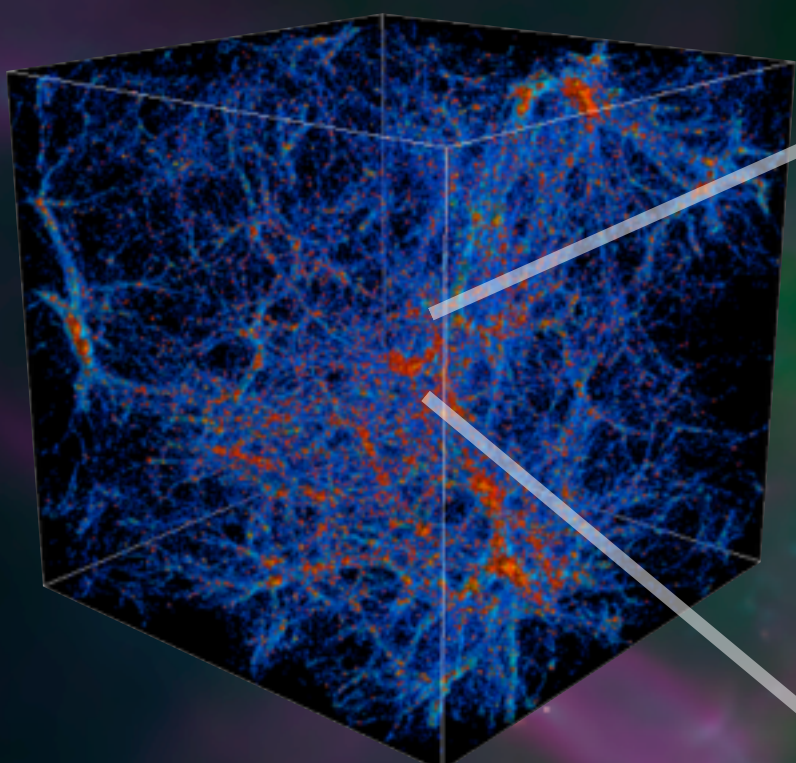
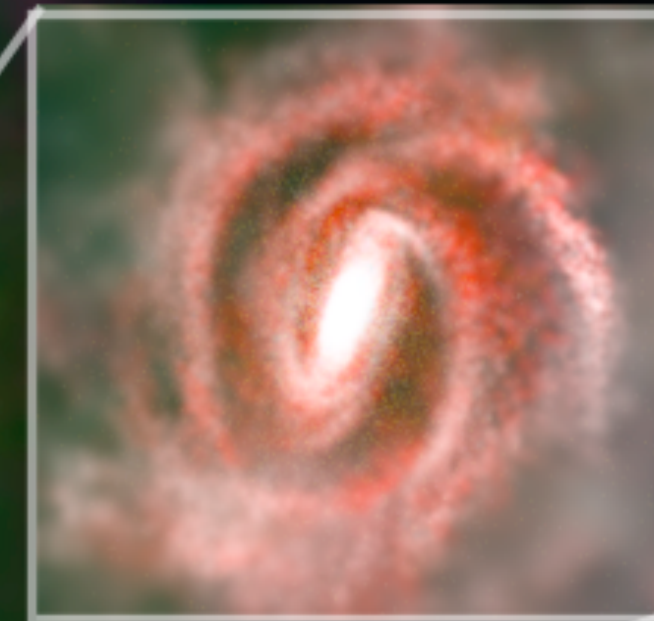
Galaxy Formation in the High-z Universe





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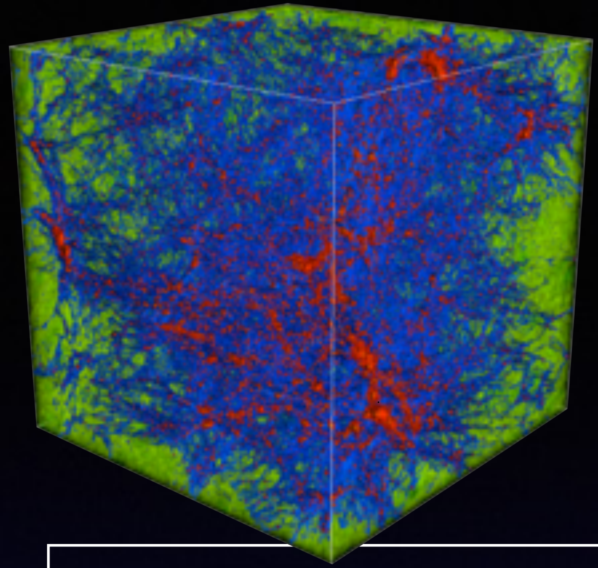
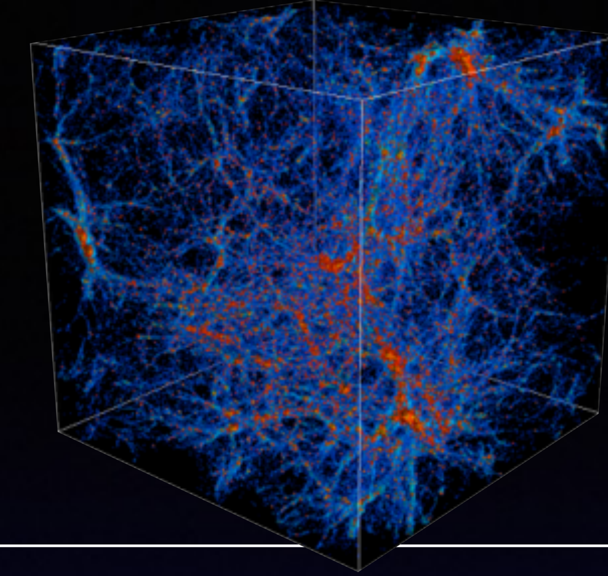
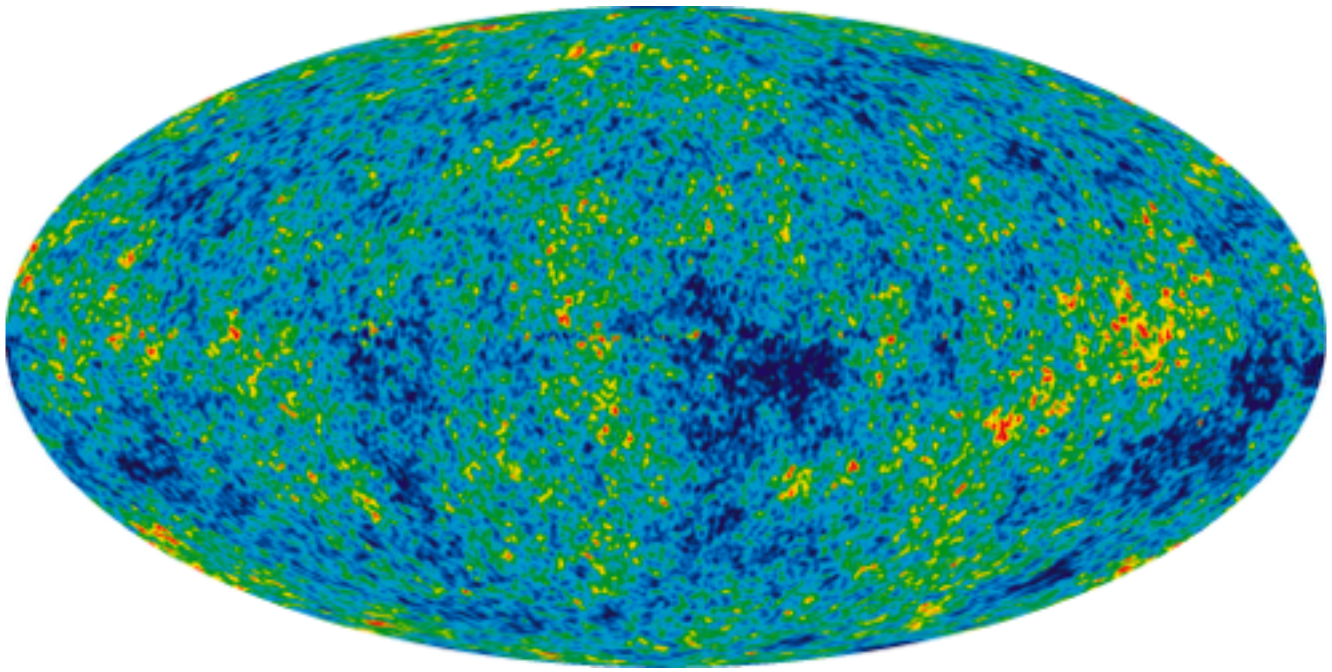


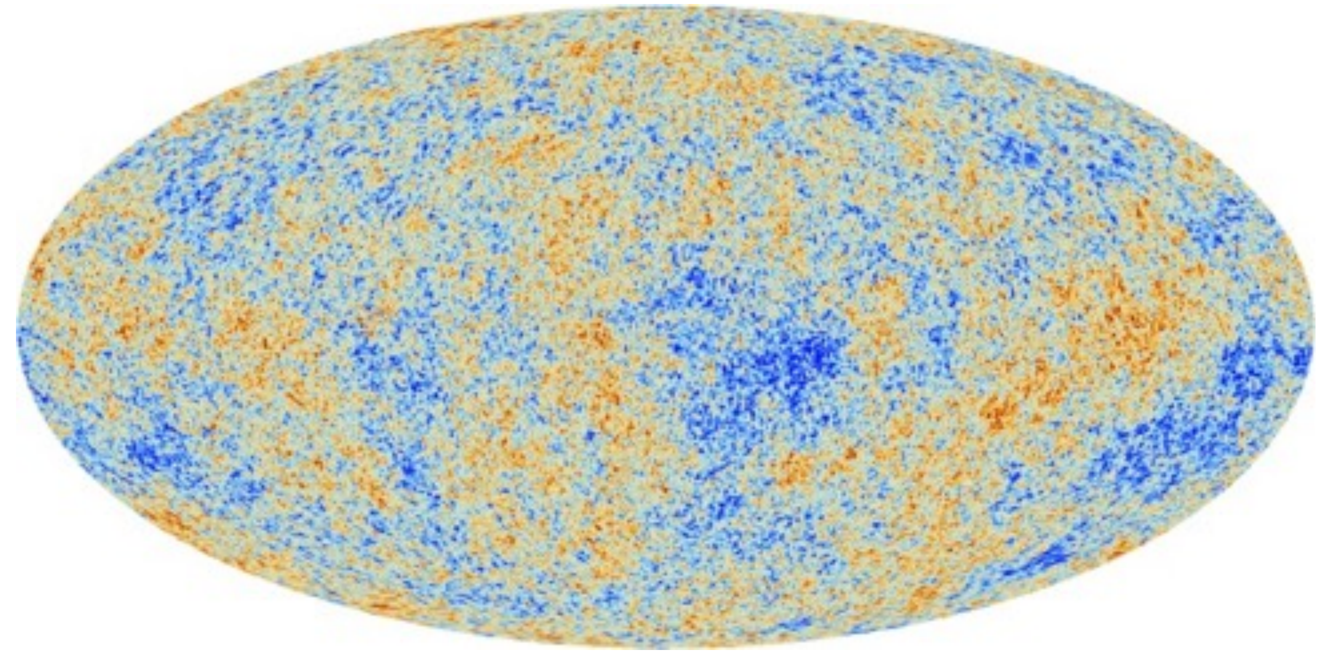
Outline

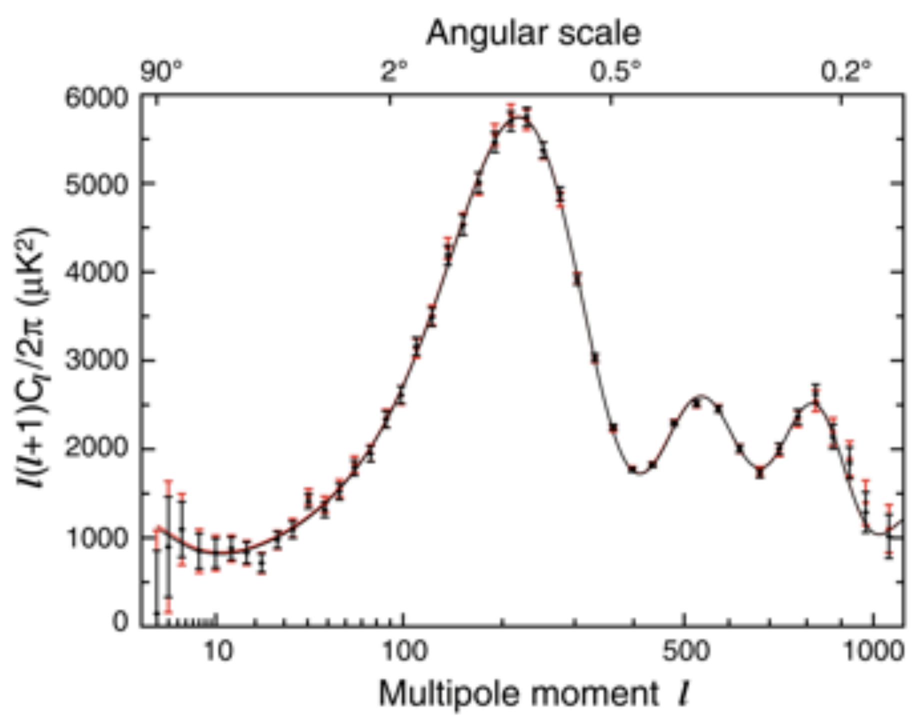


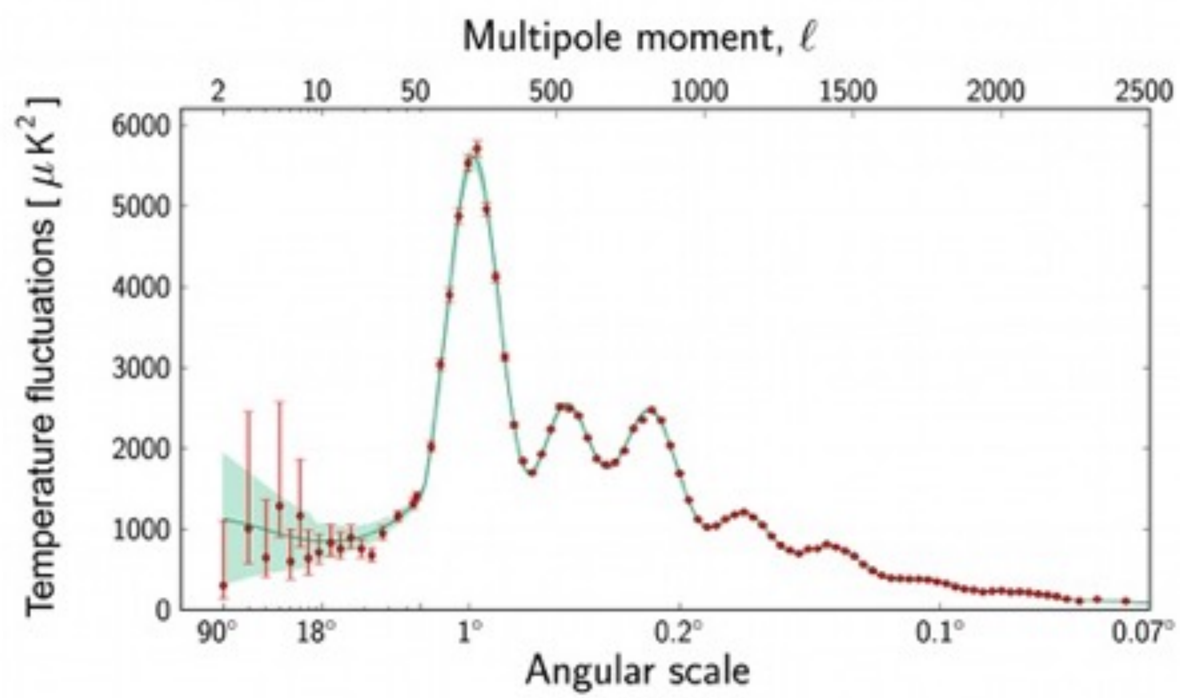
- Intro — ΛCDM model & High-z Gal Formation
- Observations & Computational Cosmology:
  Global quantities & Reionization of the Universe
  Ω_*, SFRD, Galaxy MF/LF, …
- the 3rd Revolution: Zoom-in Cosmo Hydro Simulation
- Massive Gal. Formation at High-z — disk, dust, f_{esc}
- Accretion vs. Mergers — In Situ SF & Downsizing
- Importance of Feedback in fully non-linear regime
- Conclusions & Issues — Towards 2020s

WMAP & Planck satellite results







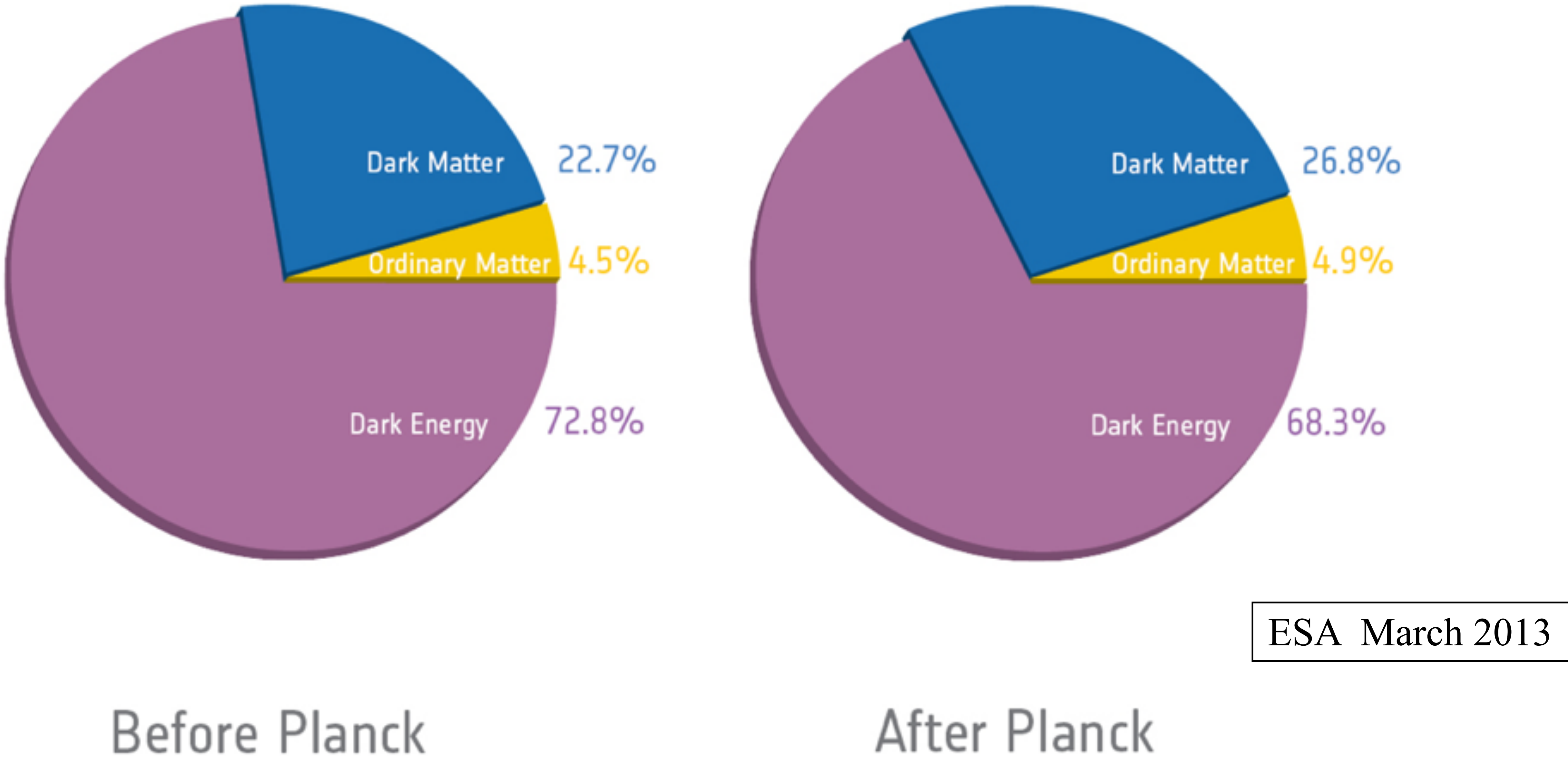


(WMAP9; Hinshaw+ '13)

(ESA March 2013)

T ~ 2.73K black body with ~10^{-5} fluctuations

Cosmic Energy Budget



$$\Omega_M \approx 0.27 - 0.32$$
$$\Omega_\Lambda \approx 0.68 - 0.73$$

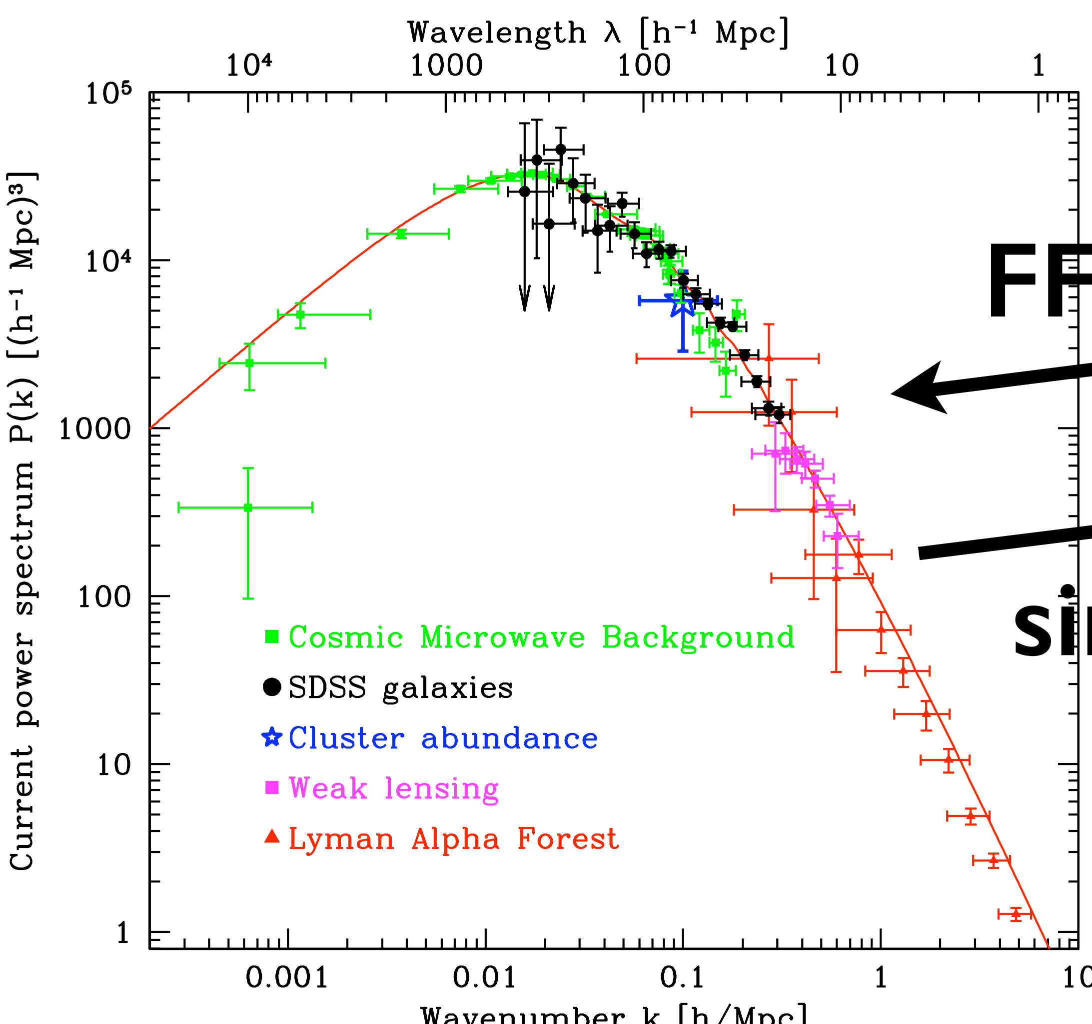
$$(\Omega_M, \Omega_\Lambda, \Omega_k) \approx (0.3, 0.7, 0.0)$$

Concordance ΛCDM model

WMAP, Planck:
SN Ia

$$(\Omega_M, \Omega_\Lambda, \Omega_b, h, \sigma_8, n_s) \approx (0.3, 0.7, 0.04, 0.7, 0.8, 0.96)$$

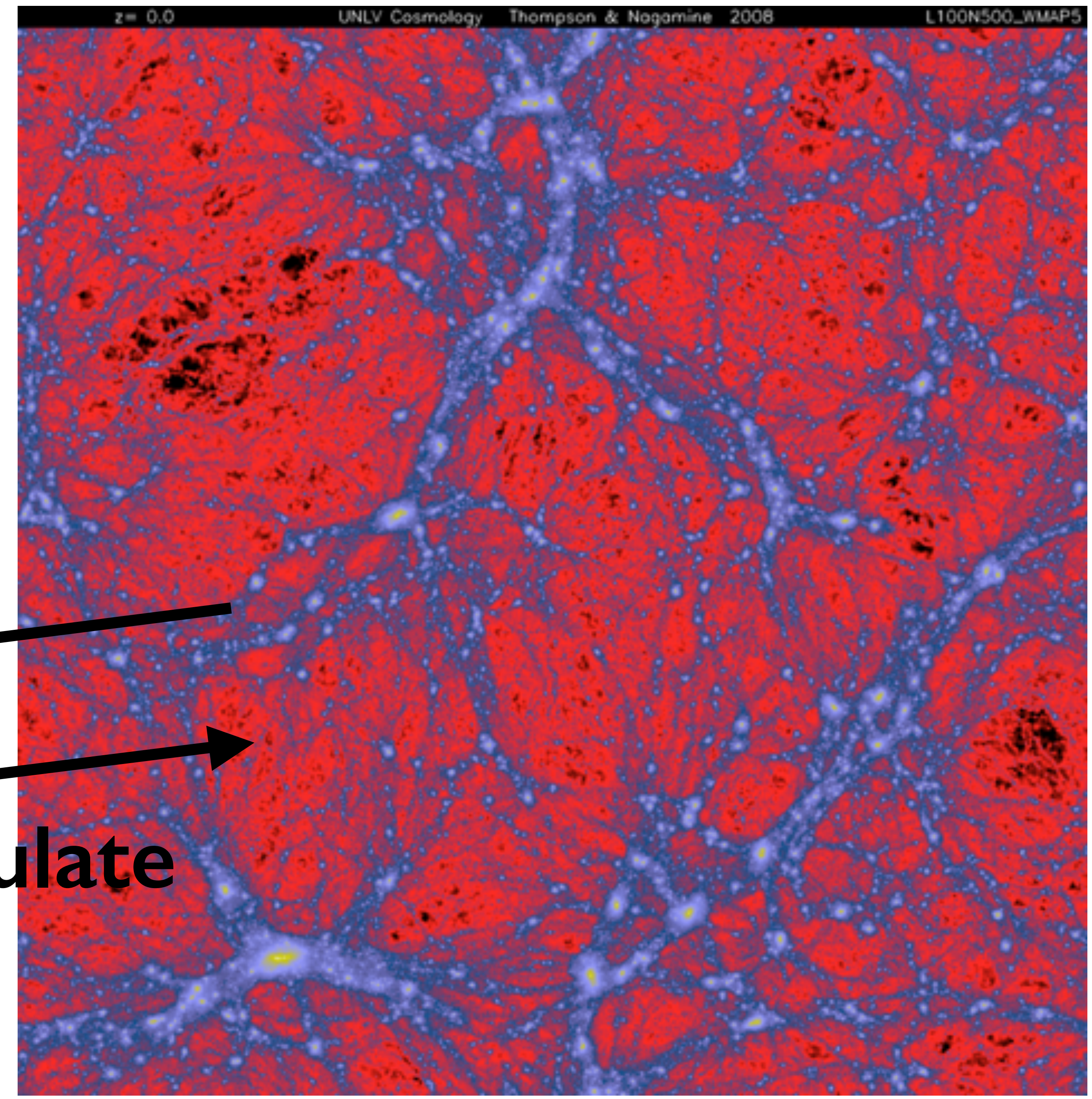
- Successful on large-scales
- Can we understand galaxy formation in the context of ΛCDM model?



Tegmark+ (2004)

FFT

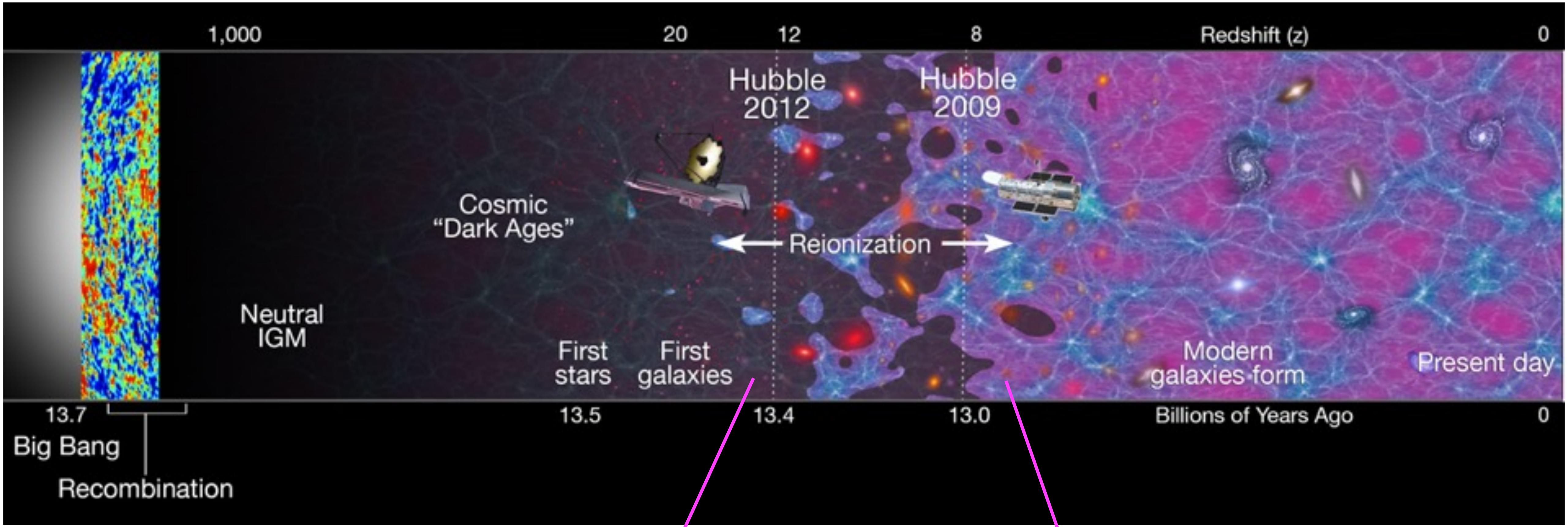
simulate



"Back-bone of structure"

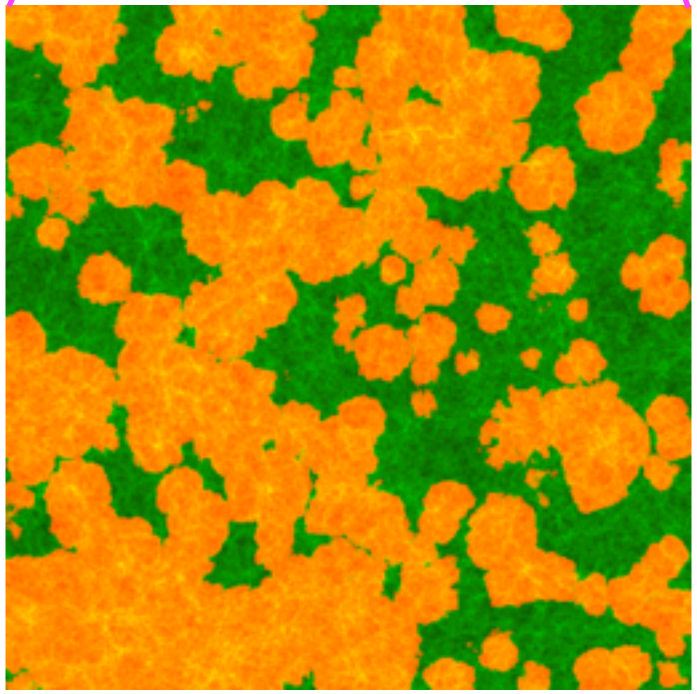
(cf. パリティ 11月号記事)

Cosmic Timeline

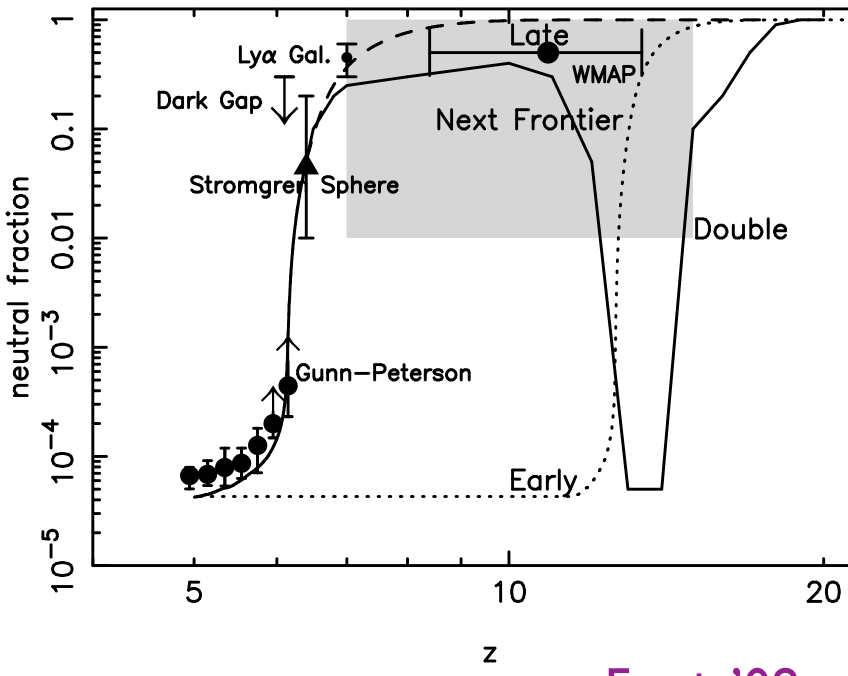


Observations are rapidly approaching the **first galaxies**

What are the sources responsible for reionization & early chemical enrichment?

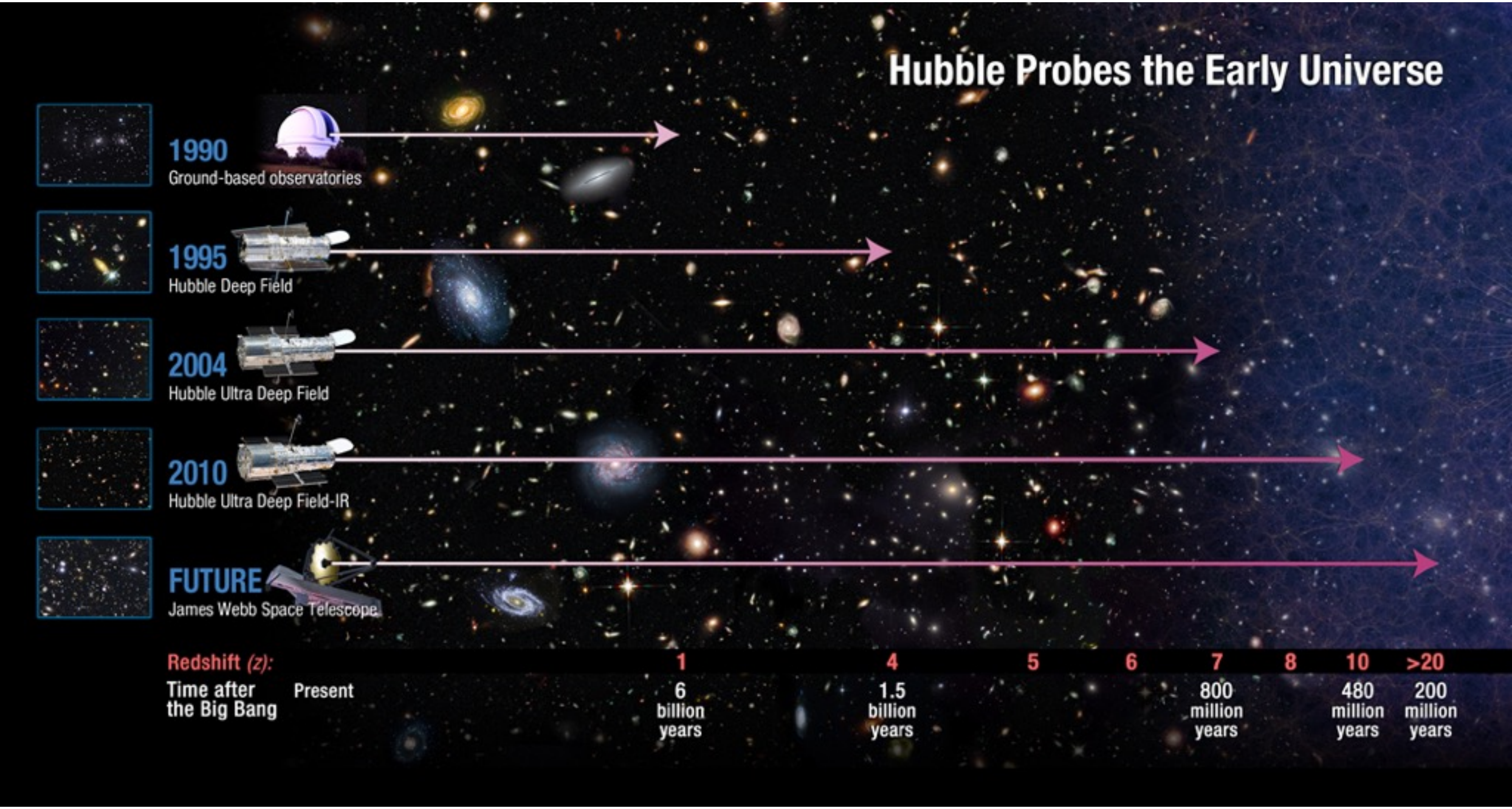


Illiev+ '06



Fan+ '08

Redshift Frontier



NASA

HUDF

Deepest universe that the humankind have ever seen.

2003~2004

↓

Hubble Extreme Deep Field (XDF)

2012

Mon. Not. R. Astron. Soc. **283,** 1388–1404 (1996)

1996

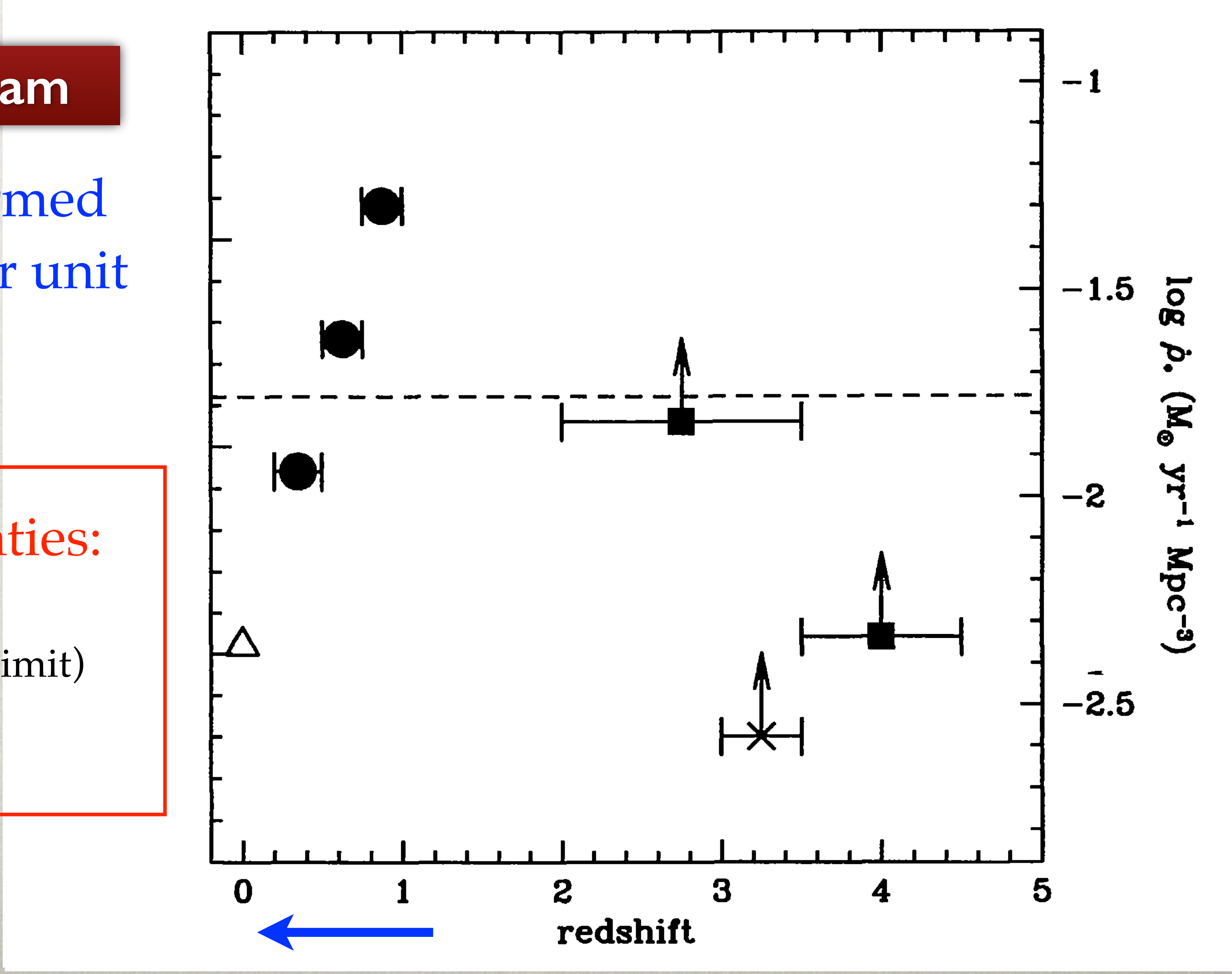
High-redshift galaxies in the *Hubble Deep Field*: colour selection and star formation history to $z \sim 4$

Piero Madau,[1★] Henry C. Ferguson,[1★] Mark E. Dickinson,[1★] Mauro Giavalisco,[2★†] Charles C. Steidel[3★‡§] and Andrew Fruchter[1★]

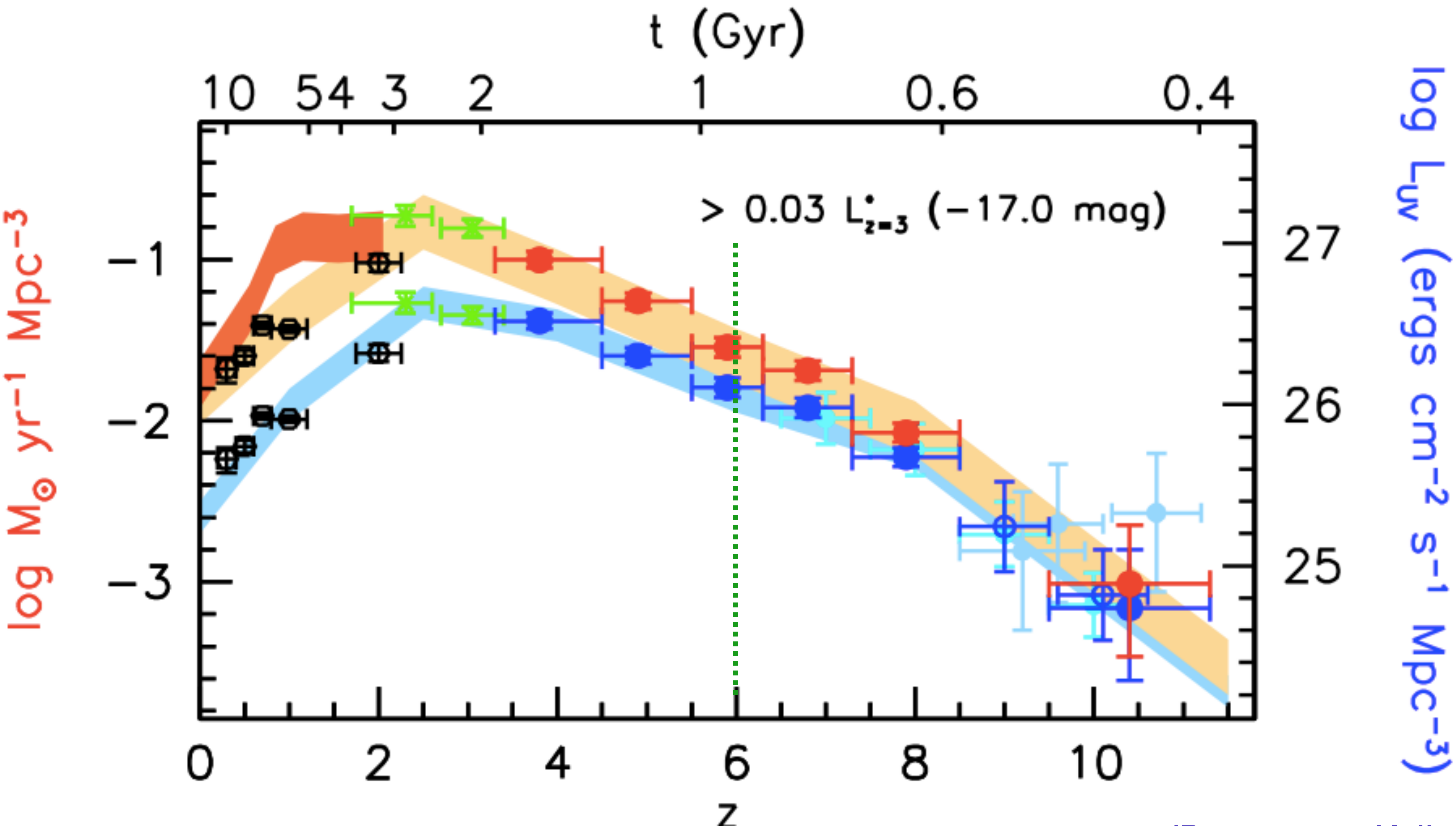
Lilly-Madau Diagram

Stellar mass formed per unit time per unit volume

- 3 major uncertainties:
  - dust extinction
  - faint-end of LF (flux limit)
  - IMF



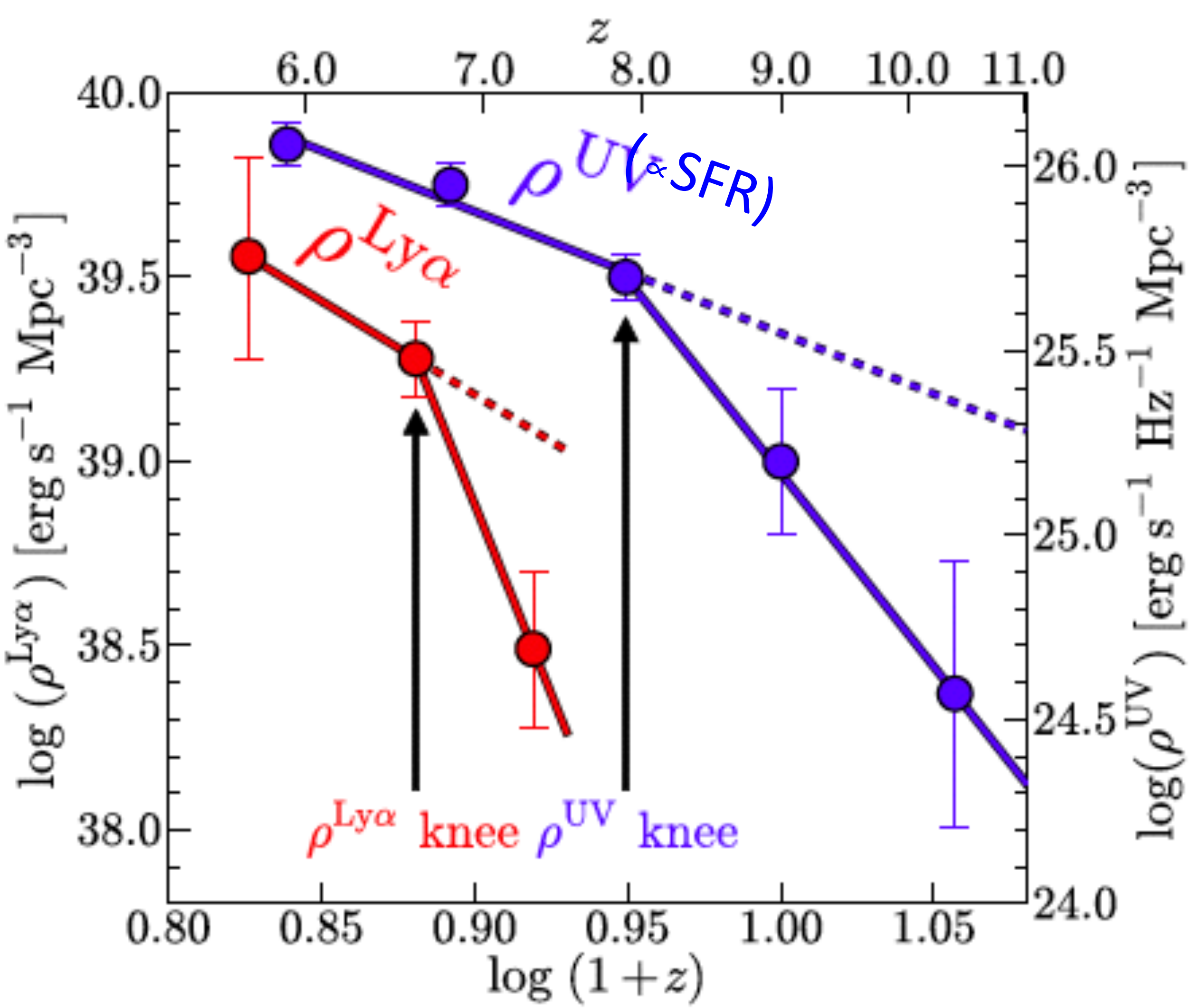
SFRD & UV Lum. Density



(Bouwens+ '14)

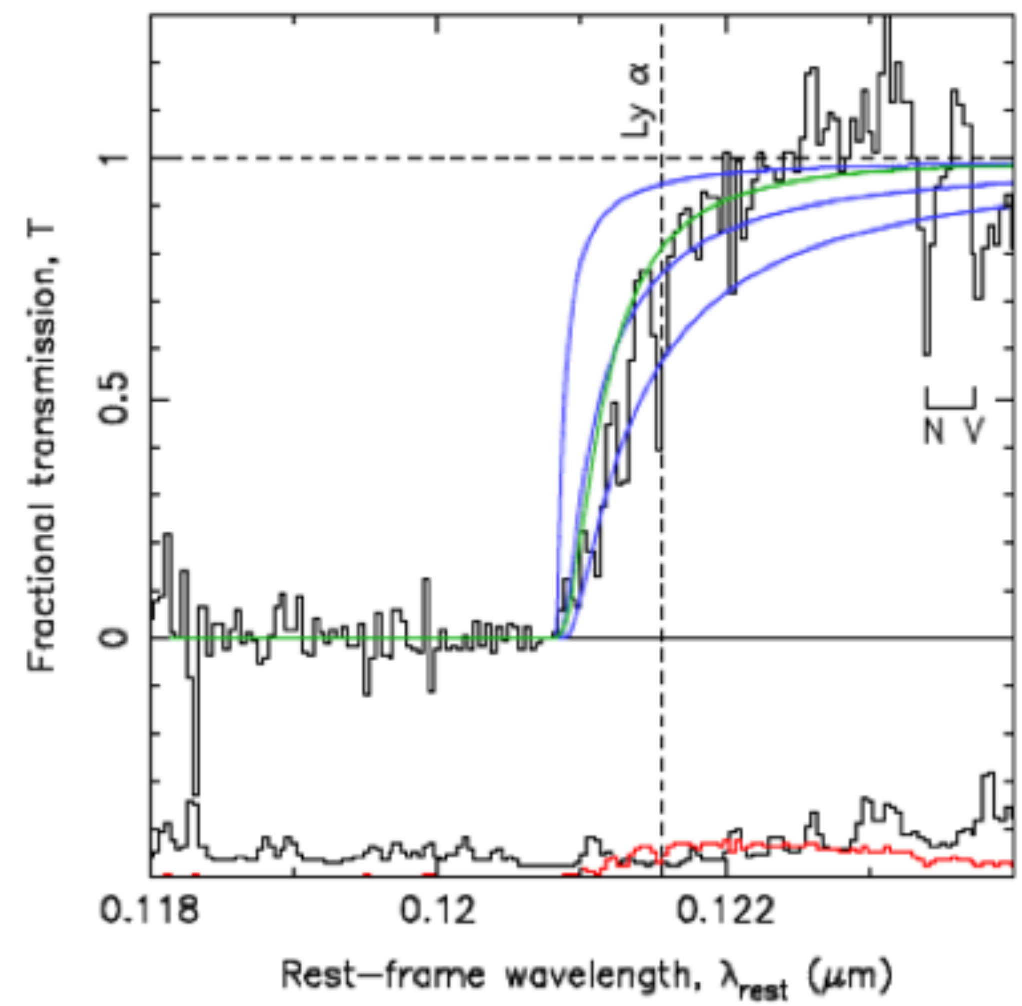
(cf., Dunlop+, Ellis+, Finkelstein+, McLure+, Oesch+, Ouchi+, Schenker+, etc.)

Signatures of Reionization



Konno+'14

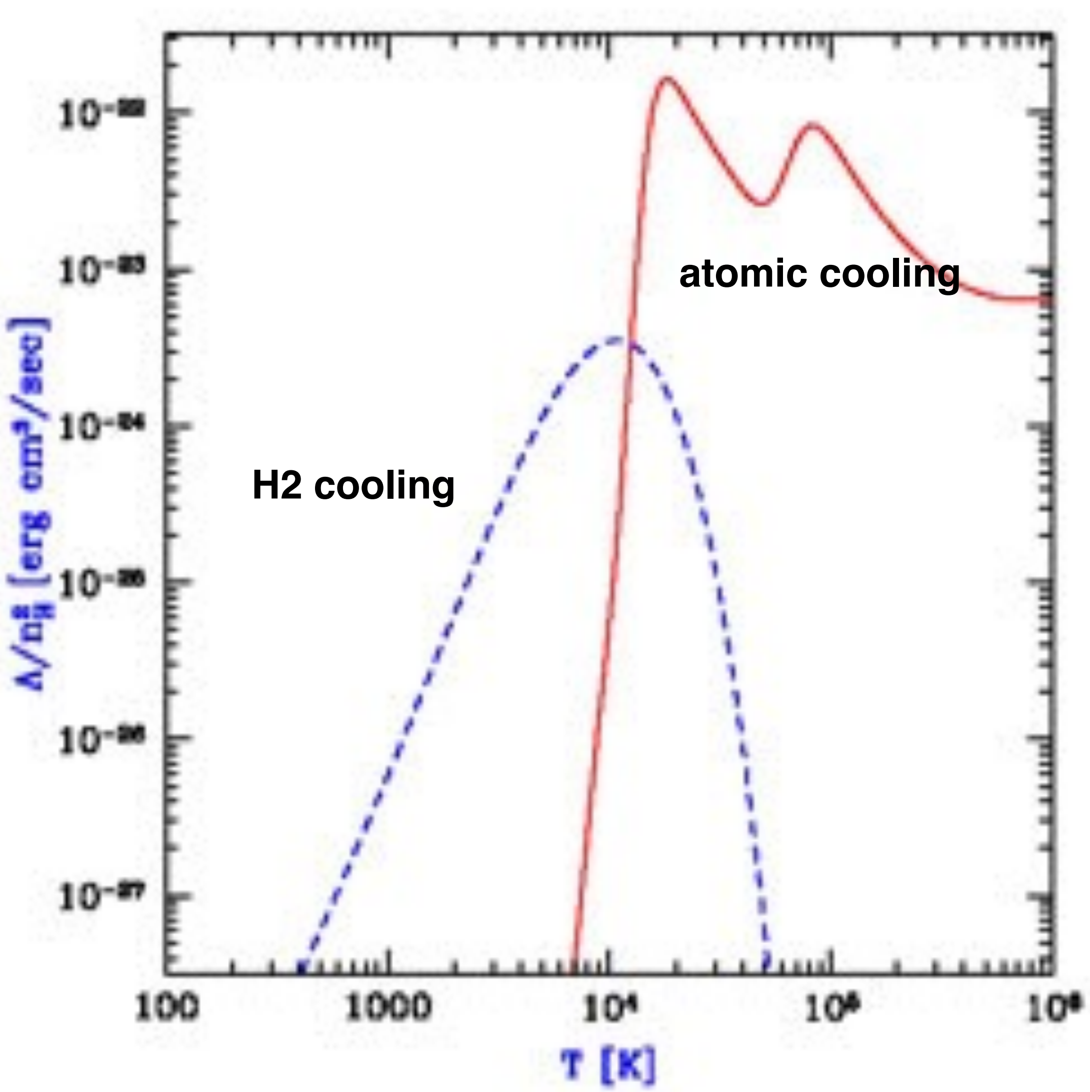
High-z Quasar Spectrum

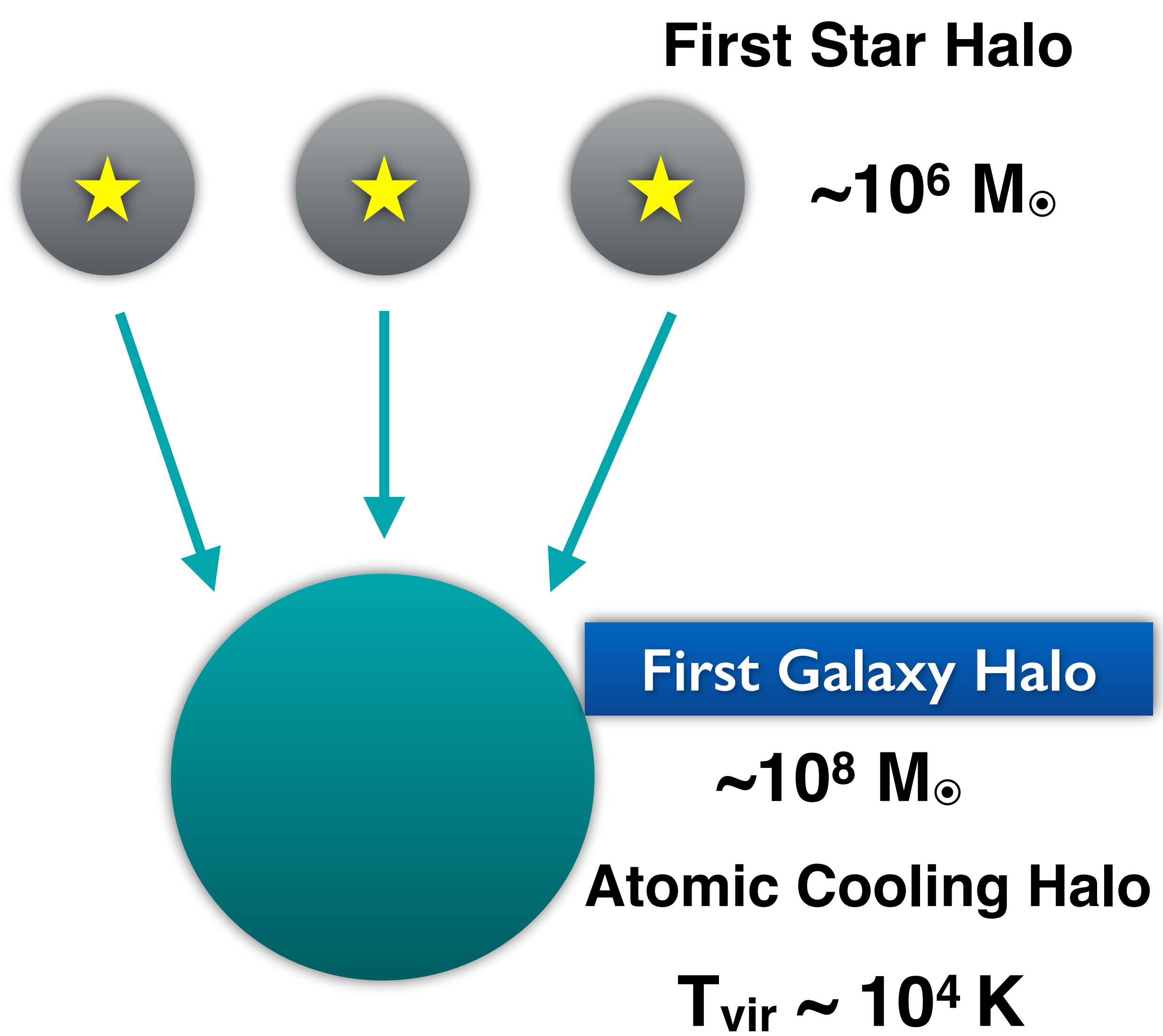


Mortlock+'11

- Lya/continuum is absorbed by HI in IGM at z>6
  - Declining fraction of LAEs (Stark+11, Ono+12, Pentericci+11,14, Schenker+12,14, Treu+13, Finkelstein+14)
  - Accelerated decline at z≳7 (stronger for LAE? Konno+14)
  - QSO/GRB Lya damping wing —> Large X_{HI} (>10% at z=6-7; Mortlock+11, Totani+14)
  - Natural that no LAEs detected at z≳8?

First Galaxy Formation in Atomic Cooling Halos



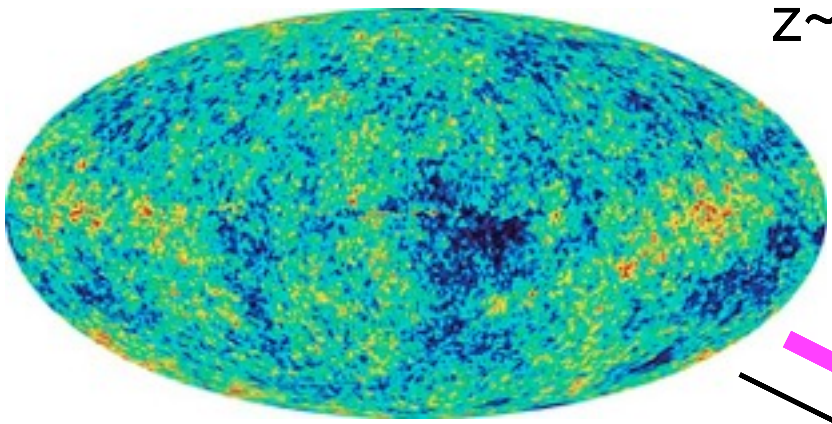


$$T_{\rm vir} = \frac{\mu m_{\rm H} V_c^2}{2k_{\rm B}} \simeq 10^4 \left(\frac{\mu}{0.6}\right)\left(\frac{M}{10^8 M_\odot}\right)^{2/3}\left[\frac{\Delta_c}{18\pi^2}\right]^{1/3}\left(\frac{1+z}{10}\right) \rm{K},$$

Bryan & Norman ’98

Computational Cosmology

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



z~1100

Initial conditions

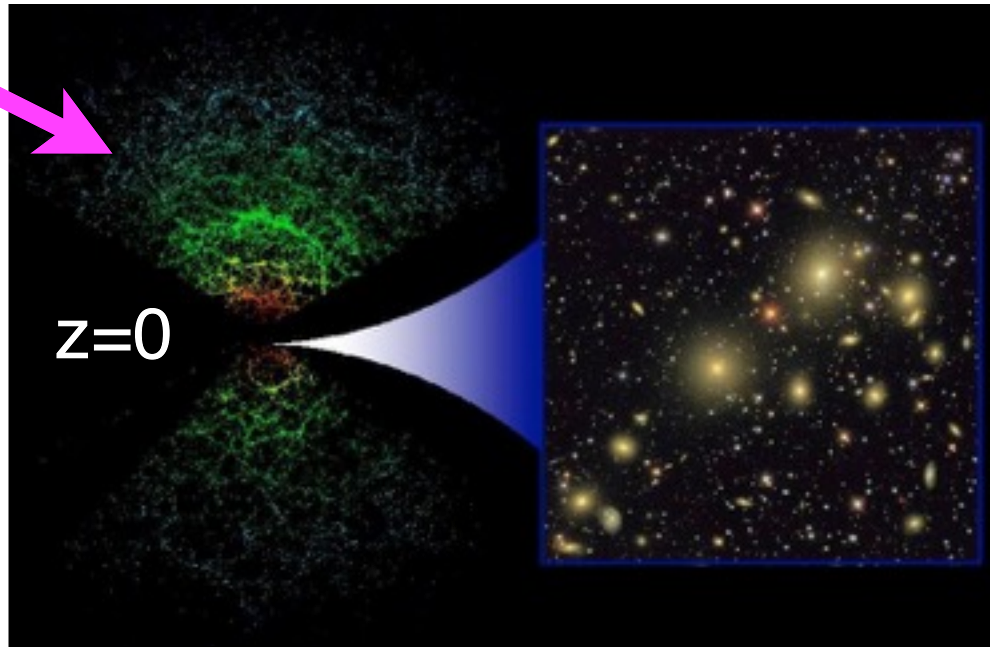
Cosmological params,
Dark energy, Dark matter,
Baryons
(+expanding universe)

z=100

z=10

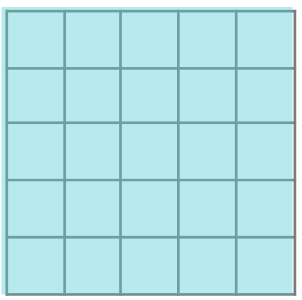
z=3

Radiative cooling/heating,
Star formation,
& Feedback



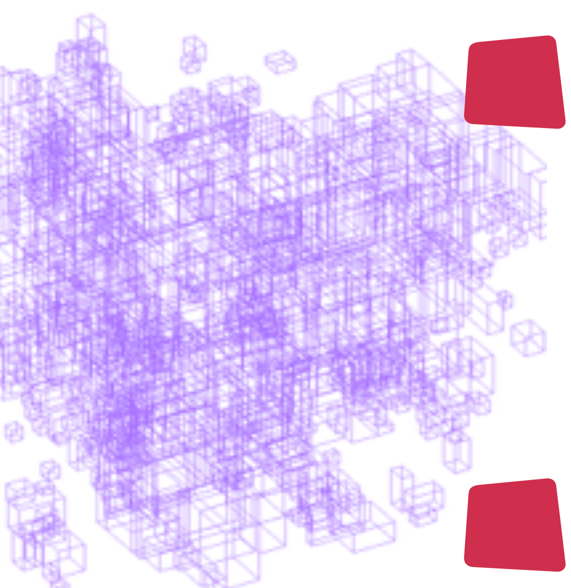
Gravity + Hydrodynamics

Cosmological Hydrodynamic Codes



Eulerian mesh (e.g. Cen & Ostriker ’92; Katz+’96; KN+’01)

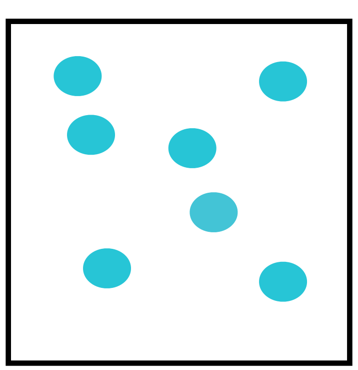
- Eulerian mesh, PM gravity solver, shock capturing hydro
- fast; good baryonic mass res. at early times
- low final spatial resolution in high-ρ regions, but good at low-ρ regions



AMR (adaptive mesh refinement: e.g. Enzo, RAMSES, …)

- Eulerian root grid, refine as necessary
- multi-grid PM gravity solver, ZEUS hydro, PPM hydro
- high dynamic range, but slower

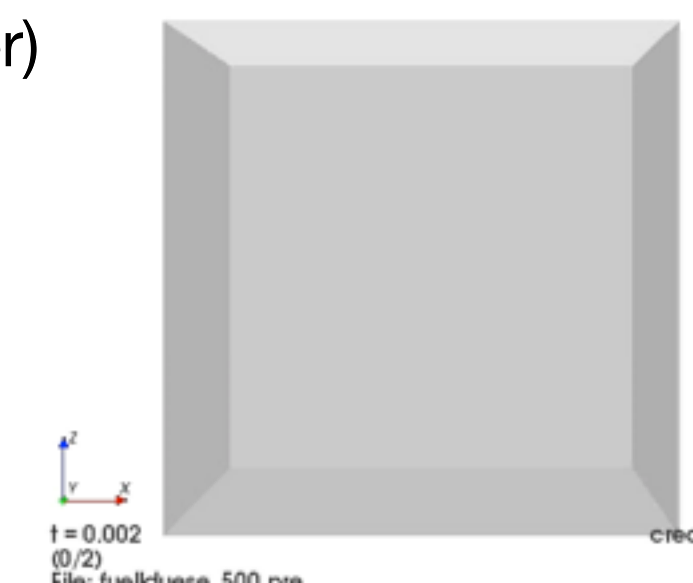
AMR-SPH comparison: O’Shea, KN+ ‘05



SPH (Smoothed Particle Hydrodynamics: e.g. GADGET, GASOLINE, …)

- Lagrangian, particle-based (both gas & dark matter)
- Tree-PM for gravity
- SPH for hydro
- fast; good spatial resolution in high-ρ region, but not so good in low-ρ region

Moving Mesh (e.g. AREPO)



Cosmological SPH Simulations

- **modified GADGET-3 SPH code** (Springel '05 + additional physics)
  radiative cooling/heating (w/ metals), SF model, SN & galactic wind feedback with multicomponent variable velocity (MVV) model (Choi & KN '11), self-shielding correction (KN+10)
- **Advantage over zoom-in runs: larger statistical samples of galaxies**

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

Fiducial: Pressure-based SF model — Schaye & Dalla Vecchia '08; Choi & KN '09, '10, '11

H_2-SF model — Thompson, KN+ '13

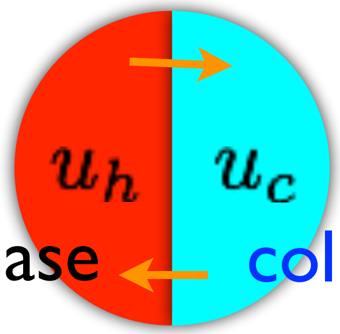
Sub-grid Multiphase ISM model

Each SPH ptcl is pictured as a multiphase hybrid gas.

(Yepes+ '97)

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

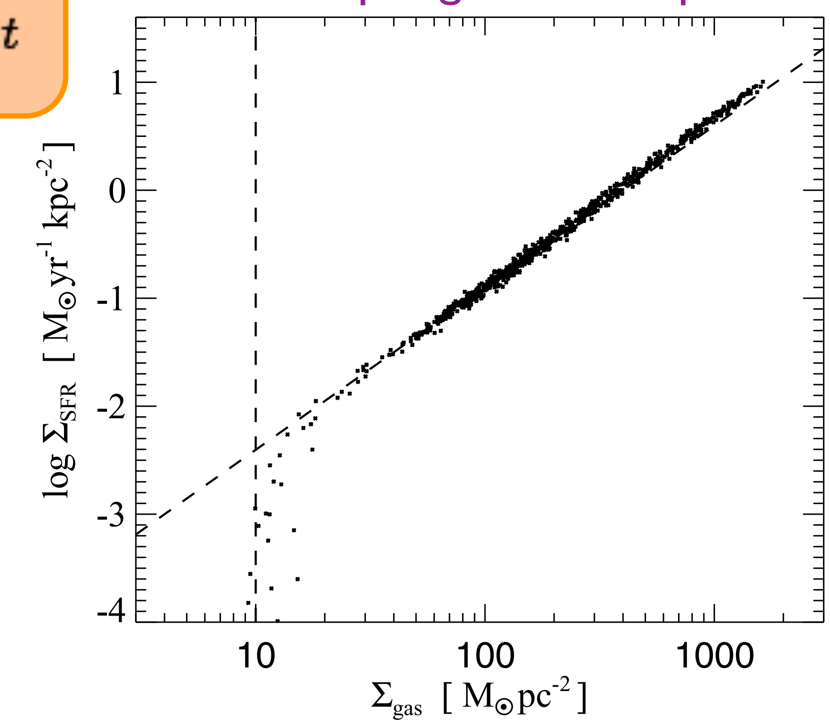
$$u_c = \text{const.}$$



hot phase

cold phase

Springel & Hernquist '03



SFR:

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

cold gas

gas recycling fraction

For each star ptcl:

$$(m_\star, t_{form}, Z)$$

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

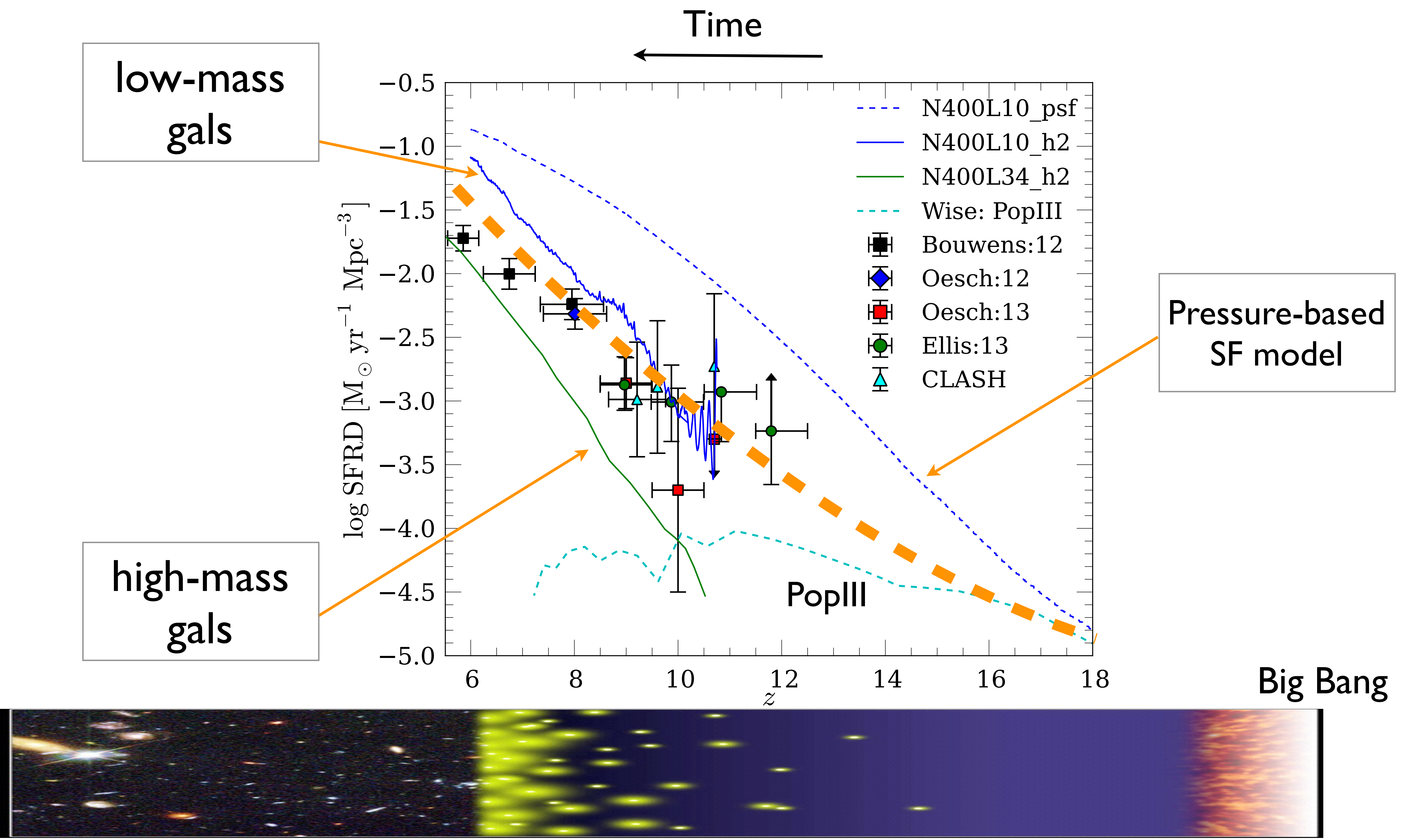
$$t_\star^0 = 2.1\,\text{Gyr}$$

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

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

Population Synthesis Model
Chabrier IMF (~Kroupa)
[0, 100] Msun
6 metallicity
various filters
E(B-V)=0 ~ 1.0

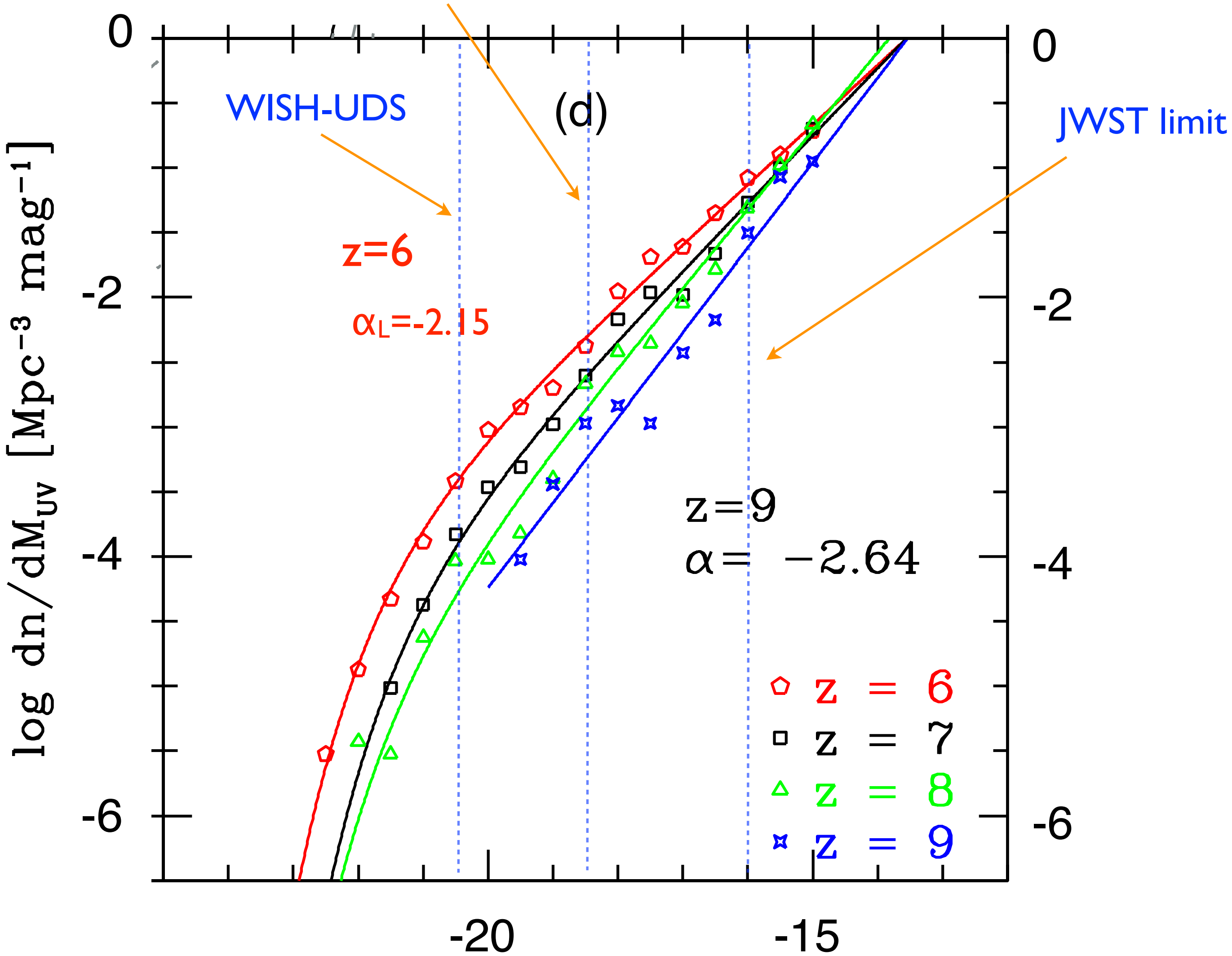
SF in the Reionization Epoch



Redshift Evolution of LF & MF@z=6-9

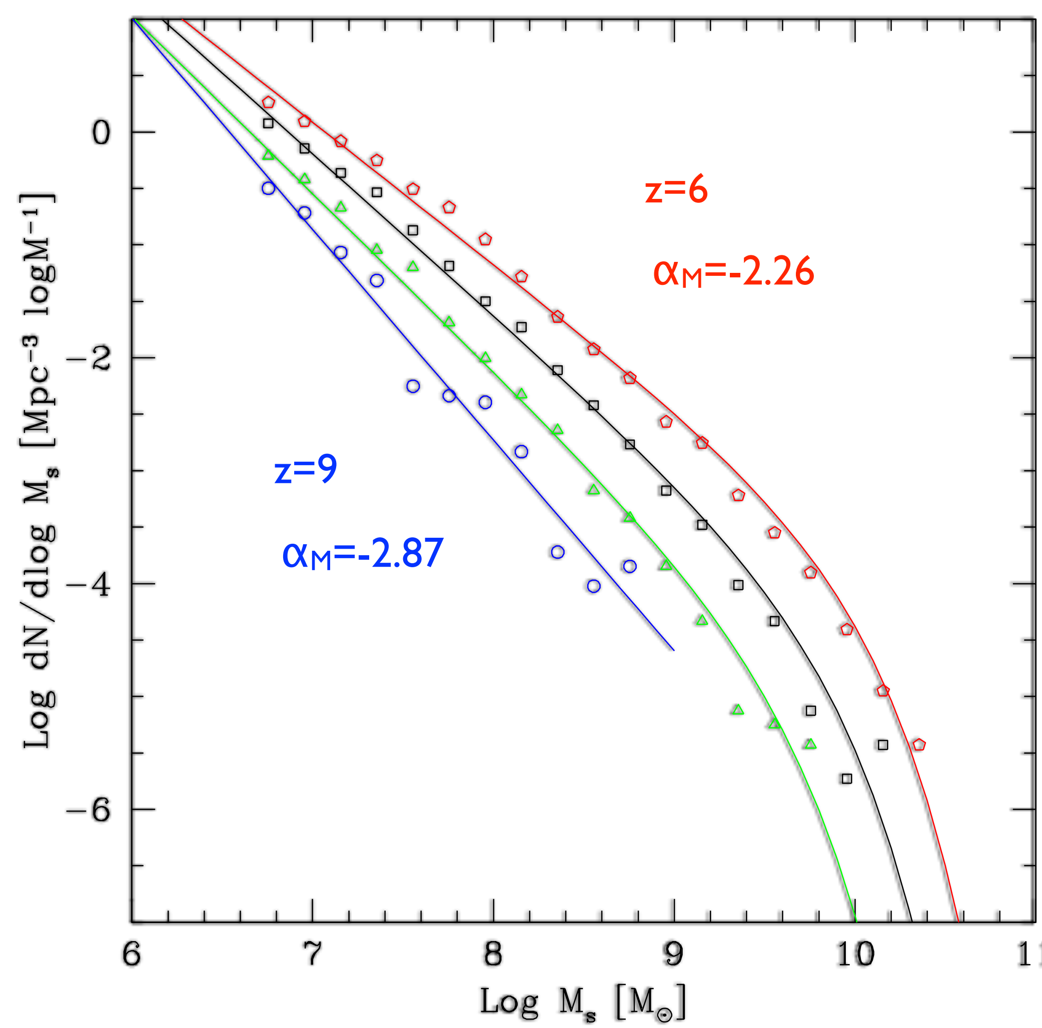
(3-param Schechter fits)

Rest-frame UV LF



Rest-frame UV mag

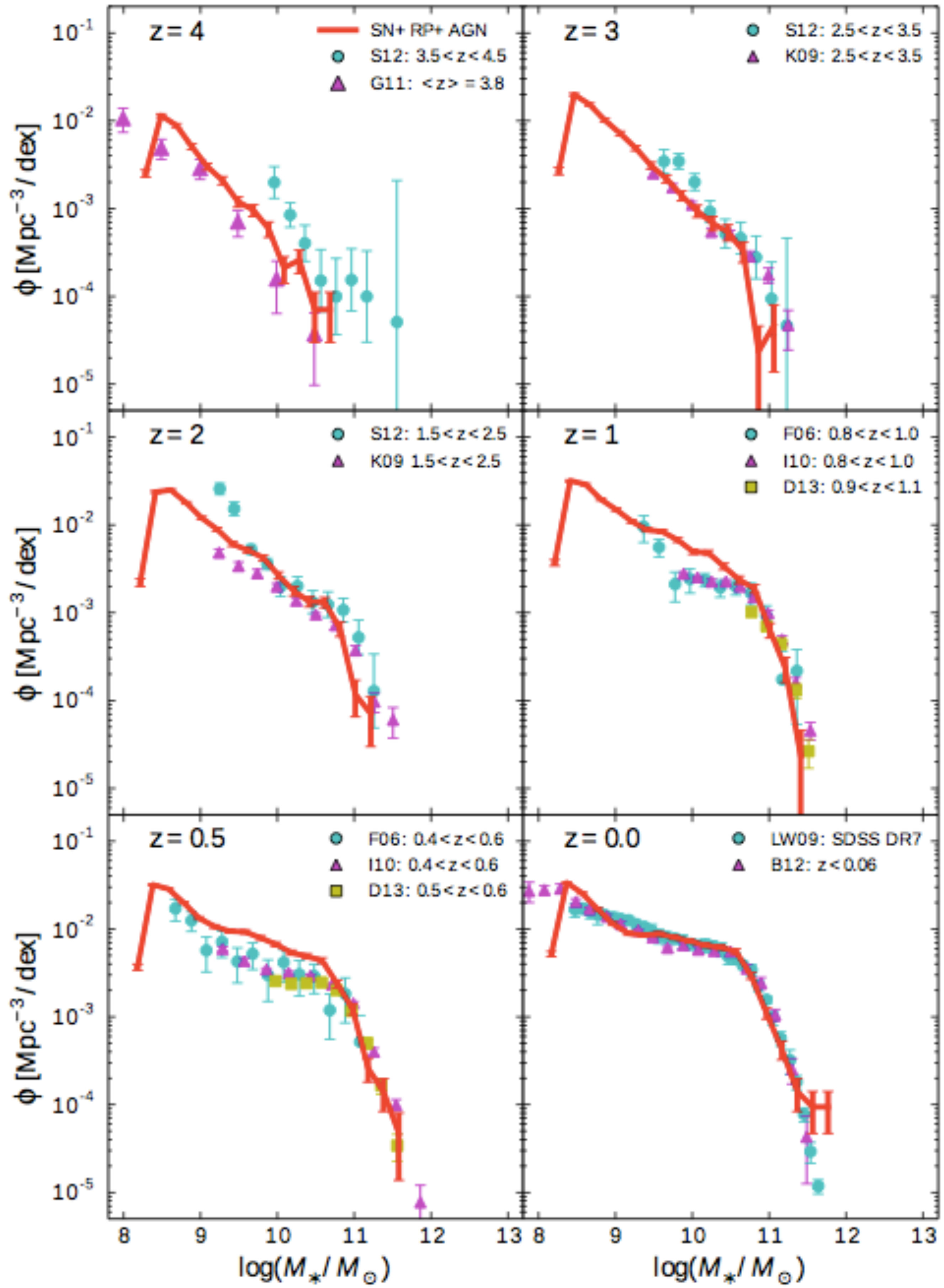
Galaxy Stellar Mass Fcn



Log (Stellar Mass)

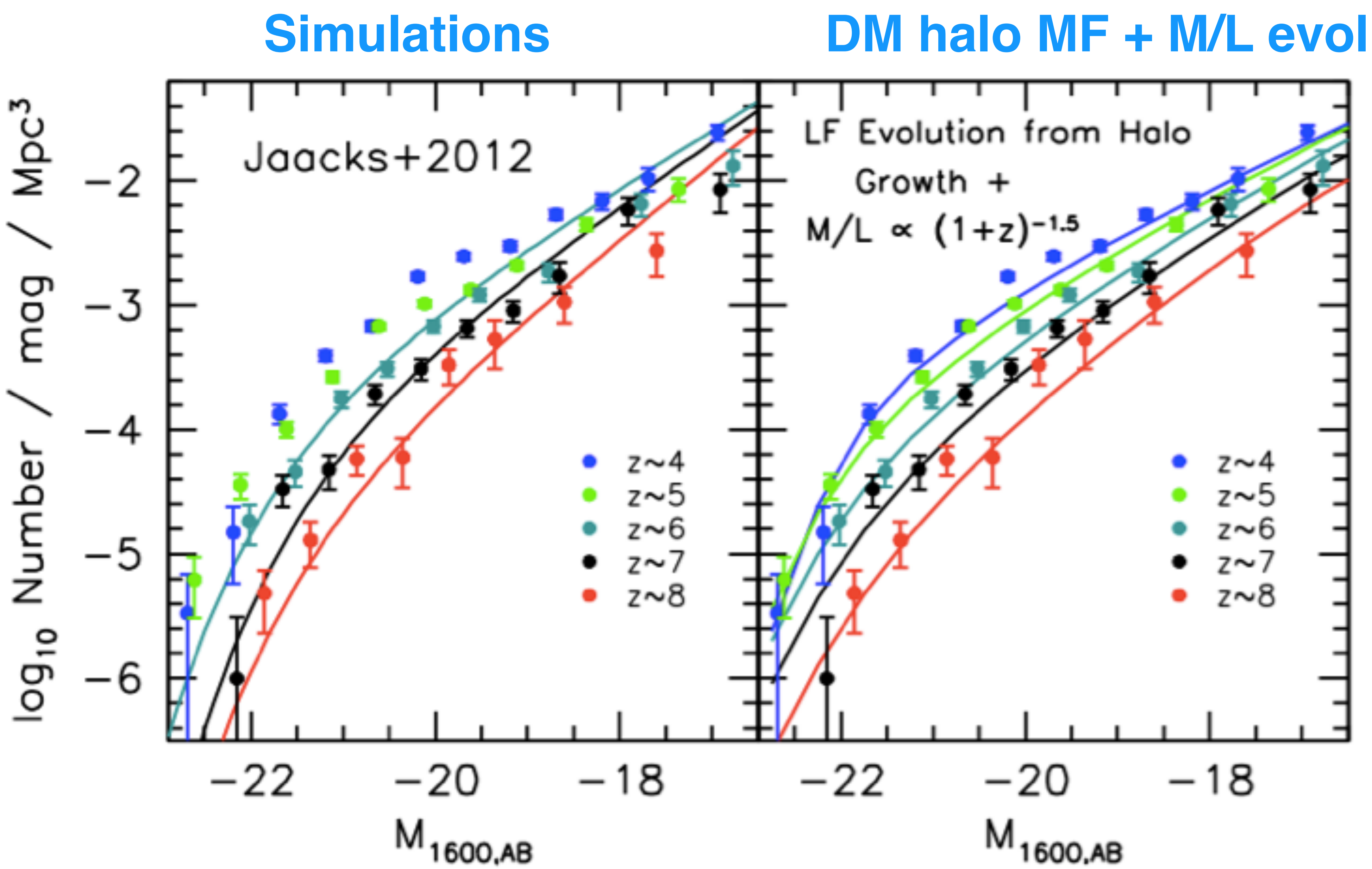
Steep faint-end slope is a generic prediction of ΛCDM model

KN+ '04; Night+ '06; Finlator+ '06 Jaacks+ '12a,b



Okamoto+ '14
Shimizu+ '14
Gadget-3 SPH
w/ AGN feedback

UV LFs at z=4-8: Obs vs. Sim

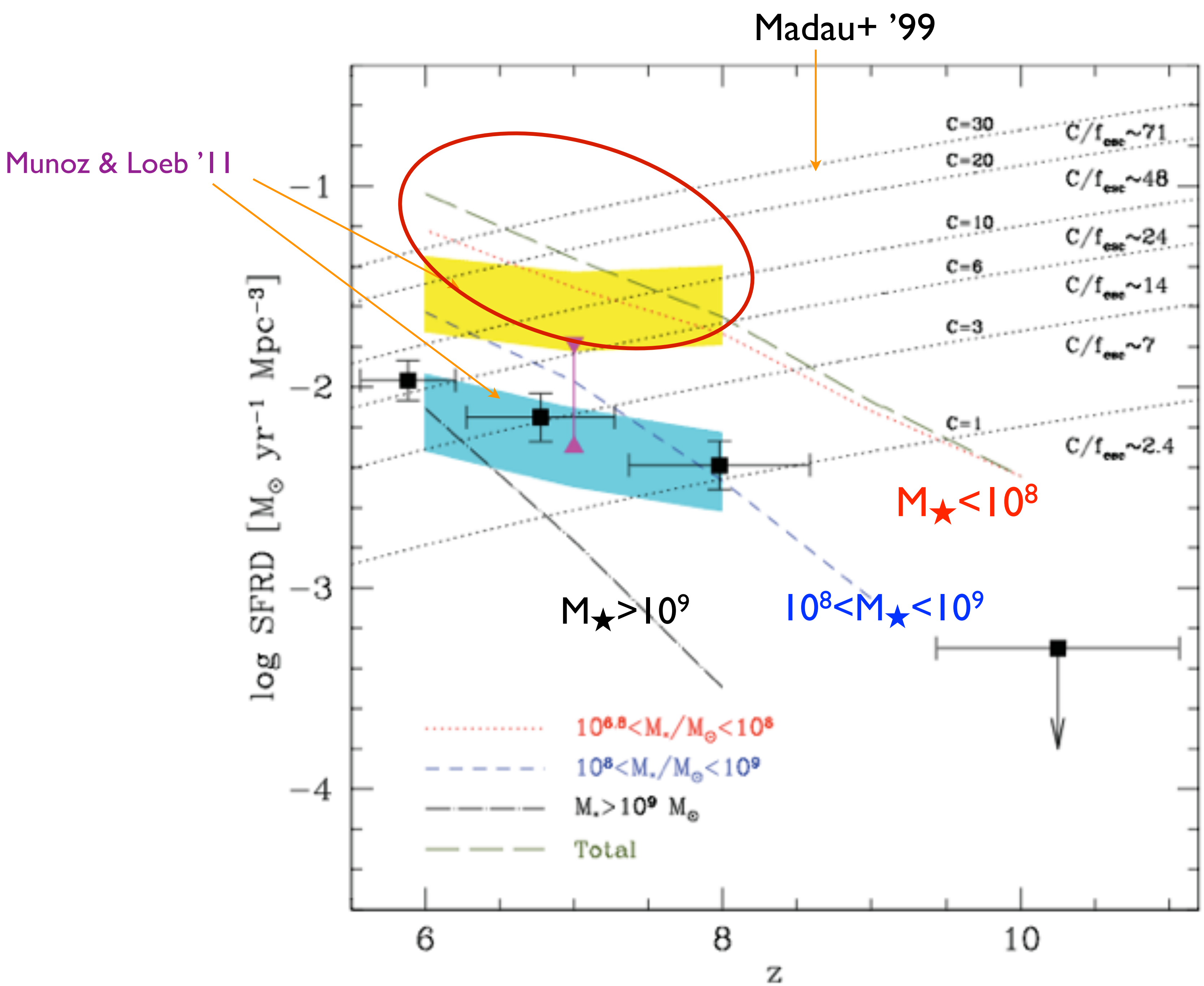


Steepening of the faint-end slope towards high-z even to α≲-2

(Bouwens+ '14)

(cf., Dunlop+, Ellis+, Finkelstein+, McLure+, Oesch+, Ouchi+, Schenker+, etc.)

Reionization of the Universe

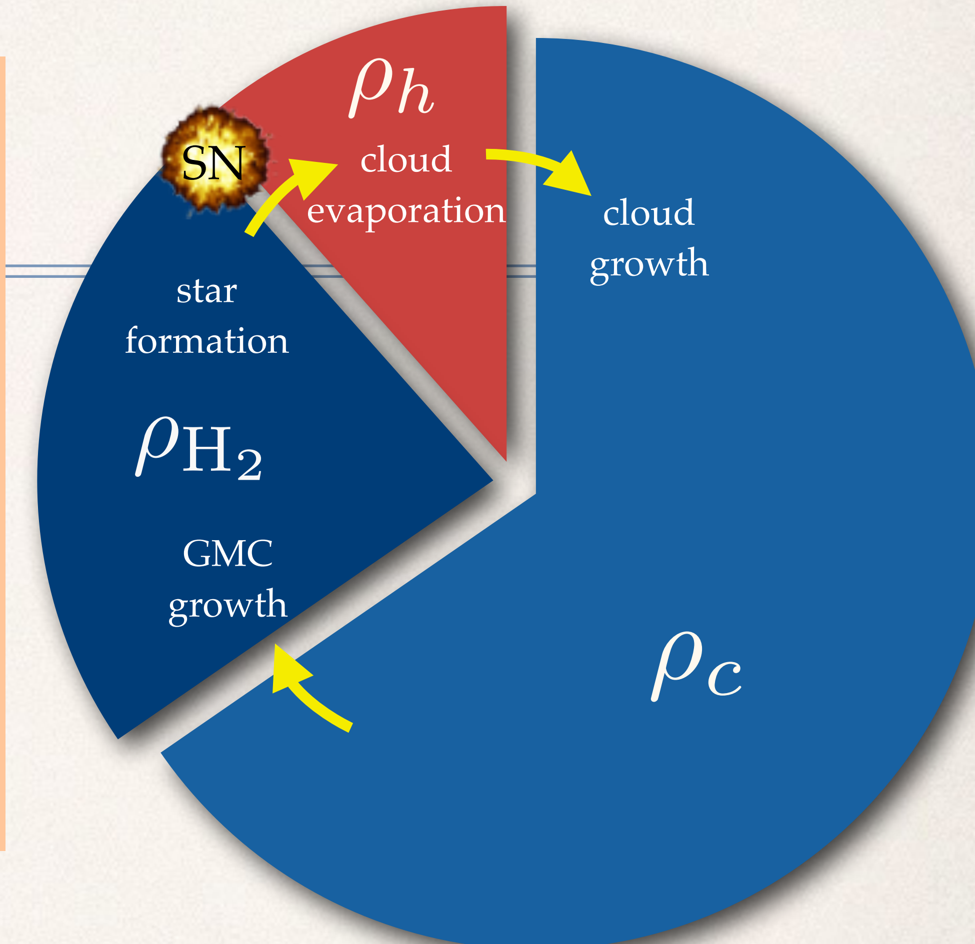


Jaacks, Choi & KN '12a

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

SPH implementation of H_2-SF model

- We modify the multiphase model to include the H_2 mass fraction.
- Change t_* --> *free-fall time* of the region.
- SF efficiency: $\varepsilon_{ff} = 0.01$ (Krumholz & Tan 2007, Lada et al. 2010).



one SPH particle

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

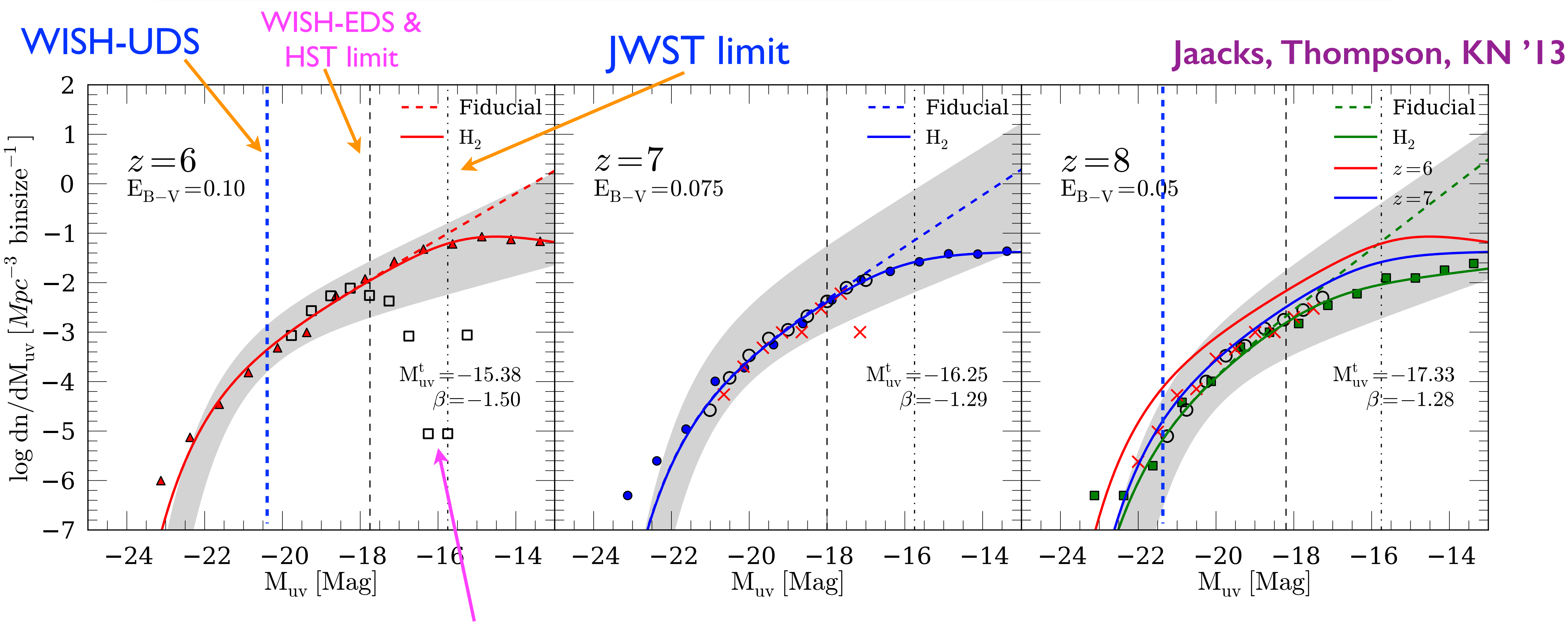
where

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

Thompson, KN+ '13

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

LFs with H_2-SF model



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

Modified Schechter Func.

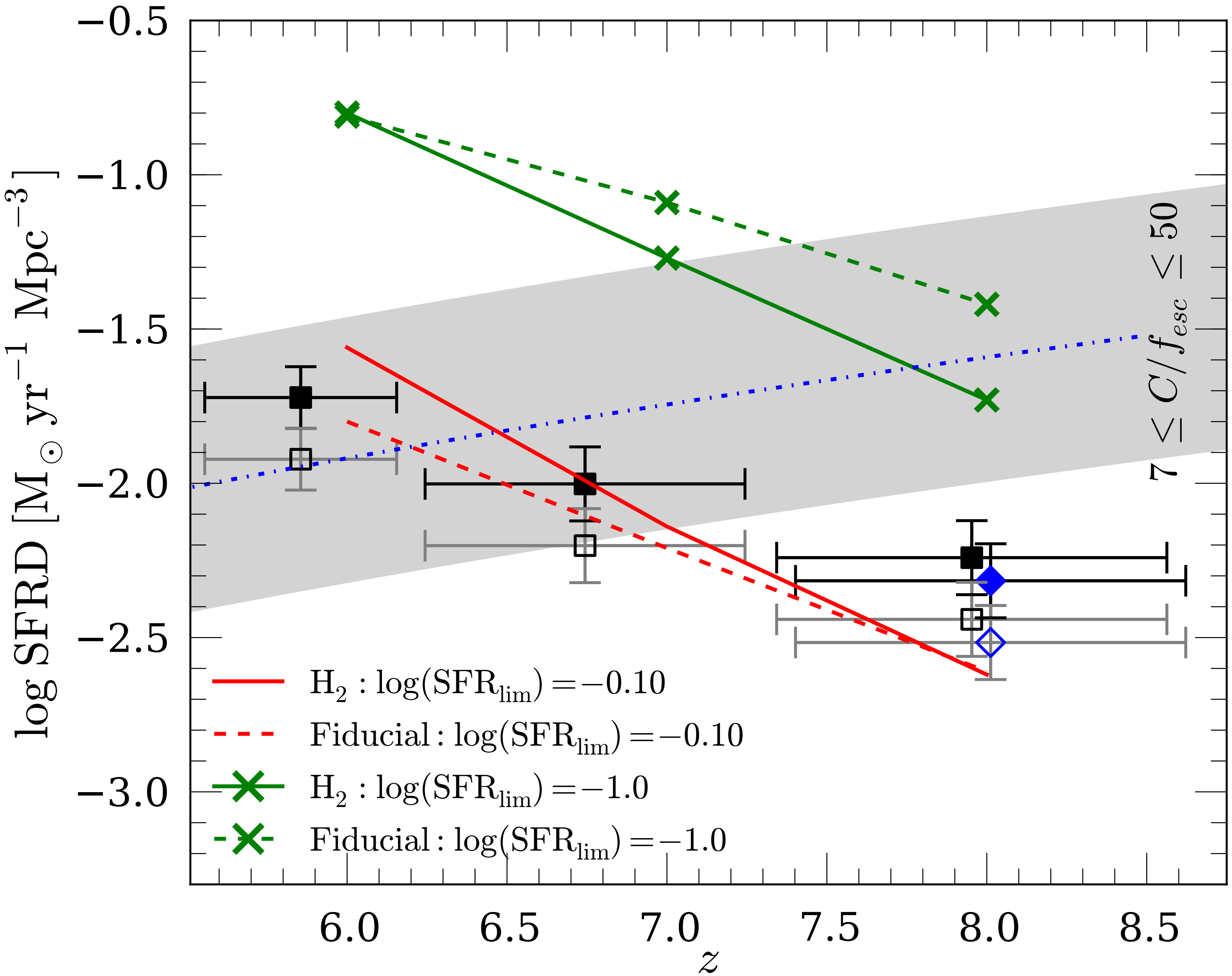
$$\Phi(L) = \phi^* \left(\frac{L}{L^*}\right)^{\alpha} \exp\left(-\frac{L}{L^*}\right) \left[1 + \left(\frac{L}{L^t}\right)^{\beta}\right]^{-1},$$

(cf. Loveday+ '97)

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

Future test with JWST.

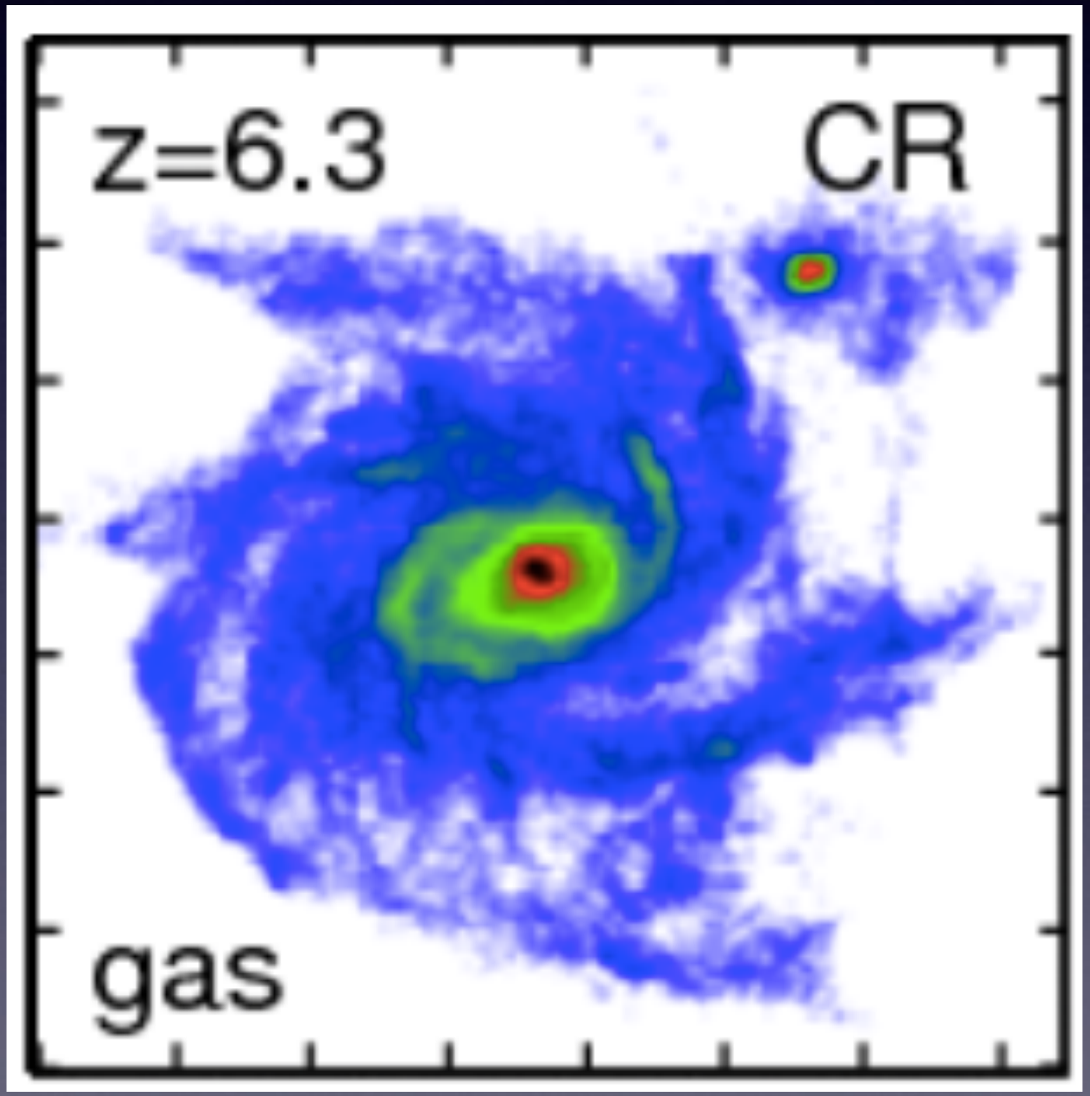
Reionization of the Universe



Jaacks, Thompson, KN '13

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

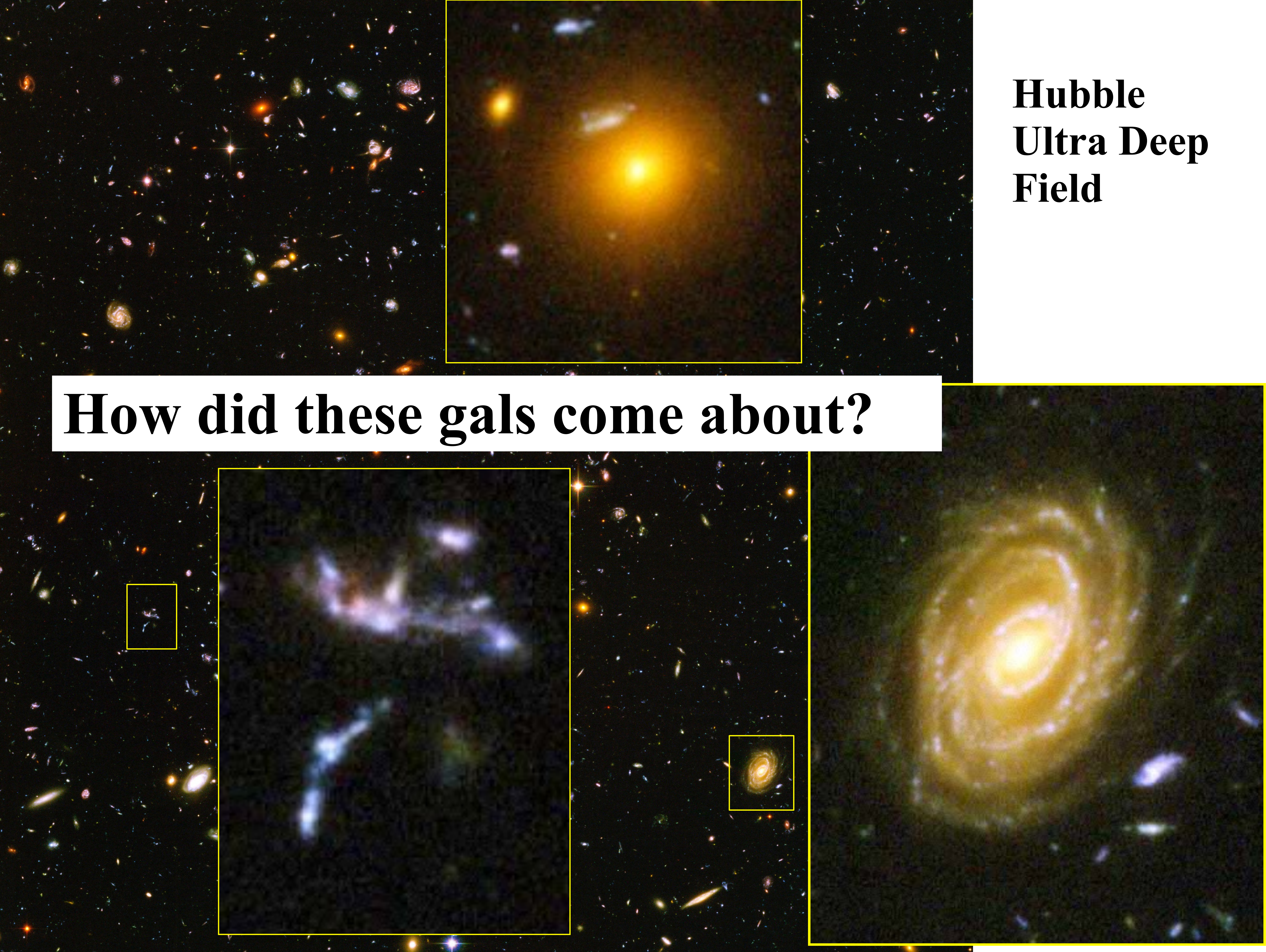
後半：Massive Gals & Downsizing



Romano-Diaz '14
Yajima+ '14

Hubble Ultra Deep Field

How did these gals come about?

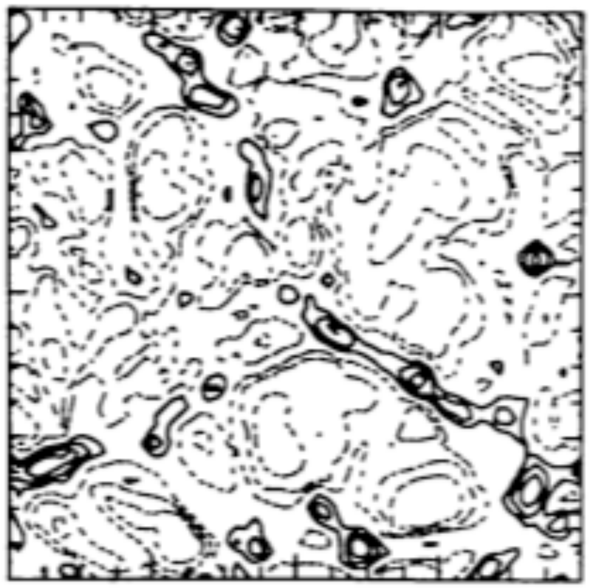


Three Revolutions in Cosmological Hydro Simulations

1990': 1st Revolution

2001-2011 2nd Rev.

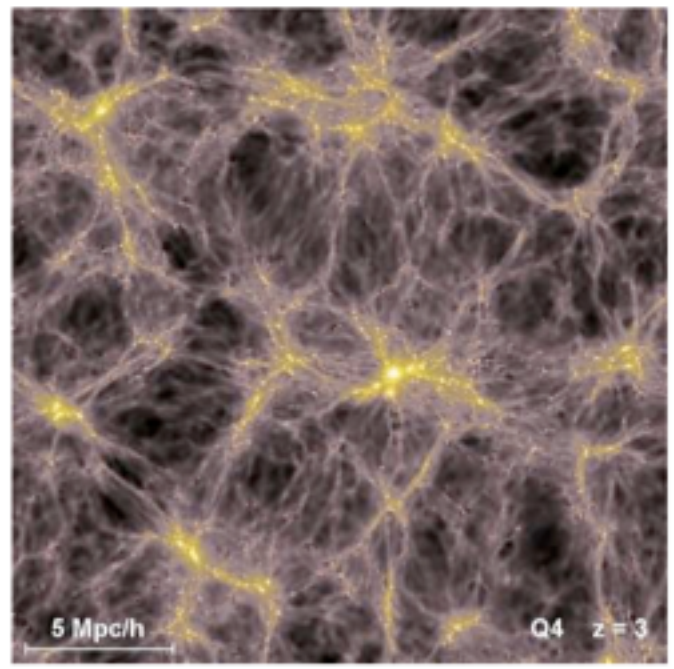
2012~ 3rd Rev.



First cosmological, but coarse calculation

Resolution~100 kpc

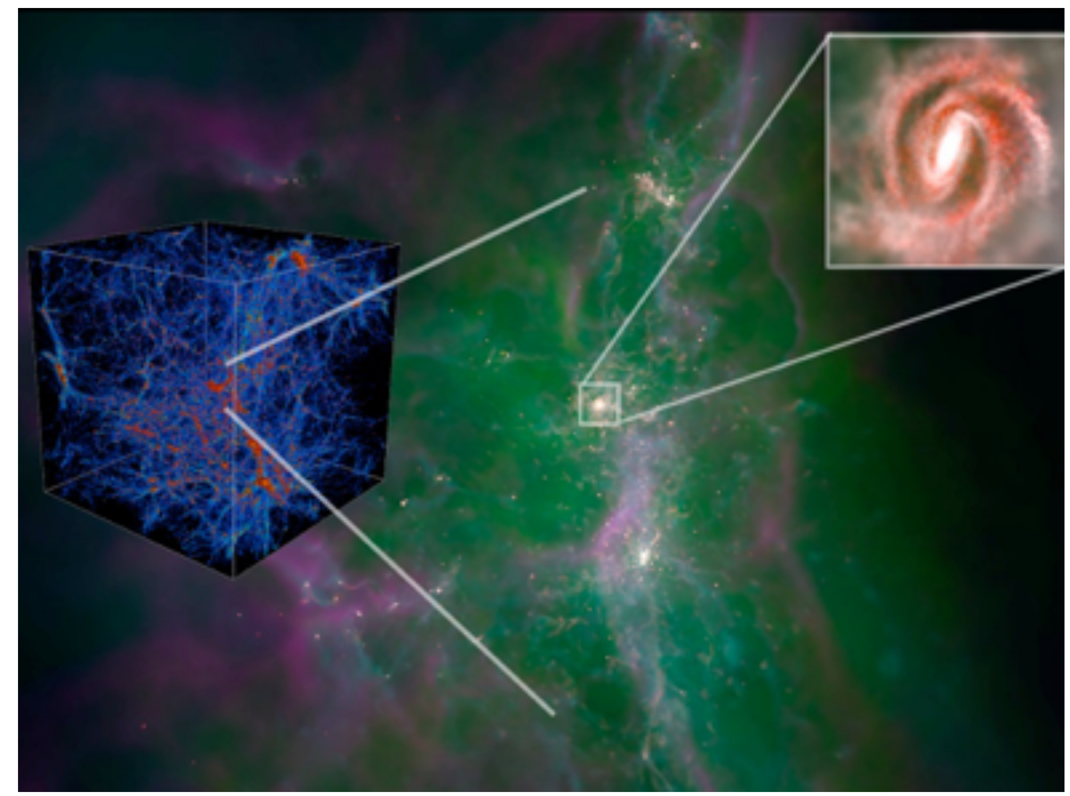
E.g., Cen '92
Katz+ '96



Larger scale, medium resolution **w. subgrid models**

Resolution~ few kpc

E.g., KN+ '01
Springel & Hernquist '03

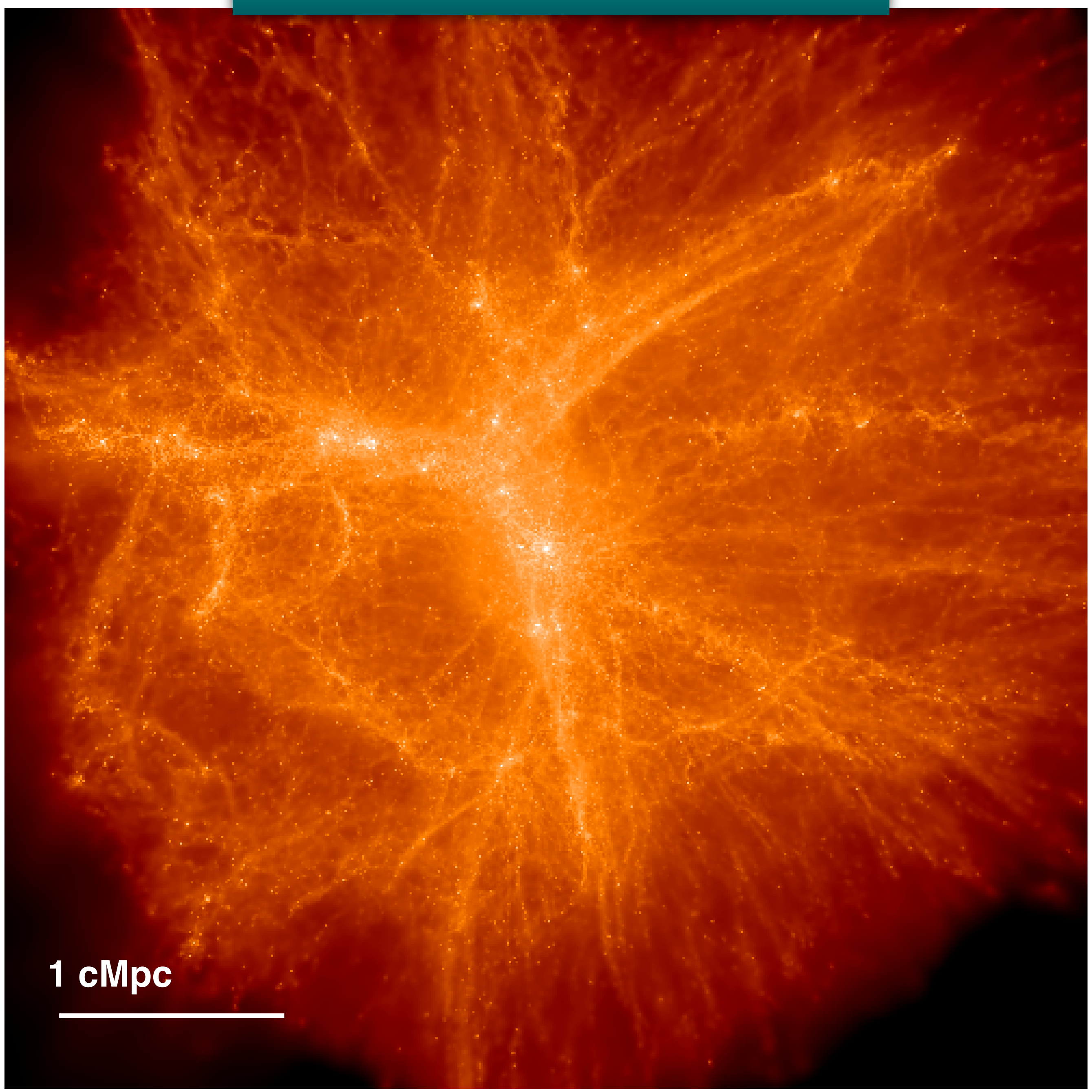


Zoom-in method allows much higher res.

Resolution~ 20-100pc

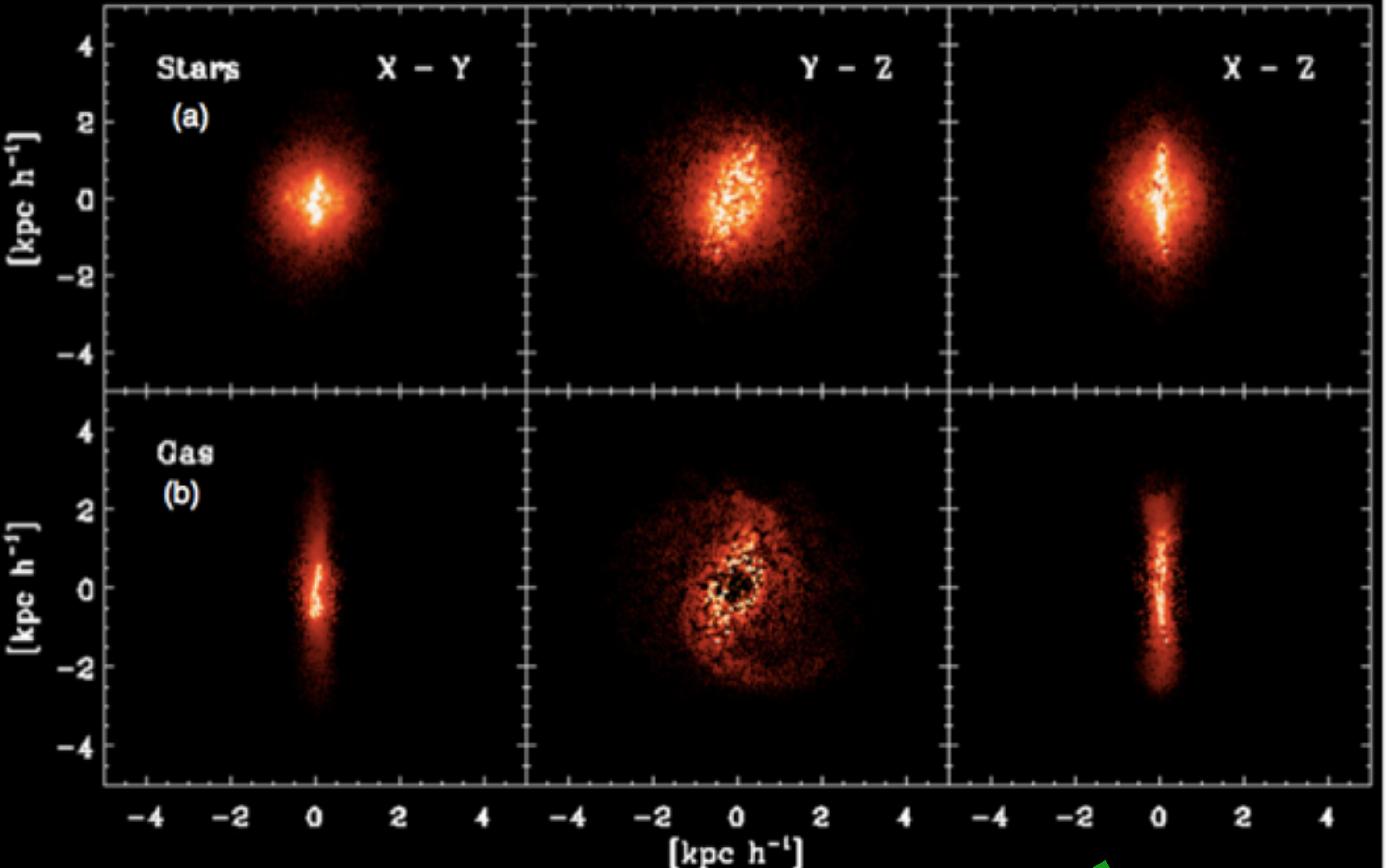
Example Zoom-in Sim

Constrained Realization



(Romano-diaz+'11, '13 sim)

- Quasar host-like 5-σ region (20 cMpc/h)
- 3.5 cMpc/h zoom-in region
- ϵ=300 com pc; ~30pc (proper @z~10)
- m_{dm}~5e5 $M_\odot$
- m_{gas}~1e5 $M_\odot$



z=10.2

Romano-Diaz+ '11

resolution ~ 30 pc (proper)

Distinct massive disk gal already at z~10

$M_{tot} \sim 1.1 \times 10^{10}\ h^{-1}\ M_\odot$

total disk mass is $\sim 2.9 \times 10^9\ h^{-1}\ M_\odot$

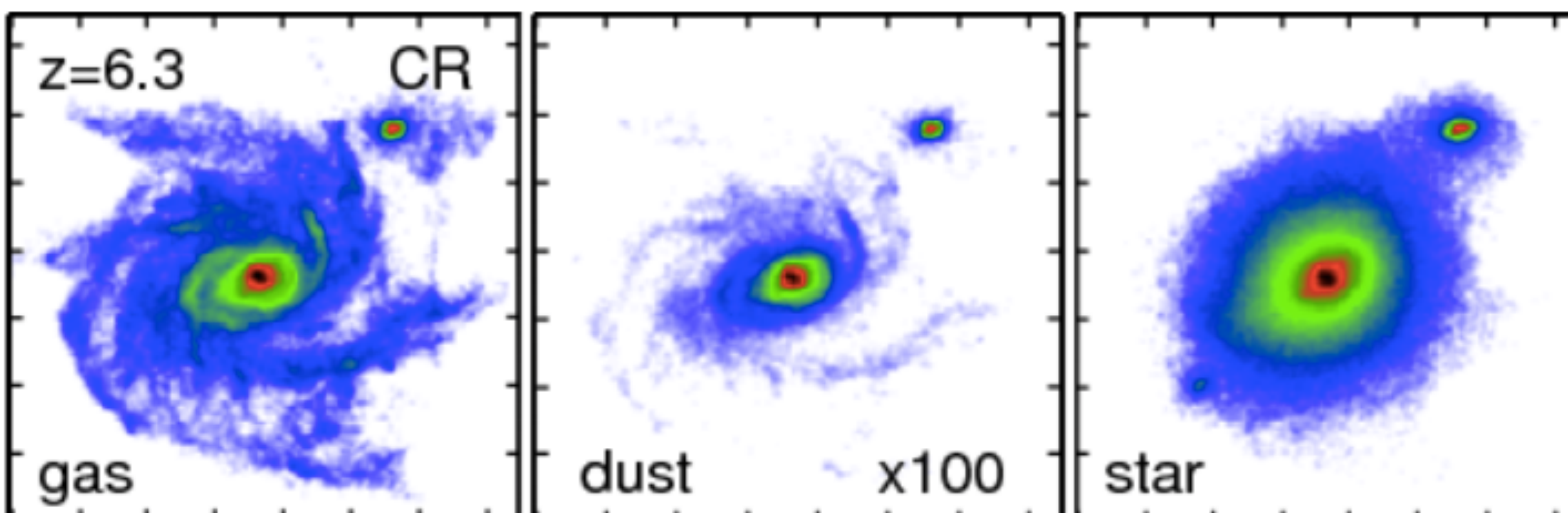
$M_{star,disk} \sim 8 \times 10^8\ h^{-1}\ M_\odot$

$M_{gas} \sim 4.8 \times 10^{10}\ M_\odot$

$M_{star} \sim 4.1 \times 10^{10}\ M_\odot$

z=6.3

Yajima+ '14



$M_{dust}/M_{metal} = 0.4$, i.e., $M_{dust} = 0.008\ M_{gas}\ (Z/Z_\odot)$

Yajima+ '14

Very high SFR

The most massive galaxy:

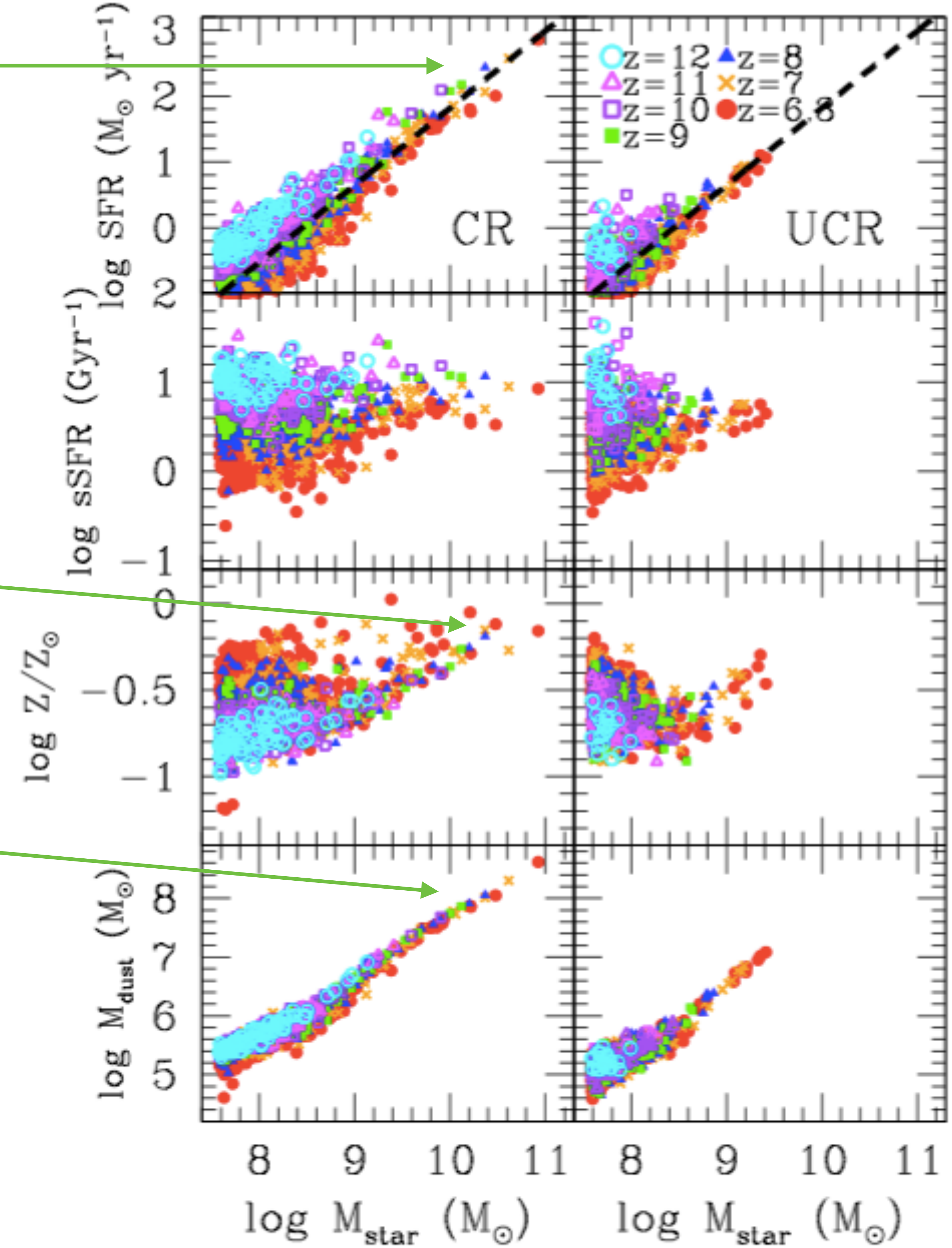
$M_{star} \sim 8.4 \times 10^{10}\ M_\odot$,

$M_{dust} \sim 4.1 \times 10^{8}\ M_\odot$,

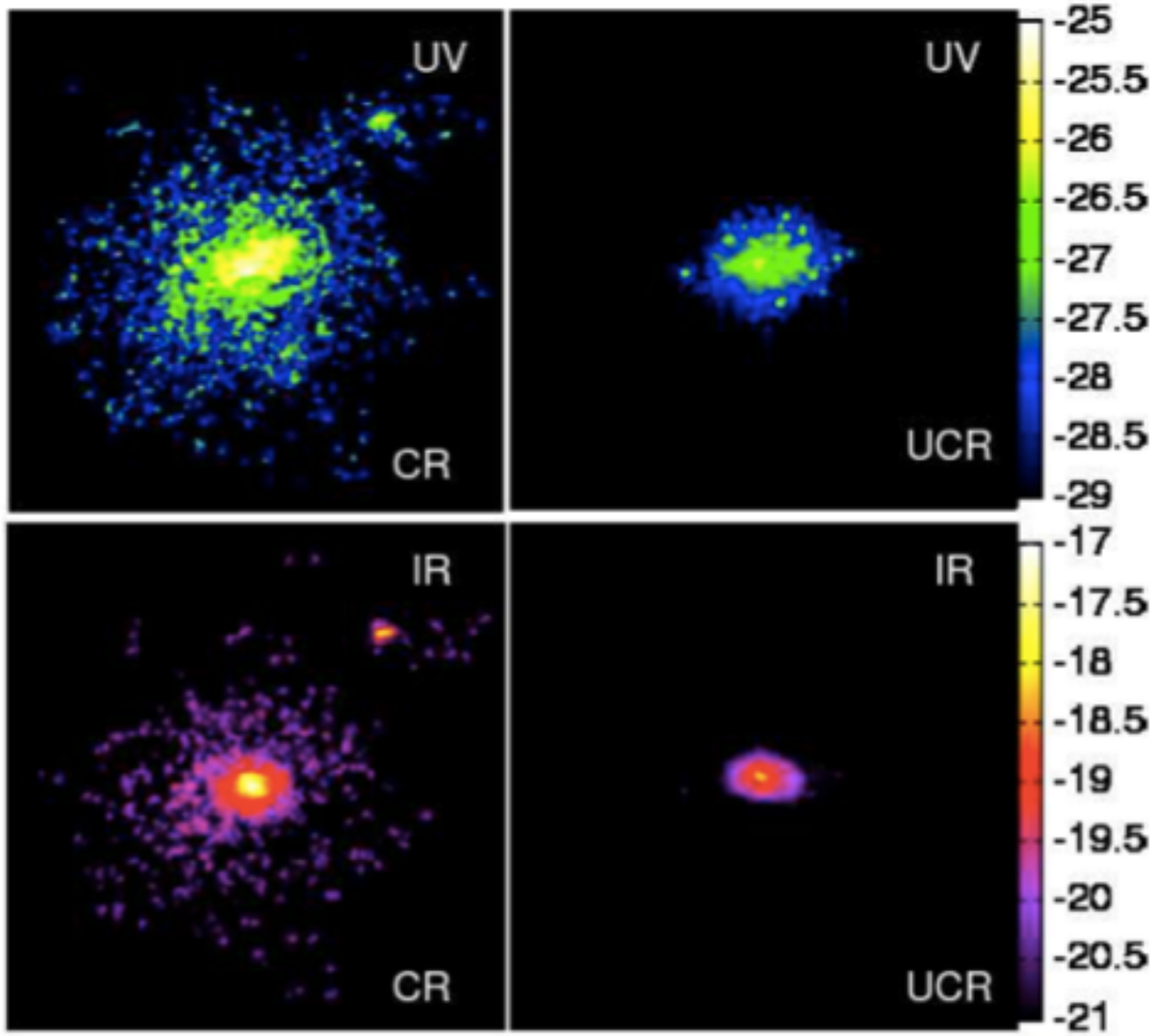
$SFR \sim 745\ M_\odot\ yr^{-1}$ $(z = 6.3)$

Close to solar metallicity

Large amount of dust in massive gals

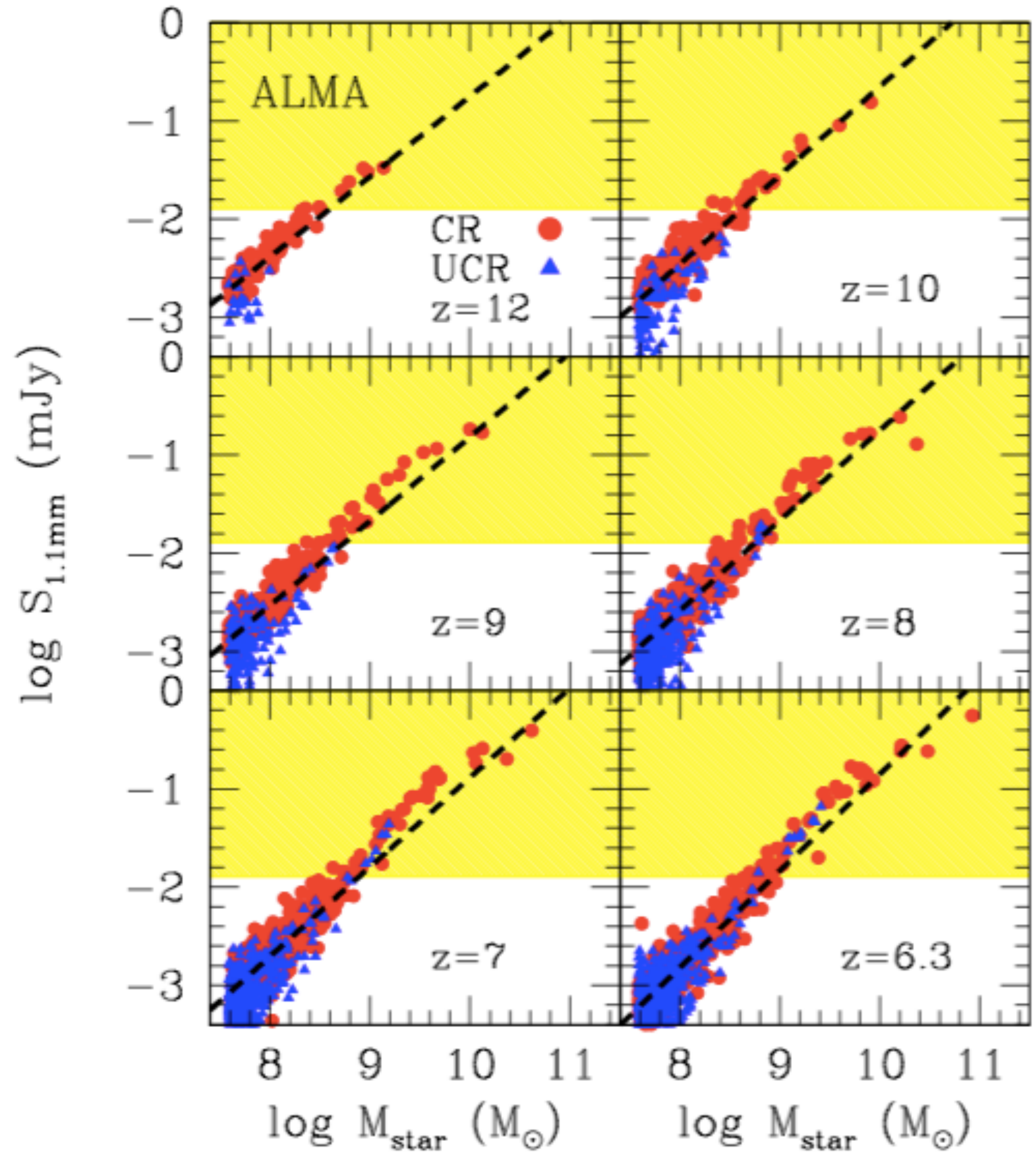


UV: 1600 A rest-frame



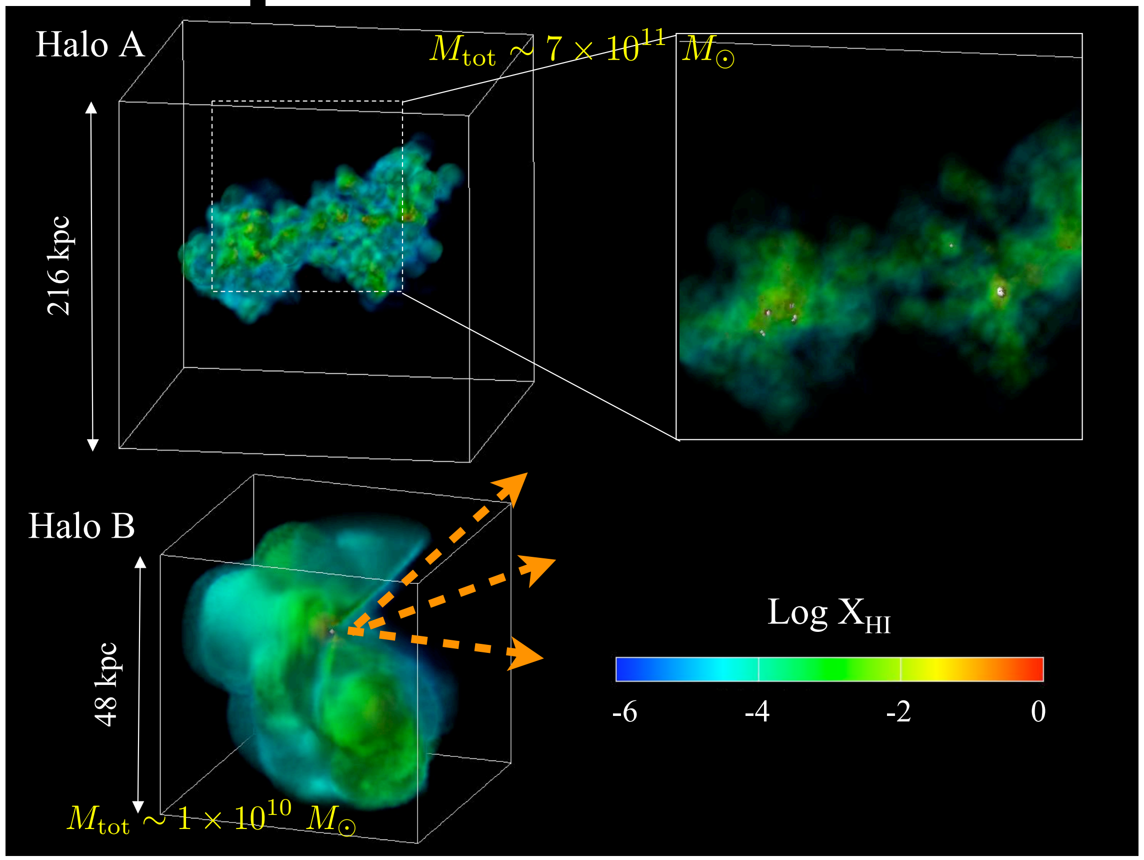
IR: 106 μm rest (850 μm obs)

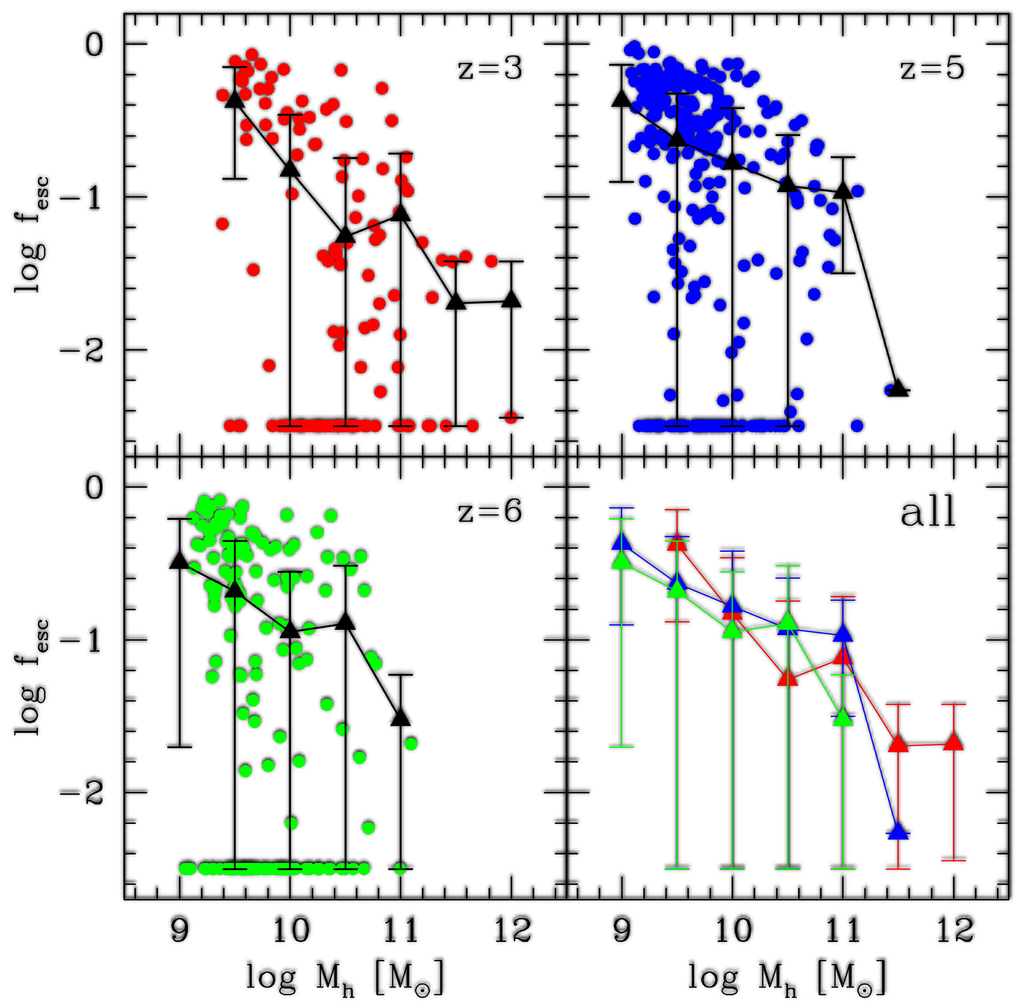
surface brightness in the log scale in units of erg s^{-1} cm^{-2} Hz^{-1} $arcsec^{-2}$.

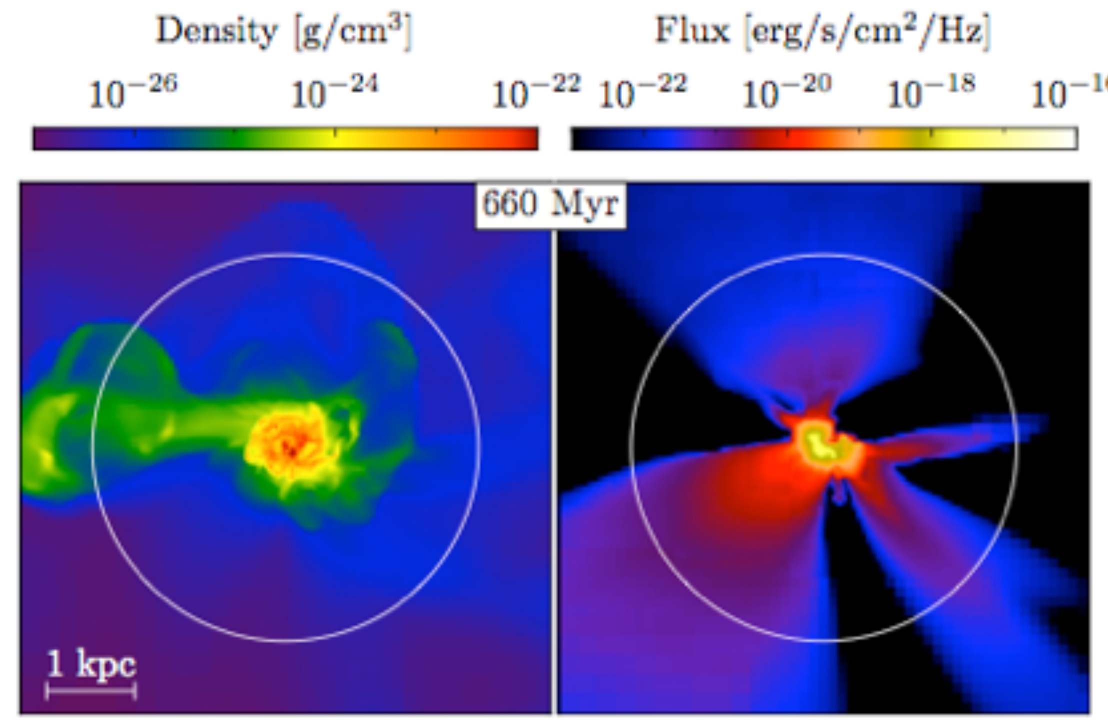


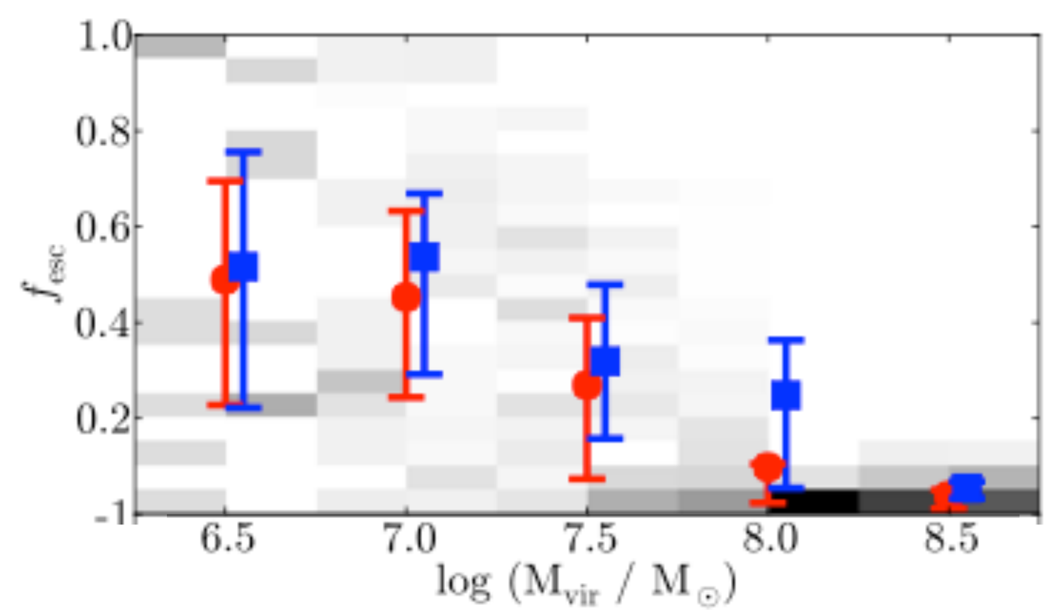
Yajima+ '14

Escape Fraction of Ionizing Photons





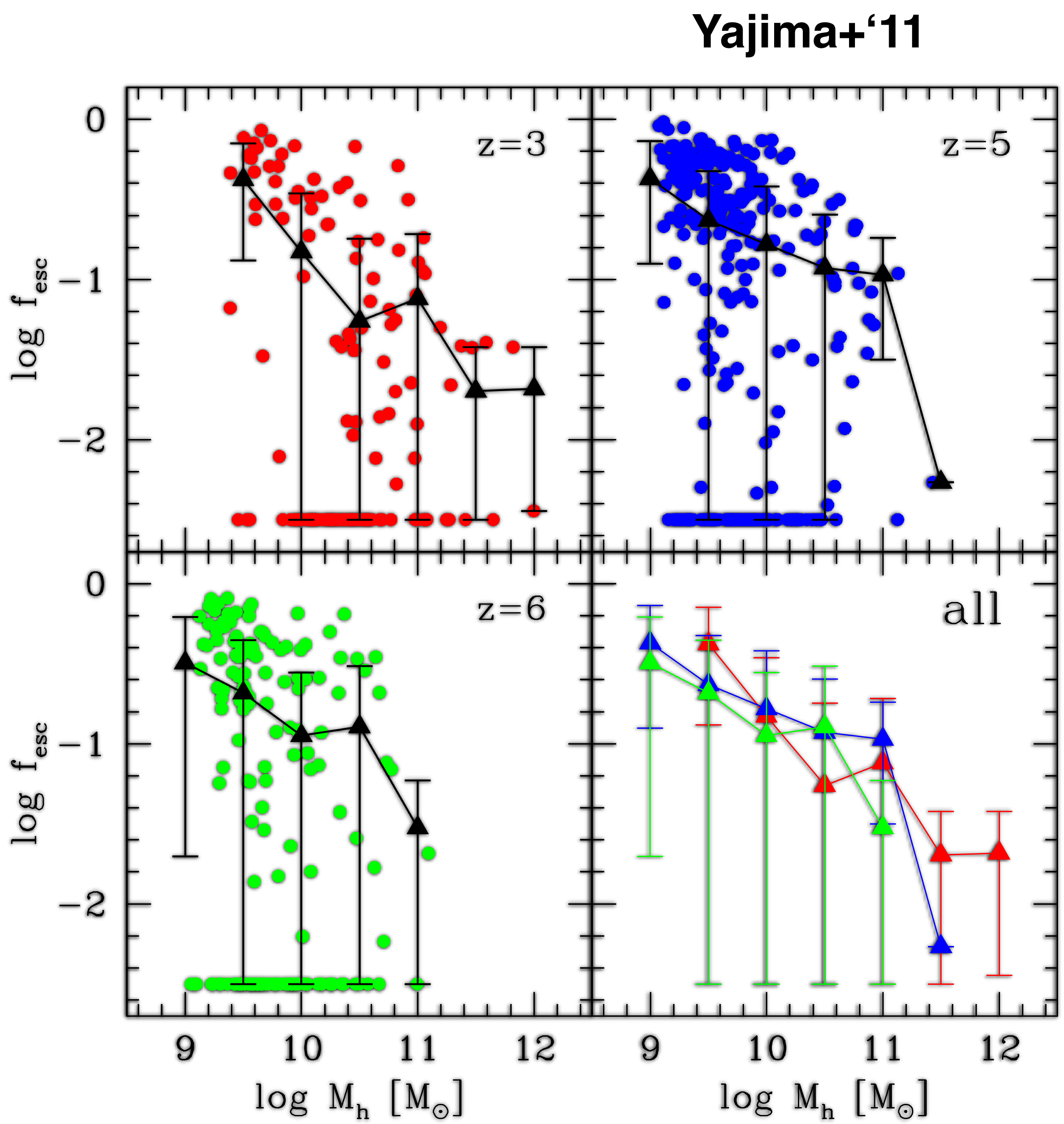


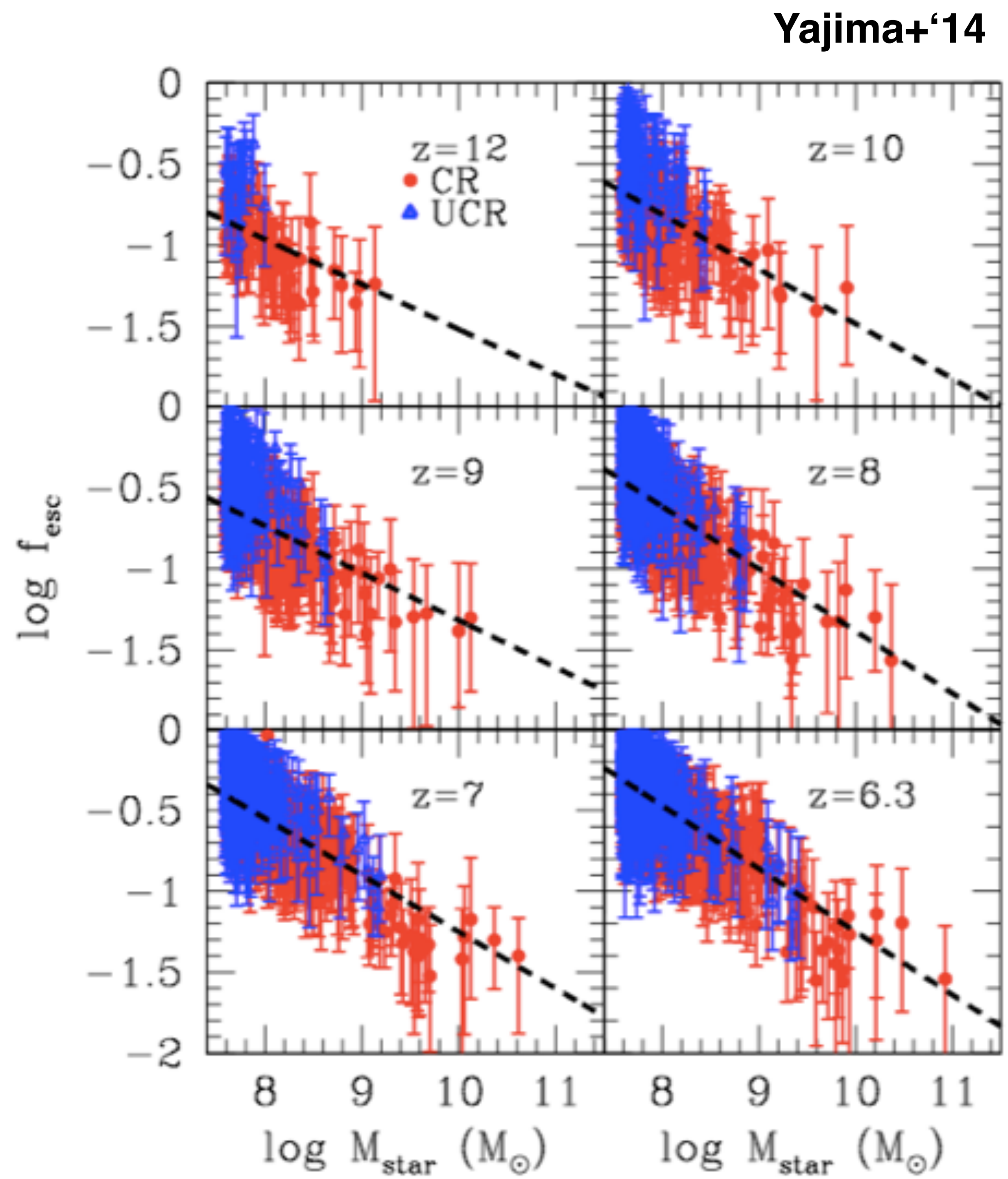


Wise+ '14

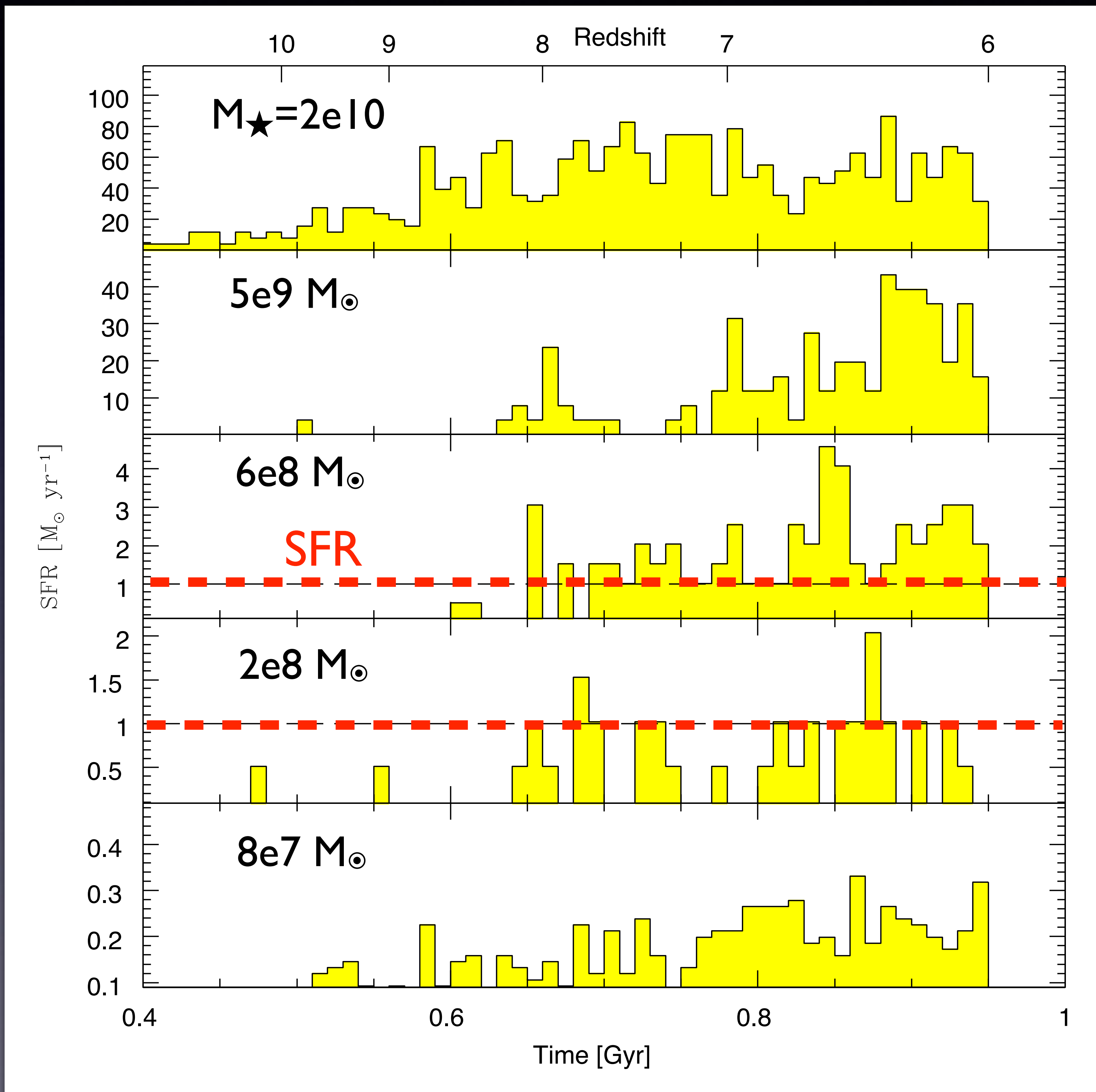
Yajima, Choi, KN '11

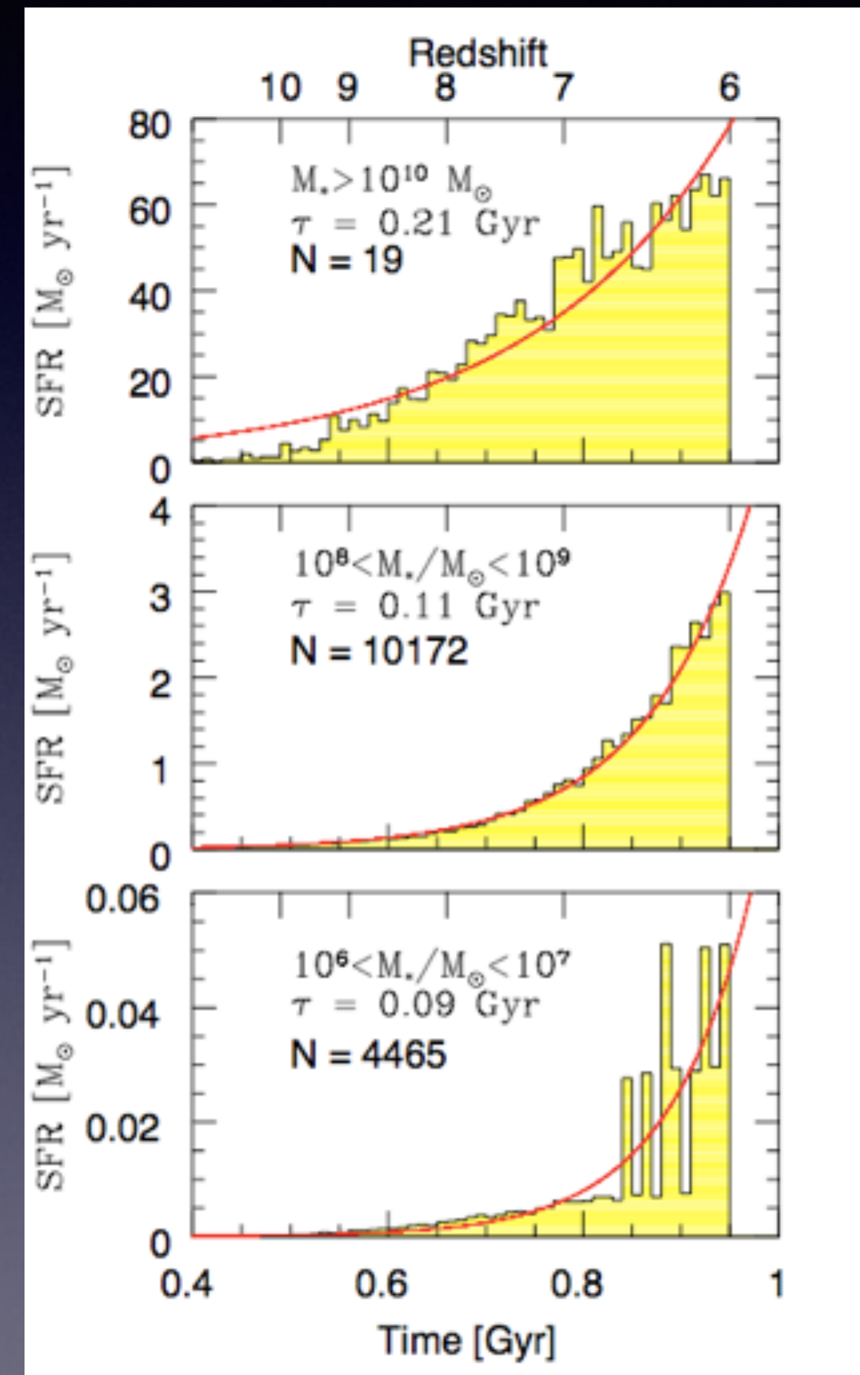
Escape Fraction of Ionizing Photons





Smooth Accretion vs. In Situ SF

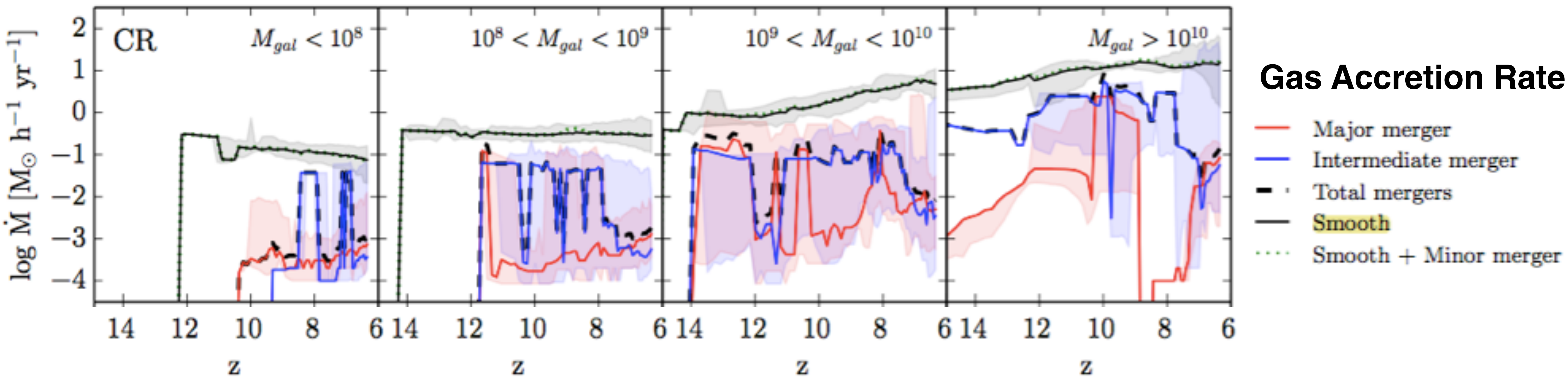


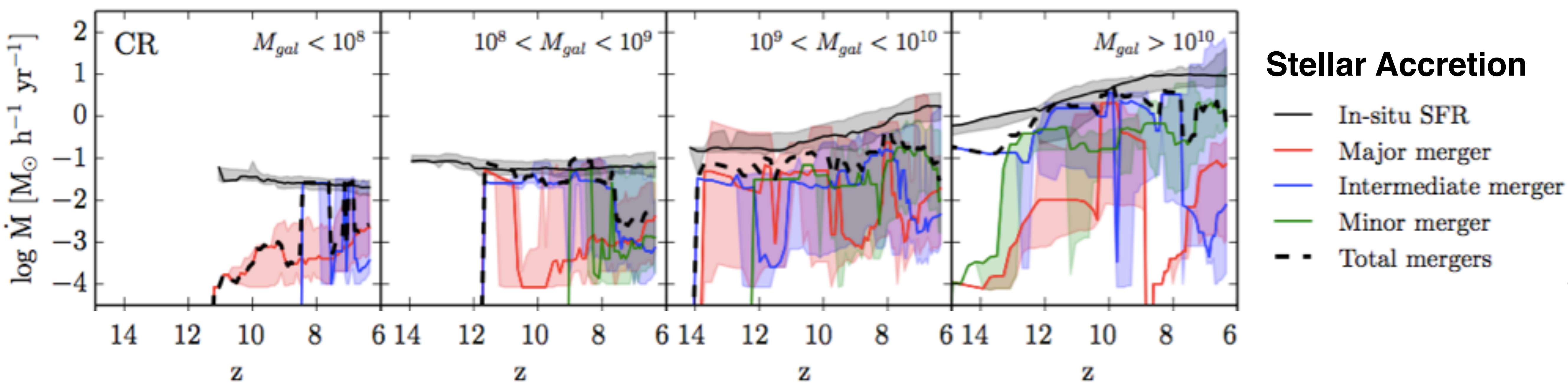


Jaacks, Choi & KN, 12b

Accretion vs. In Situ?

Romano-Diaz+ '14





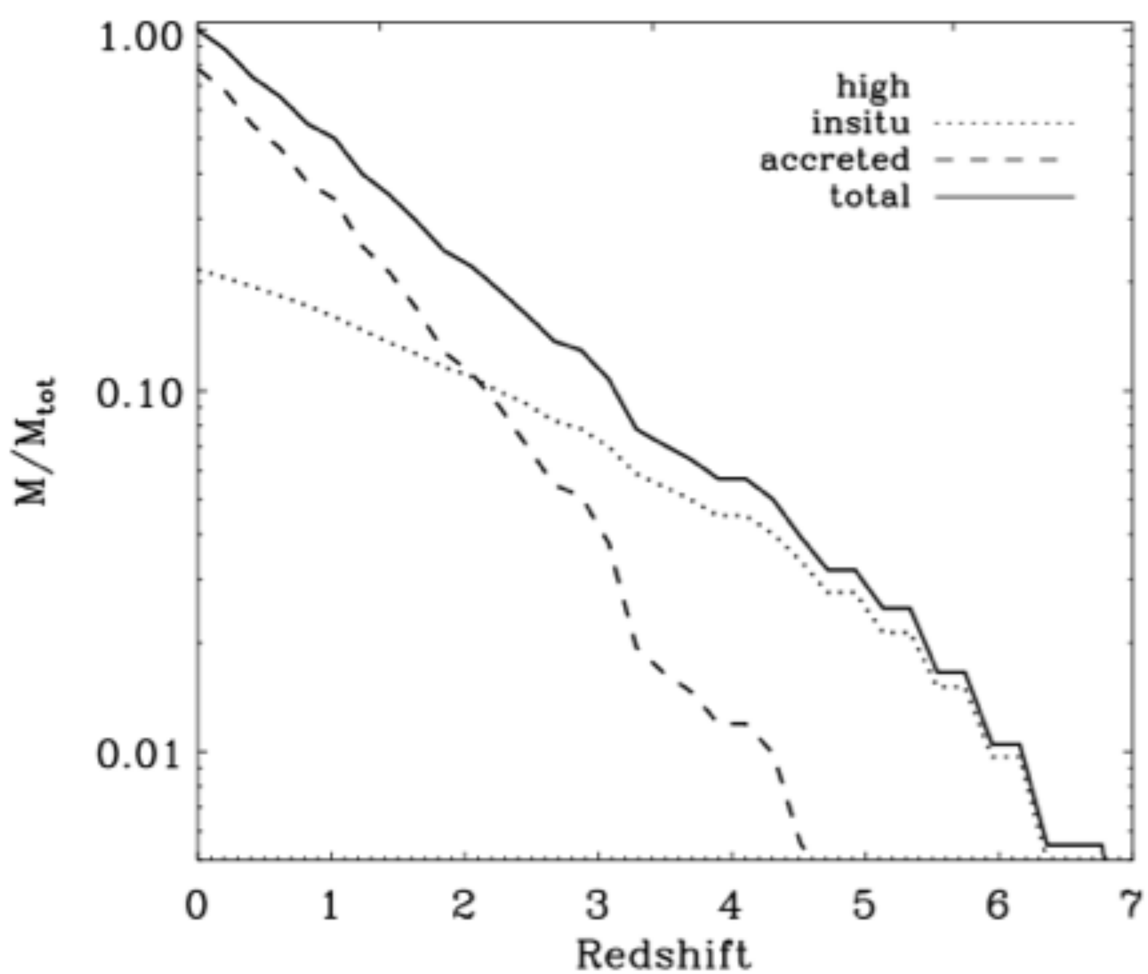
Smooth gas accretion & In Situ SFR >> Mergers

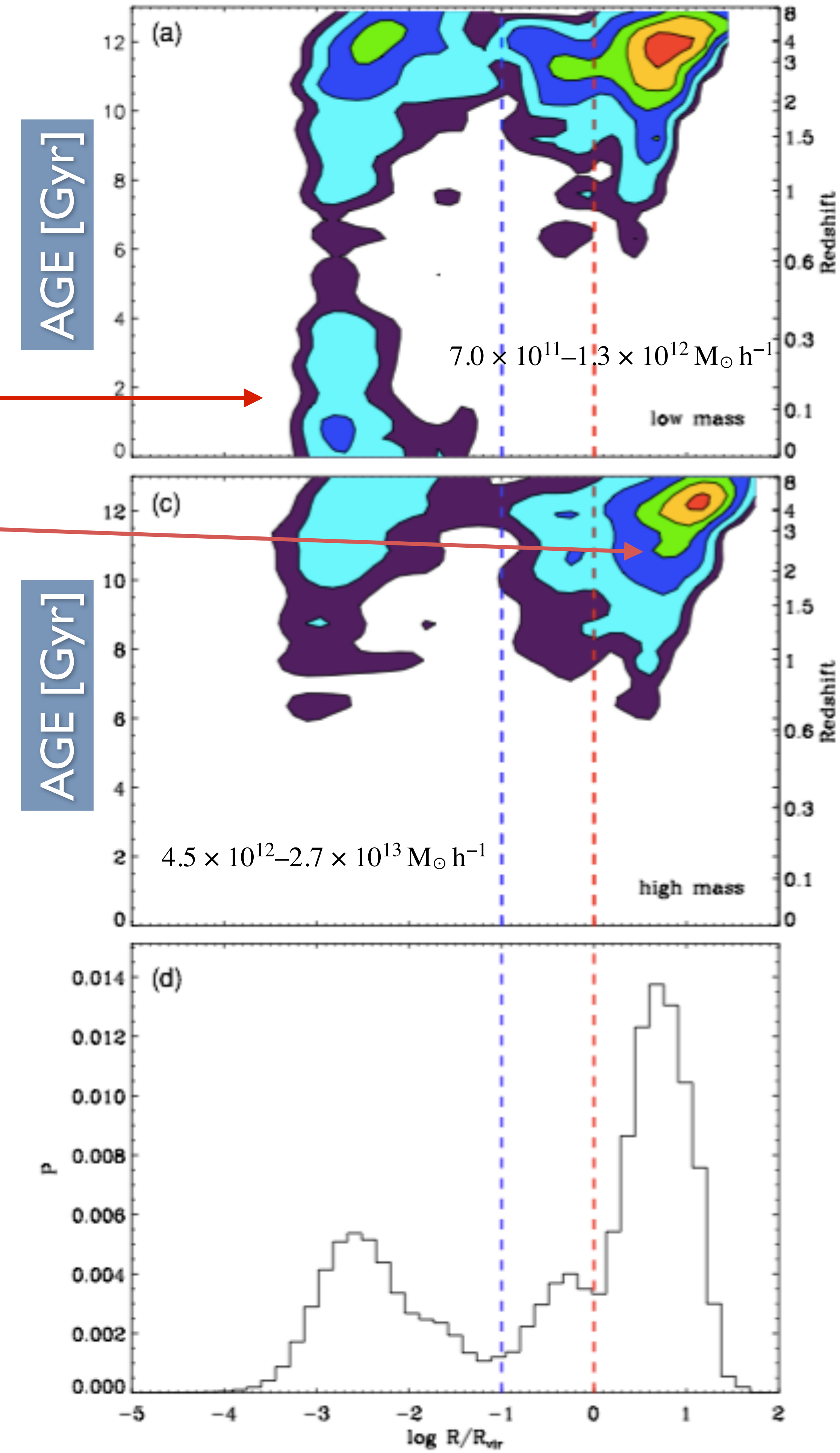
Two-phase Formation & Downsizing

Oser+'14 : zoom-in cosmo hydro sim

late in-situ SF

Formed at high-z outside, but accreted later on.





Importance of In-situ SF!

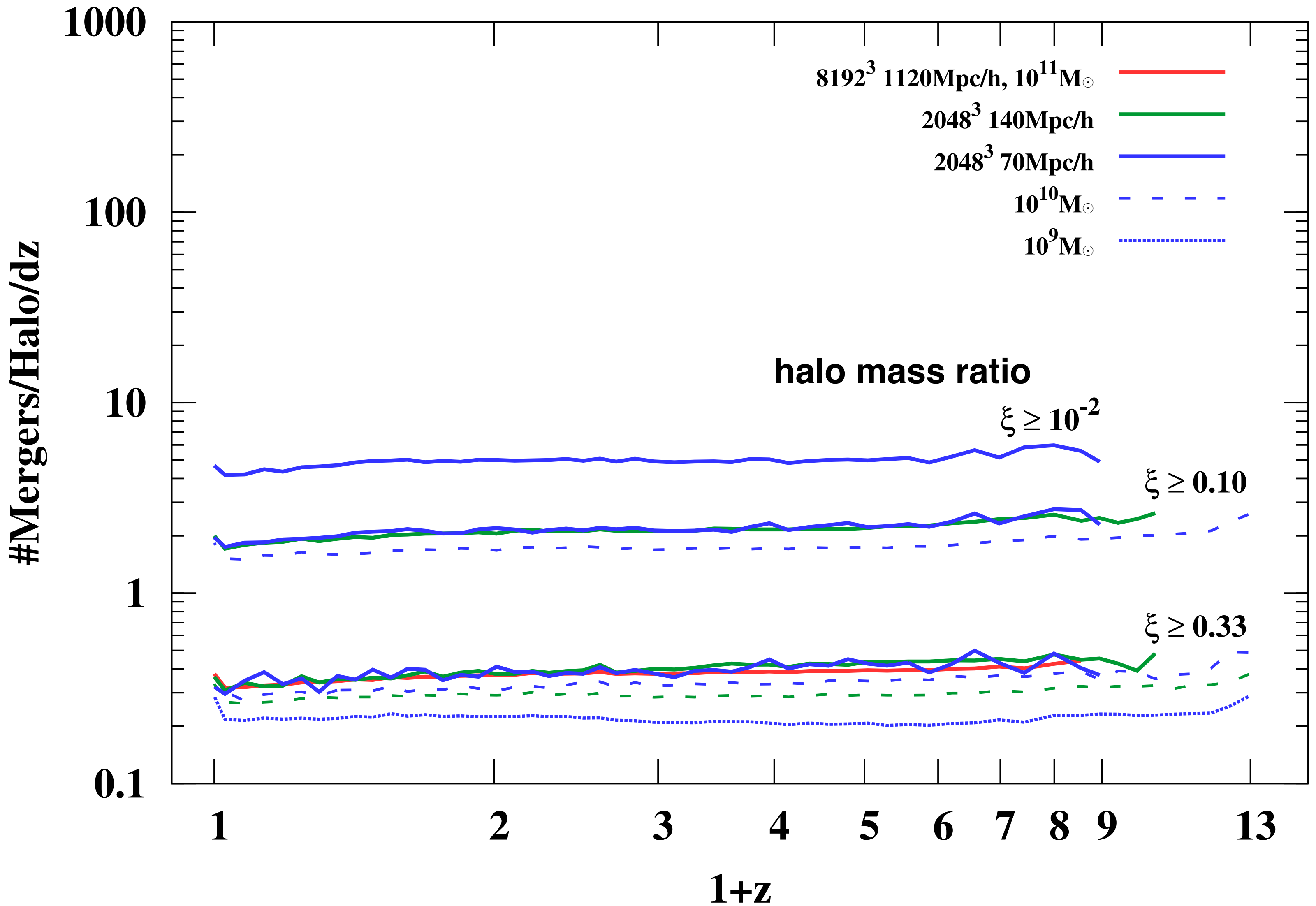
Halo Merger Rate

Ishiyama '14: large N-body simulation
— results consistent with Millenium sim (Fakhouri+'10)

Very low merger rate!

Almost no z-evolution, but weak M_{halo} dependence

But note: only primary infall with HOP grouping is followed. No secondary infall included.

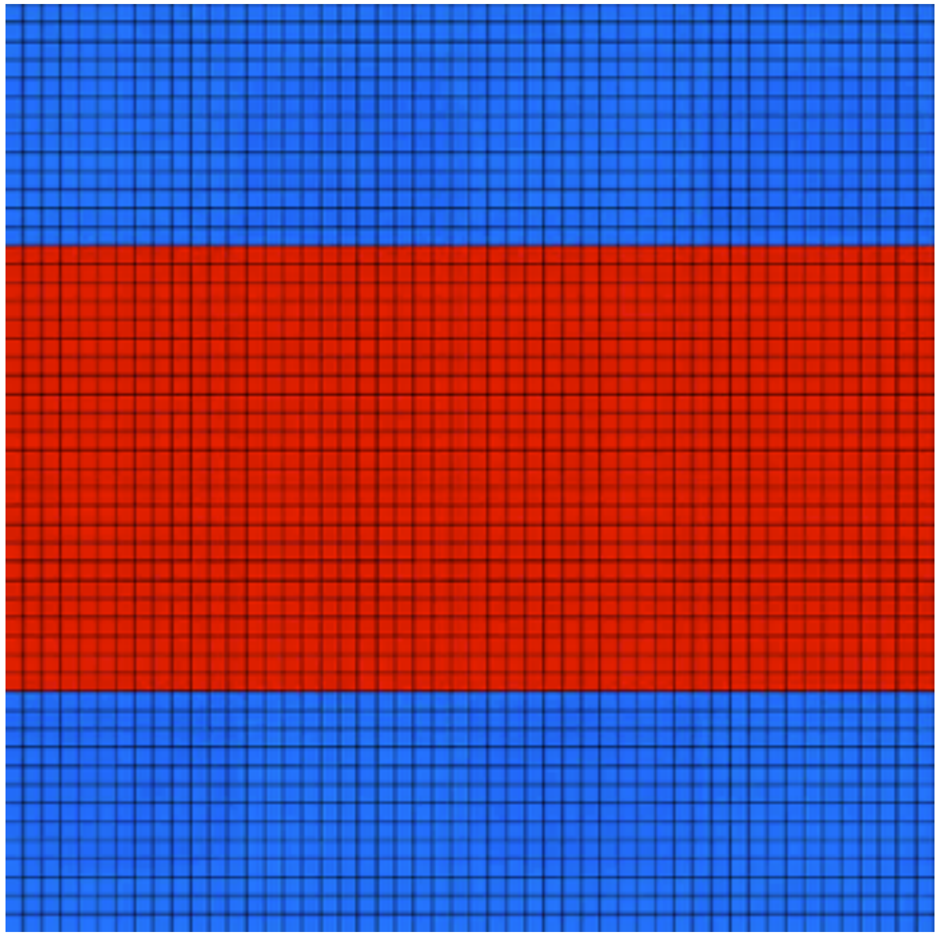


Also suggests the importance of smooth gas accretion & in-situ SF

AREPO (Springel '12)

Based on a moving unstructured mesh defined by the Voronoi tessellation of a set of discrete points.

Galilean-invariant cosmological hydrodynamical simulations on a moving mesh

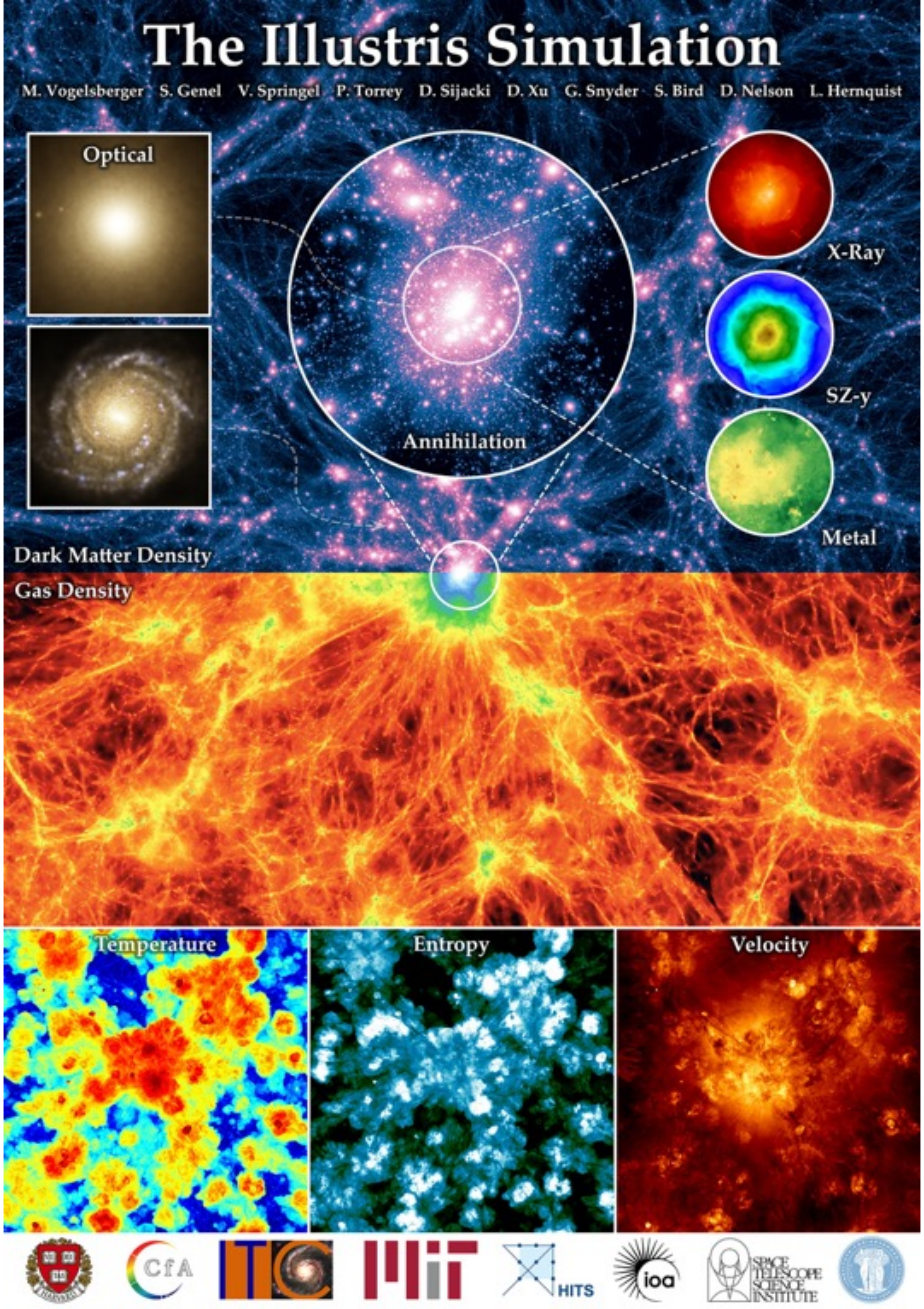


Kelvin-Helmholz instability

Rayleigh-Taylor instability

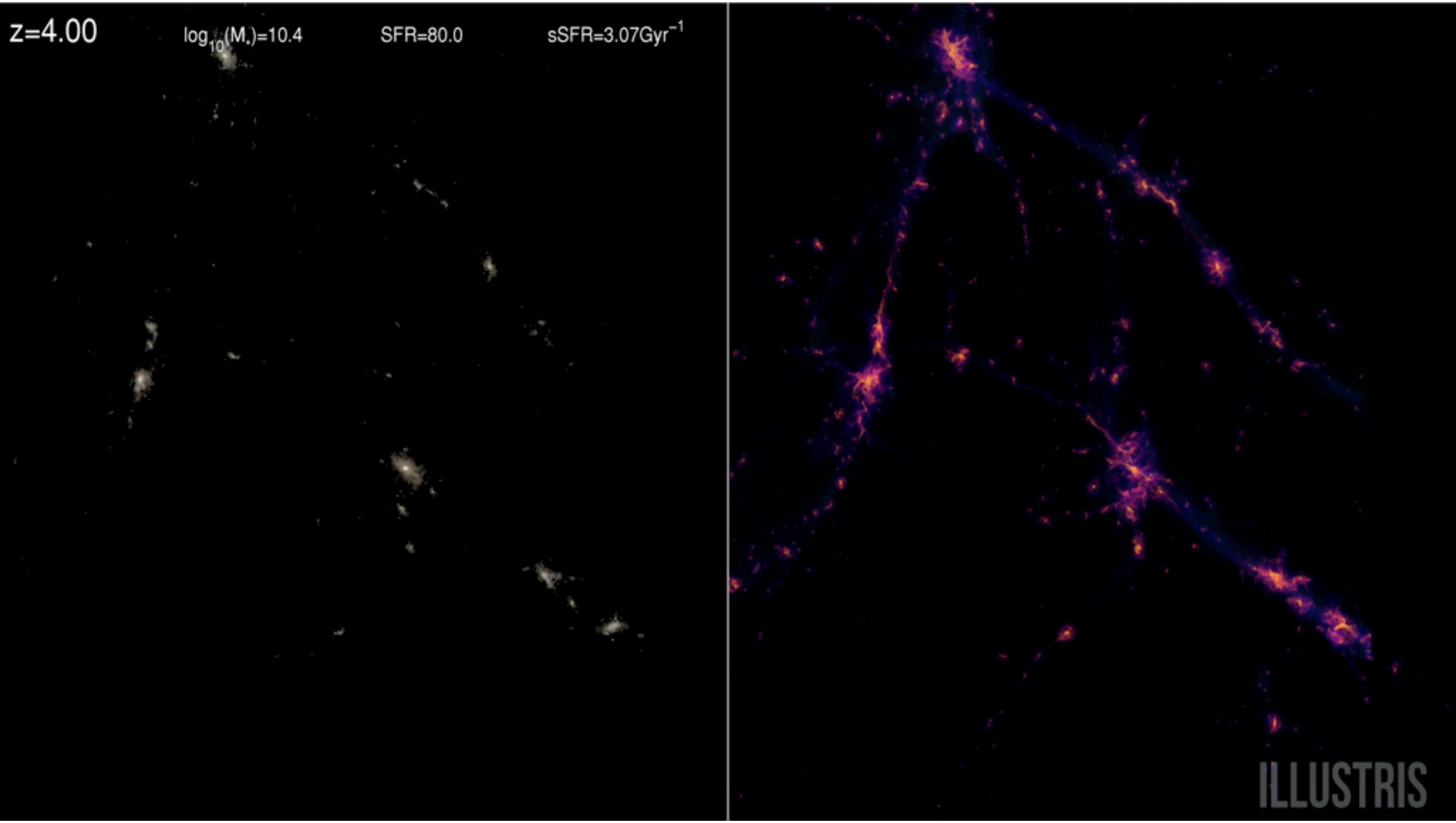
Have the advantages of both AMR & SPH

cf., DISPH (Saitoh & Makino '13; Hopkins '13) and GIZMO (meshless FV; Hopkins'14)



http://www.illustris-project.org/

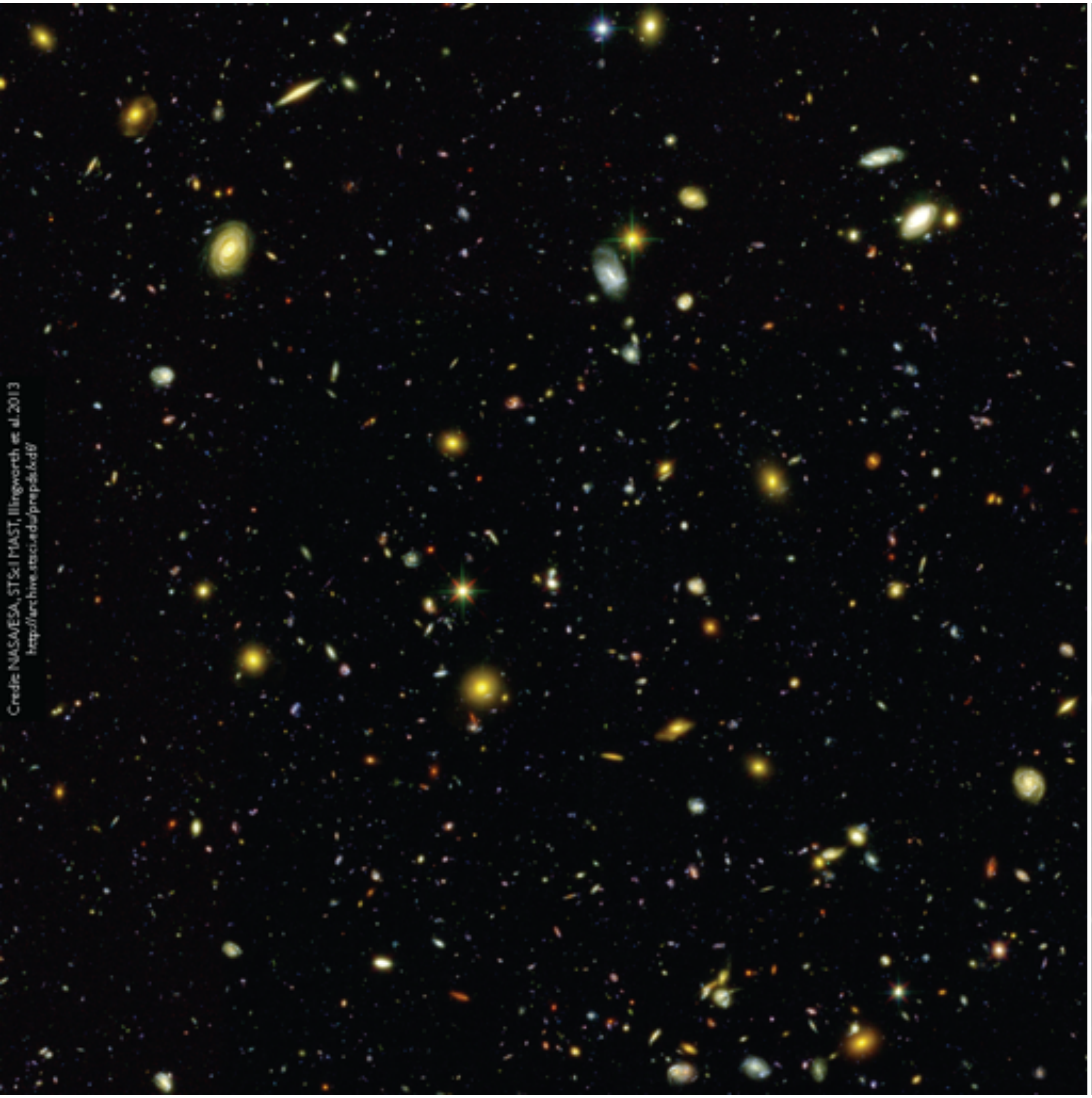
Stellar Light | Gas Density

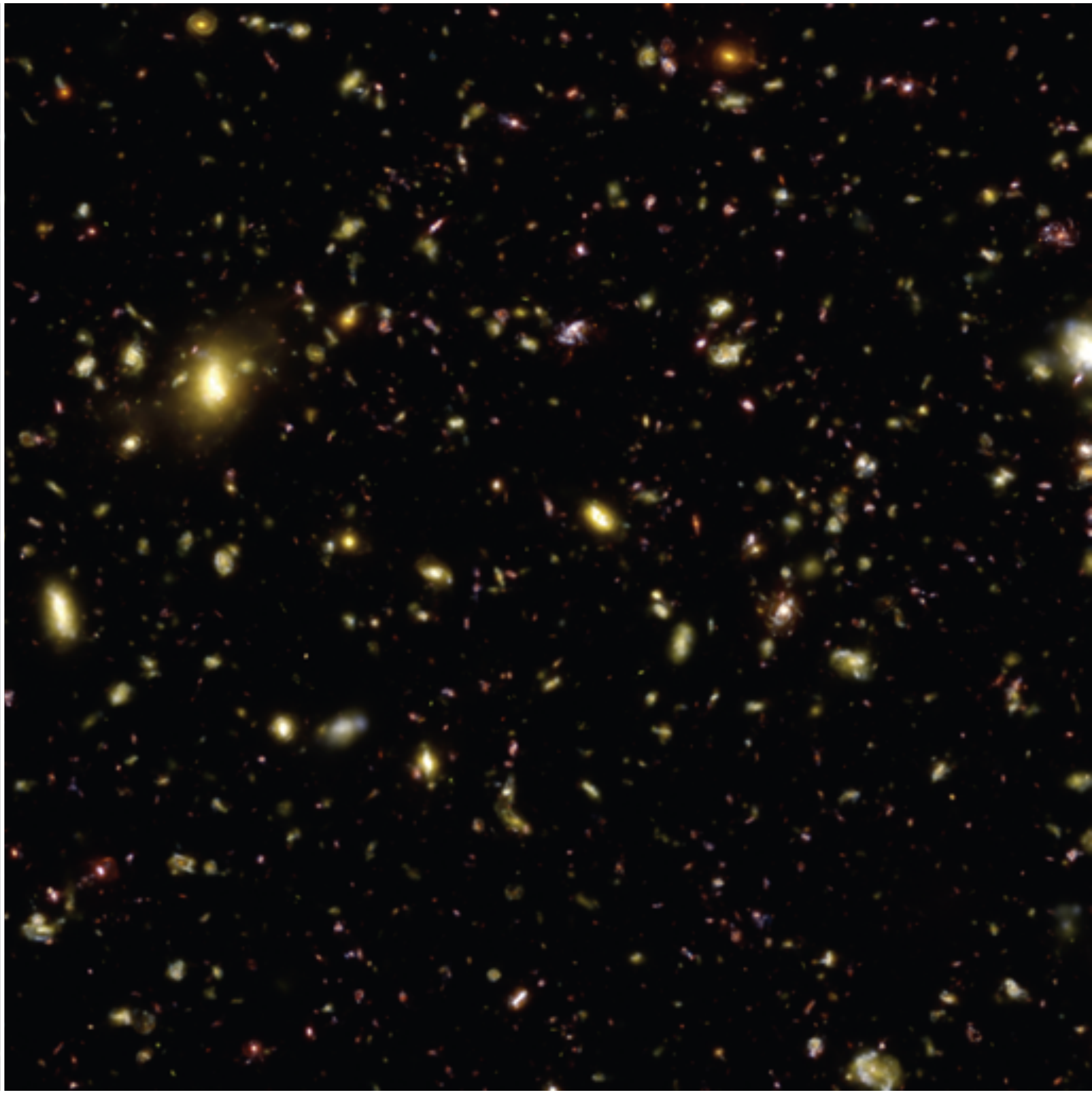


Formation of massive elliptical, “red & dead” gal.


ellipticals
disk galaxies
irregular

Which is the true HUDF observation?





Conclusions & Future

- `*Computational Cosmology*' provides useful insights for ***nonlinear structure formation***
- *Both* full-box & zoom-in cosmo runs are useful.
- ***Star Formation & Feedback*** (from MS, SN & BHs) remains to be the key → *Radiation Hydro Sims. w/ dust & metals*
- Remaining challenges: gal color bimodality, downsizing (gal & AGN), gal-SMBH coevolution, reionization history, Hubble sequence, metal enrichment, dust.

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