Molecules in the Interstellar Media of Dwarf Galaxies

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Lowell Dwarf Galaxy Workshop, June 2012

What you get if you google image search "interstellar medium"…

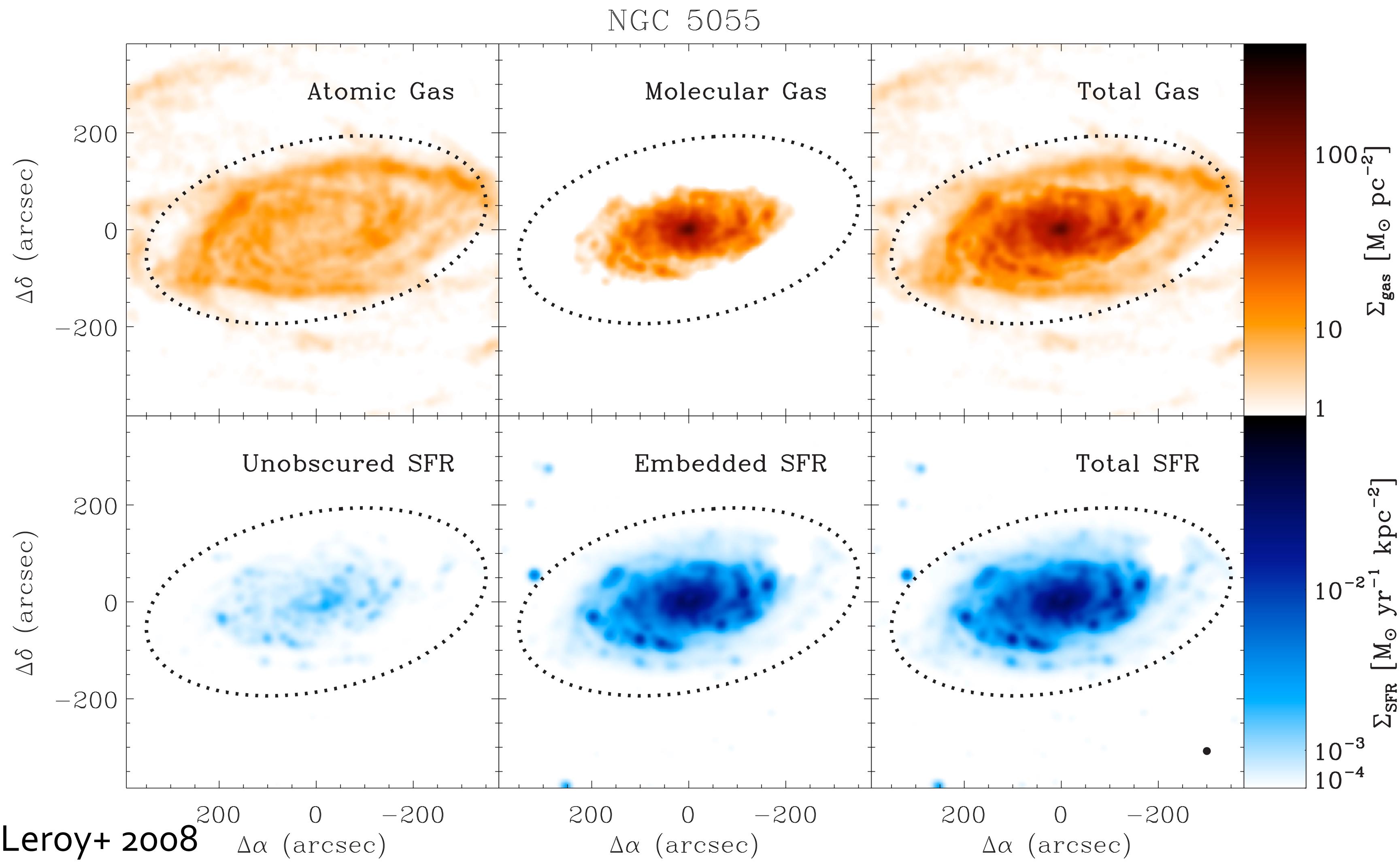
"The black light of the interstellar medium of deep space illumines all that is not, to be seen and not to 'Be'. To 'Be' and not seen – this is the path of the Panther woman.

From the hydrogen oceans of Deep Space she condenses rain.
Water precipitates from Her Vast Womb, falling onto planets open to Her Life–giving moisture."

Outline

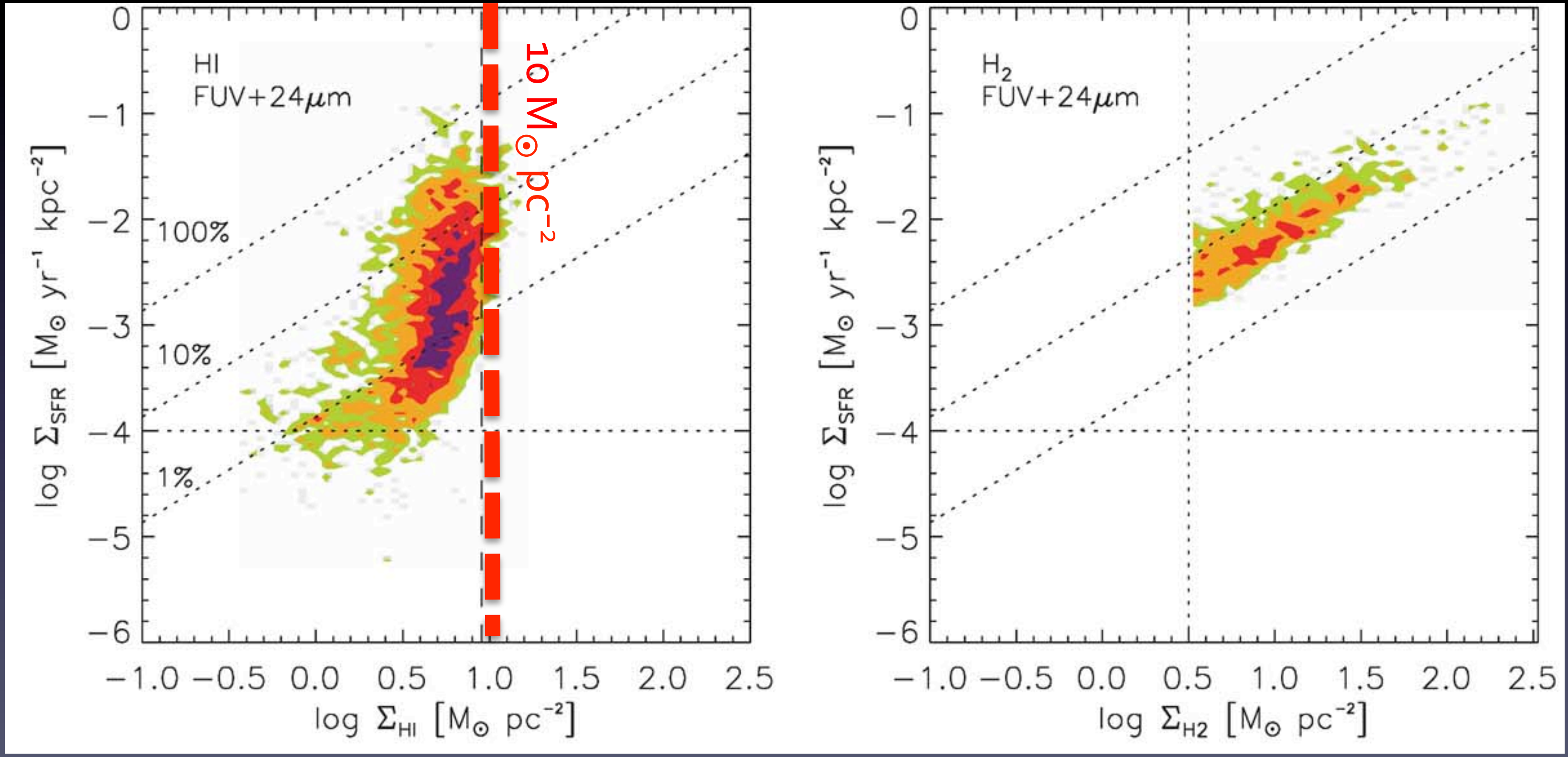
- Why do we care about H_2?
- Three questions for theory
- Implications for dwarf galaxies in cosmological context

Maps of HI, H_2, and SFR



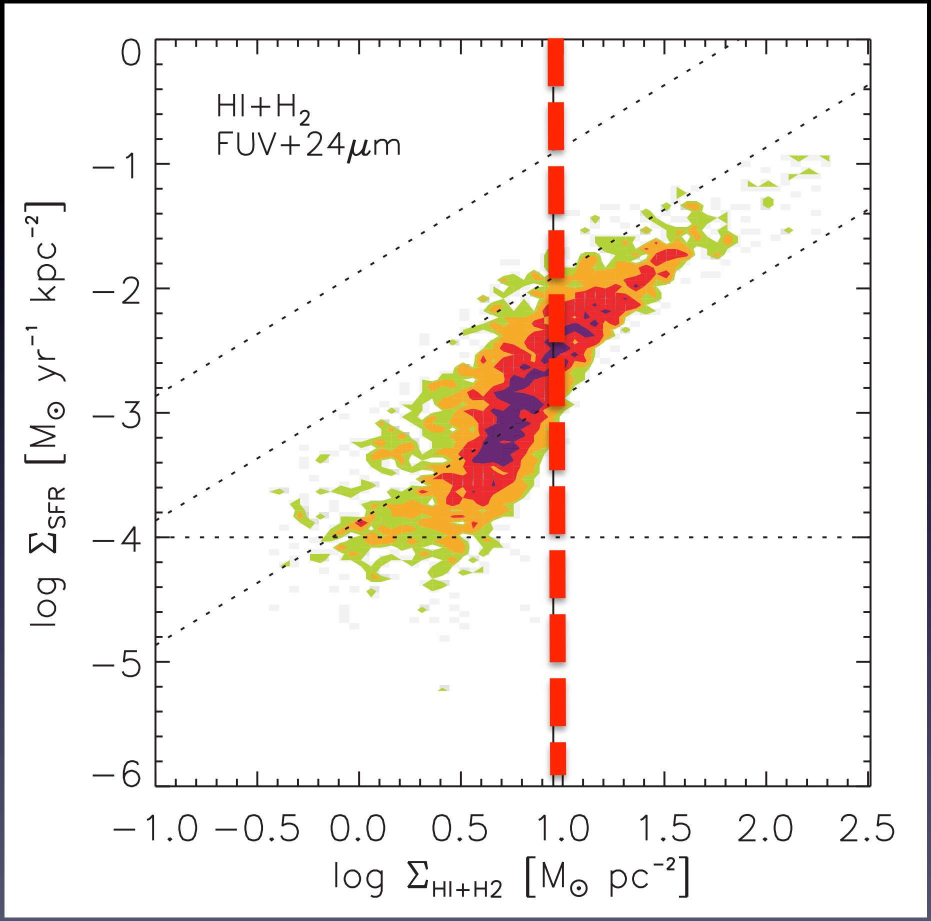
Leroy+ 2008

SF Follows H_2, not HI



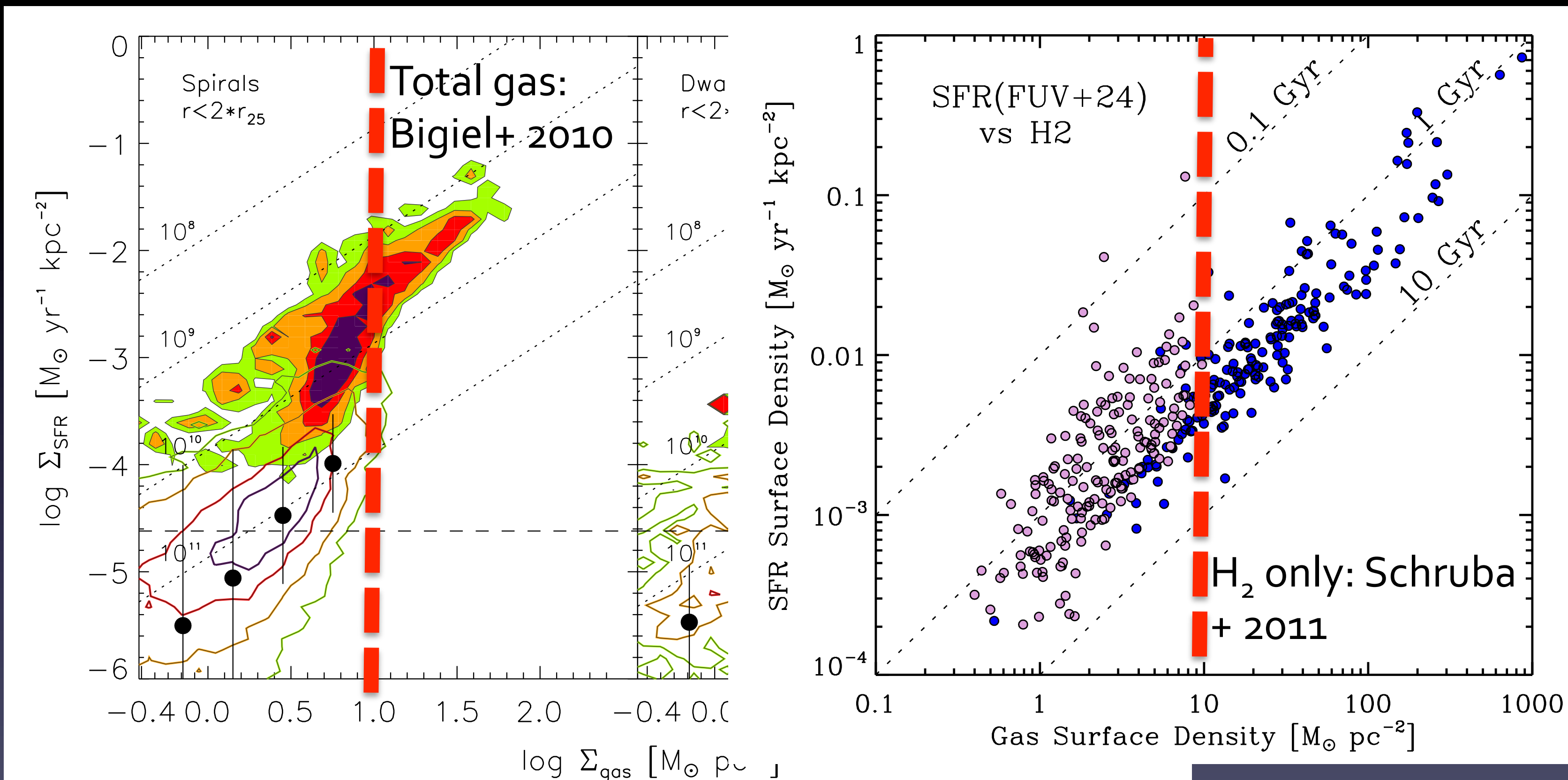
Bigiel+ 2008

SF Follows H_2, not HI



Bigiel+ 2008

H_2 and SF at Low Column / Z



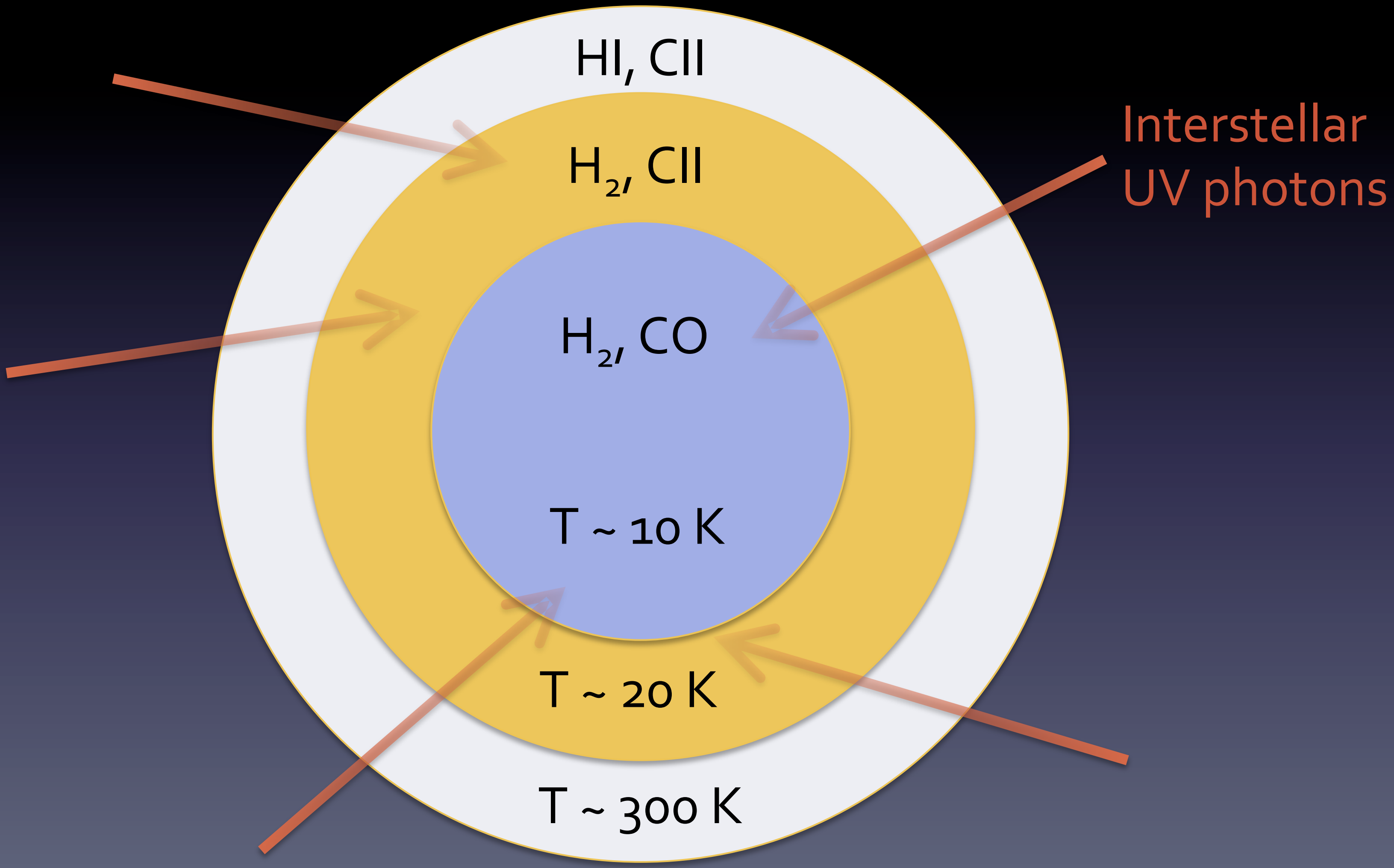
H_2 and SF do not go to 0 at low column; instead, there seems to be a floor: f_{H2} ~ 0.02, $t_{dep,H2}$ ~ 2 Gyr

Three Questions for Theory

A first order description of star formation in nearby galaxies appears to be SFR = M_{H_2} / 2 Gyr

- What sets the H_2 fraction?
- Why does SF care about H_2?
- How is H_2 related to CO? Deferred to talk by Desika Narayanan; also see Narayanan+ (2011, 2012), Shetty+ (2011, 2012) and Feldmann+ (2012a, 2012b)

Chemical Structure



Chemical and Thermal Balance

H_2 formation — H_2 photodissociation

$$n_{\mathrm{HI}} n \mathcal{R} = n_{\mathrm{H_2}} \int d\Omega \int d\nu \, \sigma_{\mathrm{H_2}} f_{\mathrm{diss}} I_\nu / (h\nu)$$

$$\hat{e} \cdot \nabla I_\nu = -(n_{\mathrm{H_2}} \sigma_{\mathrm{H_2}} + n \sigma_{\mathrm{d}}) I_\nu$$

Decrease in rad. intensity — Absorption by dust, H_2

Line cooling — Photoelectric heating

$$n^2 \Lambda = n \int d\Omega \int d\nu \, \sigma_d E_{\mathrm{PE}} I_\nu / (h\nu)$$

$$\hat{e} \cdot \nabla I_\nu = -n \sigma_d I_\nu$$

Decrease in rad. intensity — Absorption by dust

Caveat: this is assumes equilibrium, which may not hold

Calculating Molecular Fractions

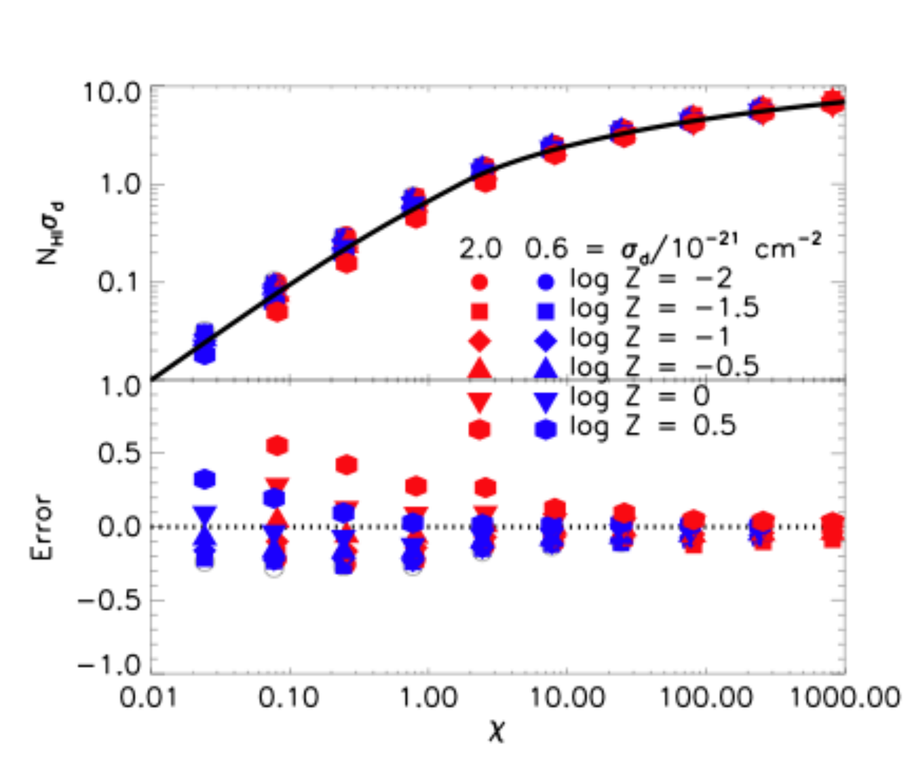
To good approximation, solution only depends on two numbers:

$$\tau_R = n\sigma_d R$$

$$\chi = \frac{f_{diss}\sigma_d E_0^*}{nR}$$

An approximate analytic solution can be given from these parameters.

τ_R depends only on galaxy Σ, $Z \Rightarrow$ can be measured directly



Analytic solution for location of HI / H_2 transition vs. exact numerical result

Calculating f_{H_2}

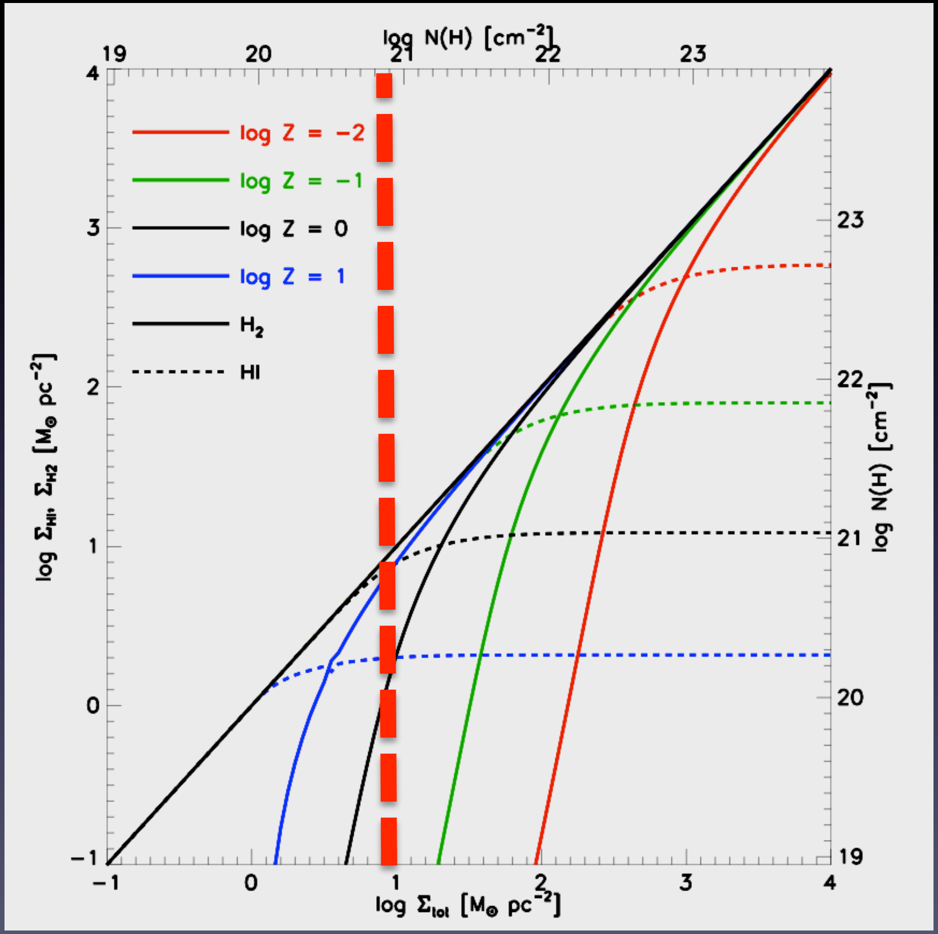
- Approximate solution:

$$f_{H_2} \approx 1 - \frac{3}{4}\left(\frac{s}{1+0.25s}\right)$$

$$s \approx \frac{\ln(1+0.6\chi+0.01\chi^2)}{0.04\left(\frac{Z}{Z_\odot}\right)\left(\frac{\Sigma}{M_\odot\ \mathrm{pc}^{-2}}\right)}$$

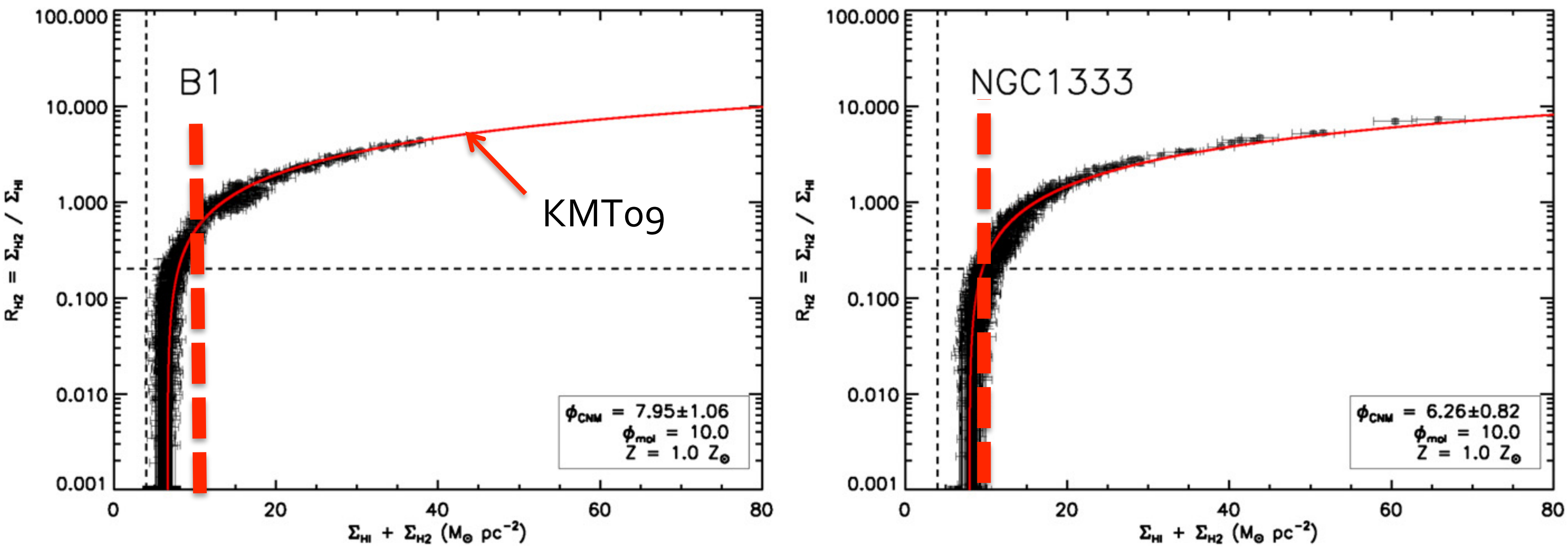
$$\chi \approx 3.1\frac{1+3.1\left(\frac{Z}{Z_\odot}\right)^{0.365}}{4.1}$$

- Qualitative effect: f_{H_2} goes from ~0 to ~1 when ΣZ ~ 10 $M_\odot$ pc^{-2}



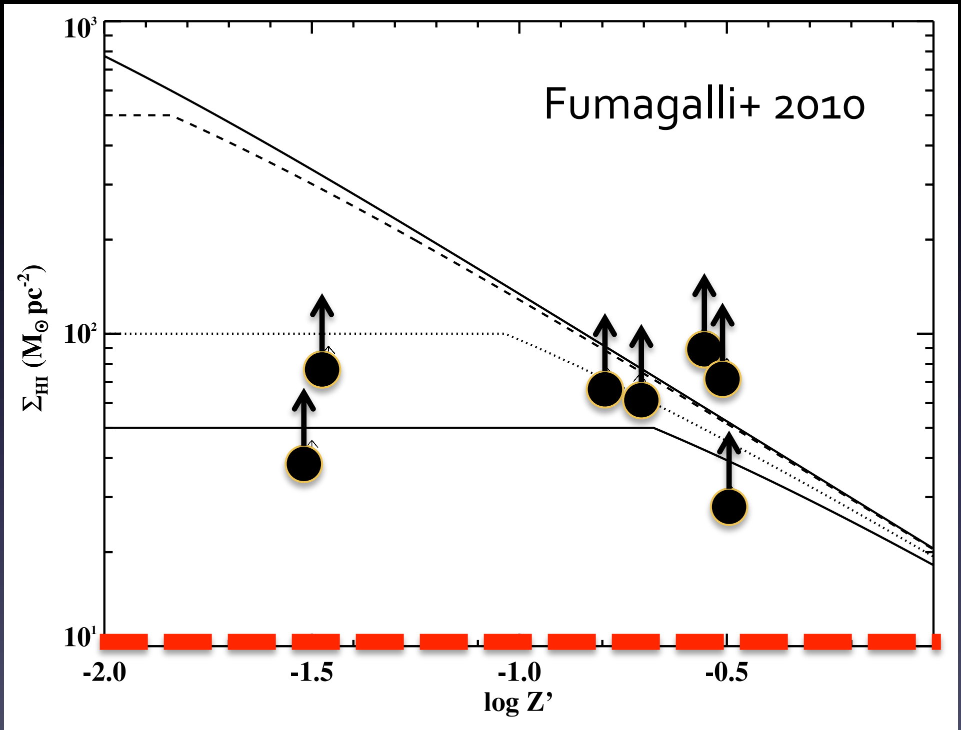
Krumholz, McKee, & Tumlinson (2008, 2009); McKee & Krumholz (2010)

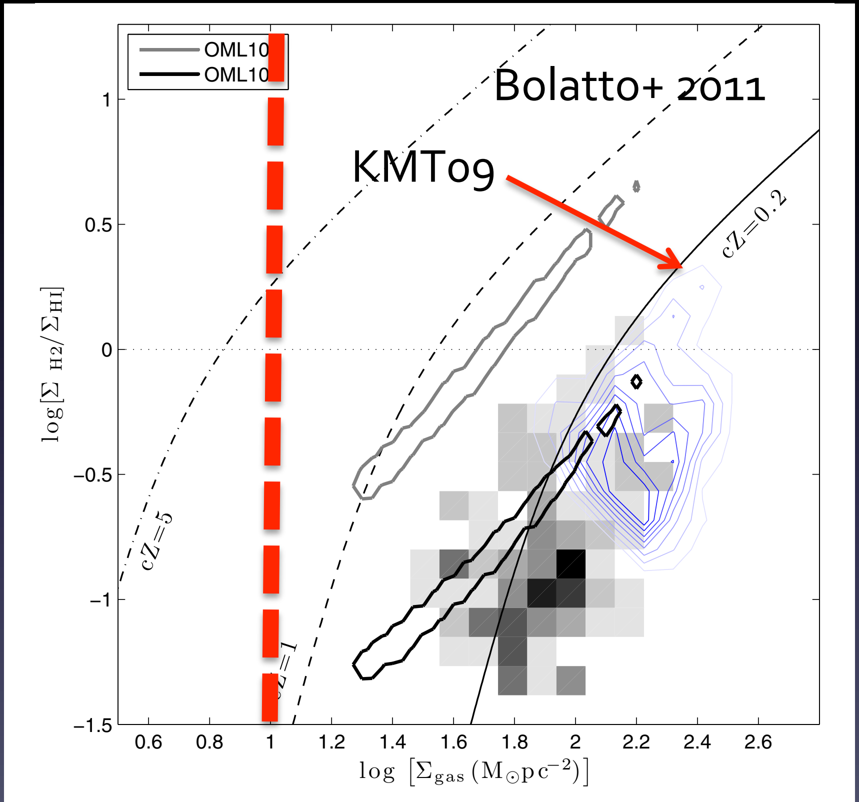
Observational Test: Individual Clouds in the MW



Lee+ 2012

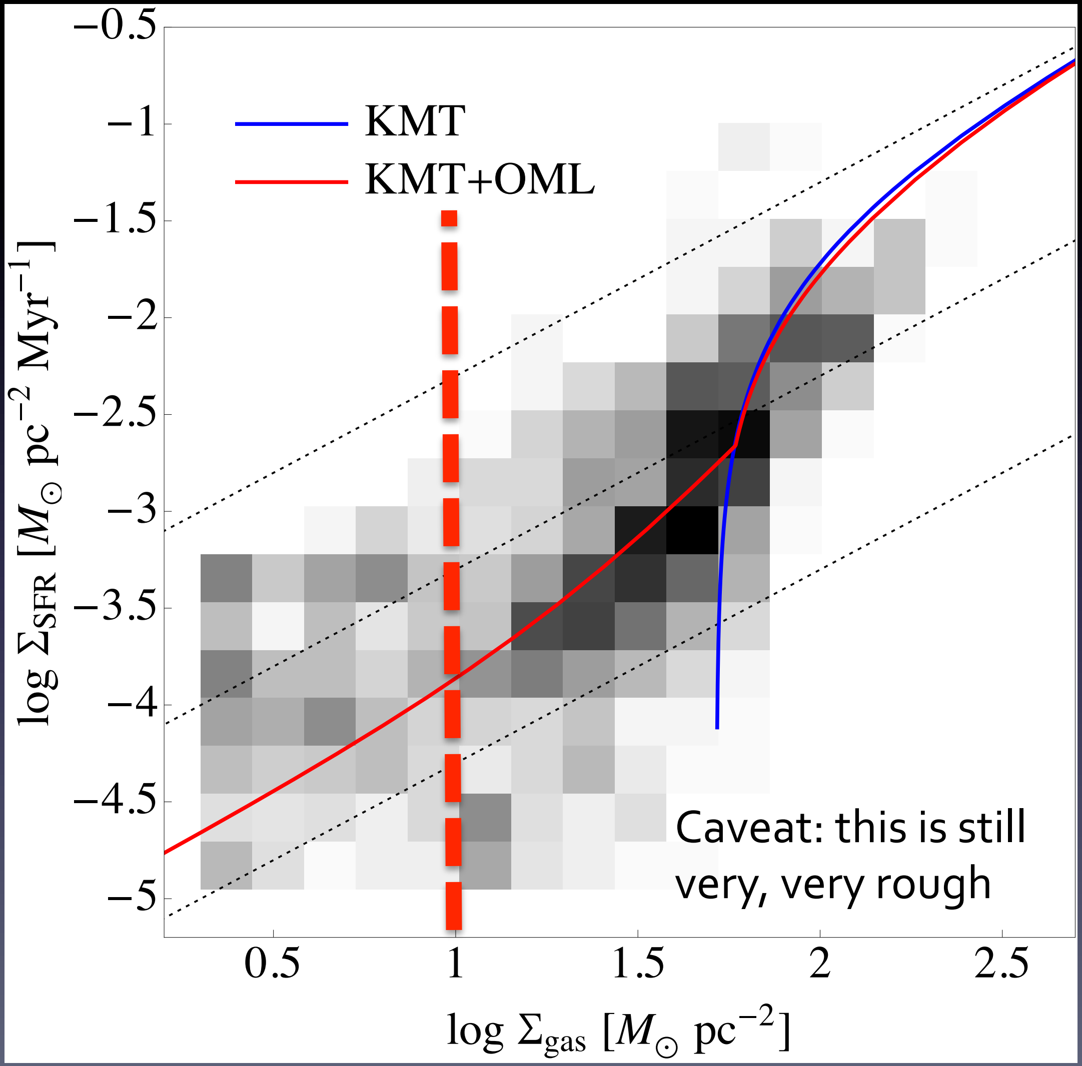
Tests at Low Metallicity





Also see talk by Dana Ficut-Vicas on Monday

What Explains the H_2 Floor?

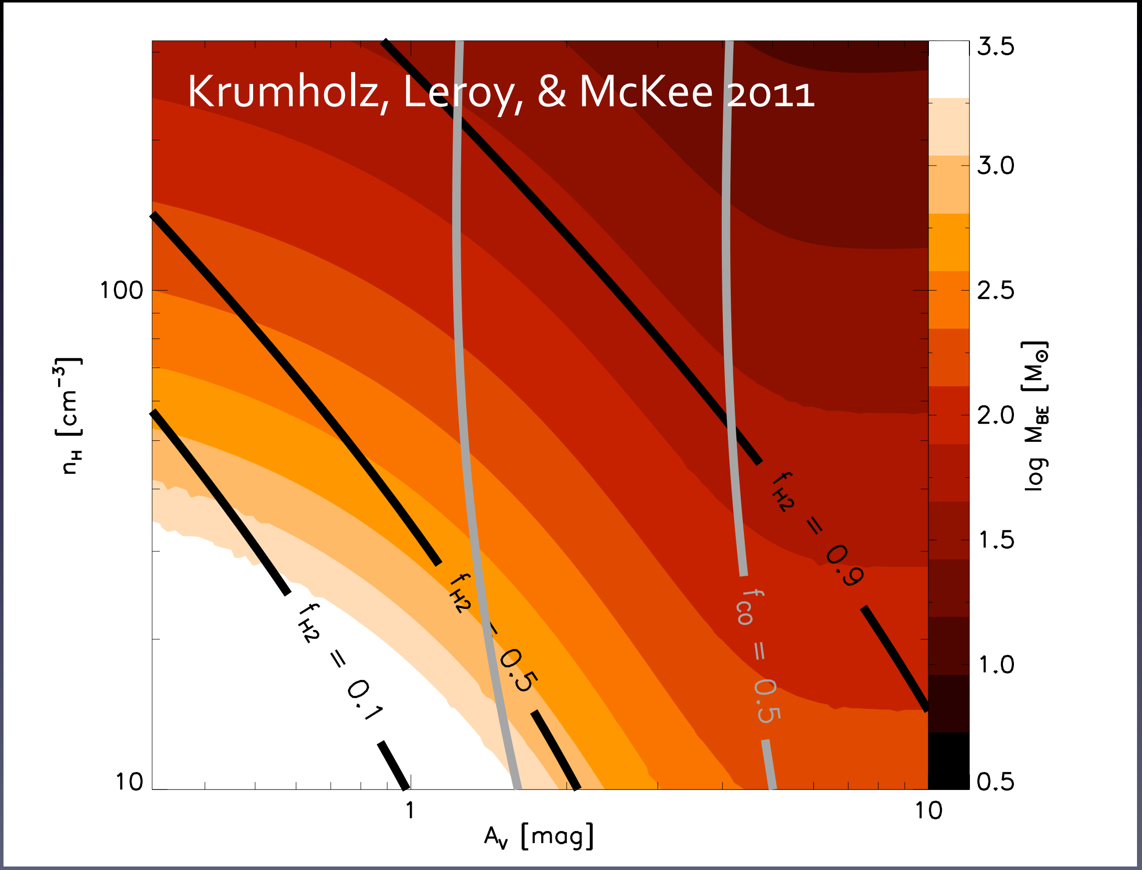


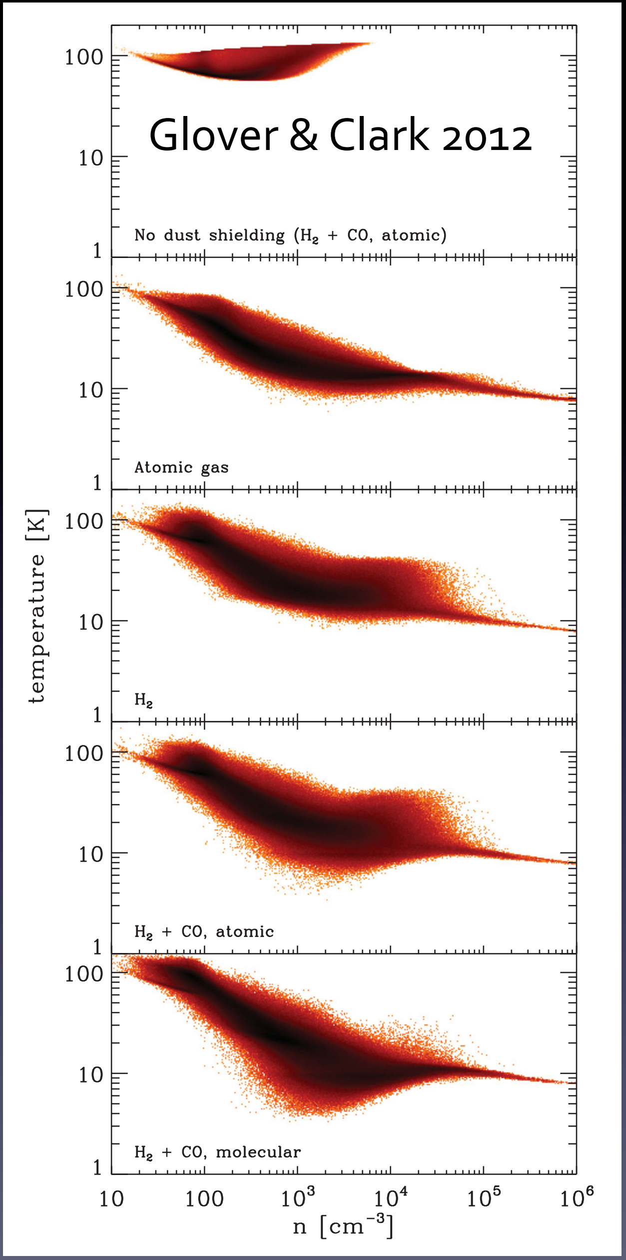
Gray: SMC data (Bolatto+ 2011)

Blue: KMT

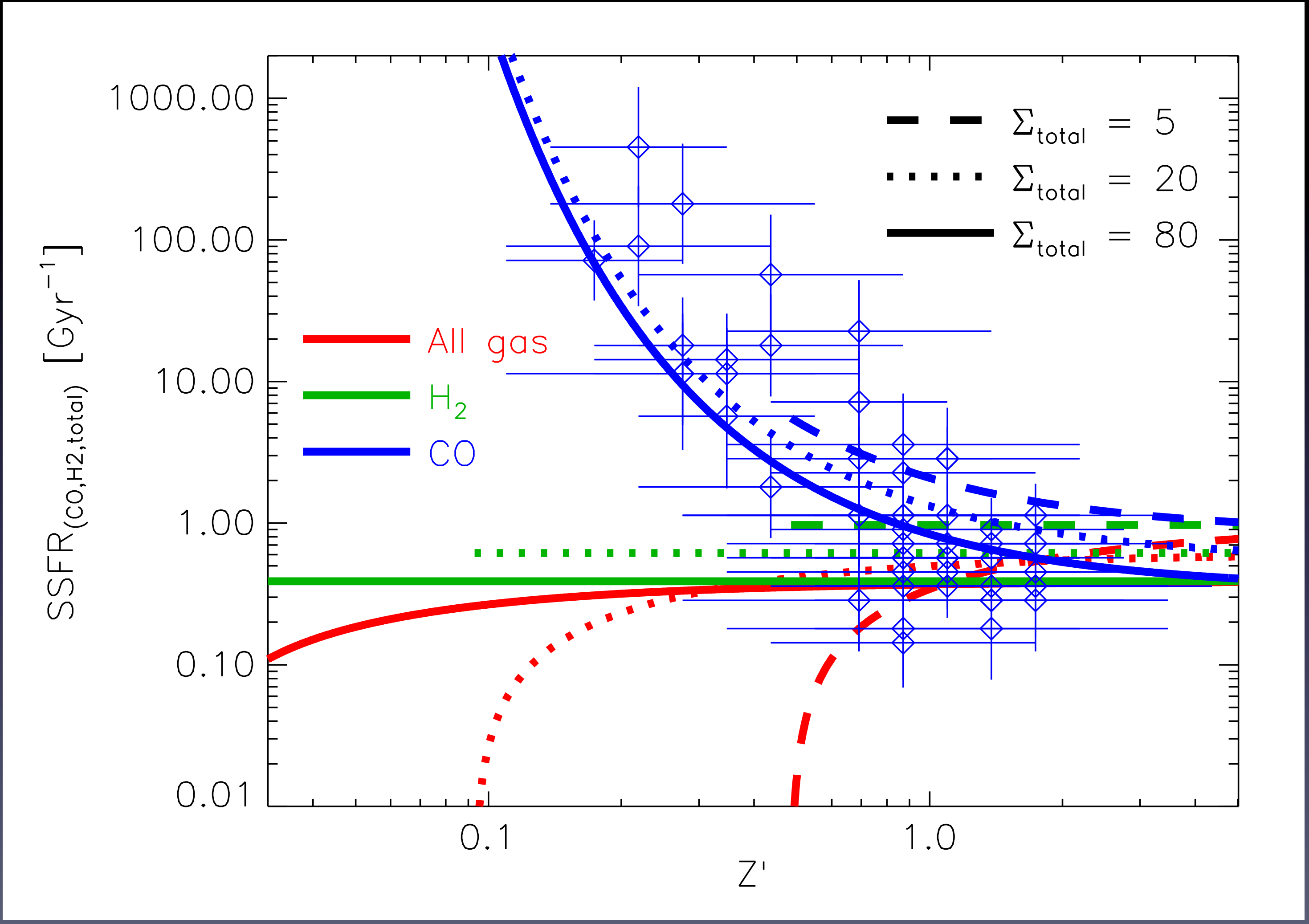
Red: KMT model with minimum f_{H_2} to maintain 2-phase equilibrium, pressure computed using Ostriker, McKee, & Leroy (2010) model

Why Does SF Follow H_2?



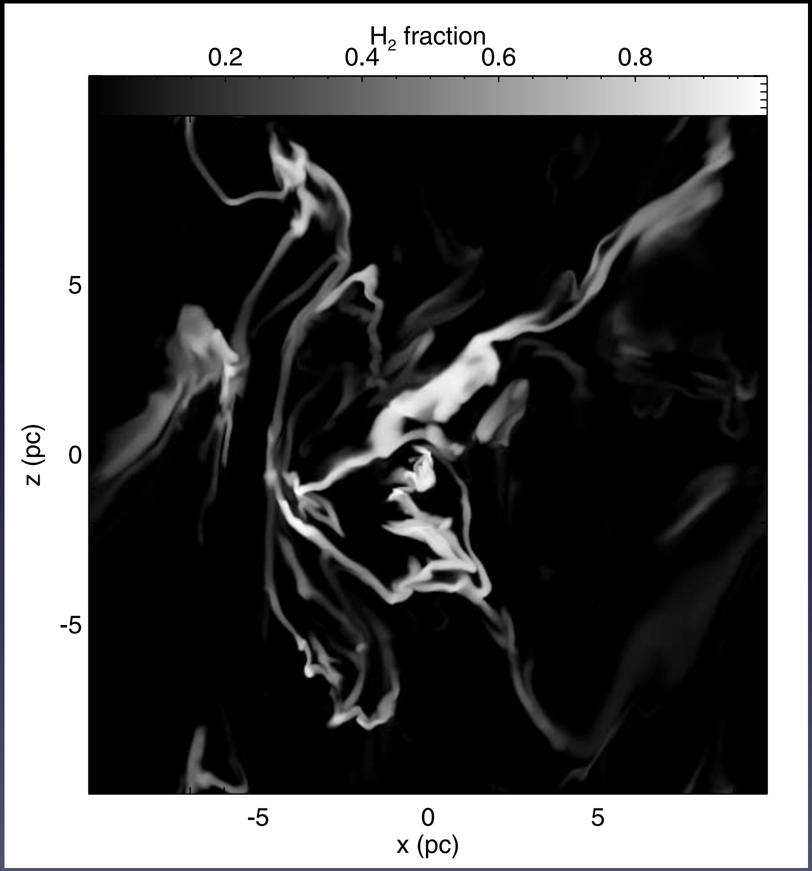


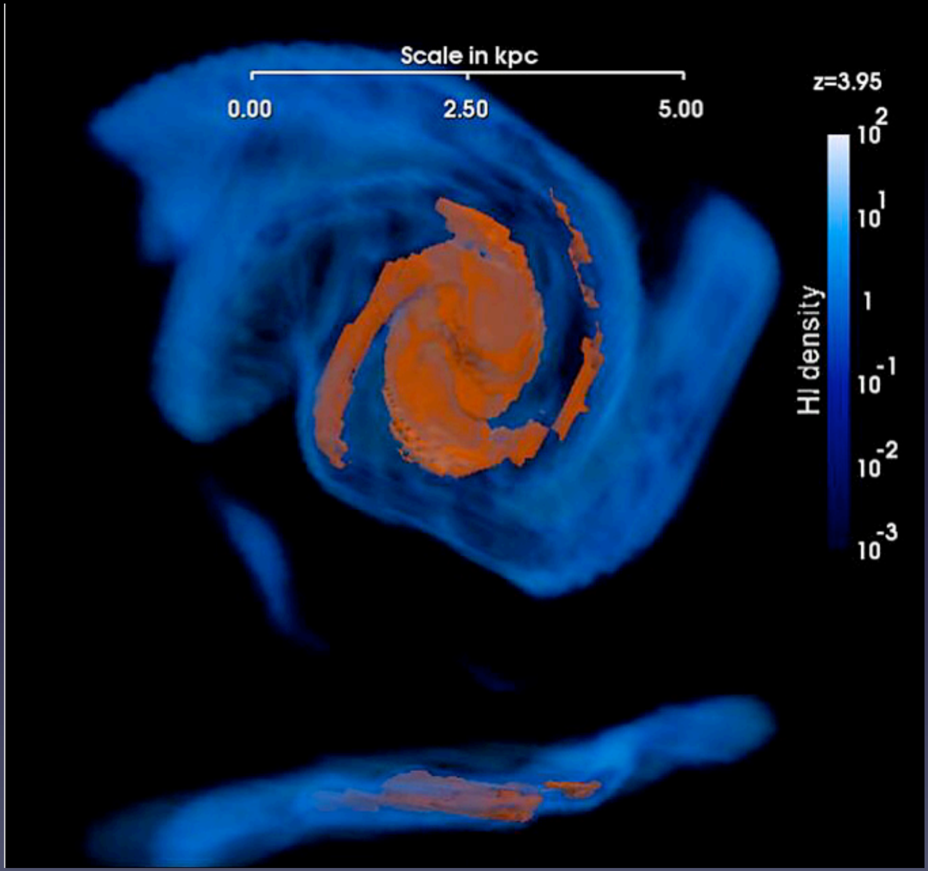
SF Follows H_2, not CO



Krumholz, Leroy, & McKee 2011; see also Bolatto+ 2011, Genzel+ 2011, Leroy+ 2011

Time-Dependent H_2 Formation



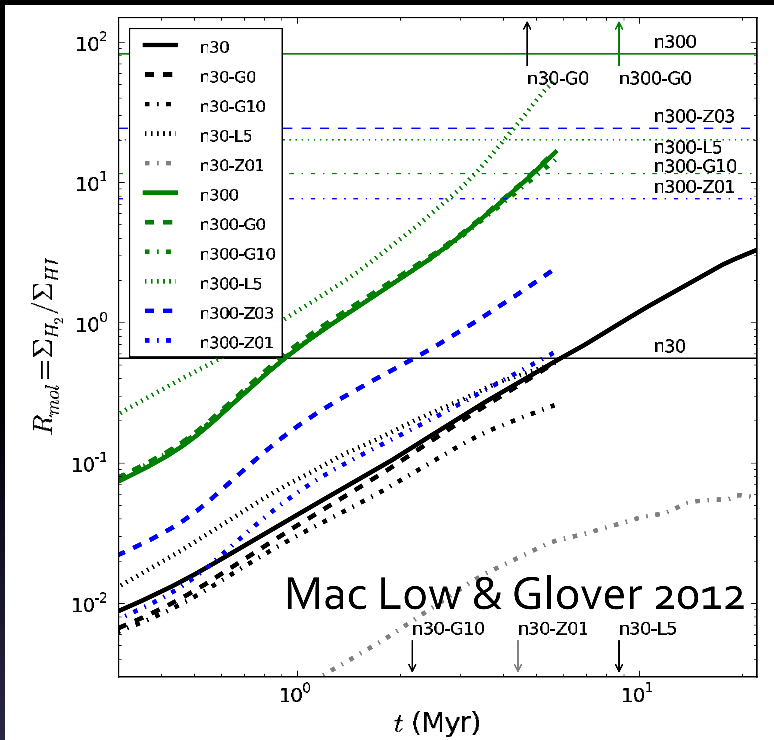


L ~ 10 pc; Glover & Mac Low 2007

L ~ 1 kpc; Gnedin+ 2009

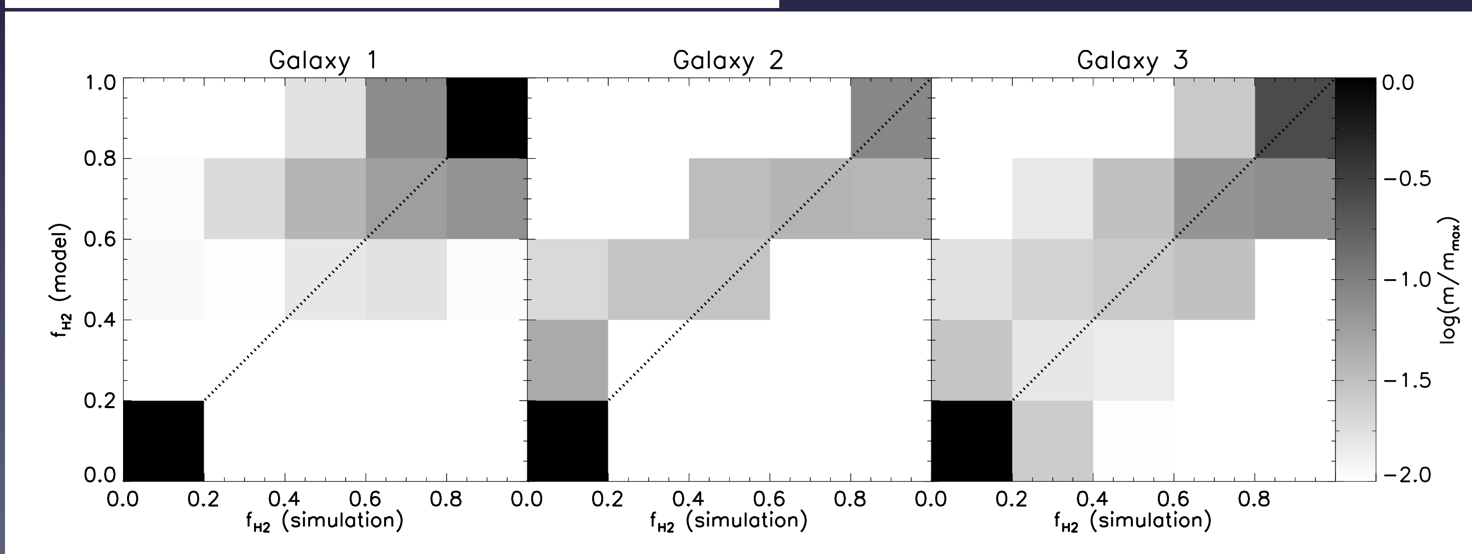
See also Pelupessy+ 2009, Christensen+ 2012

Is H_2 in Equilibrium?



Depends on size scale and gas metallicity:

- > 100 pc scales: yes on average
- ~10 pc scales: maybe; simulations suggest no, but observations suggest yes,

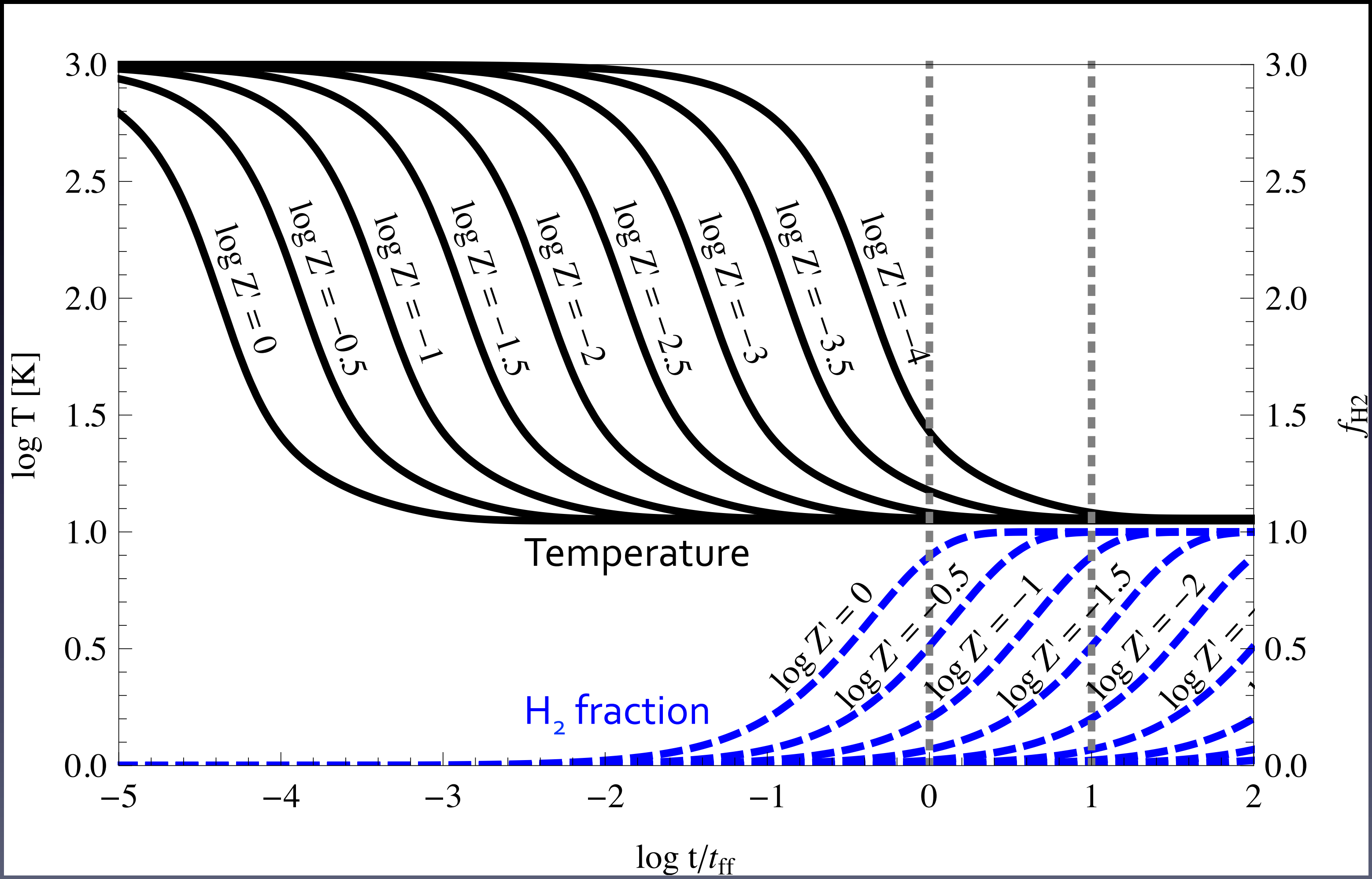


Krumholz & Gnedin 2011

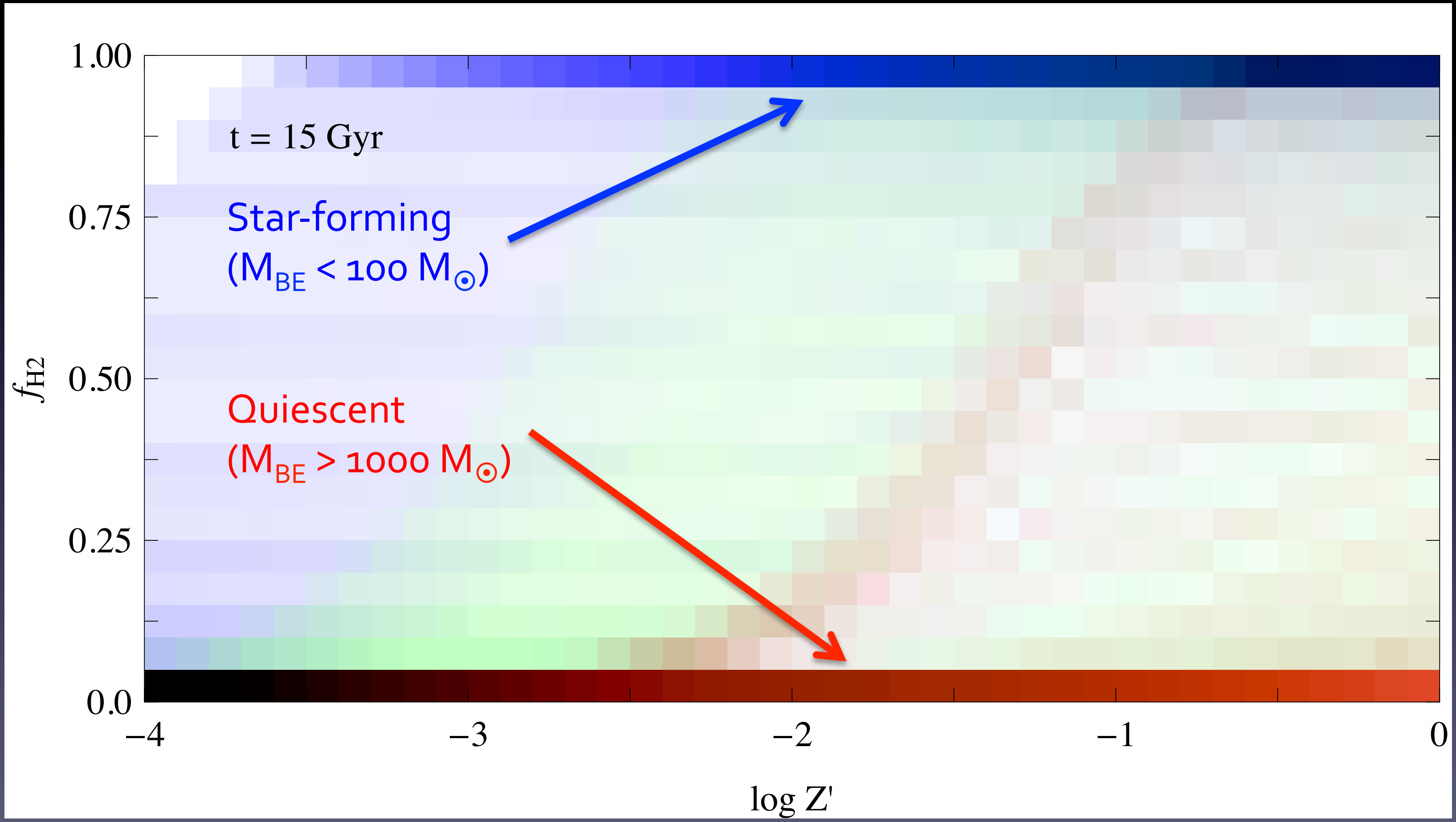
Equilibrium Timescales

- H_2 forms slowly: $t_{H_2} \sim 1/n\mathcal{R} \approx 100$ Myr/$n_1 \mathcal{C}$ Z′
- Gas cools quickly: $t_{cool} \sim (T/91\ K) / k_{CII\text{-}H}\ \delta_C\ n$ = 0.04/$n_1 \mathcal{C}$ Z′ (T/91 K) exp(91 K/T) Myr
- At low Z′, can have $t_{cool} << t_{ff} << t_{H_2}$ ➔ SF should take place before bulk of gas forms H_2

Equilibrium Timescales



Implication: SF in HI!



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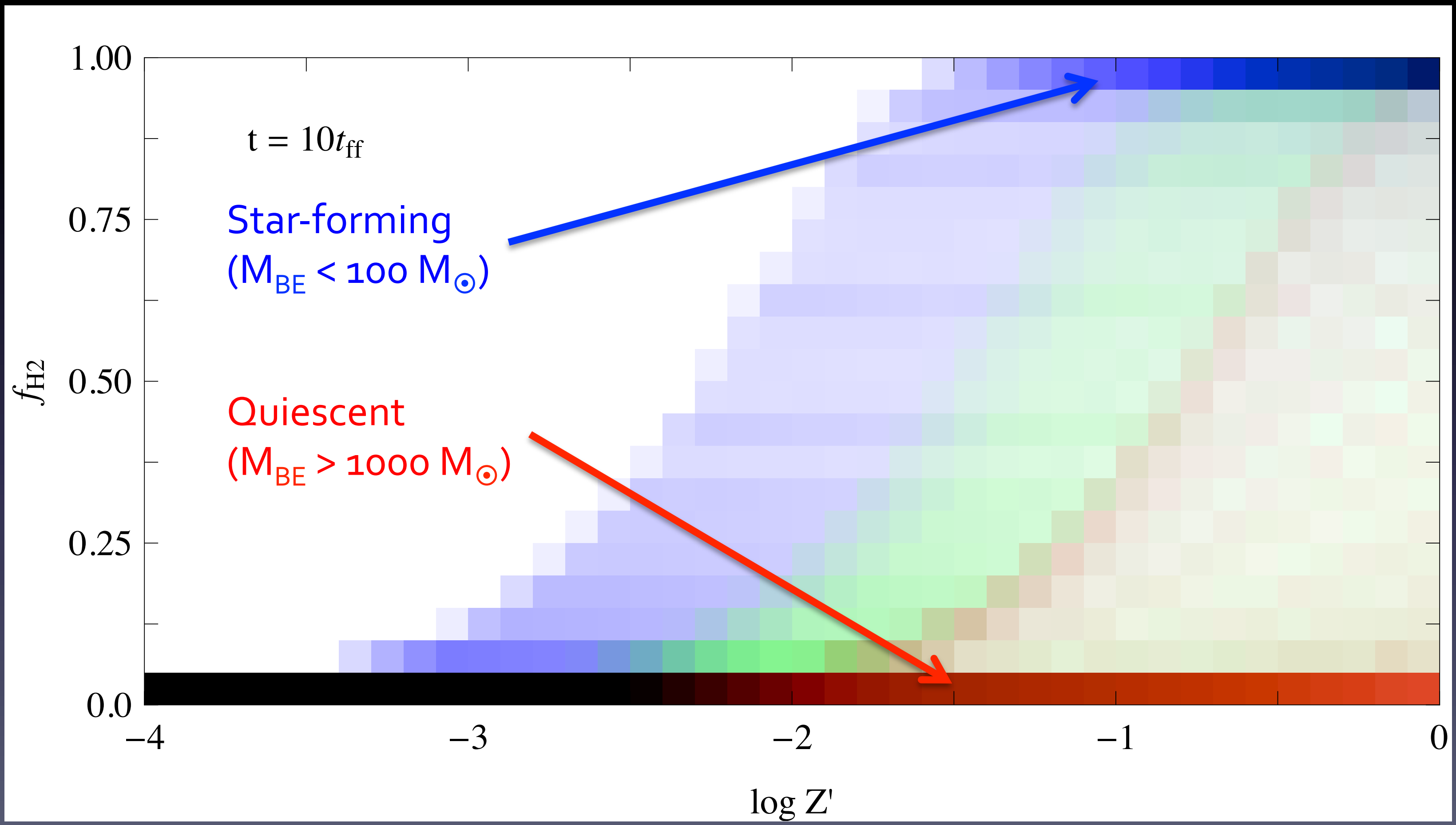

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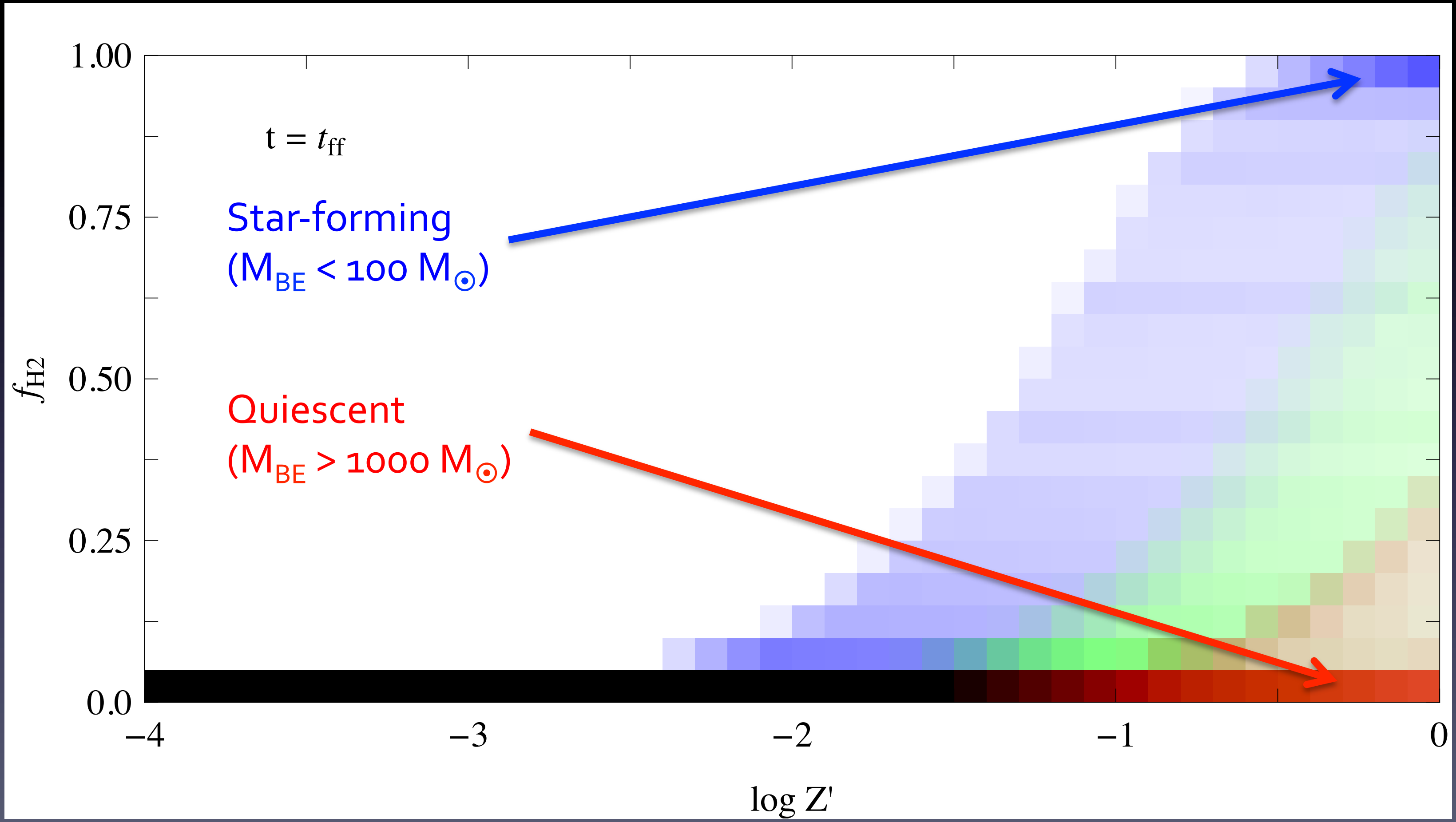
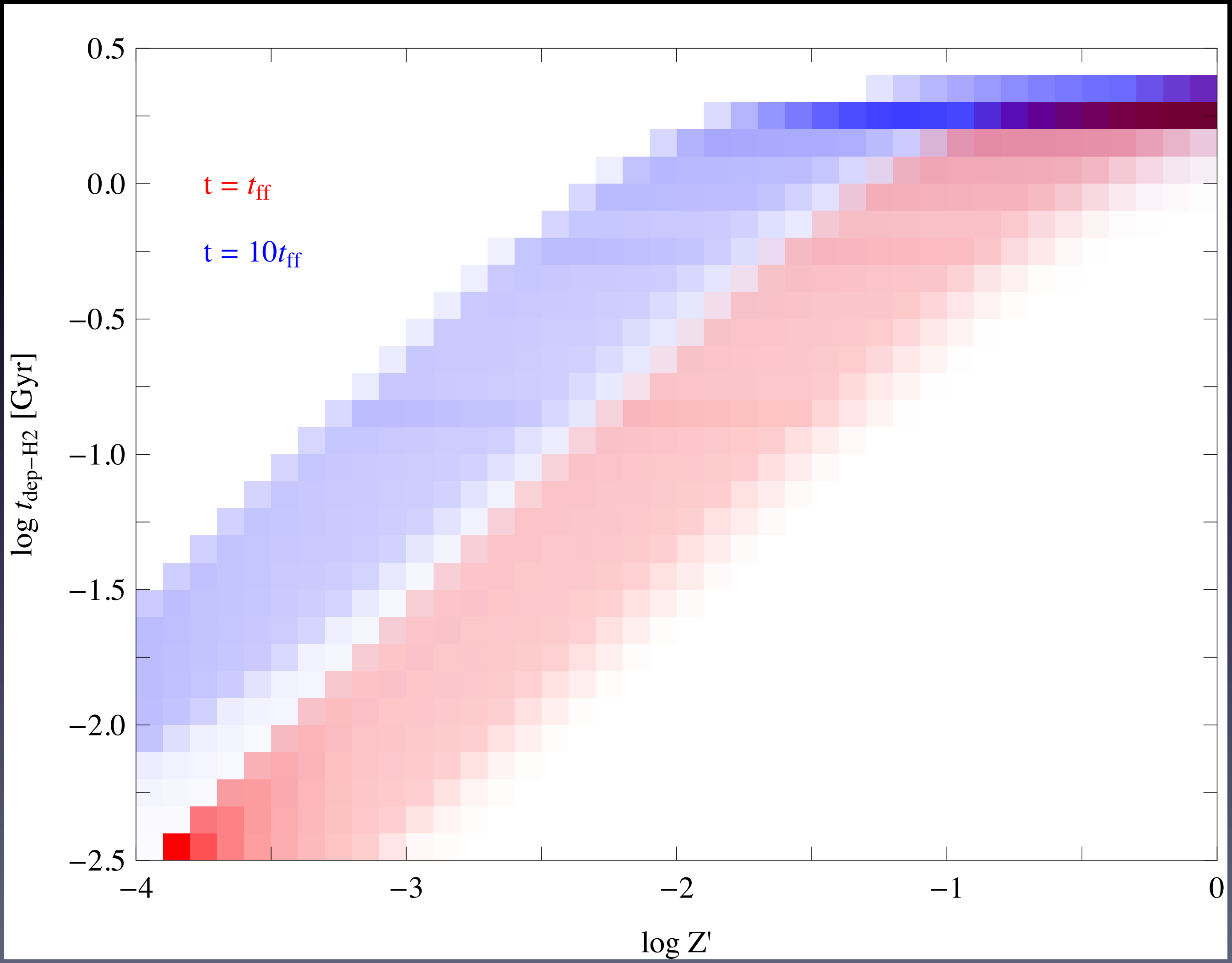
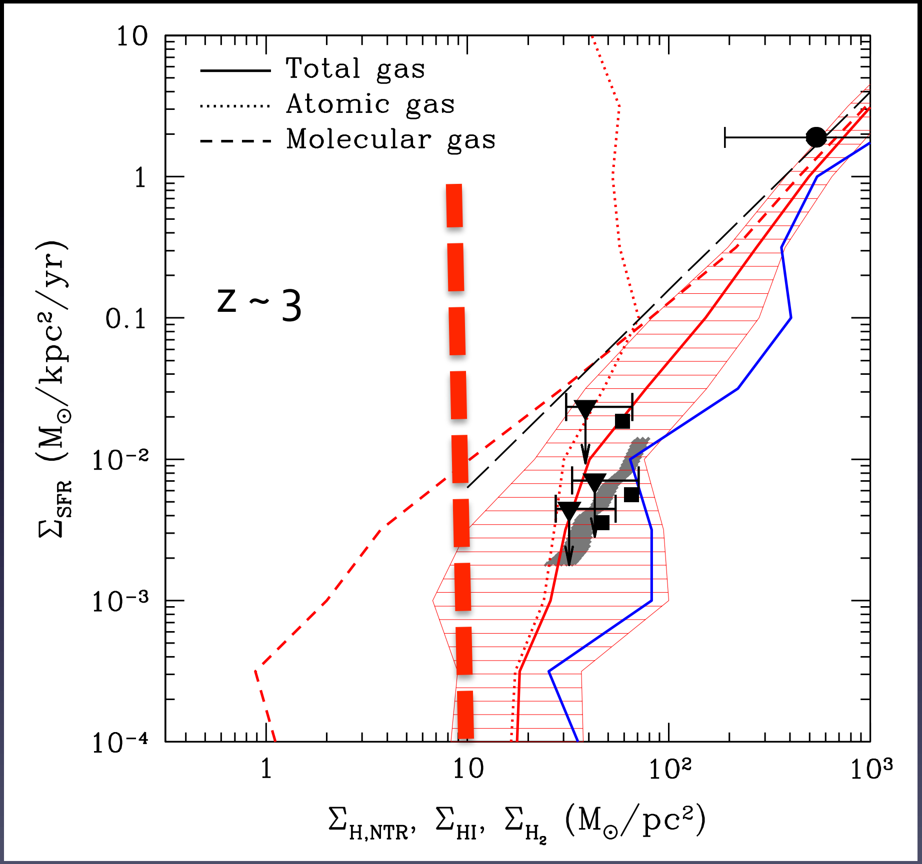


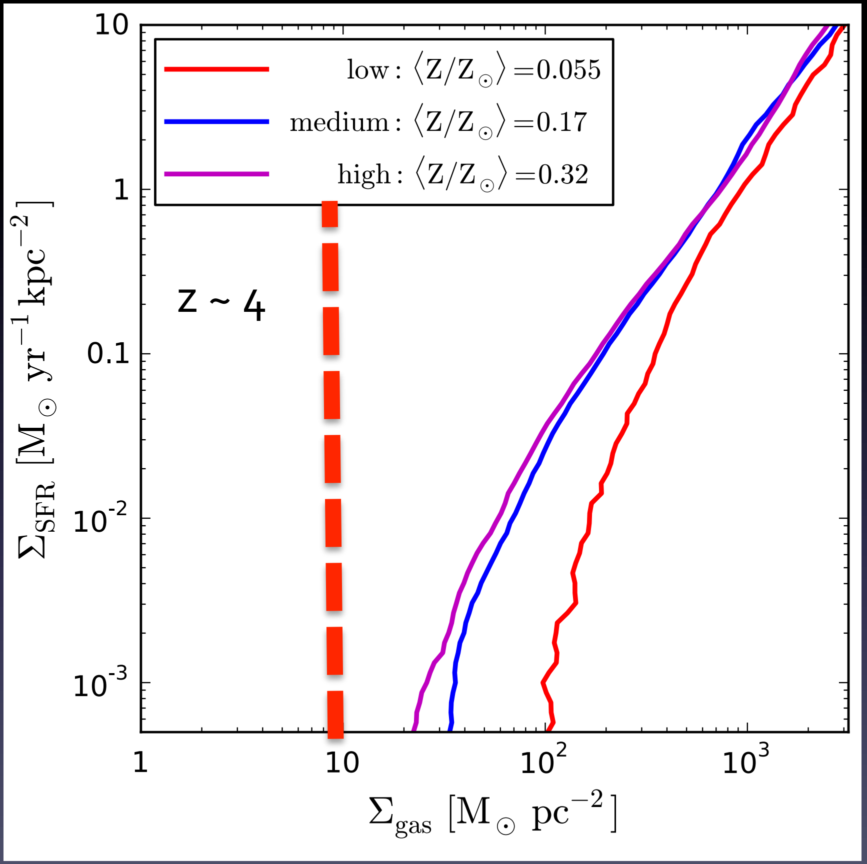
Implication: SF in HI!



Cosmological Implications

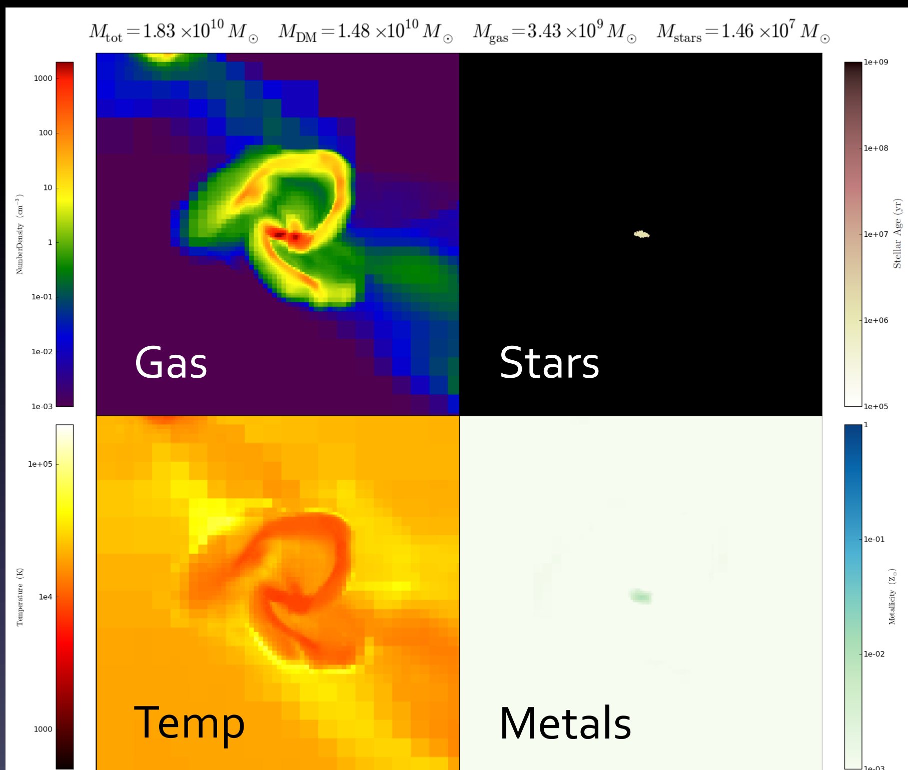


Gnedin & Kravtsov 2010

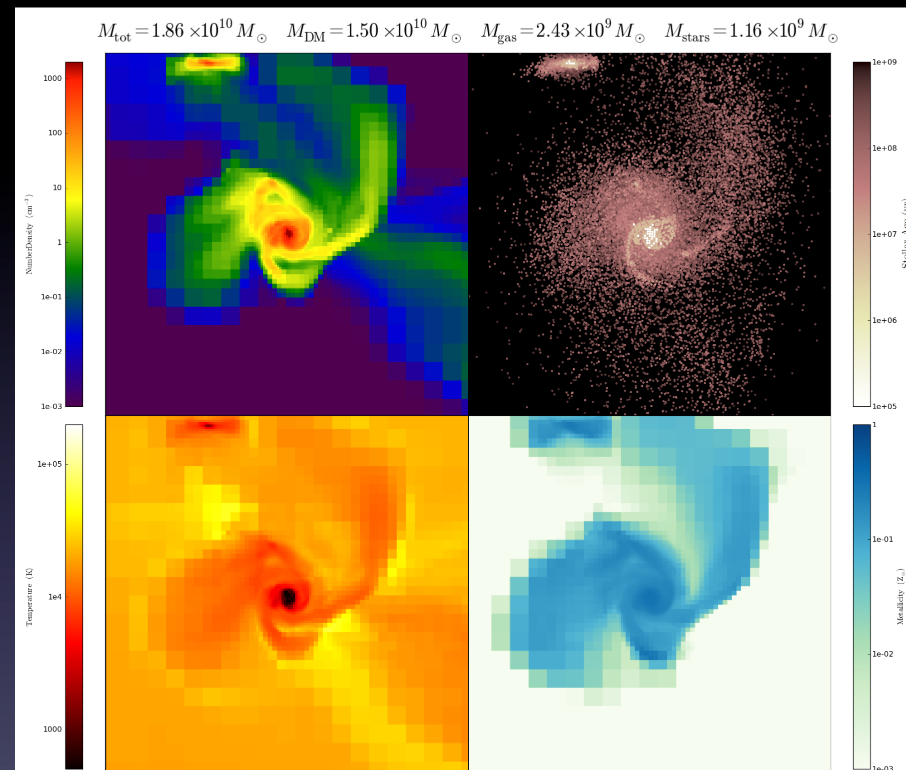


Kuhlen+ 2012

Implications for Dwarf Galaxies



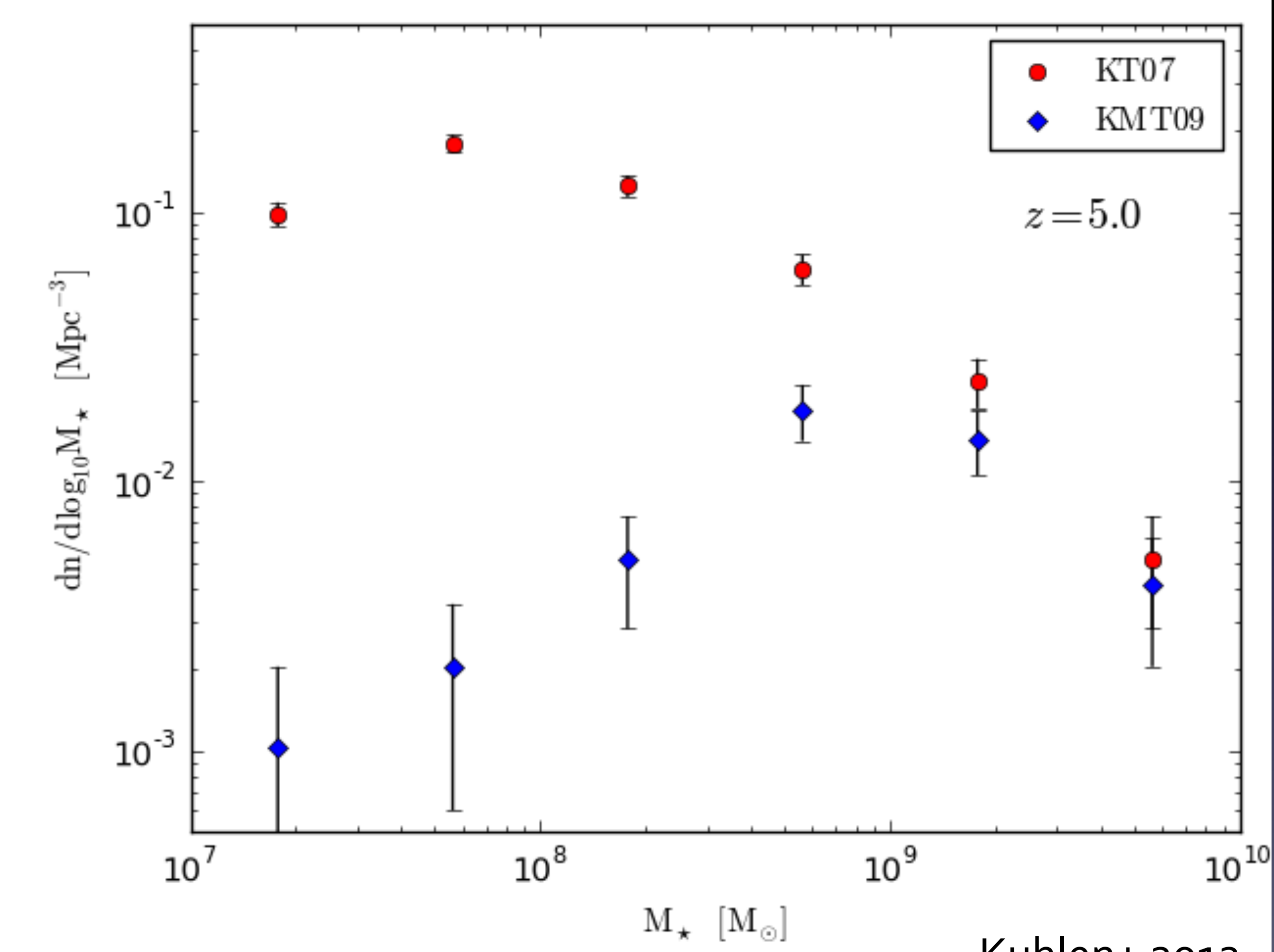
Metallicity-dependent SF



Metallicity-independent SF

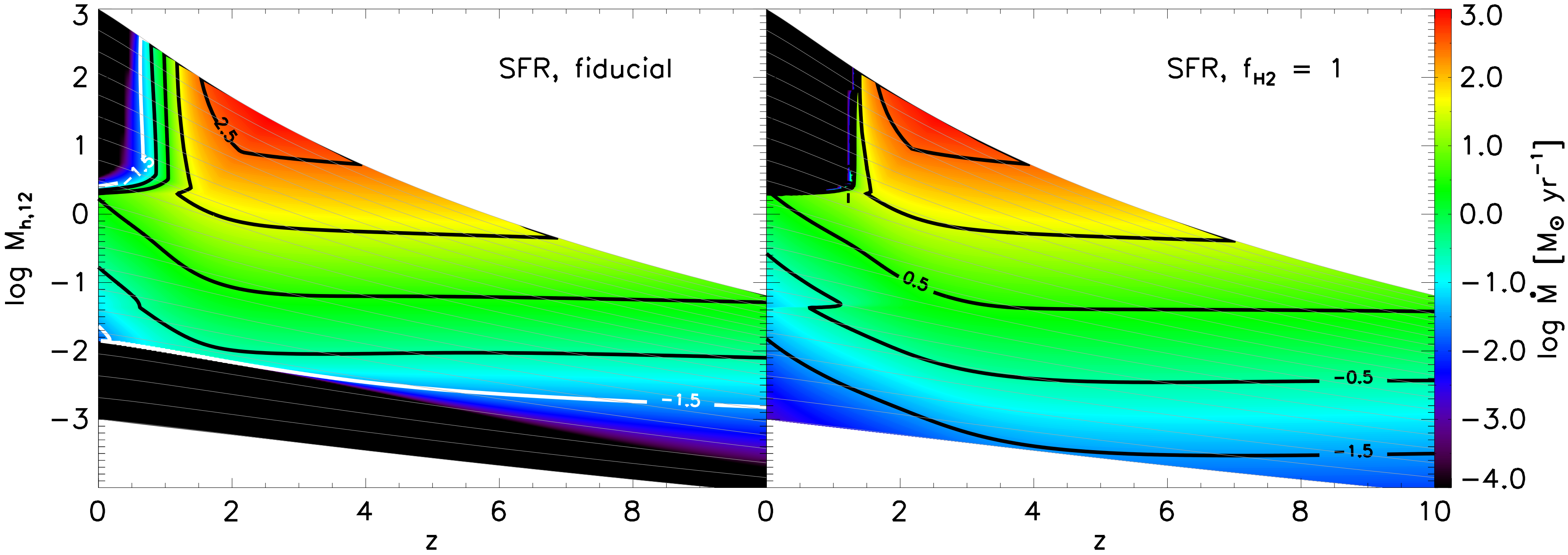
Same halo (~10^{10} $M_\odot$, z~5) in two simulations with different SF recipes (Kuhlen+ 2012)

Mass Function at High z



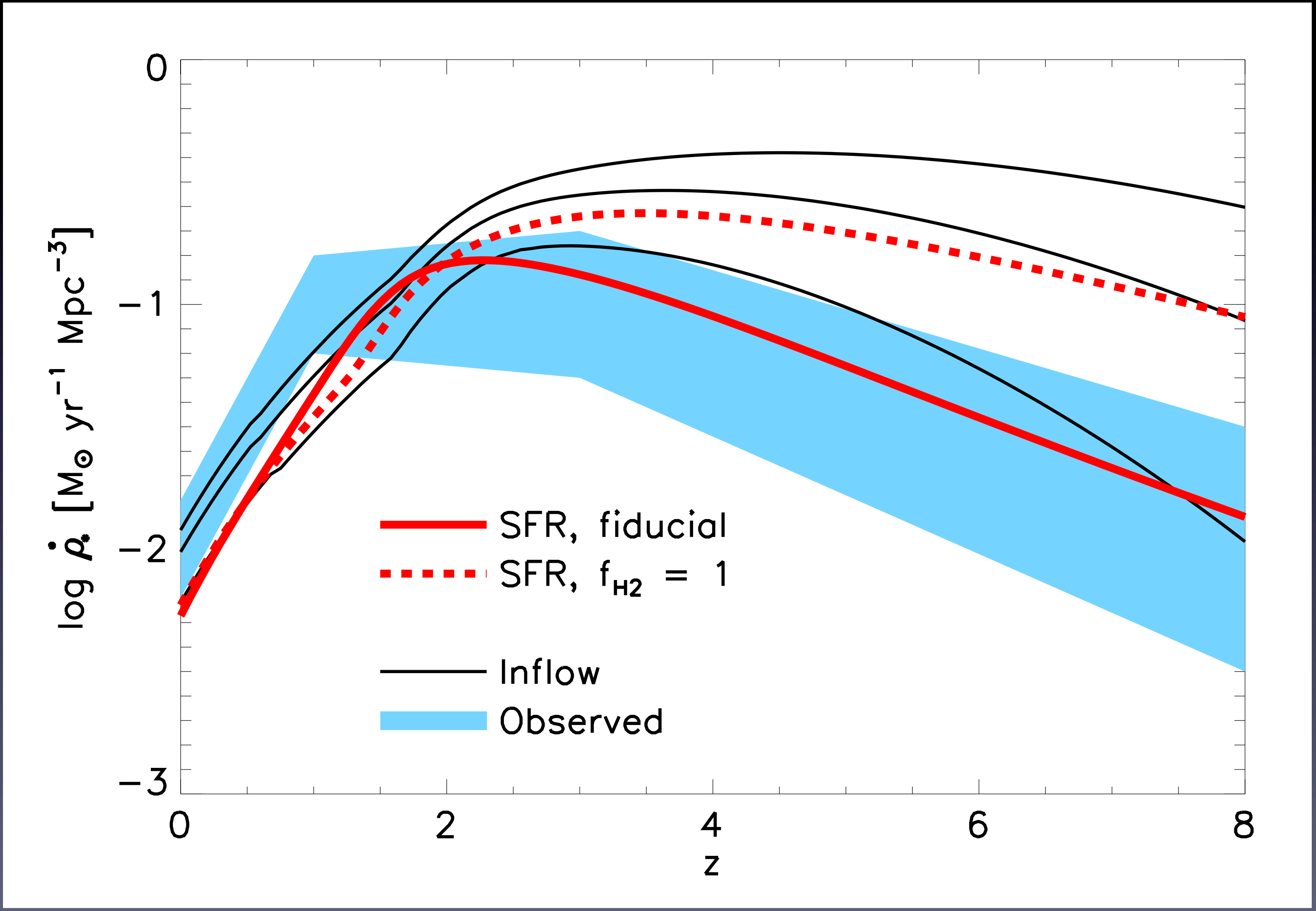
Kuhlen+ 2012

Press-Schecter-Based Model

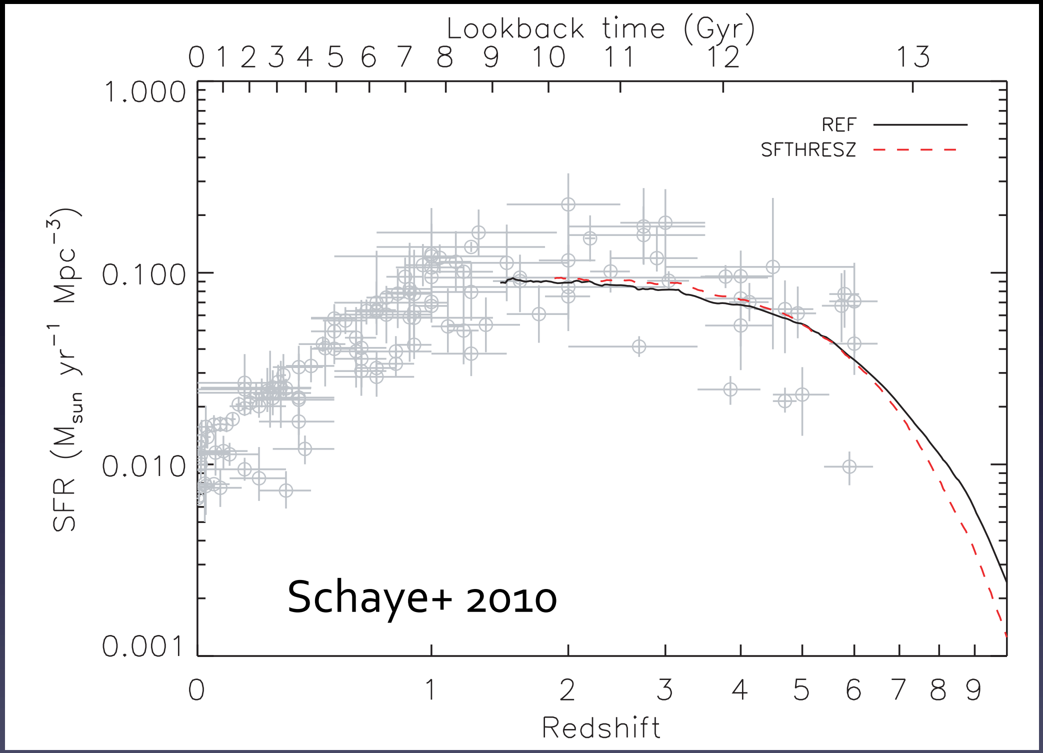


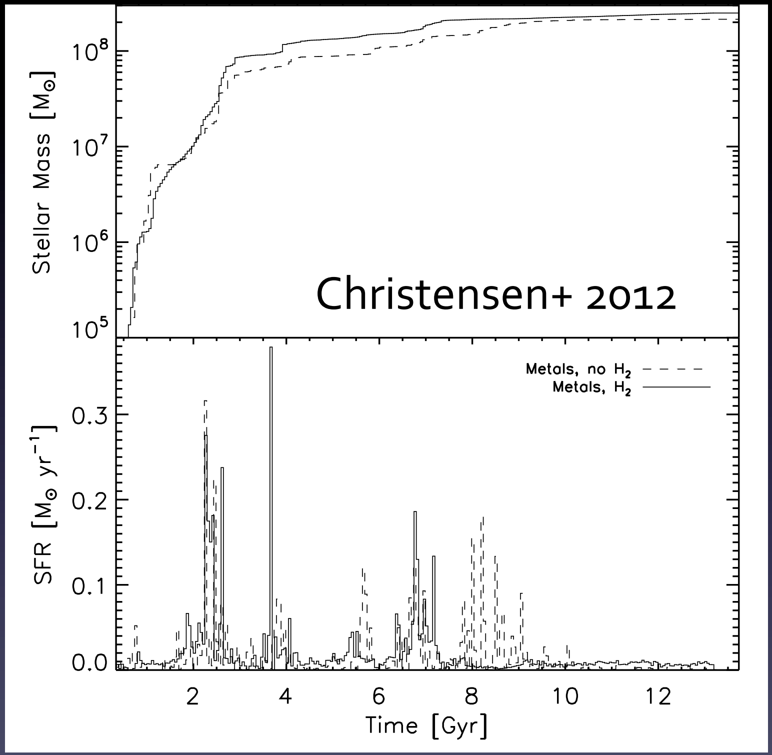
Krumholz & Dekel 2012

Observed vs. Model SF History



Not Quite So Simple





Why different than Kuhlen+, Krumholz & Dekel?
Probably feedback.

Summary

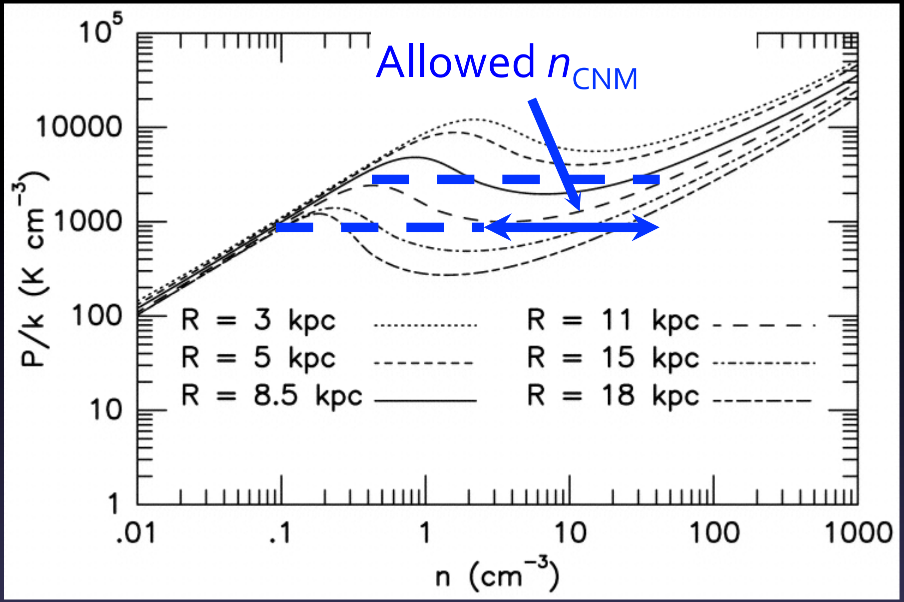
- HI / H_2 transition tracks warm / cold transition due to radiation-shielding competition
- Non-equilibrium effects become important at low Z
- Shielding depends on Z, resulting in SF rate that depends on metallicity
- This may have important effects for galaxy formation at the dwarf end, but this depends on the feedback

Computing f_{H_2} in Galaxies

(Krumholz, McKee, & Tumlinson 2008, 2009; McKee & Krumholz 2010)

What is $\chi \propto (\sigma_d / \mathcal{R}) (E_0^* / n)$?

- Dust opacity σ_d and H_2 formation rate R both $\propto$ Z, so σ_d / R ~ const
- CNM dominates shielding, so n is the CNM density



FGH curves for MW (Wolfire et al. 2003)

- CNM density set by pressure balance with WNM, and $n_{CNM} \propto E_0^*$, with weak Z dependence.

$\Rightarrow$ $\chi \propto (\sigma_d / R) (E_0^* / n) \sim 1$ in all galaxies!

The Star Formation Law