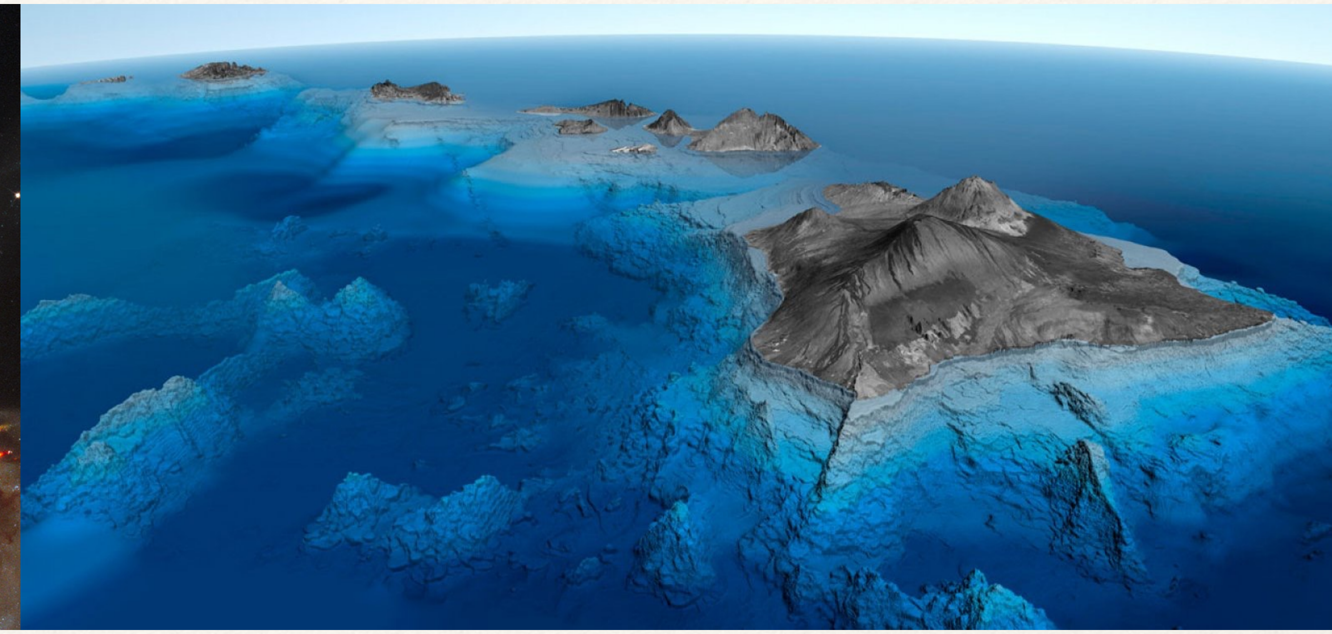


Getting to know the "island universes" out there.

Galaxies I

ASTR 555
Dr. Jon Holtzman

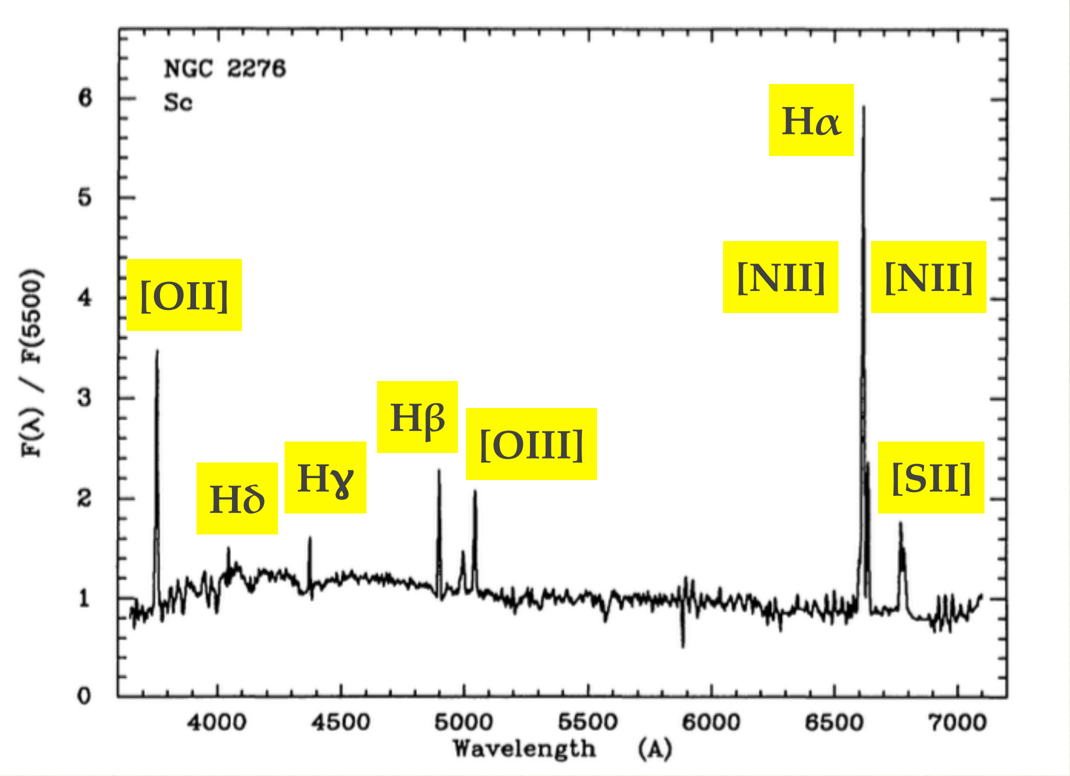
Outline for Today

- Building Blocks - Gas:
  - Denser Ionized Gas
    - Star Formation
    - Density, Temperature, Metallicity, Ionization

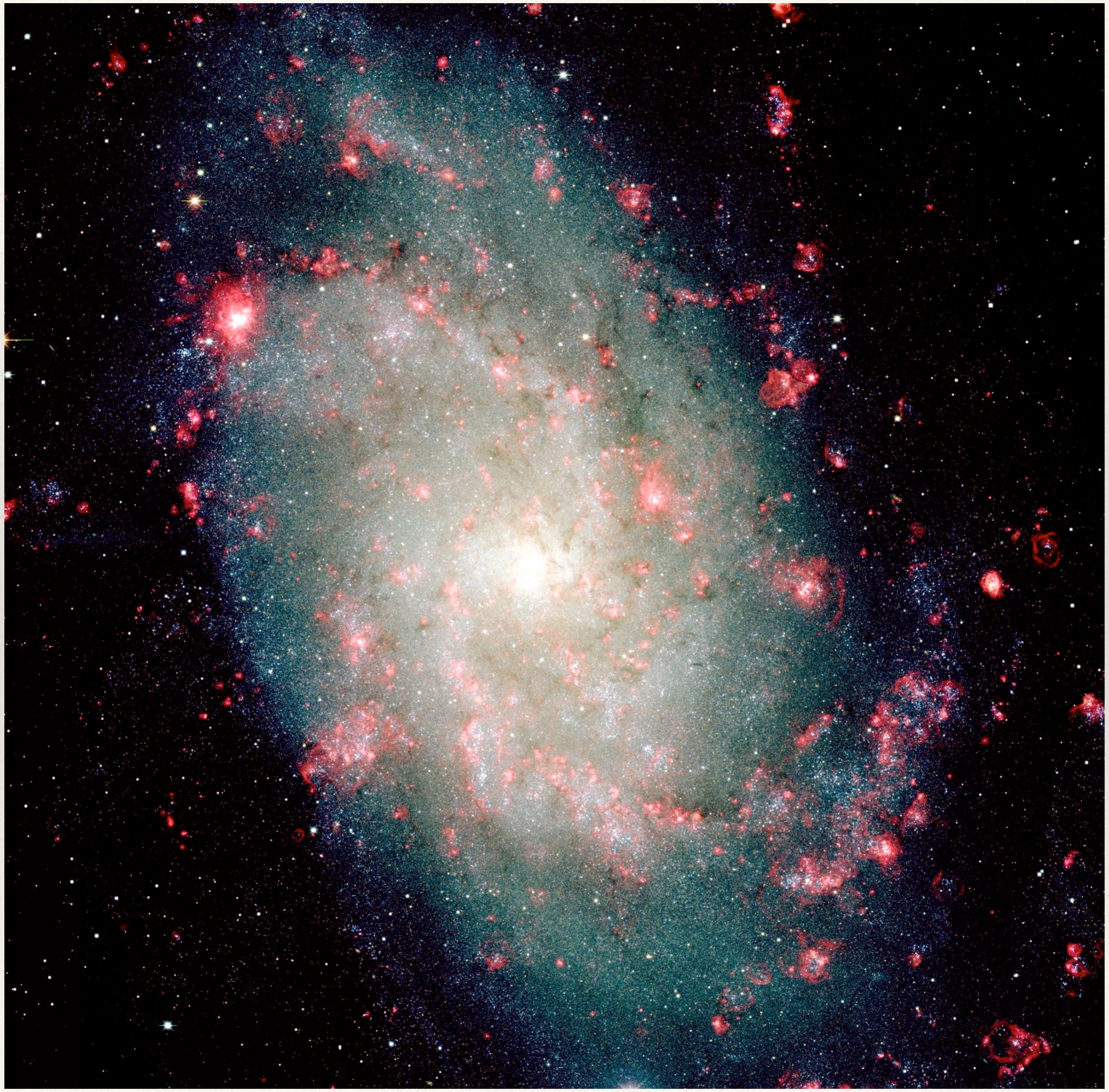
NGC 6240 (Credit: Hiroshima University / NAOJ)

Building Blocks - Gas

- **Denser Ionized Gas (e.g., HII regions)**
  - Lots of strong emission lines
  - Easiest gas to observe in galaxies
  - Opportunity to study gas inside galaxies (and outside!) in detail



Kennicutt 1992b



M33 (Credit: Lowell Observatory)

Building Blocks - Gas

- **HII regions** — ionized regions around young stars
  - Rough size set by statistical balance: number of ionizations = number of recombinations

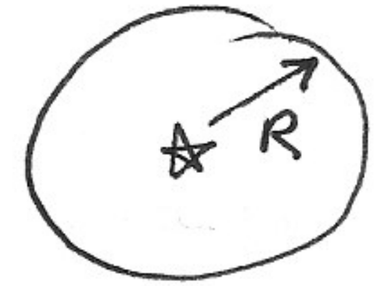
Rosette Nebula (Credit: Caelum Observatory)

Thought question

- Given a population of recently formed stars, write an expression for how many ionizing photons are produced.
    - what is an ionizing photon?
    - what stars produce them?
    - how many?

Rosette Nebula (Credit: Caelum Observatory)

Pure H nebula ionized by single star



In equilibrium

photoionizations of H per second = recombinations of protons & electrons → H per second

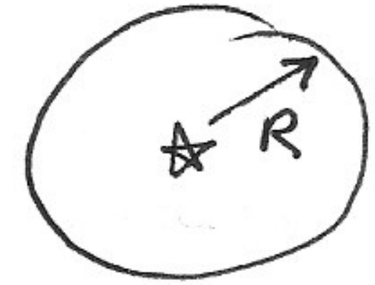
$$N_{ioniz.} = N_{rec}$$

↙

$$Q_{\star}(H) = \int_{\nu_0}^{\infty} \frac{L_\nu}{h\nu}\, d\nu$$ = number of H ionizing photons emitted by star per second

where $h\nu_0 = 13.6$ eV (ionization potential of H).

Pure H nebula ionized by single star



In equilibrium

photoionizations of H per second = recombinations of protons & electrons → H per second

$$N_{ioniz.} = N_{rec}$$

$$N_{rec} = n_p \, n_e \, V \, \alpha$$

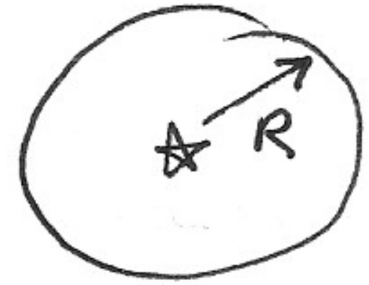
- n_p → protons per volume
- n_e → electrons per volume
- V → volume
- α → recombination coefficient in units of $\frac{\text{volume}}{\text{time}}$

For assumption of a simple spherical nebula:

$$V = \frac{4}{3}\pi R^3$$

$$Q_\star(H) = \frac{4}{3}\pi R^3 n_p n_e \alpha$$

Pure H nebula ionized by single star



In equilibrium

photoionizations of H per second = recombinations of protons & electrons → H per second

$$N_{ioniz.} = N_{rec}$$

$$Q_\star(H) = \frac{4}{3}\pi R^3 n_p n_e \alpha$$

Assuming nearly completely ionized

$$n_p \simeq n_e \simeq n_H$$

$$Q_\star = \frac{4}{3}\pi R^3 n_H^2 \alpha$$

so $R = \left(\frac{3Q_\star}{4\pi\alpha n_H^2}\right)^{1/3} = R_S$ Strömgren Radius

Building Blocks - Gas

- **HII regions** — ionized regions around young stars

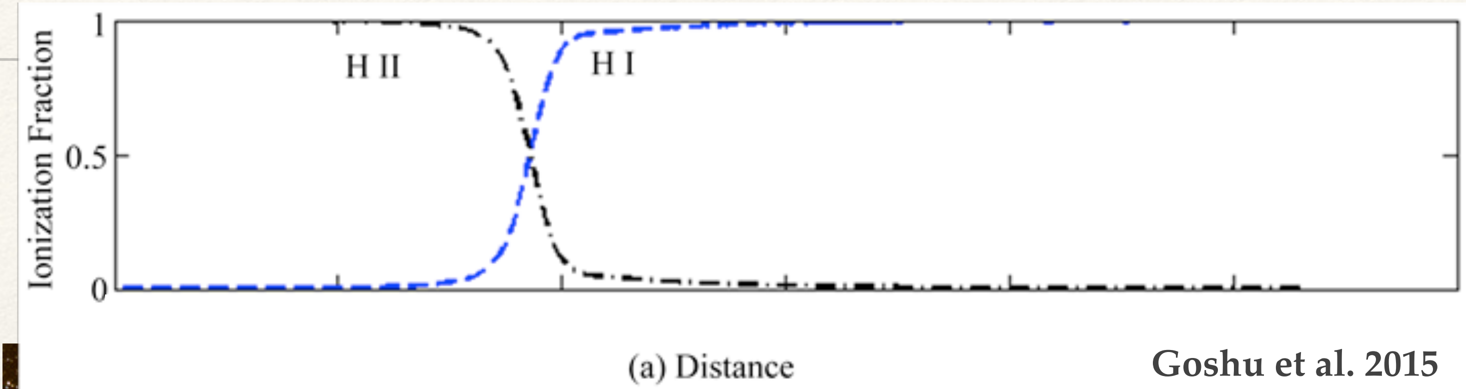
$$Q_* = \int_{h\nu=13.6\ \mathrm{eV}}^{\infty} \frac{L_\nu}{h\nu} d\nu$$

$$\mathbf{N_{rec}} = n_p n_e \alpha(T)$$

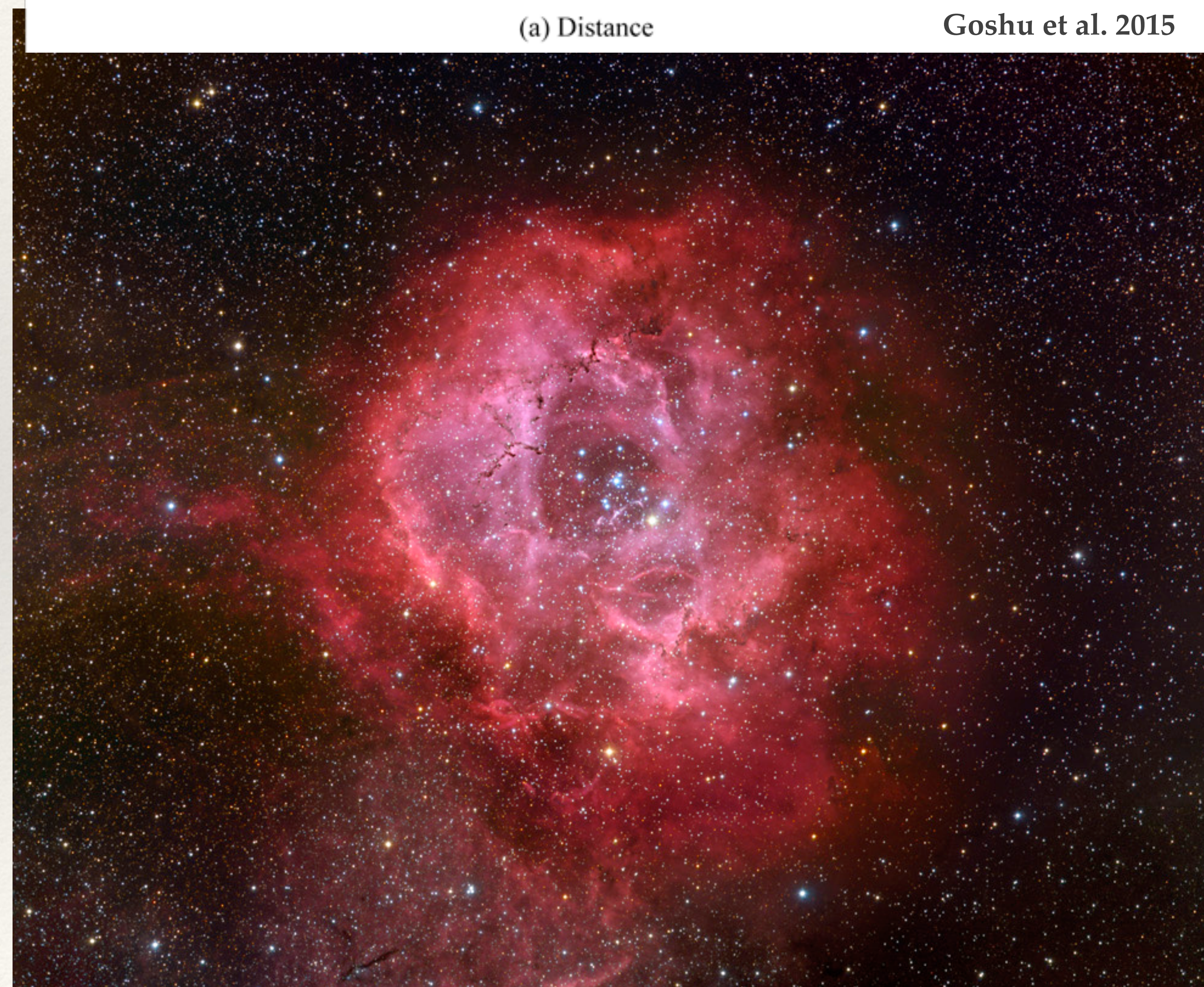
Strongren Radius:

$$r_{strom} = \left(\frac{3Q_*}{4\pi\alpha n_H^2}\right)^{\frac{1}{3}}$$

- However, ISM isn't uniform density, so Stromgren sphere concept is only an idealization
- Concepts of density-bounded ("leaky") vs ionization-bounded regions



Goshu et al. 2015



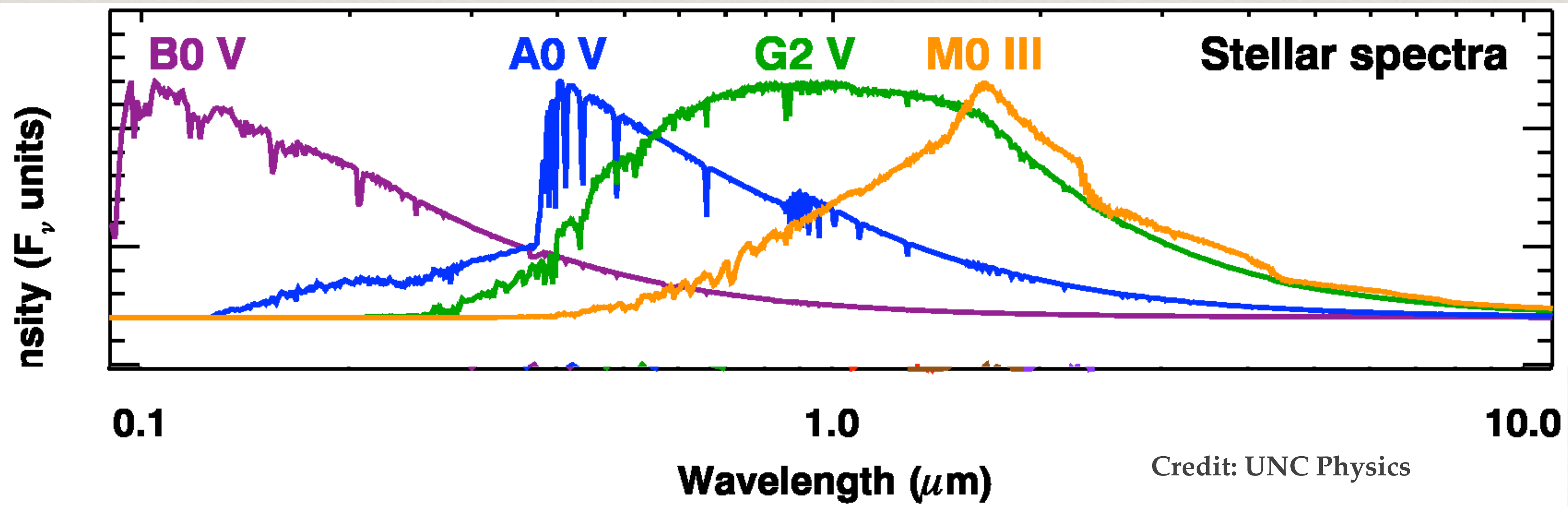
Rosette Nebula (Credit: Caelum Observatory)

Building Blocks - Gas

- What wavelength corresponds to 13.6 eV?
- Only massive stars (O & early B stars; t < 10^7 yrs) are hot enough ionize H

Spectral type	T_e /K	log Q /s^{-1}	R_s/ pc
O6	40,000	49.23	74
O7	35,000	48.84	56
B0	30,000	47.67	23

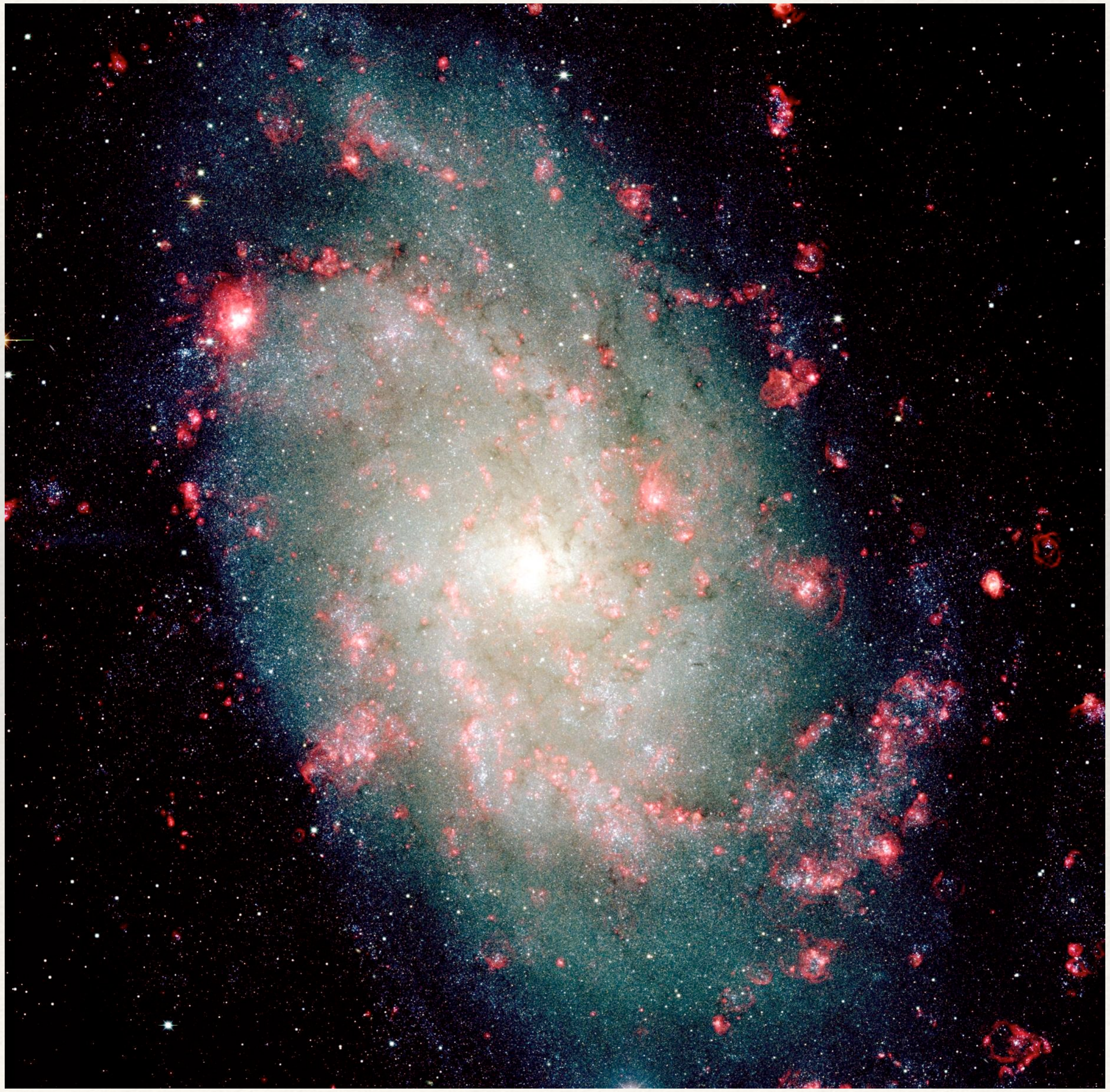
http://www-star.st-and.ac.uk/~kw25/teaching/nebulae/L15_2020.pdf



Credit: UNC Physics

Building Blocks - Gas

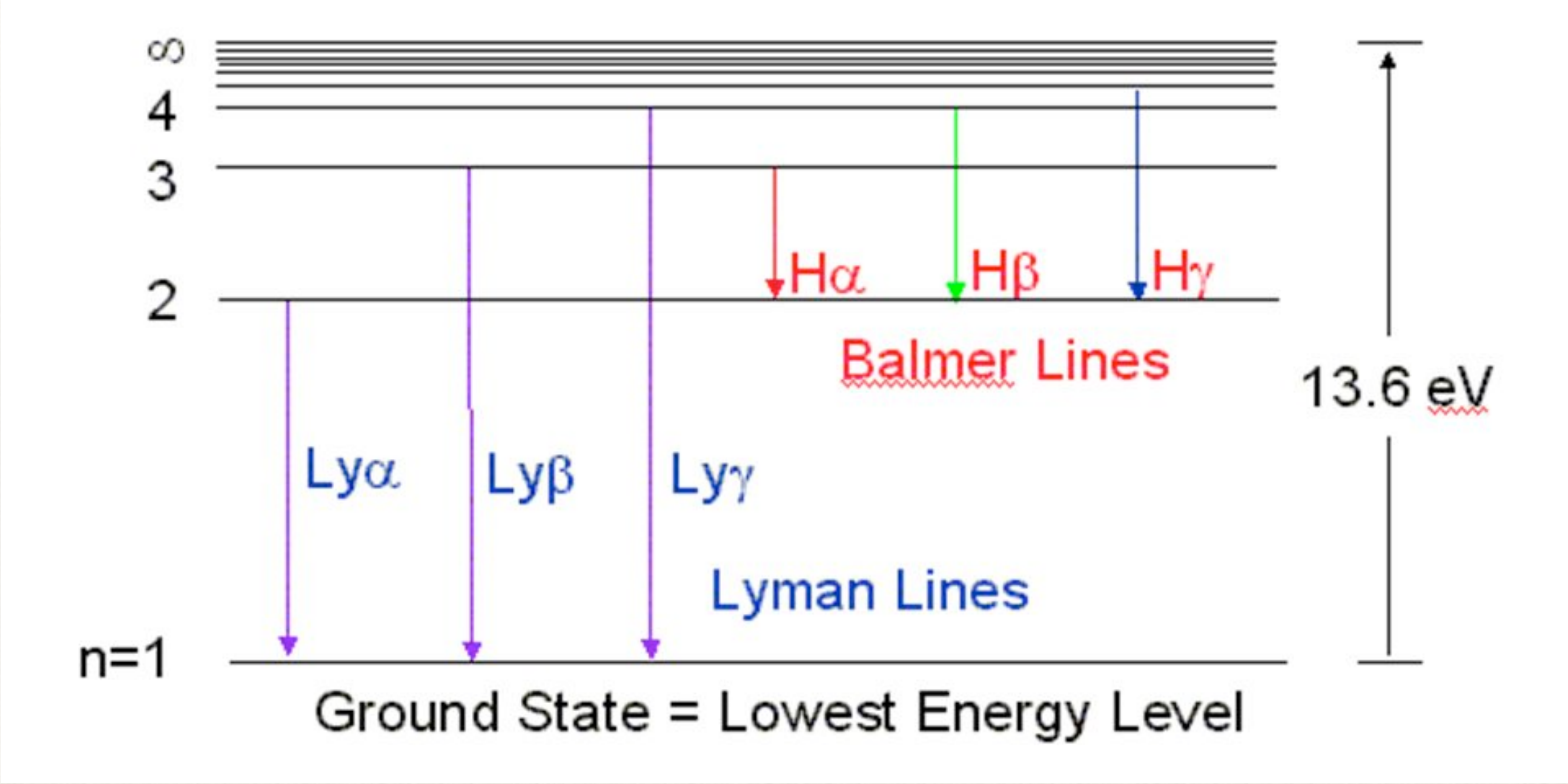
- Only massive stars (O & early B stars; t < 10^7 yrs) are hot enough ionize H
  - HII regions only last as long as the stars that ionize them (~10 Myr)
  - HII region emission is closely tied to **recent star formation**



M33 (Credit: Lowell Observatory)

Building Blocks - Gas

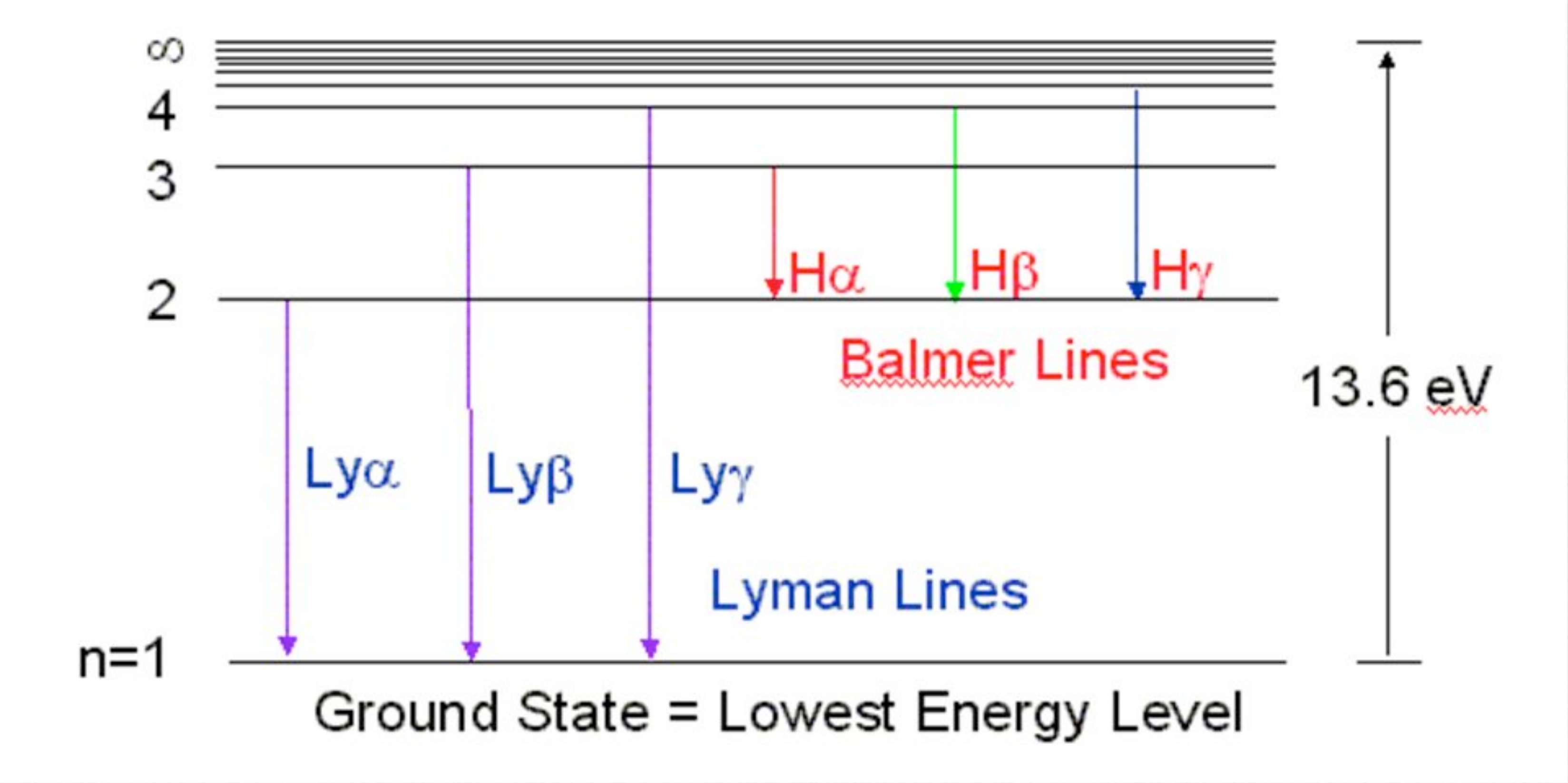
- HII region line emission is very important for estimating **Star Formation Rates (SFR)**:
  - Photons with >13.6 eV (<912 A) ionize H
  - Free electrons recombine with H+ (excited state) —> recombination lines (e.g., Hα flux)



- **Recombination line flux is directly related to the number of ionizing photons (under certain assumptions)**

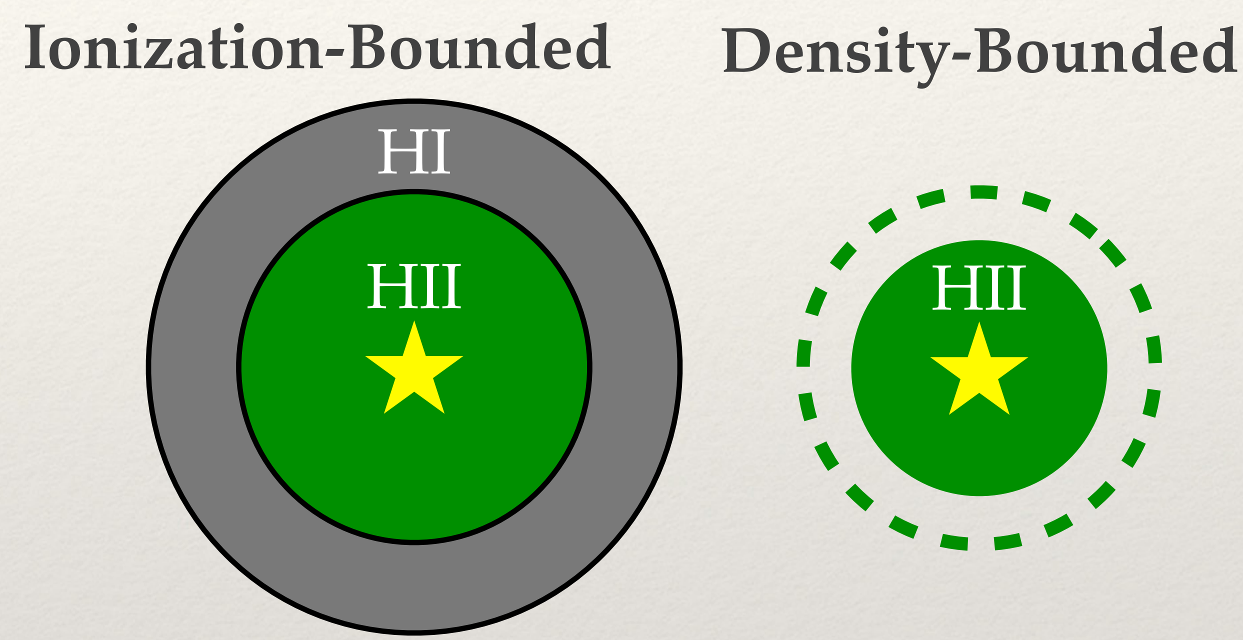
Thought Question

- What steps/assumptions do we have to make to use a measured Hα flux to estimate the star formation rate (SFR)?
- What might throw off our SFR estimates?

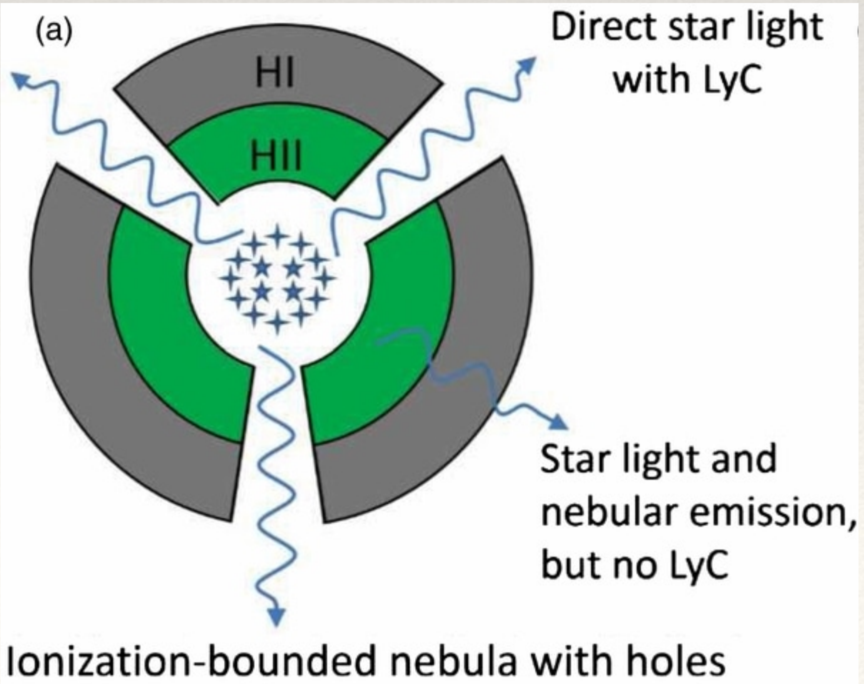


Building Blocks - Gas

- Using HII region line emission to estimate **Star Formation Rates (SFR)**:

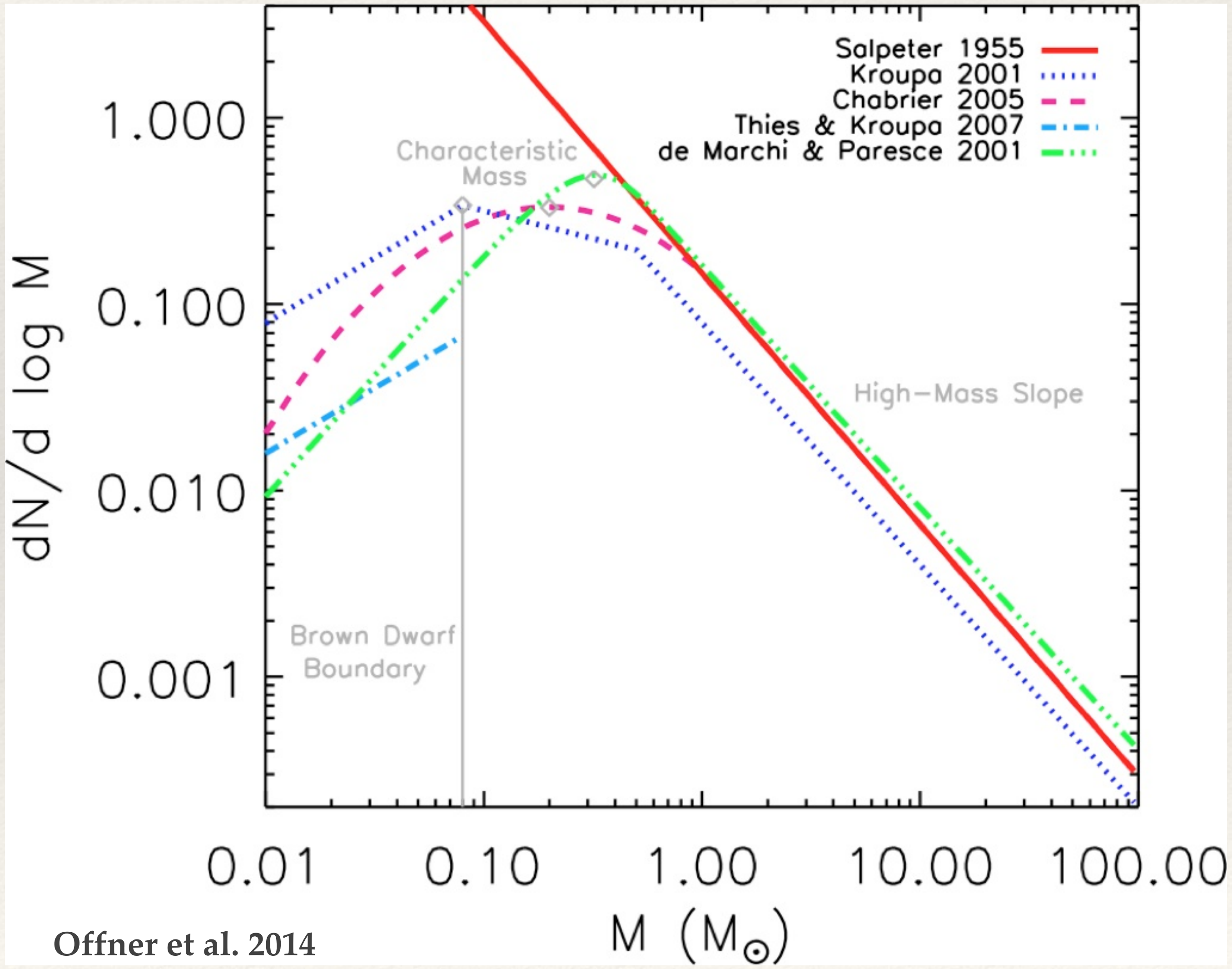


  - **If no ionizing photons are leaking out**, then number of ionizing photons directly related to number of massive stars



Building Blocks - Gas

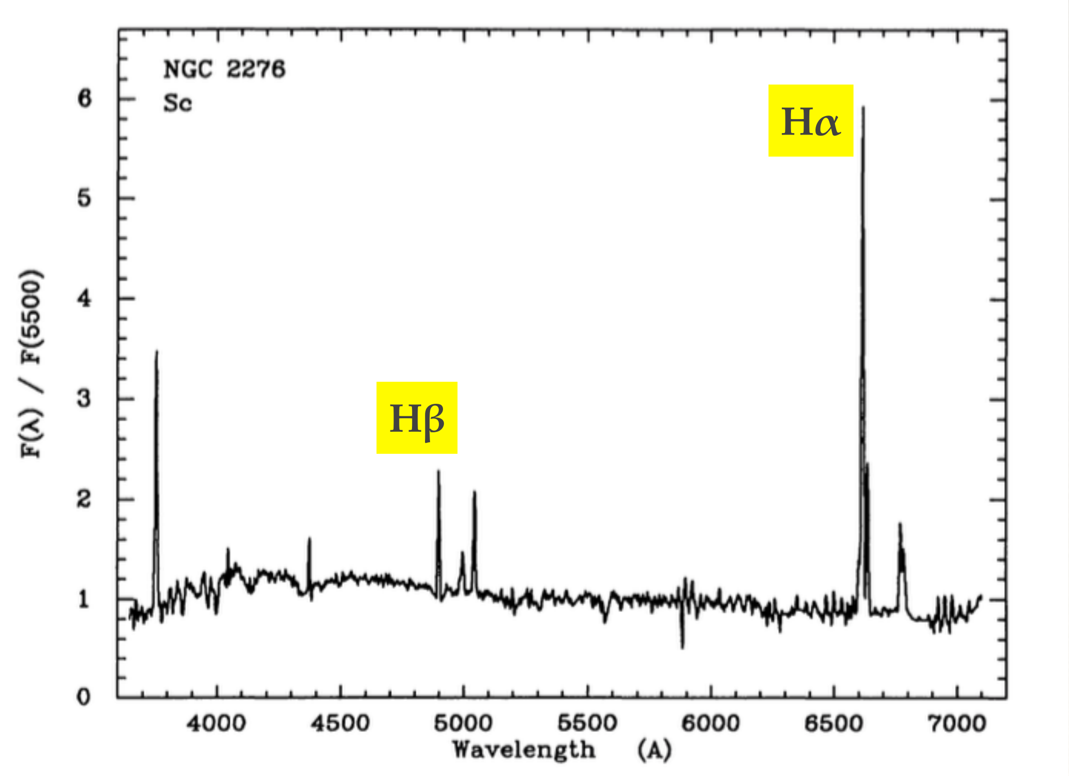
- Using HII region line emission to estimate **Star Formation Rates (SFR)**:
  - Only massive stars (O & early B stars) are hot enough ionize H
  - **Given an IMF**, the number of ionizing photons —> number (mass) of young stars —> total mass of stars formed



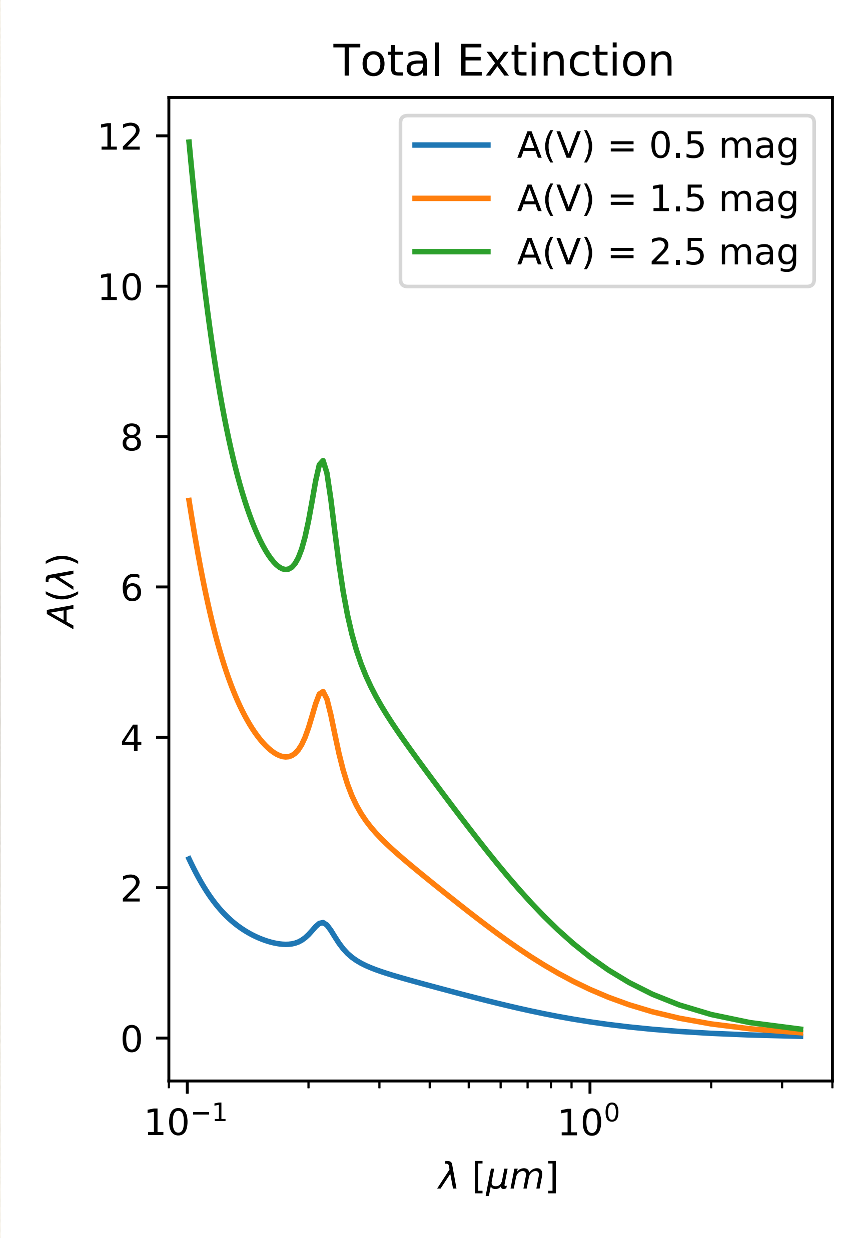
Offner et al. 2014

Building Blocks - Gas

- Using HII region line emission to estimate **Star Formation Rates (SFR)**:
  - Must correct for dust extinction — often use **Balmer decrement** (Hα/Hβ ~ 3, from atomic physics)



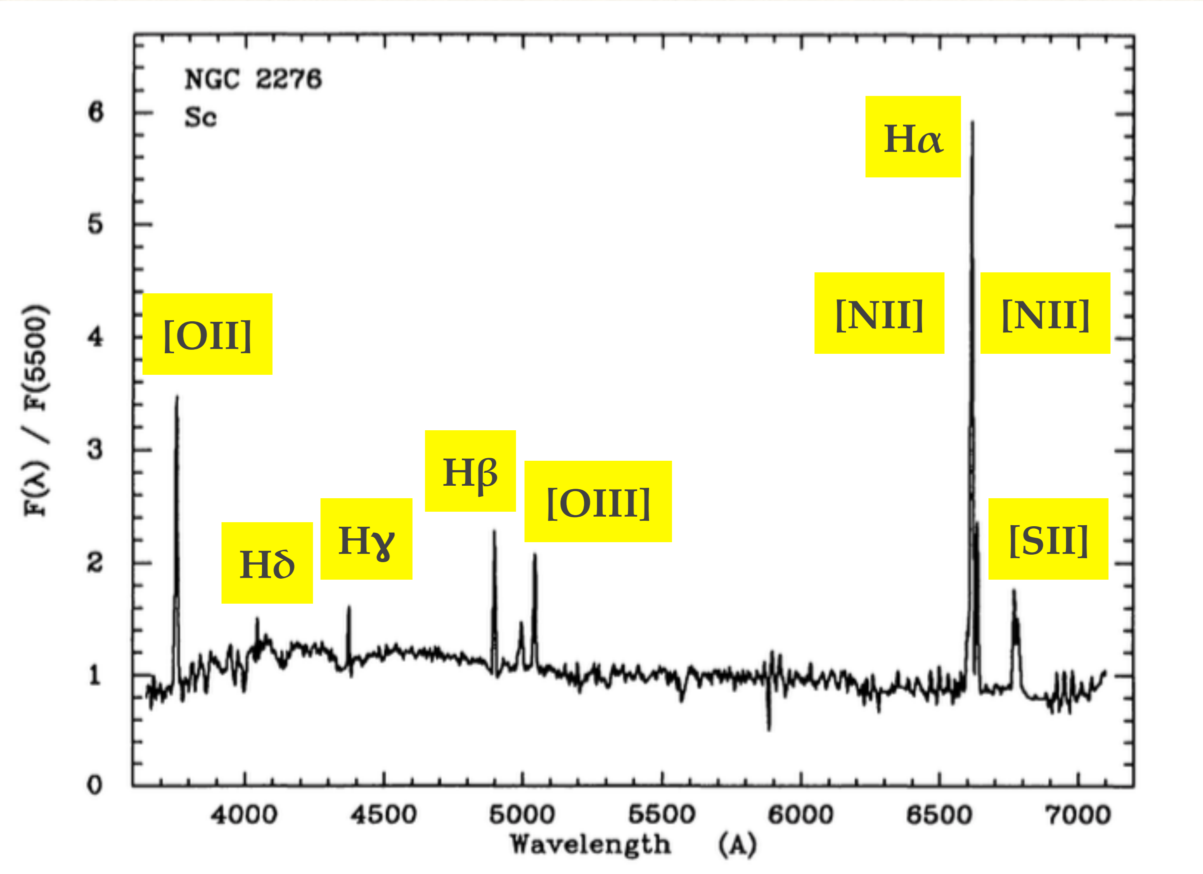
Kennicutt 1992b



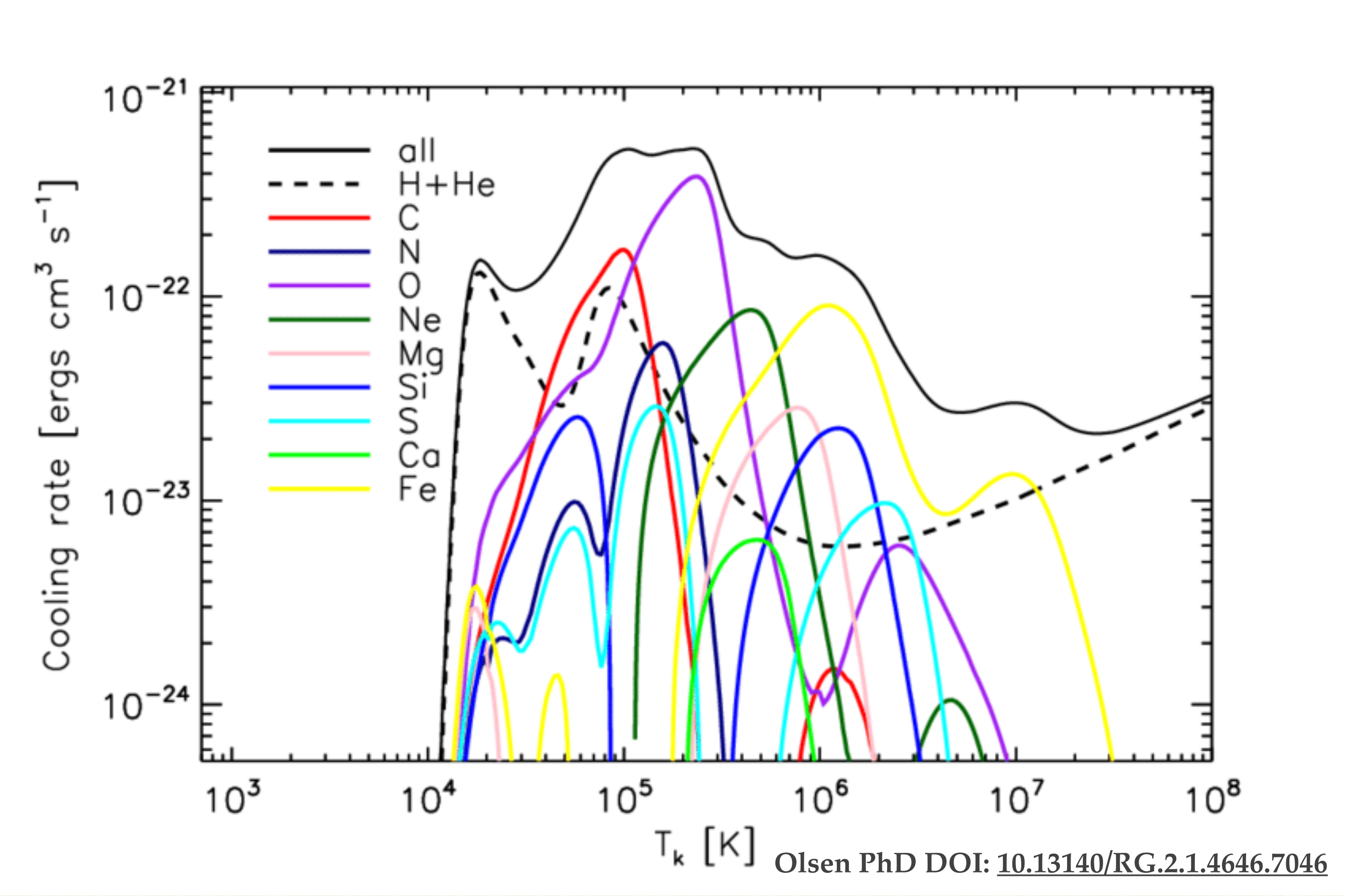
https://dust-extinction.readthedocs.io/en/stable/dust_extinction/extinction.html

Building B

- **HII regions** — ionized regions around young stars
  - Not just HII!
  - Trace amounts of metals provide important cooling channels



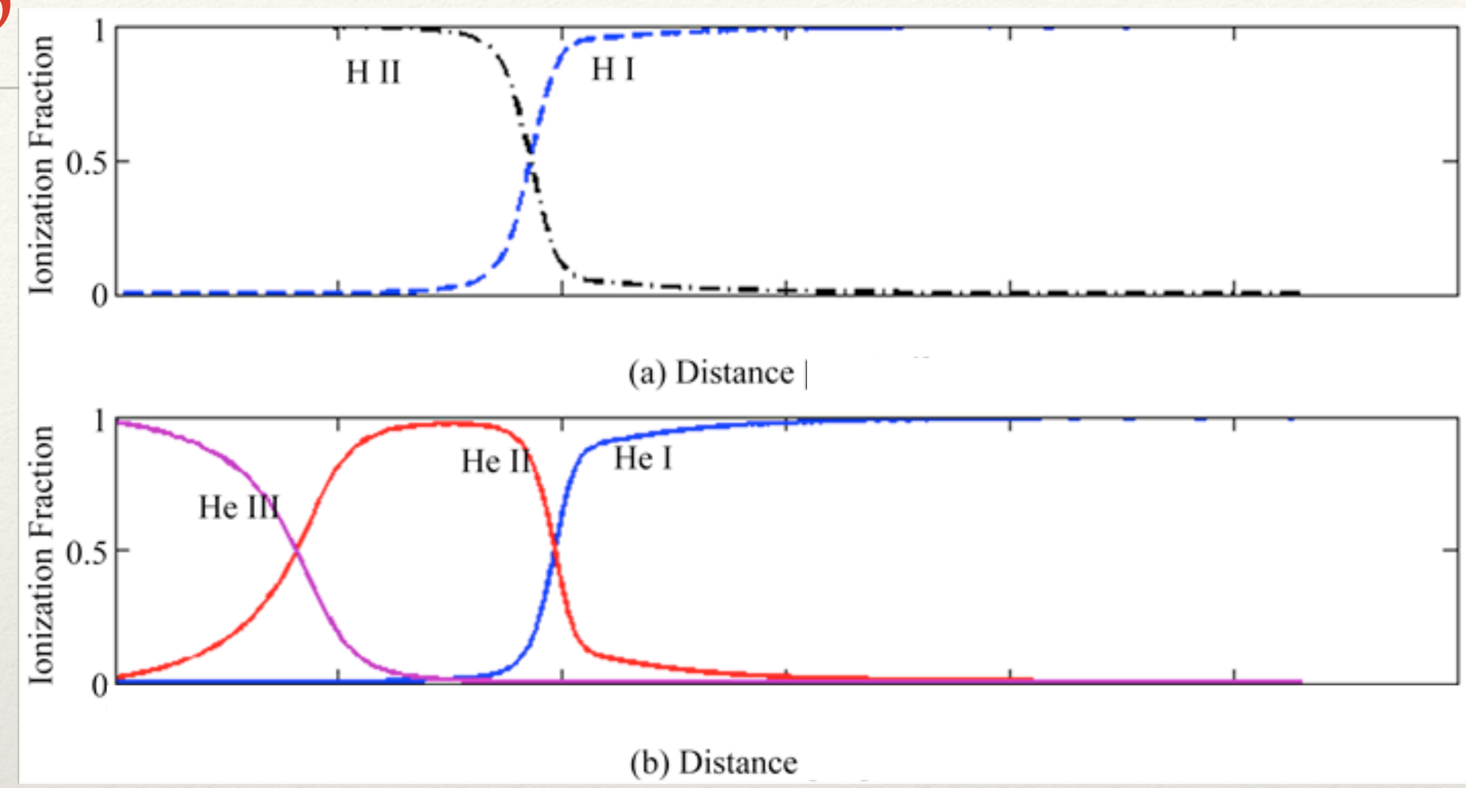
Kennicutt 1992b



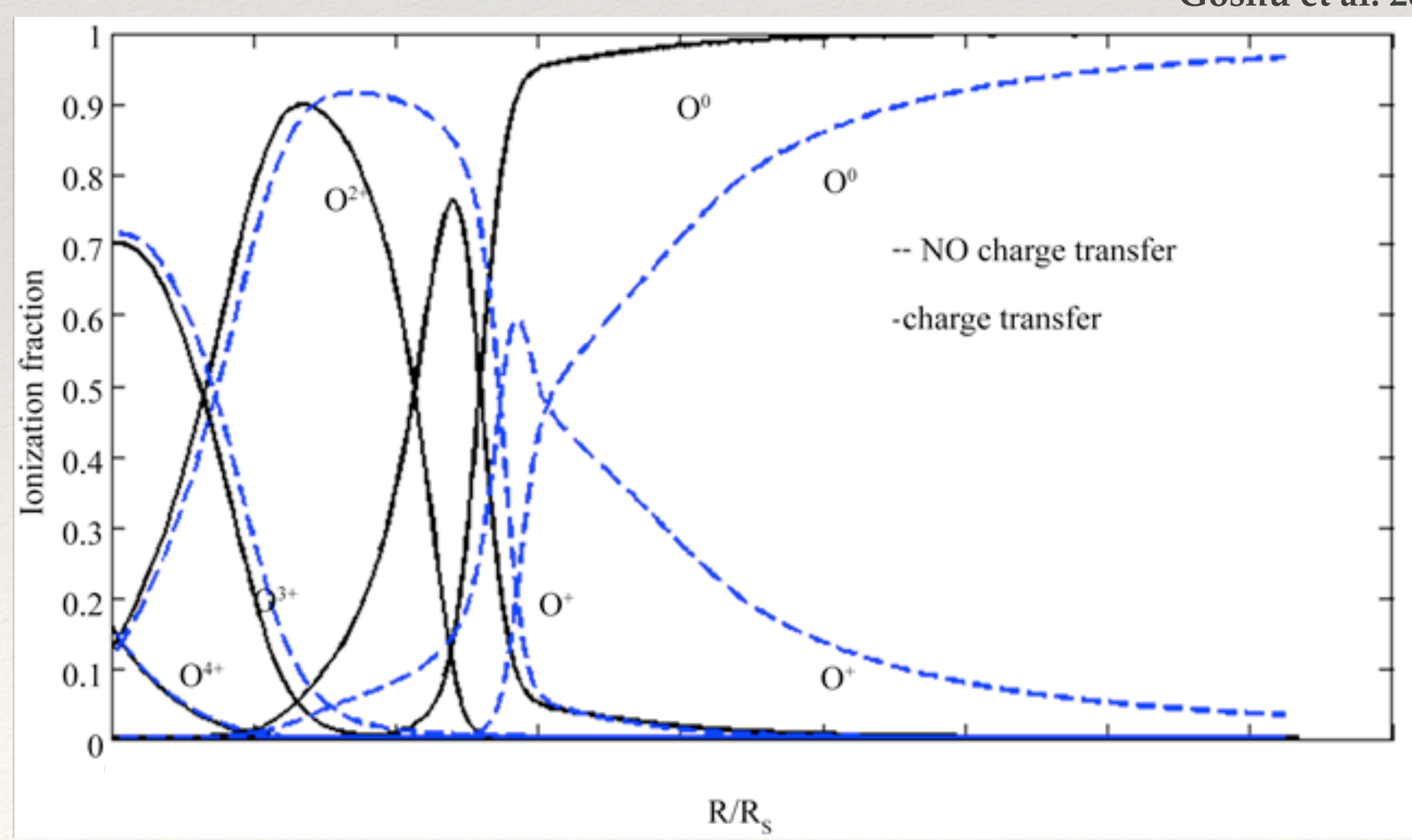
Olsen PhD DOI: 10.13140/RG.2.1.4646.7046

Building Blocks - Gas

- **HII regions** — ionized regions around young stars
    - Not just HII!
    - Ionization fraction profiles, with higher ionization species closer to ionizing source

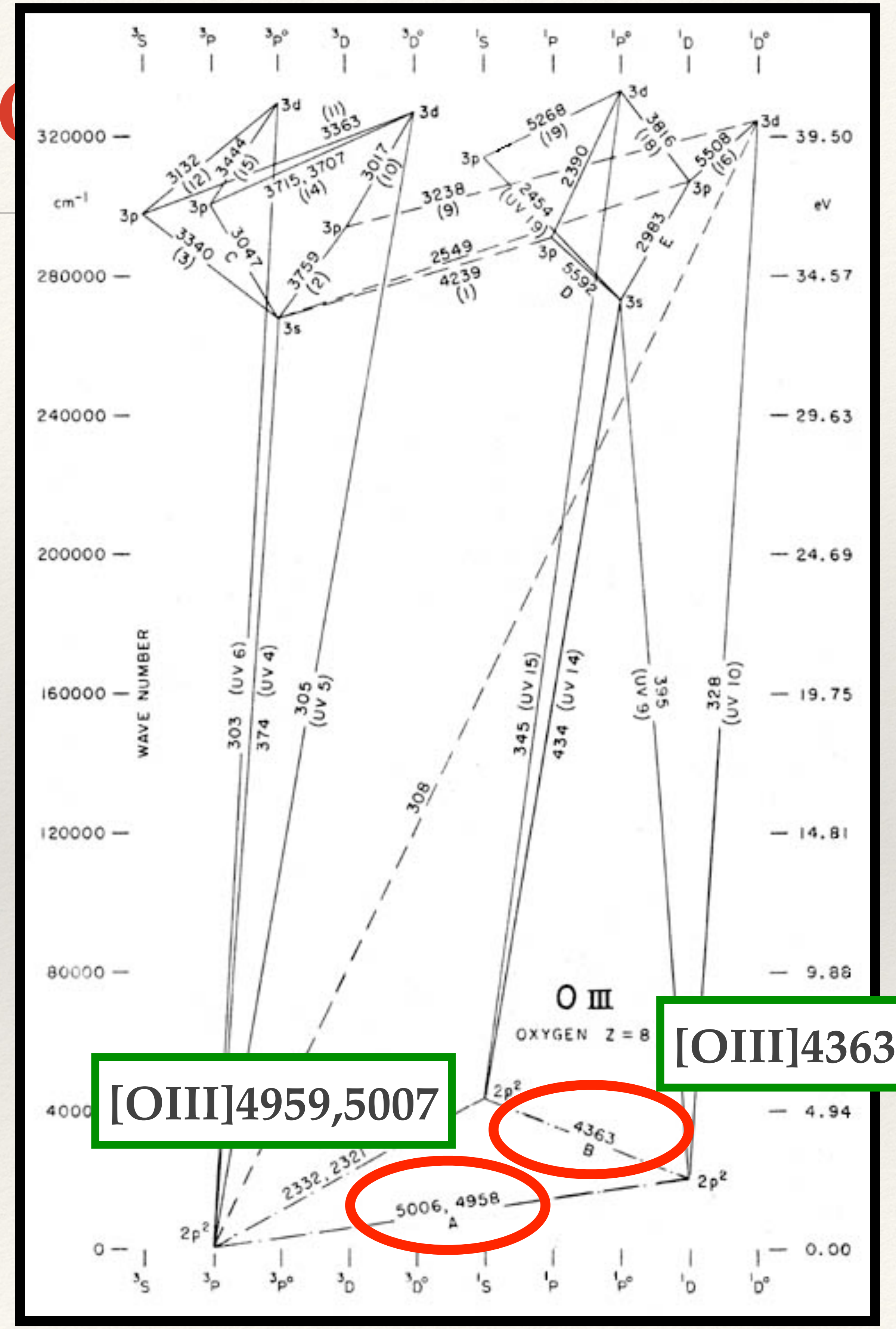


Goshu et al. 2015



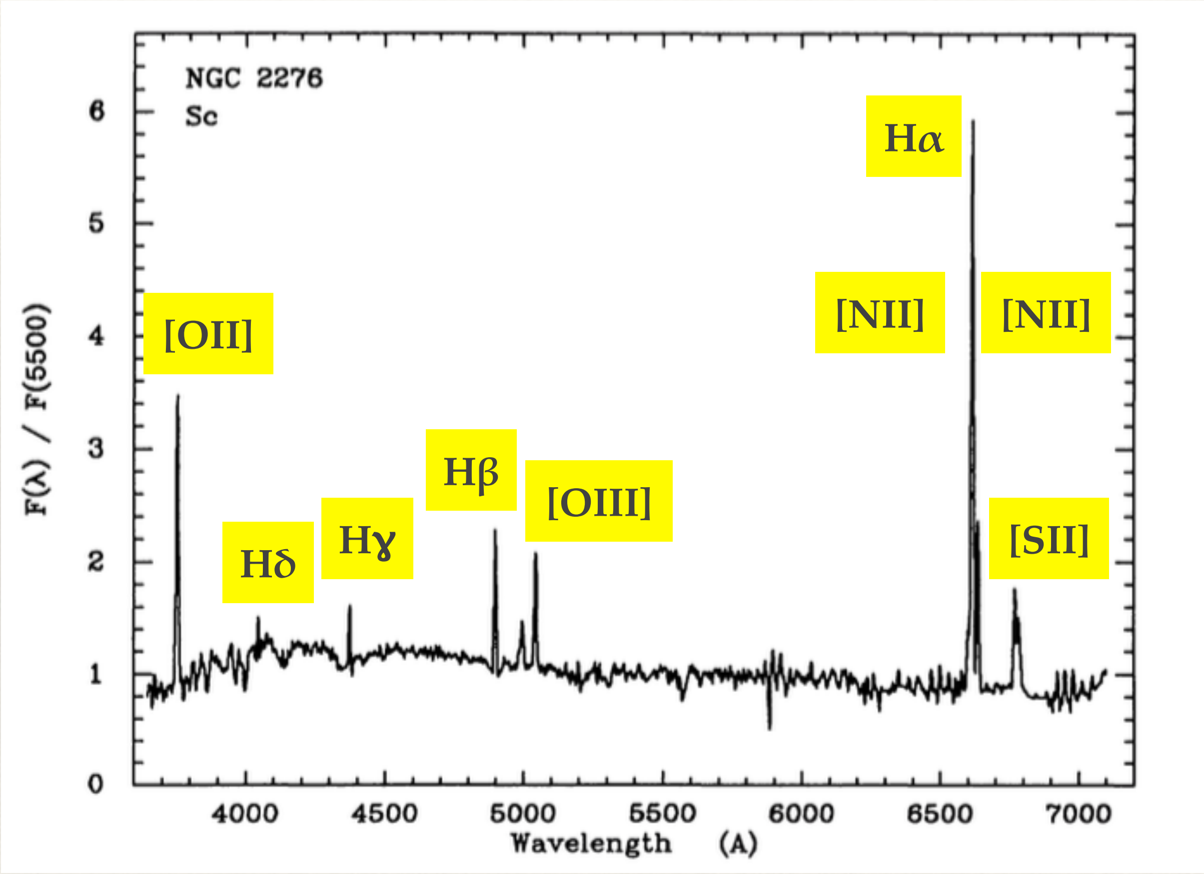
Building Blo

- Many of the metal lines in galaxy spectra are “forbidden”:
  - [OIII]4363, [OIII]4959,5007
  - [NII]6548,6584
  - [SII]6716, 6731
- **Can** be collisionally excited
- Visible in regions with density lower than **critical density** (where radiative decays before collisional de-excitation)



Thought Question

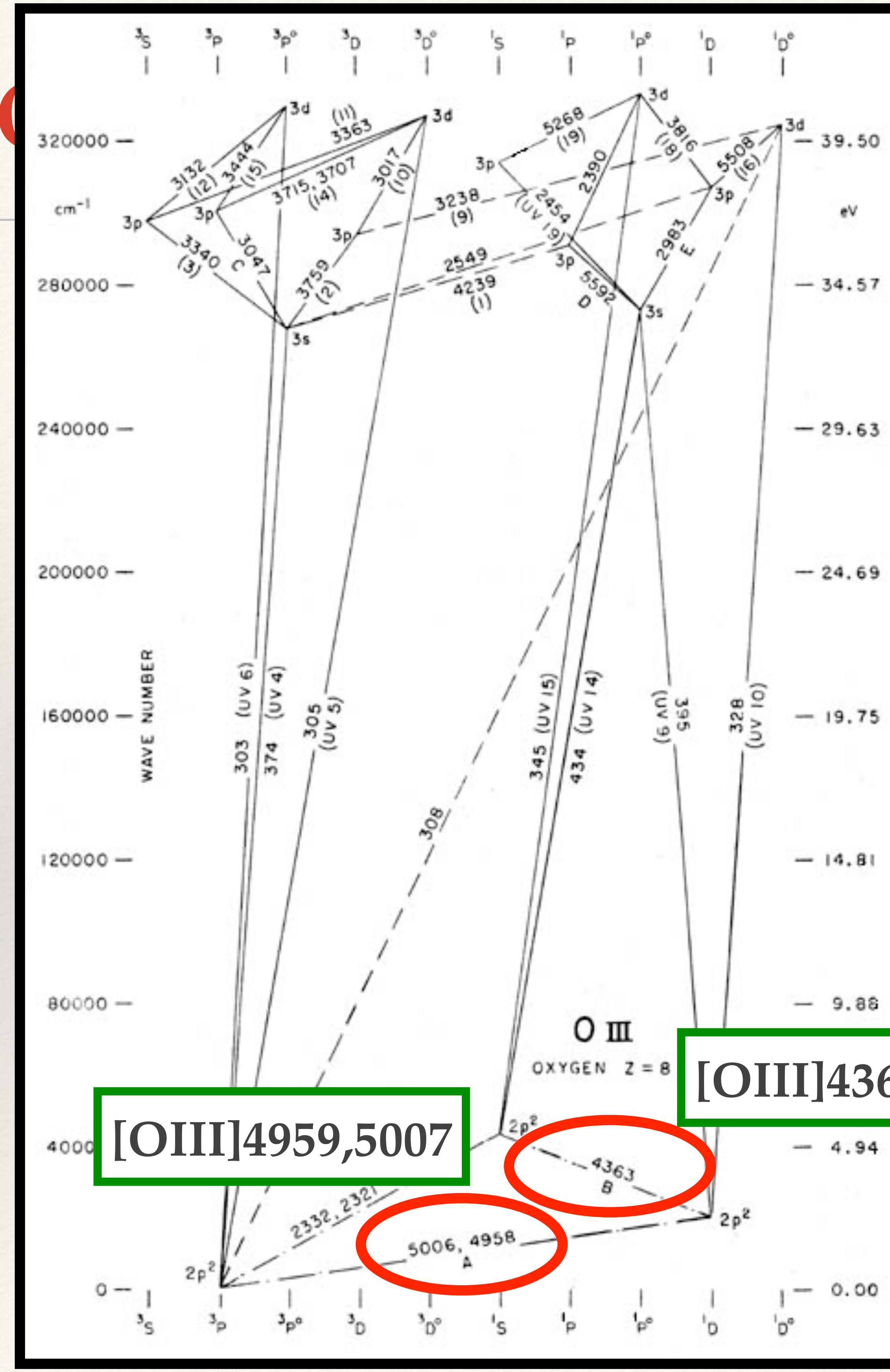
- What can metal emission lines tell us about the properties of gas in galaxies?



Kennicutt 1992b

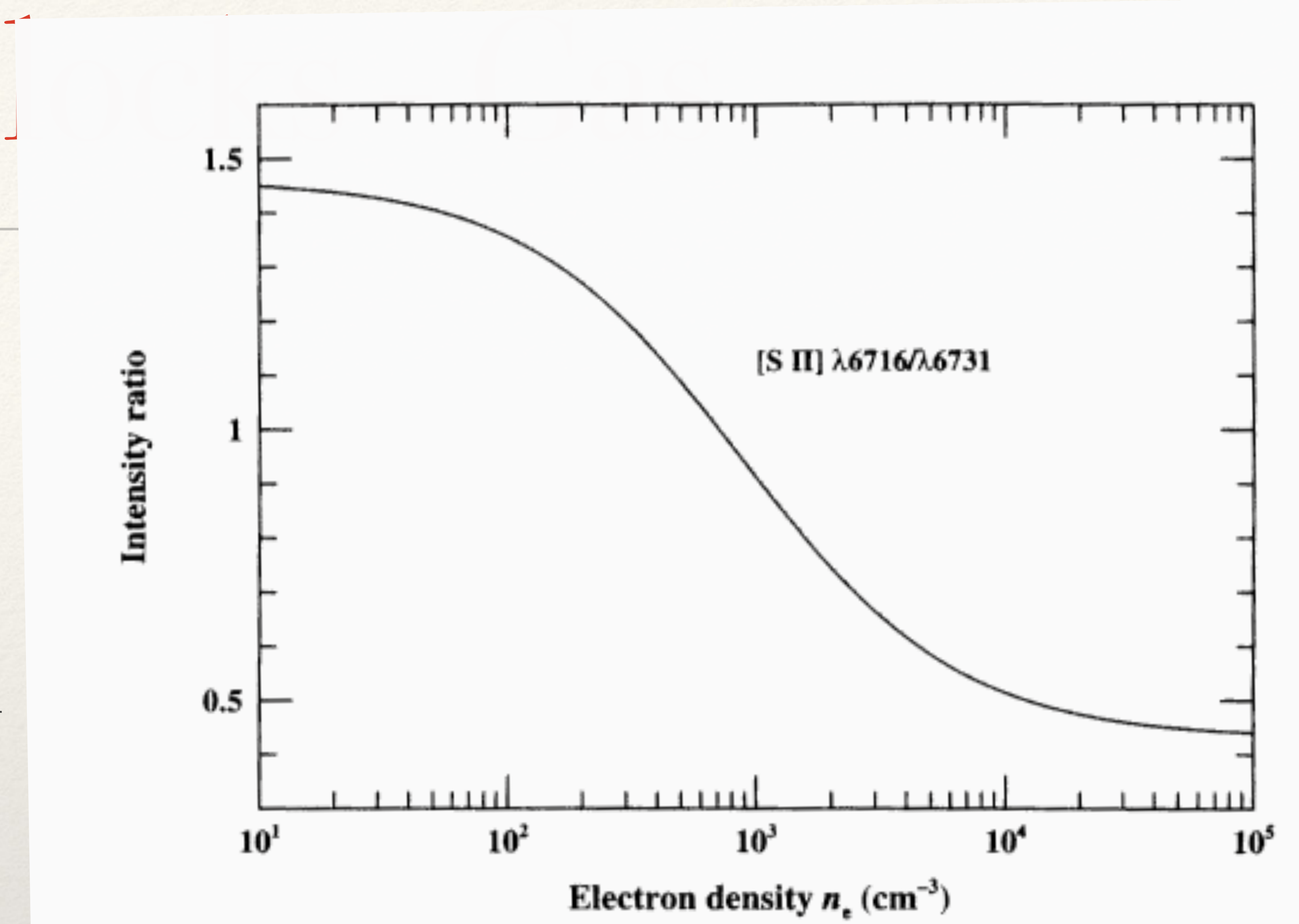
Building Bloc

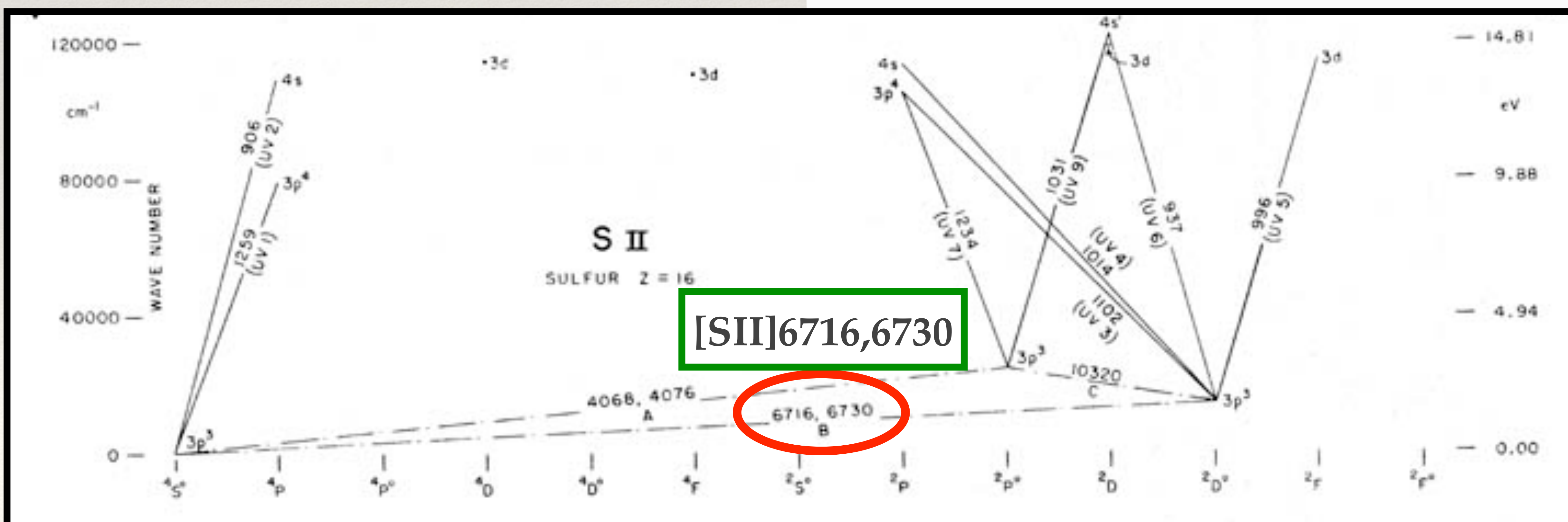
- Forbidden metal lines provide opportunity to measure **temperature**:
  - Ratio of collisional excited lines of same ion but different ground state — e.g., [OIII]4959,5007 / [OIII]4363



Building Bl

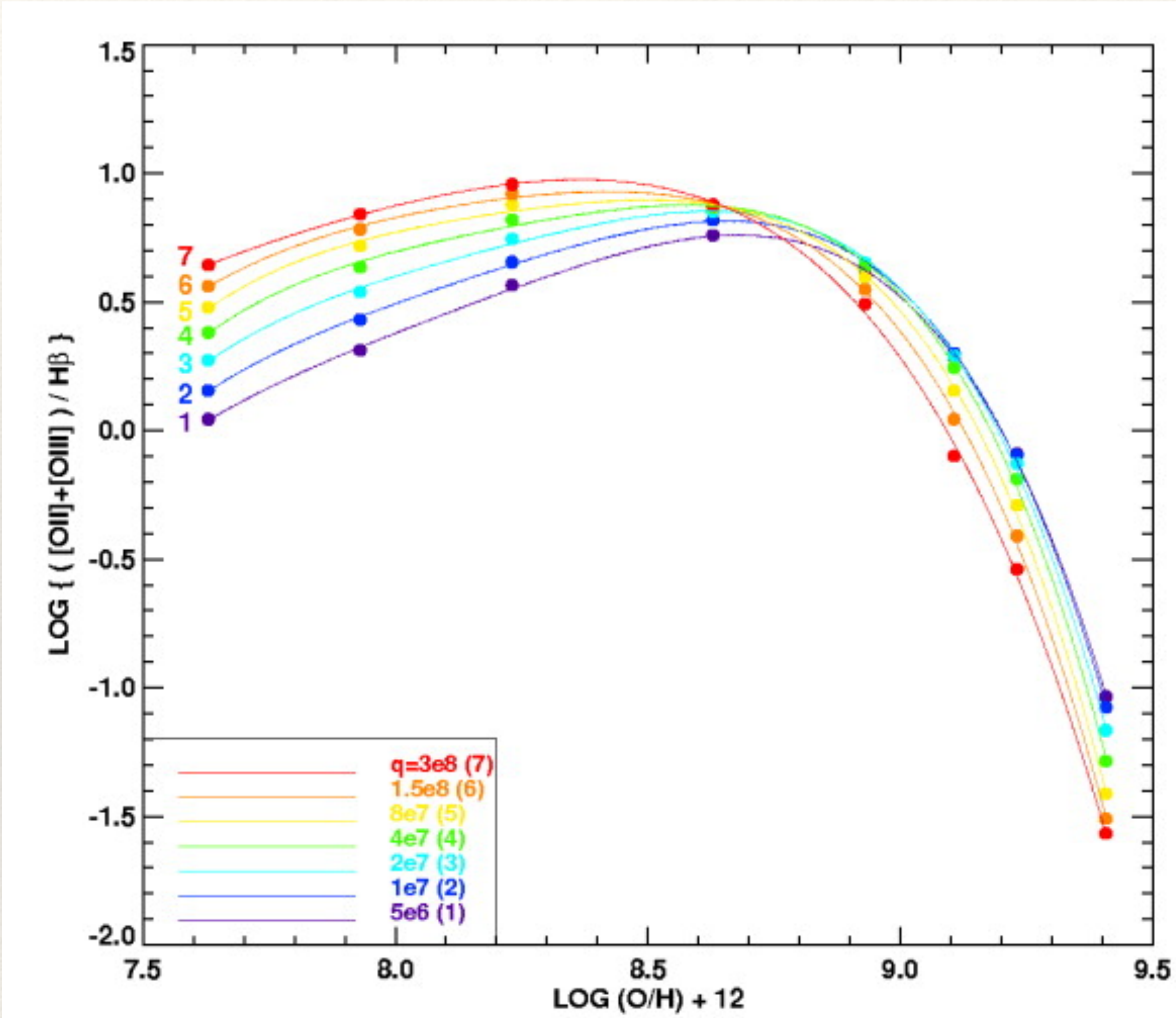
- Forbidden metal lines provide opportunity to measure **density**:
  - Ratio of collisionally excited lines of same ion with nearly the same energy spacing but different critical densities — e.g., [SII]6716 / [SII]6731





Building Blocks - Gas

- Forbidden metal lines provide opportunity to measure **metallicity**:
  - If know temperature and density, can estimate metallicity
    - Requires measuring fainter lines like [OIII]4363 and resolving doublets like [SII]6716,6731 --> HARD!
  - Instead, metallicity often inferred from "strong-line" indices like R_{23}:

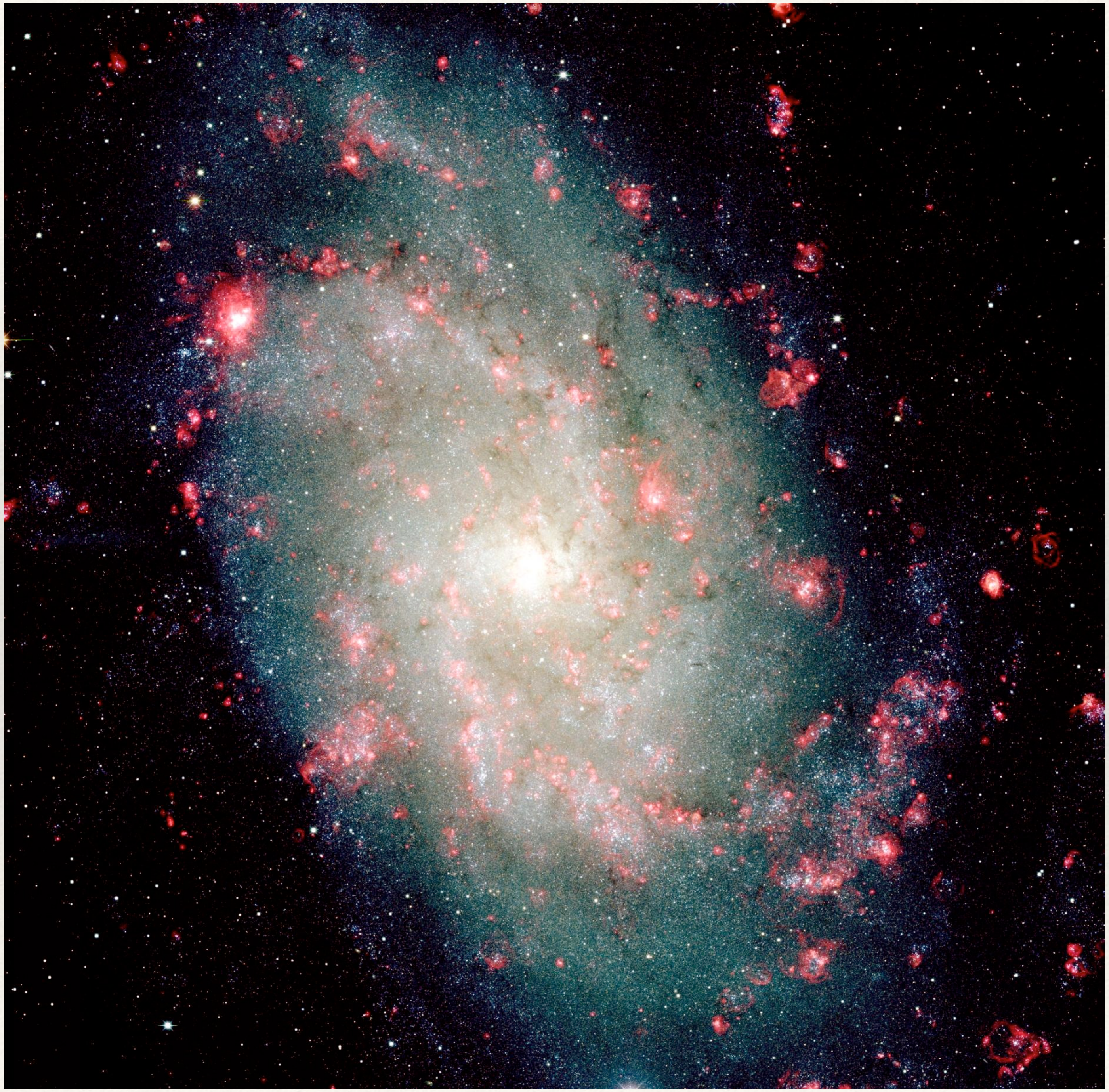


$$R_{23} = \frac{F([OII]3727) + F([OIII]4959) + F([OIII]5007)}{F(H\beta 4861)}$$

but these require modeling to interpret

Building Blocks - Gas

- **Not all dense ionized gas is from HII regions!**
- **Ionization mechanisms:**
  - Photoionization — massive stars (star formation), planetary nebulae, active galactic nuclei (AGN)
  - Shock ionization
- **How do we recognize different types of dense ionized gas, in particular for distant galaxies?**



M33 (Credit: Lowell Observatory)

Schirmer et al. 2013