Molecular SFR Indicators in Galaxies

Desika Narayanan
Harvard-Smithsonian CfA

Radiative Transfer Modeling
Yancy Shirley
Romeel Dave
Chris Walker

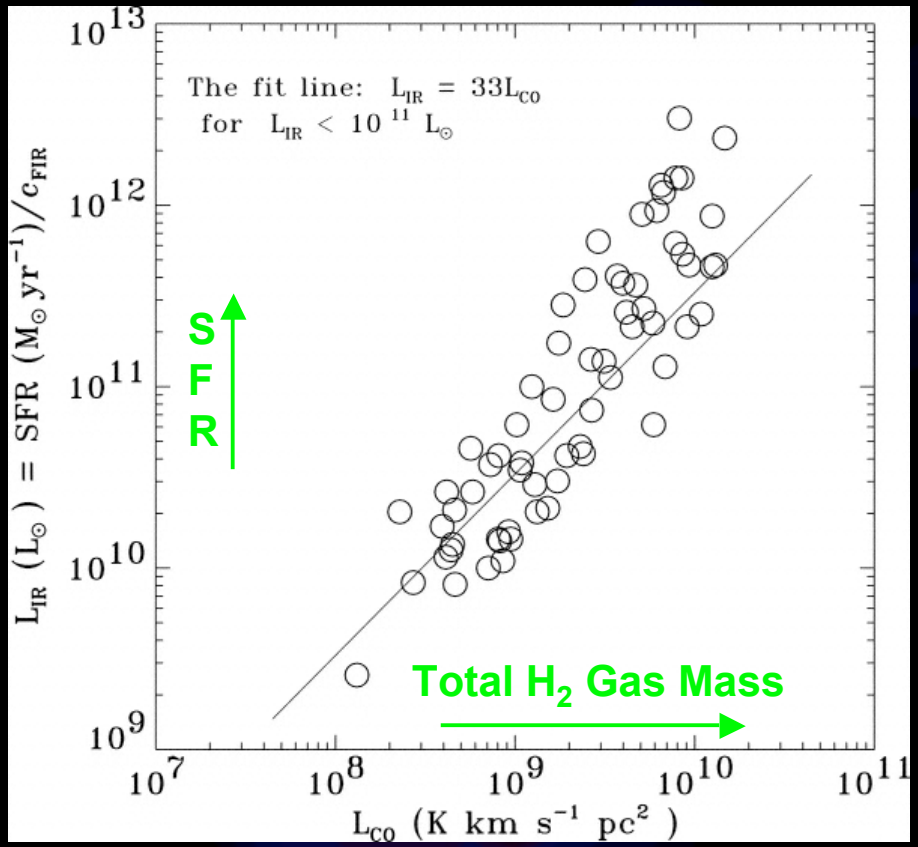
Hydrodynamic Modeling
T.J. Cox
Lars Hernquist

Observations
Shane Bussmann
Stephanie Juneau
John Moustakas
Yancy Shirley
Phil Solomon
Paul Vanden Bout
Jingwen Wu

Molecular SFR Laws
(much ado about exponents)

CO J=1-0

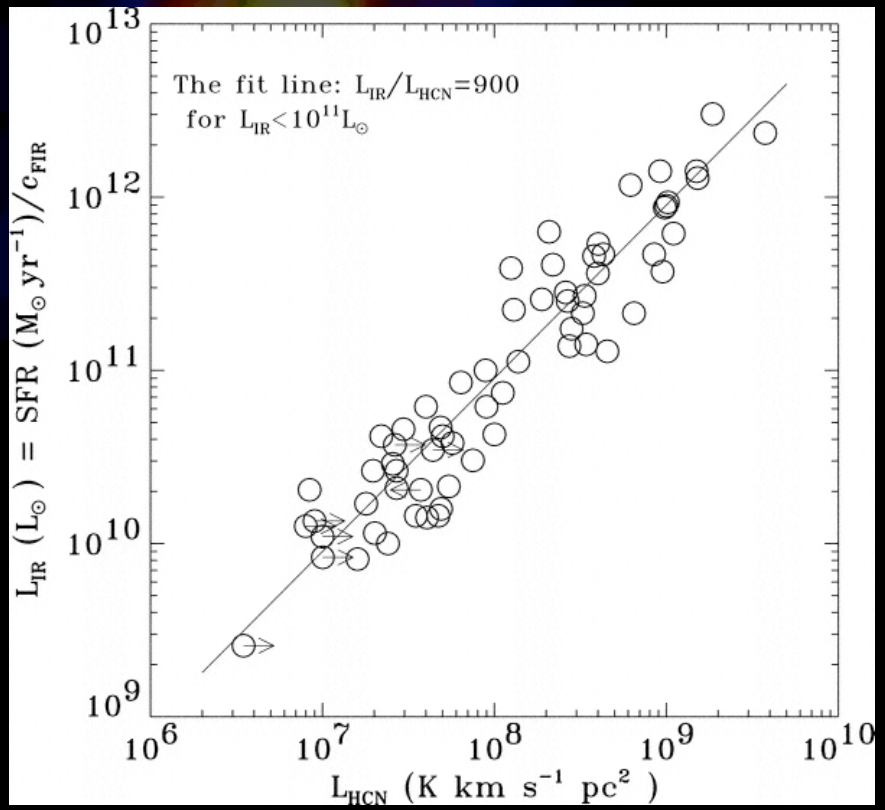
$SFR \propto \rho_{(>100 cm^{-3}) gas}^{1.5}$



Gao & Solomon, 2004

HCN J=1-0

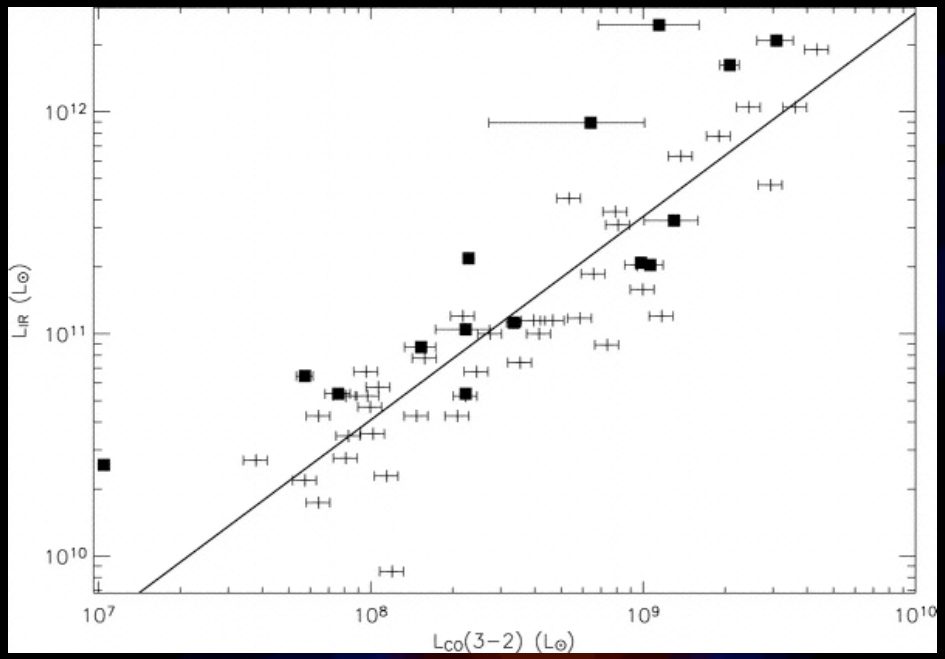
$SFR \propto \rho_{(>10^5 cm^{-3}) gas}^{1}$



Molecular SFR Laws

CO J=3-2

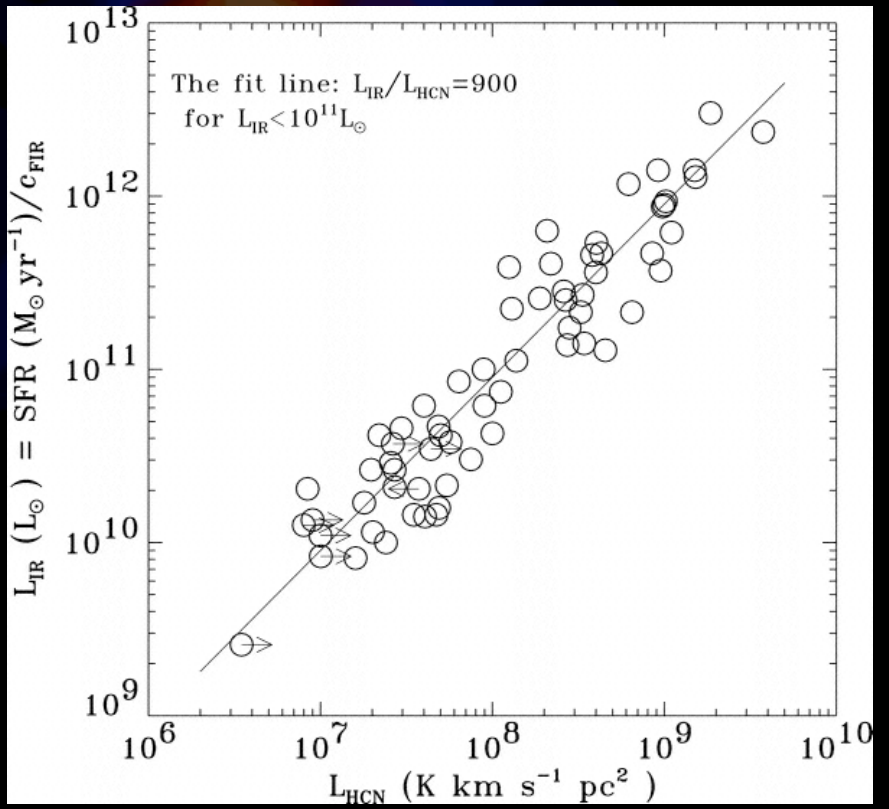
SFR α $\rho_{(>10^5 cm^{-3}) gas}$ **0.92**



Narayanan et al 2005

HCN J=1-0

SFR α $\rho_{(>10^5 cm^{-3}) gas}$ **1**



Gao & Solomon 2004

Chicken or Egg?

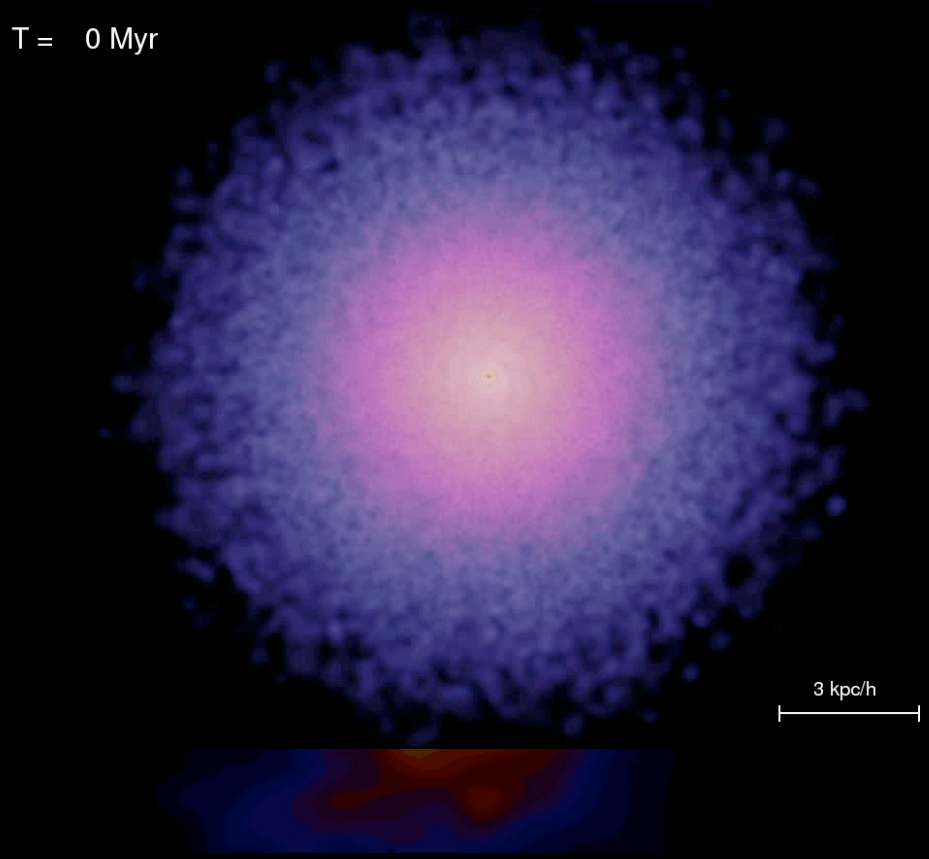
- SFR is linearly dependent on dense gas (N=1). Where does SFR-CO(1-0) index come from?
  - » SFR ~ ρ_{dense}

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

- KS index of N=1.5 is underlying; Where does SFR-HCN (1-0) index come from.
  - » SFR ~ $\rho^{1.5}$

Krumholz & Thompson 2007, Narayanan et al. 2008, Bussmann et al. 2008, Juneau et al. (in prep.)

GADGET SPH Simulations



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

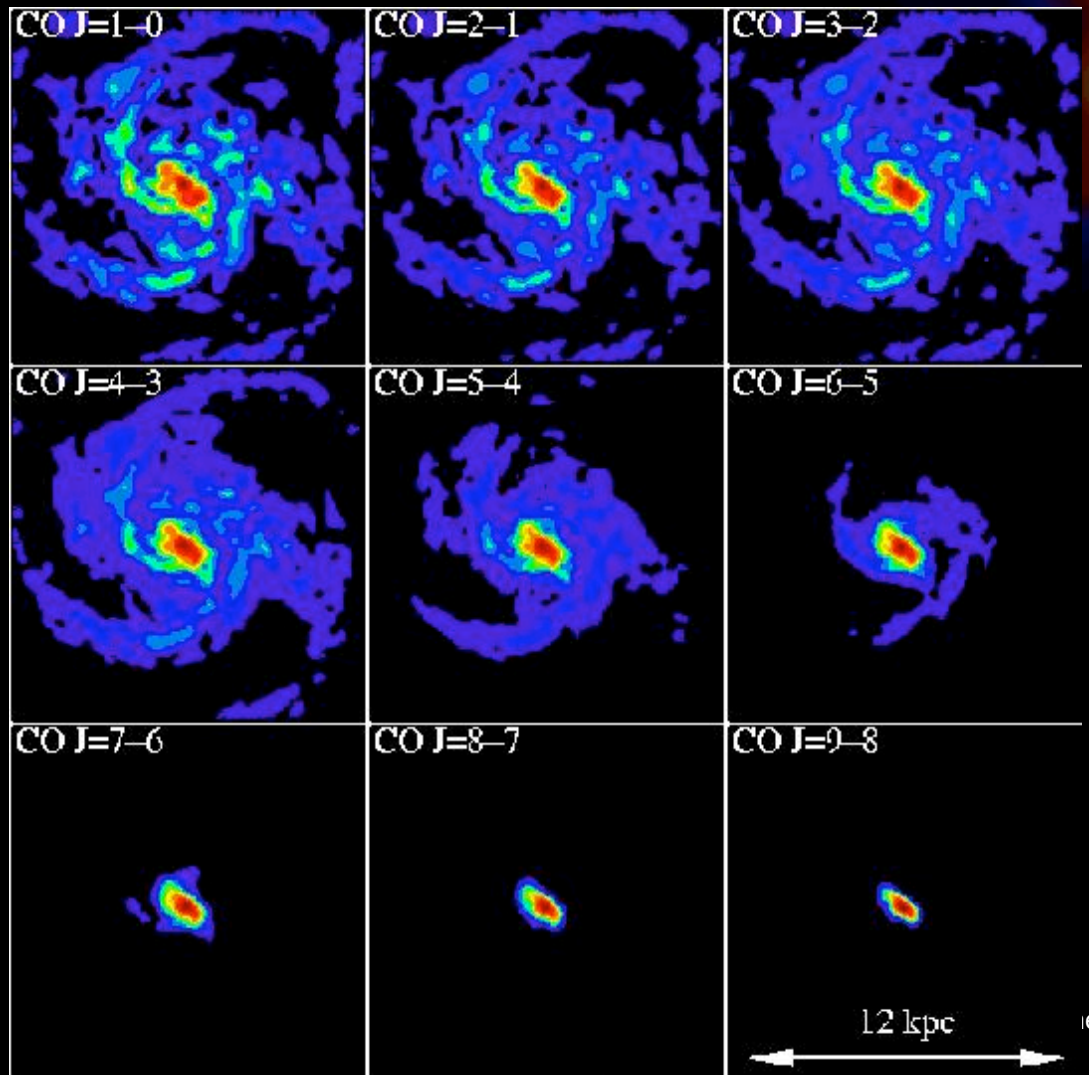
100 galaxies used:
20 disk Galaxies
80 merger snapshots

SF follows SFR α $\rho^{1.5}$

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)
- $M_{cloud}=10^4$-10^6 $M_\odot$, Uniform Galactic CO Abundance, 10 CO transitions, 10 million rays per iteration



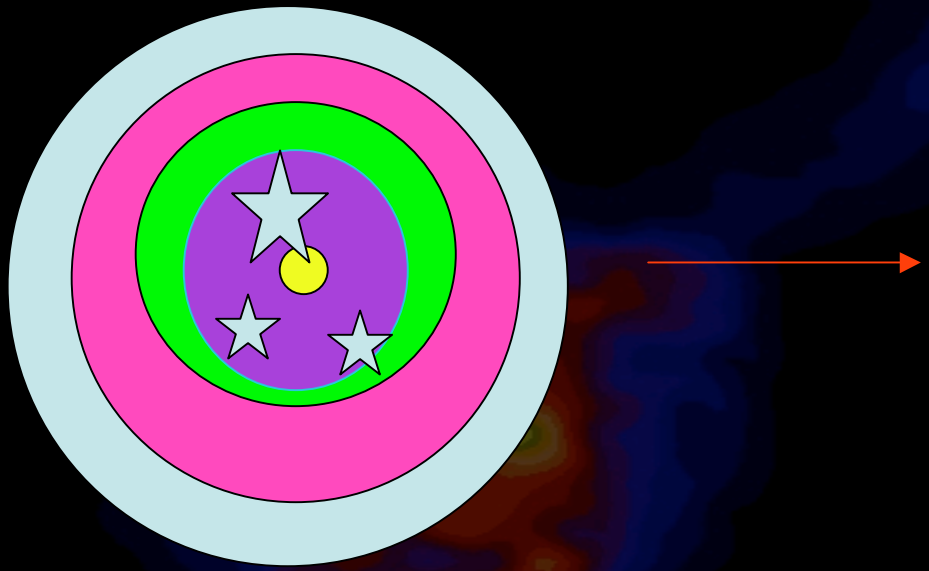
Included 100 galaxies:
20 isolated disks
80 mergers in various stages of evolution

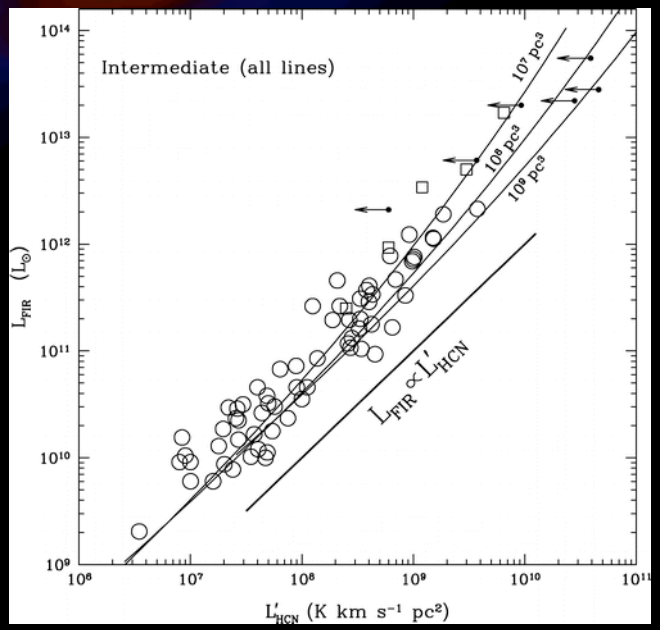
Narayanan+ 2006,2008

Krumholz & Thompson GMC models

- Escape Probability Radiative Transfer + analytic models of GMCs
  = SFR-Lmol relation

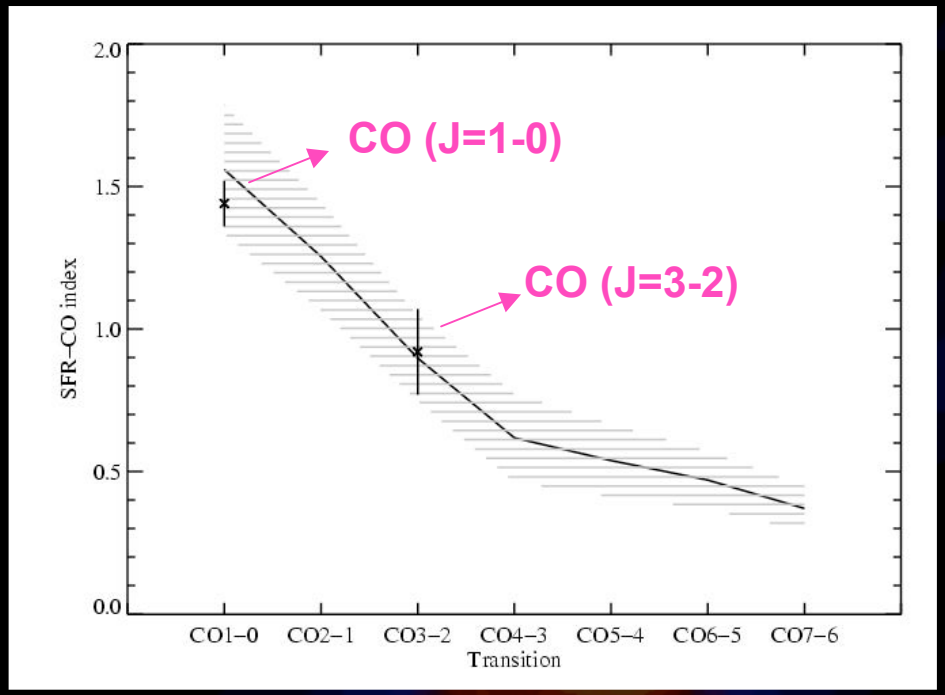
(SF follows SFR α $\rho^{1.5}$)



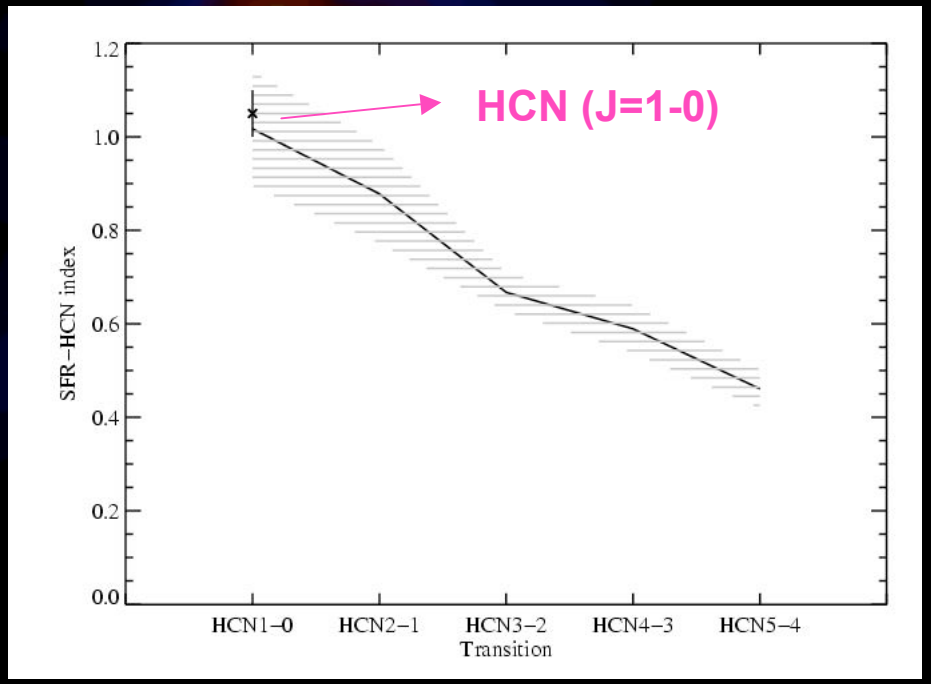


Can we Recover the Basic Relations?

SFR-CO index



SFR-HCN index

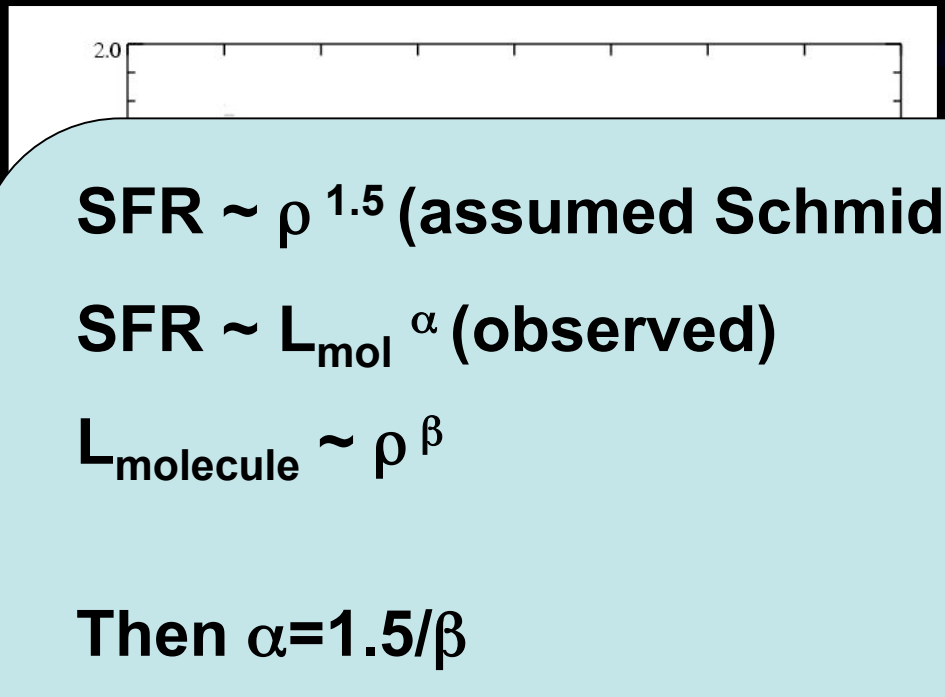


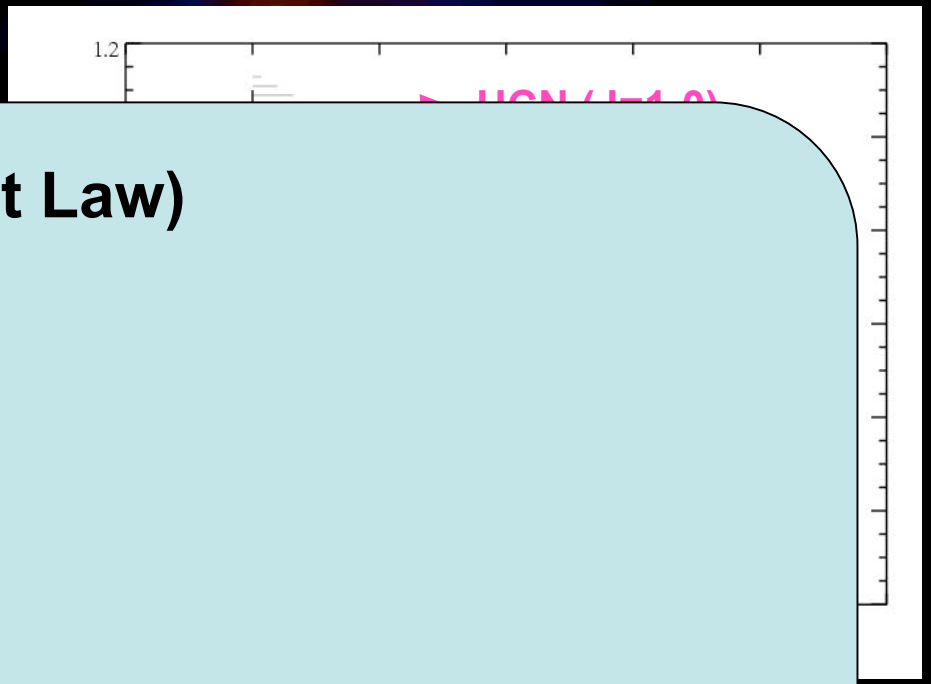
Narayanan et al. 2008

SF follows SFR α $\rho^{1.5}$

Can we Recover the Basic Relations?

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





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

SFR ~ L_{mol}^{α} (observed)

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

Then α=1.5/β

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

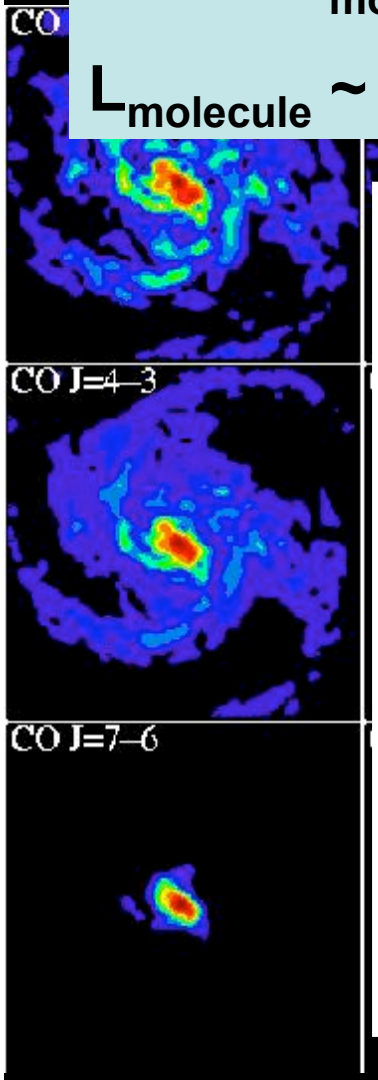
SF follows SFR α $\rho^{1.5}$

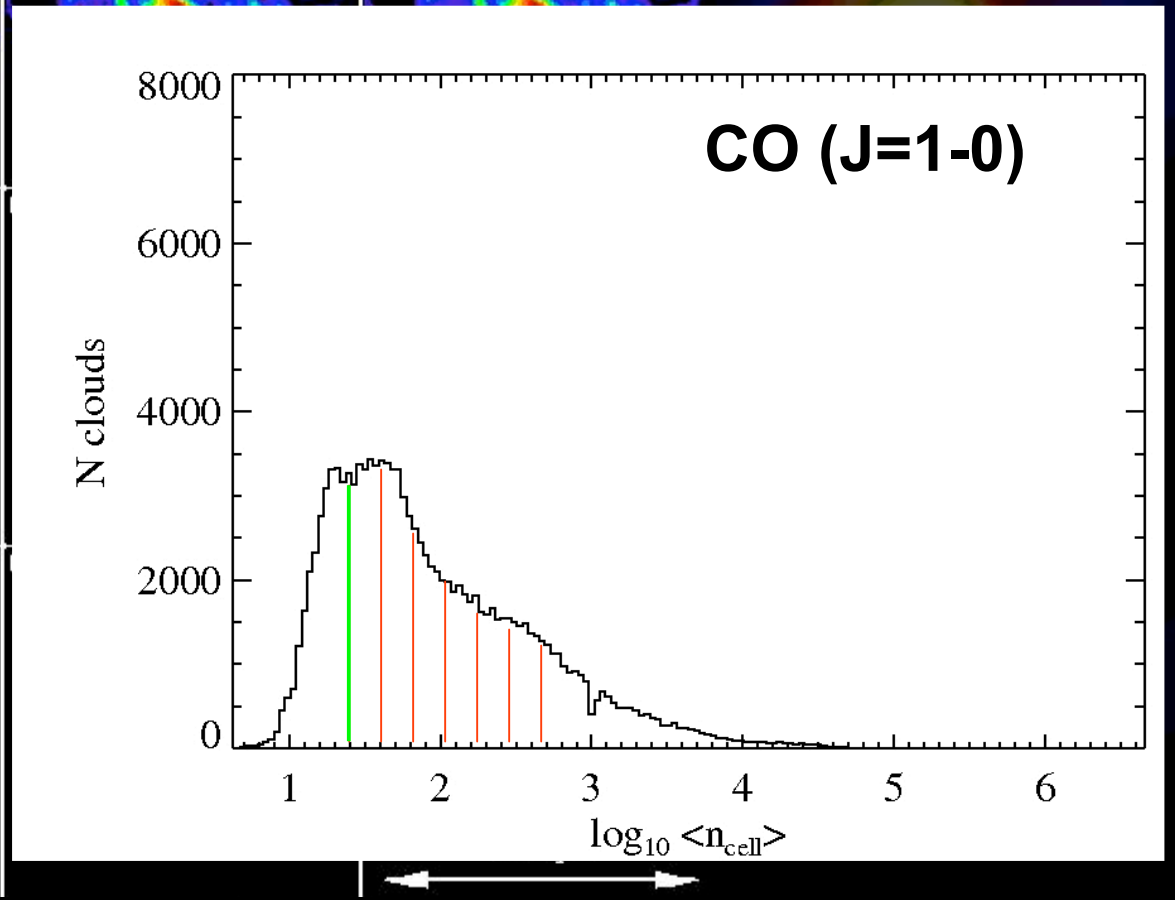
Narayanan et al. 2008

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

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

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



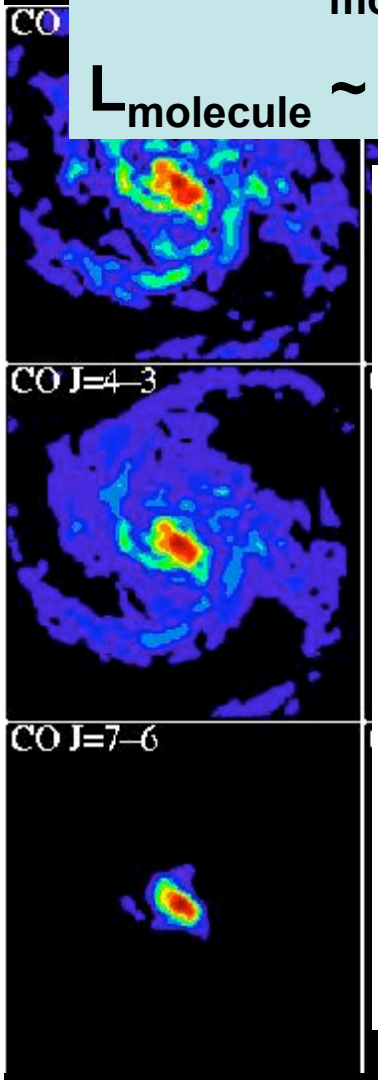


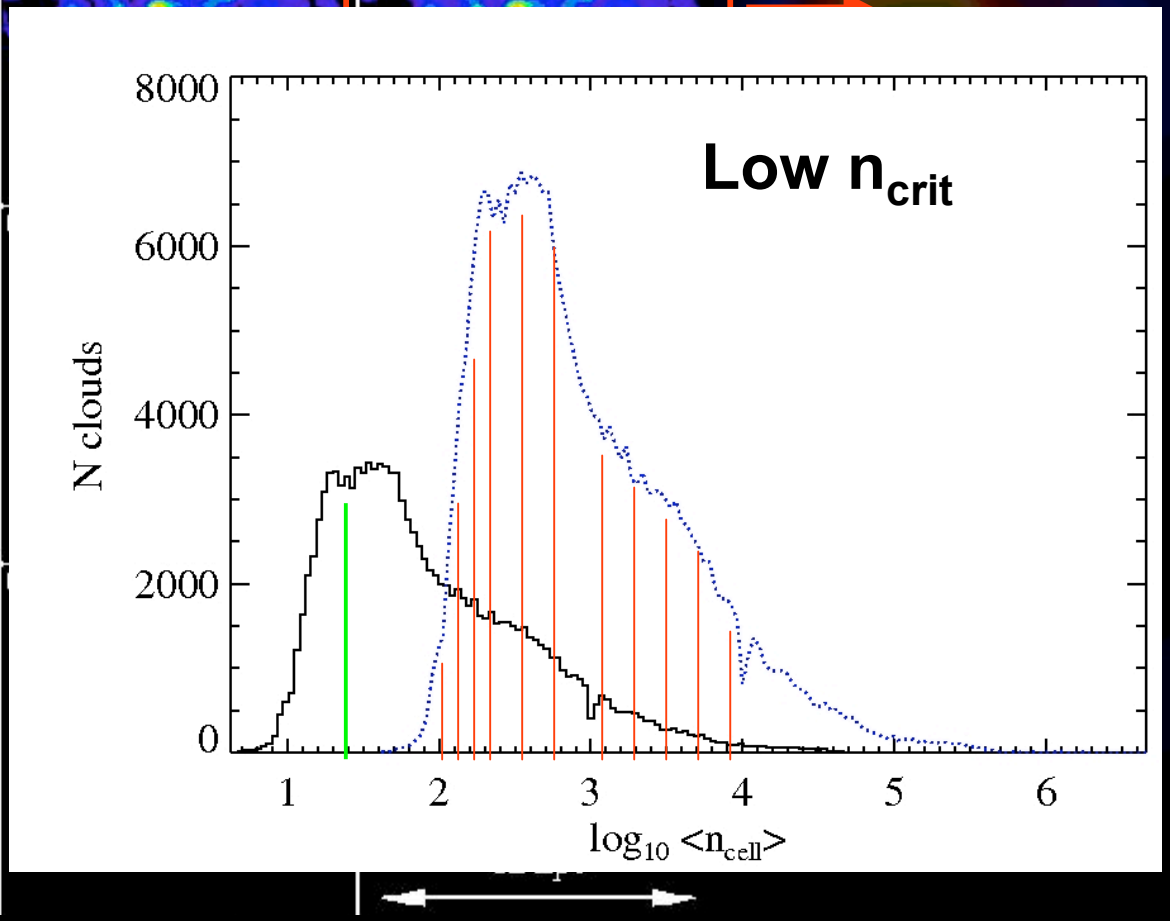
Narayanan et al. 2008

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

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

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



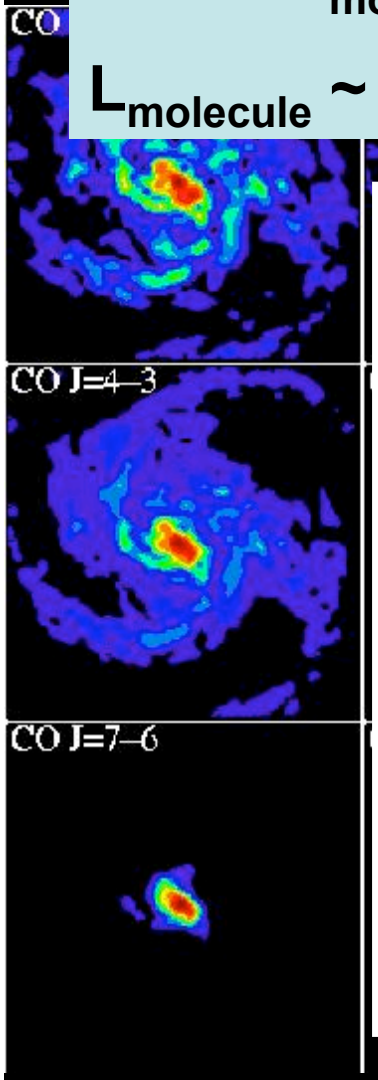


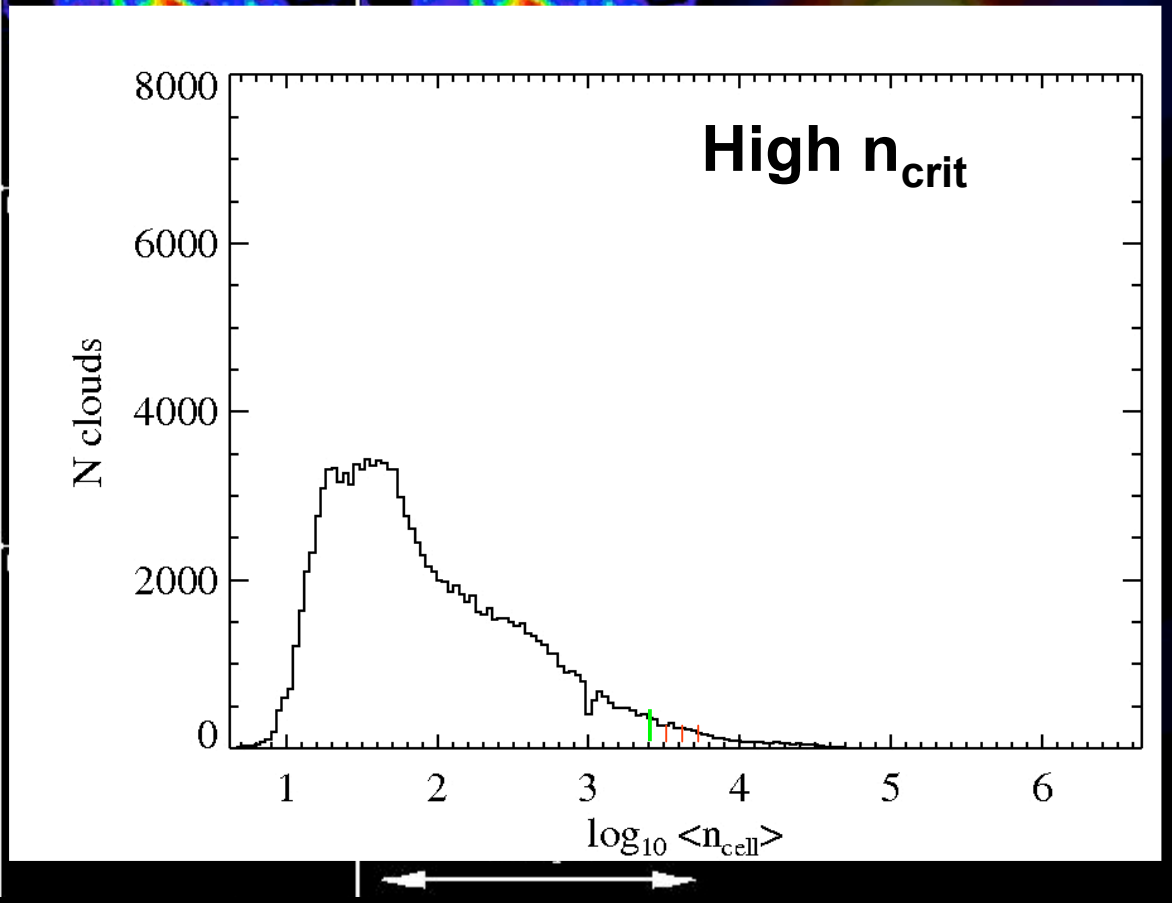
Narayanan et al. 2008

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

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

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



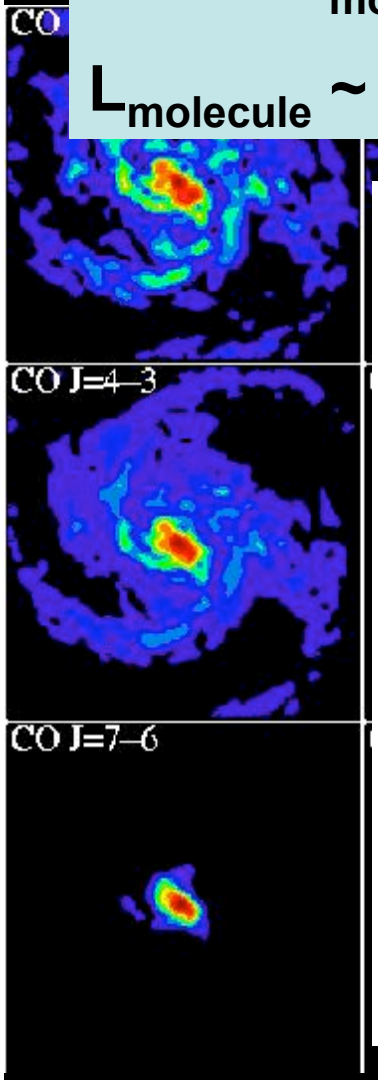


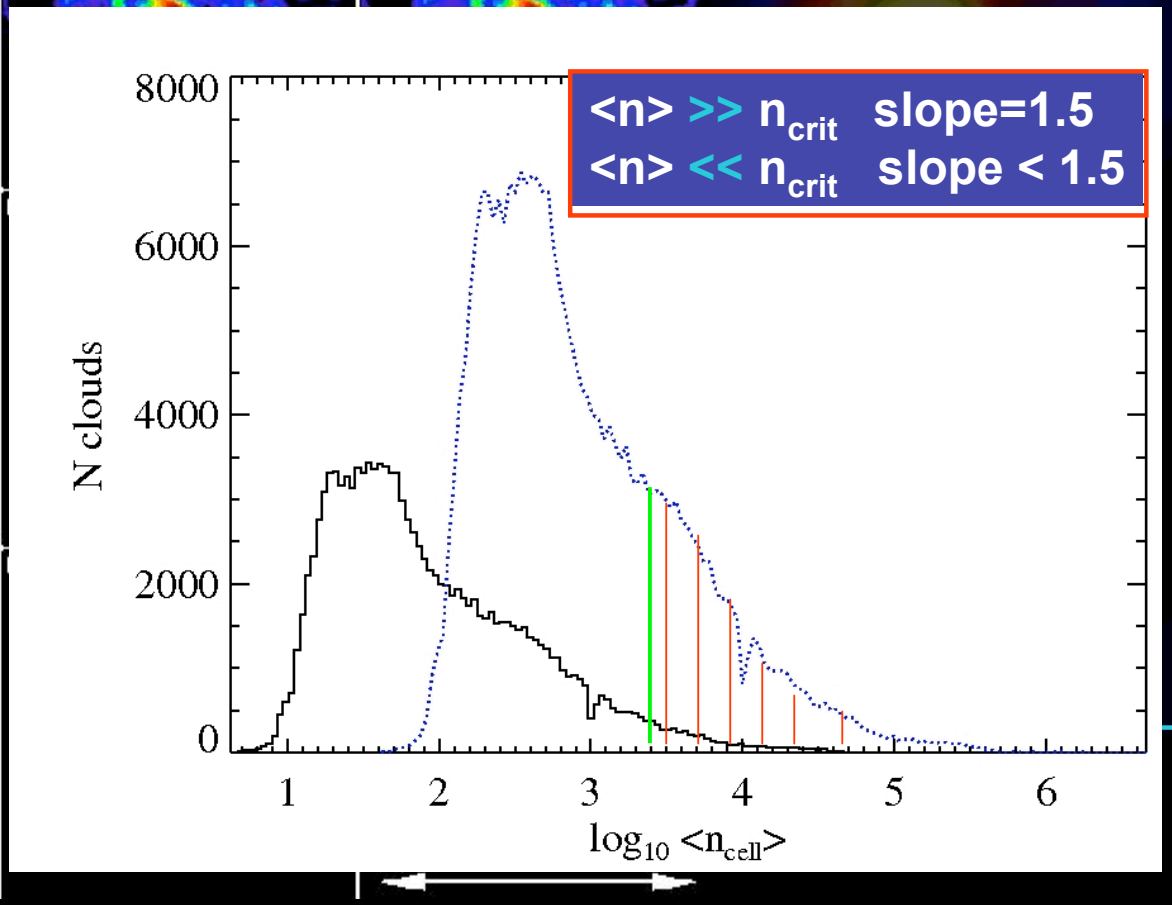
Narayanan et al. 2008

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

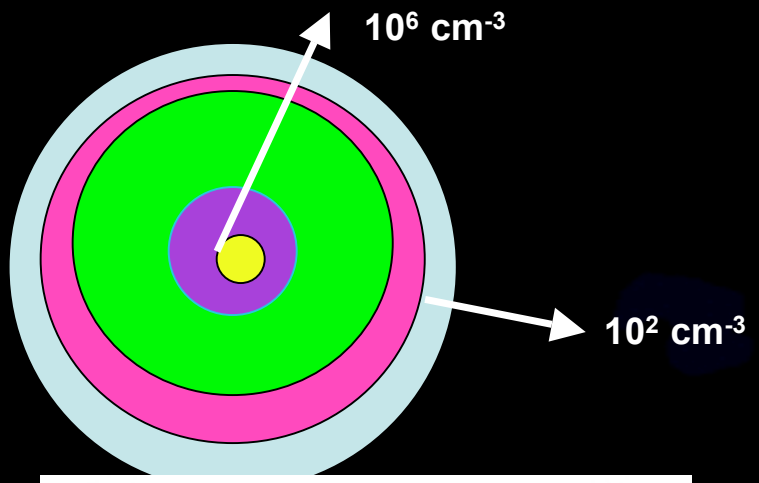
$SFR \sim L_{molecule}^{\alpha}$ (observed)

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

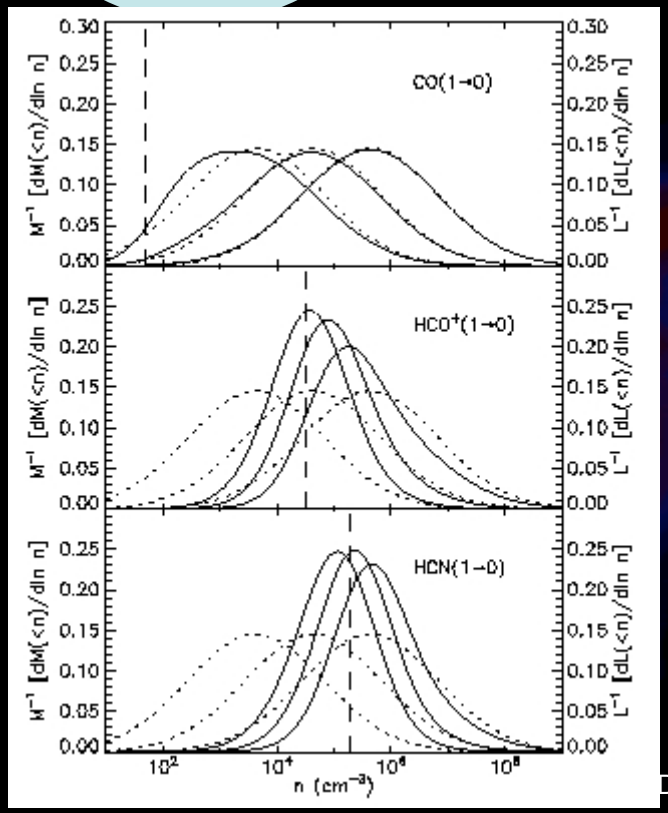


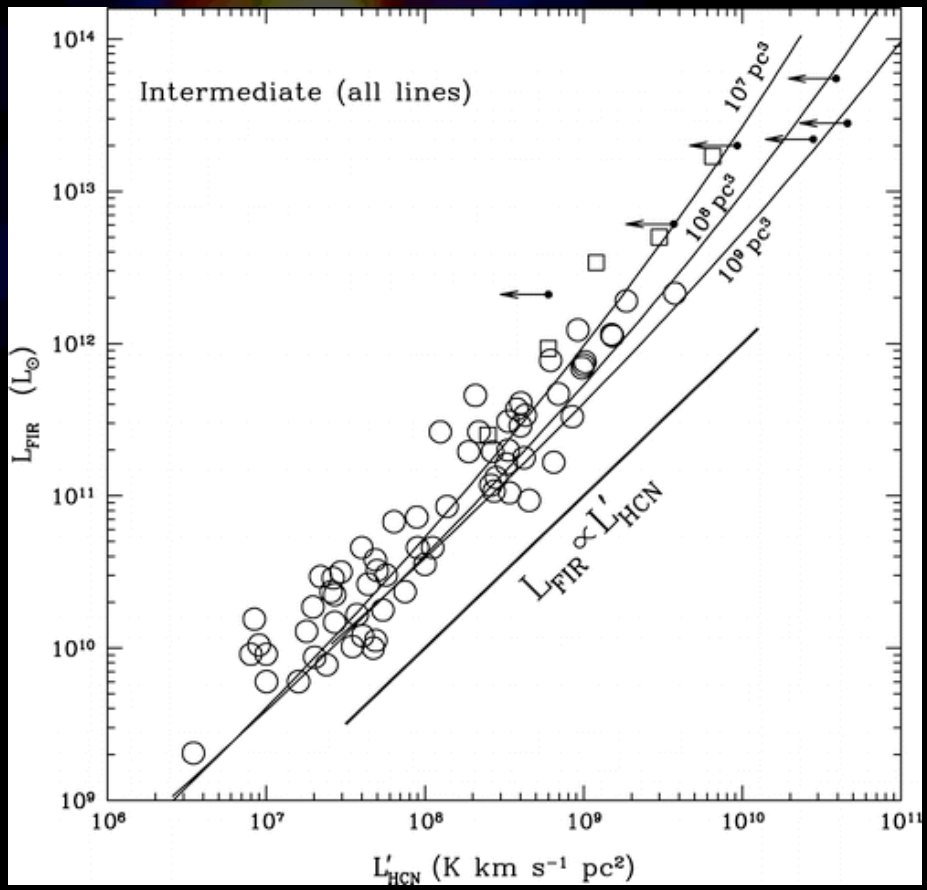


Krumholz & Thompson Models for GMCs



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





Krumholz & Thompson 2007

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; 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>;

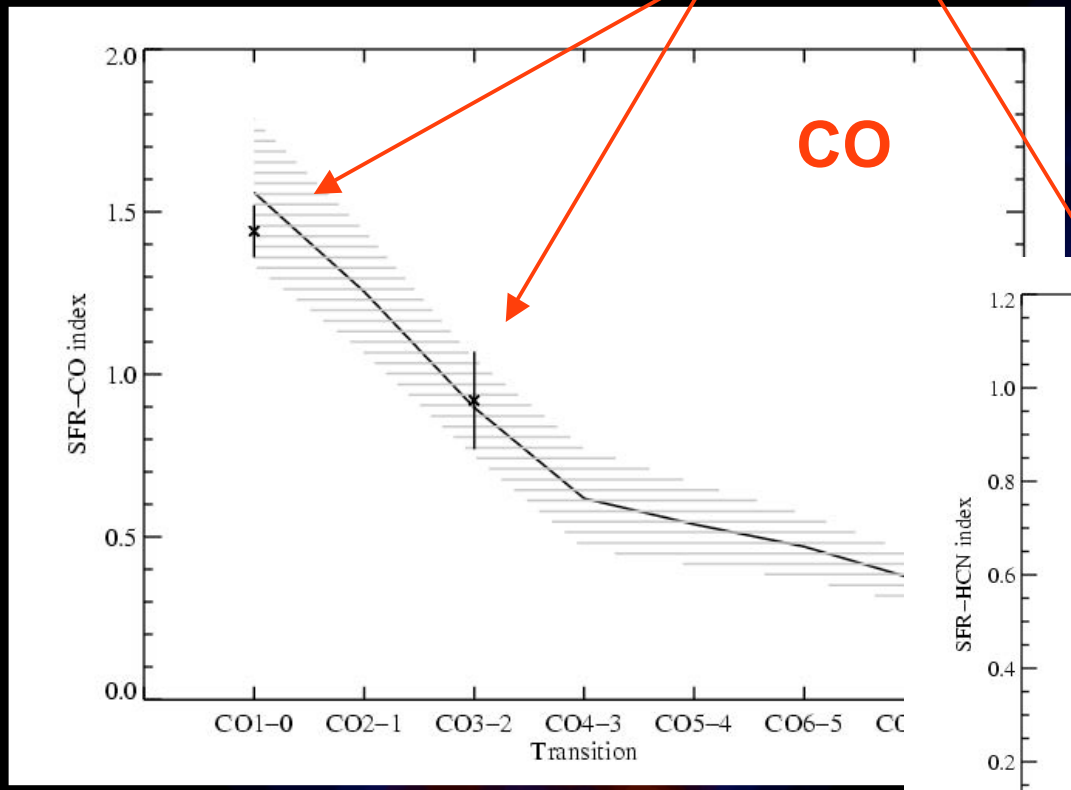
-observed SFR-L_{mol} relation will change with increasing n_{crit}

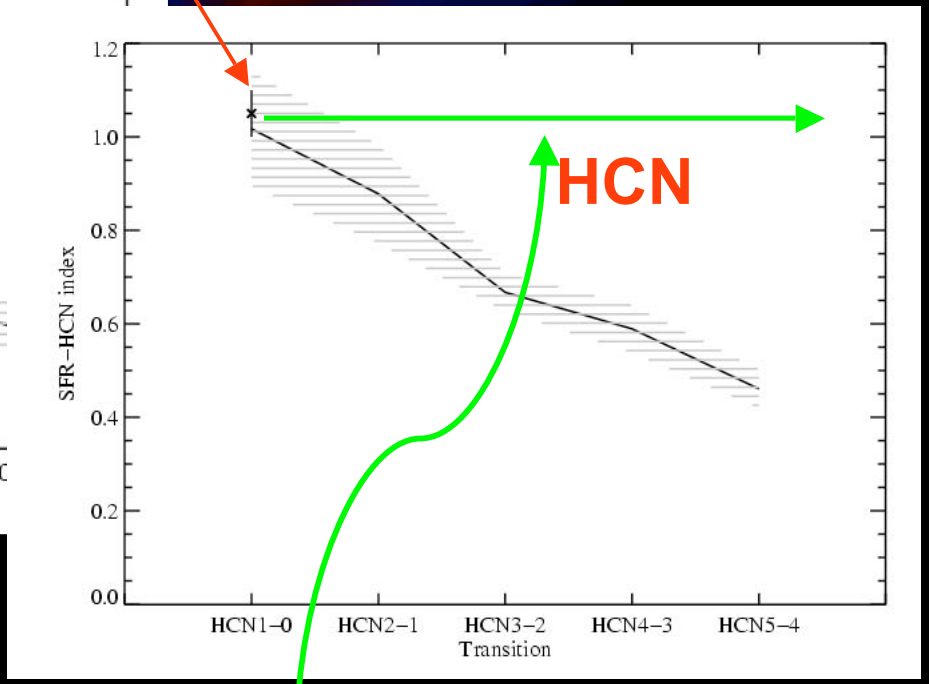
- Krumholz & Thompson 2007, DN et al. 2008

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

Predicted Slopes for CO and HCN

Observational Points



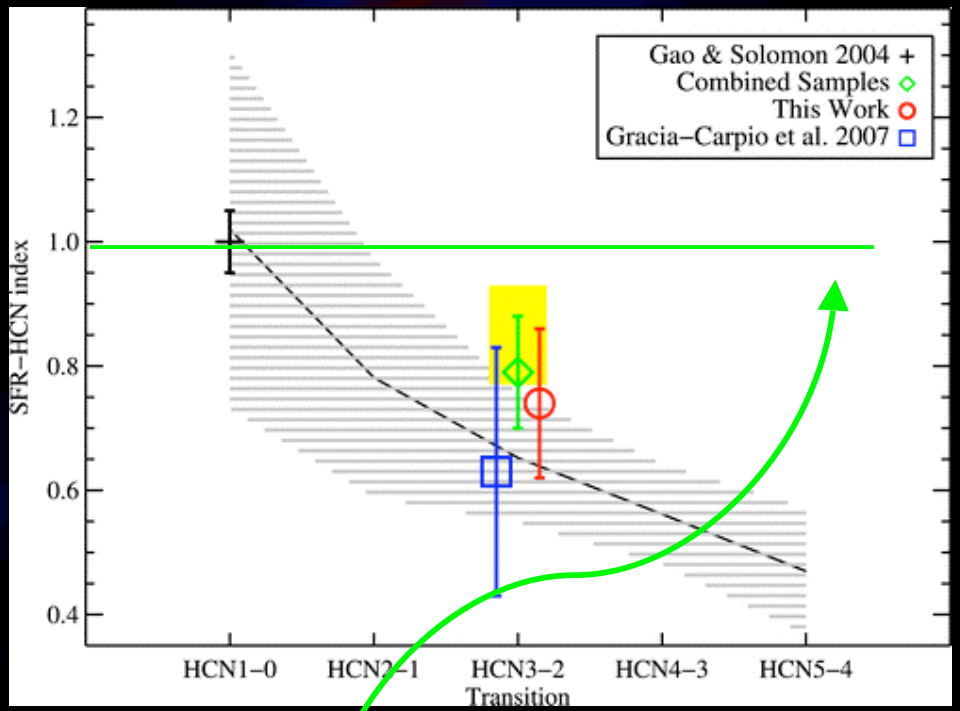


$\langle n \rangle \gg n_{crit}$ slope=1.5
$\langle n \rangle \ll n_{crit}$ slope < 1.5

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

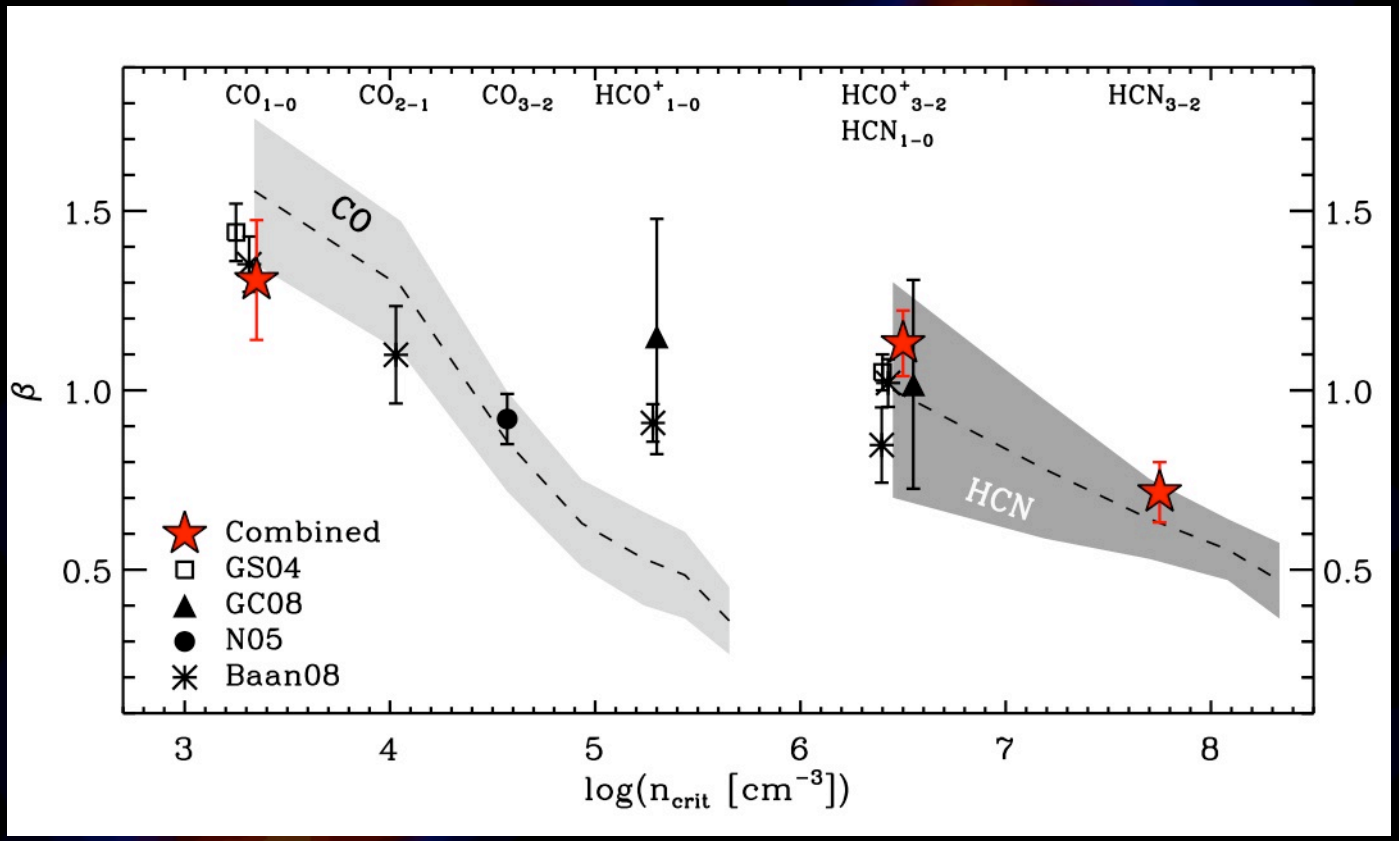


Linear SFR-Lmol relation expected for high ncrit tracers if SFR~ρ_{dense}

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

SFR-Lmol is a fn of n_{crit}

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



Juneau et al. (2009), Bussmann et al. (2008)

(with DN, Shirley, Wu, Moustakas, Kennicutt, Vanden Bout, Solomon)

General Conclusions

- SFR-dense gas relations naturally explained if underlying KS law of N=1.5 controlls SFR
- SFR-L_{mol} index in galaxies and GMCs dependant on the average relation between n_{crit} and the <n>

What do these models NOT say

- Where Schmidt-Kennicutt laws come from
- That stars don't form in dense gas

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