

Schmidt's Conjecture and Star Formation in Giant Molecular Clouds and Galaxies



João Alves, University of Vienna

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With:

Charles Lada, CfA

Marco Lombardi, University of Milan

Jan Forbrich, University of Vienna

Carlos Roman-Zuniga, UNAM

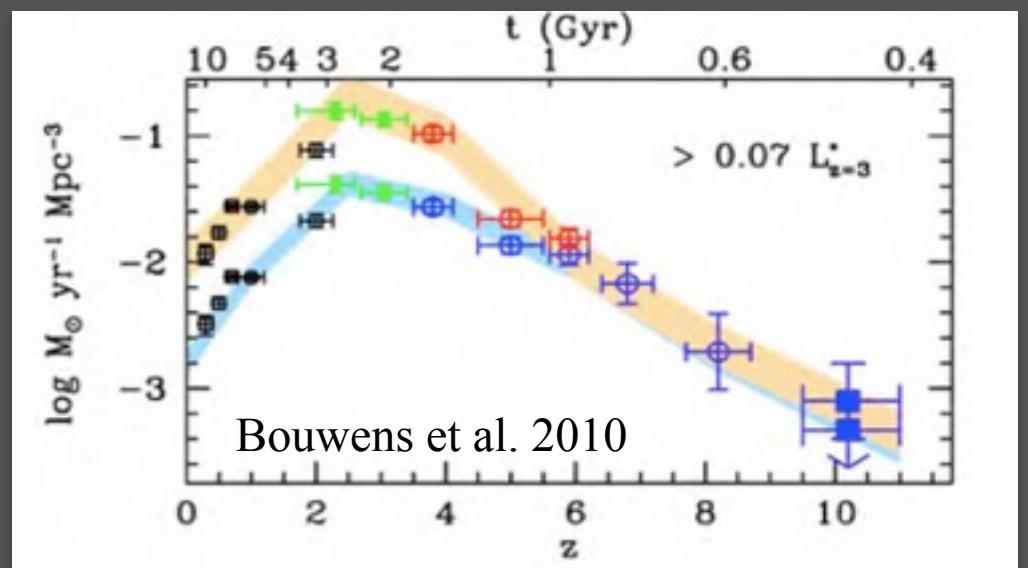
Chris Faesi, CfA

João Alves, University of Vienna

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)



$$\Sigma_{\text{SFR}} = K (\Sigma_g)^\beta \quad [\text{M}_\odot \text{ pc}^{-2}]$$

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Schmidt (1959)



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

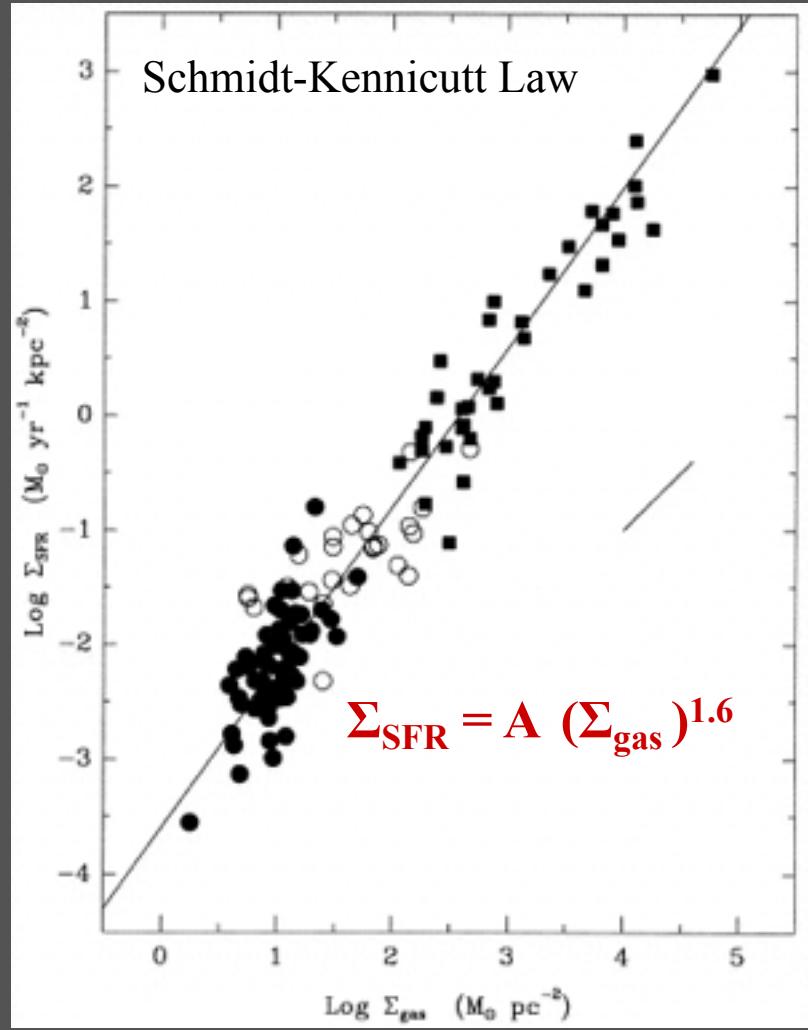
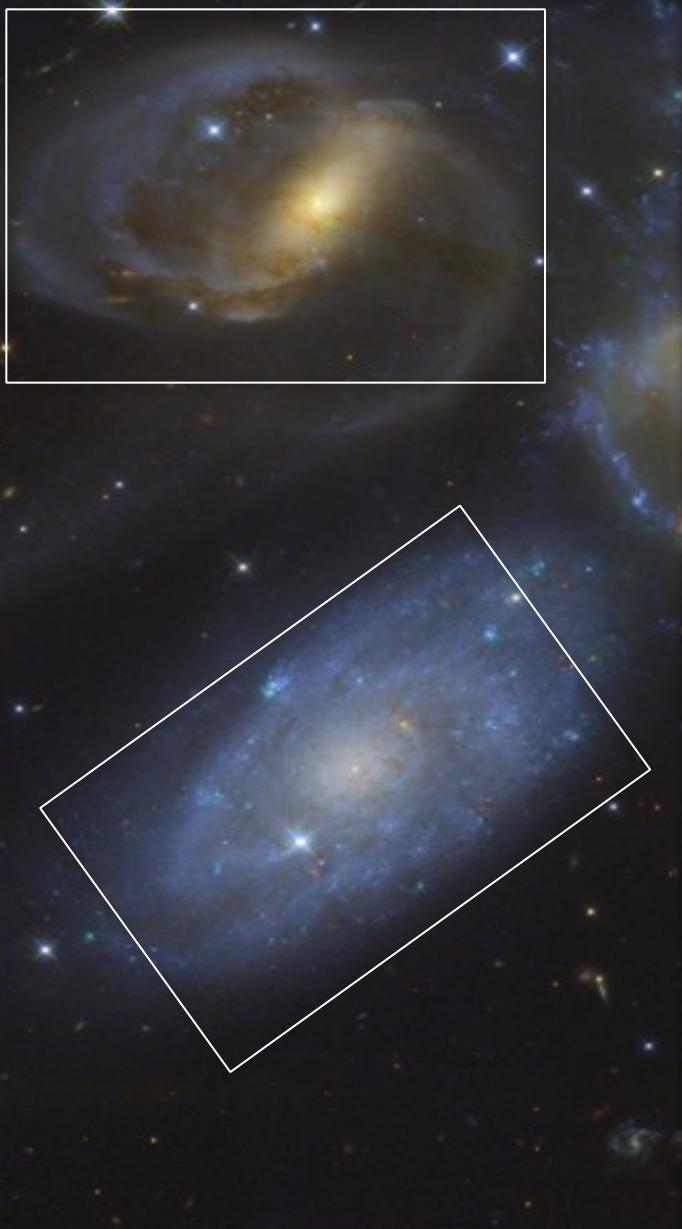
Galaxies (z ~ 0)



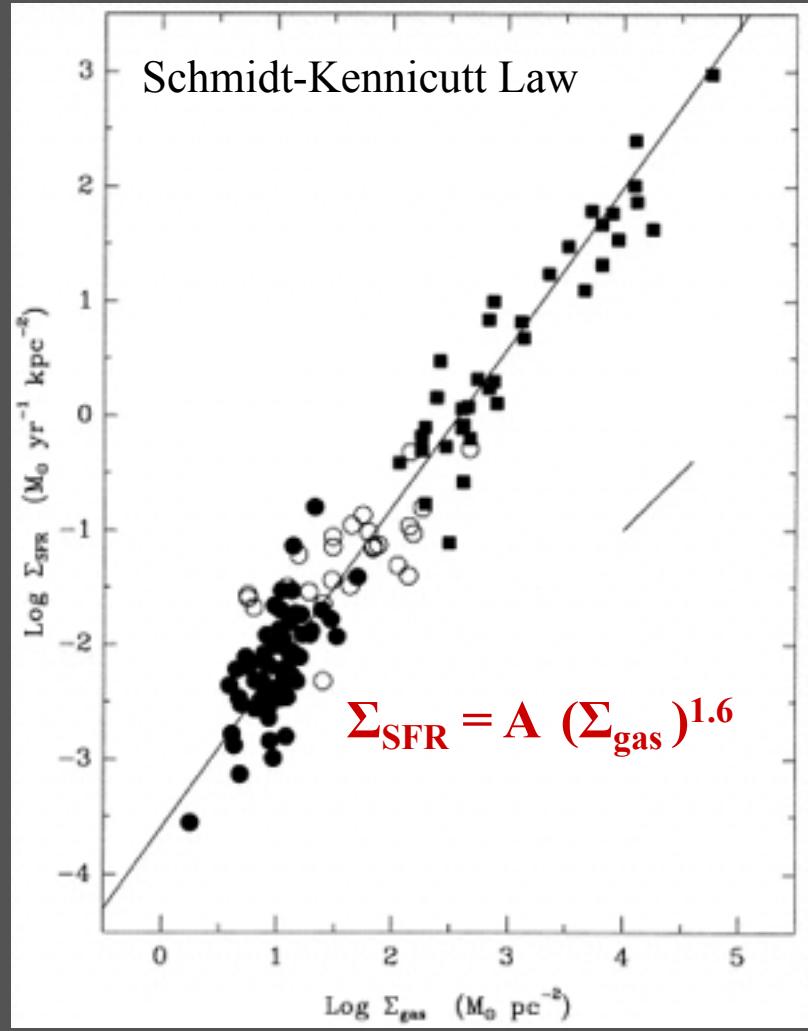
Galaxies (z ~ 0)



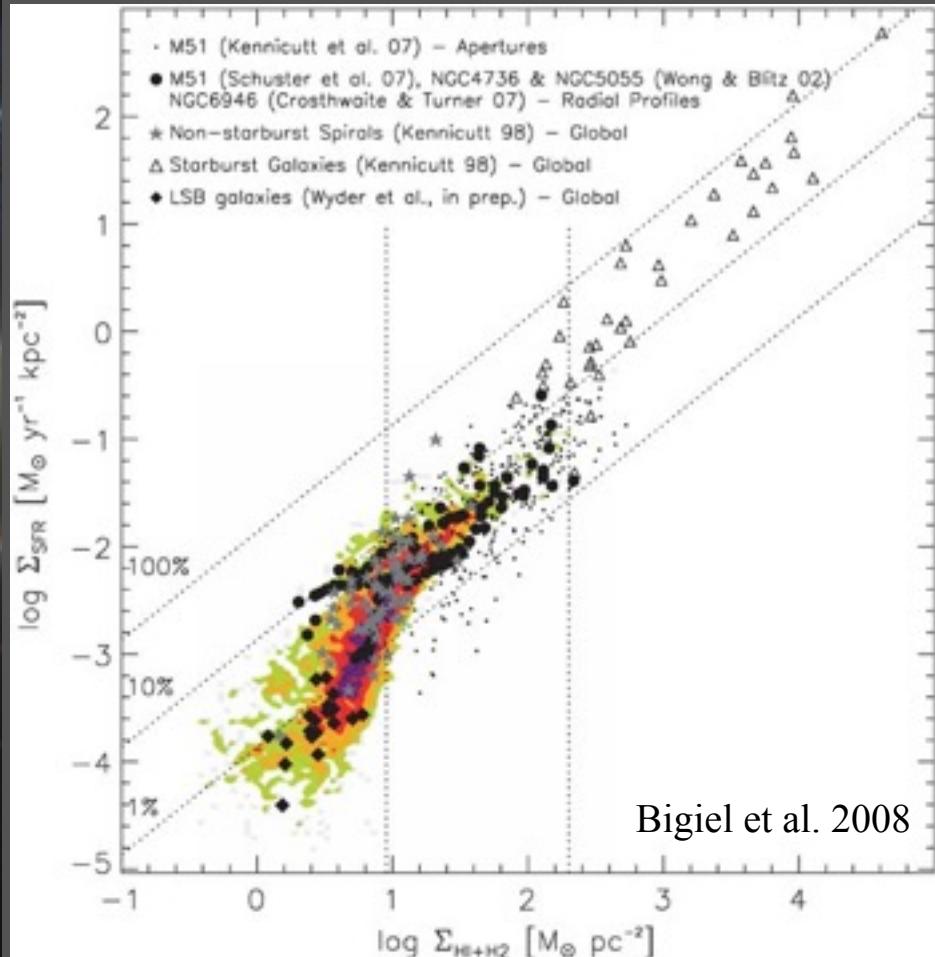
Galaxies (z ~ 0)



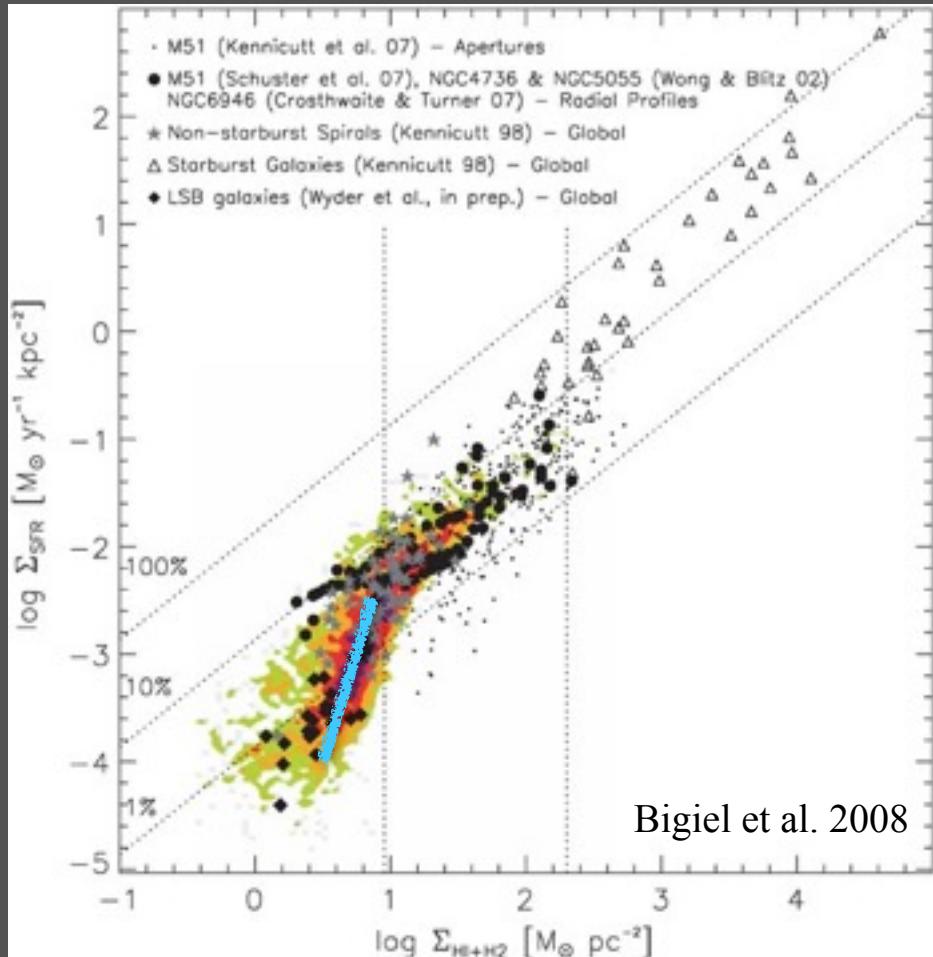
Galaxies (z ~ 0)



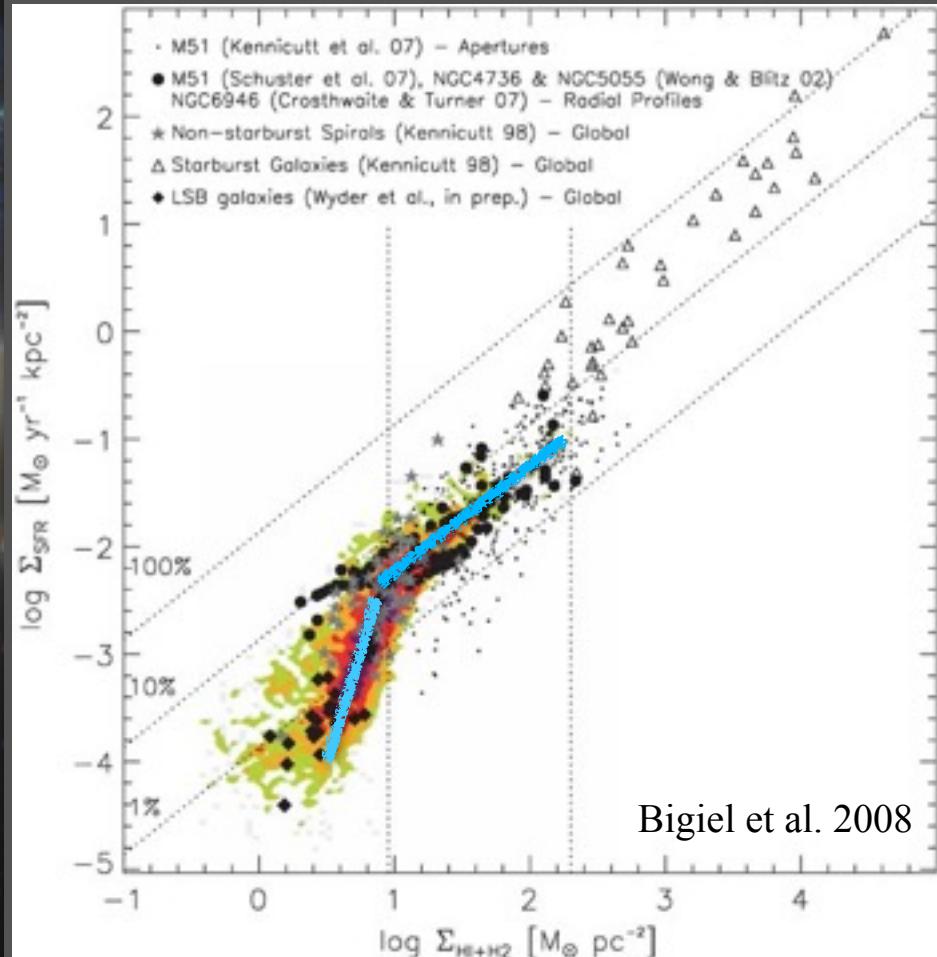
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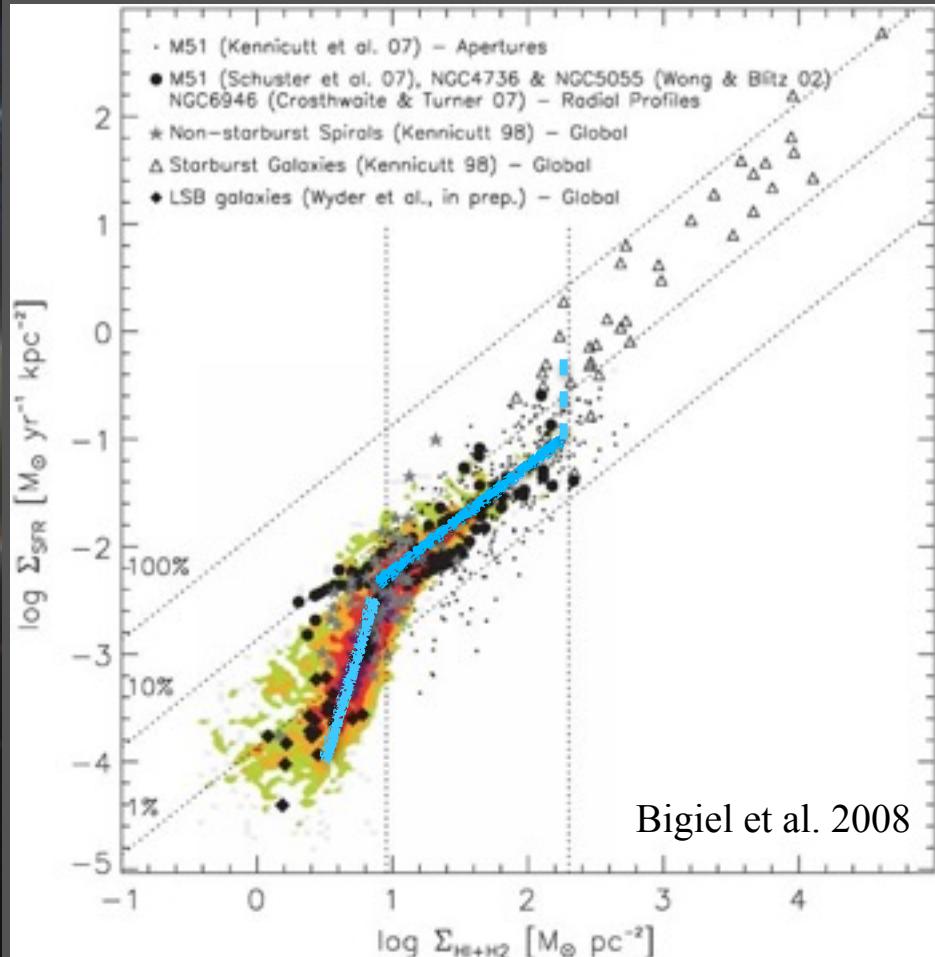
Galaxies (z ~ 0)



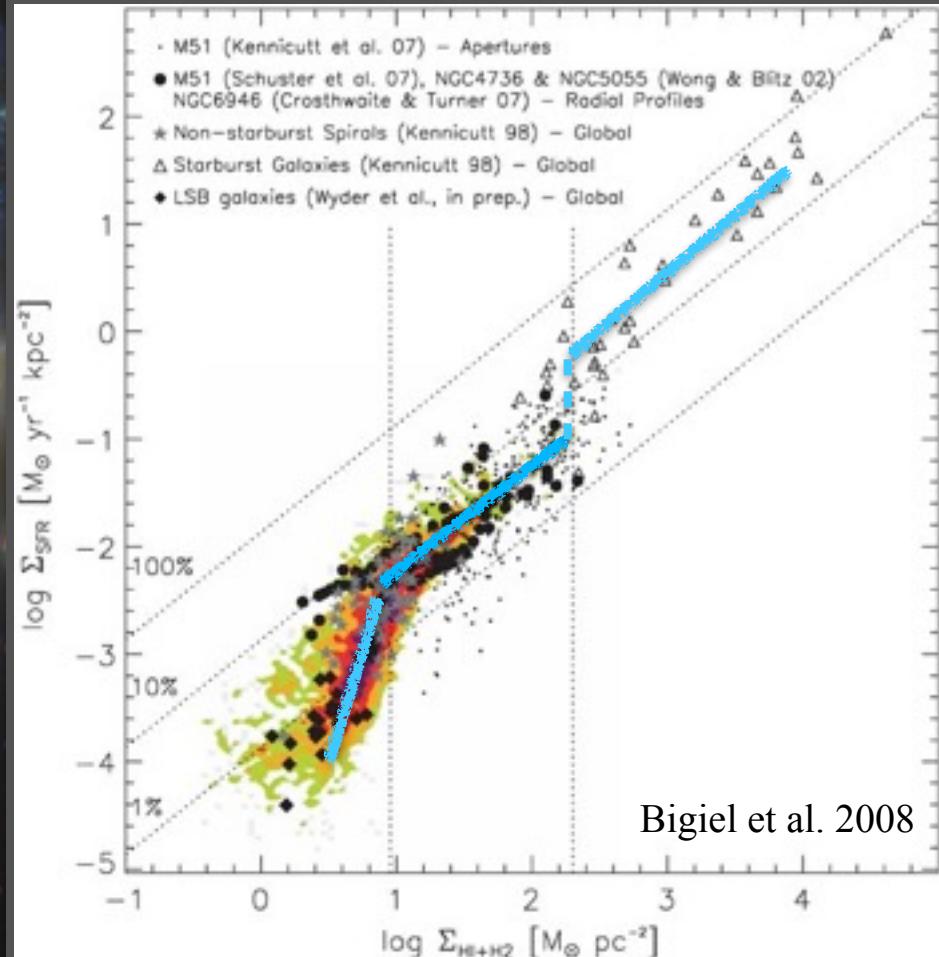
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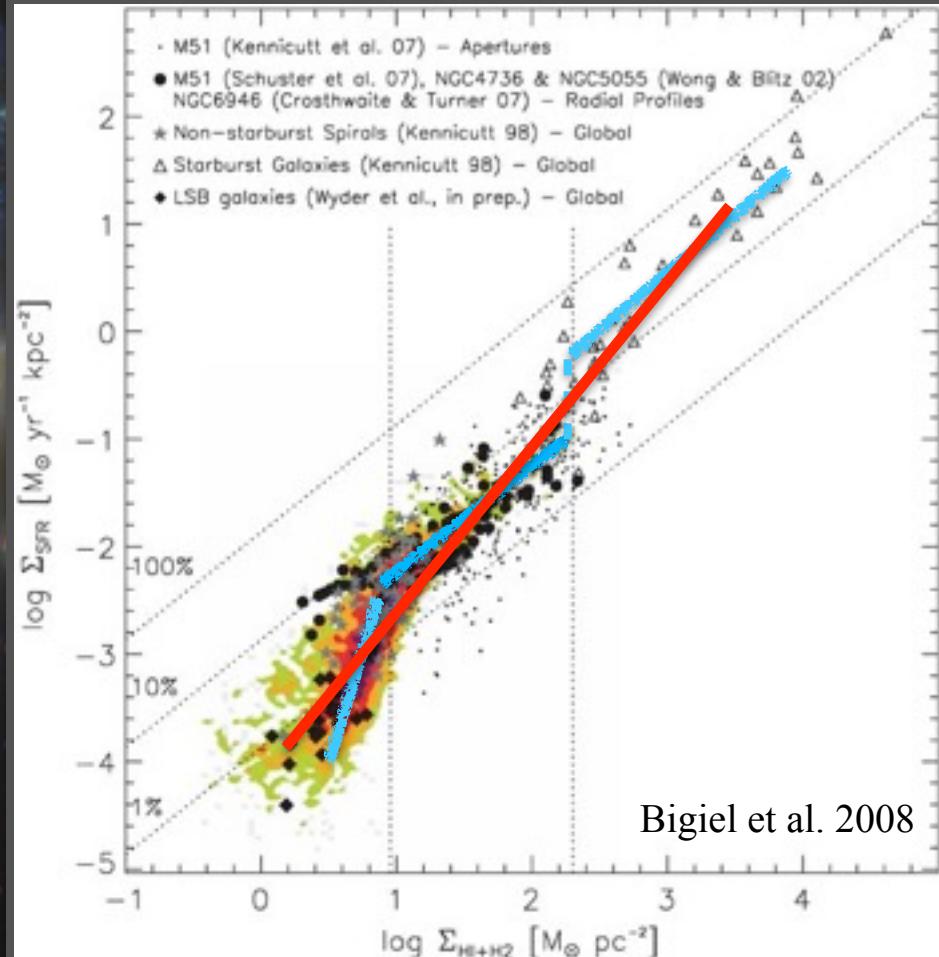
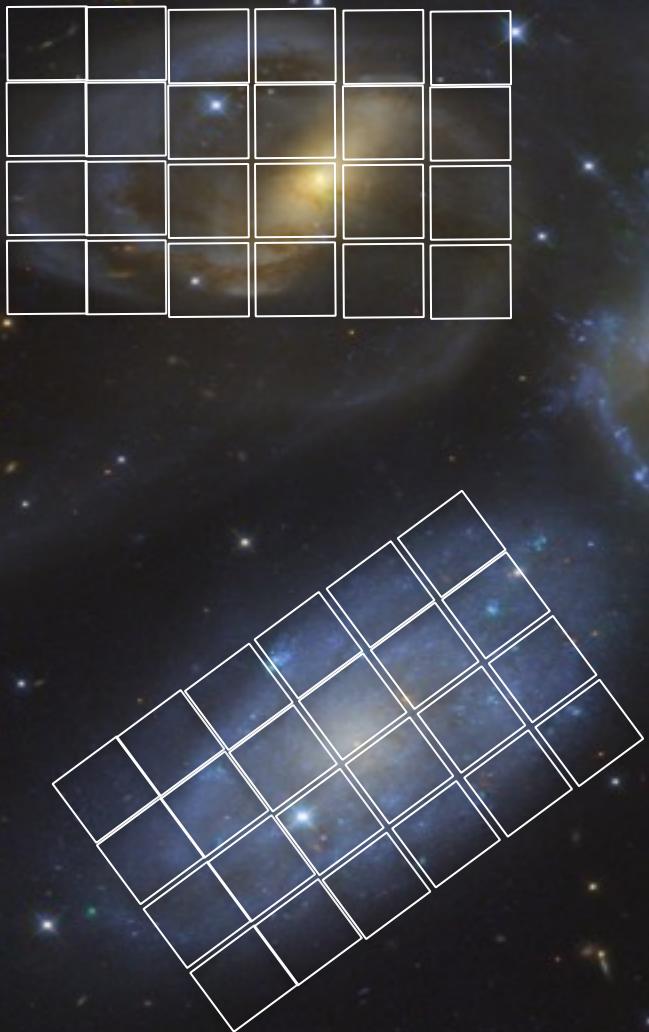
Galaxies (z ~ 0)



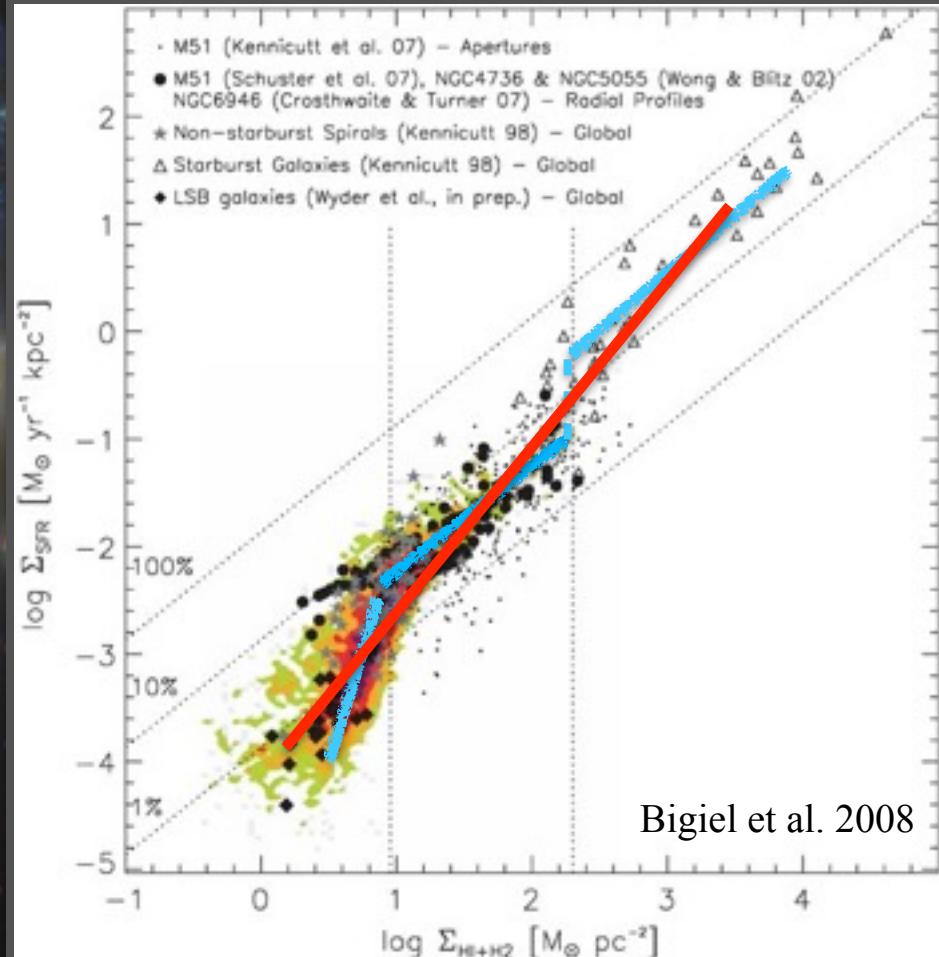
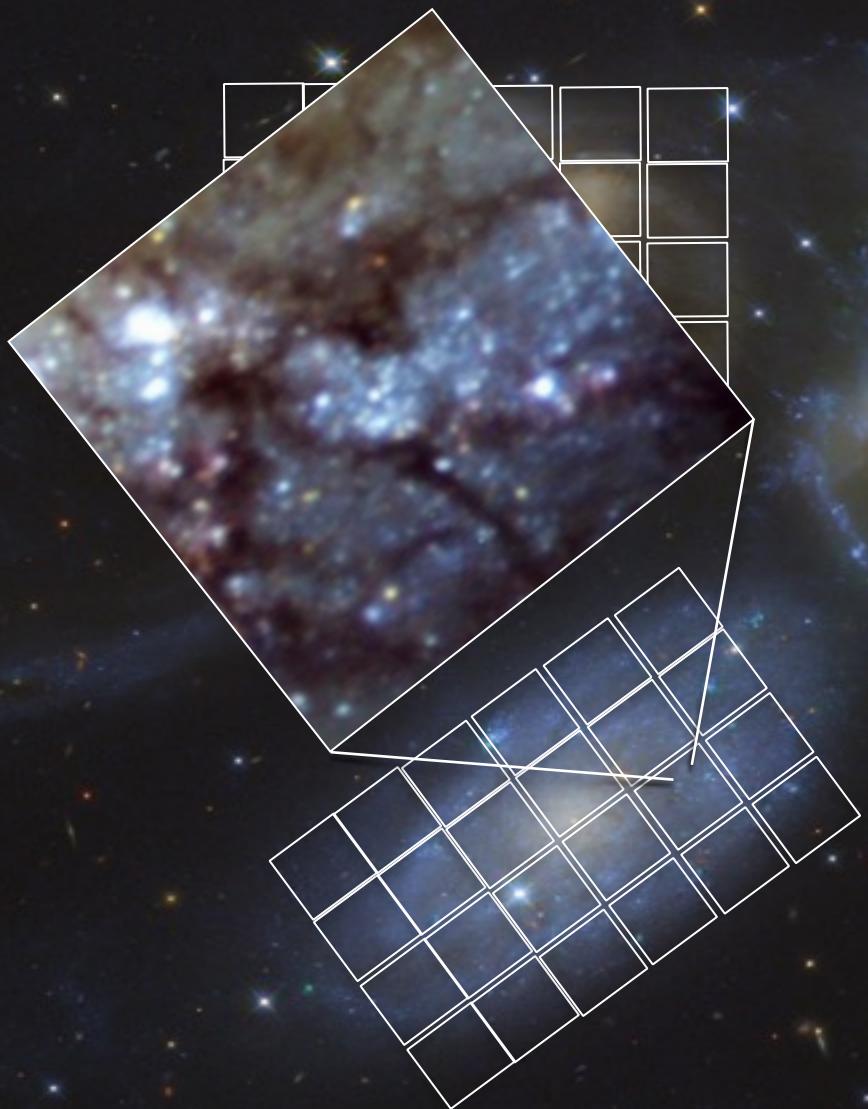
Galaxies (z ~ 0)



Galaxies (z ~ 0)



Galaxies ($z \sim 0$)



Giant Molecular Clouds



?



Milky Way GMCs



Milky Way GMCs

SFRs: Direct Counting of YSOs and measured ages.



Milky Way GMCs

SFRs: Direct Counting of YSOs and measured ages.

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

Dust Column Densities



Dust Column Densities

Optical



Dust Column Densities

Optical



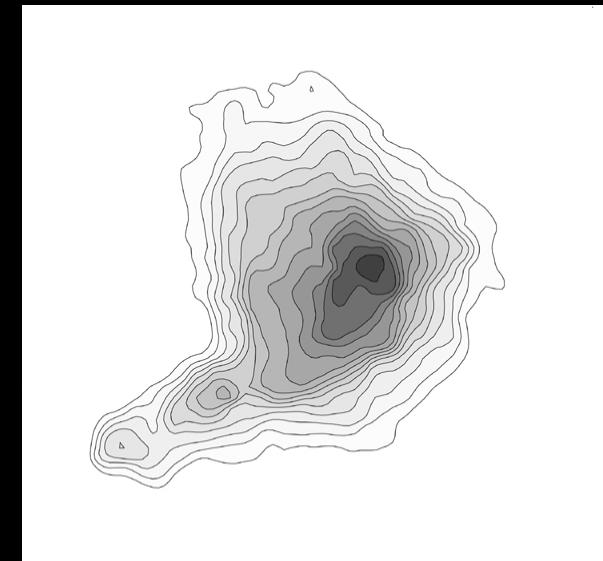
Near infrared



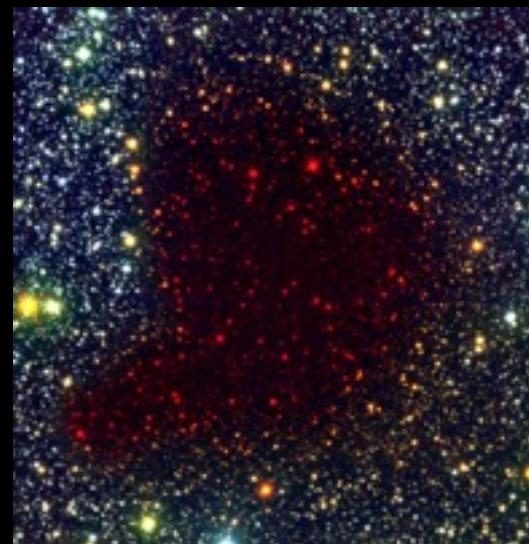
Alves+01

Dust Column Densities

Optical



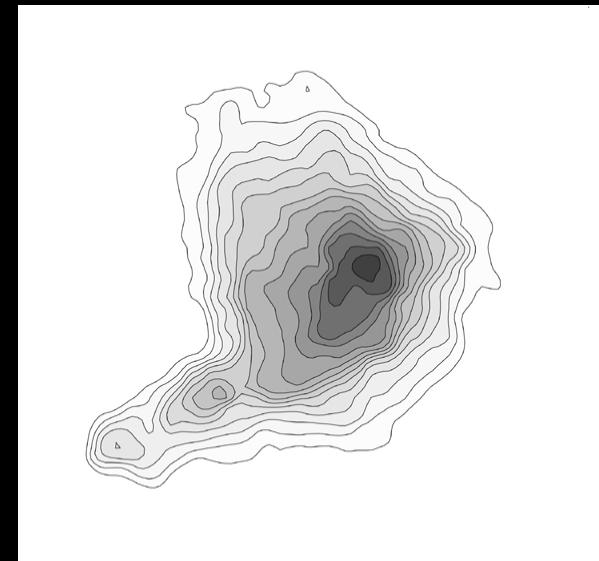
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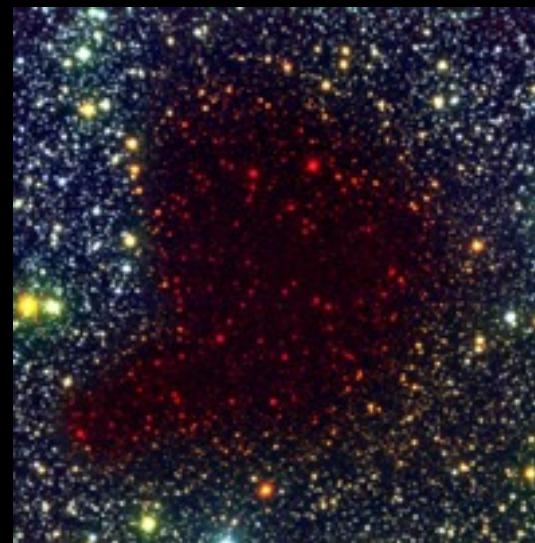
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Dust Column Densities

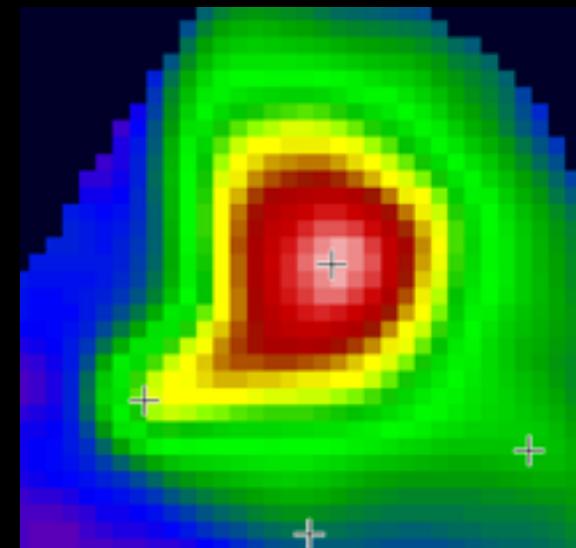
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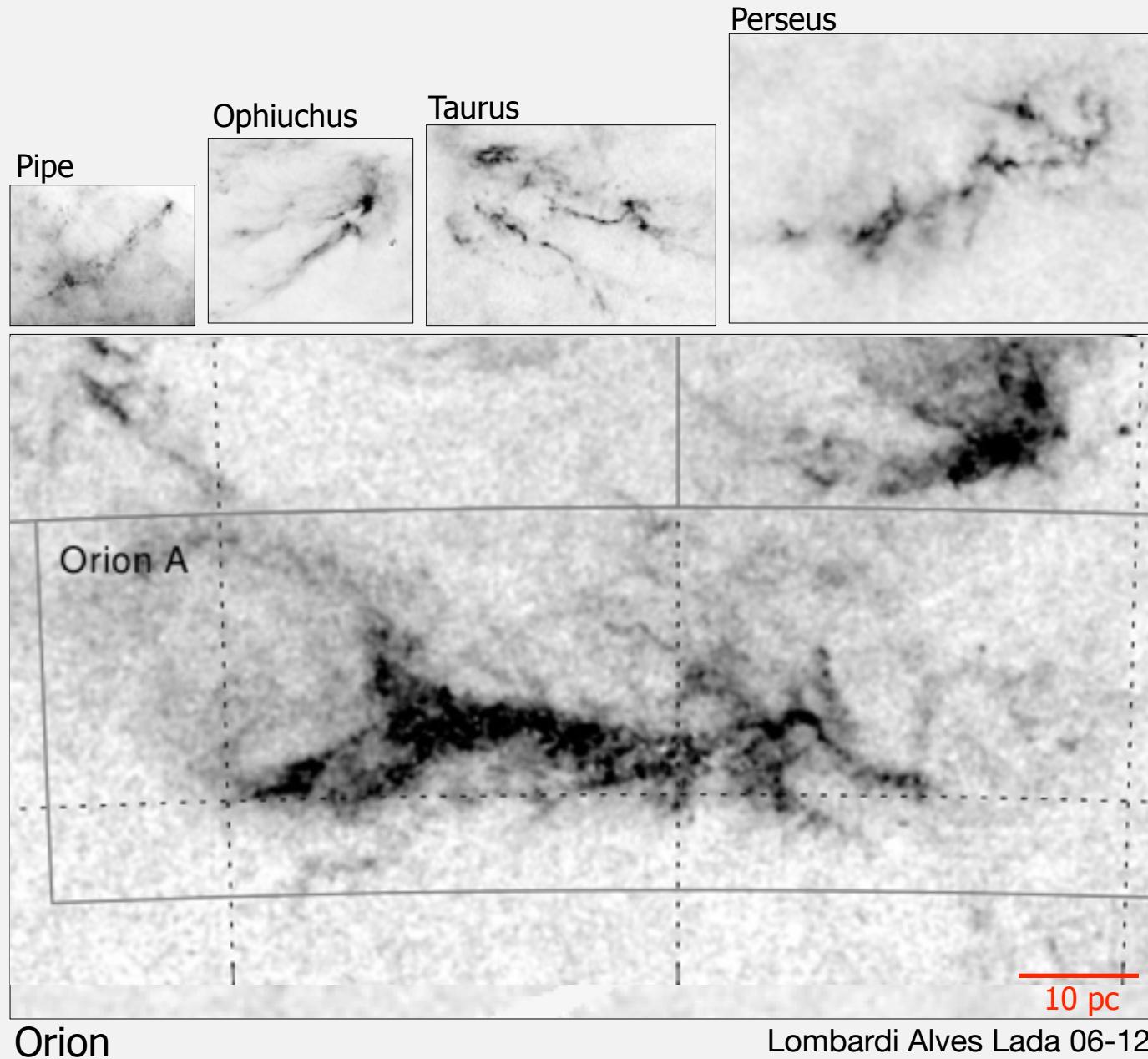


Alves+01



Nielbock+13, Roy+14

Local molecular clouds (same size scale)

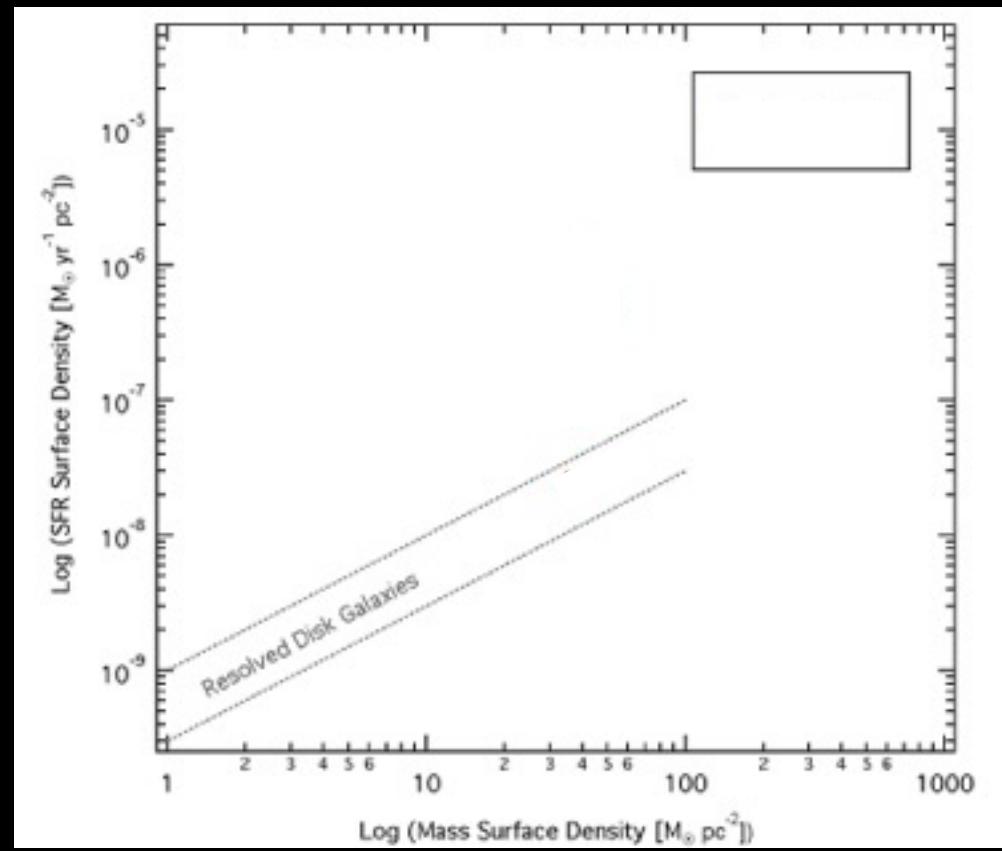


Giant Molecular Clouds

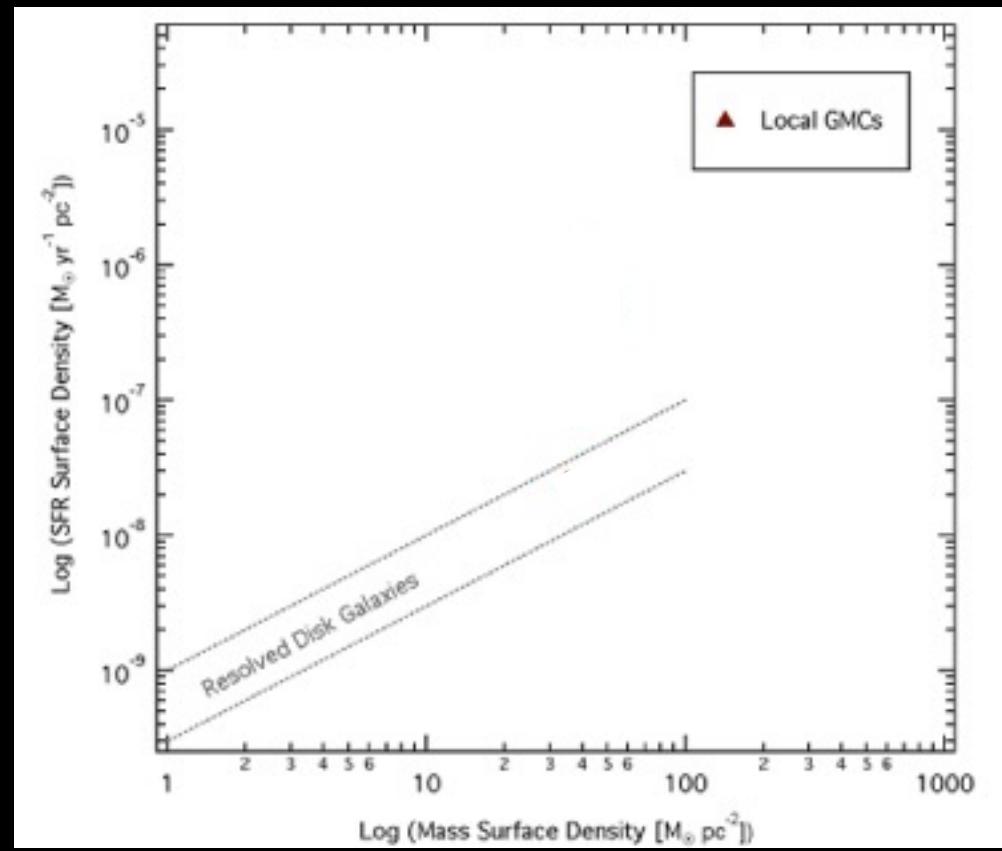


Does a Schmidt Law
exist for MW GMCs?

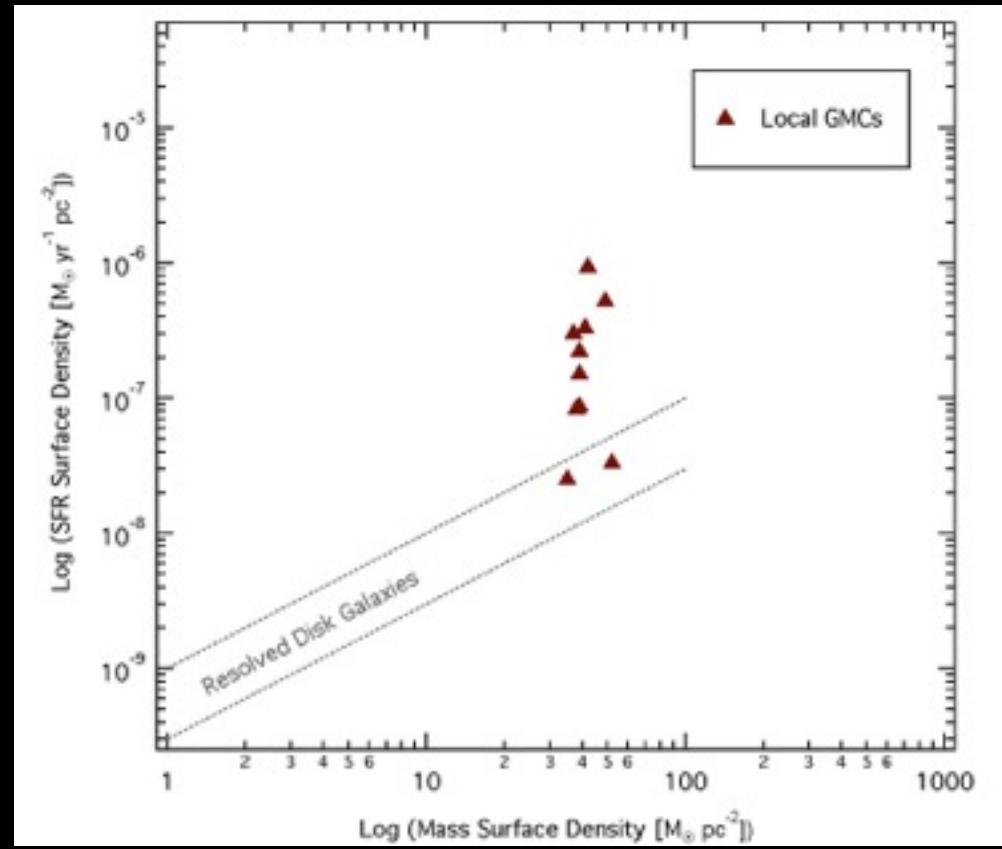
Giant Molecular Clouds



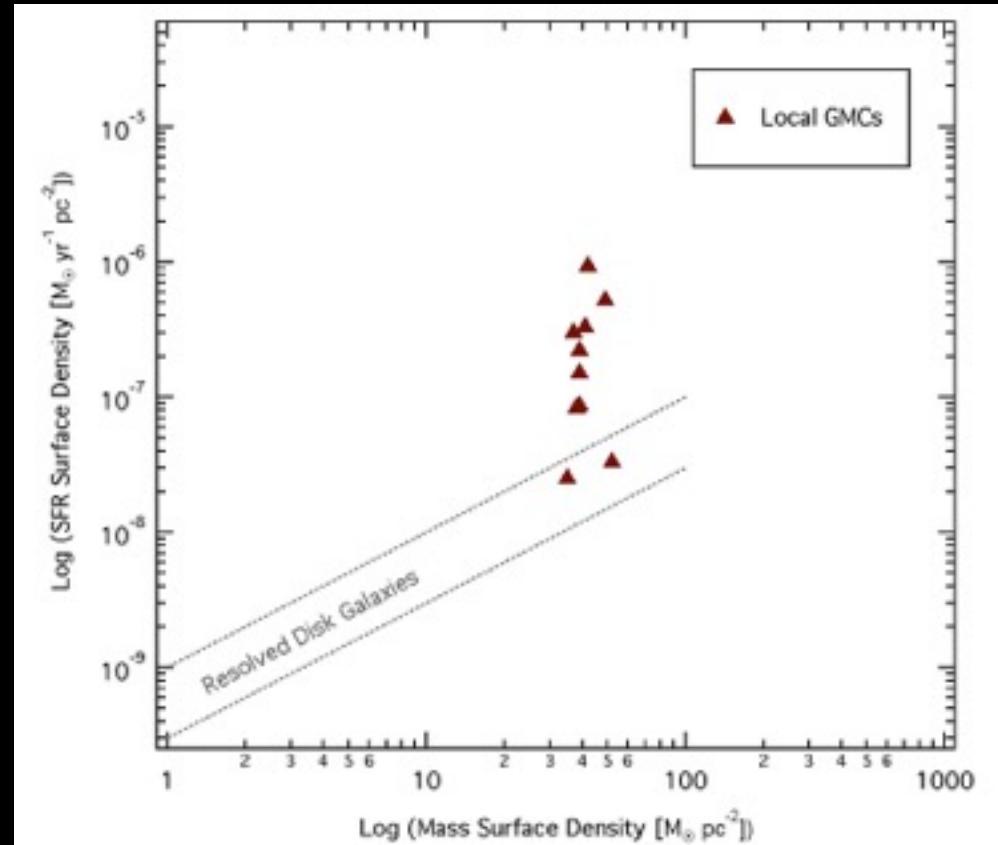
Giant Molecular Clouds



Giant Molecular Clouds

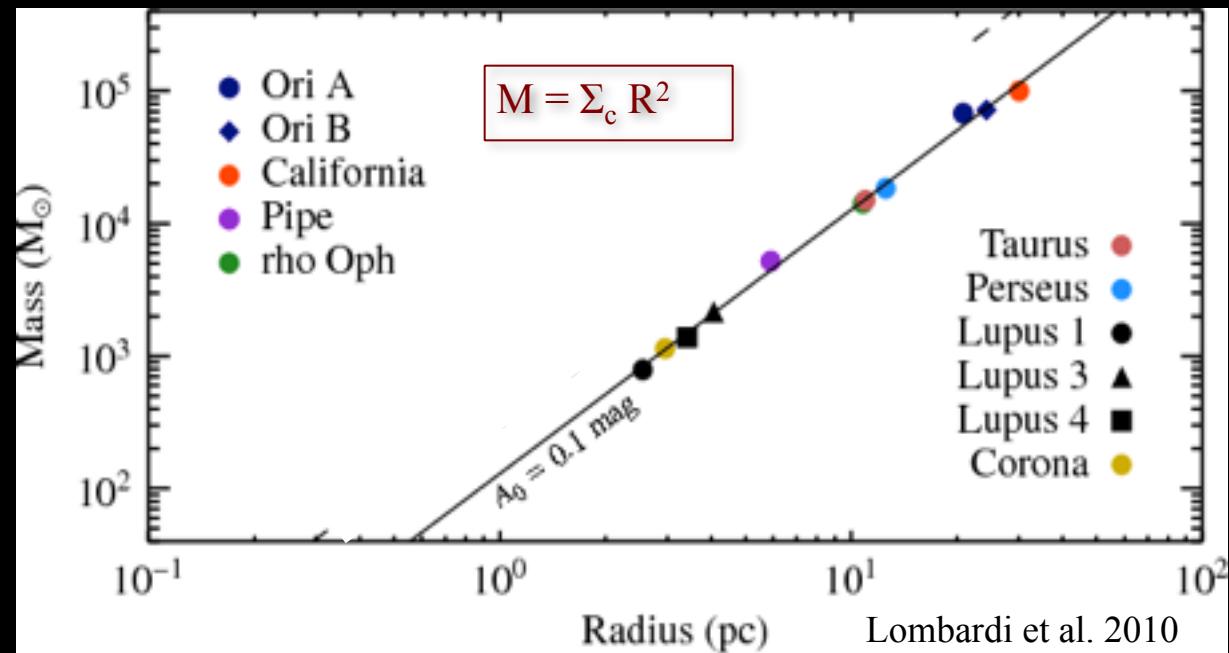


Giant Molecular Clouds

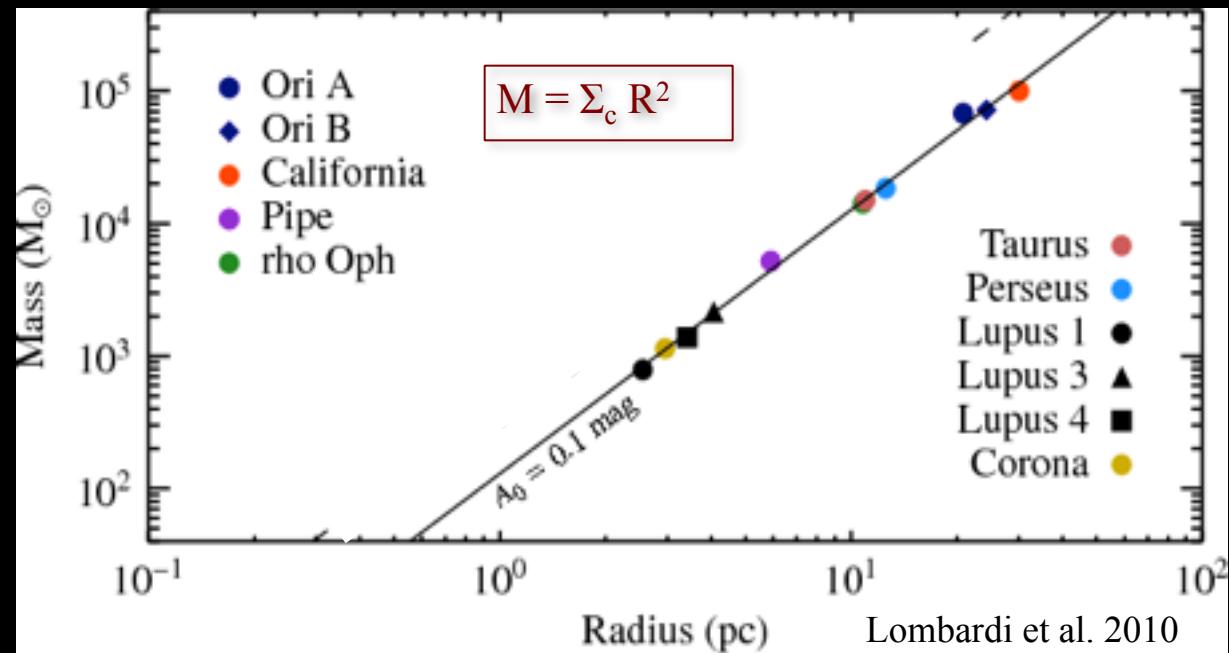


A Schmidt Law does NOT exist between GMCs

Giant Molecular Clouds

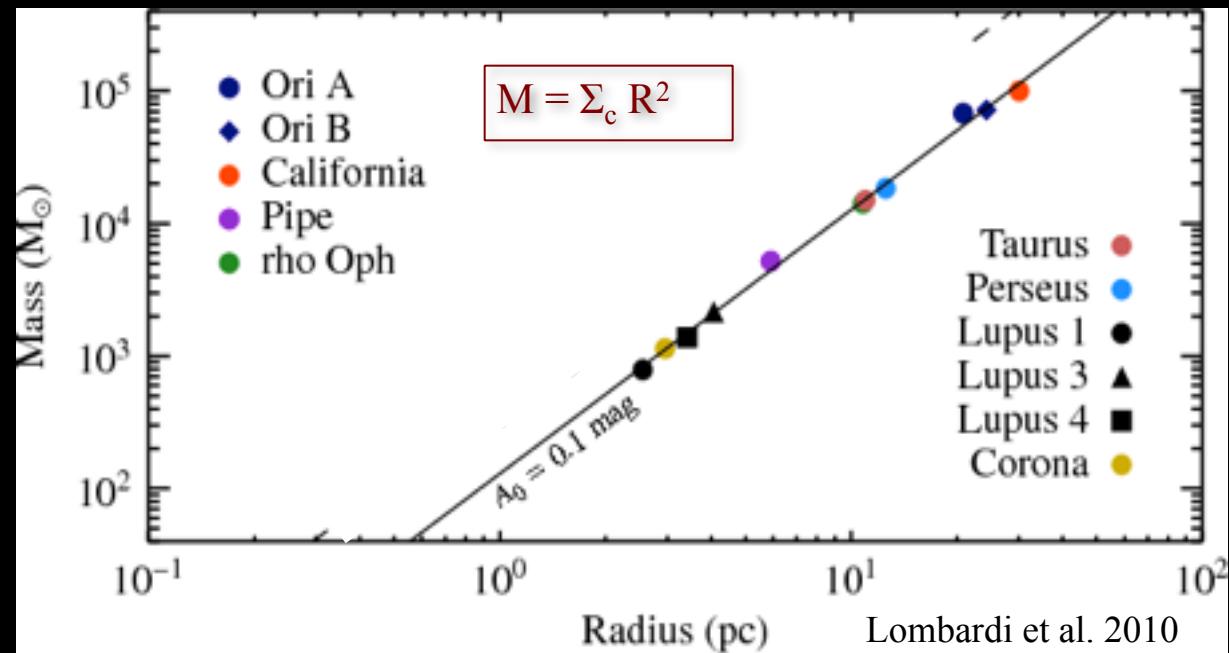


Giant Molecular Clouds



Well known scaling relation of Larson (1981)

Giant Molecular Clouds



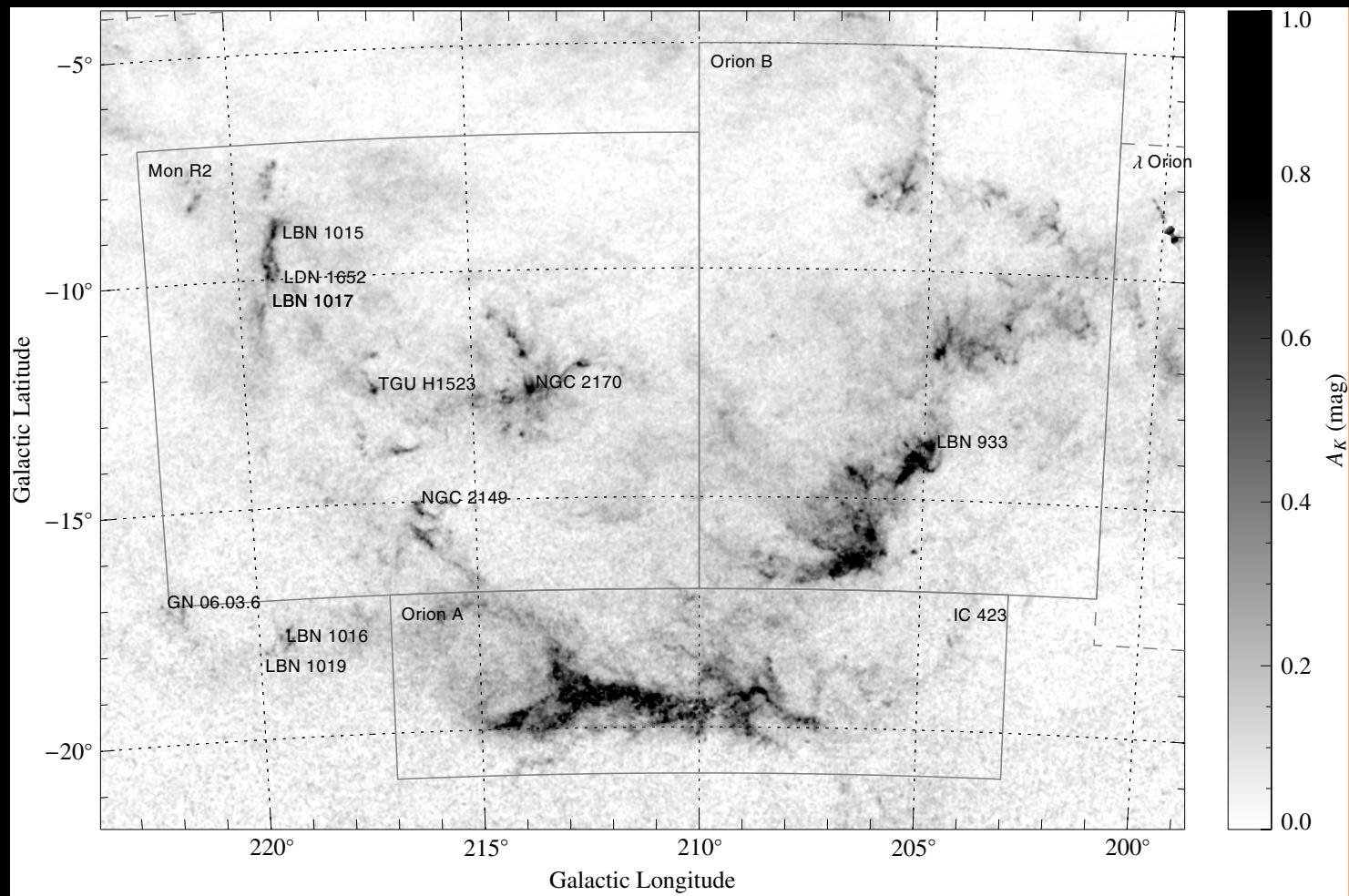
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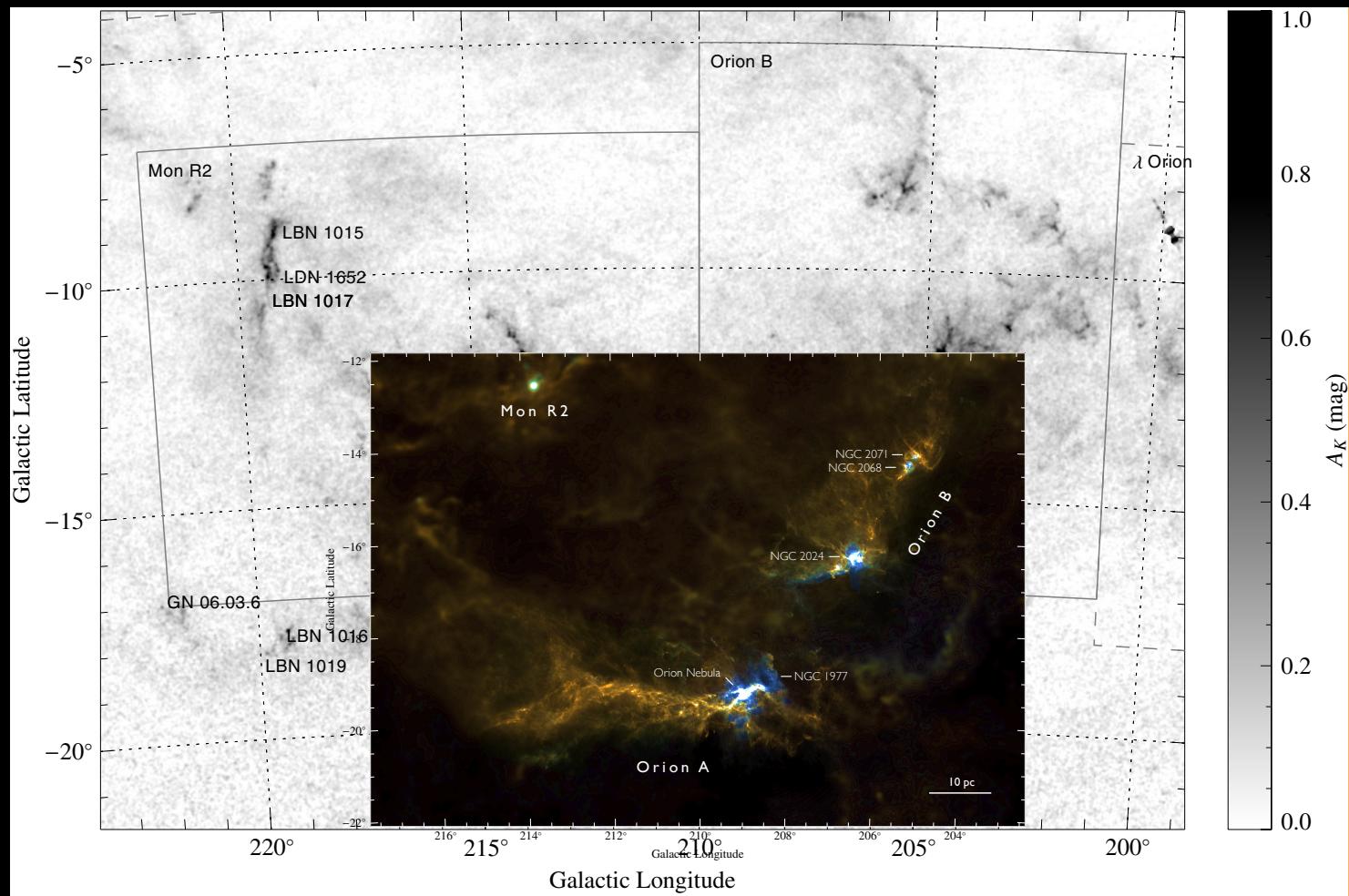
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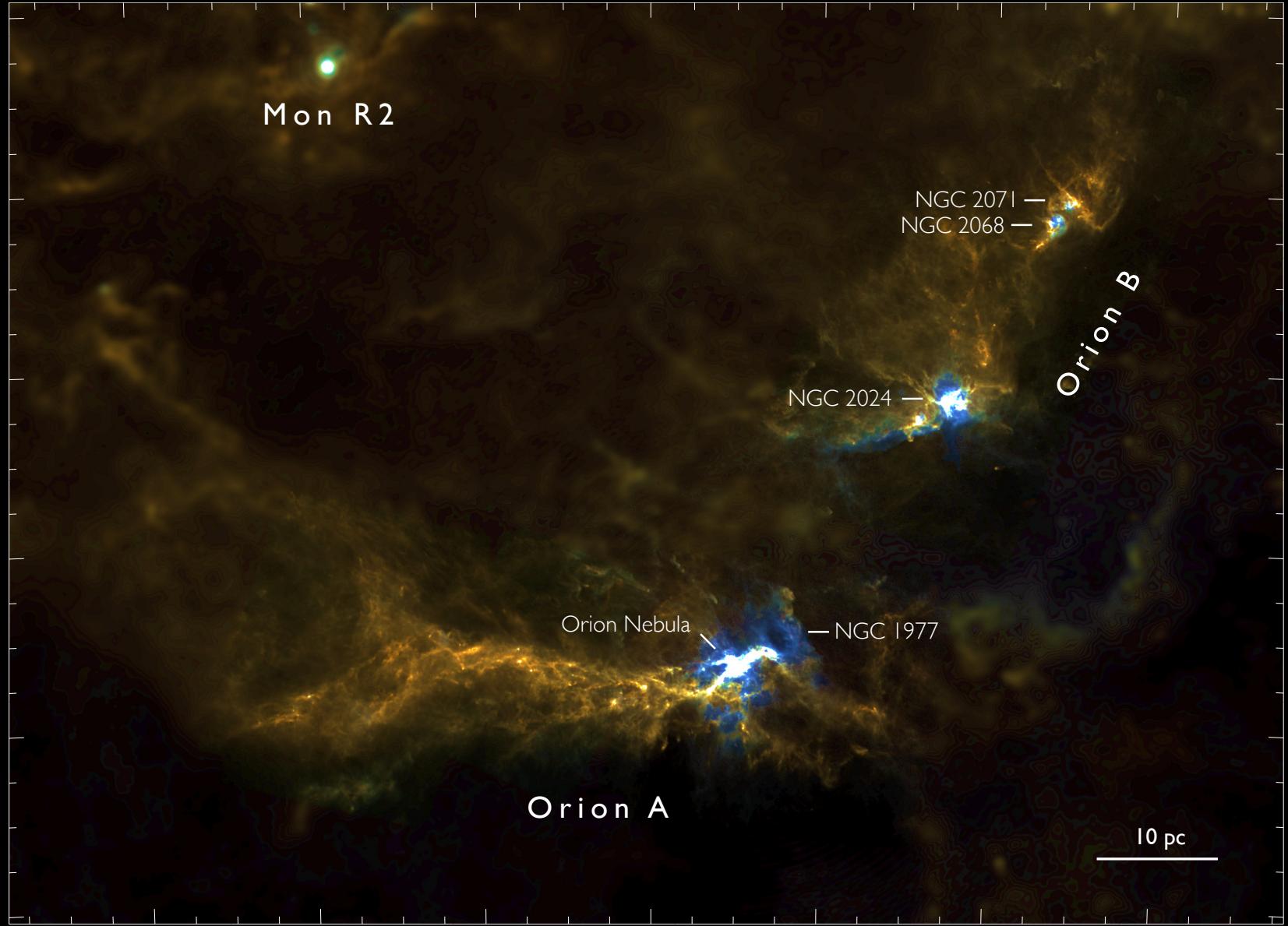
Giant Molecular Clouds



Does a Schmidt Law
exist *within* GMCs ?

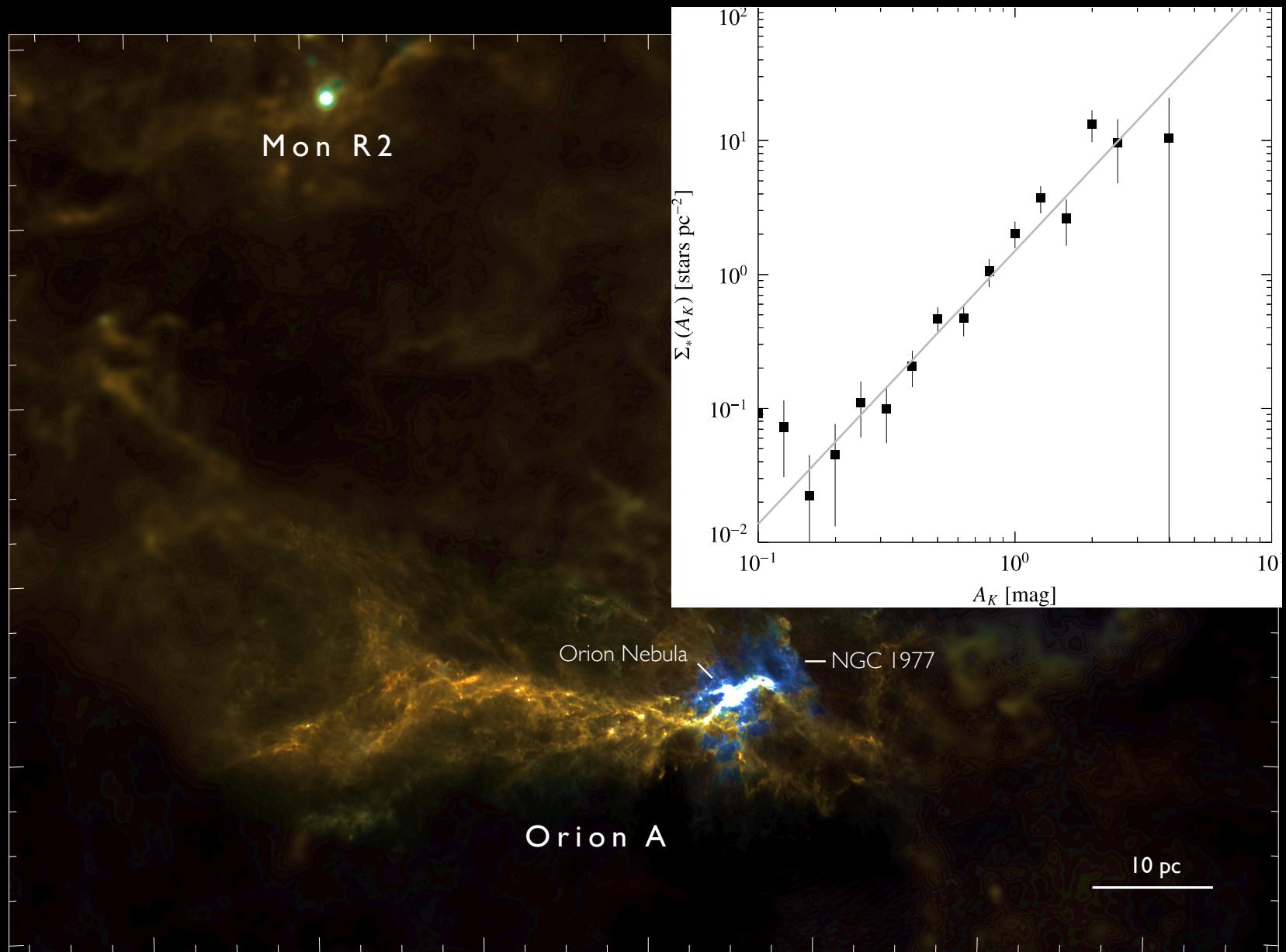






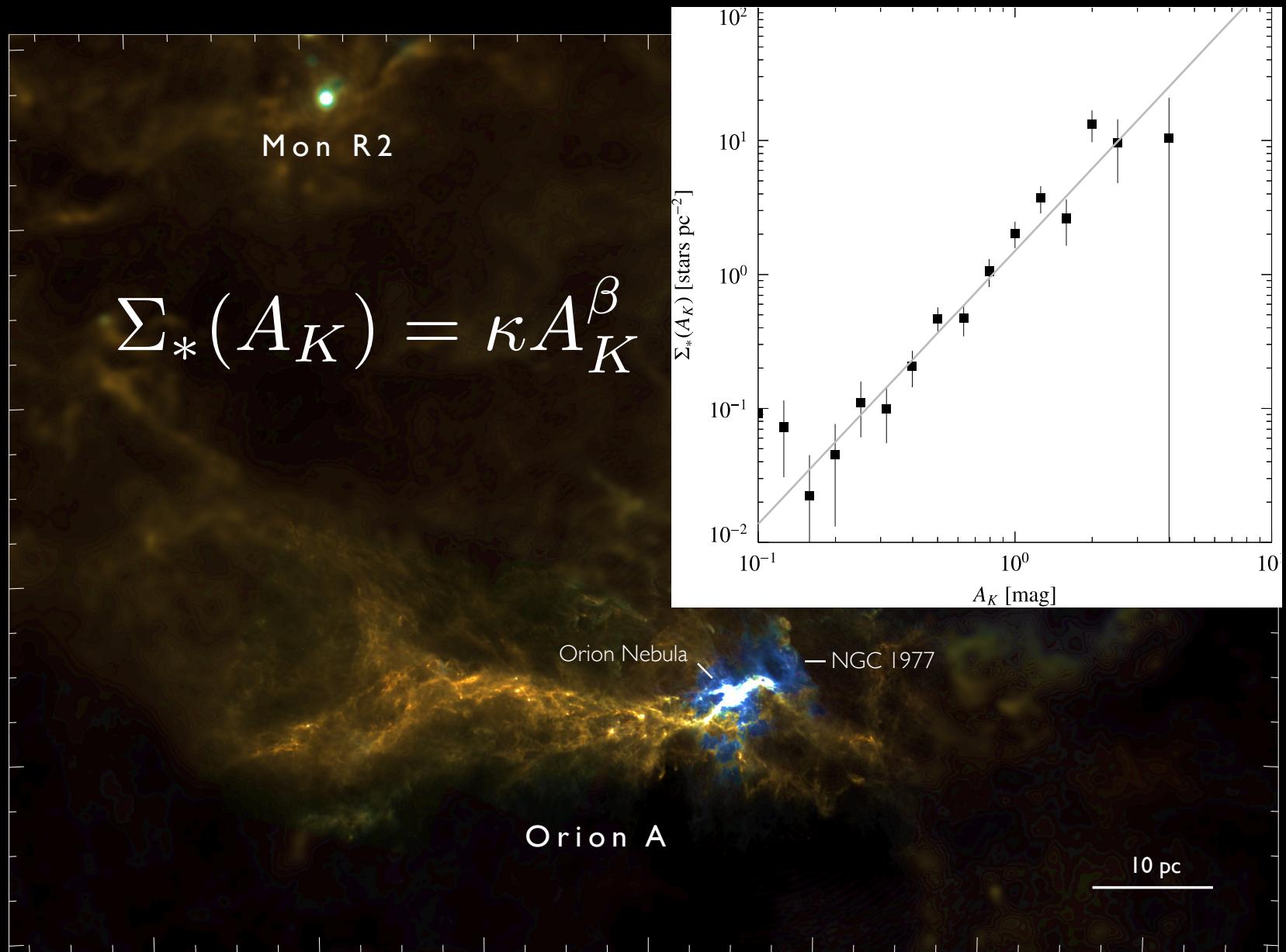
Lombardi et al. 2014

Planck+Herschel+2MASS



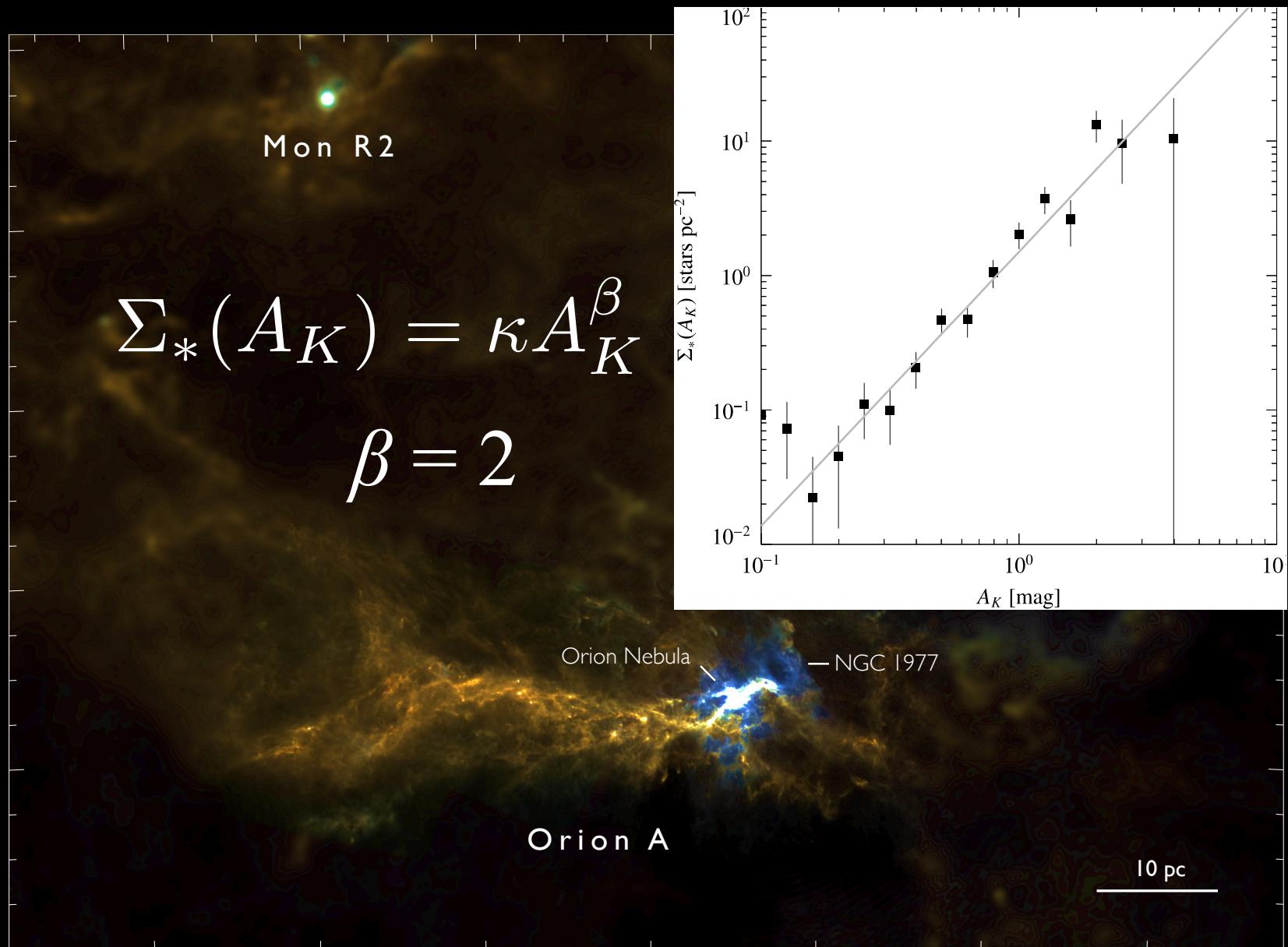
Lombardi et al. 2014

Planck+Herschel+2MASS



Lombardi et al. 2014

Planck+Herschel+2MASS

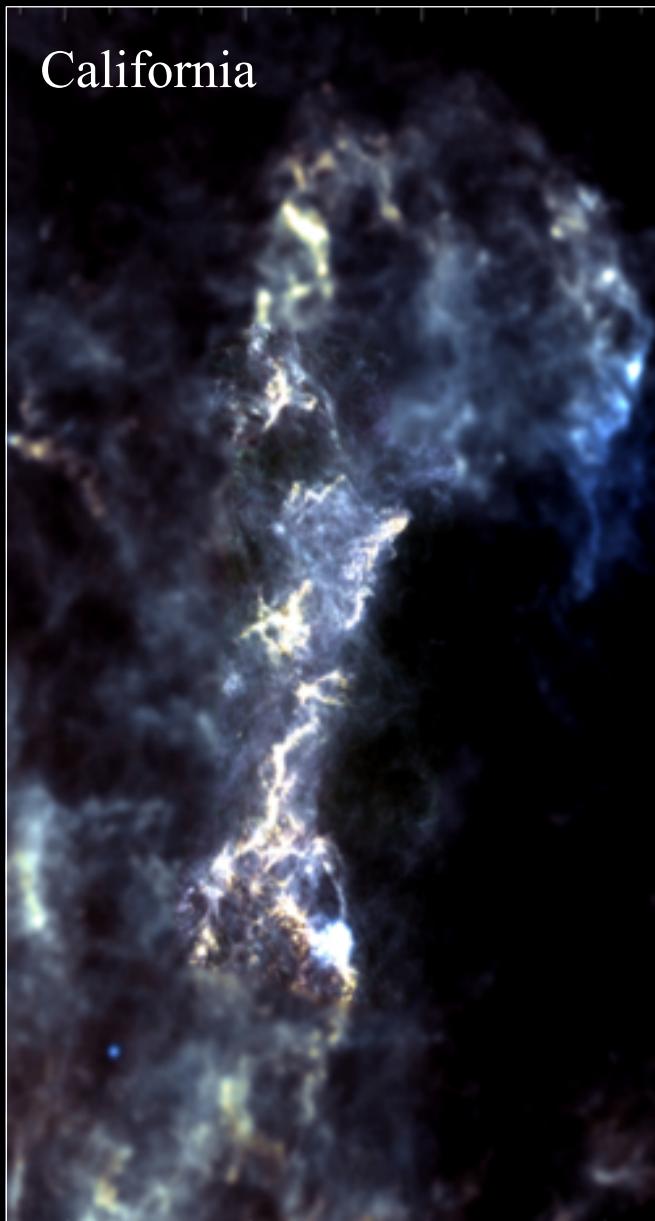


Lombardi et al. 2014

Planck+Herschel+2MASS

Schmidt Law in Giant Molecular Clouds

California



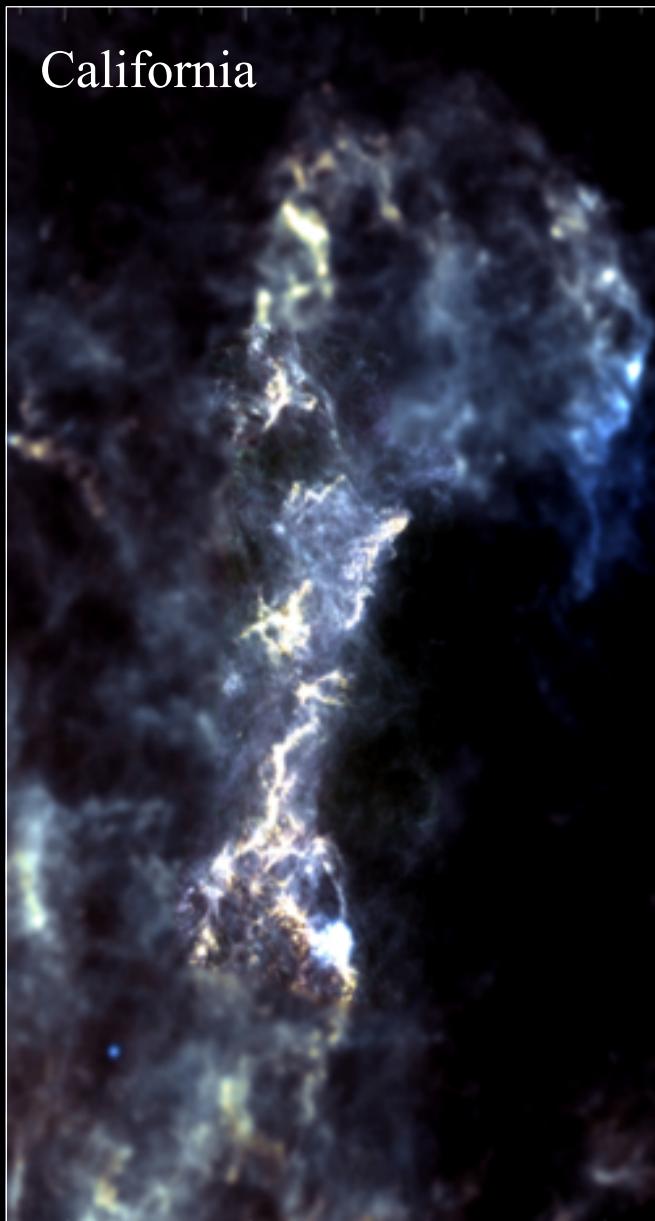
Results:

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

	Orion A	Taurus	California	Orion B
β	2.0 ± 0.1	2.1 ± 0.1	2.0 ± 0.3	3.3 ± 0.2
κ	1.6 ± 0.1	2.1 ± 0.3	2.0 ± 0.4	0.8 ± 0.1

Schmidt Law in Giant Molecular Clouds

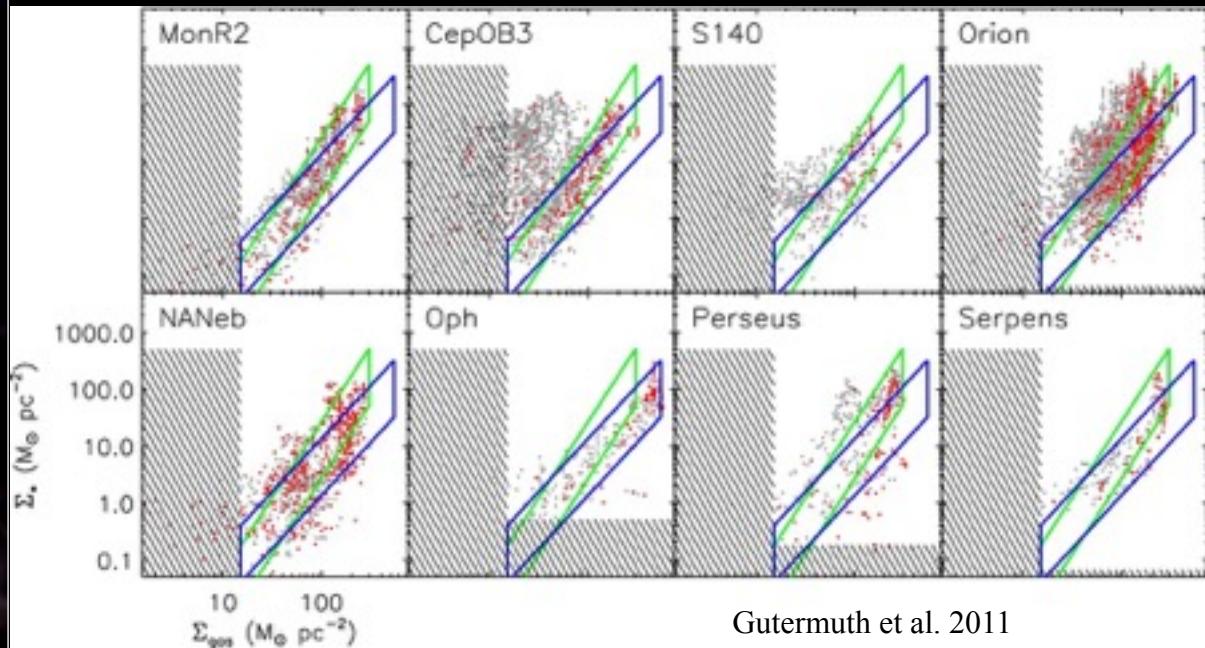
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Gutermuth et al. 2011

Schmidt Law in Giant Molecular Clouds

California

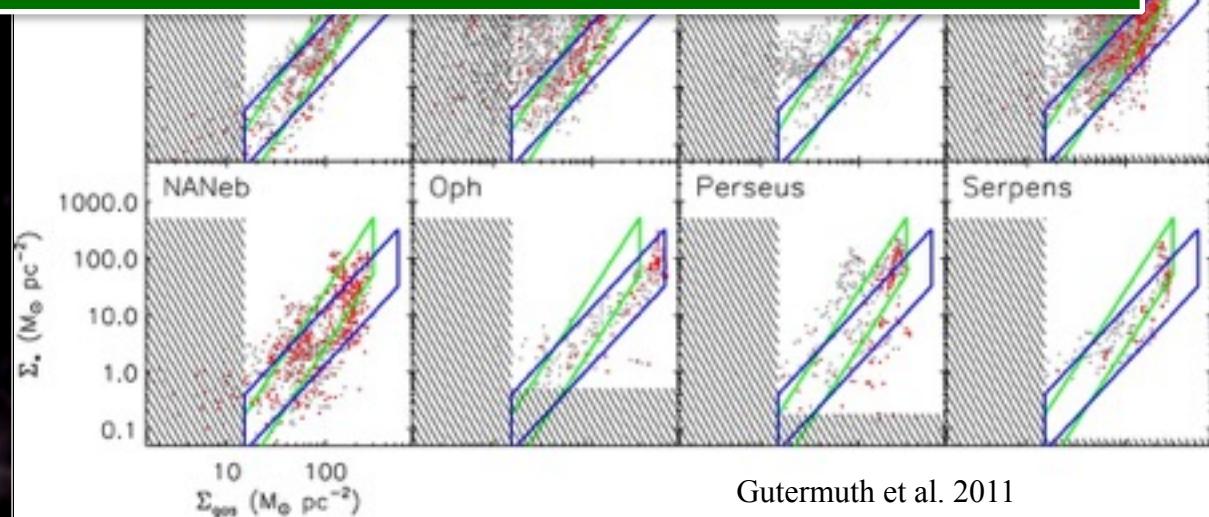
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A Schmidt Law Exists *within* GMCs

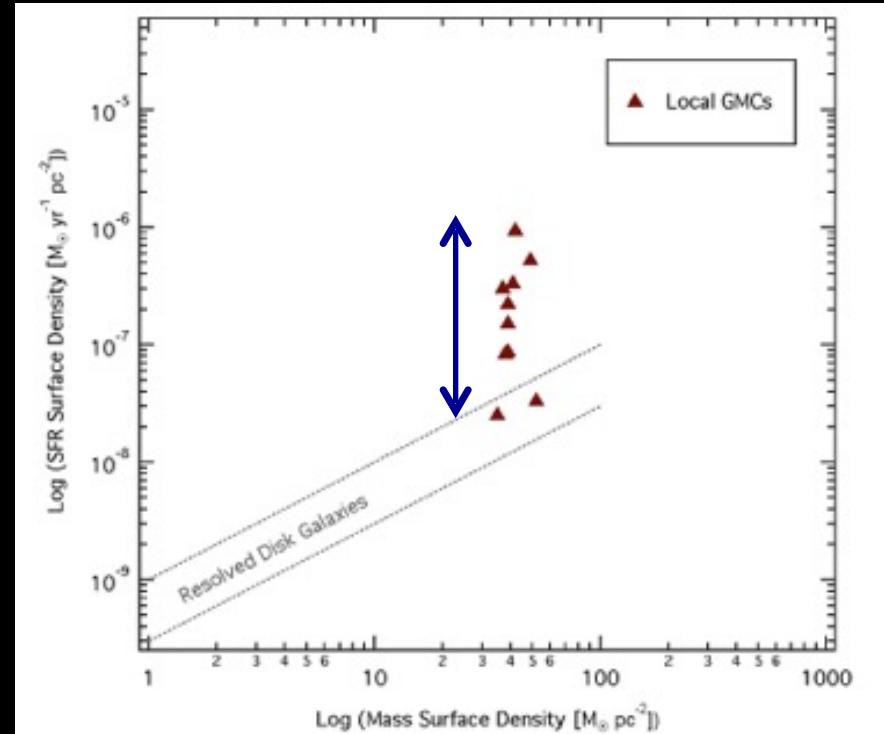
Heidermann et al. 2010, Gutermuth et al. 2011, Lombardi et al. 2013,

Lada et al. 2013, Evans et al. 2014



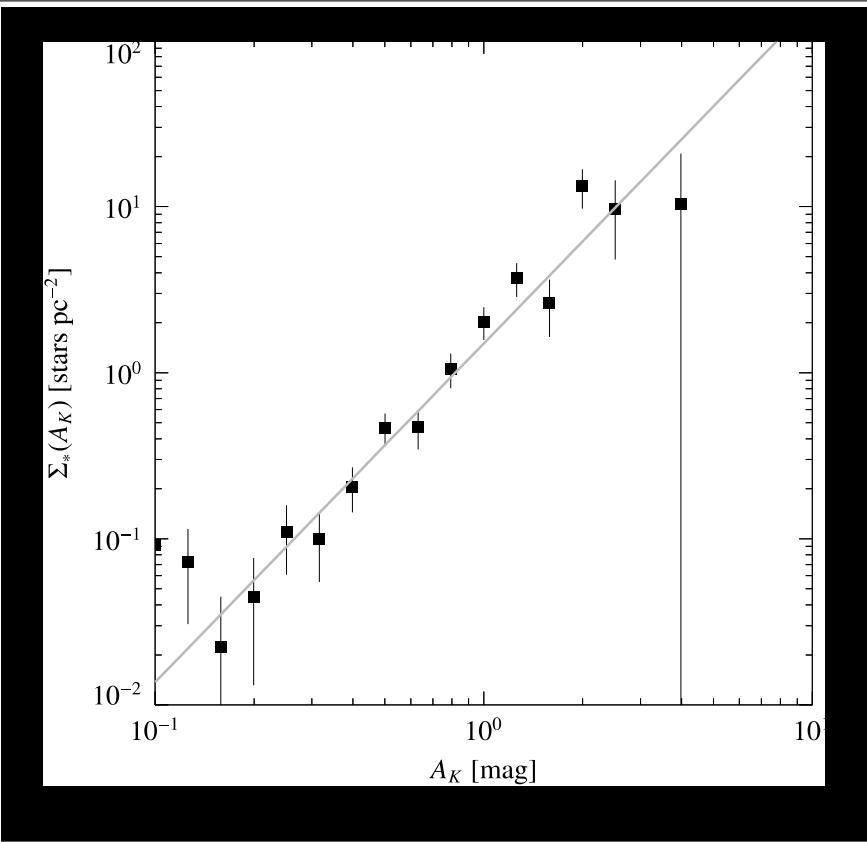
Gutermuth et al. 2011

Giant Molecular Clouds

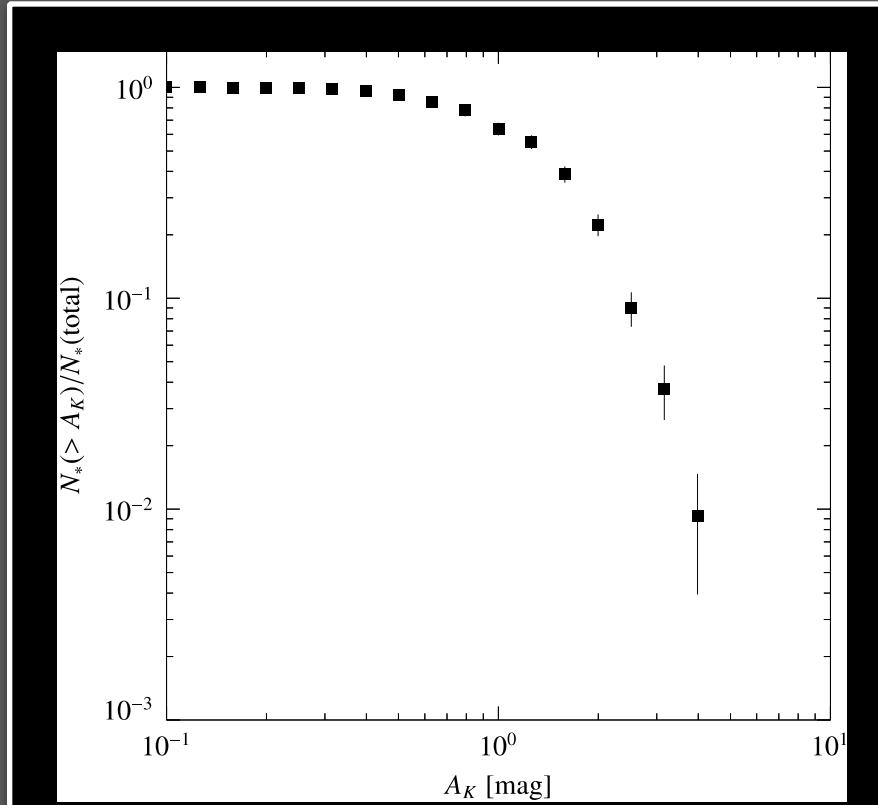
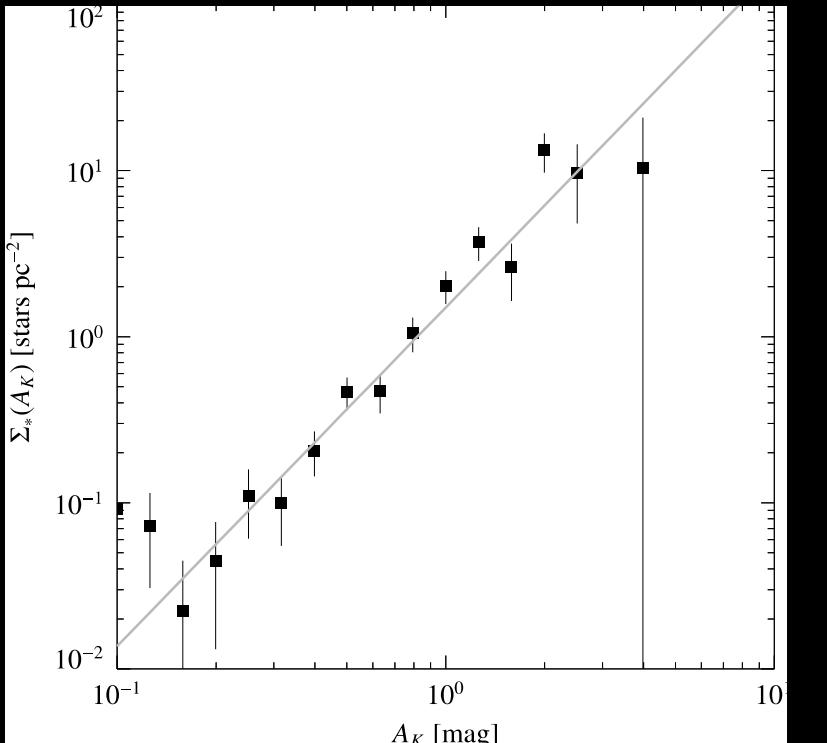


A Schmidt Law within clouds does NOT explain variations in SFRs between clouds.

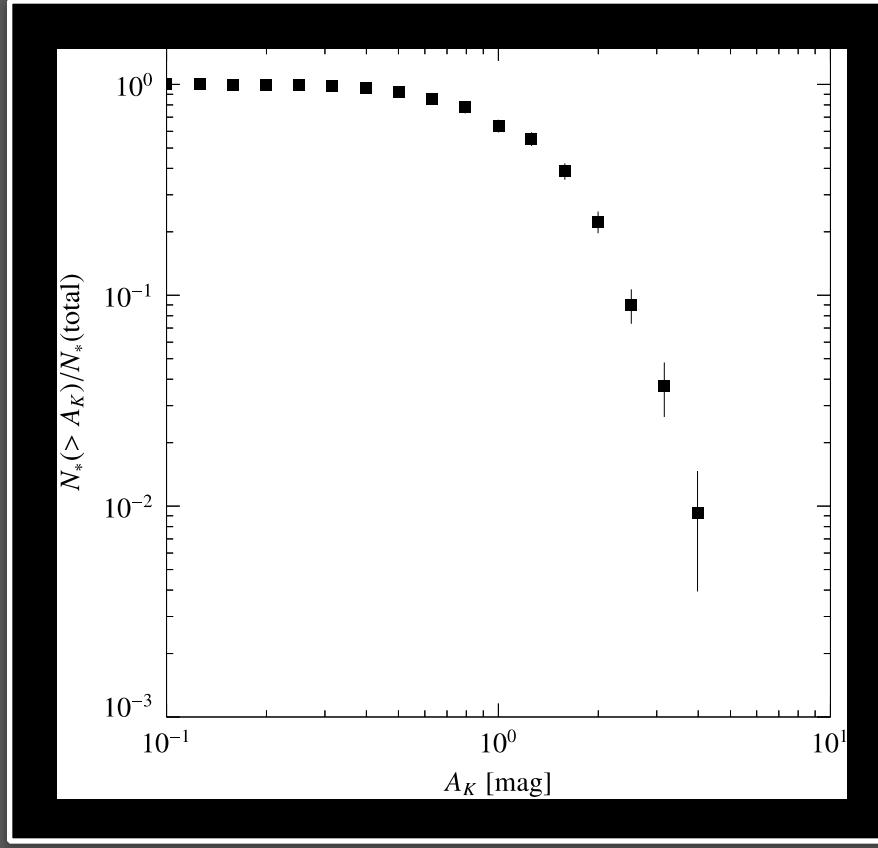
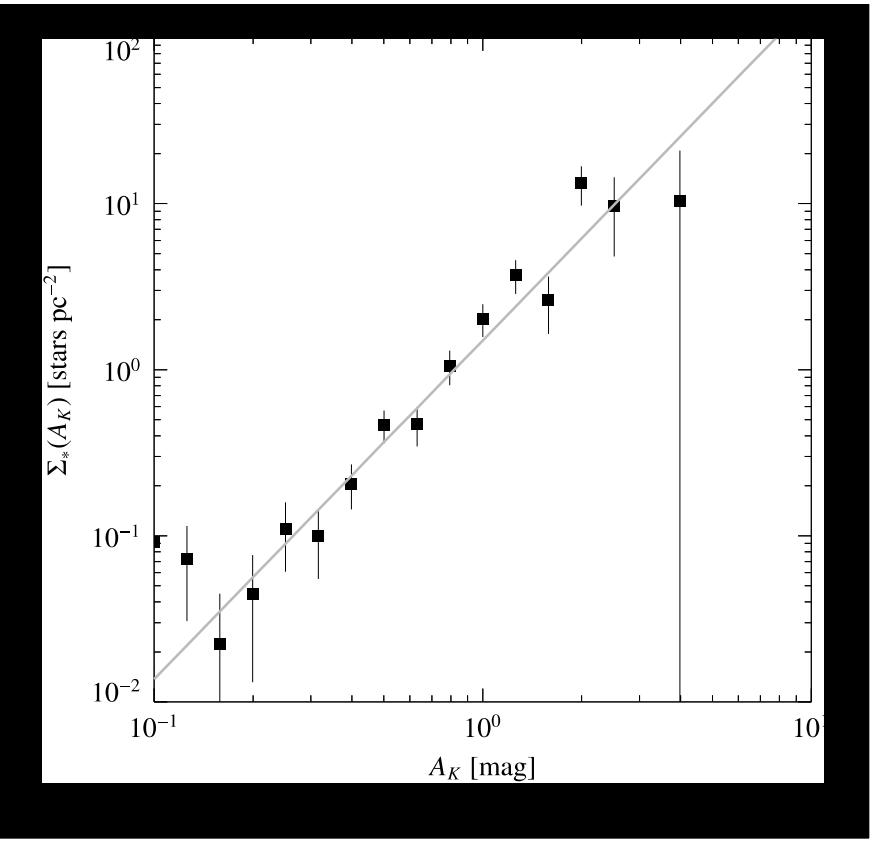
Schmidt Law and Star Formation in GMCs



Schmidt Law and Star Formation in GMCs



Schmidt Law and Star Formation in GMCs

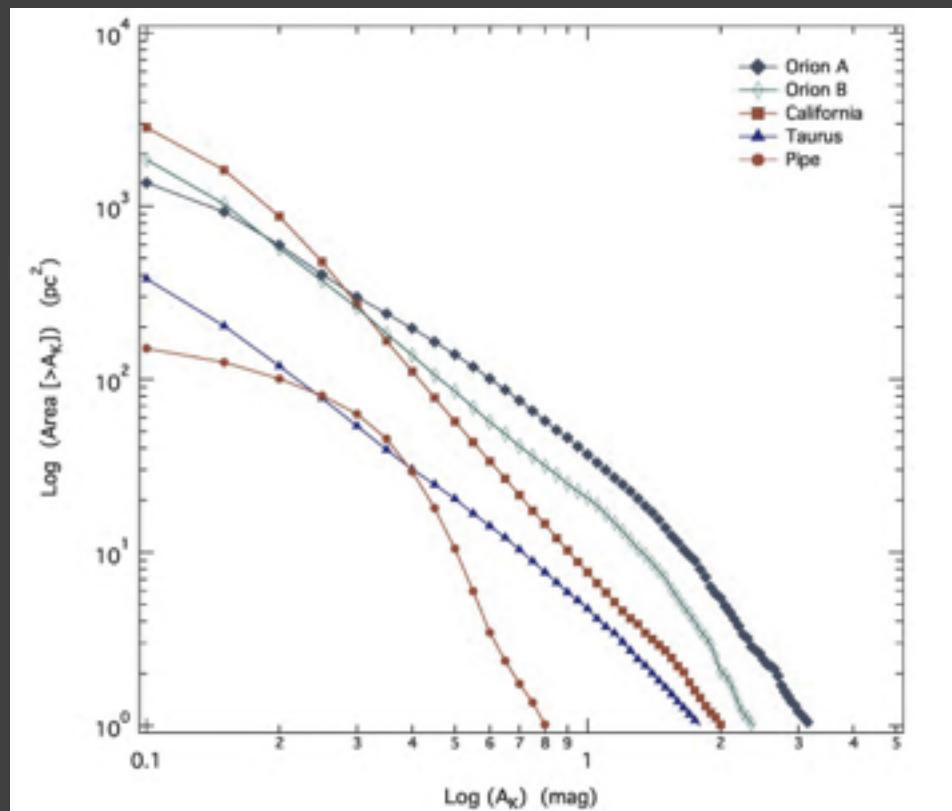


$$N_*(>A_K) = \Sigma_*(>A_K) \times S(>A_K)$$



$$SFR = \int \Sigma_{\text{SFR}} dS$$

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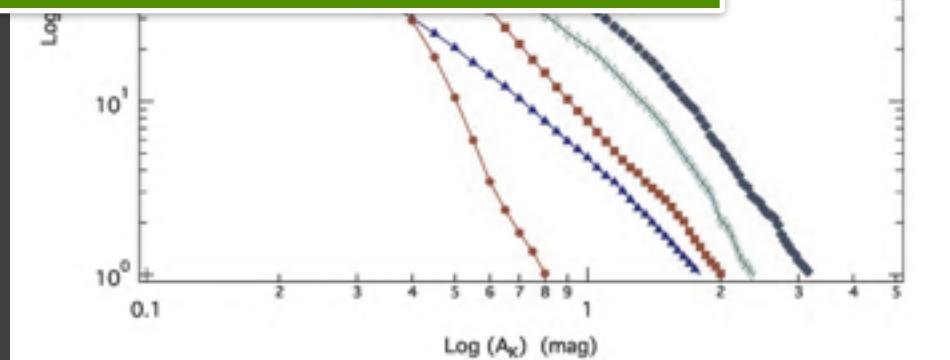


Surface Area Distribution Function, $S(>A_K)$

$$SFR = \int \Sigma_{\text{SFR}} dS$$



Cloud structure plays a critical role
in determining the SFR in clouds!

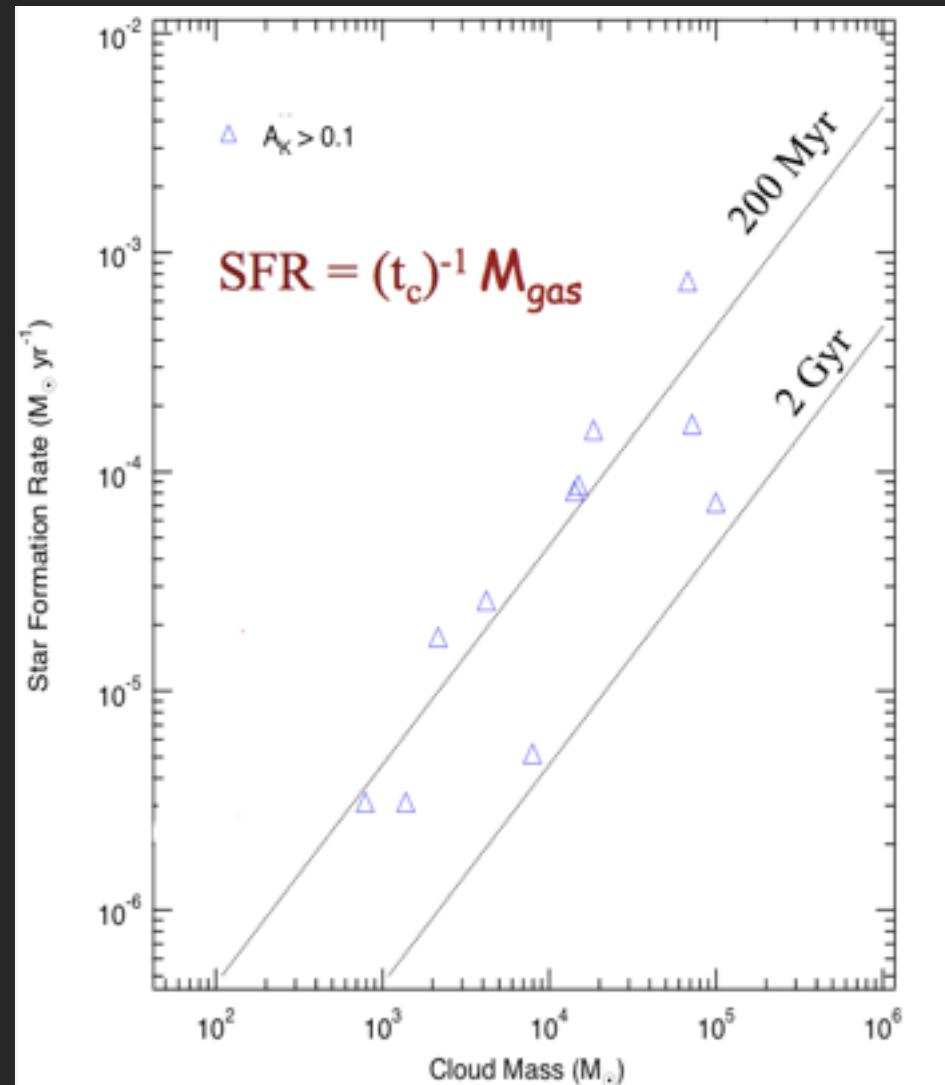


Surface Area Distribution Function, $S(>A_K)$

Scaling Relations for Local GMCs



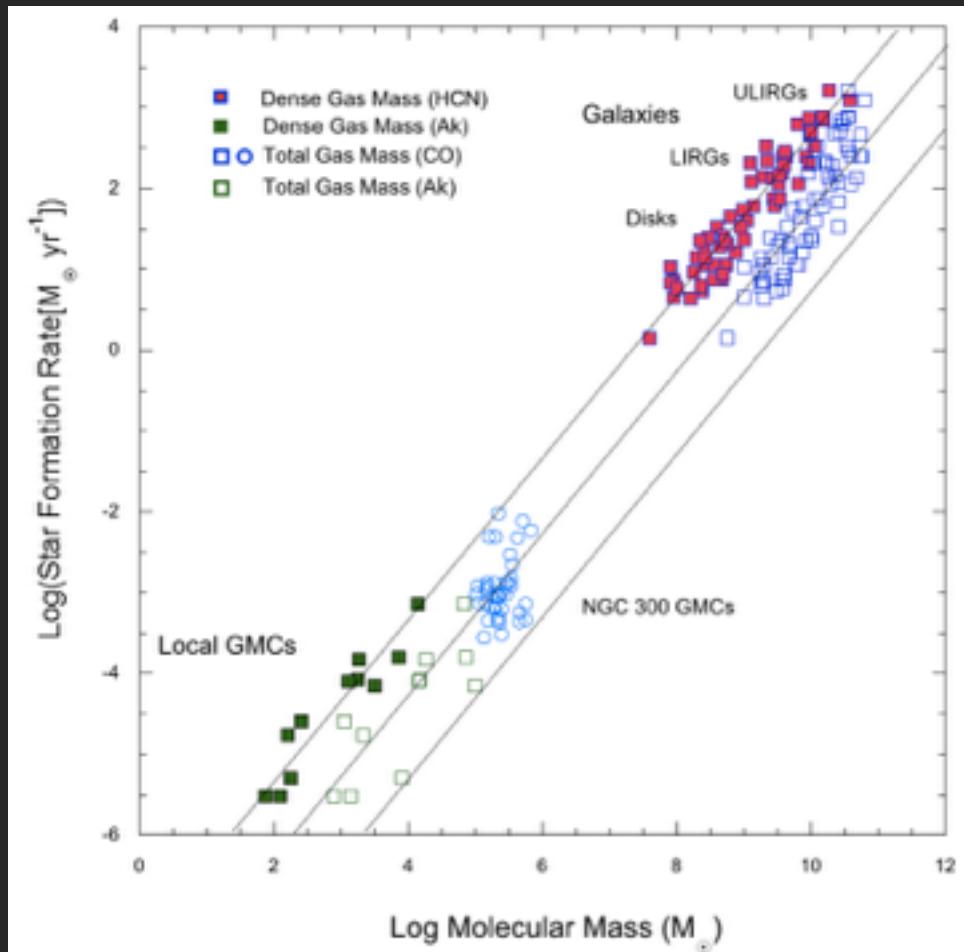
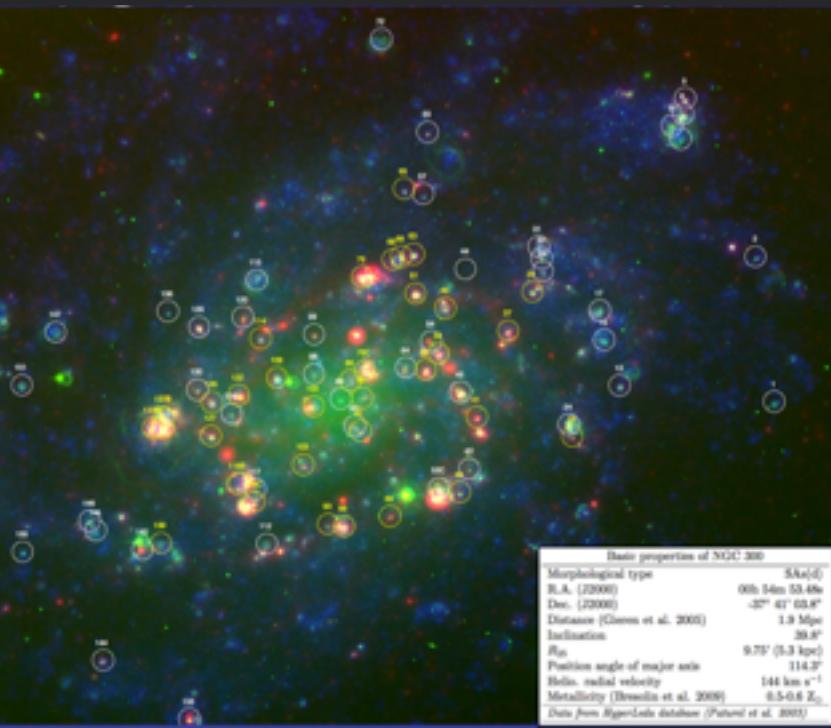
Need to consider *integrated* quantities



Extending the Scaling Relation to Higher Masses and SFRs: the Nearby Galaxy NGC 300

Scaling Relations for GMCs: Nearby Galaxies

NGC 300

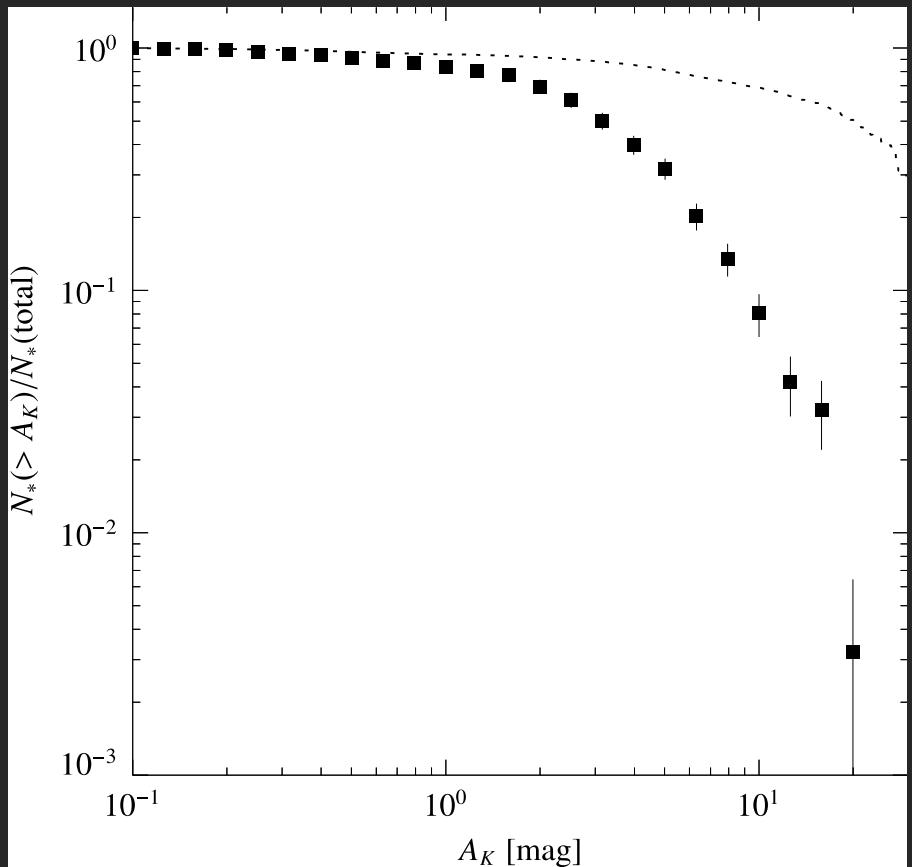


Faesi et al. 2014

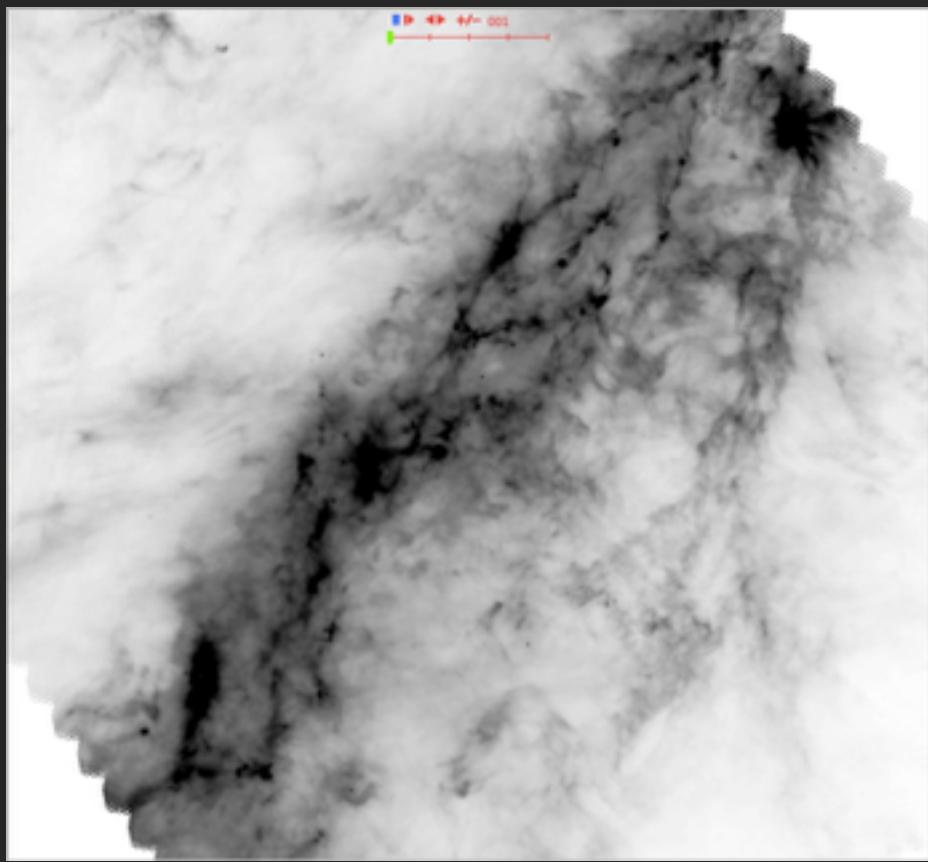
A Column Density Threshold for Star Formation

Column Density “Threshold” for Star Formation

Orion A



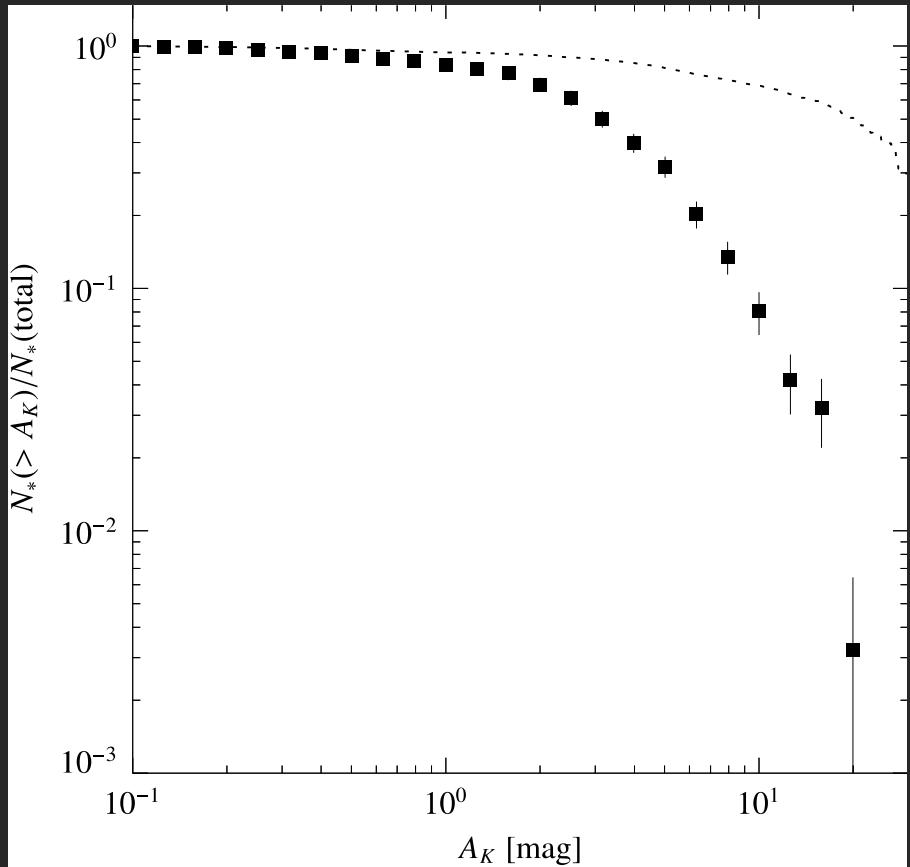
Herschel: 250 μm



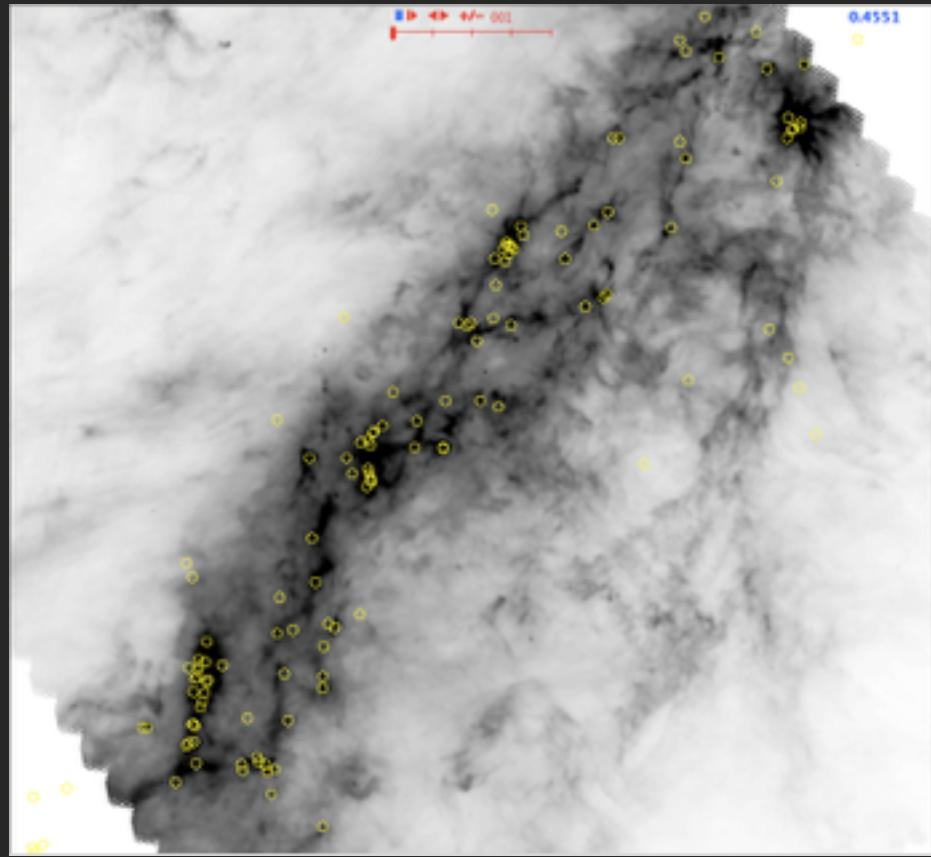
Lombardi et al. 2014

Column Density “Threshold” for Star Formation

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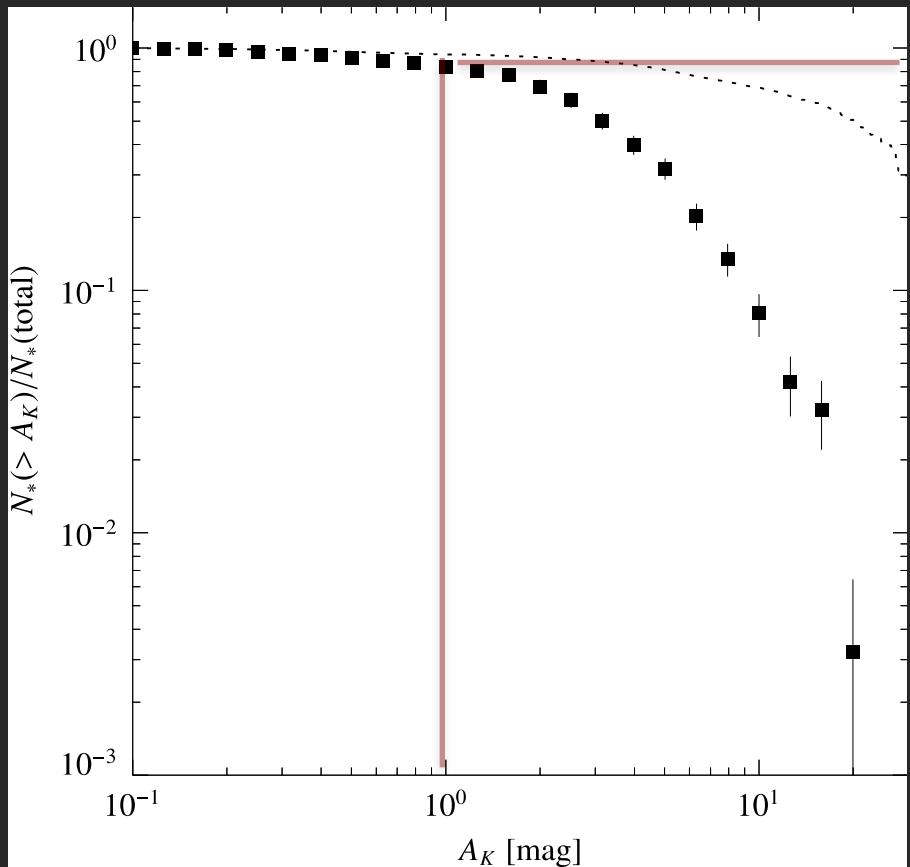
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Lombardi et al. 2014

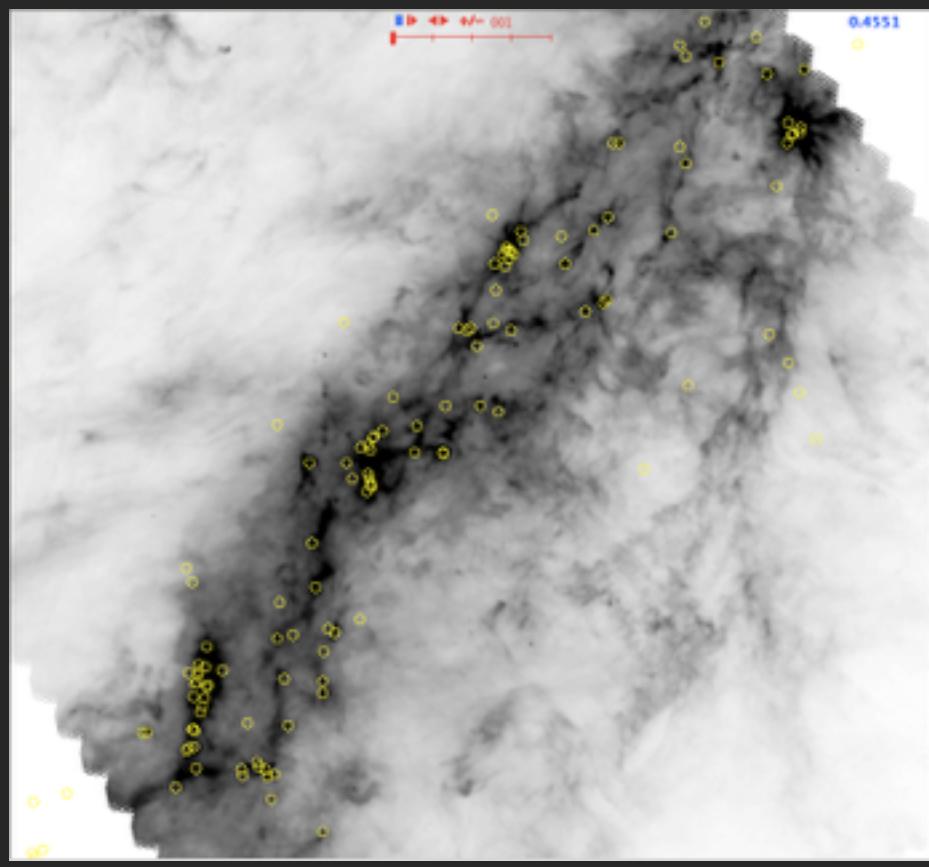
Column Density “Threshold” for Star Formation

Orion A



90% of Protostars at $A_K > 1.0$ mag

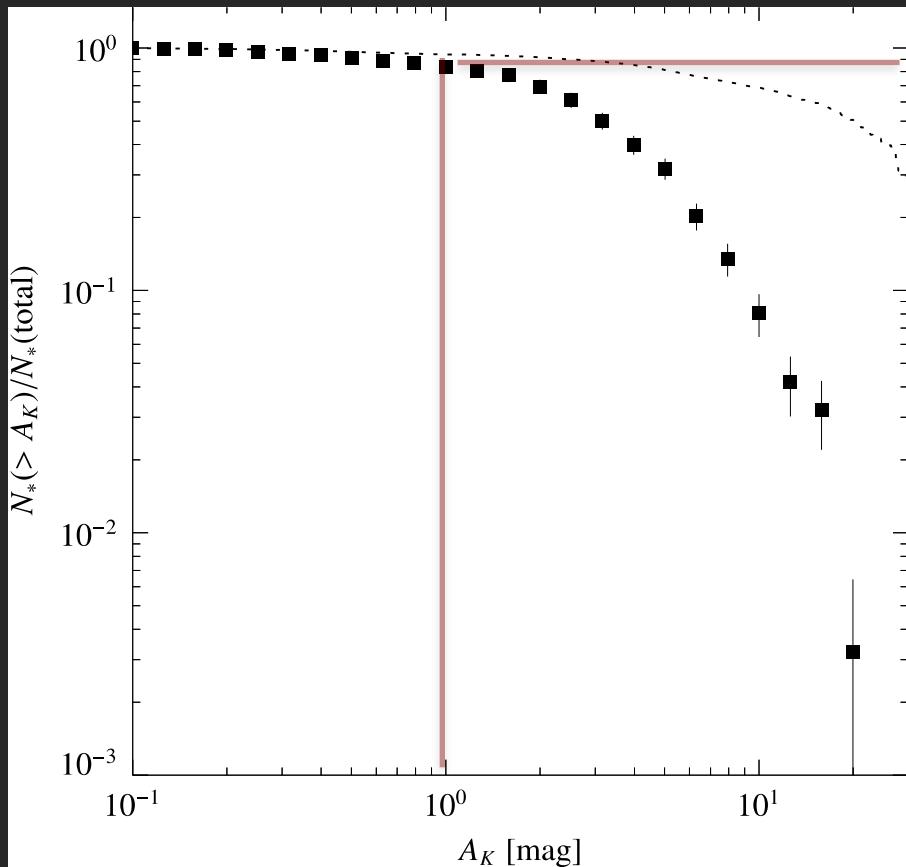
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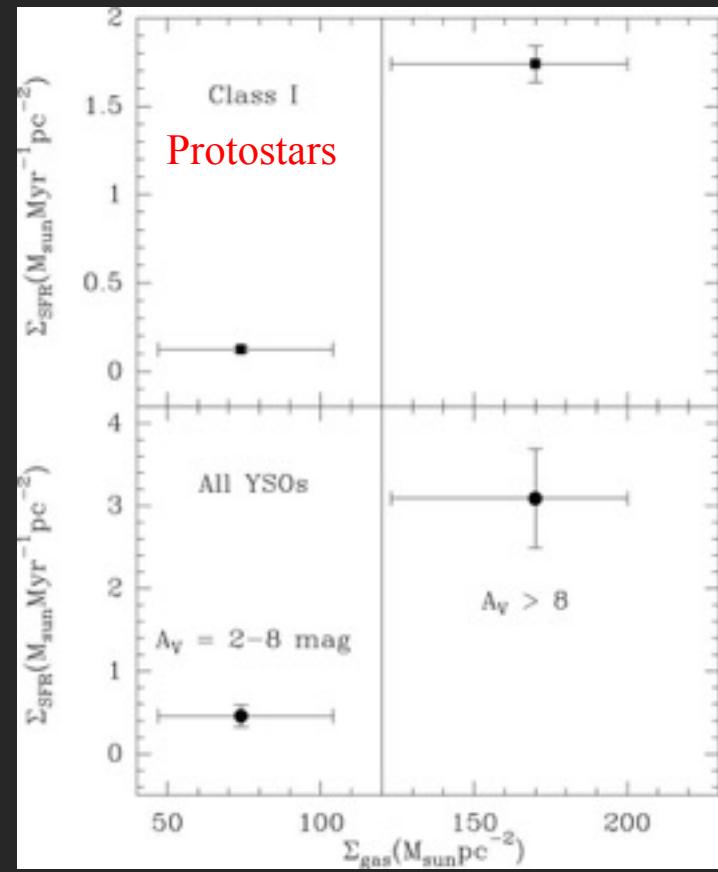
Lombardi et al. 2014

Column Density “Threshold” for Star Formation

Orion A



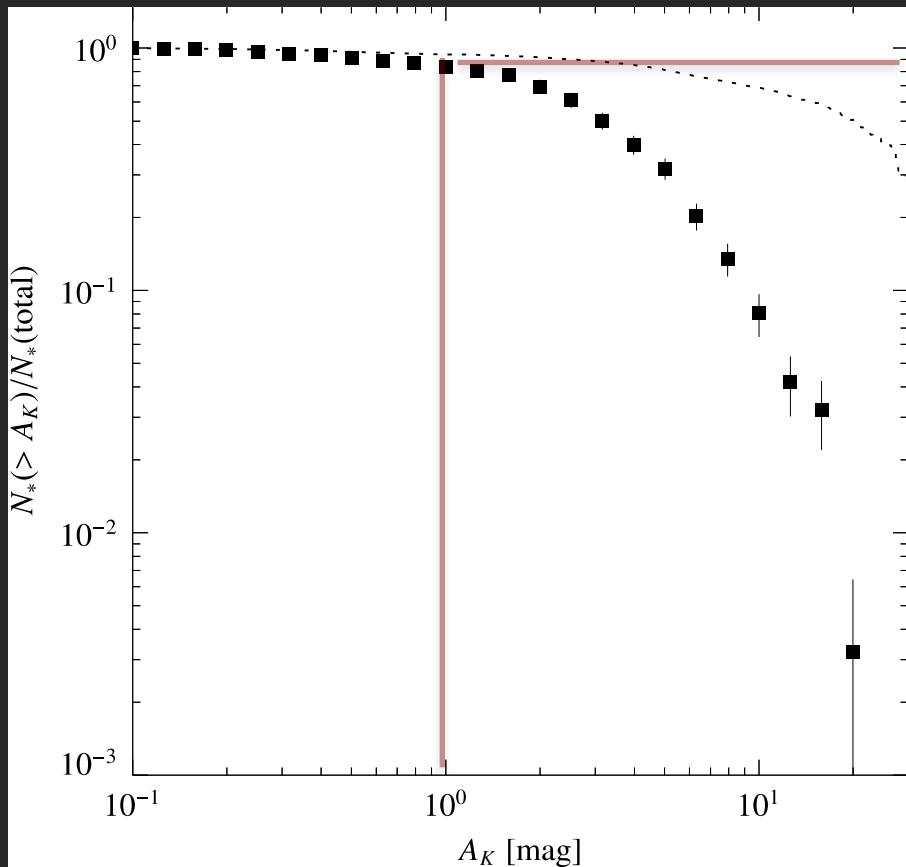
Local Dark Cloud Sample



Evans et al. 2014

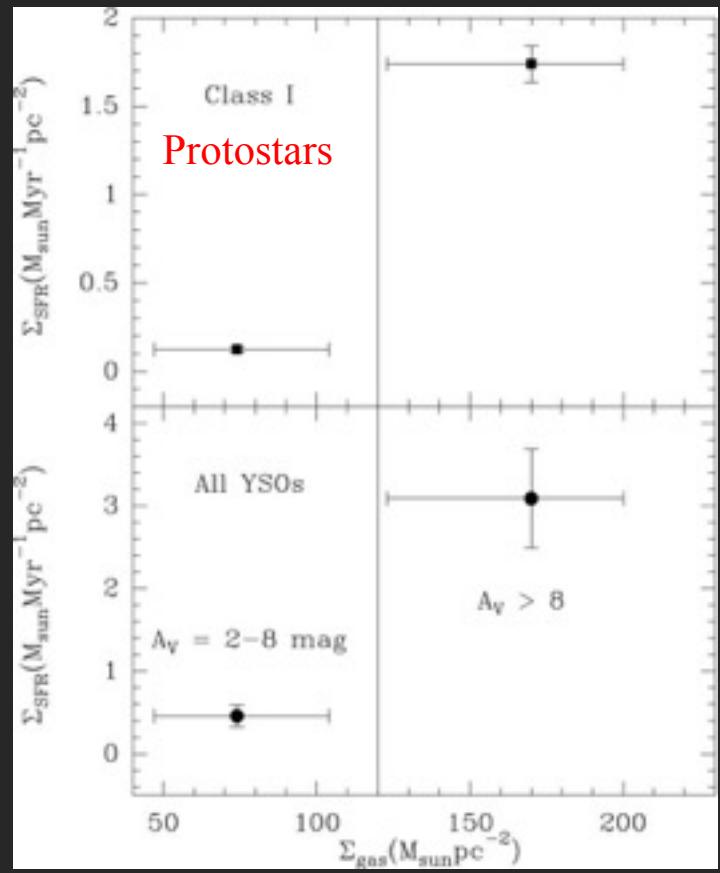
Column Density “Threshold” for Star Formation

Orion A



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Local Dark Cloud Sample



Evans et al. 2014

Column Density “Threshold” for Star Formation?

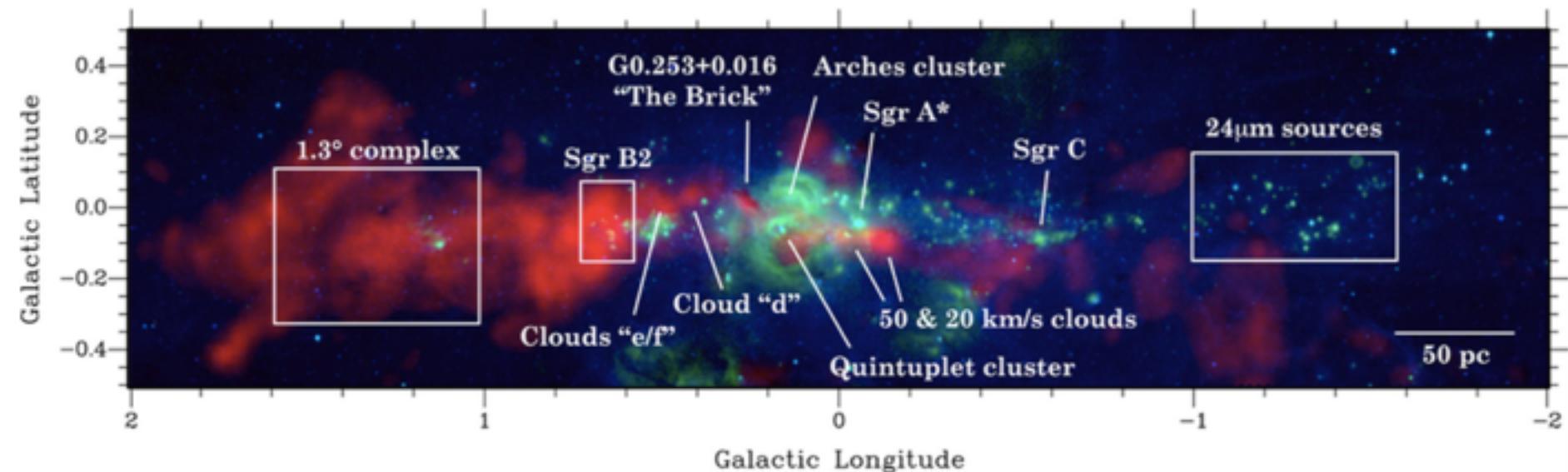
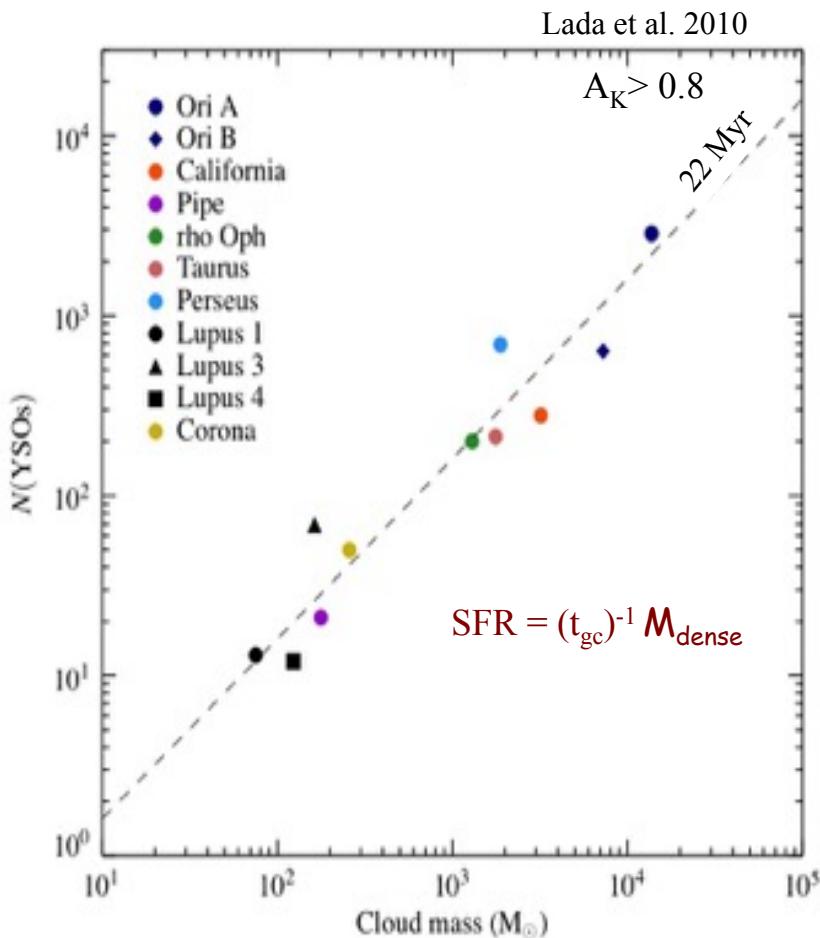


Figure 1. Three-colour composite of the CMZ, with in red the HOPS $\text{NH}_3(1, 1)$ emission (Walsh et al. 2011; Purcell et al. 2012) to indicate the gas with a volume density above a few times 10^3 cm^{-3} , in green the MSX 21.3 μm image (Egan et al. 1998; Price et al. 2001), and in blue the MSX 8.28 μm image. The MSX data show PAH emission (mostly tracing cloud edges), young stellar objects, and evolved stars. The labels indicate several key objects and regions.

Kruijssen +2014
Longmore+2013

Star Formation Scaling Law for Local Clouds

A linear scaling relation¹



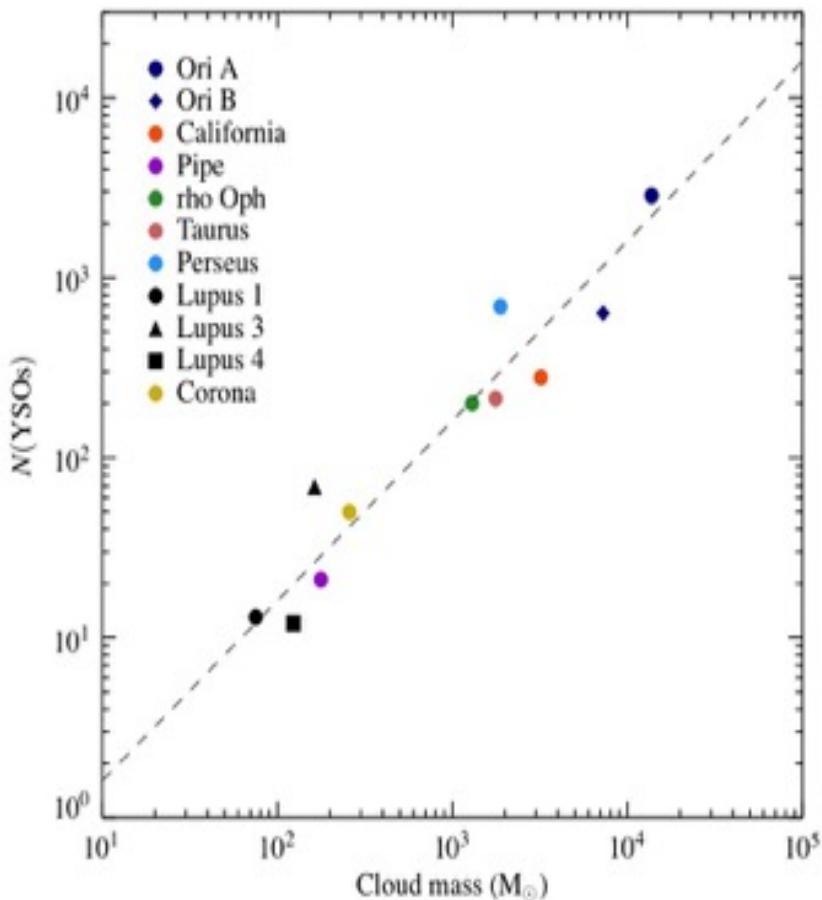
The SFR is controlled by the mass or total amount of dense gas contained within molecular clouds

$t_{gc} = \text{gas consumption time}$
 $= 2.2 \times 10^7 \text{ yrs}$

¹ $SFR = 2.5 \times 10^{-5} N(\text{YSOs}) M_{\odot}/\text{yr}$

Star Formation Scaling Law for Local Clouds

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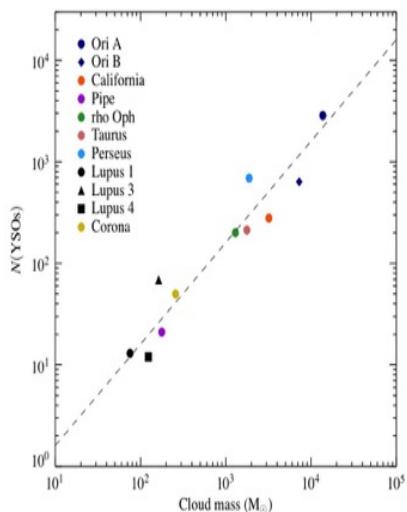
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Star Formation Scaling Law for Local Clouds

A linear scaling relation¹



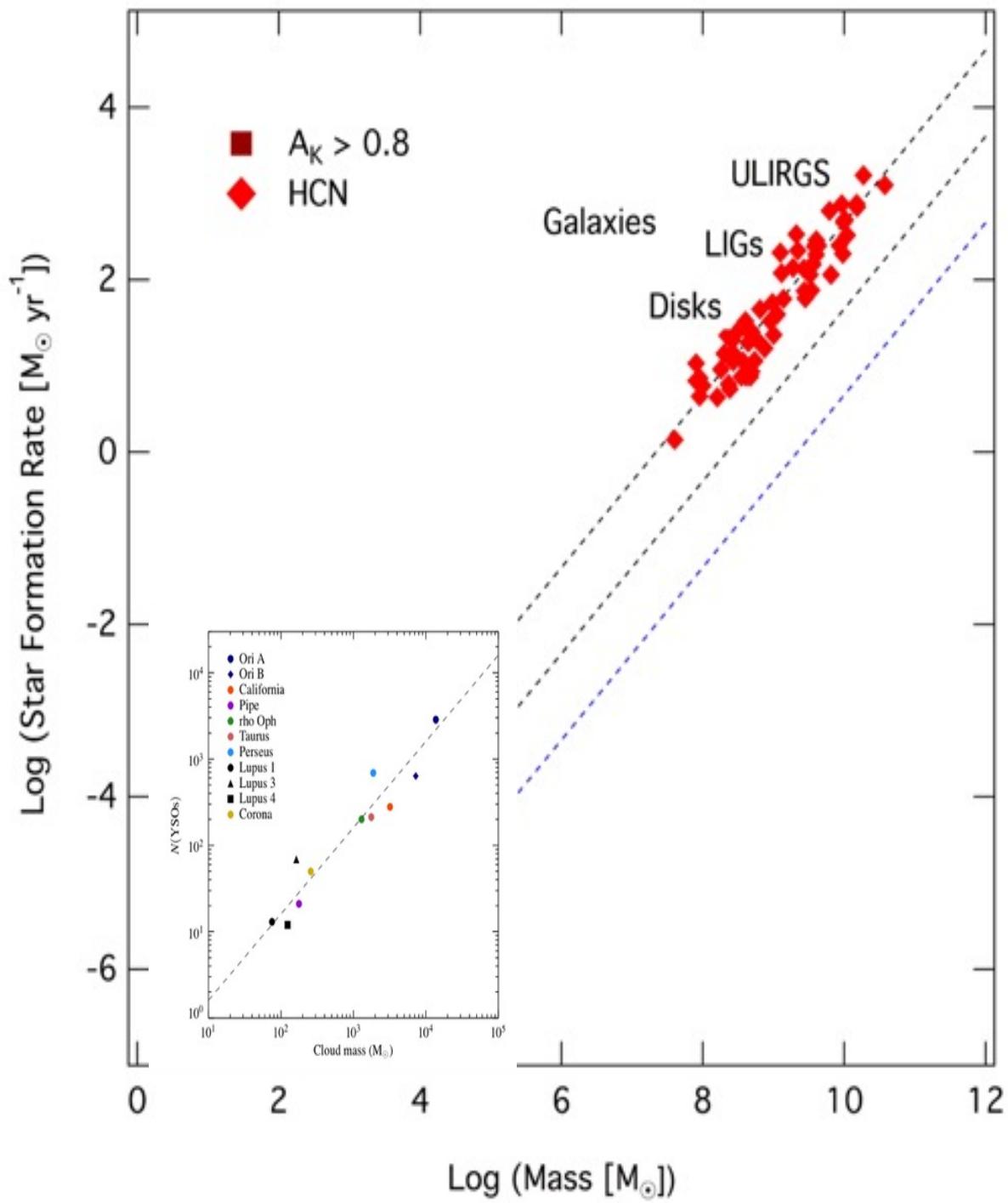
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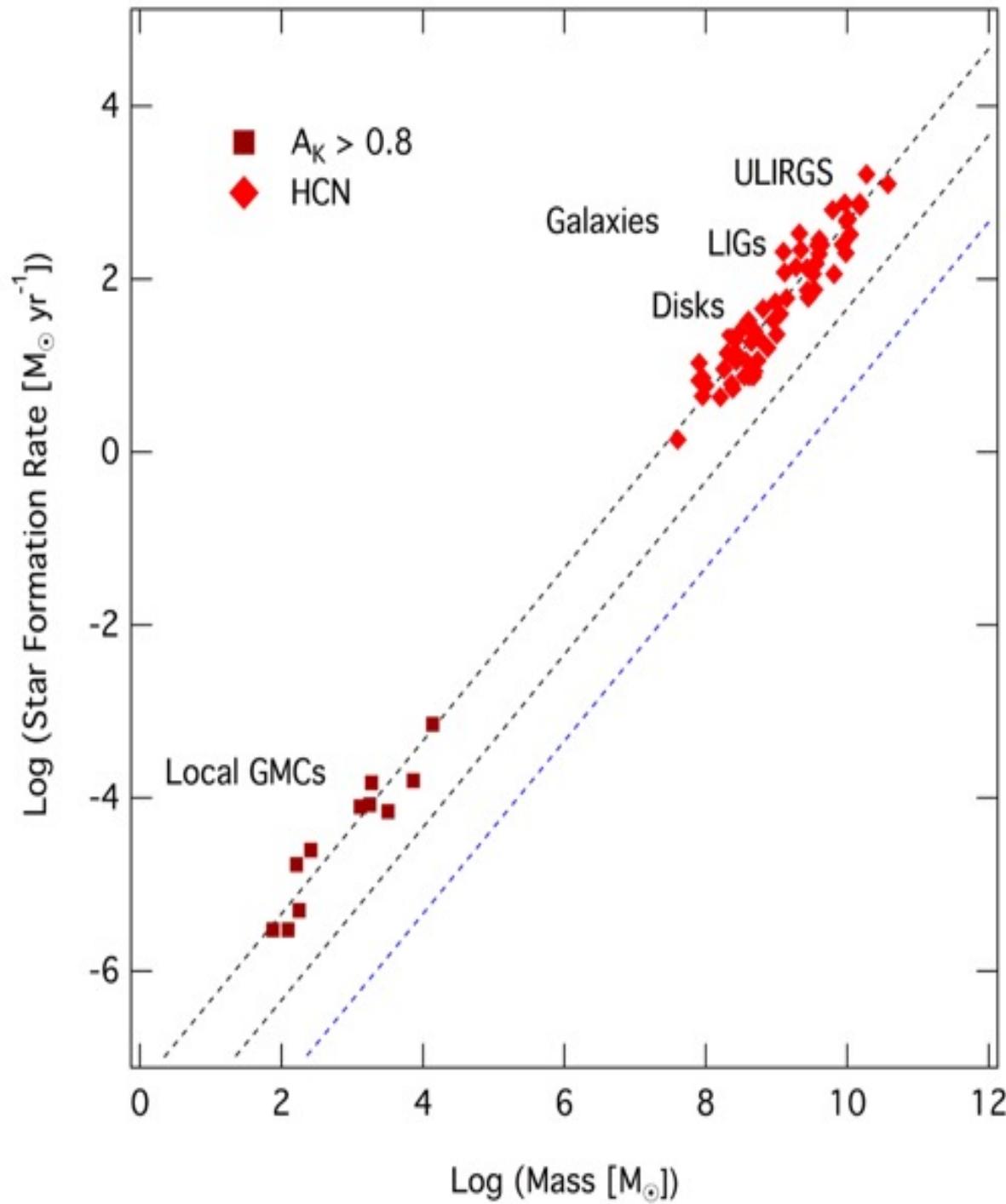
From GMCs to Galaxies

$$\text{SFR} = (t_{\text{gc}})^{-1} M_{>0.8}$$



◆ ○ Gao & Solomon 2004

From GMCs to Galaxies

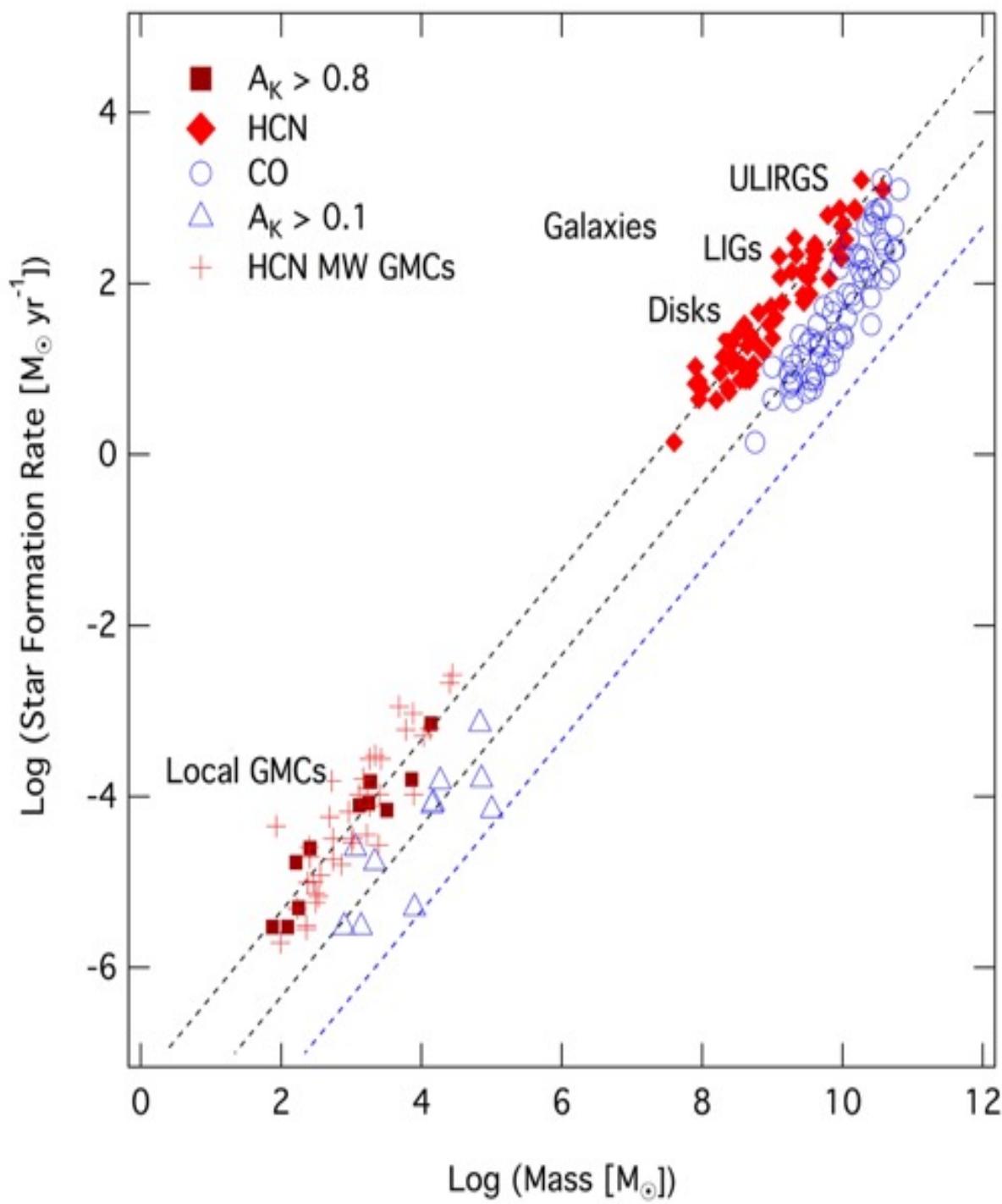


$$\text{SFR} = (t_{\text{gc}})^{-1} M_{>0.8}$$

The SFR is controlled by the mass of dense molecular gas within GMCs and galaxies.

◆ ○ Gao & Solomon 2004

Star Formation Scaling Law from GMCs to Galaxies



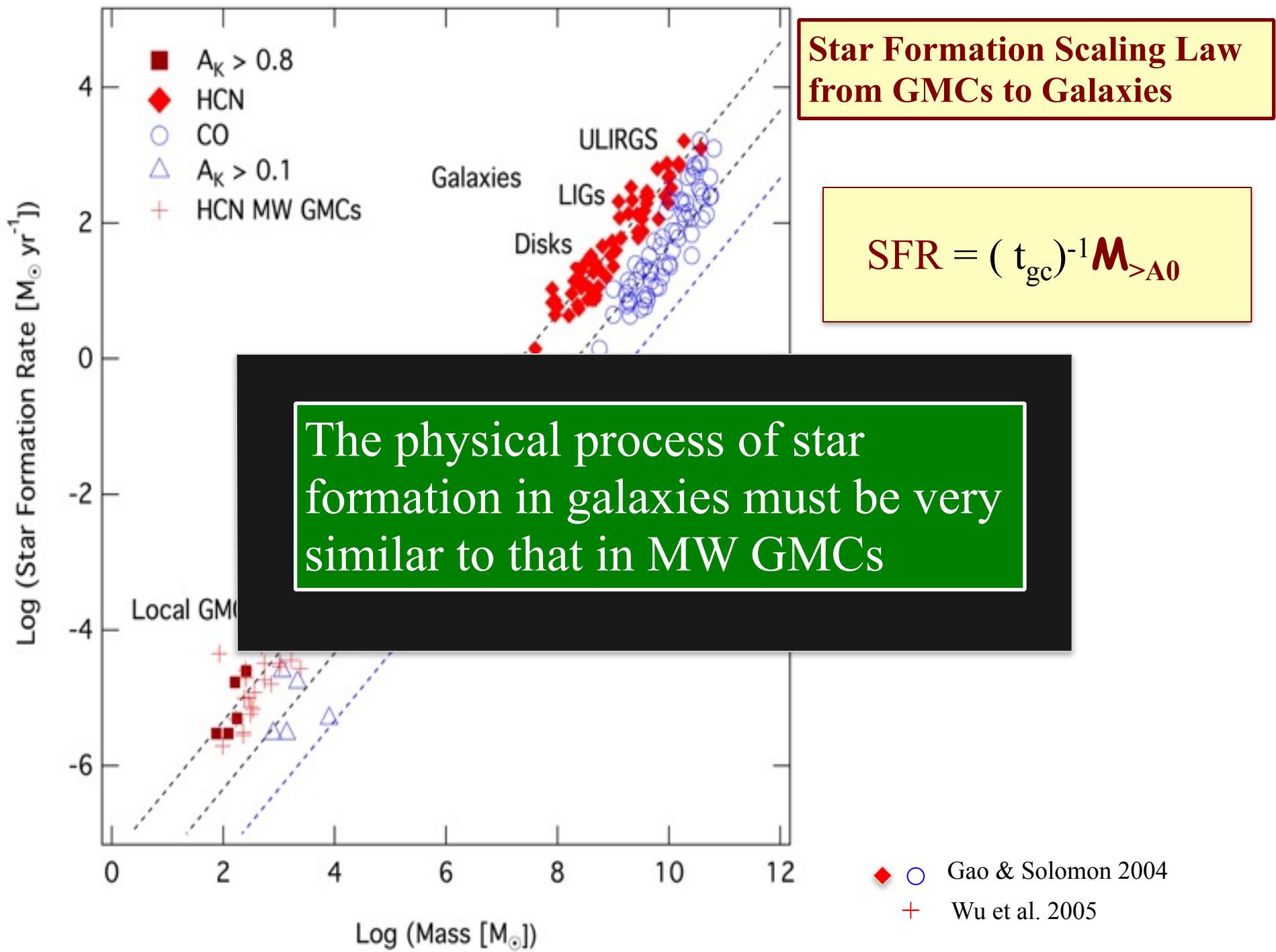
$$SFR = (t_{gc})^{-1} M_{>A0}$$

◆ ○ Gao & Solomon 2004
+ ■ Wu et al. 2005

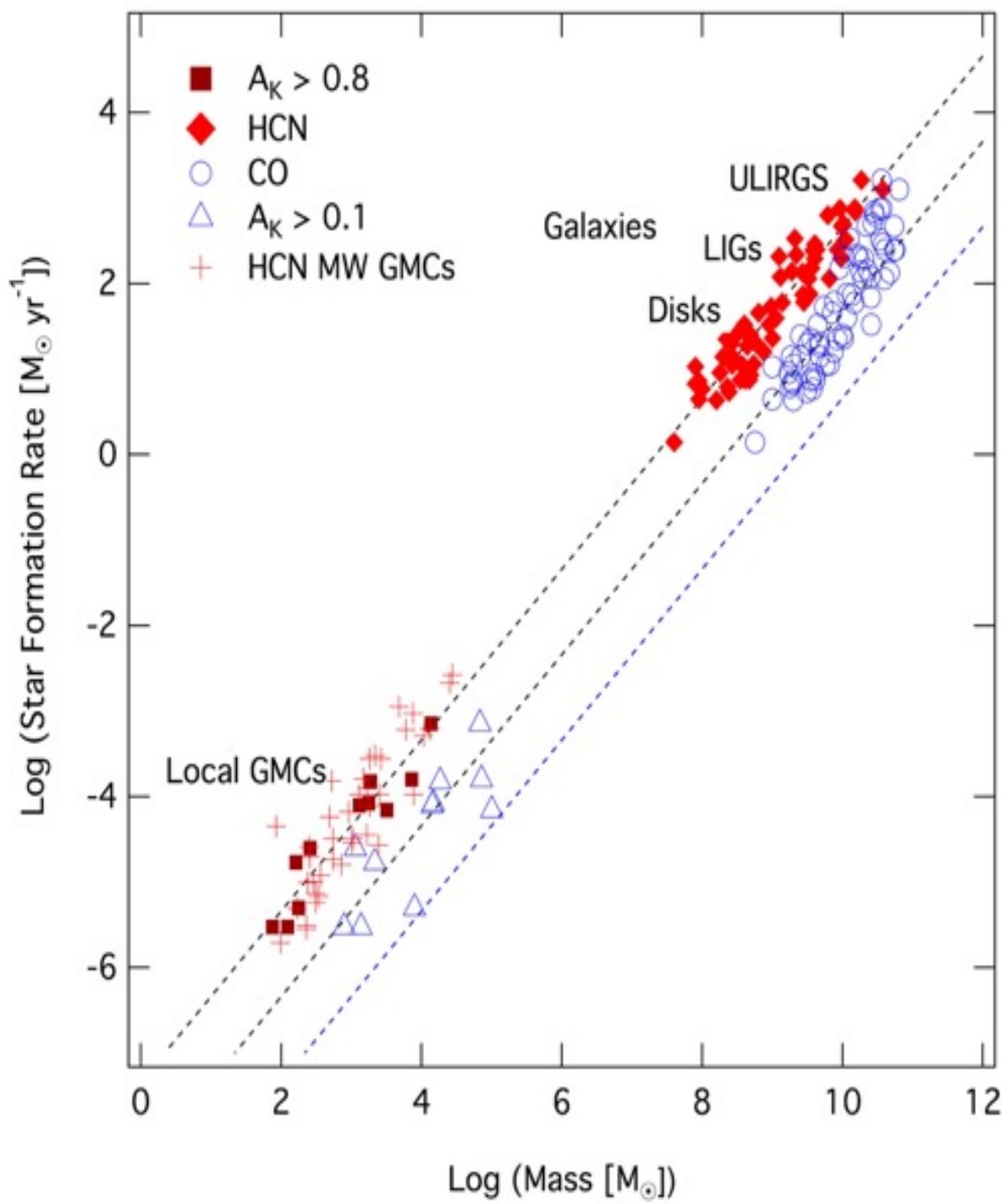
Star Formation Scaling Law from GMCs to Galaxies

$$\text{SFR} = (t_{\text{gc}})^{-1} M_{>A0}$$

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



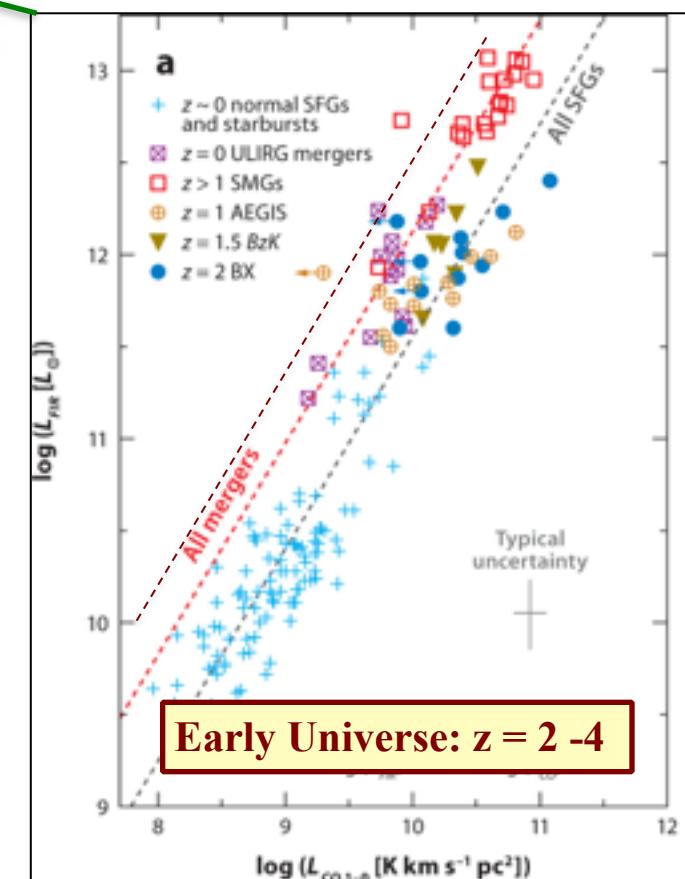
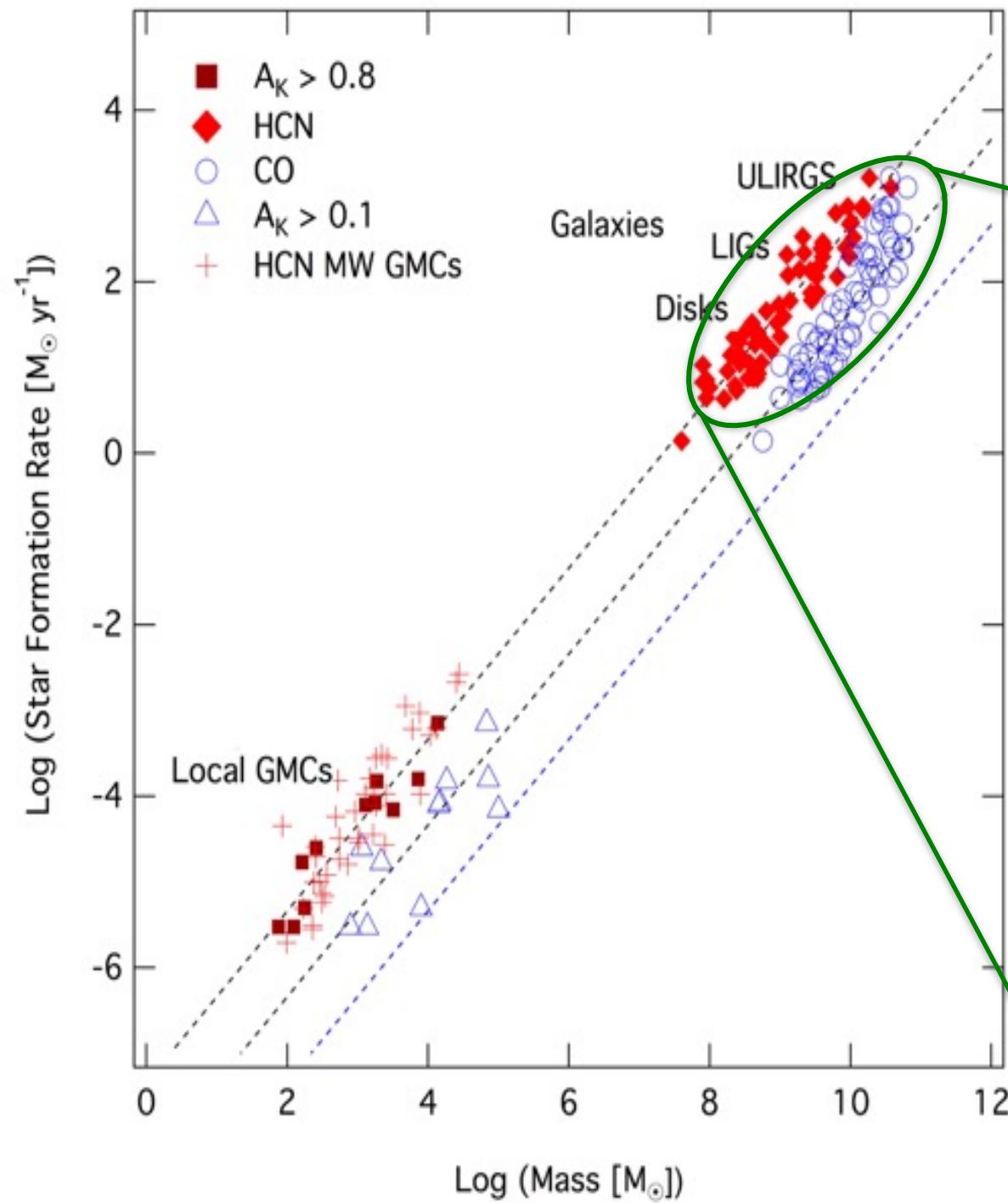
Star Formation Scaling Law from GMCs to Galaxies



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◆ ○ Gao & Solomon 2004
+ ■ Wu et al. 2005

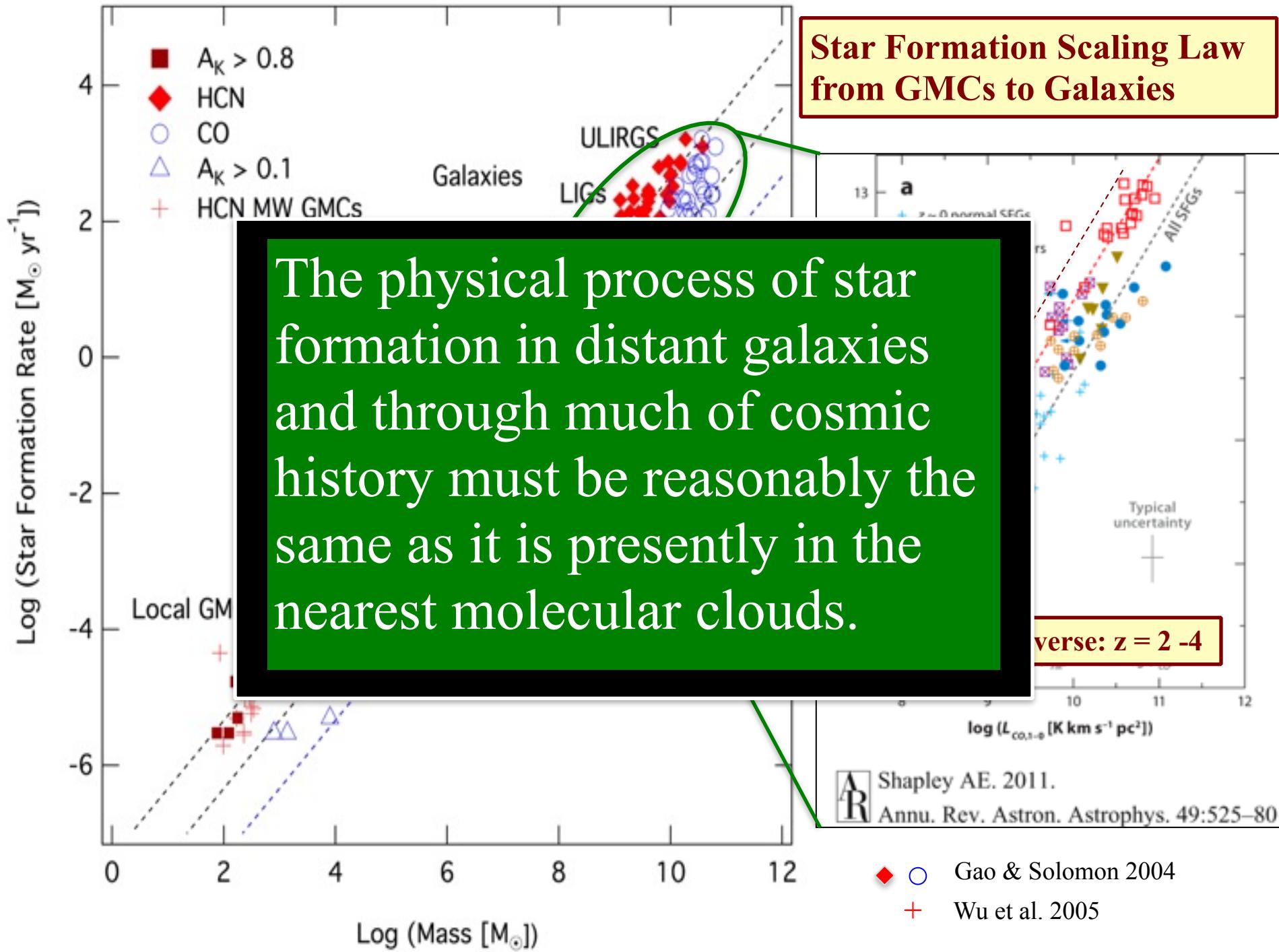
Star Formation Scaling Law from GMCs to Galaxies



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

\blacklozenge Gao & Solomon 2004
 $+$ Wu et al. 2005

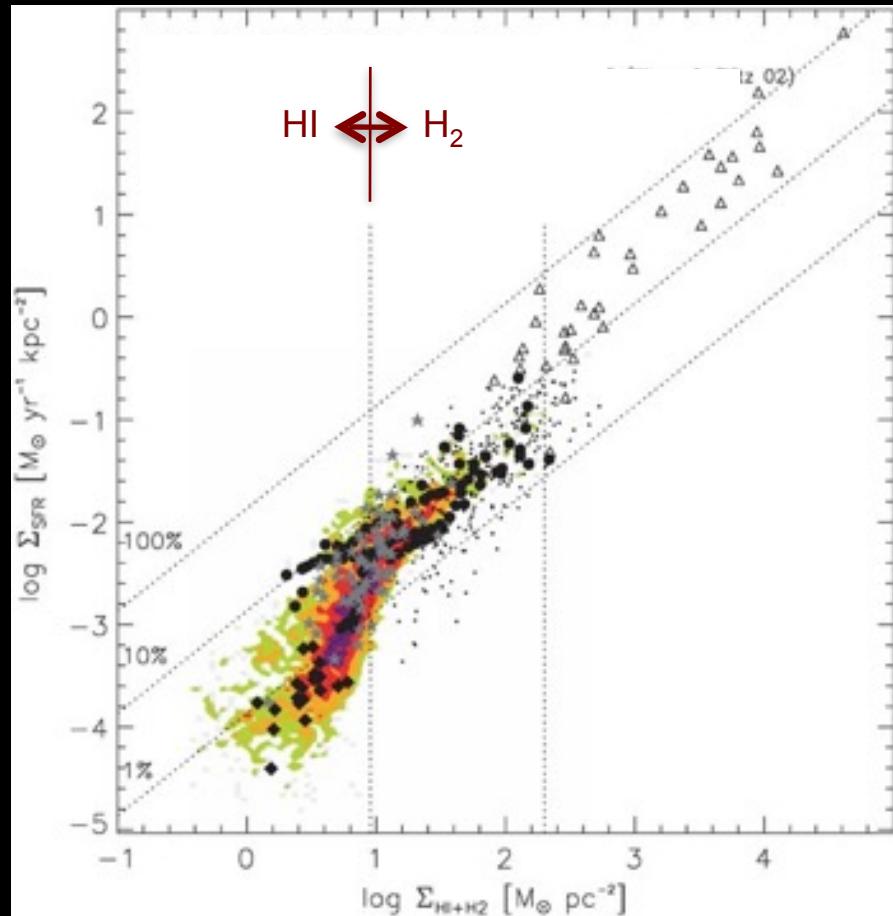
Star Formation Scaling Law from GMCs to Galaxies



Deconstructing the Kennicutt-Schmidt Scaling Relation

Deconstructing the Kennicutt-Schmidt Law:

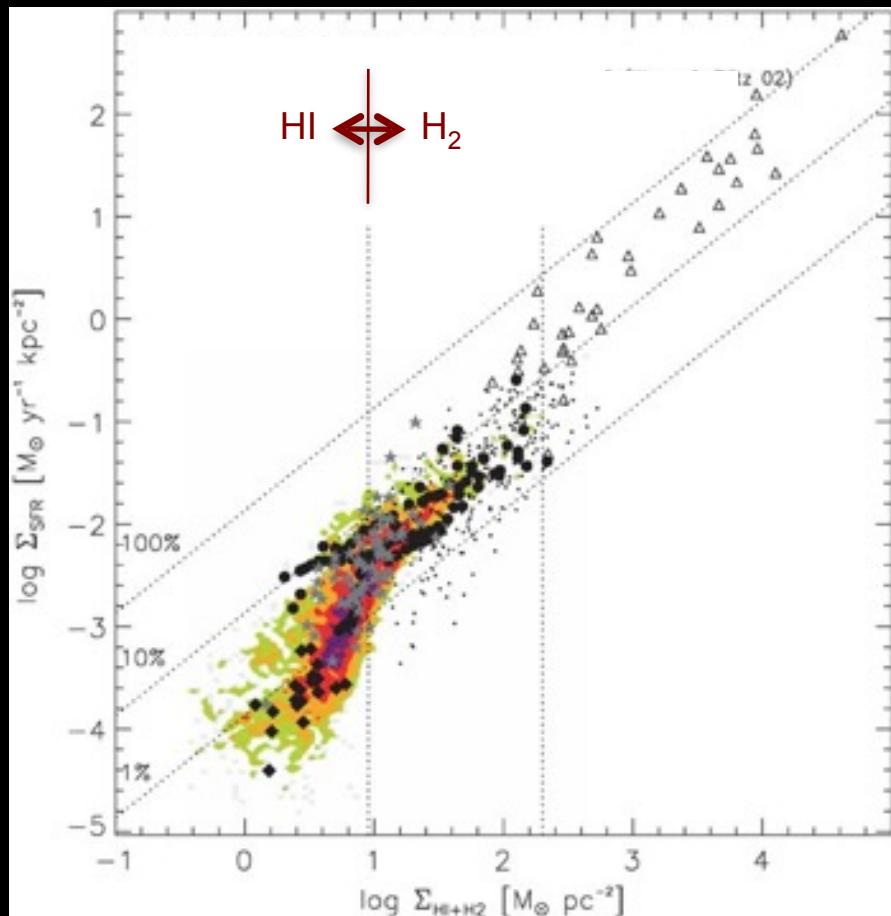
Galaxies



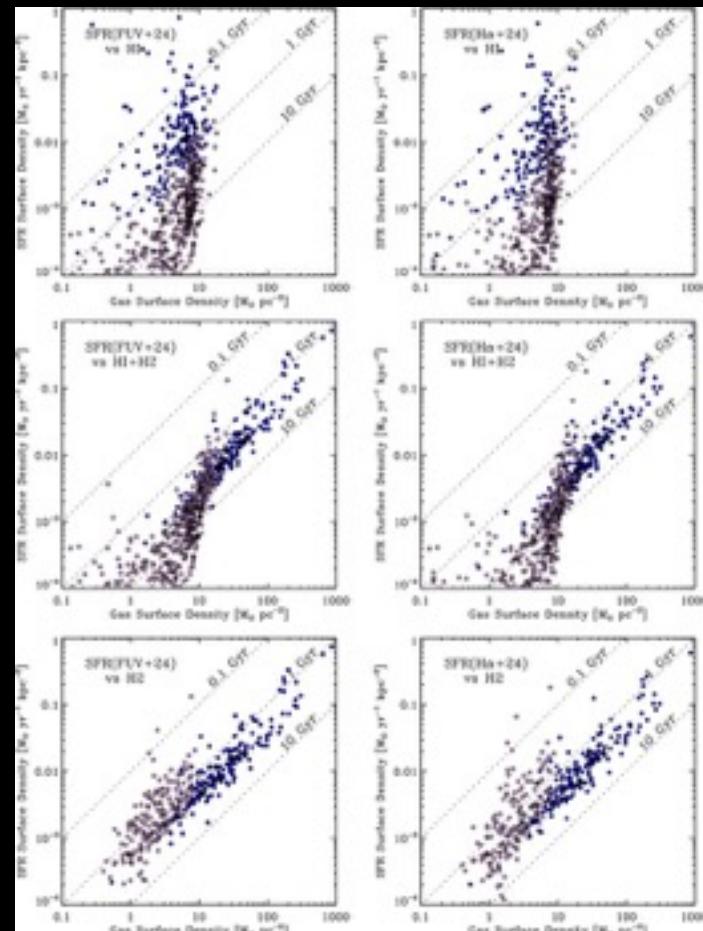
Bigiel et al. 2008 AJ 136:2846

Deconstructing the Kennicutt-Schmidt Law:

Galaxies



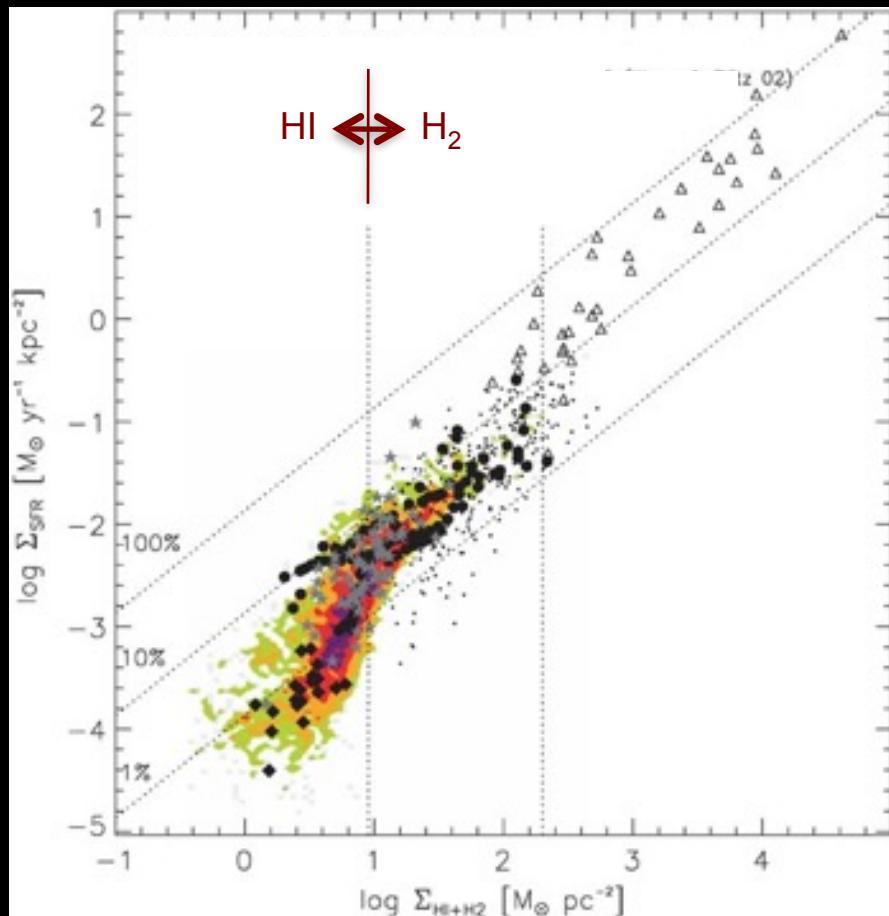
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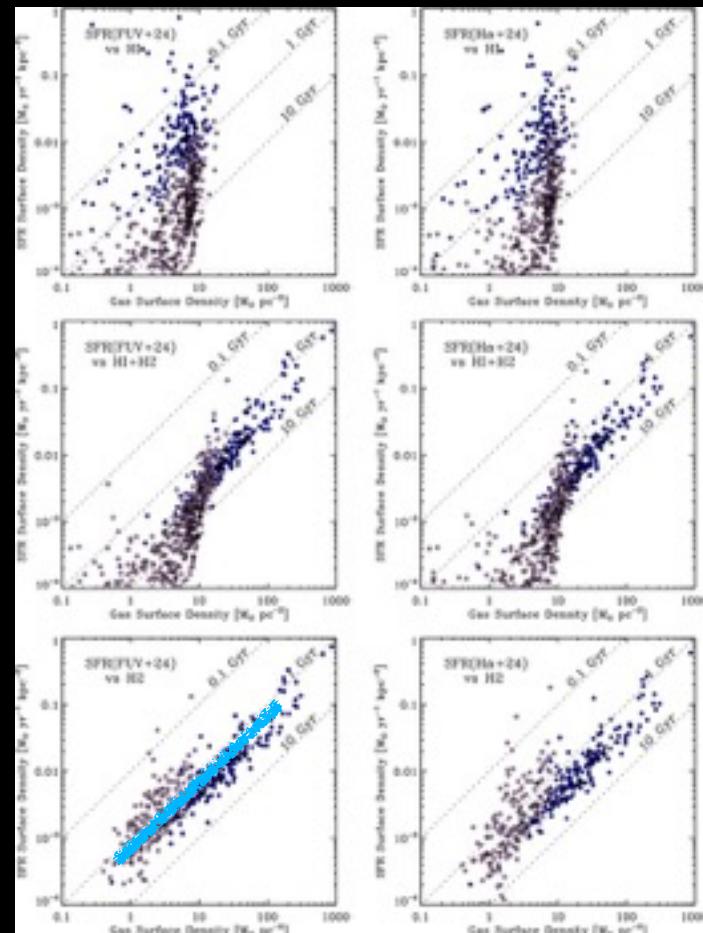
Schruba et al. 2011 AJ 142:37

Deconstructing the Kennicutt-Schmidt Law:

Galaxies



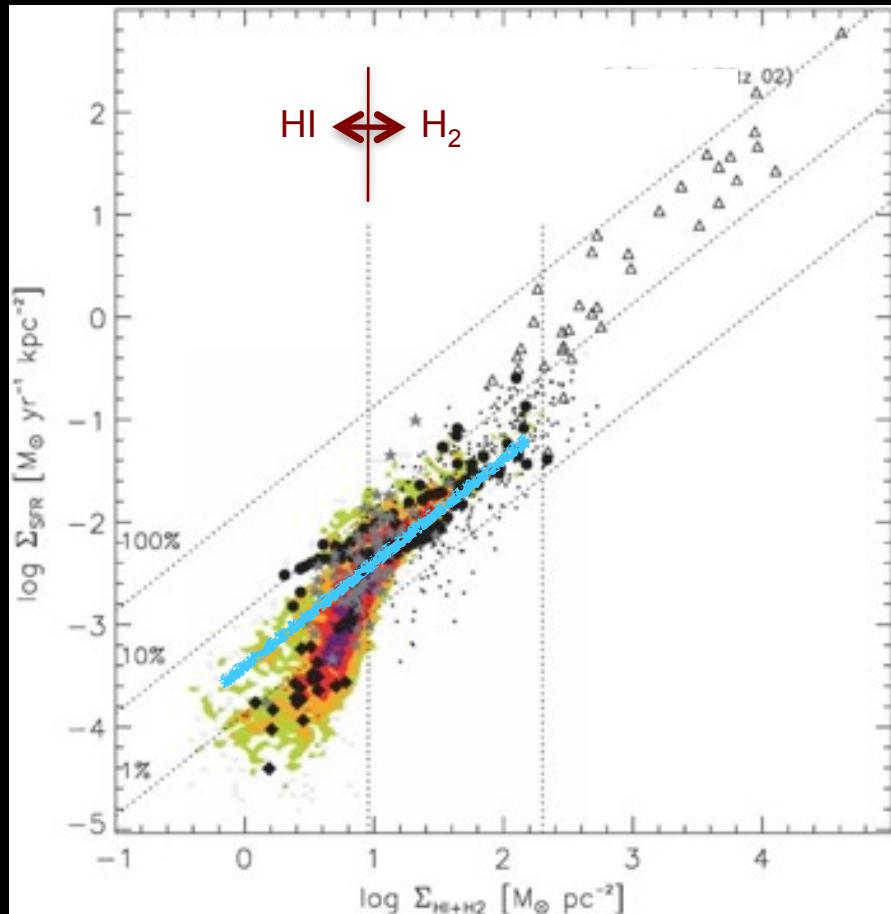
Bigiel et al. 2008 AJ 136:2846



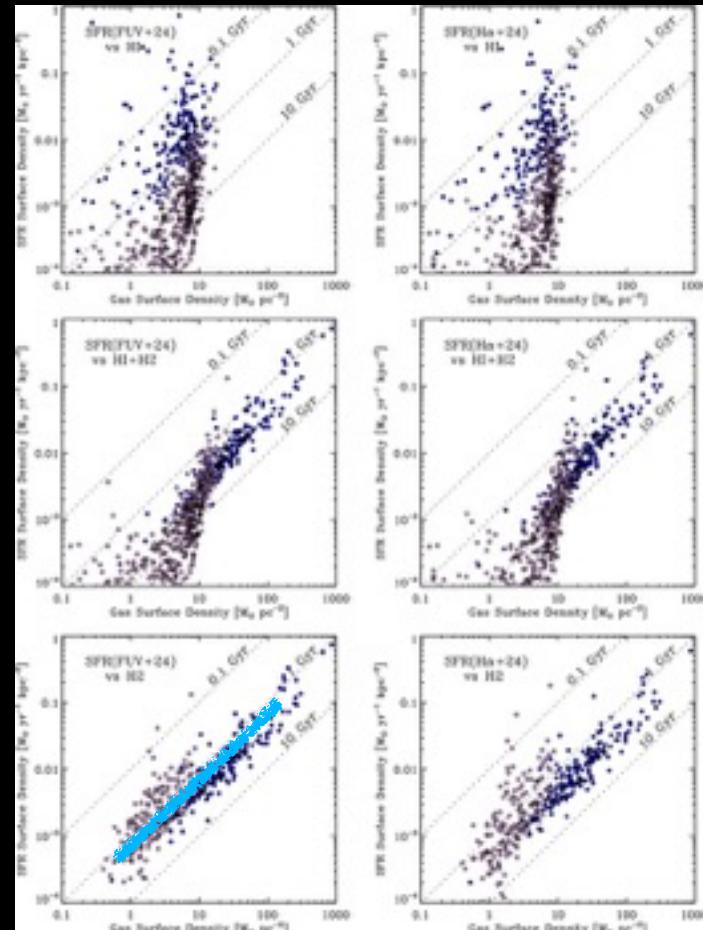
Schruba et al. 2011 AJ 142:37

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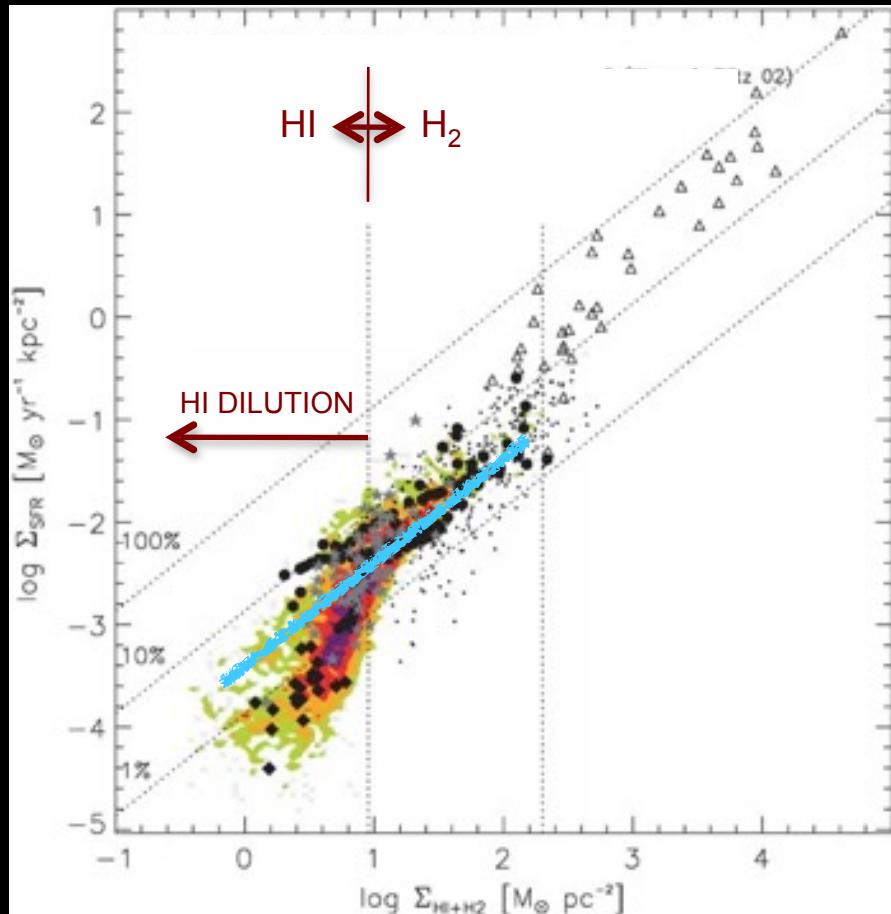
Bigiel et al. 2008 AJ 136:2846



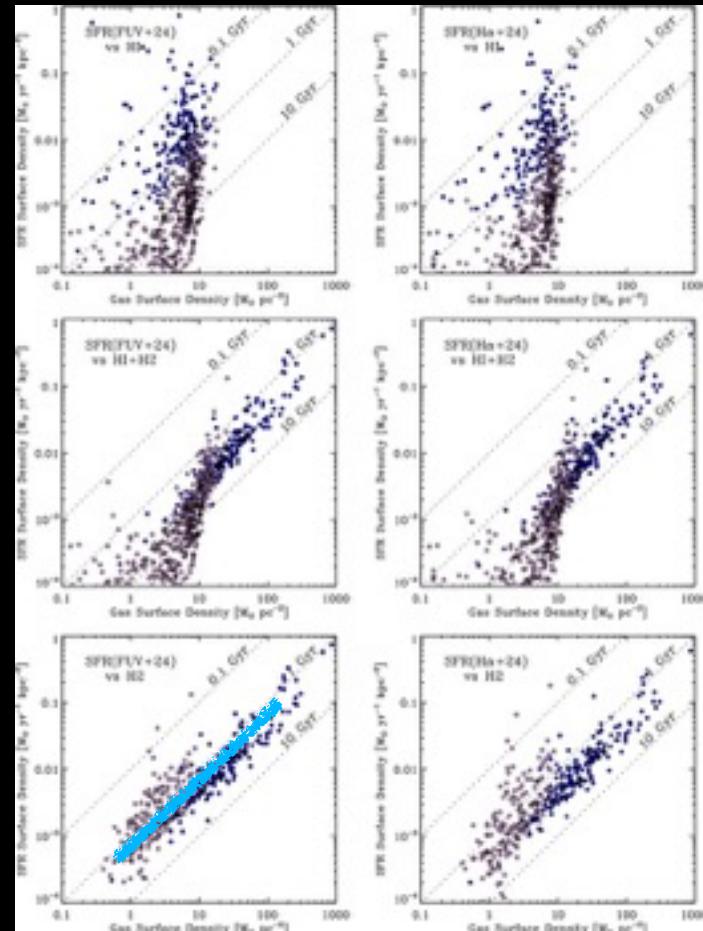
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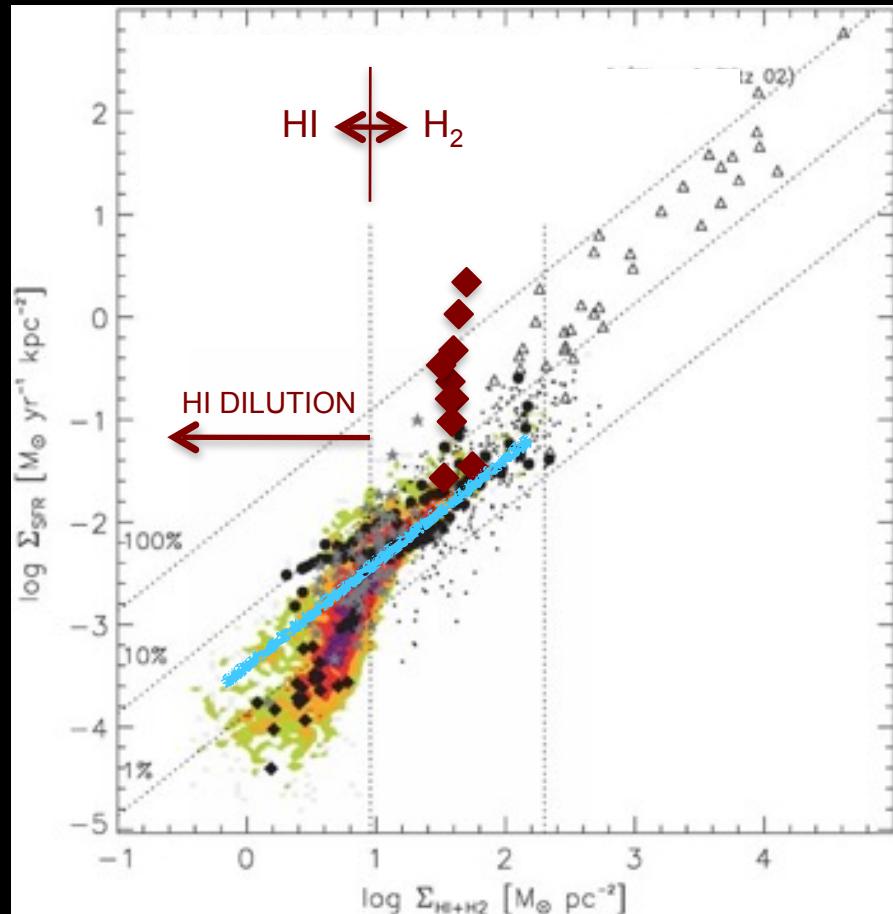
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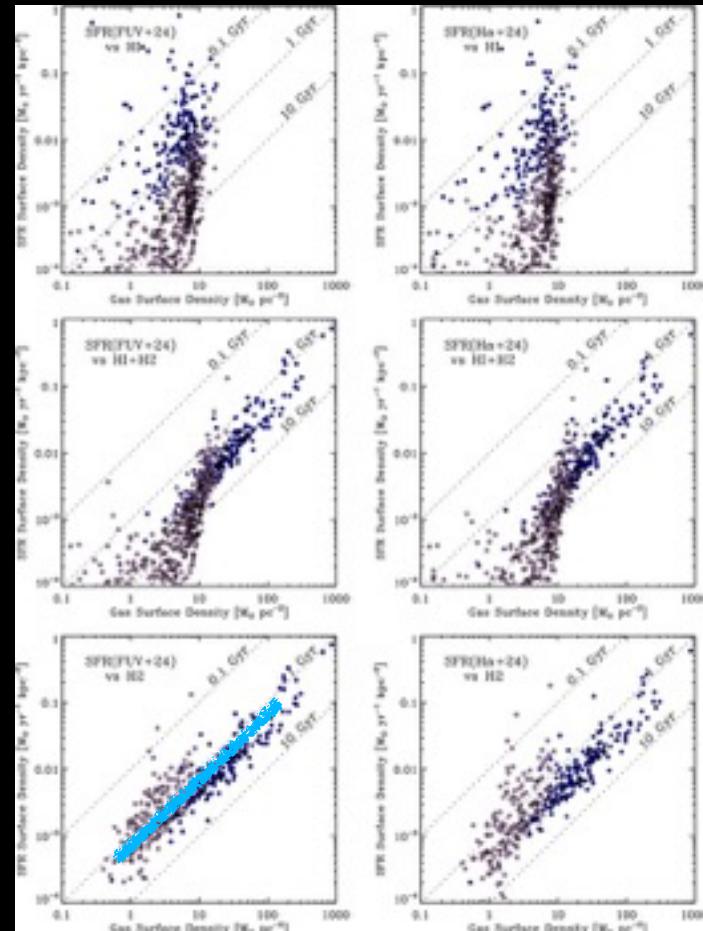
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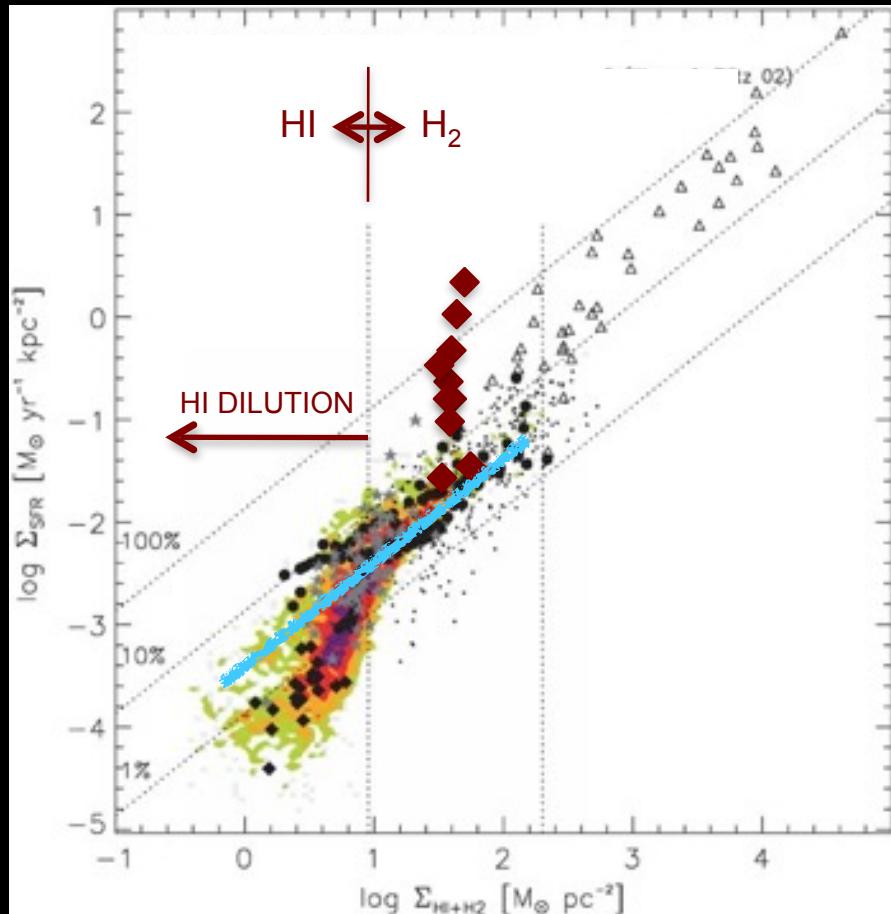
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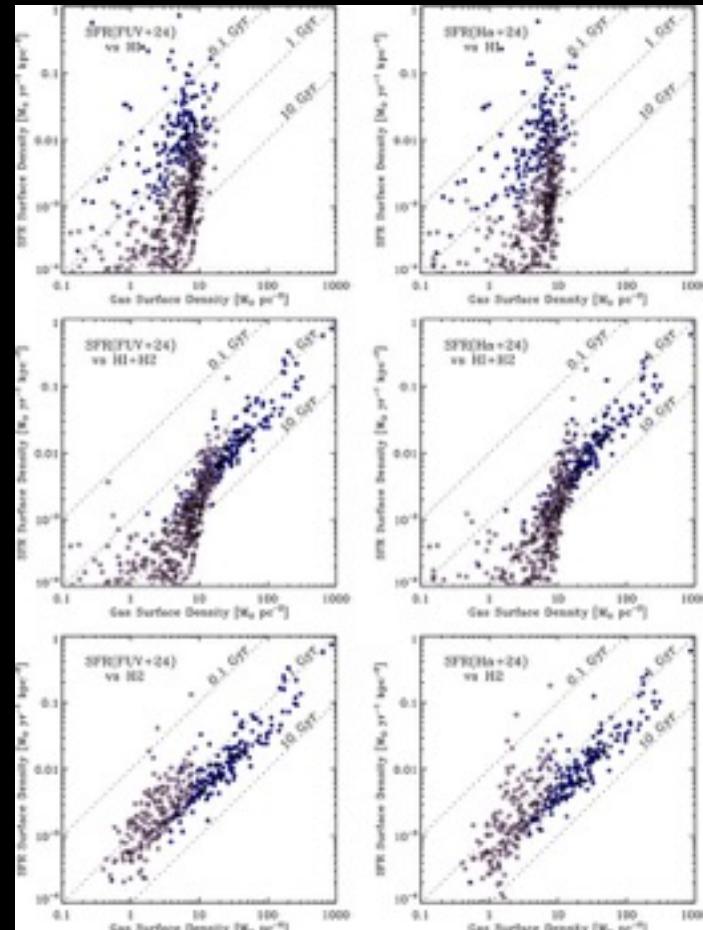
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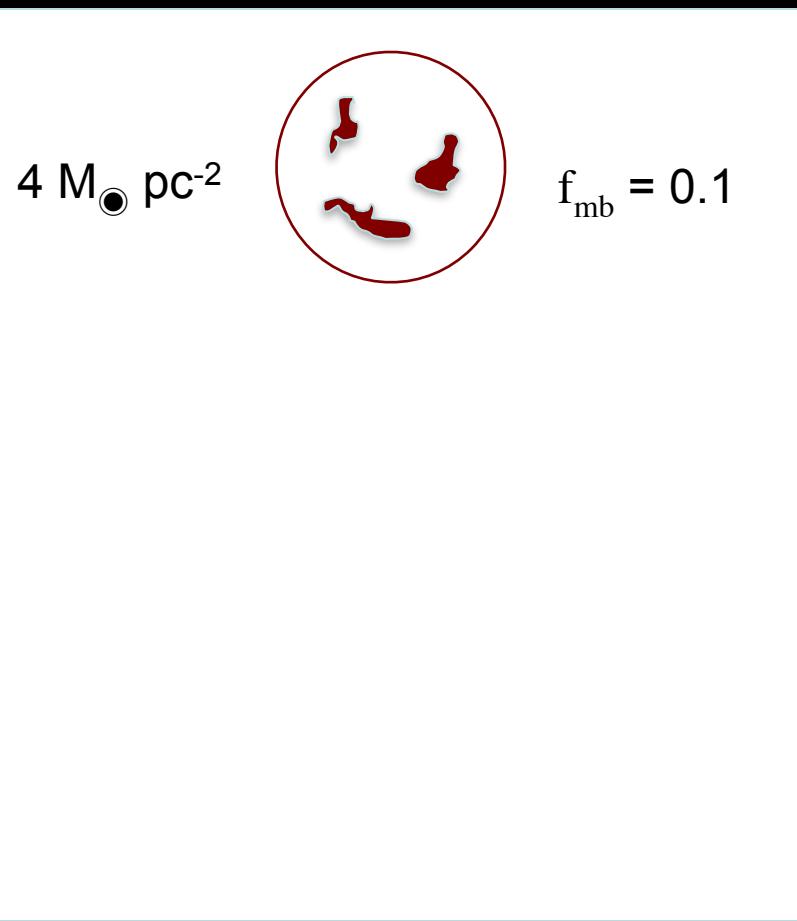
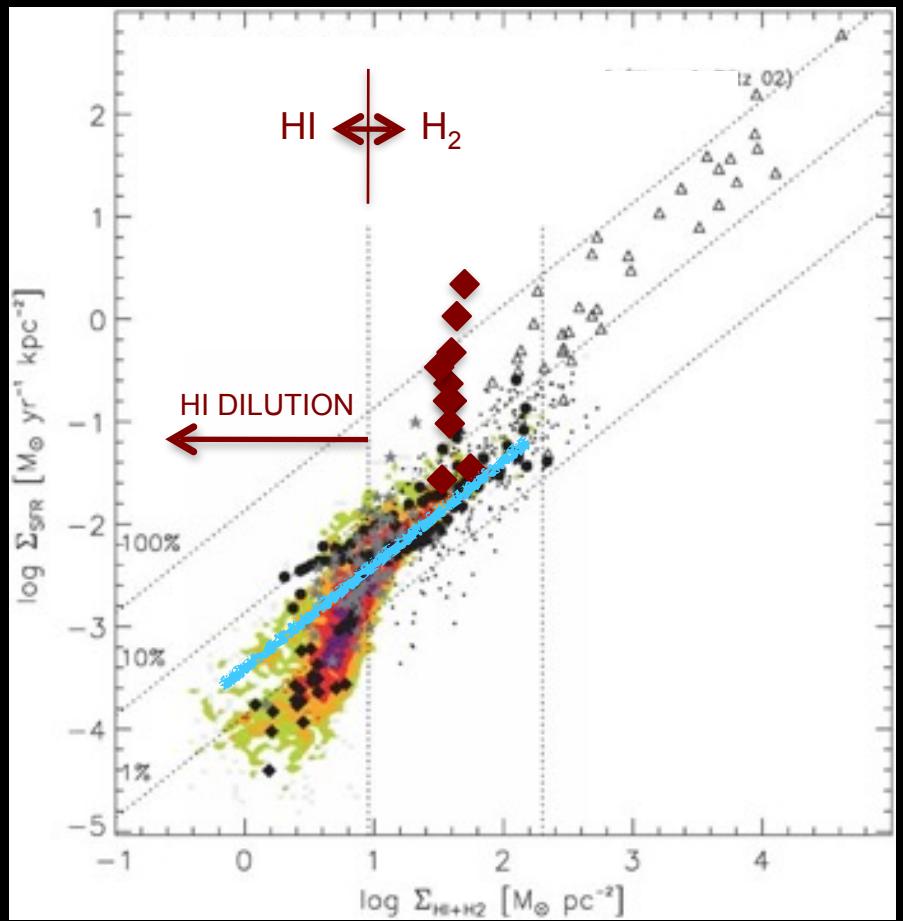
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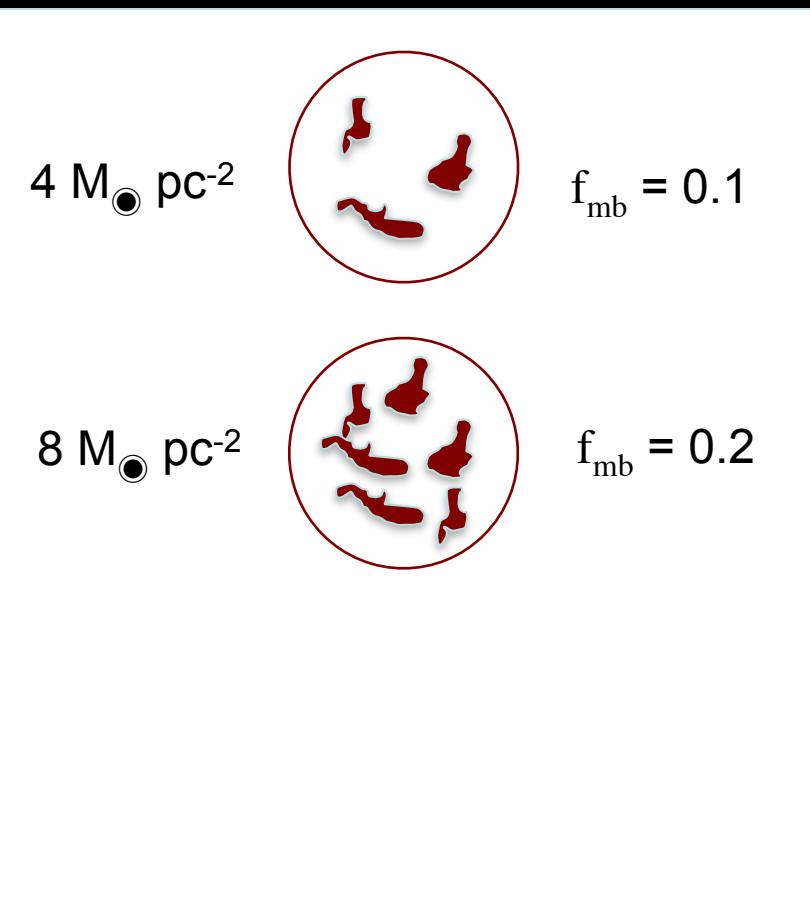
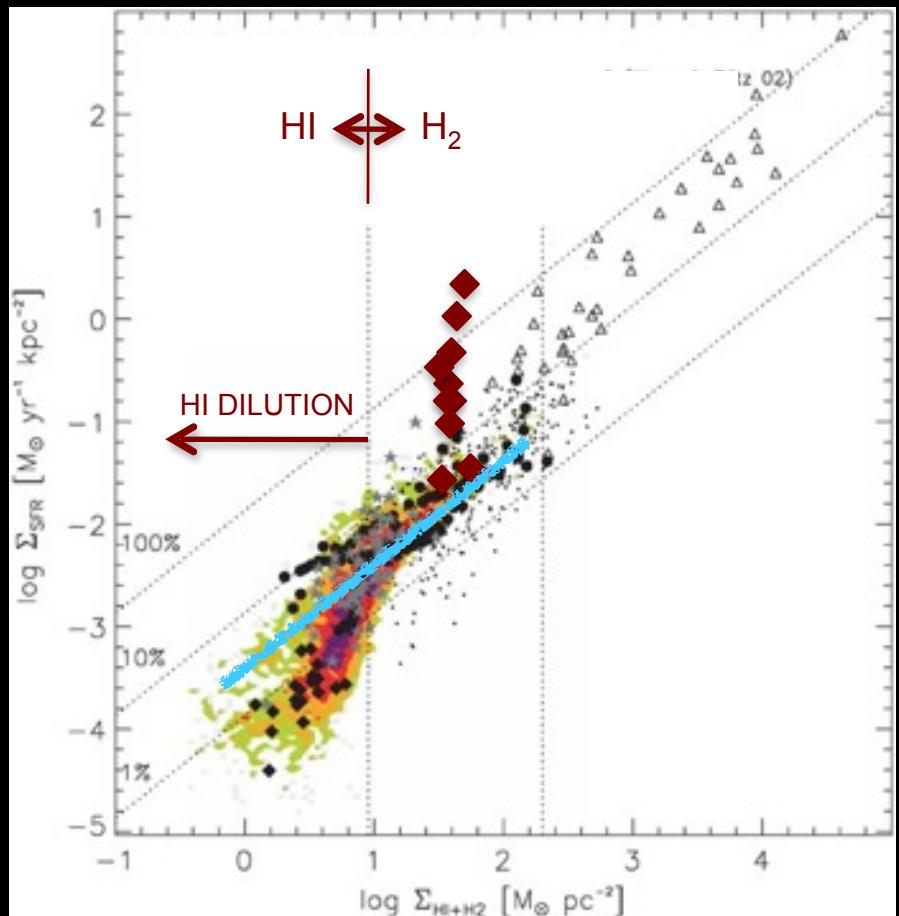
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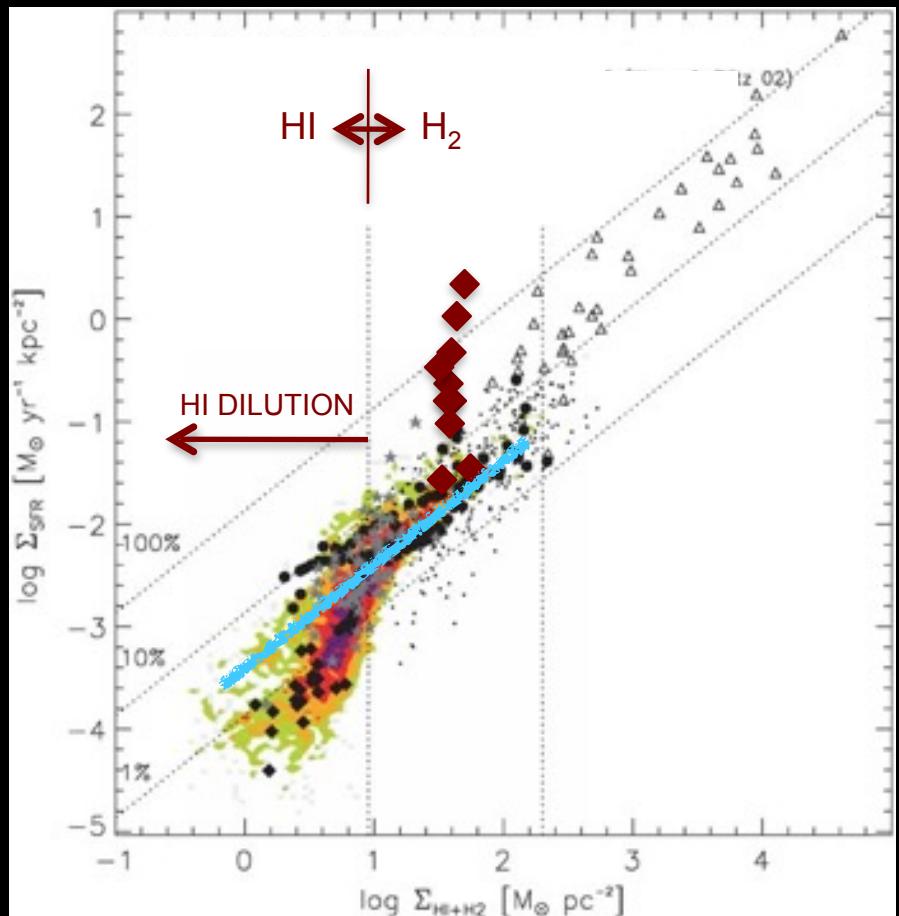
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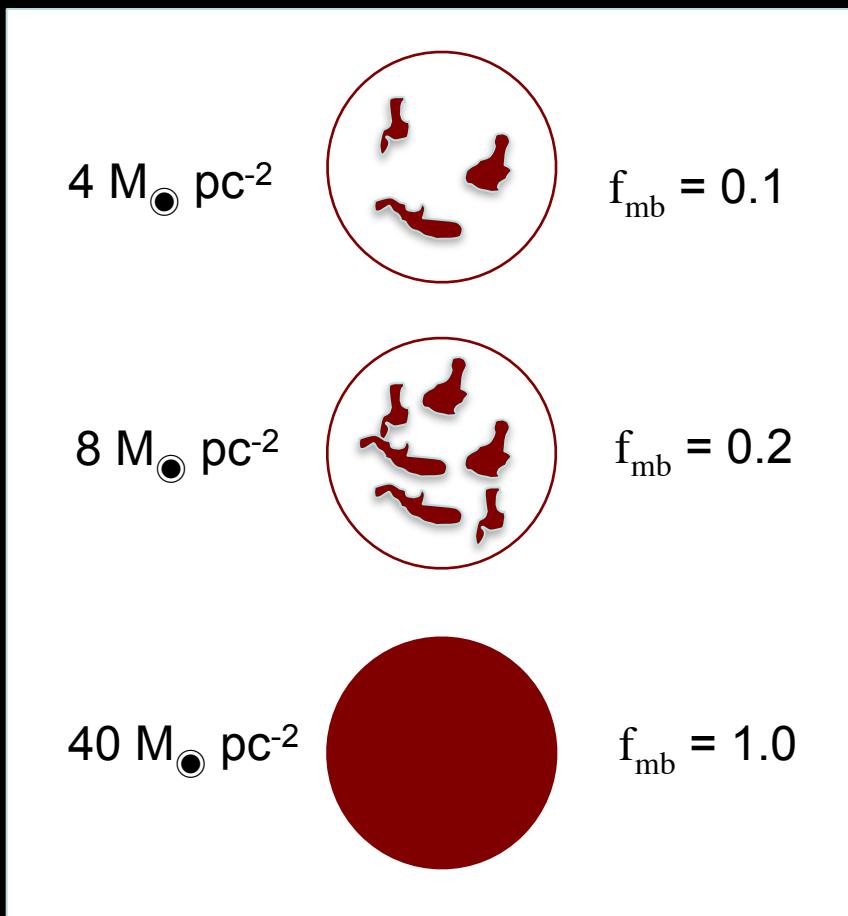
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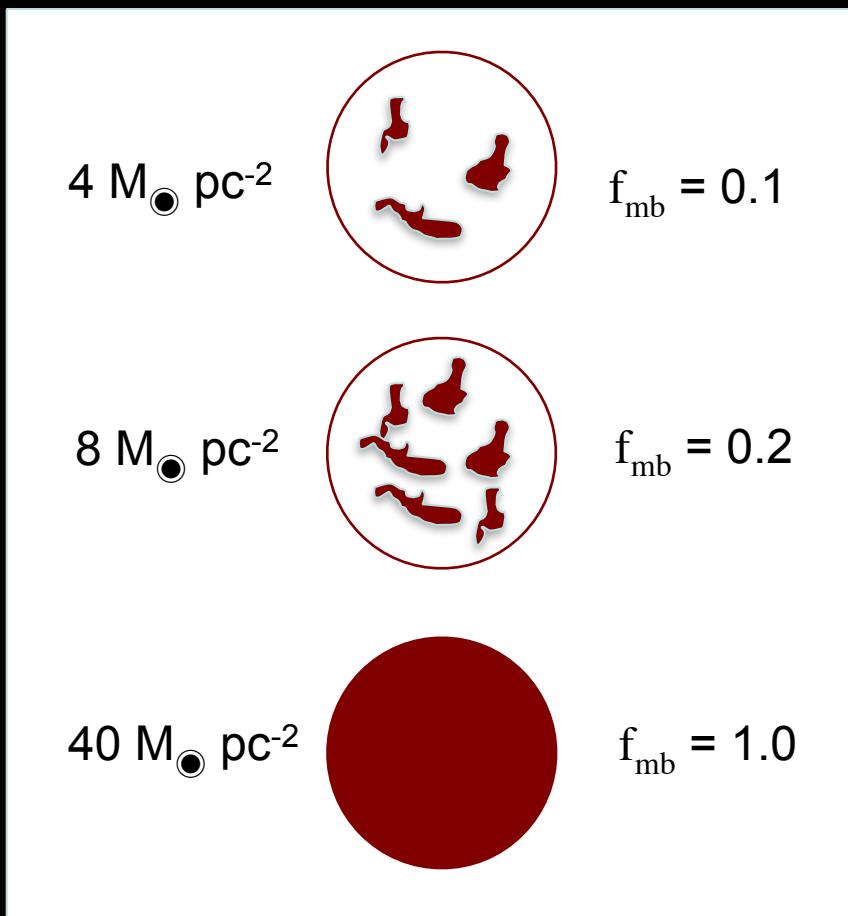
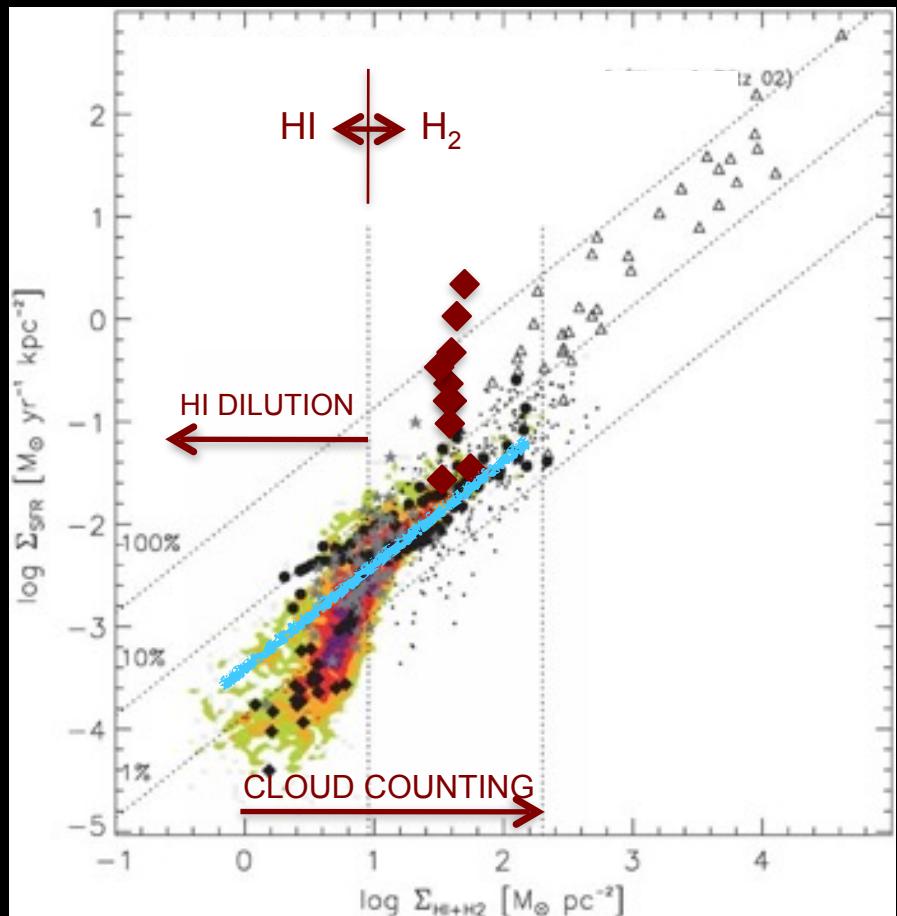


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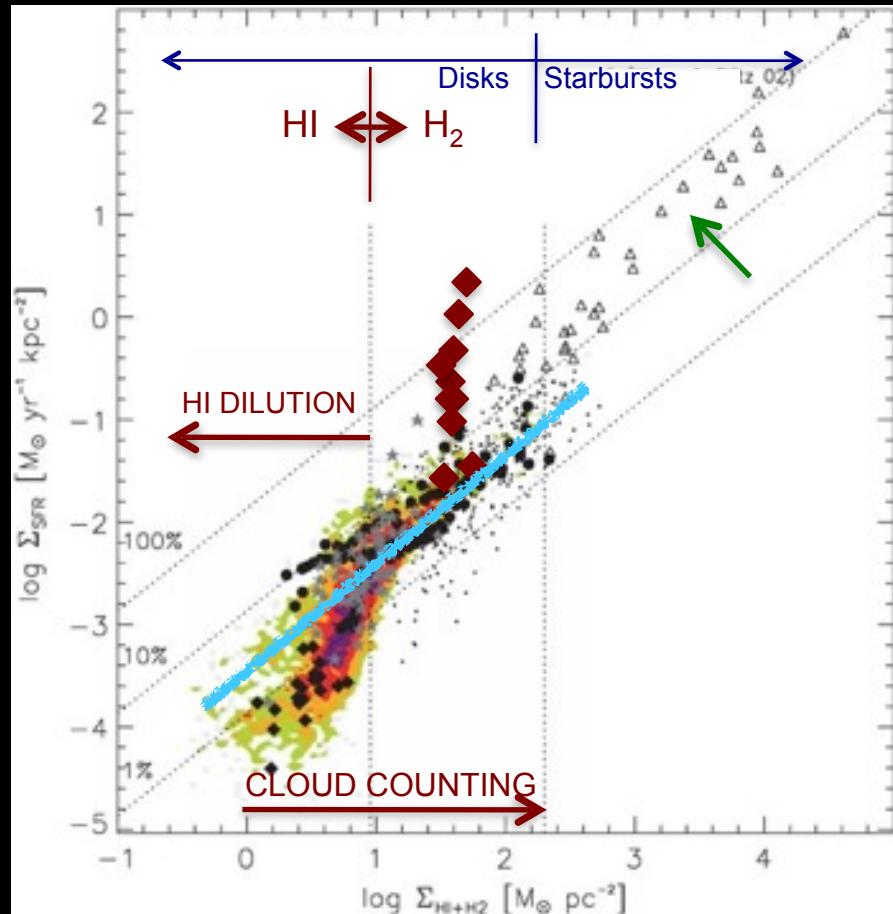
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Bigiel et al. 2008 AJ 136:2846

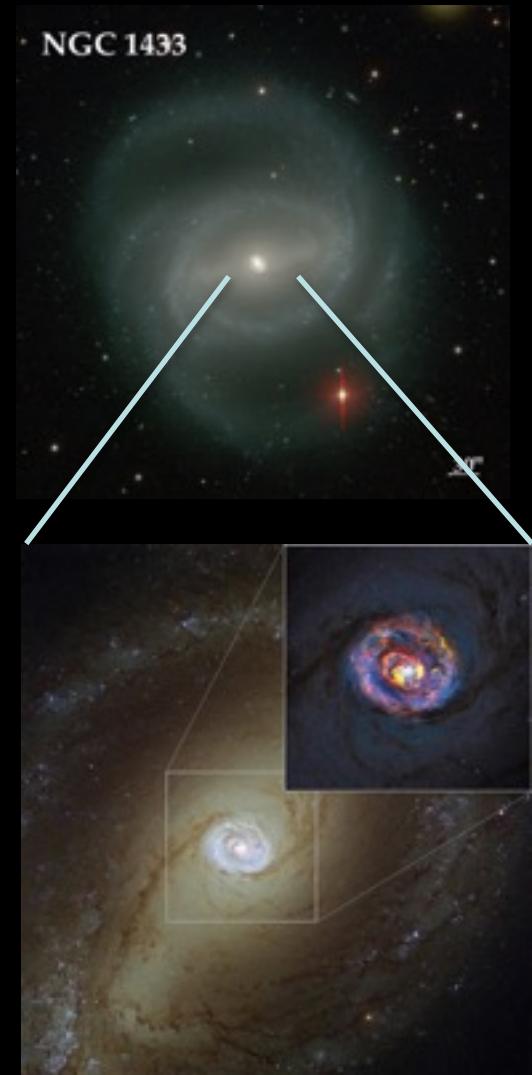
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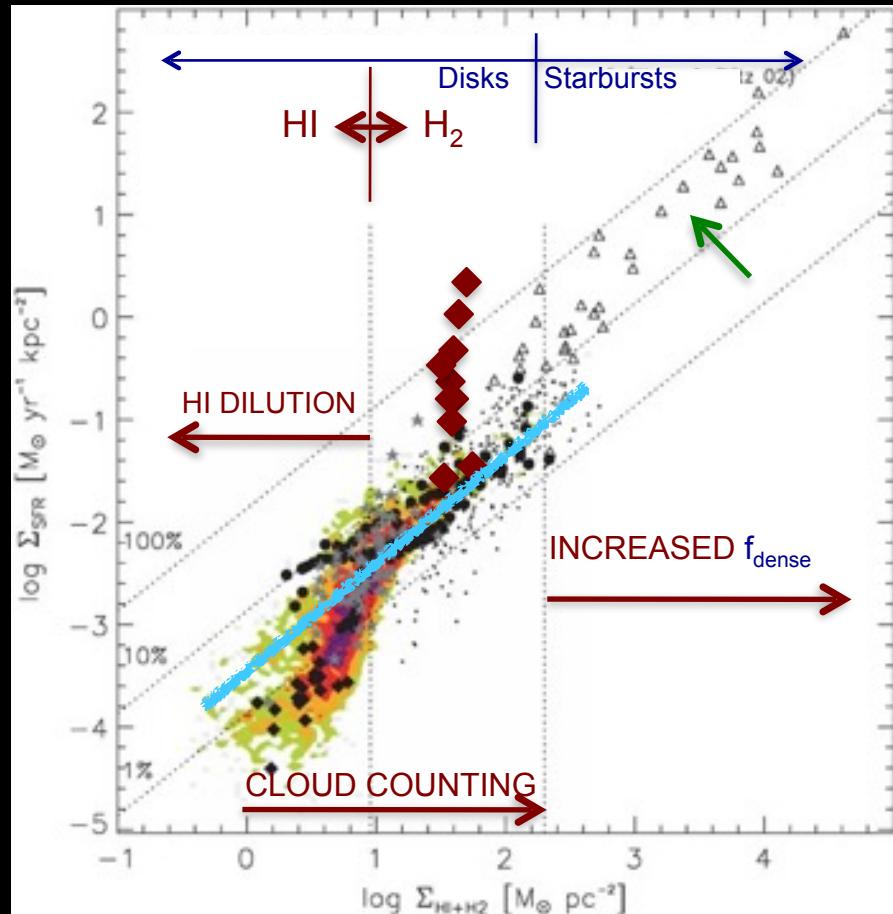
Bigiel et al. 2008

Starburst Galaxies:



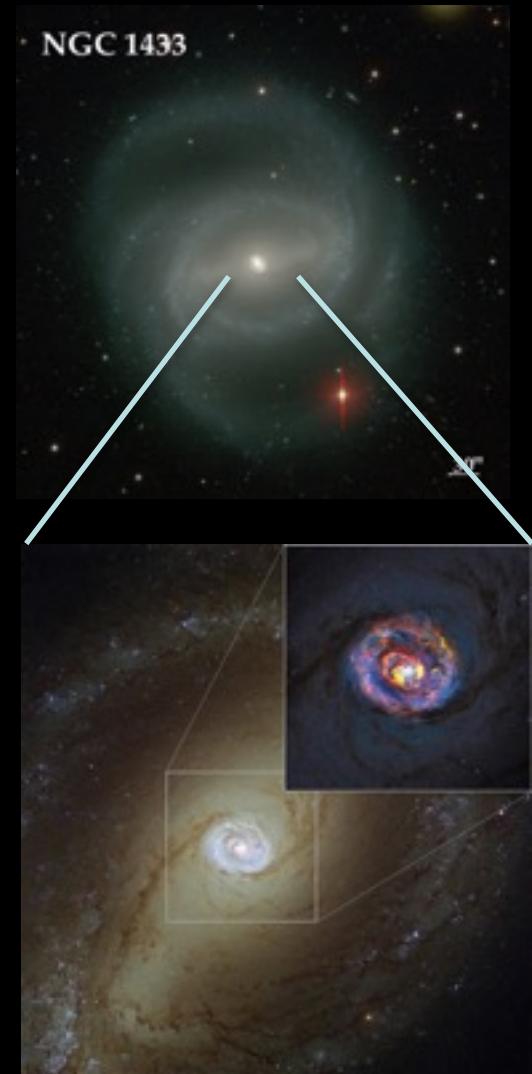
Deconstructing the Kennicutt-Schmidt Law:

Galaxies

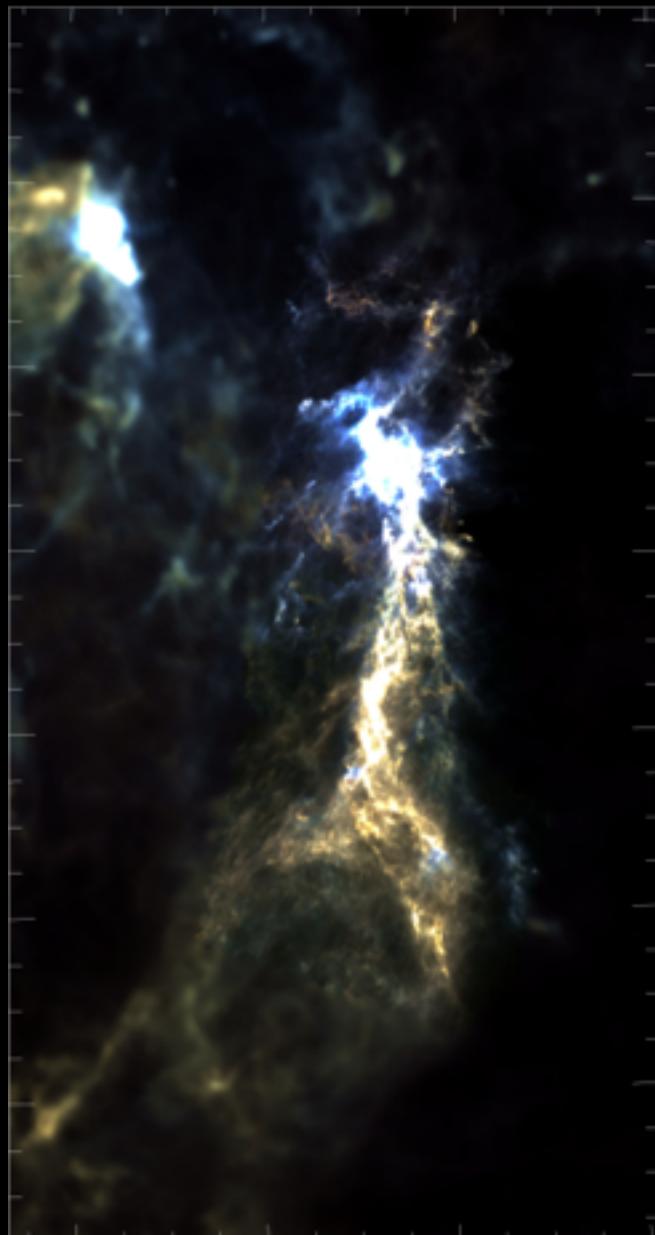


Bigiel et al. 2008

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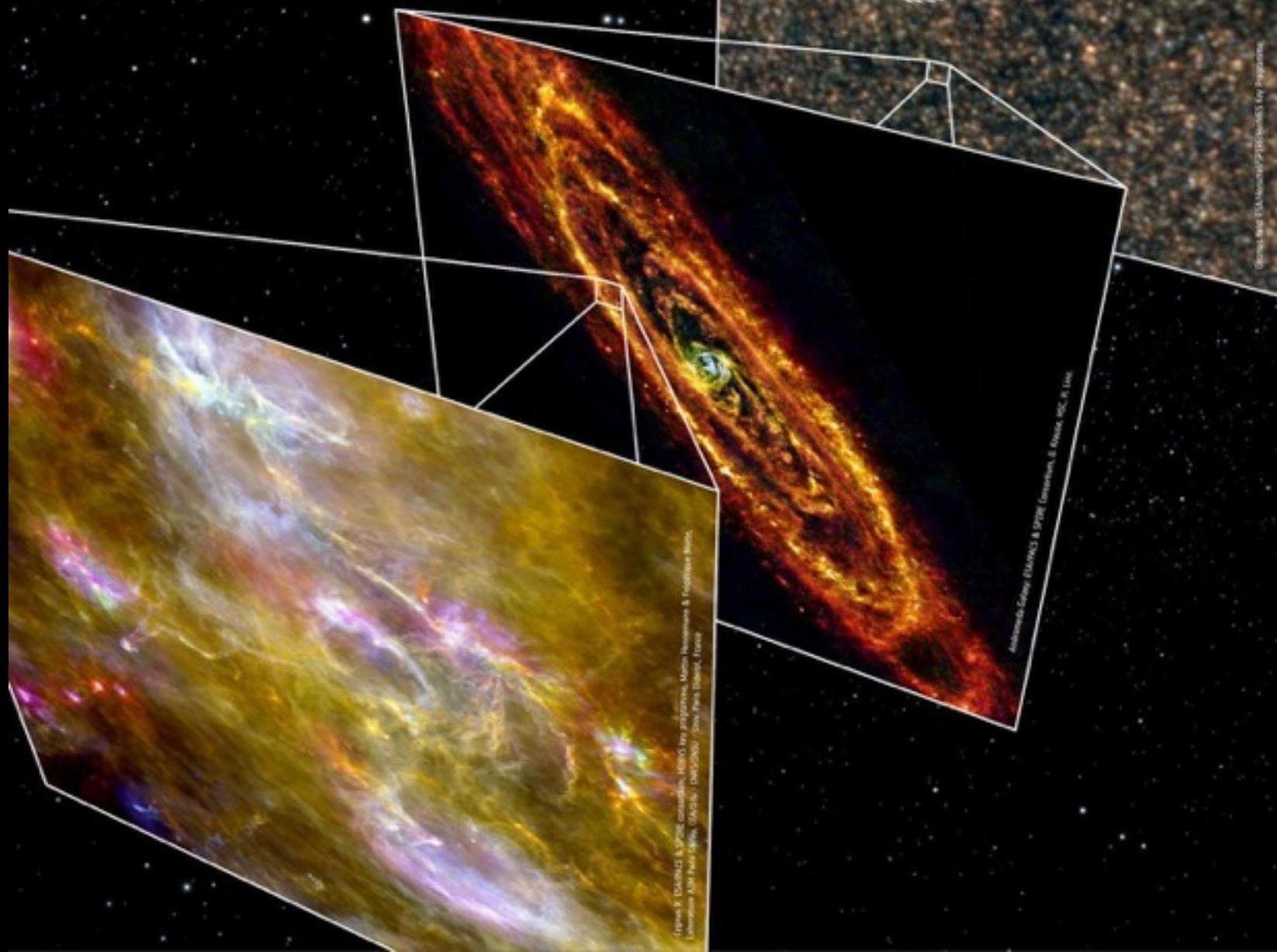


Summary



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 underlying physical law of star formation.

Conclusion



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.