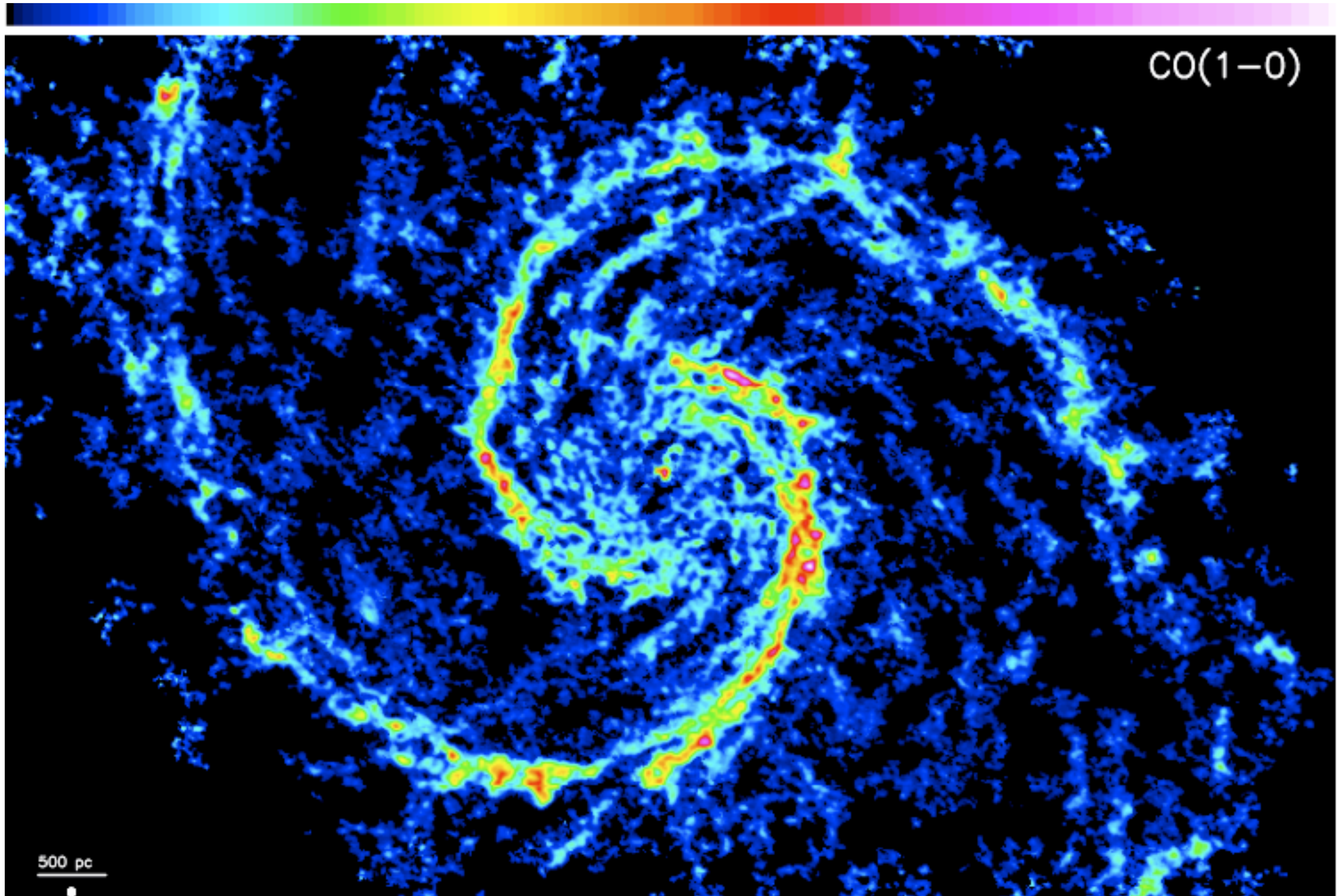
Note classic double-horn profile characteristic of rotating disks

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.

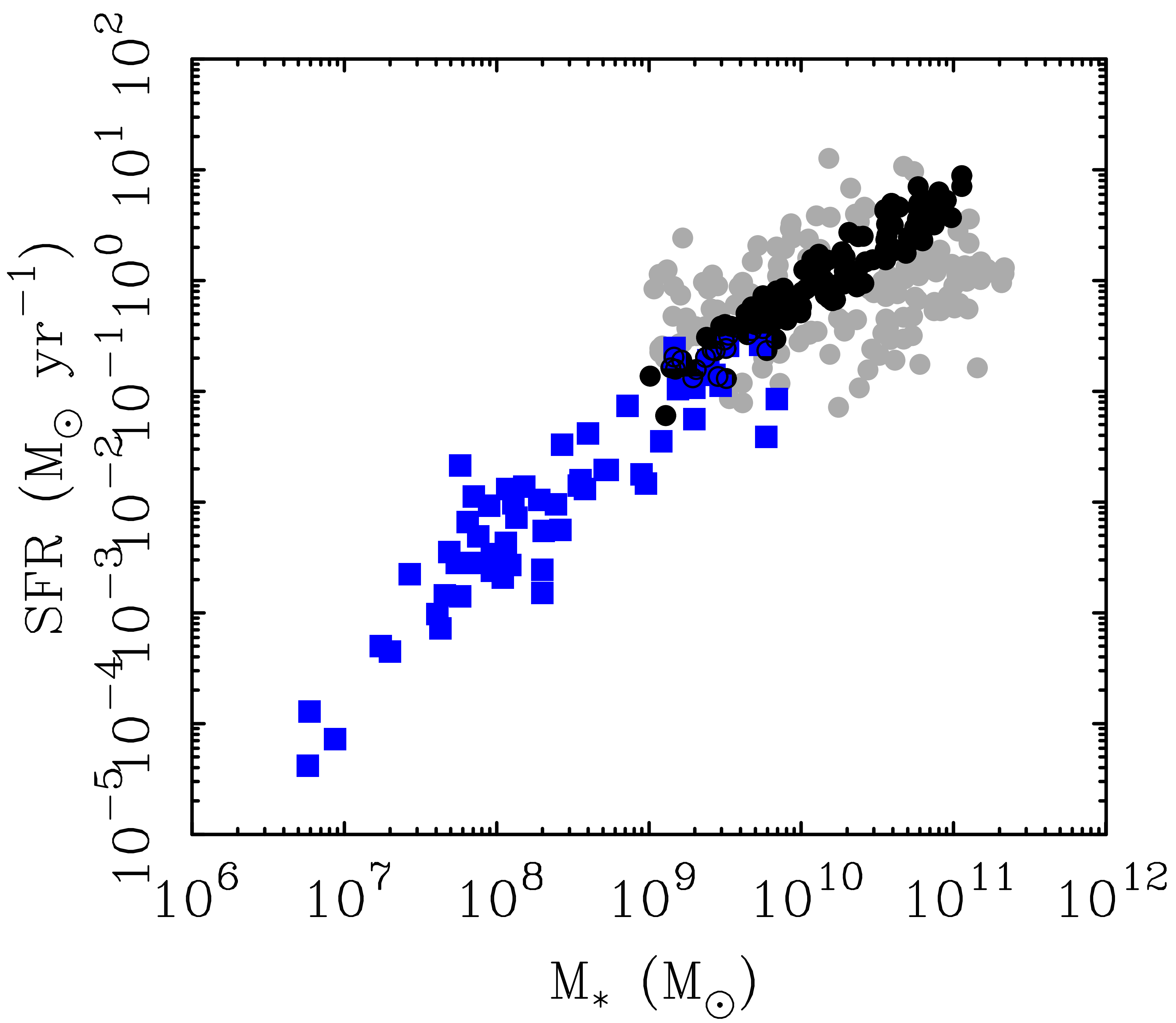
Polar molecules (esp. CO) have a permanent dipole moment thanks to asymmetry so have a rich rotational spectrum (typically in the mm or cm wavelengths).

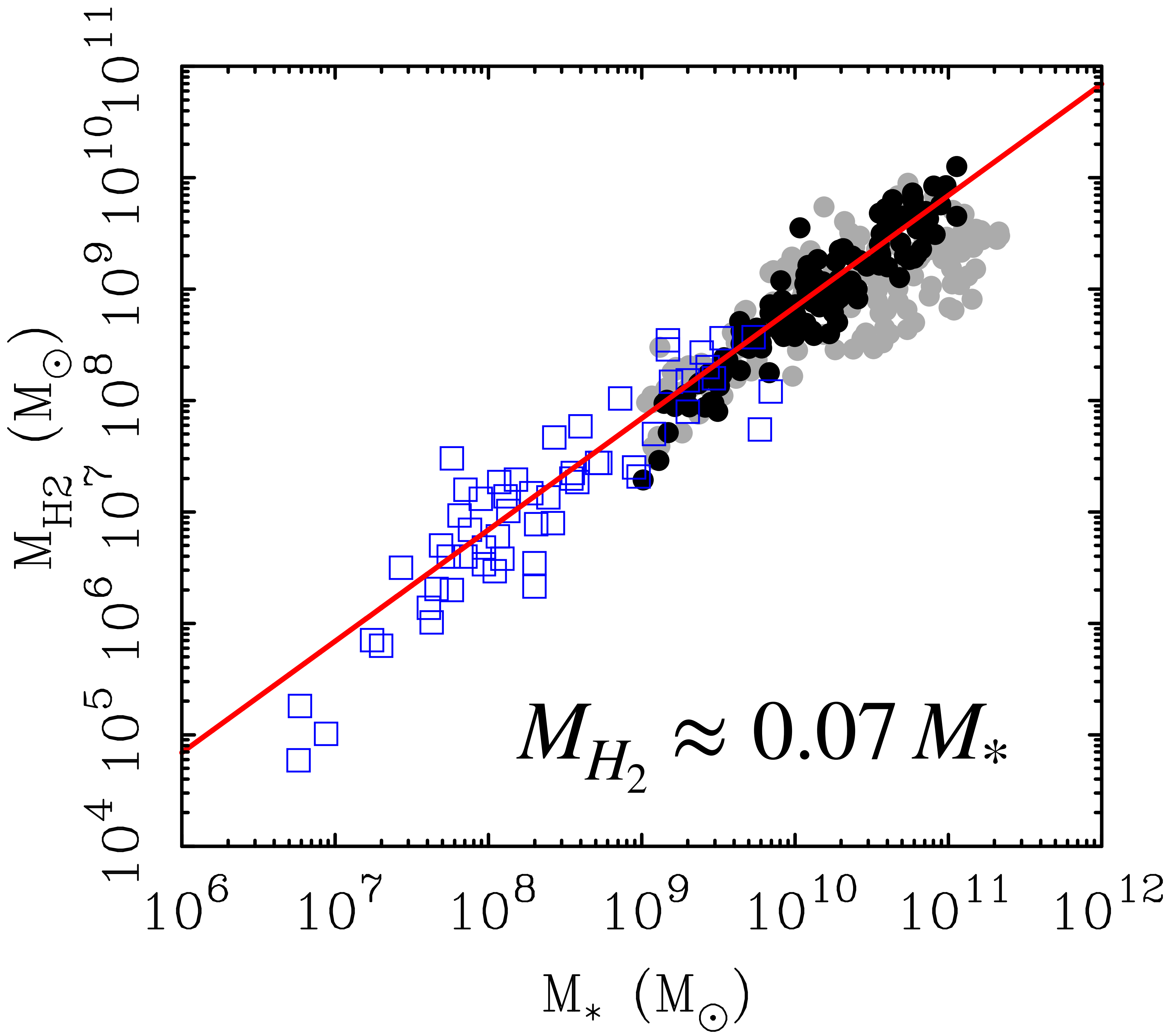
$$M_{H_2} = 1.1 \times 10^4 D^2 F_{CO}$$

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.

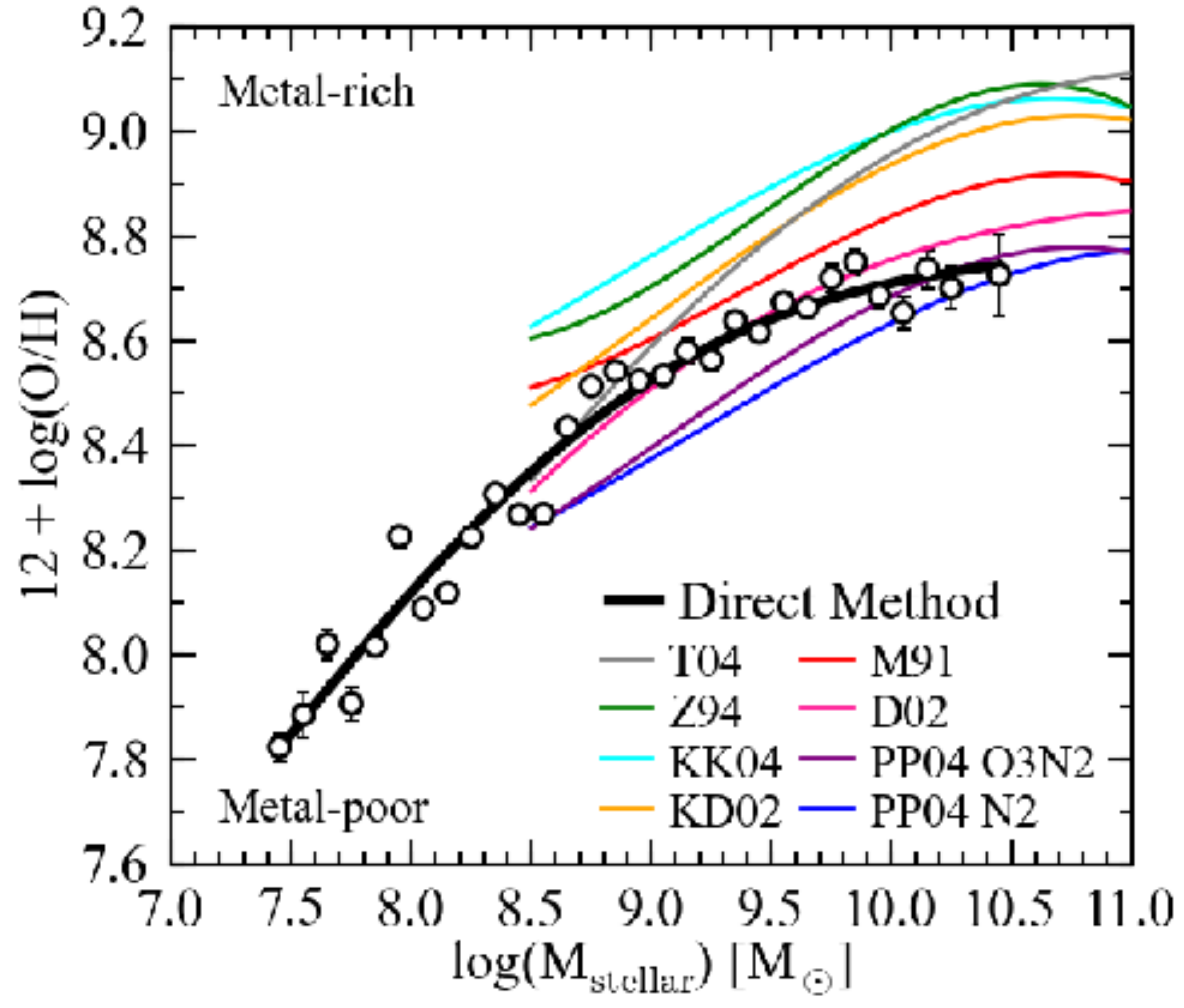
X = hydrogen fraction (primordial fraction 3/4)
Y = helium fraction (primordial fraction 1/4)
Z = everything else

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 $M_0 = 1.5 \times 10^{24}\ \mathrm{M}_\odot$

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

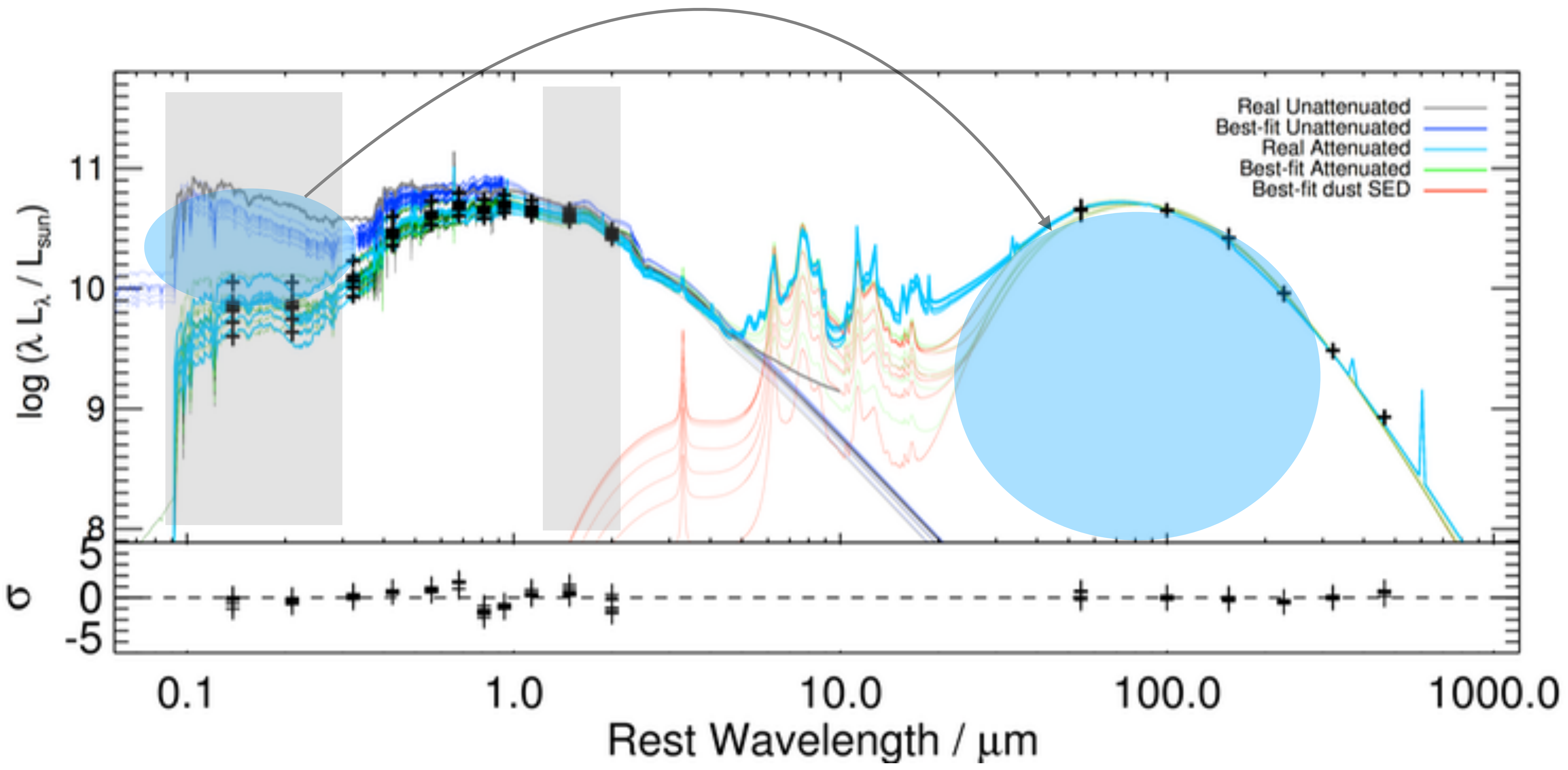


For a low mass dwarf galaxy, $X^{-1} = 1.34$, while for a Milky Way mass galaxy, $X^{-1} = 1.41$.

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

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

Stellar populations

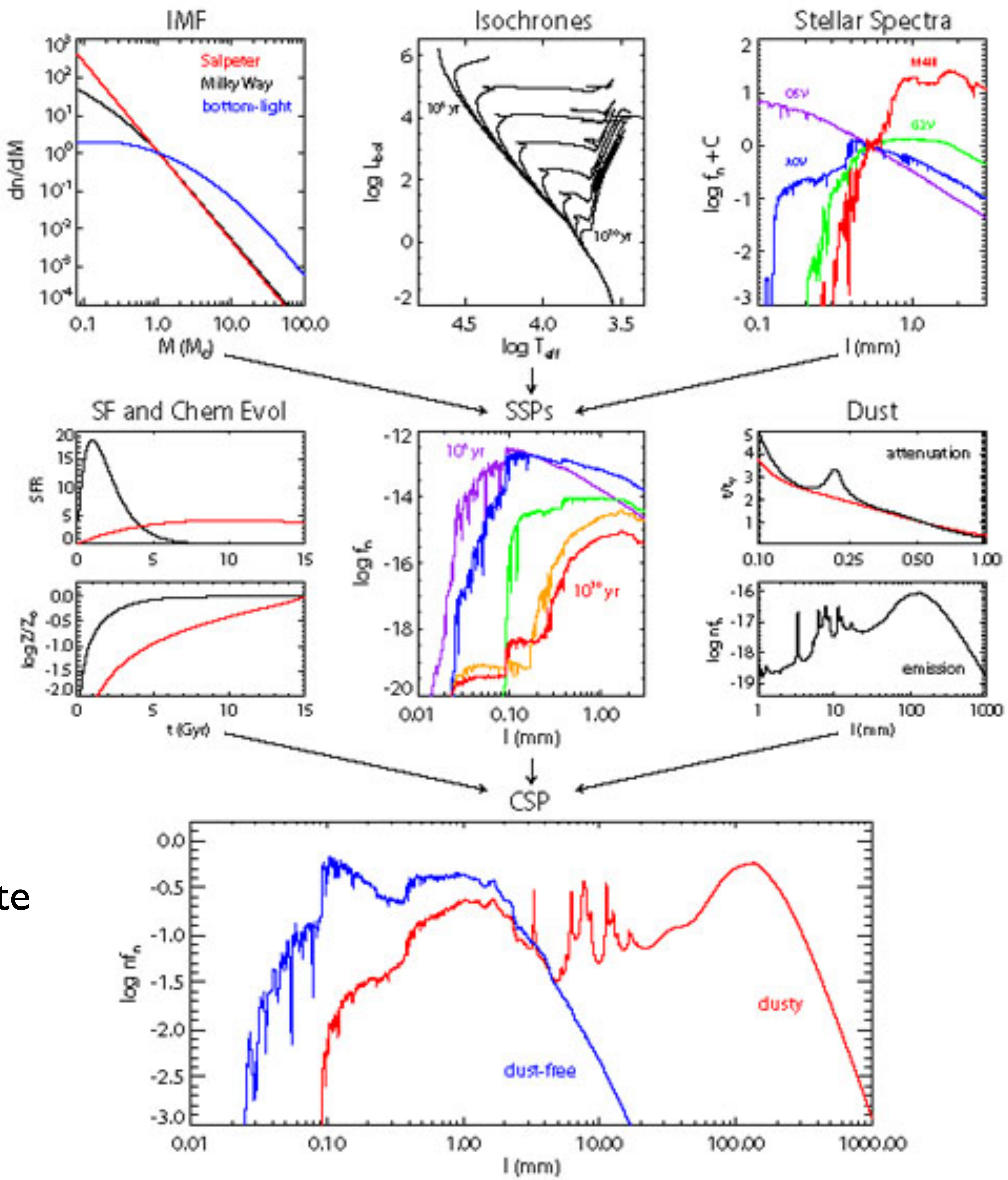
open cluster

- Simple Single Population (SSP)
  - – stars of all masses born at the same time
  - – e.g., a star cluster

- Complex stellar population
  - – Convolution of many star forming events
  - – need to know
    - IMF (initial mass function)
    - Birthrate (star formation rate history)

globular cluster

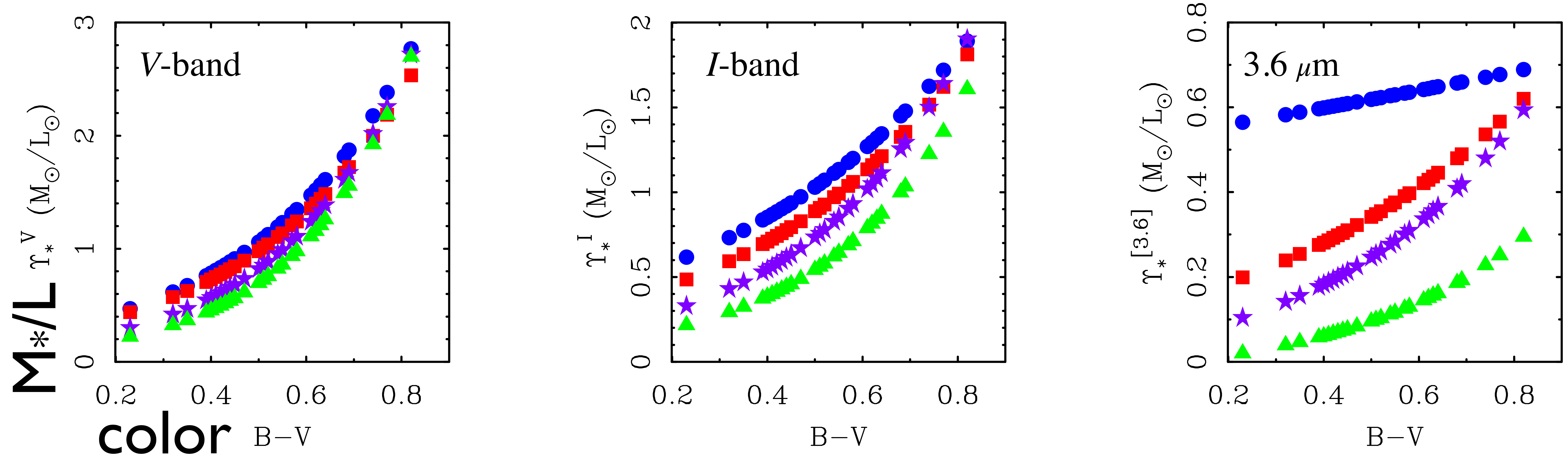
Stellar population synthesis modeling:



Stellar population synthesis modeling is on way to estimate the stellar mass-to-light ratio.

Stellar population models

Typically, redder colors mean higher mass-to-light ratios



Color-M/L relation: $$\log \Upsilon_*^i = a_i + b_i (B - V)$$

Can use multiple colors, but most of the information is in the first one.

Table 5
Self-Consistent Population Synthesis Mass-to-Light Ratios

Model	a_V	b_V	α_I	β_I	$\alpha_{[3.6]}$	$\beta_{[3.6]}$	$\Upsilon_{0.6}^V$	$\Upsilon_{0.6}^I$	$\Upsilon_{0.6}^{[3.6]}$
Bell et al. (2003)	−0.628	1.305	−0.259	0.565	−0.313	−0.043	1.43	1.20	0.46
Portinari et al. (2004)	−0.654	1.290	−0.302	0.644	−0.575	0.394	1.32	1.22	0.46
Zibetti et al. (2009)	−1.075	1.837	−0.446	0.915	−1.115	1.172	1.07	1.27	0.39
Into & Portinari (2013)	−0.900	1.627	−0.394	0.820	−0.841	0.771	1.19	1.25	0.42

Baryonic Mass of Galaxies

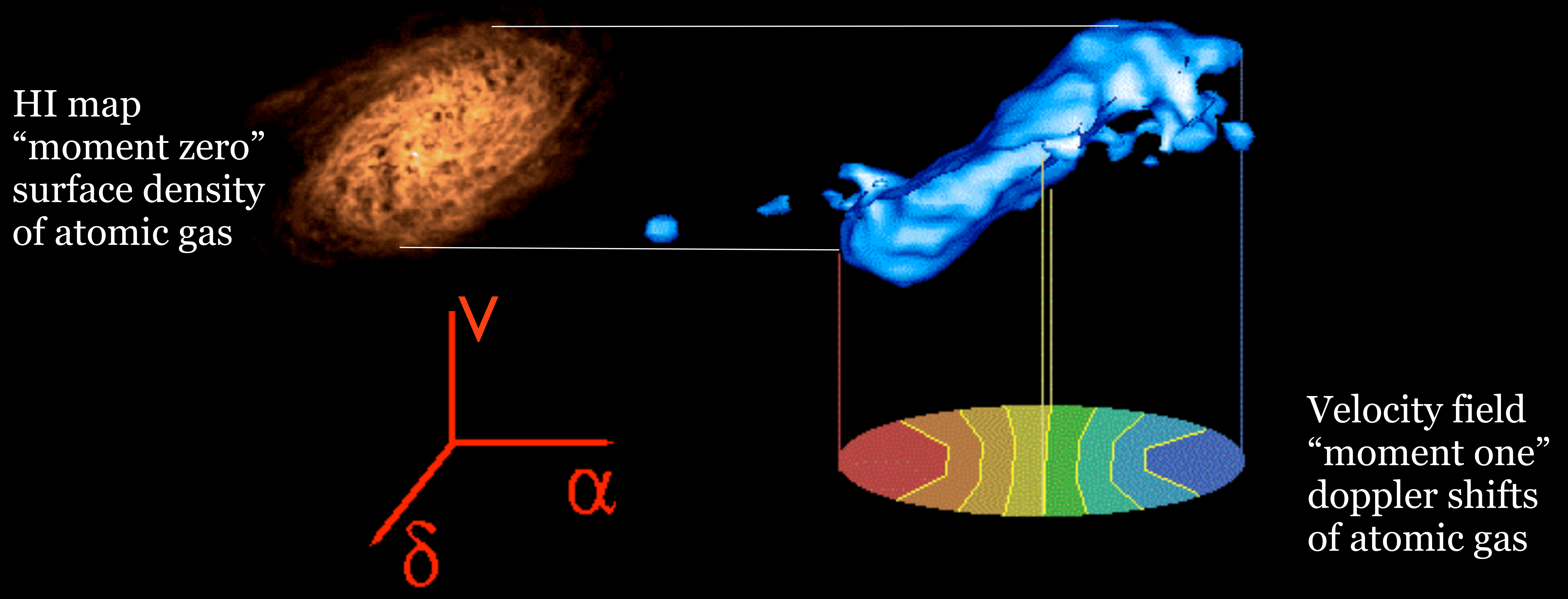
$$M_b = M_* + M_g = \Upsilon_* L + X^{-1} \left(M_{HI} + M_{H_2} \right)$$

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

- **Stars** $M_* = \Upsilon_*^i L_i$ $L_i = 4\pi D^2 F_i$
  - 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
    - $M_{H_2} = 1.1 \times 10^4 D^2 F_{CO}$

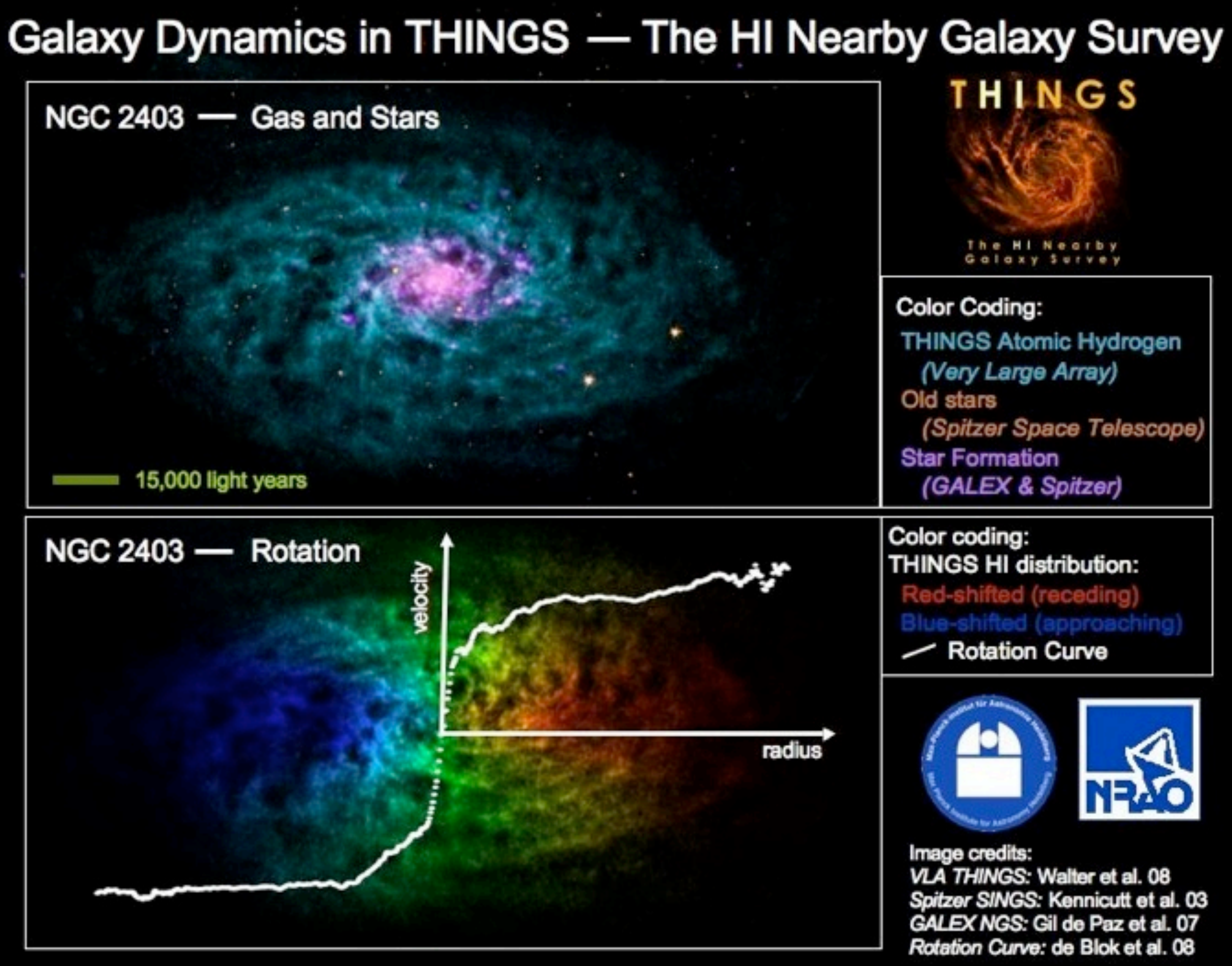
also scales with stellar mass $M_{H_2} \approx 0.07 M_*$

Multi-dish radio synthesis telescope arrays give brightness temperature (HI surface density) & velocity

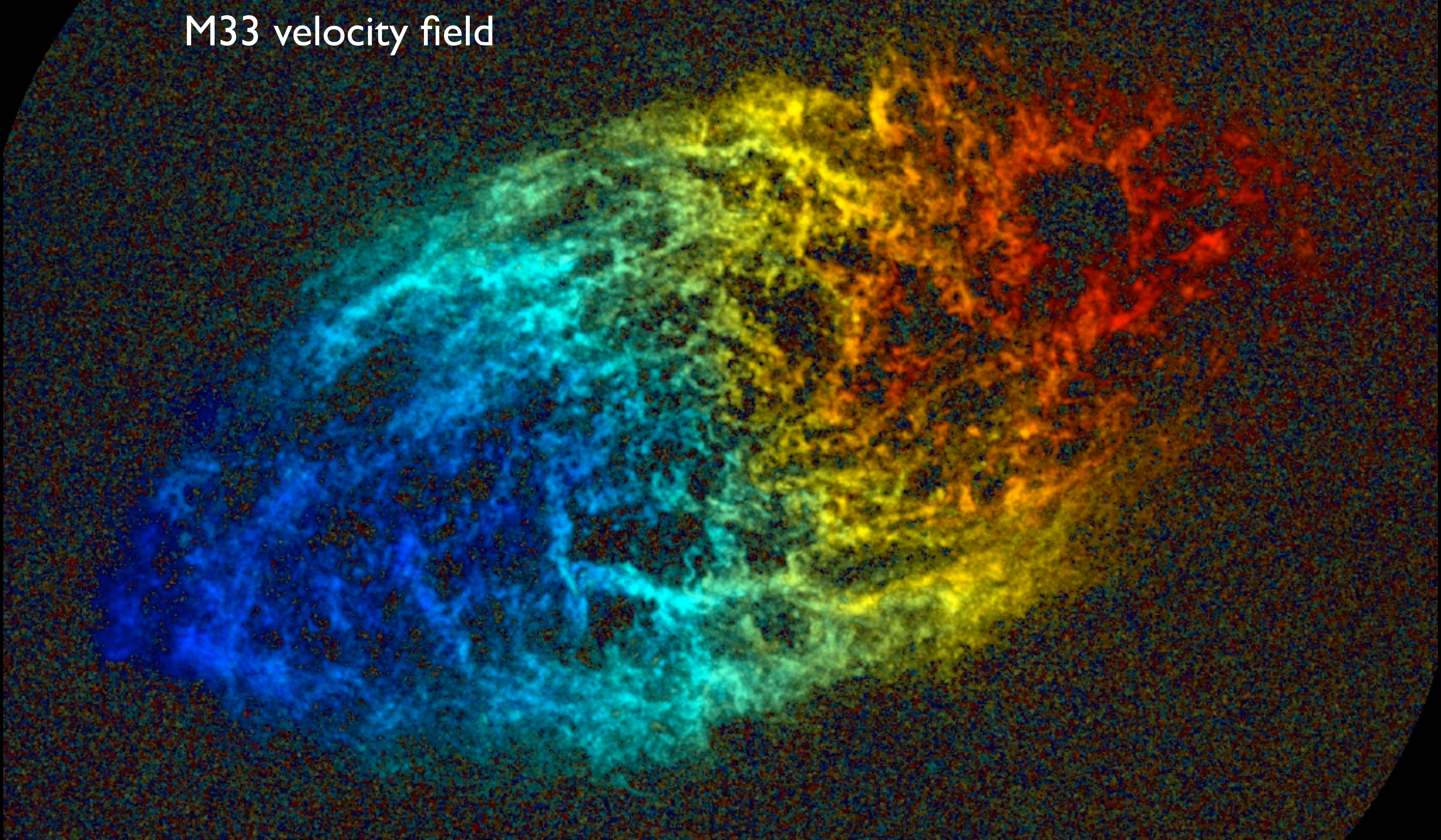


from 3D data cube of 21 cm position and redshift

Multi-dish radio telescope arrays give surface density and velocity



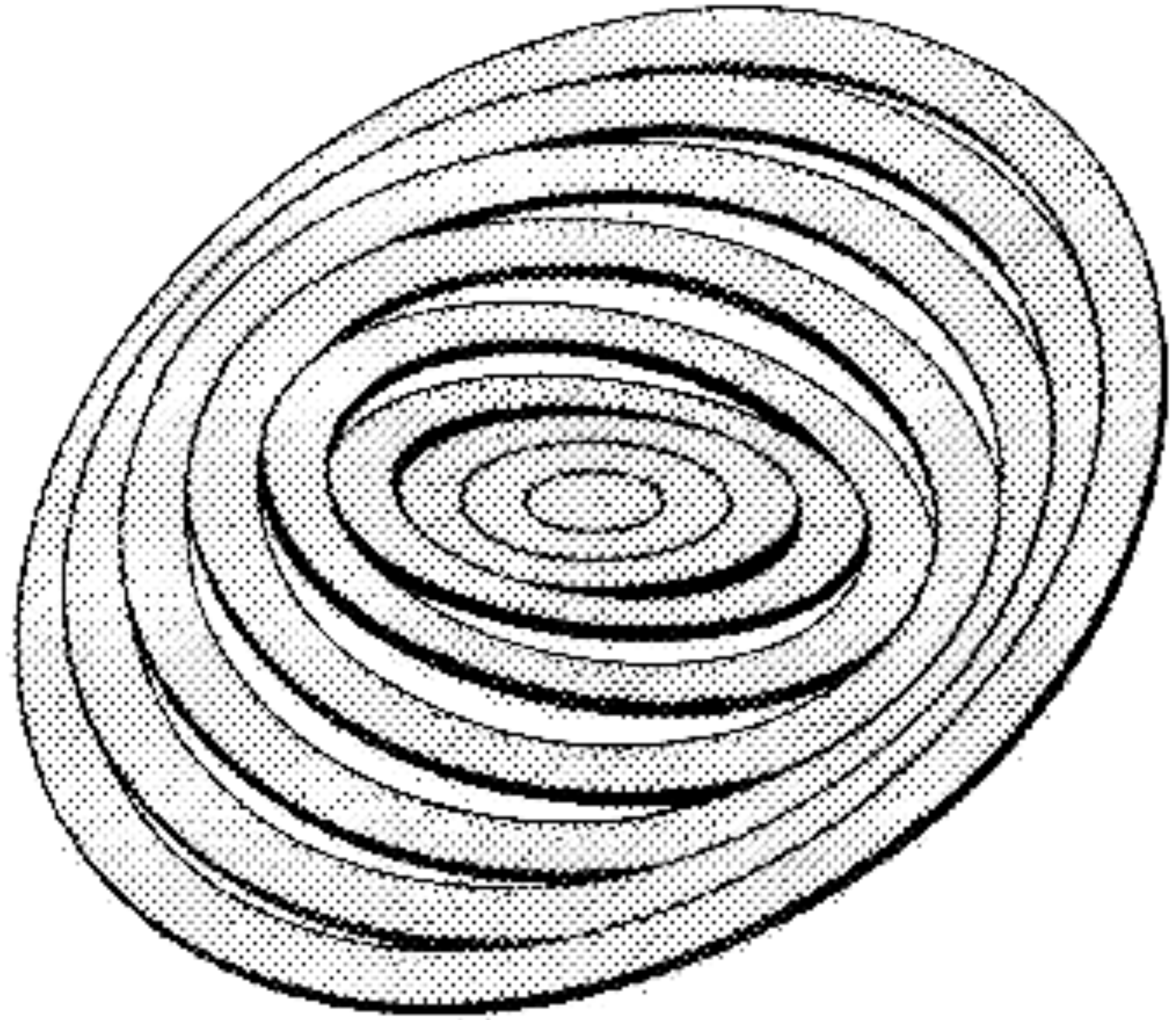
M33 velocity field

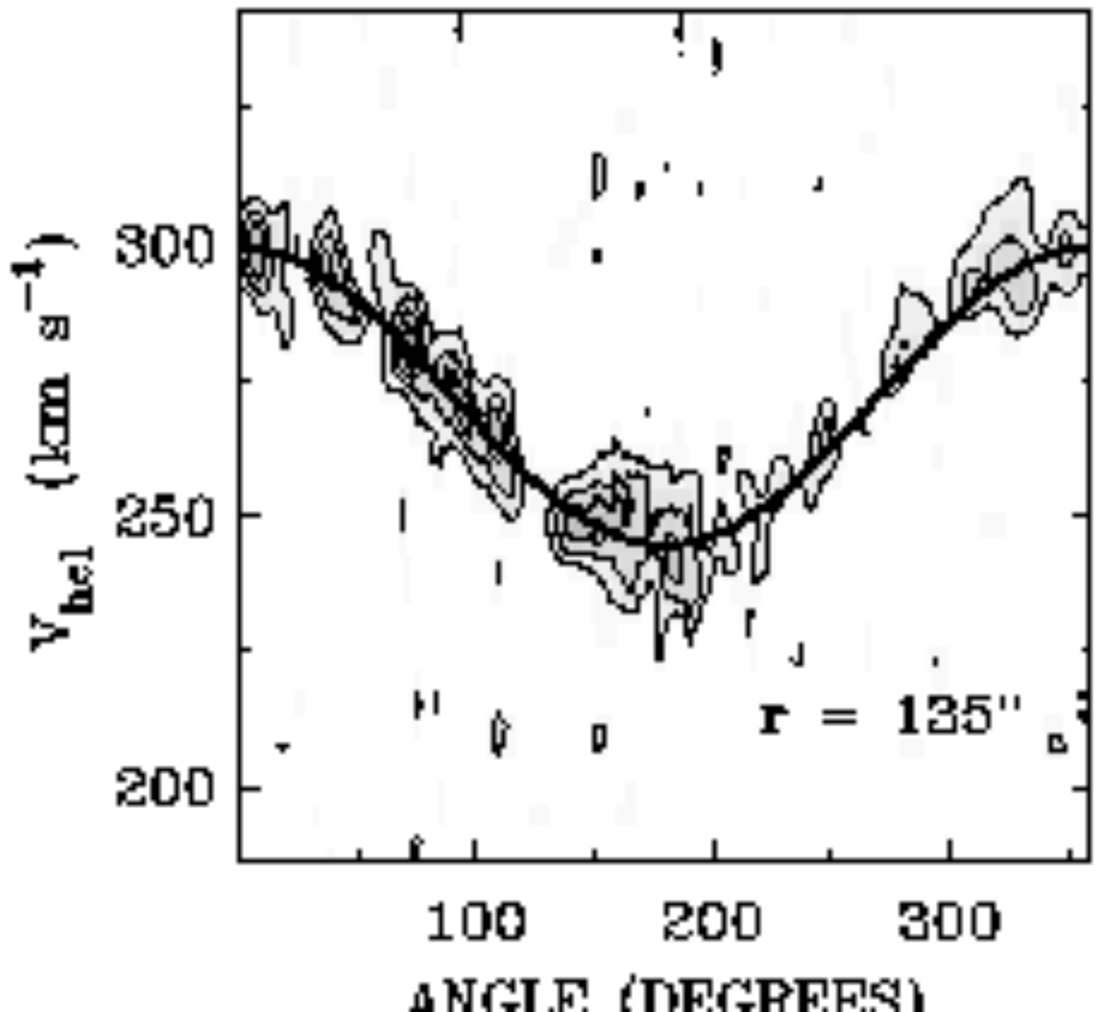


Rotation curves extracted using "tilted ring" fits

Fit ellipses that most closely match the circular velocity at a given radius. In principle, get ellipse center, position angle, axis ratio, inclination, and rotation velocity. In practice, usually have to fix some of these parameters.

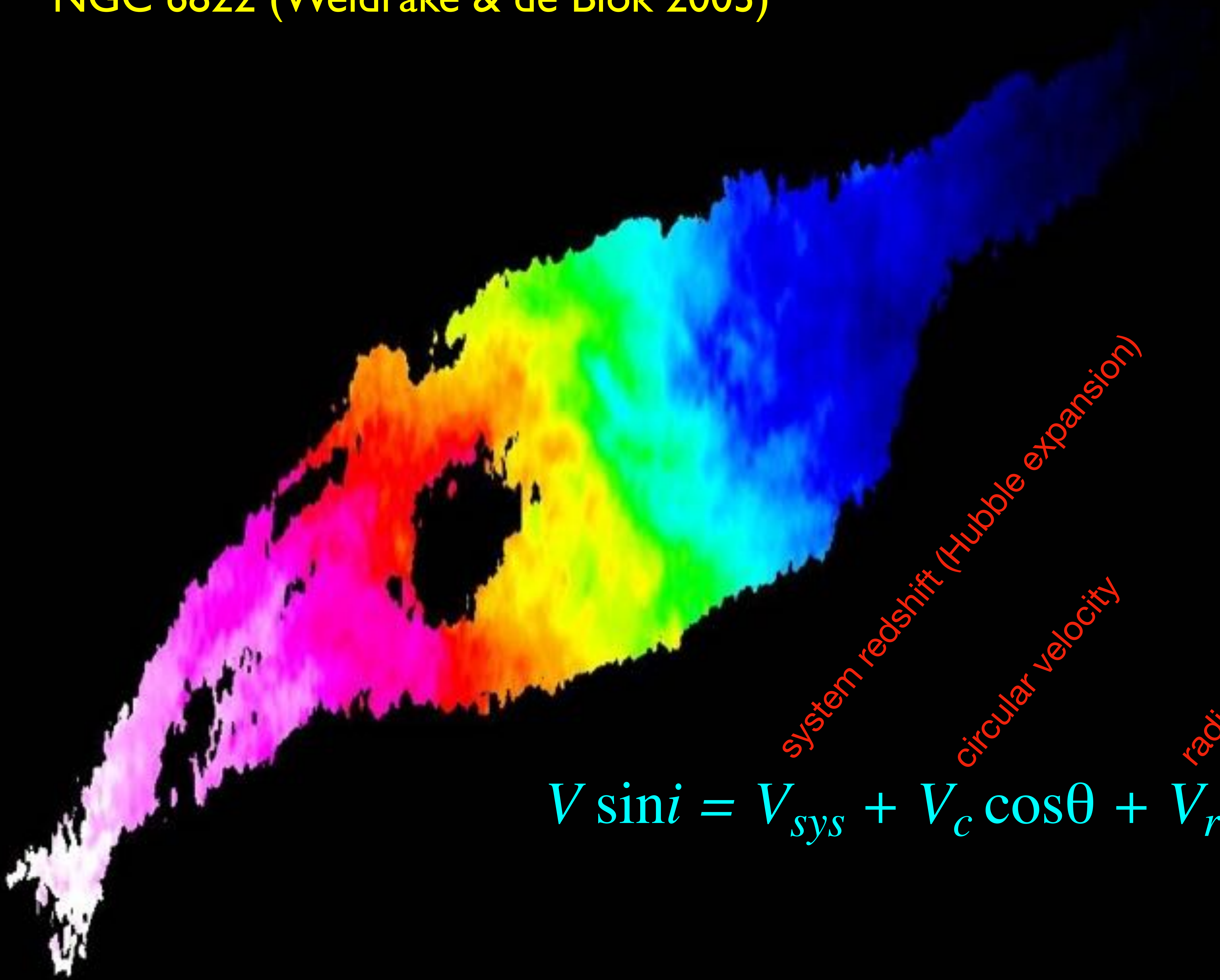
titled ring model





velocity variation along ring

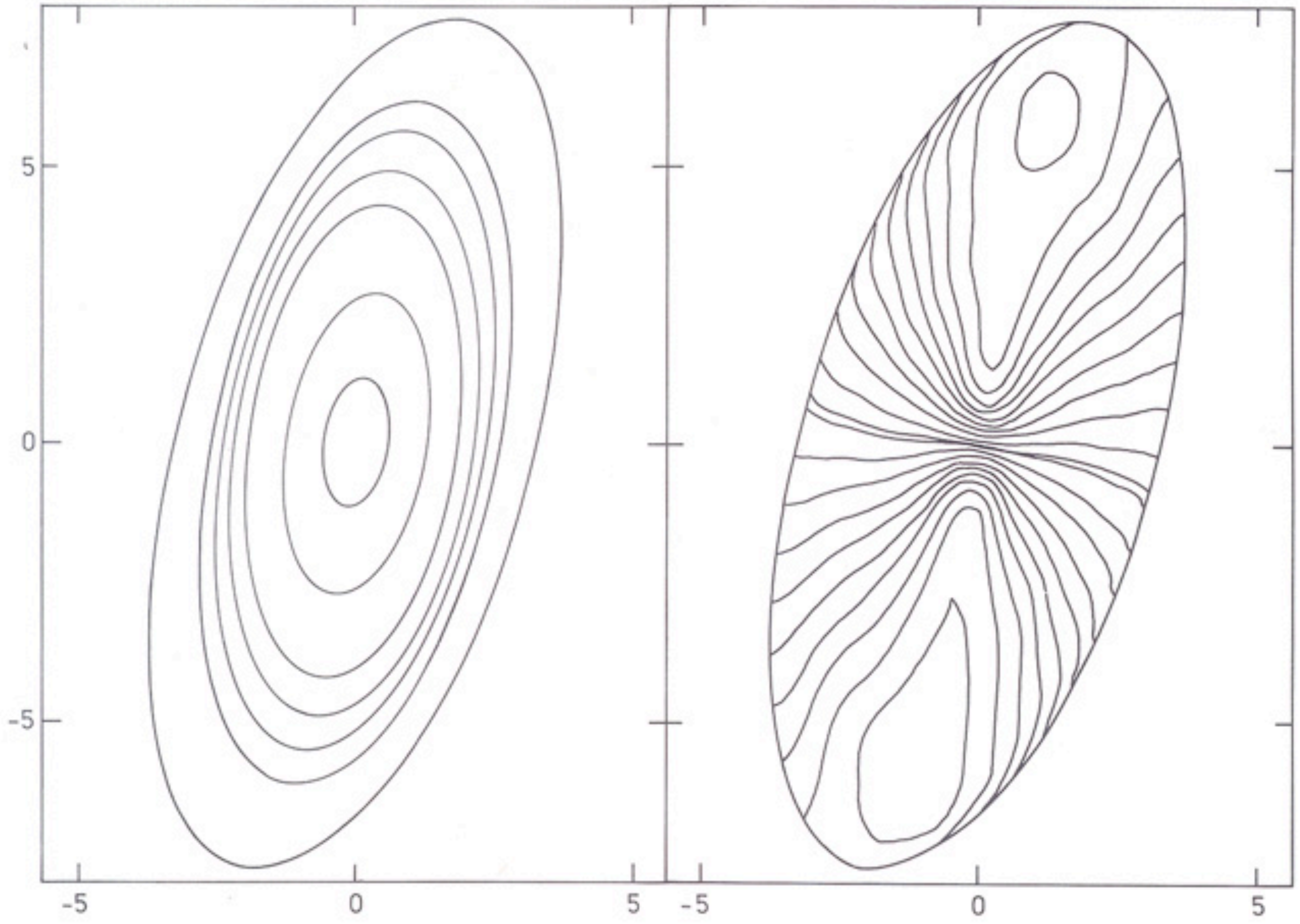
NGC 6822 (Weldrake & de Blok 2003)



$$V \sin i = V_{sys} + V_c \cos\theta + V_r \sin\theta$$

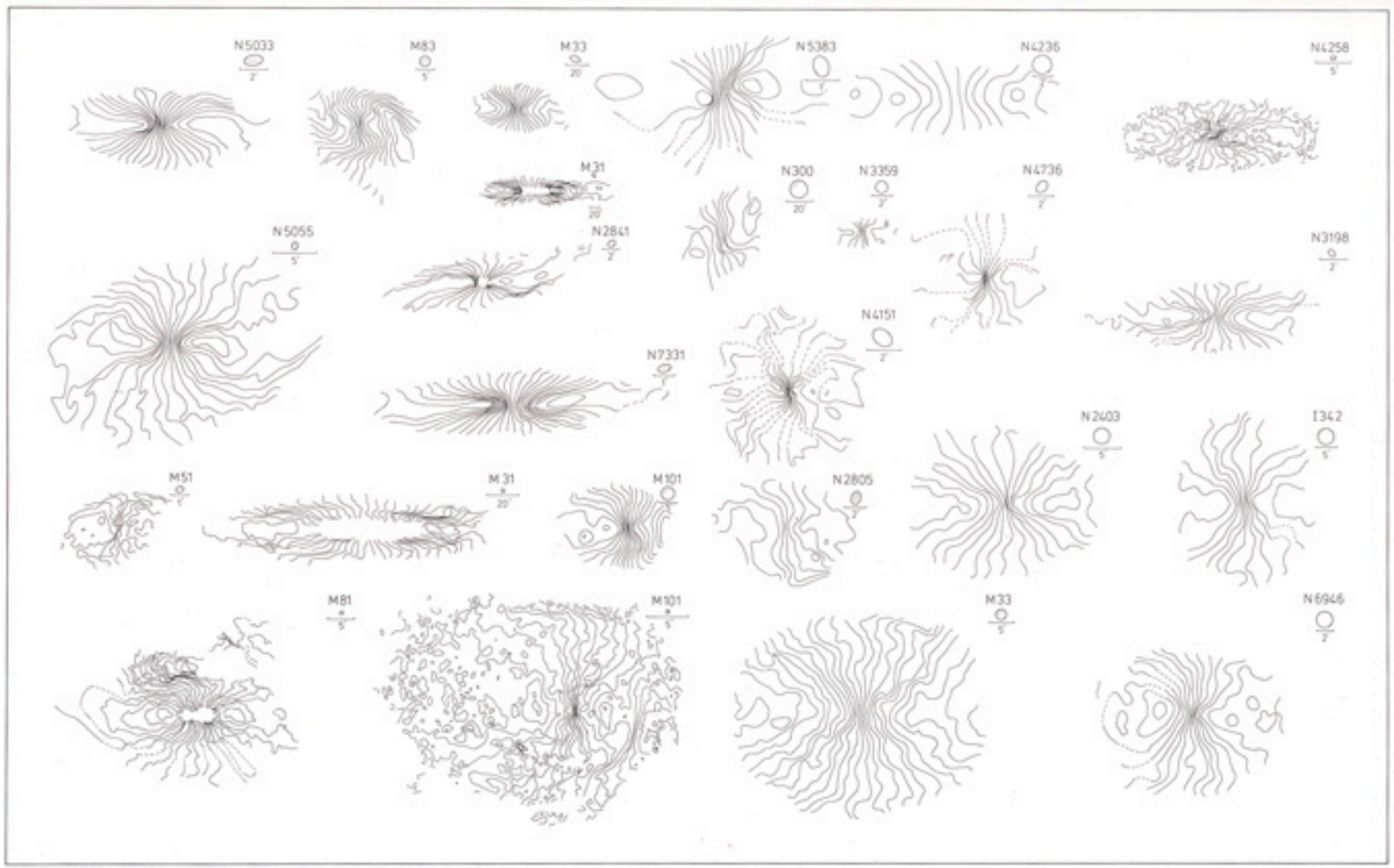
system redshift (Hubble expansion)
circular velocity
radial velocity

titled ring model



isovelocity contours

observed velocity fields



Bosma (1981)

HI velocity fields demonstrated flat rotation curves to large radii