

The Kennicutt-Schmidt Star Formation Relation at z~2

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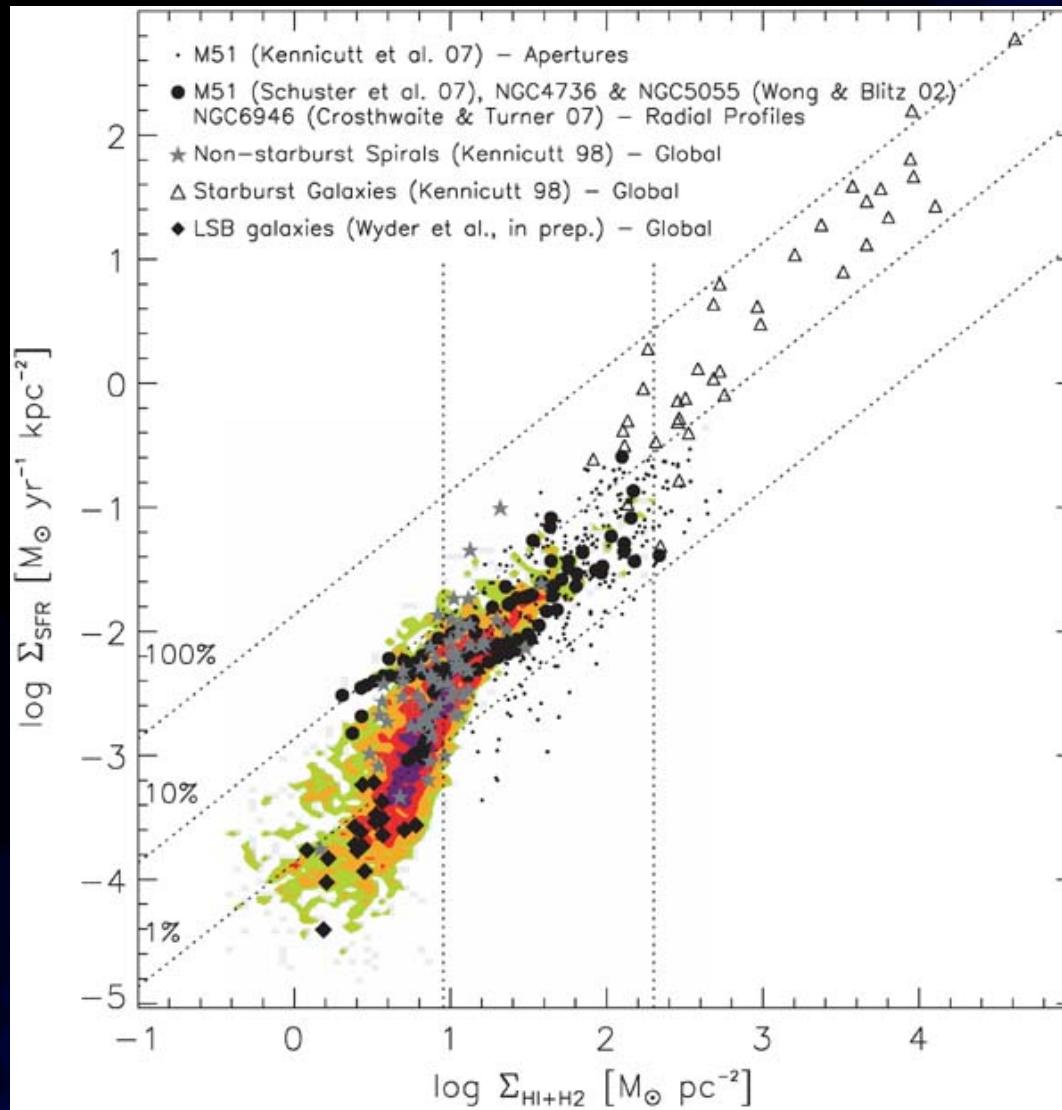
T.J. Cox
Carnegie



Lars Hernquist
Harvard



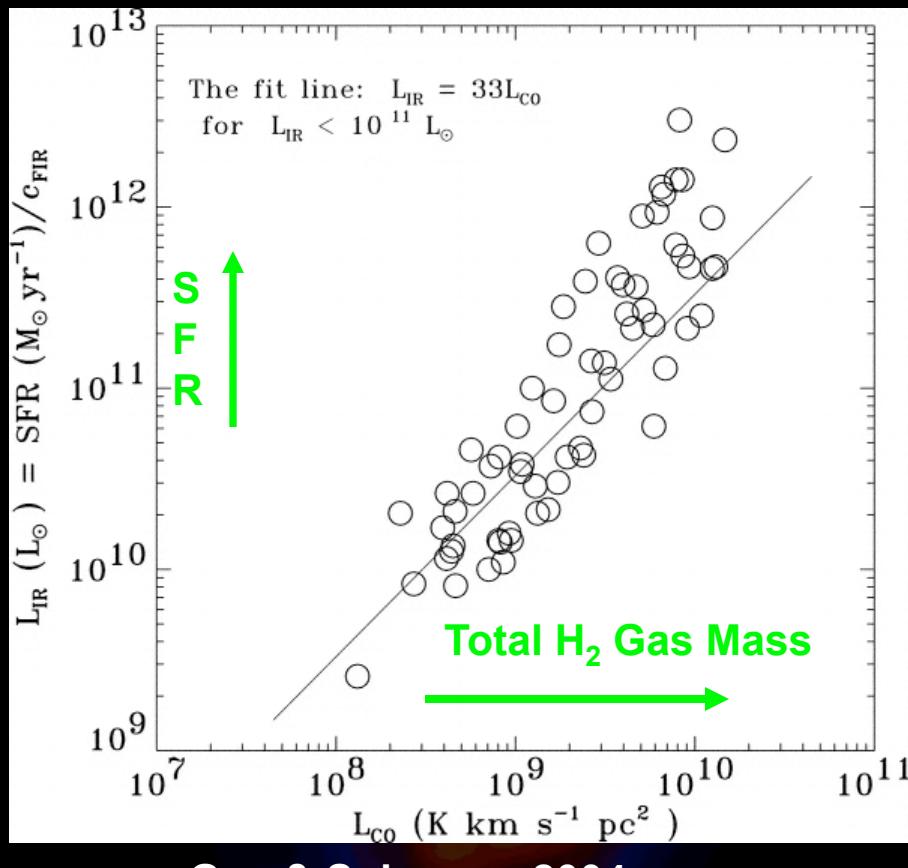
Kennicutt-Schmidt SFR Laws



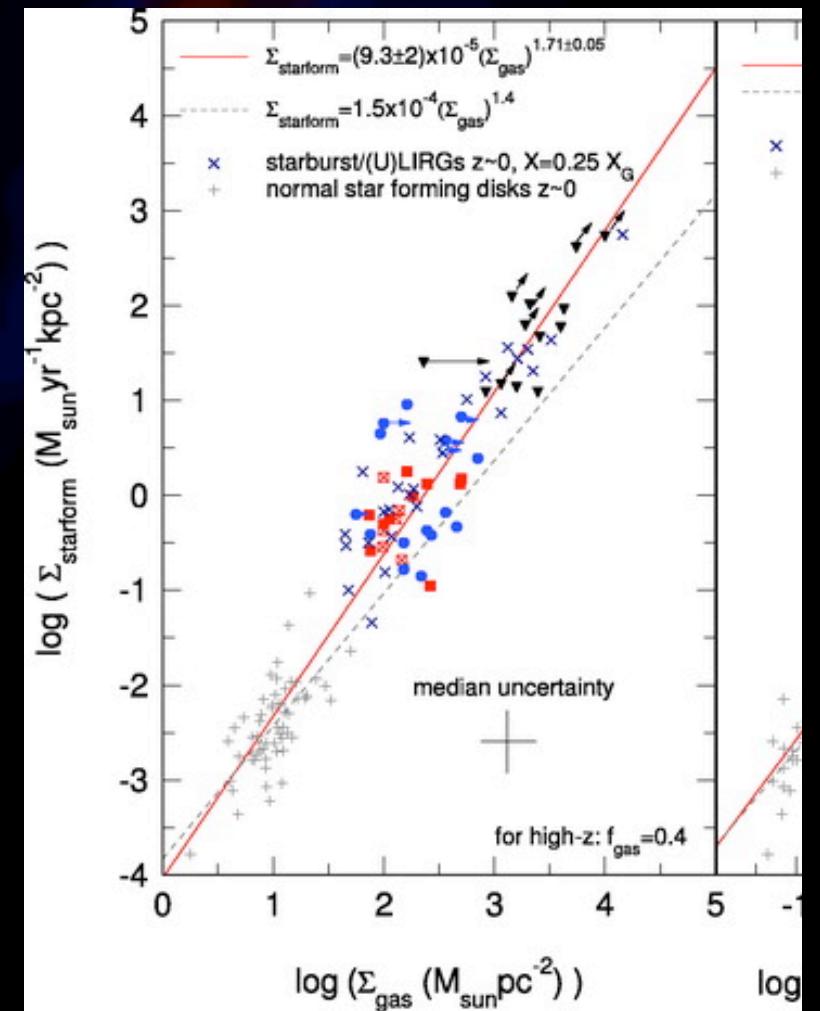
Locally: Bigiel 2008; Krumholz et al. 2009

Molecular Kennicutt-Schmidt SFR Laws

**Local: CO J=1-0
n=1.5**

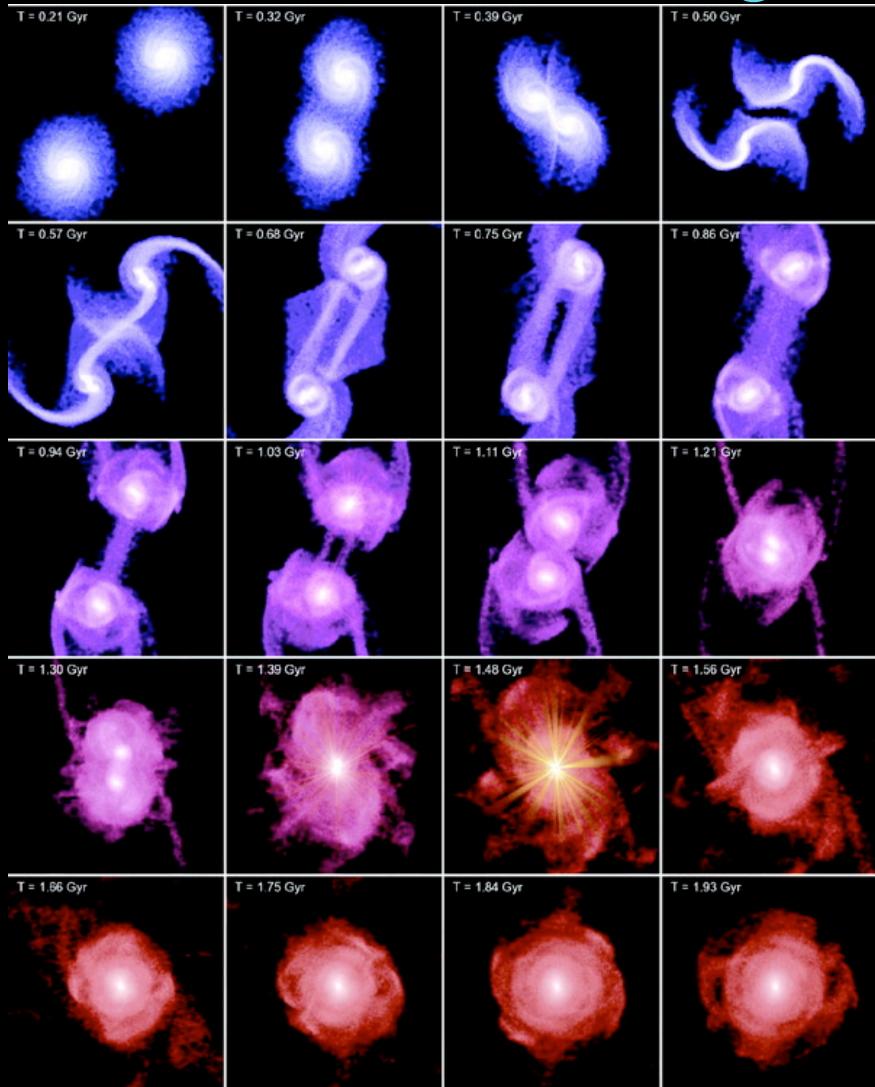


z~2: CO (J=3-2)



z~2 Bouché et al. 2007

Theoretical Approach: SPH simulations of galaxies



Springel et al. (2003-2005), Hopkins et al. 2006

Prescriptions for multi-phase ISM (McKee-Ostriker)

SF (volumetric Schmidt law)

BH growth and associated Feedback

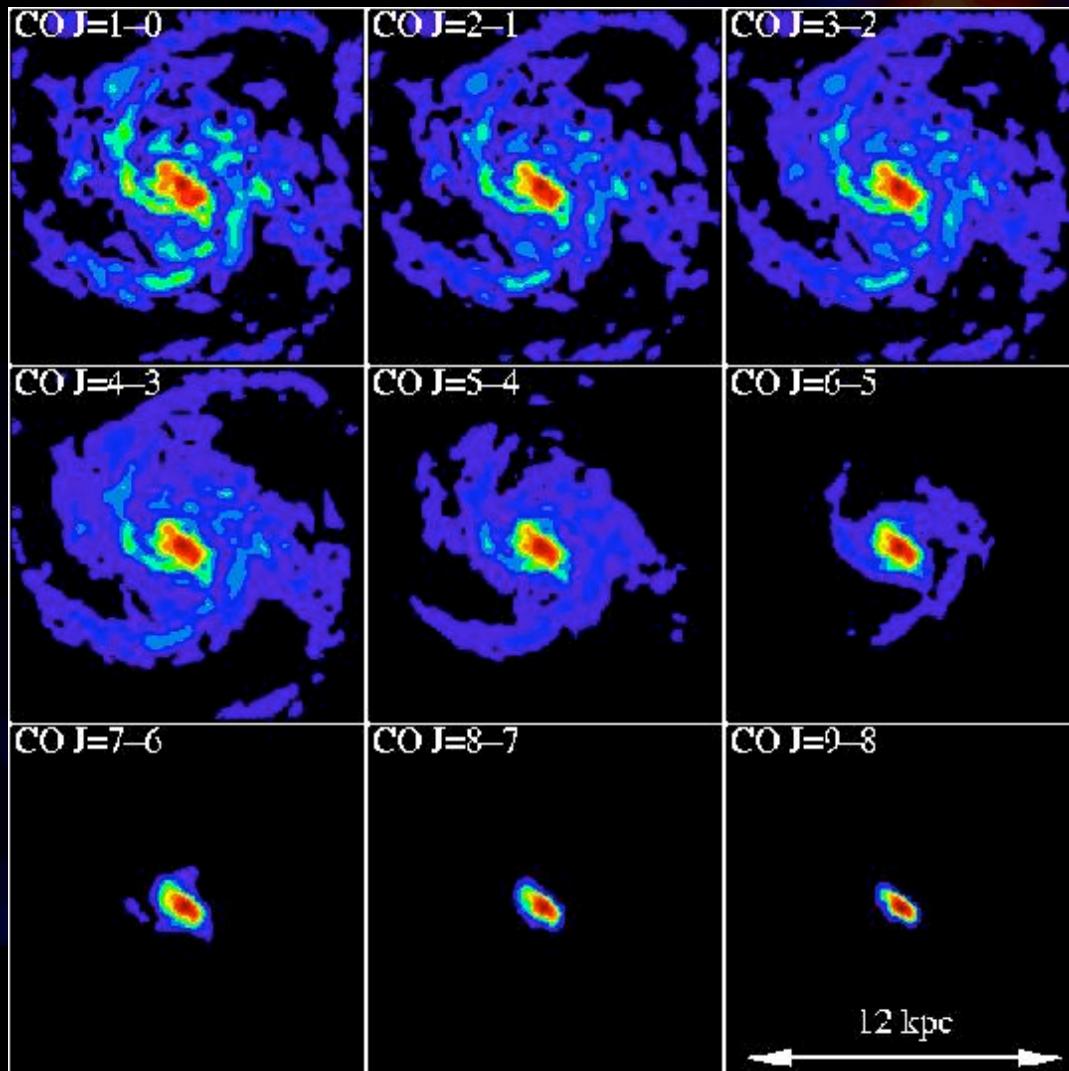
Halos scaled to z~2 concentration

For z~2 study, isolated galaxies
 $M_{\text{bar}} \sim 10^{11} M_{\odot}$, MMW disks

SF follows SFR \propto $1, 1.5, 2$

Non-LTE Radiative Transfer (Synthetic Molecular Line Emission)

- 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; $M_{\text{cloud}} = 10^4 - 10^6 M_{\odot}$,
(Blitz et al. 2006, Rosolowsky 2007)
- Uniform Galactic CO Abundance, no H₂ at N_H < 10²¹ cm⁻²



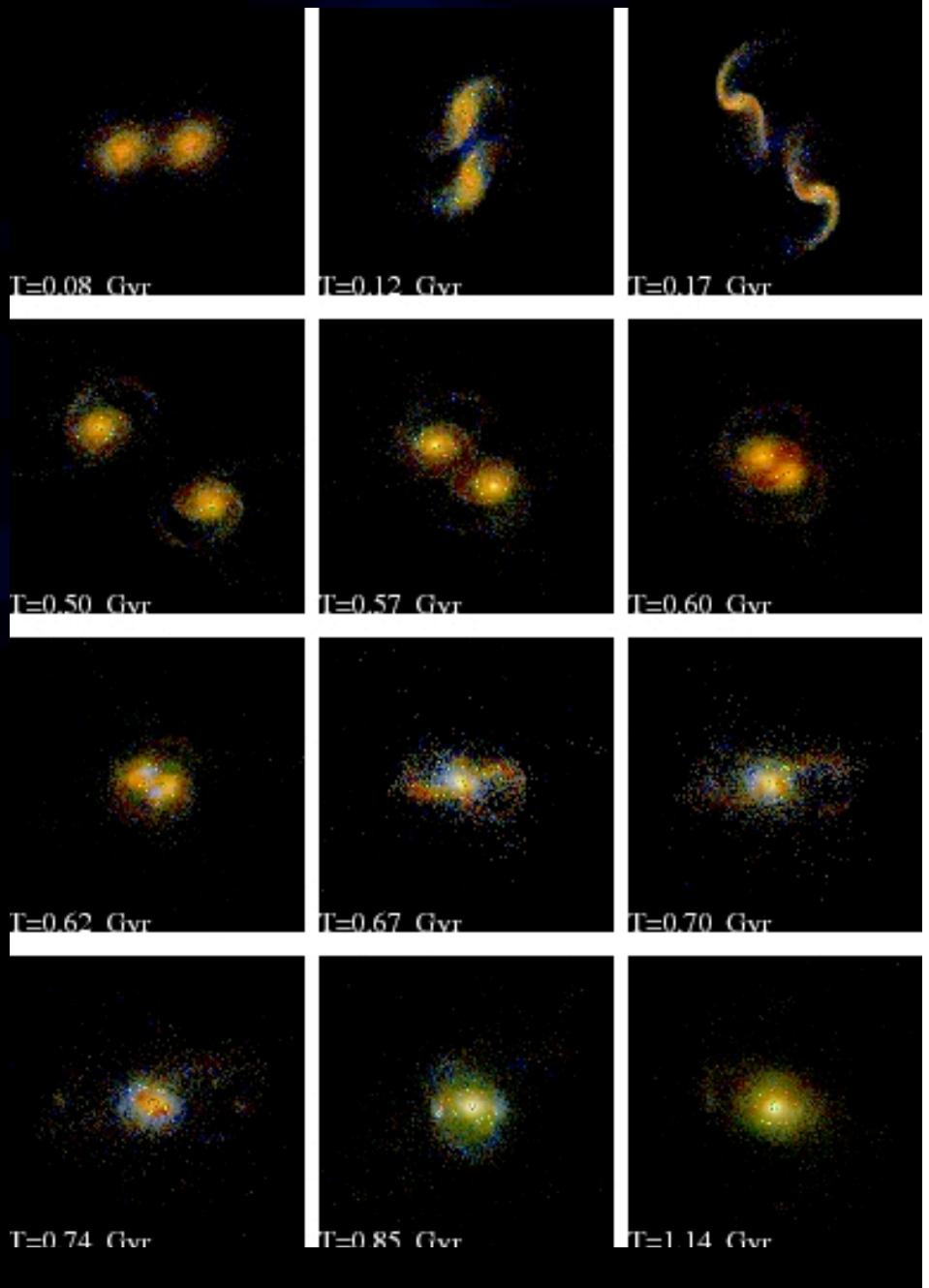
SUNRISE (dust RT) to 'Select' Galaxies



Physics Included in Monte Carlo IR RT:

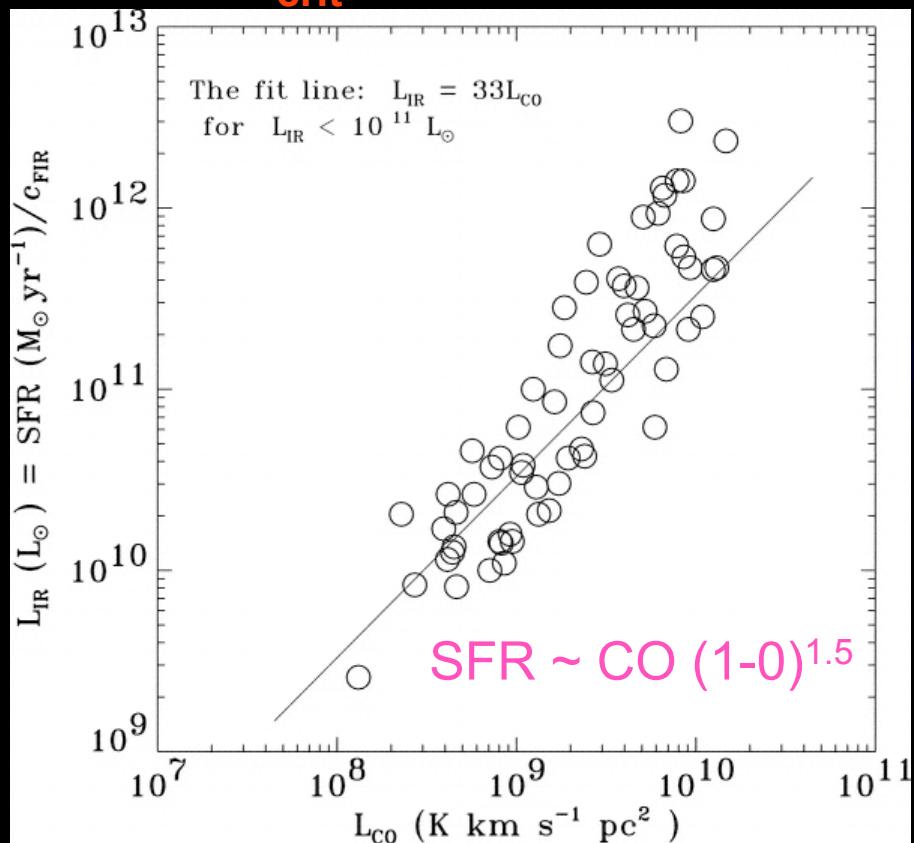
- IR transfer of stellar and AGN spectrum
(starburst 99 for stars and Hopkins+ 07 for AGN)
- dust radiative equilibrium
- Kroupa IMF, MW DTM, Draine & Li Dust
- Stellar Clusters surrounded by HII regions and PDRs (MAPPINGS; Groves et al. 2008)

Jonsson, Groves & Cox (2009)

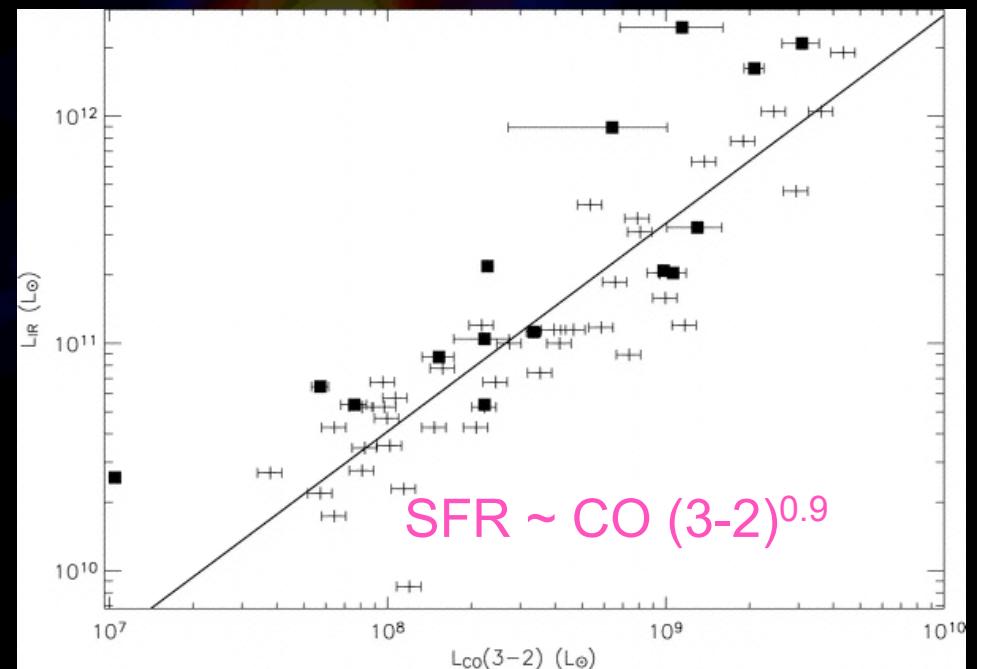


Does Differential Excitation Matter?: Local Universe Example

CO (J=1-0)
 $n_{\text{crit}} \sim 10^2 \text{ cm}^{-3}$



CO (J=3-2)
 $n_{\text{crit}} \sim 10^4 \text{ cm}^{-3}$

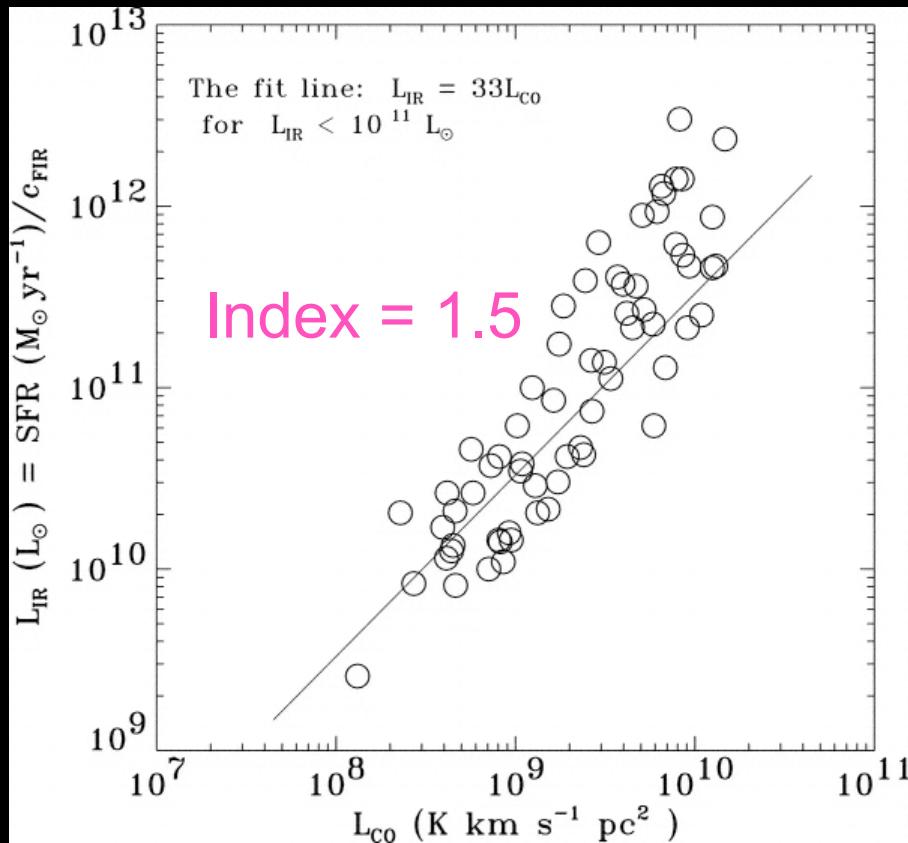


Gao & Solomon 2004

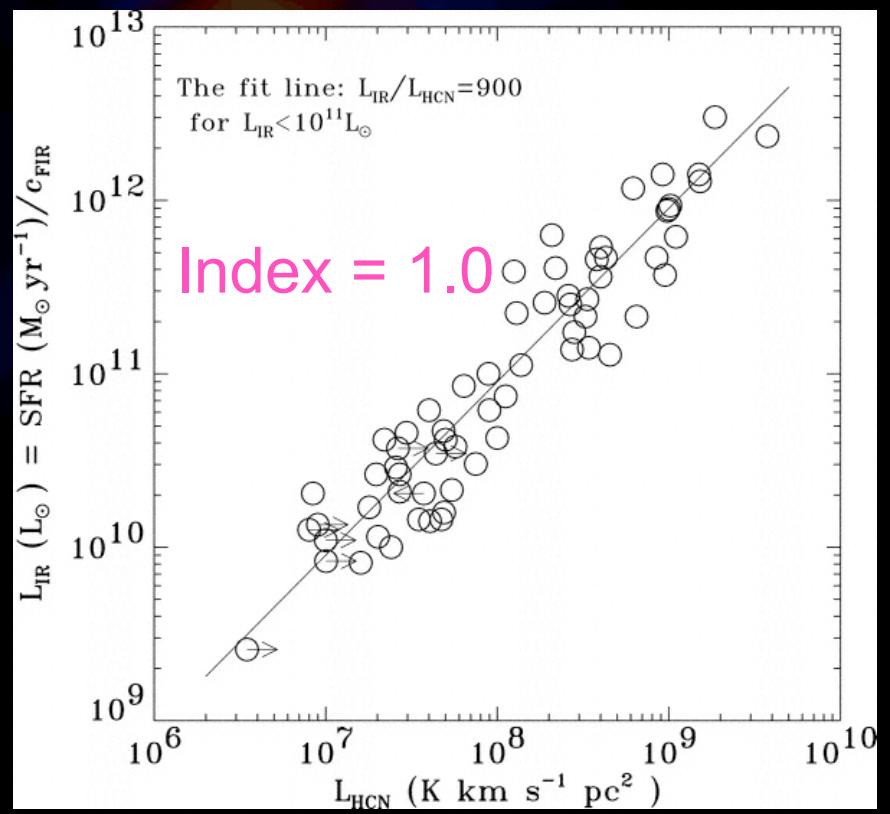
Narayanan et al. 2005
Iono et al. 2008

Molecular Kennicutt-Schmidt SFR Laws

CO J=1-0
 $n_{\text{crit}} \sim 10^2 \text{ cm}^{-3}$



HCN J=1-0
 $n_{\text{crit}} \sim 10^5 \text{ cm}^{-3}$

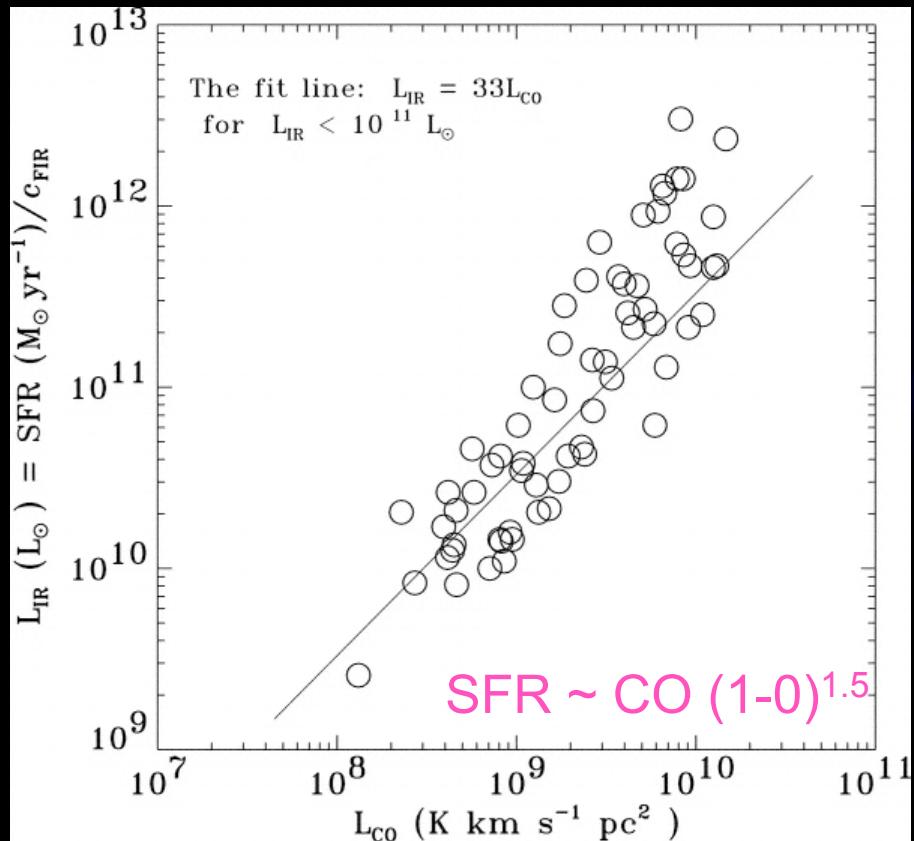


Gao & Solomon (2004)

SF follows SFR $\propto L^{1.5}$

Molecular Kennicutt-Schmidt SFR Laws

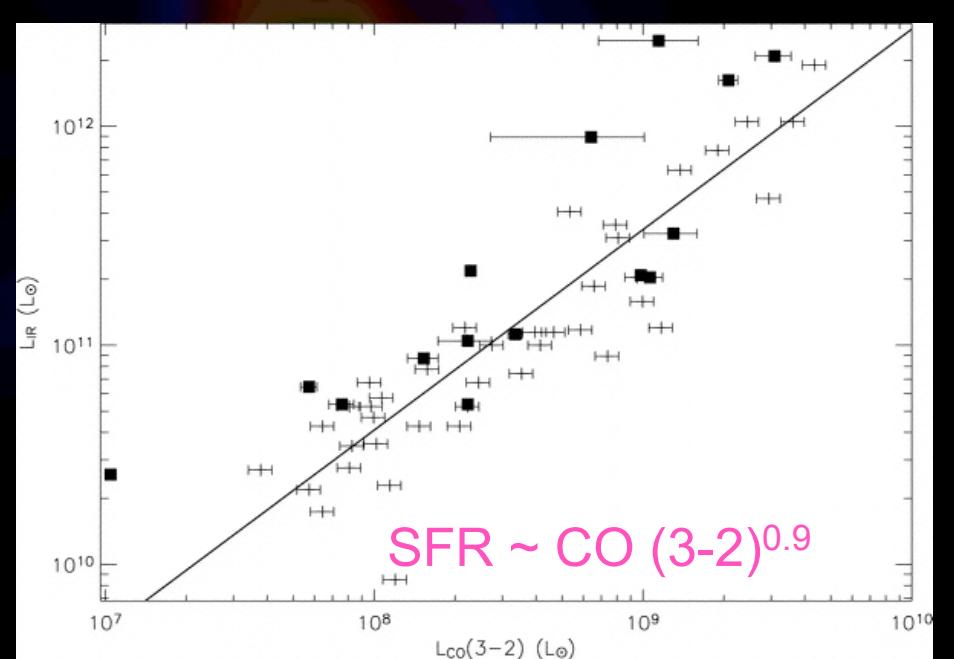
CO (J=1-0)
 $n_{\text{crit}} \sim 10^2 \text{ cm}^{-3}$



Gao & Solomon 2004

SF follows SFR $\text{W} \text{ W}^{1.5}$

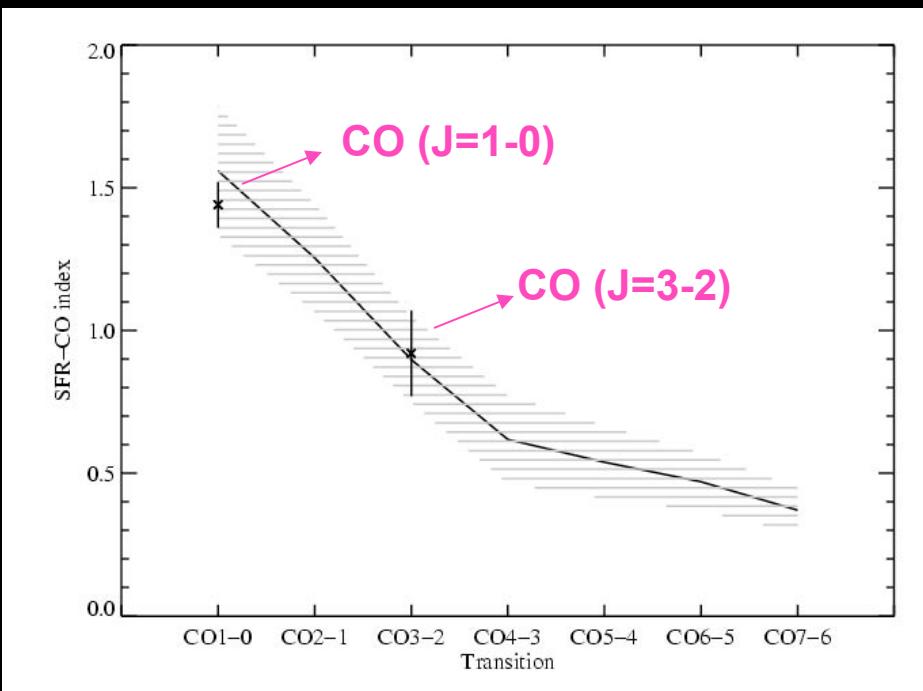
CO (J=3-2)
 $n_{\text{crit}} \sim 10^4 \text{ cm}^{-3}$



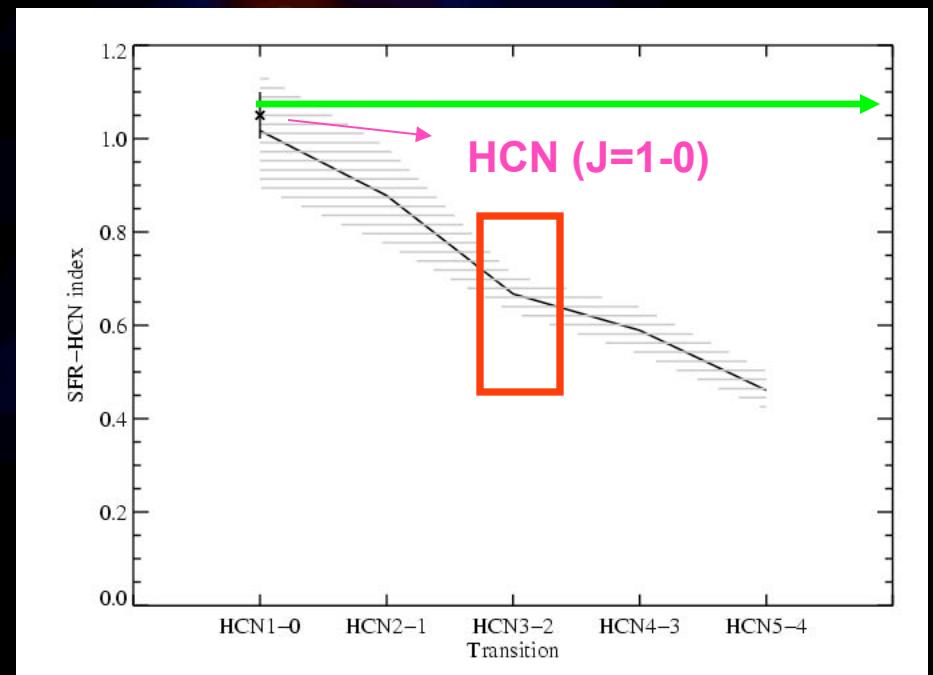
Narayanan et al. 2005
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Differential Excitation; Underlying $n=1.5$ KS Index

SFR-CO $\frac{W}{W}$ index



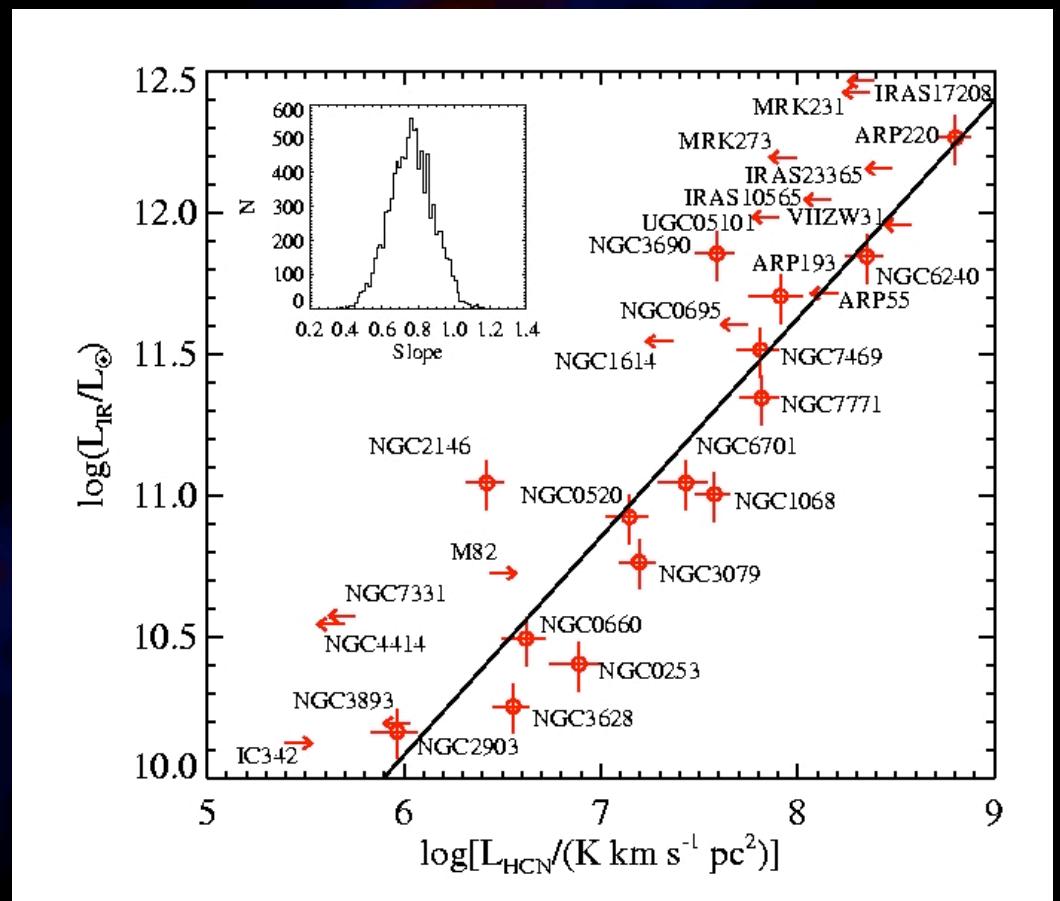
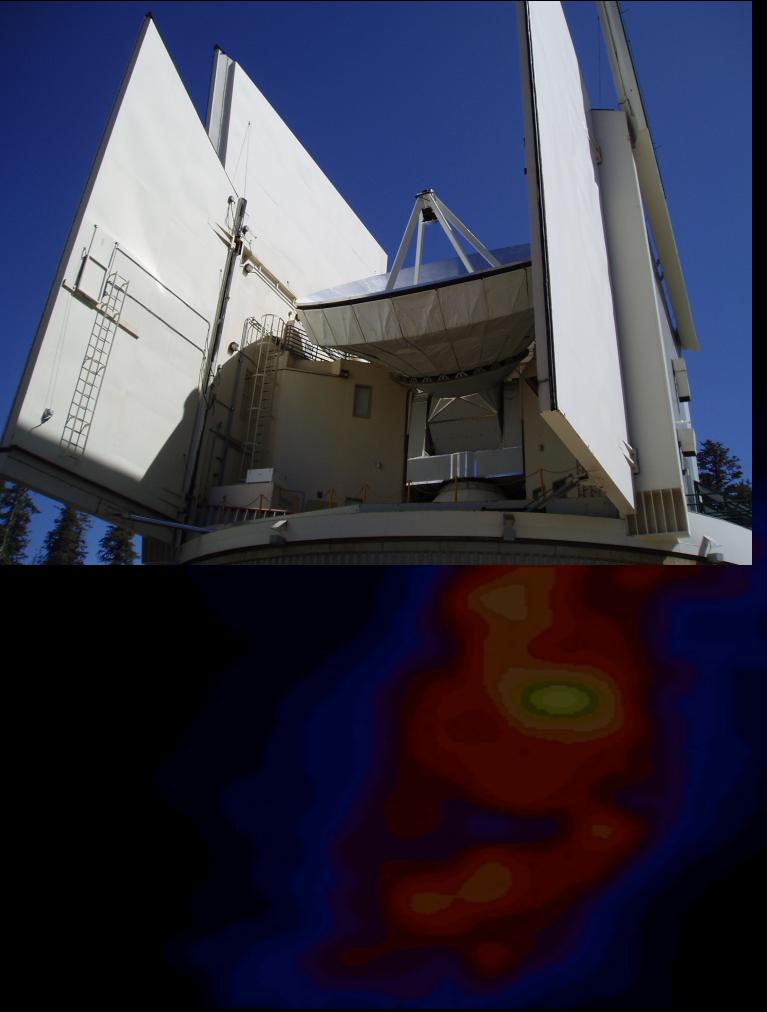
SFR-HCN $\frac{W}{W}$ index



Krumholz & Thompson 2007
Narayanan et al. 2008a,b

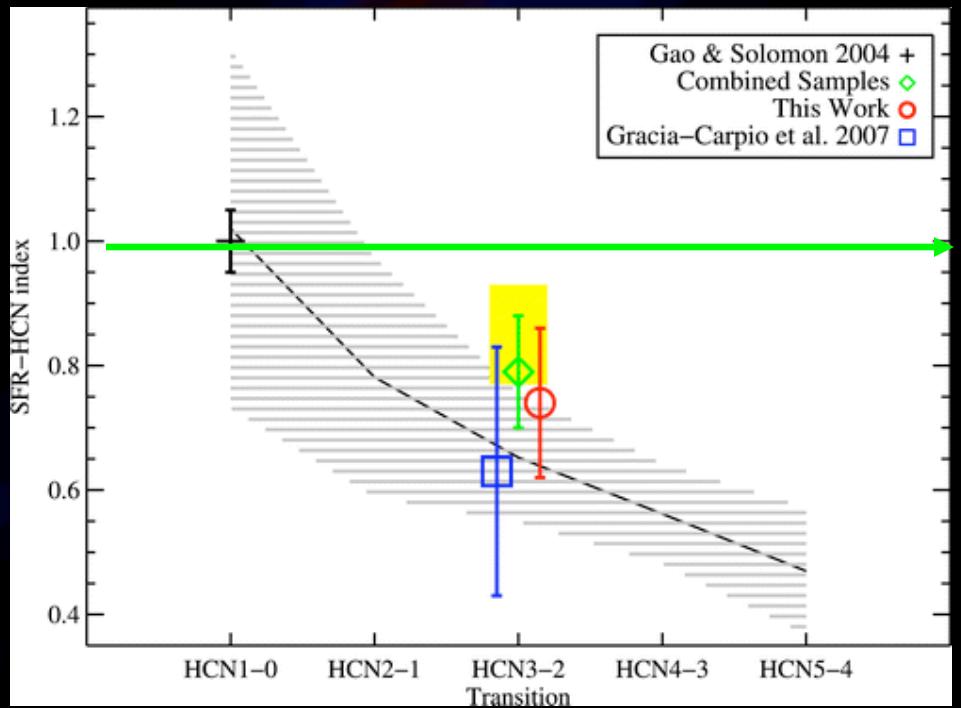
SF follows SFR $\frac{W}{W}^{1.5}$

HCN (J=3-2) Observational Survey



Bussmann, DN, Shirley, Wu, Juneau et al. (2008)
Juneau, DN, Moustakas, Shirley et al. (2009)

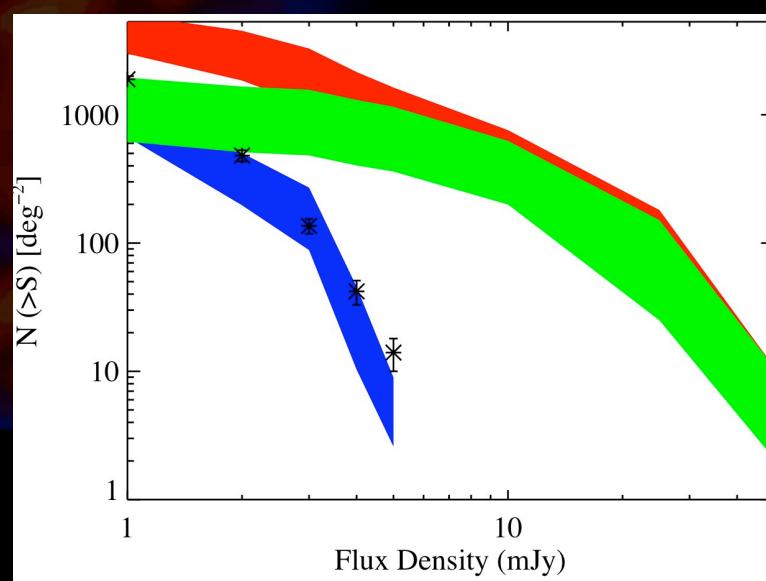
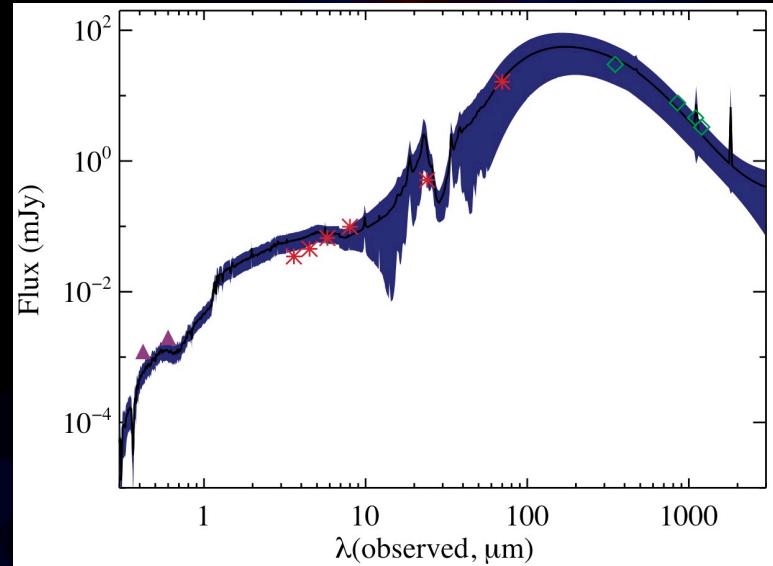
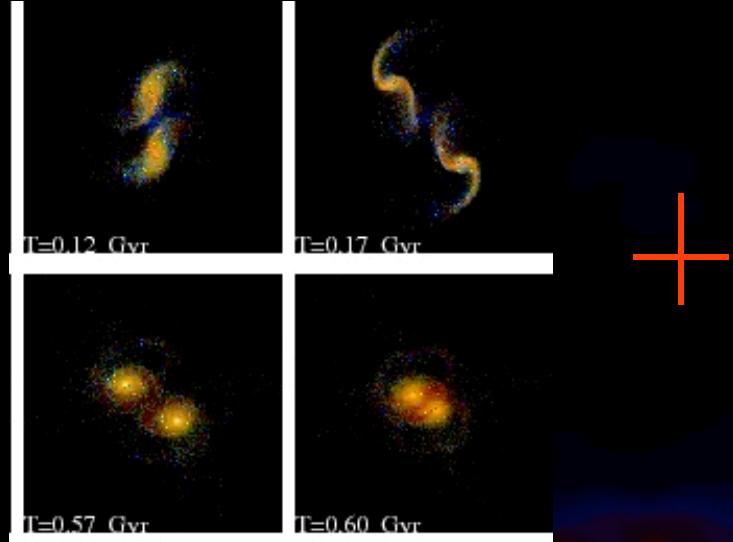
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Bussmann, DN, Shirley, Juneau et al. (2008)
Juneau, DN, Moustakas, Shirley et al. (2009)

Getting to the KS Relation at $z \sim 2$: Models of High- z Galaxies (SMGs, BzKs)

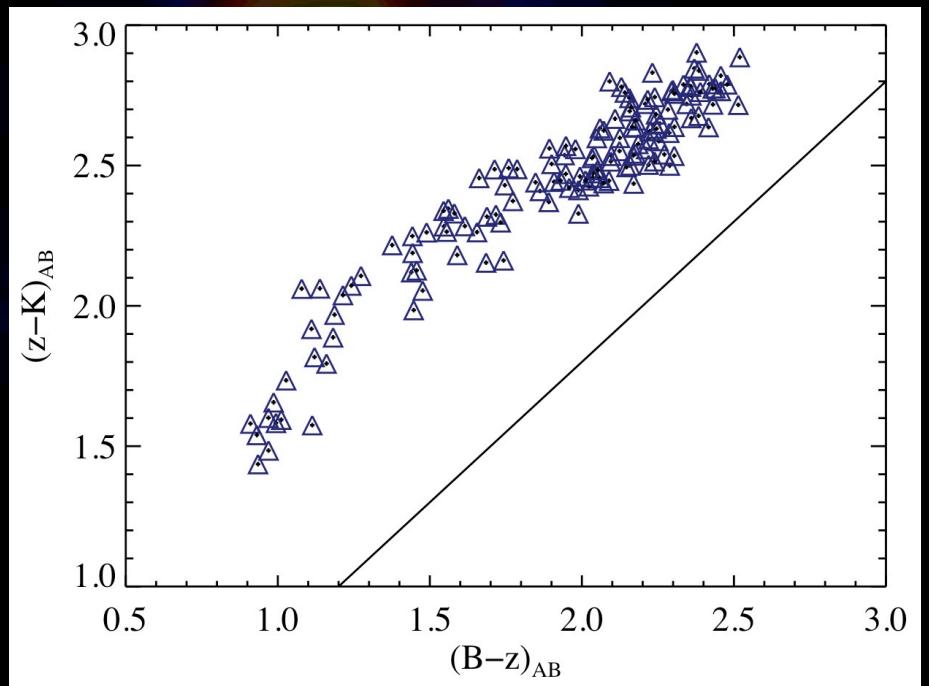
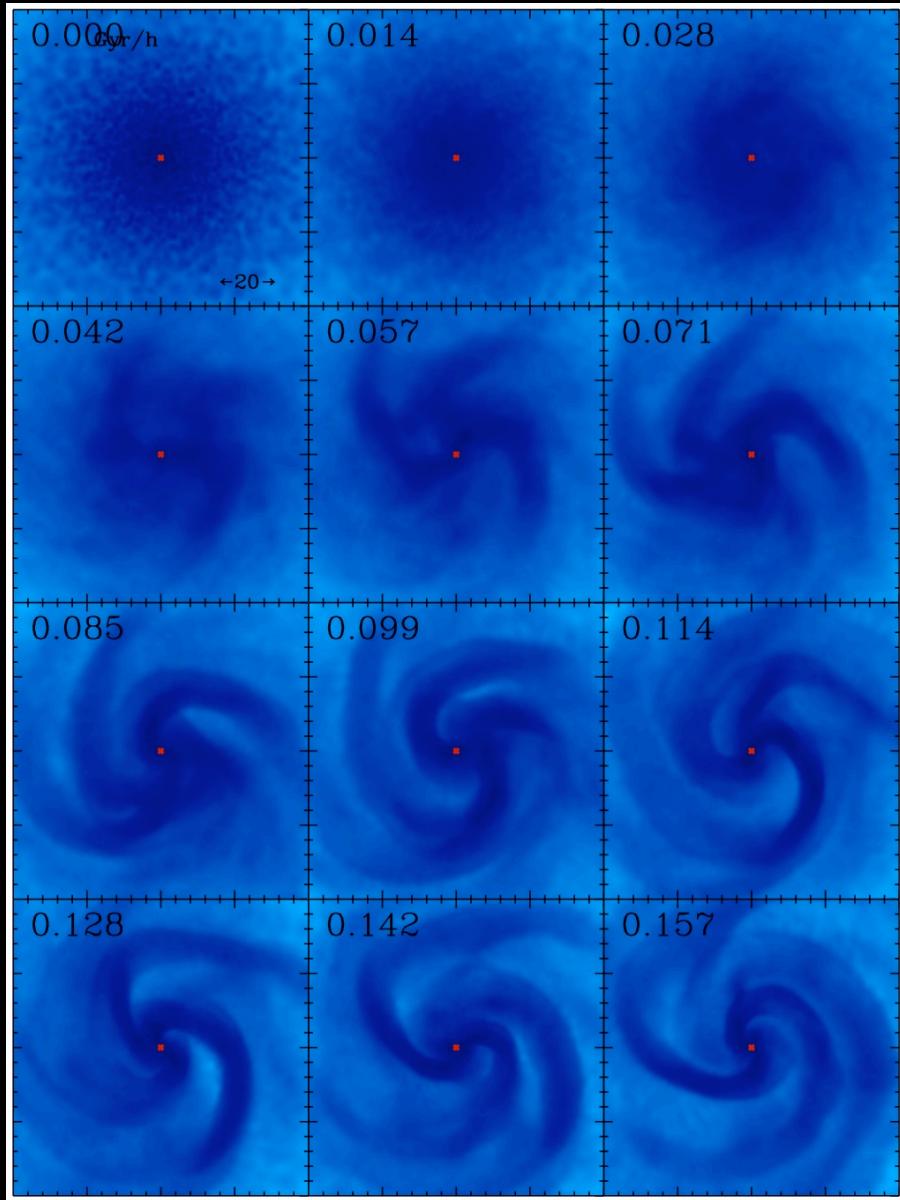
(Narayanan, Hayward et al. 2009, 2010)



Hayward, Narayanan et al. in prep.

Getting to the KS Relation at $z \sim 2$

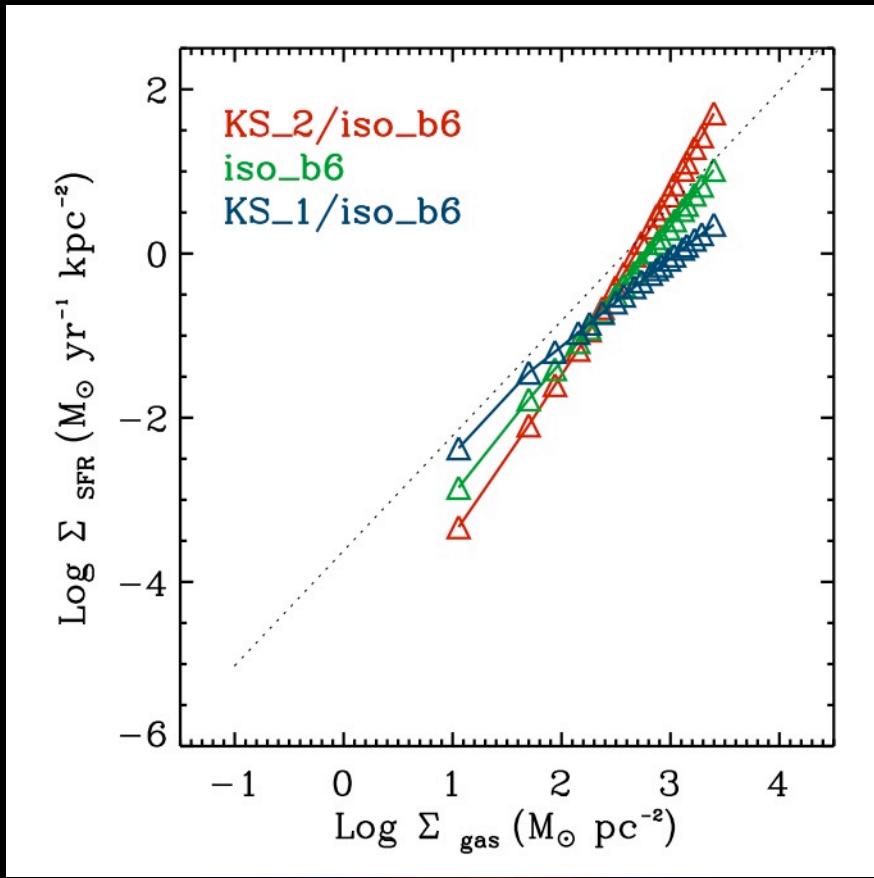
Narayanan, Cox, Hayward, Hernquist in prep.



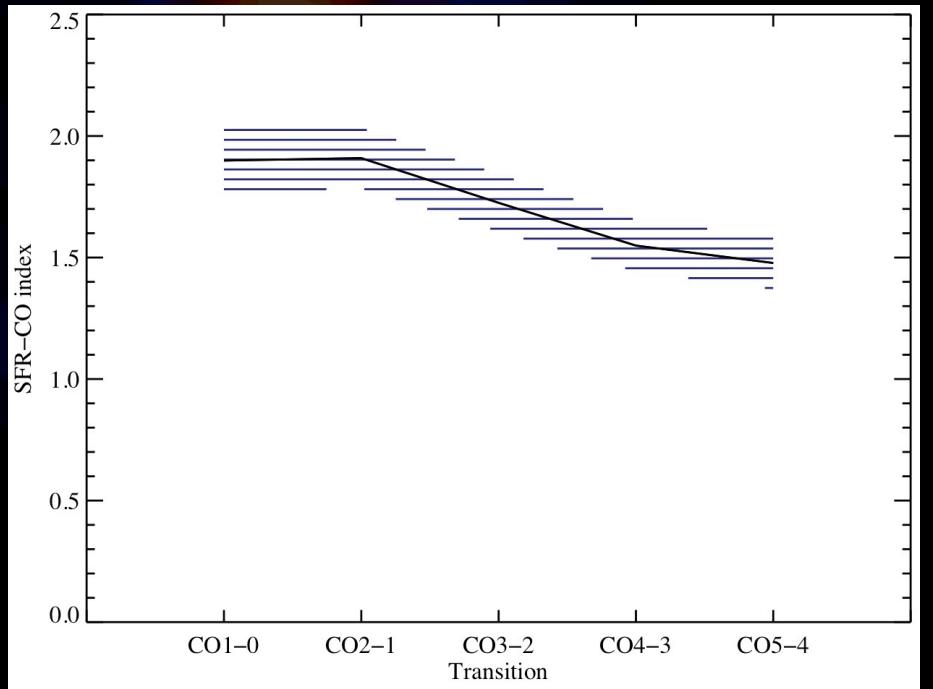
SF follows SFR $\mathbb{W} \mathbb{W}^1, 1.5, 2$

Getting to the KS Relation at z~2

Narayanan, Cox, Hayward, Hernquist in prep.



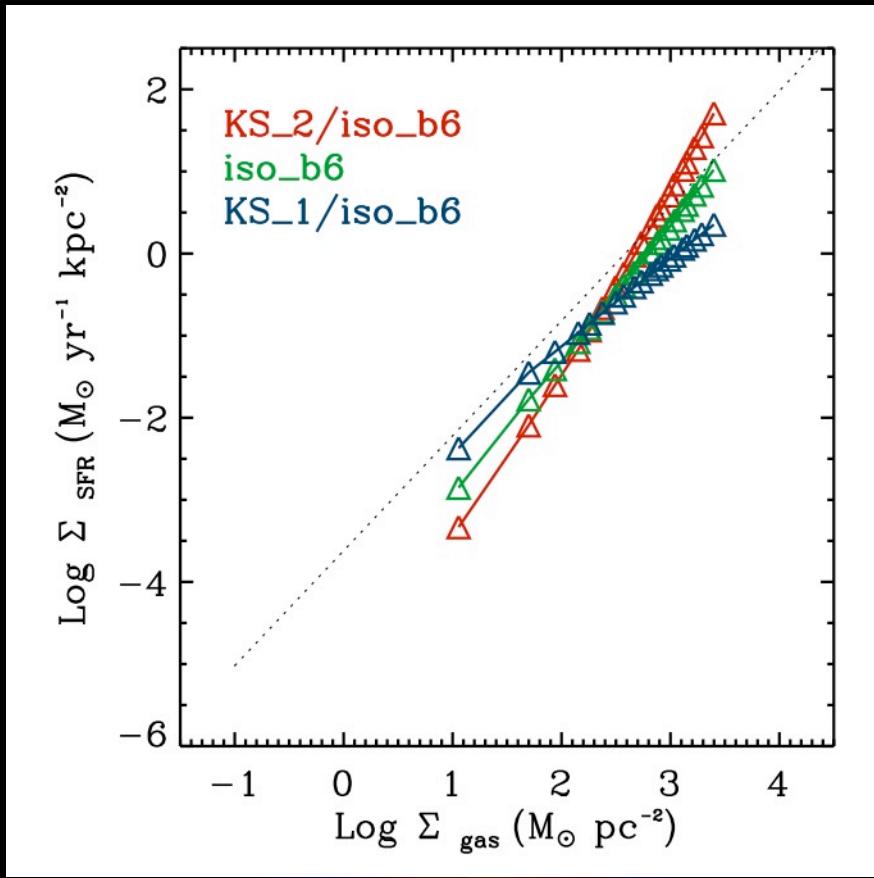
SF follows SFR $\text{W} \text{ W}$ 1, 1.5, 2



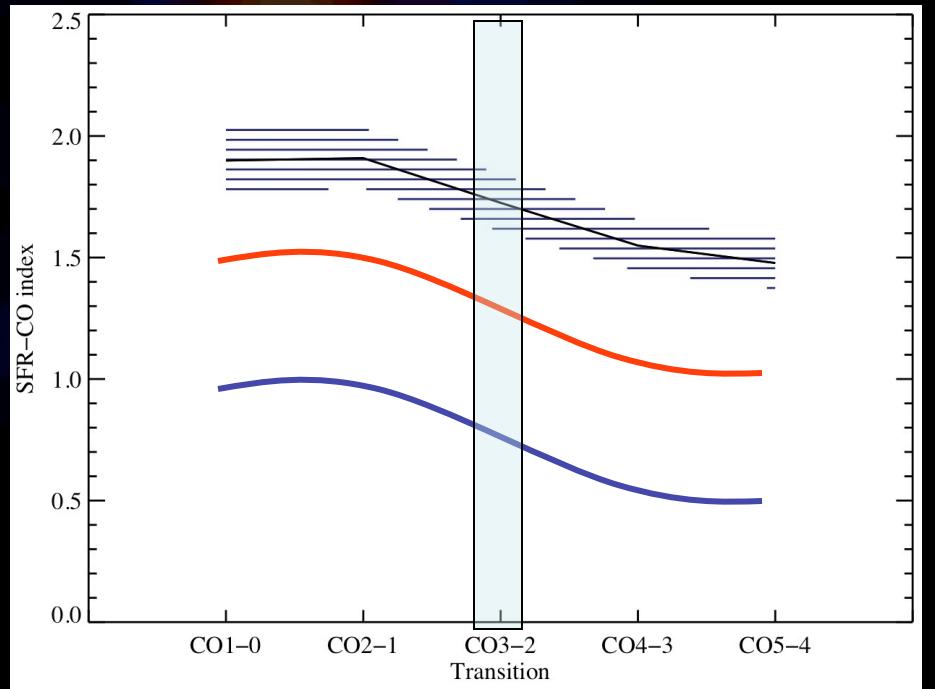
**SFR-L_{CO} index versus Transition
for KS = 2 galaxies**

Getting to the KS Relation at z~2

Narayanan, Cox, Hayward, Hernquist in prep.



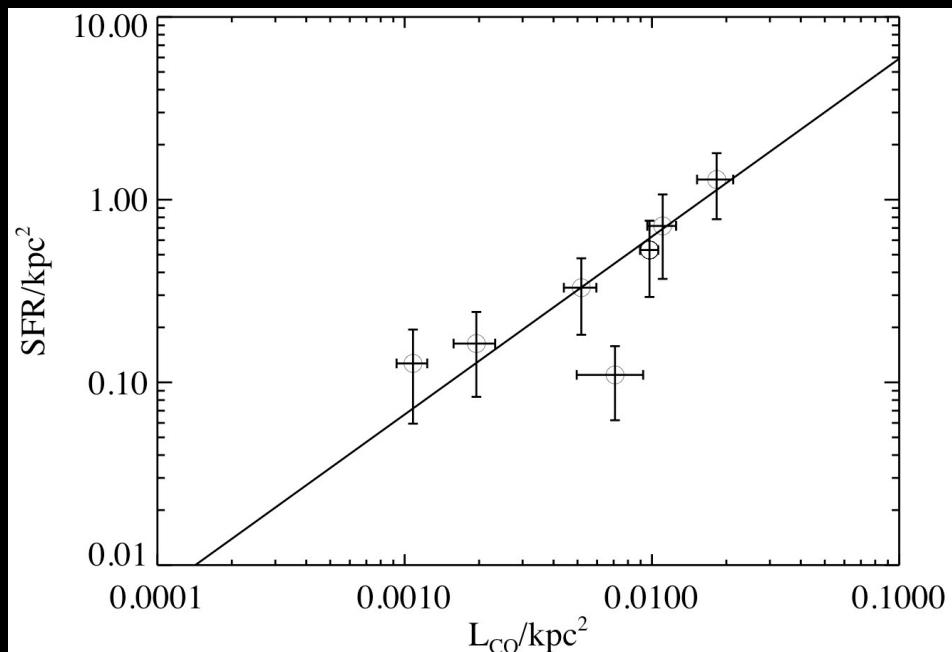
SF follows SFR 1, 1.5, 2



**SFR-L_{CO} index versus Transition
for KS = 2 galaxies**

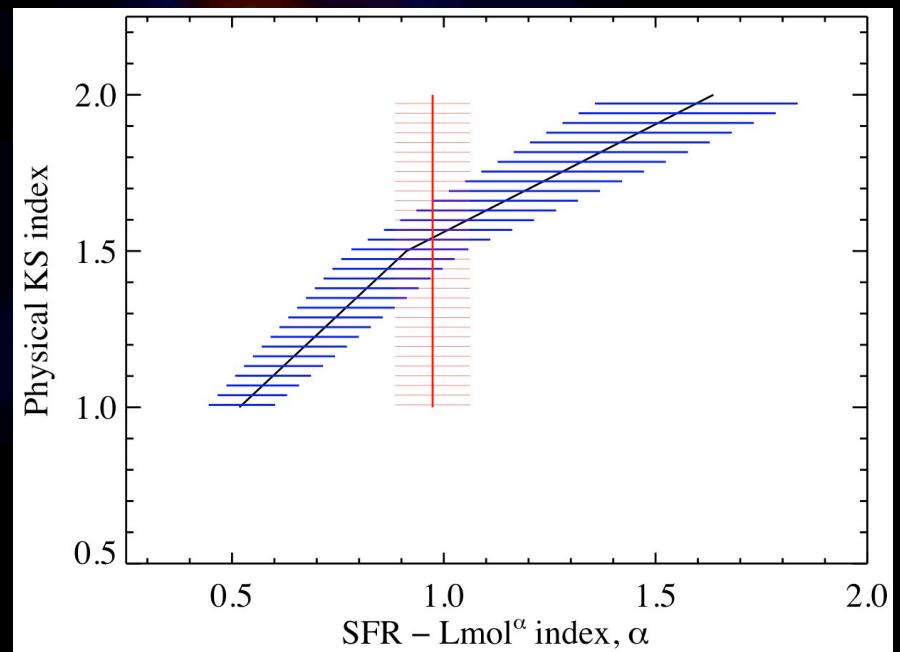
Mapping the CO 3-2 KS relation at z~2 to the underlying volumetric Schmidt Relation

Narayanan, Cox, Hayward, Hernquist in prep.



Data from Tacconi et al. 2010:

$$\text{SFR} \sim L_{(\text{CO}3-2)}^{0.97}$$

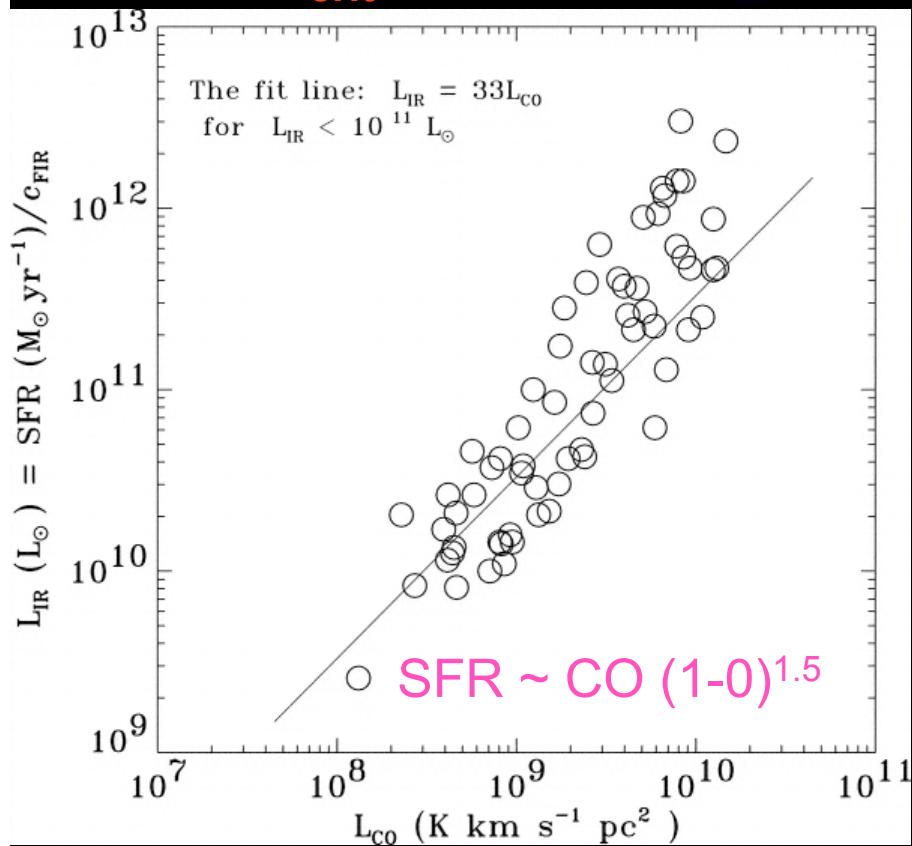


Physical KS index vs. SFR-CO (J=3-2) index

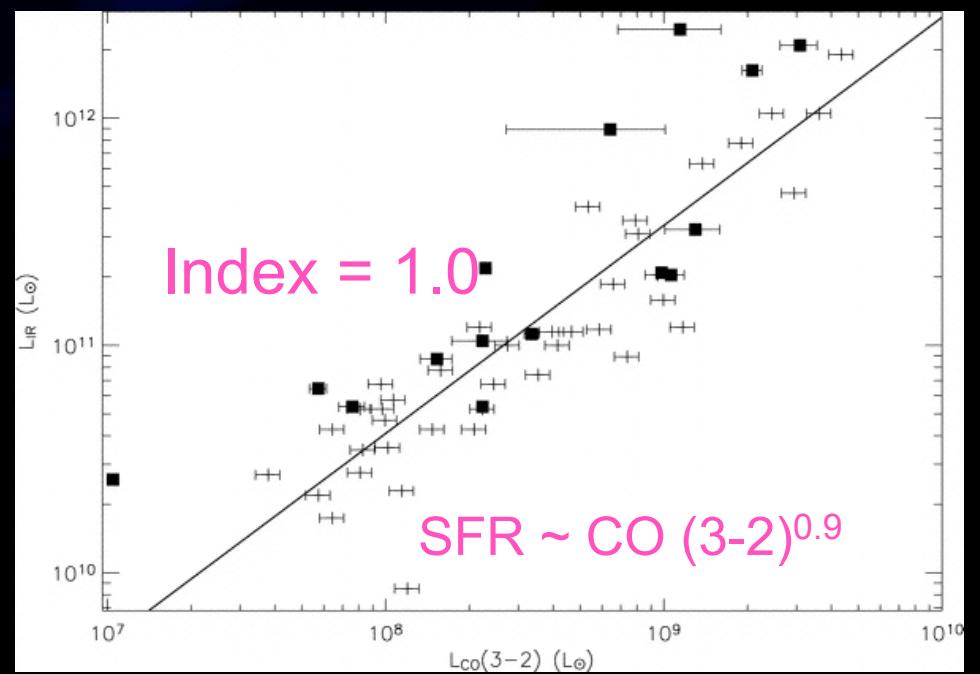
Conclusions

1. Excitation Matters

CO (J=1-0)
 $n_{\text{crit}} \sim 10^2 \text{ cm}^{-3}$



CO (J=3-2)
 $n_{\text{crit}} \sim 10^4 \text{ cm}^{-3}$



Conclusions

2. At High- z KS Relation may be consistent with 1.5

