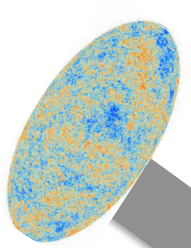
Cosmological Simulations of High-redshift Galaxies in the Epoch of Reionization

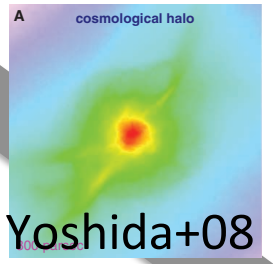
Hidenobu Yajima (Tohoku University)

Ultimate-Subaru Science Workshop 2016

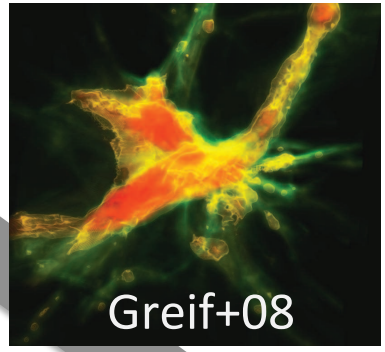
Galaxy evolution



First Stars/Galaxies



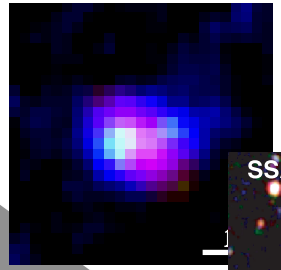
Yoshida+08

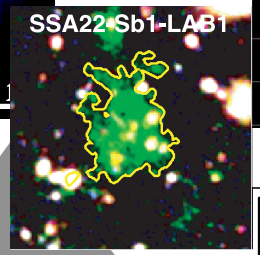


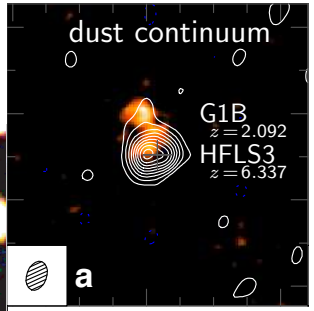
Greif+08

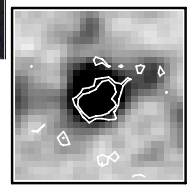
z = 10 ~ 20

LAEs, LABs, LBGs, SMGs, pBzK







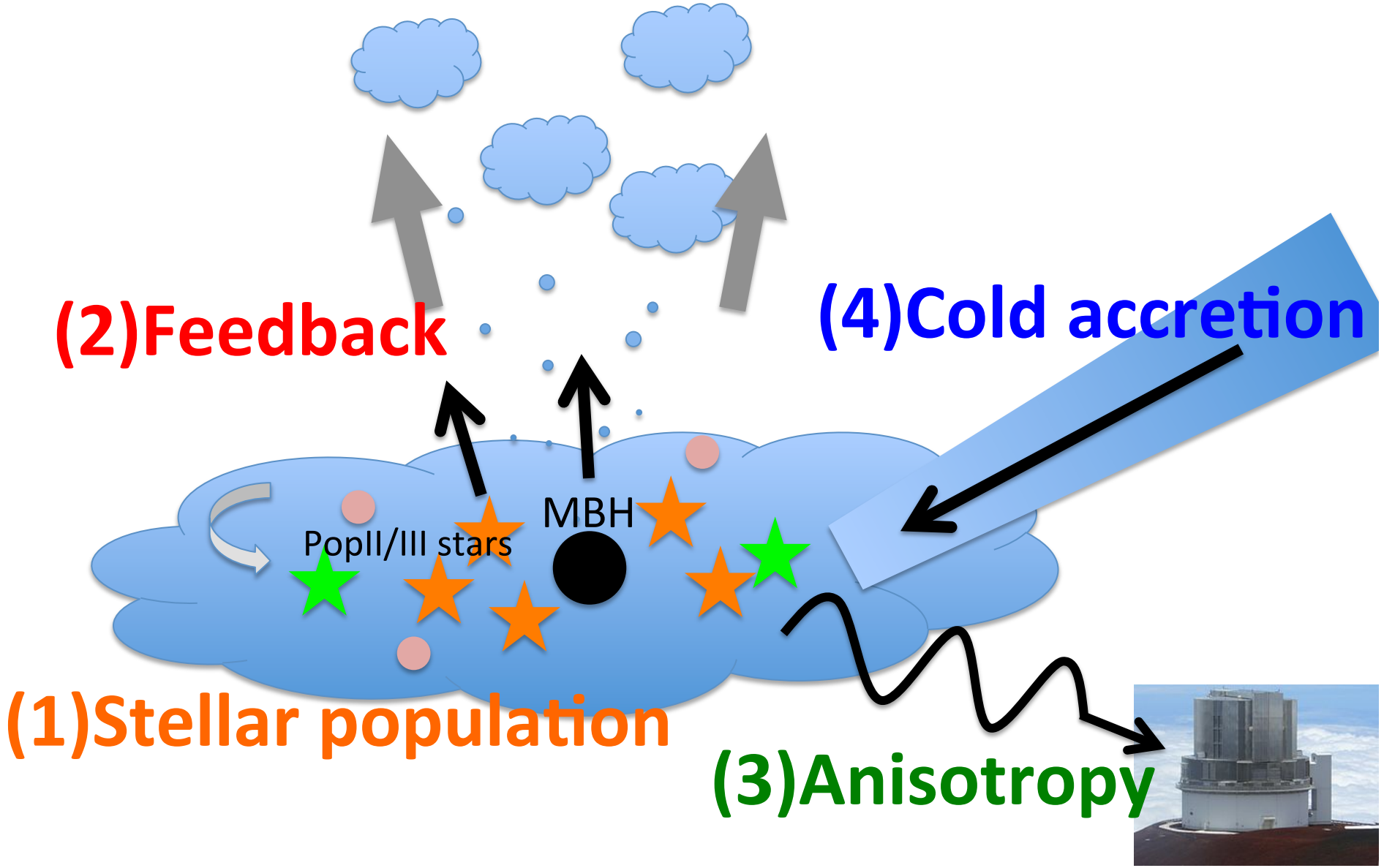


How did first galaxies form and evolve to LAEs, LBGs or SMGs?

What is the origin of the diversity of galaxies at z=3~7?

z = 3 ~ 7

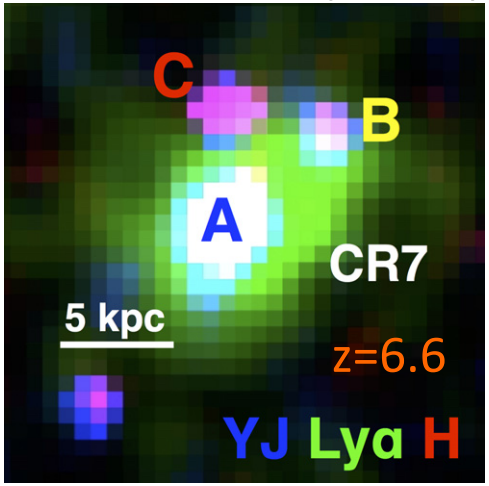
Key items

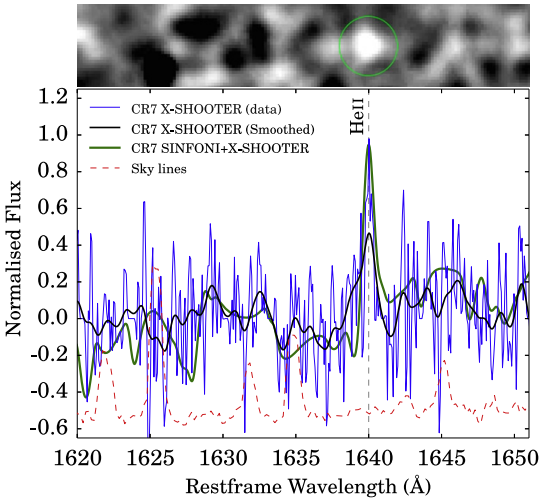

(2)Feedback
(4)Cold accretion
MBH
PopII/III stars
(1)Stellar population
(3)Anisotropy

(1) Stellar Population/Very high-z objects

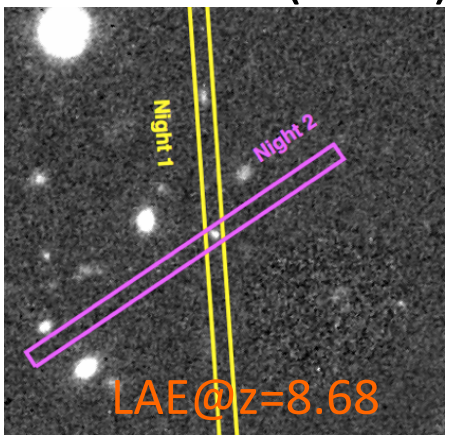
Population III-dominated galaxies/LAEs

Sobral et al. (2015)





Zitrin et al. (2015)

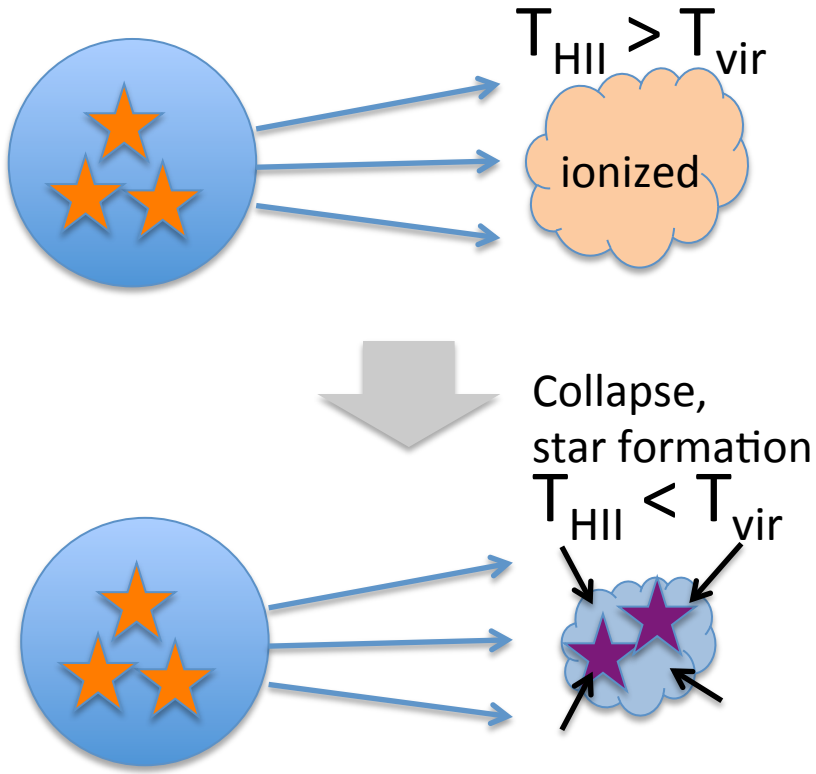


HeII line : 1640 Å
Lya: 1216 Å

e.g.,
NB1244, NB1261, NB1292, NB1326,
NB1630, NB1875
->
LAEs @ z=9.2, 9.4, 9.6, 9.9, 12.4, 14.4
HeII emitters @ z=6.6, 6.7, 6.9, 7.1, 8.9, 10.4

Condition for the massive PopIII starburst

e.g., Visbal et al. (2016)



Collapse of haloes has to be suppressed due to photo-ionization

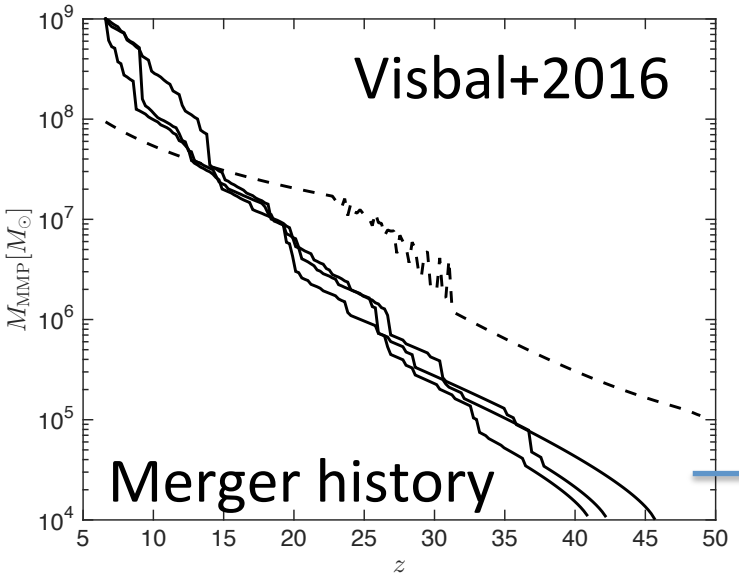
Then, they collapse when $T_{HII}<T_{vir}$ and cause star burst

Number density

Massive PopIII star cluster with $M_{*,popIII}$~10^7Msun (like CR7)

L_{lya}~10^{44} erg/s, L_{HeII}~0.2xL_{lya} -> NB_{AB}(HeII) ~24 mag @z=6.6

Survey with NB_{AB}~27 mag allows us to detect HeII line from Pop III-dominated galaxies with $M_{*,popIII}$~5x10^5 Msun



Critical distance

$$\dot{N}_{\rm ion}\frac{\pi r_{\rm vir}^2}{4\pi D^2} > \frac{4\pi r_{\rm vir}^3}{3}\alpha_{\rm B} n_{\rm H}^2 + \pi r_{\rm vir}^2 D \alpha_{\rm B} n_{\rm IGM}^2 C$$

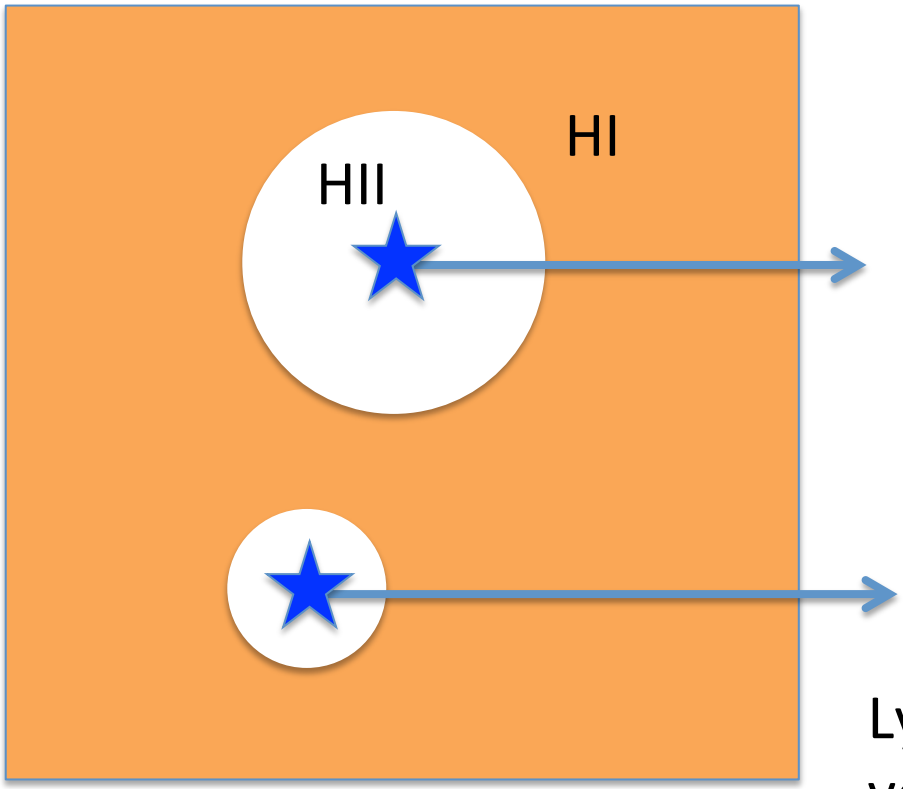
$$D < 73\,{\rm kpc}\left(\frac{f_{\rm esc}^{\rm ion}}{0.1}\right)\left(\frac{\rm SFR}{10\ {\rm M}_\odot\ {\rm yr}^{-1}}\right)\left(\frac{M_{\rm h}}{10^9\ M_\odot}\right)^{-1/3}\left(\frac{1+z}{8}\right)^{-5}$$

Number density of Pop III-dominated galaxies: N ~ 10^{-6} Mpc^{-3}

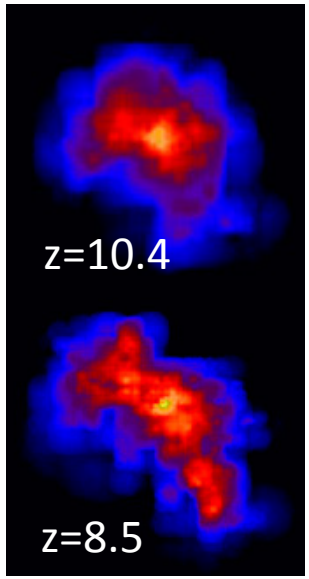
Survey around bright LBGs at z>6 may detect HeII emitters efficiently

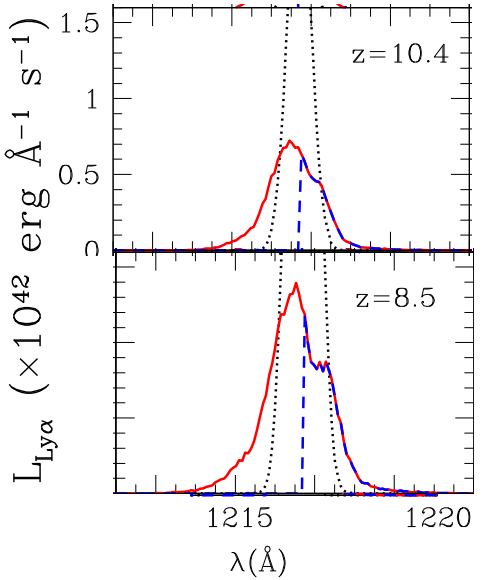
Can LAEs be detectable at z>9?

In order to detect Lya line from very high-z galaxies, they have to be in giant HII bubbles



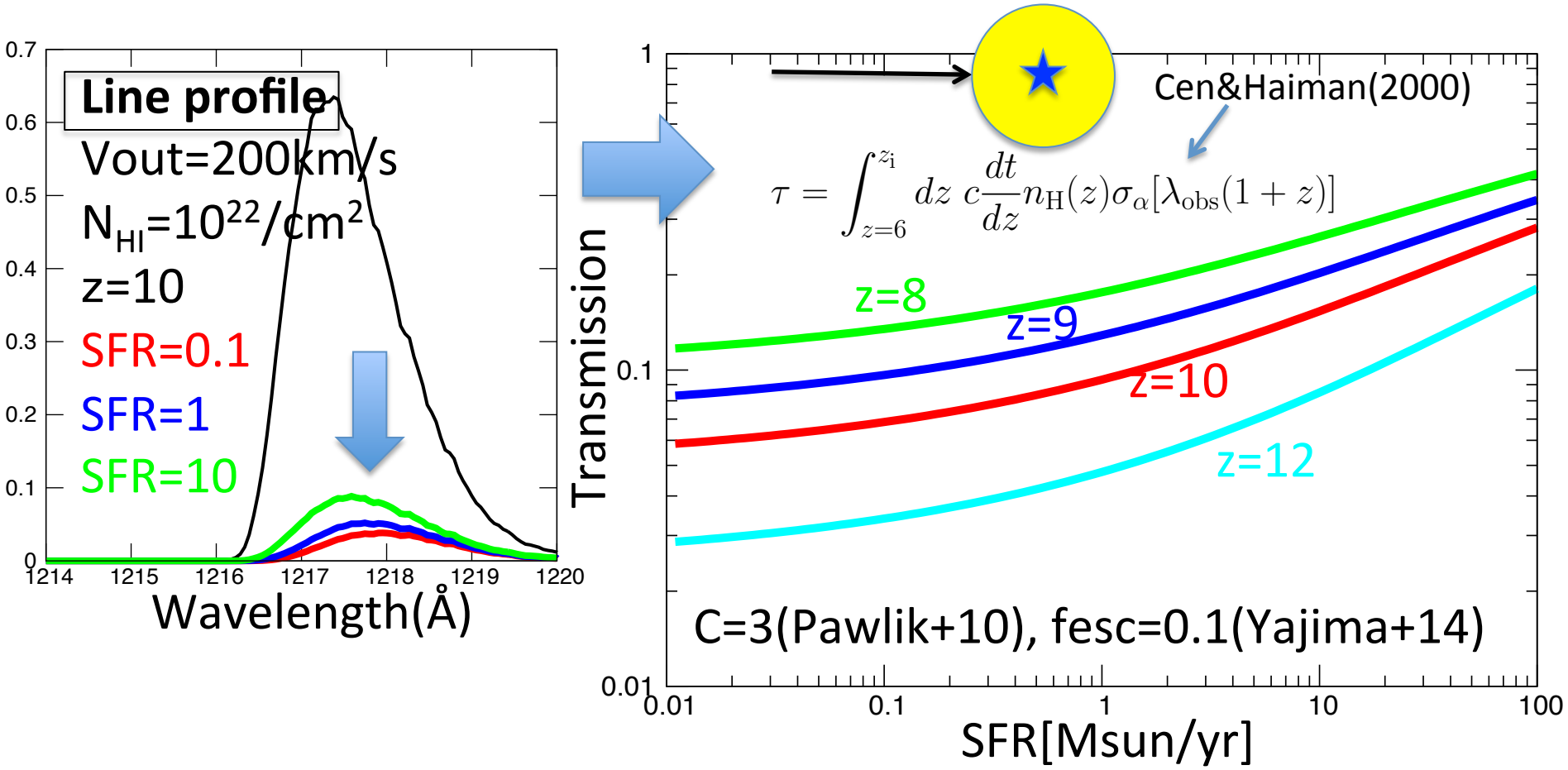
Yajima et al. (2015)





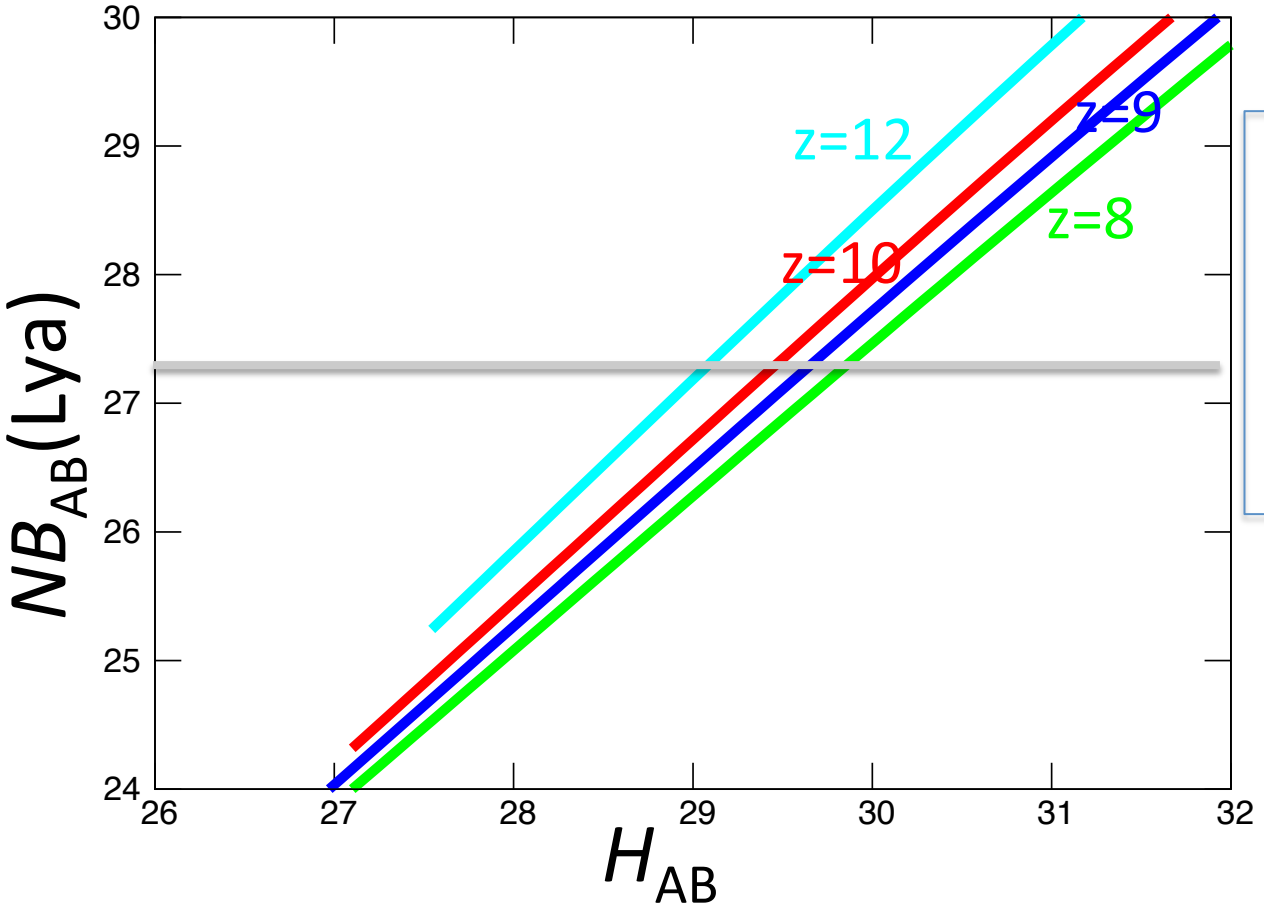
Lya flux can penetrate IGM even at very high-z?

IGM transmission



Due to own HII bubbles, Lya flux of a few % ~ 10% can penetrate IGM?

Can SSP survey detect LAEs at z~10?



Note: this is an optimistic case assuming the radius of HII bubble reaches Stromgren radius, fesc(Lya)=1.0, and line profile is outflow type

ULTIMATE SSP survey may detect Lya lines from bright galaxies of H_{AB} <~ 29.5 at z~10

N_{LBG}(z~9, H<27)~10^{-3}/Mpc^3(Bouwens et al. 2014) ➔ ≥1000LAEs at z~9-10

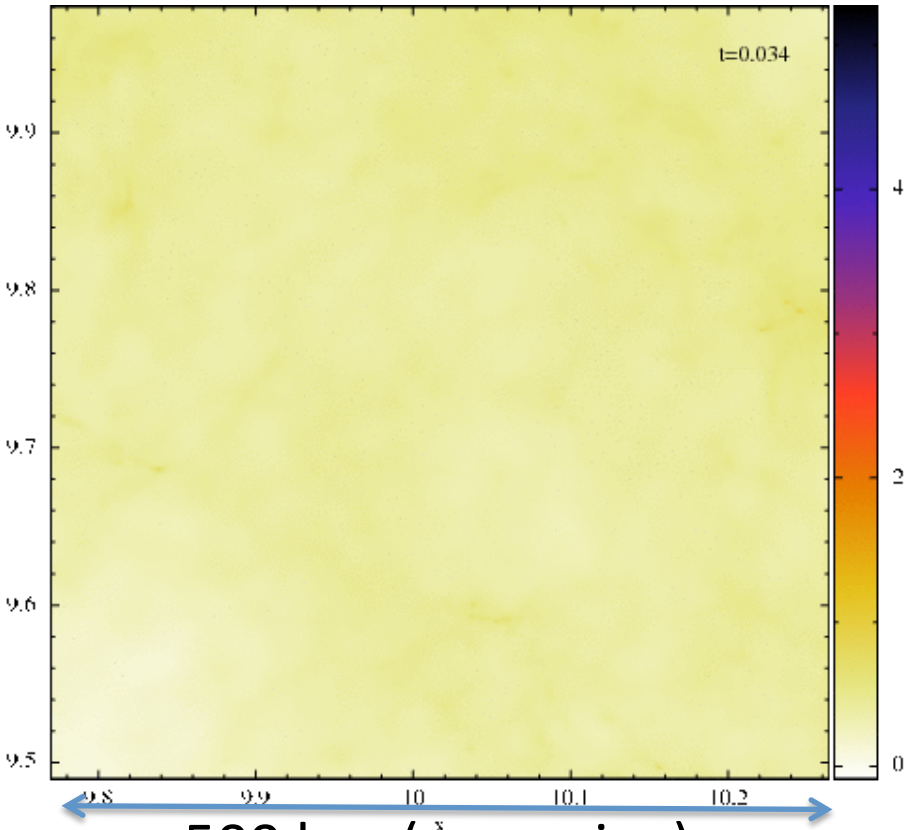
The survey may also constrain the size of HII bubbles before SKA era!?

(2) Feedback

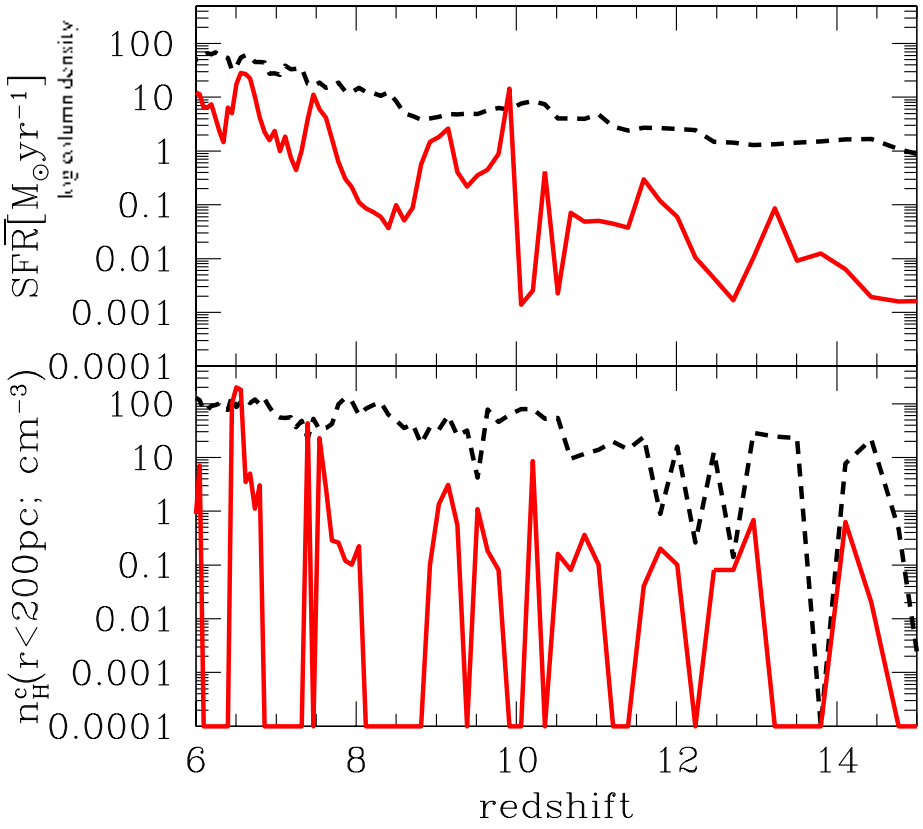
Formation of first galaxies

Cosmological simulations of first galaxies with stellar feedback

(Mh=2x10^{11} Msun at z=6)

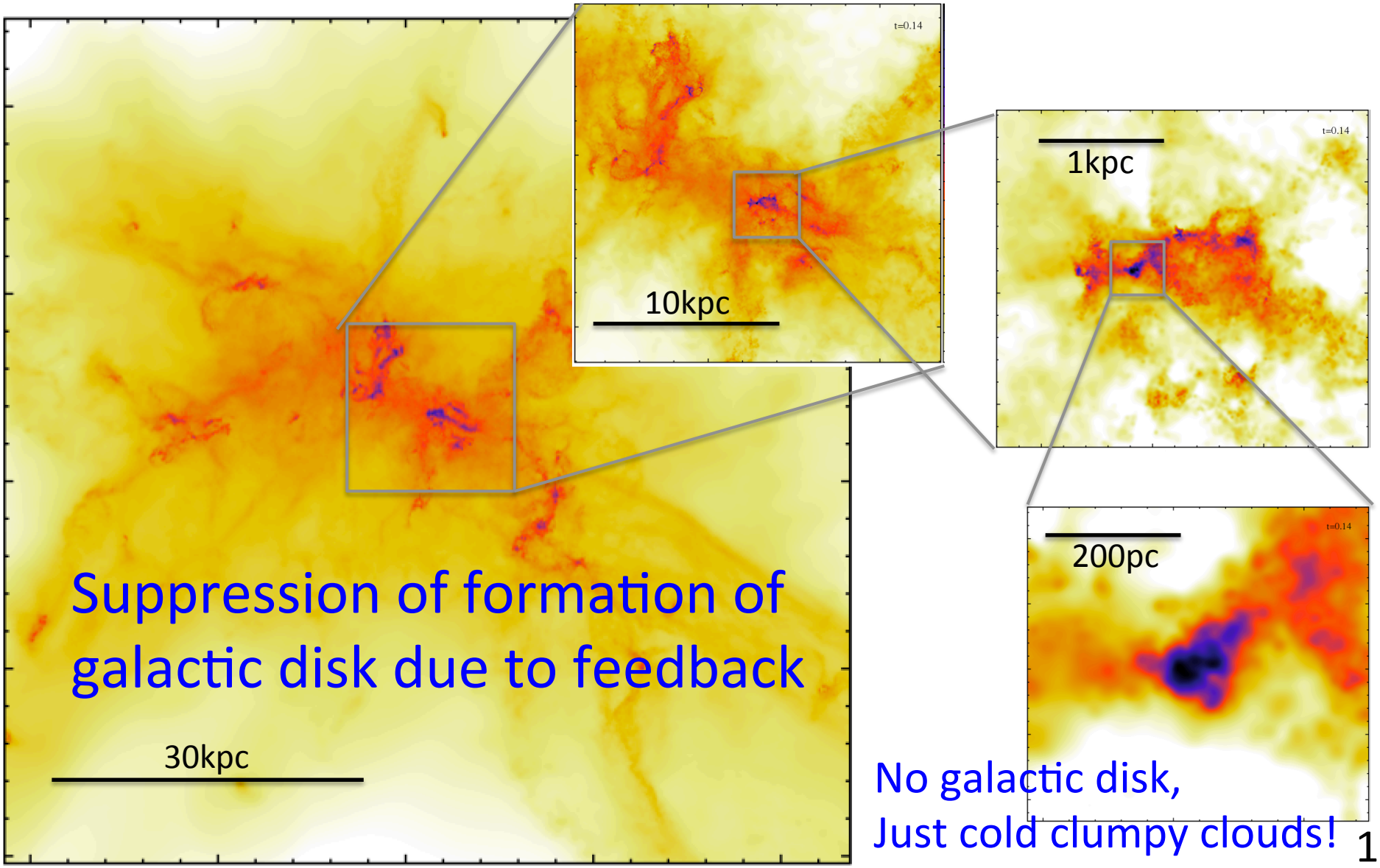


500 kpc (comoving)
~2x Rvir



(Yajima et al. in prep.)

Clumpy structure



Gravitational Force vs. Feedback

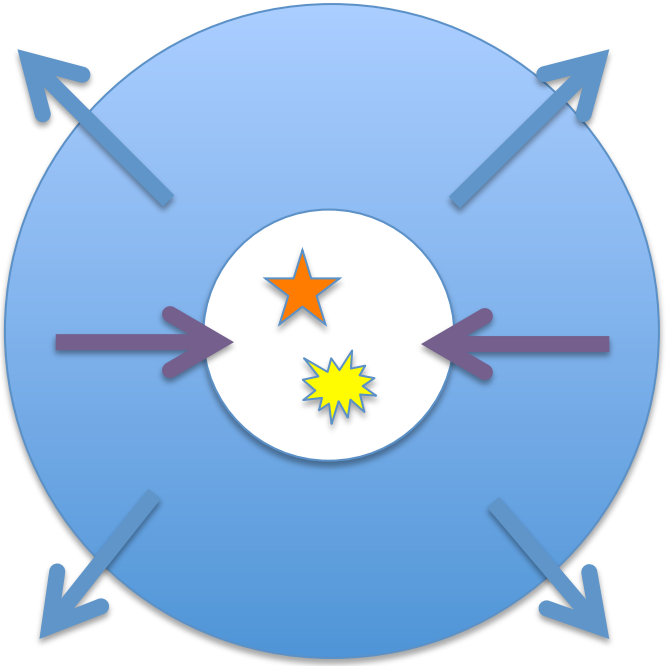
1D spherical shell model

$$\mathrm{SFR} = \epsilon_{\mathrm{SF}} \frac{M_{\mathrm{h}} f_{\mathrm{gas}}}{t_{\mathrm{dyn}}}$$

$$f_{\mathrm{conv}}^{\mathrm{SN}} \sim 2 \times 10^{33}\ f_{\mathrm{SN}}\ \mathrm{dyn}/[\mathrm{M}_\odot\ \mathrm{yr}^{-1}]$$

$$F_{\mathrm{SN}} = f_{\mathrm{conv}}^{\mathrm{SN}} \times \left(\frac{\mathrm{SFR}}{1\ \mathrm{M}_\odot\ \mathrm{yr}^{-1}} \right)$$

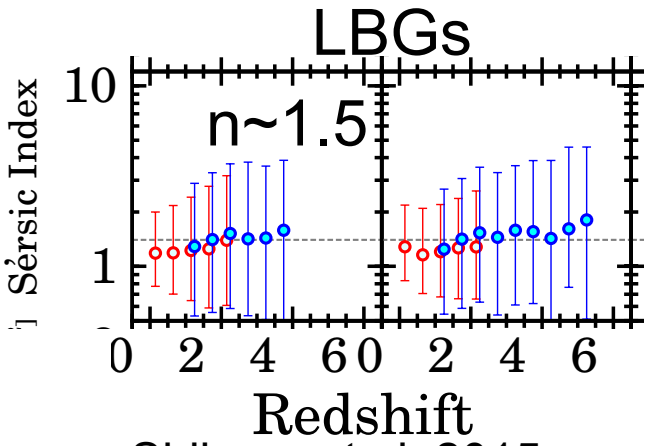
$$F_{\mathrm{grav}} \sim \frac{\mathrm{G} M_{\mathrm{h}}^2 f_{\mathrm{gas}}}{R_{\mathrm{vir}}^2}$$



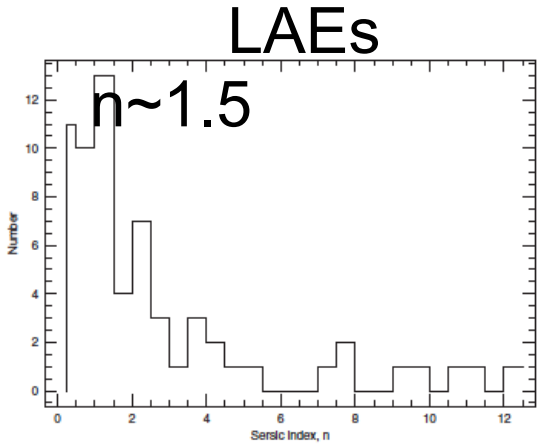
$$M_{\mathrm{crit}} = 4.4 \times 10^{11}\ \mathrm{M}_\odot \left(\frac{\epsilon_{\mathrm{SF}}}{0.1} \right)^3 \left(\frac{f_{\mathrm{SN}}}{20} \right)^3 \left(\frac{1+z}{11} \right)^{-3/2}$$

~Halo mass of LAEs and LBGs?
(e.g., Kashikawa+2006; Ouchi+2010)

Do LAEs and LBGs have disks?



Shibuya et al. 2015



Gronwall et al. 2011

LAEs/LBGs @z~2-6 might be star-forming disk galaxies
Faint LAEs/LBGs (lower mass) may be in the transition phase from feedback dominated mode to stable star formation mode in disk

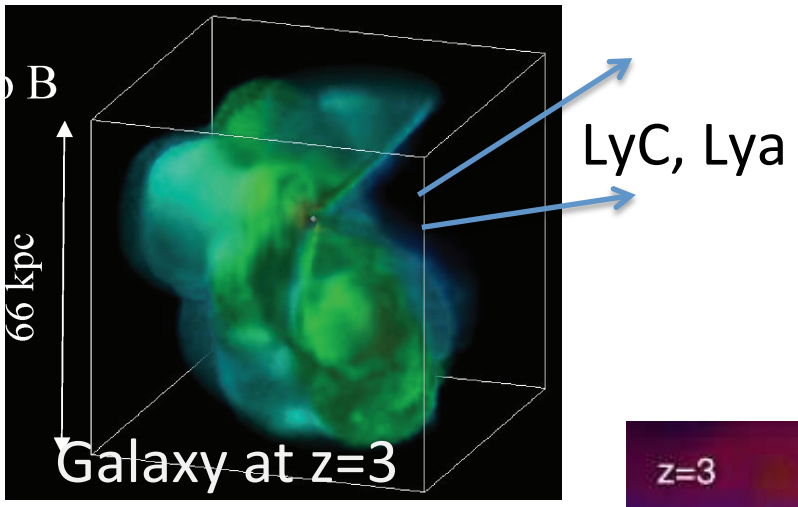
Key: Relation between stable disk formation and halo mass

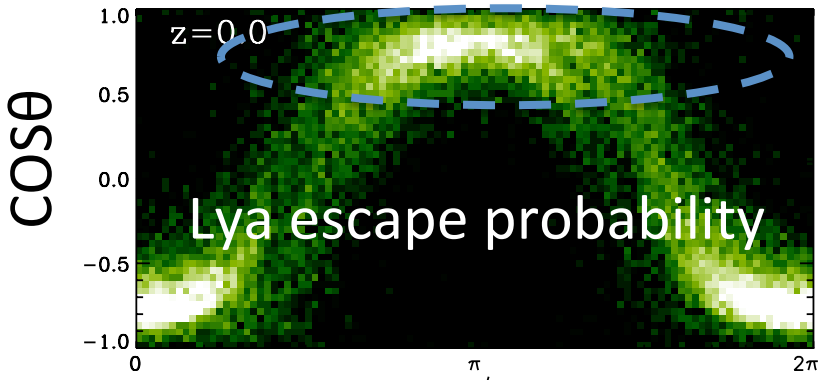
Clustering analysis + Sersic index estimated from *K*-band imaging

(3) Anisotropy

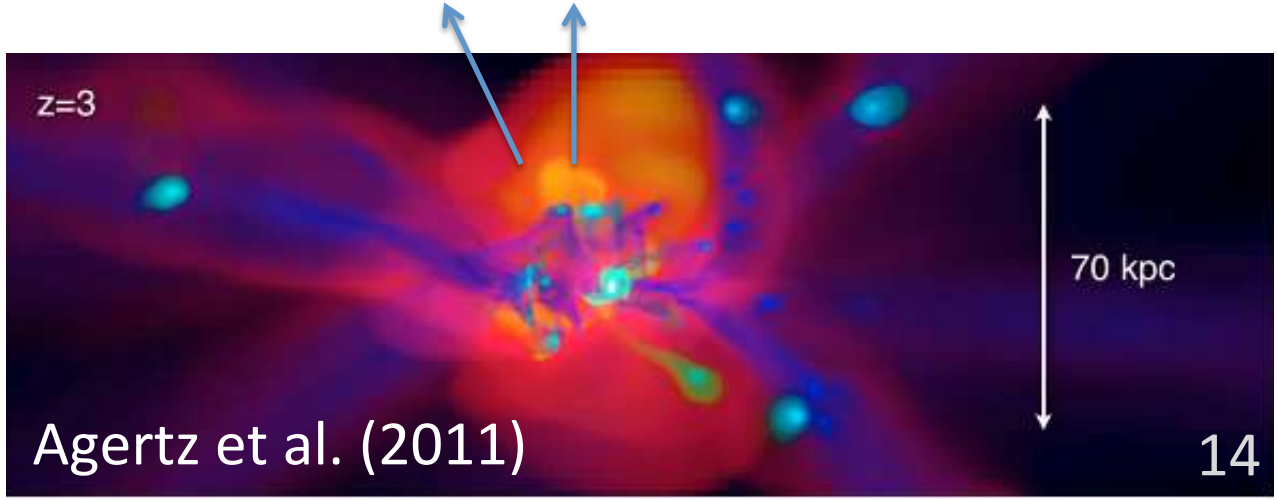
Lya and LyC emissions from galaxies are probably anisotropic

Yajim et al. (2011)



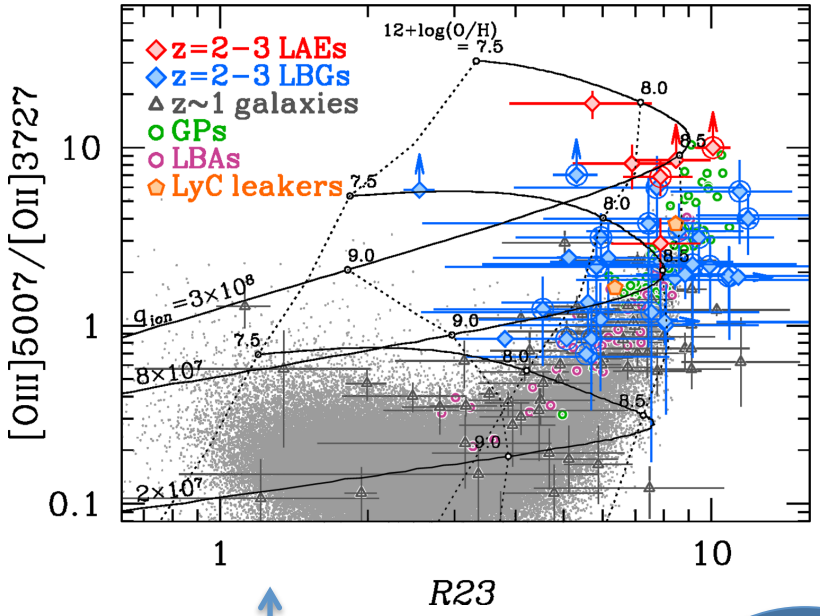


Yajima et al. (2012)



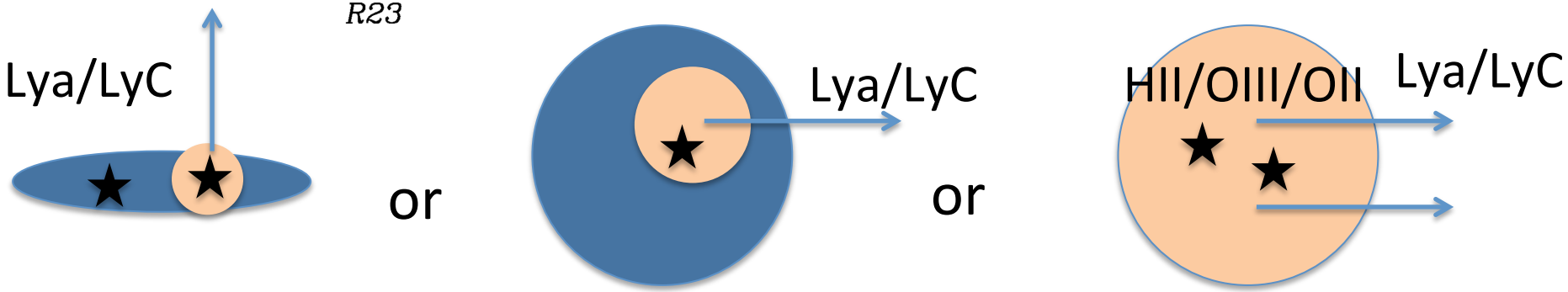
Whole ionization or ionized hole?

Nakajima&Ouchi (2014)



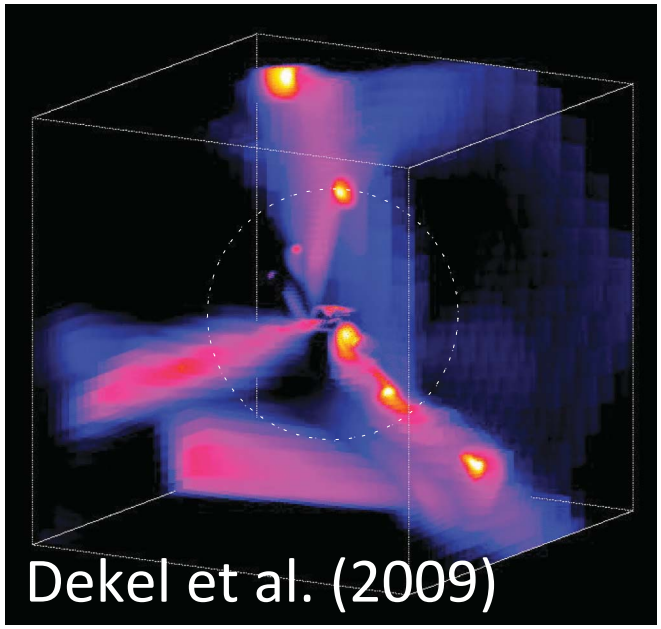
[OIII], [OII] emissions are almost isotropic -> the ionization parameter indicates mass averaged ionization degree

Lya and LyC emissions come from highly ionized galaxies or ones viewed along ionized holes, or face-on angle of disk galaxies



Relation between Lya, LyC SB and Hα, [OIII] SB should be investigated

(4)Cold Accretion



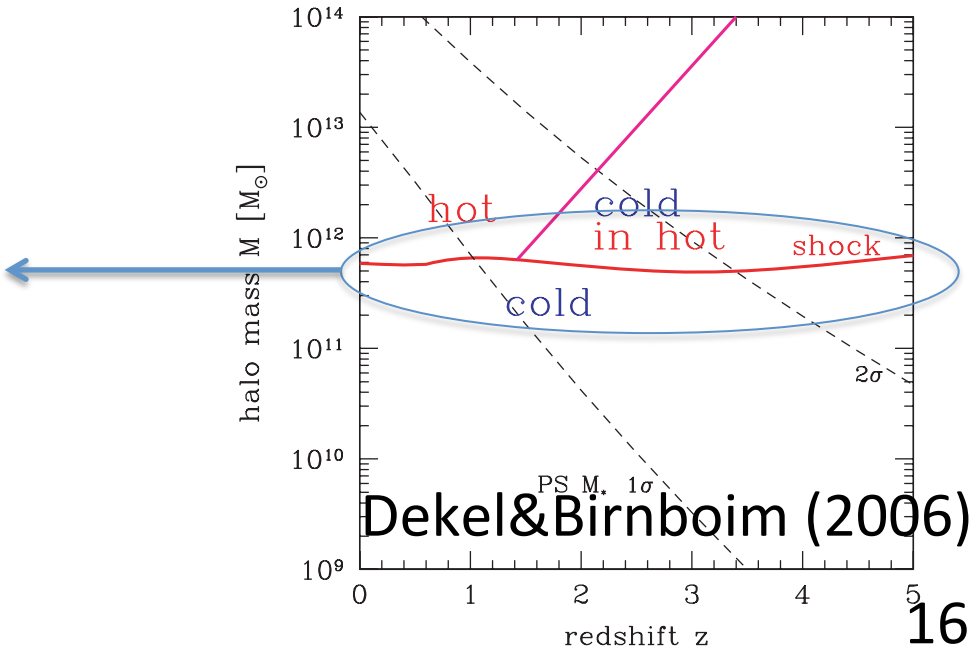
Condition for allowing cold accretion (Birnboim&Dekel 2003)

$$\frac{\rho_0 r_s \Lambda(T_1)}{|u_0|^3} < 0.0126.$$

Quantities relating with halo mass and redshift

~Halo mass of LAEs and LBGs

LAEs and LBGs may also be in the transition phase from cold to hot accretion mode



Dekel&Birnboim (2006)

Is the cold accretion important?

Maybe yes, because..

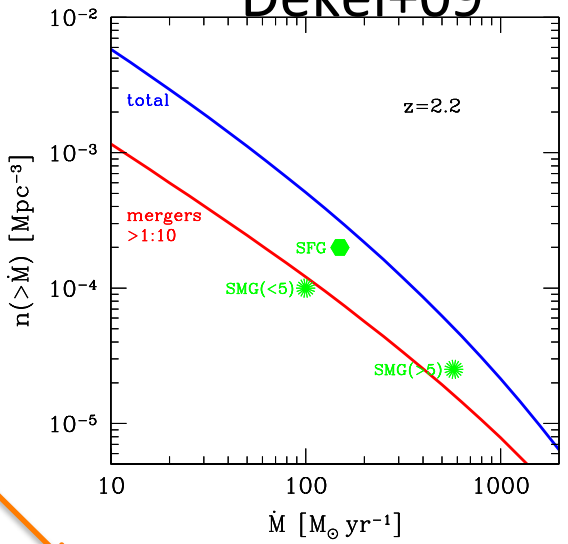
***Star burst**

***Massive disk formation**

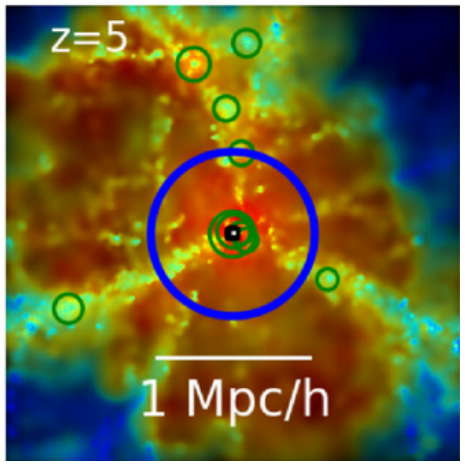
***High EW of Lya**

***Rapid growth of BHs**

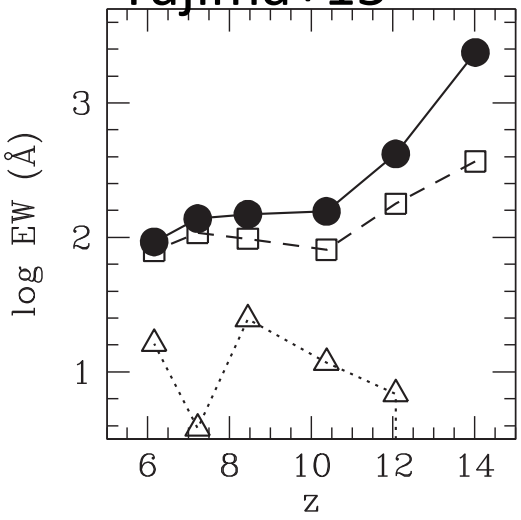
Dekel+09

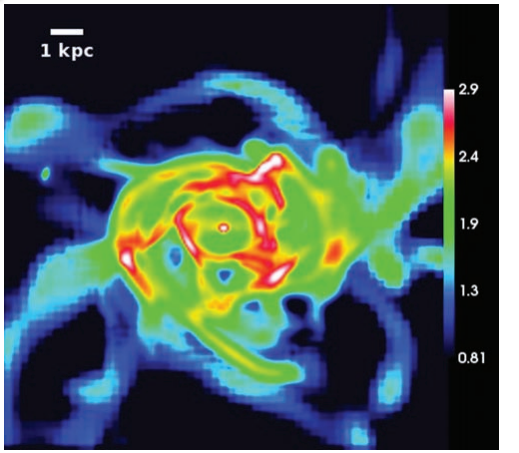


Di Matteo+12



Yajima+15

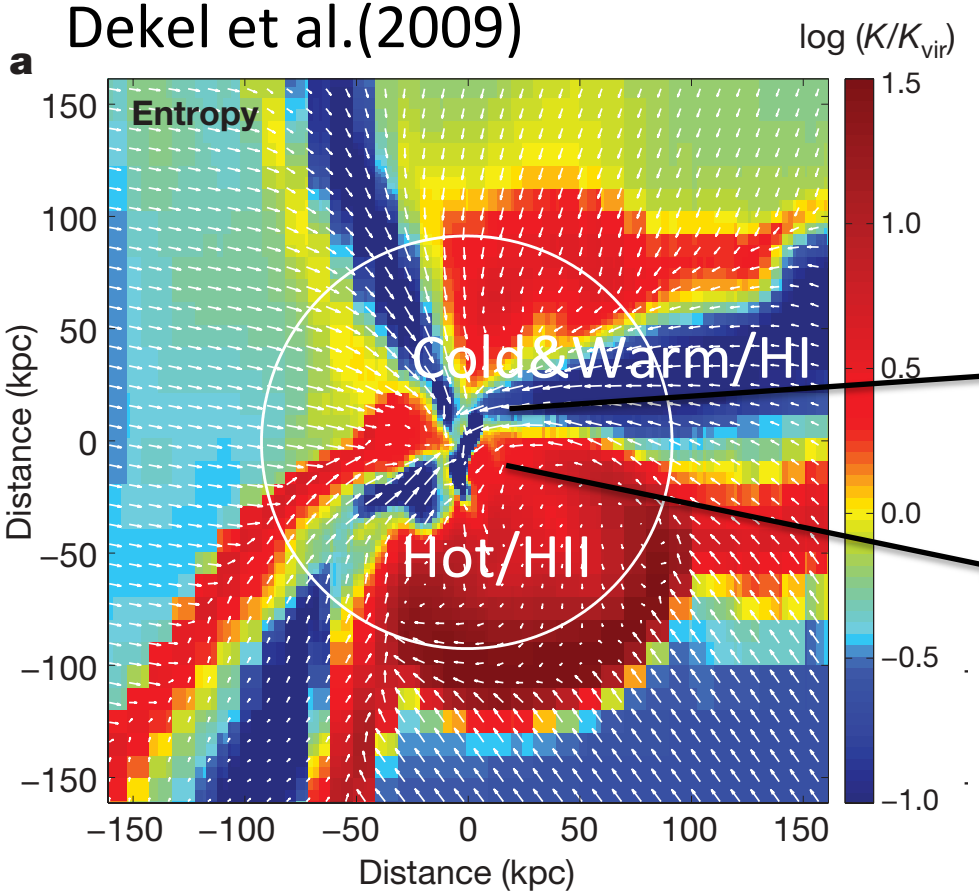




Ceverino+10

Structure of various emission lines

Dekel et al.(2009)



[CII] (ALMA), CO(ALMA), Lyα

[OIII/II], Hα, LyC, Lyα

Detailed structure of various emission lines would reveal how gas accretes onto galaxies, and star formation occurs

Questions

Q1: What do you think is the “KEY” science/observations for ULTIMATE in your research field?
A: Very high-z objects, Pop III-dominated gals, HII bubbles in IGM

Q2: Which instrument do you think is 1st priority for ULTIMATE?
A: WFC. It has potential to detect various objects over 2<z<10

Q3: Do you have good science cases to be done with GLAO +MOIRCS during the period of ~2020-2032
A: Revealing ISM with various emission lines, Lya, [OIII], LyC, and ALMA data, e.g., CO, CII, and dust continuum

Q4: Which survey design sounds best for you?
A: NB-only survey

Summary

- NB imaging surveys may be a powerful tool to search very high-redshift LAEs and HeII emitters

- Faint LAEs/LBGs are still interesting objects, because they are probably in the transition phase of different galaxy evolution modes, e.g., from SNe feedback dominated to stable star formation mode, and from cold to hot accretion mode.