Star Formation Rates in Molecular Gas and the Nature of the Extragalactic Scaling Relations

With:
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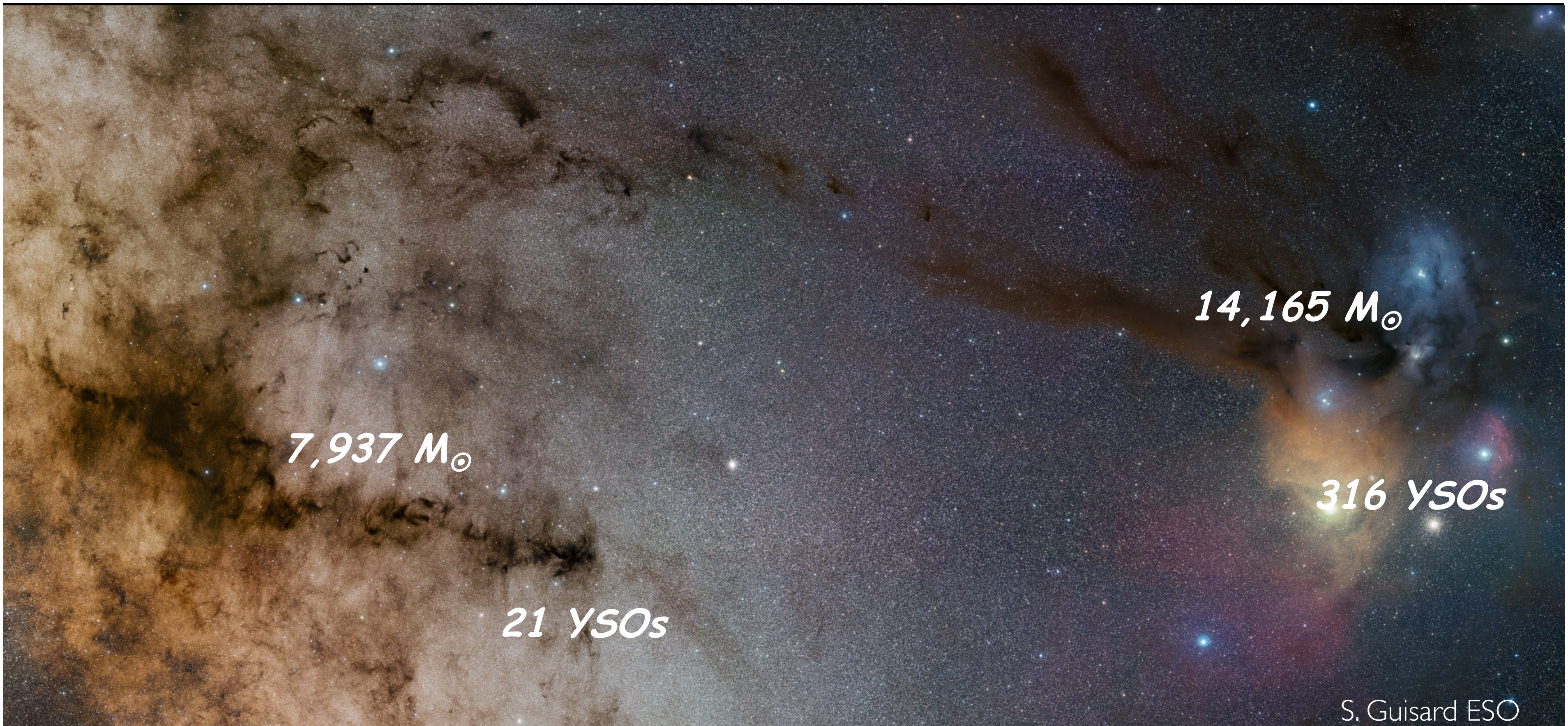


Pipe Nebula

Rho Ophiuchi Cloud

$$SFR_{Oph} = 15 \times SFR_{Pipe}$$

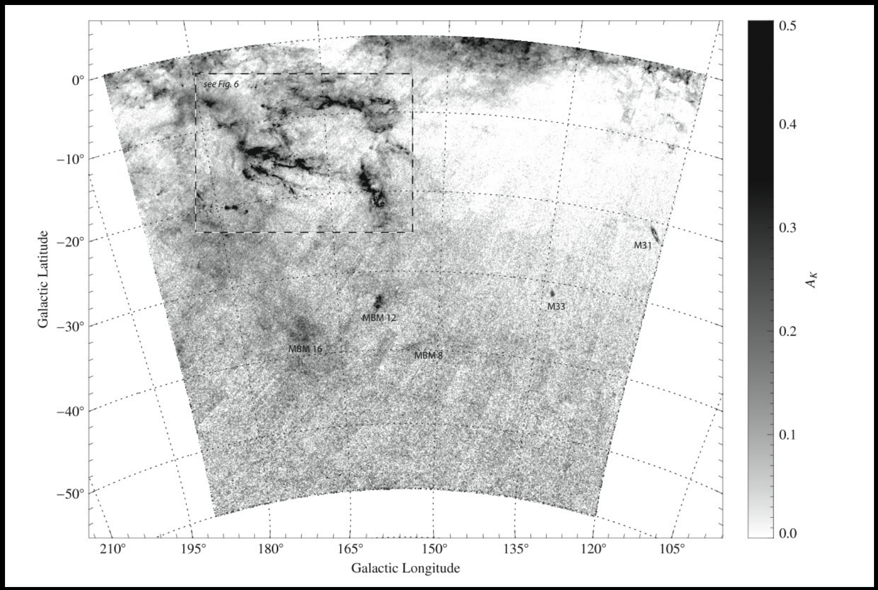
Inventory of Local Star Formation Activity

Infrared Extinction & Cloud Masses

Inventory of Local Star Formation Activity: Molecular Clouds

Cloud Sample:

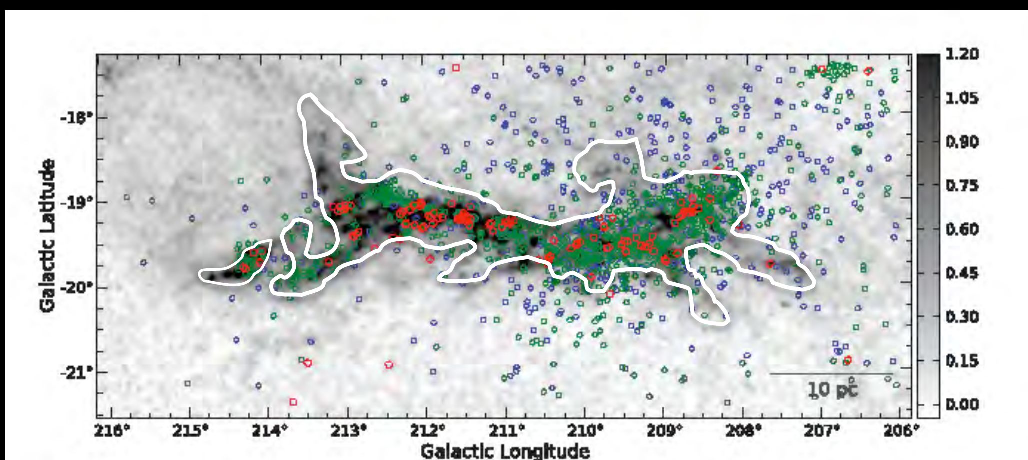
Wide-Field 2MASS Extinction Survey of 11 Local (<0.5 kpc) Clouds



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 Local Star Formation Activity: Young Stellar Objects

Mining the Literature; mostly IR (e.g., SPITZER)

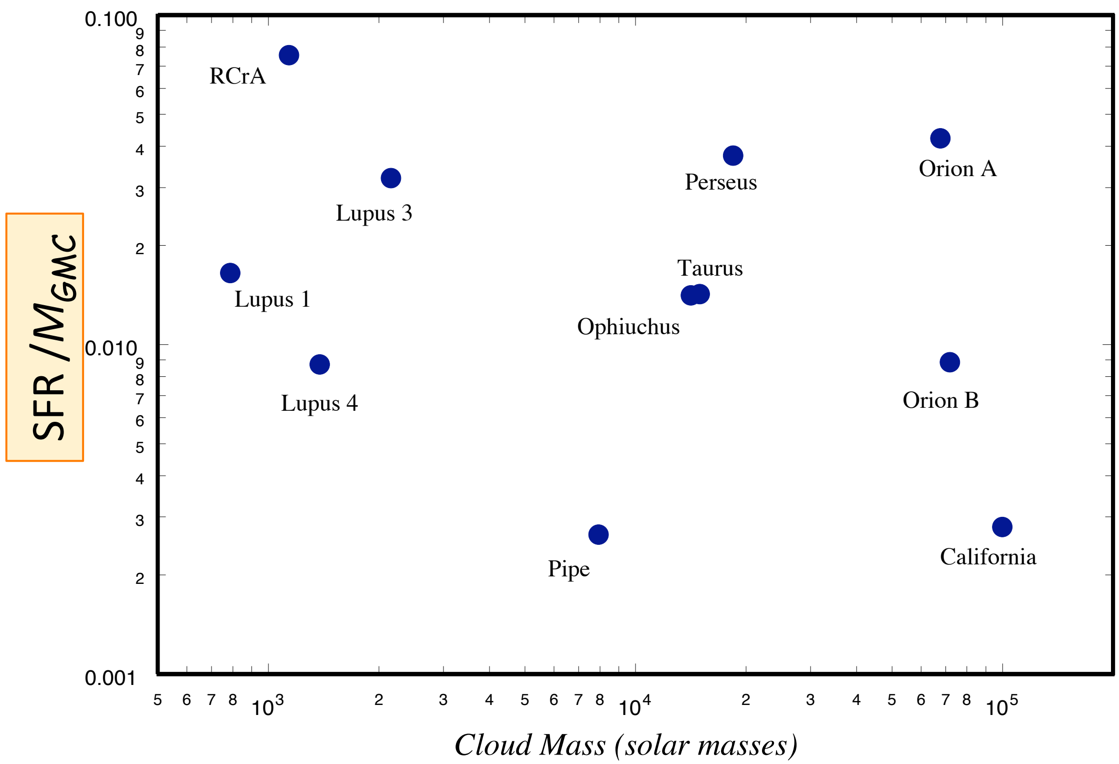


Cloud:	YSOs
Orion A	2862
Orion B	635
California	279
Perseus	598
Taurus	335
Ophiuchus	316
RCrA	100
Pipe	21
Lupus 1	13
Lupus 3	69
Lupus 4	12

Large Variation in Specific Star Formation Rate

Variations in the Efficiencies & Star Formation Rates of Local GMCs

$$SFR = (\langle m_* \rangle / t_{sf})\ x\ N(YSOs) = 0.25 \times 10^{-6}\ N(YSOs) \quad M_\odot/yr$$



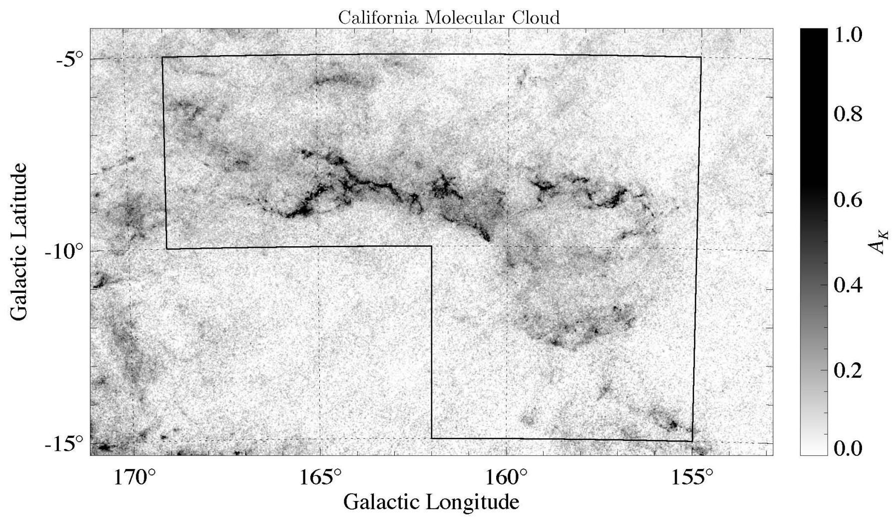
Greater than an order of magnitude variation, *independent* of cloud mass !

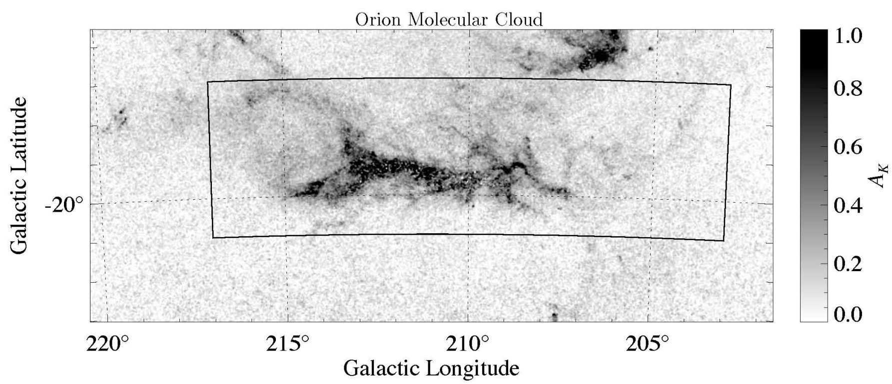
What Determines the Star Formation Rate?

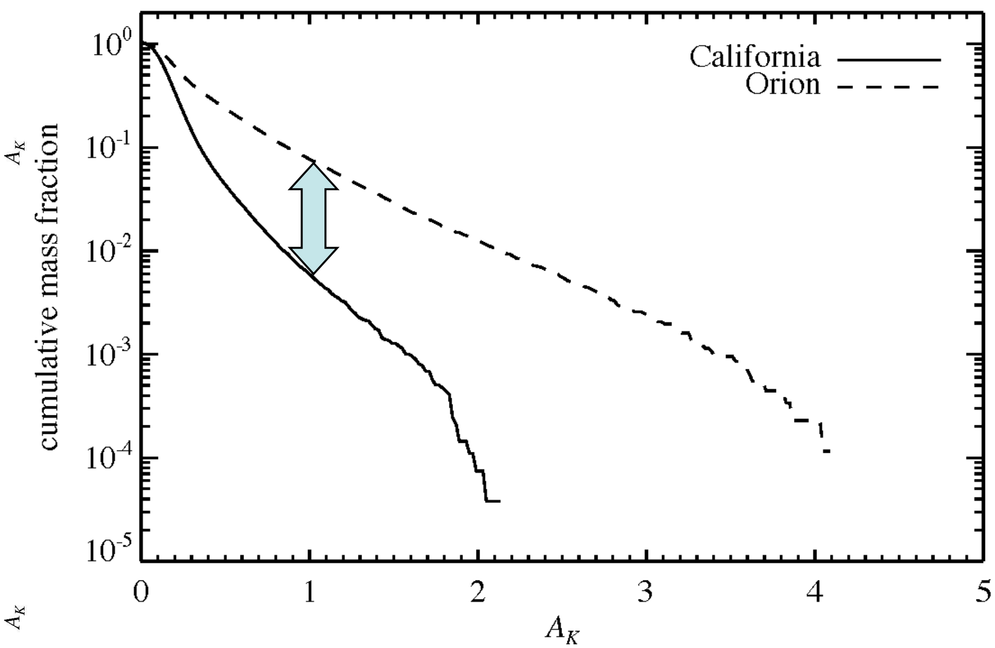
Comparing the California and Orion Molecular Clouds

The two clouds are nearly identical in mass & size

YSOs(Orion) > 10 x YSOs(Califoria)
SFR(Orion) > 10 x SFR(California)

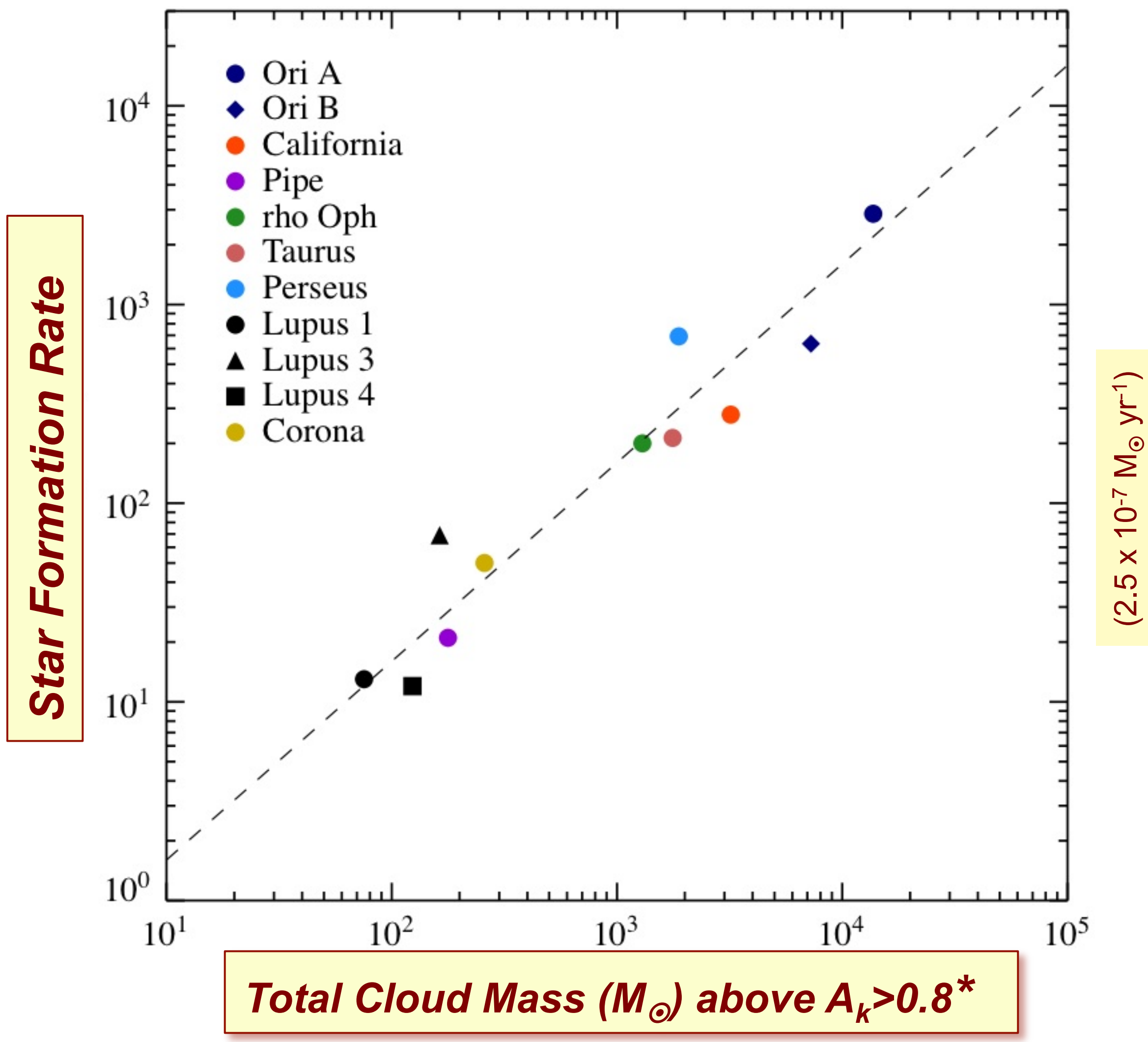






OMC has 10 x as much material at A_k >1 mag as the CMC

*SFR is directly proportional to total gas mass at A_k>0.8**



*A_k > 0.8 corresponds to Σ_{H2} > 116 $M_\odot$ pc^{-2} & Σ_{H2+He} > 158 $M_\odot$ pc^{-2}

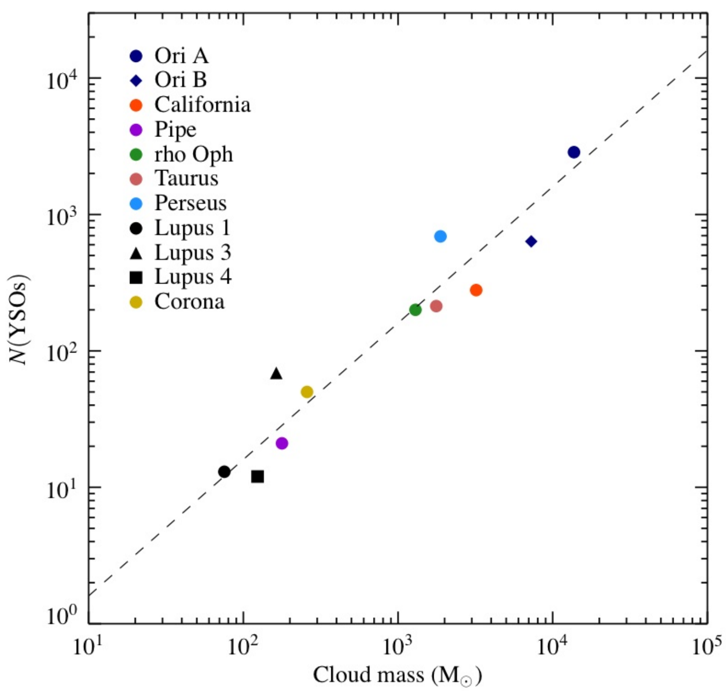
Star Formation Scaling Laws for Local Clouds

Star Formation Scaling Law for Local Clouds

$$SFR = 4.6 \times 10^{-8}\ \mathbf{M}_{0.8}\quad (M_o\ yr^{-1})$$

Where:

$$M_{0.8} = \int_{0.8}^{\infty} M(A_K)\,dA_K$$



$SFR = (t_{gc})^{-1} \mathbf{M}_{0.8}$

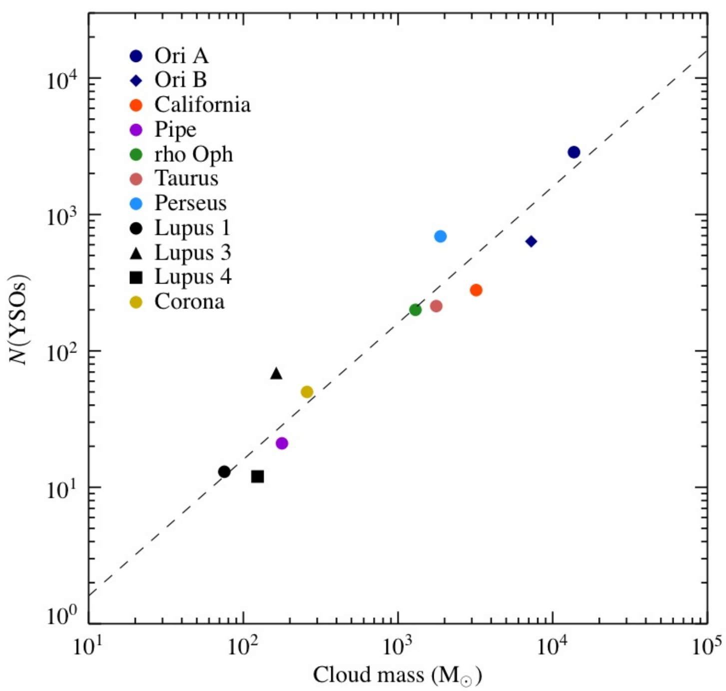
t_{gc} = gas consumption time

$= 2.2 \times 10^7$ yrs

Star Formation Scaling Law for Local Clouds

$$SFR = 4.6 \times 10^{-8}\ M_{0.8}\quad (M_o\ yr^{-1})$$

$$M_{0.8} = \int_{Volume} \rho_{0.8}(V)\,dV = <\rho_{0.8}> V_{0.8}$$



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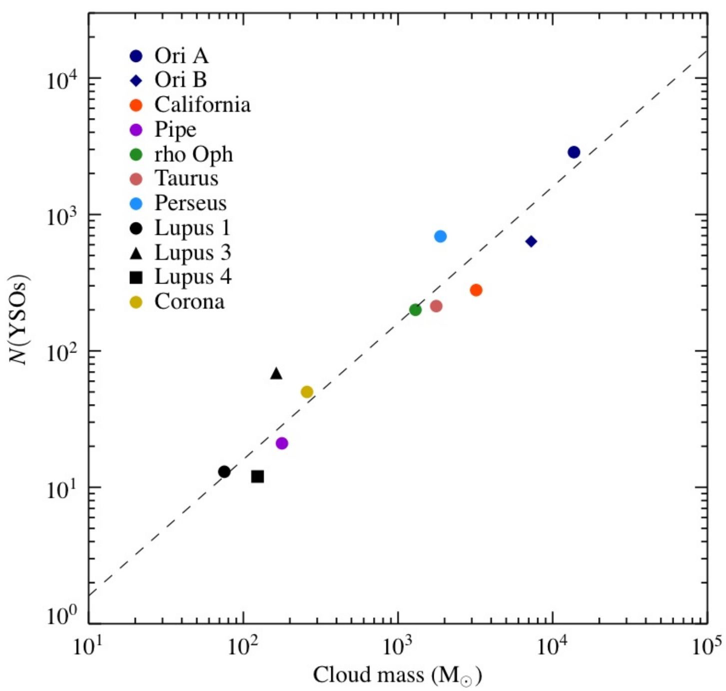
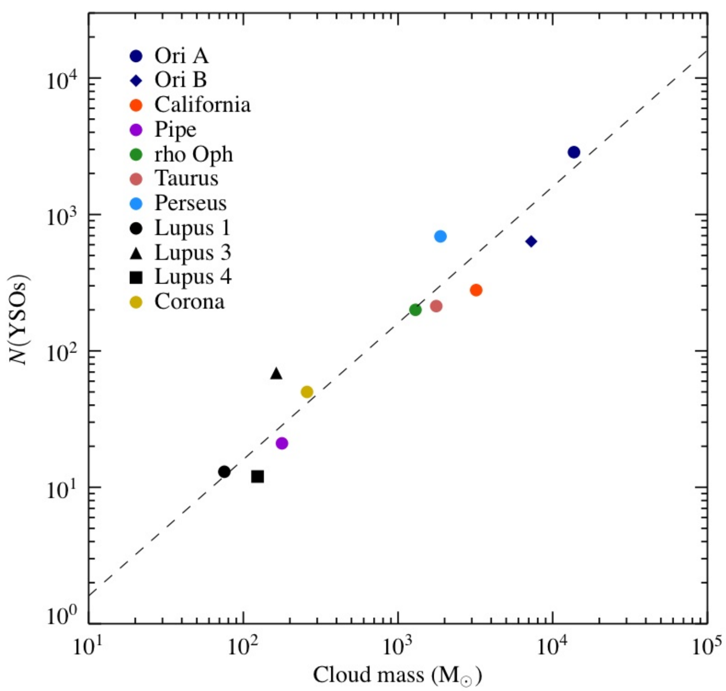
$$SFR = 4.6 \times 10^{-8}\ \langle \rho_{0.8} \rangle V_{0.8}$$



Star Formation Scaling Law for Local Clouds

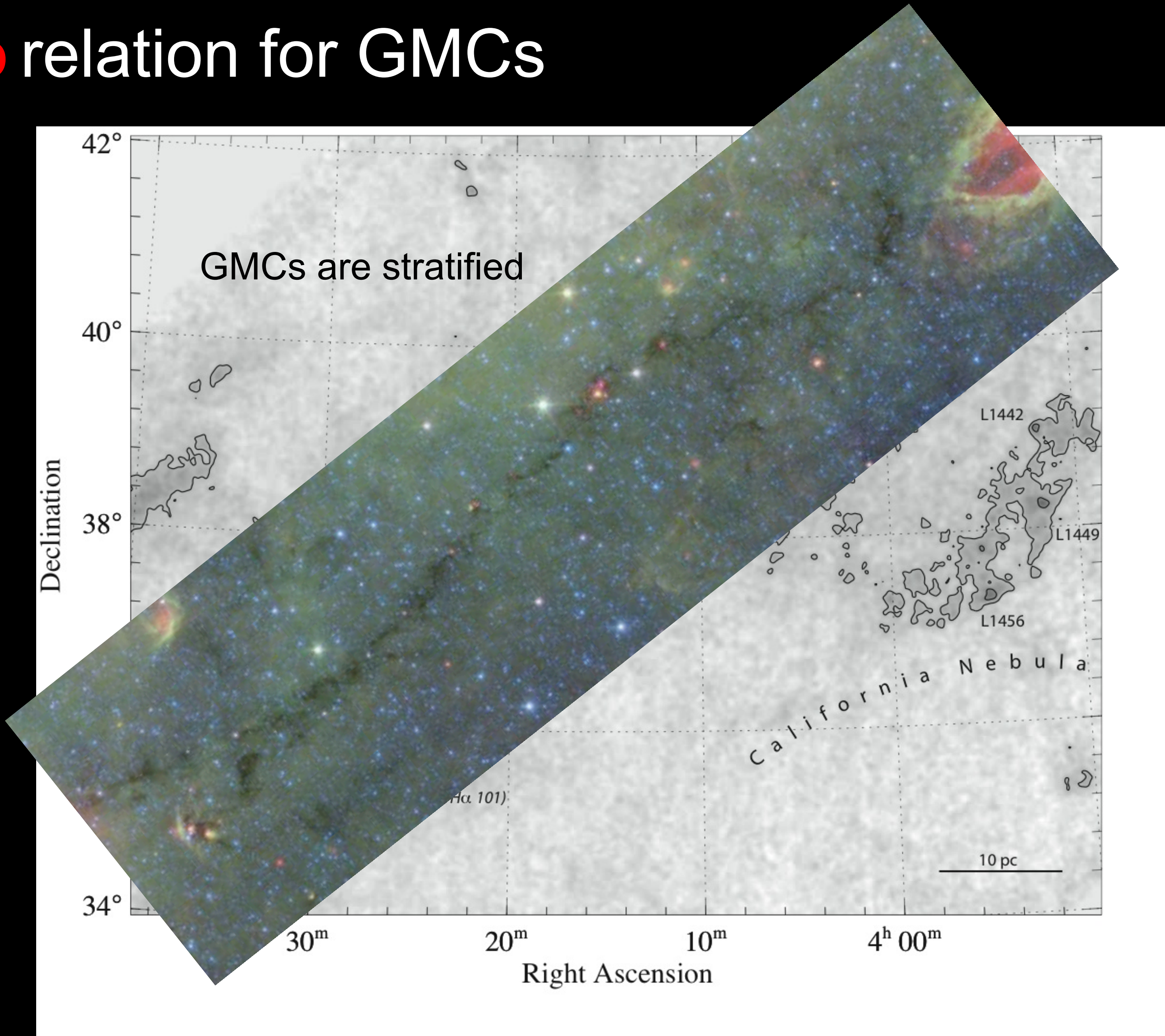
$$SFR = 4.6 \times 10^{-8}\ M_{0.8}\ \ (M_o\ yr^{-1})$$

A *Linear* Volumetric Scaling Law for Star Formation

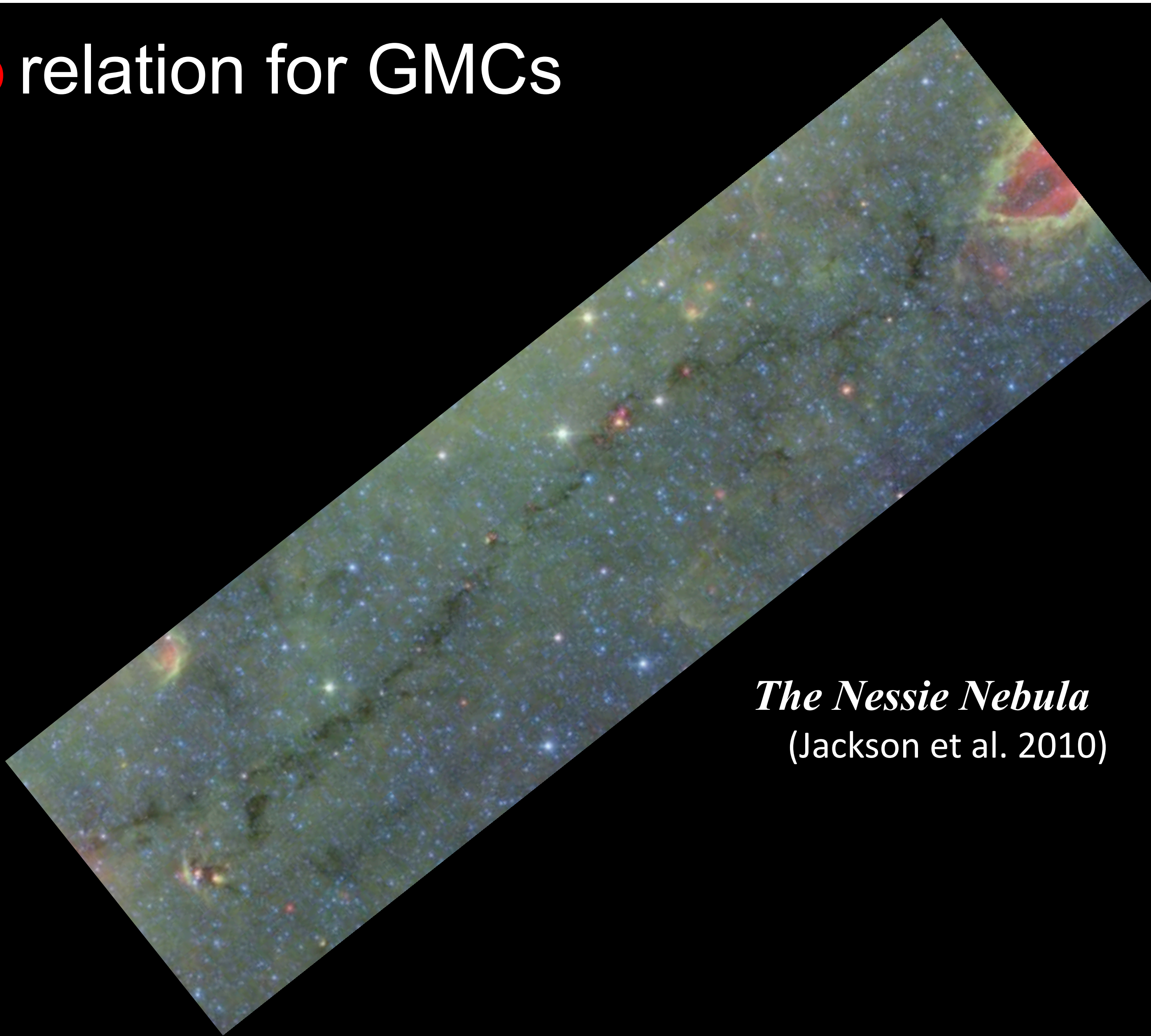


$$\rho_{SFR} = 4.6 \times 10^{-8} \langle \rho_{0.8} \rangle$$

A Σ-ρ relation for GMCs



A Σ-ρ relation for GMCs



The Nessie Nebula
(Jackson et al. 2010)

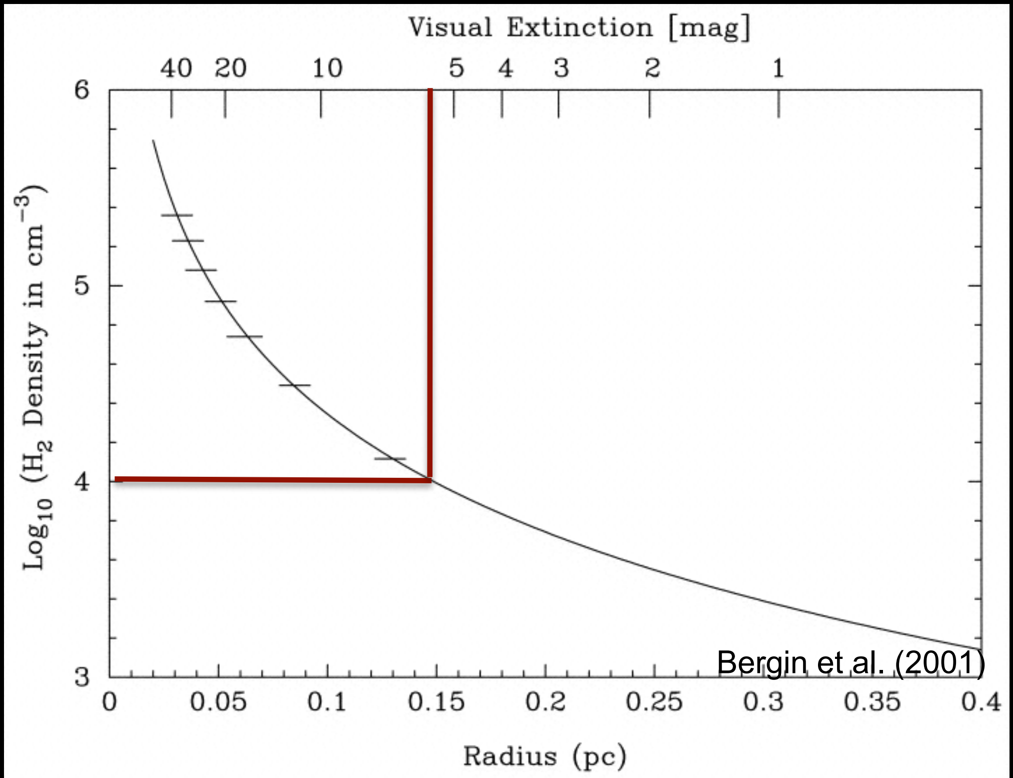
Infrared Dark Clouds

A Σ-ρ relation for GMCs

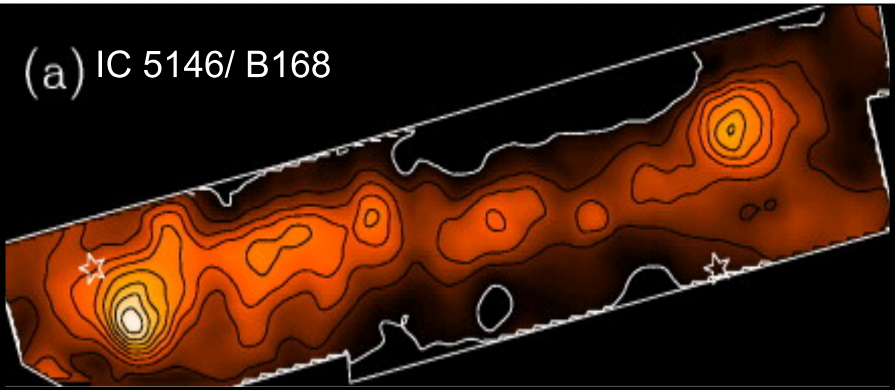
Assume: $M_{0.8} = M(\rho > \rho_t)$

$n_t \approx 10^4\ cm^{-3}$

$\rho_t = 400\ M_\odot/pc^3$



Bergin et al. (2001)



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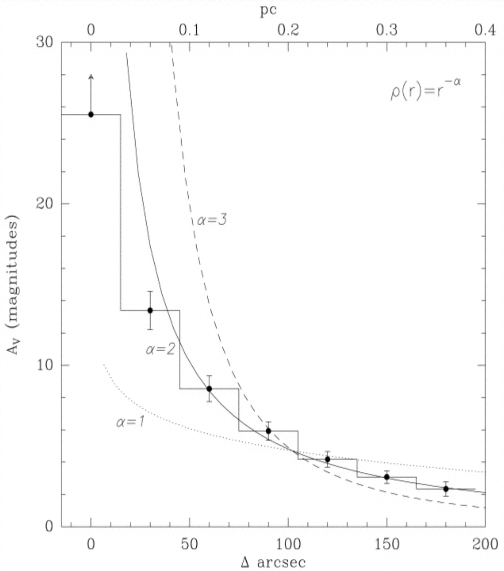


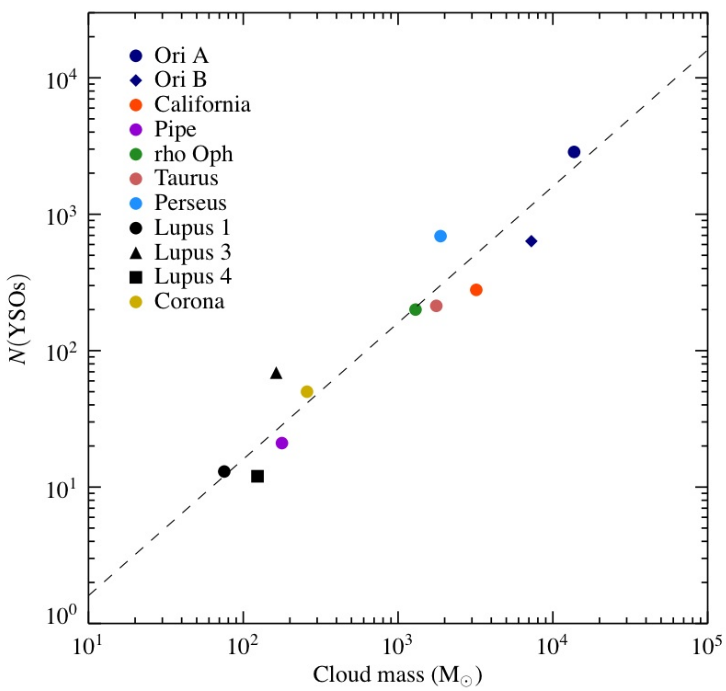
Lada, Alves, Lada (1999)

Star Formation Scaling Law for Local Clouds

$$SFR = 4.6 \times 10^{-8}\, \mathbf{M}(\rho > \rho_t) \qquad \text{for } \rho \geq \rho_t$$

Where:

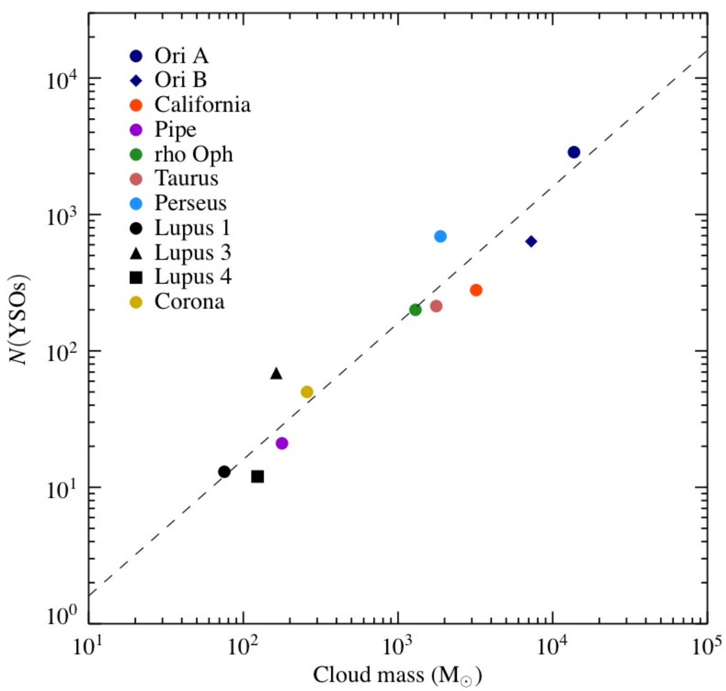
$$M(\rho > \rho_t) = \int_{\rho_t}^{\infty} M(\rho)\, d\rho$$



$$\rho_{SFR} = 4.6 \times 10^{-8}\ \langle \rho_{0.8} \rangle$$

Star Formation Scaling Law for Local Clouds

$$SFR = 4.6 \times 10^{-8}\, M(\rho > \rho_t) \quad \text{for } \rho \geq \rho_t$$

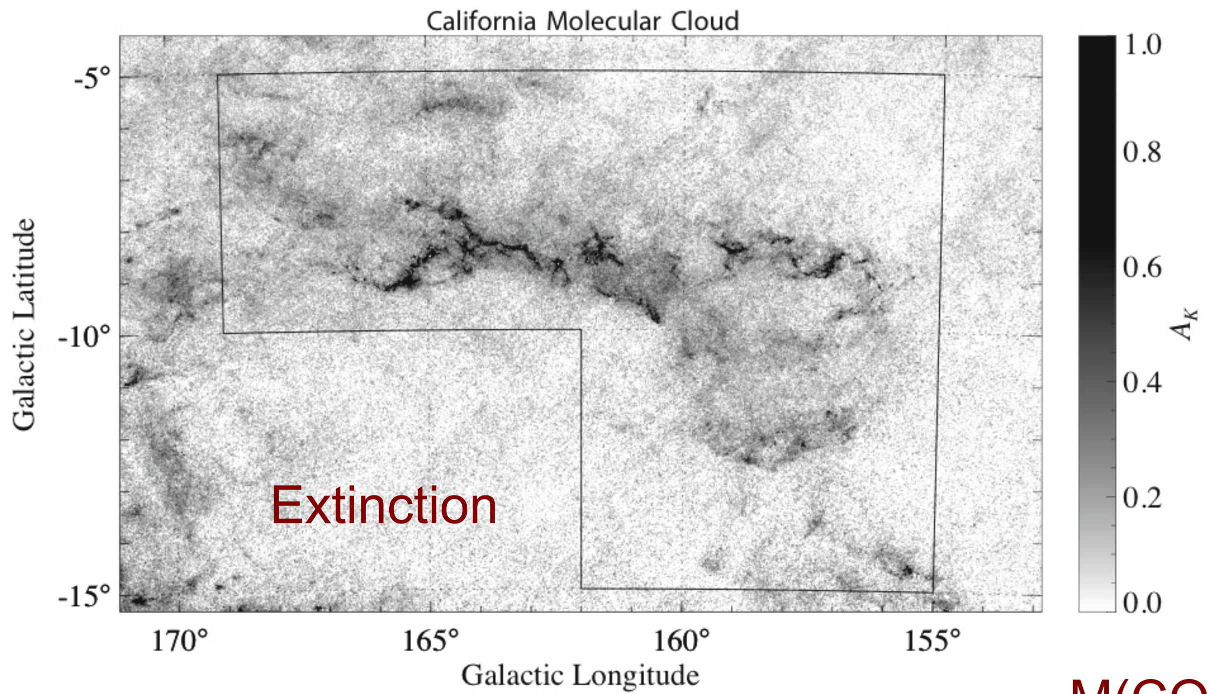


$$\rho_{SFR} = 4.6 \times 10^{-8} \langle \rho_{0.8} \rangle$$

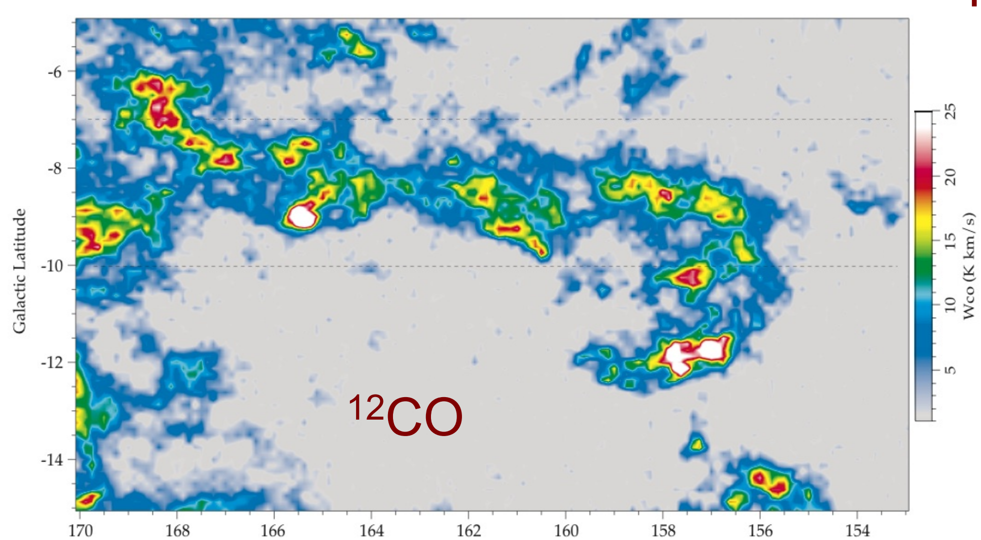
$$\langle \rho_{0.8} \rangle = \langle \rho \rangle \quad \text{for } \rho > \rho_t$$

$$n_t \approx 10^4\ \text{cm}^{-3}$$

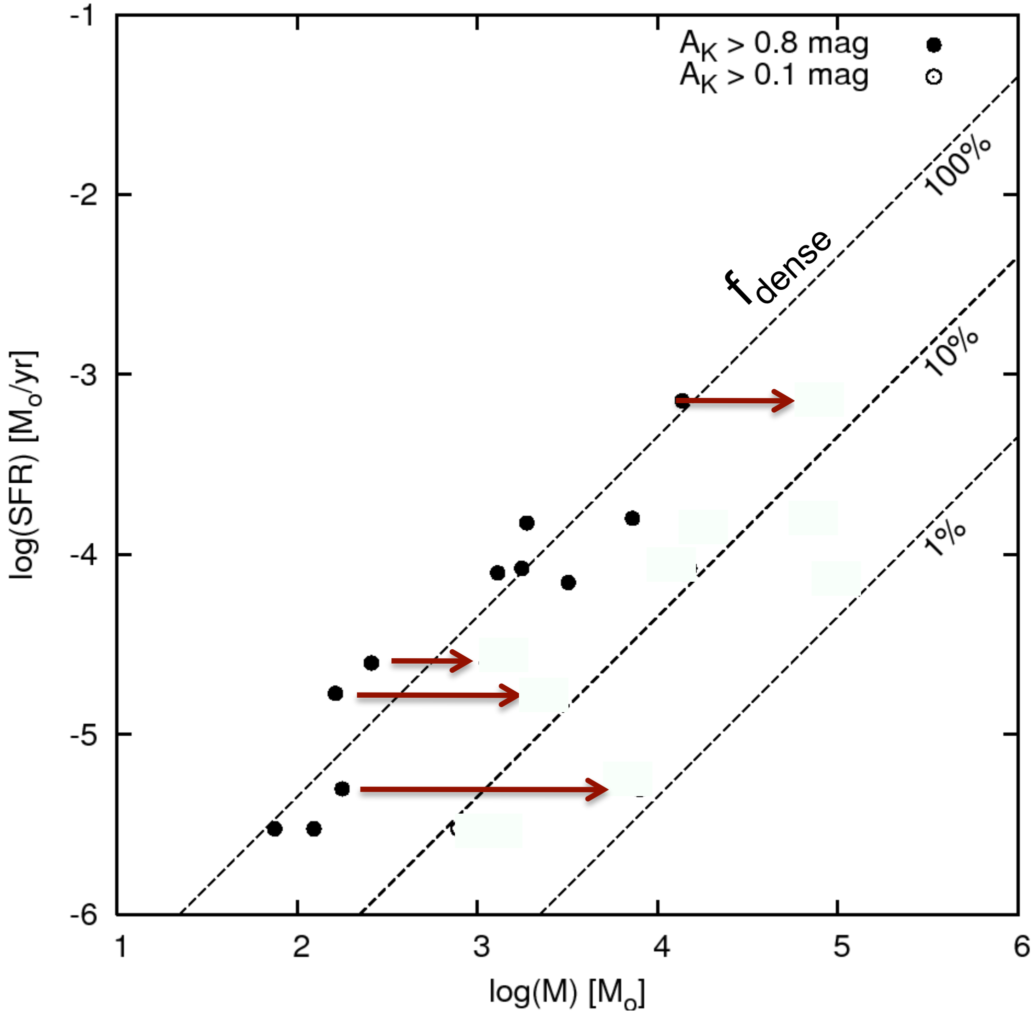
SF Scaling Law for Low Density Gas



$M(CO) \approx M(A_K > 0.1)$



Star Formation Scaling Laws for Local Molecular Clouds



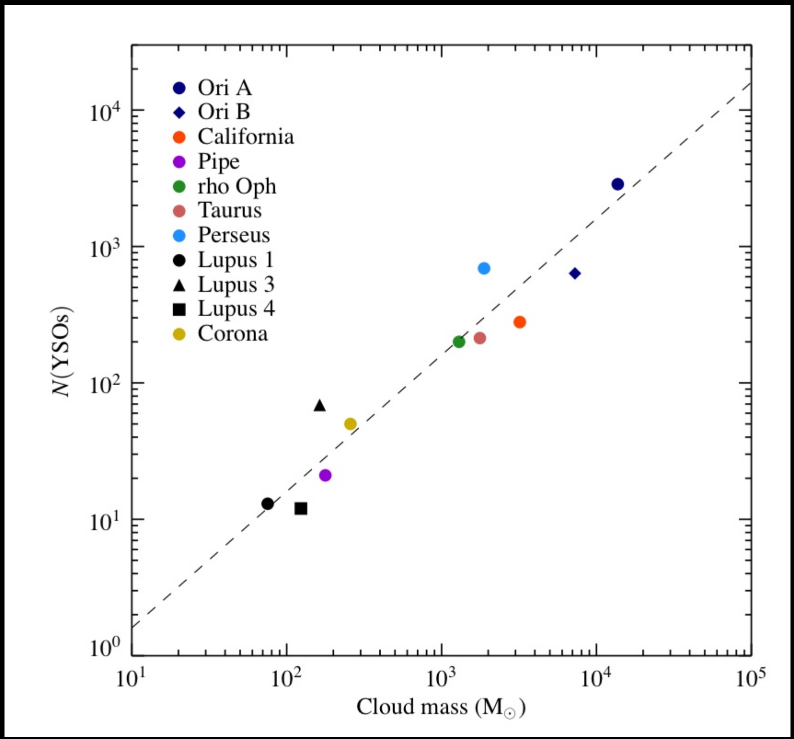
$$SFR = 4.6 \times 10^{-8}\, M_{dense} \;=\; 4.6 \times 10^{-8}\; f_{dense} M_{gas}$$

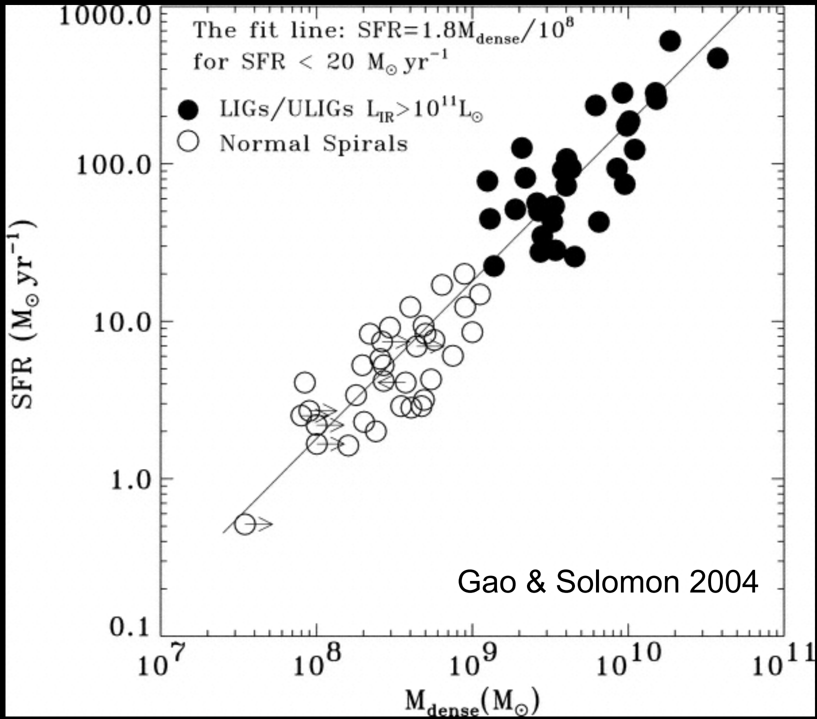
From Clouds to Galaxies

SF Scaling Laws for Dense Gas

Local GMC SF Scaling Law: $SFR_{gmc} = 4.6 \times 10^{-8}\ M_{0.8}\quad (M_\odot\ yr^{-1})$

Extragalactic SF Scaling Law: $SFR_{xgal} = 1.8 \times 10^{-8}\ M_{HCN}\quad (M_\odot\ yr^{-1})$





HCN: critical density ~ 2-3 x 10^4 cm^{-3}

SF Scaling Laws for Dense Gas

Local GMC SF Scaling Law: $SFR_{gmc} = 4.6 \times 10^{-8}\ M_{0.8}\ (M_\odot\ yr^{-1})$

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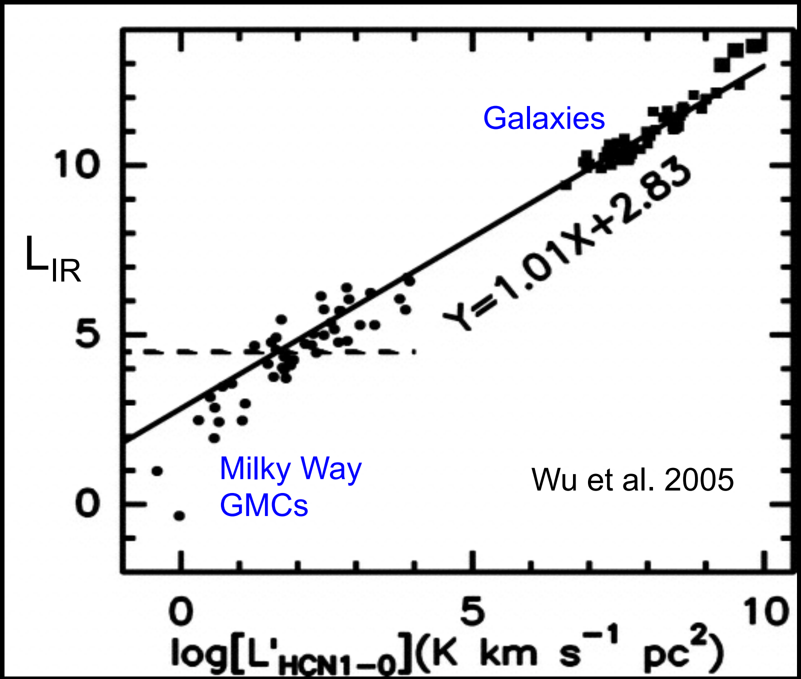
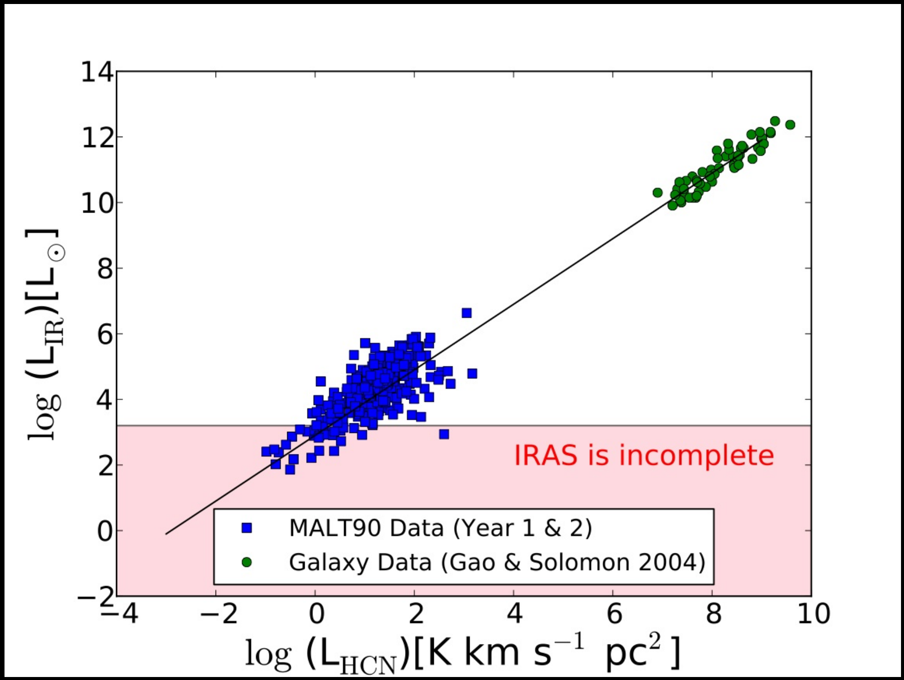
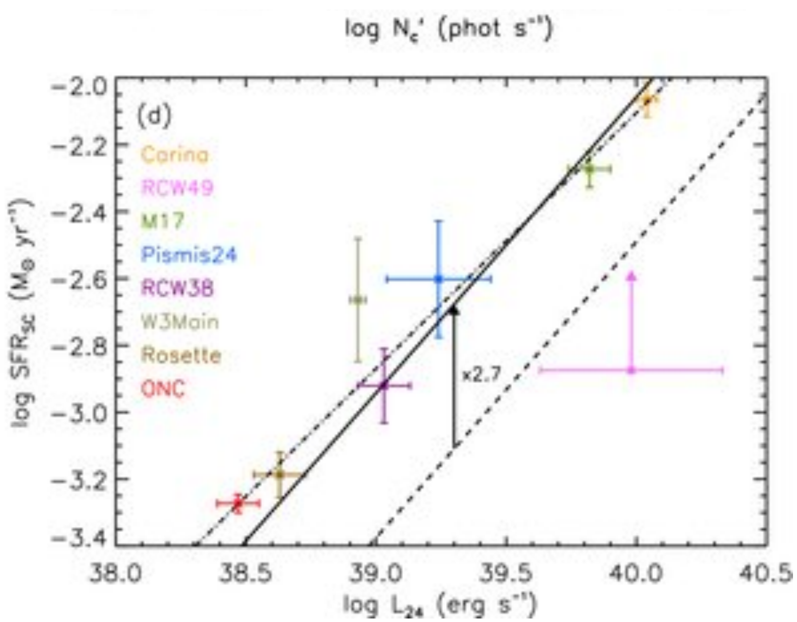




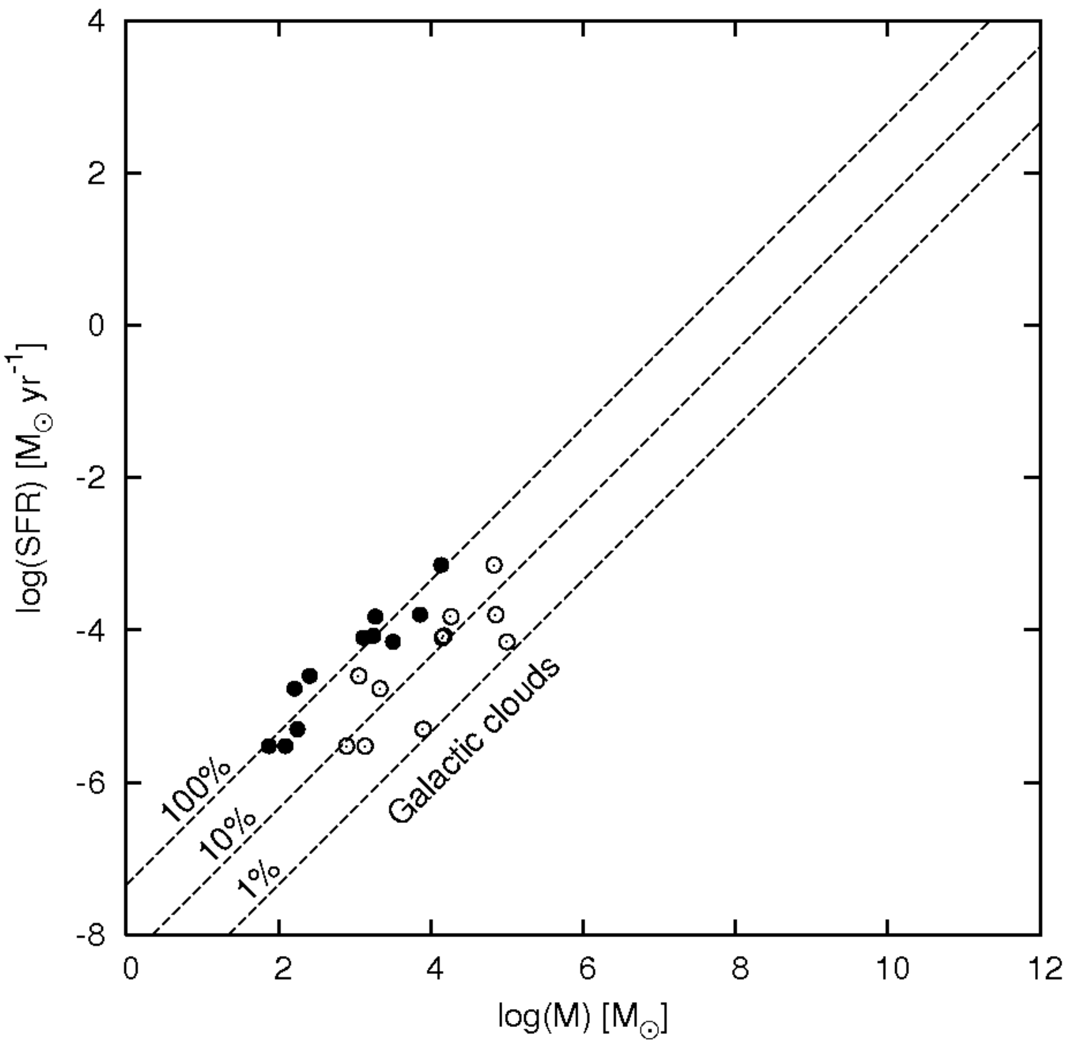
Comparison of SFRs for Galactic clouds



Chomiuk & Povich 2011 AJ, 142, 197

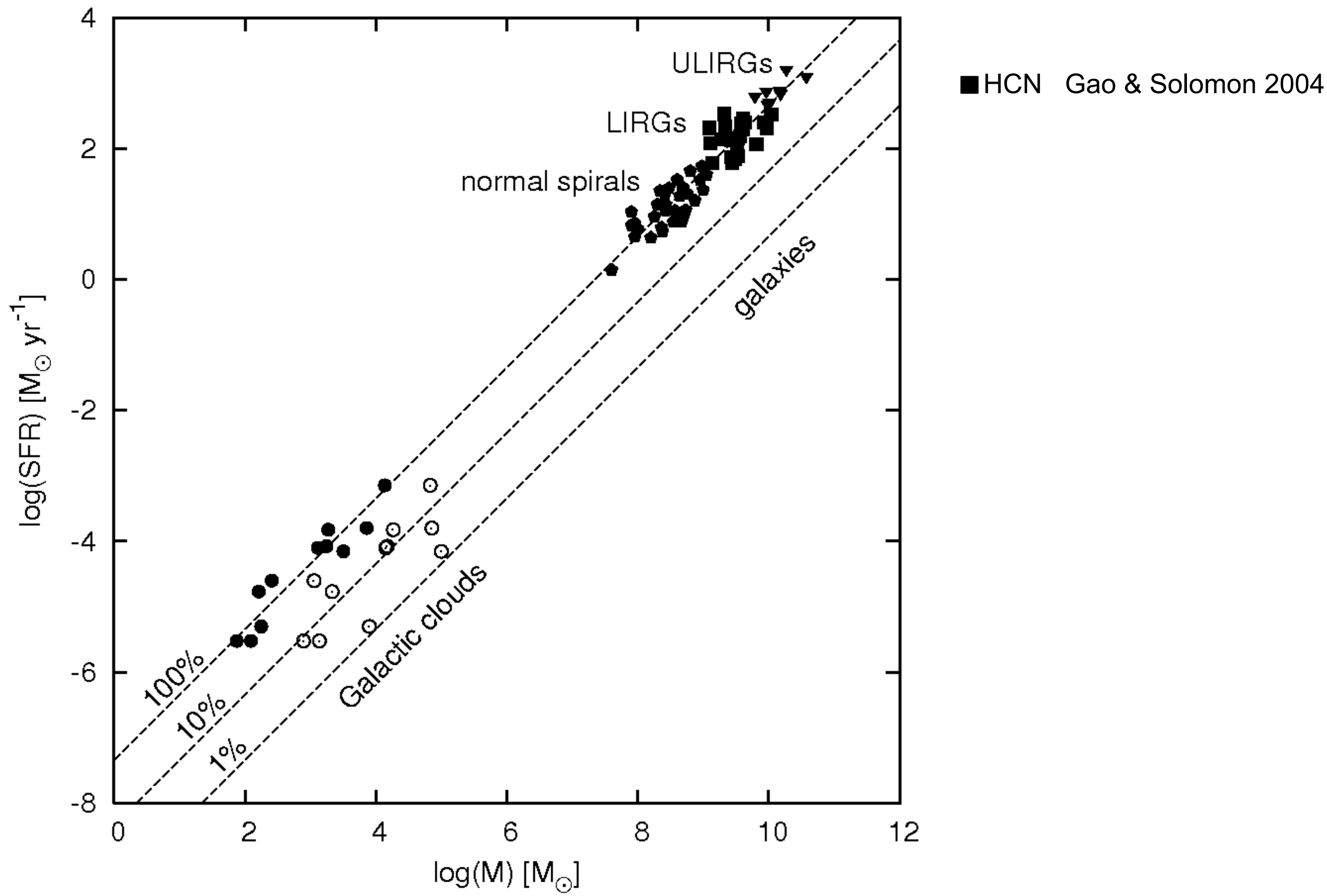
$$SFR_{GMC} = \quad 2.7\ x\ SFR_{SB99}$$

Star Formation Scaling Laws from Local Clouds to Galaxies

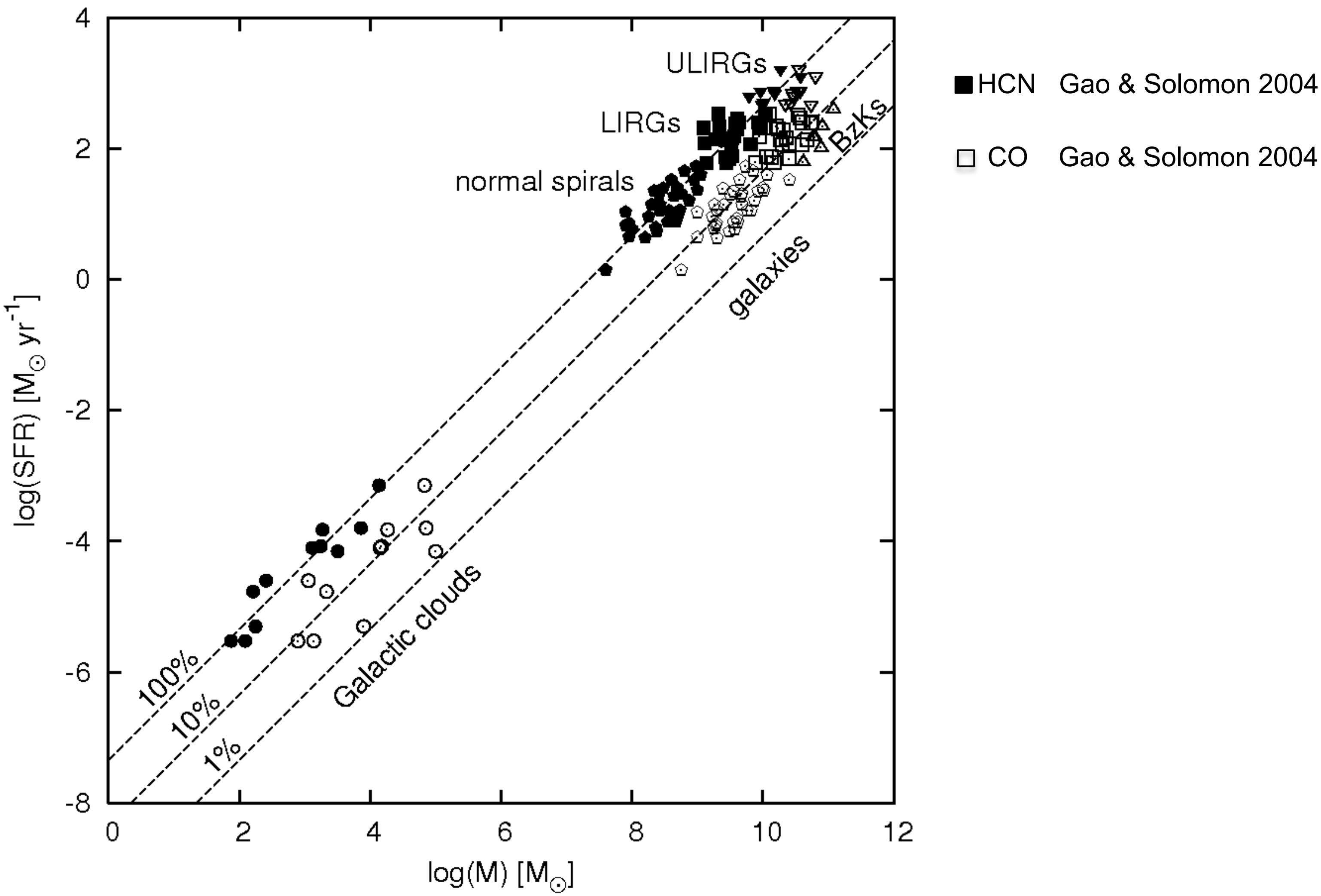


$$SFR = 4.6 \times 10^{-8} M_{dense}$$

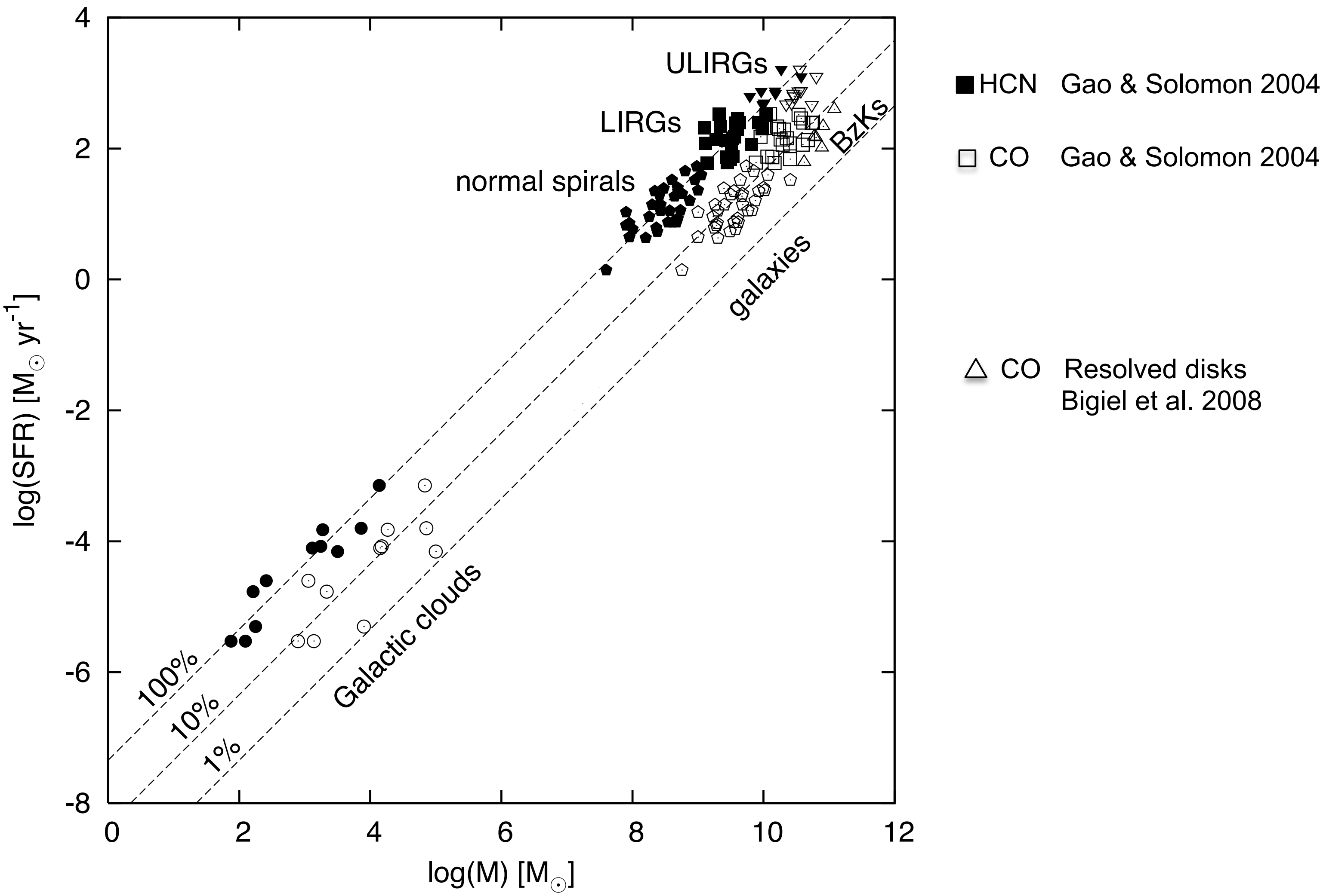
Star Formation Scaling Laws from Local Clouds to Galaxies



Star Formation Scaling Laws from Local Clouds to Galaxies

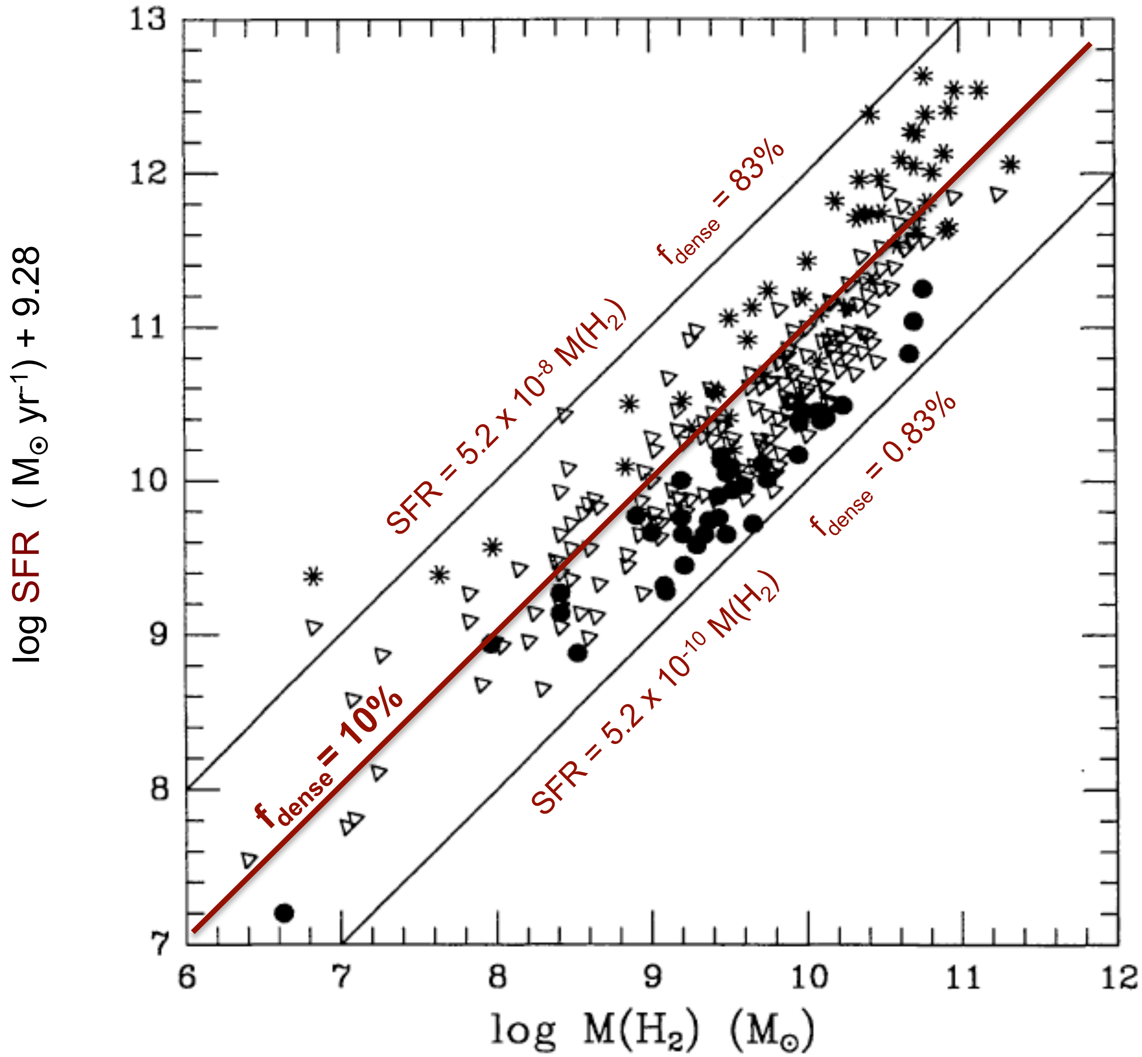


Star Formation Scaling Laws from Local Clouds to Galaxies

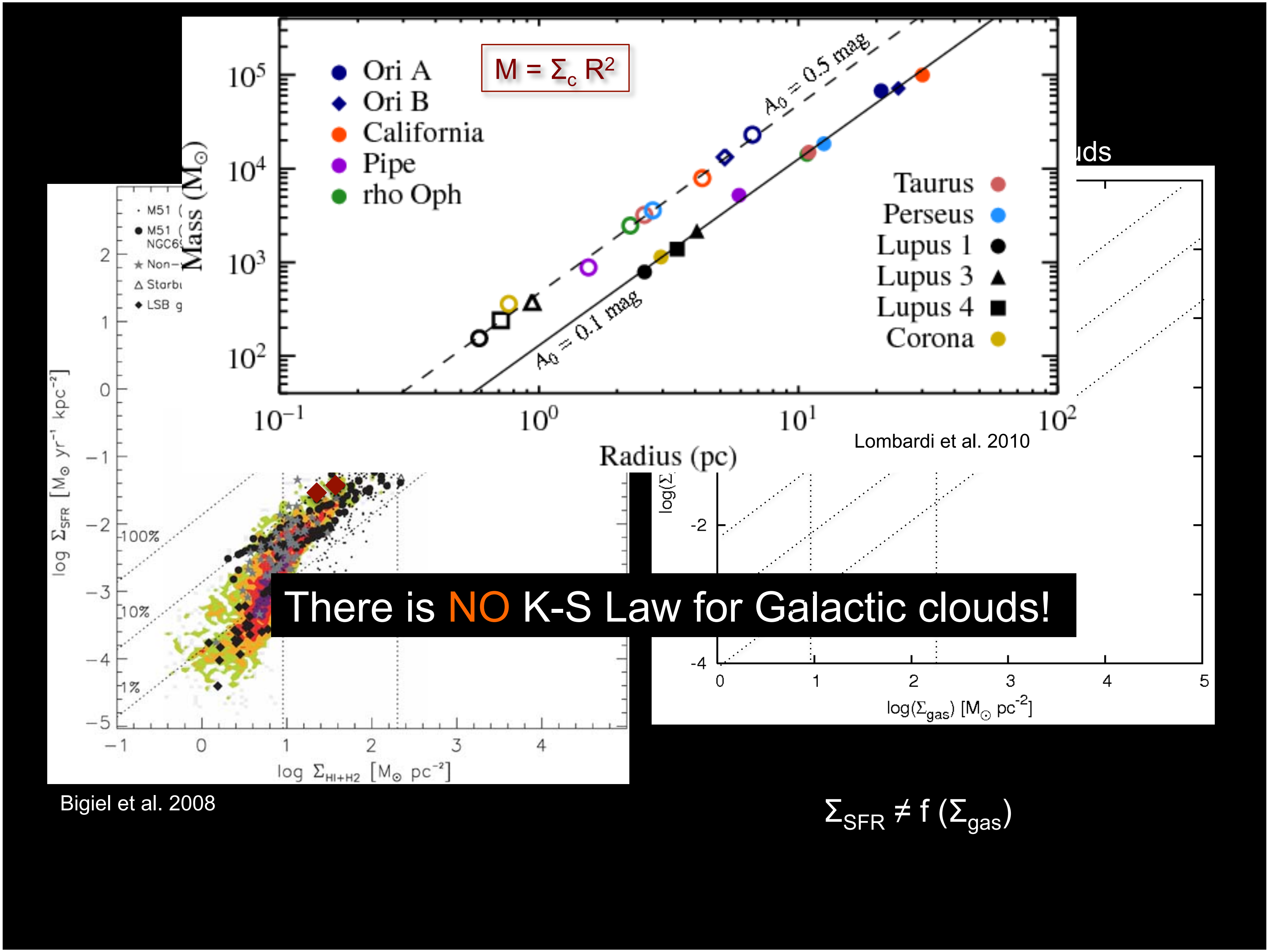


A Linear Scaling Law for Galaxies

Young & Scoville 1991, ARAA 32, 581

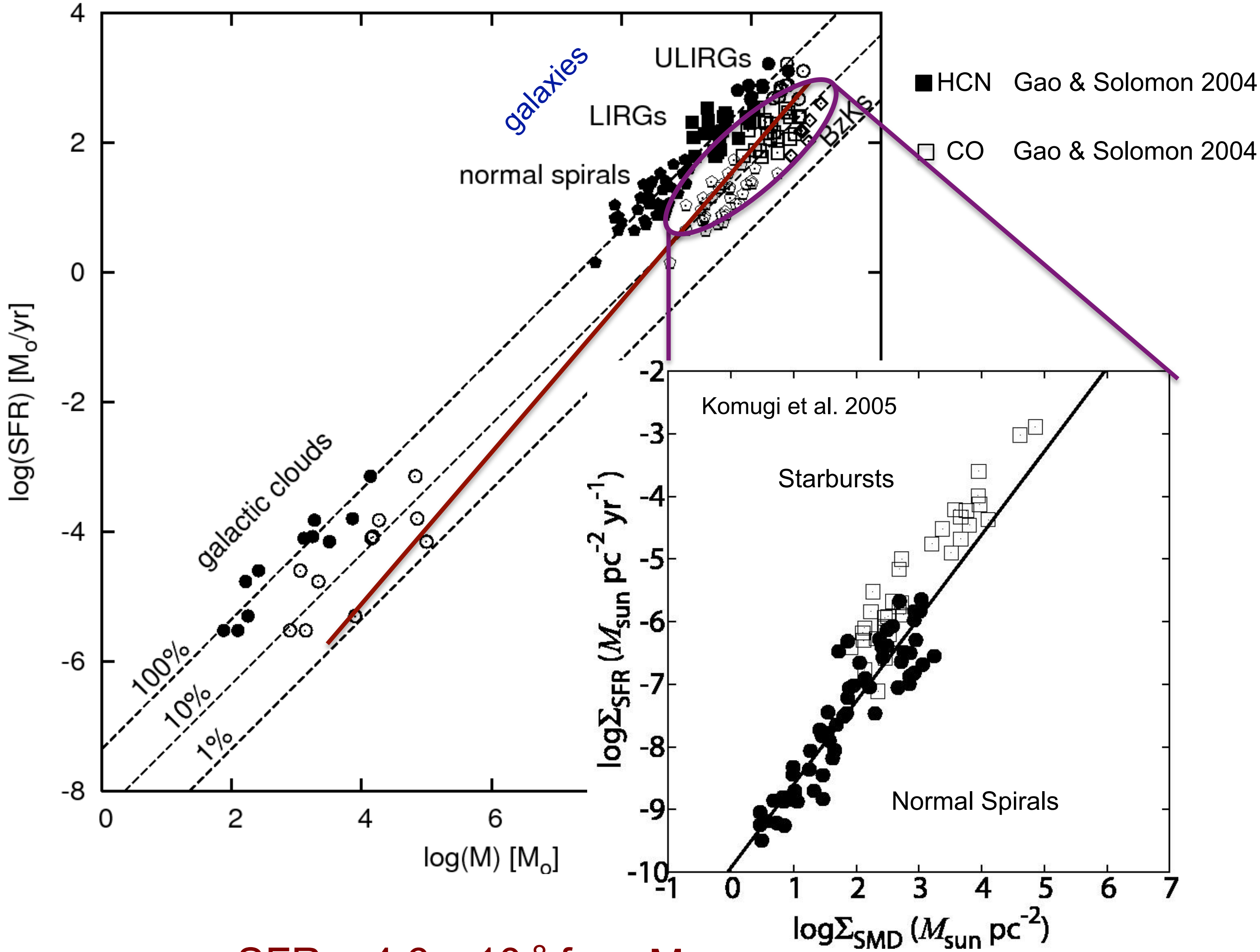


The Nature of the Schmidt-Kennicutt Scaling Relation



M = Σc R2
Ori A
Ori B
California
Pipe
rho Oph
Taurus
Perseus
Lupus 1
Lupus 3
Lupus 4
Corona
A0 = 0.5 mag
A0 = 0.1 mag
Mass (M⊙)
Radius (pc)
Lombardi et al. 2010
M51
NGC6
Non-
Starb
LSB g
100%
10%
1%
log ΣSFR [M⊙ yr-1 kpc-2]
log ΣHI+H2 [M⊙ pc-2]
Bigiel et al. 2008
uds
log(Σgas) [M⊙ pc-2]
There is NO K-S Law for Galactic clouds!
ΣSFR ≠ f (Σgas)

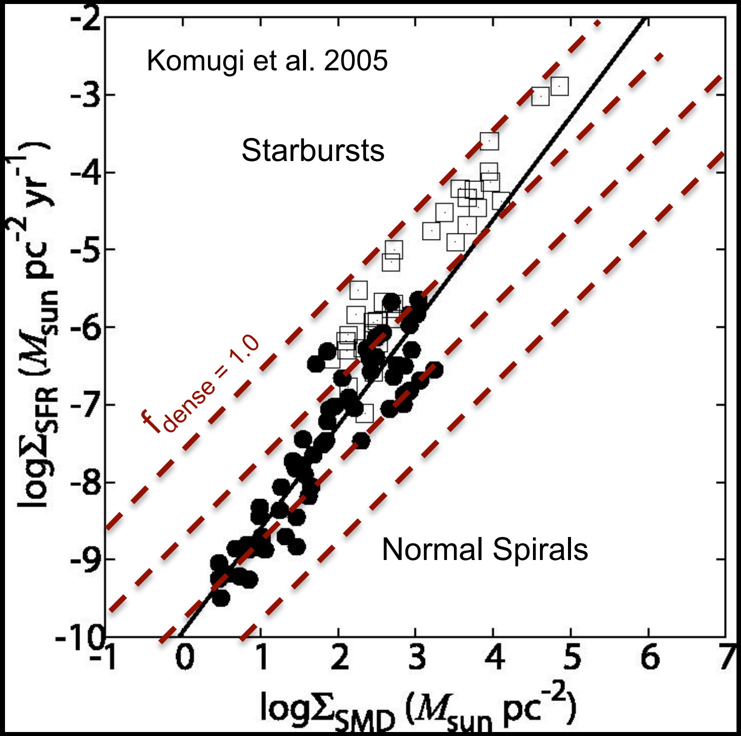
Star Formation Scaling Laws from Local Clouds to Galaxies



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

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

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



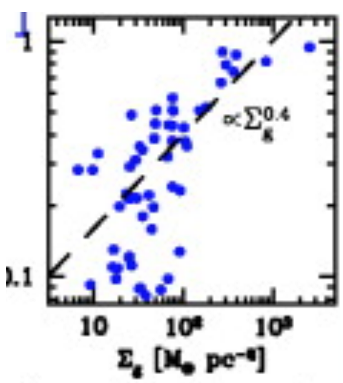
Implications for Modelling Star Forming Galaxies

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

t_{sf} = Constant

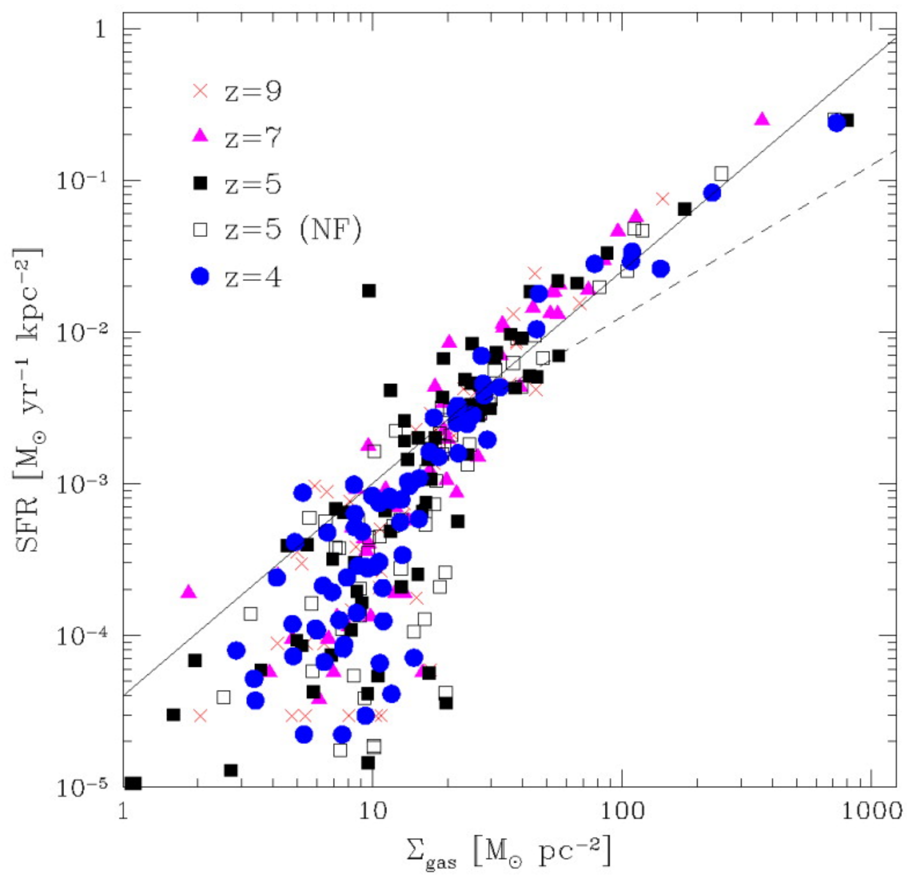
Input ≠ Output

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



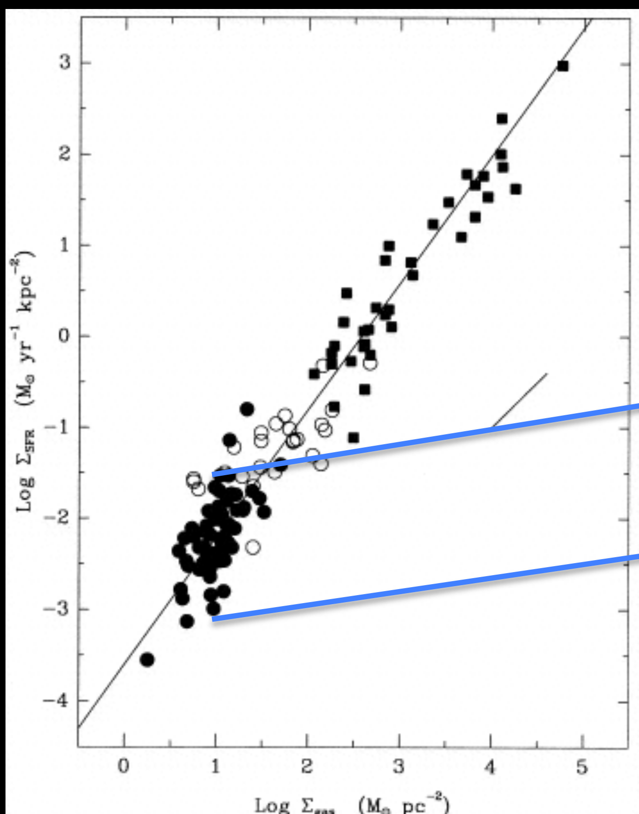
$f_{dense} \sim (\Sigma_{gas})^{0.4}$

Kravtsov (2003)

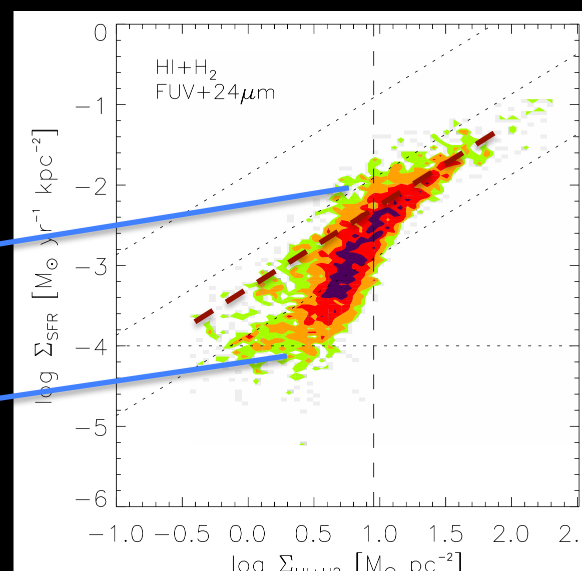


Schmidt-Kennicutt Law for Star Formation

$$\Sigma_{SFR} = A\,(\Sigma_g)^{1.6}$$



HI gas dilutes specific SFR signal!

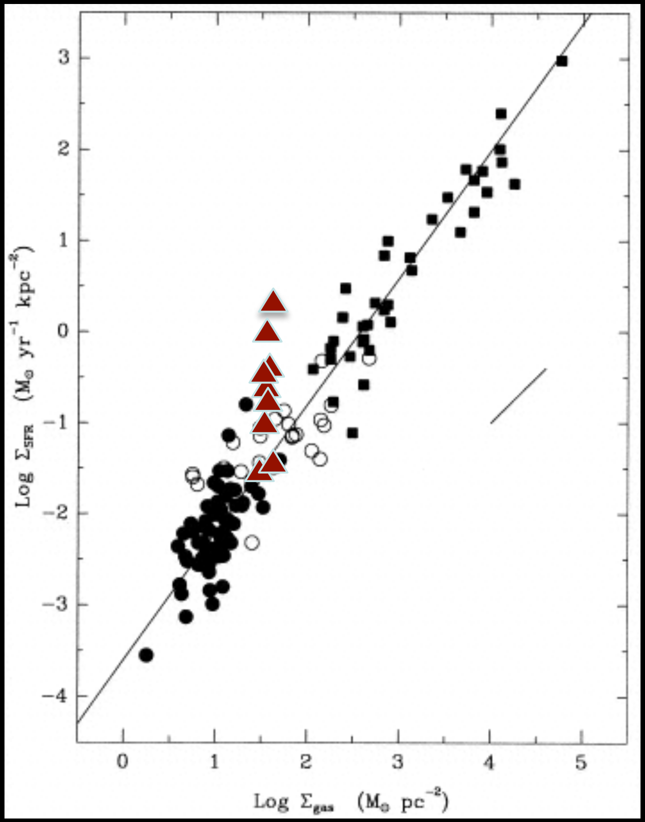


$\Sigma_{gas} = \Sigma(HI + H_2)$

Bigiel et al 2008

Schmidt-Kennicutt Law for Star Formation

$$\Sigma_{SFR} = A\,(\Sigma_g)^{1.6}$$



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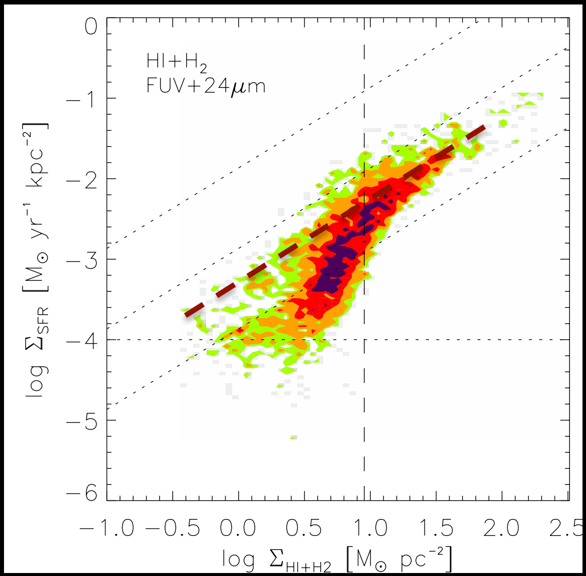


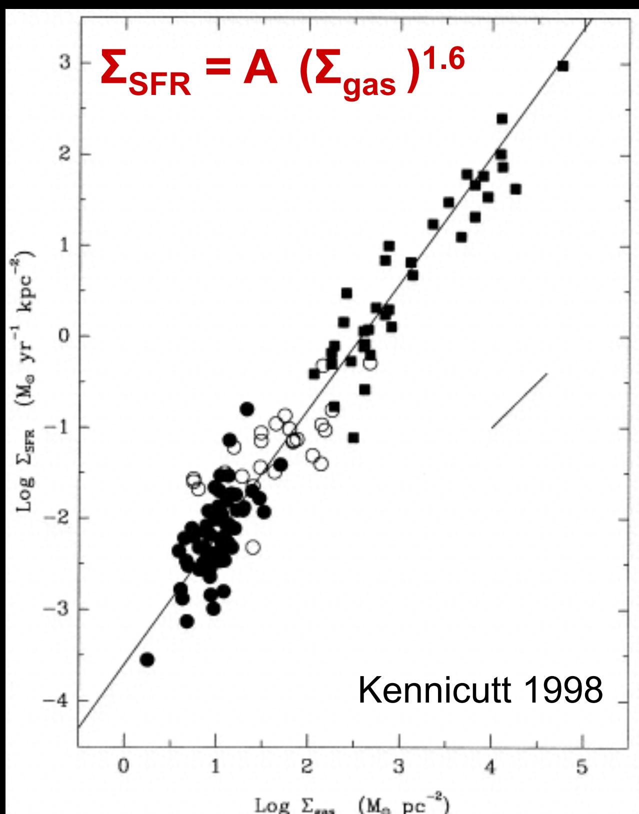
$\Sigma_{gas} = \Sigma(HI + H_2)$

Bigiel et al 2008

Schmidt - Kennicutt Law for Star Formation

Unlike Individual GMCs, for galaxies there is no underlying relation between Σ and ρ, i.e., $\Sigma \neq f(\rho)$

Theoretical Explanation:



Consider that:

$SFR \sim M_{gas} / t_{SF}$

And since $M_{gas} \sim \rho$

If $t_{SF} \sim (G\rho)^{-1/2}$ then $SFR \sim \rho^{3/2}$


The End