Galaxy Structure: The Sérsic Profile

Instead of using exponential or $r^{1/4}$ fits, use a generalized fitting function called a **Sérsic profile**:

$$I(R) = I_e \exp\left(-b_n\left[\left(\frac{R}{R_e}\right)^{1/n} - 1\right]\right)$$

or, in mag/arcsec^2

$$\mu(R) = \mu_e + \frac{2.5 b_n}{\ln(10)}\left[\left(\frac{R}{R_e}\right)^{1/n} - 1\right]$$

Three parameter fits:

- n : Sérsic index ($b_n \approx 2n - 0.333$)
- R_e : effective radius (radius containing half the total light)
- μ_e : surface brightness at R_e

Note:

- n can be anything, but galaxies generally span n ≈ 0.5 − 10.
- n=1: exponential profile
- n=4: de Vaucouleurs $r^{1/4}$ law.

Galaxy Structure: The Sérsic Profile

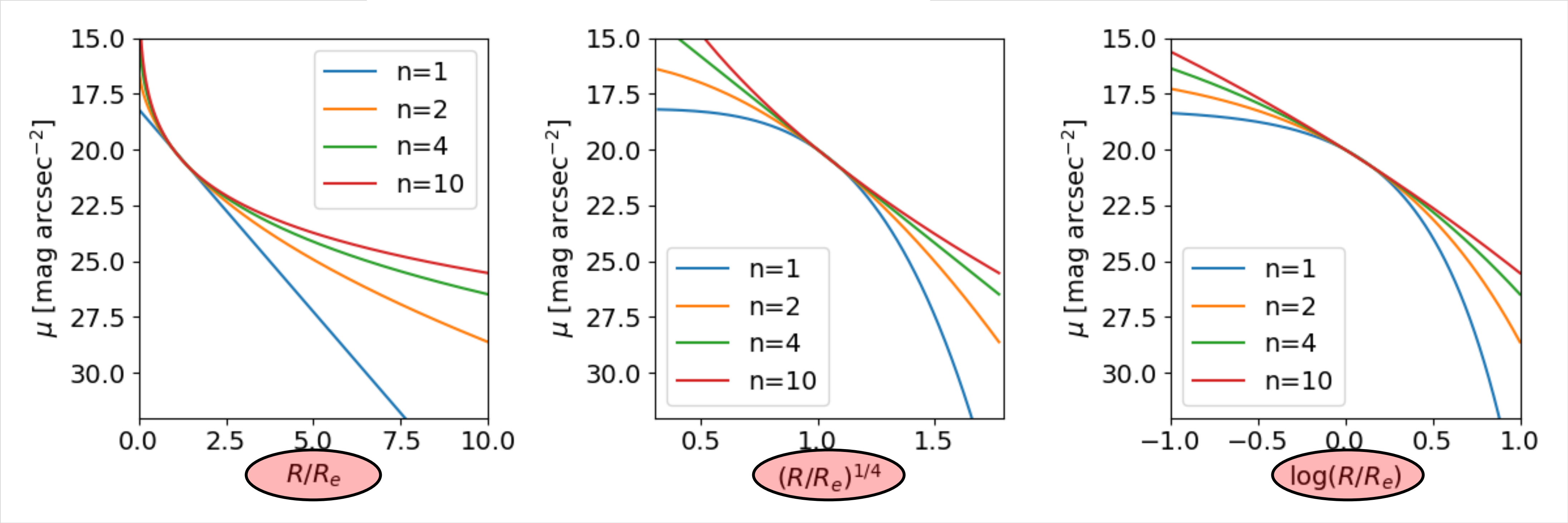
$$\mu(R) = \mu_e + \frac{2.5 b_n}{\ln(10)}\left[\left(\frac{R}{R_e}\right)^{1/n} - 1\right]$$

Remember:
n=1: exponential
n=4: de Vaucouleur

Three parameter fits:
- n : Sérsic index
- R_e : effective radius (half light)
- μ_e : surface brightness at R_e

also can work out:
- $\langle\mu\rangle_e$: average surface brightness within R_e.
- m_{tot}: total (apparent) magnitude

Three projections of the Sérsic profile



Higher n: more light at both small and large radius compared to exponential.

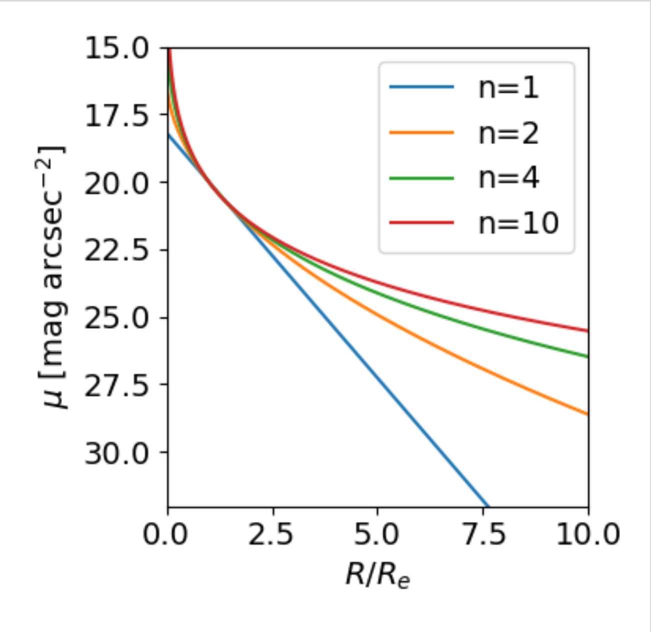
Galaxy Structure: The Sérsic Profile

μ(R) vs R
disk+bulge
Boroson 81

$$\mu(R) = \mu_e + \frac{2.5 b_n}{\ln(10)}\left[\left(\frac{R}{R_e}\right)^{1/n} - 1\right]$$

Disk galaxies are generally a combination of bulge (n≈4) and disk (n≈1). As bulge-to-disk ratio increases, the **total profile** can often be described by intermediate values for n.

Thus the Sérsic index (n) can be used as a tracer of B:D, and thus, crudely, Hubble type.



But remember, a composite profile represented by a given value of Sérsic-n is not conceptually the same as a single component Sérsic profile!

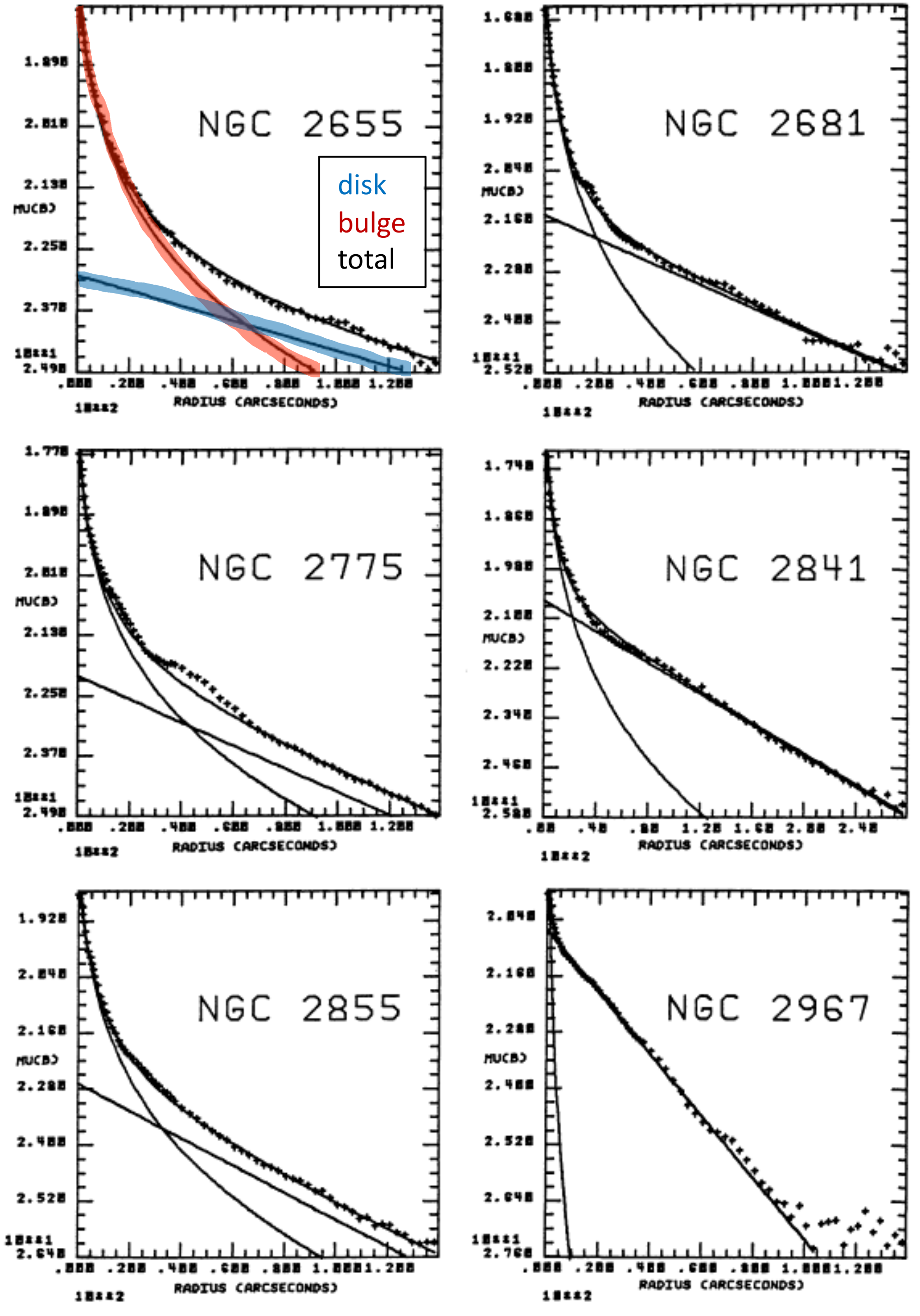


FIG. 6.—*Continued*

Galaxy Structure: SDSS and the Deluge of Data

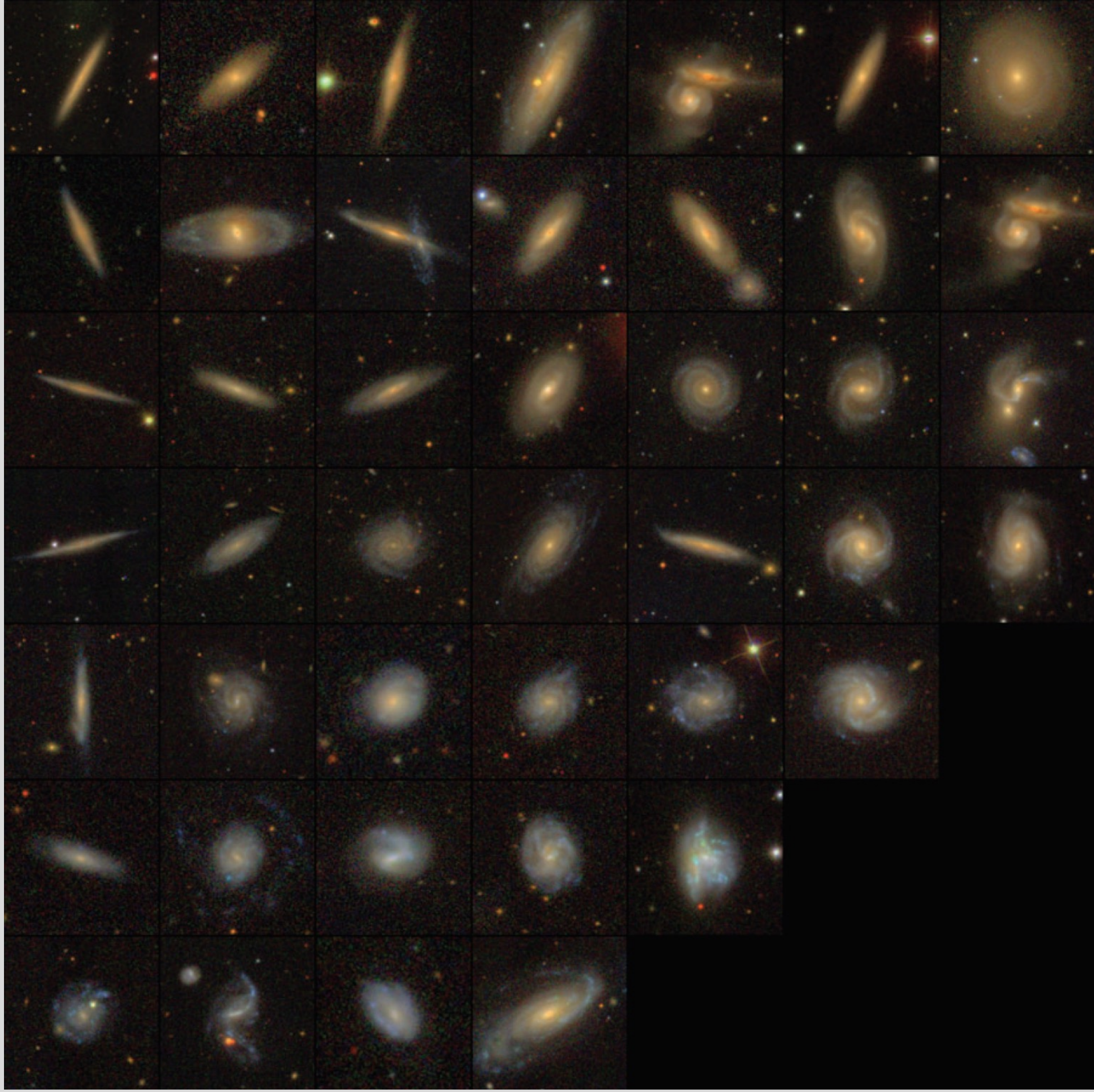
SDSS: Sloan Digital Sky Survey

Over the early 2000s, SDSS began releasing data for millions of galaxies.

Spirals (Sa–Sd)

Blanton & Moustakas 2009
ARAA

redder



bluer

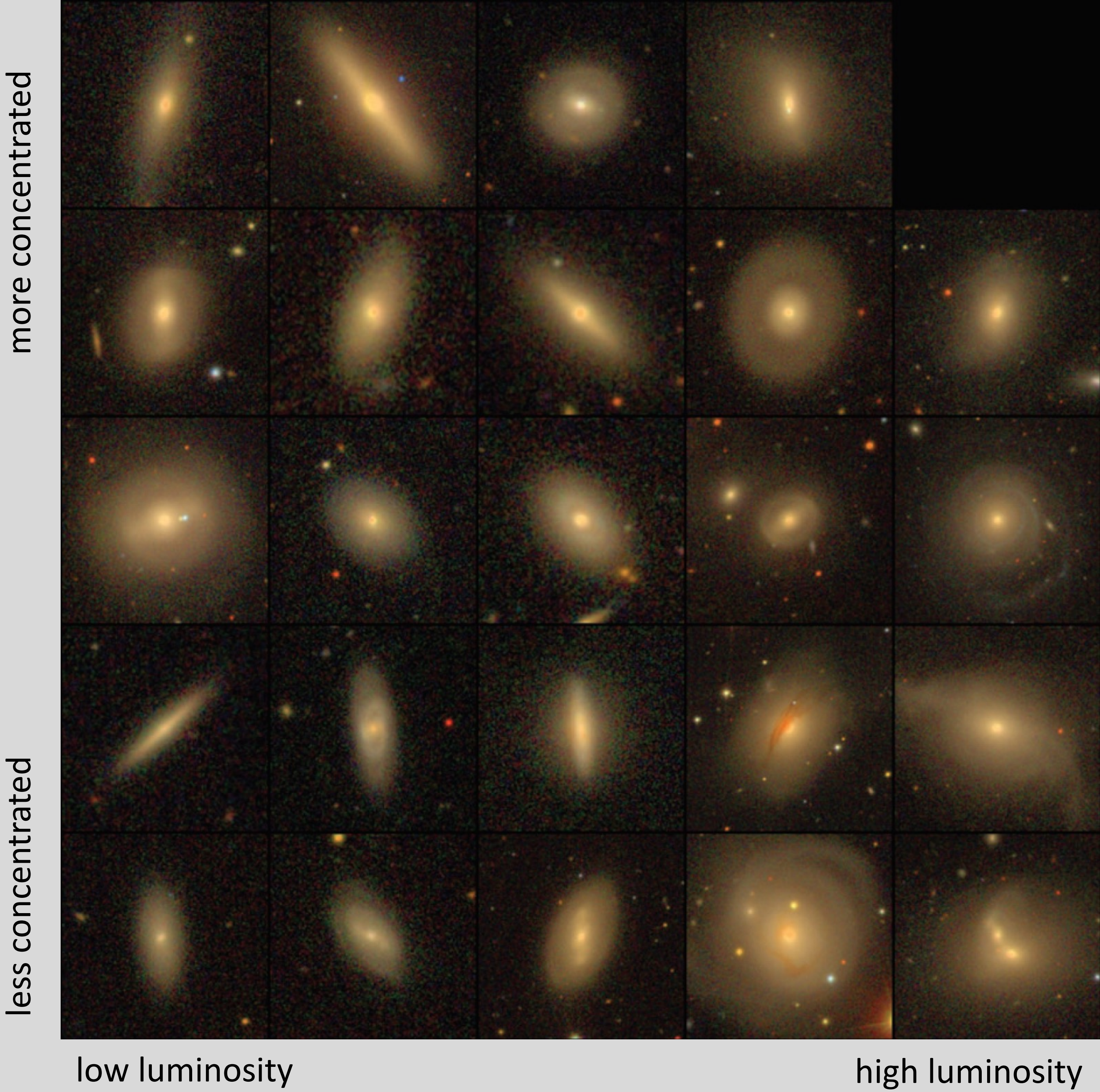
low luminosity

high luminosity

Galaxy Structure: SDSS and the Deluge of Data

SDSS: Sloan Digital Sky Survey

Over the early 2000s, SDSS began releasing data for millions of galaxies.



S0 / Lenticular Galaxies

Blanton & Moustakas 2009

ARAA

Galaxy Structure: SDSS and the Deluge of Data

SDSS: Sloan Digital Sky Survey

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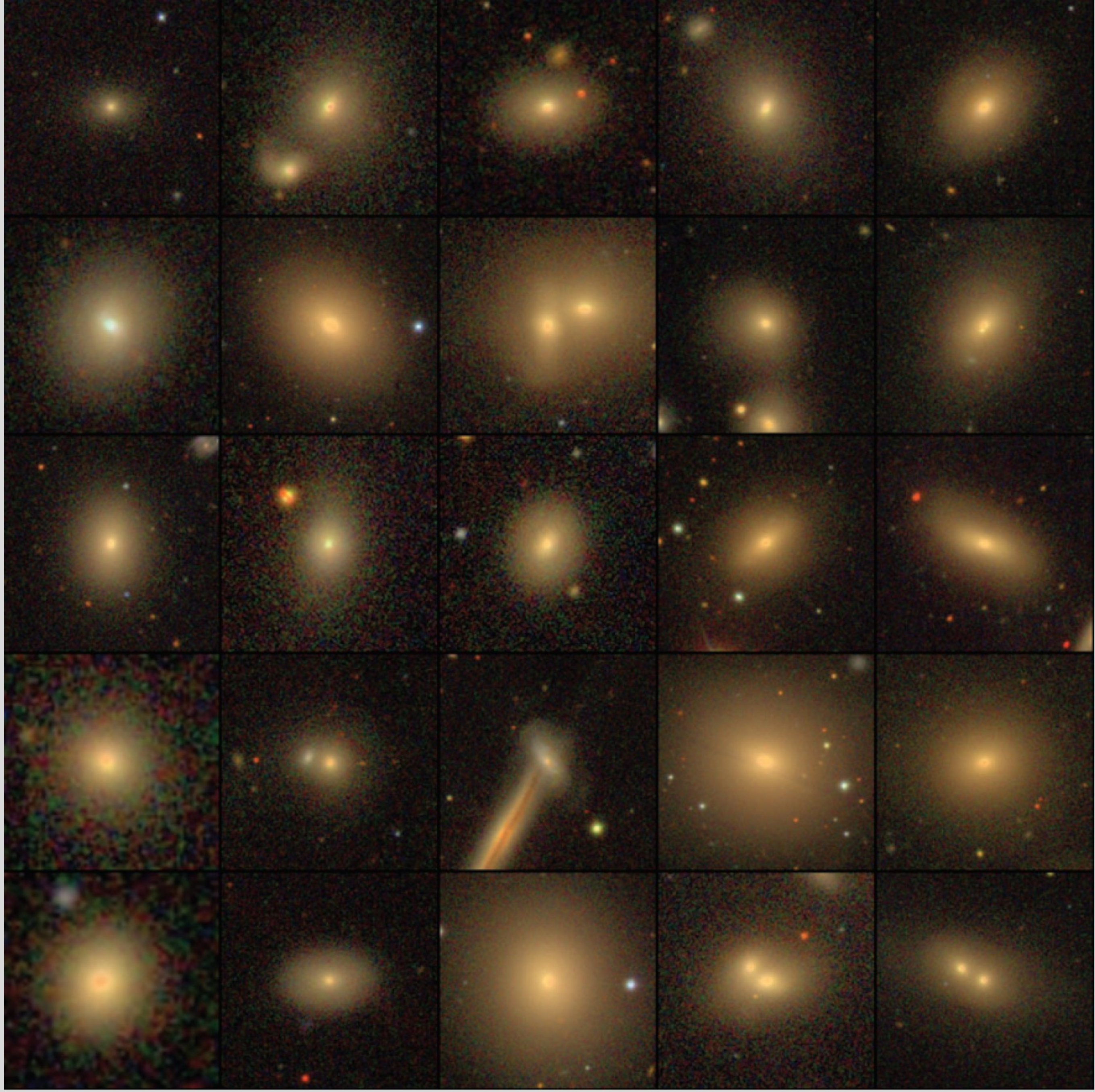


Elliptical Galaxies
Blanton & Moustakas 2009
ARAA

Galaxy Structure: SDSS and the Deluge of Data

Careful multicomponent fitting is time intensive, easier just to autofit a single Sérsic profile to each galaxy.

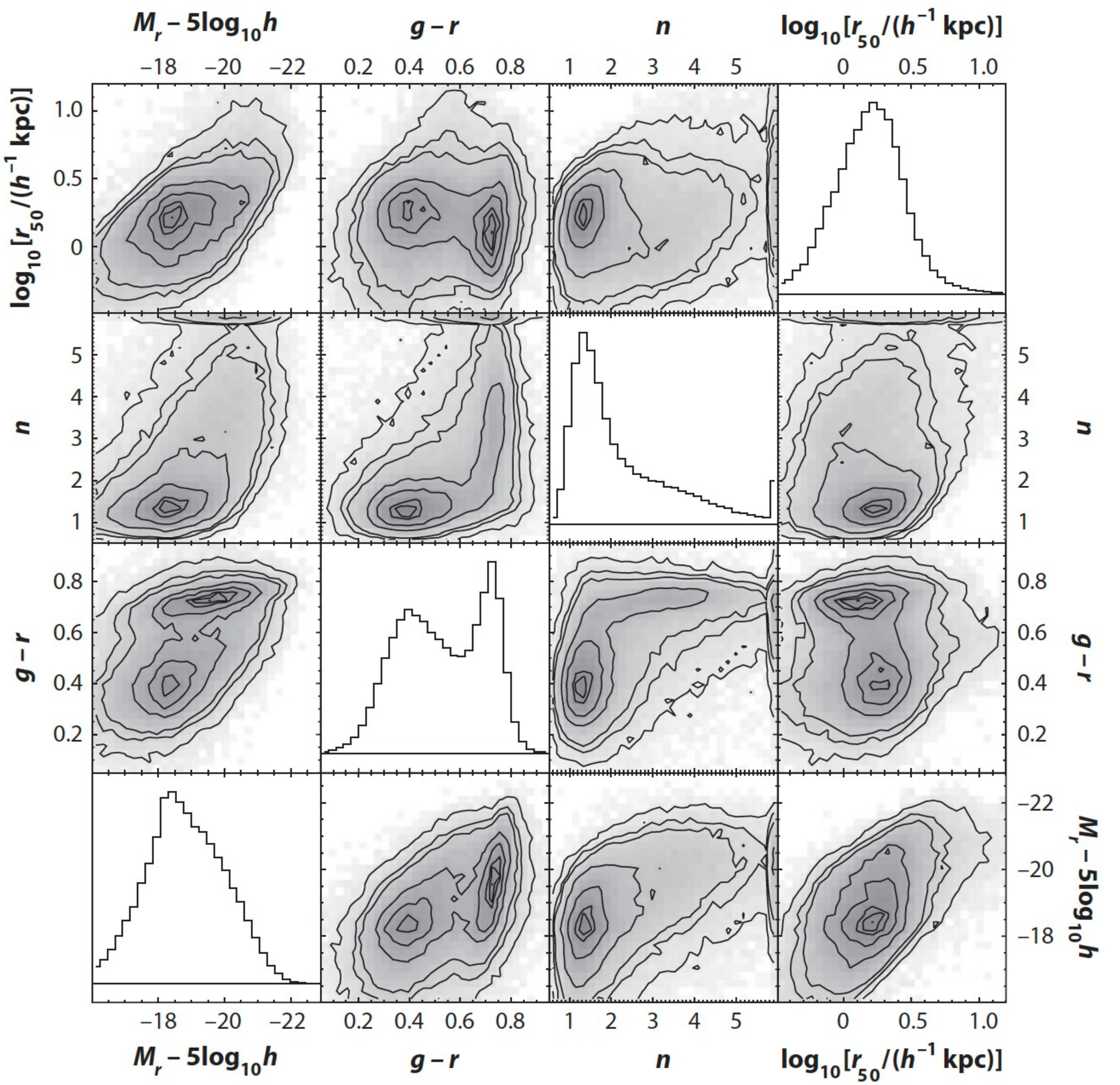
This gives you:

- Sérsic index (n)
- effective radius (r_e, also called r_{50})
- total magnitude (m)

Multiband data, so also color (g-r)

Sérsic n becomes a proxy for galaxy type

Spectroscopy gives you a Hubble distance, can work out absolute magnitude (M) and physical size. Distance-dependent values have an h ($\equiv H_0/100$) term.



77, 153 galaxies
Blanton & Moustakas 2009
ARAA

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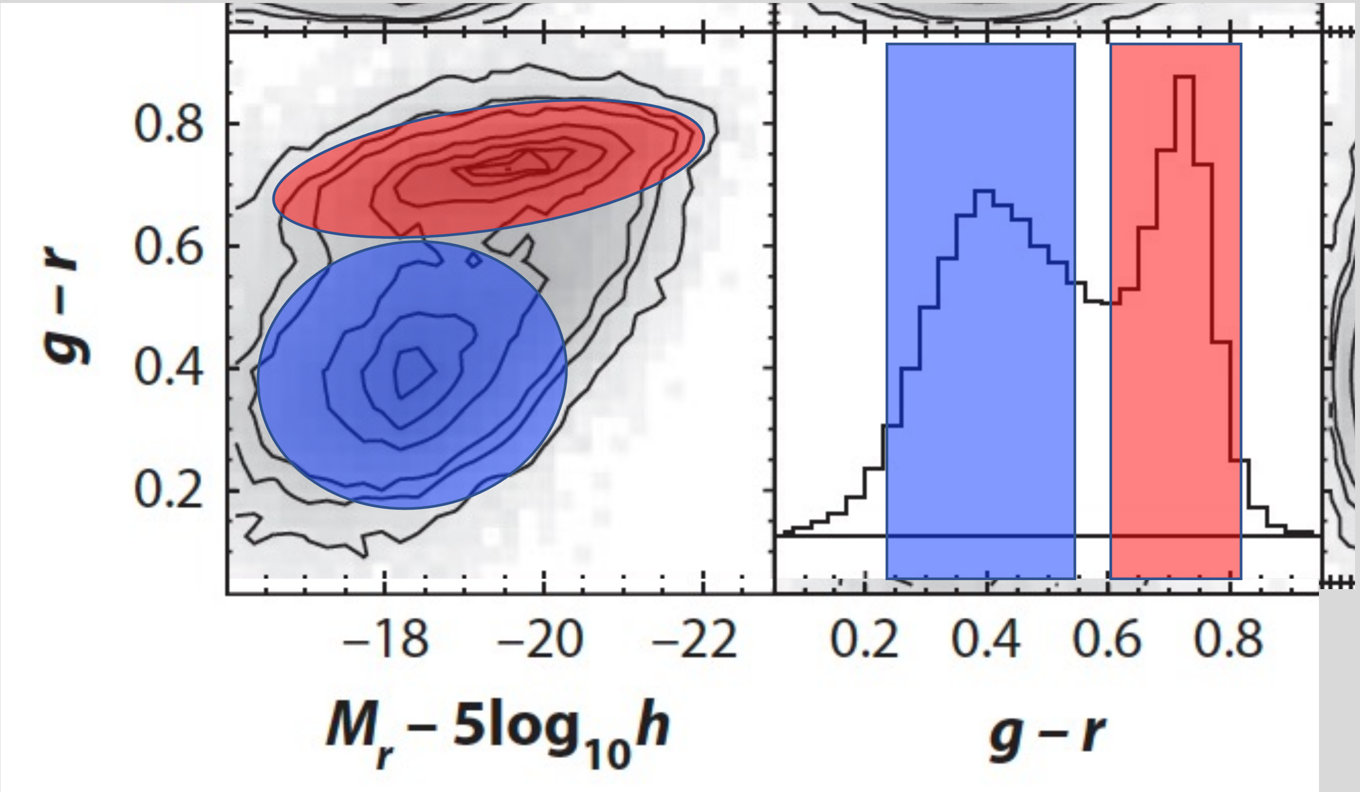

Color vs Luminosity:
galaxies segregate into “red sequence” and “blue cloud”.

77, 153 galaxies
Blanton & Moustakas 2009
ARAA

Galaxy Structure: SDSS and the Deluge of Data

Careful multicomponent fitting is time intensive, easier just to autofit a single Sérsic profile to each galaxy.

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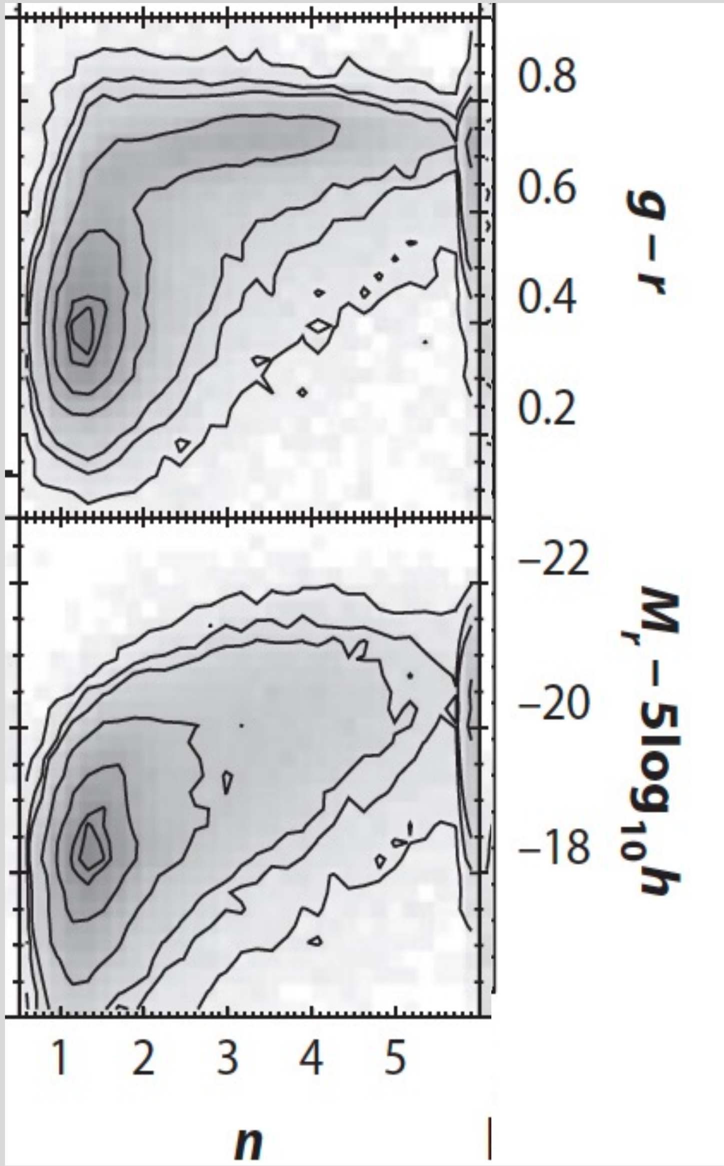
77, 153 galaxies
Blanton & Moustakas 2009
ARAA

Color and Luminosity vs Sérsic n :

- Red galaxies span a range of Sérsic n.
- Blue galaxies tend to have lower n.
- Luminous galaxies tend to be high n and red.



Blanton & Moustakas 2009
ARAA

Galaxy Structure: SDSS and the Deluge of Data

Can derive **stellar mass** from colors and luminosities

Also have spectroscopic information which tells us

Metallicity: 12+log(O/H) (Solar ≈ 8.75)

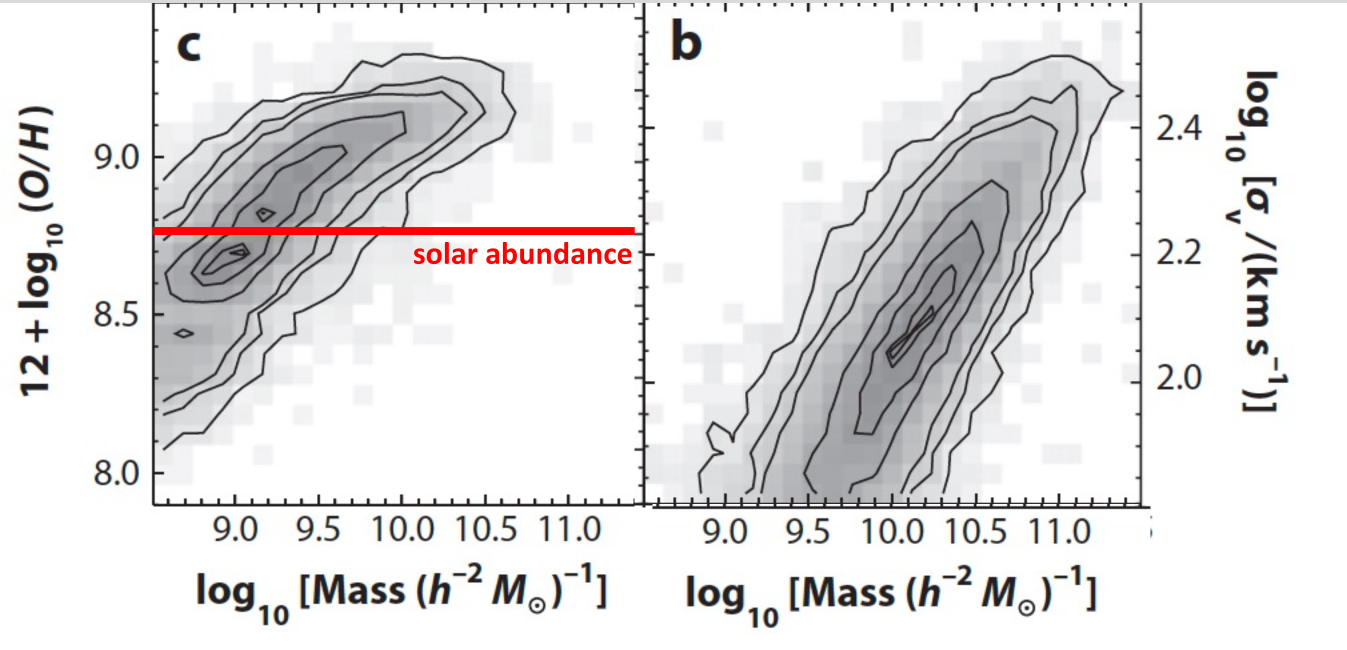
> Galaxies follow a **mass-metallicity relation**: more massive galaxies are more metal-rich

Velocity dispersion: σ, in km/s. the characteristic random speeds of stars, a tracer of total mass.

> Galaxies with higher stellar mass have higher velocity dispersion.

mass - metallicity

mass – velocity dispersion



stellar mass

Important Caveats: Observational Bias

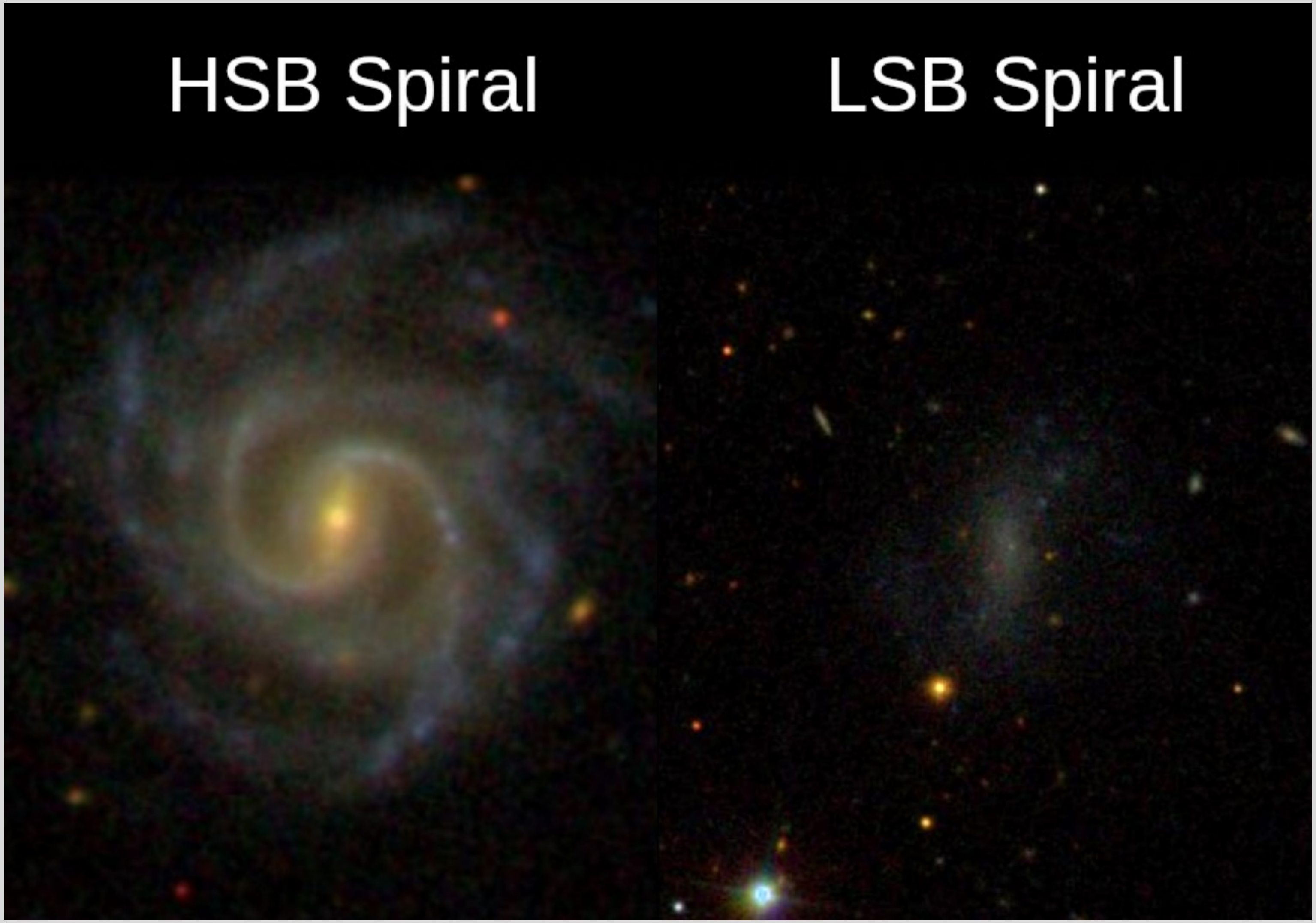
SDSS is both **flux limited** and **surface brightness limited**. This means it it is likely to miss galaxies that are faint, small, and low in surface brightness.

Night Sky Surface Brightness:

- Full Moon: $\mu_{B,sky} \approx 19.5$ mag/arcsec^2
- New Moon: $\mu_{B,sky} \approx 22.7$ mag/arcsec^2

It quickly become hard to detect objects (or measure profiles) when their surface brightness is significantly “below sky.”

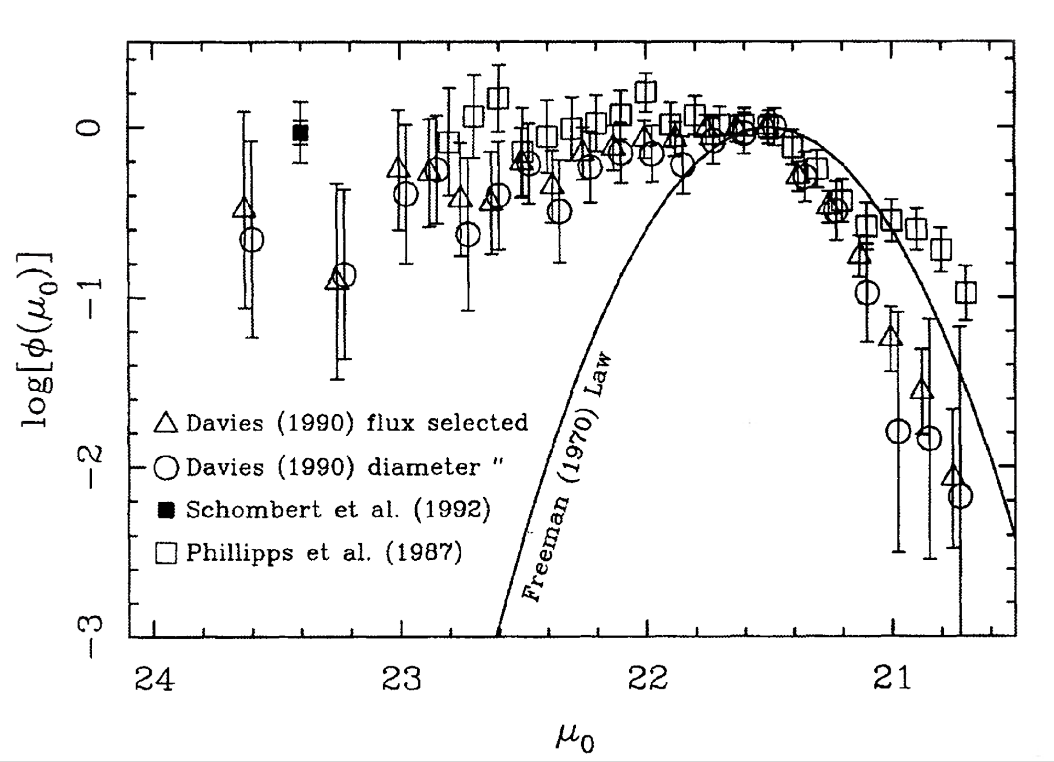
Particularly problematic for low luminosity galaxies (which are typically low surface brightness: “LSB”).



Low surface brightness (LSB) galaxies

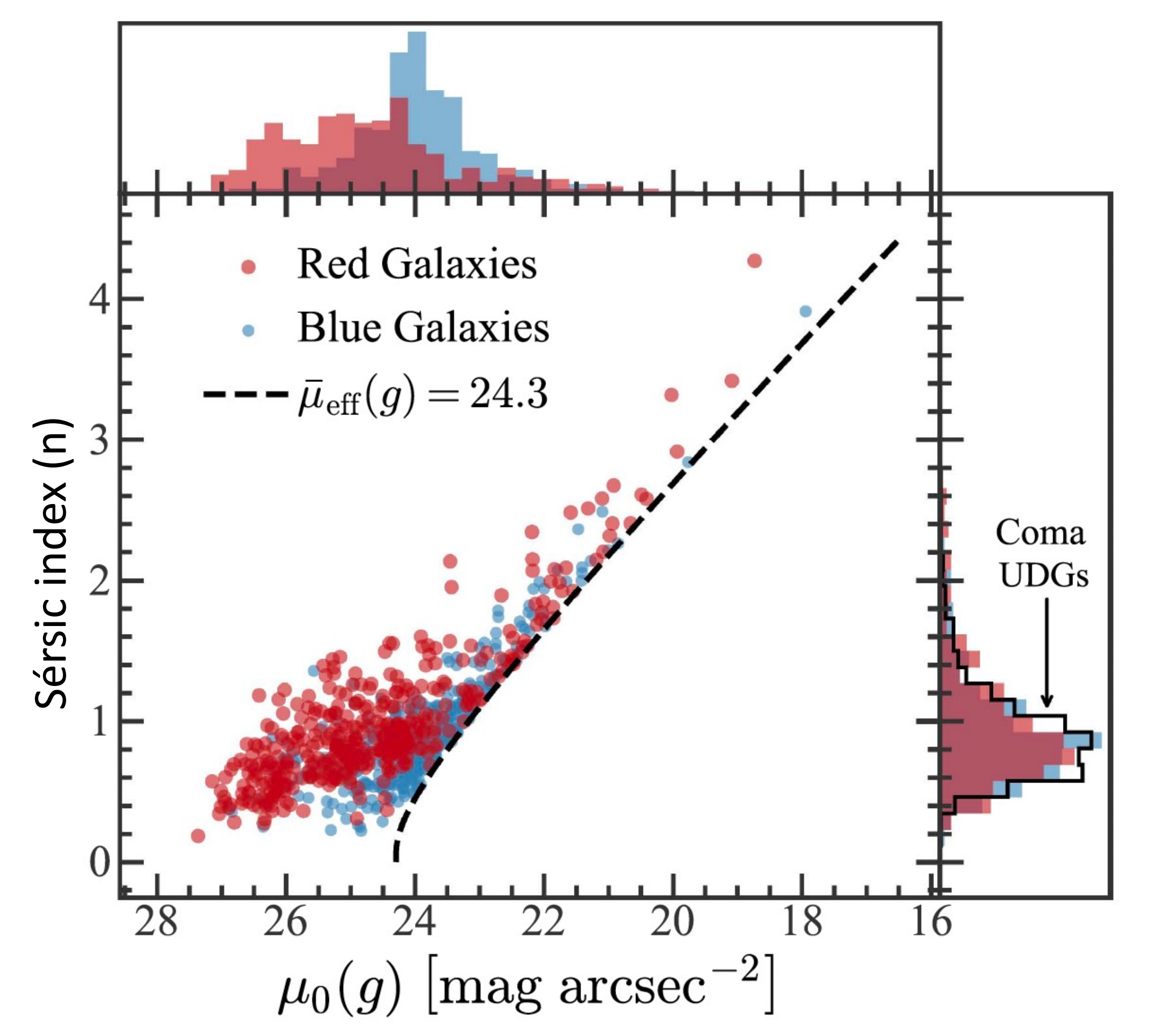
There are lots of them out there!

Number of galaxies per Mpc^3 as a function of surface brightness (McGaugh 95)



LSB HSB

Recent surveys show lots of galaxies exist at really low surface brightness! (Greco+18).



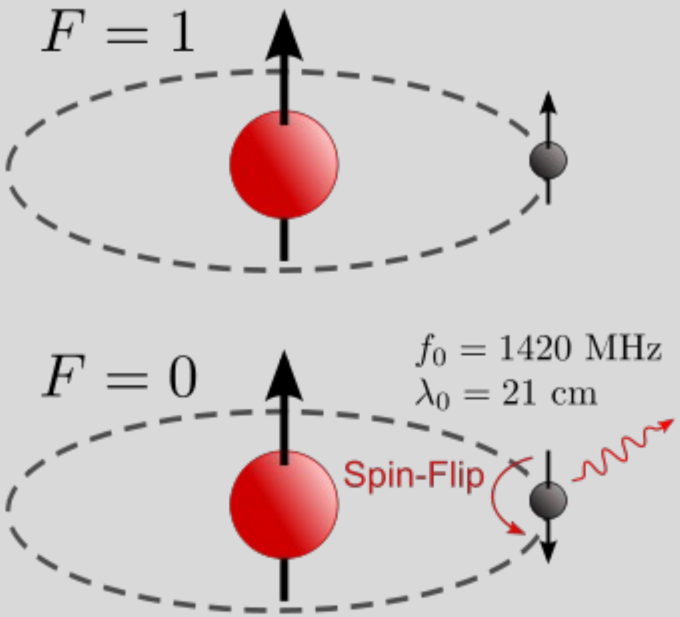
VLSB VHSB

Phases/Components of the Interstellar Medium **("the stuff between the stars")**

Phase	Temperature	Density	Filling Factor	Radiative Process	Wavelength
Cold Molecular gas *(where star formation happens!)*	10K	10^4 cm^{-3}	Low	molecular emission lines (vibration/rotation modes)	radio, mm
Cool Atomic gas	100K – 1000K	10^3 cm^{-3}	Low	e$^-$ spin flip	21cm radio
Warm Ionized gas	10,000K	10^2 cm^{-3}	Moderate	Recombination emission lines, plus some free-free continuum emission	optical, radio
Hot Ionized gas	10^5 K – 10^6 K	1 cm^{-3}	High	free-free continuum emission	X-rays
Dust grains	10K – 30K		Patchy	hydrocarbon emission lines, blackbody	mid-IR, far-IR

Neutral Hydrogen (HI)

Cool gas (100K – 1000K): atoms are in ground state. No optical emission lines.



Radiates via spin-flip of the electron. Flip happens spontaneously, with 10 million year timescale.

One flip produces one photon, with $\lambda = 21$ cm. Radio emission!

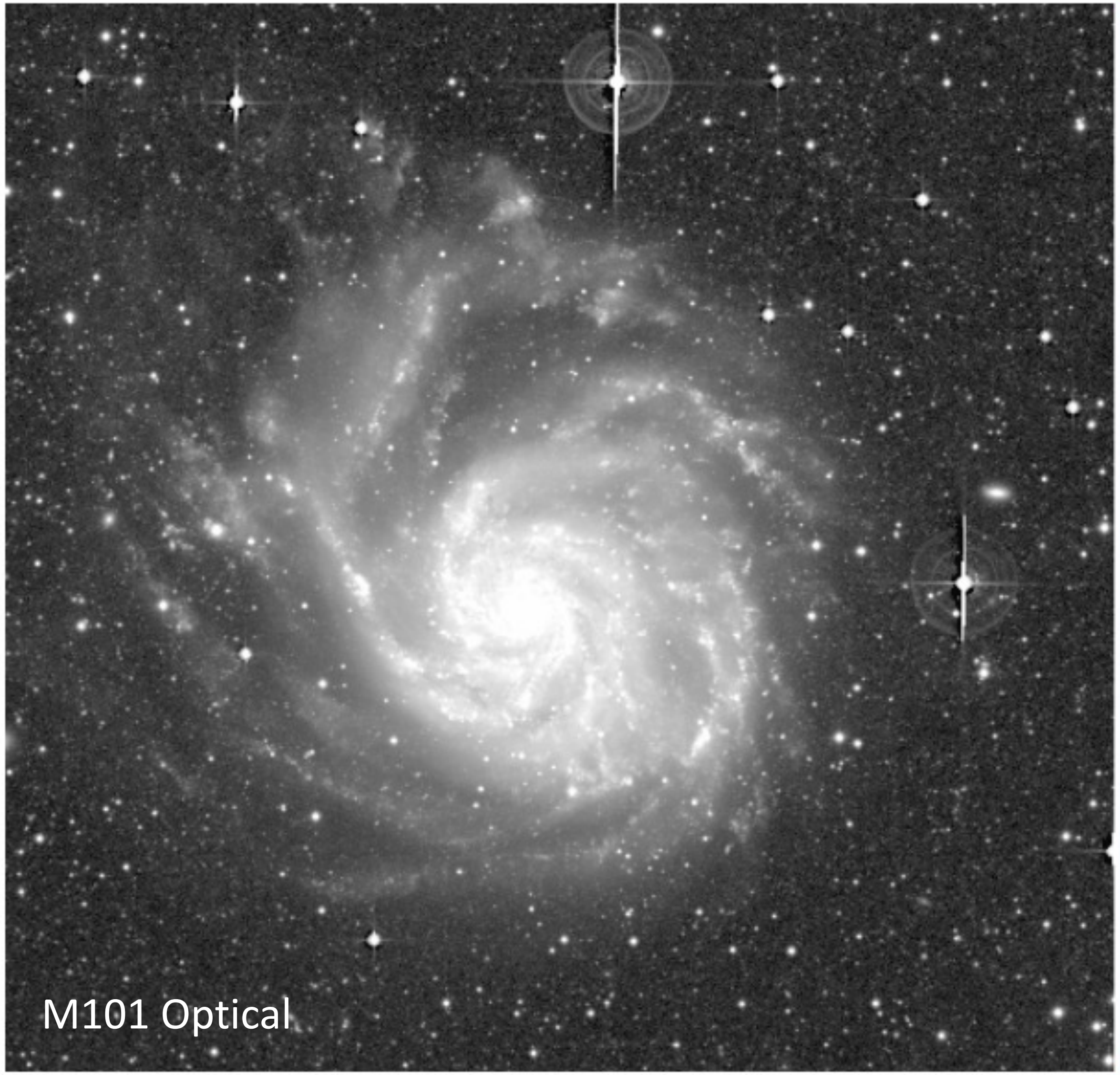
If the gas is optically thin (i.e., no absorption, we see all the photons), then:

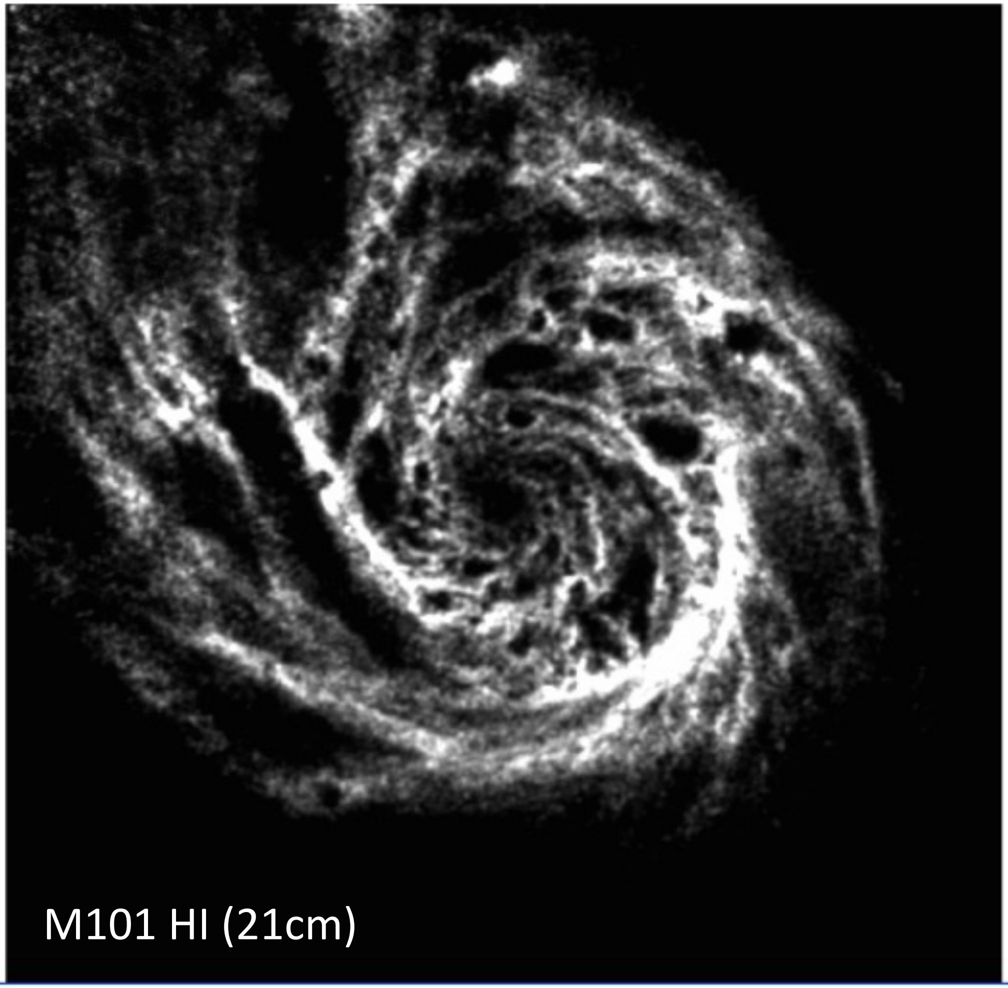
- 21cm surface brightness ➝ surface density of atomic gas
- 21cm luminosity ➝ total mass of atomic gas

Also, since it is an emission line:

- wavelength ➝ gas velocity
- line width ➝ gas turbulent velocity

Neutral Hydrogen (HI)

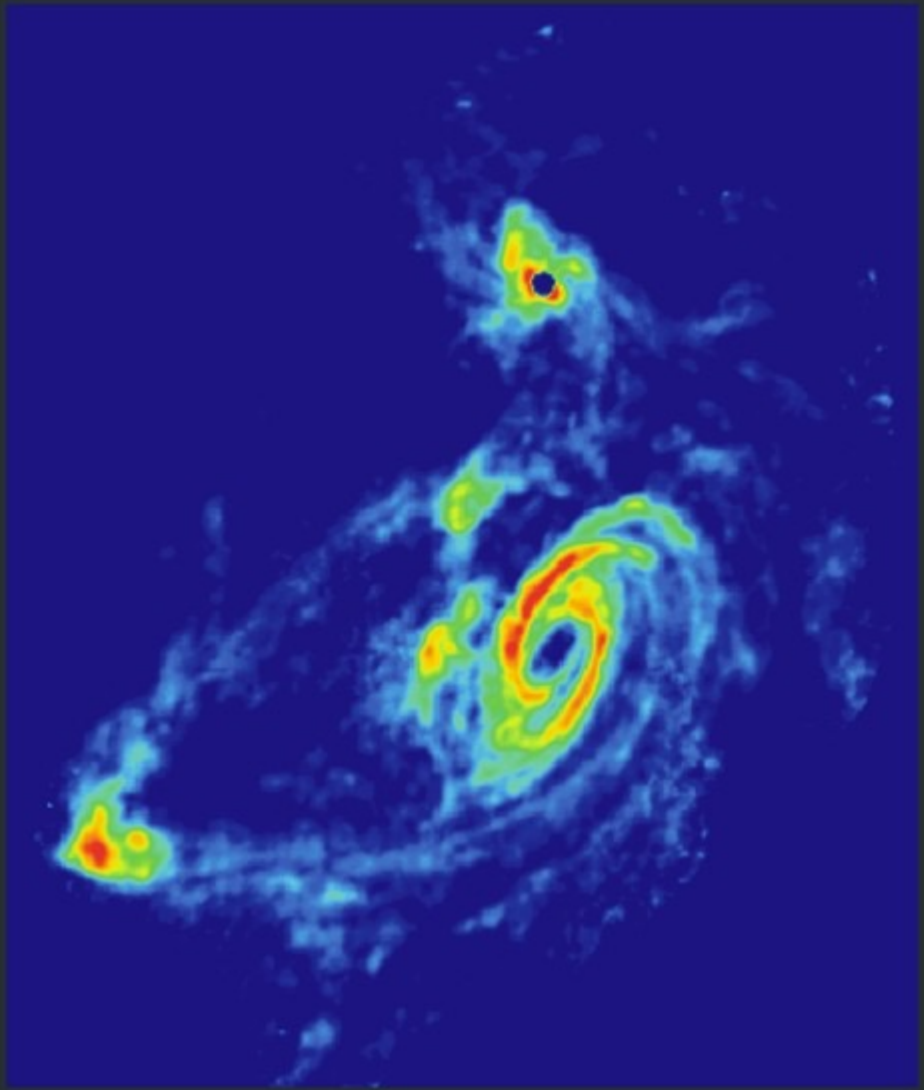

M101 Optical


M101 HI (21cm)

TIDAL INTERACTIONS IN M81 GROUP

Stellar Light Distribution

21 cm HI Distribution



Molecular Gas

Molecular gas radiates through vibration and rotation modes.

Need a changing dipole moment to produce radio waves. For example, the CO_2 molecule ➞

The most common molecule is H_2, but that has no dipole moment, so does not radiate (much).

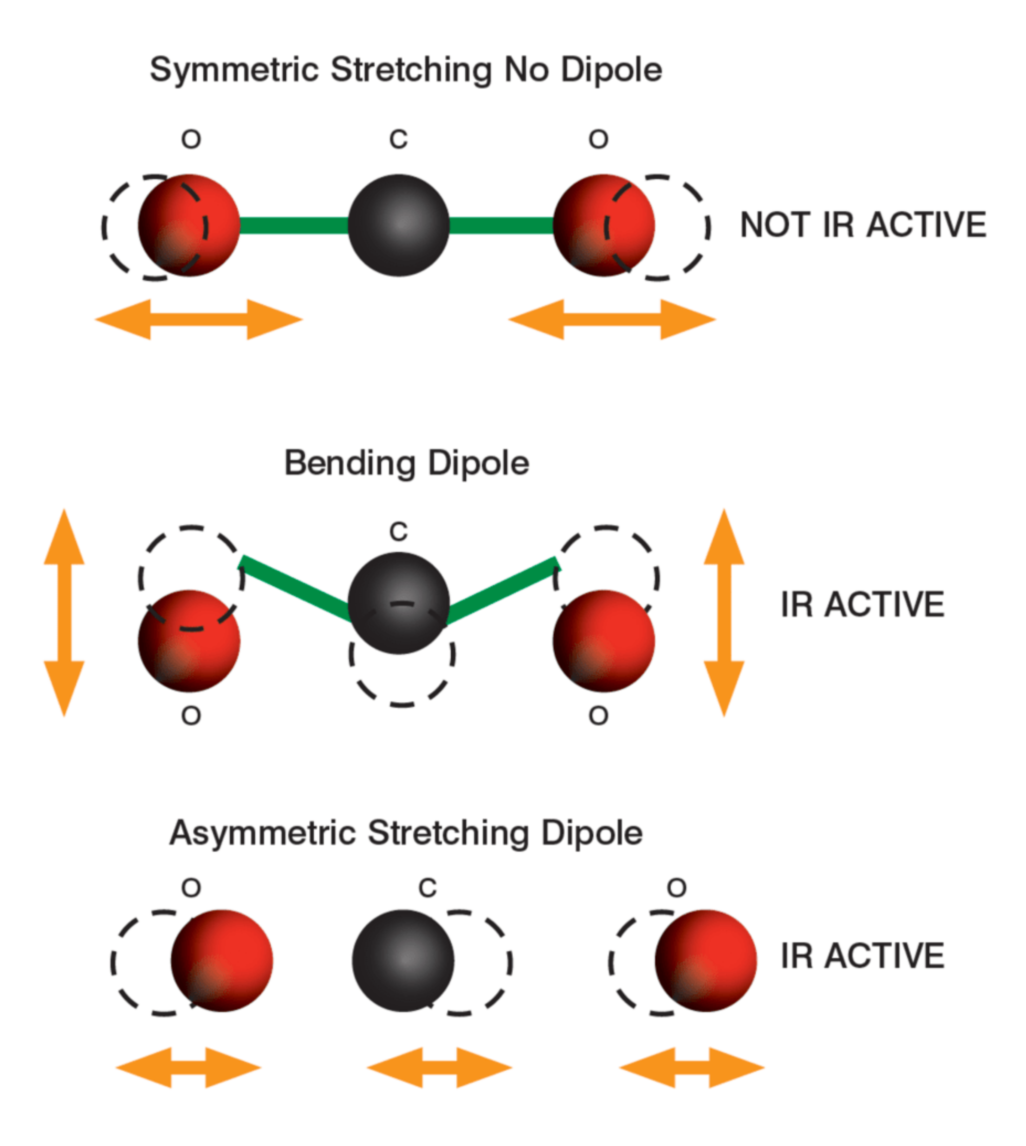
CO is common, and bright, so we use that as a tracer. If there is molecular CO, there must be tons of molecular H_2 as well.

$M(H_2) = X_{CO}\ L_{CO}$ where

L_{CO} = Luminosity of CO emission
X_{CO} = Conversion factor (but is it the same everywhere?)

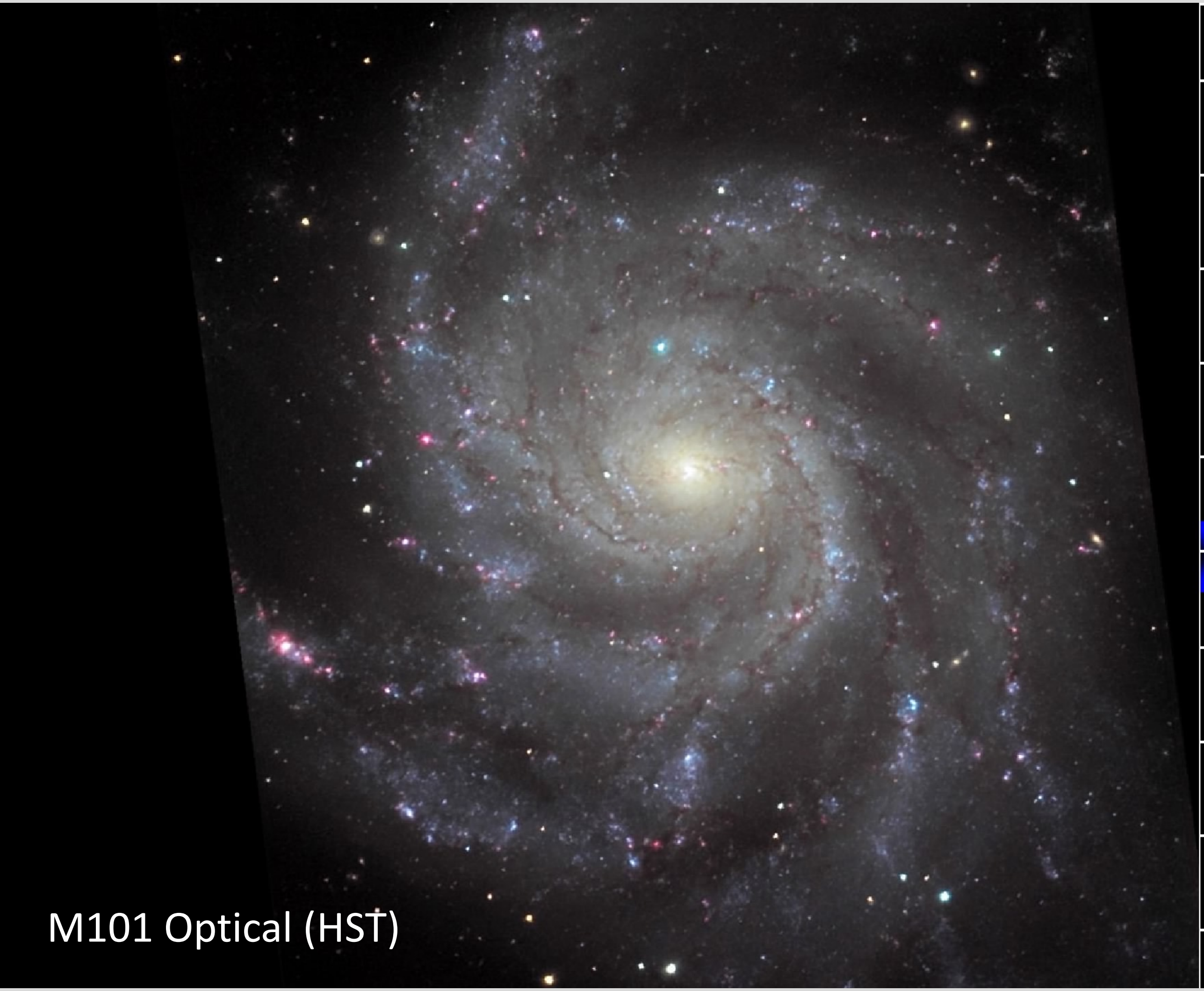
Other molecules trace even higher density gas, eg ^{13}CO, HCN, CO_2

Vibration modes in the CO_2 molecule

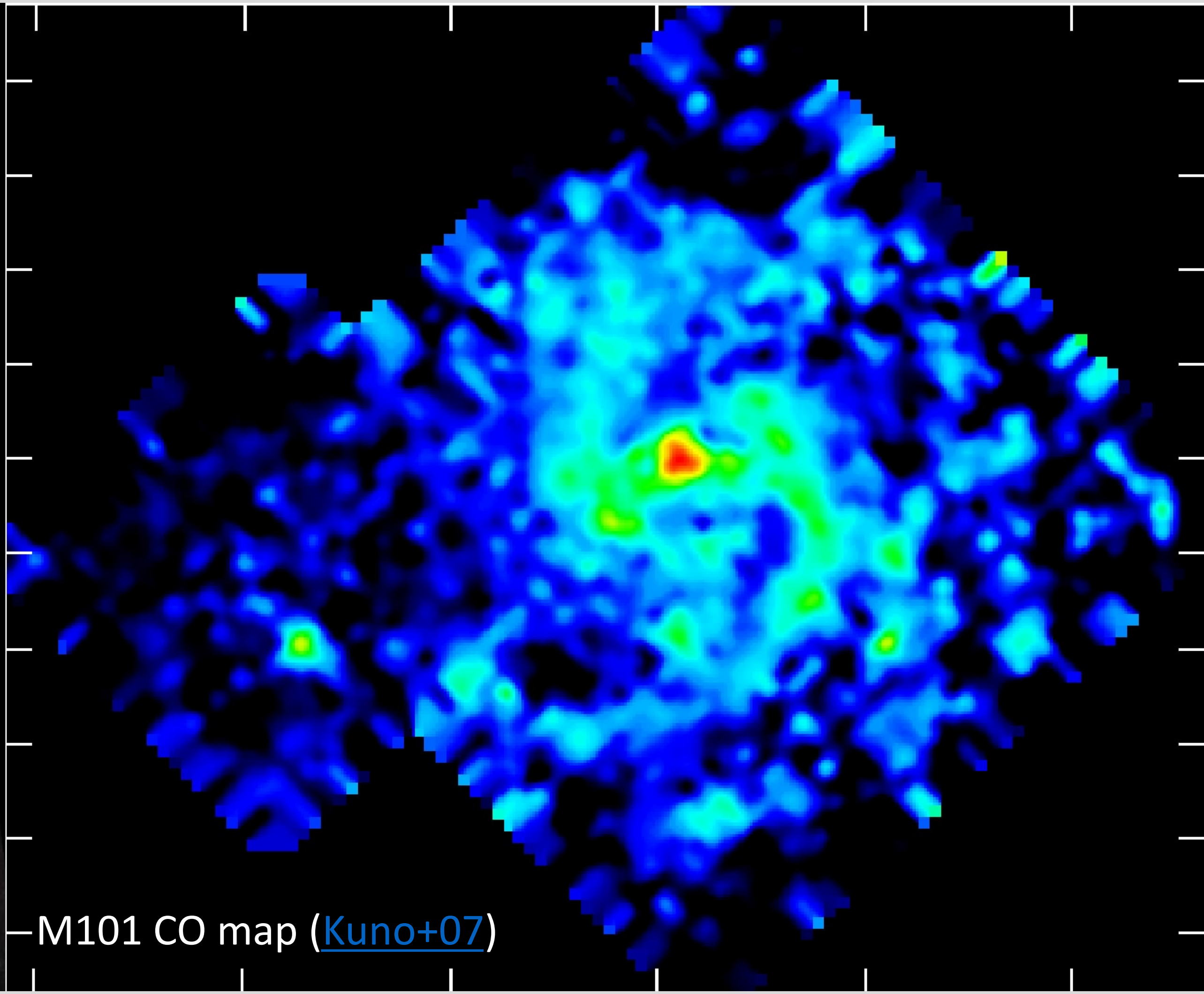


Molecular Gas

Much more centrally concentrated the the HI (neutral hydrogen) gas. Strongly associated with star formation.



M101 Optical (HST)

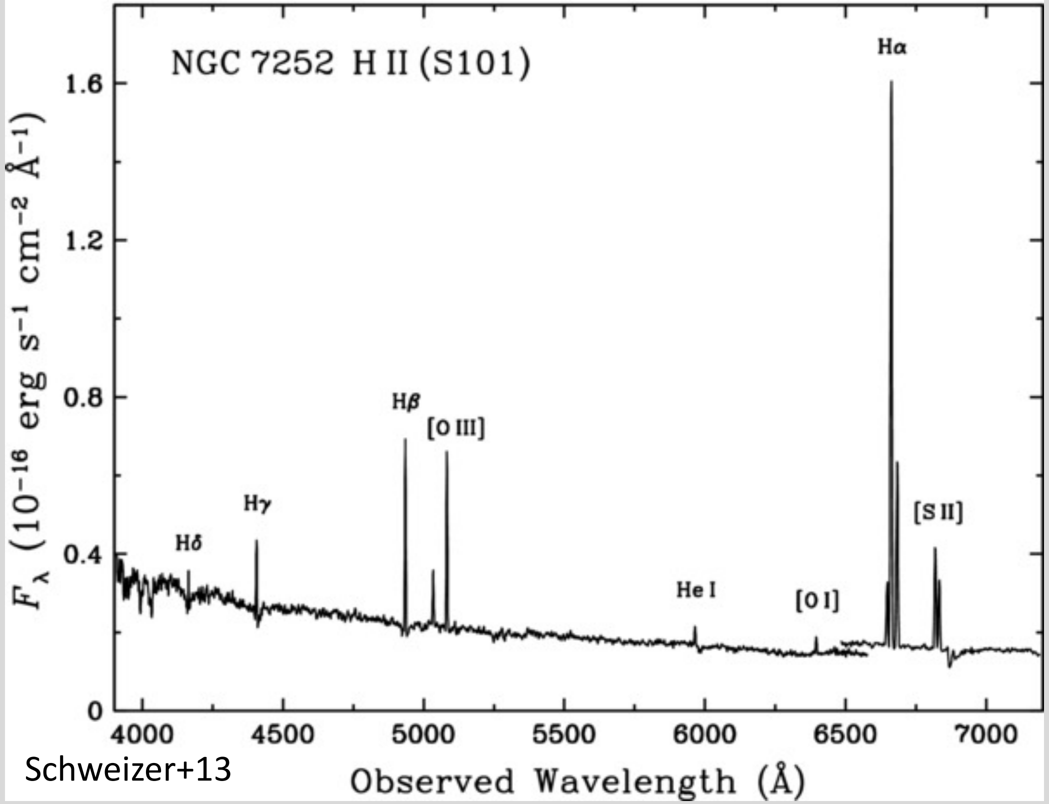


M101 CO map (Kuno+07)

Ionized Gas

Gas heated by photoionization (from young stars or AGN) or collisional ionization in shocks (turbulence, stellar/AGN winds).

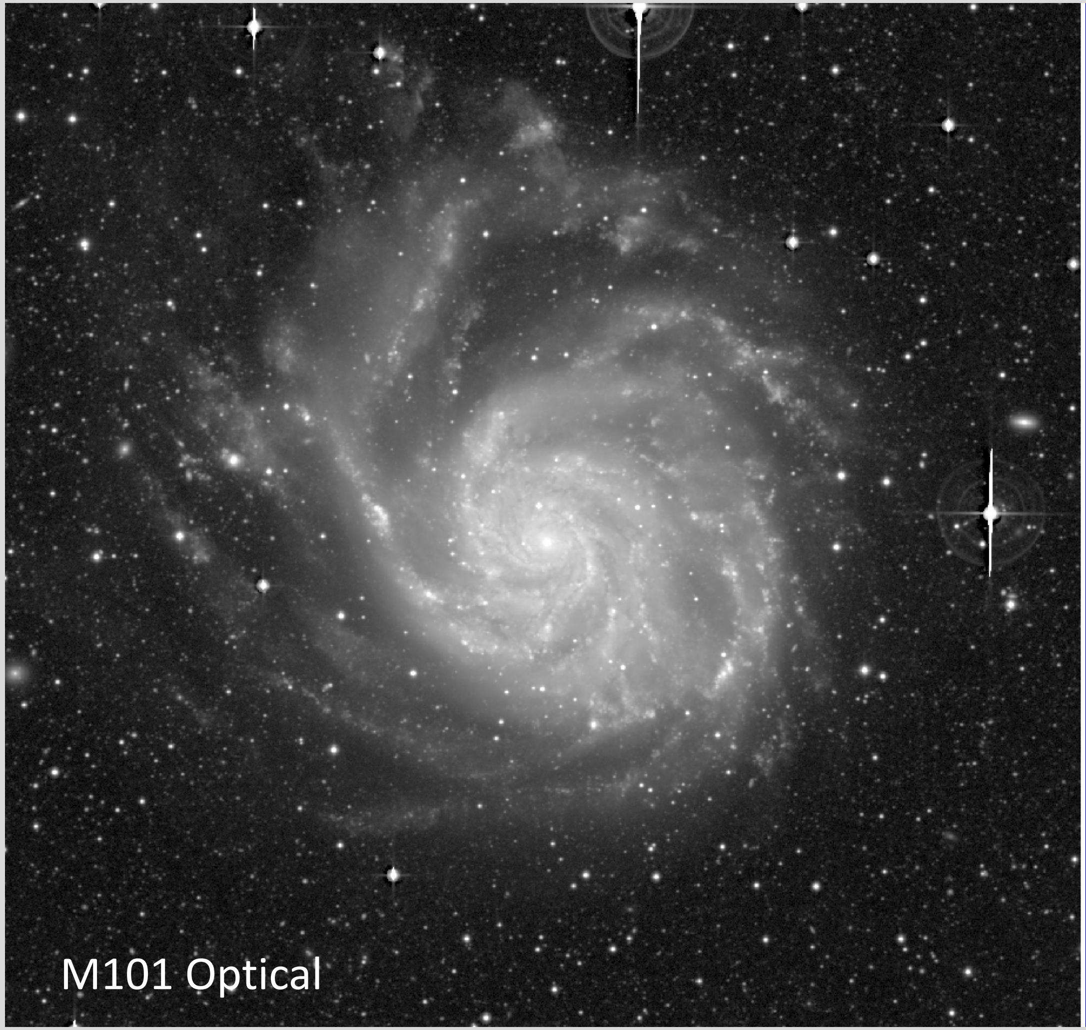
Radiates through recombination and subsequent downward cascades through atomic energy levels. Predominantly emission line radiation.

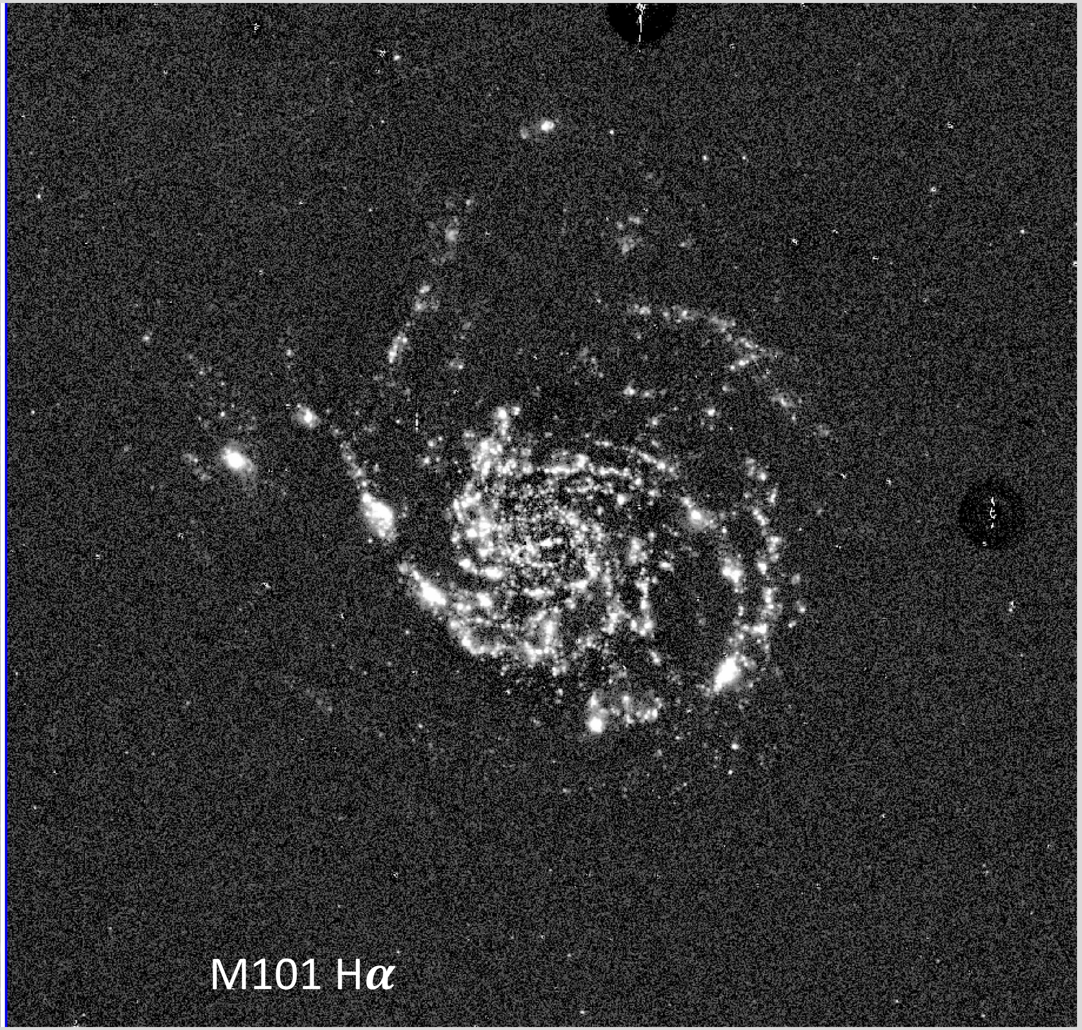


Schweizer+13

The Great Nebula in Orion (or just “Orion”)

Ionized Gas





Ionized Gas: Line Nomenclature

Forbidden lines: At higher densities, atoms can de-excite collisionally rather than through a radiative cascade. Emission lines coming from transitions which are collisionally suppressed at higher densities (ie in the lab) are called “forbidden” and are usually denoted with brackets.

Ionization state: denoted via roman numerals: I=neutral, II=once ionized, III=twice ionized, etc.

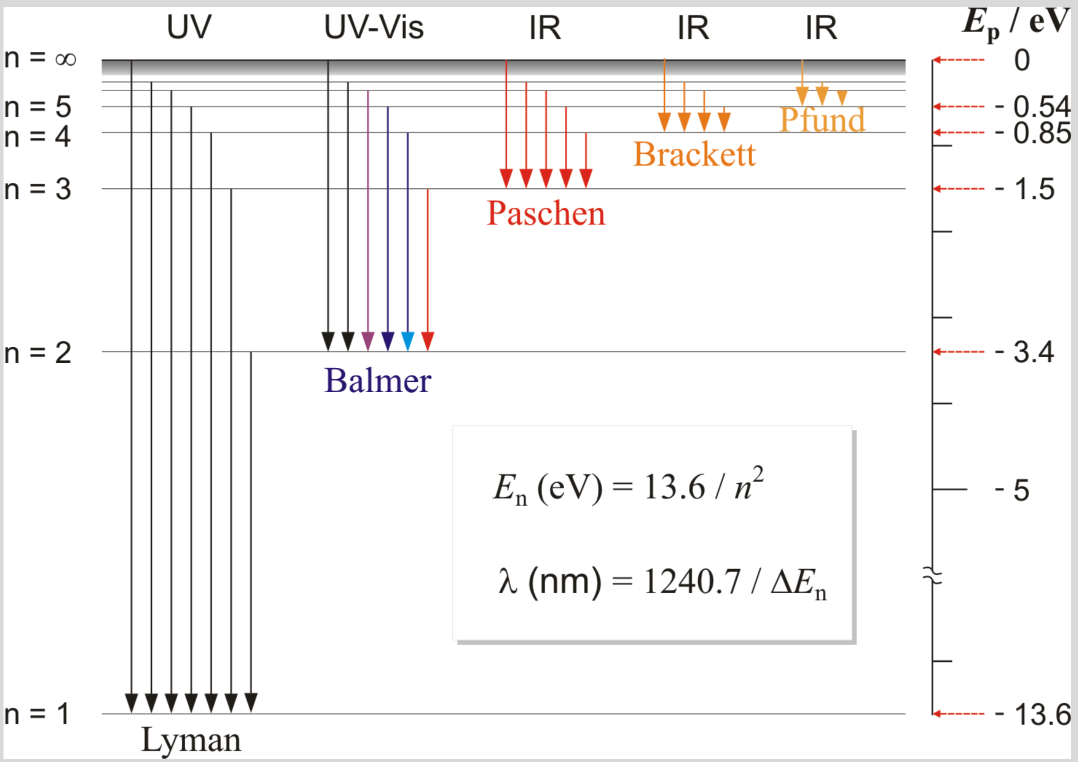
Wavelength: if included, written as λxxxx at the end.

So:
- **[OIII]** : a forbidden line from twice-ionized oxygen.
- **[SII]λ6718** : forbidden line at 6718Å from once-ionized sulfur.

Hydrogen series use special notation:

Lyman (transitions to n=1: Lyα, Lyβ, Lyγ, etc, in UV)
Balmer (transitions to n=2: Hα, Hβ, Hγ, etc, in optical)
Paschen (transitions to n=3: Paα, Paβ, Paγ, etc, in IR)

Hydrogen transitions



Emission Line Diagnostics

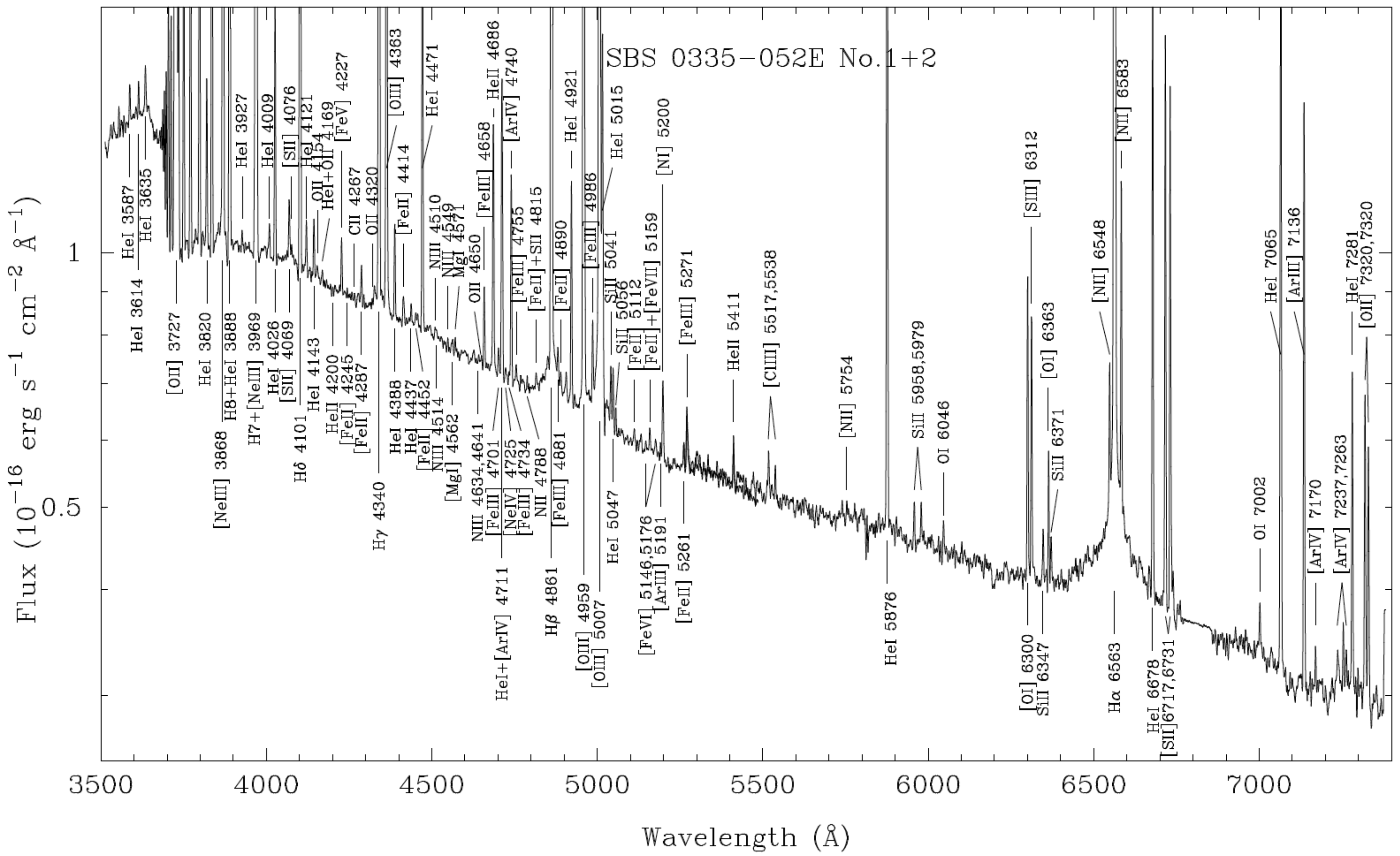
Emission lines sensitive to temperature, density, metallicity, ionization source.

Reddening by Dust: Transition probabilities in Hydrogen are purely a quantum mechanical property of the atom, rather than the environment, and under most situations the line ratios reflect these probabilities. Common conditions ("Case B approximation") give $H\alpha/H\beta$ flux ratio ≈ 2.7. If the observed ratio is different, it is because dust is preferentially extincting the bluer $H\beta$ line.

Gas temperature: line ratios for ions with different ionization potentials give information on the gas temperature and/or the ionization mechanism (stars/AGN/shocks).

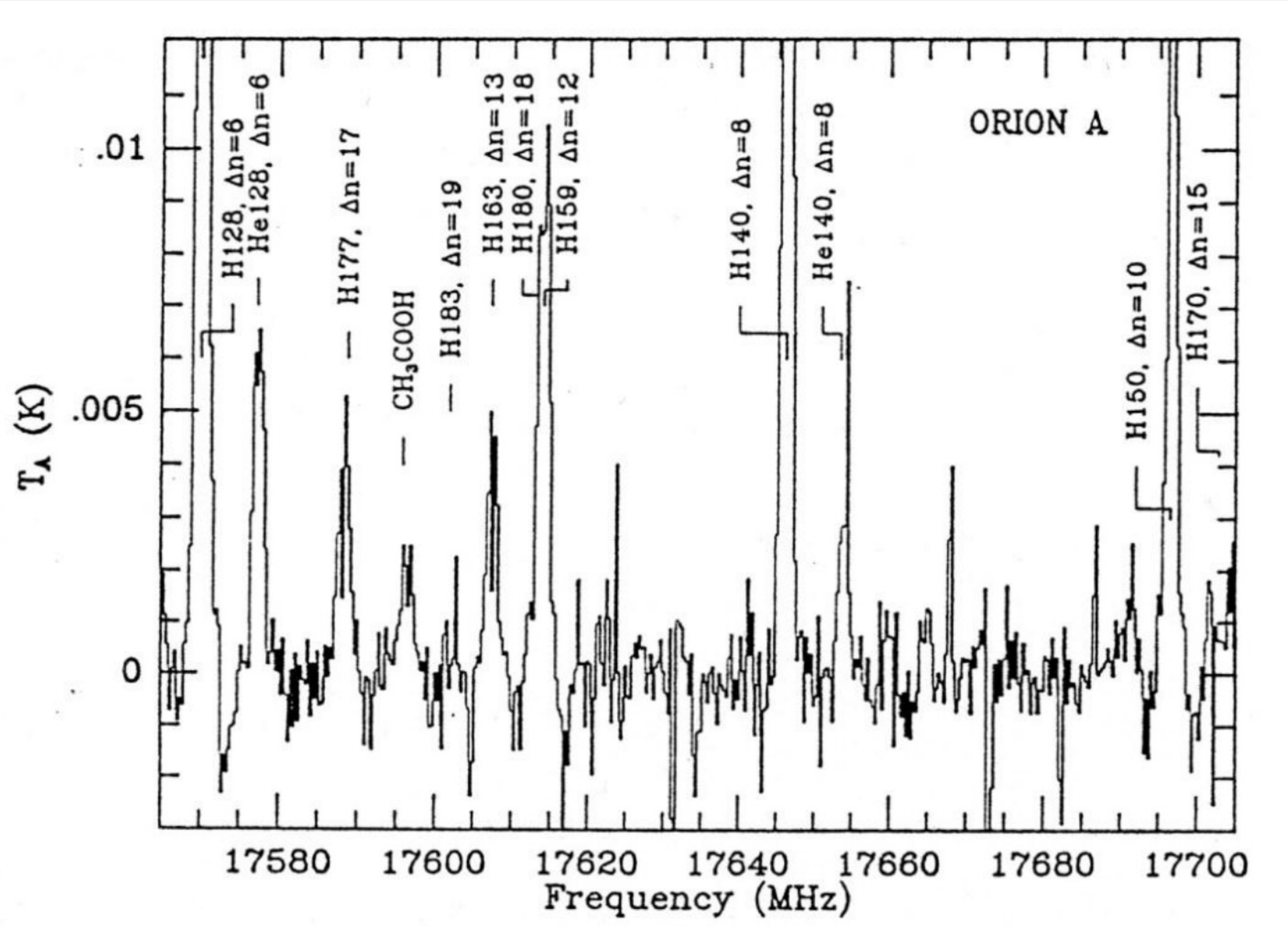
Gas density: Consider doublet lines (eg [SII]$\lambda\lambda$6717,6731). The have same ionization potential, but different sensitivity to collisional de-excitation. These line ratios give information on the density of the gas.

Optical Emission Lines



Radio Emission Lines

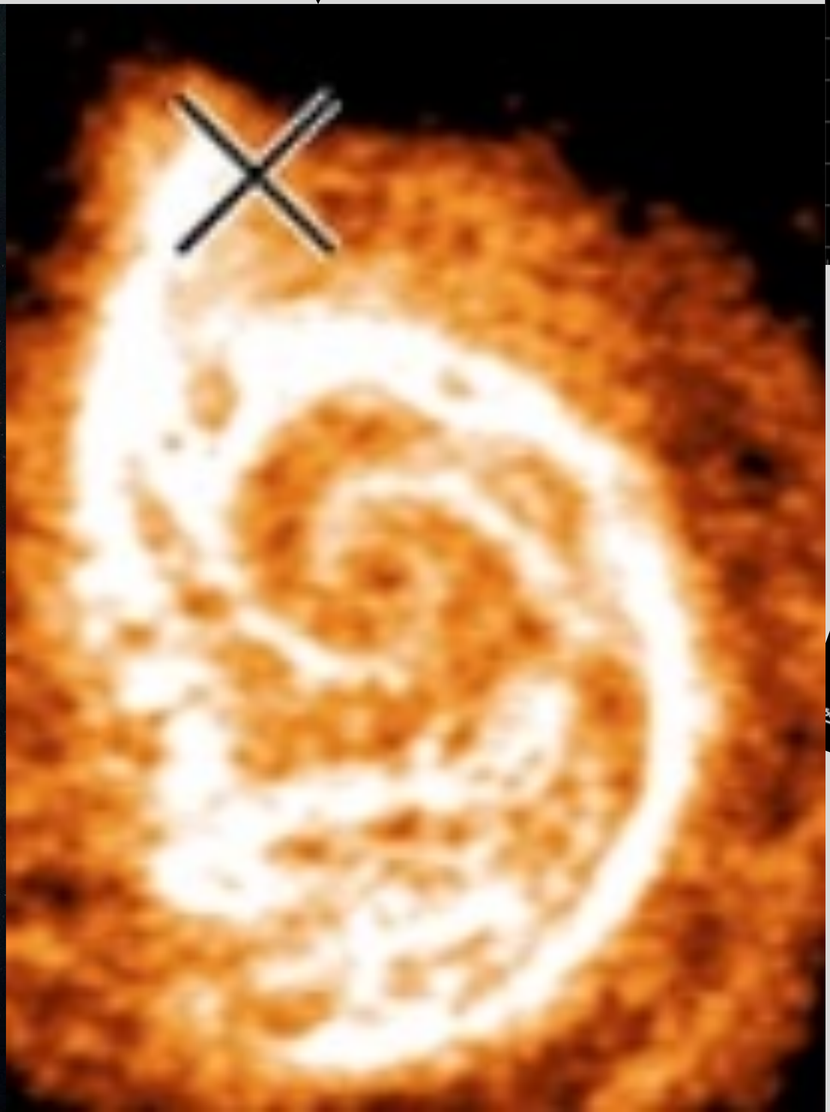
(also called “Radio recombination lines”)

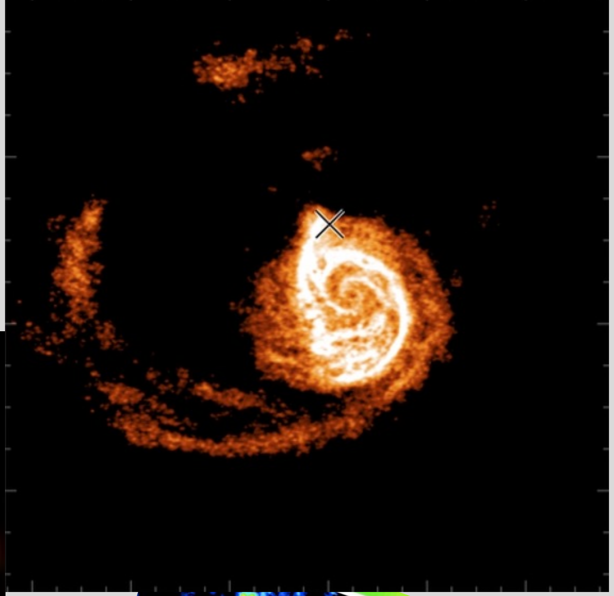


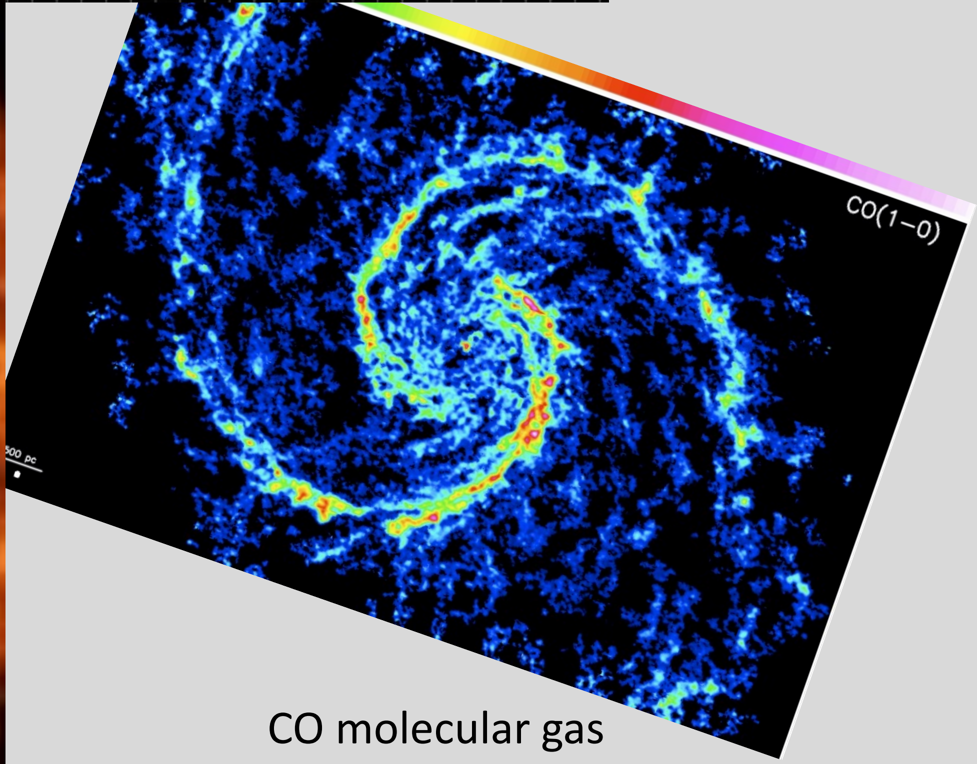
M51: The Whirlpool Galaxy

21 cm neutral hydrogen

Optical with Hα







CO molecular gas

M51: CO and CO velocity field