GAS

The other baryonic component- **sec 2.4 in S+G**

Material scattered in Ch 8-9 of MWB

See web page of Alyssa Goodman at Harvard Astronomy 201b : Interstellar Medium and Star Formation http://ay201b.wordpress.com/

I will be going thru material a bit too fast for derivations and **strongly recommend looking at the above pages for details**

See also

Molecular Gas in Galaxies ARA&A Vol. 29: 5811991J. S. Young and N. Z. Scoville

Dopita, M., & Sutherland, R.: Astrophysics of the Diffuse Universe 2005

Lequeux, J.: The Interstellar Medium, Springer, Berlin, 2003

Osterbrock, D.E., & Ferland, G.J.: Astrophysics of Gaseous Nebulae and Active Galactic Nuclei, Palgrave Macmillan, 2006

Spitzer, L.: Physical Processes in the Interstellar Medium1978

Thronson, H.A., Shull, J.M. (Herausgeber) : The Interstellar Medium in Galaxies, Kluwer Academic Publishers, 1990

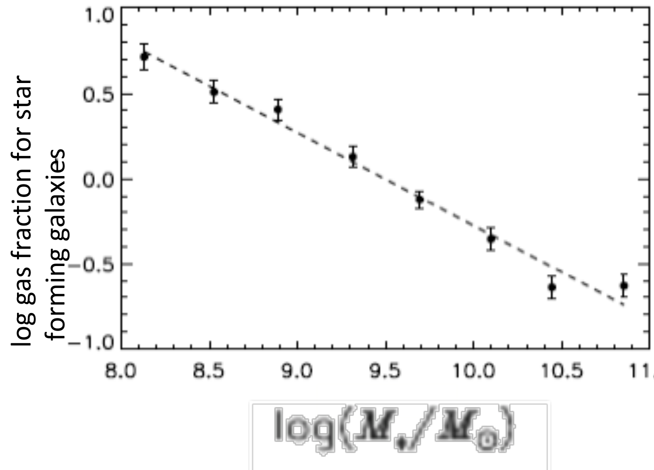
Gas- Big Picture

- Big Bang- its all dark matter, gas and radiation
- Dark matter halos grow by merging and accretion (e.g. Galaxies can grow by accretion of gas, by merging with gas rich galaxies and by merging with gas poor galaxies)

- Gas falls into these halos, cools and forms stars.
- How does this occur- the physics of gas accretion,
  - How and when did galaxies accrete their gas and what do they do with it (e.g. form ISM, stars, expel the gas, feed the supermassive black hole ....)

Gas

- Other than stars the baryons in galaxies lie in 3 forms
  - gas
  - rocks
  - dust (0.1% of mass)
    - the % mass in rocks and dust is small<u>- but lots of metals in dust</u>
- A vast array of spectral diagnostics for the gas in both emission and absorption which can reveal
  - chemical composition
  - temperature
  - velocities
  - ionization mechanism
  - dark matter distribution

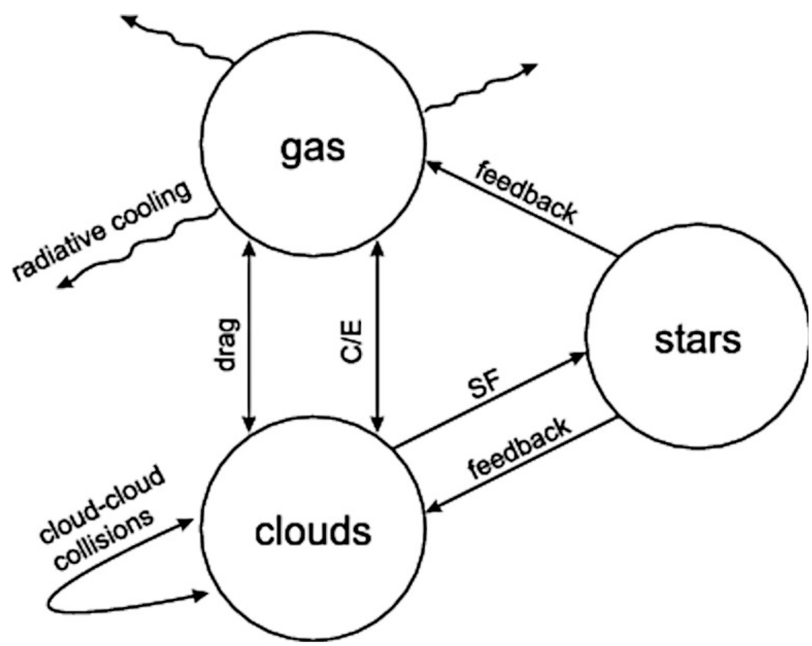


Peeples and Shankar 2011

As Stellar mass of galaxy increases, fraction of baryonic mass in gas decreases

Gas

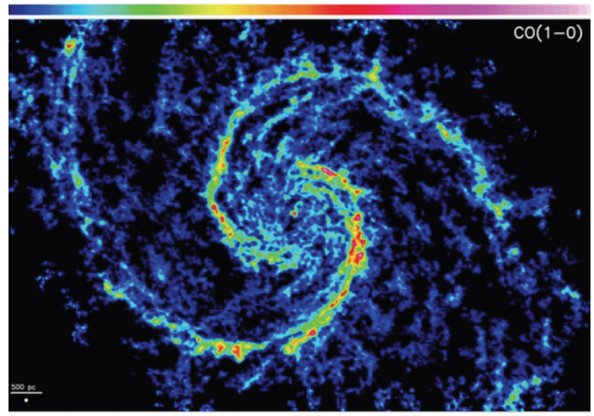
- interplay between the stars and gas
  - stars form out of the gas
  - enriched gas being ejected back into the interstellar medium from evolved stars.



Peeples and Shankar 2011

GAS-ISM

- 'Cold' gas: dominates in **Spirals**-*many phases*
  - neutral hydrogen
  - molecular gas-Dense molecular clouds, have most of the total mass of the interstellar gas
    - of key importance for star formation, occupy a negligible fraction of the total volume
  - warm ionized gas-has persistent transient states much of it is out of thermal pressure balance



CO Image of M51

Milky-Way-like galaxies cold gas mass~10% of the stars

CO is major tracer of molecular gas but ~ one CO molecule for every 10^4 of H_2.

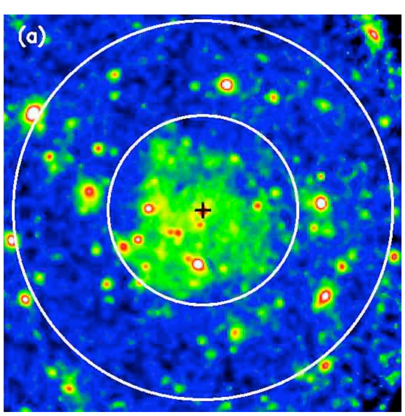
GAS-ISM

Hot gas ($T\sim10^{6\text{-}7}$ k) <u>dominant</u> ISM in **elliptical** galaxies

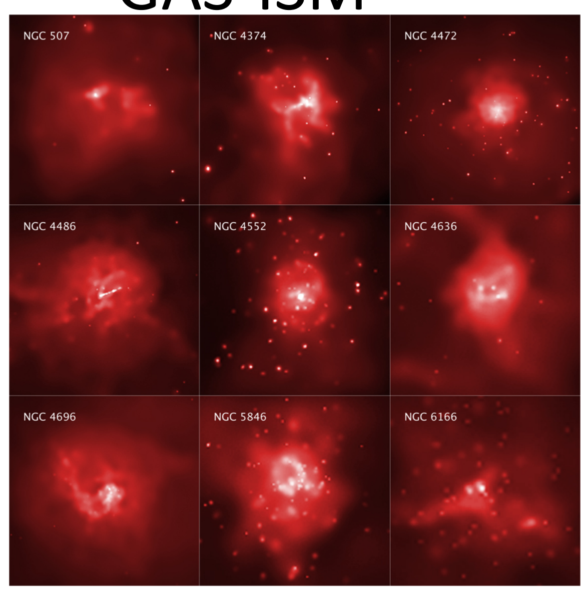
- seen via x-ray emission

In spirals

- hot gas volume filling (sponge-like topology) but low total mass



X-ray image of M101



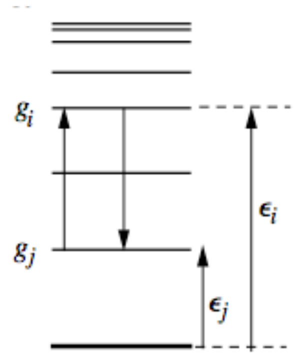
x-ray images of elliptical galaxies emphasizing structure

A Bit of Physics- see MBW B1.3

Radiative Processes

- The rates of ionization and recombination are important (see eqs → 2.21,2..22 in S+G); e.g. X^++e X+γ or

  X^0+γ →X^-+e
- the rate at which ions recombine depends on
  - the ion density, X^+ ,
  - the electron density
  - the recombination coefficient, α



In steady state # of ionizations= # of recombinations

Ionization is from
- collisions with hot electrons
- photoionization from stars
- shocks
- cosmic rays
- AGN

Collisional Excitation (Pg 28 S&G)

- When atom A collides with atom B (or an electron) to form the *excited* state A∗, can have the reaction
- A + B −→ A∗ + B, A∗ −→ A +$h_P \nu$.
- However, photon is emitted only if state A∗ decays before colliding yet again.
- Either the decay must be rapid, or the gas density quite low (e.g. probability of collision low).

(h_P= Plancks constant)

Ionization +Excitation Mechanisms

- Collisional Ionization and Collisional Excitation
  - 'hot' electrons collide with atoms/ions
- Photoionization and excitation
  - photons interaction with atoms/ions
- Shocks

Motions that are faster than the local speed of sound, give rise to *shocks.* Energy of motion is converted into heat which excites/ionizes gas

- Cosmic rays- relativistic particles collide with gas

A Bit of Physics

- Recombination rate for a given ion X^{+}+ is (S&G eq 2.21)
- $-dn_e/dt = n^2_e \alpha(T_e)$

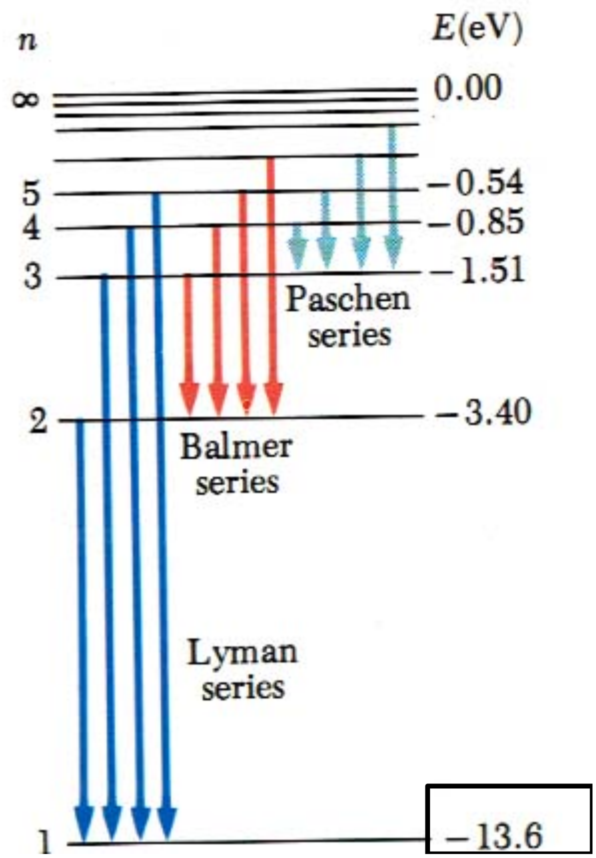
$\alpha(T_e) \approx 2 \times 10^{-13}(T_e/10^4)^{-3/4}$ cm^3 s^{-1} (temperature sensitive)

Recombination time (eq. 2.22) is
$t_{rec} = n_e|dn_e/dt| = 1/n_e\alpha(T_e) \approx 1500$ yr x $(T_e/10^4)^{-3/4}(100$ cm$^{-3}/n_e)$

n_e is the number density
the recombination time is the #of electrons/ the rate
$n_e/dn_e/dt$ ~ a few thousand years in a HII region- without continual ionization input gas recombines rapidly and becomes unionized
This is NOT the same as the cooling time

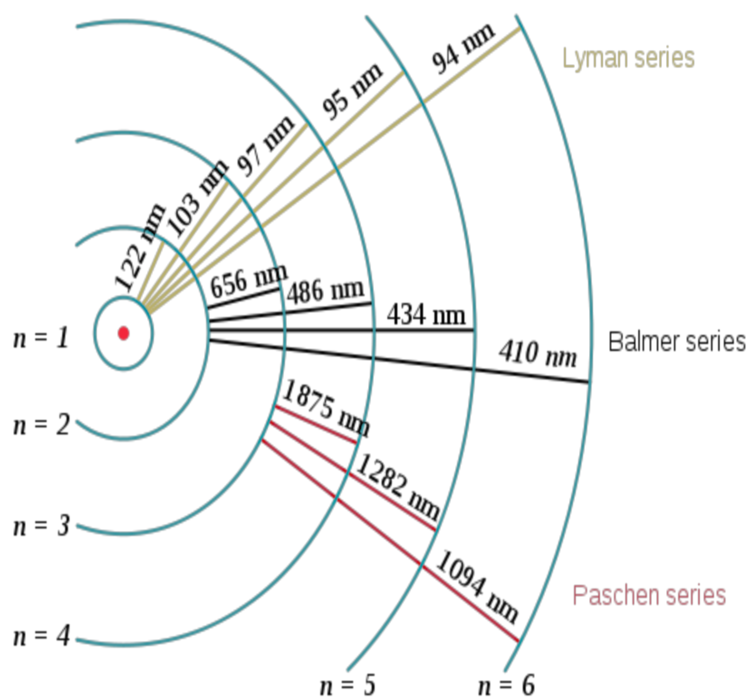
Atomic Lines

- The energy levels and transitions for **hydrogen**
  - **e.g Lyman is n ➔ 1**
  - Balmer is **n ➔ 2**
- Each element and ionization set has a similar (but more complex) set of lines
- The probability of emitting a given line depends on the temperature and density of the gas+quantum mechanics



Hydrogen Line Wavelengths

- Lyman lines are in the UV
- Balmer lines in the optical
- Paschen in the IR

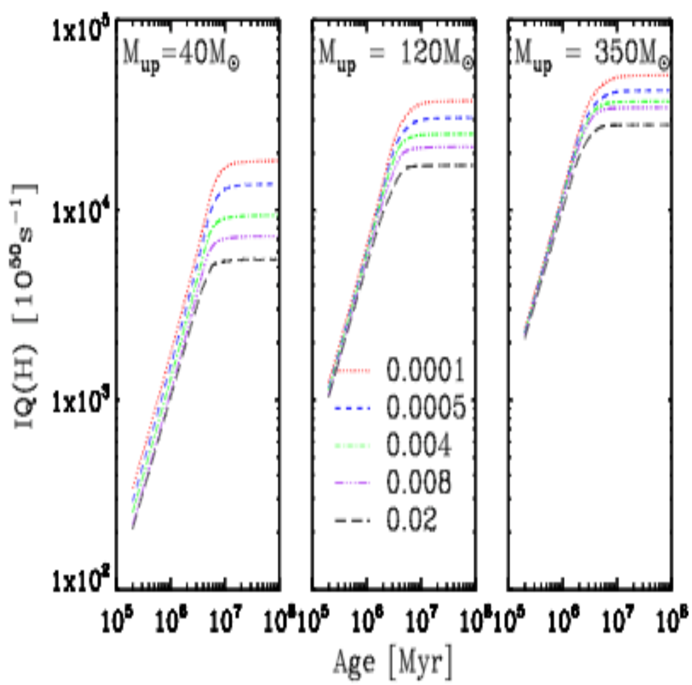


A Bit of Physics-Ionizing Photons

- One can estimate the number of ionizing photons from a star using the black body formula (e.q. 1.35 in S&G) and integrating over the photons more energetic than the ionization potential of the ion of interest (e.g. H with13.6 eV)
- These photons ionize and heat the gas
- The gas responds by emitting lines characteristic of the chemical composition, temperature, ionization state, density etc ...
- Pg 477 and ff in MWB also see https://ay201b.wordpress.com/2011/04/12/course-notes/#the_sound_speed for a LOT more detail (also covered in radiative processes course for graduate students)

How Number of Ionizing Photons Changes

- The number of ionizing photons is VERY sensitive to the age of the system AND the maximum mass of the stars in the IMF (Obi et al 2017)
  - somewhat sensitive to metallicity (colored lines)
- Young hot stars (or AGN) control ionization of gas in galaxies



Physics of Emission from Gas-MWB sec 10.3.7

- Gas is heated/excited/ionized by photons (stars, AGN), shocks (supernova) and gravity
- Atomic transitions reveal the ionization state, temperature, density, velocity structure and chemical composition of the gas.
- Three 'main modes of excitation
  - Photoionization: photon from source eject electron from ion- to do this photon needs to have energy greater than ionization potential (e.g. 13.6 eV for Hydrogen; O,B stars, AGN)
  - Collisional ionization: gas is excited by collisions with 'hot' electrons (again electron energy has to be above threshold). Electrons have Maxwell-Boltzman energy distribution in equilibrium (S&G eq. 3.58)
  - Shocks due to supernova

Physics of Emission from Gas-MWB sec 10.3.7

- Wide range of types of transitions: 2 'basic' types
  - permitted: fast transition rate, line is emitted before ions state is altered
  - forbidden: violate transition rule, ion can be collisionally de-excited when density exceeds critical density; presence of line thus places constraint on gas density.
  - - ***jargon*** forbidden lines are indicated by [OII] (OII is the ionization state of the gas, once ionized oxygen) (see page 29 in S&G, table 1.7)

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
  - nuclear lines in γ-ray (will not discuss in class)
- 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

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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 luminosity corresponding to a transition between states 1 and 2 is
- $L_{12}=4\pi\varepsilon_{12}V=h\nu_{12}VN_pN_e\alpha$
- This gives for $T=10^4$K
- $\mathcal{F}=0.45hN_pN_eV\nu_{H\alpha}$ and $H\alpha/H\beta=3.8$
- **Thus, by measuring the luminosity of a *HII region* in a recombination line, one can in principle infer the rate which, in turn, can be used to infer the number of OB stars that generate the ionizing photons**

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

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 supersonic (e.g. gas is turbulent)

A Bit of Physics-TimeScales

- 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

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**)

- $\tau_J \sim 1/\mathrm{sqrt}(4\pi G\rho)$ 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)

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

- *Jeans length* $\lambda_J = c_s\, \mathrm{Sqrt}(\pi/G\rho)$ *S&G 2.24,pg 108*

n_H is the particle density

ρ is the mass density

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

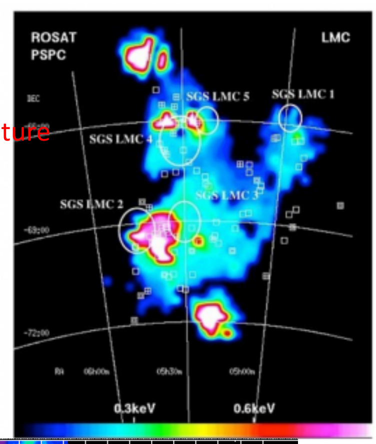
Simple Derivation of Jeans Collapse S&G 8.5.1

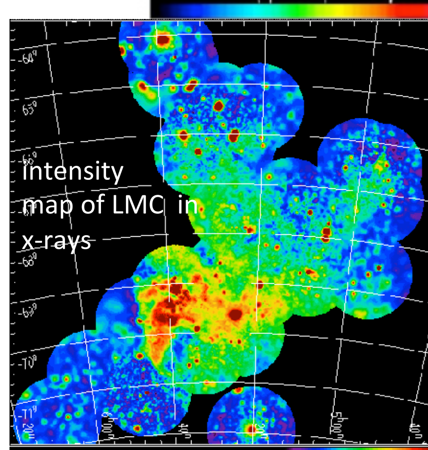
- Kinetic energy in cloud is $KE=(3/2kT)N$; N is the number of particles, T is the temperature
- The gravitational (binding) energy $U=-3/5GM^2/R$ (uniform density sphere- derivation later in class)
- Using the viral theorem (lots more later)
  system is in equilibrium if $3NkT=(3/5)GM^2/R$
- So to collapse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

ISM-Big Questions

- What is the volume filling factor of the hot ISM?
- What is the distribution of the temperature, density, and velocity
- What are typical scales in the ISM and why?
- What is the effect of turbulence , magnetic fields and cosmic rays?
- How is the ISM related to star formation?
- Why is the ISM in spirals and ellipticals so different in density and temperature?
- What is the mass and chemical composition ?
- What is its 'dynamical' state?

x-ray temperature map of LMC





Intensity map of LMC in x-rays

Importance of the ISM

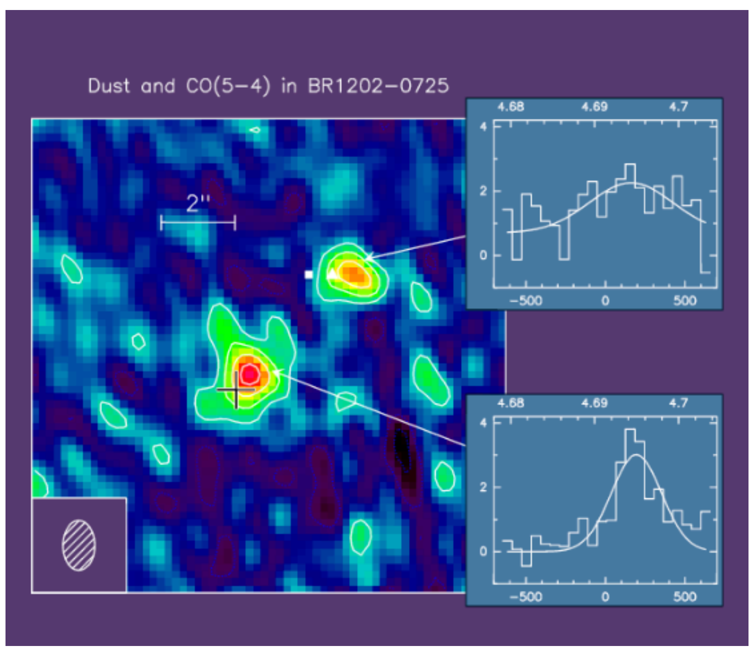
- **Despite its low mass, the ISM is very important**
- Crucial role in the star-gas cycle in spirals and irregulars,
  - it *facilitates* ongoing (& current) star formation
  - it is a repository for elements created in SNR and stars and therefore is a key to measure chemical evolution
- Because it can cool, its collapse is **dissipational**
  - stars can form !! hot gas→cold gas →stars:

its emission & absorption provides enormous diagnostic information

- Doppler motions reveal galaxy dynamics
- Abundance measurements allow study of chemical evolution
- physical conditions: density; temp; pressure; turbulence; gas column density; mass,
  - can all be derived from observations of emission/ absorption lines
  - lines are bright and can be seen (relatively) easily at cosmological distances.

Molecular Gas at High Redshift

- Observations of CO at z=4.69 when the universe was 2.1 Gyrs old
- ALMA has the capability to detect molecular and atomic lines at very high redshift !

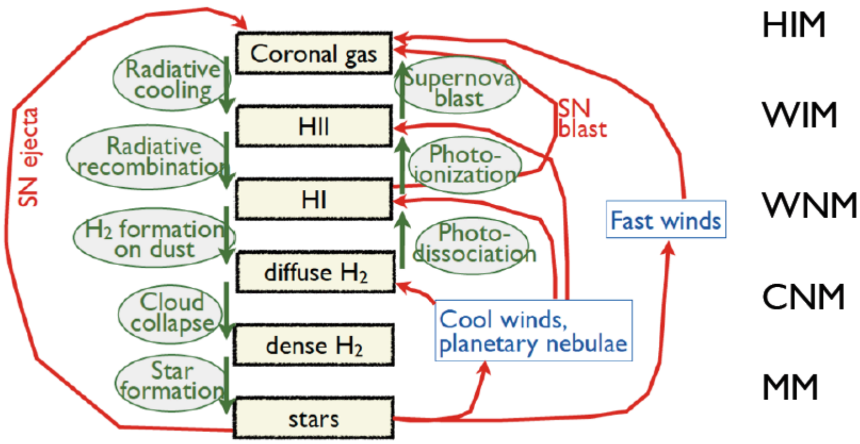


The ISM in Spirals is DYNAMIC- Driven by Star Formation

- 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)

Complex interaction between different phases

Fabian Walter



Its not so clear if ISM in ellipticals is dynamic in the same way; AGN seem to be more important