Amelie Saintonge & Barbara Catinella

2022, ARA&A, 60, 319

The cold interstellar medium of galaxies in the local universe

Resources:
Physics of the interstellar medium – Draine (book)
Optical astronomical spectroscopy – Kitchen (book)
The 3-phase ISM re-visited – Cox, 2005 ARA&A
Grad ISM course: http://www.tapir.caltech.edu/~chirata/ay102

There are usually considered to be 5 gas phases in the interstellar medium:

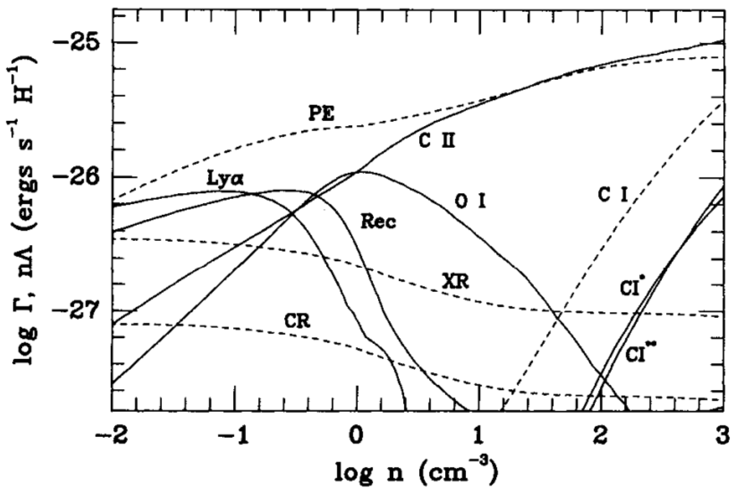
- The hot ionized medium (HIM, e.g. X-rays)
- The warm ionized medium (WIM, e.g. H alpha)
- The warm neutral medium (WNM, e.g. HI)
- The cold neutral medium (CNM, e.g. HI)
- The molecular medium (MM, e.g. H_2)

	MM	CNM	WNM	WIM	HIM
n (cm^{-3})	$10^2 - 10^5$	4–80	0.1–0.6	$\approx 0.2\ cm^{-3}$	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%	$\approx 30\%$	$\approx 20\%$	$\approx 50\%$
f_{mass}	$\approx 20\%$	$\approx 40\%$	$\approx 30\%$	$\approx 10\%$	$\approx 1\%$

Values for a typical star forming galaxy.

Why are there 2 neutral medium phases?

heating/cooling:



dashed lines: heating rates
PE: photoelectric heating from grains and PAHs
CR: cosmic ray heating
XR: soft X-ray heating
CI: heating by photoionization of CI

full lines: colling rates
fine structure lines
electron recombination lines
resonance and metastable lines
(e.g. Ly alpha)

Heating occurs if $\boldsymbol{\Gamma} > n\boldsymbol{\Lambda}$ i.e. $\boldsymbol{\Gamma} > (P/k)(\boldsymbol{\Lambda}/T)$
Cooling occurs if $\boldsymbol{\Gamma} < n\boldsymbol{\Lambda}$ i.e. $\boldsymbol{\Gamma} < (P/k)(\boldsymbol{\Lambda}/T)$

Recall P=nkT

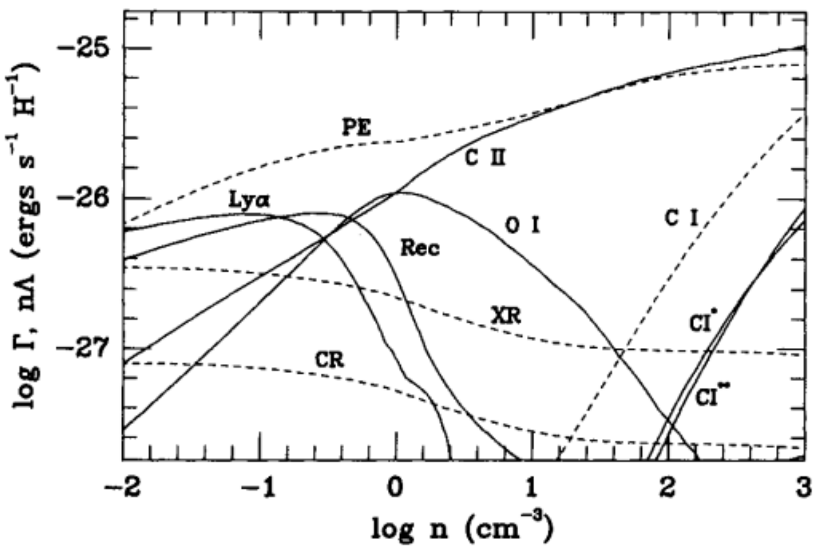
Equilibrium therefore occurs when $\boldsymbol{\Lambda}/T$ crosses $k\boldsymbol{\Gamma}/P$.

If $\boldsymbol{\Lambda}/T$ is increasing we have stability: small increase in T leads to increased cooling rate: equilibrium restored.

If $\boldsymbol{\Lambda}/T$ is decreasing we have instability: small increase/decrease in T leads to runaway heating/cooling.

Why are there 2 neutral medium phases?

heating/cooling:



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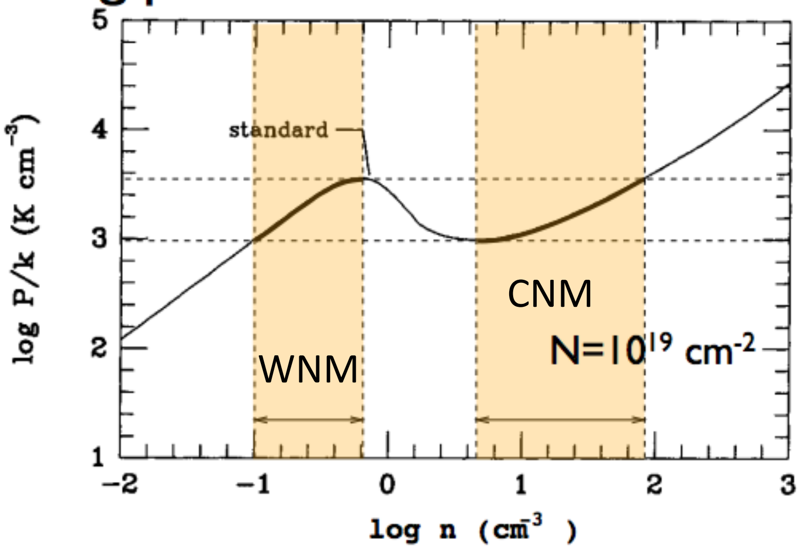
resulting pressure:

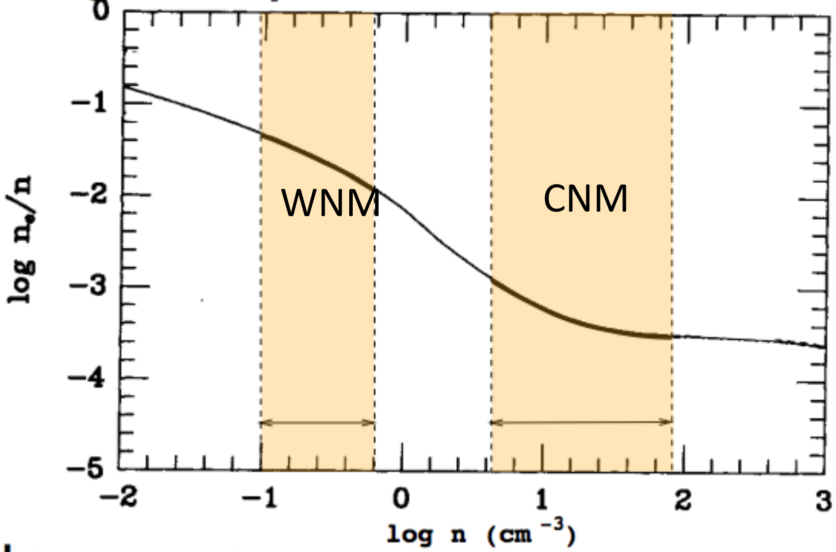


pressure vs. density:
- only regions with d(log P)/d(log n) >0 are stable
- assuming pressure equilibrium: 2 stable phases.

CNM: n=[4.2 80] cm^{-3}
WNM: n=[0.1, 0.59] cm^{-3}

Wolfire et al. (1995)

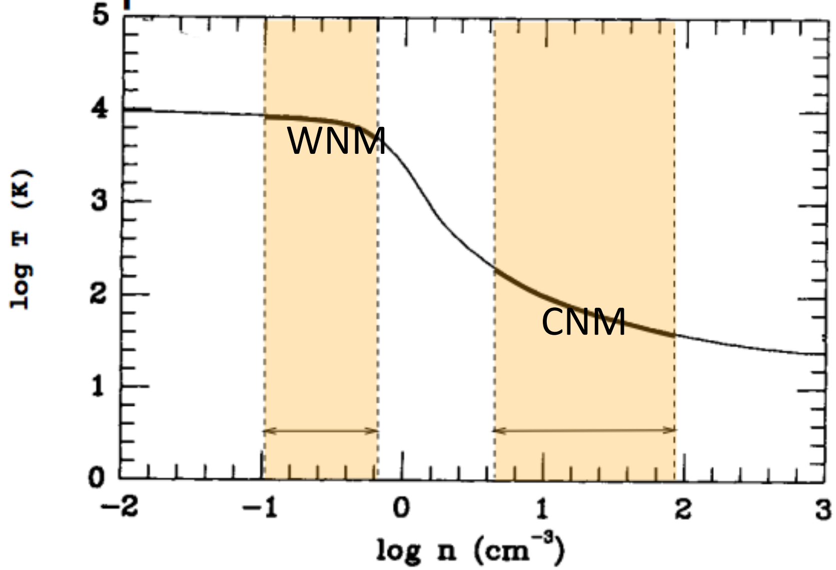
resulting density:



electron fraction vs. density:

CNM: n=[1.3 10^{-3}, 3.2 10^{-4}]
WNM: n=[4.6 10^{-2}, 1.3 10^{-2}]

...and temperature



temperature vs. density:

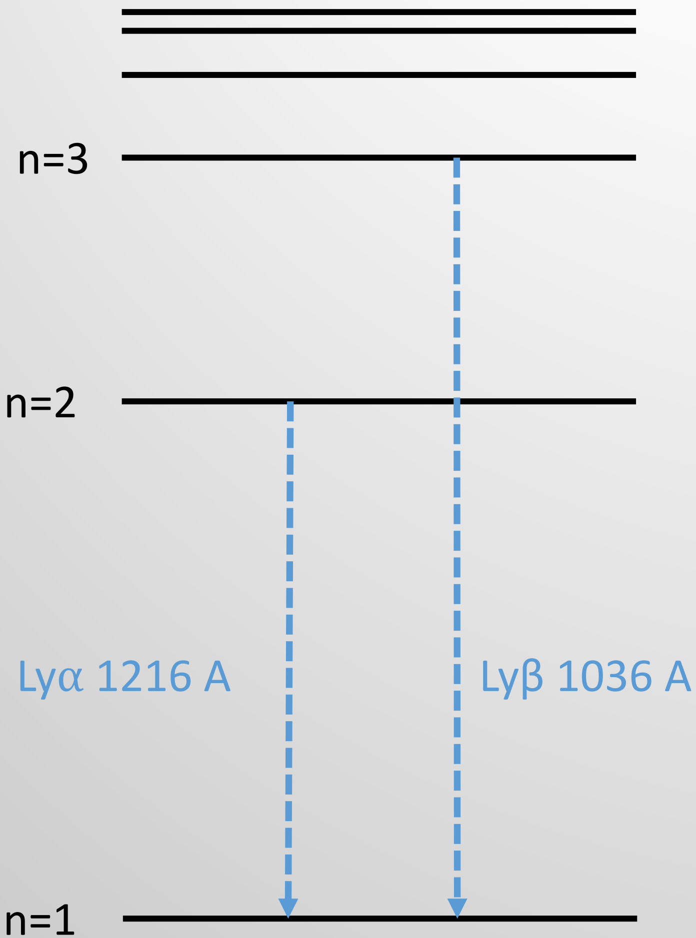
CNM: n=[41 210] K
WNM: n=[5500 8700] K

these are the two phases of the ISM

Wolfire et al. (1995)

Both phases contribute to emission and absorption of HI

Observing the neutral medium – mostly HI

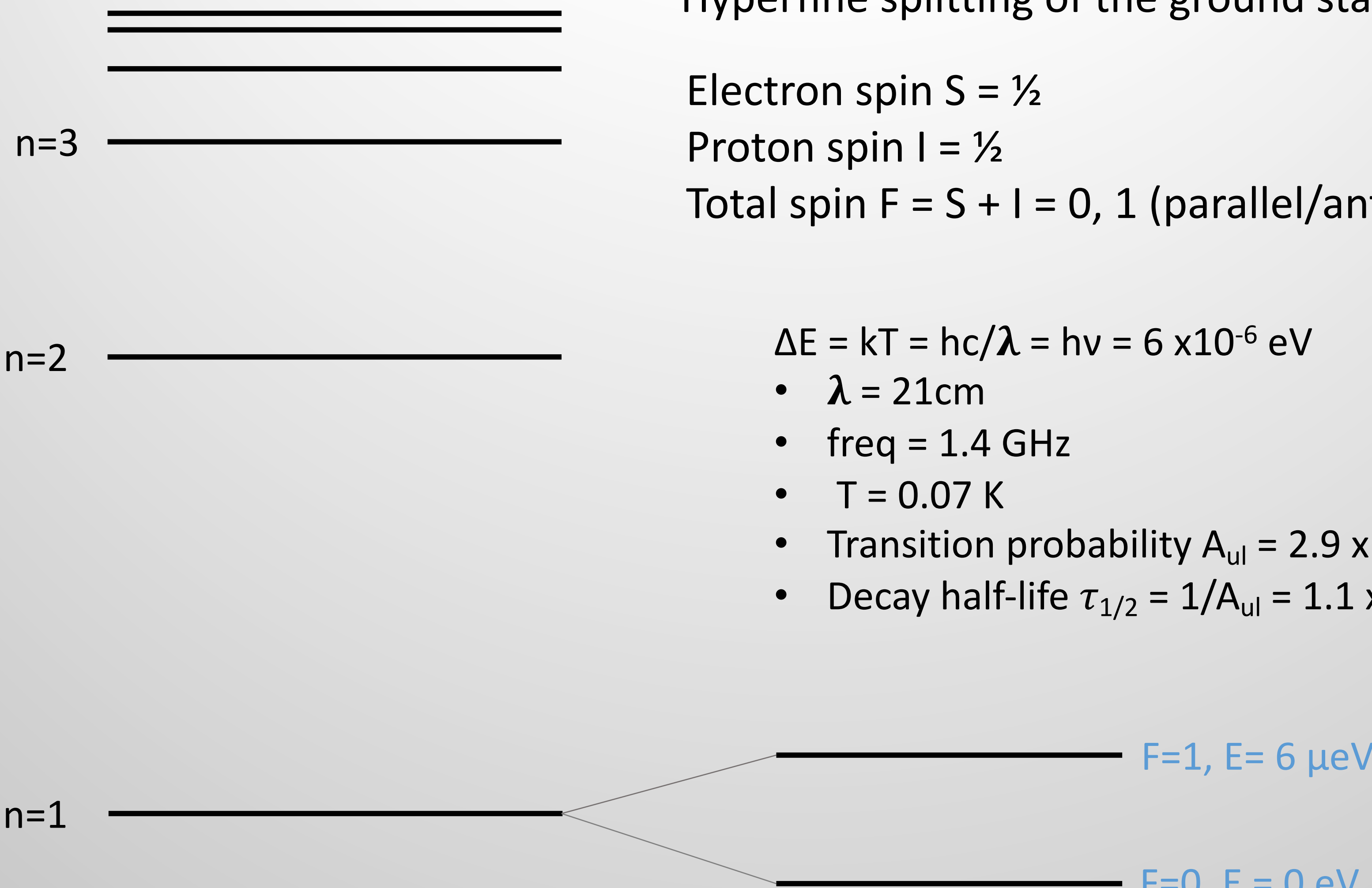


Lyman series transitions in the UV:

- Hard to observe
- Easily extinguished (in emission)
- Easily scattered (in emisson)

… but readily observed in absorption, especially when redshifted at z>1.6 (more on this in a future lecture).

Observing HI



Hyperfine splitting of the ground state

Electron spin S = ½
Proton spin I = ½
Total spin F = S + I = 0, 1 (parallel/anti-parallel)

$\Delta E = kT = hc/\lambda = h\nu = 6 \times 10^{-6}$ eV

- λ = 21cm
- freq = 1.4 GHz
- T = 0.07 K
- Transition probability $A_{ul} = 2.9 \times 10^{-15}\ s^{-1}$
- Decay half-life $\tau_{1/2} = 1/A_{ul} = 1.1 \times 10^{7}$ years

Single dish observations of HI 21cm

Workhorse telescopes for extragalactic surveys in the 2000-2020s.

Parkes telescope D = 64 metres
HIPASS survey, Barnes et al. (2001)
5000 galaxies z<0.04

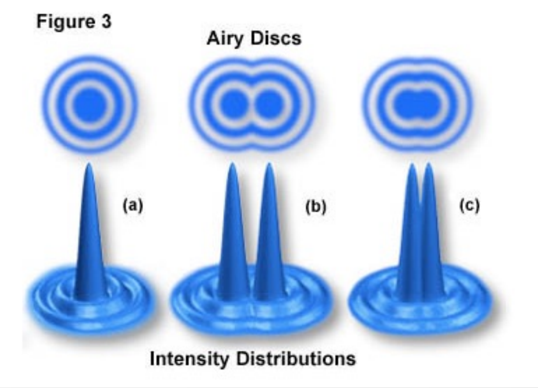
Arecibo telescope (RIP) D = 305 metres

- ALFALFA survey, Haynes et al. (2018)
  31,500 galaxies z<0.06. Blind & shallow.
- GASS, Catinella et al. (2013)
  800 galaxies at z<0.05. SDSS, deep.

Single dish observations of HI 21cm

Five hundred-metre Aperture Spherical Telescope (FAST; China)

Single dish telescopes suffer from poor resolution, so most measurements of HI are 'global'.

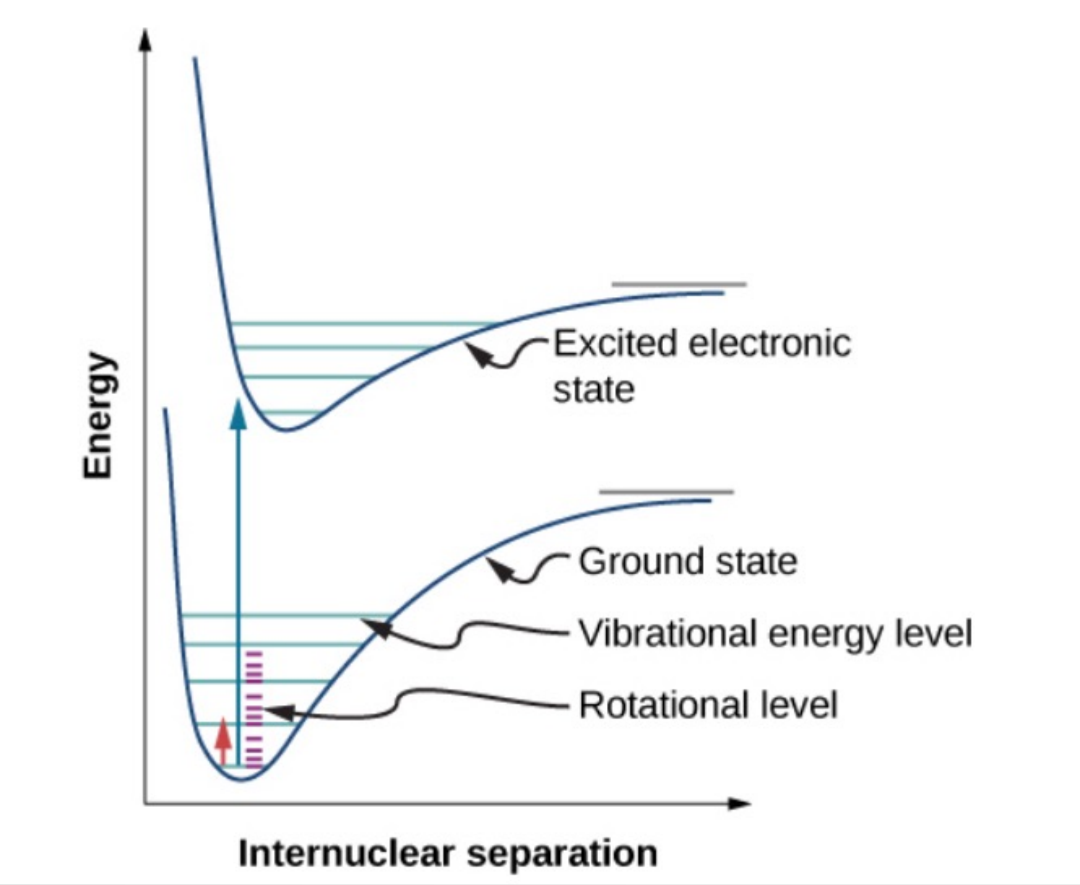


Diffraction limit equation:
$\Delta\theta$ (rad) = 1.22 λ/d
~ several arcmin

$$M_{\rm HI}[M_\odot] = \frac{2.356\times10^5}{(1+z)^2} D_L^2 \int S_\nu \, dv$$

D_L in Mpc
S_ν in Jy; 1 Jy = 10^{-23} erg/s/cm2/Hz
v in km/s

Observing the molecular medium

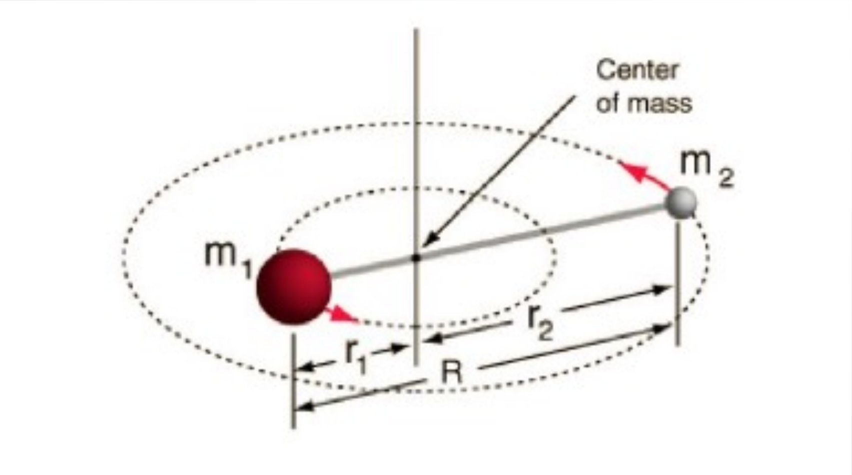


Molecules not only have atomic, but also rotational and vibrational transitions.

- Electronic transitions in UV.
- Vibrational transitions in the mid-IR.
- Rotational transitions in the mm/radio

Of these, the rotational transitions are those most readily accessible from the ground (and brightest).

Rotational spectroscopy



Diatomic molecules usually modelled as "dumb bell" rigid rotators. Schrodinger's equation for this simple model leads to angular momentum, p, being quantized as

$$p = \frac{h}{2\pi}\sqrt{J(J+1)}$$

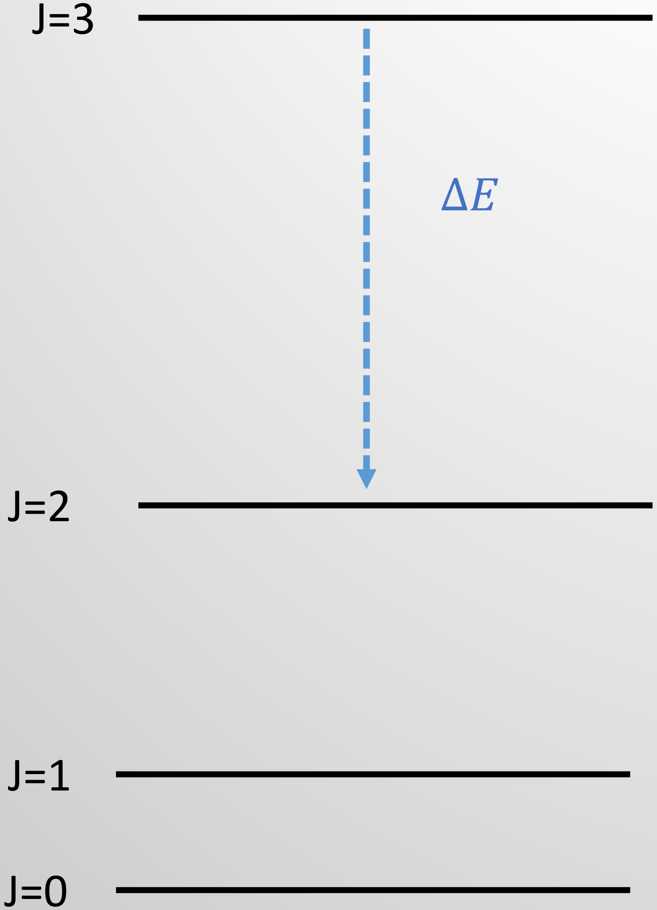
The energy of the corresponding J level uses the classical formula for rotational energy (recalling that $p = I\omega$ where I is the moment of inertia and ω is the angular velocity):

$$E = I\omega^2/2 = \frac{h^2\,J(J+1)}{8\,\pi^2 I}$$

Sometimes written in terms of rotational constant $B = \frac{h^2}{8\,\pi^2 I}$ i.e. $E = B\,J(J+1)$

For a diatomic molecule the moment of inertia is $I = R^2\,\frac{m1.m2}{m1+m2}$

Rotational spectroscopy



Rotational dipole selection rules:

1) Must have dipole moment
2) ΔJ = +/- 1

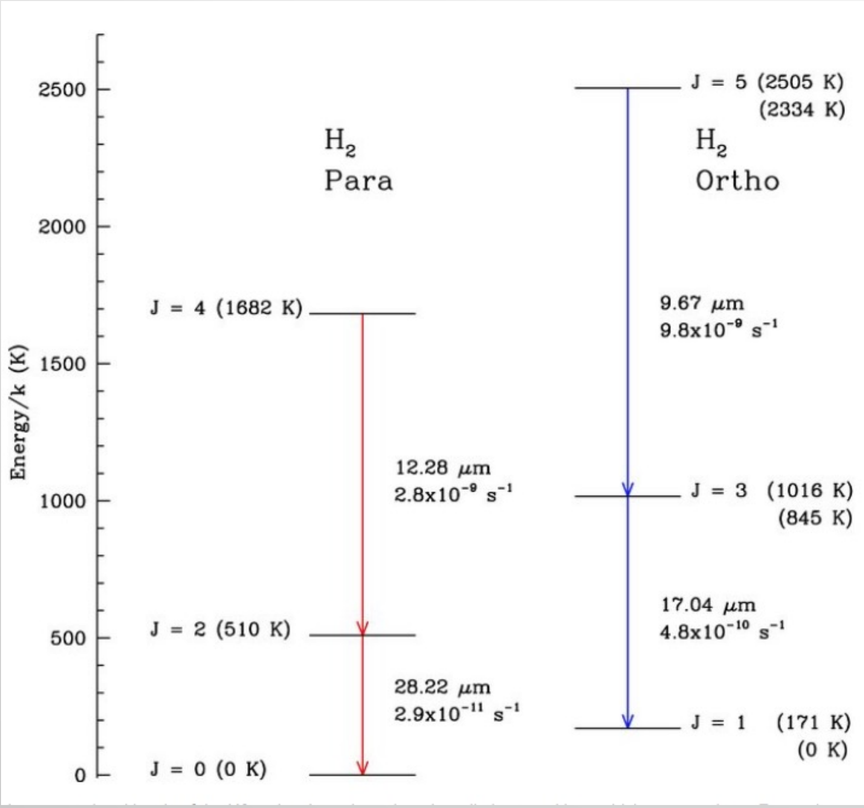
From the equation for E and the selection rule J +/- 1 we derive

$$\Delta E = \frac{h^2(J+1)}{4\pi^2 I}$$

Note that energy levels *increase* with J, which is opposite to the structure for the atomic case (e.g. Bohr atom with energy proportional to $1/n^2$).

Rotational spectroscopy – problems with H_2

- No dipole moment – rotational dipole transitions are forbidden.
- This issue aside, the lowest energy state for H_2 is 175K – most of the CNM is colder.

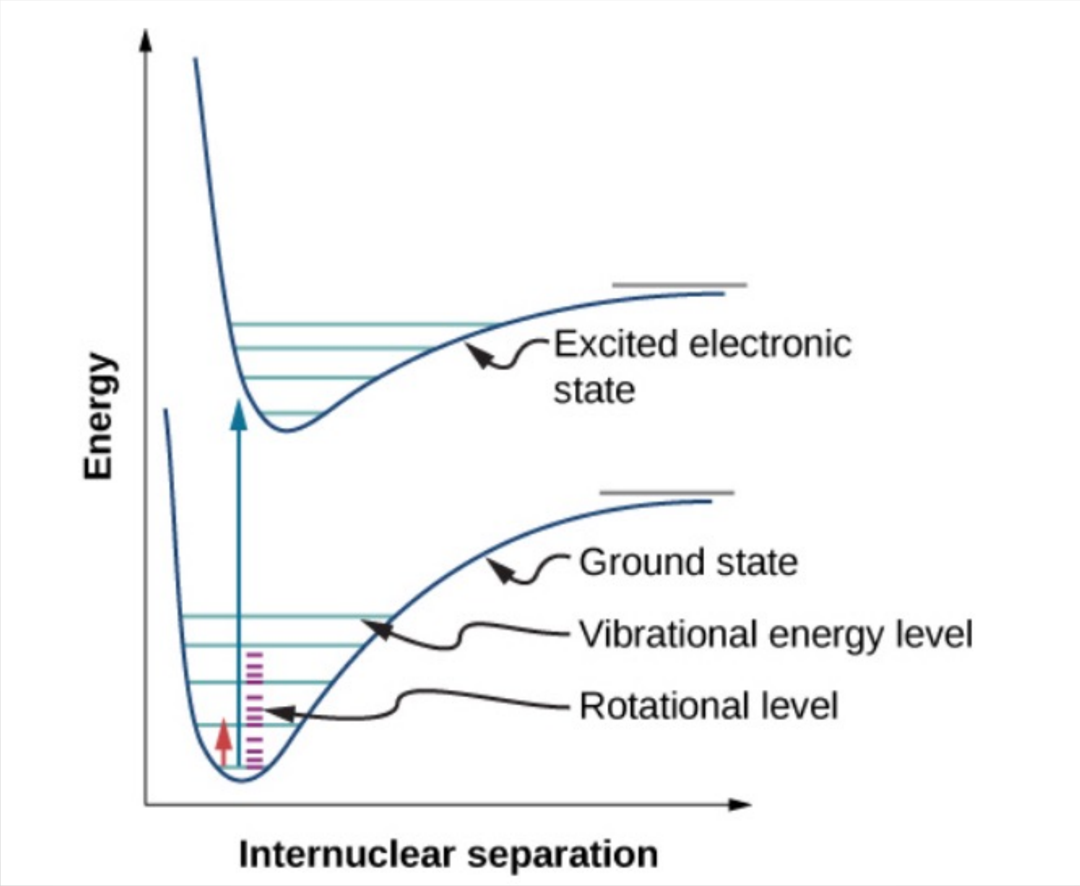


- Rotational quadrupole transitions (ΔJ = +- 2) are allowed but …
- the lowest energy transition is very weak due to long spontaneous decay time (~100 years).
- Inconvenient wavelength (28 microns) in far-IR
- Requires excitation temperature of 510K (most molecular clouds are not this warm).

Vibrational and Rotational-vibrational emission

Both v and (usually) J change (within the same electronic state).

Dipole transitions (ΔJ=+-1) still forbidden for H_2 due to lacking a dipole moment, but quadrupole (ΔJ =0, +-2) allowed.



Vibrational and Rotational-vibrational emission

Both v and (usually) J change (within the same electronic state).

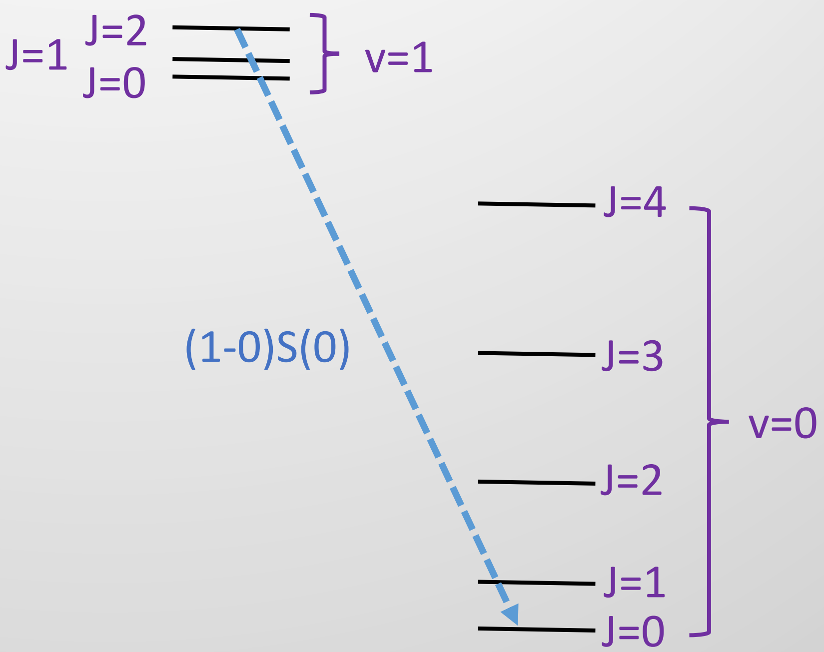
Dipole transitions (ΔJ=+-1) still forbidden for H_2 due to lacking a dipole moment, but quadrupole (ΔJ =0, +-2) allowed.

Notation:

$(v_{up} - v_{low})$ O/P/Q/R/S (J_{low})

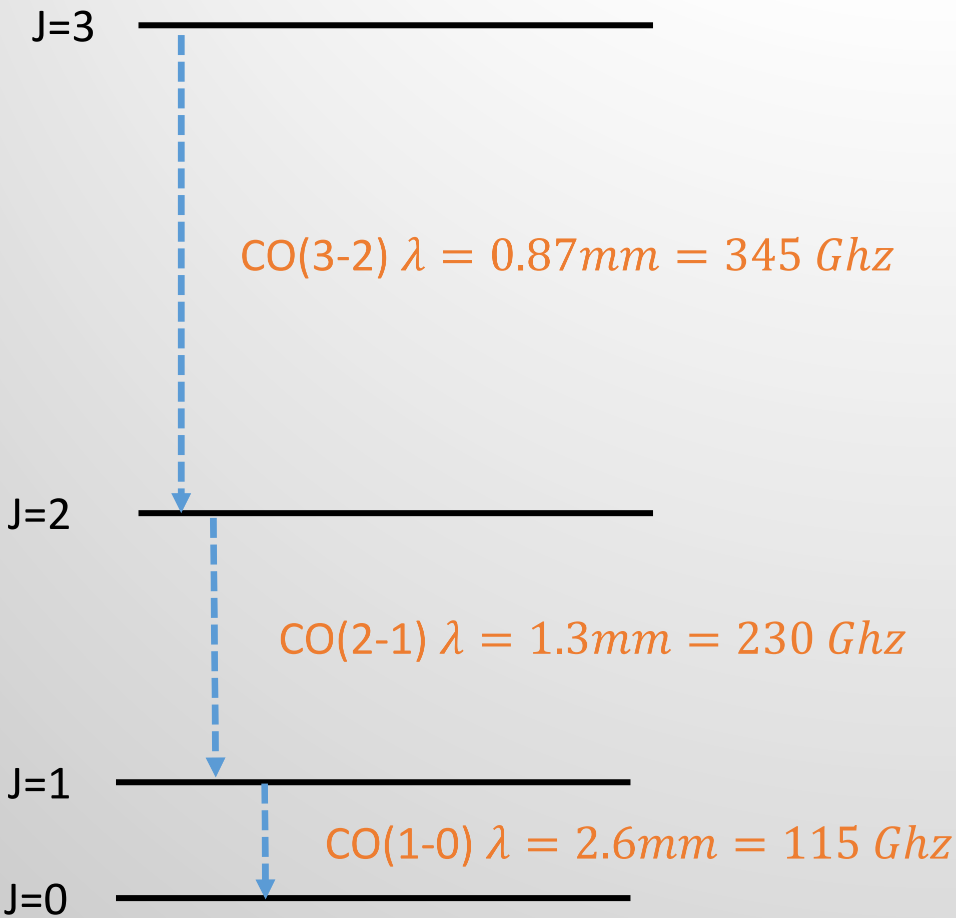
Where:

O branch is for ΔJ = +2
P branch is for ΔJ = +1
Q branch is for ΔJ = 0
R branch is for ΔJ = -1
S branch is for ΔJ = -2



Lowest vibrational state for H_2 is (1-0)S(0) at 2.2 microns requiring E/k ~ 6500 K -> very warm

CO as an alternative to H_2

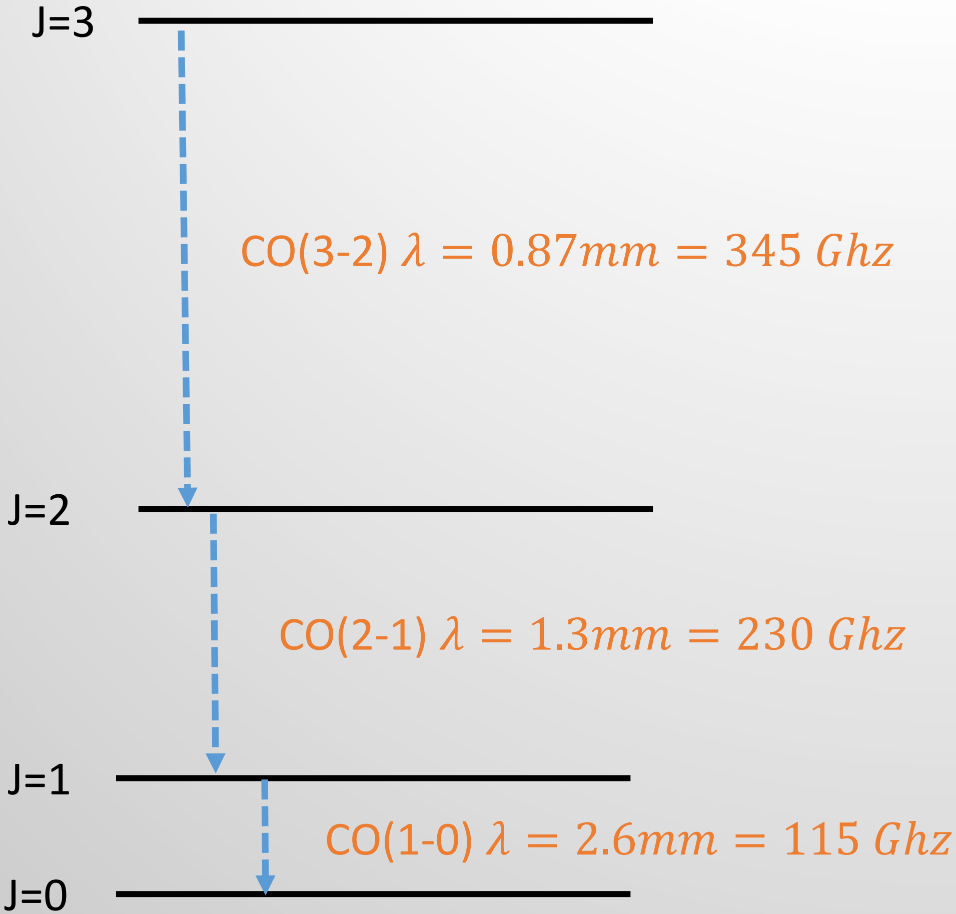


$$\Delta E = \frac{h^2(J+1)}{4\pi^2 I}$$

Benefits of CO

- Has a permanent dipole moment (rotational dipole transitions allowed)

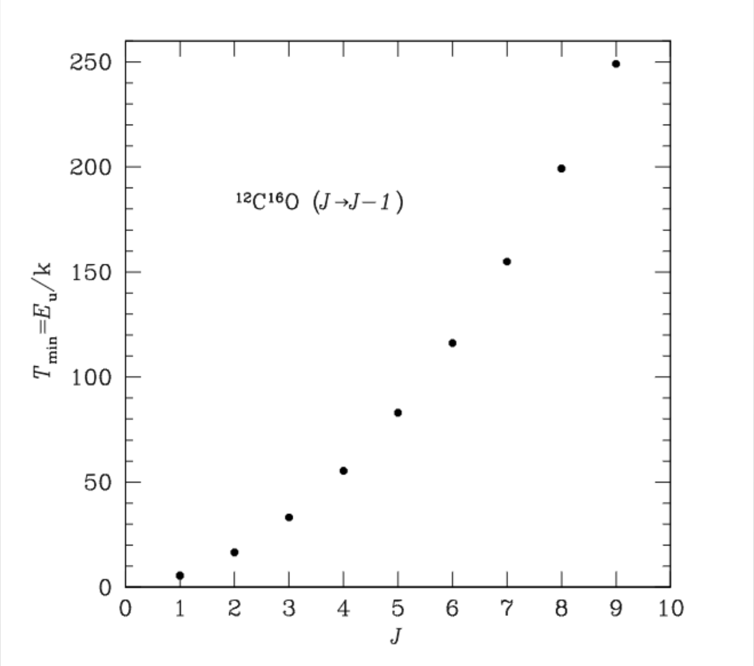
CO as an alternative to H_2



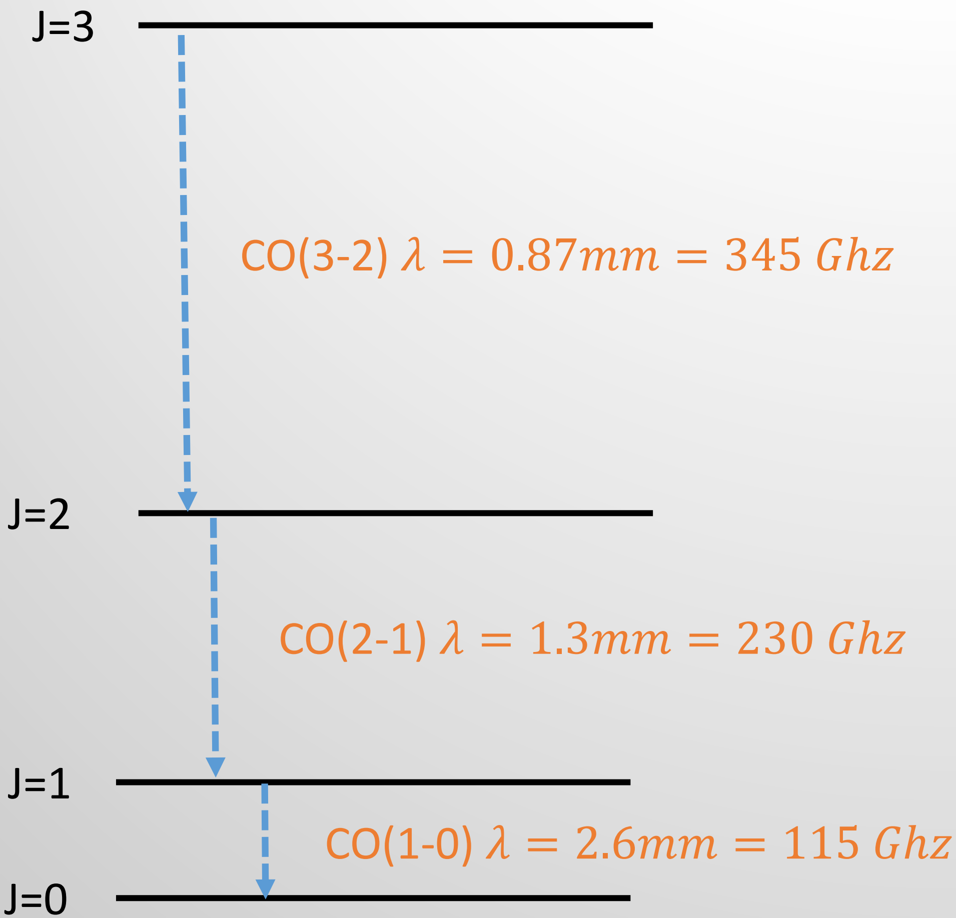
$$\Delta E = \frac{h^2(J+1)}{4\,\pi^2 I}$$

Benefits of CO

- Has a permanent dipole moment (rotational dipole transitions allowed)
- Lowest energy level corresponds to E/k ~ 5K (easily excited)

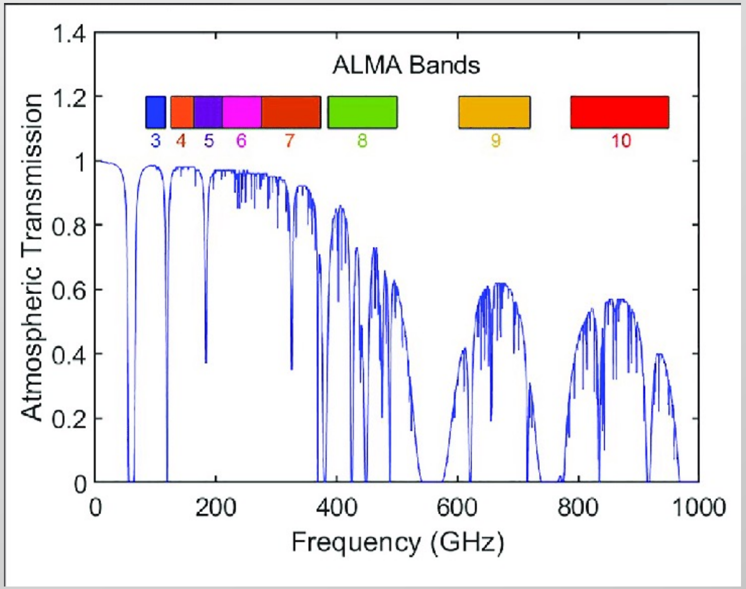


CO as an alternative to H_2

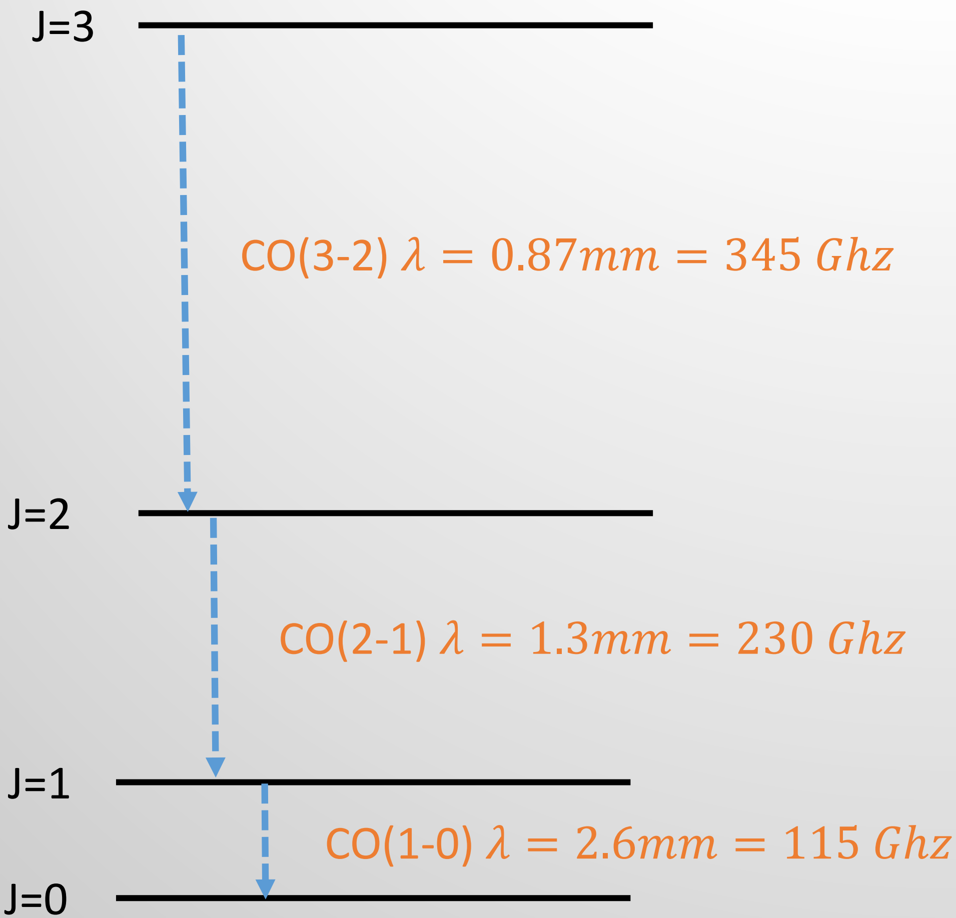


Benefits of CO

- Has a permanent dipole moment (rotational dipole transitions allowed)
- Lowest energy level corresponds to E/k ~ 5K (easily excited)
- Lowest energy level in a convenient atmospheric window.



CO as an alternative to H_2



Benefits of CO

- Has a permanent dipole moment (rotational dipole transitions allowed)
- Lowest energy level in a convenient atmospheric window.
- Lowest energy level corresponds to E/k ~ 5K (easily excited)
- Low critical density of ~ 2000 cm^{-3}

Jargon alert: critical density

In addition to an E/k threshold (e.g. 5K for CO(1-0)), there is also a critical density which essentially requires sufficient collisions (with H_2) compared with the spontaneous decay rate to keep the J+1 level populated.

$$n_{crit} = \frac{A_{UL}}{\sigma v}$$

Where A_{UL} is the spontaneous emission coefficient (s^{-1}), σ is the collision cross section (cm^2) and v is the velocity (cm/s).

$$A_{UL} = \frac{64\pi^4}{3hc^3}\nu_{UL}^3|\mu_{UL}|^2$$

Where μ is the mean electric dipole. Notice that A_{UL} is proportional to the frequency cubed so higher J transitions have higher critical densities.

Species	Transition	č (GHz)	Einstein A (s^{-1})	n_{crit} (cm^{-3})
CO	J = 1-0	115.27	7.2×10^{-8}	2.1×10^3
	J = 2-1	230.54	6.9×10^{-7}	1.1×10^4
	J = 3-2	345.80	2.5 × 10−6	3.6×10^4
	J = 4-3	461.04	6.1 × 10−6	8.7×10^4
	J = 5-4	576.27	1.2 × 10−5	1.7×10^5
	J = 6-5	691.47	2.1 × 10−5	2.9×10^5

Aside: critical density

Other molecules other than CO used if you want to trace the truly dense gas

Molecule	$j \rightarrow k$	ν_{jk} (GHz)	E_j/k (K)	A_{jk} (s^{-1})	$n_{ph}(T_{cmb})$	$n_{\mathrm{crit}}^{\mathrm{thin,nobg}}(T_k)$ cm^{-3} 10 K	20 K	50 K	100 K
HCO^+	1–0	89.189	4.28	4.3E-5	0.264	6.8E+4	4.5E+4	2.9E+4	2.3E+4
	2–1	178.375	12.84	4.1E-4	0.046	5.6E+5	4.2E+5	2.8E+5	2.2E+5
	3–2	267.558	25.68	1.5E-3	0.009	1.6E+6	1.4E+6	1.0E+6	8.1E+5
	4–3	356.734	42.80	3.6E-3	0.002	3.6E+6	3.2E+6	2.5E+6	2.0E+6
$H^{13}CO^+$	1–0	86.754	4.16	3.9E-5	0.279	6.2E+4	4.1E+4	2.7E+4	2.0E+4
	2–1	173.507	12.49	3.7E-4	0.050	5.1E+5	3.8E+5	2.6E+0	2.0E+5
	3–2	260.255	24.98	1.3E-3	0.011	1.5E+6	1.3E+6	9.5E+5	7.3E+5
	4–3	346.998	41.63	3.3E-3	0.002	3.4E+6	2.9E+6	2.3E+6	1.8E+6
N_2H^+	1–0	93.174	4.47	3.6E-5	0.242	6.1E+4	4.1E+4	2.6E+4	2.0E+4
	2–1	186.345	13.41	3.5E-4	0.040	5.0E+5	3.7E+5	2.6E+5	1.9E+5
	3–2	279.512	26.83	1.3E-3	0.007	1.4E+6	1.2E+6	9.2E+5	7.1E+5
	4–3	372.673	44.71	3.1E-3	0.001	3.2E+6	2.8E+6	2.2E+6	1.7E+6
HCN	1–0	88.632	4.25	2.4E-5	0.268	4.7E+5	3.0E+5	1.7E+5	1.1E+5
	2–1	177.261	12.76	2.3E-4	0.047	4.1E+6	2.8E+6	1.6E+6	1.1E+6
	3–2	265.886	25.52	8.4E-4	0.010	1.4E+7	1.0E+7	5.7E+6	3.8E+6
	4–3	354.505	42.53	2.1E-3	0.002	3.0E+7	2.3E+7	1.4E+7	9.1E+6

Shirley (2015)

Measuring the molecular mass

The CO line luminosity is usually seen expressed in one of two ways:

$$L_{CO} = 1.04 \times 10^{-3}\, S_{CO}\, \nu_{obs}\, D_L^2 \qquad \text{in units of } L_\odot$$

Where S_{CO} is the velocity integrated line flux in Jy km/s, D_L is the luminosity distance in Mpc and $\nu_{obs} = \nu_{rest} /(1+z)$ is the observed frequency in GHz.

Perhaps more commonly, the line luminosity is often written as a product of the source brightness (radio astronomers like to use temperature units for this) per area:

$$L'_{CO} = 3.25 \times 10^{7}\, S_{CO}\, \nu_{obs}^{-2}\, D_L^2\, (1+z)^3 \qquad \text{in units of K km/s pc}^{-2}$$

See Solomon & vanden Bout (2005) for more details

Measuring the molecular mass

Next we need to convert the CO line luminosity to an H_2 mass by using a "conversion factor" that is expressed in one of two ways, with conversion factors of different units and assigned either α_{CO} or X_{CO} to distinguish them.

1). Most commonly we want the total mass of molecular gas so use

$$M(H_2) = \alpha_{CO} L'_{CO}$$

Where α_{CO} has units of $M_\odot$ (K km/s pc^{-2})$^{-1}$ and $M(H_2)$ has units of $M_\odot$. "Galactic" value of $\alpha_{CO} = 4.3\ M_\odot\ (\mathrm{K\ km/s\ pc^{-2}})^{-1}$ (accounts for 36% correction for He and metals; otherwise $\alpha_{CO} = 3.2\ M_\odot\ (\mathrm{K\ km/s\ pc^{-2}})^{-1}$).

2) Alternatively, for column densities we can use

$$N(H_2) = X_{CO}\ I_{CO}$$

Where I_{CO} is the integrated intensity in units of K km/s (compared with a the L'_{CO} luminosity that has units of K km/s pc^{-2}), X_{CO} has units of (K km/s)$^{-1}$cm^{-2} and $N(H_2)$ has units of cm^{-2}. "Galactic" value of $X_{CO} = 2 \times 10^{20}\ (\mathrm{K\ km/s})^{-1}\mathrm{cm}^{-2}$.

See Bolatto et al. (2013) for a whole review on conversion factors

Single dish observations of CO

Five College Radio Astronomy Observatory (RIP) 14-metre dish located in Massachusetts. FCRAO survey of 300 nearby galaxies: Young et al. (1985).

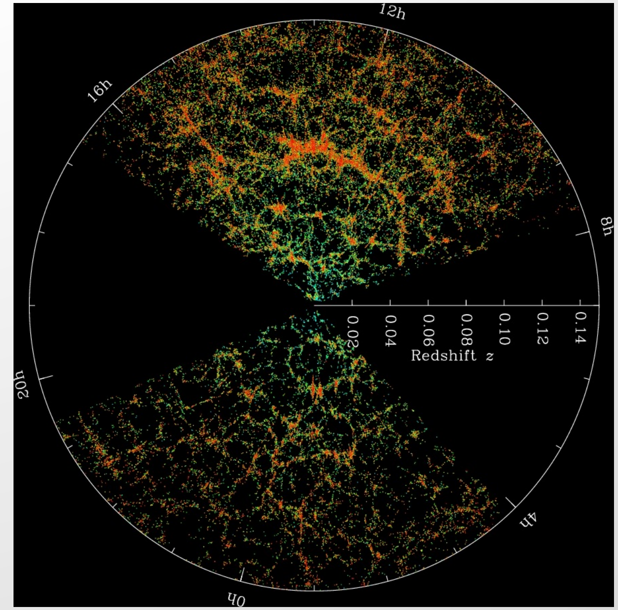
Resolution ~ 45 arcsec

IRAM 30-metre Pico Veleta (Spain). CO Legacy Database for GASS (COLDGASS): Saintonge et al. (2017)

Resolution ~ 22 arcsec

Larger dishes start to require aperture corrections.

Complementary optical spectroscopic observations



The Sloan Digital Sky Survey (SDSS) has been the workhorse spectroscopic survey of the 21st century.

2.5-metre telescope at Apache Point in New Mexico.

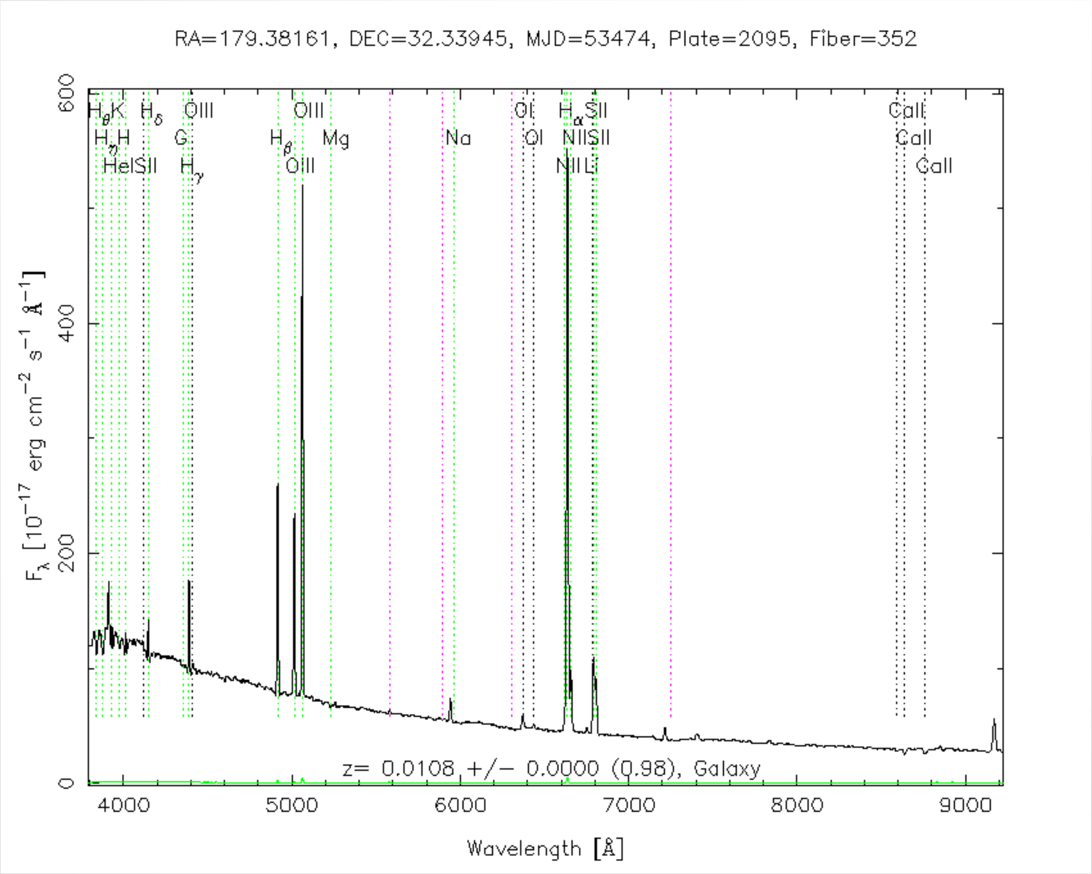
Observations begin in 2000. Currently SDSS is in its 5th generation of surveys.

Imaging (*ugriz*) and fibre fed spectroscopy for ~ 1 million galaxies.

2.5” fibre covers 2.5 kpc for galaxy at z=0.05. Aperture corrections needed for global values.
(useful to remember: at z=0.05 1” ~ 1 kpc)

All data become public.

Star formation rate from optical spectroscopy



Step 1: Correct spectrum for Galactic extinction.

Step 2: Correct spectrum for internal extinction.

Step 3: Correct Balmer emission line fluxes for stellar absorption.

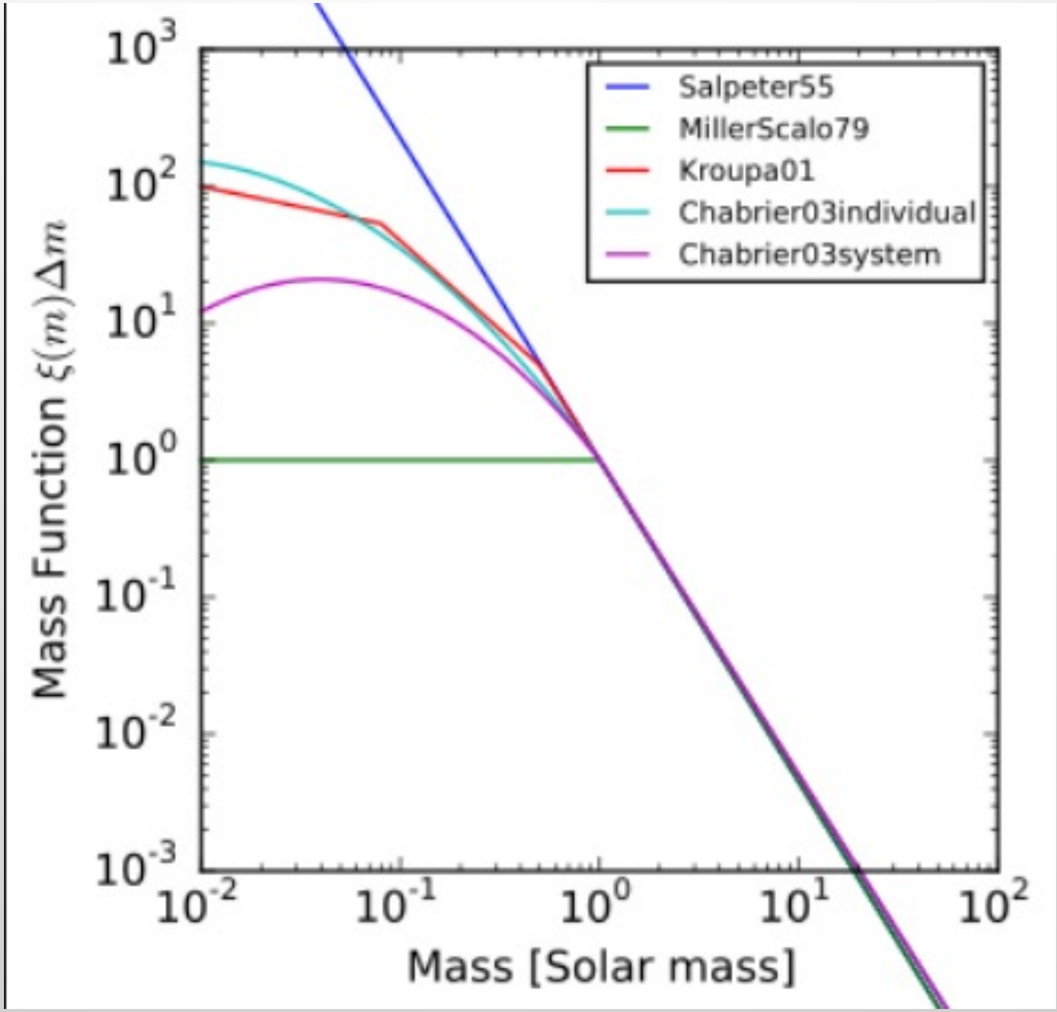
Step 4: $L_{H\alpha} = F_{H\alpha} * 4\pi D_L^2$

Step 5: For a Kroupa IMF
$\log SFR (M_\odot/yr) = \log L_{H\alpha} (erg/s) - 41.27$

Star forming galaxy dominated by strong emission lines (from HII regions) and blue continuum due to the presence of hot young stars.

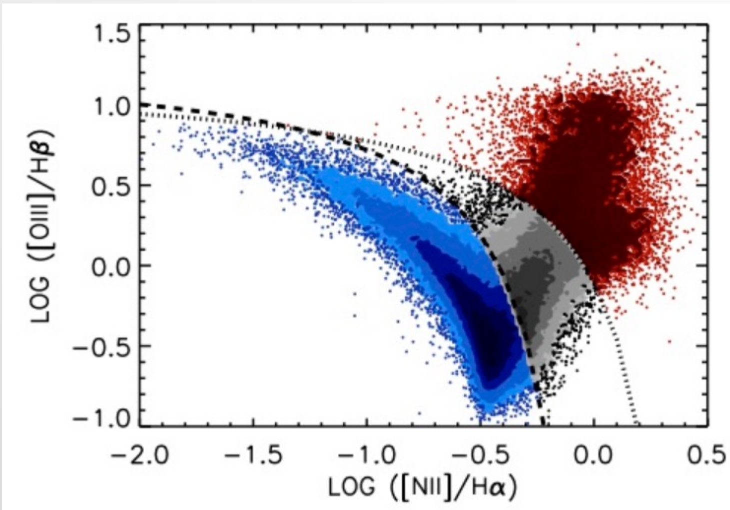
See Kennicutt & Evans (2012) ARA&A for a review on SFR indicators

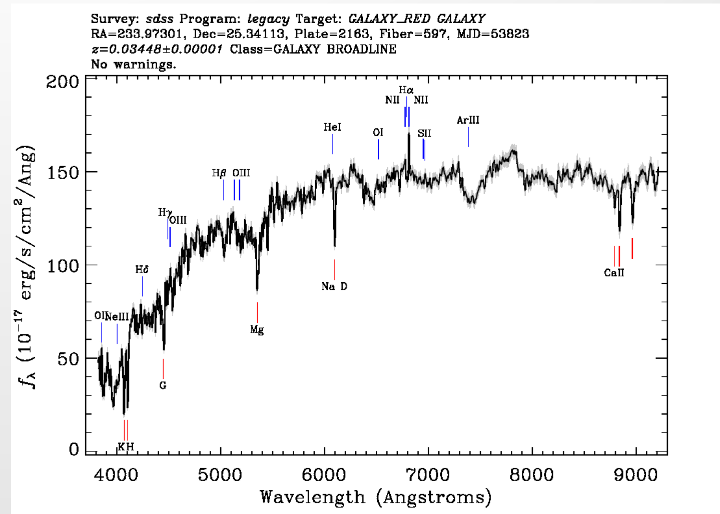
Jargon alert: The initial mass function (IMF) describes the distribution of stellar masses in a stellar population at birth. The choice of IMF impacts conversion of observed quantities to SFR and stellar mass.



Star formation rate from optical spectroscopy

Two main situations when Hα can't be used: 1) Low SFR galaxies (emission lines are weak), 2) AGN – the Hα line is contaminated

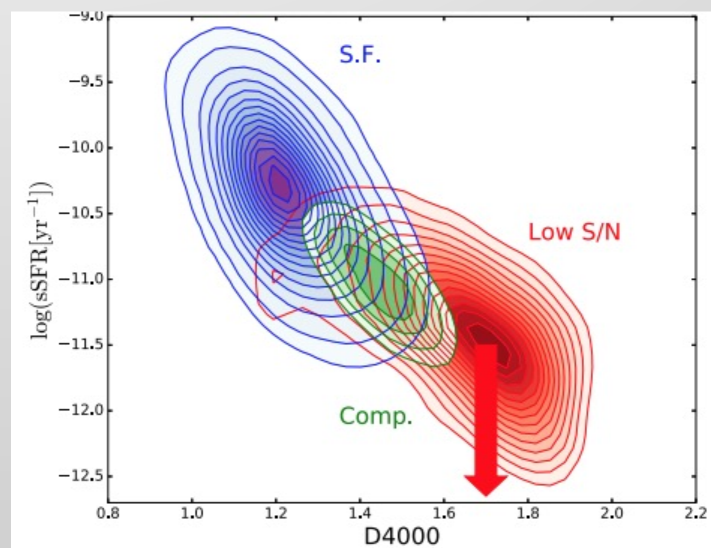




Solution: Measure 4000A (Balmer) break (AKA D4000). Calibrated with star forming galaxies. Jargon alert:

Specific SFR = sSFR = SFR/M_*

E.g. Bluck et al. (2019, 2020)



Also measured/derived from optical spectrum:

- Stellar mass in units of $M_\odot$ via modelling of stellar populations (see review by Courteau et al 2014). SPS fitting (many public codes available) yields a M/L ratio, which can then be multiplied by the observed luminosity to yield a stellar mass.

- Stellar population fitting also gives stellar ages….

- … and stellar metallicities.

- Gas phase metallicity quoted as 12 + log(O/H) where solar metallicity = 8.69 (more on measuring metallicities in a future lecture). Measured on a log scale, e.g. 12 +log(O/H) = 7.69 is 1/10 solar.

Table 2
SPS Grid Parameters

Parameter	Description	Range of values
τ	*e*-folding time	$8 \leq \log(\tau/\mathrm{yr}) \leq 10$ in 16 steps
Z	stellar metallicity	$-1.8 \leq \log(Z/Z_\odot) \leq 0.2$ in 11 steps
E(B−V)	color excess	$0 \leq \mathrm{E(B-V)} \leq 1$ in 21 steps
t	population age	$8 \leq \log(t/\mathrm{yr}) \leq 10.1$ in 43 steps
IMF	stellar IMF	Chabrier 2003
$k(\lambda)$	extinction law	Calzetti et al. 2000

Note. — Metallicities are computed adopting $Z_\odot = 0.019$. See Section 3.1 for details of the SPS grid construction.

Example stellar population grid from Mendel et al. (2013).

See Conroy et al. (2013) for a detailed review of stellar population fitting.

Scaling relations: The Kennicutt-Schmidt relation

Schmidt (1959).

The expected relation between the gas and SFR rate can be derived simplistically by arguing that

1) stars form with a characteristic timescale equal to the free–fall time in the gas disk

$$\rho_{SFR} \propto \frac{\rho_{gas}}{\tau_{ff}}$$

2) The freefall time depends inversely on the square root of the gas volume density

$$\tau_{ff} \propto \rho_{gas}^{-0.5} \qquad \rho_{SFR} \propto \rho_{gas}^{1.5}$$

Observationally, we measure the surface density, not volume density and aspire to measure directly the value of the exponent *N:*

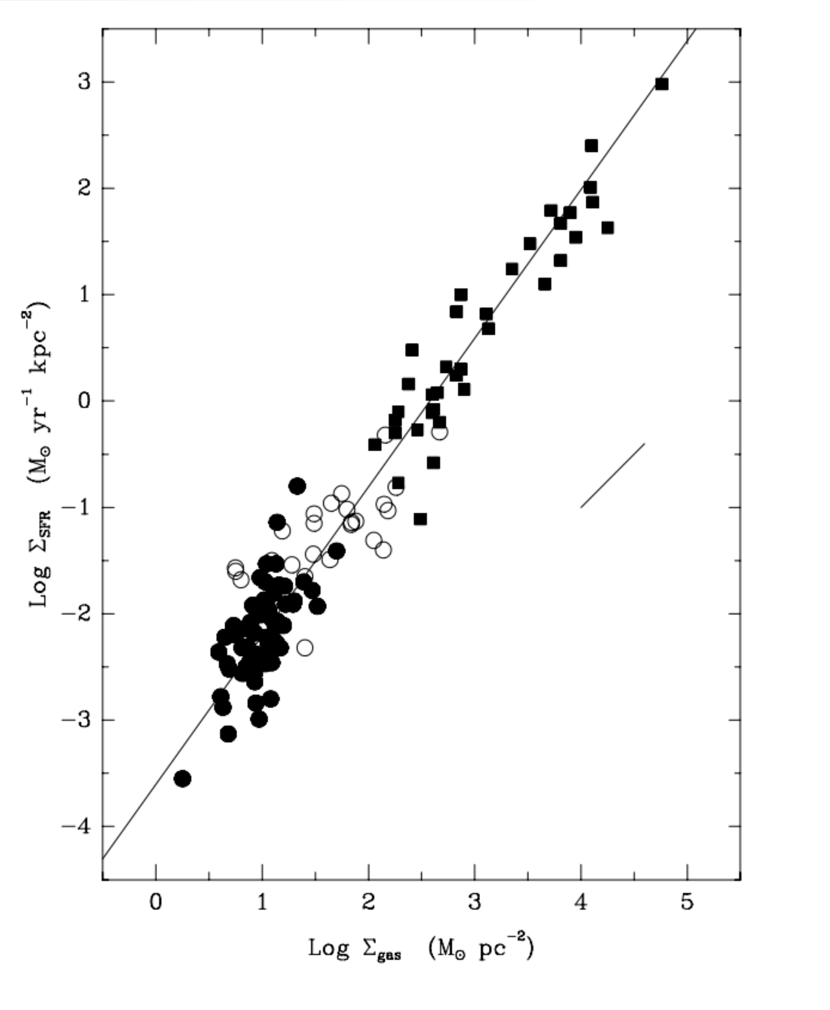
$$\Sigma_{SFR} \propto \Sigma_{gas}^{N}$$

Some works argue for a “modified” KS relation, e.g. Shi et al. (2011)

$$\Sigma_{SFR} \propto \Sigma_{gas}\Sigma_{*}^{0.5}$$

Jargon alert: Σ for surface density

Scaling relations: The Kennicutt-Schmidt relation



Seminal assessment of the KS relation made by Kennicutt (1998) for 60 nearby galaxies with measured HI and CO.

Kennicutt (1998) determined a value of *N= 1.4.* Remarkably close to the value of 1.5 determined from basic arguments.

The empirical KS relation is still used in many simulations as a “sub-grid recipe”, as star formation can not be directly modelled unless at extremely high resolution.

Scaling relations: The Kennicutt-Schmidt relation

Jargon alert: depletion time and star formation efficiency

Normalization of KS relation often quoted as either:

1). Depletion time, i.e. time required to use up the current gas reservoir given the current SFR, in units of inverse time.

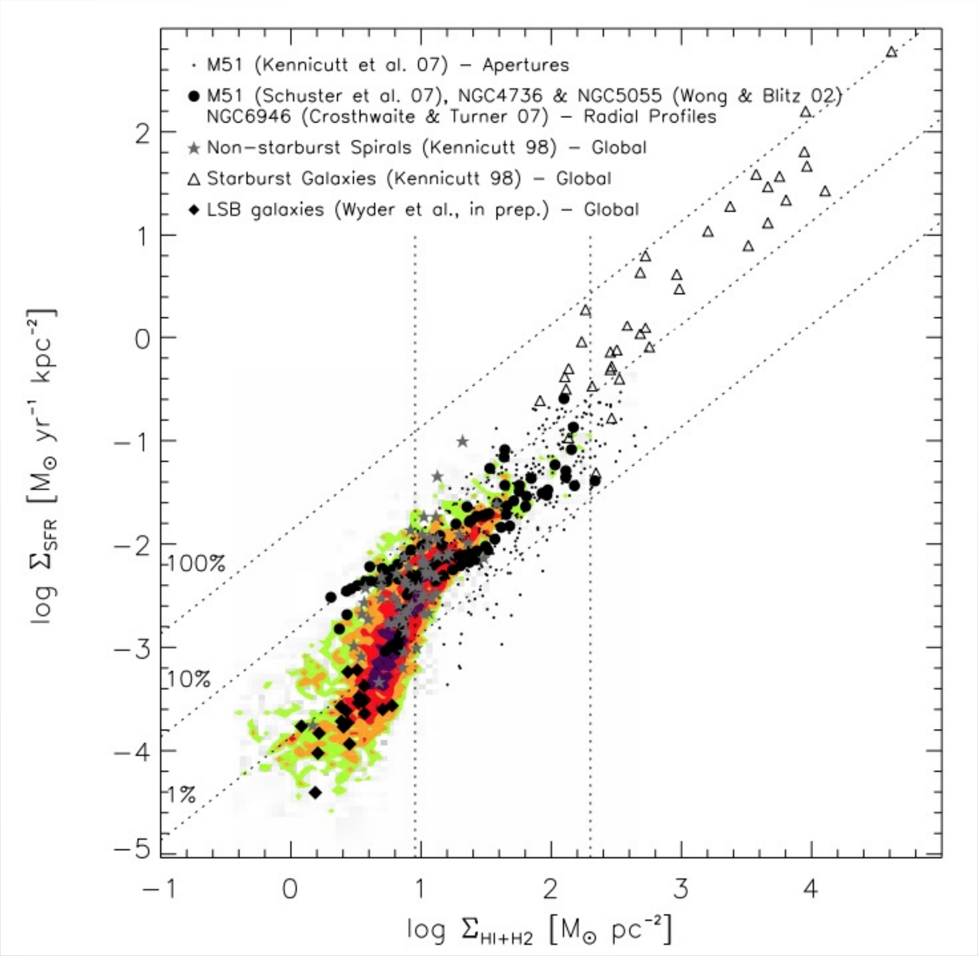
$$\tau_{dep} = \frac{\Sigma_{gas}}{\Sigma_{SFR}}$$

2) Star formation efficiency (SFE), which is the inverse of depletion time

$$SFE = 1/\tau_{dep} = \frac{\Sigma_{SFR}}{\Sigma_{gas}}$$

Many star formation folks don't like SFE because, having units of time, it is not truly an efficiency (which should be dimensionless). Purists will quote a SFE per freefall time, but this timescale is difficult to measure observationally and usually requires some assumptions.

Scaling relations: The Kennicutt-Schmidt relation



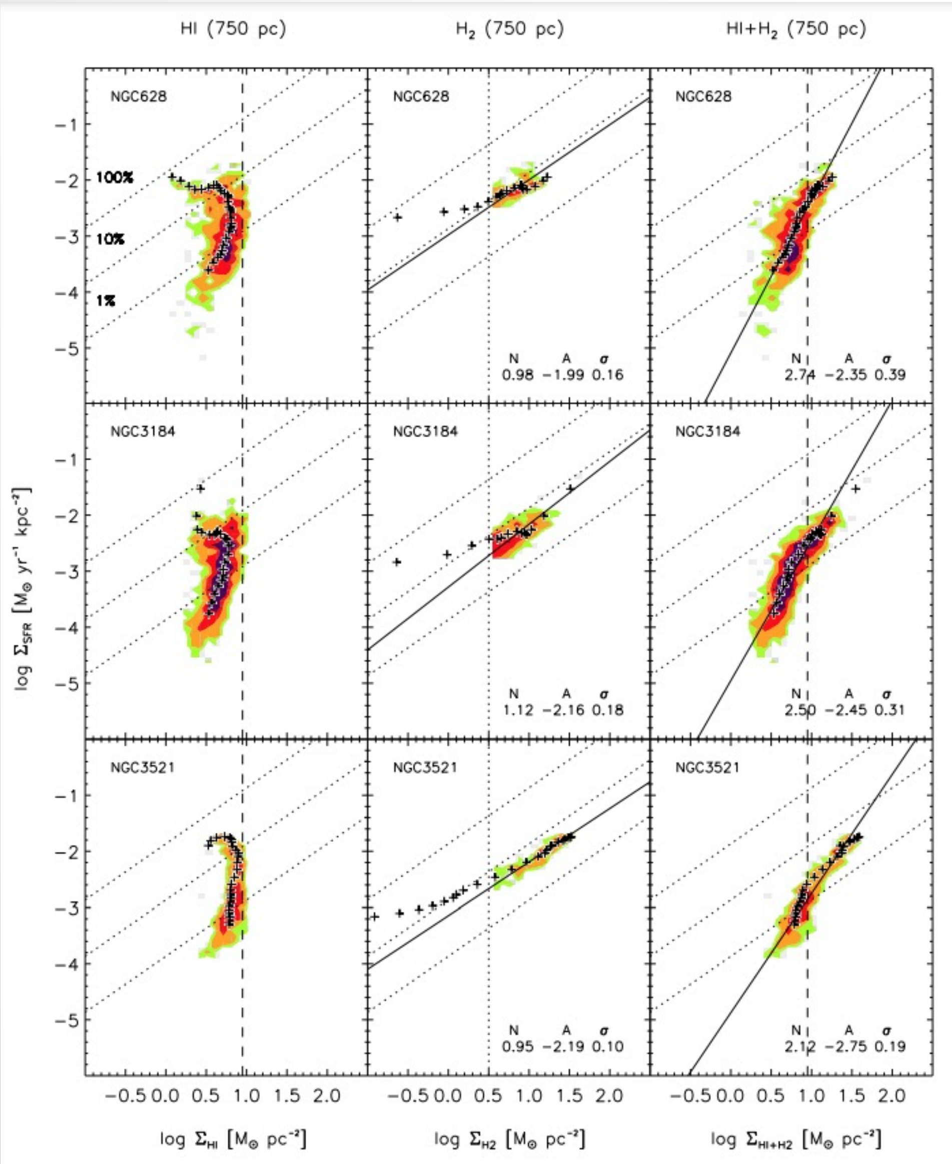
Bigiel et al. (2008)

Diagonal lines correspond to depletion times of 10^8, 10^9, 10^{10} years.

Starburst galaxies have shorter depletion times.

Major step forwards by HERACLES + THINGS surveys. Clearly not a single power law.

Scaling relations: The Kennicutt-Schmidt relation

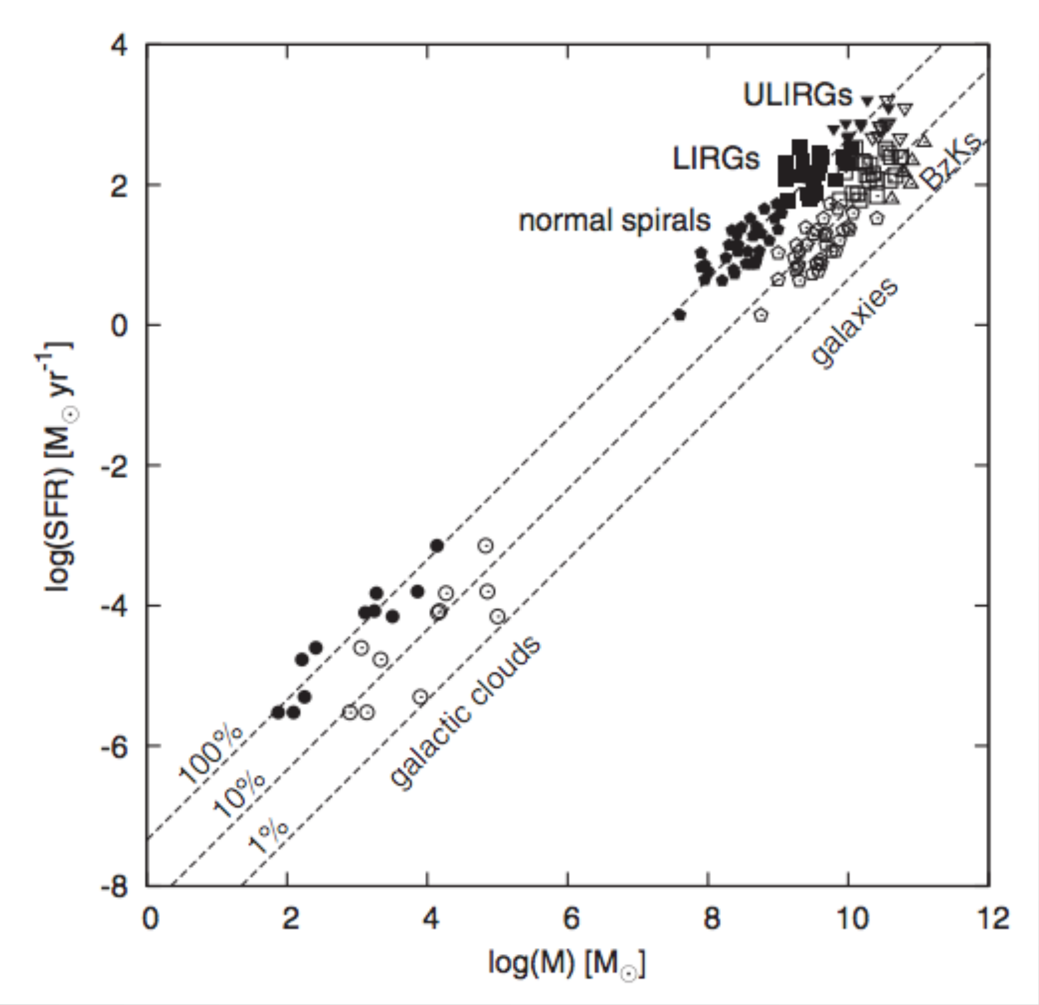


Bigiel et al. (2008)

HERACLES + THINGS revealed several important conclusions:

- At low gas surface densities, Σ_{HI} dominates. At high gas surface densities Σ_{H2} dominates.
- The HI surface density saturates at $\Sigma_{HI} \sim 9\ M_{\odot}\ pc^{-2}$.
- The surface density of SFR is unrelated to Σ_{HI}.
- Instead, it is the molecular gas that drives the relation between Σ_{gas} and Σ_{SFR}.
- The typical depletion time in the local universe is ~ 2 Gyr.

Scaling relations: The Kennicutt-Schmidt relation

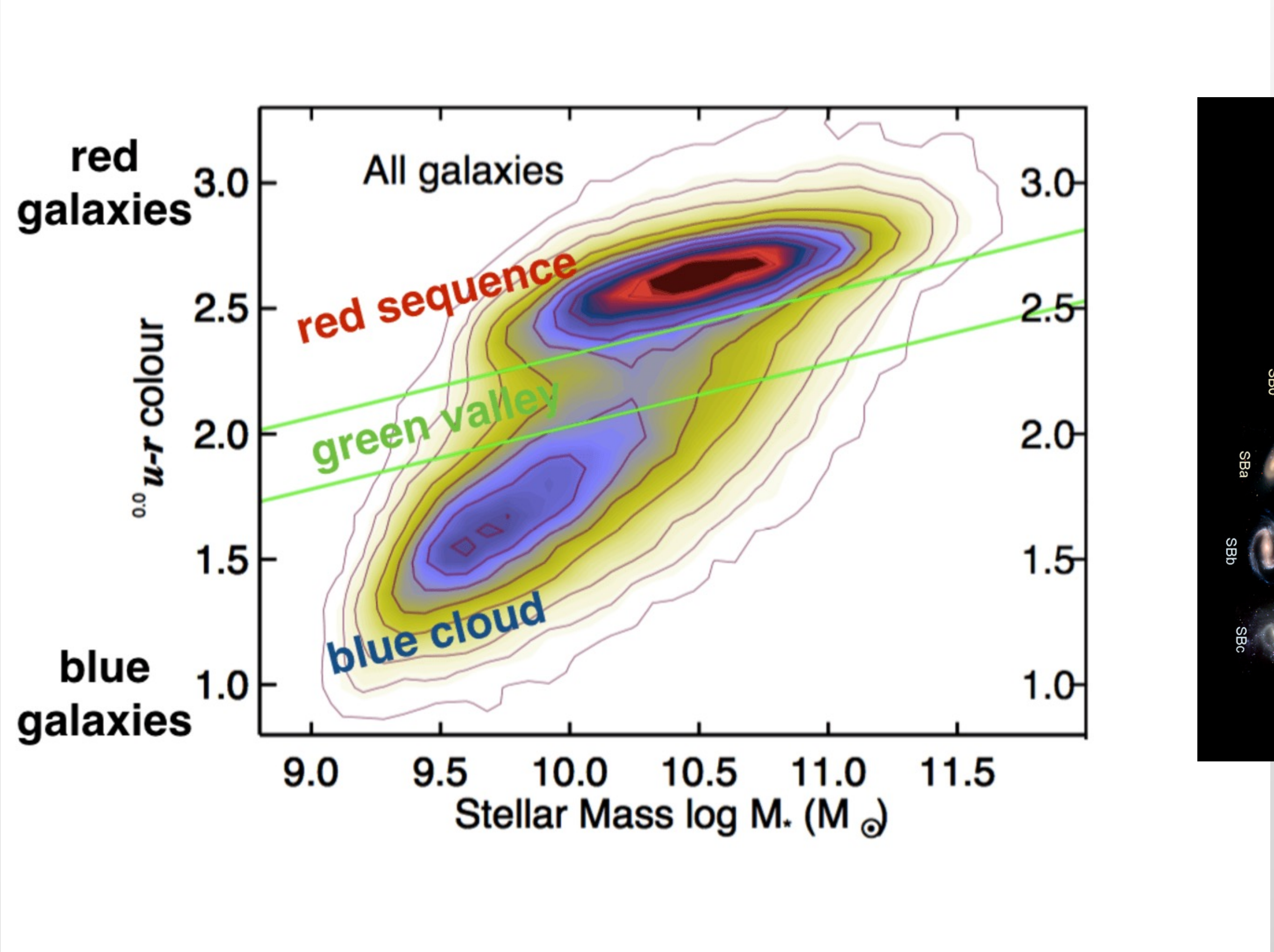


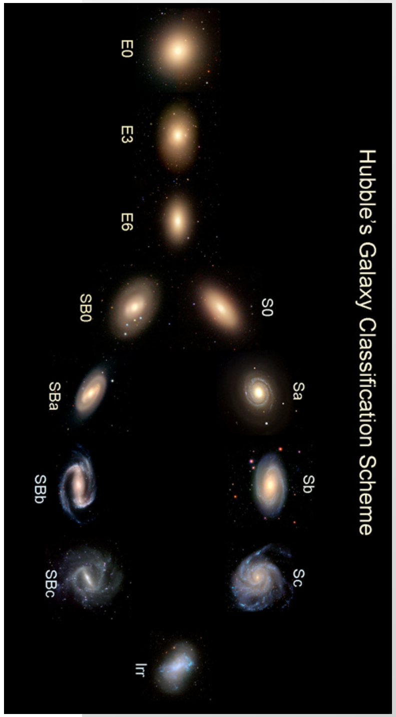
Some studies have suggested that the "fundamental" scaling between gas and star formation is actually with the dense gas, as traced by HCN, not with CO.

Lada et al. (2012) showed that the same "law" connects individual clouds and whole galaxies for HCN (solid symbols).

Lada et al. (2012)

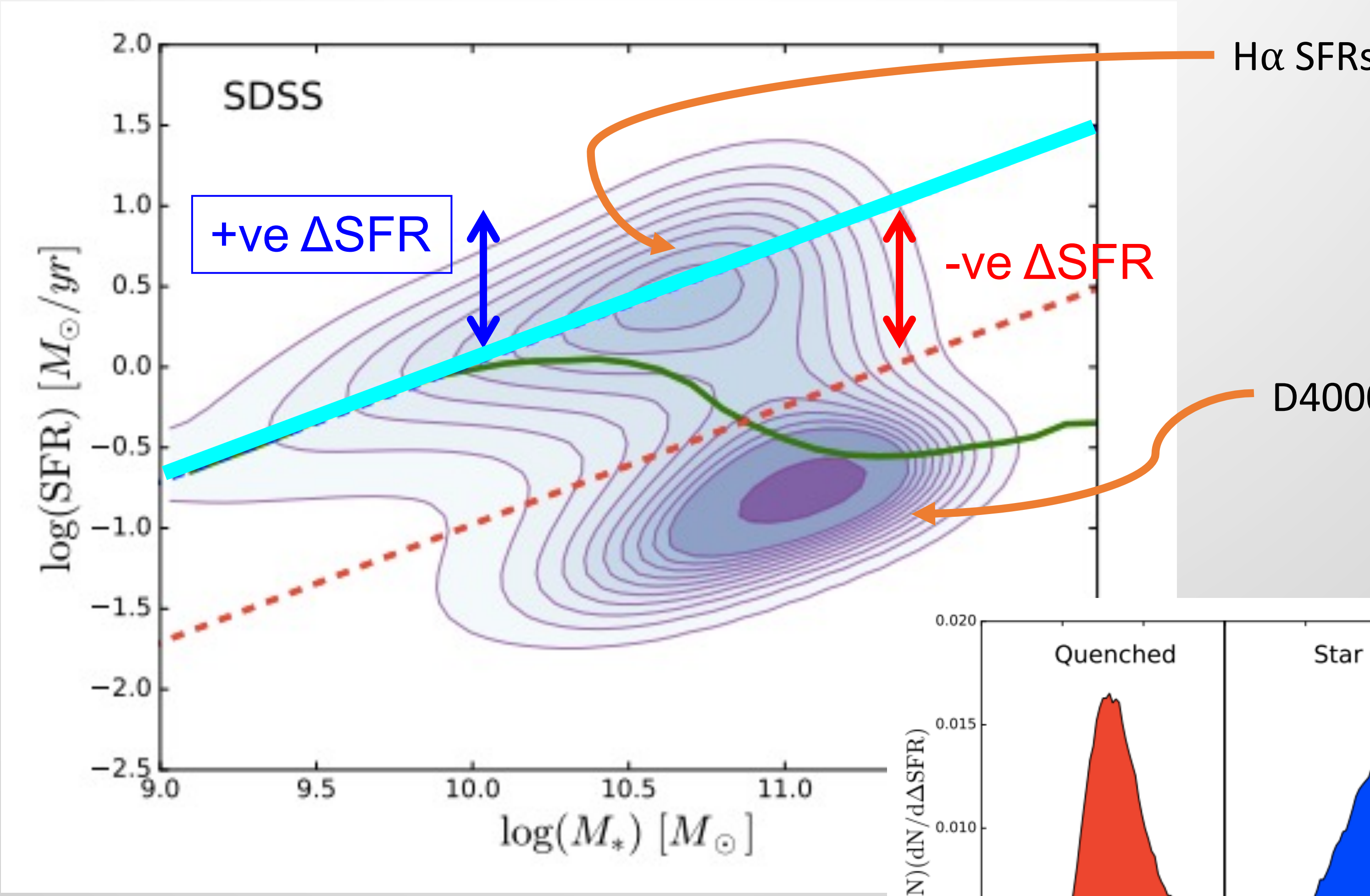
Scaling relations: The star forming main sequence

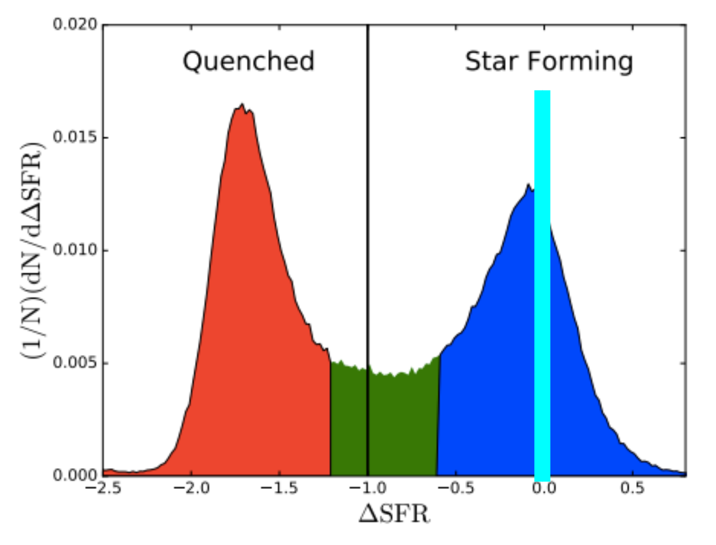




Schawinski et al. (2014)

Scaling relations: The star forming main sequence

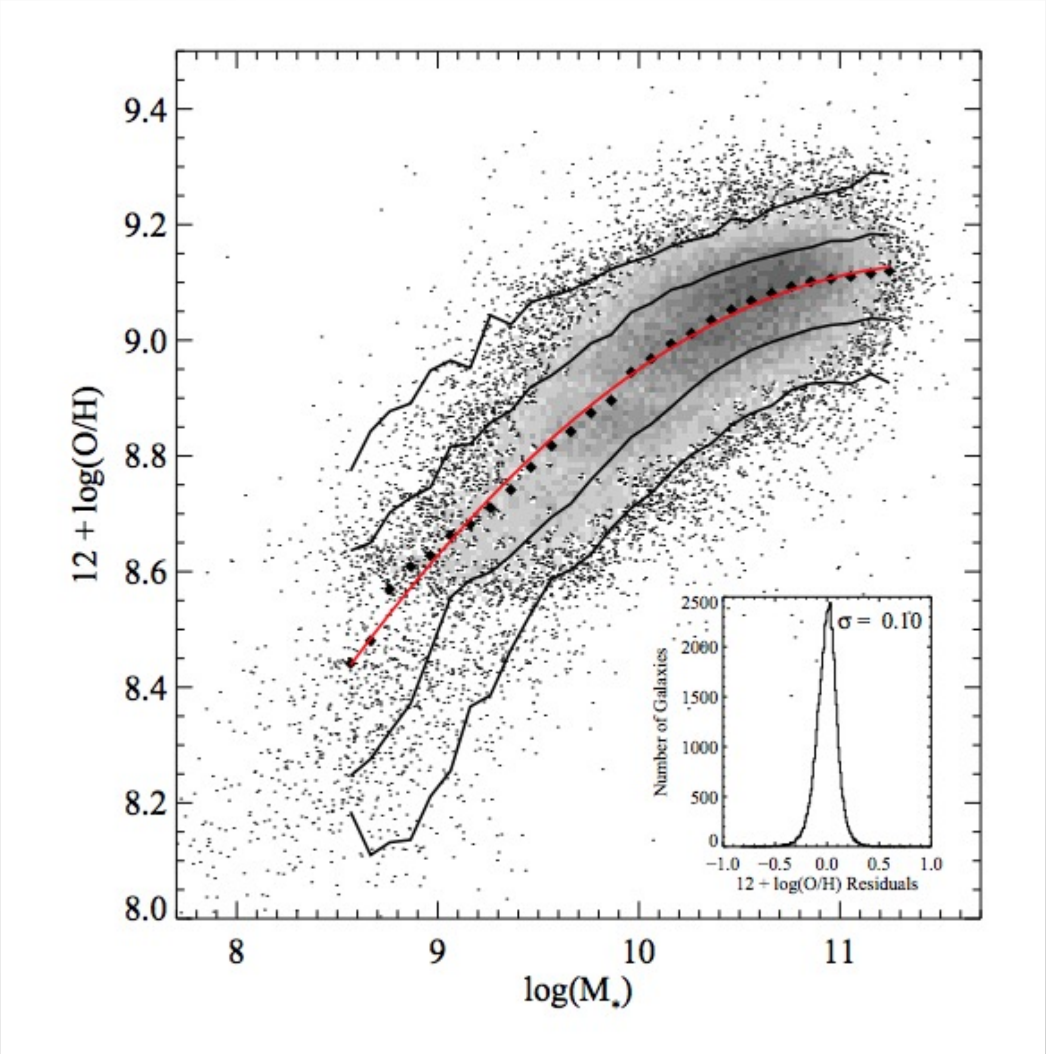




ΔSFR = ΔMS

Bluck et al. (2016)

Scaling relations: The mass-metallicity relation

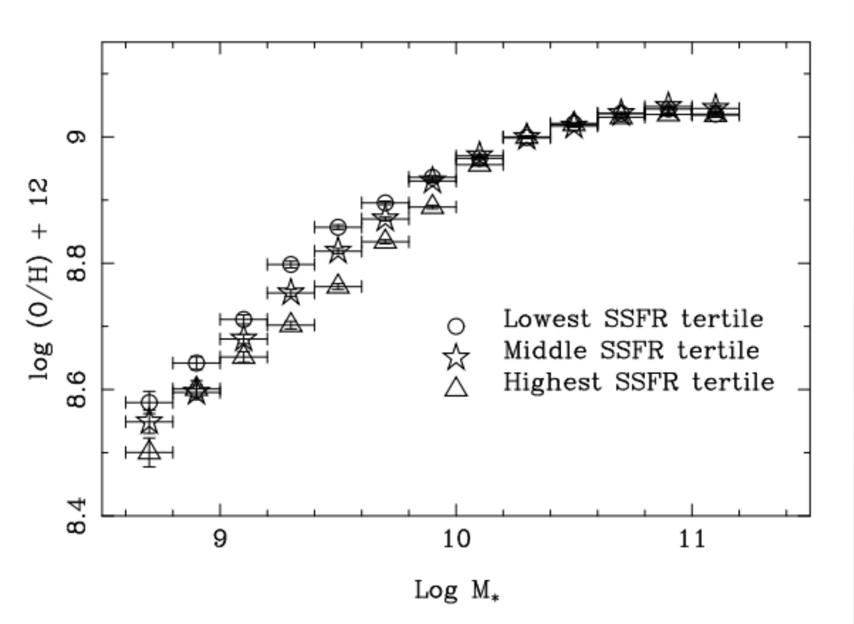


(Measuring emission line metallicities coming in more detail in a later lecture)

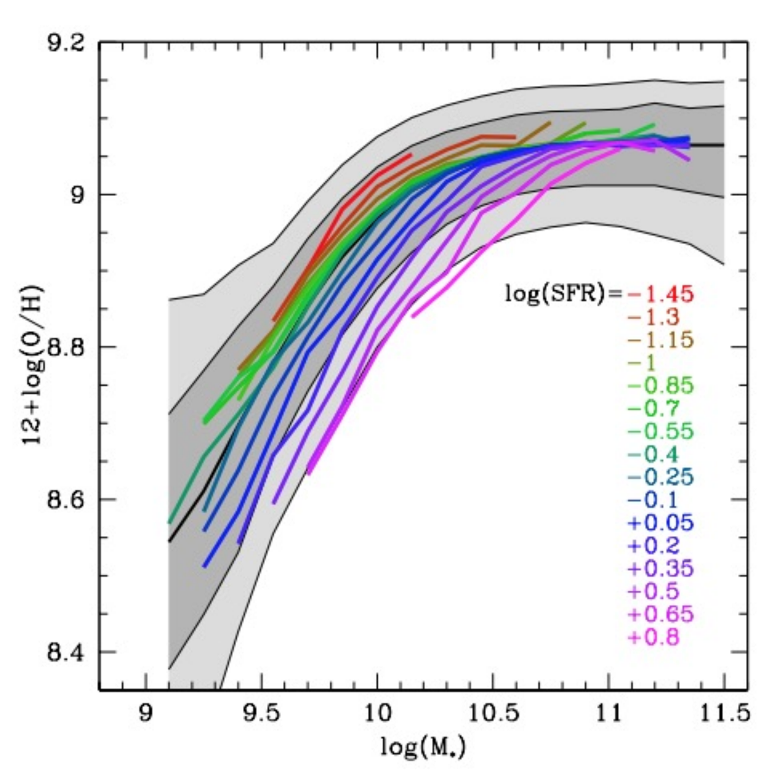
Tremonti et al. (2004)

An extra dimension to the mass-metallicity relation (MZR)

Jargon alert: the fundamental metallicity relation (FMR)



Ellison et al. (2008) discovery that MZR was higher for lower SFRs.



"Re-discovery" and better branding done by Mannucci et al. (2010).

Summary

- There are 5 phases in the ISM – this review focuses on the molecular and atomic (CNM+WNM)
- HI primarily observed (at low z) via 21cm hyperfine transition.
- H_2 not directly observable due to lack of dipole moment and high excitation temperature
- CO (1-0) is a standard substitute, but requires a conversion factor.
- Denser gas can be traced with either higher J lines or different molecules ($n_{crit} \propto \mu^2 \nu^3$)
- Single dish radio/mm telescopes have large beams (confusion risk) but not always big enough to avoid aperture corrections.

- Optical spectroscopy provides a vital complement, allowing us to measure SFR, stellar mass and metallicity
- The Kennicutt-Schmidt relation is $\Sigma_{H2} – \Sigma_{SFR}$
- The star-forming main sequence is M_* - SFR
- The mass metallicity relation is M_* - O/H