Star Formation from Nearby Clouds to Distant Galaxies: Common Features and Common Myths

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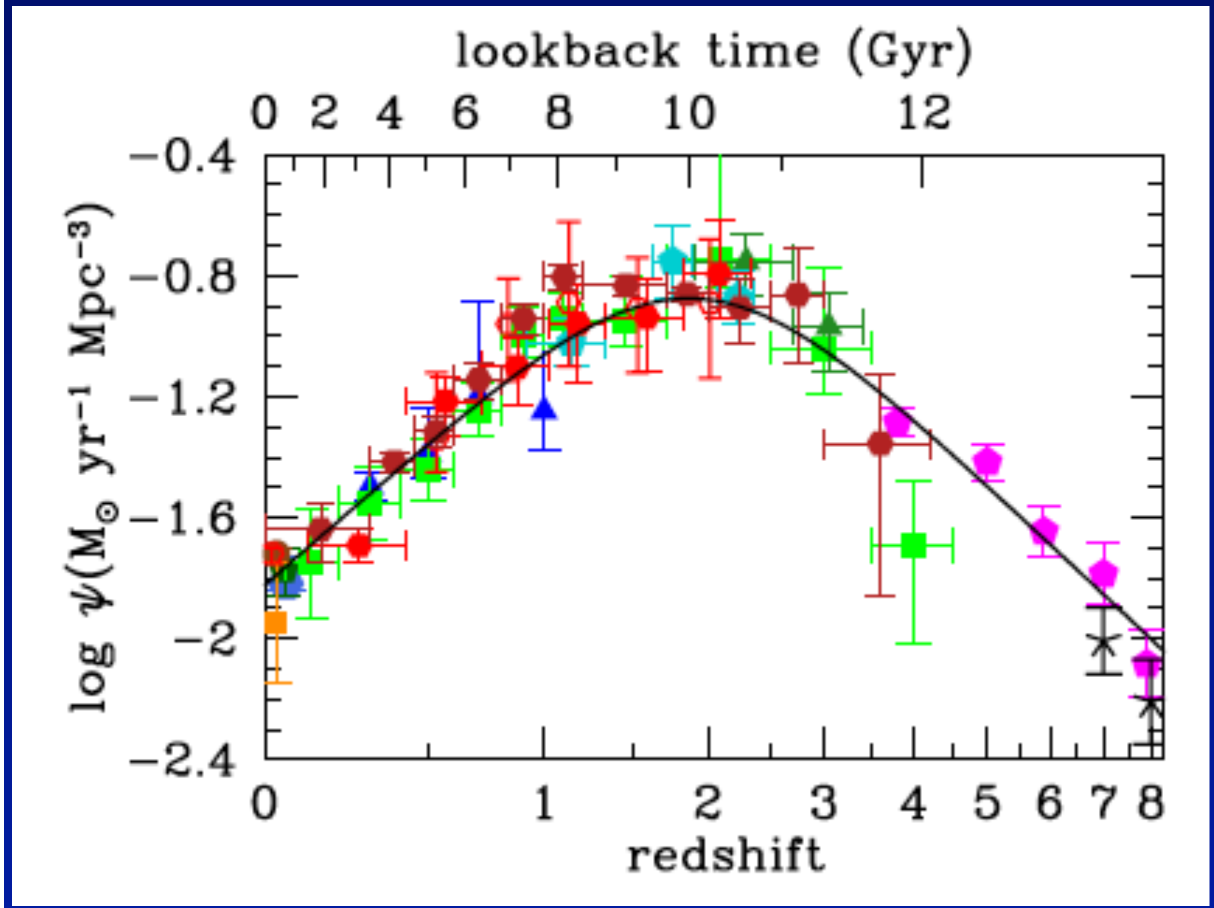
KASI

The Basic Problem of Star Formation

- It is slower and less efficient than expected
- For Milky Way, $M_{mol} = 1 \times 10^9\ M_{sun}$
- Typical $t_{ff} = 3 \times 10^6$ yr
- Simple estimate: SFR = 300 M_{sun}/yr
- 100 times higher than average over last Gyr
    - Zuckerman & Palmer 1974, ARAA, 12, 279
- Roughly applies to other galaxies, Universe as a whole

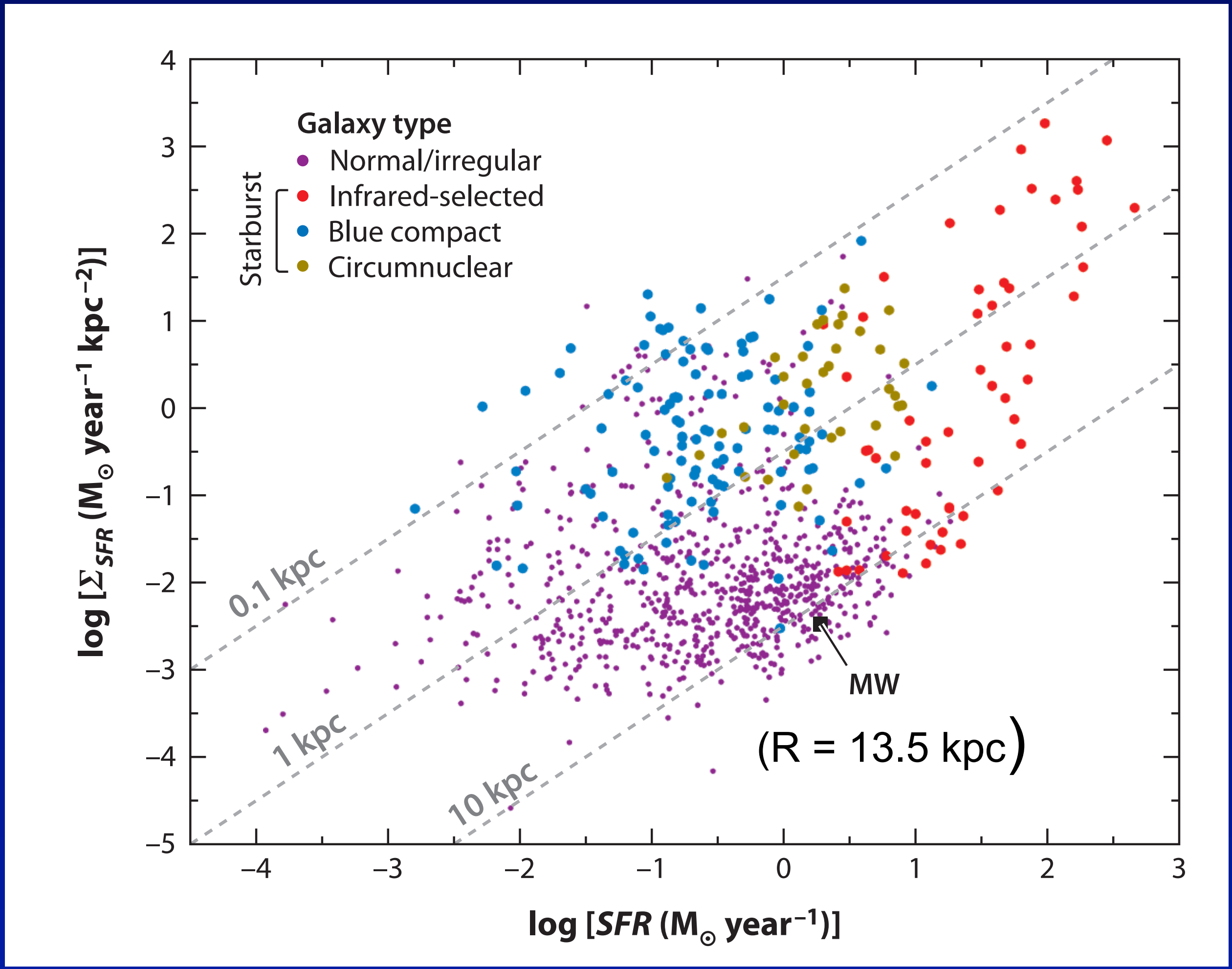
Cosmic Scale SFR(t)



Only a few percent of the baryons are in the form of stars. Simulations predict most (e.g., Hopkins et al., 2014, MNRAS, 445, 581).

Madau & Dickinson 2014 ARAA

Galaxy Scale: Extreme Diversity

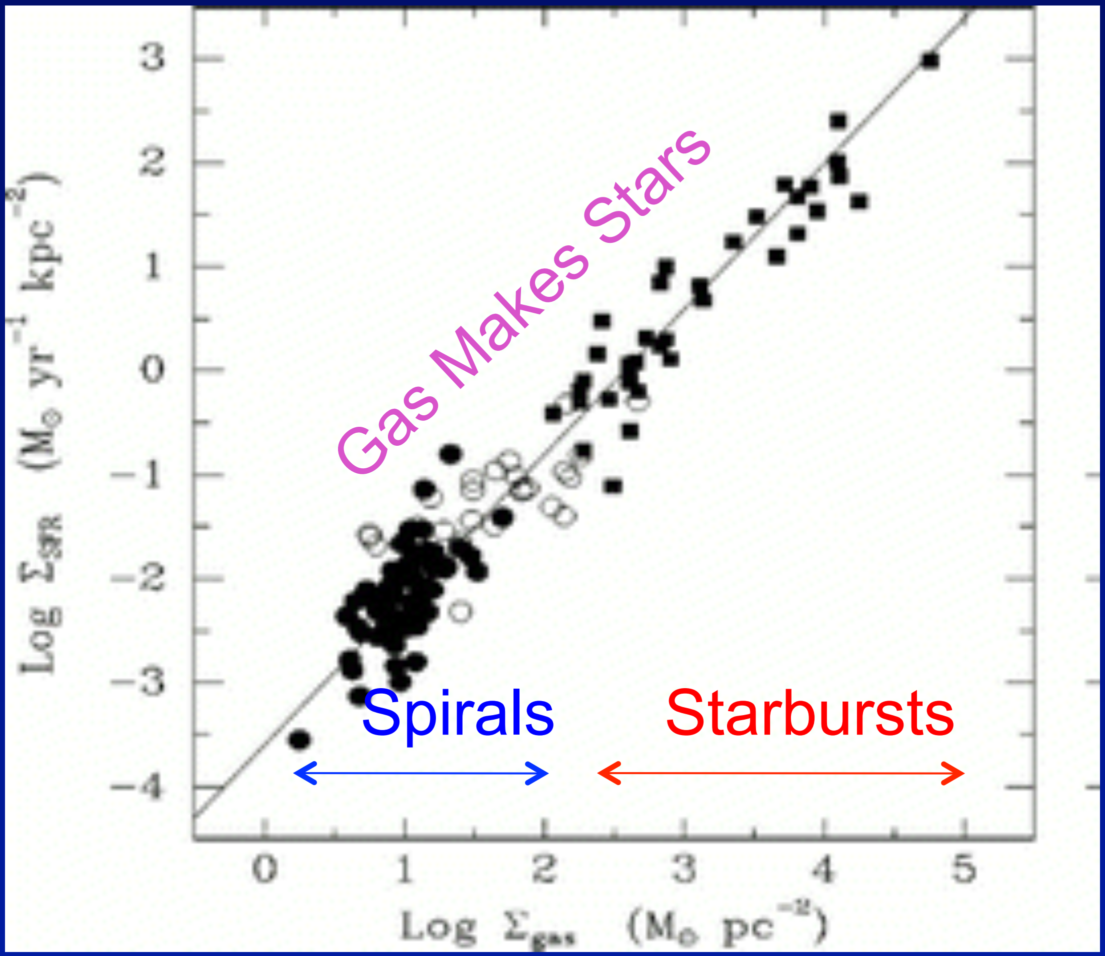


log Σ(SFR)

log SFR

Kennicutt & Evans 2012

Collapses to KS Relation



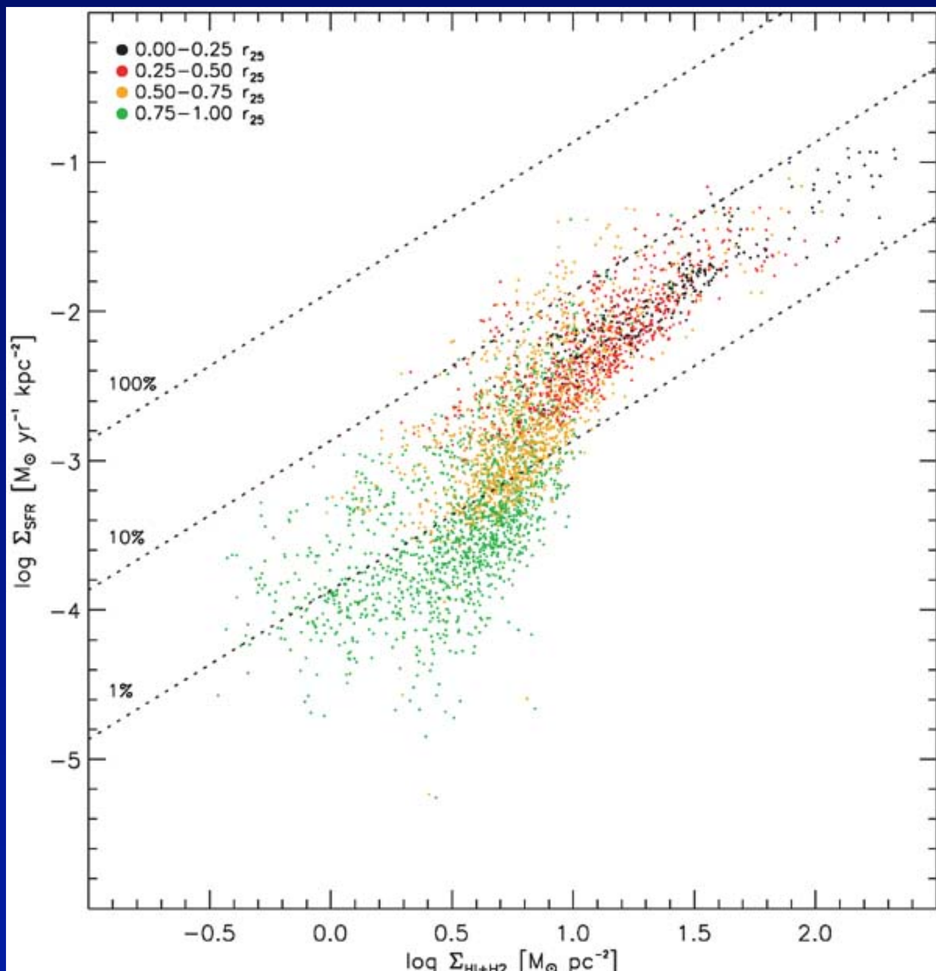
Solid circles are disk-averaged normal spirals
Open circles are central regions of normal disks
Squares are circumnuclear starbursts

$\Sigma_{SFR} = A\,\Sigma_{gas}^{N}$
N = 1.4±0.15

Kennicutt 1998, ARAA 36, 189

SFR Linear above Threshold Σ_{gas}

Log Σ (SFR)



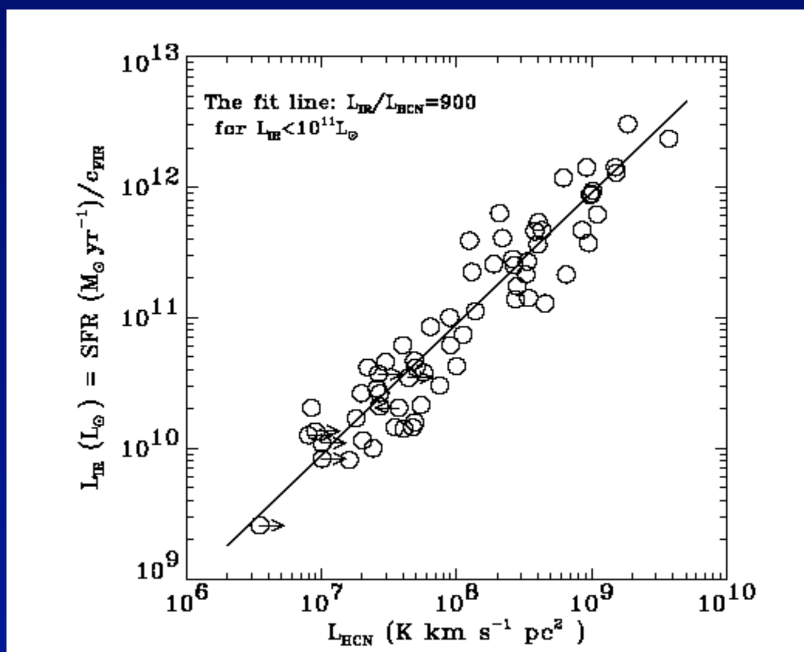
Log Σ (HI + H_2)

Study of 18 nearby galaxies with sub-kpc resolution in HI, CO.
SFR from UV+24 micron
Color code is location in galaxy.
Threshold around 10 $M_{sun}pc^{-2}$ in total gas: transition from HI to H_2
Linear above threshold
Typical depletion time 1-2 Gyr

Bigiel et al. 2008

SFR in Starburst Galaxies

Star formation rate

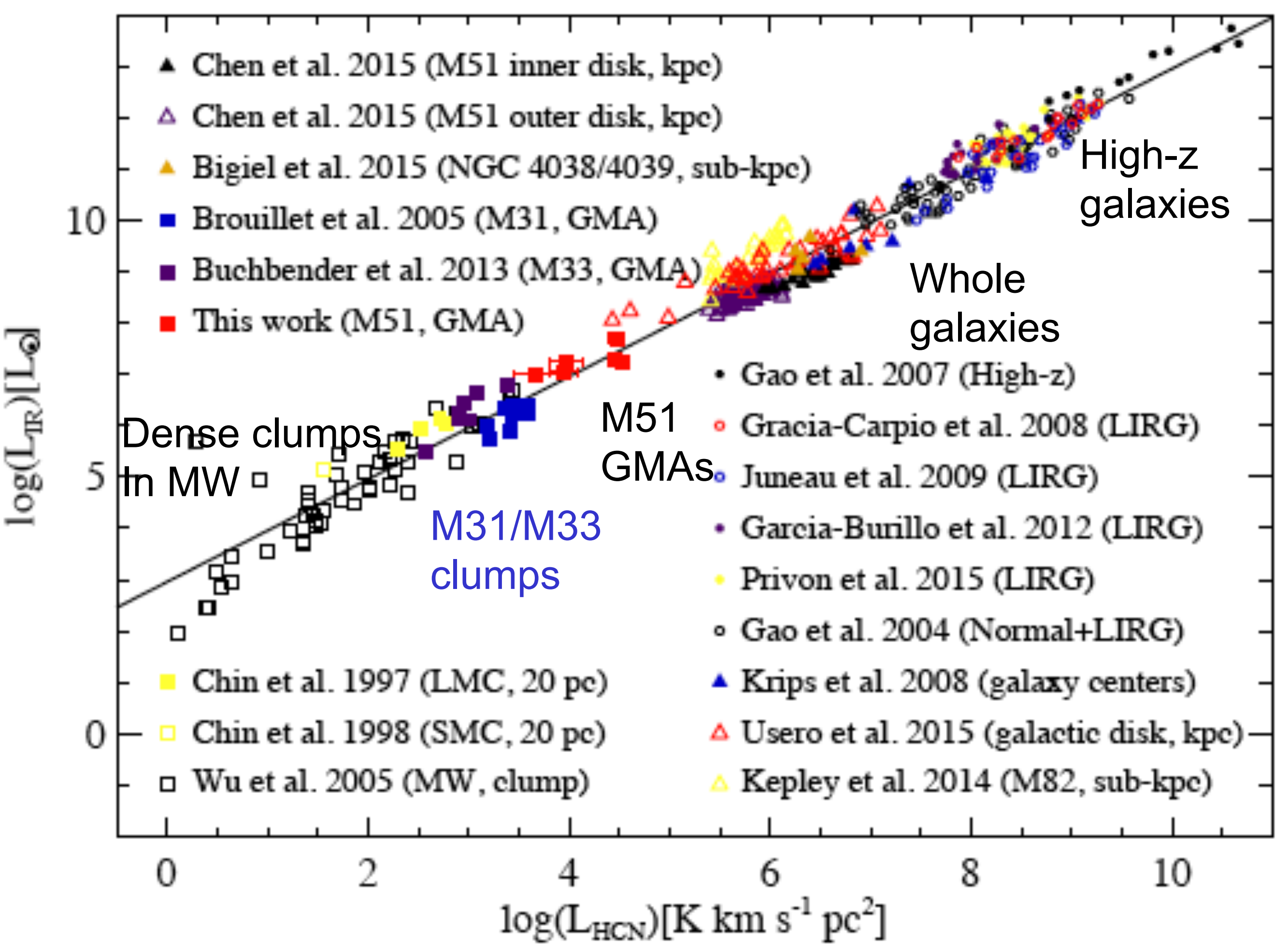


Amount of **dense** molecular gas

- L_{IR} correlates better with L(HCN)
- Smaller scatter
- Higher SFR/Gas
- SFR rate linearly proportional to amount of dense gas
- "Efficiency" for dense gas constant and high

Gao & Solomon (2004) ApJ 606, 271

Extends Across Many Scales



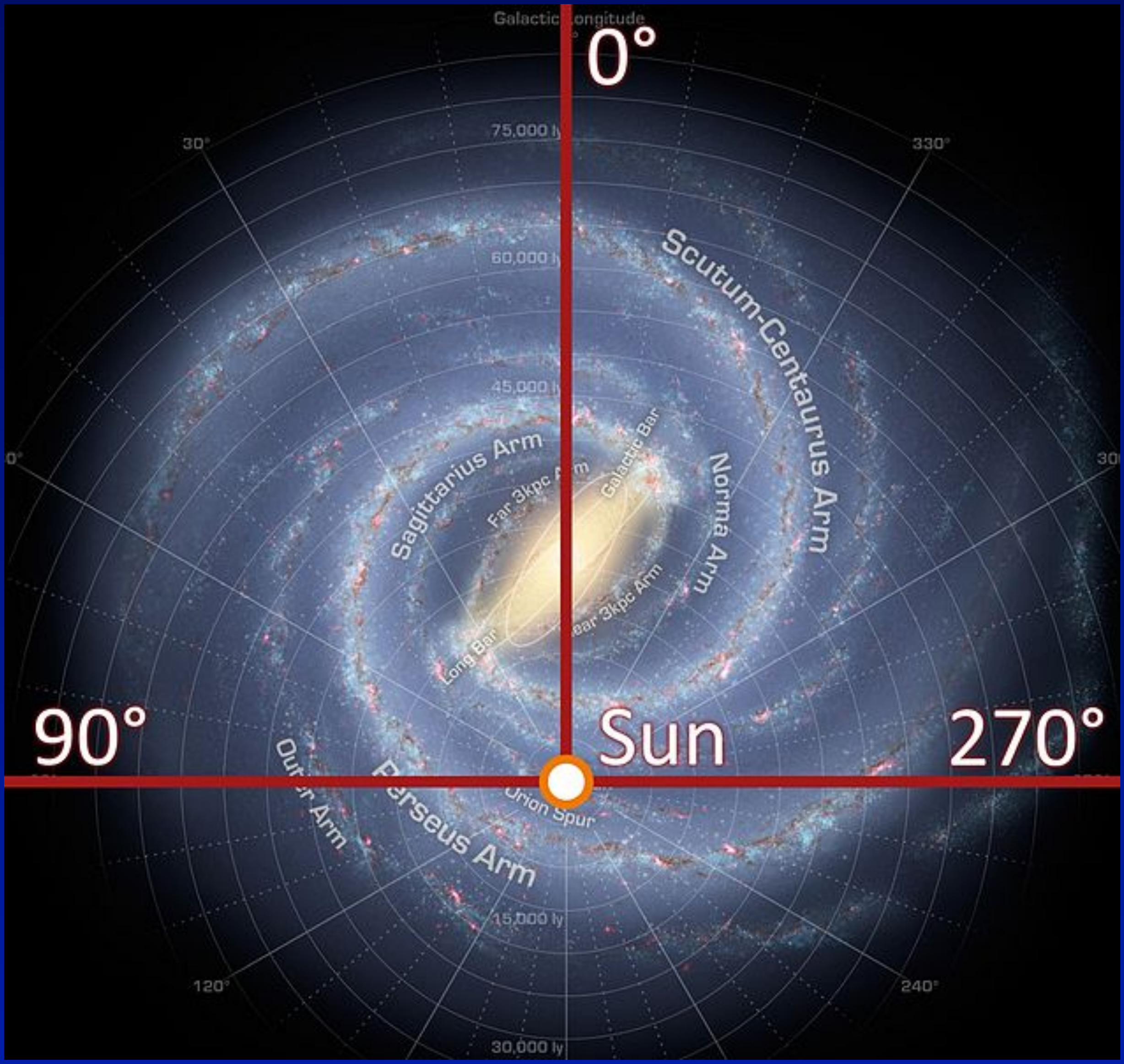
Extends from MW dense clumps to high-z starbursts: Linear with standard deviation about half that for CO

From talk by Yu Gao on Tuesday

Testing Star Formation Prescriptions

- Use Star Formation "Efficiency"
  - SFE = SFR/X
  - Units of 1/Myr, inverse of depletion time
  - A linear SFR "law" becomes flat with SFE
  - Better measure of scatter
  - What is the best predictor?
    - Mass of molecular gas
    - Mass of molecular gas divided by free-fall time
    - Mass of dense gas

Use the Milky Way to Study

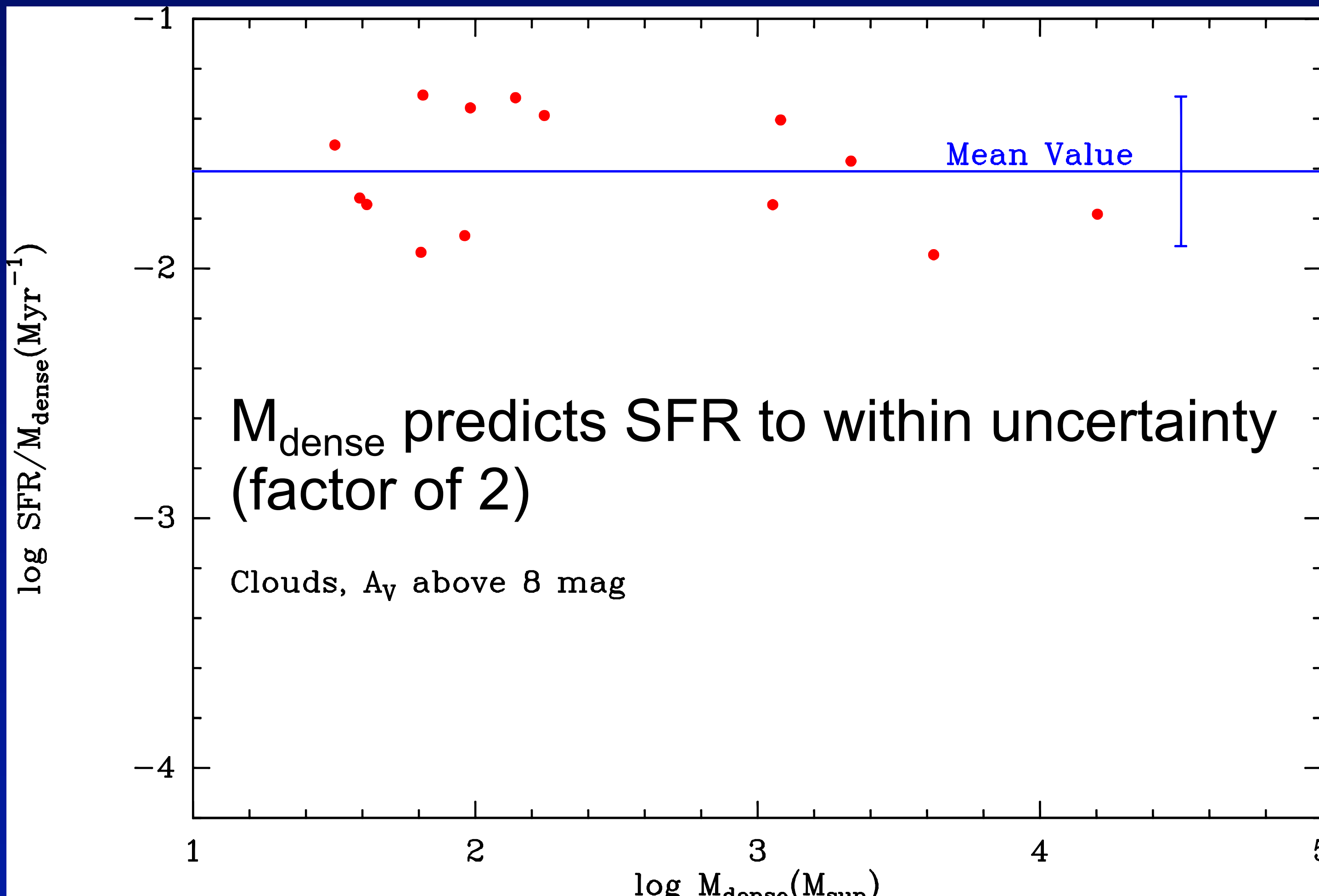


Star Formation in Nearby, "Large" (3-10pc) Clouds

- c2d+GB Survey
  - Survey 29 large clouds with Spitzer (if split into individual regions)
- Where do stars form?
- Which SFE predictor works best?

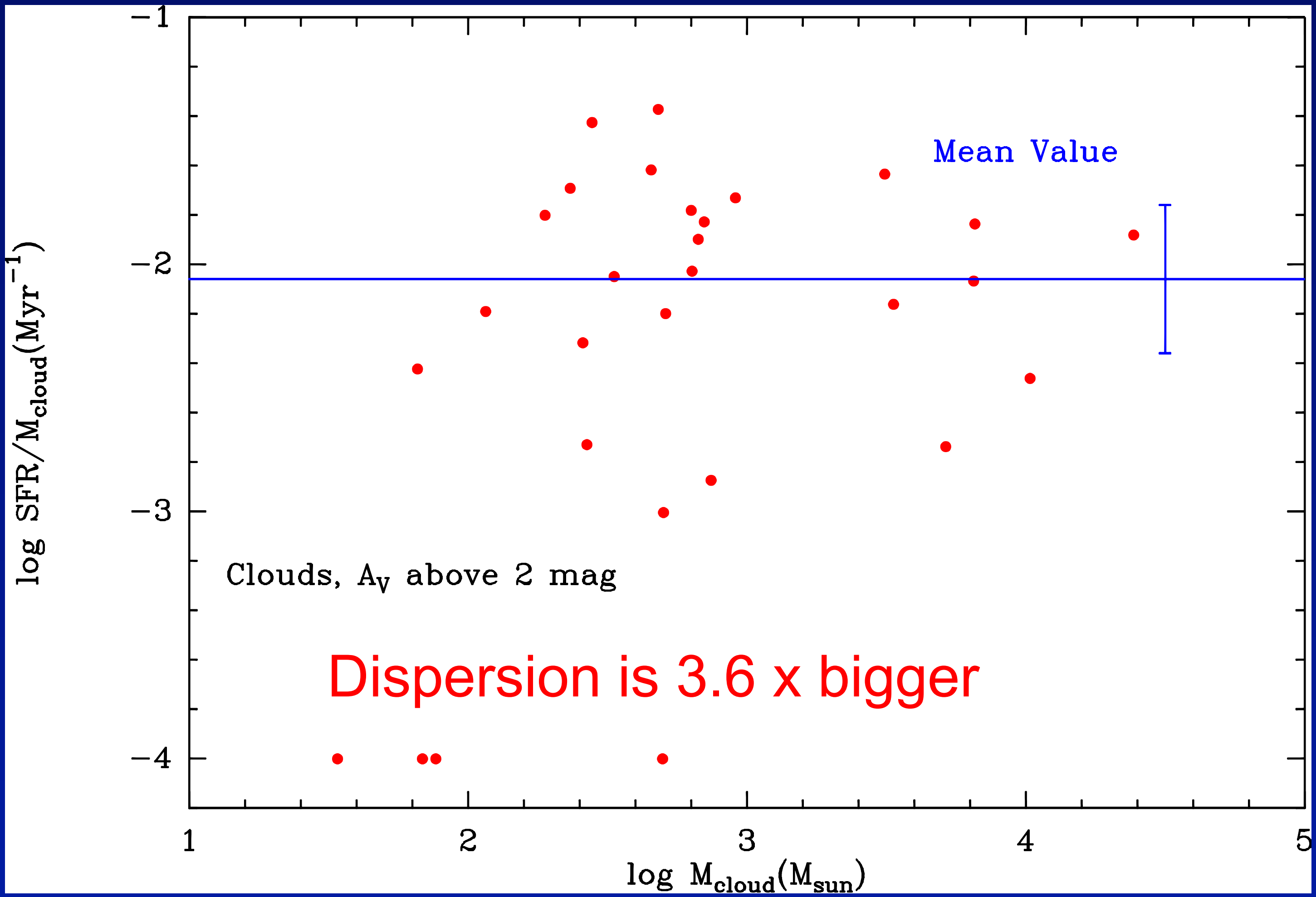
SFE for Dense Gas

Log SFR/M_{dense} (Myr^{-1})



Log M_{dense} (M_{sun})

SFE for Cloud Mass



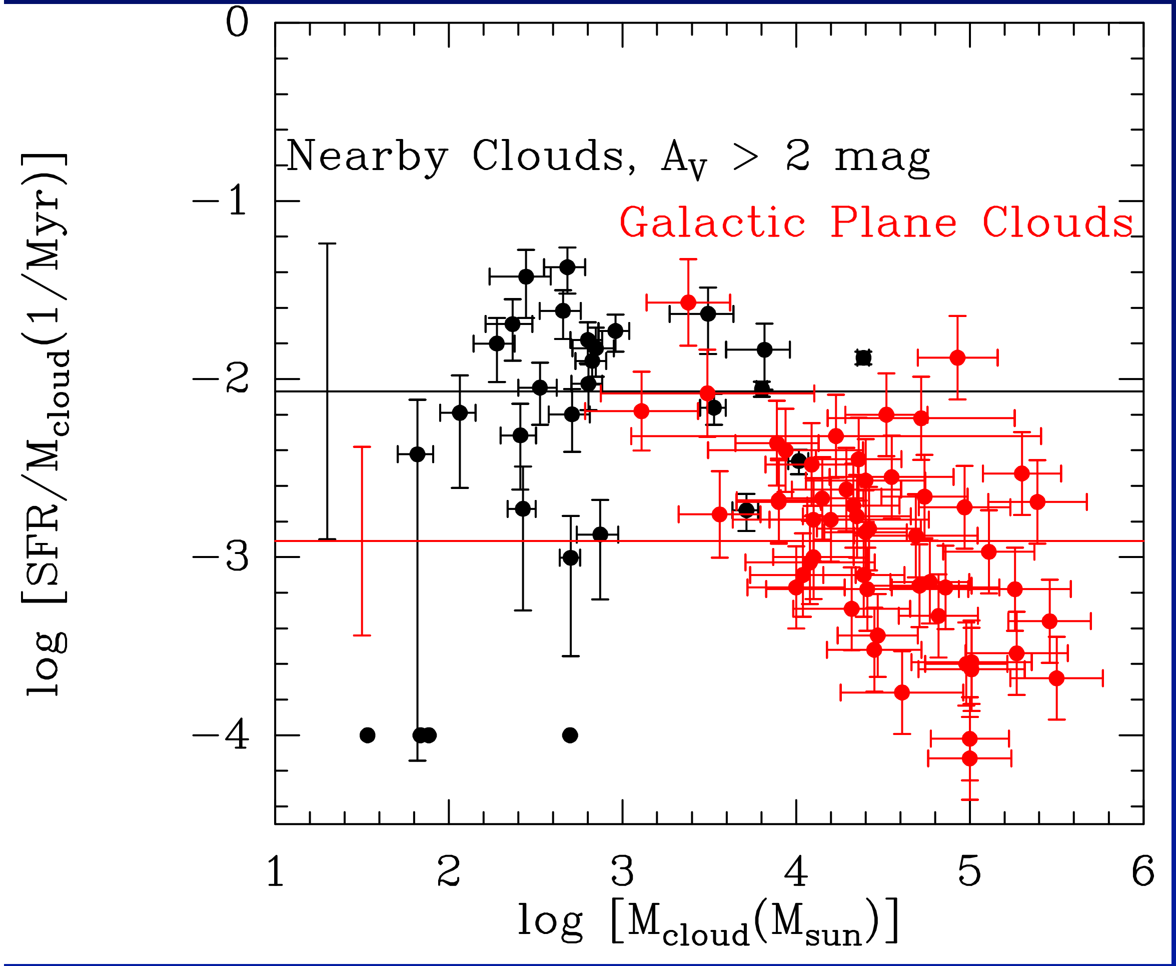
Log SFR/M_{cloud} (Myr^{-1})

Log M_{cloud} (M_{sun})

What About Massive Stars?

- Need to study more distant clouds
- Can’t get SFR by counting YSOs (yet!)
- Use tracers of massive stars (MIR, free-free, RRL)

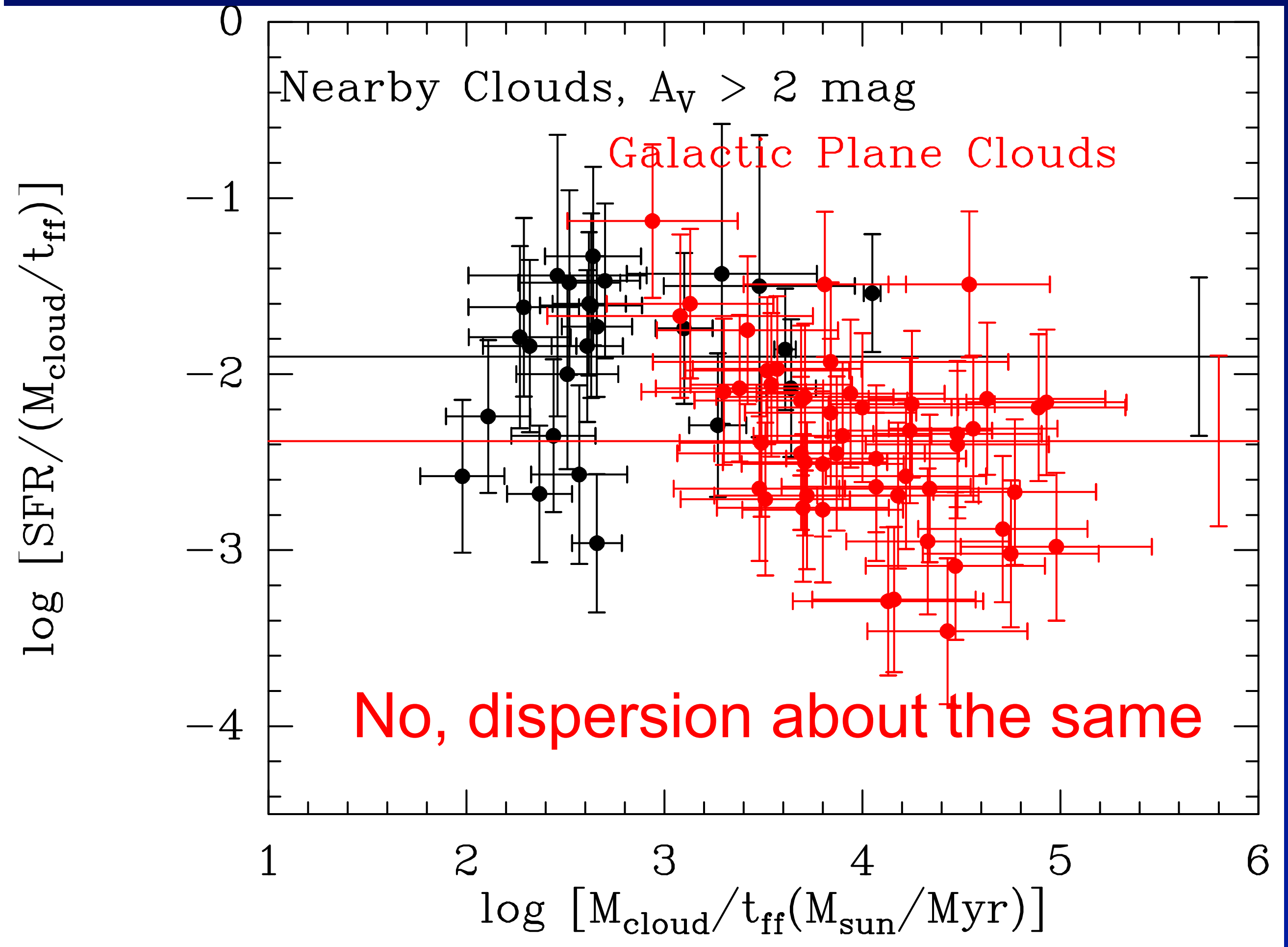
Mass of Molecular Cloud



GP clouds systematically less efficient by nearly factor of 10
Dispersion is large (recall Onodera talk)

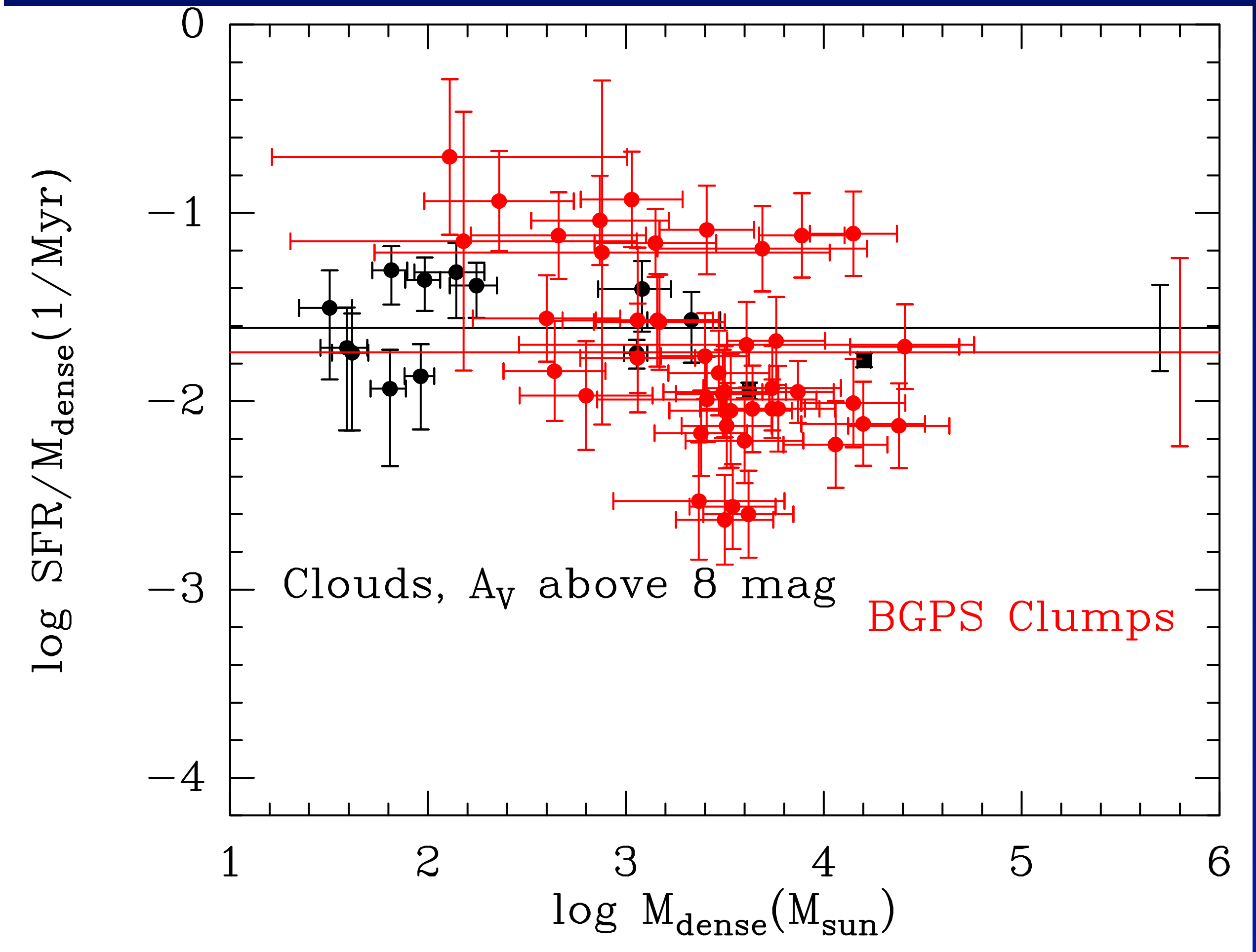
N. Vutisalchavakul et al.

Does t_{ff} decrease dispersion?



N. Vutisalchavakul et al.

Mass of Dense Gas



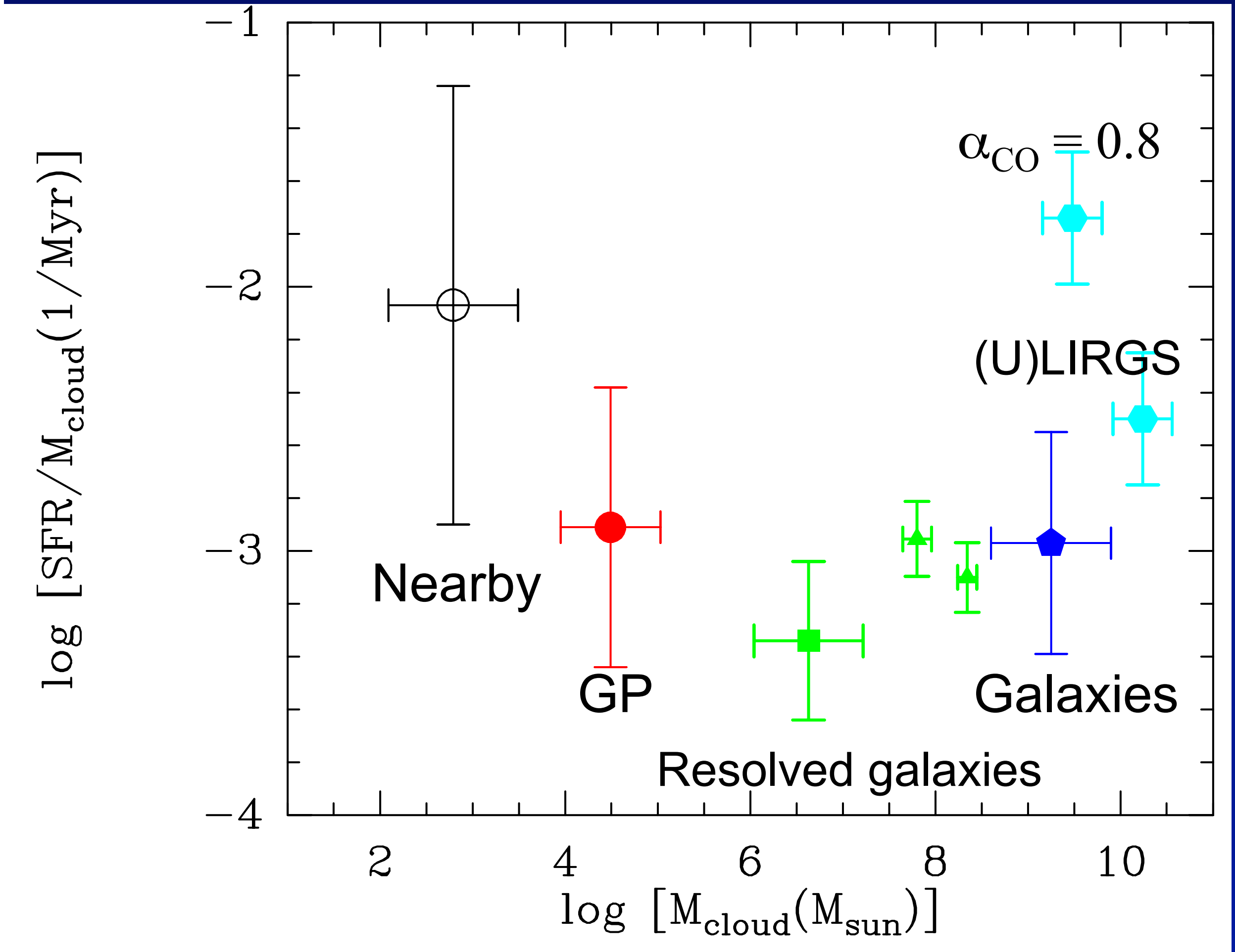
Nearby, GP agree
Dispersion smaller
but still large

N. Vutisalchavakul et al.

What about other galaxies?

- Big picture
  - Take mean and std deviation (in log) of all the nearby clouds and all the GP clouds
  - Do the same for exgal samples
  - Leroy (30 galaxies, CO) (~ 1 kpc res)
  - Chen (M51, CO, HCN) (~ 1 kpc res)
  - Liu (115 spirals, 66 (U)LIRGS, CO, HCN)

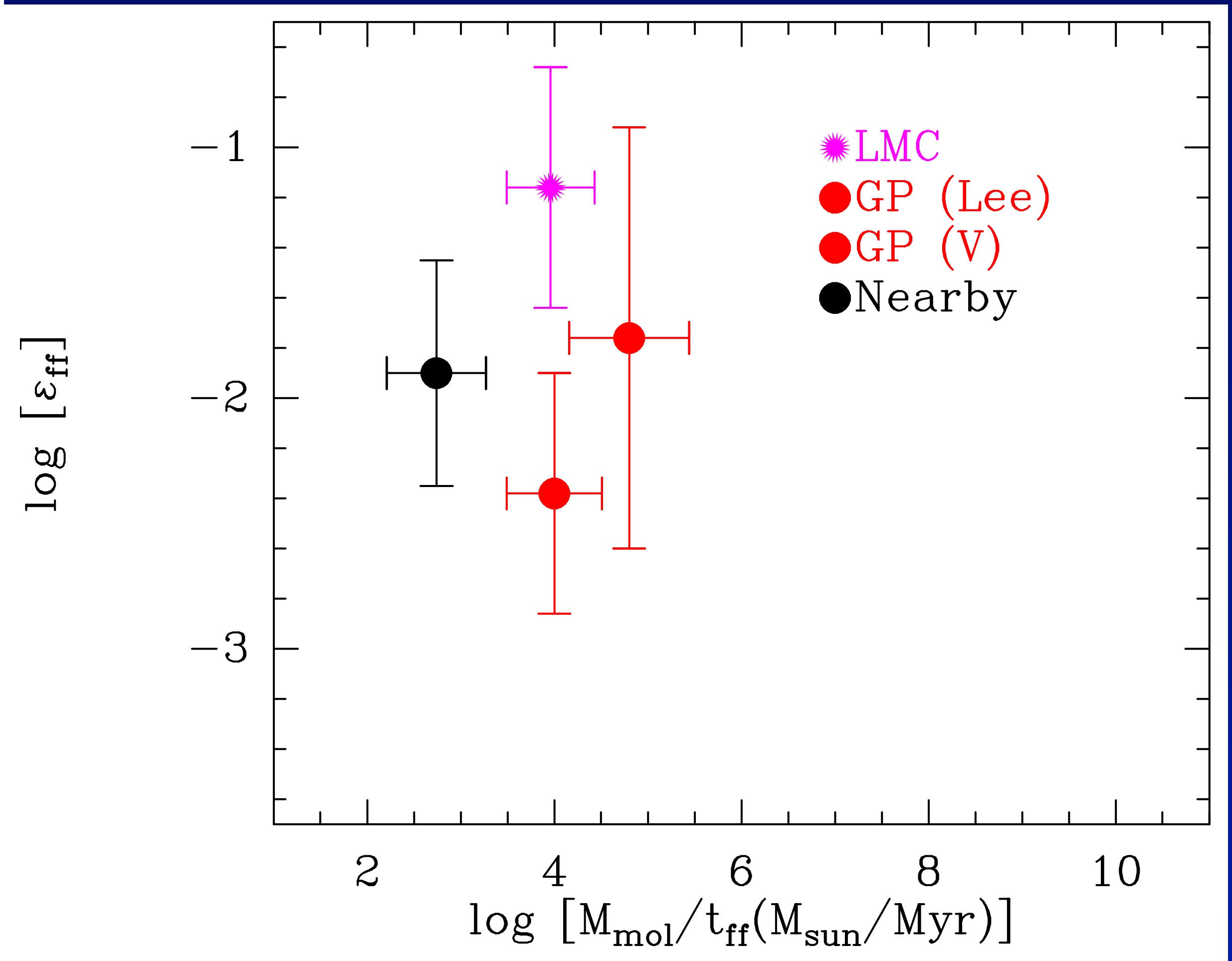
Star Formation Efficiency



Efficiency per molecular gas varies by a lot.

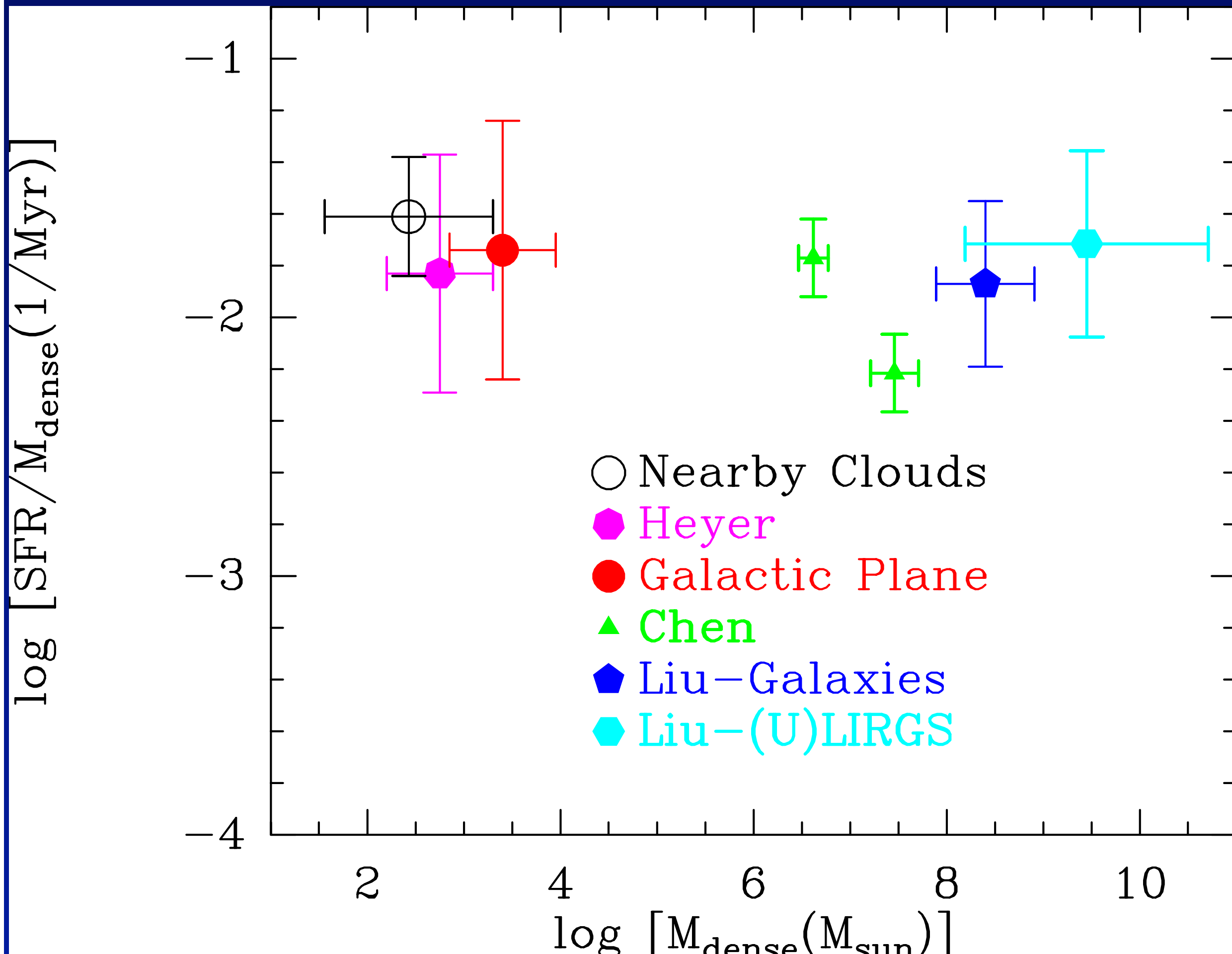
N. Vutisalchavakul et al.

M/t_{ff}



$\langle Log[\varepsilon_{ff}] \rangle = -1.80 +/- 0.50$

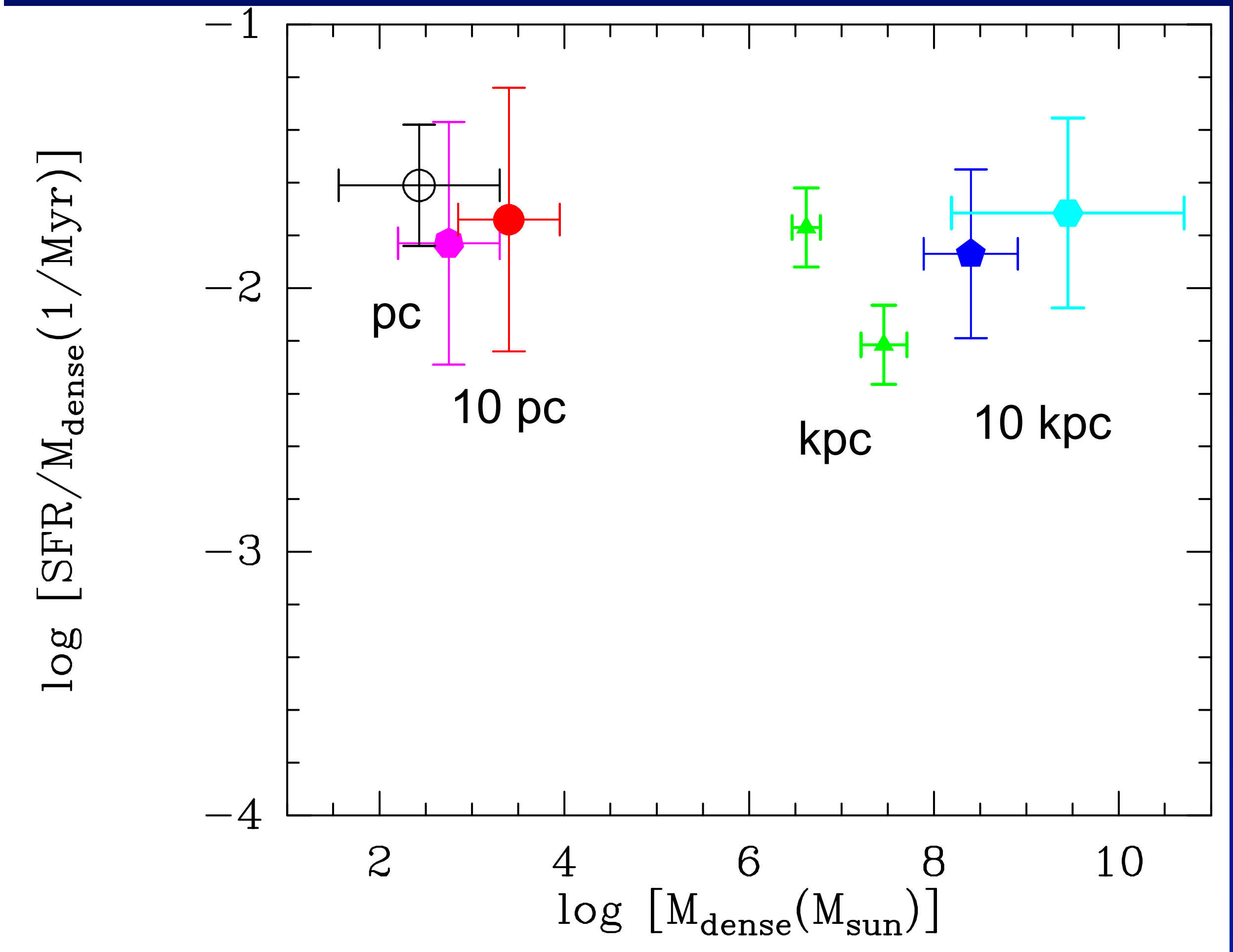
SFE for Dense Gas



Note: plotted on the same scale.
Scatter is much less.

N. Vutisalchavakul et al.

SFE for Dense Gas



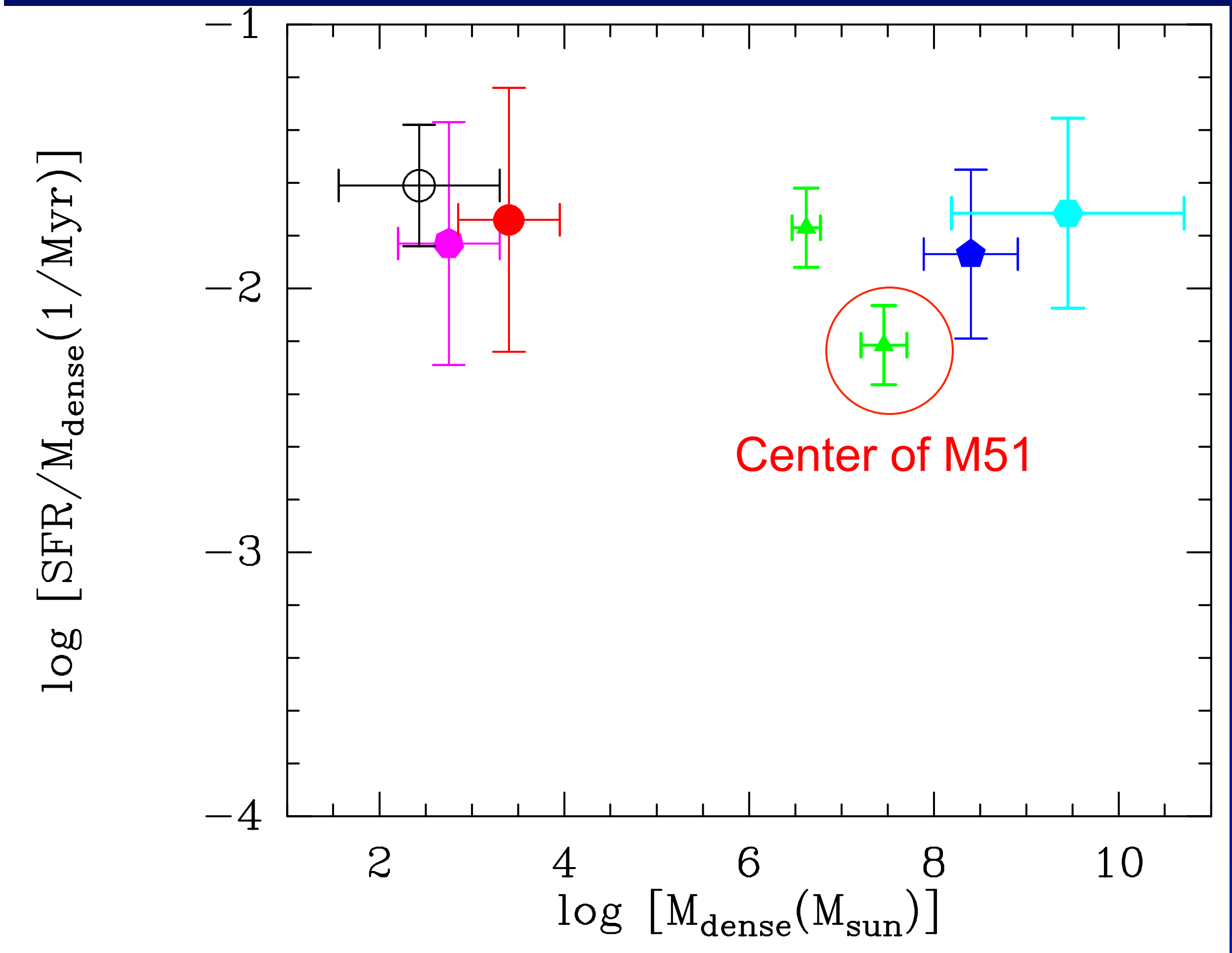
SFE for dense gas is remarkably constant from scales of pc to 10 kpc.

N. Vutisalchavakul et al.

What is the Best Predictor?

- Grand average of log(SFE)
  - For M_{cloud}, std dev = 0.42
    - 0.59 if use (U)LIRG α(CO)
  - Total range, factor of 40
  - For M_{dense}, std dev = 0.19
  - Total range, factor of 4
  - Including center of M51

SFE for Dense Gas



Similar effect seen in central molecular zone of MW. Kruijssen et al. (2014) suggest that threshold density there is $>10^7$ cm^{-3}, rather than about 10^4 cm^{-3}, as in other regions.

N. Vutisalchavakul et al.

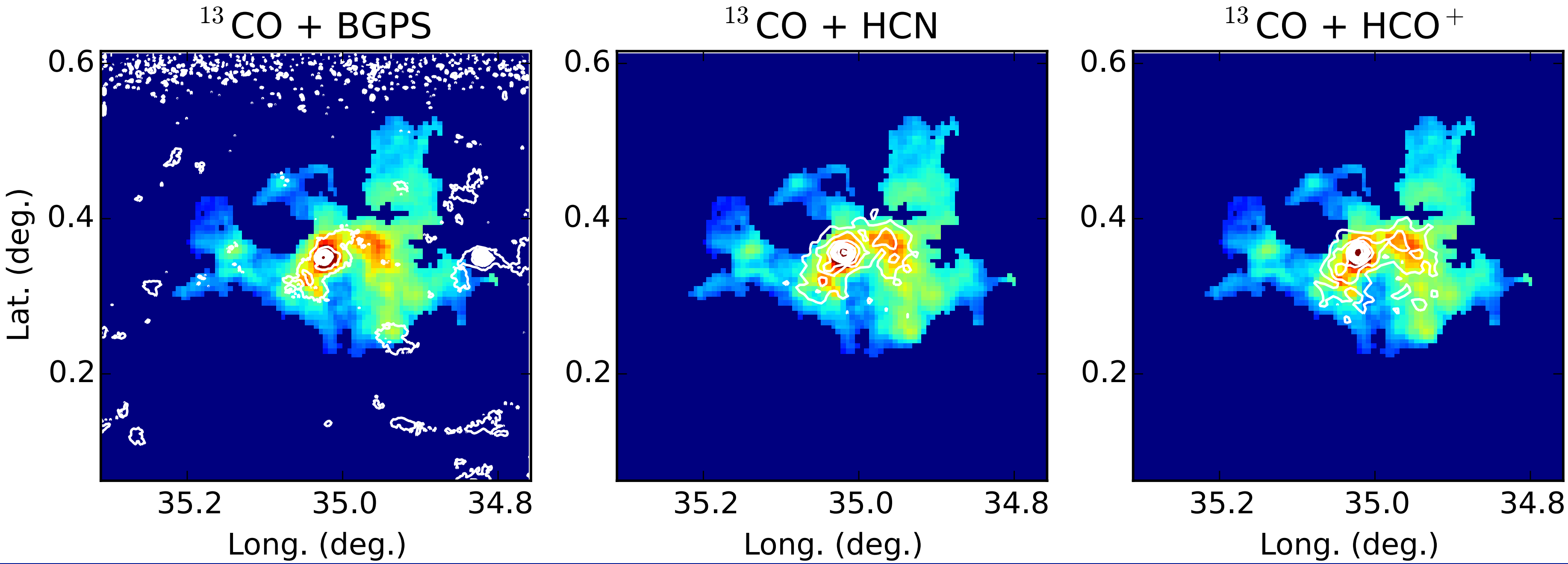
What do we mean by "dense"?

- A_V > 8 mag (nearby clouds)
- Clumps defined by mm/smm continuum emission (Galactic Plane)
- Regions emitting HCN J = 1-0 line (exgal)
- Need cross-calibration!
- Look for second parameters

HCN as a Probe

- M_{dense} = (20+/–5) L(HCN 1-0) Wu+ 2010
- M_{dense} = 10 L(HCN 1-0) Liu+ 2015
- Pety et al. (2016) map of Orion B
  - 38% of HCN 1-0 from $A_V < 6$ mag.
  - Conversion to mass depends on G_0
- Higher J transitions will work better
- Ongoing studies at TRAO

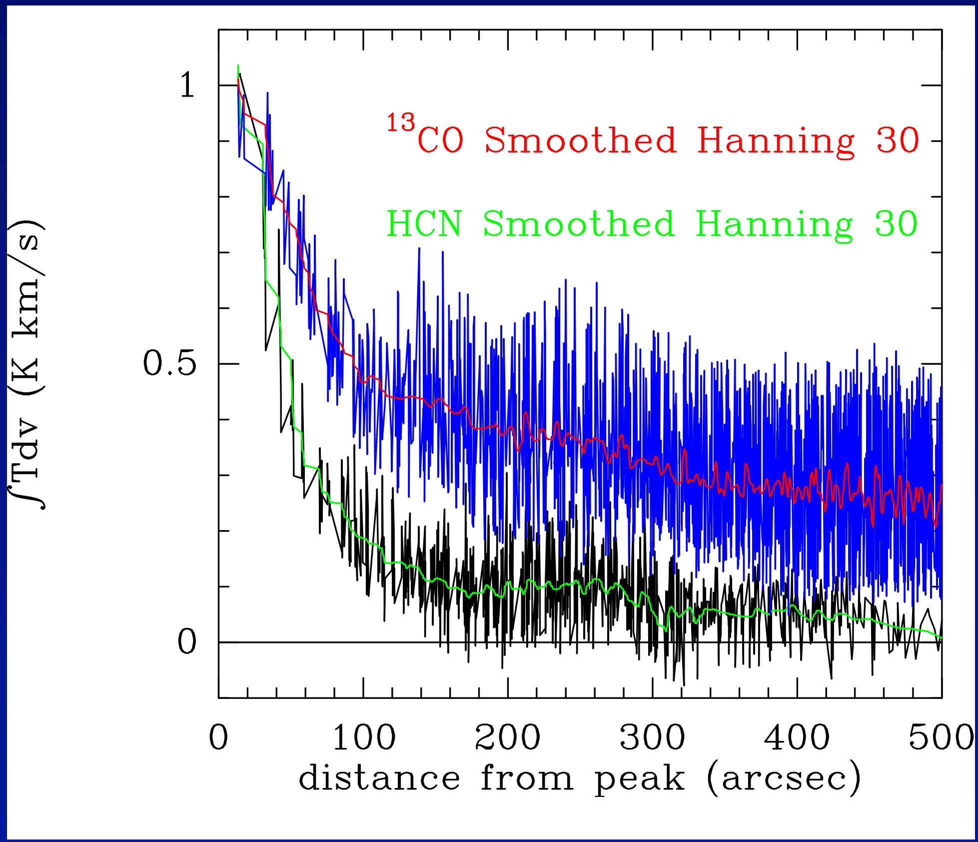
HCN vs 1.3 mm Continuum



Preliminary result: HCN, HCO^{+} agree with dust continuum, but are somewhat more extended. Significant line luminosity from less dense regions.

Significant Emission from Outer Parts of Cloud

Normalized to peak



Recall point by Jens on Tuesday; much of L(HCN) arises from lower density part of cloud. But still biased toward dense.

Summary So Far

- Among empirical relations, SFR-M_{dense} works best
- Centers of galaxies, other special regions need more parameters
- Probably gas has to be still denser in regions of high turbulence
- Need to calibrate tracers of dense gas

Common Features, Common Myths

- Common feature is star formation in dense gas
- Now let’s examine some common myths
- Recall the basic problem of star formation

The Basic Problem of Star Formation

- It is slower and less efficient than expected
- For Milky Way, $M_{mol} = 1 \times 10^9 M_{sun}$
- Typical $t_{ff} = 3 \times 10^6$ yr
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- 100 times higher than average over last Gyr
  - Zuckerman & Palmer 1974, ARAA, 12, 279
- Roughly applies to other galaxies, Universe as a whole

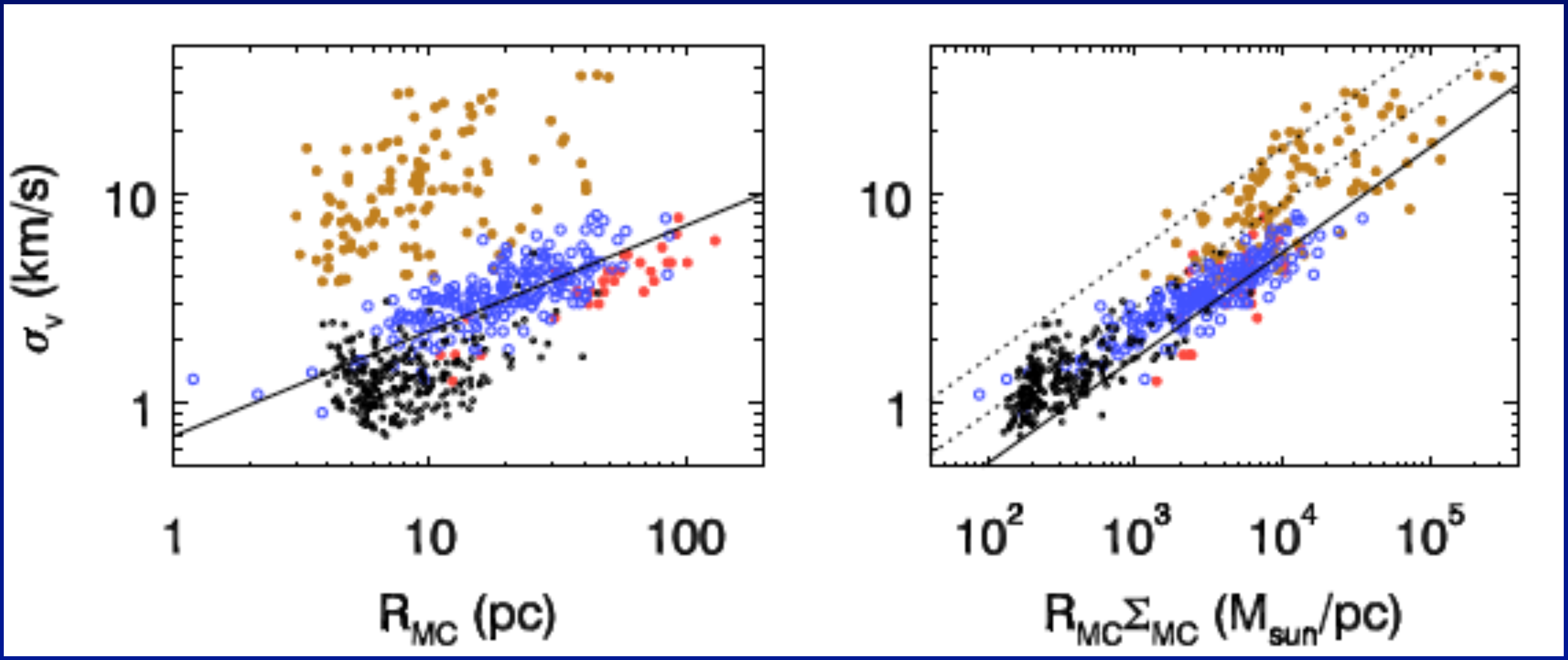
Reconsidering Some Myths

- Two definitions of "Myth":
  - an unfounded or false notion
  - a popular belief or tradition that has grown up around something
- By myth, I mean the second definition
  - Things we tend to believe because they are constantly repeated
  - May or may not be true
  - As scientists, we should re-examine them critically

Myth 1

- Molecular clouds are gravitationally bound
- What is the actual evidence?

Virial Ratio for Molecular Clouds



Dotted lines are α_v = 3 and 10, solid line α_v ~ 1

Heyer and Dame 2015 ARAA, 53, 583

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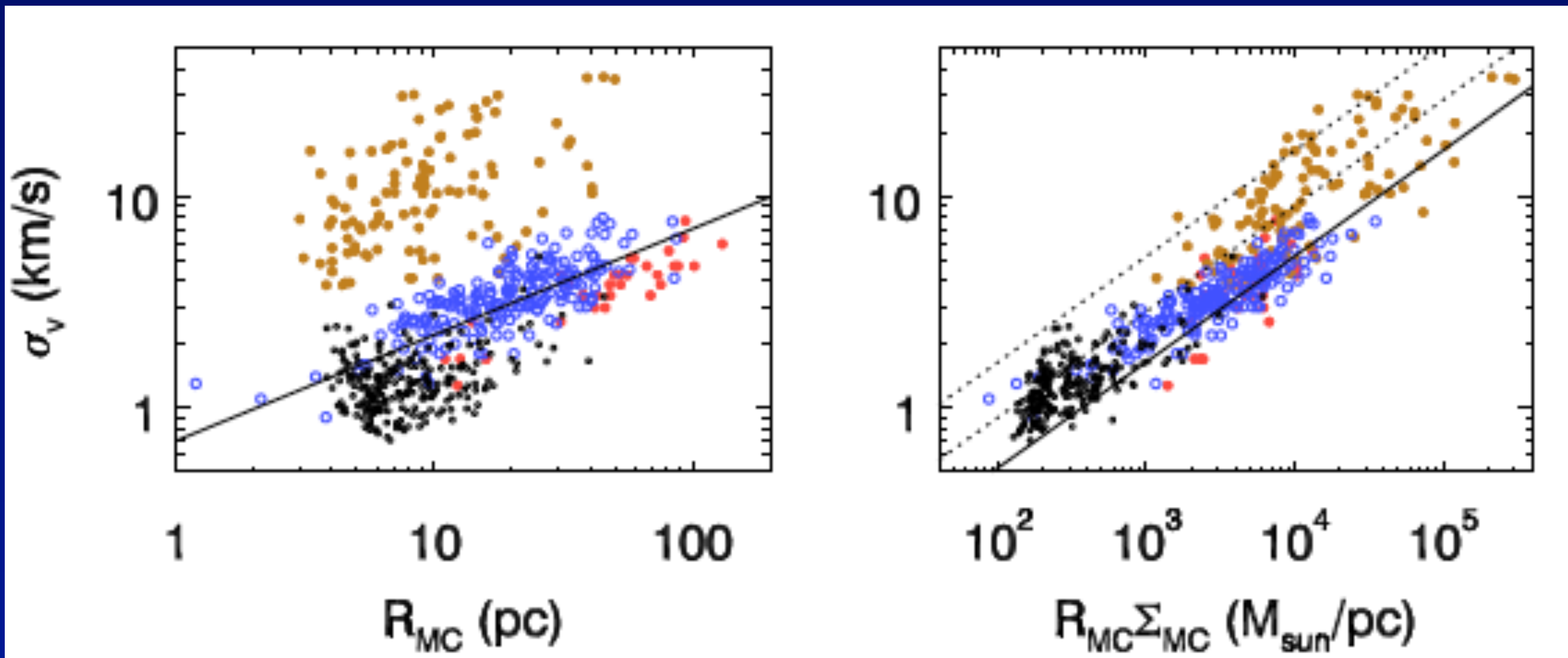
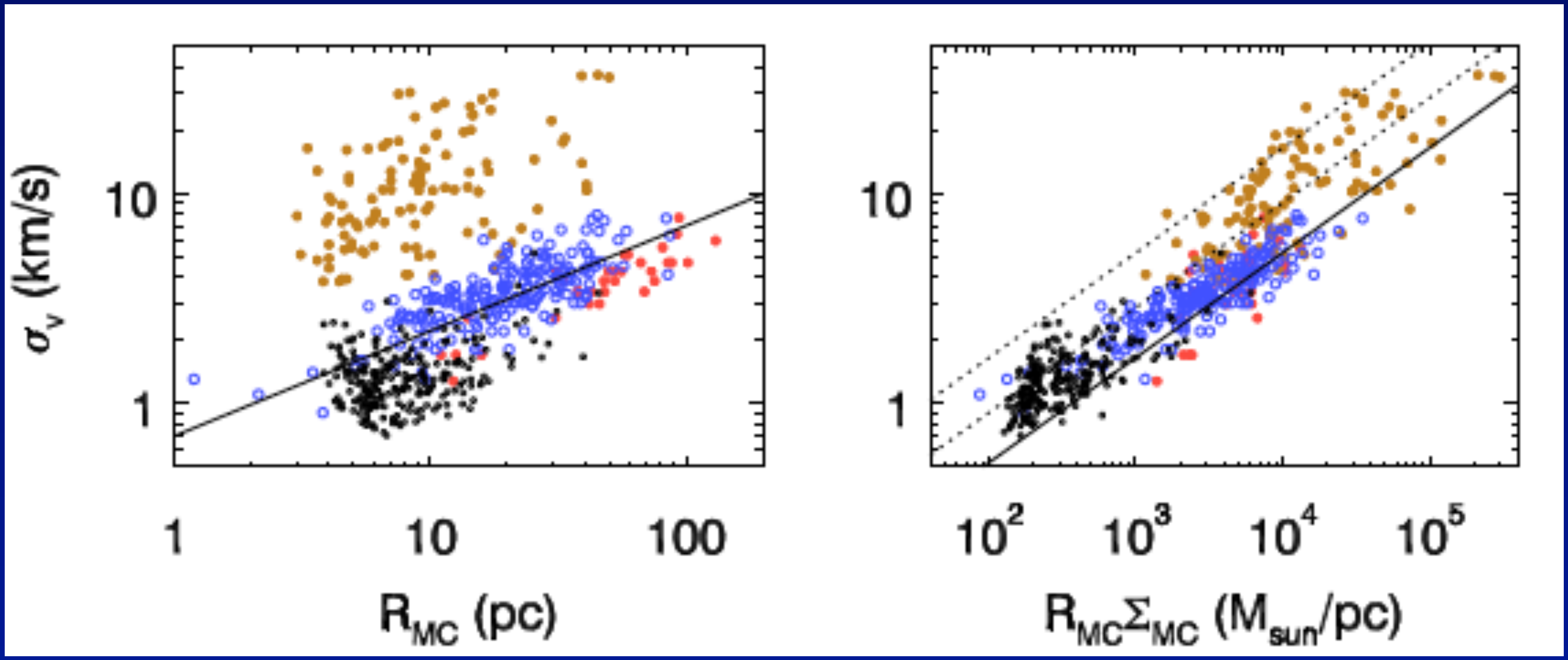
A True Statement



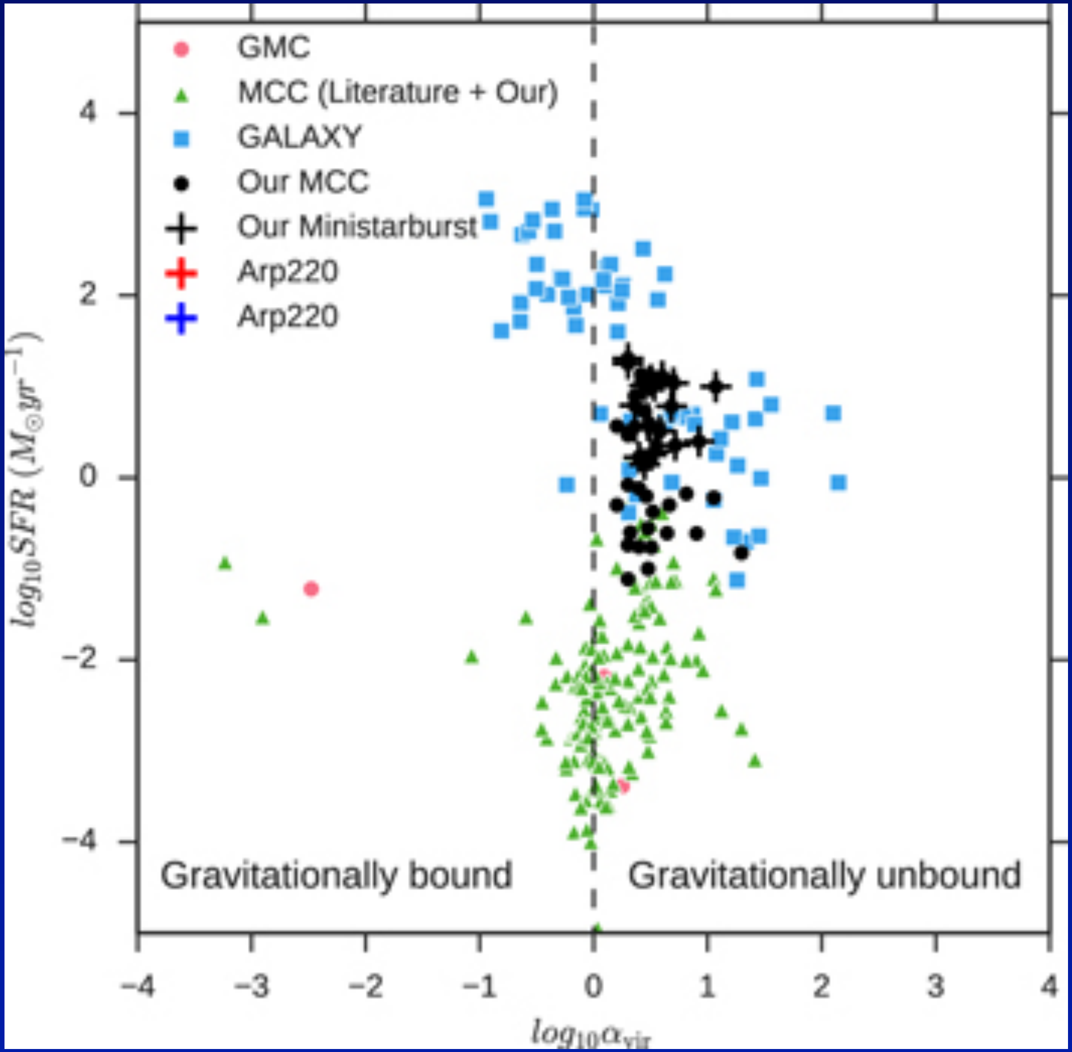
Heyer and Dame comment:
"Clouds within the Galactic disk have virial ratios between 1 and 3 that are consistent with being gravitationally bound, given the systematic errors of recovering cloud properties.".

An Equally (or more?) True Statement



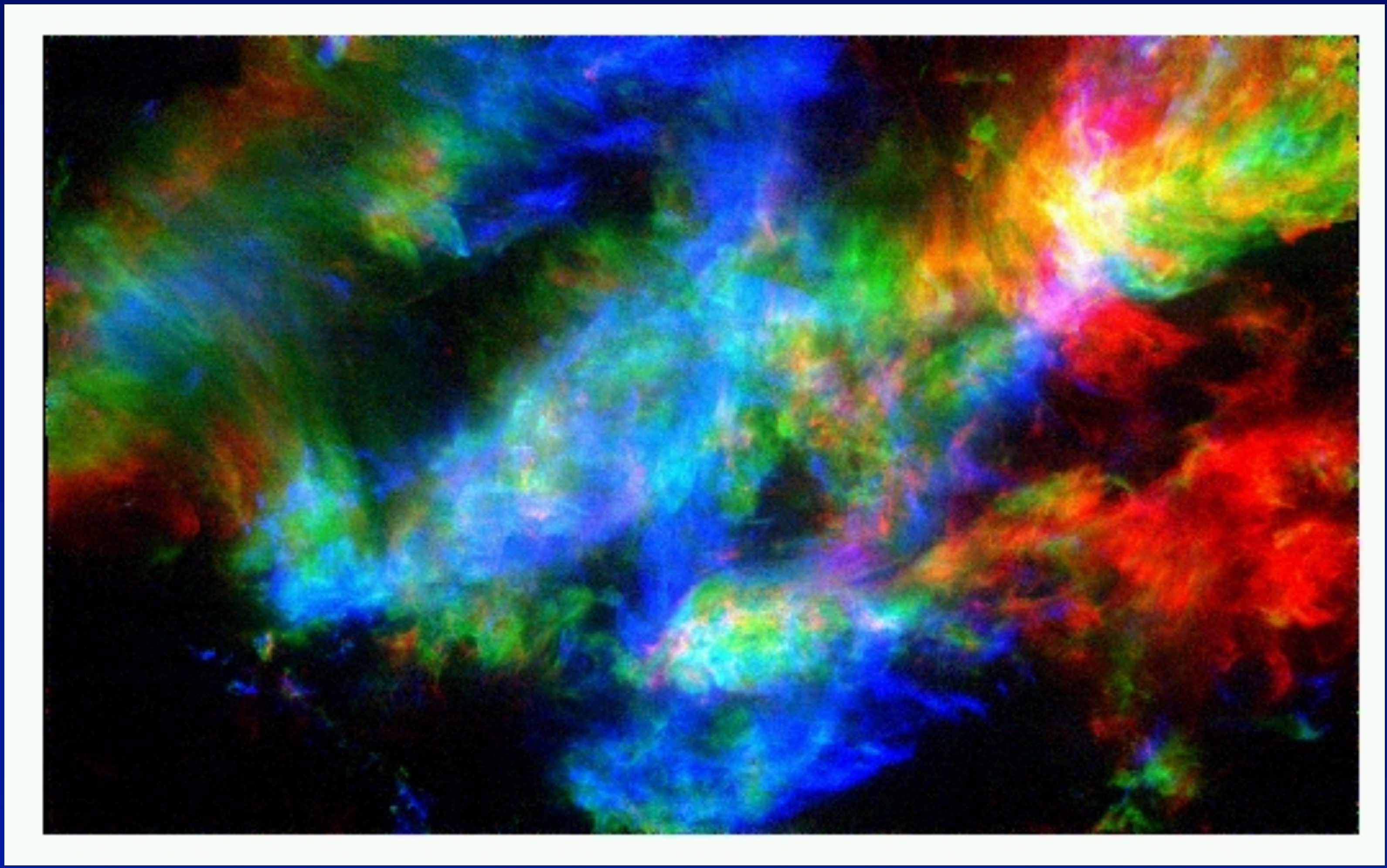
With my slight edit:
"Clouds within the Galactic disk have virial ratios between 1 and 3 that are consistent with NOT being gravitationally bound, given the systematic errors of recovering cloud properties.".

Or, from Talk by Quang



Almost all are nominally unbound. Many by large margins; note log scale.

Does this look bound?



The Taurus Cloud R. Snell: three colors for velocity components

More like which of these?

Cirrus
No precip.

Cumulonimbus
Precipitates

A Proposal

Molecular “clouds” are unbound structures.

Heresy!

Ralf to the Rescue

"Low SFE **requires** initially unbound clouds even with radiative feedback."
(emphasis added)

Myth 2

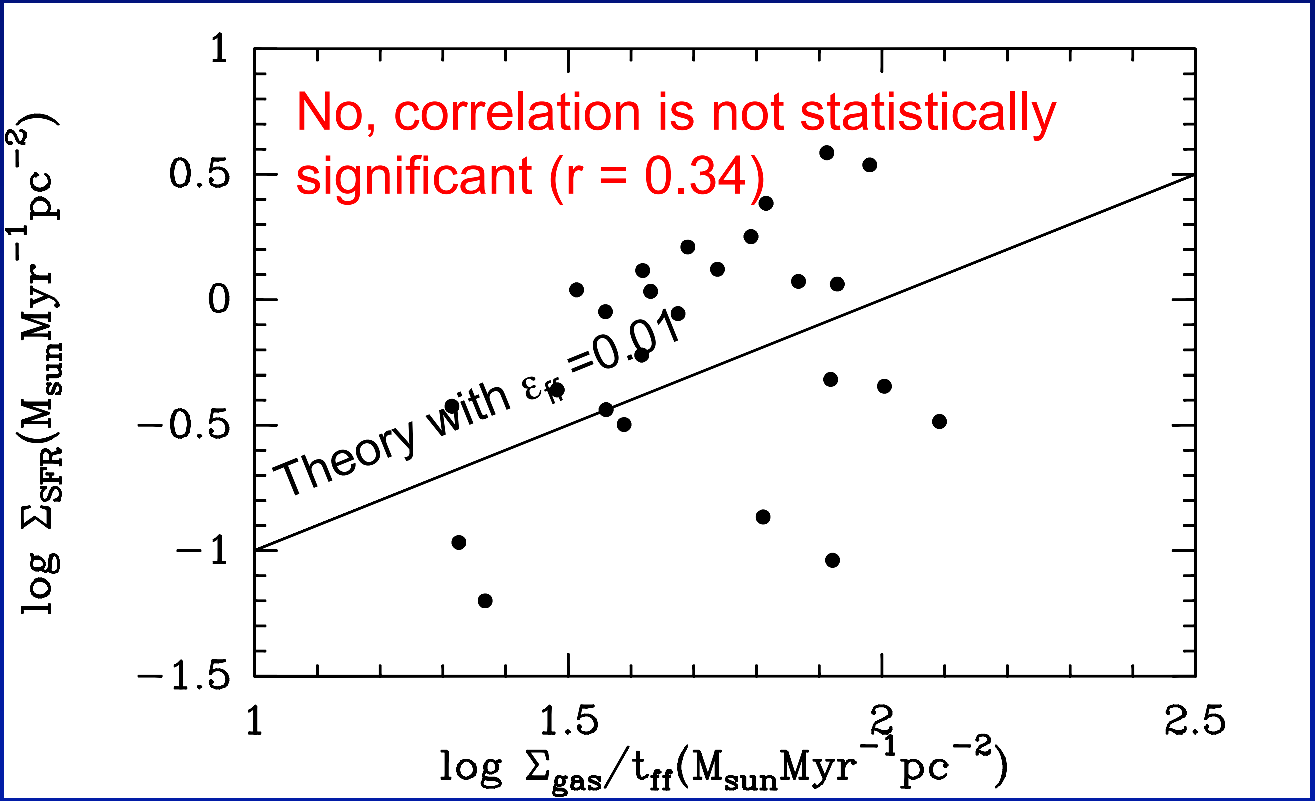
- The free-fall time is the characteristic timescale for molecular cloud evolution
  - If clouds are not bound, this is clearly not true
- What is the actual evidence?
  - If true, M_{cloud}/t_{ff} should predict SFR
  - Requires factor of 50-100 fudge factor (ε_{ff})
  - Does not decrease dispersion

Theorists LOVE t_{ff}

- For example, Krumholz, Dekel, McKee (2012)
- Many talks at this meeting
- Observers generally skeptical

Is t_{ff} Predictive at cloud level?

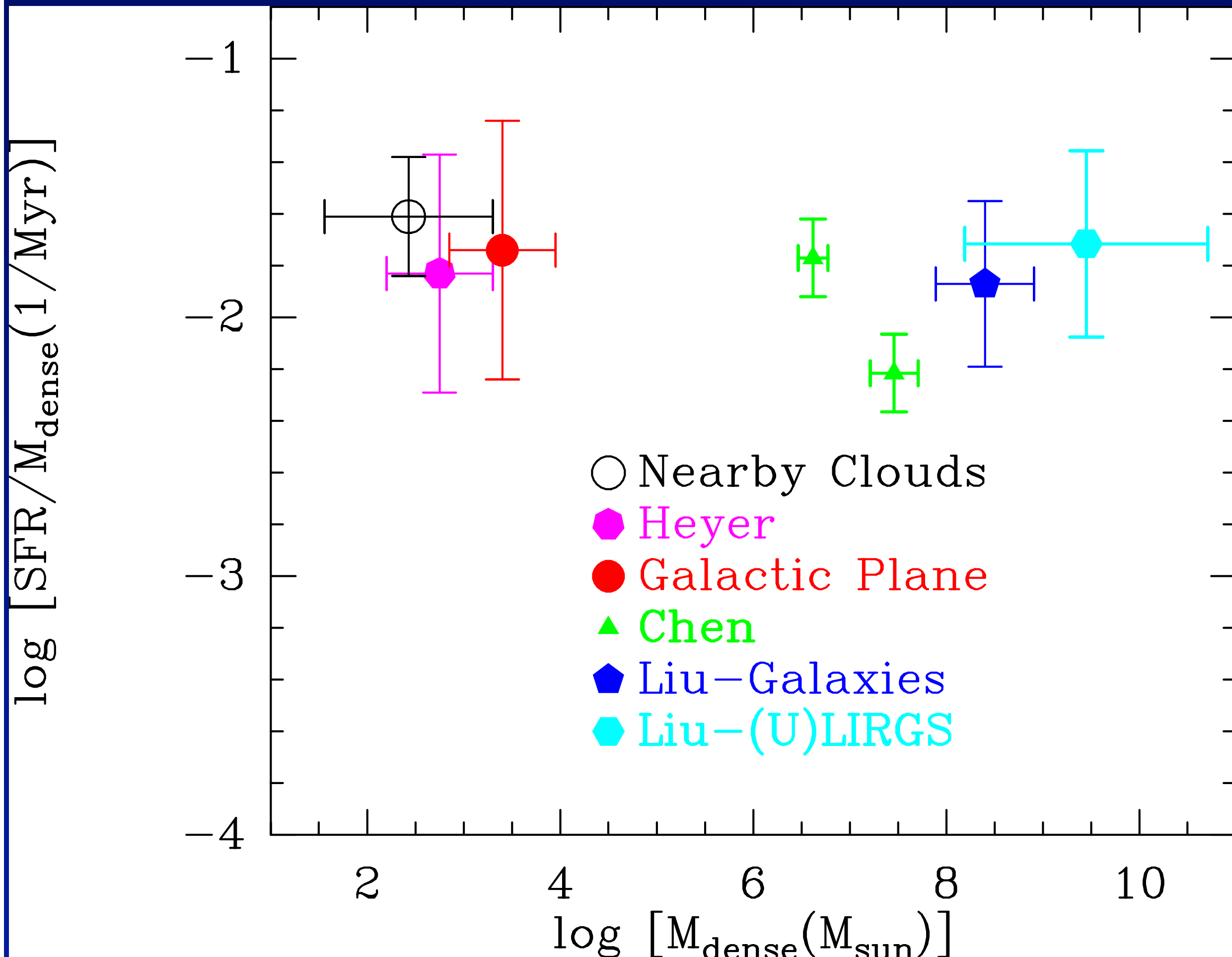
- **Does SFR of a cloud depend on free-fall time of the cloud (t_{ff} based on mean ρ)?**



Myth 3: Feedback Solves Everything!

- The current favorite of theorists
- No doubt it is important for starbursts, high mass star forming regions
- But invoking feedback by SNe, HII regions cannot explain low SFE in nearby clouds
- Why is the SFE (or the ε_{ff}) for dense gas about the same from nearby clouds to starburst galaxies?

Remember this one



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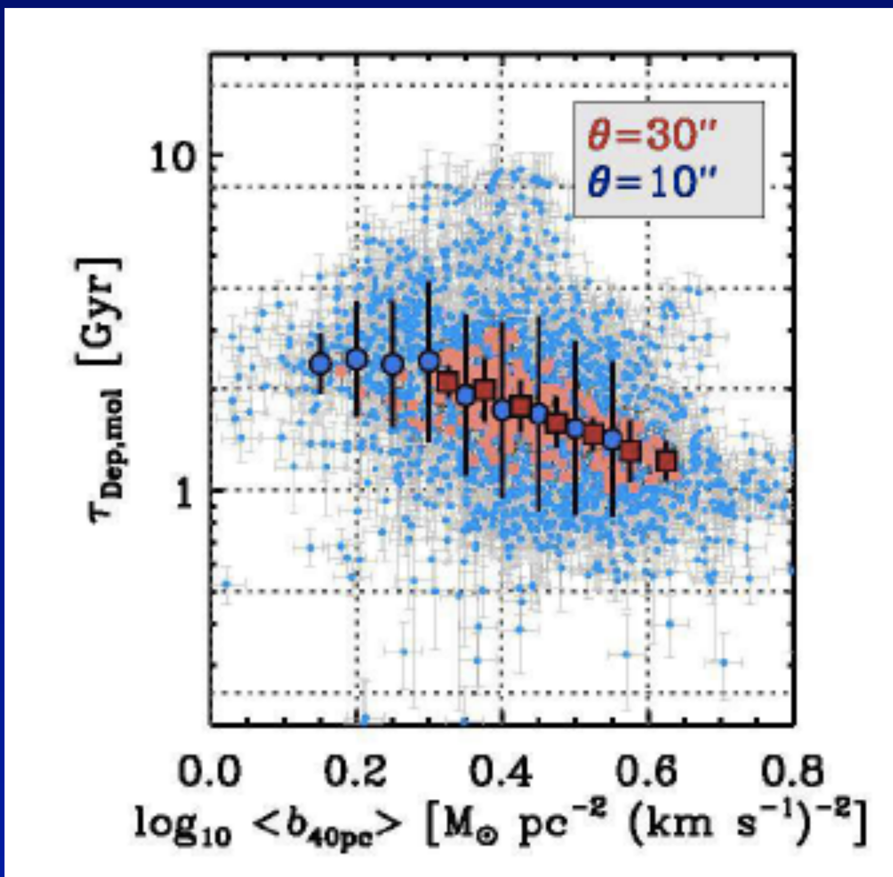
A Modest Suggestion

- Suppose molecular clouds are not bound
  - Just part of the mostly atomic flow that becomes molecular for a while
  - Collisions, turbulence causes a small fraction (few percent) to become bound dense clumps
  - The rest of the molecular gas rejoins the atomic flow
  - Galactic feedback keeps ISM stirred up, unbound
- The basic problem of slow star formation goes away
- Consistent with talks by Federrath, Padoan?

Best Correlation is with "boundedness"



Leroy et al. 2017

Analysis of M51

No good correlations with any model predictions.

Only good correlation was t_{dep} with "boundedness" = Σ_{gas}/σ_v^2

Upside down and backwards: SFE ~ $1/\alpha_v$

These are measured as 40 pc averages. None are remotely close to bound. Better to think of b ~ U_g/E_k << 1

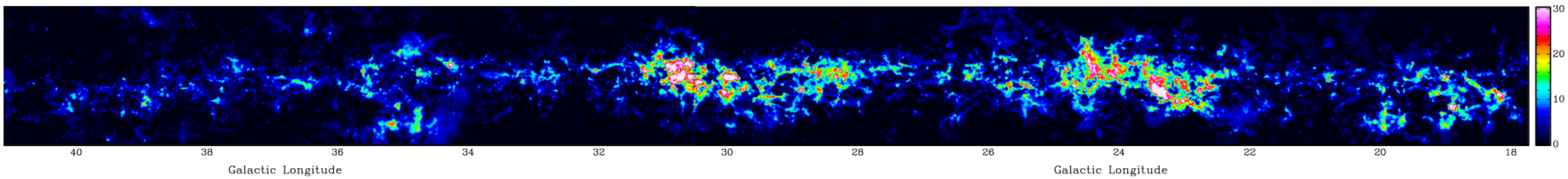
Summary

- Dense gas best predicts SFE
- We need to improve understanding of tracers
- The concept of “clouds” may be misleading
- Free-fall time is meaningless when nothing is falling

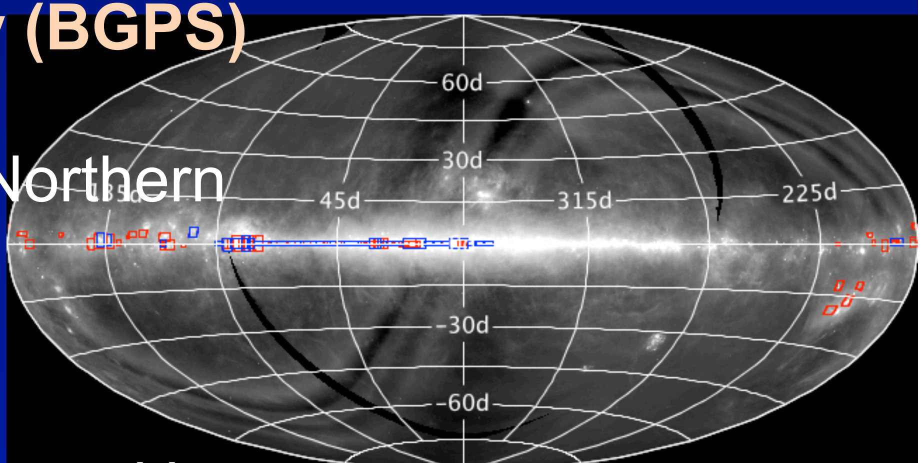
Back-up slides

Surveys of the Galactic Plane

- **Galactic Ring Survey** (Jackson et al. 2006) - 13CO1-0
A peak in molecular gas column density around 5kpc.
Observed the galactic plane at L = 18 – 55 degree.



Bolocam Galactic Plane Survey (BGPS)
(PI: John Bally)
1.1 mm continuum survey of the Northern Galactic Plane
-10.5 < l < 90.5
with follow up observations in
CS 5-4, HCO^+ 3-2, and N_2H^+ 3-2 transitions



Selection

- Need "high" SFR, velocity information
- Use radio recombination line (RRL) survey
  - Anderson et al. 2011, 2014
  - Several lines around n = 90 (H90α)
  - Essentially equivalent to Hα, but no extinction
  - Pick regions with RRL, radio continuum, covered by other surveys
  - This is a SFR-selected sample
- SFR from radio and mid-infrared agree

Associating Clouds and Clumps

- **With HII region position and velocity**
  - **Search ^{13}CO survey for matches**
  - **Require $|v_{CO} - v_{RRL}| < 10$ km s^{-1}**
  - **Careful examination to avoid contamination**

Associating Clumps

- Use mm-wave dust continuum
  - Bolocam Galactic Plane Survey (BGPS)
  - Follow-up survey in dense gas tracers for v
- Associated with molecular cloud
  - In space and velocity
  - Add up if more than one to get M_{dense}

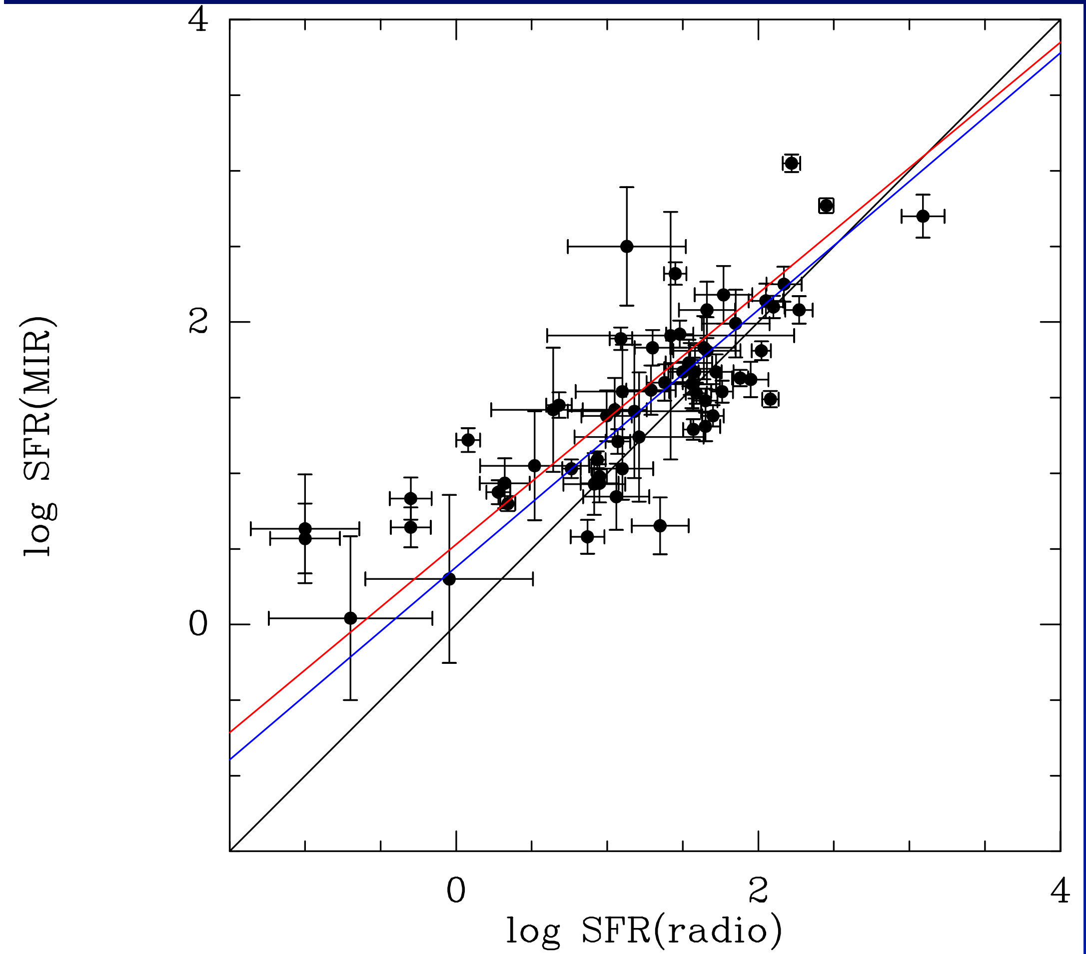
SFR(radio)

- NOT the exgal relation!
  - For other galaxies, radio beam dominated by extended synchrotron emission
  - SFR(radio) reflects past star formation (maybe 100 Myr averaging time)
- In MW, free-free dominates
  - SFR(radio) averages over about 3-10 Myr
  - Will underestimate SFR unless IMF well sampled up to O stars

SFR(MIR)

- Use exgal relation
- Known to fail below about 5 M_{sun} Myr^{-1}
- Limit sample to sources above that rate
- Leaves 51 regions

Do IR and Radio Agree?



Generally yes…
Black line is 1:1
Blue line is fit
Red line is fit from previous, smaller sample

Fitted slope is 0.85+/-0.02
Points higher at low SFR(radio)
MIR less sensitive to IMF
Use SFR(MIR) but only include if SFR>5 $M_{sun}yr^{-1}$

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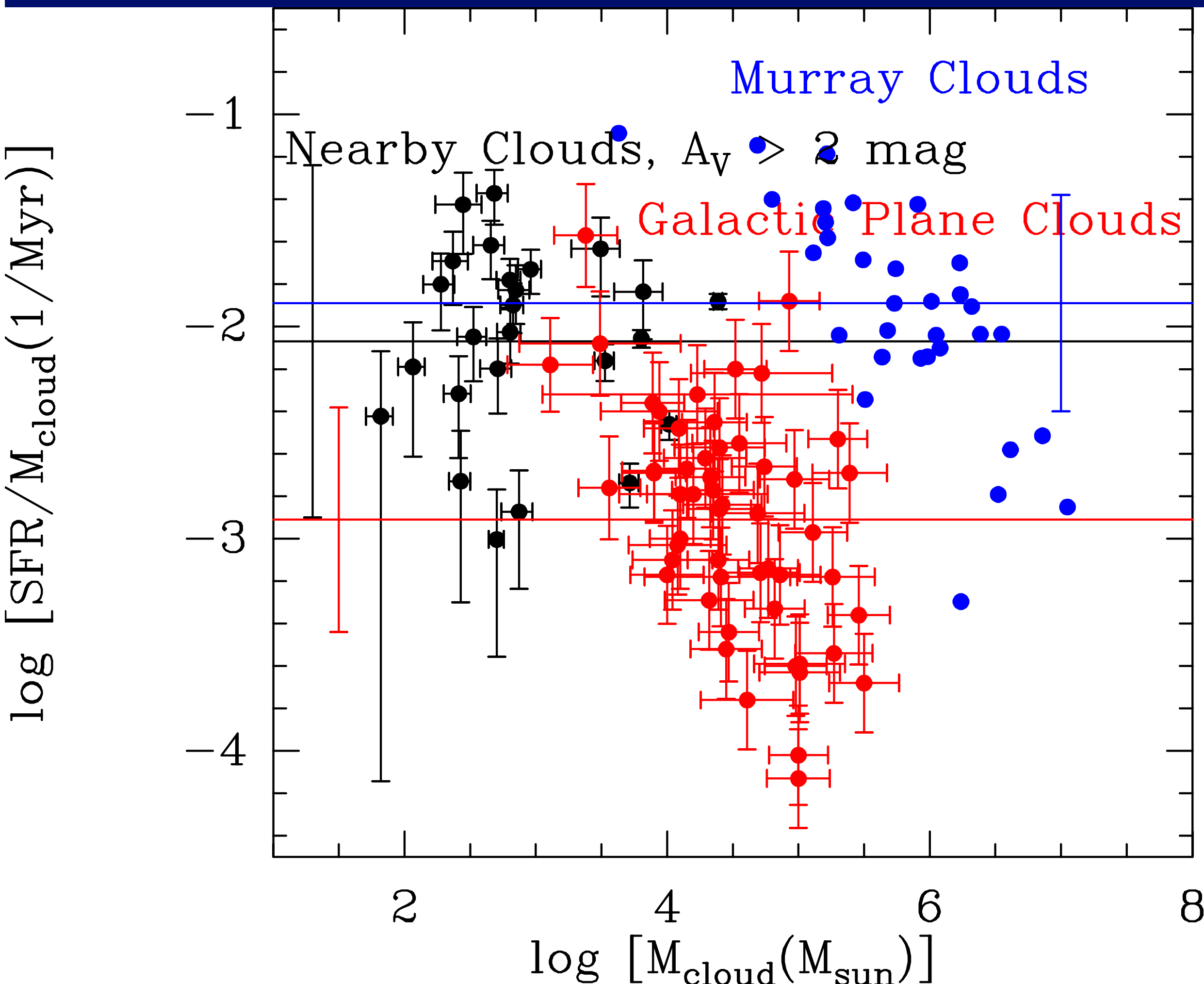
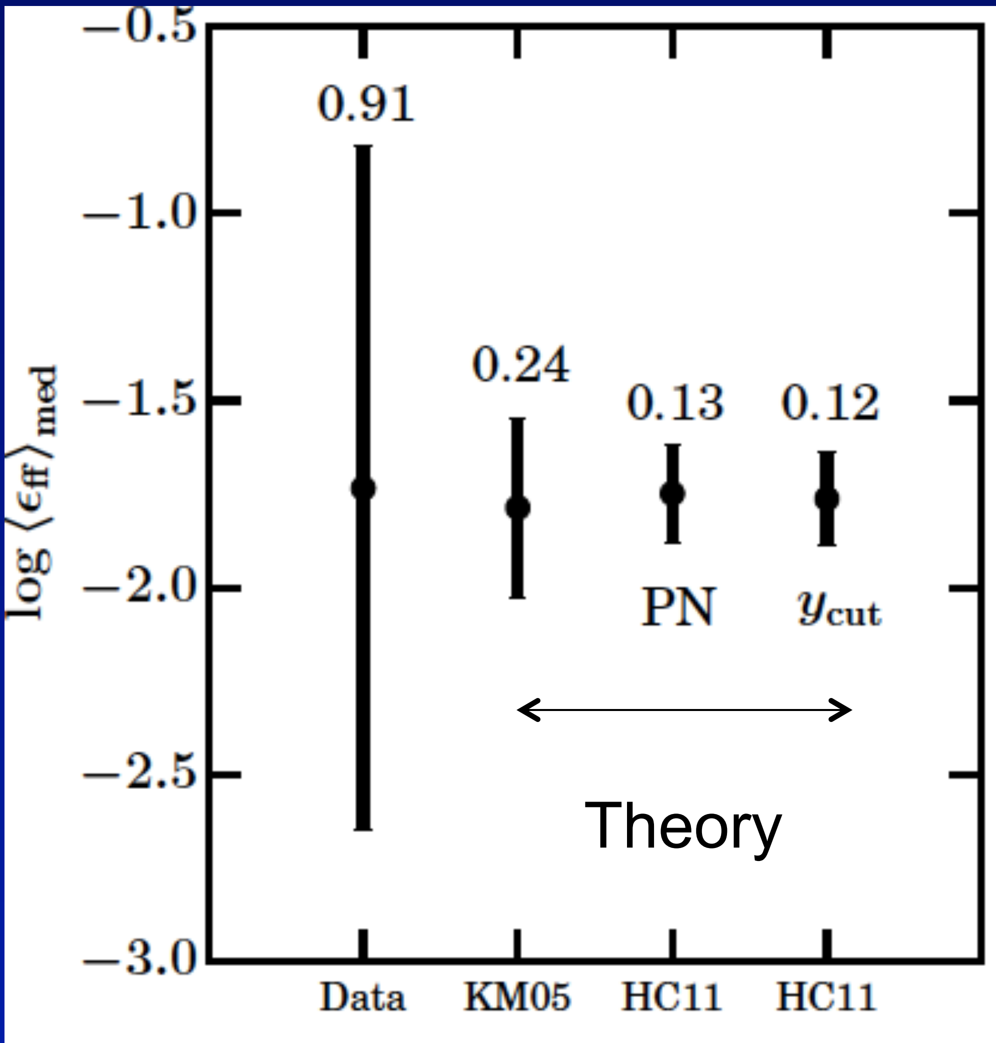
Adding Data from Murray



Murray (2011) selected most radio-luminous sources from WMAP; connection to cloud mass not so clear. Including them increases the SFE and the scatter (std dev. (Log SFE) = 0.72)

Dispersion in SFE >> Theory

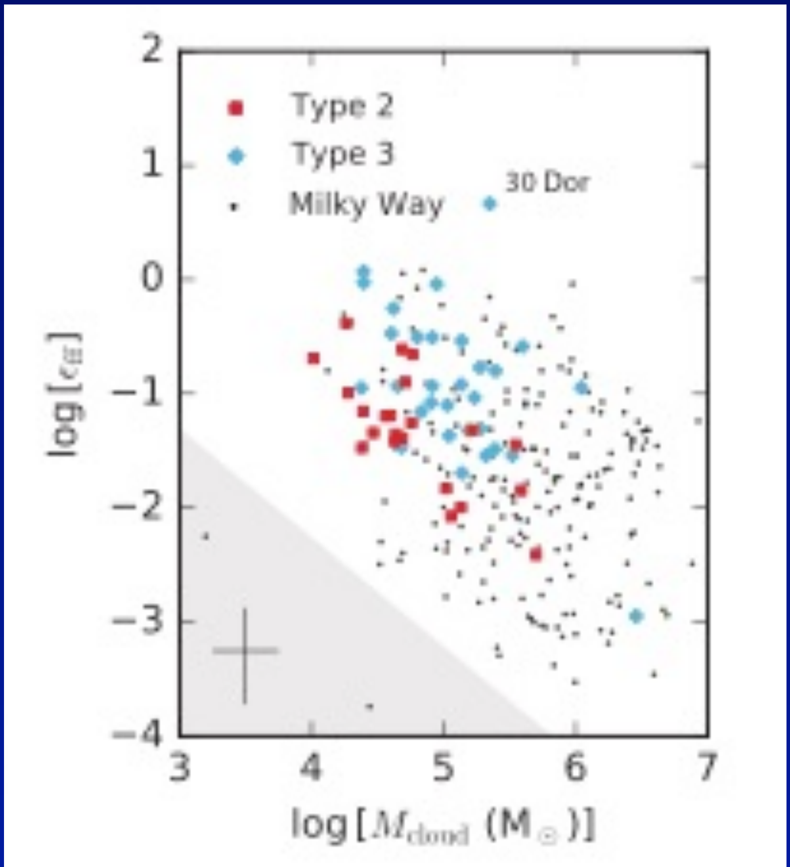


E. Lee et al. find similar result for inner Galaxy. Std dev. of Log(SFE) is ~ 1, or about factor of 10 in SFE.

No theories of steady state SFR predict this.

They argue that SFE is function of time.

Supported by Cloud Type



Log ε_{ff}

Log M_{mol} (M_{sun})

- **Red points: HII regions**
- **Blue points: HII regions and stellar clusters**
- **Blue more evolved**

Ochsendorf et al. 2017