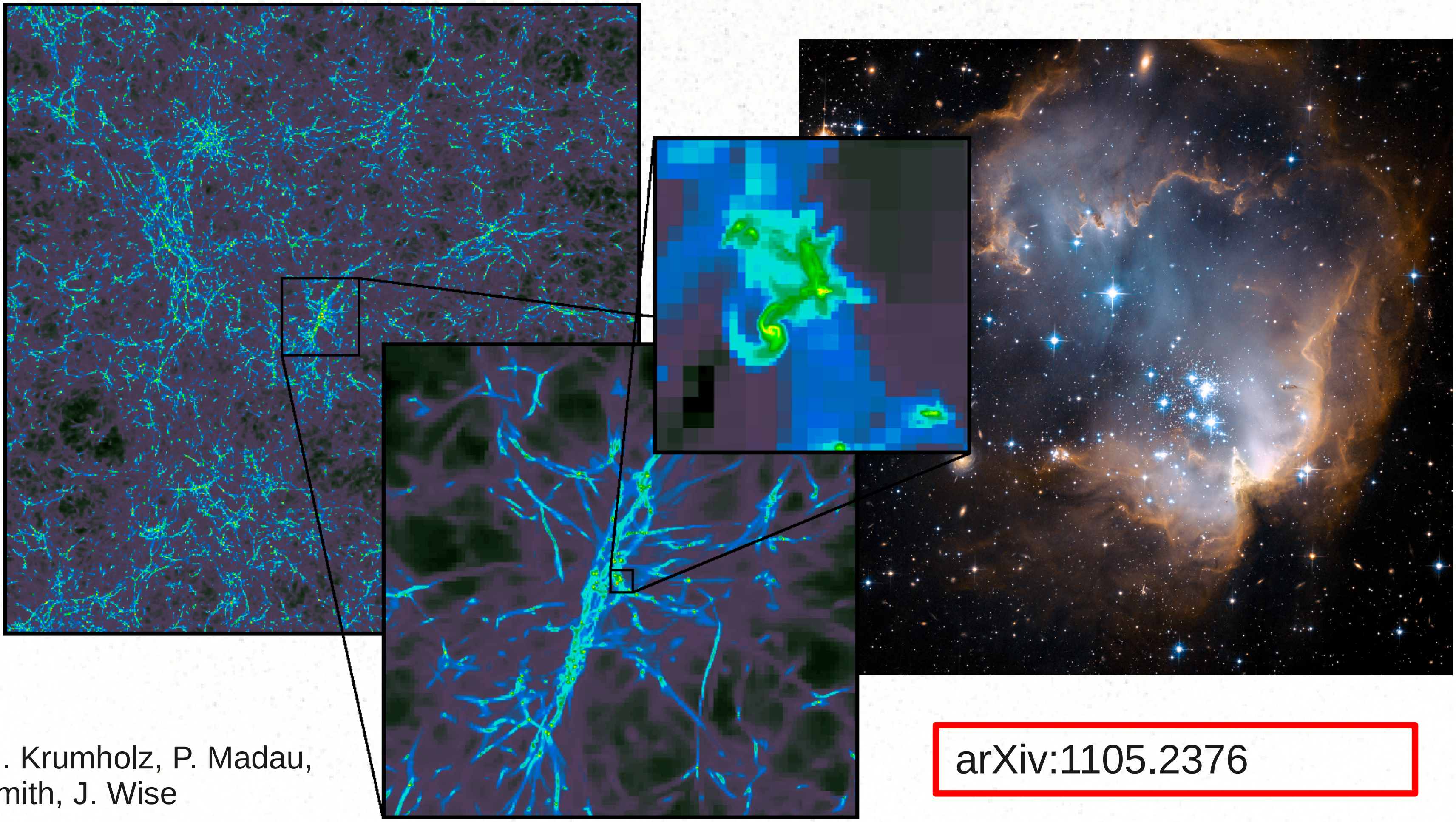
Dwarf Galaxy Formation with H_2-regulated Star Formation

Michael Kuhlen, UC Berkeley



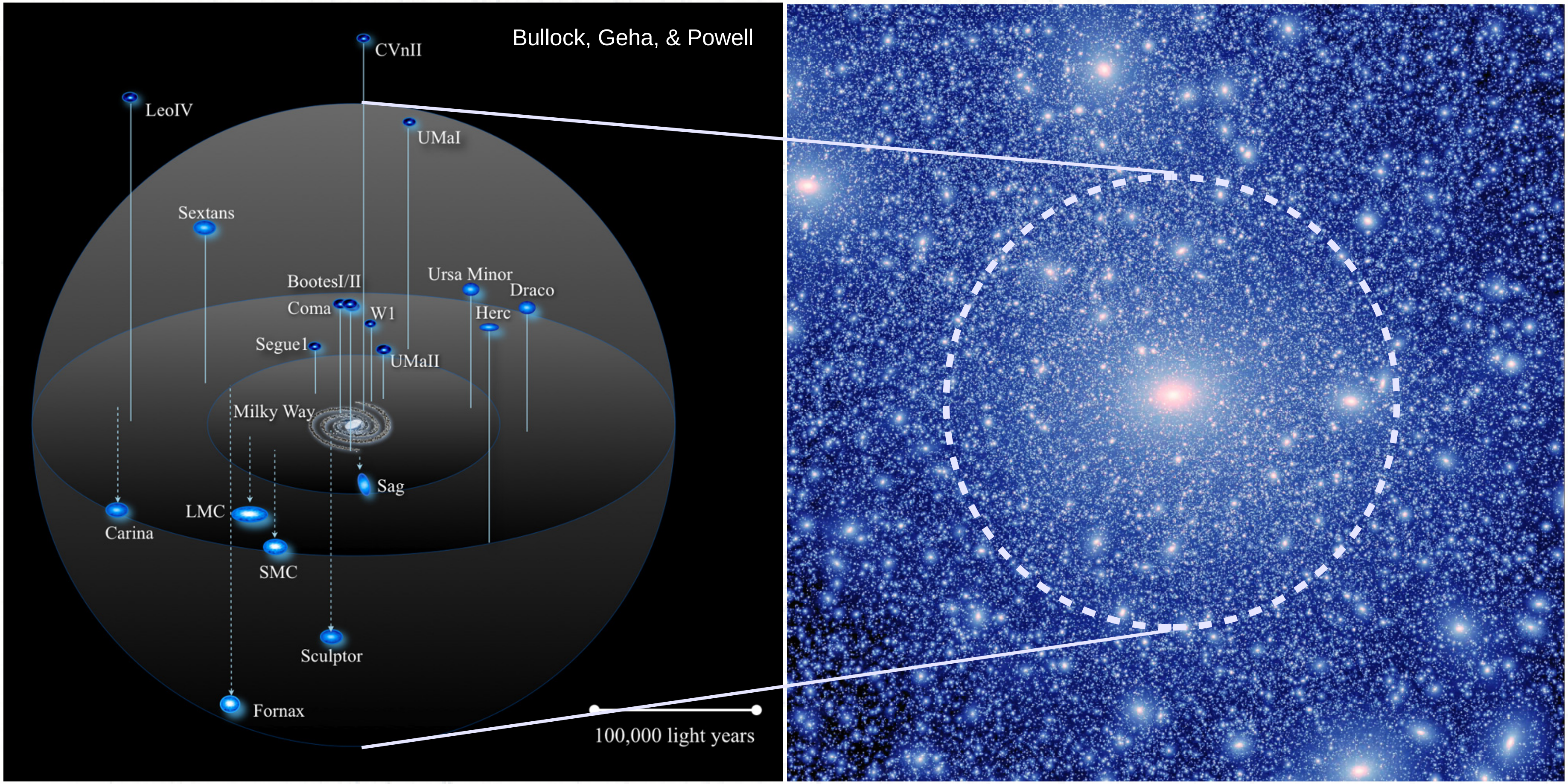
w/ M. Krumholz, P. Madau,
B. Smith, J. Wise

arXiv:1105.2376

The Missing Satellites Problem

Reality

Dark Matter Simulation



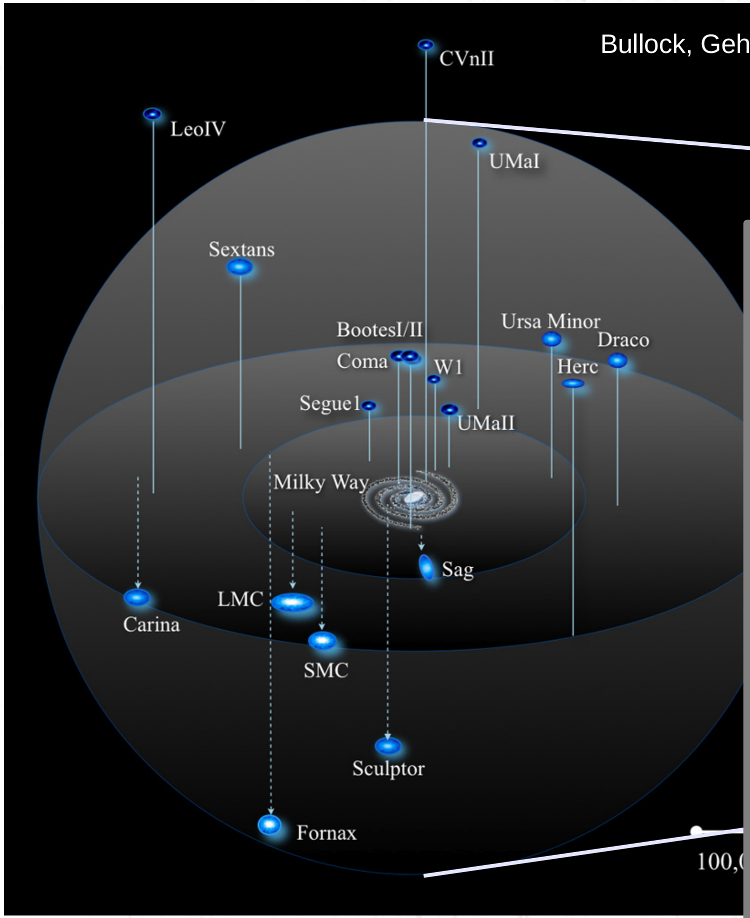
Bullock, Geha, & Powell

There is strong tension between the observed number of dwarf satellite galaxies and the predicted number of dark matter subhalos orbiting our Milky Way galaxy.

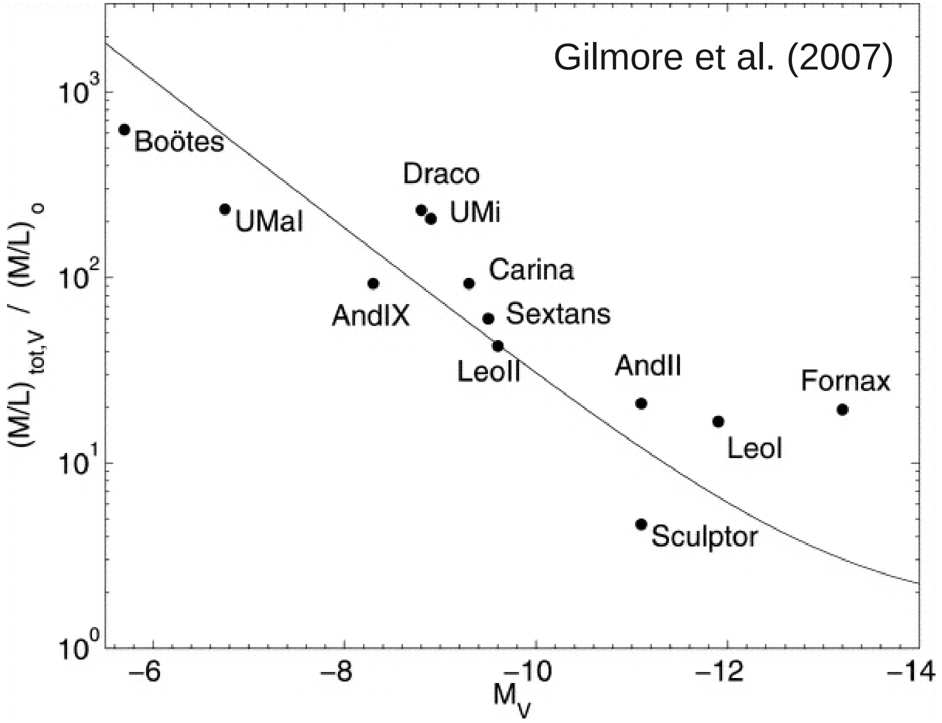
The Missing Satellites Problem

Reality

Dark Matter Simulation



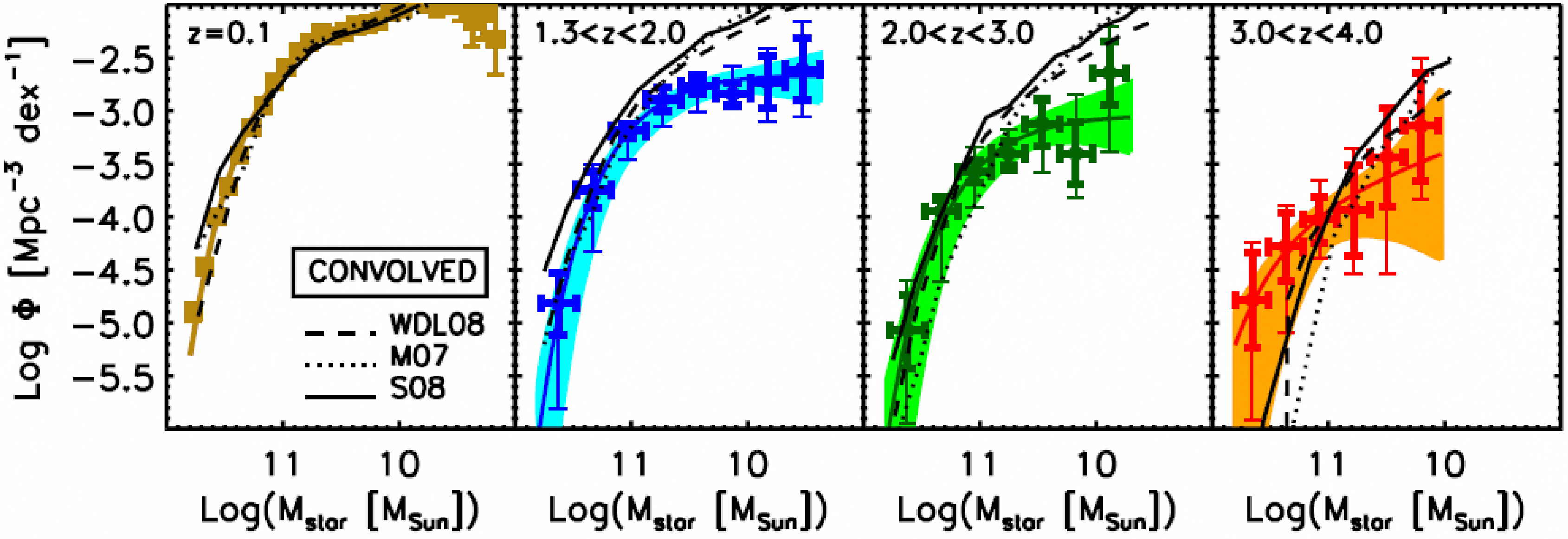
The Milky Way dwarf satellite galaxies are the most dark matter dominated objects in the universe!



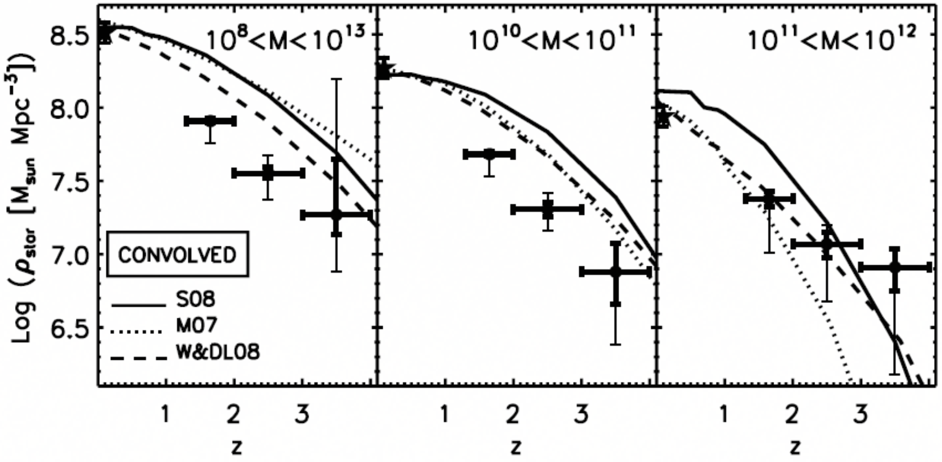
There is strong tension between
and the predicted number of da

The Field Dwarf Galaxy Problem

Marchesini et al. (2009) [see also Fontanot et al. 2009, Cirasuolo et al. 2010]

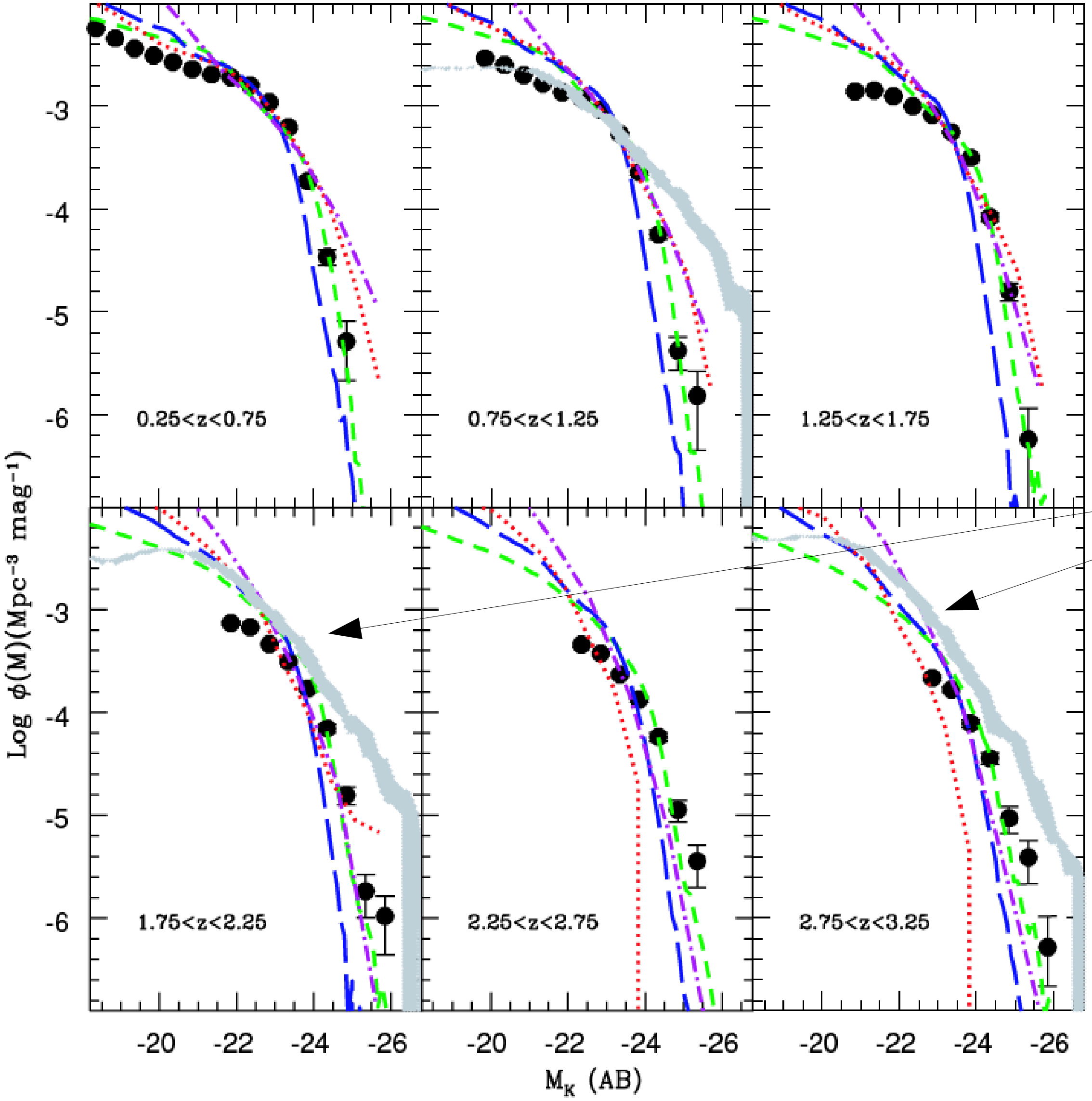


Semi-analytic models of galaxy formation (including prescriptions for SN feedback!) **over-predict the abundance of low mass galaxies and the stellar mass density** at intermediate to high redshifts.



The Field Dwarf Galaxy Problem

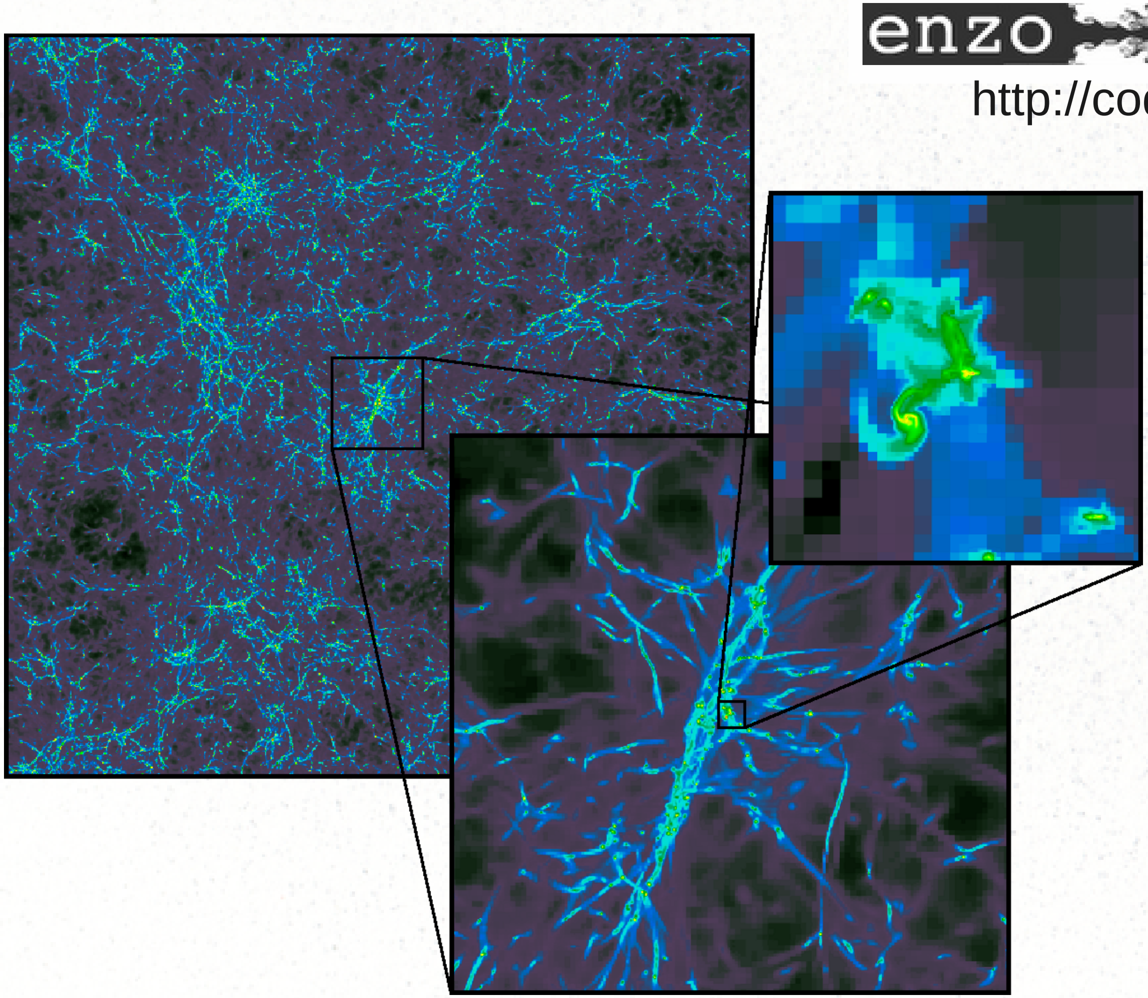
from Cirasuolo et al. 2010



Similar problems for hydrodynamic galaxy formation **simulations including SN feedback**.

Hydro Simulations:
Cen & Ostriker (2006)
Nagamine et al. (2006)

Hydrodynamical Galaxy Formation Simulations



enzo

enzo

Astrophysical Adaptive Mesh Refinement

http://code.google.com/p/enzo/

- Cosmological Adaptive Mesh Refinement
- Follows dark matter and hydrodynamics.
- Includes cooling, star formation, supernova feedback, etc.
- **Community code**
- I've been a contributing developer since 2005.

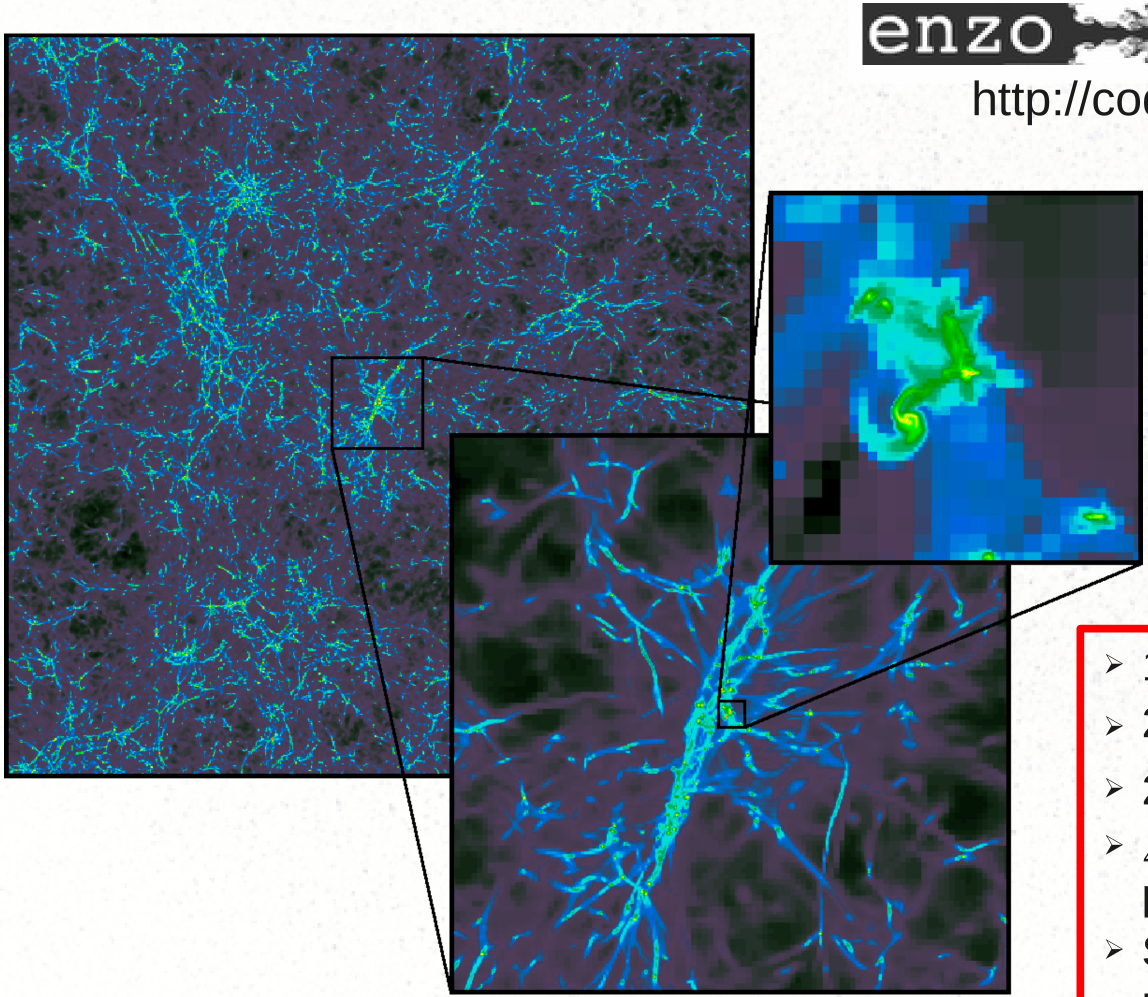
Hydrodynamical Galaxy Formation Simulations

enzo

enzo

Astrophysical Adaptive Mesh Refinement

http://code.google.com/p/enzo/

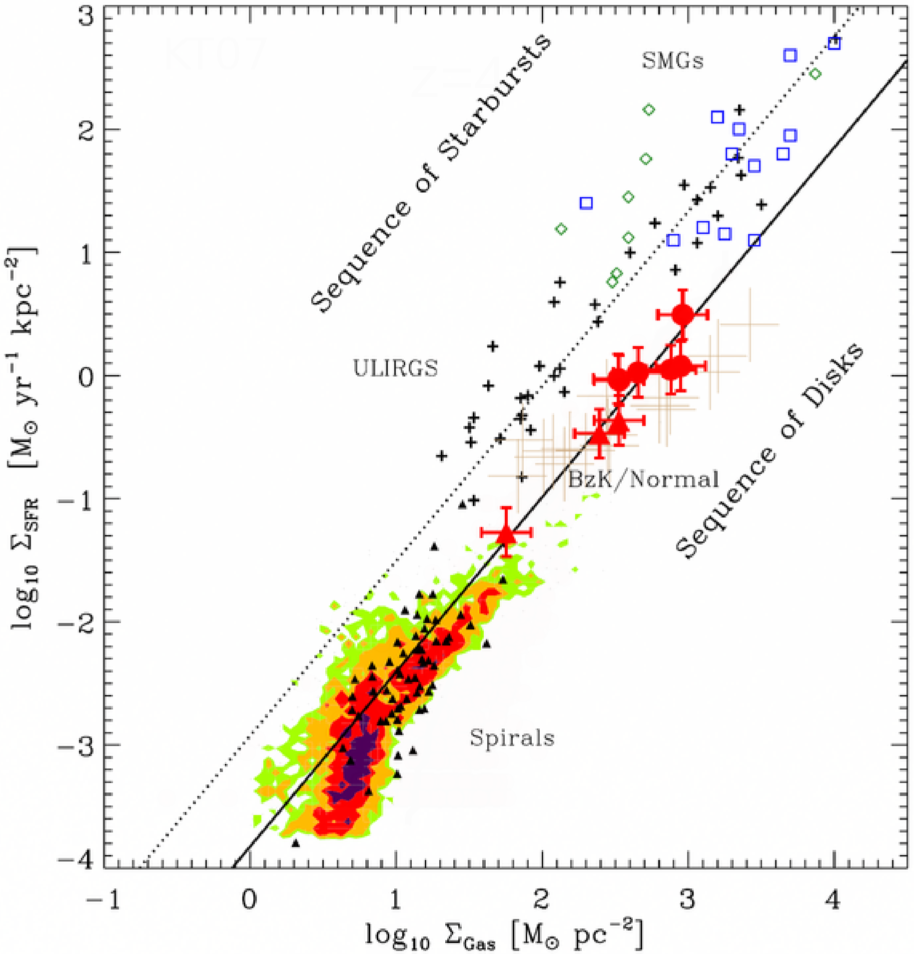


- Cosmological Adaptive Mesh Refinement
- Follows dark matter and hydrodynamics.
- Includes cooling, star formation, supernova feedback, etc.
- **Community code**
- I've been a contributing developer since 2005.

- 12.5 Mpc box
- 256^3 DM particles (3×10^6 $M_\odot$)
- 256^3 root grid + 7 levels of AMR
- $\Delta x = 54.5 \times 7/(1+z) \times 2^{7-\text{level}}$ proper pc
- Self-consistent metal cooling
- **H_2-regulated star formation**

“Standard” Star Formation Simulation

Daddi et al. (2010)



Krumholz & Tan (2007) model

Constant SFR per free-fall time

SF threshold: $n_{\rm thresh} = 50\,{\rm cm}^{-3}$

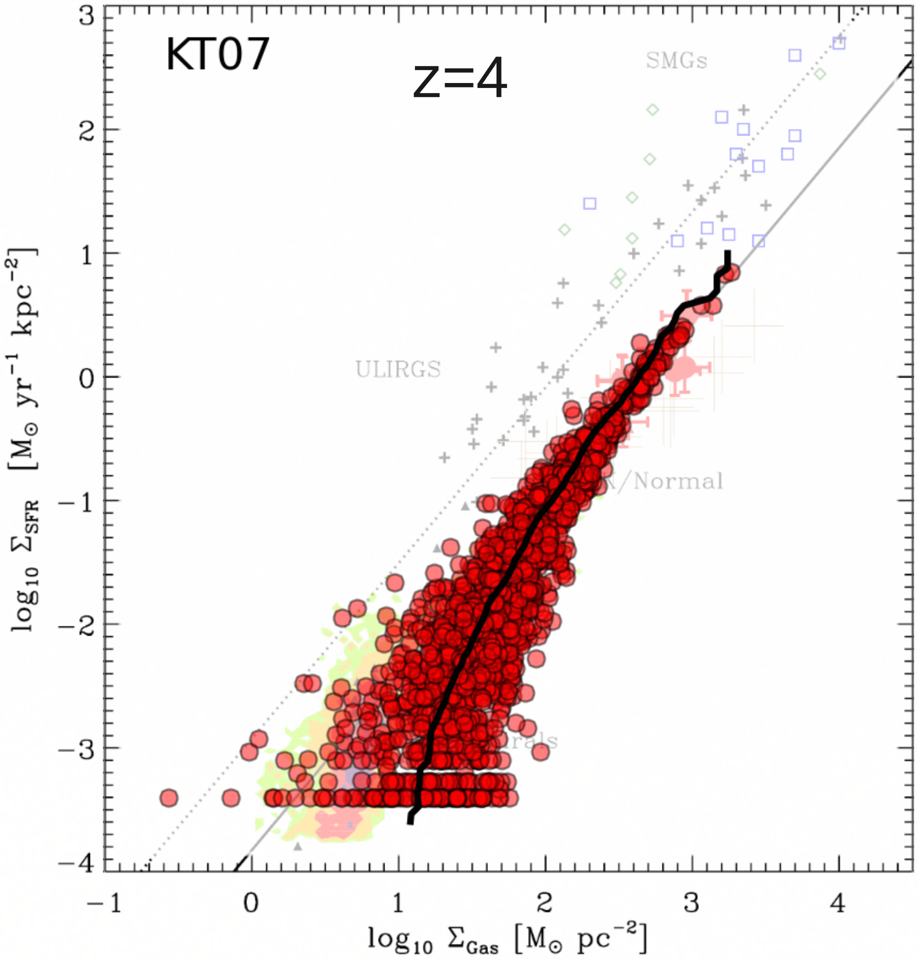
$$\dot\rho_{\rm SF} = \epsilon_\star \frac{\rho_{\rm gas}}{t_{\rm freefall}} \propto \rho_{\rm gas}^{3/2}$$

$$t_{\rm freefall} = \sqrt{\frac{3\,\pi}{32\,G\,\rho}}$$

$$\epsilon_\star = 0.01$$

Kuhlen, Krumholz, Madau, Smith, Wise (2011, arXiv:1105.2376)

“Standard” Star Formation Simulation



Krumholz & Tan (2007) model

Constant SFR per free-fall time

SF threshold: $n_{\rm thresh} = 50\,{\rm cm}^{-3}$

$$\dot\rho_{\rm SF} = \epsilon_\star \frac{\rho_{\rm gas}}{t_{\rm freefall}} \propto \rho_{\rm gas}^{3/2}$$

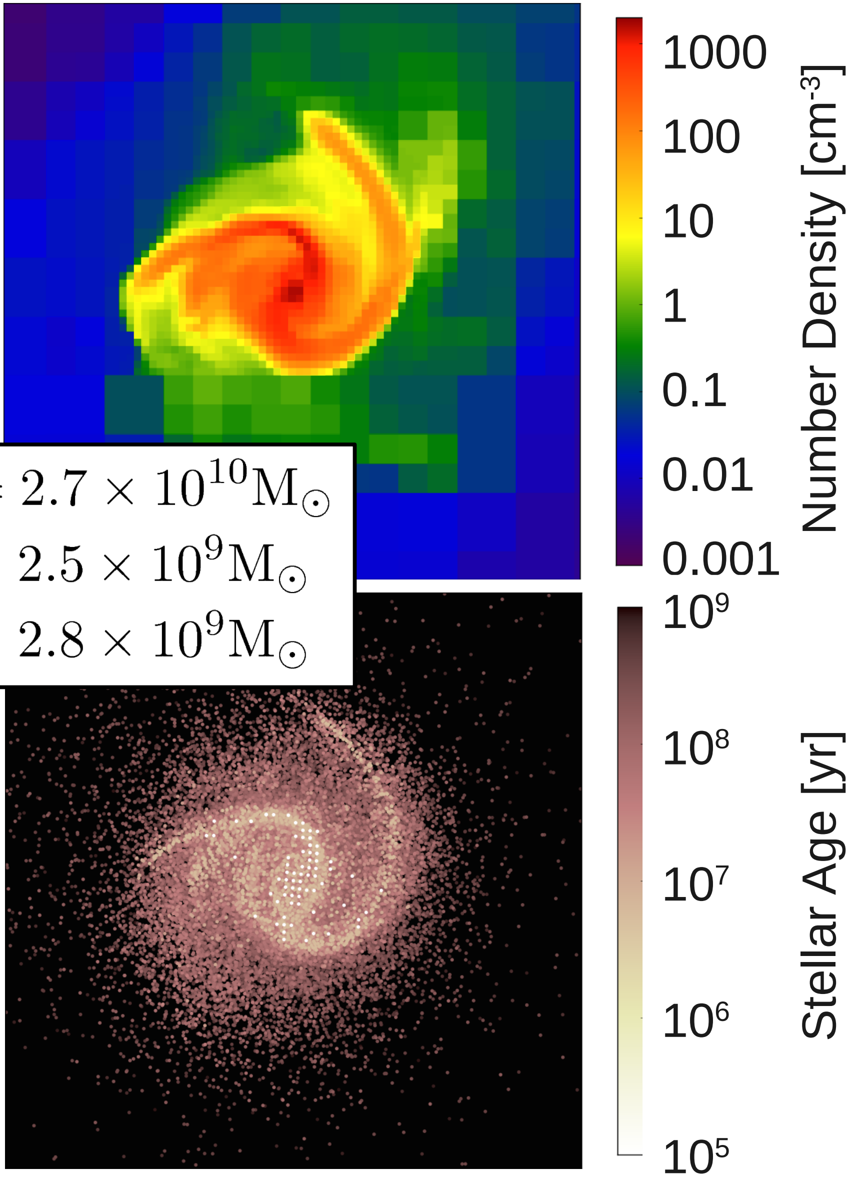
$$t_{\rm freefall} = \sqrt{\frac{3\,\pi}{32\,G\,\rho}}$$

$$\epsilon_\star = 0.01$$

$$\mathrm{SFR}_{\mathrm{ff}\text{-}X} = \frac{f_X \dot M_\star t_{\mathrm{ff}\text{-}X}}{M_X}$$

Kuhlen, Krumholz, Madau, Smith, Wise (2011, submitted)

“Standard” Star Formation Simulation



$$\mathrm{M_{tot}} = 2.7 \times 10^{10} \mathrm{M_\odot}$$
$$\mathrm{M_{gas}} = 2.5 \times 10^{9} \mathrm{M_\odot}$$
$$\mathrm{M_\star} = 2.8 \times 10^{9} \mathrm{M_\odot}$$

Krumholz & Tan (2007) model

Constant SFR per free-fall time

SF threshold: $n_{\mathrm{thresh}} = 50\,\mathrm{cm}^{-3}$

$$\dot{\rho}_{\mathrm{SF}} = \epsilon_\star \frac{\rho_{\mathrm{gas}}}{t_{\mathrm{freefall}}} \propto \rho_{\mathrm{gas}}^{3/2}$$

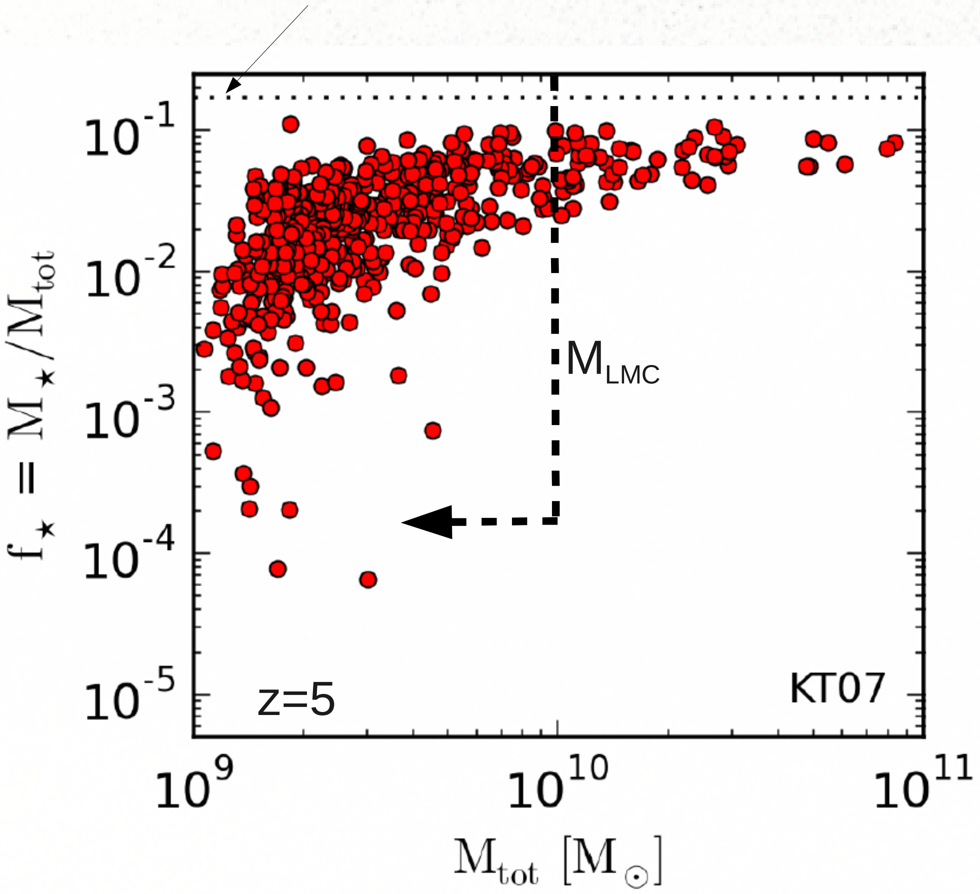
$$t_{\mathrm{freefall}} = \sqrt{\frac{3\,\pi}{32\,G\,\rho}}$$

$$\epsilon_\star = 0.01$$

Only **weak supernova feedback:**

- Injection of thermal energy ($\epsilon=10^{-5}$) in central grid cell.
- No winds!

Stellar Mass Fraction Too High in Low Mass Halos



($f_\star = \Omega_b$, i.e. 100% gas to star conversion)

Krumholz & Tan (2007) model

Constant SFR per free-fall time

SF threshold: $n_{\rm thresh} = 50\,{\rm cm}^{-3}$

$$\dot\rho_{\rm SF} = \epsilon_\star \frac{\rho_{\rm gas}}{t_{\rm freefall}} \propto \rho_{\rm gas}^{3/2}$$

$$t_{\rm freefall} = \sqrt{\frac{3\,\pi}{32\,G\,\rho}}$$

$$\epsilon_\star = 0.01$$

Only **weak supernova feedback:**

- Injection of thermal energy (ϵ=10^{-5}) in central grid cell.
- No winds!

Star formation efficiency is too high in low mass halos!

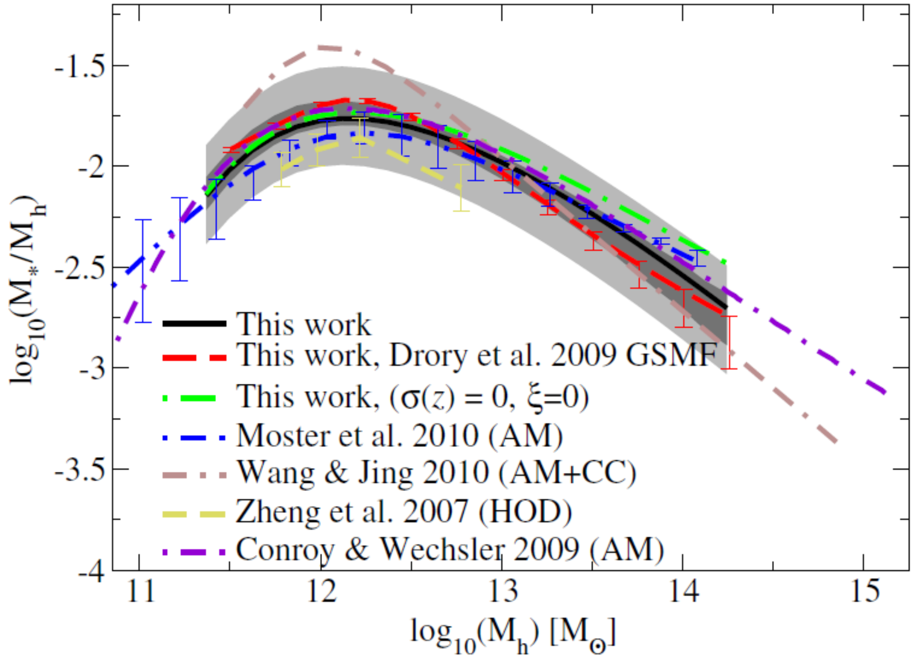
This would greatly overproduce the dwarf galaxy luminosity/mass function.

Kuhlen et al. (2011, arXiv:1105.2376)

Stellar Mass Fraction Too High in Low Mass Halos

($f_\star = \Omega_b$, i.e. 100% gas to star conversion)

Behroozi et al. (2010)



Krumholz & Tan (2007) model

Constant SFR per free-fall time

SF threshold: $n_{\rm thresh} = 50\,{\rm cm}^{-3}$

$$\dot{\rho}_{\rm SF} = \epsilon_\star \frac{\rho_{\rm gas}}{t_{\rm freefall}} \propto \rho_{\rm gas}^{3/2}$$

$$t_{\rm freefall} = \sqrt{\frac{3\,\pi}{32\,G\,\rho}}$$

$$\epsilon_\star = 0.01$$

Only **weak supernova feedback:**

- Injection of thermal energy (ϵ=10^{-5}) in central grid cell.
- No winds!

Star formation efficiency is too high in low mass halos!

This would greatly overproduce the dwarf galaxy luminosity/mass function.

Kuhlen et al. (2011, arXiv:1105.2376)

How to suppress SF in low mass halos

The most commonly invoked mechanism to suppress star formation in low mass dark matter halos is **Supernova/Stellar Wind Feedback** and **UV Photoheating**.

1) UV Photoheating
   - Typically only effective below few x 10^9 $M_\odot$ halos.
   - Difficult to explain complicated SF histories if Milky Way dwarfs

2) Supernova/Stellar Wind Feedback
   - Undoubtedly plays an important role in nature!
   - Its effectiveness in numerical simulations is very implementation dependent.
   - Even hydro simulations with SN feedback have trouble matching observed stellar mass functions.
   - In SAMs it typically just means a removal of some/all gas from the SF reservoir below some halo mass, or a halo-mass-dependent SF efficiency.

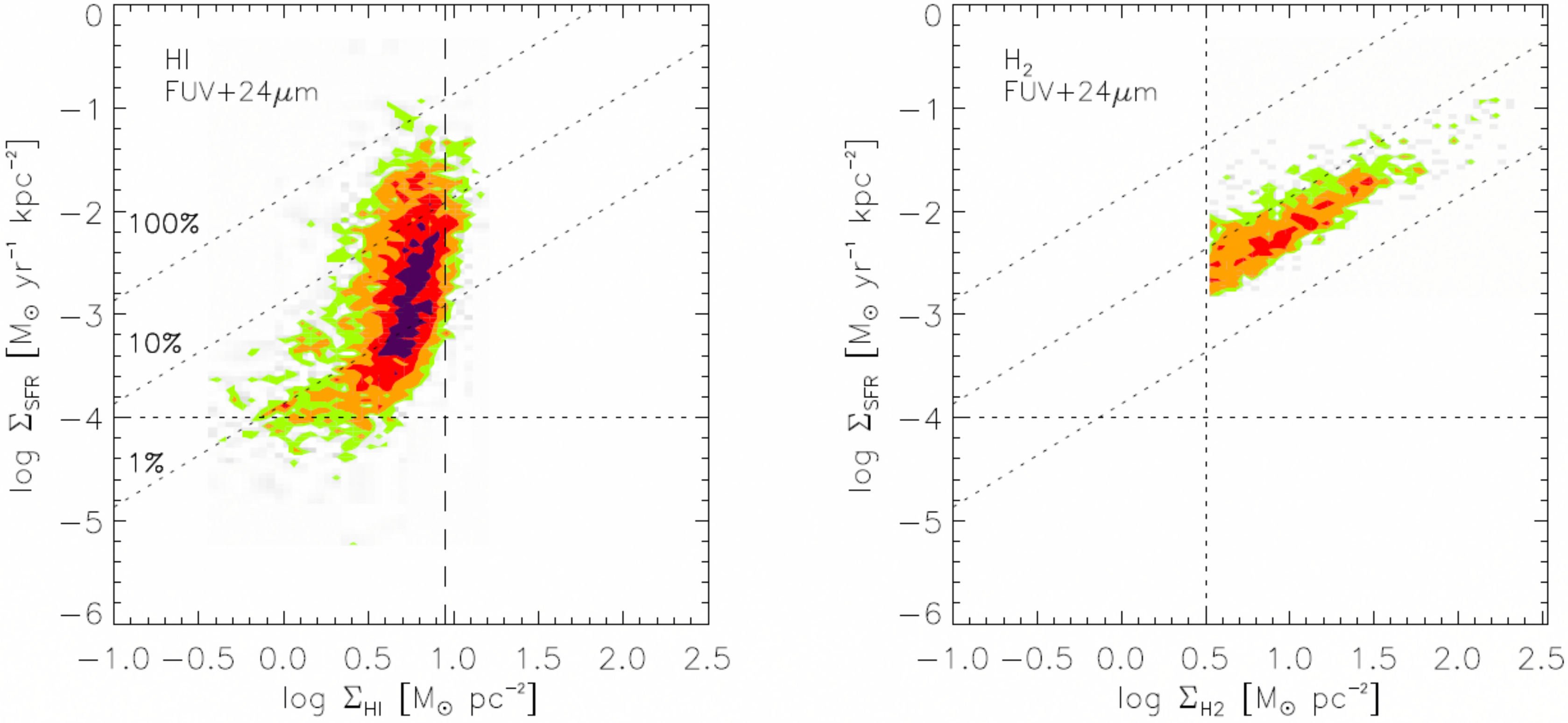
Is it the whole story? Are we just putting the answer we want in by hand? In my opinion other mechanisms should be considered...

For example: Molecular Hydrogen Regulated Star Formation.

cf. Gnedin et al. (2009), Gnedin & Kravtsov (2010, 2011)

H_2-regulated Star Formation

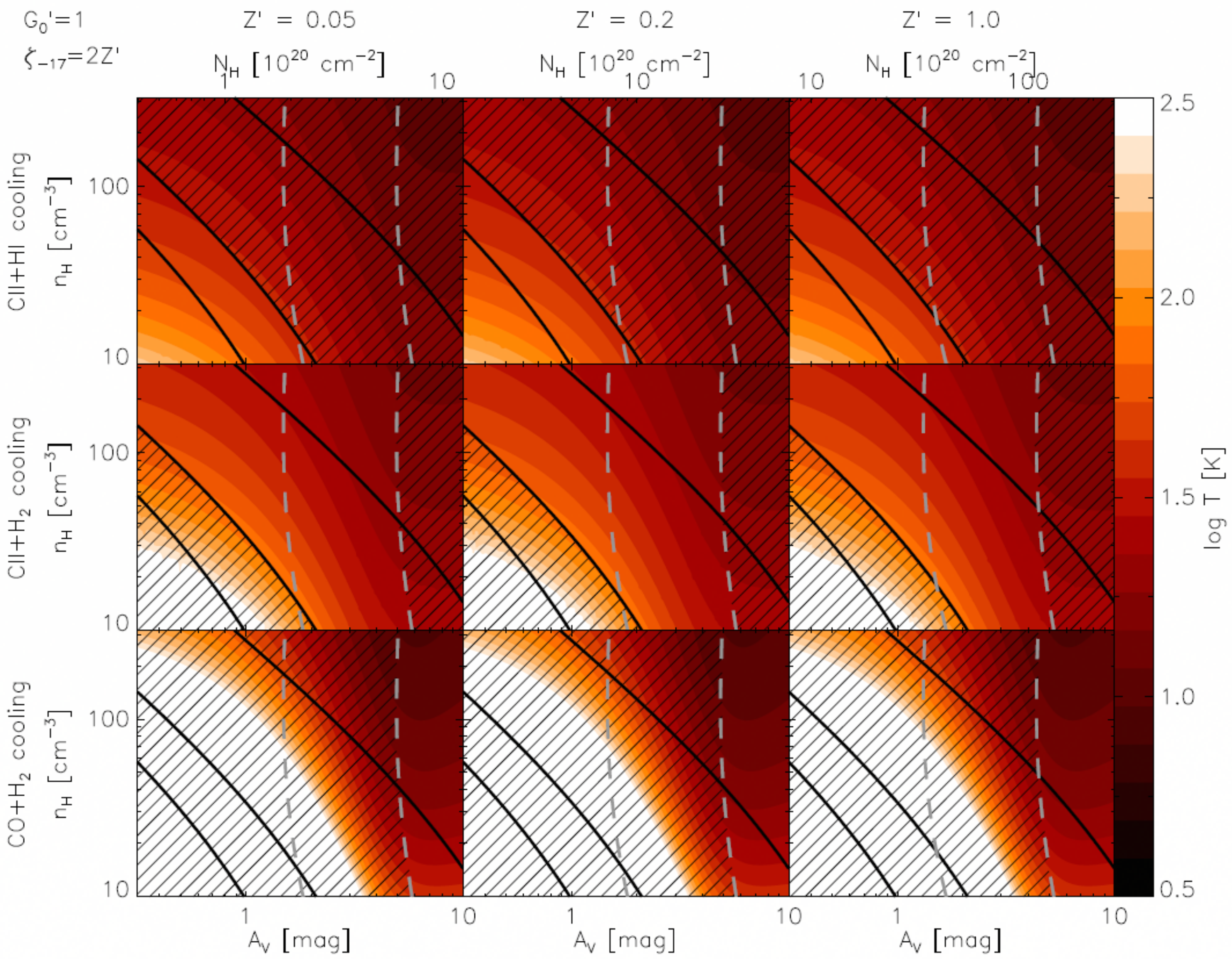
Bigiel et al. (2008): observational Kennicutt-Schmidt relation from spatially resolved (< 1 kpc) **radio, IR, and UV** observations of 7 nearby spiral galaxies.



The star formation rate correlates better with molecular gas (H2) than with atomic gas (HI) surface density.

H_2-regulated Star Formation

SFR correlates with H_2 even though it's not the primary coolant (CII, CO)!



Krumholz, Leroy, & McKee (2011)

H_2-regulated Star Formation

Pelupessy et al. (2006), Robertson & Kravtsov (2008), Gnedin et al. (2009), Feldmann et al. (2010), Krumholz & Gnedin (2010)

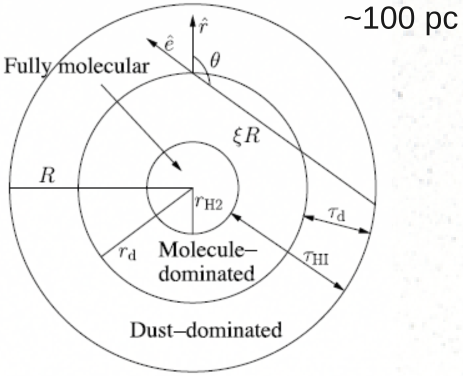
Make SFR proportional to ρ_{H_2}: $$\dot{\rho}_{\rm SF} = \epsilon_\star \frac{\rho_{\rm H_2}}{t_{\rm freefall}} \propto f_{\rm H_2}\, \rho_{\rm gas}^{3/2}$$

How to get f_{H_2} during simulation runtime:

1) Full non-equilibrium chemistry with H_2 formation on dust grains, coupled to radiation transfer with Lyman Werner shielding (e.g. Gnedin et al. 2009, Feldman et al. 2010).
2) Use results from idealized 1-D RT calculations of H_2 formation-dissociation balance in giant atomic-molecular cloud complexes (KMT09: Krumholz, McKee, & Tumlinson (2008, 2009), McKee & Krumholz (2010)).

Radiative transfer: $$\hat{e}\cdot\nabla I_\nu = -n\left(\frac{1}{2} f_{\rm H_2}\sigma_{\rm H_2,\nu} + \sigma_{d,\nu}\right) I_\nu$$

H_2 formation-dissociation balance: $$f_{\rm H\,I}\, n^2 \mathcal{R} = \frac{f_{\rm H_2}}{2} n \int d\Omega \int_{\nu_1}^{\nu_2} d\nu\, \frac{I_\nu}{h\nu} \sigma_{\rm H_2,\nu} f_{\rm diss,\nu}$$



$$f_{\rm H_2} \simeq 1 - \frac{3}{4}\frac{s}{1+0.25s}$$

$$s = \frac{\ln(1+0.6\chi+0.01\chi^2)}{0.6\,\tau_c}$$

LW-shielding opacity $$\tau_c = \Sigma_{\rm HI}/\mu_H\, Z'\, \sigma'_d$$

$$\chi = 71\left(\frac{\sigma_{d,-21}}{\mathcal{R}_{-16.5}}\right)\frac{G'_0}{n_{\rm H,0}}$$

Ratio of the dust cross section per H nucleus to the rate coefficient of H2 formation on dust grains ≈ 1

FUV intensity in units of the Milky Way's, 7.5×10^{-4} cm^{-3} (Draine 1978)

H_2-regulated Star Formation

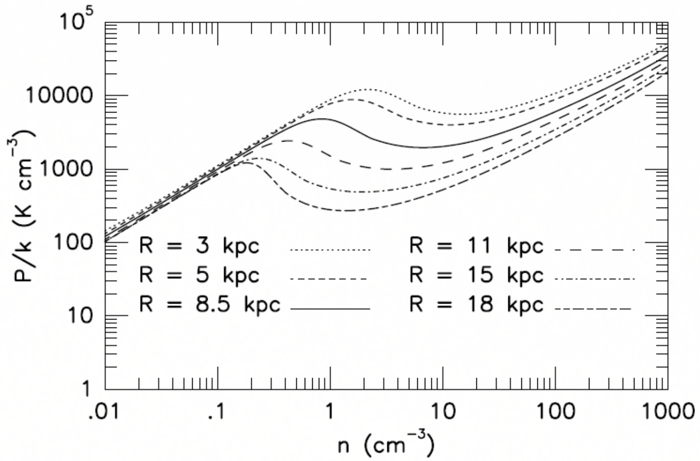
Pelupessy et al. (2006), Robertson & Kravtsov (2008), Gnedin et al. (2009), Feldmann et al. (2010), Krumholz & Gnedin (2010)

Make SFR proportional to ρ_{H_2}:
$$\dot{\rho}_{\rm SF} = \epsilon_\star \frac{\rho_{\rm H_2}}{t_{\rm freefall}} \propto f_{\rm H_2}\, \rho_{\rm gas}^{3/2}$$

How to get f_{H_2} during simulation runtime:

1) Full non-equilibrium chemistry with H_2 formation on dust grains, coupled to radiation transfer with Lyman Werner shielding (e.g. Gnedin et al. 2009, Feldman et al. 2010).
2) Use results from idealized 1-D RT calculations of H_2 formation-dissociation balance in giant atomic-molecular cloud complexes (KMT09: Krumholz, McKee, & Tumlinson (2008, 2009), McKee & Krumholz (2010)).

With the assumption of 2-phase equilibrium between a Cold Neutral Medium and a Warm Neutral Medium, the minimum CNM density is proportional to the LW flux



Wolfire et al. (2003)

$$n_{\rm min} \approx 31 G_0' \frac{Z_d'/Z_g'}{1 + 3.1(G_0' Z_d'/\zeta_t')^{0.365}} \ {\rm cm}^{-3},$$

and the KMT09 prescription for f_{H_2} becomes **independent of the LW intensity**.

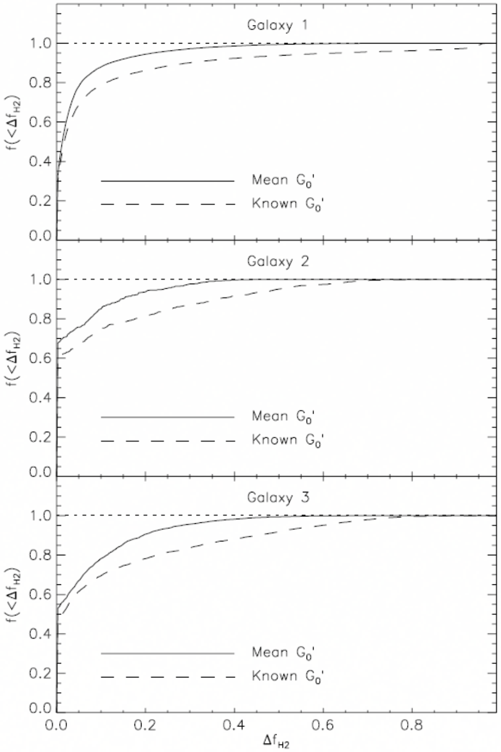
$$\chi = 2.3 \left(\frac{\sigma_{d,-21}}{\mathcal{R}_{-16.5}}\right) \frac{1 + 3.1\,(Z/Z_{\rm SN})^{0.365}}{\phi_{\rm CNM}}$$

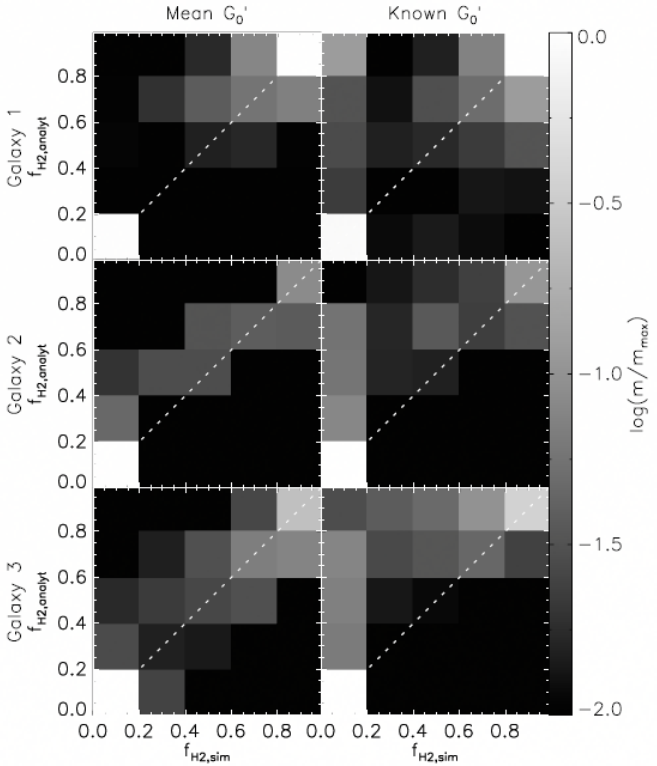
H_2-regulated Star Formation

Krumholz & Gnedin (2010): direct comparison between self-consistent cosmological simulations (ART) and KMT09 model at z=3.

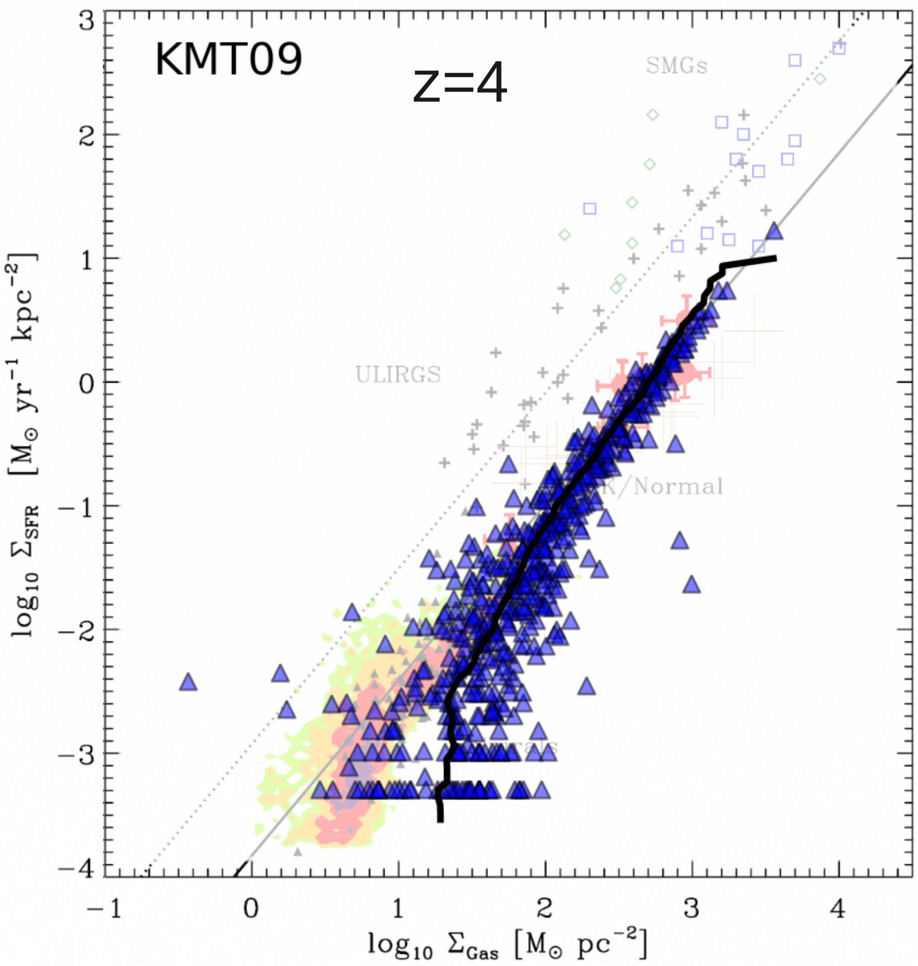
Simulations:

- Cosmological zoom-in simulations of 3 disk galaxies ($Z/Z_\odot$=0.5, 0.01, 0.18).
- Non-equilibrium chemical network with H_2 formation on dust (local Z).
- Star formation, metal enrichment, and “live” radiation transfer of ionizing radiation.
- LW shielding with Sobolev-like approximation: $S_{\rm D} = e^{-D_{\rm MW}\sigma_0(n_{\rm H\,I} + 2n_{\rm H_2})L_{\rm Sob}}$ $L_{\rm Sob} \equiv \rho/(2|\nabla\rho|)$





H_2-regulated Star Formation



Make SFR proportional to ρ_{H2}

No SF density threshold!

$$\dot{\rho}_{\rm SF} = \epsilon_\star \frac{\rho_{\rm H_2}}{t_{\rm freefall}} \propto f_{\rm H_2}\, \rho_{\rm gas}^{3/2}$$

$$\epsilon_\star = 0.01$$

$$f_{\rm H_2} \simeq 1 - \frac{3}{4}\frac{s}{1+0.25s}$$

$$s = \frac{\ln(1+0.6\chi+0.01\chi^2)}{0.6\,\tau_c}$$

$$\chi = 0.77\left(1+3.1\,Z'^{0.365}\right)$$

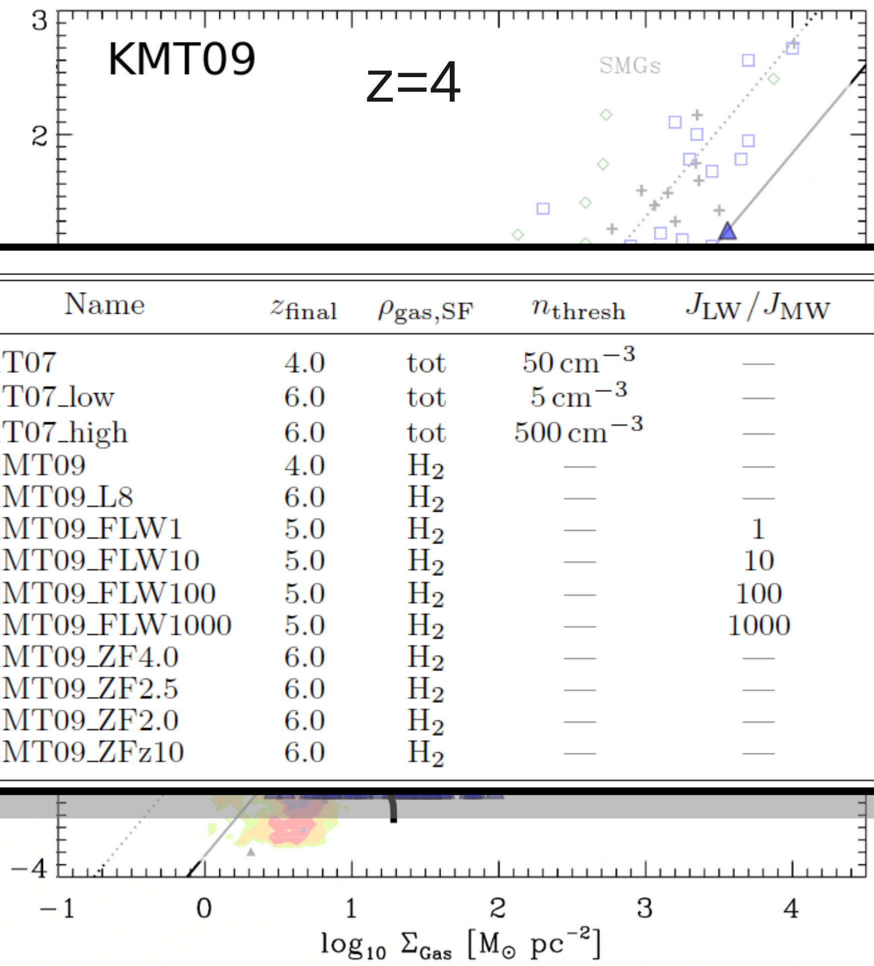
$$\tau_c = \Sigma_{\rm HI}/\mu_H\, Z'\, \sigma'_d$$

10^{-3} $Z_\odot$ metallicity floor at z=10.

Further metal enrichment from SN injection: 0.25 M_*, yield=0.02.

Kuhlen et al. (2011, arXiv:1105.2376)

H_2-regulated Star Formation



Make SFR proportional to ρ_{H_2}

No SF density threshold!

$$\dot{\rho}_{SF} = \epsilon_\star \frac{\rho_{H_2}}{t_{freefall}} \propto f_{H_2}\,\rho_{gas}^{3/2}$$

Name	z_{final}	$\rho_{gas,SF}$	n_{thresh}	J_{LW}/J_{MW}	[Z_{floor}]	Comment
KT07	4.0	tot	50 cm^{-3}	—	—	Krumholz & Tan (2007) SF law
KT07_low	6.0	tot	5 cm^{-3}	—	—	lower SF threshold
KT07_high	6.0	tot	500 cm^{-3}	—	—	higher SF threshold
KMT09	4.0	H_2	—	—	-3.0	Krumholz et al. (2009): 2-phase equilibrium
KMT09_L8	6.0	H_2	—	—	-3.0	one additional refinement level (maxlevel=8)
KMT09_FLW1	5.0	H_2	—	1	-3.0	KMT09 with uniform LW
KMT09_FLW10	5.0	H_2	—	10	-3.0	background of
KMT09_FLW100	5.0	H_2	—	100	-3.0	increasing
KMT09_FLW1000	5.0	H_2	—	1000	-3.0	intensity
KMT09_ZF4.0	6.0	H_2	—	—	-4.0	lower Z_{floor}
KMT09_ZF2.5	6.0	H_2	—	—	-2.5	higher Z_{floor}
KMT09_ZF2.0	6.0	H_2	—	—	-2.0	even higher Z_{floor}
KMT09_ZFz10	6.0	H_2	—	—	-3.0	Z_{floor} at $z = 10$

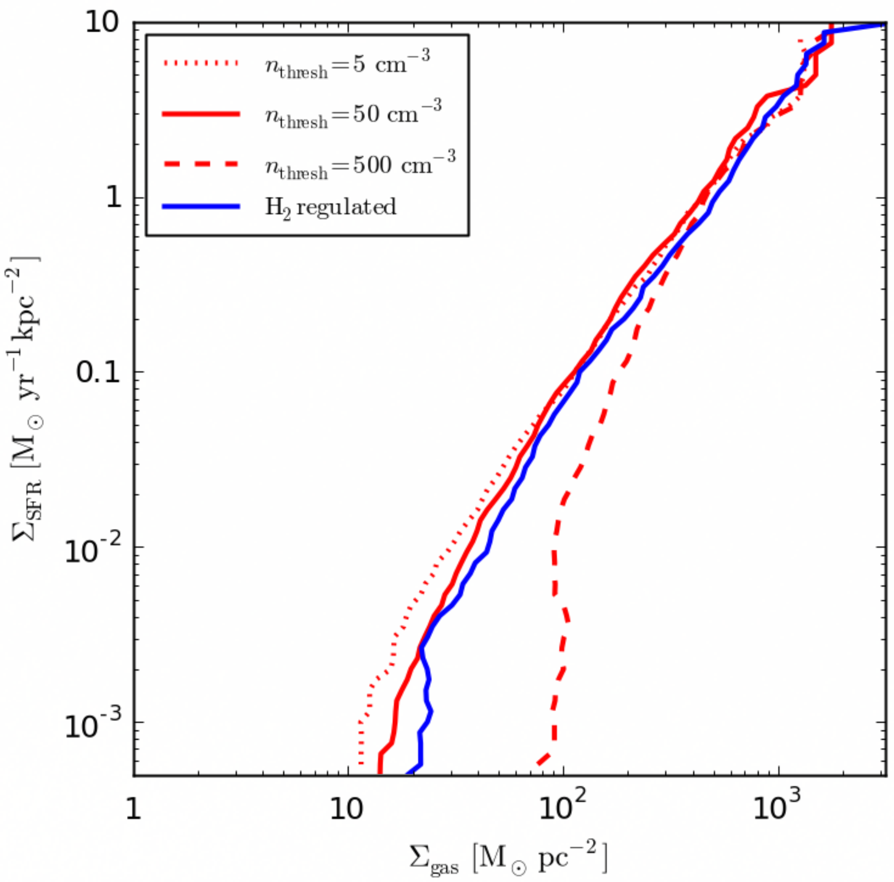
10^{-3} $Z_\odot$ metallicity floor at z=10.

Further metal enrichment from SN injection: 0.25 M_*, yield=0.02.

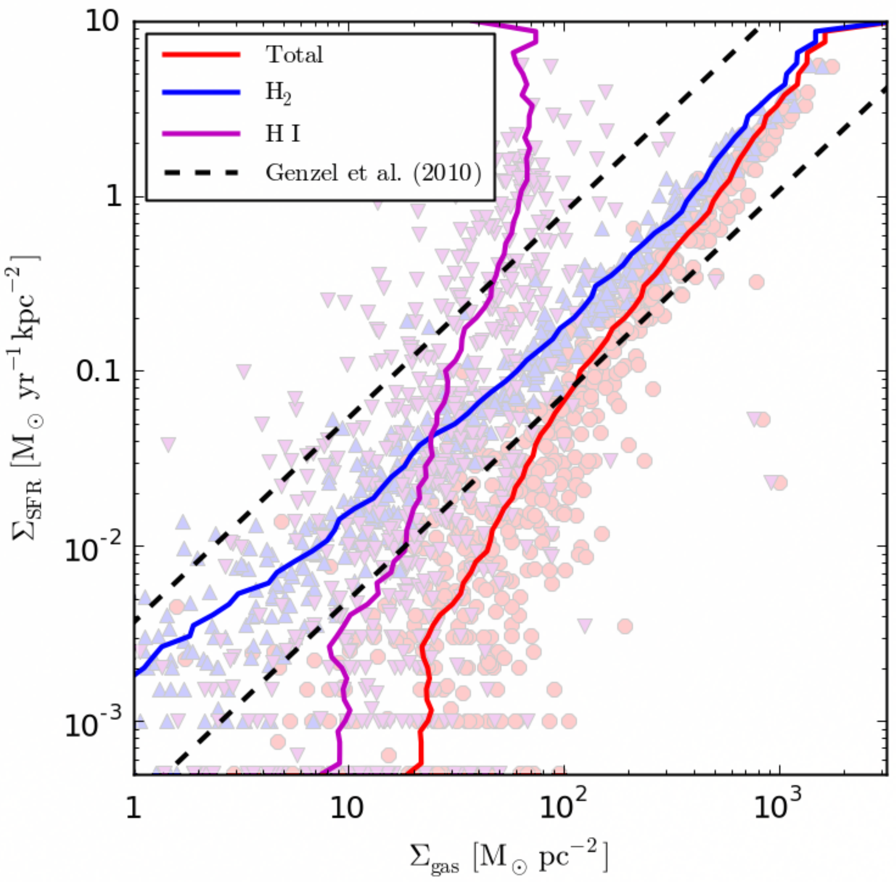
Kuhlen et al. (2011, arXiv:1105.2376)

Comparisons with observational SF scaling laws

See also: Gnedin, Tassis, & Kravtsov (2009), Gnedin & Kravtsov (2010, 2011), Feldmann & Gnedin (2010)



The H_2-regulated model reproduce the turnover in $\Sigma_{\rm SFR}$ without an artificial density threshold.

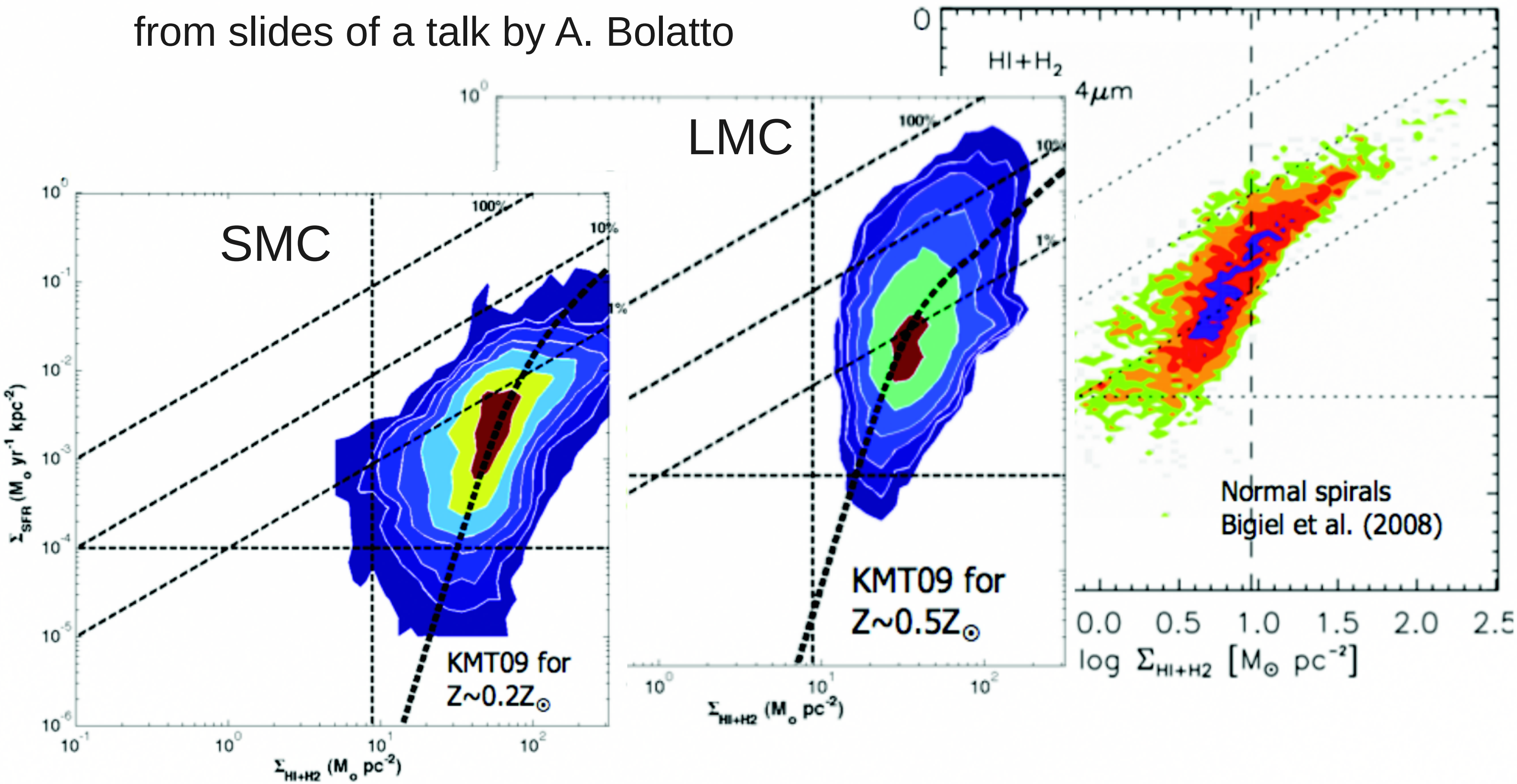


The H_2-KS relation lies between the Genzel et al. (2010) z=0 – 3.5 relations for “normal” and “luminous mergers”.

Kuhlen et al. (2011, arXiv:1105.2376)

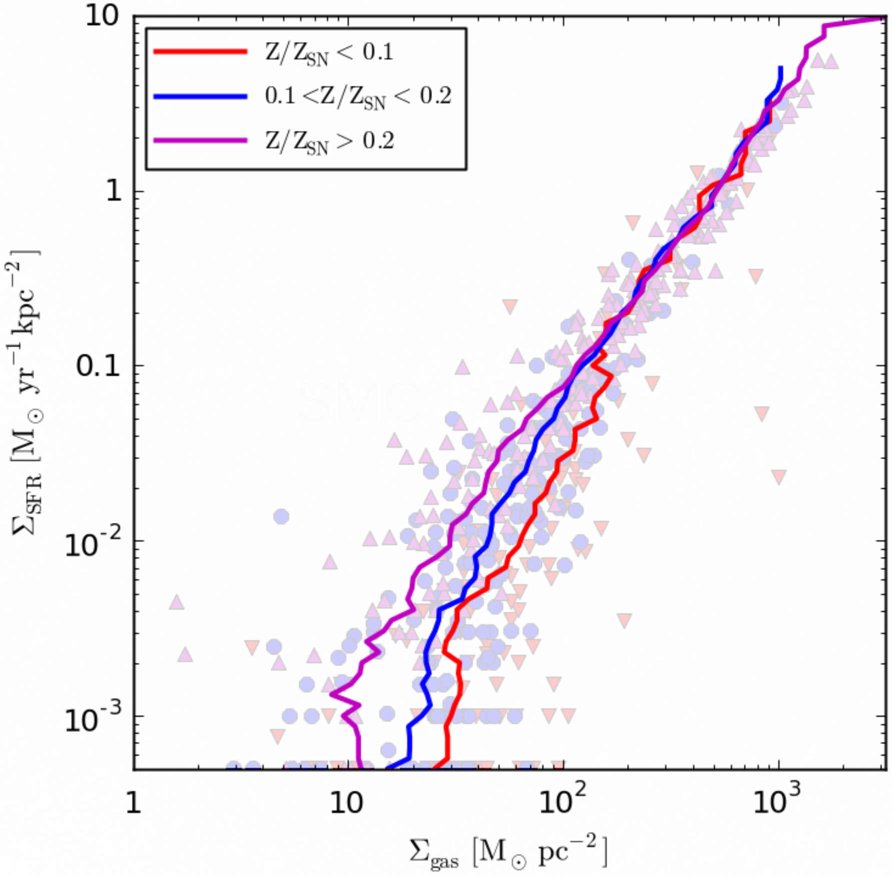
Metallicity Dependence

from slides of a talk by A. Bolatto

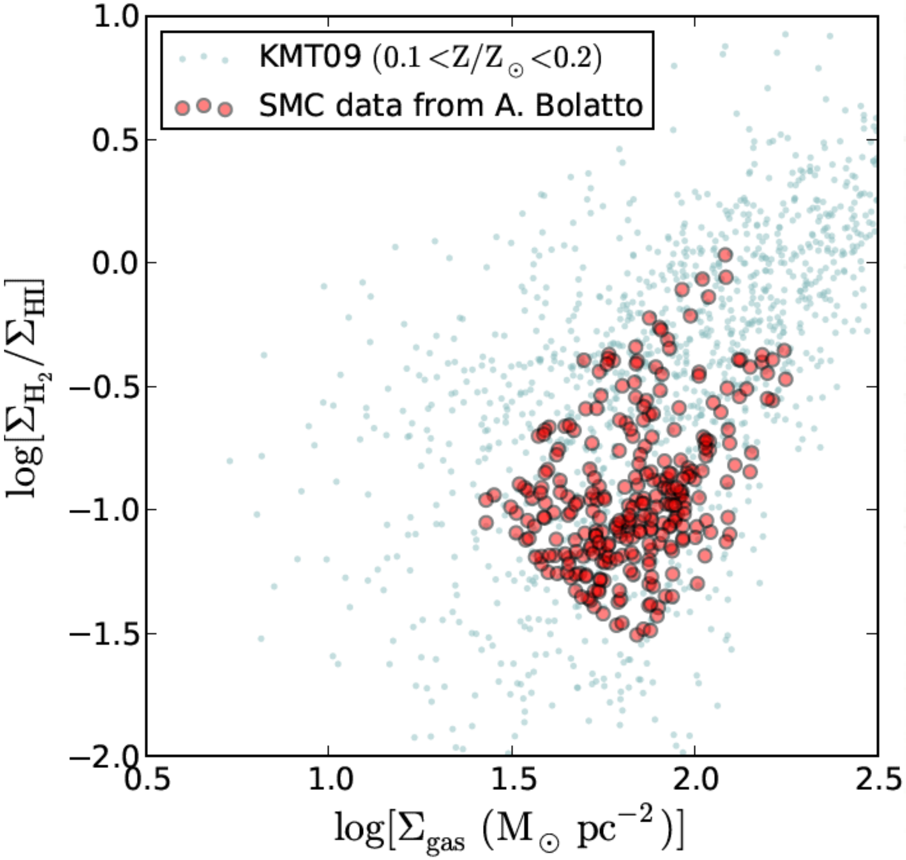


see also Bolatto et al. (2011, arXiv:1107.1717)

Metallicity Dependence



Our model is able to capture the metallicity-dependence of the rollover in the KS relation.



H_2 fractions as a function of total Σ_{gas} compare favorably with recent direct measurements in the SMC (Bolatto et al. 2011, arXiv:1107.1717).

Kuhlen et al. (2011, arXiv:1105.2376)

H_2-regulated Star Formation

Example halo in KT07 simulation:

$M_{tot} = 1.86\times10^{10}\ M_\odot$

$M_{gas} = 2.43\times10^{9}\ M_\odot$

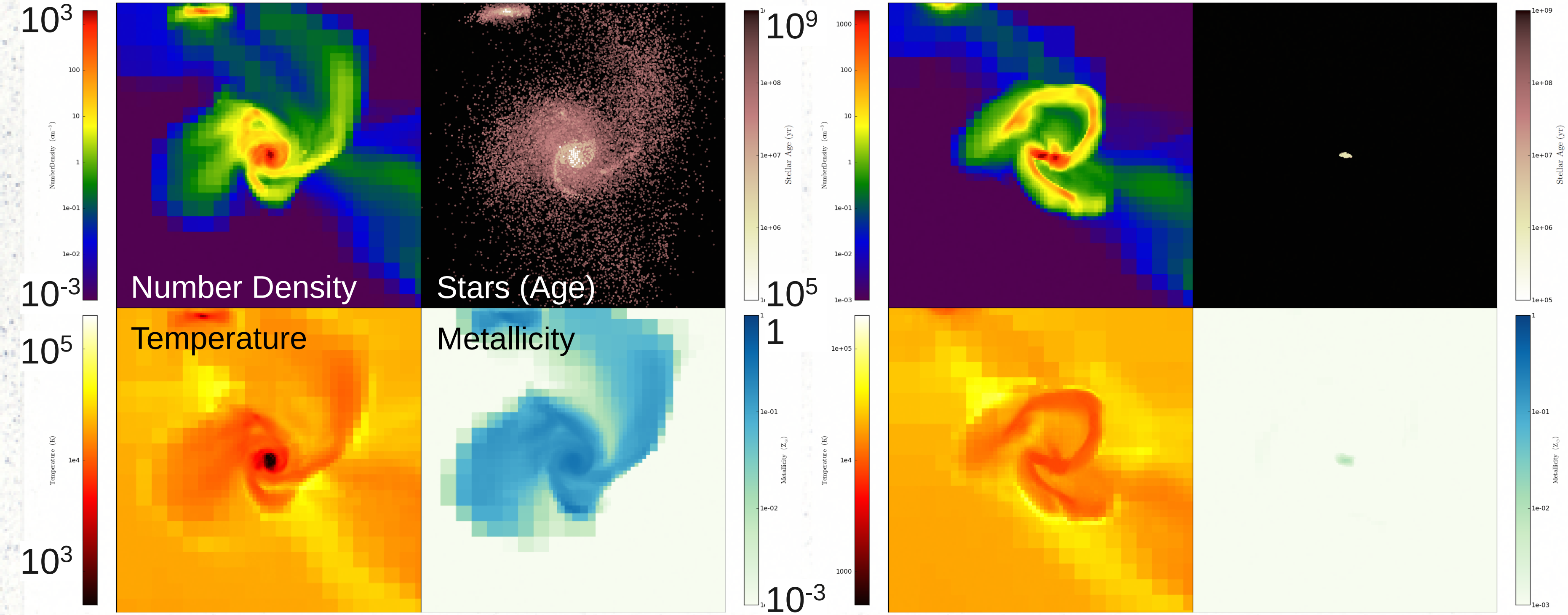
$M_\star = 1.16\times10^{9}\ M_\odot$

Same halo in KMT09 simulation:

$M_{tot} = 1.83\times10^{10}\ M_\odot$

$M_{gas} = 3.43\times10^{9}\ M_\odot$

$M_\star = 1.46\times10^{7}\ M_\odot$



Kuhlen et al. (2011, arXiv:1105.2376)

H_2-regulated Star Formation

High Mass Halo:

$M_{tot} = 2.8 \times 10^{10}\,M_\odot$

$M_{gas} = 3.0 \times 10^{9}\,M_\odot$

$M_\star = 2.4 \times 10^{9}\,M_\odot$

$\boxed{f_\star = 8.6 \times 10^{-2}}$

Both KMT09

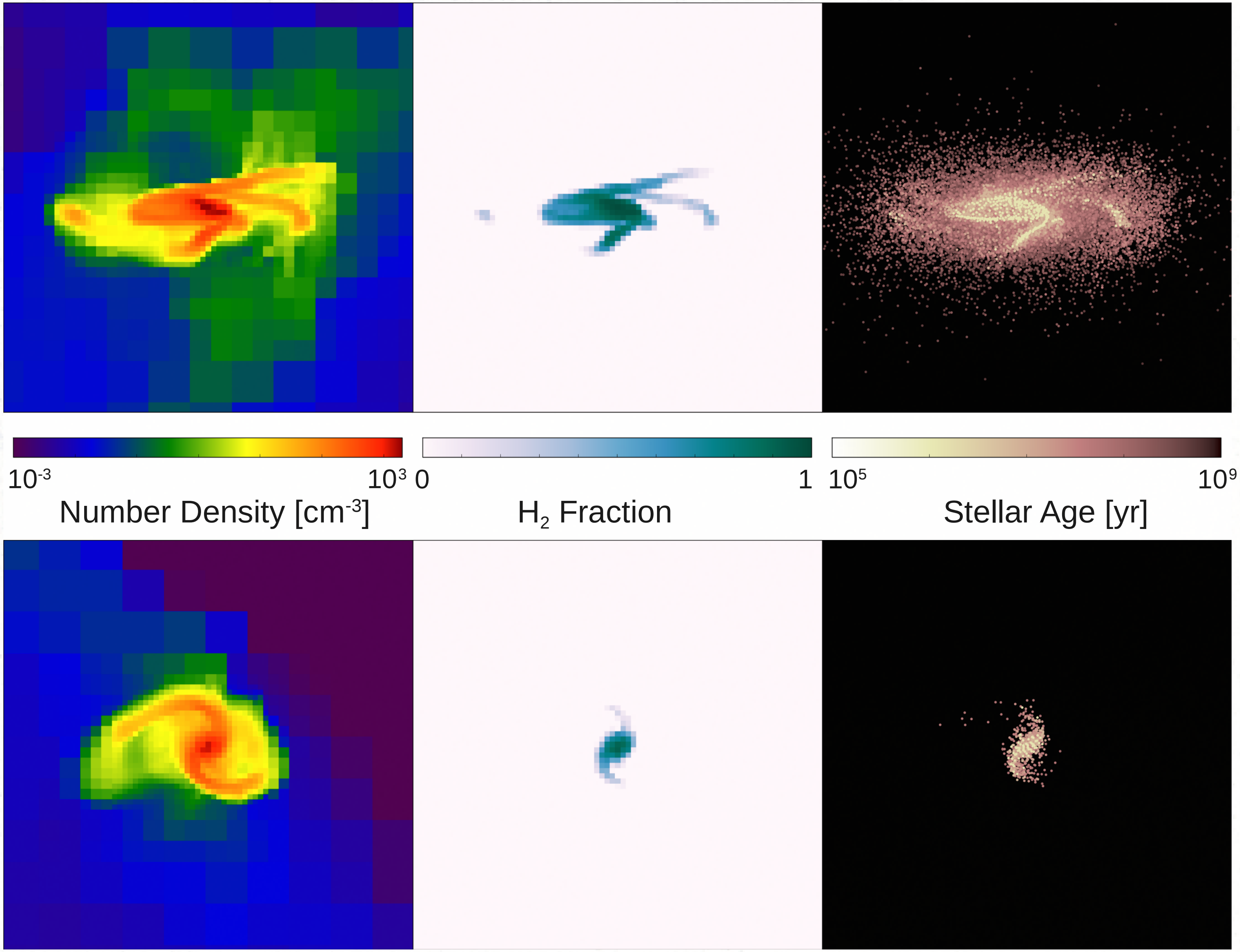
Low Mass Halo:

$M_{tot} = 4.7 \times 10^{9}\,M_\odot$

$M_{gas} = 7.8 \times 10^{8}\,M_\odot$

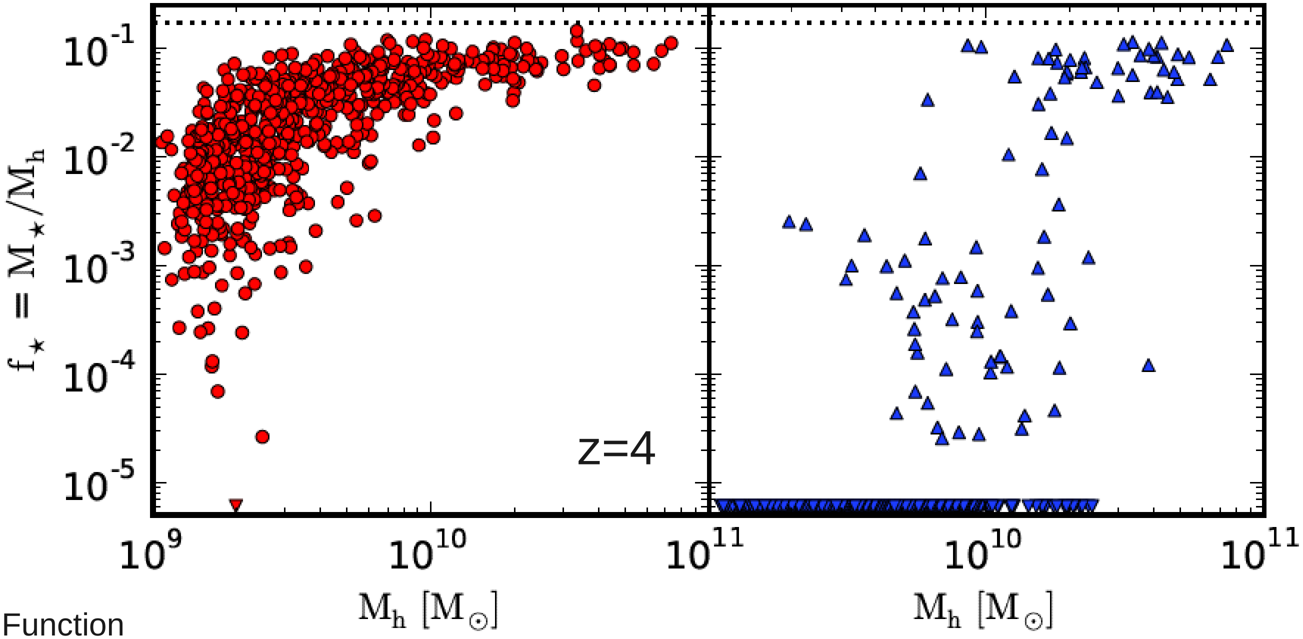
$M_\star = 5.7 \times 10^{7}\,M_\odot$

$\boxed{f_\star = 1.2 \times 10^{-2}}$

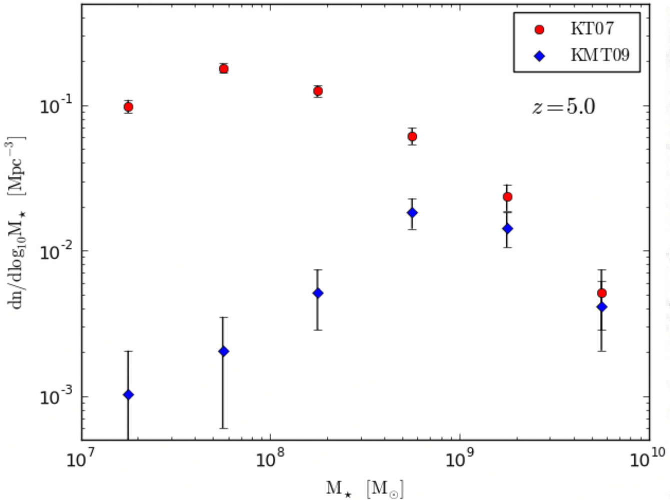


Kuhlen et al. (2011, arXiv:1105.2376)

H_2-regulated Star Formation



Stellar Mass Function

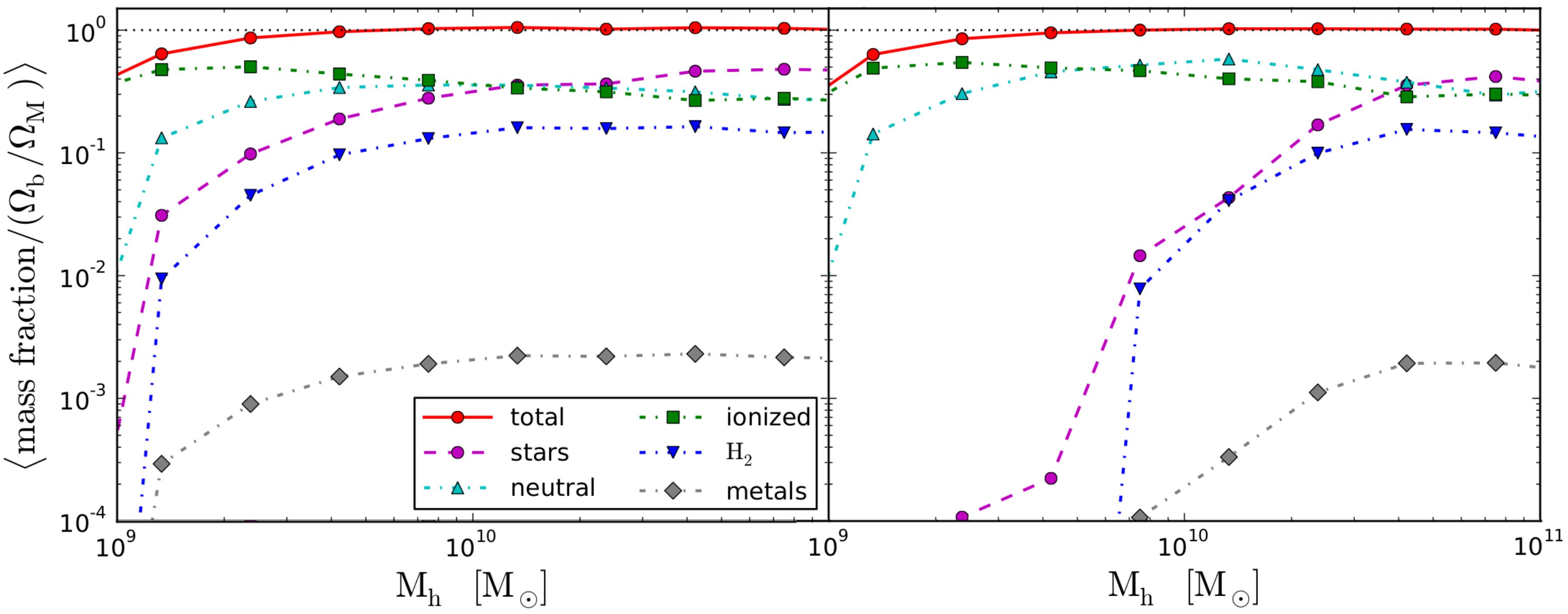


Regulating star formation by the H_2 abundance greatly reduces the star formation efficiency in low mass halos.

This helps to resolve the **Dwarf Galaxy Problems**.

Kuhlen et al. (2011, arXiv:1105.2376)

Baryon Content



Standard SF

H_2-regulated SF

Lower mass halos have lower star formation efficiency ($f_\star = M_\star/M_{tot}$) owing to their **lower metallicity**.

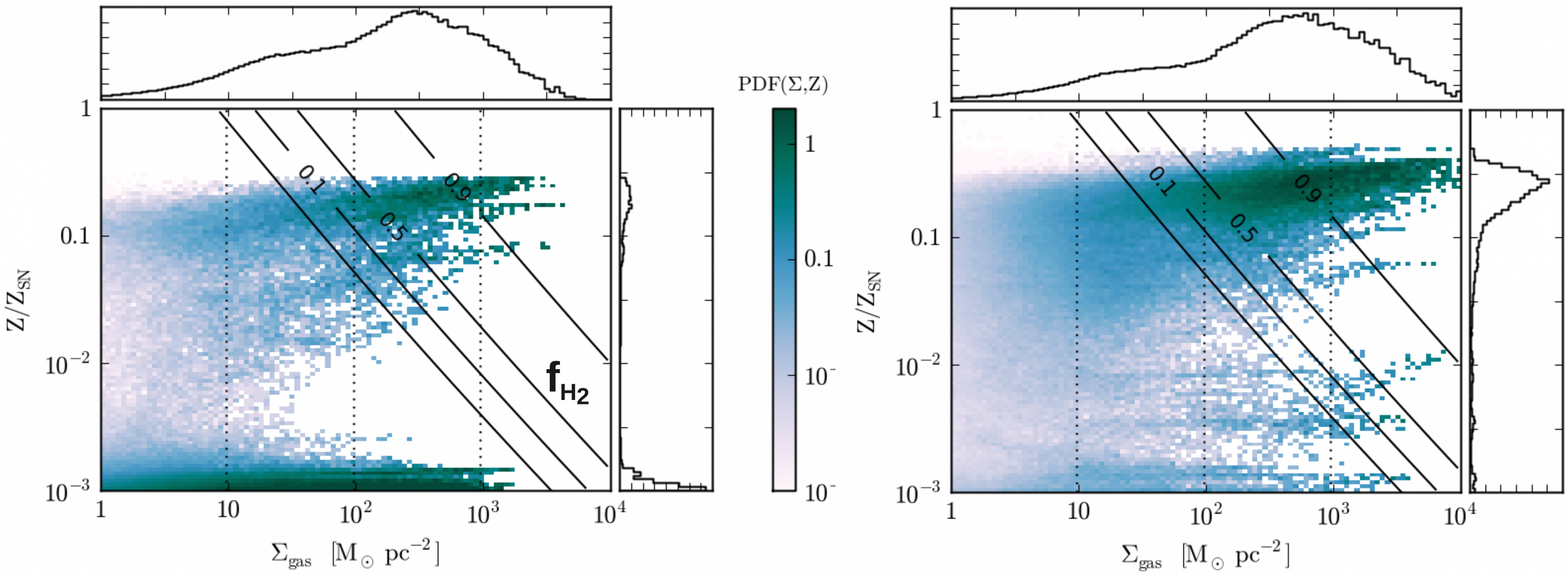
Lower Z ⇒ Less Lyman-Werner shielding ⇒ Smaller f_{H_2} ⇒ Reduced star formation

Kuhlen et al. (2011, arXiv:1105.2376)

Halo Mass Dependence of $f_\star$

Low Mass Halos ($M < 10^{10}\ M_\odot$)

High Mass Halos ($M > 10^{10}\ M_\odot$)



Lower mass halos have lower star formation efficiency ($f_\star = M_\star/M_{tot}$) owing to their **lower metallicity**.

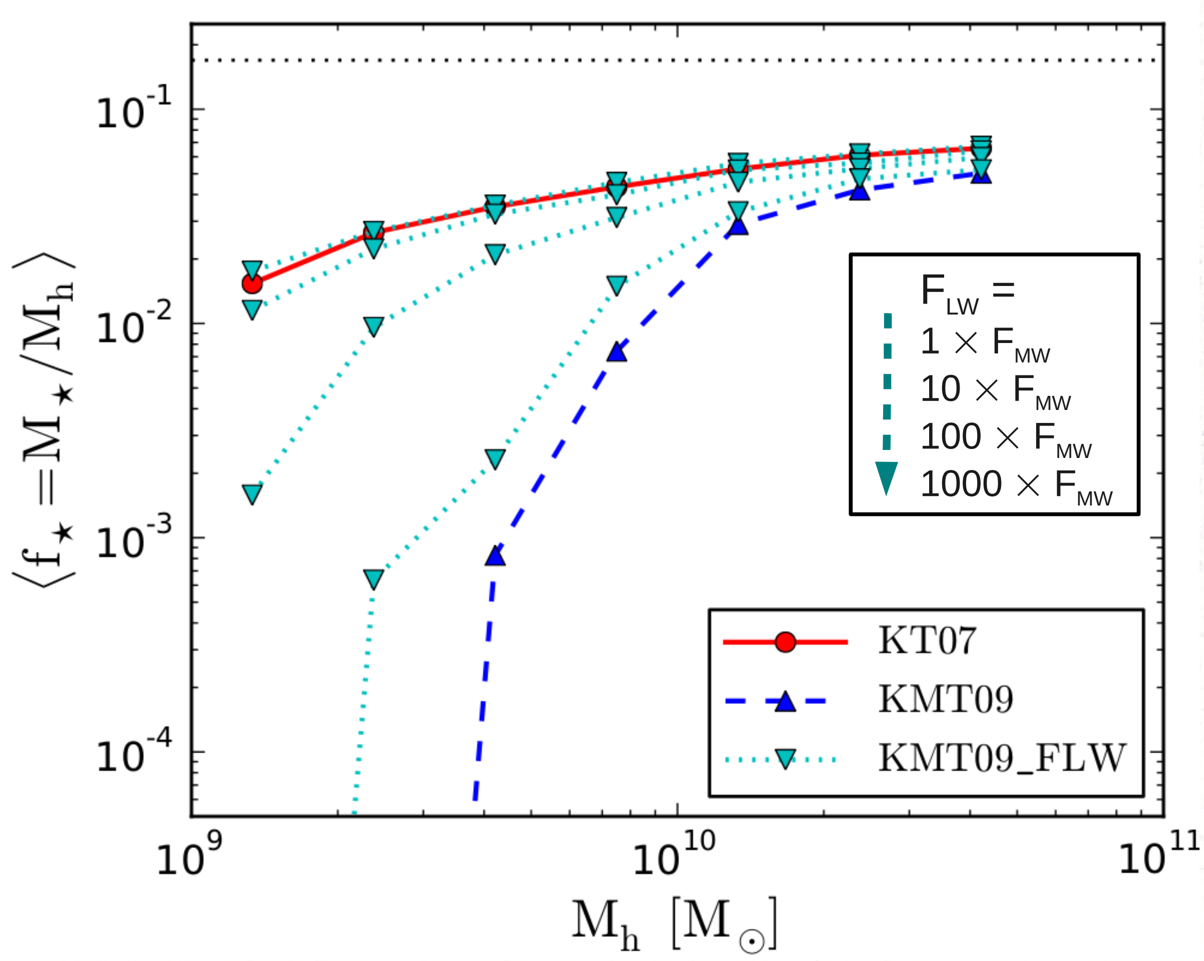
Lower Z ⇒ Less Lyman-Werner shielding ⇒ Smaller f_{H_2} ⇒ Reduced star formation

Kuhlen et al. (2011, arXiv:1105.2376)

H_2-regulated Star Formation

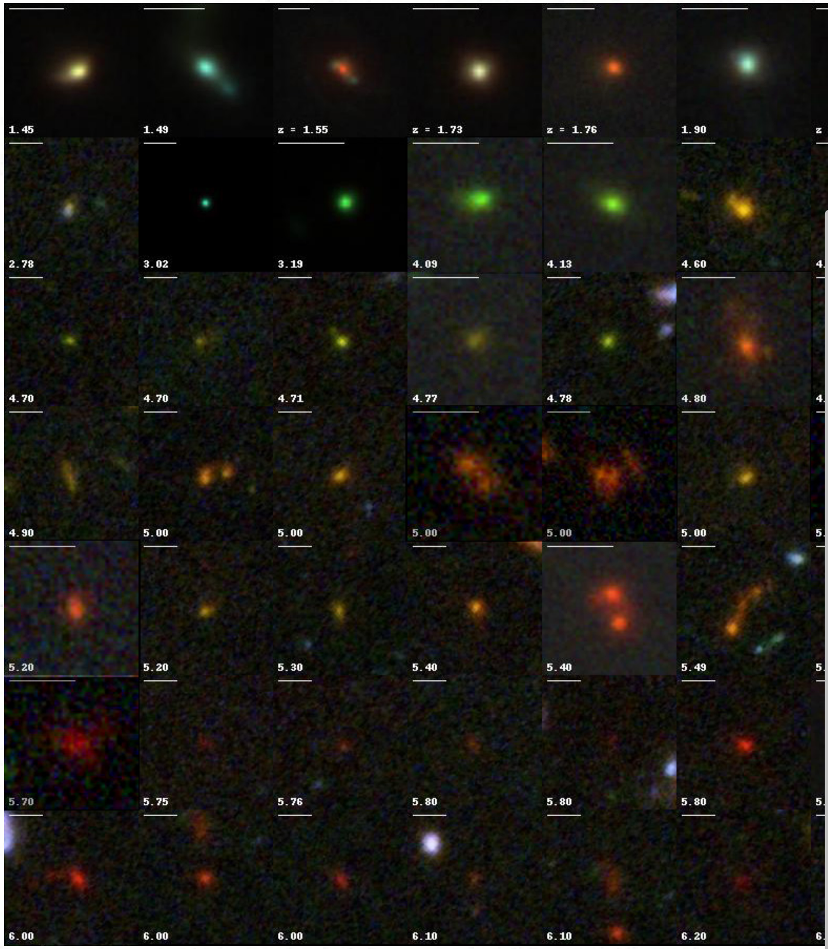
Without the 2-phase equilibrium assumption the $f_\star$-suppression mass scale depends on the strength of the LW background.

[It also becomes dependent on a subgrid clumping factor, set to 30 here (Krumholz & Gnedin 2010).]



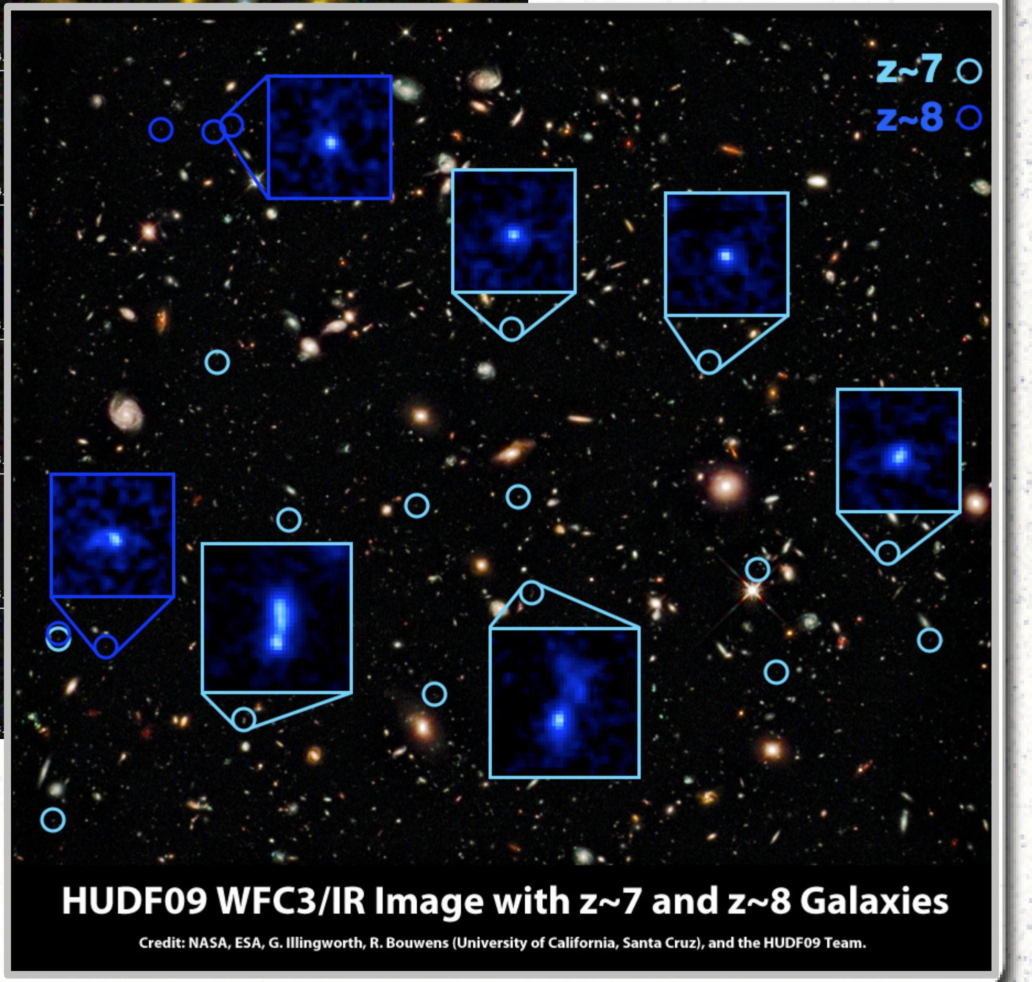
Kuhlen et al. (2011, arXiv:1105.2376)

Comparison with high-z observations



Malhotra et al. (HUDF-GRAPES)

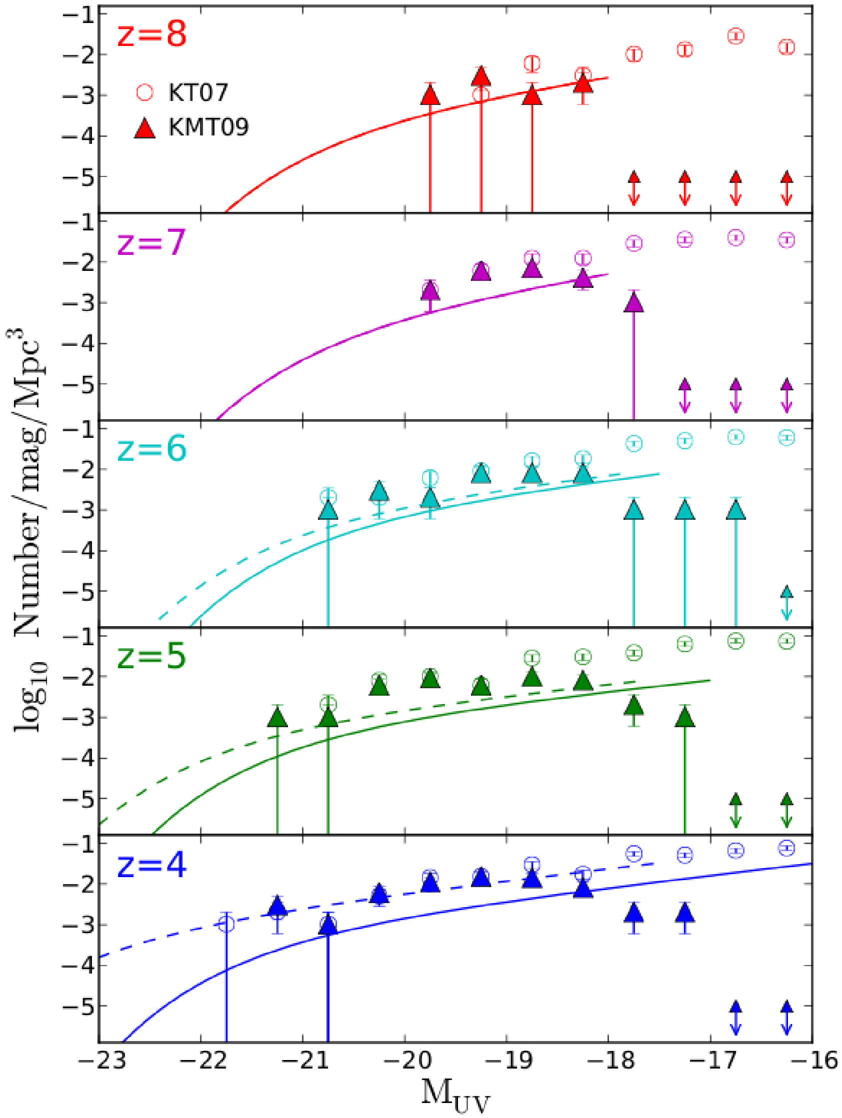
Illingworth et al. (HUDF09)



HUDF09 WFC3/IR Image with z~7 and z~8 Galaxies

Credit: NASA, ESA, G. Illingworth, R. Bouwens (University of California, Santa Cruz), and the HUDF09 Team.

H_2-regulated Star Formation



Observational luminosity functions from Bouwens et al. 2007, 2010.

Dust corrections very important!

[Bouwens et al. 2010:
1.55, 0.625, 0.375, 0, 0 mags at z = 4, 5, 6, 7, 8.]

We calculate L_{UV} from SFR:

$$L_{\rm UV} = 8.0 \times 10^{27}\,({\rm SFR}/M_\odot\,{\rm yr}^{-1})\,{\rm erg}\,s^{-1}\,{\rm Hz}^{-1}$$

Standard SF overpredicts LF.
[except at z=4?]

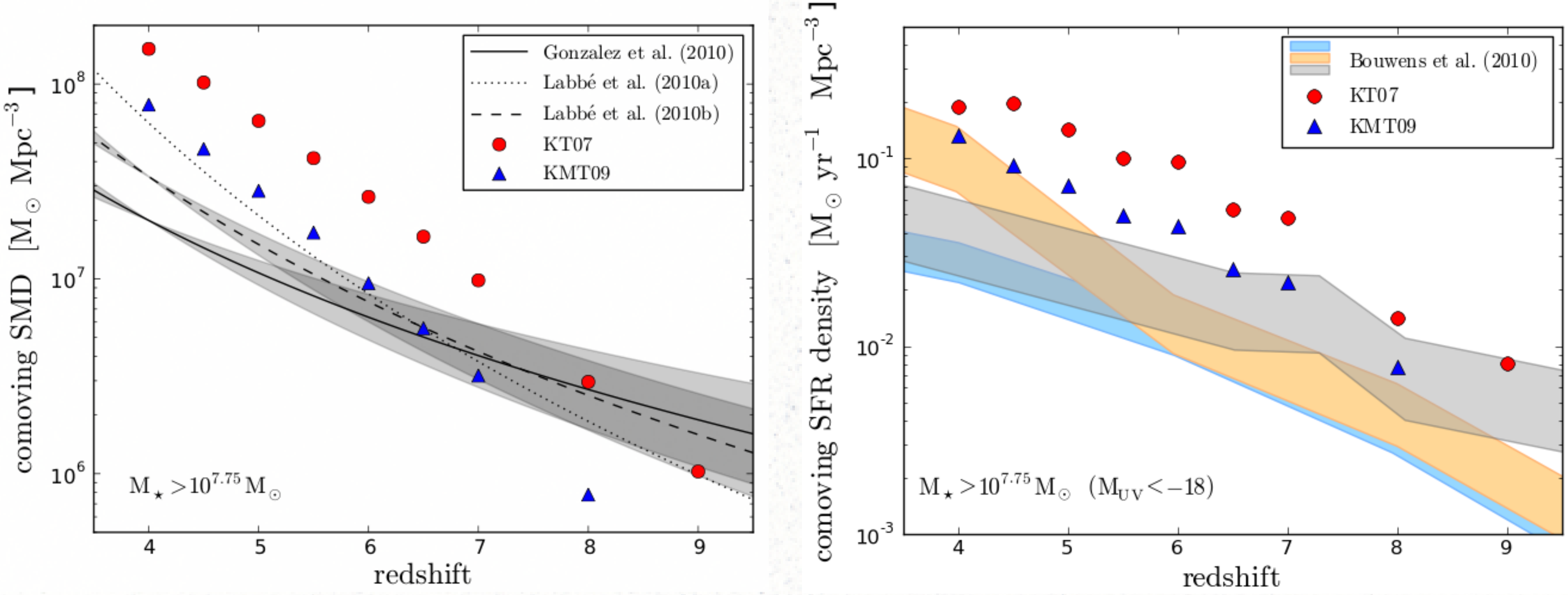
H_2-regulated SF improves agreement around sensitivity limit (MUV=-18).

H_2 suppression in this realization may be too strong for fainter systems.

Kuhlen et al. (2011, arXiv:1105.2376)

H_2-regulated Star Formation

Evolution of Stellar Mass Density... and ...Star Formation Rate Density



Compares favorably with current (uncertain!) determinations utilizing ultra-deep rest-frame UV HST ACS/WFC3 observations coupled with stellar masses estimated from Spitzer rest-frame optical measurements.

[Bouwens et al. 2009, 2010, Gonzalez et al. 2010, Labbé et al. 2009, 2010, Stark et al. 2009]

Kuhlen et al. (2011, arXiv:1105.2376)

Conclusions

- The are **two dwarf galaxy problems** in our understanding of the galaxy formation process:
  1) The Missing Satellites Problem
  2) The Field Dwarf Galaxy Problem
- Both are typically explained by invoking “supernova feedback”, but other explanations should be considered. One example is **H_2-regulated star formation**.
- Cosmological **AMR hydrodynamical galaxy formation simulations** with Enzo show that regulating SF by the H_2 abundance:
  - Reproduces the cutoff in Σ_{SFR} in the Kennicutt-Schmidt relation at ~10 $M_\odot/pc^2$ without the need for a SF density threshold.
  - Matches the observed H_2-KS relation as reported by Genzel et al. (2010) at z=0-3.5.
  - Suppresses star formation in $M < 10^{10}$ $M_\odot$ halos, because these galaxies aren't able to self-enrich as well as more massive halos.
  - Improves the agreement with (uncertain) observational determinations of the cosmic stellar mass density and SFR density evolution at z>4.
  - **Helps to alleviate the dwarf galaxy problems.**