Testing Star Formation Prescriptions in the Milky Way

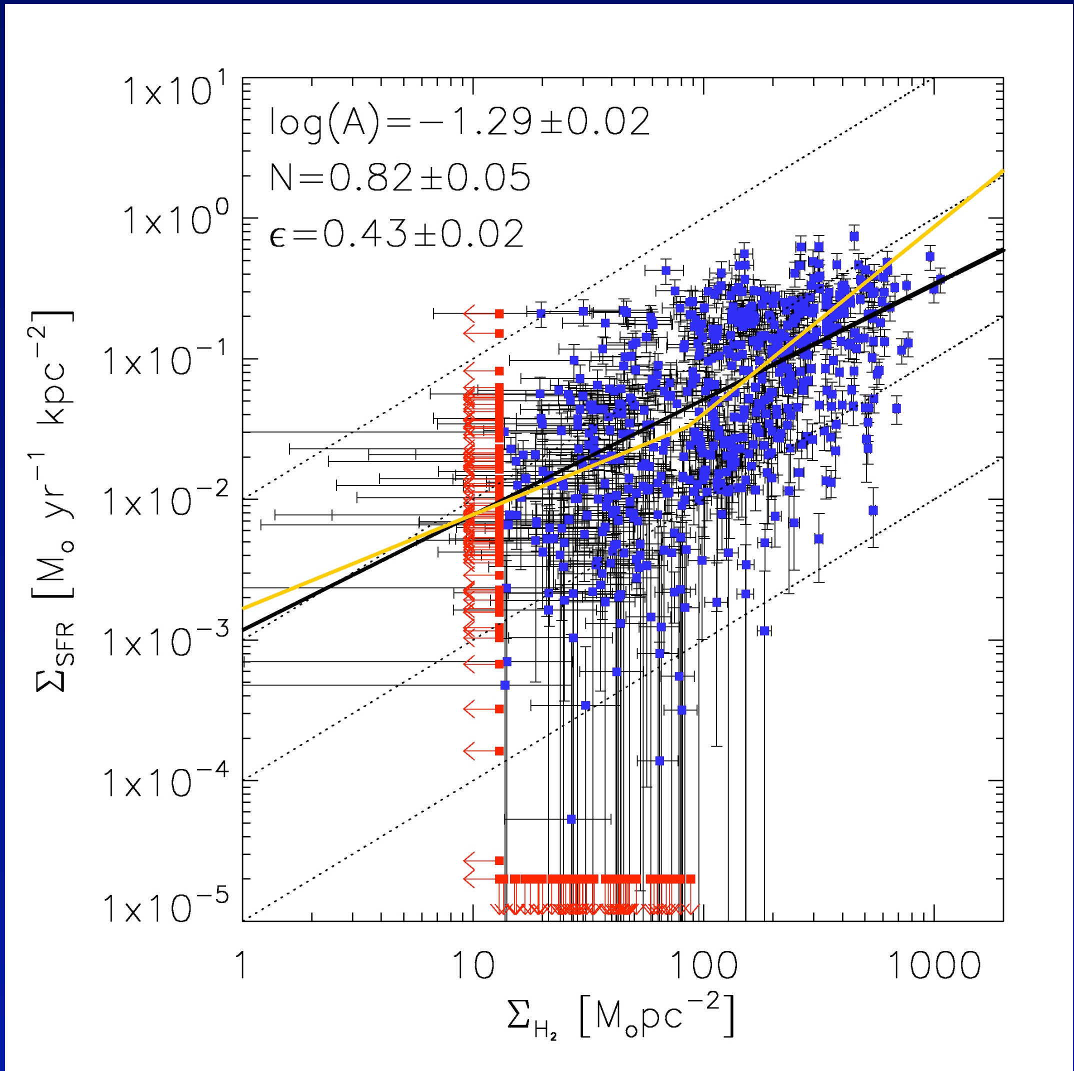
and Elsewhere…

Neal J. Evans II

Star Formation Prescriptions

- **Schmidt (1959)**
  - **SFR ~ ρ^n, n = 1 or 2**
- **Kennicutt (1998)**
  - **$\Sigma_{SFR}(M_{sun}\ yr^{-1}\ kpc^{-2}) = 2.5\times10^{-4}\ \Sigma^{1.4}{}_{gas}(M_{sun}\ pc^{-2})$**
  - **$\Sigma_{SFR}(M_{sun}\ yr^{-1}\ kpc^{-2}) = 6.3\times10^{-3}\ \Sigma^{1.4}{}_{gas}(10\ M_{sun}\ pc^{-2})$**
- **Bigiel et al. (2008)**
  - **$\Sigma_{SFR}(M_{sun}\ yr^{-1}\ kpc^{-2}) = 7.9\times10^{-3}\ \Sigma^{1.0}{}_{mol}(10\ M_{sun}\ pc^{-2})$**
- **Krumholz et al. (2009)**
  - **$\Sigma_{SFR} = f(\Sigma_{gas}, f(H_2), Z, \text{clumping})$**
  - **Nearly linear with Σ_{mol} below ~ 100 $M_{sun}\ pc^{-2}$**
  - **Steepens above 100 $M_{sun}\ pc^{-2}$**

New Results on M51



$S_{SFR} = A \; S_{gas}^{N}$

x $10^{\mathcal{N}(0,\ e)}$,

$\mathcal{N}$ a Gaussian

e is intrinsic scatter in log (0.43)

Blanc et al. Poster

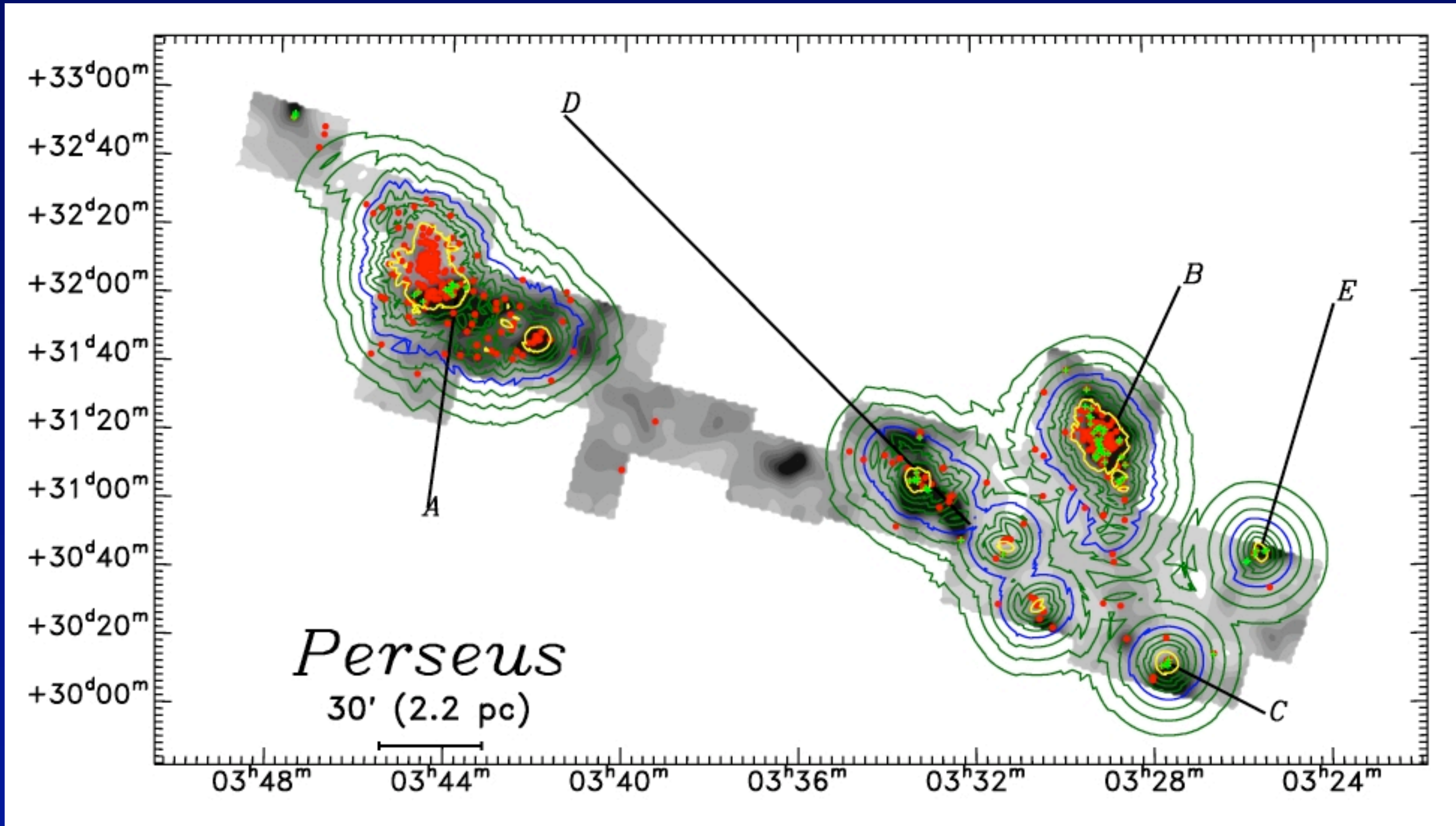
Testing Locally

- Observing Clouds in the Milky Way
  - Advantage is good resolution
    - Ability to count stars in some cases
  - Disadvantage is good resolution
    - Hard to compare on scales ~ galaxies
    - Progress from large surveys with Spitzer, Herschel, mm telescopes

Star Formation in Nearby, "Large" (3-10 pc) Clouds

- **c2d Survey**
  - **Survey 5 large clouds with Spitzer**
  - **Survey 3 of them with Bolocam, and COMPLETE**
- **Where do stars form in large molecular clouds?**
- **How efficient is star formation?**
- **Local star formation prescriptions**

Where do Stars Form?



Gray is extinction, red dots are YSOs, contours of volume density (blue is 1.0 M_{sun} pc^{-3}; yellow is 25 M_{sun} pc^{-3})

YSOs, Dense Cores are Clustered

- Only 9% of YSOs outside contour of 1 M_{sun} pc^{-3}
- Distributed YSOs are more evolved
- Distributed population could come from dispersed clusters [t_{cross} ~ t(ClassII) ~ 2 Myr]
- Densities of YSOs are high in clusters
  - But < 0.1 that in Orion, …
- Dense cores are even more clustered than YSOs

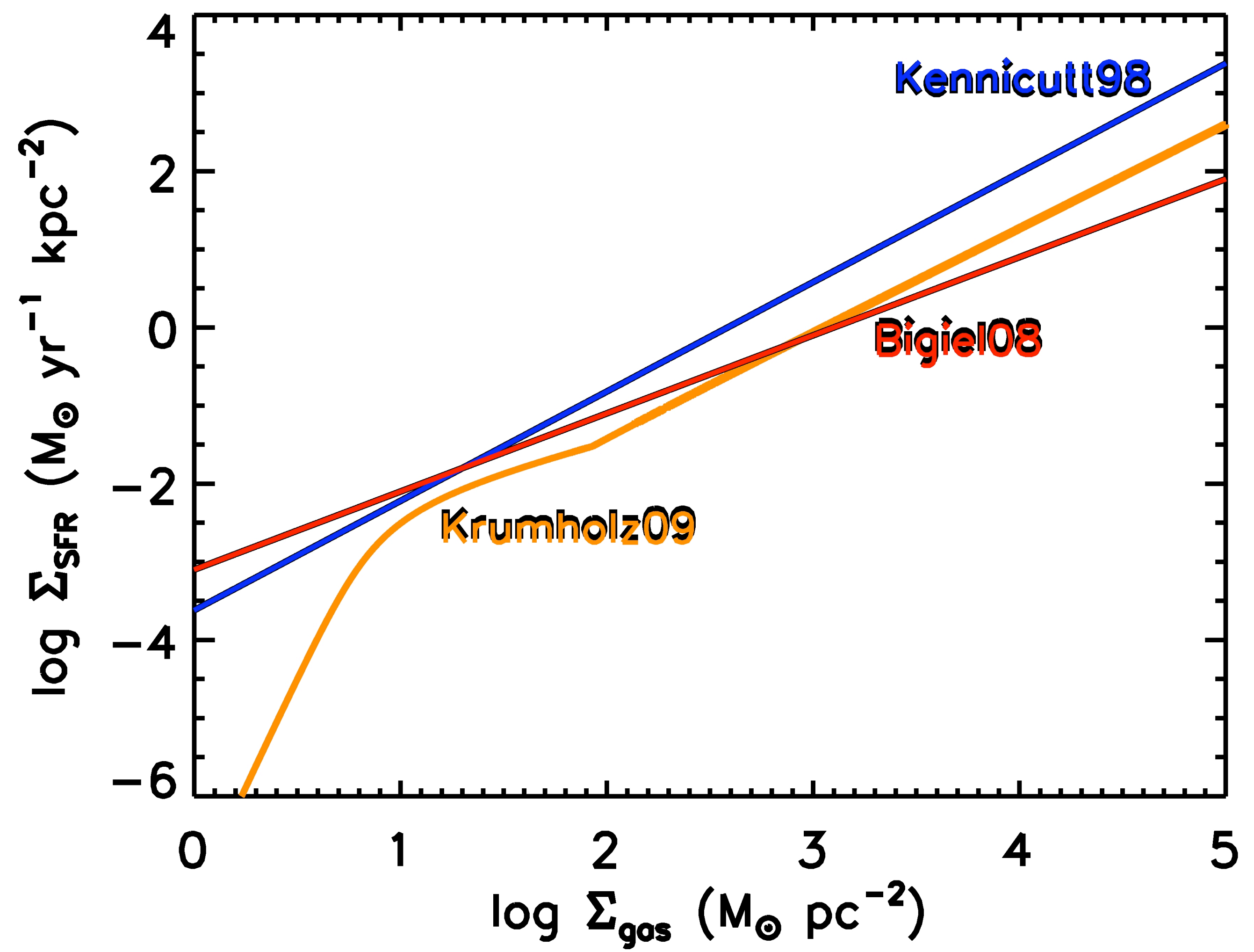
How “Efficient” is Star Formation?

- Not very for the cloud as a whole
  - 1% to 4% of mass with A_V > 2 is in dense cores
    - (Enoch et al. 2007)
  - 2% to 4% is in stars (assume $\langle M_* \rangle = 0.5\ M_{sun}$)
  - Cloud depletion time at current rate 40-100 Myr
  - Longer than cloud lifetimes
- Quite efficient in dense gas
  - Current TOTAL M_* similar to M_{dense}
  - Core depletion time is 0.6 to 2.9 Myr

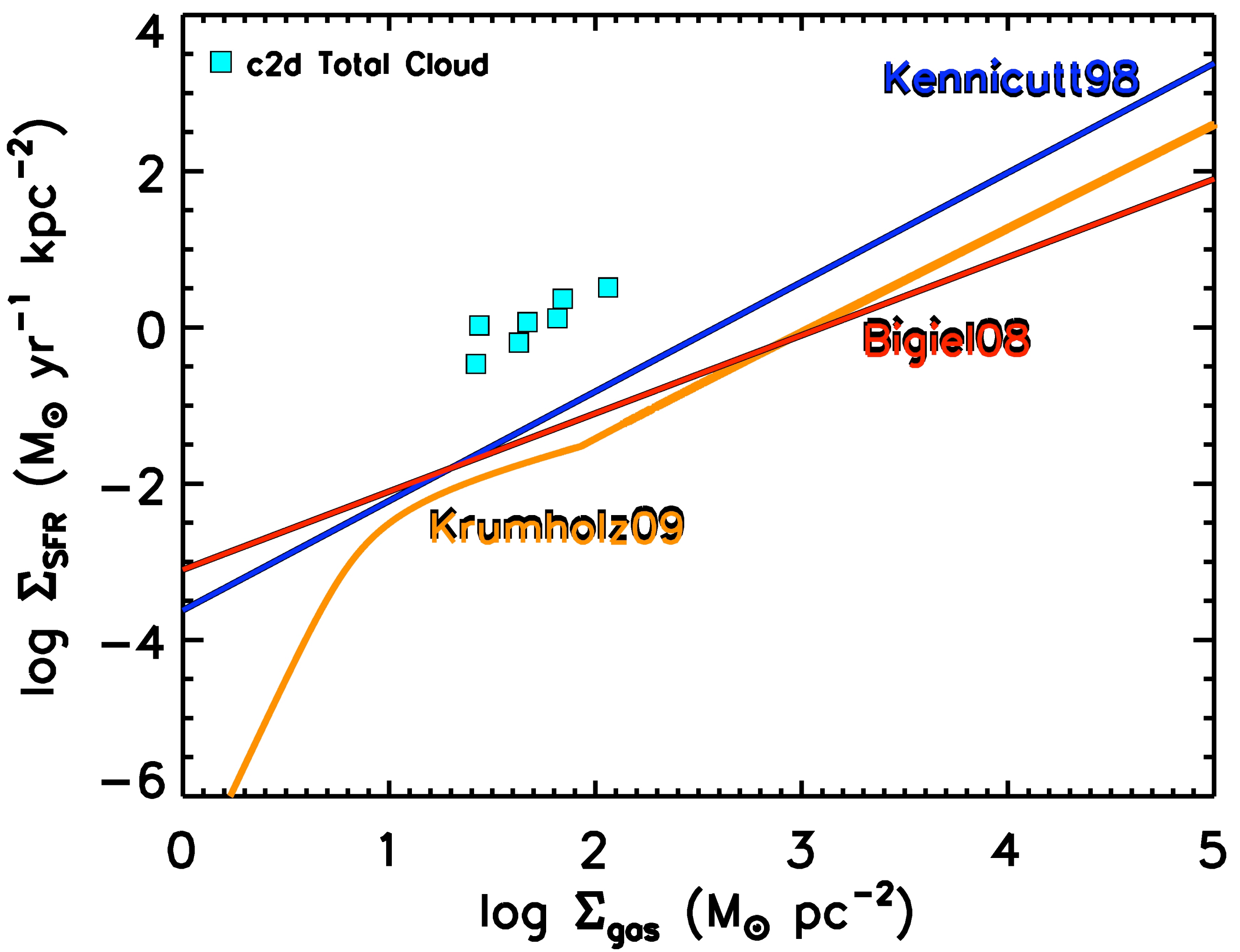
Testing Prescriptions

- Prescriptions were developed from large-scale observations
  - Would they work for an individual cloud?
  - Accurate Σ_{SFR} from counting YSOs, timescale of 2 Myr for Class II
  - Σ_{gas} from extinction maps
    - Much more accurate than masses from CO
    - Applies to the same region as Σ_{SFR}

The Predictions



The Test, Part I



What are the Implications?

- No prescriptions work on the scale of these molecular clouds
  - Even the “inactive” clouds lie far above the relation.
  - Not enough to define a relation, but…
  - 14 more local clouds surveyed
    - Gould Belt Legacy Project with Spitzer
    - Bigger range of star formation rates

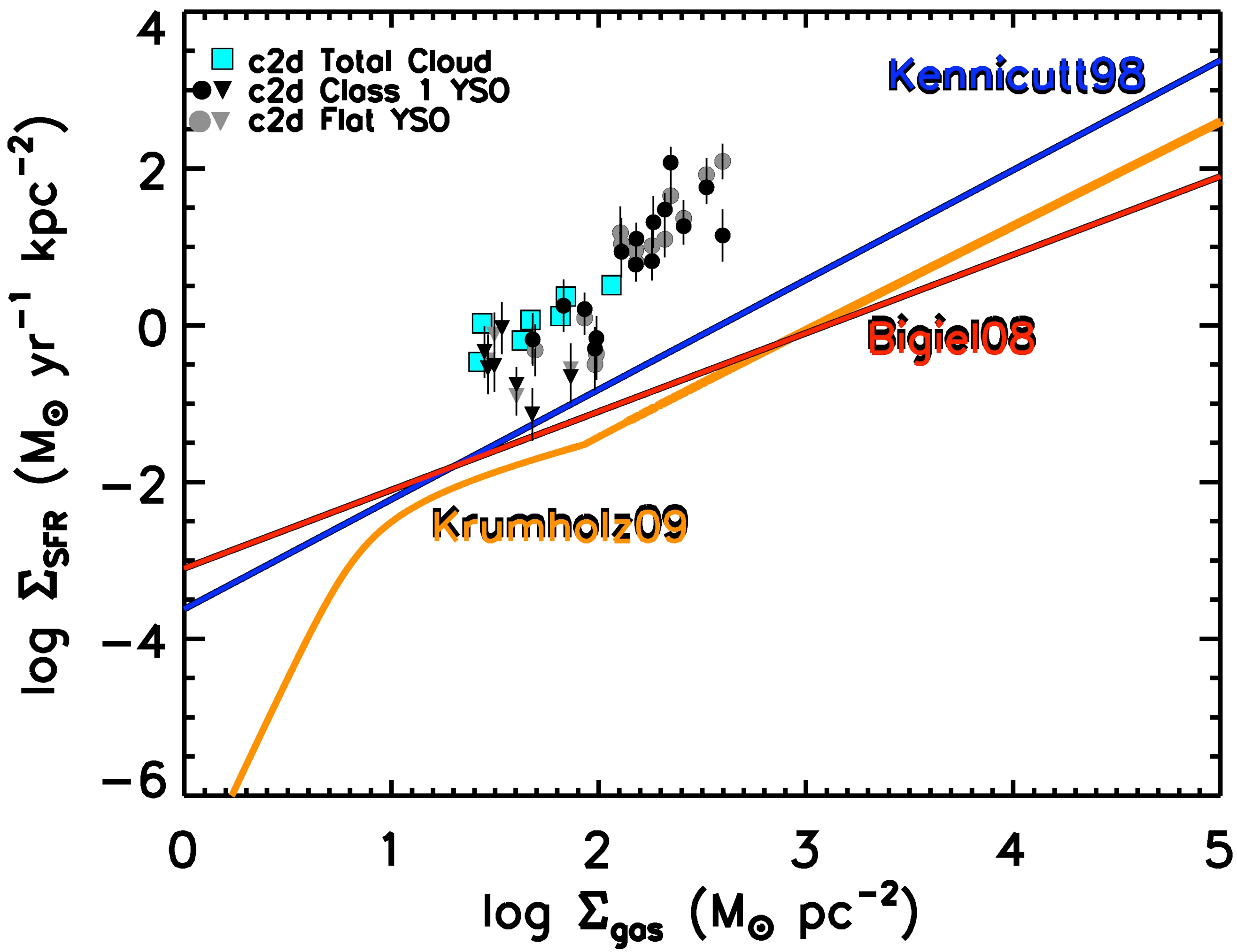
Test on Smaller Scales?

Star formation mostly in high extinction

Cloud average biased toward lower S_{gas}

- Count YSOs in contours of A_V
- YSOs can wander out of formation region
- Count only Class I, Flat
  - Use suitable lifetimes (~0.5 Myr each)
- Checking for fakes at low A_V
  - Poster by Amanda Heiderman

The Test, Part II



Lessons from Nearby Clouds

- Σ_{SFR} >10 times prediction of relations for galaxies
- These regions are forming only low mass stars
  - Would not even be seen in most exgal SFR tracers
- On scales where SF actually happens…
  - Dependence on S_{mol} may be very strong
- SFR determined on sub-pc scales << exgal resolution

What About Massive Stars?

- Goal is to do studies similar to those in nearby clouds
- More distant clouds, usually can't count stars
- Use water masers as signposts
  - Plume, Mueller, Shirley, Wu
  - Latest study by Wu et al. (2009)
  - 50 massive, dense clumps
  - CS 2-1, 5-4, 7-6; HCN 1-0, 3-2 maps

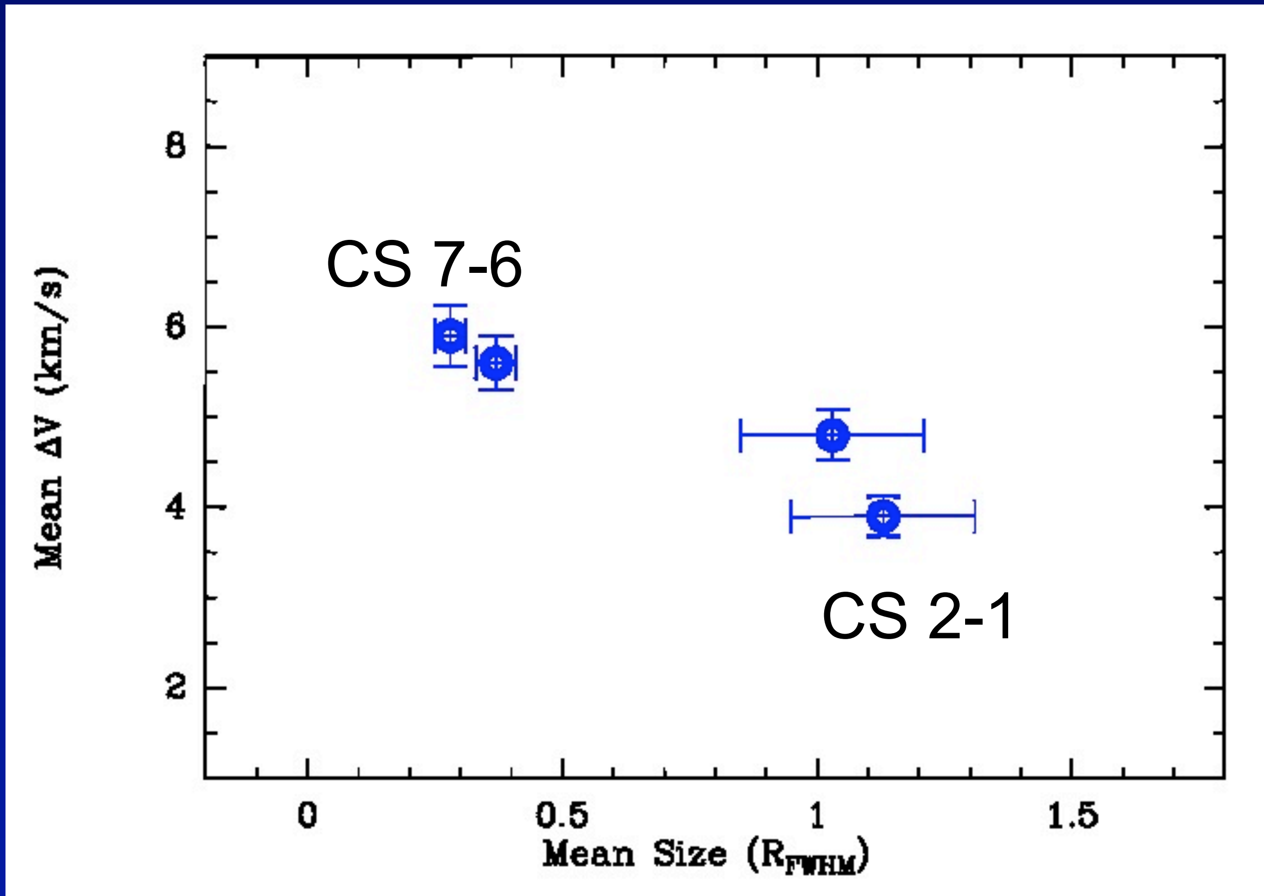
Massive Dense Clumps: Gross Properties

- **Massive, Dense, Turbulent, Inflow**
  - **CS 2-1 or HCN 1-0 trace lower densities, higher masses**
  - **<M> = 5000 M_{sun}; Median 2000 M_{sun}**
  - **Mass distribution closer to clusters than to GMCs**
  - **Much more turbulent than low mass cores**
    - **Linewidths about 16 times wider**
    - **Well above "Larson law" for size-linewidth**
  - **Evidence of inward motions in at least some**

Internal Properties

- **Clumps have internal gradients in n, T**
  - **$n \sim r^{-p}$, p ~ 1.8 on average**
- **Lines with higher n_{crit} , DE trace inner parts**
- **Surface density increases with n_{crit} , DE**
  - **Mean S = 0.29, 0.33, 0.78, 1.1 gm cm^{-2}**
  - **From CS2-1, HCN1-0, HCN3-2, CS7-6**
- **Linewidth INCREASES with n_{crit} , DE**
  - **Inverse Larson Law**

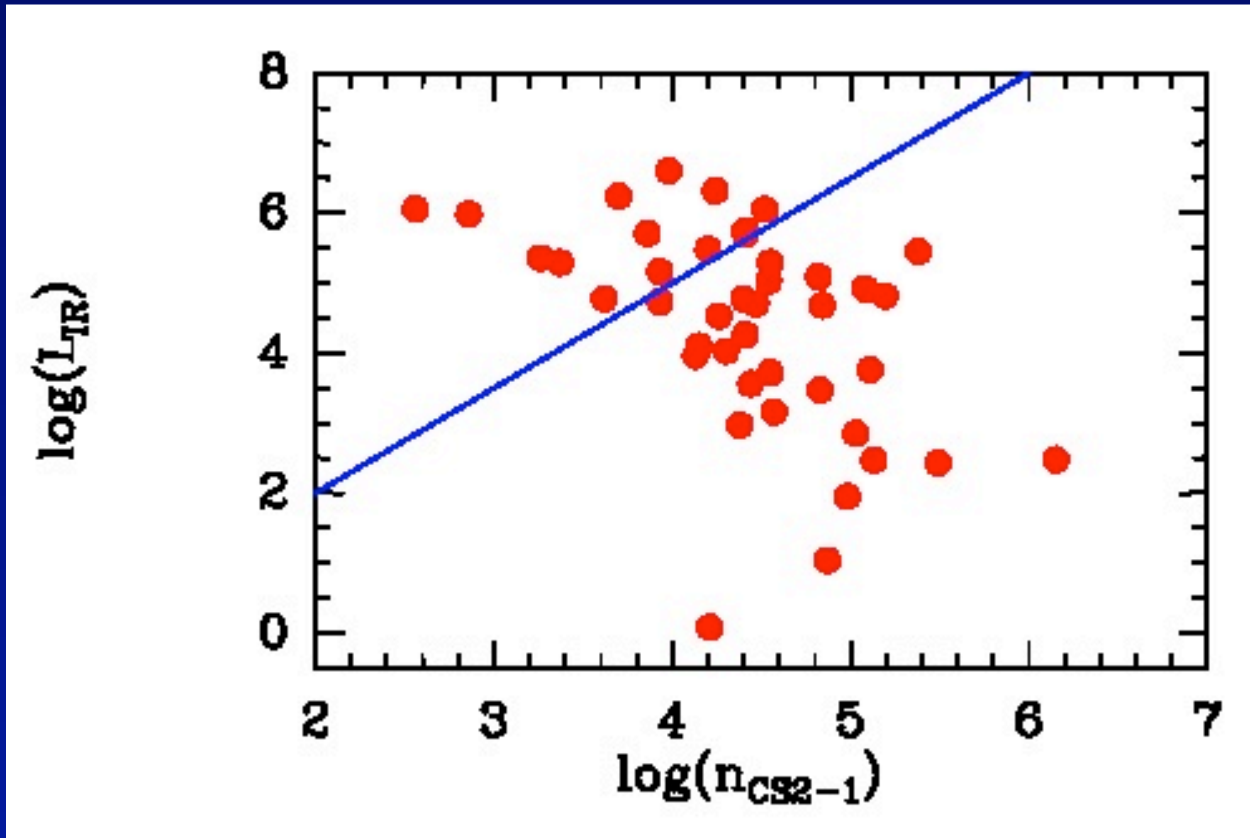
Inverse Size Linewidth Relation



Does SFR Depend on Volume Density?

- Free-fall time depends on volume density
  - $t_{ff} \sim r^{-0.5}$
- Common theoretical approach
  - Krumholz and Thompson
  - Narayanan et al.
  - SFR ~ Mass/t_{ff}
  - $dr_*/dt \sim r/r^{-0.5} \sim r^{1.5}$
  - Local version of Kennicutt relation

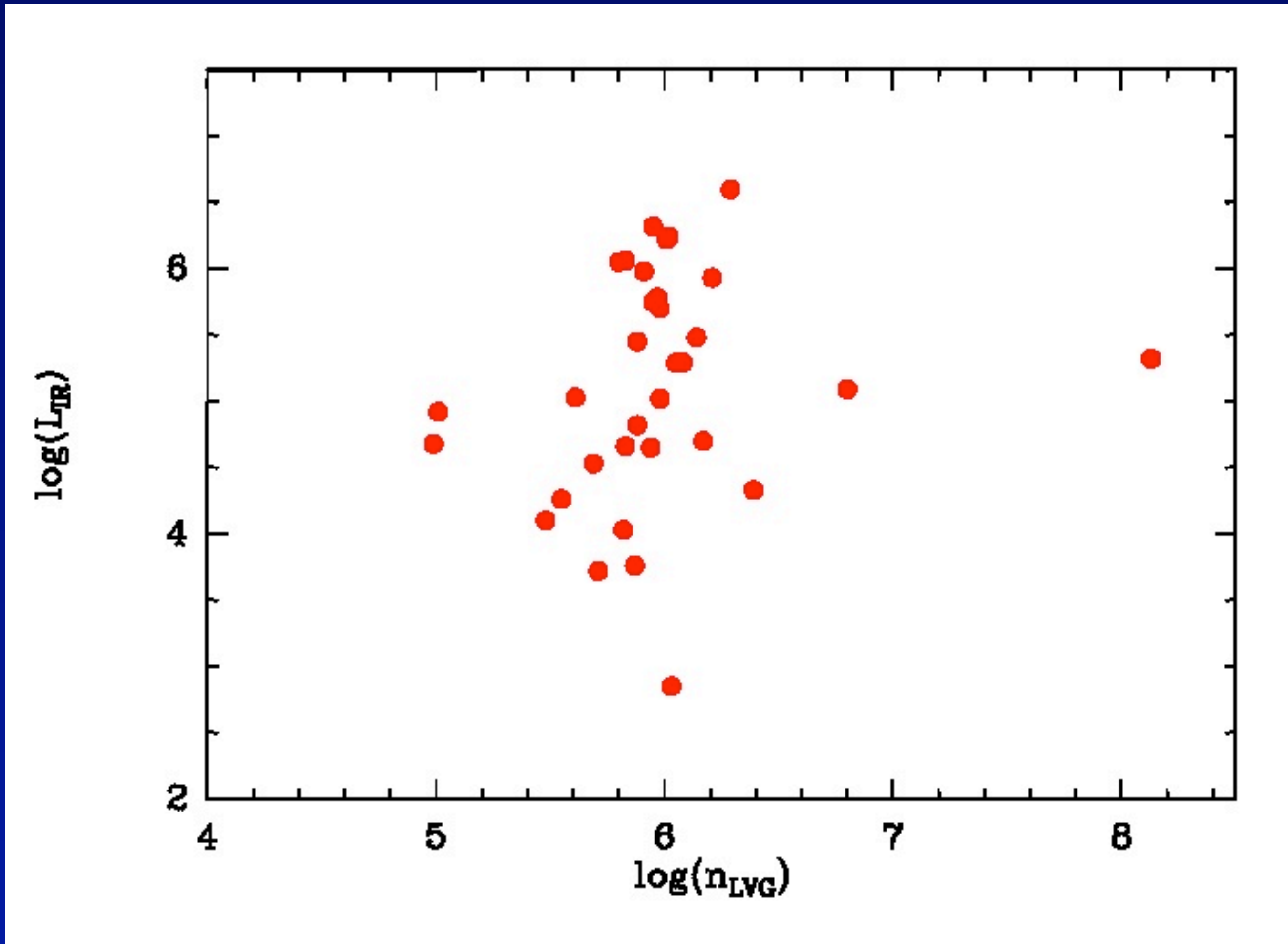
Does SFR ~ $\langle n \rangle^{1.5}$?



Mean density from virial mass and radius

$\langle n \rangle \sim M/r^3$

Does SFR ~ $n^{1.5}$?

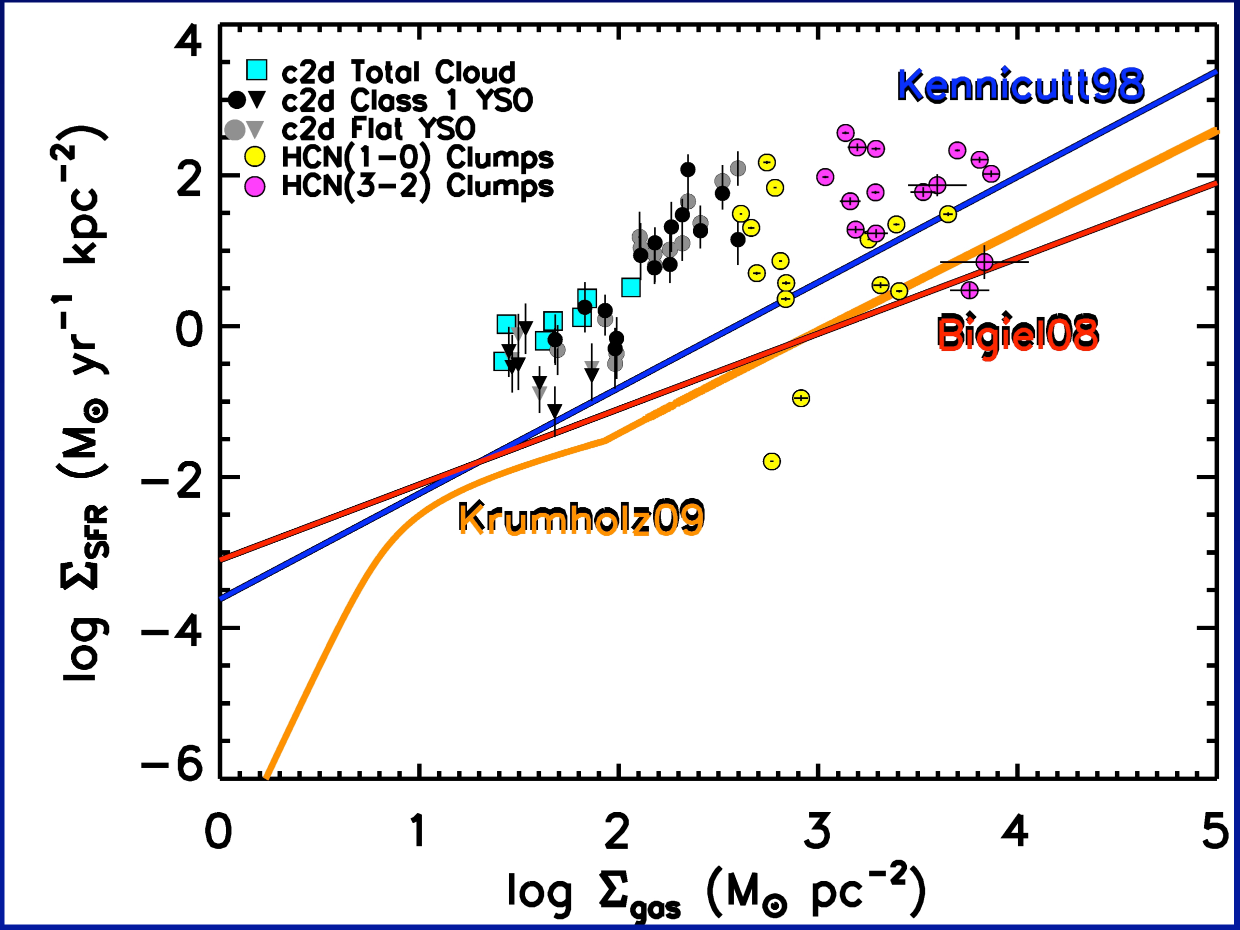


Density from LVG models of multi-transition CS (Plume et al.)

Testing Prescriptions with Massive, Dense Clumps

- **These are the places where massive stars form**
- **What exgal studies would see**
- **Use M_{vir} and size to get S_{gas}**
- **Use L_{IR} to get SFR**
  - **Usual prescription from exgal**
  - **May underestimate SFR**
  - **Divide by size to get S_{SFR}**

The Test, Part III



RMS scatter in HCN is 0.4 in the log

Massive Star Formation in Galactic Context

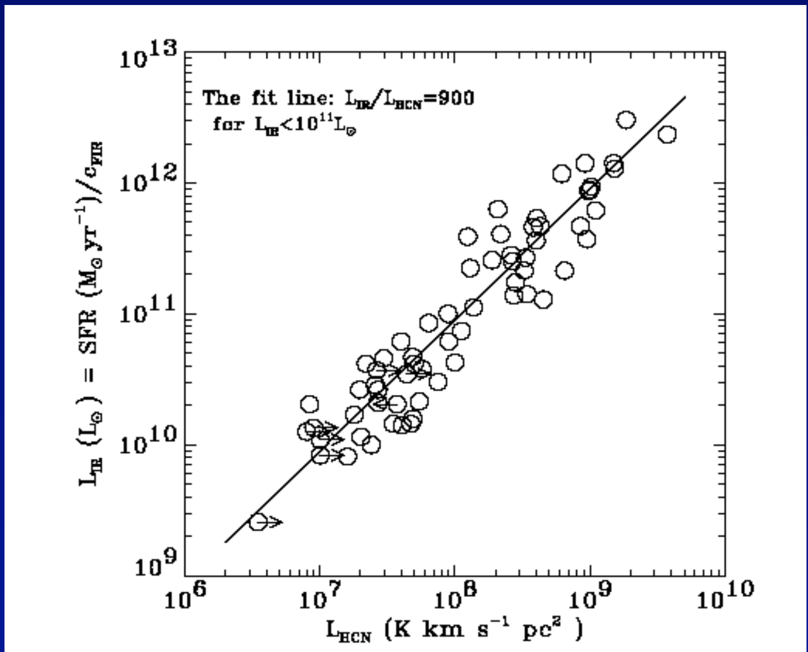
- Surveys in mm continuum finding 1000's of dense clumps
  - Bolocam Galactic Plane Survey (>8000 sources)
  - http://irsa.ipac.caltech.edu/data/BOLOCAM_GPS/
  - ATLASGAL survey from APEX
  - Future SCUBA2 survey
  - Herschel Galactic Plane Survey (HIGAL)
- Infrared Dark Clouds (IRDC)
  - MSX, GLIMPSE, MIPSGAL
- New models of Galaxy, VLBA distances, …
- Provide link to extragalactic star formation

Galactic-galactic connection?

- Galactic massive clumps have some similarities to starburst galaxies
- We can study them in some detail
- Linear relation between L_{IR} and L(CS) and L(HCN)

L_{IR} Correlates Linearly with L_{HCN} in Starburst Galaxies

Star formation rate



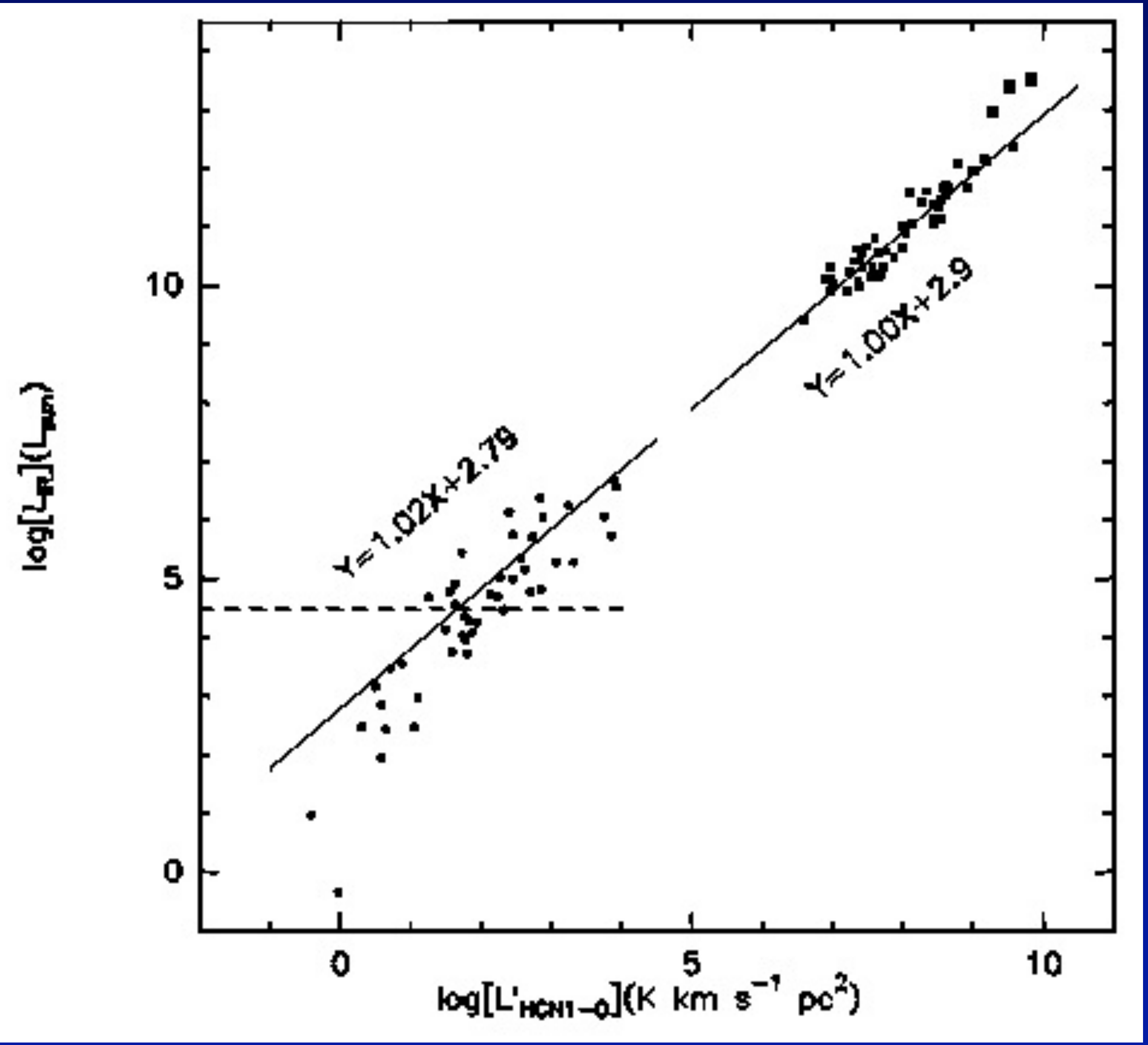
Amount of **dense** molecular gas

- L_{IR} correlates better with L(HCN)
- Smaller scatter
- Linear
- SFR rate linearly proportional to amount of dense gas
- "Efficiency" for dense gas stays the same

Gao & Solomon (2004) ApJ 606, 271

The Galactic-galactic Connection

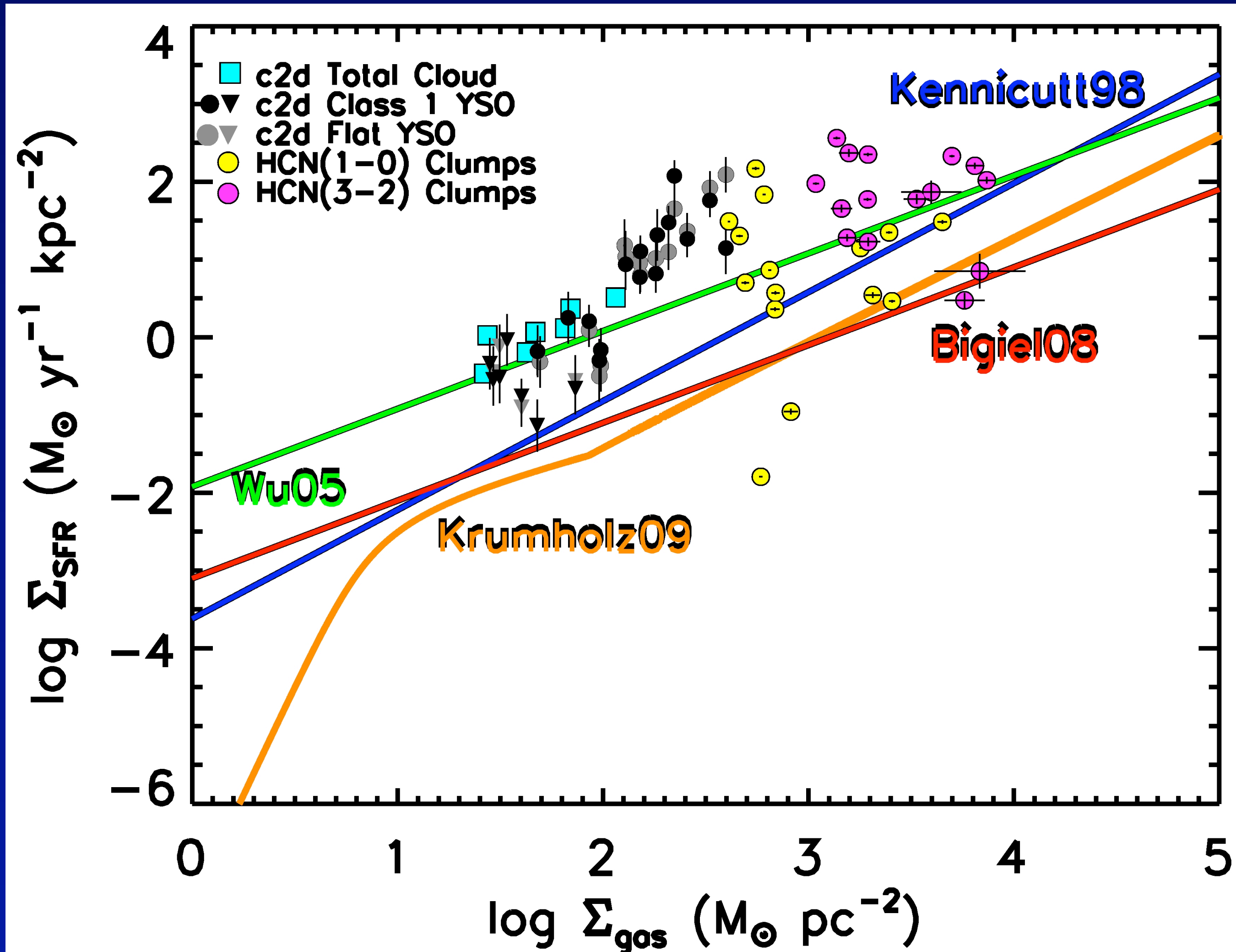
L(IR)



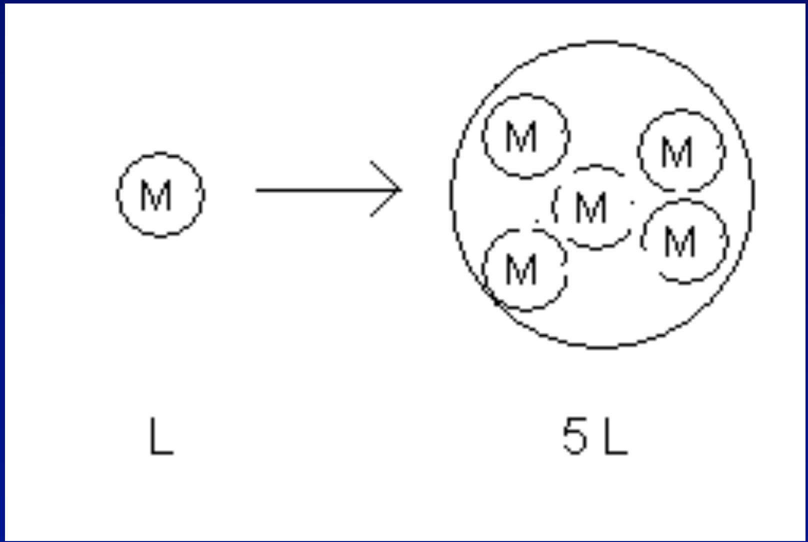
L(HCN J = 1-0)

Wu et al. (2005)

The Test, Part IV



The Basic Unit Model



The linear correlation and the Luminosity cutoff can be explained if there exists a basic unit for clustered star formation.

$M > M_{crit}$

Each unit provides the same luminosity

Critical mass of **dense** gas

Luminosity depends strongly on mass available

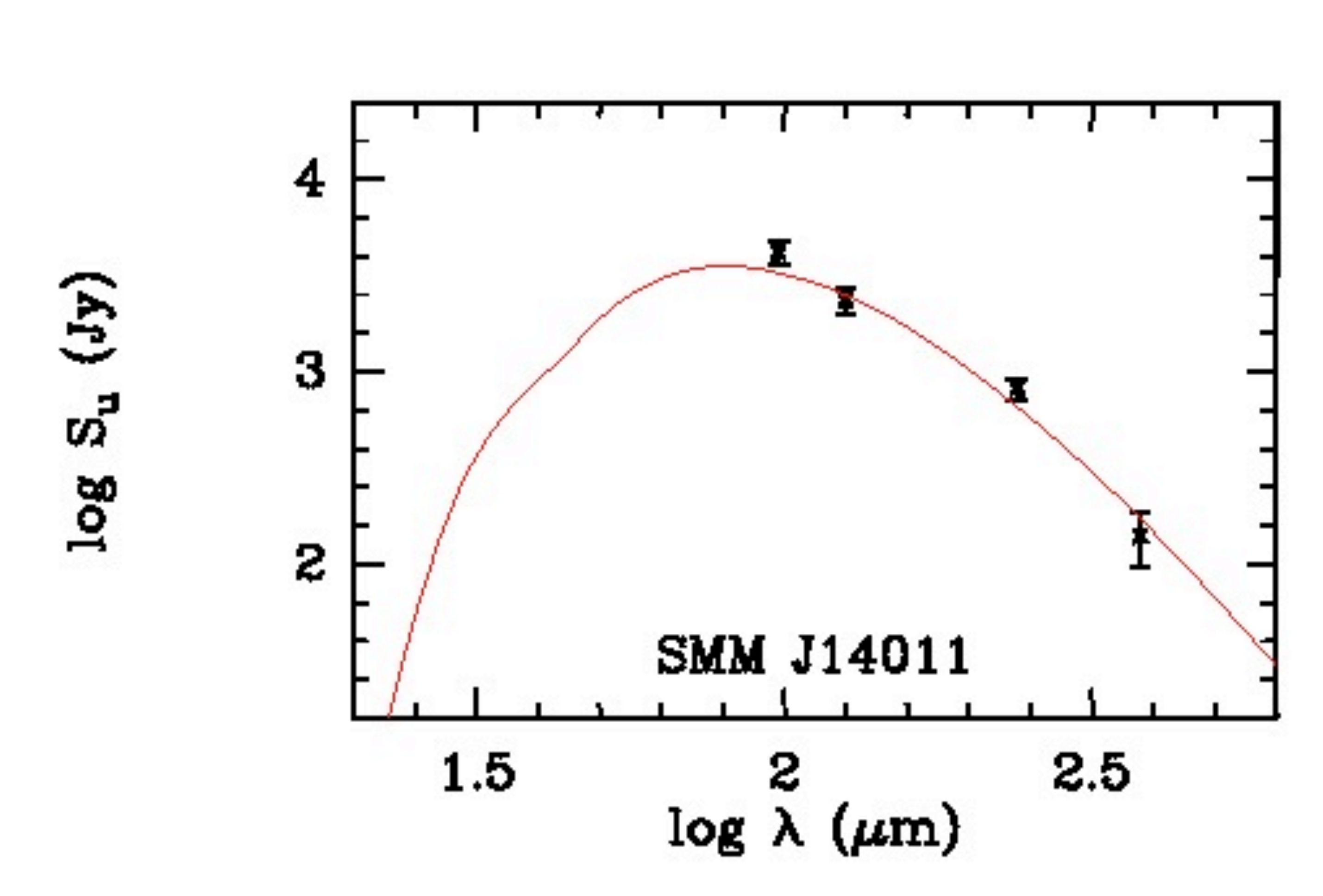
$M < M_{crit}$

Wu et al. 2005

Test Basic Unit Model

- Detections of 8 high-z galaxies at 350 mm
  - SFR from 11 to 2500 M_{sun} yr^{-1}
- Model as collections of basic units of SF
  - Use mean L_{dust} of massive, dense clumps from Wu et al. (2009) (5 x 10^5 L_{sun})
  - Need 0.6 to 30 x 10^6 units
  - SEDs can be modeled with differing masses of the units

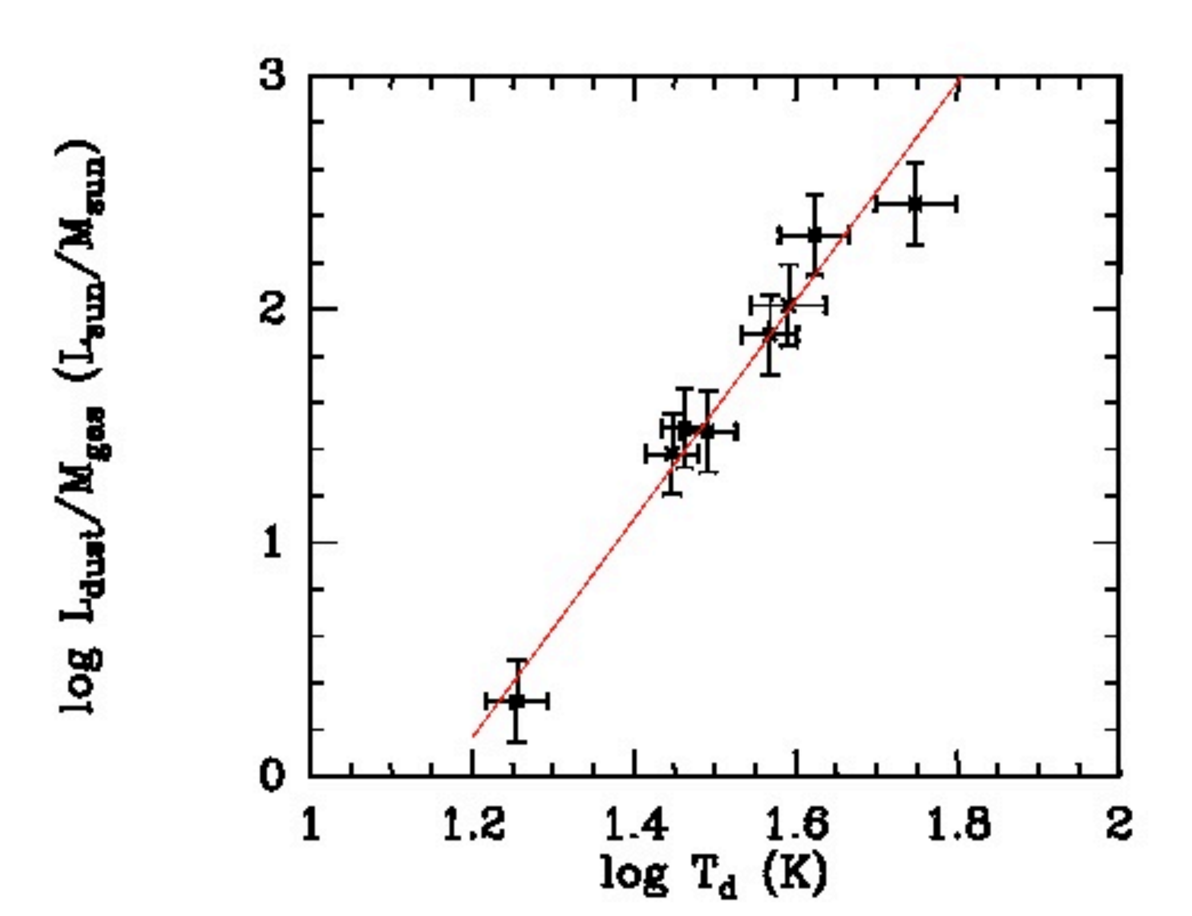
Model of one clump



Get L_{dust}/M_{gas} for All

- **Big range in values**
- **L_{dust}/M_{gas} ranges from 2.1 to 283**
- **Usual fit to single T_d not realistic, but…**
- **T_d correlates very well with L/M ~ "SFE"**
  - **Can use "T_d" to measure "SFE" and t_{dep}**

"T_d" Really Measures L/M



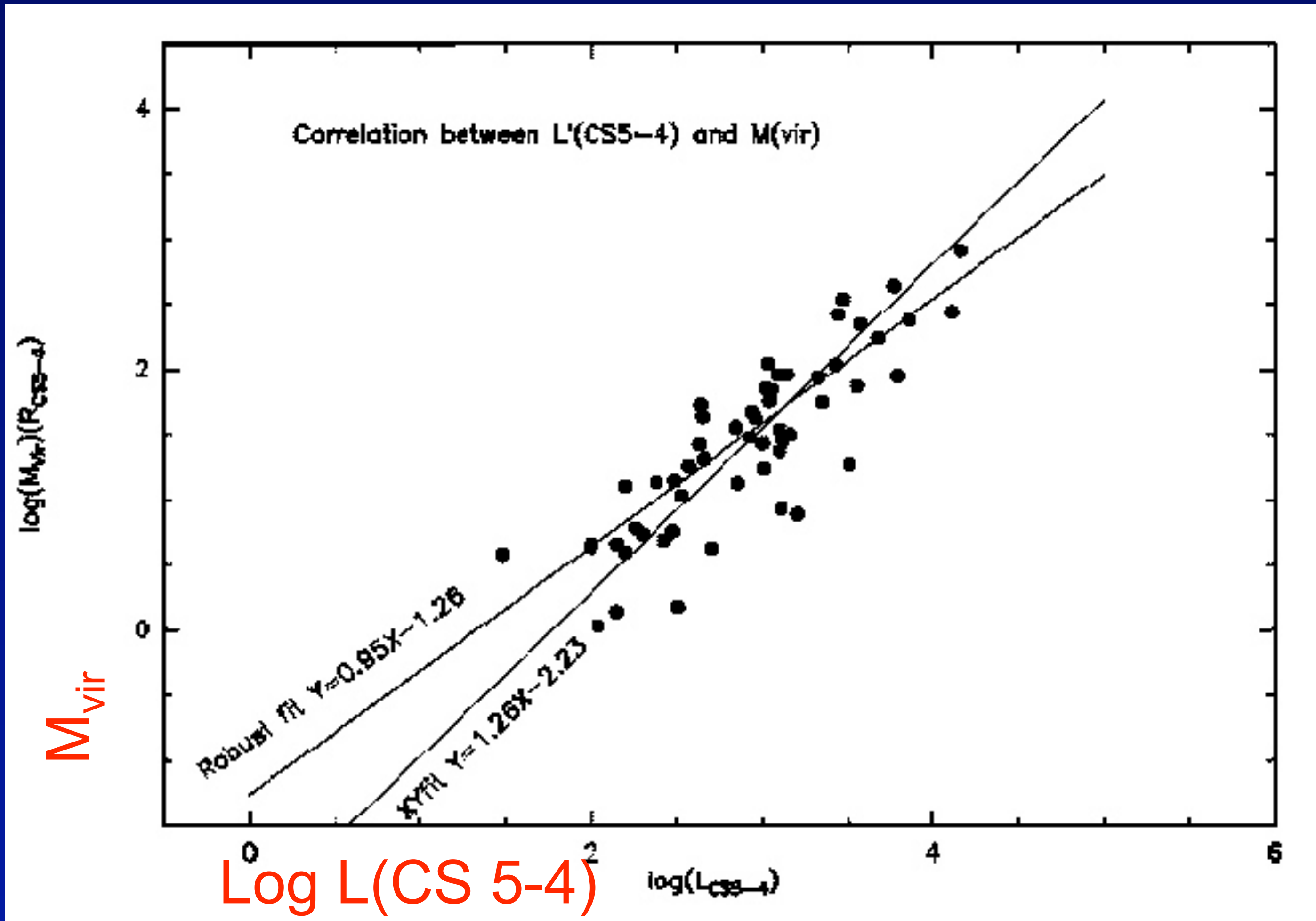
$L/M = 3.5 \times 10^{-6}\, T_d^{4.7}$ $\quad$ $t_{dep} = 5.6 \times 10^{9}\, (L/M)^{-1}$

Summary

- Star formation is mostly clustered
- Efficiency is low in clouds, high in cores
- But much more SF than predicted by any prescriptions
- Massive clumps denser, much more turbulent
- No evidence that SFR ~ $r^{1.5}$ on local scales
- Basic unit of massive SF consistent with many observations
- SFR ~ Mass of gas above a threshold density
- With a LOT of scatter

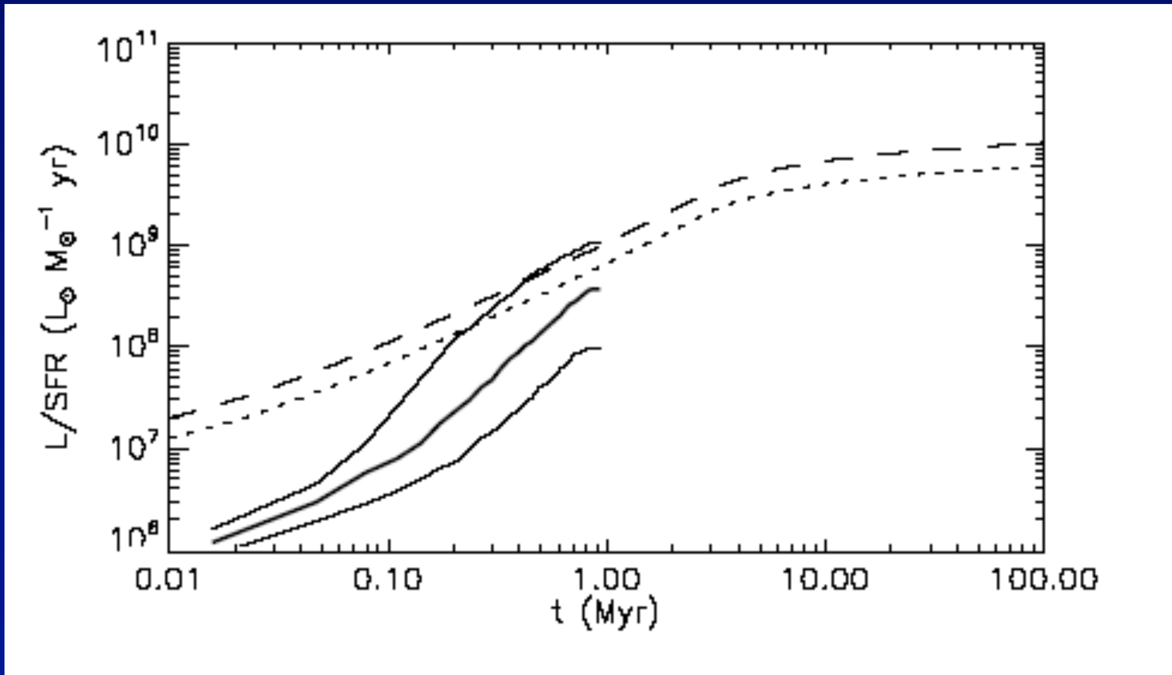
Backup Slides

L(HCN) Measures M_{vir}(dense)



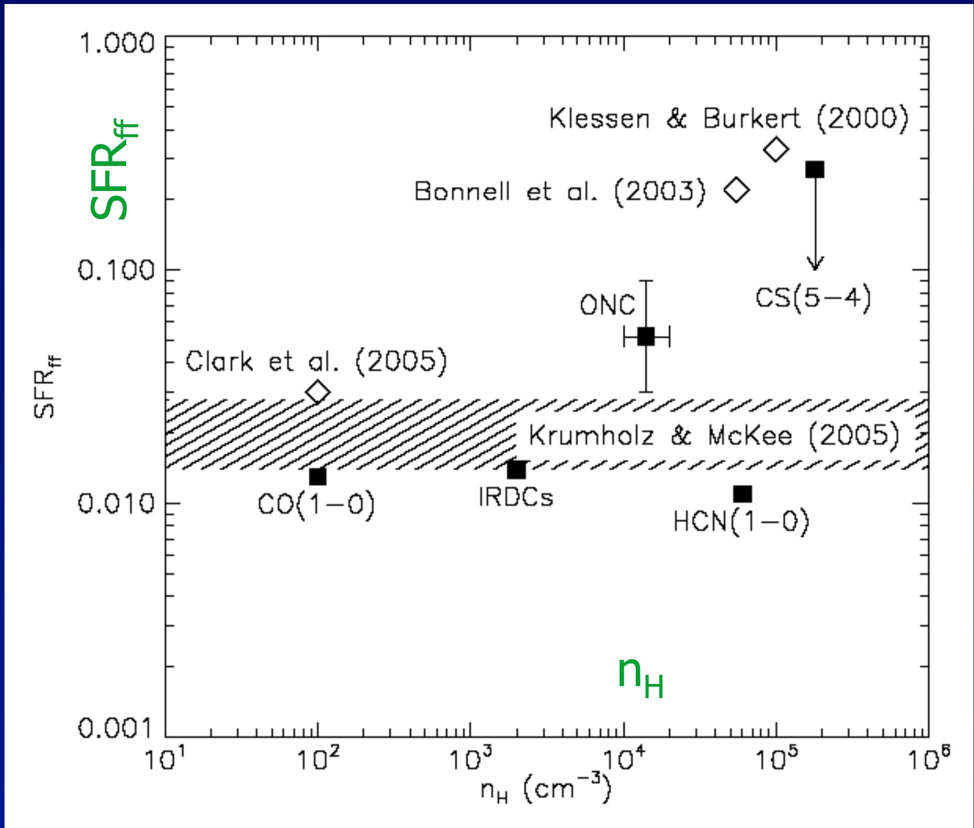
Essentially linear relationships

L_{IR} Measures SFR (given time…)



The evolution of light to star formation rate with various models (Krumholz & Tan 2006).
L_{IR} measures SFR well if enough time to form full sample of IMF. There will be variations.
L_{IR} may underestimate SFR at early times, cf. higher L/M if there is an HII region.

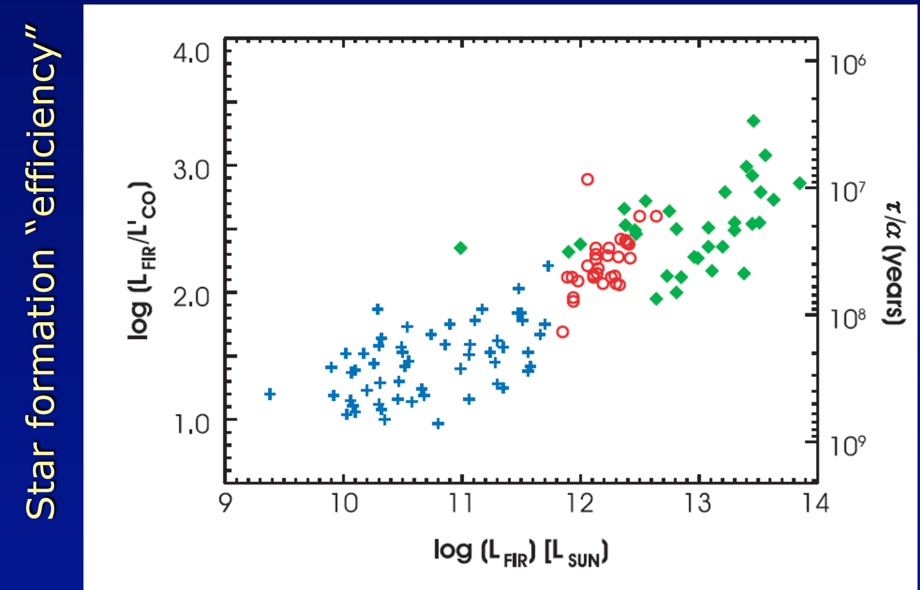
Massive, Clustered Star Formation is Also "Slow"



Hard to assess t_{dep} directly.
Indirect arguments support similar small values of t_{ff}/t_{dep}.
These support an equilibrium cluster star formation mode, which is suggested by the turbulence-regulated massive star formation model (Krumholz and Tan 2006).

Star formation fraction per free-fall time Vs.
effective density of the tracer (Krumholz & Tan 2006)

SFR/Mass(CO) Increases with SFR

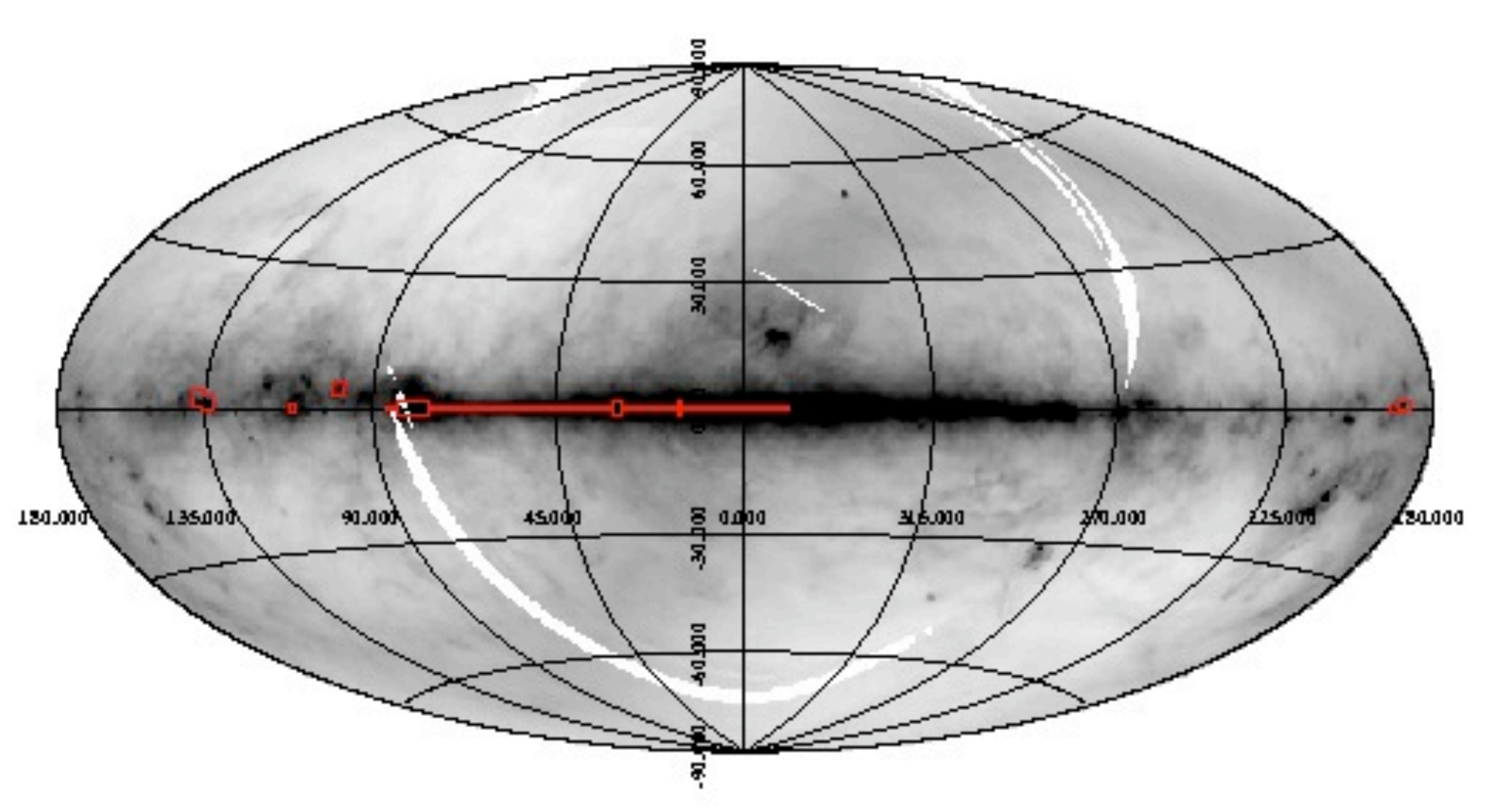


Star formation Rate

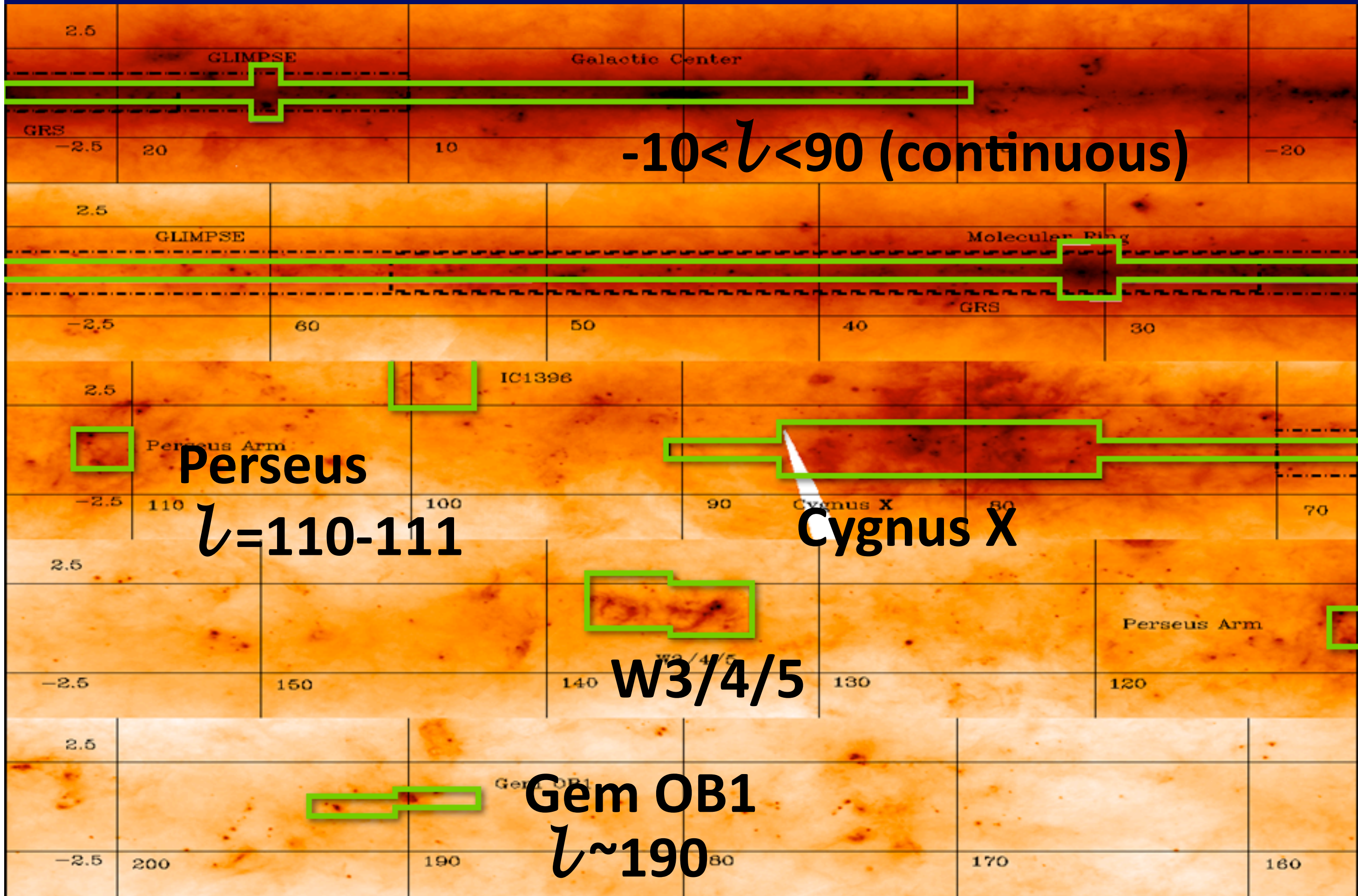
- **SFR/Mass of molecular gas increases with SFR**
- **Factor of ~ 100**
- **"Efficiency" increasing**
- **But what does this really mean?**

Solomon & Vanden Bout (2005 ARAA)

Bolocam Galactic Plane Survey



The Bolocam Galactic Plane Survey (BGPS)



4 Months over two years on CSO
At 1.1 mm
Covered
153 sq. deg.
<rms> = 30 mJy
At T_d = 20 K,
$M_{rms} = 0.4\ D^2_{kpc}\ M_{sun}$

Background is IRAS 100 microns; Dashed lines are GLIMPSE
Complementary survey in South (ATLASGAL with APEX)
JCMT Galactic Plane Survey (JPS) will go much deeper in a few years

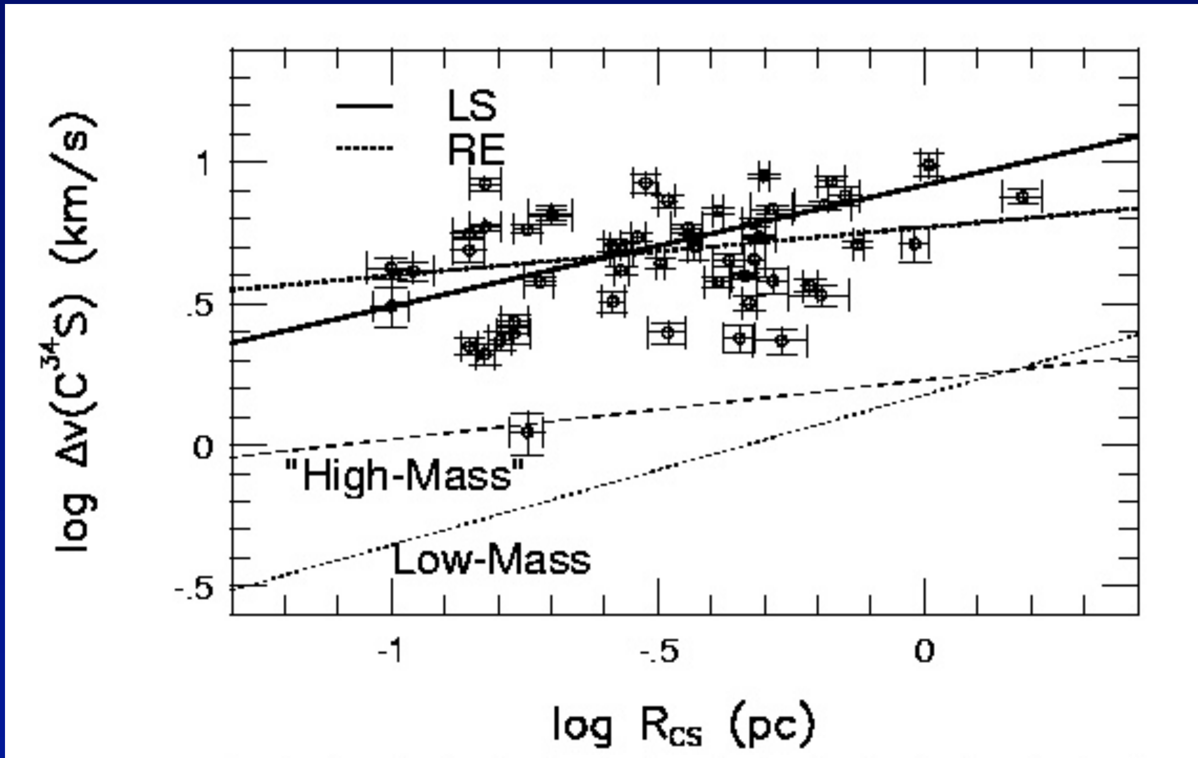
The Center of MW

Red: 1mm BGPS

Cyan: 8 micron Spitzer

Purple: 20 GHz VLA

Turbulence is High



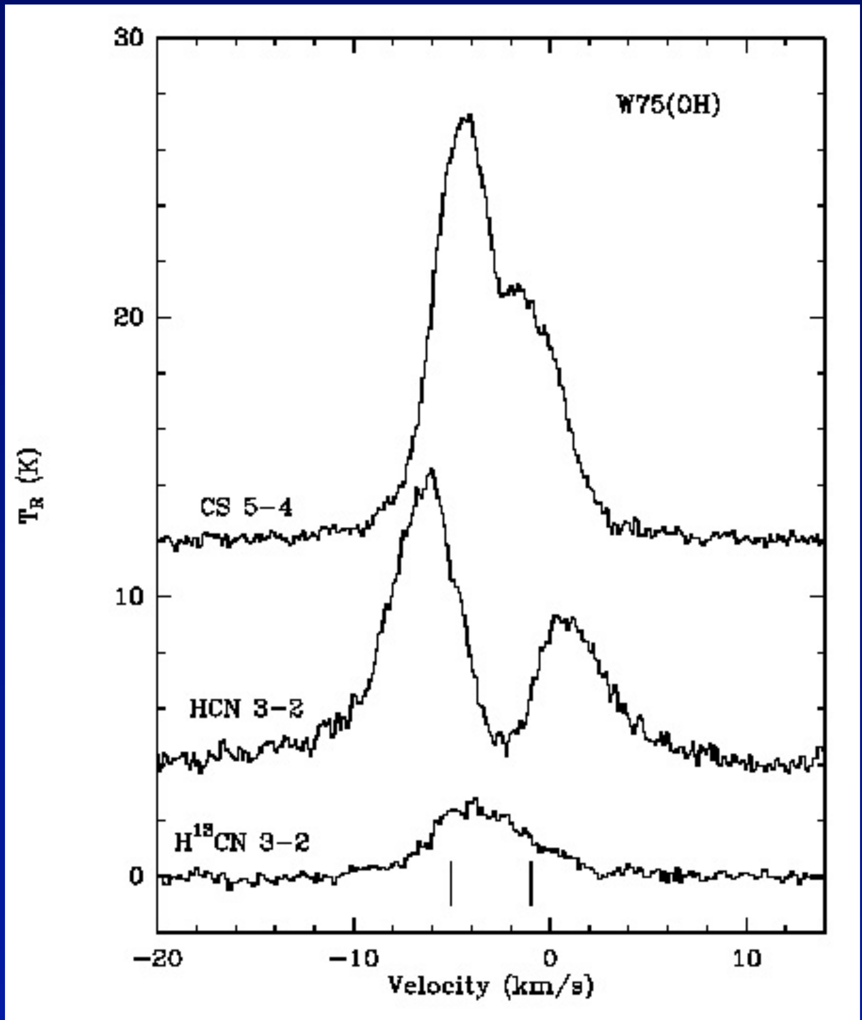
Correlation is weak.

Linewidths are 4-5 times larger than in samples of lower mass cores.

Massive clusters form in regions of high turbulence, pressure.

Shirley et al. 2003

Some Evidence of Inflow



J. Wu et al. (2003)

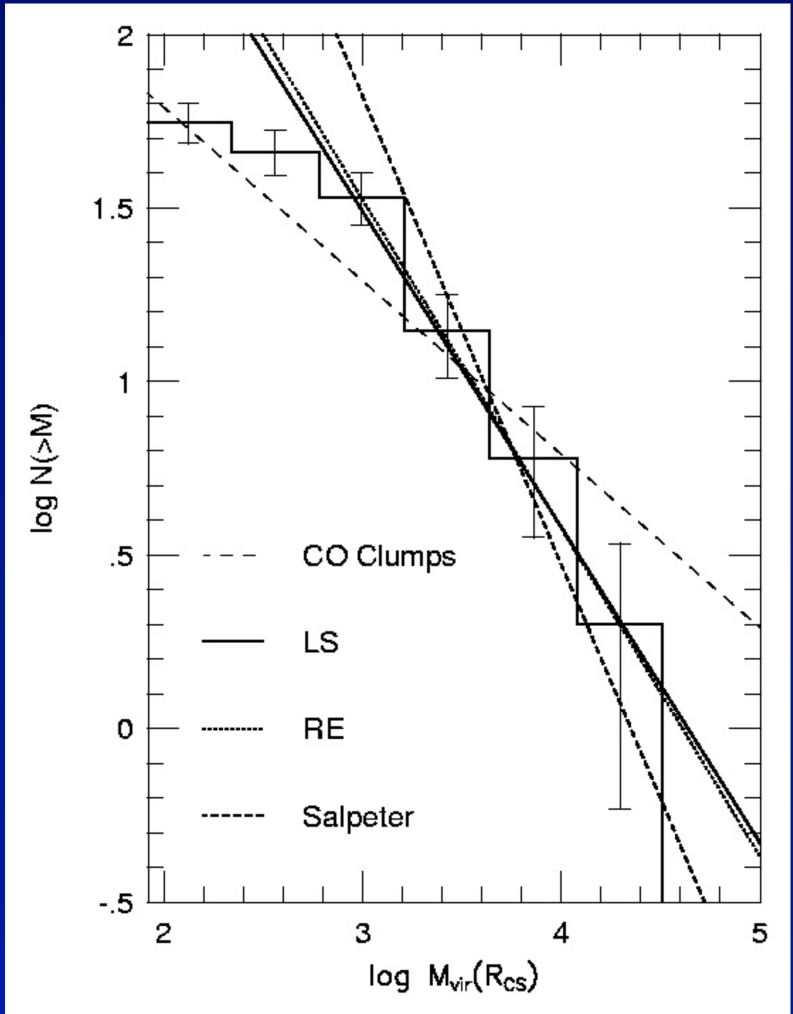
A significant fraction of the massive core sample show self-reversed, blue-skewed line profiles in lines of HCN 3-2.
Of 18 double-peaked profiles, 11 are blue, 3 are red.

Suggests inflow motions of overall core.

V_{in} ~ 1 to 4 km/s over radii of 0.3 to 1.5 pc.

Also, Fuller et al. (2005) found 22/77 sources with blue profiles using HCO^+ 1-0 and H_2CO lines. V_{in} ~ 0.1 to 1 km/s
dM_*/dt ~ 10^{-4} to 10^{-3} M_{sun}/yr

Mass Function of Dense Clumps



Cumulative Mass Function Determined from M_{vir}.
Incomplete below 1000 M_{sun}

Steeper than Cloud or CO clump mass functions.
Best fits: –0.91 to –0.95

Salpeter is –1.35 on this plot, but relevant comparison is to **total** masses of OB Associations
Massey et al. (1995) found –1.1+/-0.1 for 13 OBAs.
McKee and Williams (1997) predict –1.