Gas Cooling

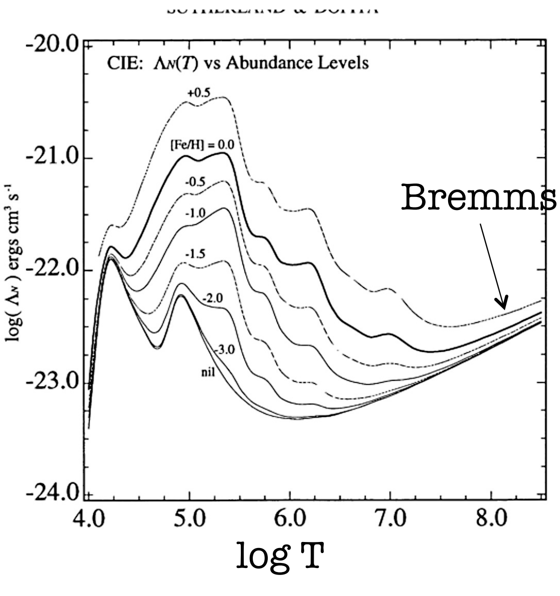
- Collisional excitation: free electron impact knocks a bound electron to an excited state; it decays, emitting a photon.
- Collisional ionization: free electron impact ionizes a formerly bound electron, taking energy from the free electron.
- Recombination: free electron recombines with an ion; the 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**)

Reference on Cooling via molecular rotational lines and dust emission (Neufeld, Lepp and Melnick (1995, Ap.J.Supp., 100, 132)

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

MWB sec 8.1.3, 8.4

- $T>10^7$k thermal bremmstrahlung $L \sim n^2T^{1/2}V$
- $10^7>kT>10^{6.3}$k Fe L lines
- $10^{4.5}>kT>10^{6.3}$k K and L lines of 'metals'
- $10^4>kT>10^{4.5}$k Hydrogen
- At lower temperatures fine structure lines and molecules dominate

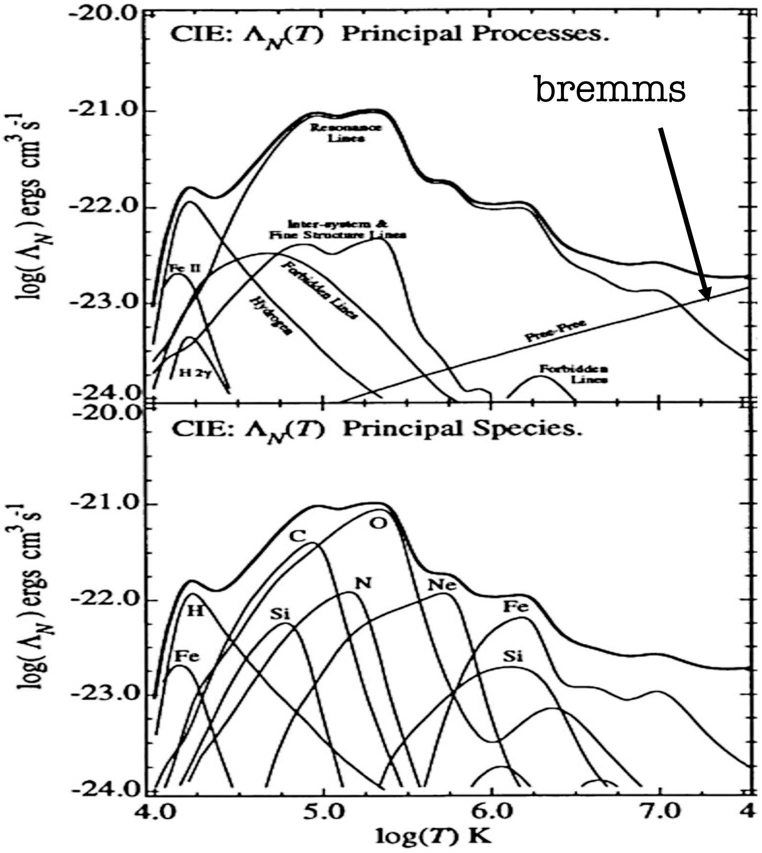


Cooling curve as a function of kT and metallicity-for gas in collisional equilibrium
Sutherland and Dopita
table 2.5 in S&G

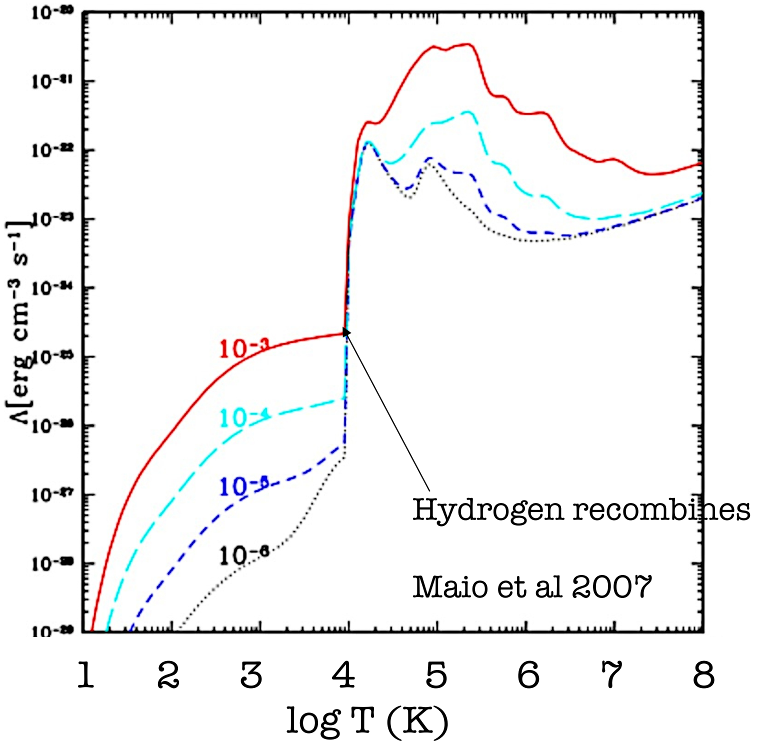
Gas Cooling

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

In the case of primordial gas, cooling below 10^4K is only possible if significant amounts of molecular hydrogen can form in the gas.

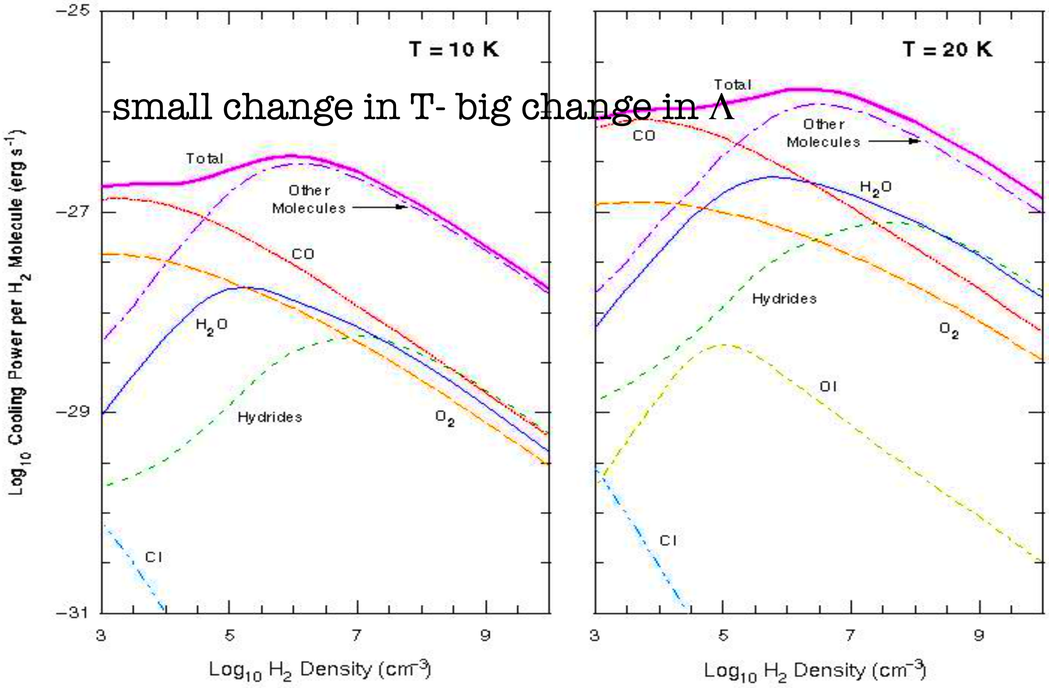


- Cooling function including hydrogen, helium, metals lines, H_2 and HD molecules as function of temperature- (appropriate for early universe)
- Notice that even a tiny metallicity has a big effect on cooling



Different metallicities 10^{-3}-10^{-6} solar

Molecular Cooling- Function of Density as well as T (not just n^2)



small change in T- big change in Λ

Star Formation and the Cooling of Molecular Clouds-

https://www.cfa.harvard.edu/swas/science1.html

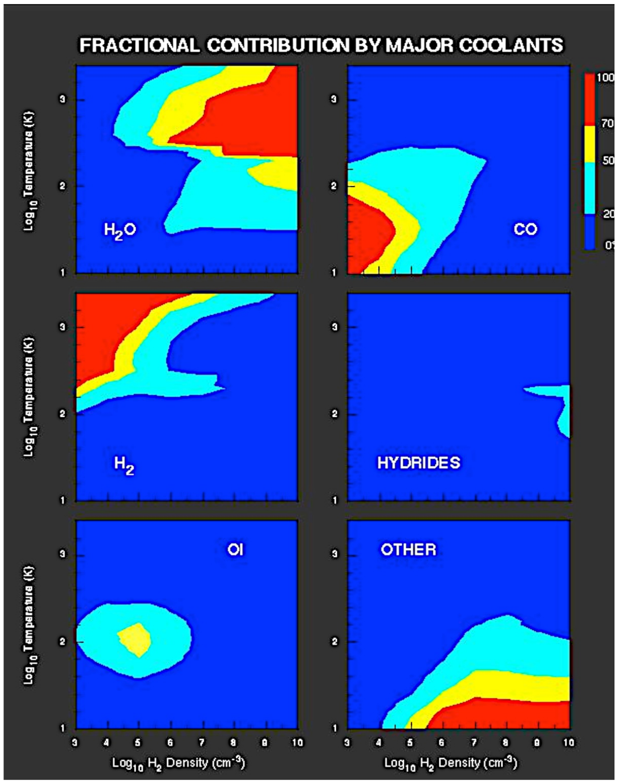
- Even though hydrogen and helium are the most abundant elements in interstellar clouds they are very poor coolants because they cannot be collisionally induced to emit photons at the low gas temperatures characteristic of molecular clouds.
- theoretical studies predict that a large fraction of the total cooling is dominated by gaseous water (H_2O), carbon monoxide (CO), molecular oxygen (O), and atomic carbon (C).
- at lower densities and temperatures CO and O are the dominant coolants, but at high densities H_2O along with a host of other molecules, dominate the cooling. However, this situation changes dramatically when the temperature is raised.

Gas Cooling

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

Major Molecular Coolants

log T
3
2
1



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

- Read S&G pg104-107

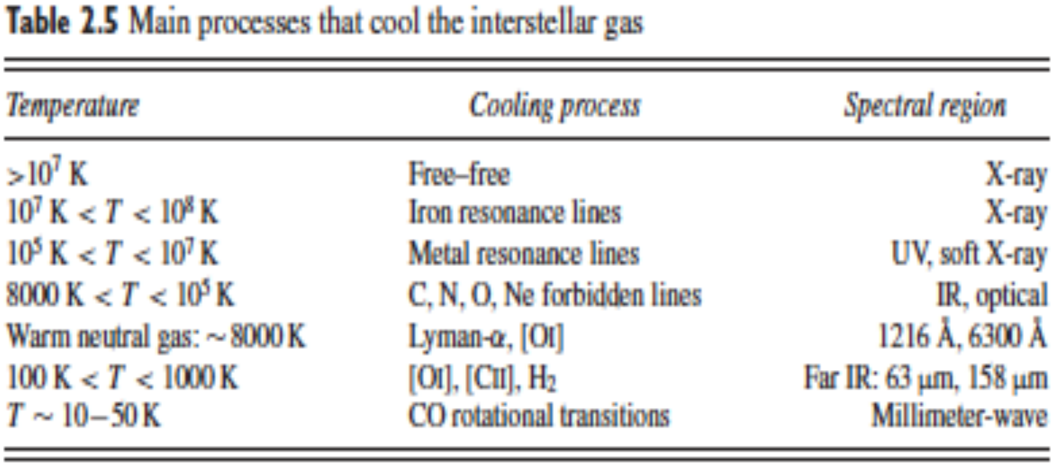


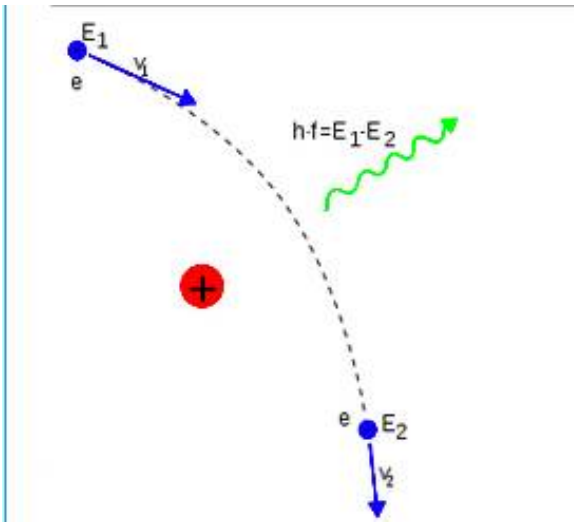
Table 2.5 Main processes that cool the interstellar gas

Temperature	*Cooling process*	*Spectral region*
$>10^7$ K	Free–free	X-ray
$10^7 \text{ K} < T < 10^8$ K	Iron resonance lines	X-ray
$10^5 \text{ K} < T < 10^7$ K	Metal resonance lines	UV, soft X-ray
$8000 \text{ K} < T < 10^5$ K	C, N, O, Ne forbidden lines	IR, optical
Warm neutral gas: ~8000 K	Lyman-α, [OI]	1216 Å, 6300 Å
$100 \text{ K} < T < 1000$ K	[OI], [CII], H_2	Far IR: 63 μm, 158 μm
$T \sim 10$–50 K	CO rotational transitions	Millimeter-wave

Thermal Bremmstrahlung- Often Called Free-Free

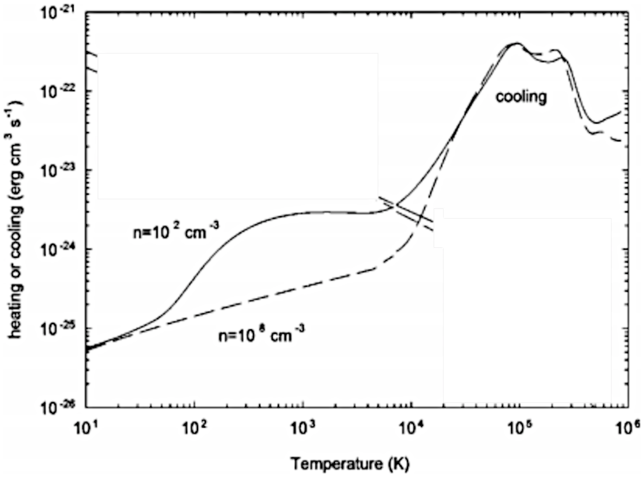
$C_{\mathrm{ff}} =\approx 1.4x10^{-23} T_8^{1/2} [n_e \mathrm{cm}^{-3}]^2$ $\mathrm{ergs}^{-1}\ \mathrm{cm}^{-3}$,

- 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 $E^{-0.4} \exp(-E/kT)$
- Main non-line coolant- important at high temperatures or in gas with very low metallicity



Photoionized Gas Cooling

- The functions are very different for photoionized gas which is usually **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
- Things are of course more complex in a non-equilibrium system



Physics of Photoionized Plasmas
G. Ferland
ARAA. 2003. 41:517

Cooling Time (BW 8.4.1)

- Dimensional analysis gives cooling time $t_{cool} \sim \varepsilon/(d\varepsilon/dt)$ where ε is the thermal energy in the gas
- e.g. $L = n^2\Lambda(T)$, so tcool $\propto T/[n\Lambda(T)]$:$\Lambda(T)$ depends only on the temperature, so denser gas cools more rapidly. (S&G 2.23)

- $t_{coo\ l} \sim \varepsilon\,\rho/\Lambda$; since energy release goes as ρ^2 ;$t_{cool} \sim \varepsilon/\rho$

- Alternatively (MWB e.q. 8.94)
- energy in gas per particle is nE and cooling rate is Λ; $t_{cooll} \sim nE/\Lambda$
- for an ideal gas $nE_{ll} \sim 3/2nkT$ and

by definition the cooling rate is $n^2\Lambda(T)$ so $t_{cool} \sim 3/2nkT/n^2\,\Lambda\,(T)$

- In general $t_{cool} \sim 3.3x10^9\ (T/10^6K)\ /(n/10^3)\Lambda_{-23}$

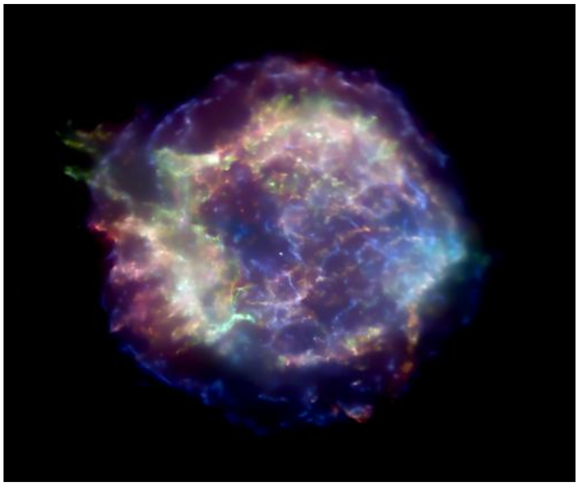
Λ_{-23} is the value of the cooling function in units of 10^{-23} ergcm^3/sec

Cooling Time (BW 8.4.1)

- $t_{cool}=3.3x10^9\ T_6/\ n_{-3}\Lambda_{-23}(T)$ yr, *MBW eq. 8.94*
- with the cooling function $\Lambda = 10^{-23}\Lambda_{-23}$ ergcm^3 s^{-1}.

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

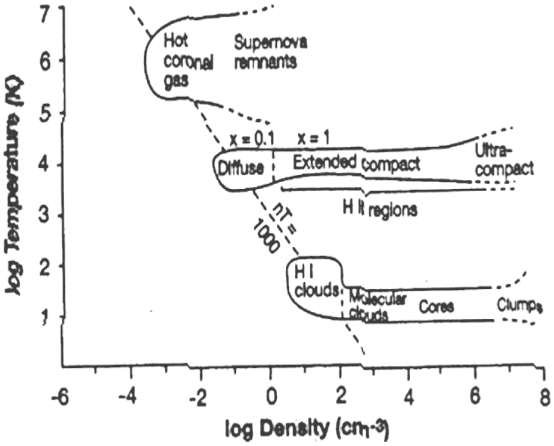


X-ray image of Cas-A youngest SNR in MW

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)

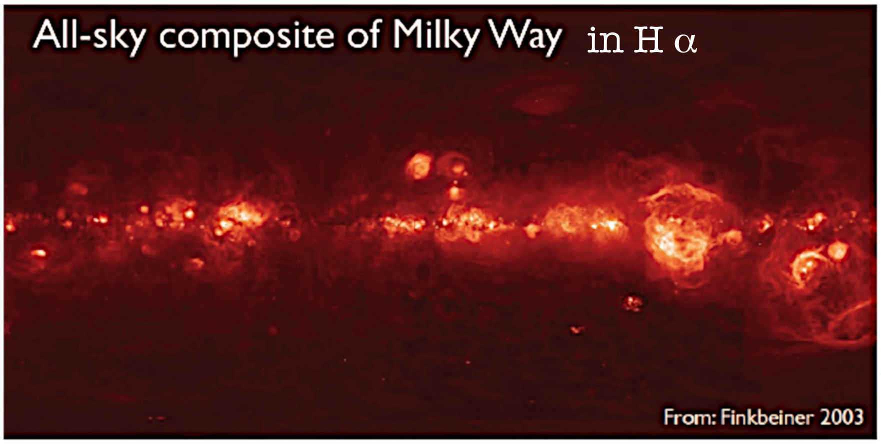


See lecture notes by Fabian Walter for lots more detail (on class web page)

Warm Ionized Medium

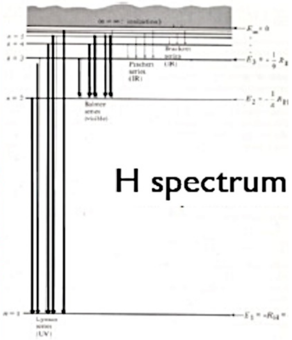
Fabian Walter

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



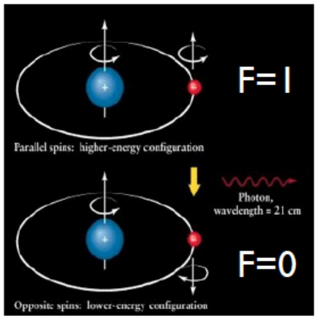
All-sky composite of Milky Way in H α

From: Finkbeiner 2003



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

Read Heiles and Troland ApJ 596,1067



- 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 $F = 1$:
  - $\nu = 1420$ MHz, $\lambda = 21.11$ 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

21 Cm line

Due to the spin–spin coupling of proton and electron, the ground (n = 1) state of a neutral hydrogen atom is split into two hyperfine states; a singlet state corresponding to anti-alignment of the two spins, and a degenerate triplet state corresponding to alignment of the two spins- call them 1 and 0

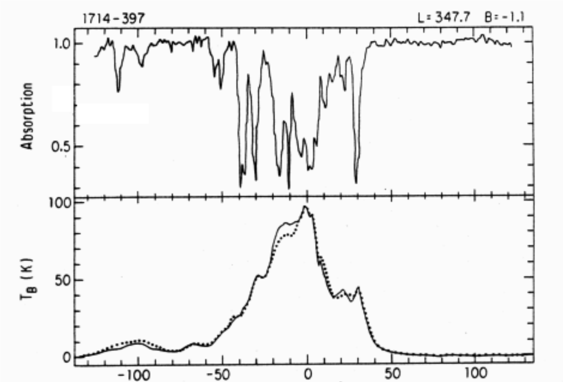
The energy difference ,between the two states is $E_{10} = E_1 - E_0 \approx 5.9\times10^{-6}$ eV, corresponding to $\lambda_{10} \approx 21$cm,or frequency $\nu_{10} \approx$ 1,420MHz, and a temperature $T_{10} \equiv E_{10}/k_B \approx 0.068$K.

In equilibrium, the population ratio in these two states is determined by the spin temperature,T_s,

$n_1/n_0 = 1/3 \exp[-T_{10}/T_s]$

T_s is not necessarily a kinetic temperature but a description of the distribution of states.

HI emission vs. absorption



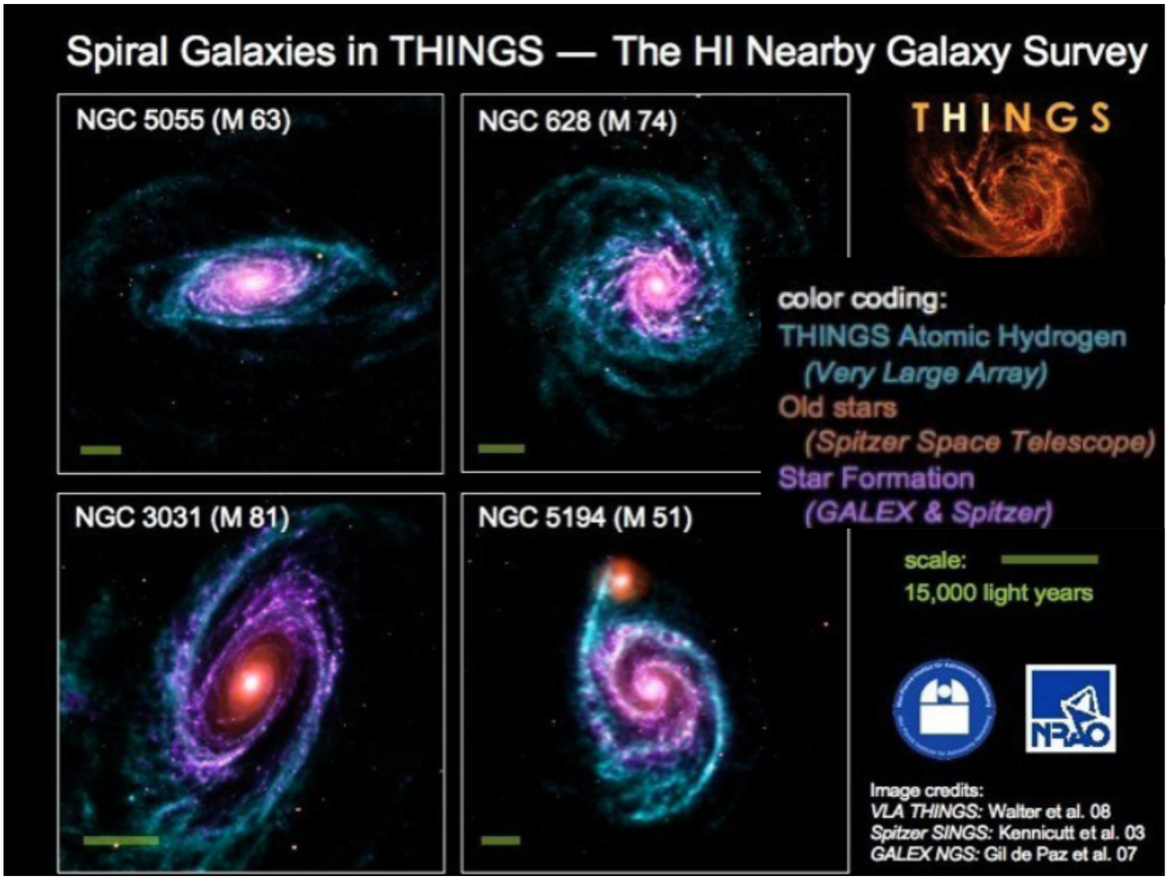
Dickey et al. 1983

$$
\begin{aligned}
j_\nu &= \frac{h\nu}{4\pi}\frac{3n_H}{4}A_{10}\Phi(\nu), \\
\kappa_\nu &= \frac{(h\nu)^2}{c}\frac{n_H B_{01}}{4kT_{\rm ex}}\Phi(\nu)
\end{aligned}
$$

emission and absorption coefficient of a 2-level system:

Spectra taken towards same direction within our galaxy
This first suggested that the neutral ISM consists of 2 phases

From H. Rix and F. Walter



Spiral Galaxies in THINGS — The HI Nearby Galaxy Survey

NGC 5055 (M 63)

NGC 628 (M 74)

NGC 3031 (M 81)

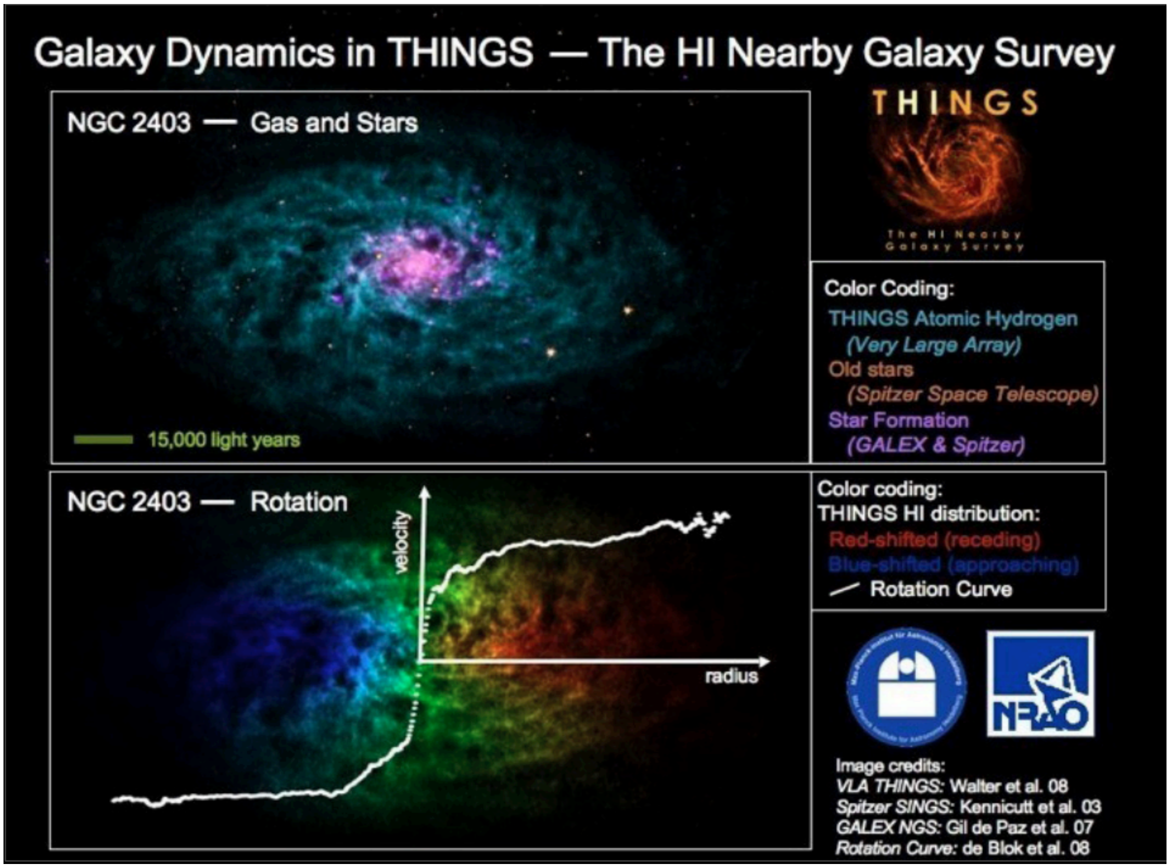
NGC 5194 (M 51)

THINGS

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



Galaxy Dynamics in THINGS — The HI Nearby Galaxy Survey

NGC 2403 — Gas and Stars

15,000 light years

THINGS
The HI Nearby Galaxy Survey

Color Coding:
THINGS Atomic Hydrogen
(Very Large Array)
Old stars
(Spitzer Space Telescope)
Star Formation
(GALEX & Spitzer)

NGC 2403 — Rotation

Color coding:
THINGS HI distribution:
Red-shifted (receding)
Blue-shifted (approaching)
Rotation Curve

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

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=$3.3\times10^7\gamma/B$(gauss)cm ; γ is the relativistic factor sqrt($1/(1-v^2/c^2)$)

With B~5μG the gyroradius of a proton with $\gamma\sim10^4$ (a typical value) is ~10^{-4} pc.

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

Energy density in cosmic rays comparable to other components of ISM

- Thermal IR from dust
- Starlight
- Thermal kinetic energy (3/2 nkT)
- Turbulent kinetic energy
- Magnetic fields ($B^2/8\pi$)
- Cosmic rays

.

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 Lyα ; [CII] 158μ) can be major coolants

ISM in Spirals

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

    $\rho(z) \sim 0.58 \exp[-(z/81\ \mathrm{pc})^2]$

    and has a mean T~15k
  - 'warm' gas has a density distribution

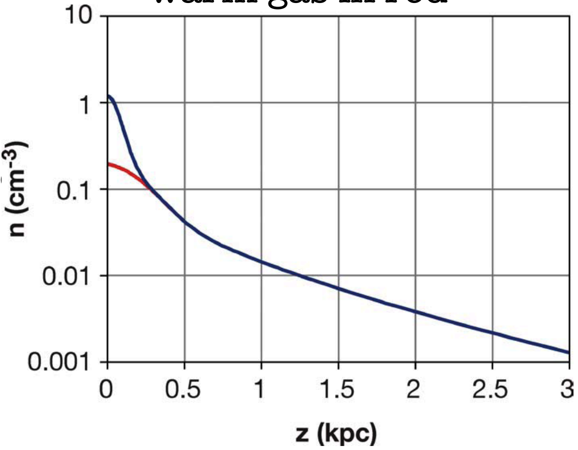
    $\rho(z) \sim 0.57 * 0.18 \exp[-(z/318\ \mathrm{pc})^2]$

    where z is the distance abov the disk midplane

    has a mean T~5000k

Roughly magnetic (~5μG), 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

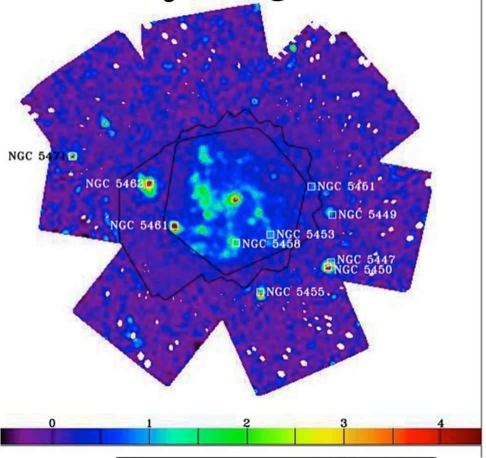


Cox+Reynolds ARA&A 1987 25,303

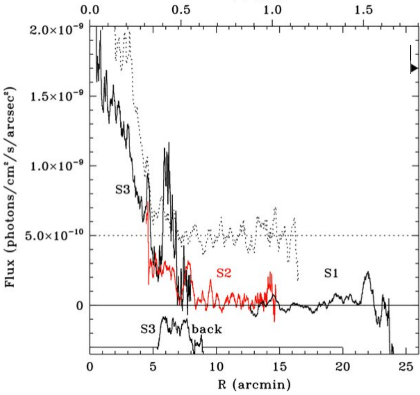
X-ray ISM in M101

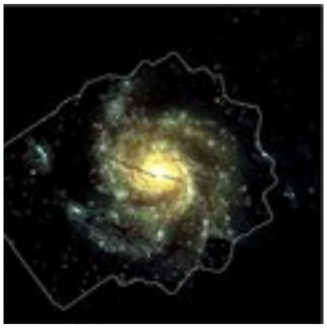
- Hot phase of ISM in M101- dominated by ionized oxygen OVII/ OVIII and T~2×10^6k is the temperature of the dominant component.
- The emission is centrally concentrated
- Such data exists for only a few objects

x-ray image



x-ray surface brightness





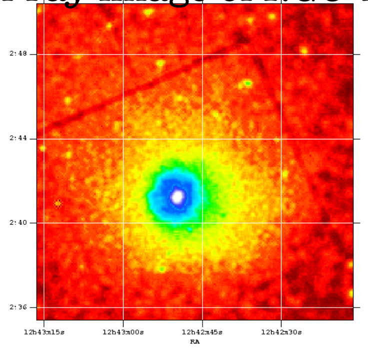
X-ray Emission from Star formation

- Star forming region in M33 (Chandra in blue HST in red)
- X-rays from hot gas produced by young stars+ SNR.

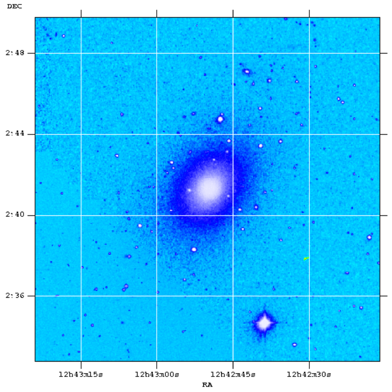
ISM In Ellipicals-pg 272 in S+G

- Predominately hot kT~10^6-10^7K 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

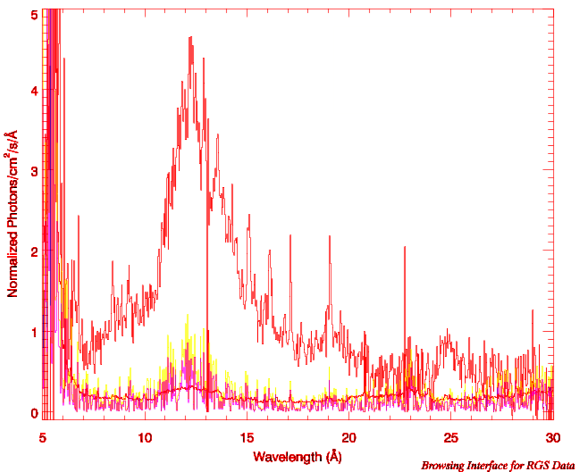


X-ray Spectral Diagnostics

- The strongest lines in the x-ray spectra of gas between 10^6-$2x10^7$ K are the L shell lines of Fe and the He-like triplets of N, O, Ne, Mg, Si,S
- The strength of the lines is very sensitive to temperature and roughly linearly sensitive to abundance
- Gas is optically thin and one can measure the electron temperature by measuring the shape of the continuum (not possible in UV,optical, IR)

X-ray Spectra of NGC1399

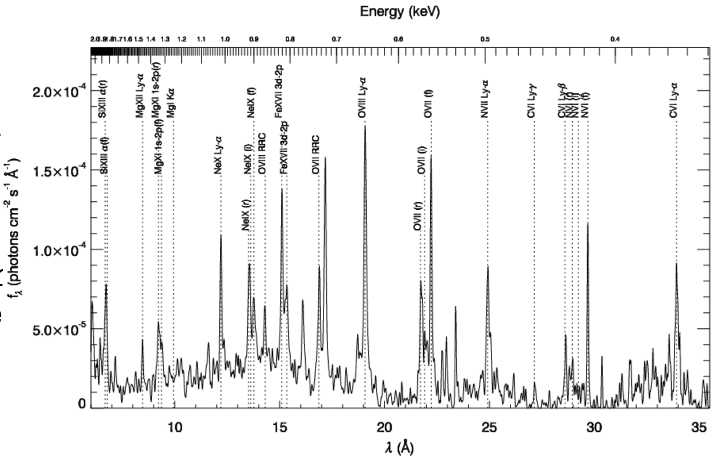
- At certain temperatures (~4-16x10^6k) the spectrum is dominated by Fe lines from the L shell whose energy is very sensitive to temperature.
- Thus x-ray images and spectra (obtained simultaneously with CCDs) get the density and temperature and estimates of the chemical composition of the ISM in ellipticals



wavelength Å

Hot Gas and Metallicity

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



- 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)

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

Image of x-ray source determines the gas density since L~Λ(T)Vn^2

Astro-H

- Will revolutionize studies of the hot ISM of elliptical galaxies

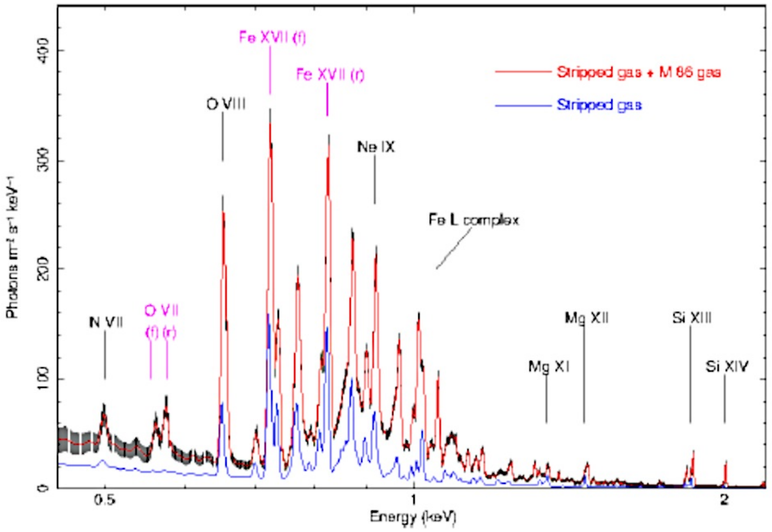
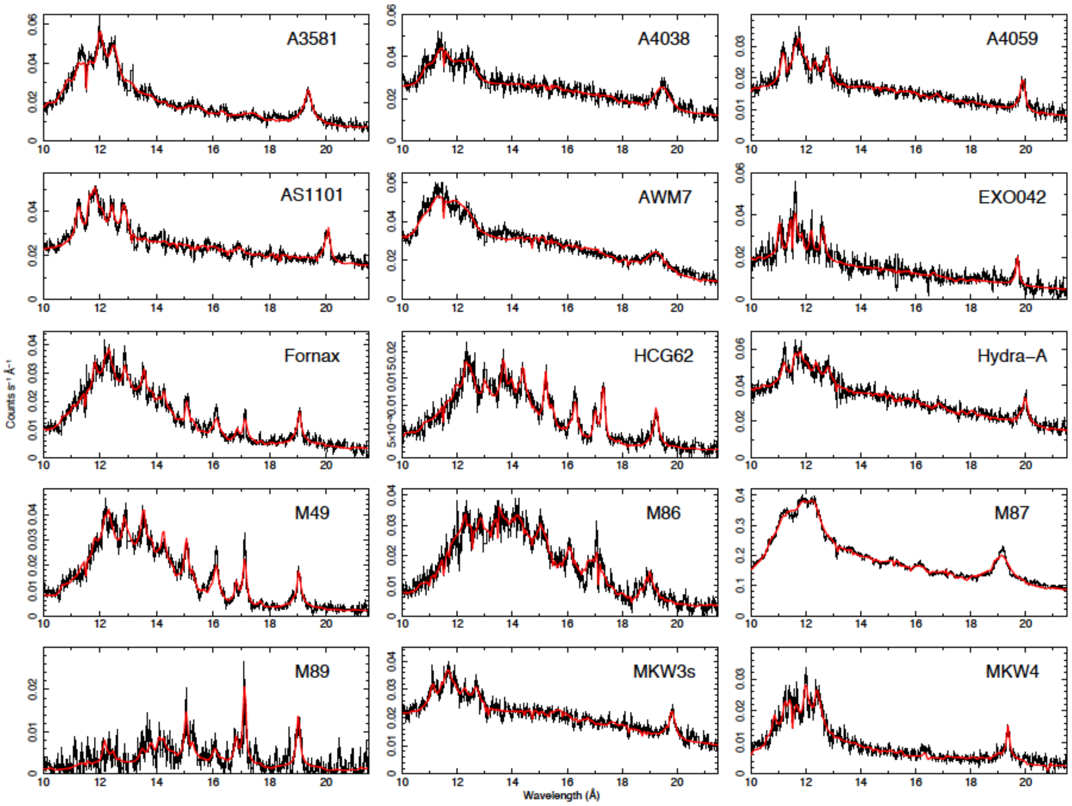


Figure 1: Simulated SXS spectrum of M 86 for an exposure of 75 ks. The model of the total emission is in red and the stripped gas is in blue. Both the resonance and forbidden lines of O VII will be detected. A turbulence of 100 km/s was adopted for all the emission components.



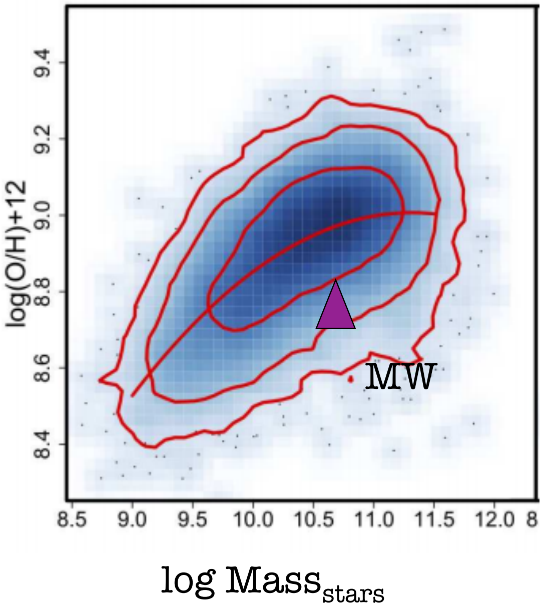
Why Metals are Important (sec 10.4 MBW)

- 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.

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~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

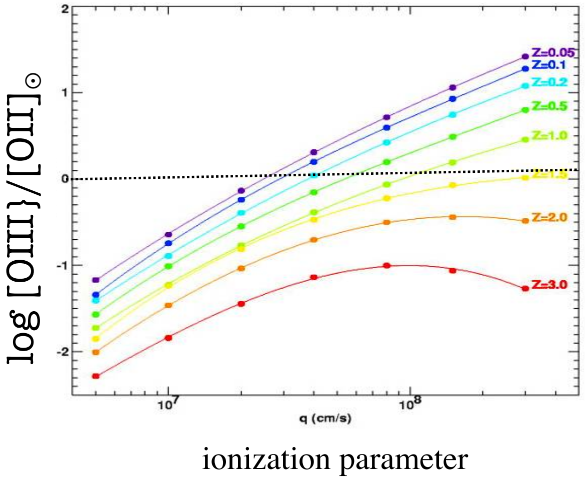


GAMA collaboration Foster et al 2012

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:($U \sim L/n_e r^2$)



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. (Kewley et al 2010)

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.