Star Formation Rate and Gas Relations in Galactic Clouds

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Co-Conspirators

+ many more

Empirical Relations

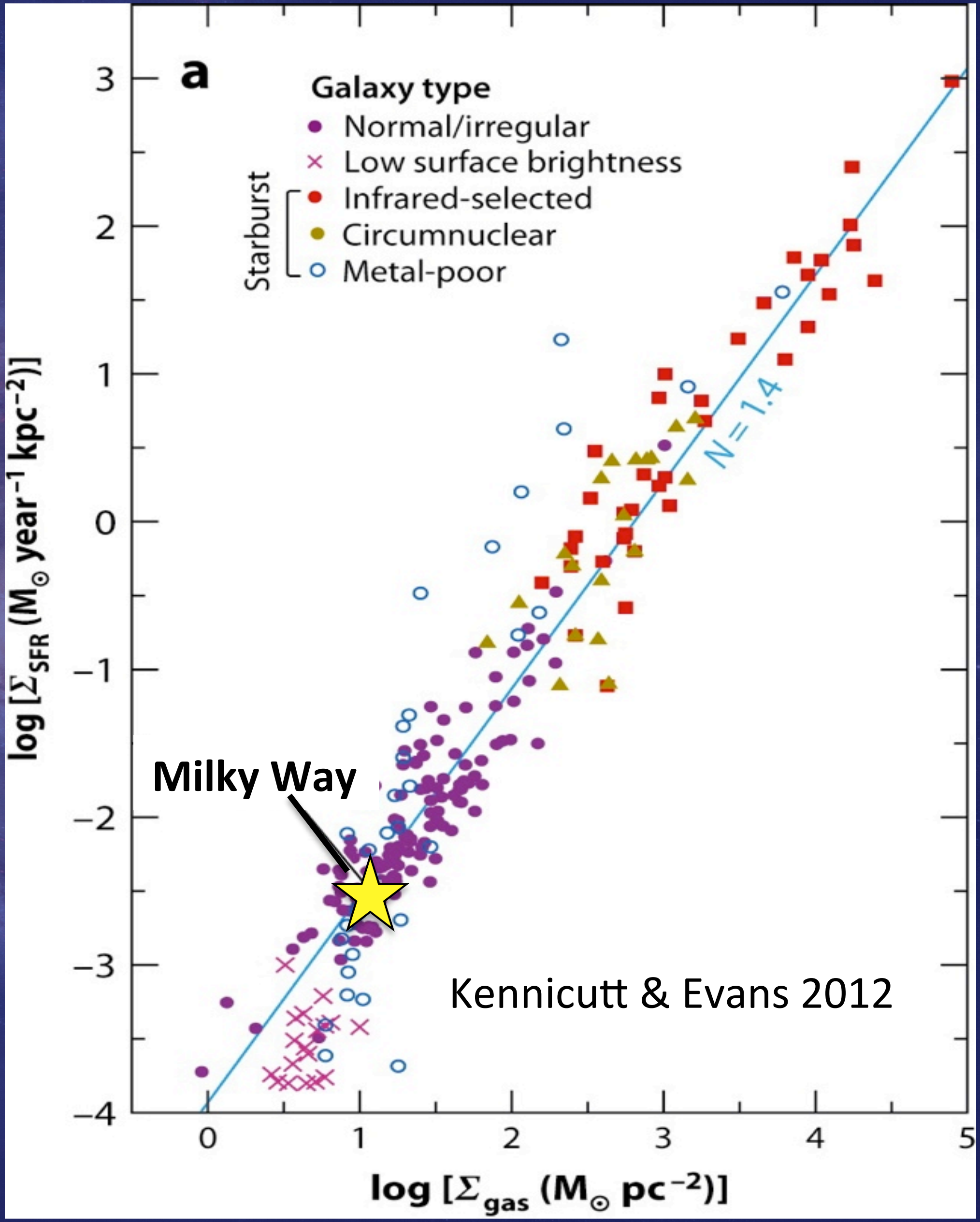
- Global system-average scales
  - in spiral & starburst galaxies

- Common Parameterization:

$$\Sigma_{SFR} = A\Sigma^{N}_{gas}$$

(Schmidt 1959; Kennicutt 1998)

N~1.4 (molecular + atomic H gas)



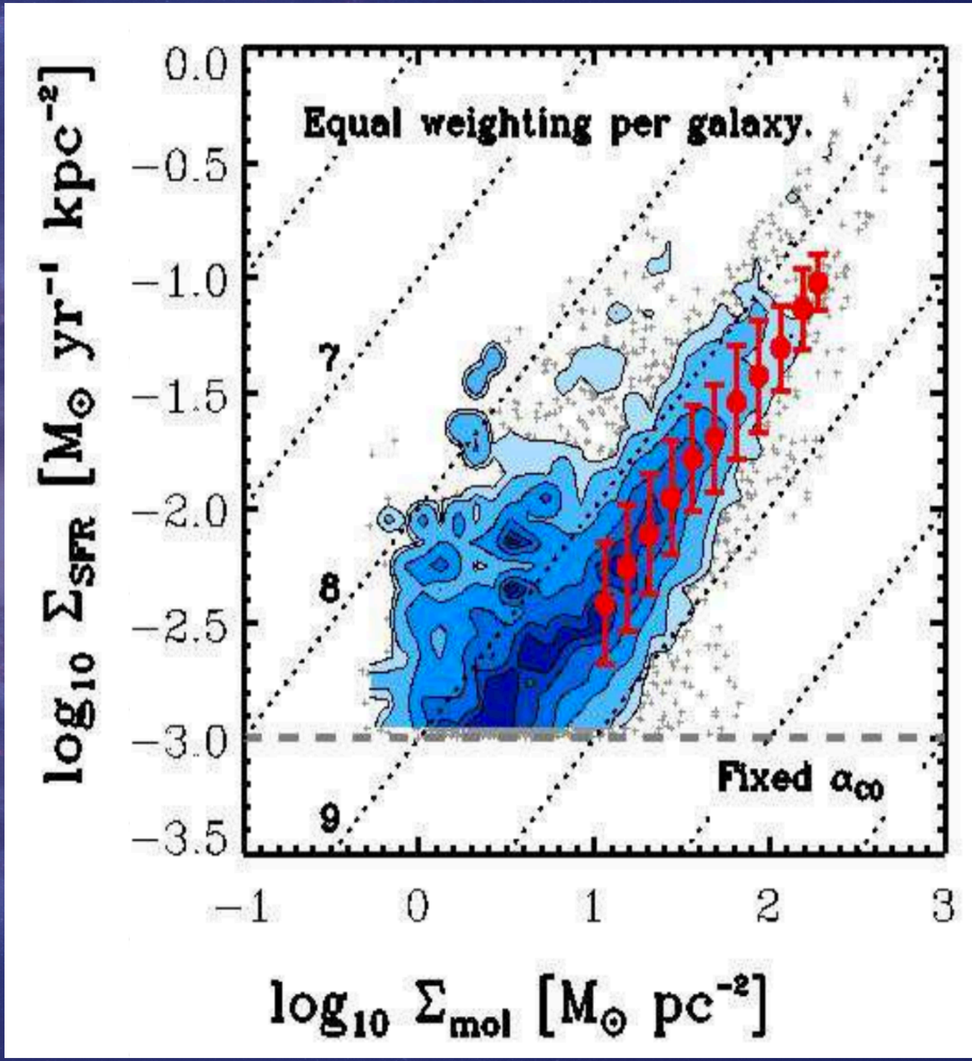
Empirical Relations

- 1 kpc scale regions in nearby spiral galaxies
- Common Parameterization:

$$\Sigma_{SFR} = A\Sigma^{N}_{gas}$$

(Schmidt 1959; Kennicutt 1998)

N~1 (molecular H gas)



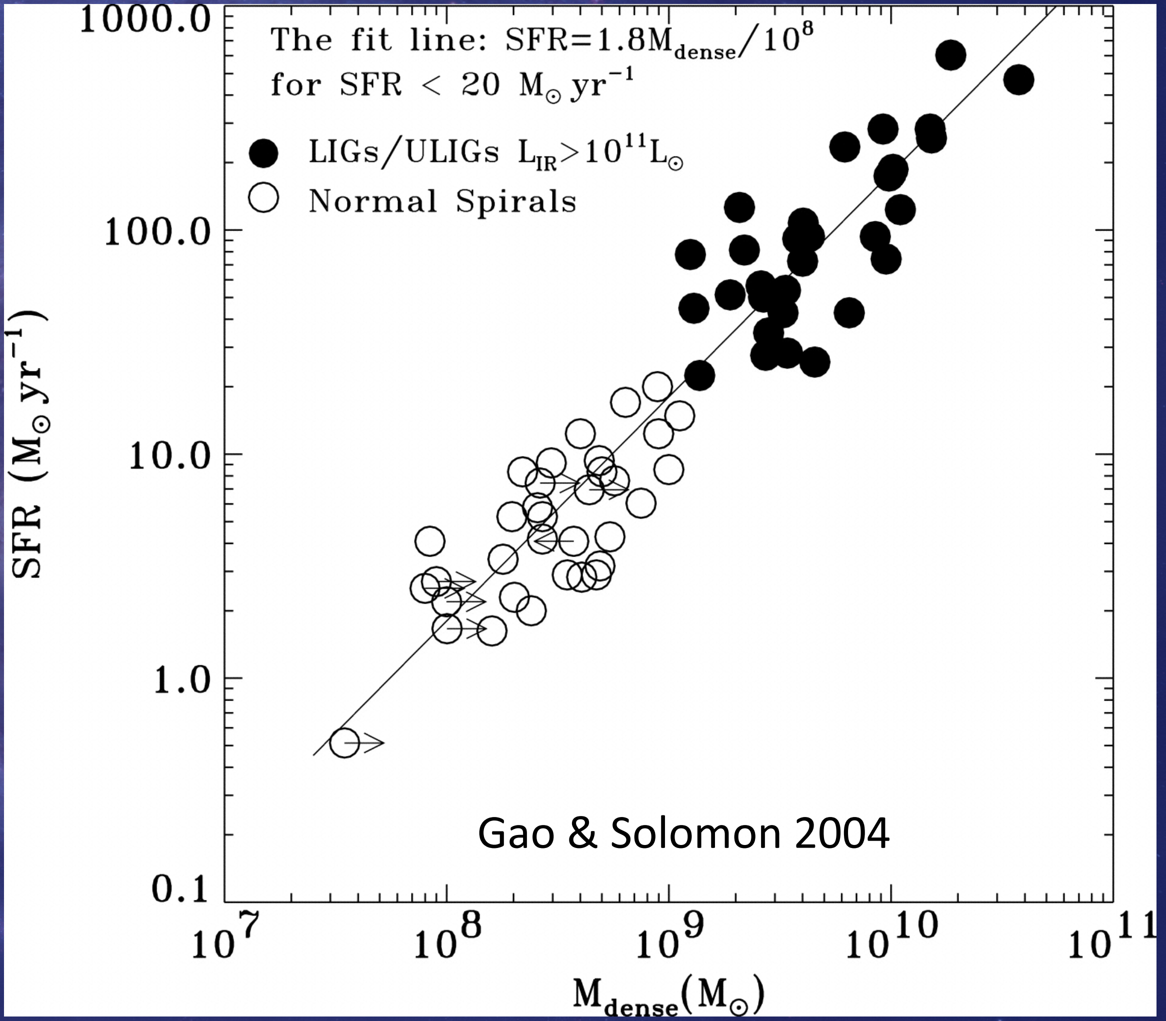
Leroy et al. 2013 (see also Bigiel et al. 2008,2011 & Schruba et al. 2011)

Extragalactic Dense Gas Relation

- Dense gas (traced by HCN)
- SFR ∝ amount of dense gas

$SFR_{dense} \propto M_{dense}$

- Dense gas tracers select gas above a higher density threshold than CO- roughly “Clumps”

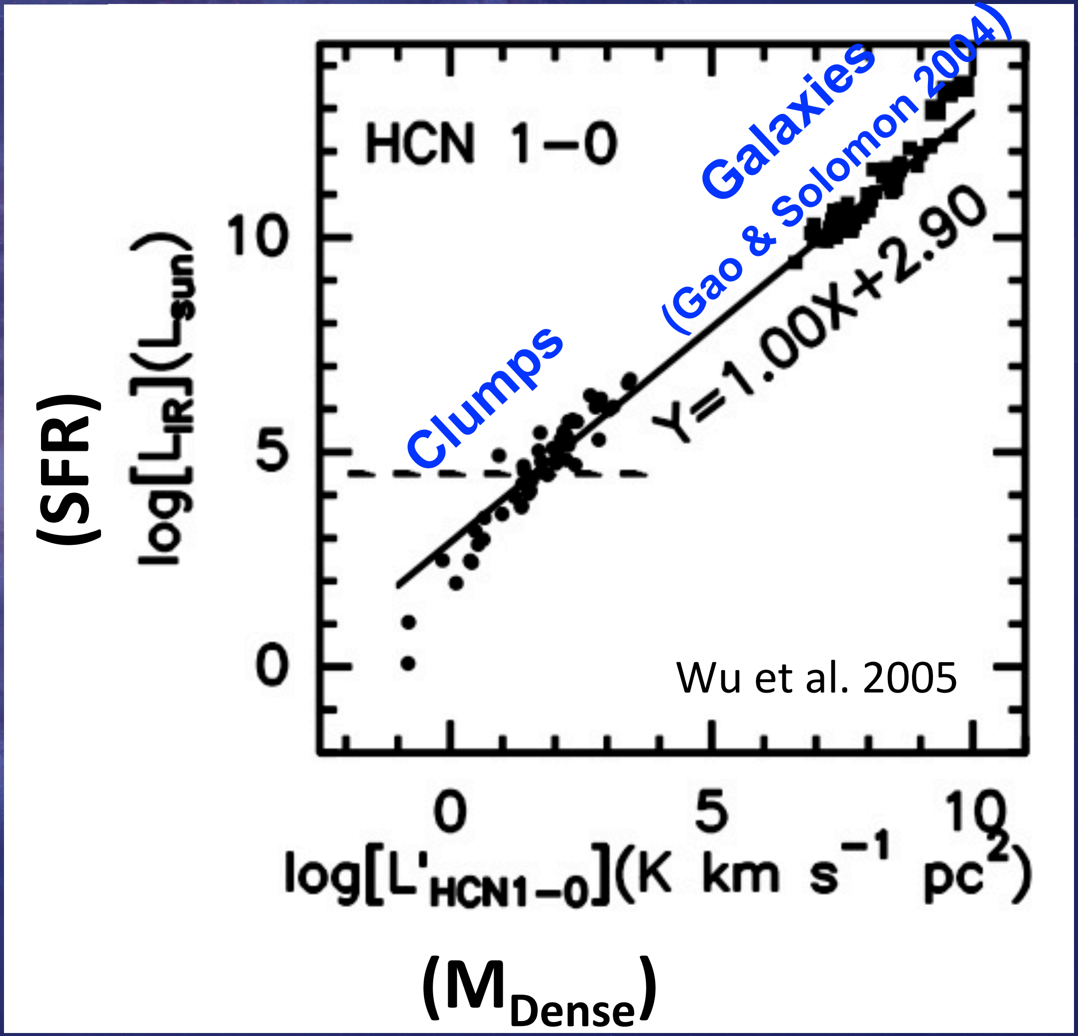


Extragalactic + Galactic Dense Gas Relation

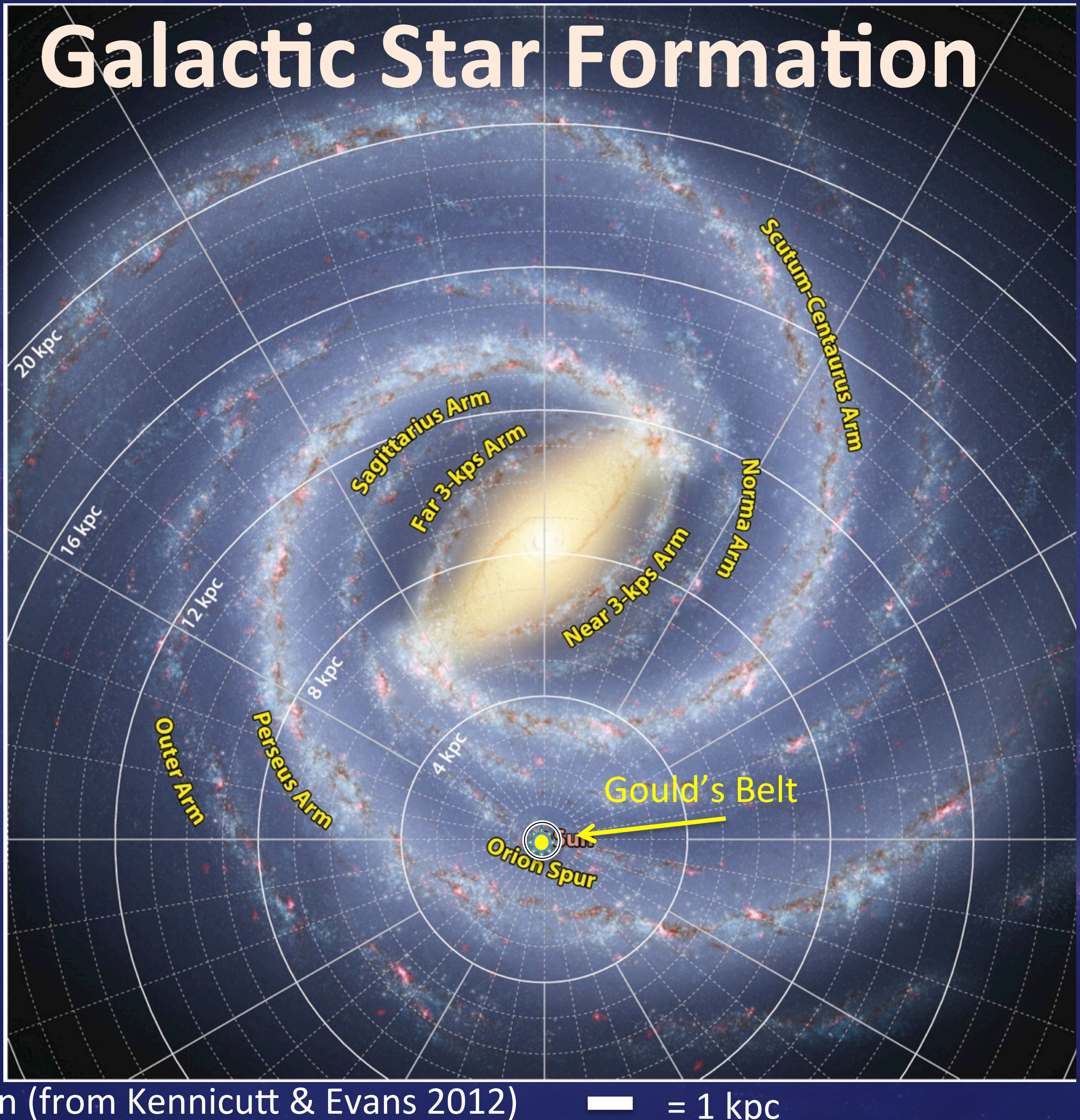
- Extragalactic relation (Gao & Solomon 2004) extends to Galactic massive clumps

$SFR_{dense} \sim 1.2x10^{-8} M_{dense}$

(Wu et al. 2005)

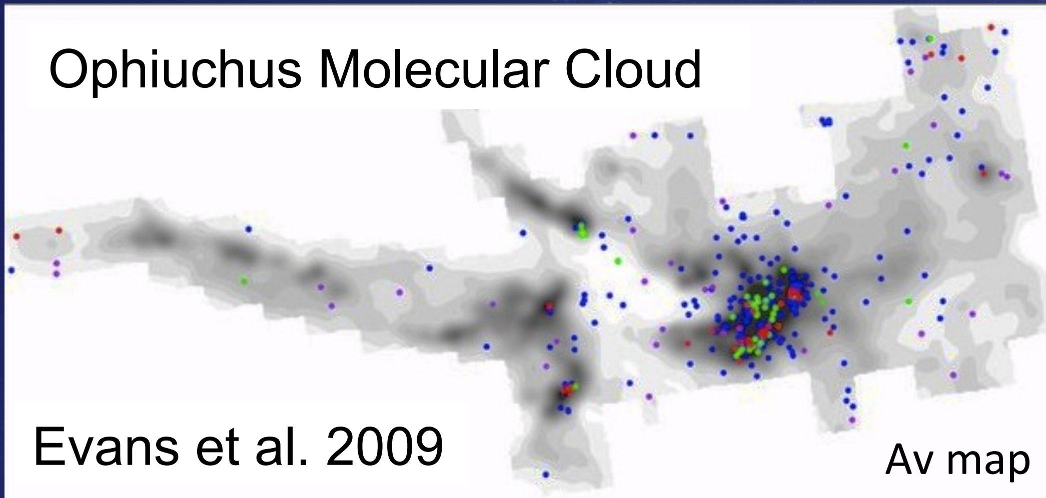


Galactic Star Formation



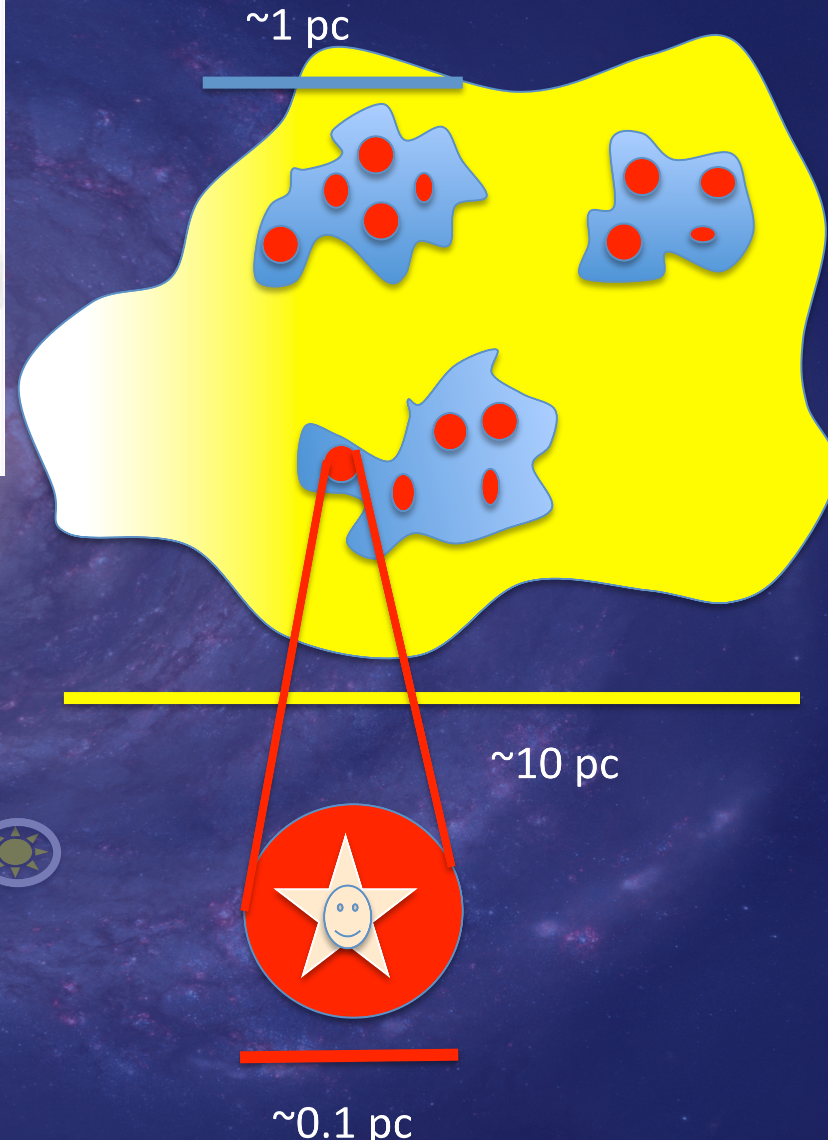
R. Benjamin (from Kennicutt & Evans 2012)

Galactic Star Formation

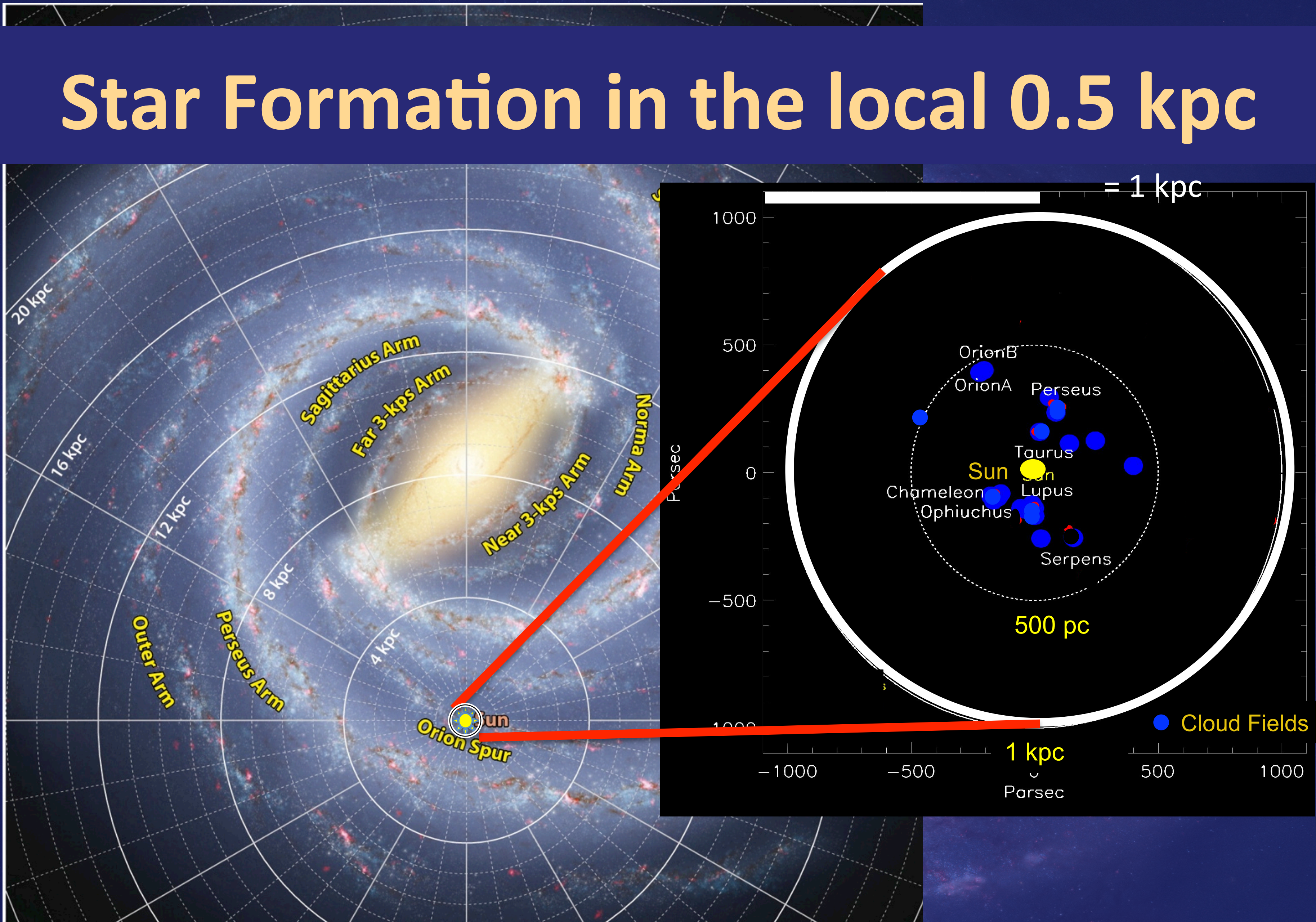


clouds are large structures of molecular gas and dust which fragment into

clumps containing multiple dense cores, which form individual stars



Star Formation in the local 0.5 kpc



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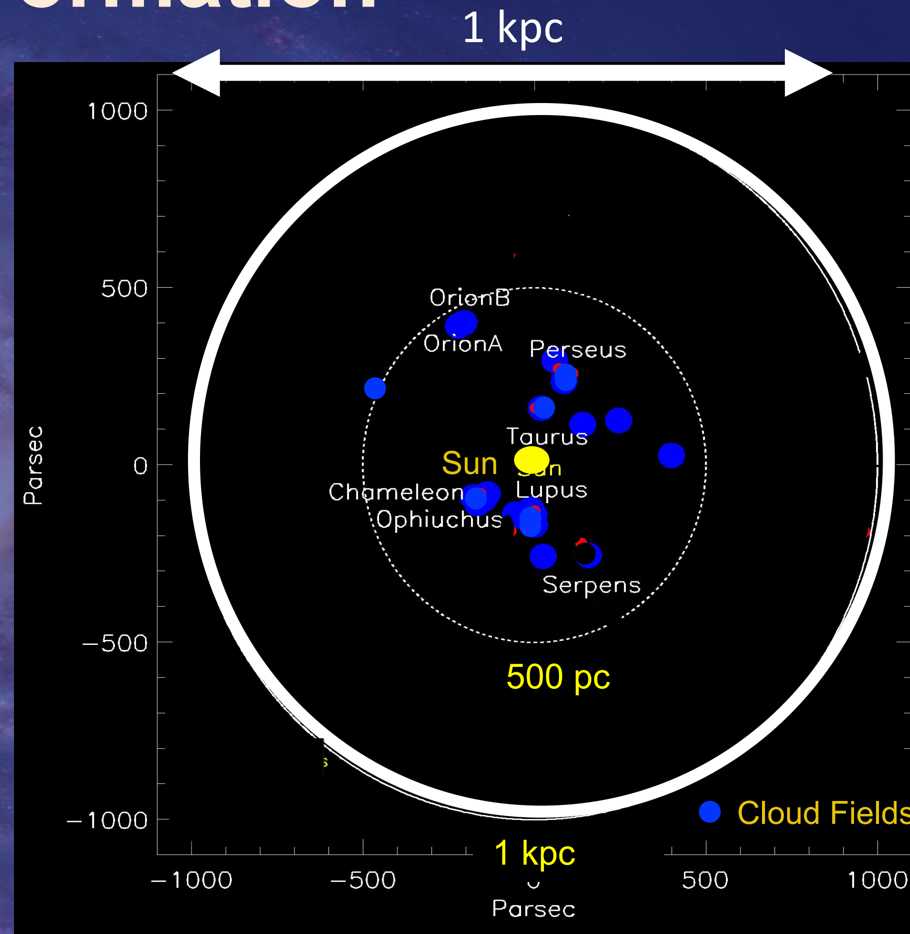
Using Nearby ~20 Clouds to Trace *low-mass* Star Formation

- *Spitzer* Legacy Surveys*:*
  - "cores to disks" (c2d; Evans et al. 2009)
  - Gould's Belt (GB; L. Allen et al., in prep.)

- Cloud masses/ Σ_{gas} from extinction maps:

  $\Sigma_{gas} = 15A_V$ ($M_\odot$ pc^{-2})

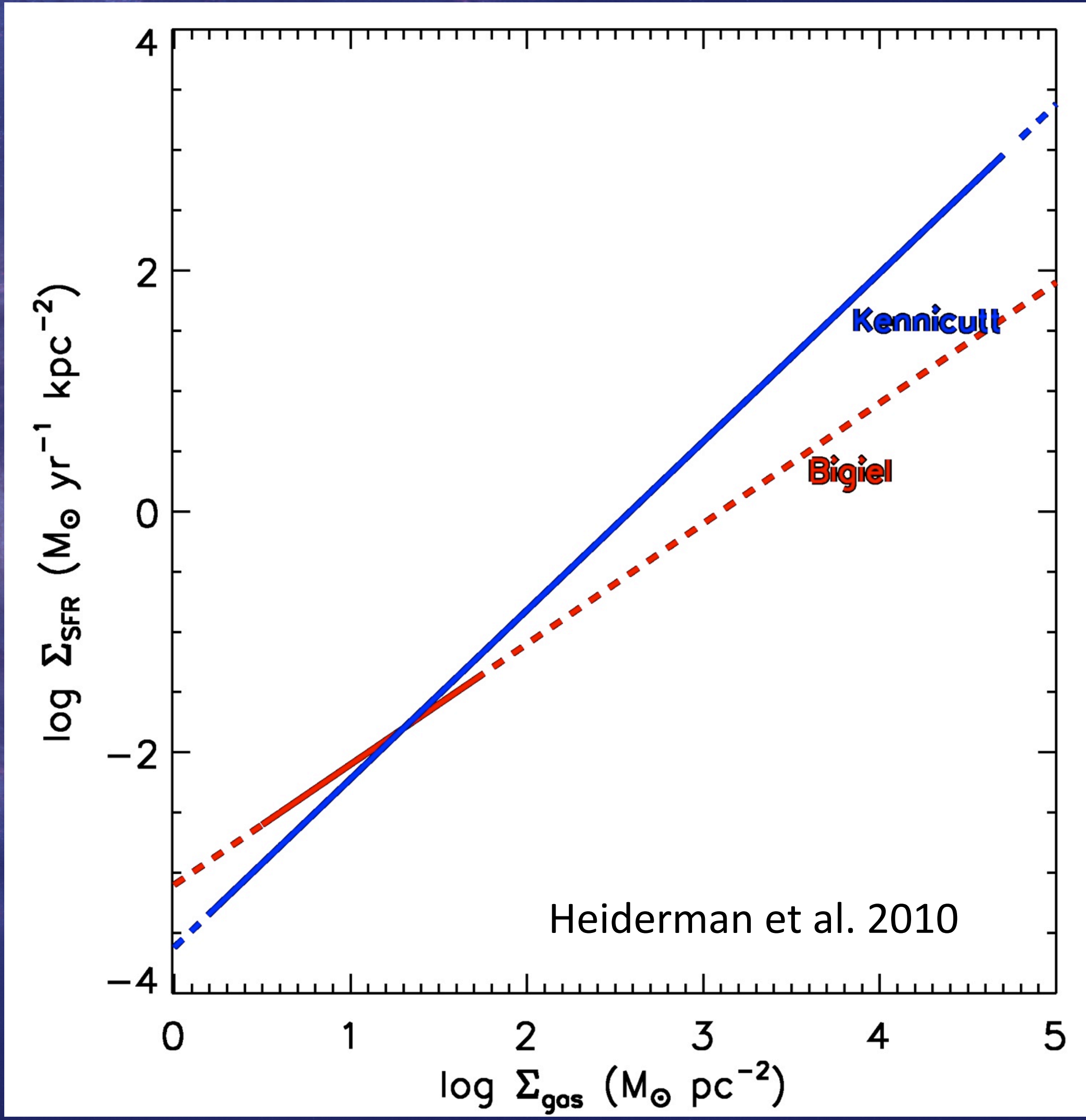
- SFR= $N_{YSO} \times M_{YSO} / t_{YSO}$ ($M_\odot$ Myr^{-1})
  - from YSO counts, mean mass 0.5 $M_\odot$, & lifetimes



$<\Sigma_{gas}>$ ranges 30-50 $M_\odot$ pc^{-2} (similar to Heyer et al. 2009; 42 $M_\odot$ pc^{-2})

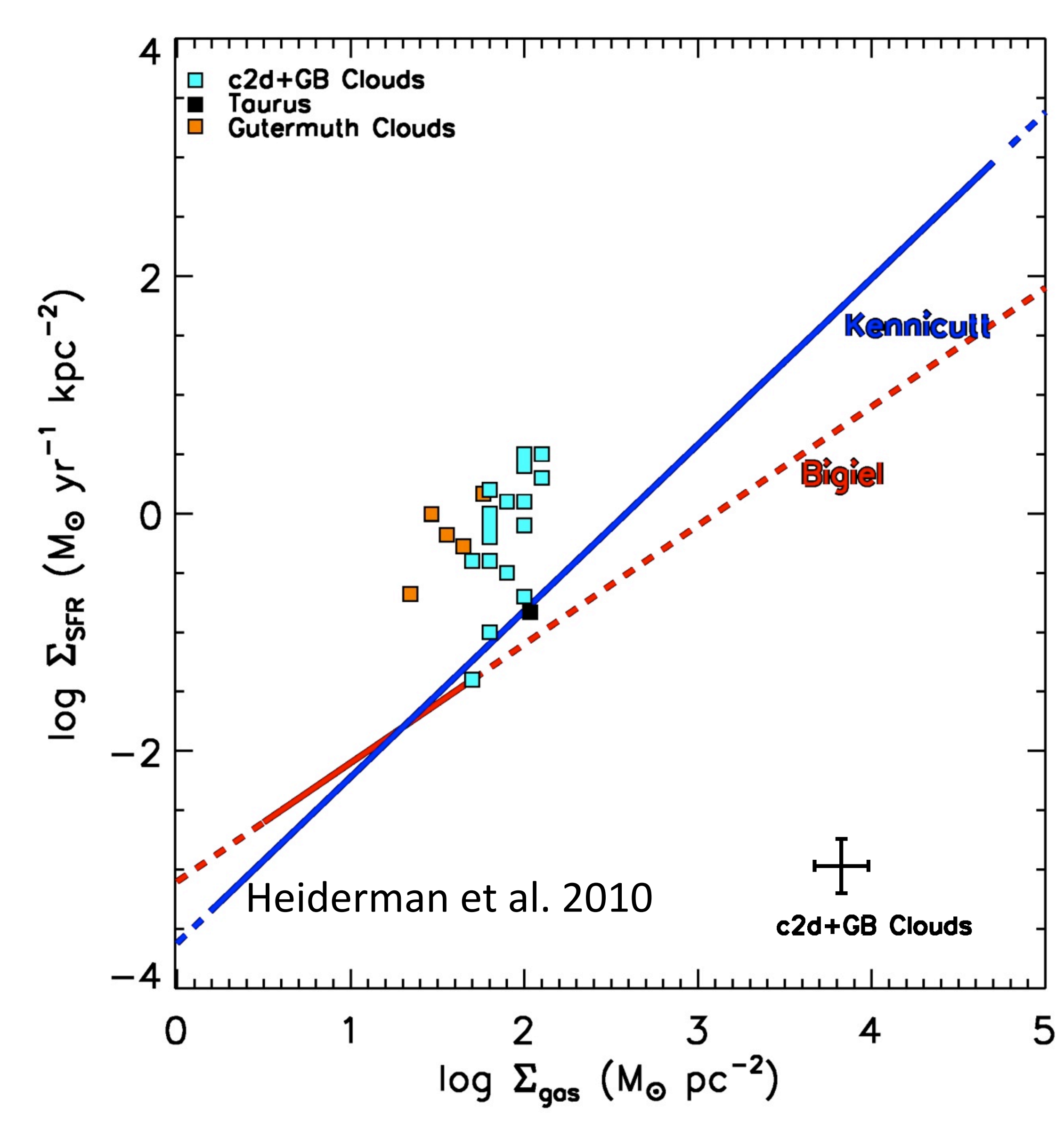
Testing Extragalactic Relations in Local Clouds

- Prescriptions developed over large scales
- trace *massive* star formation
- Will they work in a low-mass star forming cloud?

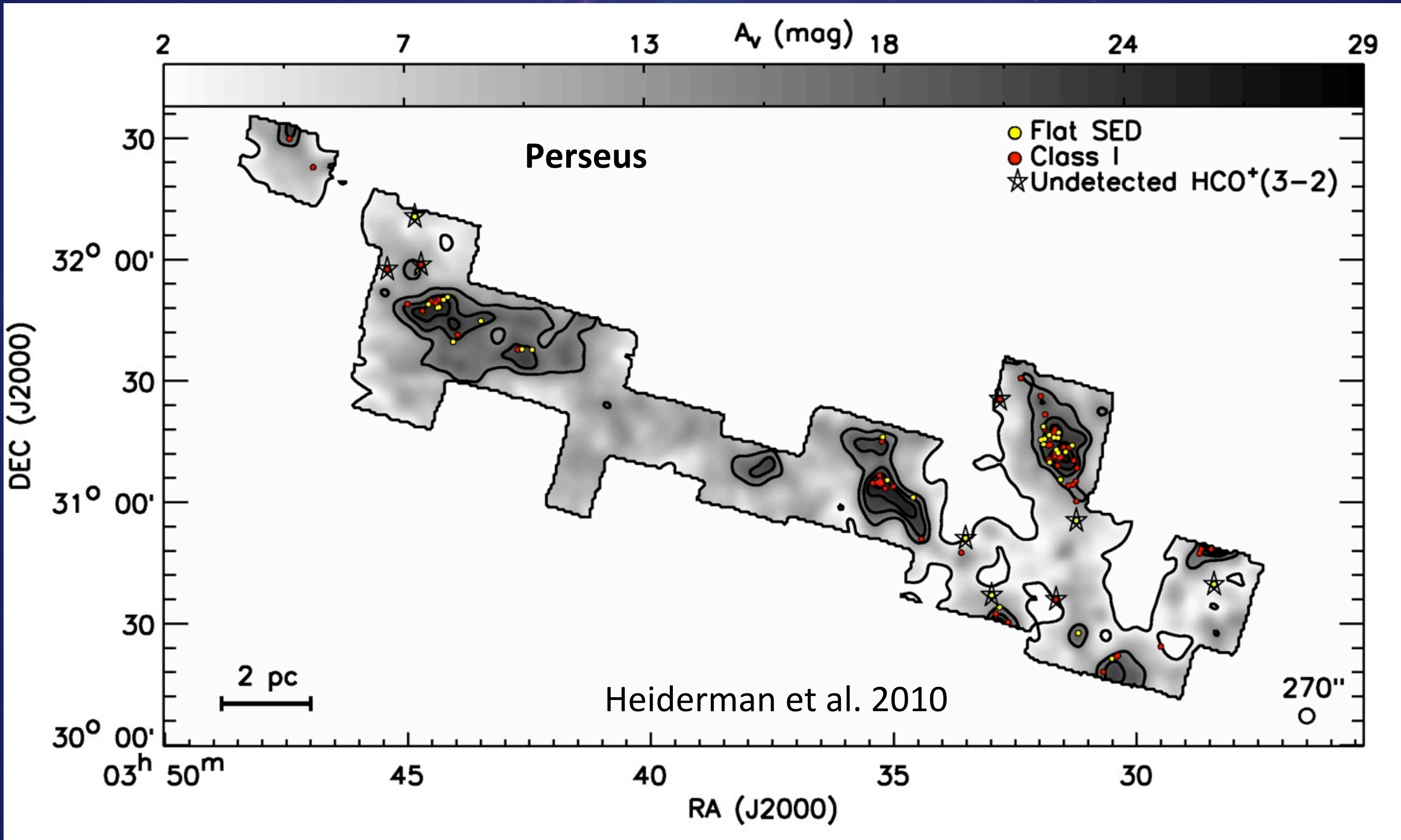


SFR-gas Relation in Local Clouds

- 20 c2d+GB clouds, Taurus (Rebull et al. 2010), & Gutermuth et al. 2011 cloud sample
- Clouds lie factor of ~10 on average above extragalactic relations
- “inactive” clouds (Taurus, Cha III) lie near relations



Youngest YSOs

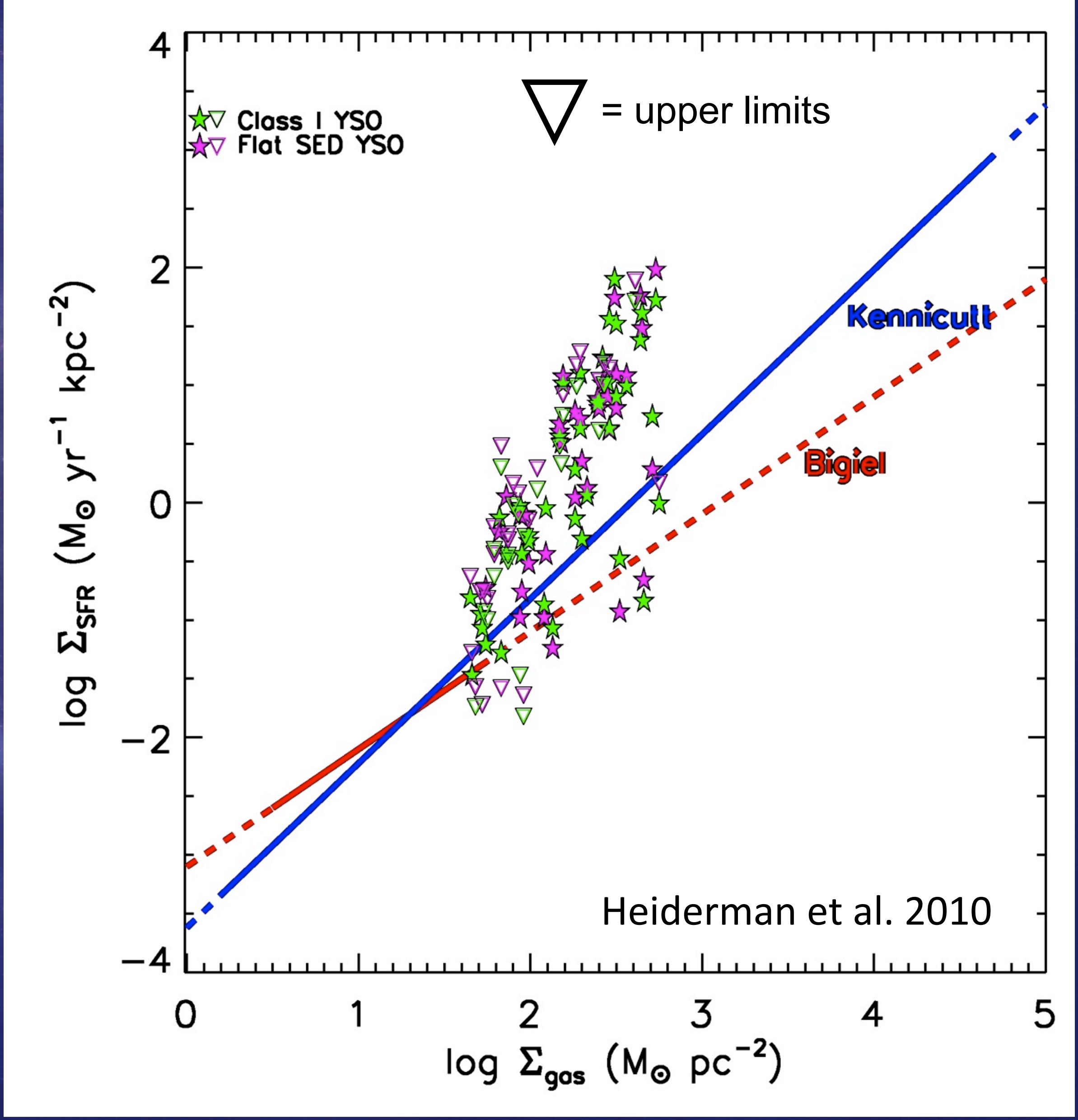


HCO$^+$ survey at CSO & APEX to confirm YSO (detect dense gas envelope; Heiderman in prep)

Youngest YSOs

- factors of ~20-50 above extragalactic relations

→ What accounts for this discrepancy?



Possible Explanations

(1) Σ_{gas} from CO (exgal) ≠ Σ_{gas} from A_V?

=> differences seen, but doesn't explain discrepancy

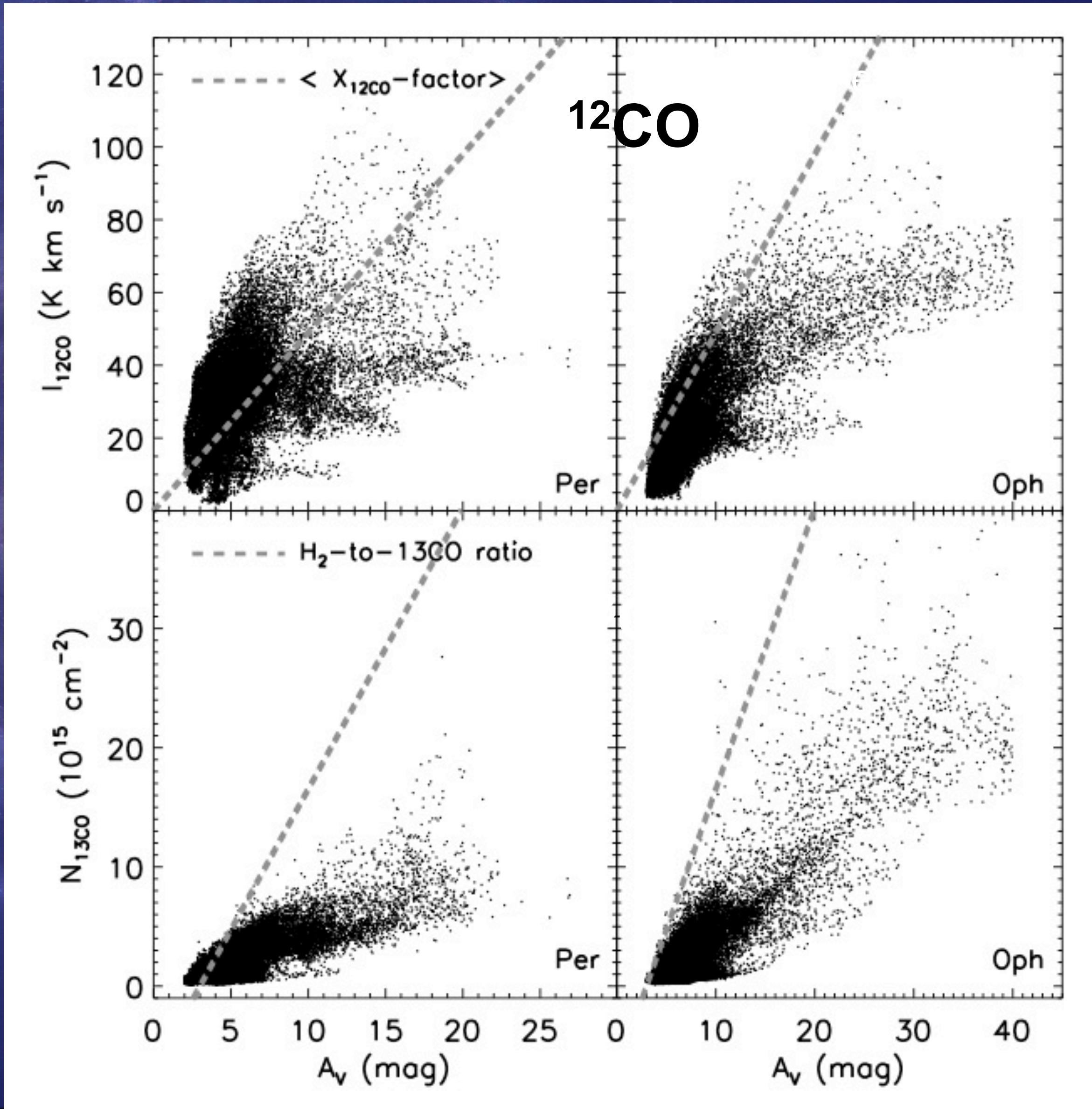
(2) Does Low-mass star formation behave different from high-mass star formation?

=> YSOs & high-mass clumps behave similarly

(3) Extragalactic *average* measurements are unresolved (include non- star forming molecular gas maybe below some threshold)?

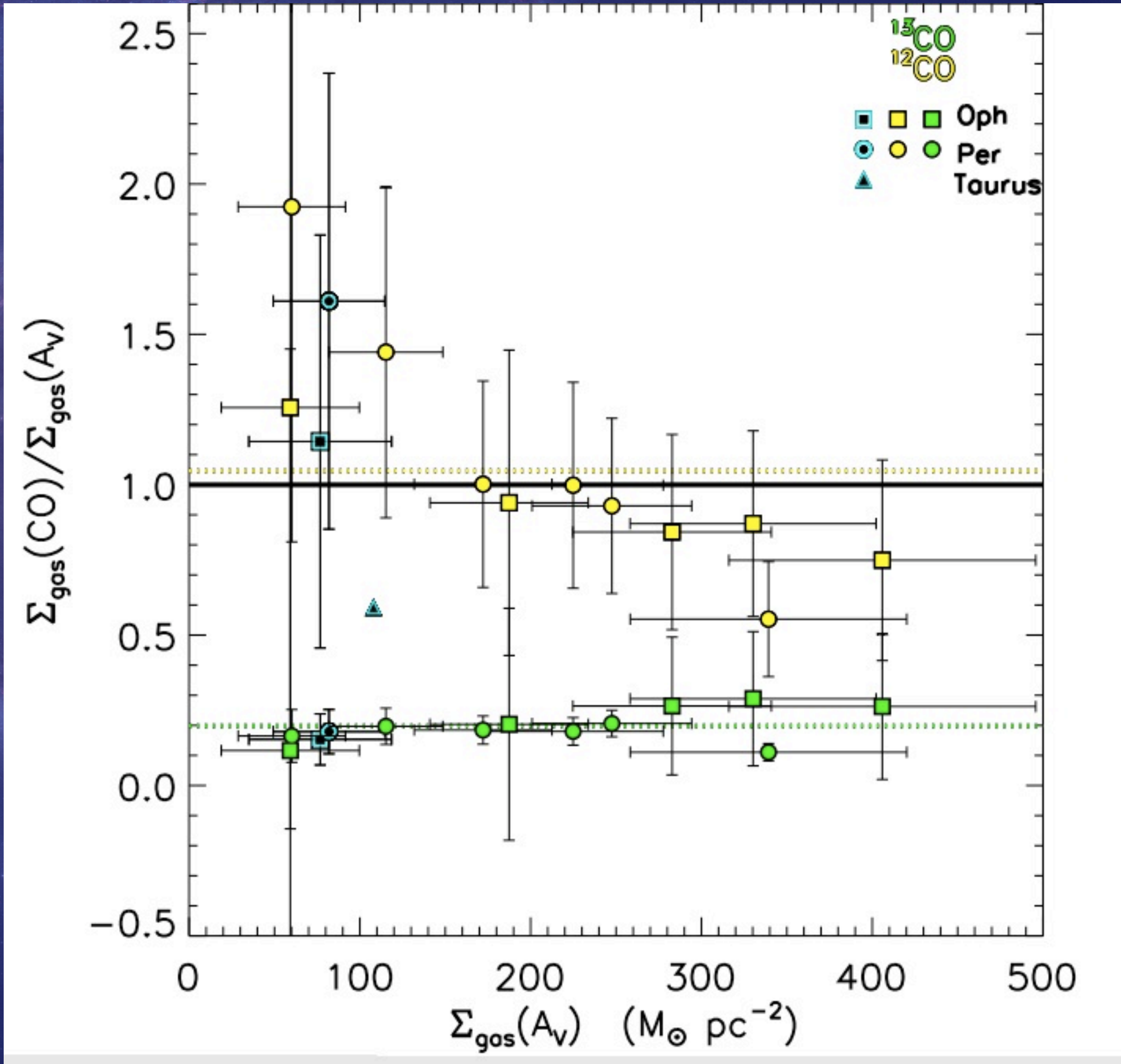
(1) Σ_{gas} from CO (exgal) ≠ Σ_{gas} from A_V?

- ^{12}CO correlates with A_V out to A_V~7-10, but largely varies beyond that
- ^{13}CO turns over around A_V~7-10, due to increase in optical depth



(1) Σ_{gas} from CO (exgal) ≠ Σ_{gas} from A_V?

- Constant value of ^{13}CO vs Σ_{gas}, underestimating Σ_{gas} by factors of 4-5
- ^{12}CO underestimates A_V at Σ_{gas} > 200 $M_\odot$ pc^{-2} by 30%
- Correcting for ^{12}CO, would flatten the slope of the Kennicutt-Schmidt relation



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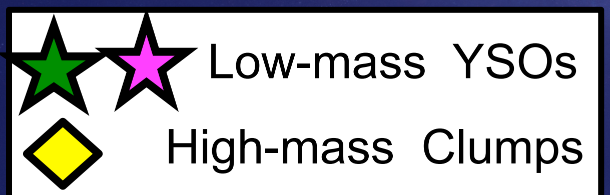
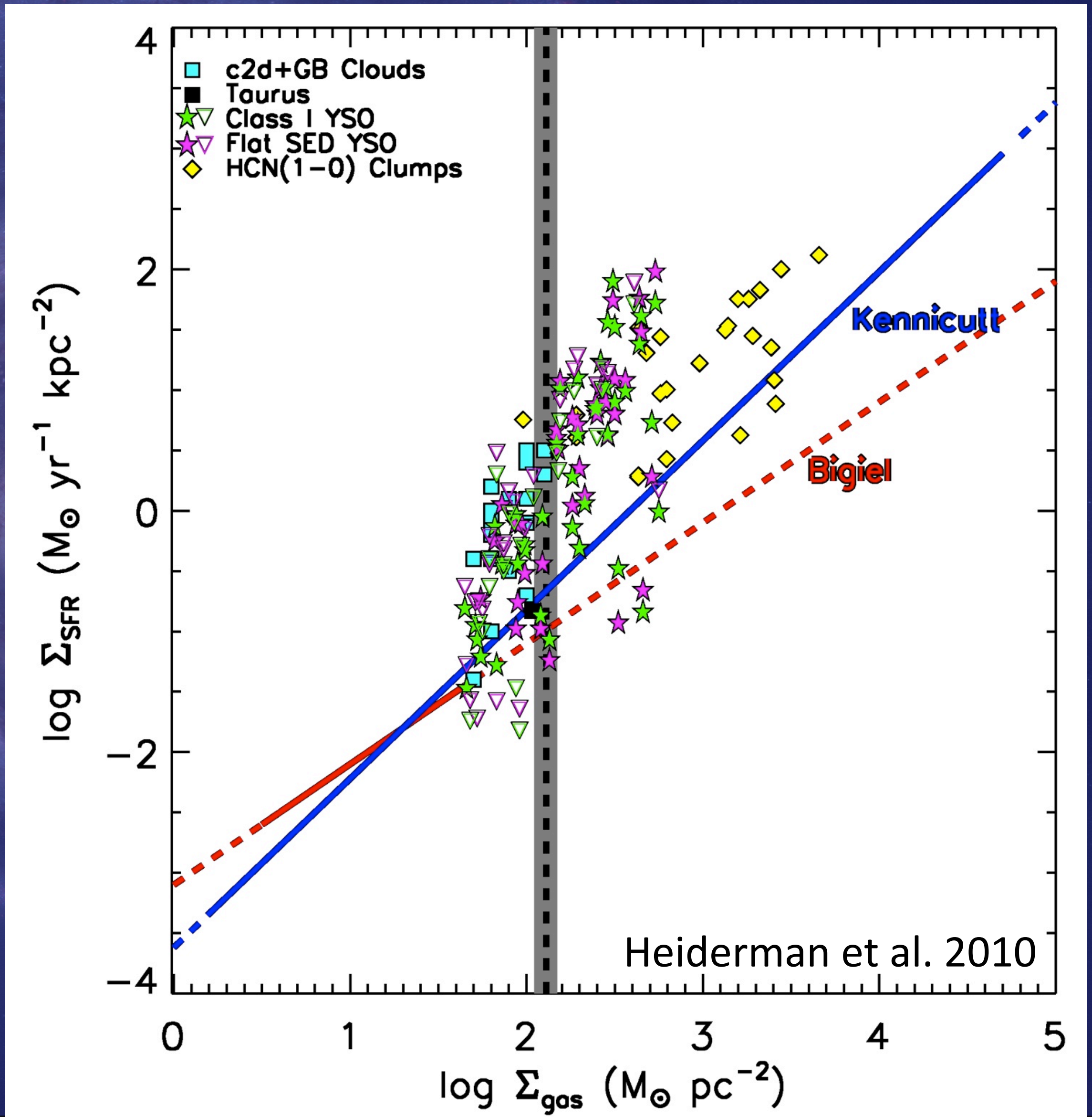
(2) Do Massive Star Forming Regions Behave Differently?

- YSOs + Clumps behave similarly
- Steep increase & *possible* leveling off at ~100-200 $M_\odot$ pc^{-2}





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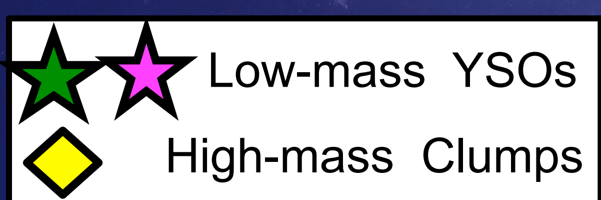
Gas Surface Density Threshold (Σ_{th})

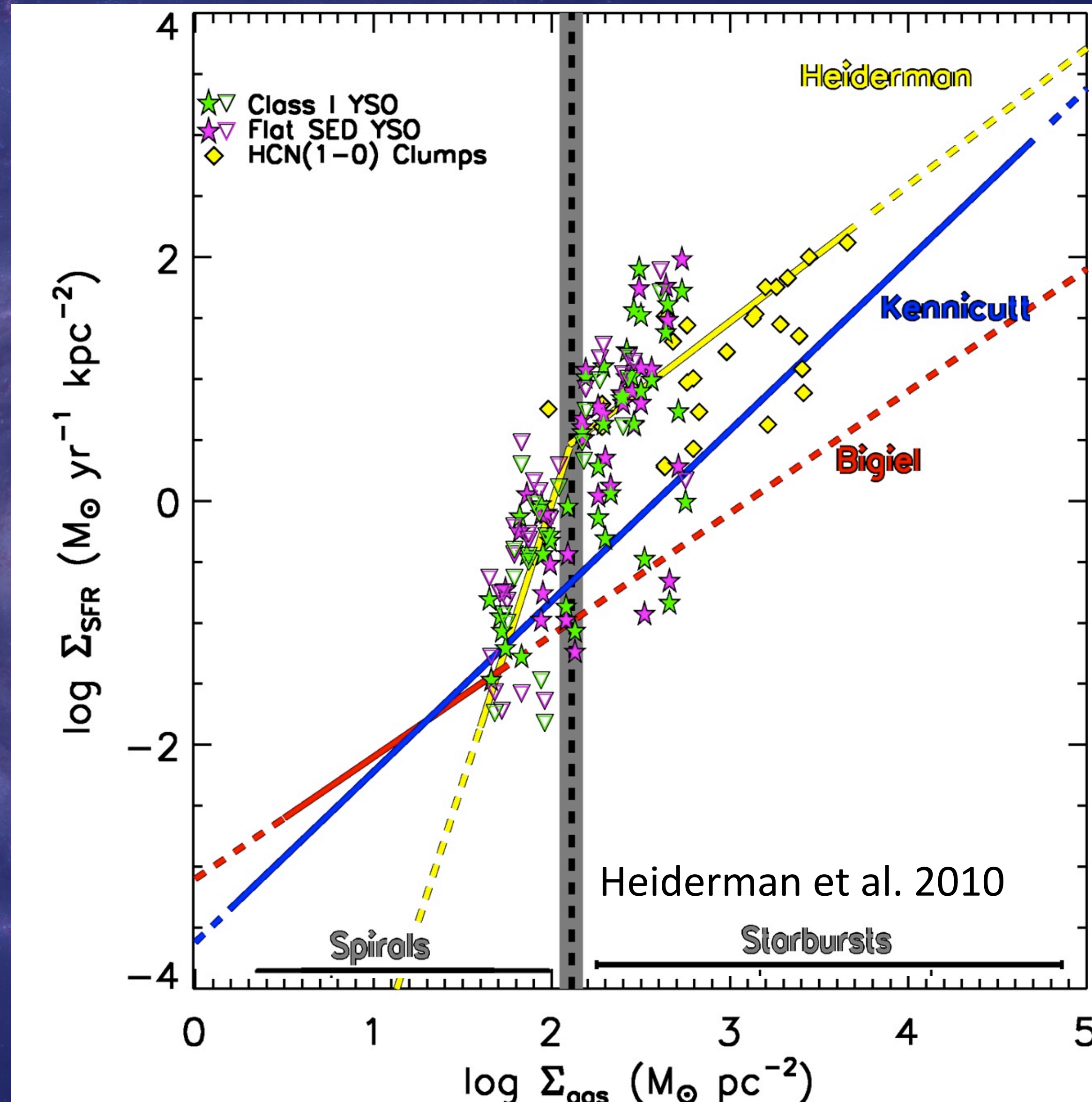
- YSOs + clumps are *similar* beyond gas threshold surface density:

  $\Sigma_{gas} > \Sigma_{th}$

- $\Sigma_{th} = 129 \pm 14\ M_\odot\ pc^{-2}$
  - Slope changes from ~5 to ~1 at $\Sigma_{gas} > \Sigma_{th}$

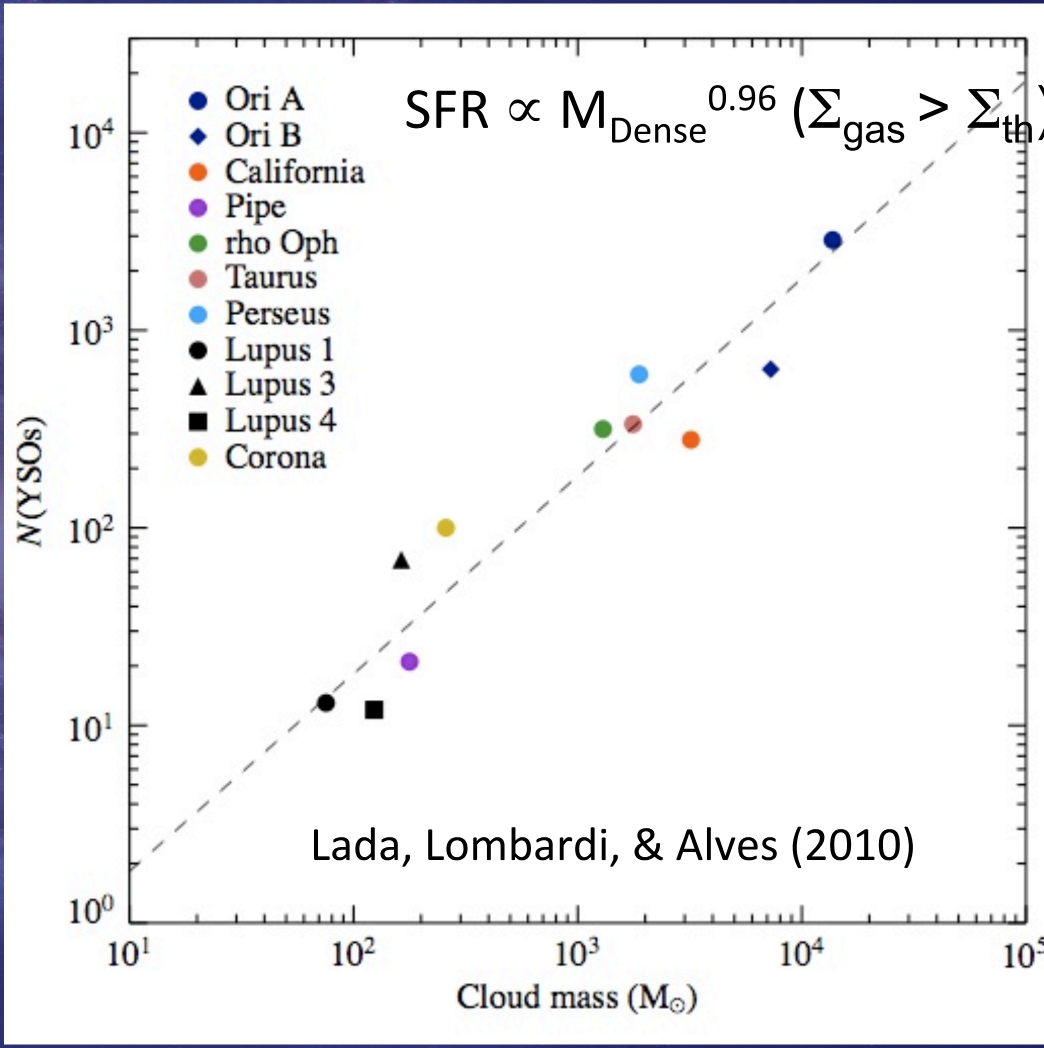
- On average, "normal" spirals lie below Σ_{th} and starburst galaxies lie above





Gas Surface Density Threshold (Σ_{th})

- Lada, Lombardi, & Alves 2010 (independent methods) found
  - Σ_{th} ~116 $M_{\odot}$ pc^{-2} (A_V ~7.3 mag)
  - recovered a tight linear relation between SFR and total gas mass $\Sigma_{gas} > \Sigma_{th}$
- Observational studies find Σ_{th} ~120-150 $M_{\odot}$ pc^{-2} (Onishi 1998; Johnstone 2004, Enoch et al. 2007; Andre et al. 2010)



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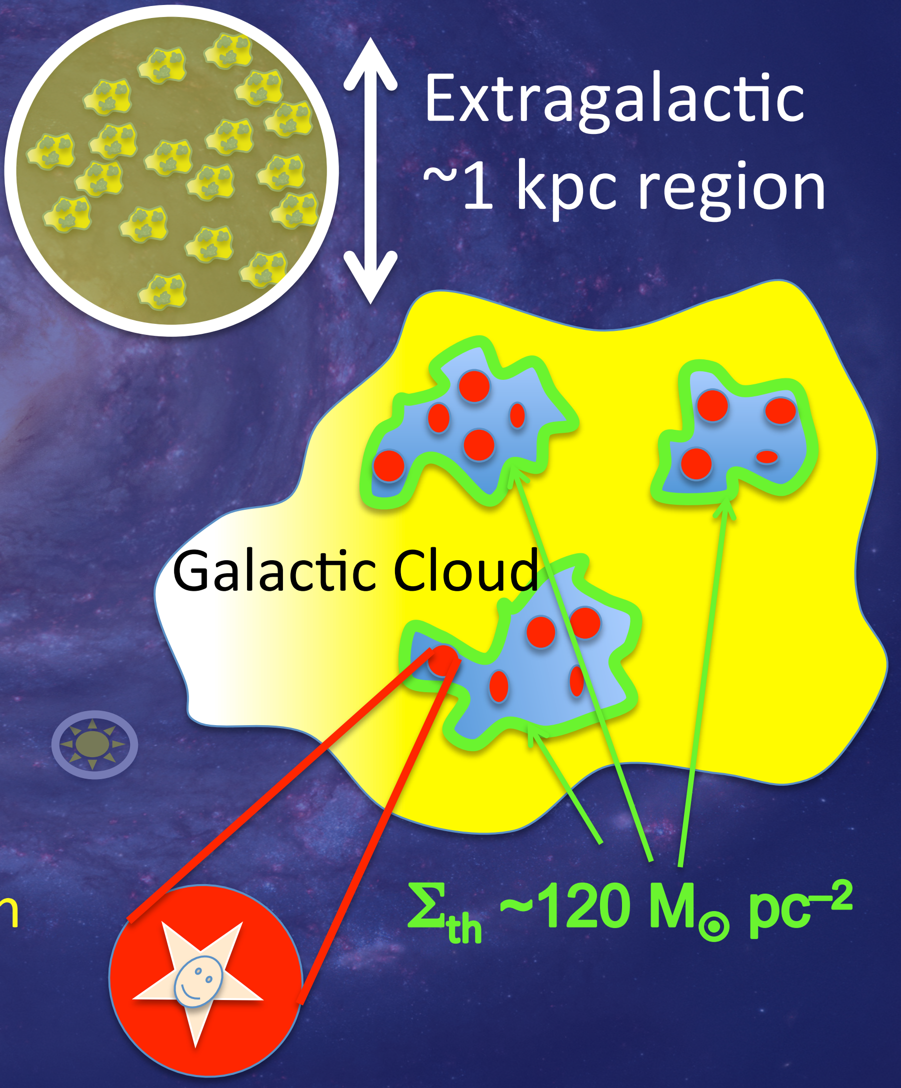
(3) Extragalactic *averages* include non- star forming molecular gas?

- Compare
  $M_{gas}(\Sigma_{gas} < \Sigma_{th}) / M_{gas}(\Sigma_{gas} > \Sigma_{th})$
- ~4.6 (c2d+GB clouds; A_V>2)
- ~5.1 (Orion; A_V>2 - Heyer, priv. comm.)
- A_V<2, factor of ~2 more molecular mass in Taurus (Goldsmith et al. 2008)



→ factor of ~10 more $M_{gas}(\Sigma_{gas} < \Sigma_{th})$ plausible, yielding agreement between Galactic clouds & Kennicutt-Schmidt relation

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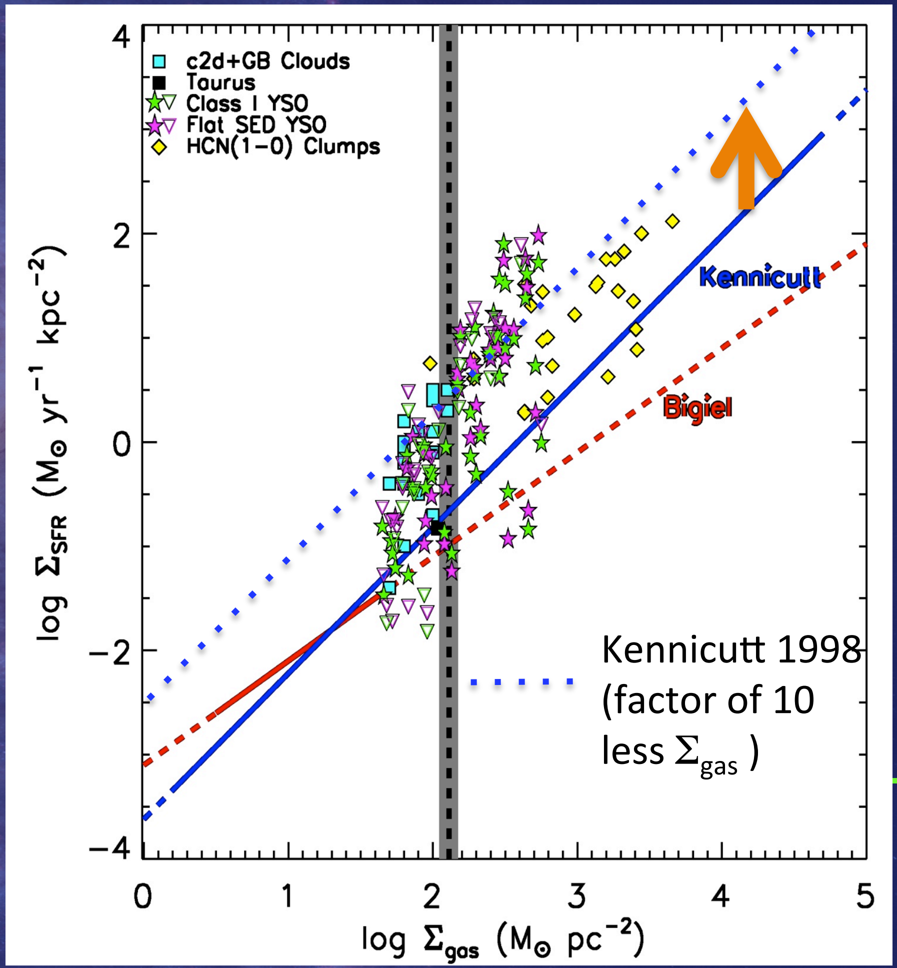


Predictions from this work

- Extragalactic studies average over large areas, star forming regions unresolved
- Measurements contains both diffuse & dense molecular gas
- Predictions and observational tests:

assume: $\Sigma_{SFR} \propto < \Sigma_{gas} >^{1.4}$ (K-S relation)

if: $\Sigma_{SFR} \propto \Sigma_{dense}$ $(\Sigma_{gas} > \Sigma_{th})$ (Galactic regions)

then: $\Sigma_{dense} \propto f_{dense} < \Sigma_{gas} > \propto \Sigma^{1.4}{}_{gas}$

or $f_{dense} \propto < \Sigma_{gas} >^{0.4}$ (Heiderman et al. 2010)

  - At $<\Sigma_{gas}> \cong 300\ \Sigma_{th}, f_{dense} \sim 1$
  - Star formation is most efficient → maximal starburst

Testing Models of Star Formation

- Empirical relations have motivated two contradicting models:

1) free-fall model: $\rho_{SFR} \propto \rho_{gas}^{1.5}$ (Krumholz & McKee 2005, Krumholz & Thompson 2007)

2) Observations of density thresholds in Galactic clouds: SFR $\propto M_{dense}$ ($\Sigma_{gas} > \Sigma_{th}$) (Lada et al. 2010, 2012)

Semi-empirical Free-fall Model

- $t_{ff} \propto \rho^{-0.5} \rightarrow \rho_{SFR} \propto \rho_{gas}^{1.5}$ (Krumholz & McKee 2005, Krumholz & Thompson 2007)

  → Consistent to the Kennicutt-Schmidt relation (N~1.4) within uncertainties

Theory: $\rho_{SFR} = f_{H2}\, \varepsilon_{ff}\, \rho_{gas}/t_{ff}$ (Krumholz, Dekel, & McKee 2012)

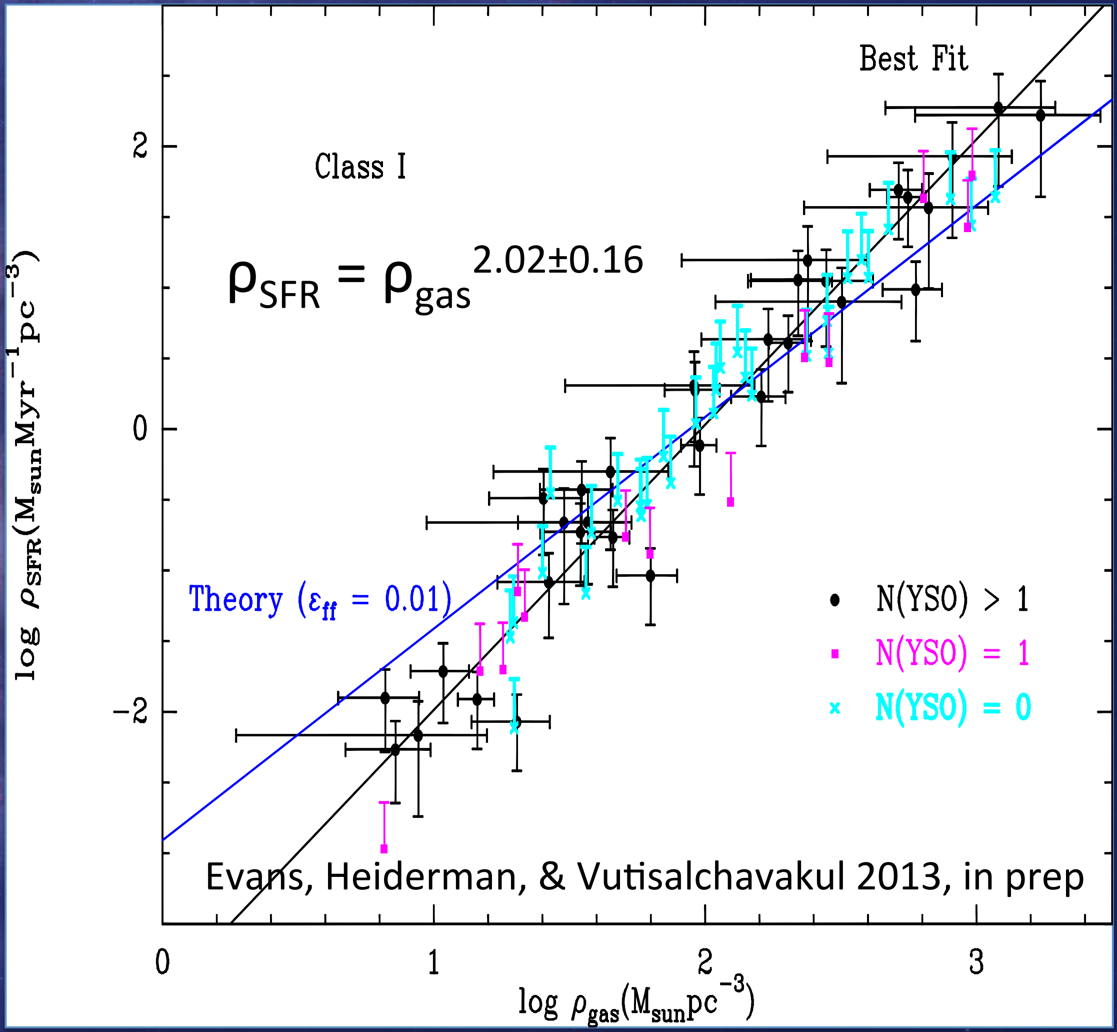
or: $\rho_{SFR}\,(M_\odot\ \mathrm{Myr}^{-1}\ \mathrm{pc}^{-3}) = 0.12\varepsilon_{ff}\, \rho_{gas}^{1.5}\,(M_\odot\ \mathrm{pc}^{-3})$

(ε_{ff} =0.01; Krumholz & McKee 2005)

Testing the Free-fall Model

– Find correlation between Class I YSOs and ρ_{gas} with a slope of 2

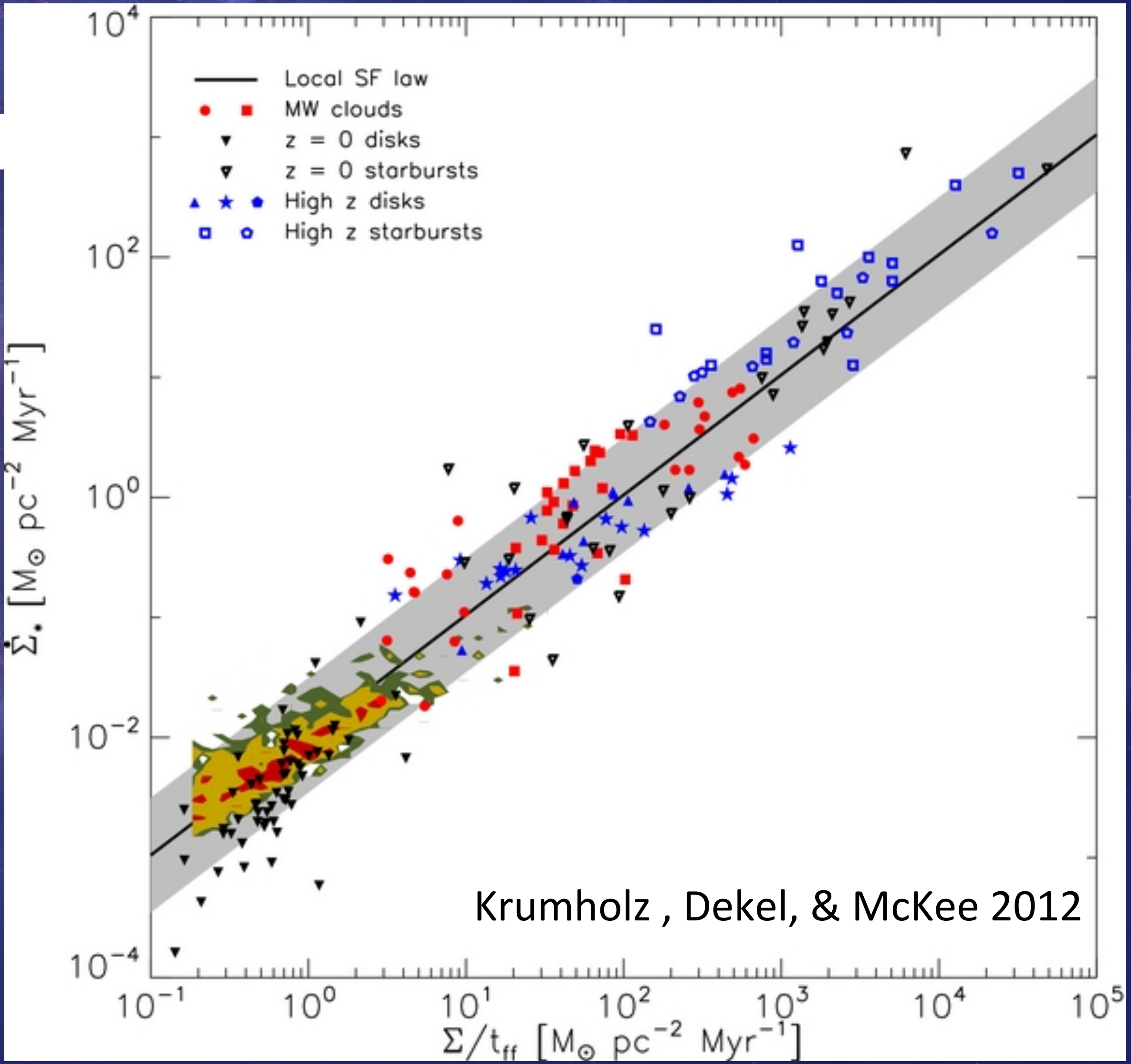
→ inconsistent with the t_{ff} model prediction



Testing the Free-fall Model

- Krumholz, Dekel & McKee 2012 predict:

$\Sigma_{SFR} = f_{H2}\ \varepsilon_{ff}\ \Sigma_{gas}/t_{ff}$



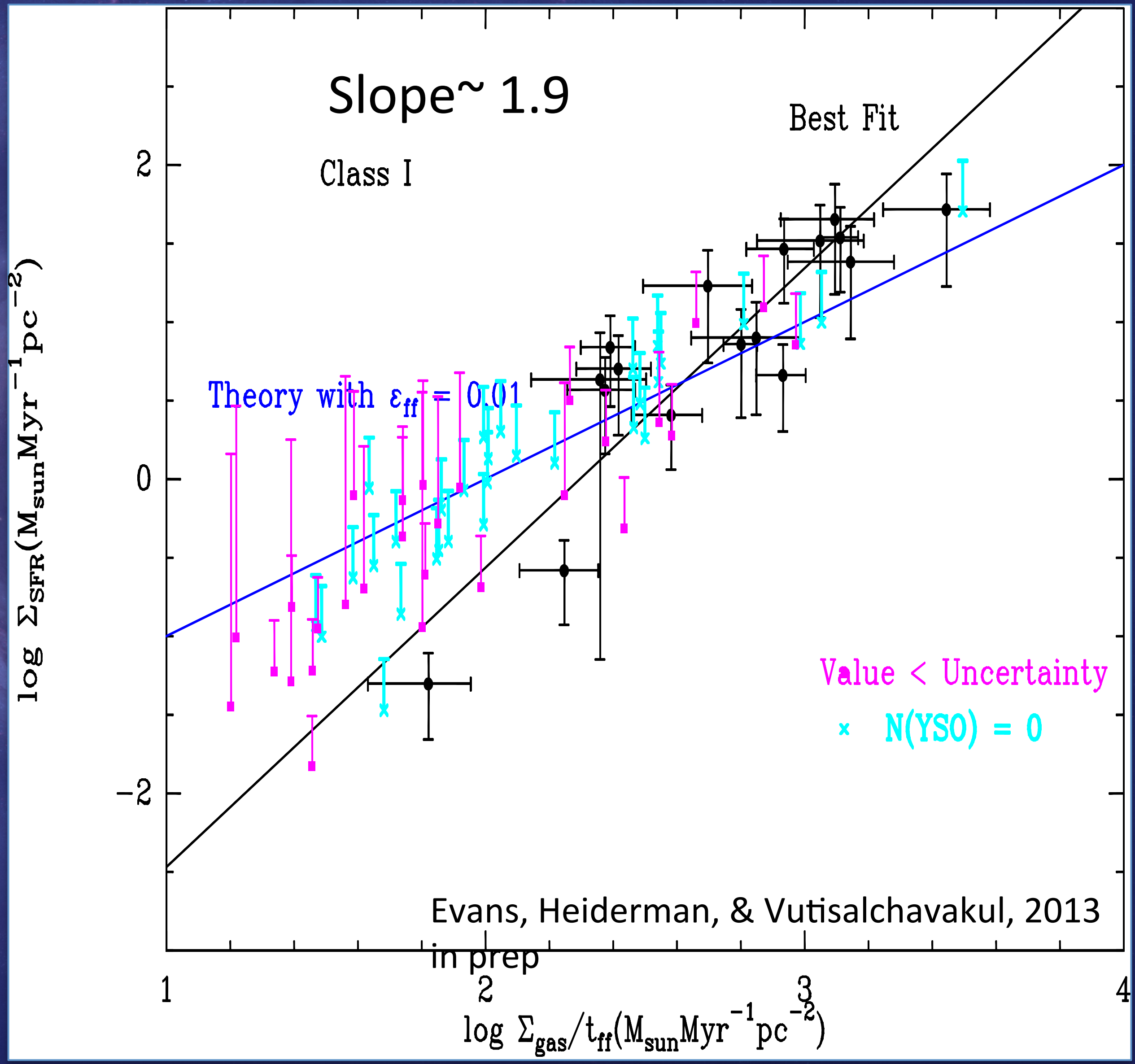
Testing the Free-fall Model

- Krumholz, Dekel, & McKee 2012 predict:

$\Sigma_{SFR} = f_{H2}\ \varepsilon_{ff}\ \Sigma_{gas}/t_{ff}$

- Find steeper slope of ~1.9 in Galactic clouds

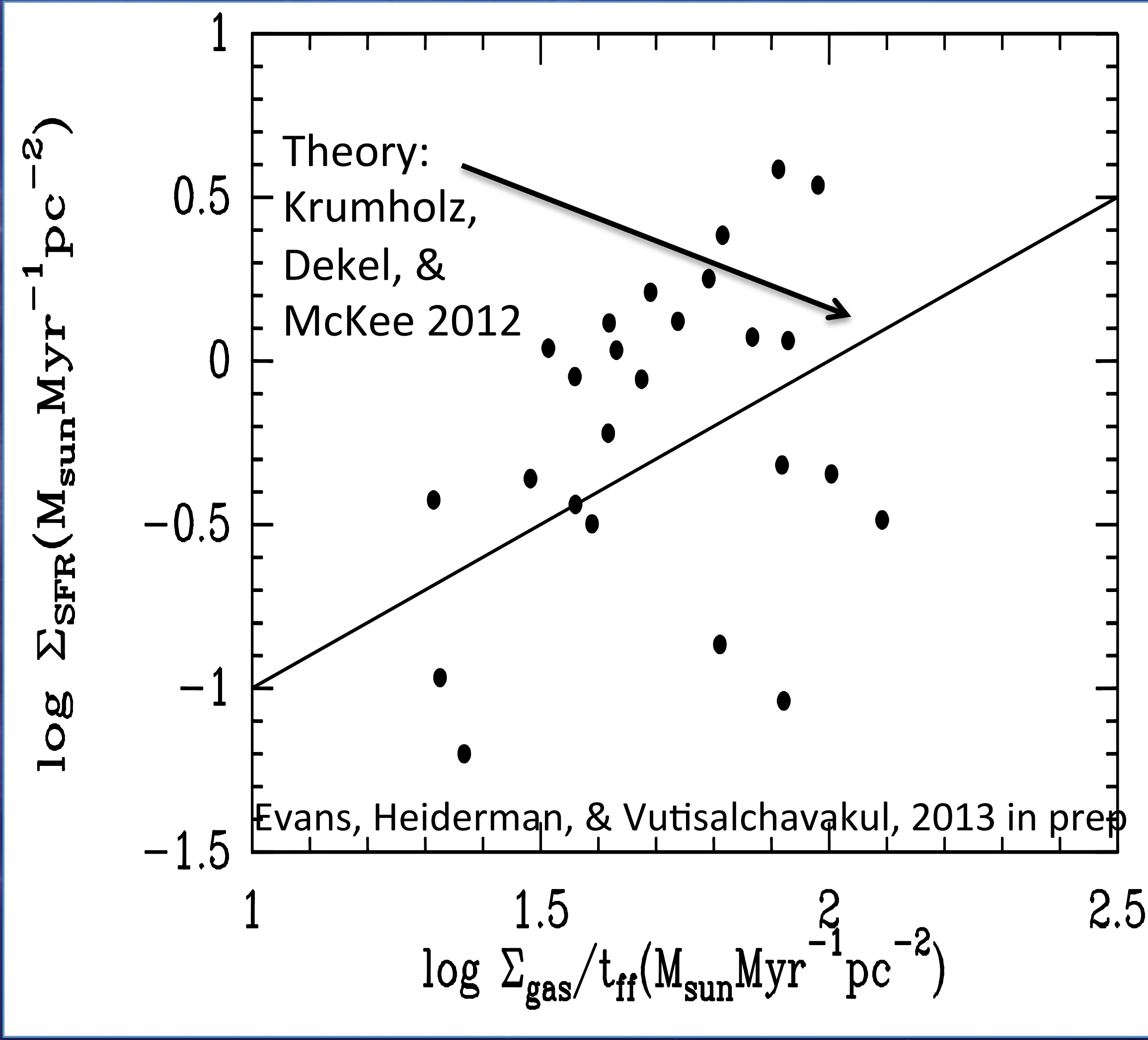
→ inconsistent with the t_{ff} model prediction



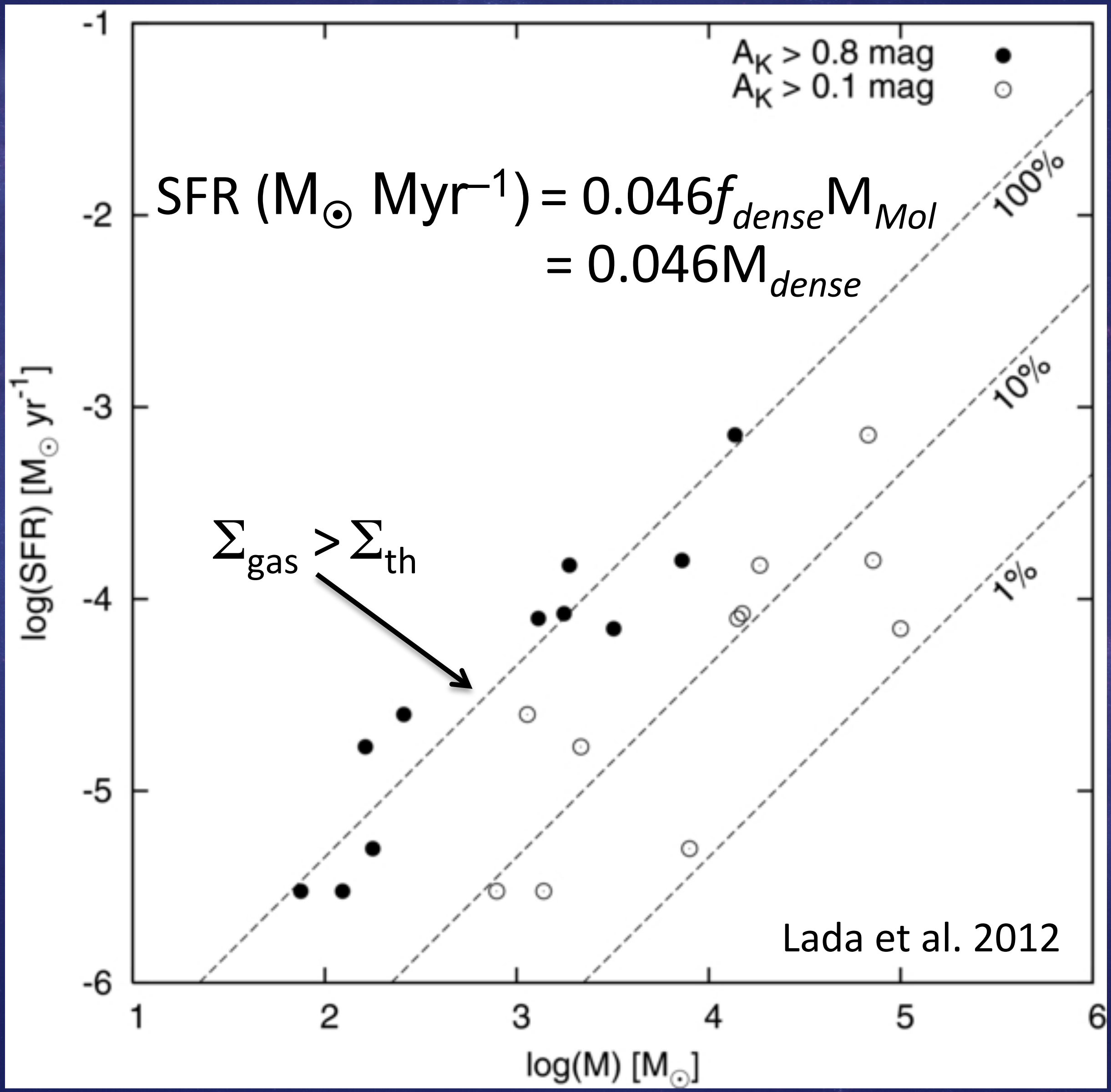
Evans, Heiderman, & Vutisalchavakul, 2013 in prep

Testing the Free-fall Model

- No convincing correlation for Galactic clouds compared to theory



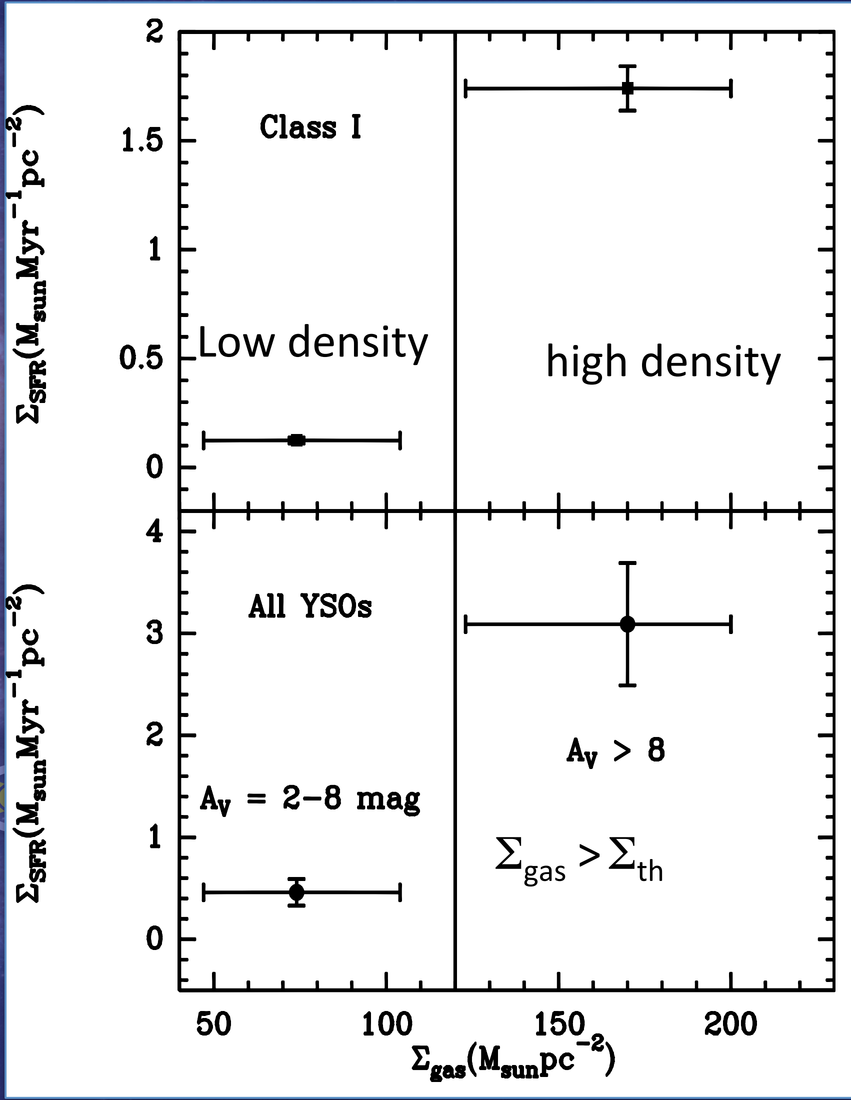
Gas Density Threshold Model



Testing the Threshold Idea

- Measure avg Σ_{SFR}, Σ_{gas}
  - Low density: A_V<8 ($\Sigma_{gas} < \Sigma_{th}$)
  - High density: A_V>8 ($\Sigma_{gas} > \Sigma_{th}$)
- YSO surface densities are factor of ~7-14 higher for A_V>8

→ 64% of all YSOs (77% Class I) lie in regions of dense gas (20% of total cloud area)



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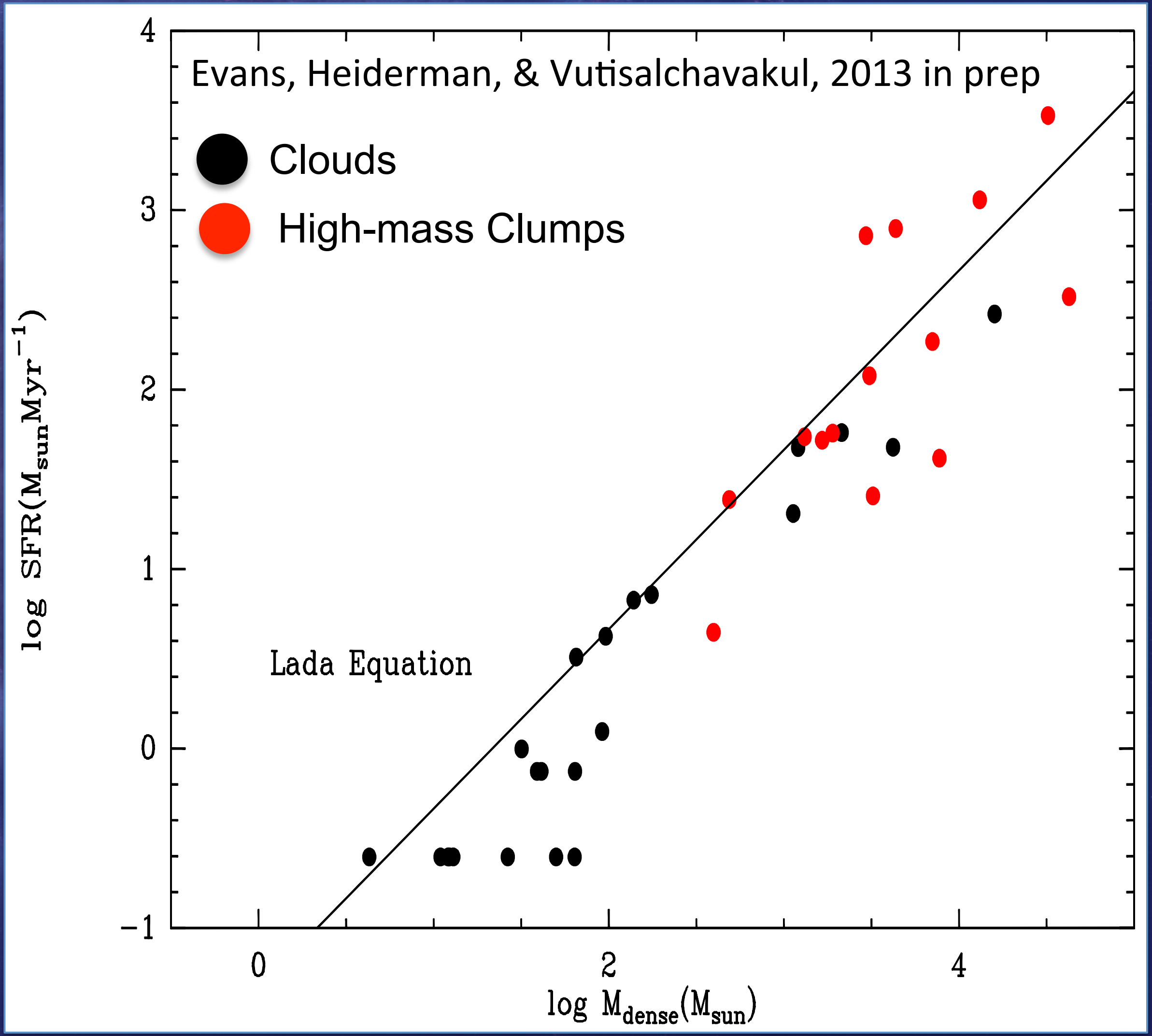
Testing the Threshold Model

- Total YSOs (A_V>8; Σ_{gas} > Σ_{th})
- YSOs only:
  - SFR ($M_\odot$ Myr^{-1}) = $0.032M_{dense}^{0.95}$
- YSOs + Clumps (w/ new SFR radio continuum (Vutisalchavakul & Evans 2013):
  - SFR ($M_\odot$ Myr^{-1}) = $0.016M_{dense}^{1.1}$



Summary

- ~10 times more SF in Galactic clouds than predicted by extragalactic prescriptions (e.g. Kennicutt-Schmidt relation)
- Averaging over large scales may contribute to discrepancy between Galactic and extragalactic SFR-gas relations
- Tight linear relation between *dense* gas mass and SFR in nearby Galactic clouds
  - HCN is reasonable proxy for dense gas in galaxies
- free-fall time not important for predicting the SFR on small scales in Galactic clouds (steeper dependencies seen)