Dark Matter

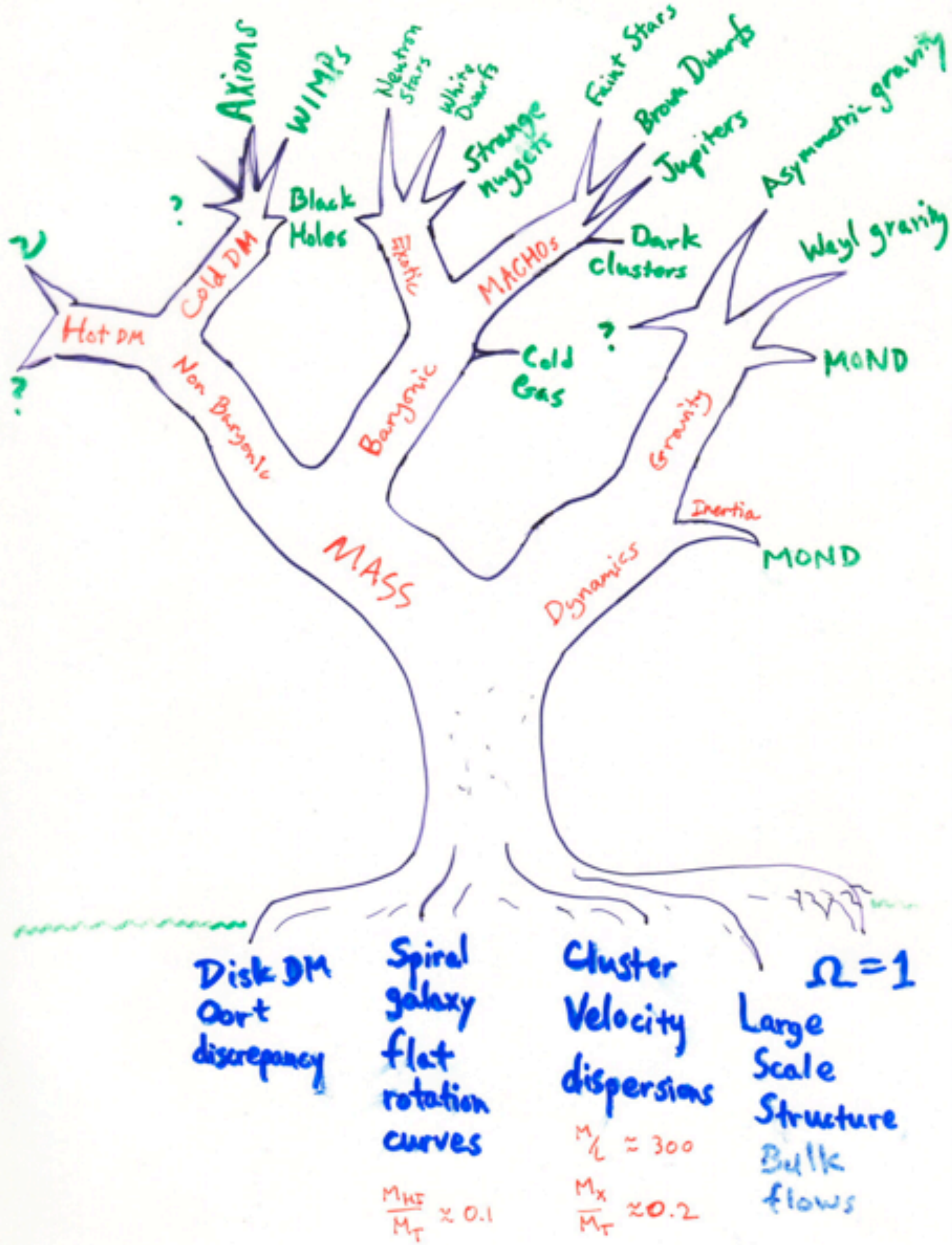
ASTR 333/433
Spring 2016

Today
Stars & Gas

essentials about
stuff we can see

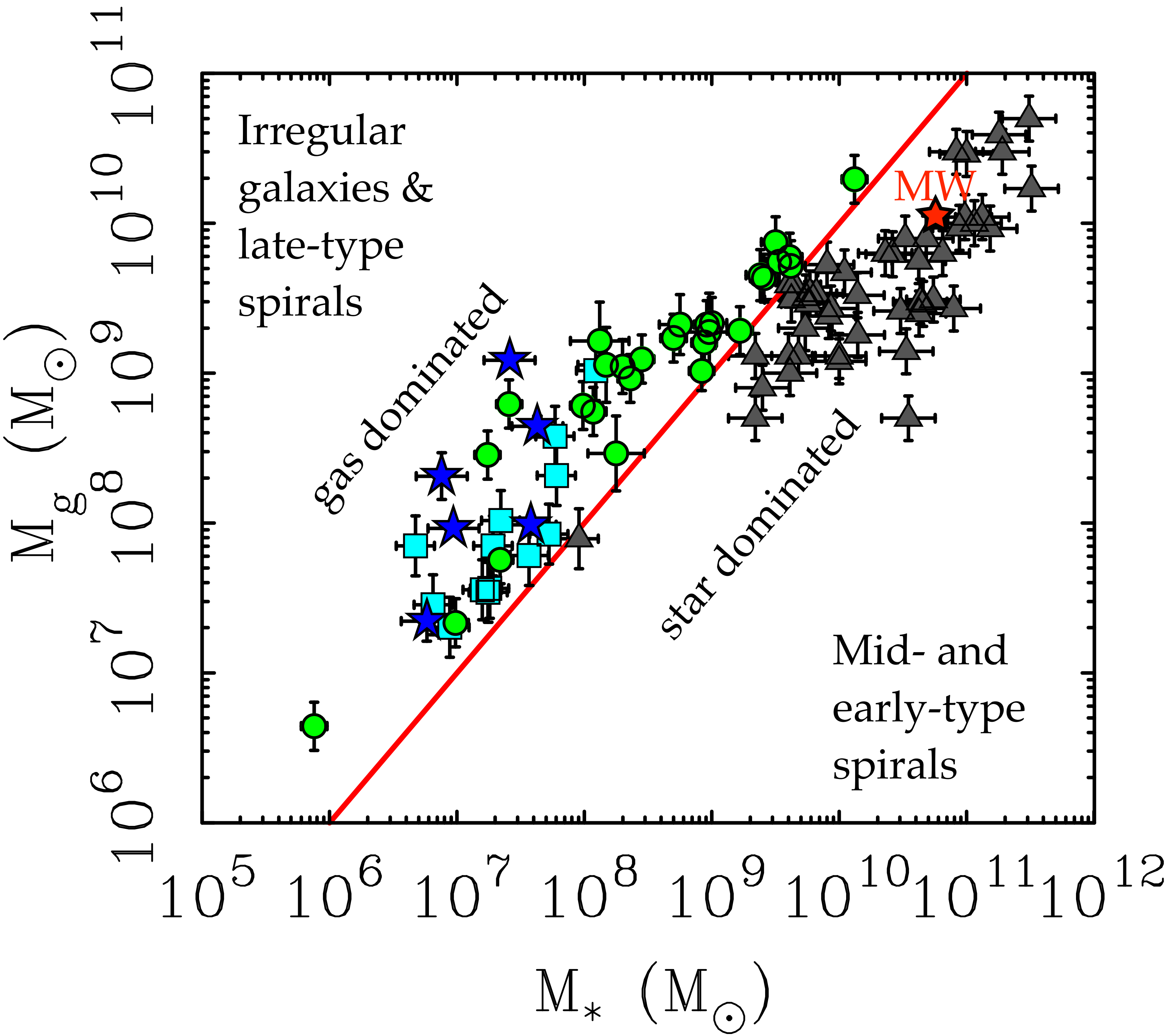
First Homework on-line
Due Feb. 4

Case Western Reserve
University
Est. 1826



"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.


Irregular
galaxies &
late-type
spirals
gas dominated
star dominated
Mid- and
early-type
spirals
MW
M_g ($M_\odot$)
M_* ($M_\odot$)
10^6
10^7
10^8
10^9
10^{10}
10^{11}
10^5
10^6
10^7
10^8
10^9
10^{10}
10^{11}
10^{12}

Typical Stellar composition

- Hydrogen mass fraction $X = 0.74$
- Helium mass fraction $Y = 0.25$
- Heavier elements ("metals"): $Z \approx 0.01$

Abundances of H & He set during Big Bang.
Heavier elements made in previous generations of stars.
Z often called "metallicity" and sometimes referenced to the iron abundance, [Fe/H].

open cluster

Stellar populations

- 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

Galaxy spectra composed of complex stellar populations

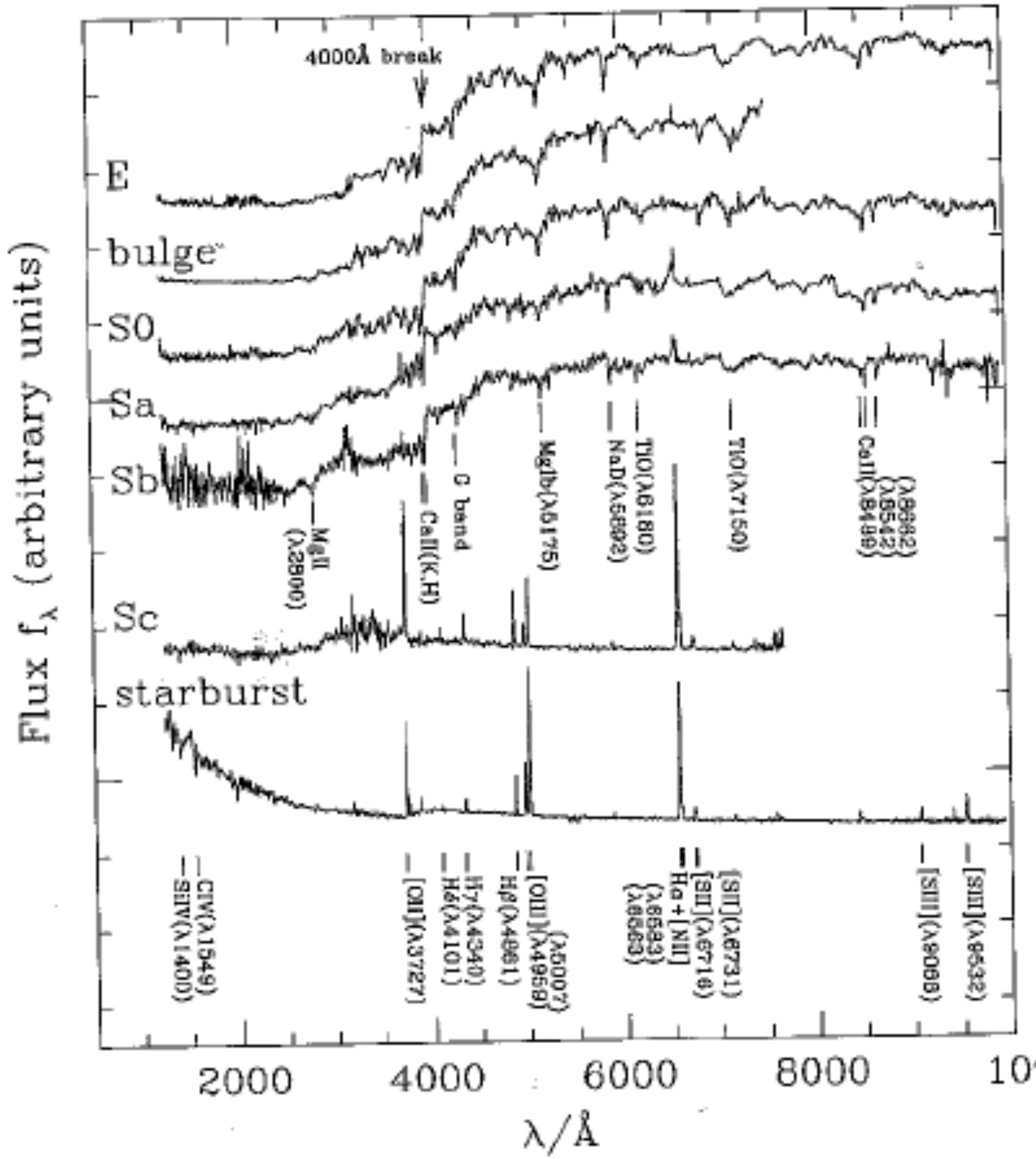
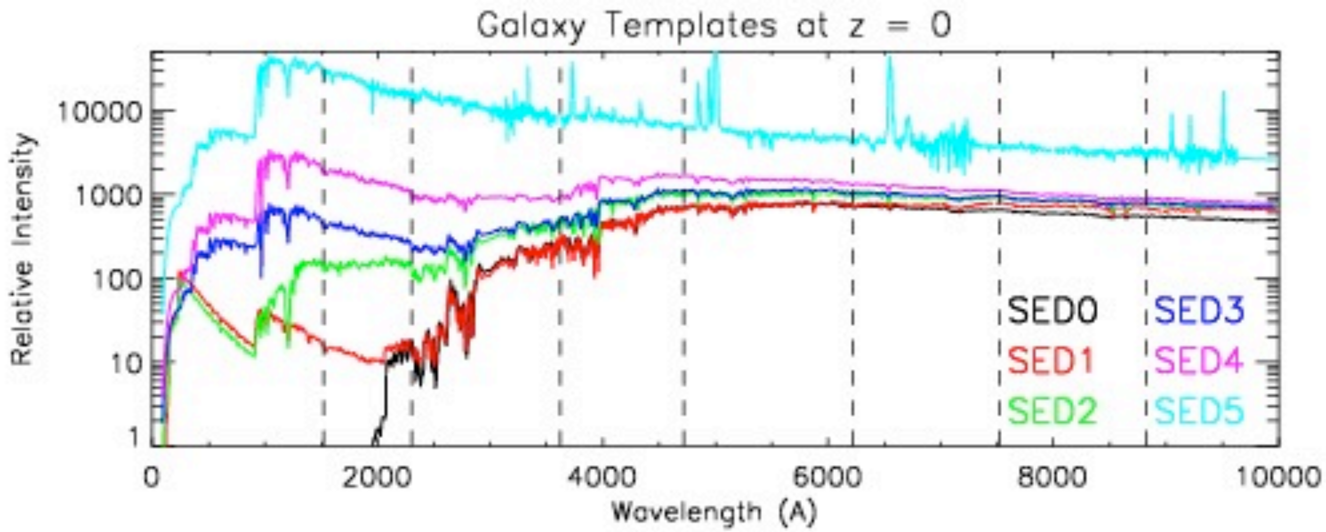
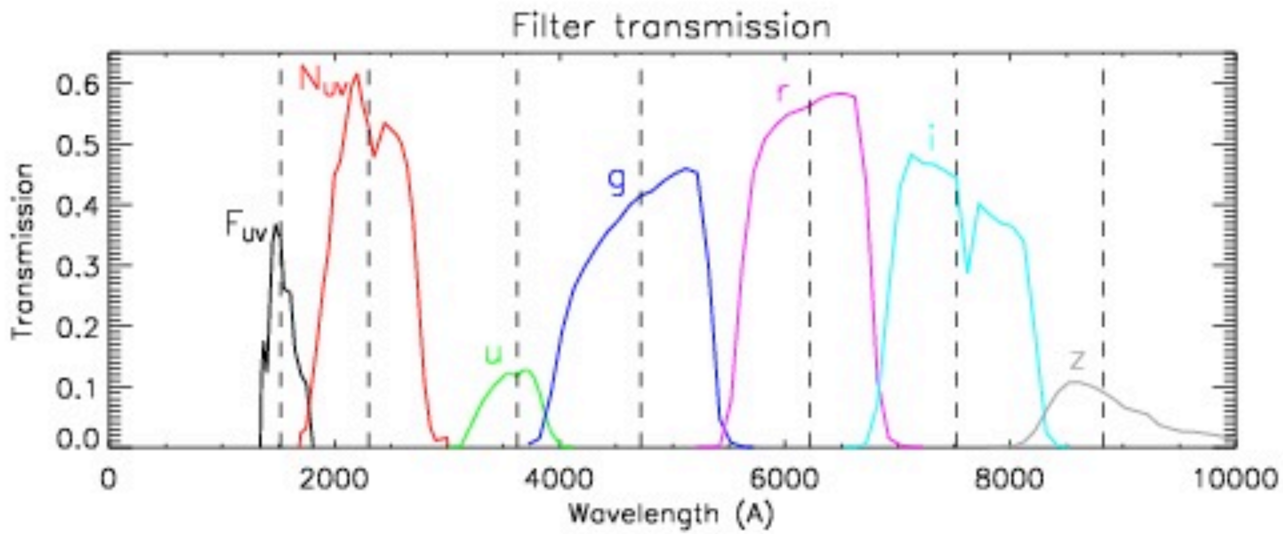


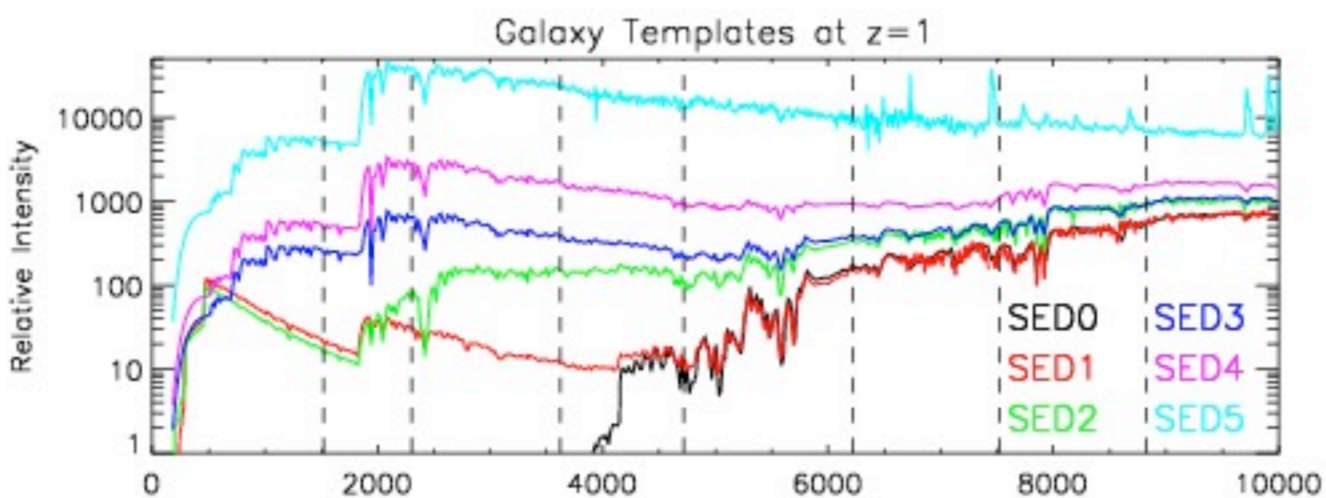
Fig. 2.12. Spectra of different types of galaxies from the ultraviolet to the near-infrared. From ellipticals to late-type spirals, the blue continuum and emission lines become systematically stronger. For early-type galaxies, which lack hot, young stars, most of the light emerges at the longest wavelengths, where one sees absorption lines characteristic of cool K stars. In the blue, the spectrum of early-type galaxies show strong H and K absorption lines of calcium and the G band, characteristic of solar type stars. Such galaxies emit little light at wavelengths shorter than 4000 Å and have no emission lines. In contrast, late-type galaxies and starbursts emit most of their light in the blue and near-ultraviolet. This light is produced by hot young stars, which also heat and ionize the interstellar medium giving rise to strong emission lines. [Based on data kindly provided by S. Charlot]

The effect of age variations

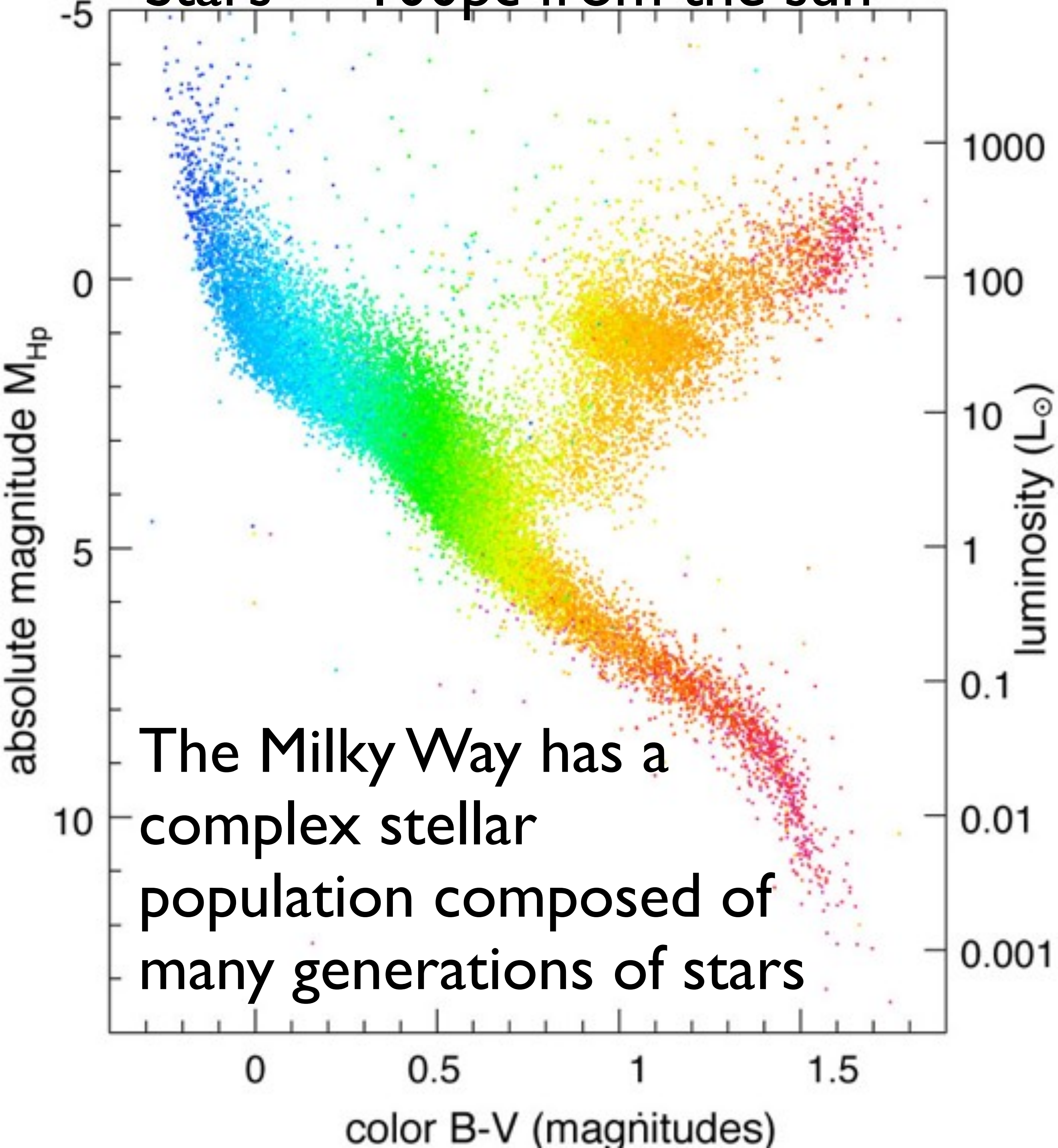




The effect of redshift



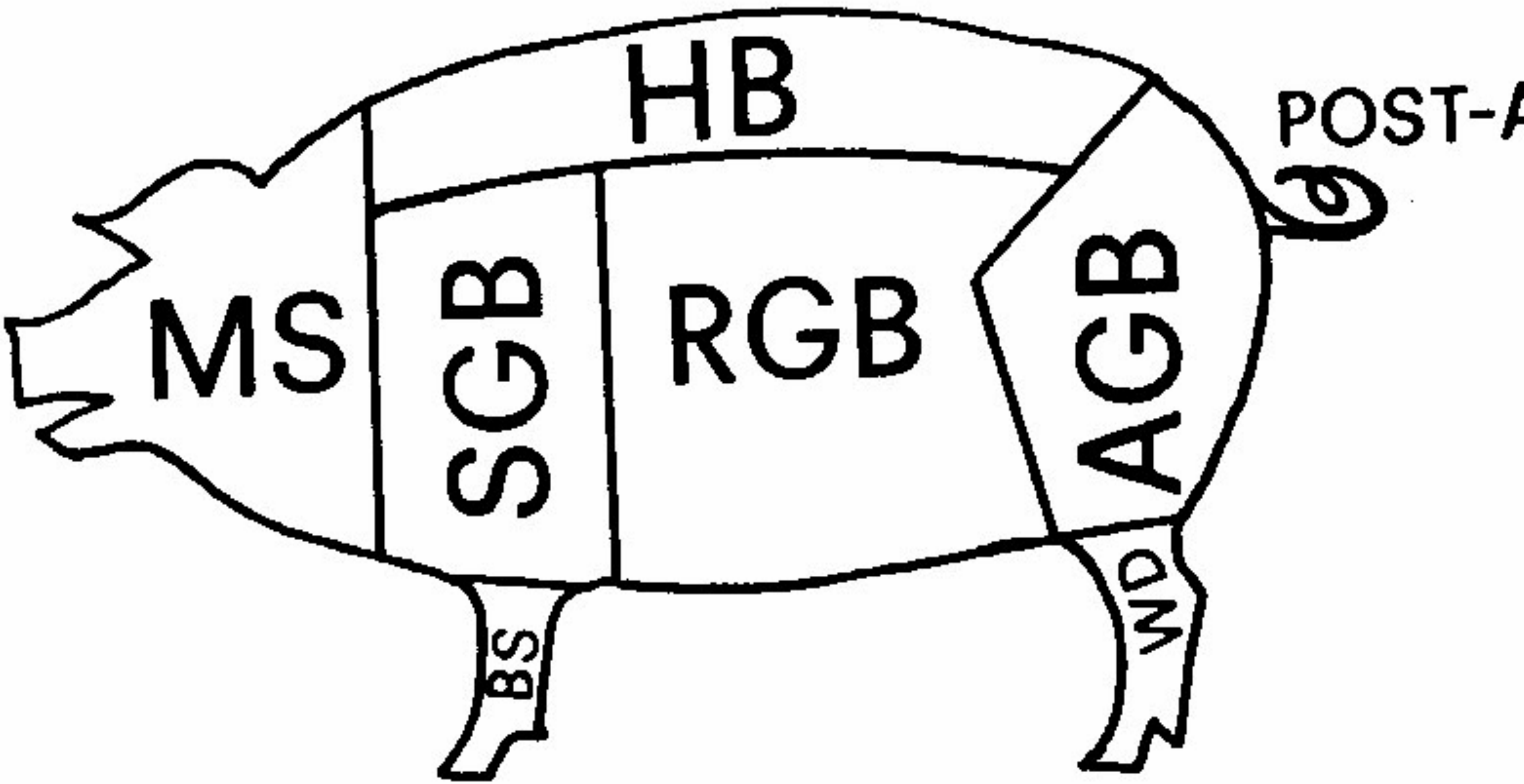
Stars < 100pc from the sun



The Milky Way has a complex stellar population composed of many generations of stars

Energy budget by evolutionary phase

Red giants and Main Sequence stars make the biggest contribution to the total light, but other phases also important.



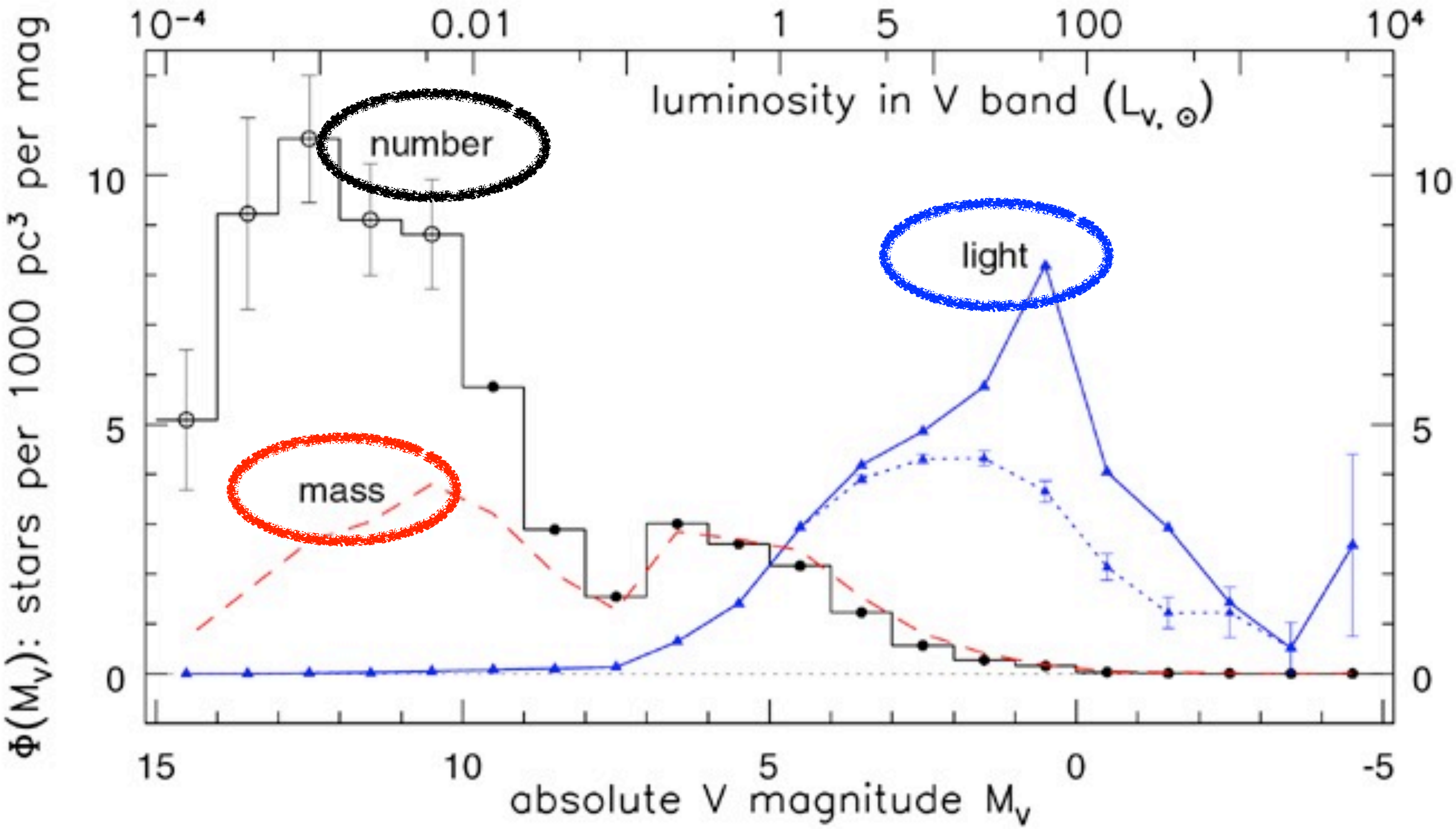


Fig 2.3 'Galaxies in the Universe' Sparke/Gallagher CUP 2007

Low mass stars exist in the greatest numbers and contain most of the mass.
High mass stars produce most of the light.

IMF vs PDF

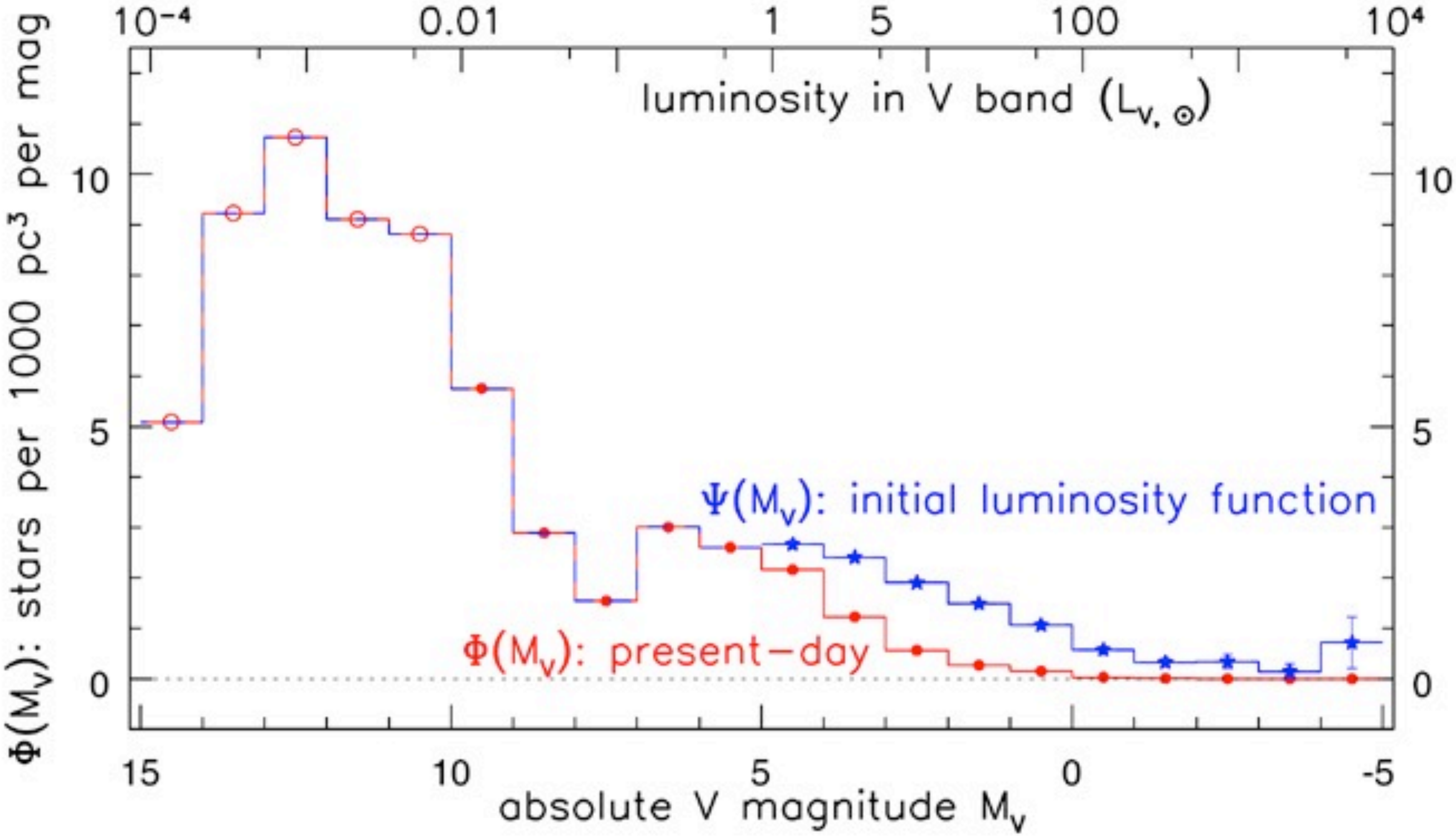


Fig 2.4 'Galaxies in the Universe' Sparke/Gallagher CUP 2007

Pleiades:

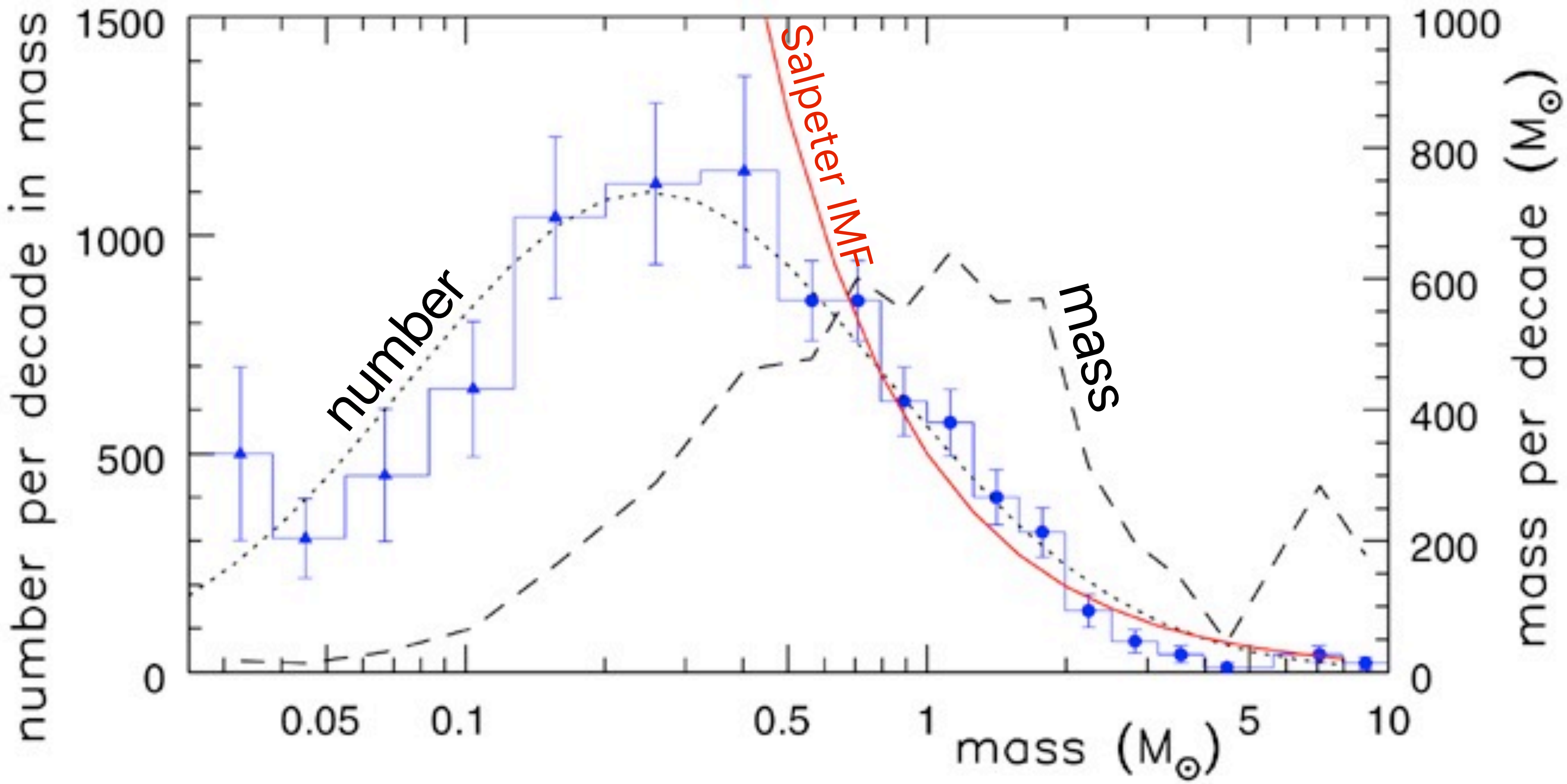
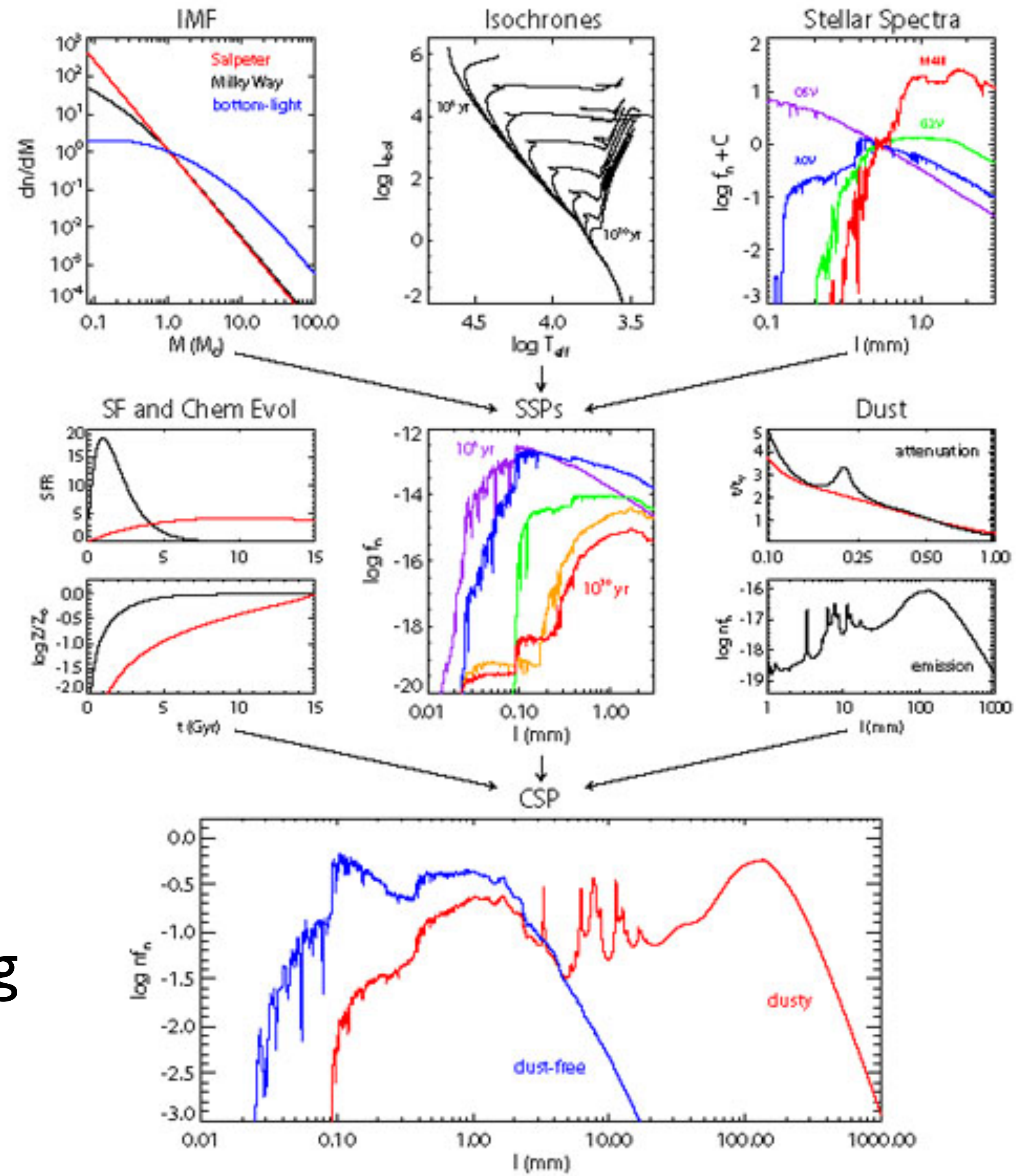
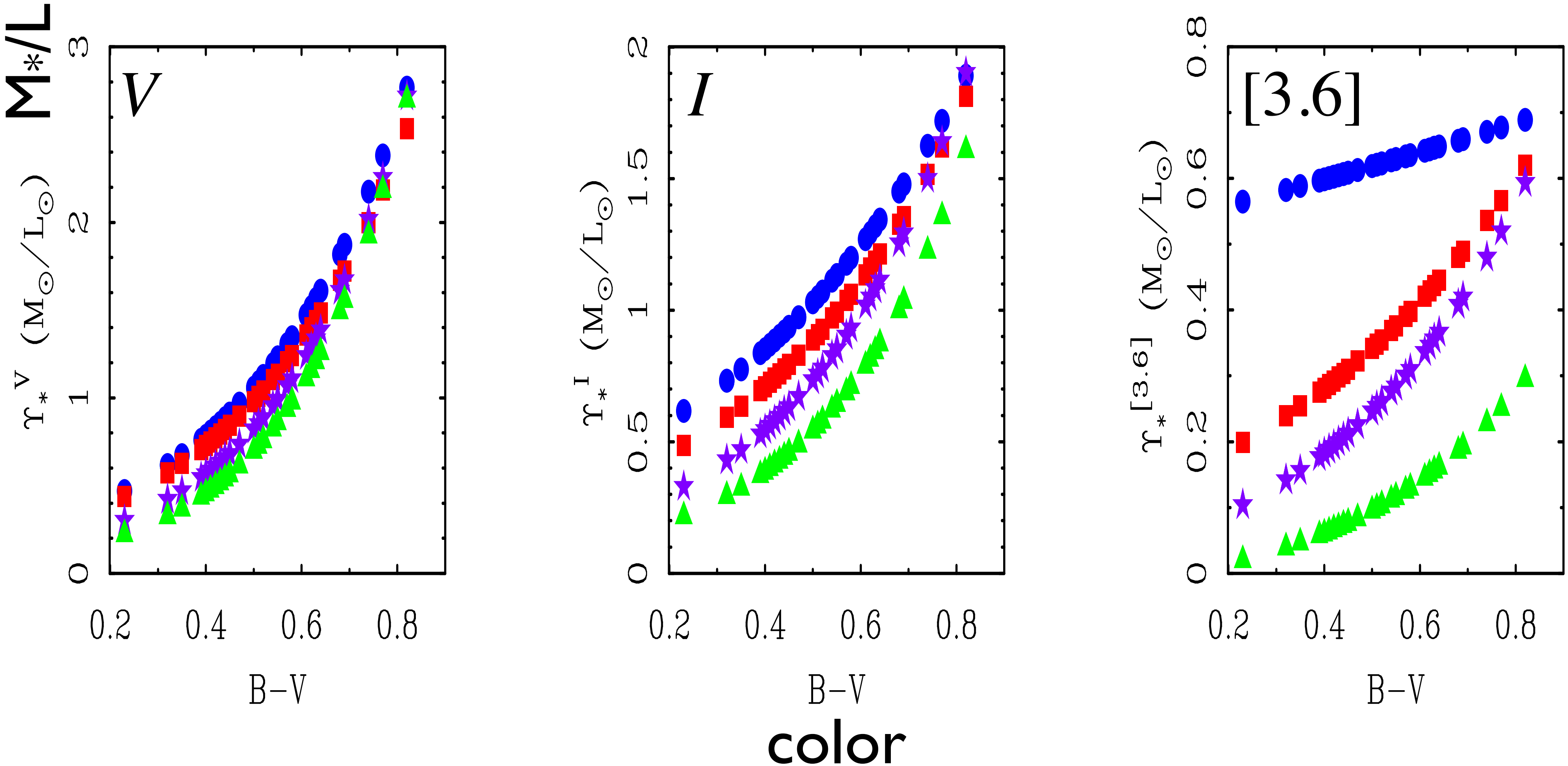


Fig 2.5 (E. Moreau) 'Galaxies in the Universe' Sparke/Gallagher CUP 2007



Stellar population synthesis modeling technique

Stellar population synthesis models predict the light produced by a given mass of stars



Typically M*/L of order unity.
Redder colors mean higher mass-to-light ratios

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

Note. — Stellar mass-to-light ratios in the V, I, and K-bands given by the formula $\log \Upsilon_*^j = \alpha_j + \beta_j(B-V)$. For each model, the V-band is identical to that in Table 3, but the I and [3.6] bands have been revised to attain self-consistency with the V-band (see text). For reference, the mass-to-light ratio at $B-V = 0.6$ is also given.

$$\log\left(\frac{M_*}{L_i}\right) = a_i + b_i(B-V)$$

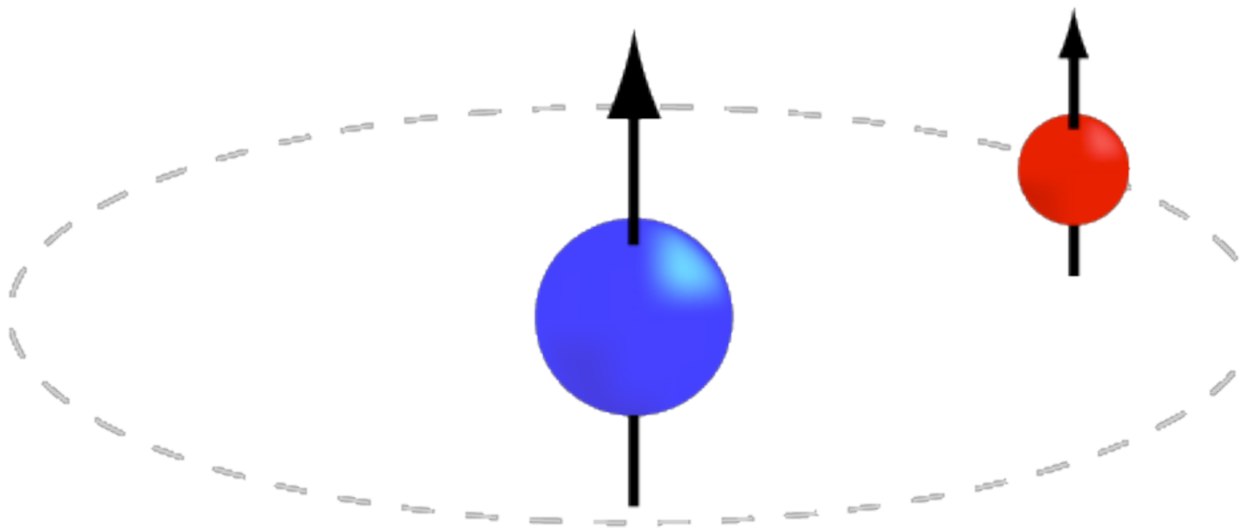
Older populations (like in Elliptical galaxies) can have larger mass-to-light ratios, but usually $\left(\frac{M_*}{L}\right) < 5\ \frac{\mathrm{M}_\odot}{\mathrm{L}_\odot}$

ISM

The stuff between the stars

Atomic gas
Molecular gas
Ionized gas
Dust

HI: atomic hydrogen in the interstellar medium



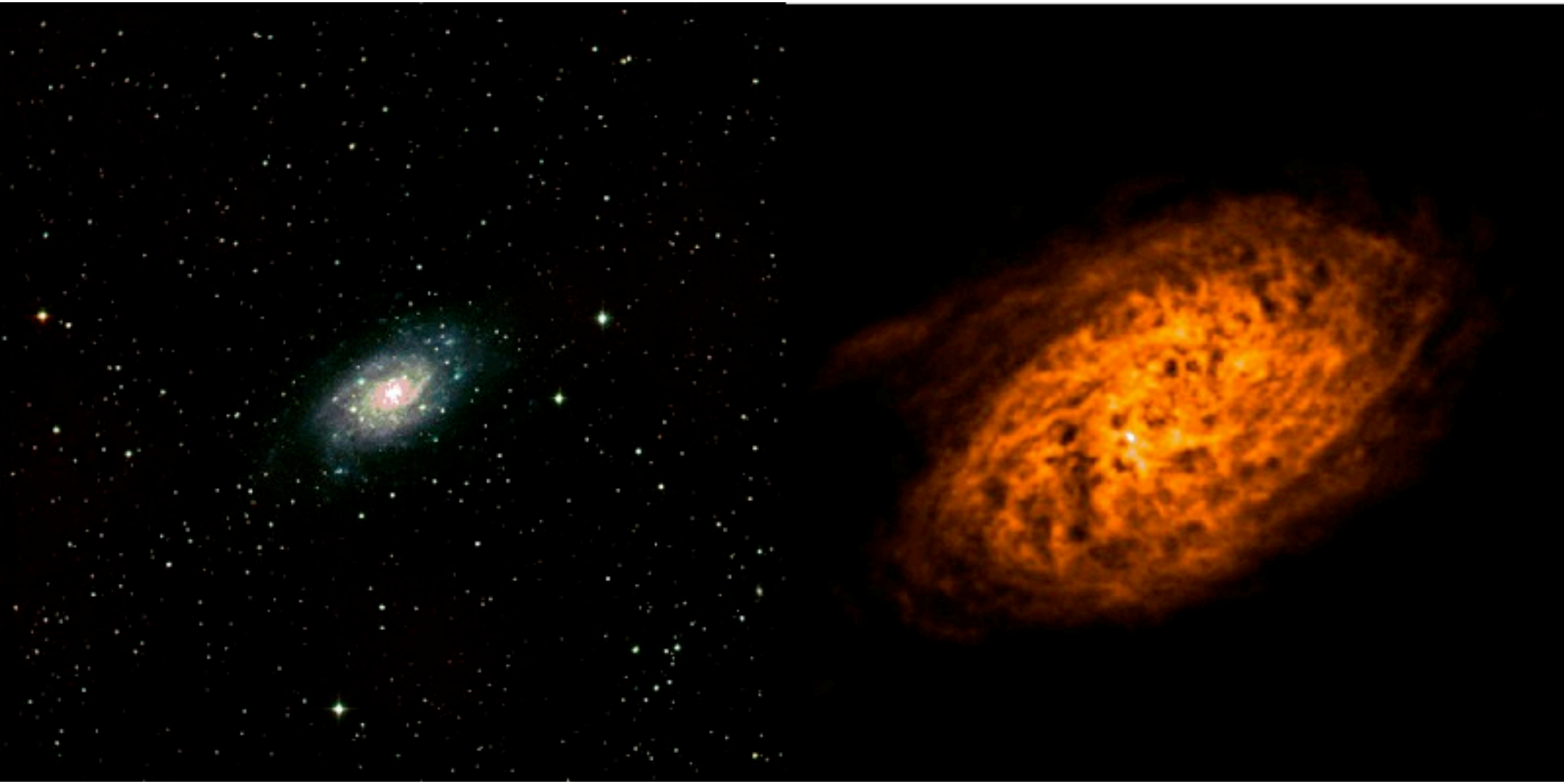
21 cm emission from hyperfine transition: parallel to anti-parallel spins

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

Radio line!

NGC 2403

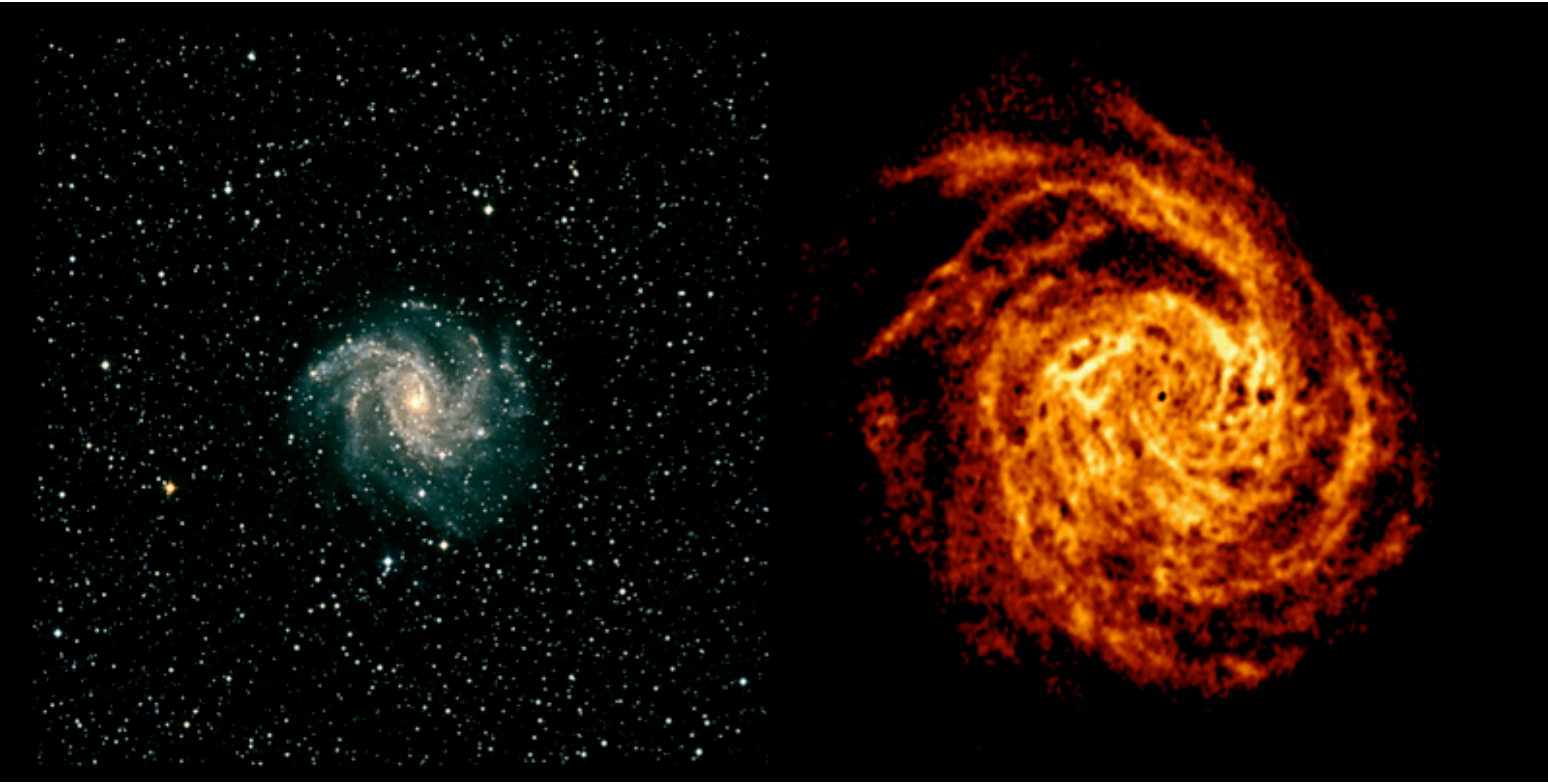
Stars | HI gas



Fraternali, Oosterloo, Sancisi, & van Moorsel 2001, ApJ, 562, L47

NGC 6946

Stars | Hı gas

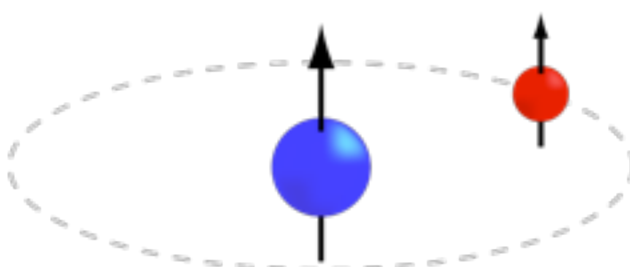


Boomsma 2005

emission coefficient

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

Bohr magneton



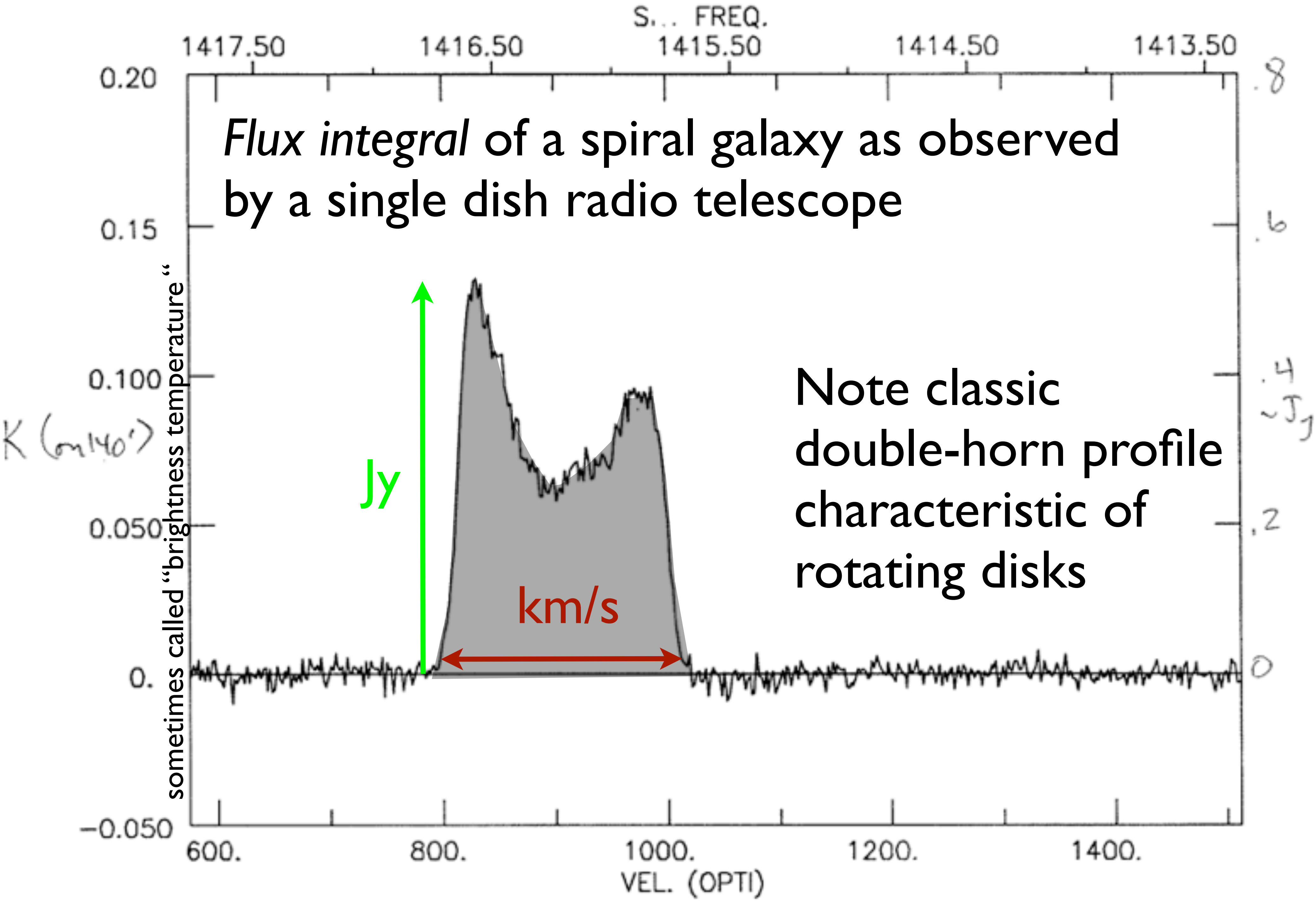
The radiative half-life of this transition is 11 Myr. This is readily maintained in equilibrium even in a cool (~100 K), diffuse ISM (< 1 atom/cc)

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

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

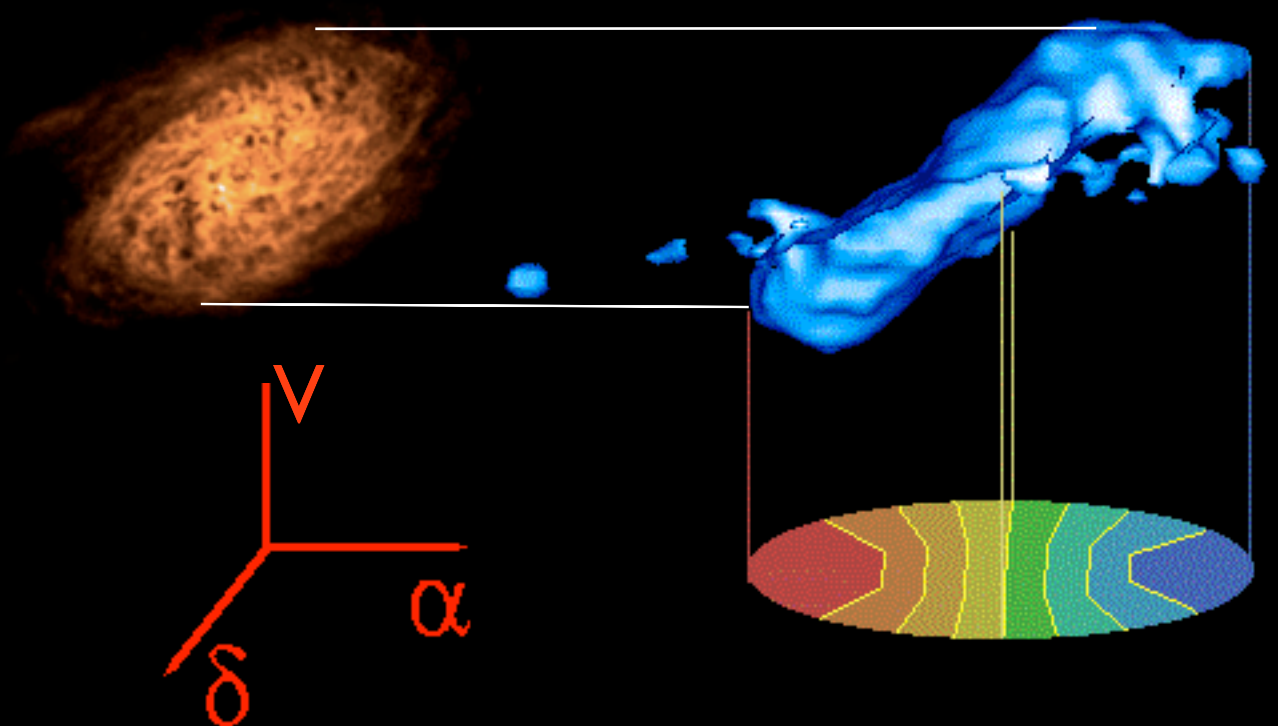
Give mass in solar masses for D in Mpc and measured F_{HI}, the flux integral in Jy-km/s

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



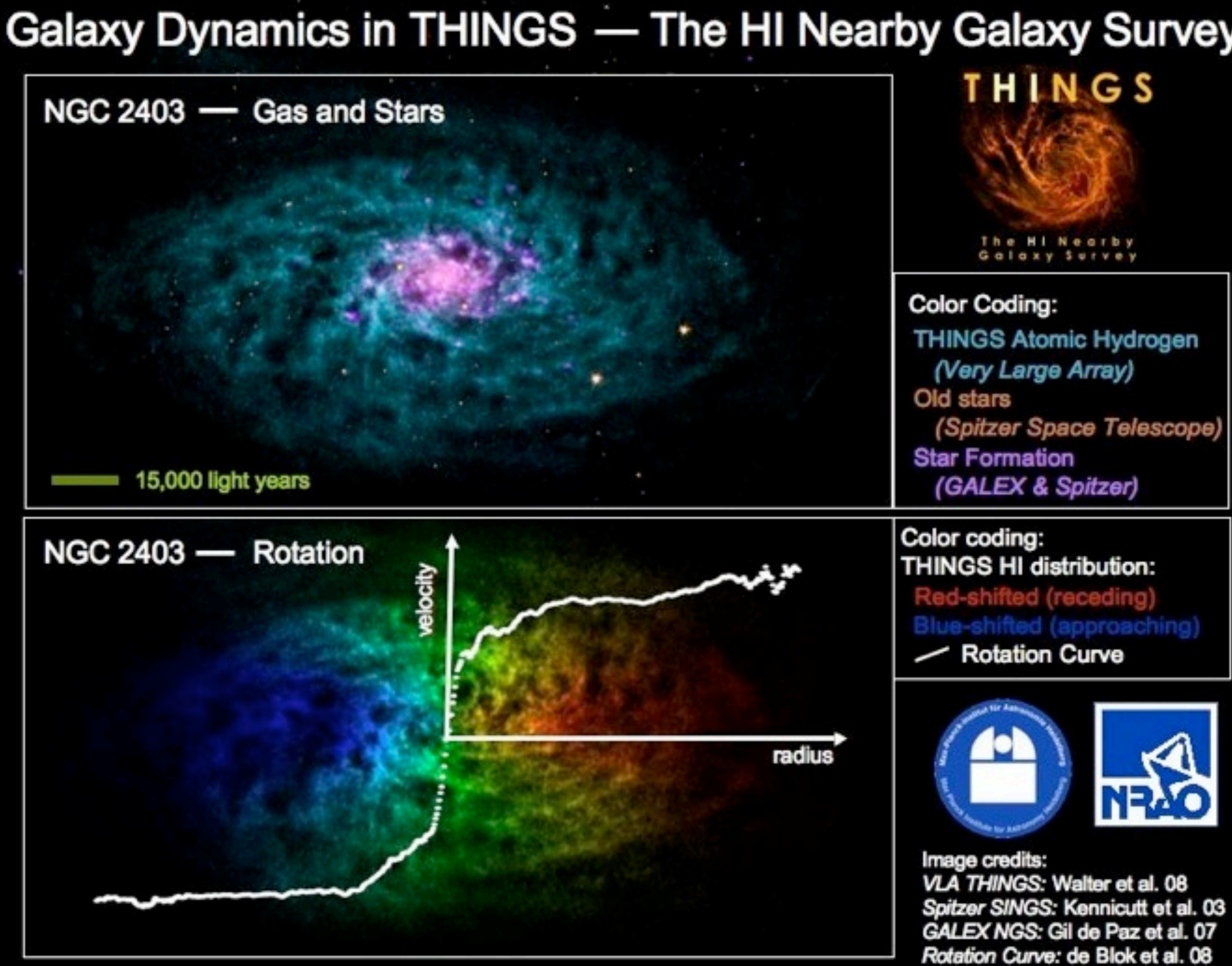
Flux integral of a spiral galaxy as observed by a single dish radio telescope
Note classic double-horn profile characteristic of rotating disks
Jy
km/s
sometimes called "brightness temperature"
S... FREQ.
1417.50
1416.50
1415.50
1414.50
1413.50
0.20
0.15
0.100
0.050
0.
−0.050
600.
800.
1000.
1200.
1400.
VEL. (OPTI)
.8
.6
.4
.2
0

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

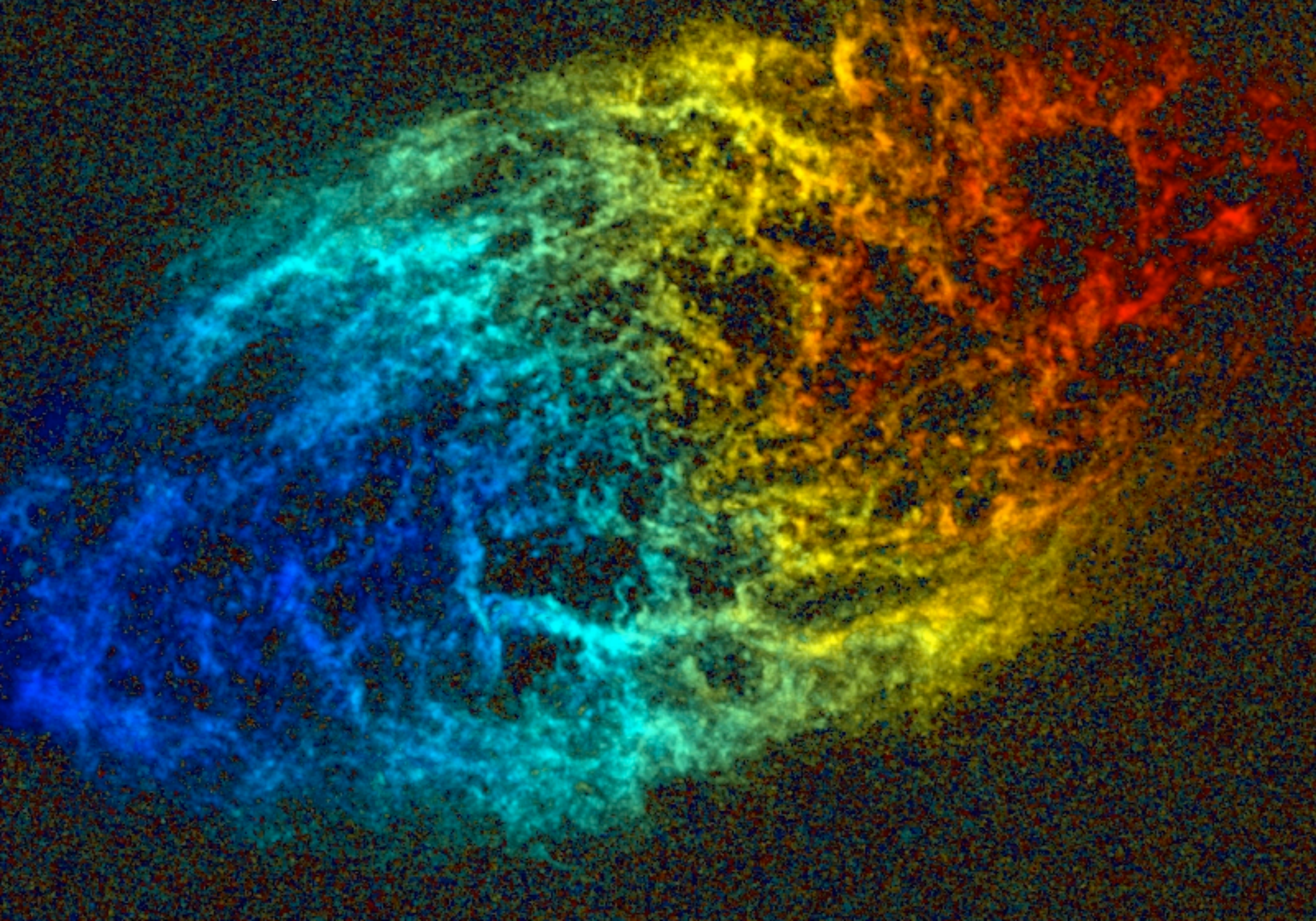


from 3D data cube of 21 cm position and redshift

Multi-dish radio telescope arrays give surface density and velocity



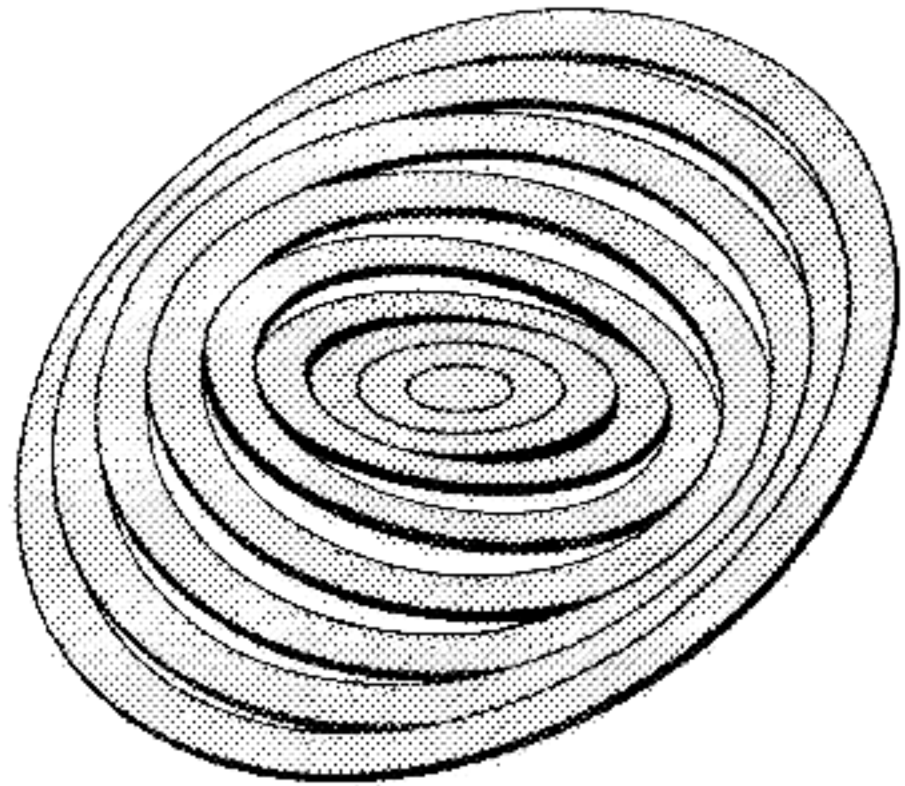
M33 velocity field

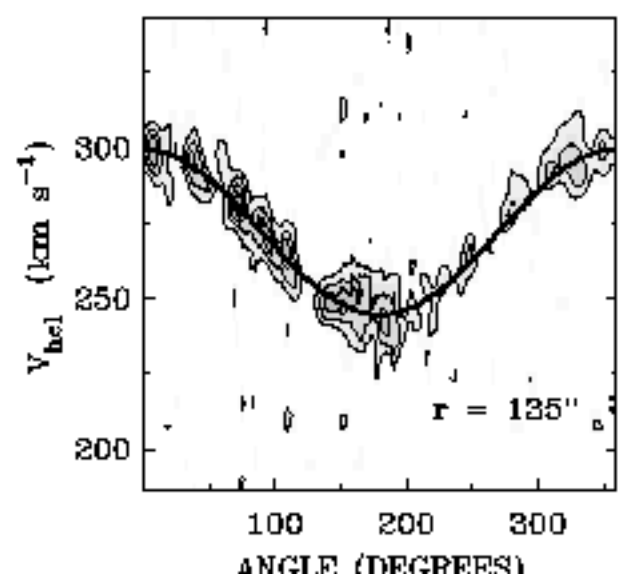


Rotation curves extracted using “tilted ring” fits

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.

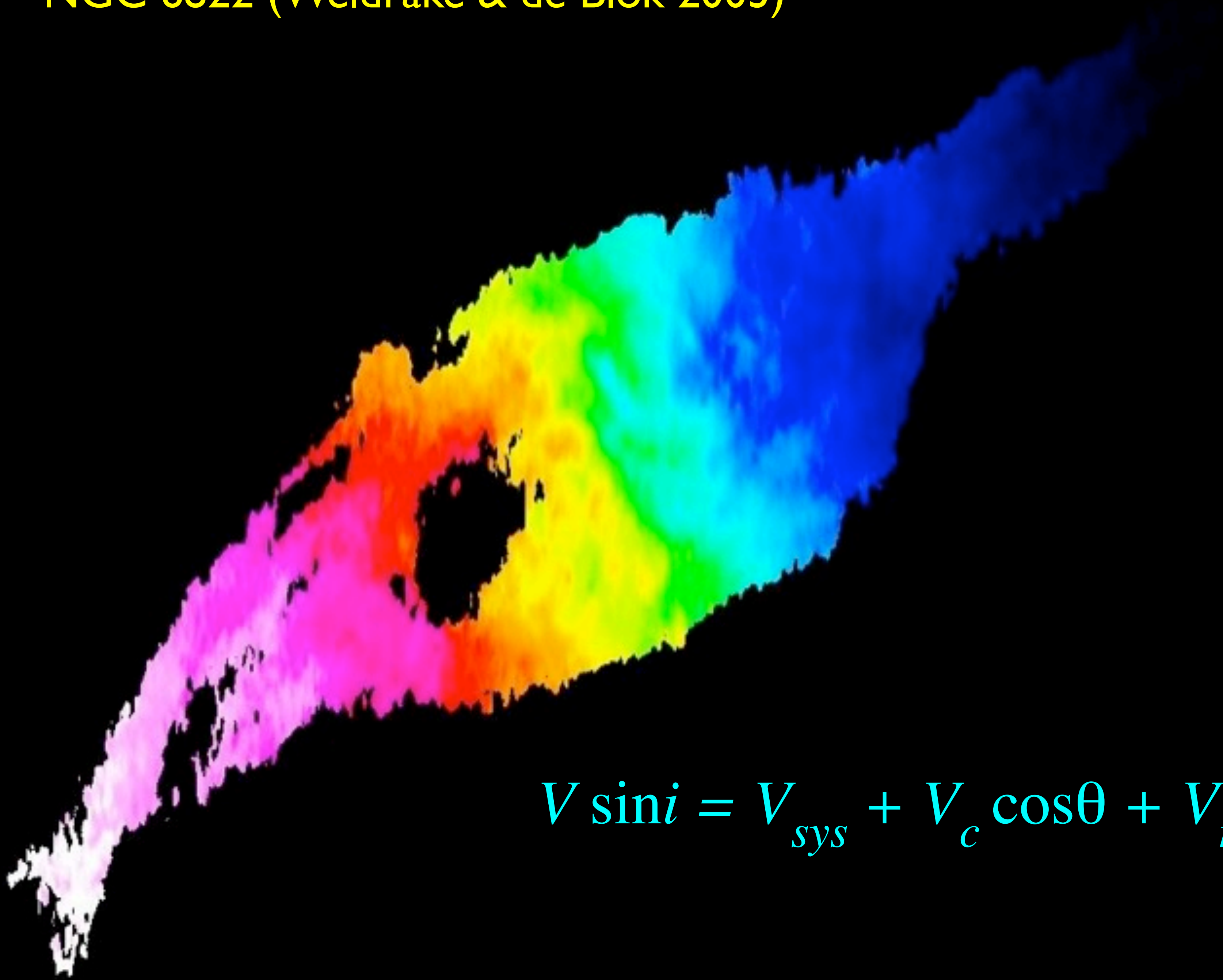
titled ring model





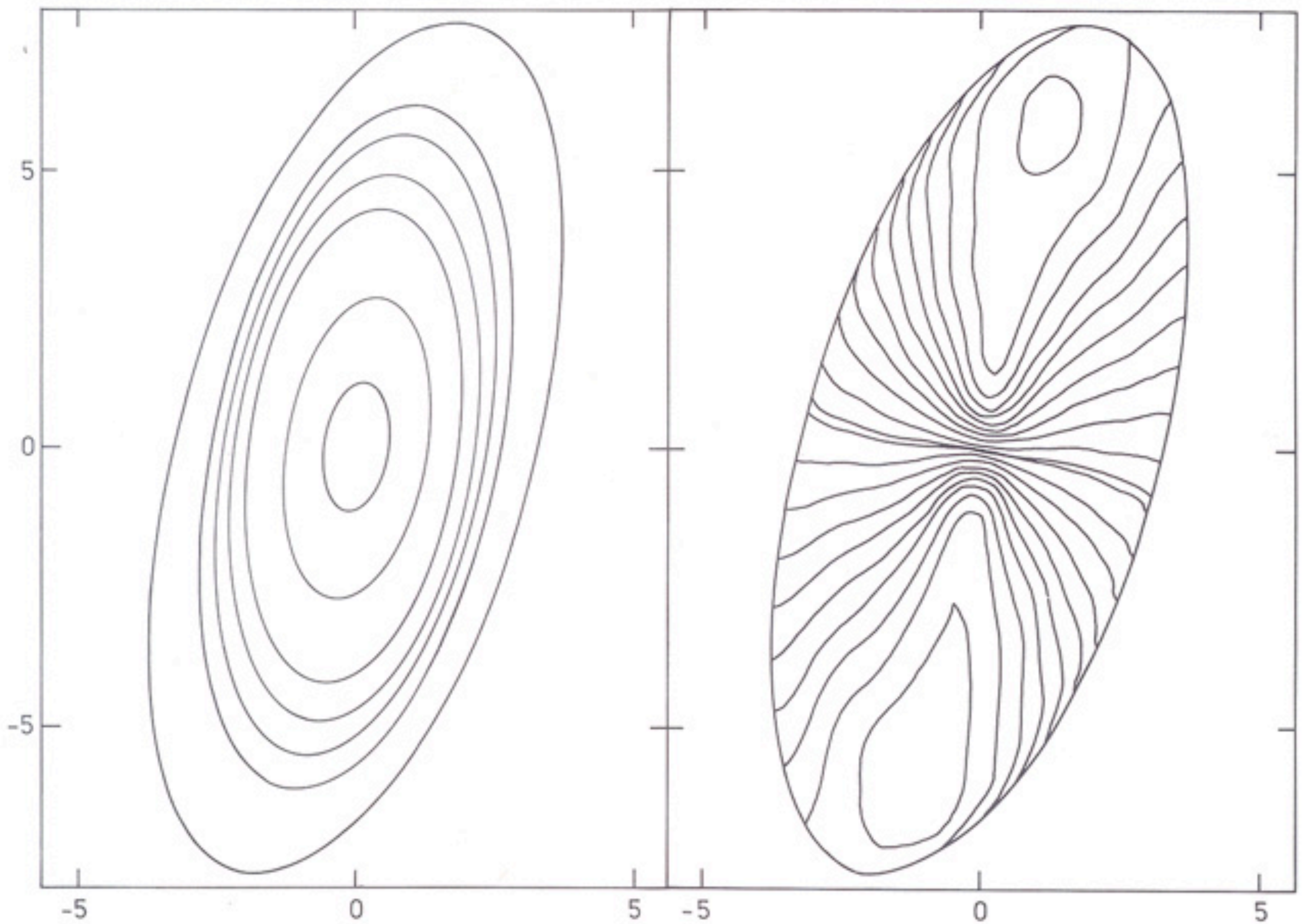
velocity variation along ring

NGC 6822 (Weldrake & de Blok 2003)



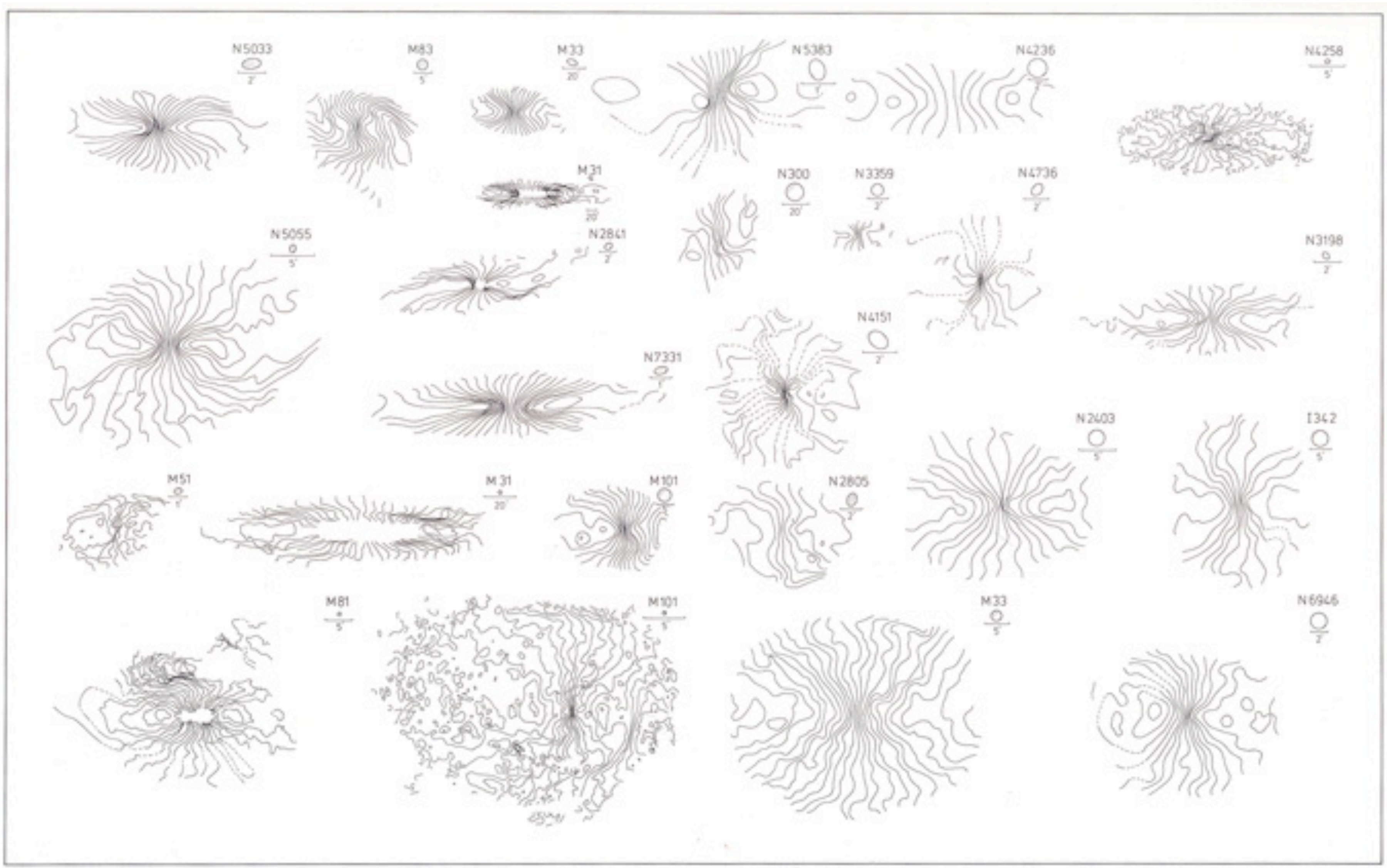
$$V \sin i = V_{sys} + V_c \cos\theta + V_r \sin\theta$$

titled ring model

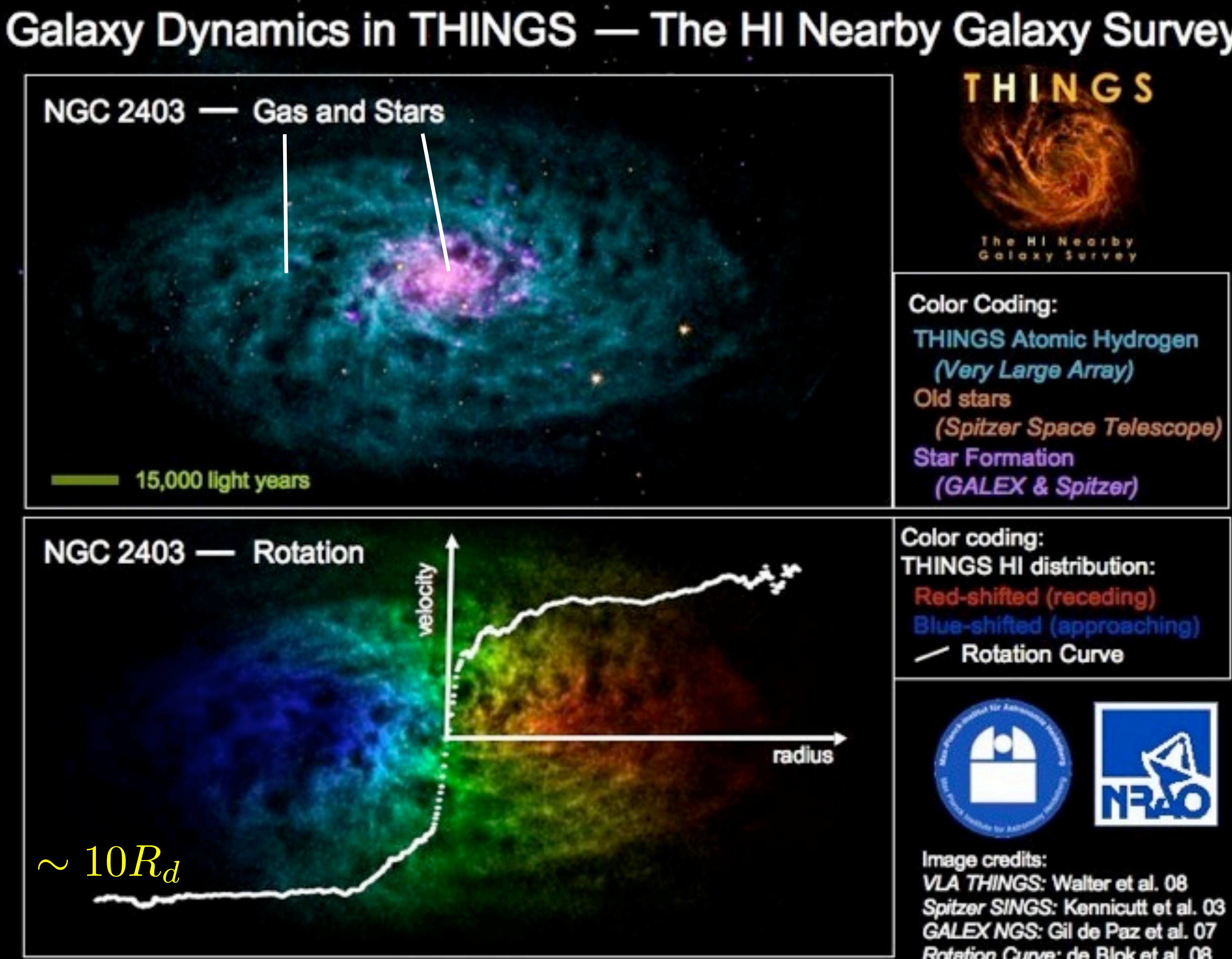


isovelocity contours

observed velocity fields



HI velocity fields demonstrated flat rotation curves to large radii

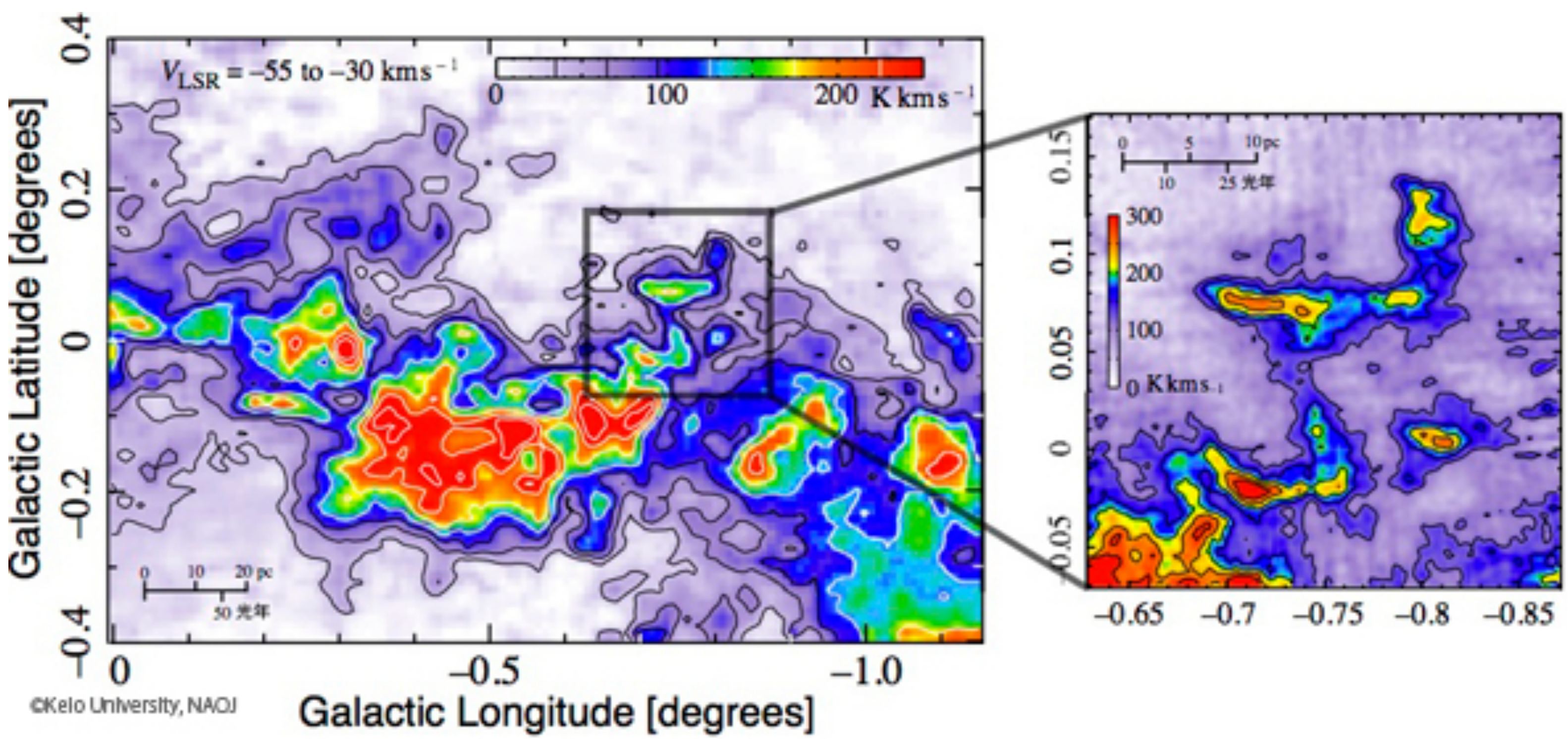


$\sim 10 R_d$

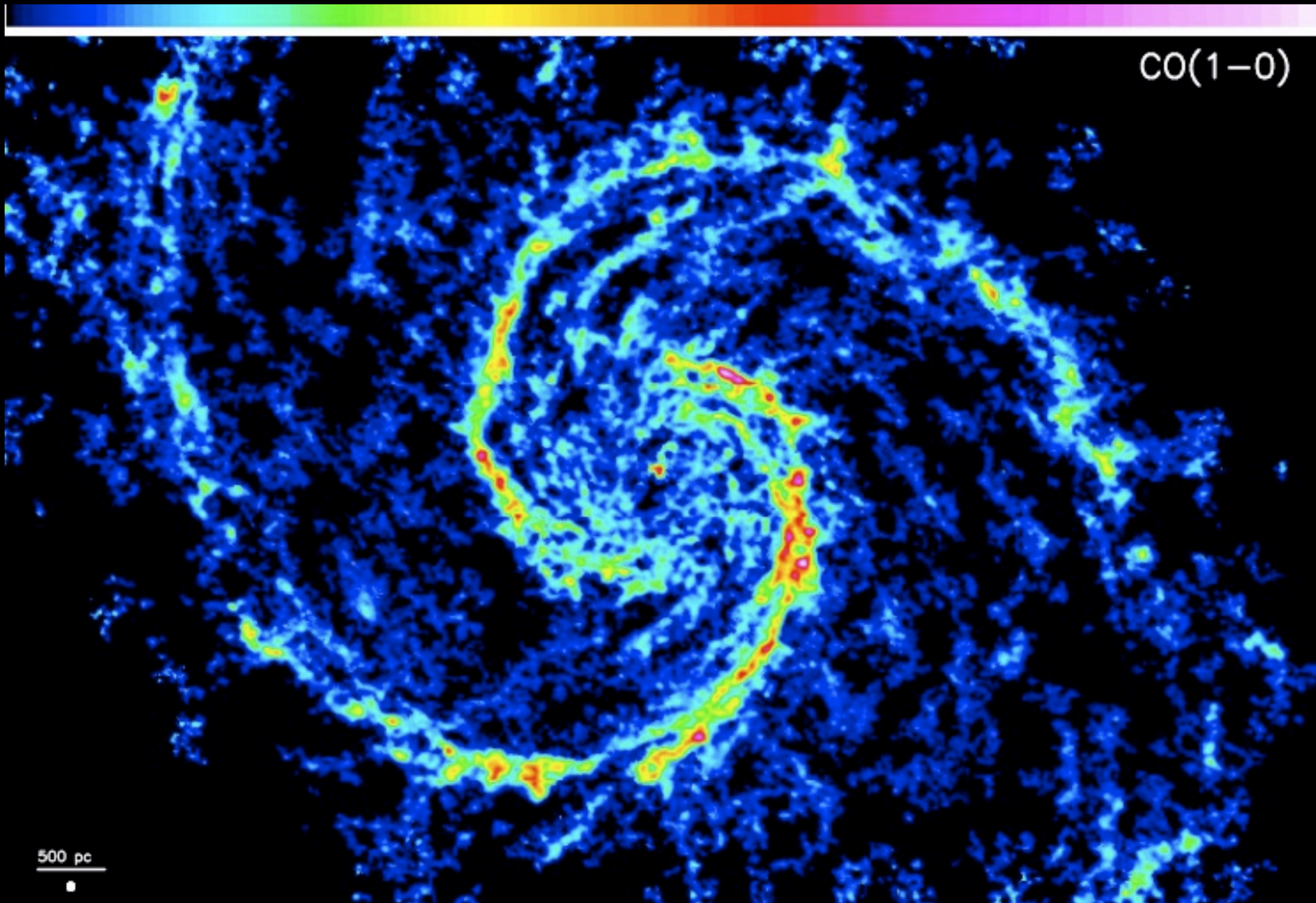
Molecular ISM

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

Very clumpy, with low filling factor - much of the 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.

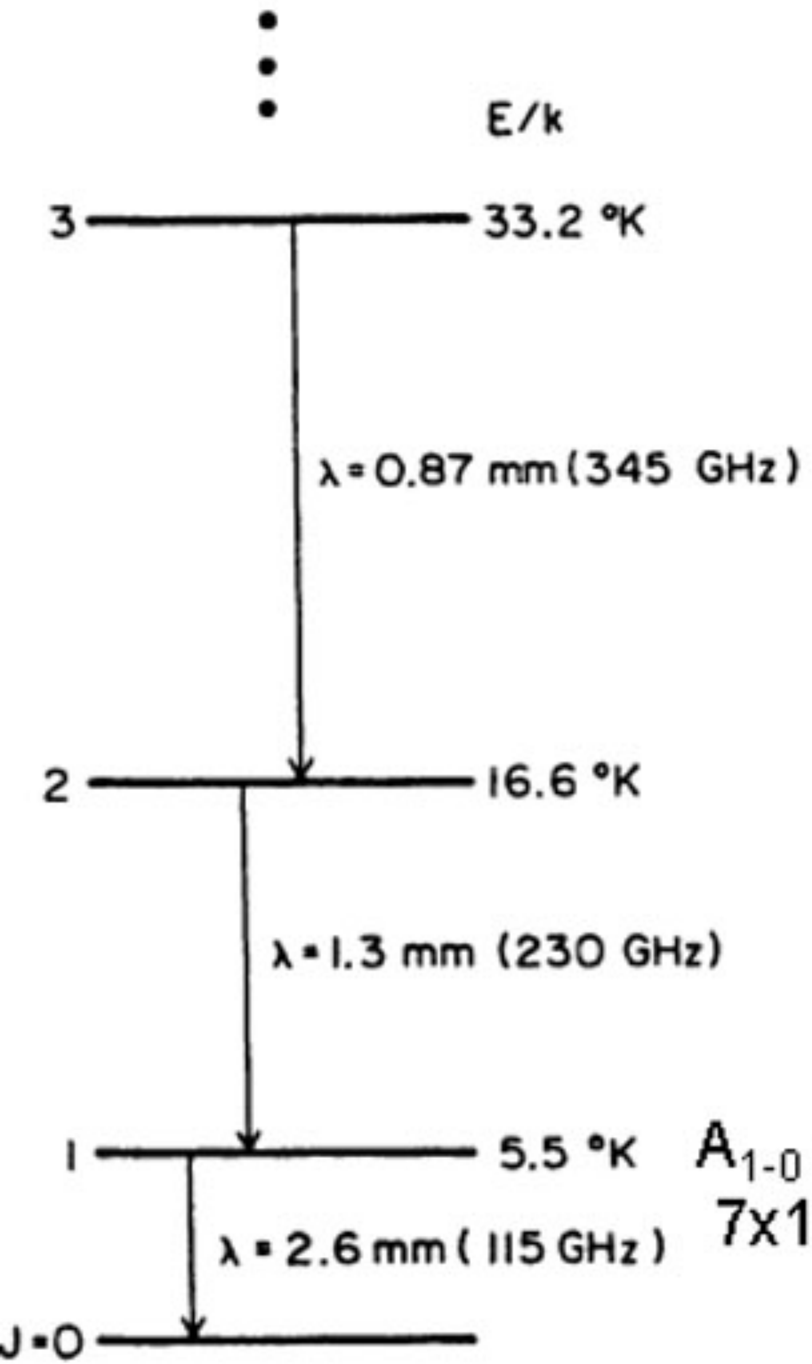
Polar molecules (esp. CO) have a permanent dipole moment thanks to asymmetry so have a rich rotational spectrum (typically in the mm or cm wavelengths).

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

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

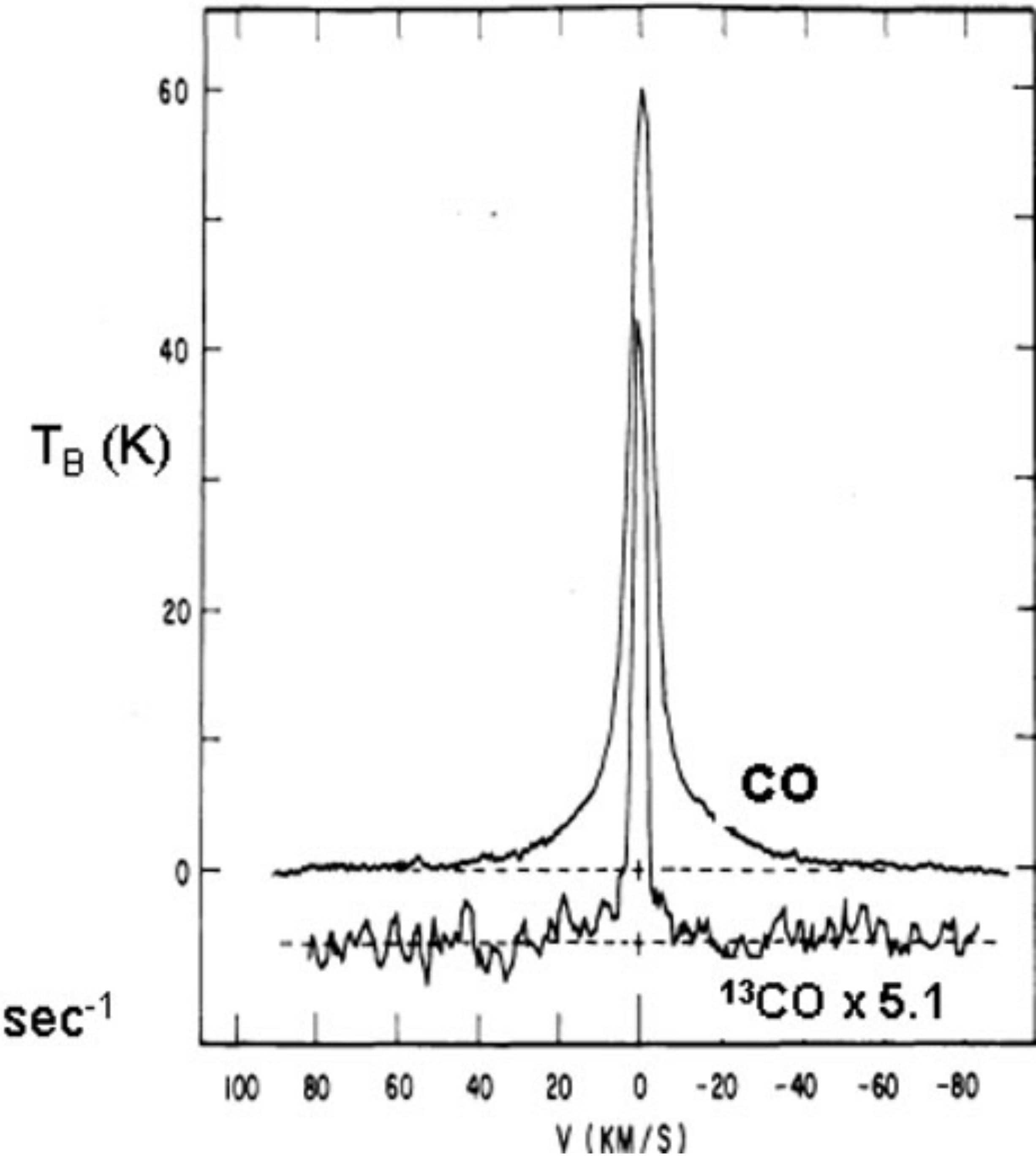
$$X_{CO} = 2.8 \times 10^{20} \mathrm{cm}^{-2} (\mathrm{K\ km/s})^{-1}$$

CO Rotational Levels



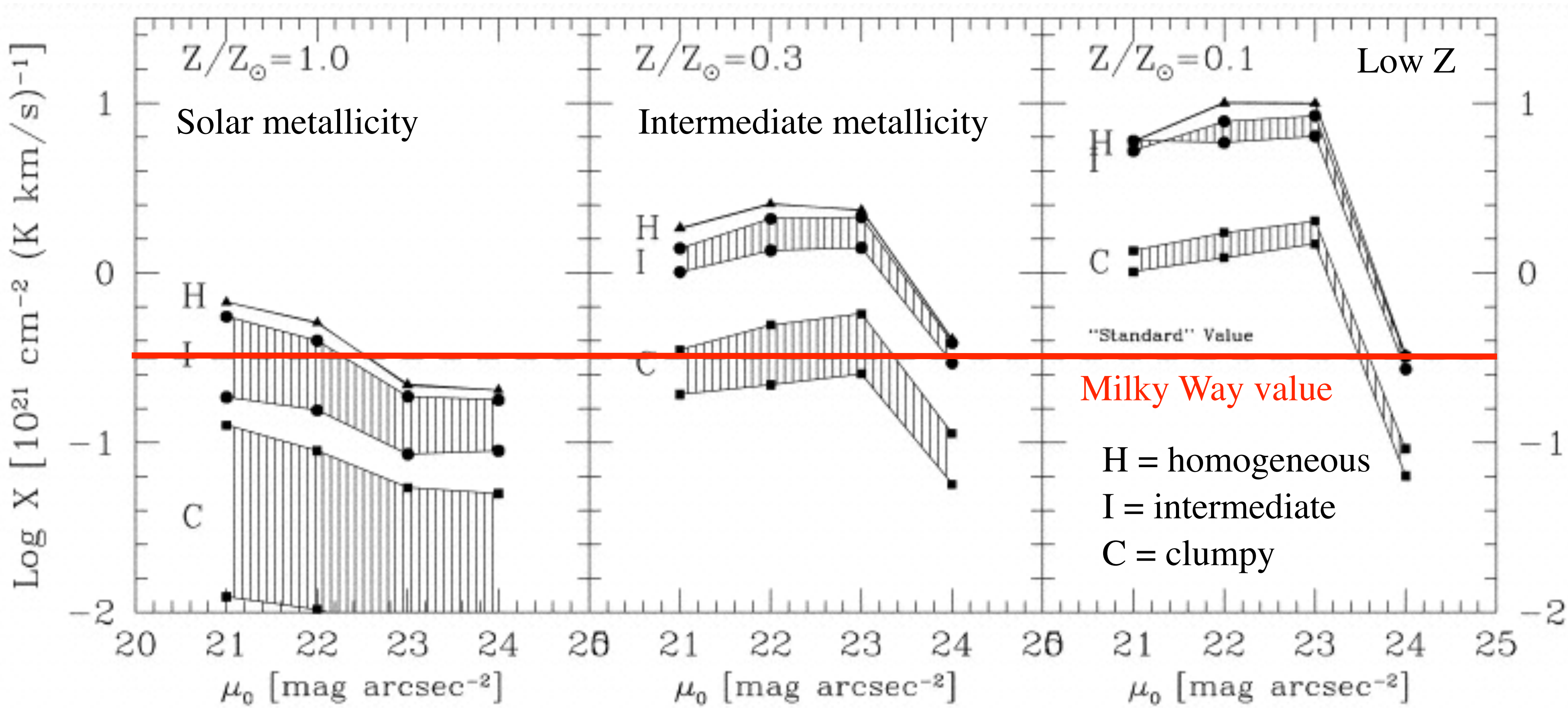
$A_{1\text{-}0} = 7 \times 10^{-8}\ \mathrm{sec}^{-1}$

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