The Lifecycle of (radiative) feedback-regulated GMCs

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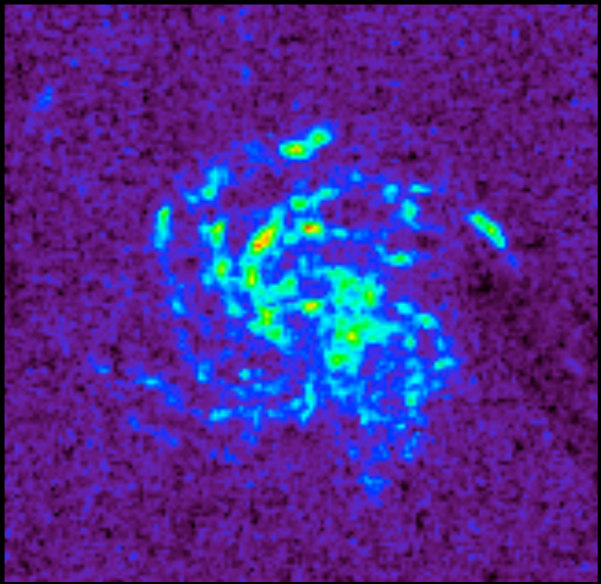
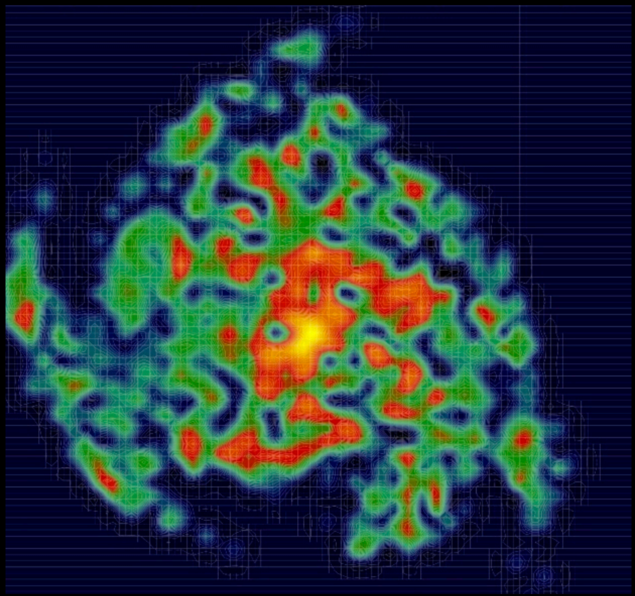
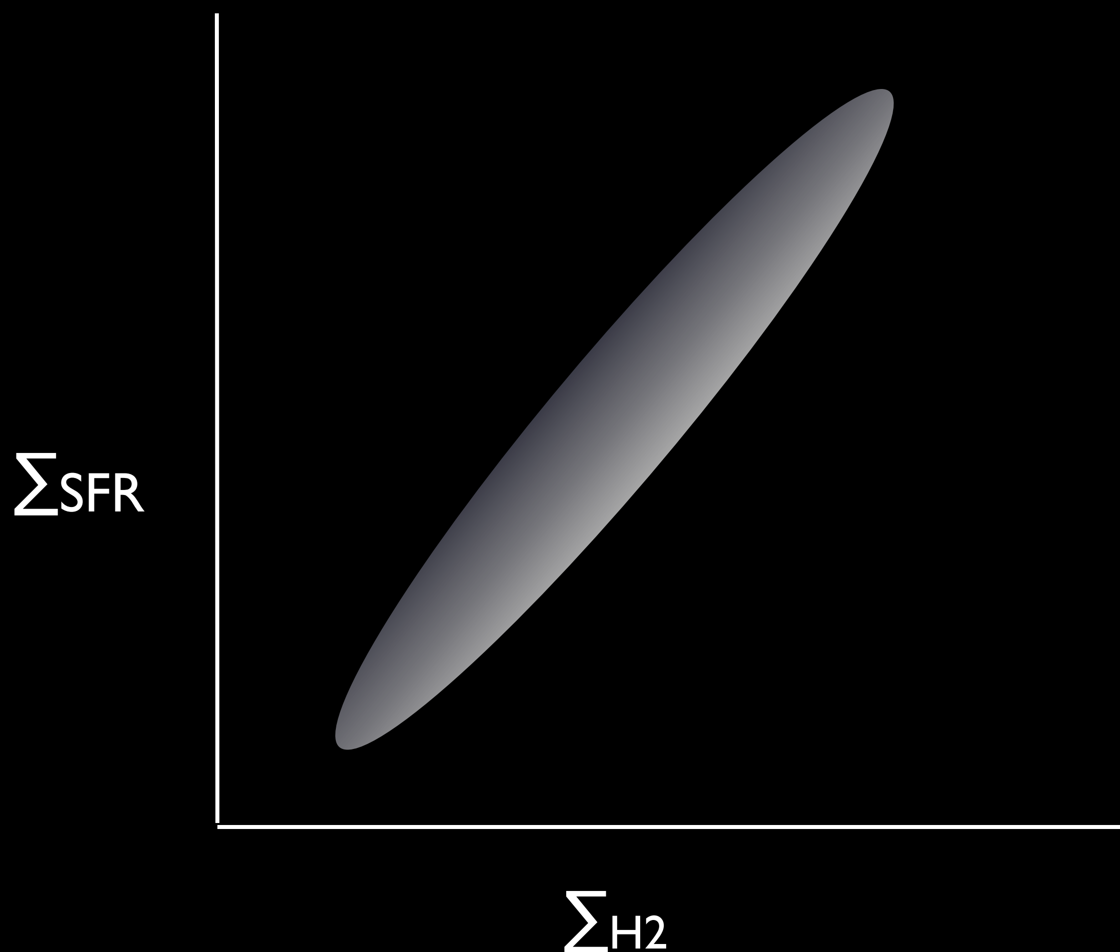
(with Phil Hopkins, Mark Krumholz, Eve Ostriker)

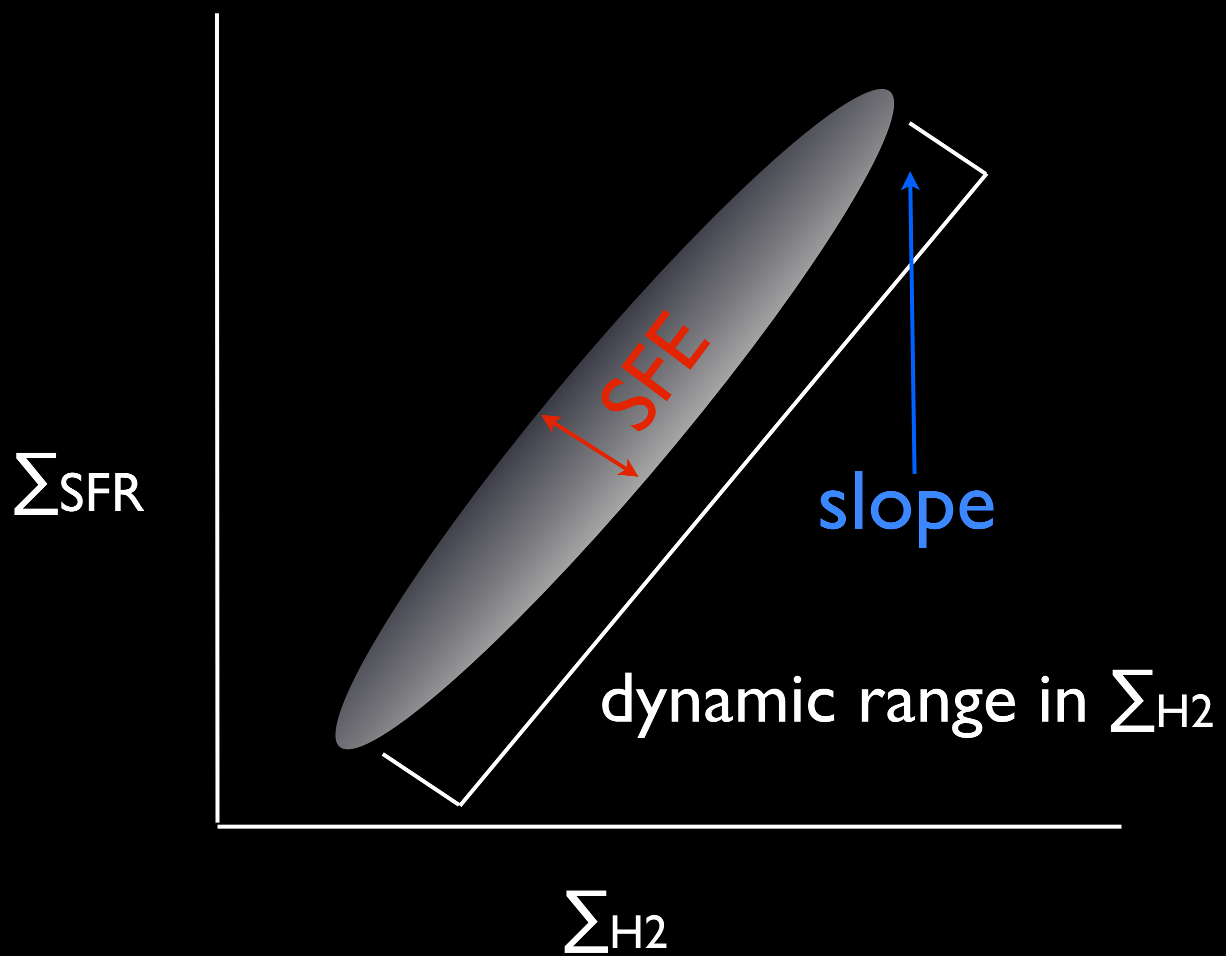


awesome galaxy picture by adam leroy

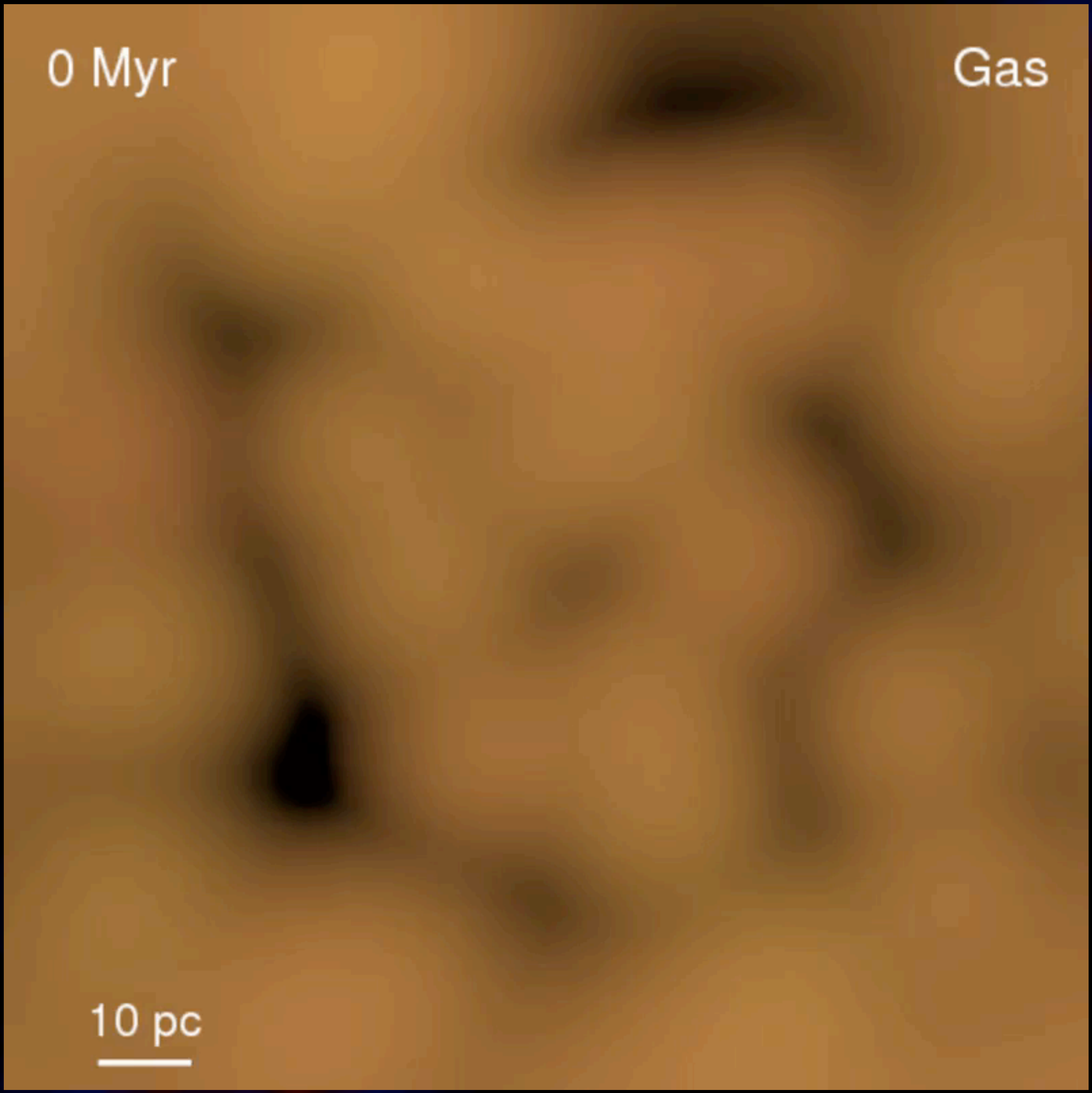


awesome galaxy simulation by desika narayanan


Σ_{SFR}
Σ_{H2}



Σ_{SFR}
SFE
slope
dynamic range in Σ_{H2}
Σ_{H2}



Simulations

1. 1 pc res. GADGET
2. T < 100 K cooling
3. H_2-HI breakdown (KMT)
4. GMCs ID'd with FOF

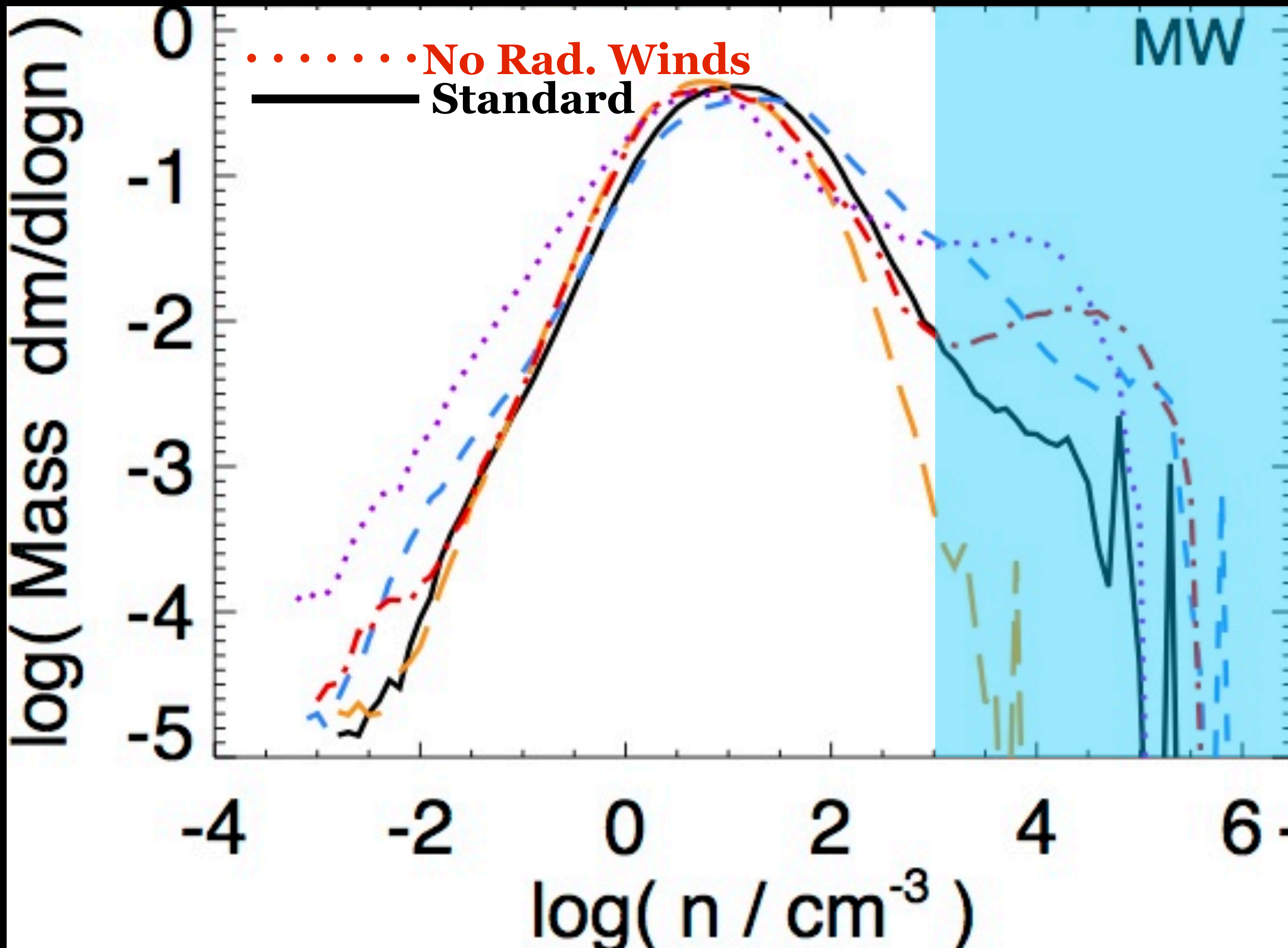
Star Formation

5. $\rho_{SFR} \sim \varepsilon \times \rho_{H2}(n>1000)/t_{ff}$
6. $P = P_{sn} + P_w + P_{rad}$
7. $P_{rad} \sim (1+\Sigma^* \kappa)L/c$

Galaxy

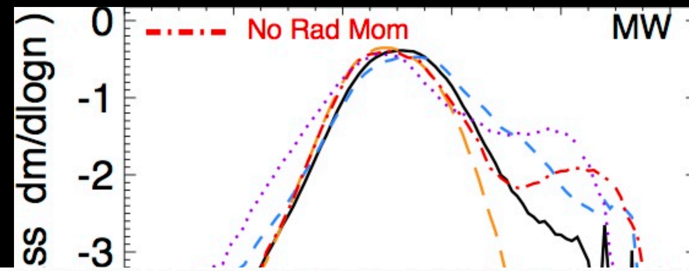
8. M_{halo} = 1.6e12
9. M_{bar} = 7.1e10

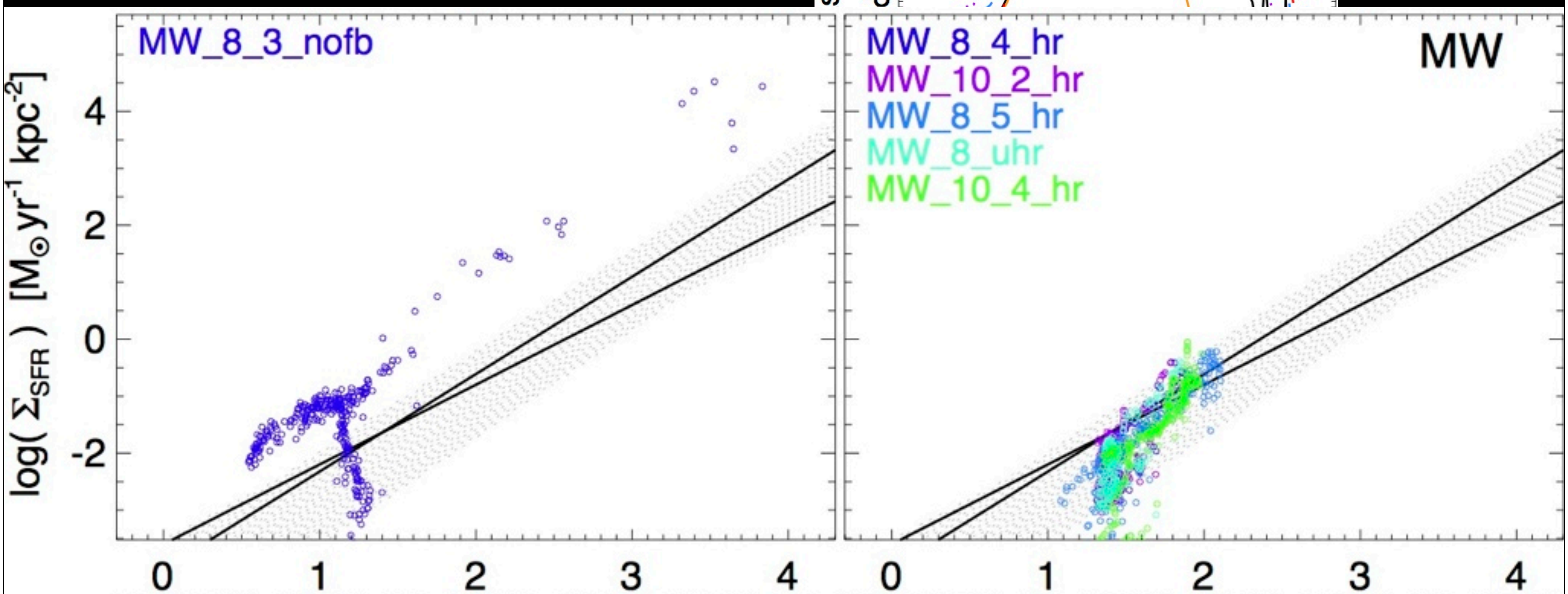
$$\rho_{SFR} \sim \varepsilon \times \rho_{H2}(n>1000)/t_{ff}$$



Hopkins, Narayanan, Murray & Quataert (2013)

$\rho_{SFR} \sim \mathcal{E} \times \rho_{H2}(n>1000)/t_{ff}$



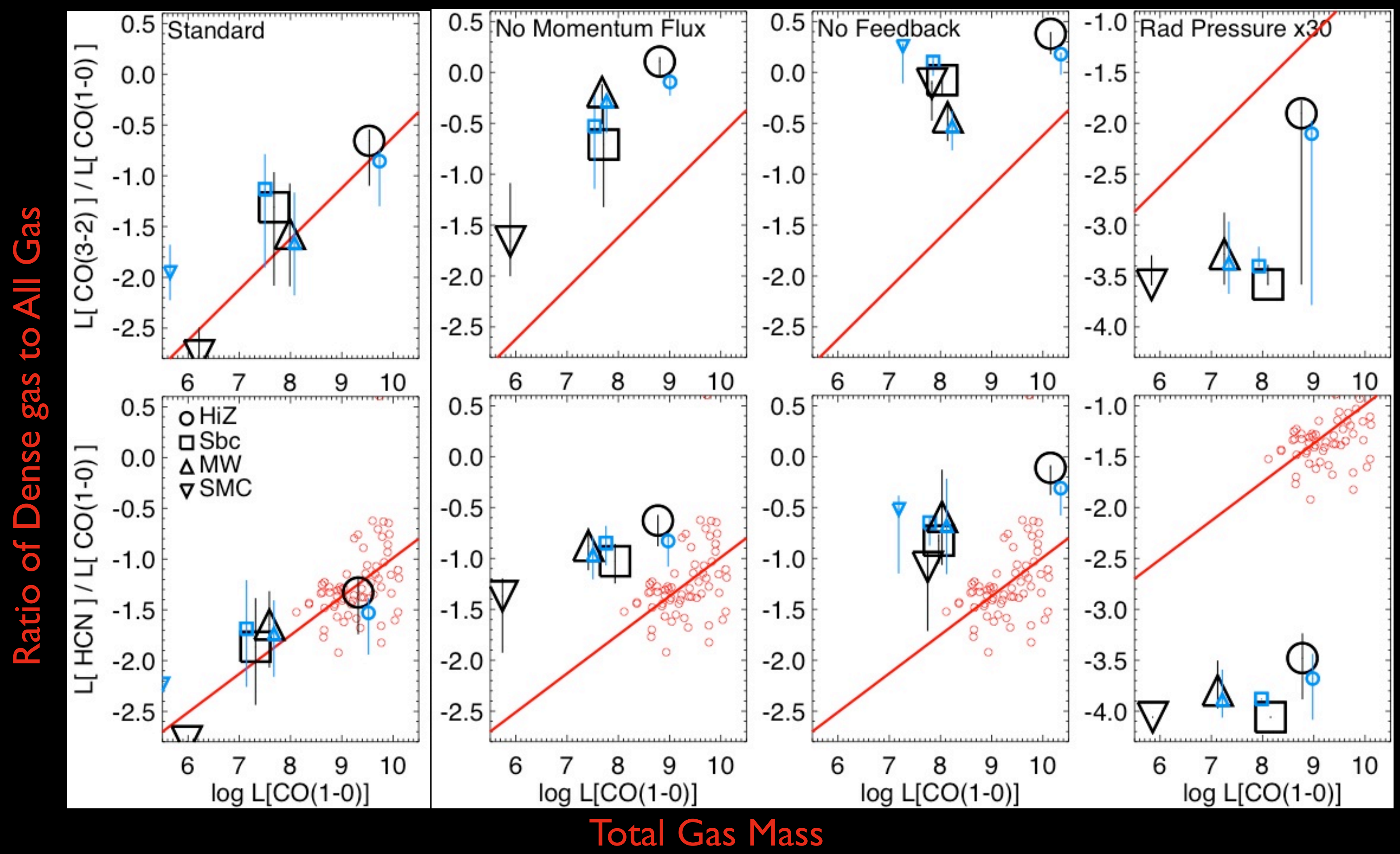


Σ_{H2} Σ_{H2}

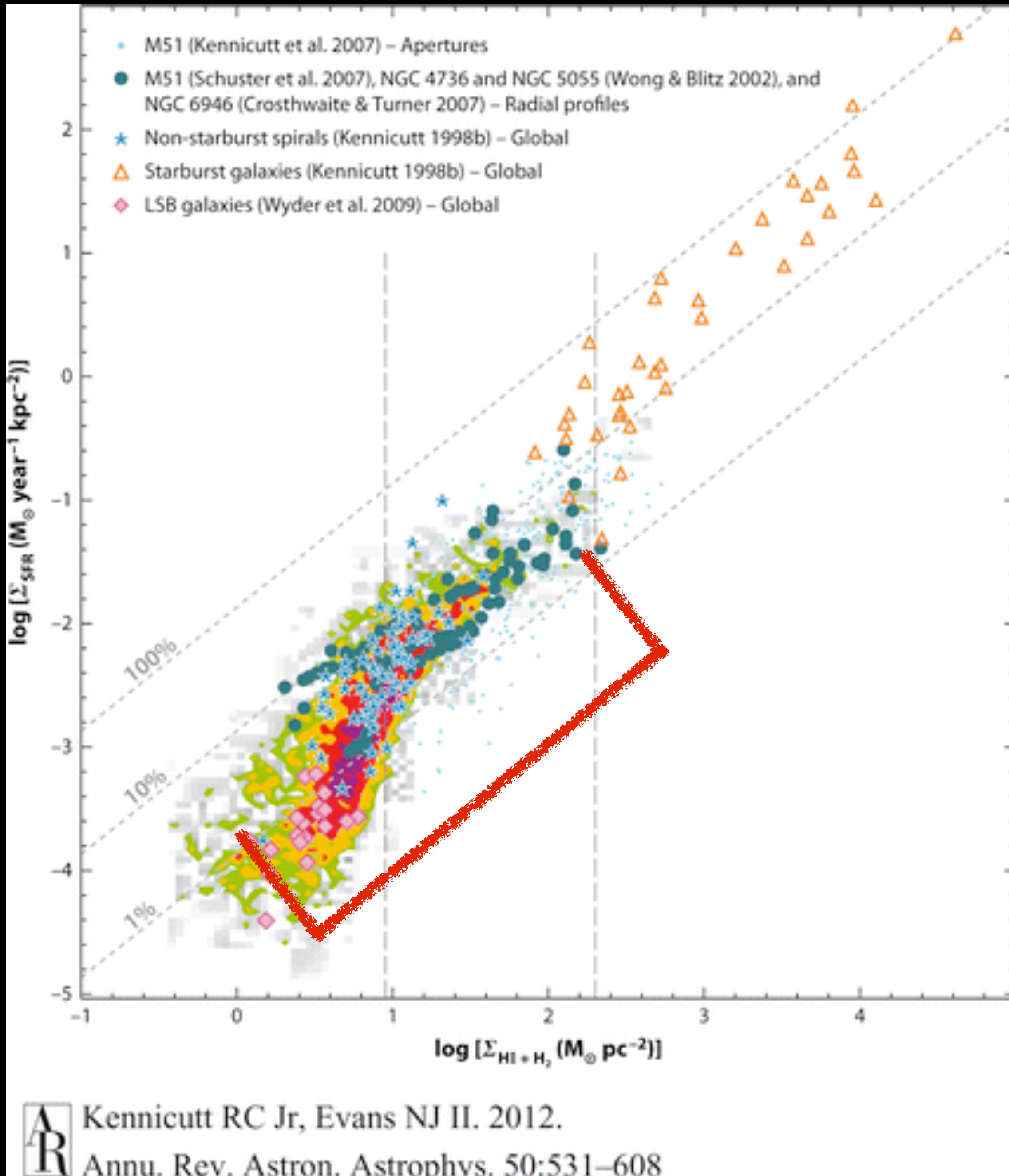
Hopkins+ 2011

Narayanan, Hopkins & Murray (in progress)

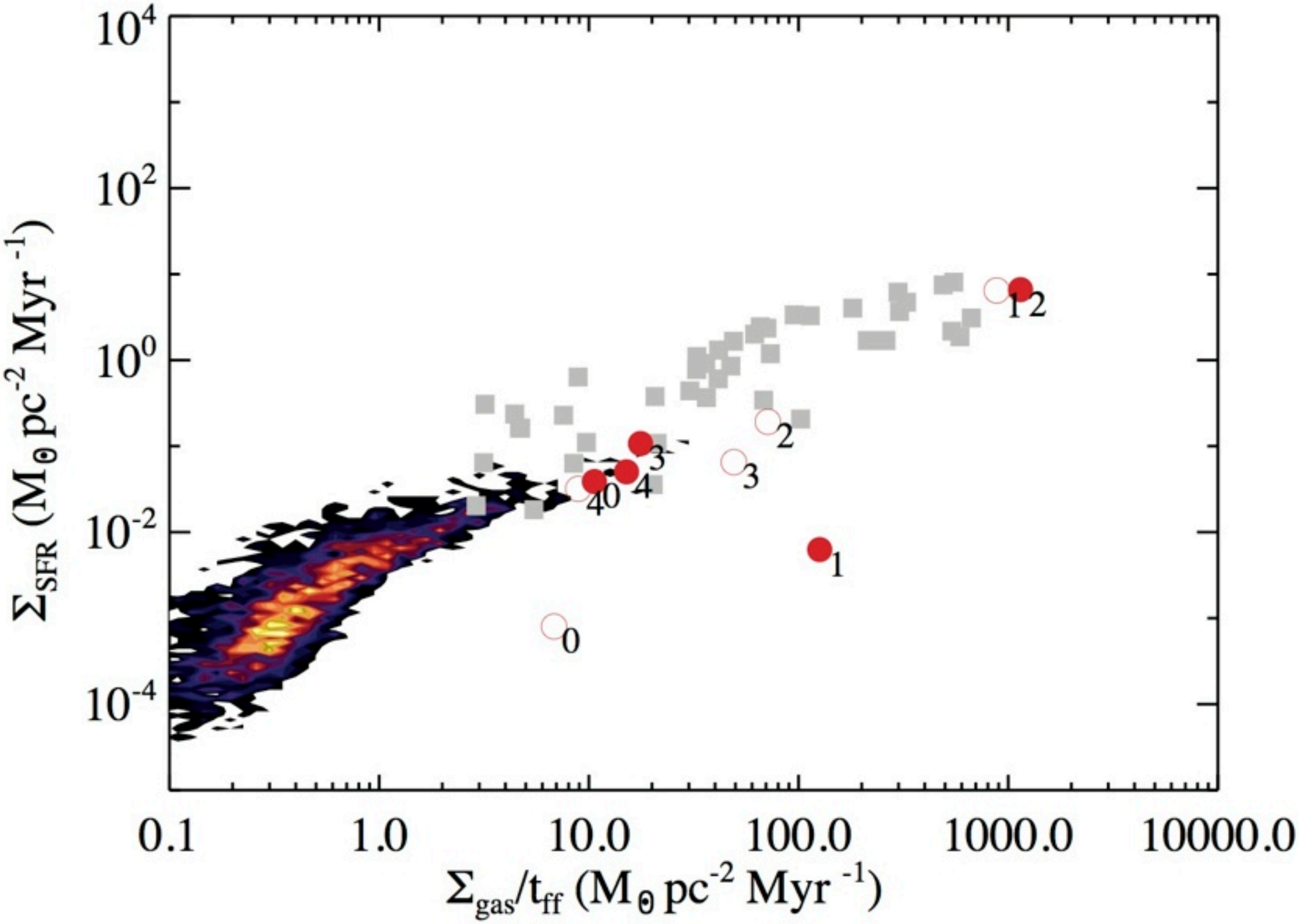
Dense Gas Distribution Constraints on Feedback Model



Hopkins, Narayanan, Murray & Quataert (2012)

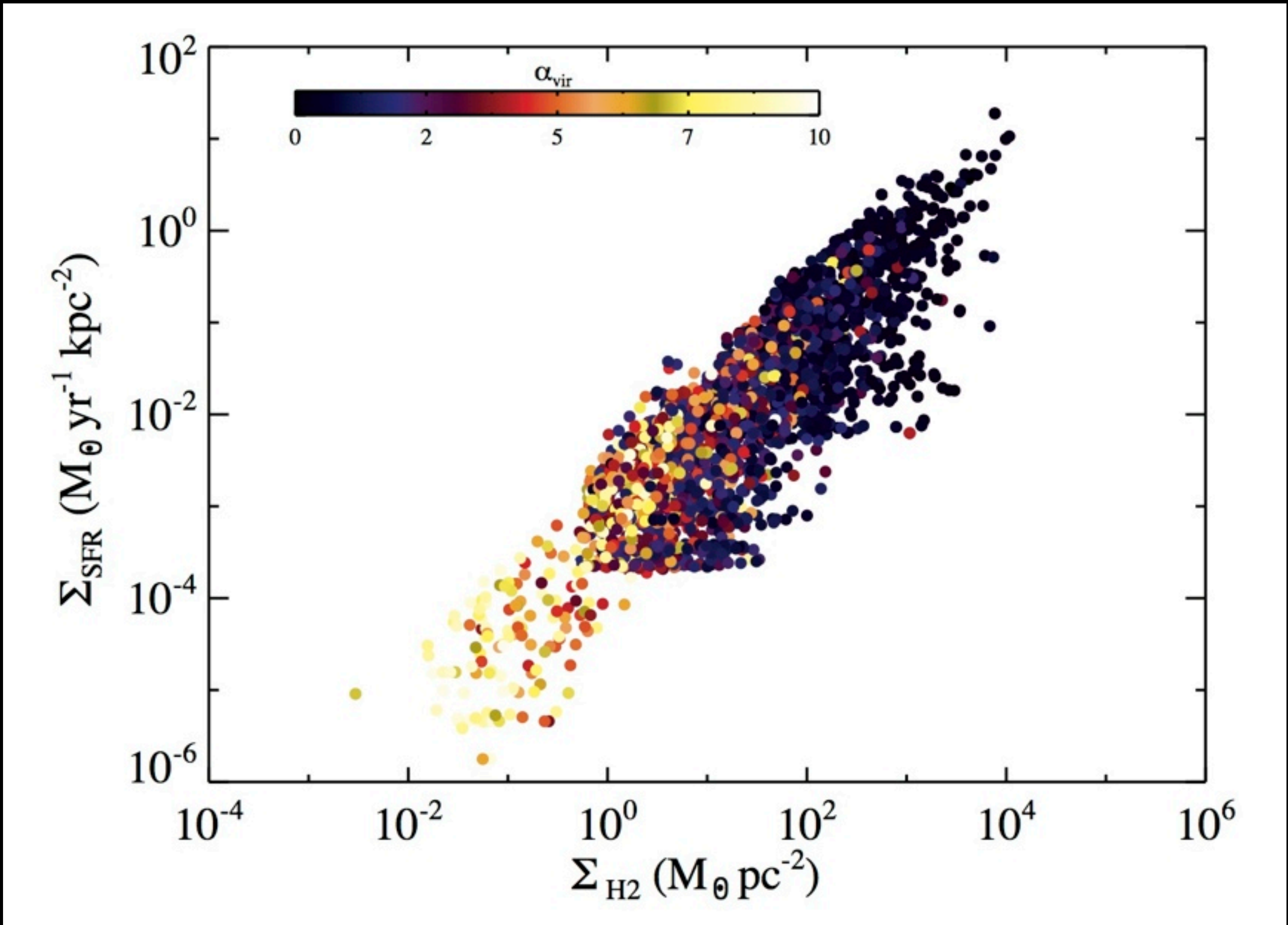


data by many people; plot by Kennicutt & Evans (2012)



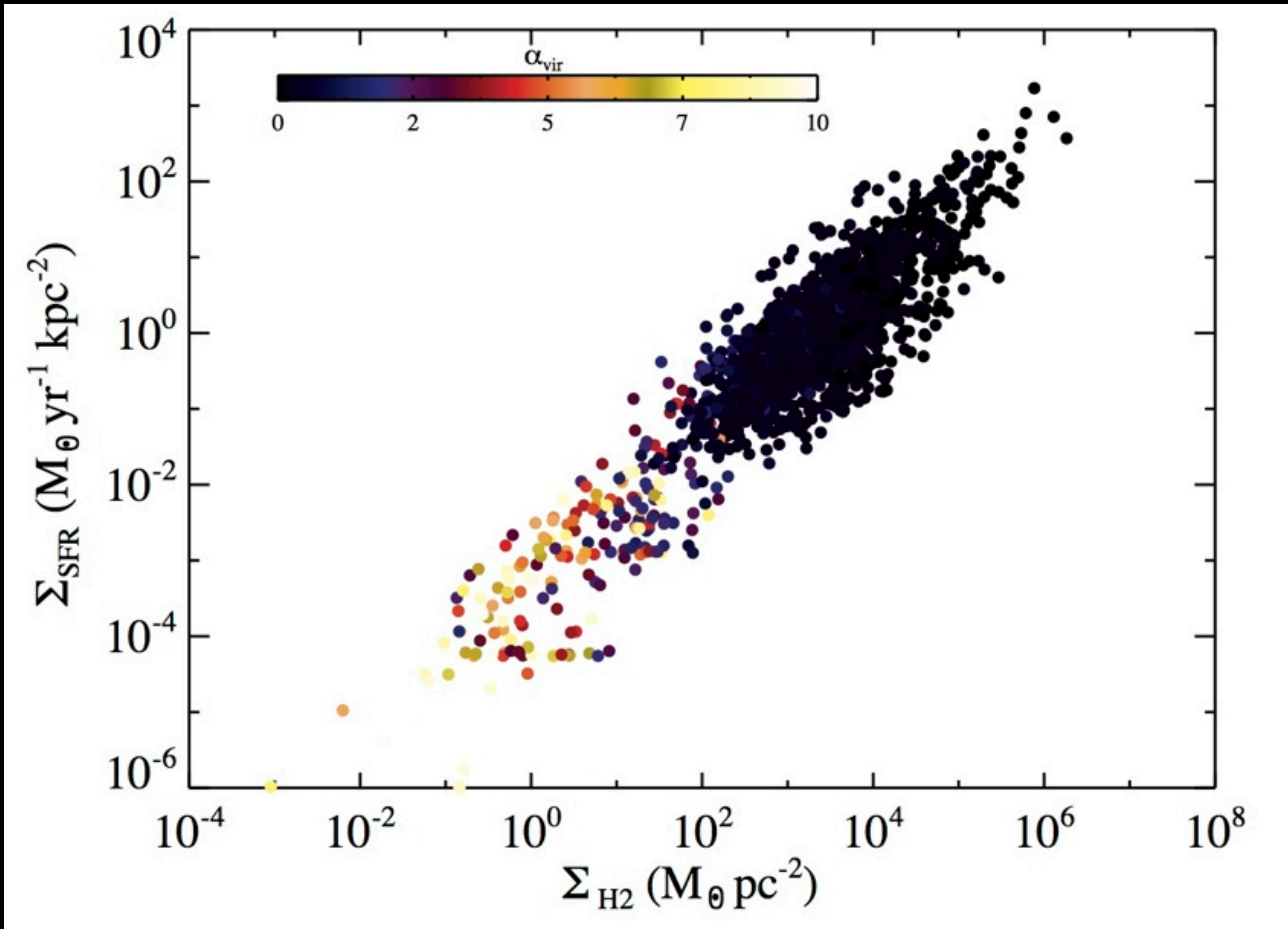
Narayanan, Hopkins & Murray in prep.

virial parameter on KS plot - standard model

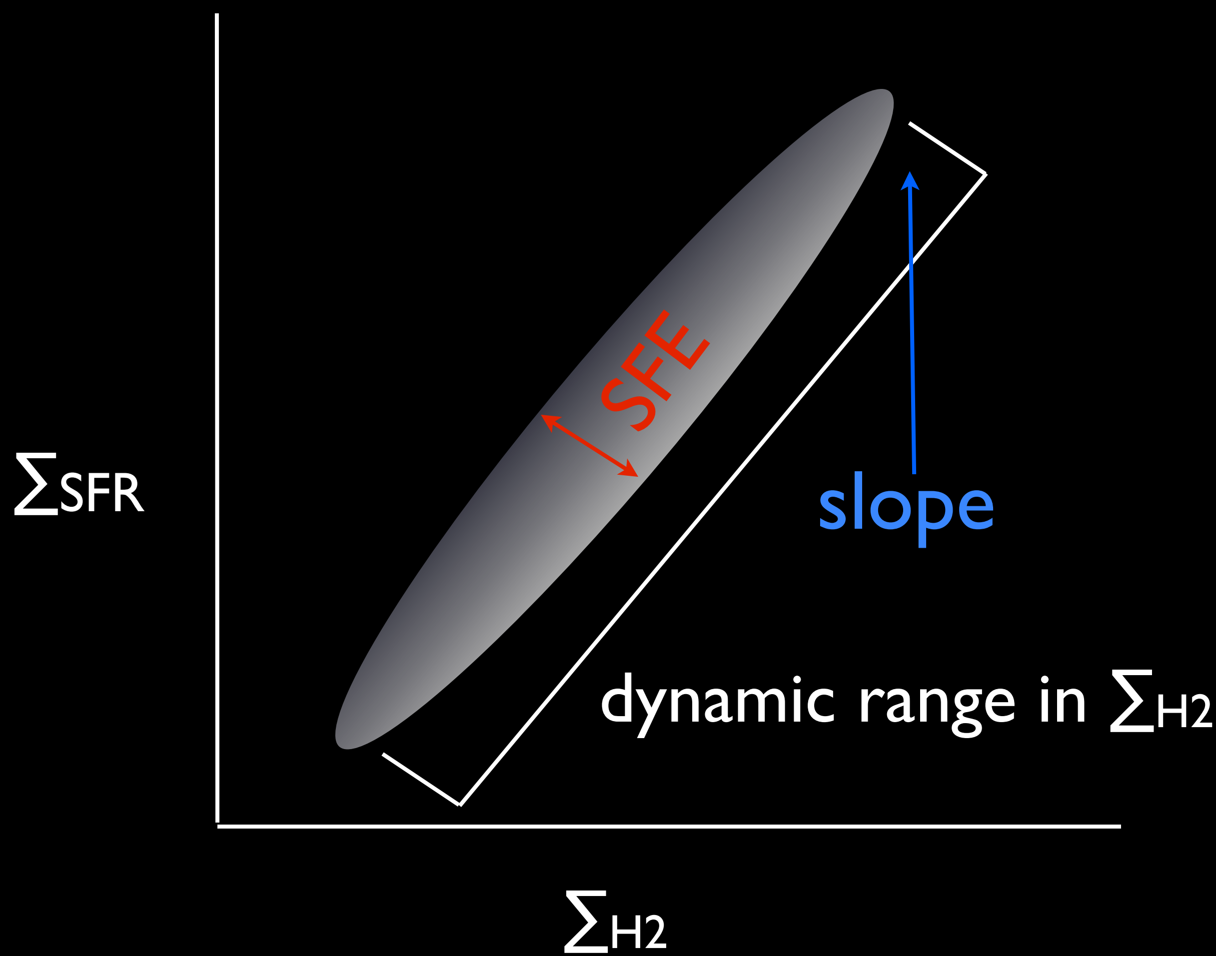


Narayanan, Hopkins & Murray in prep.

virial parameter on KS plot - no radiative feedback

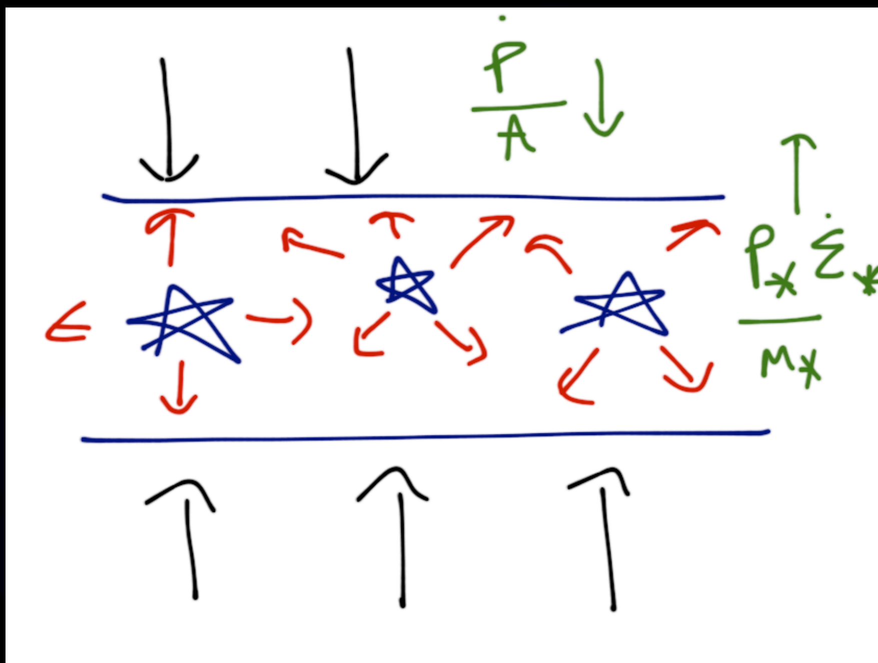


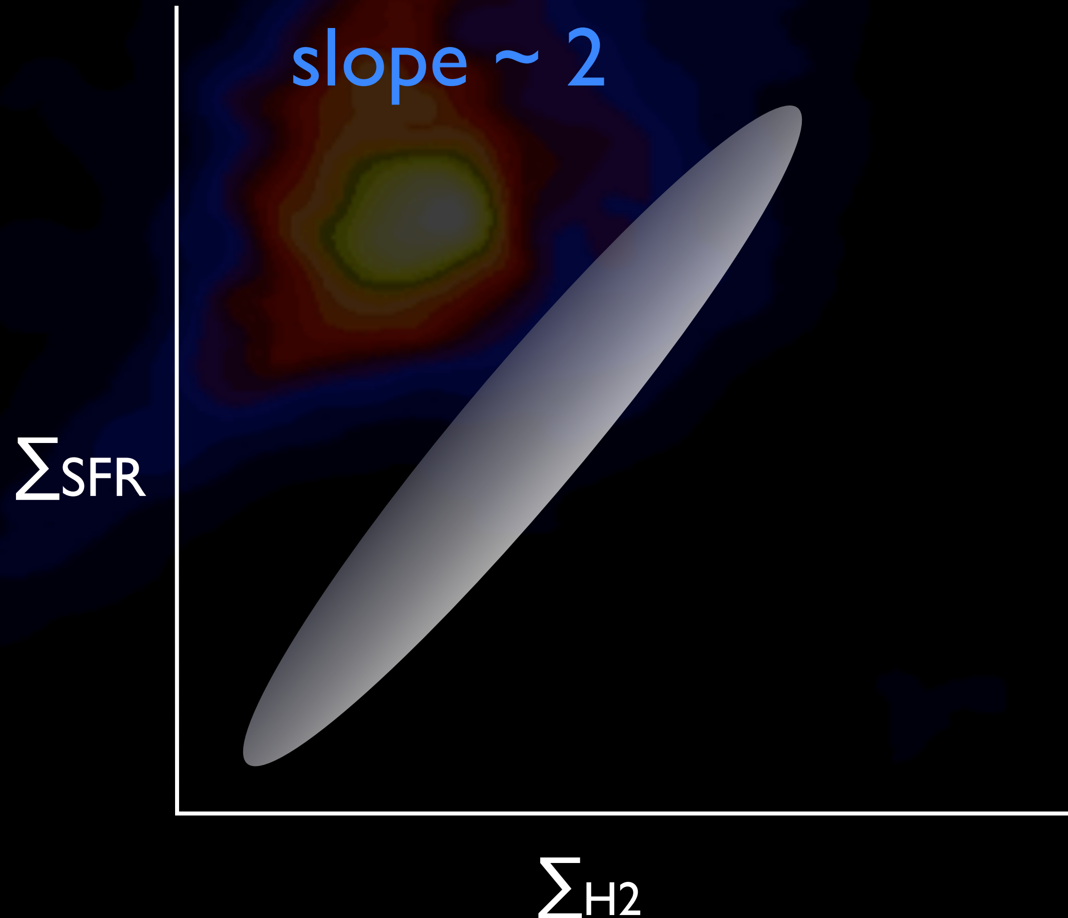
Narayanan, Hopkins & Murray in prep.



Σ_{SFR}
SFE
slope
dynamic range in Σ_{H2}
Σ_{H2}

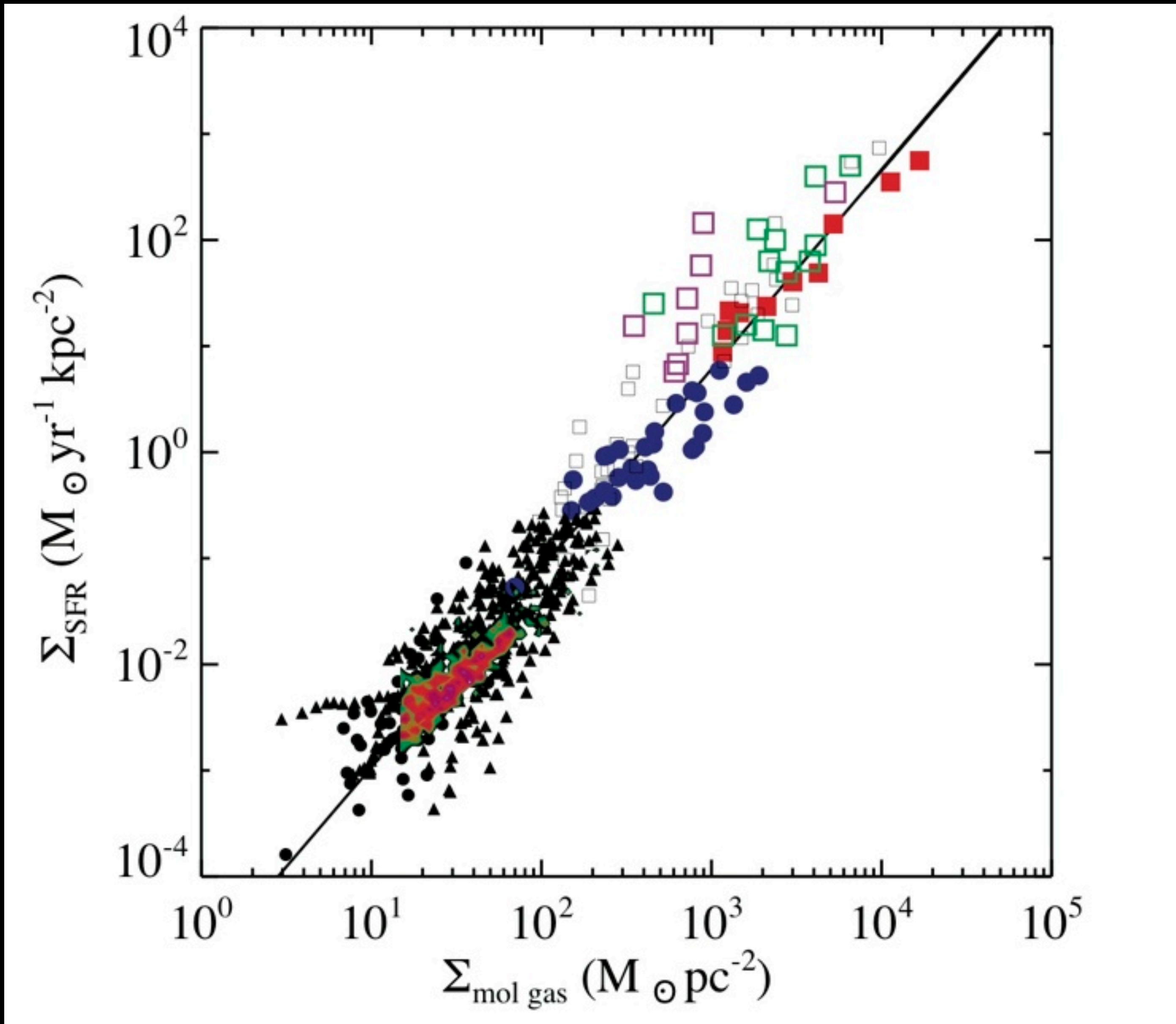
Radiative Feedback Dominated ISM in Starbursts



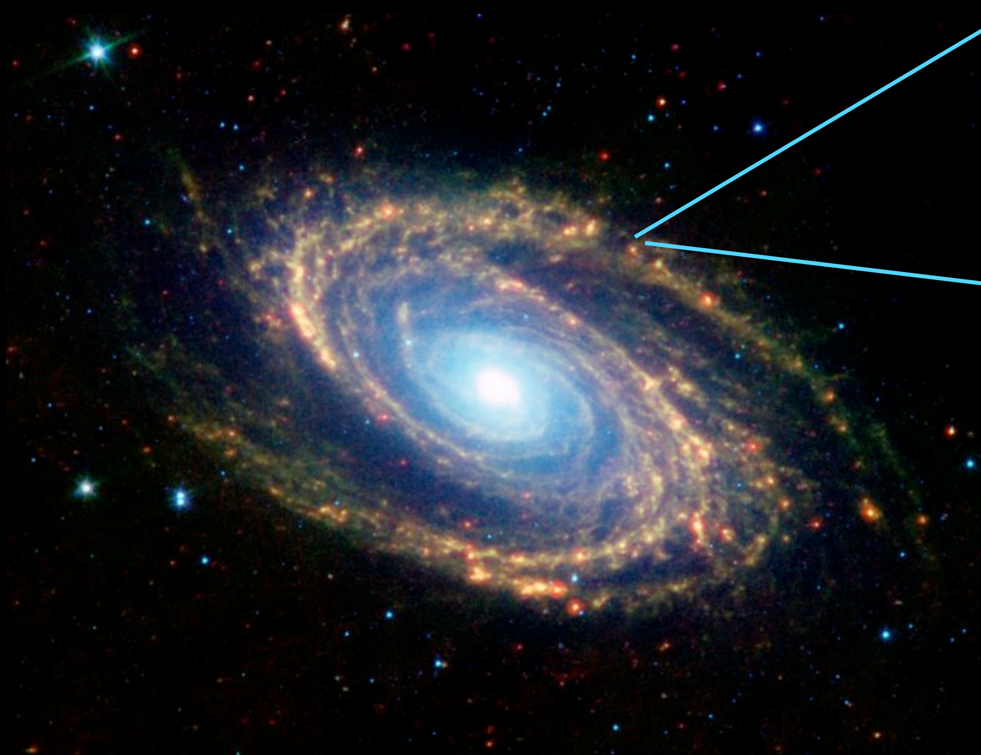


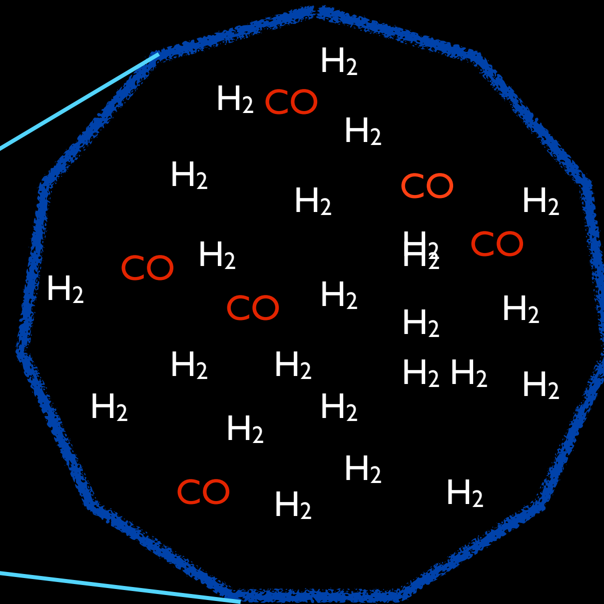
Ostriker & Shetty 2011
Shetty & Ostriker 2012

How do we get the X-axis?



Bolatto, Wolfire, Leroy ARA&A 2013



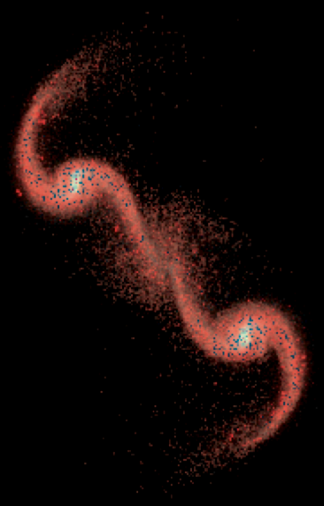


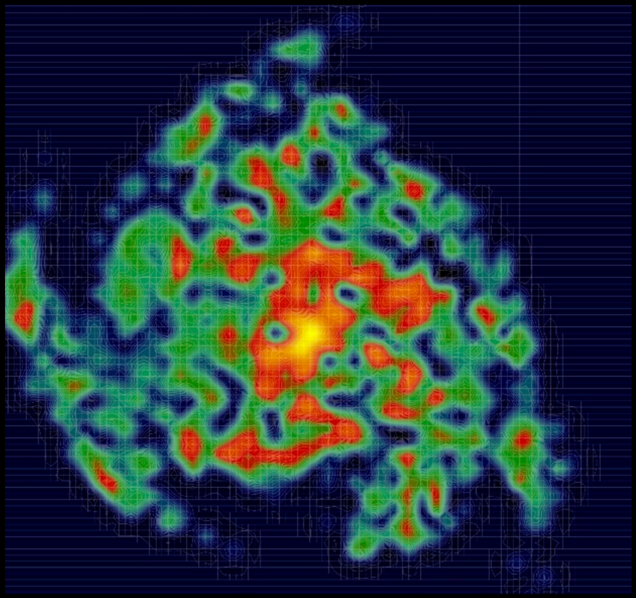
I. Assume GMC is viralized and use CO line width as mass measurement

II. Assume a DTG ratio and get dust masses

III. CR + H_2 --> γ-ray

$X_{co} = N_{H2}/I_{co} = 2\text{-}4 \times 10^{20}$ cm^{-2}/K-km s^{-1}



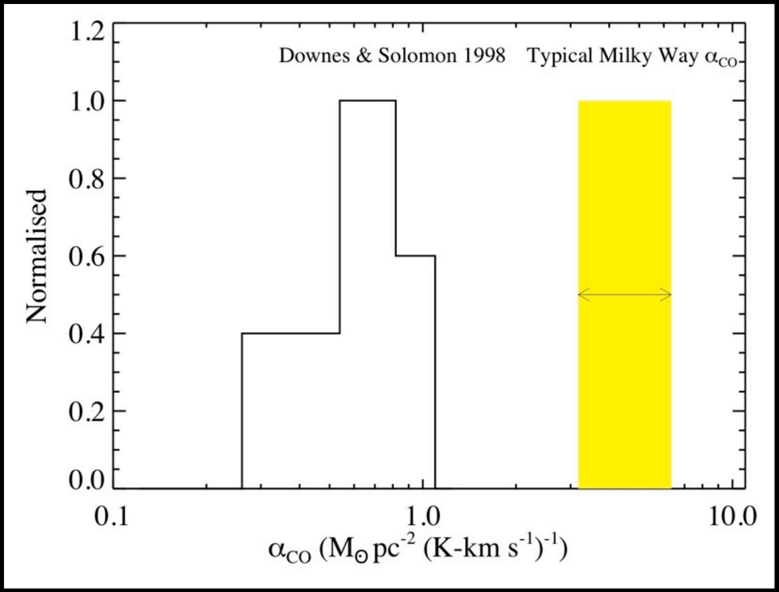


"Merger Value"

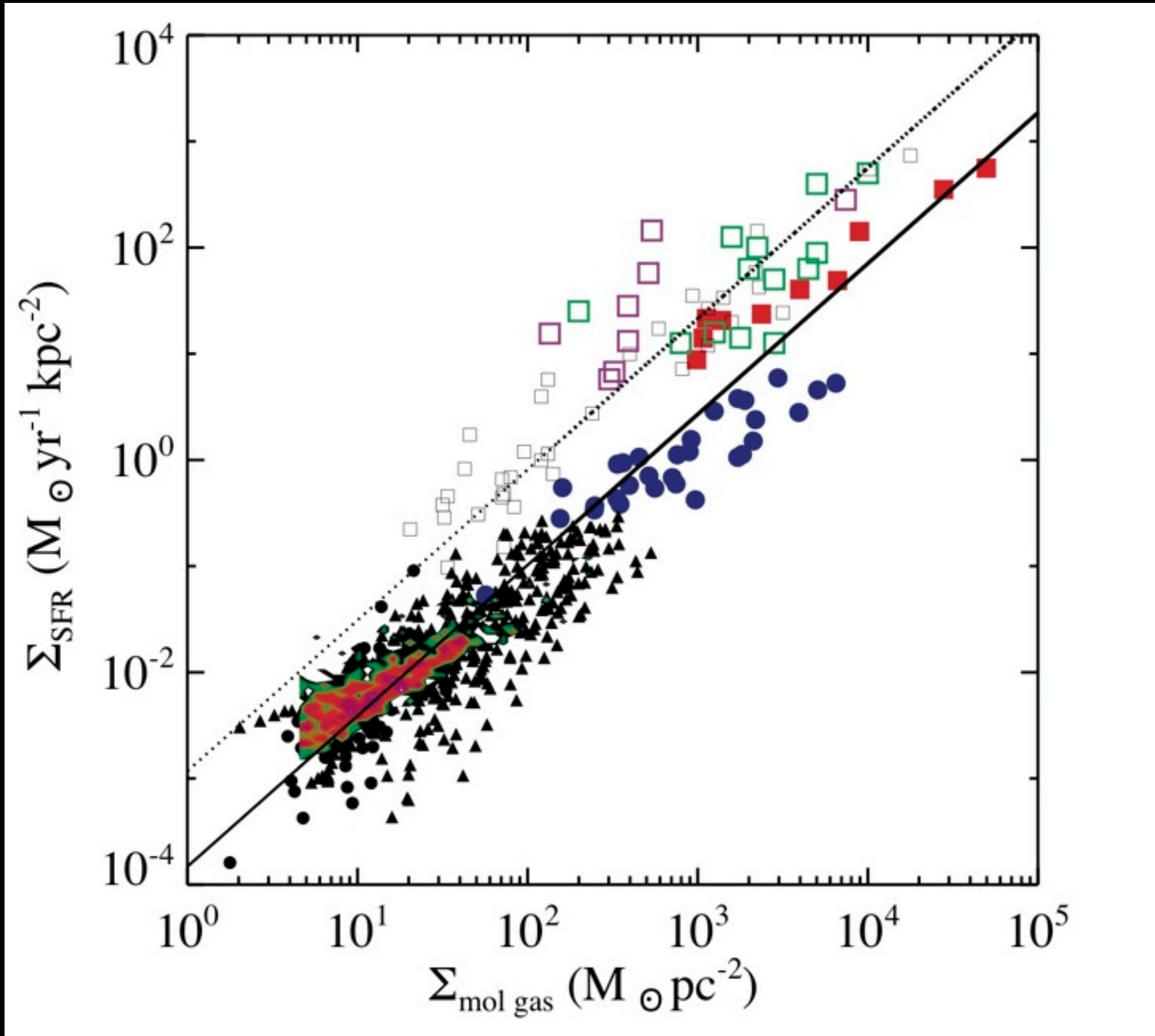
X_{CO} ~ few x10^{19} cm^{-2}/K km s^{-1}

"Disk Value"

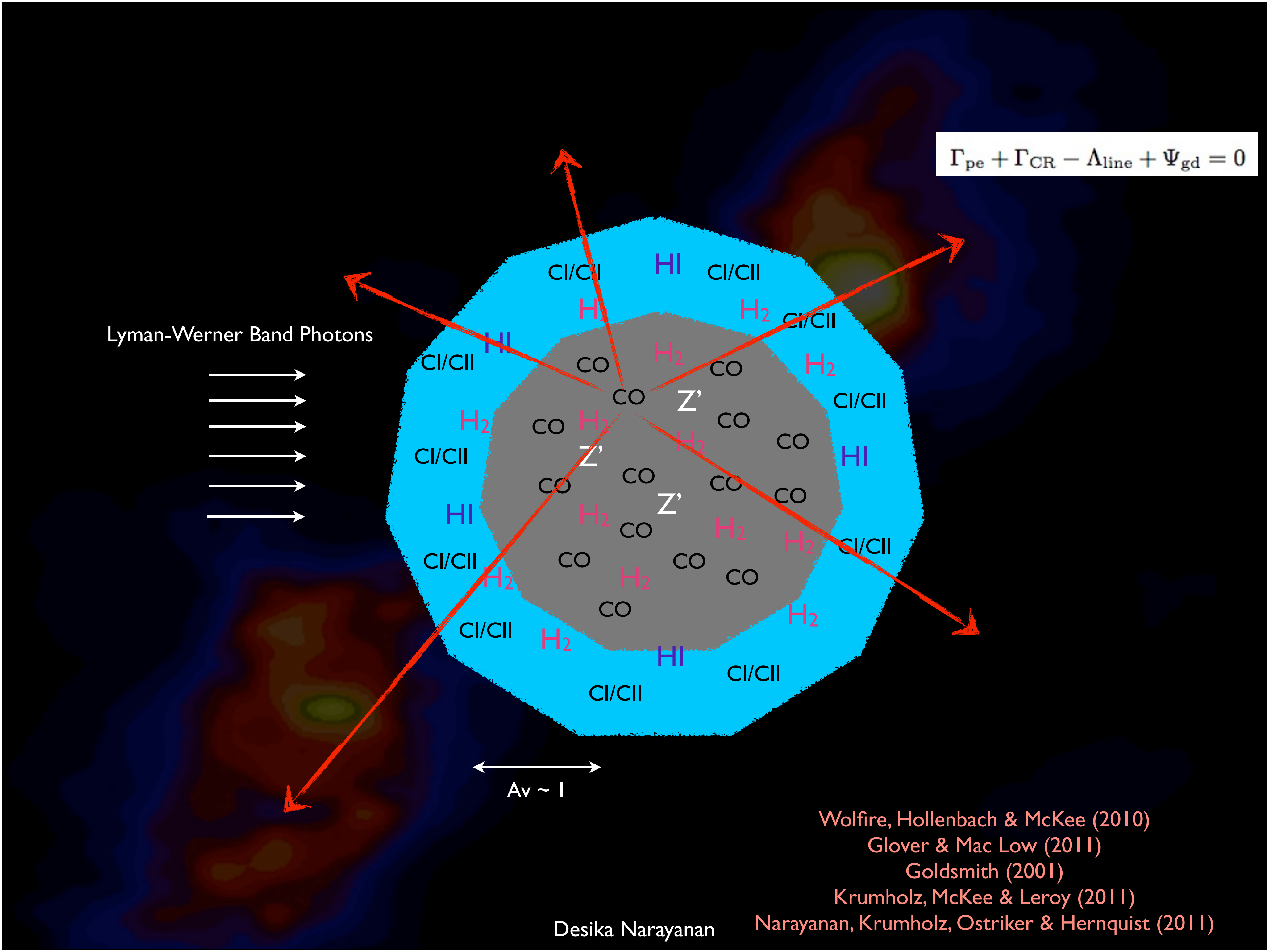
X_{CO} ~ 2x10^{20} cm^{-2}/K km s^{-1}



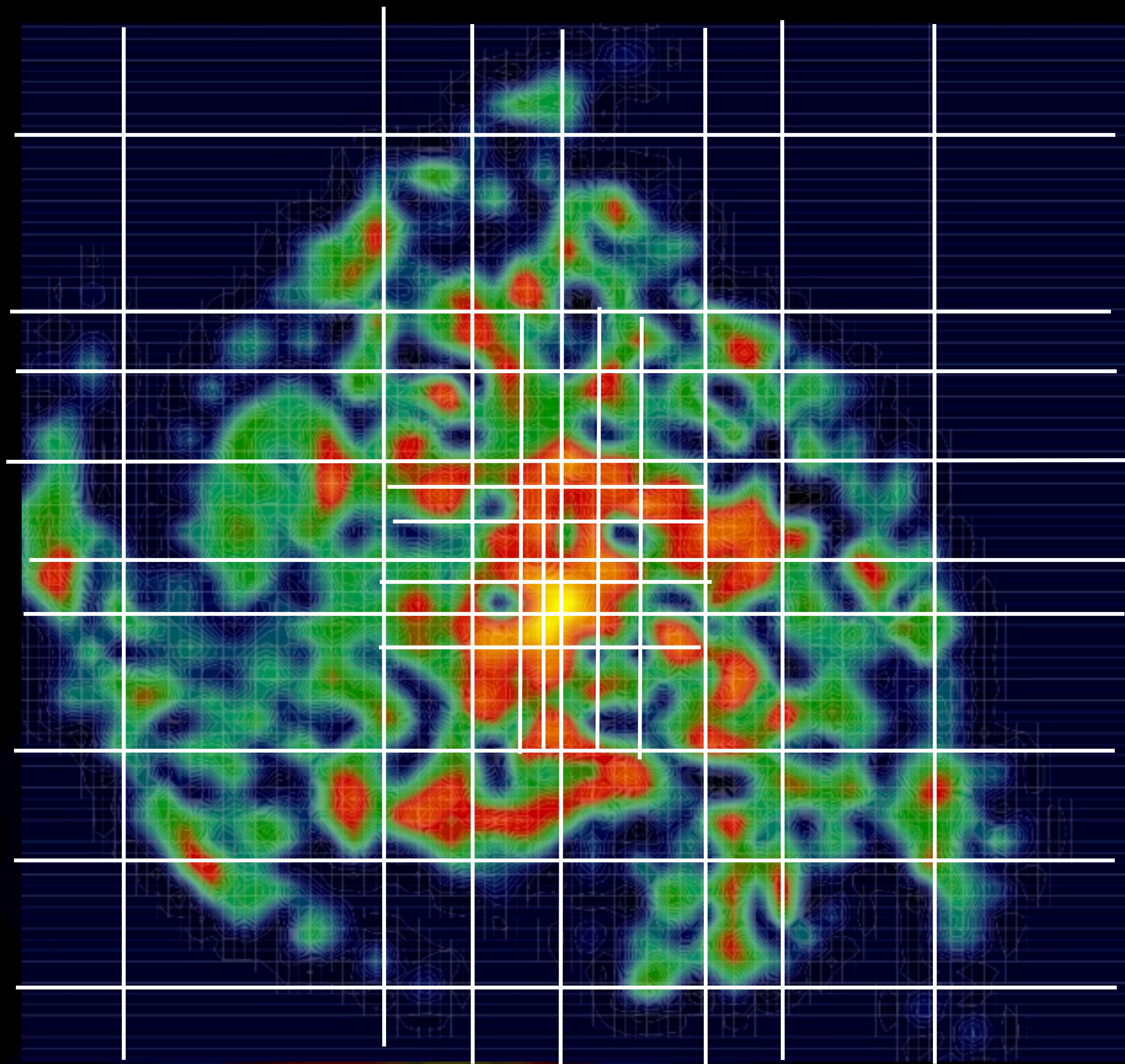
Narayanan (2011)

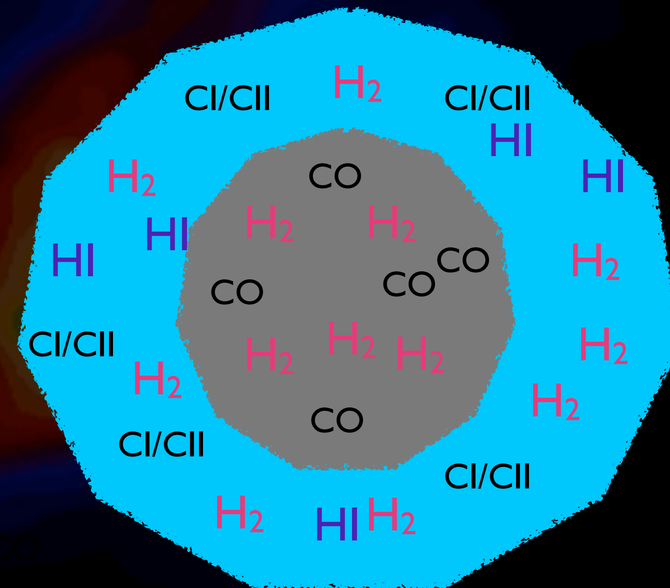


Daddi+ 2010; Genzel+ 2010



$\Gamma_{\rm pe} + \Gamma_{\rm CR} - \Lambda_{\rm line} + \Psi_{\rm gd} = 0$
Lyman-Werner Band Photons
CI/CII
HI
CI/CII
H_2
H_2
CI/CII
HI
CI/CII
CO
H_2
CO
H_2
CO
Z'
CI/CII
H_2
CO
H_2
CO
CI/CII
Z'
H_2
CO
HI
CO
CO
CO
CO
HI
Z'
H_2
CO
H_2
CI/CII
H_2
CI/CII
CO
CO
CO
H_2
H_2
CO
H_2
CI/CII
H_2
HI
CI/CII
CI/CII
Av ~ 1
Wolfire, Hollenbach & McKee (2010)
Glover & Mac Low (2011)
Goldsmith (2001)
Krumholz, McKee & Leroy (2011)
Narayanan, Krumholz, Ostriker & Hernquist (2011)
Desika Narayanan

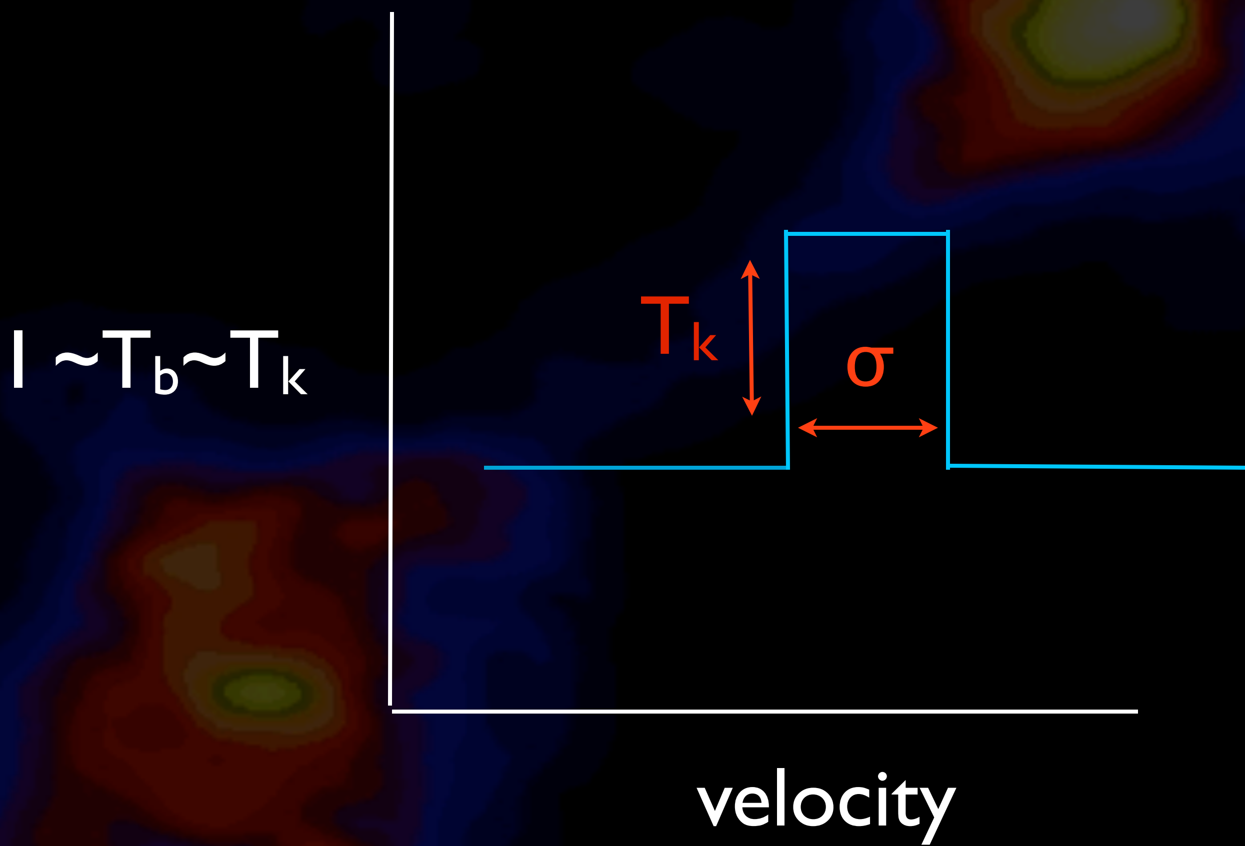




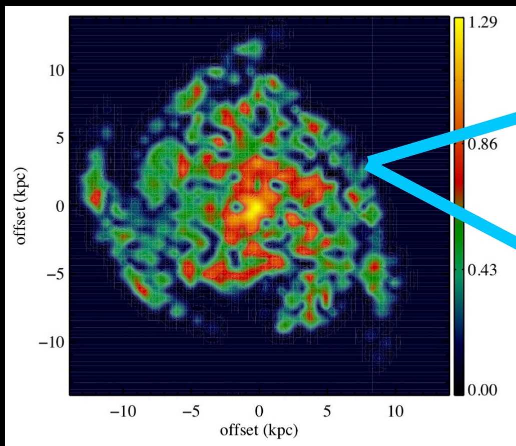
TURTLEBEACH; Narayanan et al. 2006,2008

The Physics Controlling X_{CO} 1: Gas Kinematics and Thermal Structure

$$X_{CO} = N_{H2}/W_{CO} \sim N_{H2}/(T^{*}\sigma)$$



$X_{CO} = N_{H2}/W_{CO} \sim N_{H2}/(T^*\sigma)$

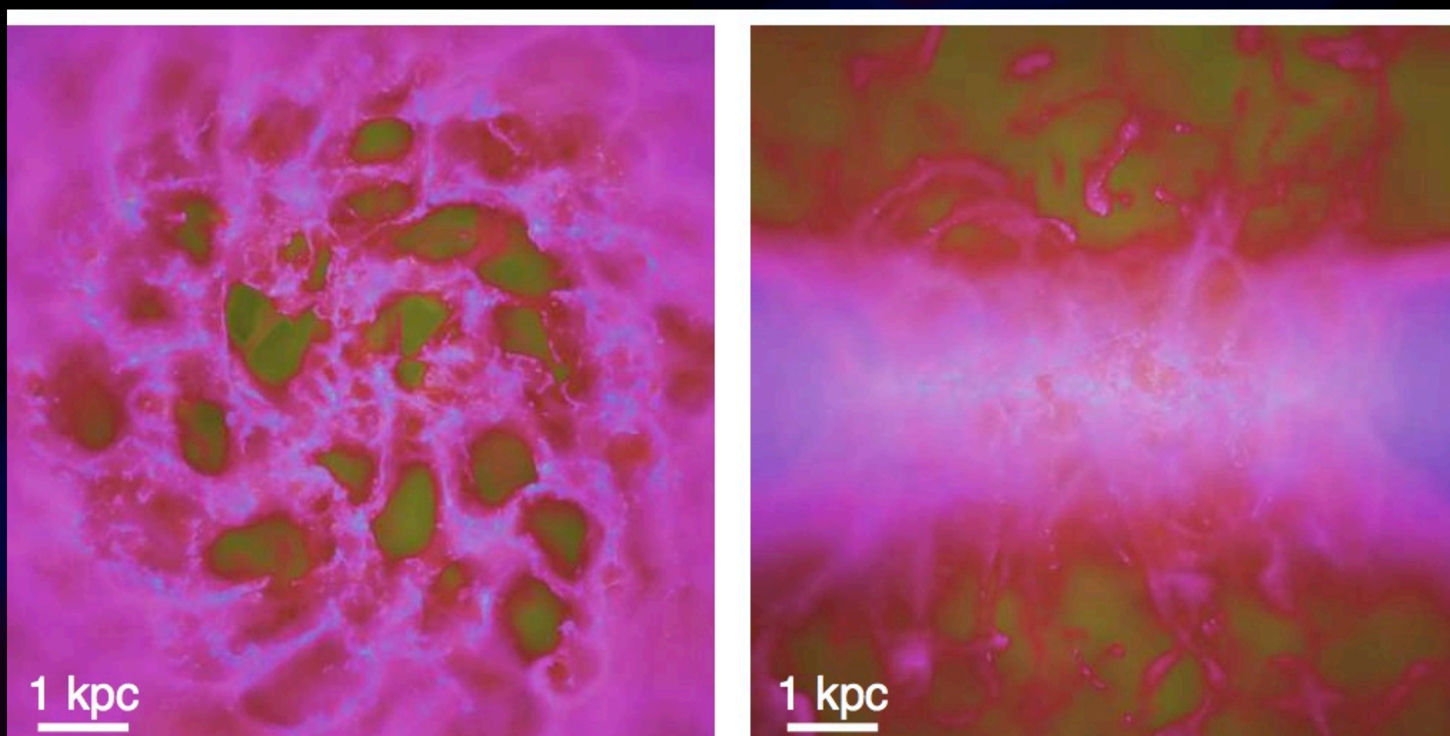


$N_{H2} \sim 10^{22}$ cm^{-2}

$T \sim 10$ K

$\sigma \sim 5$ km/s

$X_{CO} \sim 2\times10^{20}$ cm^{-2}/K km s^{-1}

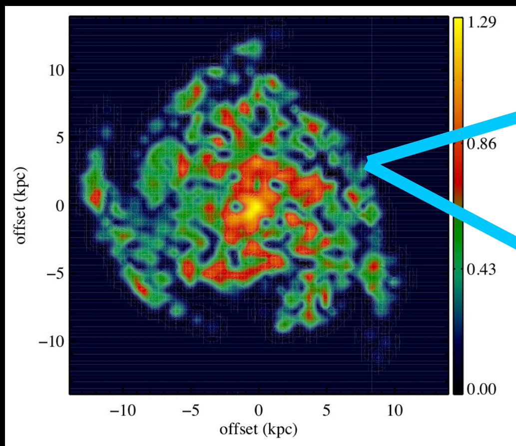


Narayanan, Krumholz, Ostriker & Hernquist 2011,2012

Narayanan & Hopkins (2012)

Shetty, Glover+ 2011,2012

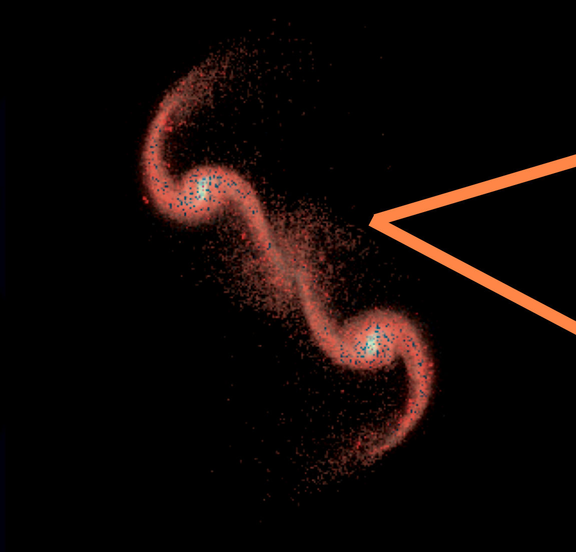
$X_{CO} = N_{H2}/W_{CO} \sim N_{H2}/(T^{*}\sigma)$



$N_{H2} \sim 10^{22}$ cm^{-2}
$T \sim 10$ K
$\sigma \sim 5$ km/s

Virialized GMCs unaffected by galactic environment

$X_{CO} \sim 2\mathrm{x}10^{20}$ cm^{-2}/K km s^{-1}



$N_{H2} \sim 10^{23}$ cm^{-2}
$T \sim 50$ K
$\sigma \sim 50$ km/s

non-virialized GMCs strongly affected by galactic environment

$X_{CO} \sim$ few $\mathrm{x}10^{19}$ cm^{-2}/K km s^{-1}

Narayanan, Krumholz, Ostriker & Hernquist 2011,2012
Narayanan & Hopkins (2012)

This results in a relation between $X_{\rm CO}$, Z', and $\langle W_{\rm CO}\rangle$:

$$X_{\rm CO} = \frac{6.75 \times 10^{20} \langle W_{\rm CO}\rangle^{-0.32}}{Z'^{0.65}}$$

Surface Brightness (K-km/s)

(units of $Z_\odot$)

~~"merger Xco"~~
~~"disk Xco"~~

Narayanan, Krumholz, Ostriker, Hernquist 2011,2012

Narayanan, Krumholz, Ostriker & Hernquist 2011,2012

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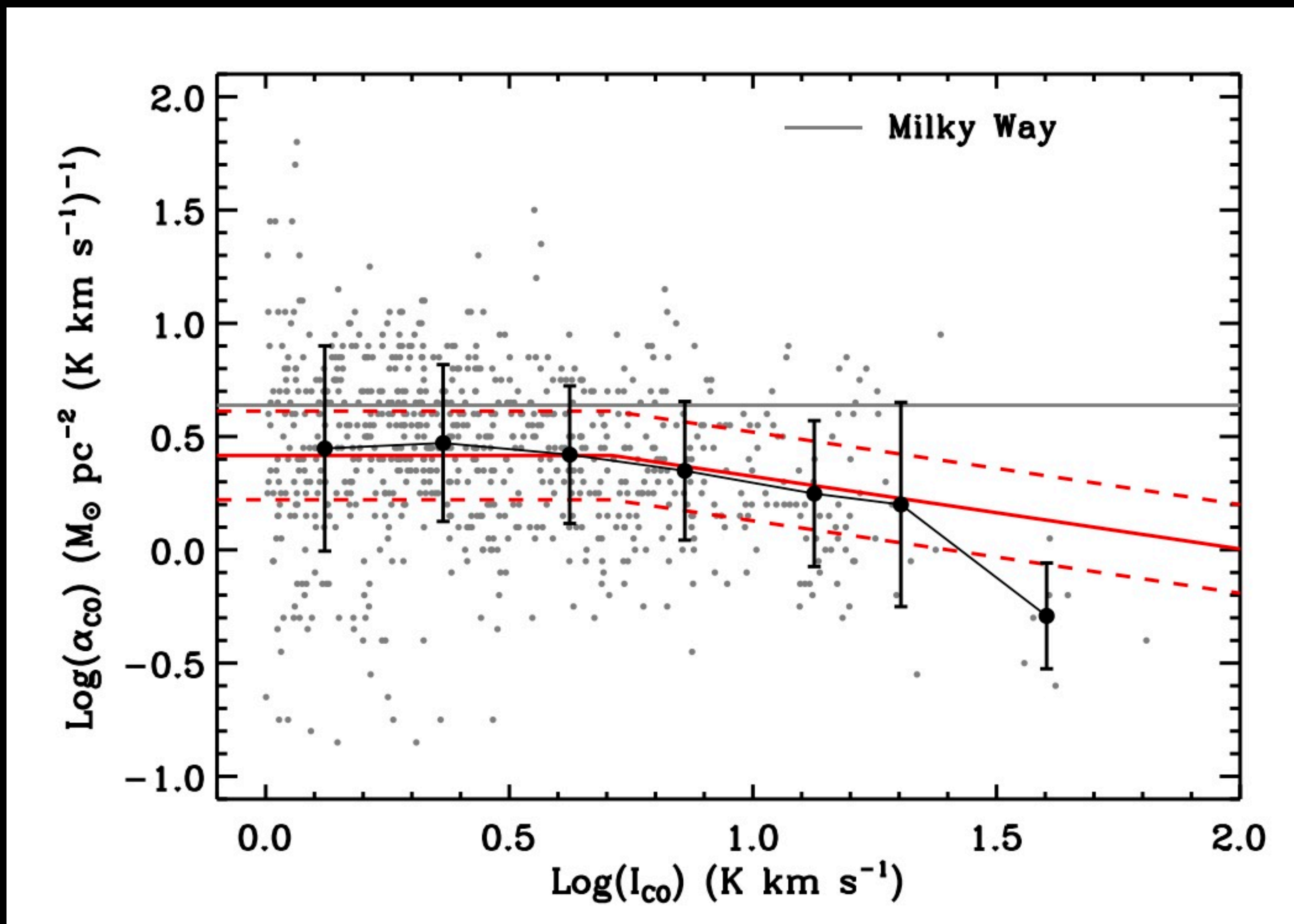

Sandstrom et al. (2012)

Narayanan, Krumholz, Ostriker, Hernquist 2011,2012

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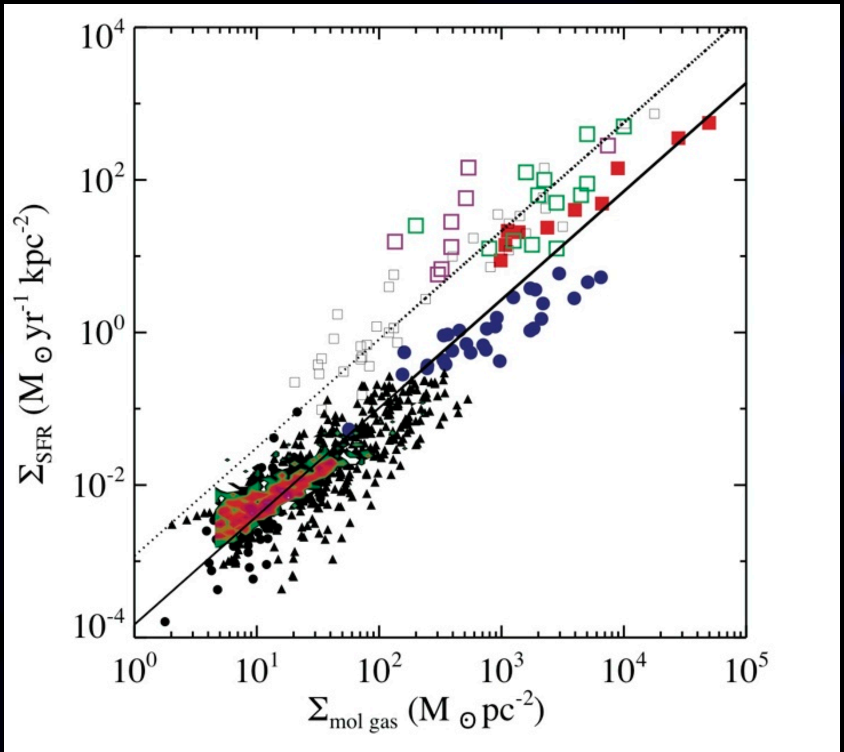

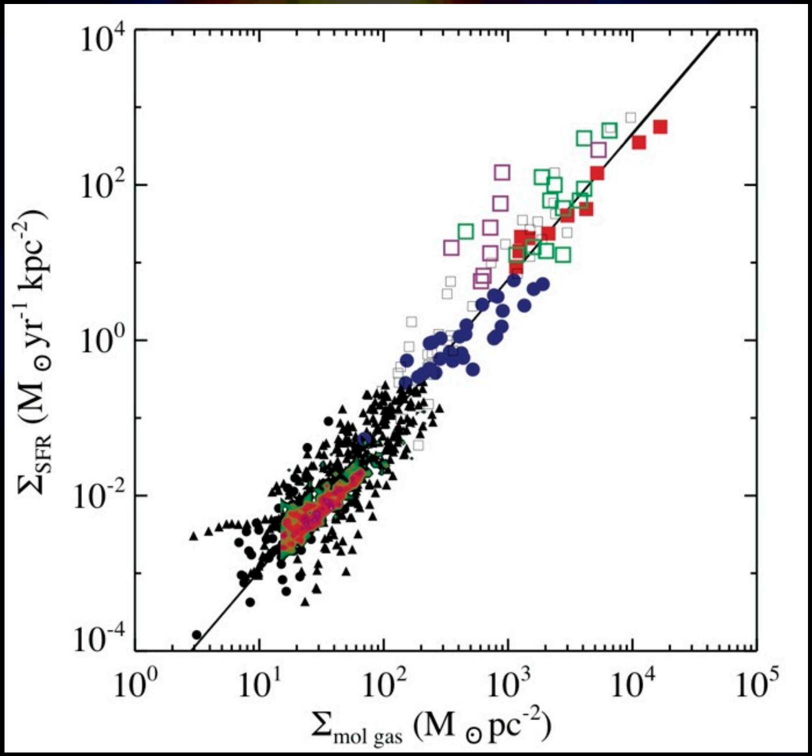

Daddi et al. 2010
Genzel et al. 2010

Narayanan, Krumholz, Ostriker, Hernquist 2012

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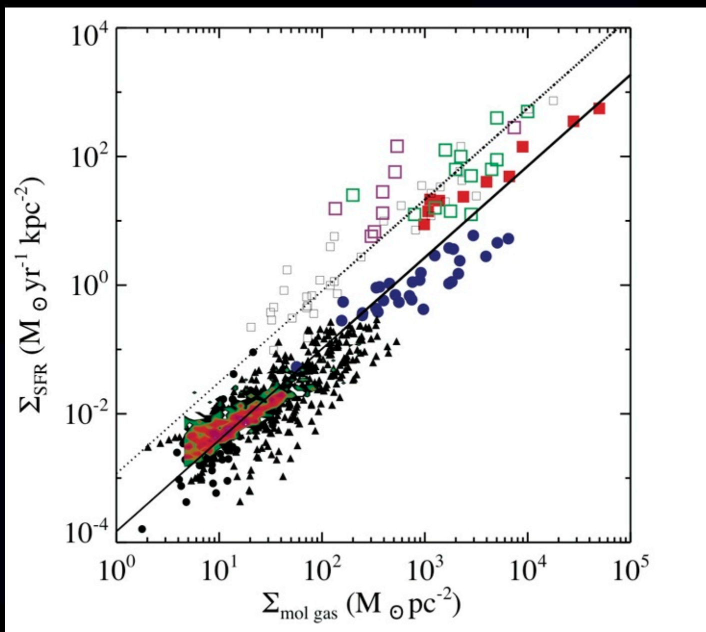
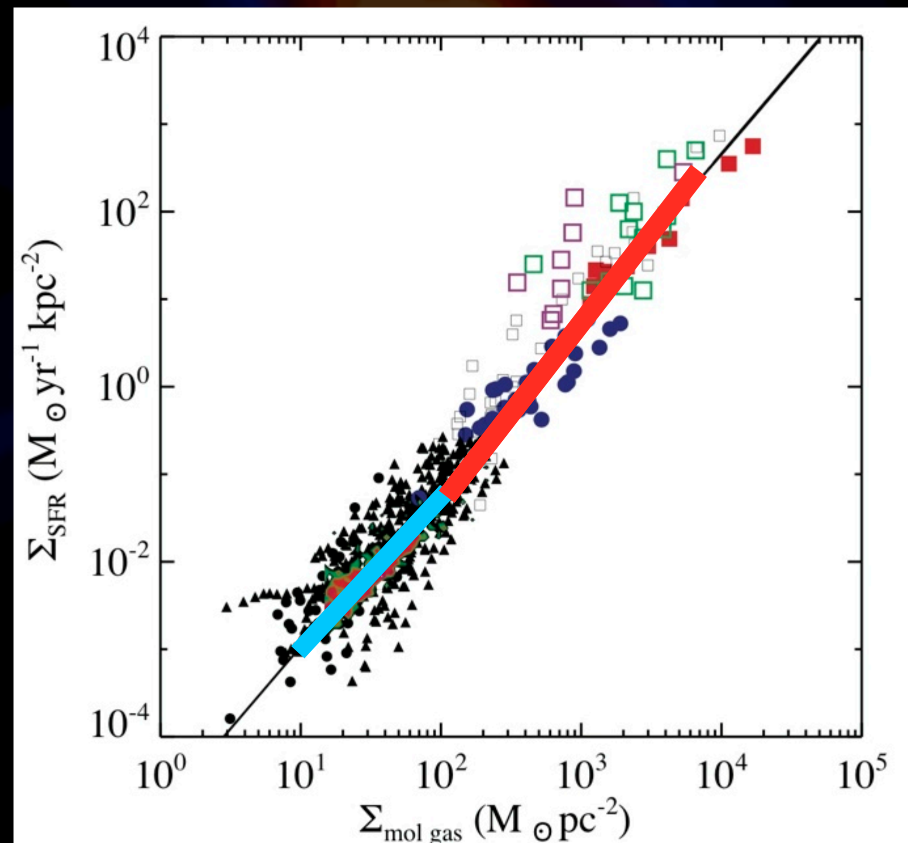


N~1.2-1.5



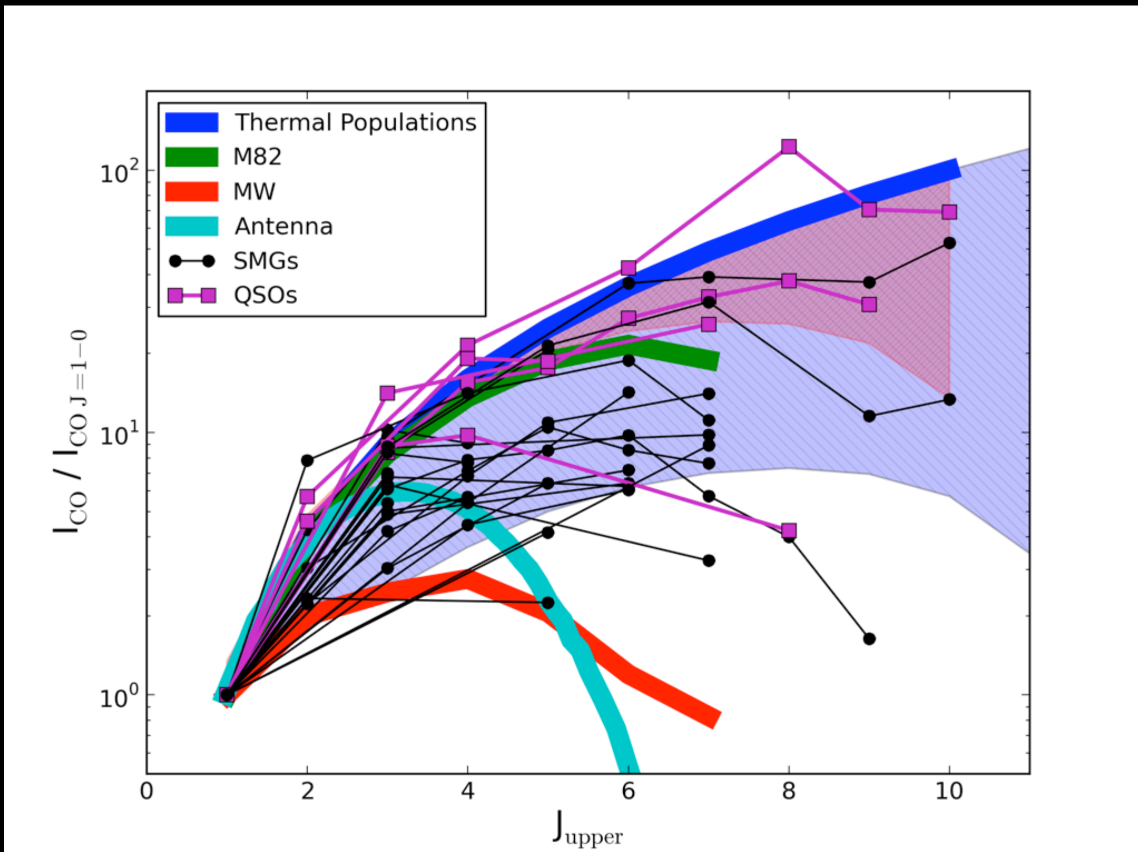
N~1.8

$\Sigma_{\rm SFR} \sim \Sigma_{\rm H2}$ ($\Sigma_{\rm H2} \lesssim 100\ M_\odot\ {\rm pc}^{-2}$)

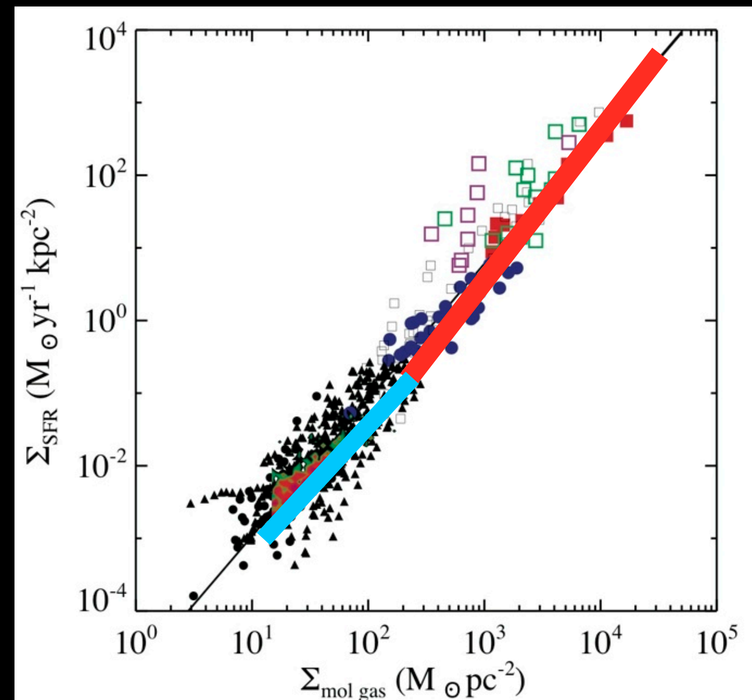
$\Sigma_{\rm SFR} \sim \Sigma_{\rm H2}^2$ ($\Sigma_{\rm H2} \gtrsim 100\ M_\odot\ {\rm pc}^{-2}$)

(Ostriker & Shetty, 2011)

Ways Forward: CO Excitation Modeling

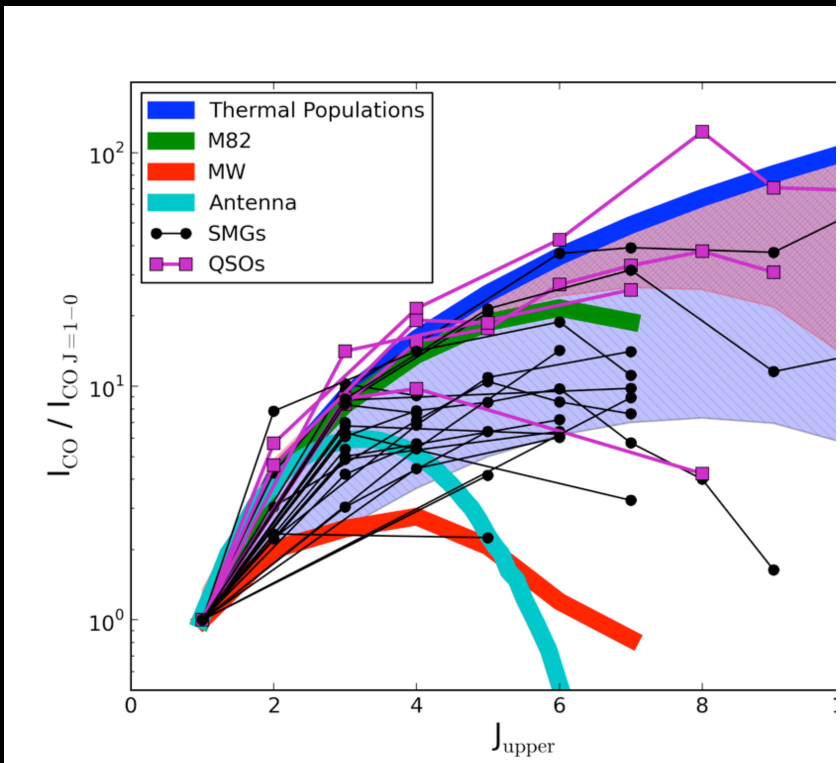


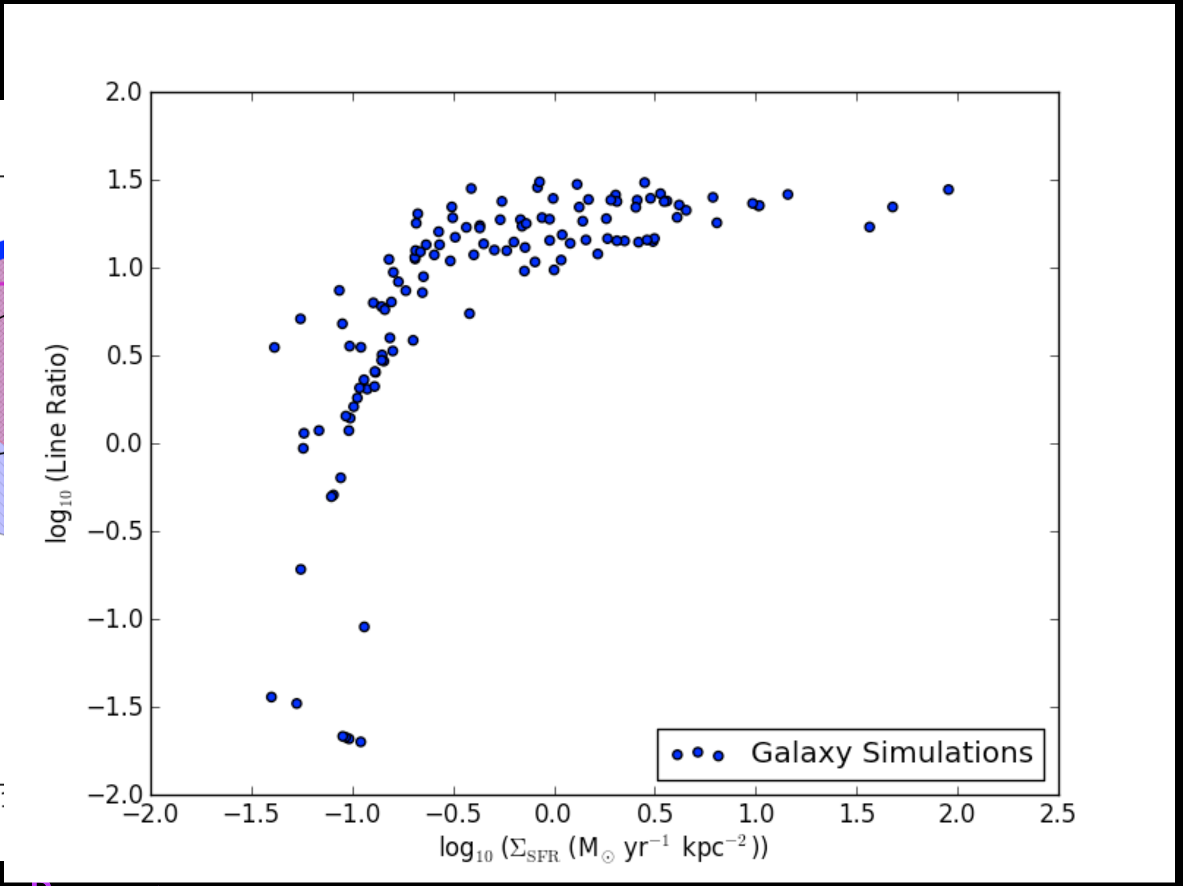
Cooray, Casey & Narayanan 2013 Physics Reports



Ways Forward: CO Excitation Modeling

CO (J= 6-5) line ratio vs. $\sum_{SFR}$



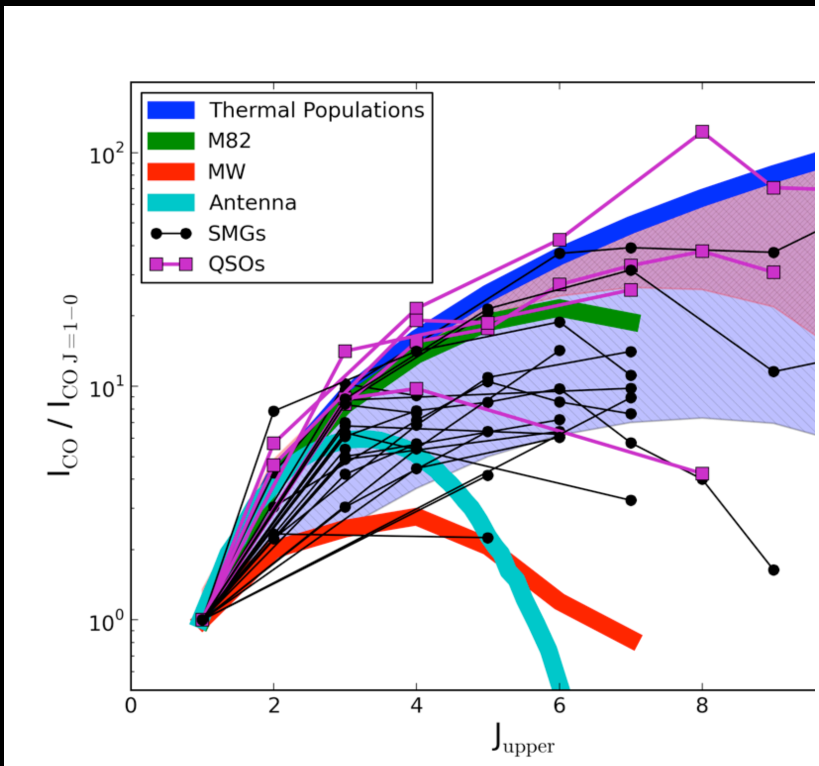


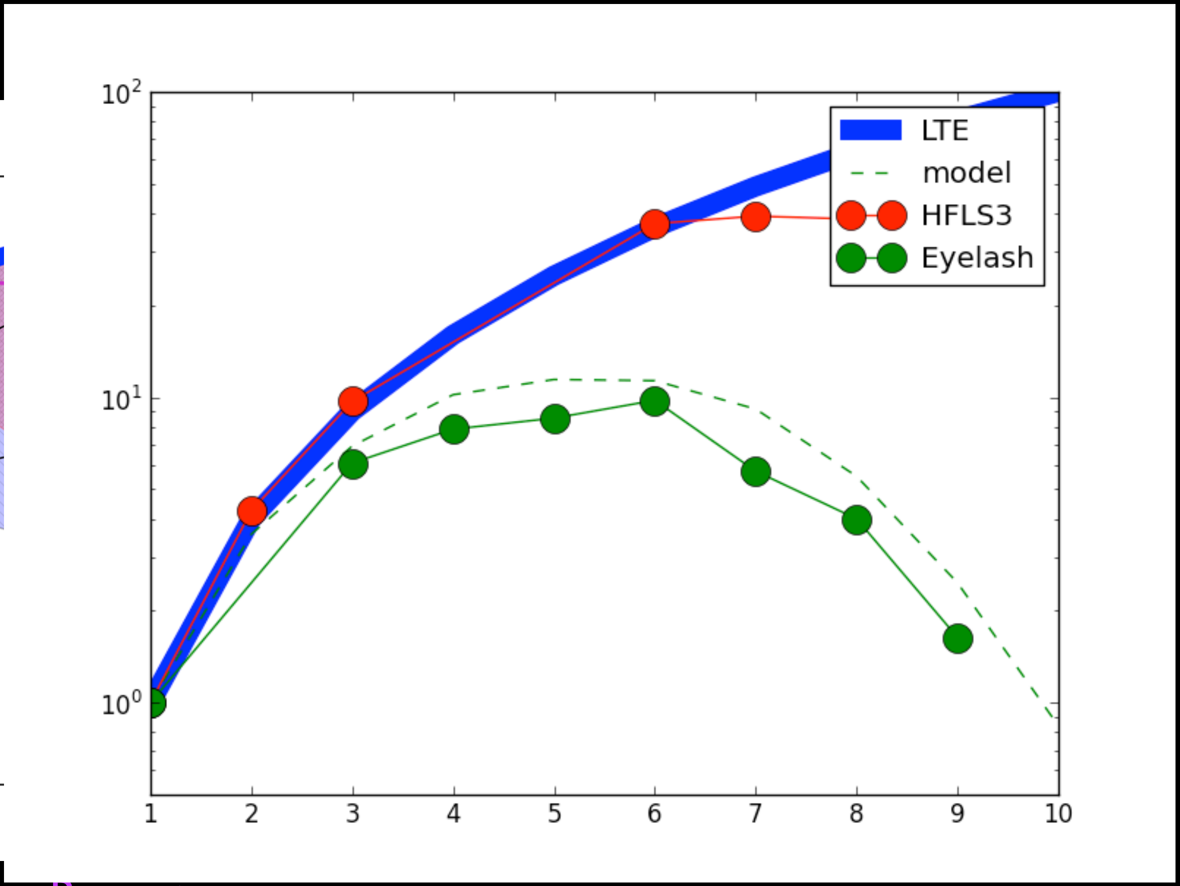
Cooray, Casey & Narayanan 2013 Physics Reports

Narayanan & Krumholz (in progress)

Ways Forward: CO Excitation Modeling

Example CO SLED: Eyelash (Lensed SMG at z~2)





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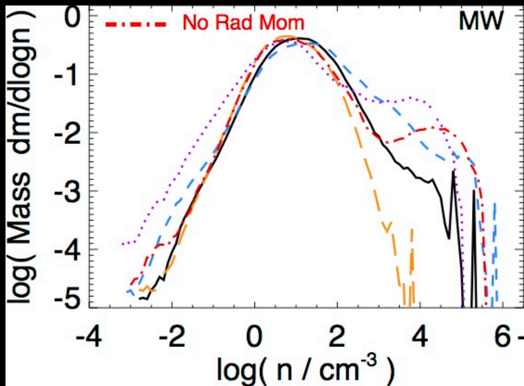
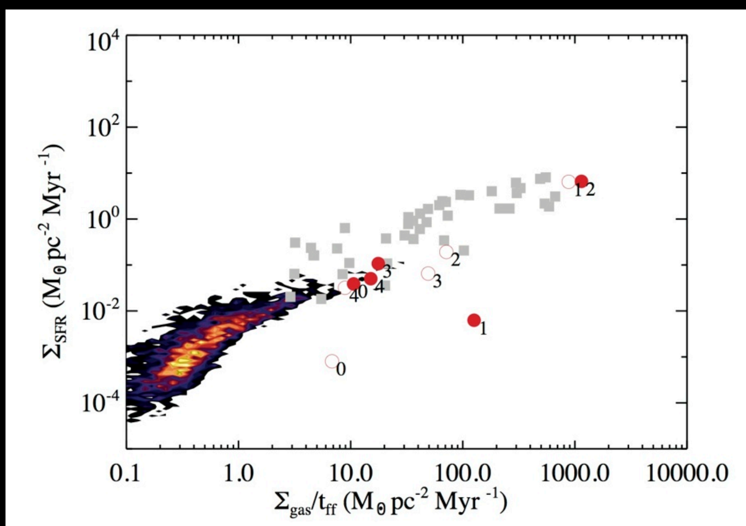
Narayanan & Krumholz (in progress)

Summary



1. Dense gas tail of density PDF strongly dependent on feedback strength - sets the SFE of galaxies



2. GMCs dominated by radiative feedback have a natural life cycle that limits the $\Sigma_{H2} \sim 1000\ M_\odot\ pc^{-2}$

This results in a relation between $X_{\rm CO}$, Z', and $\langle W_{\rm CO}\rangle$:

$$X_{\rm CO} = \frac{6.75 \times 10^{20} \langle W_{\rm CO}\rangle^{-0.32}}{Z'^{0.65}}$$

With a smoothly varying model for Xco, at face value, KS relation has index ~2 (modulo excitation effects)