Schmidt's Conjecture and Star Formation Scaling Relations in GMCs and Galaxies

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Schmidt's Conjecture:

"It would seem most probable that the rate of star formation depends on the gas density and we shall assume that the number formed per unit interval of time varies with a power of the gas density ..." Schmidt (1959)

Formulating the Schmidt Scaling Law

Areal (Empirical)[1]:

$$\Sigma_{SFR} = \kappa\,(\Sigma_g)^{\beta}$$

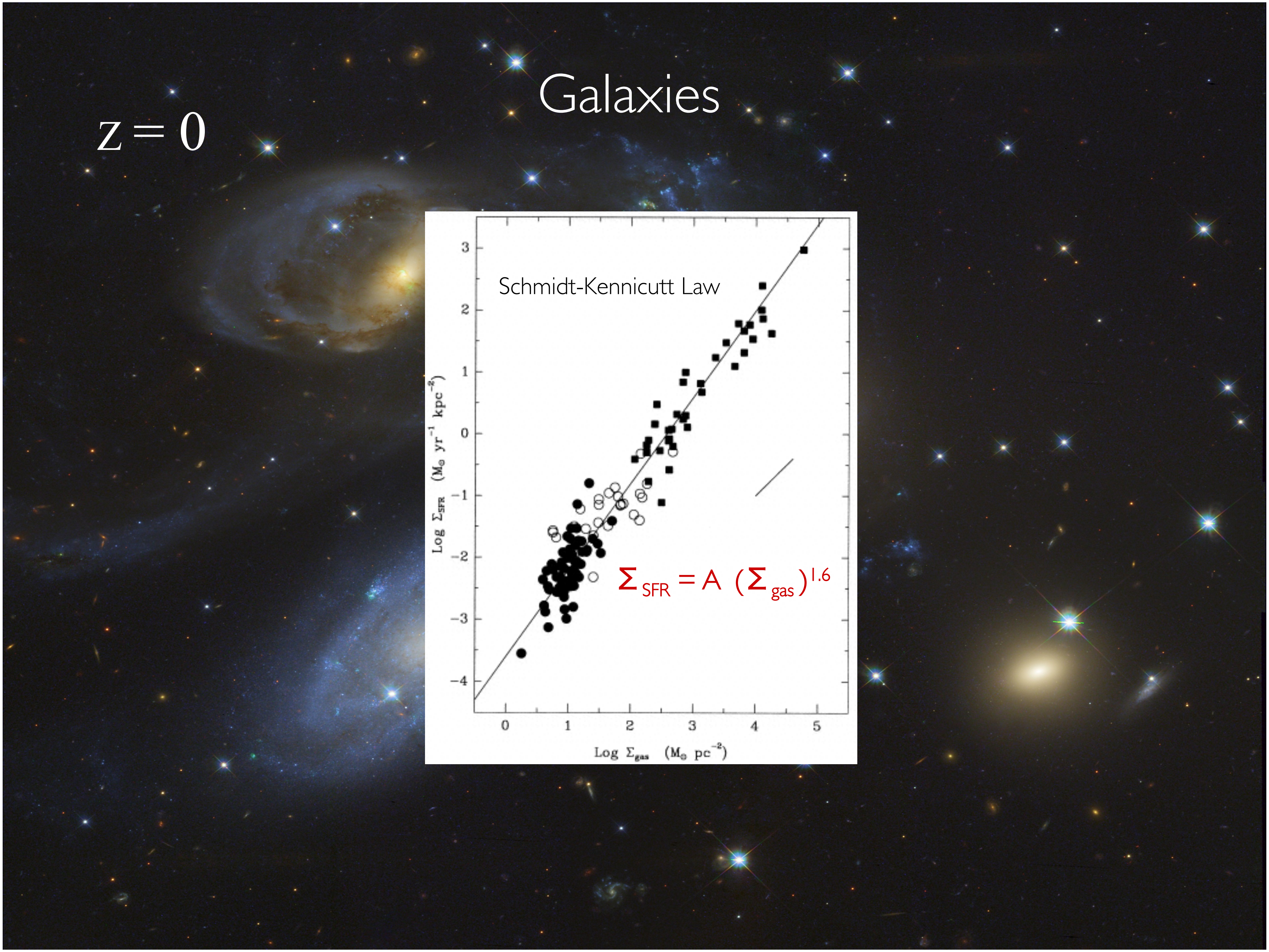
Volumetric (Theoretical):

$$\rho_{SFR} = K(\rho_g)^{\alpha}$$

[1]Kennicutt-Schmidt Law

Galaxies

$z = 0$



Schmidt-Kennicutt Law
$\Sigma_{SFR} = A \; (\Sigma_{gas})^{1.6}$
Log Σ_{SFR} ($M_\odot$ yr^{-1} kpc^{-2})
Log Σ_{gas} ($M_\odot$ pc^{-2})
3
2
1
0
−1
−2
−3
−4
0
1
2
3
4
5

Molecular Clouds

A Bayesian Approach

The Areal Schmidt Law

$$\Sigma_*(A_K) = \kappa (A_K)^\beta$$

Σ_* = Protostellar surface density (stars pc^{-2})

A_K = Extinction (dust surface density)

κ = Star formation coefficient

β = Power-law scaling index

The Areal Schmidt Law

Relation between Σ_{SFR} and Σ_*

$$\Sigma_{SFR} = (<m_*>/t_{sf})\ \Sigma_*(A_K)$$

Bayes' Theorem

$$P(\theta|D) = P(D|\theta)\, p(\theta) \div P(D)$$

Given:

Positions: $\{x_n\}$

Extinctions: $\{(A_K)_n\}$

Model : $\Sigma_*(x|\theta)$

$$\ln \mathcal{L}\big(\{x_n\}|\theta\big) = \sum_{n=1}^{N} \ln \Sigma_*(x_n|\theta) - \int \Sigma_*(x|\theta)\, \mathrm{d}^2 x$$

Lombardi 2013

Bayes' Theorem

$$P(\theta|D) = P(D|\theta)\; p(\theta) \div P(D)$$

Given:

Positions: $\{x_n\}$

Extinctions: $\{(A_K)_n\}$

Model : $\Sigma_*(x|\theta)$

Infer:

Parameters: θ

$$\Sigma_* = \kappa \mathrm{A}_K^{\beta}(x)$$

κ = star formation coefficient

β = power-law index

$$\Sigma_*^{(0)}(x) = \kappa H(A_K(x) - A_0)\left(\frac{A_K(x)}{1\ \mathrm{mag}}\right)^{\beta}$$

$$H(z) = \begin{cases} 1 & \text{if } z > 0\,, \\ 0 & \text{if } z \leq 0\,. \end{cases}$$

A_0 = extinction threshold (mag)

$$\Sigma_*(x) = \int \frac{1}{2\pi\sigma^2}\; e^{|x-x'|^2/2\sigma^2}\Sigma_*^{(0)}(x')\,d^2x'$$

σ = diffusion coefficient (pc)

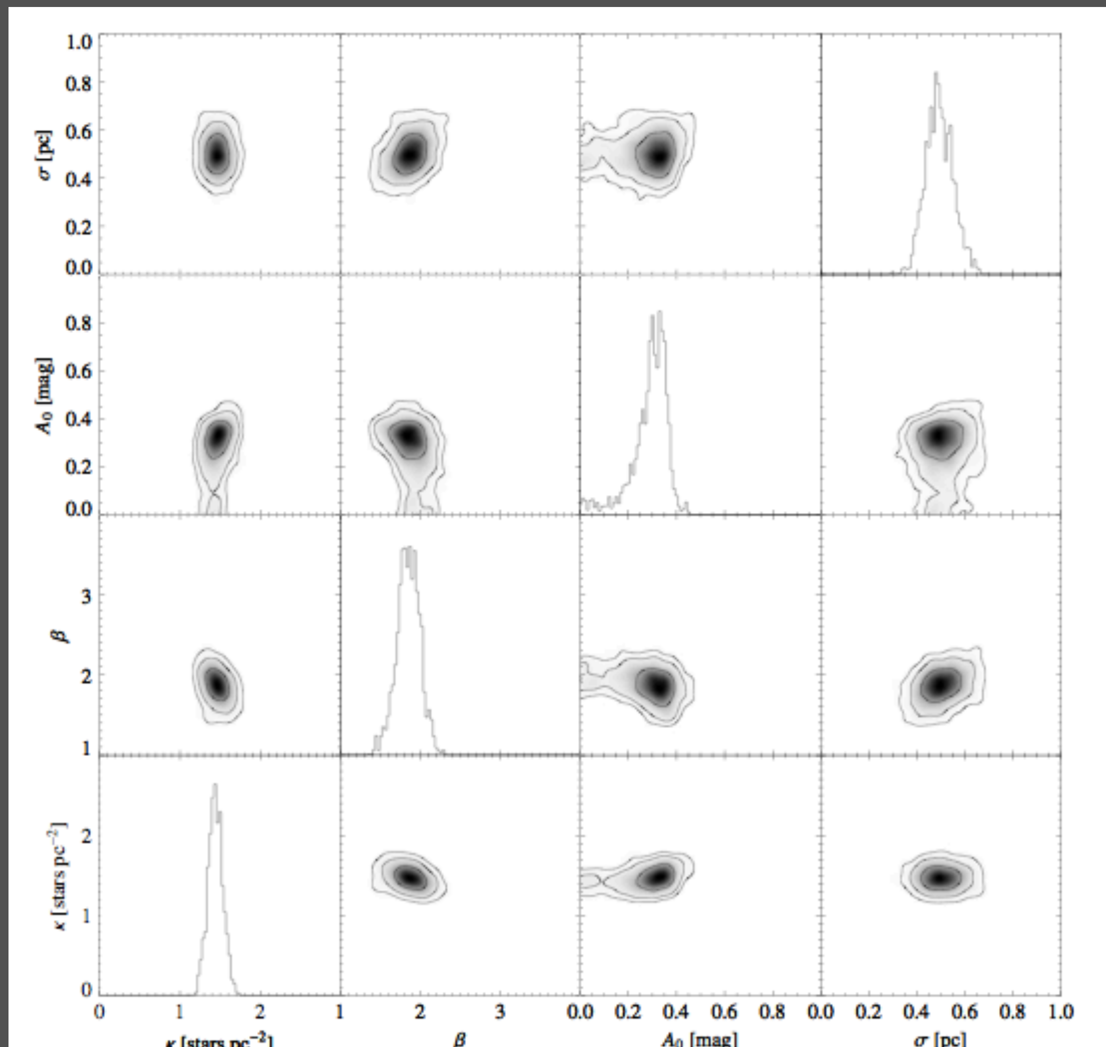
Results

An Areal Schmidt Law Within GMCs

Method Verification with Simulations

Input: $\beta = 1.8$; $\kappa = 1.5$ $\sigma = 0.5$; $A_0 = 0.3$

Output:



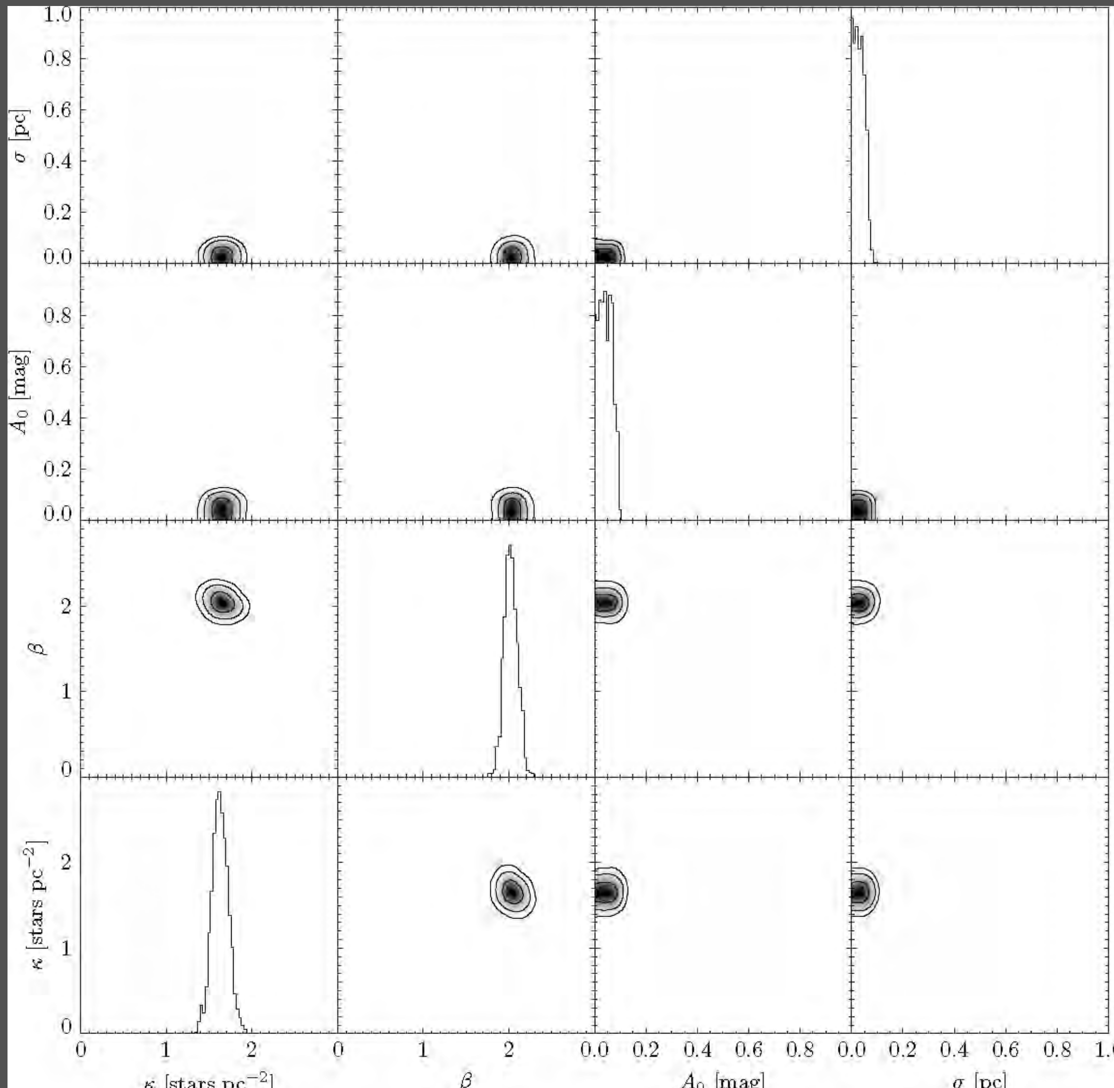
Data: Protostellar Catalogs

Orion A + B: Megeath et al. 2012

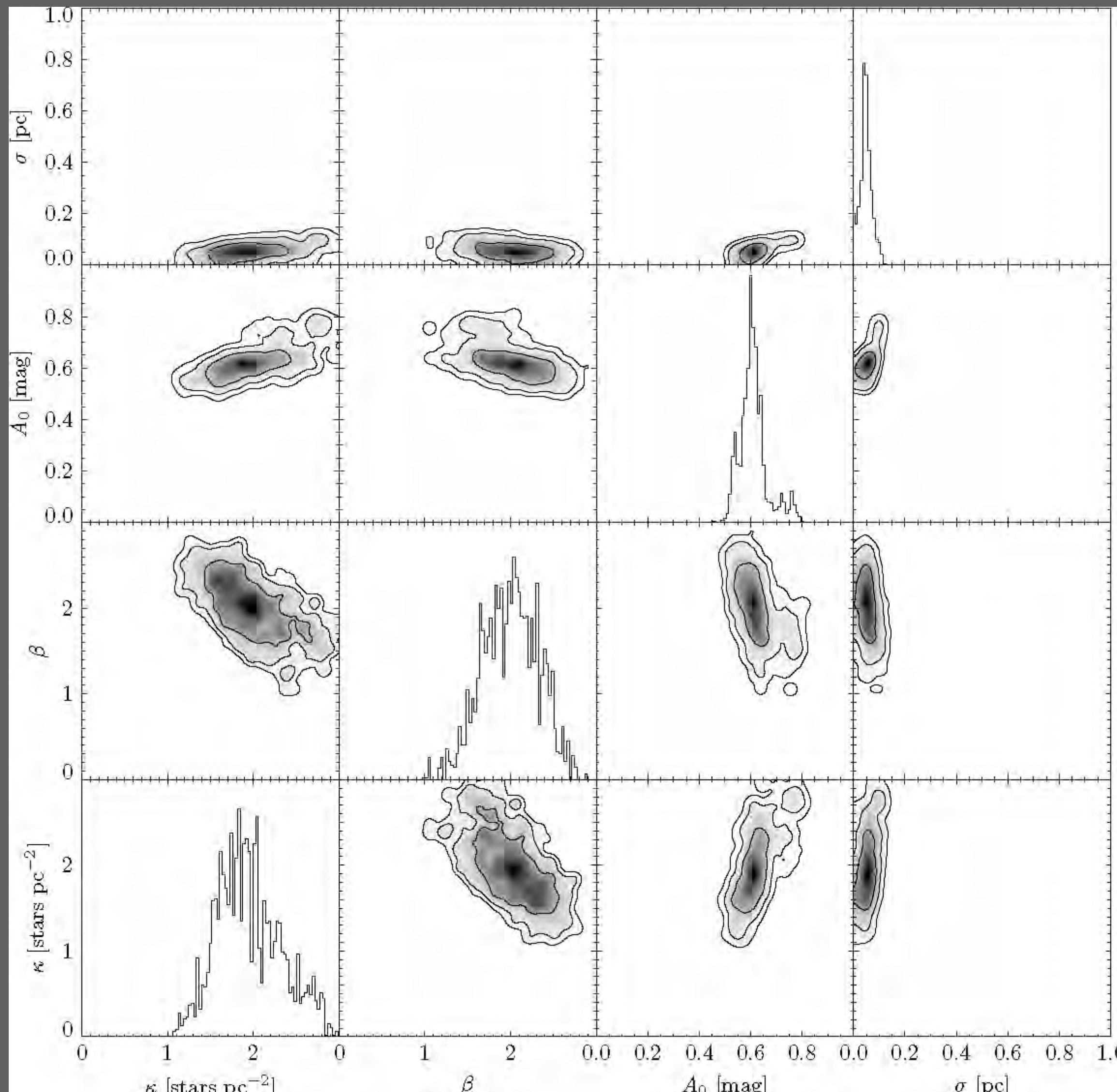
TAURUS: Rebull et al. 2011

California: Harvey et al. 2013

Probabilities for parameters in Orion A



Probabilities for parameters in California Cloud

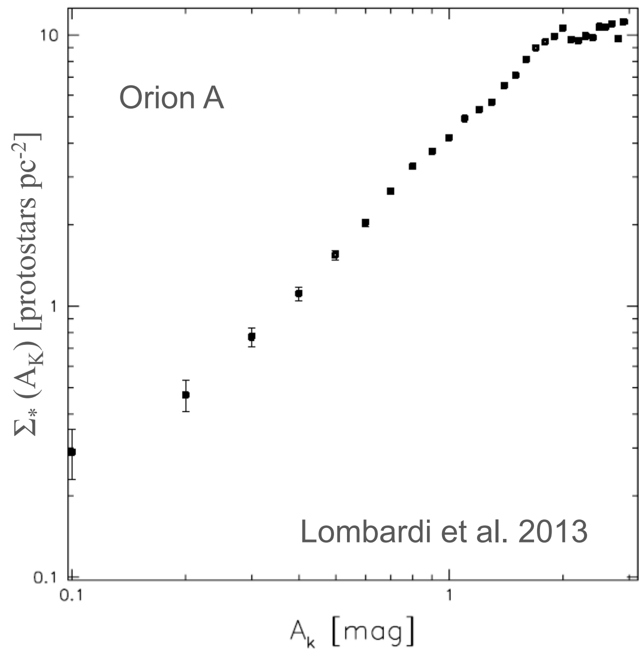


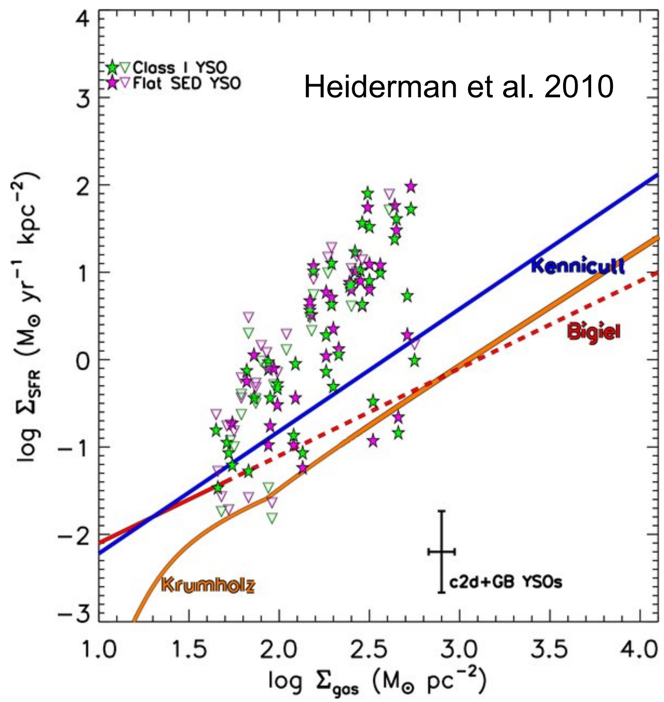
$$\Sigma_* = \kappa (A_K)^\beta \quad \text{protostars pc}^{-2}$$

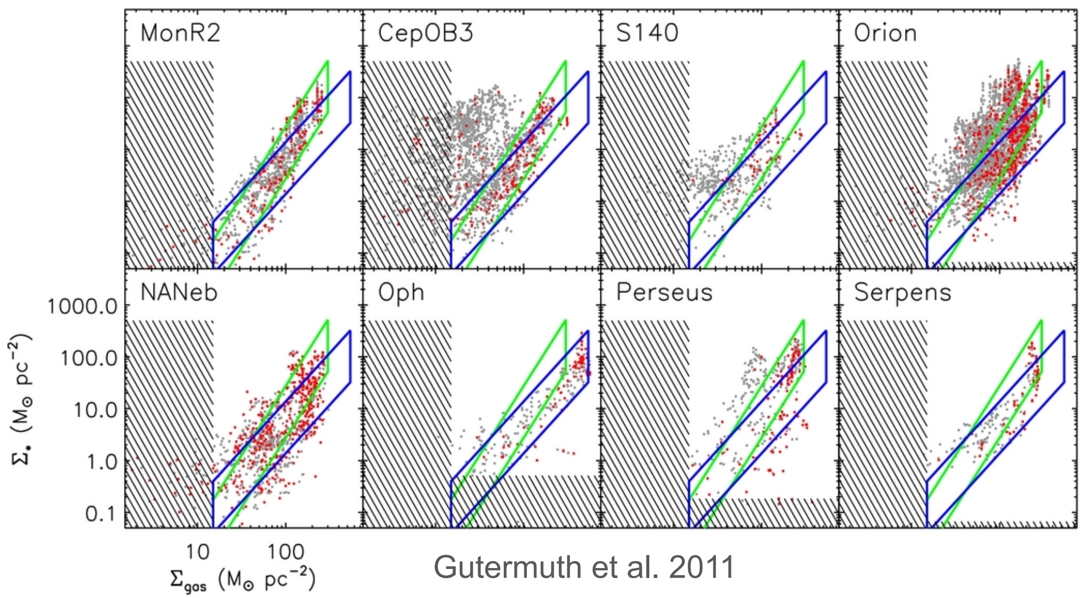
Derived Parameters:

	Orion A	California	Taurus	Orion B
β	2.03 +/- 0.08	1.99 +/- 0.32	2.09 +/- 0.14	3.30 +/- 0.21
κ	1.65 +/- 0.09	2.05 +/- 0.40	2.08 +/- 0.30	0.77 +/- 0.11
σ	0.03 +/- 0.02	0.05 +/- 0.02	0.01 +/- 0.01	0.04 +/- 0.02
A_0	0.04 +/- 0.03	0.62 +/- 0.04	0.03 +/- 0.02	0.26 +/- 0.14

An Areal Schmidt Law Exists *within* GMCs





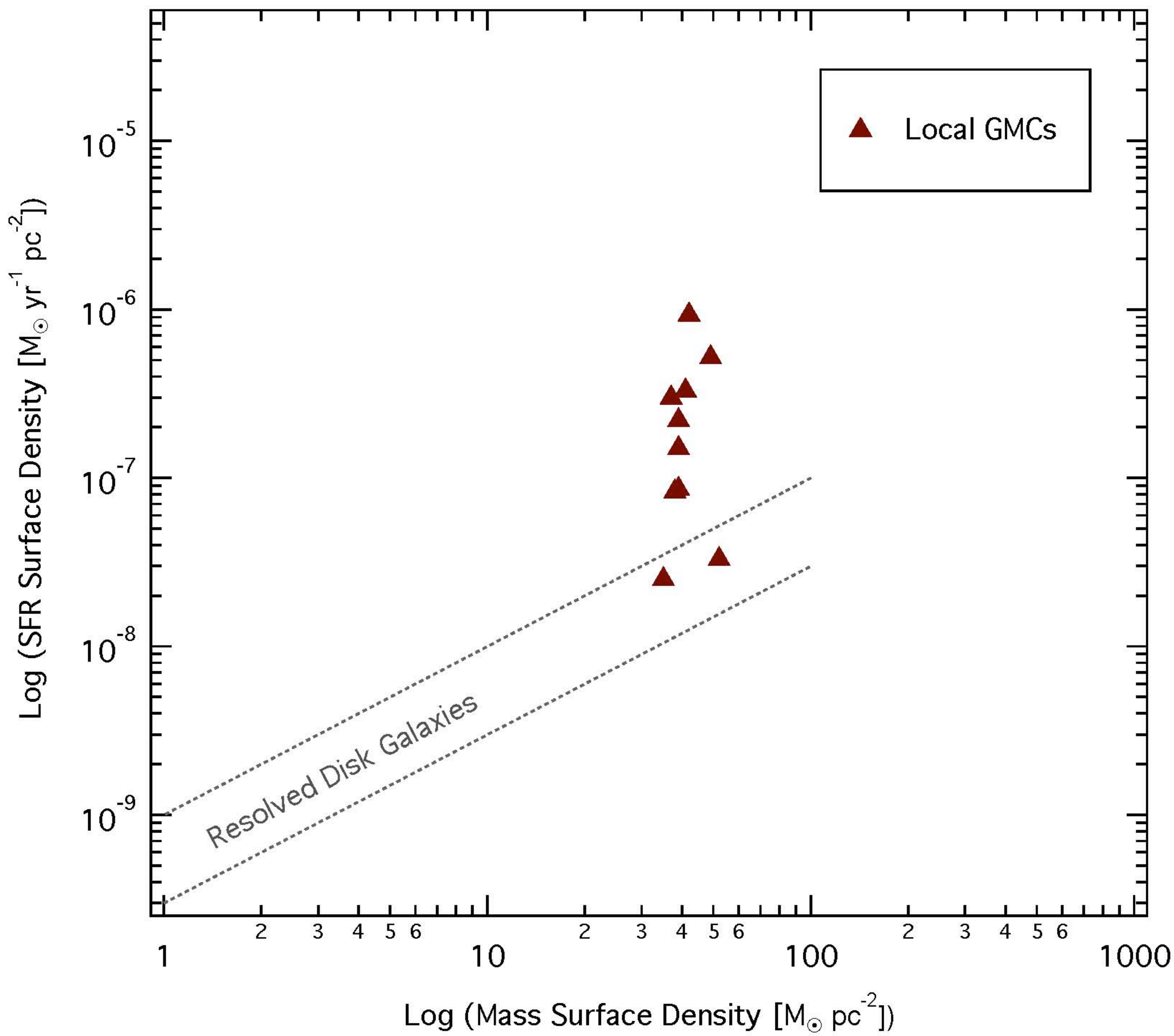


Gutermuth et al. 2011

Between GMCs ?

NO Schmidt Law Between Clouds

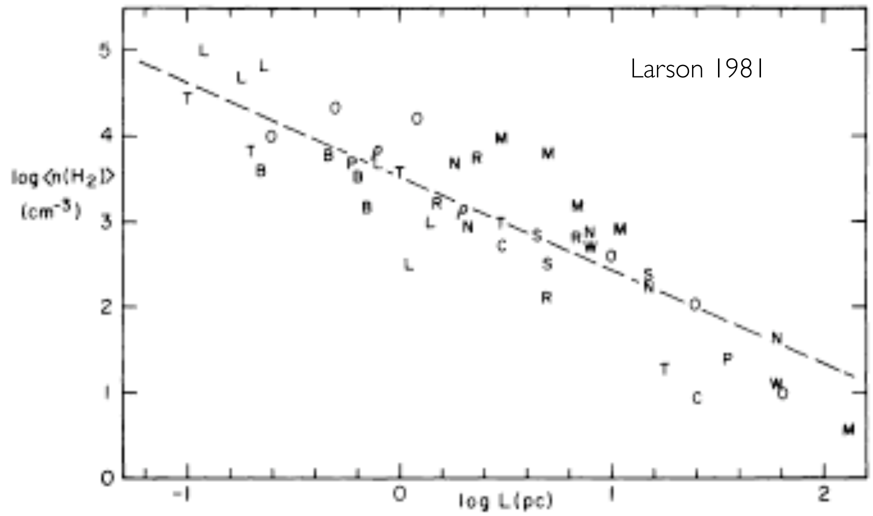
An Areal Schmidt Law Does NOT Exist *between* GMCs



An Areal Schmidt Law Does NOT Exist *between* GMCs

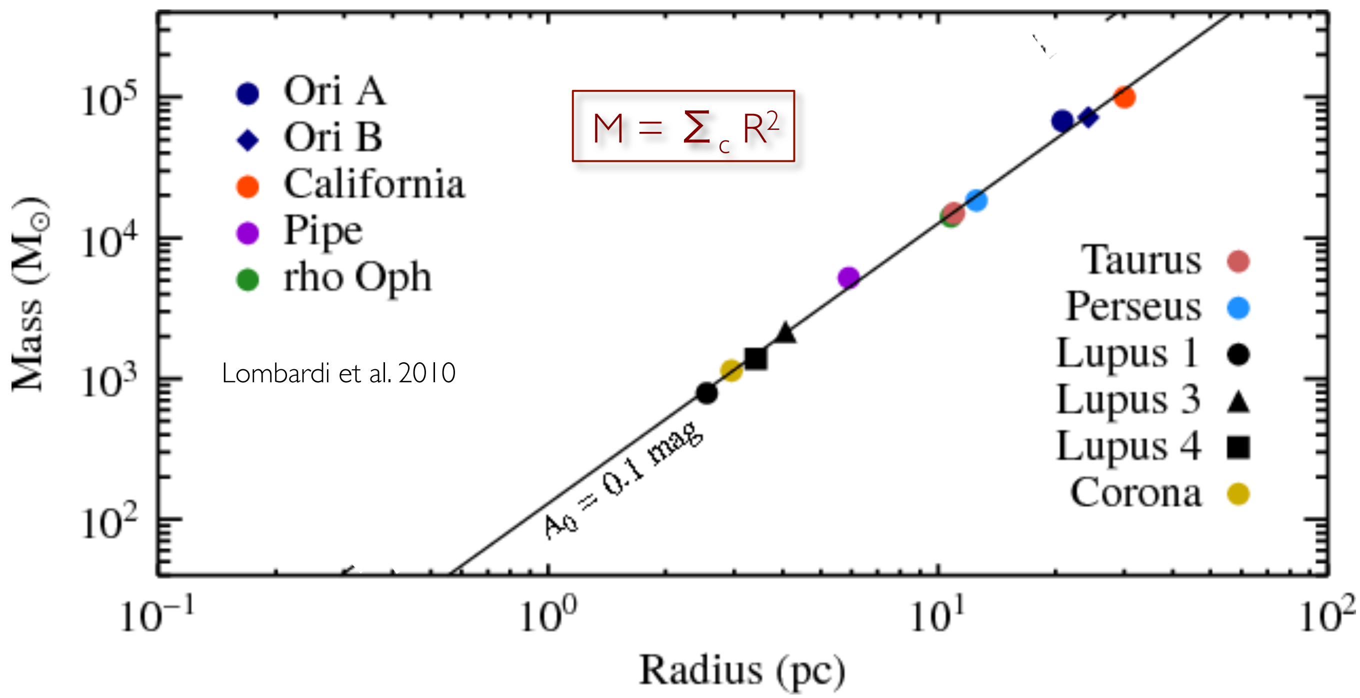
Because of the

GMC Scaling Laws:

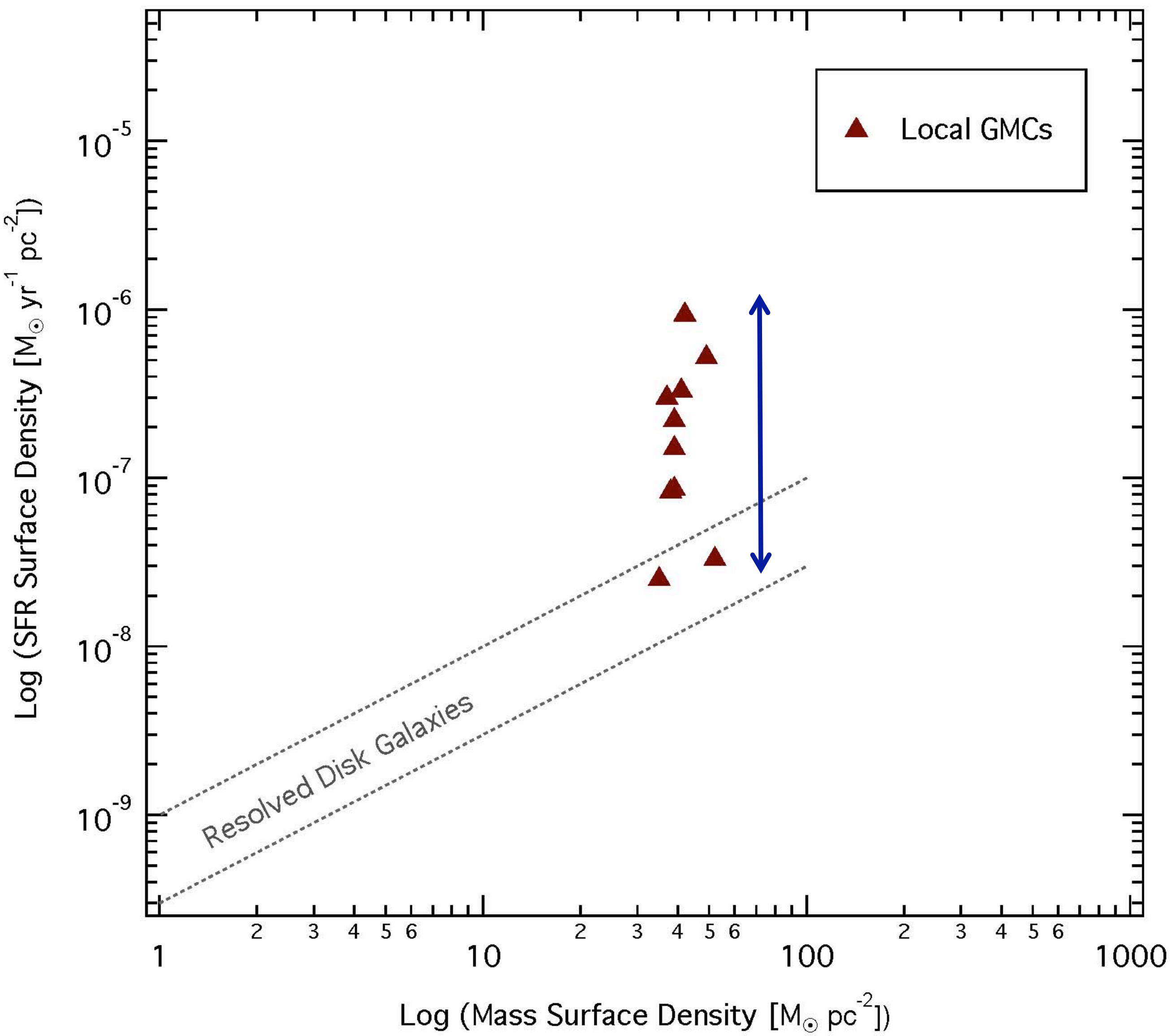


$n(H_2) \sim L^{-1}$

or $M \sim R^2$

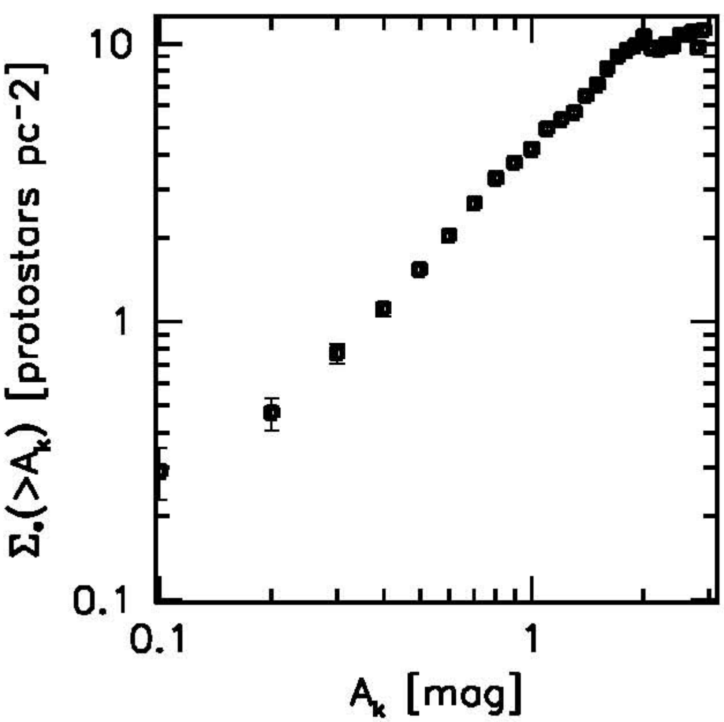


An Areal Schmidt Law Does NOT Exist Between GMCs

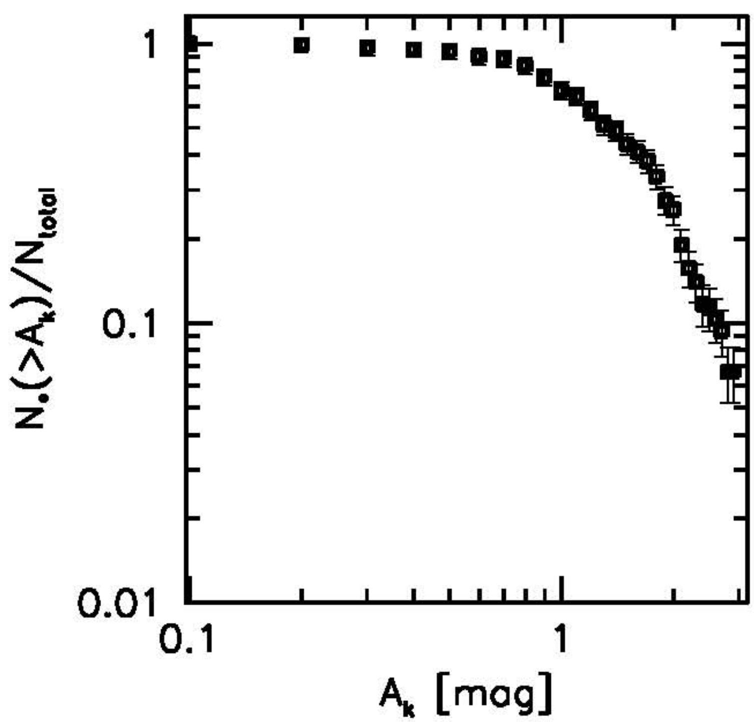


Integral Protostellar Distribution Functions in Orion A

Protostellar Surface Density (A_K)



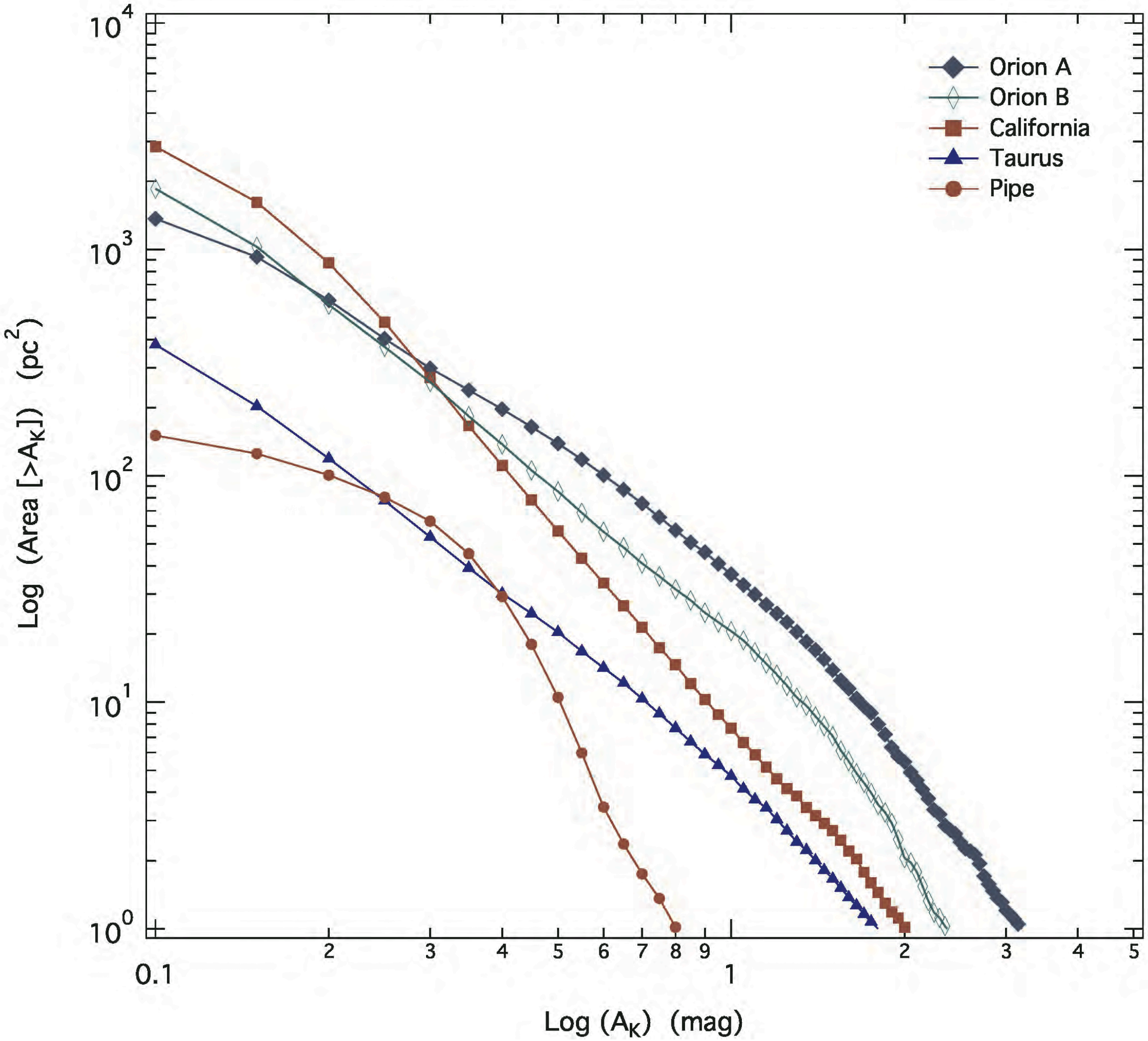
$f_{proto}(A_K)$



$$N_*(>A_K) = \Sigma_*(>A_K)\ x\ \text{Surface area}(>A_K)$$

Lada et al (2013)

Surface Area Distribution Function S(>A_K)



Complete Description of Star Formation in Clouds:
Requires Including the Critical Role of Cloud Structure

$$N_* = \int \Sigma_*(A_\mathrm{K})\,\mathrm{d}S = \int \Sigma_*(A_\mathrm{K}) \left| S'(> A_K) \right| \mathrm{d}A_\mathrm{K}$$

$S'(>A_K)$ = Differential Surface Area Distribution Function

Complete Description of Star Formation in Clouds: Requires Including the Critical Role of Cloud Structure

$$N_* = \int \Sigma_*(A_{\mathrm{K}})\,\mathrm{d}S = \int \Sigma_*(A_{\mathrm{K}}) \left| S'(> A_K) \right| \mathrm{d}A_{\mathrm{K}}$$

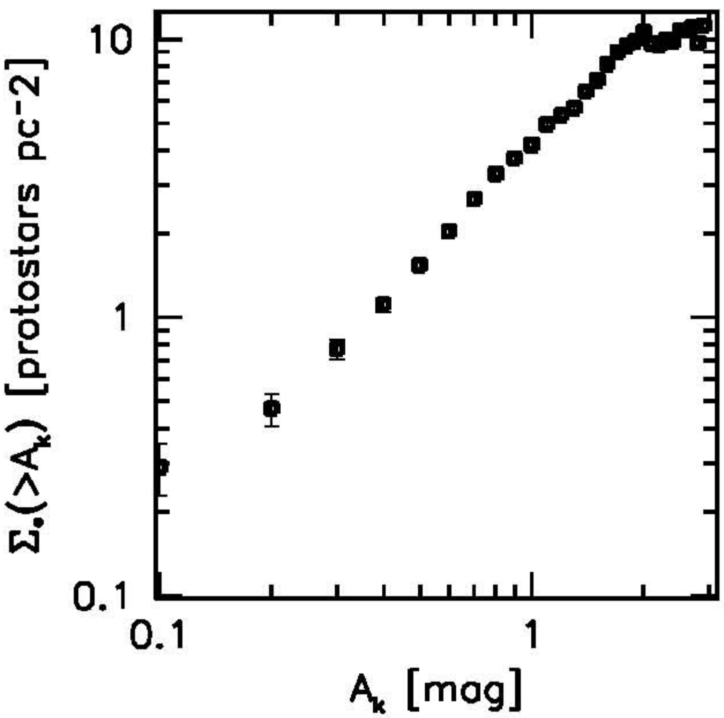
For Clouds with similar $\Sigma_*(A_K)$, differences in SFRs due to differences in $S(>A_K)$!

The Star Formation Scaling Law Between Clouds

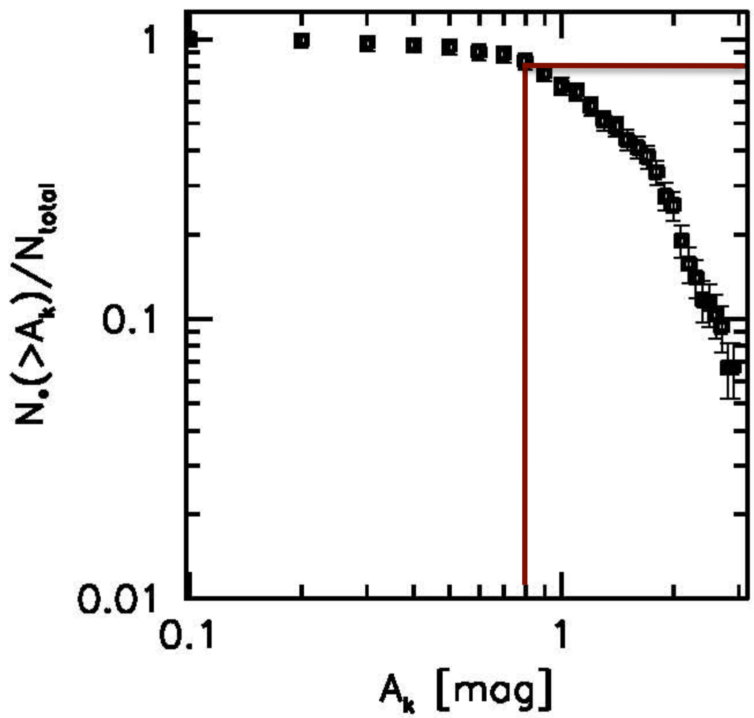
Integral Protostellar Distribution Functions in Orion A

80% of protostars @ $A_K > 0.8$ mag.

Protostellar Surface Density (A_K)

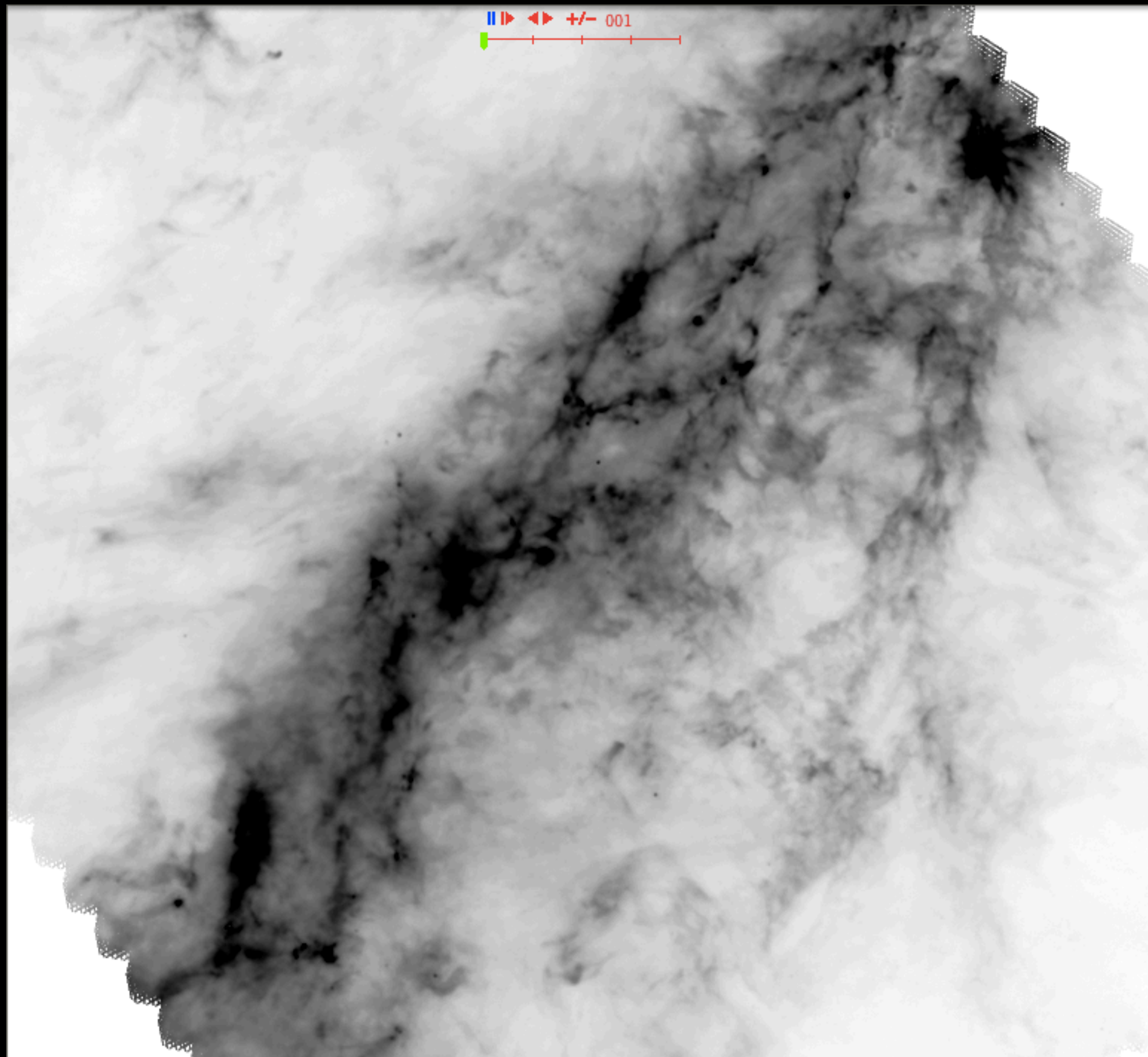


$f_{proto}(A_K)$



Lada et al (2013)

Orion: Herschel (250μm)



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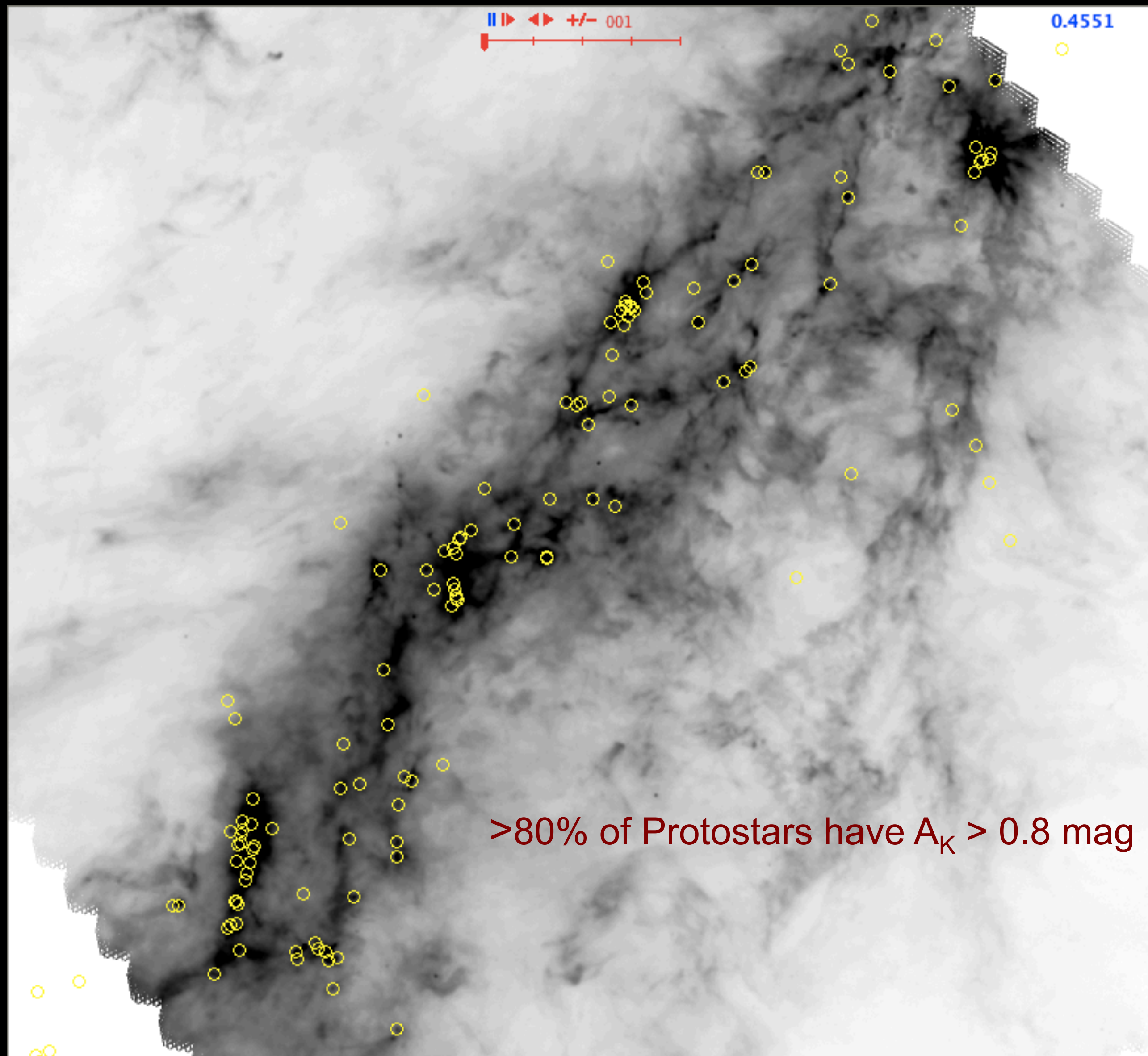
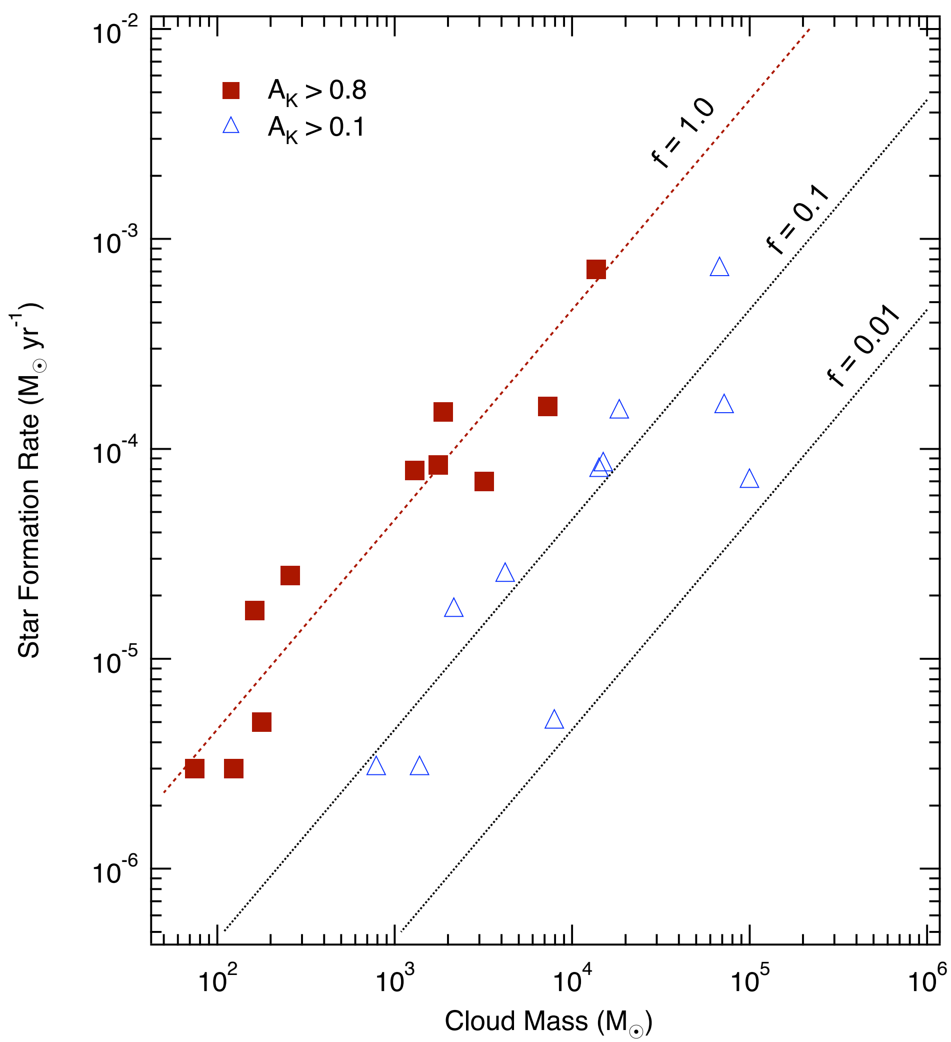


Star Formation Scaling Law between Local Clouds

$$SFR = (4.6 \times 10^{-8}\, f)\, M_{gas} \quad (M_o\ yr^{-1})$$



Where:

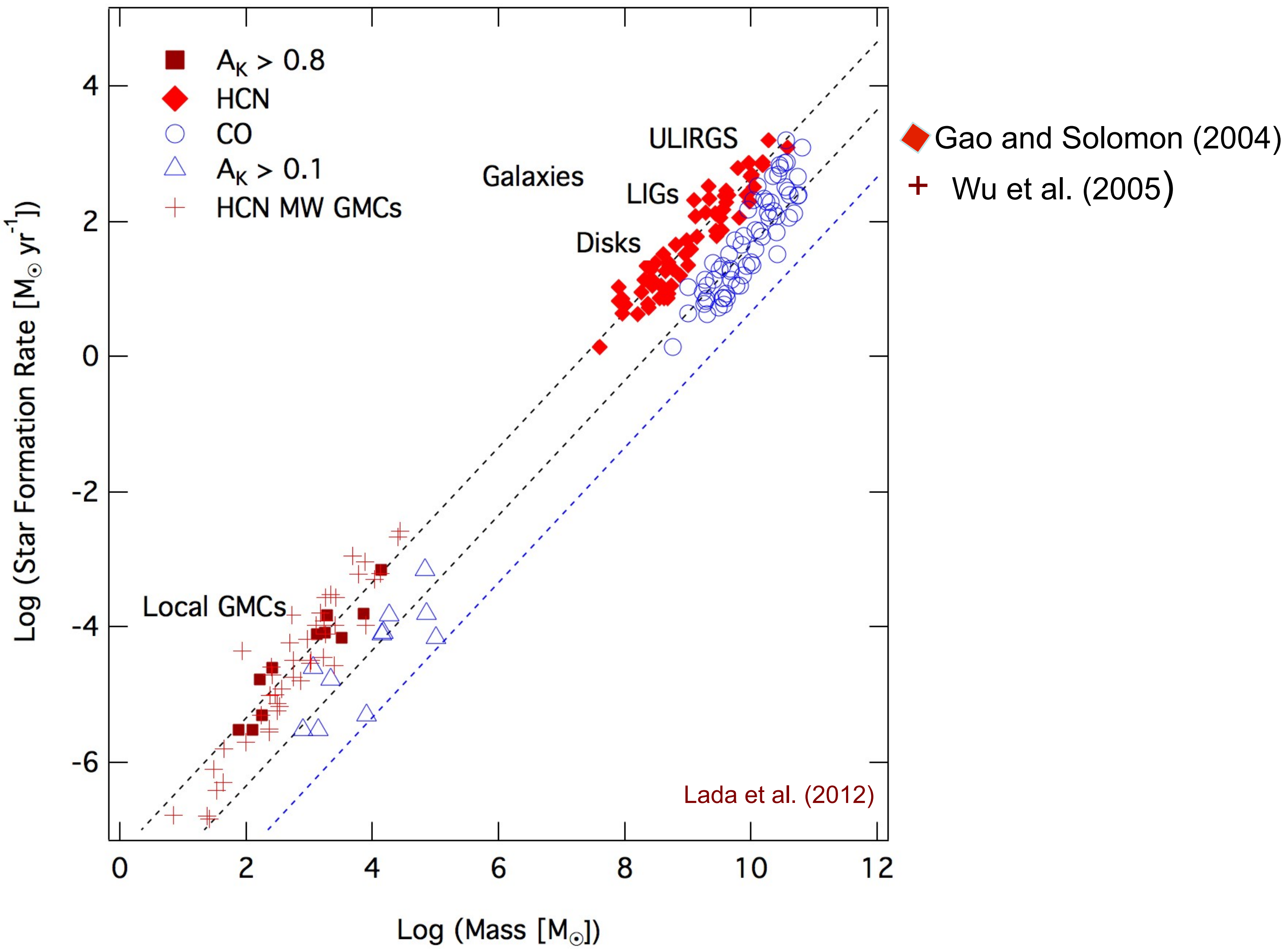
$$f = M_{0.8} / M_{gas}$$

$$SFR = (t_{gc})^{-1} M_{gas}$$

t_{gc} = gas consumption time

$= 2.2 \times 10^{7} / f$ yrs

Extending SCALING LAWS to z=0 GALAXIES

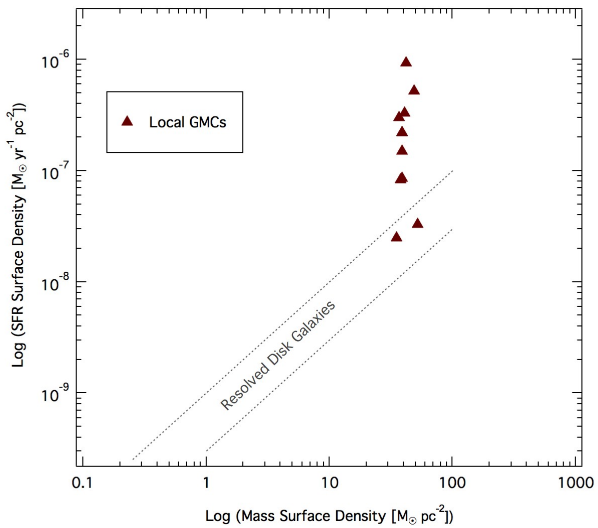


Extragalactic Kennicutt-Schmidt Law

Surface Densities: The Kennicutt-Schmidt Law

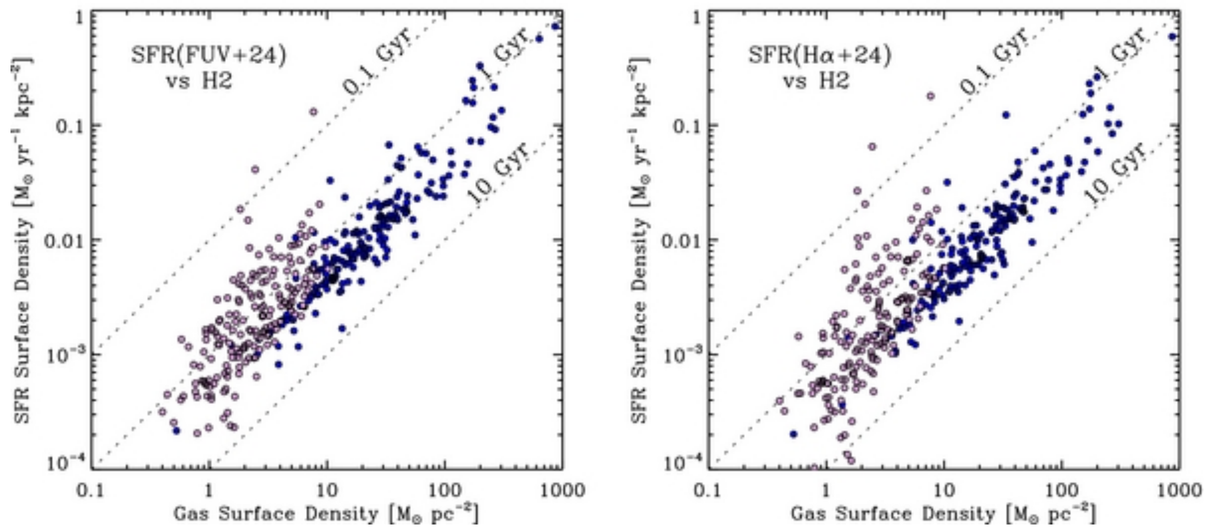
Local GMCs

Lada et al. (2013)



Resolved Nearby Galaxies

Schruba et al. (2011)



The Importance of Beam Dilution

For GMCs:

$\Sigma_{gas} = 40\ M_{\odot}\ pc^{-2}$

For Galaxies:

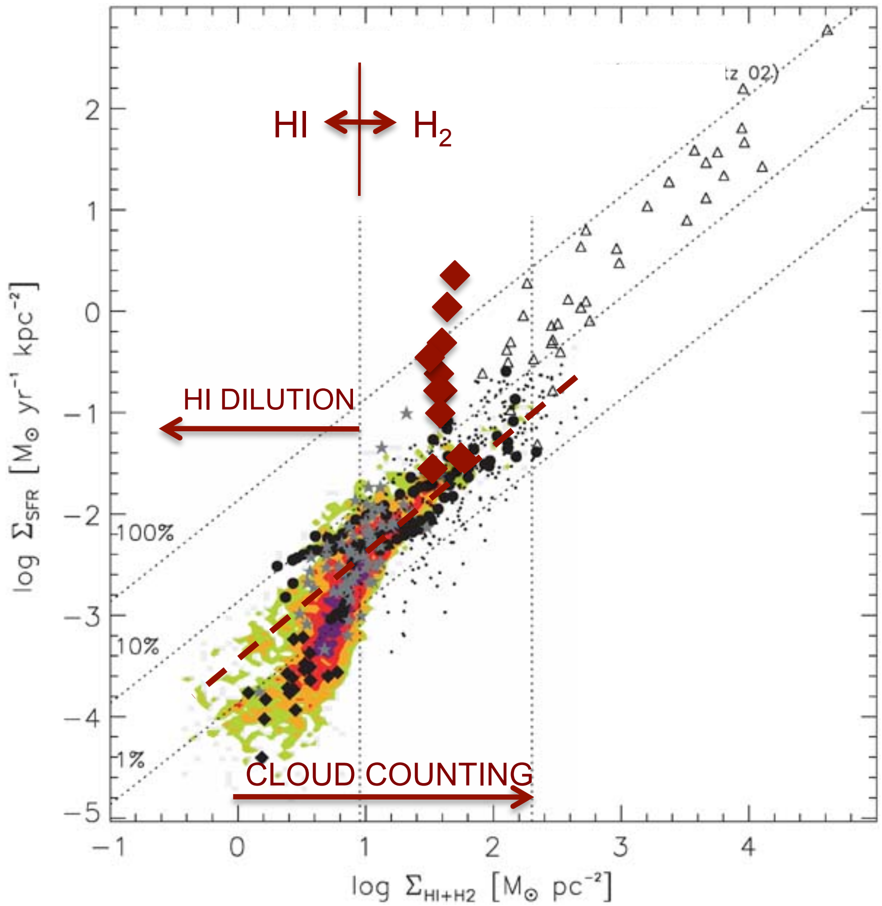
$\Sigma_{gas} = \Sigma_{GMCs}$

$4\ M_{\odot}\ pc^{-2}$ — $f_{mb} = 0.1$

$8\ M_{\odot}\ pc^{-2}$ — $f_{mb} = 0.2$

$40\ M_{\odot}\ pc^{-2}$ — $f_{mb} = 1.0$

Interpreting the Kennicutt-Schmidt Law



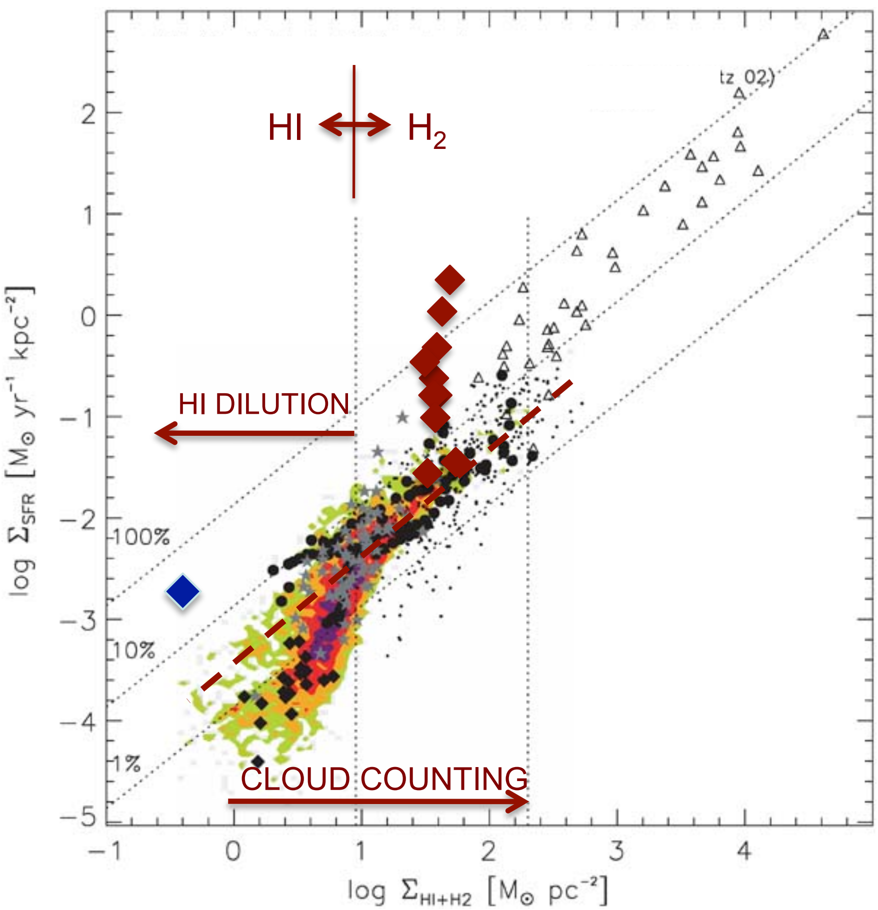
Bigiel et al. 2008

Σ_{H2} measures surface density of clouds not gas.

Σ_{SFR} measures surface density diluted SFR.

Interpreting the Kennicutt-Schmidt Law

SFRs from direct counting >> Indirect SFRs from FIR & SB99



Bigiel et al. 2008

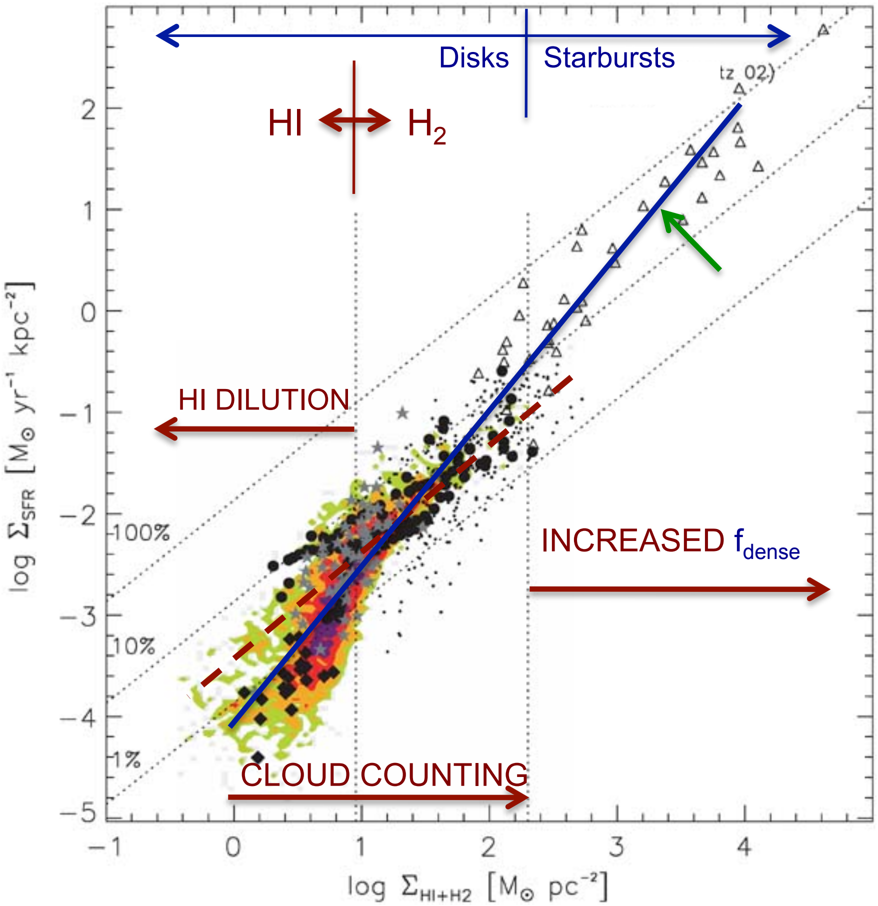
$\tau_{depletion}$(GMCs) << $\tau_{depletion}$ (galaxies)

~(250 Myr) ~(2 Gyr)

Σ_{H2} measures surface density of clouds not gas.

Σ_{SFR} measures surface density diluted SFR.

Interpreting the Kennicutt-Schmidt Law



Bigiel et al. 2008

$\tau_{depletion}$(GMCs) << $\tau_{depletion}$ (galaxies)

Σ_{H2} measures surface density of clouds not gas.

Σ_{SFR} measures surface density diluted SFR.

KS Law is not a result of any underlying star formation law.

Summary

A local Schmidt SF Law ($\Sigma_*(A_K) = \kappa(A_K)^\beta$) applies within GMCs

Total SFR depends on product of $\Sigma_*(A_K)$ and $S'(A_K)$ and is sensitive to cloud area at high extinction

There is no Schmidt Law between clouds

Differenes in Σ_{SFR}s between clouds primarily due to differences in cloud structure at high extinction

Depletion Times for GMCs ~ 250 Myr

Exgal SK Law does not describe any fundamental physical law of star formation

The End