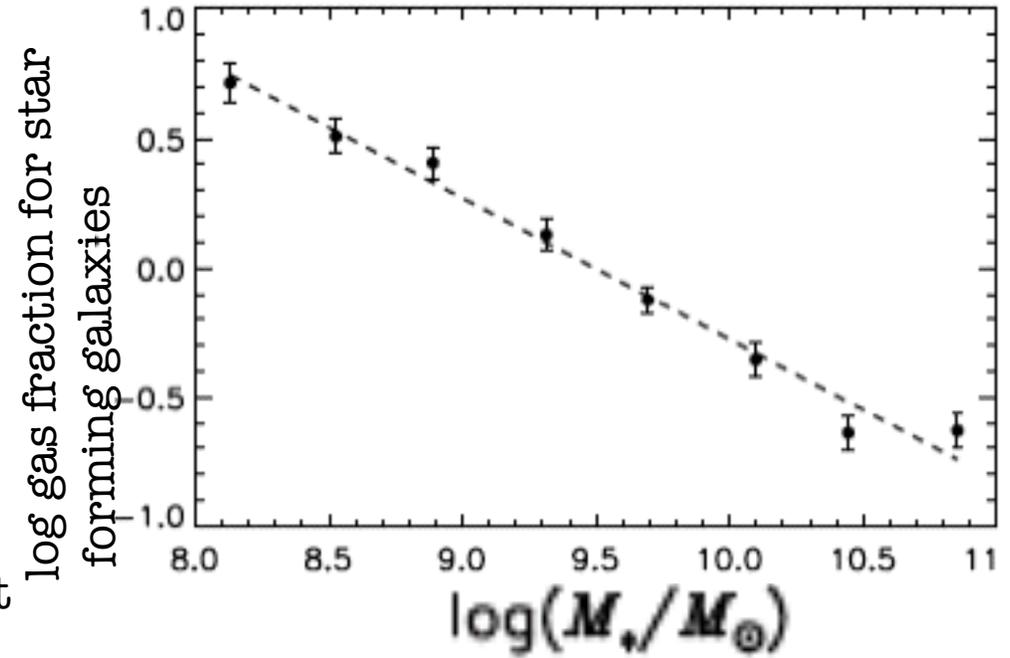


GAS

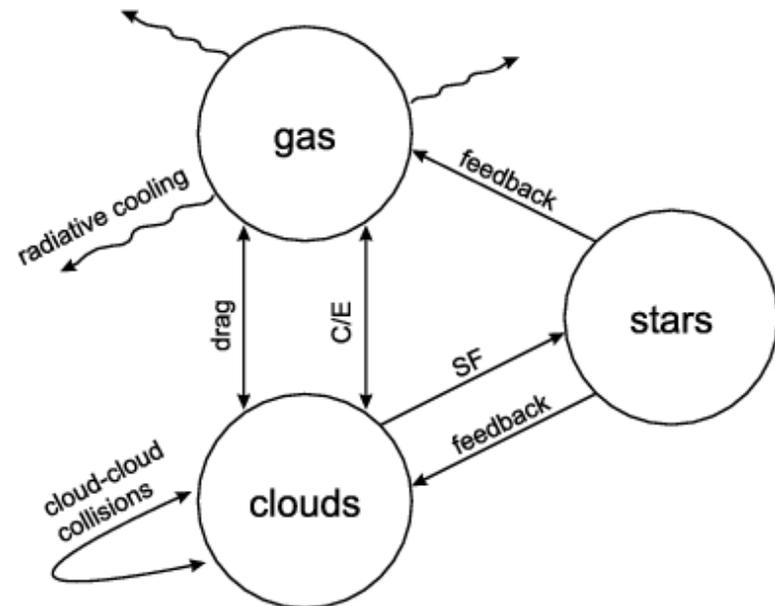
The other baryonic component- sec 2.4 in
the text

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
- There is an interplay between the stars and gas, with stars forming out of the gas and with enriched gas being ejected back into the interstellar medium from evolved stars.
- There exist a vast array of spectral diagnostics for the gas in both emission and absorption which can reveal
 - chemical composition
 - temperature
 - velocities
 - ionization mechanism



Peeples and Shankar 2011



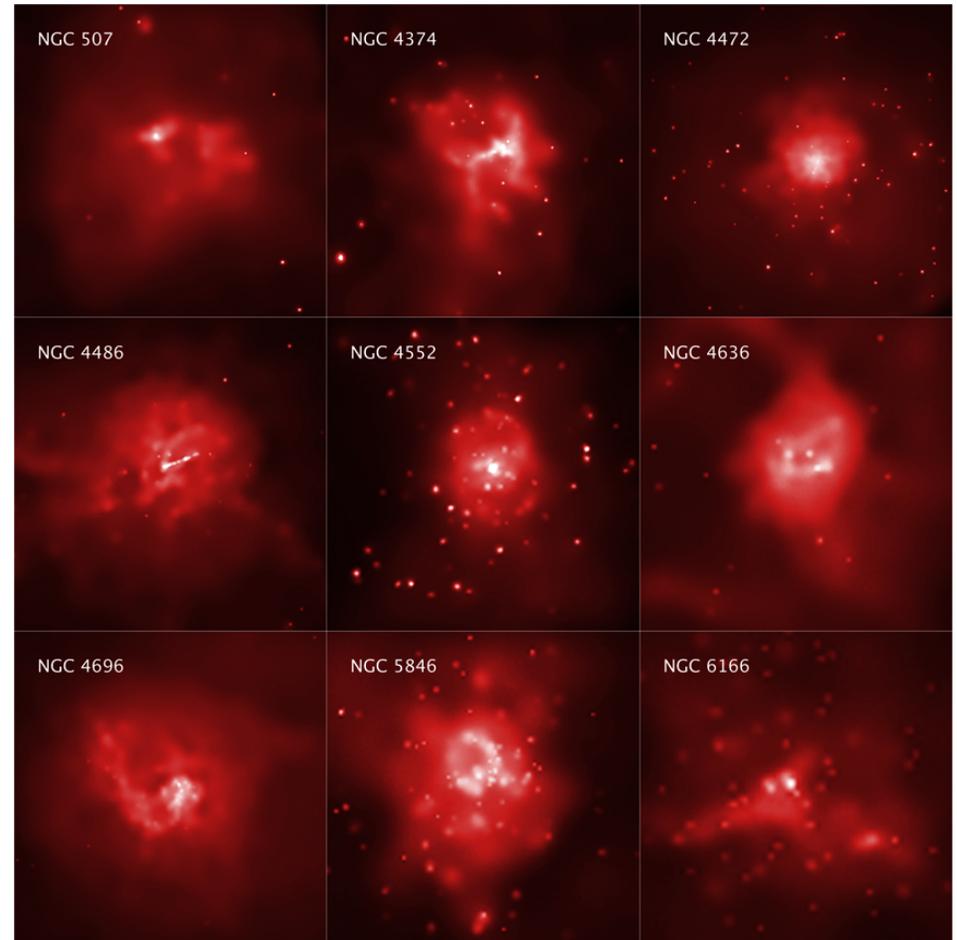
Gas- Big Picture

- 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-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 and are of key importance for star formation, occupy a negligible fraction of the total volume
 - warm ionized gas-has persistent transient states out of thermal pressure balance
- Milky-Way-like galaxies cold gas mass $\sim 10\%$ of the stars
- For lower mass galaxies the baryonic fraction in gas is larger; at $M_{\text{halo}} < 10^{11} M_{\odot}$ gas dominates the baryonic content
- Hot gas ($T \sim 10^{6-7} \text{ k}$) dominant ISM in **elliptical** galaxies

In spirals hot gas fills the volume but low total mass



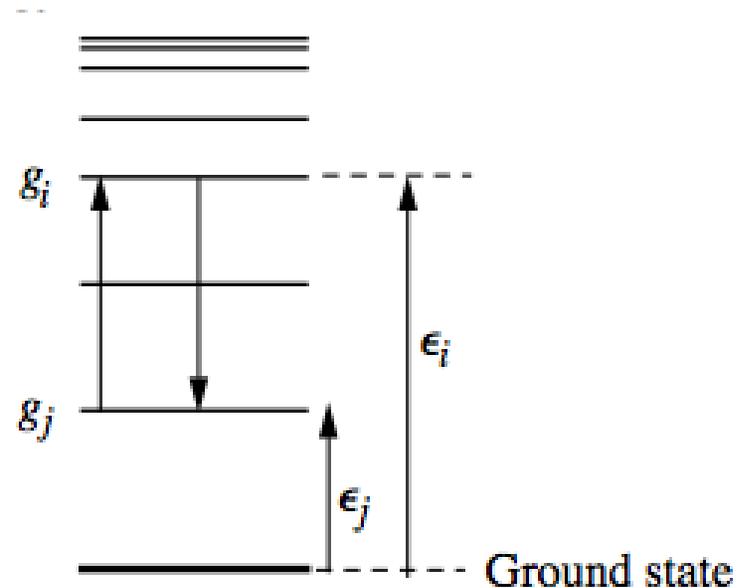
x-ray images of elliptical galaxies emphasizing structure

Physics of Emission from Gas

- Gas is heated/excited/ionized by photons (stars, AGN), shocks (supernova)
- Atomic transitions reveal the ionization state, temperature, density, velocity structure and chemical composition of the gas.
- 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-Boltzmann energy distribution in equilibrium
- 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).

A Bit of Physics

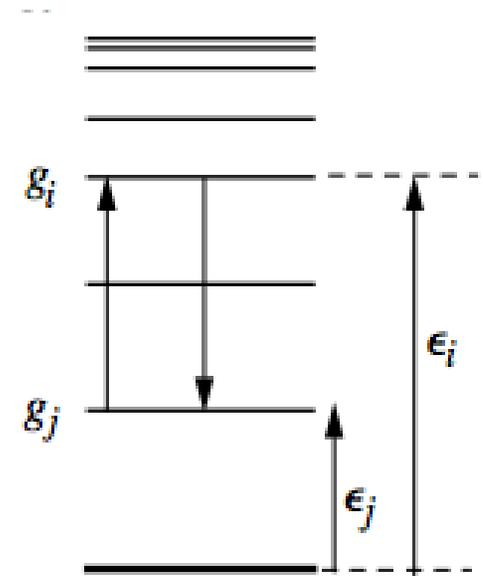
- Saha equation describes the ionization balance of the gas which depends on the temperature, quantum mechanical transition probabilities and densities
- An atom with multiple energy states in thermal equilibrium with a radiation field will find itself in one or another of these energy states.
- Frequent transitions to and from other states will occur as photons interact with the atoms.
- transitions from the upper of the states of figure take place by photo deexcitation and by induced deexcitation. Transition in the upward direction is by photoexcitation or collisional excitation



For lots of details
see MBW appendix B

A Bit of Physics

- The rates of ionization and recombination are important (see eqs 2.21, 2.22 in S+G); e.g. $X^+ + e^- \longrightarrow X + \gamma$
- the rate at which ions recombine thus clearly depends on the ion density n_{X^+} and the electron density and the recombination coefficient α , which depends on the ion, (e.g. the number of electrons it has and its atomic number)
- Thus recombination rate of electrons for a given ion X^+ is
- $dn_e/dt = n_{X^+} n_e \alpha(T_e)$;
- the recombination time is the # of electrons / the rate: $n_e / dn_e/dt$
a few thousand years in a HII region - α the recombination rate depends on QM and Boltzmann's law



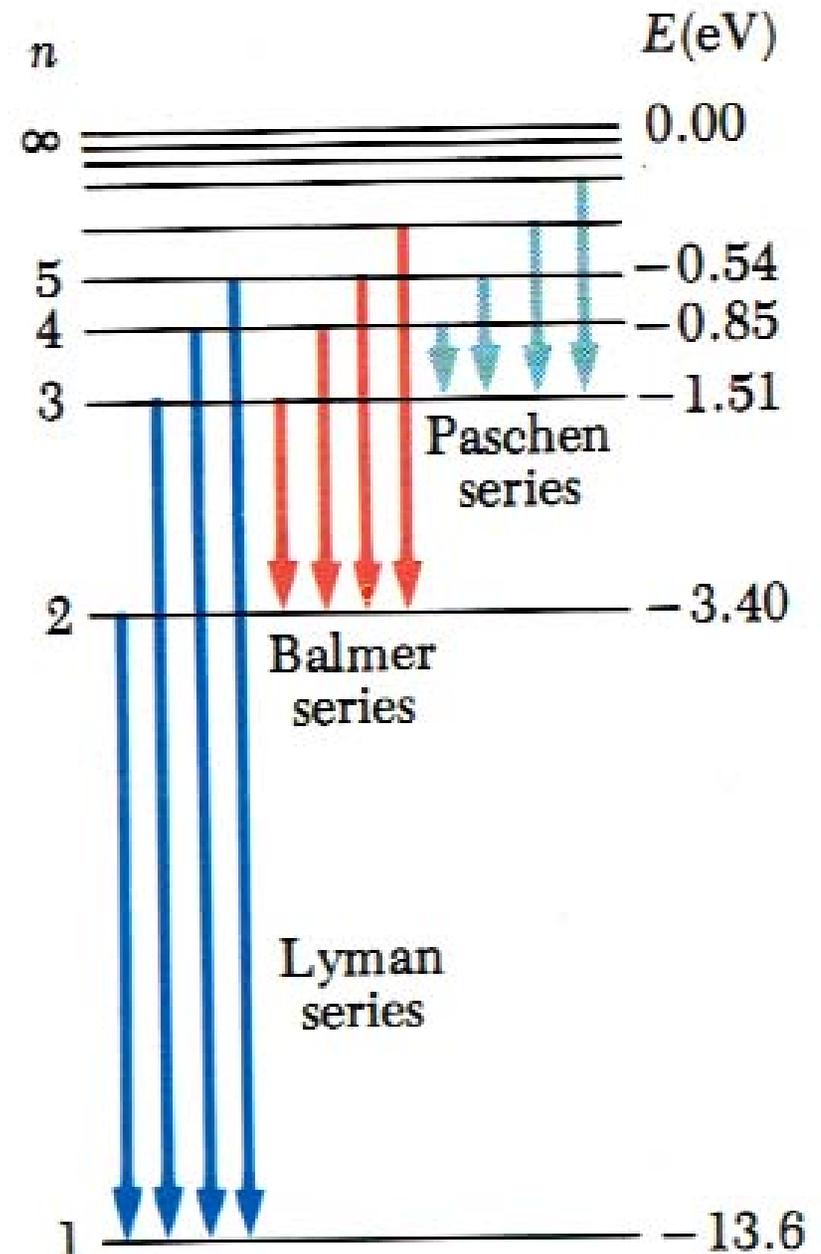
In steady state # of ionizations = # of recombinations

Ionization is from

- collisions with hot electrons
- photoionization from stars
- shocks

Atomic Lines

- The energy levels and transitions for hydrogen
- 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



A Bit of Physics-Ionizing Photons

- One can estimate the number of ionizing photons from a star using the black body formula (e.g. 1.35 in text) and integrating over the photons more energetic than the ionization potential of the ion of interest (e.g. H with 13.6 eV)
- These photons ionize and heat the gas
- The gas responds by emitting lines characteristic of the chemical composition, temperature, ionization state, density etc ...

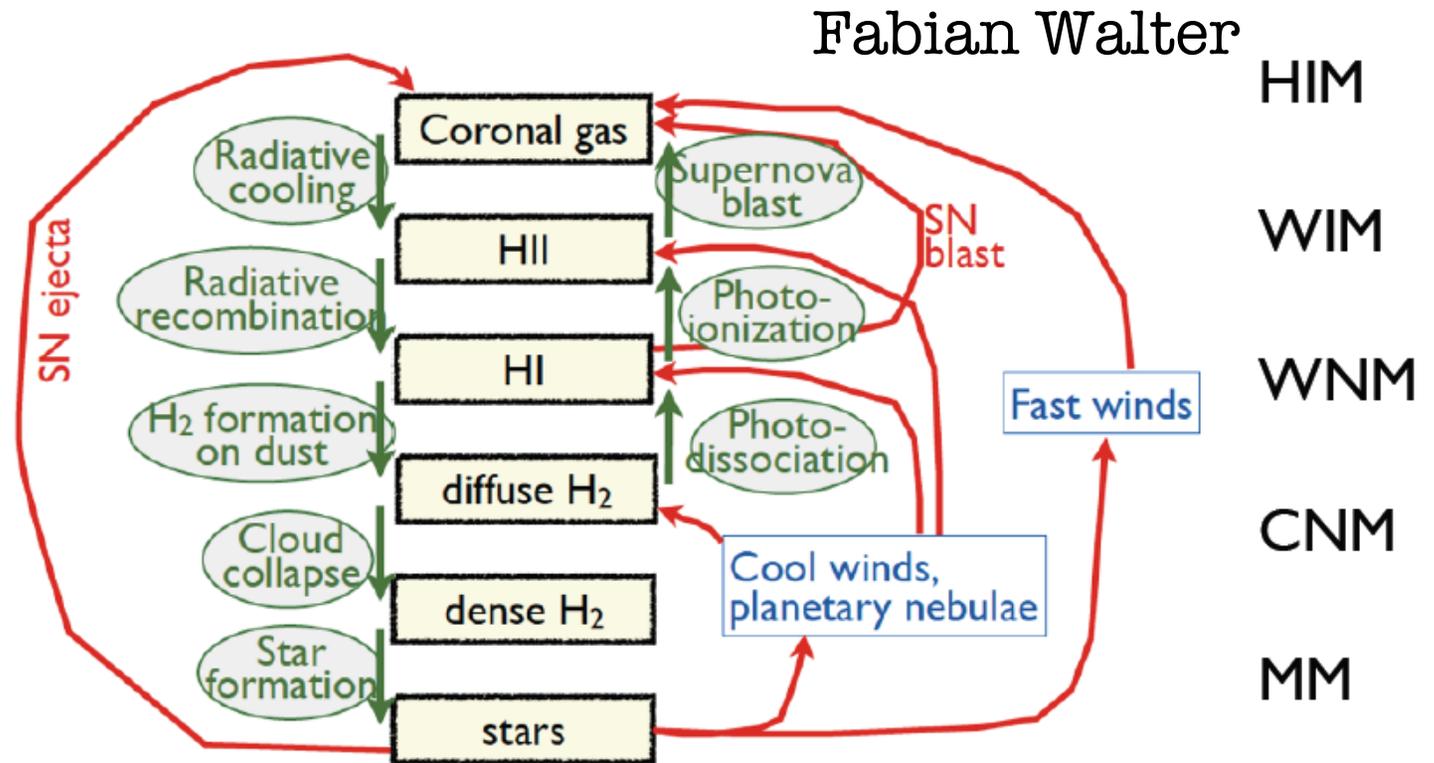
Importance of the ISM

- 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:
 - galaxies are smaller than dark matter halos !
- 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 lines
 - lines are bright and can be seen (relatively) easily at cosmological distances.

The ISM in Spirals is DYNAMIC

- 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



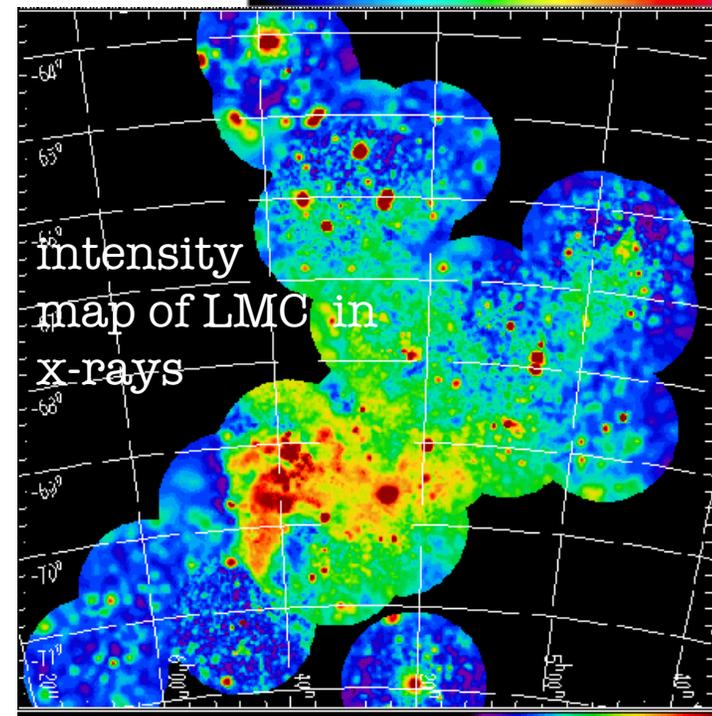
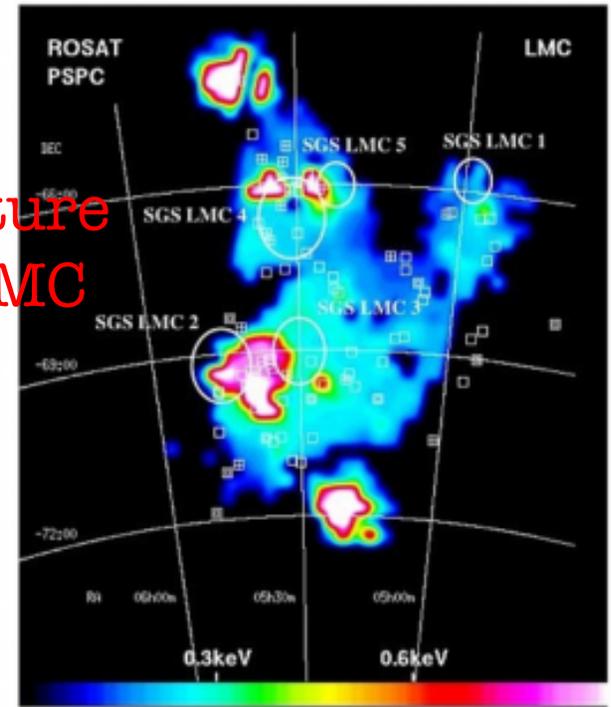
At low redshift ISM in spirals not affected much by AGN

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

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
- What causes density and pressure inhomogeneities in the evolution of the ISM
- How is the ISM related to star formation

temperature
map of LMC



Spiral ISM 'States'- f is the filling factor

- Molecular Medium (MM): $T \sim 20$ K, $n > 10^3$ cm $^{-3}$, $f < 1\%$. The MM is mostly cold dense molecular clouds which are gravitationally bound. Although, on average, this phase contains as much mass as the atomic hydrogen, it occupies only a very small fraction of the ISM.
- Cold Neutral Medium (CNM; $T \sim 100$ K, $n \sim 20$ 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 absorption.
- - Warm Neutral Medium (WNM; $T \sim 6000$ K, $n \sim 0.3$ cm $^{-3}$, $f \sim 30\%$). This phase provides the bulk of the HI seen in emission line surveys.
- - Warm Ionized Medium (WIM; $T \sim 8000$ K, $n \sim 0.3$ cm $^{-3}$, $f \sim 15\%$). 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; $T \sim 10^6$ K, $n \sim 10^{-3}$ cm $^{-3}$, $f \sim 50\%$). The hot gas produced by supernova explosions and their after effects - long cooling time, a **large fraction of the ISM** is filled with this component.
- <http://ned.ipac.caltech.edu/level5/March01/Brinks/Brinks4.html>

ISM- Phases

- Hot ionized medium (e.g. X-rays)
- Warm ionized medium HII region(e.g. H α)
- Warm neutral medium (e.g. HI emission)
- Cold neutral medium (e.g. HI absorbtion)
- 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 ³ | 4–80 | 0.1–0.6 | ≈0.2 cm ⁻³ | 10 ⁻³ –10 ⁻² |
| T (K) | 10–50 | 50–200 | 5500–8500 | ≈ 8000 | 10 ⁵ –10 ⁷ |
| h (pc) | ≈ 70 | ≈ 140 | ≈ 400 | ≈ 900 | >1 kpc |
| f _{volume} | < 1% | ≈ 2–4% | ≈ 30% | ≈ 20% | ≈ 50% |
| f _{mass} | ≈ 20% | ≈ 40% | ≈ 30% | ≈ 10% | ≈ 1% |

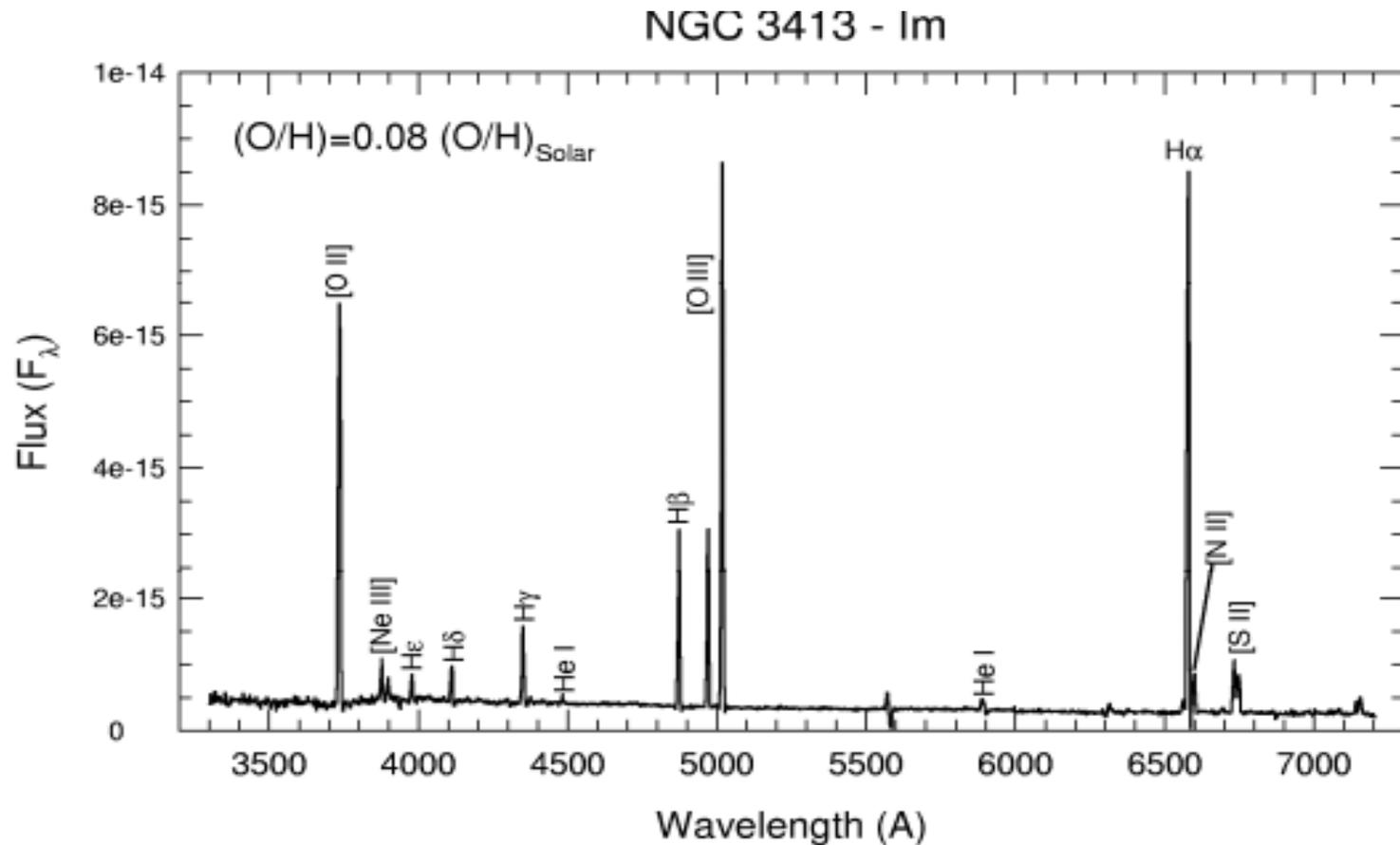
Note: the quoted numbers for each of the phases are only rough estimates. n is the particle density in cm⁻³, T the temperature in K, h the scale height in pc, f_{volume} is the volume filling factors, and f_{mass} the mass fraction.

Fabian Walter

The ISM

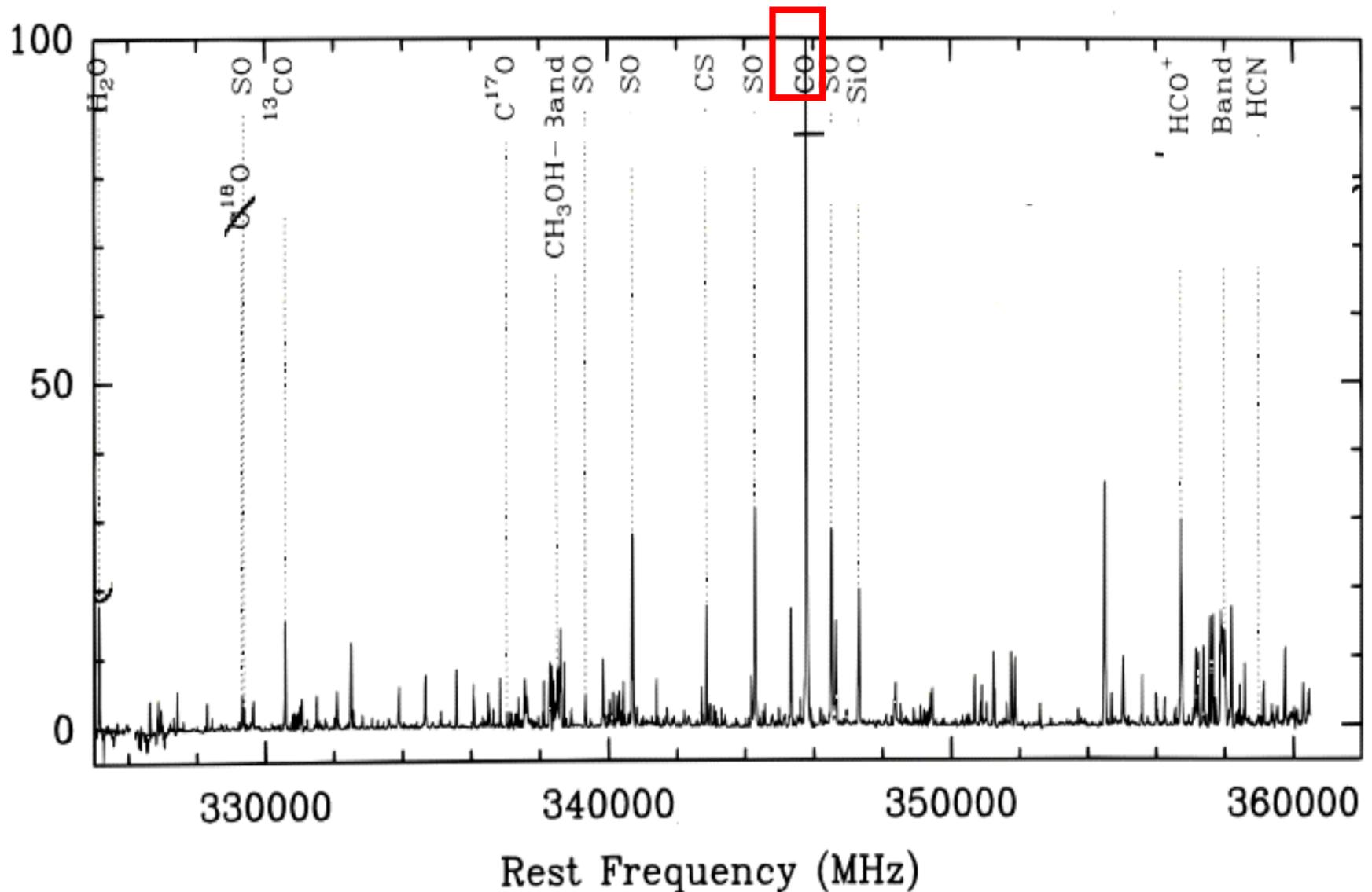
- The 5 'states' are in dynamic interaction.
 - the coldest clouds are molecular and the densest (hydrogen molecules, CO, NH₃ and other molecule)s- **this is where stars form** .
 - The dust is composed of 'refractory' elements and molecules mainly carbon, silicon, iron and is responsible for most of the absorption of optical light in the galactic plane - the energy absorbed by the dust heats it and the dust re-radiates in the IR
 - The ISM is threaded by magnetic fields. At $\sim 5\mu\text{G}$, these fields provide a pressure comparable to the pressure of the gas . The magnetic fields therefore affects the dynamics of the ISM
-
- How dense (or not) is the ISM?
 - Dense molecular cores: $n \sim 10^5 \text{ cm}^{-3}$
 - Typical ISM: $n \sim 1 \text{ cm}^{-3}$
 - sea level earth atmosphere: $1 \text{ mol} / 22.4\text{L} \sim 3 \times 10^{19} \text{ cm}^{-3}$ (oxygen)
 - Best human-made vacuum: $3 \times 10^4 \text{ cm}^{-3}$

Optical spectrum of HII Region

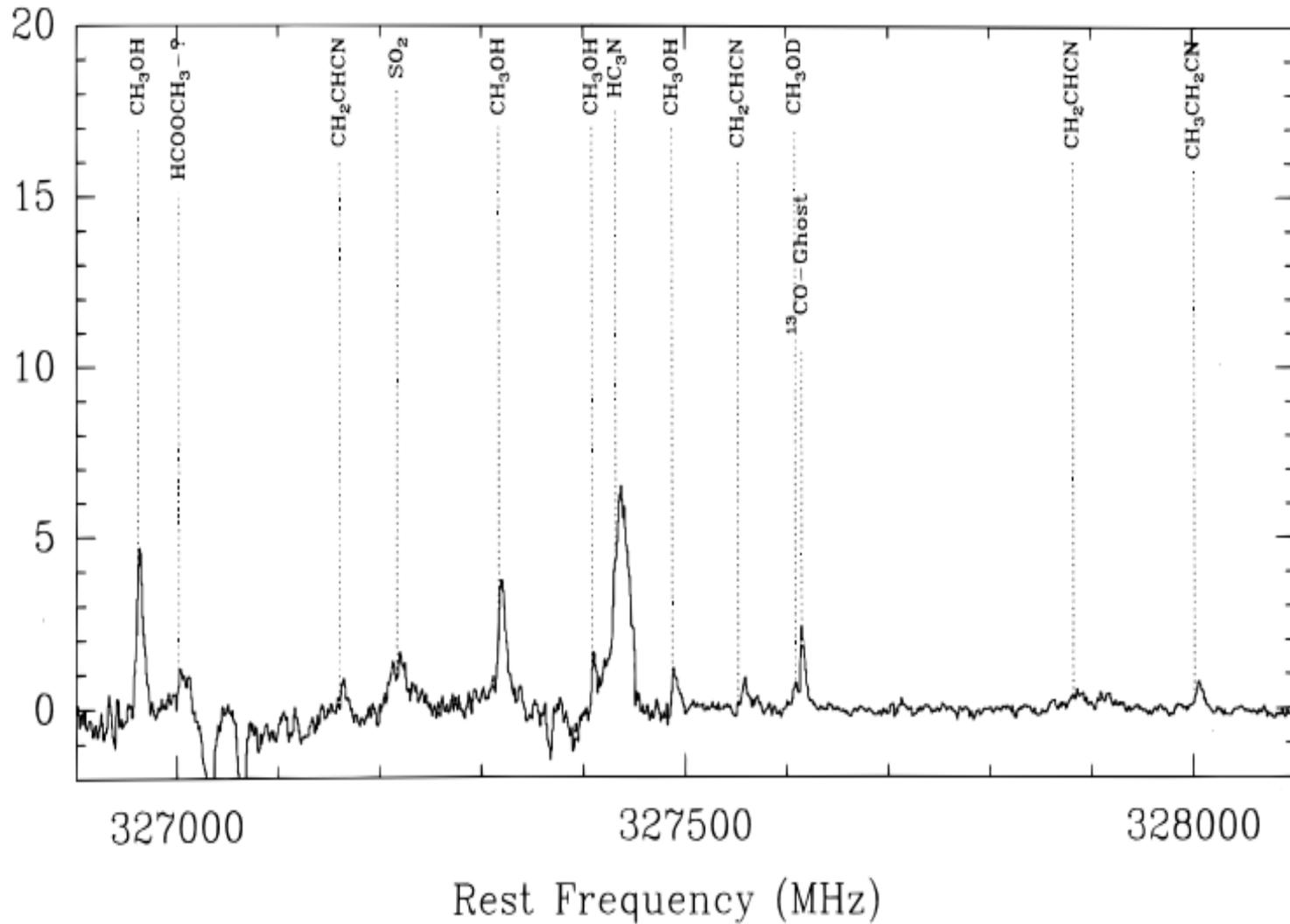


- Optical spectrum show lines due to [OII], [OIII], H α , [NII], etc

Millimeter Band Spectrum of Molecular Cloud



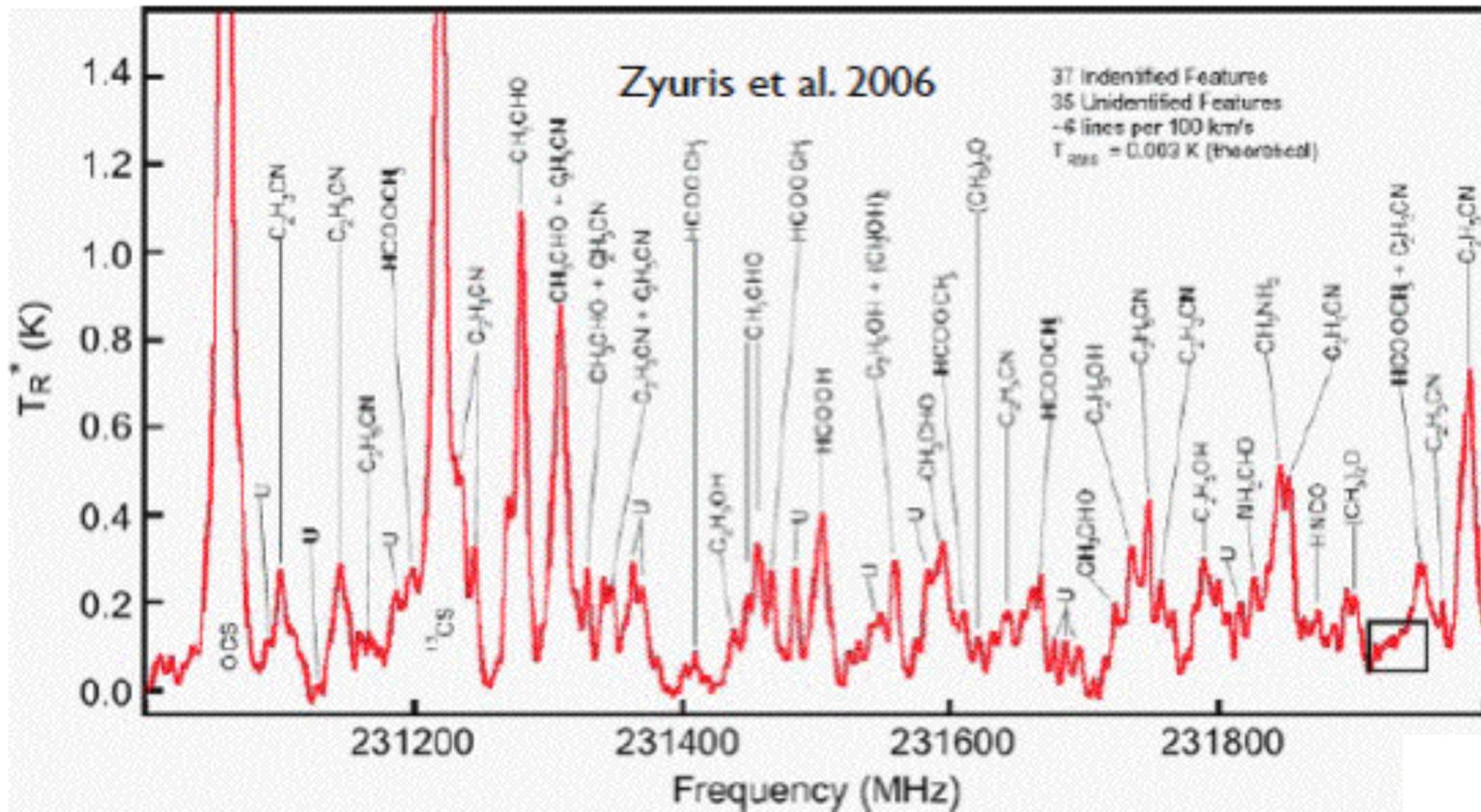
Millimeter Band Spectrum of Molecular Cloud



- zoom in on previous plot

Molecular Lines

- Molecular clouds are very rich in spectral features from a wide variety of molecules- lots of information
- Some of the lines (CO) are so strong that they can be seen at high redshift



ISM- Relevant Velocities

Some characteristic values

- galactic rotation speed 18km/sec/kpc
- Thermal sound speed ideal gas $c_s = \sqrt{kT/m_H\mu}$; μ is mean molecular weight

for Hydrogen this is 1km/sec at 100k

Alfven speed- speed at which magnetic fluctuations propagate

$$v_A = B/\sqrt{4\pi\rho} - \text{so for typical ISM values } B=1\mu\text{G}, \rho=1\text{cm}^{-3}$$

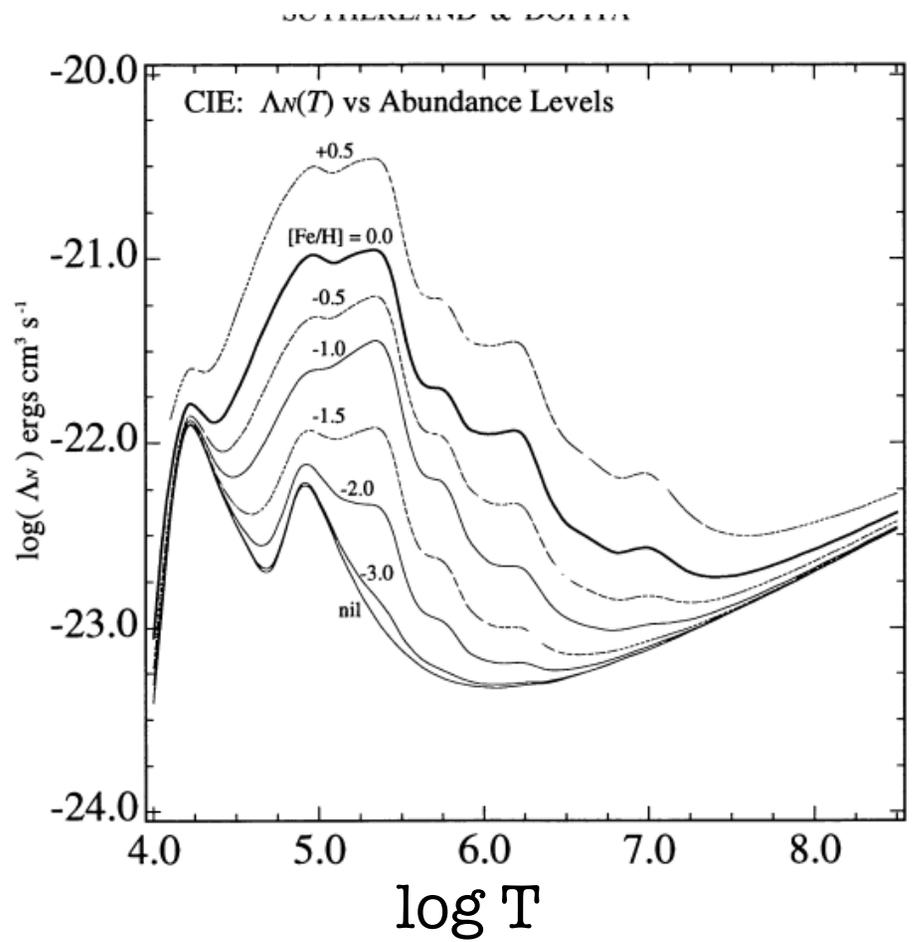
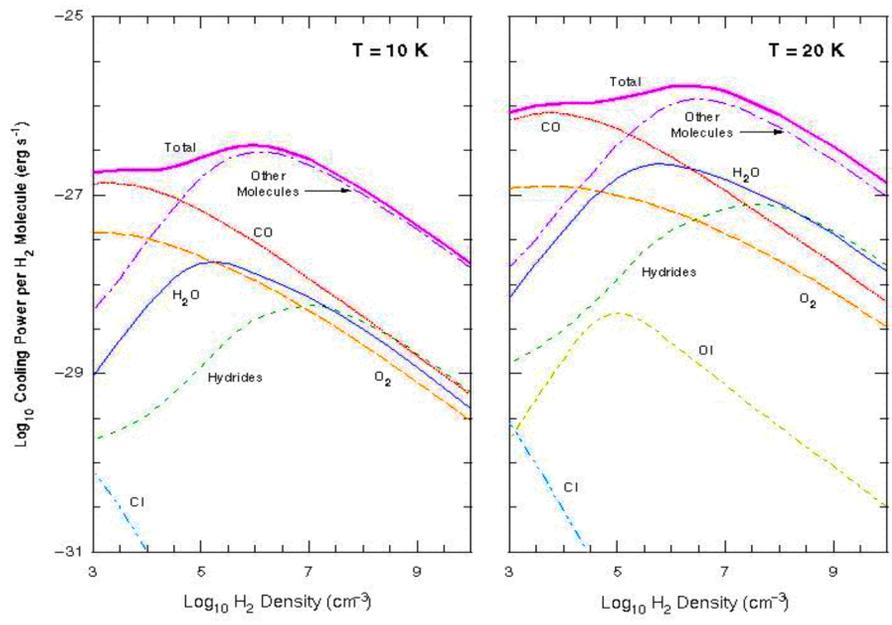
$$v_A = 2 \text{ km/sec}$$

Physics of Emission from Gas

- 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 bremsstrahlung-
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 Space Science Reviews, Volume 134, Issue 1-4, pp. 155-190, 2008m astro-ph/0801.1011 for the background physics for low density, hot gas.

Gas Cooling $L=n^2\Lambda(T)$

- $T > 10^7 \text{K}$ thermal bremsstrahlung $L \sim n^2 T^{1/2}$
- $10^7 > kT > 10^{6.3} \text{K}$ Fe L lines
- $10^{4.5} > kT > 10^{6.3} \text{K}$ K and L lines of 'metals'
- $10^4 > kT > 10^{4.5} \text{K}$
- At lower temperatures fine structure lines and molecules take over

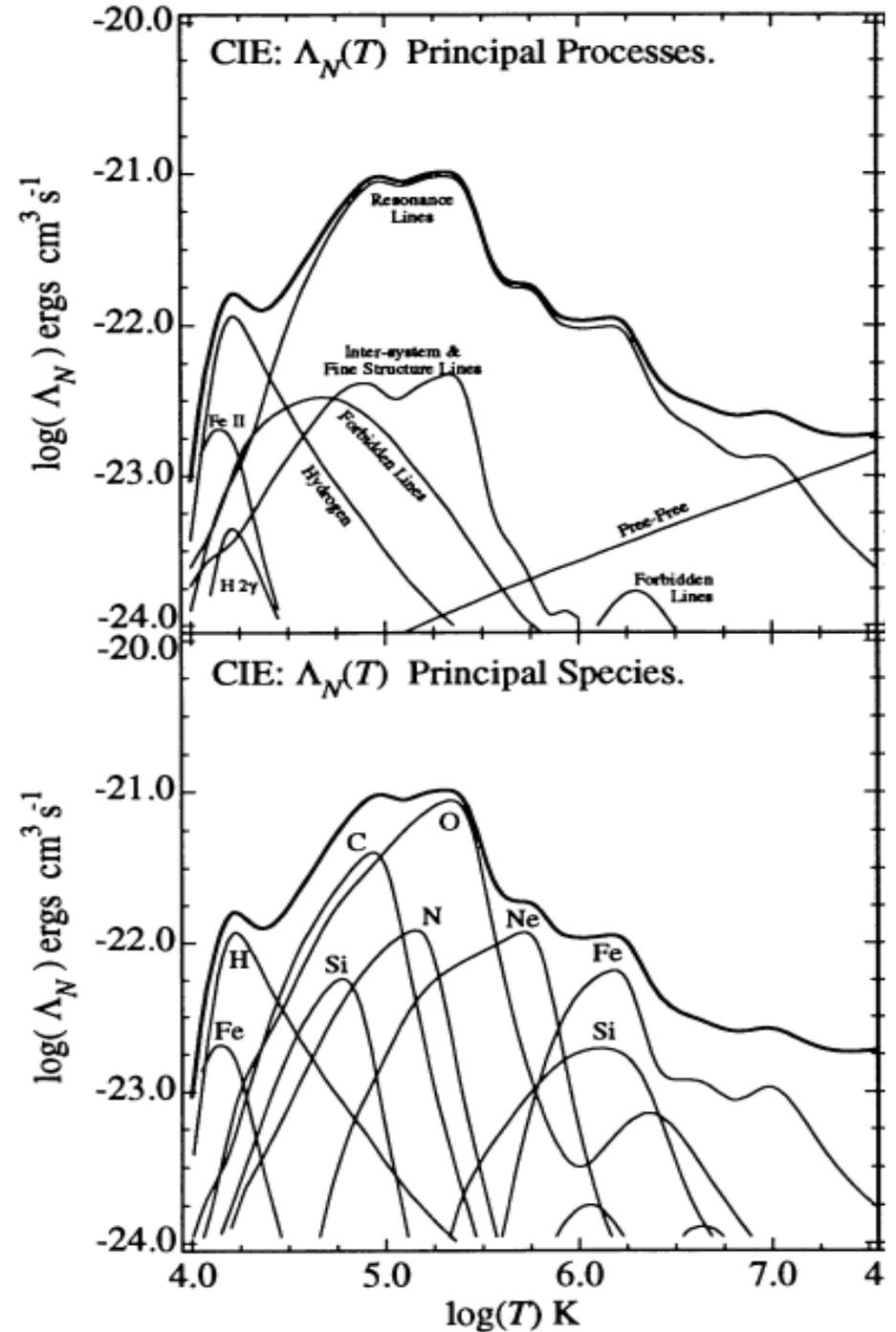
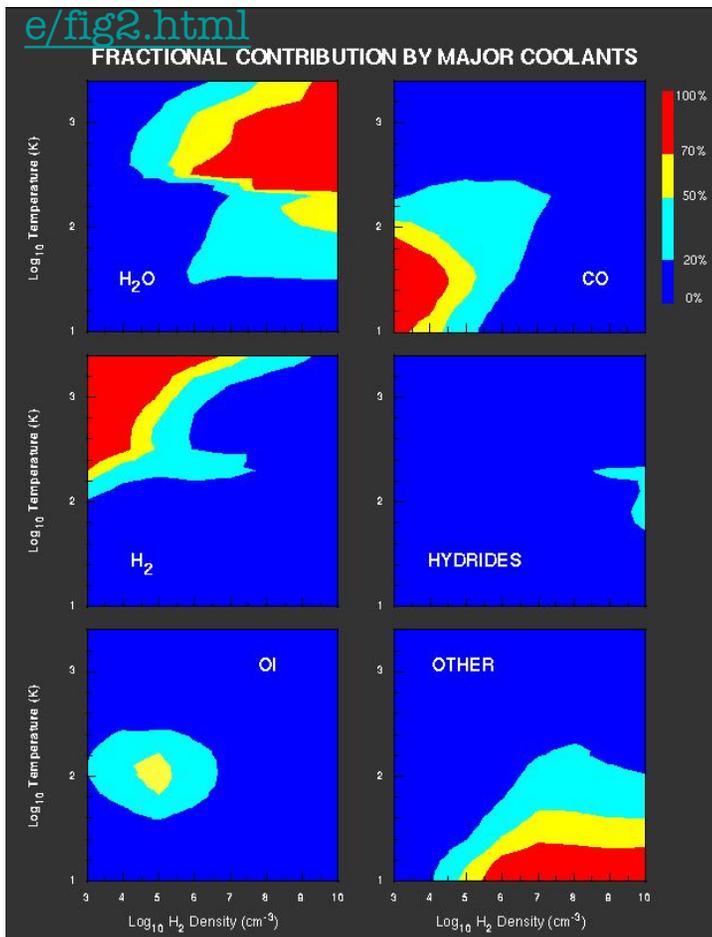


Cooling curve as a function of kT and metallicity-for gas in collisional equilibrium
 Sutherland and Dopita
 table 2.5 in text

Gas Cooling

As the temperature changes the ions responsible for cooling change as do the physical processes

<http://www.cfa.harvard.edu/swas/swasscience/fig2.html>

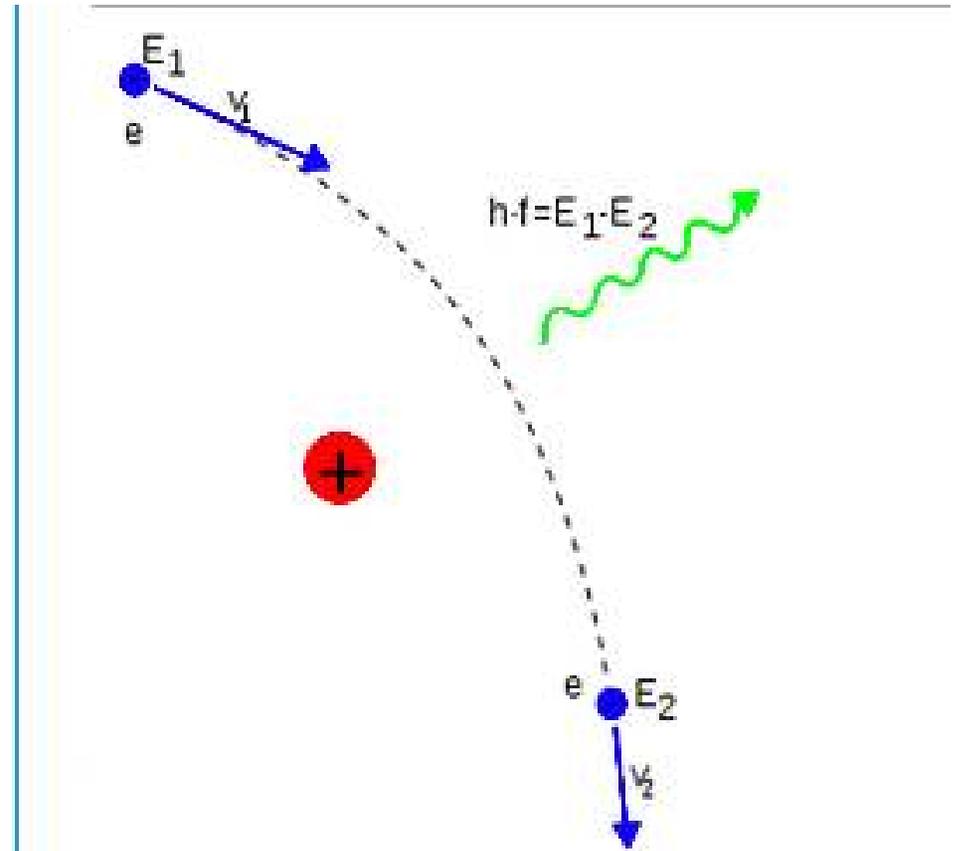


Gas Cooling

- 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
- Free-free emission: free electron is accelerated by an ion, emitting a photon. (A.k.a. Bremsstrahlung.)

Thermal Bremsstrahlung

- Electrons have a Maxwell-Boltzmann distribution
- electromagnetic radiation produced by the deceleration of a charged particle when deflected by another charged particle, typically an electron by an atomic nucleus (wikipedia)
- Bremsstrahlung has a continuous spectrum, whose shape depends on temperature roughly $E^{-0.4} \exp(-E/kT)$

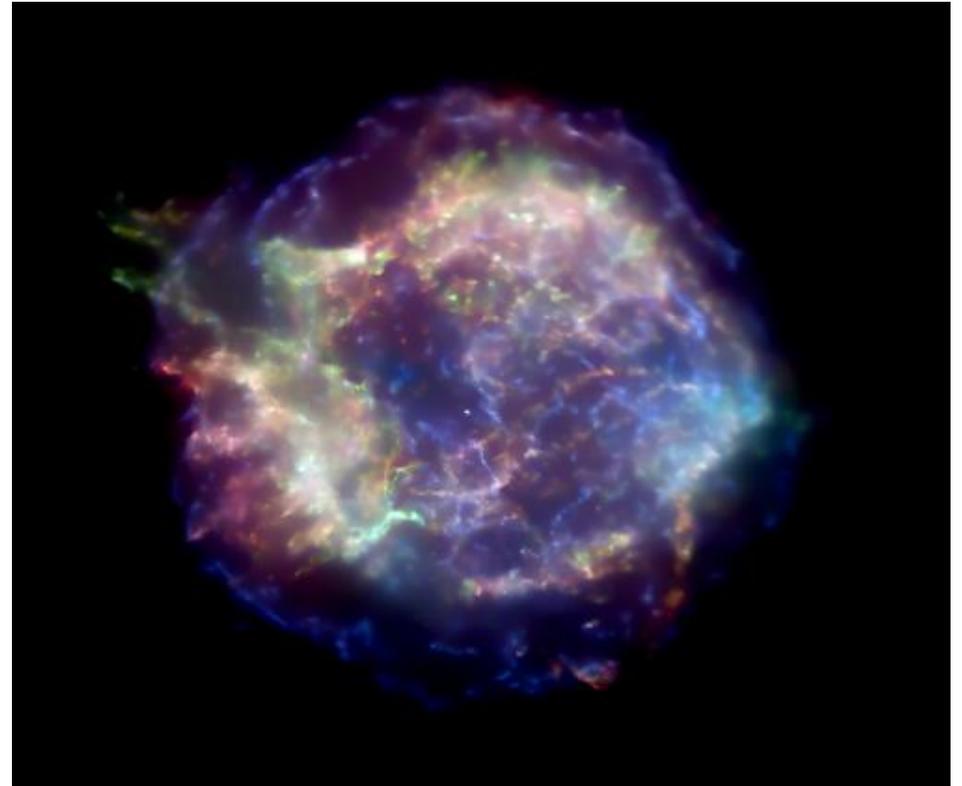


Gas Cooling

- The functions are very different for photoionized gas not in collisional equilibrium
- This depends on the shape of the photon spectrum and its intensity
- This is very important for studies of active galaxies and the intergalactic medium

Gas Heating Mechanisms in ISM

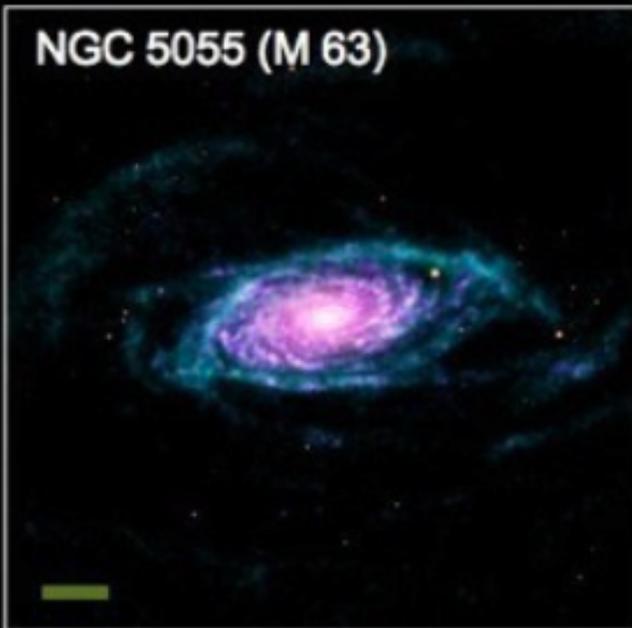
- heating by low-energy cosmic rays (dense MM)
- photoelectric heating by grains (CNM to MM)
- photoelectric heating by photoionization of atoms and molecules (HII regions)
- photoelectric heating by soft X-rays (WIM, WNM, CNM)
- chemical heating (dense MM)
- grain-gas thermal exchange (dense MM)
- hydrodynamic and magnetohydrodynamic heating (WNM, CNM)
- interstellar shocks (WNM, CNM, MM) due to supernova



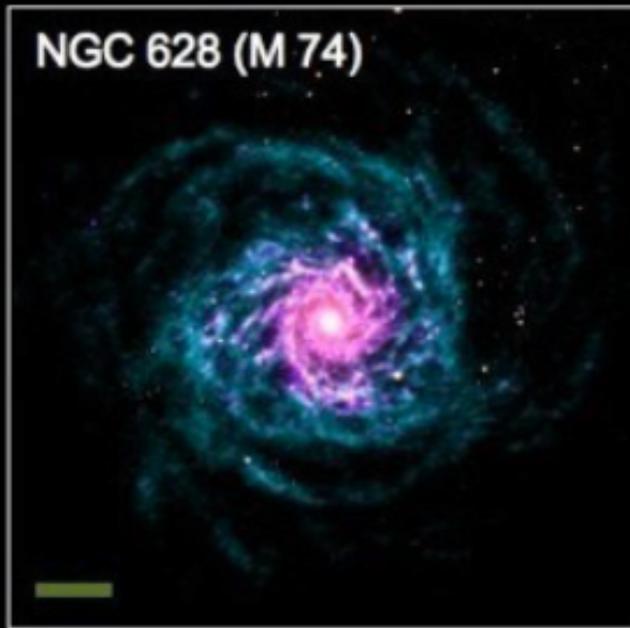
X-ray image of Cas-A
youngest SNR in MW

Spiral Galaxies in THINGS — The HI Nearby Galaxy Survey

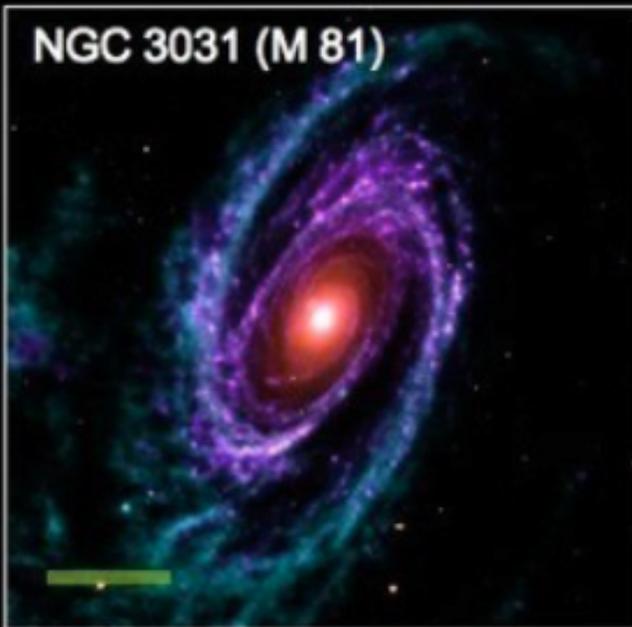
NGC 5055 (M 63)



NGC 628 (M 74)



NGC 3031 (M 81)



NGC 5194 (M 51)



THINGS

The HI Nearby
Galaxy Survey

color coding:

THINGS Atomic Hydrogen
(Very Large Array)

Old stars
(Spitzer Space Telescope)

Star Formation
(GALEX & Spitzer)

scale: 
15,000 light years



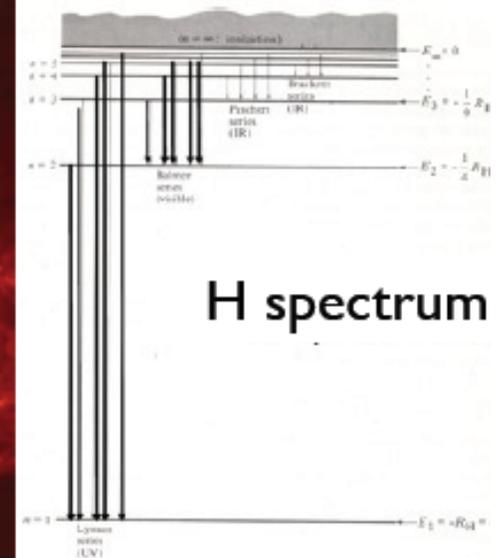
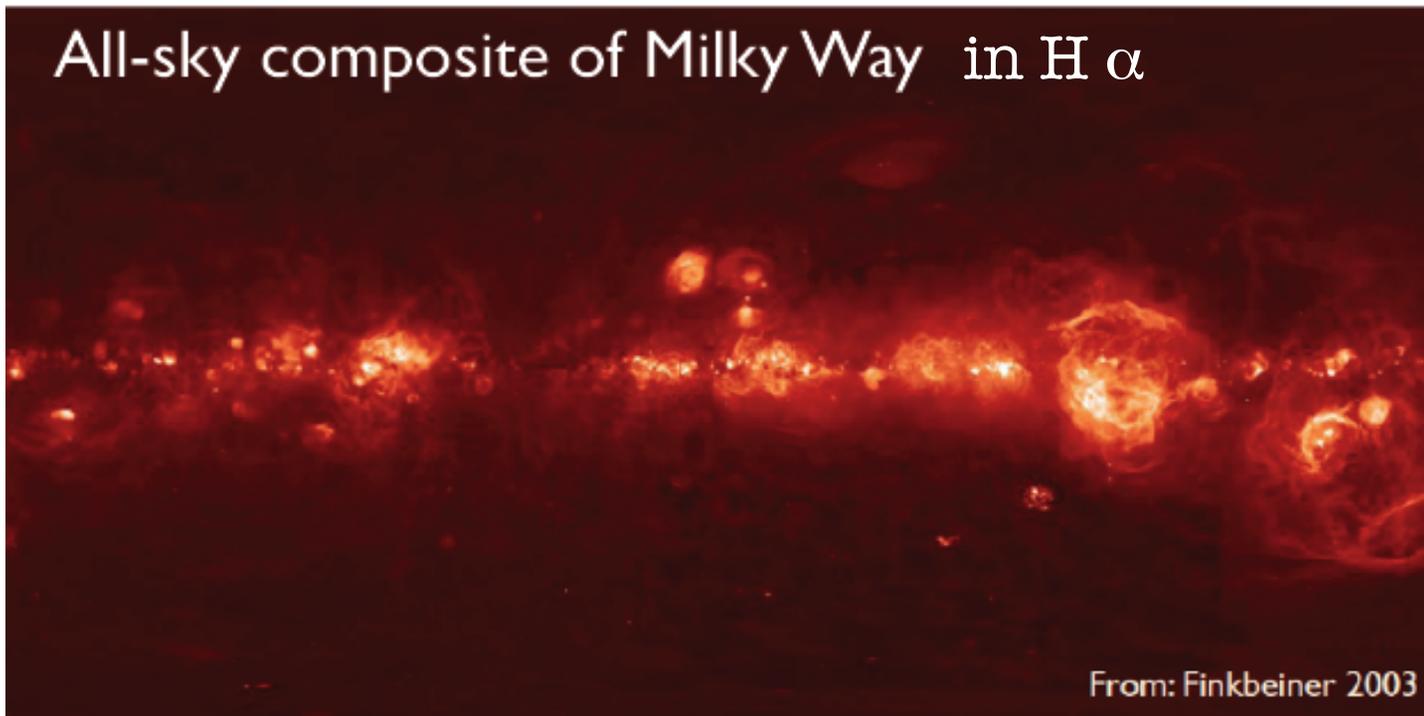
Image credits:
VLA THINGS: Walter et al. 08
Spitzer SINGS: Kennicutt et al. 03
GALEX NGS: Gil de Paz et al. 07

Warm Ionized Medium

Fabian Walter

- mainly traced by $H\alpha$
- most likely source: photoionization from OB stars
- scale height: 1 kpc
- minimum energy rate: $3 \times 10^5 \text{ kpc}^{-2} \text{ s}^{-1}$ (equiv. of 1 O4 star kpc^{-2})
- total energy requirement: $3 \times 10^8 L_{\text{sun}}$

All-sky composite of Milky Way in $H\alpha$



Cosmic Rays

- Cosmic rays, which are atomic nuclei electrons and protons which have been accelerated to nearly the speed of light- thought to be created in SNR shocks
- Gyroradius= $r_g = p/qB$

(p is the momentum of the particle, B the magnetic field, q the charge)

In handier units $r = 3.3 \times 10^7 \gamma / B(\text{gauss}) \text{cm}$; γ is the relativistic factor $\text{sqrt}(1/(1-v^2/c^2))$

With $B \sim 5 \mu\text{G}$ the gyroradius of a proton with $\gamma \sim 10^4$ (a typical value) is $\sim 10^{-4}$ pc.

so cosmic rays are trapped within the Galaxy by the magnetic fields .

Despite the wide range of densities and temperatures in the ISM, the pressure in the plane is roughly uniform .

The pressure in the ISM counteracts the gravitational force of the Galactic disk . It is highest in the plane and drops as higher galactic latitudes - but the scale height of the drop is related to the temperature of the gas.

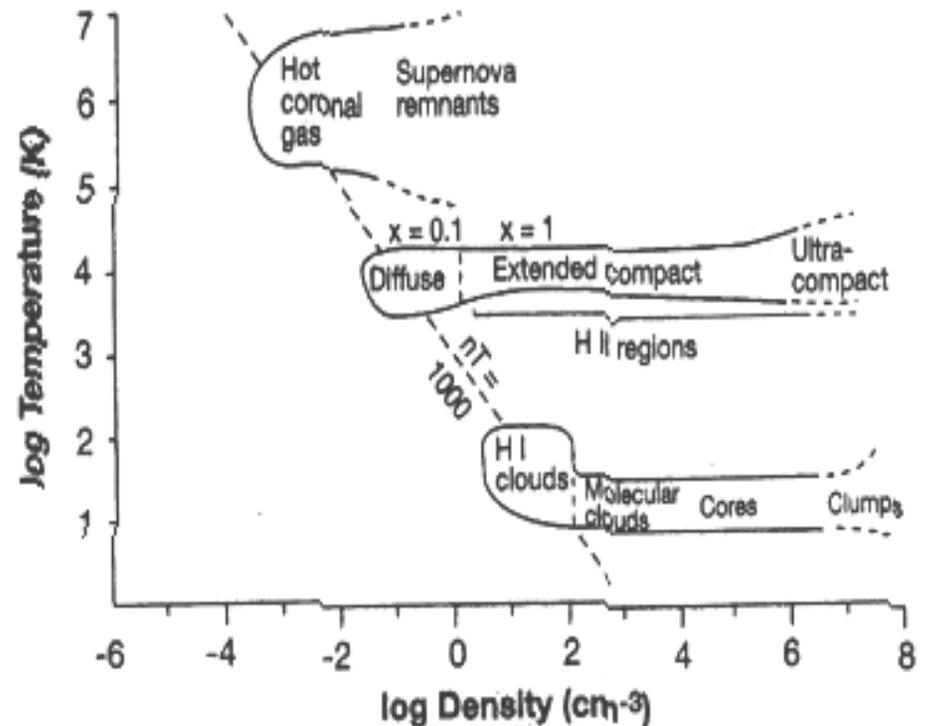
The ISM **can dominate a galaxy's integrated SED** -in the far IR and radio

- Mid-IR to Sub-mm is dominated by emission from dust, molecular lines and fine structure lines
- radio comes either from HII regions or a relativistic plasma radiating via synchrotron radiation

certain emission lines (eg $\text{Ly}\alpha$; $[\text{CII}] 158\mu$) can be major coolants

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
 - SN shocks heat/ionize/accelerate gas & are largely responsible for the ISM's complexity 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 tunnels of much lower density, hot enough to be observable via their X-ray emission (Cox ARA&A)

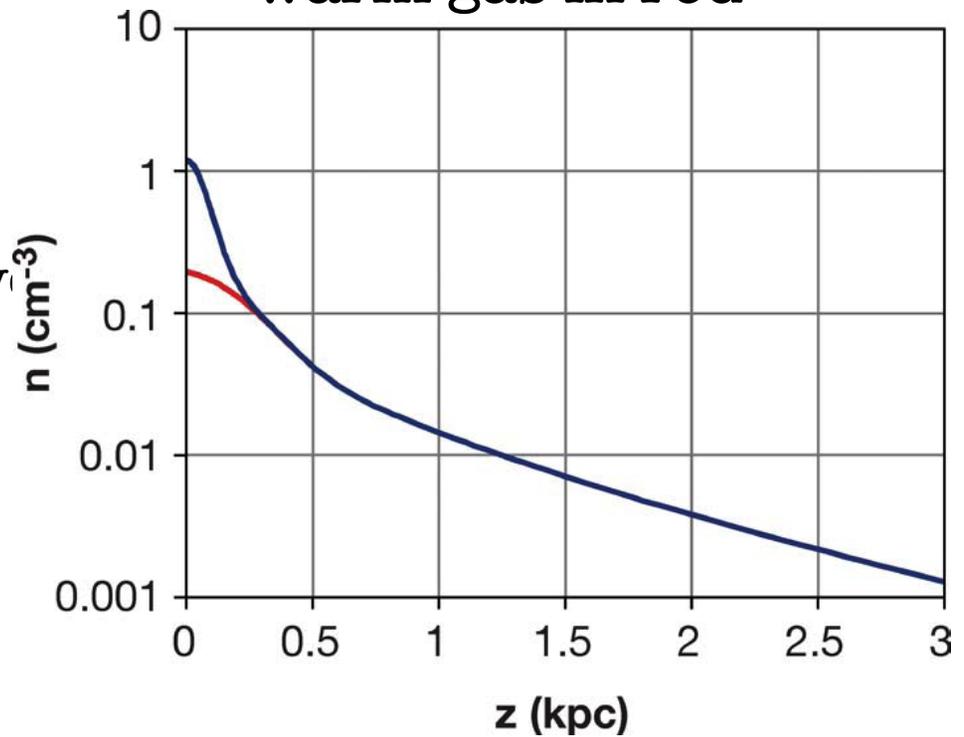


ISM in Spirals

- The phases of the gas are distributed differently
 - cold (molecular) gas is confined to a thin disk
 $\rho(z) \sim 0.58 \exp[-(z/81 \text{ pc})^2]$
 and has a mean $T \sim 15\text{k}$
 - 'warm' gas has a density distribution
 $\rho(z) \sim 0.57 * 0.18 \exp[-(z/318 \text{ pc})^2]$
 where z is the distance above the disk midplane
 has a mean $T \sim 5000\text{k}$

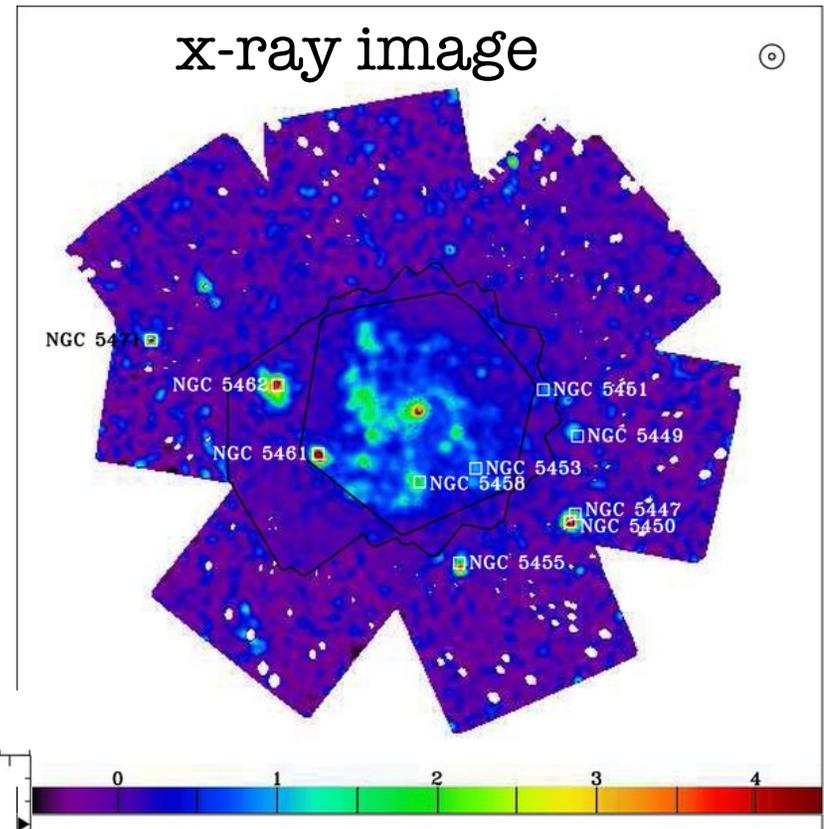
Roughly magnetic ($\sim 5\mu\text{G}$),
 cosmic ray, and dynamical
 pressures are equal $\sim 10^{-12}$
 dyne mid-plane

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

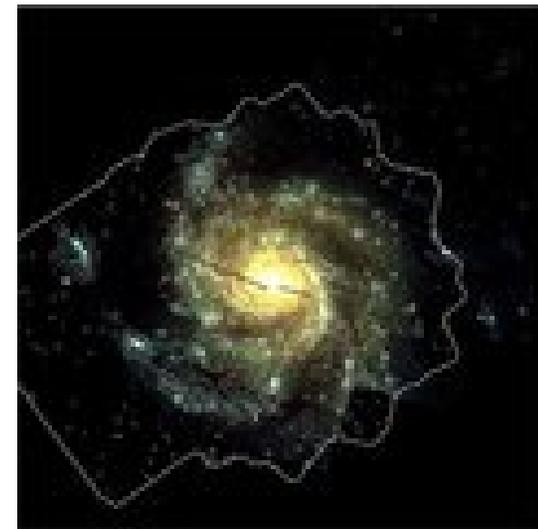
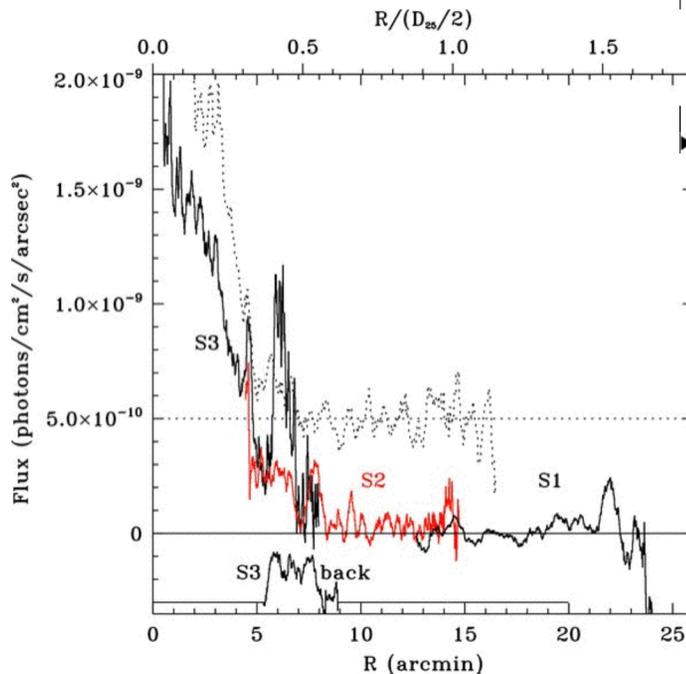


X-ray ISM in M101

- Hot phase of ISM in M101- dominated by ionized oxygen OVII/OVIII and $T \sim 2 \times 10^6 \text{K}$ is the temperature of the dominant component.
- The emission is centrally concentrated
- Such data exists for only a few objects



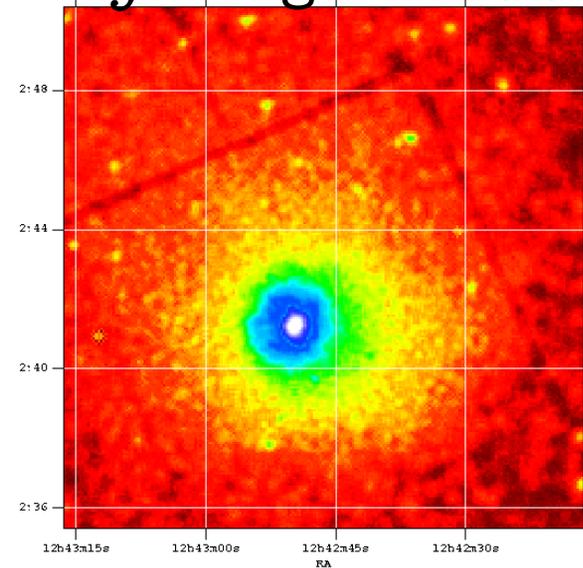
x-ray
surface
brightness



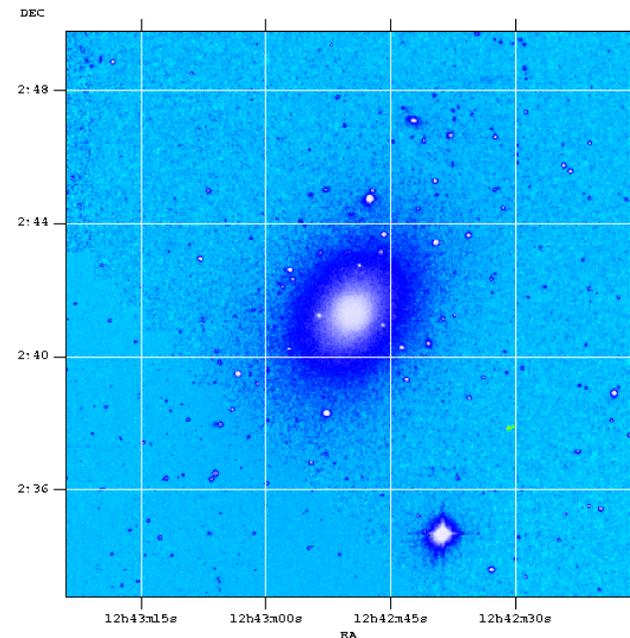
ISM In Ellipicals-pg 272 in S+G

- Predominately hot $kT \sim 10^6 - 10^7 K$ and thus visible only in the x-ray
 - the temperature is set, predominantly by the depth of the potential well of the galaxy (if it were hotter it would escape, if colder fall)
 - The metallicity of the gas is roughly solar

x-ray image of NGC 4636

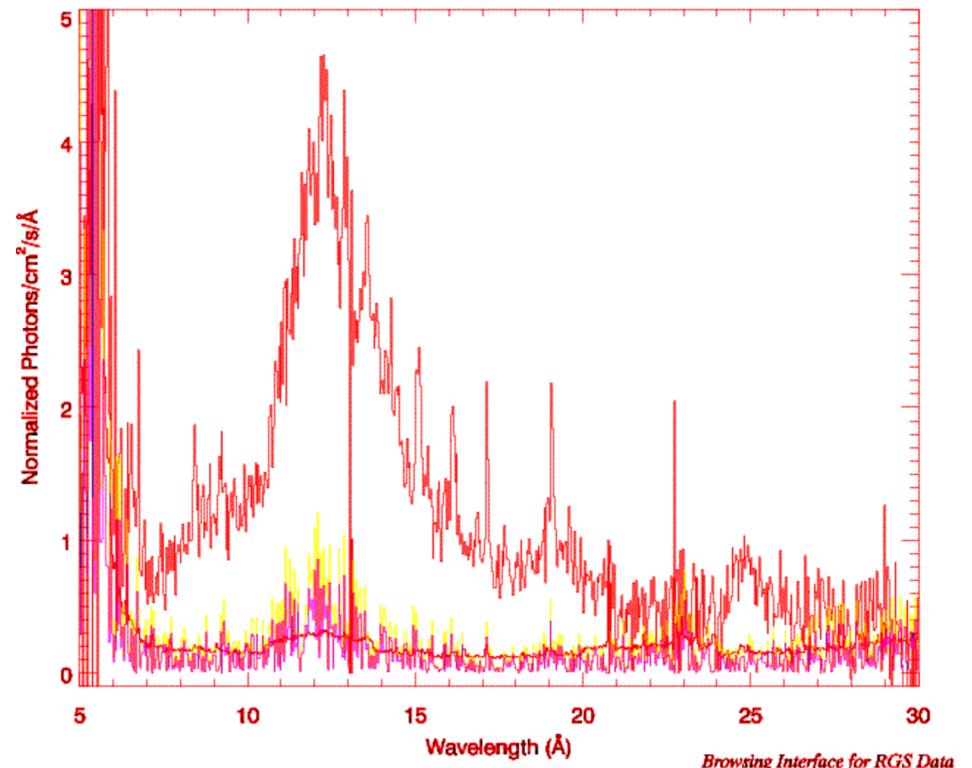


Optical Image of NGC4636



X-ray Spectra of NGC1399

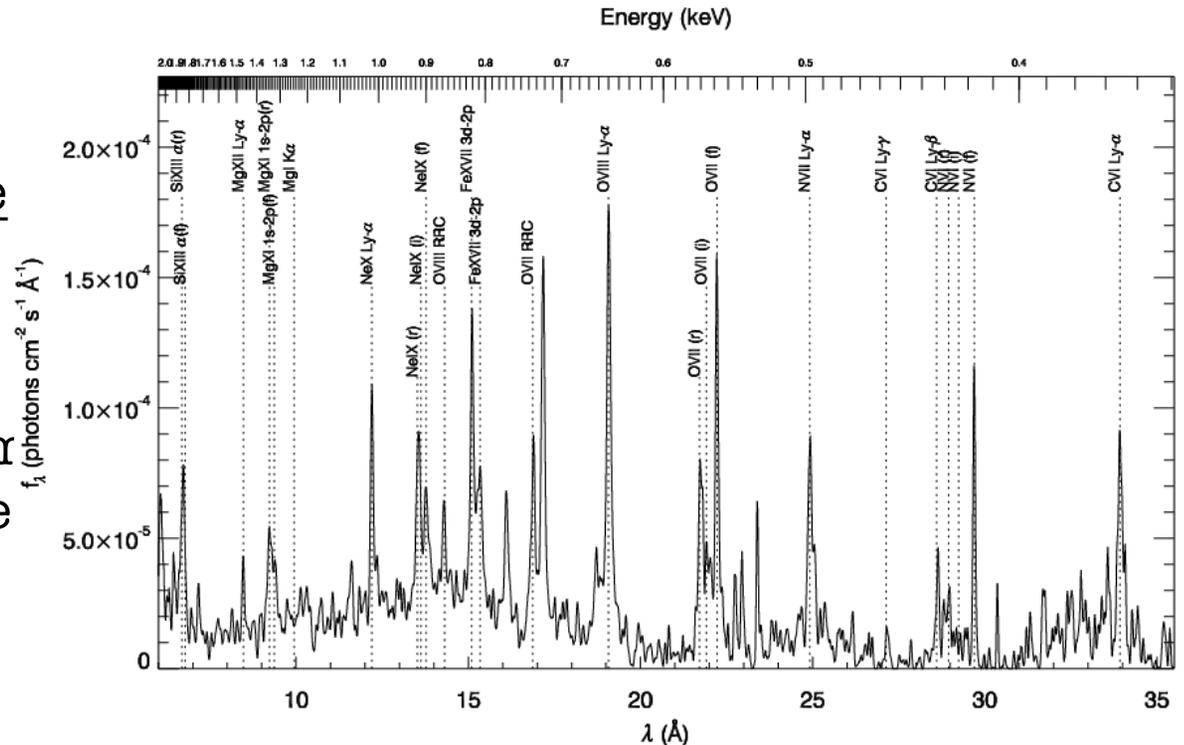
- At certain temperatures ($\sim 4-16 \times 10^6 \text{k}$) the spectrum is dominated by Fe lines from the L shell whose energy is very sensitive to temperature.
- Thus x-ray images and spectra (obtained simultaneously with CCDs) get the density and temperature and estimates of the chemical composition of the ISM in ellipticals



wavelength Å

Hot Gas and Metallicity

- In elliptical galaxies , clusters of galaxies and star forming galaxies the ISM is hot and emits primarily via thermal bremsstrahlung with strong emission lines from abundant elements (O, Ne Si, S, Fe)



X-ray spectrum of hot gas in a star forming galaxy

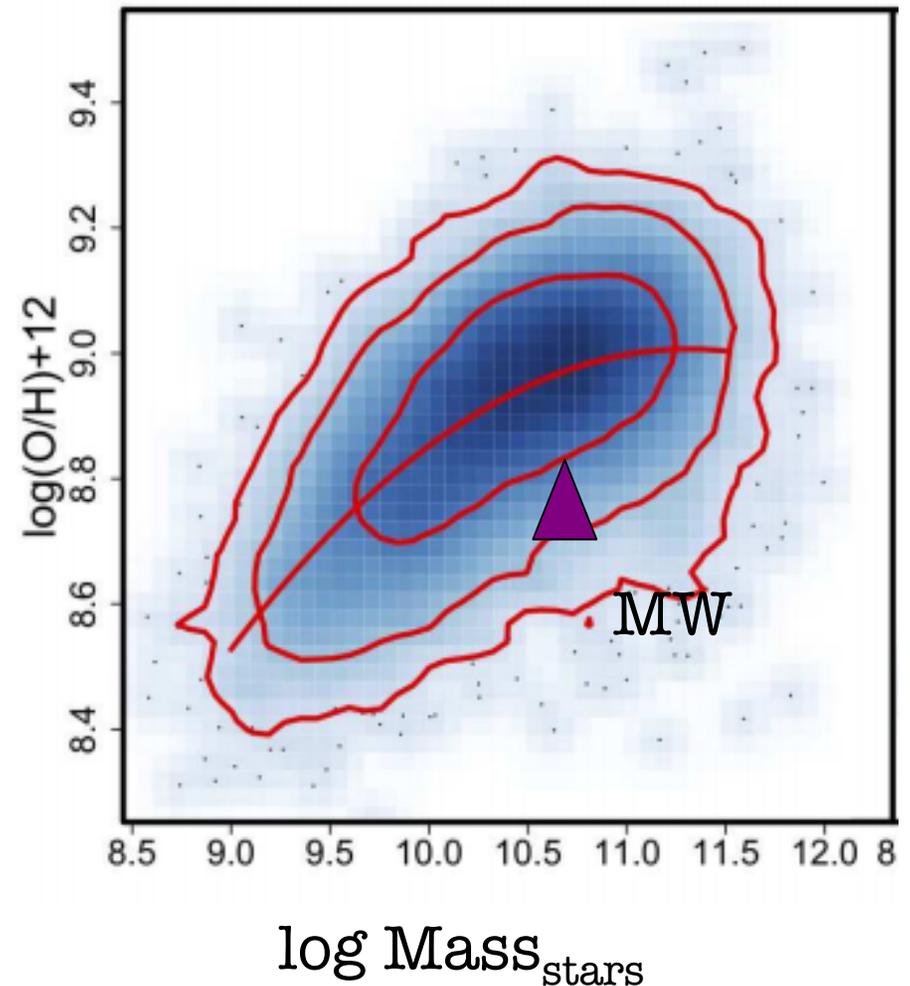
- These are fairly easy to measure and the amount of hydrogen is measured by the strength in the continuum.
- Problem is x-ray sources are weak and telescopes are small so not so many objects (~100's)

Image of x-ray source determines the gas density since $L \sim \Lambda(T)n^2$

Metallicity in Gas

- For star forming galaxies it is easier to measure the metallicity in the gas phase than in the stars-strong emission lines-but one measures different elements
- How does one do 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 $\sim 50\%$ of all the heavy elements by mass - **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 (see Lopez-Sanchez et al 2012)
 -
- More massive galaxies tend to be more metal rich

There are several methods to do this- but error of factor of 2

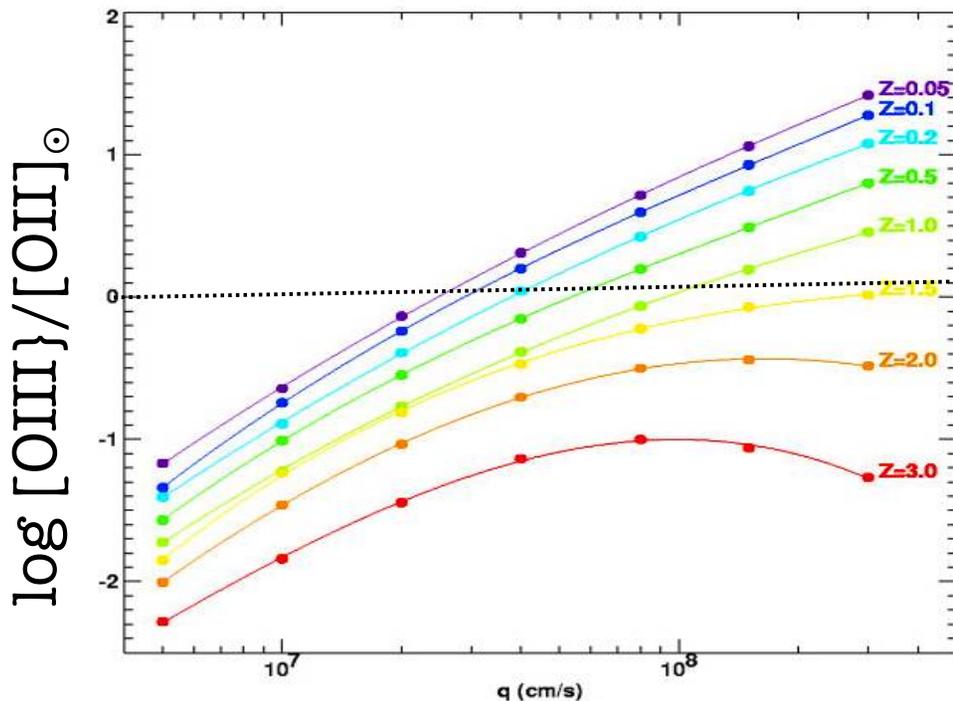


GAMA collaboration Foster et al 2012

Metallicity Issues for Distant Galaxies

Fundamental problem is that the ionization structure of the gas is unknown and the line strengths and hence the abundances depend on both

- chemical abundances,
- the ionization parameter (U) which is the ratio of ionizing photons density to gas density for photoionized gas: ($U \sim L/n_e r^2$)



ionization parameter

each line corresponds to the predicted $[OIII]/[OII]$ ratio for a different abundance (0.05-3x solar) and ionization parameter

A fixed line ratio can correspond to a factor of 20 range in abundance if ionization parameter is not simultaneously constrained.

Metallicity Issues for Distant Galaxies

Since the electron temperature, density and nature of stellar ionization field vary quite a bit over the galaxy these are 'irreducible' errors.

One resorts to calibrating the lower quality galaxy data against the excellent data for HII regions in the MW and some other nearby galaxies

Gas phase abundances are 'ok' for O, N and S (but not Fe)

Abundances determined in stars mainly measure 'Fe' via absorption lines in stellar spectra (Worthy et al 1994)- very very messy.

Why Metals are Important

- metals account for 1% of the mass, they **dominate** most of the important chemistry, ionization, and heating/cooling processes.
- 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.

