The Star Formation Rate and Gas Surface Density Relation in the Milky Way: Implications for Extragalactic Studies

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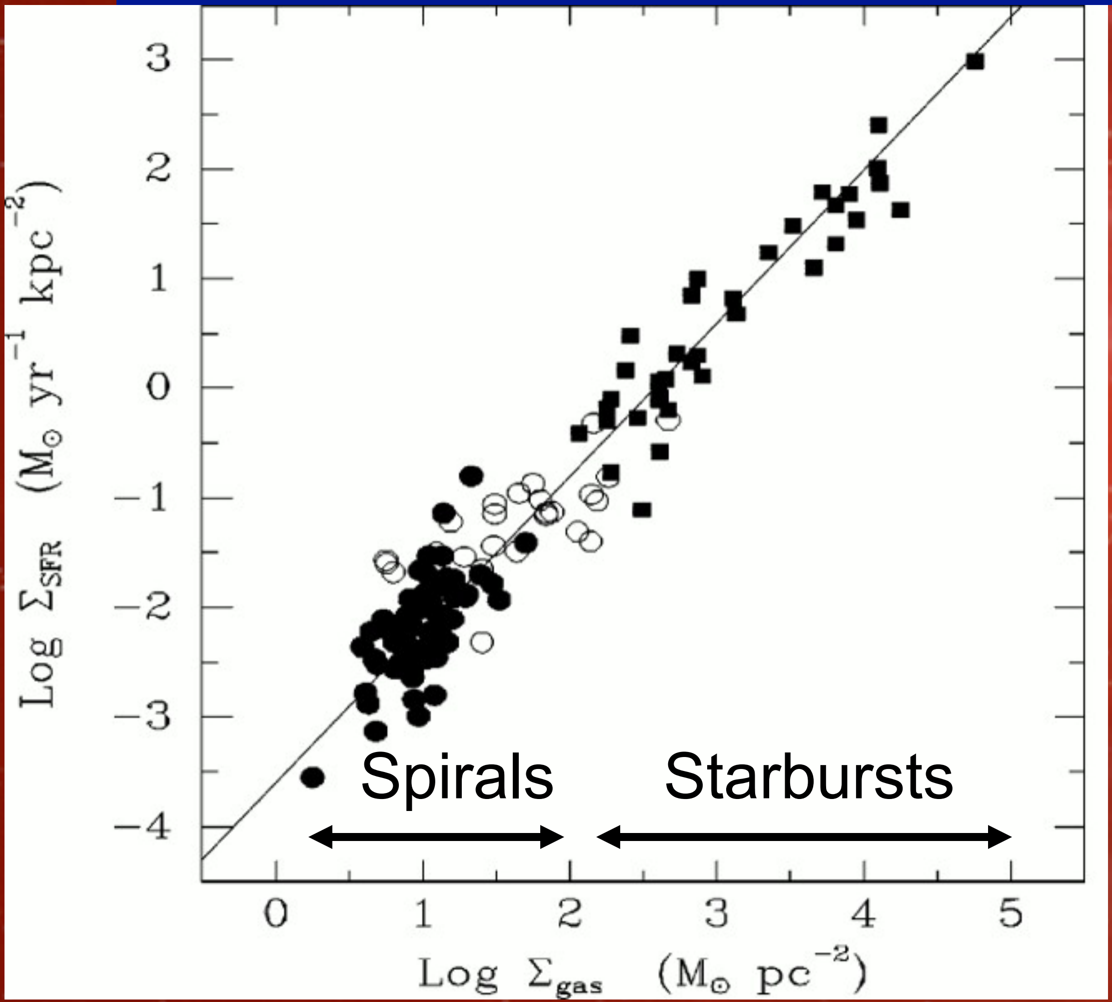
2010, ApJ, 723,1019

Spectroscopy 2011, Victoria, BC

Star Formation Rate-Gas Relations

- **Schmidt 1959**:
  - SFR~ Σ^{N}_{gas}
- **Kennicutt 1998**:
  - $\Sigma_{SFR}(M_\odot\ yr^{-1}\ kpc^{-2}) = 2.5\text{x}10^{-4}\ \Sigma^{1.4}_{gas}(M_\odot\ pc^{-2})$
- **Bigiel et al. 2008**:
  - $\Sigma_{SFR}(M_\odot\ yr^{-1}\ kpc^{-2}) = 7.9\text{x}10^{-3}\ \Sigma^{1.0}_{mol}(10\ M_\odot\ pc^{-2})$
- **Krumholz 2009 Prediction**:
  - $\Sigma_{SFR} = f(\Sigma_{gas}, f(H_2), Z, \text{clumping})$
  - linear $\Sigma_{gas} < 85\ M_\odot\ pc^{-2}$, steepens $\Sigma_{gas} > 85\ M_\odot\ pc^{-2}$

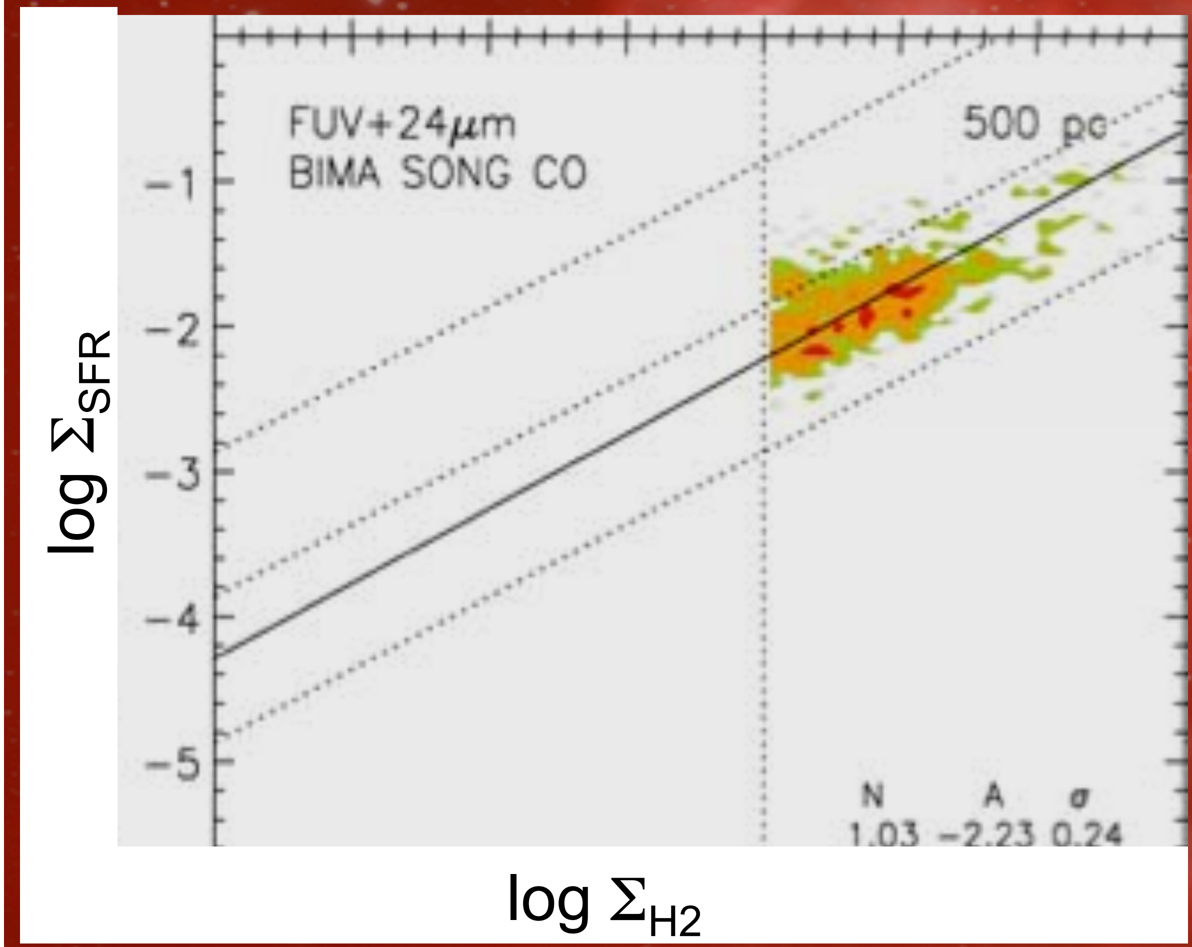
Star Formation Rate-Gas Relations



Kennicutt-Schmidt Relation
Slope: 1.4±0.15

- Kennicutt 1998:
  - $\Sigma_{SFR}(M_\odot\ yr^{-1}\ kpc^{-2}) = 2.5\times10^{-4}\ \Sigma^{1.4}_{gas}(M_\odot\ pc^{-2})$

Star Formation Rate-Gas Relations

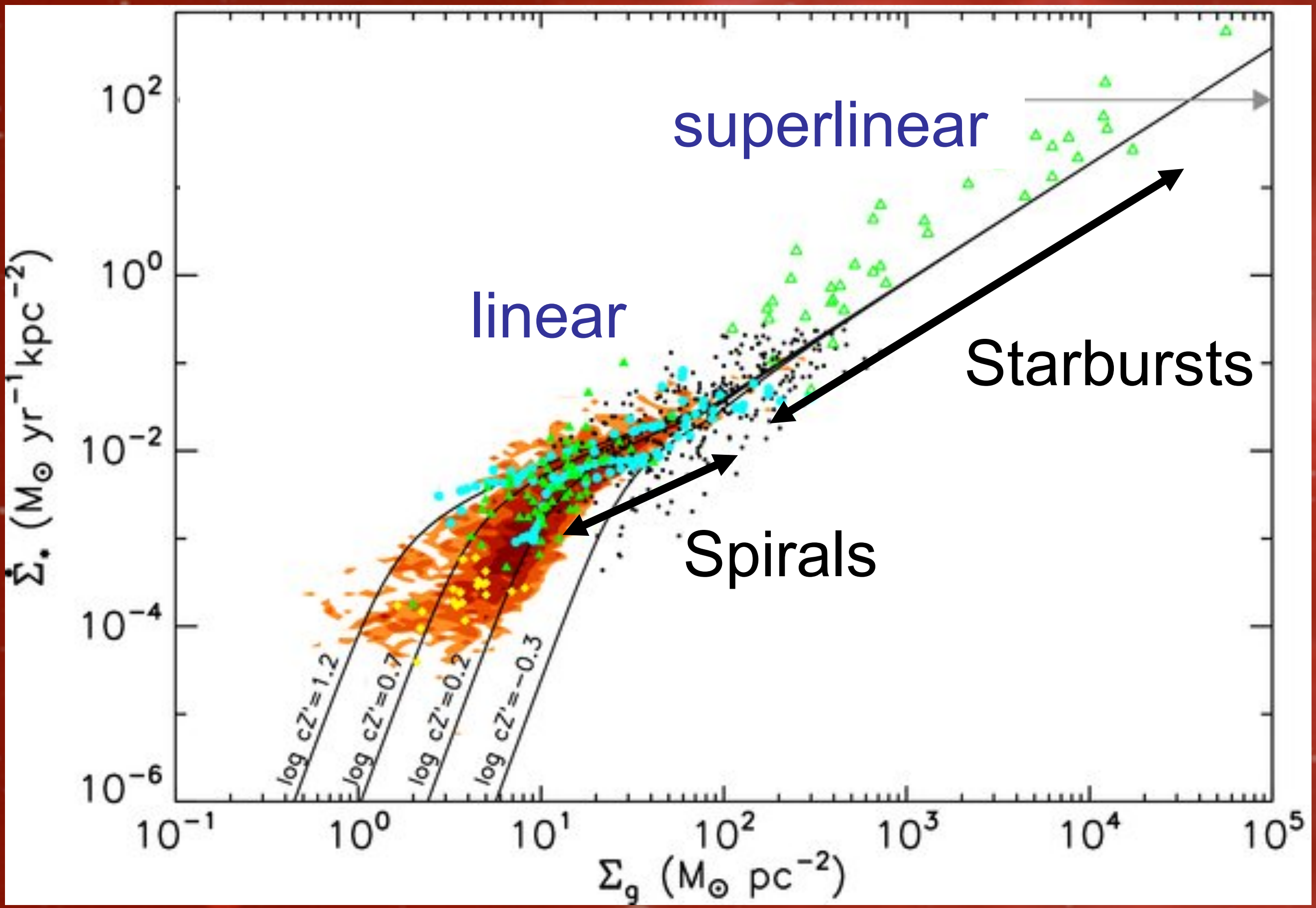


Bigiel et al. Relation
Slope: 1.0

Σ_{gas} range: 3-50 $M_\odot$ pc^{-2}

- **Bigiel et al. 2008**:
  - $\Sigma_{SFR}(M_\odot\ yr^{-1}\ kpc^{-2}) = 7.9\text{x}10^{-3}\ \Sigma^{1.0}_{mol}(10\ M_\odot\ pc^{-2})$

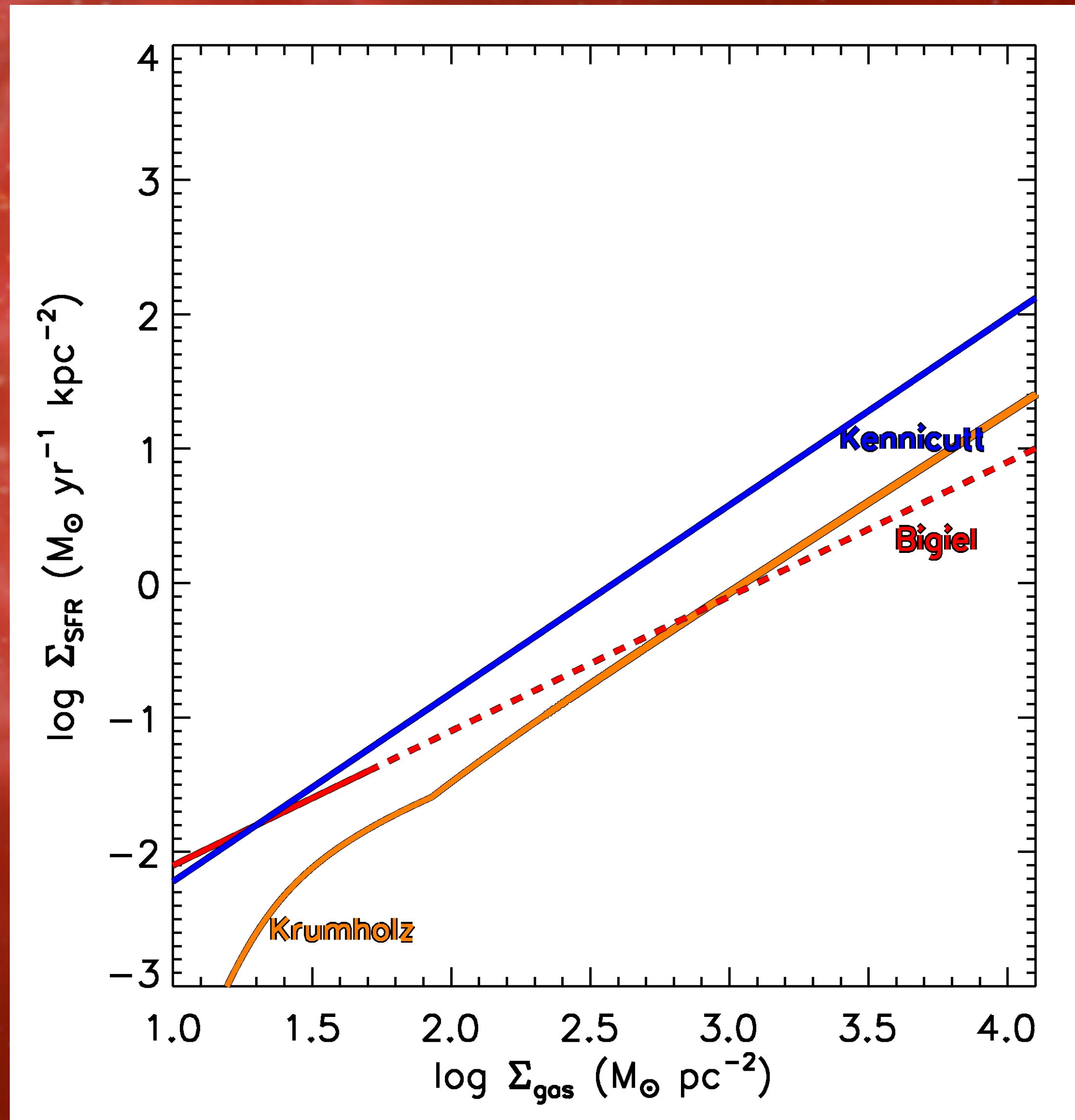
Star Formation Rate-Gas Relations



- **Krumholz, Mckee, Tumlinson 2009 Prediction**:
  - $\Sigma_{SFR} = f(\Sigma_{gas}, f(H_2), Z, \text{clumping})$
  - linear $\Sigma_{gas} < 85\ M_\odot\ pc^{-2}$, steepens $\Sigma_{gas} > 85\ M_\odot\ pc^{-2}$

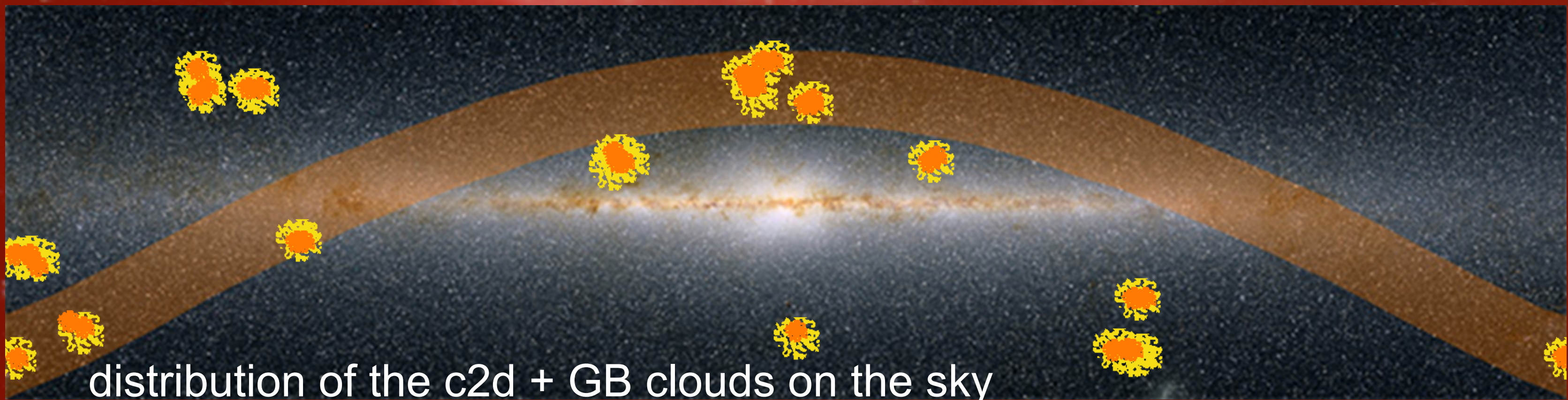
Testing Extragalactic Relations in Local Clouds

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



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

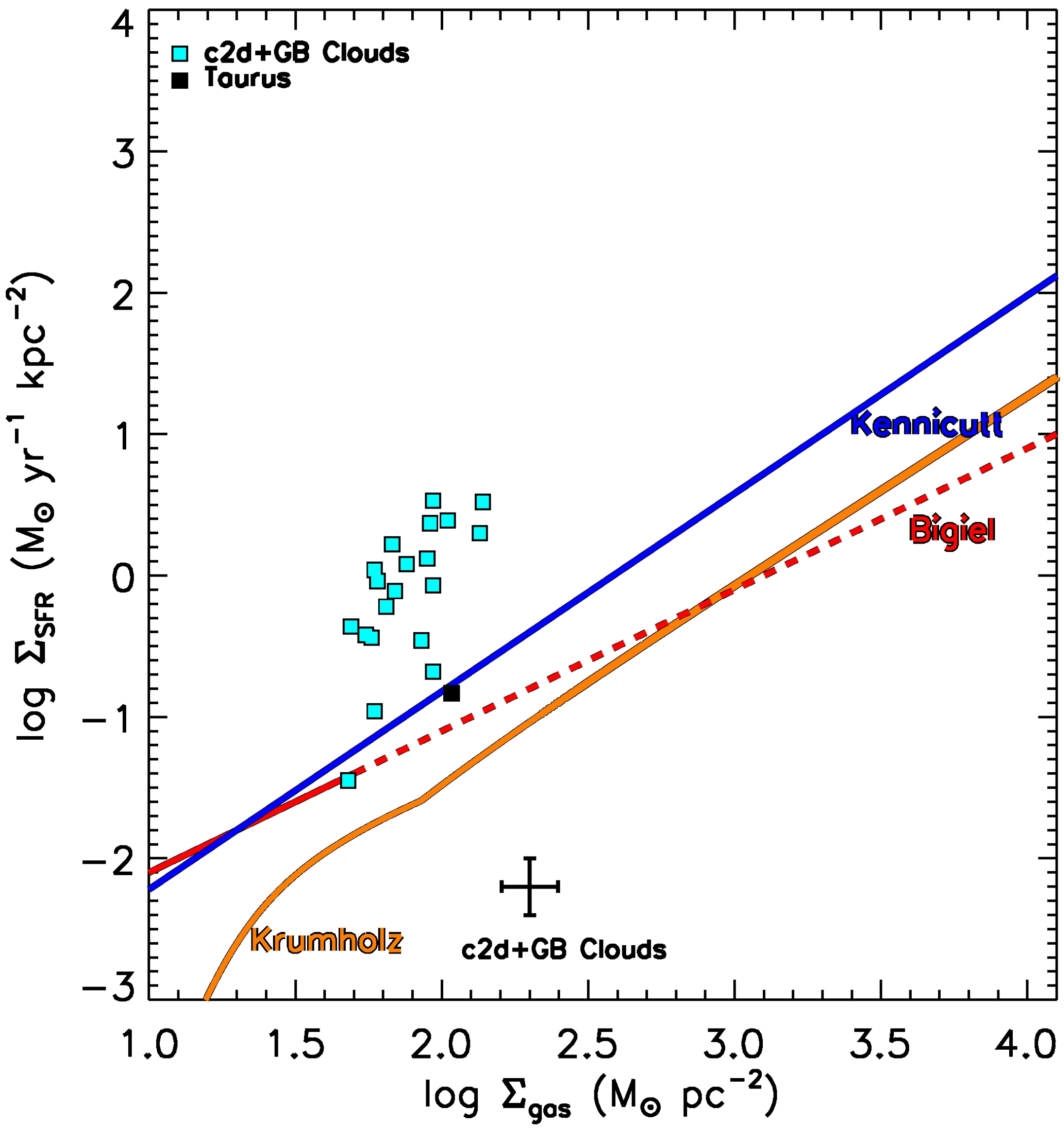
- *Spitzer* Legacy Surveys*:*
  - "cores to disks" (c2d; Evans et al. 2009)
  - Gould's Belt (GB; L. Allen et al., in prep.)
- 7 c2d + 13 GB clouds
- Cloud mass, Σ_{gas} from extinction maps, $A_V > 2$ mag
  - $\Sigma_{gas} = 15A_V$ ($M_\odot$ pc^{-2})
- SFRs from YSO counts, mean mass 0.5 $M_\odot$, & lifetimes



distribution of the c2d + GB clouds on the sky

c2d+GB Clouds

- 20 c2d+GB clouds and Taurus
- Clouds lie factor of 9-17 above exgal relations
- Average Σ_{gas} = 92 $M_{\odot}$ pc^{-2}
- Kennicutt-Schmidt relation predicts Σ_{SFR} ~0.13 $M_{\odot}$ yr^{-1} kpc^{-2}, average point is 1.2 $M_{\odot}$ yr^{-1} kpc^{-2}
- "inactive" clouds (Taurus, Cha III) lie near predictions



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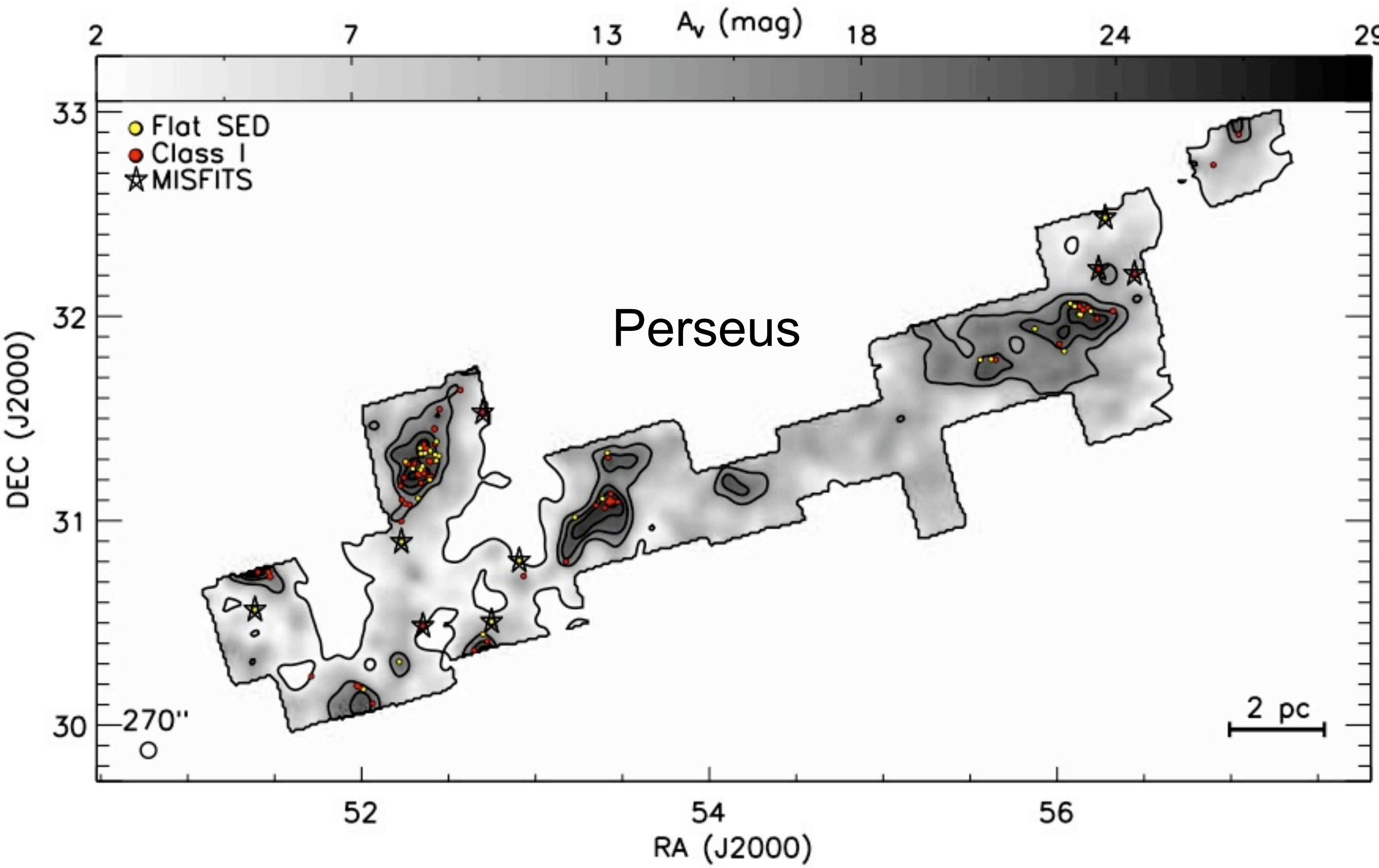
Youngest YSOs

- YSOs wander out of birthplace
  - 2 Myr old YSO in a core with velocity dispersion ~1 km/s wander ~2pc
- Count only young (t~0.5 Myr) YSOs (Class I, Flat SED)
- Measure $\Sigma_{gas,}$ Σ_{SFR} in A_V contours

Youngest YSOs



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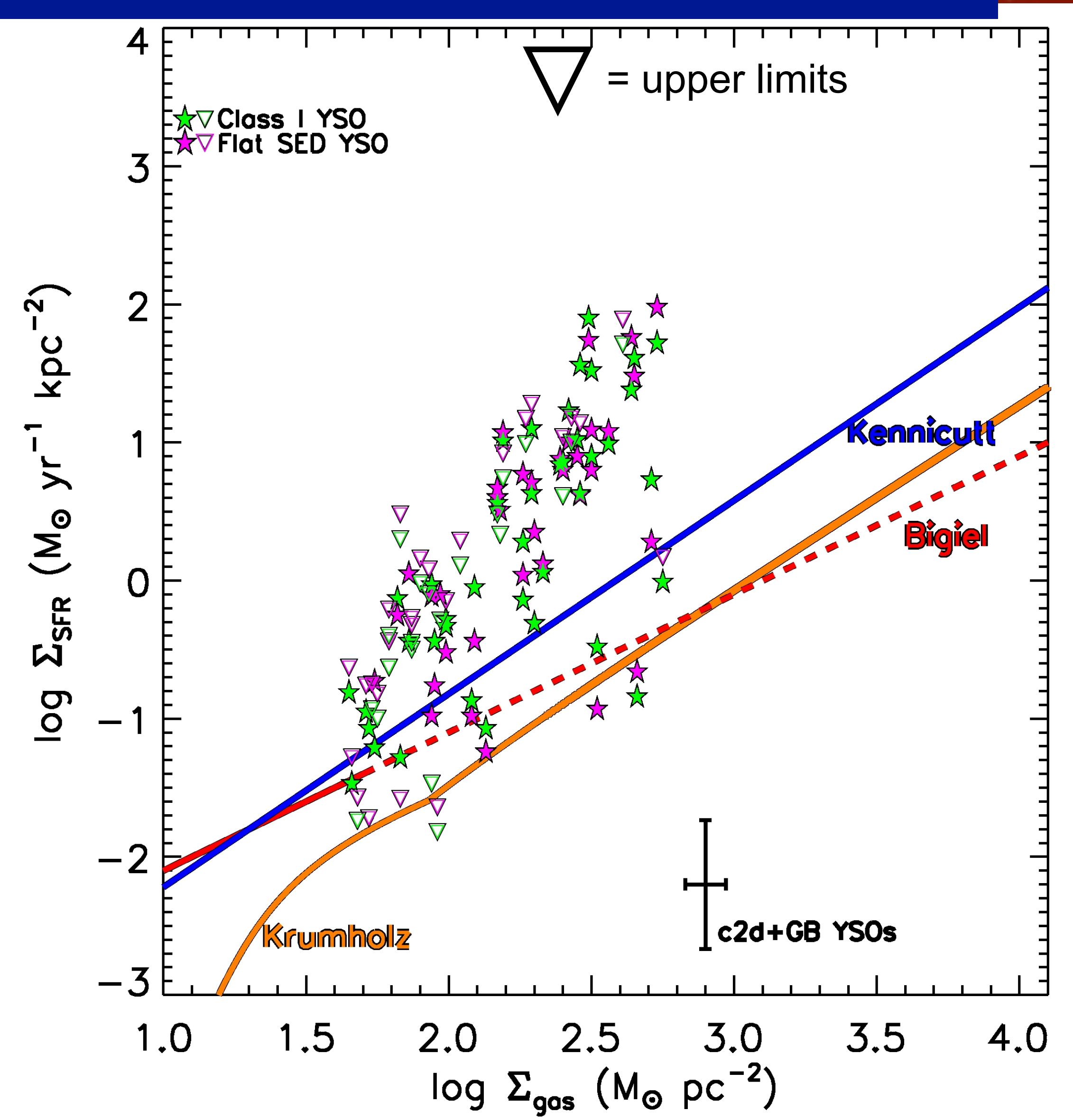
MISidentified YSOs from SED FITS (MISFITS)

- Check suspicious YSOs at low A_V "MISFITS"
- Ongoing HCO^+ J=3-2 line survey, CSO
  - All northern clouds
- This study: 98 suspicious sources (45 Flat; 53 Class I)
- 73/98 (74%) undetected
- 3/45 (7%) Flat SED, and 22/53 (42%) Class I detected

=> Take non-detections (MISFITS) out of sample

Youngest YSOs

- factor of 21-54 above exgal relations
- Average Σ_{gas} = 225 $M_{\odot}$ pc^{-2}
- Kennicutt-Schmidt relation predicts Σ_{SFR} ~0.47 $M_{\odot}$ yr^{-1} kpc^{-2}, average point is 9.7 $M_{\odot}$ yr^{-1} kpc^{-2}



Possible Explanations

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

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

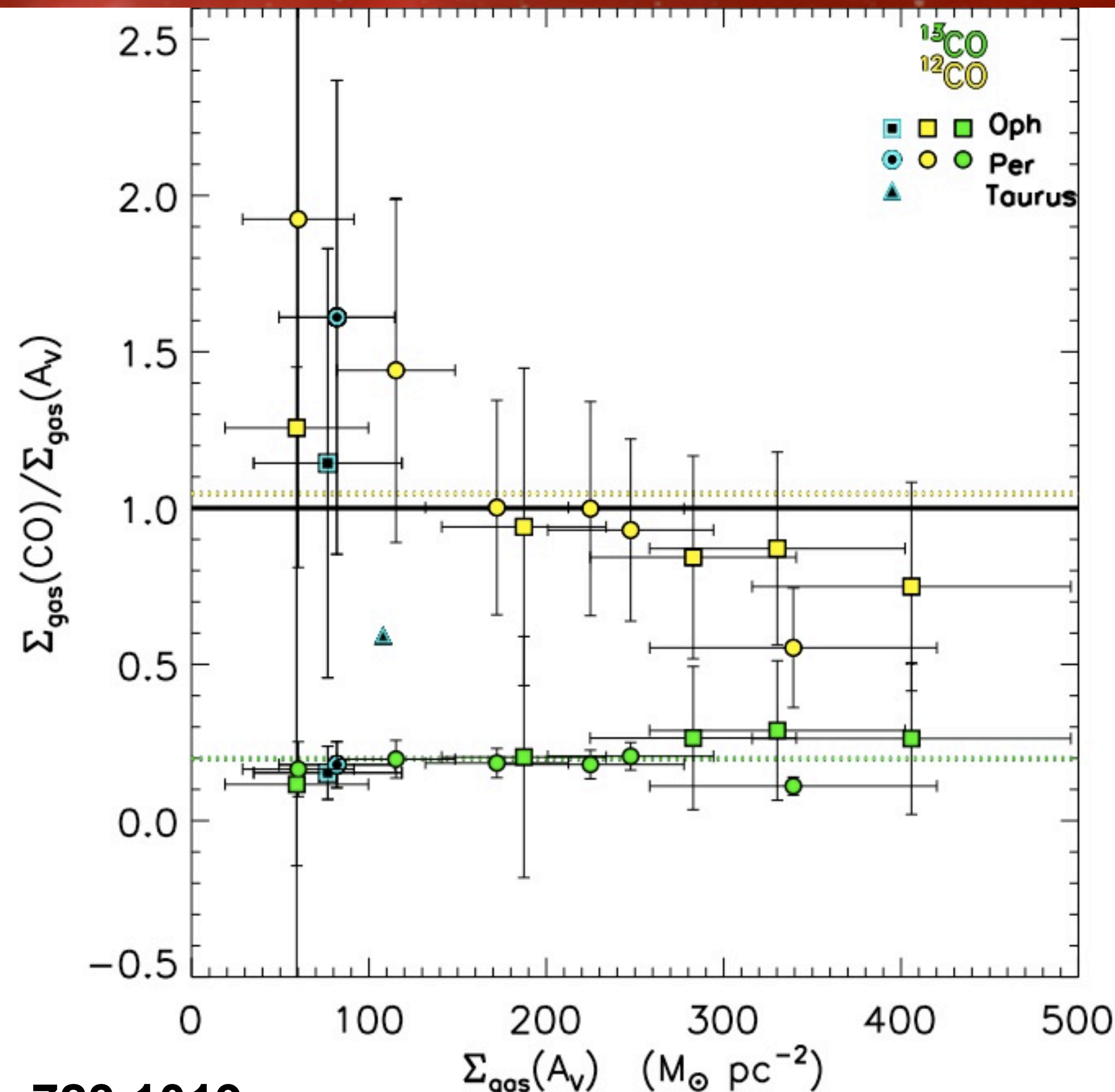
- Exgal tracers **only measure massive star formation**, missing low- mass star formation

(3) Are Exgal measurements are highly beam-diluted?

- Most gas lies below a star forming threshold Σ_{gas}

(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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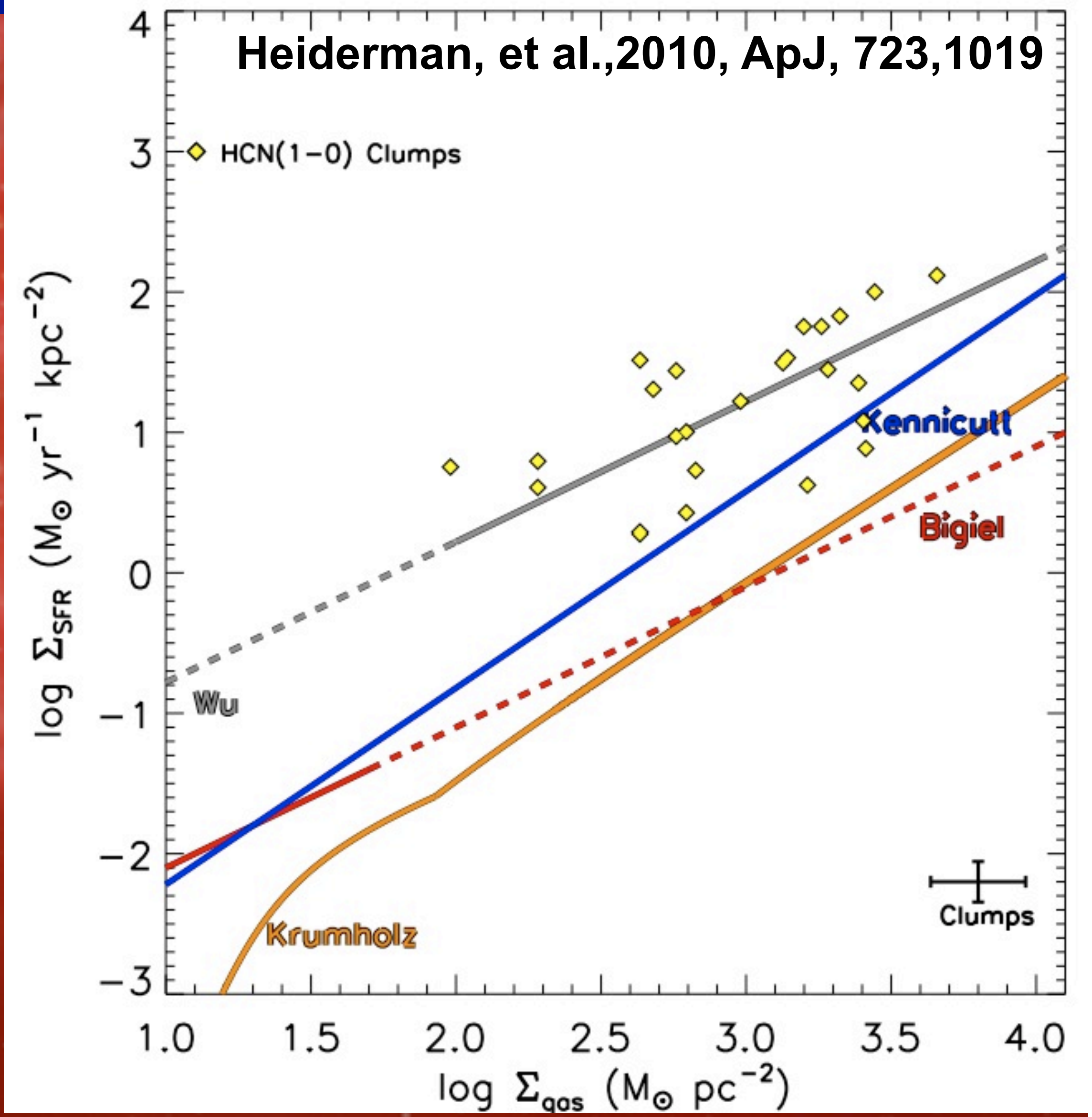
(2) Do Massive Star Forming Regions Behave Differently?

- 50 Massive, dense, clumps (Wu et al. 2010)
- Visible in exgal studies
- $L_{IR} > 10^{4.5}\ L_{\odot}$
- Σ_{gas} from size, M_{VIR}
- Σ_{SFR} from size & SFR_{IR} from L_{IR} using exgal prescription



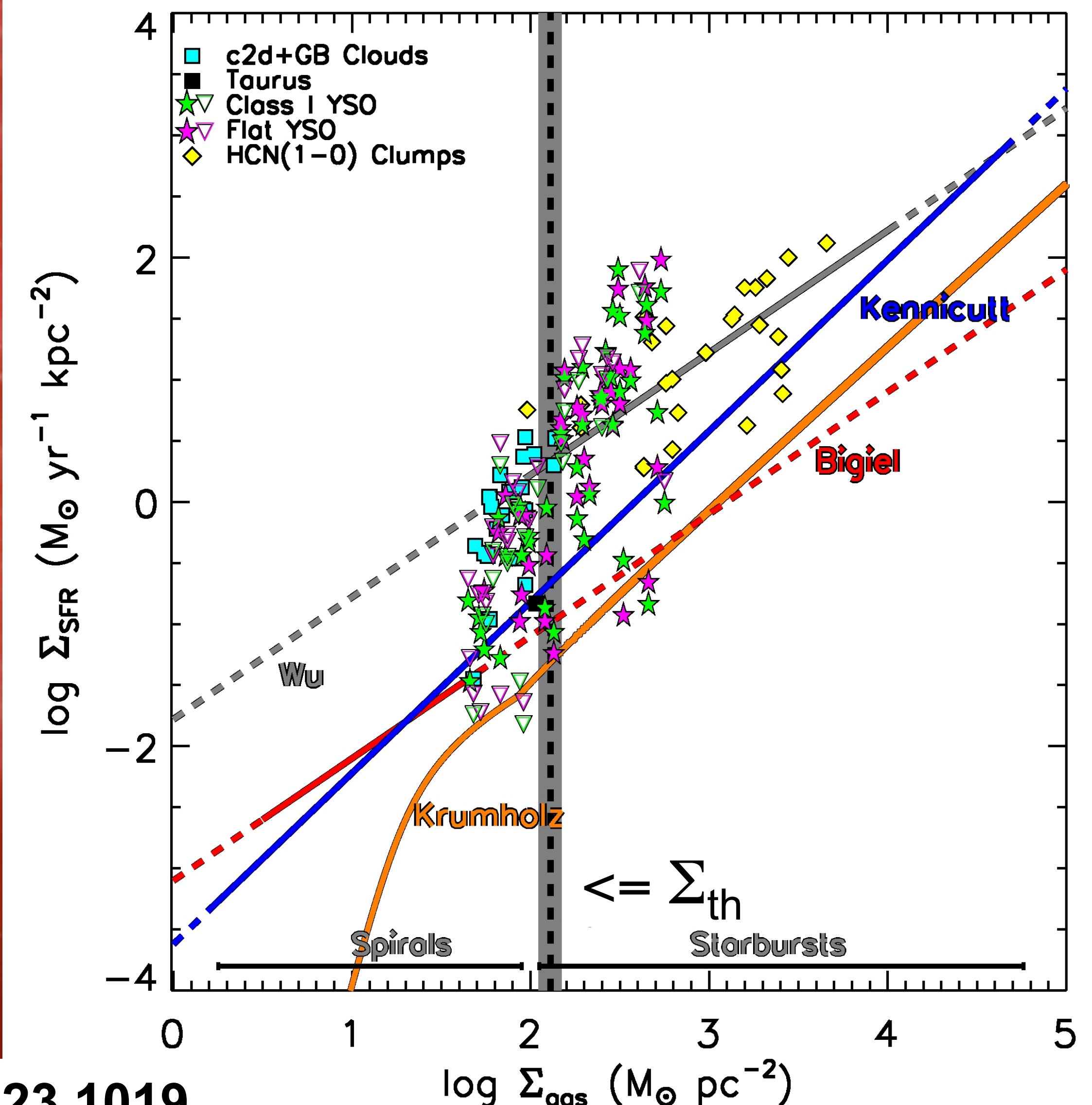
(2) Do Massive Star Forming Regions Behave Differently?

- Class I & Flat YSOs and clumps are *similar* beyond star forming threshold 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



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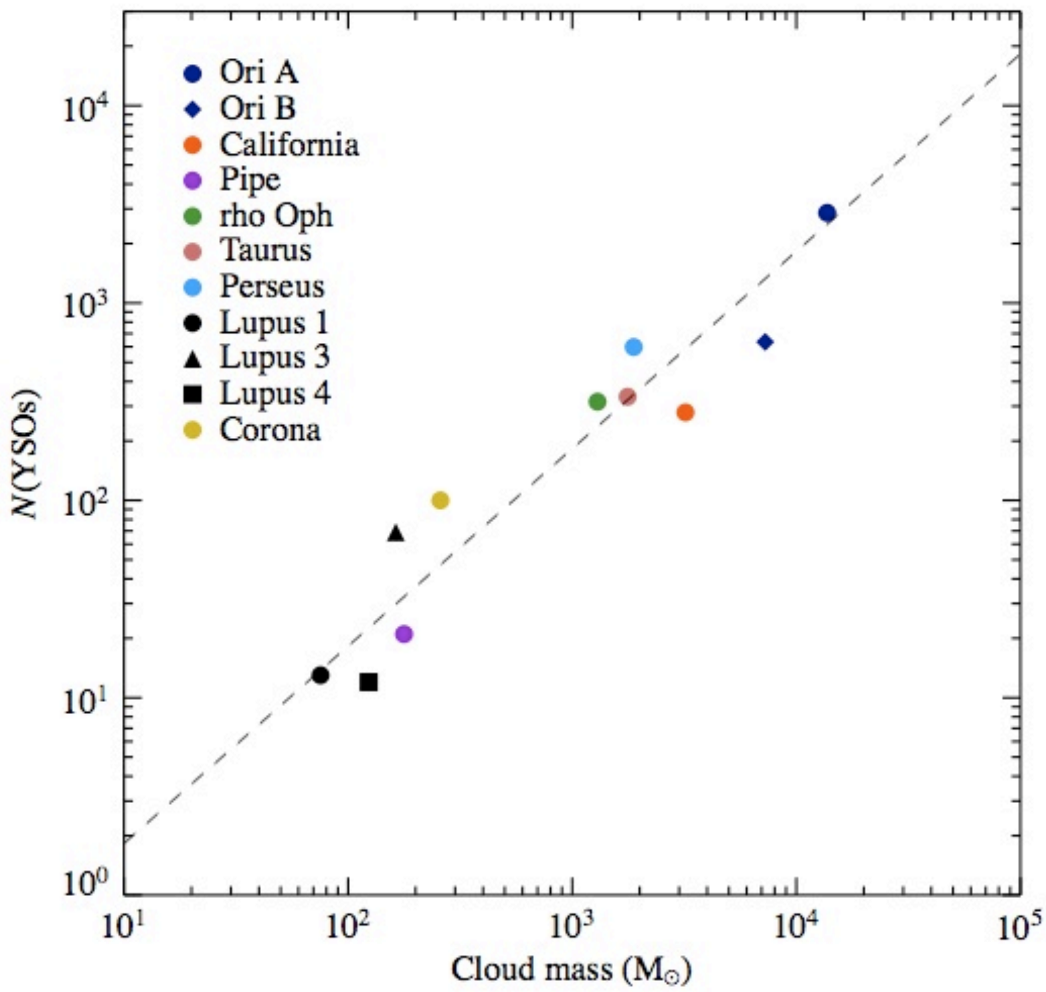
Star Forming Threshold

- Predictions for Σ_{th}
  - Σ_{crit} >50-110 $M_\odot$ pc^{-2} (B-field support against grav. collapse; Mouschovias & Spitzer 1976)
  - Σ_{crit} >60-120 $M_\odot$ pc^{-2} (photoionization regulated SF; McKee 1989)
- Observational studies find Σ_{th} ~120-150 $M_\odot$ pc^{-2} (Onishi 1998; Johnstone 2004, Enoch et al. 2007; Andre et al. 2010; Lada 2010)
- Using different methods, Lada 2010 found
  - Σ_{th} ~116 $M_\odot$ pc^{-2} (A_V ~7.3)
  - recovered a tight linear relation (slope =0.96; A_V >7.3)



Lada, Lombardi, & Alves (2010)

(3) Are Exgal Studies Beam Diluted?

- No complete census of CO in all clouds within local 0.5 kpc
- What can we say about amount of diffuse gas?
  - Mass ($\Sigma_{gas} < \Sigma_{th}$) /Mass ($\Sigma_{gas} > \Sigma_{th}$) from *Av* maps (*Av* >2)
    - 4.6 (c2d+GB clouds)
    - 5.1 (Orion - Heyer, private communication)
  - At Av < 2, factor of ~2 more molecular mass in Taurus (Goldsmith et al. 2008)
  - $M_{diffuse}/M_{dense}$ ~ 10 is plausible
- most gas in 0.5 kpc is atomic (Evans 2008), including this gas below the threshold will yield agreement between local Σ_{SFR} and Kennicutt-Schmidt

=> exgal may lack resolution: measurements include a large amount of diffuse, non- star forming gas

(3) Are Exgal Studies Beam Diluted?

- Exgal studies average over large areas, star forming regions unresolved
- Beam contains both diffuse & dense gas
- Predictions and observational tests

assume: $\Sigma_{SFR} \propto \langle \Sigma_{gas} \rangle^{1.4}$

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

then: $\Sigma_{dense} \propto f_{dense} \langle \Sigma_{gas} \rangle \propto \Sigma^{1.4}_{gas}$

or $f_{dense} \propto \langle \Sigma_{gas} \rangle^{0.4}$

  - At $\langle\Sigma_{gas}\rangle \cong 300\ \Sigma_{th}$, $f_{dense} \sim 1$
  - gas dense enough to form stars ➔ maximal starburst

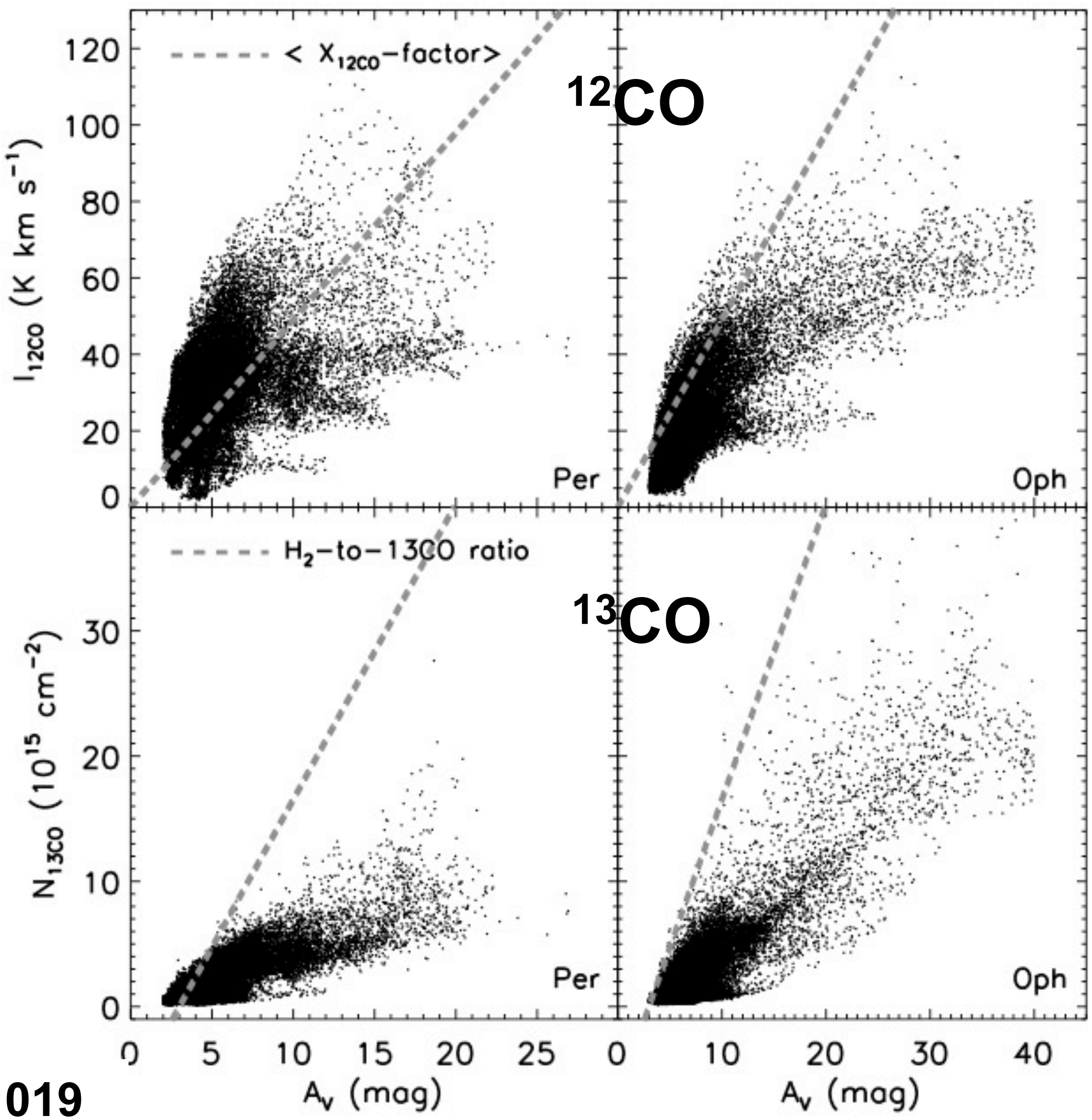
Summary

- 10-20 times more SF in Galactic clouds than predicted by exgal prescriptions
- CO poor tracer of Σ_{gas}; but does not explain discrepancy between local and exgal studies
- high-mass and low-mass star forming regions follow a similar linear relation at $\Sigma_{gas} > \Sigma_{th}$
- Averaging over large scales may contribute to discrepancy between Galactic and extragalactic studies
  - Good test for ALMA
- Non-linear nature of Kennicutt-Schmidt relation may tell us about fraction of *dense* star forming gas

Additional slides

(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



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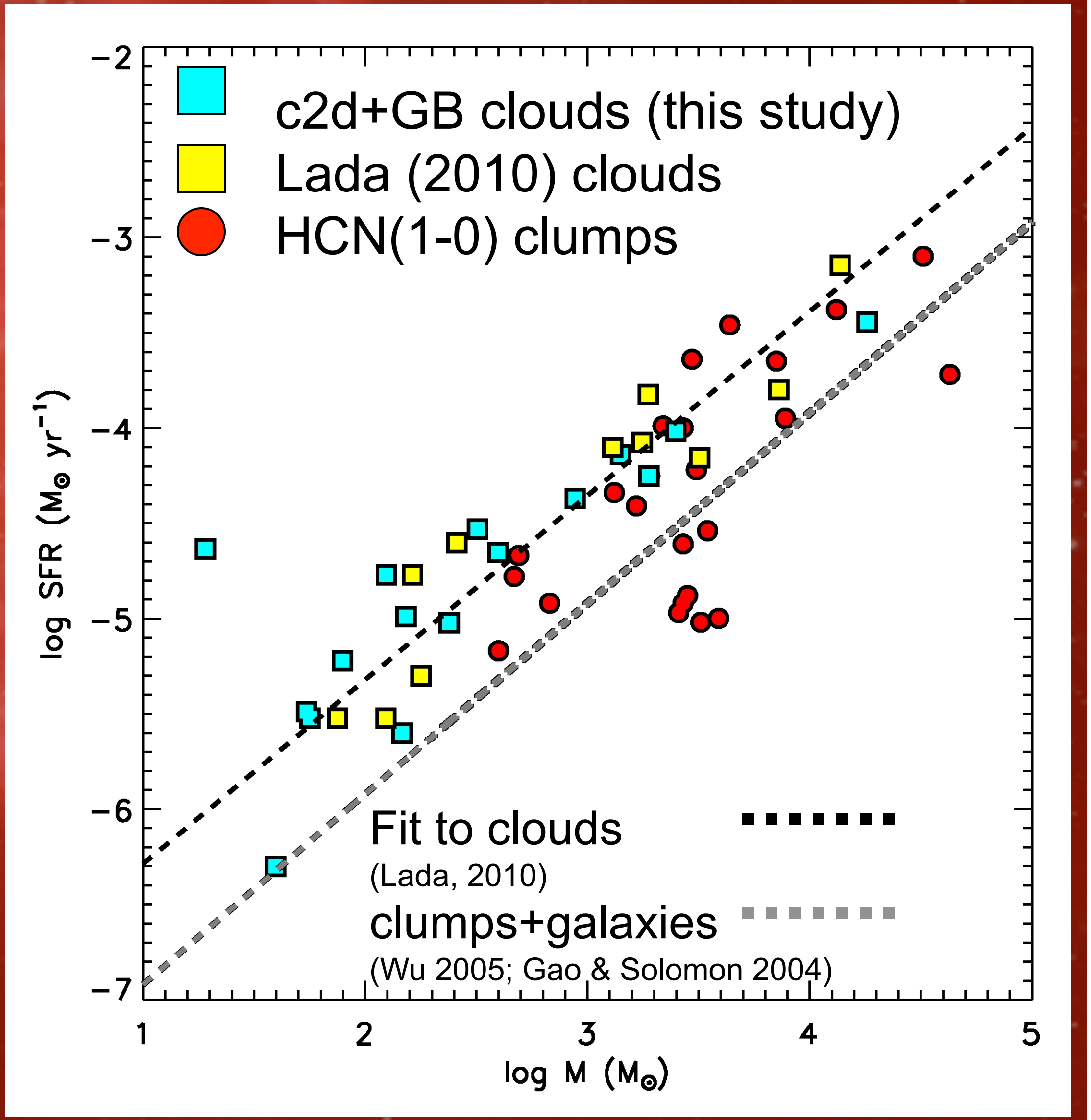
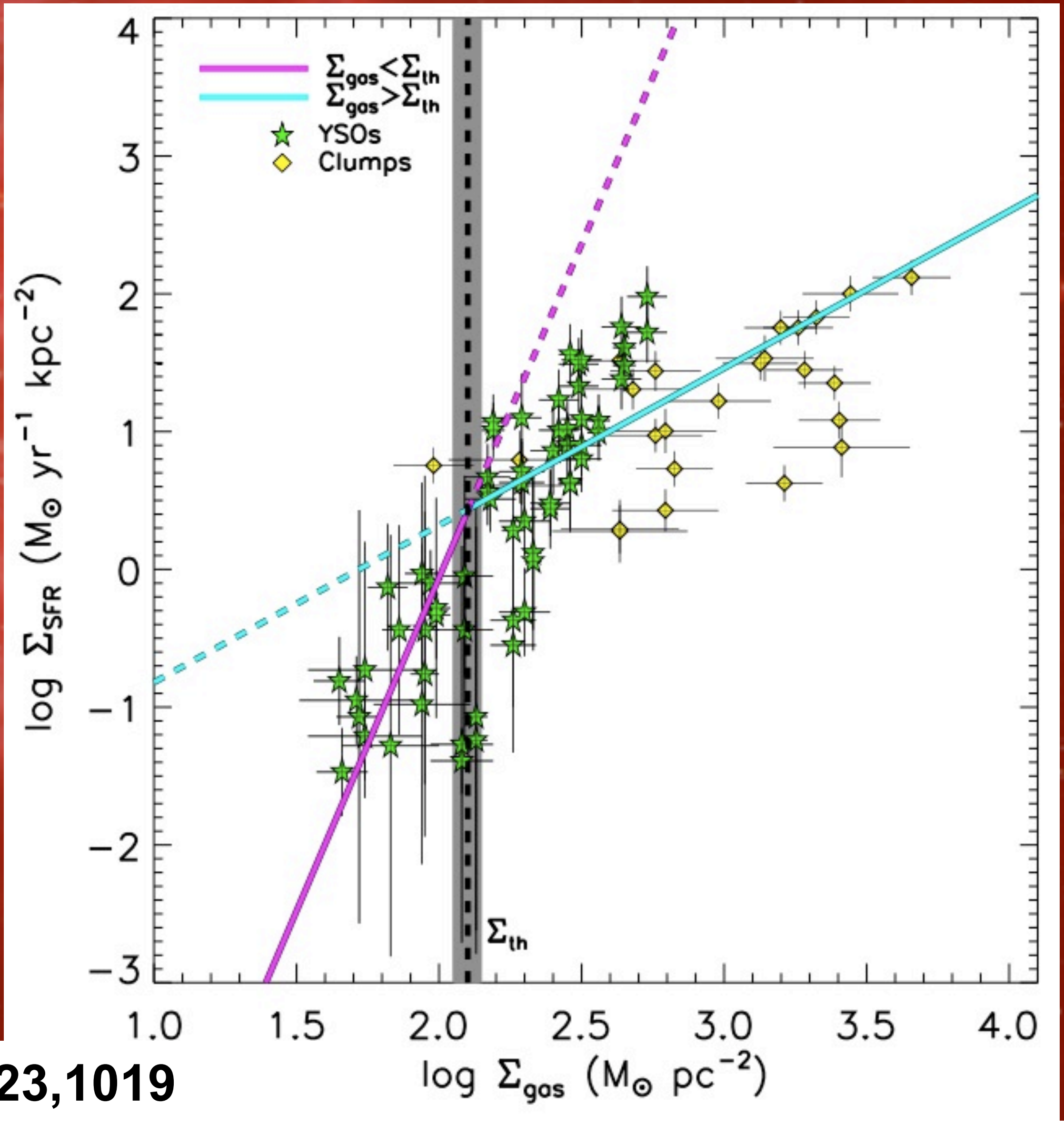
Star Forming Threshold

- Measuring cloud mass above threshold recovers a tight linear (slope =0.96) relation
- Works for most c2d+GB clouds, except clouds dominated by later stage YSOs
- Clumps+ galaxies also lie on similar relation



Star Formation Threshold (Σ_{th})

- broken power law fit to Class I & Flat YSO + Clumps
- Σ_{th} = 129±14 $M_{\odot}$ pc^{-2}
- Linear (slope 1.1) $\Sigma_{gas} > \Sigma_{th}$



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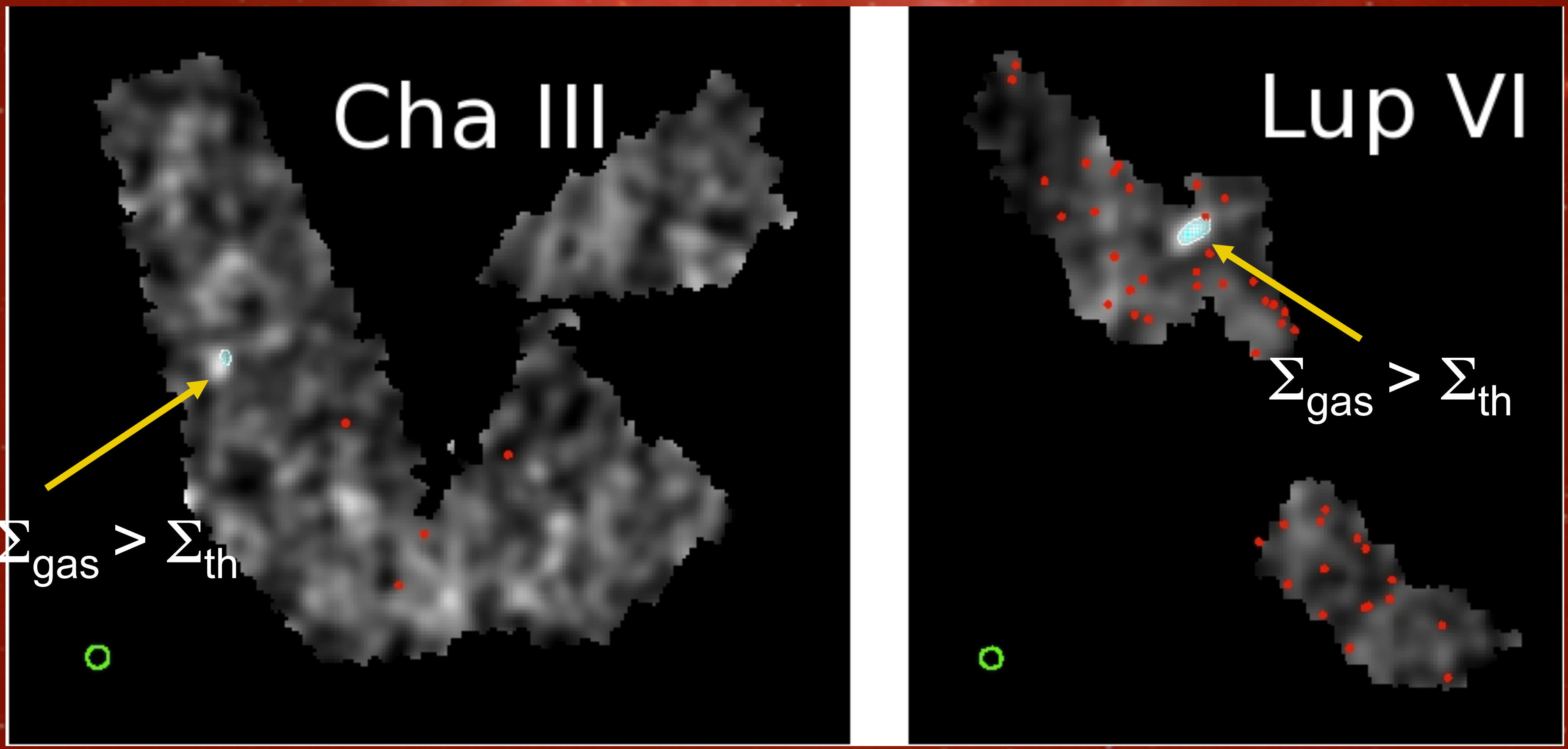
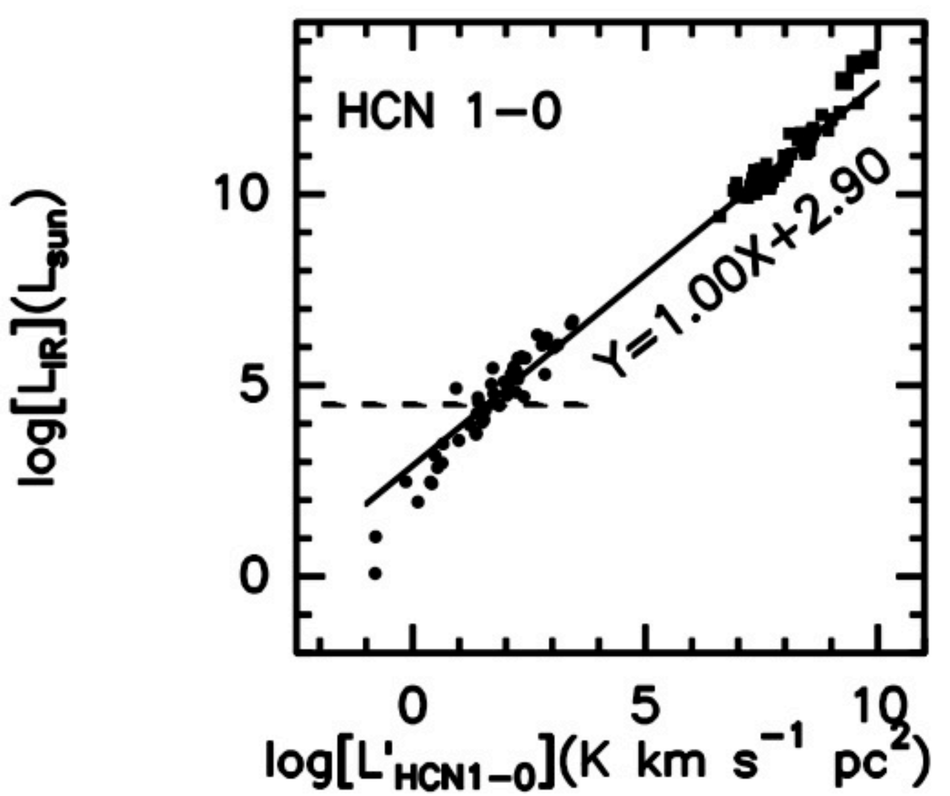
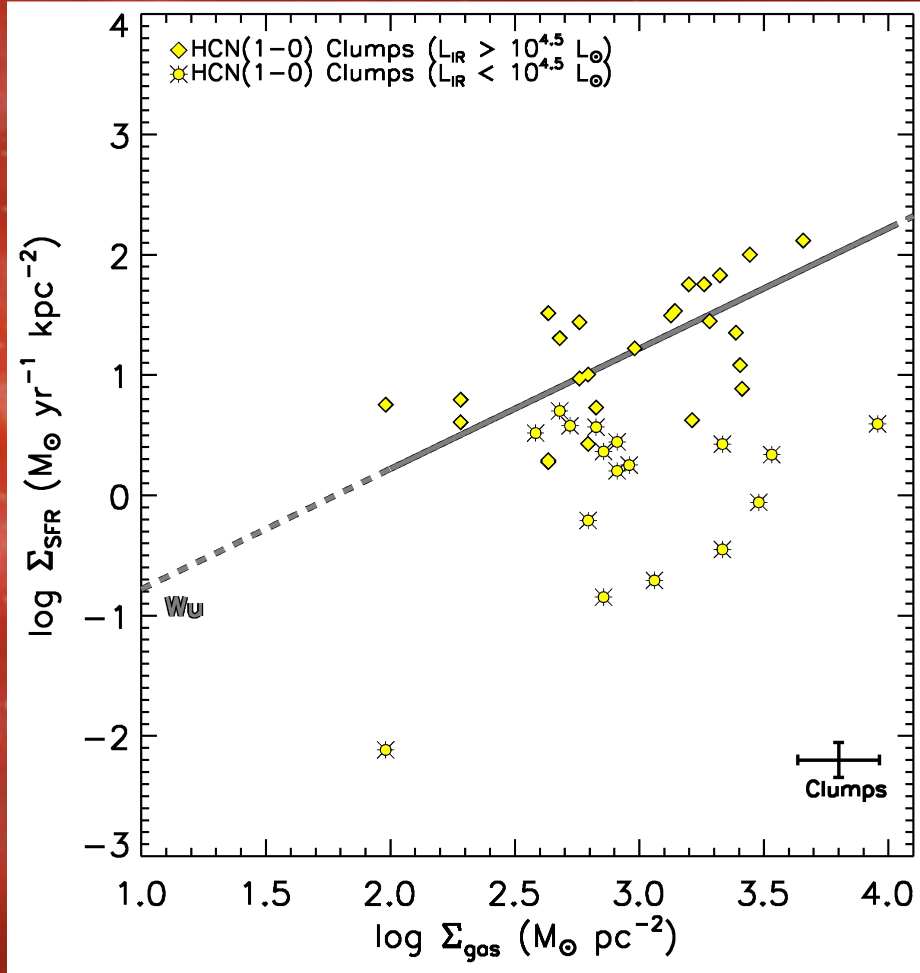
Evolved Clouds



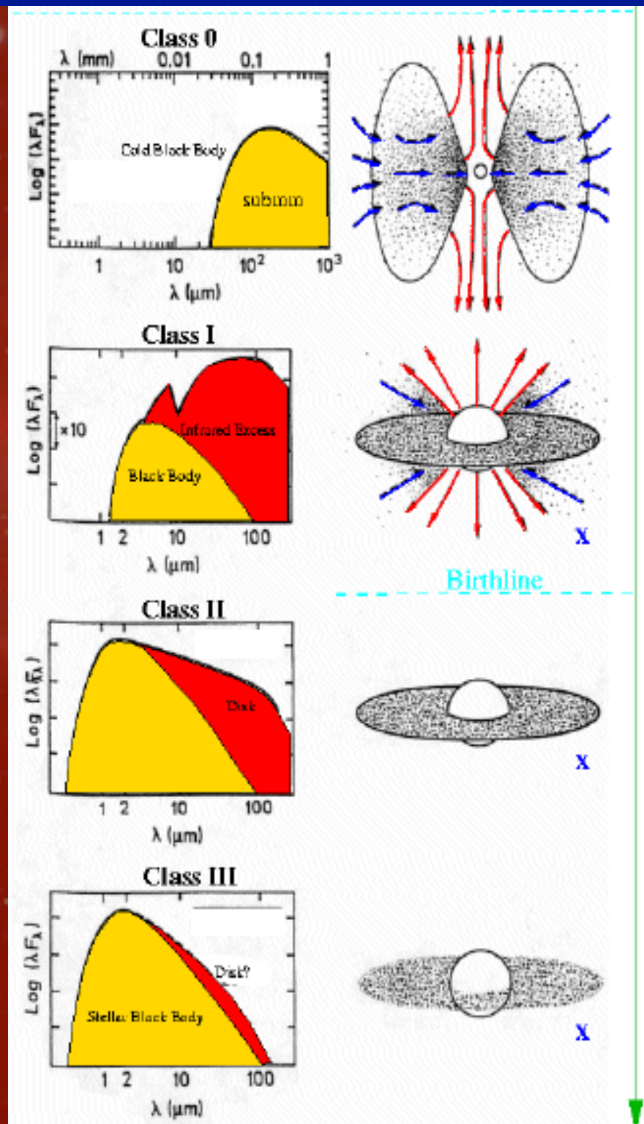
L_{IR} vs $L_{HCN(1-0)}$

- circles: massive, dense clumps (Wu et al. 2010)
- squares: galaxies (Gao & Solomon 2004a)





YSO Classes



t ~> 0.5 Myr

t ~> 2 Myr

MISidentified YSOs from SED FITS (MISFITS)

- HCO^+ J=3-2, CSO, $T_{MB} >= 3\sigma_{rms}$

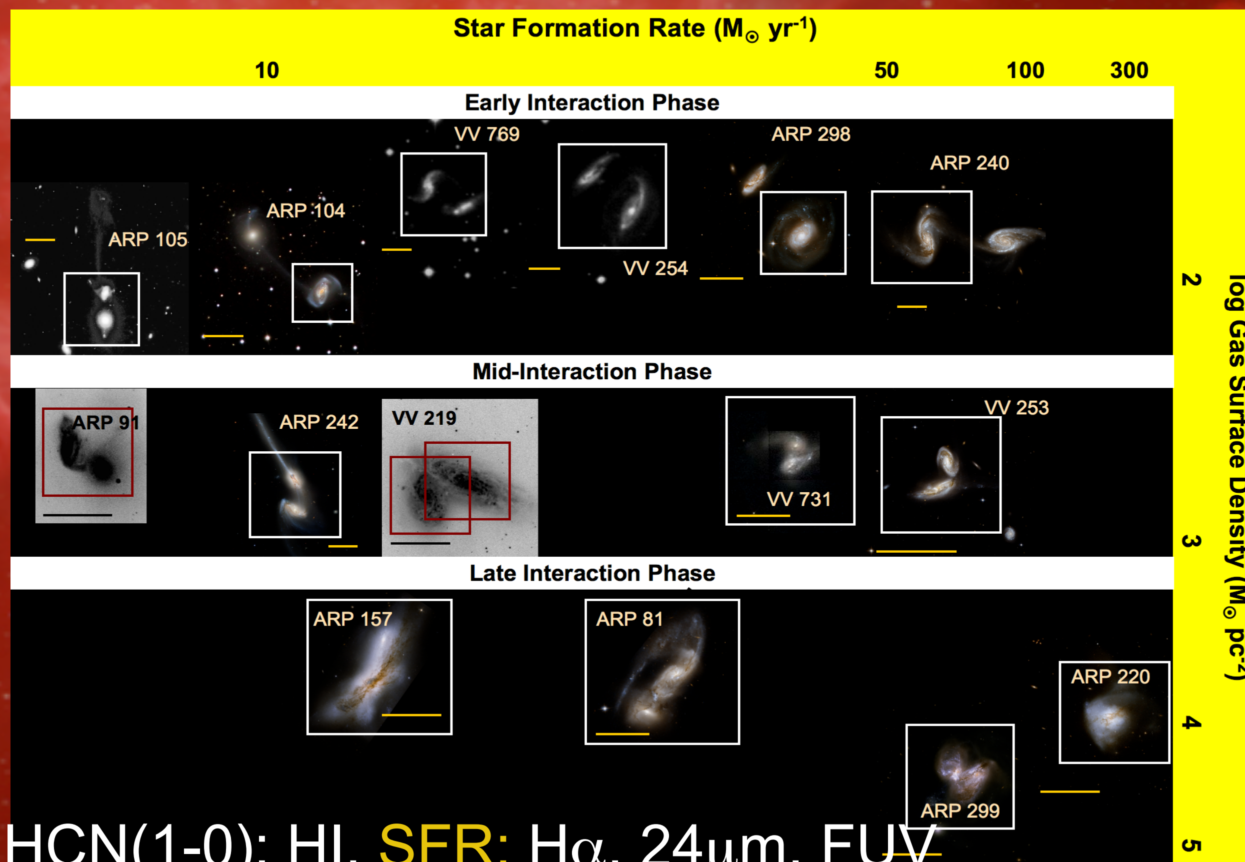
- Results:
- 71/98 (72%) undetected
- 3/43 (7%) Flat SED, and 24/55 (44%) Class I detected
- However, non-detections are a small fraction of
  – total number of YSOs: 71/3146 (2%)
  – Class I: 33/412 (8%)
  – Flat SED: 40/269 (15%)

Testing SFR-gas Relations at high Σ_{gas}, Σ_{SFR}

VIRUS-P Investigation of the eXtreme ENvironments of Starbursts

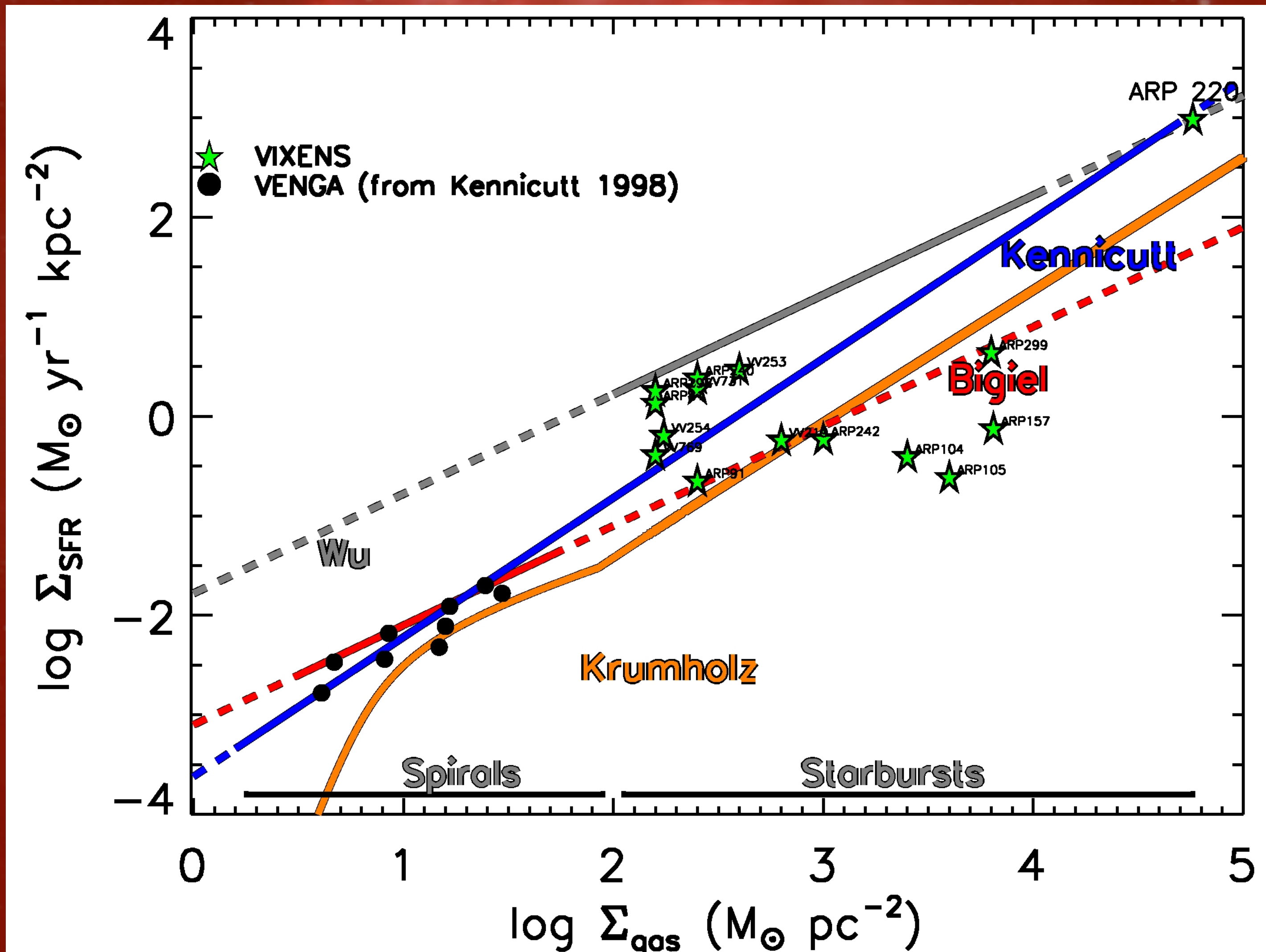
- 15 interacting systems
- Goal: Investigate the 0.1-0.8 kpc resolved SFR-gas (S-K) relation at *high* Σ_{gas} (>100 $M_\odot$ pc^{-2}) & SFR (>10 $M_\odot$ yr^{-1})

Team: Guillermo Blanc, Neal Evans, Karl Gebhardt (UT), Daisuke Iono (NRO), Casey Papovich (A&M), Min Yun (Umass)



Gas: CO(1-0); CO(3-2); HCN(1-0); HI, SFR: Hα, 24μm, FUV

Test S-K Relation & Krumholz Prediction at high Σ_{gas} & Σ_{SFR}



Preliminary Results: ARP 299