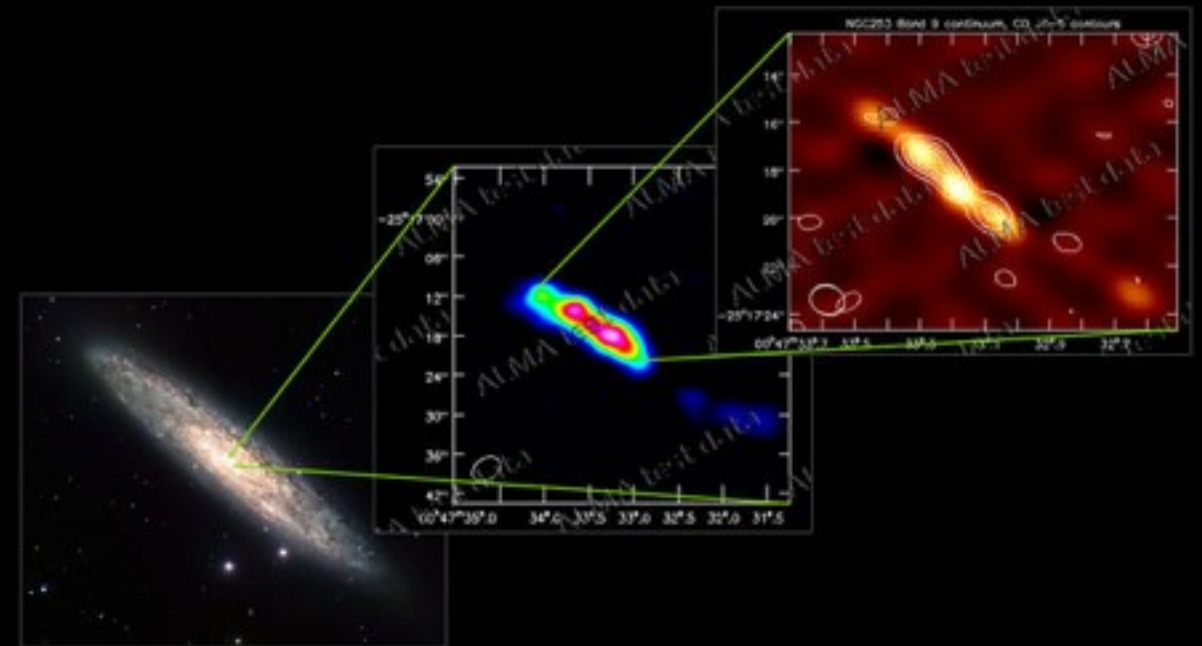
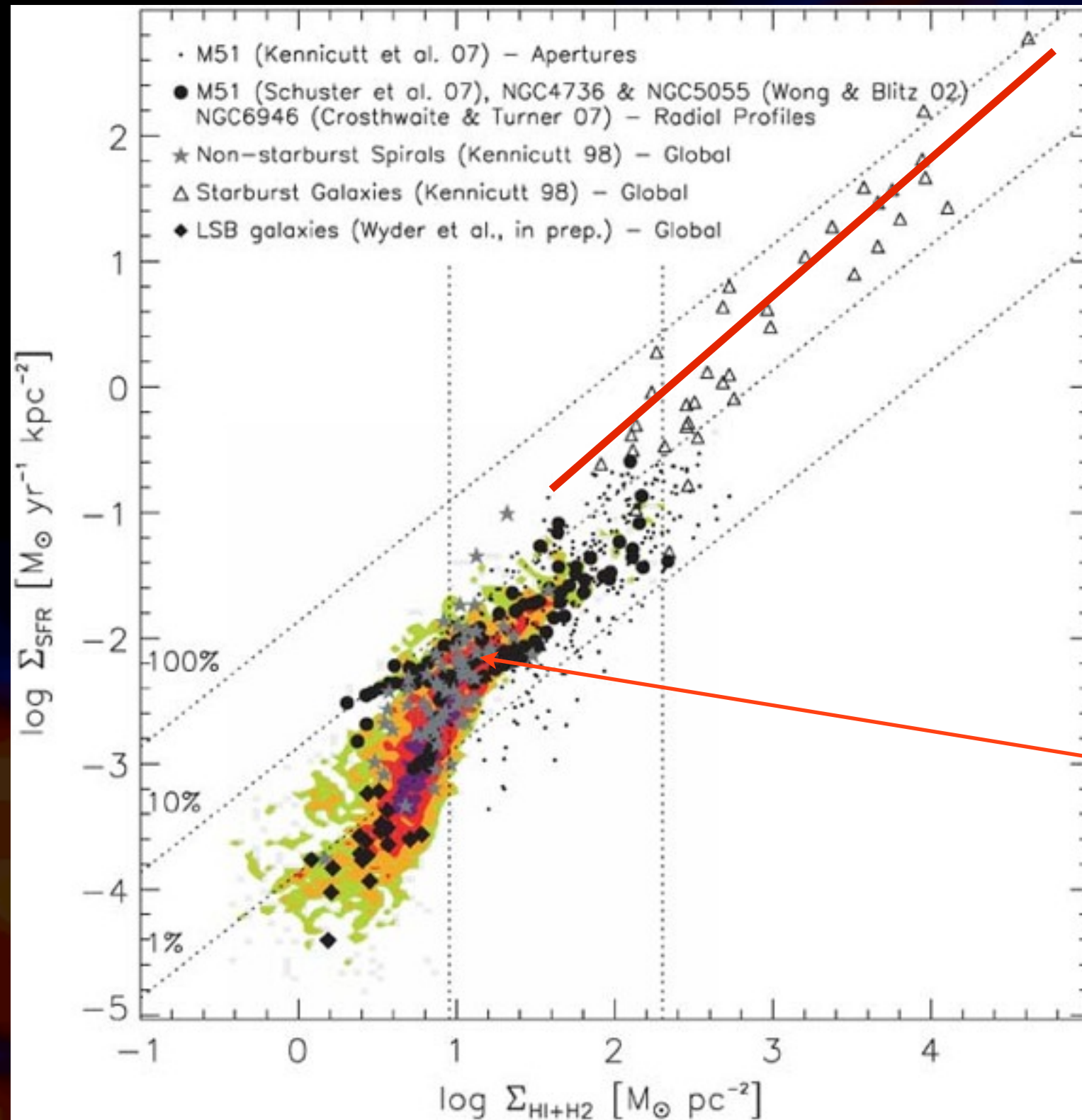


# The Molecular and Dusty ISM at $z \sim 2$

Desika Narayanan  
Bart J Bok Fellow  
University of Arizona





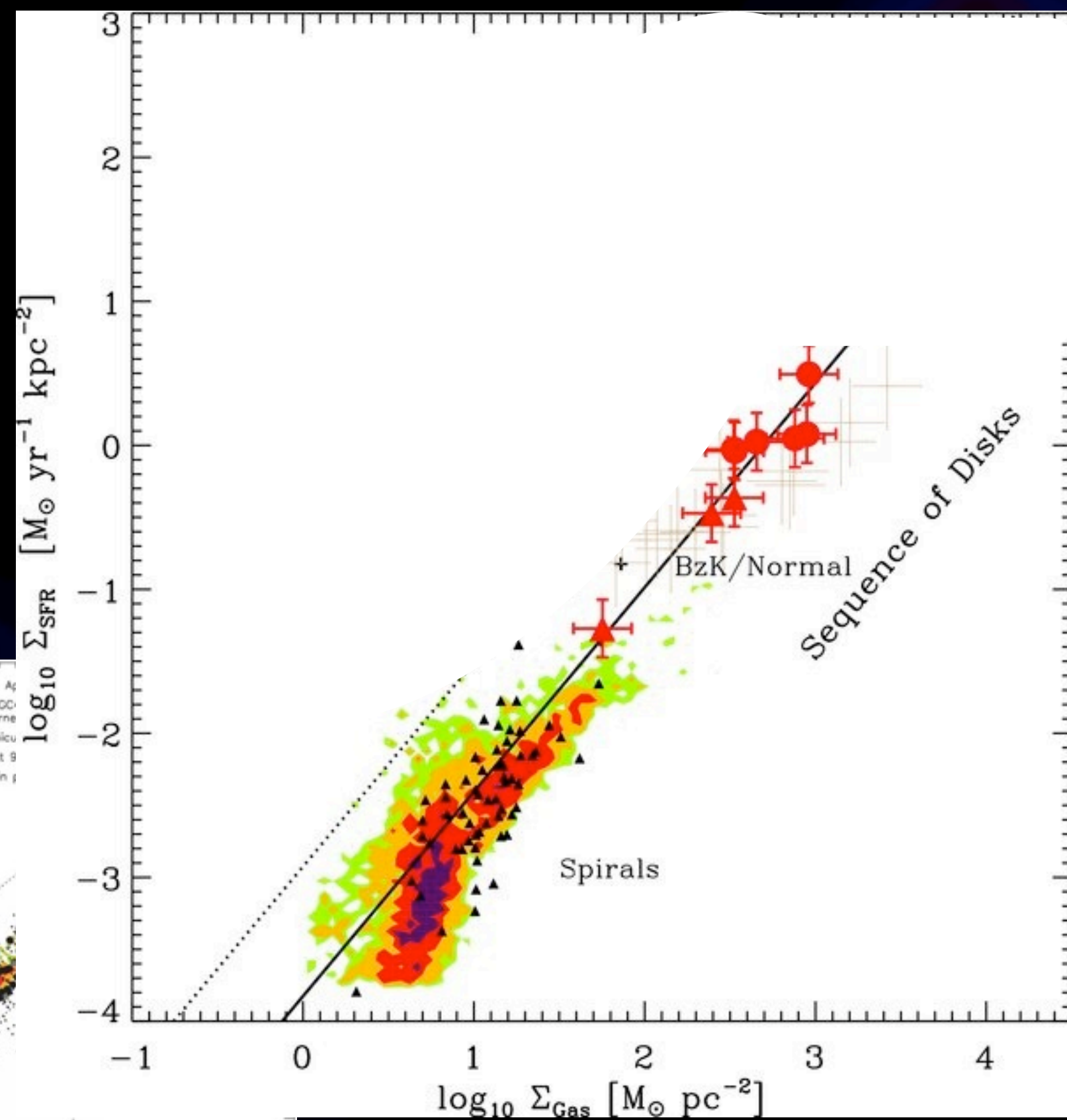
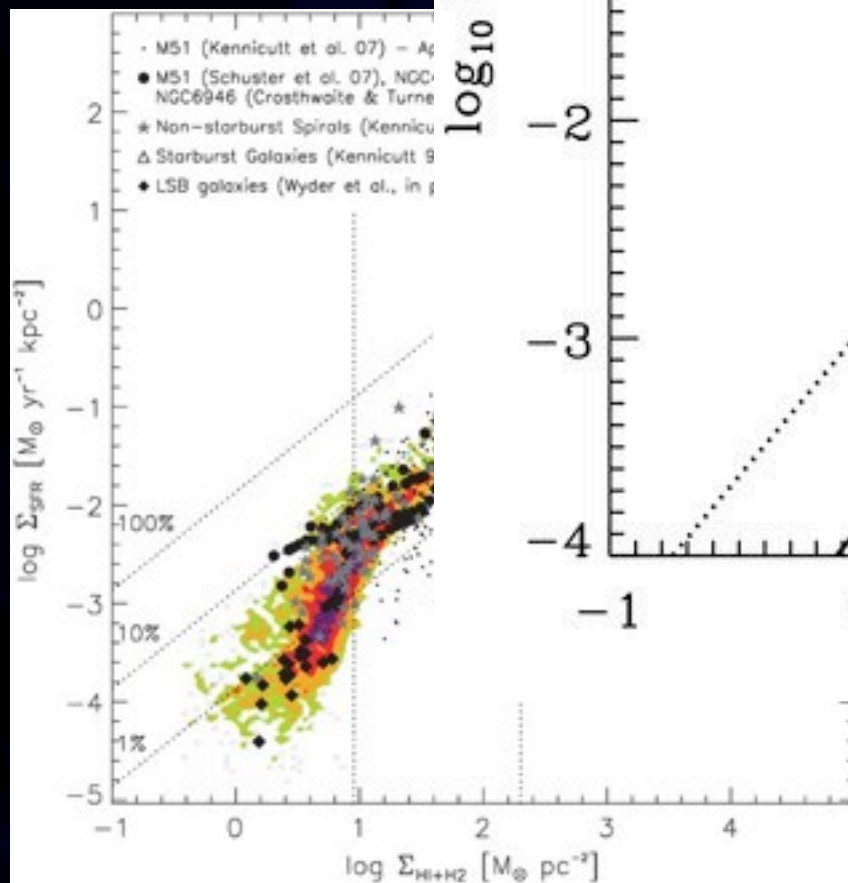
$$\text{SFR} \sim \Sigma_{\text{H}_2}^{1.5}$$

$$\text{SFR} \sim \Sigma_{\text{H}_2}^1$$

Bigiel, Walter, Leroy et al. 2008

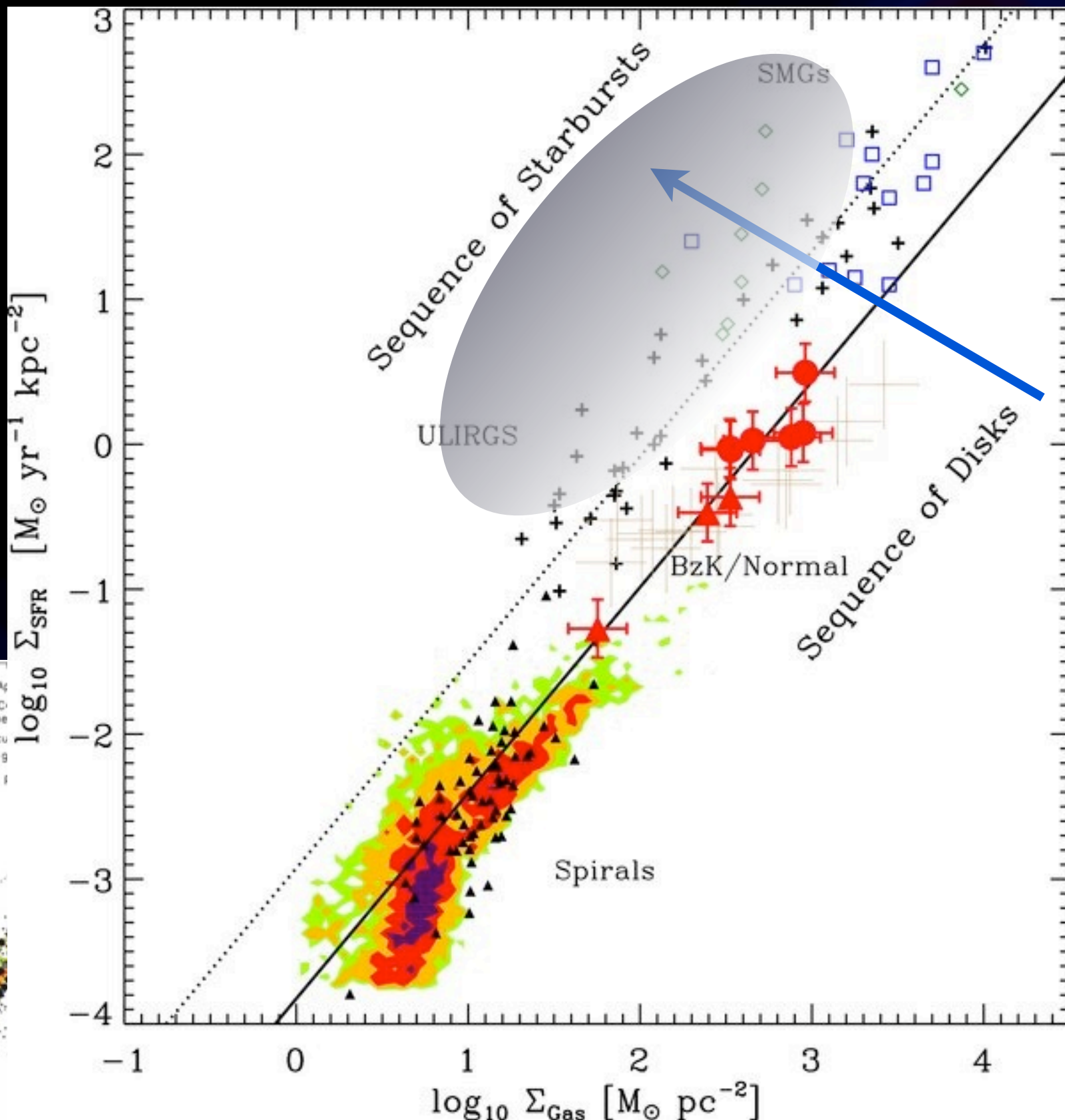
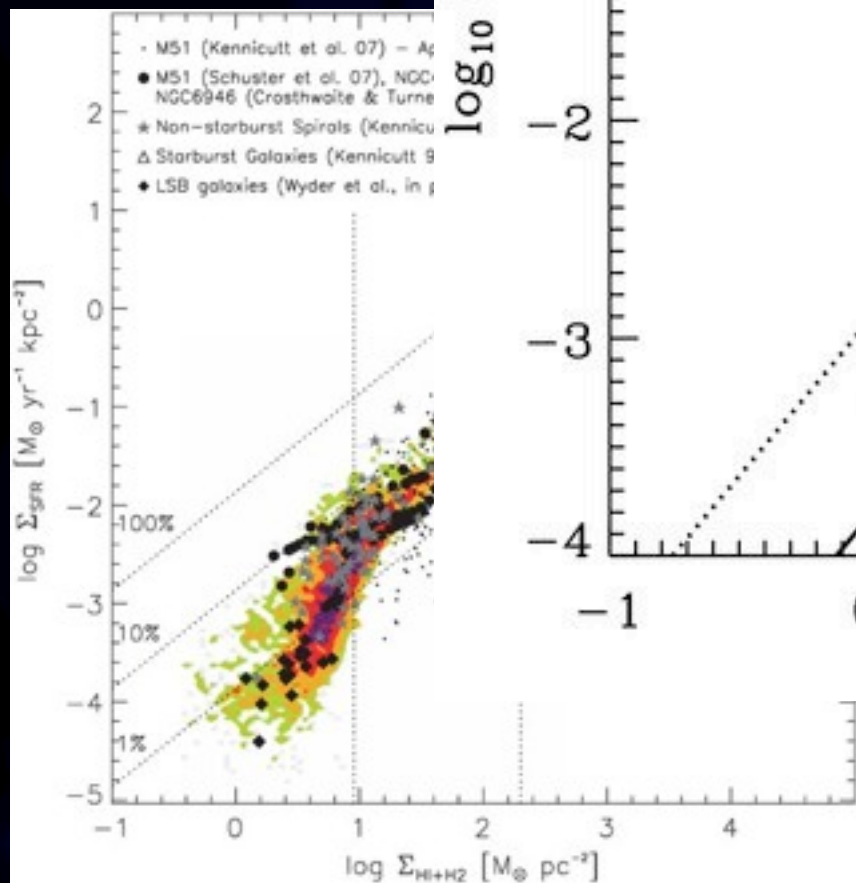
Desika Narayanan

$$I. \text{SFR} \sim \Sigma_{\text{H}_2}^{1.2}$$



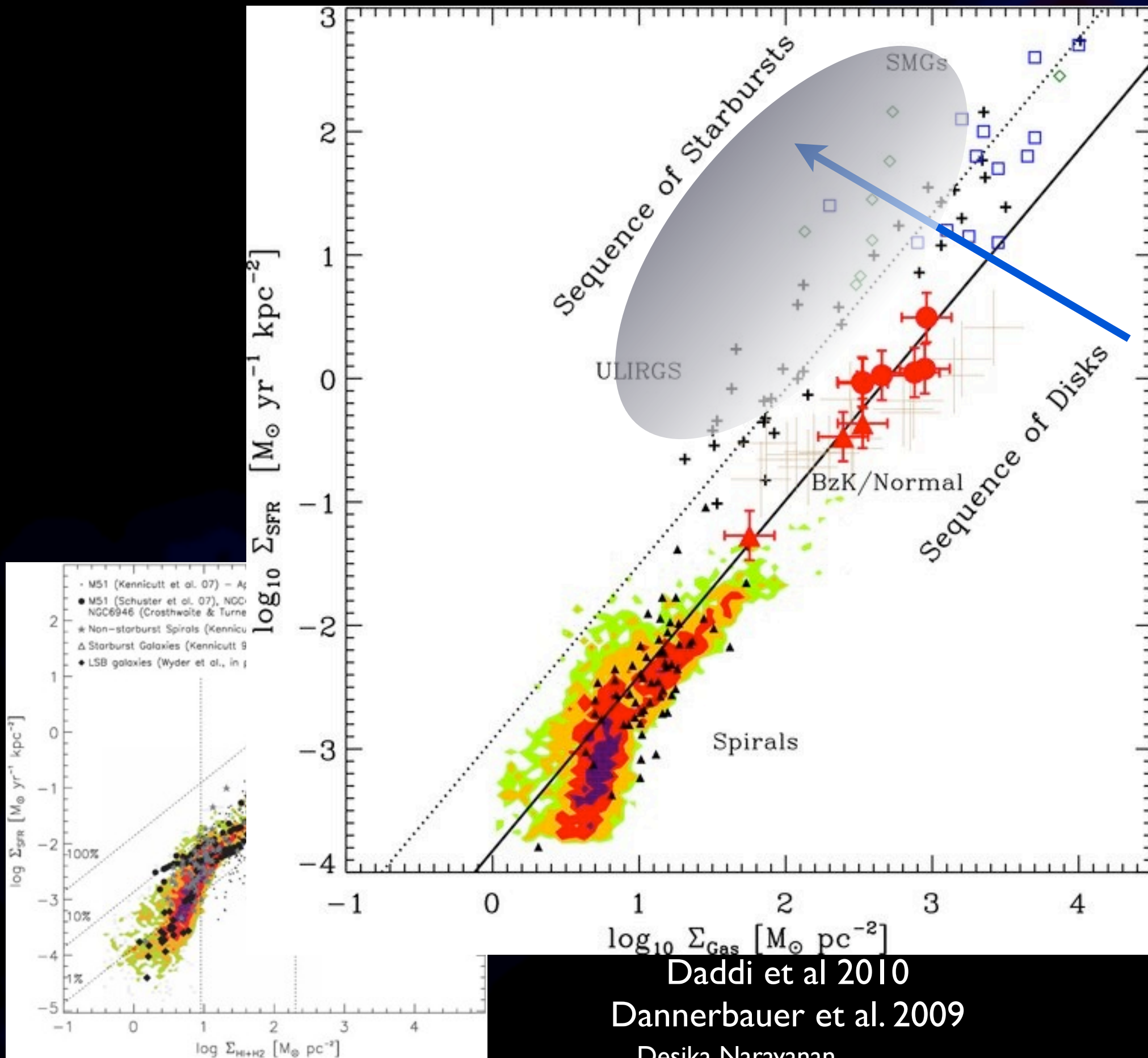
Daddi et al 2010  
 Dannerbauer et al. 2009  
 Desika Narayanan





Daddi et al 2010  
 Dannerbauer et al. 2009  
 Desika Narayanan

1.  $\text{SFR} \sim \Sigma_{\text{H}_2}^{1.2}$
2. Submm galaxies are mergers



Daddi et al 2010  
 Dannerbauer et al. 2009  
 Desika Narayanan

1.  $SFR \sim \Sigma_{H_2}^{1.2}$
2. Submm galaxies are mergers
3. Different  $X_{CO}$  for mergers

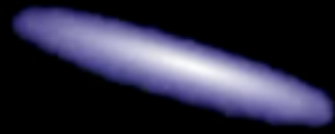
# (some) Outstanding Problems in High- $z$ Galaxy Evolution

1. What is the Physical Form of high- $z$  Galaxies? What kinds of galaxies require mergers? Are discs different at high- $z$ ?
2. Do the empirical relations that describe galaxy evolution in the local Universe hold at early times?
3. How do we derive physical parameters for high- $z$  galaxies when they may live in very different environments than today?

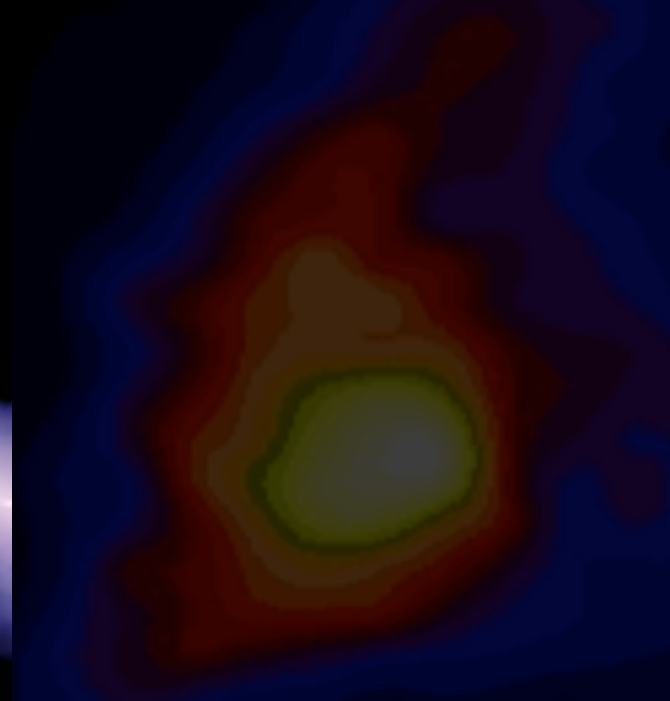
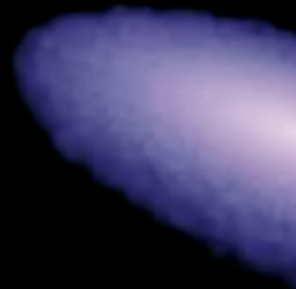


# Methods: Galaxy Evolution Simulations

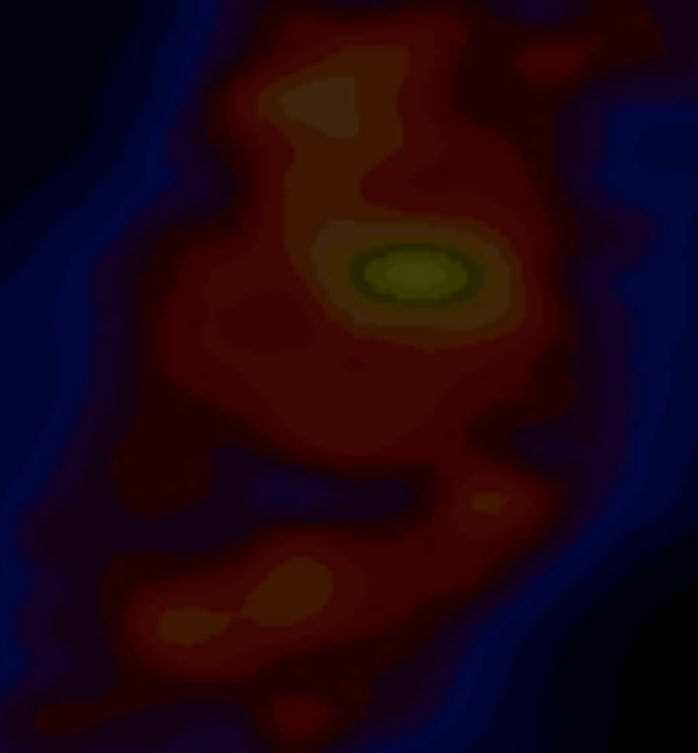
T = 0 Myr



Gas



Springel et al. 2003-2005

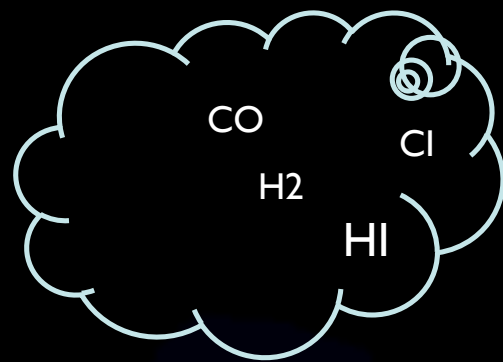
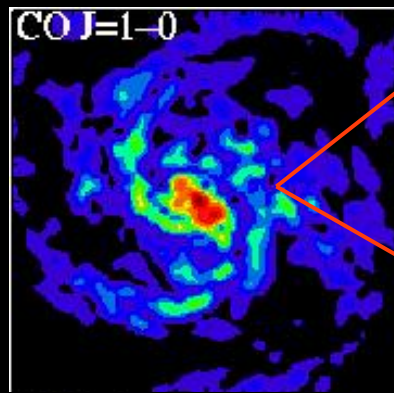


## Physics Included in Hydrodynamics:

- numerically follows DM, Gas, Stars and BH dynamics
- Multi-phase McKee-Ostriker ISM
- Star formation follows KS relations
- BH growth and associated AGN feedback
- Supernovae pressurization of ISM

Desika Narayanan

# What do the molecules look like?



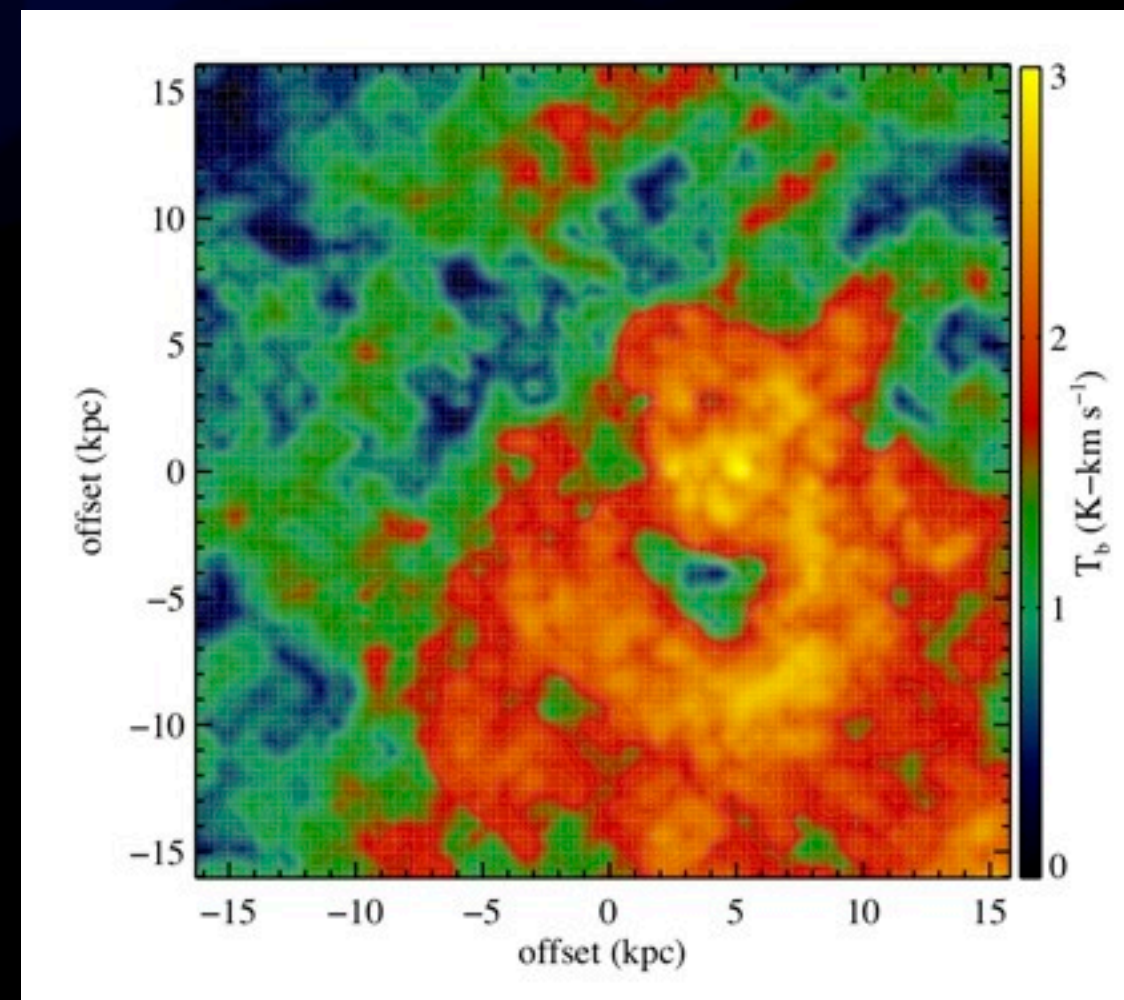
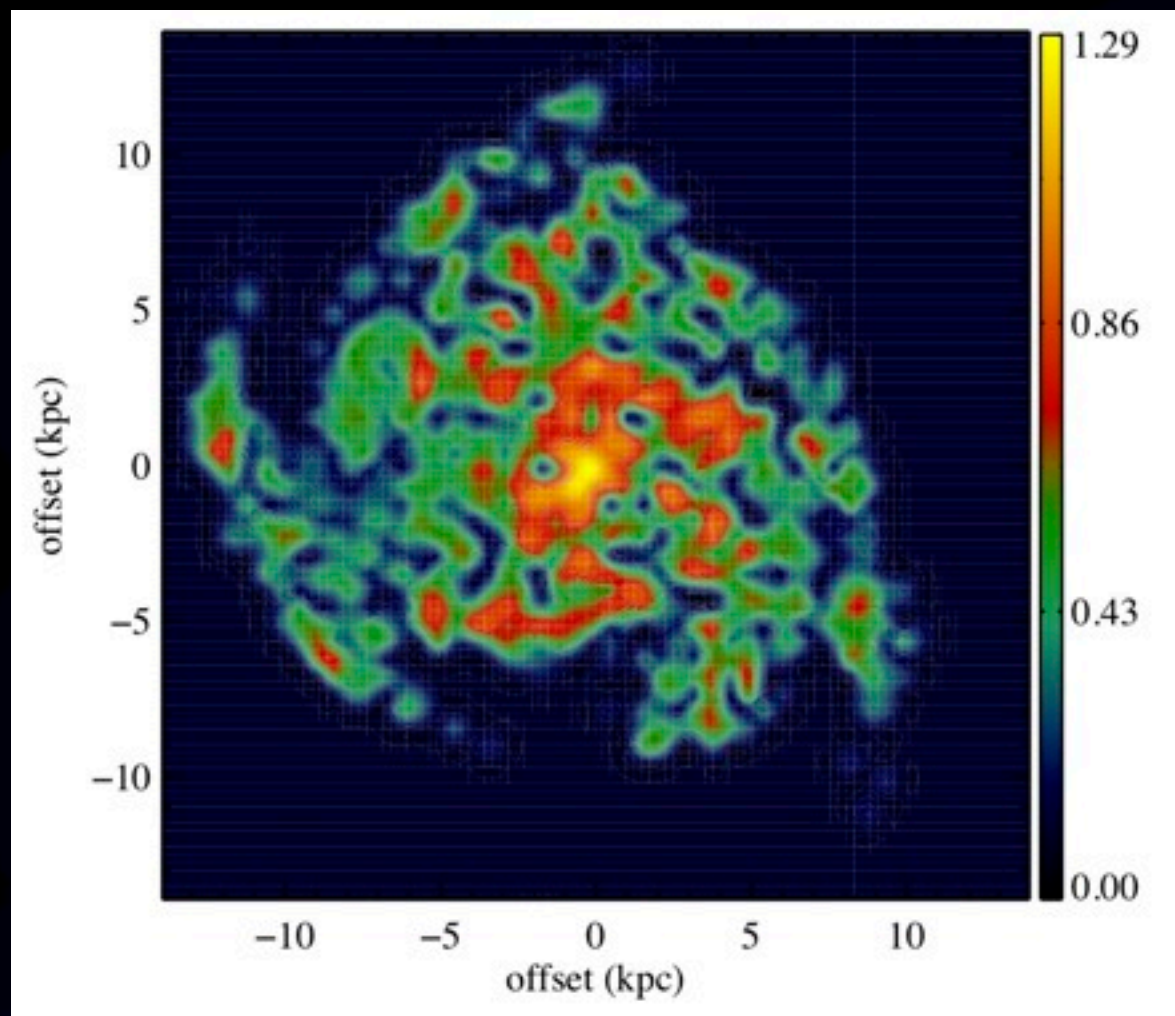
-H<sub>2</sub>-HI balance calculated by balancing growth of H<sub>2</sub> on grains with LW band photodissociation (Krumholz, McKee, Tumlinson 2010)

-CO-CI balance function of ISRF, Z (Wolfire et al. 2010)

-Temp calculated by balancing PE, CR heating, line cooling and thermal exchange with dust (Krumholz, Leroy, McKee 2011)

-Monte Carlo code: Calculates full statistical equilibrium of level populations in a 3D velocity, temp, density field (DN + 2006, 2008)

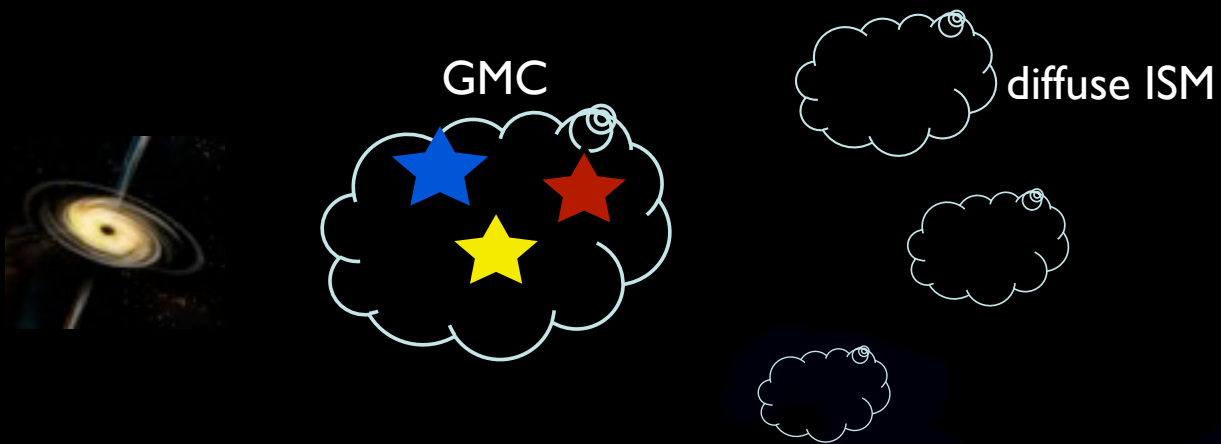
-Cloud Escape probability+Cloud-Cloud interactions accounted for (DN+ 2011)



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# What do the Galaxies look like to non-radio Observers?



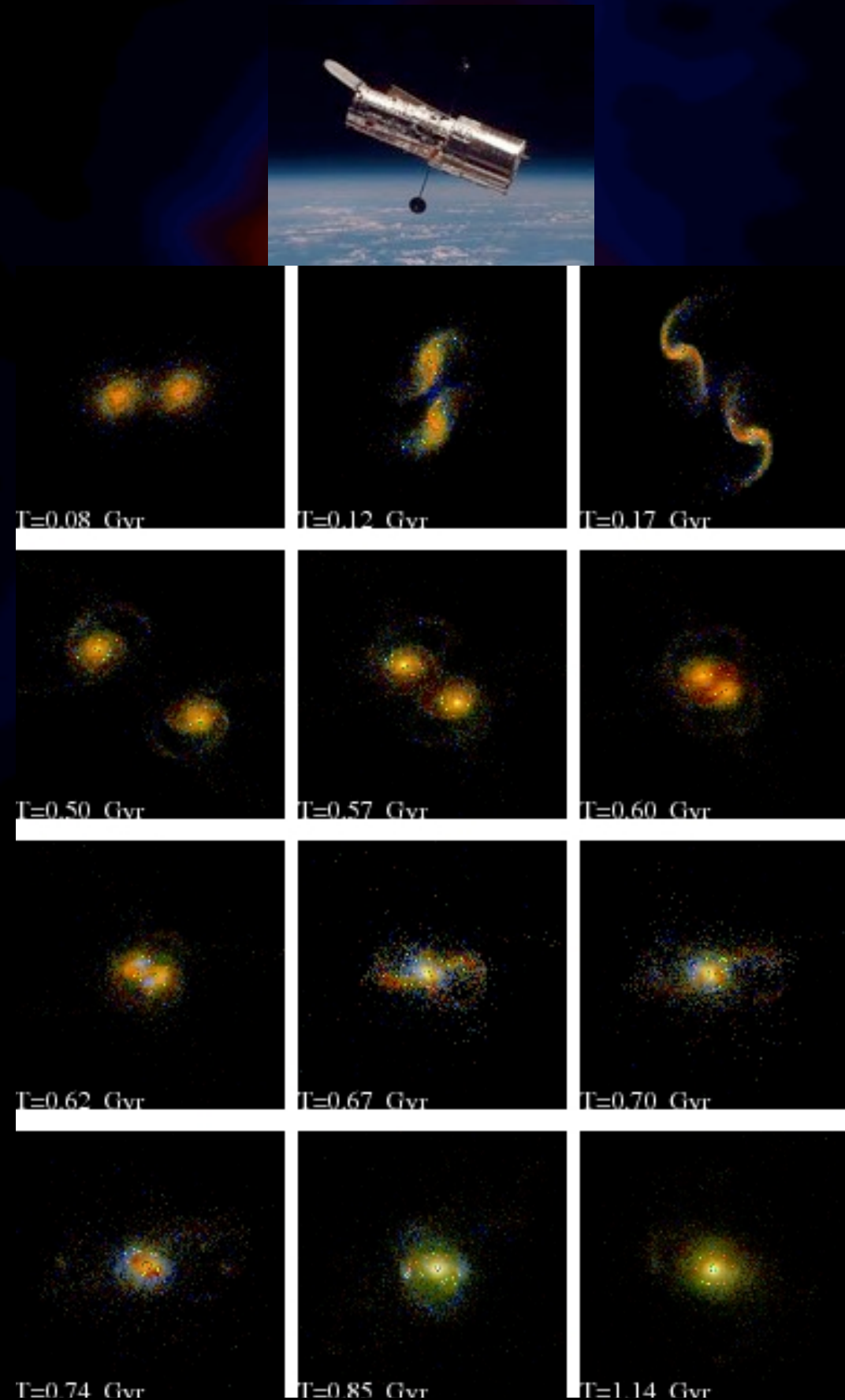
## Physics Included in Monte Carlo Dust RT

-Radiative Transfer of stellar and AGN spectrum  
(starburst99 for stars and Hopkins+07 template for AGN)

-Dust radiative equilibrium

-Kroupa IMF, MW Dust to metals

Jonsson, Groves & Cox 2009



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# (some) Outstanding Problems in High-z Galaxy Evolution

1. What is the Physical Form of high-z Galaxies? What kinds of galaxies require mergers? Are discs different at high-z?

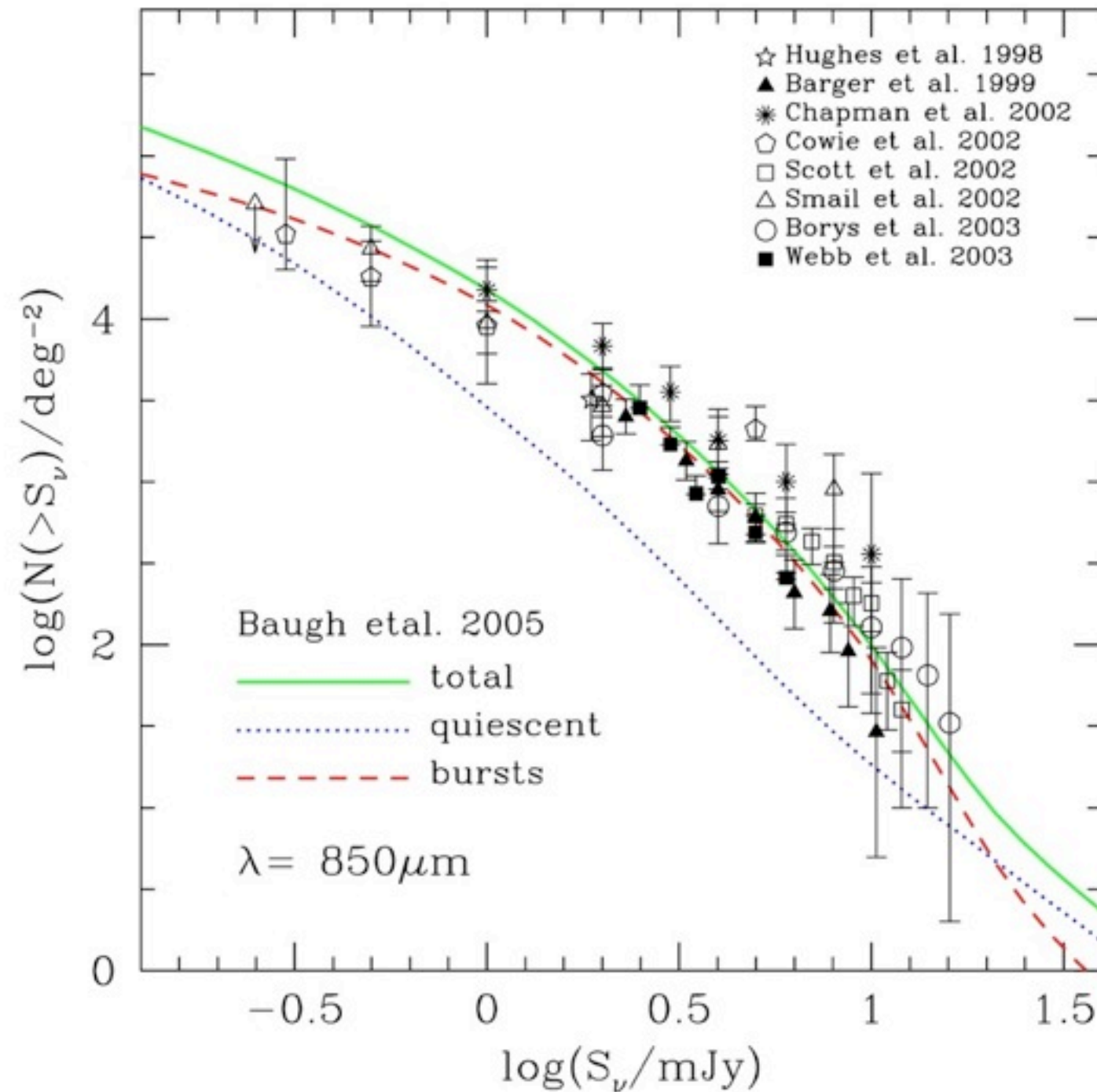
2. Do the empirical relations that describe galaxy evolution in the local Universe hold at early times?

3. How do we derive physical parameters for high-z galaxies when they may live in very different environments than today?

# $dN/d\ln M \sim M$ : Flat IMF?

Baugh et al. 2005:

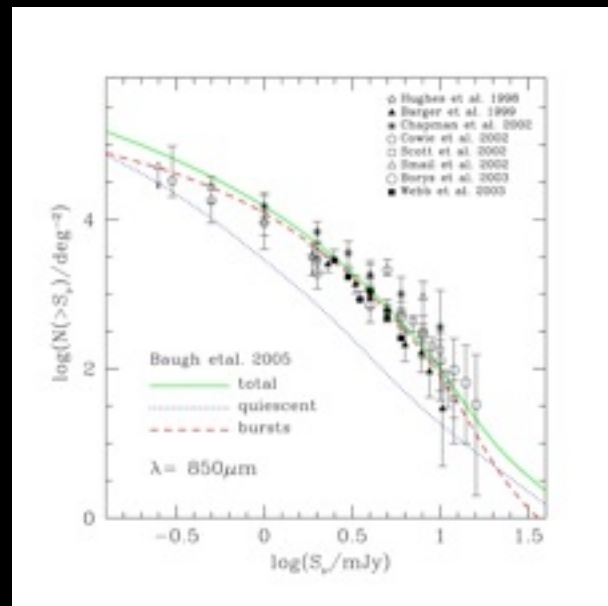
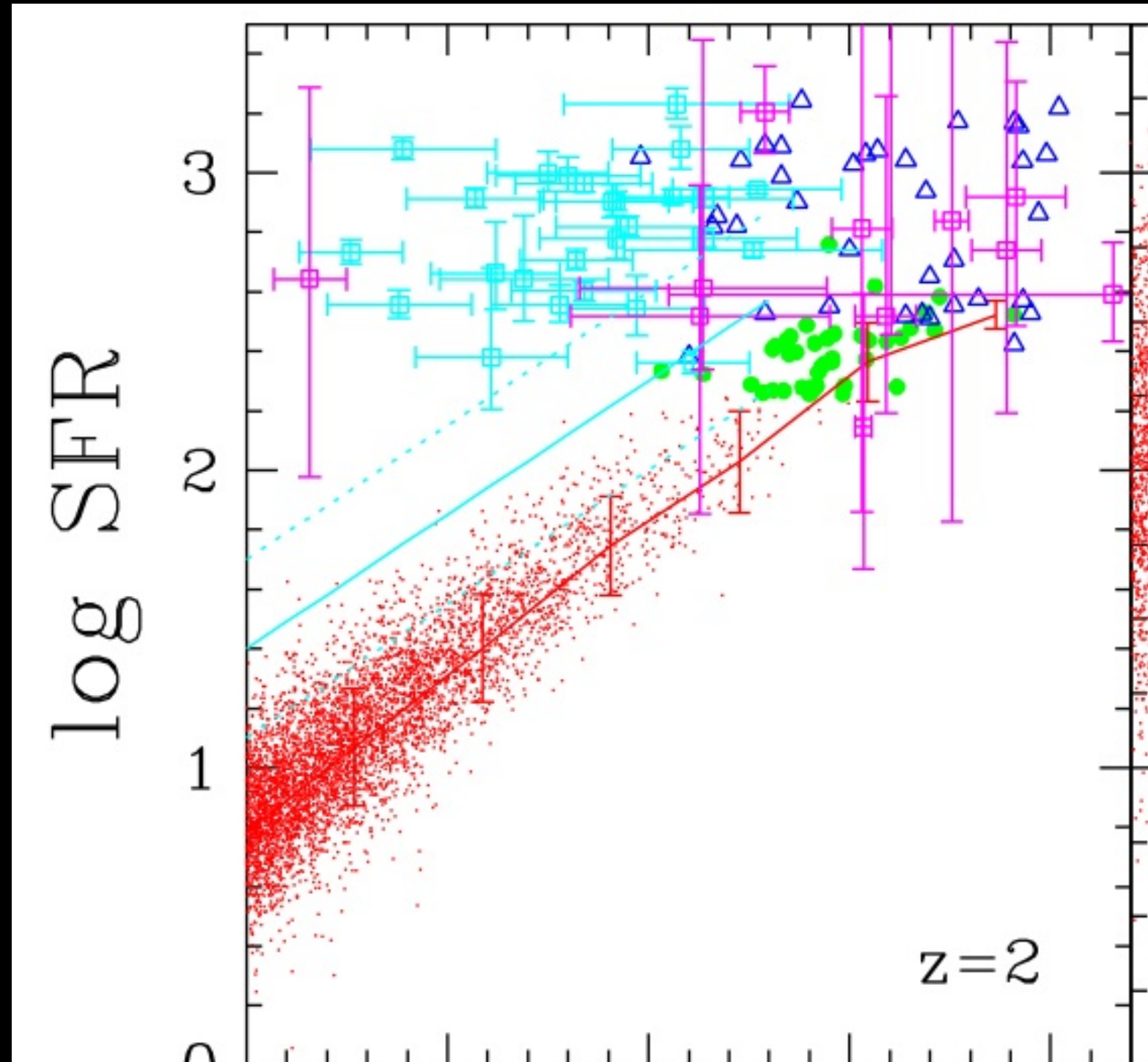
SMGs are mostly discs +  
minor mergers with a flat  
IMF



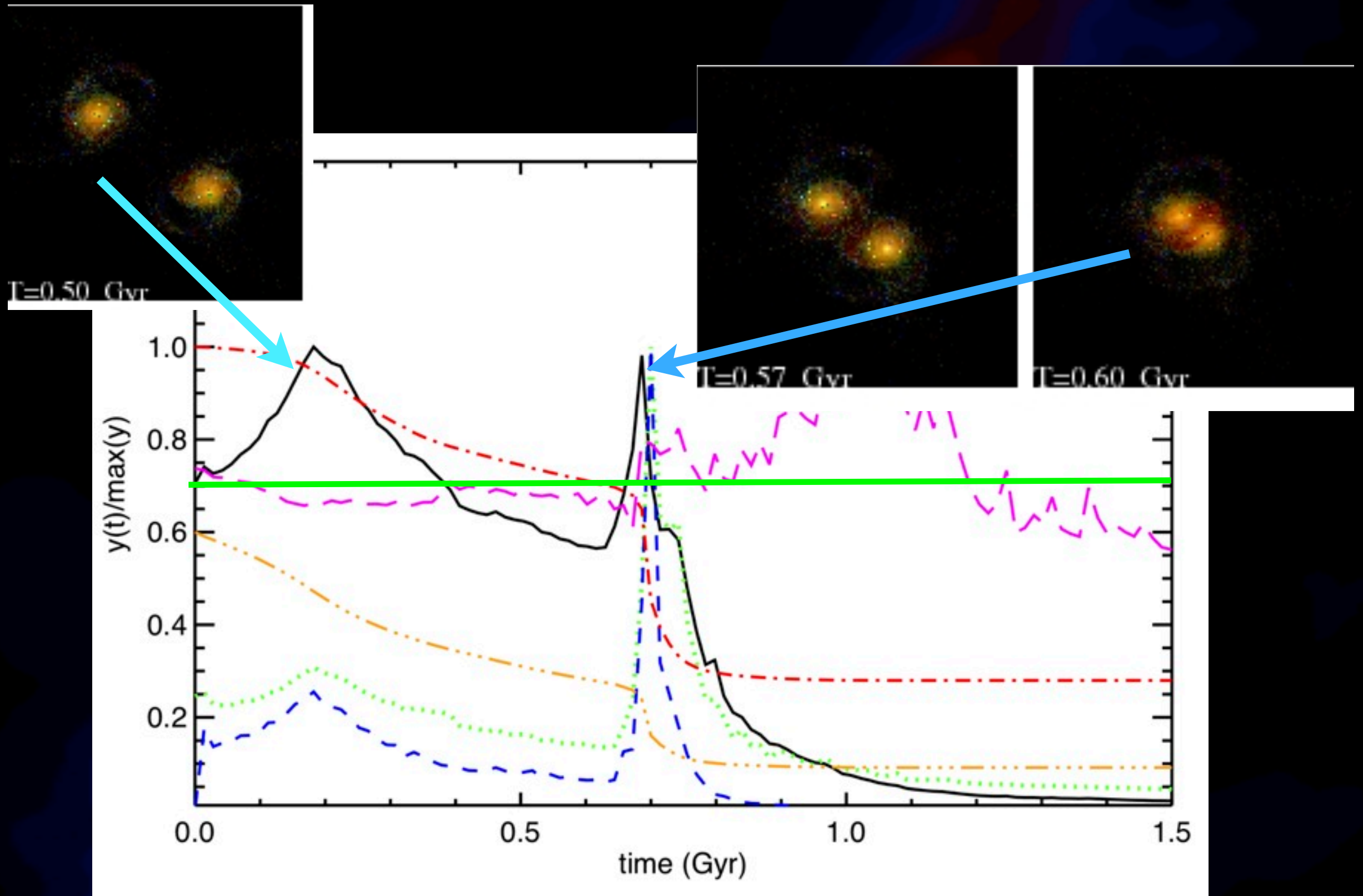


# Or a “Bottom Light” one?

Dave et al. 2009:  
SMGs are mostly discs  
with a “bottom light” IMF



# Submillimeter Galaxies are Major Mergers



Narayanan et al. 2010

Hayward et al. 2011

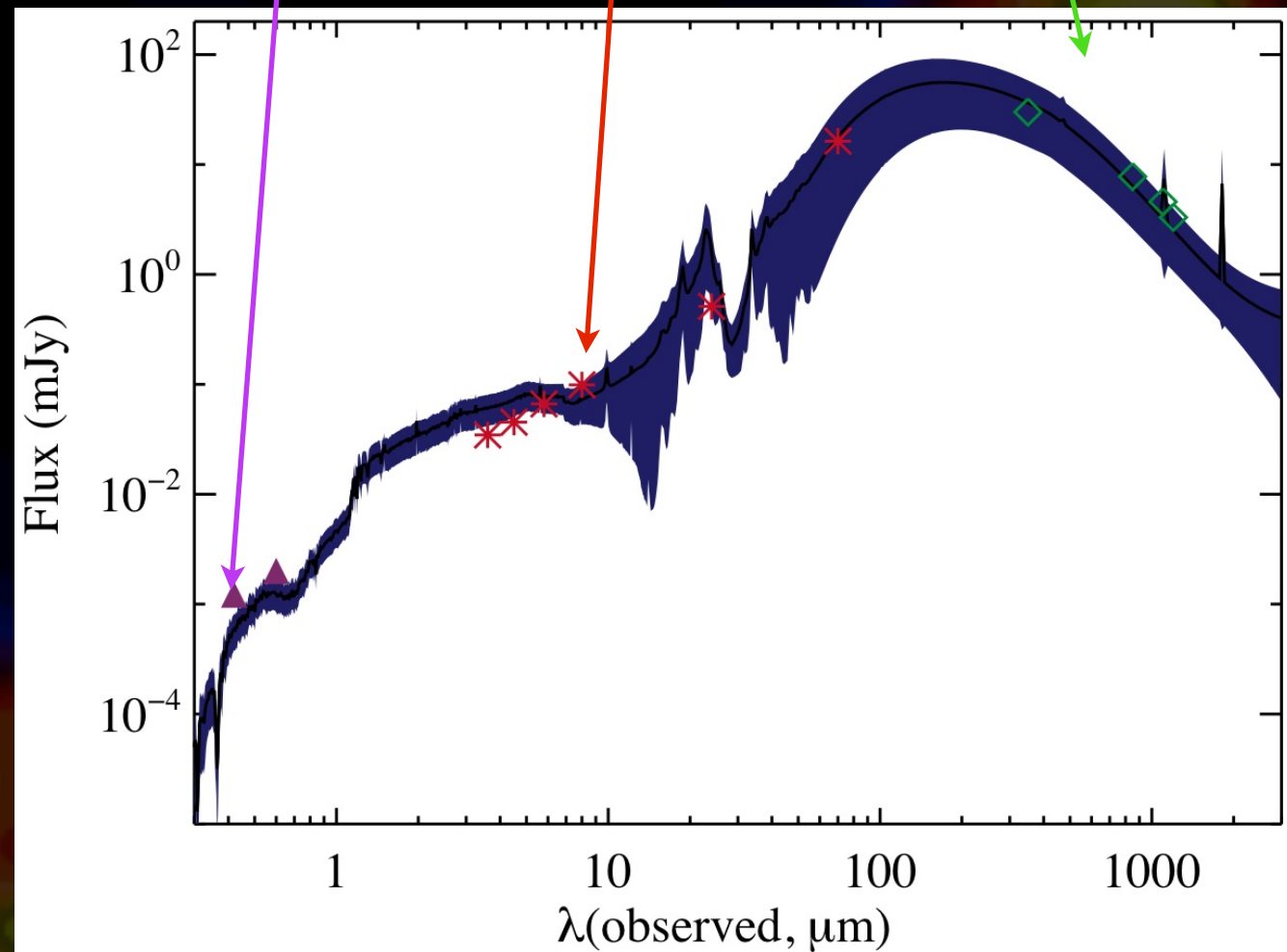
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# Merger Based Model for SMG Formation

Chapman et al. (2005)

Hainline et al. 2010

Kovacs et al. 2006



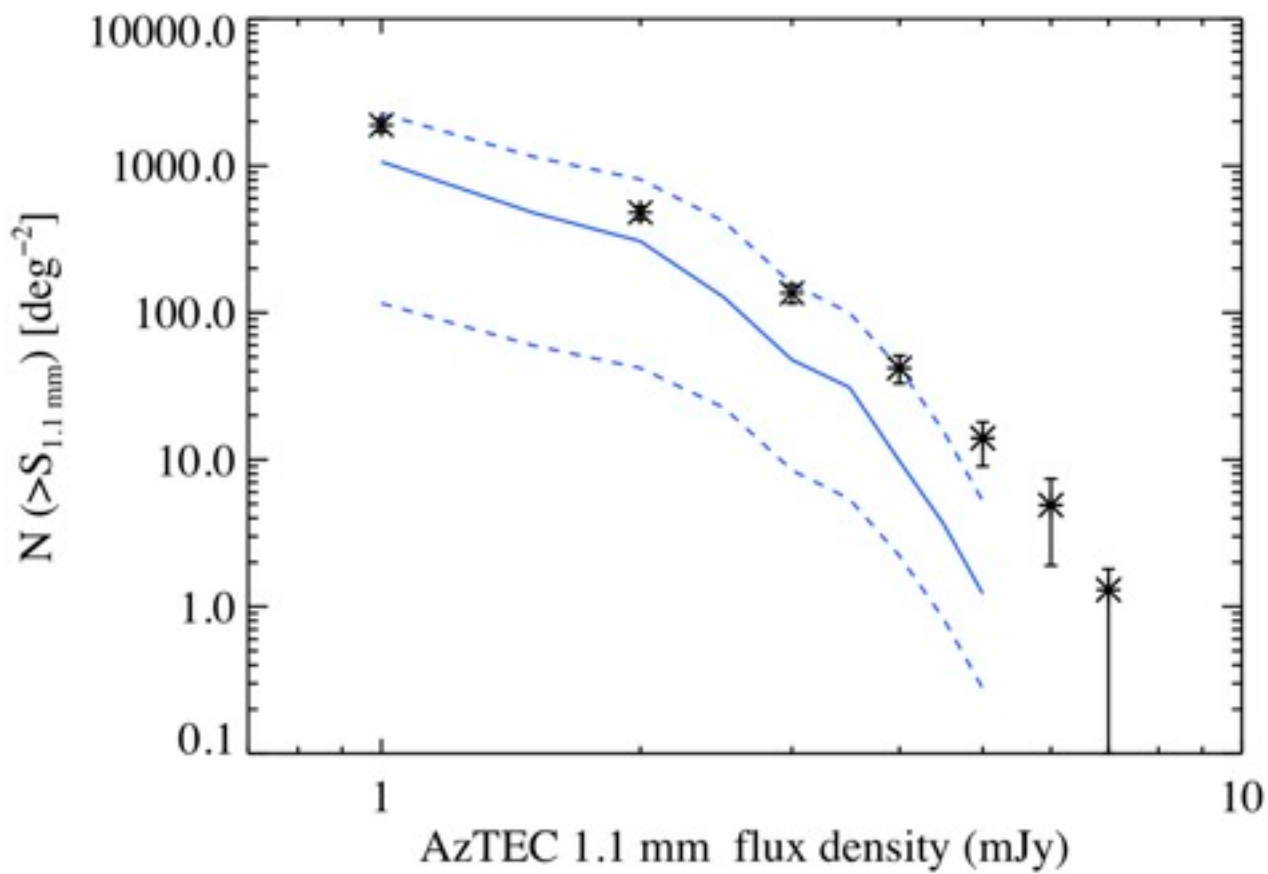
Narayanan, Hayward et al. 2010  
Hayward, Keres et al. 2011

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# Merger Based Model for SMG Formation

## Bursts Only

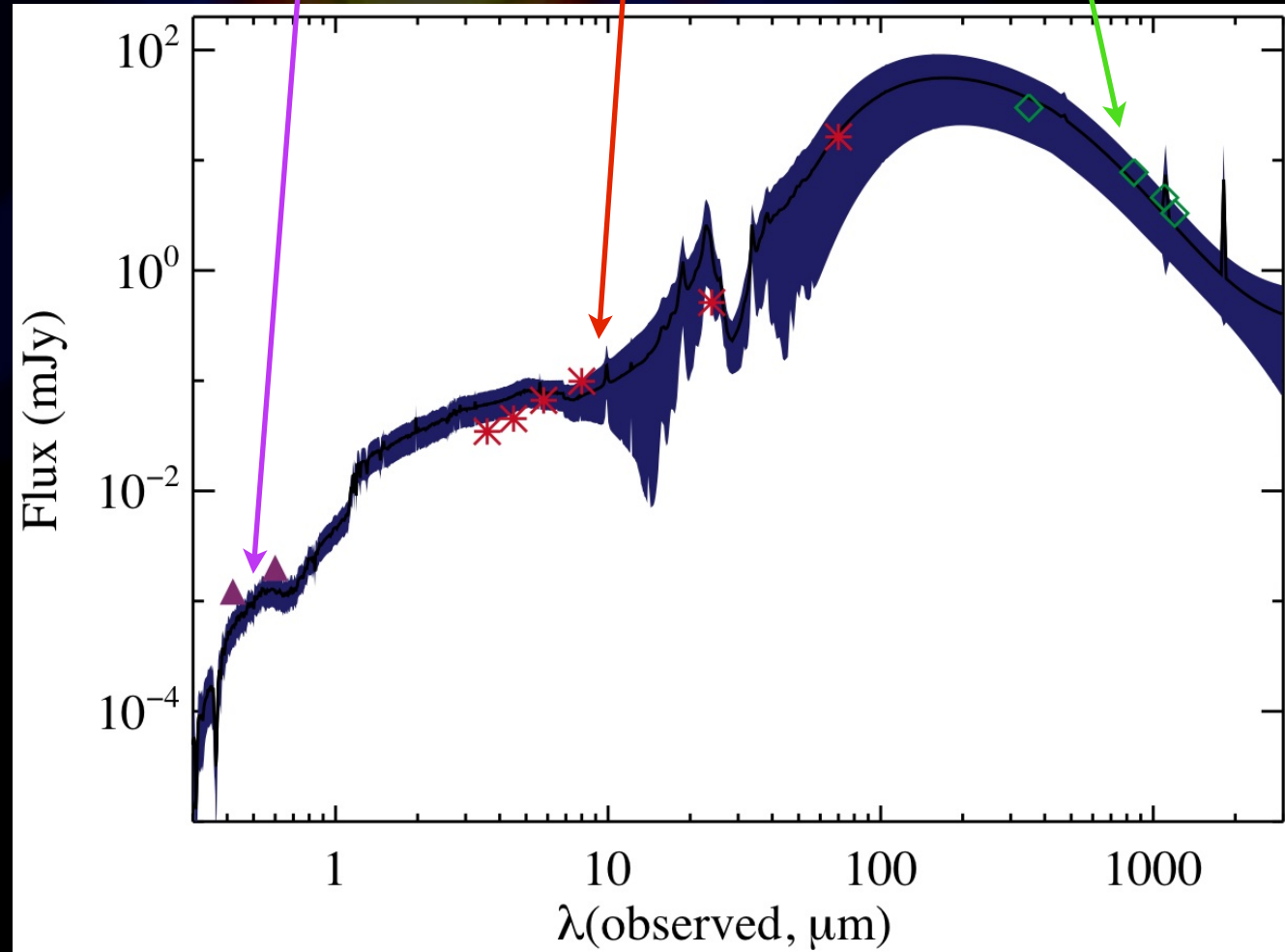


Hayward, Narayanan et al. in prep.

Chapman et al. (2005)

Hainline et al. 2010

Kovacs et al. 2006

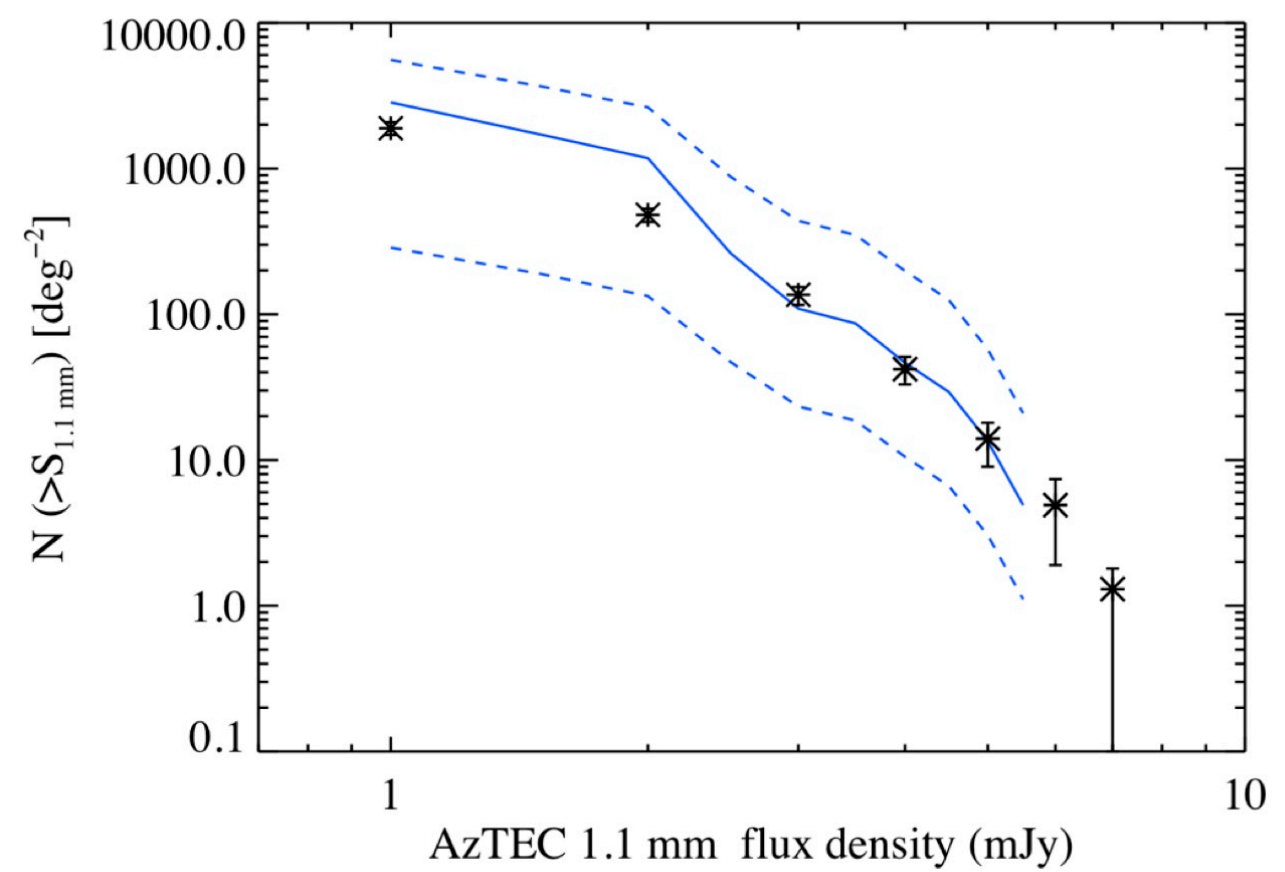
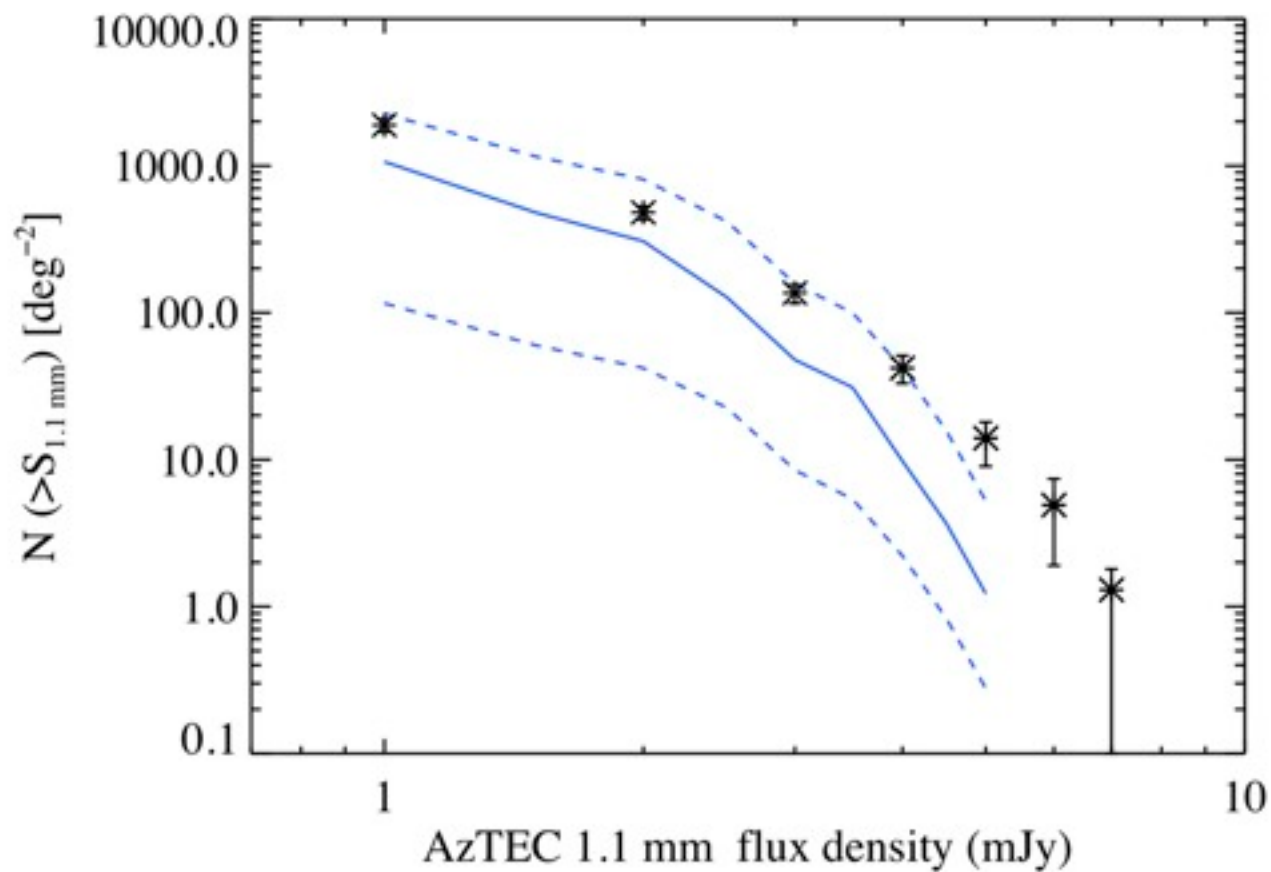


Narayanan, Hayward et al. 2010  
Hayward, Keres et al. 2011

# Merger Based Model for SMG Formation

Bursts Only

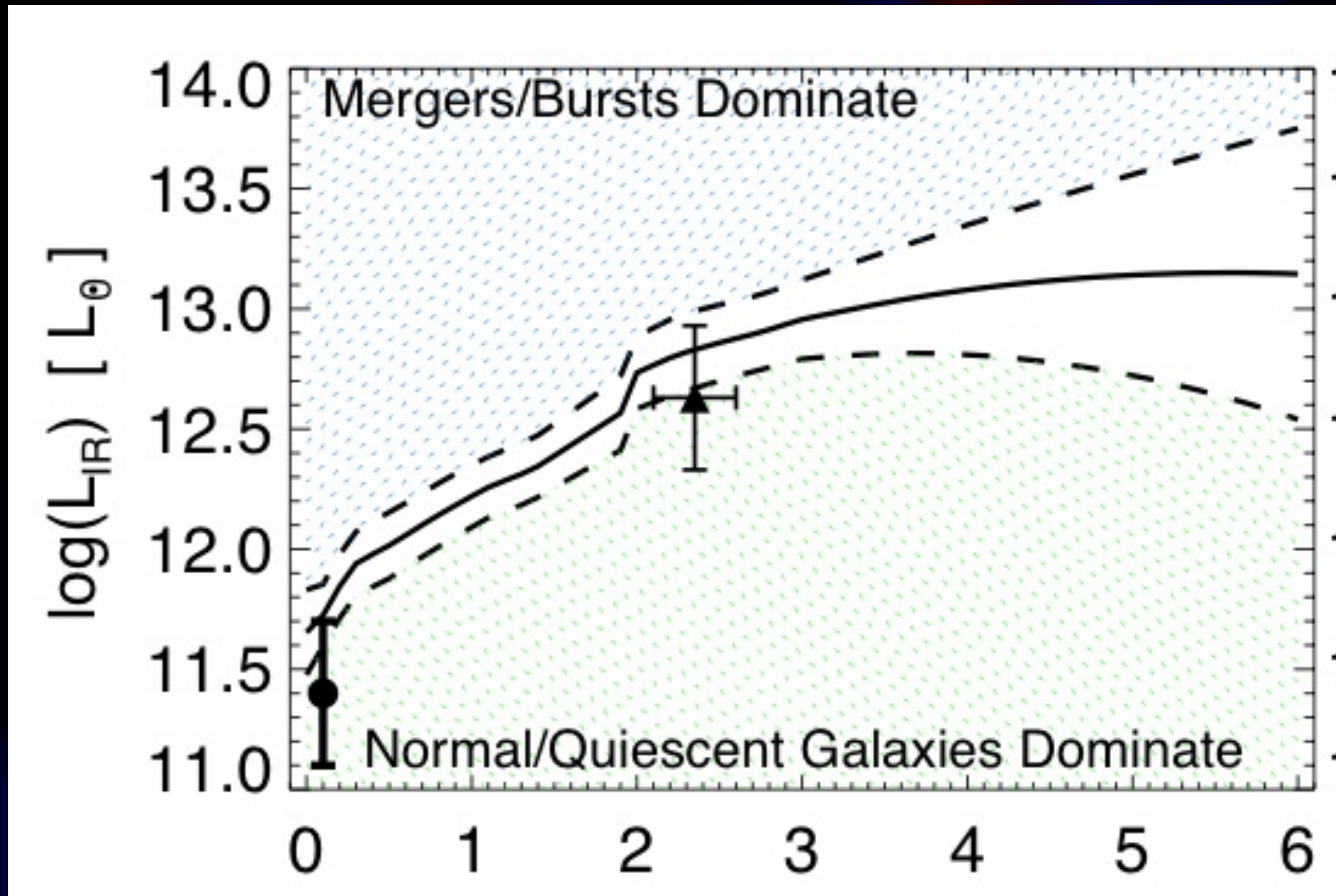
Infalling Pairs & Bursts



Hayward, Narayanan et al. in prep.

Desika Narayanan

# More Generally: When are galaxies at high-z mergers?

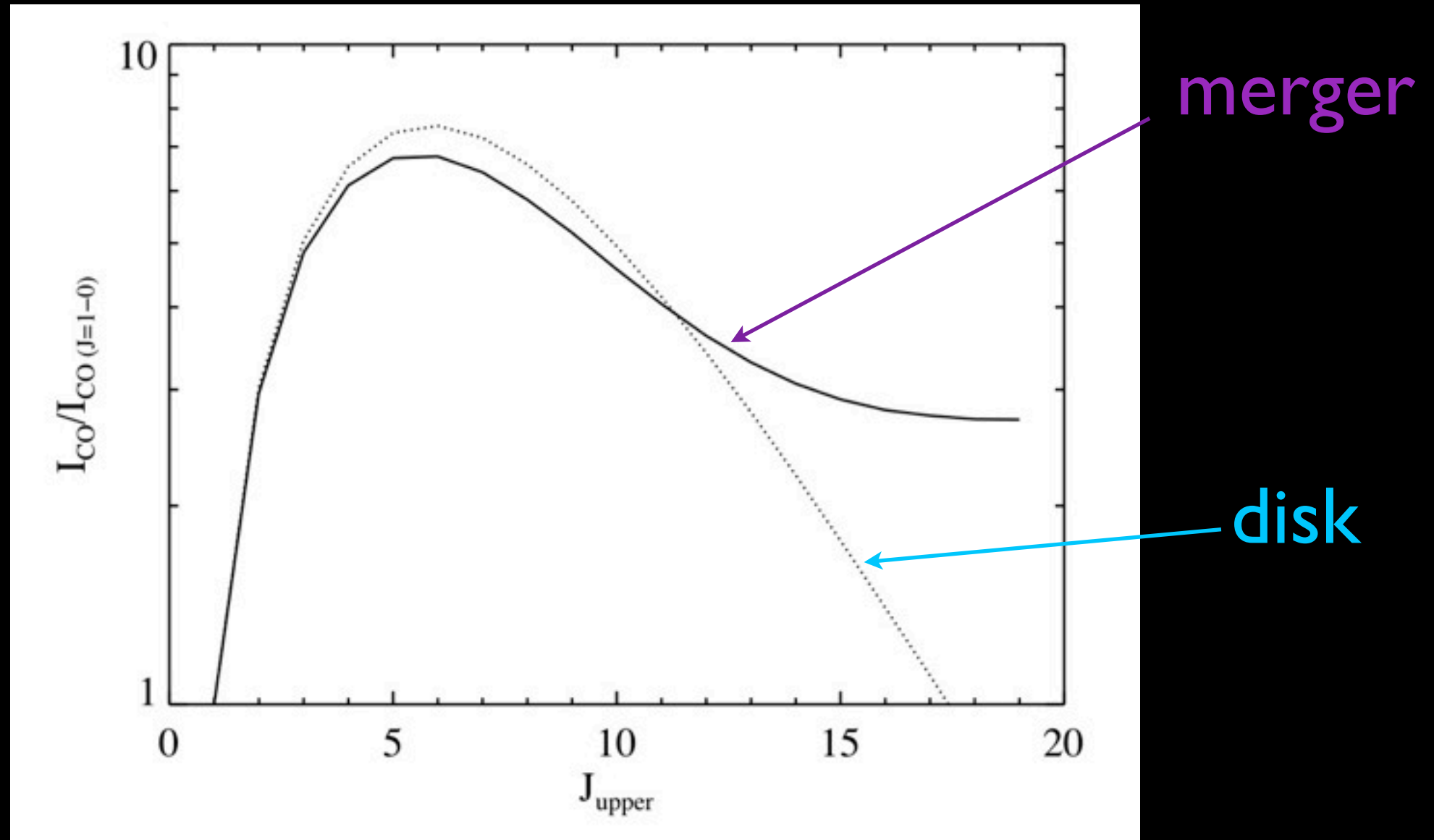


Hopkins, Younger, Hayward, DN, Hernquist 2010

Desika Narayanan



# How Can We Distinguish Mergers at High-z?: CO Excitation

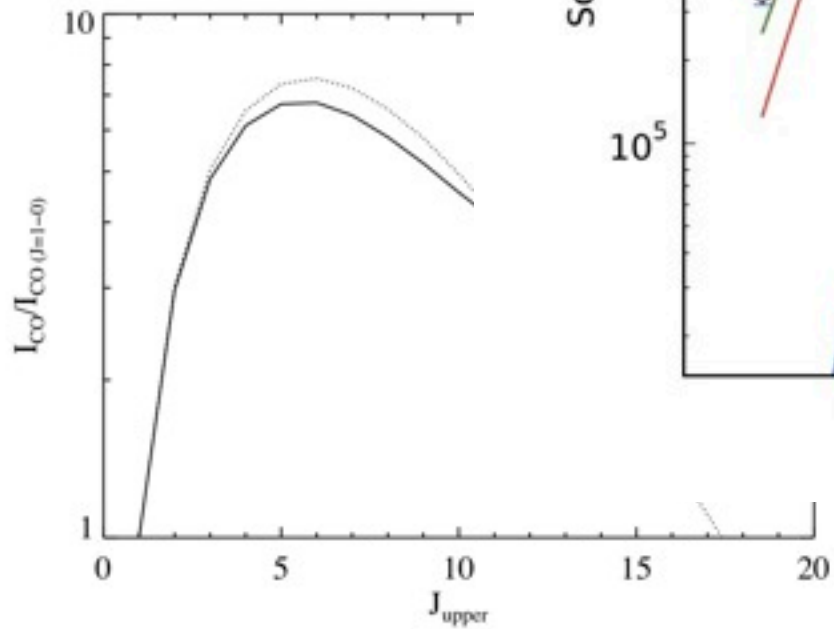
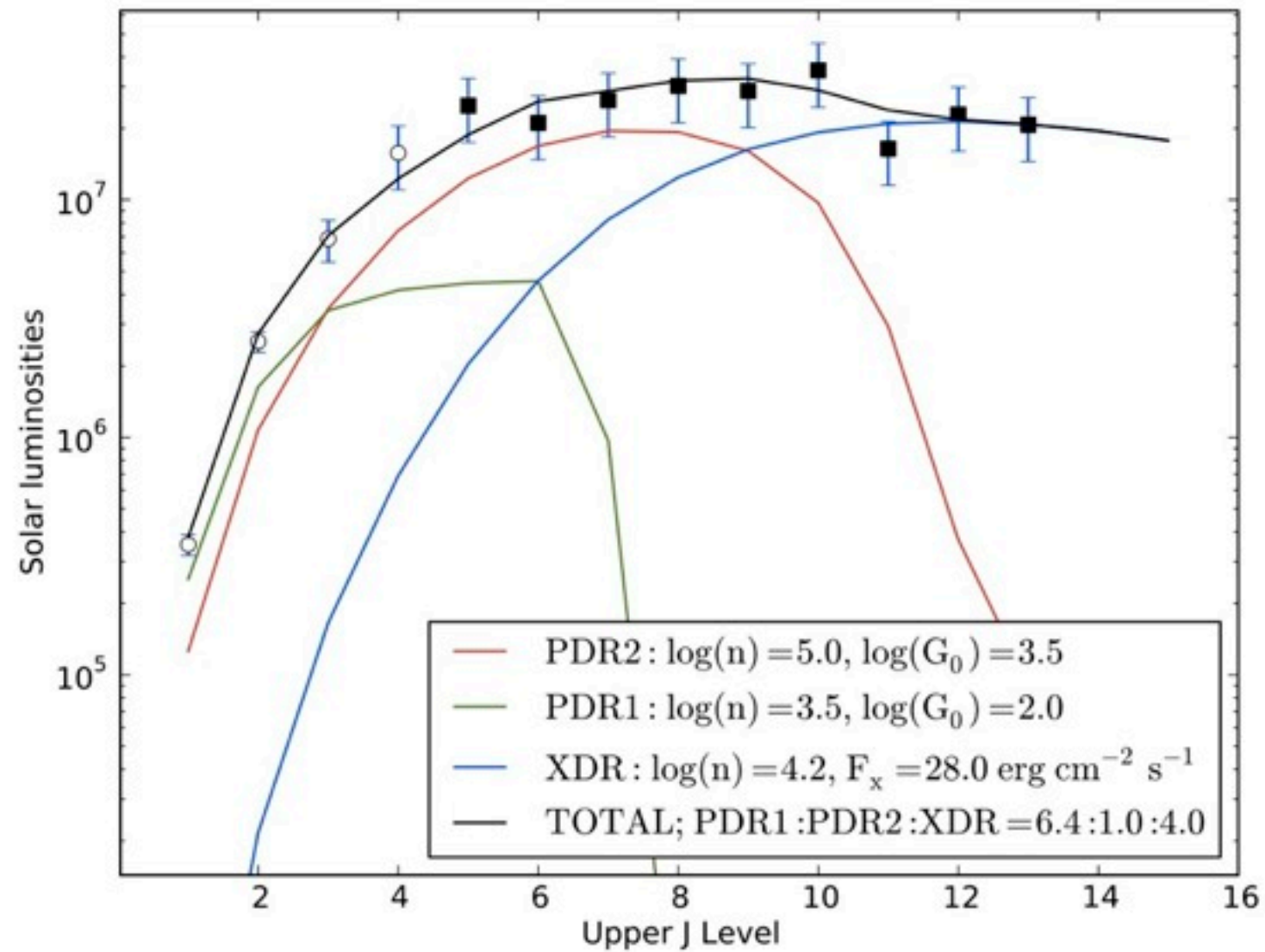


0 2 10 12 50

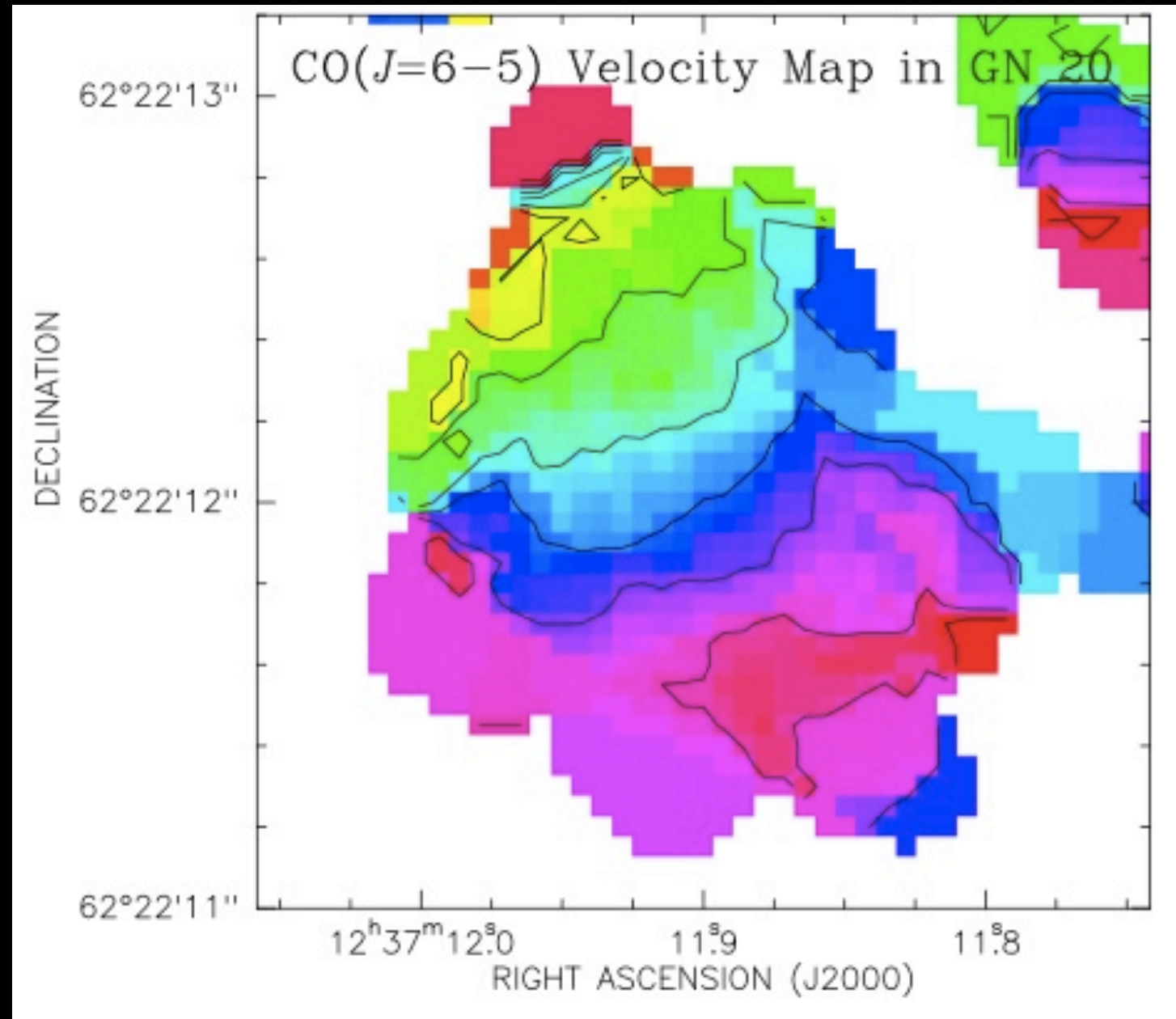
Saahil Patel & DN in prep

# How Can We Distinguish Mergers at High-z?

van der Werf et al. 2010 (Herschel)



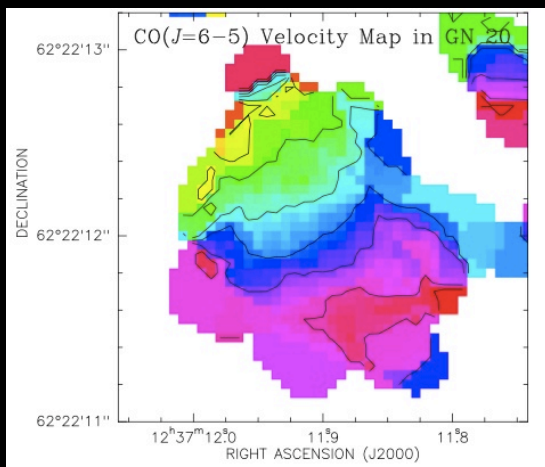
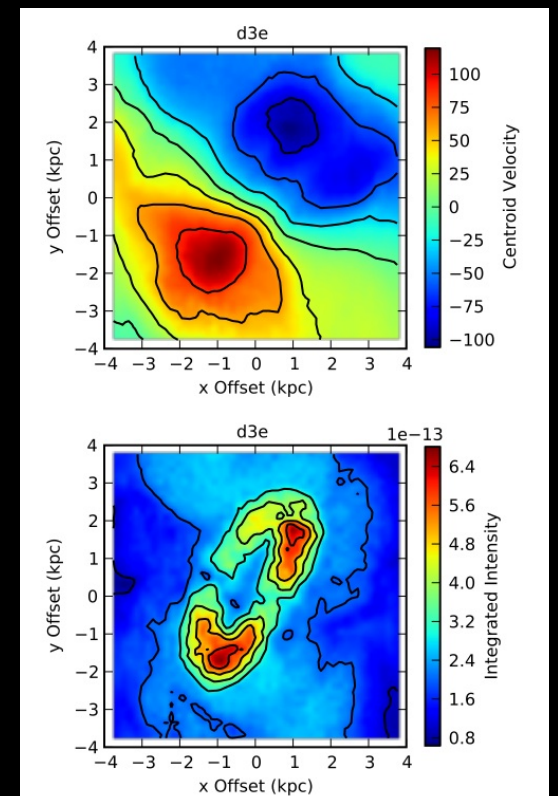
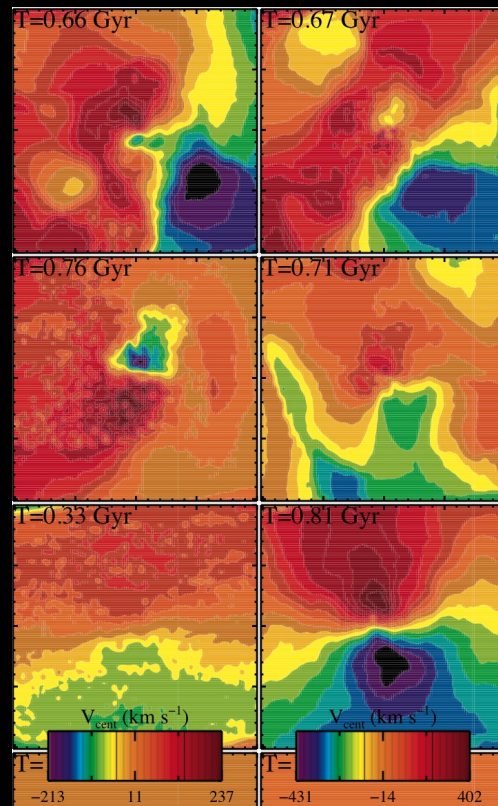
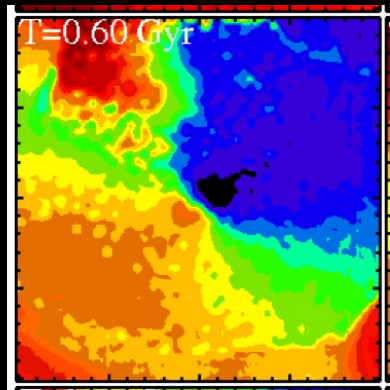
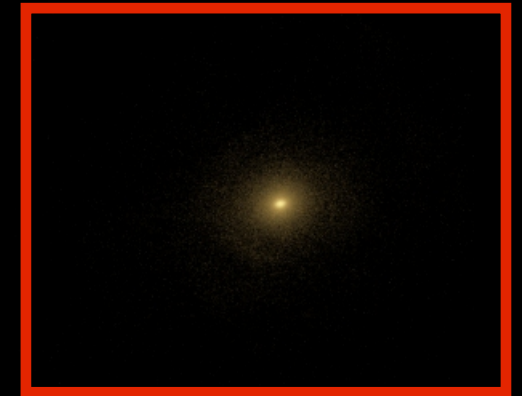
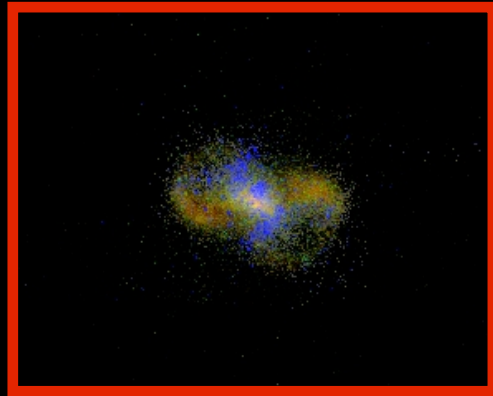
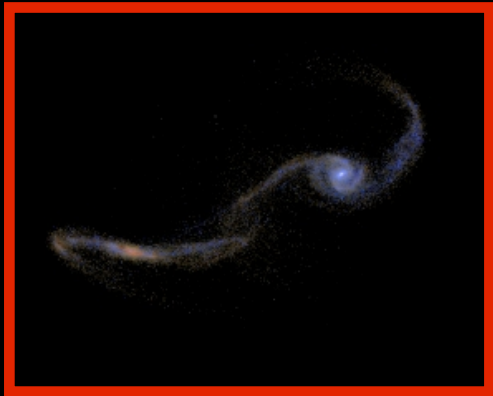
# How Can't We Distinguish Mergers at High-z?: Molecular Disks



Carilli et al. 2010

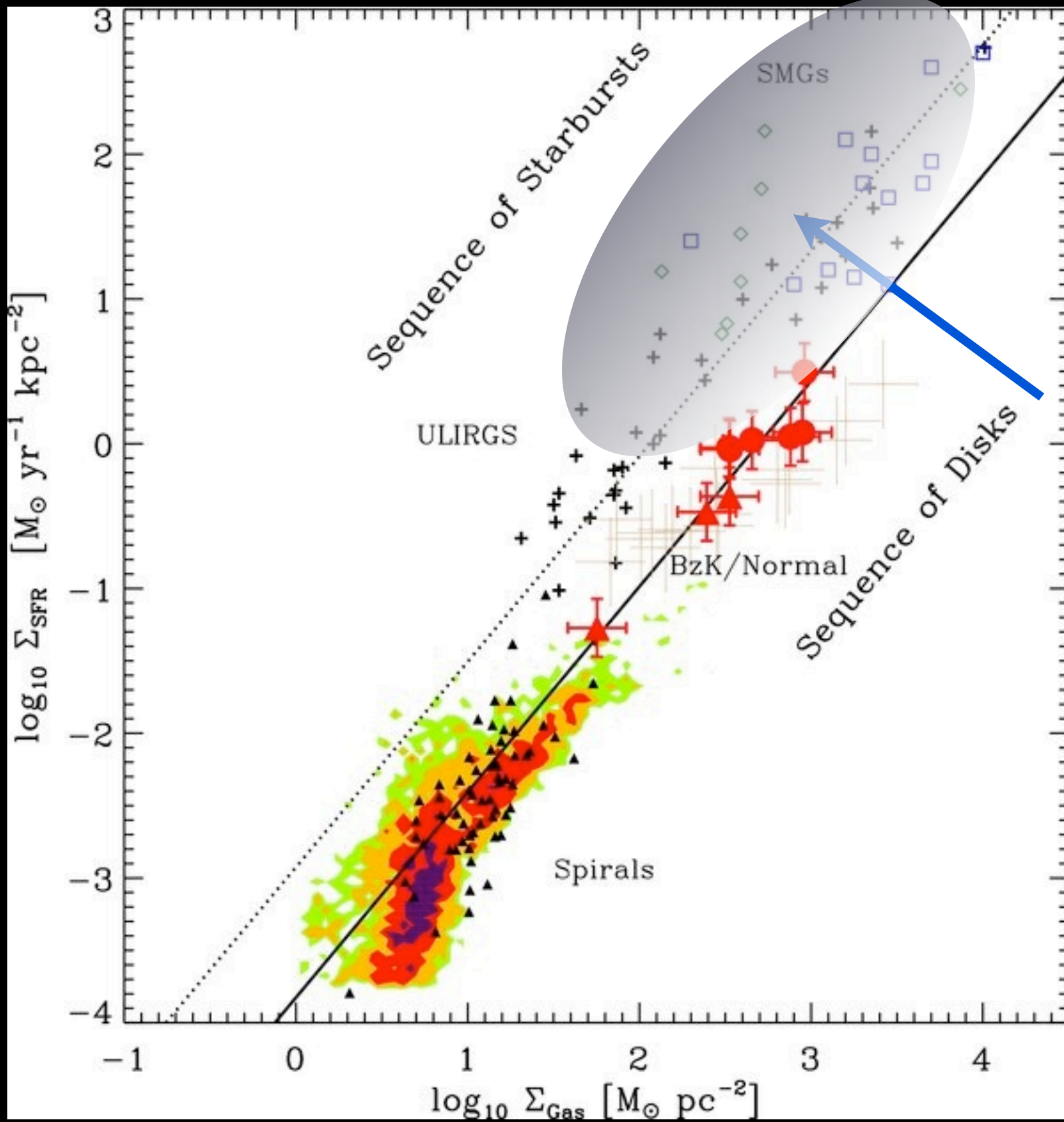


# How Can't We Distinguish Mergers at High-z?: Molecular Disks



Narayanan, Cox, Hayward et al. 2009

Xu, Narayanan & Walker 2010



Daddi et al. 2010

Desika Narayanan

# (some) Outstanding Problems in High-z Galaxy Evolution

1. What is the Physical Form of high-z Galaxies? What kinds of galaxies require mergers? Are discs different at high-z?

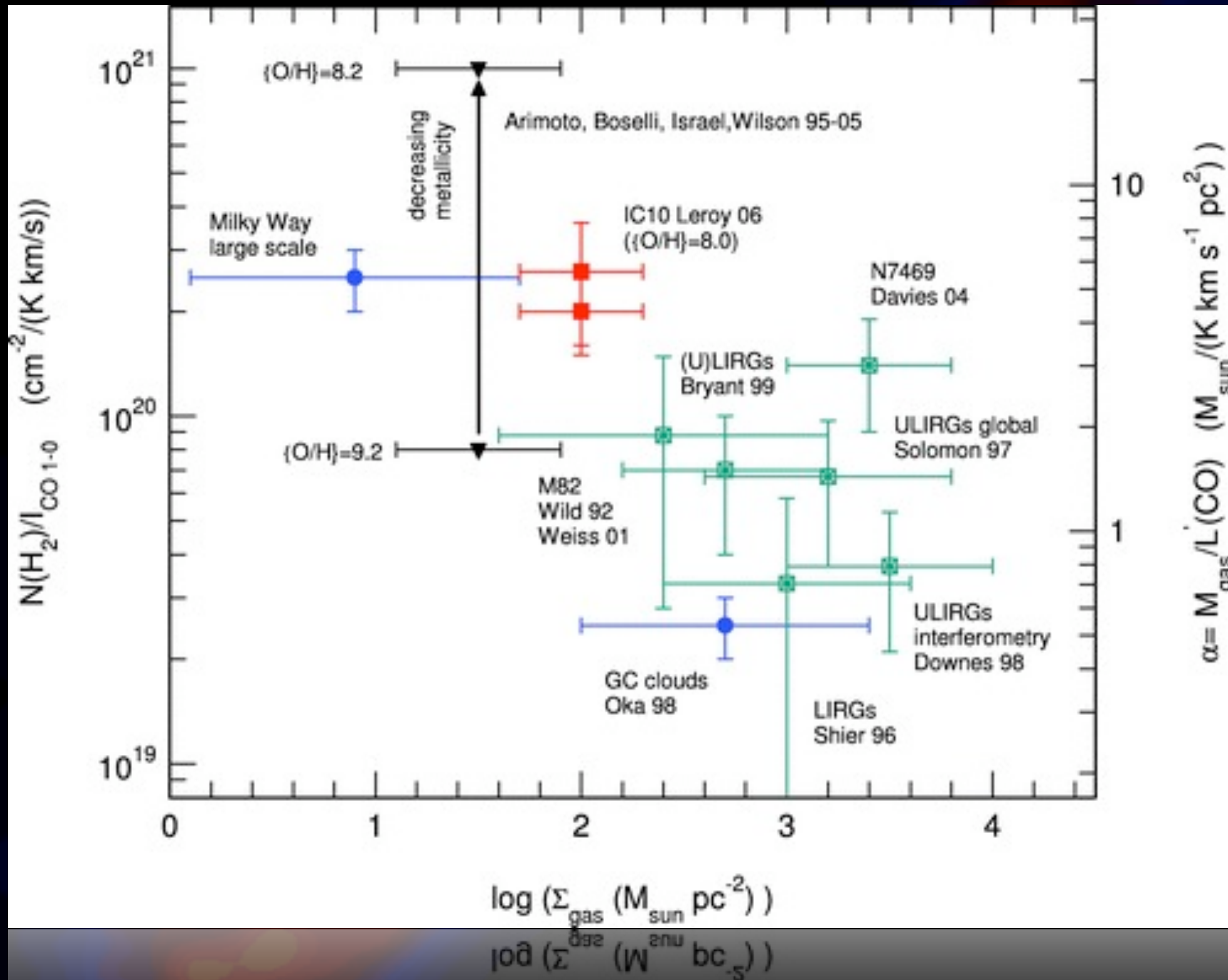
2. Do the empirical relations that describe galaxy evolution in the local Universe hold at early times?

3. How do we derive physical parameters for high-z galaxies when they may live in very different environments than today?

( $X_{\text{CO}}$  - caveat: applies to  $Z \geq Z_{\text{solar}}$  galaxies only)

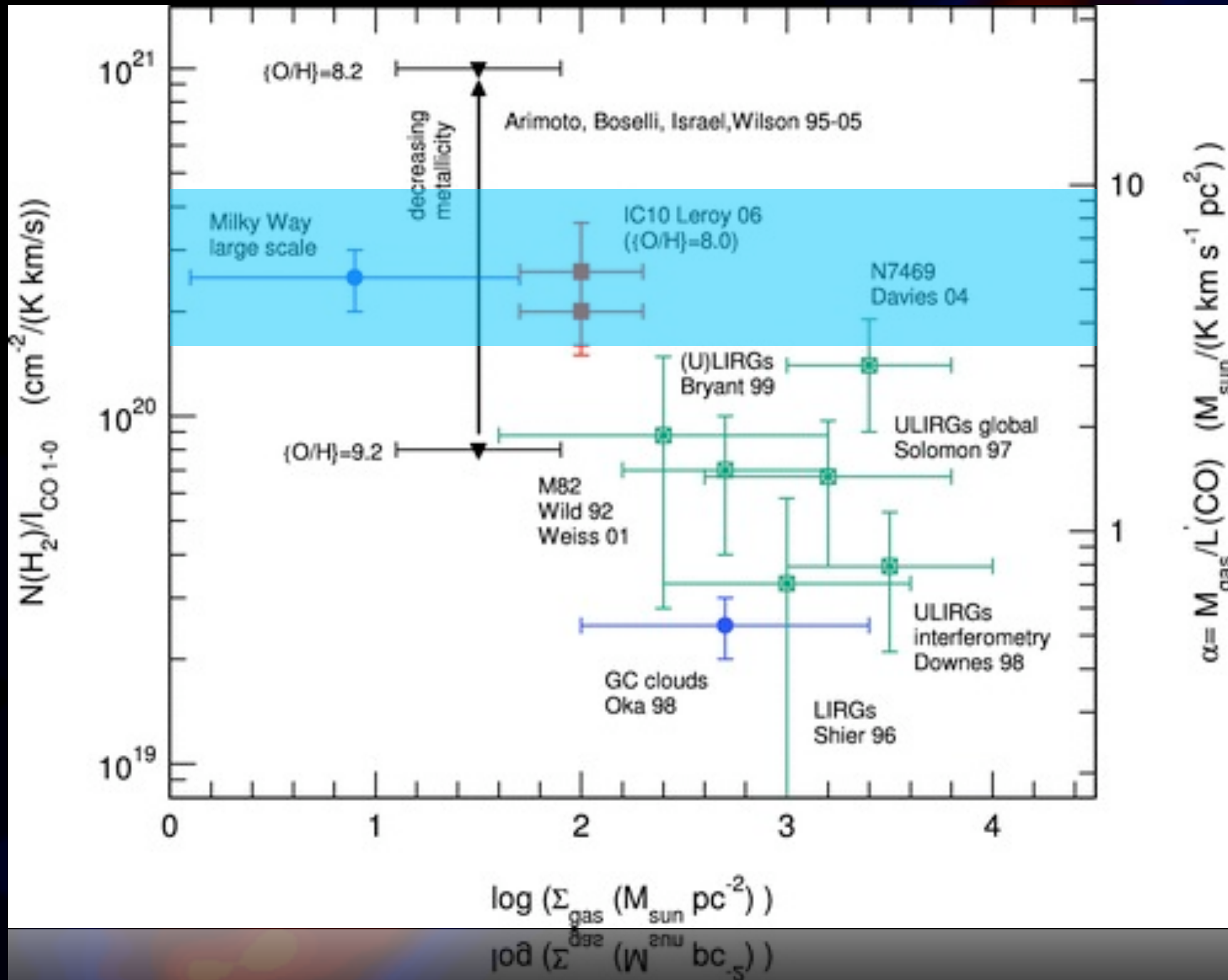


# $X_{\text{CO}} = N_{\text{H}_2}/I_{\text{CO}}$ Depends on Galactic Environment



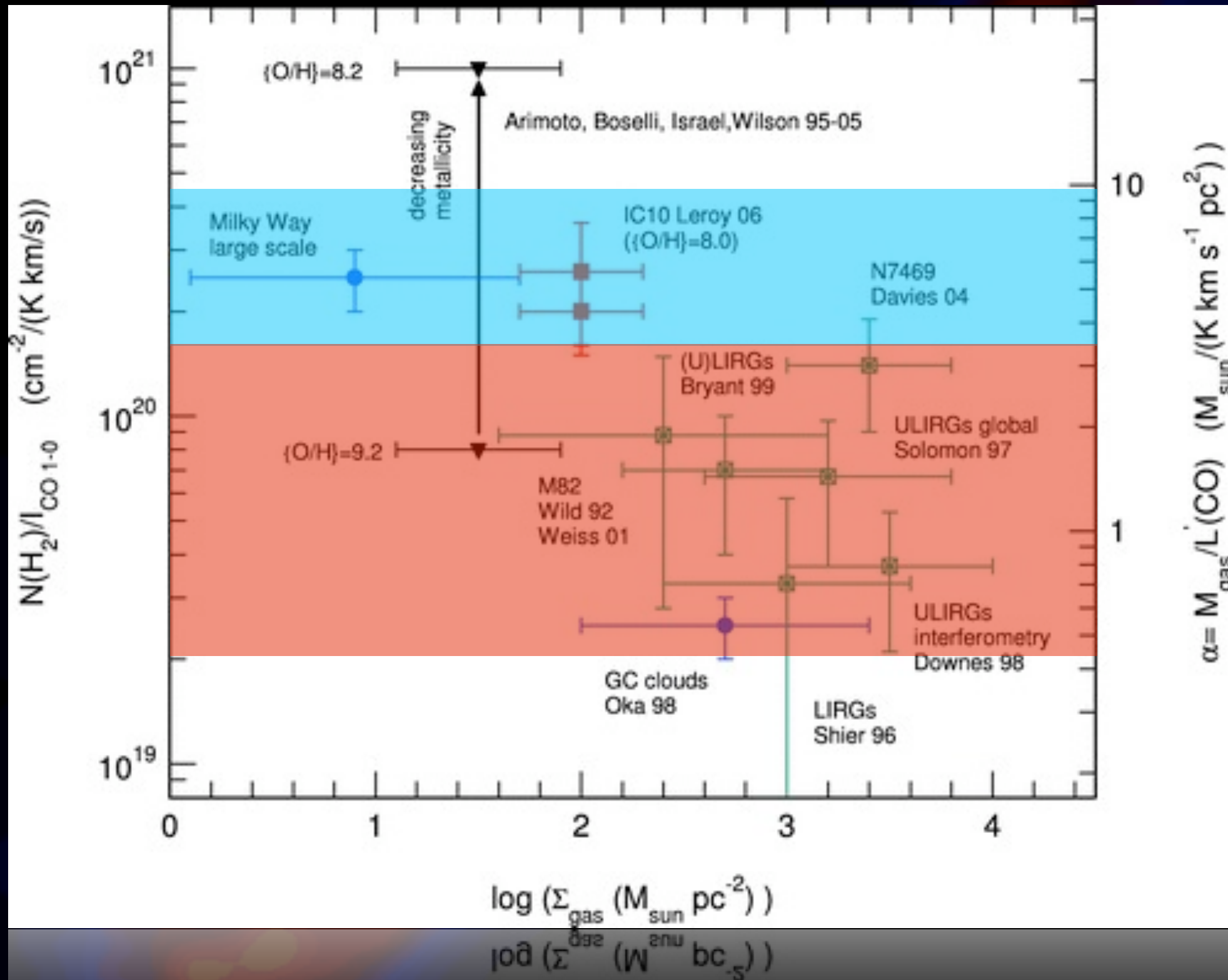
Tacconi et al. 2008

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Tacconi et al. 2008

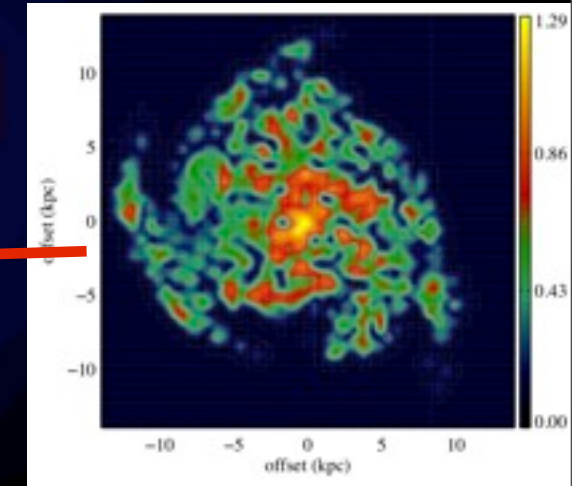
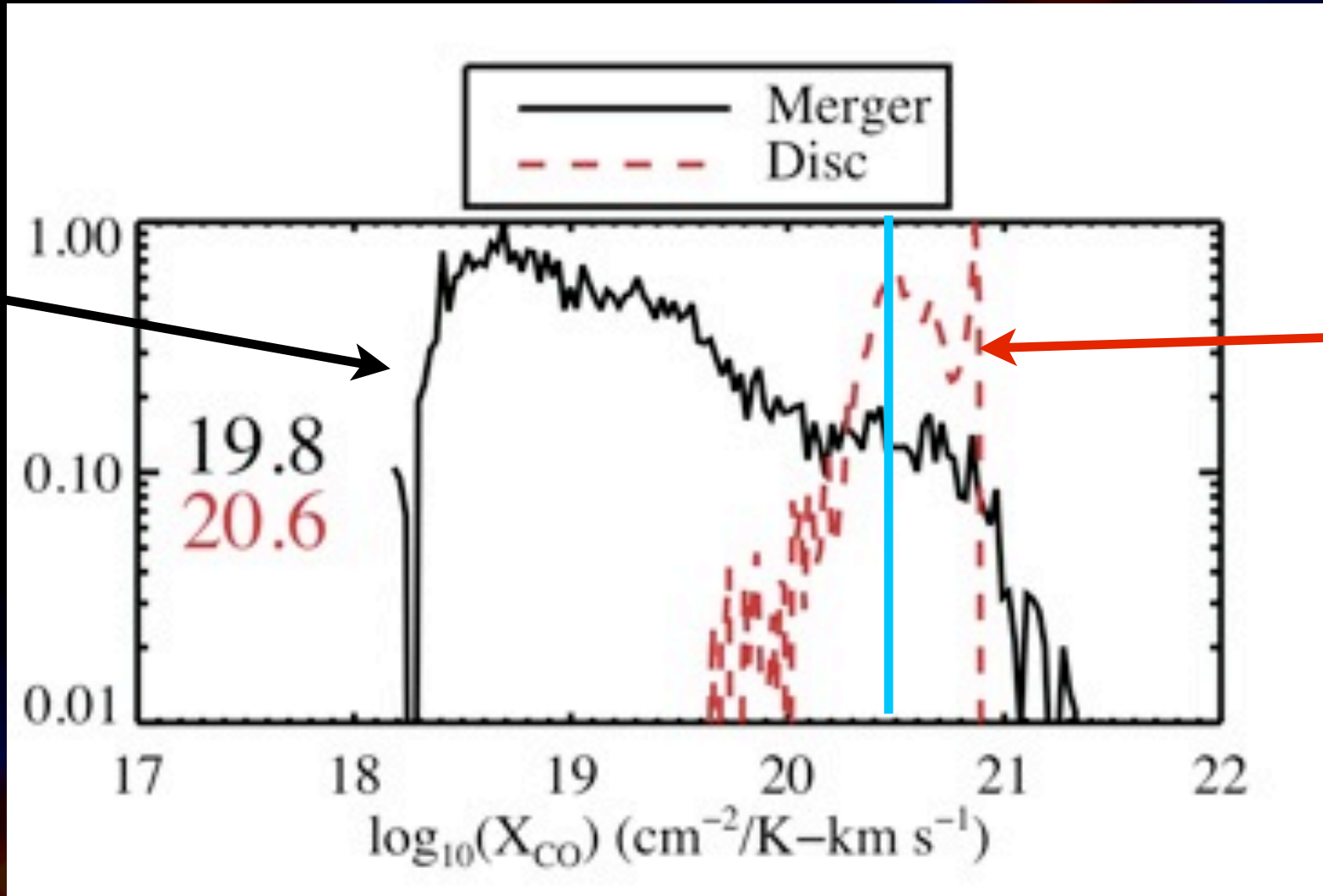
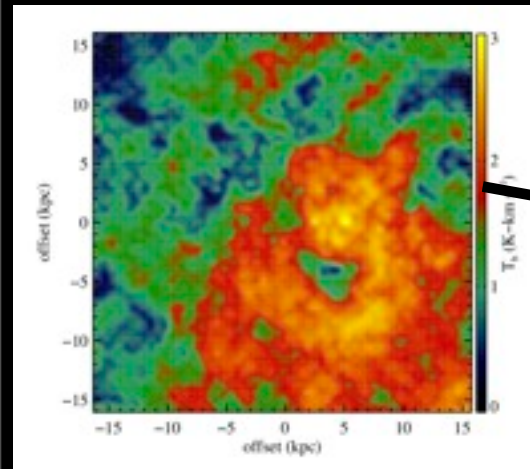
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Tacconi et al. 2008



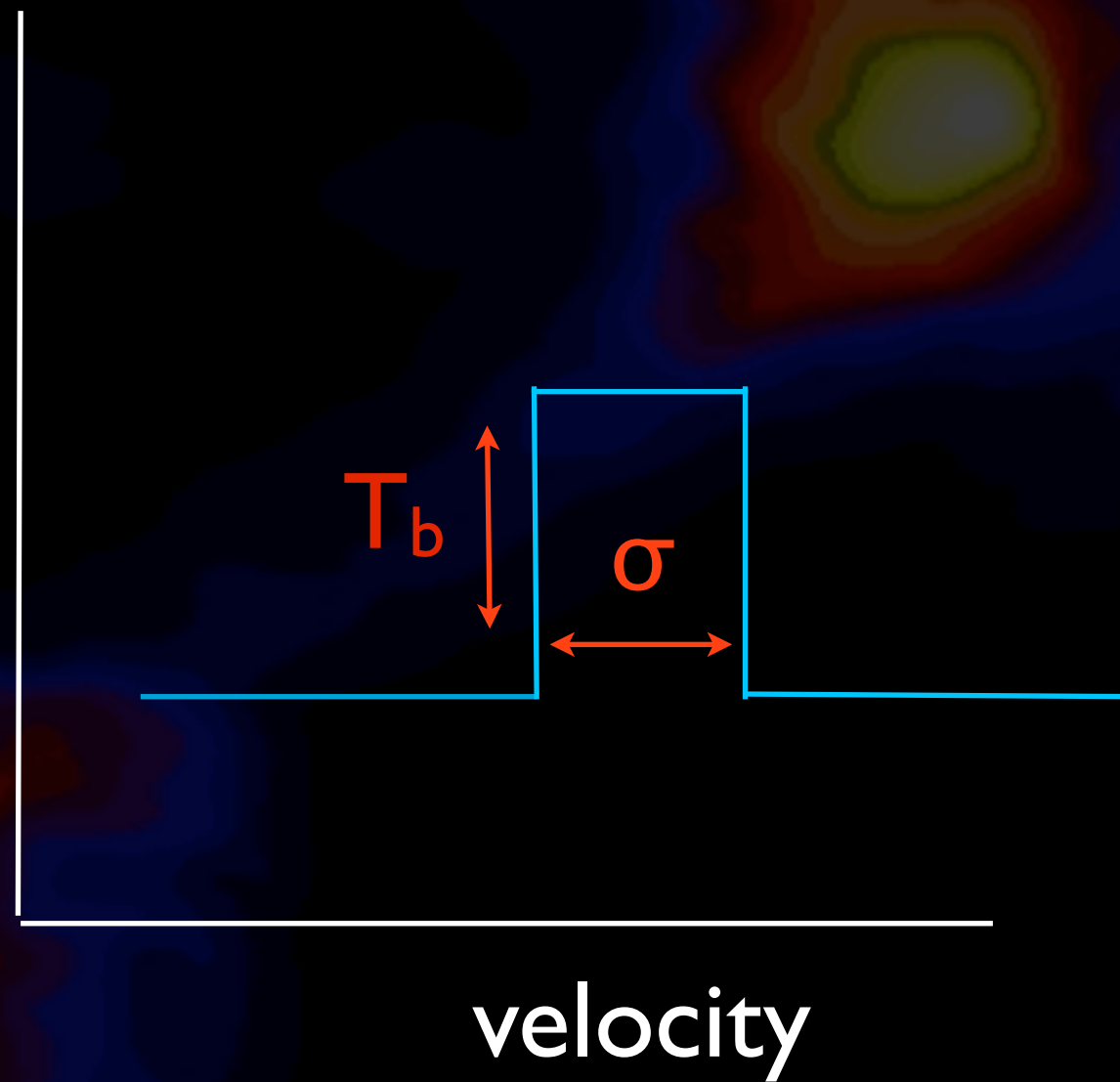
# Xco in Discs and Mergers



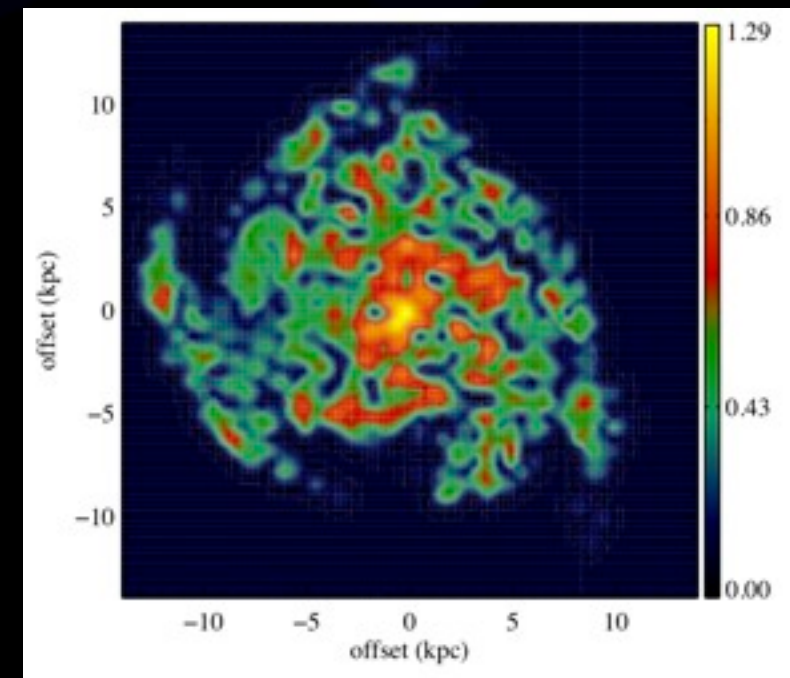
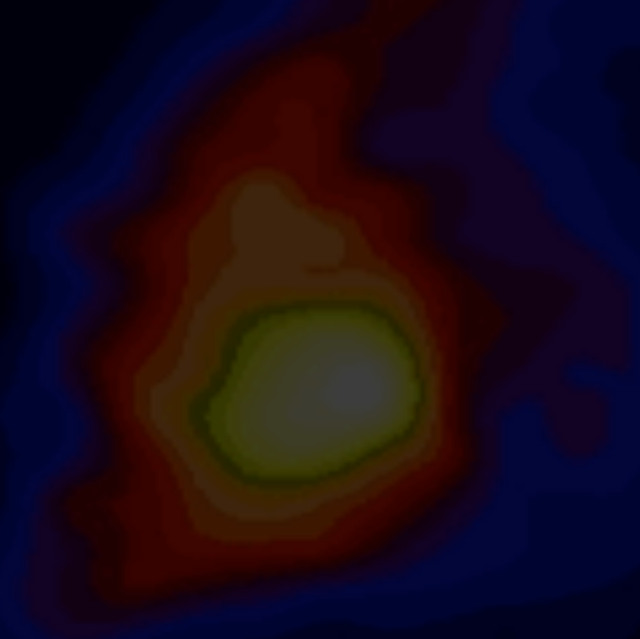
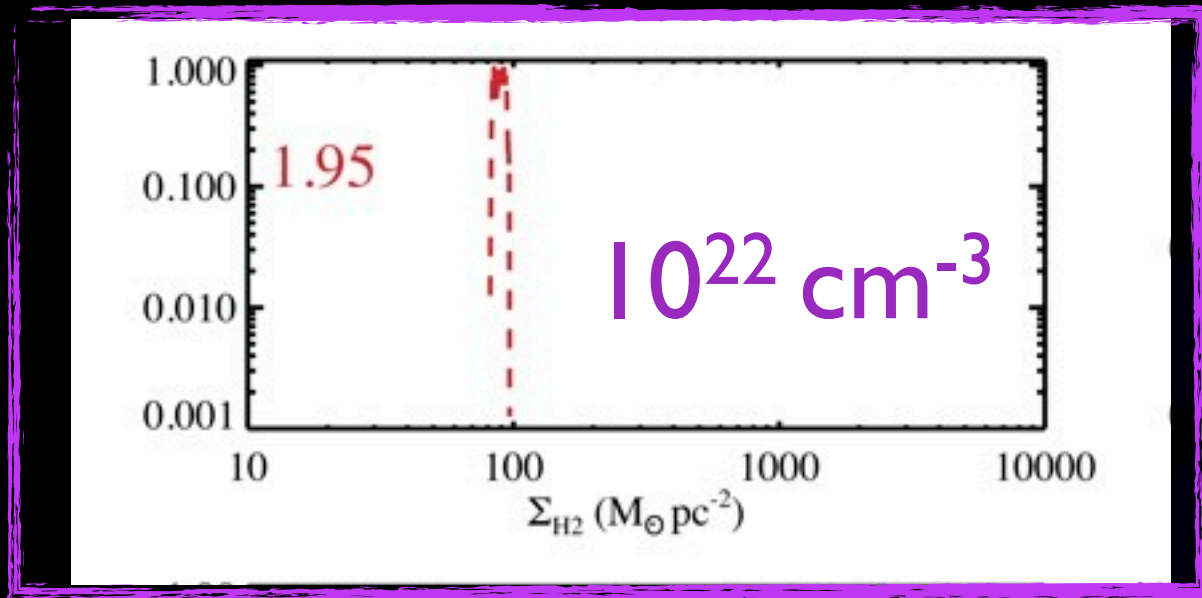
Narayanan, Krumholz, Ostriker & Hernquist 2011

$$X_{\text{CO}} = N_{\text{H}_2}/I_{\text{CO}} \sim N_{\text{H}_2}/(T^*\sigma)$$

$$I \sim T_b \sim T_k$$



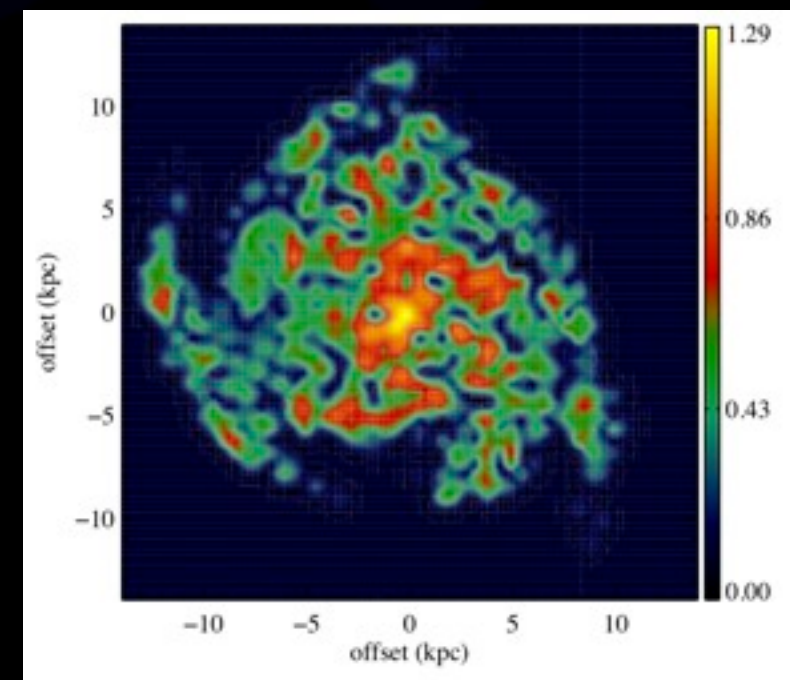
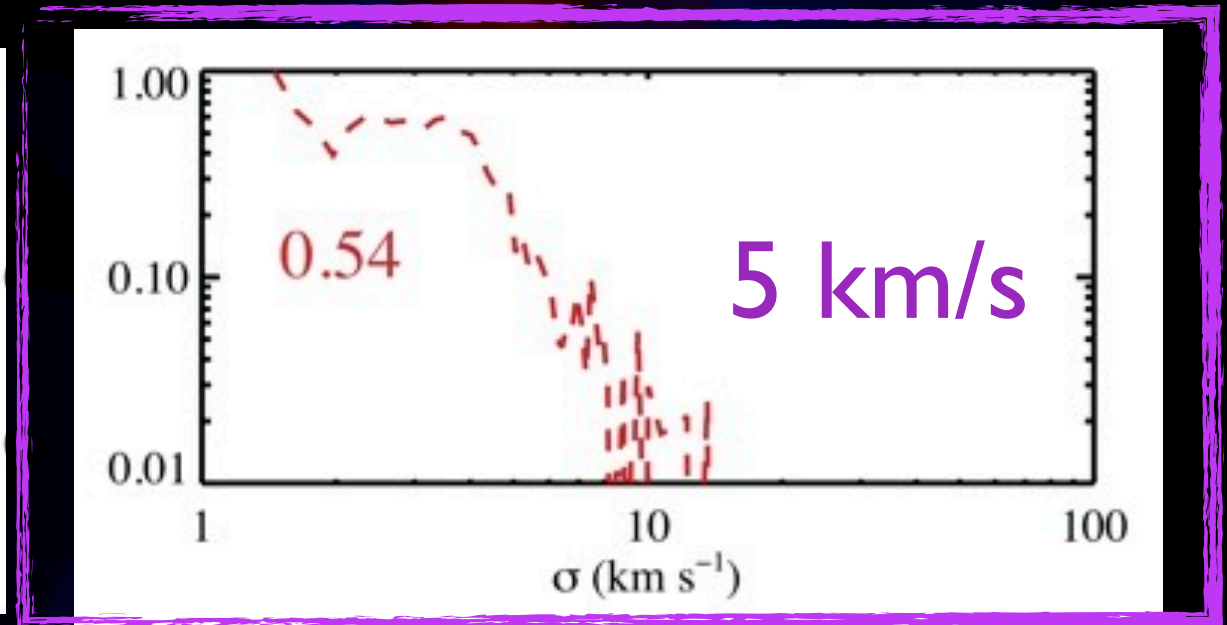
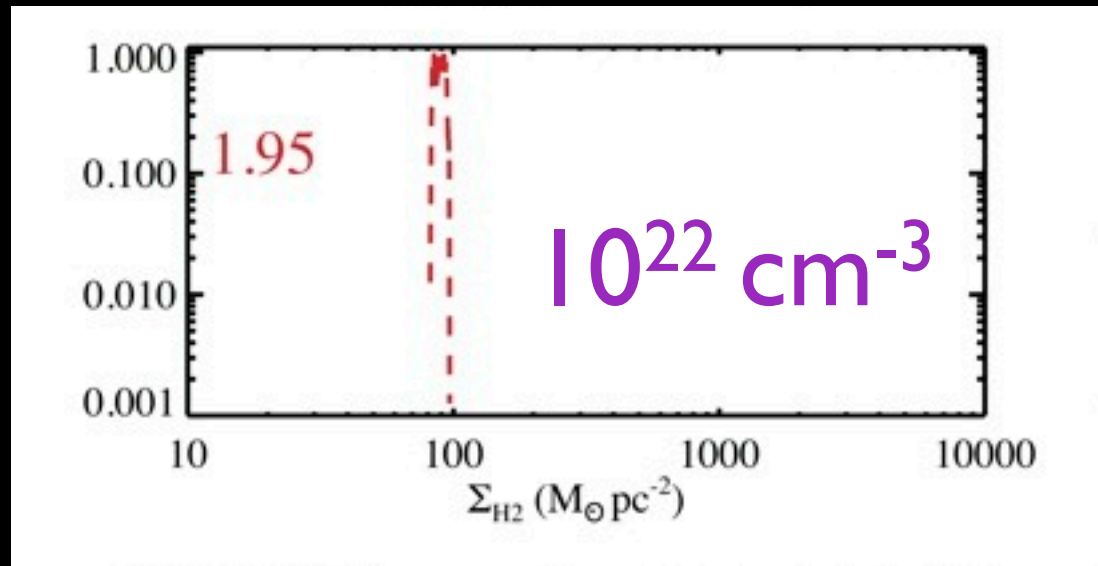
$$X_{\text{CO}} = N_{\text{H}_2}/I_{\text{CO}} \sim N_{\text{H}_2}/(T^*\sigma)$$



Narayanan, Krumholz, Ostriker & Hernquist 2011

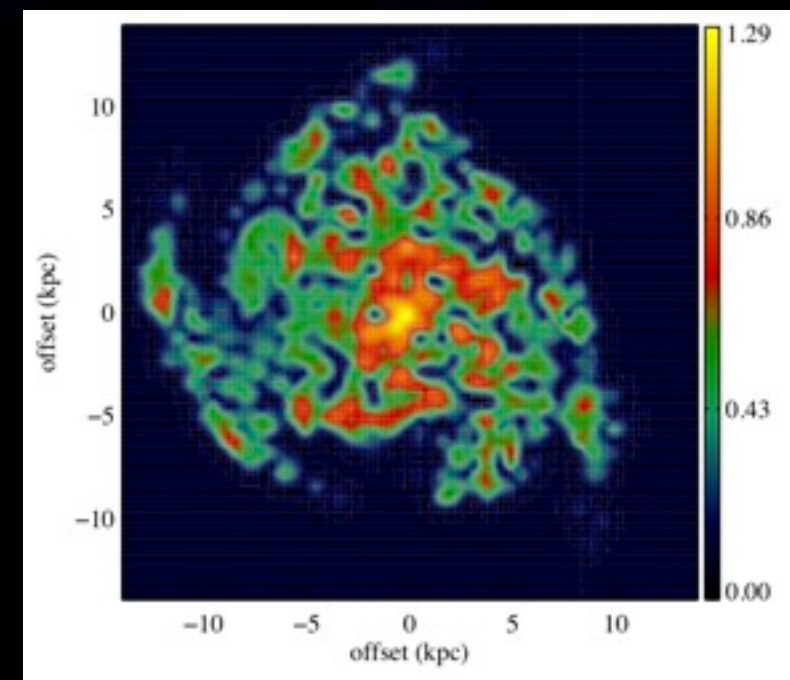
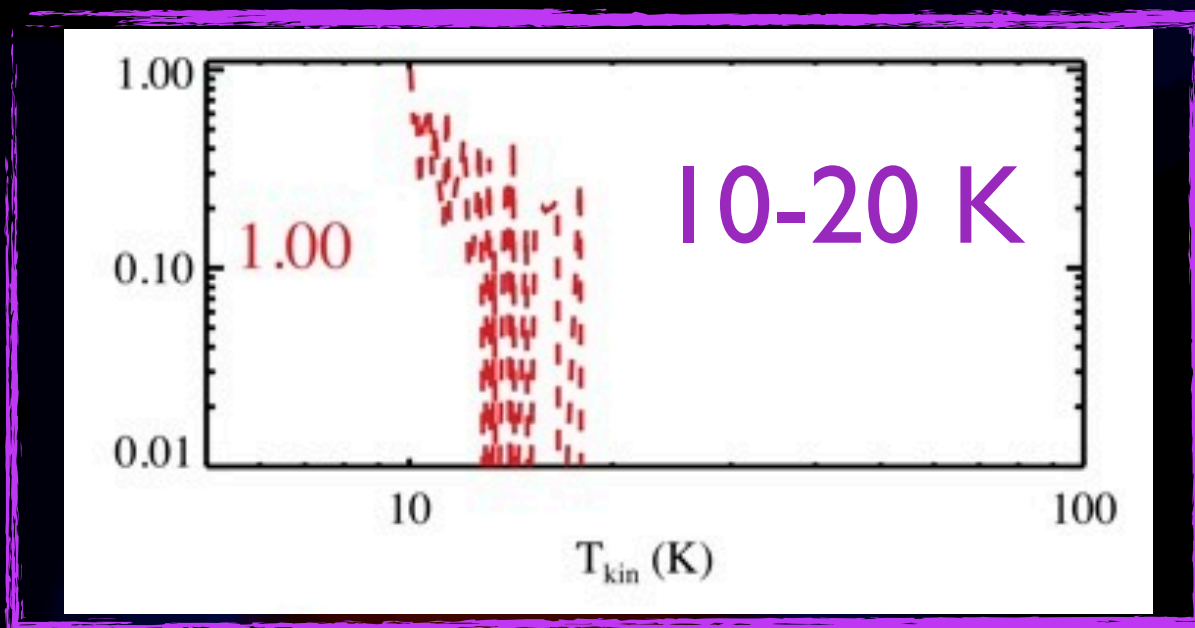
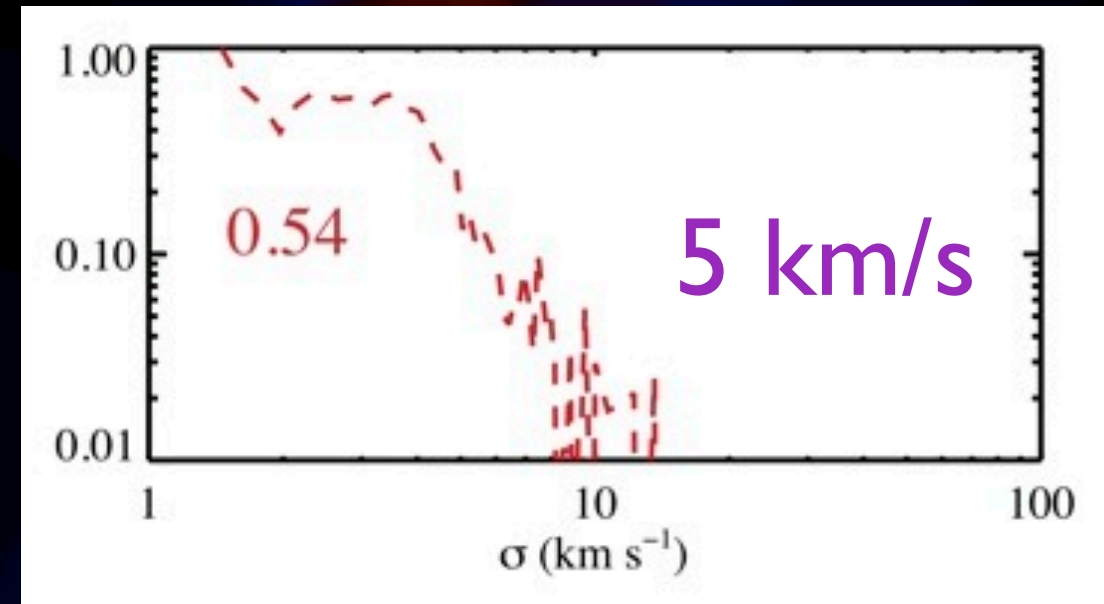
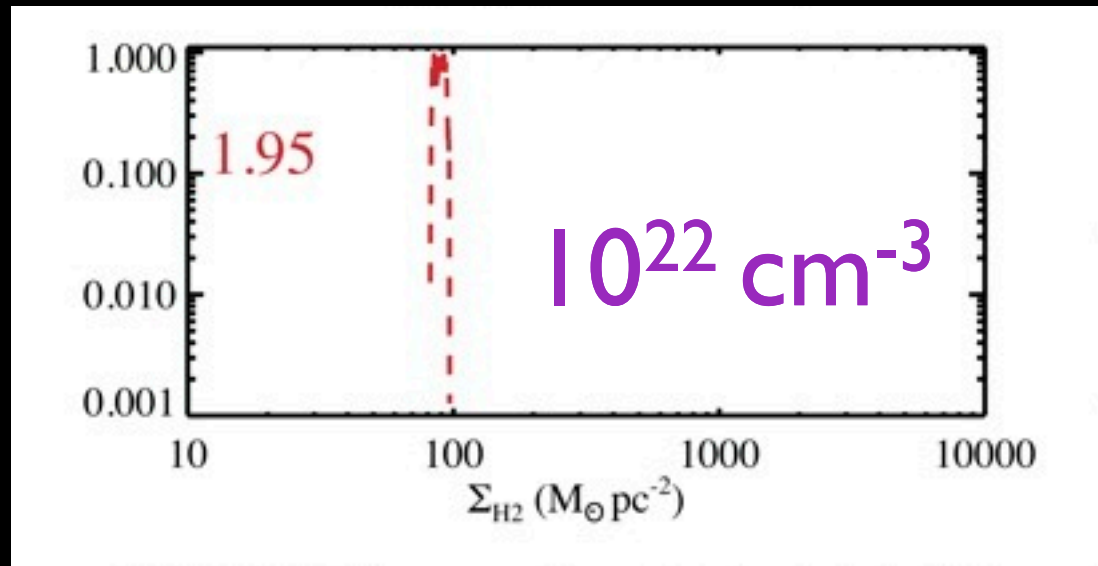


$$X_{\text{CO}} = N_{\text{H}_2}/I_{\text{CO}} \sim N_{\text{H}_2}/(T^*\sigma)$$



Narayanan, Krumholz, Ostriker & Hernquist 2011

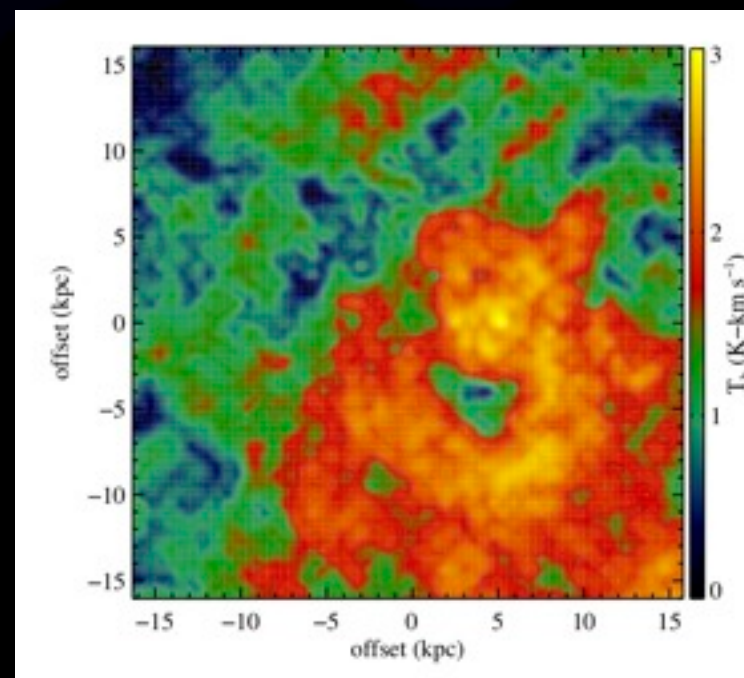
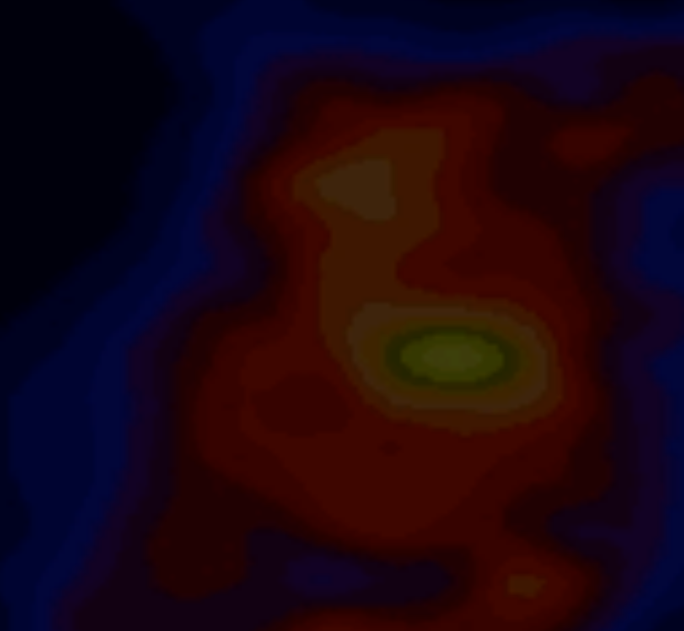
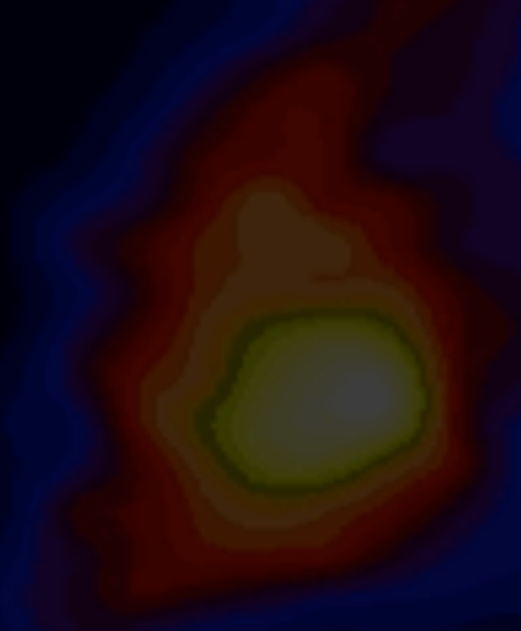
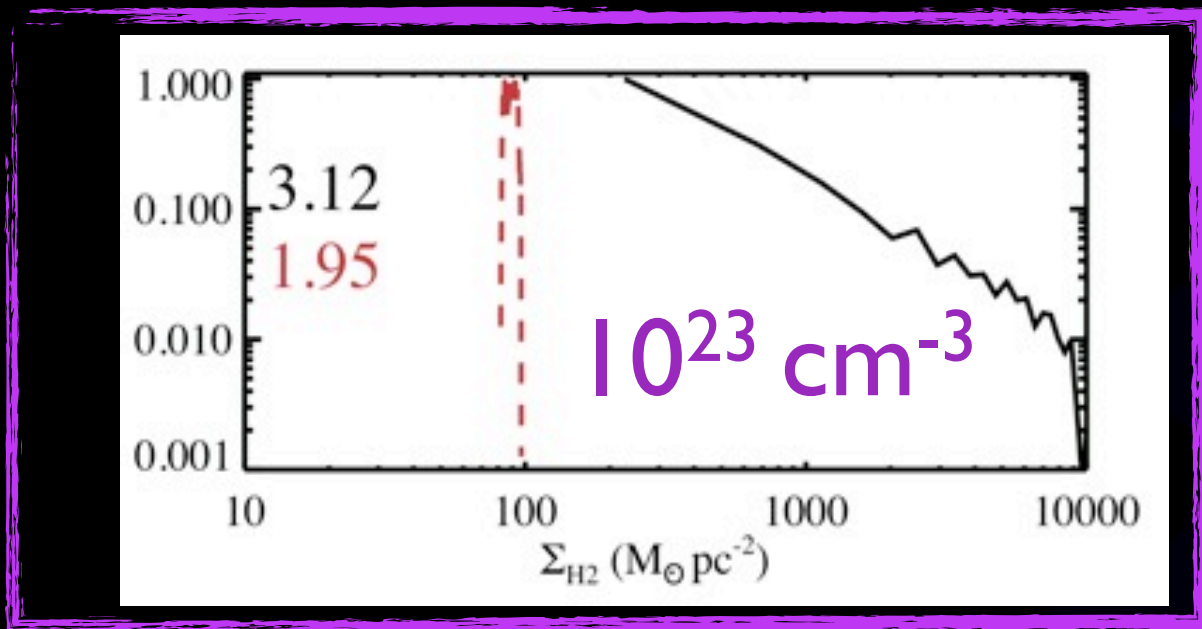
$$X_{\text{CO}} = N_{\text{H}_2}/I_{\text{CO}} \sim N_{\text{H}_2}/(T^*\sigma)$$



$$X_{\text{CO}} (\text{MW}) = \text{few} \times 10^{20} \text{ cm}^{-2}/\text{K-km/s}$$

Narayanan, Krumholz, Ostriker & Hernquist 2011

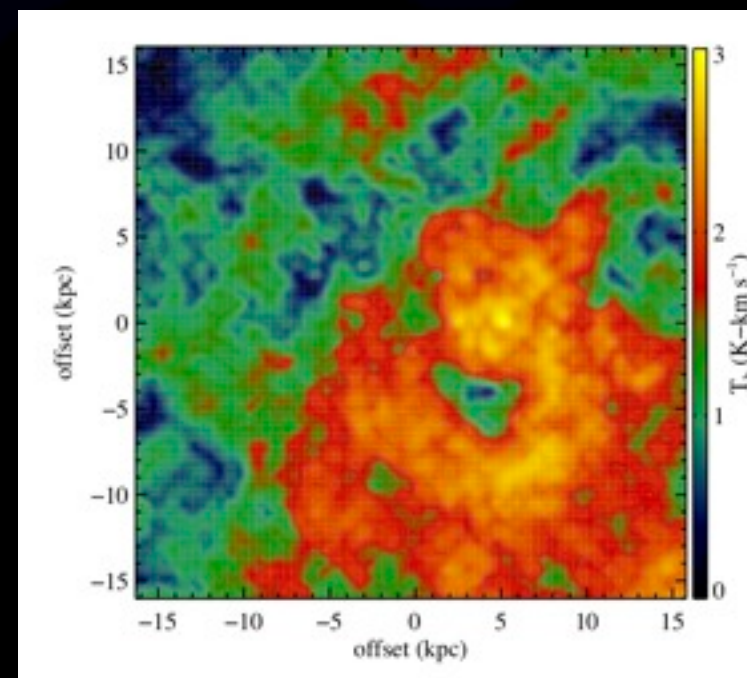
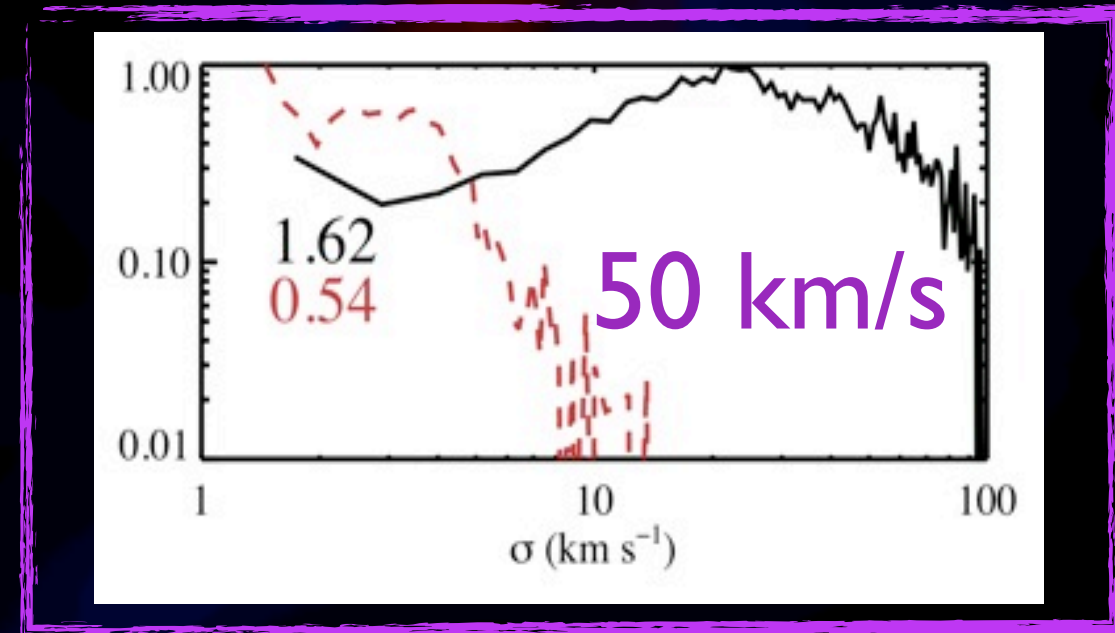
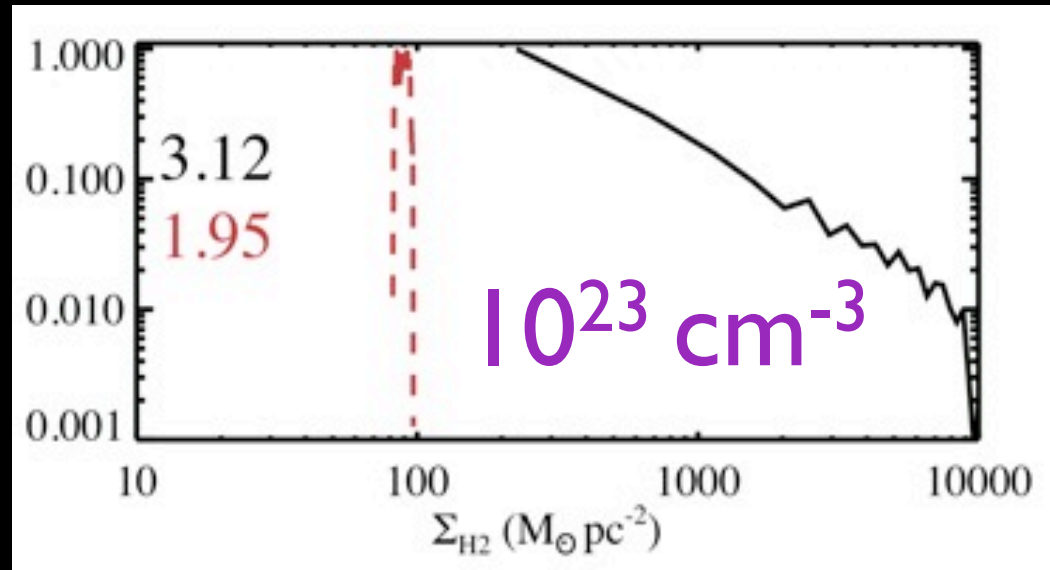
$$X_{\text{CO}} = N_{\text{H}_2}/I_{\text{CO}} \sim N_{\text{H}_2}/(T^*\sigma)$$



Narayanan, Krumholz, Ostriker & Hernquist 2011

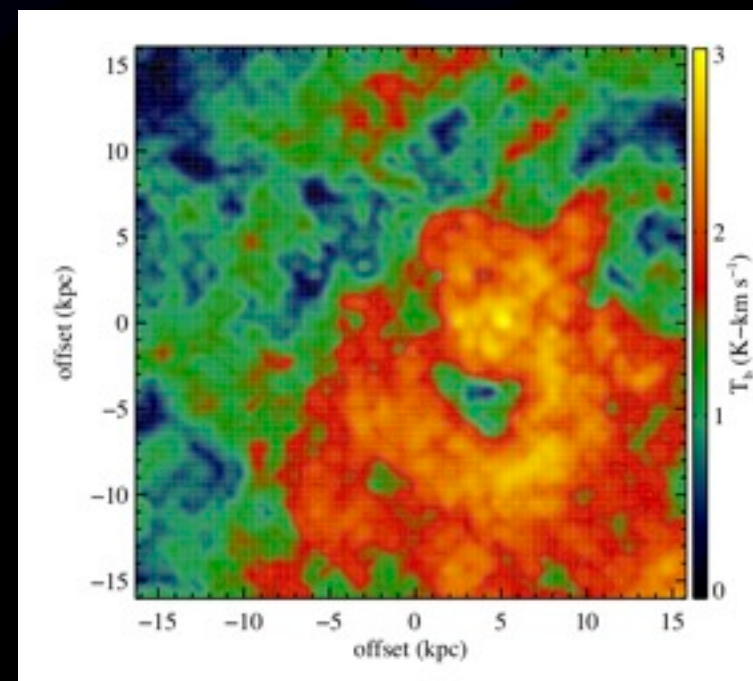
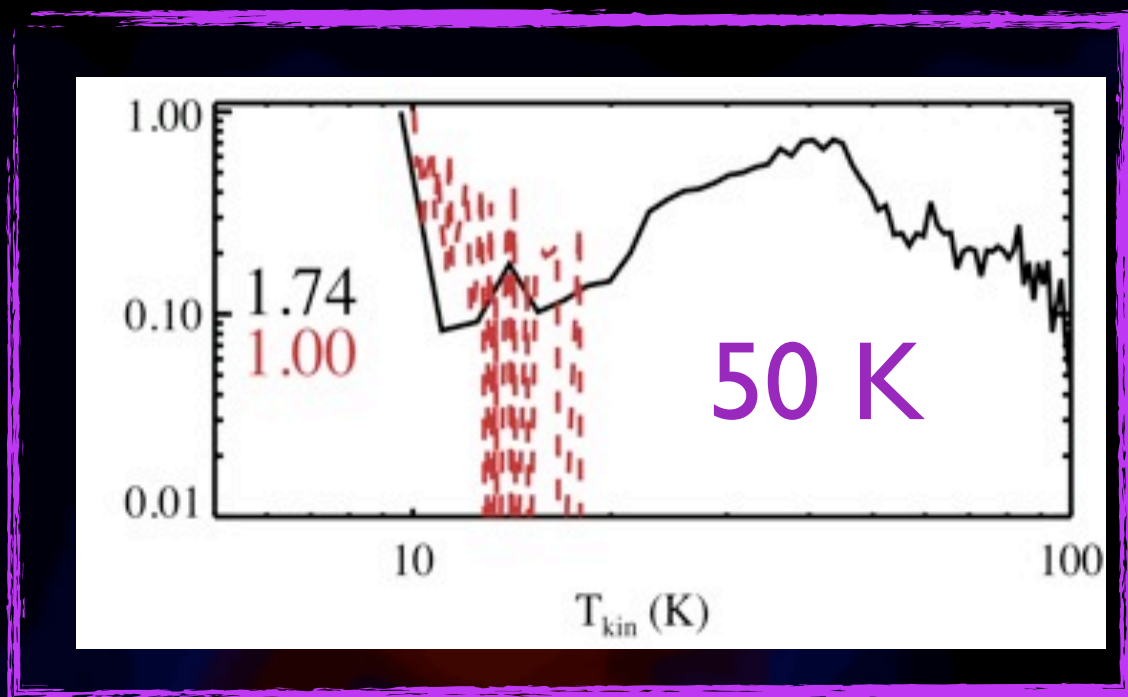
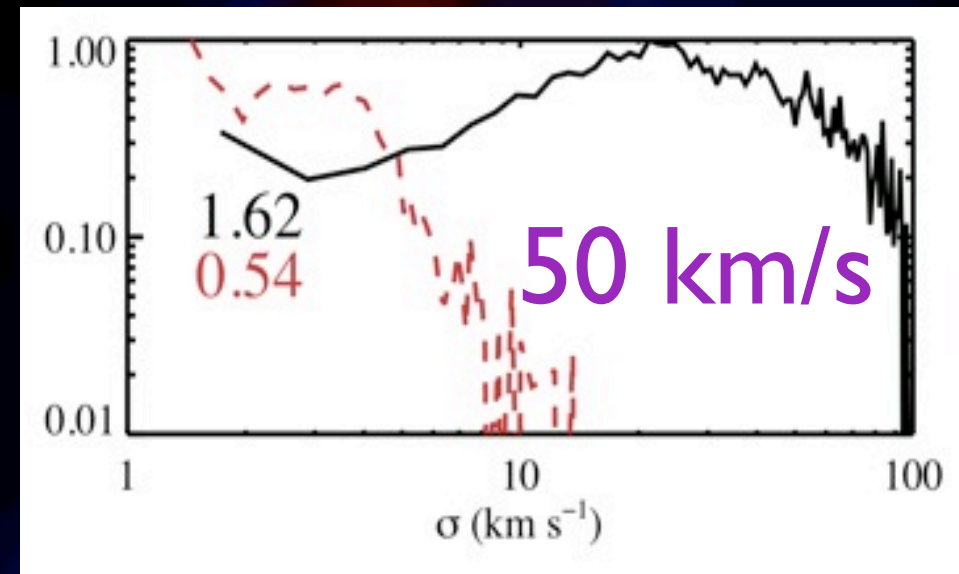
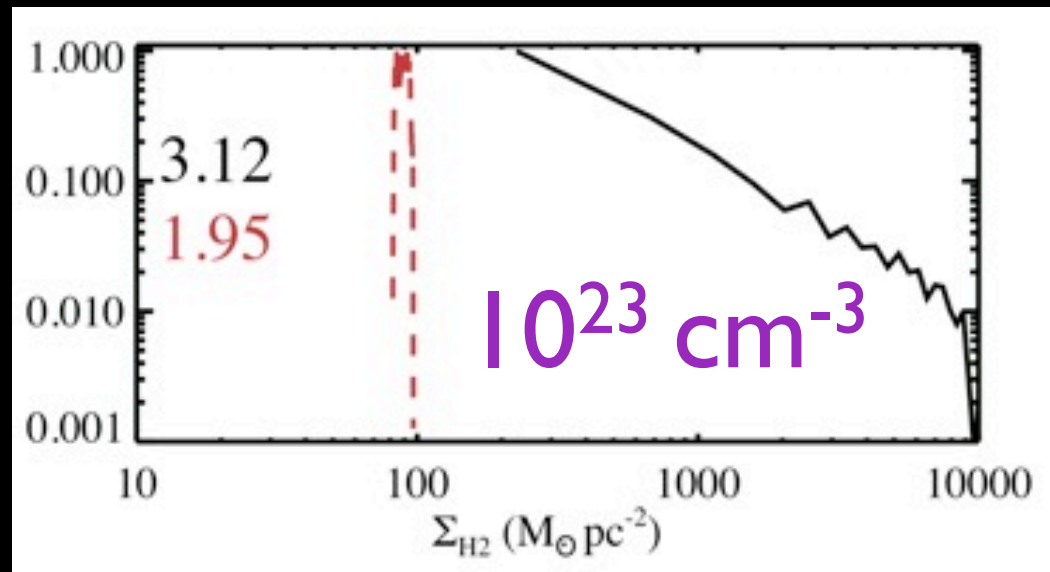


$$X_{\text{CO}} = N_{\text{H}_2}/I_{\text{CO}} \sim N_{\text{H}_2}/(T^*\sigma)$$



Narayanan, Krumholz, Ostriker & Hernquist 2011

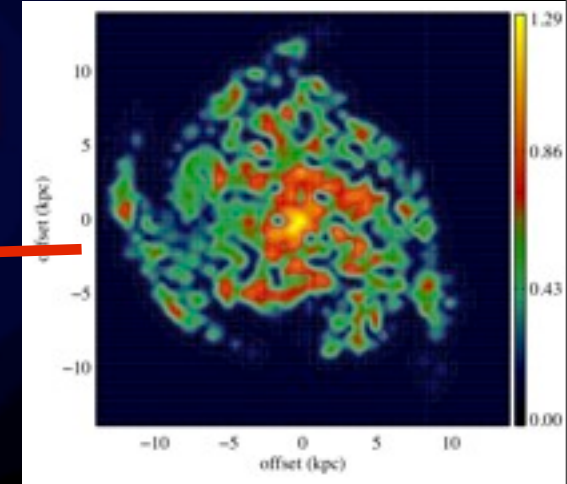
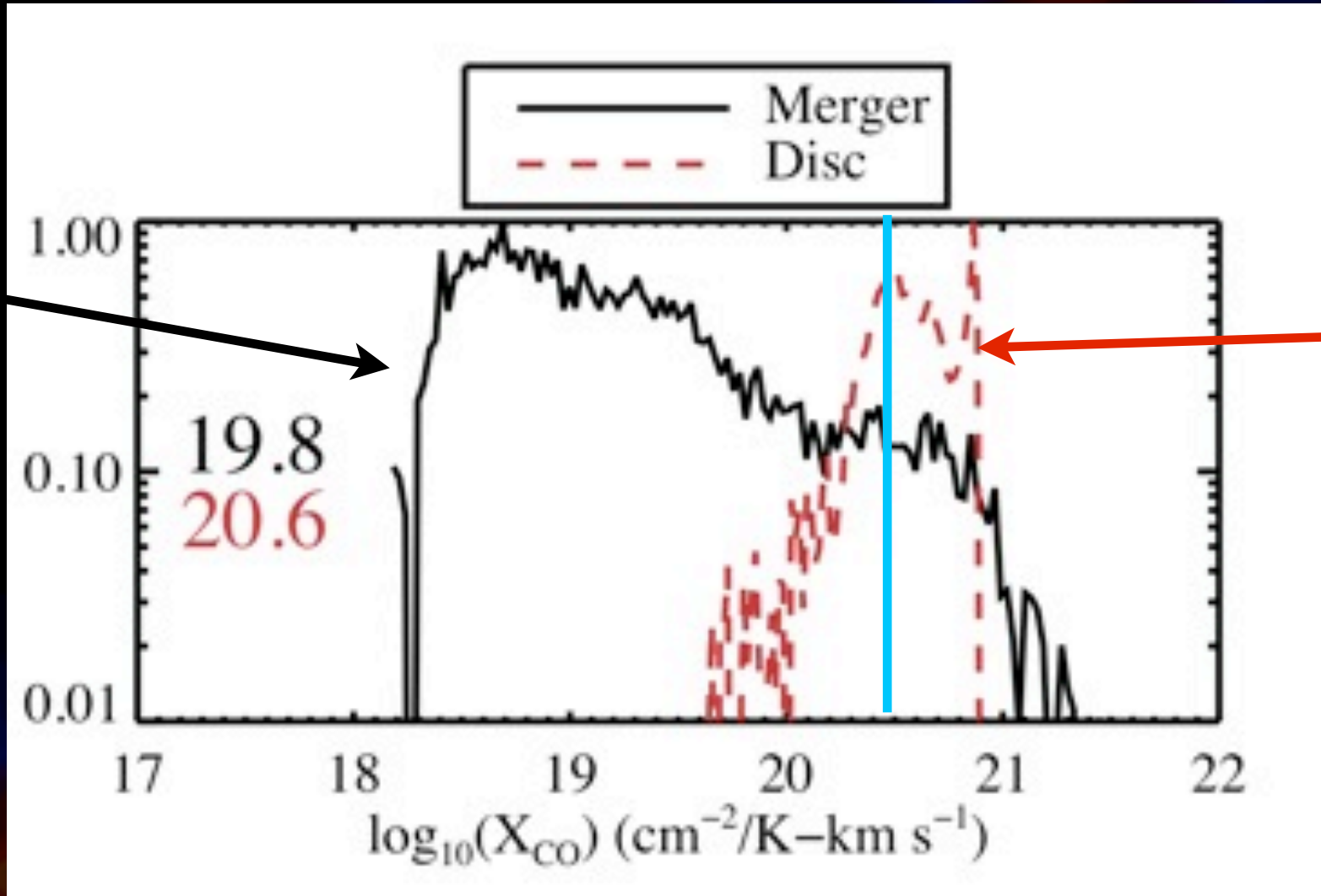
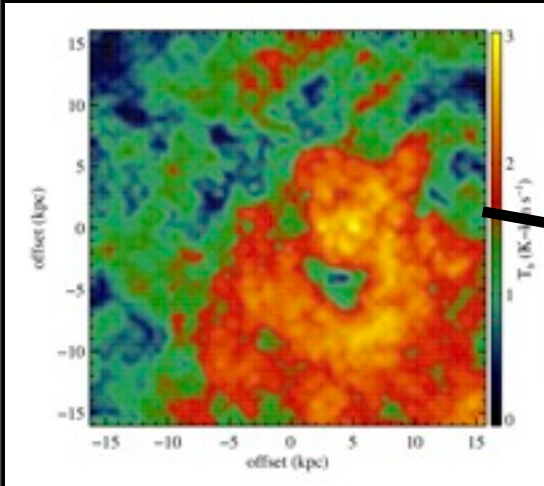
$$X_{\text{CO}} = N_{\text{H}_2}/I_{\text{CO}} \sim N_{\text{H}_2}/(T^*\sigma)$$



$$X_{\text{CO}} (\text{MW}) = \text{few} \times 10^{19} \text{ cm}^{-2}/\text{K-km/s}$$

Narayanan, Krumholz, Ostriker & Hernquist 2011

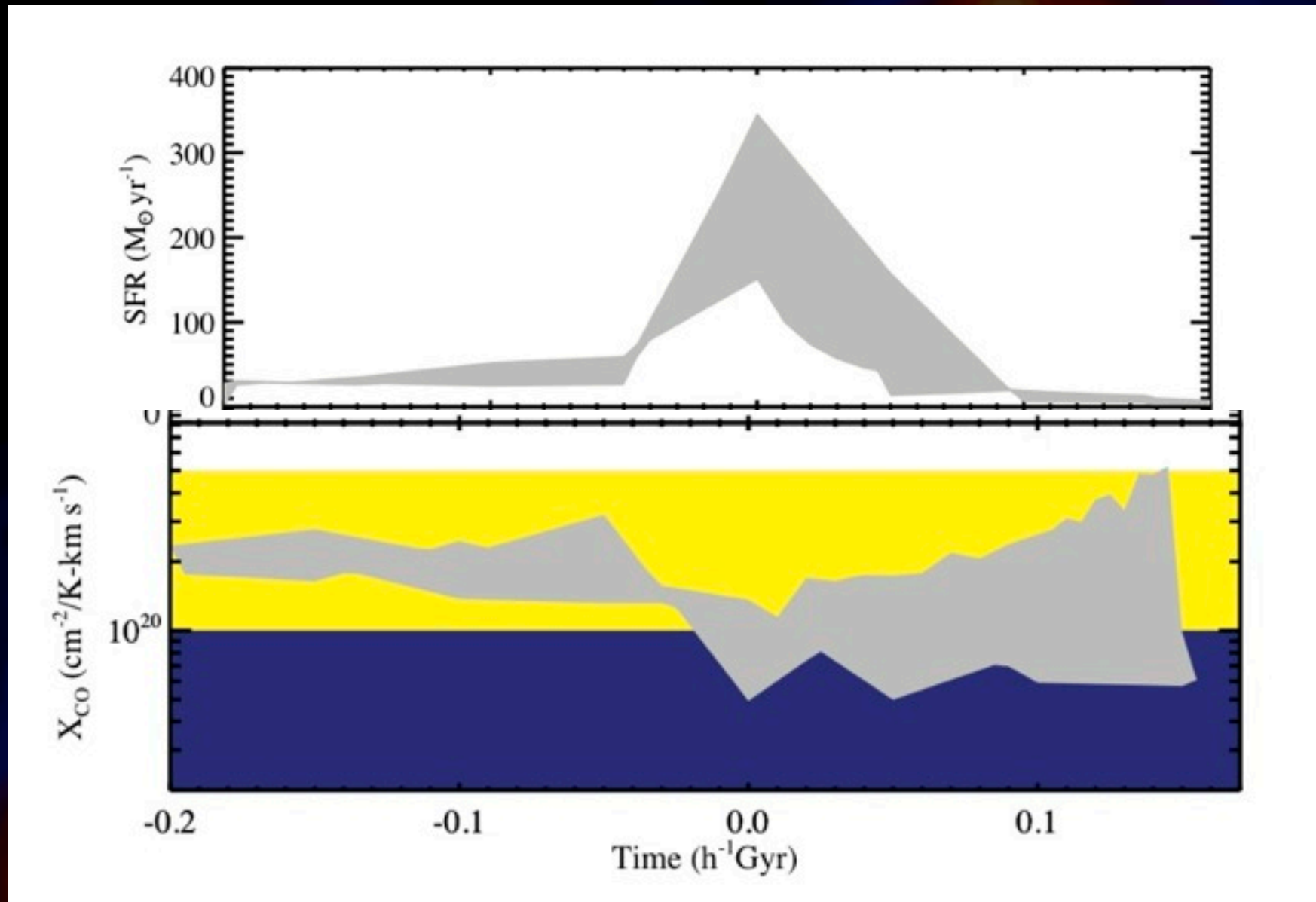
# Xco in Discs and Mergers



Narayanan, Krumholz, Ostriker & Hernquist 2011

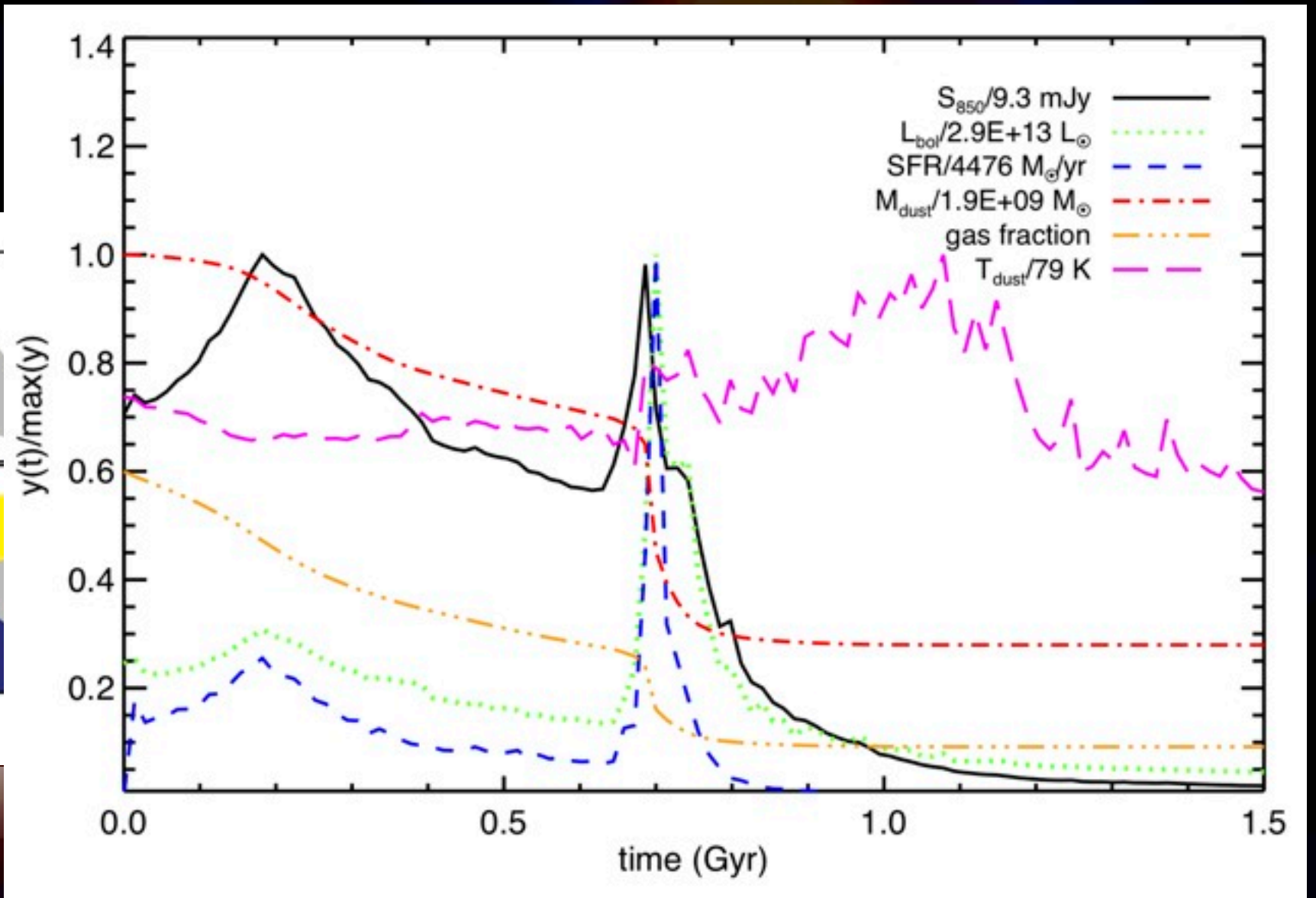
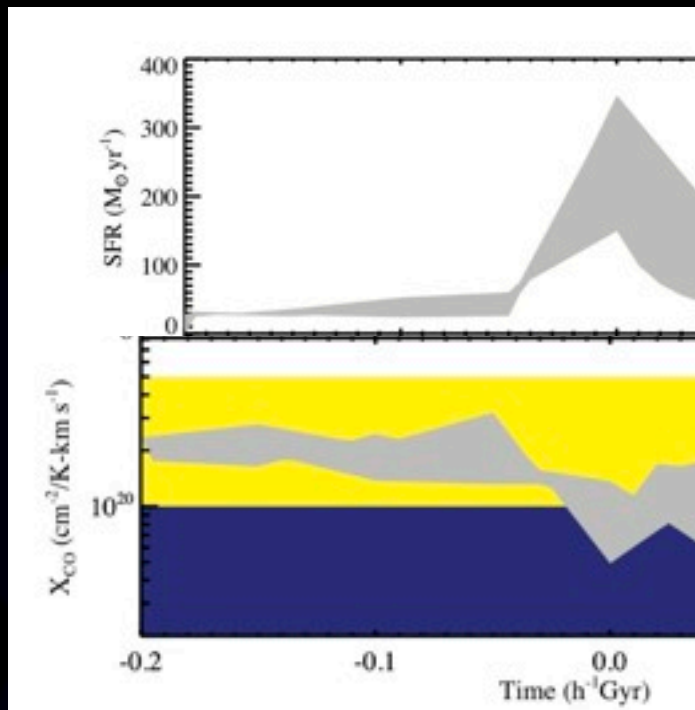


# No “merger-value” of $X_{\text{CO}}$

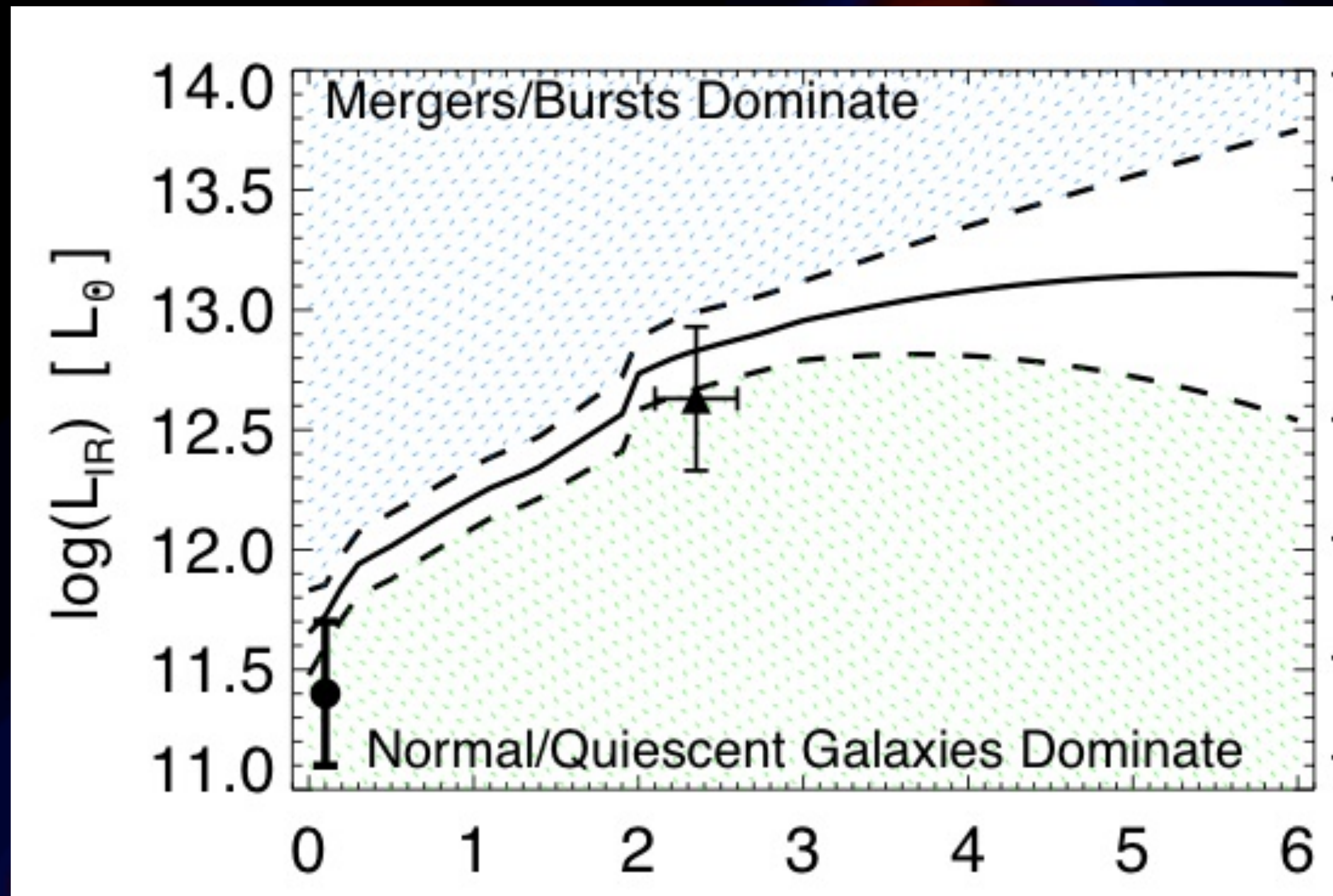


Narayanan, Krumholz, Ostriker & Hernquist 2011

# No “merger-value” of $X_{\text{CO}}$ (even worse at high-z)



# Mergers drive extreme luminosities at $z \sim 2$ : “ULIRGs” are generally plain old discs

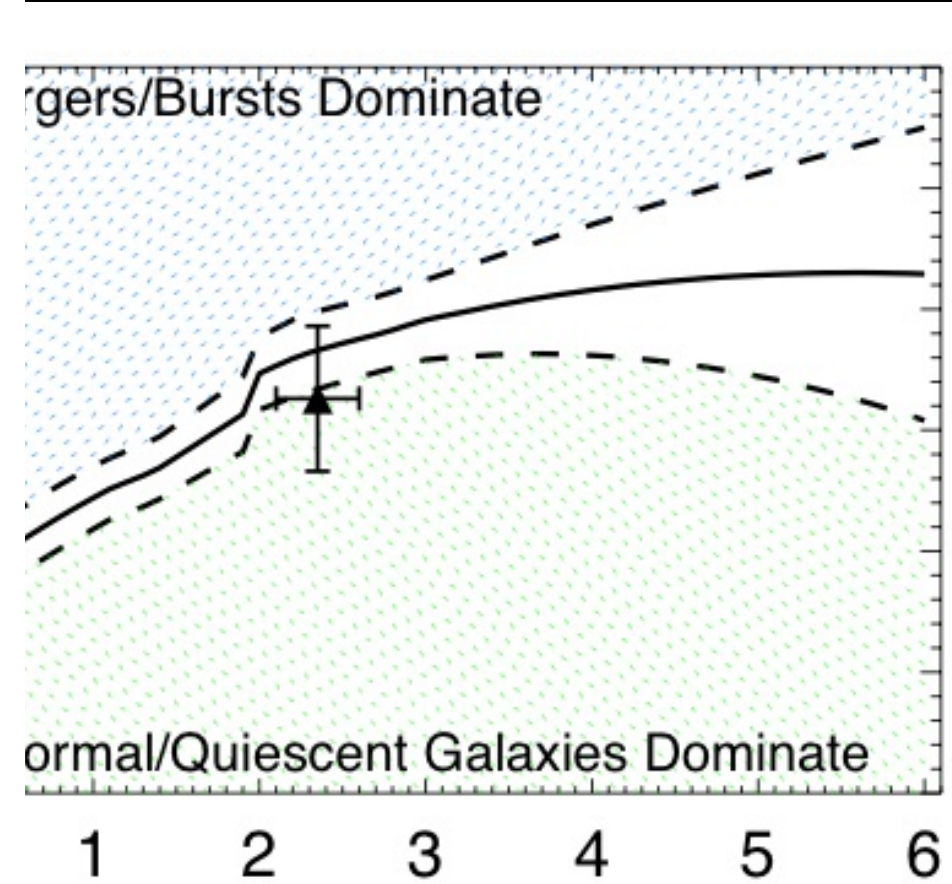
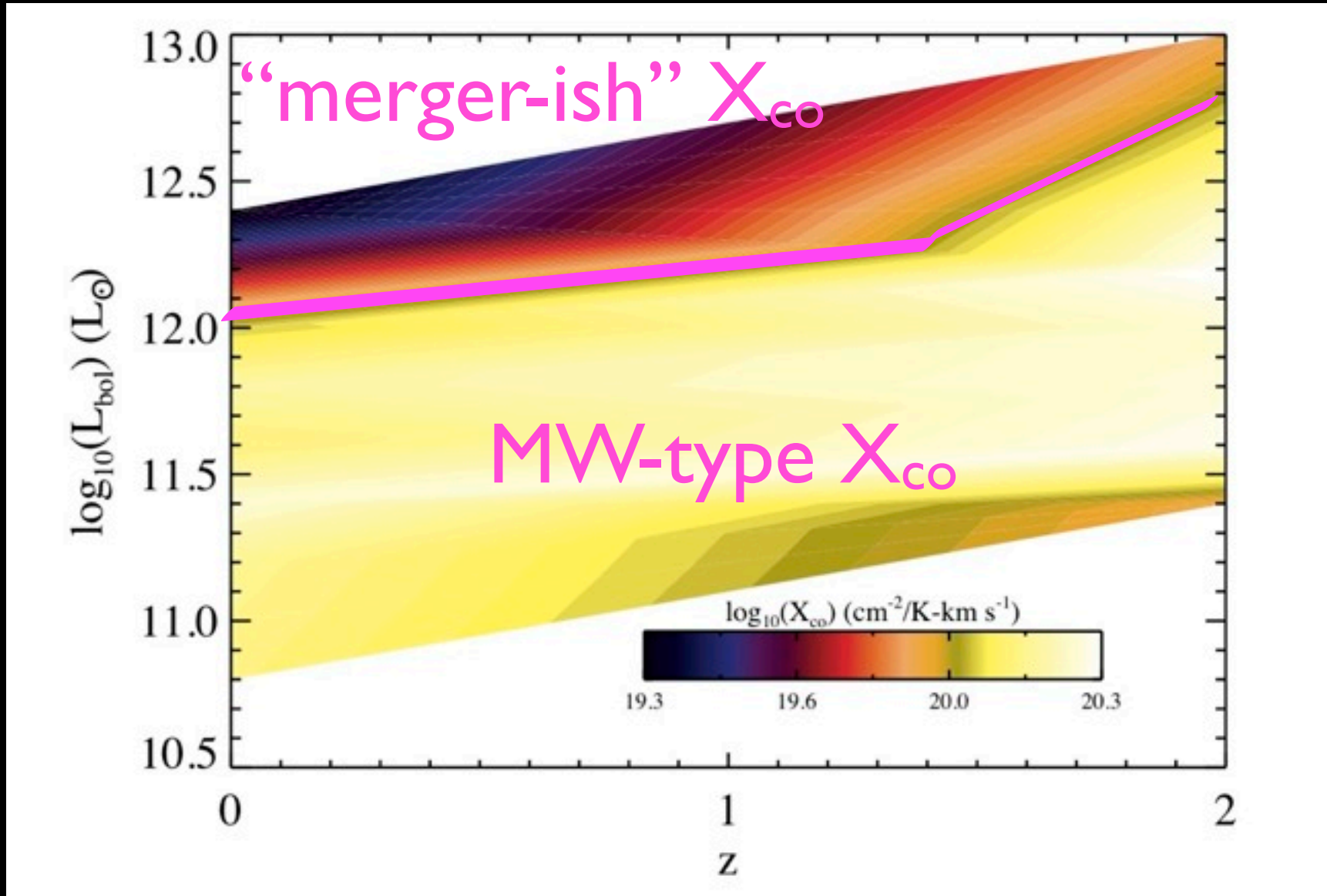


Hopkins, Younger, Hayward, DN, Hernquist 2010

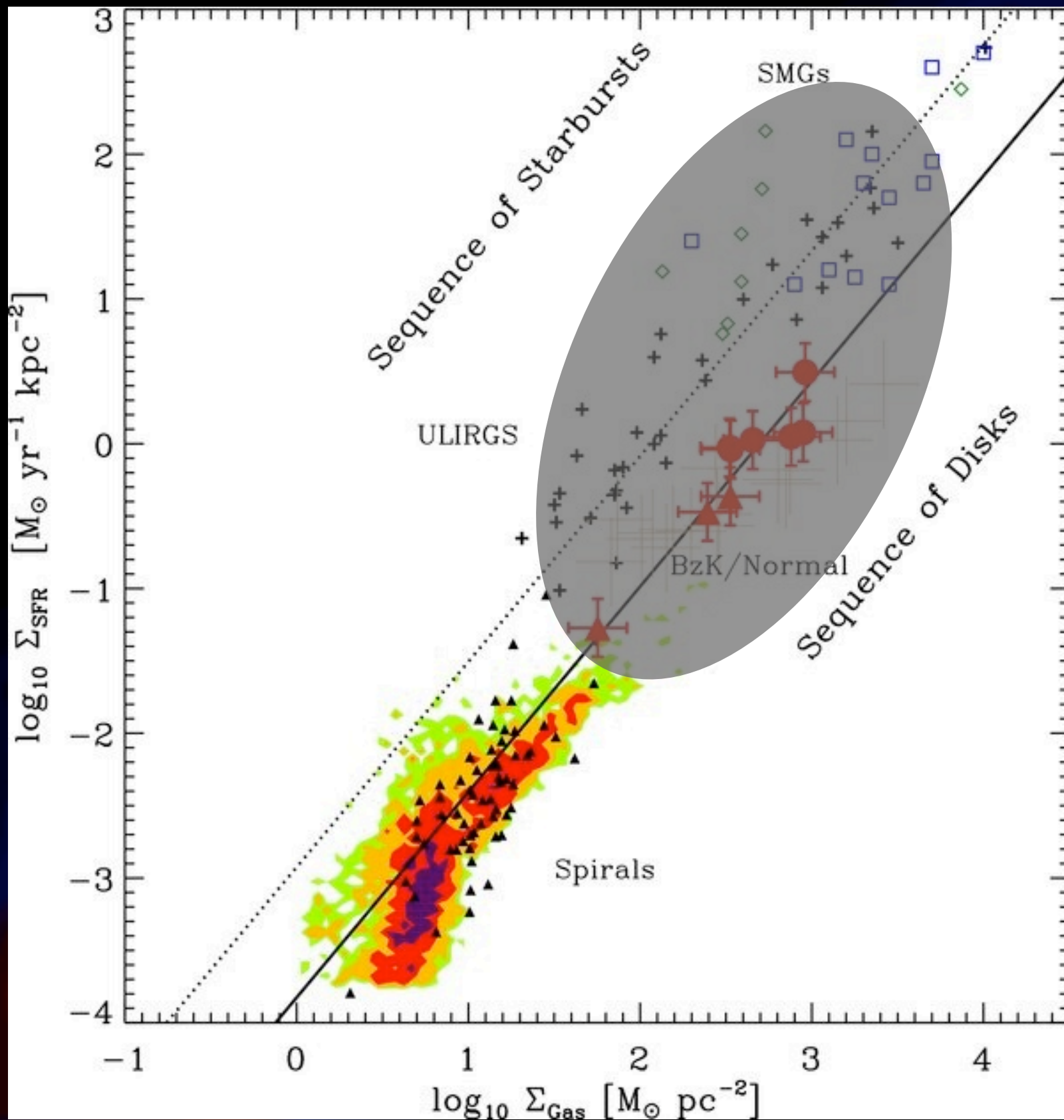
Desika Narayanan



# Mergers drive extreme luminosities at $z \sim 2$ : “ULIRGs” are generally plain old discs



DN, Krumholz, Ostriker, Hernquist in prep.

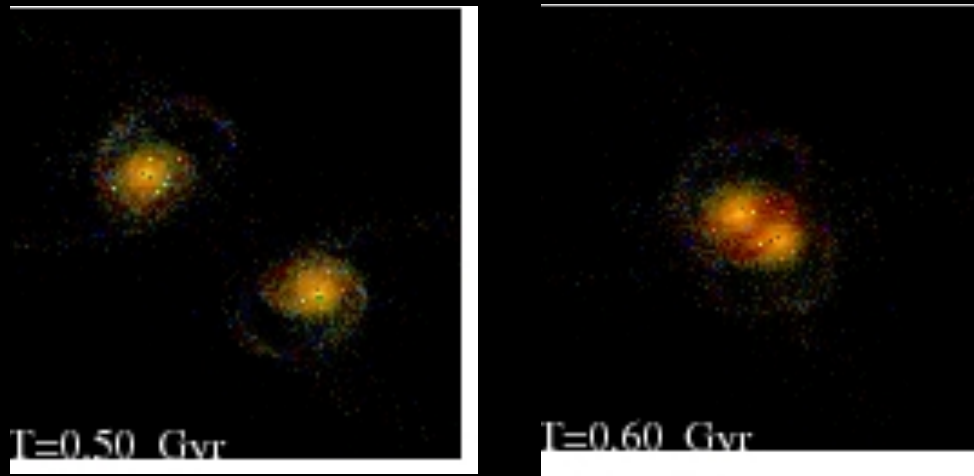


Daddi et al. 2010  
 Genzel et al. 2010

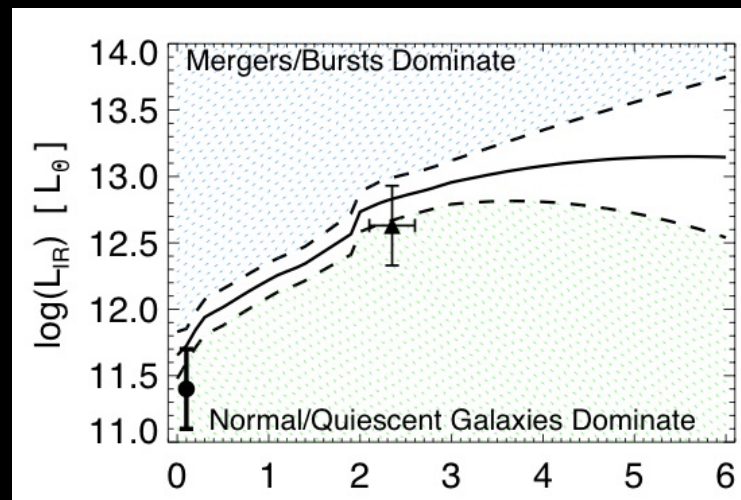
Desika Narayanan

# Summary

I.



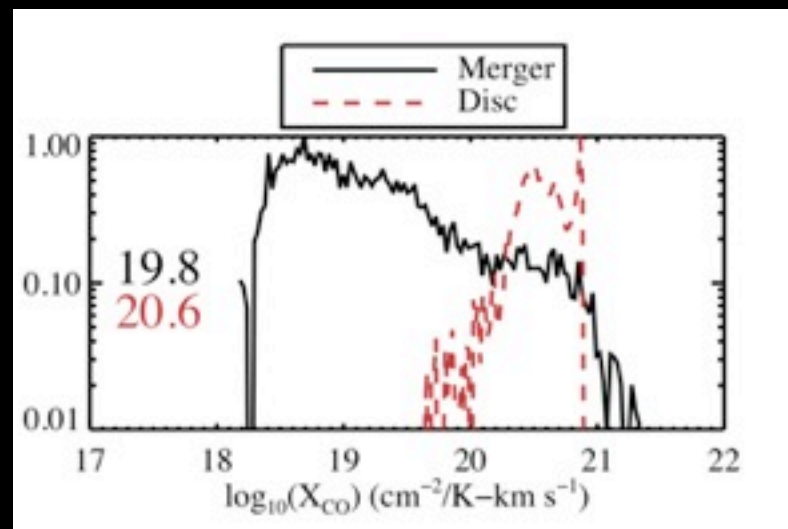
II.



Can distinguish mergers from disks from CO SED

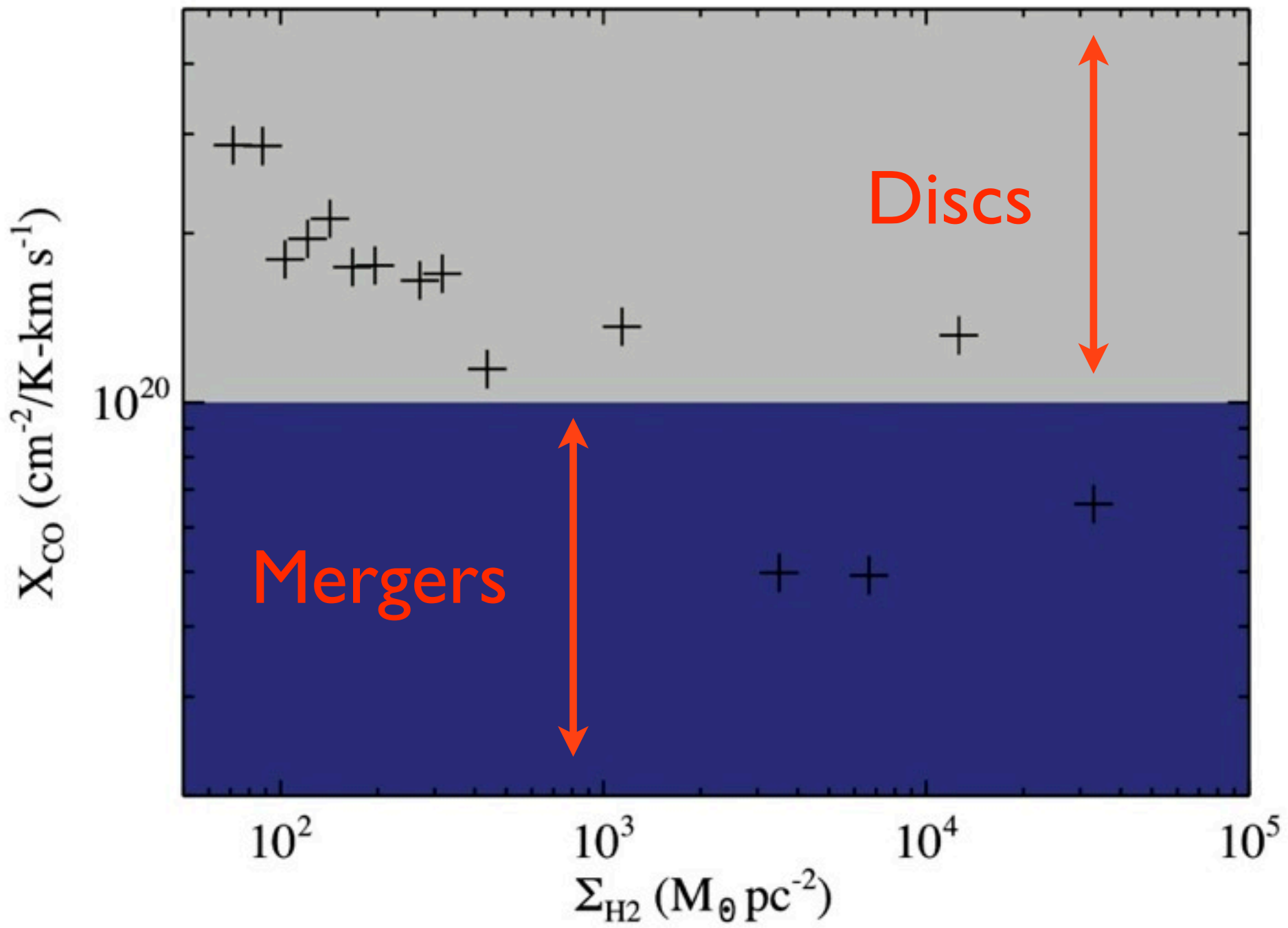
Cannot distinguish mergers from disks from CO kinematics

III.



$X_{CO}$  depends on galactic environment, though be careful of using “merger” value and “disk” value





$\Sigma^{\text{H}^{\text{I}}} \text{ (M}_\odot \text{ pc}^{-2}\text{)}$

$10_5$

$10_3$

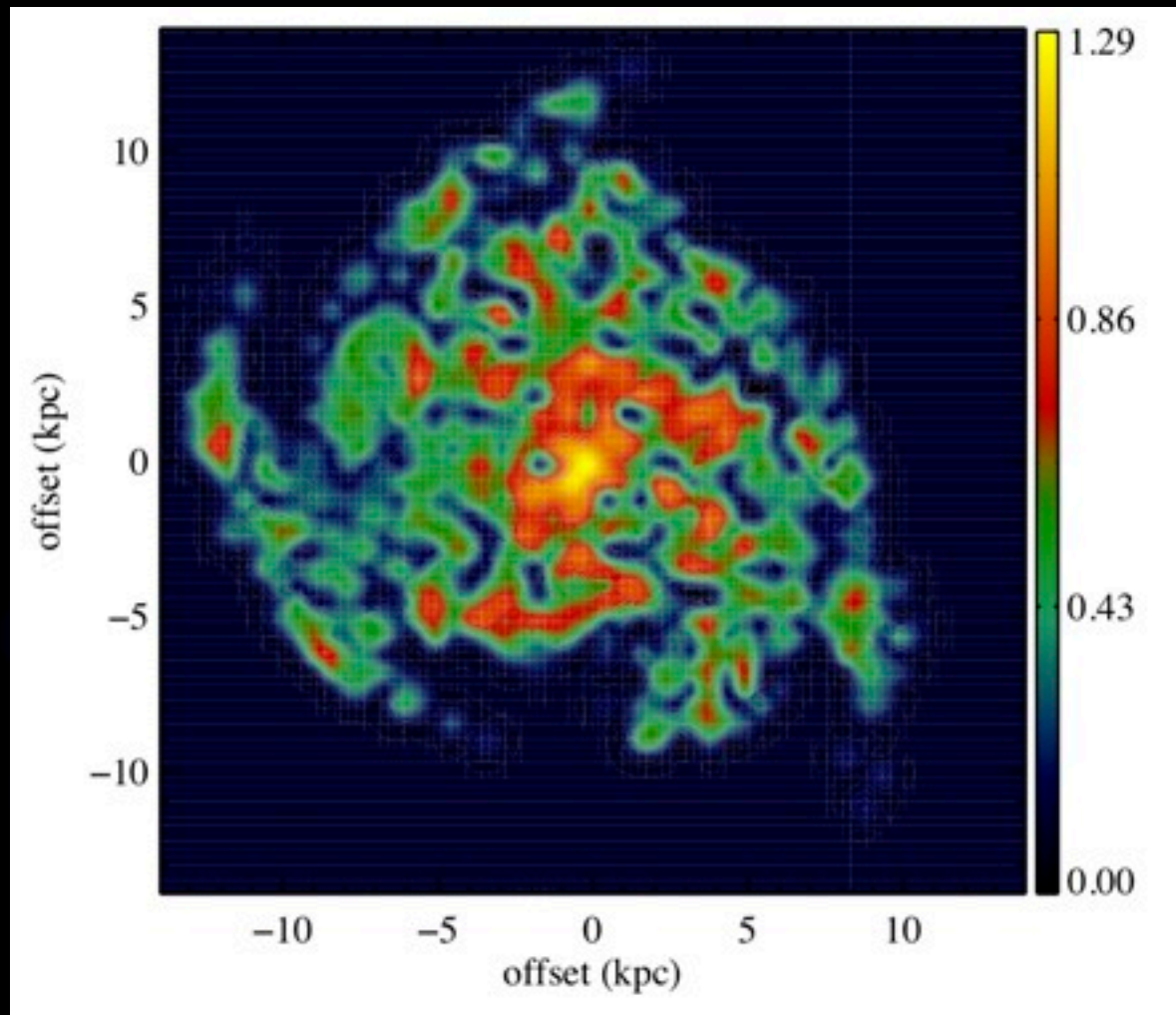
$10_4$

$10_2$

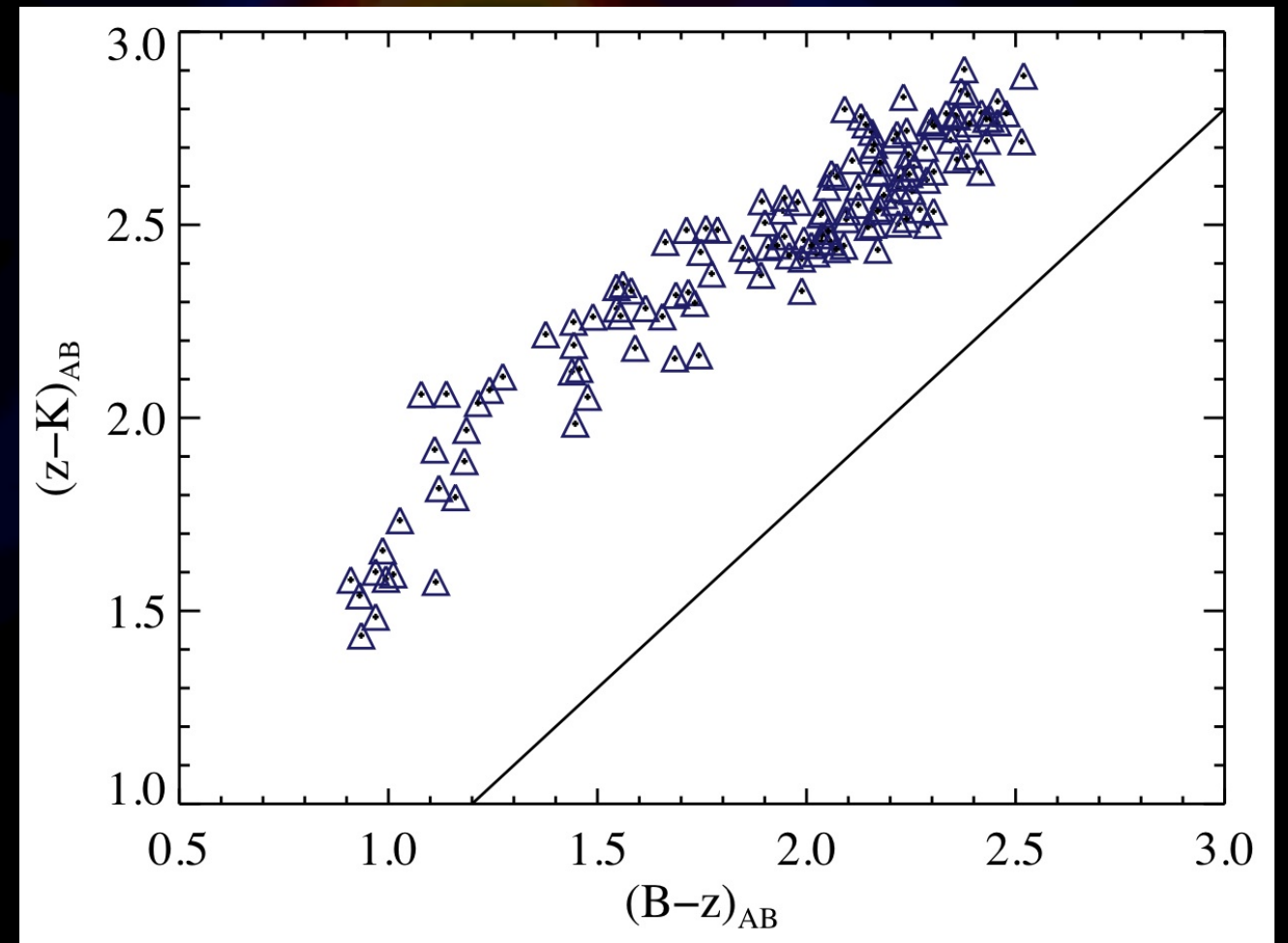
Narayanan, Krumholz, Ostriker & Hernquist 2011

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# “Clumpy” disks



# Satisfy *BzK* selection

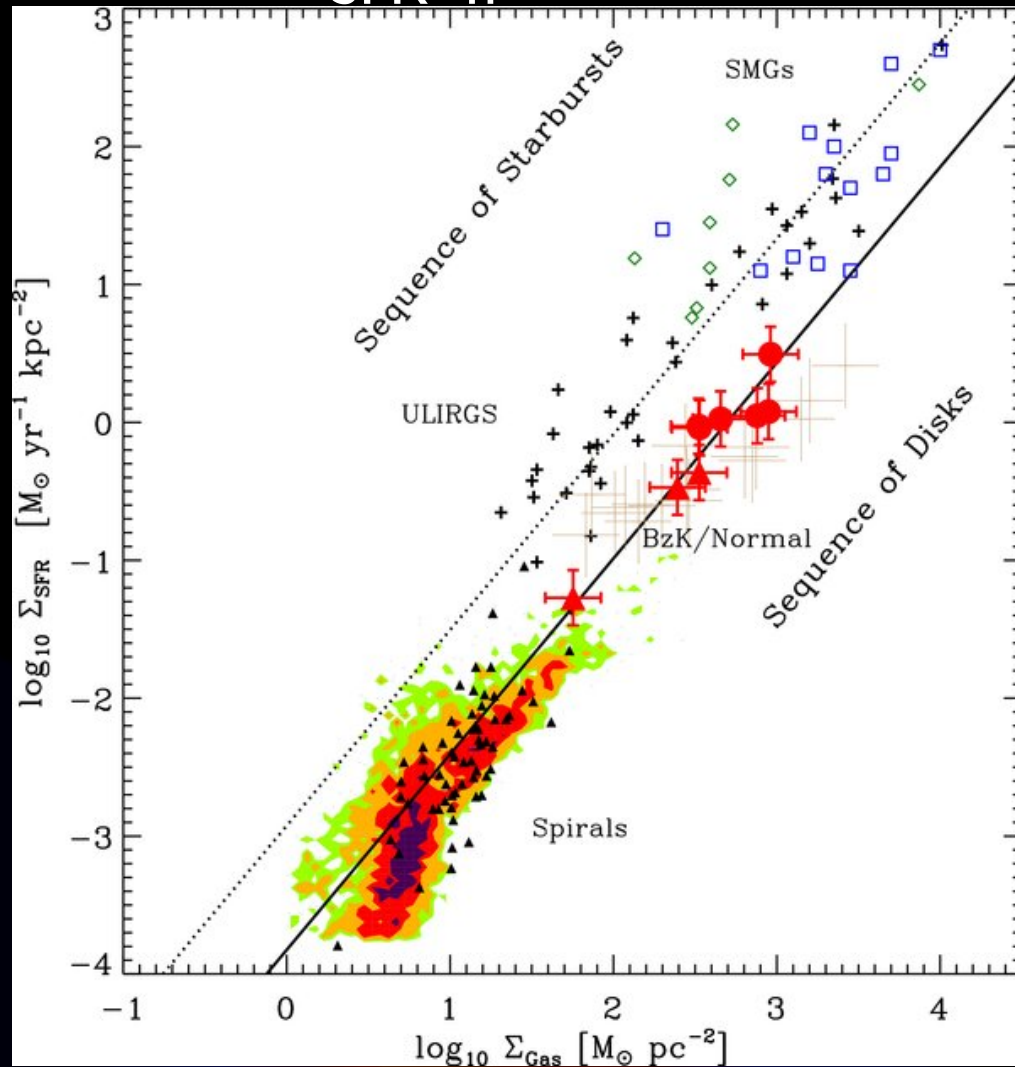


Narayanan, Cox, Hayward, Hernquist 2010

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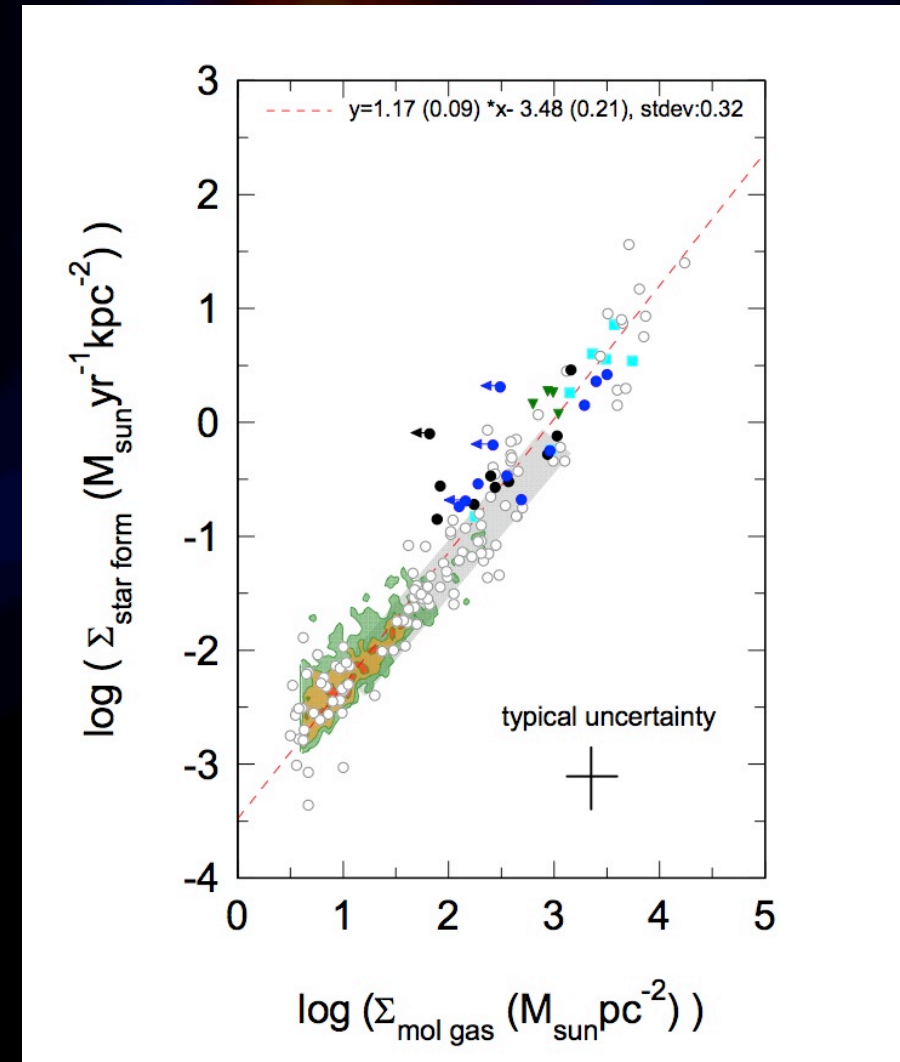
# Molecular Kennicutt-Schmidt Relations: Which Transition?: $z \sim 2$ Galaxies

CO J=2-1  
SFR  $\sim n^{1.2}$



Daddi et al. 2009

CO J=3-2  
SFR  $\sim n^1$

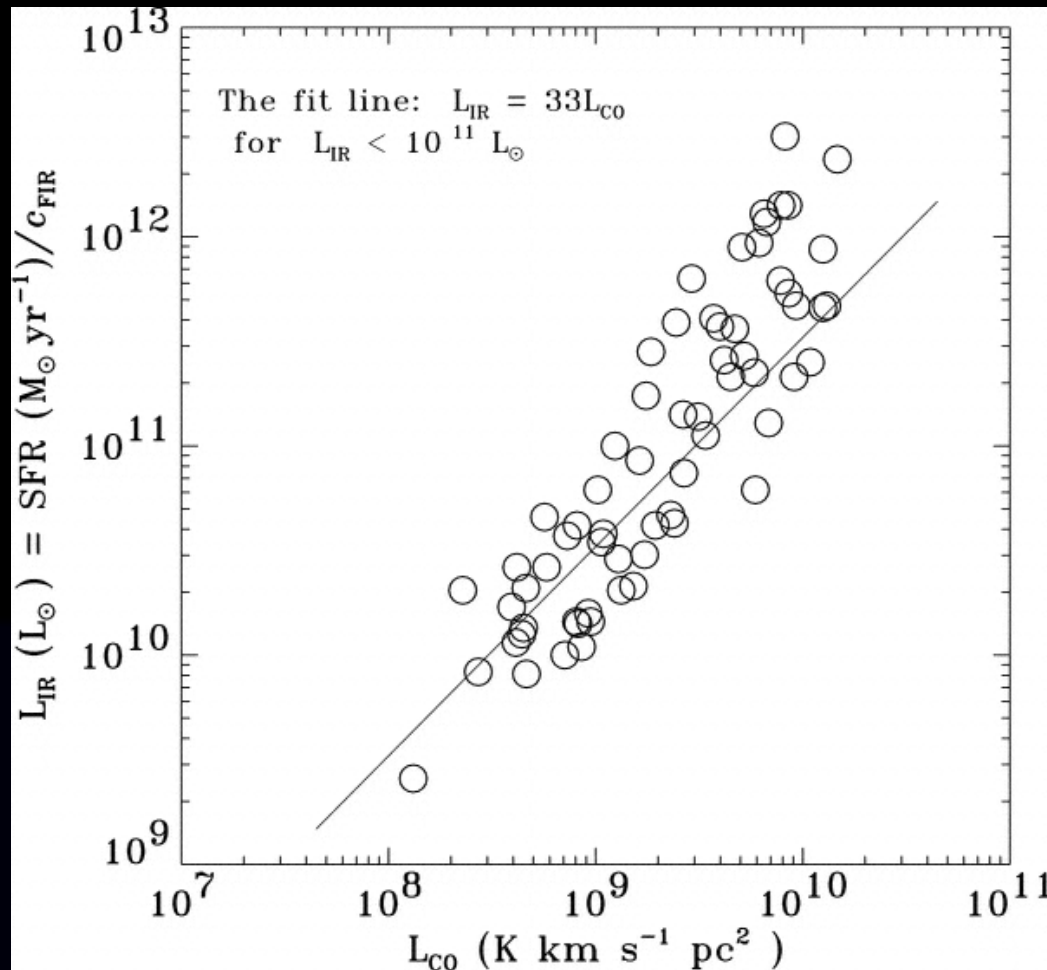


Genzel et al. 2009



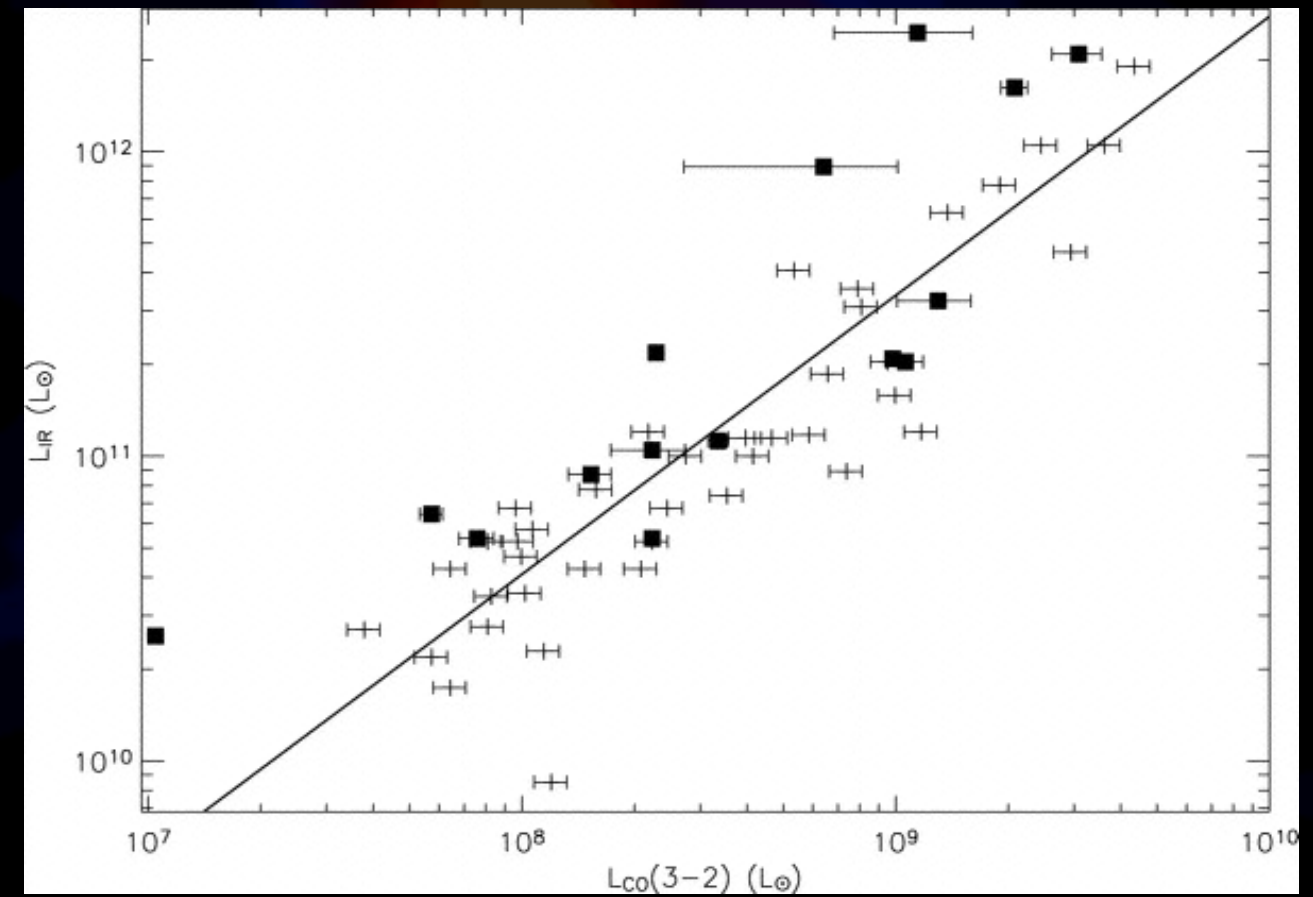
# Molecular Kennicutt-Schmidt Relations: Which Transition?: Local Galaxies

CO J=1-0  
SFR  $\sim n^{1.5}$



Gao & Solomon 2004

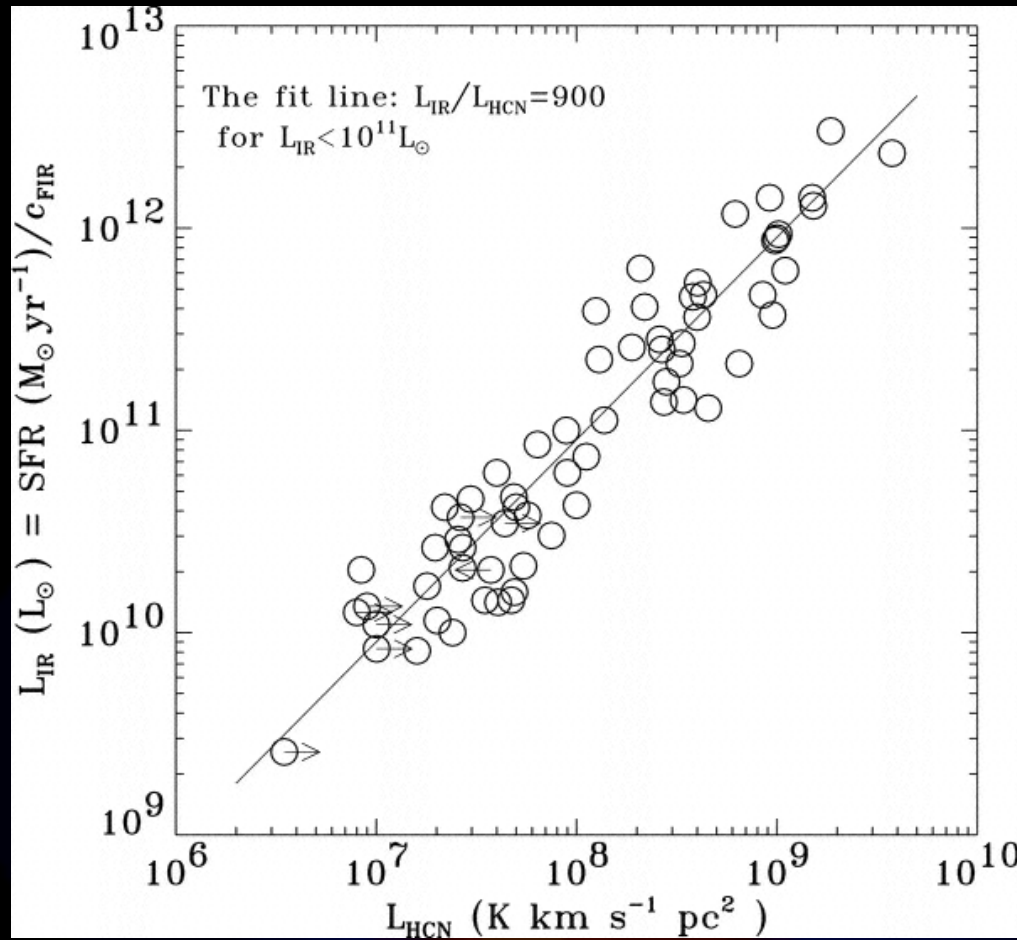
CO J=3-2  
SFR  $\sim n^1$



Narayanan et al. 2005

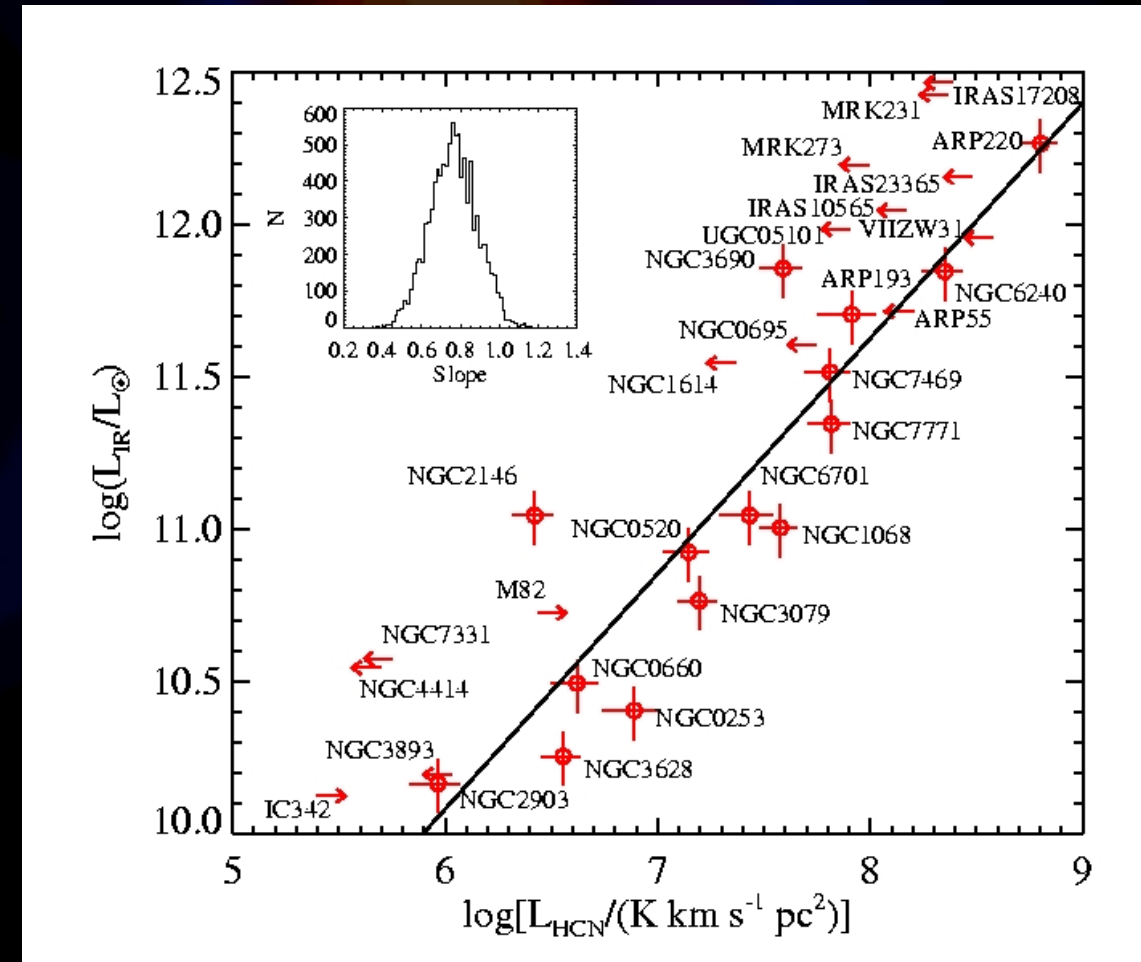
# Molecular Kennicutt-Schmidt Relations: Which Molecule?

HCN J=1-0  
SFR  $\sim n^1$



Gao & Solomon 2004

HCN J=3-2  
SFR  $\sim n^{0.7}$

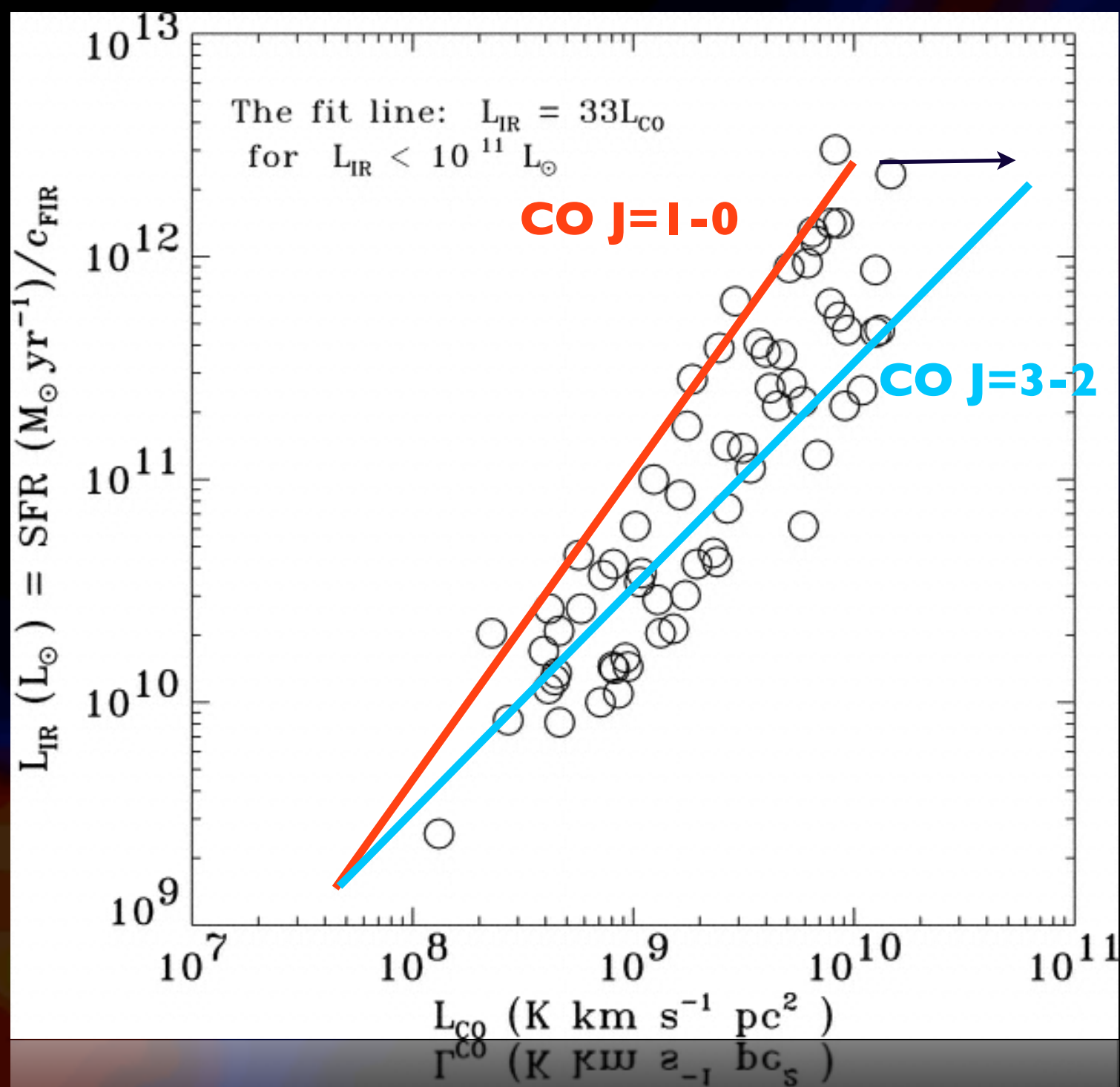


Bussmann, Narayanan et al. 2008

High-z CO	Low-z CO	Low-z HCN
CO J=2-1 N=1.2	CO J=1-0 N=1.5	HCN J=1-0 N=1
CO J=3-2 N=1	CO J=3-2 N=1	HCN J=3-2 N=0.7

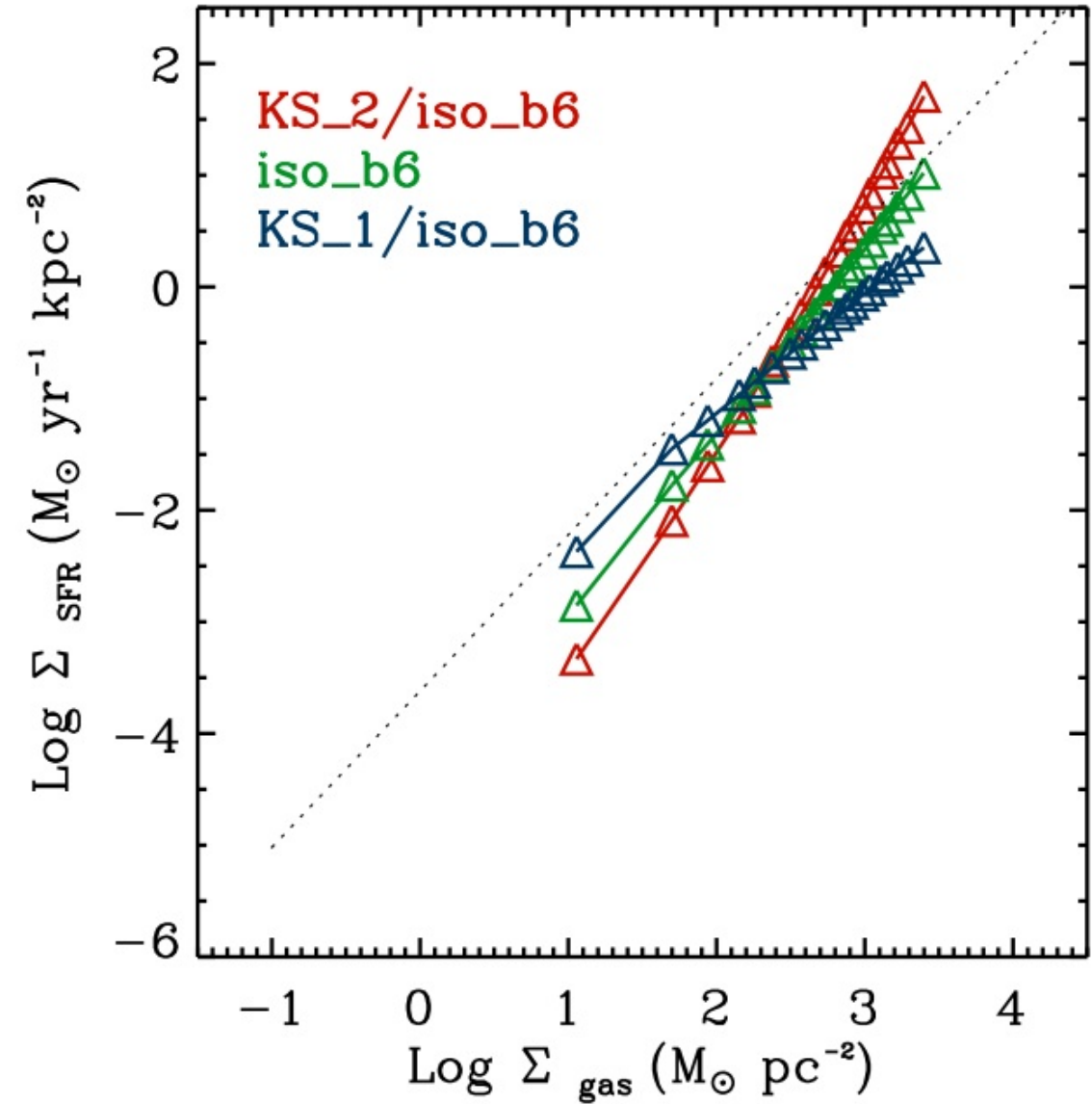
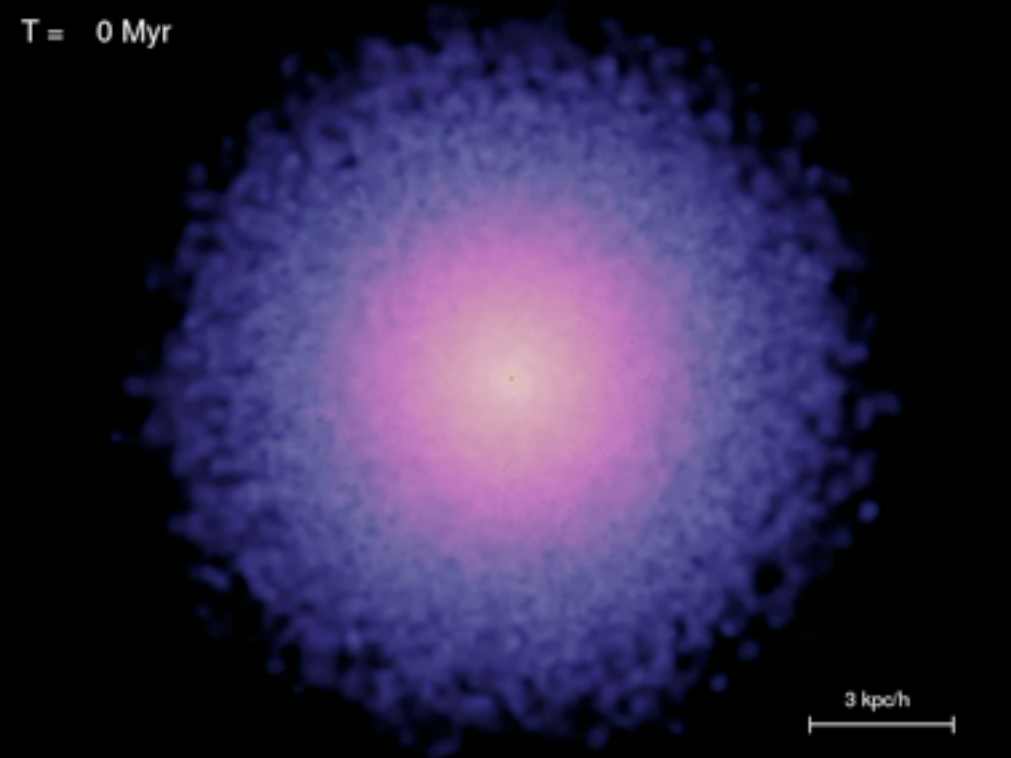


# Differential Excitation as Driver



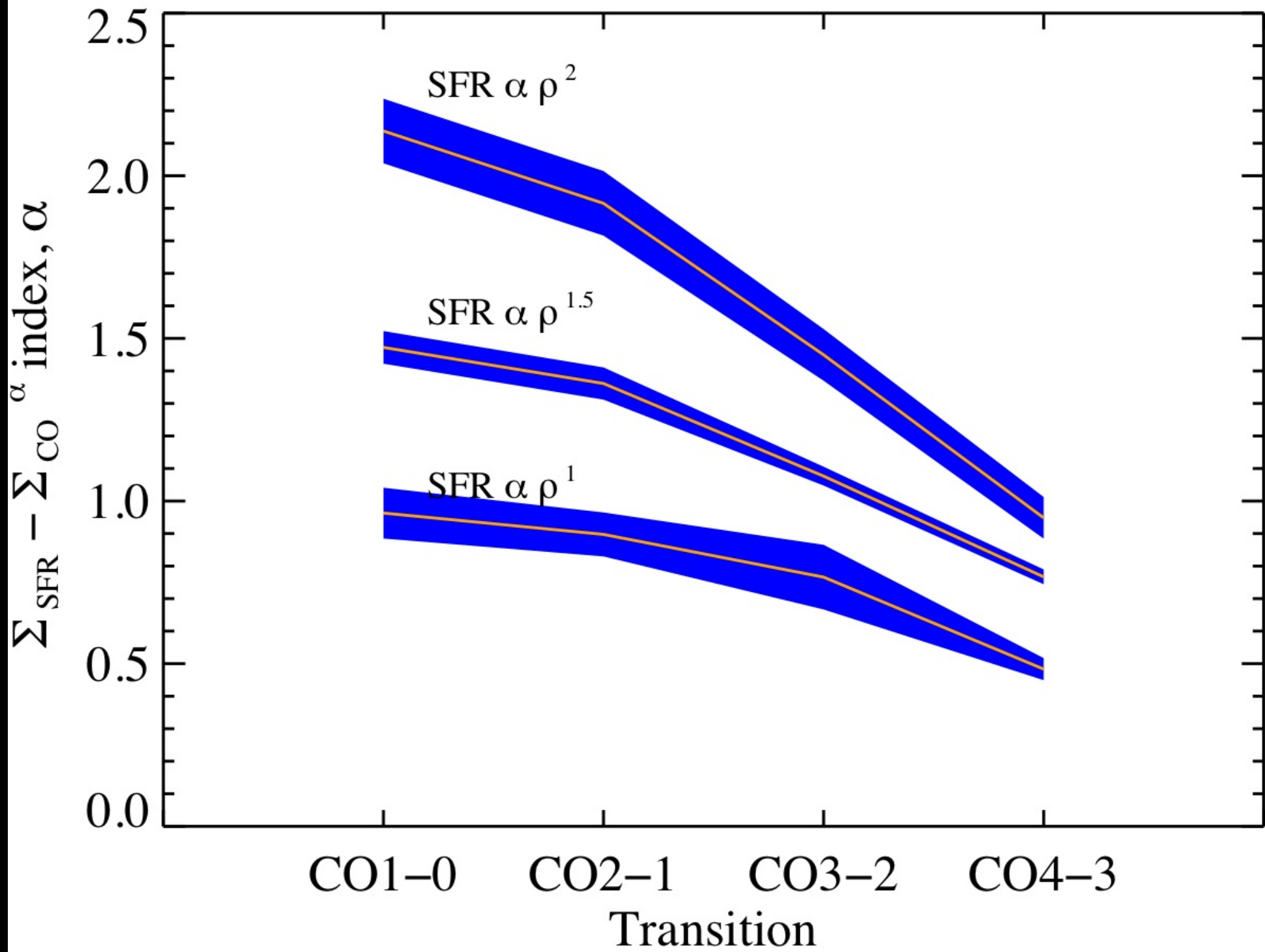
$$\text{SFR} \sim \rho^{1,1.5,2}$$

T = 0 Myr



Narayanan, Cox, Hayward, Hernquist 2010

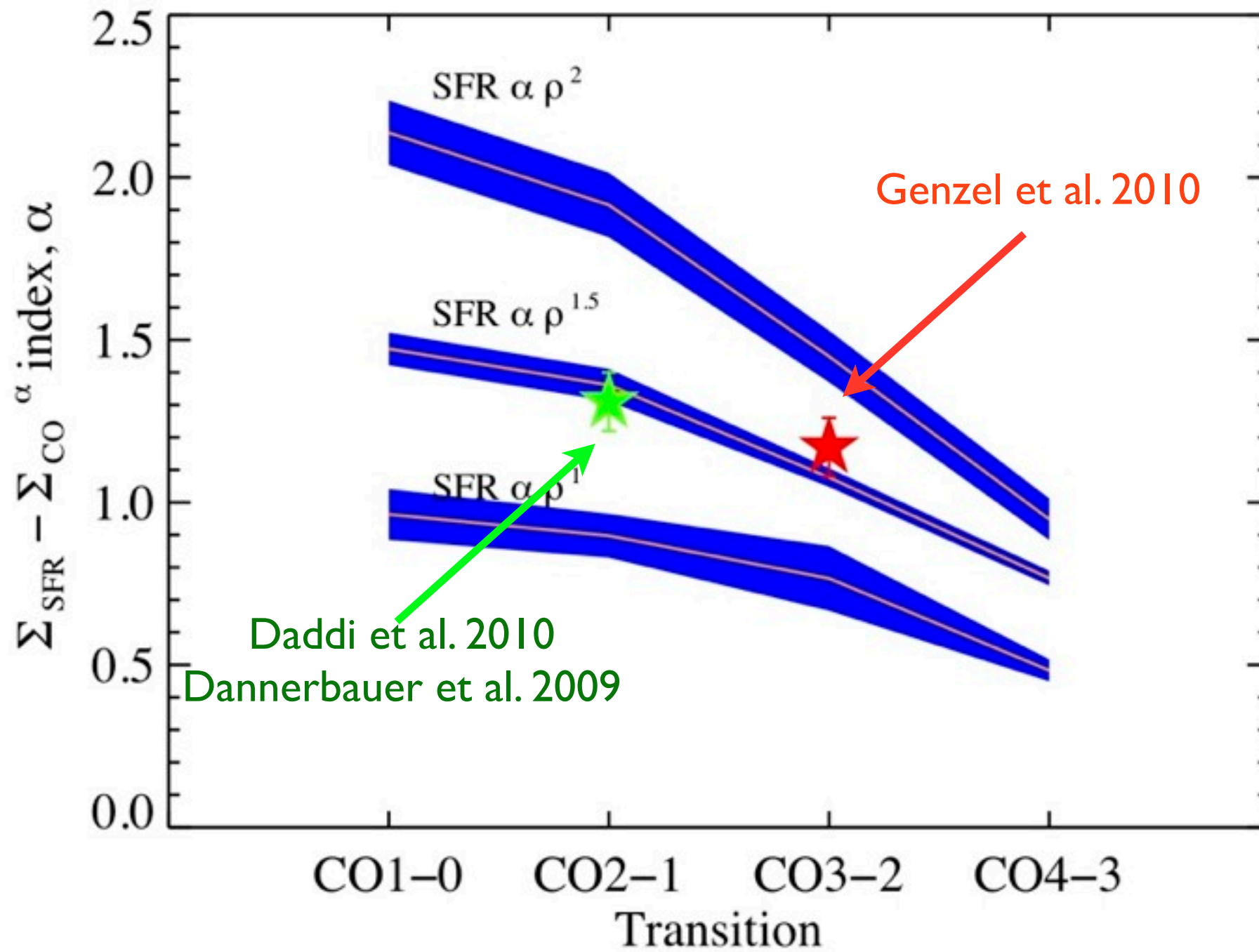
The KS index  
you observe



Narayanan, Cox, Hayward, Hernquist 2011



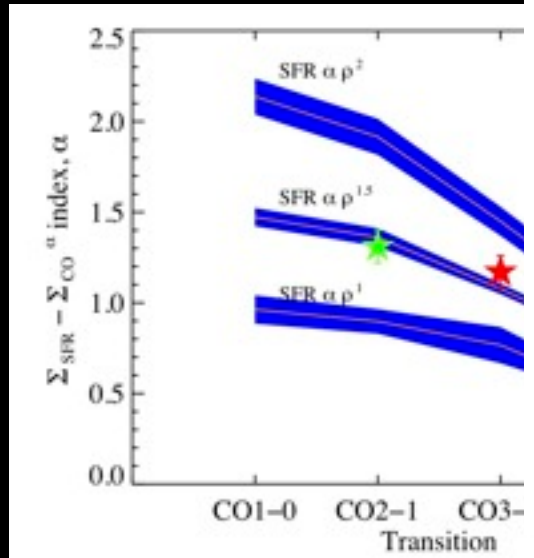
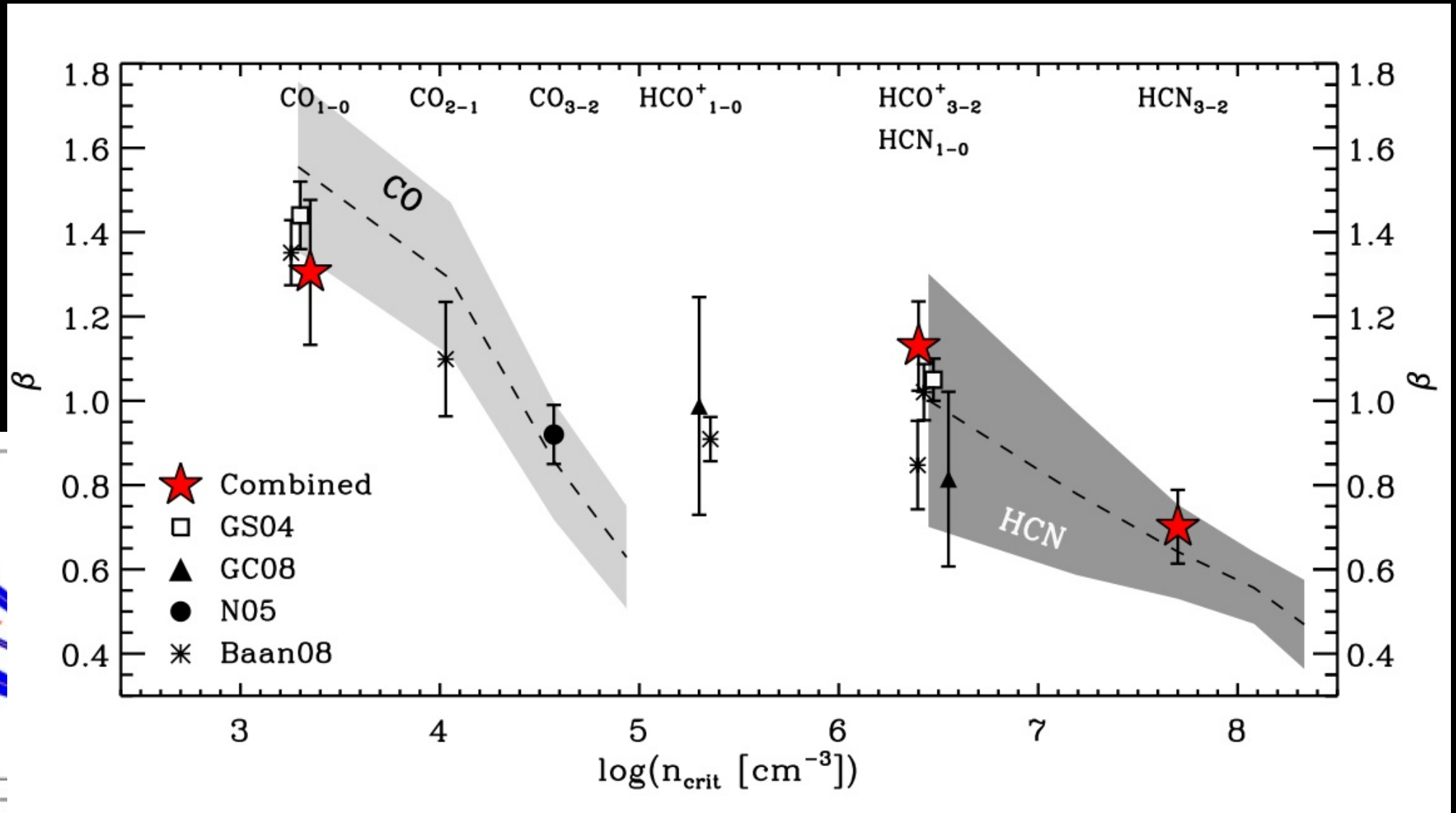
The KS index  
you observe



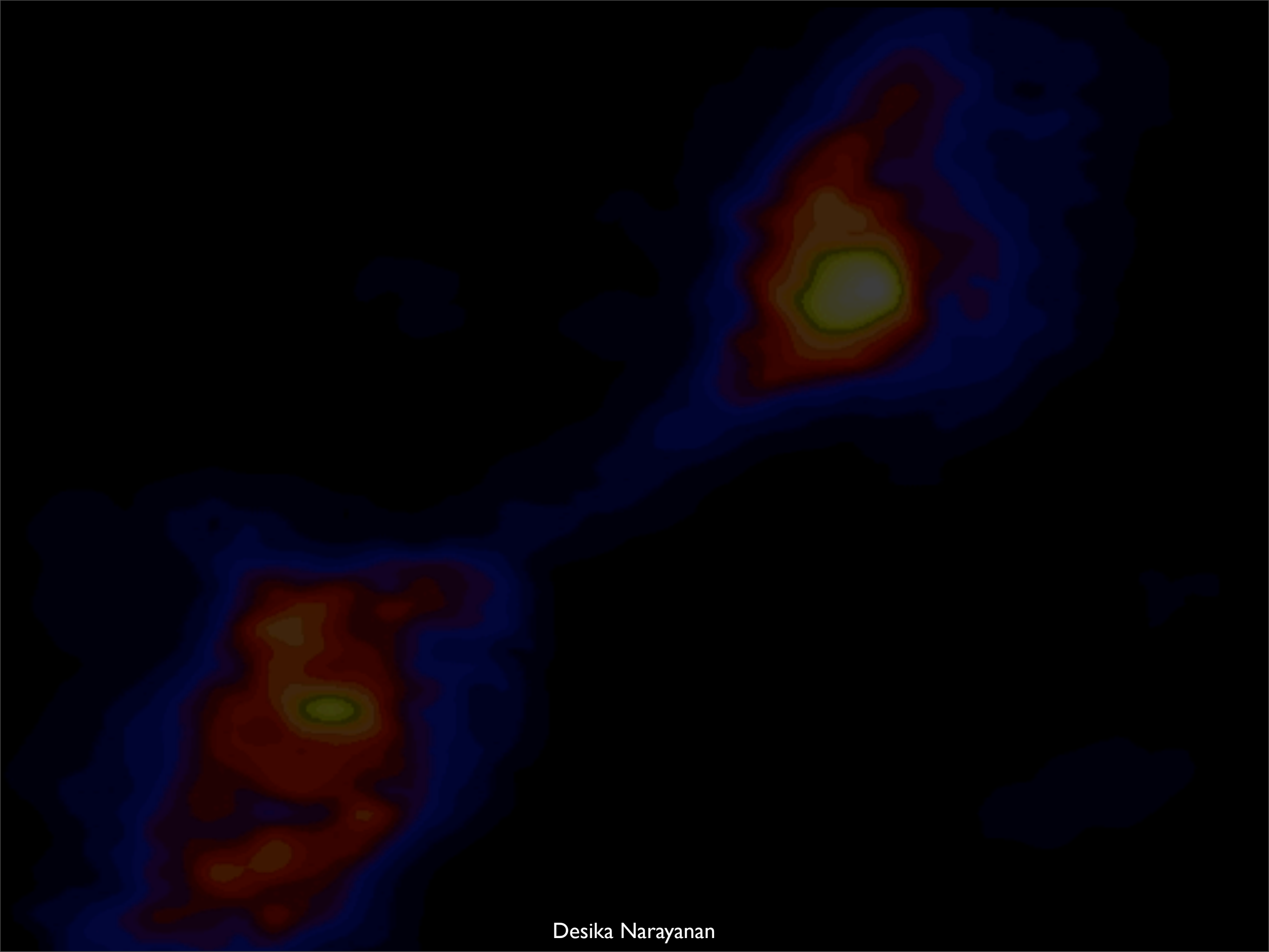
Narayanan, Cox, Hayward, Hernquist 2011

# It works in the local Universe as well

## $SFR \sim \rho^{1.5}$

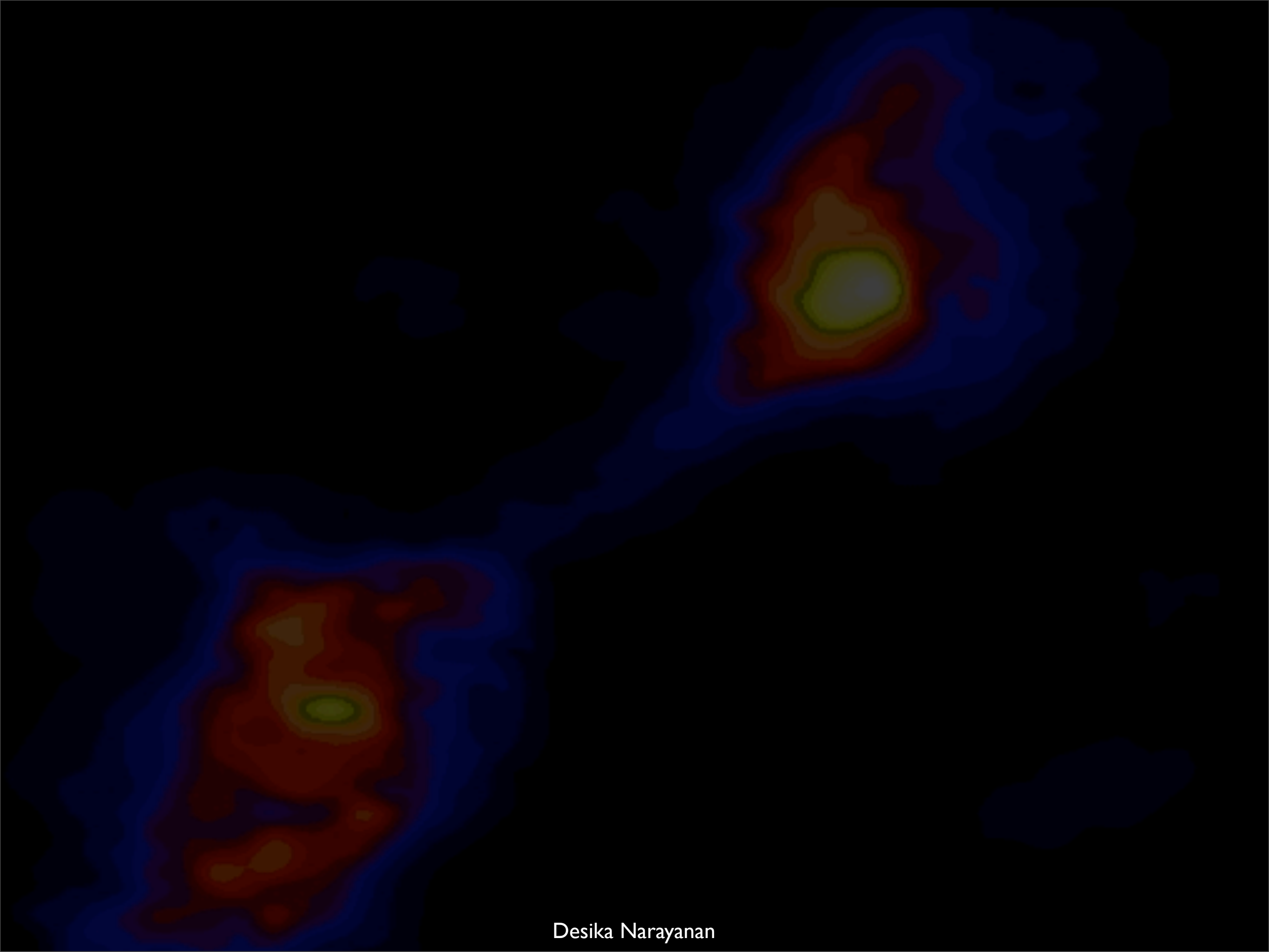


Juneau, Narayanan, Bussmann et al. 2009  
 Narayanan, Cox, Shirley et al. 2008

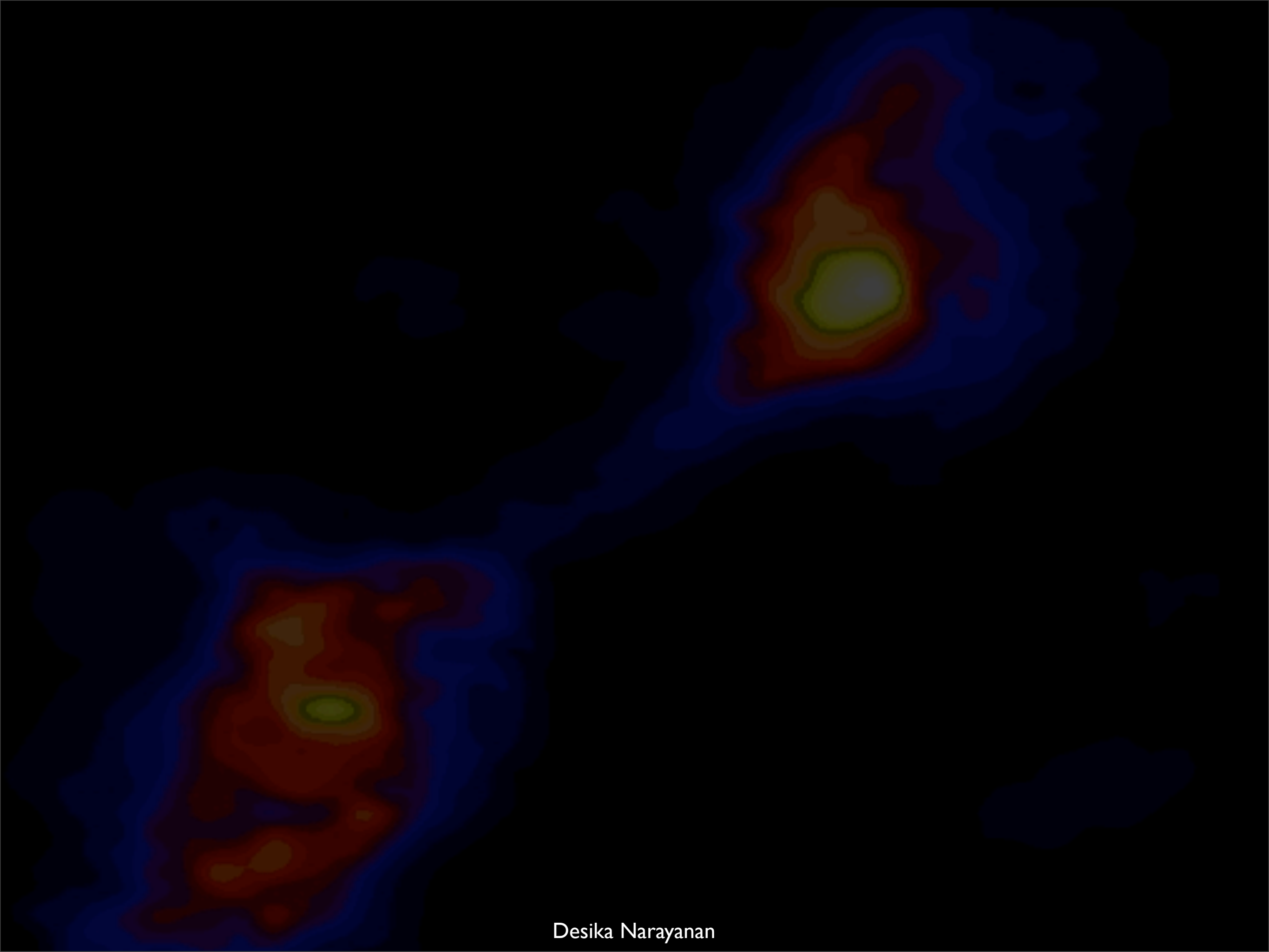


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