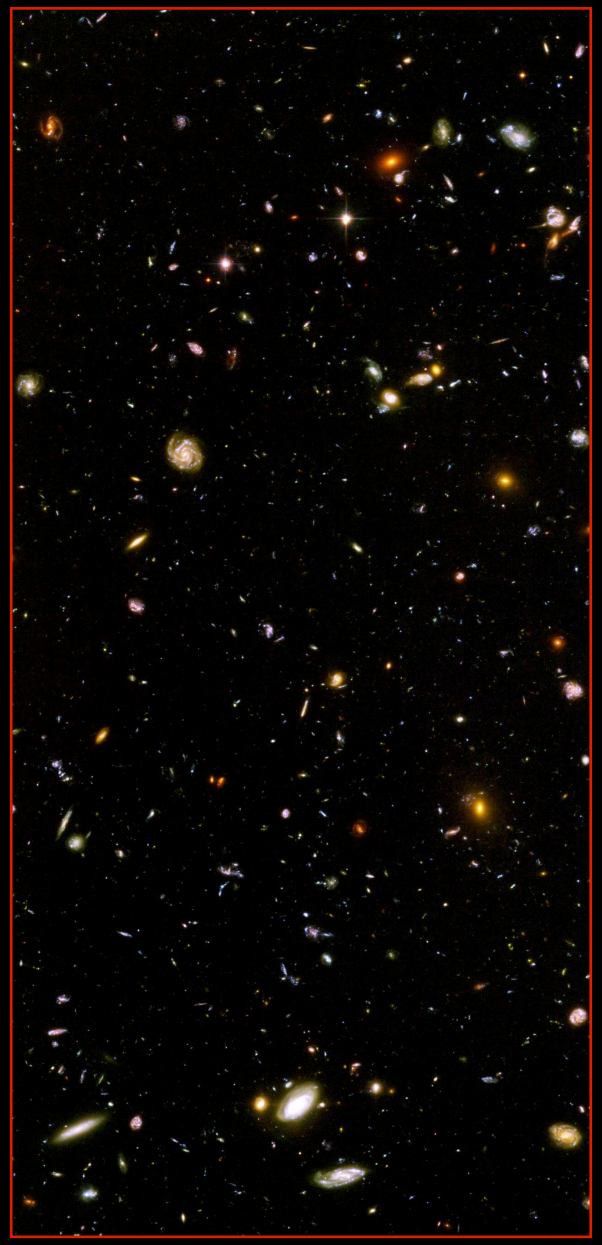
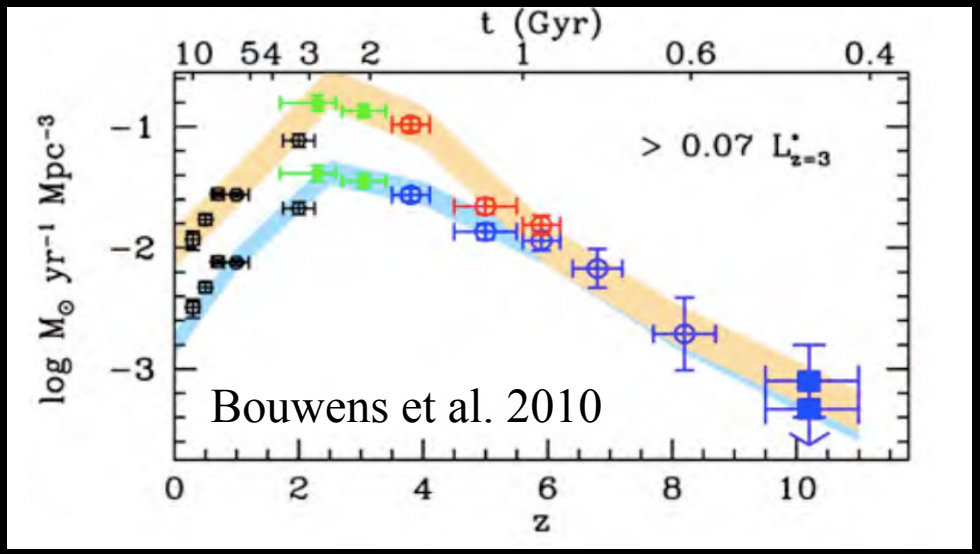
Star Formation Scaling Relations: The Local Truth

With:
Marco Lombardi, University of Milan
Joao Alves, University of Vienna
Jan Forbrich, University of Vienna
Chris Faesi, CfA

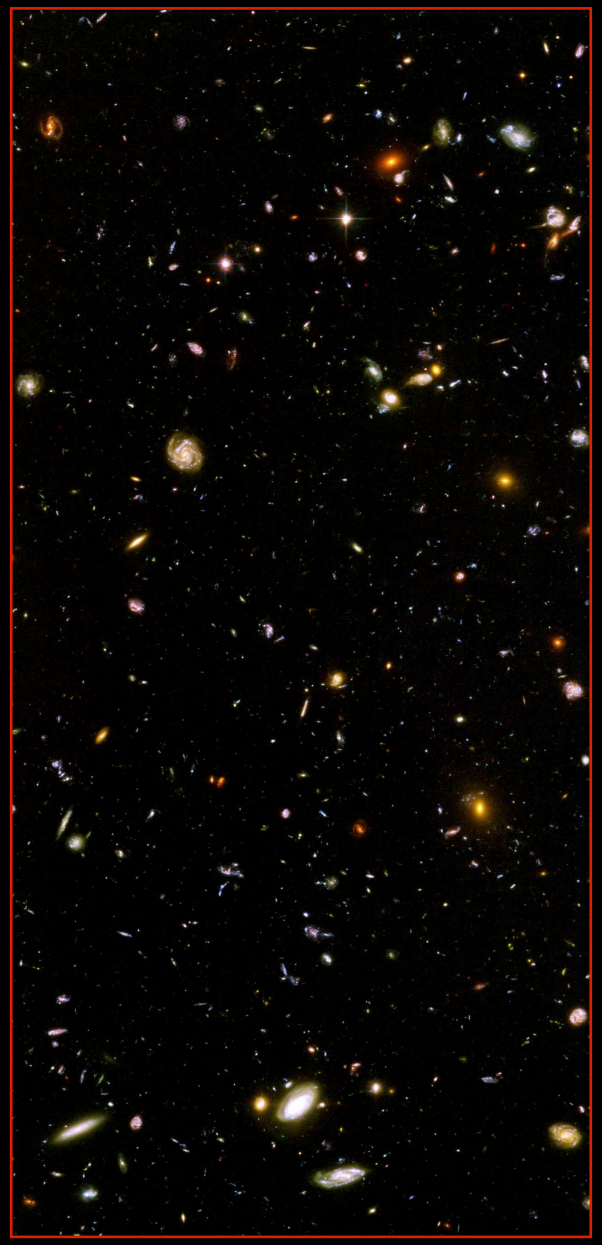
The Star Formation Rate Across Cosmic History



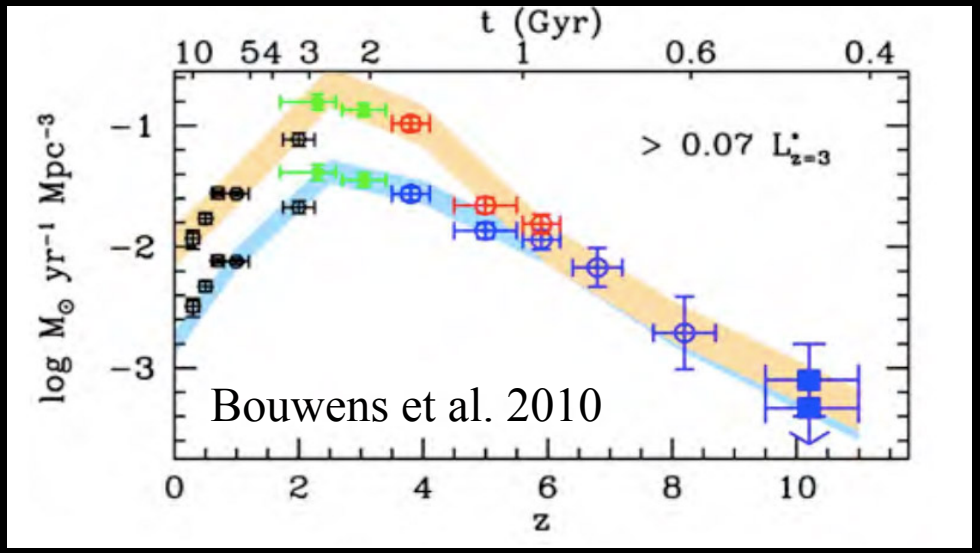
The SFR is the primary metric for describing galaxy evolution over cosmic time.



The Star Formation Rate Across Cosmic History

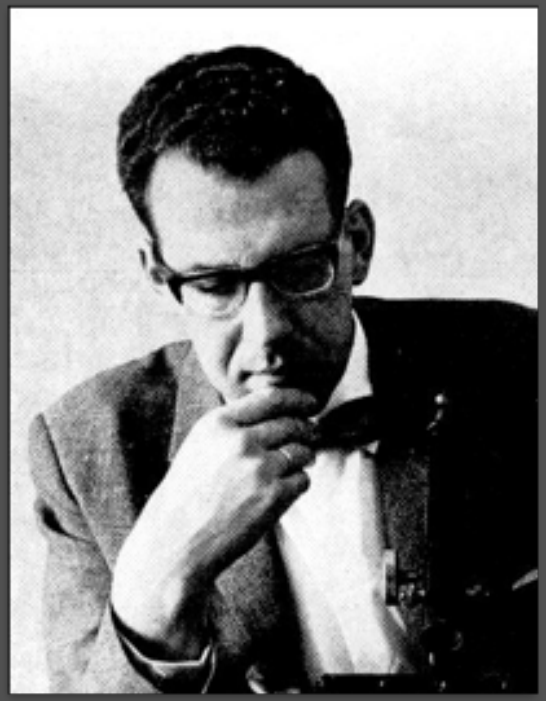


What are the physical processes that set the SFR and control galaxy evolution?



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)

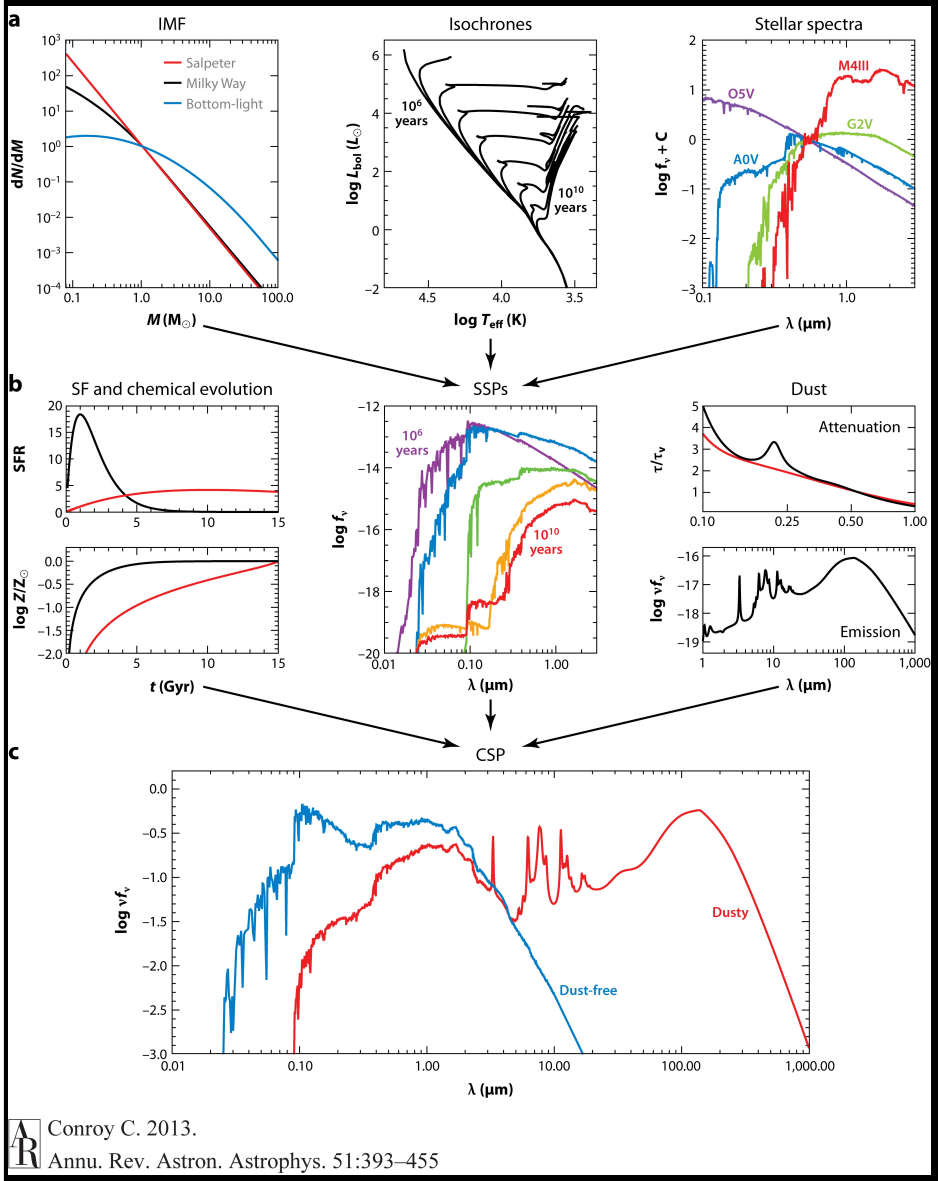


$$\Sigma_{SFR} = \kappa \, (\Sigma_g)^{\beta} \qquad (M_\odot \, pc^{-2})$$

"It is rather tempting to try to estimate the effects of star formation…in galaxies as a whole."

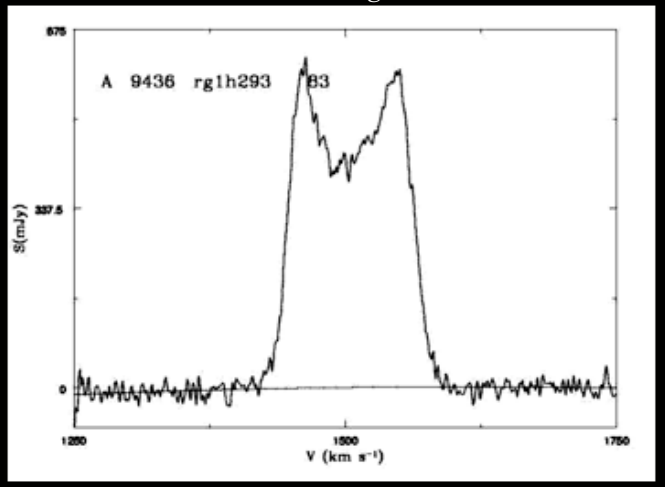
Determining SFRs and Gas Masses in External Galaxies

SFRs: population synthesis modelling

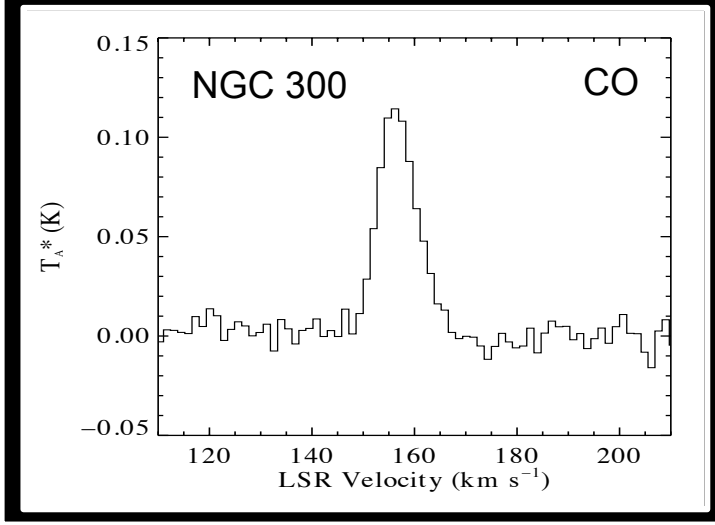


Conroy C. 2013.
Annu. Rev. Astron. Astrophys. 51:393–455

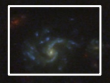
Gas Mass HI: $M_{gas} = \alpha_{HI} L_{HI}$

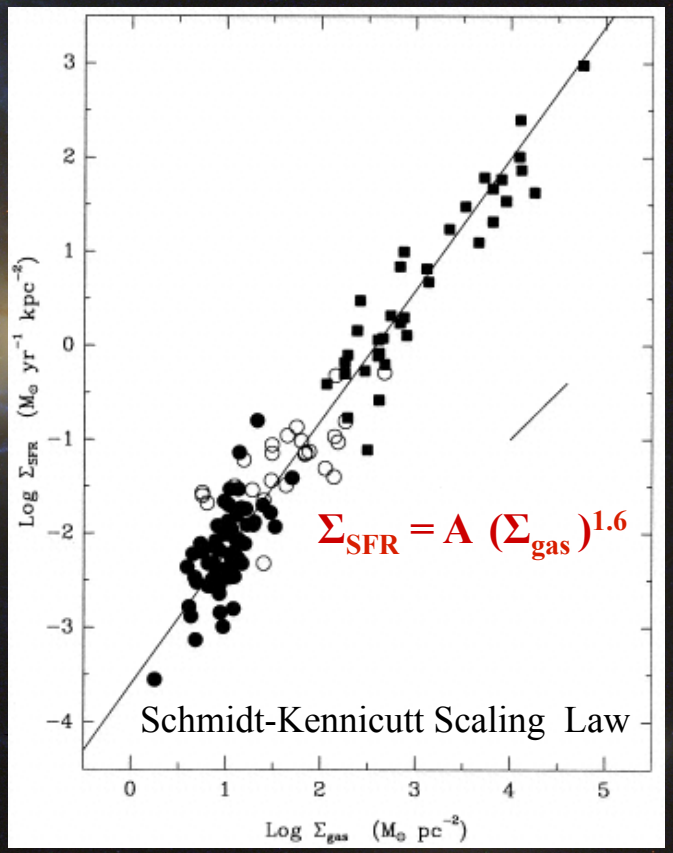


Gas Mass H_2: $M_{gas} = \alpha_{CO} L_{CO}$

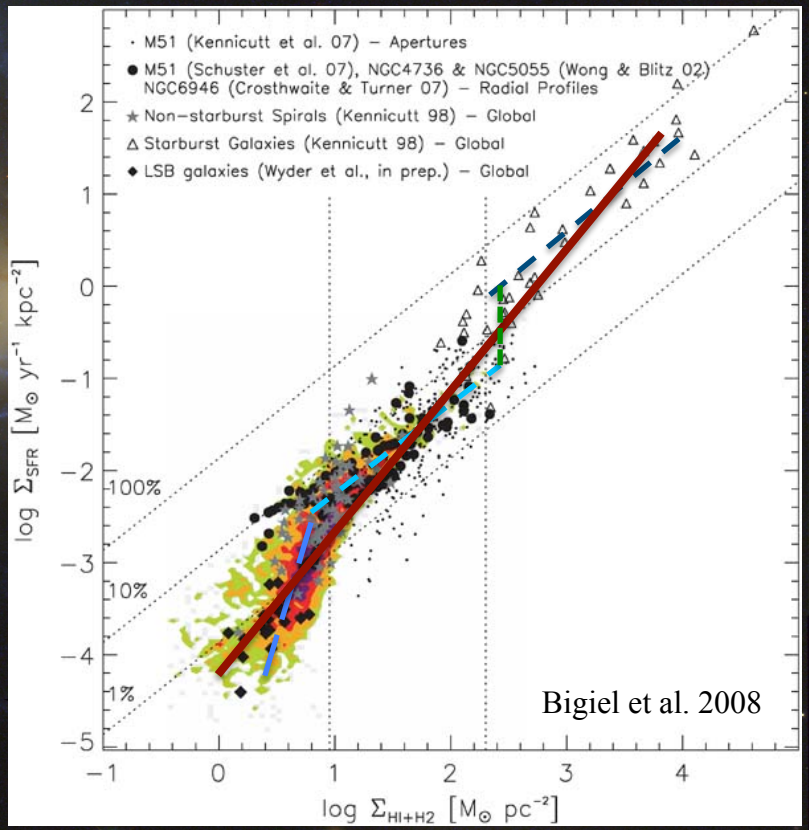


z = 0 Galaxies

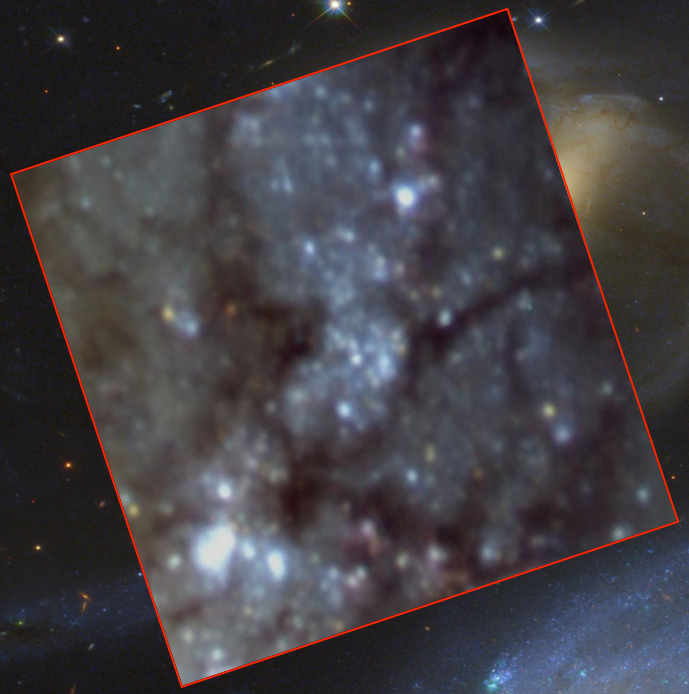



Log Σ_{SFR} ($M_\odot$ yr^{-1} kpc^{-2})
Log Σ_{gas} ($M_\odot$ pc^{-2})
$\Sigma_{SFR} = A\ (\Sigma_{gas})^{1.6}$
Schmidt-Kennicutt Scaling Law

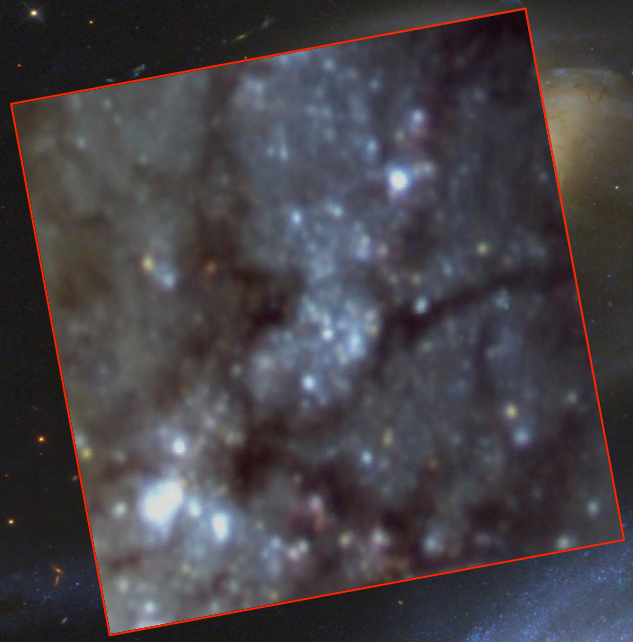
Galaxies


M51 (Kennicutt et al. 07) – Apertures
M51 (Schuster et al. 07), NGC4736 & NGC5055 (Wong & Blitz 02)
NGC6946 (Crosthwaite & Turner 07) – Radial Profiles
Non-starburst Spirals (Kennicutt 98) – Global
Starburst Galaxies (Kennicutt 98) – Global
LSB galaxies (Wyder et al., in prep.) – Global
100%
10%
1%
log Σ_SFR [M⊙ yr⁻¹ kpc⁻²]
log Σ_HI+H2 [M⊙ pc⁻²]
Bigiel et al. 2008

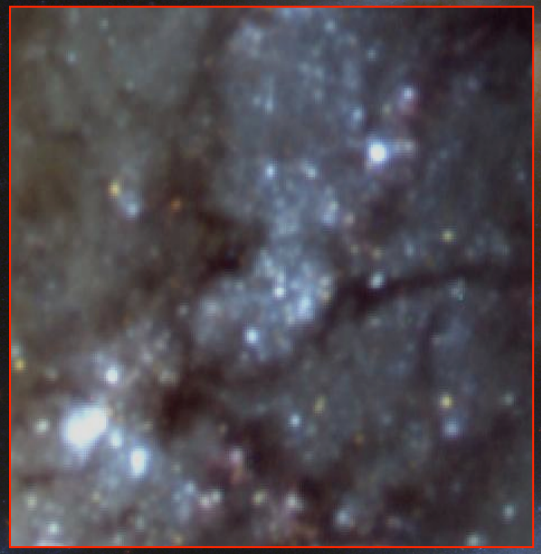
Galaxies



Galaxies



Galaxies

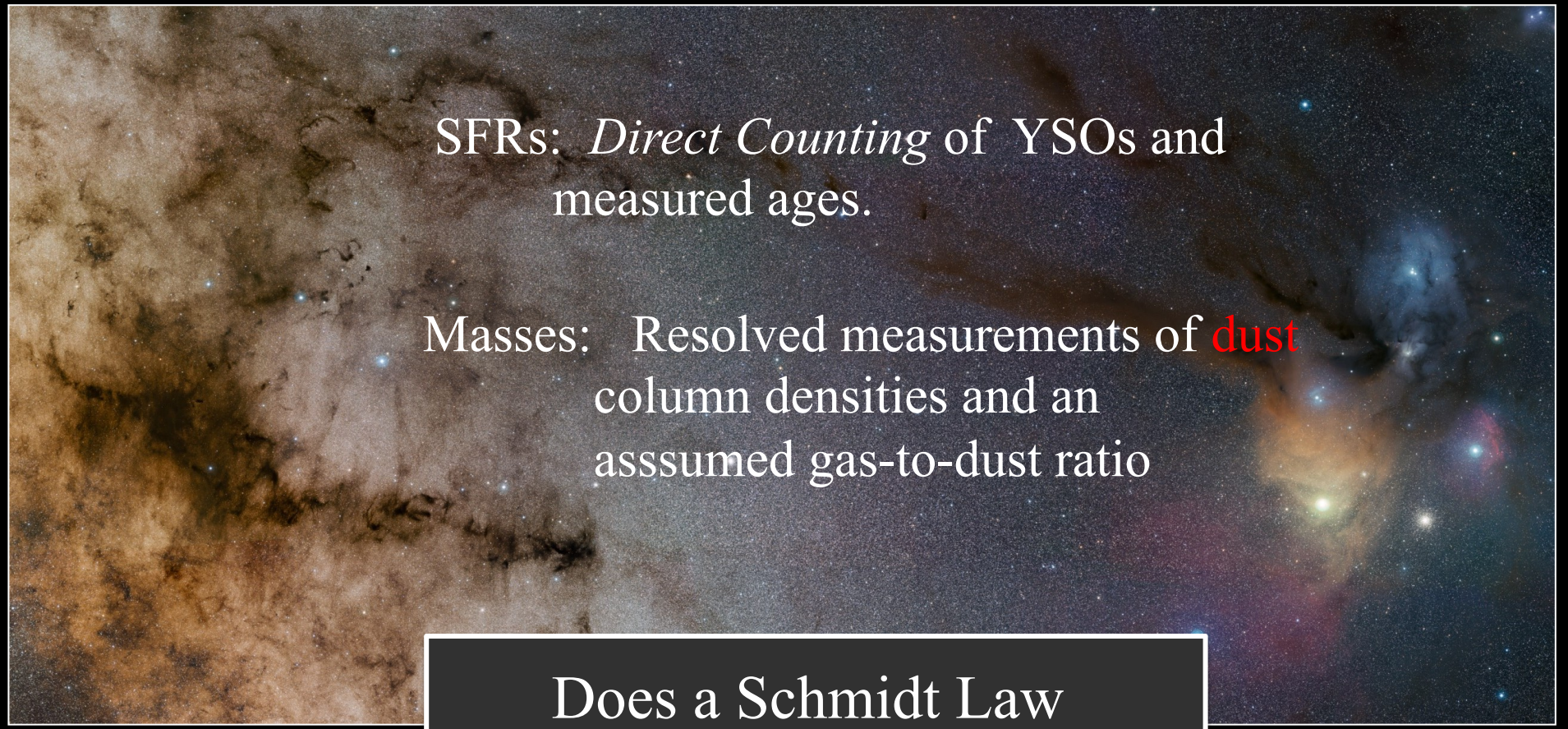


Giant Molecular Clouds

?

Giant Molecular Clouds

THE LOCAL TRUTH:

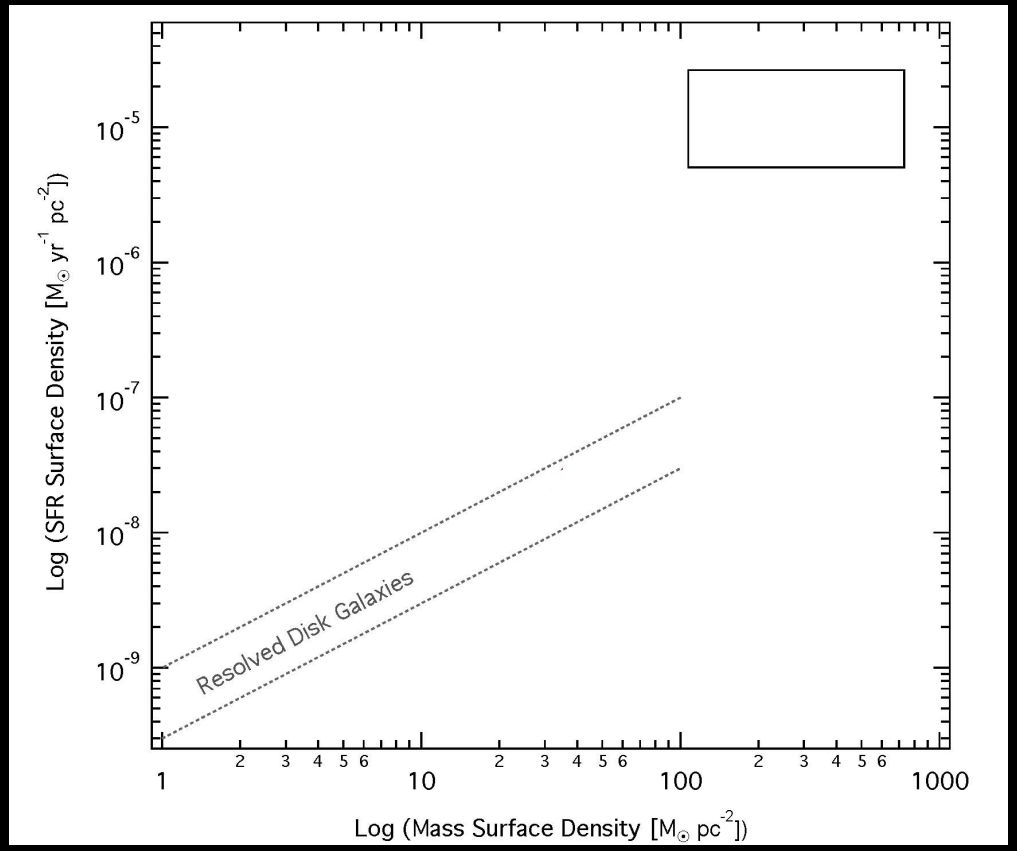


SFRs: *Direct Counting* of YSOs and measured ages.

Masses: Resolved measurements of dust column densities and an asssumed gas-to-dust ratio

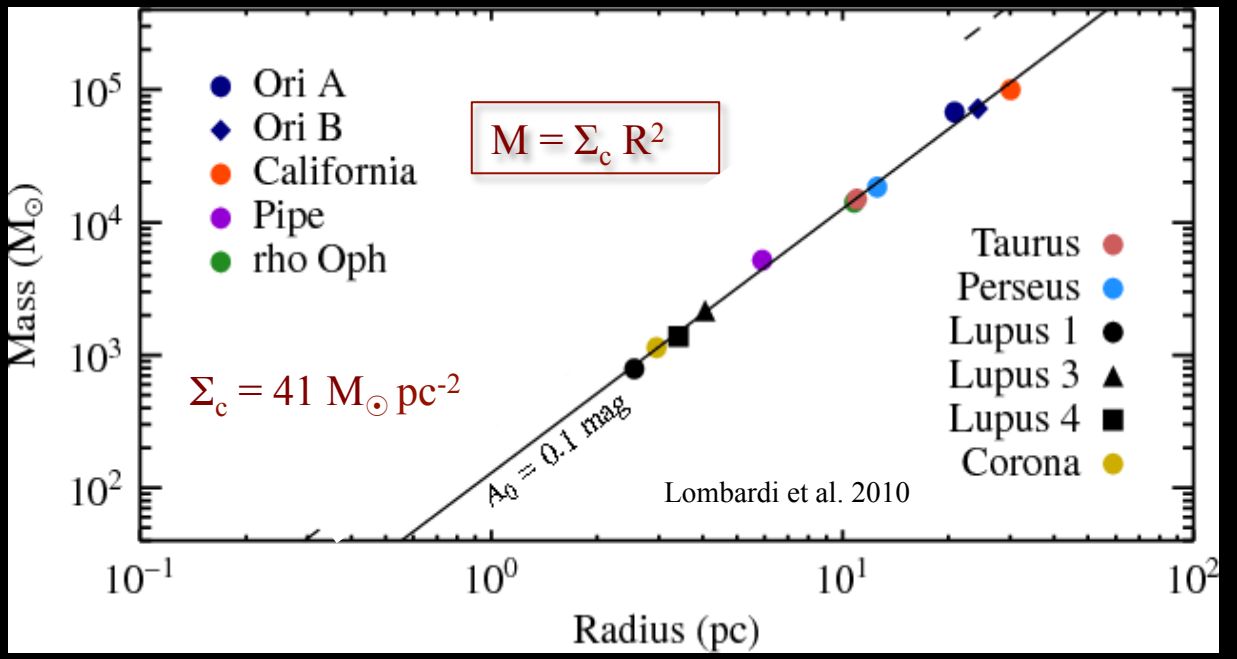
Does a Schmidt Law exist for MW GMCs?

Giant Molecular Clouds



A Schmidt Law does NOT exist between GMCs

Giant Molecular Clouds



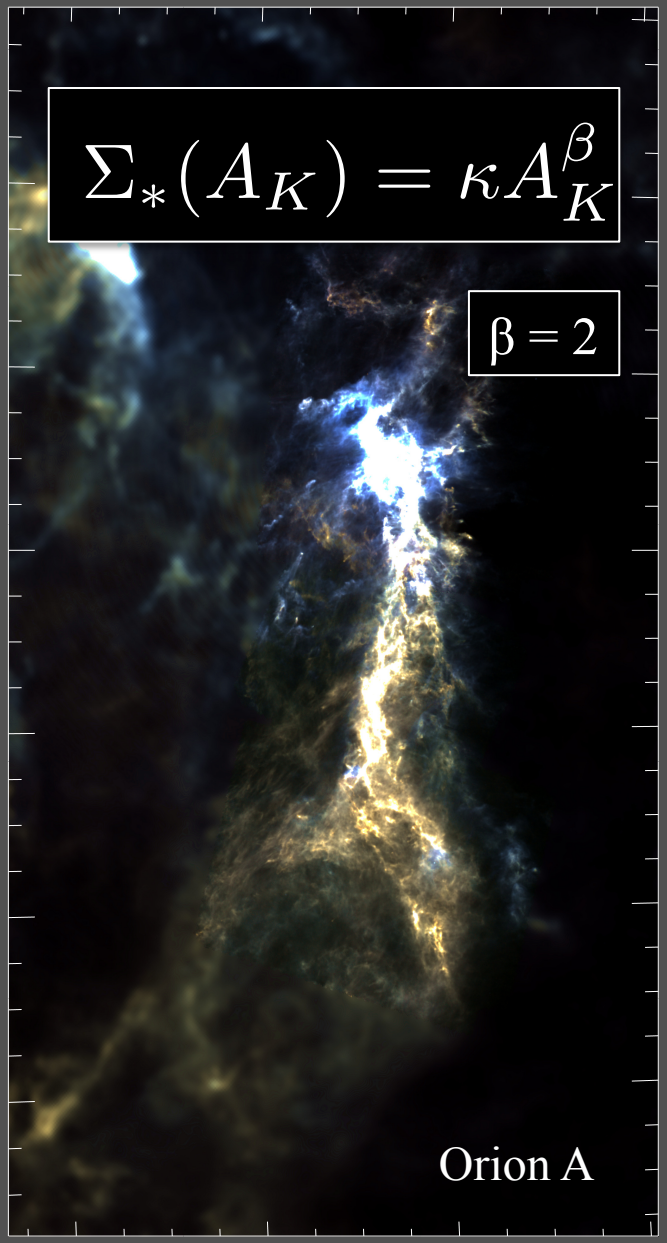
Well known scaling relation of Larson (1981)

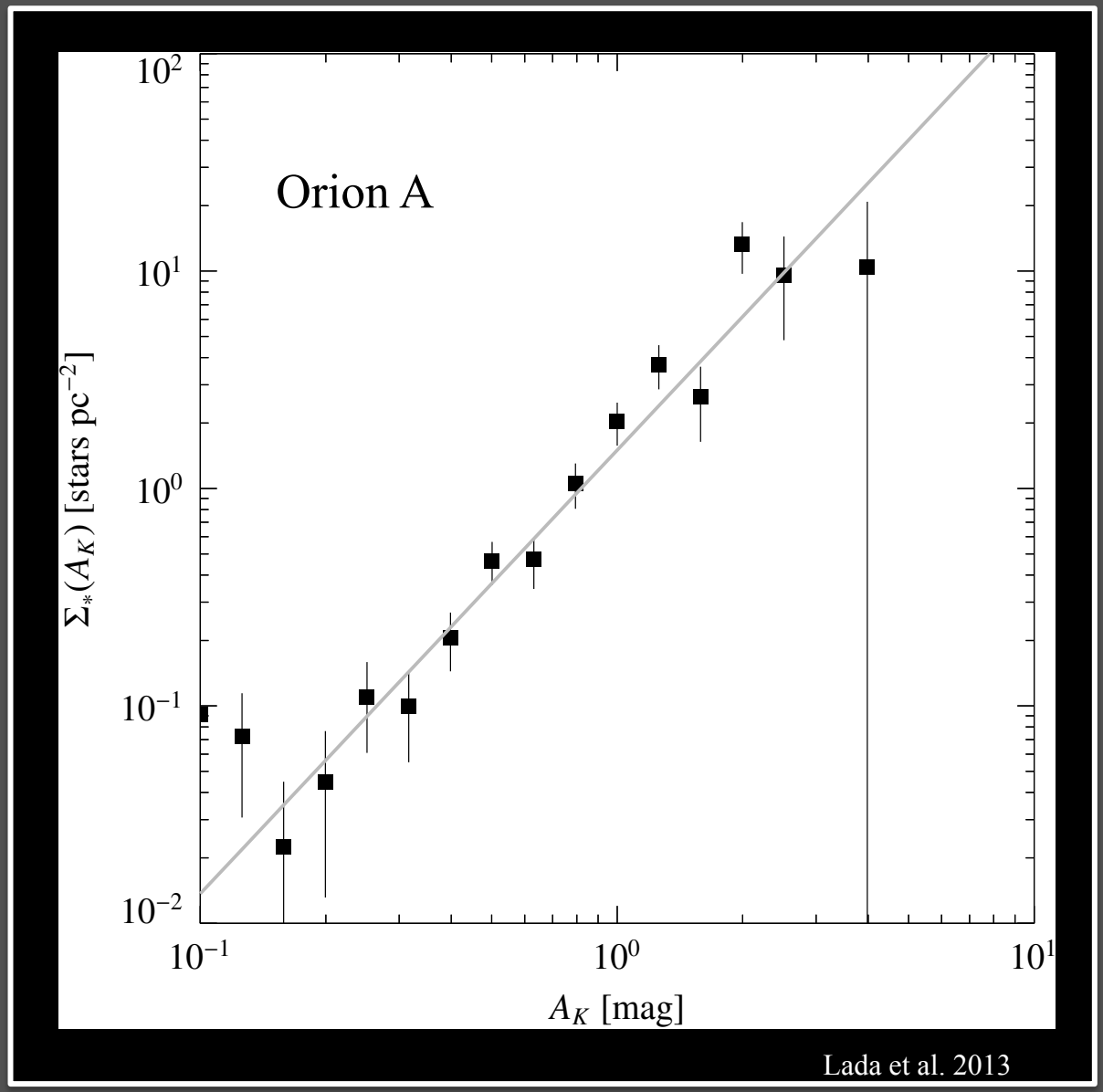
A Schmidt Law does NOT exist between GMCs

Giant Molecular Clouds

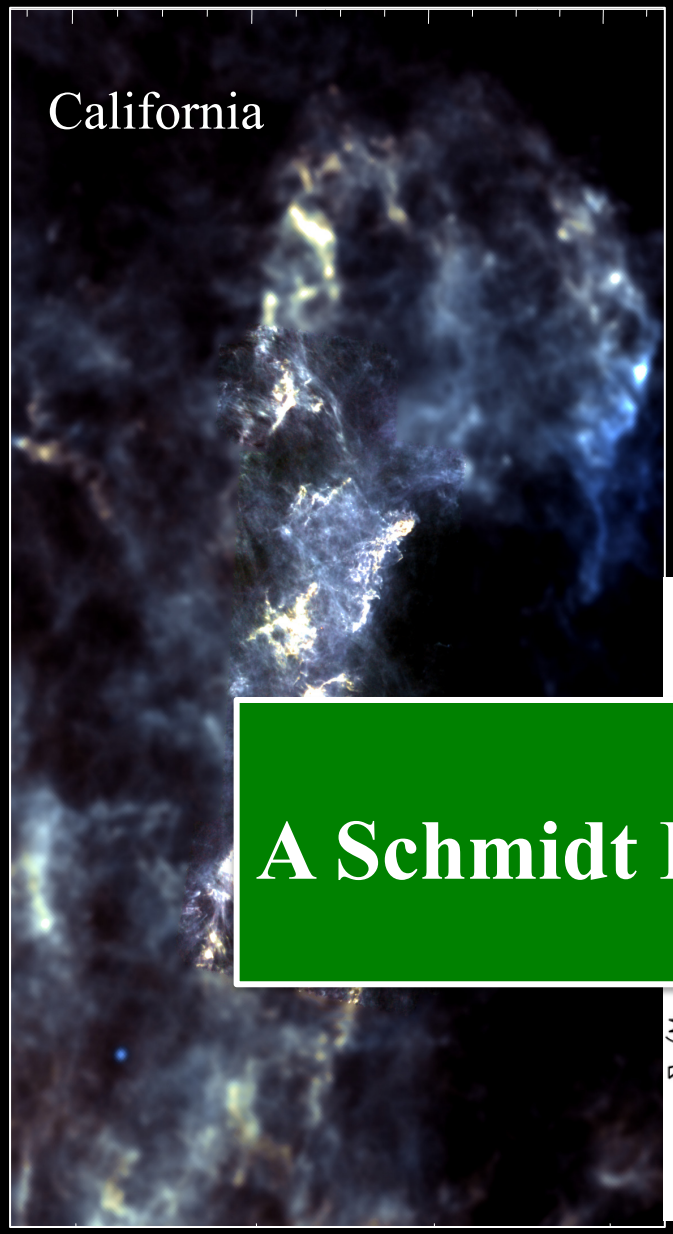
Does a Schmidt Law exist *within* GMCs, on sub-cloud scales?

Schmidt Law in Orion





Schmidt Law in Giant Molecular Clouds

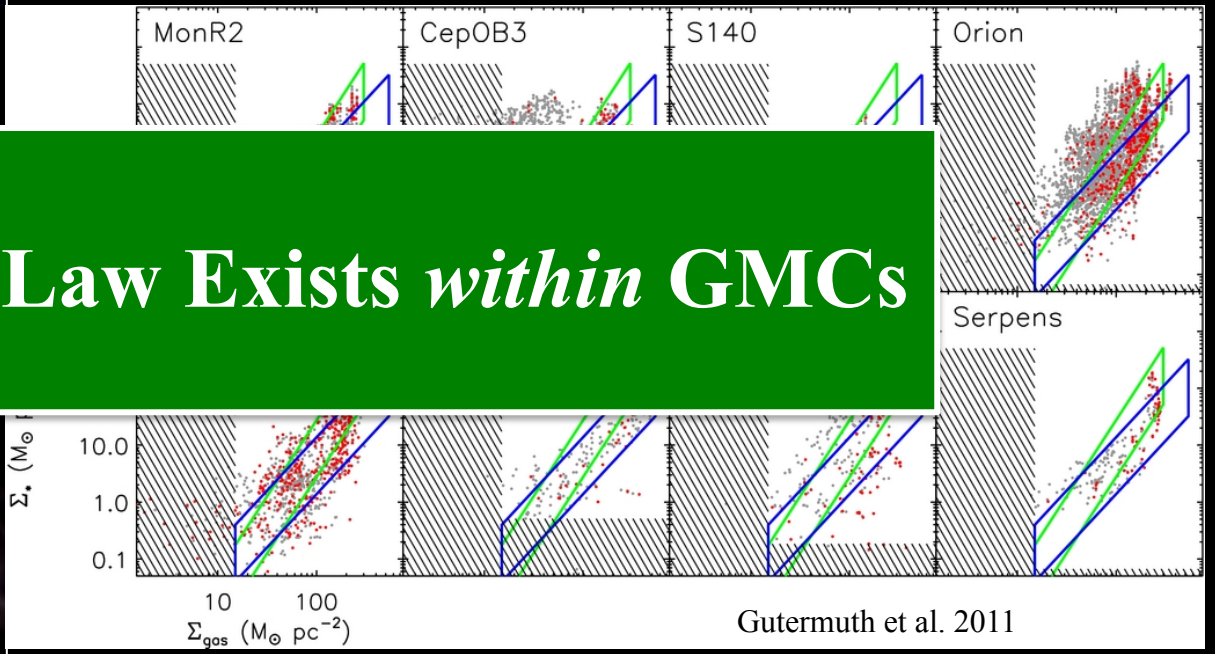


Results:

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

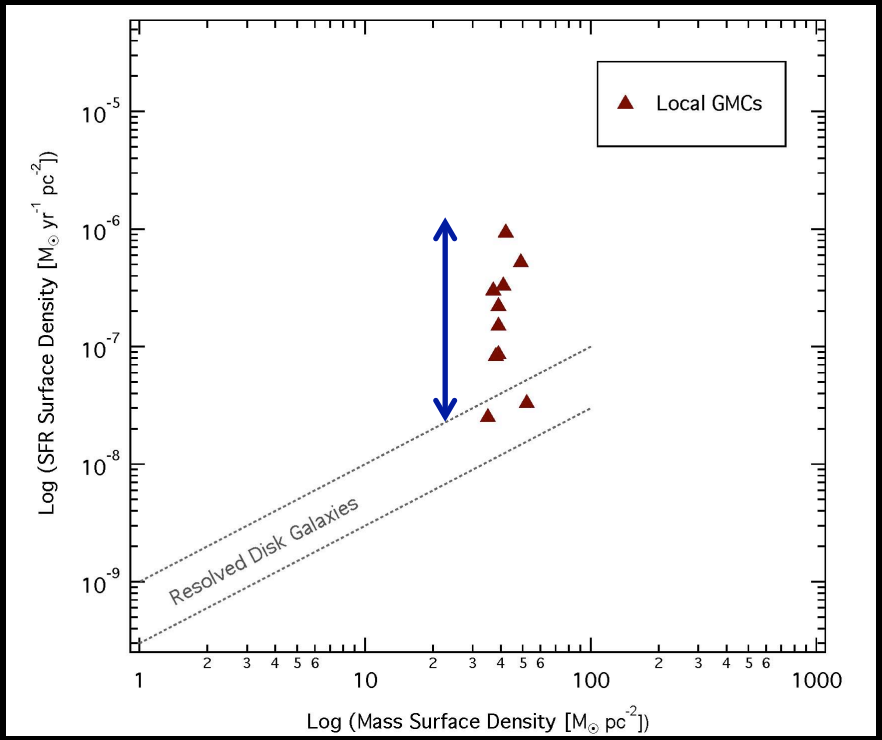
	Orion	Taurus	California	Perseus
β	2.0 ± 0.05	2.1 ± 0.1	3.1 ± 0.2	2.4± 0.6
κ	1.1 ± 0.1	2.1 ± 0.3	0.8 ± 0.2	0.2 ± 0.1

A Schmidt Law Exists *within* GMCs



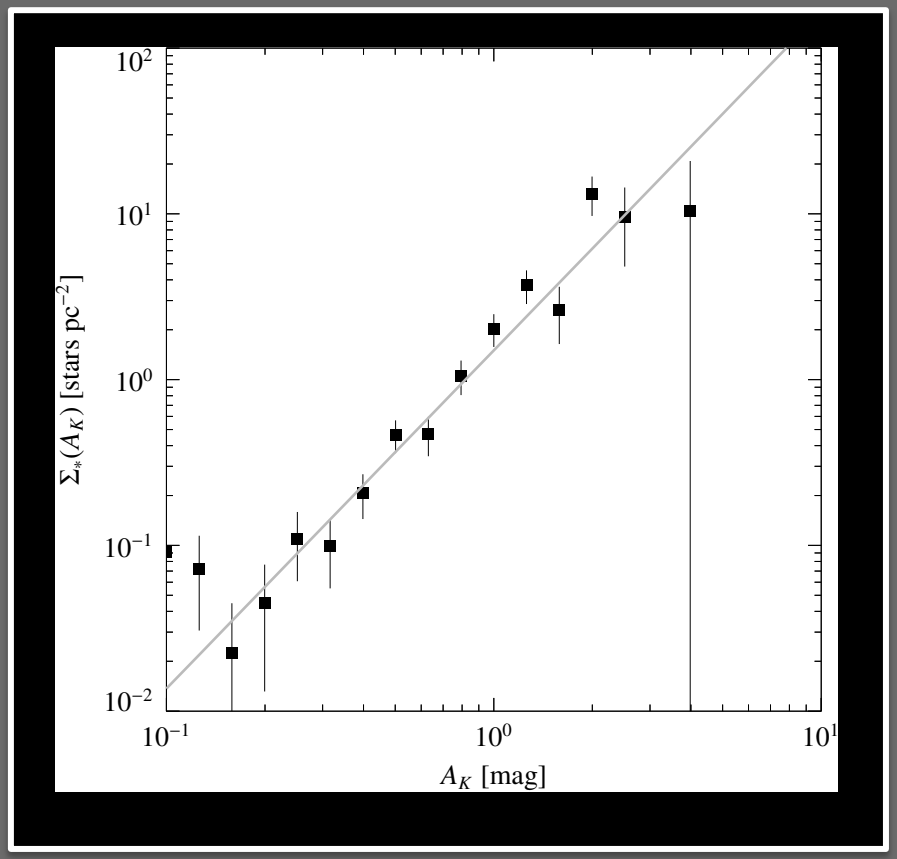
Gutermuth et al. 2011

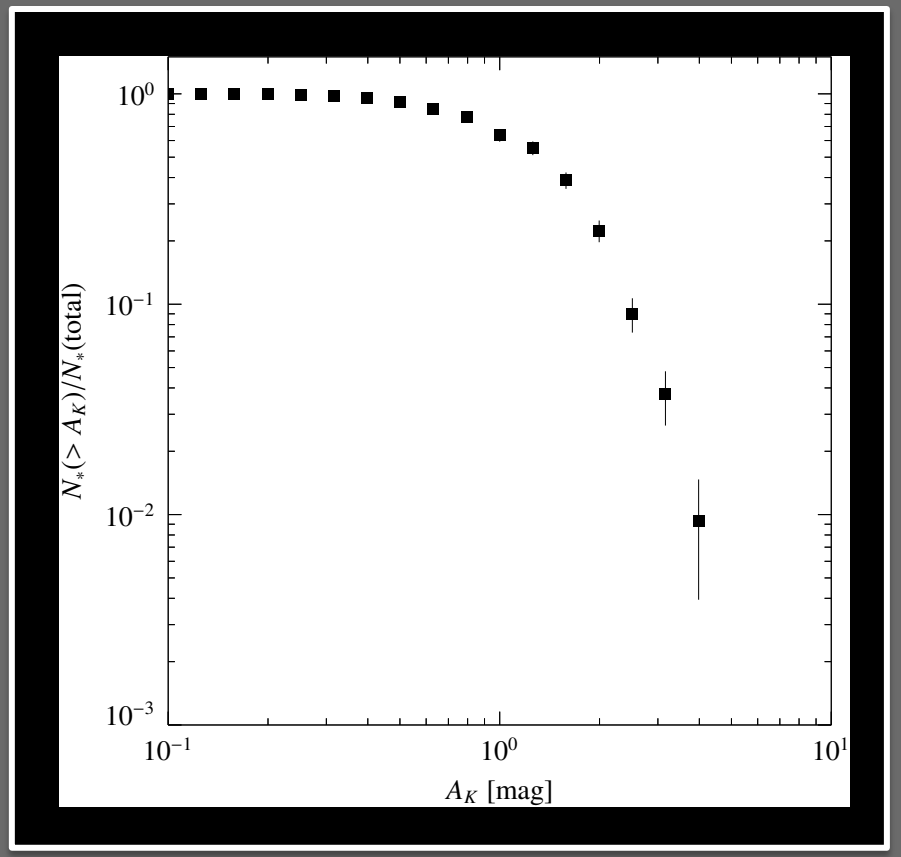
Giant Molecular Clouds



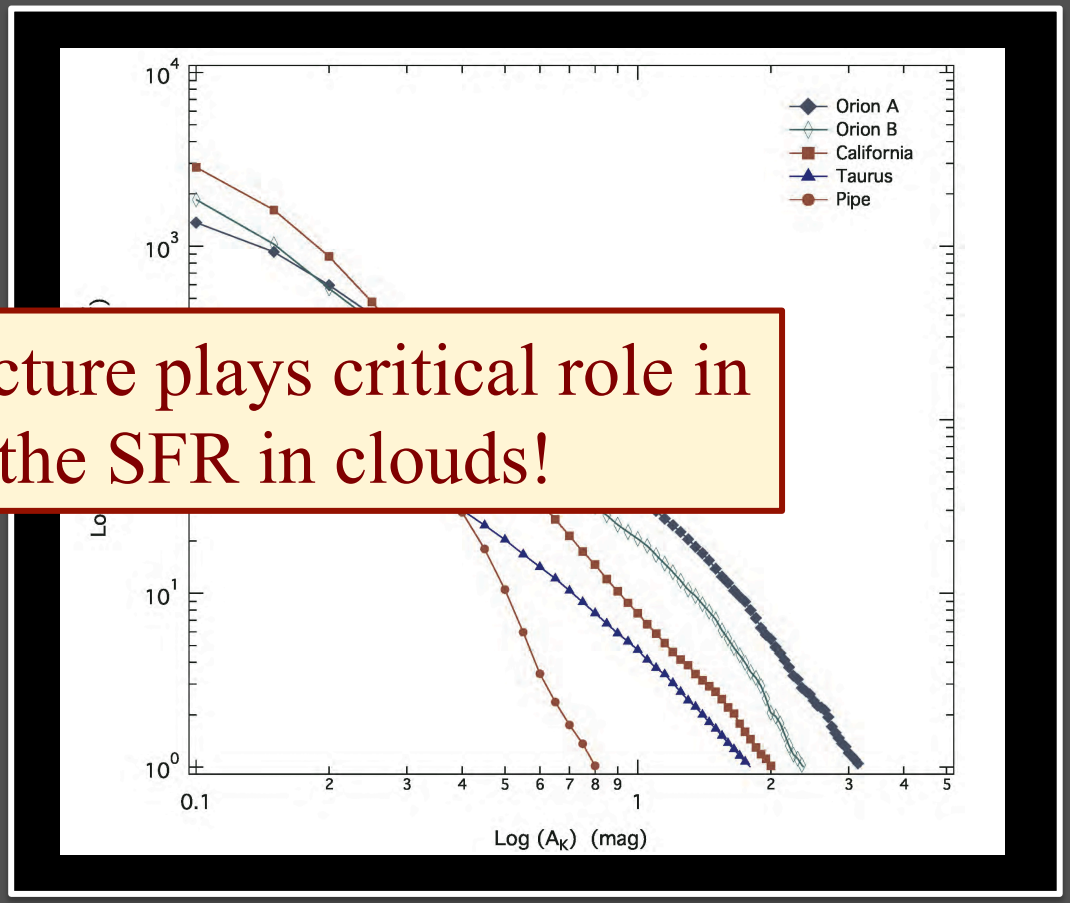
A Schmidt Law within clouds does NOT explain variations in SFRs between clouds.

Schmidt Law and Star Formation in GMCs





$$N_*(>A_K) = \Sigma_*(>A_K)\ x\ S(>A_K)$$

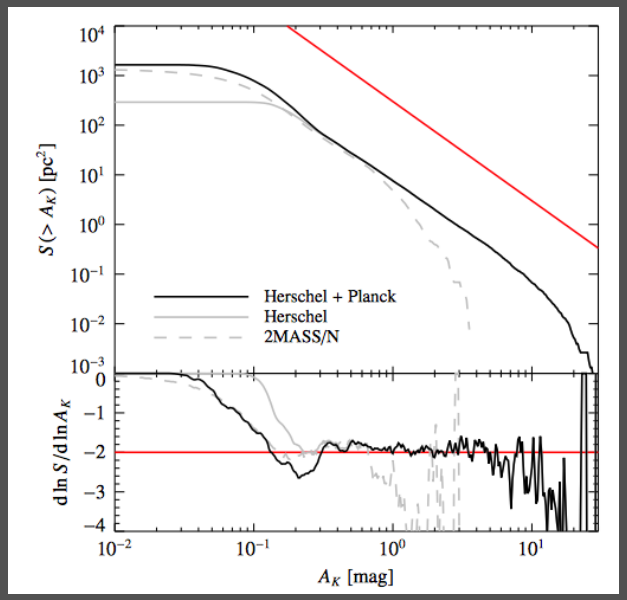


Cloud structure plays critical role in determing the SFR in clouds!

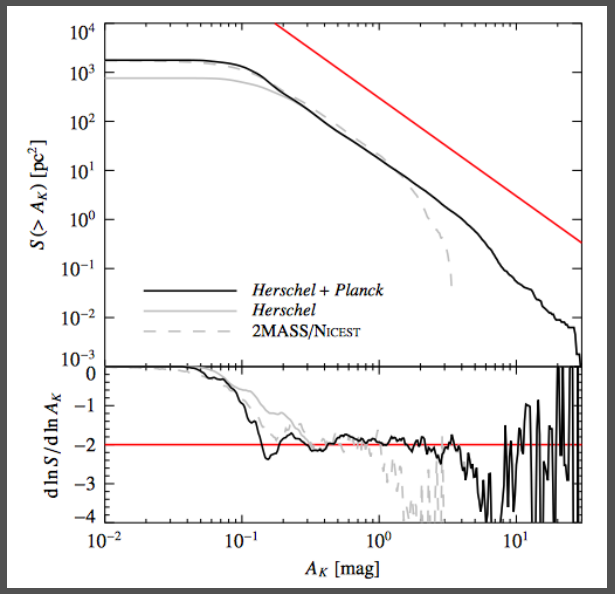
Surface Area Distribution Function, $S(>A_K)$

Scaling Law of Surface Areas

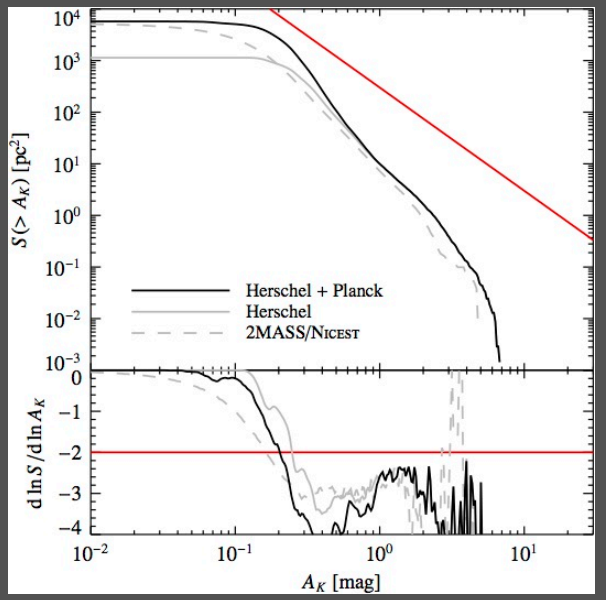
$$S(>A_K) \sim \Sigma^{-n}_{gas}$$



Perseus



Orion B

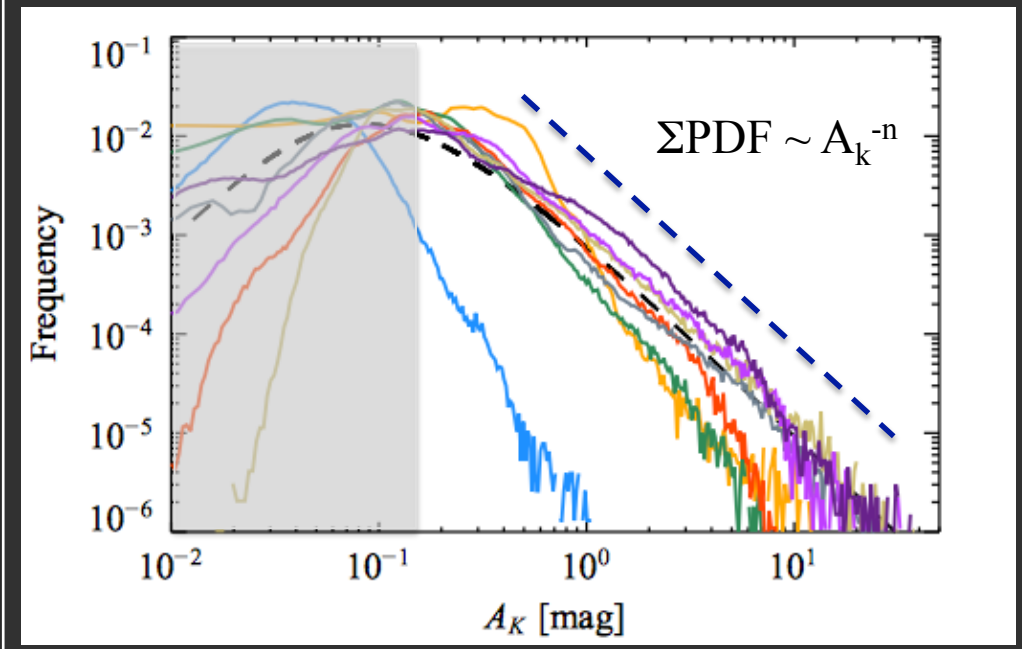


California

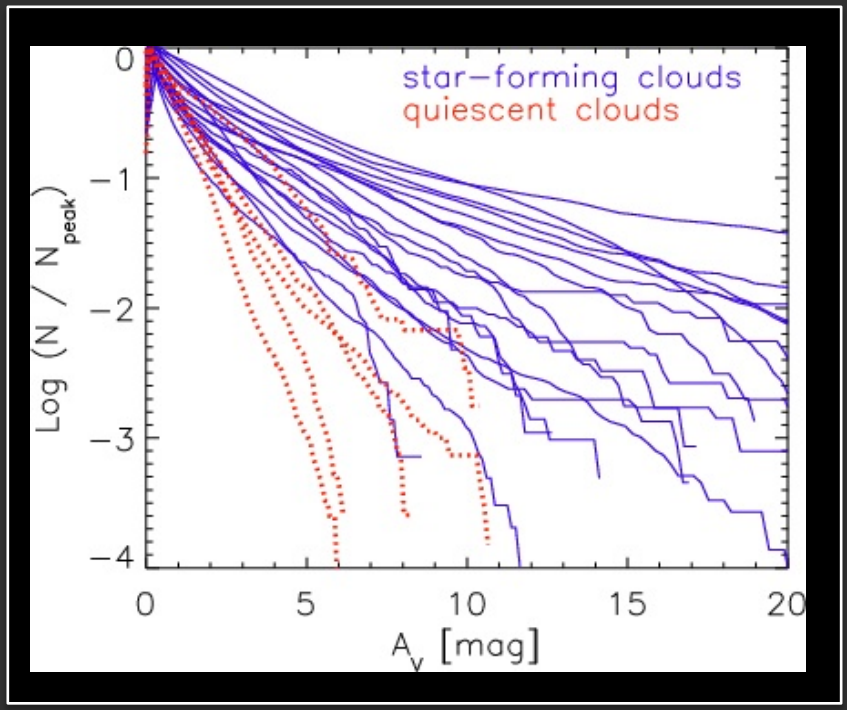
Connecting Cloud Structure to Star Formation

A Relation between Dense Gas and Star Formation

Lombardi et al. 2015



Kainulainen et al. 2009



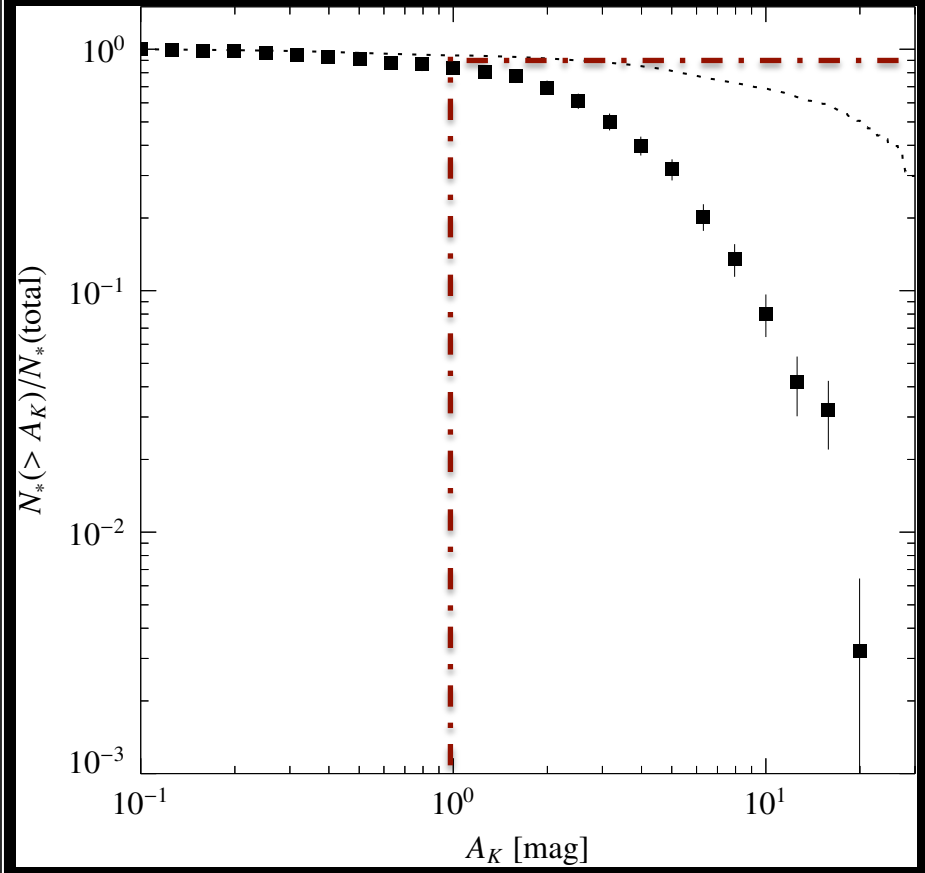
Dense Gas fraction varies between clouds!

And is correlated with the level of star formation

Dense Gas and Star Formation

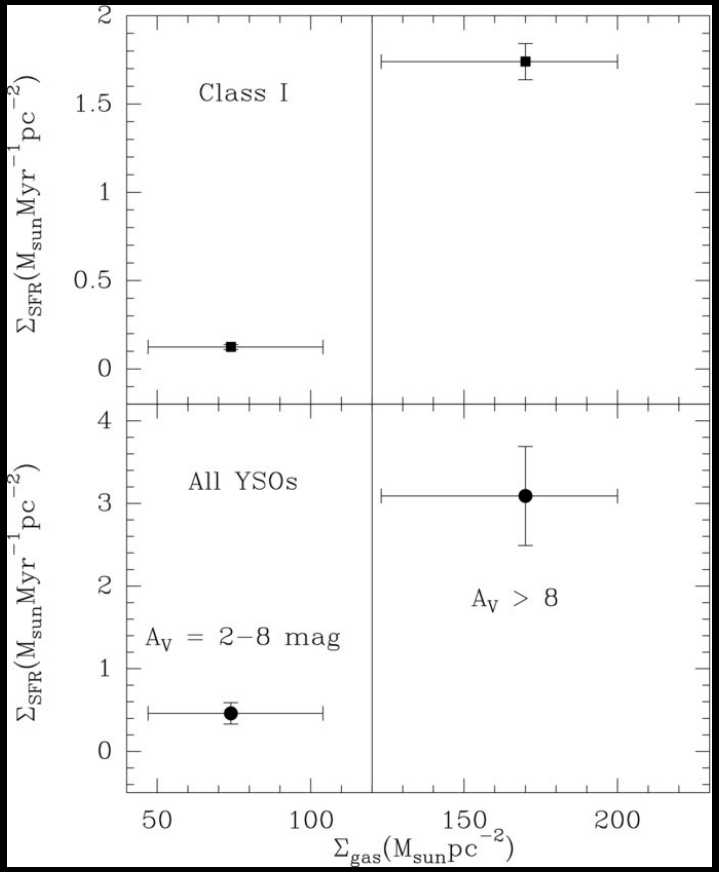
90% of Protostars at $A_K > 1.0$ mag

Orion A



Lada et al. 2013

Local Dark Cloud Sample

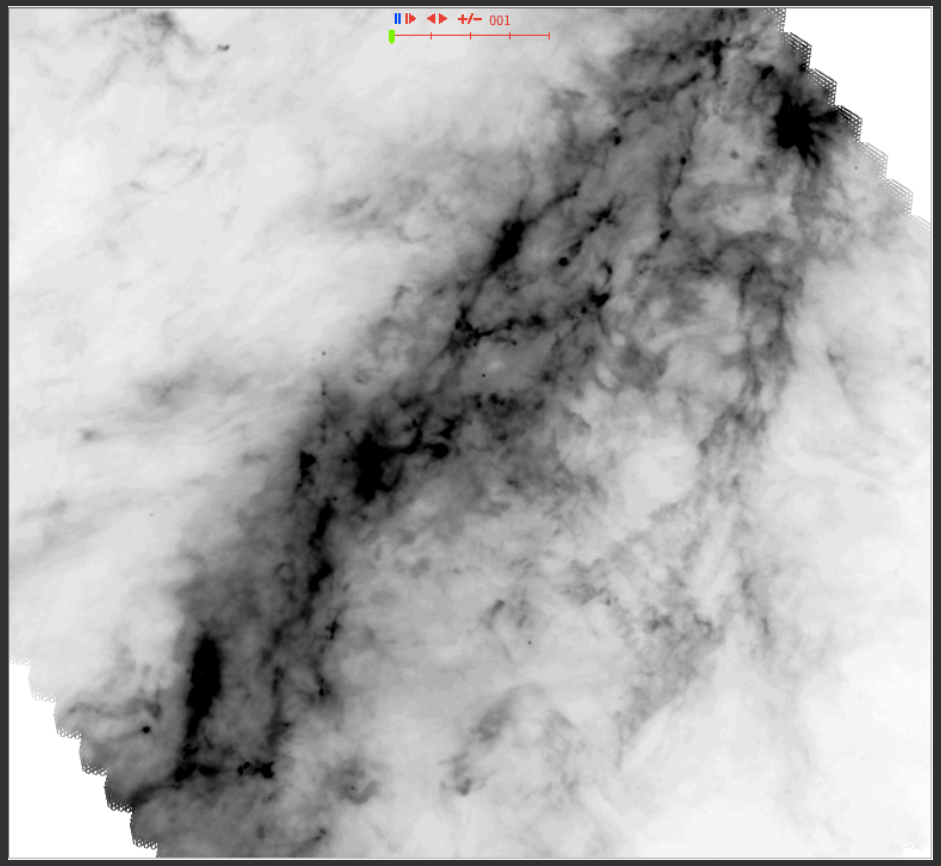


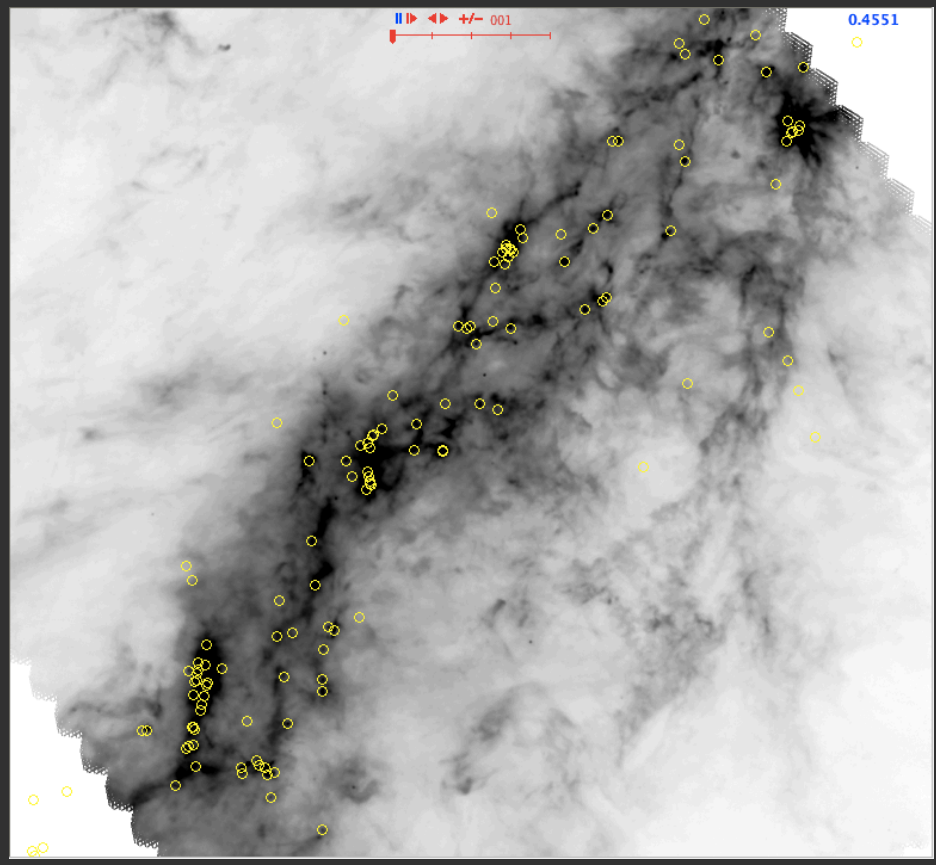
Evans et al. 2014

Consider Protostars and Dense Gas

Orion A

Lombardi et al. 2014



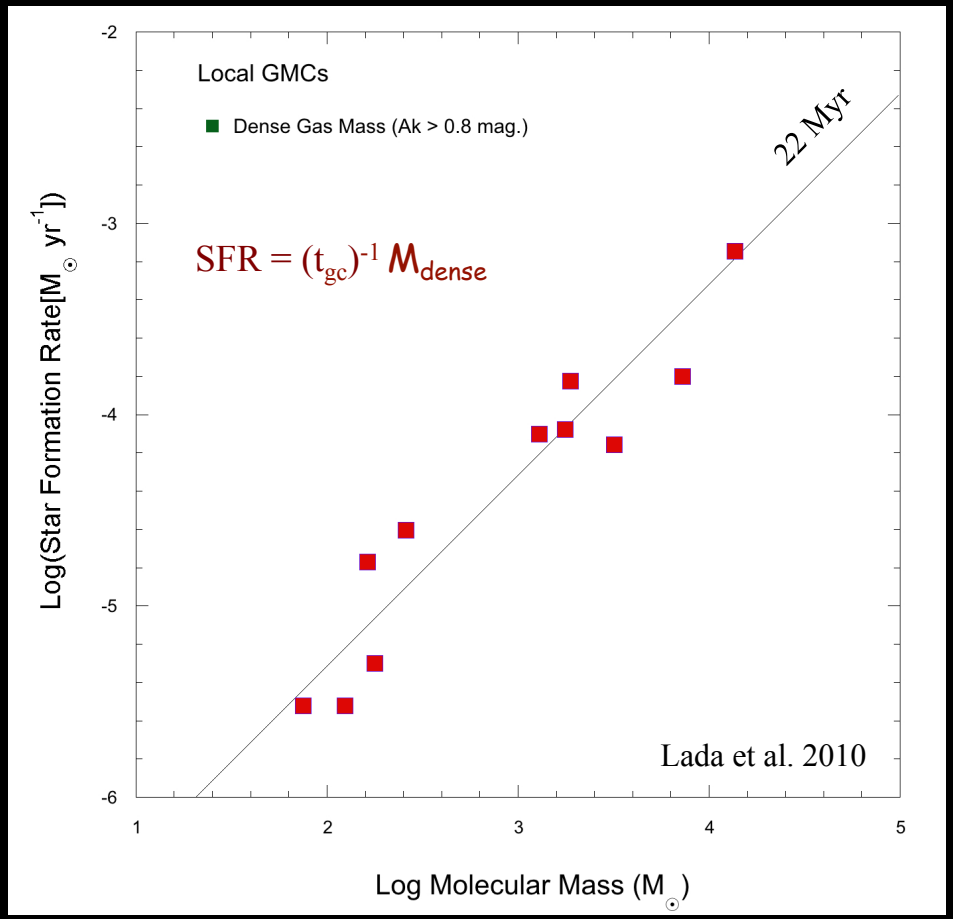


Herschel: 250 μm

Star Formation Scaling Laws *Between* Local GMCs

The *Dense Gas* Scaling Law for Local Star Formation

A linear scaling relation for integrated quantities!



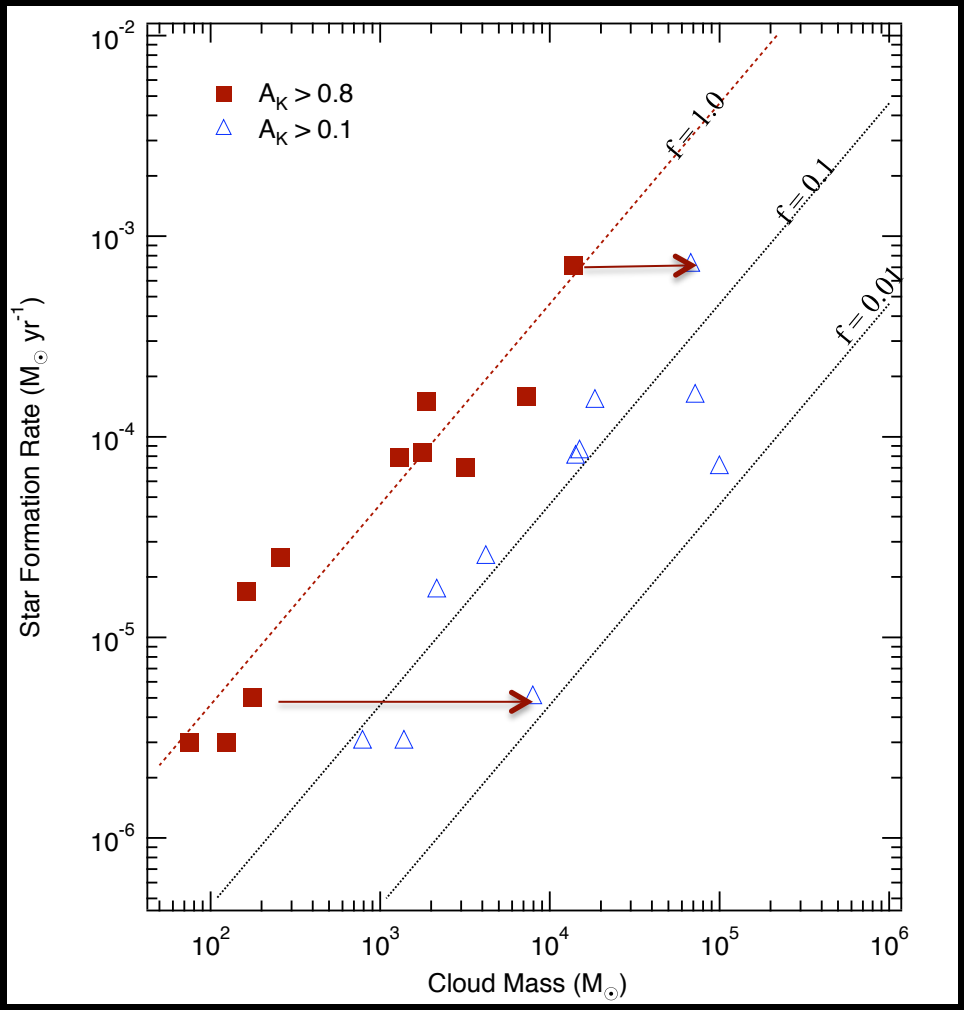
The SFR is most directly correlated with the dense gas mass.

Star Formation Timescale in Dense Gas:

$t_{gc} \approx 22$ Myr

A *Generalized* Star Formation Scaling Law for Local GMCs

$$\mathrm{SFR} = (4.6 \times 10^{-8})\ f_{dg}\ M_{gas} \quad (M_\odot\ \mathrm{yr}^{-1})$$



Family of linear scaling relations parameterized by the dense gas fraction f_{dg}

$$f_{dg} = M_{0.8} / M_{gas}$$

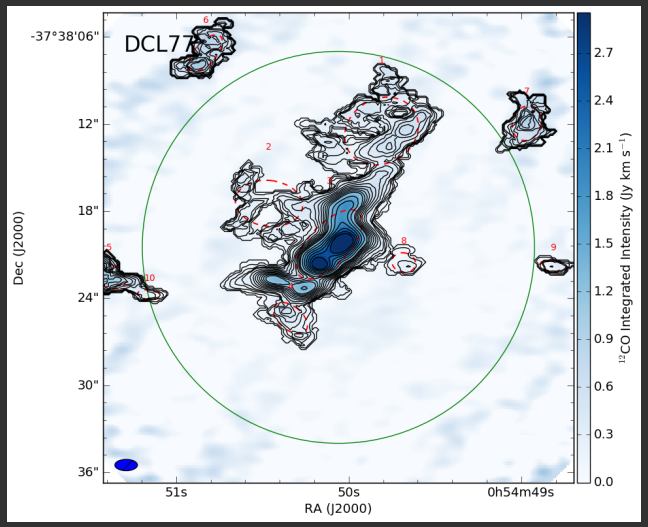
Star Formation Timescale :

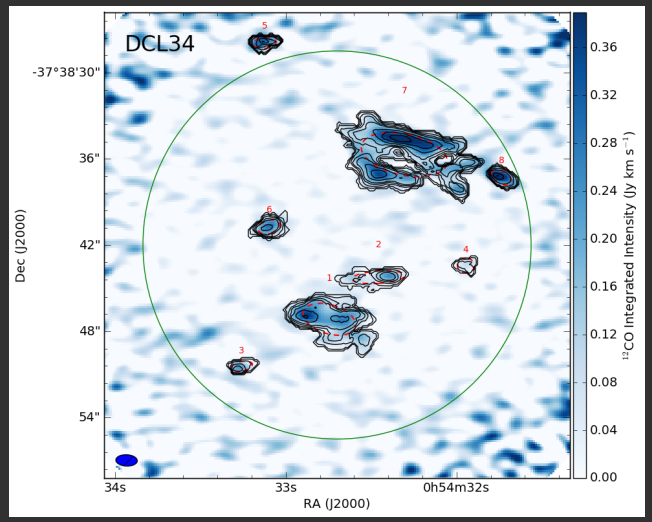
$$t_{gc} \approx 22\, f^{-1}\ \mathrm{Myr}$$

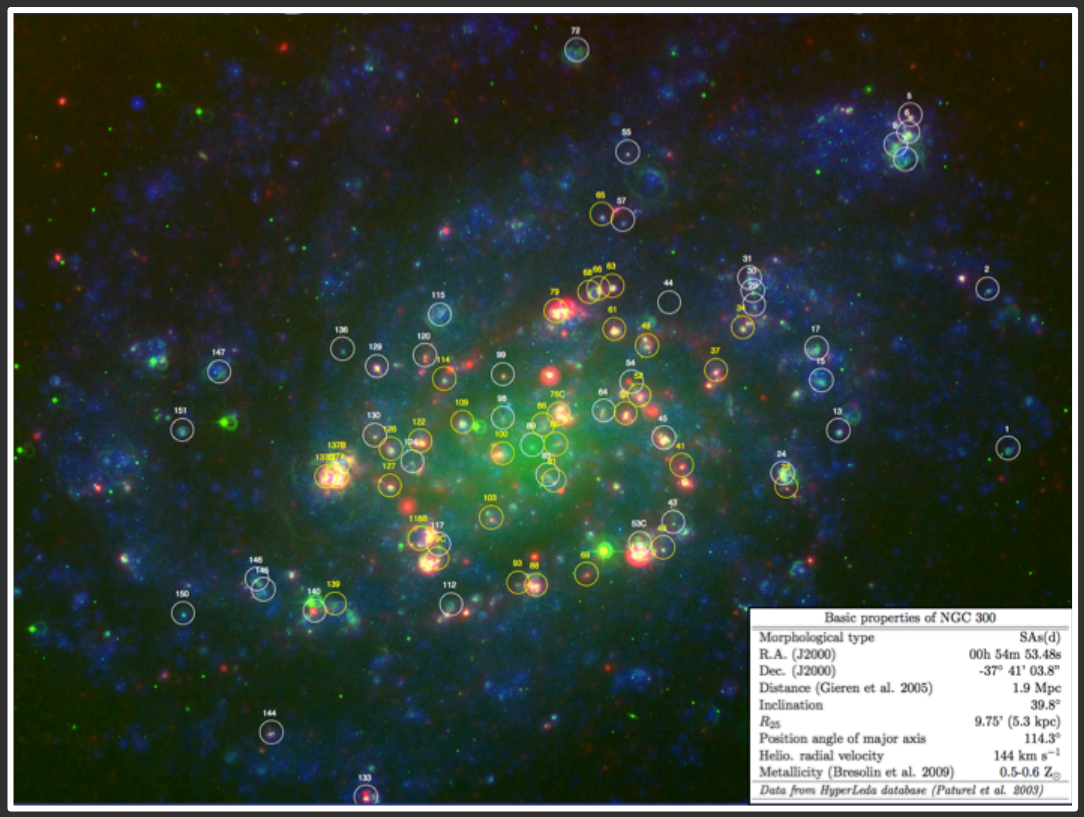
Extending SFR Scaling Relations to Nearby Galaxies

Extending SFR Scaling Relations to Nearby Galaxies

NGC 300 (ALMA)



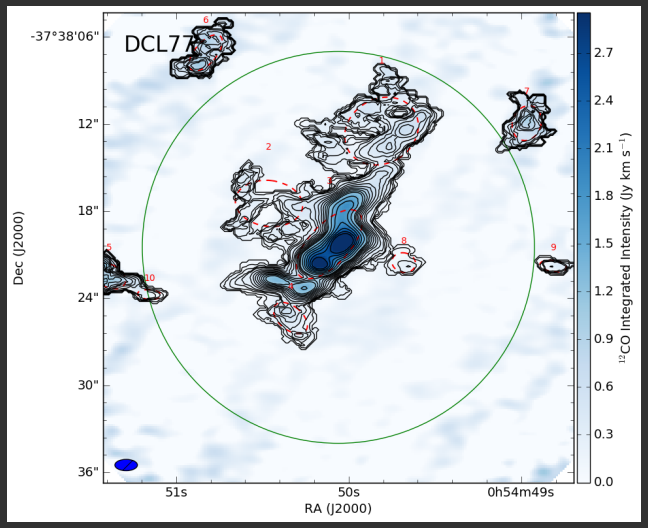


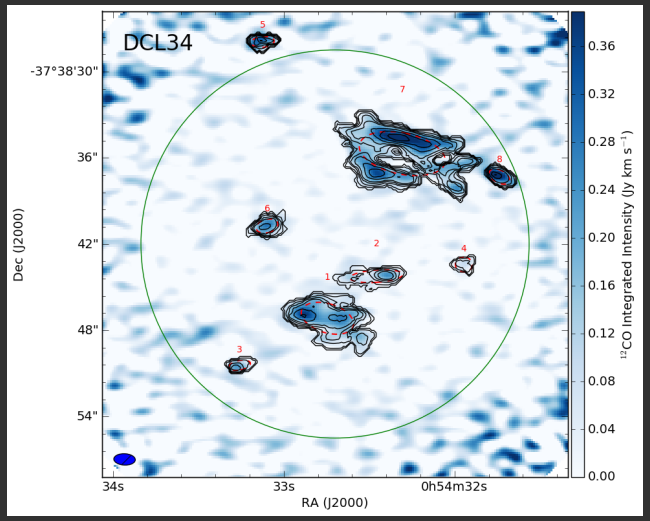


Faesi et al. 2016

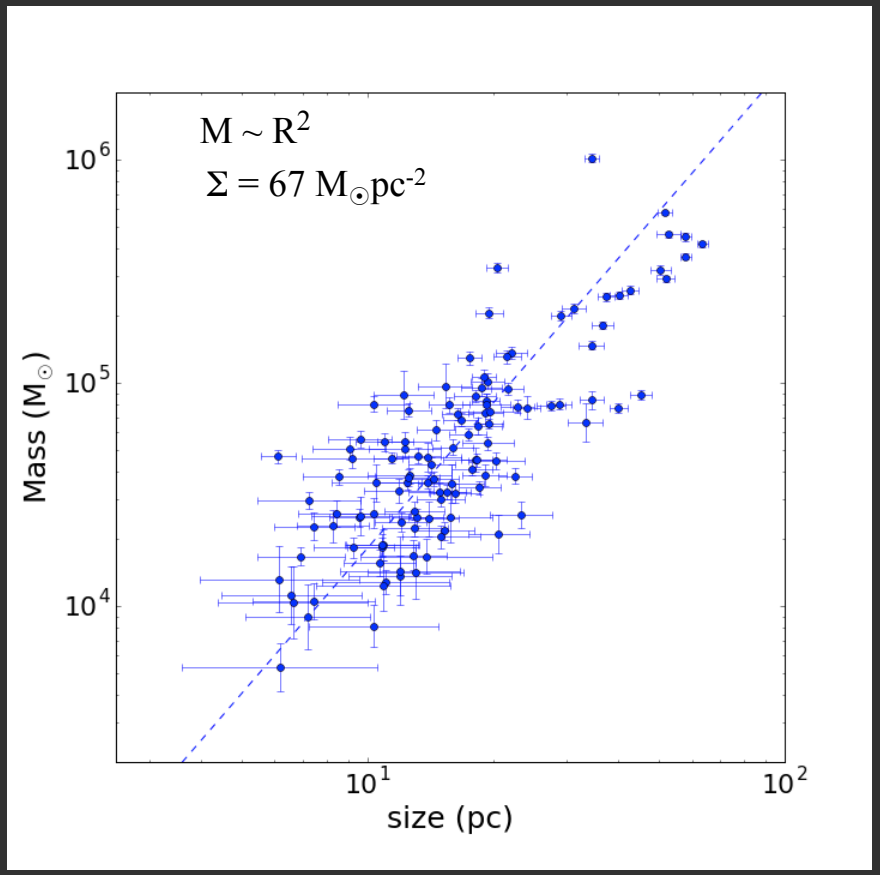
Extending SFR Scaling Relations to Nearby Galaxies

NGC 300 (ALMA)



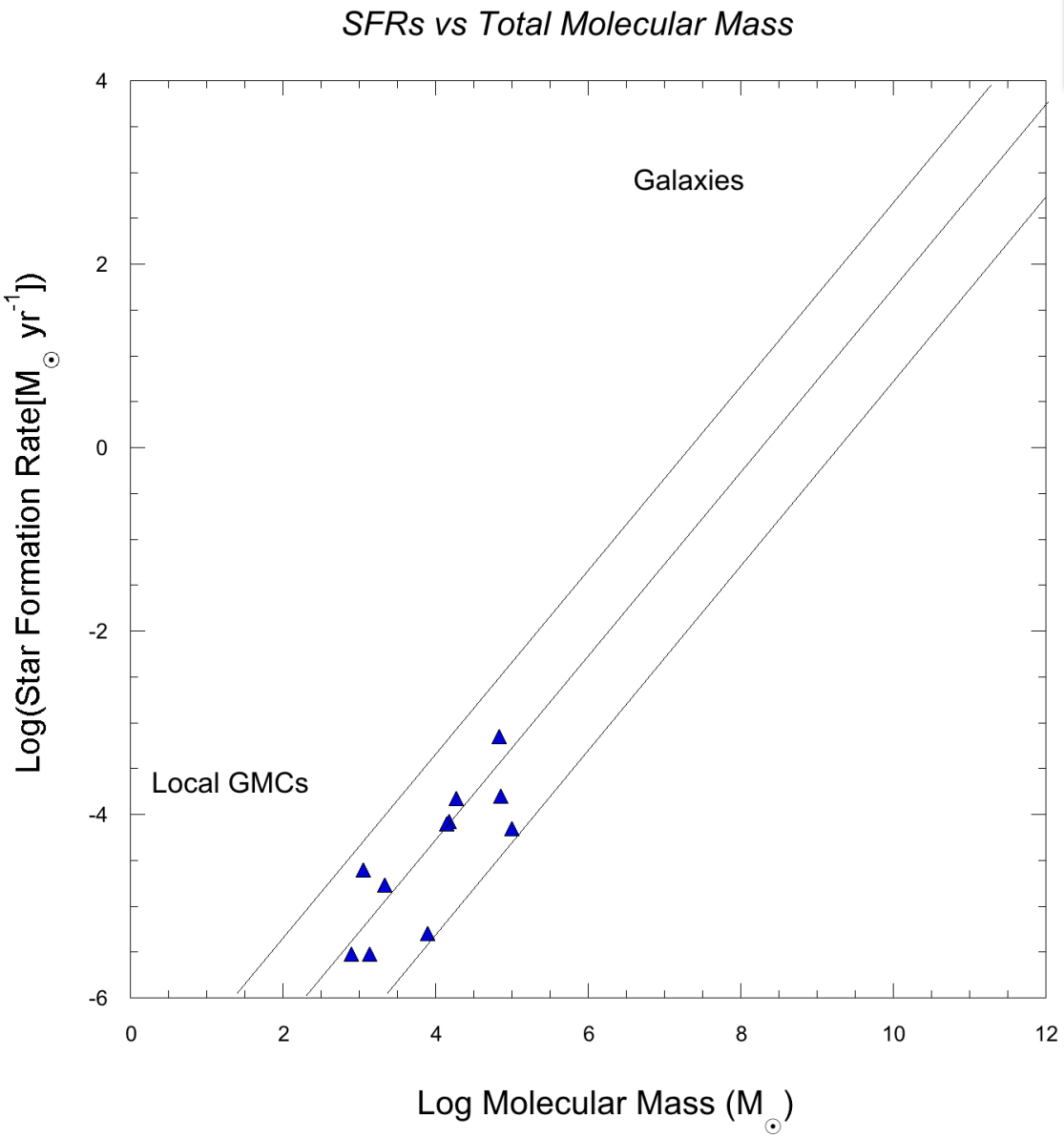


Constant Column Density Scaling Law



Faesi et al. 2016

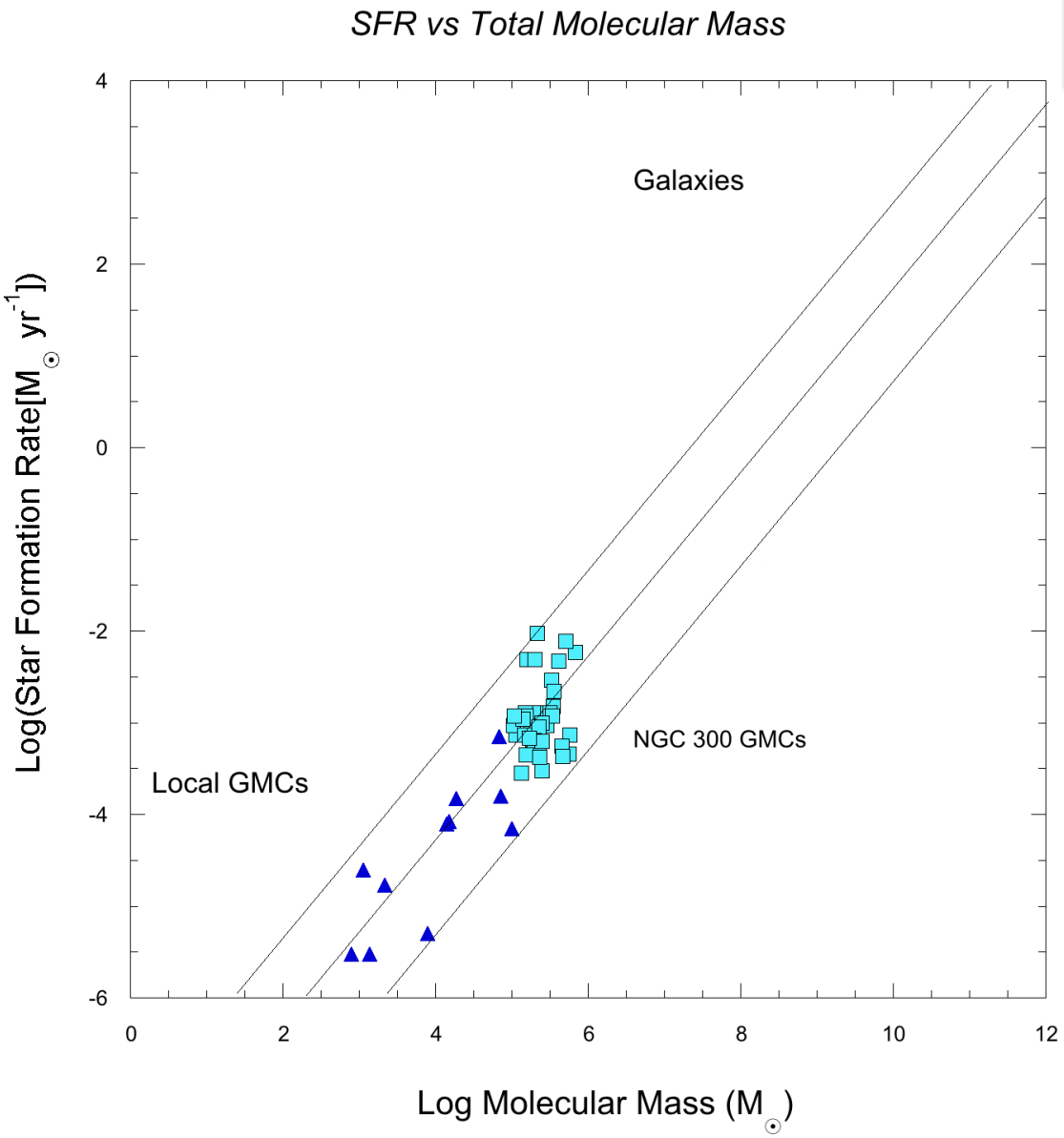
Extending SFR Scaling Relations to Nearby Galaxies



Total Molecular Masses

▲ Lada et al. 2012

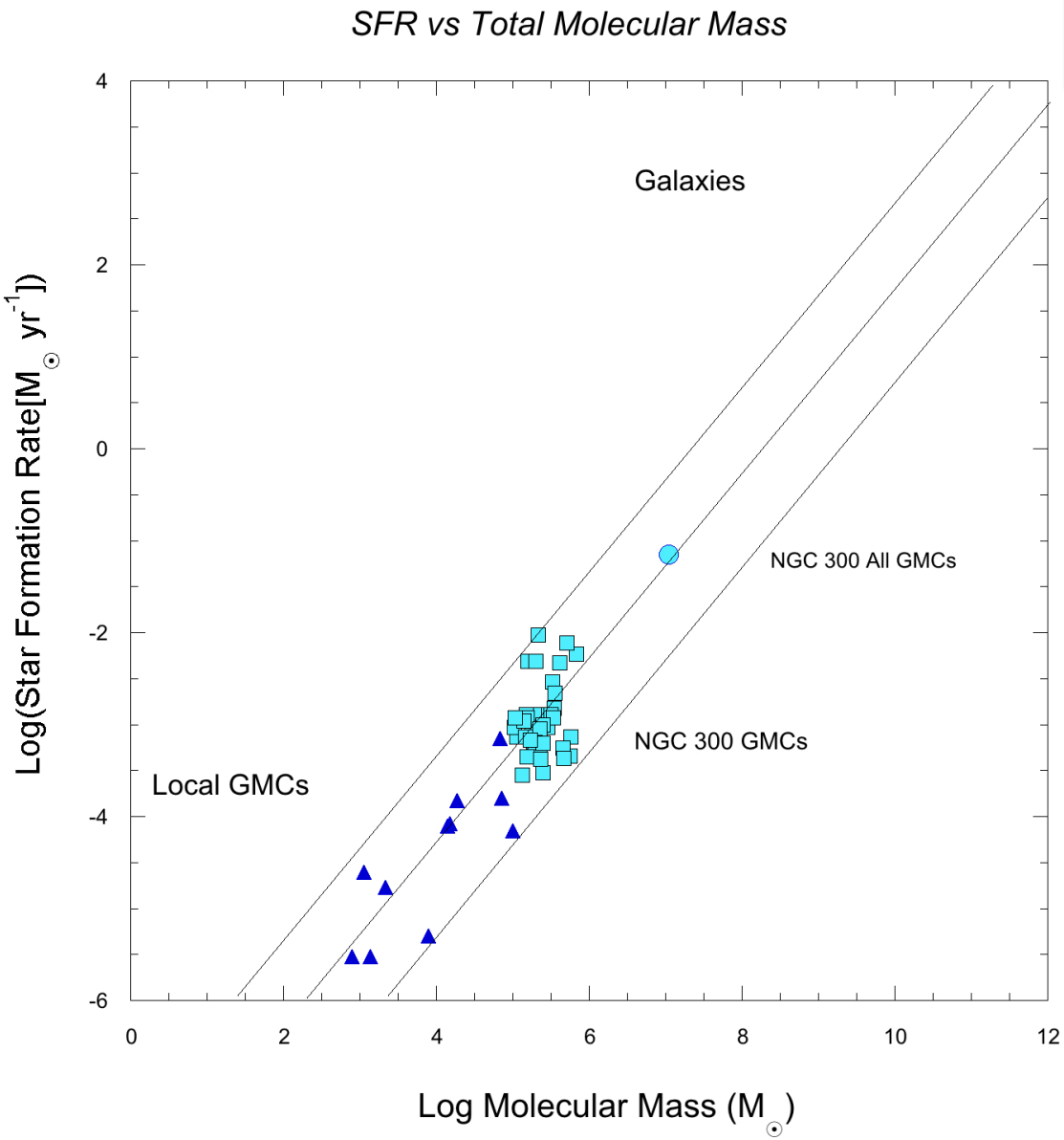
Extending SFR Scaling Relations to Nearby Galaxies



Total Molecular Masses

- Faesi et al. 2014
- Lada et al. 2012

Extending SFR Scaling Relations to Nearby Galaxies

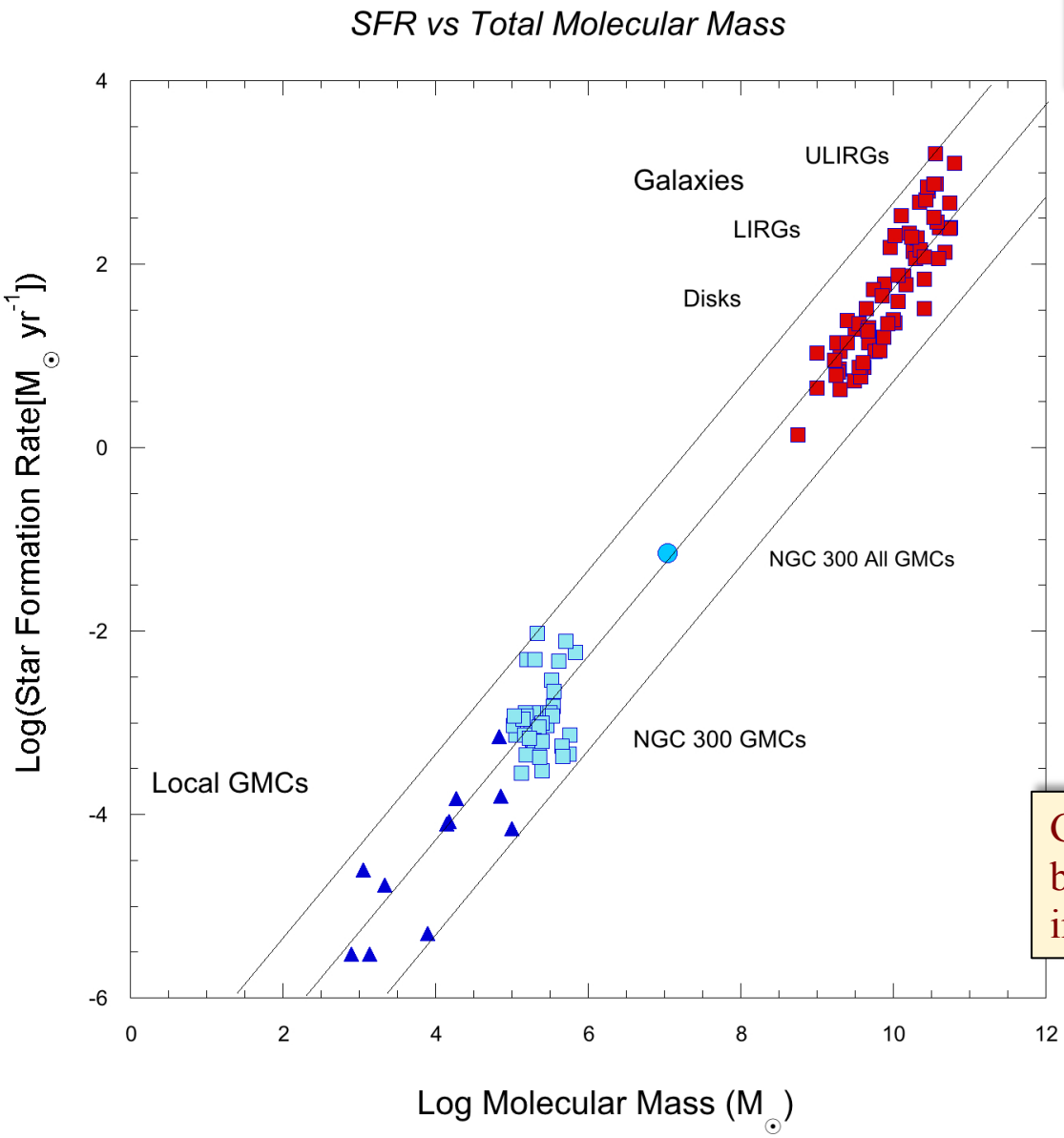


Total Molecular Masses

Faesi et al. 2014

Lada et al. 2012

Extending SFR Scaling Relations to Nearby Galaxies



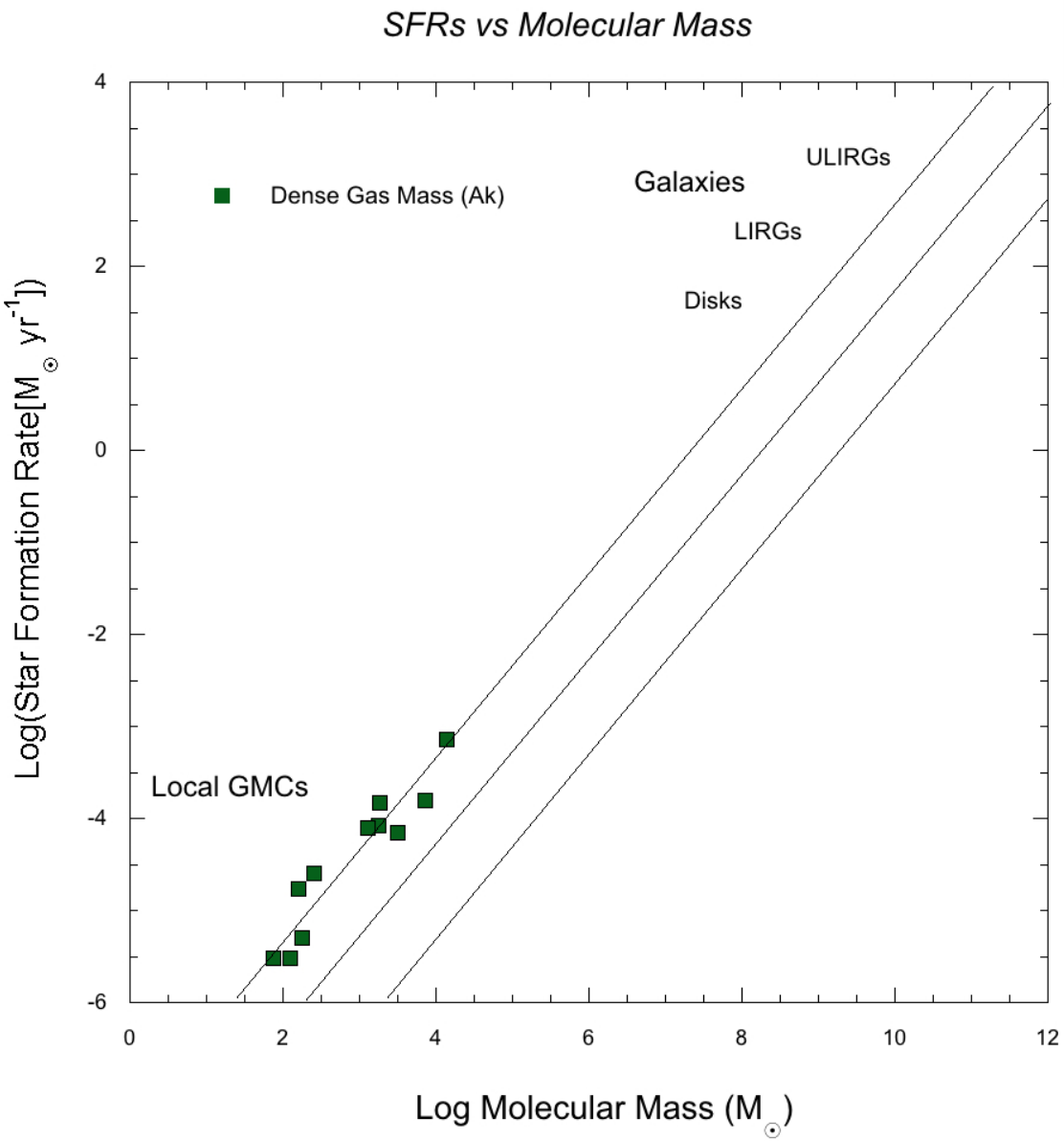
Total Molecular Masses

- Gao & Solomon 2004
- Faesi et al. 2014
- Lada et al. 2012

GMCs are the fundamental building blocks of star formation in disk galaxies.

Extending SFR Scaling Relations to Nearby Galaxies

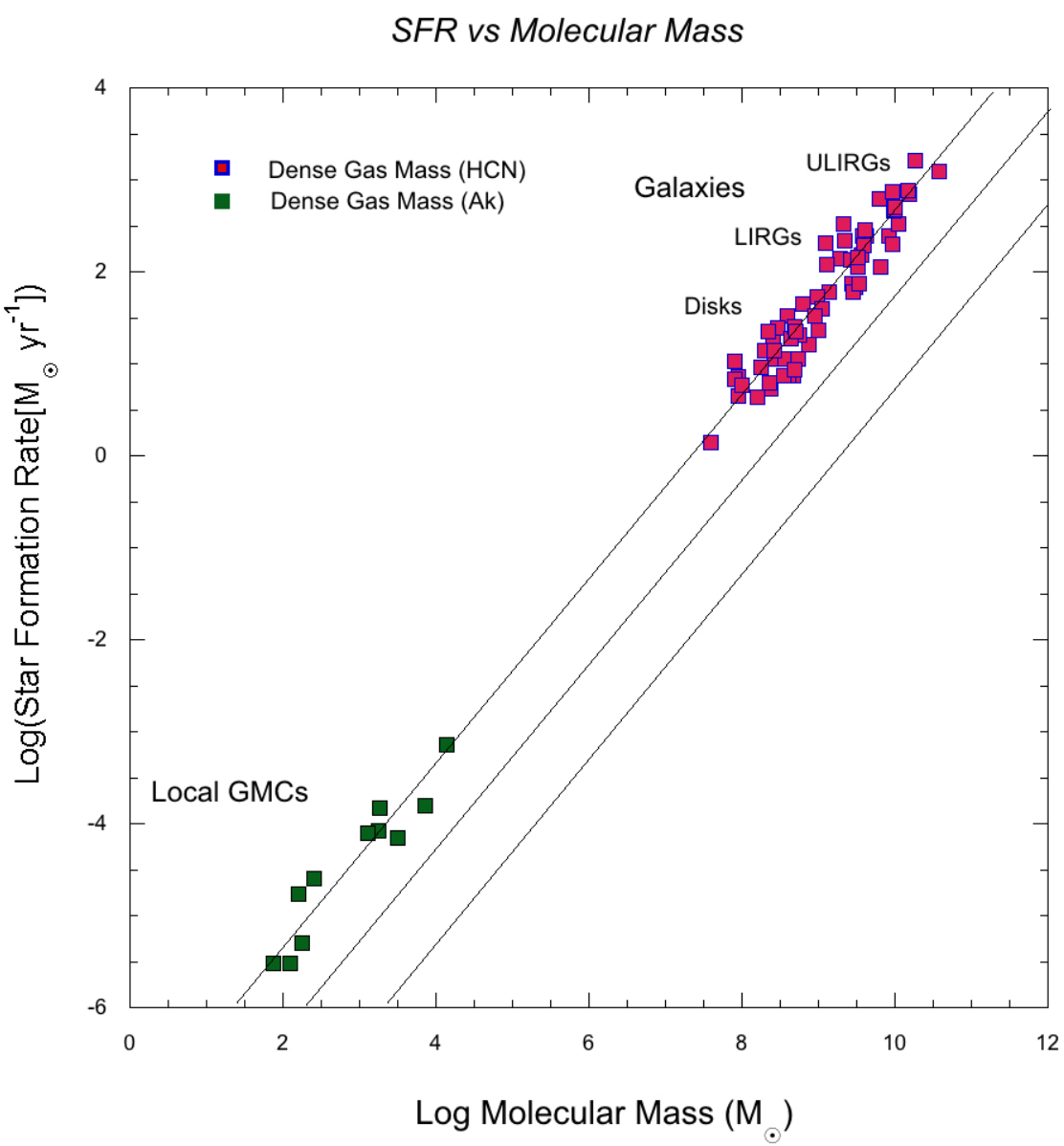
Dense Gas Masses



Gao and Solomon 2004

Lada et al. 2010

Extending SFR Scaling Relations to Nearby Galaxies



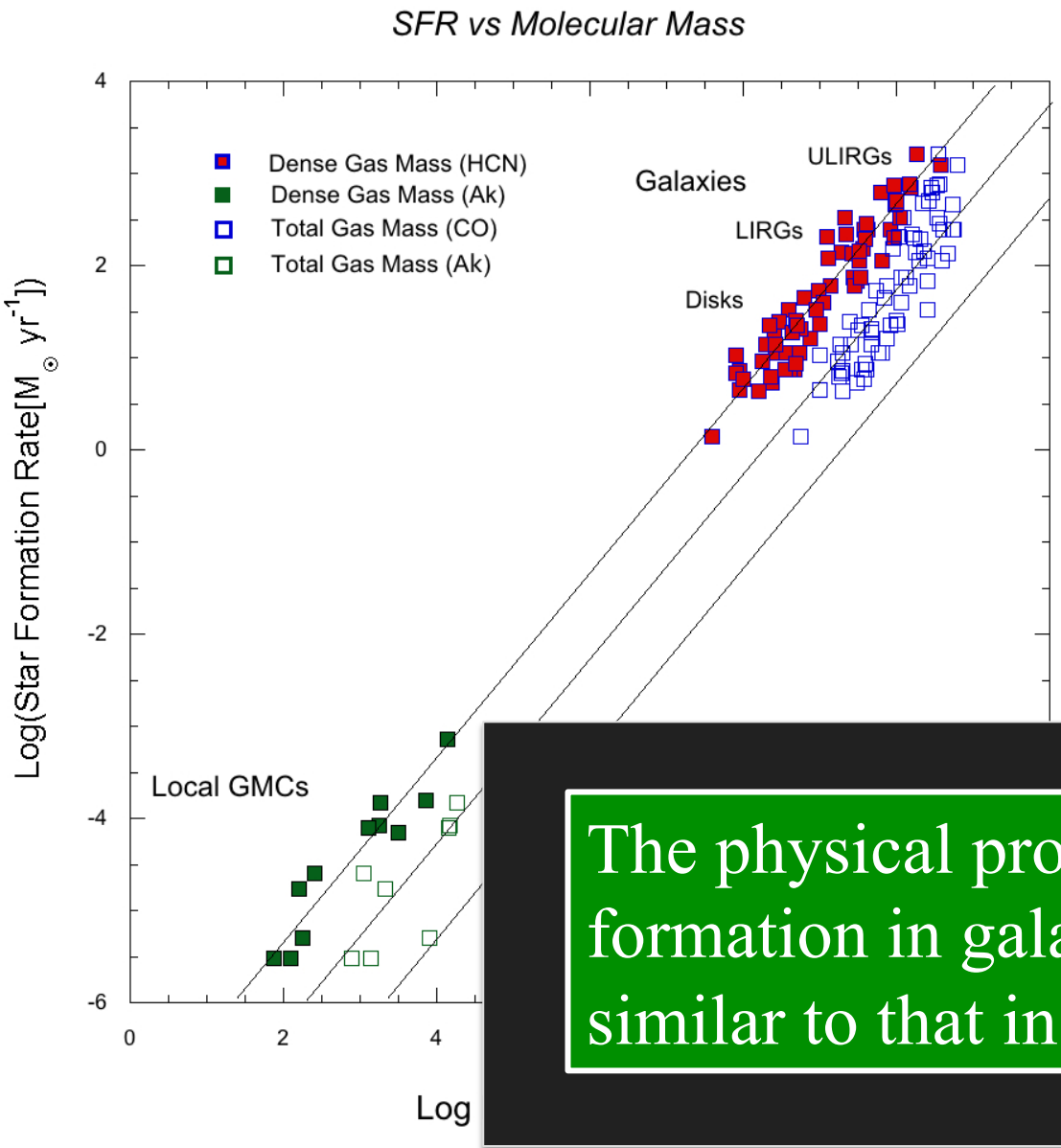
Dense Gas Masses

The SFR is controlled by the mass of dense molecular gas within GMCs AND *galaxies*

Gao and Solomon 2004

Lada et al. 2010

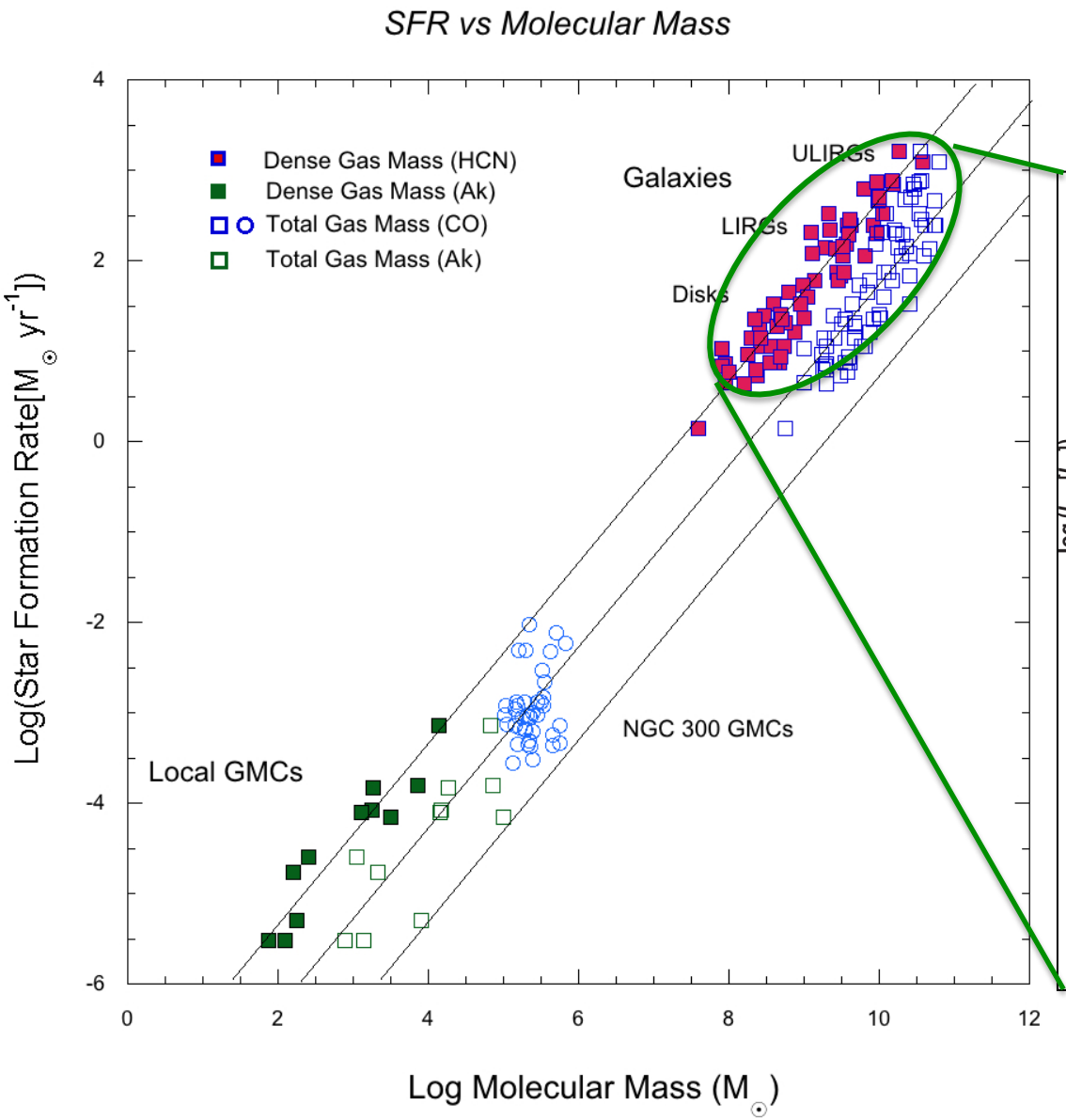
Extending SFR Scaling Relations to Nearby Galaxies



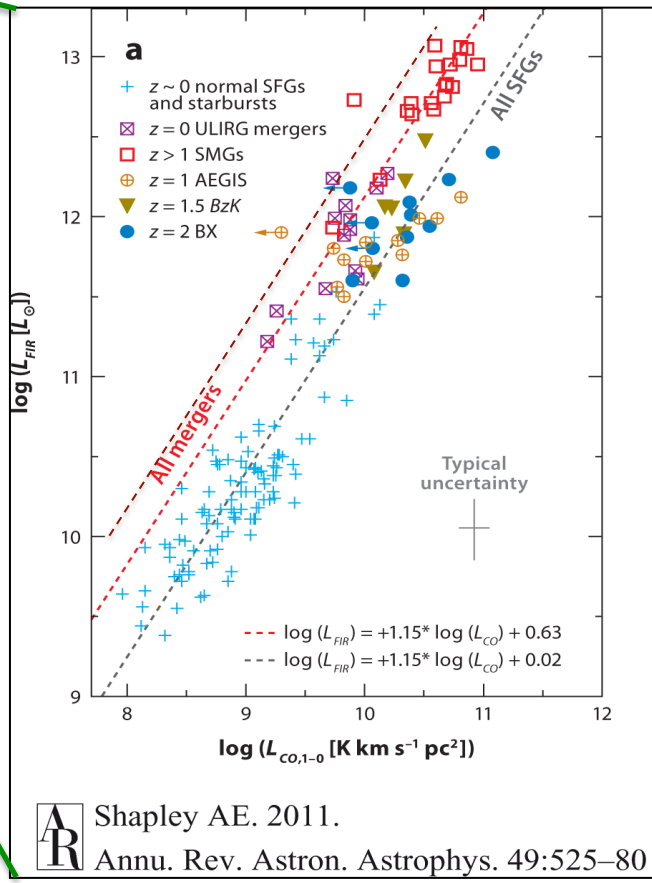
Dense gas fractions and depletion times are similar across wide range in environments from local clouds to whole galaxies.

The physical process of star formation in galaxies must be very similar to that in MW GMCs

Extending SFR Scaling Relations to Nearby Galaxies

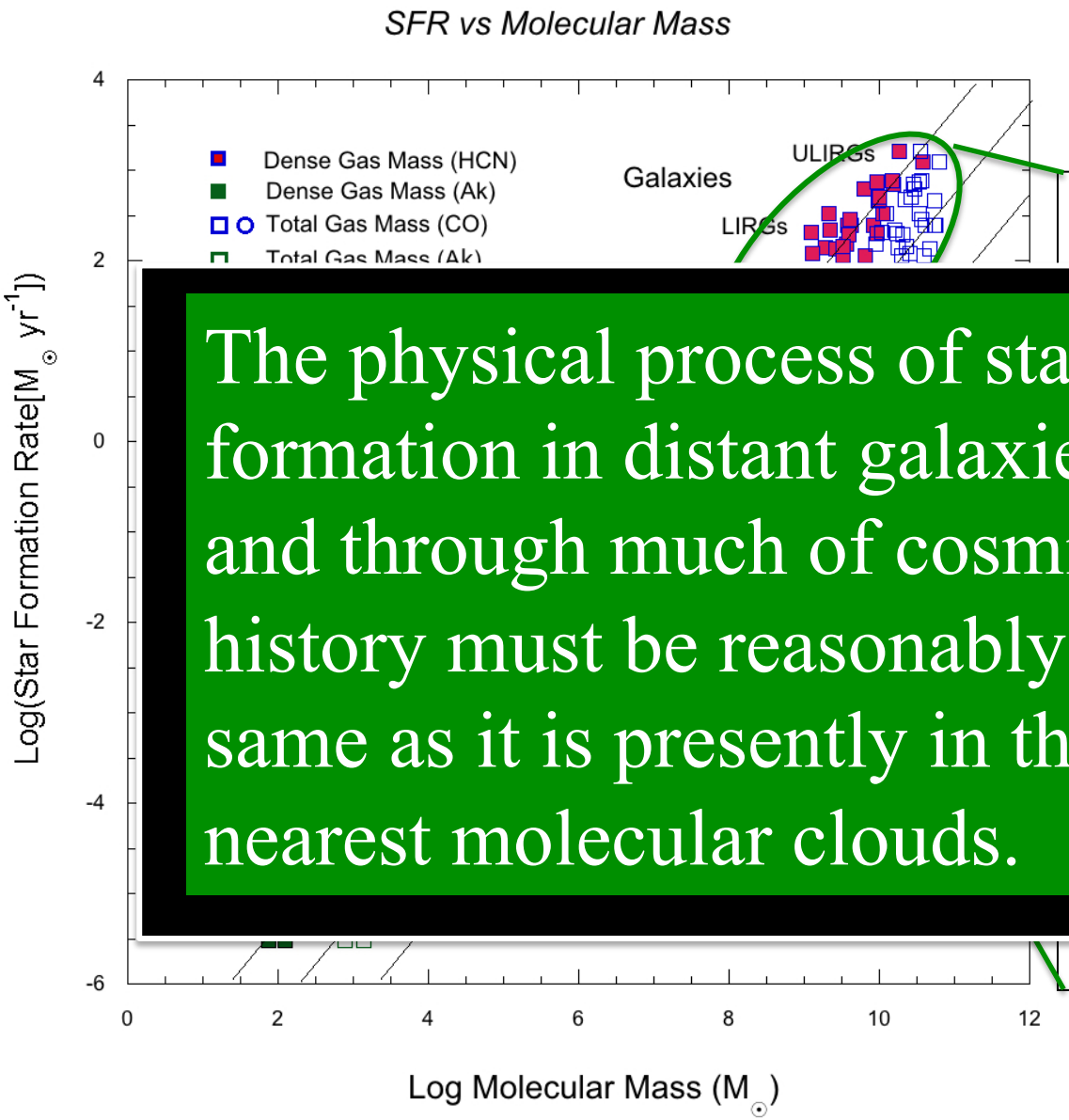


Early Universe: z = 2 -4

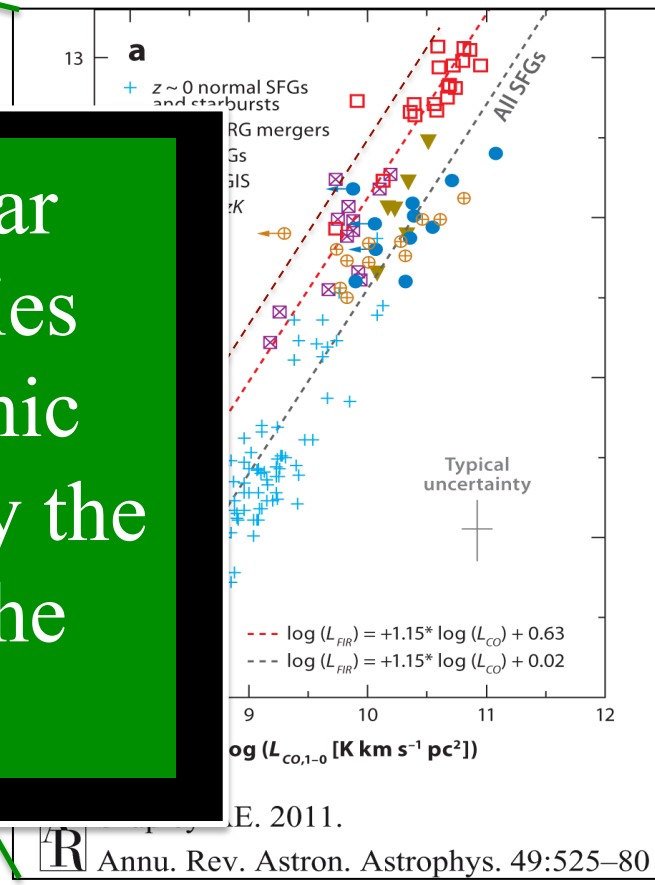


Shapley AE. 2011.
Annu. Rev. Astron. Astrophys. 49:525–80

Extending SFR Scaling Relations to Nearby Galaxies



Early Universe: z = 2 -4



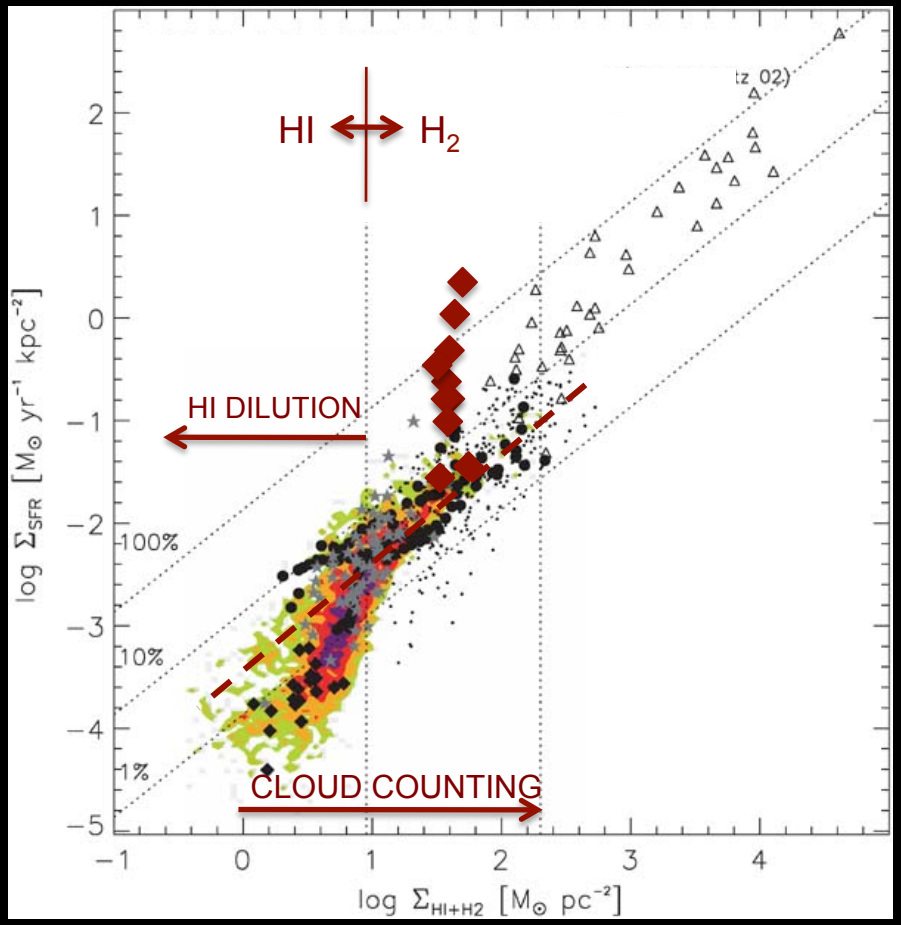
The physical process of star formation in distant galaxies and through much of cosmic history must be reasonably the same as it is presently in the nearest molecular clouds.

E. 2011.
Annu. Rev. Astron. Astrophys. 49:525–80

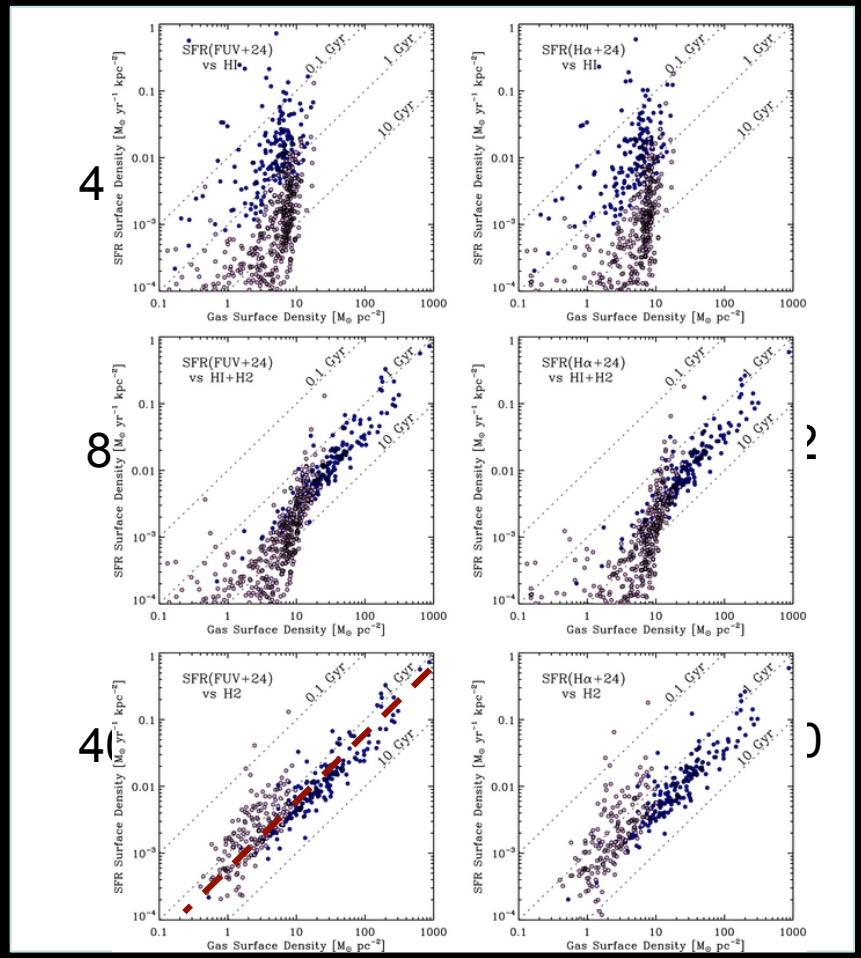
Deconstructing the Kennicutt-Schmidt Scaling Relation

Deconstructing the Kennicutt-Schmidt Law:

Galaxies



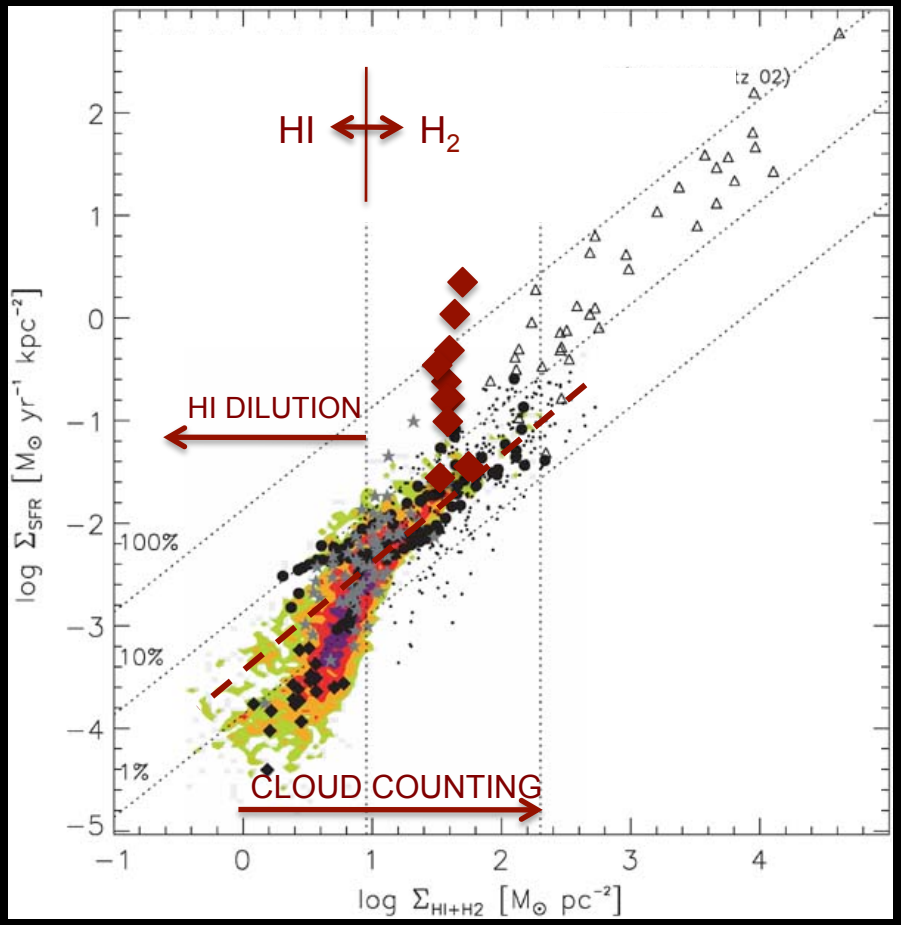
Bigiel et al. 2008 *AJ* 136:2846



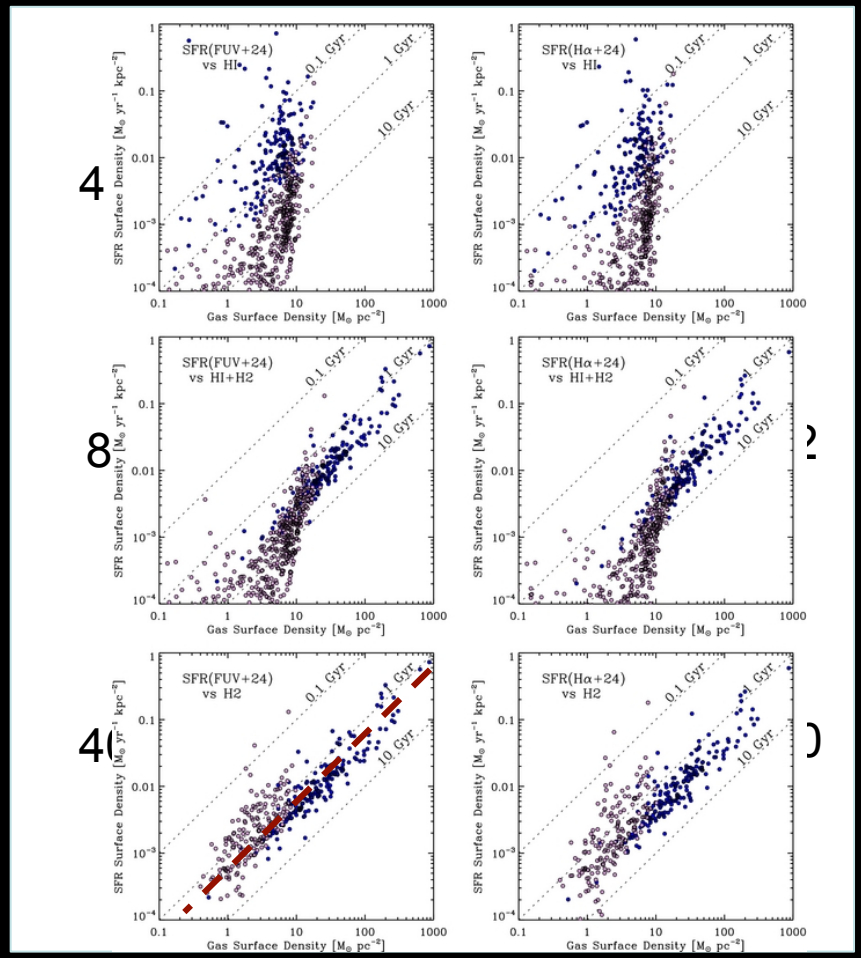
Schruba et al. 2011 *AJ* 142;37

Deconstructing the Kennicutt-Schmidt Law:

Galaxies



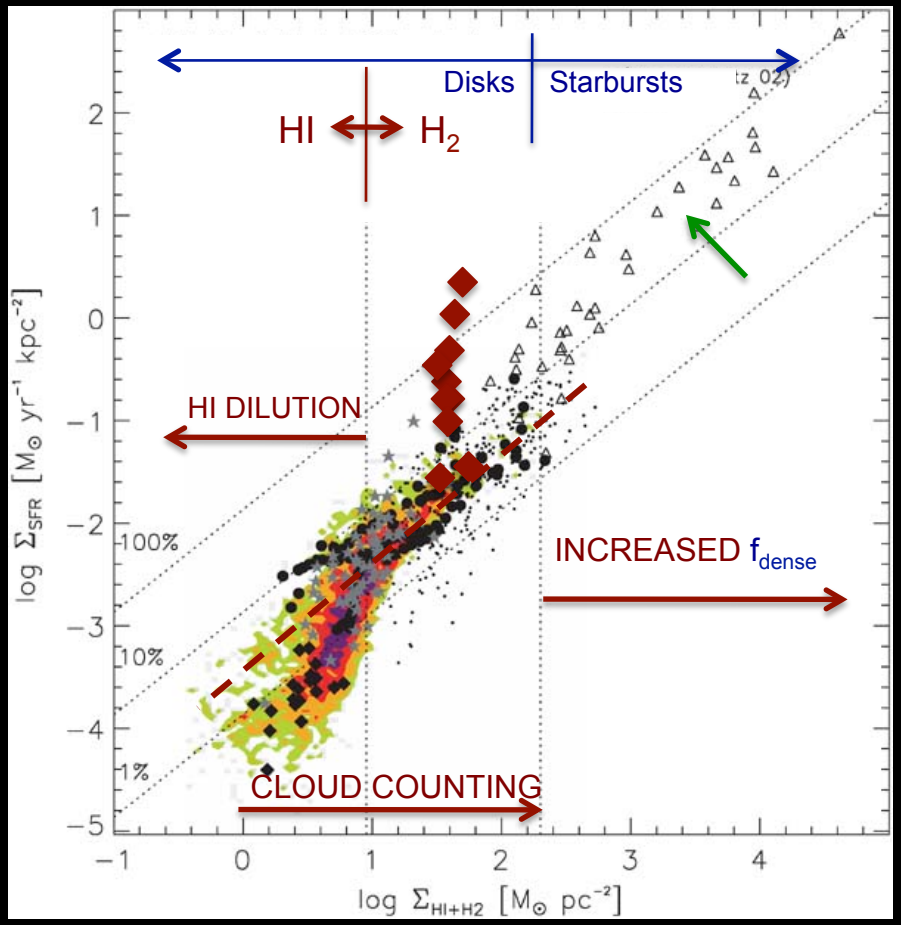
Bigiel et al. 2008 *AJ* 136:2846



Schruba et al. 2011 *AJ* 142;37

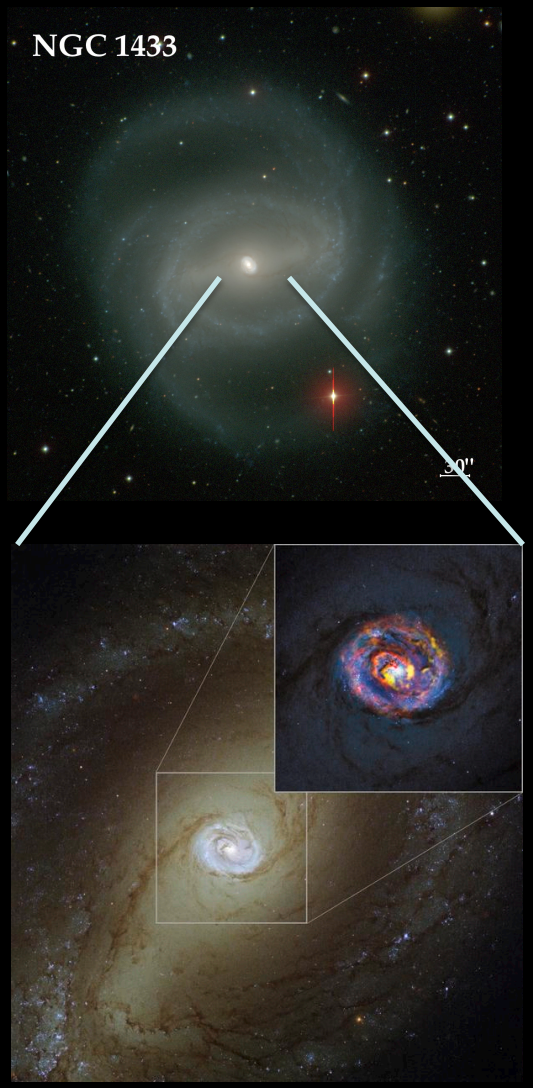
Deconstructing the Kennicutt-Schmidt Law:

Galaxies

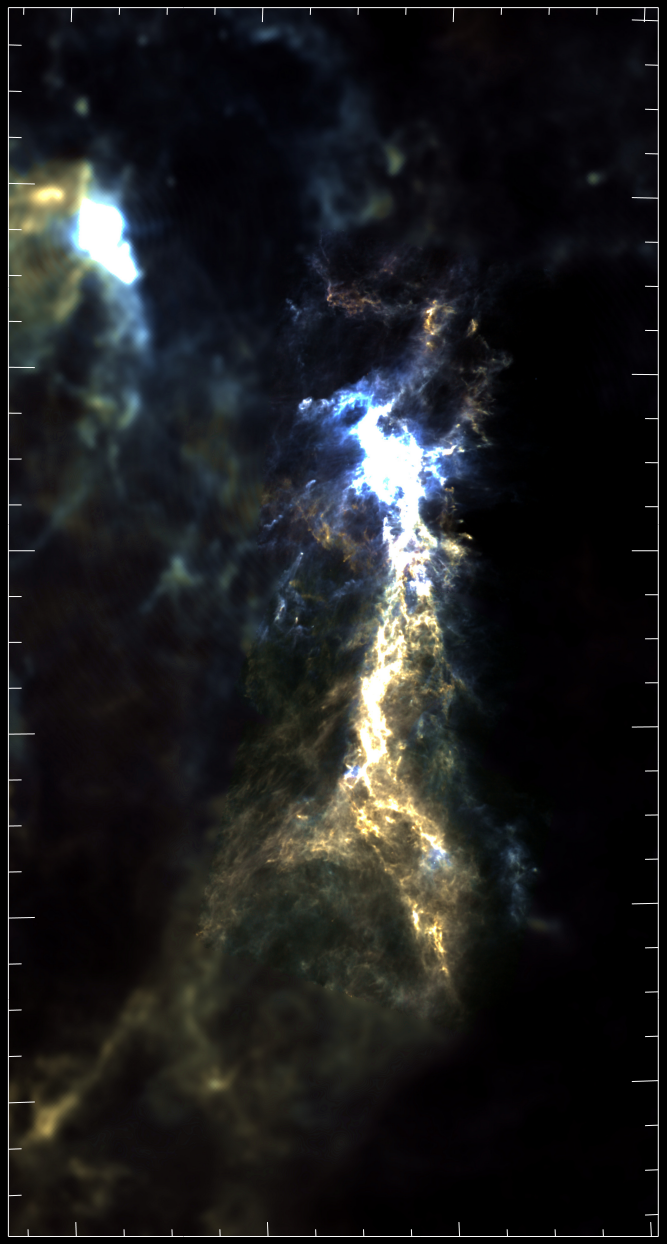


Bigiel et al. 2008

Starburst Galaxies:



Summary: The Local Truth



1. There is no Schmidt Law *between* GMCs

2. A Schmidt Law *does* exist within GMCs but it does not provide a complete description of a cloud's star formation activity.

3. The structure of a cloud plays a pivotal role in setting its global SFR and the overall level of its star formation activity.

4. The integrated SFR scales *linearly* with, and is most reliably traced by, the dense gas mass in a star forming region.

5. The amount of dense gas sets the SFR in systems ranging from individual GMCs to entire galaxies.

6. The Kennicutt-Schmidt law for galaxies is largely the result of unresolved measurements of GMCs and not a result of any underyling physical law of star formation.

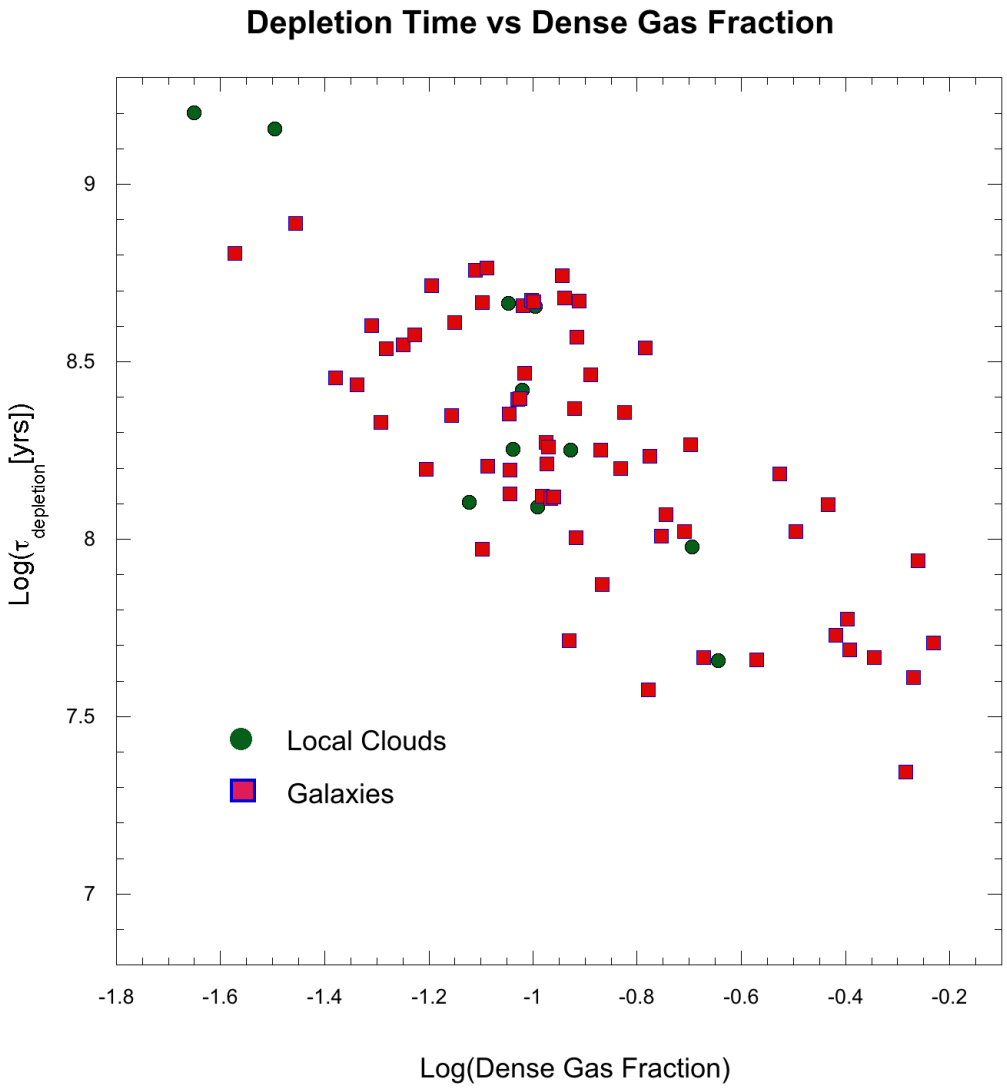
Conclusion

The physical process of star formation in distant galaxies and through much of cosmic history may be reasonably the same as it is presently in the nearest molecular clouds.

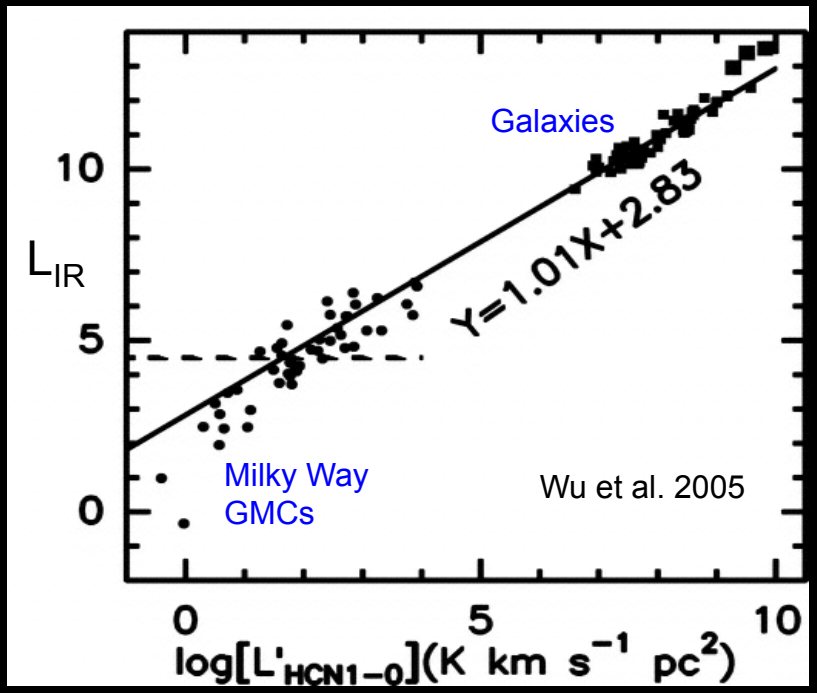
The Local Truth → The Cosmic Truth

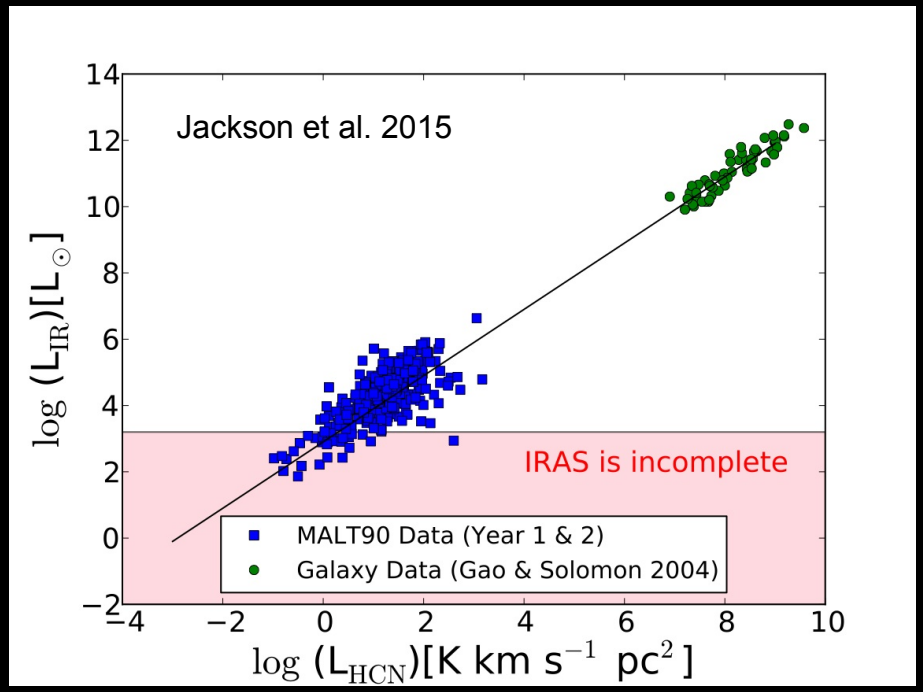
Supplementary Material

Star Formation Scaling Laws



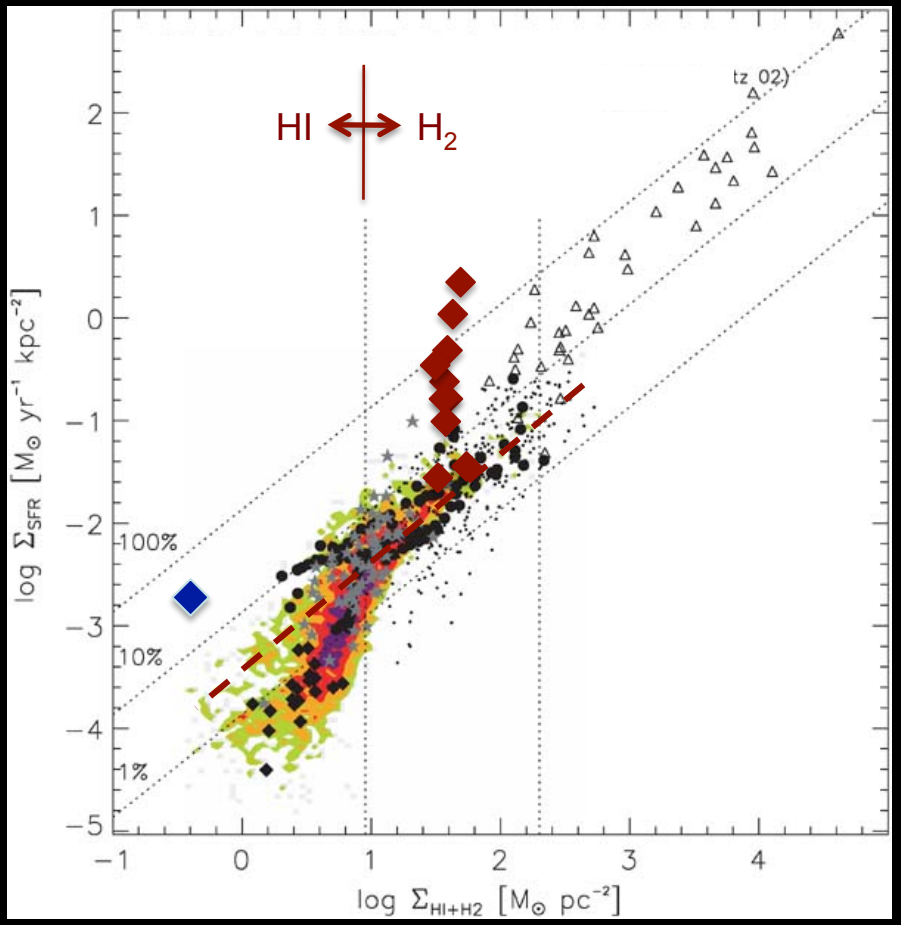
SF Scaling Laws for Dense Gas





Deconstructing the Kennicutt-Schmidt Law:

Galaxies



Bigiel et al. 2008

A Puzzling Discrepancy:

Galaxies: $t_{depletion}$ = 2-3 Gyrs

MW GMCs: $t_{depletion}$ = 220 Myrs

N300 GMCs: $t_{depletion}$ = 270 Myrs

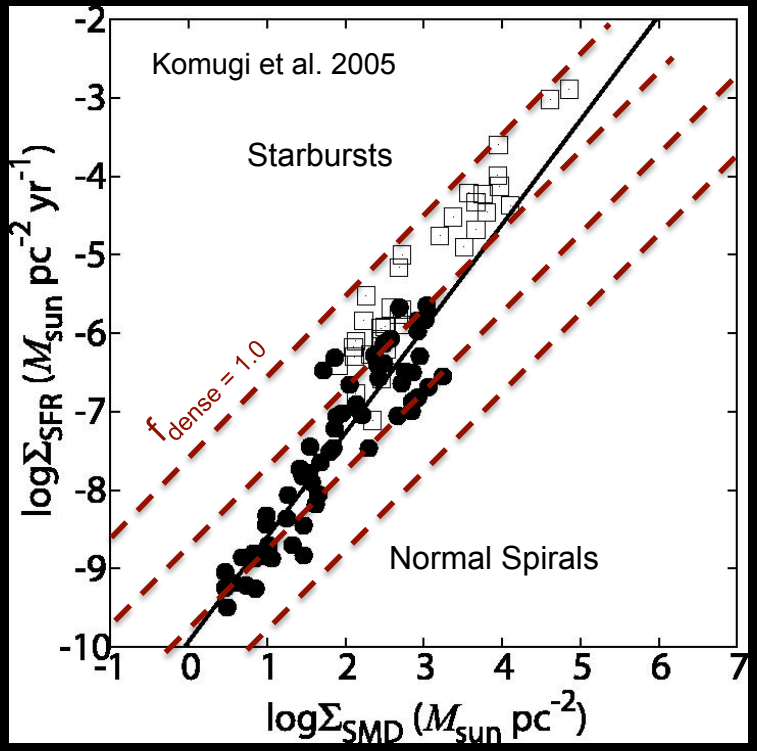
Diffuse, inert CO clouds?

SFR Calibrations?

Both?

$$\Sigma_{SFR} = 4.6 \times 10^{-8} f_{dense} \Sigma_{gas}$$

$$f_{dense} \sim (\Sigma_{gas})^{0.5}$$



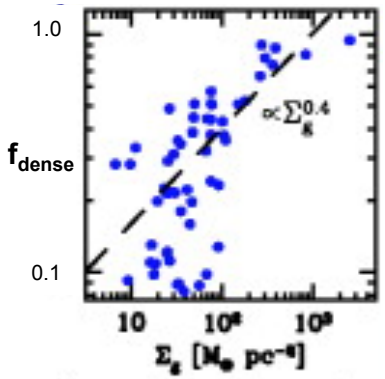
Implications for Modelling Star Forming Galaxies

SF threshold density: $n_{gas} > 50\ cm^{-3}$

t_{sf} = Constant

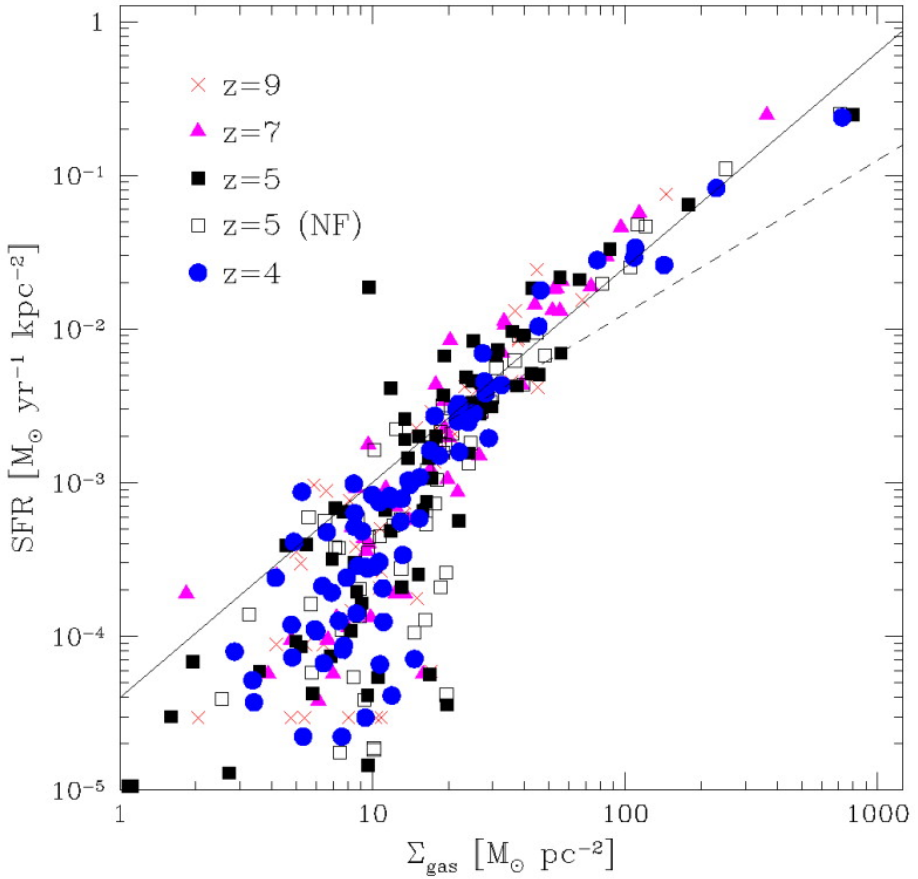
Input ≠ Output

$\rho_{SFR} = A(\rho_{gas})^{1.0}$ $\Sigma_{SFR} = B(\Sigma_{gas})^{1.4}$



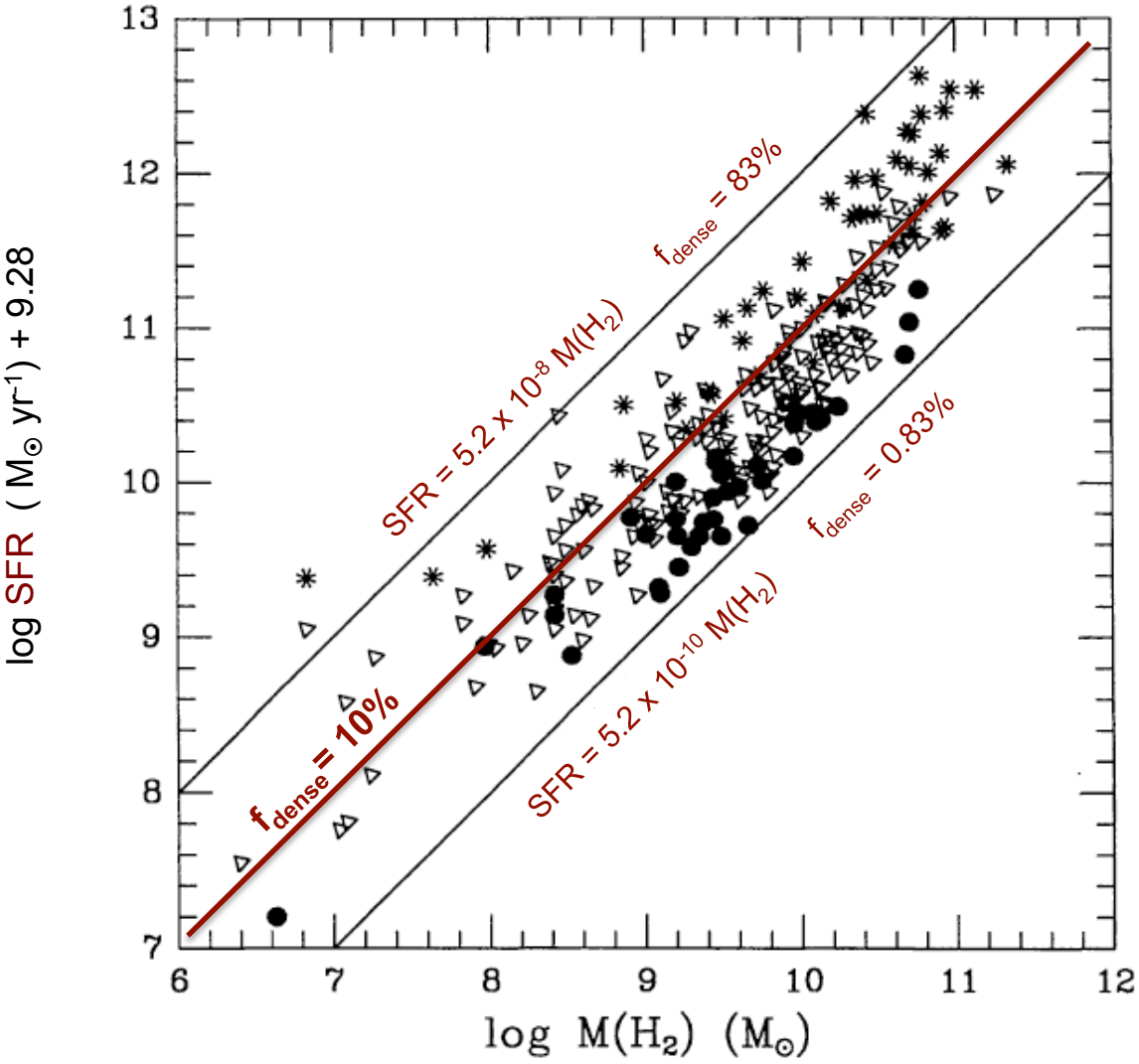
$f_{dense} \sim (\Sigma_{gas})^{0.4}$

Kravtsov (2003)

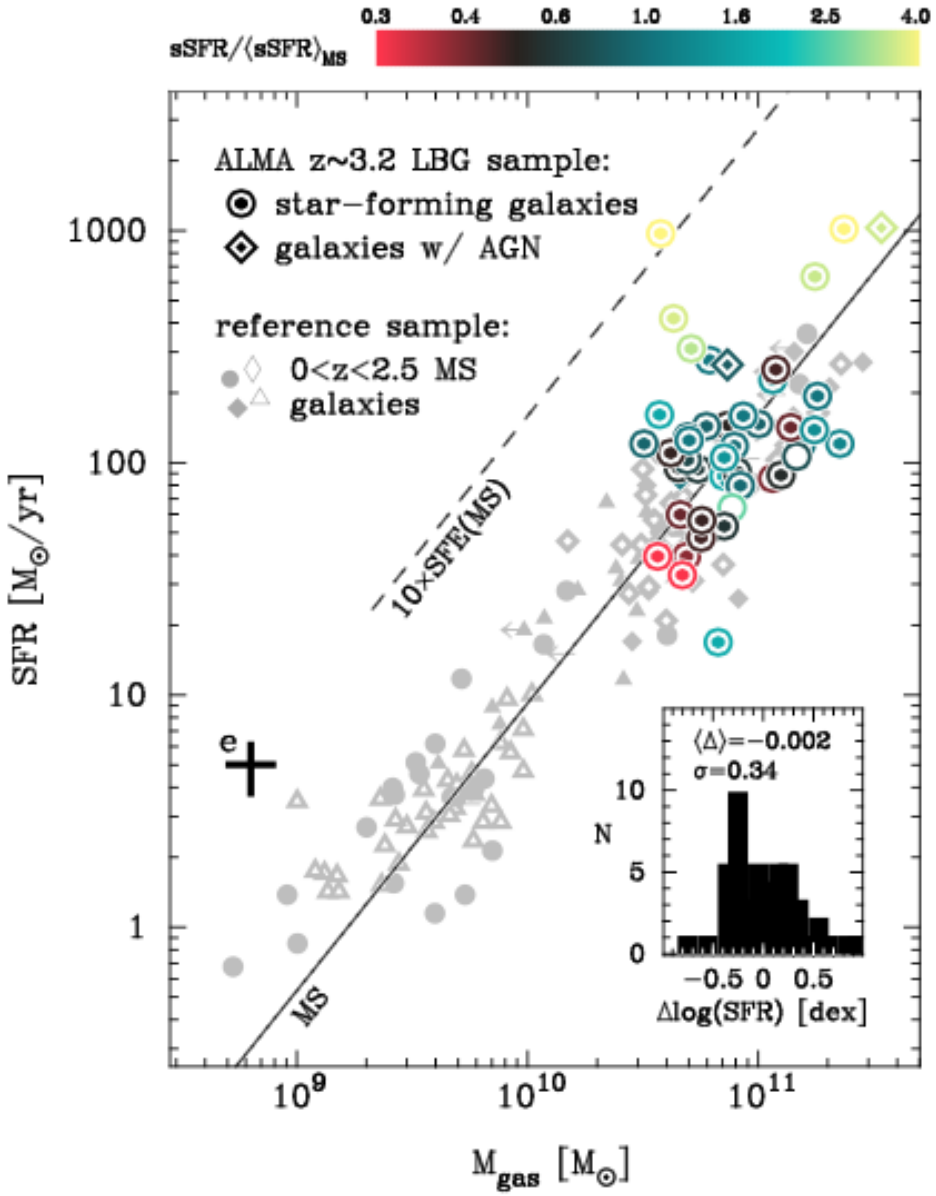


A Linear Scaling Law for Galaxies

Young & Scoville 1991, ARAA 32, 581

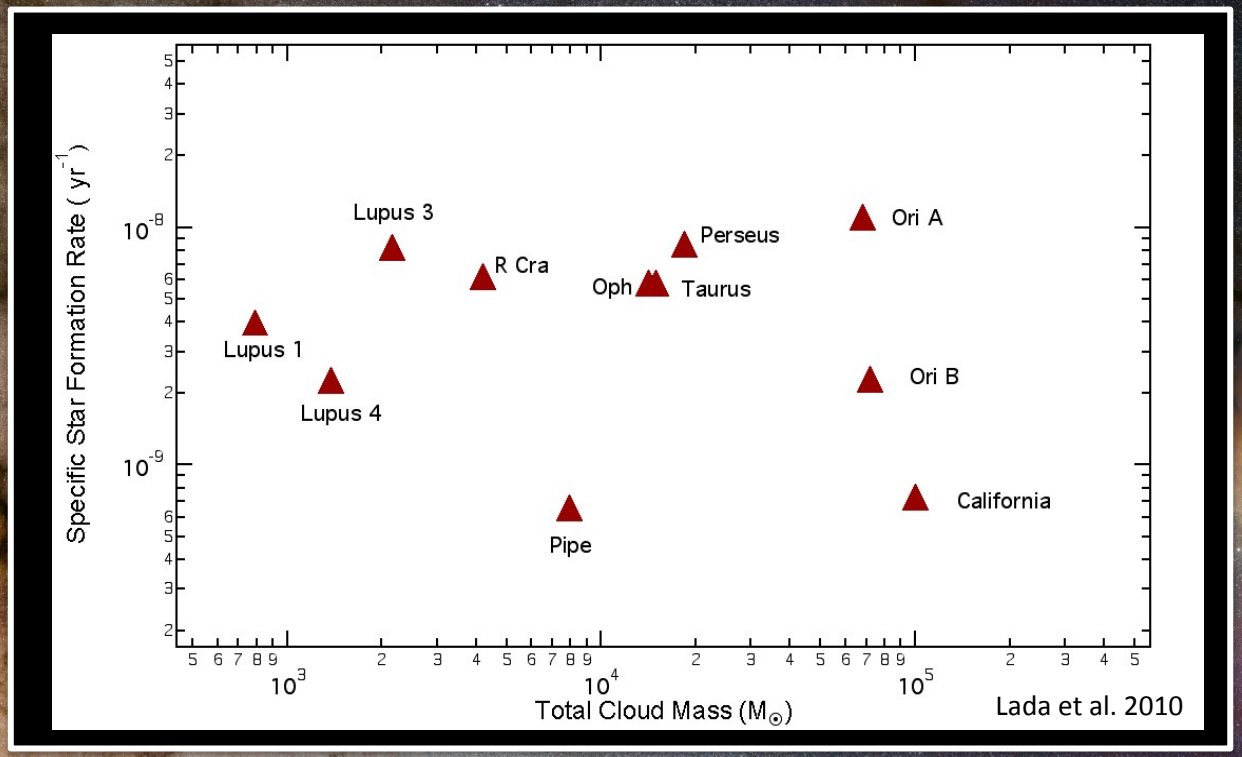


A Linear Scaling Law at High Z



Schinnerer et al. 2016

The Star Formation Rate In Molecular Gas



Greater than an order of magnitude variation, *independent* of cloud mass !

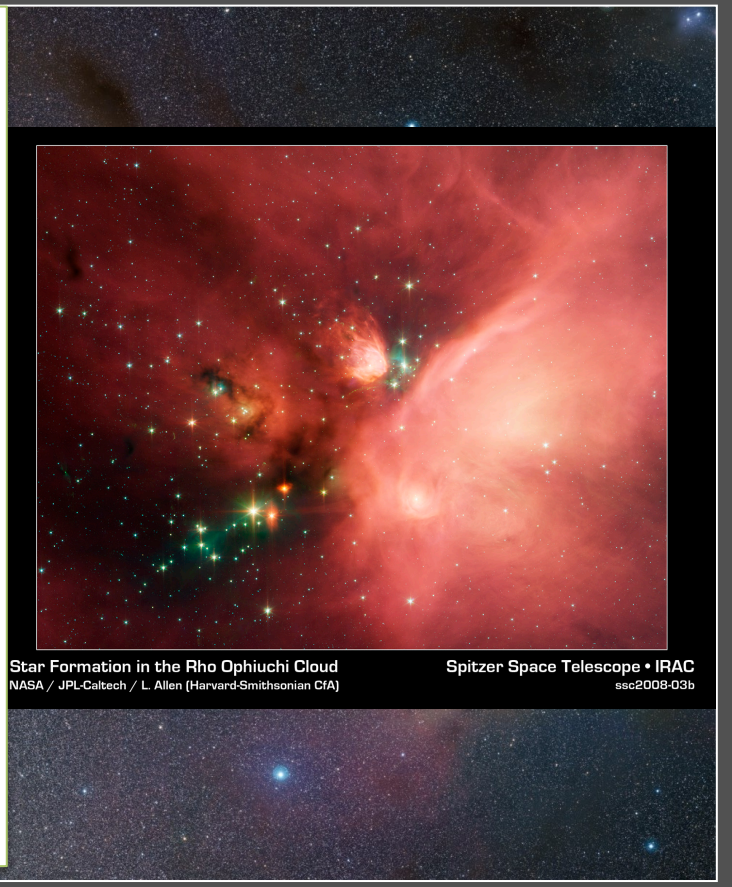
$\tau_{gc} \approx 220$ Myr

Inventory of Local GMC Masses

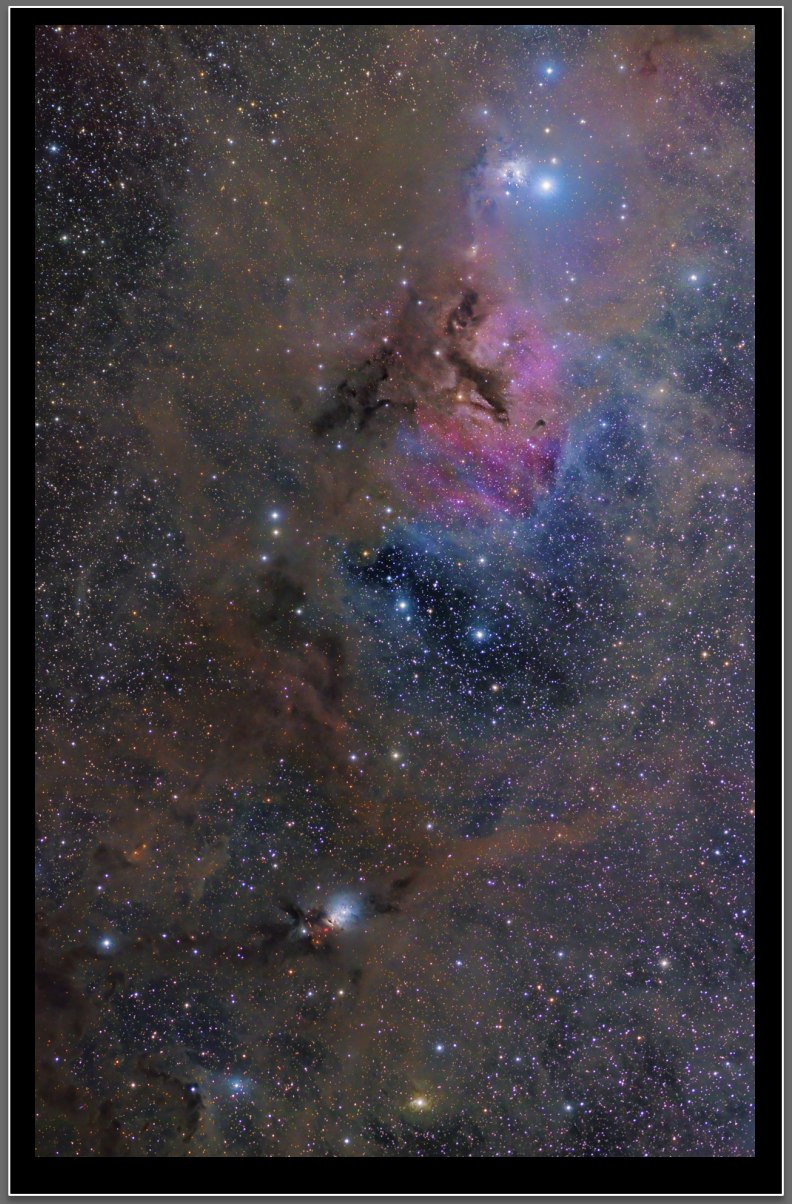
Cloud:	Mass (10^4 $M_\odot$)
Orion A	6.77
Orion B	7.18
California	9.99
Perseus	1.84
Taurus	1.49
Ophiuchus	1.41
RCrA	0.11
Pipe	0.79
Lupus 3	0.22
Lupus 3	0.14
Lupus 4	0.08

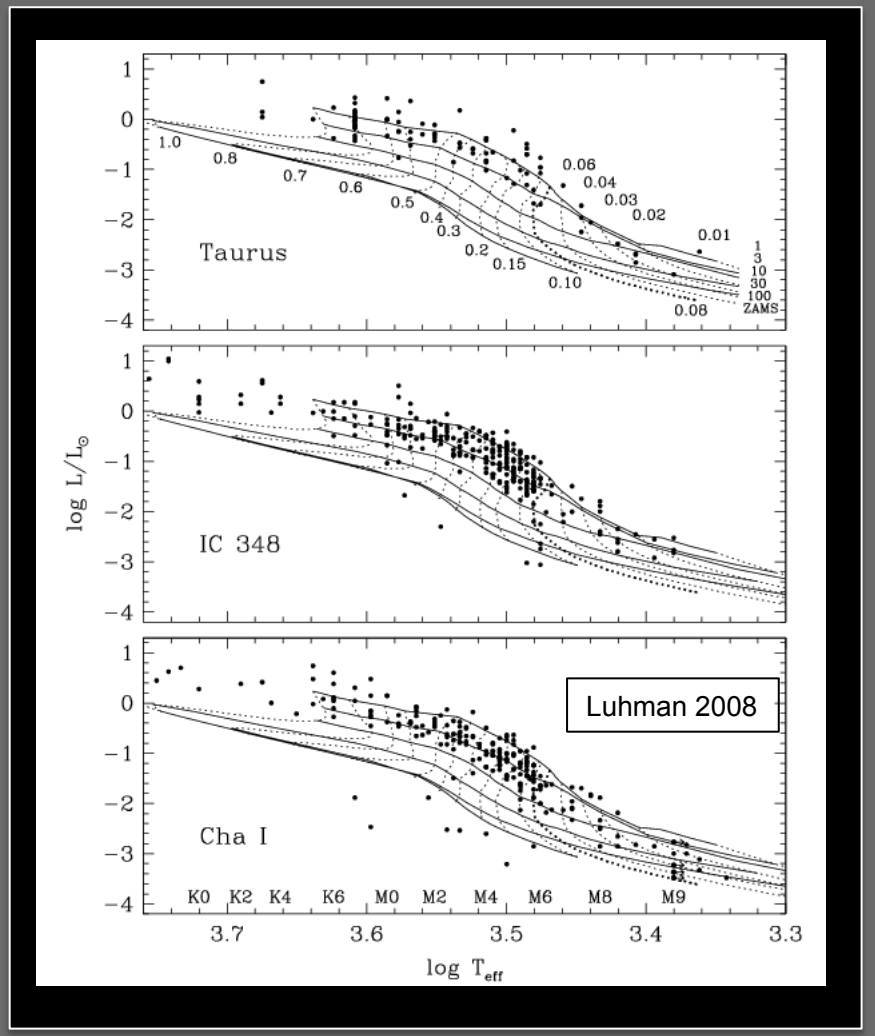
Inventory of YSOs in Local Clouds

Cloud:	YSOs
Orion A	2862
Orion B	635
California	279
Perseus	598
Taurus	335
Ophiuchus	316
RCrA	100
Pipe	21
Lupus 1	13
Lupus 3	69
Lupus 4	12



The Timescales for Star Formation





$\tau_{sf} \approx$ 1-3 Myr