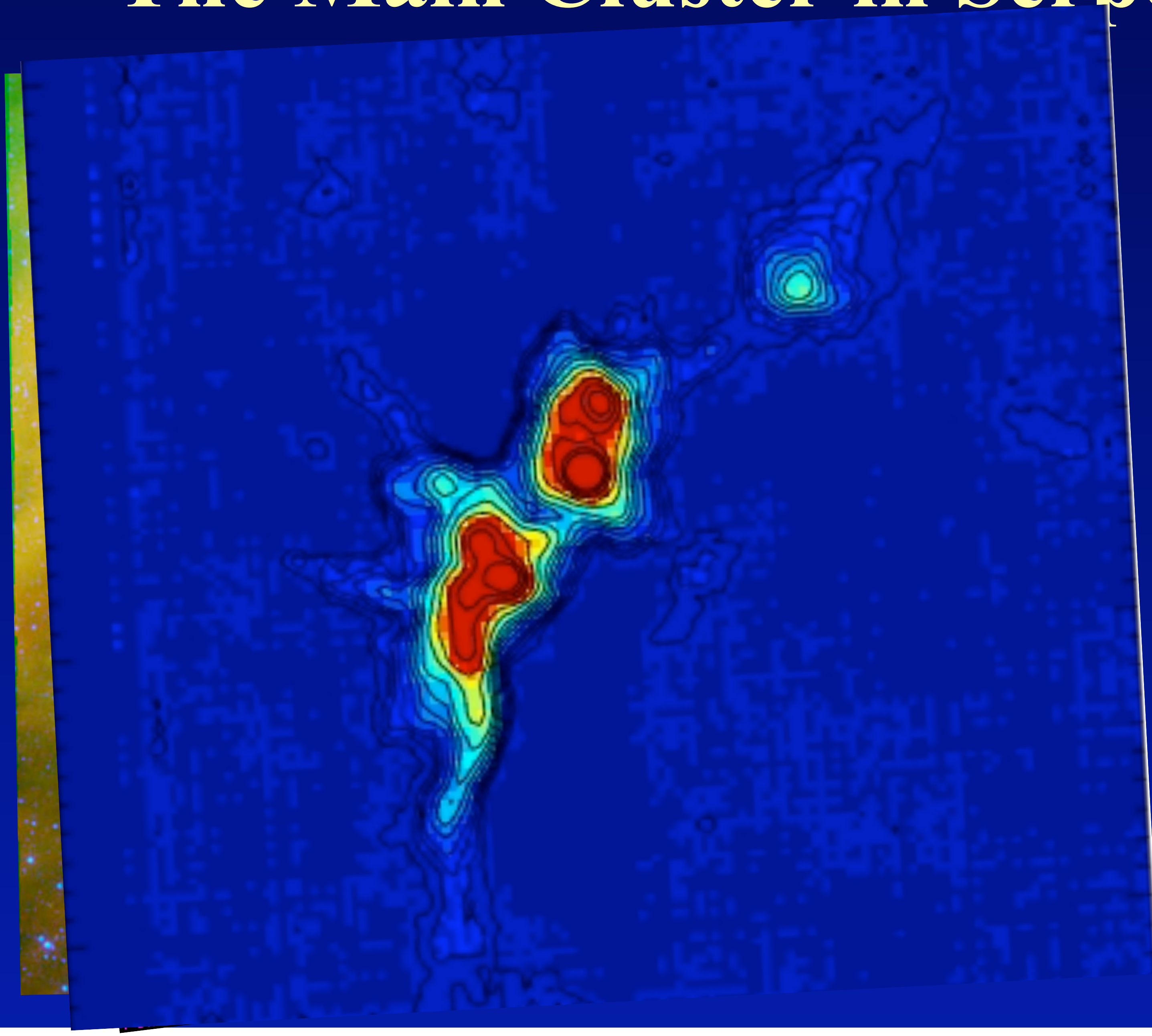
Observed Properties of Massive Molecular Cores (Clumps)

Neal J. Evans II

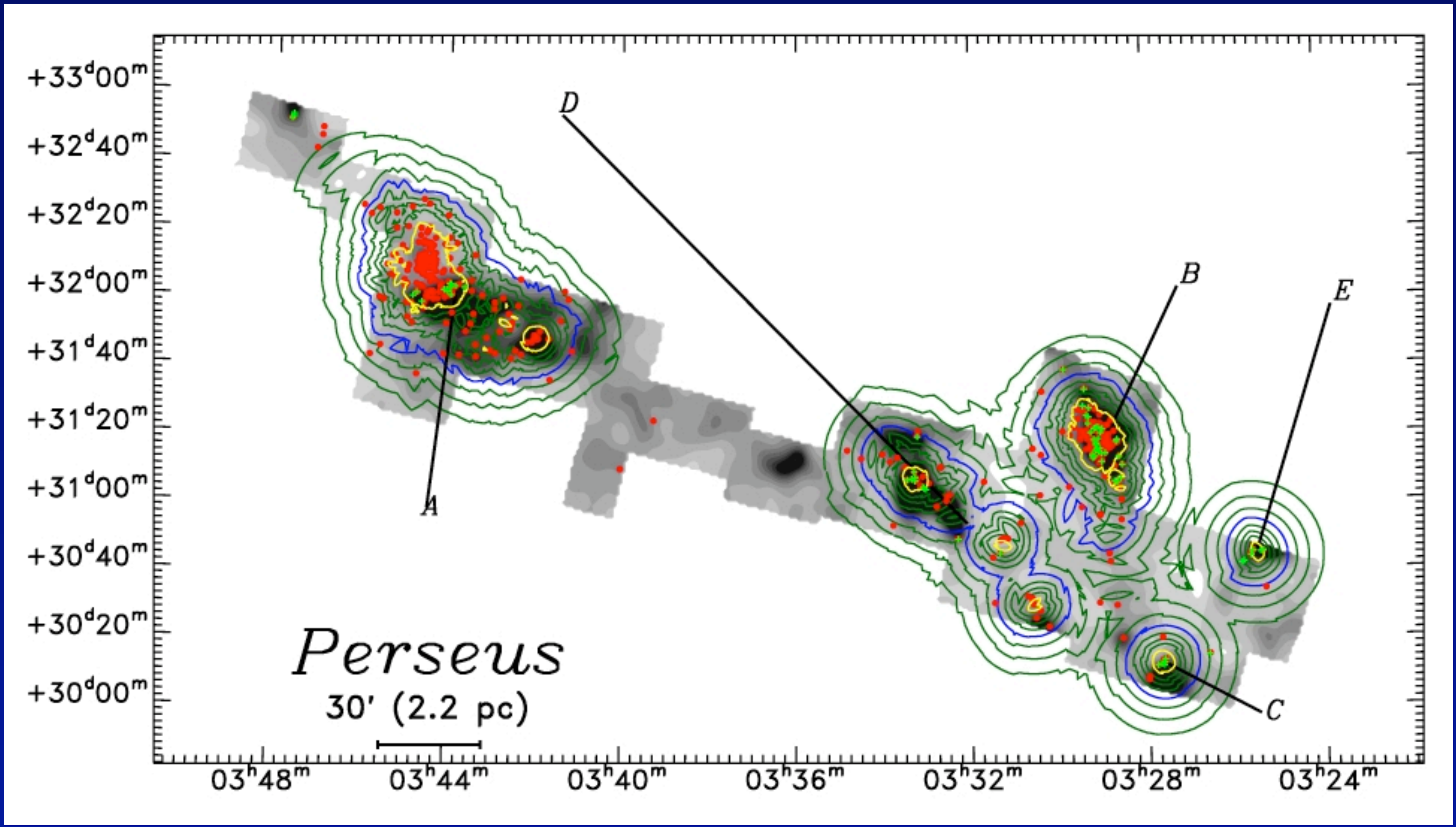
Star Formation in Nearby, "Large" (3-10pc) Clouds

- **Where do stars form in large molecular clouds?**
- **What are the properties of the star-forming entities?**
- **How efficient is star formation?**
- **How long does star formation take?**
- **c2d Survey**
  - **Survey 5 large clouds with Spitzer**
  - **Survey 3 of them with Bolocam, and COMPLETE**
  - **Will focus on Perseus and Serpens as examples**

The Main Cluster in Serpens



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})

Dense Cores, YSOs 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
- Core collisions not common at present
  - t_{coll} ~ 10 x t(ClassI) in Serpens

Mass Functions

- We can constrain Core Mass Function
  - 3 Clouds with Bolocam maps
  - Starless cores only
  - Masses from 1 mm dust
  - Absolute uncertainties substantial
  - But shape is not as sensitive

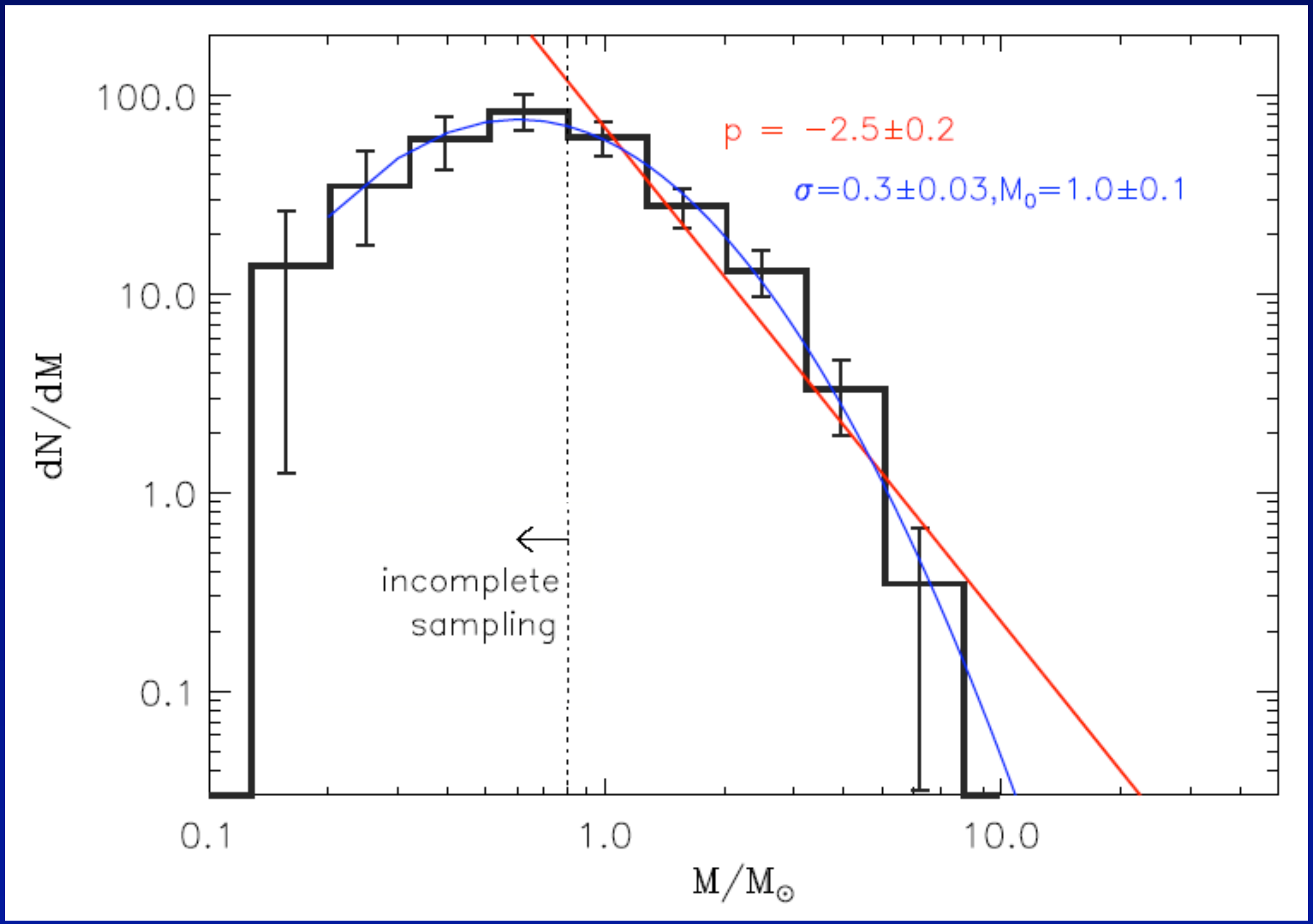
Combined starless core mass distribution

Masses:

$T_D = 10K$

$\kappa_\nu = 0.0114\ cm^2/g$

- Best fit power law: p ~ 2.5 or Lognormal
- IMF:
  Salpeter (p~2.4)
  Chabrier 03
  (p~2.7 M>1$M_\odot$)



⟹ "Not inconsistent" with a scenario in which stellar masses are determined during core formation. If so, >25% goes into star.

Enoch et al. 2008

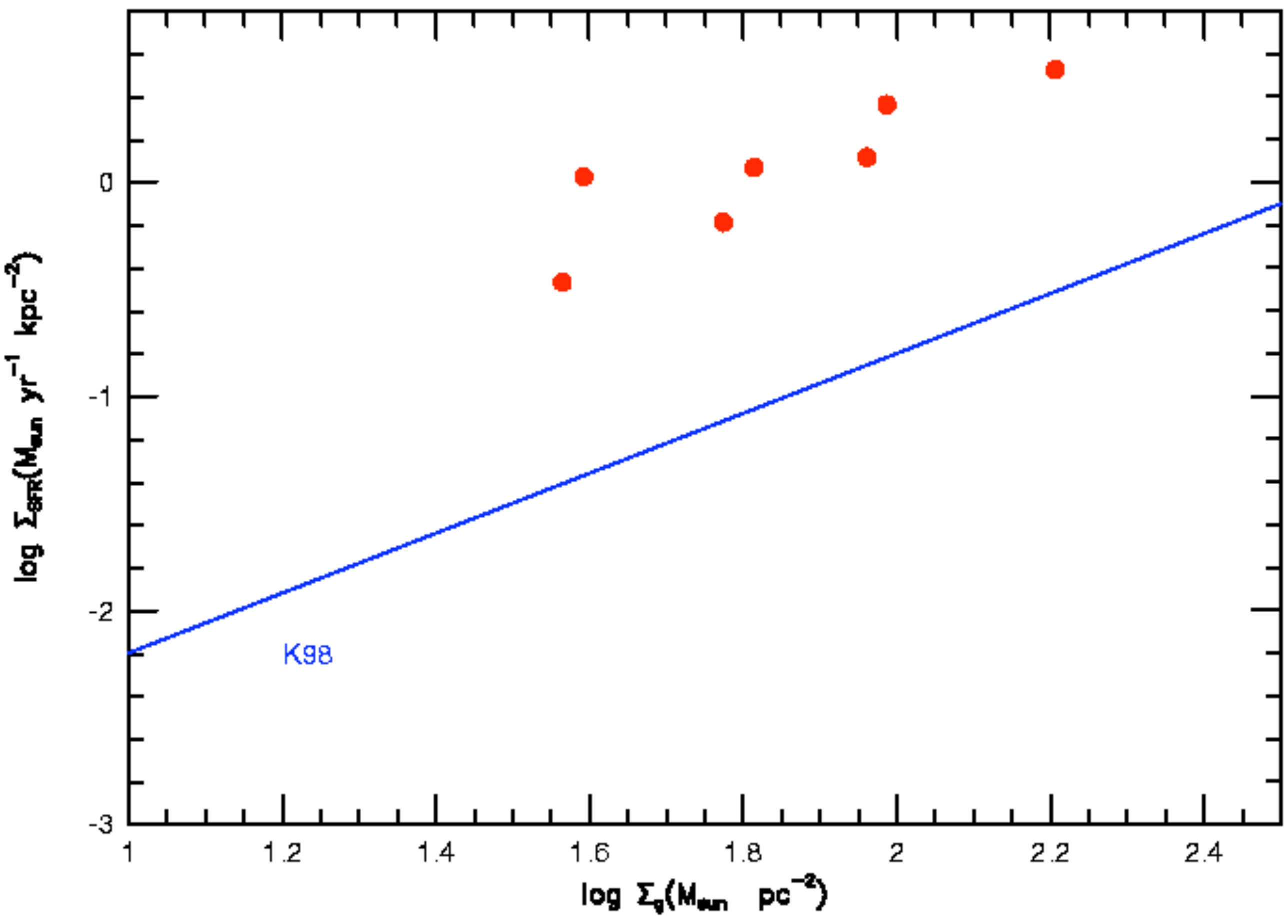
How “Efficient” is Star Formation?

- 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

What would Kennicutt Relation Predict?

- **Kennicutt (1998) relation for SFR**
  - **On scales of kpc in other galaxies**
  - **$\Sigma_{SFR}(M_{sun}\ yr^{-1}\ kpc^{-2}) = 2.5x10^{-4}\ \Sigma^{1.4}{}_{gas}(M_{sun}\ pc^{-2})$**
  - **Includes normal galaxies and starbursts**
  - **Theory: SFR ~ $\rho^{1.5}$ makes sense**
    - **Mass/t_{ff} ~ $\rho/\rho^{-0.5}$ ~ $\rho^{1.5}$**
    - **Does it work for an individual molecular cloud?**
    - **Accurate Σ_{SFR} from counting YSOs, Σ_{SFR} from extinction**

Where do our data lie?



What are the Implications?

- Kennicutt relation does not apply to these molecular clouds
  - Does work well for average over molecular, atomic gas
  - In local kpc^2, 85% HI, K98 works pretty well
  - Averaging scale > individual molecular clouds
  - Expect more studies as more local clouds surveyed

Lessons from Nearby Clouds

- Stars form in dense cores (not clouds)
  - Cores are not located randomly over cloud (in “clumps”)
  - A small fraction of cloud mass is in cores
- The mass function of cores may determine the IMF
- Star formation in clouds is very inefficient (2-4%)
- Star formation in dense cores is very efficient (> 25%)
- Focus on dense cores (n > about 10^5 cm^{-3})
- Lifetime of embedded protostellar phase ~ 0.5 Myr
- Σ_{SFR} >10 times prediction of Kennicutt relation

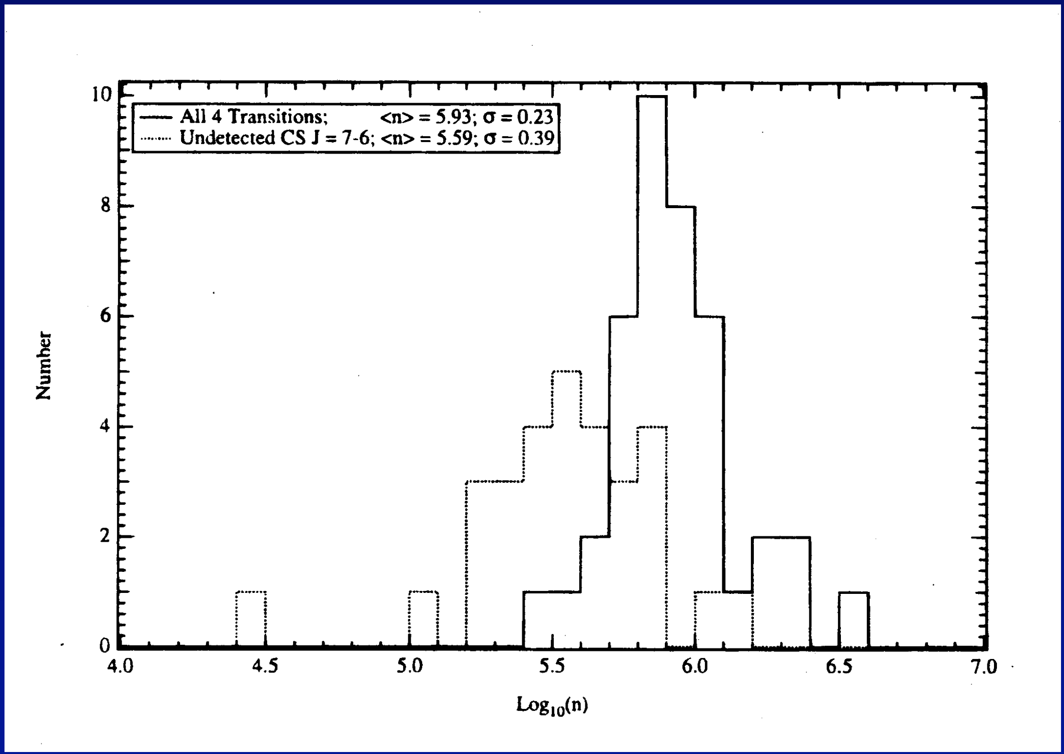
What About Massive Stars?

- Goal is to do studies similar to those in nearby clouds
- Need to study more distant clouds
  - Less biased sample (Galactic plane surveys)
  - Need better resolution (ALMA and JWST)
    - Get core mass function
    - Resolve motions
    - Count stars
  - Need improved theoretical predictions

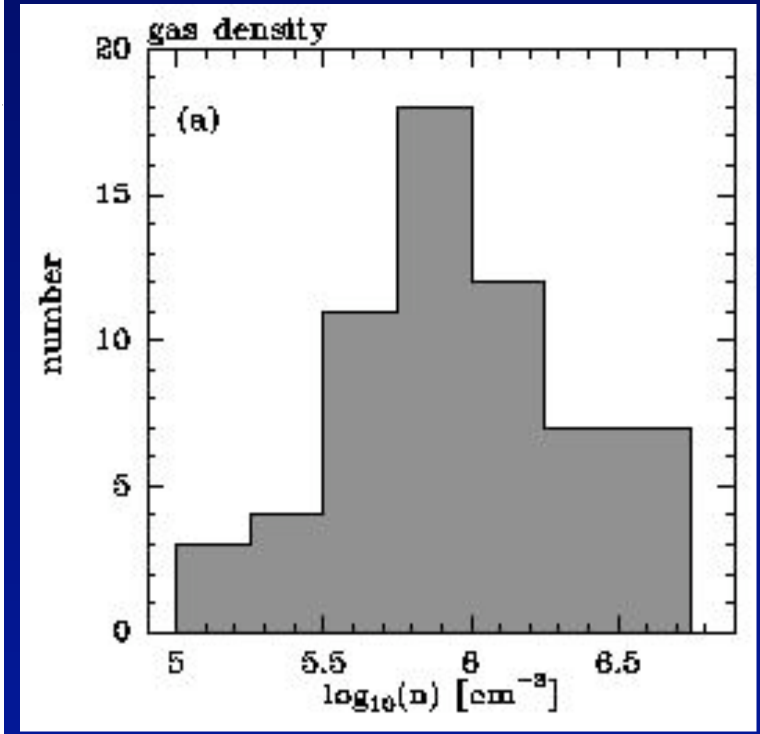
Studies of Galactic Regions of Cluster Formation

- **Existing surveys of dense gas**
  - **Water masers as signposts**
    - **Plume et al., Mueller et al., Shirley et al., Wu et al.**
    - **Studied with dust continuum, CS, HCN…**
  - **IRAS + CS + radio-quiet (HMPOs)**
    - **Sridharan et al., Beuther et al. (2002)**
    - **Outflows ubiquitous before HII**
  - **Infrared Dark Clouds (IRDCs)**
    - **Egan et al., Carey et al. Simon et al. (2006)**
    - **Studies with molecules (Rathborne et al., Pillai et al. 2006)**

Mean Density is High



Plume et al. 1997



Beuther et al. 2002

Dense: <log n> = 5.9, Plume et al. (1991, 1997),
Same result from Beuther et al. (2002)

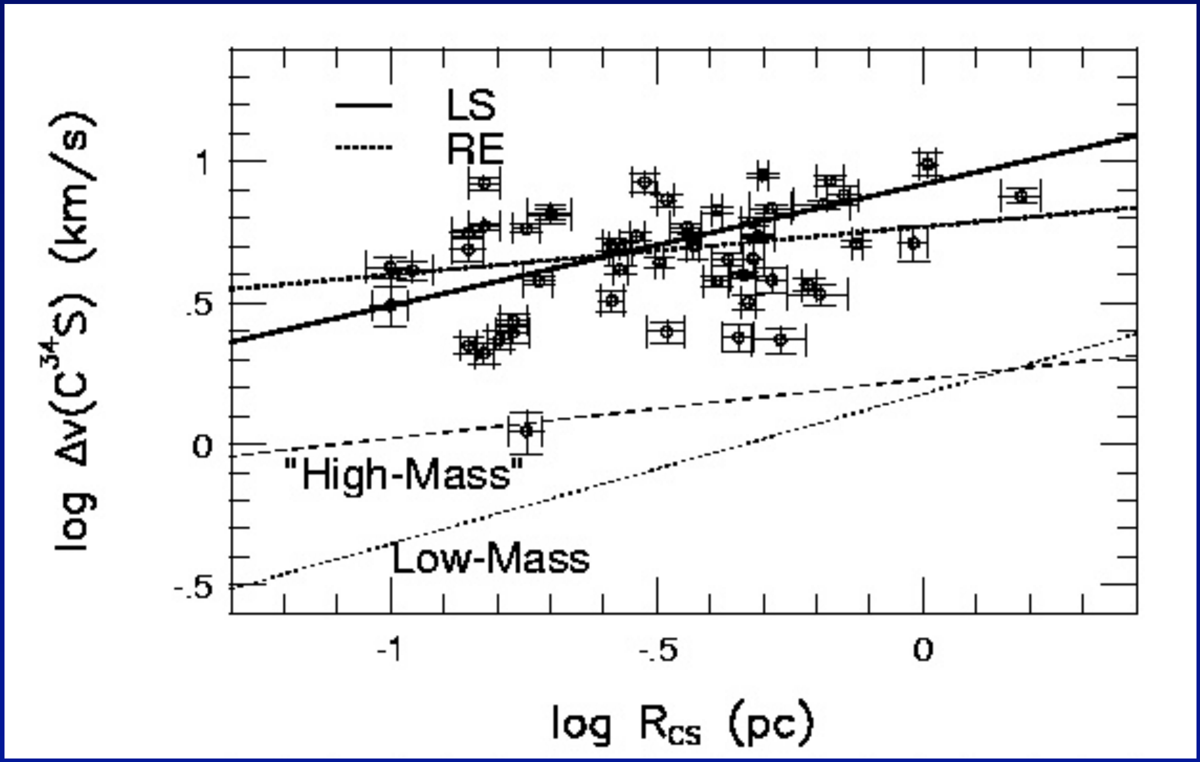
Overall Density Gradients

Property	Low	High
p	~1.6 to 1.8	~1.6 to 1.8
n_f (median)	2×10^5	1.5×10^7
Linewidth	0.37	5.8

$$n(r) = n_f\,(r/r_f)^{-p}\,;\ r_f = 1000\ \mathrm{AU}$$

Mueller et al. 2002, Beuther et al. 2002, Shirley et al. 2003, …

Turbulence is High



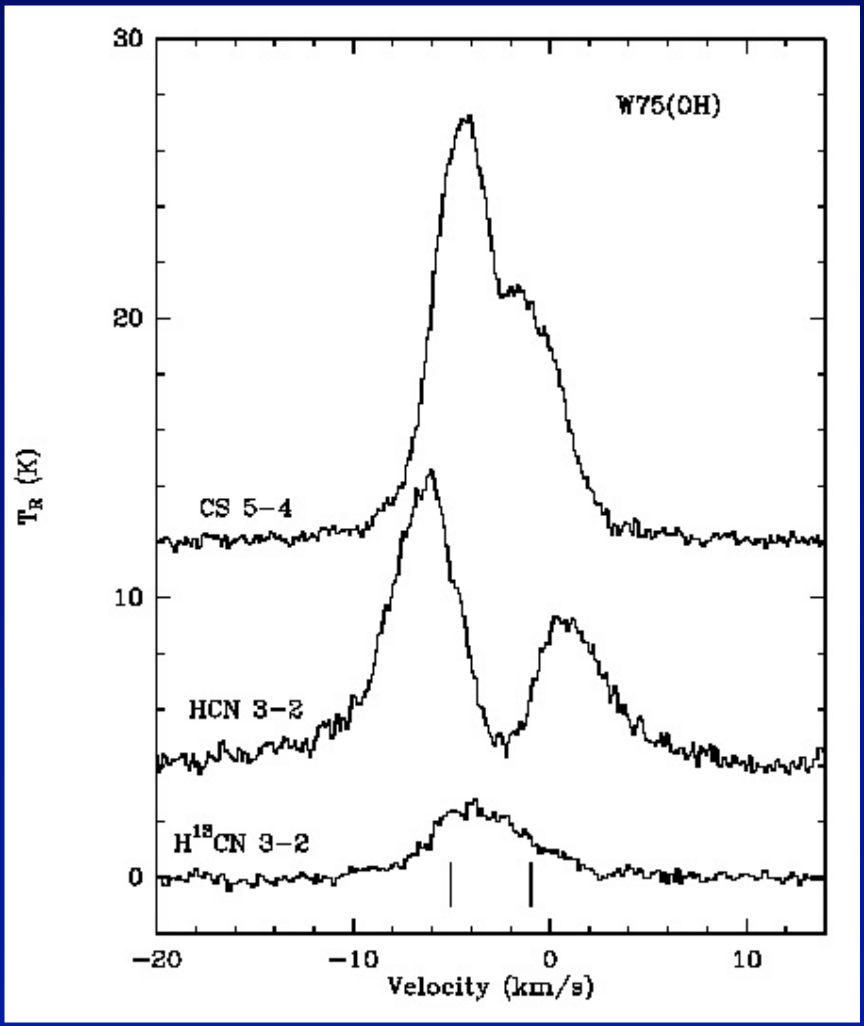
Correlation is weak.

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)

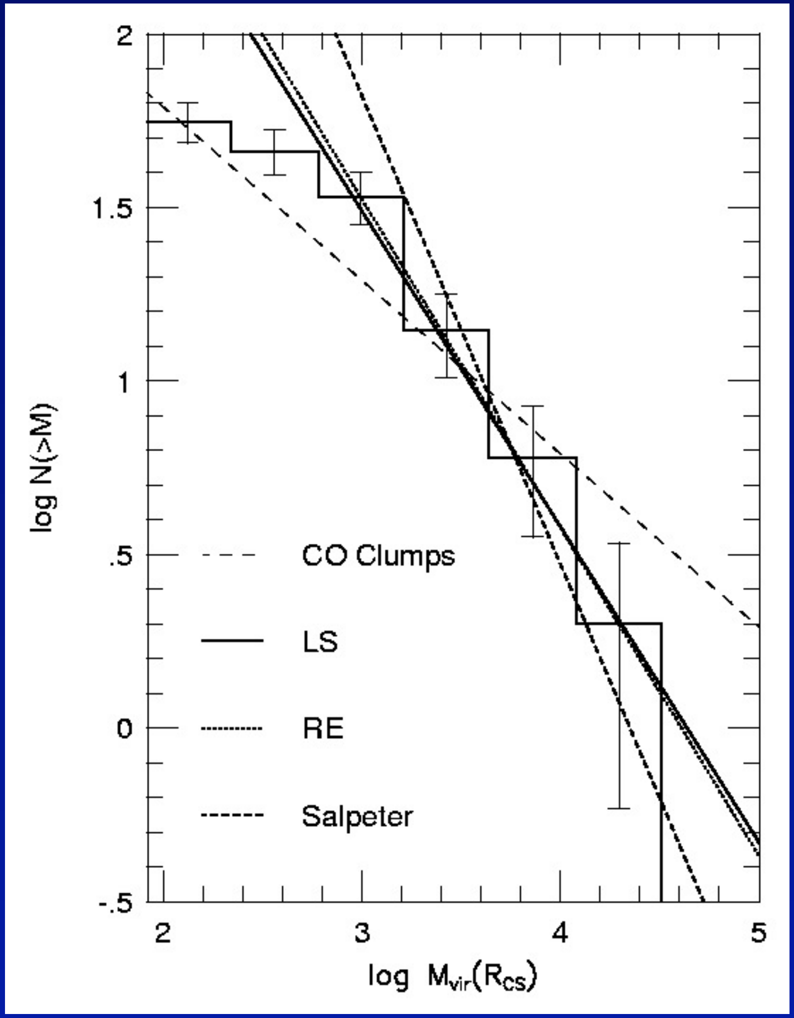
A significant fraction of the massive core sample show self-reversed, blue-skewed line profiles in lines of HCN 3-2.
Of 18 double-peaked profiles, 11 are blue, 3 are red.

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



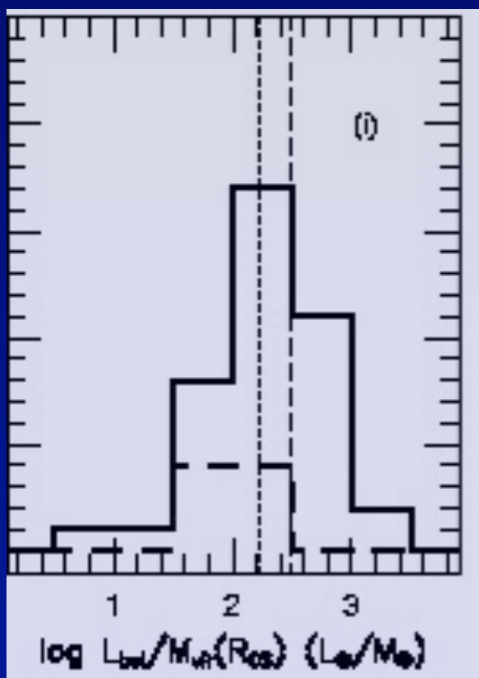
Cumulative Mass Function Determined from M_{vir}.
Incomplete below 1000 M_{sun}

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.

L/M Less for Radio-Quiet

Number



Log L/M

Shirley et al. 2003

Mean L/M is 3-5 times higher in clumps with HII regions. (Shirley et al. 2003, Sridharan et al. 2002)

Massive Clumps: Gross Properties

- Massive, Dense, Turbulent
  - Mean mass 1800 M_{sun}, median 920 M_{sun} (masers)
  - Similar overall power law shape to low mass cores
    - About 100 times denser
  - 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
  - Mass distribution closer to clusters than to GMCs
  - L/M increases as HII regions form

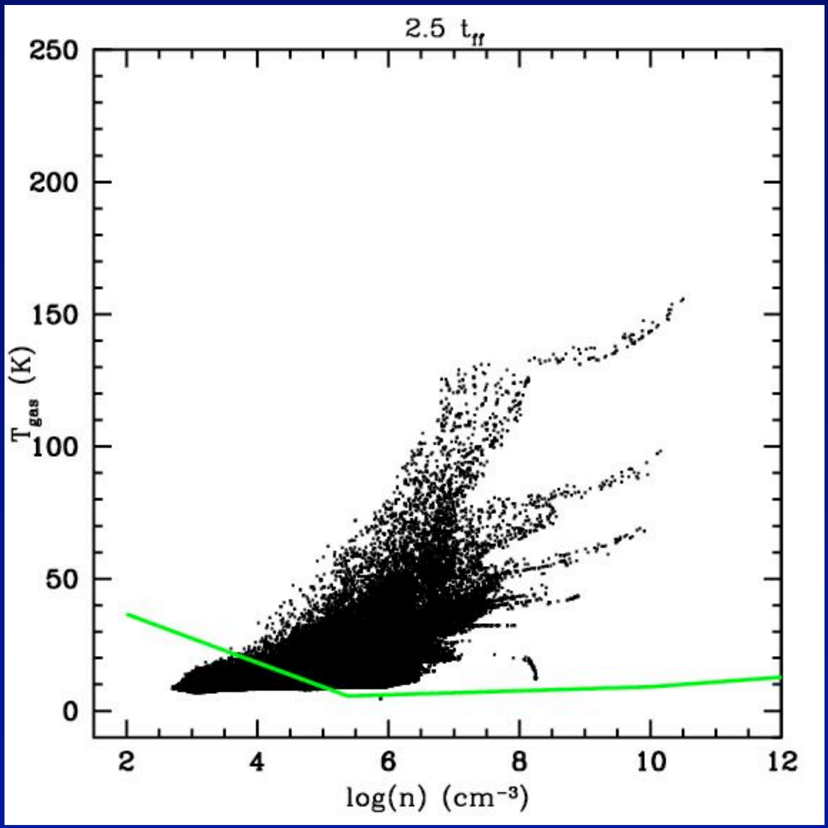
What Do These Clumps Make?

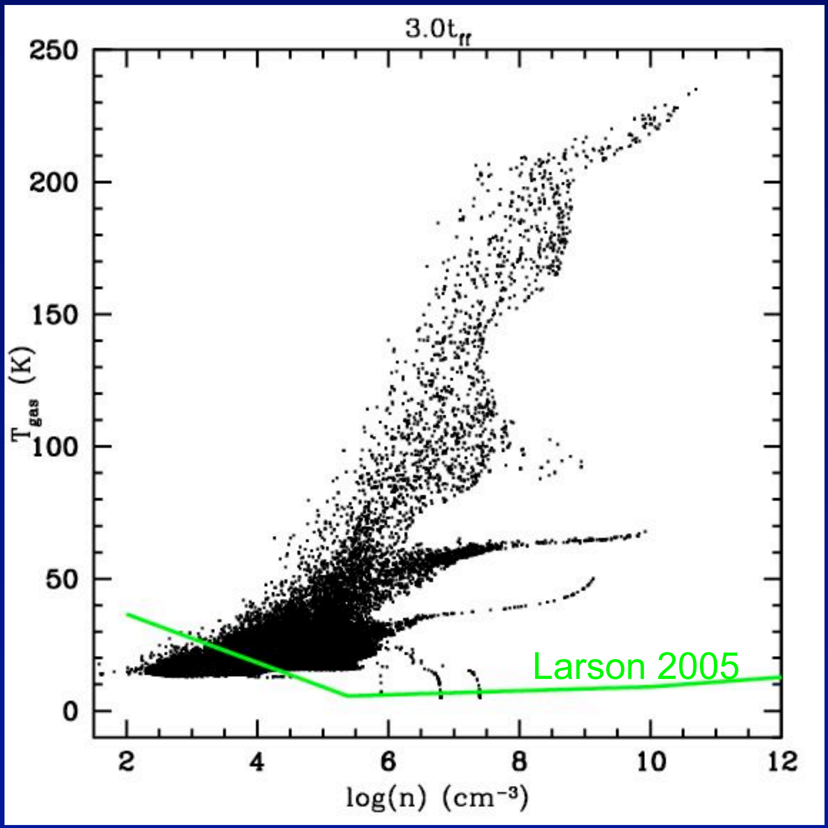
- Star Clusters and Associations
- Much of this has been hidden by dust
- 2MASS and GLIMPSE/Spitzer revealing the clusters
- May allow more quantitative measures of stellar production as function of gas properties

In Theory…

- Simulations of clumps (many M_{Jeans})
  - Klessen, Bonnell, Bate, Martel, …
- Produce clusters of stars
  - Debate over accretion mechanism
- Predict IMF
  - Isothermal gas: only very low mass stars
- Once stars form, feedback is important
  - First protostars heat dust, dust heats gas

The Equation of State

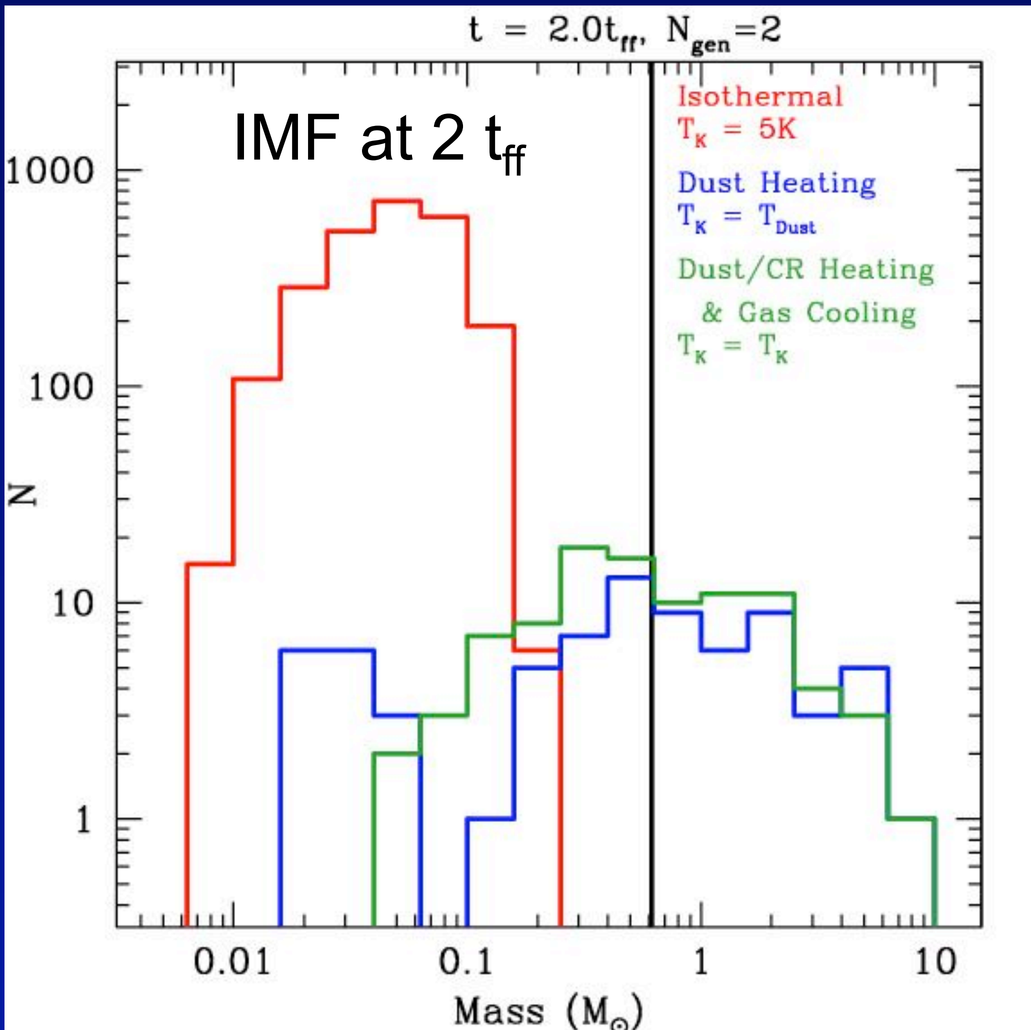




Andrea Urban dissertation

Once stars form and heat their surrounding, representing the EOS by $P = K\rho^{\gamma}$ does not capture the situation.

The IMF and Feedback



Andrea Urban dissertation

Box of about 1 pc^3

Mass = 671 M_{sun}

Initial n = 1.2 x 10^4 cm^{-3}

Initial M_{Jeans} = 0.6 M_{Sun}

1088 M_{Jeans}

t_{ff} = 0.3 Myr

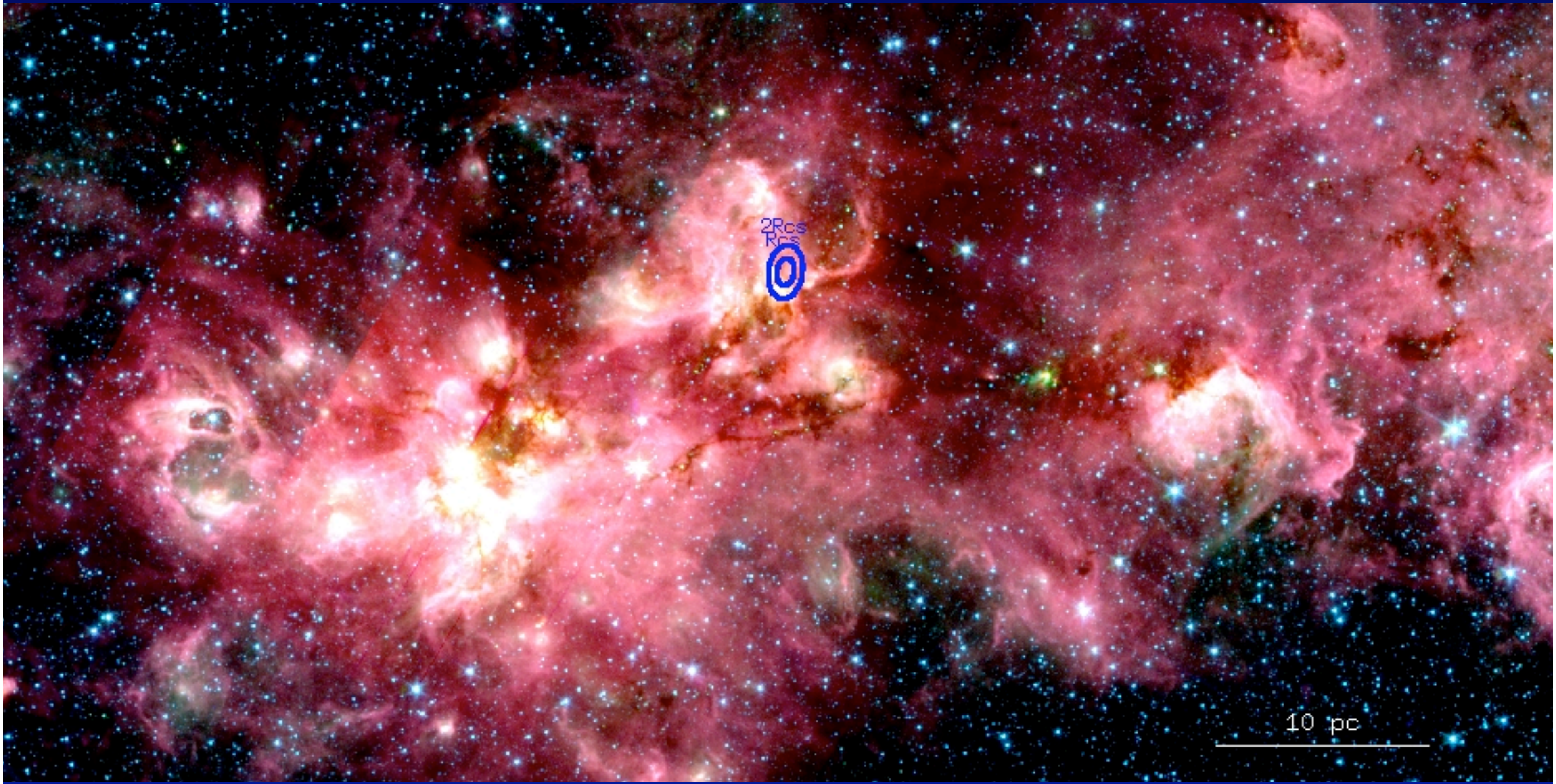
With particle splitting, n_{max} ~ 0.5-1.5 x 10^6 particles

Including energy flow (stars to dust to gas) in molecular gas is essential.

Other Comparisons

- Spherical average around each sink
  - Density structure fit by power law
    - Very similar to observations (<p> = 1.6 to 1.8)
    - Simulations: <p> = 1.6 to 1.7
- Mass accretion rates high, but highly variable
  - $\langle dM_*/dt \rangle \sim$ 1-5 x 10^{-5} M_{sun} yr^{-1}
  - Similar results to Offner et al. (2008)
    - Decaying versus driven turbulence, but barotropic EOS

What Do Clumps Make? Observations



W51W: R_{cs} = 0.64+/-0.08 pc, M_{vir} =1100 M_{sun}, Dist=7.0kpc

blue [3.6], green [4.5], red [8.0] Red dominated by PAH emission

G35.58-0.03

D = 3.5 kpc

R_{cs} = 0.20 +/- 0.02 pc

M_{vir} = 1280 M_{sun}

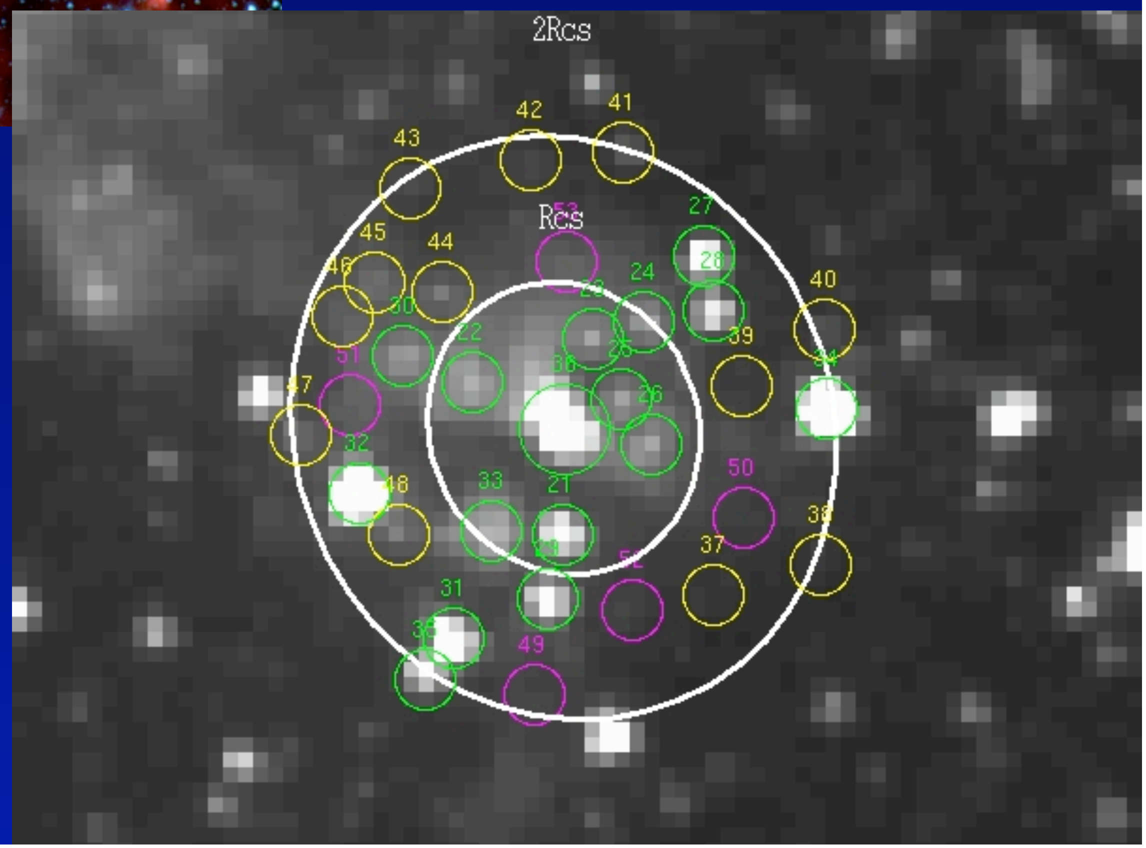
Nordhaus et al.

White: R_{cs} ellipses

Circles: Sources identified for photometry

Difficulties with nebulosity, confusion, membership, …

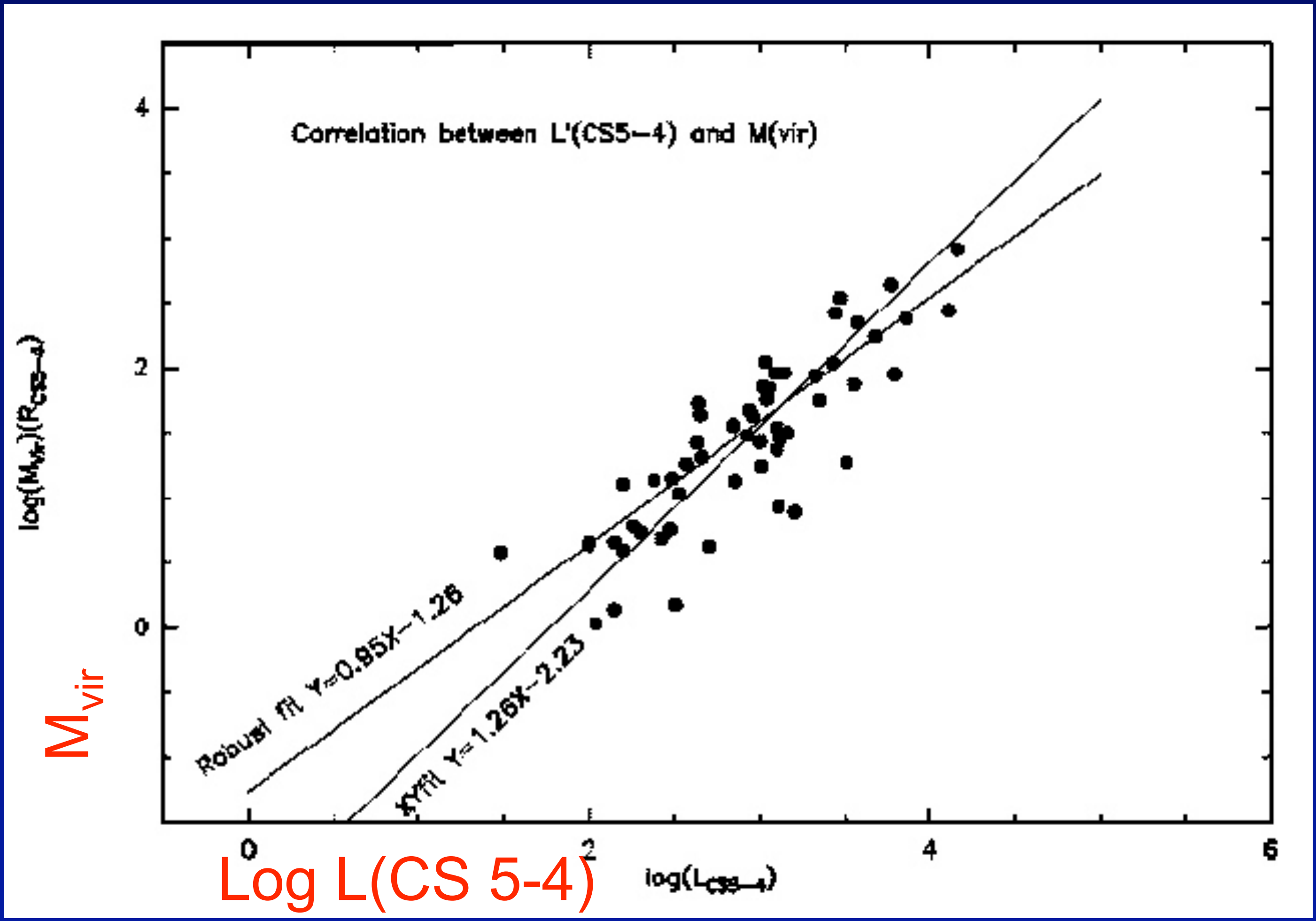
Green: chosen from IRAC1 and IRAC2; Yellow: chosen from 2MASS; Magenta: diffuse emission apertures



Global Measures

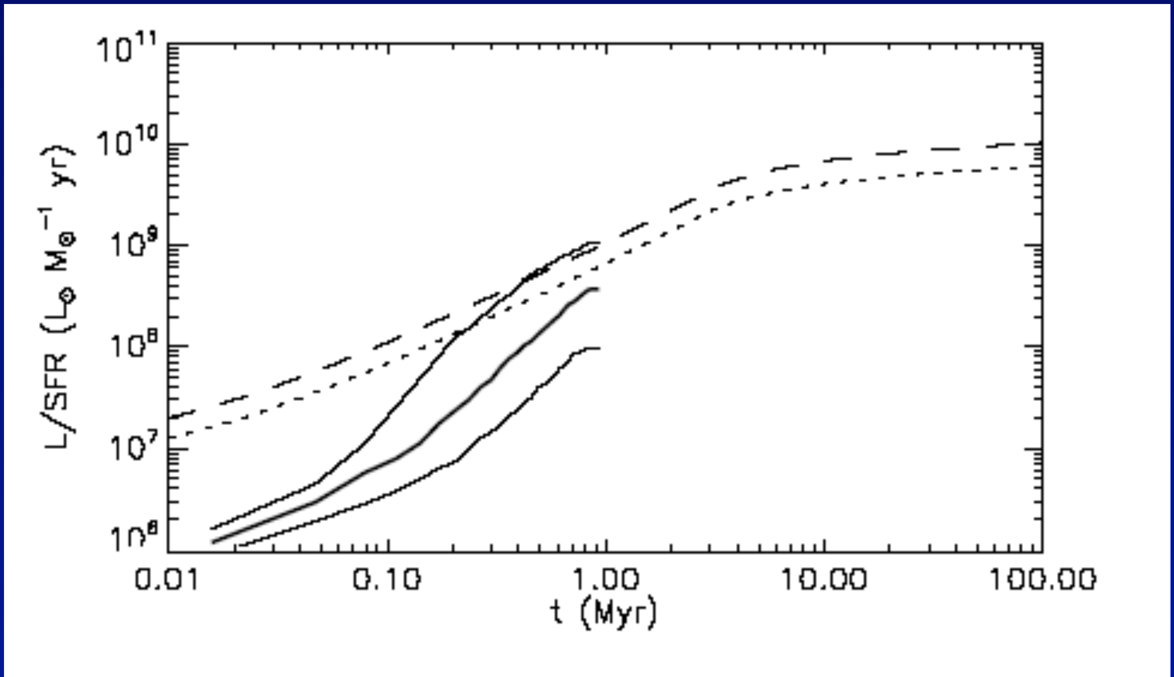
- For now, stick to global measures
  - Star formation rate
  - Mass of dense gas (e.g., virial mass)
- Or Observables
  - Far-infrared Luminosity (L_{IR})
  - Molecular line luminosity (L_{mol})
  - Or, emission from dust at long wavelengths

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



Essentially linear relationships

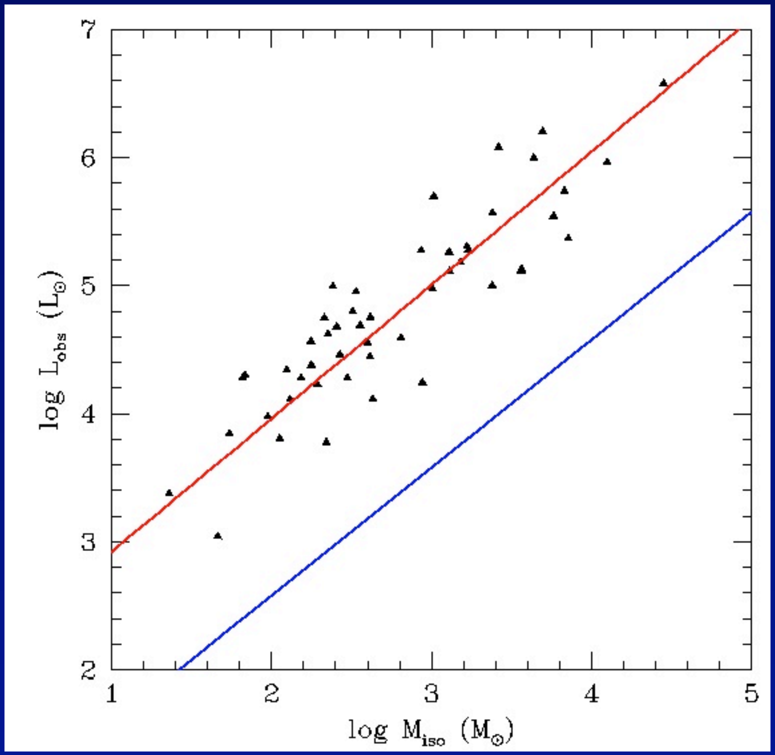
L_{IR} Measures SFR (given time…)



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.

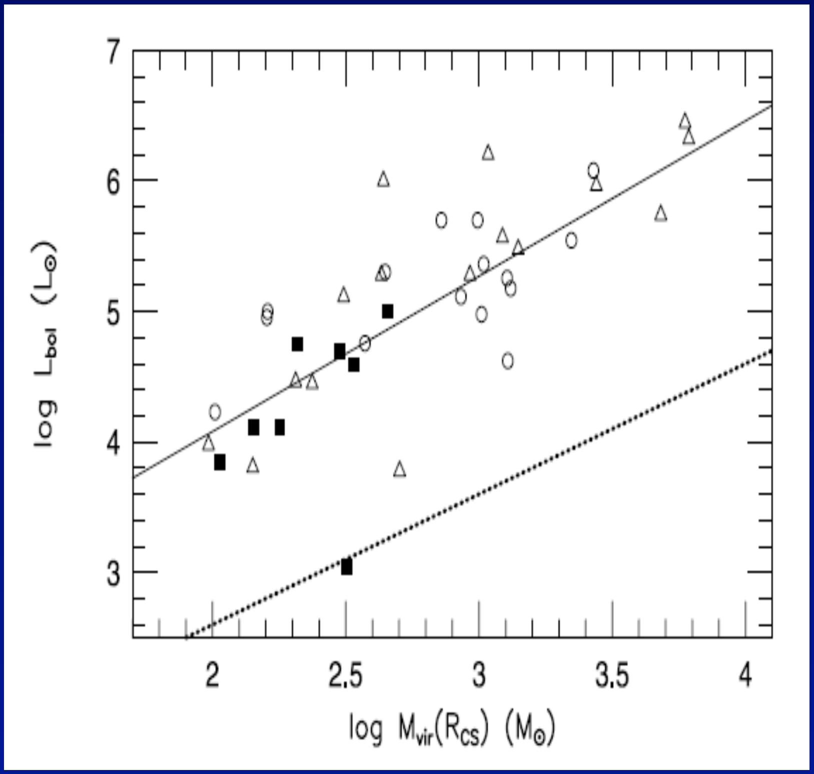
L_{IR} Correlates well with Emission from Dust, Dense Gas Tracers

"Star formation rate"



Mass of dense gas traced by dust emission
Slope ~ 1

"Star formation rate"



Mass of dense gas traced by CS 5-4
Slope ~ 1.2

(Mueller et al. 2002)

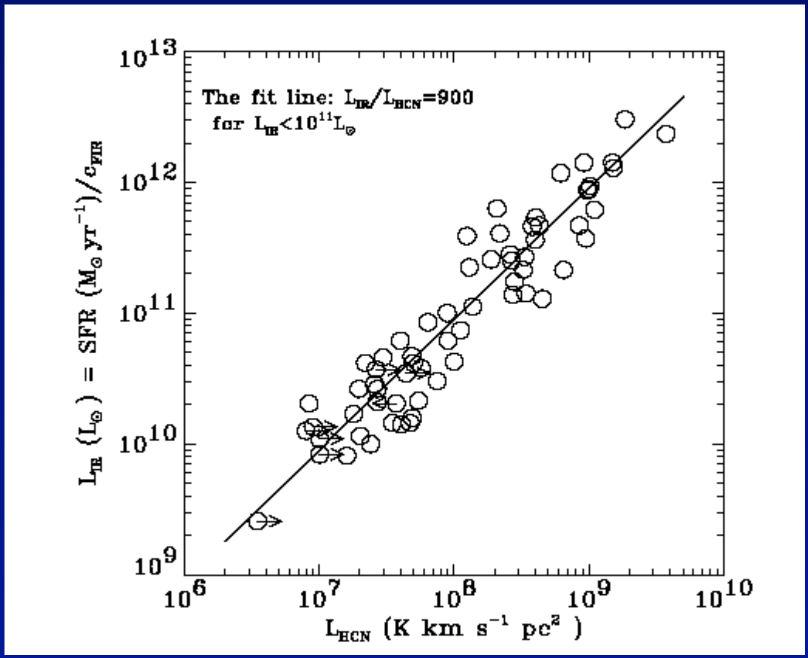
(Shirley et al. 2003)

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



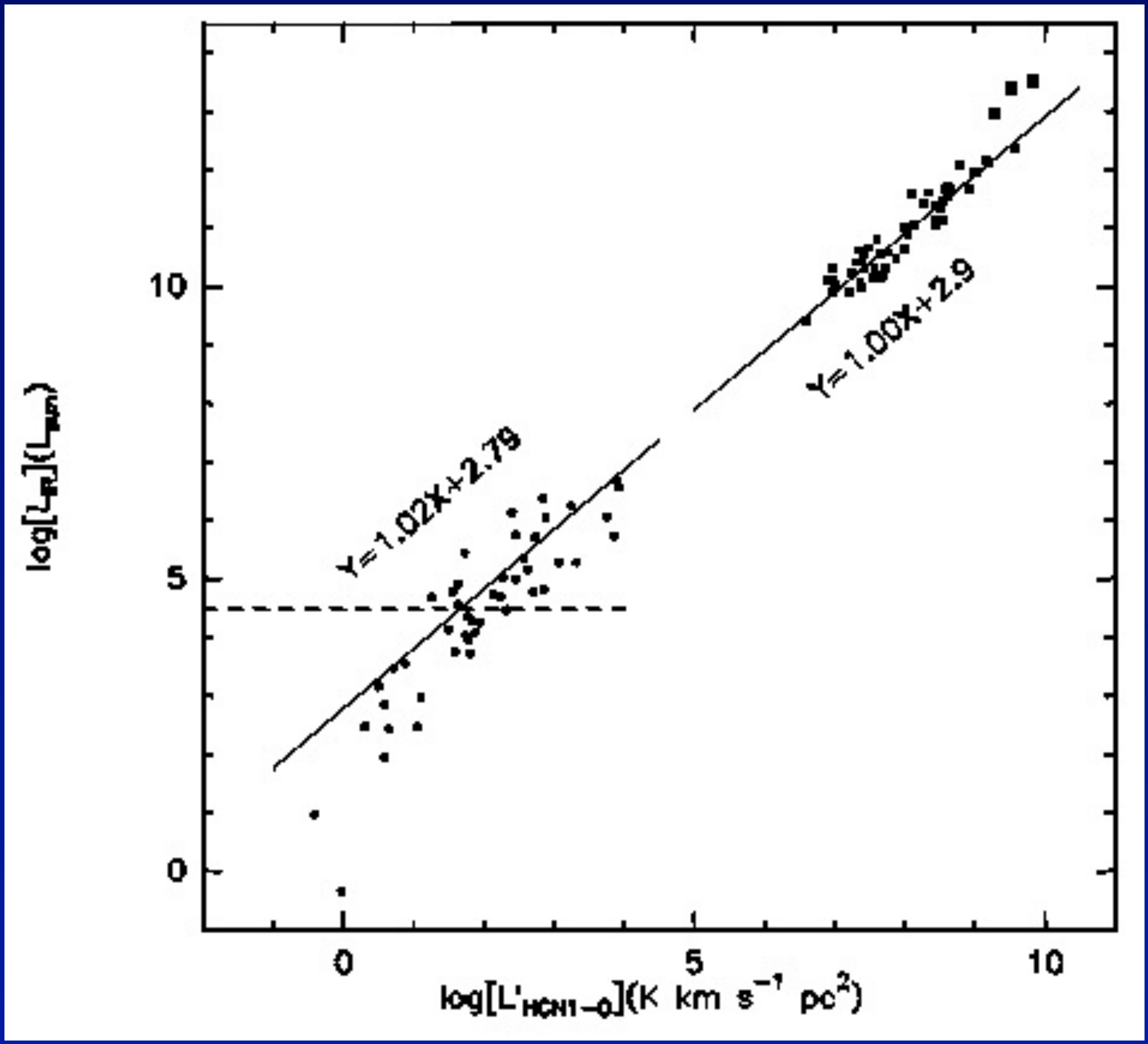
Amount of **dense** molecular gas

- **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)



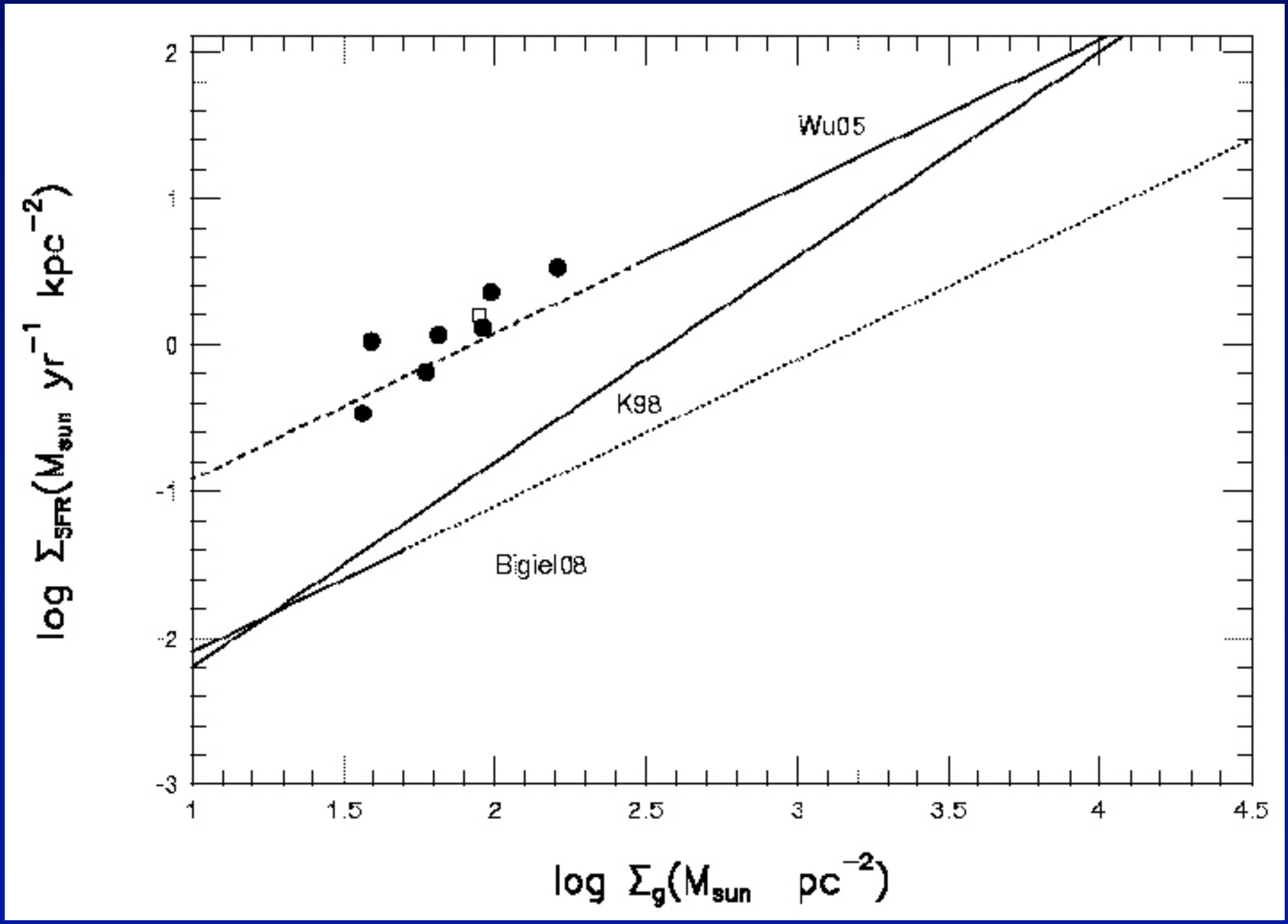
L(HCN J = 1-0)

Wu et al. (2005)

There Must be a Transition

- **Where does the non-linear relation switch to linear?**
  - **K98 finds SFR ~ $\Sigma^{1.5}$ on scales larger than individual clouds**
    - **Works on scale of local kpc in our Galaxy**
    - **Underestimates SFR on scale of individual clouds**
  - **Formation of stars from dense molecular gas is linear**
    - **SFR ~ $\Sigma^{1.0}$**
  - **Is it linear or non-linear for whole molecular clouds?**

Back to the Nearby Clouds…



Star formation rate surface densities closer to extrapolation of HCN relation than to K98.

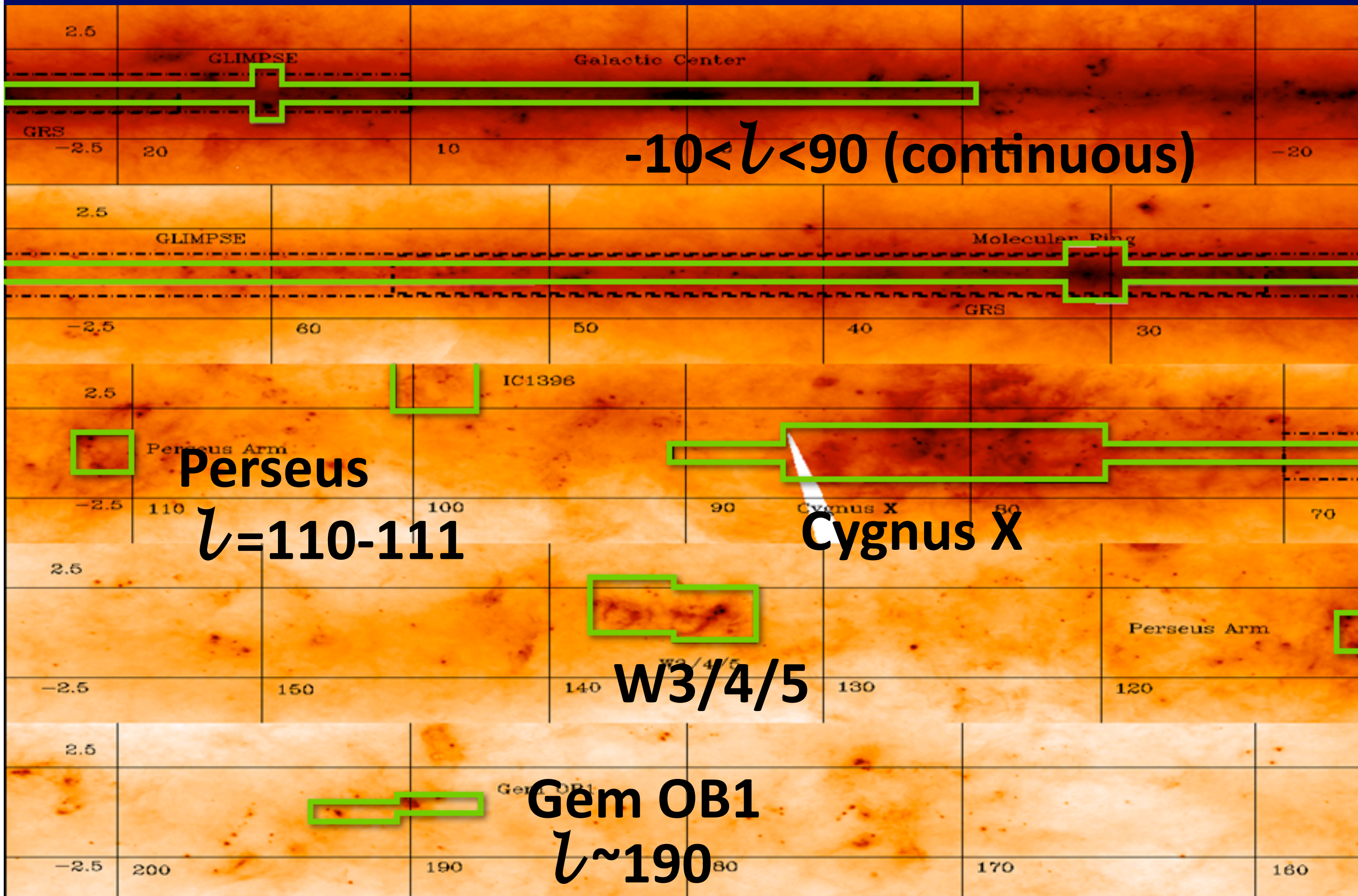
What is the Relevant Scale?

- Nearby clouds behave more like dense clumps ($\Sigma_{SFR} \sim \Sigma_{gas}$)
- On scales > kpc, non-linear ($\Sigma_{SFR} \sim \Sigma^{1.4}_{gas}$)
  - Still averaging over HI, H_2
  - Counting clouds?
- Is the key step making a molecular cloud?
  - M(dense) prop. to M(cloud) on average
- Resolve molecular clouds in nearby galaxies
  - ALMA and JWST

Massive Star Formation in Galactic Context

- Surveys in mm continuum finding 1000's of dense clumps
  - Bolocam Galactic Plane Survey
  - Complementary survey from APEX
- Infrared Dark Clouds (IRDC)
  - MSX, GLIMPSE, MIPSGAL
- New models of Galaxy, VLBA distances, …
- Provide link to extragalactic star formation

The Bolocam Galactic Plane Survey (BGPS)

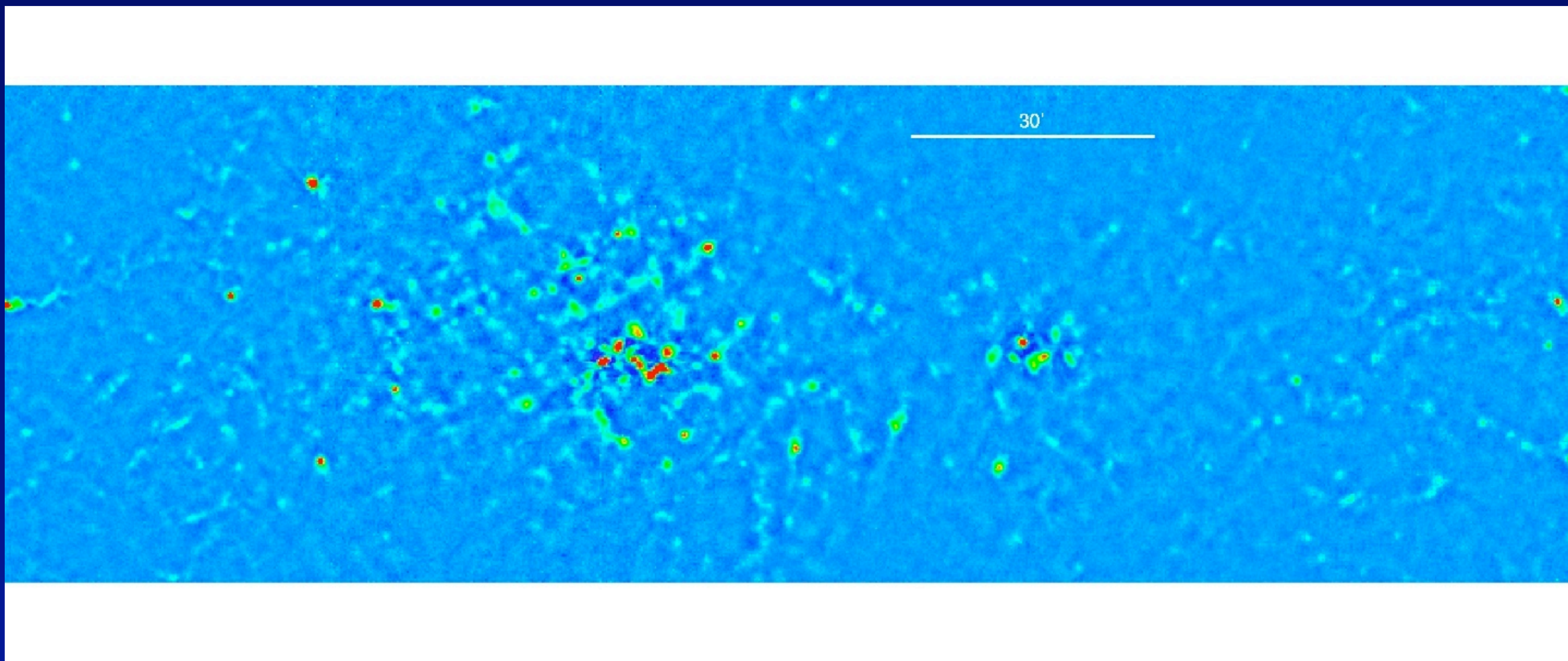


4 Months over two years on CSO
At 1.1 mm
Covered
153 sq. deg.
<rms> = 30 mJy
At T_d = 20 K,
$M_{rms} = 0.4\ D^2_{kpc}\ M_{sun}$

Find 1000s of sources

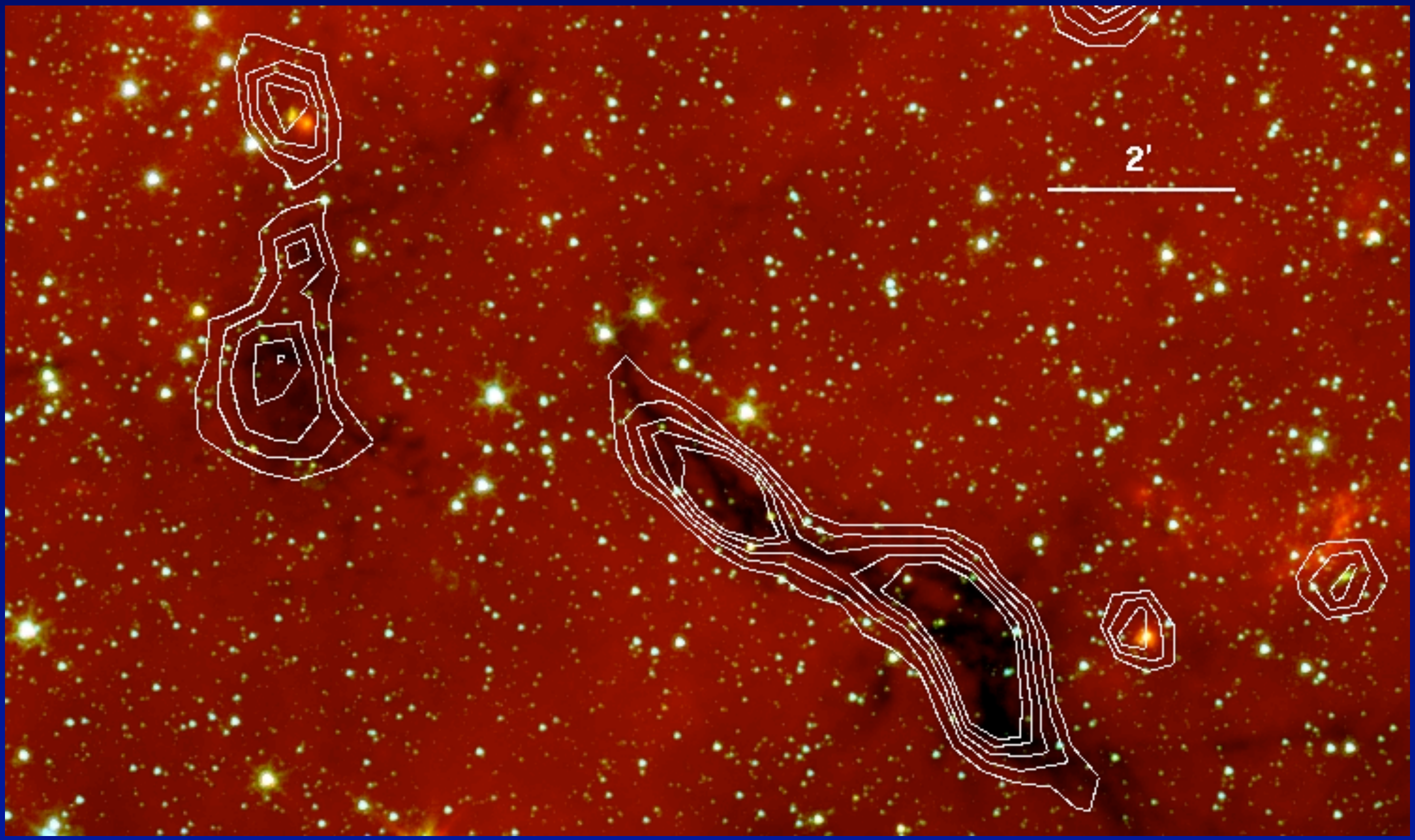
Background is IRAS 100 microns; Dashed lines are GLIMPSE
Complementary survey in South (ATLASGAL with APEX)
JCMT Galactic Plane Survey (JPS) will go much deeper in a few years

A Piece of the Plane



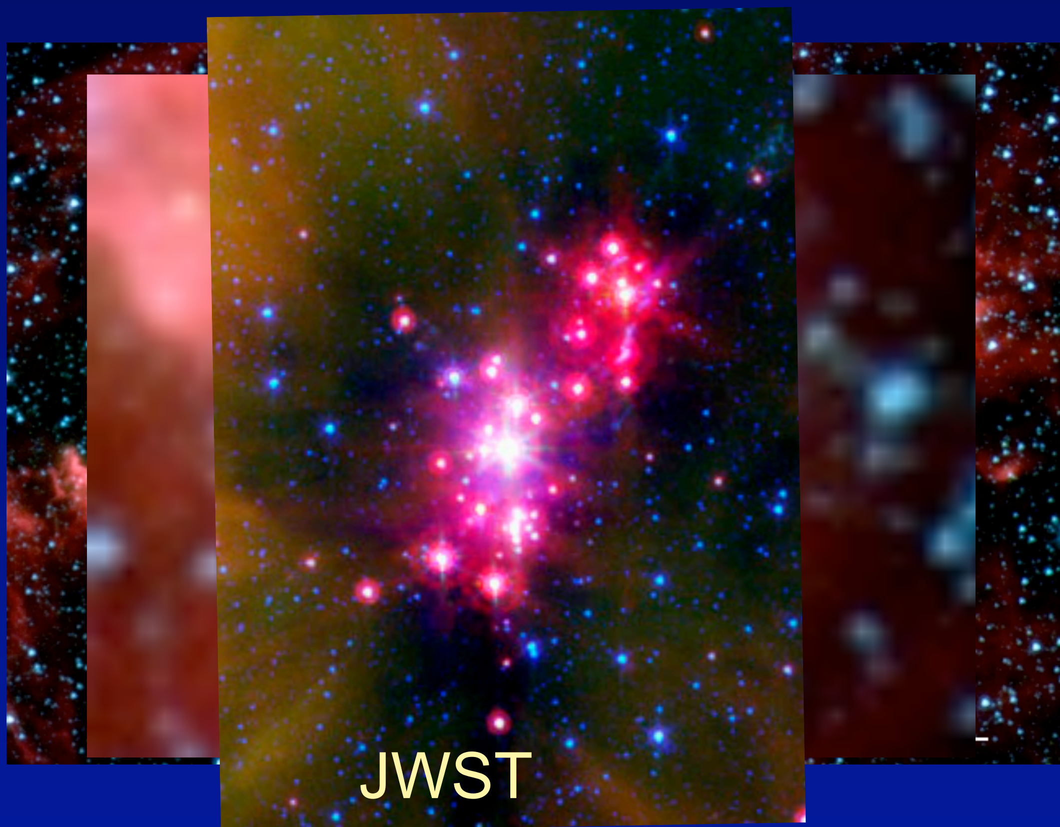
A very small piece of the BGPS showing the wealth of sources. Many, but not all, will be IRDCs

An Example



G035.59-00.24 is compact dense core (Rathborne et al. 2006)
B (3.6) G (4.5) R (8.0). Contours are Bolocam 1.1 mm.

What will ALMA see?



Summary

- Star formation is mostly clustered
- Efficiency is low in clouds, high in cores
- But much more SF than predicted by K98
- Massive clumps denser, much more turbulent
- Simulations must include heating feedback
- Surveys providing large samples on scale of MW
- We can begin to connect MW and exgal SF
- We need ALMA and JWST for resolution

Overall Clustering

- Taking all 5 clouds together
- Cluster (N_* >35 members)
  - 90% in loose (1 M_{sun} pc^{-3} < N_* < 25 M_{sun} pc^{-2})
  - 54% in tight (25 M_{sun} pc^{-3} < N_*)
- Groups (N_* < 35)
  - 7% are in loose groups
  - 13% are in tight groups
- 9% distributed
  - Distributed are "older" (fewer I and Flat SEDs)

Estimating Star Formation Efficiency

- Much more complete sample
- Complete (90%) down to about 0.05 L_{sun}
- Uniform photometry
- Caveats
  - Low L embedded objects
    - Dedicated search (Dunham) finds these
  - More evolved PMS (no significant IR excess)

For Serpens

Region	Cluster A	Cluster B	Rest	Total
$\frac{I+F}{II+III}$	3.0	1.4	0.14	0.37
t_{cross} (Myr)	0.45	0.38	4.1	4.2
t_{coll} (Myr)	3.1	4.8	1200	

$t_{cross} = A^{0.5}/v$, $v = 1$ km/s; $t_{coll} = (n\,\pi r^2\, v)^{-1}$, $r = 0.03$ pc, $v = 1$ km/s
$n = N(\text{cores})/\text{Volume}$. t_{coll} is the time between core collisions.

Overall Star Formation Rates

	Cha II	Lupus	Perseus	Serpens	Ophiuchus
SFR (M_{sun}/Myr)	**6.5**	**24**	**96**	**59**	**73**
SFR/Area (M_{sun}/Myr-pc^2)	**0.65**	**0.83**	**1.3**	**3.4**	**2.3**
$\frac{M_*}{M_{cl}+M_*}$	**0.021**	**0.040**	**0.028**	**0.041**	**0.046**

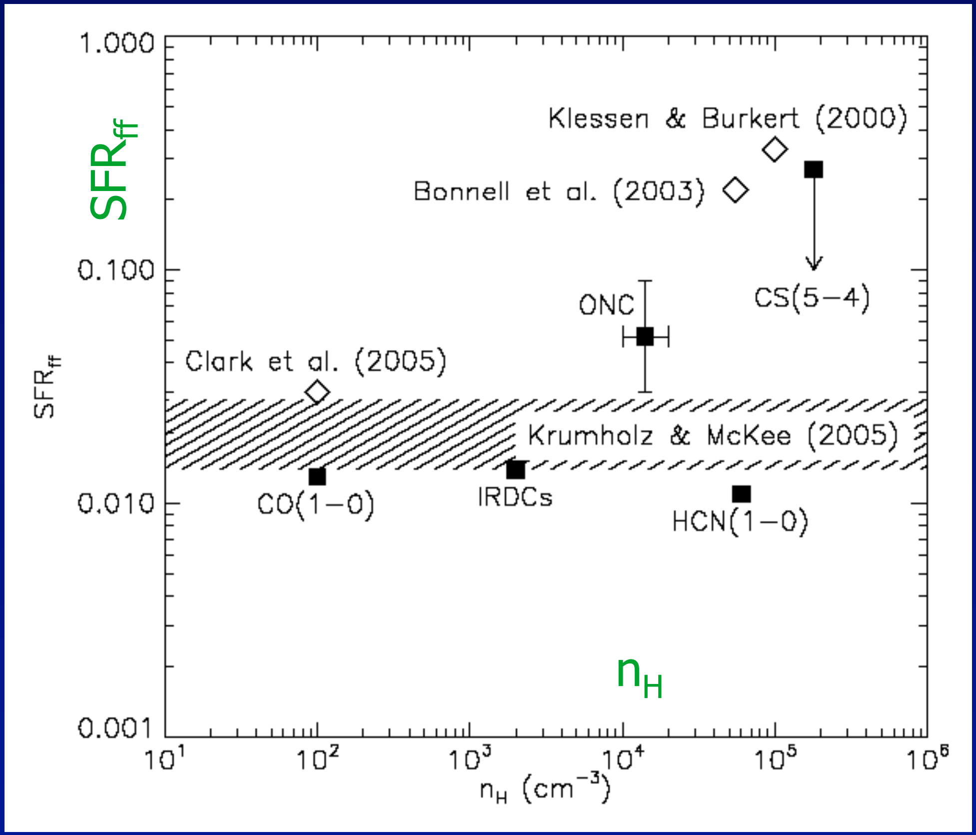
SFR assumes <M_*> = 0.5 M_{sun}; t_{SF} = 2 Myr

Comparison to Dense Gas

Cloud	Perseus	Serpens	Ophiuchus
M_*(tot)	193	118	145
M_{dense}	278	92	44
t_{dep} (Myr)	2.9	1.6	0.6

M_*(tot) assumes <M_*> = 0.5 M_{sun}; Depletion time: $t_{dep} = M_{dense}/SFR$
M_{dense} is total mass in dense cores from 1 mm maps.

Massive, Clustered Star Formation is Also "Slow"

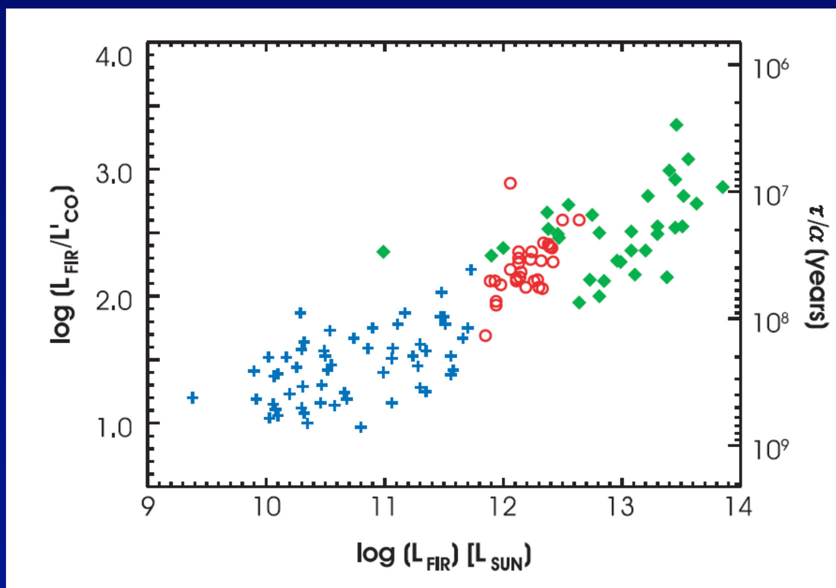


Star formation fraction per free-fall time Vs.
effective density of the tracer (Krumholz & Tan 2006)

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).

SFR/Mass(CO) Increases with SFR

Star formation "efficiency"



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)

What are the Implications?

- SFR on scale of molecular cloud may be linear (Bigiel et al.)
  - If so, formation of molecular clouds from atomic gas is the source of the non-linearity.
  - But see Kennicutt et al. (2007) which finds non-linear to 0.5 kpc
- If relation is linear for whole clouds (Bigiel)
  - The key step is making molecular clouds
  - Theorists’ rationale is suspect
  - t_{ff} unlikely to be relevant to molecular cloud formation
- If relation is non-linear for clouds, but linear for dense clumps
  - The key step is making dense clumps
  - SFR depends only on how much mass you have above the threshold for star formation