[CII] during the Epoch of Reionization

Desika Narayanan
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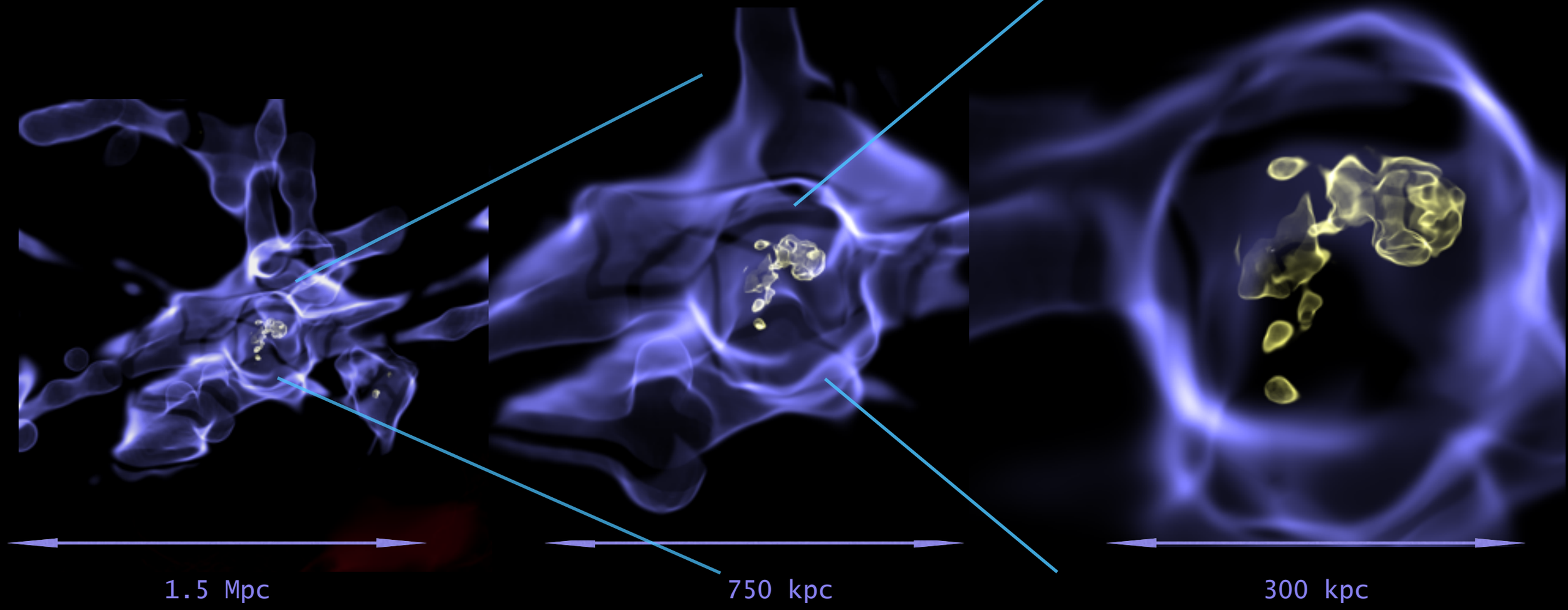
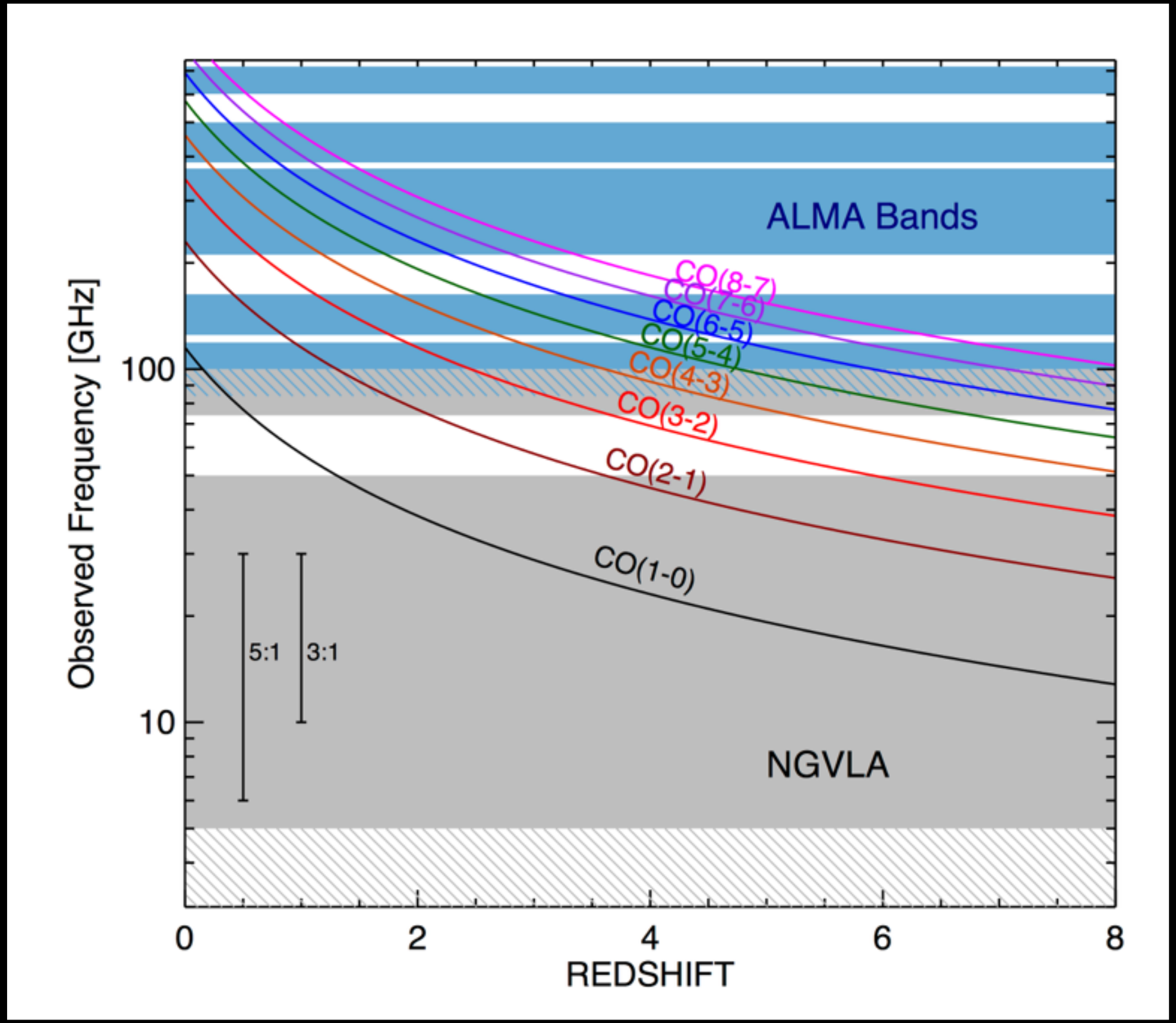


With Mark Krumholz (ANU) and Romeel Davé (UWC)

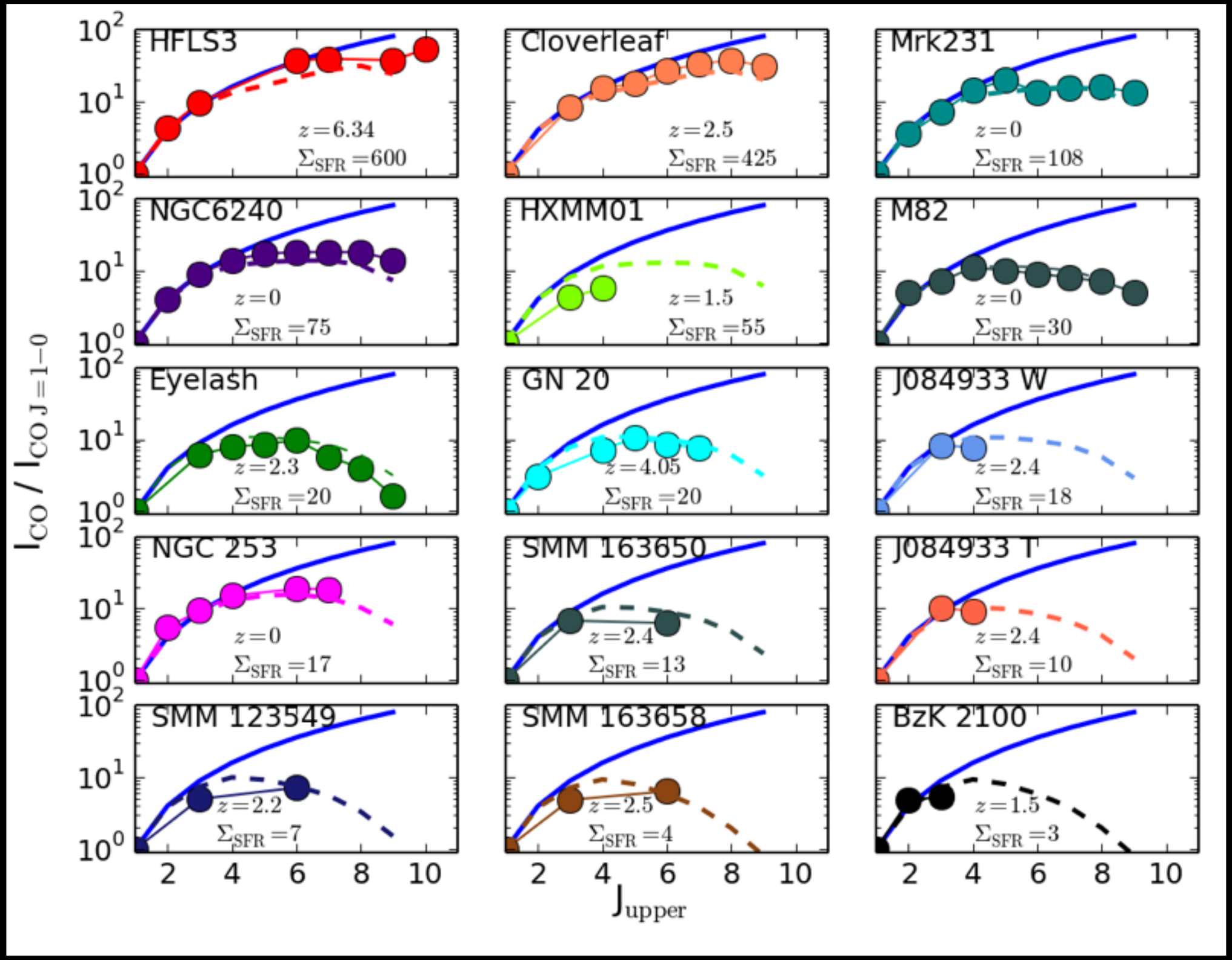
ALMA wrong frequencies for CO 1-0 during EoR



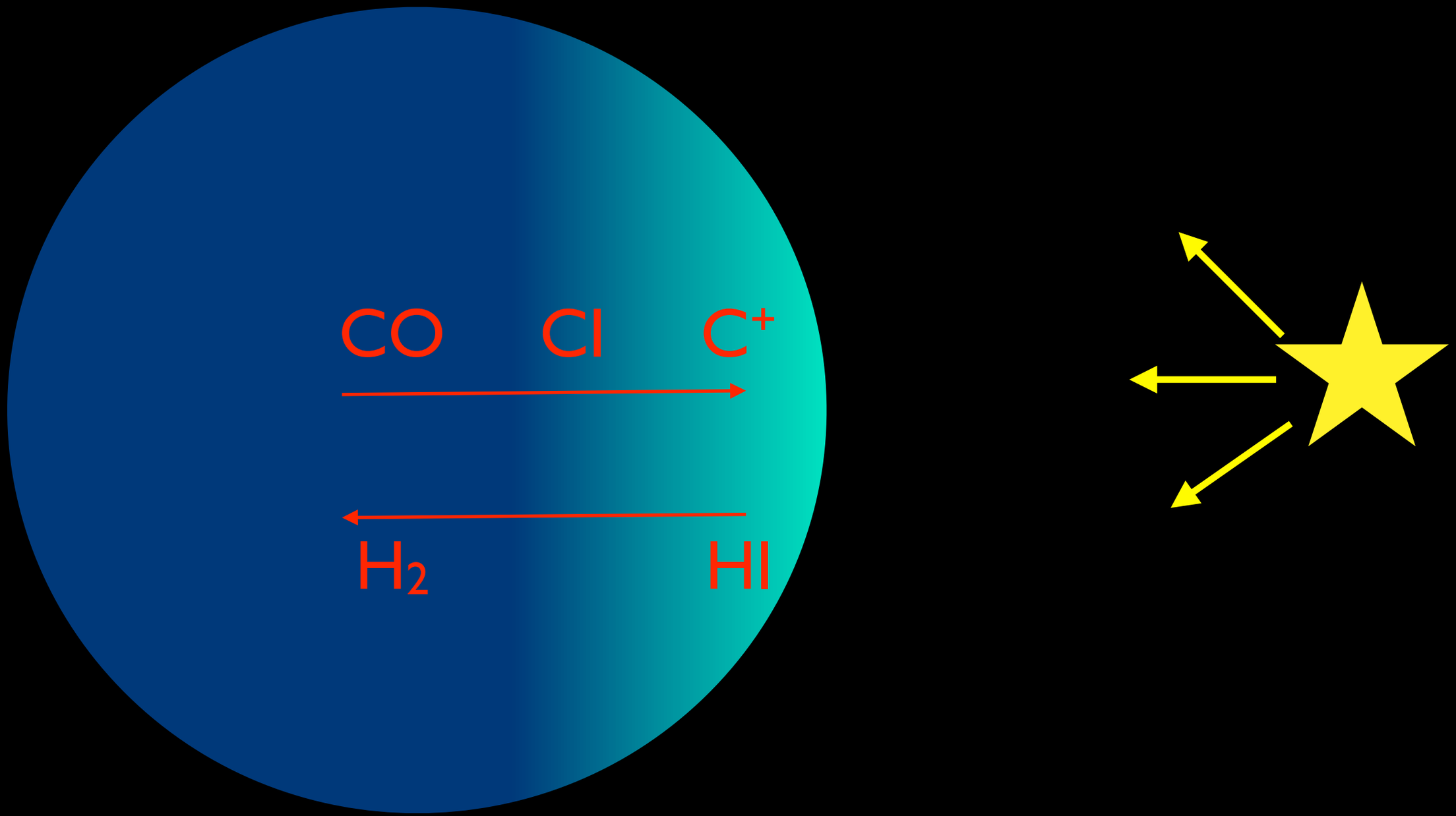
Casey et al. + SWG 3 2015 — NGVLA Memo No. 8

$$\log_{10}\left[\frac{I_{IJ}}{I_{1-0}}\right] = A \times \left[\log_{10}\langle\Sigma_{\rm SFR}\rangle - \chi\right]^{\beta} + C$$

Narayanan & Krumholz 2014



The physics (and chemistry) of C^+



how do you destroy CO and make C^+?

Reaction	Rate Coefficient
Cosmic Ray Reactions [s^{-1} molecule^{-1}]:	
$cr + H \rightarrow H^+ + e$	ζ
$cr + H_2 \rightarrow H_3^+ + e + H + cr$	2ζ
$cr + He \rightarrow He^+ + e + cr$	1.1ζ
Photoreactions [s^{-1} molecule^{-1}]:	
$\gamma + H_2 \rightarrow 2\ H$	$5.6 \times 10^{-11} \chi_{\rm FUV} f_{\rm shield}(N_{\rm H_2}) e^{-3.74 A_V}$
$\gamma + CO \rightarrow C + O$	$2 \times 10^{-10} \chi_{\rm FUV} f_{\rm shield}(N_{\rm CO}, N_{\rm H_2}) e^{-3.53 A_V}$
$\gamma + C \rightarrow C^+ + e$	$3 \times 10^{-10} \chi_{\rm FUV} e^{-3 A_V}$
$\gamma + CH_x \rightarrow C + H$	$1 \times 10^{-9} \chi_{\rm FUV} e^{-1.5 A_V}$
$\gamma + OH_x \rightarrow O + H$	$5 \times 10^{-10} \chi_{\rm FUV} e^{-1.7 A_V}$
$\gamma + M \rightarrow M^+ + e$	$3.4 \times 10^{-10} \chi_{\rm FUV} e^{-1.9 A_V}$
$\gamma + HCO^+ \rightarrow CO + H$	$1.5 \times 10^{-10} \chi_{\rm FUV} e^{-2.5 A_V}$
Ion-Neutral Reactions [$cm^3\ s^{-1}$ molecule^{-1}]:	
$H_3^+ + CI \rightarrow CH_x + H_2$	2×10^{-9}
$H_3^+ + OI \rightarrow OH_x + H_2$	8×10^{-10}
$H_3^+ + CO \rightarrow HCO^+ + H_2$	1.7×10^{-9}
$He^+ + H_2 \rightarrow He + H + H^+$	7×10^{-15}
$He^+ + CO \rightarrow C^+ + O + He$	$1.4 \times 10^{-9} / \sqrt{T/300}$
$C^+ + H_2 \rightarrow CH_x + H$	4×10^{-16}
$C^+ + OH_x \rightarrow HCO^+$	1×10^{-9}

Narayanan & Krumholz 2016
Glover & Clark 2010

n_H

cosmic rays

CO CI C^+

H_2 HI

Av

FUV radiation

Calculating Thermo-Chemical Equilibrium

Ion-Neutral Reactions [$cm^3\ s^{-1}$ $molecule^{-1}$]:	
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$C^+ + H_2 \rightarrow CH_x + H$	4×10^{-16}
$C^+ + OH_x \rightarrow HCO^+$	1×10^{-9}
Neutral-Neutral Reactions [$cm^3\ s^{-1}$ $molecule^{-1}$]:	
$OI + CH_x \rightarrow CO + H$	2×10^{-10}
$CI + OH_x \rightarrow CO + H$	$5 \times 10^{-12}\sqrt{T}$
Recombinations and Charge-Transfers [$cm^3\ s^{-1}$ $molecule^{-1}$]:	
$He^+ + e \rightarrow He + \gamma$	$1 \times 10^{-11}/\sqrt{T} \times$ $(11.19 - 1.676 \times \log_{10}(T) - 0.2852 \times \log_{10}(T^2) + 0.04433 \times \log_{10}(T^3))$
$H_3^+ + e \rightarrow H_2 + H$	$2.34 \times 10^{-8}(T/300)^{-0.52}$
$H_3^+ + e \rightarrow 3H$	$4.36 \times 10^{-8}(T/300)^{-0.52}$
$C^+ + e \rightarrow CI + \gamma$	$4.67 \times 10^{-12}(T/300)^{-0.6}$
$HCO^+ + e \rightarrow CO + H$	$2.76 \times 10^{-7}(T/300)^{-0.64}$
$M^+ + e \rightarrow M + \gamma$	$3.8 \times 10^{-10}T^{-0.65}$
$H_3^+ + M \rightarrow M + \gamma$	2×10^{-9}

$$\Gamma_{PE} + \Gamma_{CR} - \Lambda_{line} + \Psi_{gd} = 0$$

SFR SFR SFR ($n_H > 10^4$ cm^{-3})

Narayanan & Krumholz 2016

Calculating Thermo-Chemical Equilibrium

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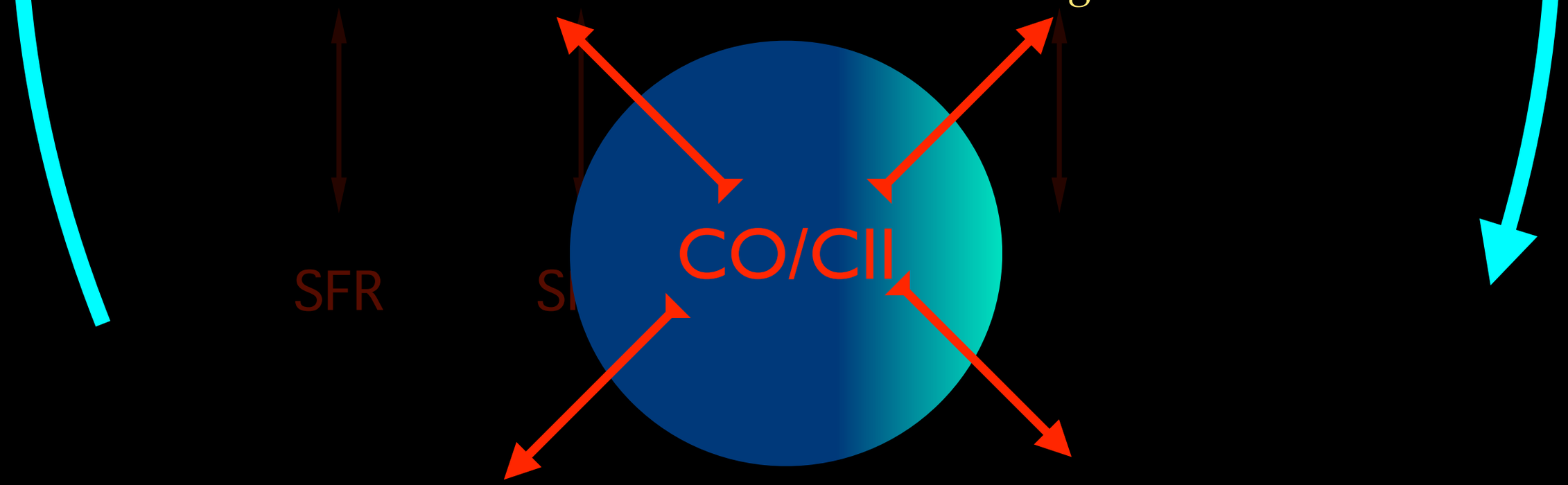
$$\Gamma_{PE} + \Gamma_{CR} - \Lambda_{line} + \Psi_{gd} = 0$$



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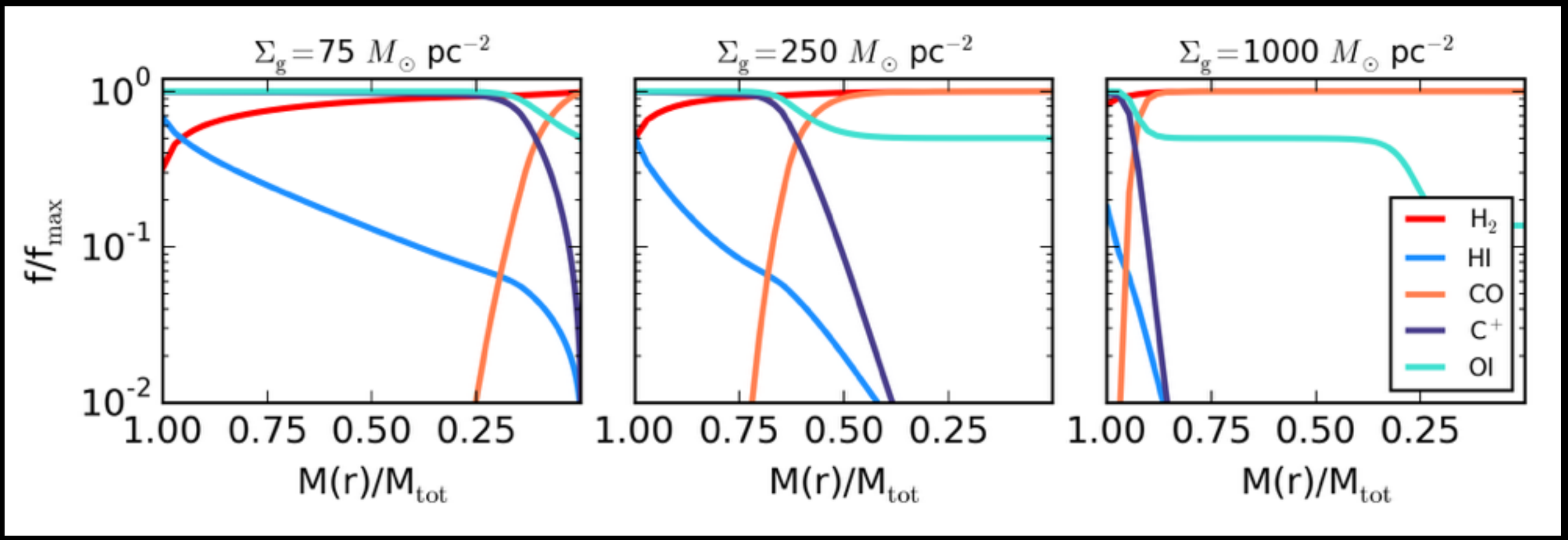
Building our intuition before going to high-z

MW-like | LIRG-like | Center of Arp 220-like



cloud surface ⟶ cloud interior

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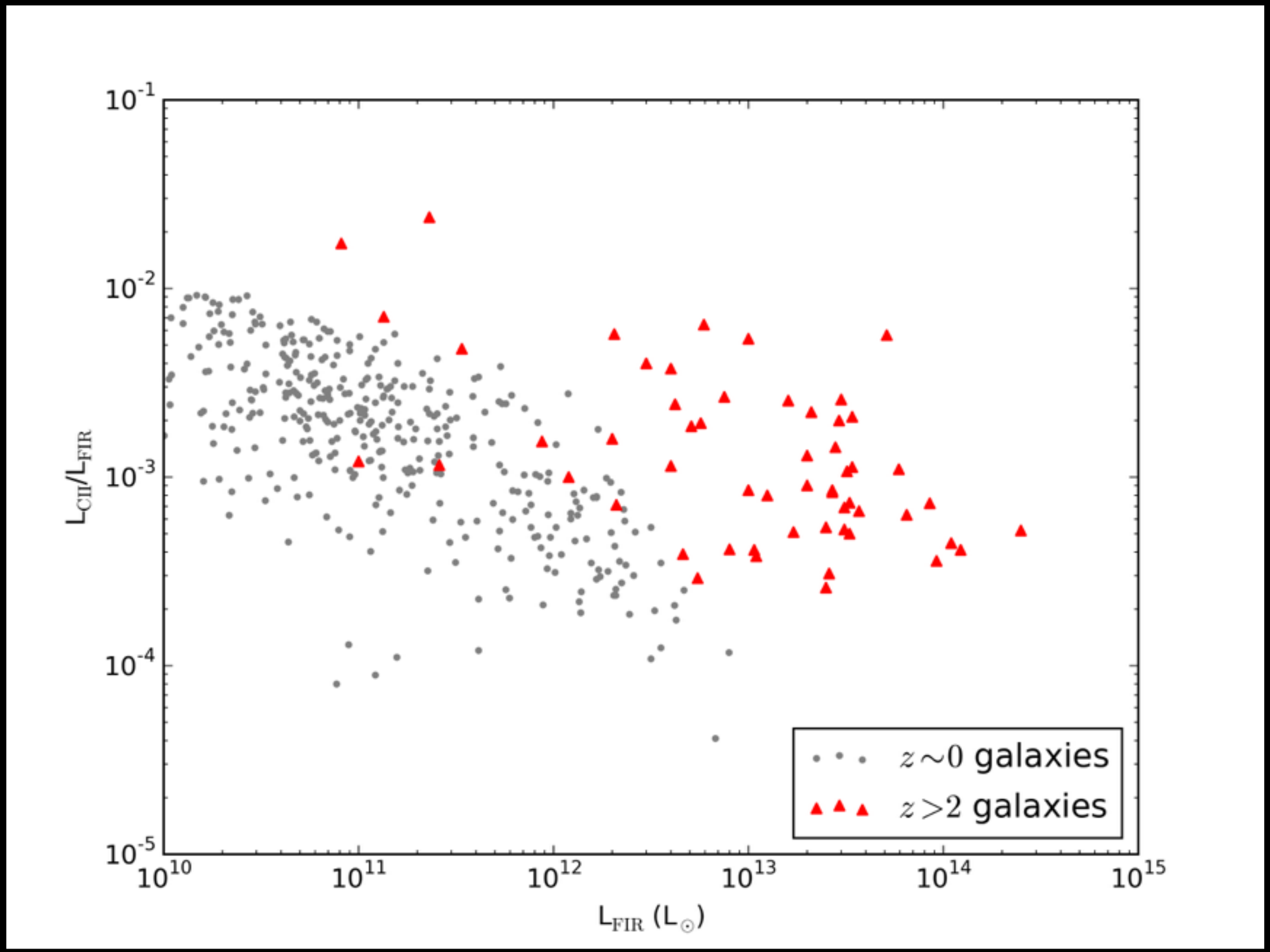
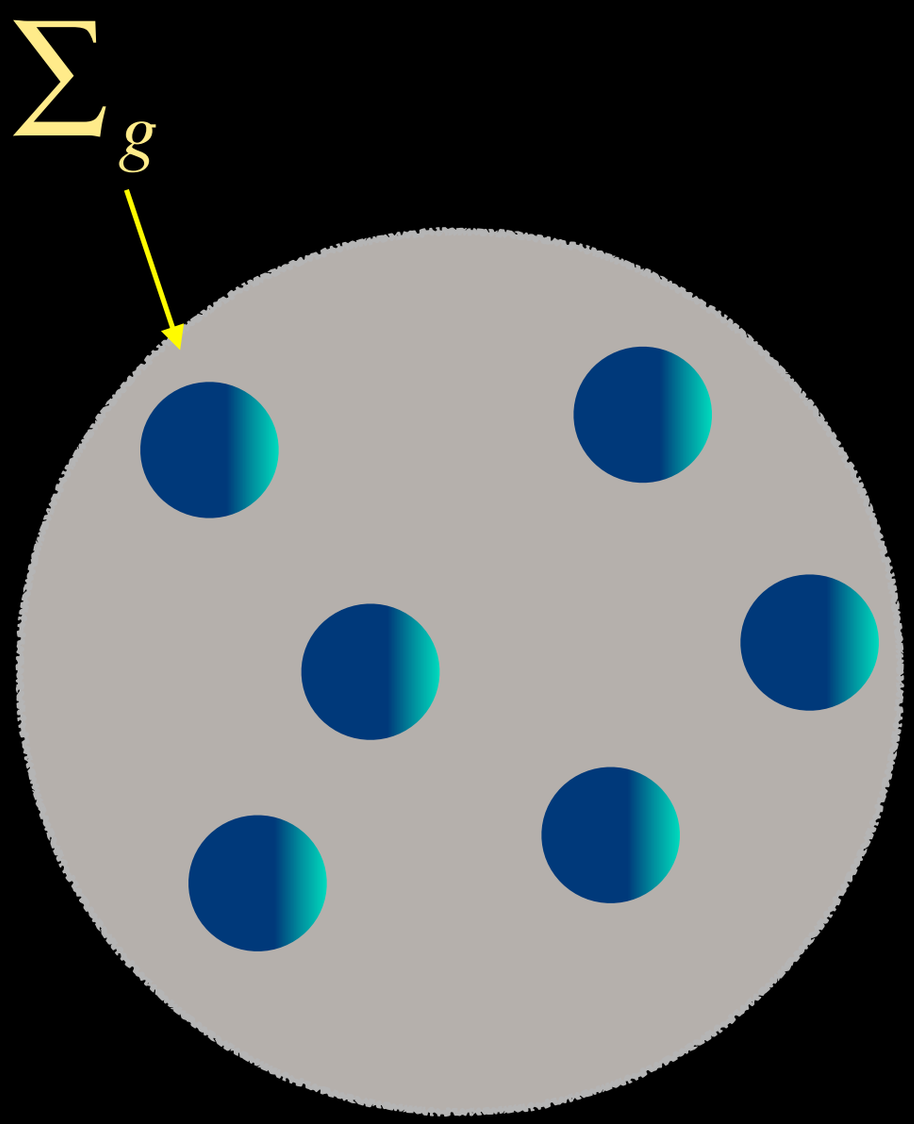
The [CII]-FIR Deficit in Luminous Galaxies



data compiled in Casey, Narayanan & Cooray 2014

Building a Galaxy full of Clouds



Theory

$$\Sigma_{SFR} = \varepsilon_{ff} \frac{\Sigma_g}{t_{ff}}$$

$$t_{ff} = \sqrt{\frac{3\pi}{32 G \rho_{H2}}}$$

$$\alpha_{vir} = \frac{5\sigma^2 R}{G M_c} \approx 1$$

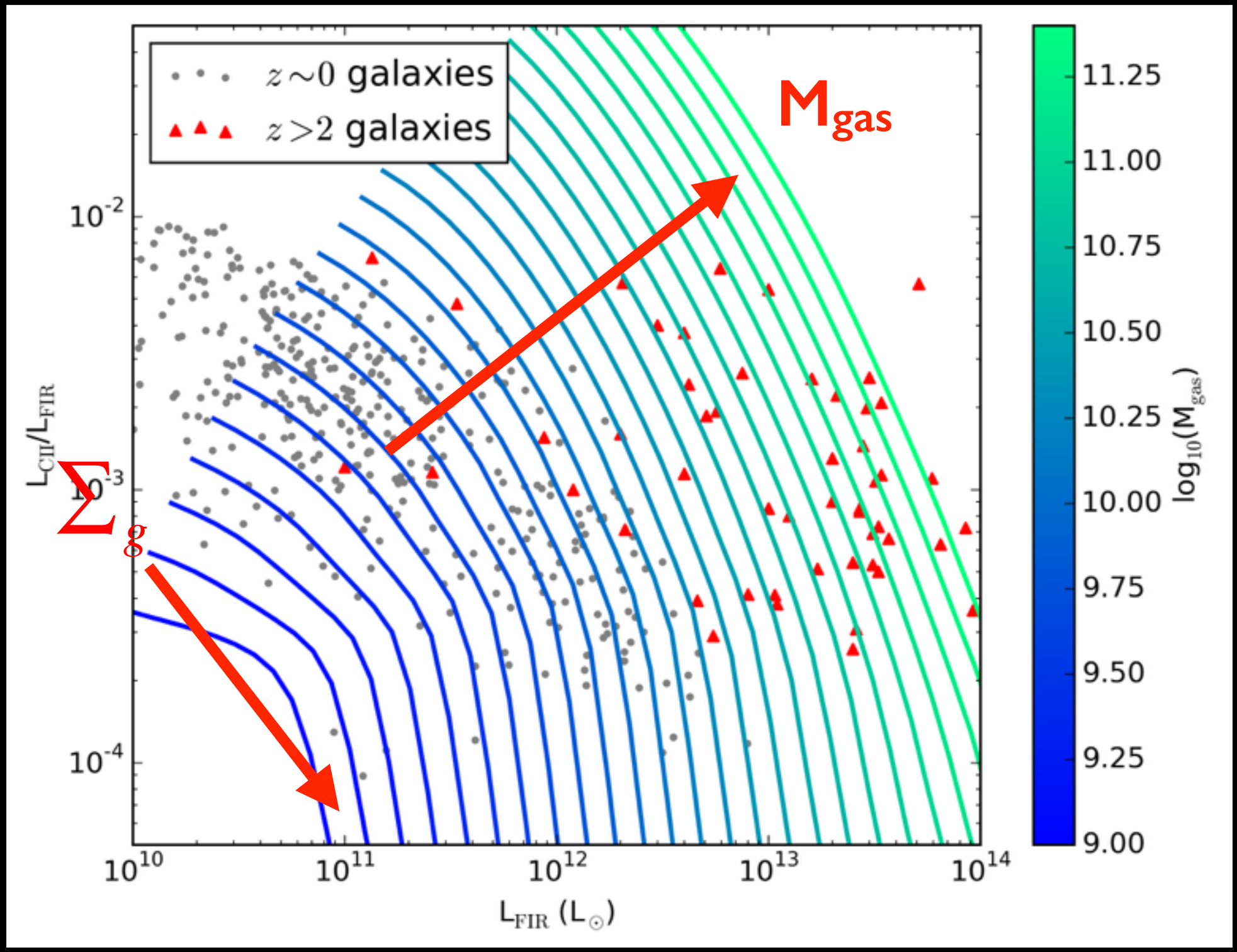
Observations

$$\Sigma_{SFR,kpc} = A \left(\frac{\Sigma_{g,kpc}}{M_\odot pc^{-2}} \right)^N$$

$$\phi_{mol} = \frac{\rho_{H2}}{\rho_{HI}} \approx 10$$

Narayanan & Krumholz 2016

The [CII]-FIR Deficit at low and high-z



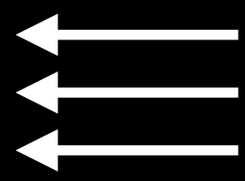
Narayanan & Krumholz 2016

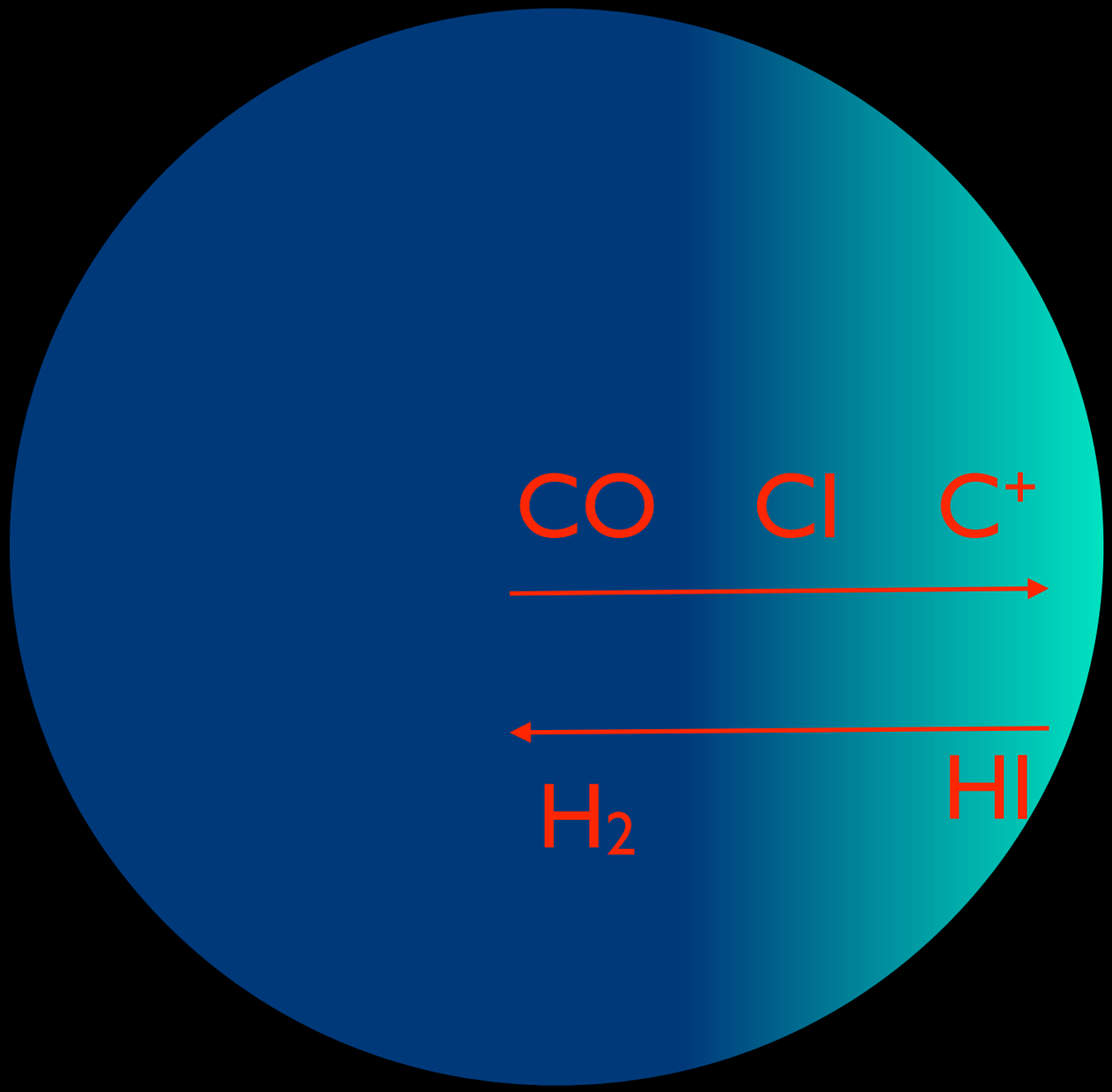
data compiled in Casey, Narayanan & Cooray 2014

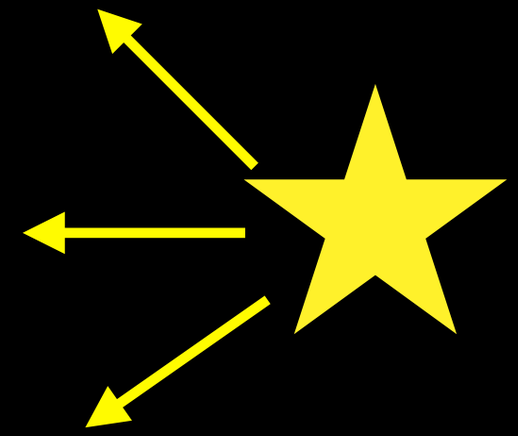
What happens at z>6?

n_H

cosmic rays

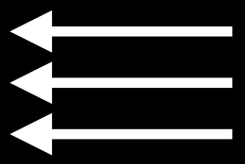






Av

FUV radiation

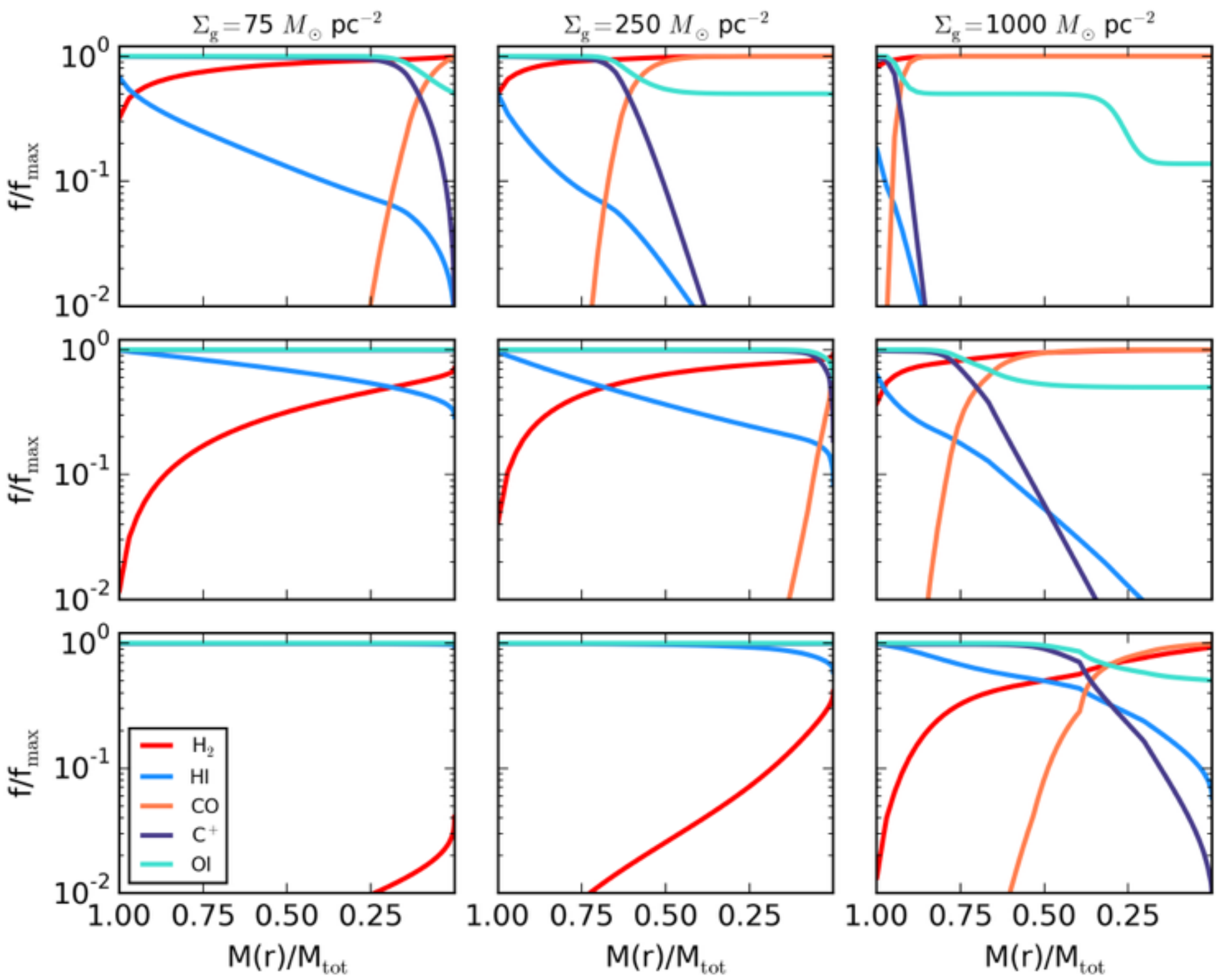


What happens at low metallicity?

Z = Z⊙

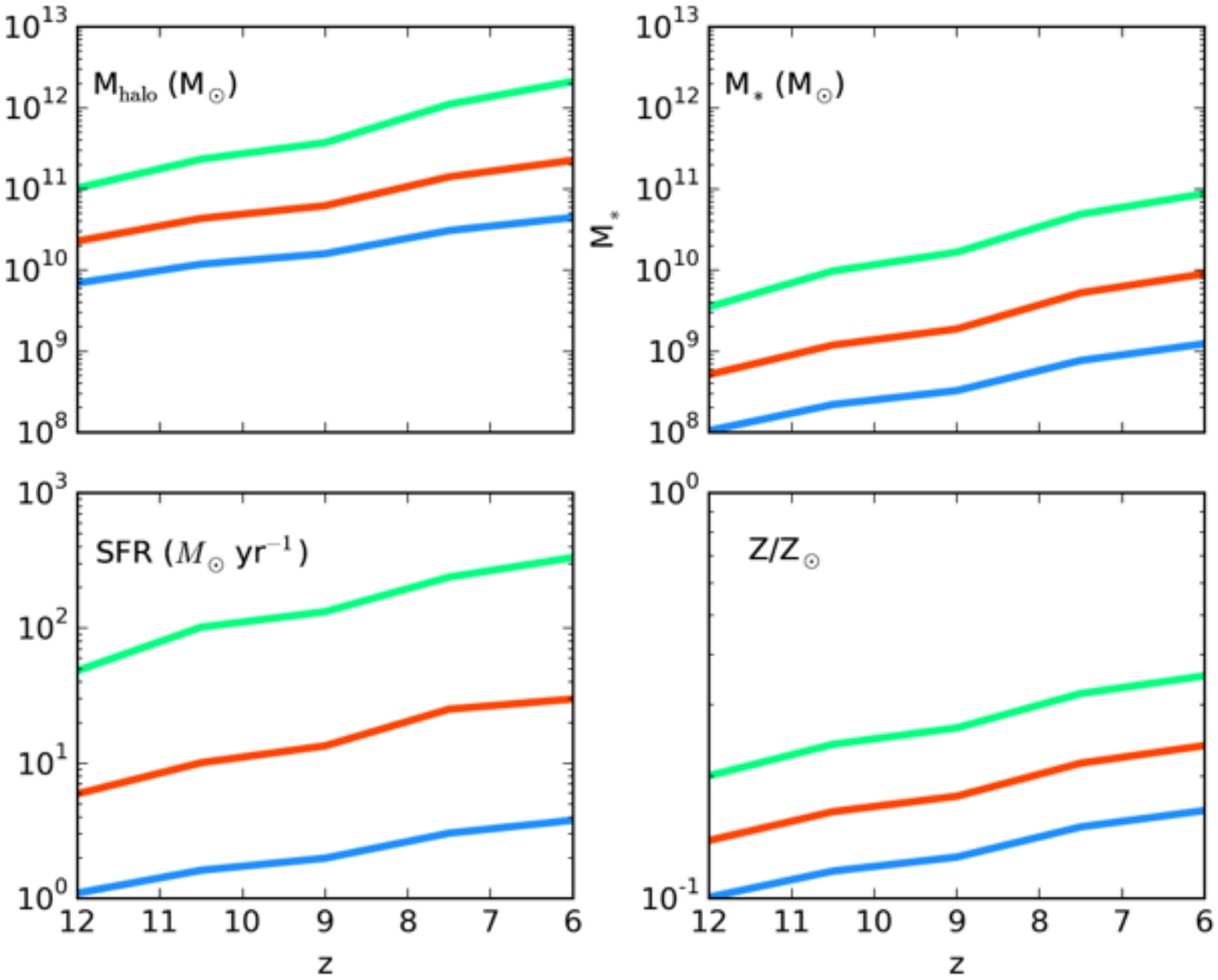
Z = 0.1 Z⊙

Z = 0.01 Z⊙



Building a Universe full of Galaxies

building into the Davé, Finlator & Oppenheimer (2011) SAM



Parameterization

I. infall

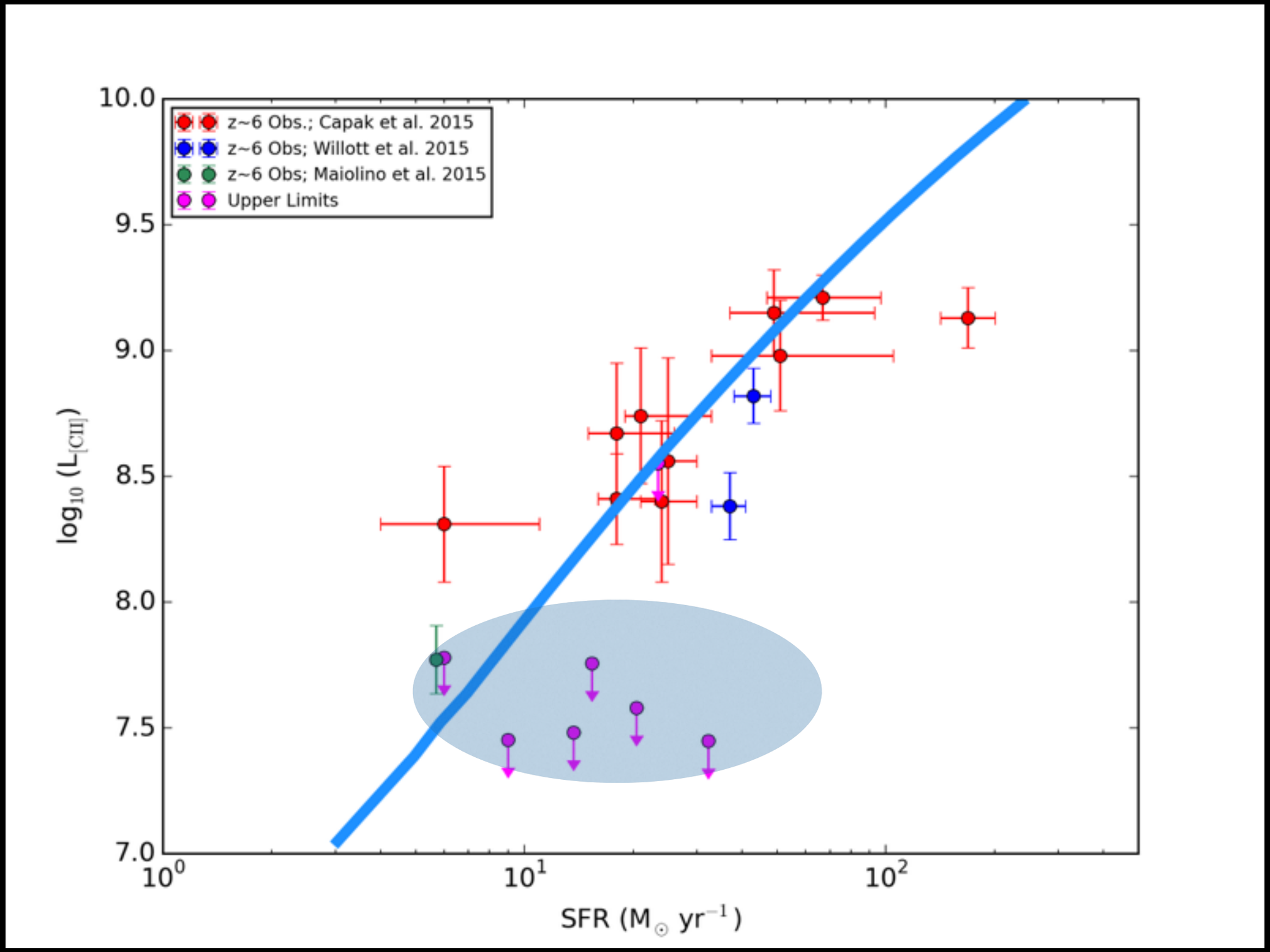
II. preventative feedback

III. recycling

IV. ejection

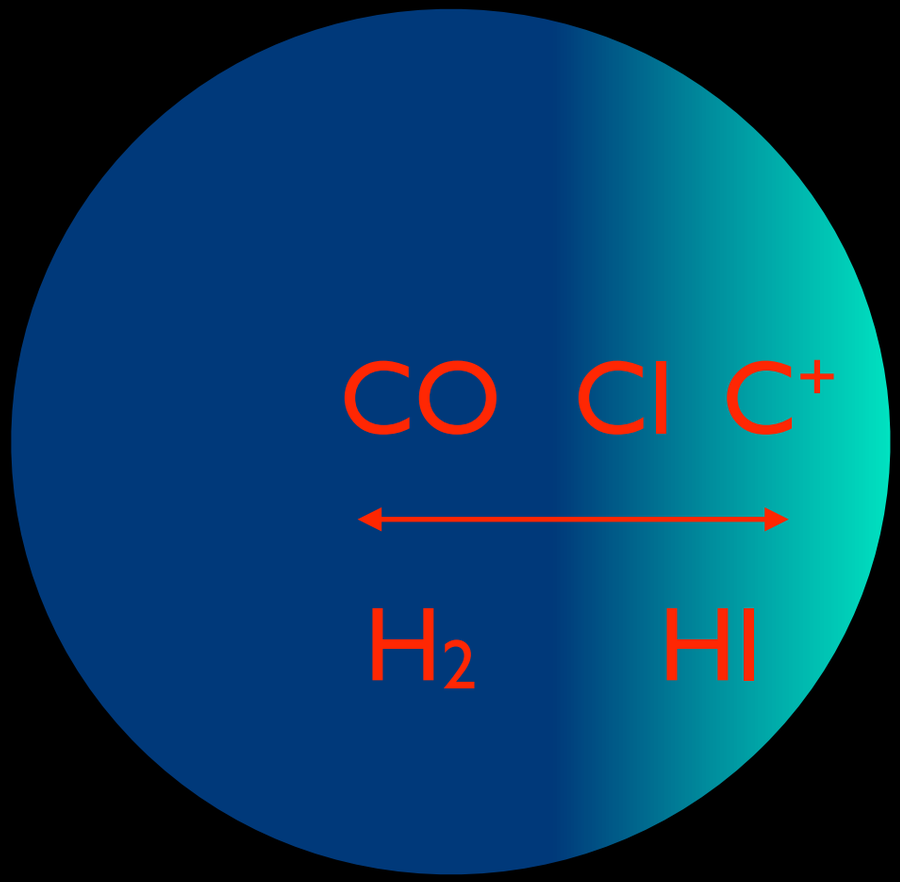
V. quenching

The [CII]-SFR Relation at z>6



Summary:

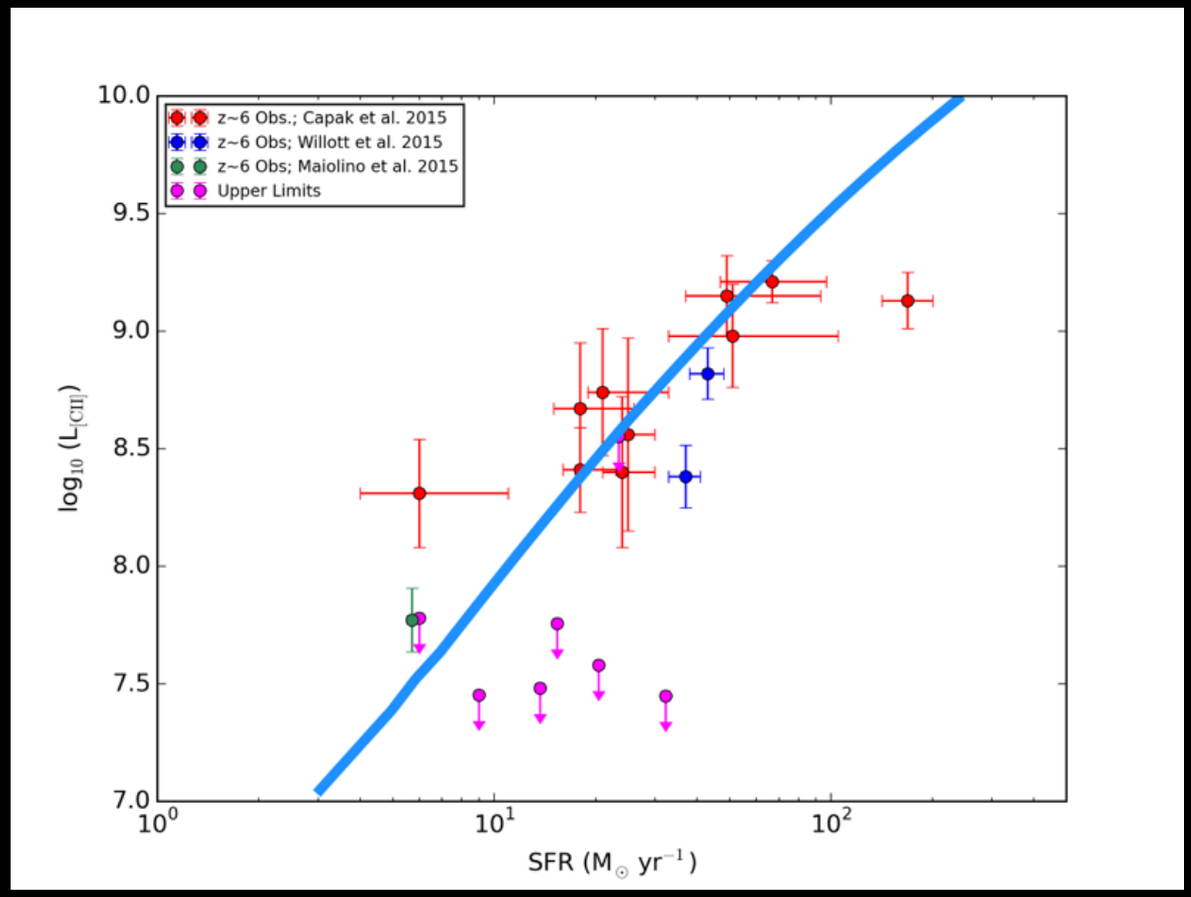
1. Developed models for the chemical and thermal structure in giant clouds in galaxies with a range of physical properties



- CO nominally confined to well-protected and shielded layers. As metallicity decreases and CRs + UV penetrate, the entire cloud becomes dominated in C^+

- The [CII]-SFR relation in low metallicity galaxies arises due to the bulk of the ISM being dominated by C^+

- CO may be excruciatingly difficult to detect



II. Combined thermo-chemical models with SAM to model galaxy growth