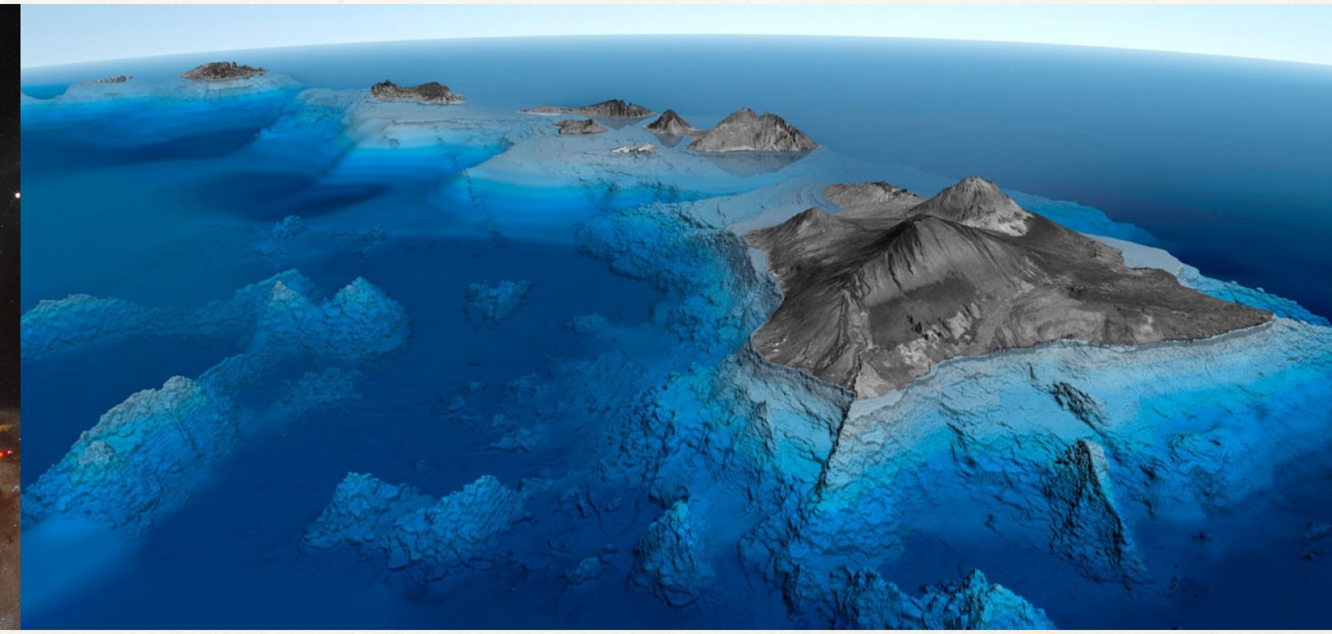


Getting to know the "island universes" out there.

Galaxies I

ASTR 555
Dr. Jon Holtzman

Outline for Today

- Building Blocks - Gas:
  - Multiphase medium
  - Observing gas via emission and absorption
  - Heating / Cooling
  -

NGC 6240 (Credit: Hiroshima University / NAOJ)

Building Blocks - Gas

- Often describe gas in galaxies in terms of distinct **phases**
- In a simple picture, can consider phases to be in rough pressure balance (in reality turbulence, magnetic fields, etc., also play a role)

Component	Temperature (K)	Density (cm^{-3})	Fractional ionization
Molecular gas	10–20	$> 10^2$	$< 10^{-6}$
Cold neutral medium (CNM)	50–100	20–50	$\sim 10^{-4}$
Warm neutral medium (WNM)	6000–10000	0.2–0.5	$\sim$0.1
Warm ionized medium (WIM)	~ 8000	0.2–0.5	1.0
Hot ionized medium (HIM)	$\sim 10^6$	$\sim 10^{-2}$	1.0

Adapted from Ferriére (2001), Caselli et al. (1998), Wolfire et al. (2003), and Jenkins (2013).

Klessen & Glover 2014

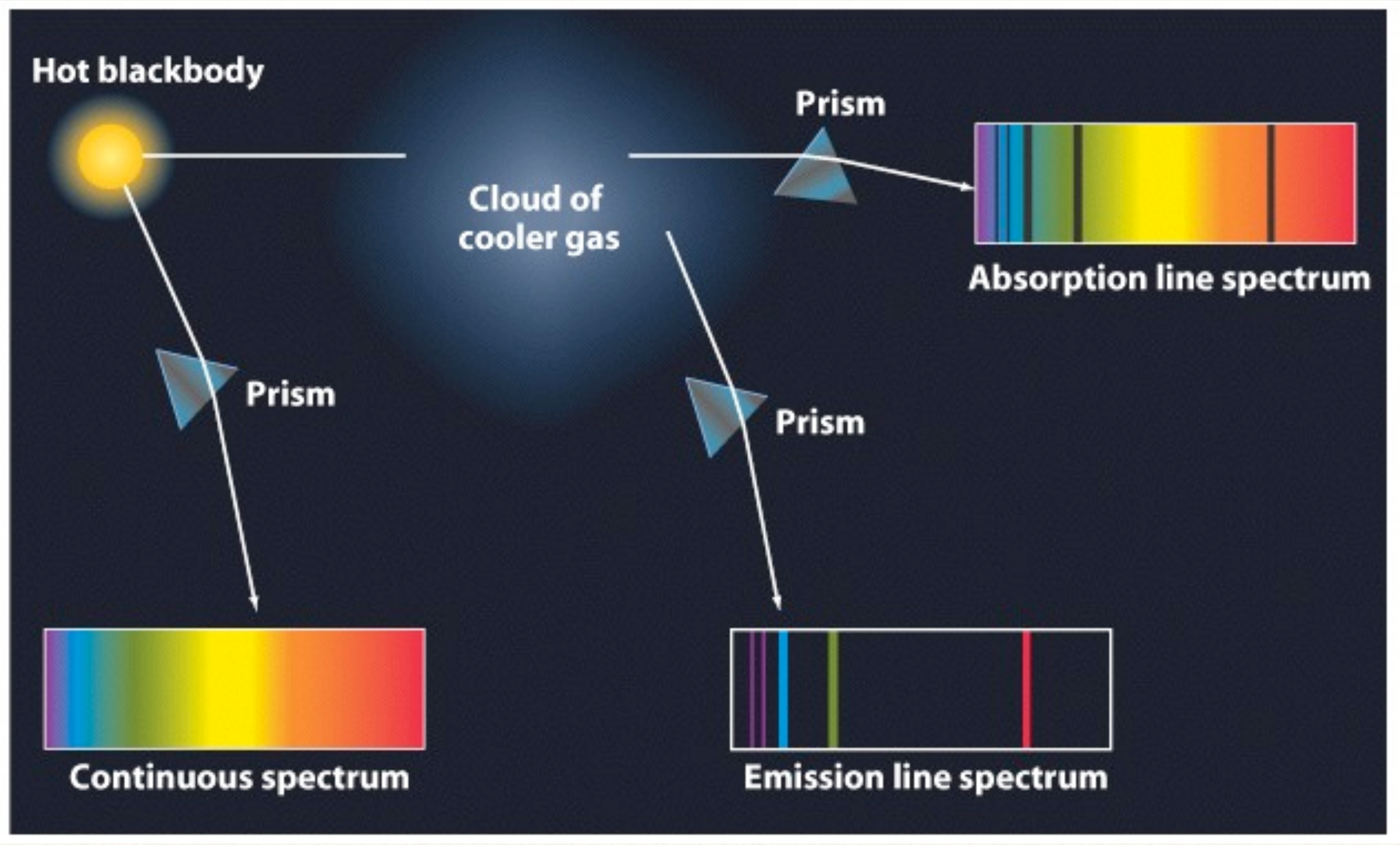
Building Blocks - Gas

- In disks:
  - Majority of the volume filled with ionized gas (25% of the mass)
  - Majority of the mass in dense clouds of atomic and molecular gas (1-2% of the volume)
  - Metallicity of gas in galaxy disks correlated with stellar mass
- In halos (CGM), low density but very large volume: potentially dominates baryonic mass!

NGC 6240 (Credit: Hiroshima University / NAOJ)

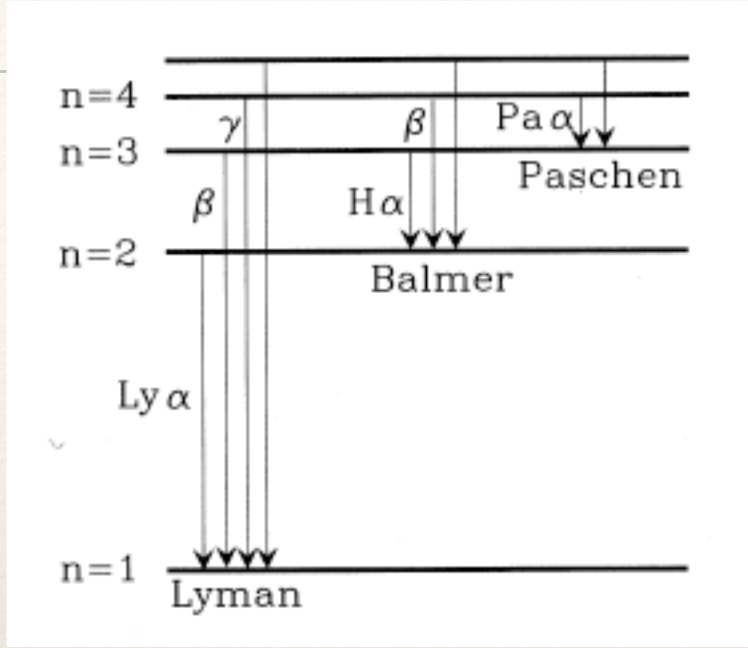
Building Blocks - Gas

- Observing gas in galaxies
  - Two general methods: emission and absorption (of light from a background source)

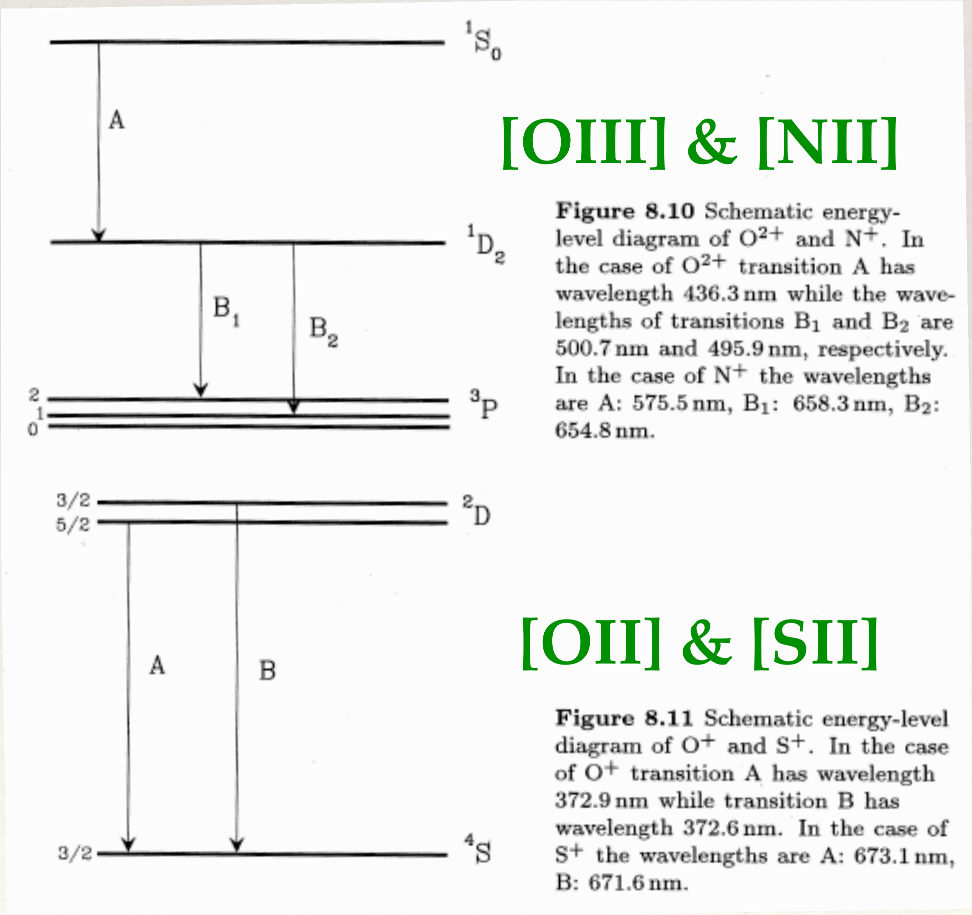


Building Blocks - Gas

- **Emission — Continuum:**
  - free-free (bremsstrahlung)
- **Emission — Atomic Lines:**
  - permitted lines, e.g., H Balmer lines
  - “forbidden” lines, e.g., [OIII], [NII] doublets in optical
  - fine-structure lines typically in FIR, e.g., [CII] 157.7μm
  - hyperfine-structure lines in radio, e.g., HI 21cm

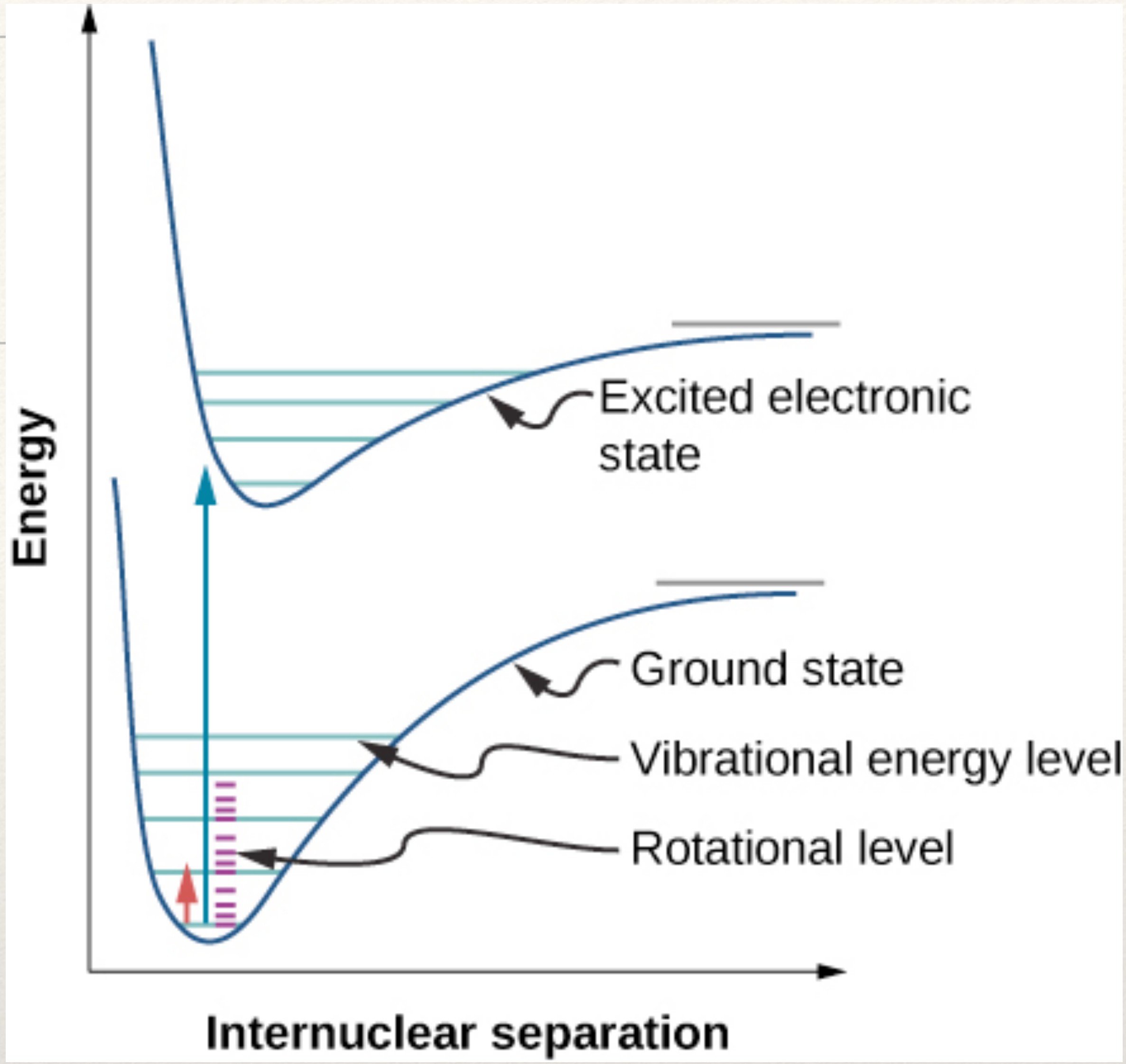


Binney & Merrifield

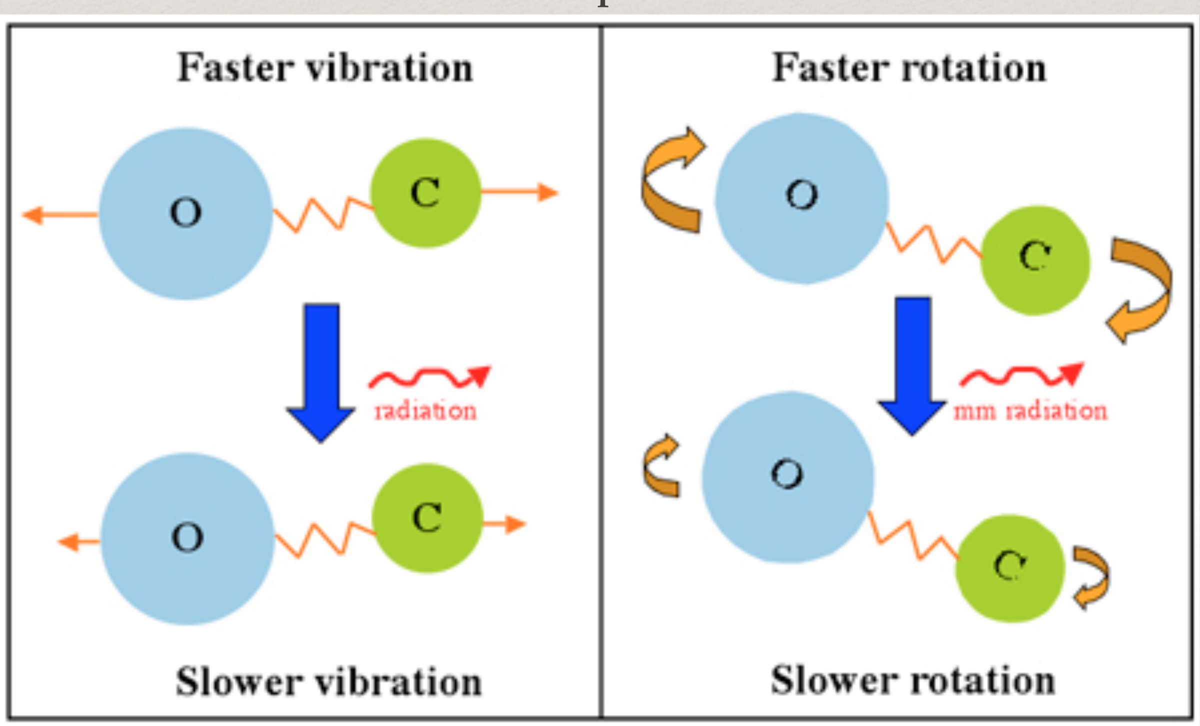


Building Blocks - Gas

- **Emission — Molecular Lines:**
  - vibrational transitions, typically in IR
  - rotational transitions, typically in millimeter
    - only strong for non-symmetric molecules (i.e., not H_2!)
    - CO most prominent



Credit: OpenStax



Swinburne University of Technology

Building Blocks - Gas

- Example: IR spectrum of the Orion Nebula:

M42 (Credit: ESO)

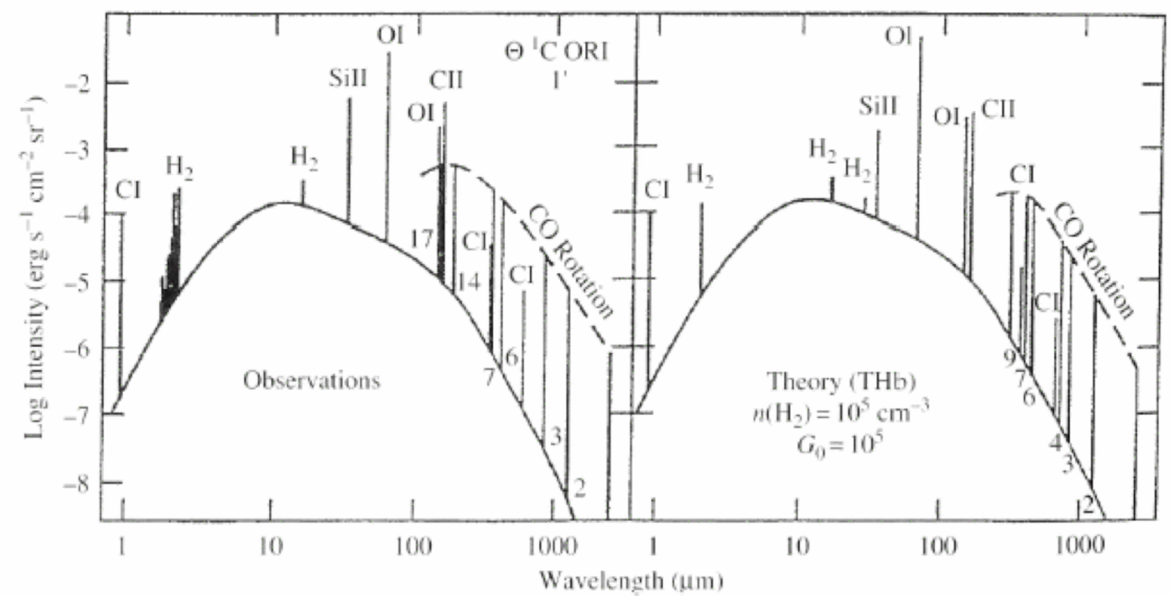


Figure 1.2: Observed IR spectrum (*left*) and model calculations (*right*) for Orion, a dense, star-forming region (Hollenbach & Tielens 1999). The most prominent emission lines are those of CO, C I, C II, and O I, responsible for the cooling of the neutral atomic and molecular ISM.

Building Blocks - Gas

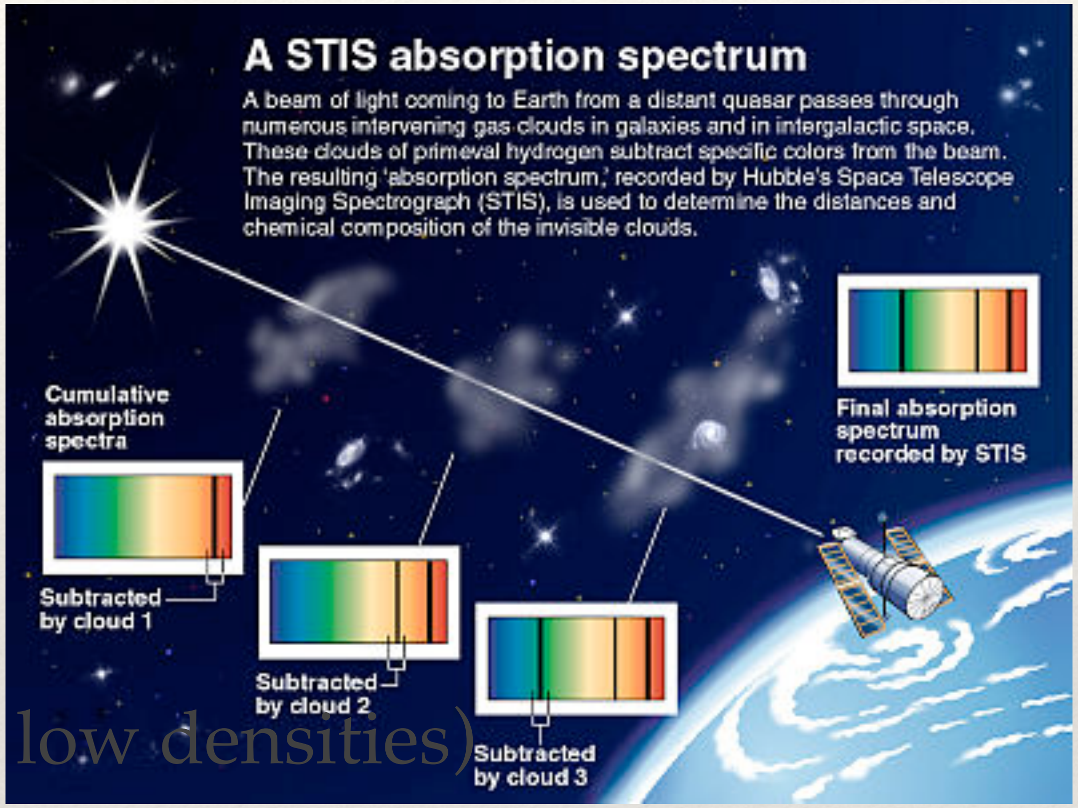
- For emission, something needs to excite/ionize the gas:
  - photoionization: atoms are excited by incident photons
  - collisional: atoms are excited by collisions with free electrons or other atoms
    - can also get collisional deexcitation
    - leads to concept of critical density for a transition; if density is higher than critical, atoms will more likely collisionally de-excite than emit photon
  - shock excitation

- If excitation is collisional, emission typically proportional to square of density (requires two particales

  - Flux **α Emission Measure** (pc cm^{-6}): EM = $\int n^2\, dl$
  - This makes it hard to estimate total mass of gas that is collisionally excited

Building Blocks - Gas

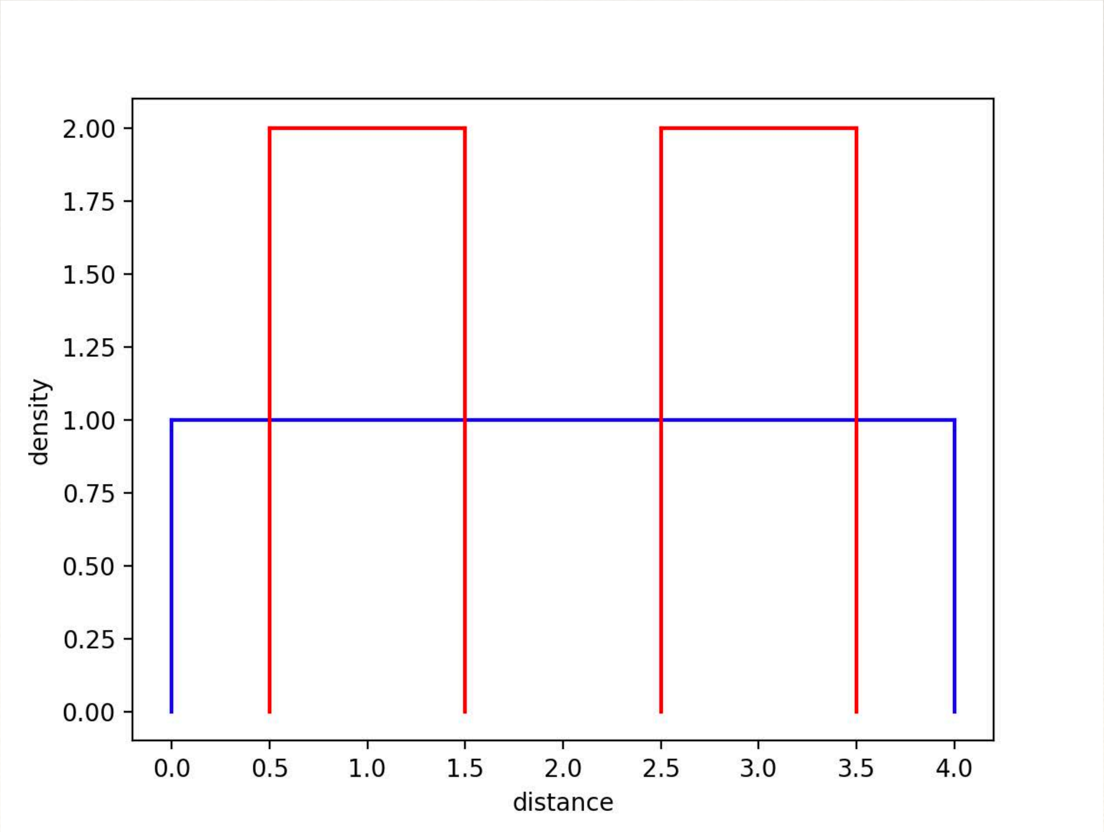
- **Absorption**
  - Atomic Lines — ground state transitions in optical, high ionization absorbers in UV
  - Molecular Lines — mostly in UV, e.g. H_2 absorption
  - More sensitive than emission (because of low densities) but need bright background sources (e.g., quasars)



- Absorption **α Column Density** (cm^{-2}): N **α** ∫ n dl
  - proportional to total mass

Thought Question

- In absorption, you measure column density : $\int n \, dl$
- In many cases in emission, you measure emission measure : $\int n^2 \, dl$
- Are these always related to each other in the same way?
  Consider a certain number of atoms spread uniformly in distance, and the same number of atoms, but in two clumps? How does the column density change? How does the emission measure change?



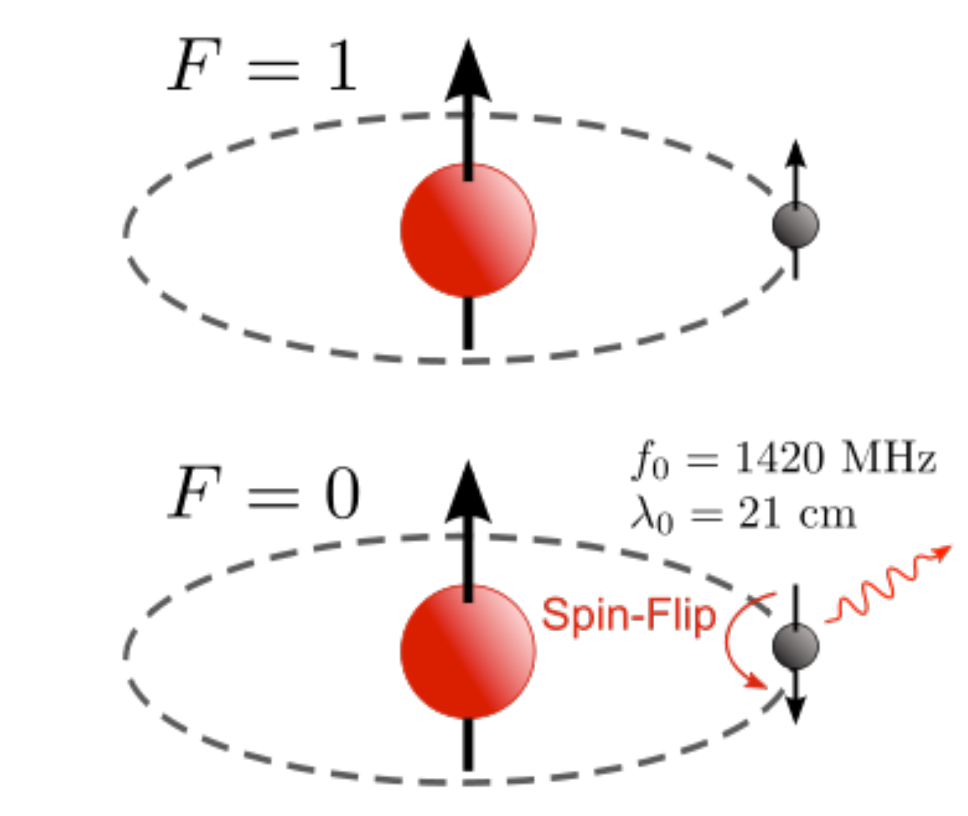
Building Blocks - Gas

- **Atomic Gas — Cold/Warm Neutral Medium (CNM/WNM): 21 cm emission**

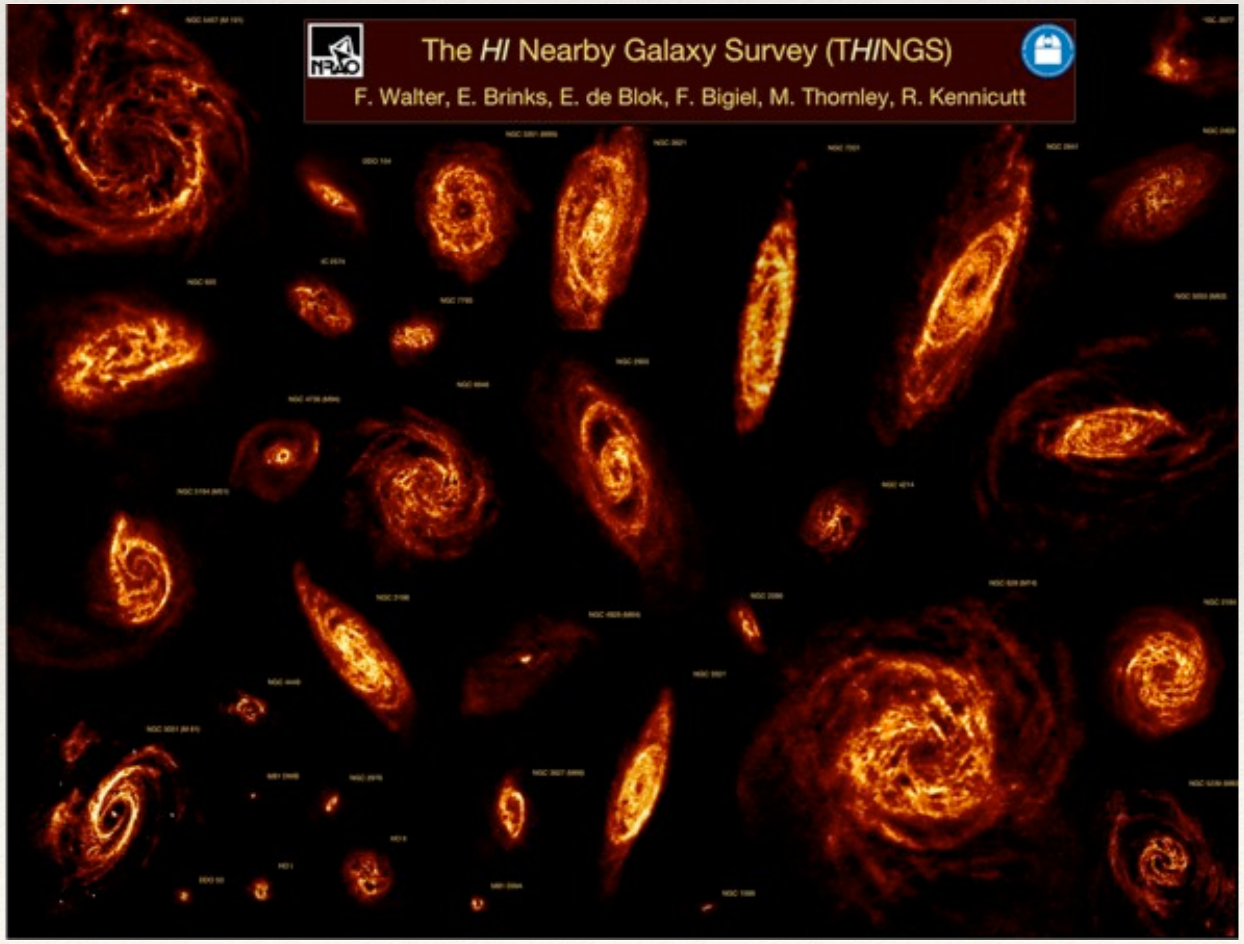
- HI 21 cm emission from spin-flip transition: very rare but HI very prevalent! Relative number in two energy states set by collisional equilibrium and proportional to statistical weights of two levels (3:1)

- Because this is not a collisionally-excited, radiatively de-excited transition, HI flux at a given location gives column density (atoms / surface area):

    - Column densities in is s typically $N_{HI} \sim 10^{20}$ cm
    - Total mass in HI can be a significant fraction of total stellar mass

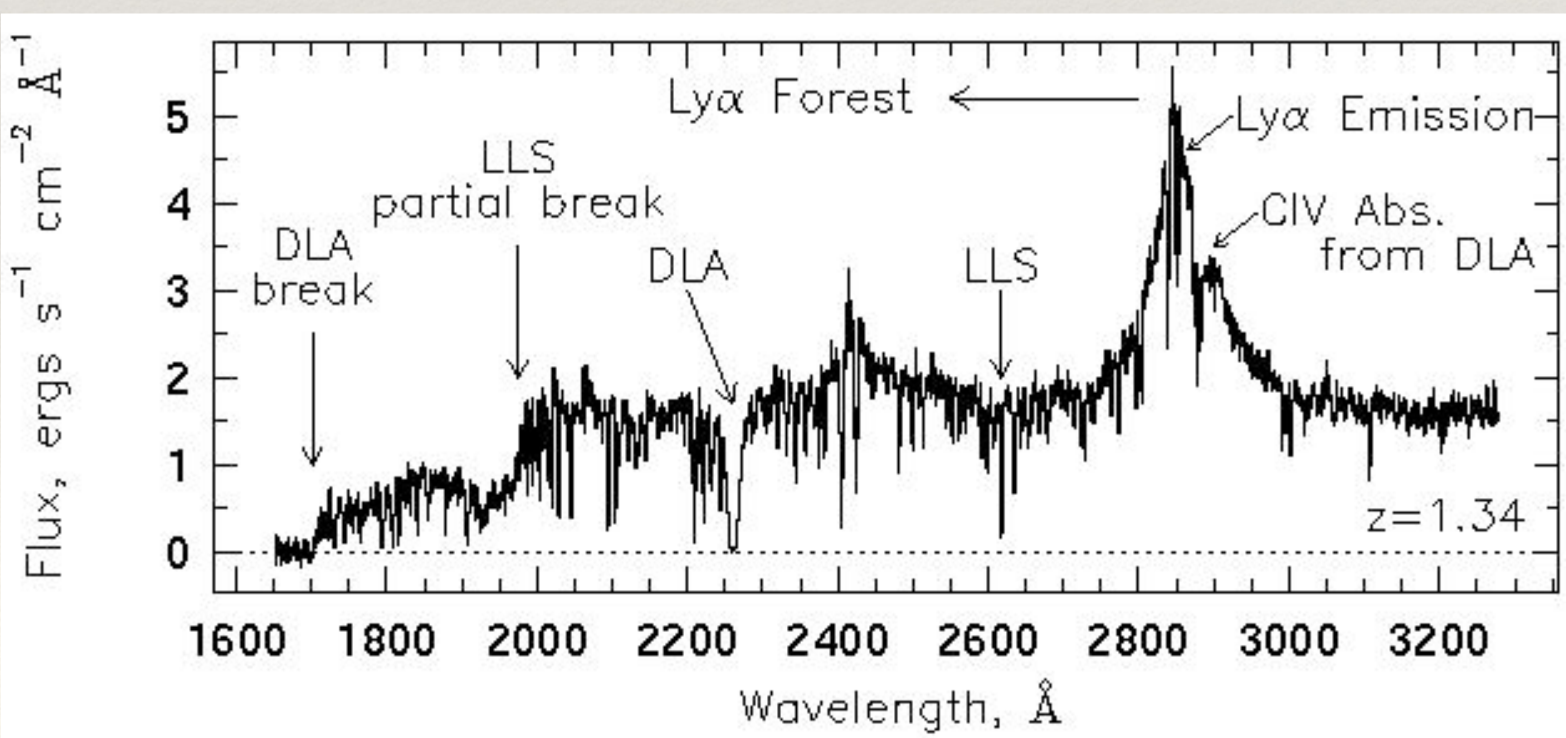


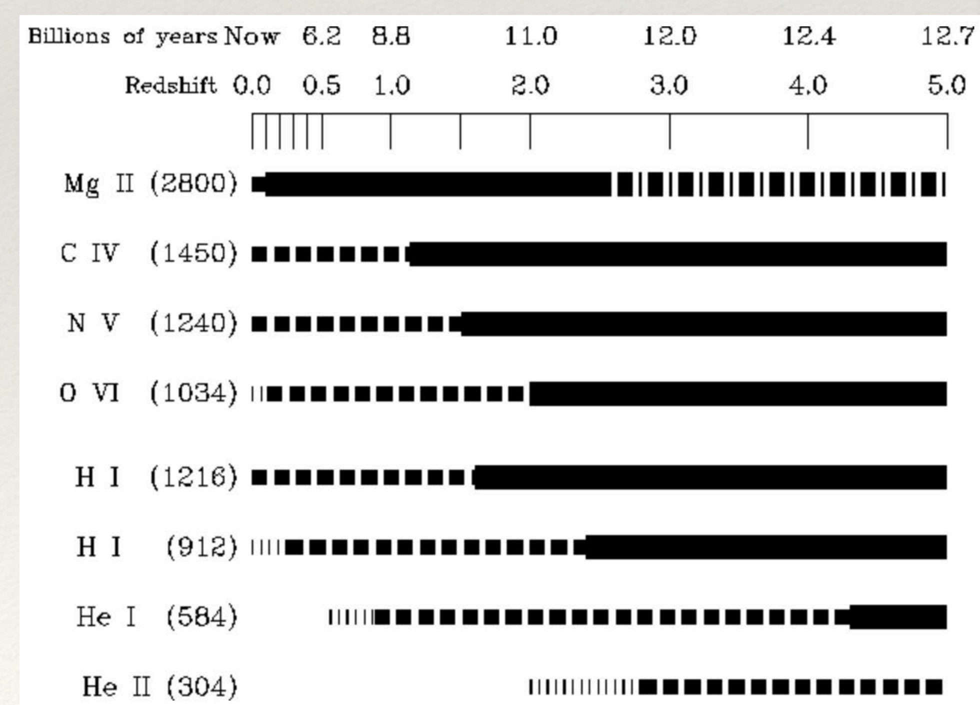
https://en.wikipedia.org/wiki/Hydrogen_line



Building Blocks - Gas

- **Atomic gas — Cold Neutral Medium (CNM): HI in absorption**
  - HI observed in absorption down to very low column densities ($N_{HI} \sim 10^{13}$ cm^{-2}) — Hydrogen Lyman series lines
    - Also primary tool for studying **circumgalactic medium** (CGM) and **intergalactic medium (IGM)**
    - typical column densities range from 10^{13} to 10^{21} cm^{-2} : in increasing column density: Lyman-alpha absorbers to Lyman limit systems, to damped Lyman alpha systems
  - Other heavier element absorbers can also be observed





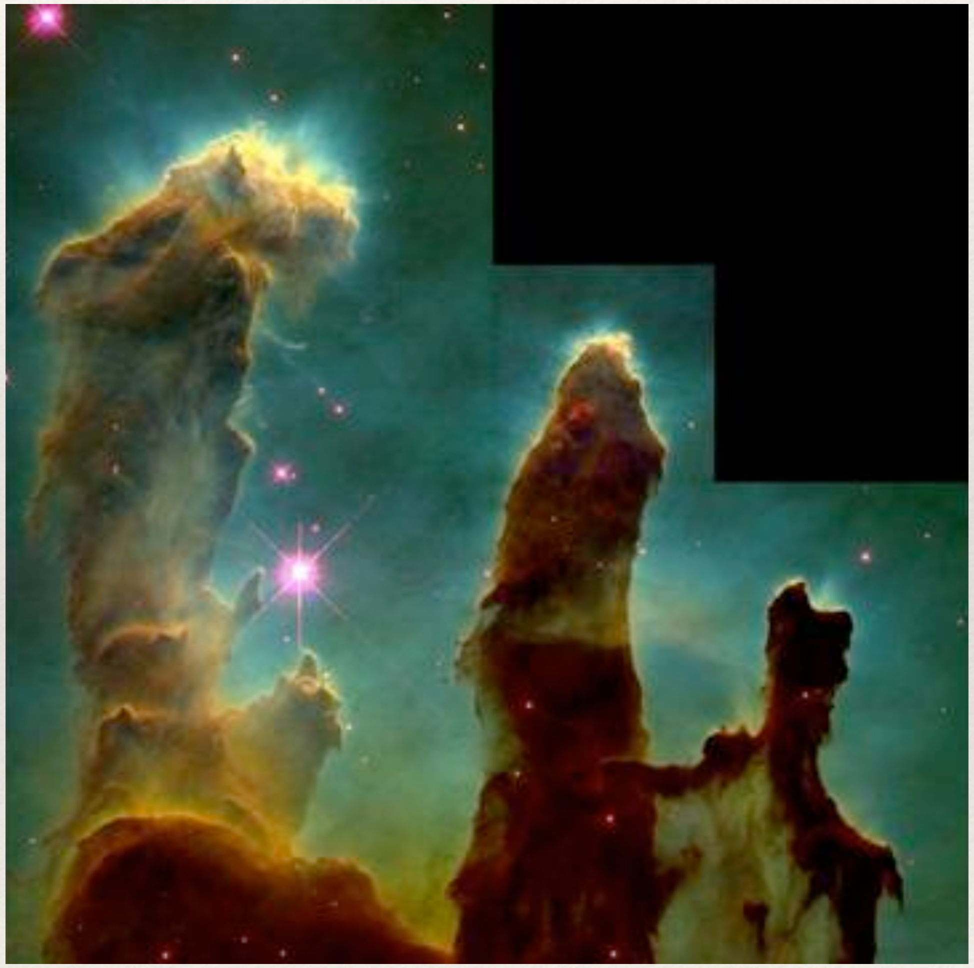
Charlton & Churchill 2000

Building Blocks - Gas

- **Molecular Gas:**
  - Dominant molecule is H2 — symmetric, so no strong rotational transitions
    - H2 and CO interact via collisions, so can trace H2 using CO emission
    - X(CO) factor relates observed CO to H2 column density:

$$X \equiv \frac{N(H_2)/cm^{-2}}{I_{CO}/K\,km s^{-1}} \sim 2 \times 10^{20}$$

    - Many uncertainties and likely depends on metallicity (e.g. Liszt et al. 2010, Leroy et al. 2011)

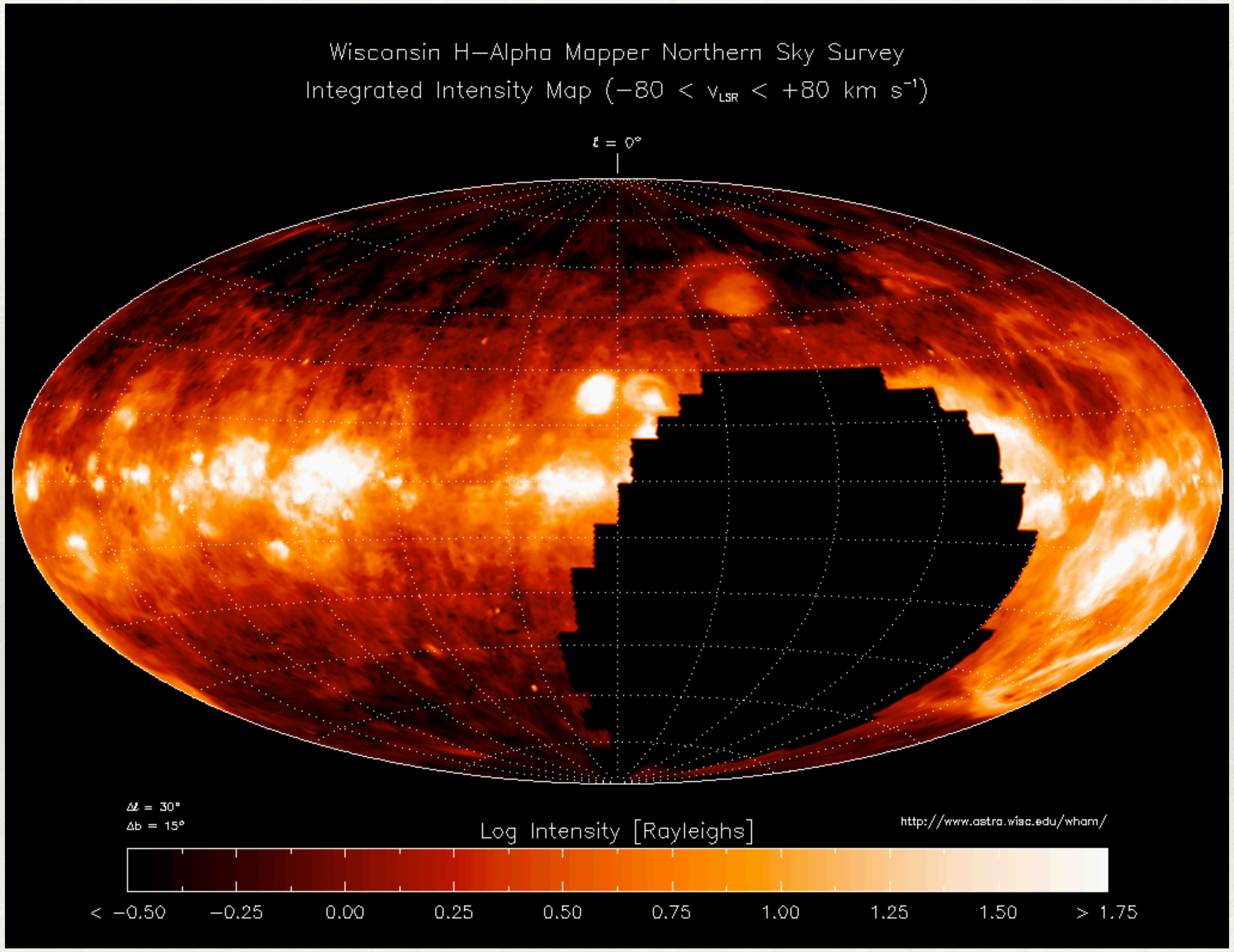


NASA, ESA, STScI, J. Hester and P. Scowen (Arizona State University)

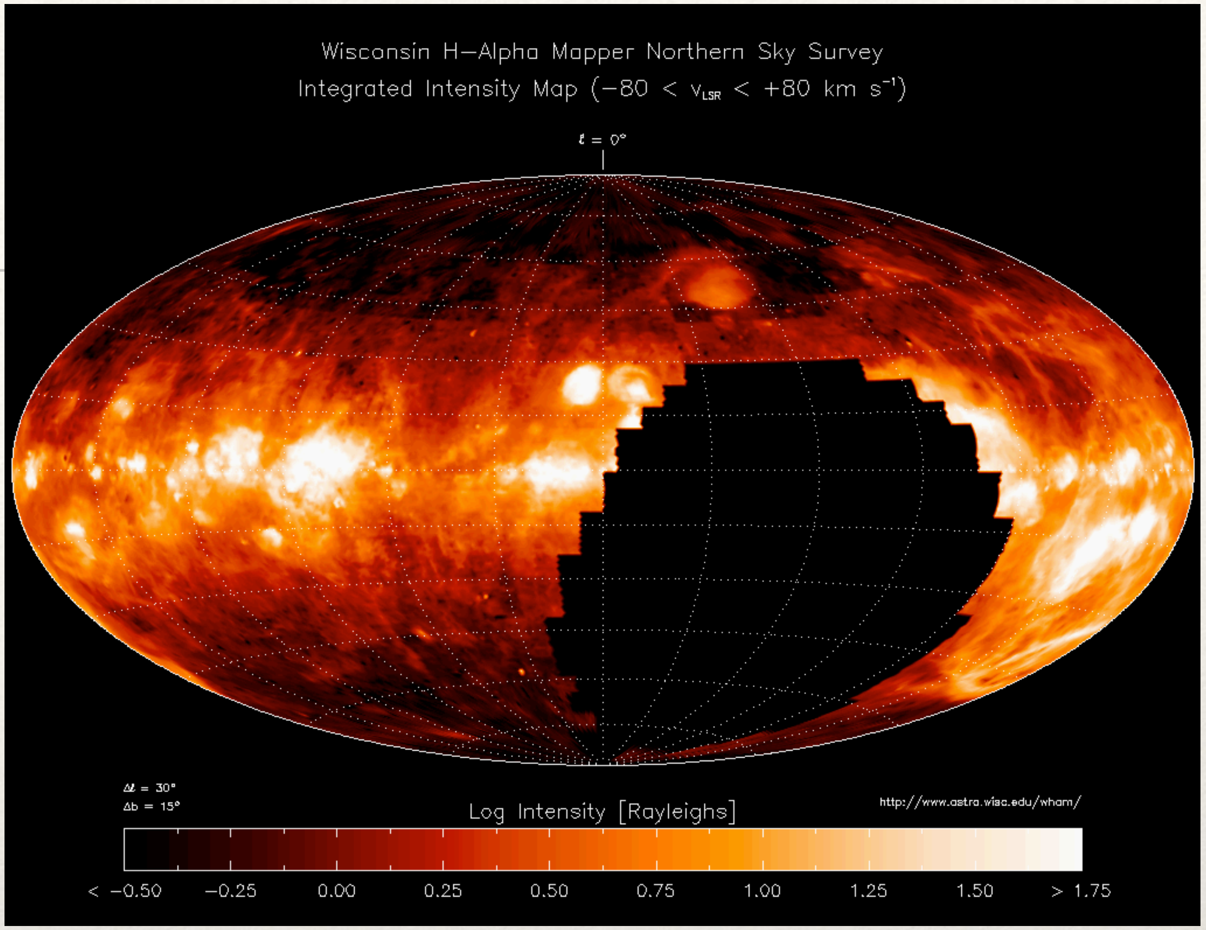
- ene a y m e cen a y c ncen a e an a mic as
- ass cia e i e i ns s a ma i n
- less mass than in atomic gas?

Building Blocks - Gas

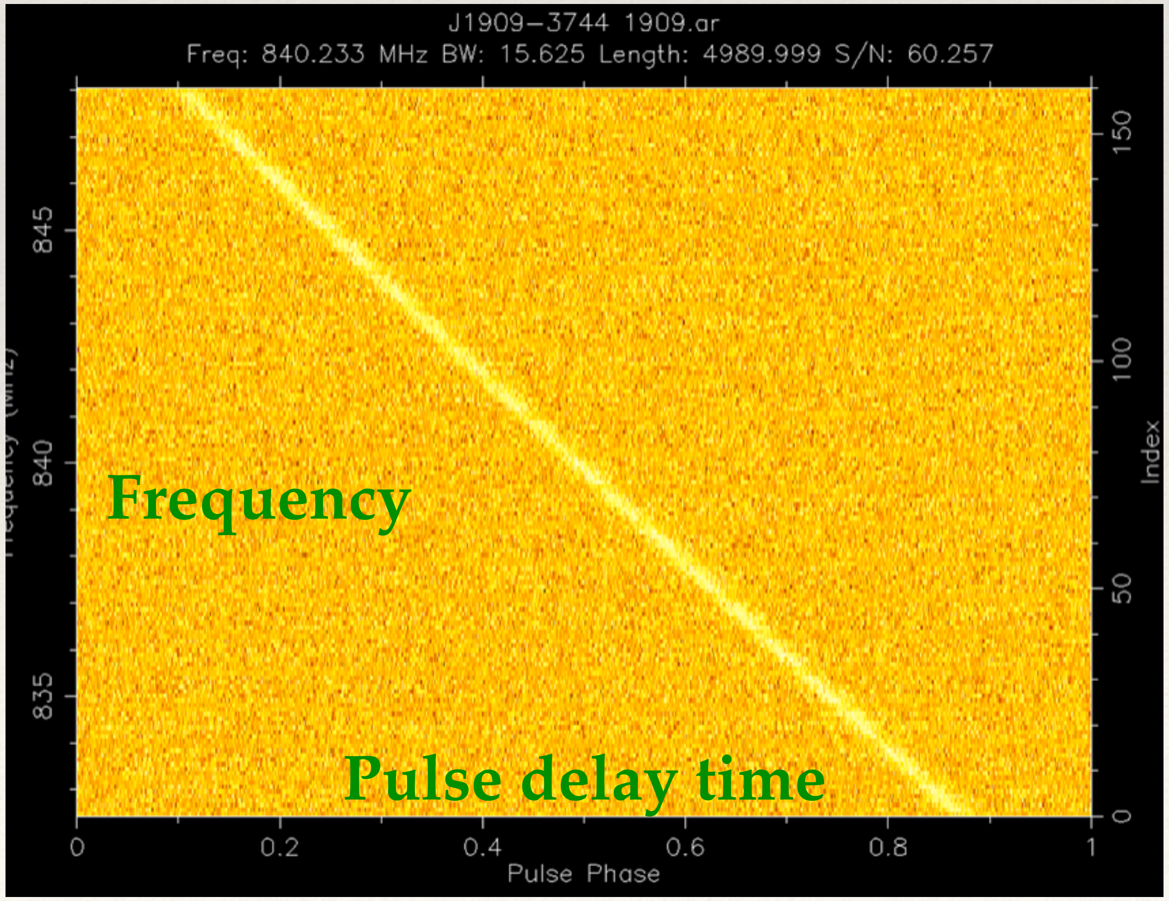
- **Warm Ionized Medium (WIM):**
  - Primarily heated via photoionization y e s a s y n s a s an e e s a s
  - Visible in recombination lines like Hα



Building Blocks - Gas

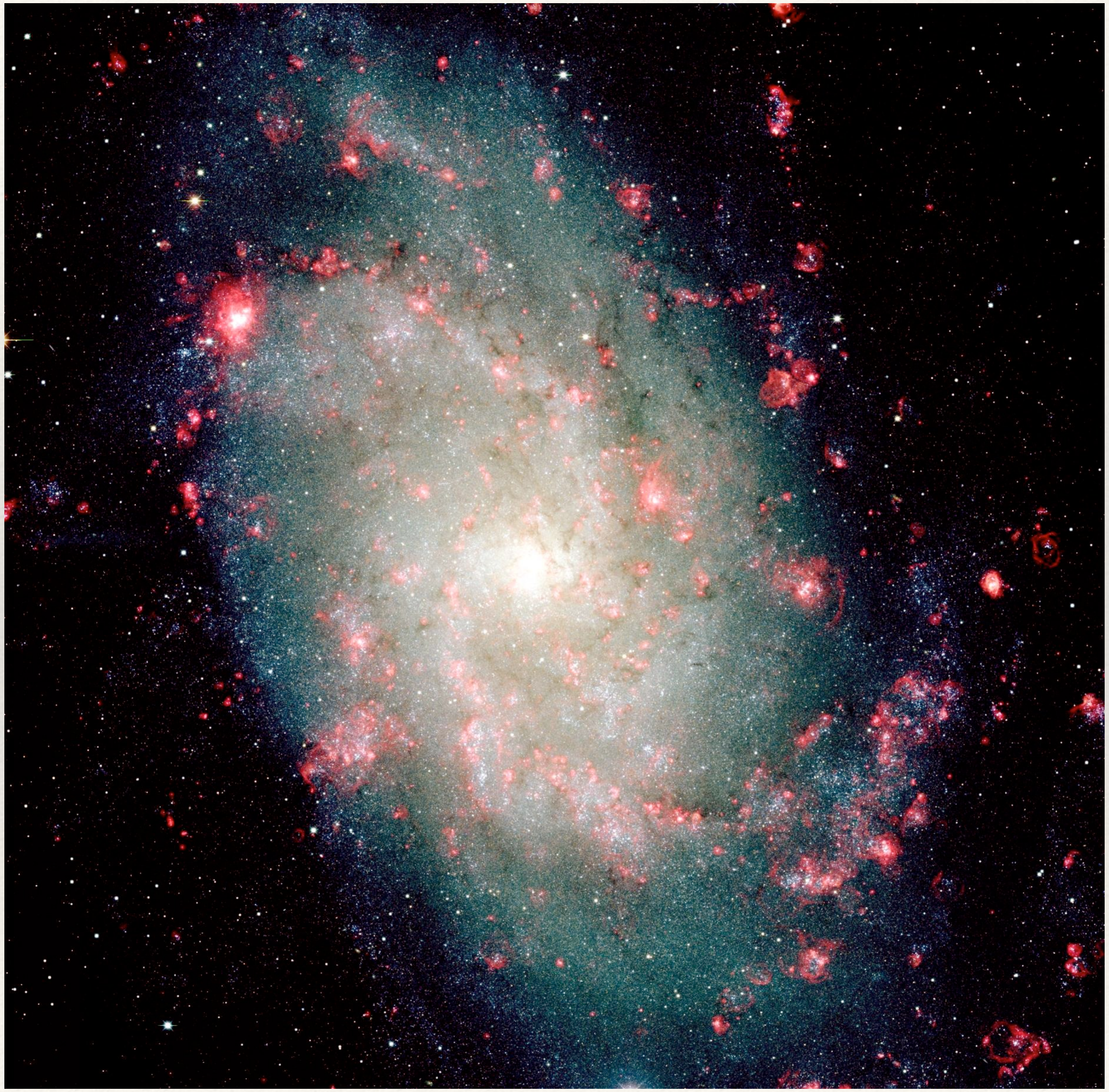


- **Warm Ionized Medium (WIM):**
  - Hard to estimate mass — recombination is a two-body process so depends on gas **clumpiness**
  - sa is e si n meas e
    se e ay s
    e ency se e i e
    c mn ensi y n
  - a mass probably less than neutral gas



Building Blocks - Gas

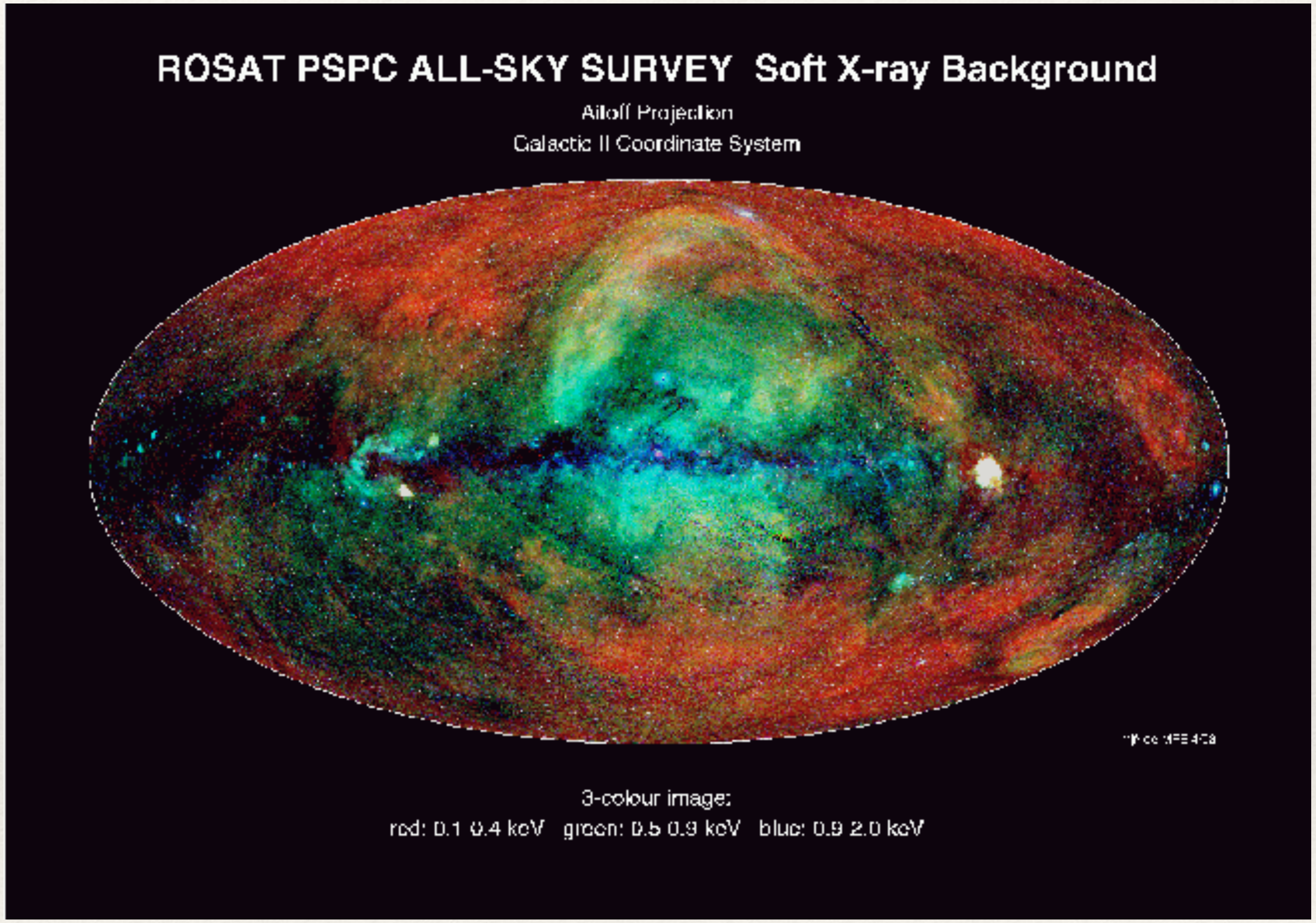
- **Denser Ionized Gas (e.g., HII regions, central regions)**
  - Easiest gas to observe in galaxies
  - Ionized by star-forming regions, shocks, Active Galactic Nuclei (AGN)
  - Often used to measure star formation rates and gas-phase metallicities of galaxies
  - (more next time!)



M33 (Credit: Lowell Observatory)

Building Blocks - Gas

- **Hot Ionized Medium (HIM):**
  - T~10^6 K — free-free emission (thermal bremsstrahlung) in X-rays
  - T~10^5 K — more difficult to detect — use absorption of high ionized metals, e.g., OVI, CIV, NV
  - Hard to determine total mass but likely very significant

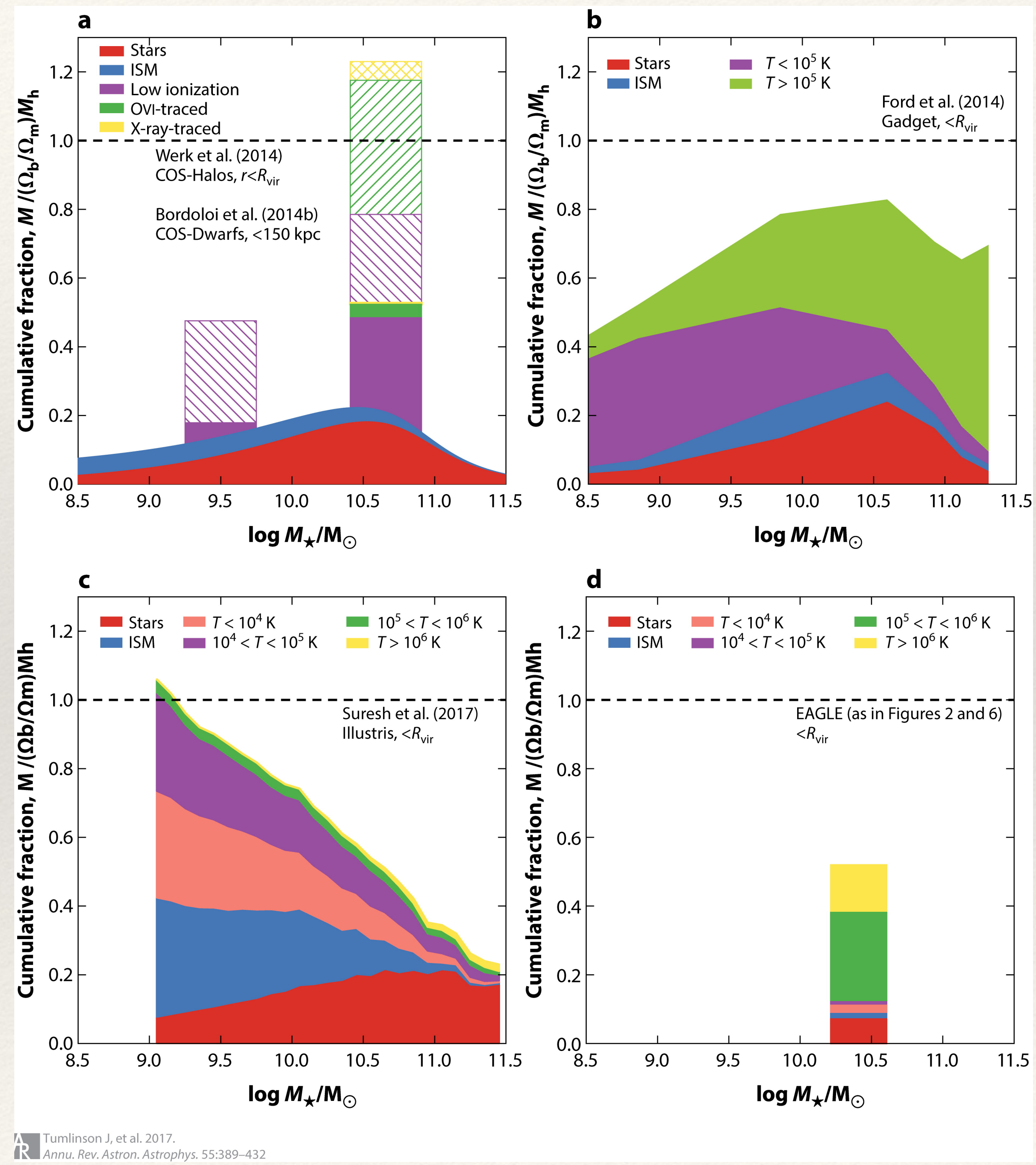


Thought question

- **Overall baryon budget**
  - Standard cosmological model **roughly** has:
    - dark energy: Omega_lambda=0.7
    - cold dark matter: Omega_CDM = 0.25
    - baryons : Omega_baryons =0.05
  - If someone gave you the total mass of a galaxy, what would you expect the baryonic mass to be?
  - What would the implication be if the baryonic mass was larger or smaller than your expectation?

Building Blocks - Gas

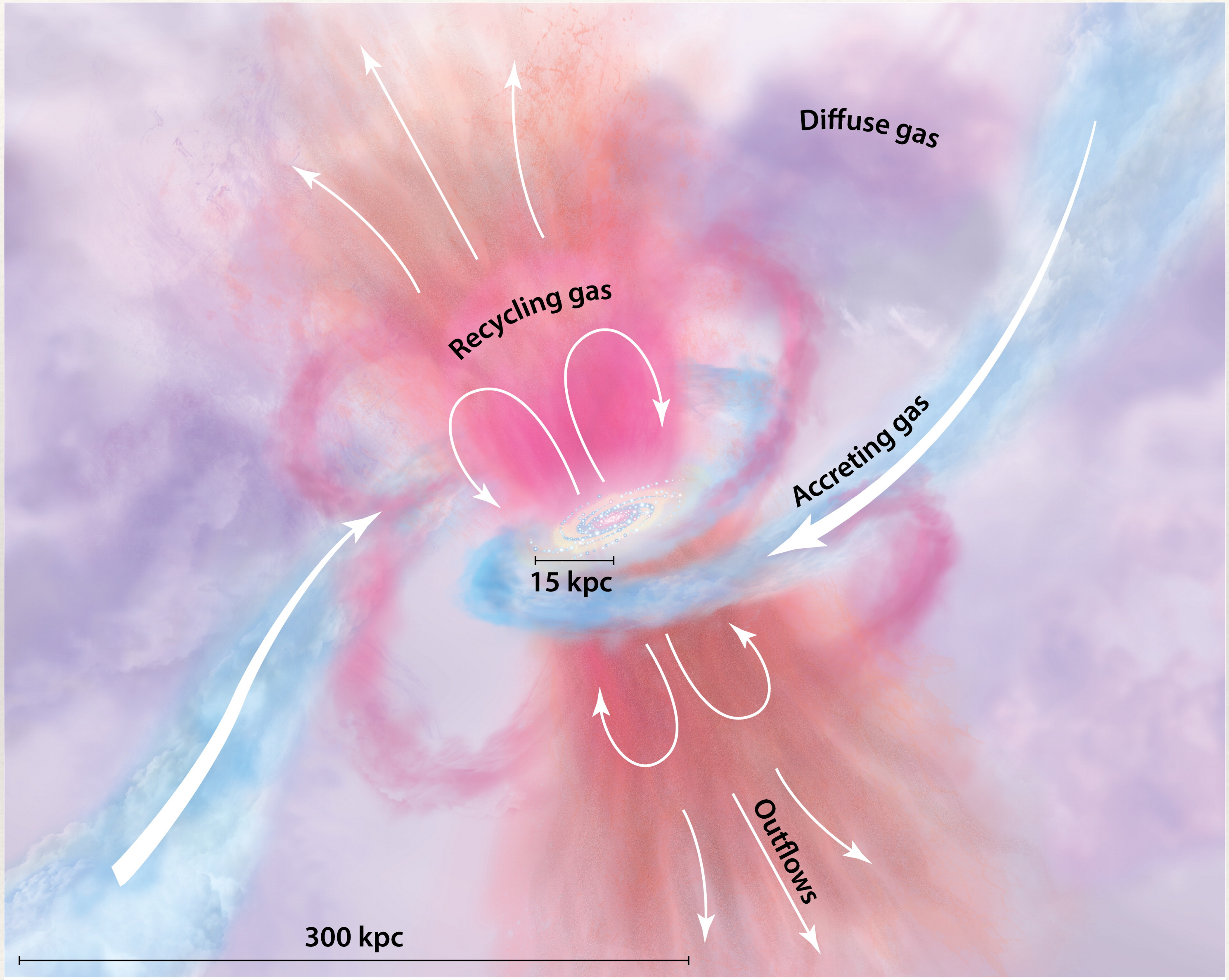
- **Overall baryon budget**
  - Historically, it has been a challenge to detect all baryons expected from cosmology ("missing baryons" problem)
  - Increasing detections of hot gas in galaxy halos and between galaxies (e.g., Gupta et al. 2012, COS Halos project)
  - i e y a m s e a y ns a e in as



m ins n e a

Building Blocks - Gas

Current picture of gas around galaxies is complex!



Tumlinson J, et al. 2017.
Annu. Rev. Astron. Astrophys. 55:389–432

m ins n e a

Building Blocks - Gas

- as in a a ies is in a m i ase me i m
- What determines the gas temperature?
  - **Heating**:
    - gravitational heating
    - radiative heating (ionization, heating of dust)
    - mechanical heating (shocks, jets, etc.)
    - cosmic rays
  - **Cooling**:
    - bremsstrahlung (free-free)
    - line emission, particularly from heavier elements and molecules

Gas cooling is very important for galaxy formation!

Building Blocks - Gas

- Cooling rate C = energy radiated away per volume per time
    - Typically two particle interaction so $C \propto n_H^2$
- $\Lambda(T) = C / n_H^2$ = "cooling function":
    - Units: ergs cm^3 s^{-1}

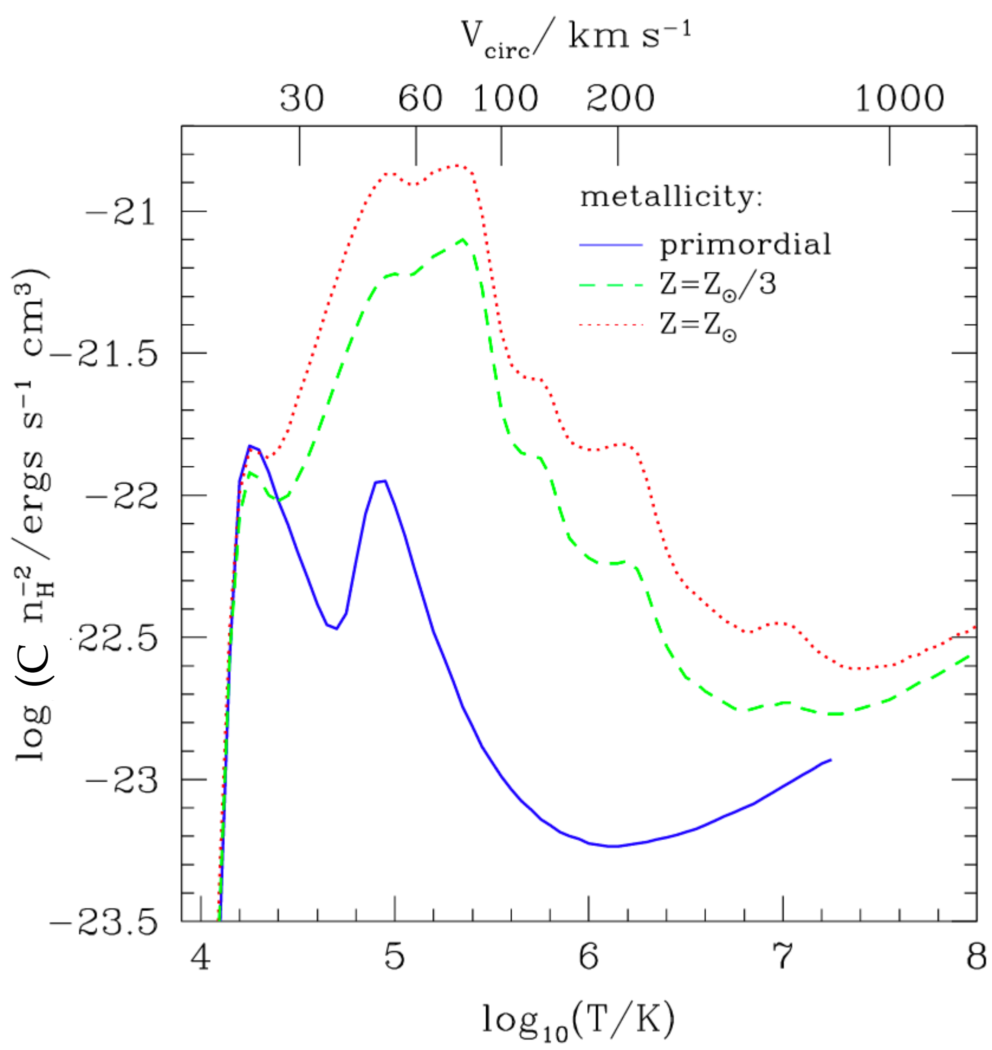


Figure 9. The cooling rate plotted as a function of the virial temperature of the hot halo gas. The equivalent circular velocity of the halo is indicated on the top axis. The different curves show how the cooling rate depends upon the metallicity of the gas, as indicated by the key.

Baugh 2006

Building Blocks - Gas

- Shape of the cooling function determined by the processes and species involved at a given temperature
- Metals are very important for cooling!
- At low metallicities, cooling from H+He

Sutherland & Dopita 1993