GAS Lecture 2

Physics of Emission from Gas (MWB B1.3)

- Lines have enormous range of energies/wavelengths
  - molecular and fine structure lines in IR/radio band
  - atomic lines in the IR, optical, UV and x-ray
- Ionized gas also emits a continuum via thermal bremmstrahlung (S&G pg 33)- shape of which is a measure of temperature, intensity goes as density squared
- Observed line energies give velocity information: redshift, velocity field
- Relative strength of lines determines ionization temperature, abundance of given element (corrected for ionization balance (go to board)).

- see **Thermal radiation processes** J.S. Kaastra, F.B.S. Paerels, F. Durret, S. Schindler, P. Richter

Space Science Reviews, Volume 134, Issue 1-4, pp. 155-190, 2008 astro-ph/0801.1011 for the background physics

- Much of what we know about the chemical composition and chemical evolution history of the universe depends upon the interpretation of the strong emission lines originating from HII regions.
- These emission lines enable us to investigate the metallicity evolution of the universe as a whole
- Measure the mass–metallicity relationship of disk galaxies
- Understand how chemical abundance gradients are formed and maintained
- They encode information about the history of star formation, mass infall, and radial mixing driven by viscous processes in galactic disks.

(adapted from Dopita et al 2013)

Why Metals are Important (sec 10.4 MBW)

- While metals account for 1% of the mass, they **dominate** most of the important chemistry, ionization, and heating/cooling processes (and life)
- Comparison of the metal content of gas and stars compared to
  - what is expected from stellar evolution
  - cosmic star formation rates indicates whether galaxies expel metals and/or accrete gas.

A Bit of Physics-Relevant Velocities

Sound speed in gas $c_s = \partial P/\partial \rho$; P and ρ are the pressure and density (mass density)

For isothermal perfect gas $P = \rho k_B T/\mu m_H$

$c_s = \mathrm{sqrt}(k_B T/\mu)$

where k_B is Boltzmann's constant and μ is the mean molecular weight of the gas (See S&G problem 2.21)

Many astrophysical situations in the ISM are close to being isothermal, thus the isothermal sound speed is often used

- Alfvén speed: The speed at which magnetic fluctuations propagate.

$v_A = B / \mathrm{sqrt}\{4\pi\rho\}$ Alfvén waves are transverse waves along the direction of the magnetic field.

ISM- Relevant Velocities

Some characteristic values

- galactic rotation gradient 18km/sec/kpc
- Thermal sound speed ideal gas for H: 0.3, 1, 3 km/s at 10 K, 100 K, and 1000 K- most of the velocities measured in galactic gas are thus supersonic (e.g. gas is turbulent)

Alfven speed- for typical ISM values B=1μG, # density $n \sim 1 cm^{-3}$

$v_A = 2$ km/sec

- Given typical ISM conditions
  - $c_s \sim v_A$ in dense gas
  - $c_s < v_A$ in diffuse gas

A Bit of Physics- Scales

- In gas at temperature T, the mean particle velocity is given by the 3-d kinetic energy: $3/2mv^2 = kT$;

- collision timescale: $\tau \sim \ell/v$: ℓ is length , v is velocity

$\ell \sim 1/ n\sigma$; n is the NUMBER density of the gas and σ is a typical cross section (hard sphere approx for ions $\pi r^2 \sim 10^{-15}$ cm^{-2})

and thus $\tau \sim \{2/3\} \{kTm\}^{-1/2}/(n\sigma) = 4.5\ 10^3 n^{-1} T^{-1/2}$ years

ℓ is mean free path

  - for a typical place in the ISM (n,T) = ($1cm^{-3}$, $T \sim 10^4$K) the collision time is 45 years

Jeans Length and Mass

- Jeans Length (smallest size that collapses)

$\lambda_J \sim \mathrm{sqrt}(kT/G\rho m)$

- Jeans Mass : (smallest mass that collapses)
- $M_j \sim \rho L^3 \sim T^{3/2} \rho^{-1/2}$

A Bit of Physics-TimeScales

For a sphere of gas, if thermal pressure is balanced by self-gravity the timescale to collapse (the **Jeans time**)

- $\tau_J \sim 1/\text{sqrt}(4\pi G\rho)$ which is similar to the free falltime (S&G eq 3.23)-The *free-fall time* t_{ff} is roughly the time that a gas cloud of density ρ would take to collapse under its own gravity (Also see MWB pg 14)

  $\tau_{ff}=(3\pi/32G\rho)^{1/2}$ = 4.4 x 10^4 yr /sqrt{n_H /10^6} if gas is hydrogen

- *Jeans length* $\lambda_J = c_s \text{Sqrt}(\pi/G\rho)$ *S&G 2.24*

n_H is the particle density

ρ is the mass density

https://en.wikipedia.org/wiki/Jeans_instability;

Simplest Derivation of Jeans Collapse

If the mass of a cold cloud, M_{cl}, exceeds the Jeans mass, *MJ*, it is subject to collapse under its own gravity

- Consider N atoms of mass min a box of size $\mathcal{L}$ and temperature T
- Thermal energy in cloud is $E_{Th} \sim kTN$; N is the number of particles, T is the temperature
- The gravitational (binding) energy $U \sim GM^2/\mathcal{L}$
- Ratio is $E_{th}/U \sim GM^2/LNkT \sim G(\rho L^3)m/LkT = \mathcal{L}/\mathcal{L}_J$ if $\mathcal{L}_j \sim \text{sqrt}(kT/G\rho m)$
- To collapse the internal energy <binding energy
- Gravity wins when $U>E_{th}$ $\mathcal{L}>\mathcal{L}_j$; Pressure wins for $\mathcal{L}<\mathcal{L}_J$

Large cool dense regions collapse.

Jeans Mass MBW Sec 4.1.3 pg 167

- Jeans length λ_J= distance a sound wave can travel in a gravitational free fall time- t_{ff} ~$(G\rho)^{-1/2}$.
- For c_s= sound speed $\lambda_J = c_s \mathrm{sqrt}(\pi/G\rho)$

$c_s = (5kT/3m)^{1/2}$ where m is the mass of the particle

$=\mathrm{sqrt}(5kT/4m\pi G\rho)$

Full up perturbation stability analysis https://ay201b.wordpress.com/2011/04/12/course-notes/#the_jeans_mass

Simple Derivation of Jeans Collapse S&G 8.5.1

If the mass of a cold cloud, M_{cl}, exceeds the Jeans mass, M_J, it is subject to collapse under its own gravity

- Kinetic energy in cloud is KE=(3/2kT)N; N is the number of particles, T is the temperature
- The gravitational (binding) energy $U=-3/5GM^2/R$ (uniform density sphere- derivation later in class)
- Using the viral theorem (lots more later)

  system is in equilibrium if $3NkT=(3/5)GM^2/R$
- So to collapse the internal energy <binding energy
- Assume all the mass is in hydrogen with a mass m per particle
- then to collapse $M_J>(5kT/Gm)^{3/2}(3/4\pi\rho)^{1/2}$ where ρ is the density (e.g. $(M/[4/3p\pi r^3])$
- M_J is called the Jeans mass

http://scienceworld.wolfram.com/physics/JeansLength.html

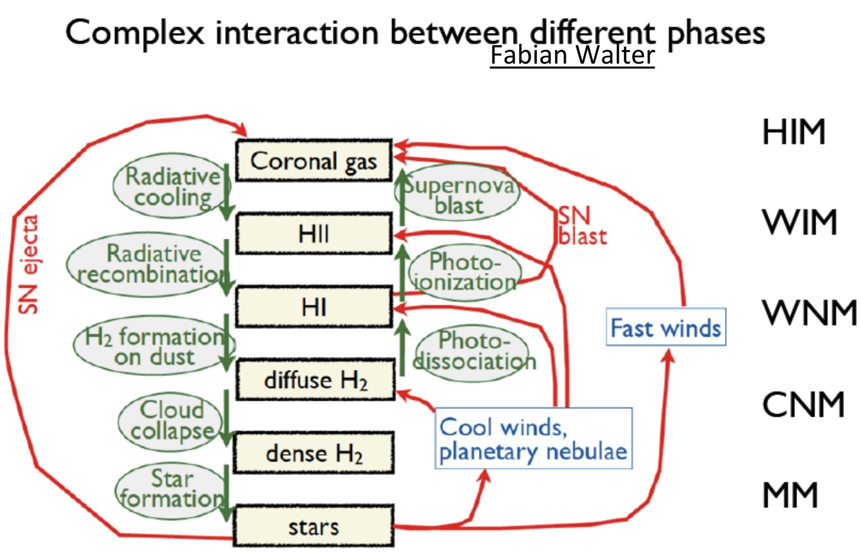
Next Presentation Monday Oct 2

- **QUALITATIVE INTERPRETATION OF GALAXY SPECTRA** J. Sánchez Almeida et al ApJ 756,163

- This is a very didactic article on interpretation of galaxy spectra –
- please focus on the diagnostic from ISM emission lines and section 6
- Jialu Li (next is Weizhe Liu, and then Liz Tarantino)

The ISM in Spirals is DYNAMIC-Driven by Star Formation

- There is strong interaction between the different phases of the ISM and feedback between star formation and the rest of the ISM
- There is lots of complex non-linear effects (and lots of jargon)

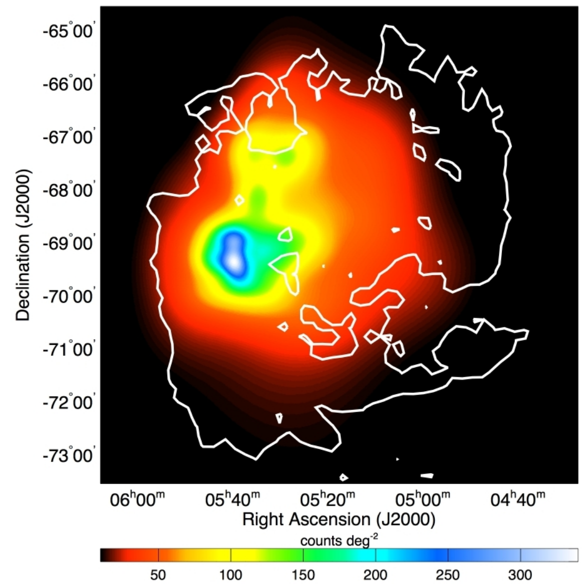


The ISM in ellipticals is **not** dynamic in the same way; AGN seem to be more important in influencing the physical status of the gas

How Does One Observe the ISM (sec 5.2 in S&G)

- Optical/UV
  - wide variety of emission and absorption lines from ionized metals (C,N,O etc) - gas is photoionized
- Soft x-ray
  - continuum and emission lines from T~10^6-10^7k gas (spirals and ellipticals) - gas is collisionally ionized
- Millimeter- molecular

γ-ray Map of LMC



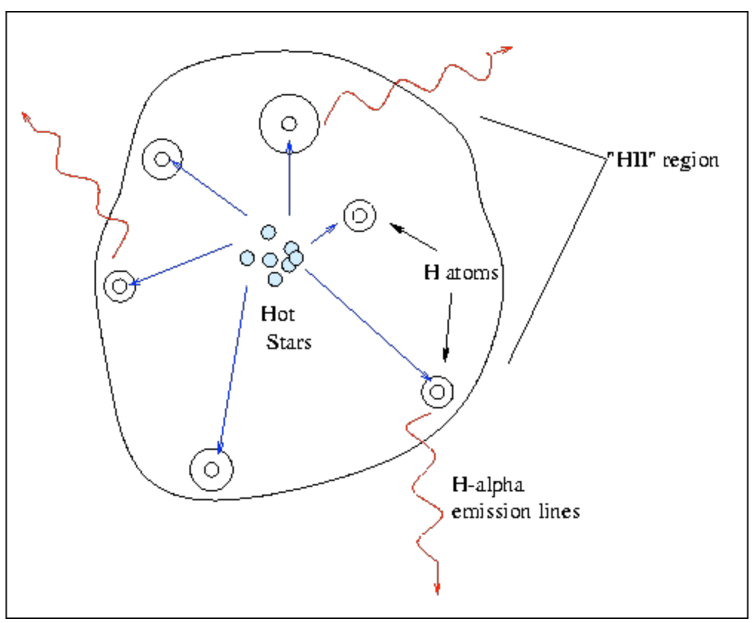
Spiral ISM 'States'- f is the filling factor

- Molecular Medium (MM): T~20 K, n > 10^3 cm^{-3}, **f < 1%.**
  - The MM is mostly cold dense molecular clouds which are gravitationally bound. This phase contains much of the ISM mass, but occupies only a very small fraction of the ISM.
- Cold Neutral Medium (CNM; T~100 K, n~20 cm^{-3}, f =2 - 4%).
  - The CNM is distributed in rather dense filaments or sheets, occupying a minor fraction of the ISM. The CNM is most readily traced by HI measured in <u>absorption</u>.
- Warm Neutral Medium (WNM; T~6000 K, n~ 0.3 cm^{-3}, f~30%)

Spiral ISM 'States'- f is the filling factor

- - Warm Ionized Medium (WIM; T ~8000 K, n ~0.3 cm^{-3} f~15%).
  - associated with **HII regions**, but a considerable fraction of the ISM outside of HII regions is also filled with ionized gas.
- Hot Ionized Medium (HIM; T~10^6 K, n~10^{-3} cm^{-3} , f~50%). The hot gas produced by supernova explosions and their after effects (in spirals), other physics in ellipticals - long cooling time , a **large fraction of the ISM** is filled with this component but **low total mass**.

HII Region



Line Emission from Hydrogen (MBW 476-478)

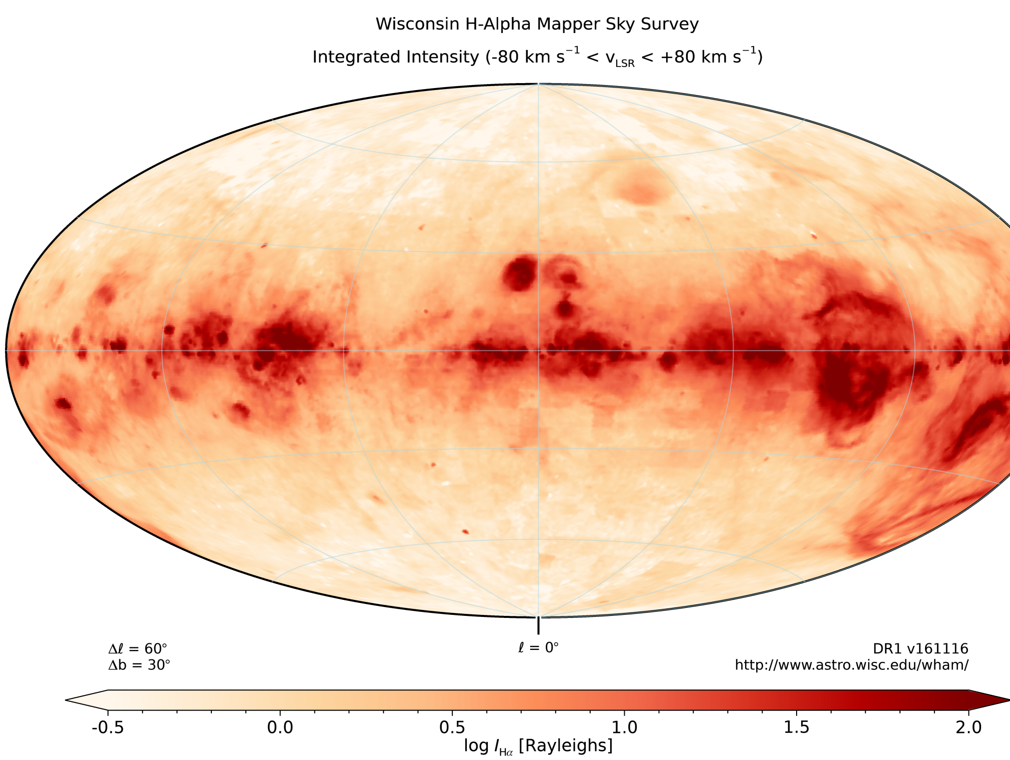
- Balance the flux $\mathcal{F}$ (number of photons per unit time) by the recombination rate.
- $\mathcal{F}=\alpha_B N_p N_e V$; α_B is the recombination coefficient, N_p is the proton density, N_e is the electron density, V is volume.

- If the region is *optically thin* the line emission corresponding to a transition between states 1 and 2 is
- $L_{12}=h\nu_{12}VN_pN_e\alpha_B$
- This gives for $T=10^4$K ; h= Plancks constant; V=colume

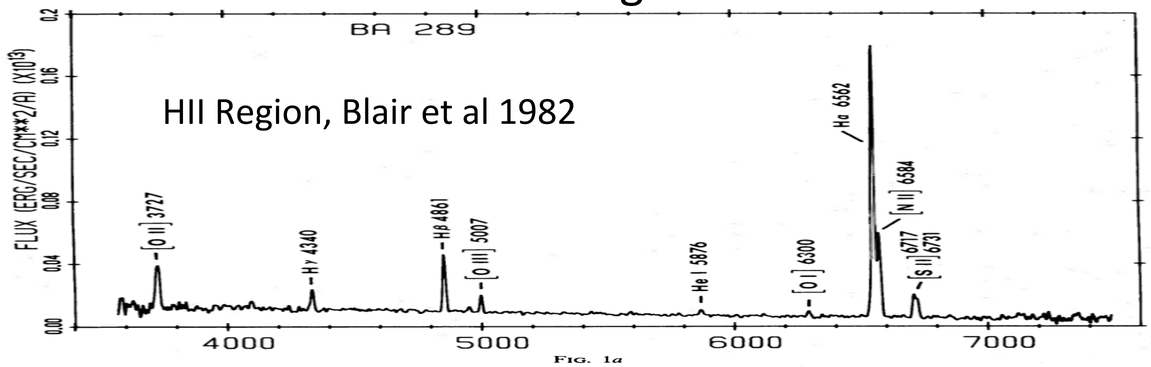
$\mathcal{F}=0.45hN_pN_eV\nu_{H\alpha}$ and $H\alpha/H\beta=3.8$

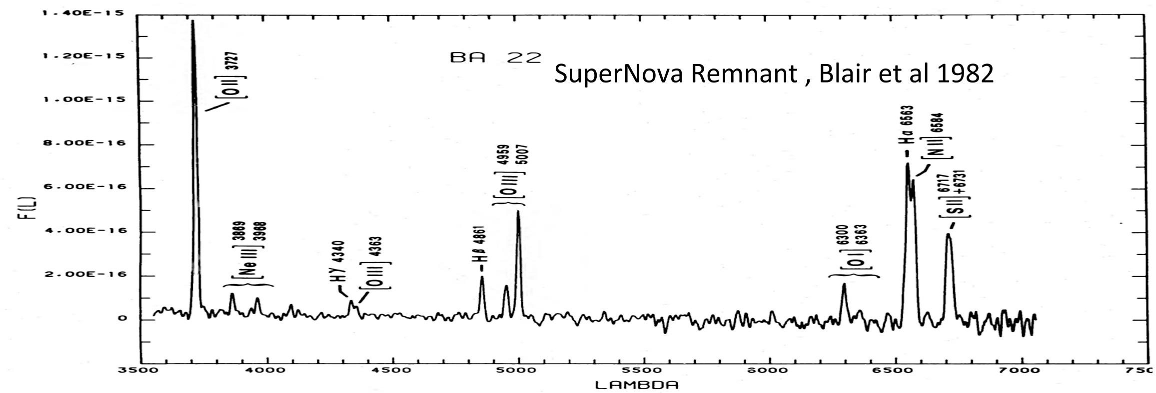
- **Thus, by measuring the luminosity of a *HII region* in a recombination line, which can be used to infer the number of ionizing photons and thus the number of O,B stars.**

Hα Emission in the MW



Other Strong Lines





ISM- Phases

- Hot ionized medium (e.g. X-rays)
- Warm ionized medium HII region(e.g. Hα)
- Warm neutral medium (e.g. HI emission)
- Cold neutral medium (e.g. HI absorption)
- Molecular medium (e.g. CO)

These phases have different distributions perpendicular to the plane- scale height

TABLE 2.1— The different phases of the ISM.

	MM	CNM	WNM	WIM	HIM
n (cm^{-3})	$10^2 - 10^5$	4–80	0.1–0.6	≈ 0.2 cm^{-3}	10^{-3}–10^{-2}
T (K)	10–50	50–200	5500–8500	≈ 8000	10^6–10^7
h (pc)	≈ 70	≈ 140	≈ 400	≈ 900	>1 kpc
f_{volume}	$<1\%$	≈ 2–4%	$\approx 30\%$	$\approx 20\%$	$\approx 50\%$
f_{mass}	$\approx 20\%$	$\approx 40\%$	$\approx 30\%$	$\approx 10\%$	$\approx 1\%$

Note: the quoted numbers for each of the phases are only rough estimates. n is the particle density in cm^{-3}, T the temperature in K, h the scale height in pc, f_{volume} is the volume filling factors, and f_{mass} the mass fraction.

Fabian Walter

ISM in Spirals

- **The phases of the gas are distributed differently**
  - cold (molecular) gas is confined to a thin disk

$\rho(z)$~ 0.6 exp[-(z/80 pc)^2] and has a mean T~15k

  - 'warm' gas has a higher scale height density distribution

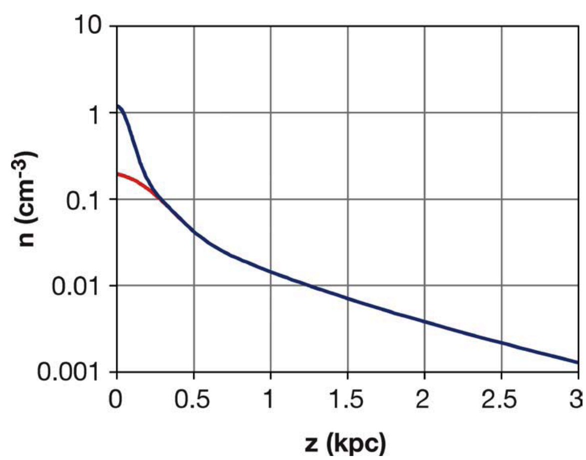
$\rho(z)$~ 0.55 * 0.2 exp[-(z/320 pc)^2]

where z is the distance above the disk midplane

has a mean T~5000k

Roughly magnetic, cosmic ray, and dynamical pressures are equal ~10^{-12} dyne mid-plane

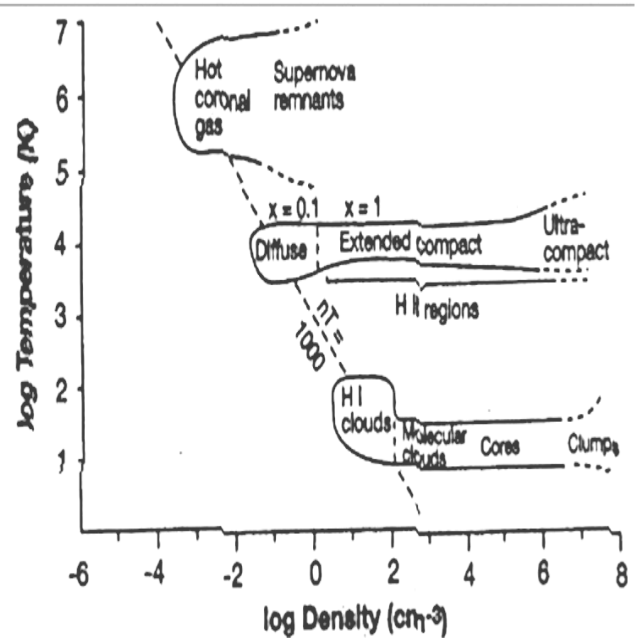
total gas density in MW
vs height above the disk (blue)
warm gas in red



Cox+Reynolds ARA&A 1987 25,303

ISM in Spirals

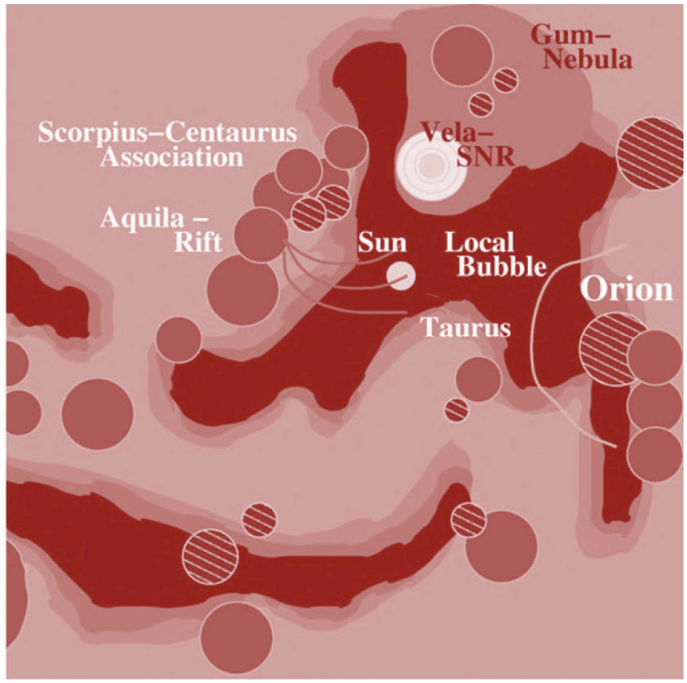
- The ISM is energized primarily by stars (starlight (dust), stellar winds, supernovae
- UV starlight photoionizes atoms & dissociates molecules; photo-ejected electrons heat gas



See lecture notes by Fabian Walter for lots more detail (on class web page)

ISM in Spirals

- The interstellar medium near the Sun has large scale structures of bubble walls, sheets, and filaments of warm gas.
- The remainder of the volume is in bubble interiors, cavities, and



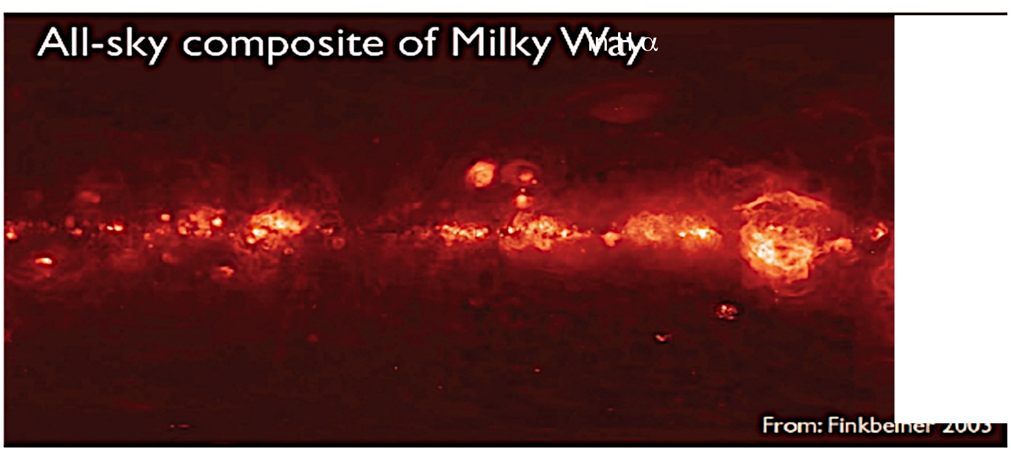
1500 ly

Norbert Schulz

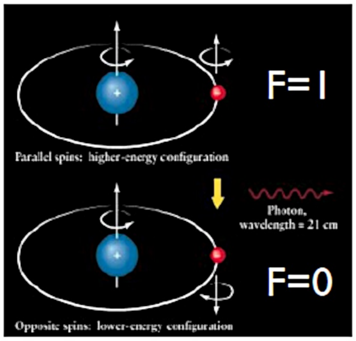
Warm Ionized Medium

Fabian Walter

- mainly traced by Hα
- most likely source: photoionization from OB stars
- scale height: 1kpc
- minimum energy rate: $3x10^5$ kpc^{-2} s^{-1} (equiv. of 1 O4 star kpc^{-2})
- total energy requirement: $3x10^8$ L_{sun}



Most important tracer for warm/cold neutral medium: HI 21cm line

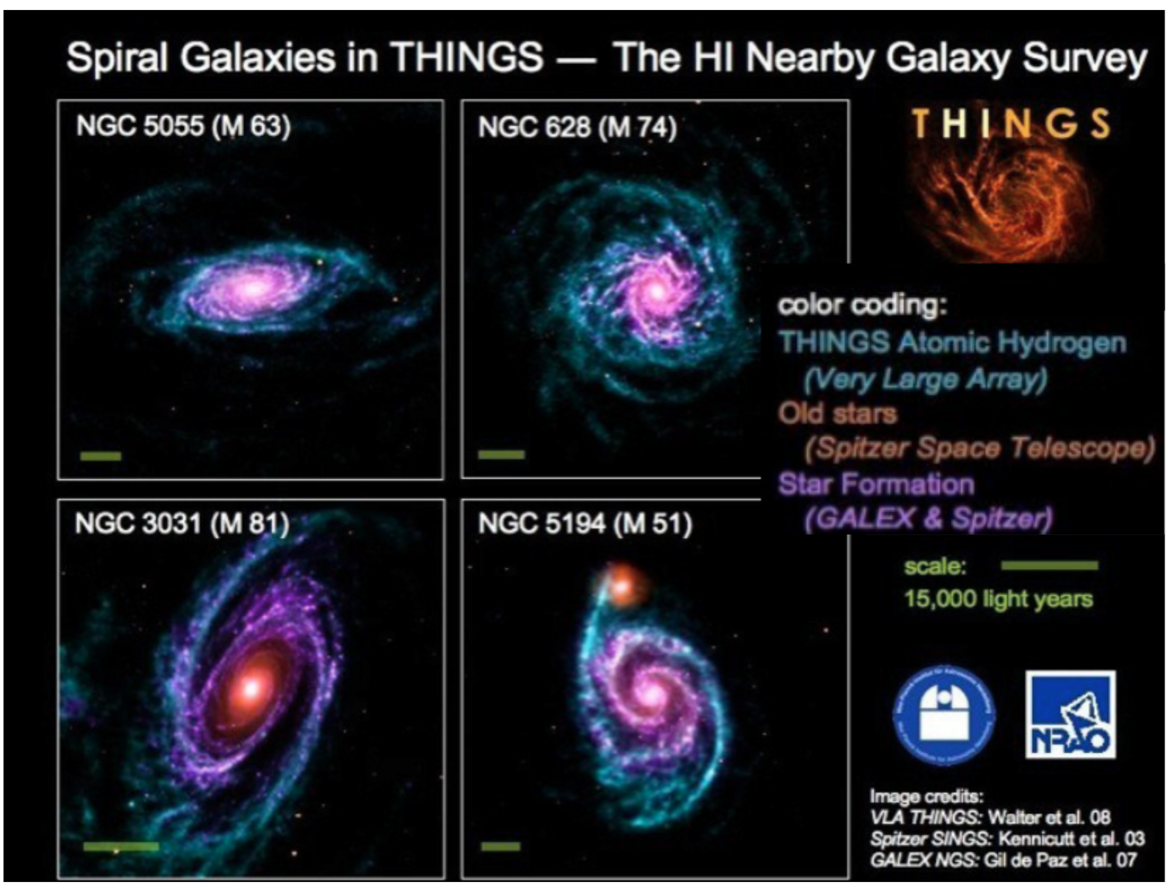


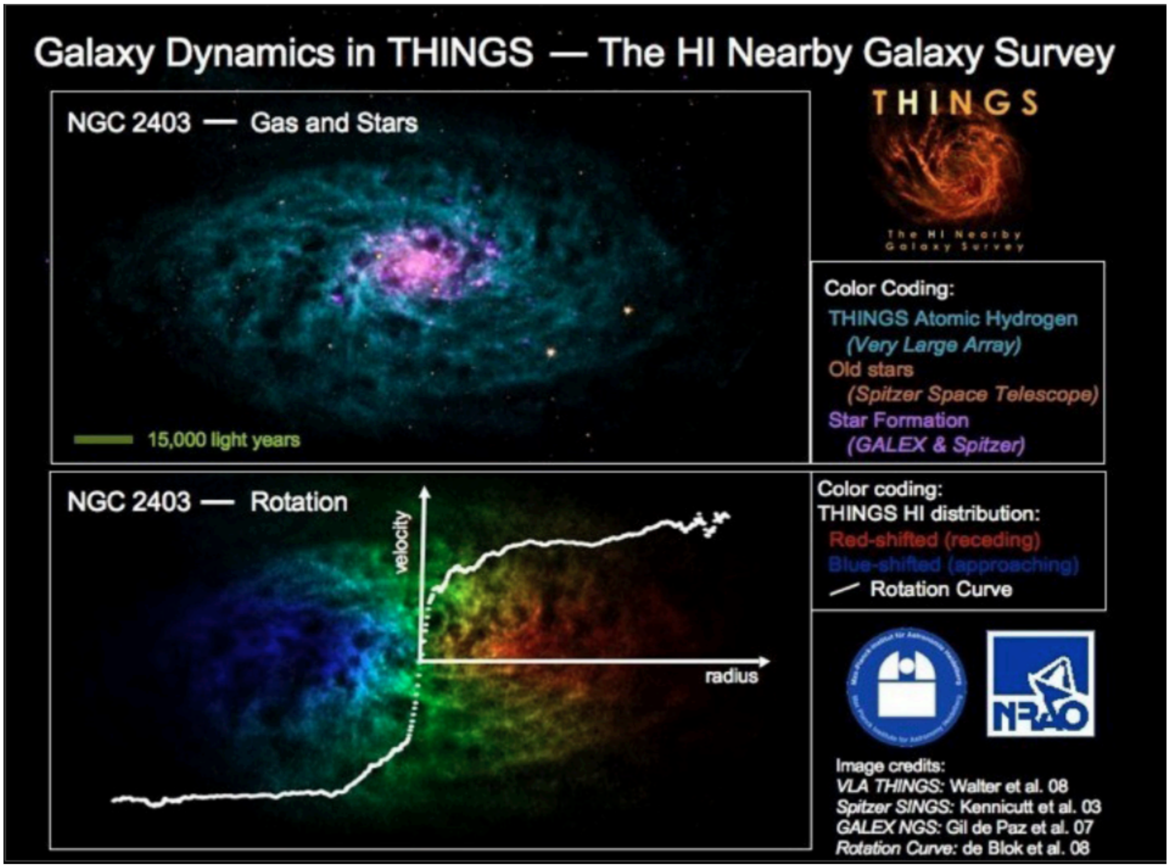
- H atom consists of 1 proton + 1 electron
  - Electron: spin S=1/2
  - Proton: nuclear spin I=1/2
  - Total spin: $F = S + I = 0, 1$
- Hyperfine interaction leads to splitting of ground level:
  - $F = 1$ $g_u = 2F+1 = 3$ $E = 5.87\times10^{-6}$ eV
  - $F = 0$ $g_l = 2F+1 = 1$ $E = 0$ eV

- Transition between $F = 0$ and $F = 1$:
  - ν = 1420 MHz, λ = 21.11 cm
  - $\Delta E / k$ = 0.0682 K
  - $A_{ul} = 2.869\times10^{-15}$ s^{-1} = $1/(1.1\times10^{7}$ yr) (very small!)

...but there is a lot of hydrogen out there!

From H. Rix and F. Walter

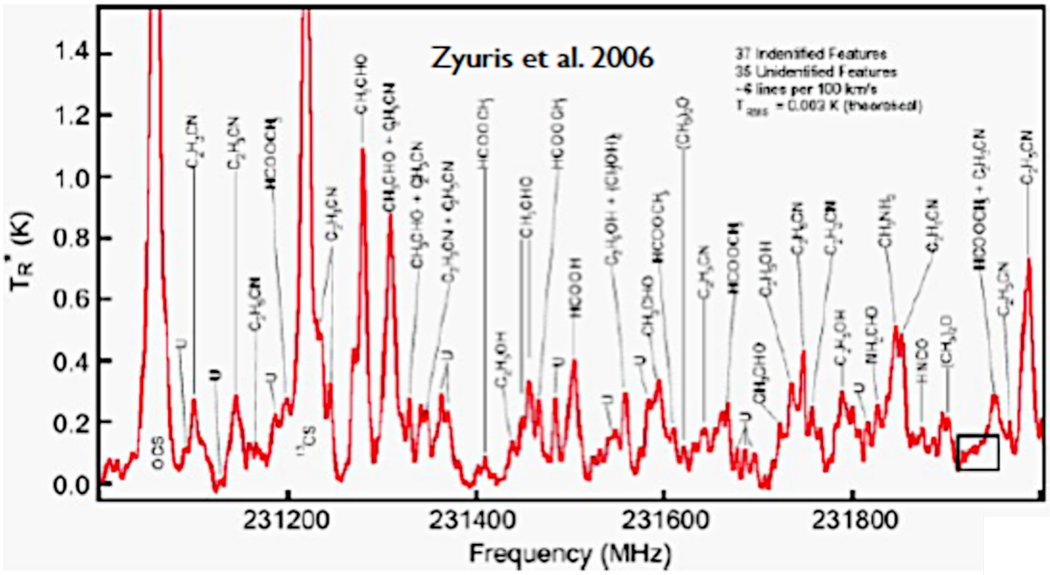




The ISM

- The 5 'states' are in dynamic interaction.
- The coldest, densest phase is molecular and the densest (hydrogen molecules, CO, NH_3 and other molecules)- **this is where stars form** .

Molecular Lines

- Molecular clouds are very rich in spectral features from a wide variety of molecules- lots of information
- 

How do Molecules Emit

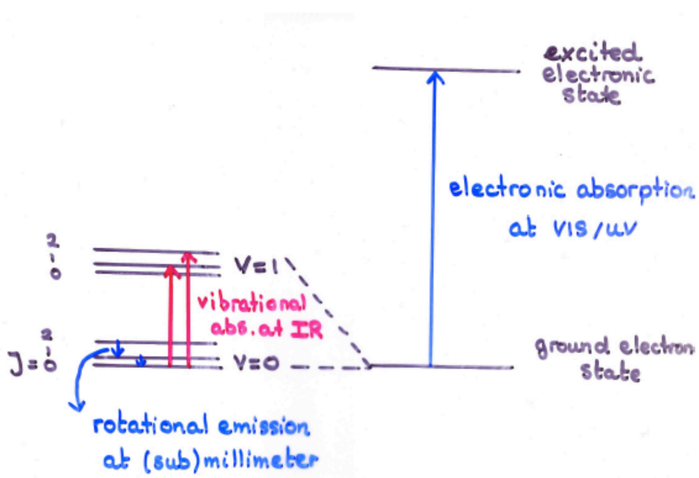
$$E = E^{el} + E^{vib} + E^{rot}$$

- Emission is primarily from rotational and vibrational levels
  - Millimeter emission: rotational transitions
- Absorption: vibrational transitions

Limitation: need background IR source => only info along line of sight

- Earth's atmosphere prevents observations of key molecules from ground: H_2O, O_2, CO_2

Ewine F. van Dishoeck

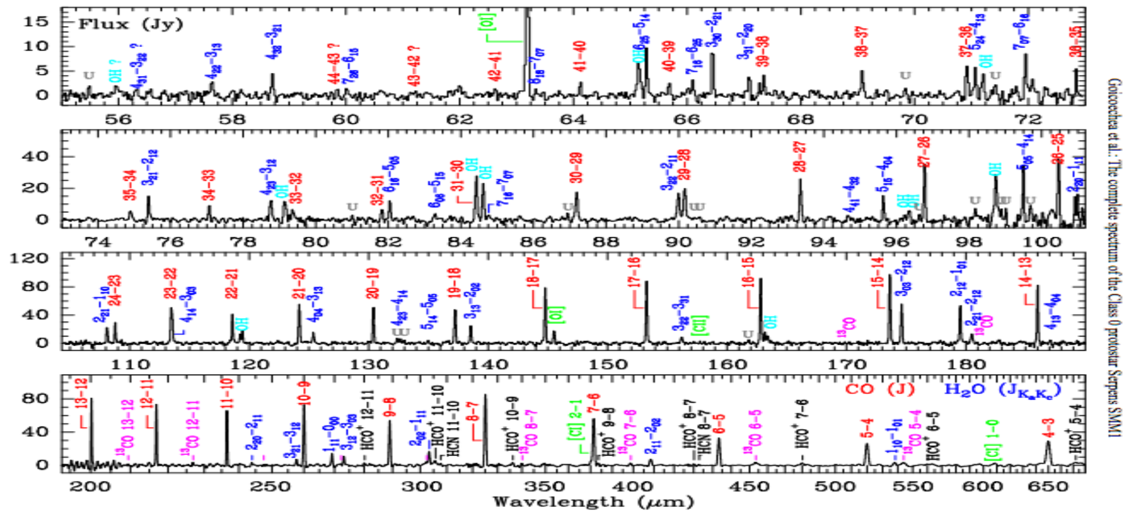


MM emission: Limitation: molecule must have permanent dipole moment => cannot observe H_2, C_2, N_2, CH_4, C_2H_2, …

Advantage: many molecules down to low abundances

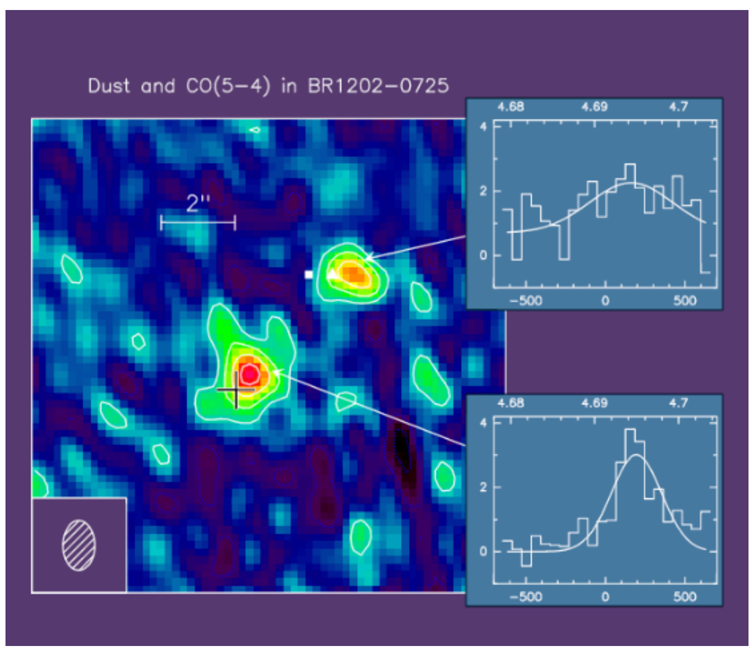
Richness of Far IR Spectra of ISM

- More than 145 lines , **most of them rotationally excited lines from abundant molecules:**
- 38 ^{12}CO lines (up to J=42-41 37 lines of both o-H_2O and p-H_2O (up to 818-717),16 OH lines 12 ^{13}CO lines (up to J=16-15) and several HCN and HCO+ lines Goicoechea et al 2015 ApJ 799 102 ; **brightest line is [OI] at 63μ**



Molecular Gas at High Redshift

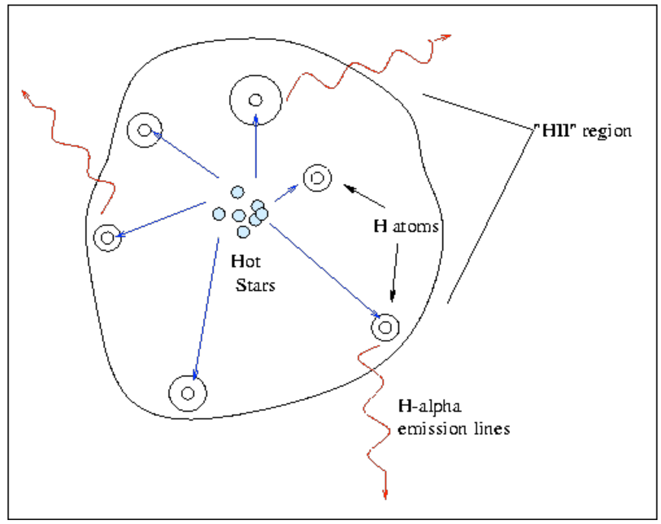
- Observations of CO at z=4.69 when the universe was 2.1 Gyrs old
- ALMA can observe CO lines from luminous star forming galaxies at high redshift



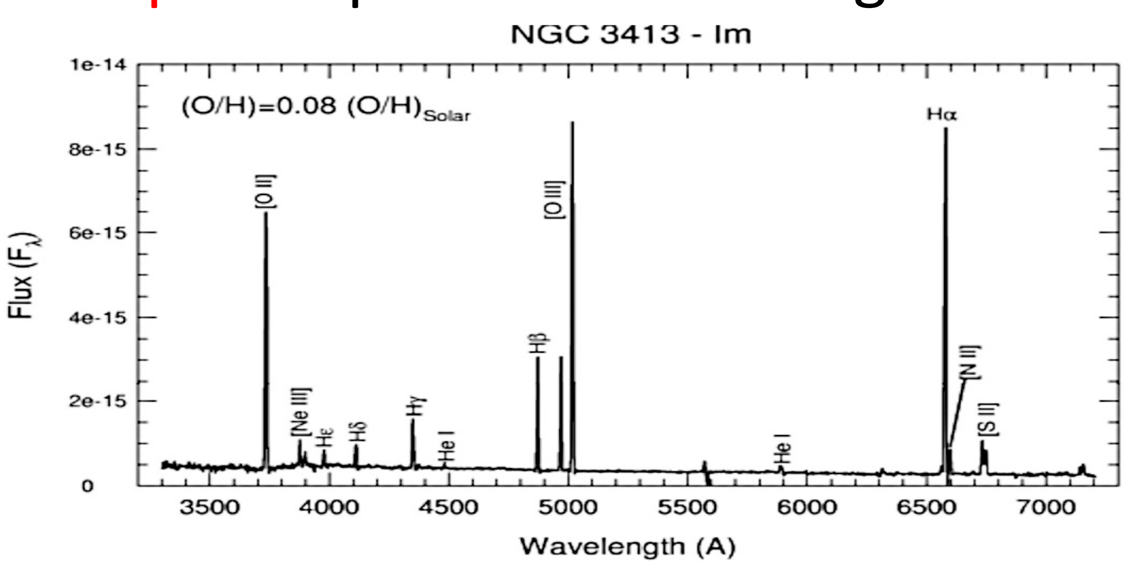
H II Region

- Regions of ionized gas around hot stars
- Complex relation to star formation (see pg 28 in S&G)

HII Region



Optical spectrum of HII Region



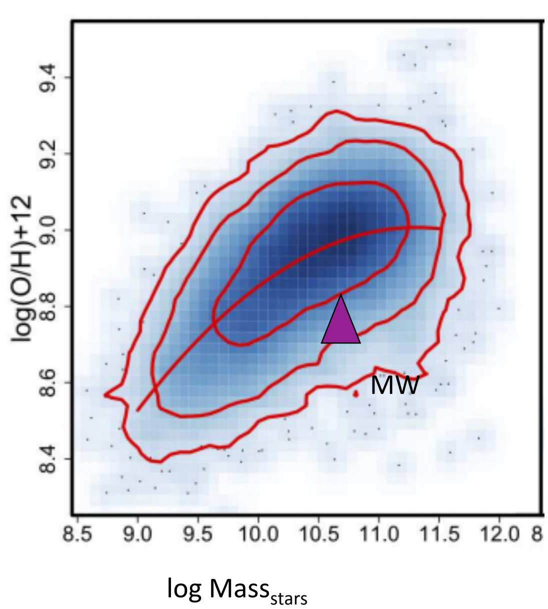
- Optical spectrum show lines due to [OII]. [OIII],Hα, [NII], etc
- the [..] symbol means a forbidden line which only arises in low density gas
- Relative poverty of lines compared to mm and far IR- BUT very large data sets!!

Next Presentation

- Planck intermediate results. XIX. An overview of the polarized thermal emission from Galactic dust 2015A&A...576A.104P 1405.0871.pdf (120 citations in 1.5 years)
- Weizhe Liu, and then Liz Tarantino ,David Vermilion, and Thoma sWhalen,
- This is a complex and long paper (skip 2.2.-2.5 and 3.3,4.3,4.4
  - please focus on
    - what does polarization tell us about dust and the magnetic field of the MW (may also want to look at the companion paper 2015A&A...576A.106P sec 1 (intro) and 8 (conclusions))

Metallicity in Gas

- How does determine it ?- Use HII region spectra (ionized gas around hot young stars) : measure oxygen lines.
  - O is an α-process element made in short-lived massive stars and is~50% of all the heavy elements by mass
    - thus **representative** of all the heavy elements made in type II SN
  - need to measure line strengths, electron temperature, density to get ionization structure of the gas.
- **More massive galaxies tend to be more metal rich**



GAMA collaboration Foster et al 2012

Gas Cooling- Physical Processes

- Collisional excitation: free electron impact knocks a bound electron to an excited state; it decays, emitting a photon.

- Collisional ionization: free electron impact ionizes a formerly bound electron, taking energy from the free electron.

- Recombination: free electron recombines with an ion; the binding energy and the free electron's kinetic energy are radiated away