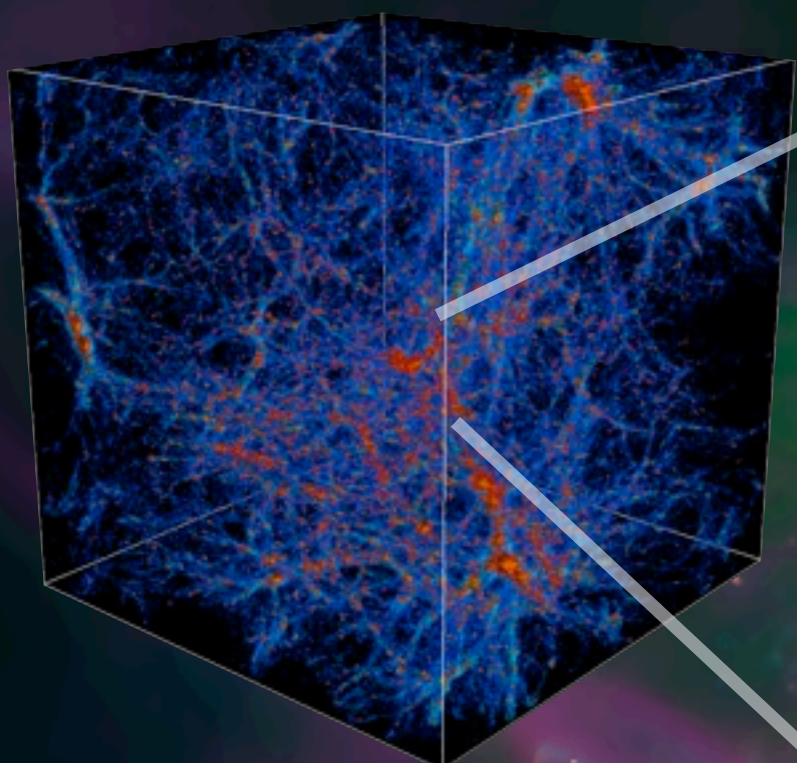
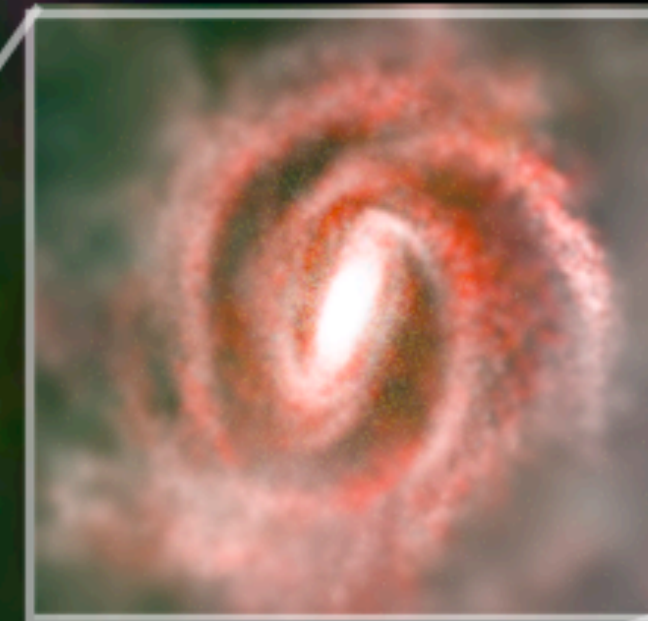
Impact of H_2 star formation model & Reionization of the Universe

+ AGORA





Ken Nagamine
UNLV / Osaka

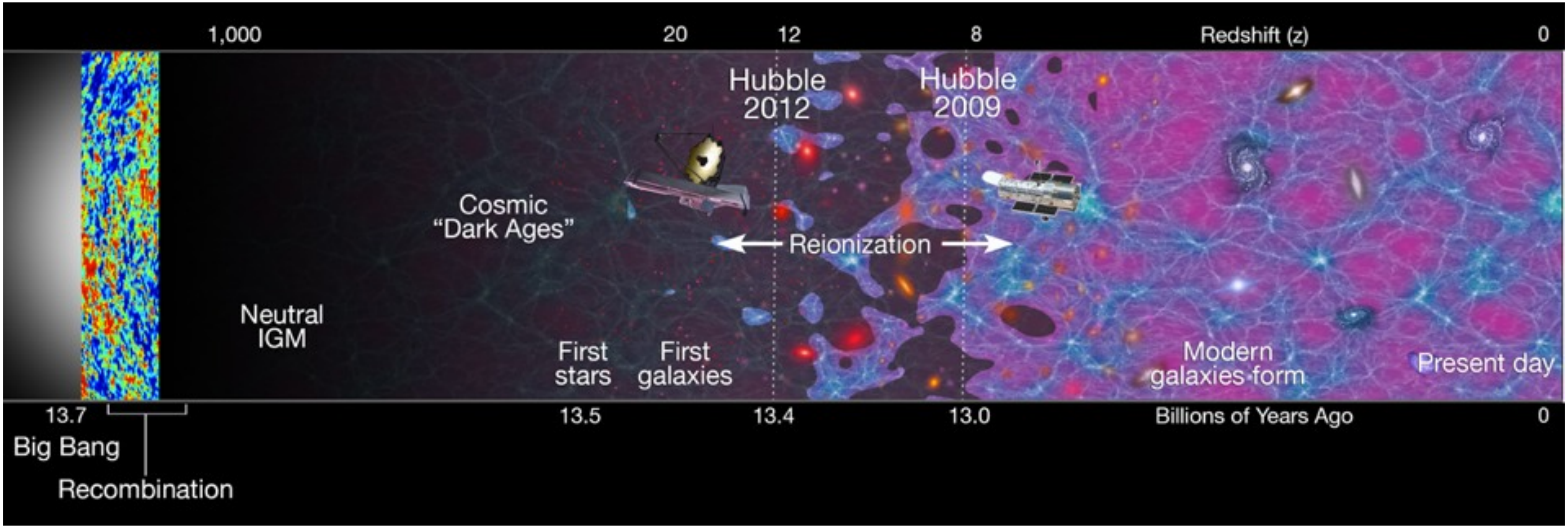
Robert Thompson (Arizona/UNLV) (H_2 SF model, DISPH)
Keita Todoroki (UNLV) (AGORA Run 1 & 2)
Jason Jaacks (UT Austin/UNLV) (Gal SMF/LF, SF history)
Jun-Hwan Choi (UT Austin/Kentucky) (SF/Wind model)
Hide Yajima (Edinburgh/Penn State) (Radiative Transfer)

Outline

- Motivation: High-z galaxy formation & Reionization in the concordance ΛCDM model
- `Standard' vs. H_2-based star formation (SF) model
- **Galaxy Mass/Luminosity Functions -- faint-end slopes & SF duty cycle**
- **Radiative Transfer & Escape Fraction**
- **Reionization of the Universe**

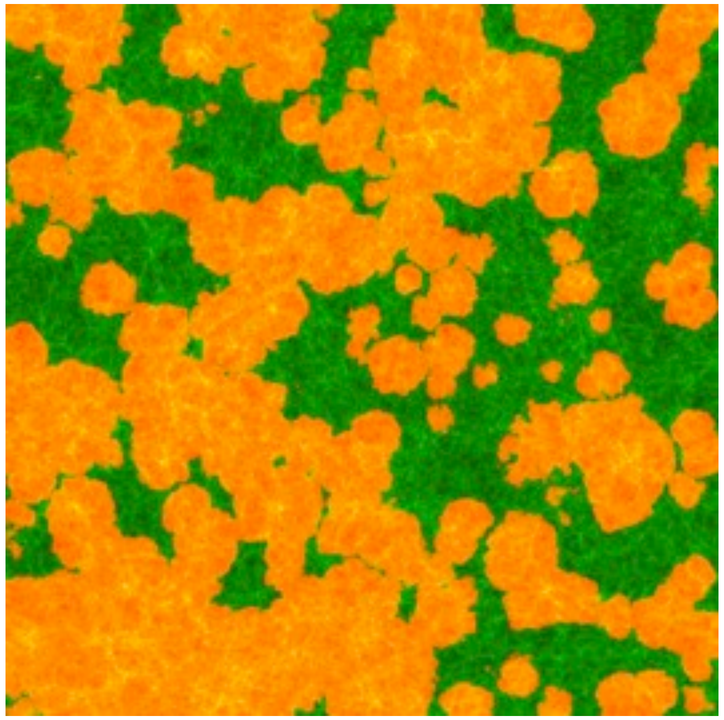
Cosmic Timeline

http://www.roe.ac.uk

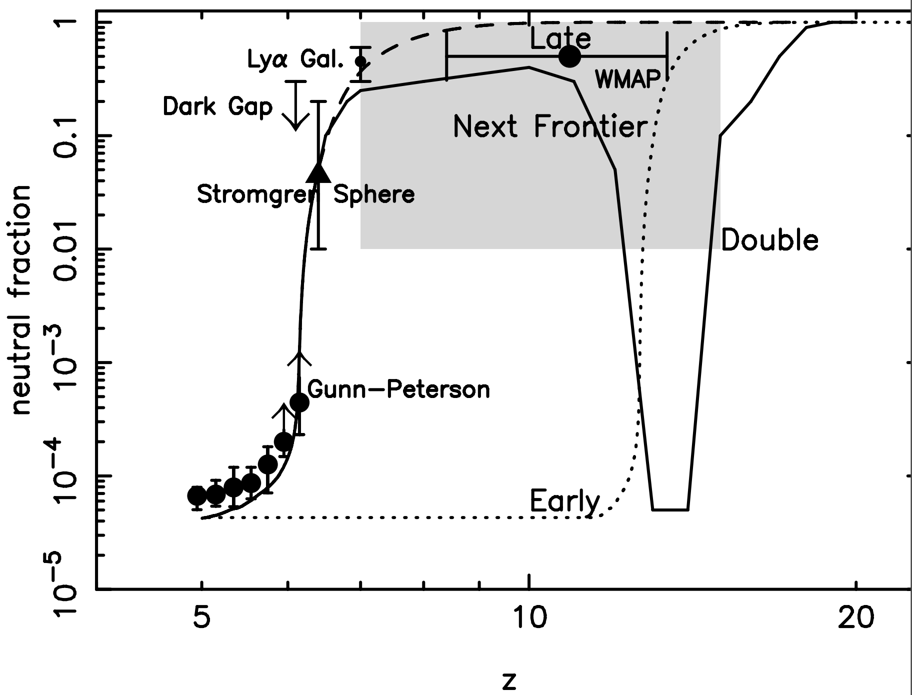


Observations are rapidly approaching the first galaxies

What are the sources responsible for reionization?



Illiev+ '06

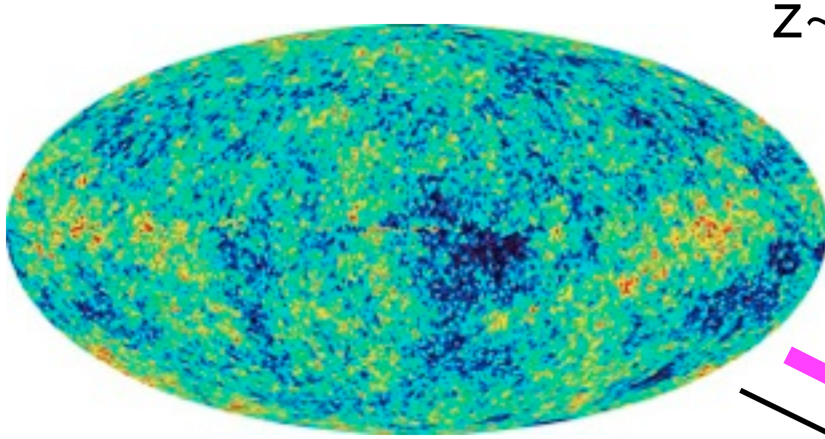


Fan+ '08

Computational Cosmology

Self-consistent galaxy formation scenario from first principles (as much as possible)

z~1000



Initial conditions

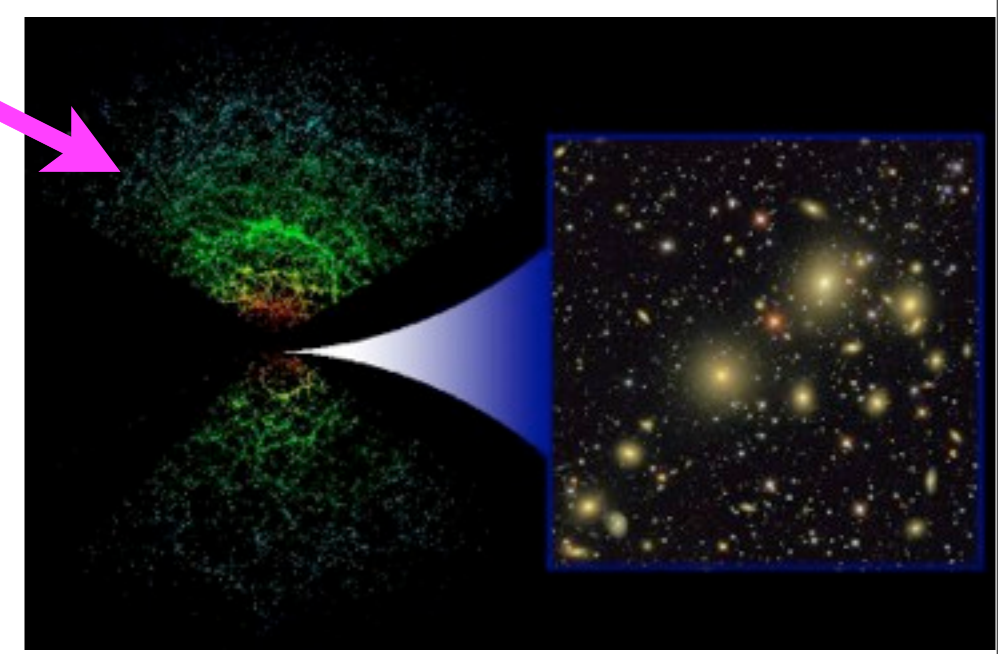
z=100

z=10

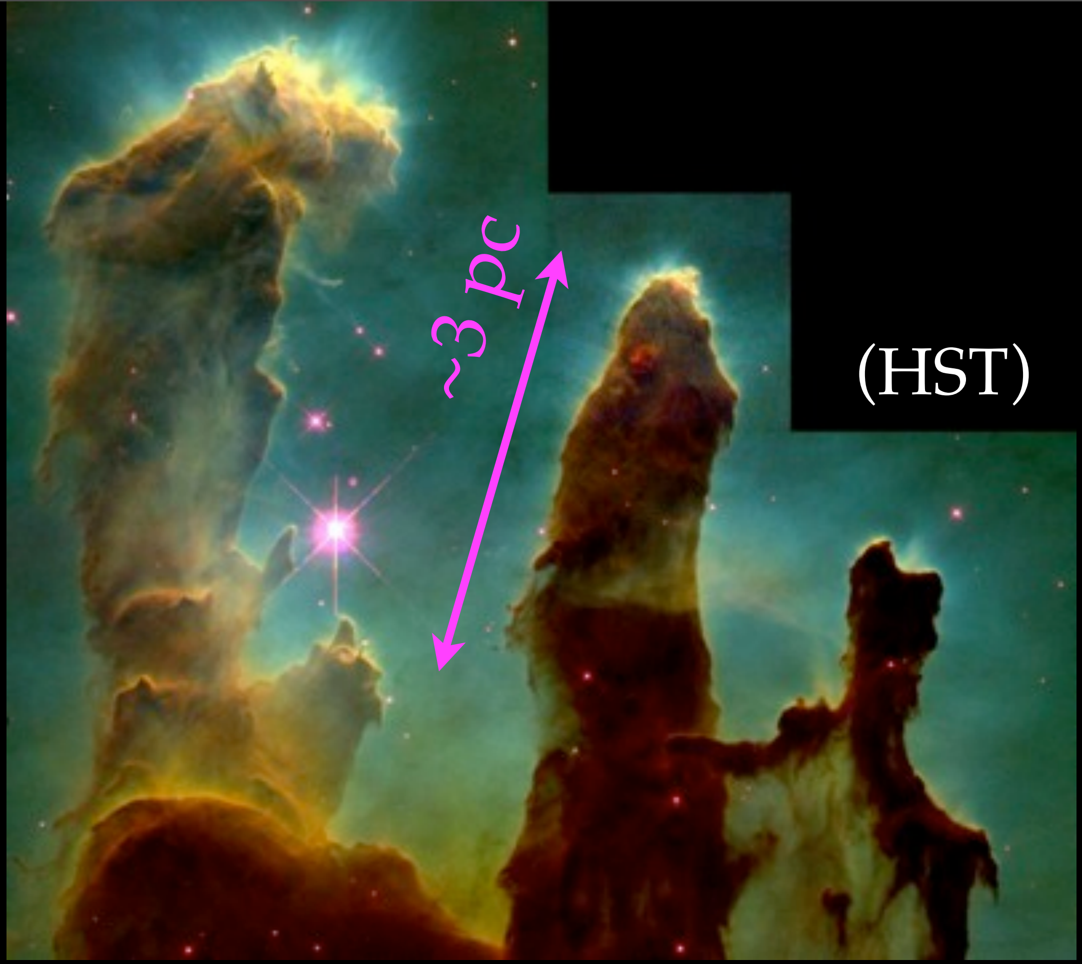
z=3

z=0

radiative cooling/heating, **star formation, feedback**



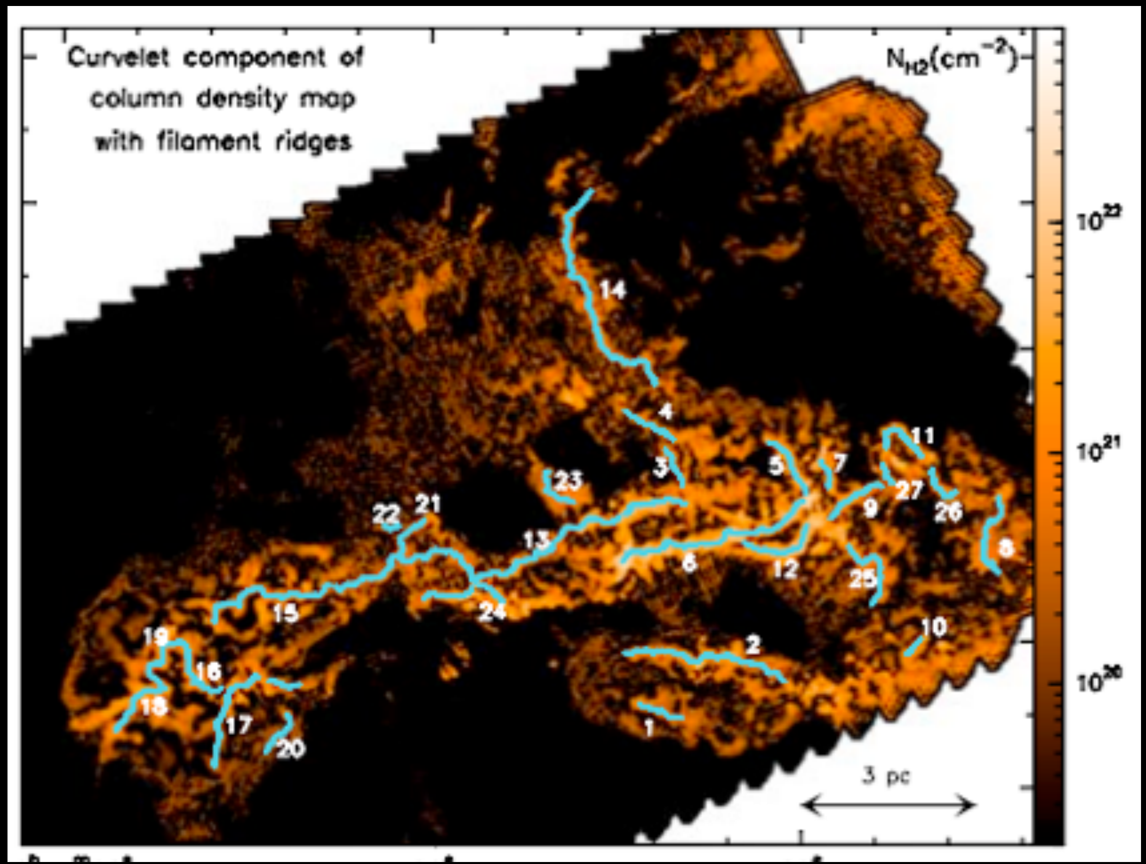
cosmological params, dark matter, **baryons**
gravity + **hydrodynamics**



`Pillars of Creation' in Eagle Nebula (M16)

- Current cosmological simulations lack the *spatial* and *mass* resolutions to resolve the small scale processes which govern star formation (SF) within the ISM.

- Thus we need a subgrid model for SF



- IC5146 molecular cloud

Filament thickness: ~0.1 pc
($N_H \gtrsim 10^{22}$ cm^{-2})

(~sonic scale below which interstellar turbulence becomes subsonic in diffuse gas)

Herschel 70-500μm (Arzoumanian+11)

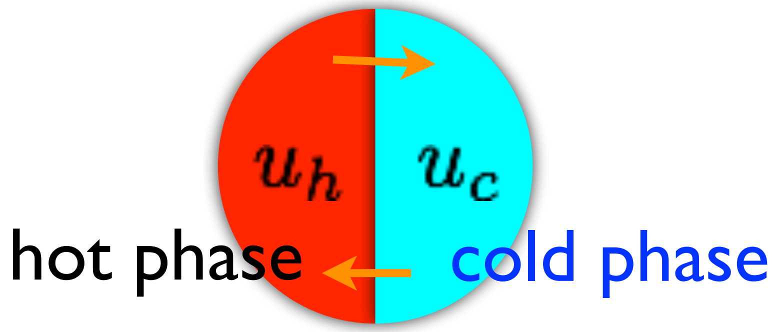
Sub-grid Multiphase ISM model

Each SPH ptcl is pictured as a multiphase hybrid gas.

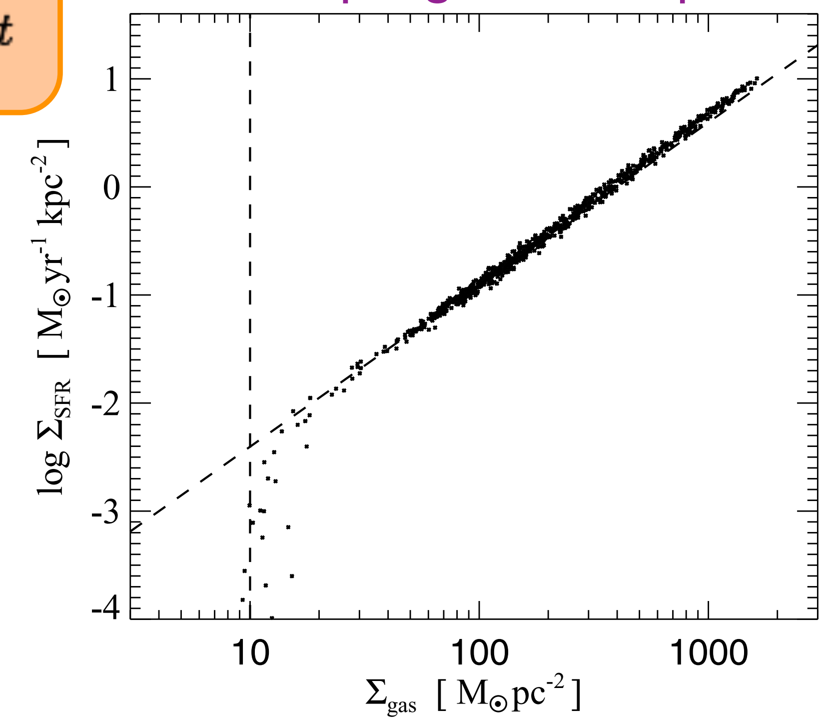
(cf. Yepes+ '97)

$$\rho_h \frac{du_h}{dt} = \beta \frac{\rho_c}{t_\star}(u_{sn} + u_c - u_h) - A\beta \frac{\rho_c}{t_\star}(u_h - u_c) - f\Lambda_{net}$$

$$u_c = \mathrm{const.}$$



Springel & Hernquist '03



SFR: $$\dot{\rho}_\star = (1-\beta)\frac{\rho_c}{t_\star}$$

cold gas

gas recycling fraction

$$t_\star = t_\star^0 \left(\frac{\rho_g}{\rho_{th}}\right)^{-0.5}$$

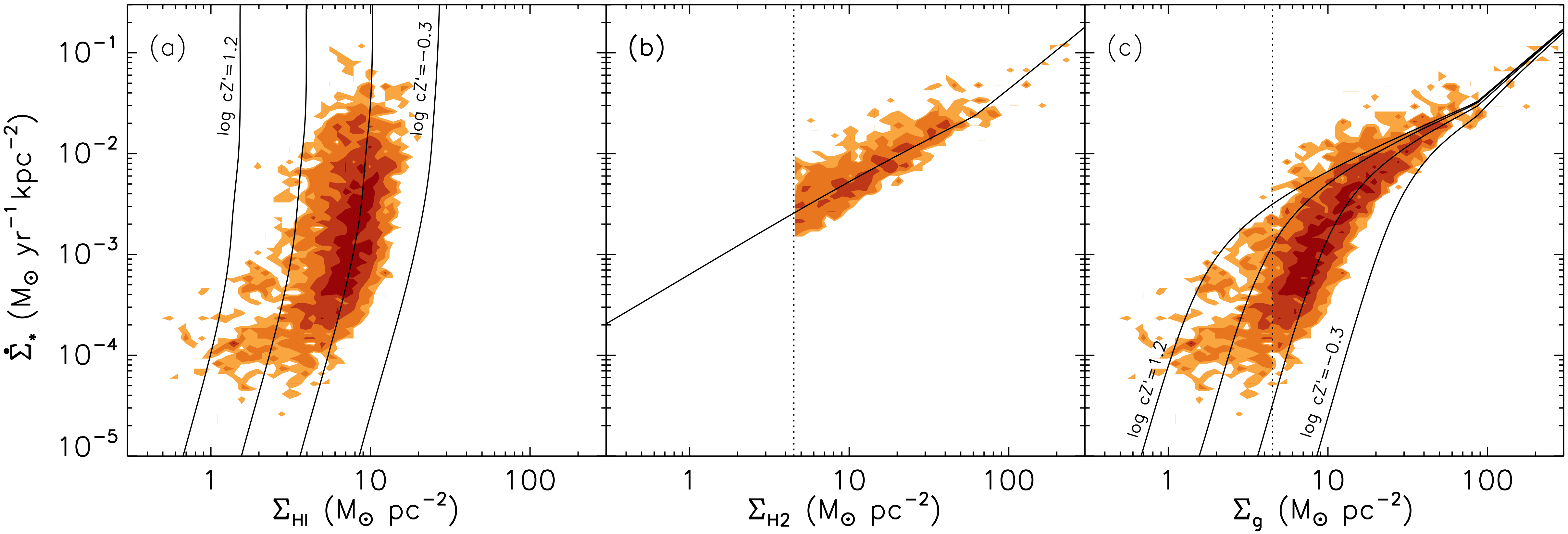
$$t_\star^0 = 2.1\,\mathrm{Gyr}$$

(controls the normalization; or equivalently, the SF efficiency.)

(n_{th} ~ 0.1 - 1 cm^{-3})

But, no manifest dependency on metallicity

H_2 dependence of SF

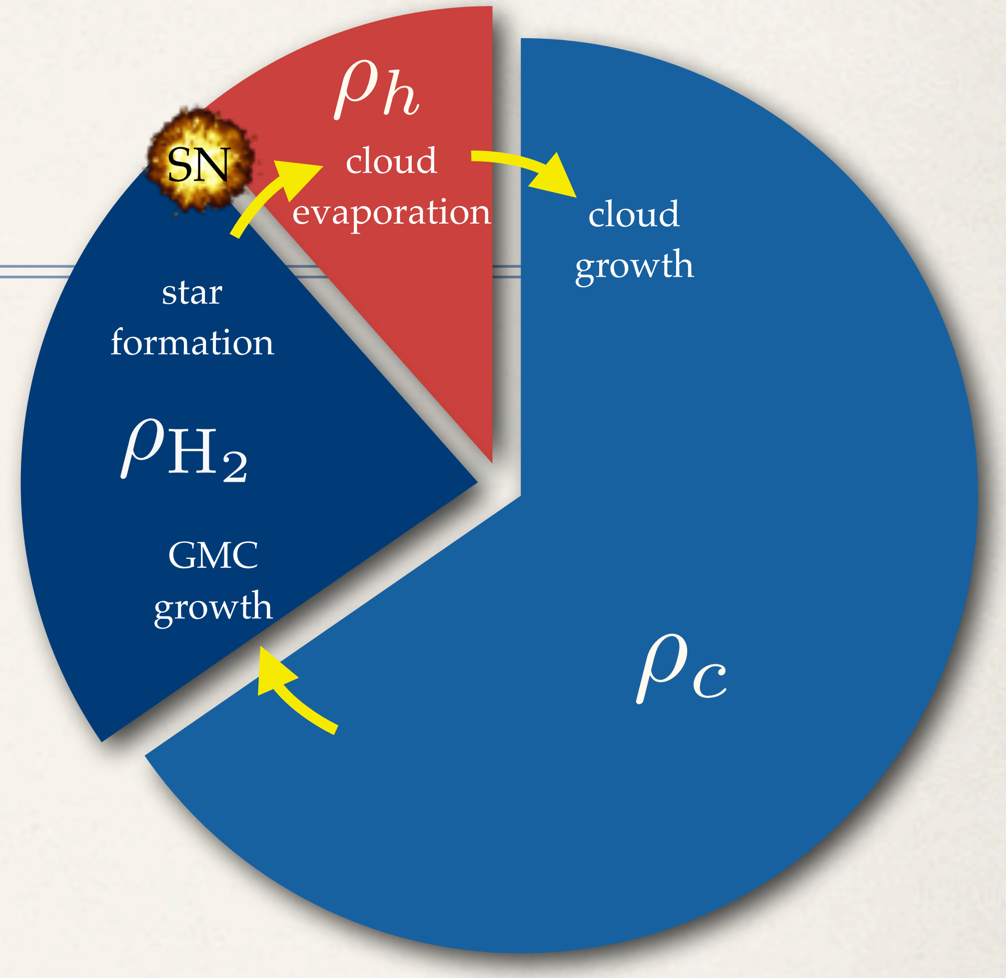


- **SF tightly correlates with molecular gas** **(e.g., Bigiel+ '08)**
- **Spread can be understood as metallicity dependence**

(Krumholz+ '09)

SPH implementation

- We modify the multiphase model to include the H_2 mass fraction.
- Change t_* to the ***free-fall time*** of material available to create stars.
- Account for SF efficiency via $\epsilon_{ff} = 0.01$ (Krumholz & Tan 2007, Lada et al. 2010).



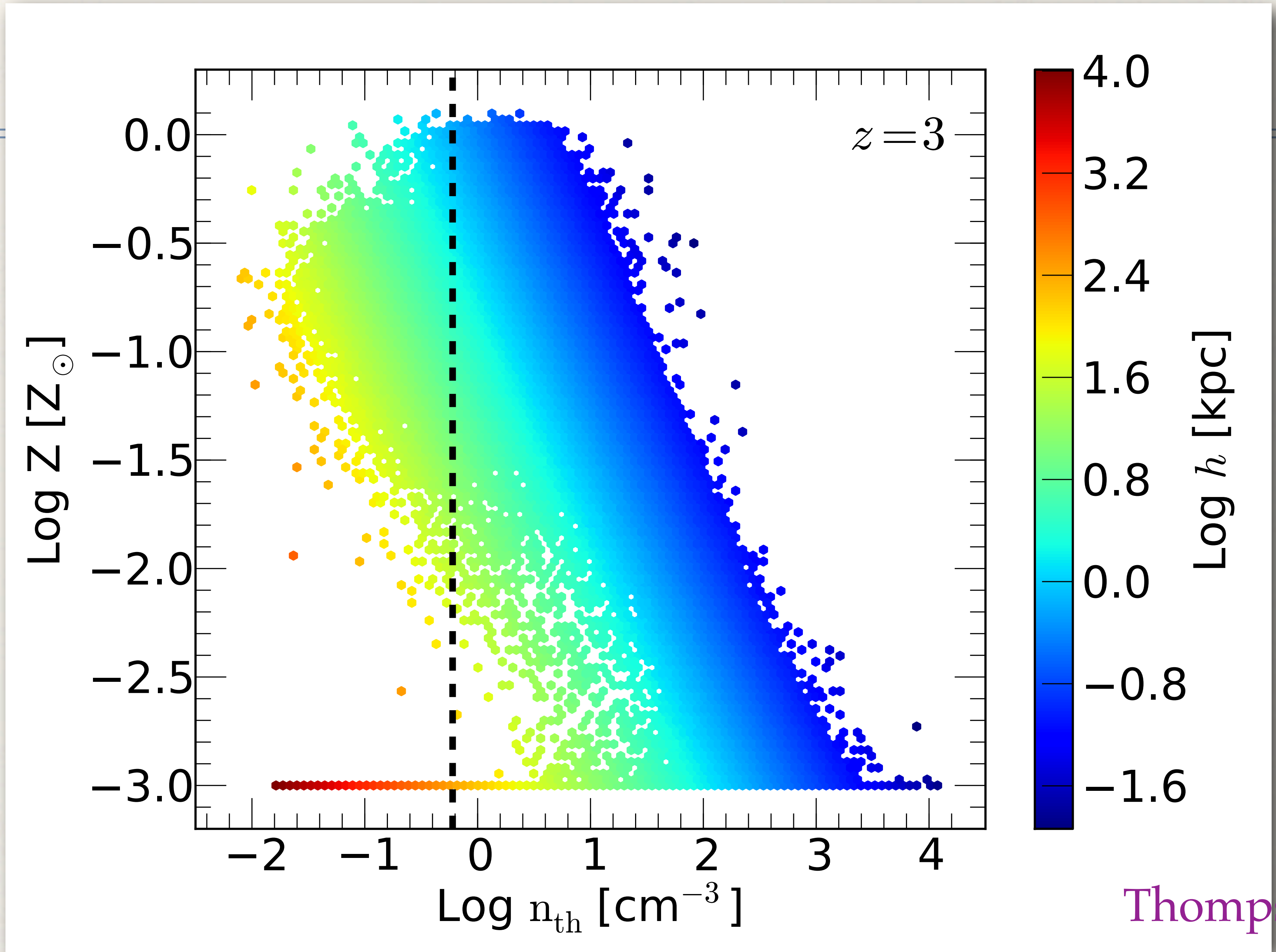
$$\dot{\rho}_* = (1-\beta)\epsilon_{ff}\frac{\rho_{H_2}}{t_*}$$

where $$t_* = t_{ff} = \sqrt{\frac{3\,\pi}{32\,G\,\rho_{H_2}}}$$

See Robert Thompson's talk for more details.

(cf. Christensen+; Gnedin+, Robertson+…..)

SF threshold for H_2 formation
(natural metallicity-dependence)



Thompson, KN+ '13

What do we do about n_{th} in AGORA?

Cosmological SPH Simulations

- modified GADGET-3 SPH code (Springel '05+α)
  radiative cooling/heating (w/ metals), SF model, SN & galactic wind feedback with multicomponent variable velocity (MVV) model, self-shielding correction (KN+10)
- Advantage over zoom-in runs: larger statistical samples of galaxies

Run Name	Box Size $[h^{-1}$ Mpc$]$	Particle Count DM & Gas	$m_{\rm dm}$ $[h^{-1}\ {\rm M}_\odot]$	$m_{\rm gas}$ $[h^{-1}\ {\rm M}_\odot]$	ϵ $[h^{-1}$ kpc$]$	$z_{\rm end}$ H_2	$z_{\rm end}$ Fiducial
N144L10	10.00	2×144^3	2.01×10^7	4.09×10^6	2.77	3.00	3.00
N500L34	33.75	2×500^3	1.84×10^7	3.76×10^6	2.70	3.00	-
N600L10	10.00	2×600^3	2.78×10^5	5.65×10^4	0.67	6.00	-
N400L10	10.00	2×400^3	9.37×10^5	1.91×10^5	1.00	6.00	5.50
N400L34	33.75	2×400^3	3.60×10^7	7.34×10^6	3.38	3.00	1.00
N600L100	100.00	2×600^3	2.78×10^8	5.65×10^7	4.30	0.00	0.00

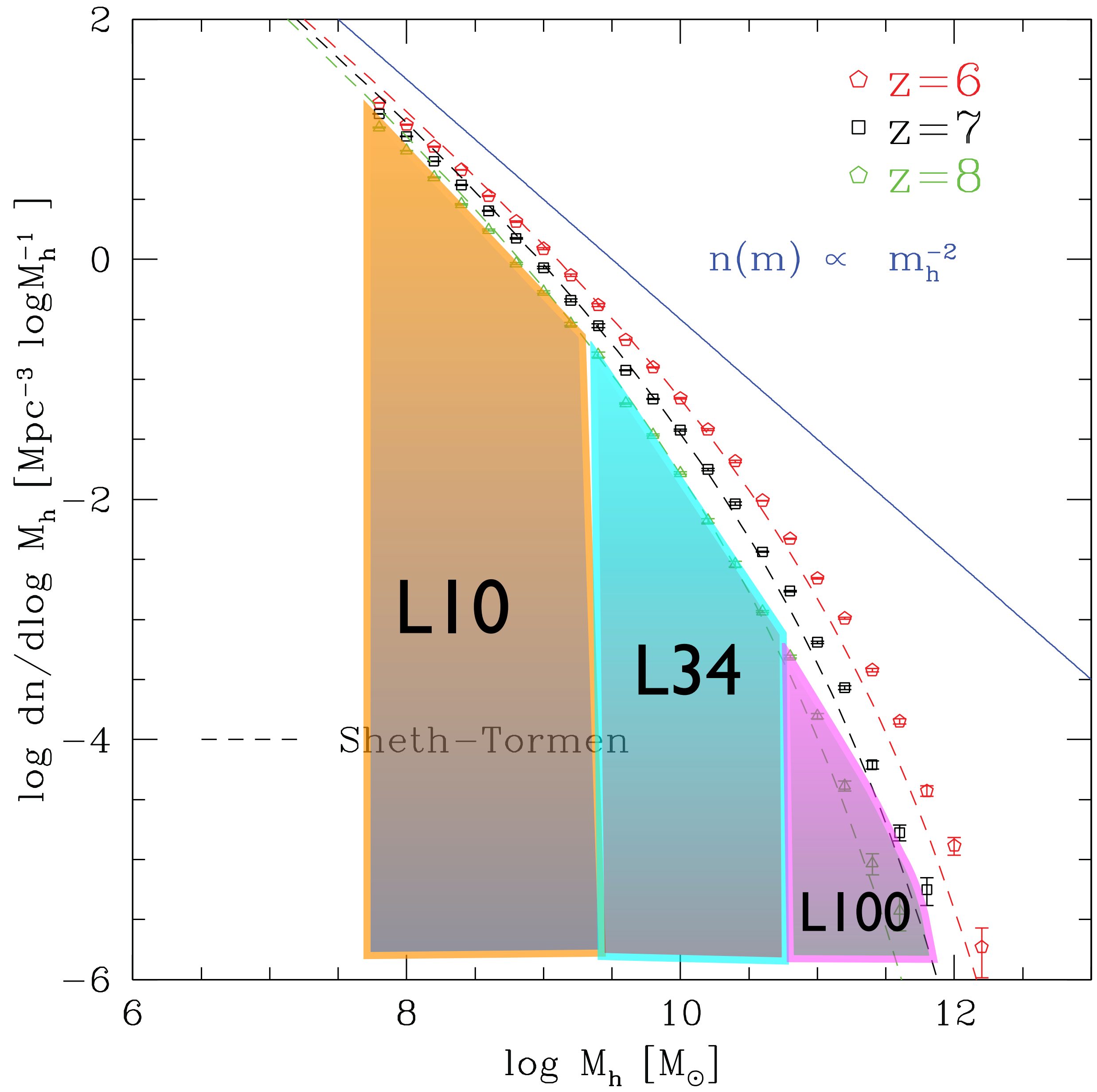
Fiducial: Pressure-based SF model

Schaye & Dalla Vecchia '08

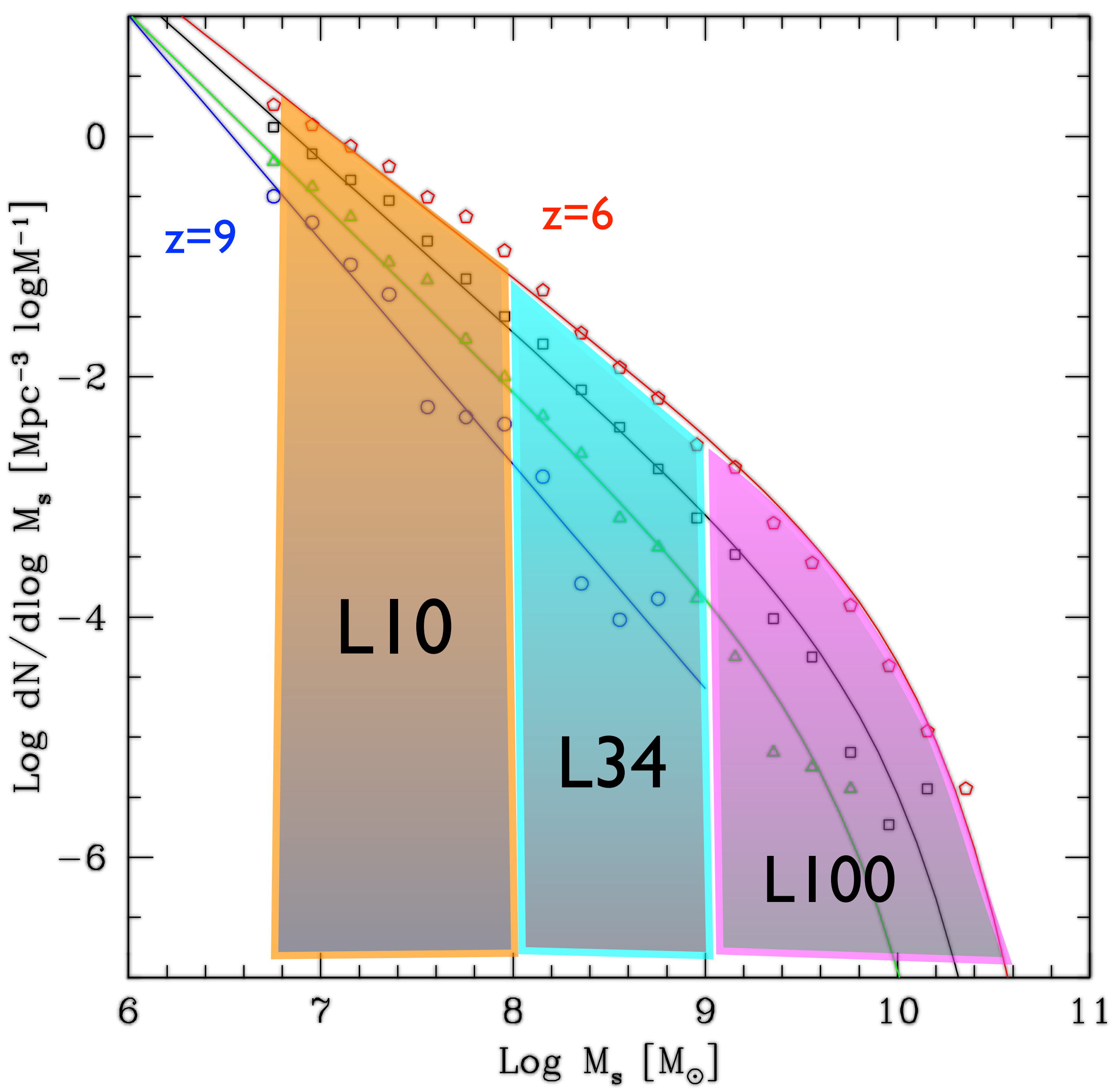
Choi & KN '09, '10, '11

Thompson, KN+ '13

Halo mass fcn



Galaxy Stellar Mass Fcn (GSMF)

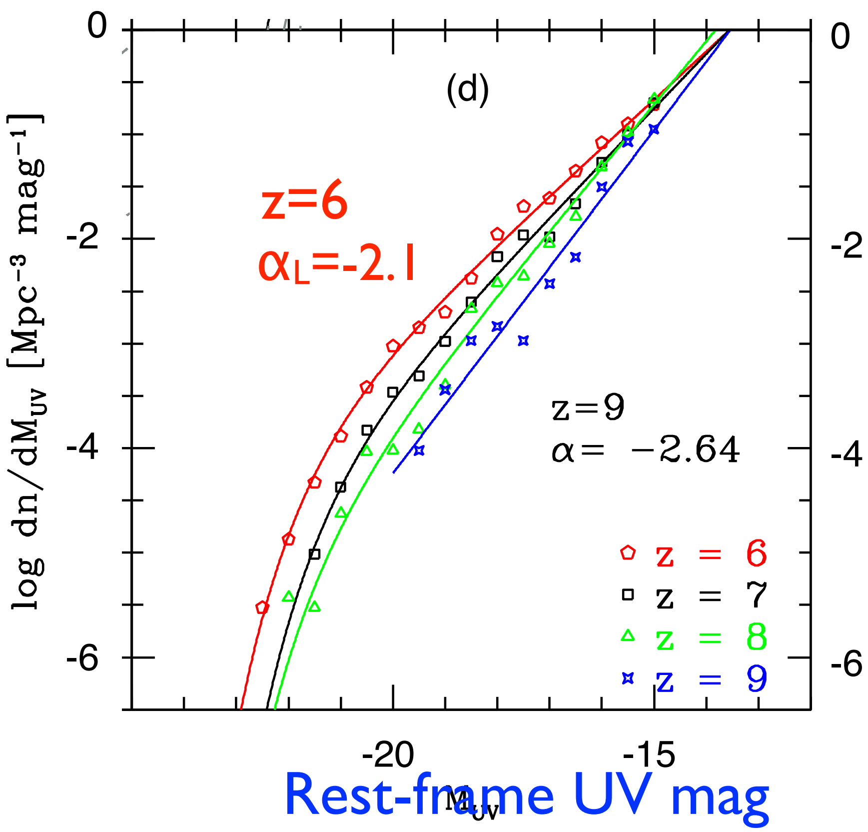


Jaacks, Choi & KN '12a

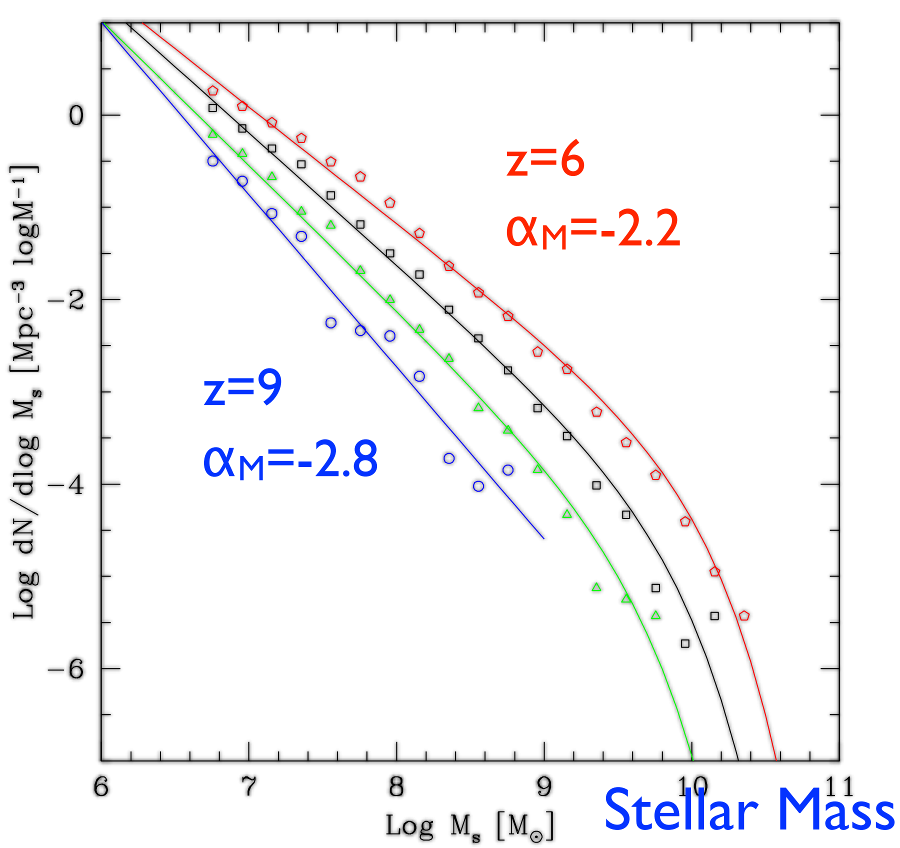
Redshift Evolution of LF & MF

3-param Schechter fits

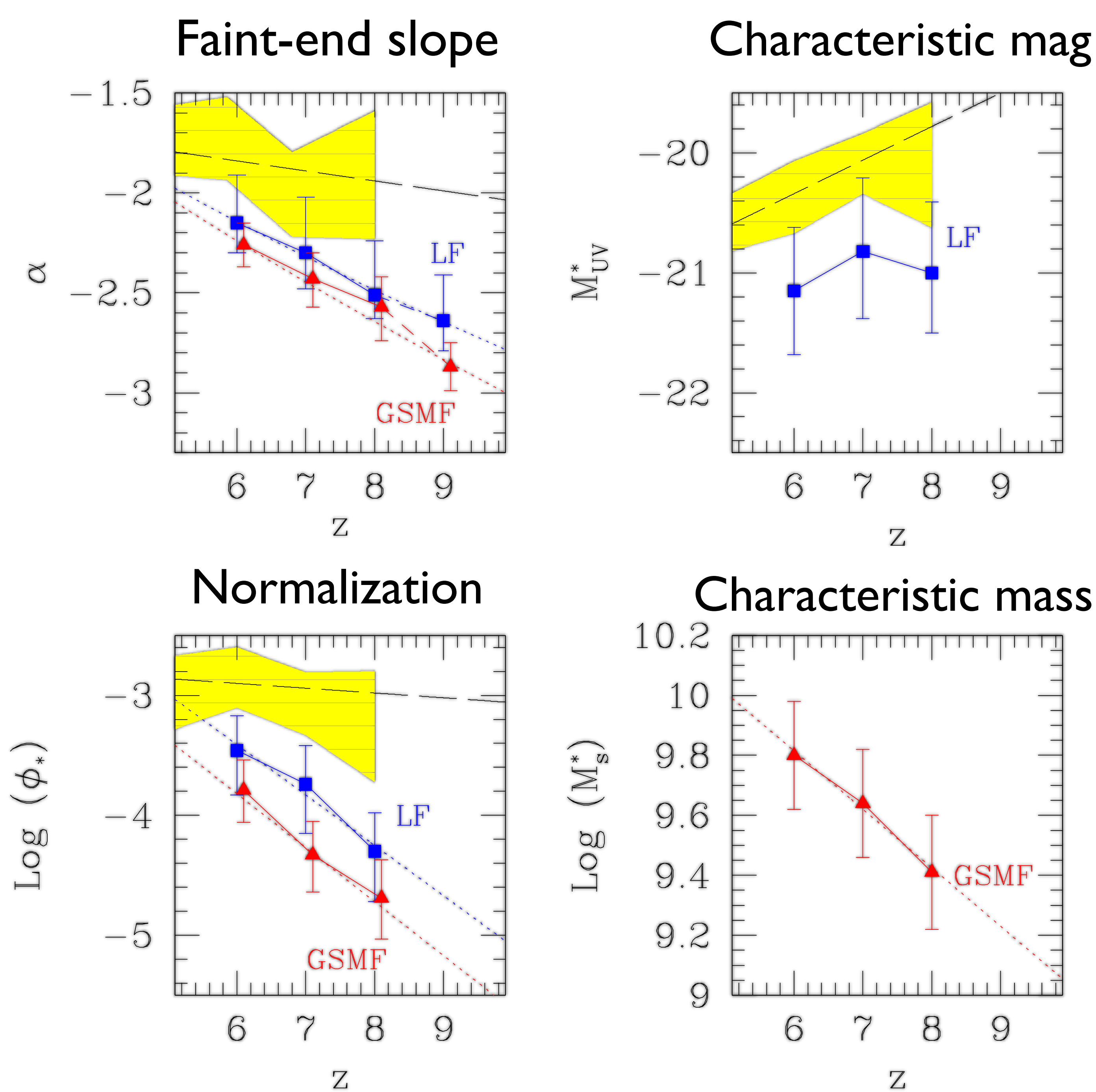
UV LF



GSMF



Evolution of Schechter Parameters



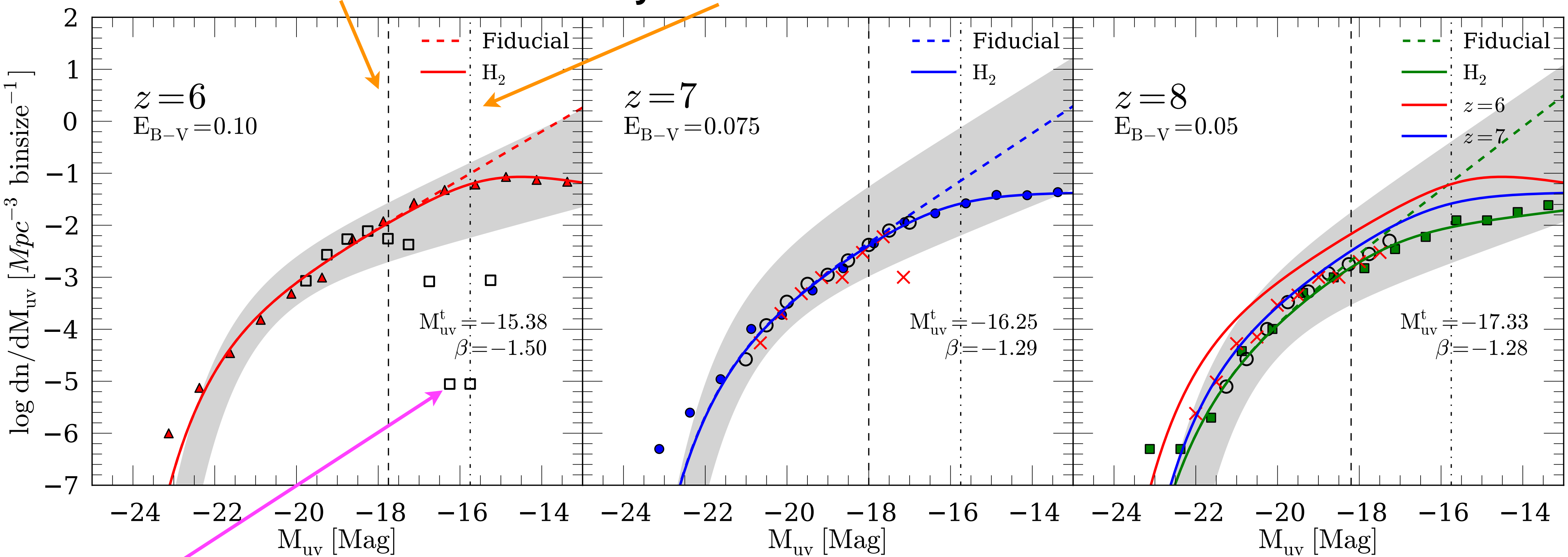
$$\alpha_M = 0.14 + 1.14\,\alpha_L,$$

Jaacks, Choi & KN '12a

LFs with H_2-SF model

HST limit

JWST limit



Kuhlen+ '12

(cf. O'Shea, KN+'05: Enzo-Gadget comparison)

Modified Schechter Func.

$$\Phi(L) = \phi^* \left(\frac{L}{L^*}\right)^{\alpha} \exp\left(-\frac{L}{L^*}\right) \left[1 + \left(\frac{L}{L^t}\right)^{\beta}\right]^{-1},$$

Loveday+ '97

# of low-mass gals is significantly reduced at M_{uv}>-16

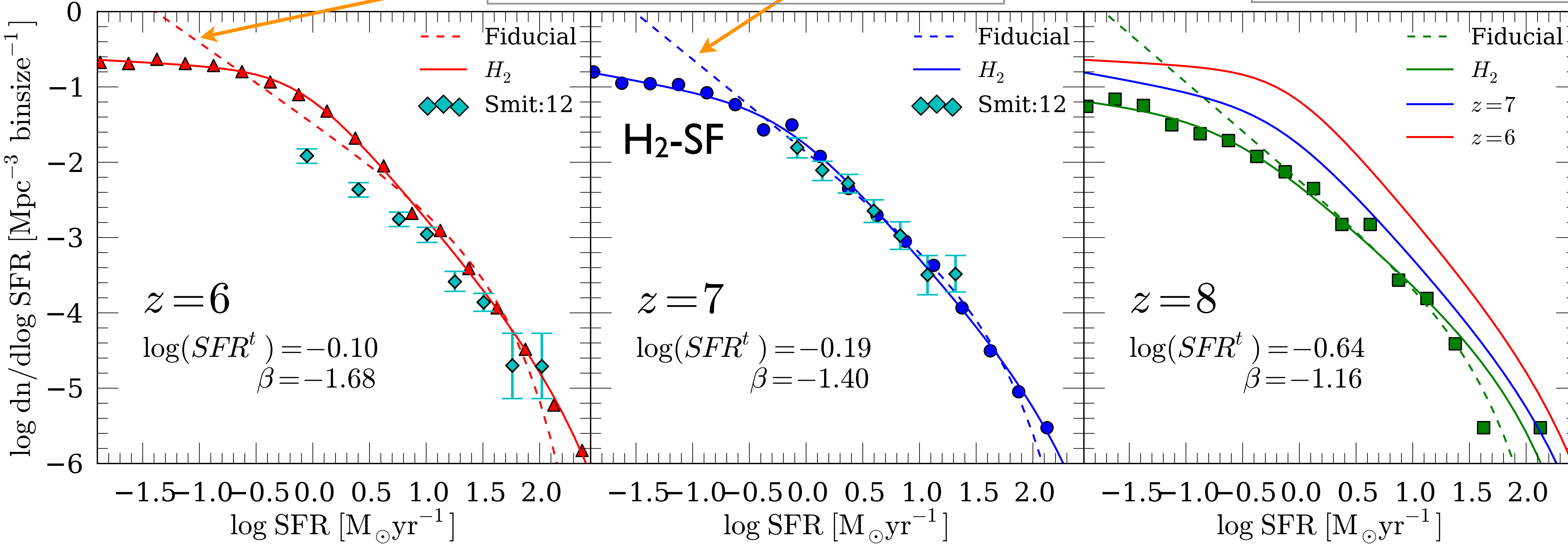
Future test with JWST.

Jaacks, Thompson, KN '13

SFR fcn w/ H_2-SF model

Previous pressure-SF model

Jaacks, Thompson, KN '13



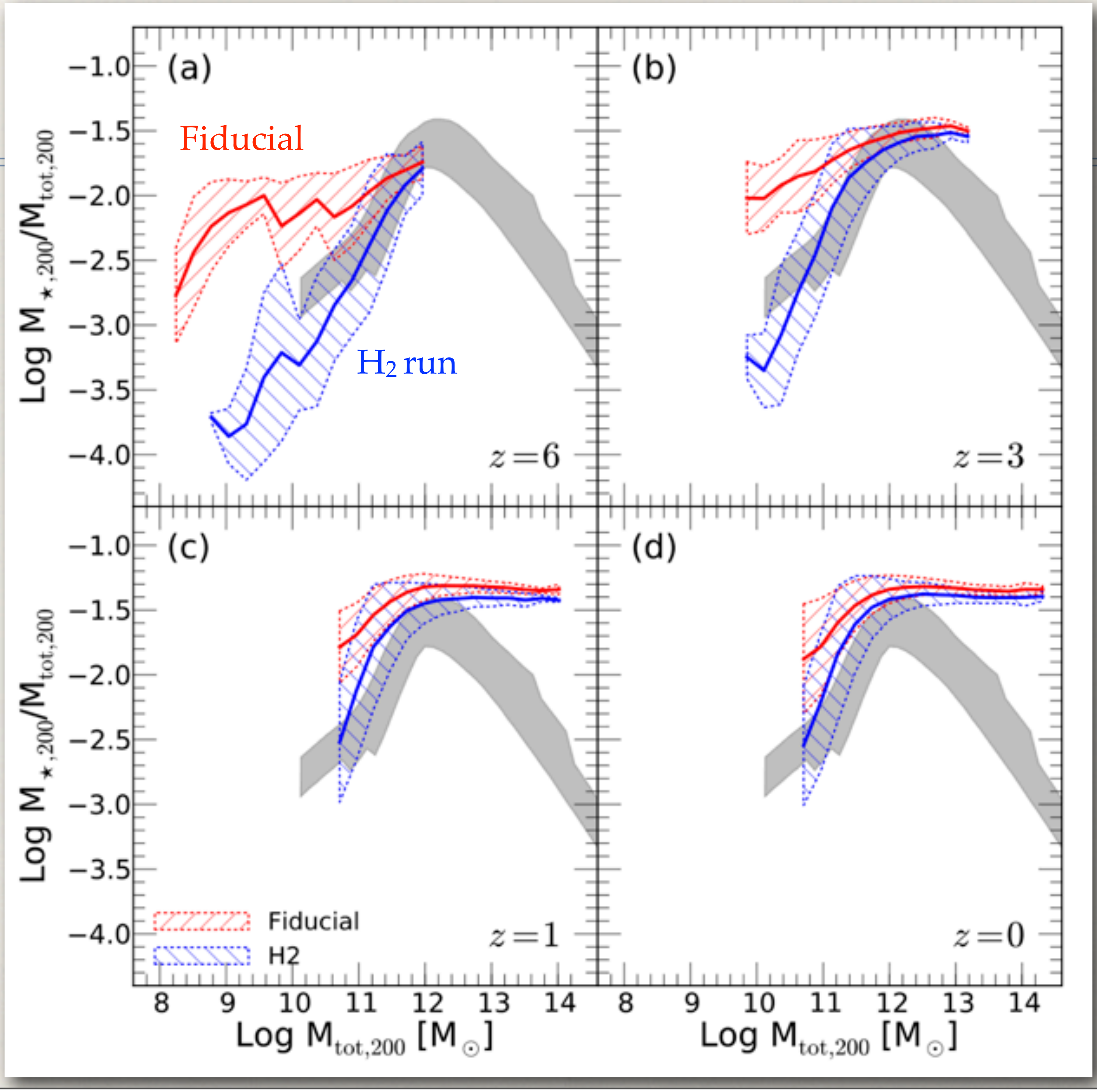
Modified Schechter SFR fcn:

$$\phi(\mathrm{SFR}) = \ln(10)\phi^* \left(\frac{\mathrm{SFR}}{\mathrm{SFR}^*}\right)^{(1+\alpha)} \exp\left(-\frac{\mathrm{SFR}}{\mathrm{SFR}^*}\right) \times \left[1 + \left(\frac{\mathrm{SFR}}{\mathrm{SFR}^t}\right)^{\beta}\right]^{-1},$$

Agrees well with current obs constraints at z=6 & 7 (Smit+ '12).

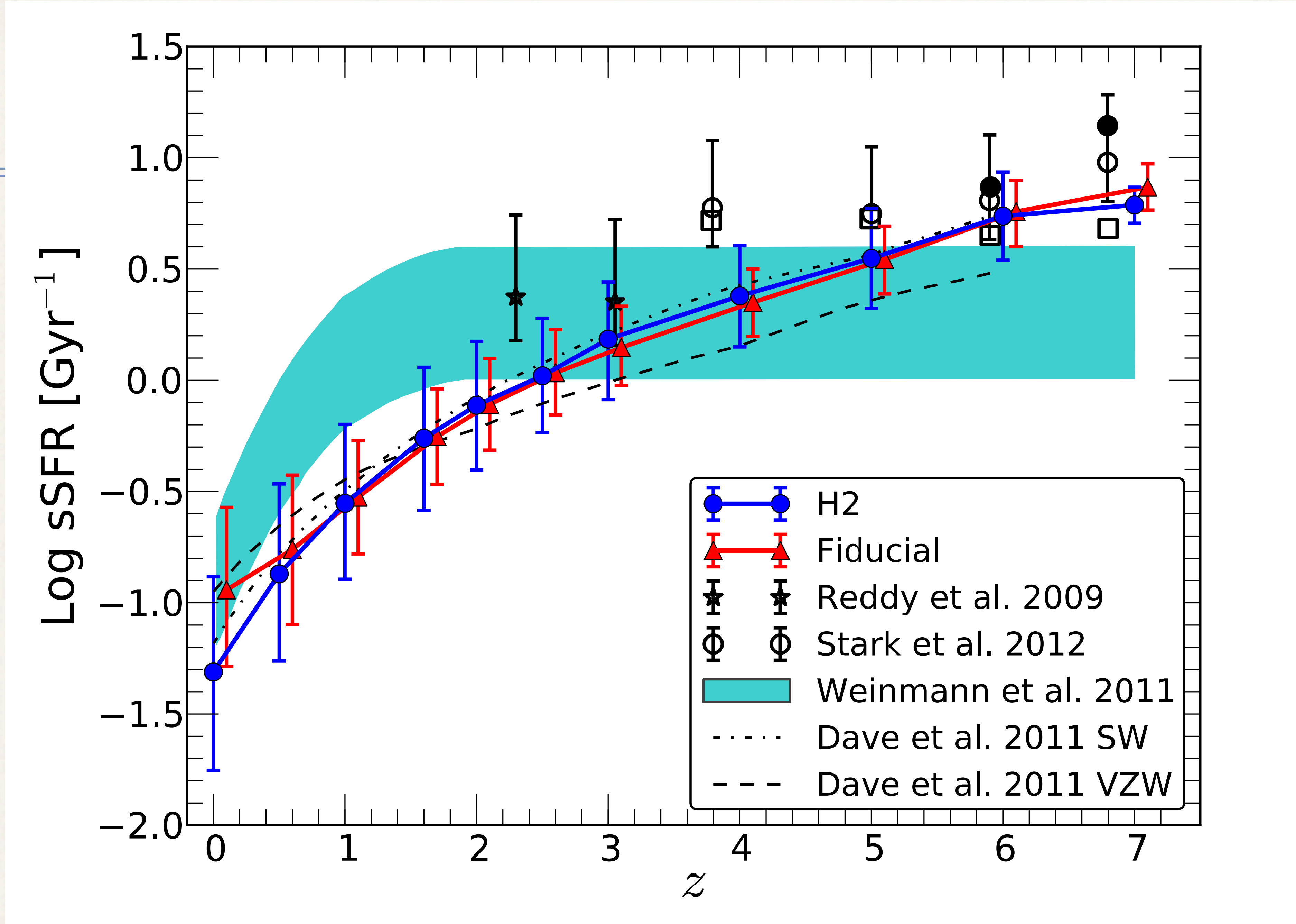
SFR fcn provides more direct comparison btw sim & obs.

Stellar-to-Halo Mass Ratio (SHMR)



Thompson, KN+ '13

Specific SFR (sSFR) vs. Redshift



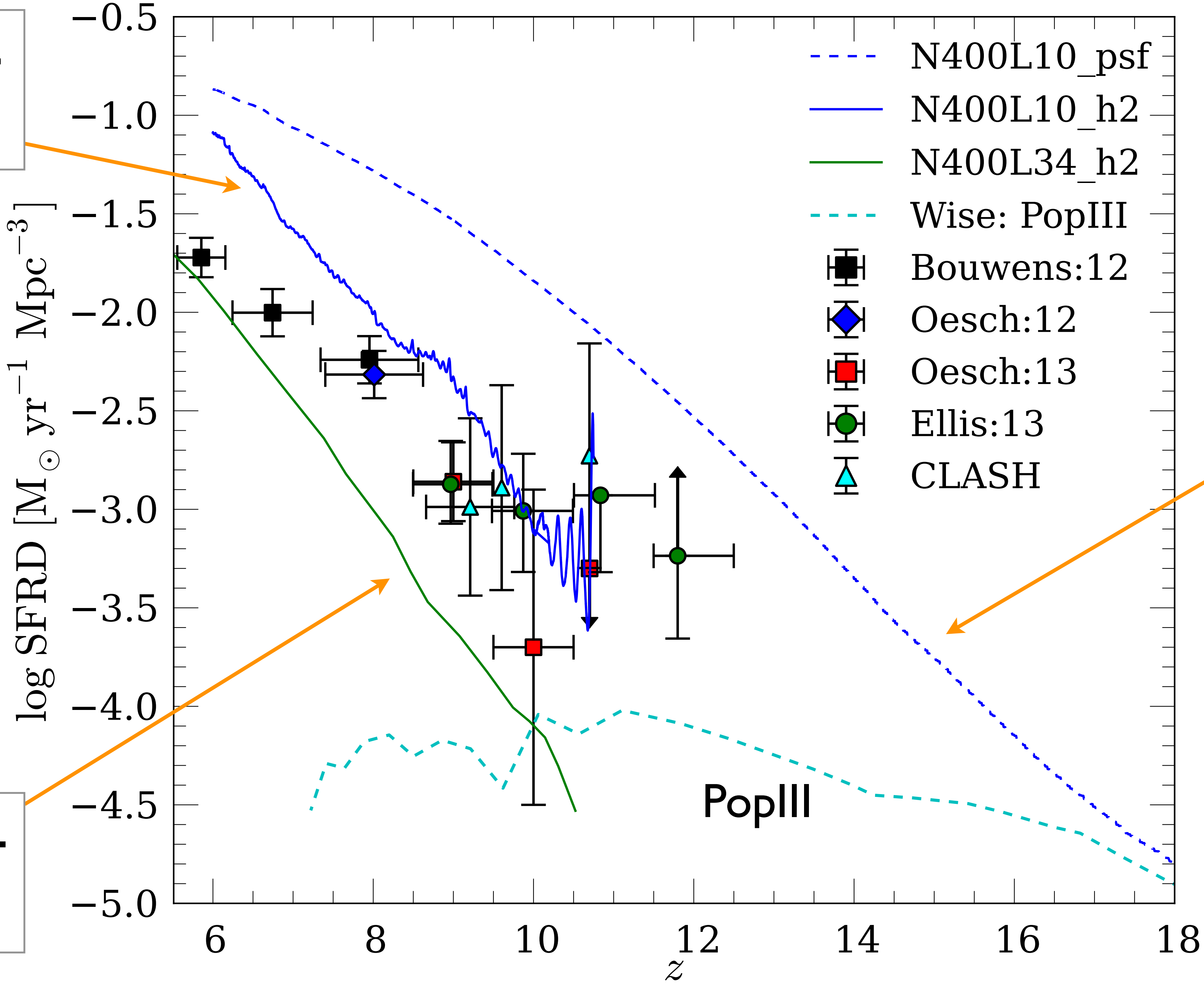
For $M_{star} \sim 10^{10}\ M_{\odot}$ galaxies.

Thompson, KN+ ’13

SFRD: Sim. vs Obs.

H$_2$-SF: low-mass gals

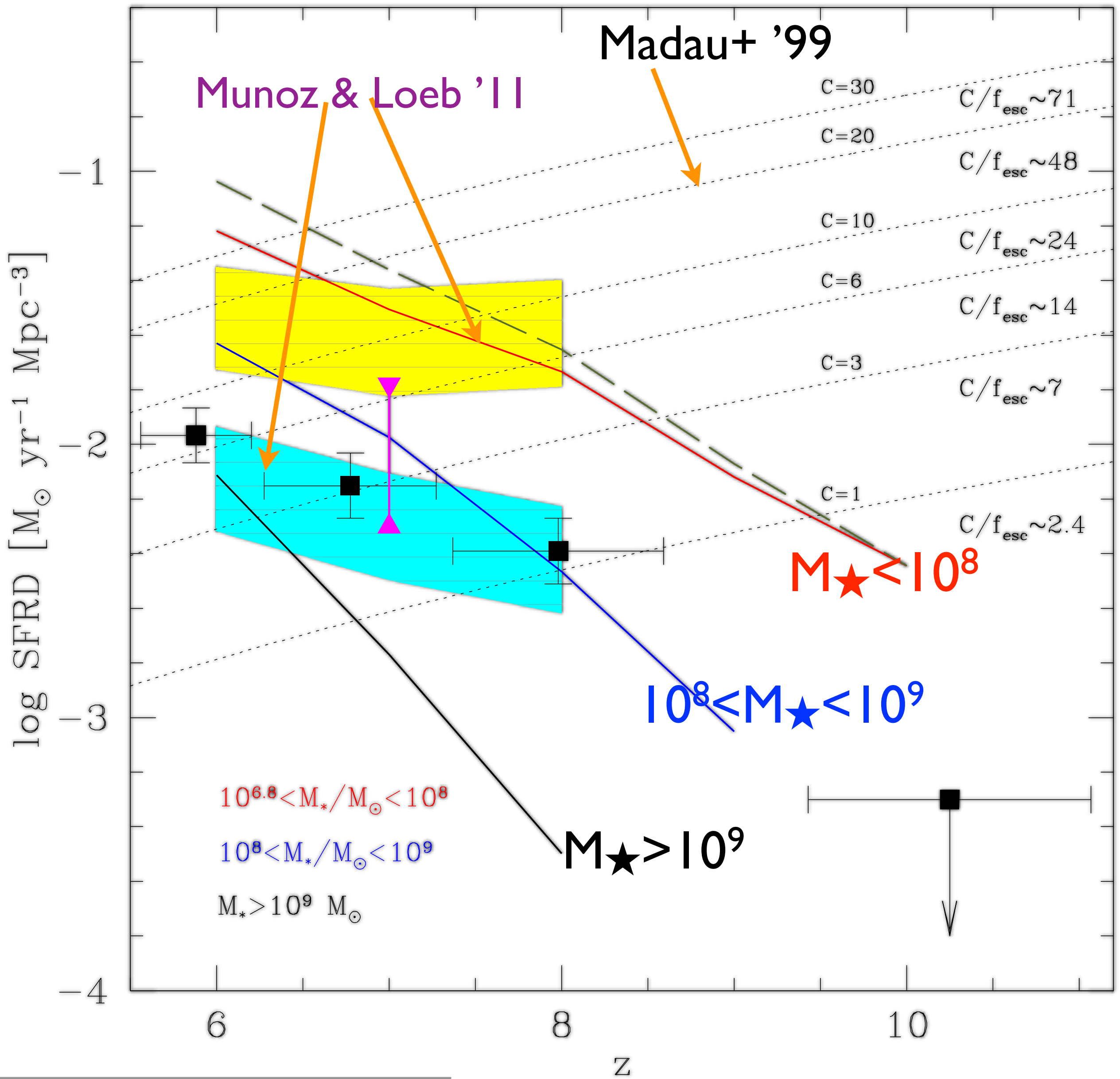
H$_2$-SF: high-mass gals



Pressure-SF model

Blitz & Rosolowsky '06
Schaye & Dalla Vecchia '08
Choi & KN '12

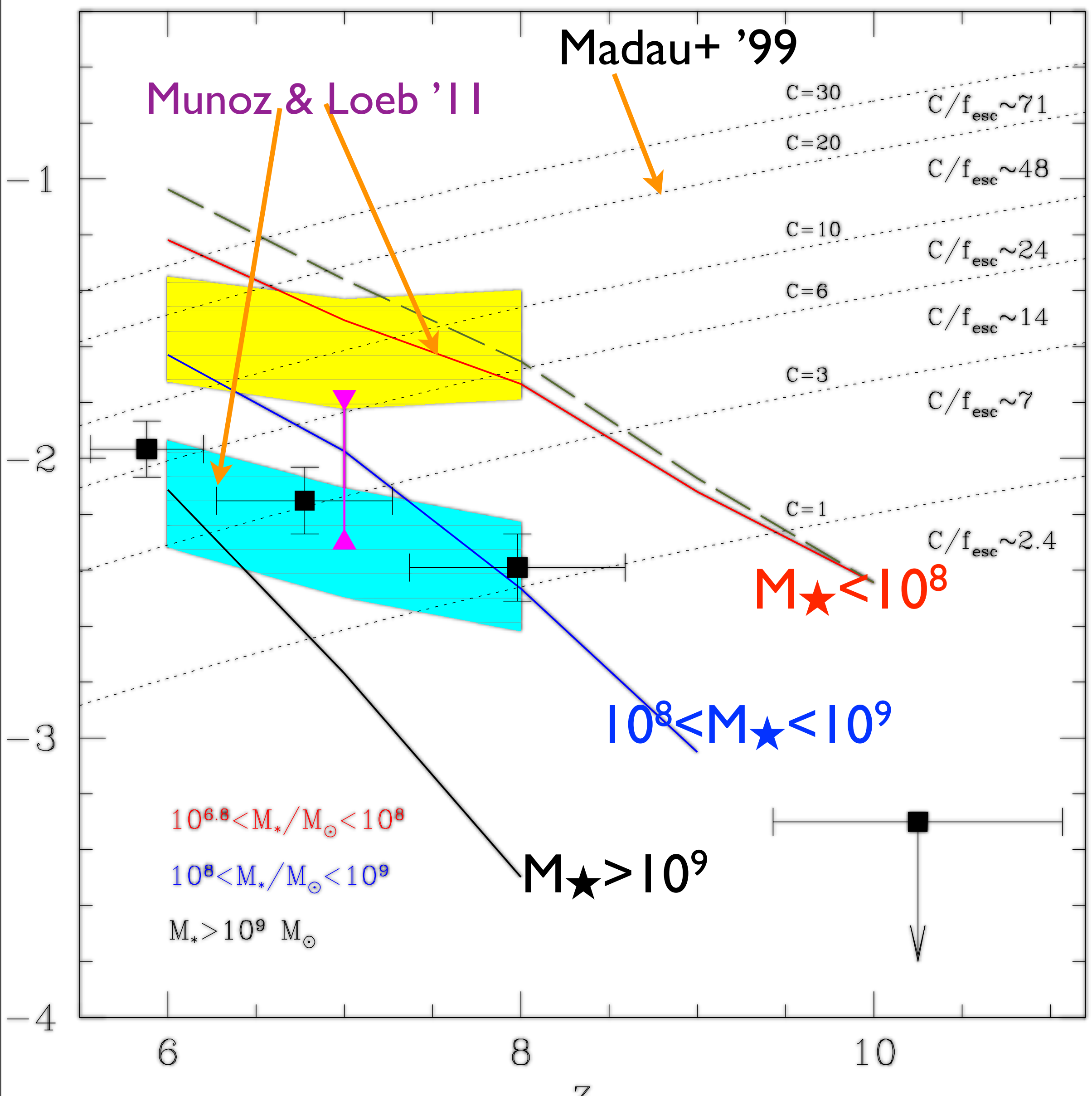
Reionization of the Universe



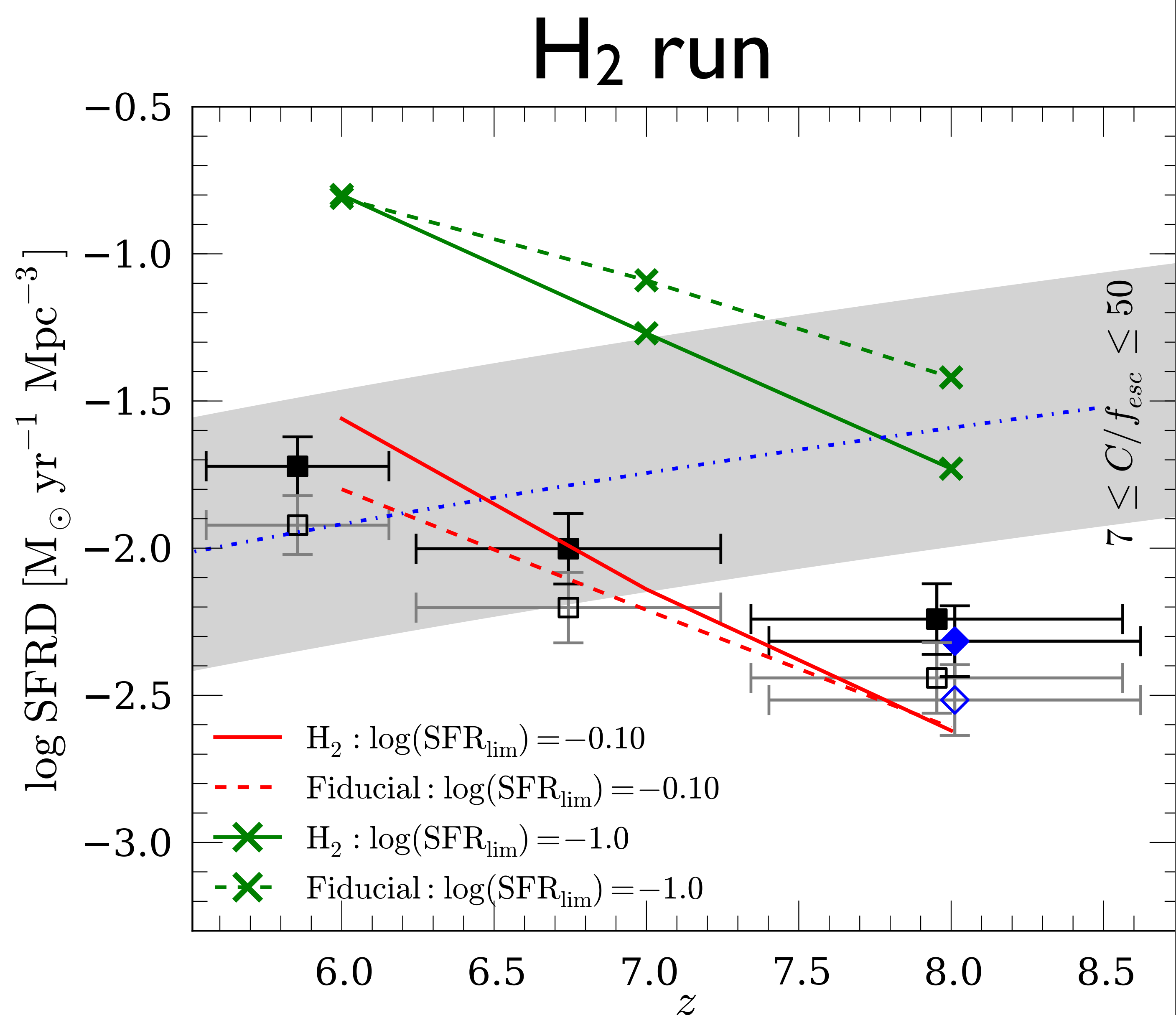
Jaacks, Choi & KN '12a

Low mass gals dominate the contrib. to the ionizing photons & they can maintain ionization to z~6

Reionization of the Universe



Jaacks, Choi & KN '12a

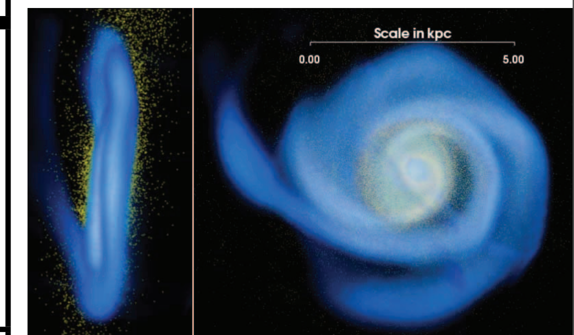


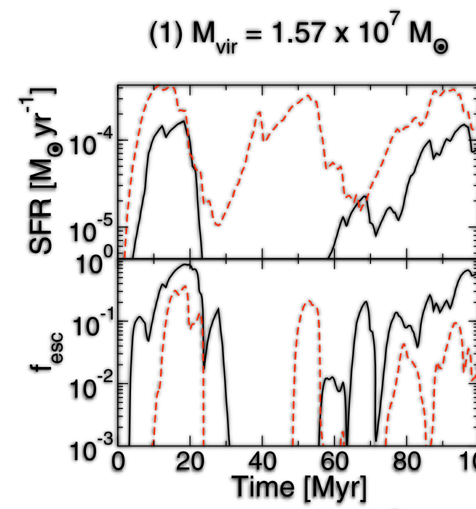
Jaacks, Thompson, KN '13

Low mass gals dominate the contrib. to the ionizing photons & they can maintain ionization to z~6

Escape Fraction of Ionizing Photons

Authors	$f_{esc,ion}$ (M_{halo})	Method
Gnedin+ '09	Very low 10^{-5}-10^{-1}, ↗ 10^{11}-10^{12} $M_{\odot}$	AMR, 6Mpc box, 65pc res, OTVET, z=3
Razoumov+'09	1.0-0.0, ↘ 10^{8}-$10^{11}M_{\odot}$	SPH, 6Mpc box, ~0.5kpc res, resim 9 gals, z=4-10
Wise & Cen +'09	Large scatter & time evol. 0-0.4, → 10^{6}-$10^{9}M_{\odot}$	AMR, 2 & 8Mpc box, 0.1pc res, z=8
Yajima+ '09	0-0.5, ↘ with time	Eulerian (Mori & Umemura '06 sim, single system, t=0-1Gyr)
Yajima, Choi, KN '11	1.0-0.0 ↘ 10^{9}-$10^{12}M_{\odot}$	SPH, 10Mpc box, ~0.5kpc res, z=3-6 100s of gals.



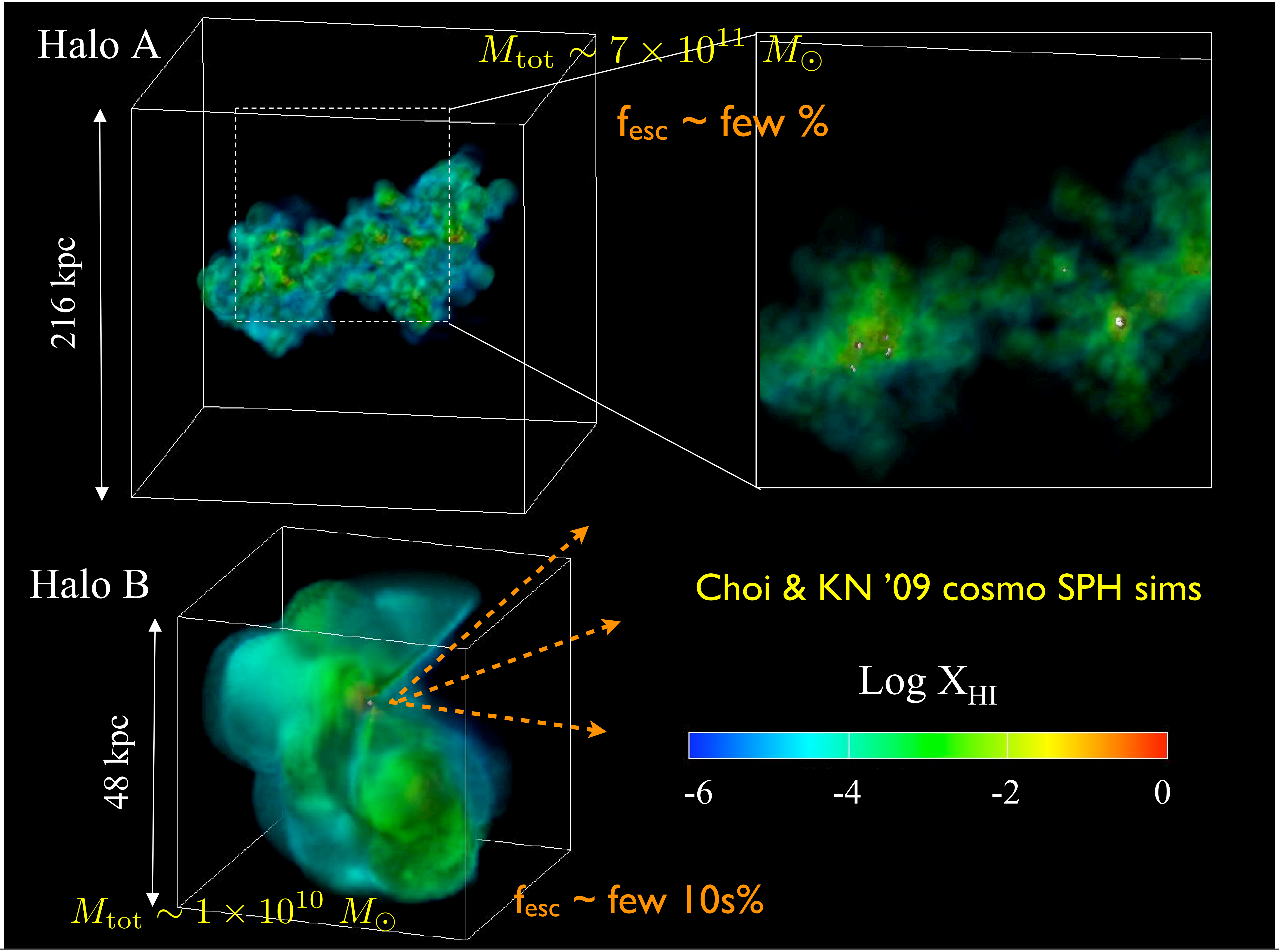


Good topic for AGORA - High-z WG?

Yajima, Choi, KN '11

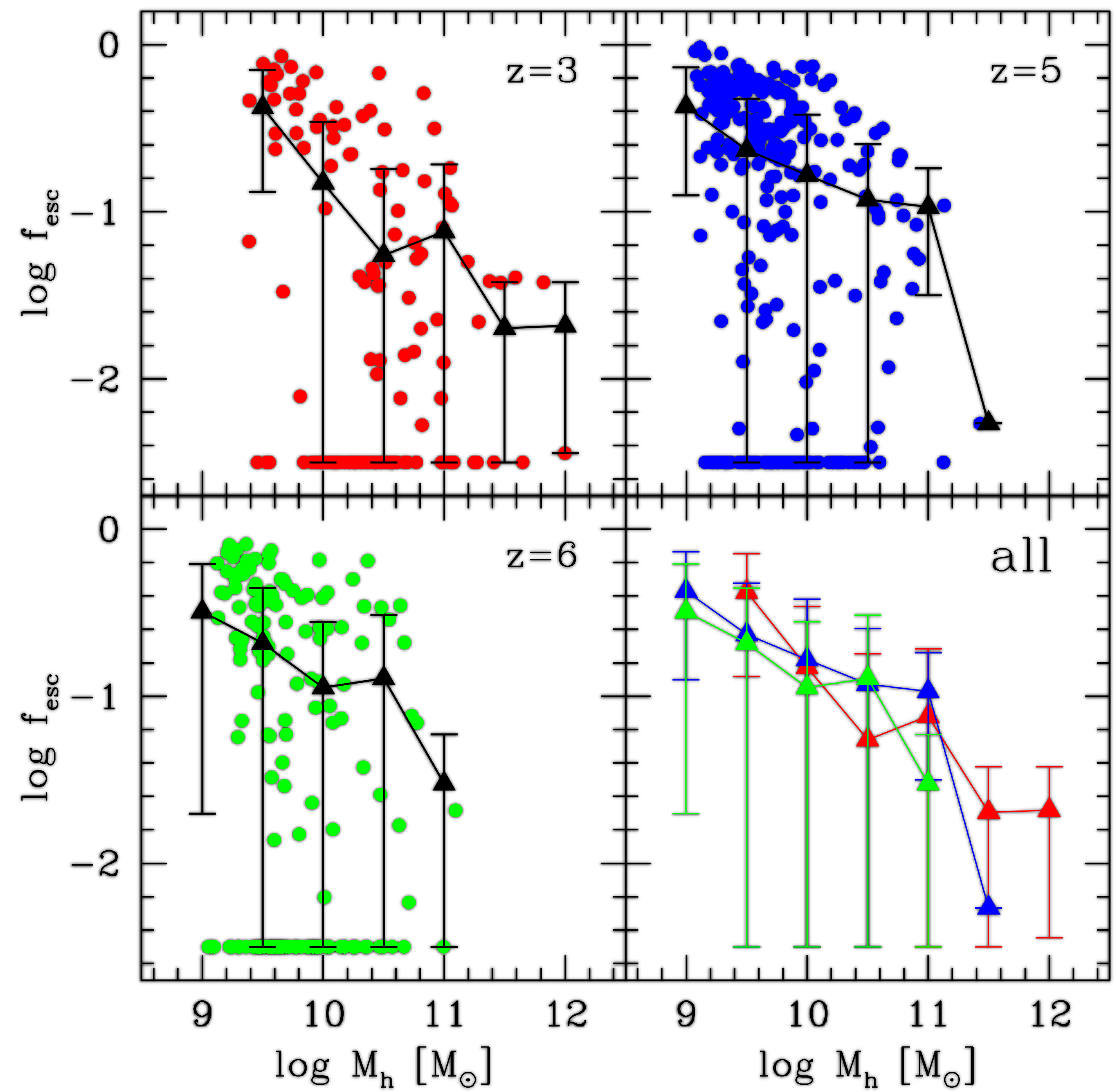
Authentic Ray Tracing method

(Nakamoto+ '01, Illiev+ '06, Yajima+ '09)



f_{esc} as a function of M_{halo} & redshift

- **Decreasing f_{esc} as a func of M_{halo}** --- roughly consistent with Razoumov +'09; but different from Gnedin+'09, Wise & Cen '09
- Simulations suggest that the Universe can be reionized by the star-forming galaxies at z=6 if C≤10.
- High f_{esc} for low-mass gals helps.

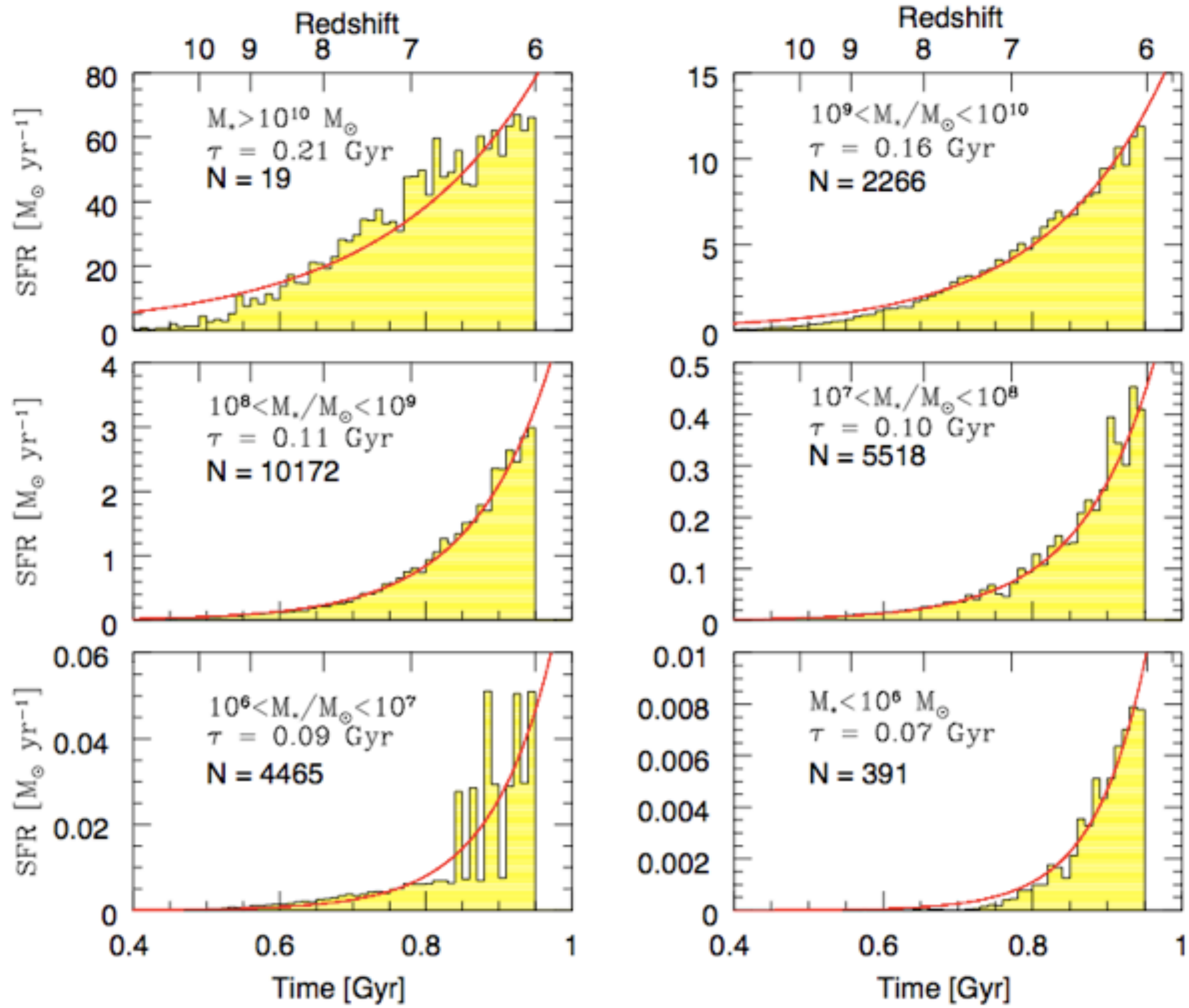


(cf. Gnedin+, Paardekooper+, Razoumov+, Wise&Cen)

Yajima, Choi, KN '11

Average SF history down @ z=6-10

- Galaxy sample divided according to M★
- SFR ∝ exp(t/τ)
- τ~70 Myr to 200Myr for low to high mass galaxies
- Early galaxy growth phase driven by gravitational instability



(cf. Finlator+, de Barros+, Schaerer+, Stark+)

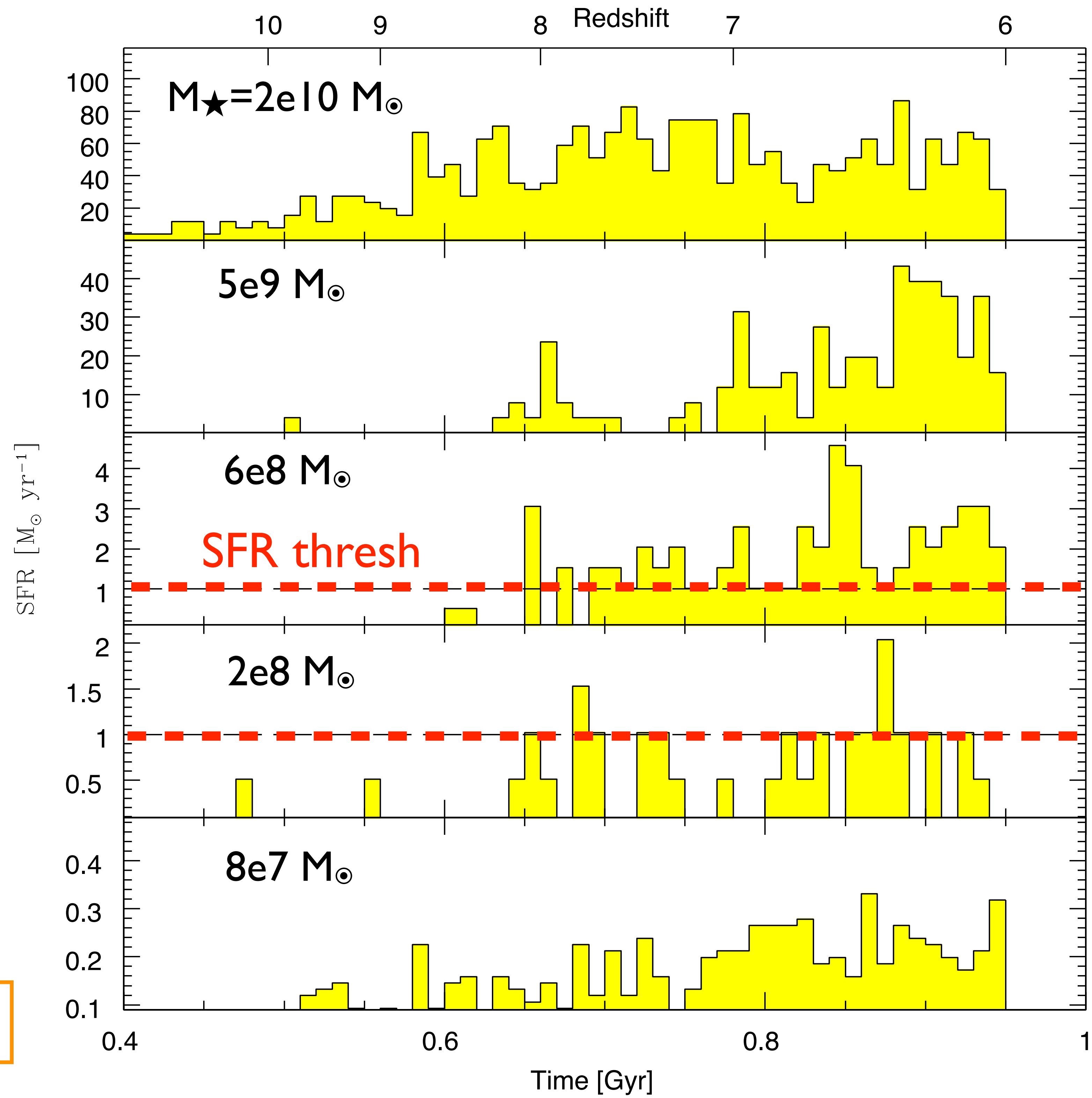
Jaacks, Choi & KN, 12b

Stochasticity of Star Formation

- 10 Myr bins
- Merger/gas infall/ FB
- What is the duty cycle of SF?

Fraction of time that a gal surpass the SFR threshold during $z_1<z<z_2$

SFR threshold ≈ M_{uv}=-18 mag



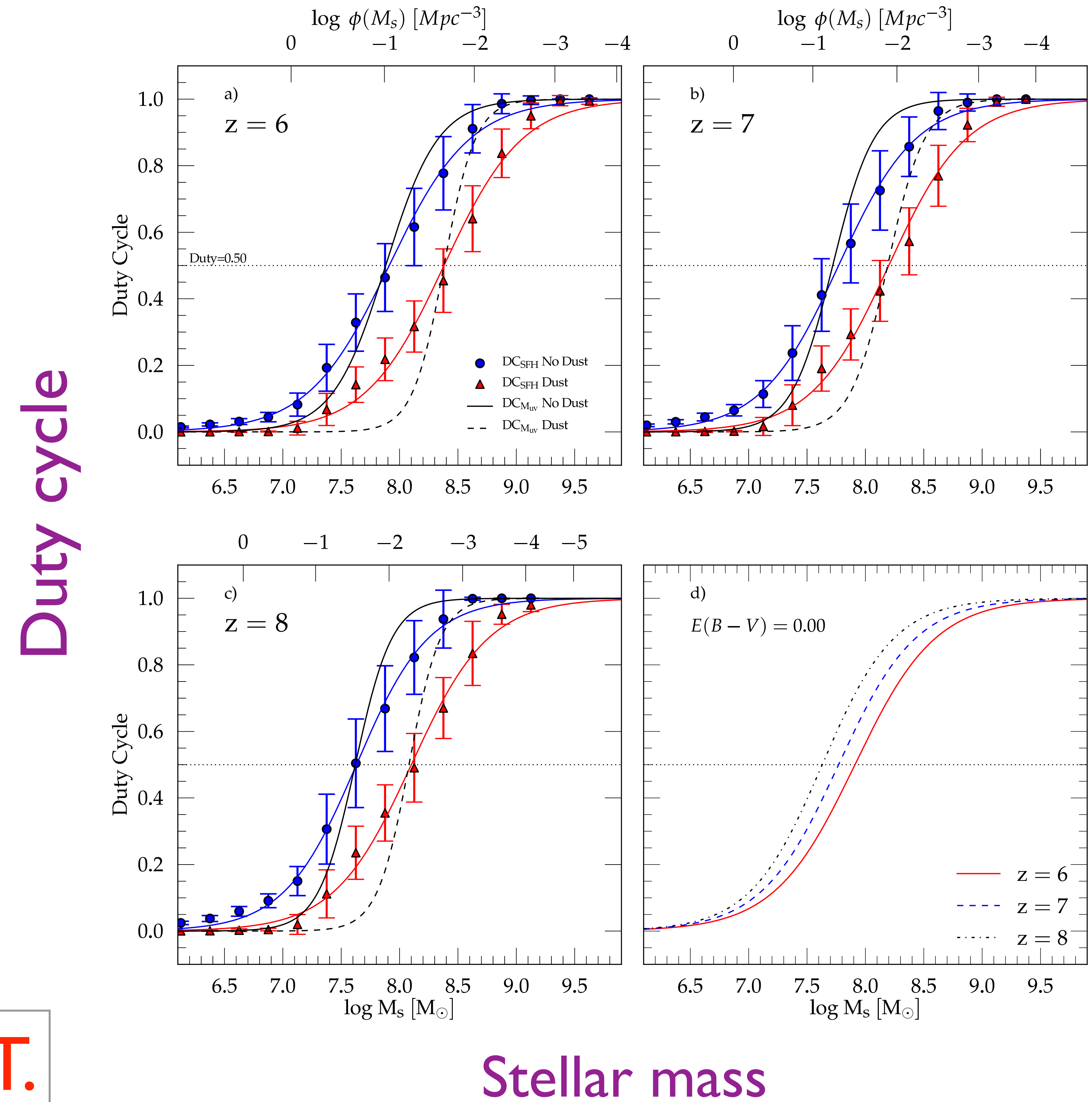
Jaacks, Choi & KN,'12b

Duty cycle of SF

Sharp transition btw $\log M_\star \sim$ 7.0-9.0 with a moderate scatter.

Good fit by the Sigmoid func:

$$DC(M_s) = \left[\exp\left(\frac{a - \log(M_s)}{b}\right) + 1\right]^{-1}$$



Future test with JWST.

Jaacks, Choi & KN, 2012b

Keita's AGORA website

http://www.physics.unlv.edu/~keitee/Agora.html

Project AGORA University of Nevada, Las Vegas

Contributors:
Keita Todoroki, Robert Thompson, Ken Nagamine

RUN1

Summary: AGORA-RUN1-results (PDF)

A	6Mpc/h	3Mpc/h	1Mpc/h	profile
B	6Mpc/h	3Mpc/h	1Mpc/h	profile
C	6Mpc/h	3Mpc/h	1Mpc/h	profile
D	6Mpc/h	3Mpc/h	1Mpc/h	profile

Redshift	0	0.5	1	2	3	6	9	15	19
Snapshot (RUN1-A)	snap	snap	snap	snap	snap	snap	snap	snap	snap

RUN2

Summary: AGORA_RUN2 (PDF)

6Mpc/h	3Mpc/h	1Mpc/h	profile

Flash files for comparison with RUN1-A:

6Mpc/h 3Mpc/h 1Mpc/h

AGORA RUN-1

DM-only cosmological 'zoom-in' runs: May, 2013

Labels	RUN1-A	RUN1-B	RUN1-C	RUN1-D
	withPM, switching at z=9	withPM, no switching	withPM, no switching	withoutPM, no switching
Softening length [kpc/h]	3.22 = comoving 0.322 = physical	0.322 = comoving = physical	0.322 = comoving = physical	0.322 = comoving = physical
Total CPU hours	633	806	980	5272
Makefile options	#--- TreePM Options **OPT += -DPMGRID=256** #OPT += -DGRIDBOOST=2 #OPT += -DASMTH=1.25 **OPT += -DRCUT=4.5** **OPT += -DPLACEHIGHRESREGION=2** **OPT += -DENLARGEREGION=1.2**	#--- TreePM Options **OPT += -DPMGRID=256** #OPT += -DGRIDBOOST=2 #OPT += -DASMTH=1.25 **OPT += -DRCUT=4.5** **OPT += -DPLACEHIGHRESREGION=2** **OPT += -DENLARGEREGION=1.2**	#--- TreePM Options **OPT += -DPMGRID=256** #OPT += -DGRIDBOOST=2 #OPT += -DASMTH=1.25 #OPT += -DRCUT=4.5 #OPT += -DPLACEHIGHRESREGION=2 #OPT += -DENLARGEREGION=1.2	#--- TreePM Options #OPT += -DPMGRID=256 #OPT += -DGRIDBOOST=2 #OPT += -DASMTH=1.25 #OPT += -DRCUT=4.5 #OPT += -DPLACEHIGHRESREGION=2 #OPT += -DENLARGEREGION=1.2
Halo center *	0.486773, 0.525076, 0.491379	0.486766, 0.525132, 0.491333	0.486478, 0.525153, 0.491899	0.484387, 0.525912, 0.492511
Mvir [M⊙]	1.675e11	1.682e11	1.661e11	1.728e11
Rvir [kpc]	144.3	144.5	143.9	145.6

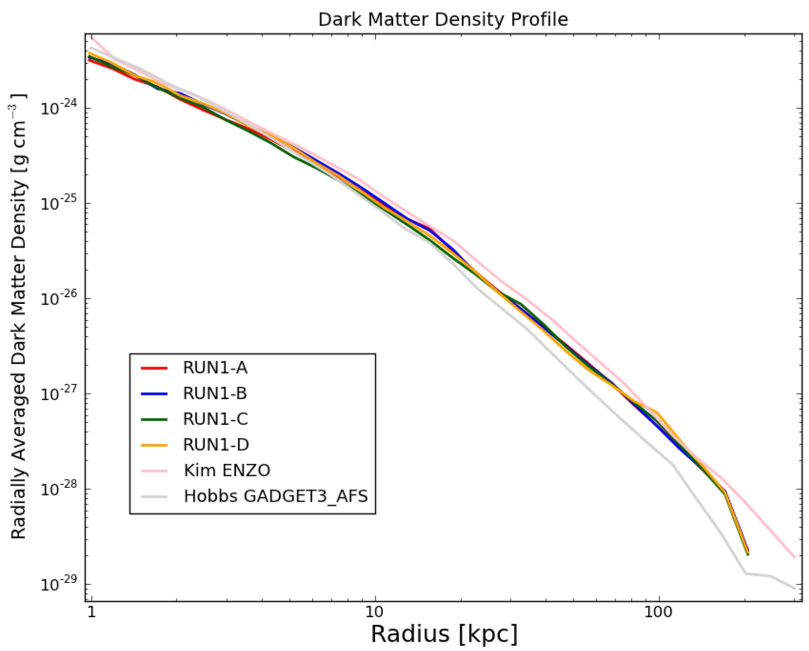
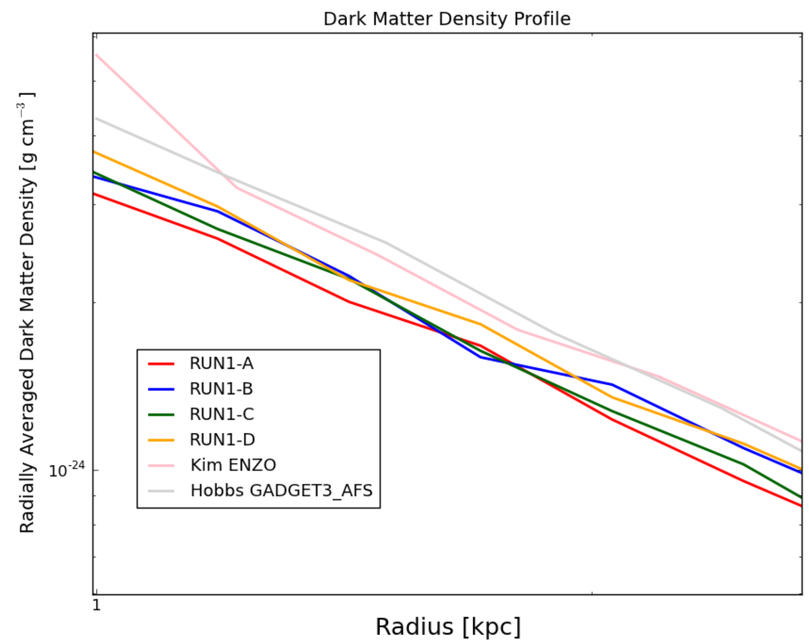
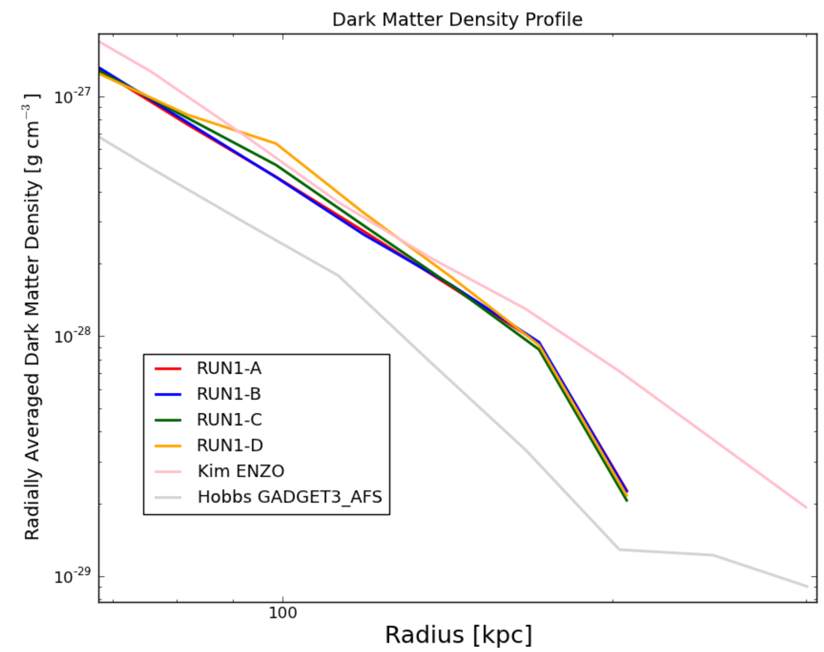
* Halos identified by **Rockstar 0.99 beta**

Other simulation parameters used for our RUN-1:

levelmax in MUSIC parameter	12
Mass resolution in the finest level	2.37267e5 Msun/h = 3.38e5 Msun
ref_offset, ref_extent in MUSIC parameter	HRC-3
Snapshots stored	z=19,15,9,6,3,2,1,0.5,0

Dark matter density profile of the target halo

Radial profile in spherical shells, including the particles that could belong to subhalos.

All 4 cases + other groups' profiles	Inner part	Outer part
		

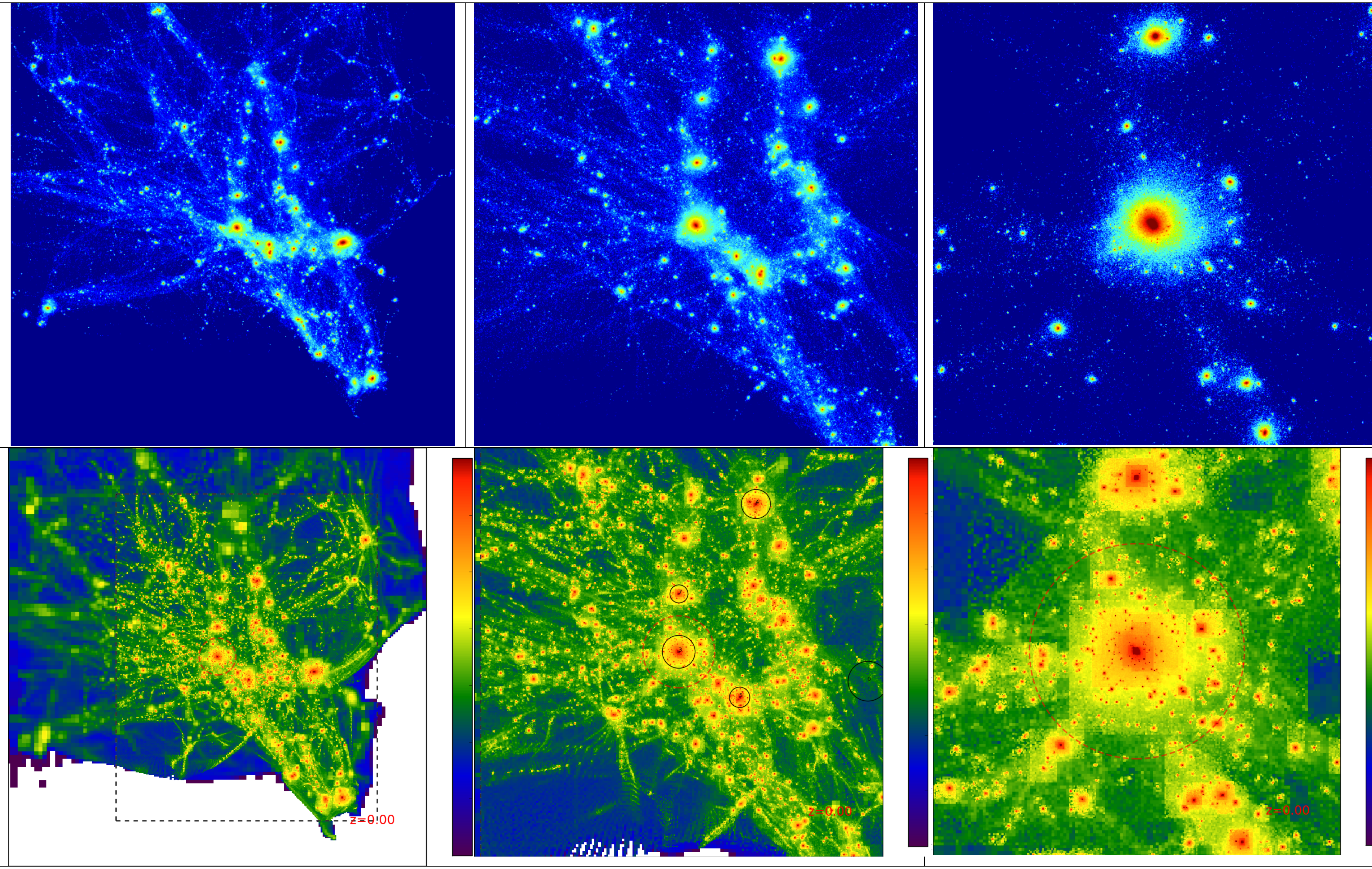
*31 data points are used for each case for plotting.

Our GADGET-3

ENZO (Kim)

(1) AMR (*see 4-A)
(2) HRC-3 vel.shift

***Described at the AGORA workspace website**



Conclusions

- H_2-SF model: lower SFRD, lower $M_\star$ in low-mass halos, lower #, *natural dependency on metallicity.*
- Faint-end slope: very steep with $|\alpha| \geq 2$ down to $M_{uv} \approx -16$
- Increasing SFH on average (power-law/exponential); individual SFH --> bursty. duty cycle.
- Escape fractions, Lyα emission --> Good topics for AGORA
- Continue comparison btw cosmo. vs. zoom sims.

R. Thompson's talk: comparison of classic SPH vs. DISPH