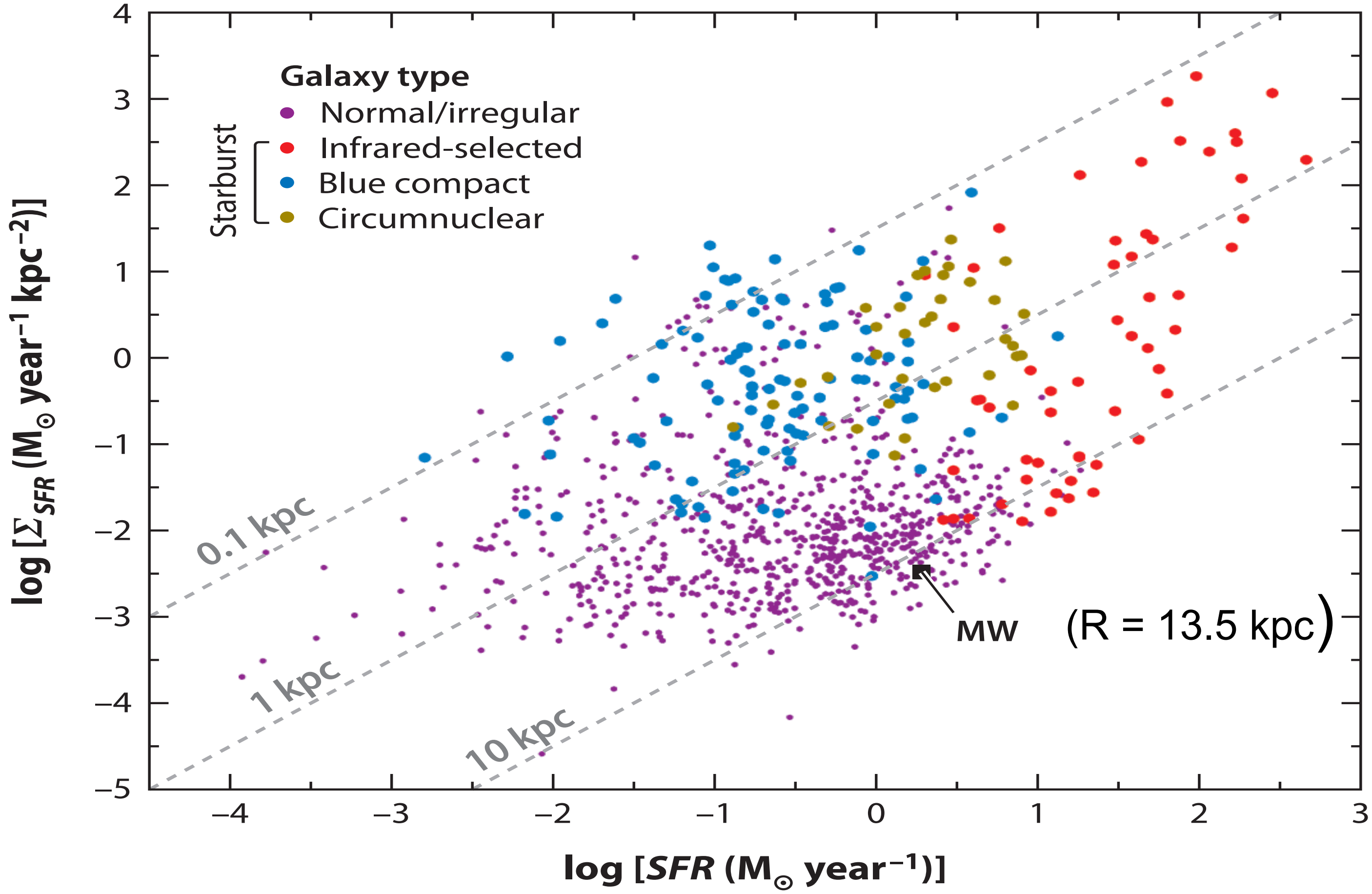
High Mass Star Formation and Connection to Galaxies

Neal J. Evans II

Galaxies: Extreme Diversity

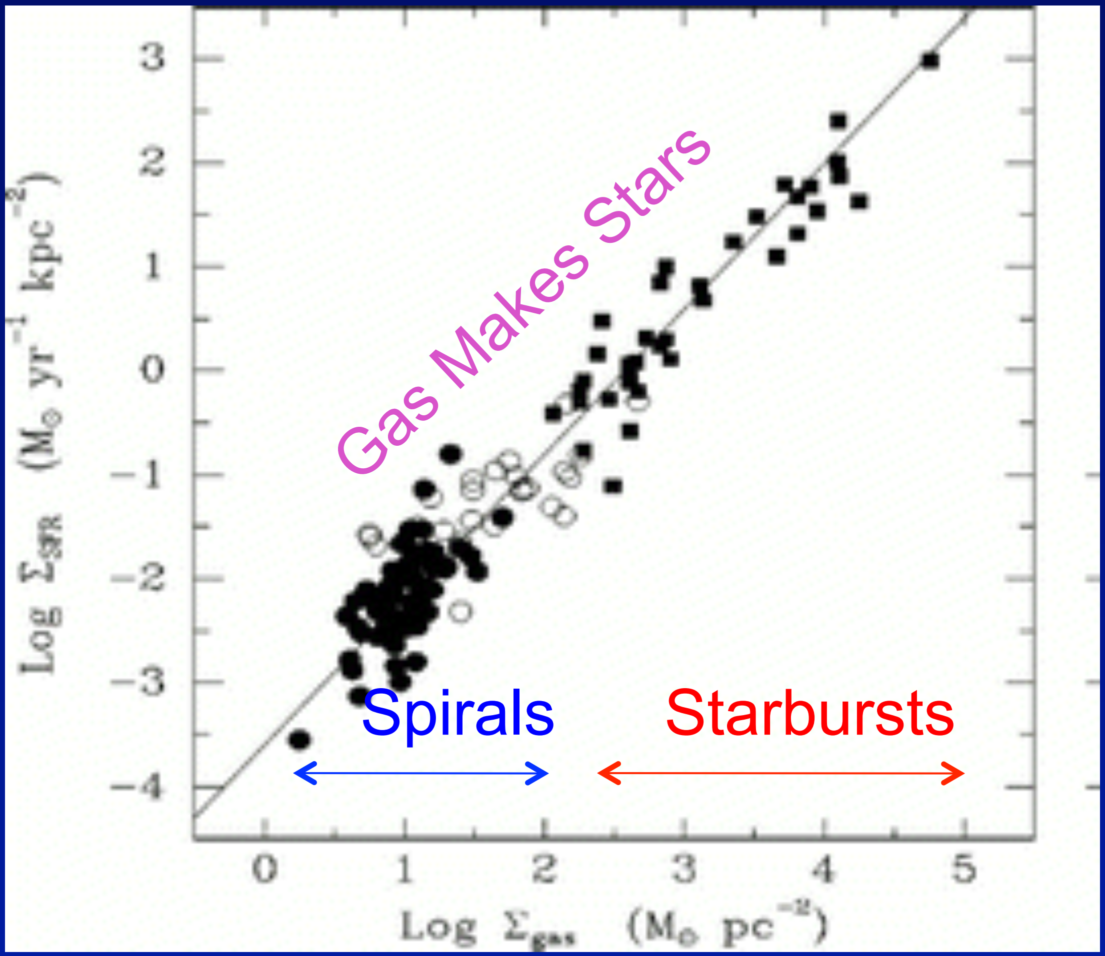


log Σ(SFR)

log SFR

Kennicutt & Evans 2012

Collapses to KS Relation



Solid circles are disk-averaged normal spirals
Open circles are central regions of normal disks
Squares are circumnuclear starbursts

Slope is 1.4±0.15

Kennicutt 1998, ARAA 36, 189

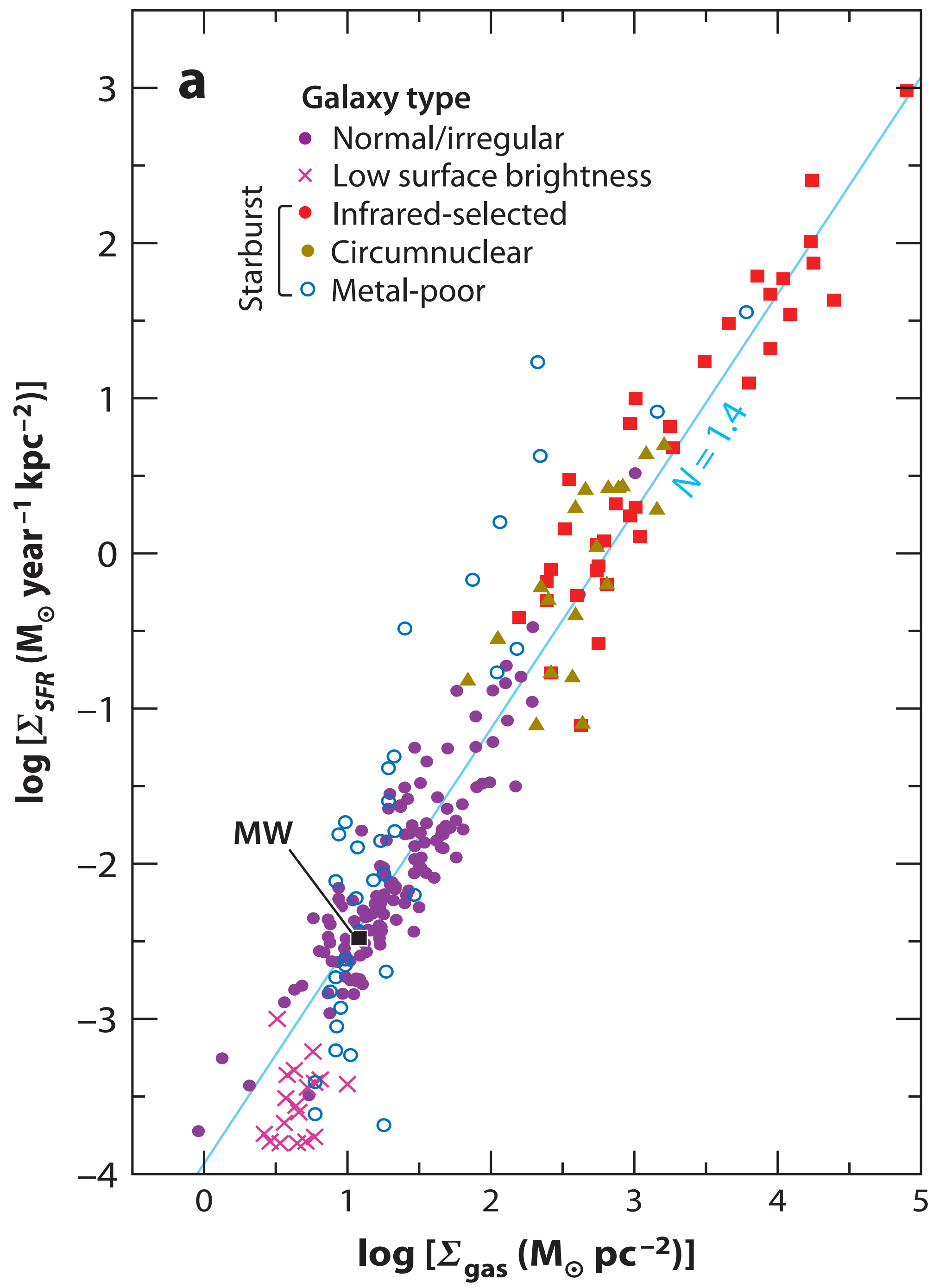
Update

blue open: Low metals (<~1/3 solar), mostly dwarfs

Blue line: slope of 1.4, not a fit

Assumes one value of α(CO) for all.

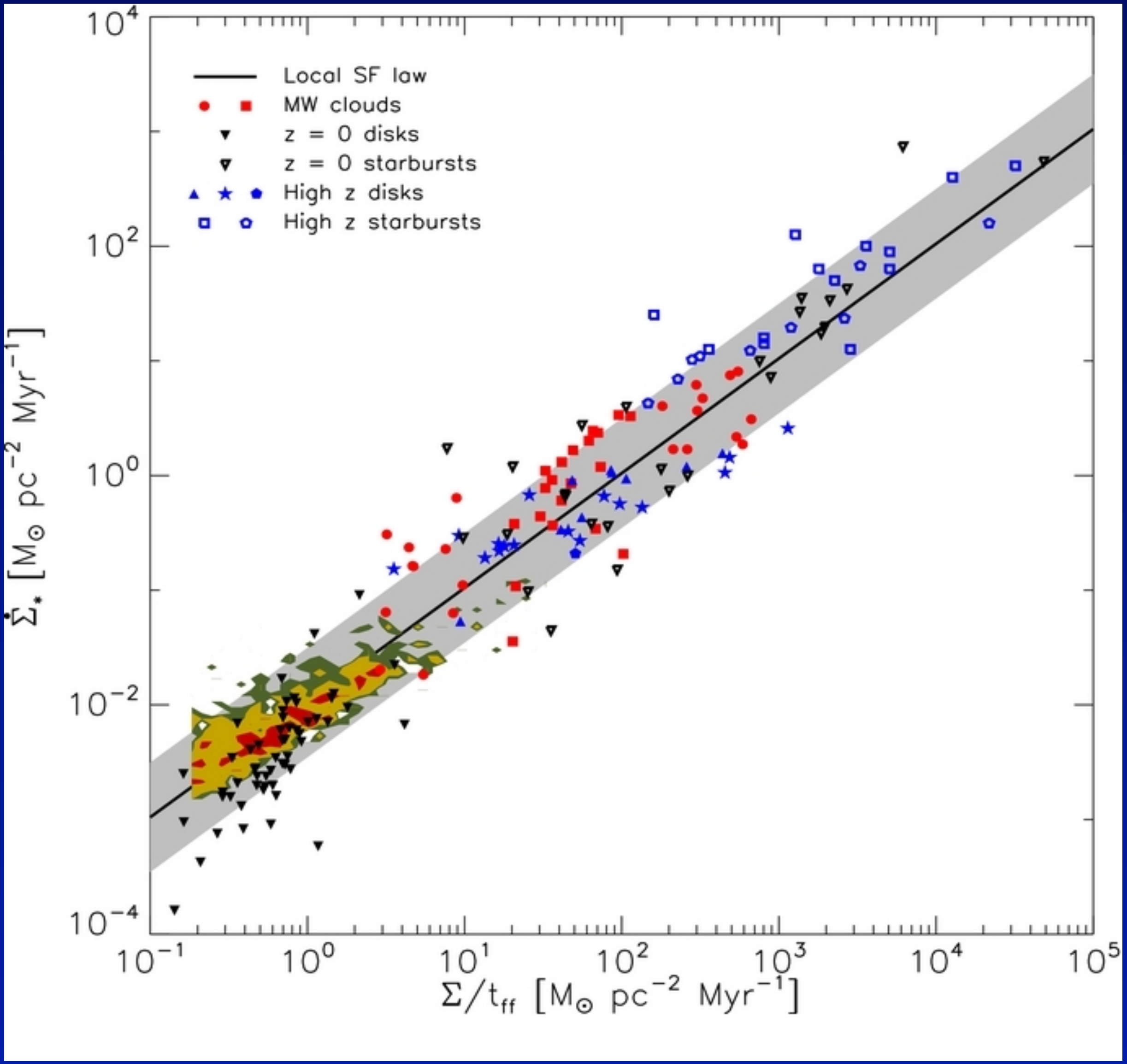
Kennicutt & Evans 2012



Total Gas Prescription

- Kennicutt (1998)
  - $\Sigma_{SFR}(M_{sun}\ yr^{-1}\ kpc^{-2}) = 2.5\text{x}10^{-4}\ \Sigma^{1.4}{}_{gas}(M_{sun}\ pc^{-2})$
  - "Gas" is molecular plus atomic
- The temptations of theorists…
  - Aha, 1.4 ~ 1.5, so SFR ~ mass/free-fall time
  - Or $\Sigma_{SFR} \sim \Sigma_{gas}/t_{ff}$
  - Or $\rho_{SFR} \sim \rho_{gas}/t_{ff} \sim \rho_{gas}{}^{1.5}$
  - I put that in my code, I recover the KS relation, and I understand everything!
  - (Except SFR 100 times too high, so ε_{ff} =0.01)

And it looks good…



A "Universal local SF law" in individual clouds explains the global relations.

Krumholz, Dekel, McKee 2012

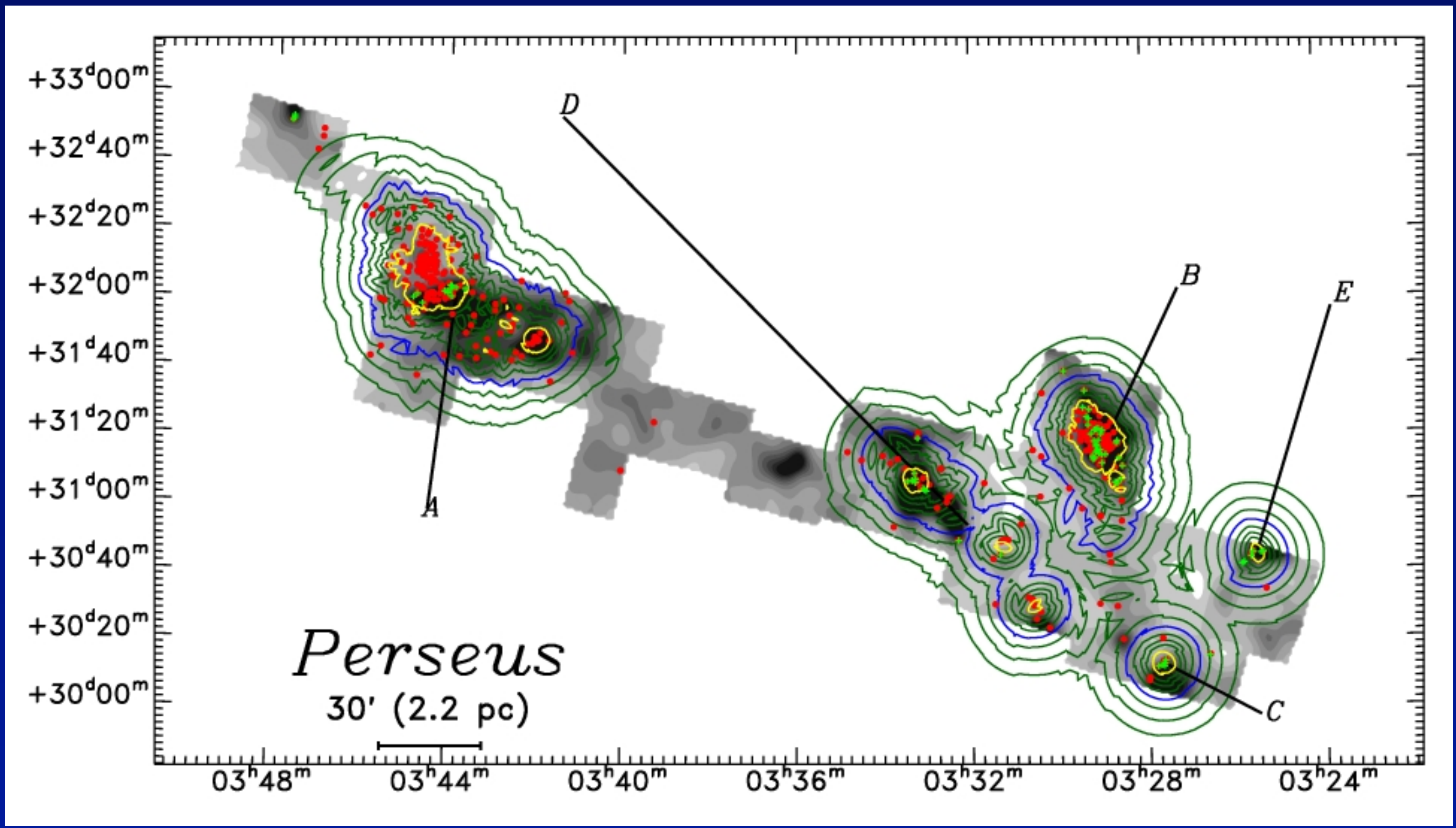
Let’s Take a Closer Look

- Studies of SFR vs gas in nearby cloud
- Studies of SFR vs gas in regions forming massive stars
- Conditions in these regions
- Competing theories of massive SF
- Observations confront theories
- Back to issues of SF “laws”

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

- **c2d+GB Survey**
  - **Survey 29 large clouds with Spitzer (if split into individual regions)**
- **Where do stars form?**
- **How efficient is star formation?**
- **How does the SFR depend on cloud properties?**

Where do Stars Form?

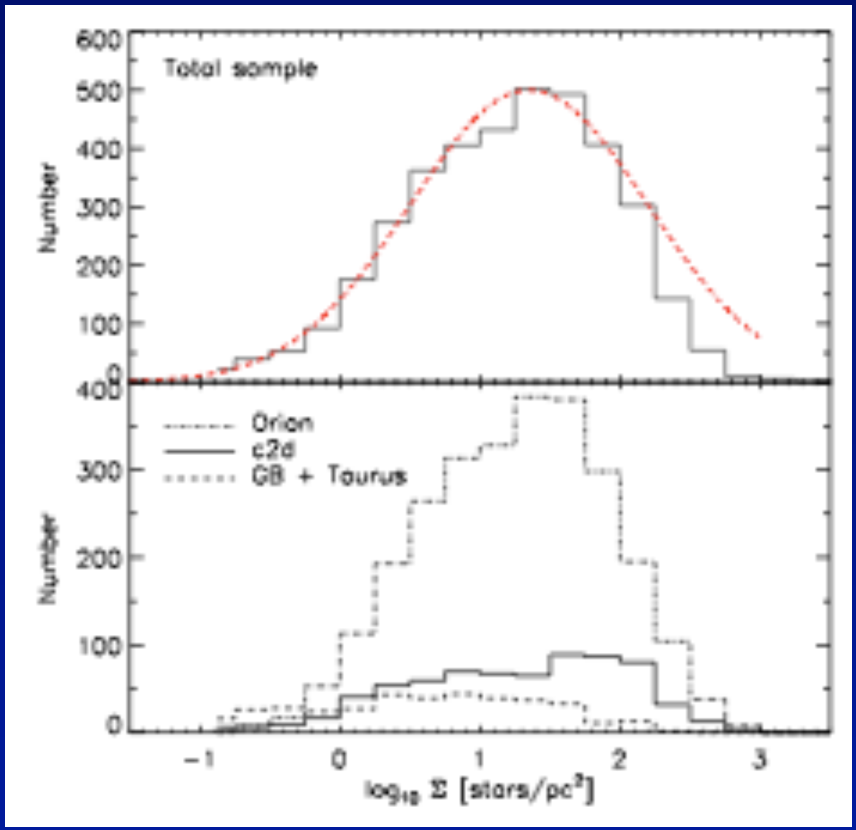


Gray is extinction, red dots are YSOs, contours of volume density (blue is 1.0 M_{sun} pc^{-3}; yellow is 25 M_{sun} pc^{-3})

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 in these clouds
  - t_{coll} ~ 10 x t(ClassI) in Serpens

Almost All Star Formation is Clustered

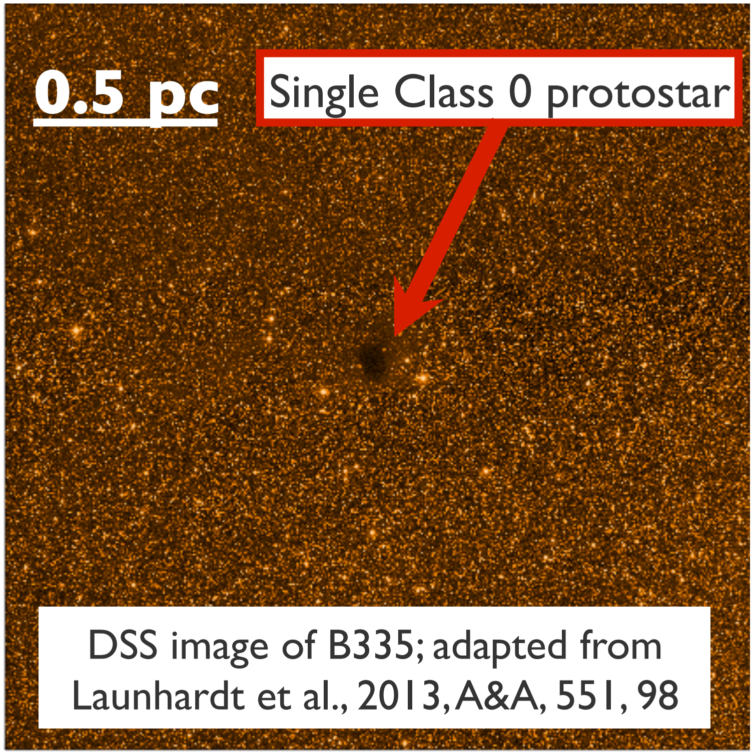


All c2d+Gould Belt+ Taurus Class I and II Sources

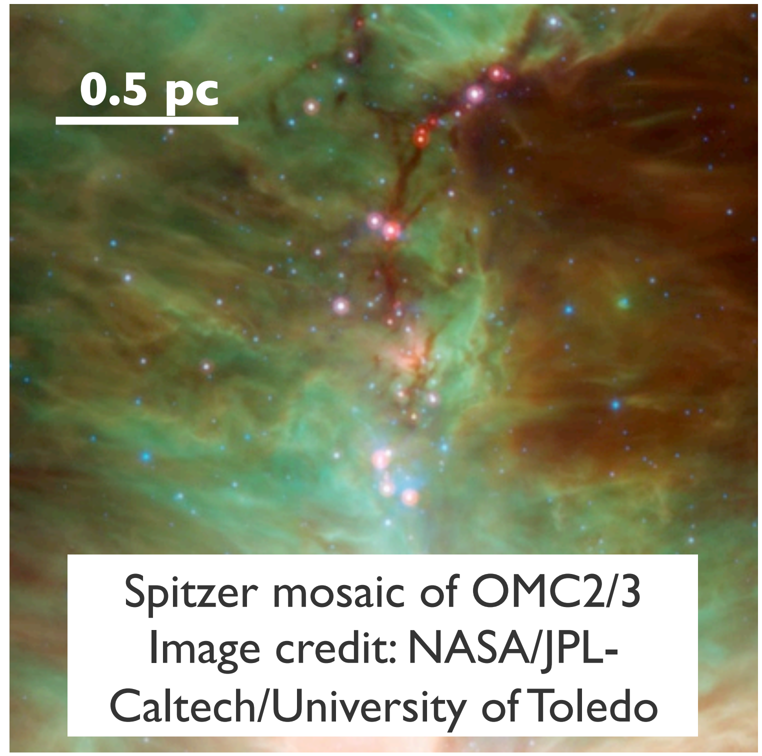
Distribution is smooth and broad. No sign of a bimodal (clustered versus distributed) distribution.
Some envelopes will overlap in Orion.

Bressert et al. 2010

But not always!



"[...] a very small black spot, B335, which looks like a defect, but is not. It is probably of the same nature as the larger ones just mentioned. It can hardly be a hole through the star cloud.'' - E. E. Barnard, from his comments on Plate 41, August 27, 1905



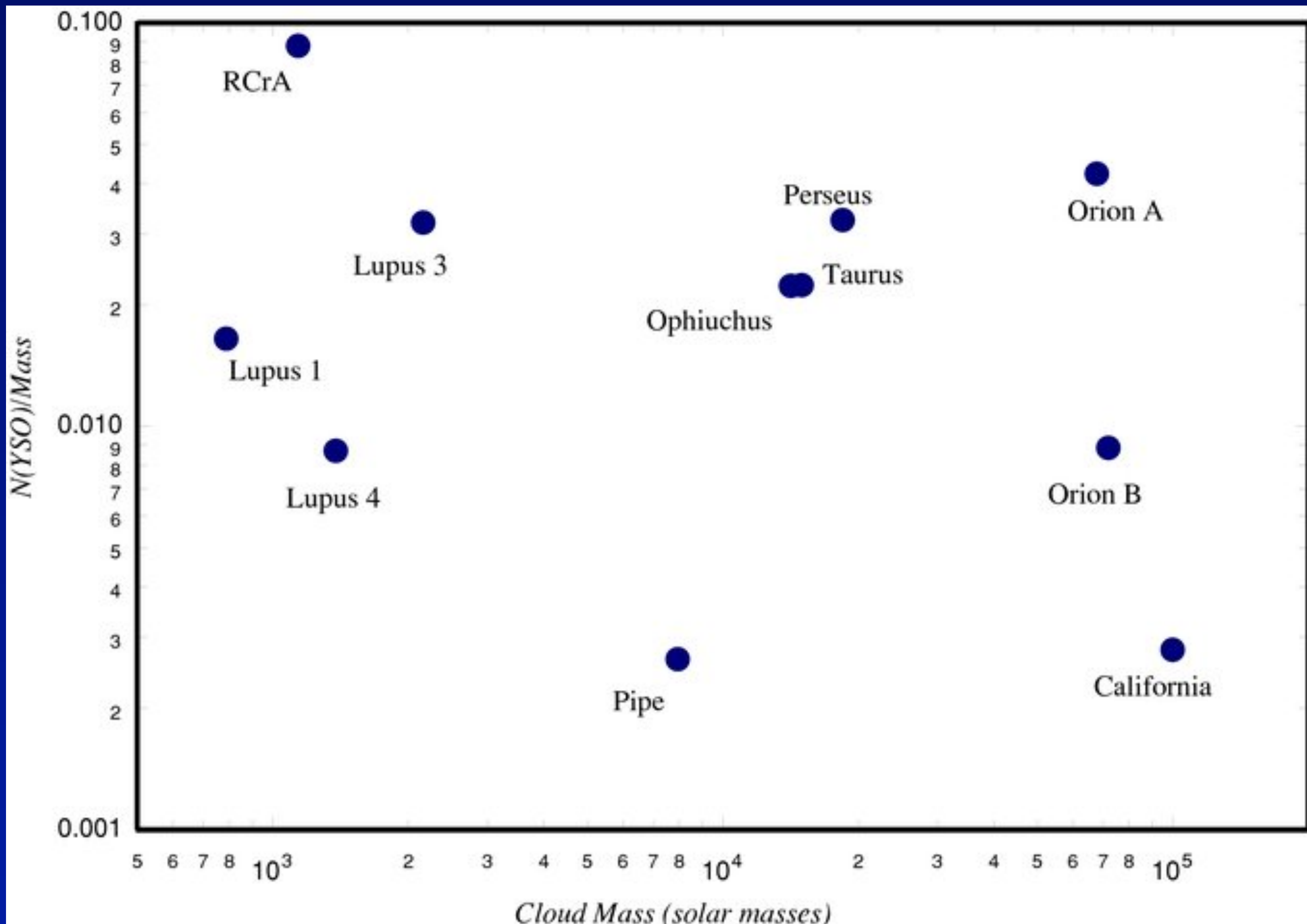
In the Orion clouds ≤ 23% of protostars have the potential to be interacting with neighbors through envelope collisions and tidal forces (Megeath et al., in prep.)

How "Efficient" is Star Formation?

- Not very for the clouds 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 $\langle t_{dep} \rangle = 136$ Myr >> cloud lifetime
  - $\langle t_{ff} \rangle = 1.5 \pm 0.6$ Myr, so $\varepsilon_{ff} = 0.011 \pm 0.004$ (slow)
- Quite efficient in dense gas
  - Current TOTAL M_* similar to M_{cores}
  - Core depletion time is 0.6 to 2.9 Myr
  - But still slow compared to $t_{ff} \sim 0.1$ Myr for $\langle n \rangle = 10^5$ cm^{-3}

Scatter is Large

N(YSOs)/Cloud Mass

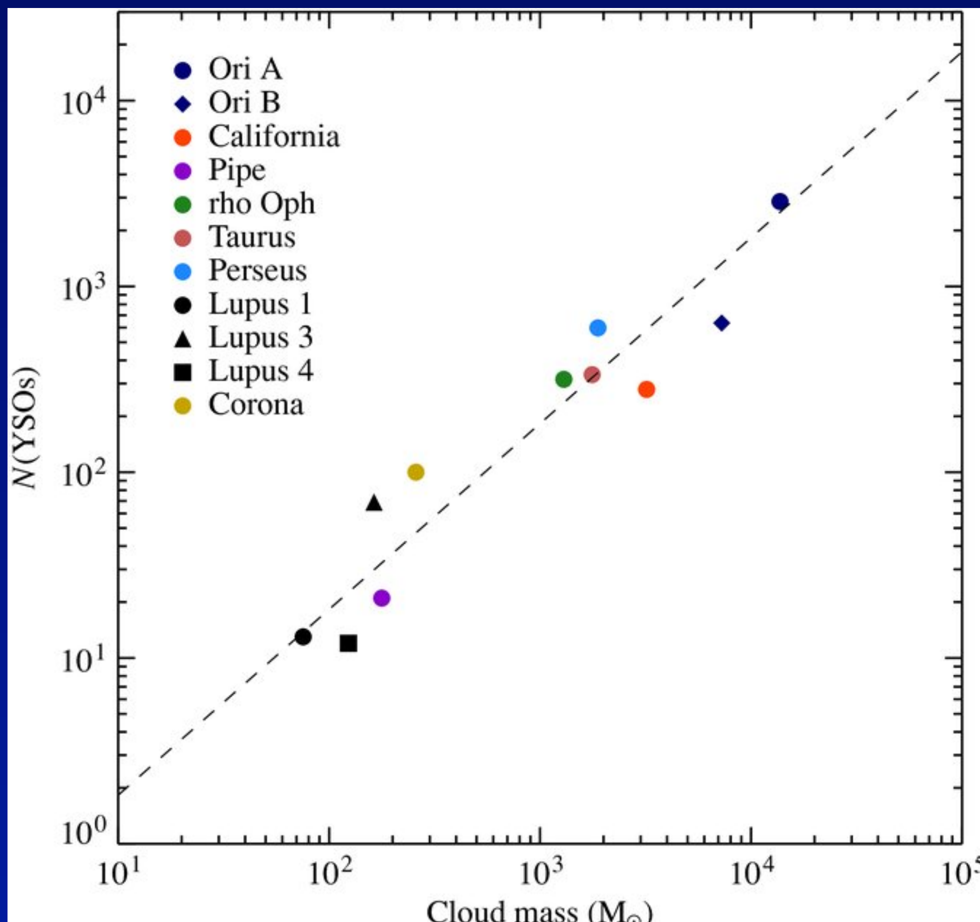


Cloud Mass

Lada et al. 2010

Versus Mass above Σ_{th}

N(YSOs)



Cloud Mass above Σ_{th}

Test various Σ_{th}
Found minimum dispersion for Σ_{th} = 116+/-28 M_{sun} pc^{-2}

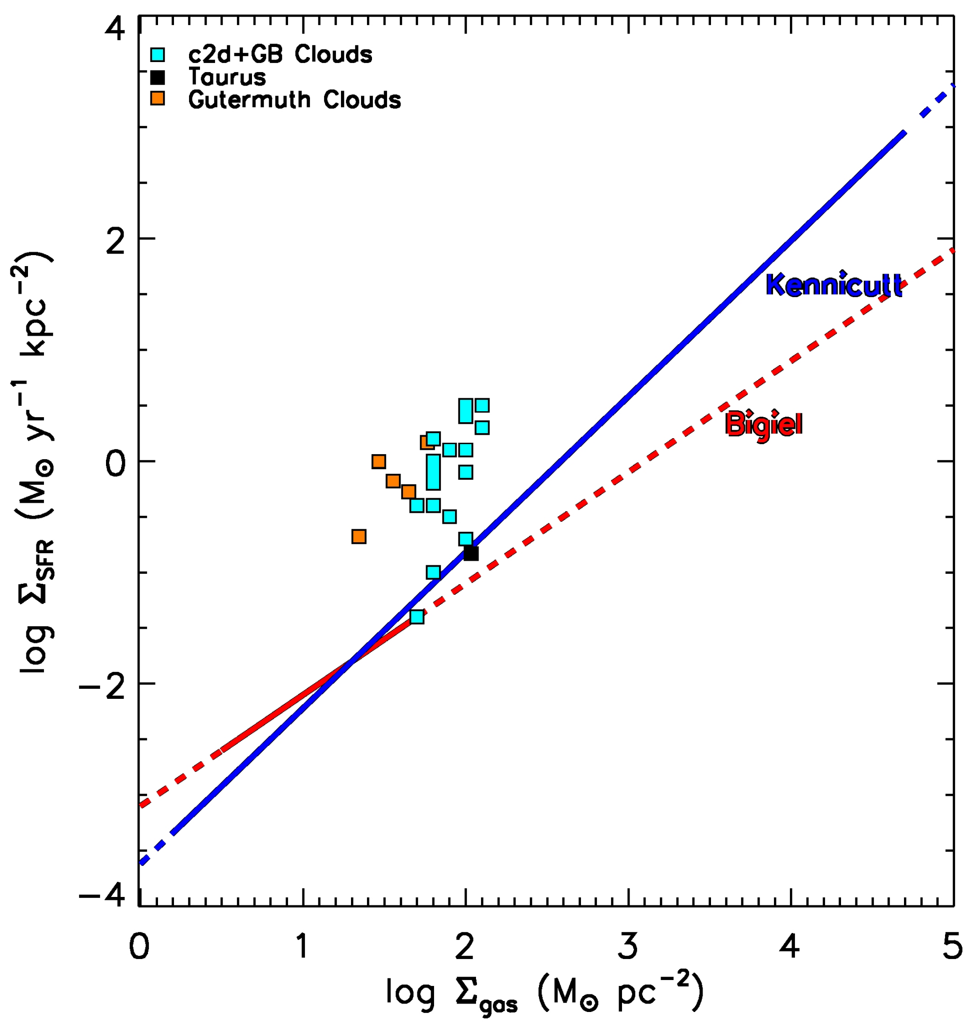
SFR = C M_{dense}
C = 0.046 Myr^{-1}
(Lada et al. 2012)

Lada et al. 2010

What Do SFR Relations Predict?

- Kennicutt (1998) relation for SFR
- Local Universal SFR (KMD)
- “Threshold” Density (Lada)
  - Also found by Heiderman (2010)
  - Average about 120 $M_{sun}pc^2$ or A_v = 8 mag

SFR Exceeds KS law



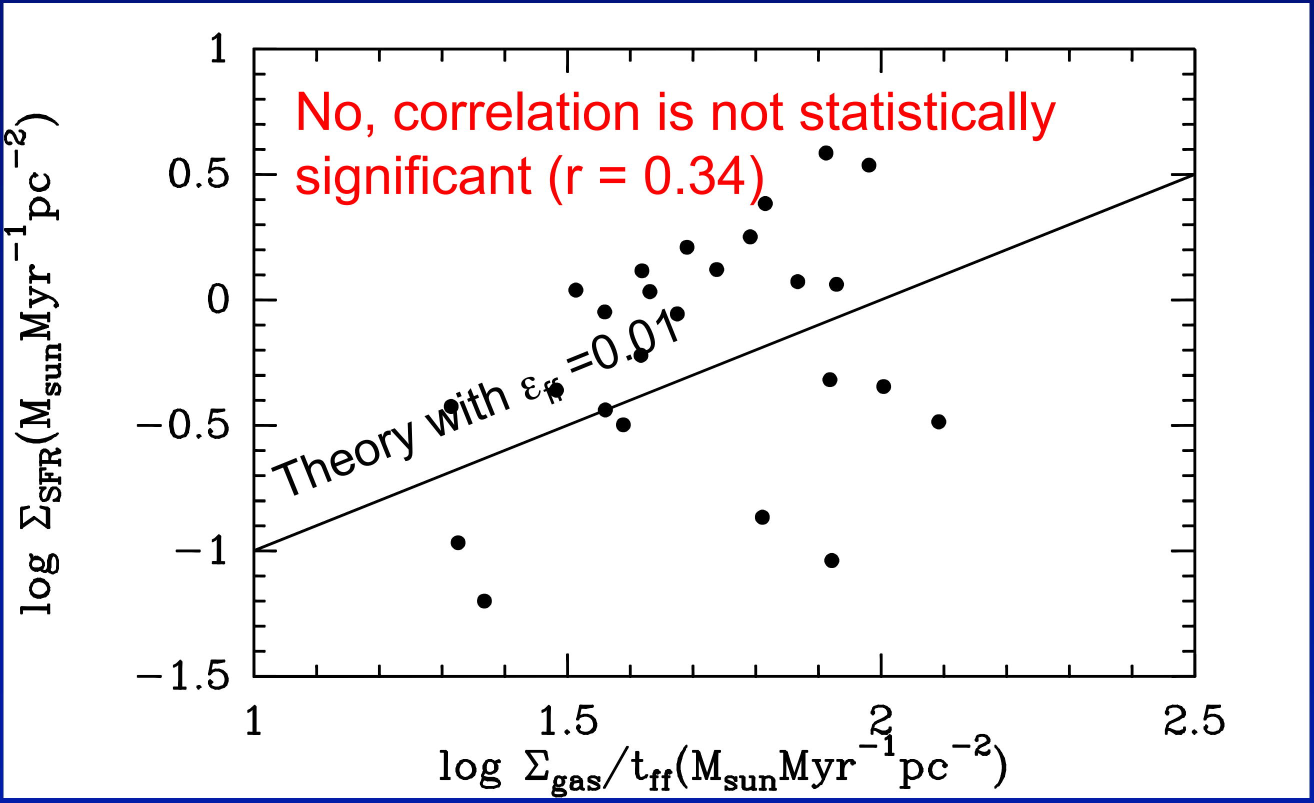
Measures on scales of 2-20 pc

Blue, black boxes:
Almost all clouds within 300 pc
Orange boxes
Adds Orion, Mon R2, S140, Cep OB3, all forming more massive stars, and North America nebula, less active

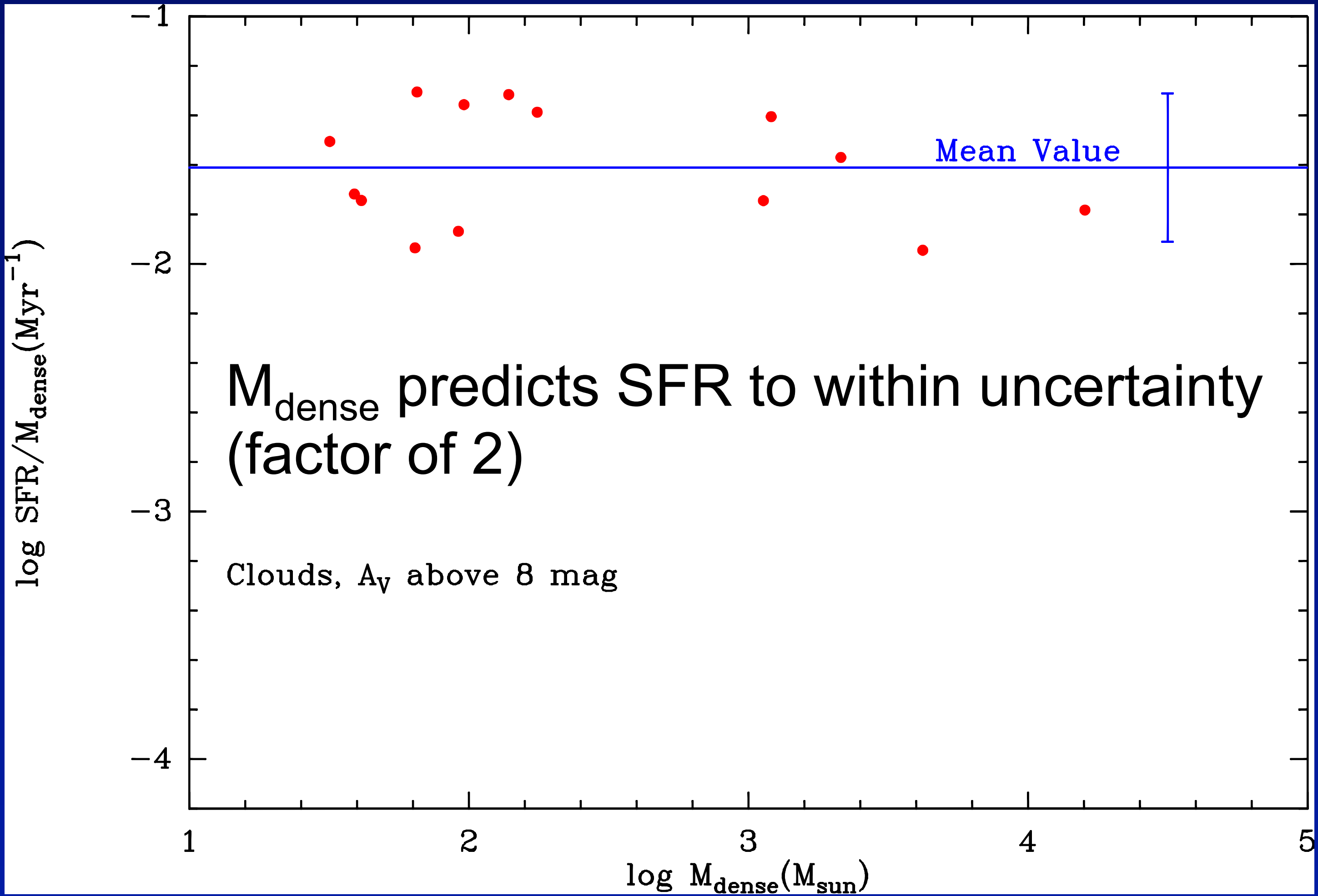
not complete to 1 kpc, but representative

Test "Universal Local" Laws

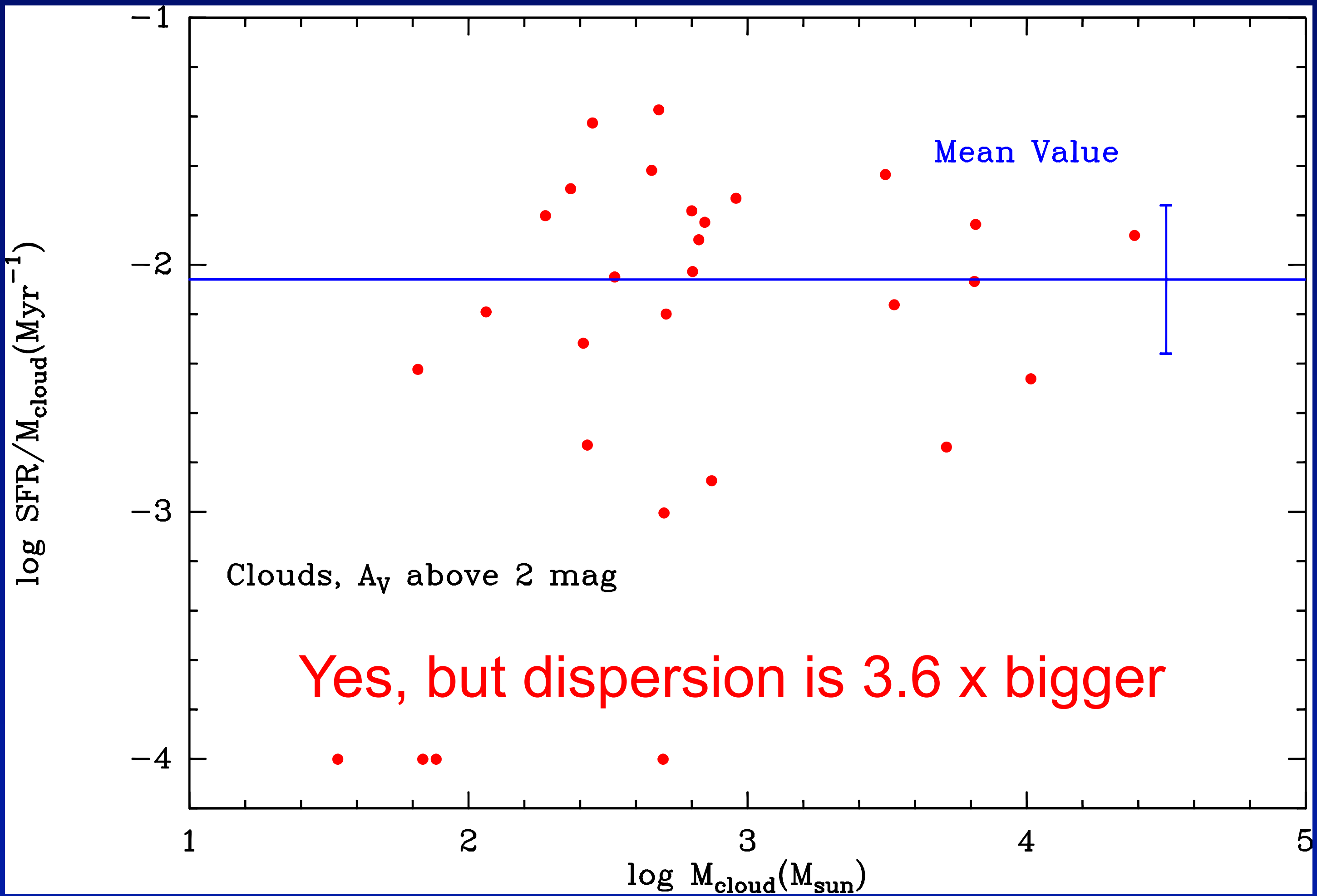
- **Does SFR of a cloud depend on free-fall time of the cloud (t_{ff} based on mean ρ)?**



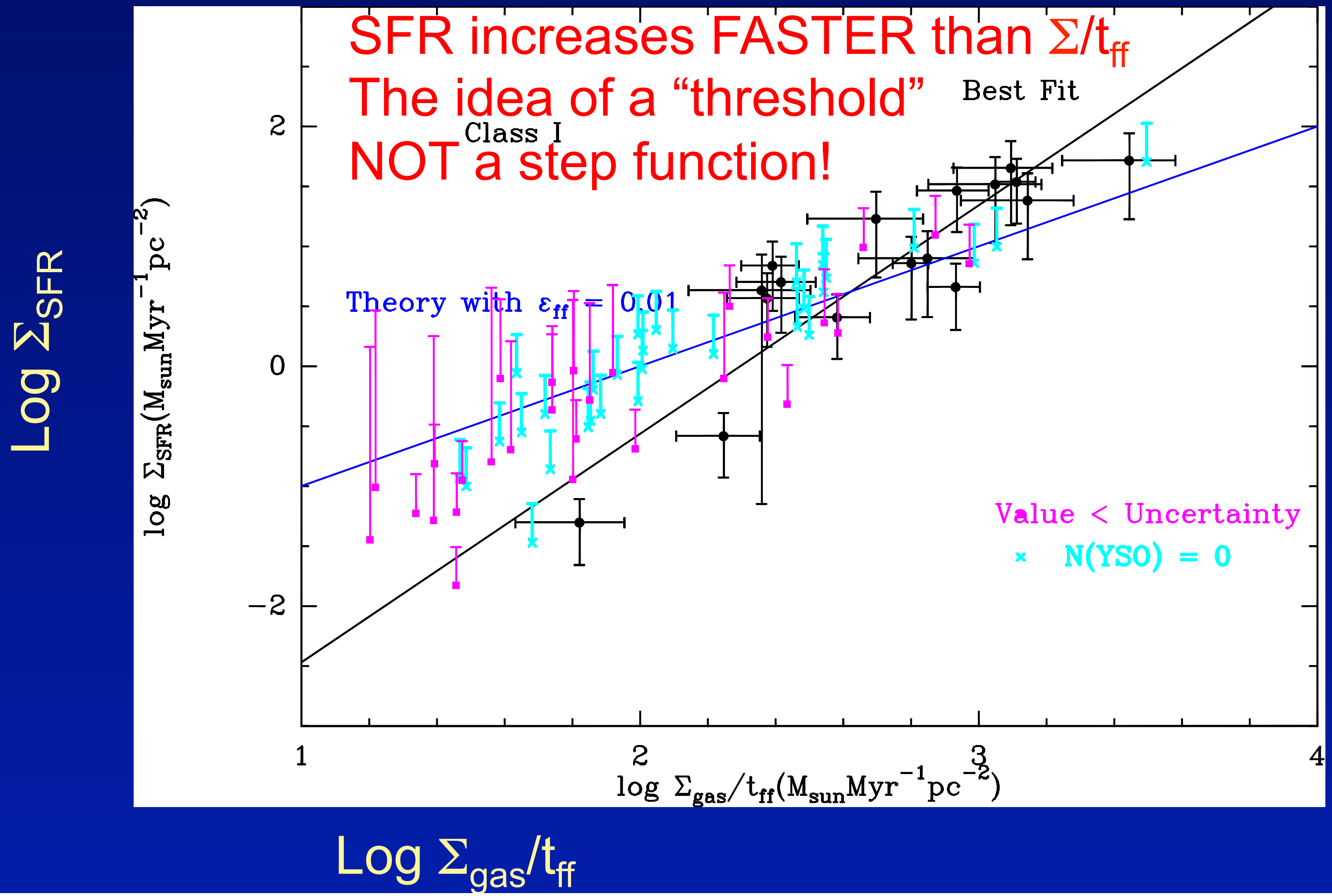
Test of Threshold Idea



What About Total M_{cloud}?



Does t_{ff} matter WITHIN a Cloud?



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**

- **Free-fall time model does not describe SFR well for local clouds**
- **Best predictor is mass of “dense” gas**
  - **“Clump” $\langle t_{dep} \rangle$ = 36 Myr, $\langle \varepsilon_{ff} \rangle$ = 0.02+/-0.01**
- **Structure of cloud (N-pdf) controls SFR?**

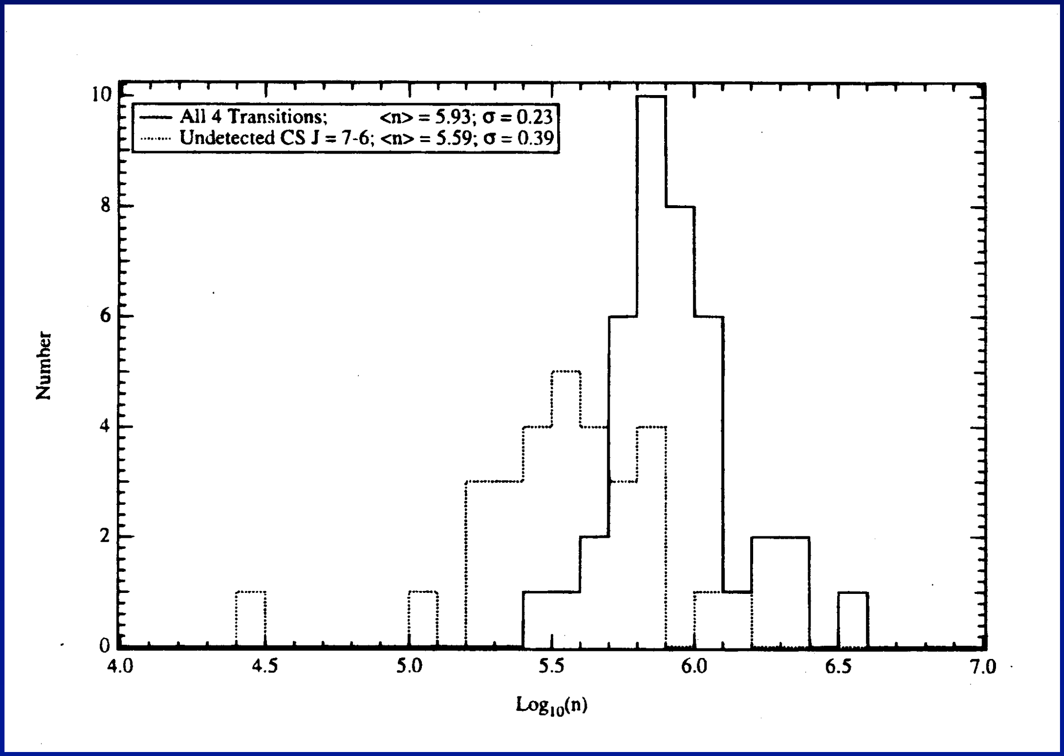
What About Massive Stars?

- 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
    - Predict more observables, not just SFR, IMF!

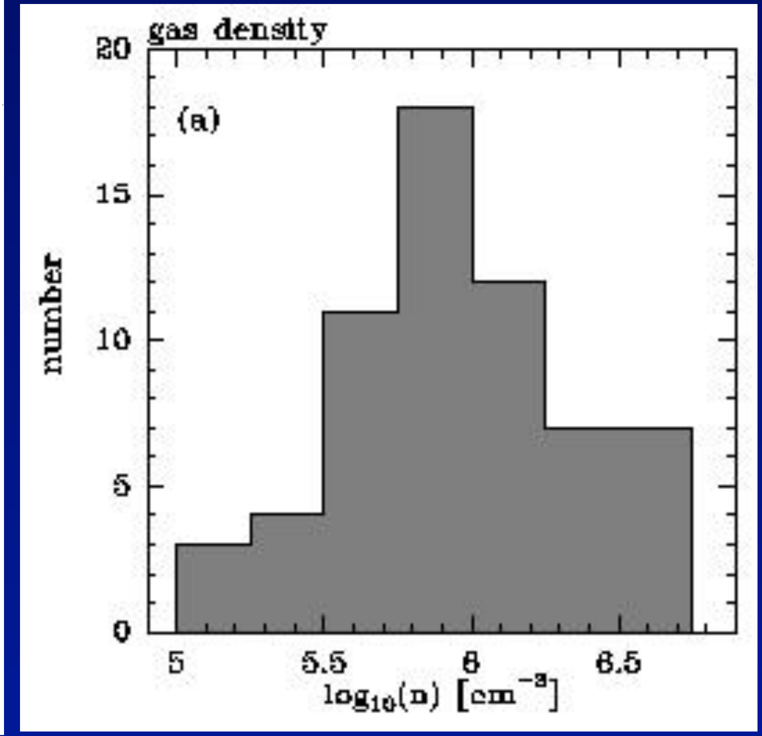
Studies of Galactic Regions of Cluster Formation

- 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)

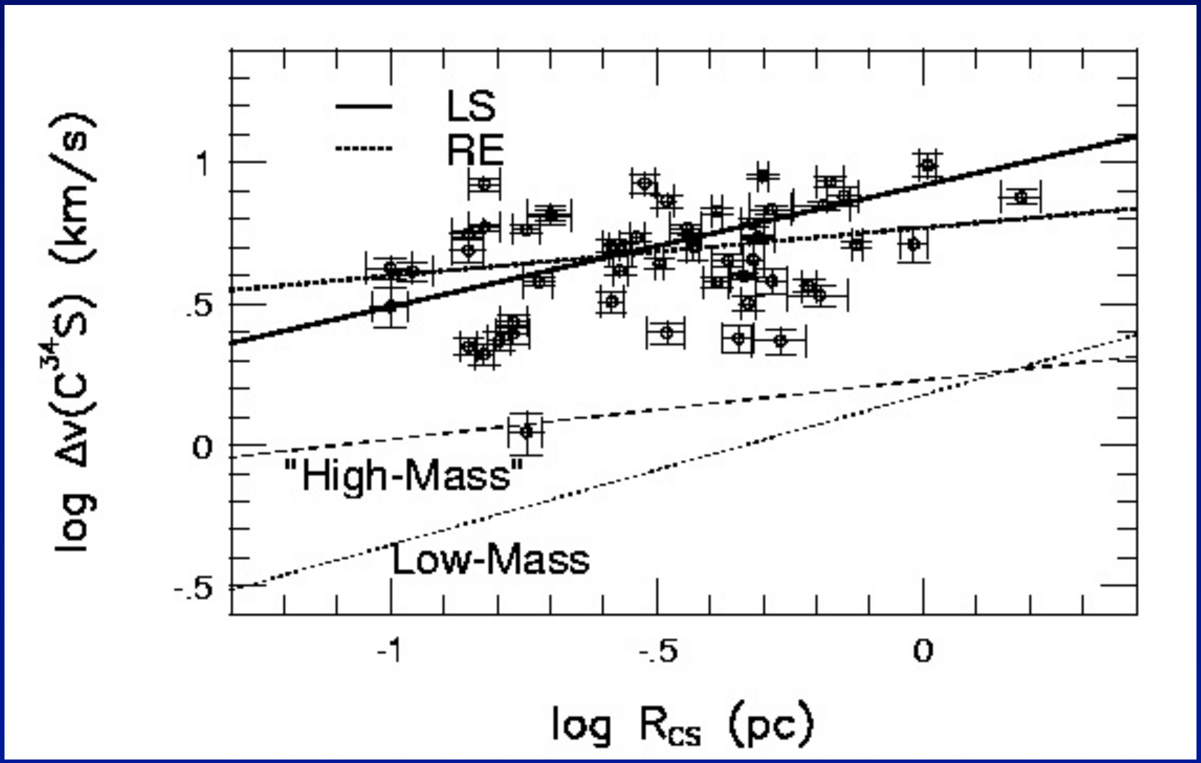
Overall Density Gradients

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

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

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

Turbulence is High



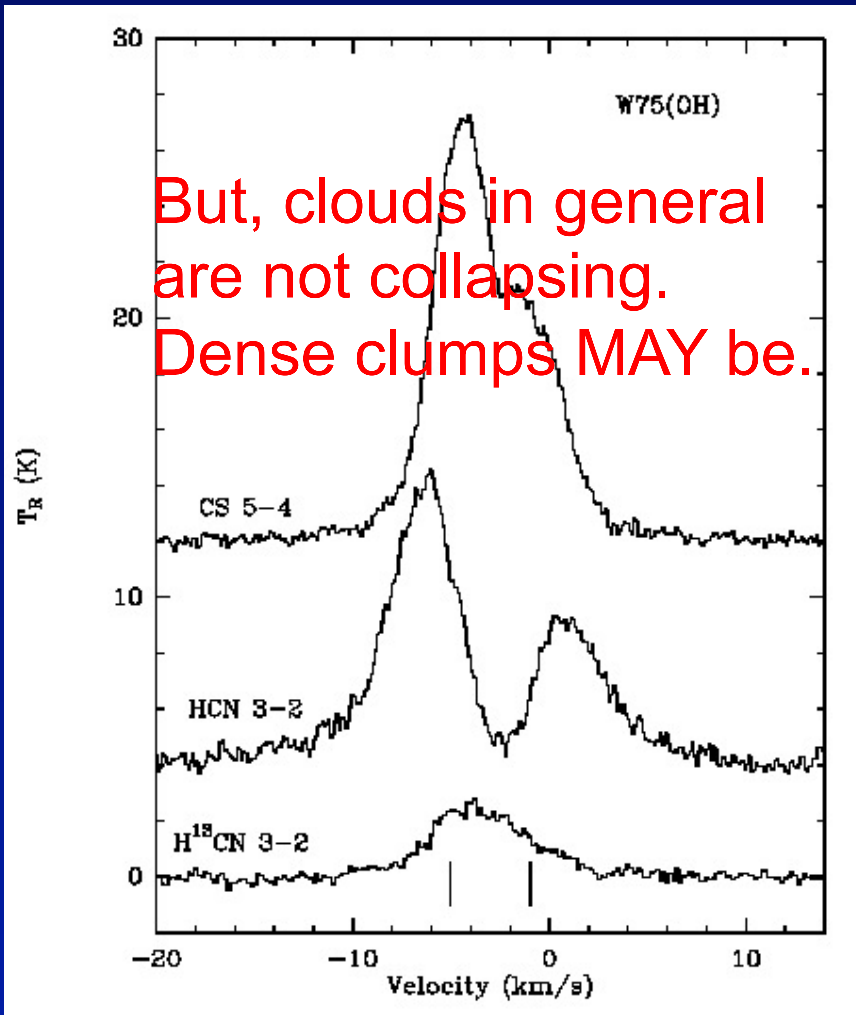
Correlation is weak.

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



But, clouds in general are not collapsing. Dense clumps MAY be.

J. Wu et al. (2003)

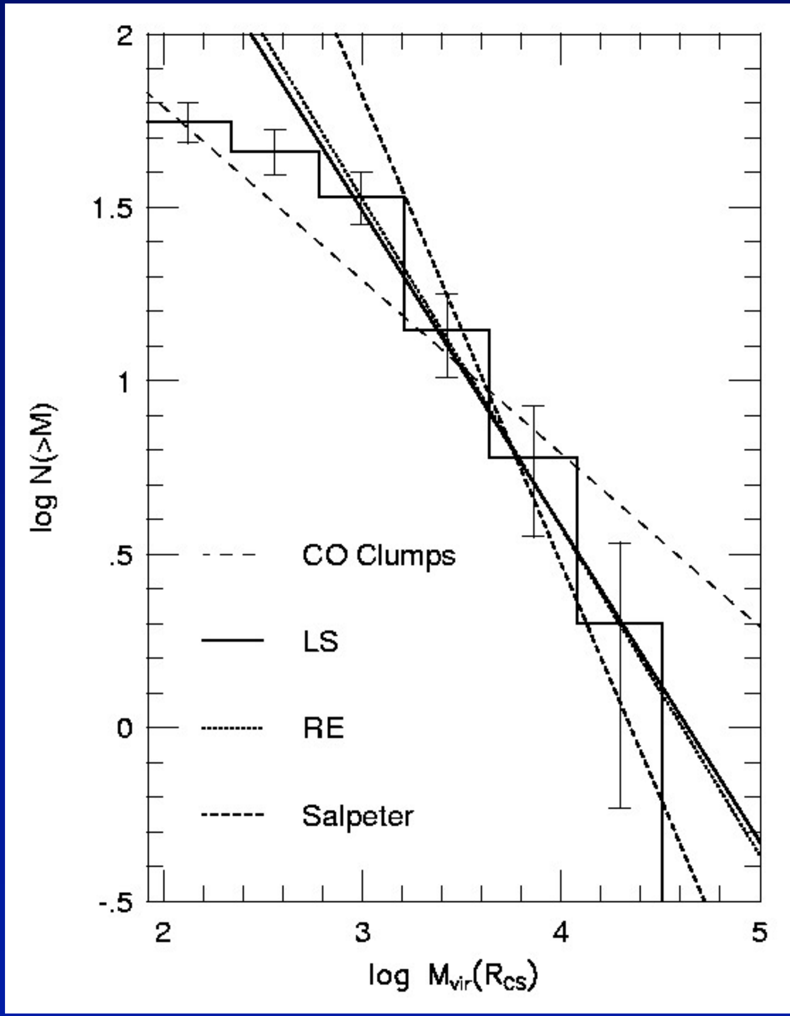
A significant fraction of the massive core sample show self-reversed, blue-skewed line profiles in lines of HCN 3-2.
Of 18 double-peaked profiles, 11 are blue, 3 are red.

Suggests inflow motions of overall clump.

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



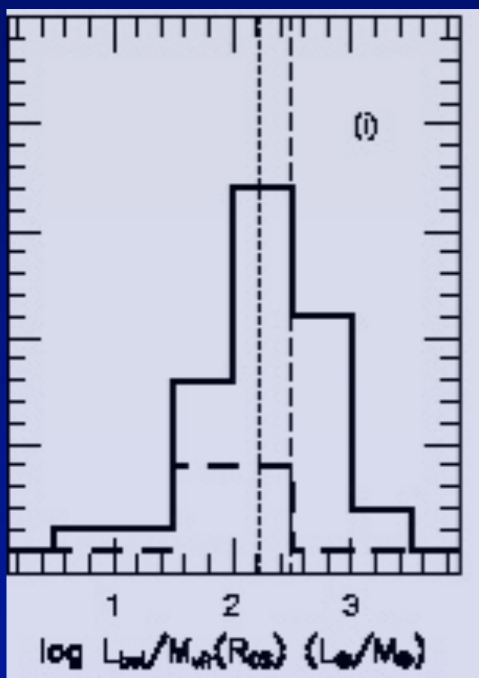
Cumulative Mass Function Determined from M_{vir}.
Incomplete below 1000 M_{sun}

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 much wider
    - Well above “Larson law” for size-linewidth
  - Evidence of inward motions in some
  - Mass distribution closer to clusters than to GMCs
  - L/M increases as HII regions form

Theories of Clustered SF

- Turbulent Cores (McKee and Tan 2002)
  - Scaled-up (turbulent speeds) from low-mass
  - Clump has cluster of cores
- Competitive Accretion
  - Klessen98, Bate03, Bonnell03
  - Small seeds form in clump, move around
  - Compete to sweep up mass
- Hybrid (Myers 2009, 10, 11)
  - Initial Core, then pull from clump

Tests of Turbulent Cores

- Cores more massive than most massive star must exist
- Core mass function must translate to IMF
- Should see infall onto individual objects
- Massive stars are fed by massive disks
- All need better sensitivity, resolution, image quality (ALMA)

Tests of Competitive Accretion

- Core mass function should not reflect IMF, but center around M_{Jeans} of clump
- Most of clump mass not in cores
- Very massive cores should not be found
- Cores/seeds should be moving around
- Global collapse needed(?)

Tests so far inconclusive

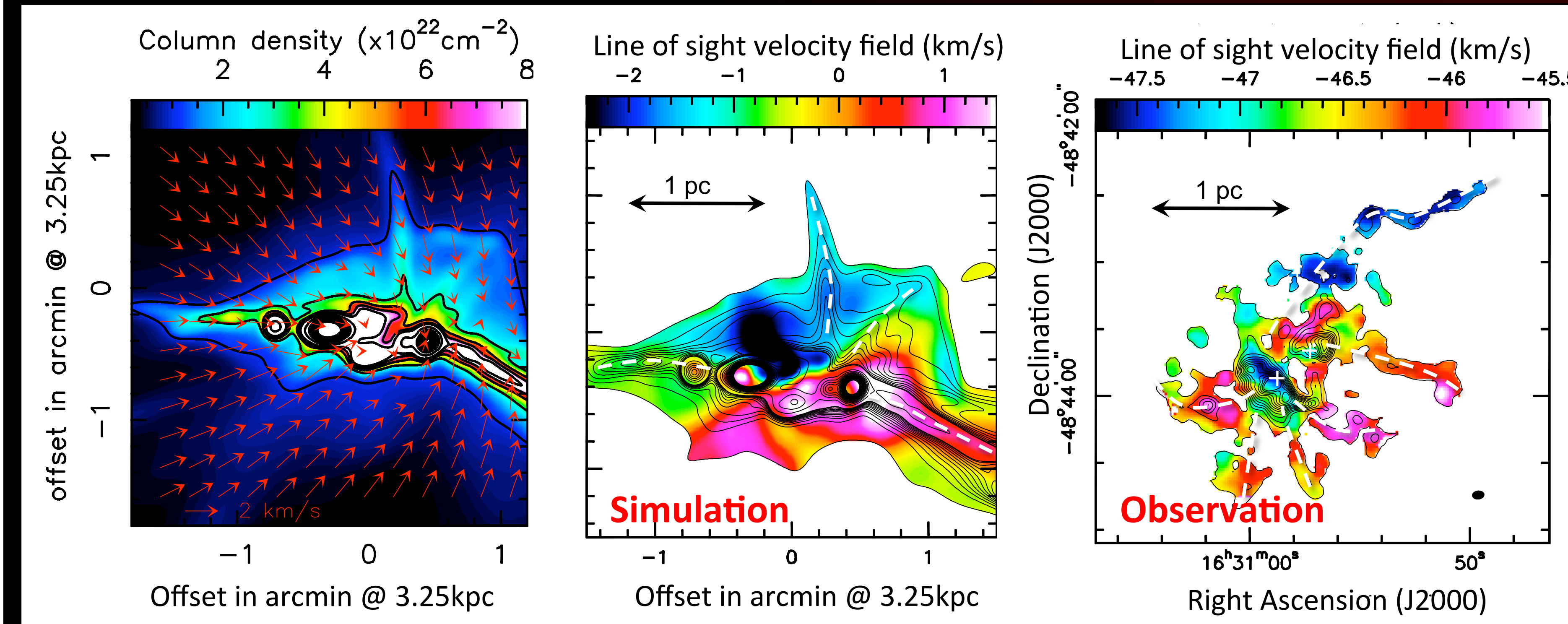
- Can only resolve cores in nearby clumps
  - Cores moving slowly (TC favored)
  - No really massive cores (CA favored)
  - Infall in individual cores (unclear)
  - But those clumps are not forming full IMF
  - Need to study more massive clumps
- What will ALMA do for us?

Global Collapse

- Global Collapse needed for Competitive Accretion Model
  - Infrared Dark Clouds
  - SDC335 = IRAS16252-4837 (Peretto 2013)
  - Converging filaments
  - ALMA: 2 sources, 545 and 65 M_{sun} in 0.05 pc
  - α_{vir} = 0.4, collapse?
  - See extended inflow signature, 1 km/s
  - ALMA map supports inflow along filaments
  - Continuous feeding of cores

Global collapse of SDC335: Expected signatures from simulations

Simulation of a magnetized 10000 M_{sun} collapsing cloud from Schneider et al. (2010)



- Similarities between simulation and observations in dynamical and density structures
- Accretion rates through filaments ≈ 1x10^{-3} M_{sun}/yr
- Less than 20% of the cloud mass is within filaments, suggesting that in SDC335 the total accretion rate should be ≈ 5x10^{-3} M_{sun}/yr towards the central pc-size region, enough to gather more than 1500 M_{sun} per cloud free-fall time

Peretto, Fuller, Duarte Cabral, et al., A&A, 2013

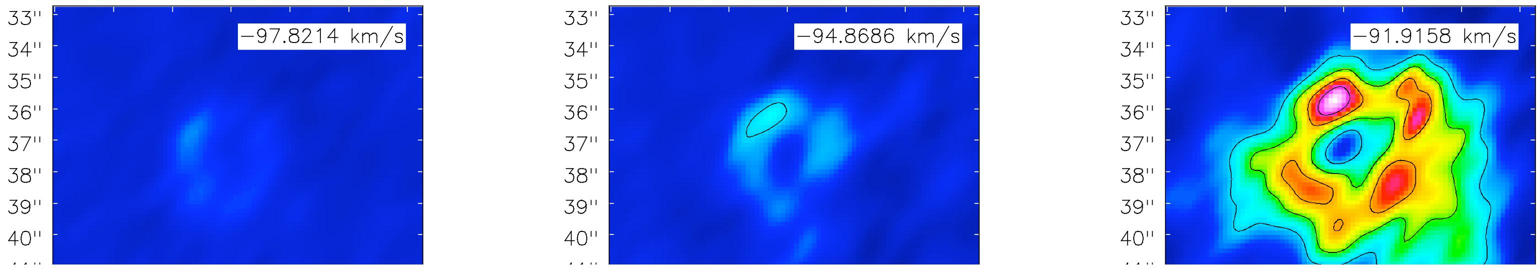
Massive Starless Cores

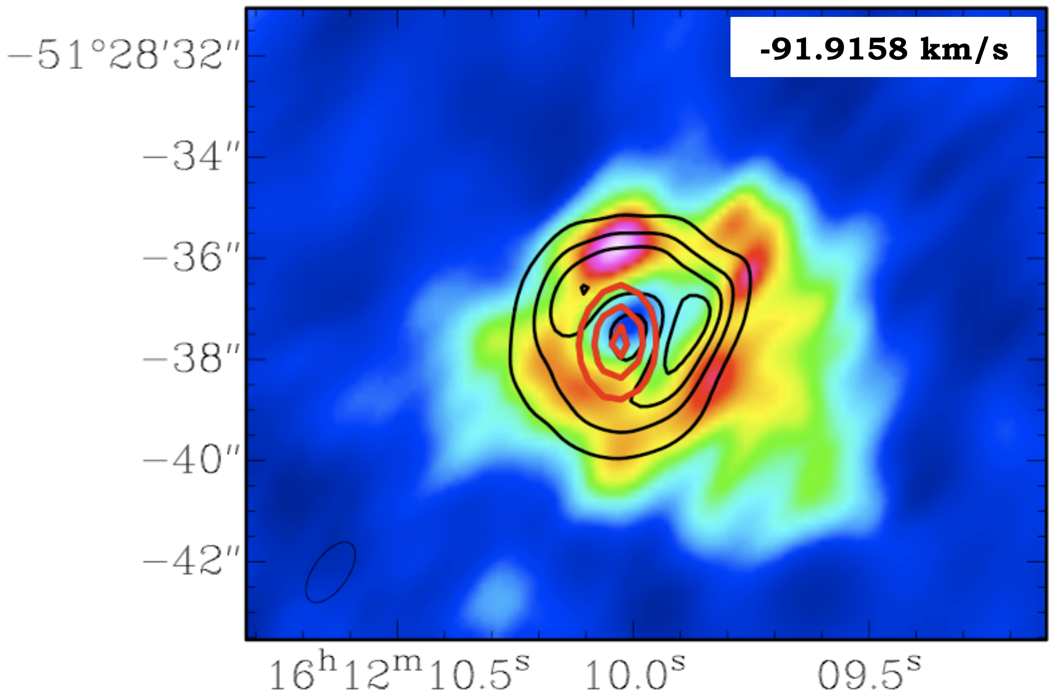
- Required for Turbulent Core model
  - Can we find them?
  - Look in IRDCs (Tan et al.)
  - ALMA using deuteration (N_2D^+/N_2H^+)
  - Find M_{core} up to 24 M_{sun}
  - Velocity dispersion about right
  - Need more, higher masses

A Young Massive "protostar"

- G331.5-0.1 (Merello et al.)
- Outflow at 160 km/s
- ALMA shows very compact shell with high velocity outflow
  - Shocked gas (SiO), $t_{dyn} \sim 800$ years
  - Surrounded by warm, dense gas
  - Hot core properties outside shocked gas

Results: $H^{13}CO+$ (4-3) emission





Colour: H13CO+(4-3)

Black contours: SiO(8-7)

Red contours: 8.64 GHz

- H13CO+ emission: size of 5.8” × 3.64”
- SiO emission centered at the cavity (black contours by 20% of peak emission)
- 3.6 cm continuum emission at the center of the SiO cavity (red contours by 30% peak emission).

IONIZED GAS

⬇

SHOCK SHELL

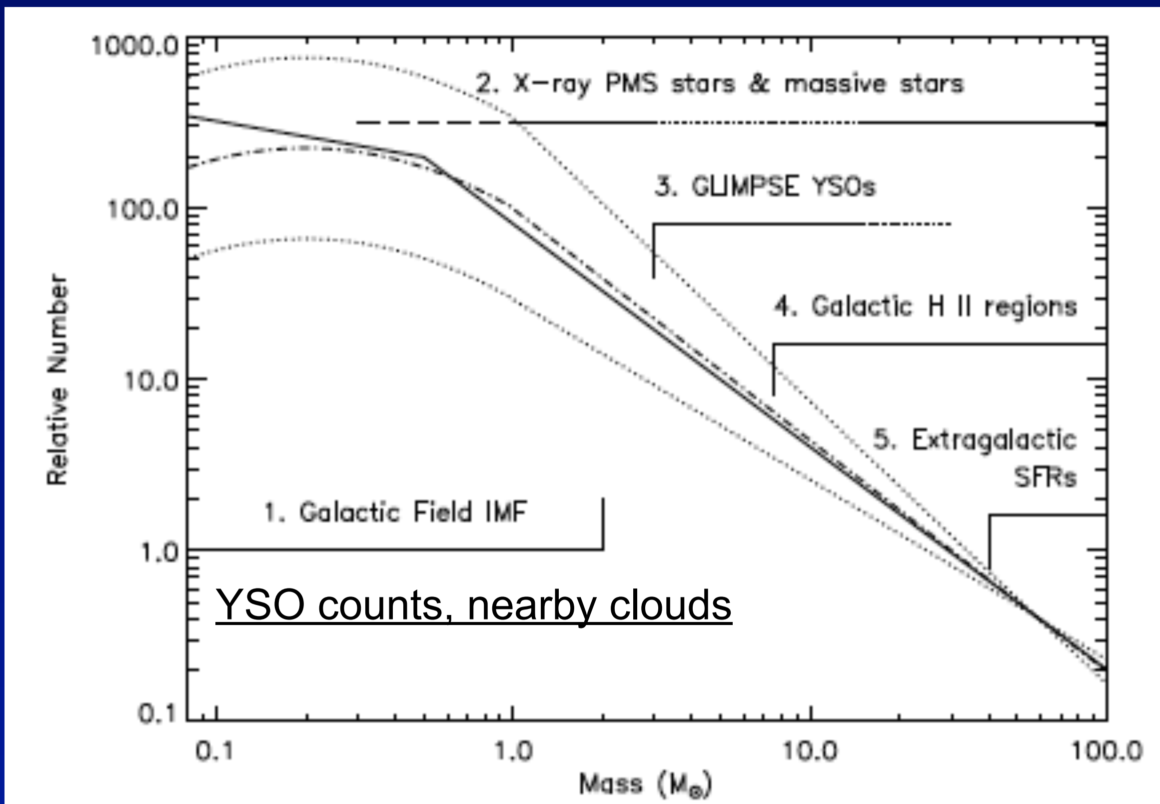
⬇

DENSE MOLECULAR GAS

How to Measure SFR

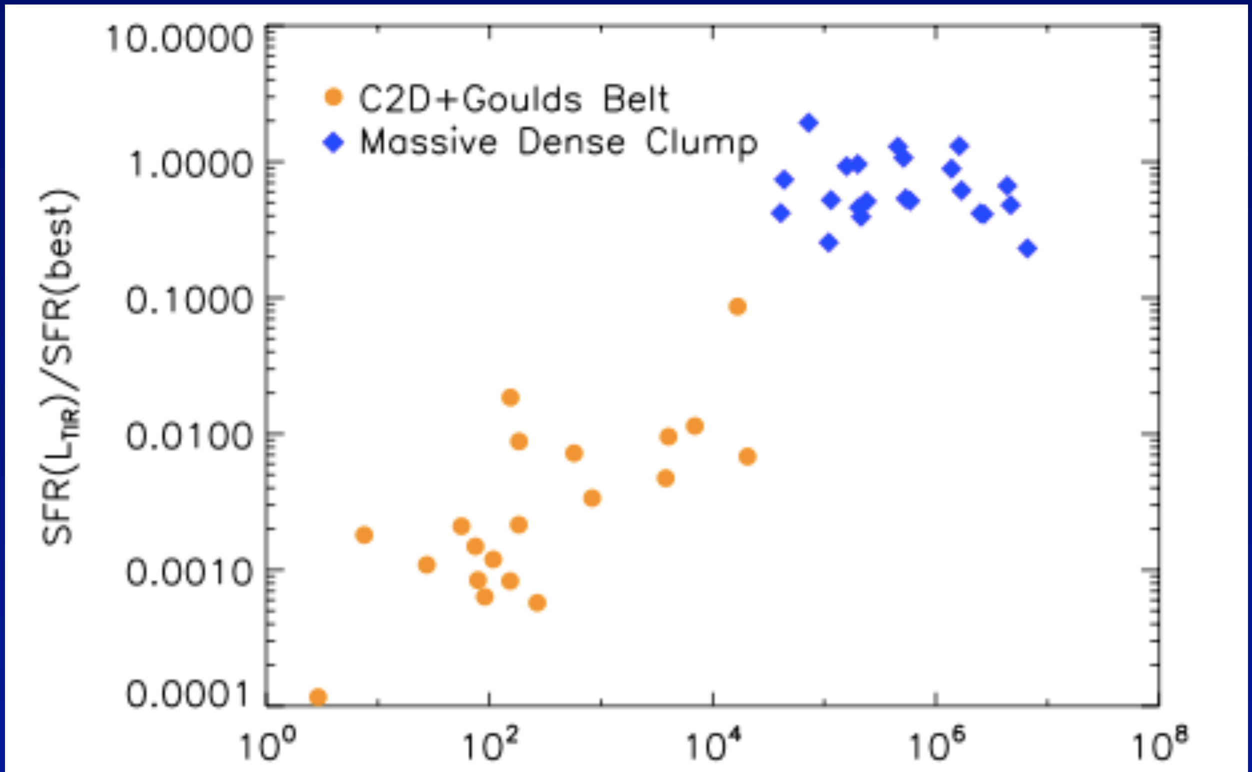
- Can’t count YSOs in regions of massive SF
  - Too distant, confused with diffuse emission
  - JWST maybe?
- Use indirect measures
  - Free-free radio (very massive plus IMF)
  - Far-infrared (pretty massive plus IMF)
- Hard to make a good connection to local clouds

Stellar Mass Ranges



Chomiuk and Povich 2011

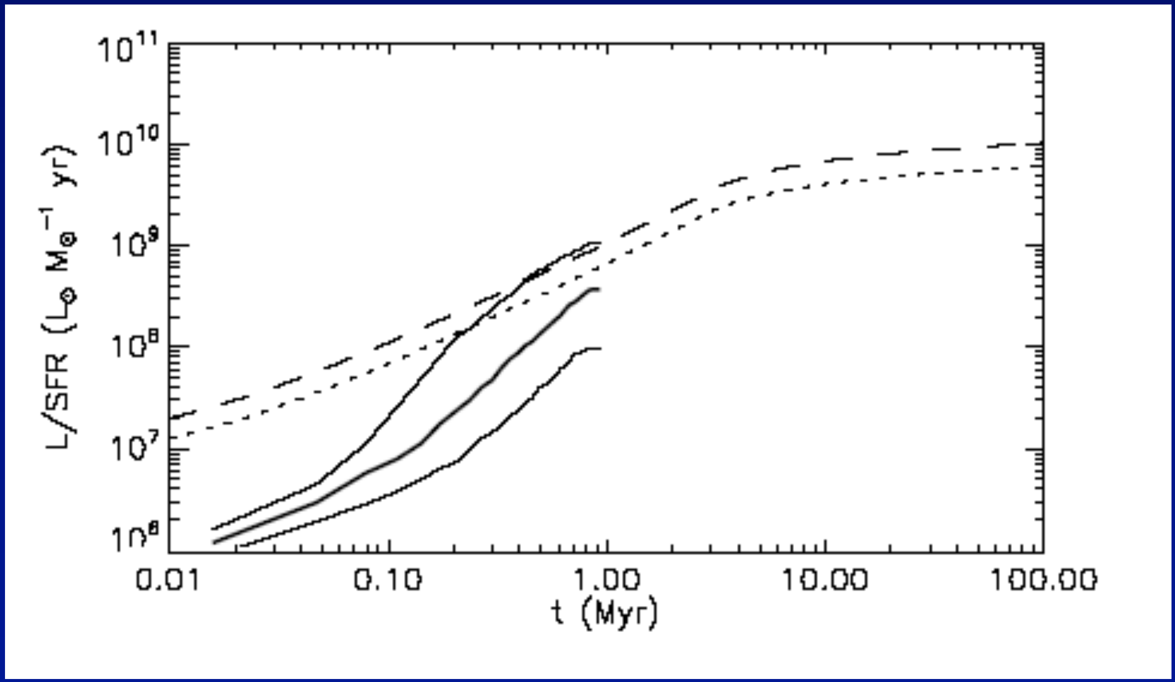
Does L_{TIR} Measure SFR?



Vutisalchavkul (2013)

L_{TIR} does not measure SFR until $L_{TIR} > 10^{4.5}\ L_{sun}$.
Then agrees with SFR(free-free)

Averaging time is 5-10 Myr

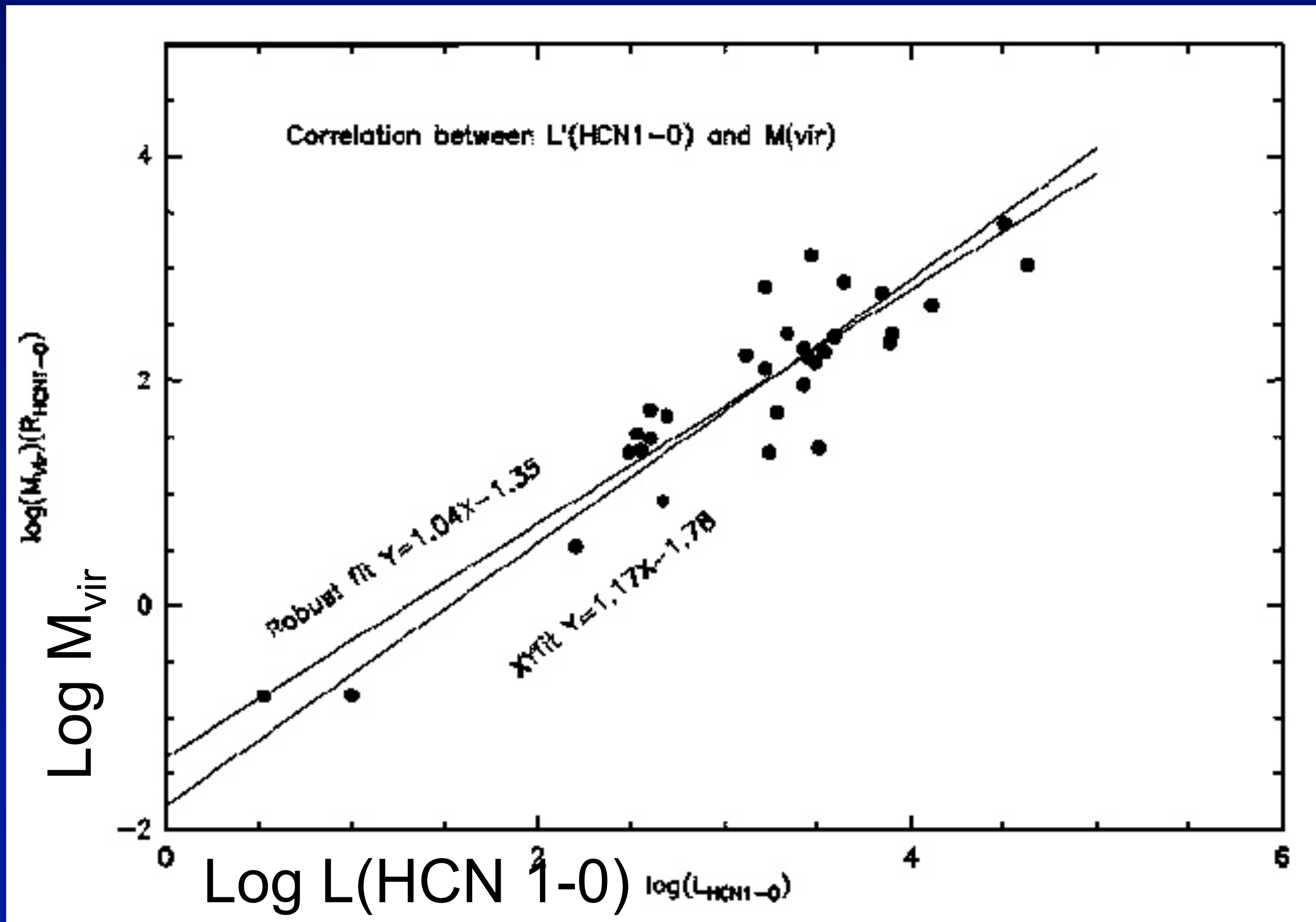


The evolution of light to star formation rate with various models (Krumholz & Tan 2006).
L_{IR} measures SFR well if enough time to form full sample of IMF. There will be variations.
L_{IR} may underestimate SFR at early times, cf. higher L/M if there is an HII region.

Global Measures

- Until higher resolution, use global measures
  - Star formation rate of the whole clump (e.g. free-free or FIR)
  - 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

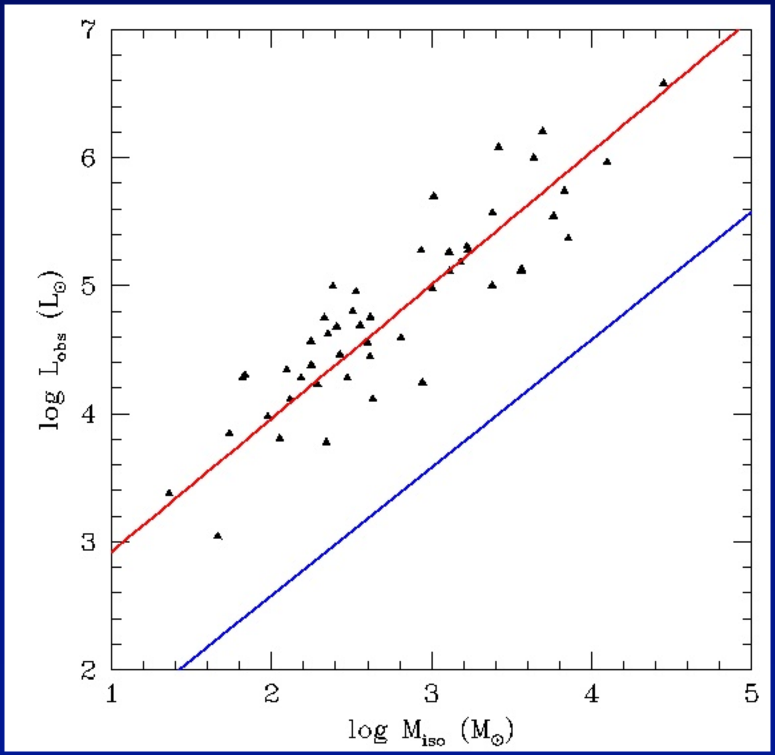
L(HCN) Measures M_{vir}(dense)



Essentially linear relationships

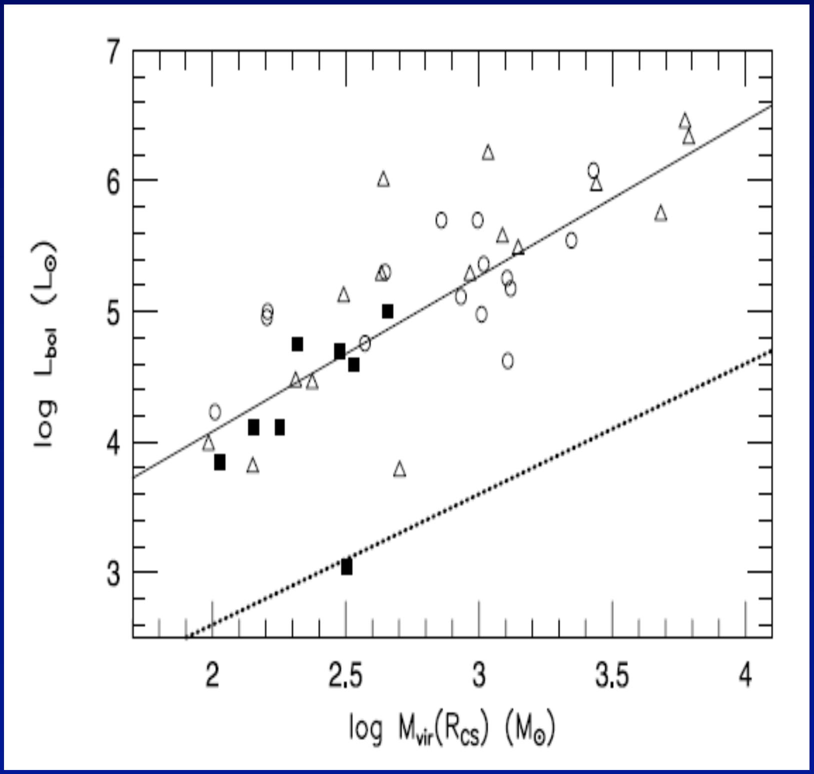
L_{IR} Correlates well with Emission from Dust, Dense Gas Tracers

"Star formation rate"



Mass of dense gas traced by dust emission
Slope ~ 1

"Star formation rate"

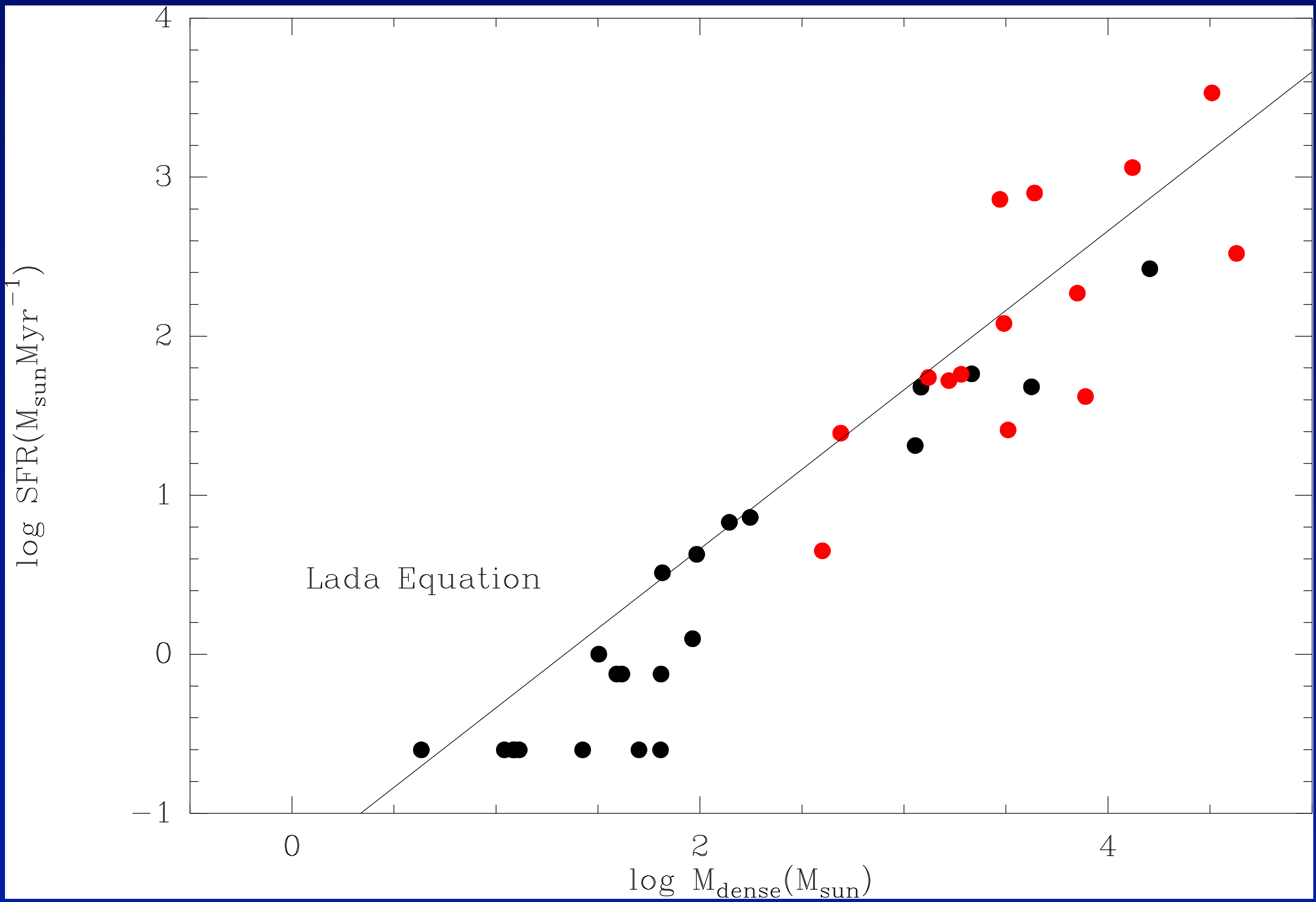


Mass of dense gas traced by CS 5-4
Slope ~ 1.2

(Mueller et al. 2002)

(Shirley et al. 2003)

Do Massive Dense Clumps agree with Nearby Clouds?

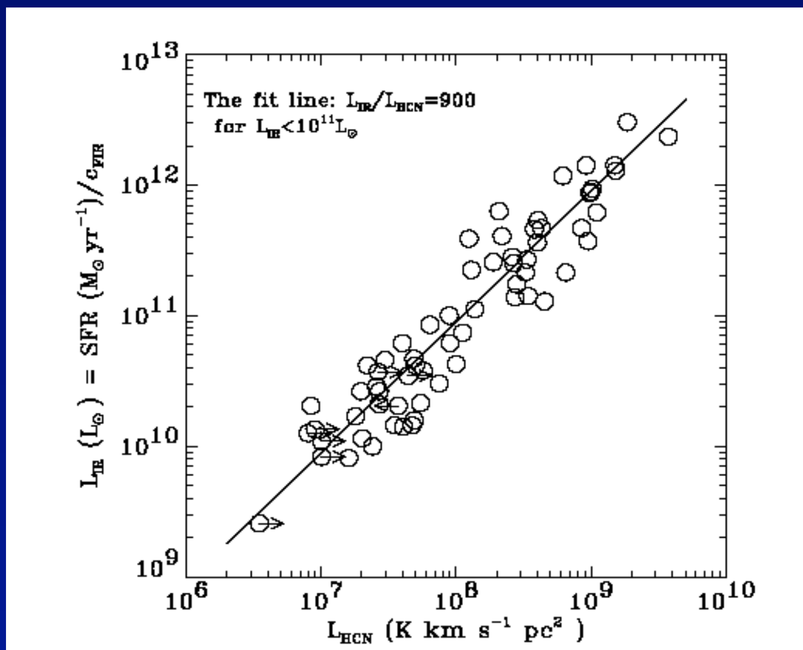


Galactic-galactic connection?

- 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



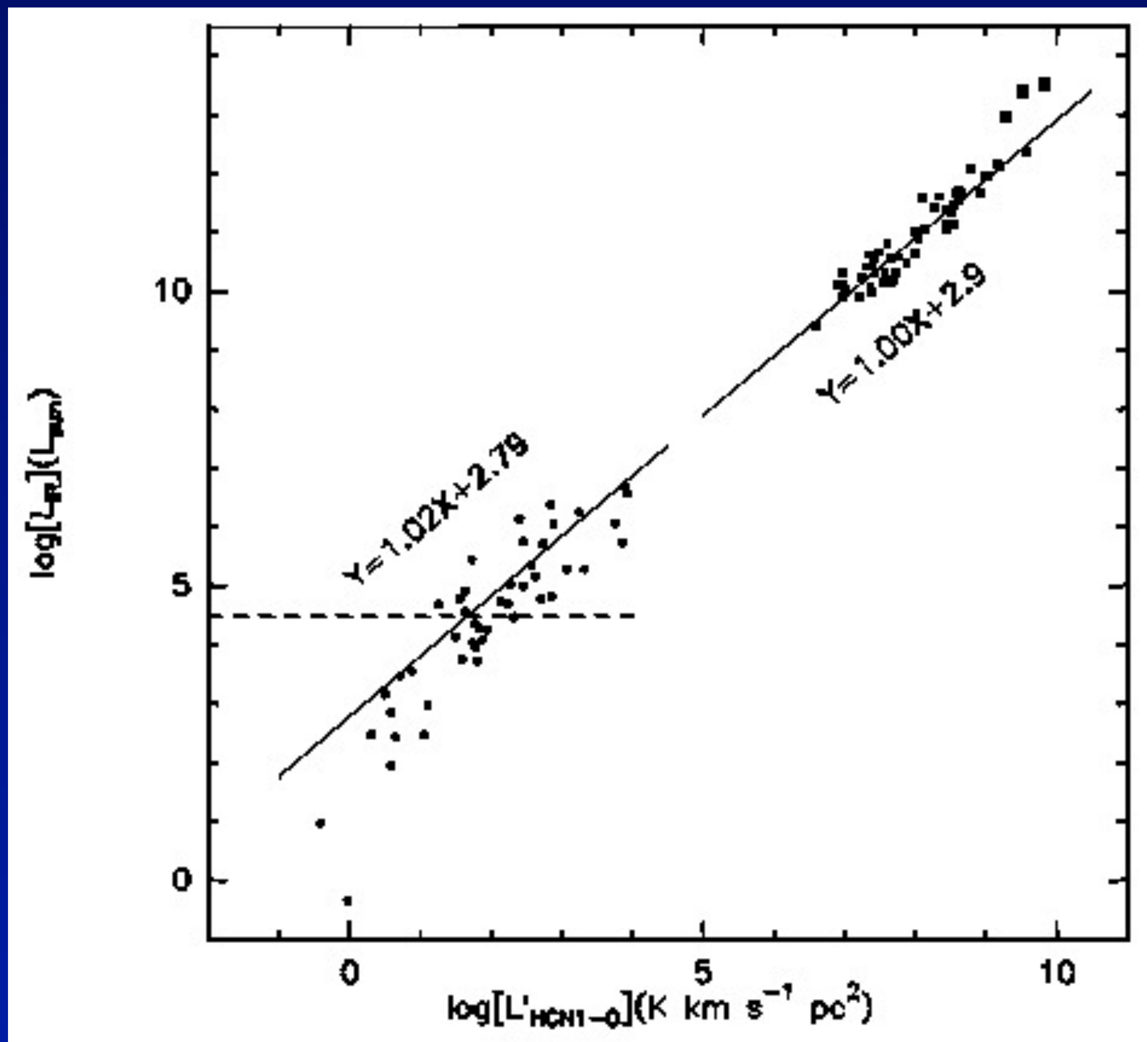
Amount of **dense** molecular gas

- **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)



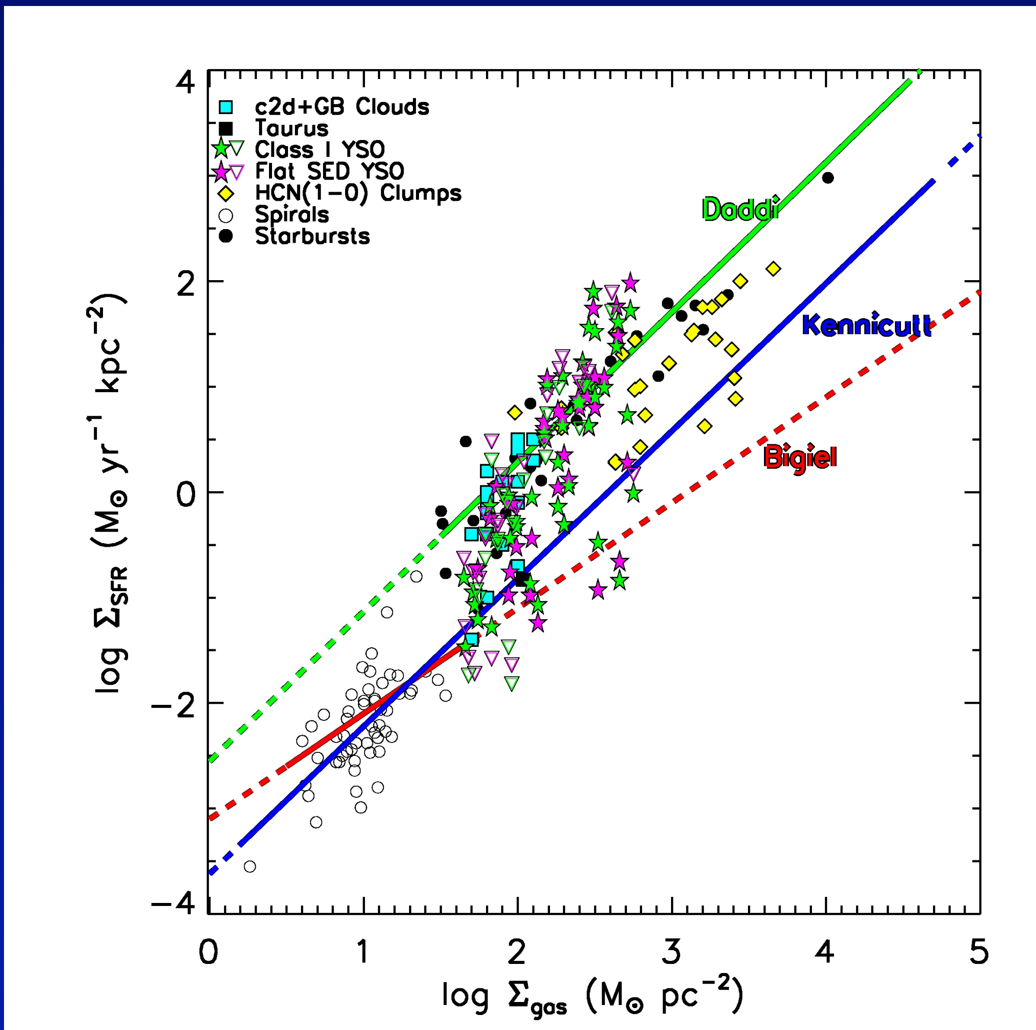
L(HCN J = 1-0)

Wu et al. (2005)

Connecting the Dots

- Can we connect to low mass star formation too?
- SFR per dense gas mass is linear.
- SFR per cloud mass is linear with bigger dispersion
- Universal local laws?

Starbursts with ULIRG α(CO)

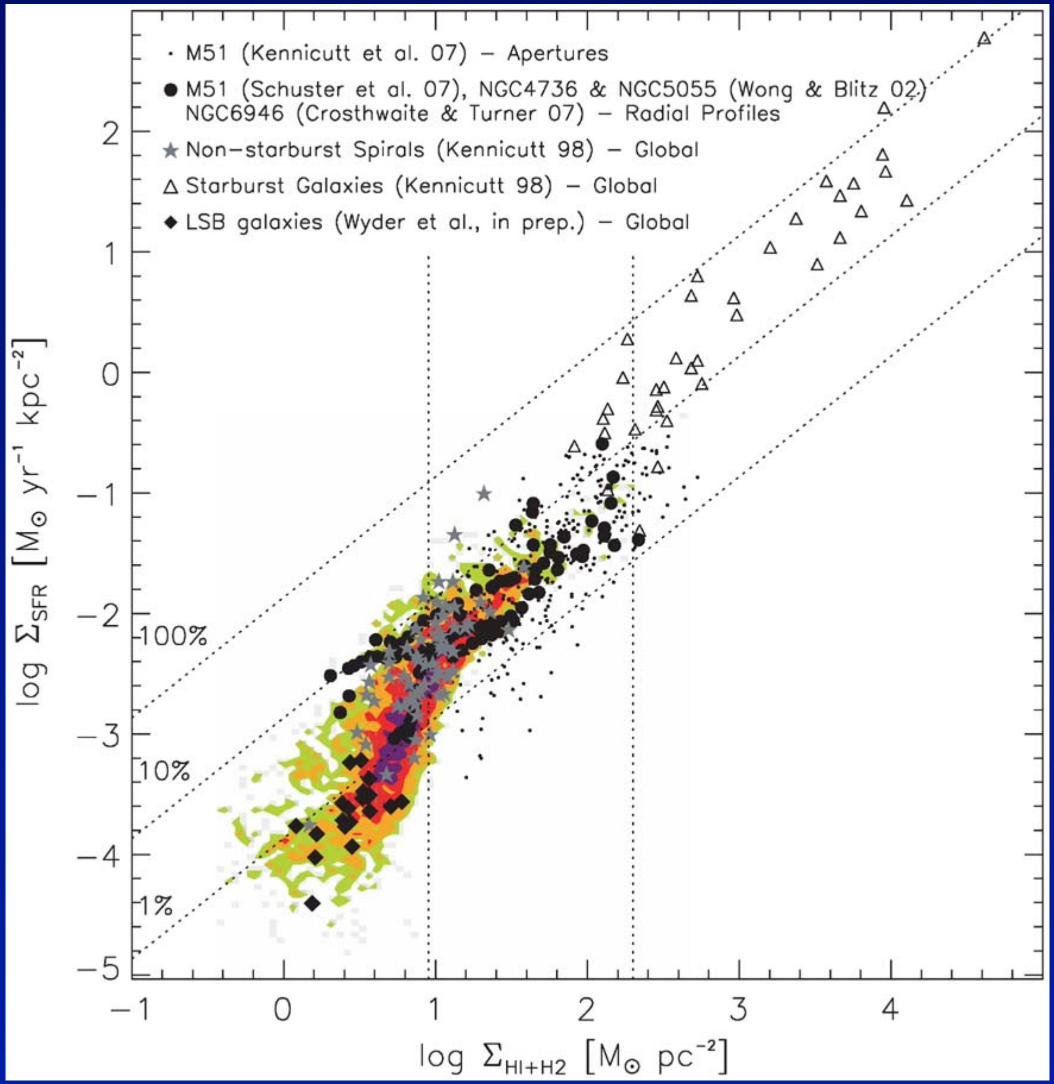


Circum-nuclear SBs with SB α(CO): smaller by factor of 5.8. [M_{mol} = 0.8 L(CO) vs. 4.6 L(CO)]

Daddi et al. 2010 fit to starbursts in green

Now agree with local clouds.

Hints of Two Thresholds



Bigiel et al. 2008

Speculation

- There are two transitions in SF Relations
  - Atomic to Molecular dominated ISM
  - $\Sigma_{mol} \sim 10\ M_{sun}\ pc^{-2}$
  - Clump/Starburst threshold
  - $\Sigma_{mol} \sim 120\ M_{sun}\ pc^{-2}$
  - Probably depends on other things like external radiation field, Mach number, …

Massive Star Formation in Galactic Context

- Surveys in mm continuum finding 1000's of dense clumps
  - Bolocam Galactic Plane Survey
  - ATLASGAL survey from APEX
  - HIGAL from Herschel
- Infrared Dark Clouds (IRDC)
  - MSX, GLIMPSE, MIPSGAL
- New models of Galaxy, VLBA distances, …
- Get better mass function for clumps, SF rates?
- Provide link to extragalactic star formation

Summary

- Star formation is mostly clustered
- Efficiency is low in clouds, high in cores
  - But always slow compared to free-fall
- But much more SF than predicted by K98
- Massive clumps denser, much more turbulent
- Mass of “dense” gas seems best SFR predictor
- Surveys begin to connect MW and exgal SF
- We need ALMA and JWST for resolution

Extras if Time Permits

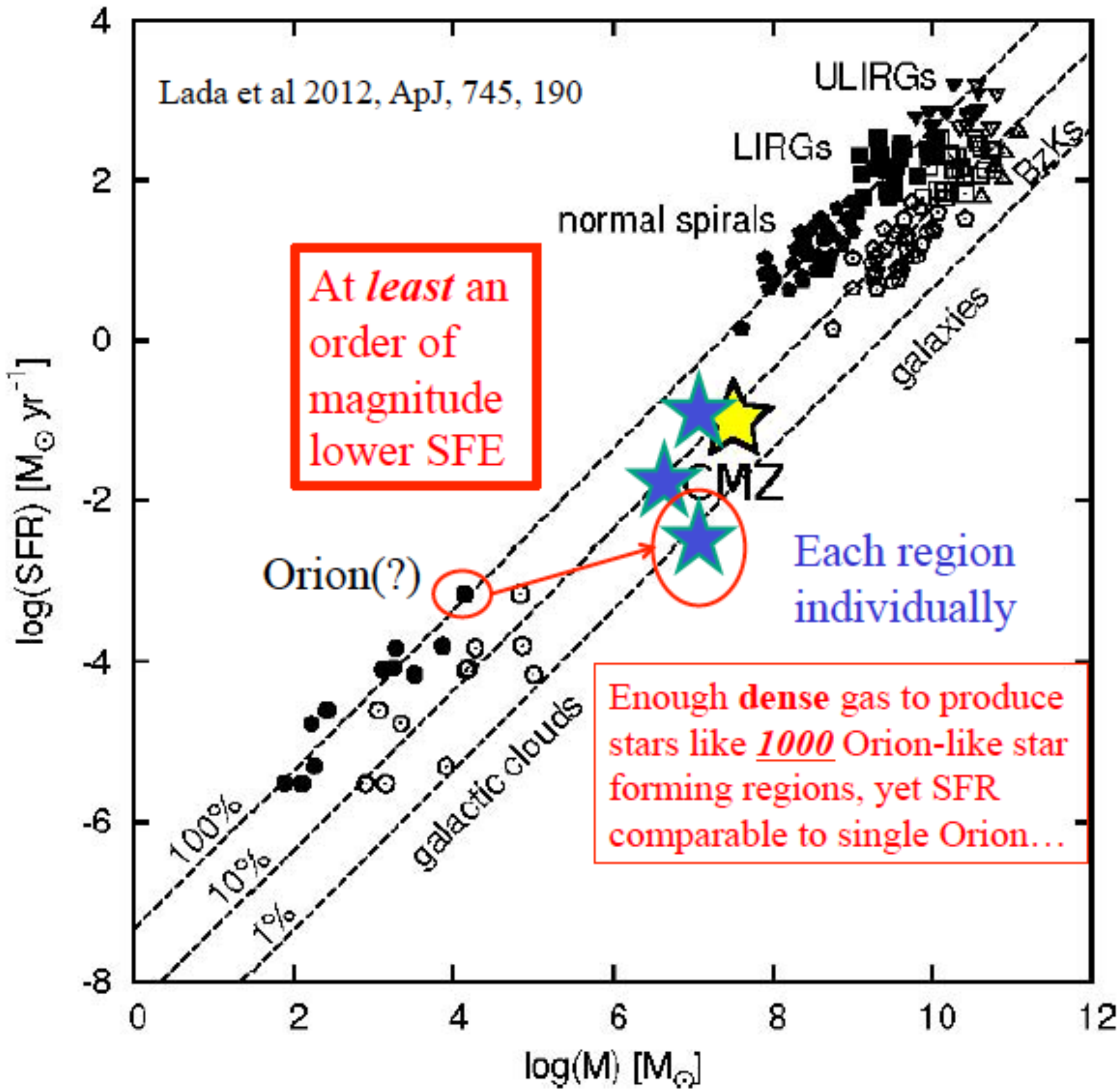
(Very) Massive Dense Clump

- The “brick” breaks up (Rathborne)
  - 0.07 pc resolution (core size)
  - Many continuum structures
  - Filaments, arcs, “cores”
  - 50 “cores” M_{vir} up to 900 M_{sun}
    - Radii ~0.15 pc, n ~ 3e6, 15% of cloud mass
    - Core mass function premature…
  - Many SiO emitting structures- shocks
  - Test case: little SF, but very dense (and turbulent)

Gas in CMZ of MW is dense, but not forming stars quickly

S. Longmore

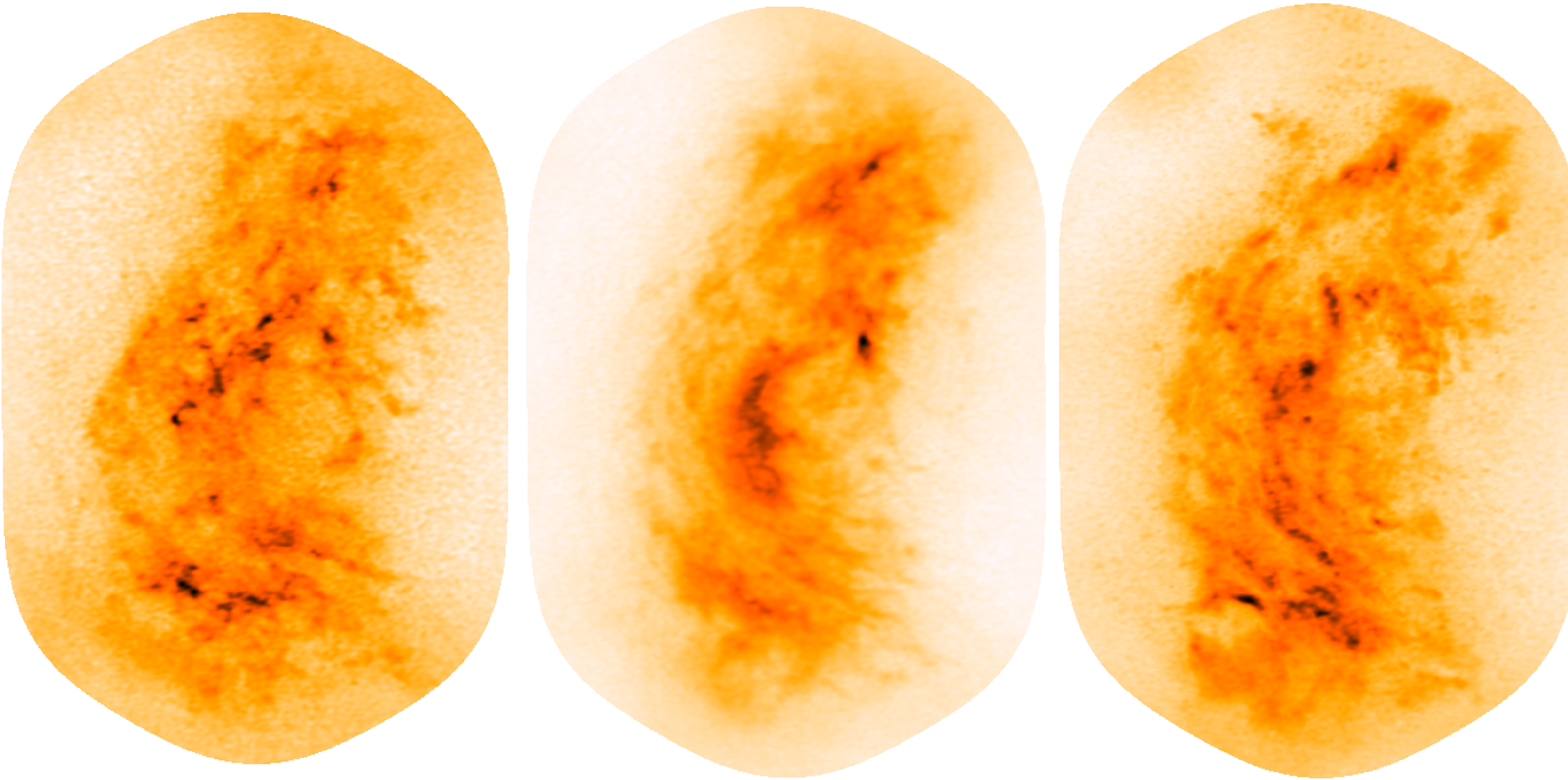
SF relations predict:
0.5-1 M_{sun}/yr
Observations:
0.01-0.1 M_{sun}/yr



How does the CMZ compare to local and extragalactic SF regions?

Complex morphology, chemistry

SiO HNCO C_2H



- Rathborne