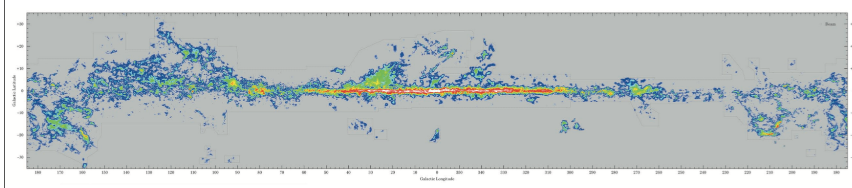
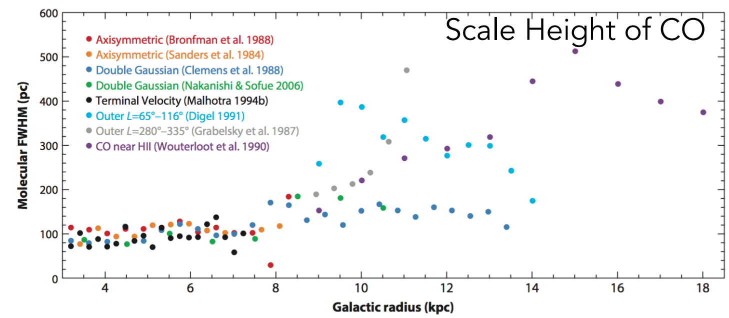
Molecular Gas

- 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

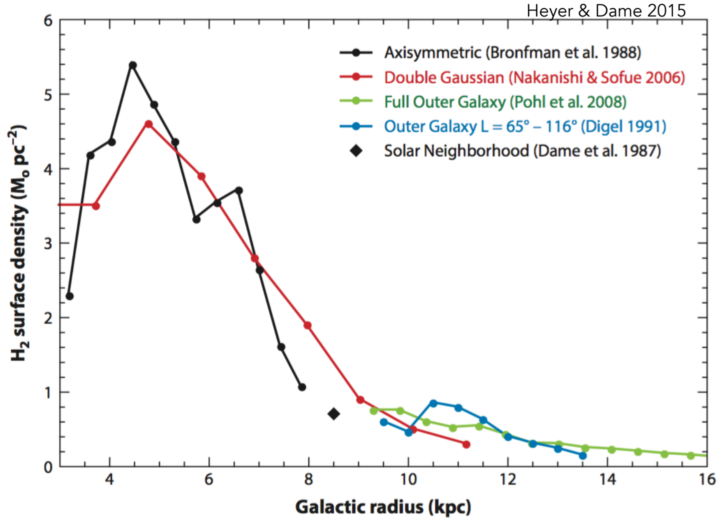


Milky Way in CO; Dame et al. 2001

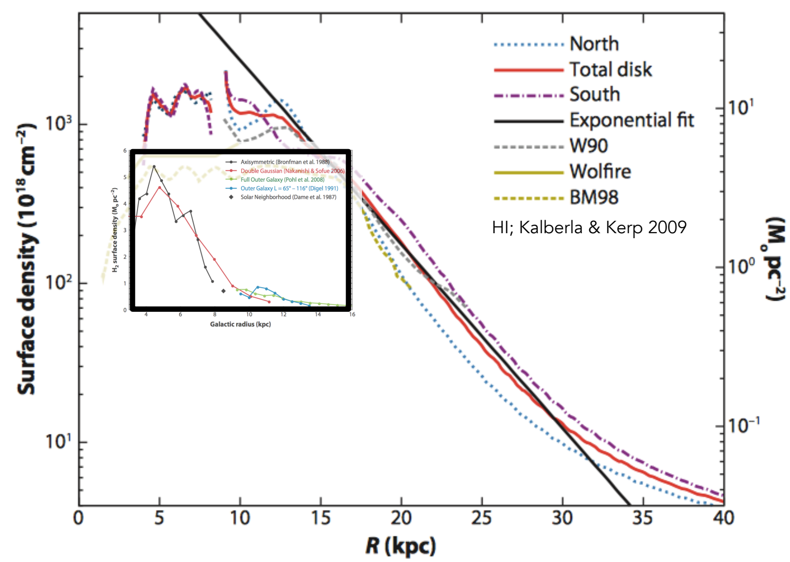


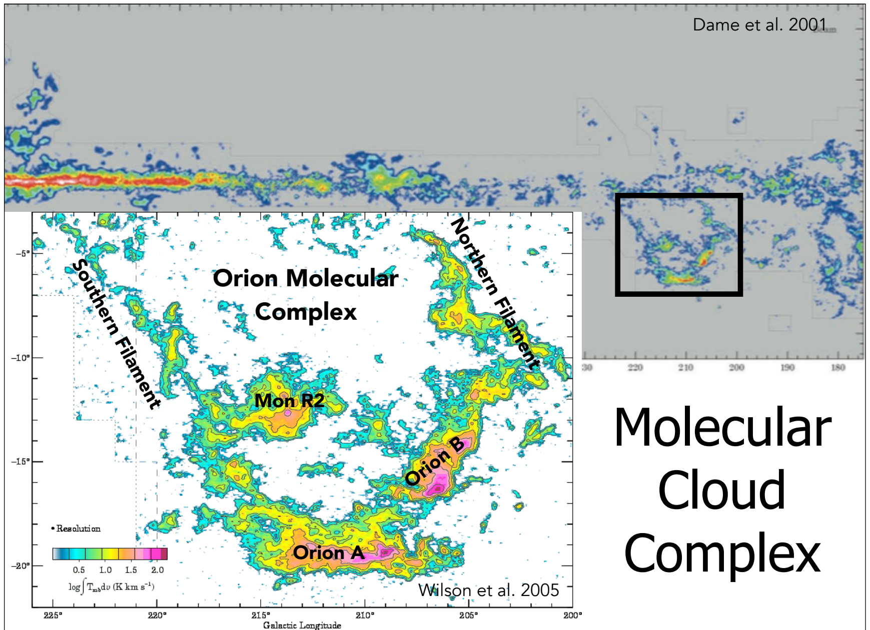
Molecular Gas: Surface density profile

Heyer & Dame 2015



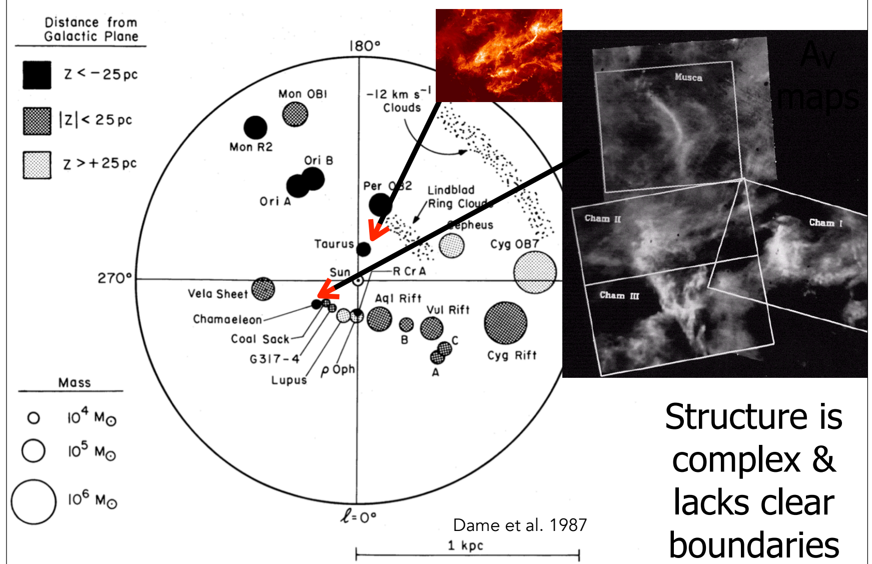
MW Surface Density: HI vs H_2





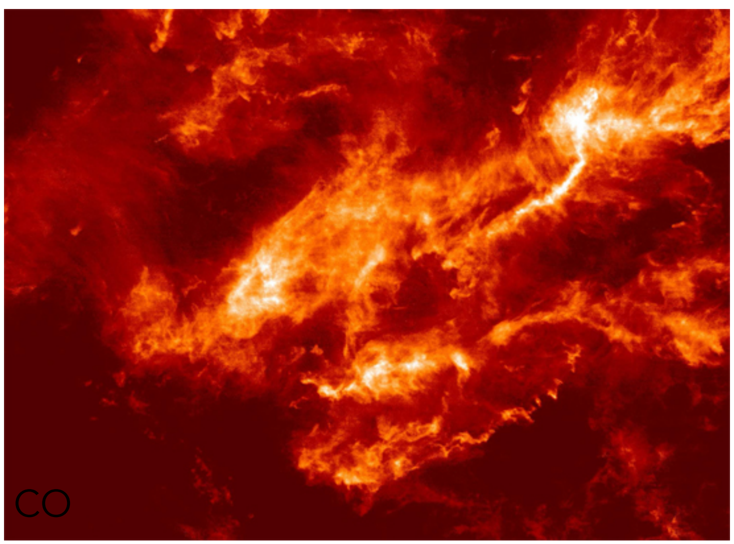
Molecular Cloud Complex

Well-studied local molecular clouds



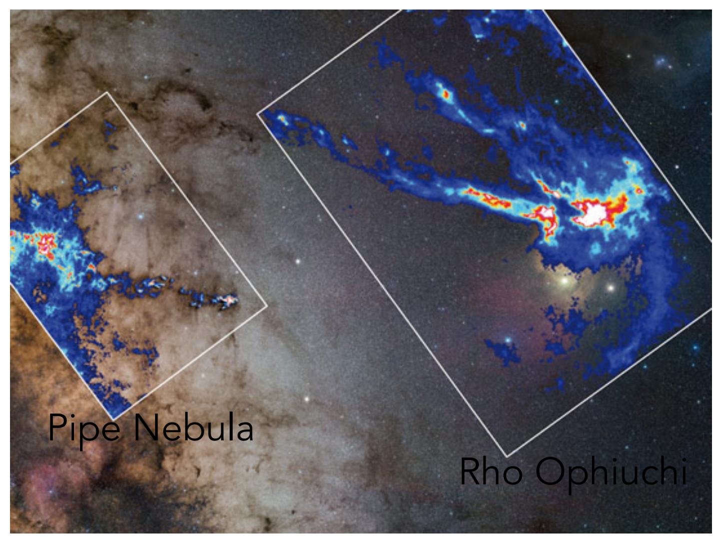
Structure is complex & lacks clear boundaries

Taurus Molecular Cloud



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

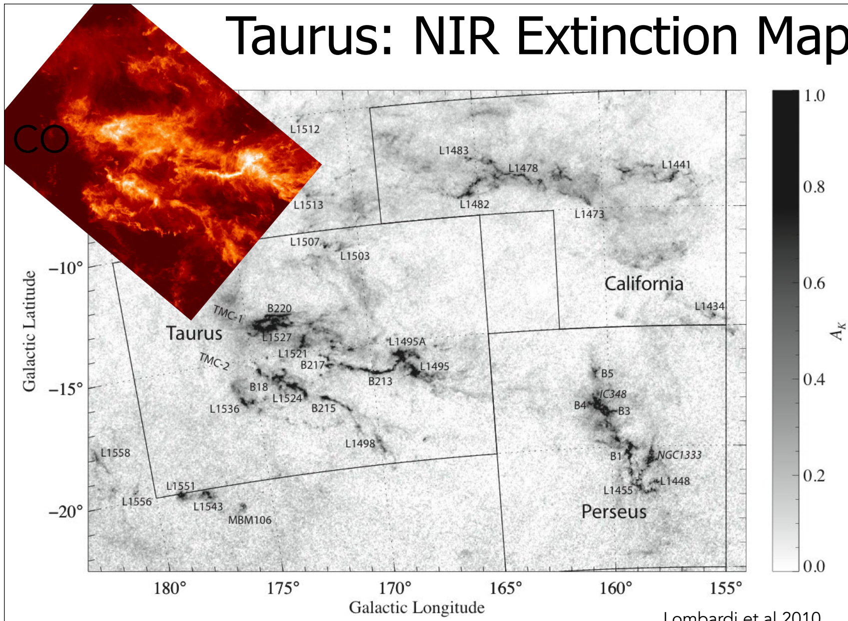
Frequently mapped via extinction



Kainulainen et al 2014

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

Taurus: NIR Extinction Map



Lombardi et al 2010

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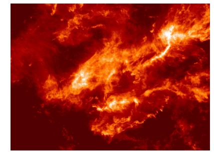
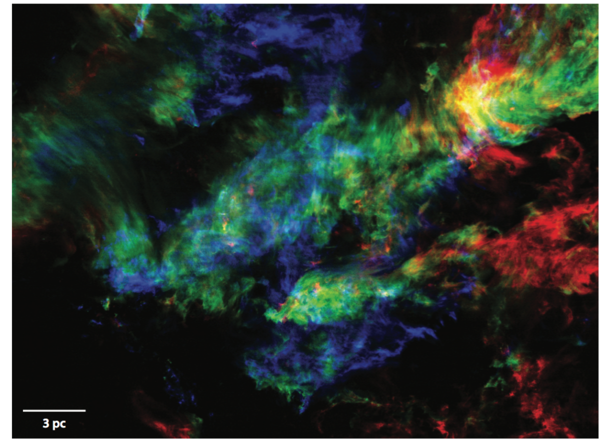
MCs have internal velocity structure





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.

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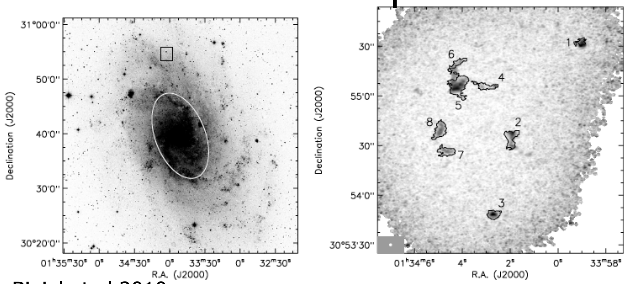
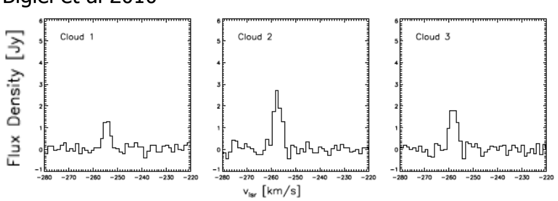
Identification requires molecular clouds to be distinct in space & velocity



7pc spatial resolution

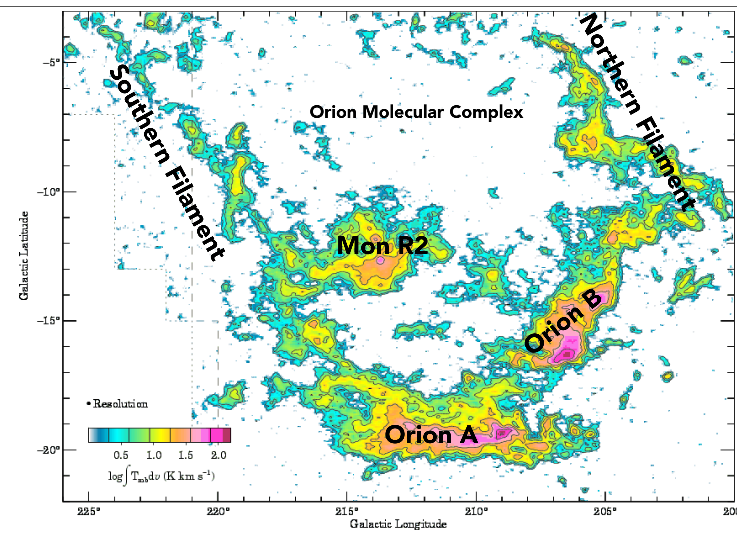
Bigiel et al 2010



1.3 km/s velocity resolution

Example of molecular cloud identification

11



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

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Giant Molecular Clouds (GMCs)

Discrete in position and velocity space

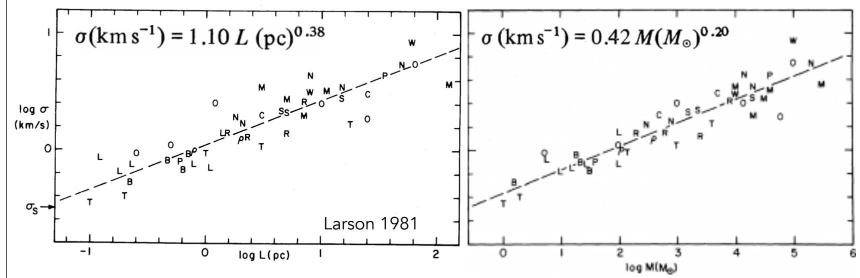
10^3-10^6 $M_\odot$

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

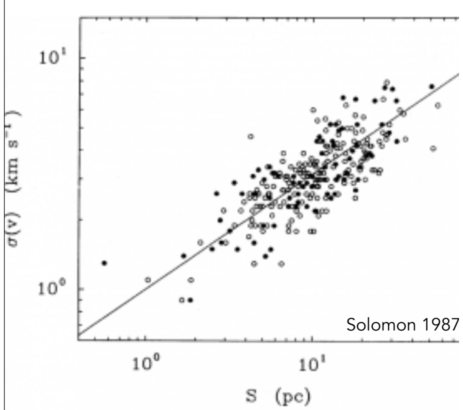


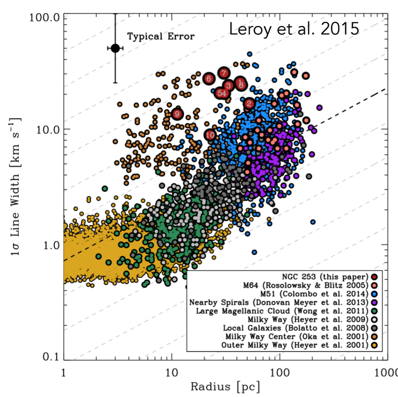
Defined for Milky Way molecular clouds

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

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

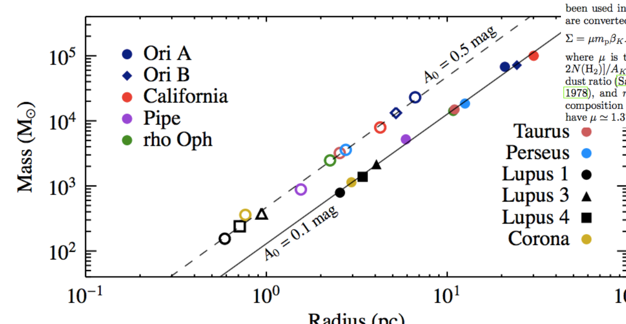
Larson's Laws vs modern data





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

$$\Sigma = \mu m_{\rm p} \beta_K A_K \,, \qquad (1)$$

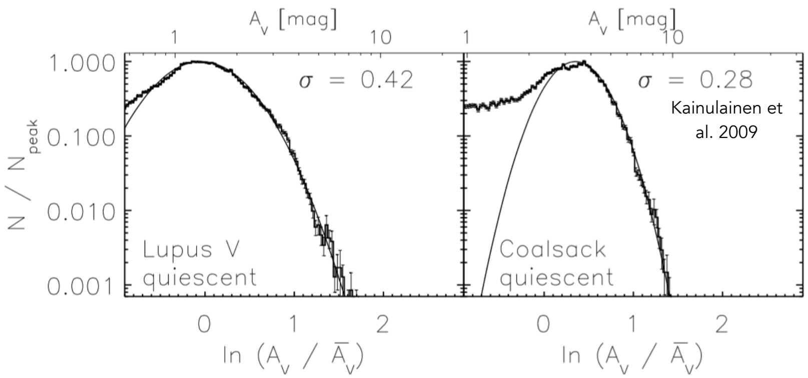
where μ is the mean molecular weight, $\beta_K \equiv [N(\mathrm{H\,I}) + 2N(\mathrm{H_2})]/A_K \simeq 1.67 \times 10^{22}$ cm^{-2} mag^{-1} is the gas-to-dust ratio (Savage & Mathis 1979; Lilley 1955; Bohlin et al. 1978), and $m_{\rm p}$ is the proton mass. With a standard gas composition (63% hydrogen, 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

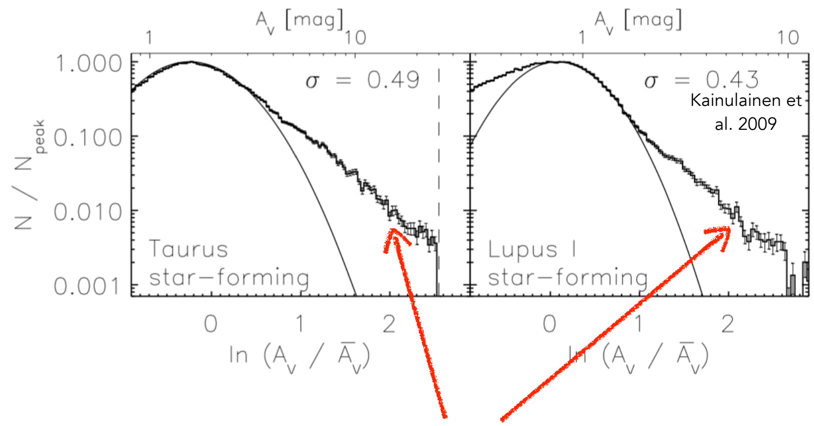
Molecular cloud internal structure



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

17

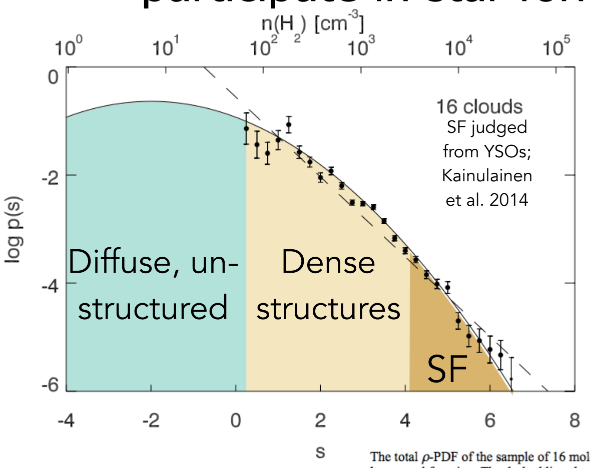
Molecular cloud internal structure



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

18

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



2.5% of molecular gas is "SF"

16% of "SF" gas turns into stars

Thus need 30M⊙ cloud to form a 0.8M⊙ star, and 70,000M⊙ to form a 20M⊙ star

$s = \ln(\rho/\rho_0)$ 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.

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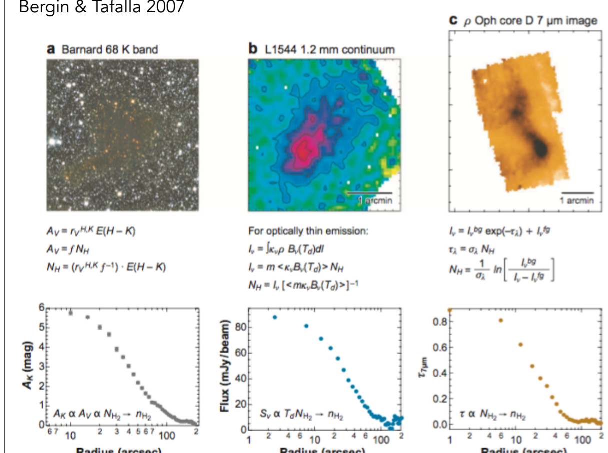
Molecular clouds host "cores"

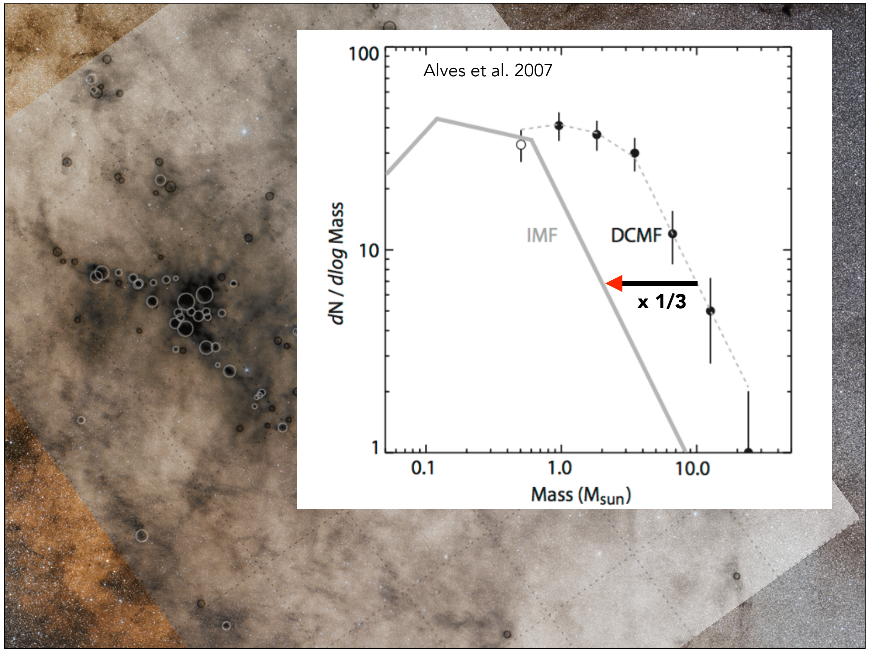
Bergin & Tafalla 2007



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

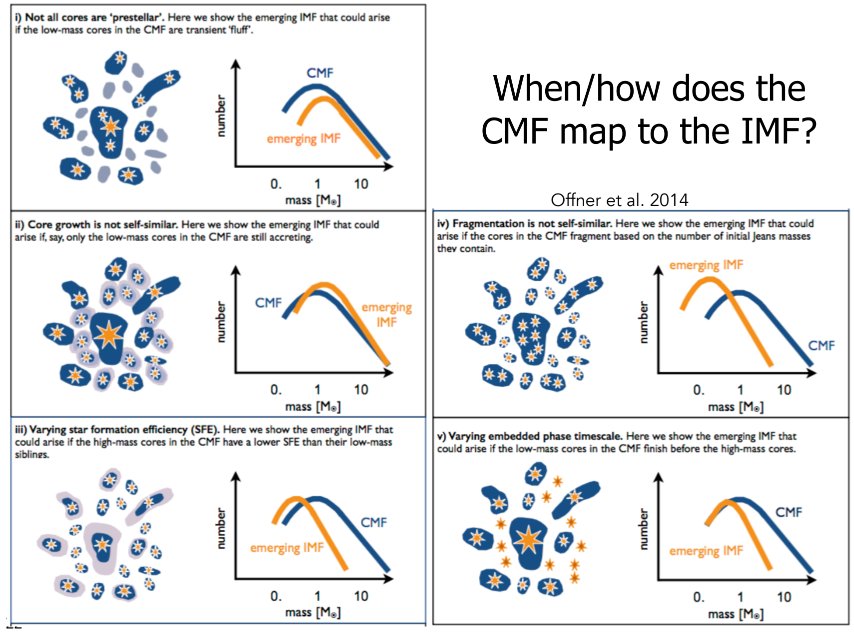
20

*See derivation of Bonner-Ebert sphere in Krumholz

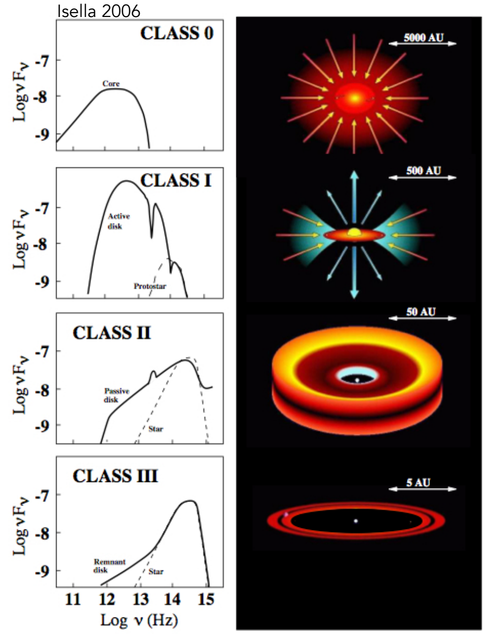


When/how does the CMF map to the IMF?

Offner et al. 2014



Isella 2006



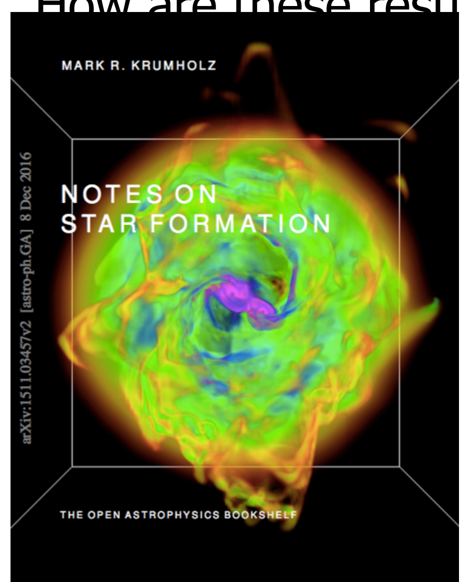
Gravitational collapse

Angular momentum
-> disk formation
-> outflows & jets

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

Most material accreted, remnant disk.

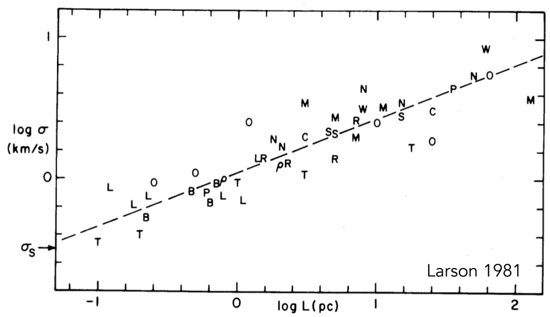
How are these results interpreted?



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": $\alpha_{\mathrm{vir}} = \dfrac{2\mathcal{T}}{|\mathcal{W}|}$

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: $\alpha_{\mathrm{vir}} = 5\sigma_v R/GM$

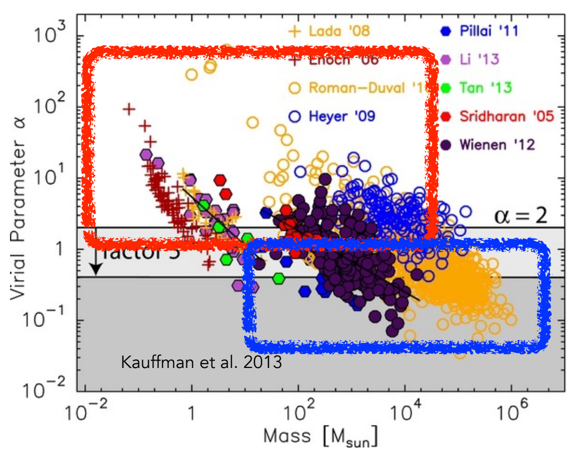
 See Chapter 6 of Krumholz: https://arxiv.org/abs/1511.03457

The physical state of molecular clouds

2. It is unclear whether clouds are gravitationally bound

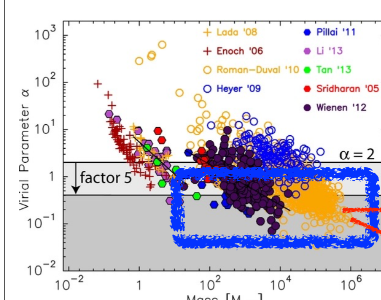
Lower mass MCs seem less likely to be bound

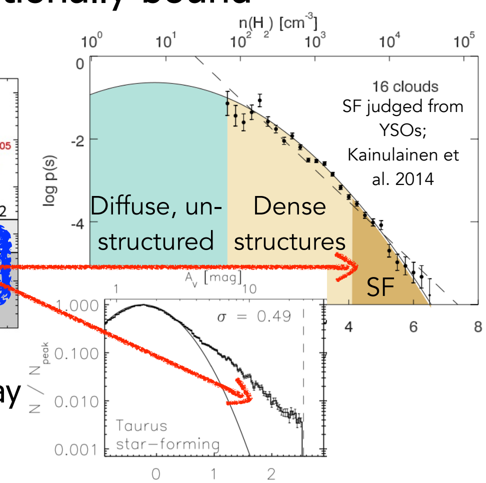
Higher mass ones do seem bound



The physical state of molecular clouds

2. It is unclear whether clouds are gravitationally bound





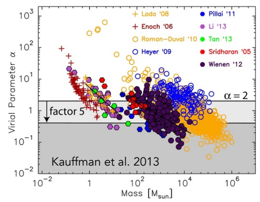
SF & high density tails may be where self-gravity is dominating evolution

The physical state of molecular clouds

3. Other factors are important for confinement

Full virial theorem*

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



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

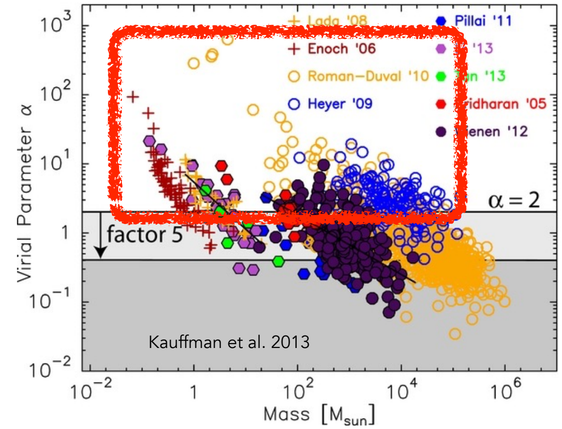
$$\mathcal{B} = \frac{1}{8\pi}\int_V (B^2 - B_0^2)\,dV$$ Net magnetic energy (for field B in cloud)

*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.