Molecular Gas

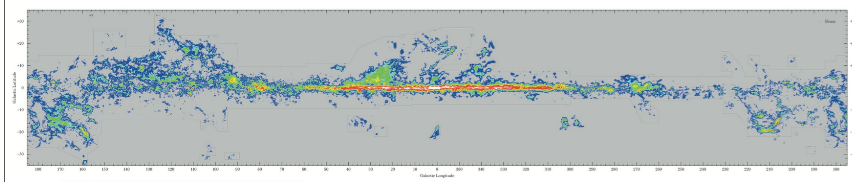
Formation of Molecular Gas

Molecular Clouds

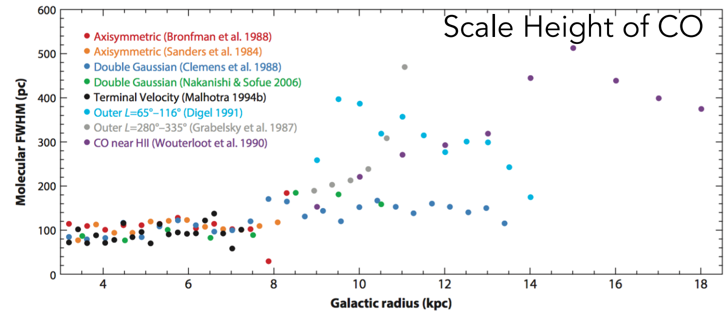
Conversion between CO measurements and mass of molecular gas

The relationship between neutral and molecular gas.

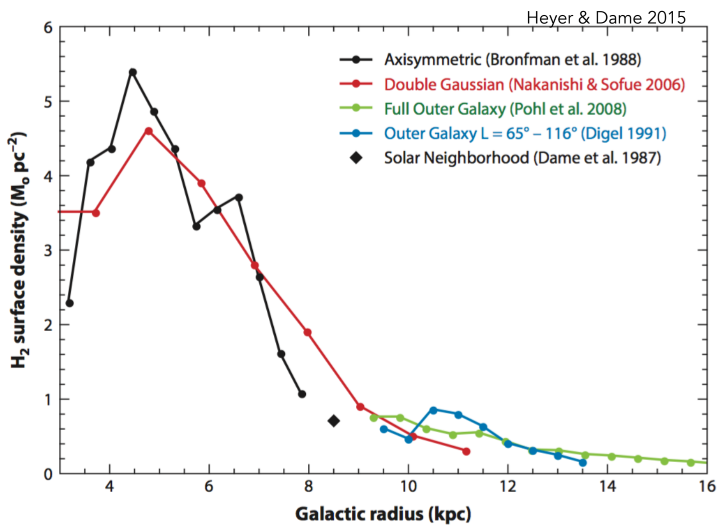
Molecular Gas: Primarily in midplane



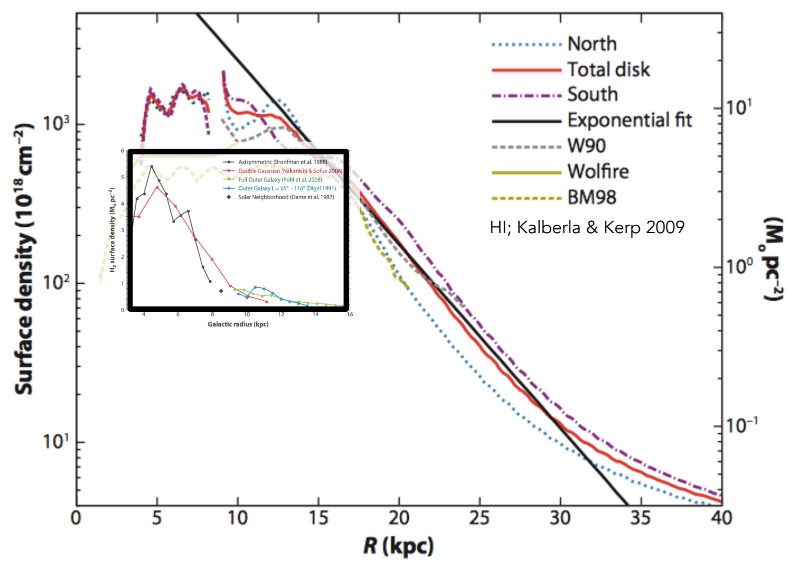
Milky Way in CO; Dame et al. 2001

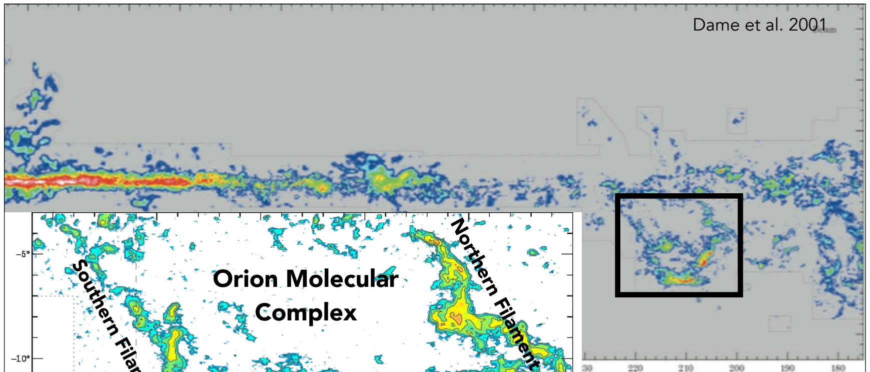


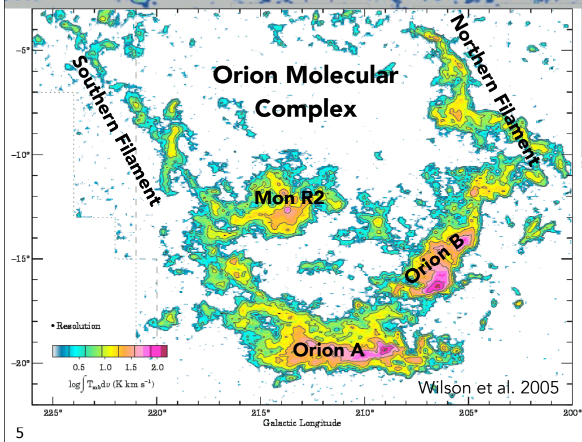
Molecular Gas: Surface density profile



MW Surface Density: HI vs H_2

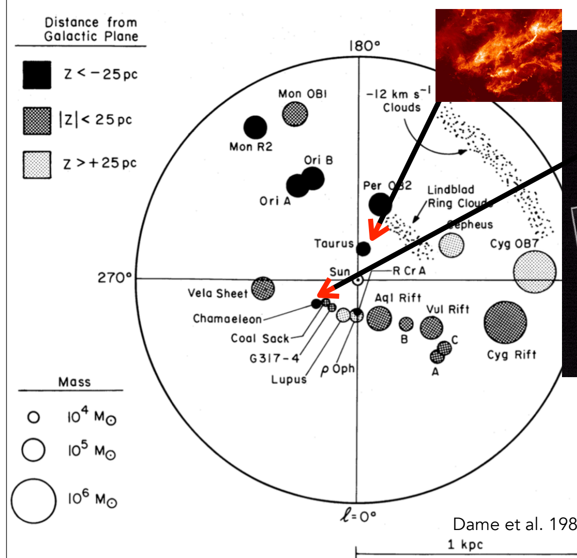


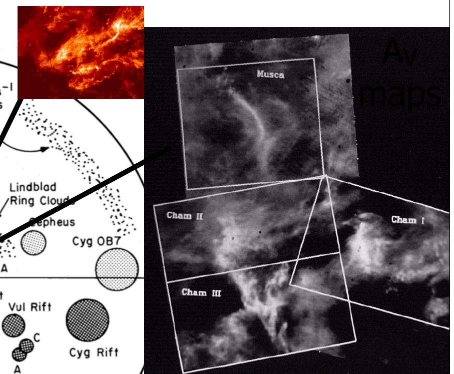




Molecular Cloud Complex

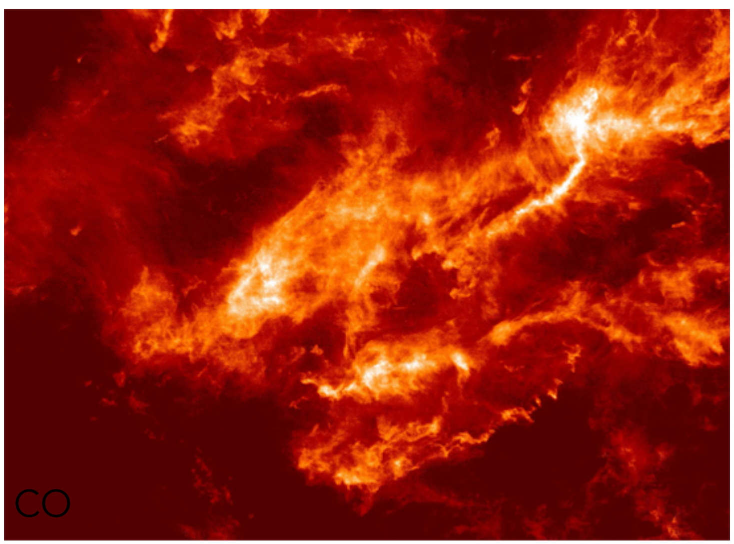
Well-studied local molecular clouds





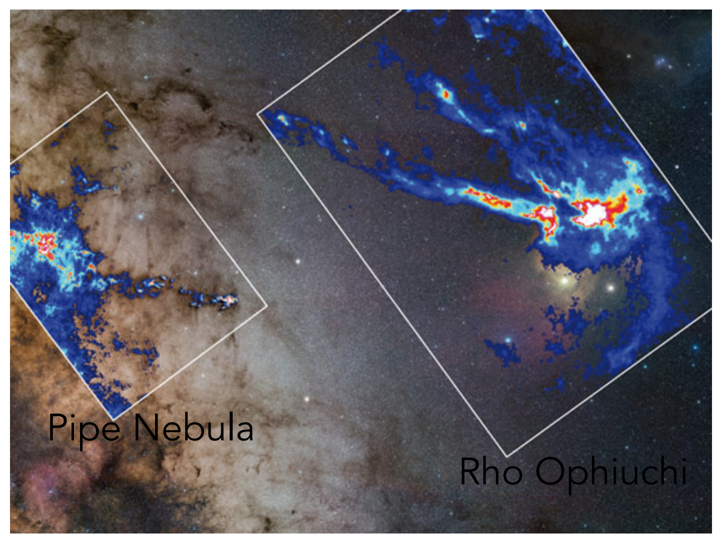
Structure is complex & lacks clear boundaries

Taurus Molecular Cloud



 https://www.astro.umass.edu/research/interstellar

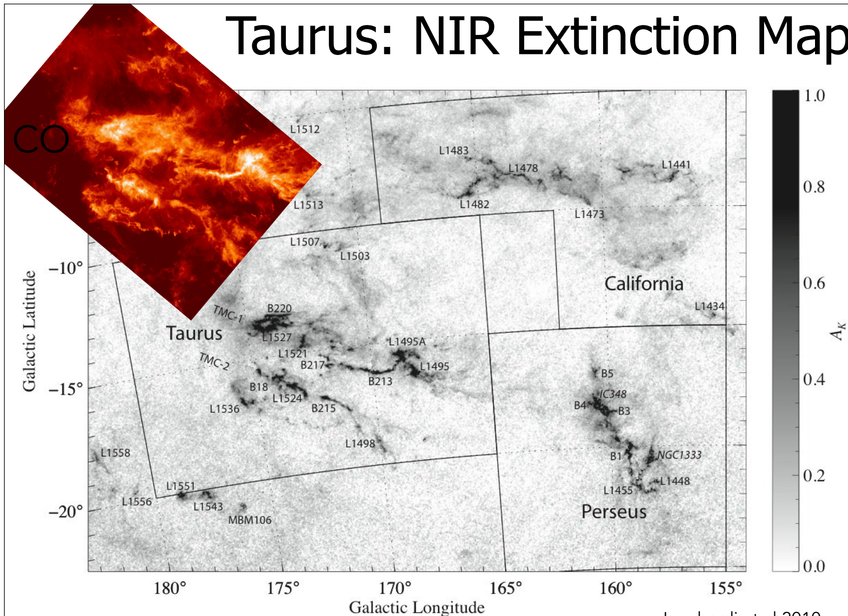
Frequently mapped via extinction



Kainulainen et al 2014

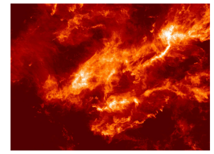
 https://scitechdaily.com/researchers-develop-model-reconstruct-spatial-structure-molecule-clouds/

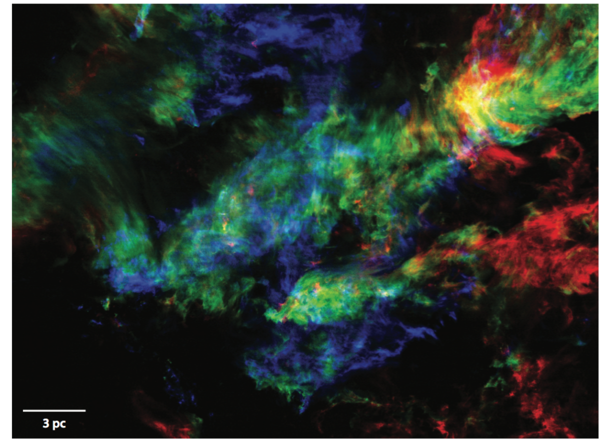
Taurus: NIR Extinction Map



Lombardi et al 2010

MCs have internal velocity structure



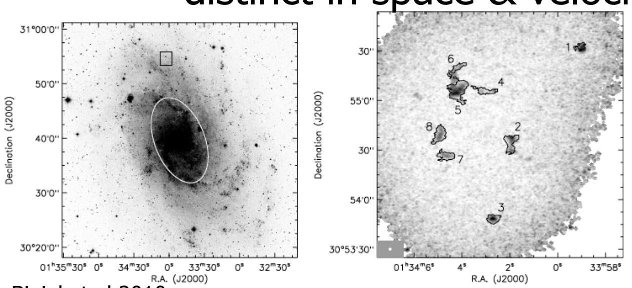


Heyer & Dame 2015

Figure 10

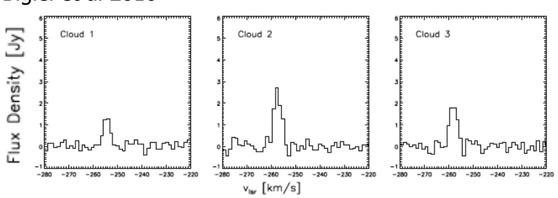
An image of ^{12}CO $J = 1$–0 emission from the Taurus molecular cloud integrated over v_{LSR} intervals 0–5 km s^{-1} (*blue*), 5–7.5 km s^{-1} (*green*), and 7.5–12 km s^{-1} (*red*), illustrating the intricate surface brightness distribution and complex velocity field of the Taurus cloud. The data are from Narayanan et al. (2008). Adapted from figure 12 of Goldsmith et al. (2008) and reproduced with permission from AAS.

Identification requires molecular clouds to be distinct in space & velocity



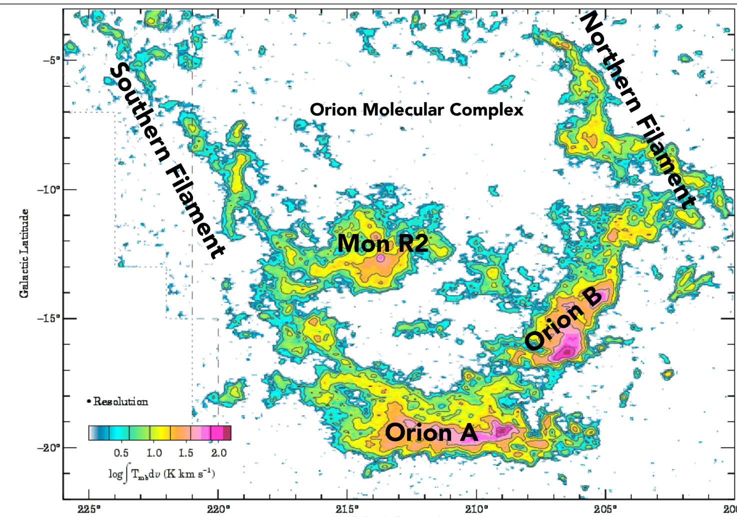
7pc spatial resolution

Bigiel et al 2010



1.3 km/s velocity resolution

Example of molecular cloud identification



But, multiple defensible cloud "units" & properties will depend on def'n

Giant Molecular Clouds (GMCs)

Discrete in position and velocity space

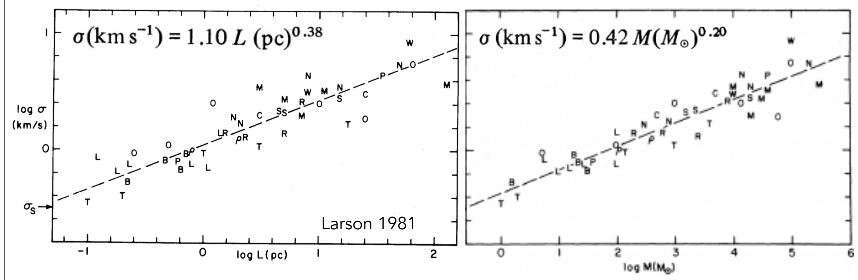
10^3-10^6 $M_\odot$

10-100 pc in size

It is rather amazing that 15 yr since the identification of giant molecular clouds, there is no generally accepted definition of what a GMC is. There seems to be little disagreement about the classification of the largest clouds as GMCs, but an all inclusive definition of what a GMC is has proven elusive. A large part of the problem is that the various studies of the mass spectrum of molecular clouds indicate that the spectrum is well fit by a power law (see below) and there is consequently no natural size or mass scale for molecular clouds. What we call a GMC is therefore largely a question of taste. For the

Blitz 1993 - review for Protostars & Planets

"Larson's Laws" for MCs

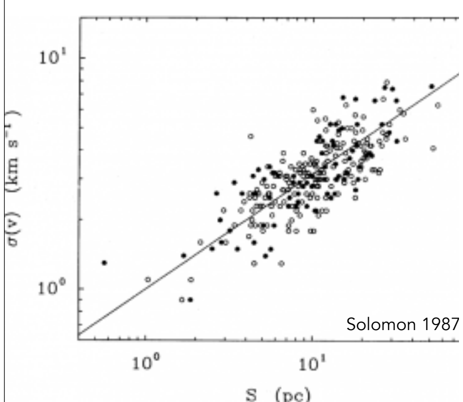


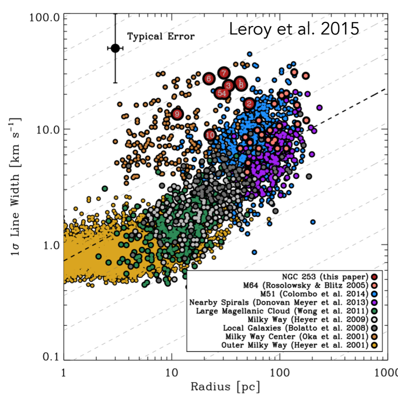
Defined for Milky Way molecular clouds

Sensitive to exact def'n of "cloud" & choice of boundary

 Nice summary at: https://astrobites.org/2012/11/18/astrophysical-classics-larsons-laws/

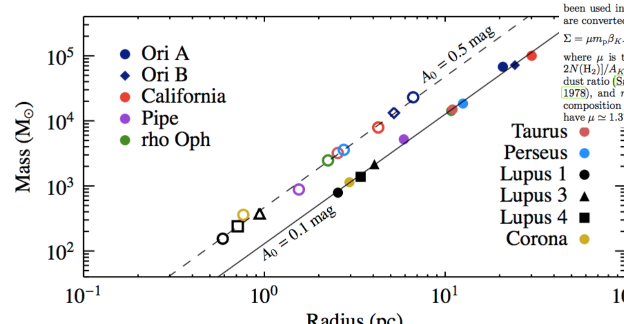
Larson's Laws vs modern data





Still largely hold, but more scatter, & somewhat different slope

Larson's 3rd Law: Constant, high Σ



been used in Lada et al. (2010). Extinction measurements are converted into surface mass densities using

$$\Sigma = \mu m_p \beta_K A_K , \quad (1)$$

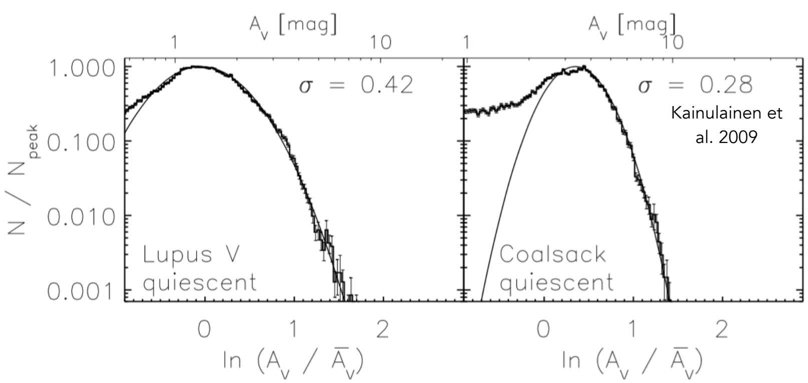
where μ is the mean molecular weight, $\beta_K \equiv [N(\mathrm{HI}) + 2N(\mathrm{H_2})]/A_K \simeq 1.67 \times 10^{22}$ cm^{-2} mag^{-1} is the gas-to-dust ratio (Savage & Mathis 1979; Lilley 1955; Bohlin et al. 1978), and m_p is the proton mass. With a standard gas composition (63% hydrogen, 36% helium, and 1% dust) we have $\mu \simeq 1.37$ and therefore $\Sigma/A_K \simeq 183\ M_\odot$ pc^{-2} mag^{-1}.

Trace MC's with NIR dust extinction; Lombardi et al 2010

Fig. 1. Cloud masses above extinction thresholds of $A_0 = 0.1$ mag (filled symbols) and $A_0 = 0.5$ mag (open symbols) as a function of their size. The two line shows the best constant surface density fits, which correspond to $\boxed{\Sigma = 41\ M_\odot\ \mathrm{pc}^{-2}}$ and $\boxed{\Sigma = 149\ M_\odot\ \mathrm{pc}^{-2}}$ respectively.

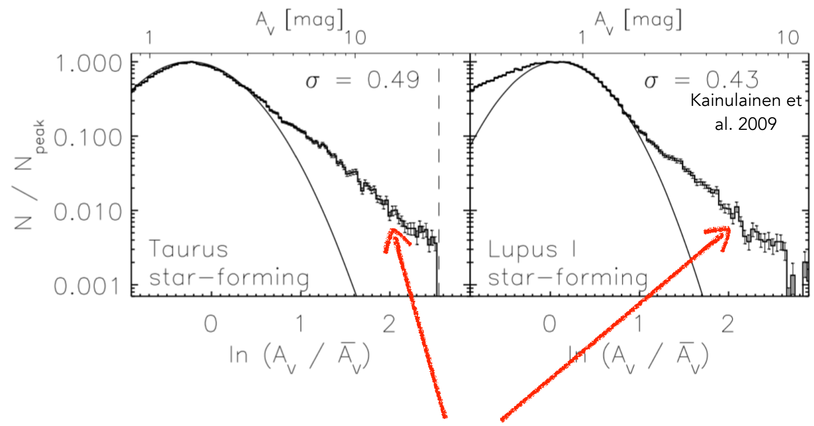
But, only holds on larger scales.
Breaks down for single clouds & cores

Molecular cloud internal structure



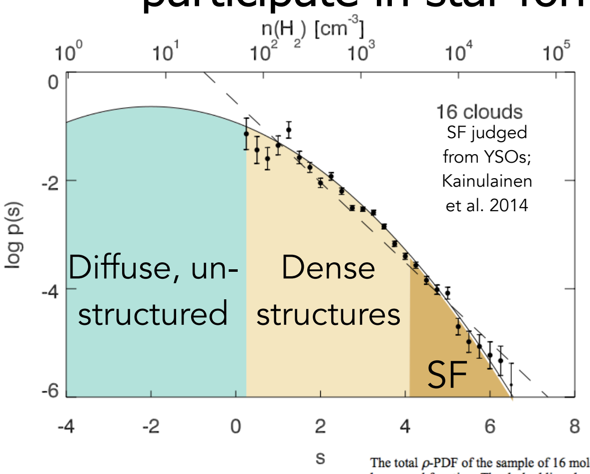
Log-normal
"probability distribution function" (PDF)
of column & space densities

Molecular cloud internal structure



Actively star forming clouds show a power-law tail to higher densities

Only highest densities (>5000 cm^{-3}) participate in star formation



$s = \ln(\rho/\rho_0)$ is the logarithmic, mean-normalized density.

The total ρ-PDF of the sample of 16 molecular clouds. The solid line shows a fit of a lognormal function. The dashed line shows a fit of an exponential function. The dark brown color refers to the star-forming gas in the cloud. The light brown color refers to the regime on which gas is organized into dense structures. The green color refers to the regime of diffuse, relatively non-structured gas. Using the total ρ-PDF, we derived the Milky Way star formation rate of 3 $M_\odot$ / yr.

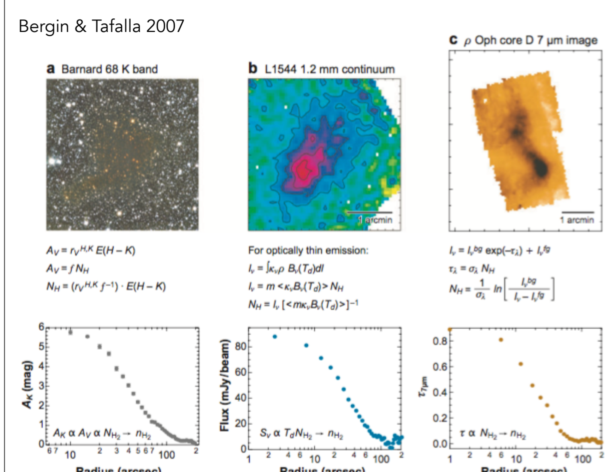
2.5% of molecular gas is "SF"

16% of "SF" gas turns into stars

Thus need 30$M_\odot$ cloud to form a 0.8$M_\odot$ star, and 70,000$M_\odot$ to form a 20$M_\odot$ star

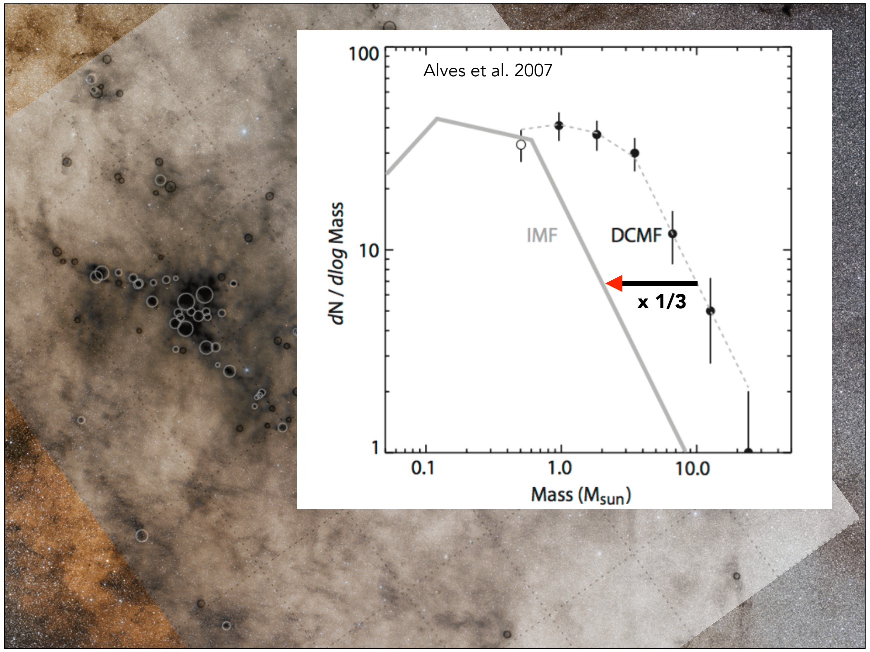
Molecular clouds host "cores"

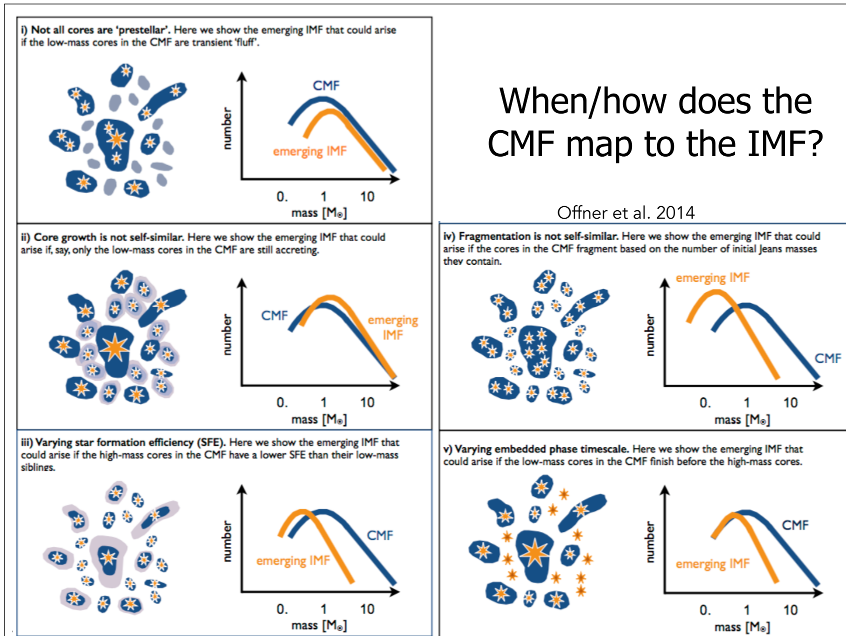
Bergin & Tafalla 2007



Column density profiles of dense cores are similar to Bonnor-Ebert* profile (isothermal, marginally stable spherical cloud)

*See derivation of Bonner-Ebert sphere in Krumholz

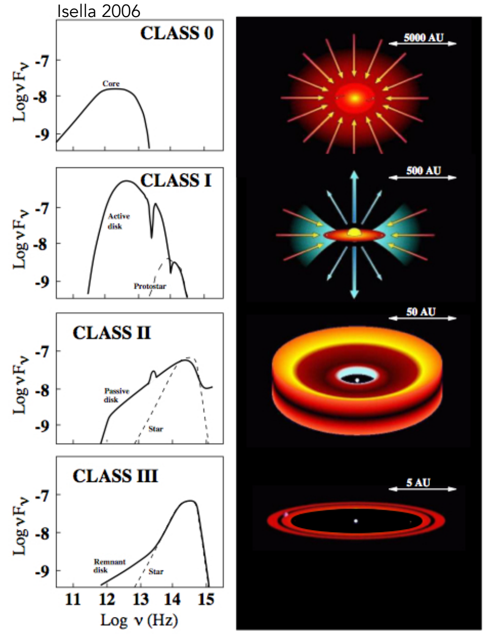




When/how does the CMF map to the IMF?

Offner et al. 2014

Isella 2006



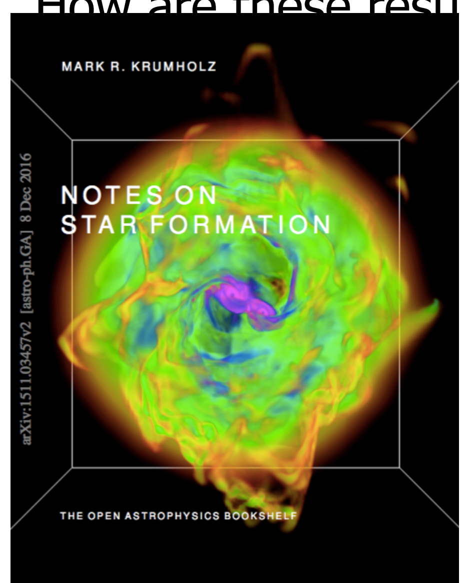
Gravitational collapse

Angular momentum
-> disk formation
-> outflows & jets

Most material is in a disk, accretion onto protostar through disk.

Most material accreted, remnant disk.

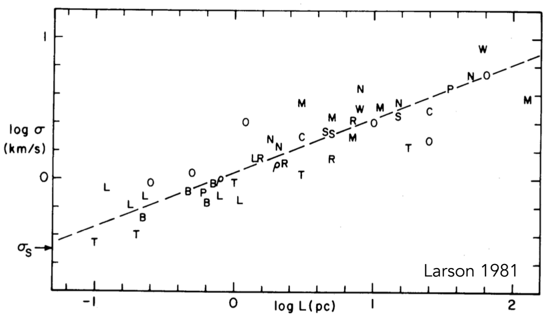
How are these results interpreted?



Superb resource, especially "Physical Processes" chapters

https://arxiv.org/abs/1511.03457

The physical state of molecular clouds



1. Velocity dispersion is >> sound speed. Supersonic turbulence provides support against gravity.

The physical state of molecular clouds

2. It is unclear whether clouds are gravitationally bound

Define a "virial parameter": $\alpha_{\text{vir}} = \frac{2\mathcal{T}}{|\mathcal{W}|}$

Where: $\mathcal{T} = \int_V \left(\frac{1}{2}\rho v^2 + \cancel{\frac{3}{2}P} \right) dV$ is KE

$\mathcal{W} = -\int_V \rho \mathbf{r} \cdot \nabla \phi \, dV$ is gravitational binding energy

Observational approximation: $\alpha_{\text{vir}} = 5\sigma_v R/GM$

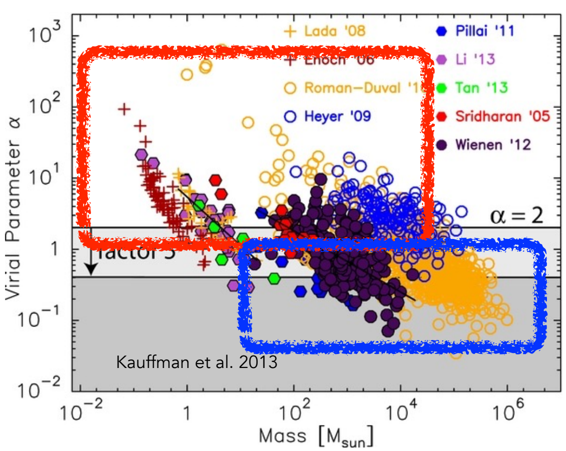
 See Chapter 6 of Krumholz: https://arxiv.org/abs/1511.03457

The physical state of molecular clouds

2. It is unclear whether clouds are gravitationally bound

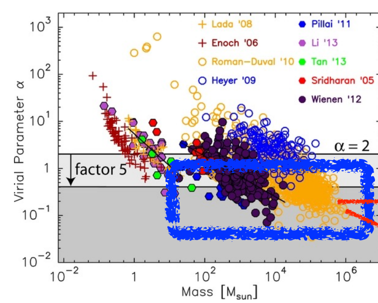
Lower mass MCs seem less likely to be bound

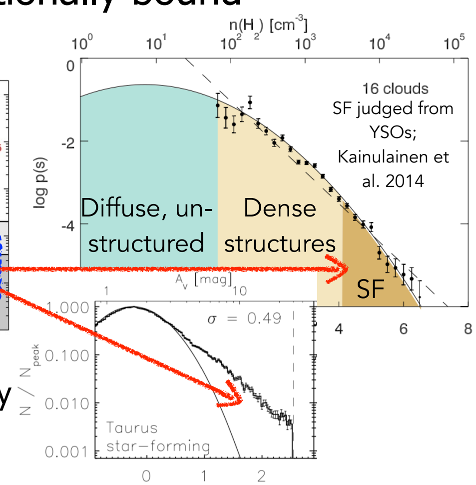
Higher mass ones do seem bound



The physical state of molecular clouds

2. It is unclear whether clouds are gravitationally bound





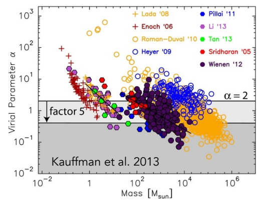
SF & high density tails may be where self-gravity is dominating evolution

The physical state of molecular clouds

3. Other factors are important for confinement

Full virial theorem*

$$\frac{1}{2}\ddot{I} = 2(\mathcal{T} - \mathcal{T}_S) + \mathcal{B} + \mathcal{W}$$



$$\mathcal{T}_S = \int_S r P \, dS$$ Confining pressure over surface

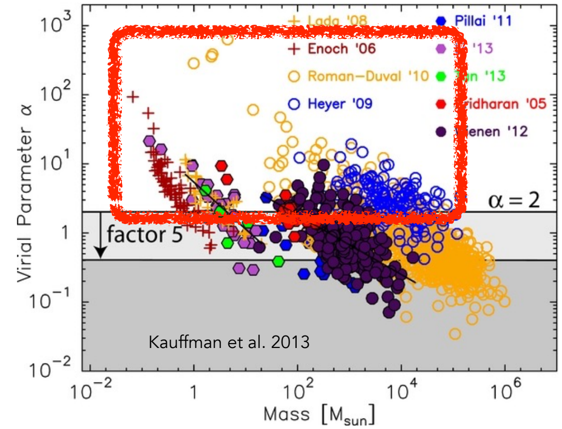
$$\mathcal{B} = \frac{1}{8\pi}\int_V (B^2 - B_0^2)\, dV$$ Net magnetic energy (for field B in cloud)

*ignoring mass flows and assuming uniform external magnetic field B_0

The physical state of molecular clouds

3. Other factors are important for confinement

Possible pressure confinement or magnetic support



$$P = \rho\sigma^2 = \frac{\pi}{2}\phi_P G \Sigma_{\rm tot}^2.$$ Galaxy midplane pressure, where φ is order unity

The physical state of molecular clouds

3. Other factors are important for confinement

GMC's are "overpressurized" compared to the diffuse ISM

WNM/CNM: P ~ 3800 cm^{-3} K
GMC (T=10, n=10^4): P ~ 10^5 cm^{-3} K

Without self-gravity, GMCs would be transient.

The physical state of molecular clouds

4. Magnetic fields may be important

$$\Phi_B = \pi B R^2$$ Magnetic flux through the cloud surface*

Can calculate a "magnetic critical mass" for a cloud**

$$M_\Phi \equiv \sqrt{\frac{5}{2}}\left(\frac{\Phi_B}{3\pi G^{1/2}}\right)$$

Clouds above this mass will collapse, and can never be halted by magnetic forces

*Assuming flux freezing, which may not always hold
**Which is constant as cloud collapses, if flux freezing holds

The physical state of molecular clouds

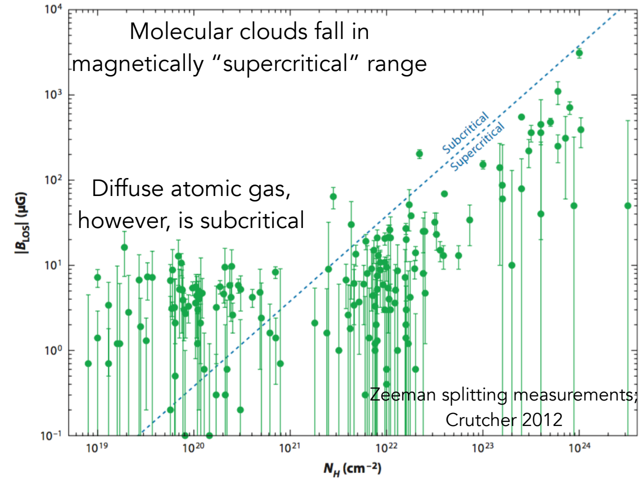
4. Magnetic fields may be important

"magnetic critical mass" $$M_\Phi \equiv \sqrt{\frac{5}{2}}\left(\frac{\Phi_B}{3\pi G^{1/2}}\right)$$

Magnetically supercritical: Will collapse anyways
Magnetically subcritical: Can never collapse*

*Resists collapse more effectively as system collapses, so W can never win, unless flux-freezing breaks (ion-neutral drift), or external pressure somehow increases

The physical state of molecular clouds



Magnetically supercritical: Will collapse anyways
Magnetically subcritical: Can never collapse*

The physical state of molecular clouds

5. Characteristic timescales are short

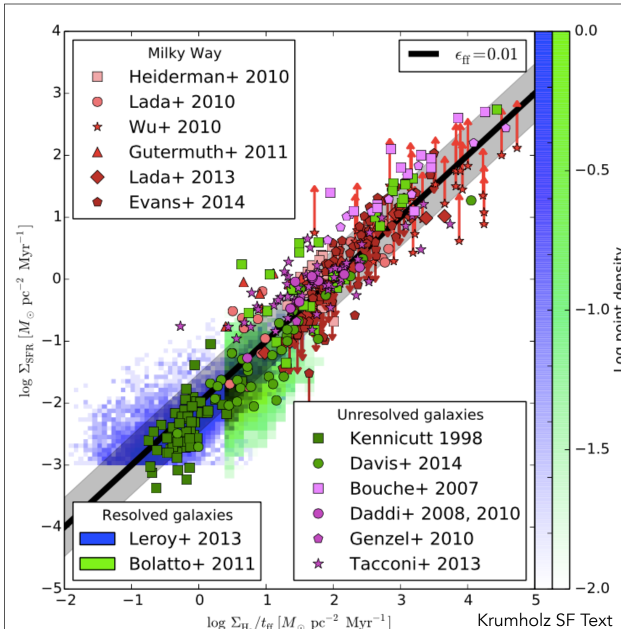
Crossing time: $$t_{\rm cr} \equiv \frac{R}{\sigma} = \frac{0.95}{\sqrt{\alpha_{\rm vir} G}}\left(\frac{M}{\Sigma^3}\right)^{1/4} = 14\,\alpha_{\rm vir}^{-1/2} M_6^{1/4} \Sigma_2^{-3/4}\ {\rm Myr}$$

Free-fall time*: $$t_{\rm ff} \equiv \sqrt{\frac{3\pi}{32 G\rho}} = \frac{\pi^{1/4}}{\sqrt{8G}}\left(\frac{M}{\Sigma^3}\right)^{1/4} = 7.0\, M_6^{1/4} \Sigma_2^{-3/4}\ {\rm Myr}$$

Of order 10 Myr**

*For pressureless collapse, which is not strictly applicable
**And based on spherical, not filamentary structures, w/ uniform density

 See Chapter 8 of Krumholz: https://arxiv.org/abs/1511.03457



Krumholz SF Text

But, only a small (1%) fraction of molecular mass converts to stars on a free-fall time

Figure 8.6: Surface density of star formation versus surface density of gas normalized by free-fall time. Blue and green pixels are the same as in Figure 8.5, while points represent measurements of marginally-resolved galaxies (~ 1 beam per galaxy). Points are color-coded: green indicates local galaxies, purple indicates high-z galaxies, and red indicates individual Milky Way clouds. The thick black line represents $\epsilon_{\rm ff} = 0.01$, while the gray band shows a factor of 3 scatter about it. Reprinted from Phys. Rep., 539, Krumholz, "The big problems in star formation: The star formation rate, stellar clustering, and the initial mass function", 49-134, 2014, with permission from Elsevier.

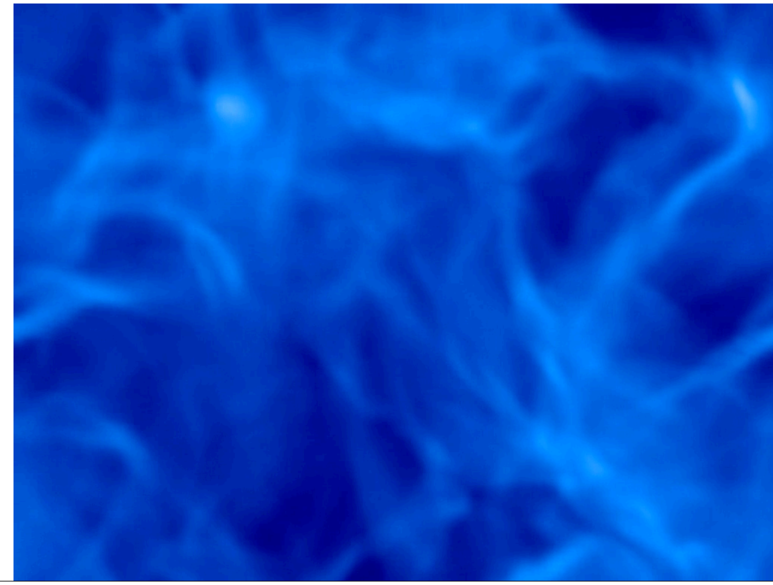
The physical state of molecular clouds

5. Characteristic timescales are short

Lifetimes are uncertain, though.
Clouds are destroyed by:

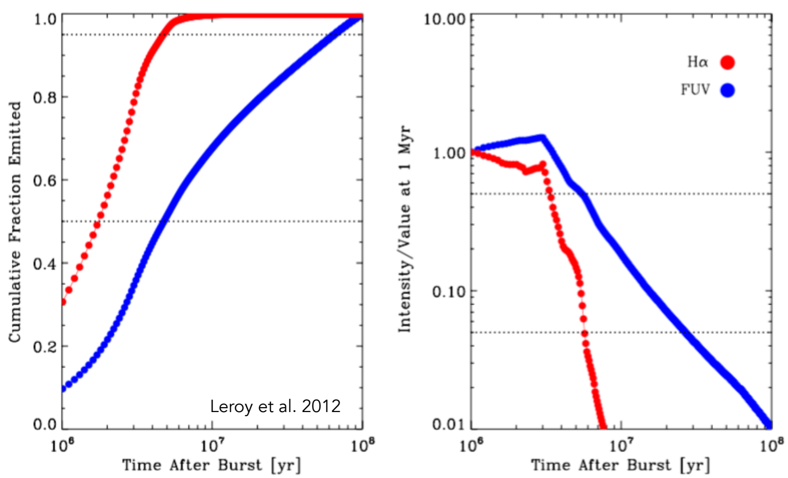
- Turbulence
- Radiative Feedback from stars
- Mechanical Feedback from stars (jets, winds, SNe)

Turbulence washes out overdensities



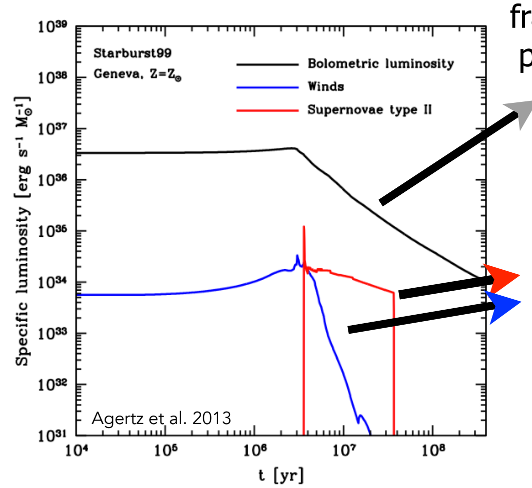
Simulations by Fedderath

Radiative Feedback



But, this is for synchronized burst w/ fully populated IMF, which may not reflect MC star formation

Mechanical Feedback



fraction into ionization, photoelectric heating, dust heating?

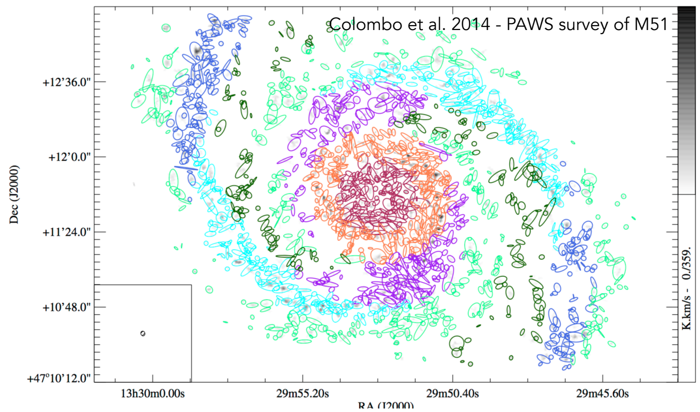
deposited where?

which phases are these deposited into, at what distances from stars?

Jets? What about stochastic IMF?

The physical state of molecular clouds

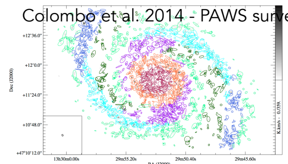
6. Masses span a range of values



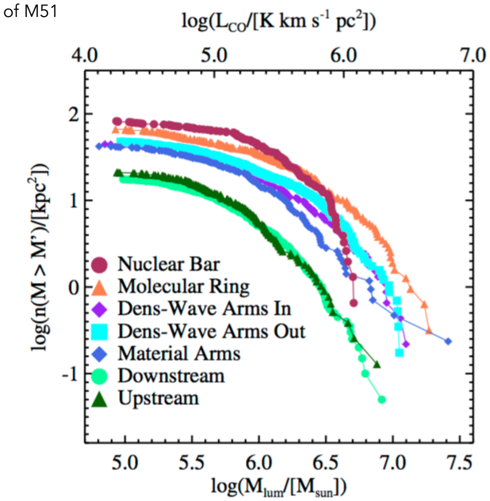
Molecular cloud identification in M51

The physical state of molecular clouds

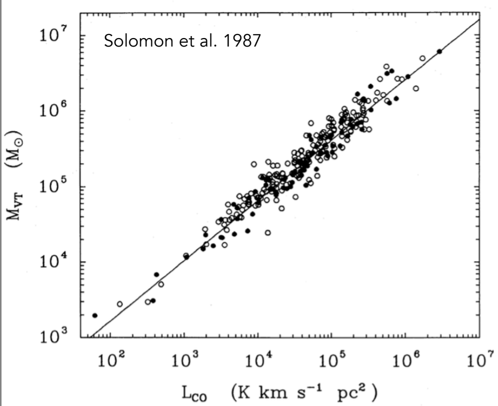
6. Masses span a range of values



Comparable distributions of GMC masses w/ environment



Measuring masses of MCs



Assume clouds are in virial equilibrium (w/ no B-field, pressure,etc).

Use velocity dispersion & sizes to calculate their mass ($\alpha_{vir} = 5\sigma_v R/GM = 1$)

Observed correlation between CO luminosity & inferred mass suggests scaling relation between the two

CO-to-H_2 Conversion Factors

2 common conventions in use

Usually expressed in terms of column density rather than total mass

column density of H_2 — integrated intensity of CO line

$$N_{H2} = X_{CO}\, I_{CO}$$

X_{CO}: $[\mathrm{cm^{-2}\ (K\ km\ s^{-1})^{-1}}]$

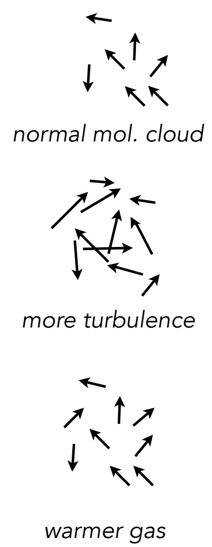
molecular gas mass surface density — integrated intensity of CO line

$$\Sigma_{mol} = \alpha_{CO}\, I_{CO}$$

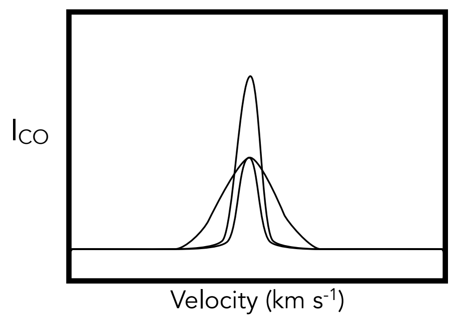
α_{CO}: $[M_\odot\ \mathrm{pc^{-2}\ (K\ km\ s^{-1})^{-1}}]$

 See ARA&A Review by Bolatto et al. 2013

Why does X_{CO} work for optically thick clouds?

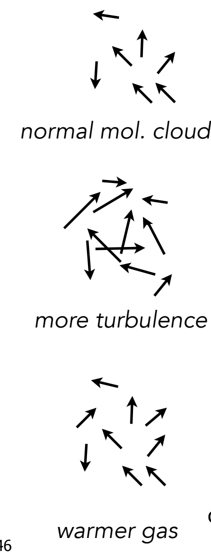


Effects of molecular cloud properties on X_{CO}.



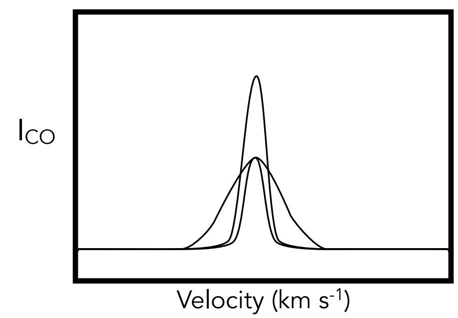
Peak brightness = excitation temperature of CO
line width = turbulent velocity dispersion

Why does X_{CO} work for optically thick clouds?



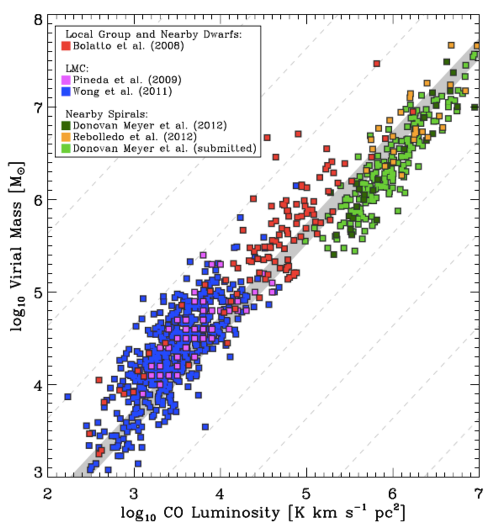
Molecular gas at near constant temp*

Empirically, turbulent velocity correlates w/ cloud's mass (Larson laws)



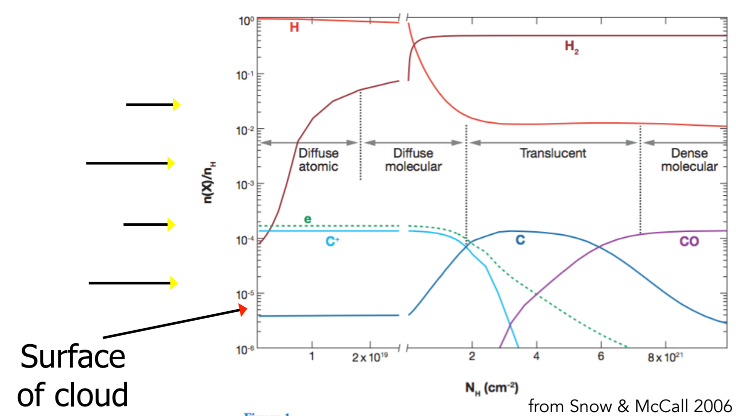
*See discussion in Chapter 3.2.3 of Krumholz text. Heating rate T dependence leads to only modest changes in T when Λ changes, and cooling timescale very short (kyrs), so hydrodynamic disturbances cool back to isothermal quickly.

Note: Scatter & offsets in scaling



Suggests environmental effects on X_{CO}

CO: Strongly affected by radiation field



from Snow & McCall 2006

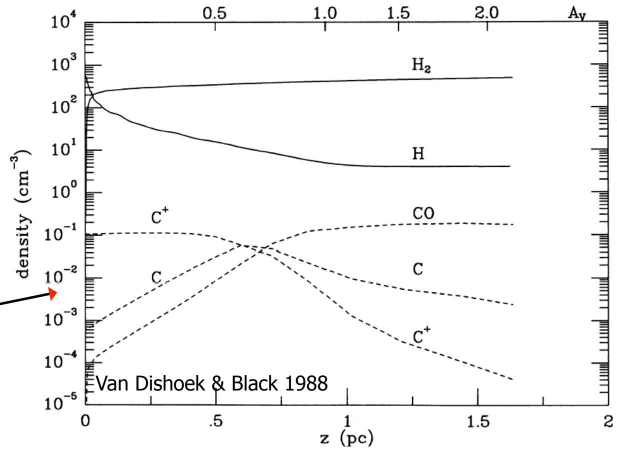
Figure 1

Results from photodissociation region model [with $n_H = 100$ cm^{-3} and $\chi_{UV} = 1$] from Neufeld et al. (2005), illustrating the revised definitions of cloud types.

"Photodissociation Region (PDR)"

General term: anywhere that far-UV (<13.6 eV) photons play key role in chemistry, ionization, etc.

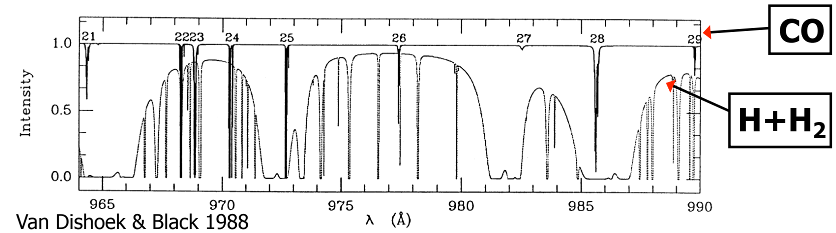
CO: Strongly affected by radiation field



Surface of cloud

More shielding of CO by dust & H_2 lines, which block dissociating UV photons

Molecular dissociation proceeds by UV line absorption

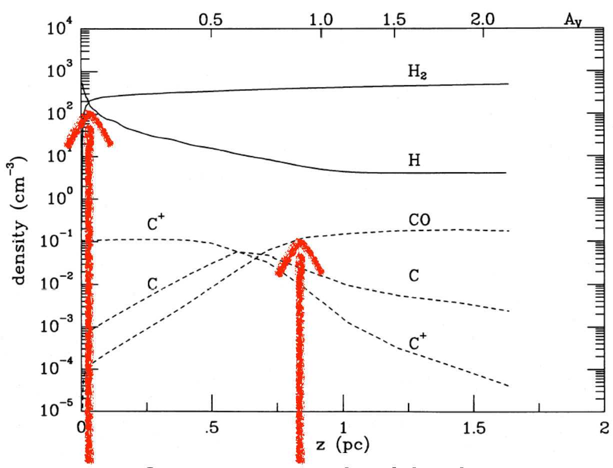


Absorption line spectrum of CO, H_2, and H

"Shielding"

If UV photons in each line have been absorbed (by molecules or dust), no more dissociation.

CO: Strongly affected by radiation field

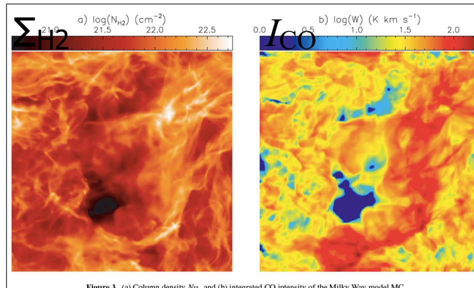


Surface of cloud

H_2 shields near surface, because abundant

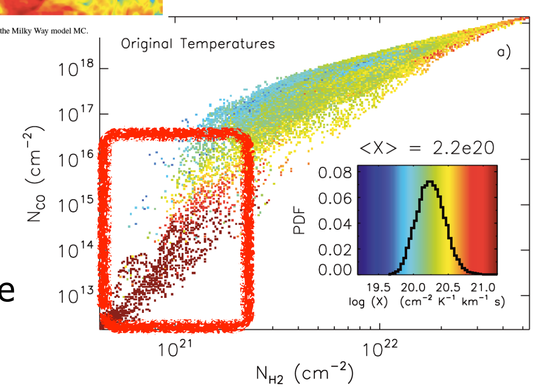
CO shields deeper in, because rarer

Simulations of MW X_{CO}

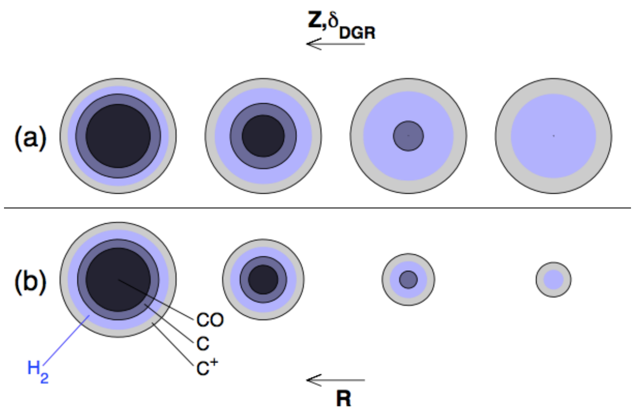


Shetty et al 2011
(see also Glover & Mac-Low 2011

- Diffuse gas: much larger corrections to get to H_2
- Global value depends on densest gas (where most gas is), so usually similar



CO-to-H_2 mass not constant



Varying metallicity & dust-to-gas ratio

Varying cloud size

FIG. 8.— Effect of metallicity on CO and H_2 in a spherical clump immersed in a uniform radiation field. Blue shading indicates the region where the gas is molecular, according to Eq. 25. Increasingly darker shading shows the regions where carbon is found as C^+, C, or CO. The top sequence (a) illustrates the effect of decreasing metallicity and dust-to-gas ratio on the distribution of C^+, CO, and H_2. Mostly because of the increase in N_H required to attain a given A_V, the CO emitting region is pushed further into the clump until, for a fixed cloud size, it disappears at low enough metallicities. The bottom sequence (b) illustrates the effect of changing the clump size or column density at a fixed metallicity (adapted from Bolatto, Jackson & Ingalls 1999; Wolfire, Hollenbach & McKee 2010).

Also, CO does not sample full kinematics of cloud

from Bolatto et al 2013

X_{CO} does increase towards low metallicity

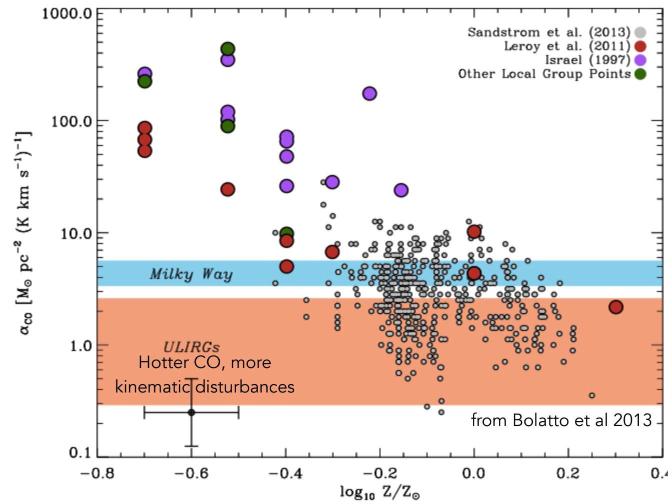
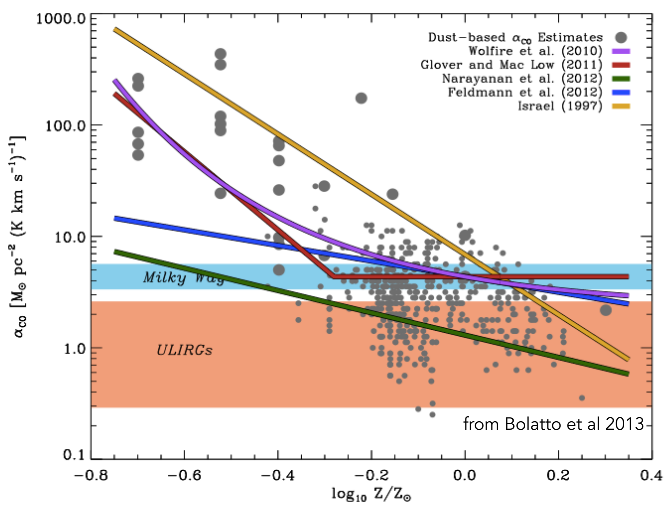


FIG. 9.— Conversion factor, estimated from dust-based approaches, as a function of gas-phase abundance. **(Left)** Color points show estimates for very nearby galaxies Israel (1997), Madden et al. (1997, based on [CII]), Leroy et al. (2007), Gratier et al. (2010), Roman-Duval et al. (2010), Leroy et al. (2011), Bolatto et al. (2011), and Smith et al. (2012). Gray points show high quality solutions from analysis of 22 nearby disk galaxies by (Sandstrom et al. 2012), with typical uncertainties illustrated by the error bars near the bottom left corner. Metallicities are from Israel (1997), Bolatto et al. (2008), and Moustakas et al. (2010) and quoted relative to solar in the relevant system ($12 + \log[O/H] = 8.7$ for the first two, $12 + \log[O/H] = 8.5$ for the latter which uses the metallicity calibration by Pilyugin & Thuan 2005). Note that significant systematic uncertainty is associated with the x-axis. The color bands illustrate our recommended ranges in α_{CO} for the Milky Way and ULIRGs. **(Right)** Colored lines indicate predictions for X_{CO} as a function of metallicity from the references indicated, normalized to $X_{CO,20} = 2$ at solar metallicity where necessary. For these predictions, we assume that GMCs have $\langle\Sigma_{GMC}\rangle = 100\ M_\odot\ pc^{-2}$, which we translate to a mean extinction through the cloud using Eq. 21. Dust-based determinations find a sharp increase in X_{CO} with decreasing metallicity below $Z \sim 1/3$–$1/2\ Z_\odot$.

X_{CO} does increase towards low metallicity



Behavior not inconsistent w/ models

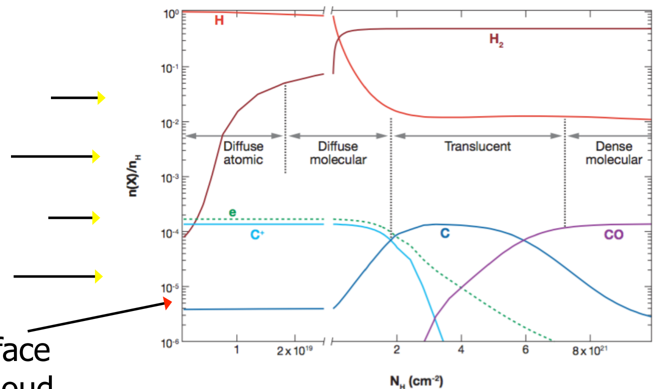
Values of X_{CO} from various techniques

Table 1 Representative X_{CO} values in the Milky Way disk

from Bolatto et al. 2013

Method	$X_{CO}/10^{20}$cm^{-2} (K km s^{-1})$^{-1}$	References
Virial	2.1	Solomon et al. (1987)
	2.8	Scoville et al. (1987)
Isotopologues	1.8	Goldsmith et al. (2008) Optically thin tracers
Extinction	1.8	Frerking, Langer & Wilson (1982)
	2.9–4.2	Lombardi, Alves & Lada (2006)
	0.9–3.0	Pineda, Caselli & Goodman (2008)
	2.1	Pineda et al. (2010b) Unaffected by photodissociation
	1.7–2.3	Paradis et al. (2012)
Dust emission	1.8	Dame, Hartmann & Thaddeus (2001)
	2.5	Planck Collaboration XIX et al. (2011)
γ-rays	1.9	Strong & Mattox (1996)
	1.7	Grenier, Casandjian & Terrier (2005)
	0.9–1.9[a]	Abdo et al. (2010c)
	1.9–2.1[a]	Ackermann et al. (2011, 2012c)
	0.7–1.0[a]	Ackermann et al. (2012a,b)

Photodissociation also affects H_2



Surface of cloud

from Snow & McCall 2006

Figure 1
Results from photodissociation region model [with $n_H = 100\ cm^{-3}$ and $\chi_{UV} = 1$] from Neufeld et al. (2005), illustrating the revised definitions of cloud types.

Larger question of when you get H_2 vs HI

The Formation of Molecular Gas

$$\boxed{\mathrm{H} + \mathrm{H} \longrightarrow \mathrm{H}_2}$$

- Energetically favorable, but…
- Neutral-neutral, so fundamentally slow, plus…
- No dipole moments, which forbids many transitions

The Formation of Molecular Gas

1. Gas-phase formation

"Fast" H^- channel

$$\mathrm{H} + e \rightarrow \mathrm{H}^- + \gamma$$
$$\mathrm{H}^- + \mathrm{H} \rightarrow \mathrm{H}_2 + e$$

Slower H^+ channel

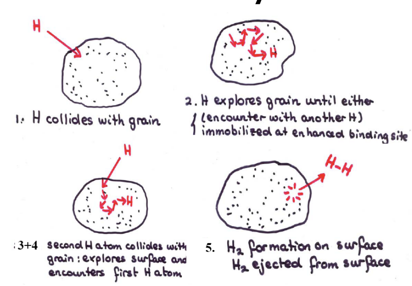
$$\mathrm{H} + \mathrm{H}^+ \rightarrow \mathrm{H}_2^+ + \gamma$$
$$\mathrm{H}_2^+ + \mathrm{H} \rightarrow \mathrm{H}_2 + \mathrm{H}^+$$

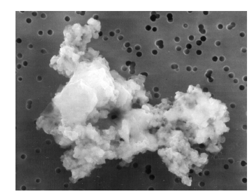
- Both are typically slow (charge-neutral) reactions
- Dominant pathway at high T and small dust-to-gas ratios (<1% of MW's)

See Glover 2007

The Formation of Molecular Gas

2. "Dust Catalyzed" formation





Dust has bigger cross-section

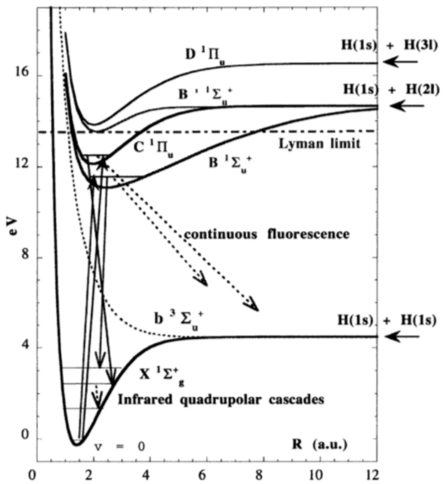
Favors H_2 formation at:

- High HI densities
- High dust-to-gas ratios
- Long H+dust lifetimes

⇨

- High gas densities
- High metallicity

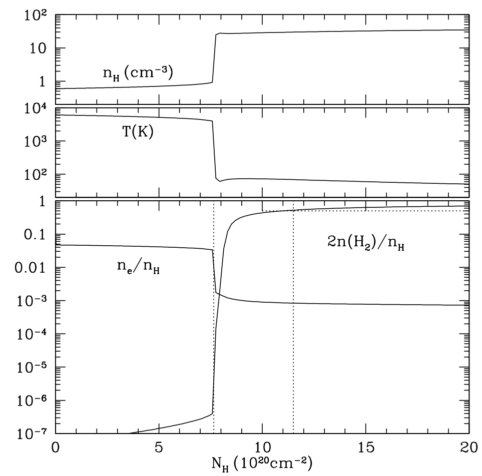
The Destruction of Molecular Gas

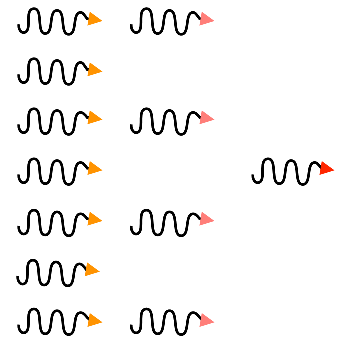


After H_2 absorbs a UV photon from ground to one of the excited levels (Lyman-Werner bands), has ~85% probability of radiative decay, ~15% probability of photo dissociating

Lyman band = ground -> B
Werner band = ground -> C

H+ to H to H_2



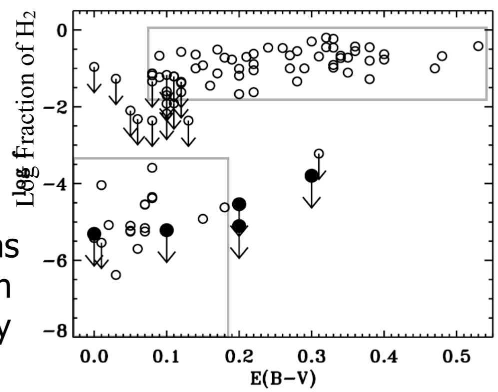


external radiation field

plane-parallel distribution of gas

Absorption constraints on H_2

Low gas column density



High gas column density

Hoopes et al 2004

FIG. 7.—*Top*, H_2 column density vs. reddening; *bottom*, molecular fraction *f* vs. reddening. The solid circles show the *FUSE* starburst upper limits, and the open circles show *Copernicus* measurements and limits for Galactic sight lines (from Savage et al. 1977). The H_2 column densities and molecular fractions in the starbursts are lower than those of the Galactic sight lines for similar reddenings (except for NGC 1705). Note that the molecular fractions for the starbursts are probably much lower than the derived upper limits due to the probable underestimation of the H I column density. The three highly reddened Galactic sight lines marked with double circles were noted by Savage et al. (1977) as possibly having strong radiation fields.

If E(B-V)<0.1, H_2 can't shield. At higher A_V, it shields unless the UV background is particularly high

Little diffuse H_2!

Quantitatively, can we predict where H_2 is found?

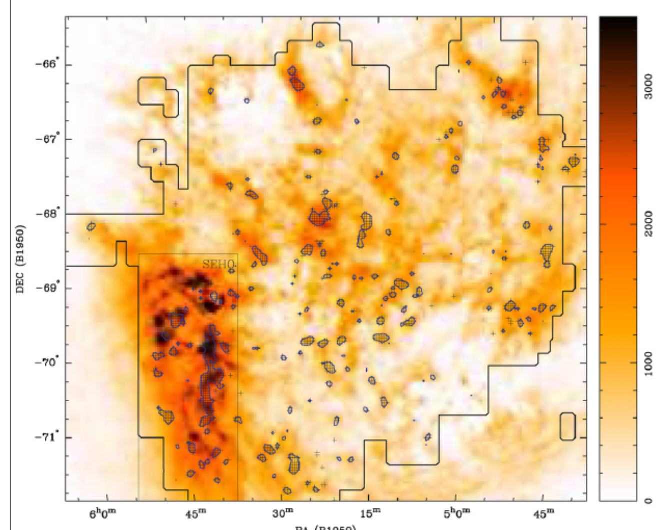


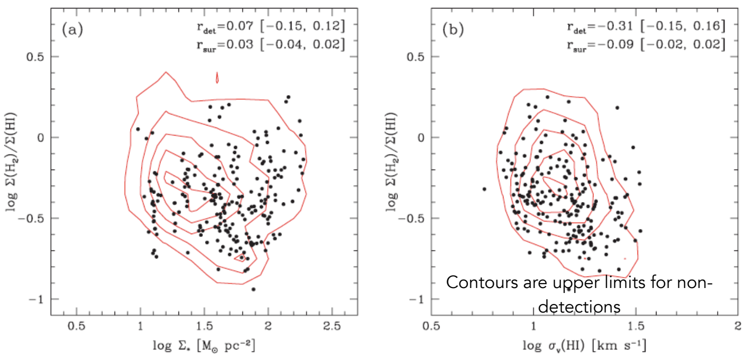
Figure 1. CO contours from NANTEN (at the 1 K km s^{-1} level) overlaid on integrated H I emission smoothed to the resolution of the CO data. Units of the H I intensity are also K km s^{-1}. To reject noise in the contour map, a blanking mask constructed with the CPROPS signal detection algorithm described in Section 3.3 has been applied. The heavy solid contour represents the region observed with NANTEN. Small crosses indicate the pixels which are considered CO detections without the use of a blanking mask. The southeastern H I overdensity (SEHO) is identified at the lower left of the map.

LMC: CO contours on HI map

Wong et al 2009

What does local molecular fraction depend on?

pixel-by-pixel

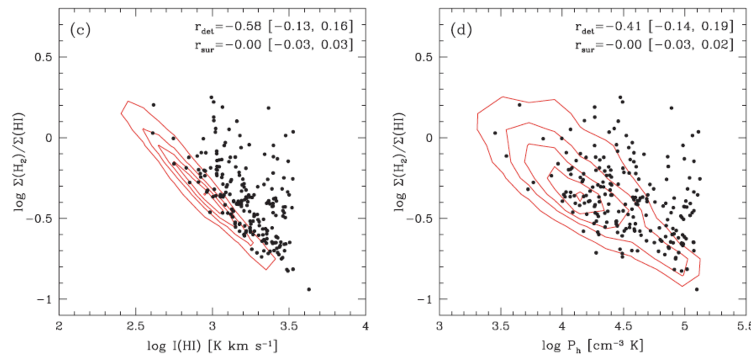


Contours are distribution of upper limits for CO non-detections

Not stellar surface density or gas velocity dispersion

Wong et al 2009

What does local molecular fraction depend on?



Contours are distribution of upper limits for CO non-detections

Maybe HI column density and/or midplane pressure?

Wong et al 2009

Blitz & Rosolowski 2004 have argued that the correlation is due the extra pressure provided by the stars,

To estimate the macroscopic, total, midplane gas pressure, P_{ism}, Elmegreen (1989) derived

$$P_{ism} = \frac{\pi}{2} G\Sigma_{gas}\left(\Sigma_{gas} + \Sigma_{stars}\frac{\sigma_{gas}}{\sigma_{stars}}\right) \quad (1)$$

from numerical solutions to equations of hydrostatic equilibrium for a combined gas and stellar disk (where the Σ and σ are the surface densities and velocity dispersions of the gas and stars). We can obtain a lower limit to P_{ism} from sum of

High mean pressure helps to confine gas clouds, keeping them dense enough that they prefer the molecular phase.

Alternate Model for HI vs H_2

Series of papers by Krumholz, McKee, & Tumlinson (2008,2009) treating dust- and self-shielding to derive analytic form for *f(H_2)*

H_2

Fraction of molecular gas depends on radius of cloud and the thickness of the dissociated shell

Paper I gives analytic expression for the latter

Molecules Shielded

Krumholz et al 2008

Alternate Model for HI vs H_2

Series of papers by Krumholz, McKee, & Tumlinson (2008,2009) treating dust- and self-shielding to derive analytic form for $f(H_2)$

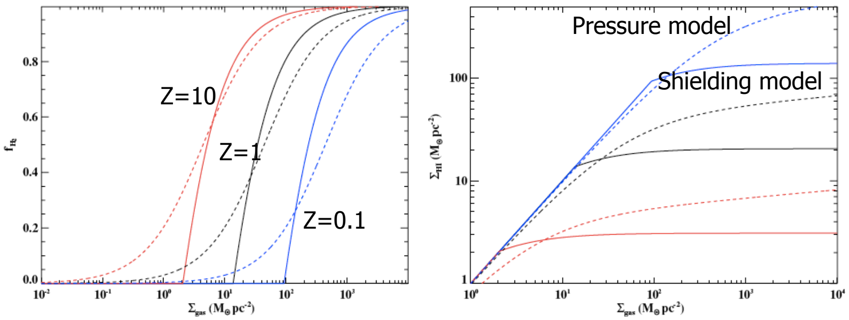


Figure 1. Left panel: molecular fractions computed for the KMT (solid lines) and BR (dashed lines) models. Different lines represent three metallicities for the KMT model (from right to left: $Z' = 0.1$, blue; $Z' = 1$, black; and $Z' = 10$, red) or three stellar densities for the BR model (from right to left: $\rho'_{star} = 0.001$, blue; $\rho'_{star} = 0.1$, black; and $\rho'_{star} = 10$, red). For the KMT model, we assume a clumping factor $c = 1$. Blue compact dwarfs (BCDs) at low metallicities and high stellar densities are the optimal systems to disentangle between the two models which are degenerate in massive spiral galaxies with solar metallicity (compare the two black lines). Right panel: models for the H I surface density as a function of the total gas column density, for the same parameters adopted in the left panel. While the KMT model exhibits a well-defined saturation in the atomic hydrogen, in the BR model Σ_{HI} increases asymptotically with Σ_{gas}.

Fumagalli et al 2010