The Gas Consumption History of the Universe

Amber Bauermeister
Leo Blitz
Chung-Pei Ma

A work in progress

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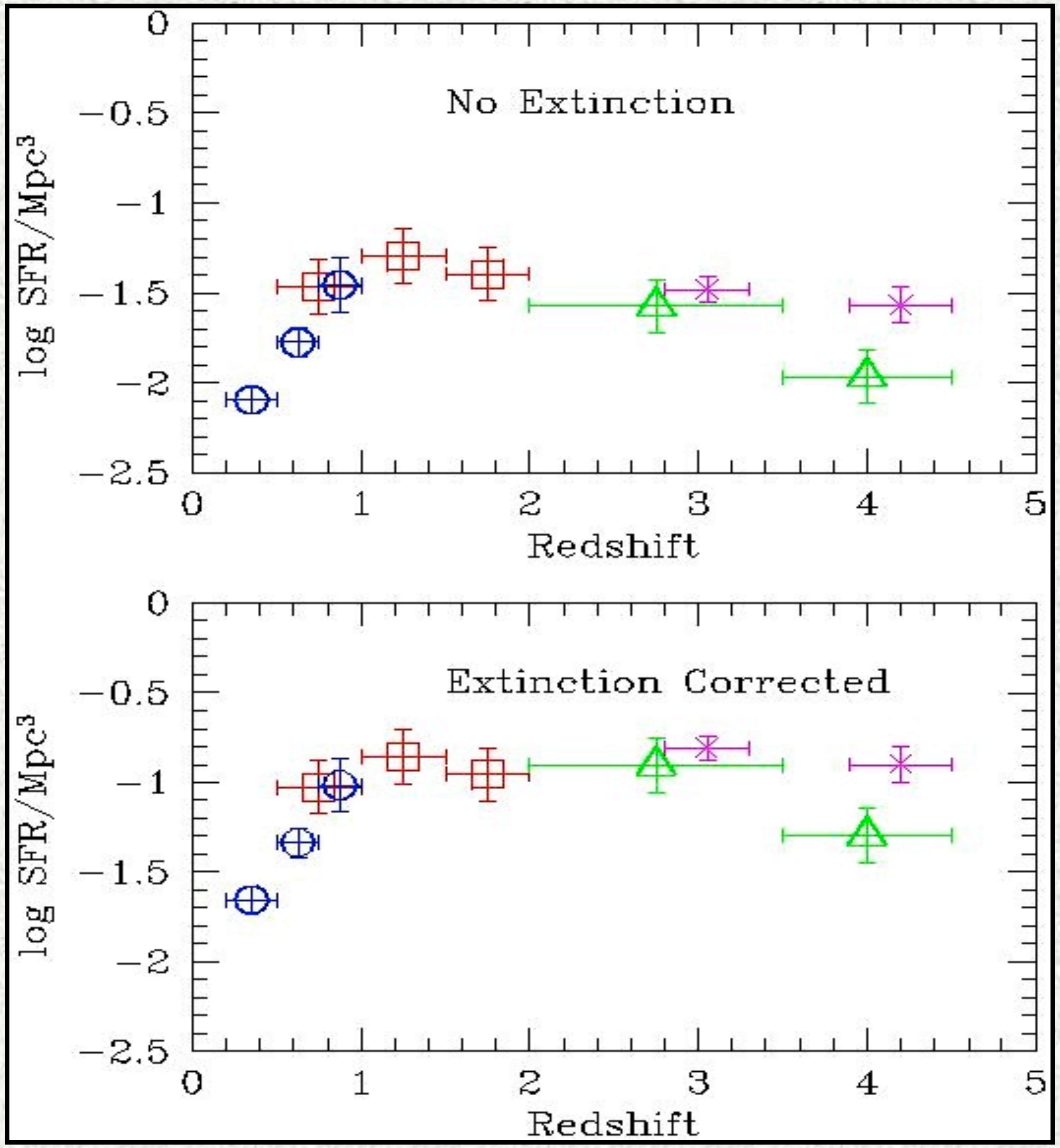
Cosmic Star Formation

How are simulations of galaxy formation and evolution usually done?

1) Use somebody's ΛCDM code
2) Add baryons
3) Add some usually insufficient physics
4) Follow evolution of the gas
5) Use Kennicutt SF law to determine star formation
6) Get as much time as possible on large cluster or supercomputer
7) Wave hands and explain why simulated galaxies are different from actual galaxies.

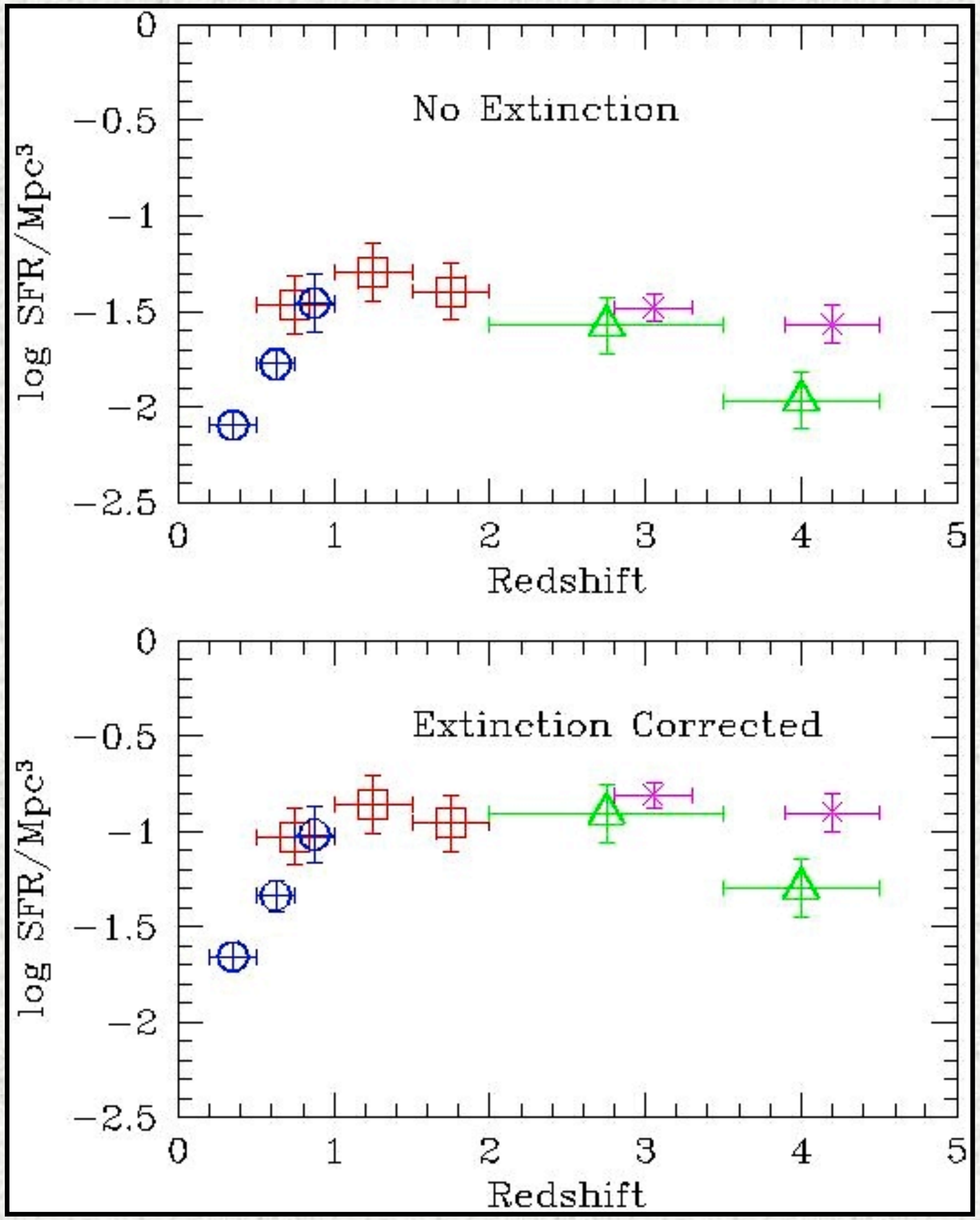
The Star Formation History of the Universe



Steidel et al. 1999; but see also Hopkins 2004

I will discuss what we can learn by doing this problem backwards.

What can we infer about the history of the gas in the Universe?



Steidel et al. 1999

Some new numbers available in the recent past.

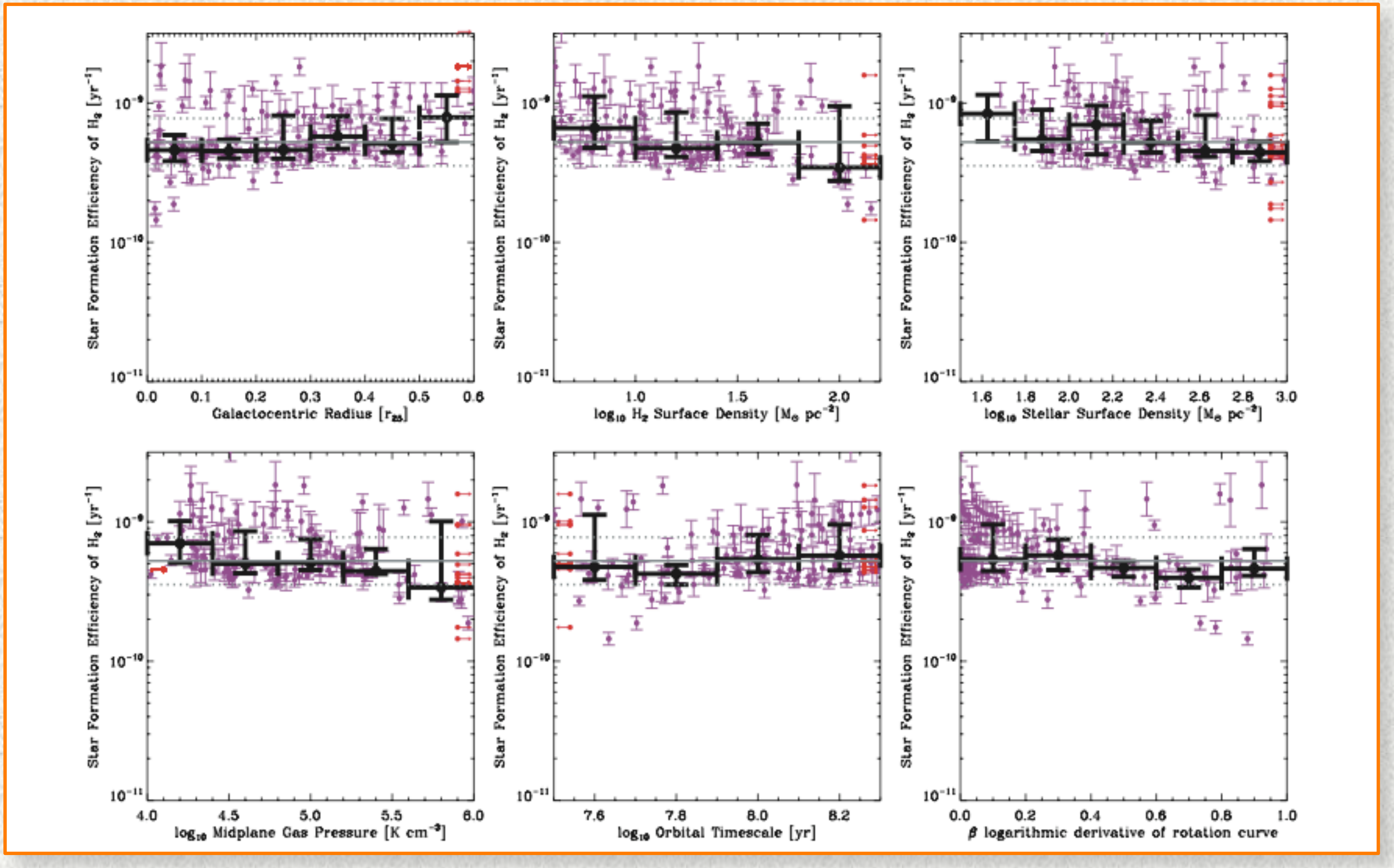
$d\log(SFR)/dt$ = 11% Gy^{-1}

SFR (z=0) = $1.6 \times 10^{-2}\ M_{\odot}\ y^{-1}$

SFR (z=1) = $1.6 \times 10^{-1}\ M_{\odot}\ y^{-1}$

Steidel et al. 1999; but see also Hopkins 2004

SFE(H_2)



Leroy et al., 2009

SFE is remarkably constant at z = 0

$$SFE(H_2) = 5.3 \times 10^{-10}\ y^{-1}$$

Fundamental Equation

$$SFR = SFE \times \rho(H_2)$$

$$SFE^{-1} = \tau$$

where τ = GDT

SFR --> $M_\odot\ Mpc^{-3}\ y^{-1}$

SFE --> y^{-1}

$\rho(H_2)$--> $M_\odot\ Mpc^{-3}$

The Molecular Gas Depletion Time Problem

$$\mathrm{SFR} = \mathrm{SFE}(H_2) \times \rho(H_2)$$

Expect SFR = GDR(H_2)

$\mathrm{SFR}_{(z\,=\,0)} = 1.8 \times 10^{-2}\, h_{70}\, M_\odot\, y^{-1}\, \mathrm{Mpc}^{-3}$ (Dib et al. 2007)

$\rho(H_2) = 1.9 – 2.7 \times 10^{7}\, M_\odot\, \mathrm{Mpc}^{-3}$ (Obreschkow & Rawlings 2009)

$\mathrm{SFE}(H_2) = 5.3 \times 10^{-10}\, y^{-1}$ (Leroy et al. 2008; Bigiel et al. 2008)

↓

$\mathrm{GDR}(H_2)_{(z=0)} = 1.0\text{-}1.5 \times 10^{-2}\, M_\odot\, y^{-1}\, \mathrm{Mpc}^{-3}$

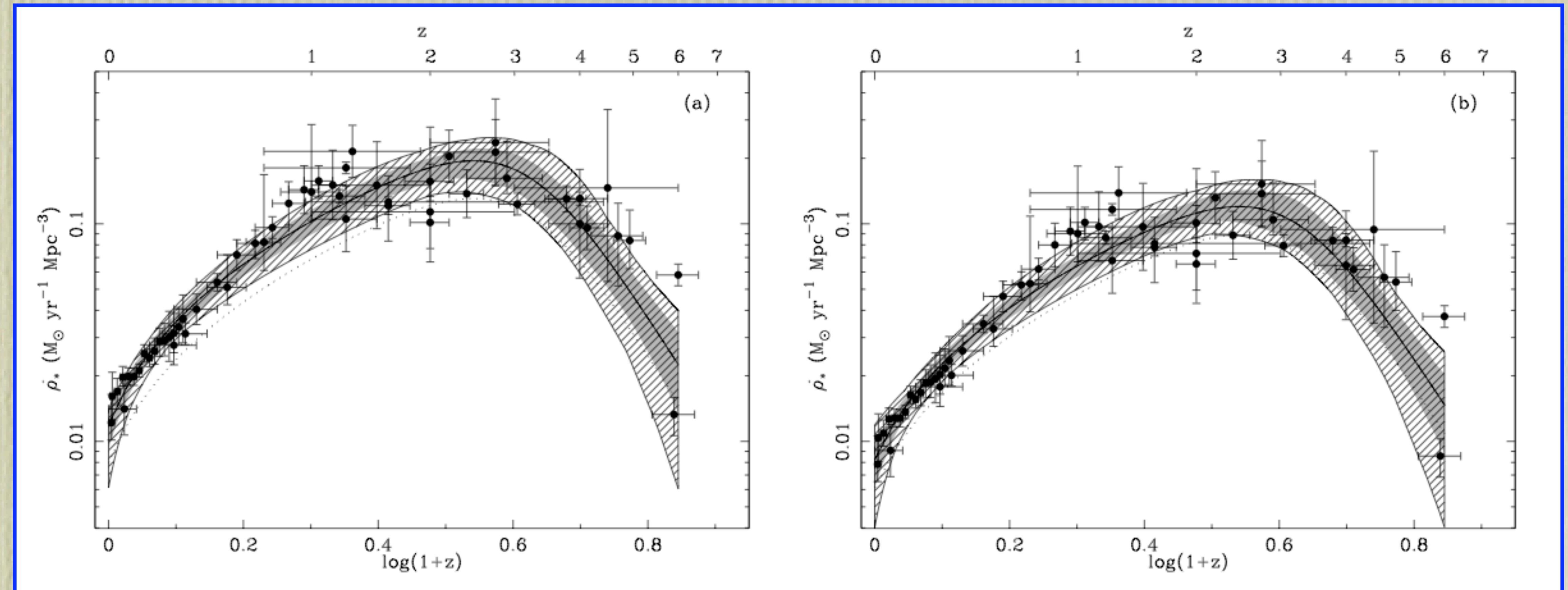
However! $\tau(H_2) = \mathrm{SFE}(H_2)^{-1} = 2 \times 10^{9}\, y$

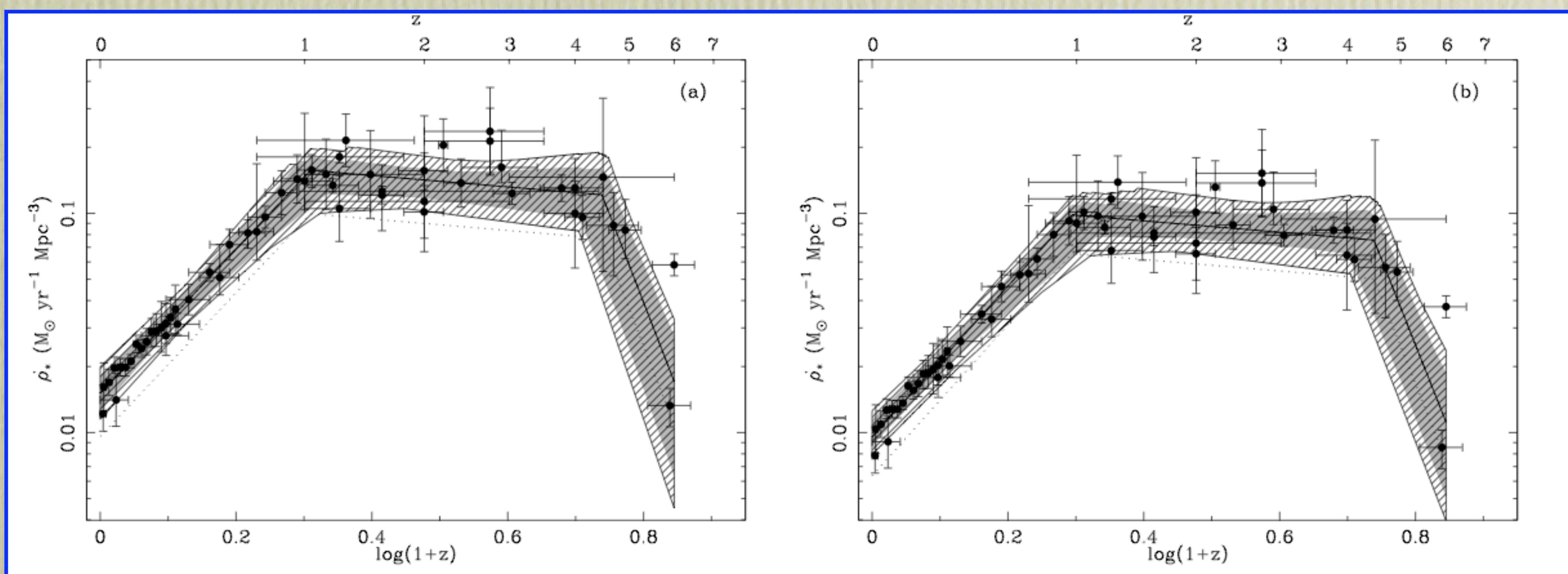
dlog(GDR)/dt = 50% Gy^{-1} *(from efficiency)*

dlog(SFR)/dt = 11% Gy^{-1} *(from slope of SFR)*

Assumes: Closed Box H_2; need fuller treatment

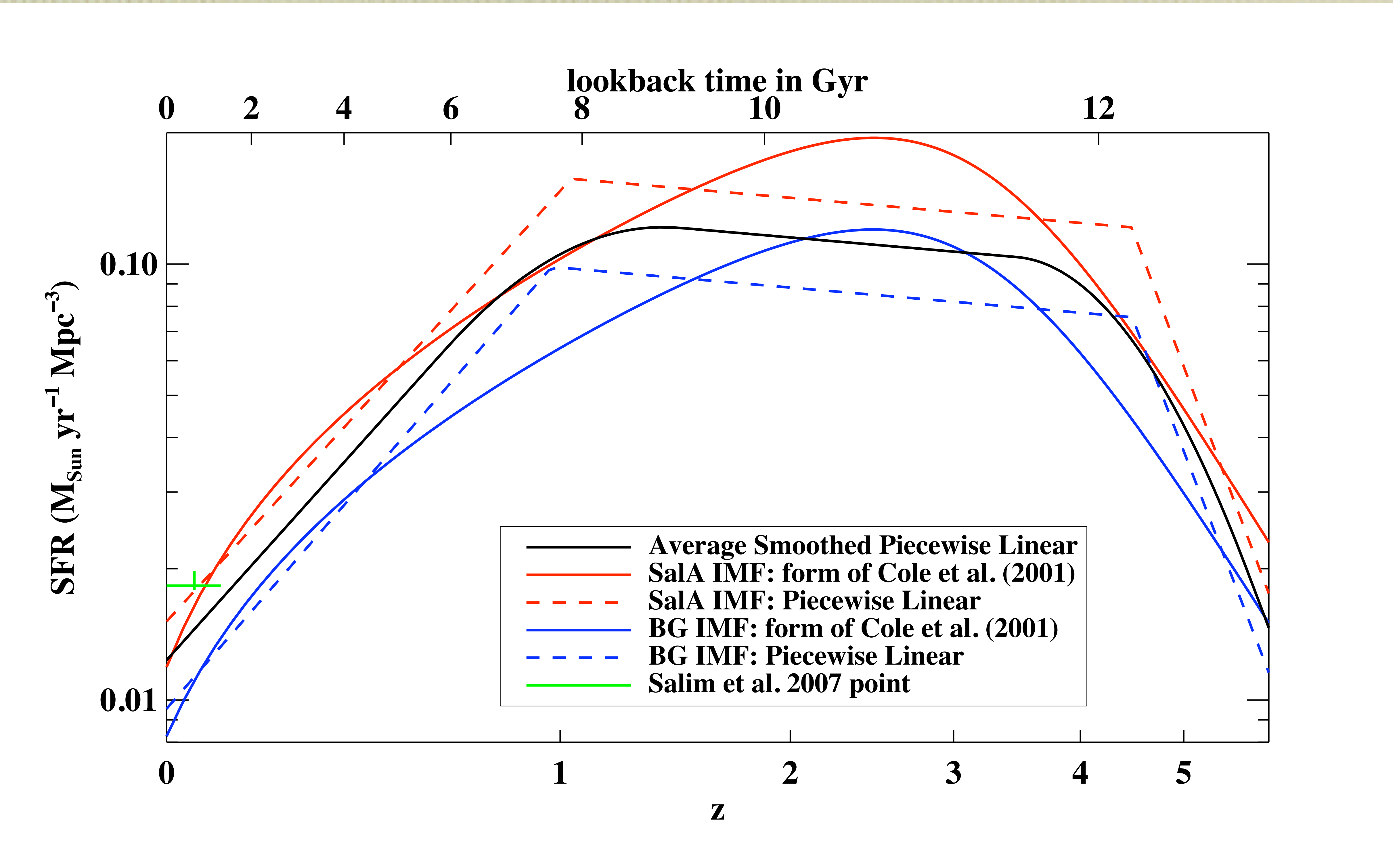
Star Formation Rate Density to z = 5





Hopkins & Beacom 2006

The Star Formation History We Use



General Case

Net change of HI, H_2, HII phases

H_2 is depleted by star formation

H_2 is generated by cooling of HI

HI is depleted by formation of H_2

HI is generated by cooling of HII

HII (WHIM) exists as reservoir from epoch of reionization and is depleted only by cooling to HI

General Case

Net change of HI, H_2, HII phases

$$\frac{d\rho_{H_2}}{dt} = -SFR + CR$$

$$\frac{d\rho_{HI}}{dt} = -CR + \frac{d\rho_{ext}}{dt}$$

$$d\rho(HII)/dt = d\rho_{ext}/dt$$

General Case

Net change of HI, H_2, HII phases

$$\frac{d\rho_{H_2}}{dt} = -SFR + CR$$

$$\frac{d\rho_{HI}}{dt} = -CR + \frac{d\rho_{ext}}{dt}$$

Time derivative of SFR definition:

$$\frac{d\log SFR}{dt} = -SFE_M + \frac{d\log SFE_M}{dt}$$

Solve for:

$\rho(H_2, HI, HII\ );\ d\rho(H_2, HI, HII)/dt$

NB:

There obs constraints on ρ(HI) dρ(HI)/dt

Assume different forms of SFE(t), X_{CO}
Take ρ(HI) from observations

General Case

Net change of HI, H_2, HII phases

$$\frac{d\rho_{H_2}}{dt} = -SFR + CR$$

$$\frac{d\rho_{HI}}{dt} = -CR + \frac{d\rho_{ext}}{dt}$$

Time derivative of SFR definition:

$$\frac{dSFR}{dt} = SFE_M \frac{d\rho_{H_2}}{dt} + \rho_{H_2} \frac{dSFE_M}{dt}$$

Rearranging:

$$\frac{d\log SFR}{dt} = -SFE_M + \frac{d\log SFE_M}{dt}$$

Solve for: $\rho(H_2, HI, HII)$; $d\rho(H_2, HI, HII)/dt$

NB: $\rho(HII)$ and $d\rho(HII)/dt$ are lower limits

Assume different forms of SFE(t), X_{CO}
Take ρ(HI) from observations

Closed Box H_2 Model

Net change in $H_2 \longrightarrow$ stars:

$$\frac{d\rho_{H_2}}{dt} = -SFR.$$

Time derivative of SFR definition:

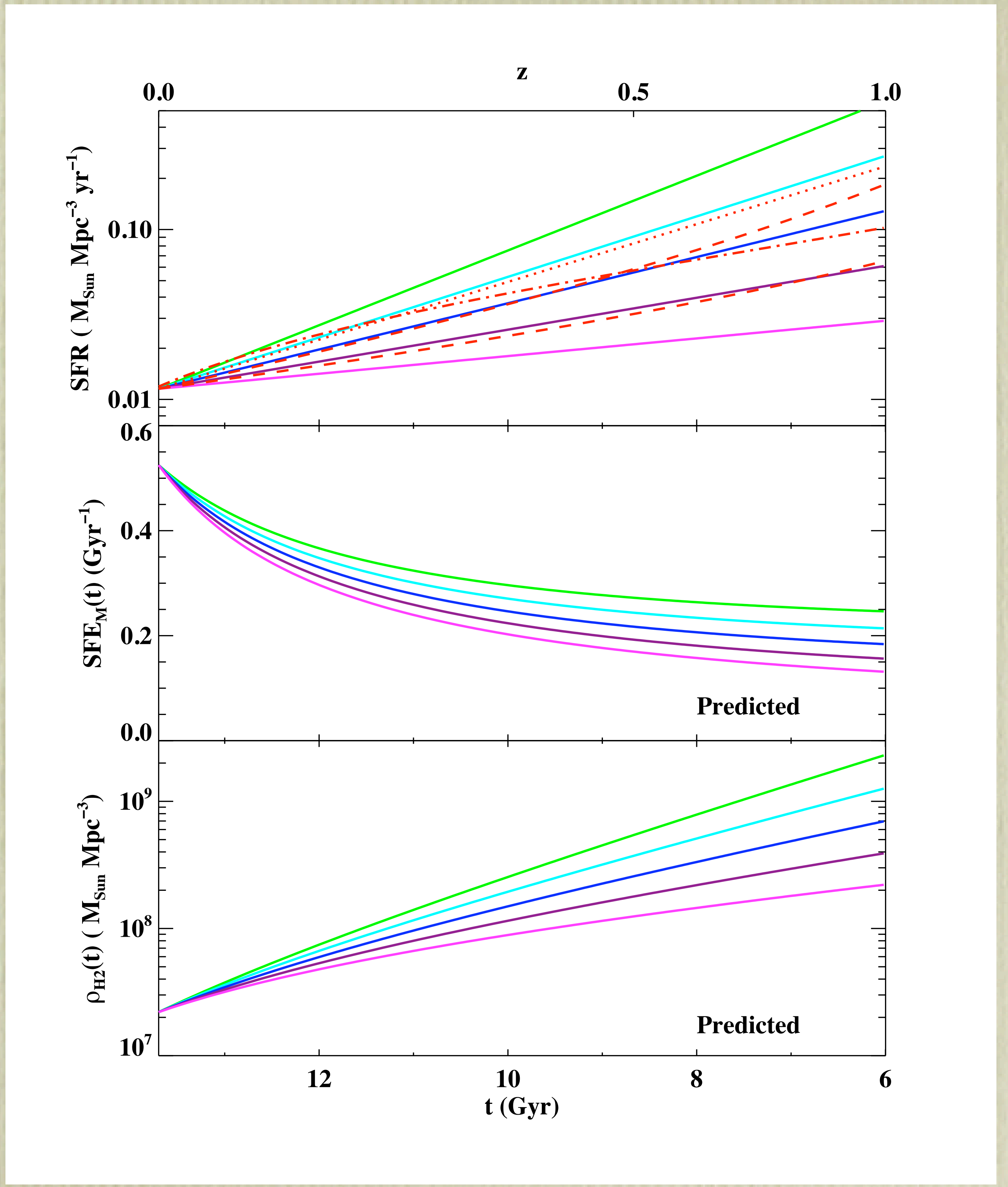
$$\frac{d\log SFR}{dt} = -SFE_M + \frac{d\log SFE_M}{dt}$$

Defining:

$$d\log SFR/dt = \alpha,$$

$$SFE_M(t) = \left[\left(1 + \frac{\alpha}{SFE_M(t_0)}\right) e^{-\alpha(t-t_0)} - 1\right]^{-1}$$

Solutions to Closed H_2 Box Equations



Consider only $z = 0$ to $z = 1$ for simplicity

Give up on Closed Box H_2 - allow HI to form H_2

Conclusion 1

The Closed Box H_2 model is inconsistent with the observations; it requires an SFE that decreases with lookback time and a ~50 fold increase of $\rho(H_2)$ in galaxies at $z = 1$.

Closed Box HI +H_2 Model

Net change of HI, H_2 phases

$$\frac{d\rho_{H_2}}{dt} = -SFR + CR$$

$$\frac{d\rho_{HI}}{dt} = -CR$$

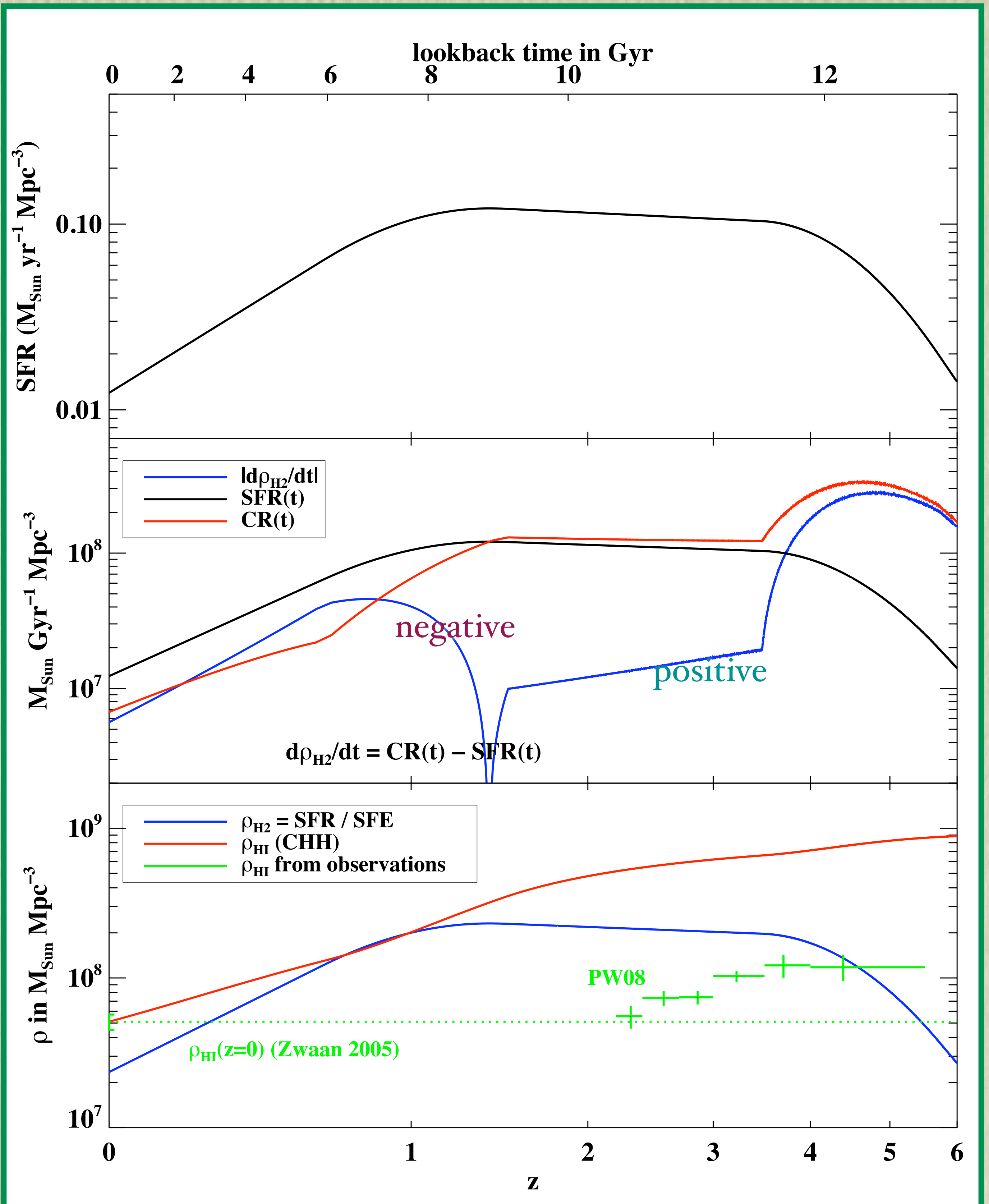
Time derivative of SFR definition:

$$\frac{d\log SFR}{dt} = -SFE_M + \frac{d\log SFE_M}{dt}$$

Integrate back in time:

$$\rho_{HI}(t_l) = \rho_{HI}(0) + \int_0^{t_l} CR(t_l')dt_l'$$

Closed H_2 + HI Model



Put in as much HI as is necessary to produce H_2 to get SFR, and measured SFE ($z = 0$); assume SFE = const

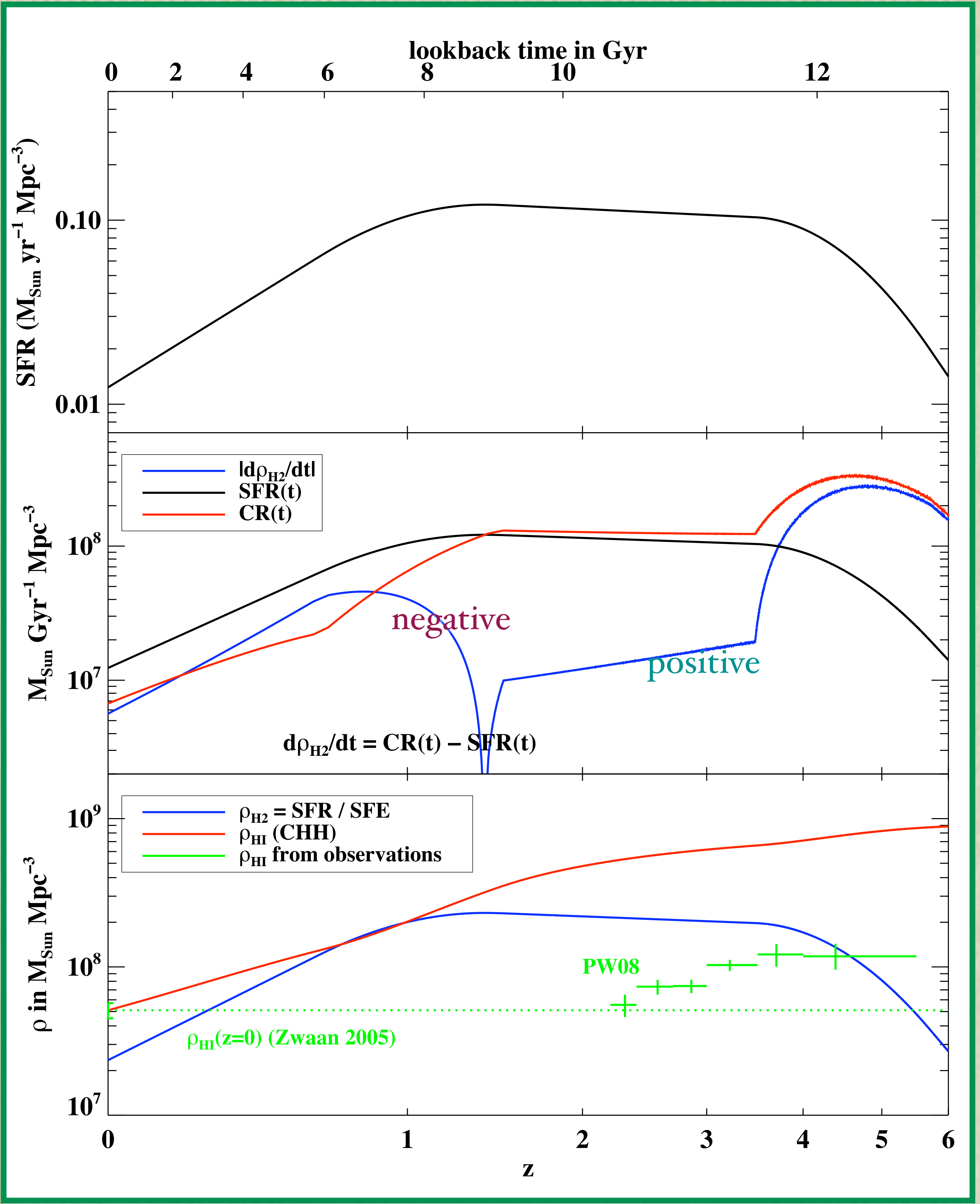
← Rate Plots

integrate over time

← Density Plots

Constraint: $\rho(\mathrm{HI})_{z=0}$ = measured value

Closed H2 + HI Model



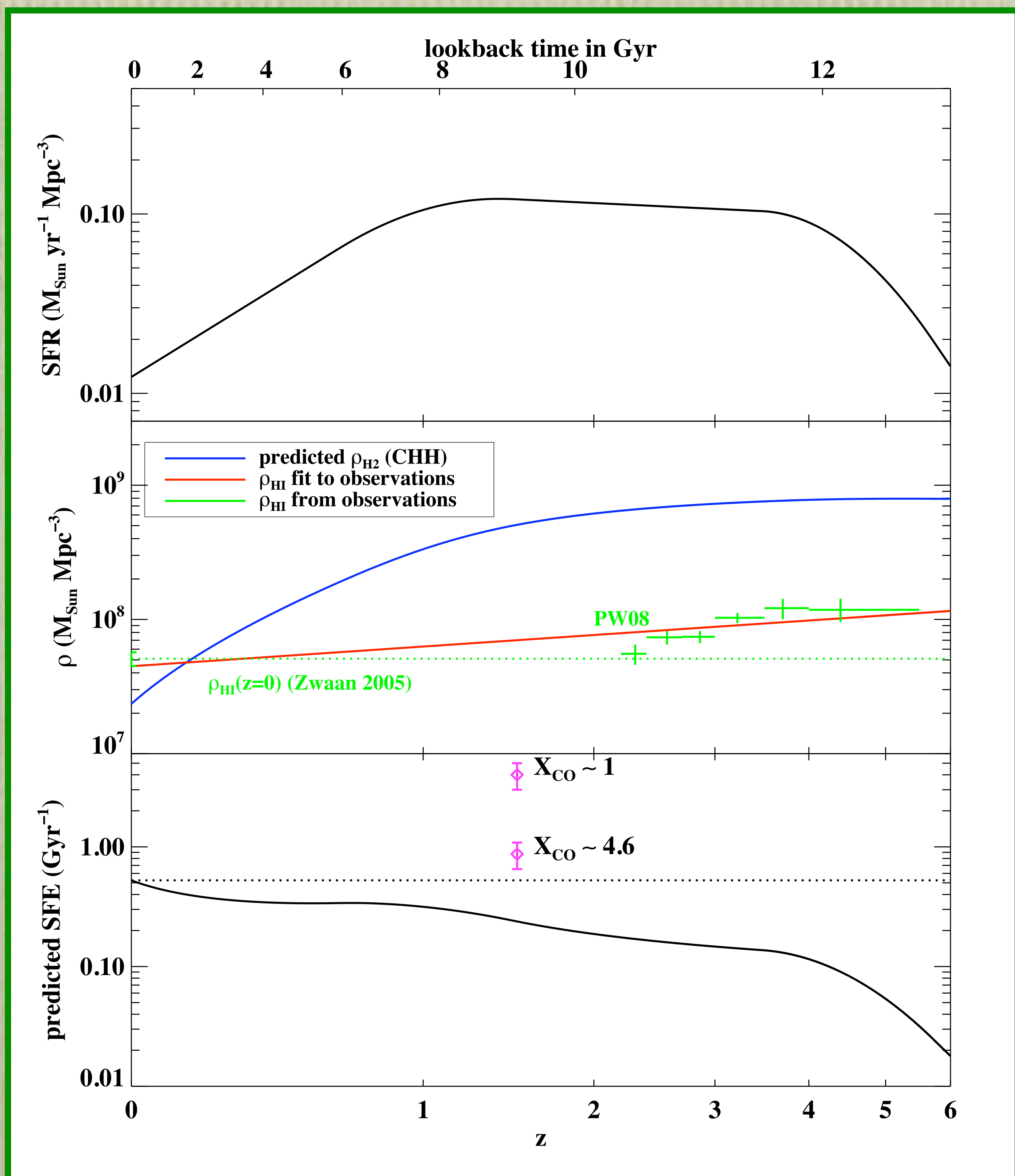
Put in as much HI as is necessary to produce H_2 to get SFR, and measured SFE (z = 0); assume SFE = const

Conclusion 2

If the measurements of ρ(HI) = *g(z)* are correct, and SFE is constant or decreasing with time, then most of the star-forming gas must come from the WHIM

SFE(t) required to fit closed (HI + H2) to data

Let SFE vary, and fix HI to observations

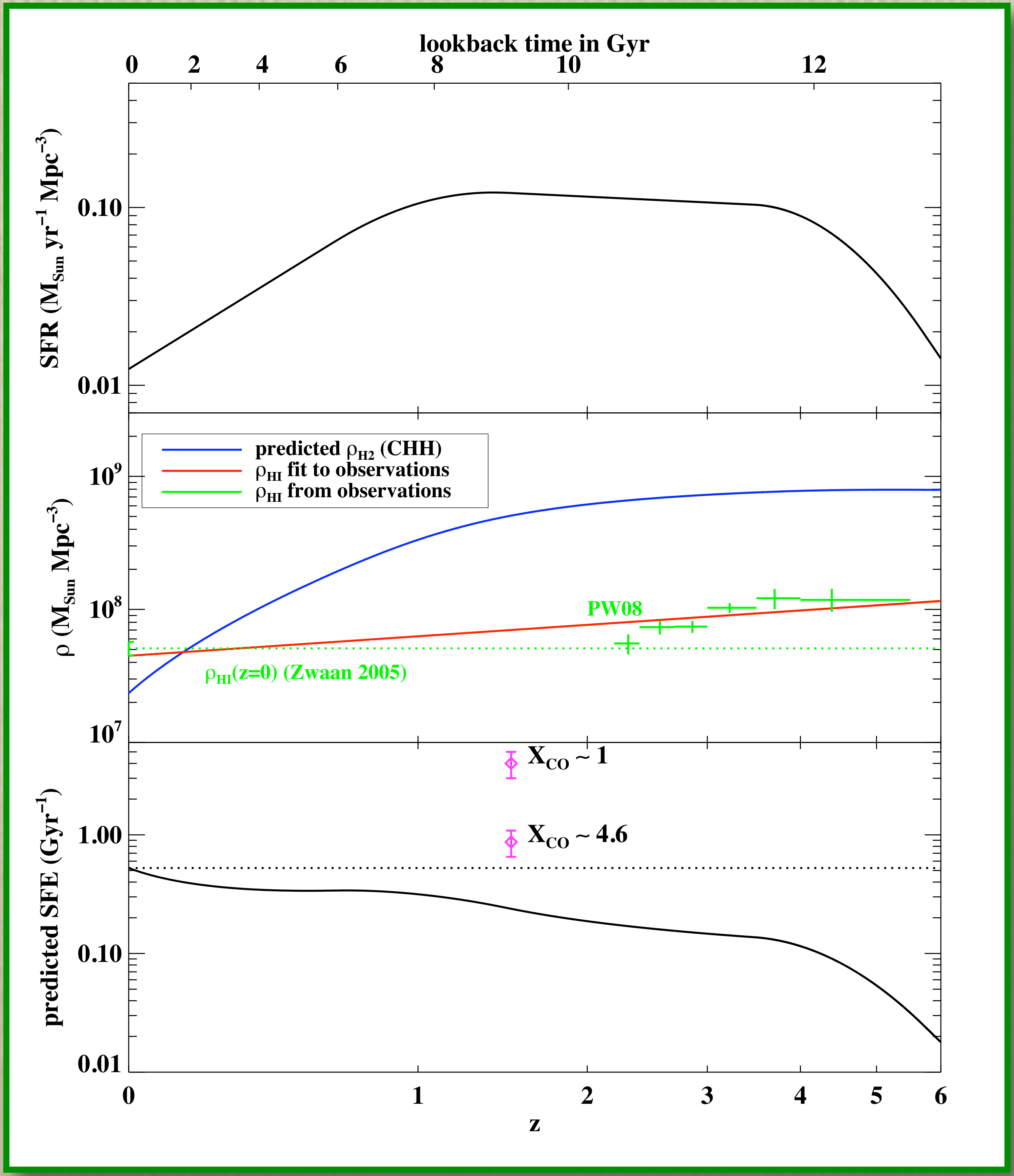


In this case, one can do it all with HI and H_2, BUT requires about two orders of magnitude more $\rho(H_2)$ than occurs at $z = 0$.

This case requires a lower SFE in the past. This is at variance with the observations.

SFE(t) required to fit closed (HI + H2) to data

Let SFE vary, and fix HI to observations



In this case, one can do it all with HI and H_2, BUT requires about two orders of magnitude more $\rho(H_2)$ than occurs at $z = 0$.

From two BzK galaxies, Daddi et al. (2007 find $\tau_M/X_{CO} = 0.2 - 0.3\ Gy^{-1}$ at $z = 1.5$; responsible for almost all SF then.

Conclusion 3

There is insufficient HI at all epochs in the past to provide the necessary reservoir of H_2 for the observed star formation history. As in closed box H_2 models, unacceptably large H_2 densities and a decreasing SFE with lookback time are required by the models. There must be gas from the WHIM fueling SF at all epochs in the past.

Open Box (HI + H_2 + WHIM) Model

Net change of HI, H_2, HII phases

$$\frac{d\rho_{H_2}}{dt} = -SFR + CR$$

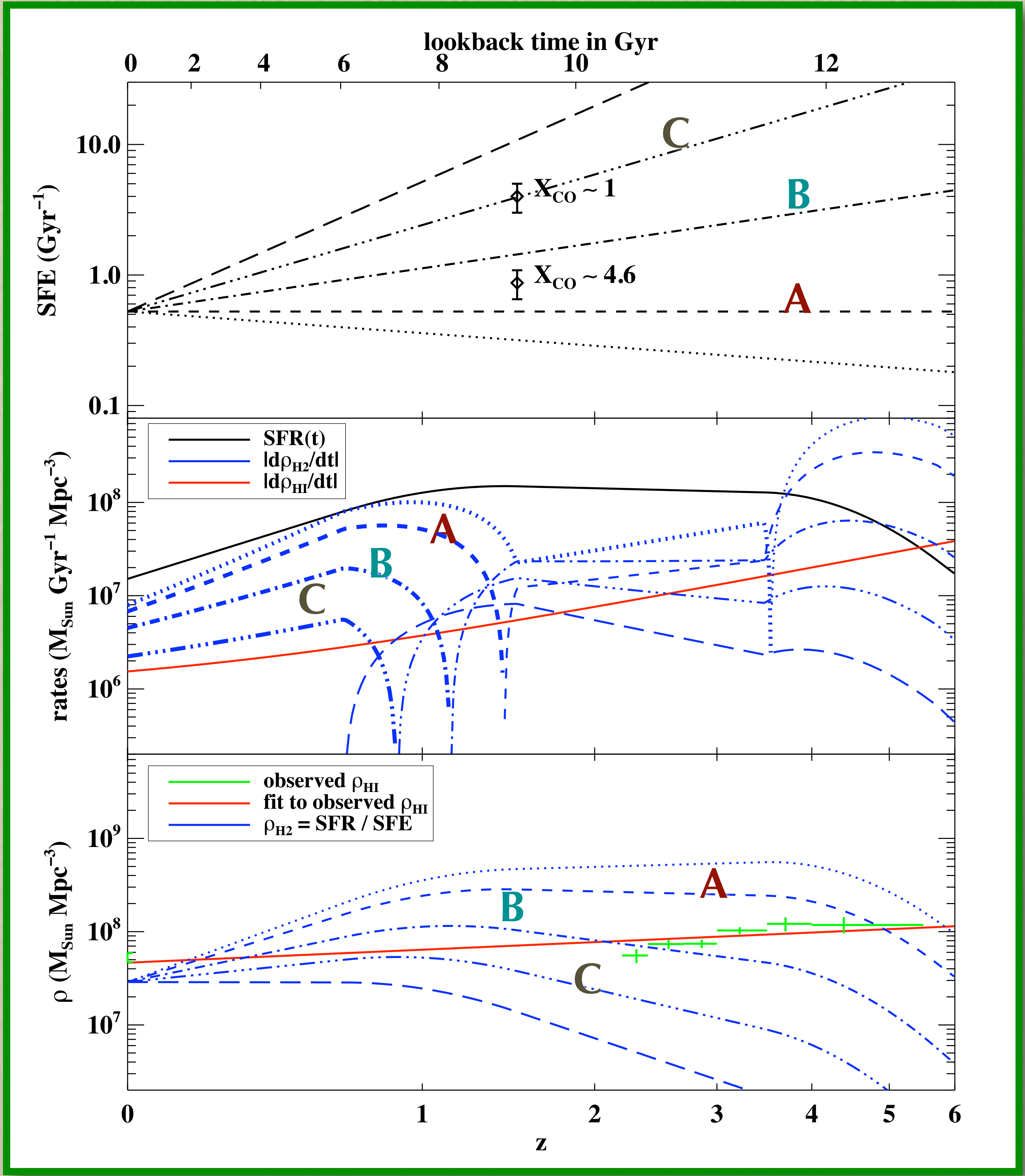
$$\frac{d\rho_{HI}}{dt} = -CR + \frac{d\rho_{ext}}{dt}$$

Time derivative of SFR definition:

$$\frac{d\log SFR}{dt} = -SFE_M + \frac{d\log SFE_M}{dt}$$

Assume different forms of SFE(t), X_{CO}
Take ρ(HI) from observations

Open Box: Behavior of $\rho(H_2)$ for SFE(t)

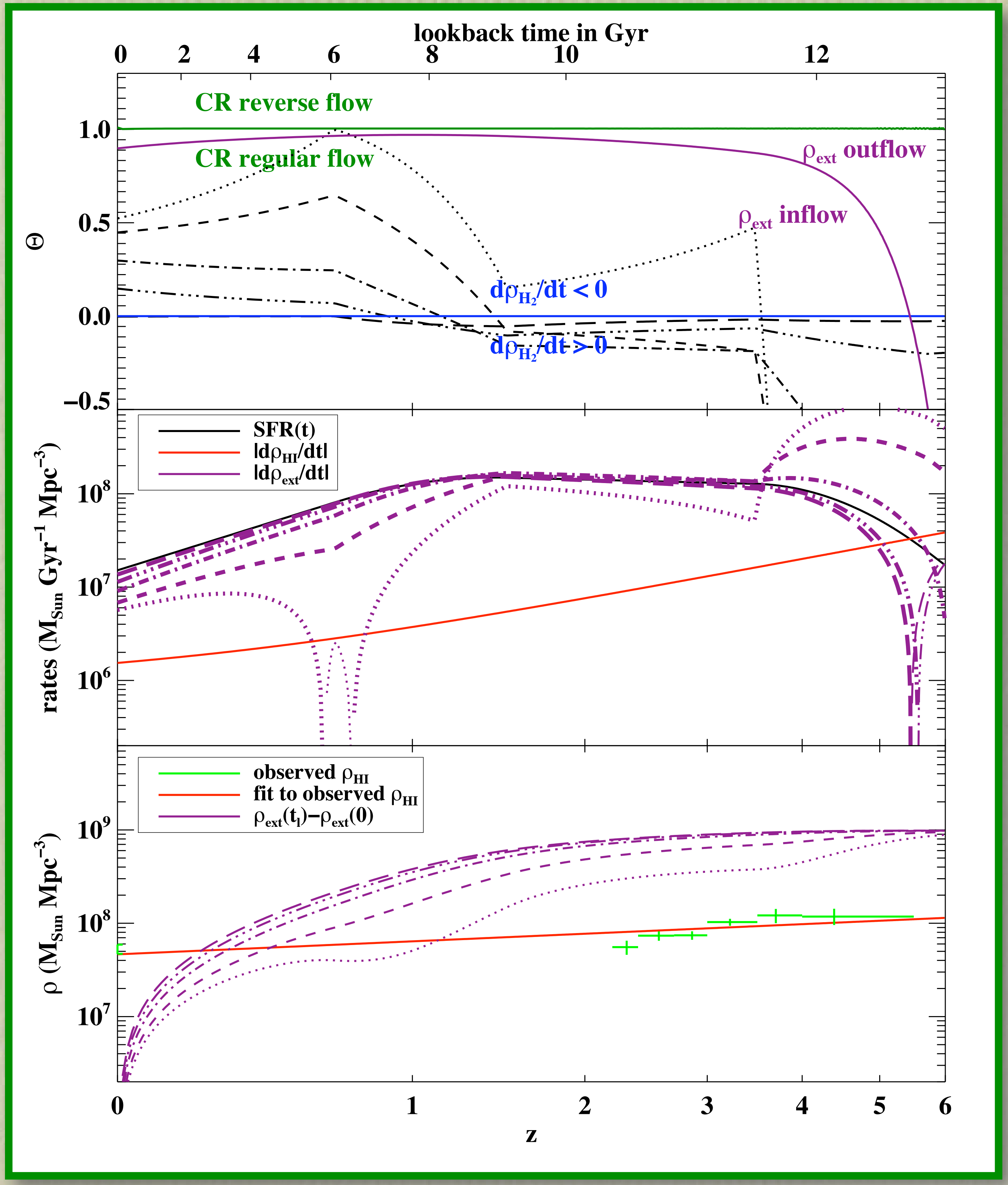


Conclusion 4

For any reasonable increase in SFE with lookback time, $\rho(H_2)$ must be higher in the past by a factor of 2-10 at z = 1-2.

This gas must reside in galaxies,
in particular, M* galaxies.

Open Box: Behavior of ρ_{EXT} for SFE(t)



Conclusion 5

dρ(HII)/dt and *ρ(HII)* dominate over the other phases at all epochs (but is poorly determined near *z* = 0).

SFR ~ dρ(HII/dt). The SFR is about equal to the mass flow rate out of the WHIM. What's left over goes into HI, H_2.

From z = 1 to z = 4, *dρ(HII)/dt* = 1 x 10^8 $M_\odot$ Mpc^{-3} Gy^{-1} , is nearly constant over this range, and is independent of SFE(t).

From z = 1 to z = 5, *ρ(HII)* ~ 1 x 10^9 $M_\odot$ Mpc^{-3}, is nearly constant over this range and is independent of SFE(t). Dominates over *ρ*(HI); *ρ*(HII) by an order of magnitude.

COLD FLOWS, IF THEY EXIST MUST BE IONIZED

Cooling Times

Assume:

$$\frac{\rho_{gas}}{t_{cool}} \sim \dot{\rho}_{ext}$$

$$t_{cool} \sim \frac{3kT}{2\Lambda(T)n_e}$$

f is filling fraction of hot gas that cools to HI; $T = 10^6$ K

$$n_e \sim \frac{2 \times 10^{-6}\ cm^{-3}}{\sqrt{f}}$$

upper limit to *f*

$$f \sim n_{L_*}\frac{4}{3}\pi R_{vir}^3 \sim 7 \times 10^{-4}$$

lower limit to n_e

$$n_e \sim 8 \times 10^{-5}\ \mathrm{cm}^{-3}$$

Conclusions and Implications

1. All solutions to the differential equations produce higher mean densities of H_2 in the past than at $z = 0$. The exact value depends on SFE(t).
2. This H_2 must reside in galaxies (insufficient pressure outside galaxies).
3. If ρ(HI) is as small as DLA measurements imply, then most star forming gas at all epochs to about $z \sim 0.3$ comes from the WHIM. At $z < 0.3$, it is not possible to determine this from the observations.
4. The densities and mass flow rates of the different phases of the gas can be determined absolutely. They depend only weakly on SFE(t).
5. Cold Flows must be nearly fully ionized.