Molecular SFR Indicators in GMCs and Galaxies

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Observations
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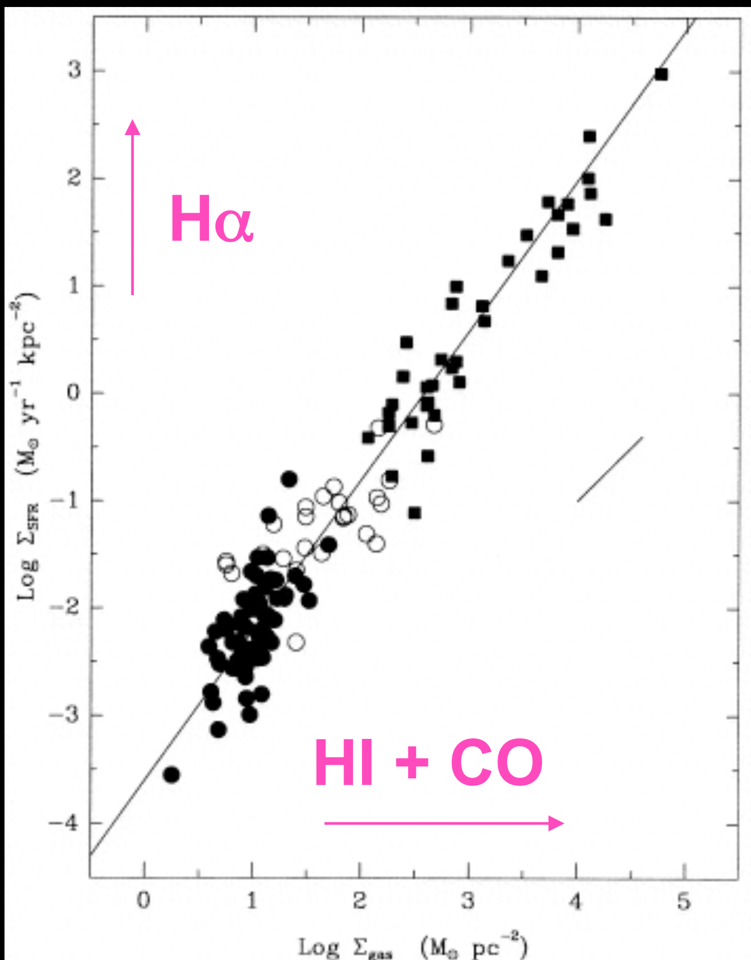
Kennicutt-Schmidt SFR Relations

$$SFR \sim \rho_{gas}^{1.5}$$

$$\Sigma_{SFR} \propto \Sigma_{gas}^{1.4}$$



Kennicutt, 1998

Theoretically

$$t_{SF} \sim \rho^{-1/2}$$

$$M_\odot \sim \rho$$

$$SFR = M_\odot / t \sim \rho^{3/2}$$

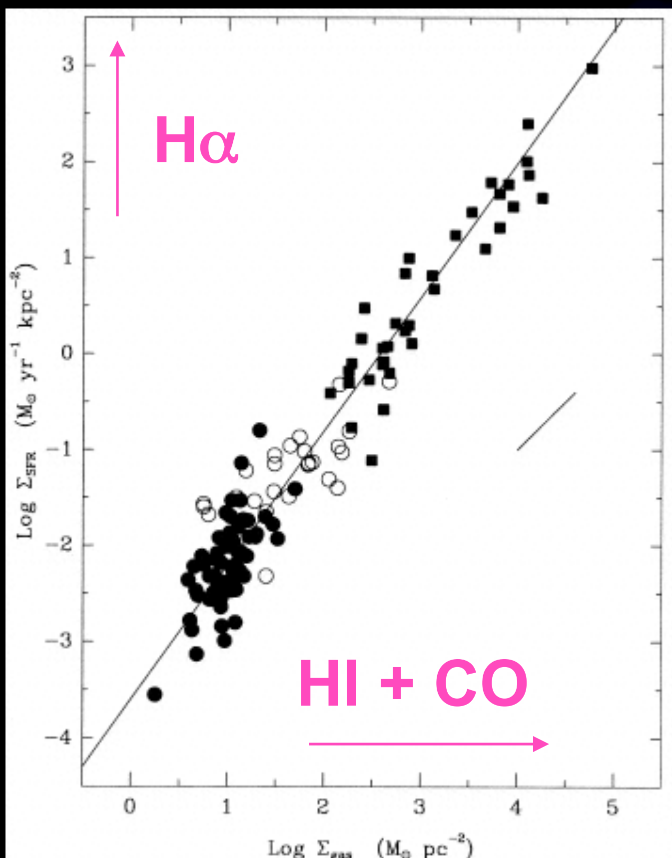
-orbital time scale of galactic disk
-cloud-cloud collision time
-turbulence crossing time
-gas accumulation time along magnetic field lines
-fractalized structure of clouds

Elmegreen (2002)
Kravtsov (2003)
Krumholz & McKee (2005)
Padoan (1995)
Silk (1997)
Shu (1987)
Tan (2000)
Tassis (2008)
Tassis & Mouschovias (2004)

Molecular Kennicutt-Schmidt SFR Laws

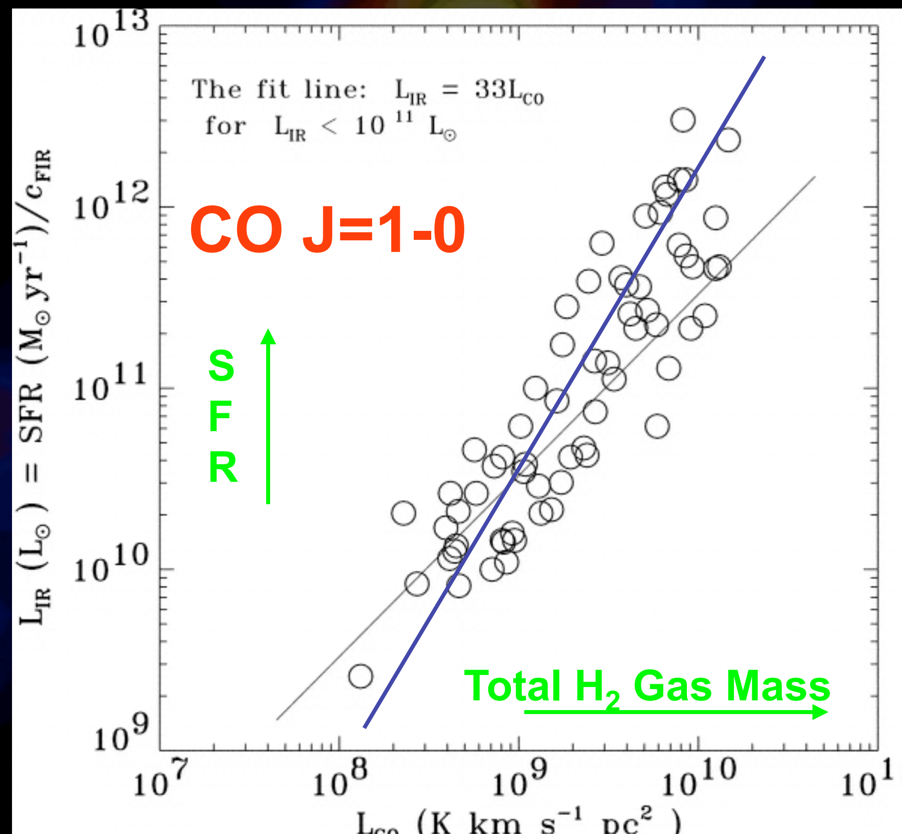
SFR ~ $\rho_{gas}^{1.5}$

$\Sigma_{SFR} \; \alpha \; \Sigma_{gas}^{1.4}$



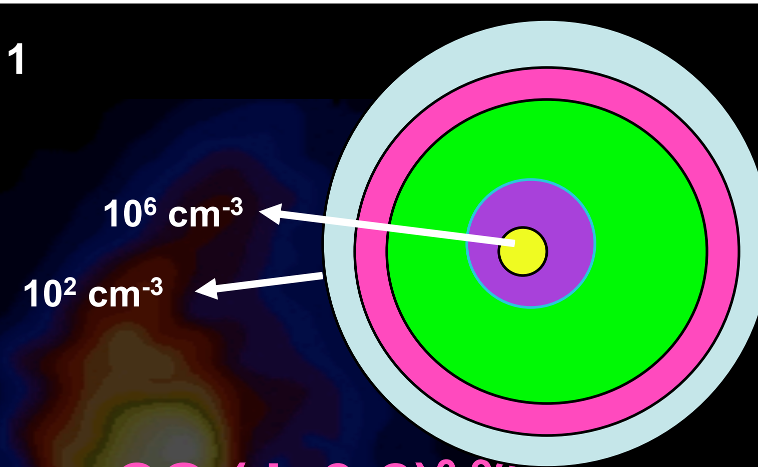
Kennicutt, 1998

SFR α $\rho_{(>100cm^{-3})\,gas}^{1.5}$

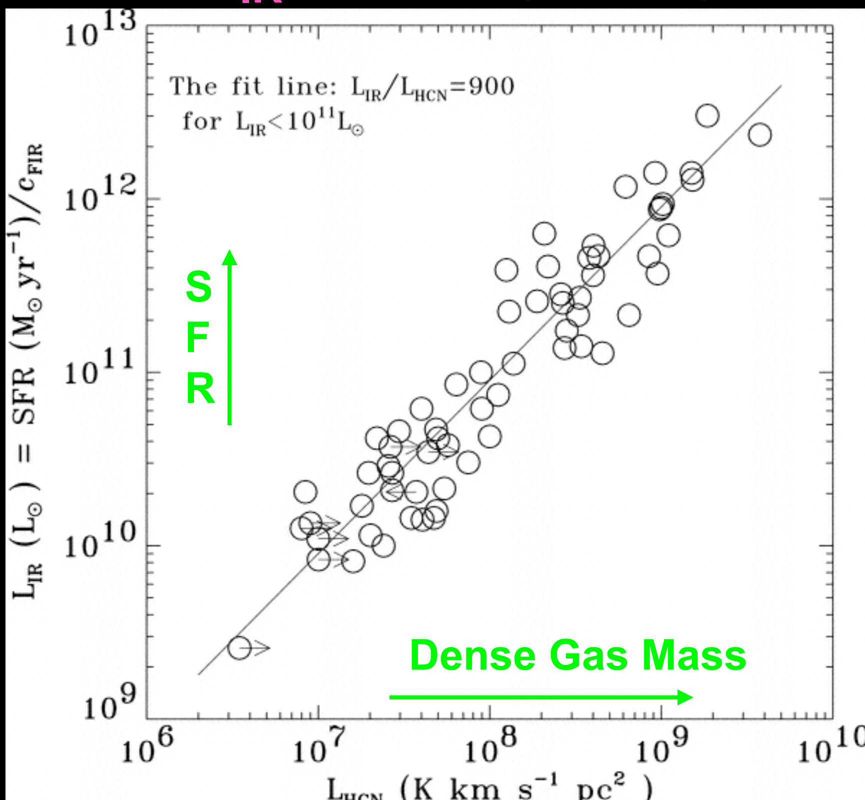


Gao & Solomon, 2004

SFR ~ $\rho_{(dense)}^{1}$



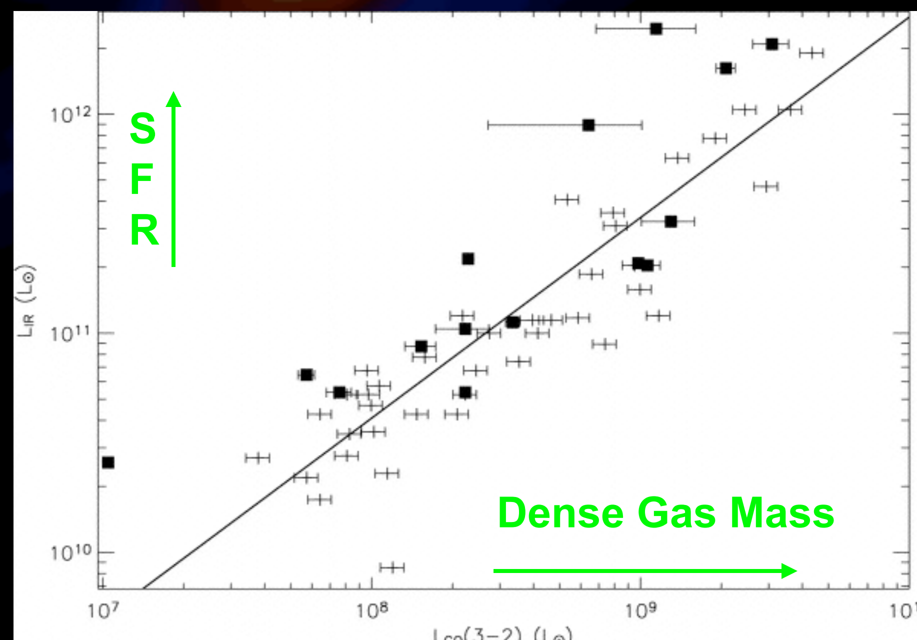
L_{IR} ~ HCN (J=1-0)^1



n_{crit} ~ 1x 10^5 cm^{-3}

Gao & Solomon, 2004

L_{IR} ~ CO (J=3-2)$^{0.92}$

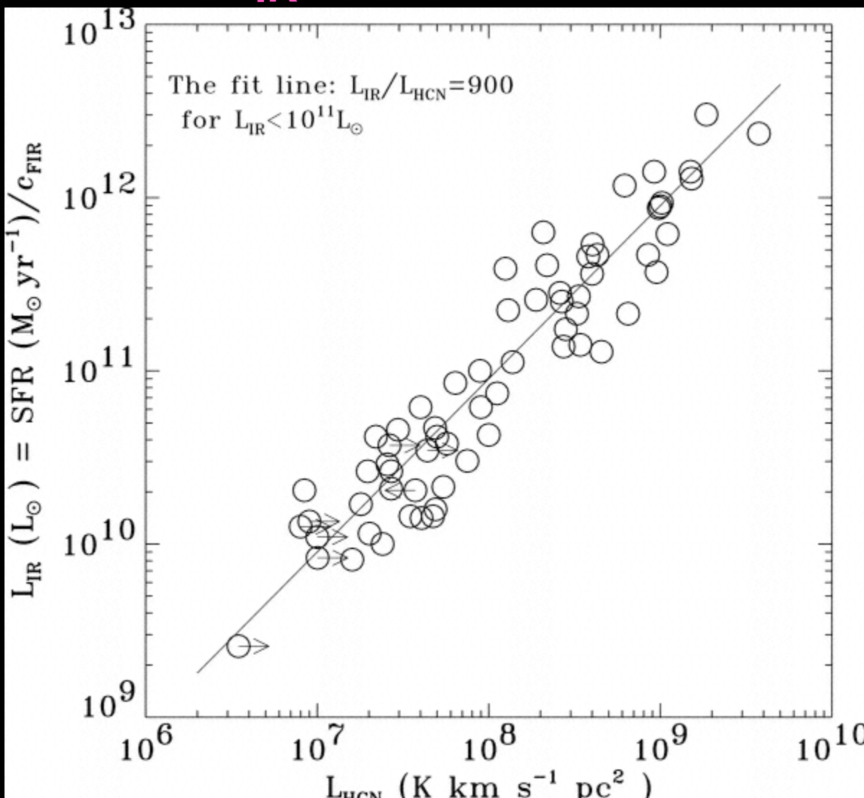


n_{crit} ~ 1x 10^4 cm^{-3}

Yao et al. (2004)
Narayanan et al. (2005)
Iono et al. (submitted)

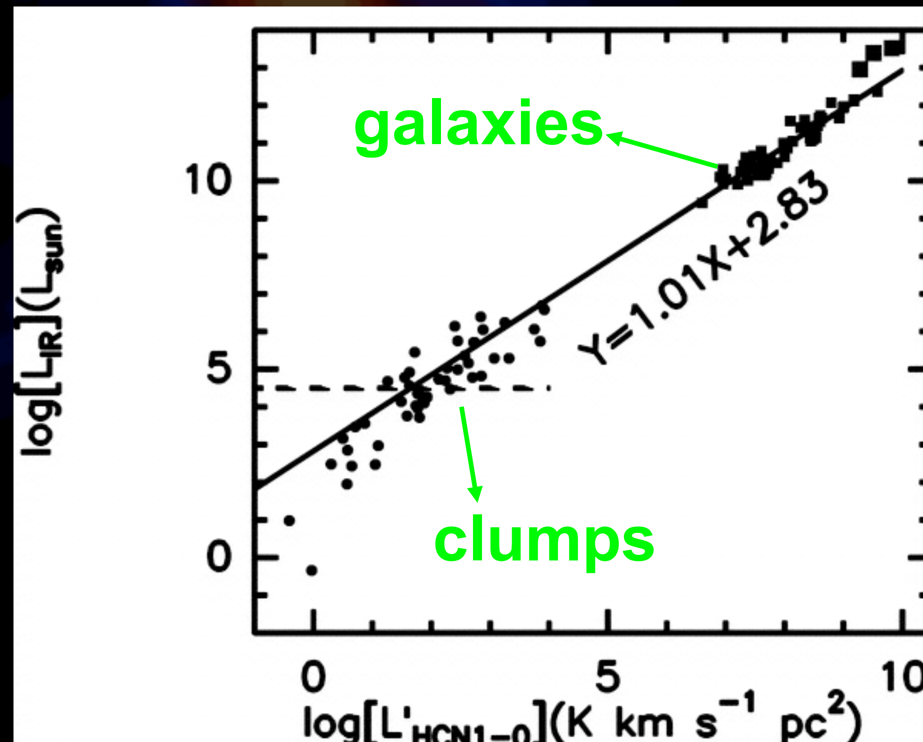
Interpretation: A more 'fundamental' SFR Relation?

L_{IR} ~ HCN (J=1-0)[1]



n_{crit} ~ 1x 10^5 cm^{-3}

Gao & Solomon 2004



LIR ~ HCN (J=1-0) Luminosity linearly even down to dense cloud core scale

Wu et al, 2005

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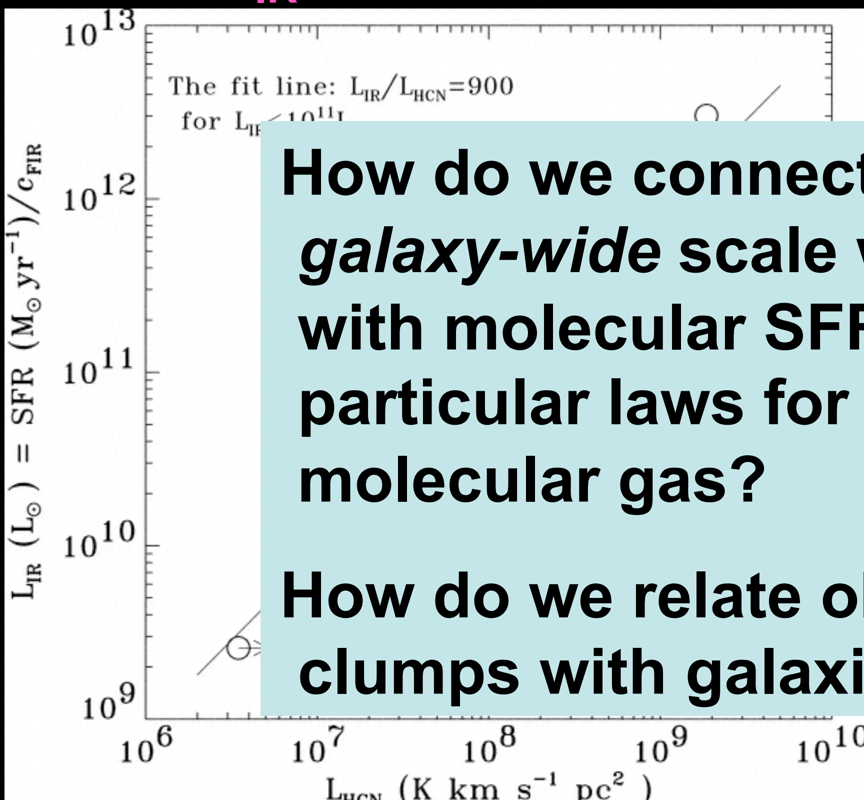
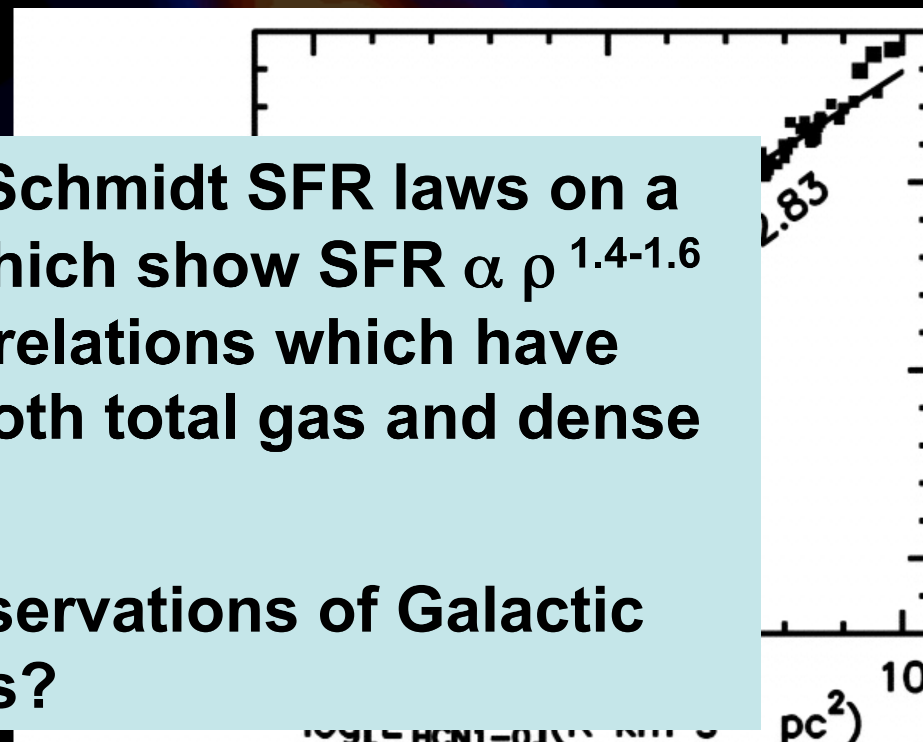


n_{crit} ~ 1x 10^5 cm^{-3}

Gao & Solomon 2004

How do we connect Schmidt SFR laws on a *galaxy-wide* scale which show SFR α $\rho^{1.4\text{-}1.6}$ with molecular SFR relations which have particular laws for both total gas and dense molecular gas?

How do we relate observations of Galactic clumps with galaxies?



LIR ~ HCN (J=1-0) Luminosity linearly even down to dense cloud core scale

Wu et al, 2005

Chicken or Egg?

- SFR is linearly dependent on dense gas (N=1); Kennicutt-Schmidt relations are consequent.
  - » SFR ~ ρ_{dense}

Gao & Solomon 2004; Wu et al. 2005; Narayanan et al. 2005; Tassis 2007

- KS index of N=1.5 is underlying; Observed SFR-dense gas relations are consequent
  - » SFR ~ $\rho^{1.5}$

Krumholz & Thompson 2007, Narayanan et al. 2008

GADGET SPH Simulations

Prescriptions for multi-phase ISM (McKee-Ostriker), SF, BH growth and associated Feedback (though BH winds turned off)

100 galaxies used:

20 disk Galaxies

80 merger snapshots

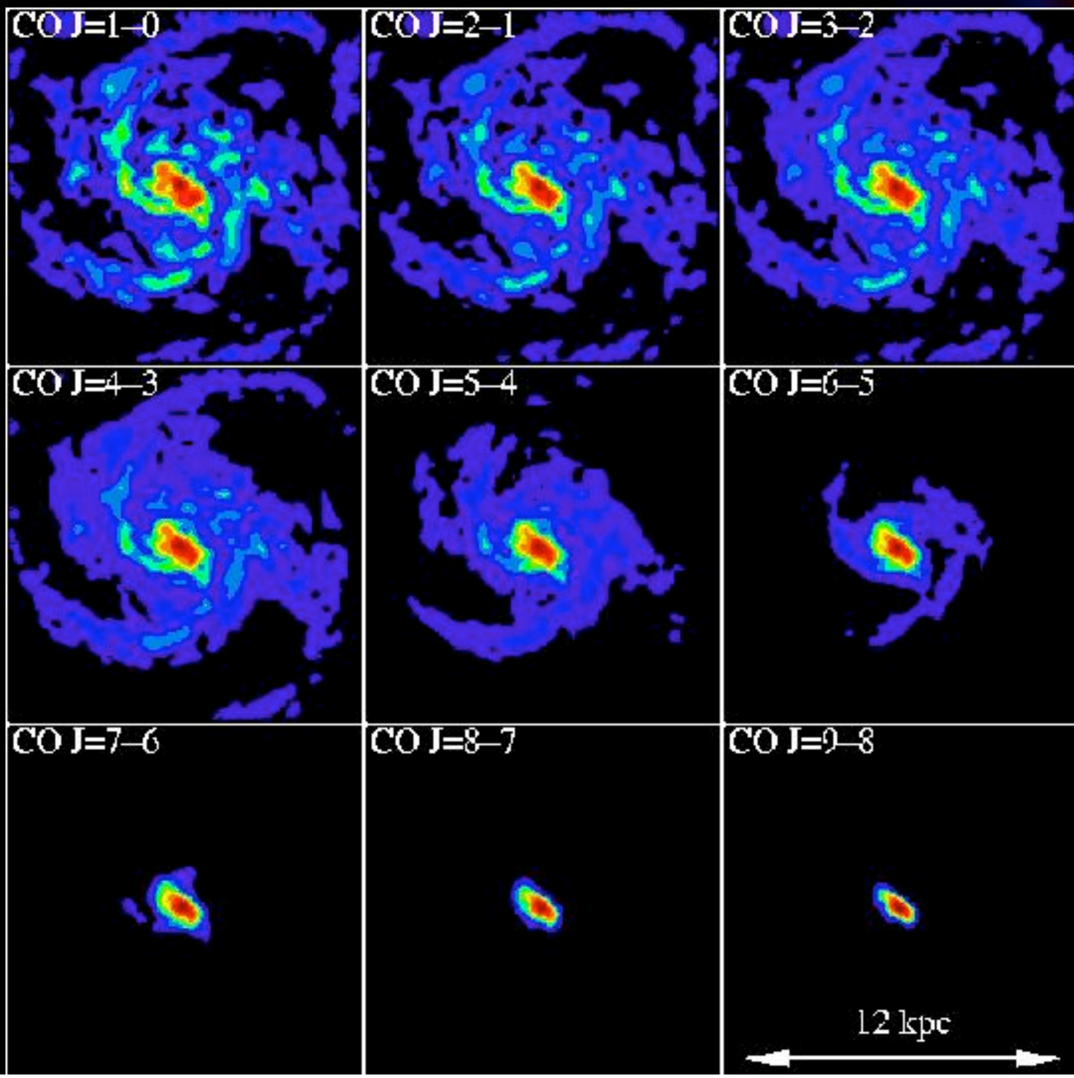
SF follows SFR α $\rho^{1.5}$

Assuming $t_{SFR} \sim \rho^{-1/2}$

Springel et al. (2003-2005)

Non-LTE Radiative Transfer

- 3D Monte Carlo code developed based on improved Bernes (1979) algorithm
- Considers full statistical equilibrium with collisional and radiative processes
- Sub-grid algorithm considering mass spectrum GMCs as SIS (Blitz et al. 2006, Rosolowsky 2007, Bolatto et al. 2008)
- $M_{cloud}=10^4$-10^6 $M_{\odot}$, Uniform Galactic CO Abundance, 10 CO transitions, 10 million rays per iteration

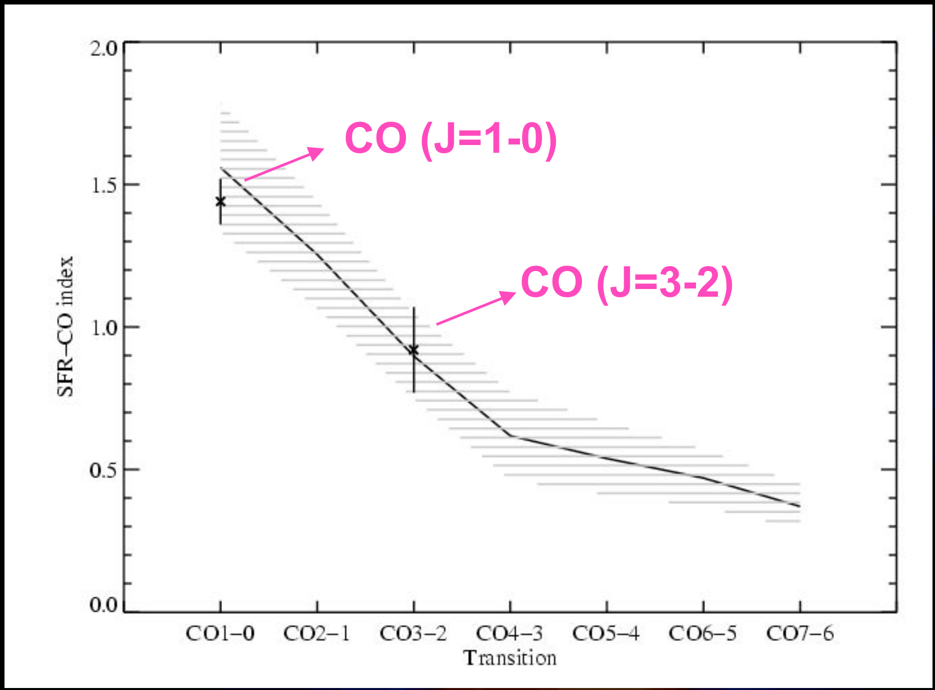


Included 100 galaxies:
20 isolated disks
80 mergers in various stages of evolution

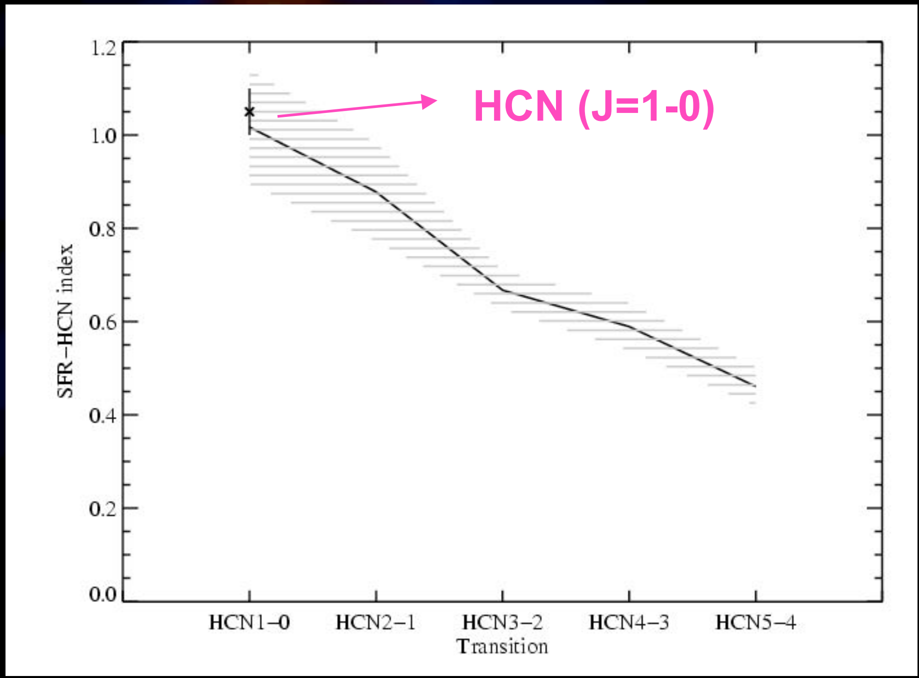
Narayanan+ 2006,2008

Can we Recover the Basic Relations?

SFR-CO index



SFR-HCN index



SF follows SFR α $\rho^{1.5}$

Narayanan et al. 2008

Can we Recover the Basic Relations?

SFR-CO index | **SFR-HCN index**

SFR ~ $\rho^{1.5}$ (assumed Schmidt Law)

SFR ~ L_{mol}^{α} (observed)

$L_{molecule}$ ~ ρ^{β}

Then $\alpha=1.5/\beta$

So we need to understand how line luminosity varies with gas density

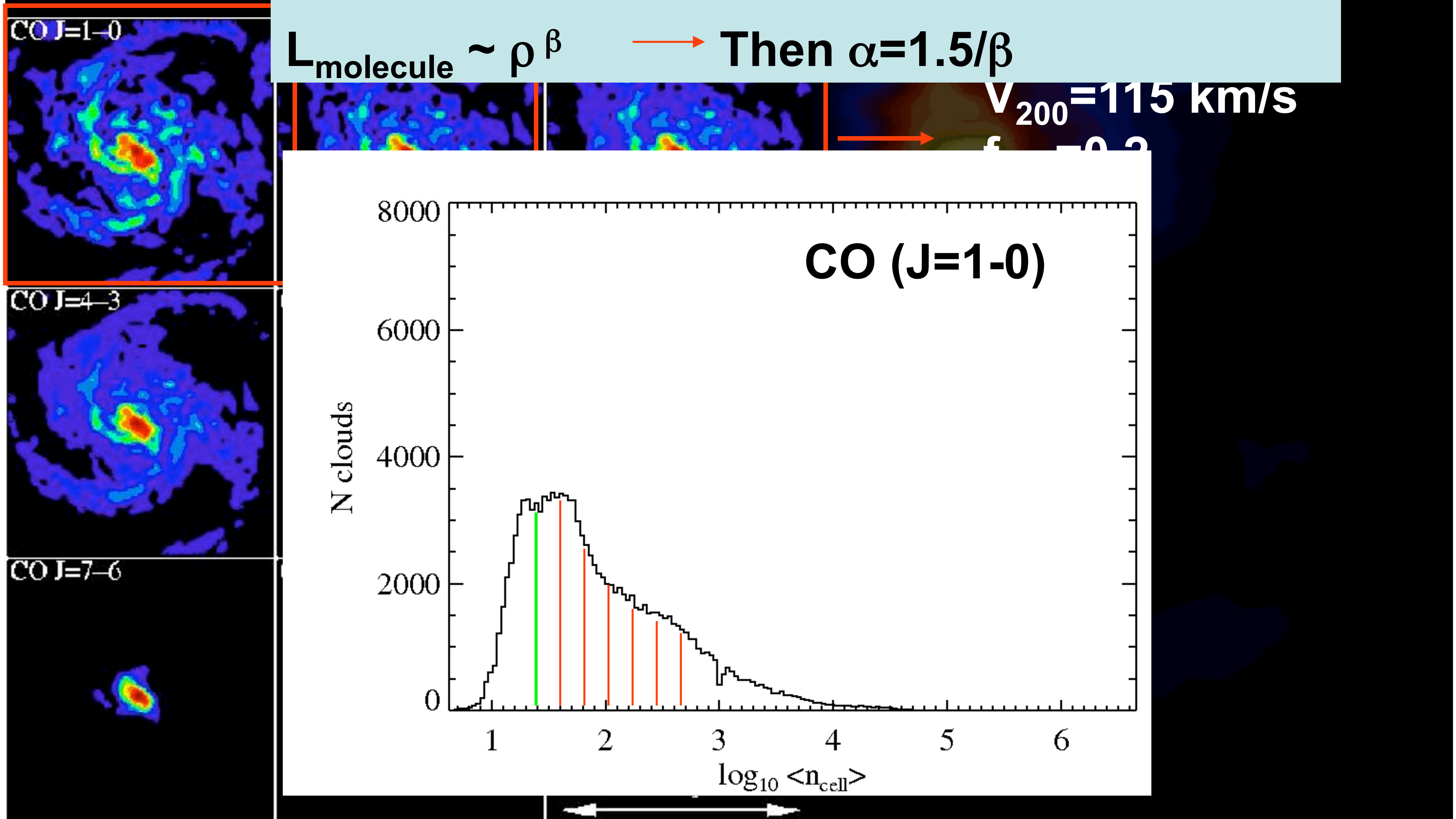
SF follows SFR α $\rho^{1.5}$

Narayanan et al. 2008

SFR ~ $\rho^{1.5}$ (assumed Schmidt Law)

SFR ~ $L_{molecule}^{\alpha}$ (observed)

$L_{molecule} \sim \rho^{\beta}$ → Then $\alpha = 1.5/\beta$



Narayanan et al. 2008

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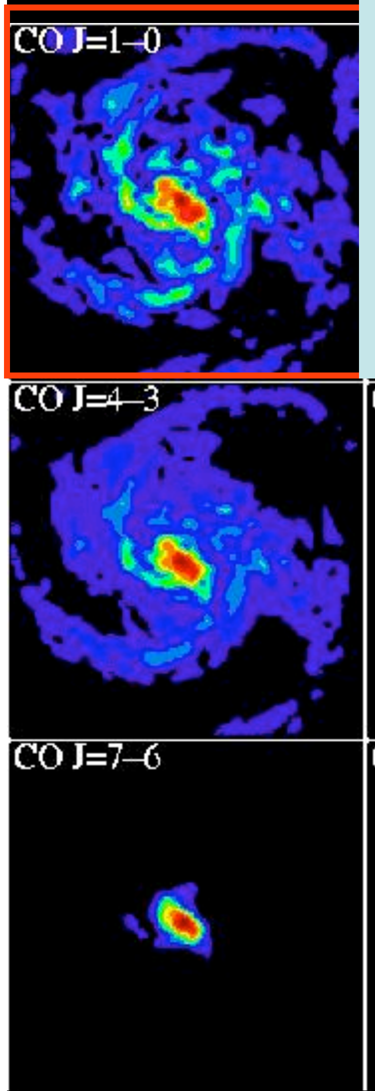

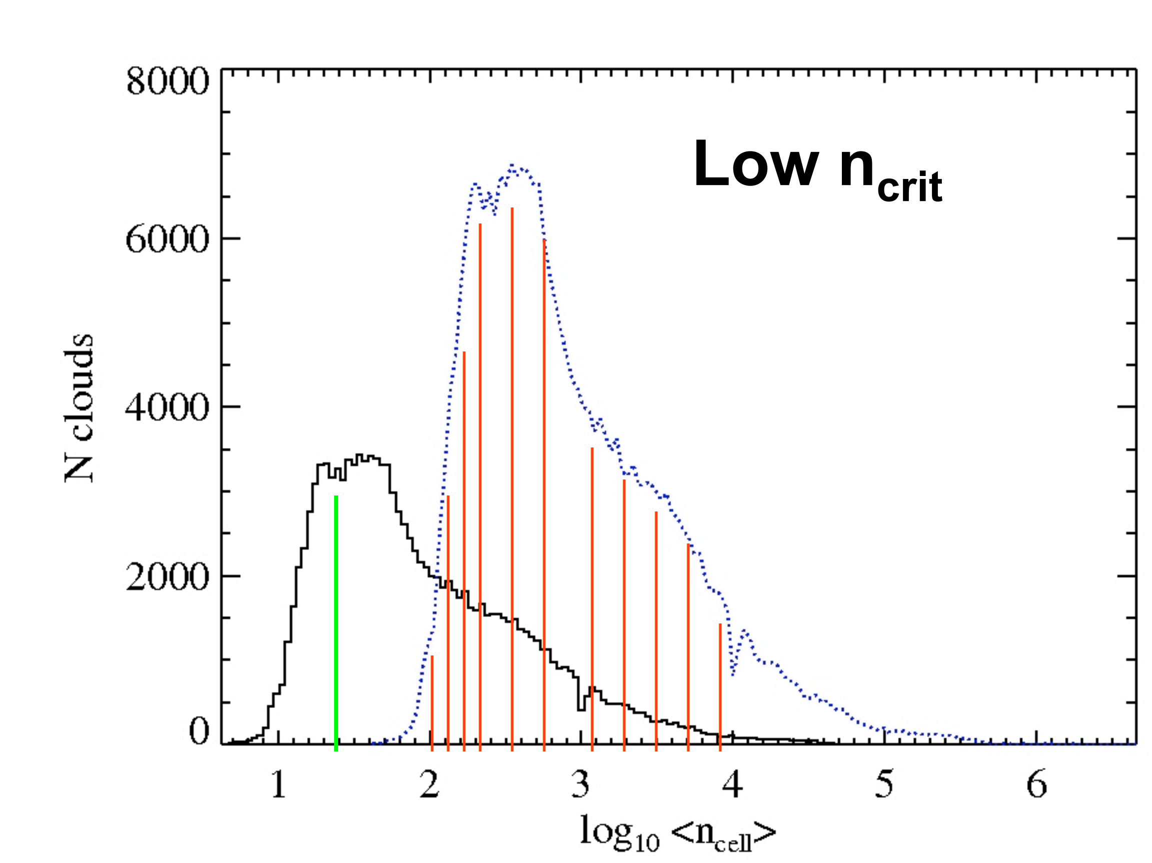

Narayanan et al. 2008

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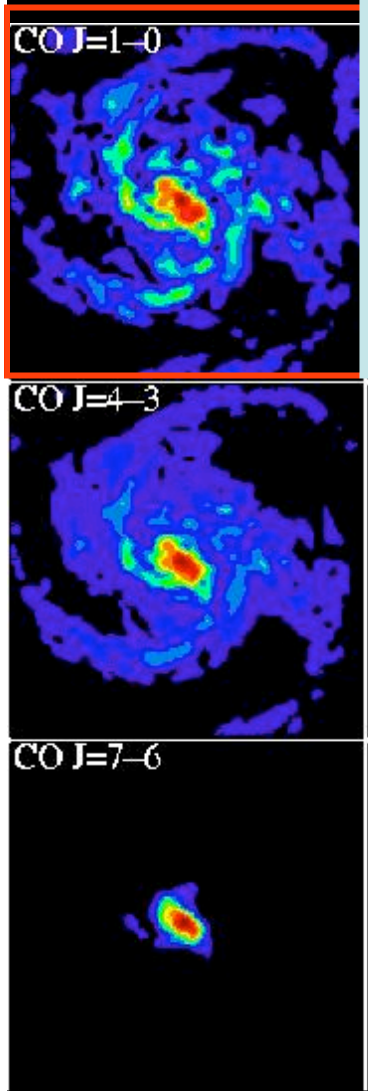

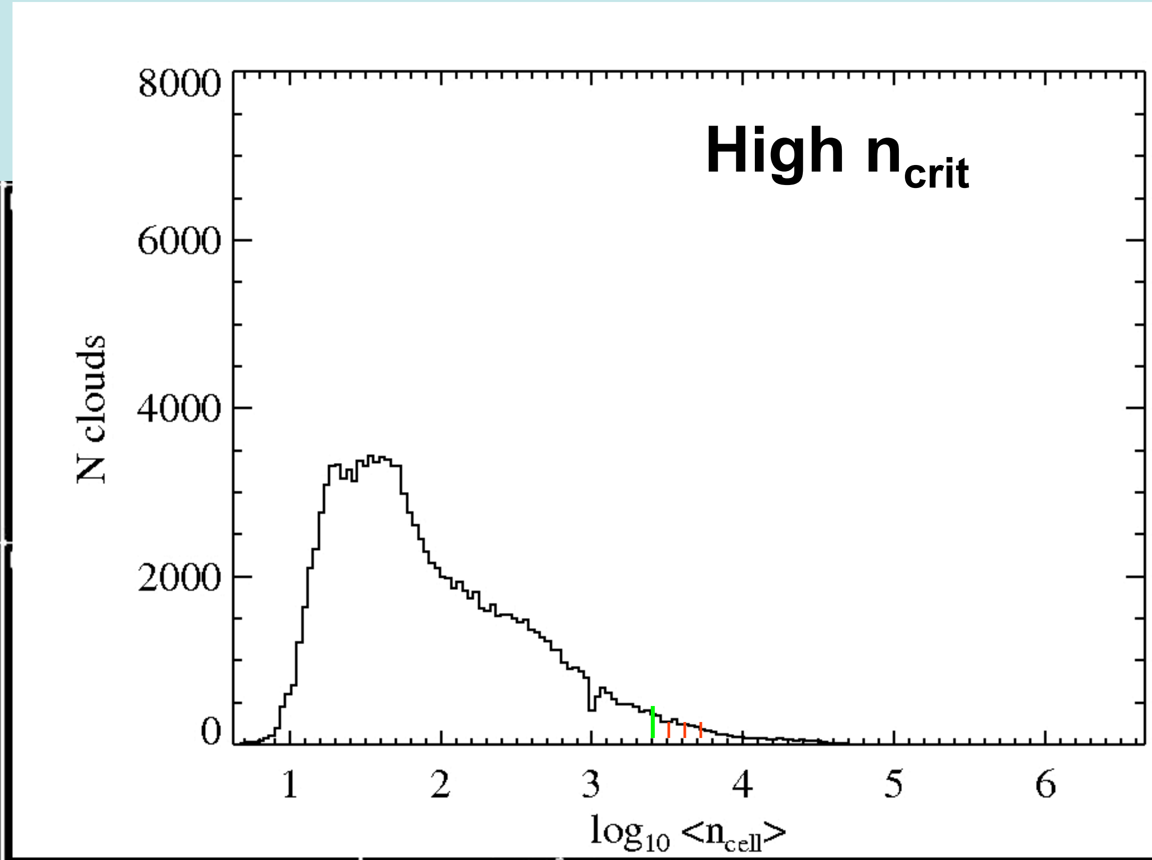

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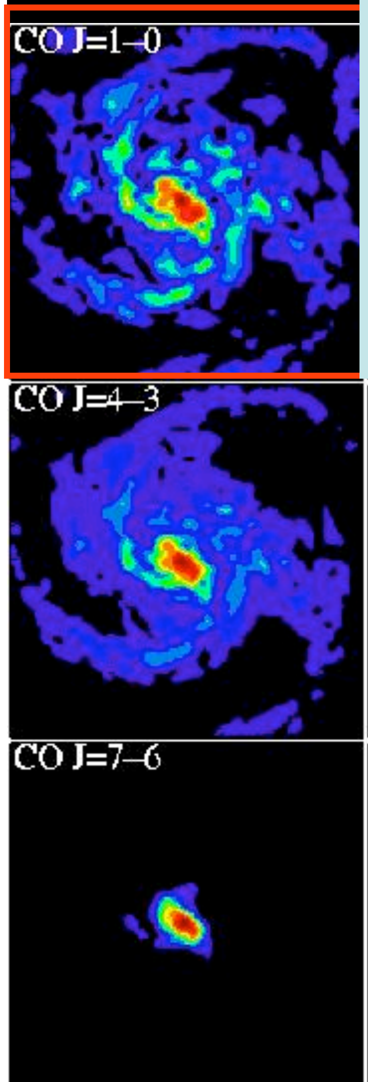
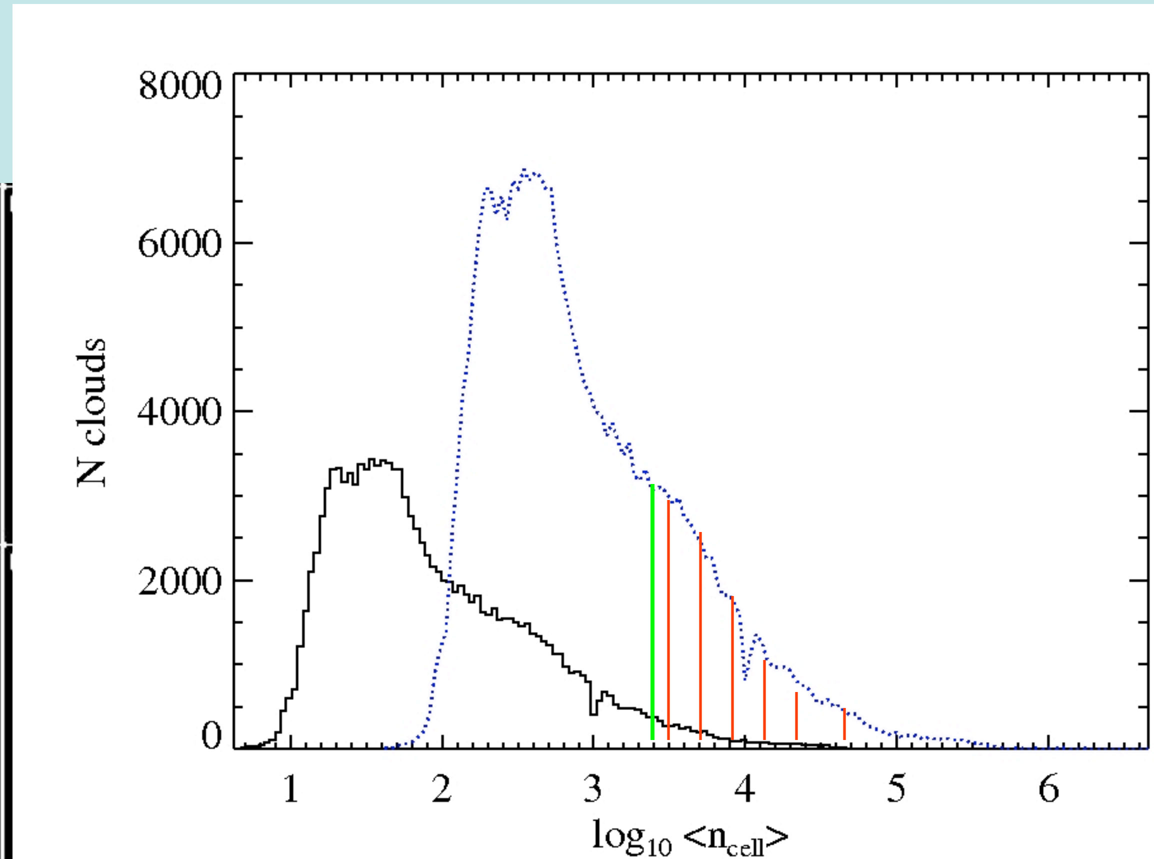
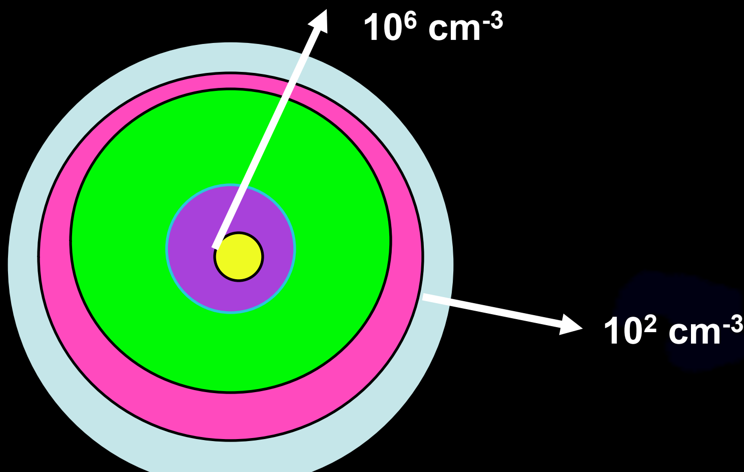


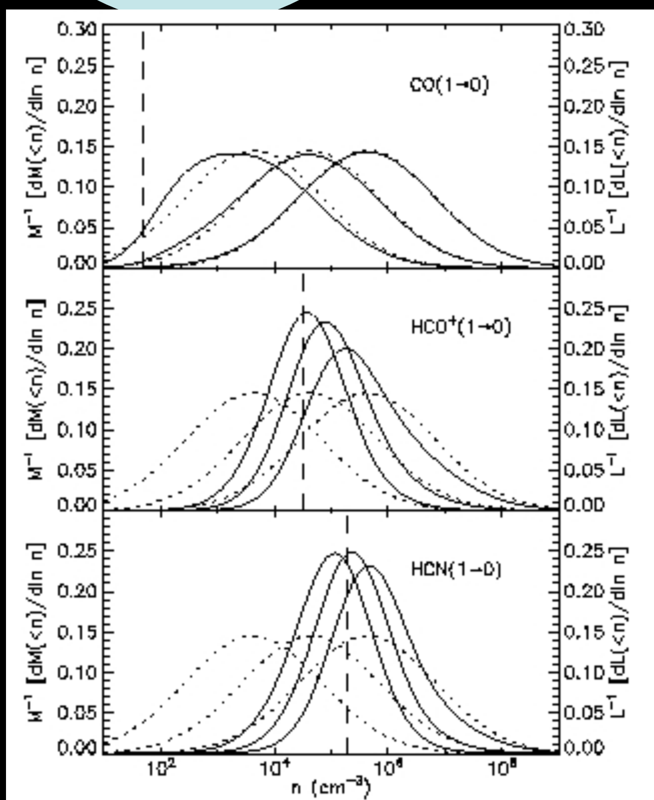


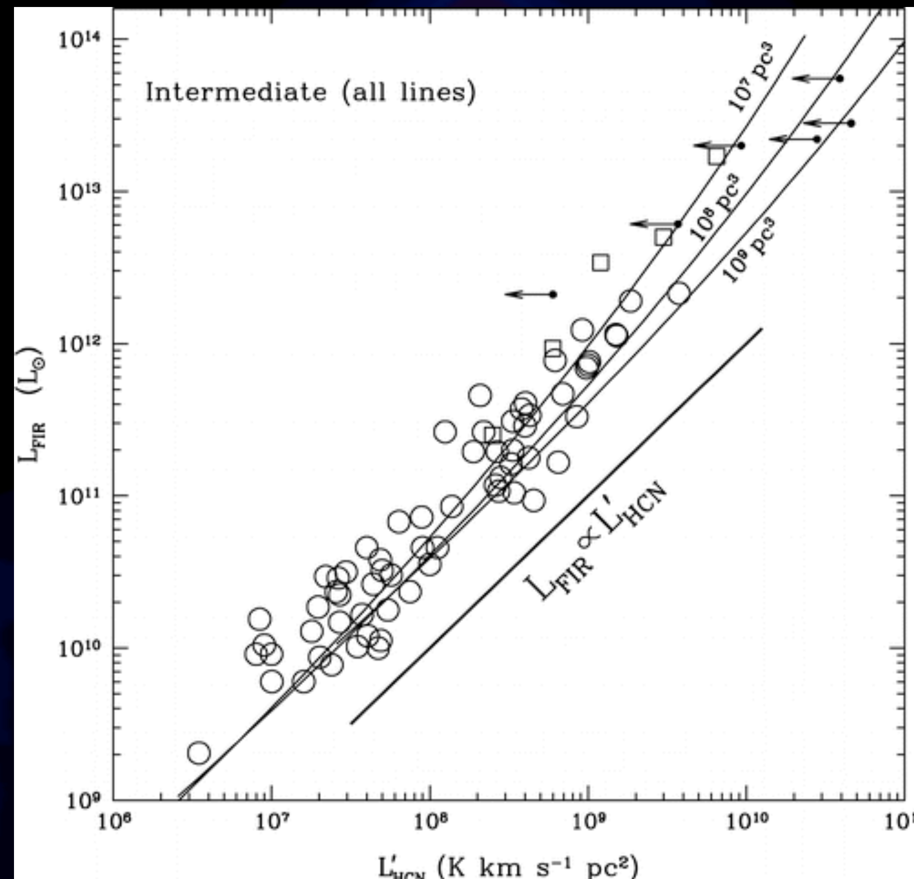
$\langle n \rangle \gg n_{crit}$ slope=1.5

$\langle n \rangle \ll n_{crit}$ slope < 1.5

Krumholz & Thompson Models for GMCs







Krumholz & Thompson 2007

$\langle n \rangle \gg n_{crit}$ slope=1.5

$\langle n \rangle \ll n_{crit}$ slope < 1.5

Two Models for Linear Molecular SFR "Laws"

- HCN, CO (J=3-2) probe *dense, star-forming cores,* and SFR~ρ_{dense}
  - SFR-L_{mol} relations will be linear for all high n_{crit} tracers

Gao & Solomon 2004; Wu et al. 2005; DN et al. 2005

n_{crit} << n_{thresh} **slope = 1.5**
n_{crit} >> n_{thresh} **slope = 1**

- SFR-L_{mol} relations dependent on relationship between n_{crit} and <n>;

  -observed SFR-L_{mol} relations will change with increasing n_{crit}

- Krumholz & Thompson 2007, DN et al. 2008

<n> >> n_{crit} slope=1.5
<n> << n_{crit} slope < 1.5

Testable Predictions

- L_{IR}-L_{mol} relation for other high critical density molecular Species/lines (Predict rather than Post-dict!)

- High mean gas density limit - slopes should tend toward the underlying Schmidt index

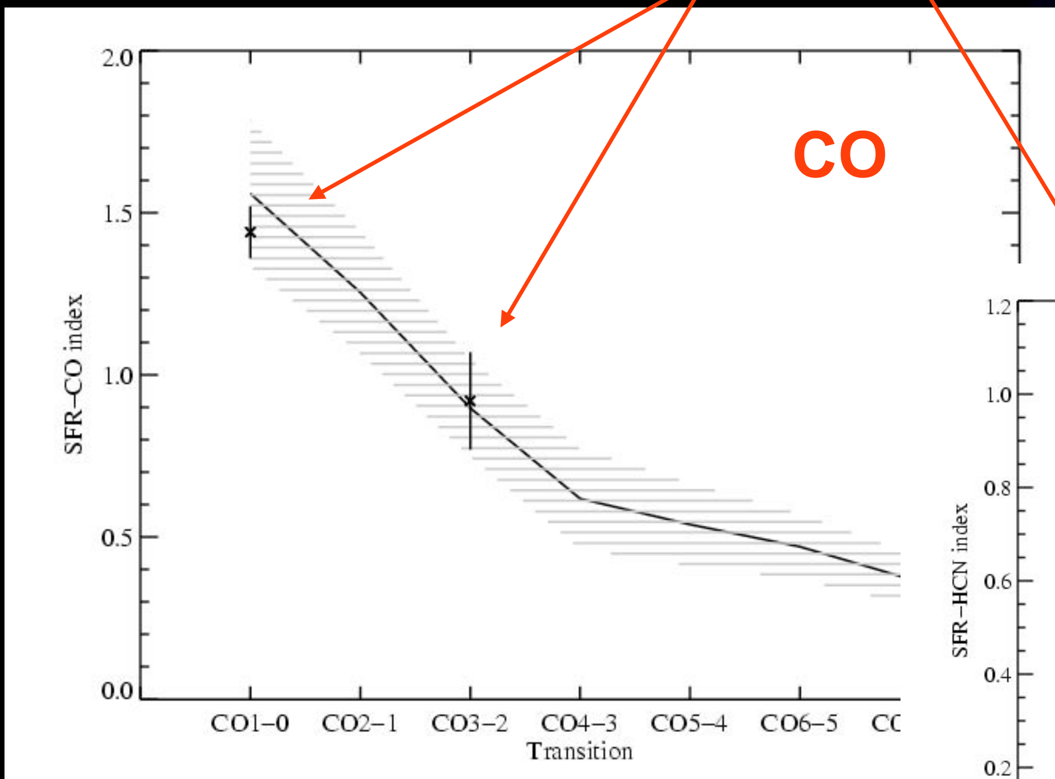
$\langle n \rangle \gg n_{crit}$	slope=1.5
$\langle n \rangle \ll n_{crit}$	slope < 1.5

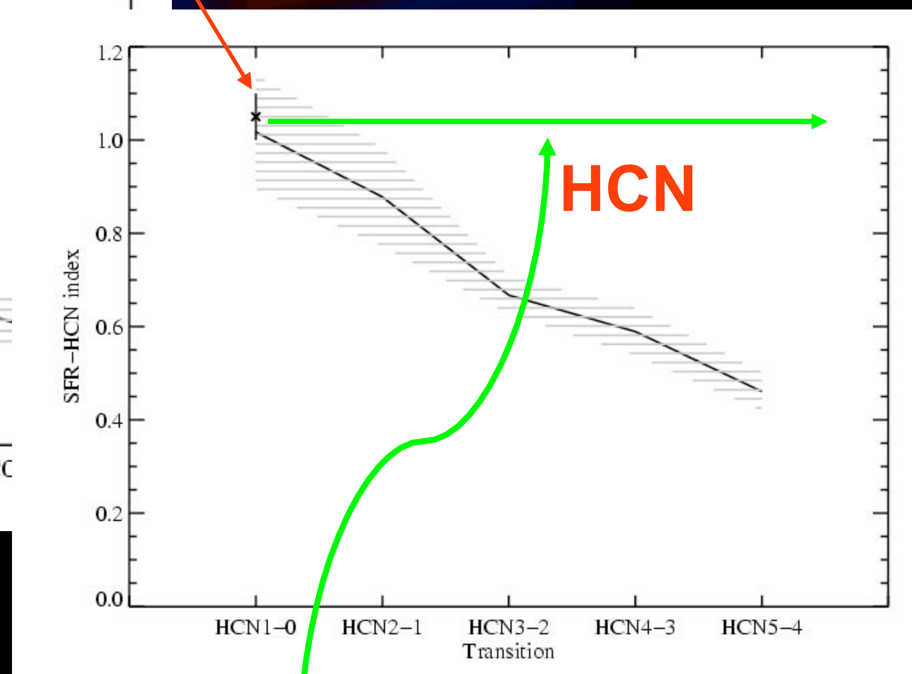
Predicted Slopes for CO and HCN

Observational Points

$\langle n \rangle \gg n_{crit}$ slope=1.5

$\langle n \rangle \ll n_{crit}$ slope < 1.5



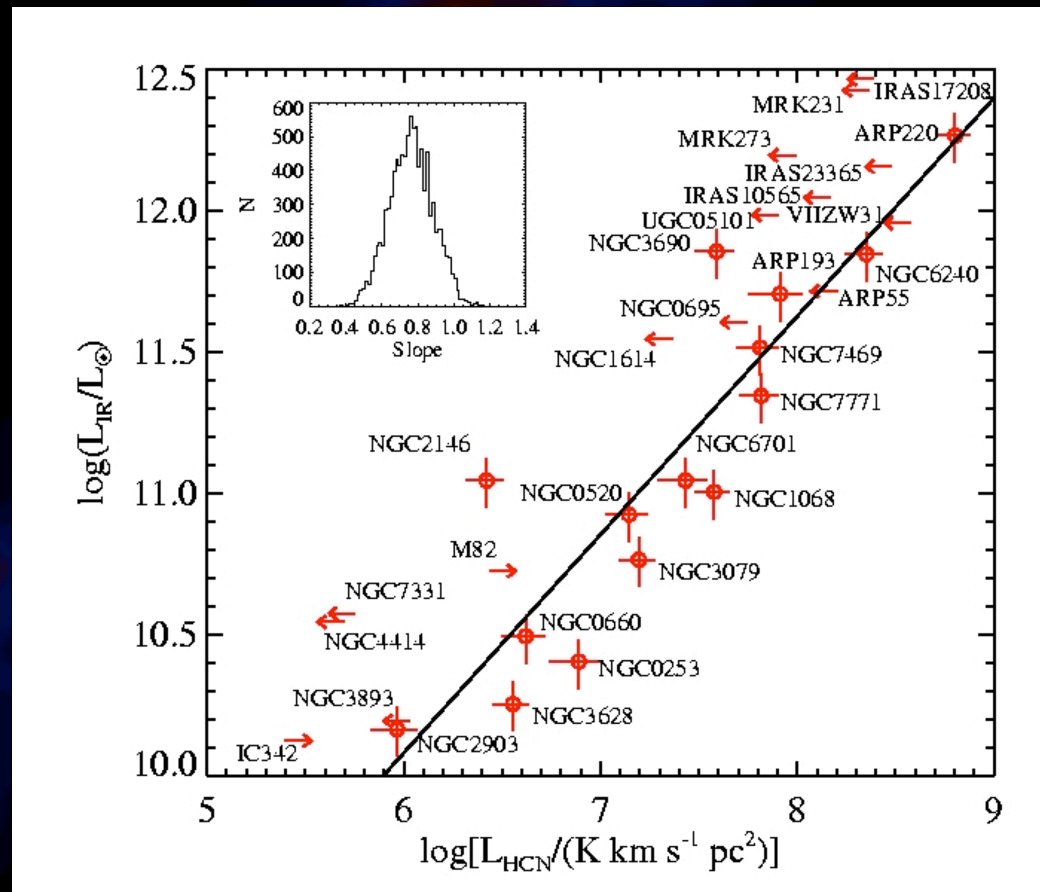


Narayanan et al. 2005, 2008

Gao & Solomon 2004

Linear SFR-Lmol relation expected for high ncrit tracers if SFR~ρ_{dense}

HCN (J=3-2) Observational Survey



Bussmann, DN, Shirley, Wu, Juneau, Vanden Bout, Solomon et al. (2008)

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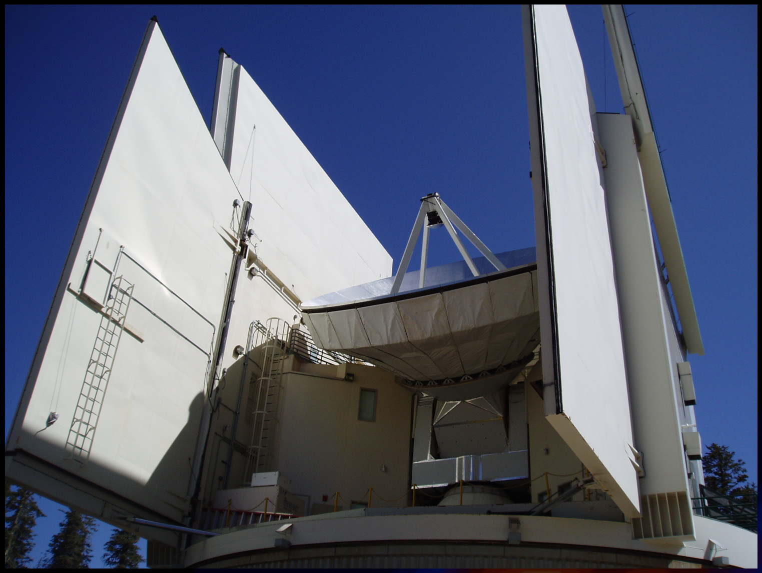
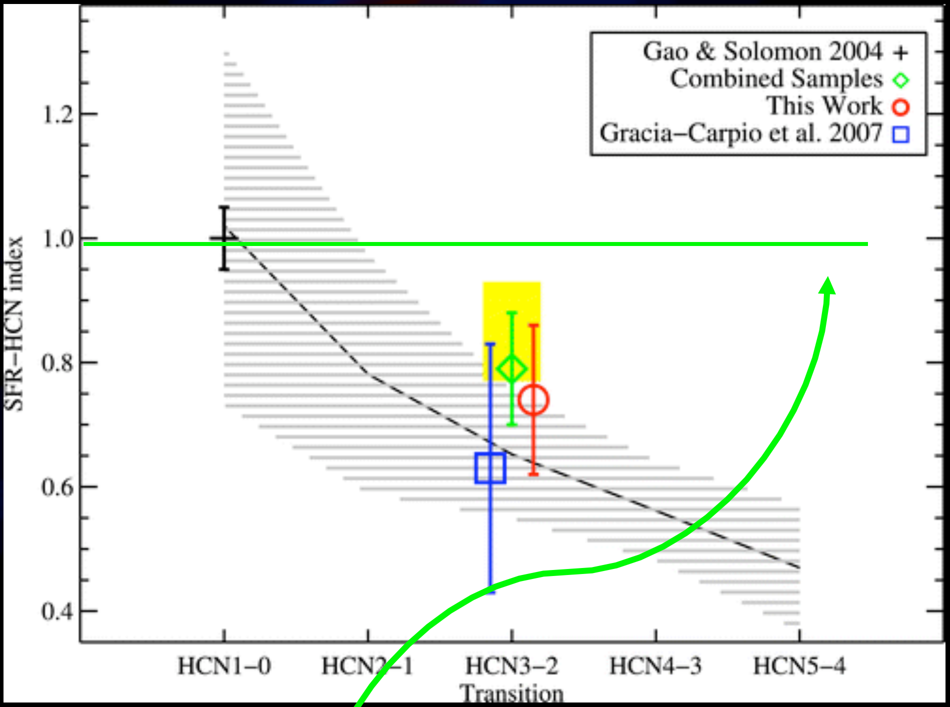
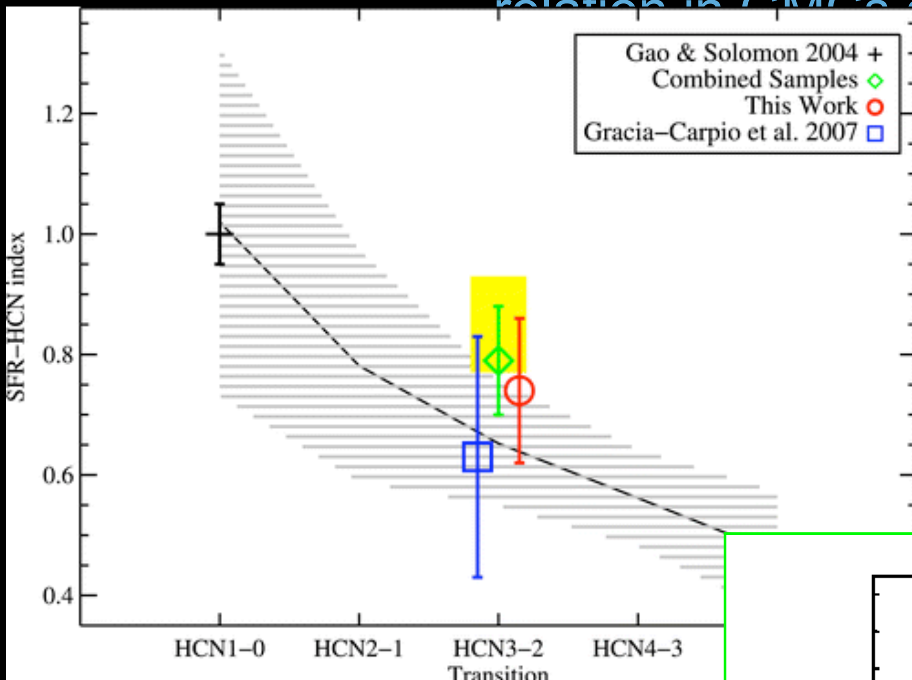




Linear SFR-Lmol relation expected for high ncrit tracers if SFR~ρ_{dense}

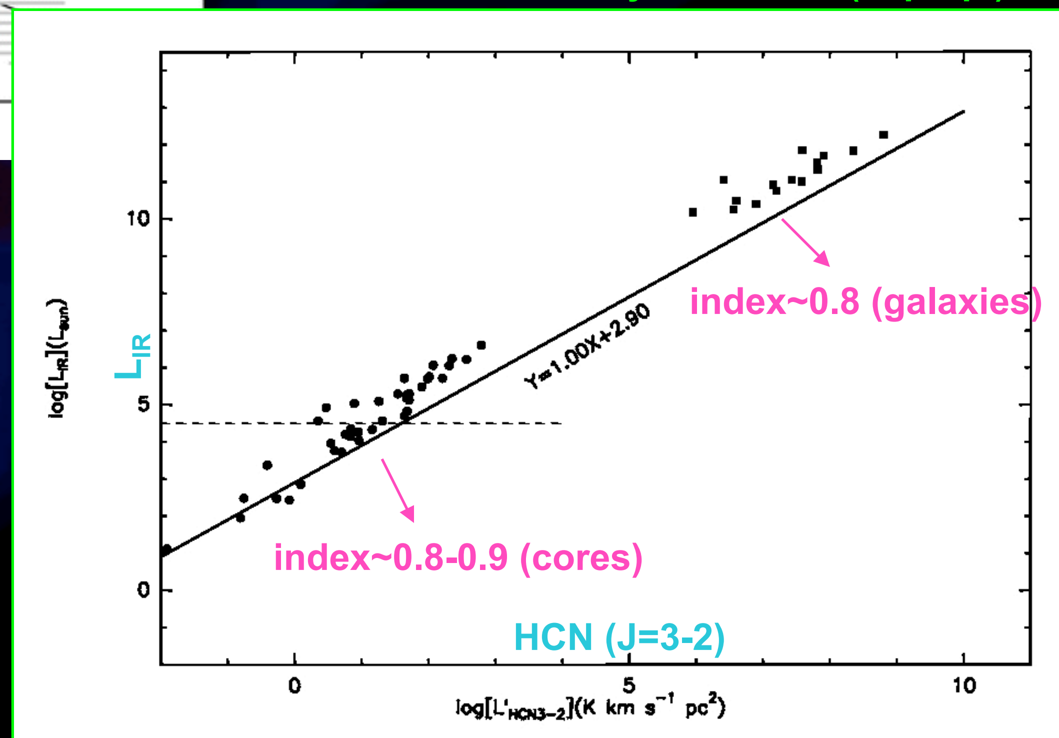
Bussmann, DN, Shirley, Juneau, Wu, Solomon, Vanden Bout et al.

The relationship between the SFR-Lmol relation in GMCs and Galaxies



Bussmann et al. 2008

J. Wu, Evans, Shirley et al. 2008 (in prep.)



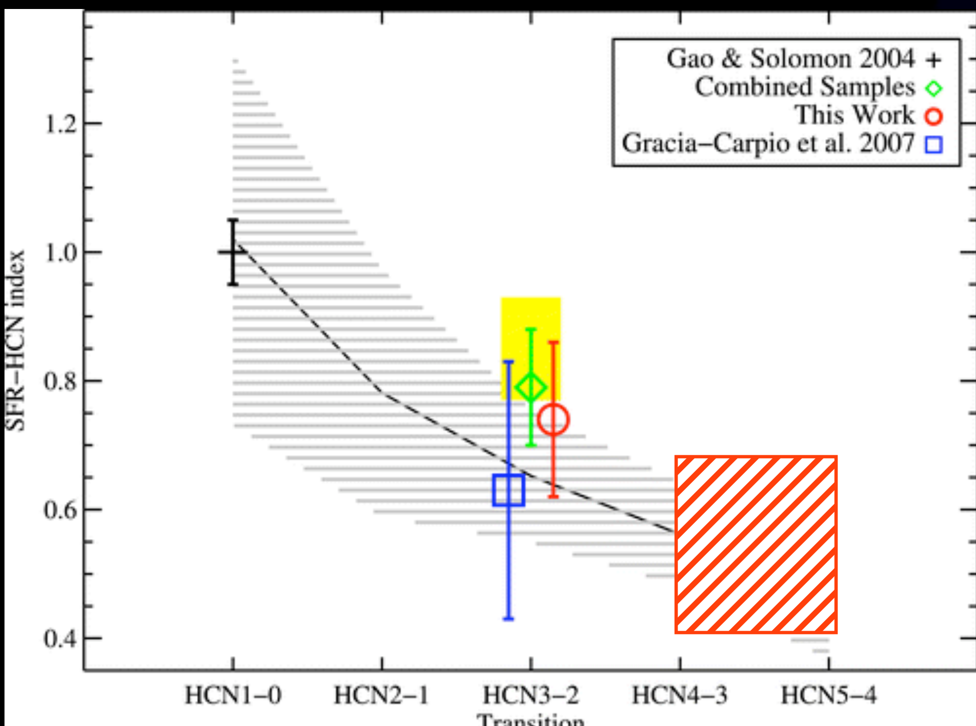
$\langle n \rangle \gg n_{crit}$ slope=1.5

$\langle n \rangle \ll n_{crit}$ slope < 1.5

General Conclusions & Directions for ALMA

- SFR-dense gas relations naturally explained if underlying KS law of N=1.5 controlls SFR

- SFR-L_{mol} index in galaxies and GMCs depedant on the average relation between n_{crit} and the <n>;   SFR $\not\approx \rho_{dense}$



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General Conclusions & Directions for ALMA

- SFR-dense gas relations naturally explained if underlying KS law of N=1.5 controlls SFR

- SFR-L_{mol} index in galaxies and GMCs depedant on the average relation between n_{crit} and the $\langle n \rangle$; $SFR \not\approx \rho_{dense}$

$\langle n \rangle \gg n_{crit}$ slope = KS
$\langle n \rangle \ll n_{crit}$ slope < KS

Testable Predictions

- L_{IR}-L_{mol} relation for other high critical density molecular Species/lines (Predict rather than Post-dict!)

- High mean gas density limit - slopes should tend toward the underlying Schmidt index

$\langle n \rangle \gg n_{crit}$ slope=1.5
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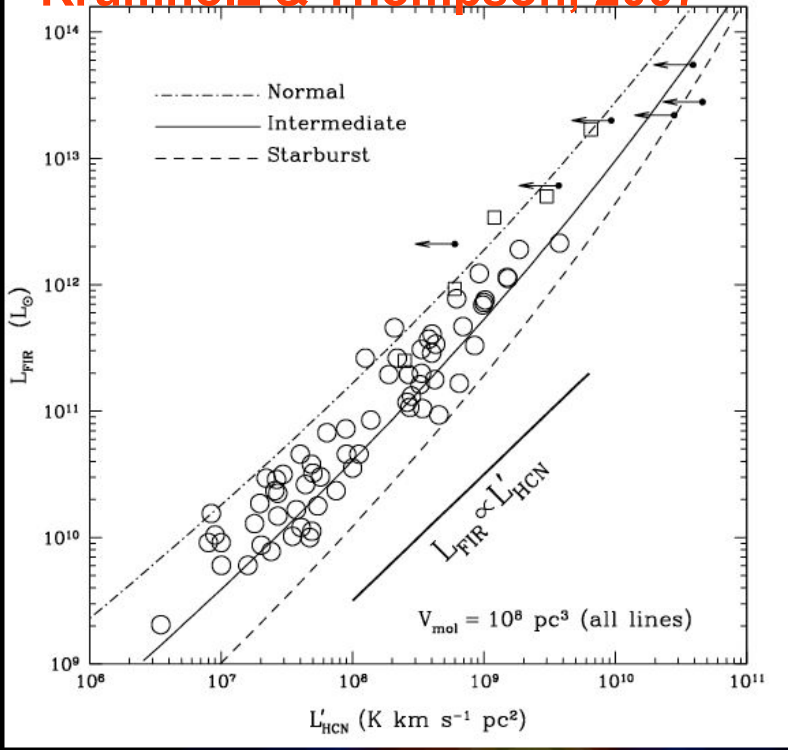
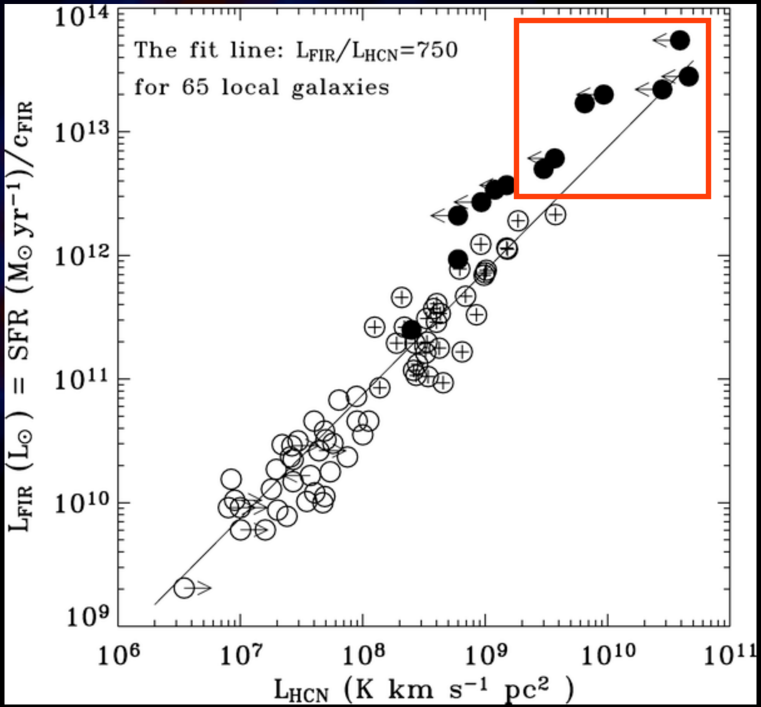
Observational Test: High Mean Density Limit

Krumholz & Thompson, 2007



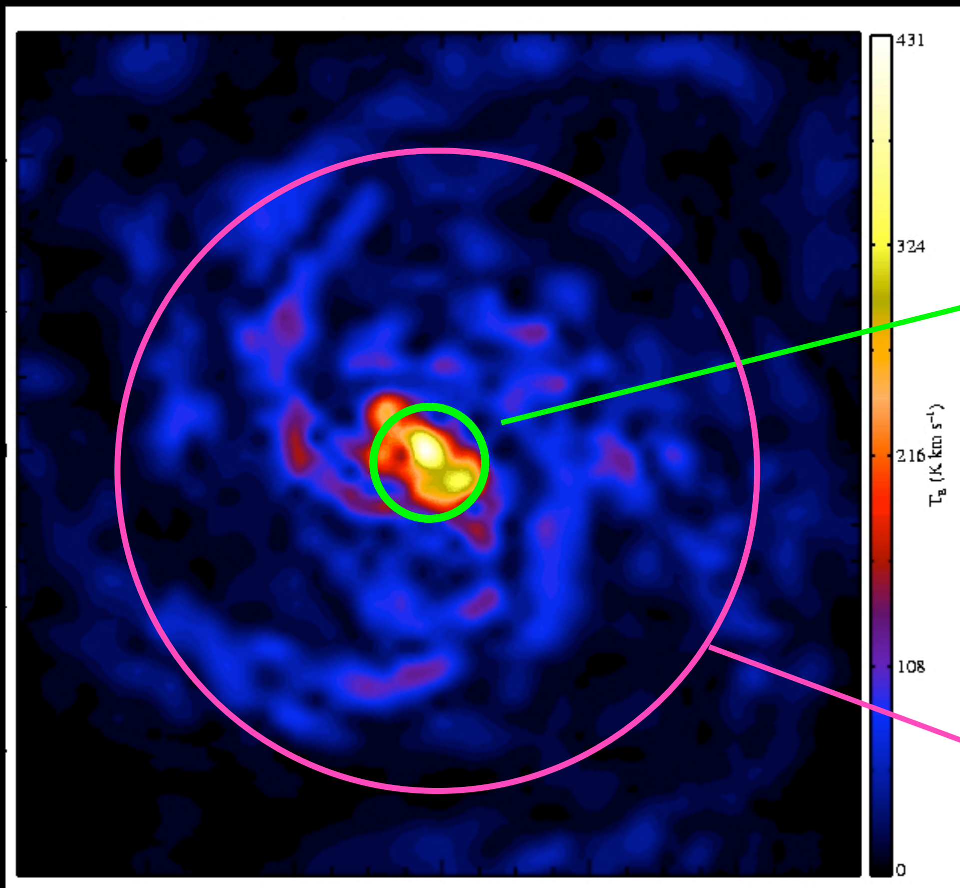


Gao et al. 2007

When <n> ~ $n_{crit,}$ β=1

Then α=1.5/β ~ 1.5

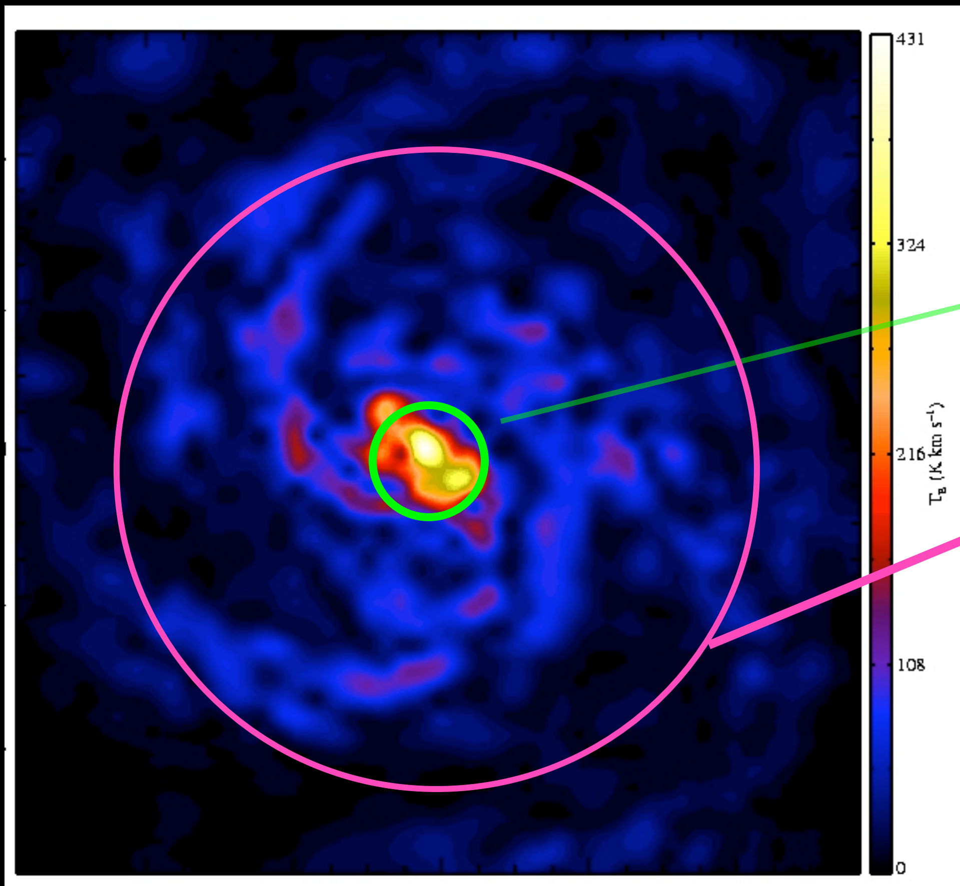
Observational Test: High Mean Density Limit

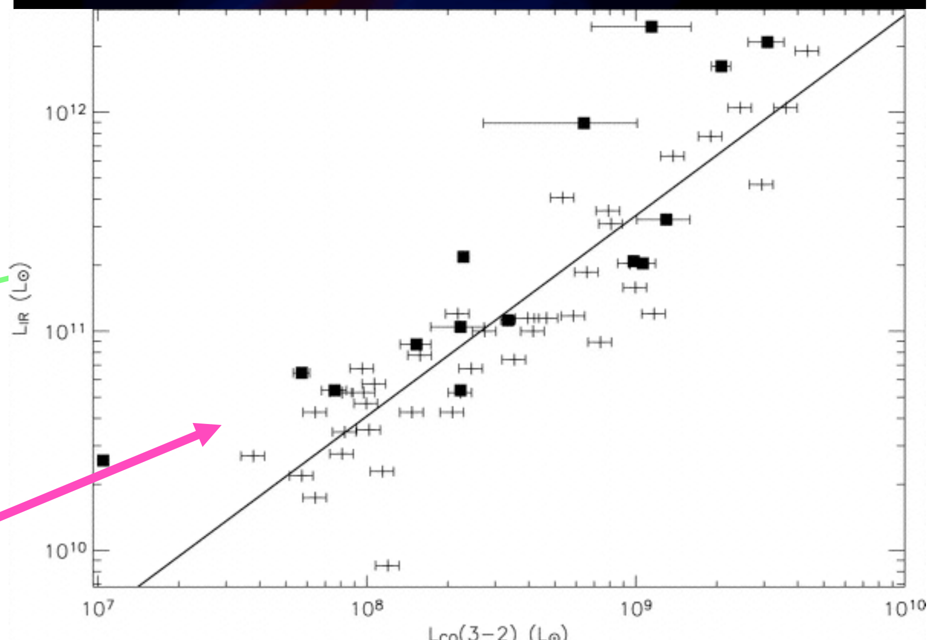


High <n> - L_{IR}-L_{mol} index should be similar to underlying Schmidt index

Global observations mean lower <n> - L_{IR}-L_{mol} index should be less than underlying Schmidt index

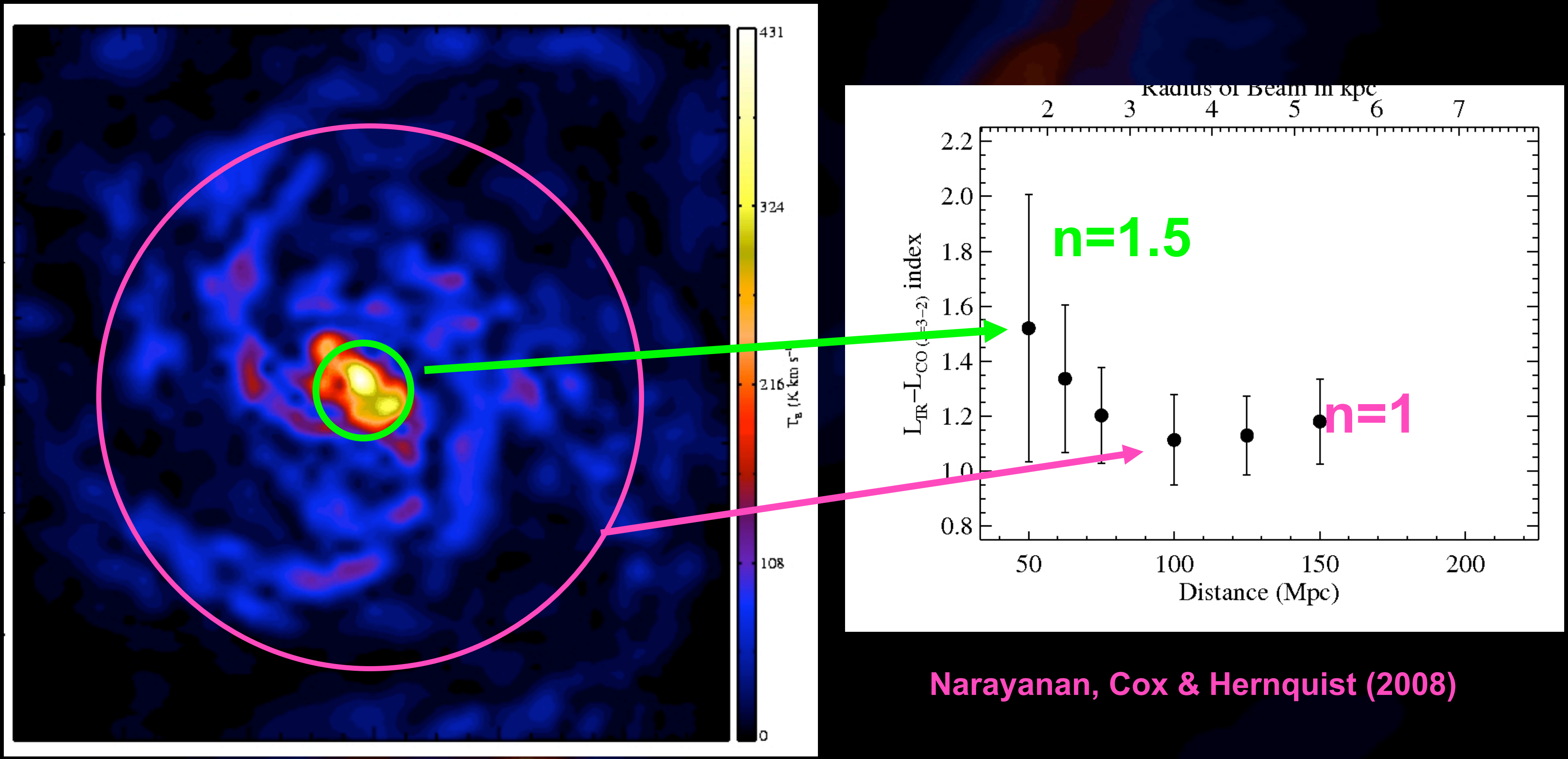
Observational Test: High Mean Density Limit





Linear L_{IR}-CO (J=3-2) relation
Found in global observations
Of local galaxies
(Narayanan et al. 2005)

Observational Test: High Mean Density Limit

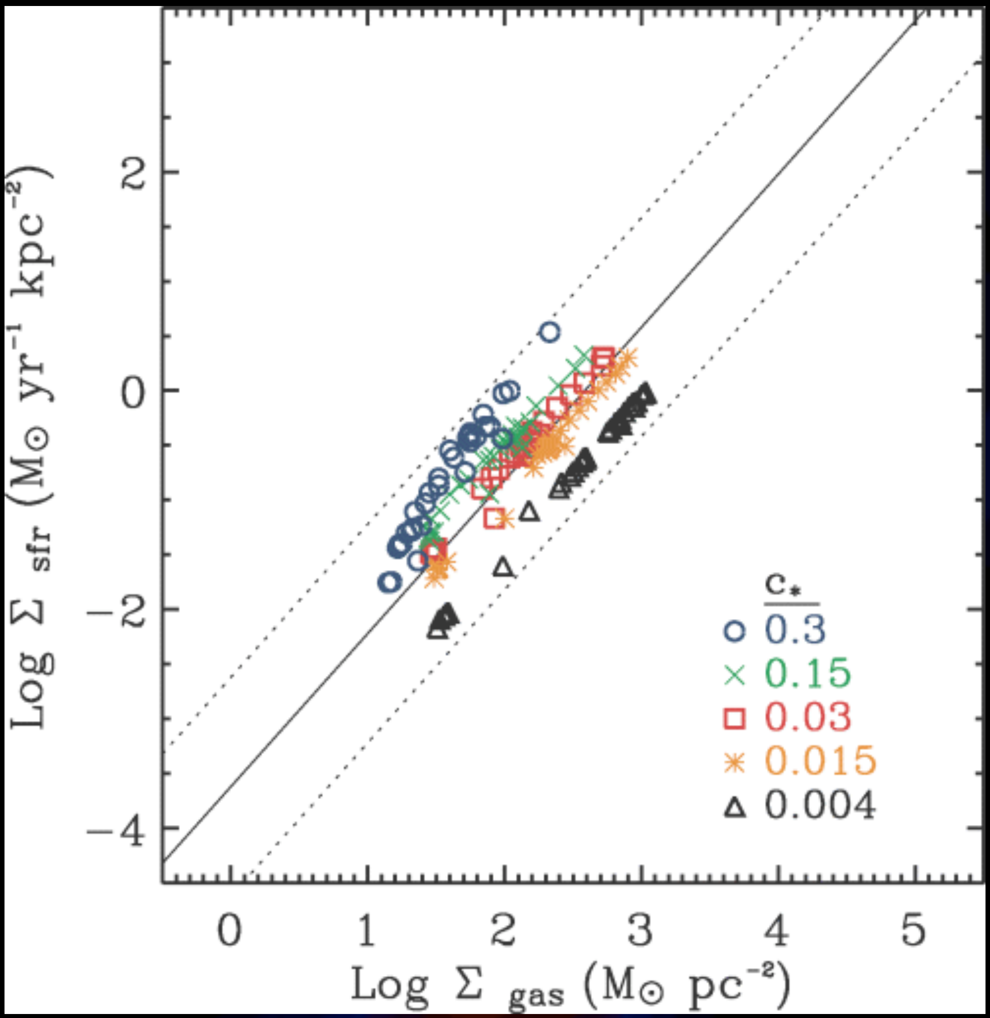


Narayanan, Cox & Hernquist (2008)

$\langle n \rangle \gg n_{crit}$ slope=1.5

$\langle n \rangle \ll n_{crit}$ slope < 1.5

GADGET SPH Simulations



T.J. Cox et al. 2006

Prescriptions for multi-phase ISM (McKee-Ostriker), SF, BH growth and associated Feedback (though BH winds turned off)

100 galaxies used:

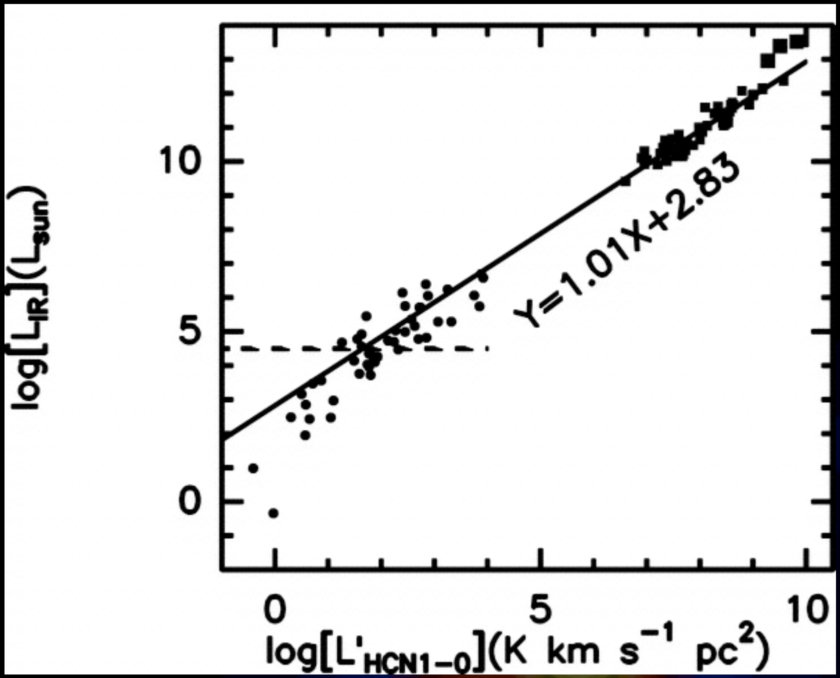
20 disk Galaxies

80 merger snapshots

SF follows SFR α $\rho^{1.5}$

Assuming $t_{SFR} \sim \rho^{-1/2}$

Caveats: What about L_{IR}-L_{mol} relation in dense GMC cores?



L_{IR} α HCN (J=1-0)

Wu et al. 2005

Two potential resolutions:

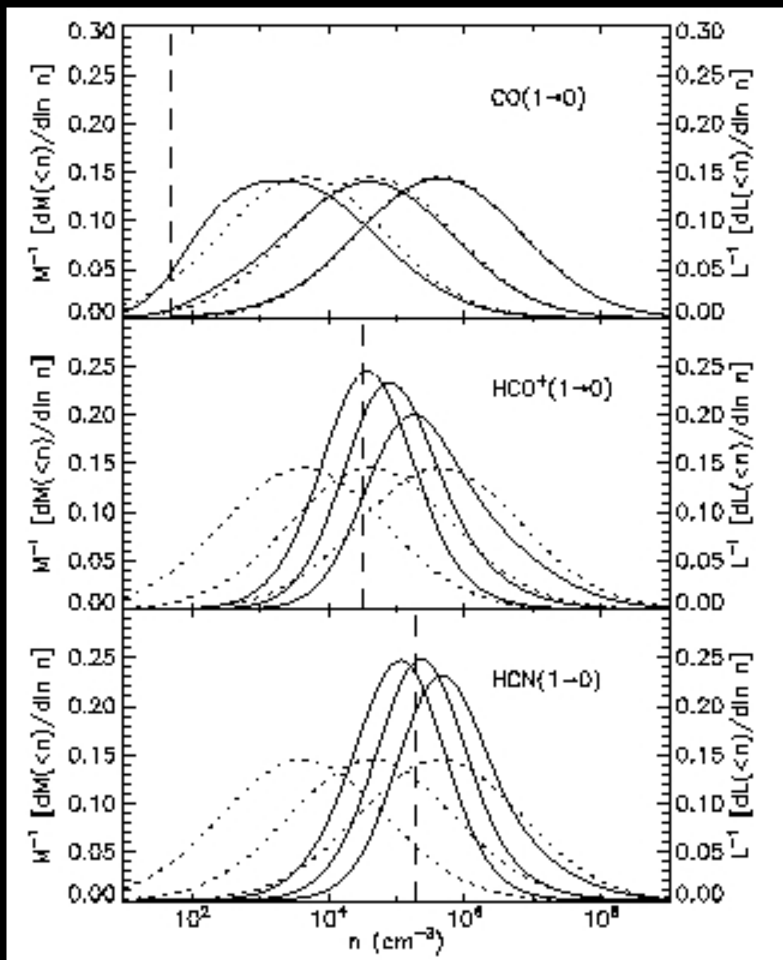
1. The dense cores observed have <ρ> << n_{crit}

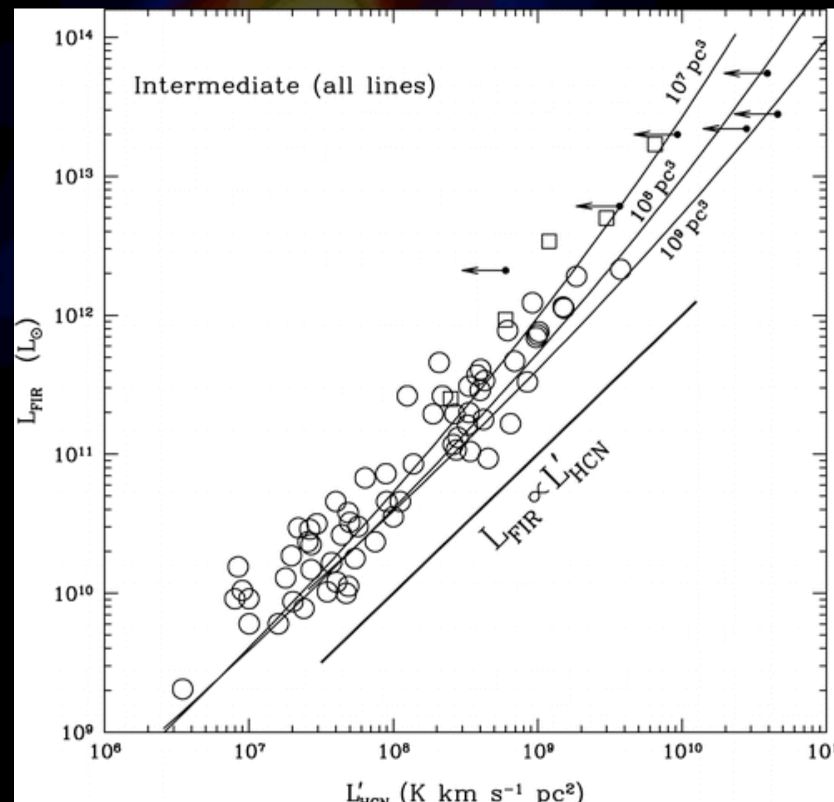
2. SFR follows a broken powerlaw:

SFR ~ $\rho^{1.5}$ < ρ> << n_{thresh}

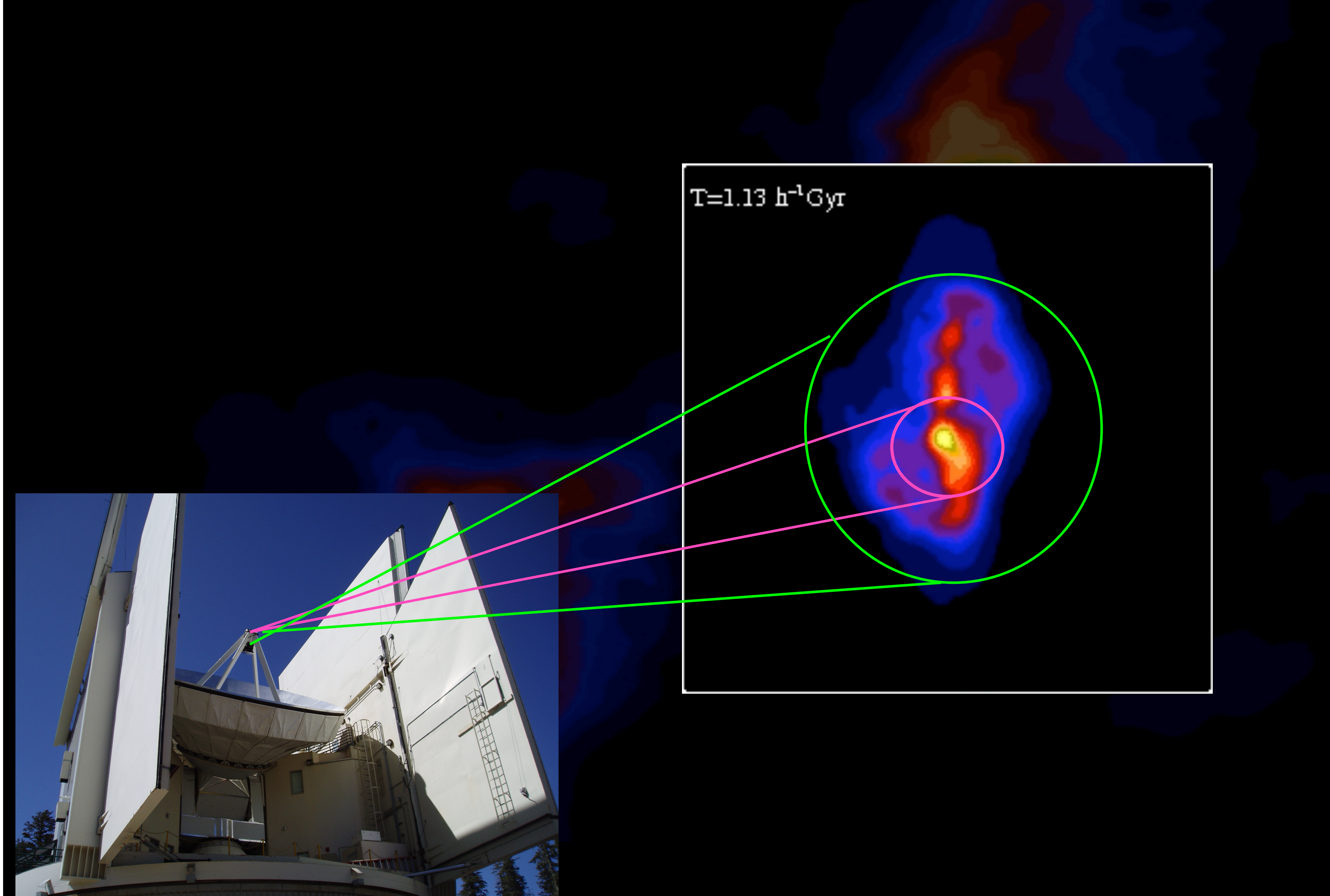
SFR ~ ρ^{1} < ρ> >> n_{thresh}

Krumholz & Thompson models for GMCs

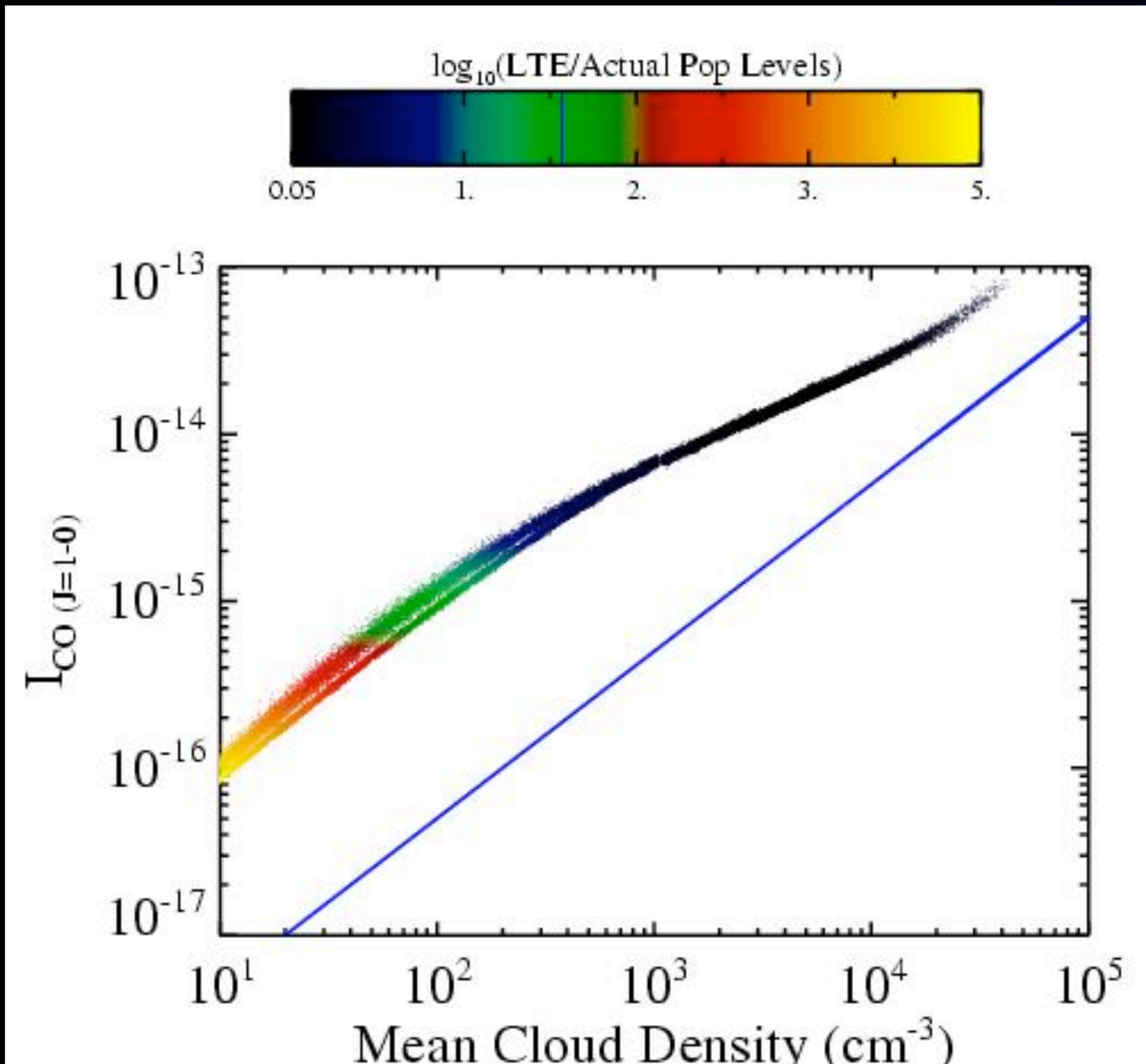




Detailed understanding of an individual galaxy



Relation Between Line Luminosity and Gas Density : CO (J=1-0)



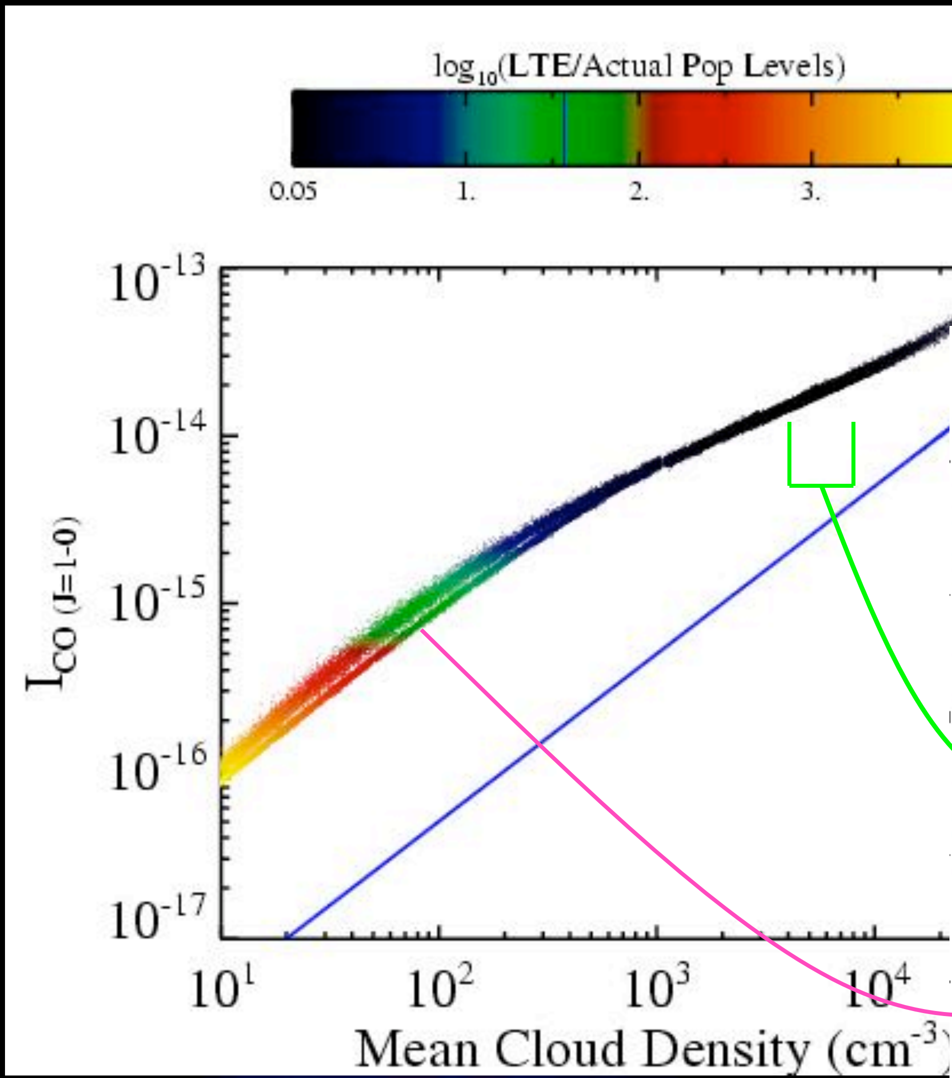
CO (J=1-0) is thermalized in most gas cells, resulting in a linear relationship between increasing gas density and CO (J=1-0) flux.

SFR ~ $L_{CO\ (J=1\text{-}0)}^{\alpha}$

$L_{CO\ (J=1\text{-}0)}$ ~ $\rho^{\beta=1}$

Then α=1.5/β = 1.5

Relation Between Line Luminosity and Gas Density : CO (J=1-0)



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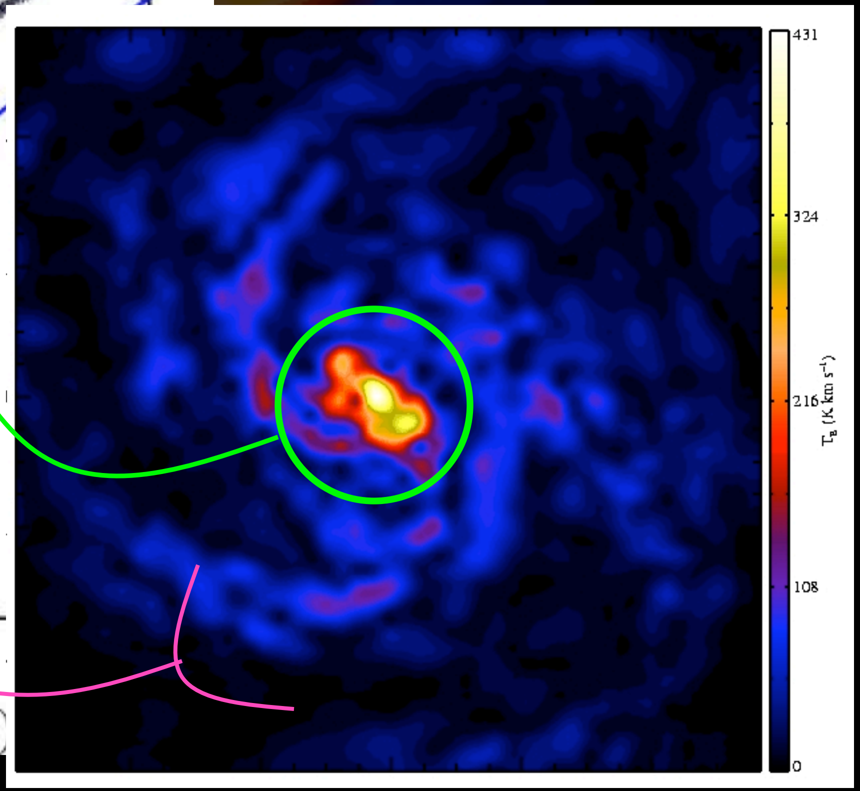
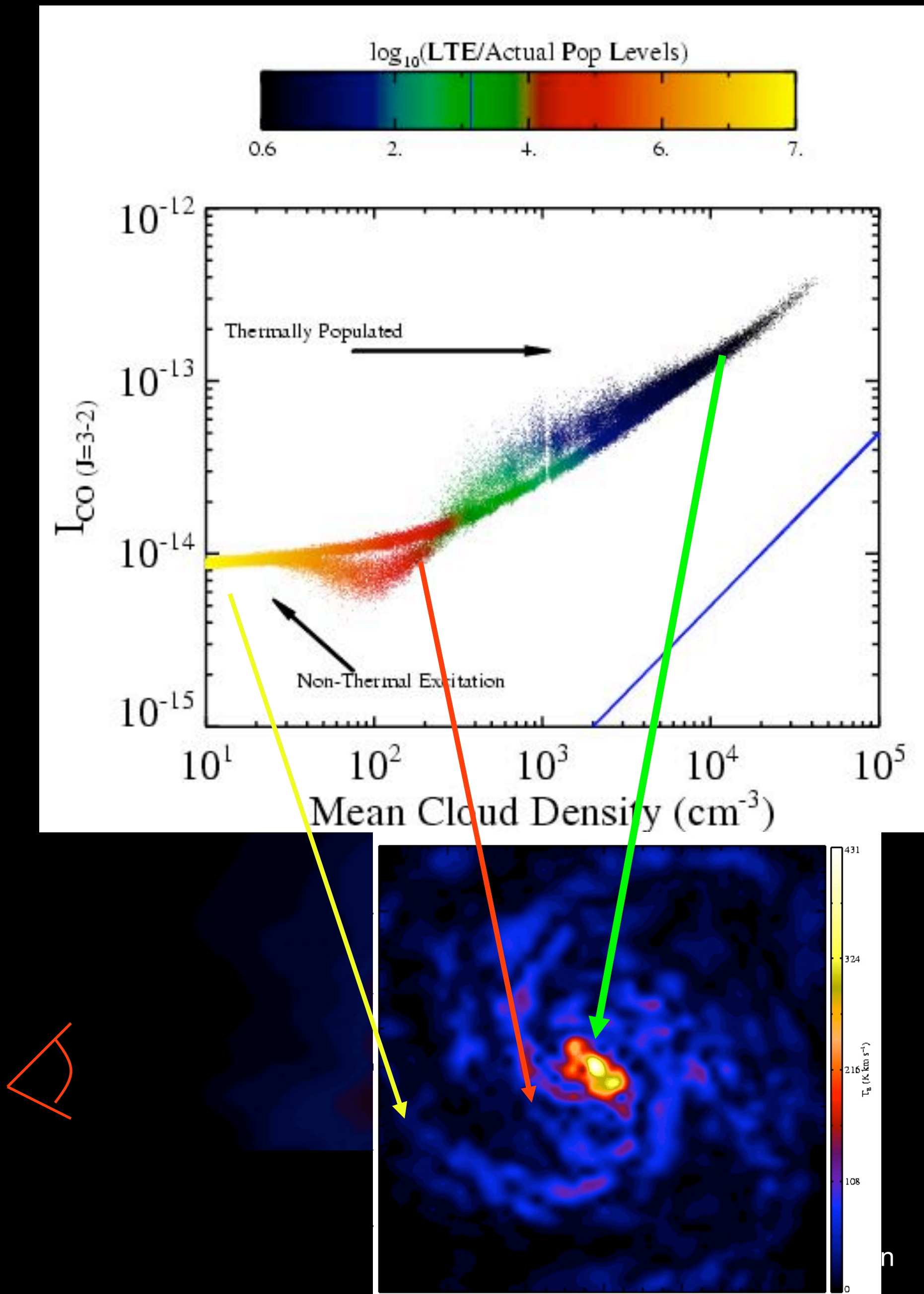


Relation Between Line Luminosity and Gas Density : CO (J=3-2)



-Emission from subthermally excited cells is characteristically higher than collisions in the diffuse gas would normally account for.

-Emission from this gas along the LOS results in superlinear relation between increasing gas density and CO (J=3-2) flux.

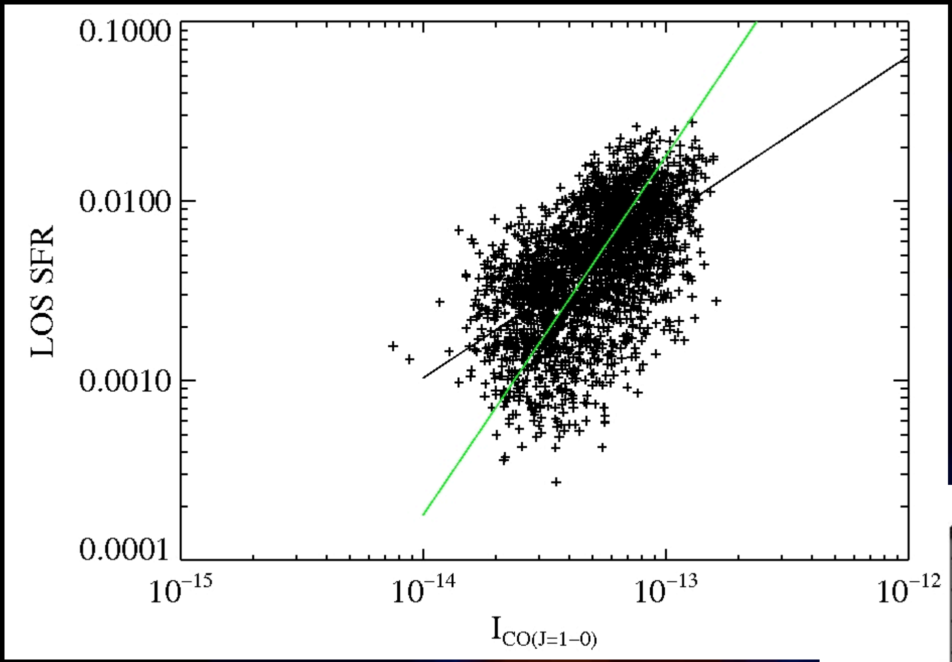
SFR ~ $L_{CO\ (J=3-2)}^{\ \alpha}$

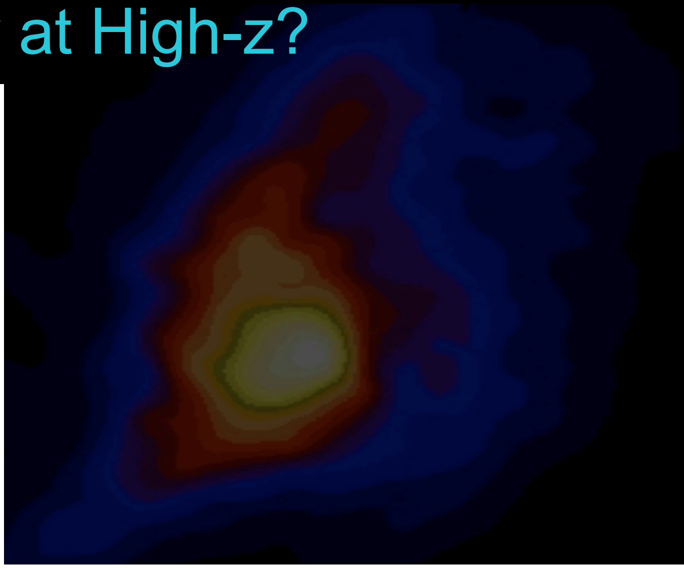
$L_{CO\ (J=3-2)} \sim \rho^{\beta}$

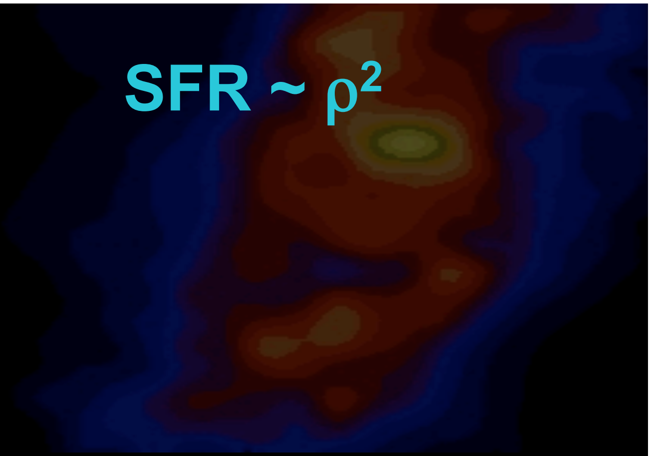
β~1.5

Then α=1.5/β ~ 1

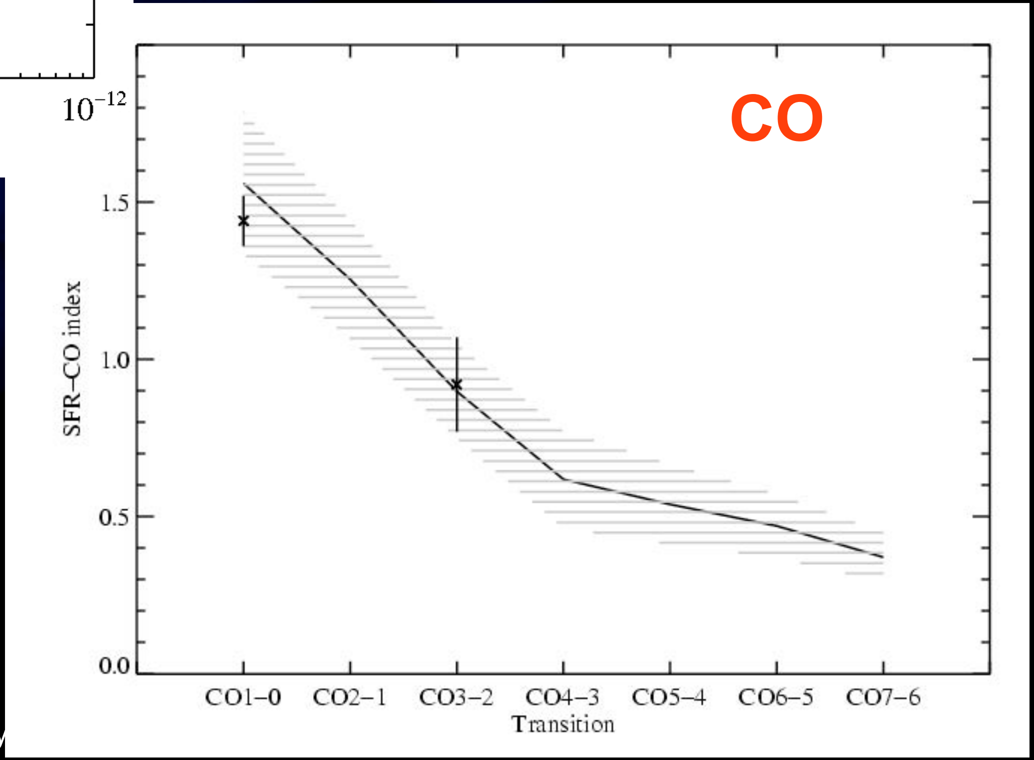
Schmidt Law at High-z?





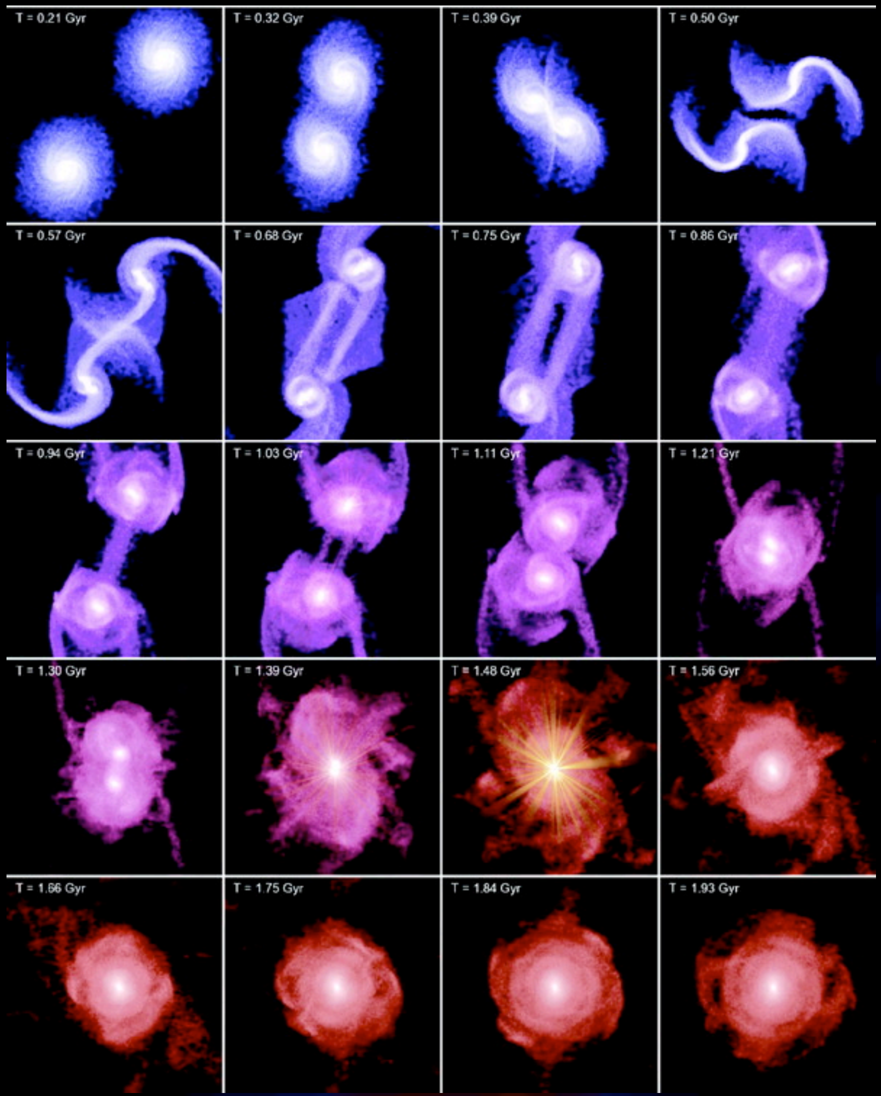


SFR ~ ρ^2



Desika Naray

GADGET SPH Simulations



Springel et al. (2003-2005),

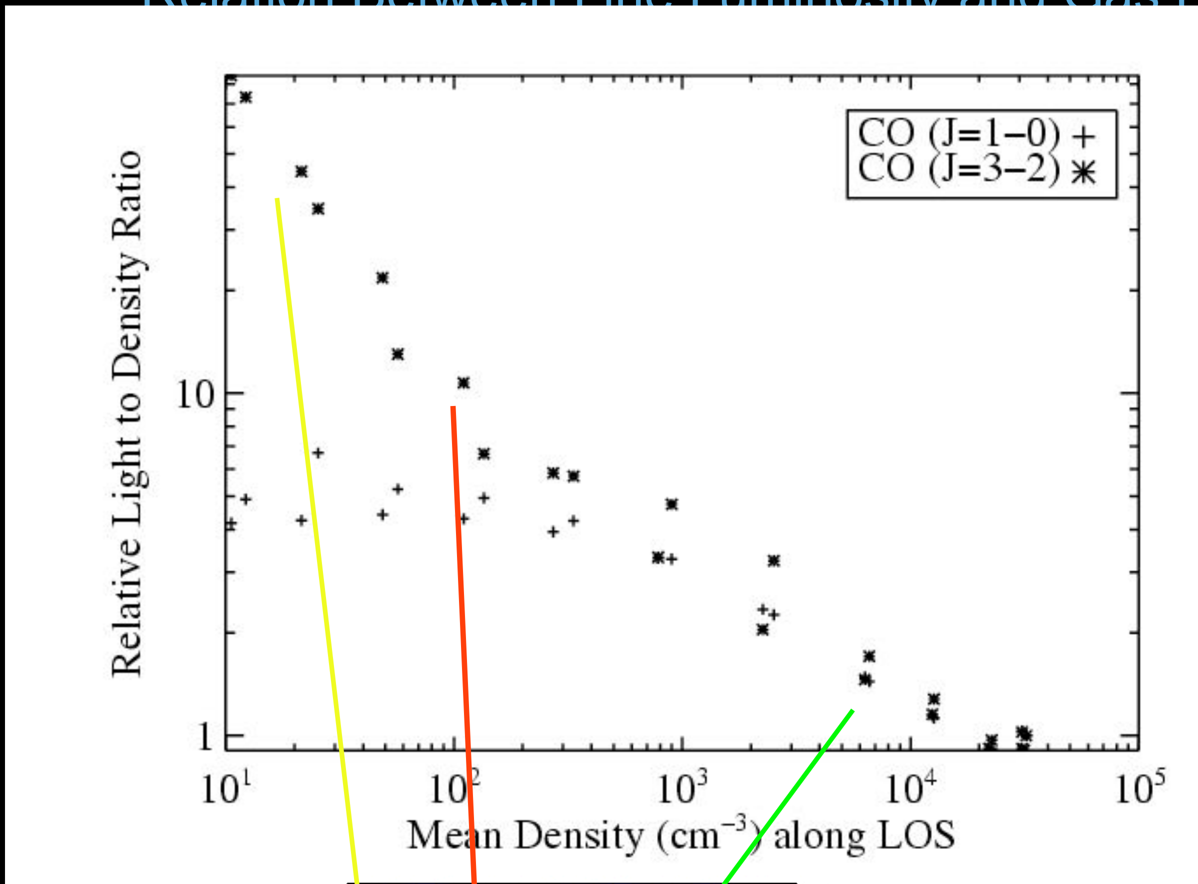
Prescriptions for multi-phase ISM (McKee-Ostriker), SF, BH growth and associated Feedback (though BH winds turned off)

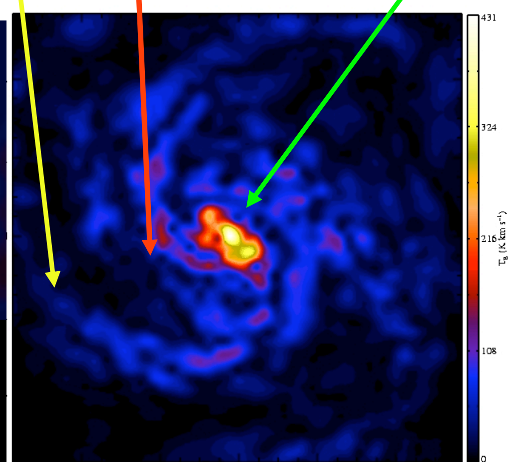
100 galaxies used:
- **20 disk Galaxies**
- **80 merger snapshots**

SF follows SFR $\alpha\ \rho^{1.5}$

Assuming the free-fall time argument for SFR ~ $\rho^{1.5}$ holds

Relation Between Line Luminosity and Gas Density : CO (J=3-2)





- Emission from subthermally excited cells is characteristically higher than collisions in the diffuse gas would normally account for.

- Emission from this gas along the LOS results in superlinear relation between increasing gas density and CO (J=3-2) flux.

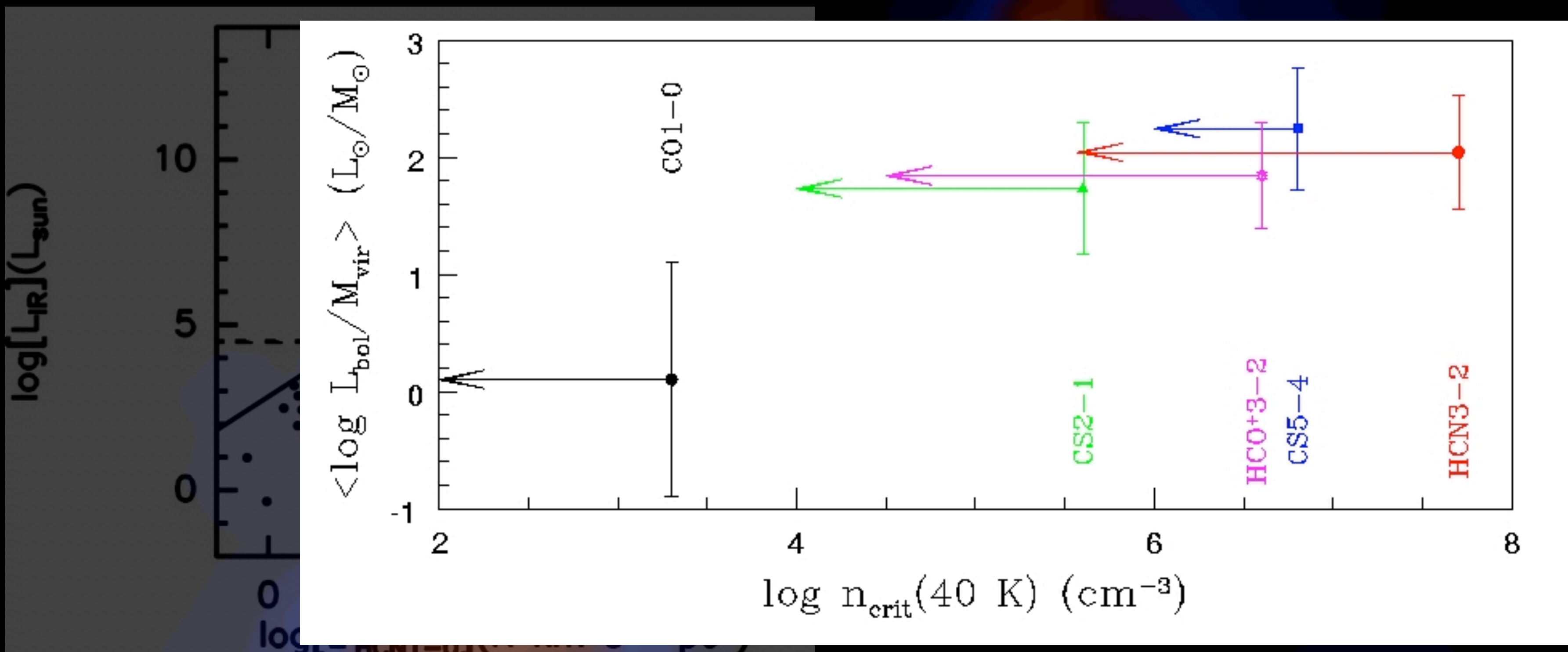
$SFR \sim L_{CO\ (J=3-2)}^{\ \alpha}$

$L_{CO\ (J=3-2)} \sim \rho^{\ \beta}$

$\beta \sim 1.5$

Then $\alpha = 1.5/\beta \sim 1$

Caveats: What about L_{IR}-L_{mol} relation in dense GMC cores?



Shirley et al. 2008

L_{IR} α HCN (J=1-0)

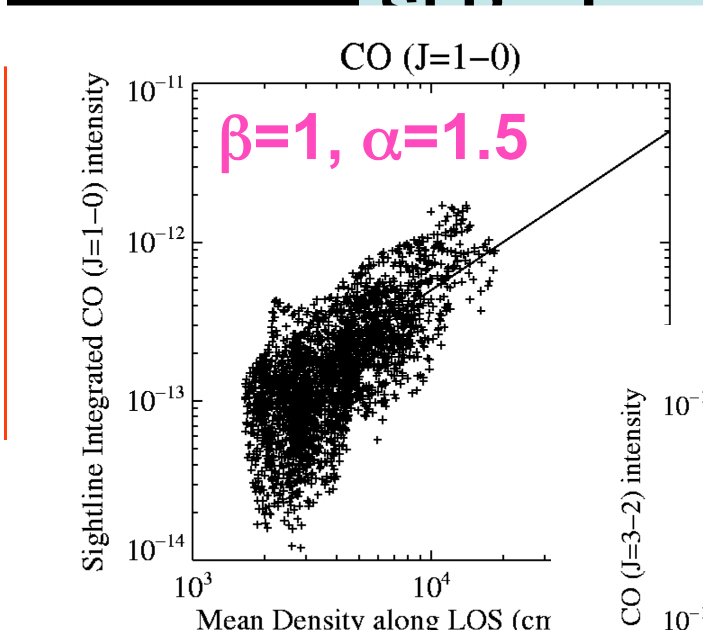
Wu et al. 2005

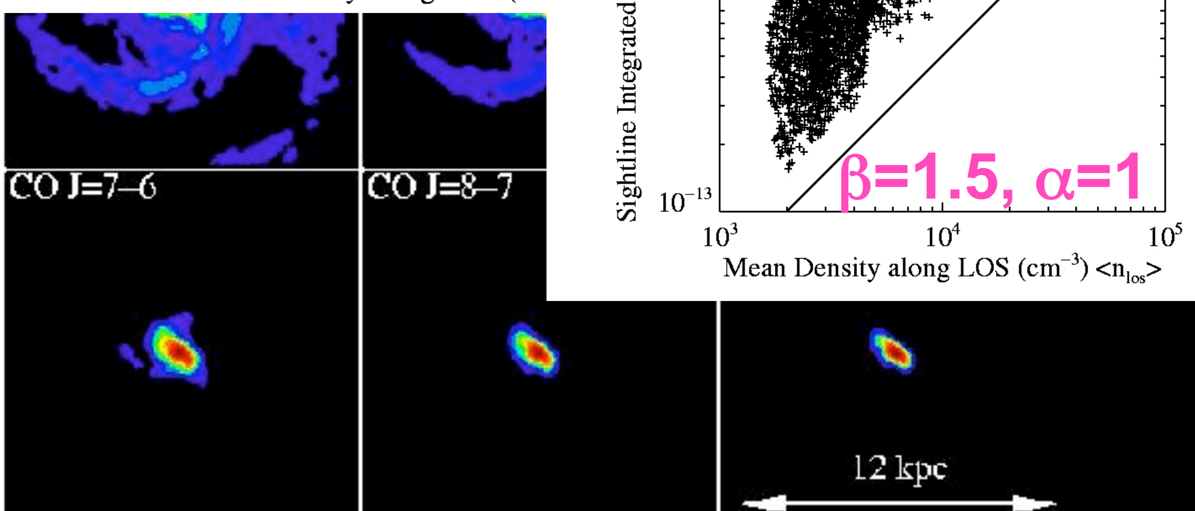
SFR ~ $\rho^{1.5}$ (assumed Schmidt Law)

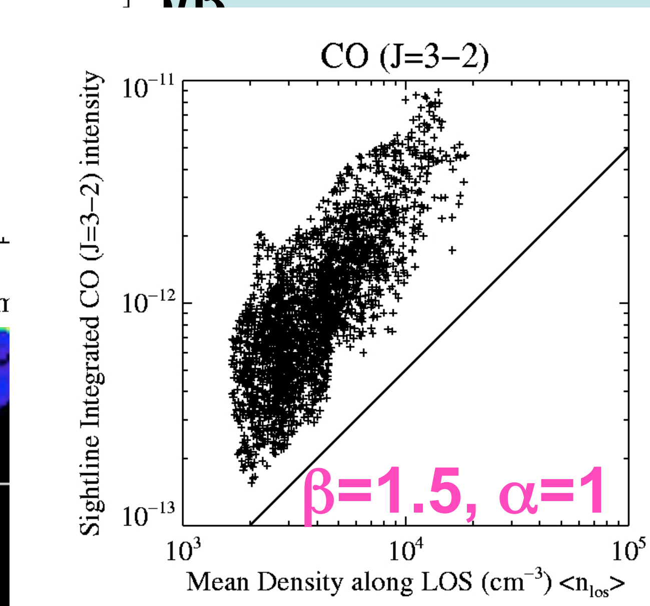
SFR ~ L ... ecule $^{\alpha}$ (observed)

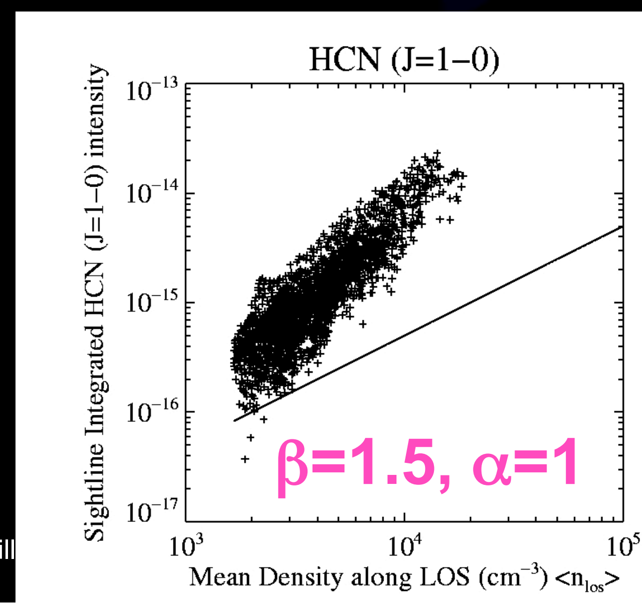
... $^{\beta}$

... 5/β

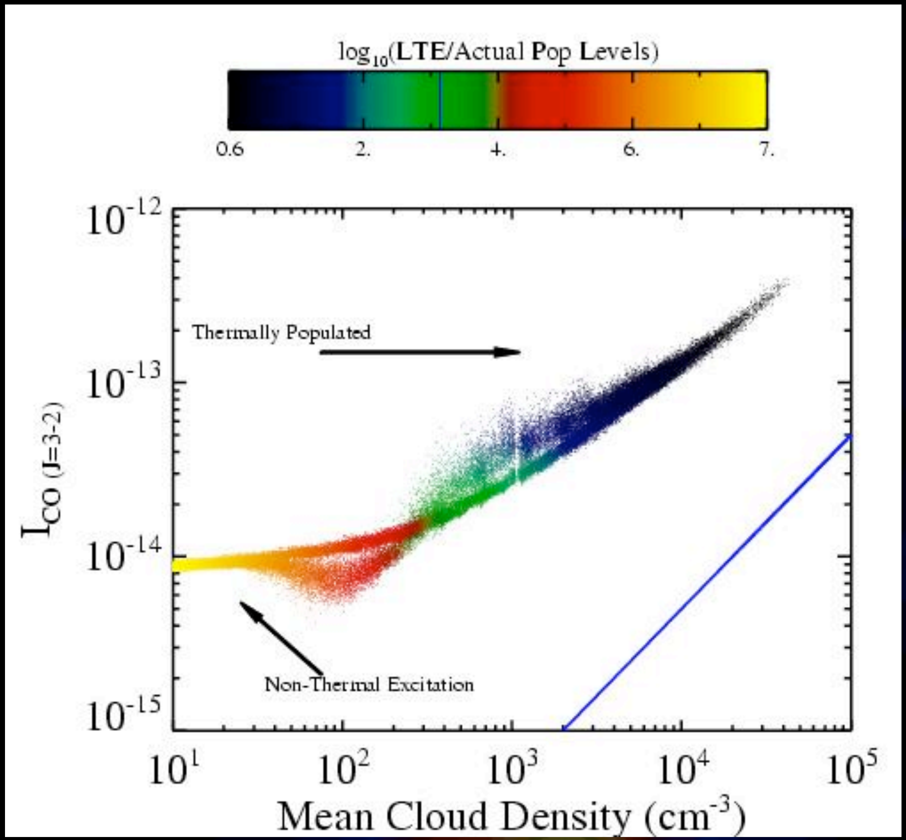


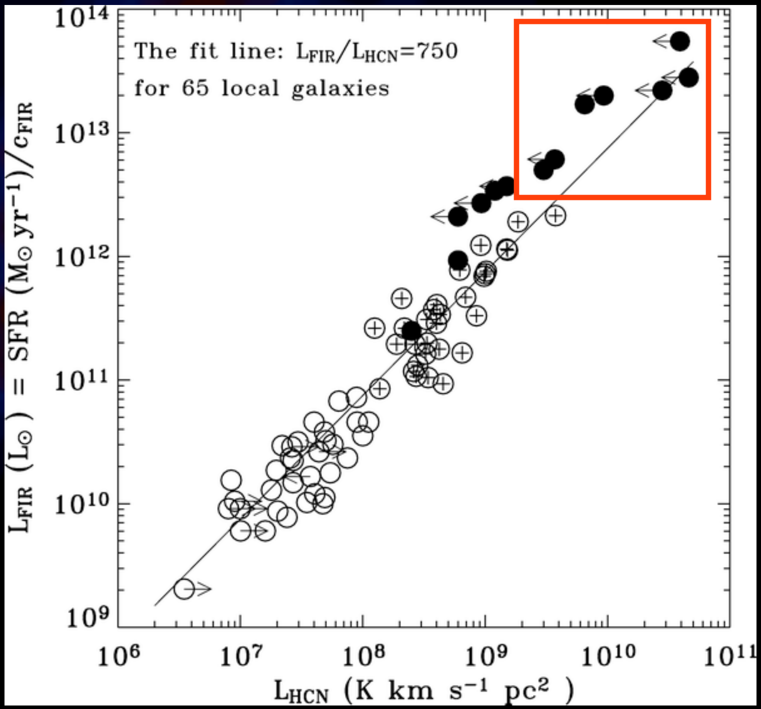






Observational Test: High Mean Density Limit





Gao et al. 2007

Mostly thermalized gas means β~1

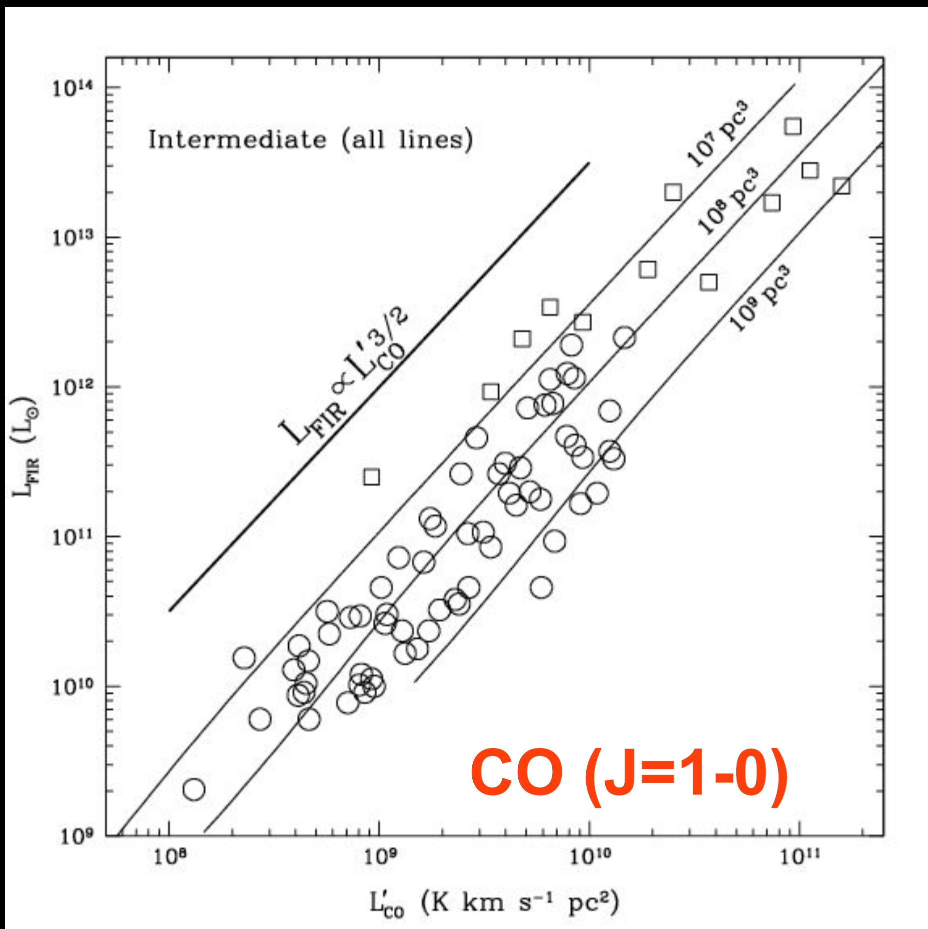
SFR ~ $L_{CO\ (J=3-2)}^{\ \alpha}$

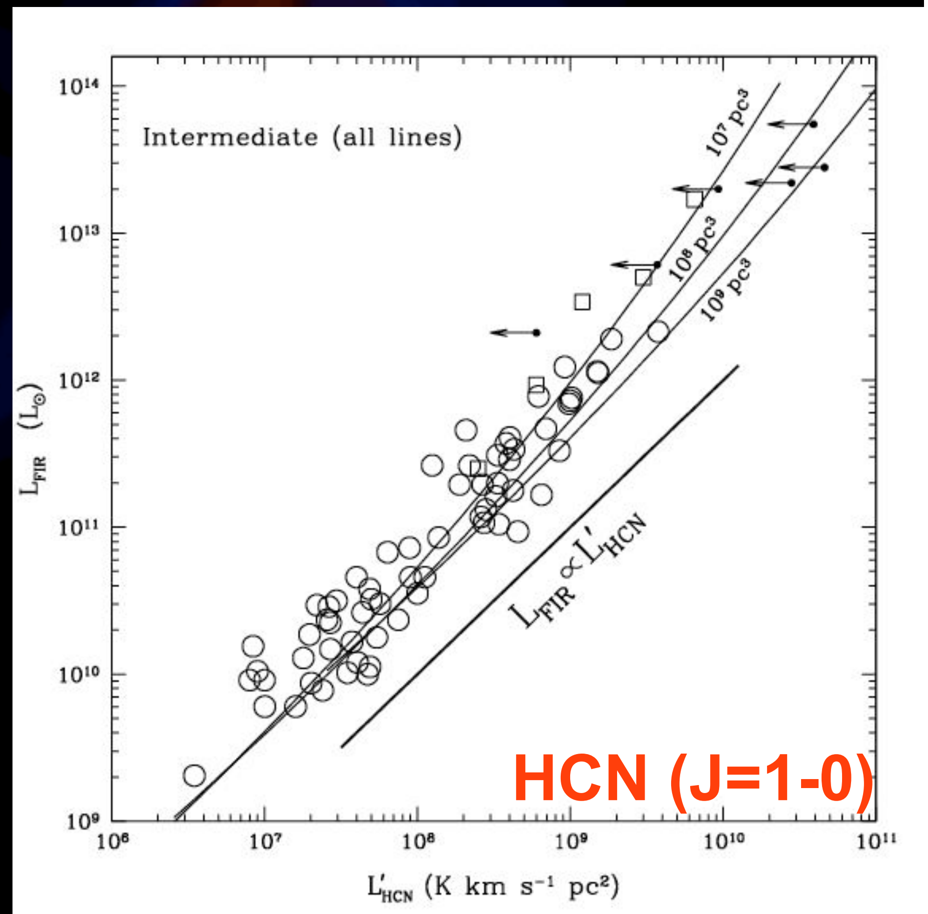
$L_{CO\ (J=3-2)} \sim \rho^{\beta}$

Mostly thermalized gas means β~1

Then $\alpha = 1.5/\beta \sim 1.5$

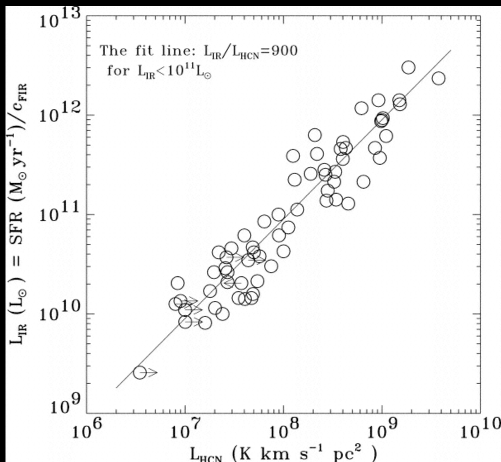
Krumholz & Thompson Models for GMCs



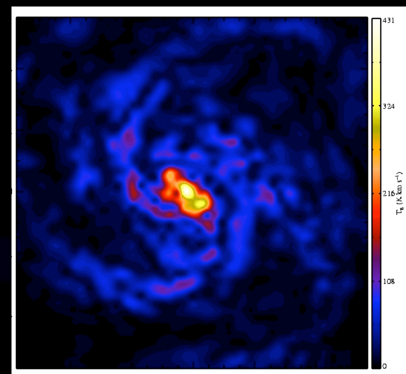


Krumholz & Thompson, 2007 - model works for individual clouds

The relationship between the SFR-Lmol relation in GMCs and Galaxies

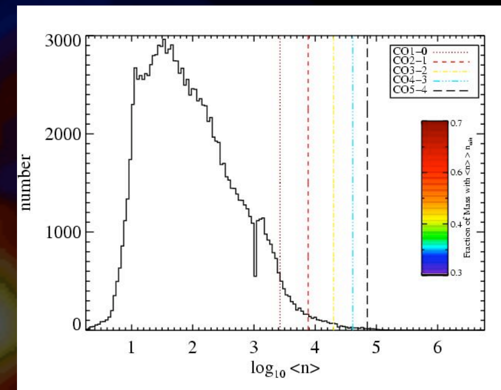


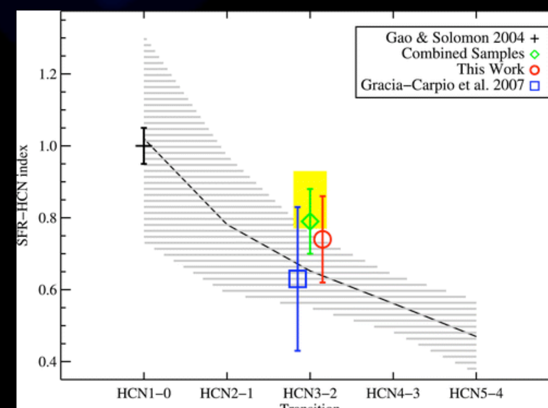
Gao et al. 2004



SFR ~ $\rho^{1.5}$

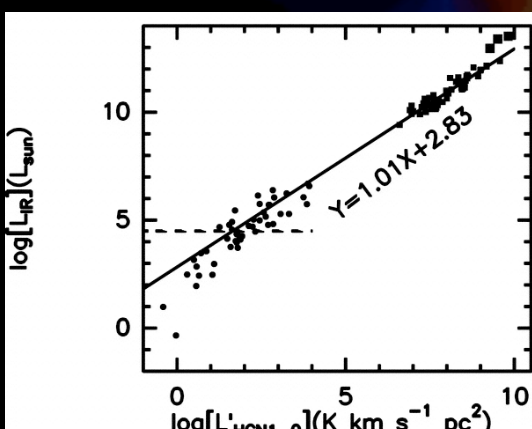
Narayanan et al. 2008



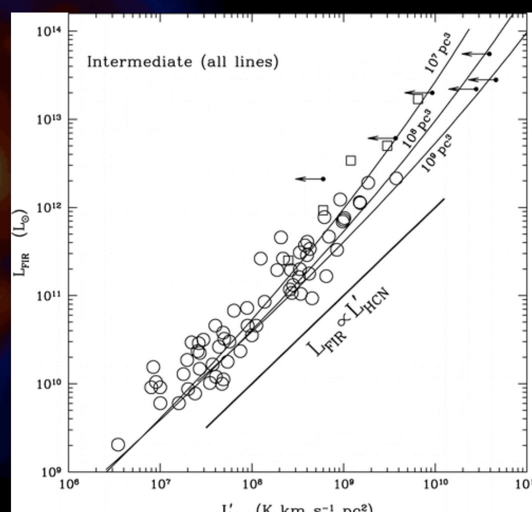


Bussmann et al. 2008

Wu et al. 2005



Krumholz et al. 2008



<n> >> n_{crit} slope=1.5

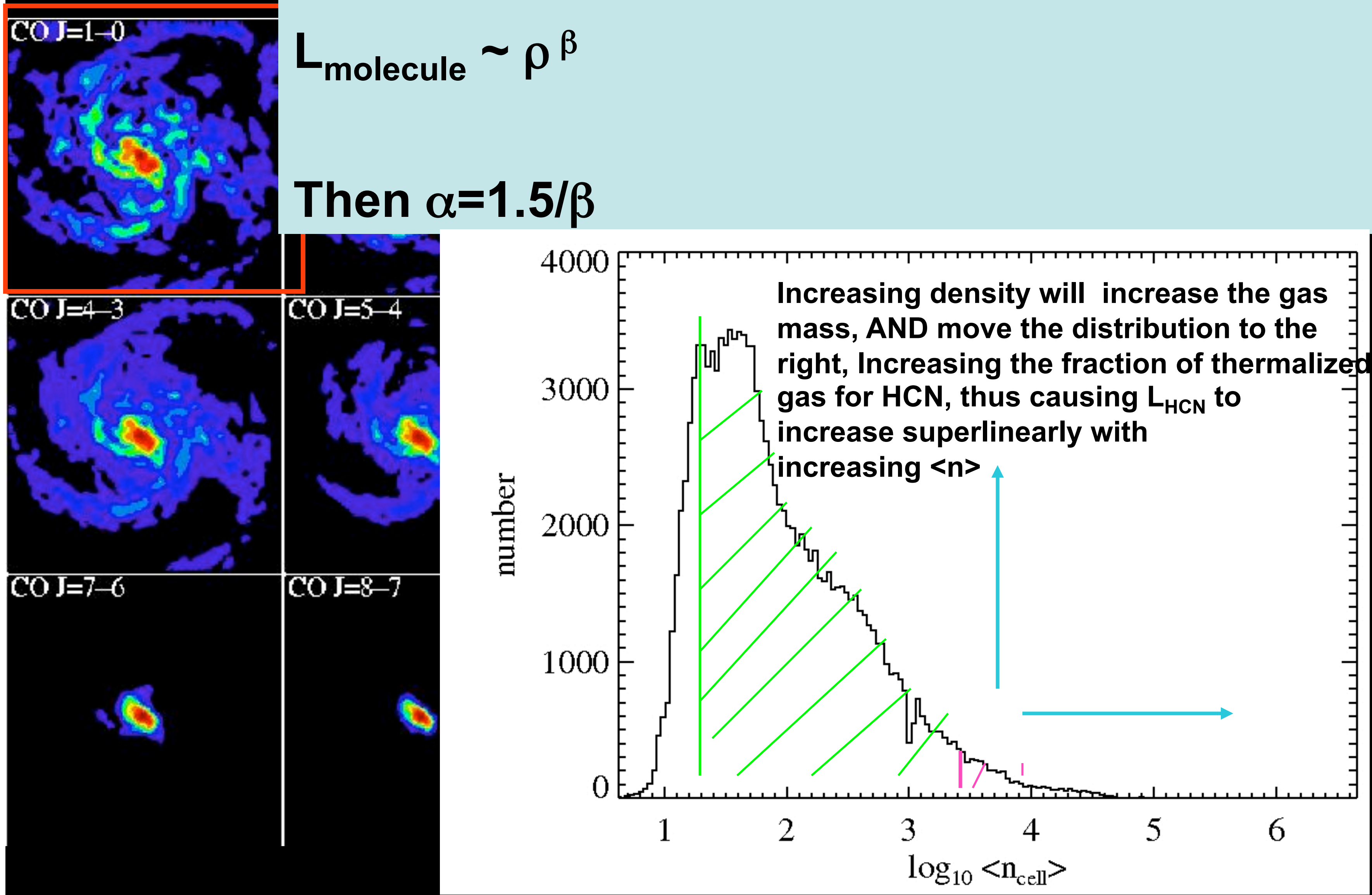
<n> << n_{crit} slope < 1.5

SFR ~ $\rho^{1.5}$ (assumed Schmidt Law)

SFR ~ $L_{molecule}^{\alpha}$ (observed)

$L_{molecule} \sim \rho^{\beta}$

Then α=1.5/β



Narayanan et al. 2008