再電離シミュレーションコードの開発
と初期成果

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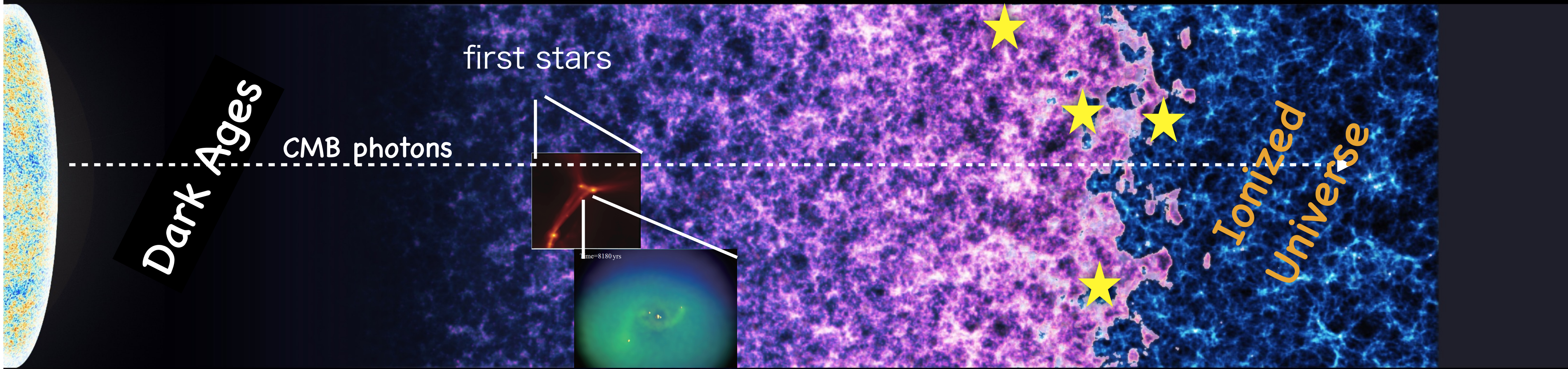
Recombination
z~1100

First Star
Formation
z~10-30

(First) galaxies
& AGN
formation?
z~10

IGM is
almost ionized.
z~6



再電離未解決問題

- いつはじまりいつ終わったか?
- 時間的空間的にどう進んだか?
- 電離光子源は何だったか?

⇔ 宇宙初期の天体形成史

再電離: 現状の理解(私見)

Question 1: 始まりと終わり

z~6ではほぼ完全電離である. 始まりは不明. 積分値(τ_e)はCMB観測から制限

Question 2: Topology

- 観: 観測的にはほとんど制限なし(clusteringから弱い制限 eg Ouchi+2010).
- 理: シミュレーションではほとんどがinside-out型を示唆(ただし、光源は星形成銀河を仮定)

Question 3: 電離光子源

- 銀河が見えているので最有力候補だが電離光子脱出割合はよくわからない.
- 初代星は理論的にはmassiveで再電離に効く可能性があるが観測的には未検出. =>SKAで検出?田中くんトーク
- ClasicalにはAGNはほとんど効かないと思われていたが、Giallongoら(2015)が多くのくらいAGNの存在を示唆(これもSKAで検出?竹内くんトーク). Giallogoの観測が本当であればAGNだけで再電離できる可能性(e.g Yoshiura, KH+)=> Topologyにも影響

研究目的

SKA：圧倒的高感度で再電離期 HI 21cm線の検出が期待=>中性水素の空間分布を3次元(x-y-z)情報を直接得られる.

時間進化はほぼ解決.しかし、Topologyや電離光子源の解明には他の観測+理論モデルが必要.

輻射輸送計算で再電離過程をシミュレートすることで観測と比較しうる理論モデルを構築

Radiative Transfer simulations

Cosmological Radiation Hydrodynamics (RHD) Simulations

- 輻射輸送と流体計算をカップルする為、高分解能計算であれば輻射による影響下での星形成率、それに伴うIGM電離過程をconsinstentに解ける. (e.g., KH, Semelin 2013)
- 計算領域を広げるのは大変なので、典型的電離史計算やPS解析、バブルカウントなどの統計的研究に不向き

Post-processing Radiative Transfer (RT) Simulations

- 小スケールの情報は潰してしまう為、比較的計算量が軽く、大きな計算領域を取りやすい(Ilievらの仕事が有名).=>大規模サーベイなどの観測と直接比較しやすい
- Feedback効果のようなややこしいものは自動的には考慮されない

輻射輸送計算

- Radiative Transfer of UV photons

- 主に電離、解離光子の輸送(加熱~10^4K, 水素分子=ガス冷却剤の破壊)
- X-rayの場合、以下の近似はそのまま成り立たないこともある

$$\frac{1}{c}\frac{\partial I_\nu}{\partial t} + \mathrm{n}\nabla I_\nu = \eta - \chi I_\nu$$

emissivity

opacity

輻射輸送方程式

(近似: 流体,光源の変動,原子の反応速度との比較、ガスからのdiffuseな放射はその場で吸収される.)

$$I_\nu(\mathrm{r}) = I_\nu(0)\exp(-\tau_\nu)$$

$$\tau_\nu = \Sigma N_{\mathrm{i}}\sigma_{\mathrm{i},\nu}$$

全ての吸収体の足し合わせ

立体角積分

化学反応率

光加熱率

輻射力

流体+化学反応式とのカップル

輻射"流体"計算

Radiation Hydrodynamics code START

SPH with Tree-based Accelerated Radiative Transfer

(KH & Umemura 2010)

- Hydrodynamics(+ Dark Matter Dynamics)

SPH (Smoothed Particle Hydrodynamics)

N-body

$$\frac{d\mathbf{v}}{dt} = -\frac{1}{\rho}\nabla p - \mathbf{g} + \mathbf{f}_{\mathrm{rad}}$$

$$\frac{du}{dt} = \frac{p}{\rho^2}\frac{d\rho}{dt} + \frac{\Gamma - \Lambda}{\rho}$$

Consistently solve Radiative transfer of UV photons from "ALL stellar particles"

- Non-equilibrium chemistry

Creation Destruction

$$\frac{dn_i}{dt} = C_i(T, n_j) - D_i(T, n_j)n_i$$

e^-, H^+, H, H^-, H_2, H_2^+, He, He^+, and He^{2+} , dust, metal

我々の数値計算戦略

小スケールの物理を考慮しつつ大領域の計算を実現し、観測の予言/比較に使用したい。

large scale *N*-body simulation data (provided by Ishiyama-san)

＋

Sub-grid models of galaxies and IGM w/ feedback (from RHD sim.)

＋

Post-processing Radiative Transfer for ionizing photons

光源モデル: 銀河ハロー質量 vs. 電離光子数(= SFRと電離光子脱出割合の積にほぼ比例), IntrinsicなLya光度の情報、(今の所使っていないが)DustからのIR放射情報

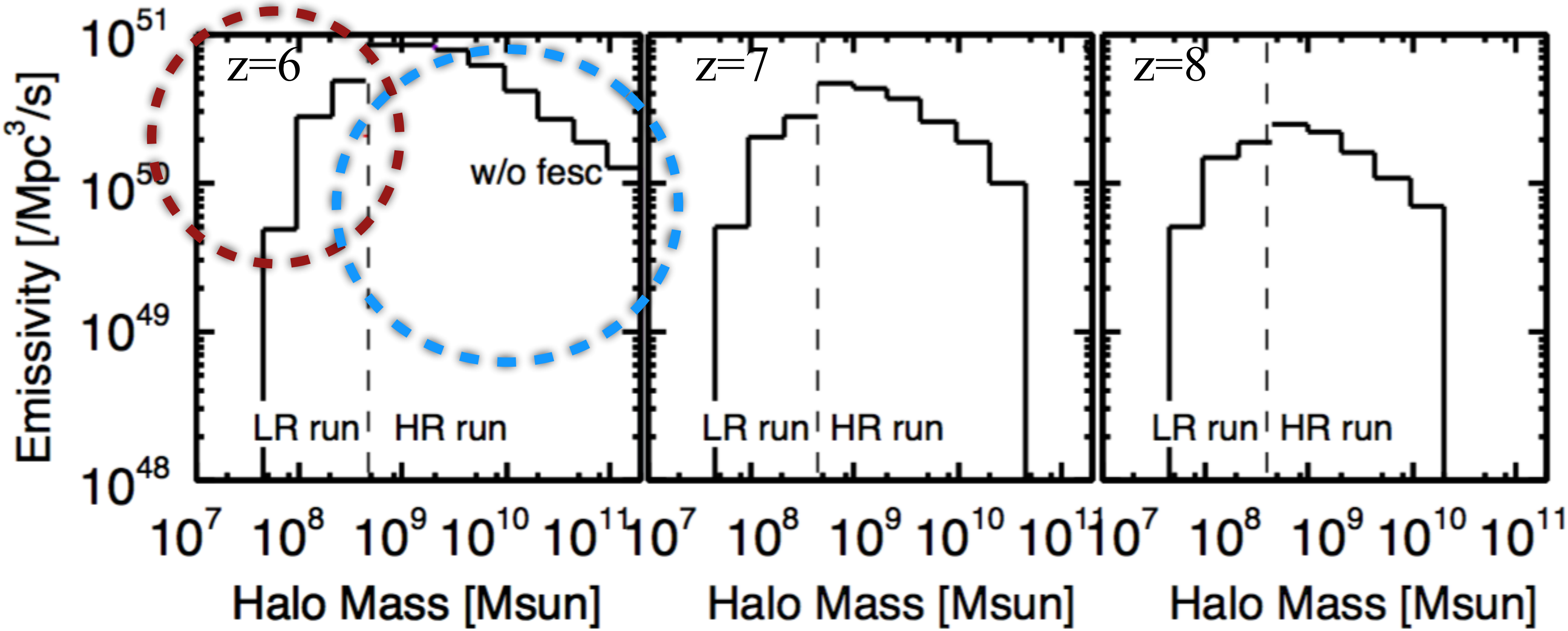
(unresolved) IGMモデル: 加熱でsmoothingされる効果込みの再結合率補正モデル

Which are galaxies responsible for reionization?

Intrinsic ionizing photon Emissivity [$Mpc^{-3}s^{-1}$]

Low-mass range:銀河はたくさんいるが、UV/SN feedbackに敏感な為、寄与は小さい

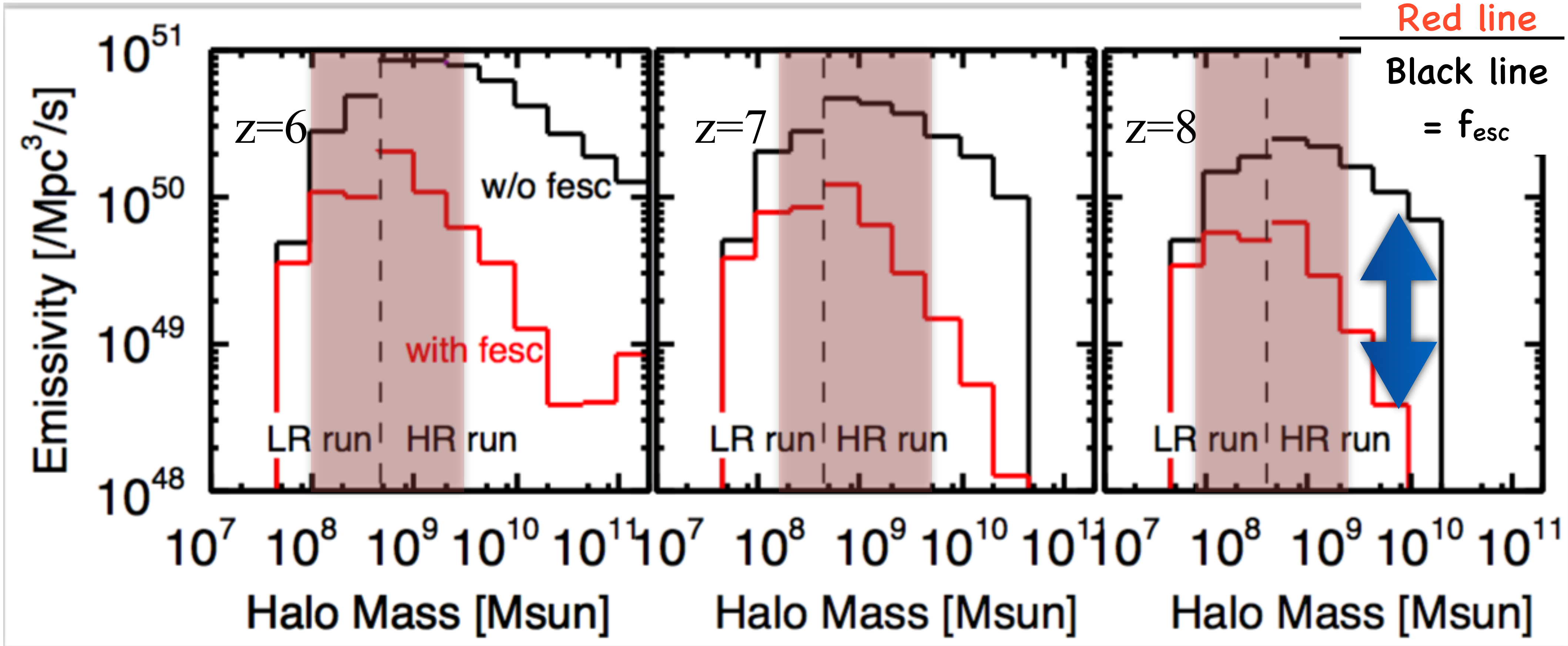
High-mass range: 大質量ほどSFRが高いが、数自体も少なくこれらが相殺



Which are galaxies responsible for reionization?

Ionizing photon Emissivity with escape fraction

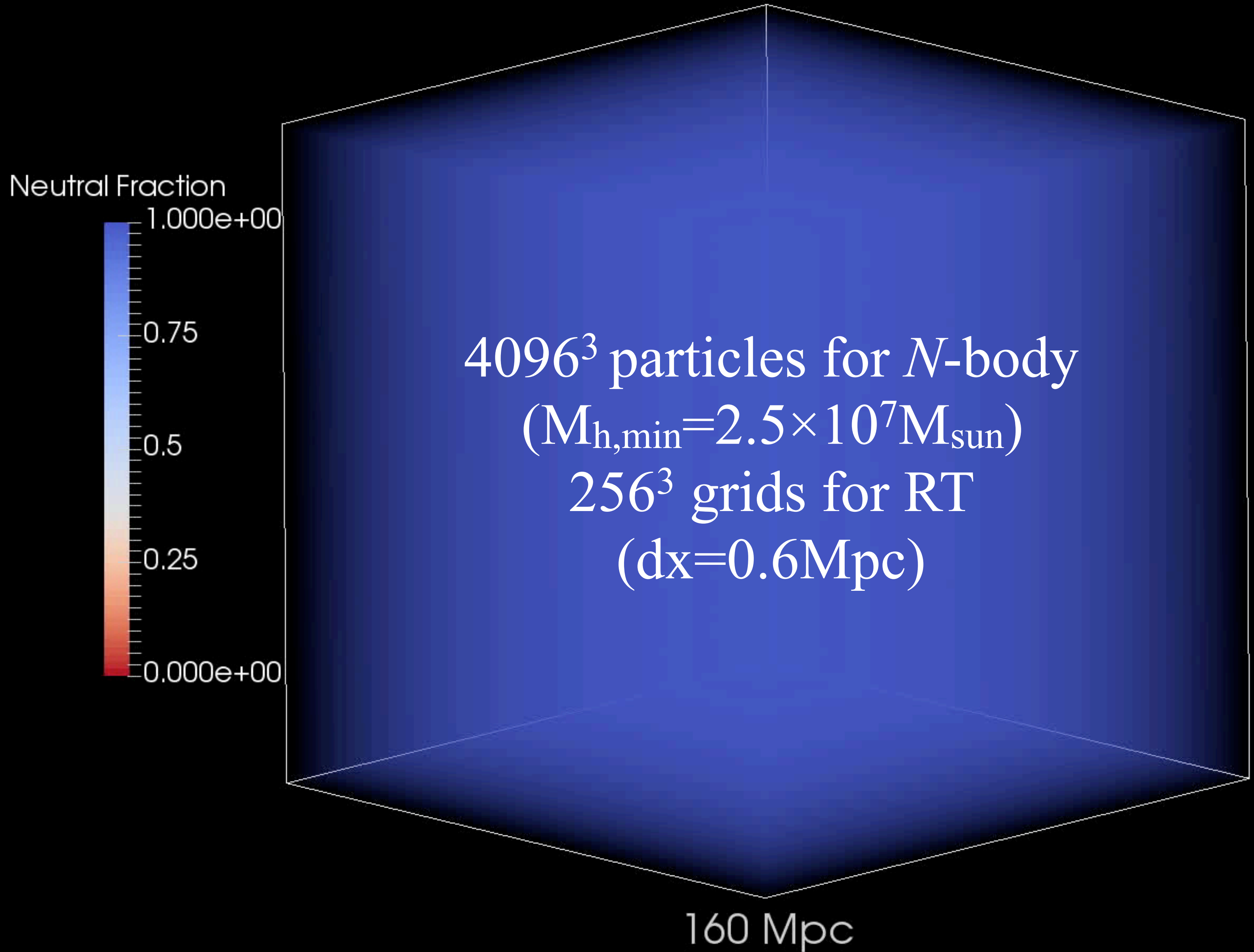
大質量ほどfescが小さく、結果として大質量銀河の寄与はさらに小さく



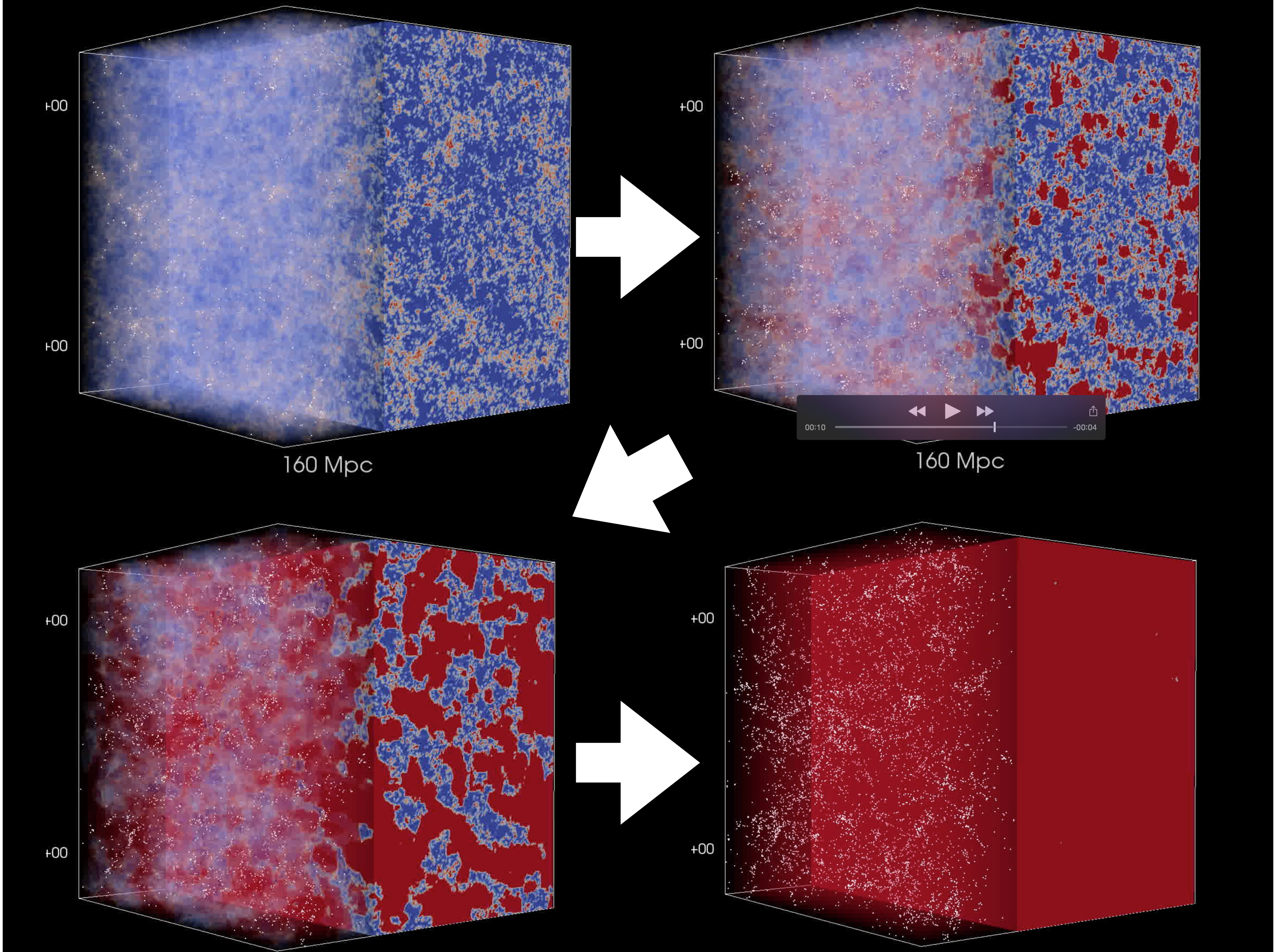
Galaxies with ~$10^9 M_{sun}$ are responsible for reionization

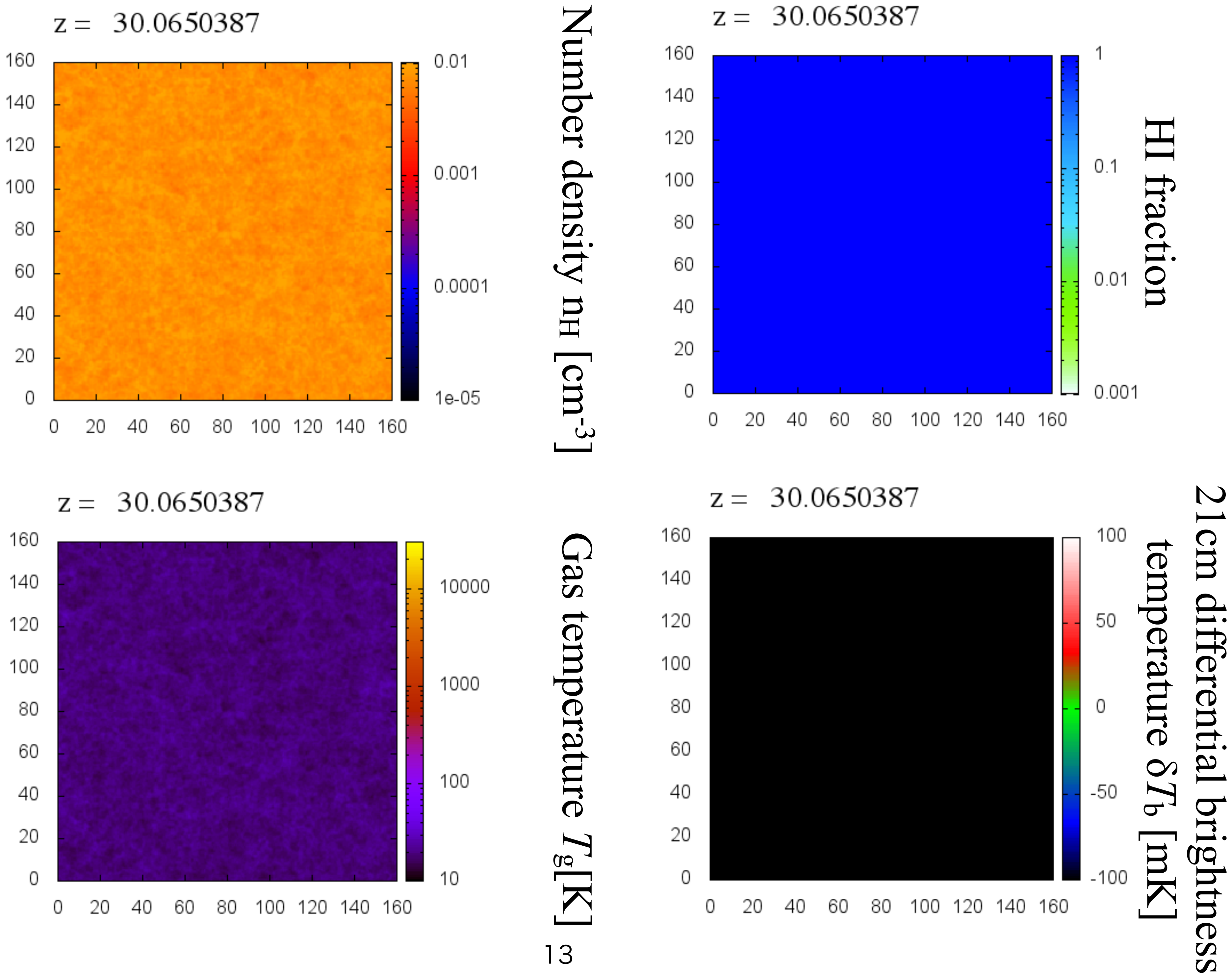
Cosmic Reionization

From z=20 to z=6



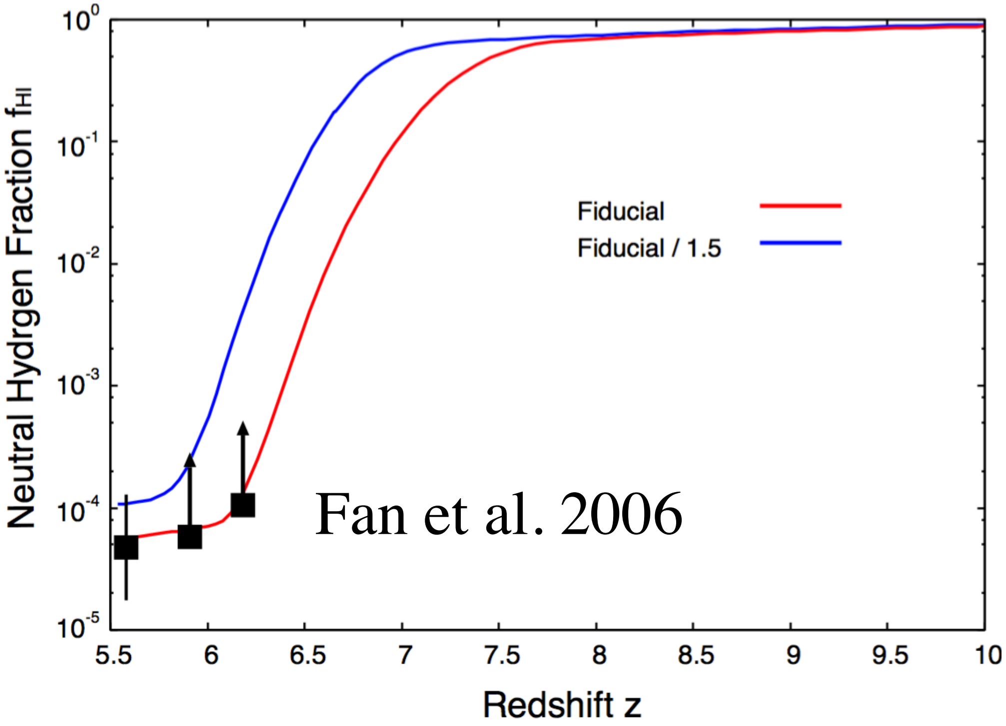
4096^3 particles for *N*-body
($M_{h,min}=2.5\times10^7 M_{sun}$)
256^3 grids for RT
(dx=0.6Mpc)


160 Mpc
00:10
-00:04
160 Mpc

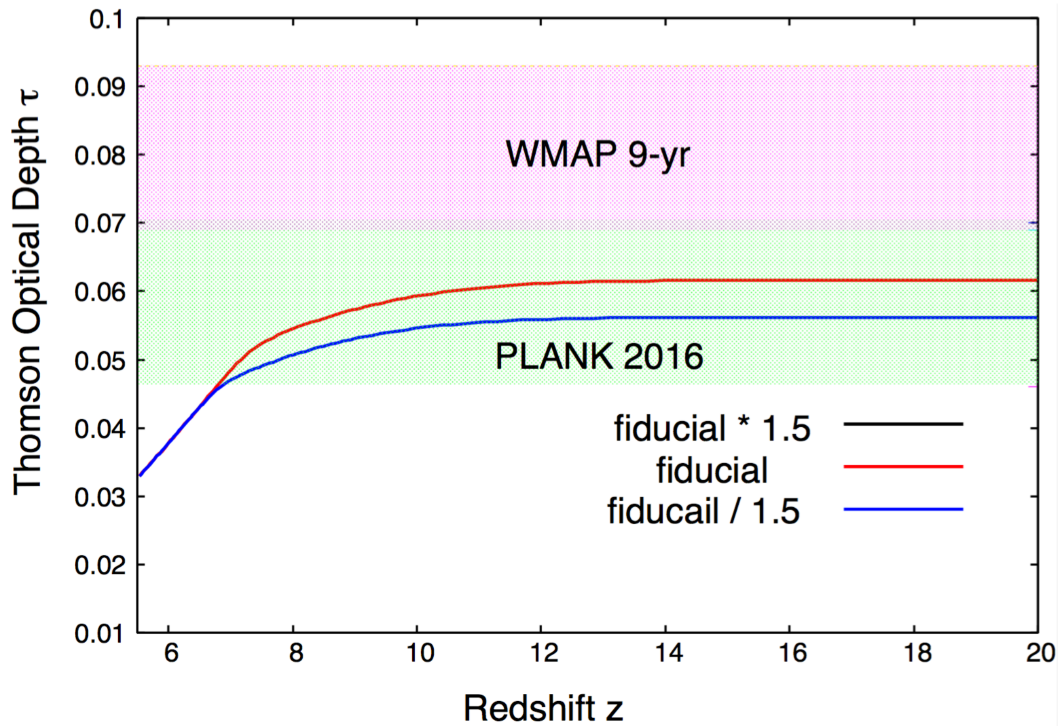

z = 30.0650387
Number density nH [cm-3]
0.01
0.001
0.0001
1e-05
HI fraction
1
0.1
0.01
0.001
Gas temperature Tg[K]
10000
1000
100
10
21cm differential brightness temperature δTb [mK]
100
50
0
-50
-100
0 20 40 60 80 100 120 140 160

Comparison : Simulations and Observations:

Constraint by QSO spectra



Thomson Opt. Depth



- 今のところ、z=6でのHI fractionやトムソン散乱の光学的的厚みなどは観測とconsistent

LAE modeling

Hyper Suprime-Cam (HSC):

=> Large Sample of high-z Lyman Alpha Emitters (LAEs)

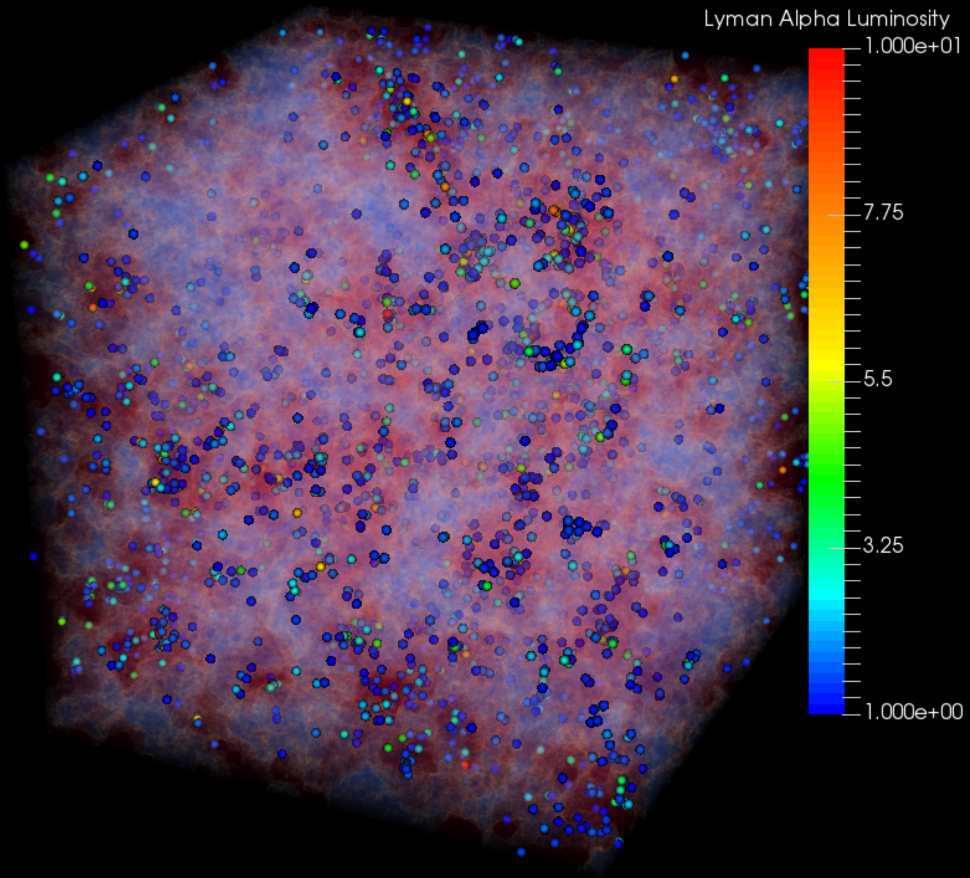
Prime Focus Spectrograph (PFS):

=> Resolve Lyα profile of each LAE

Theoretical modeling for LAEs

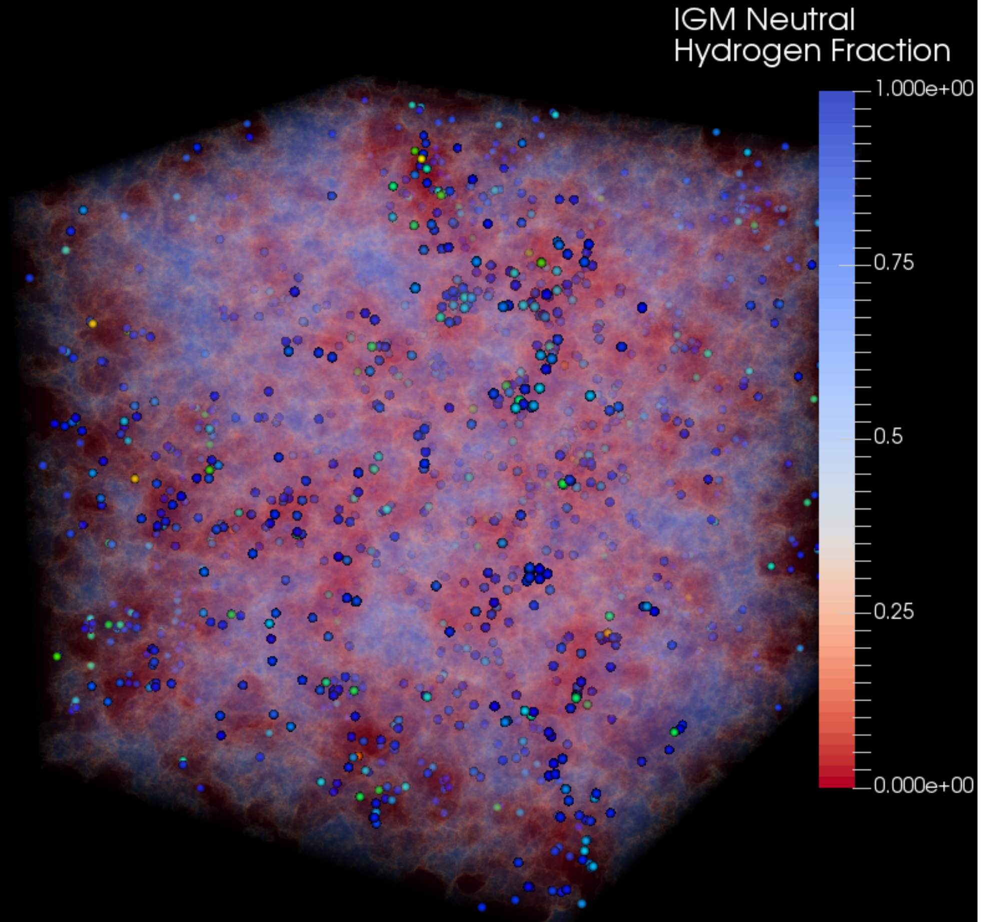
1. RHDシミュレーションの結果から直接Lya光子生成量を評価 (the recombination and collisional excitation processes in the ISM) => M_{halo}-Lα relationを取得
2. 単純な過程でLyα輻射をといてintrinsicなprofile形を計算(so far with an expanding cloud model, N_{HI}=10^{19}cm^{-2}, $v_{outflow}$=150km)
3. 再電離シミュレーションのIGM情報からすべてのLya candidatesに対してtransmissionを計算し、observableなLAEの情報を取得

Intrinsic LAEs at z=7.3



without transmission

Obserbable LAEs at z=7.3

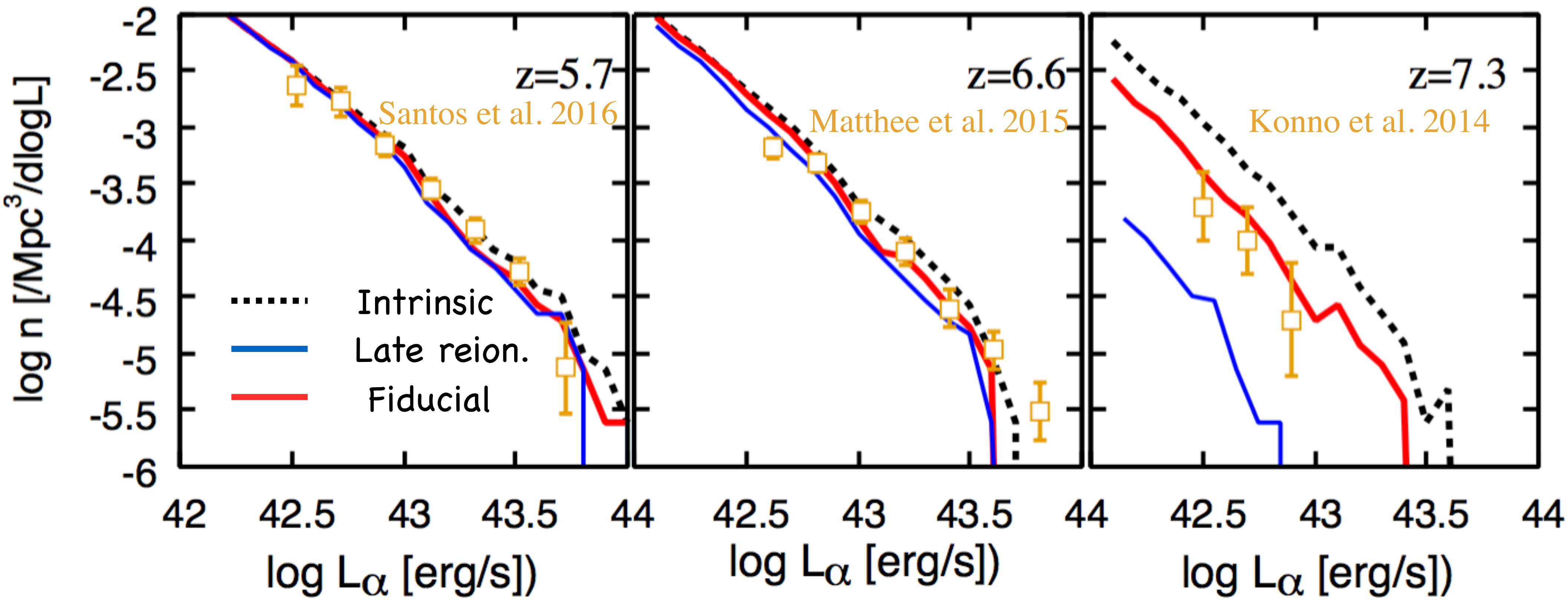


Considering transmission

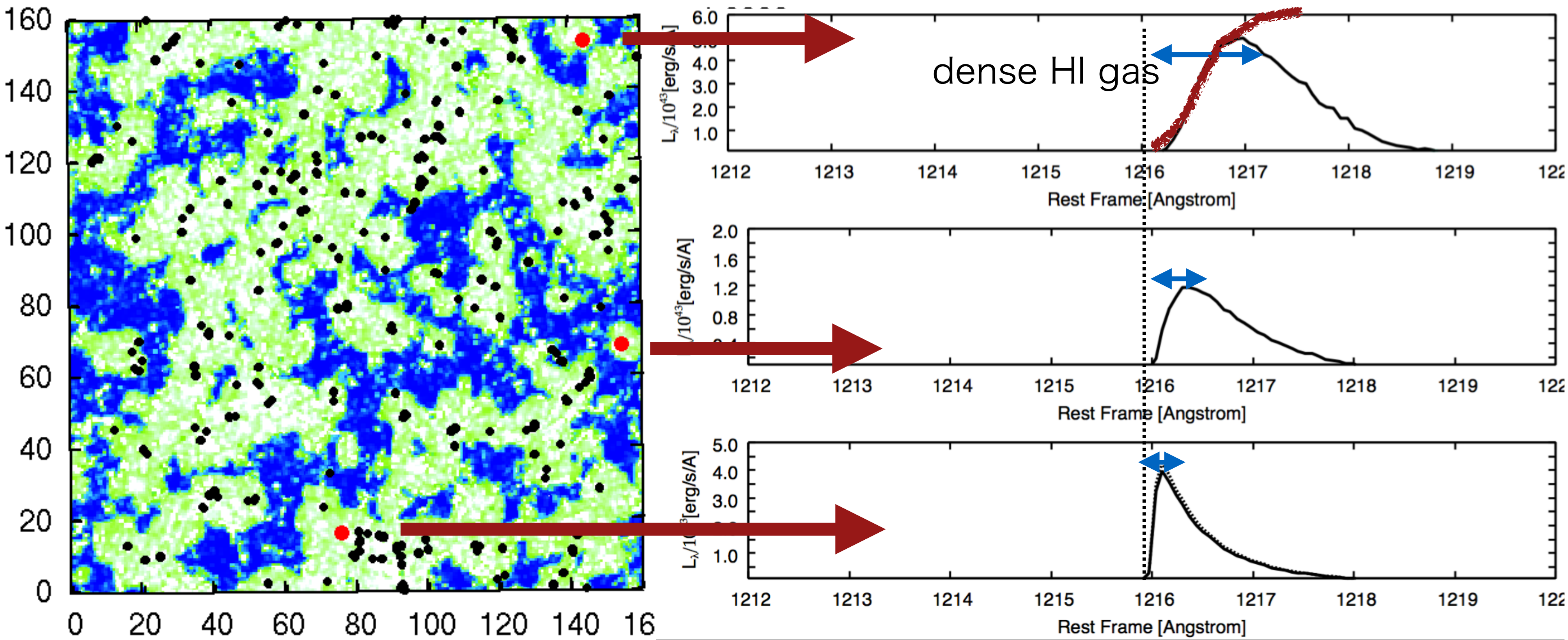
<u>LAEs are clearly obscured by neutral IGM</u>

Lyα LF: Simulation vs. Observation

- Simulated LFs at z~6-7 are well consistent with obs.
- Observed LF indeed indicates that the mean neutral fraction increases with redshift.



Lyα profiles inform sizes of HII bubbles?



- Lya profileの形(ピークシフト/Skewness)は、LAEが存在するバブルのサイズを反映
- もし観測される場所ごとにprofileの違いが見られれば、"Patchy" reionizationの間接的証拠 => PFSに期待

Summary

再電離シミュレーションコードの開発

=> "長谷川モデル"での計算は可能

- 21cmシグナル解析(PS, bubble count)LAE観測との比較に使用可能
- 21cm-LAE cross correlation解析(SKA, MWA) => 久保田君トーク

今後

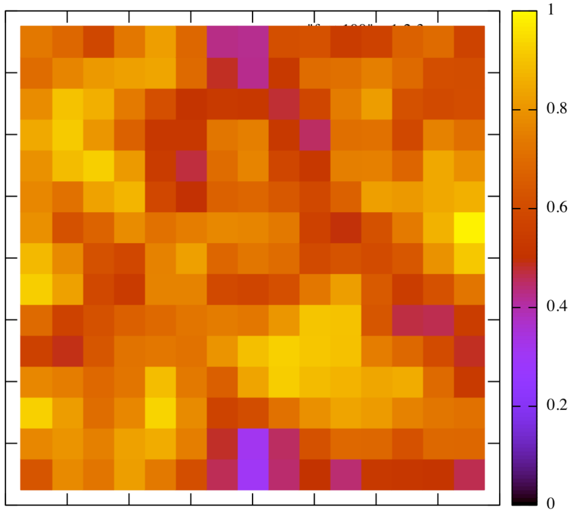
- 使い方を簡略化し、好きな銀河モデル(SFR, fesc)、AGNからの放射込みで計算で誰でも計算できるように調整.
- 電離光子源モデルと観測量との対応(e.g. LAE LF/clustering, HIIバブルサイズ分布, HI(^{3}HeII) fine structure line PS, HI21cm-LAE相互相関)の解明

Obtaining the map of HI fraction

(Coarse-grained cell size is set to be 10Mpc) @z=7.3

ionization degree

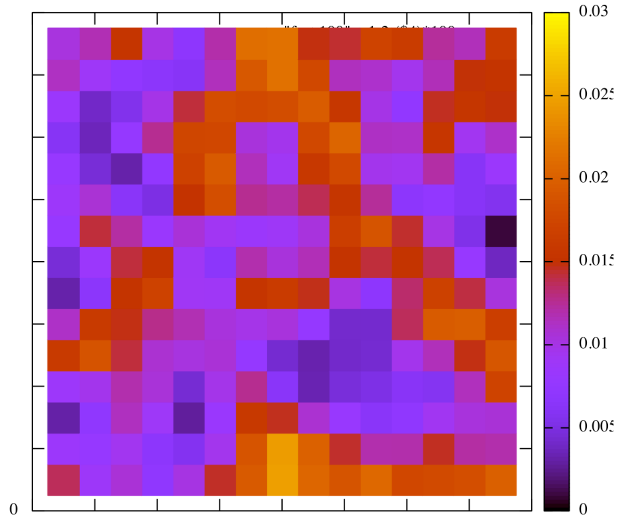
$1-x_{HI}$ (answer)



160Mpc

HI 21cm signal

differential T_b [K]



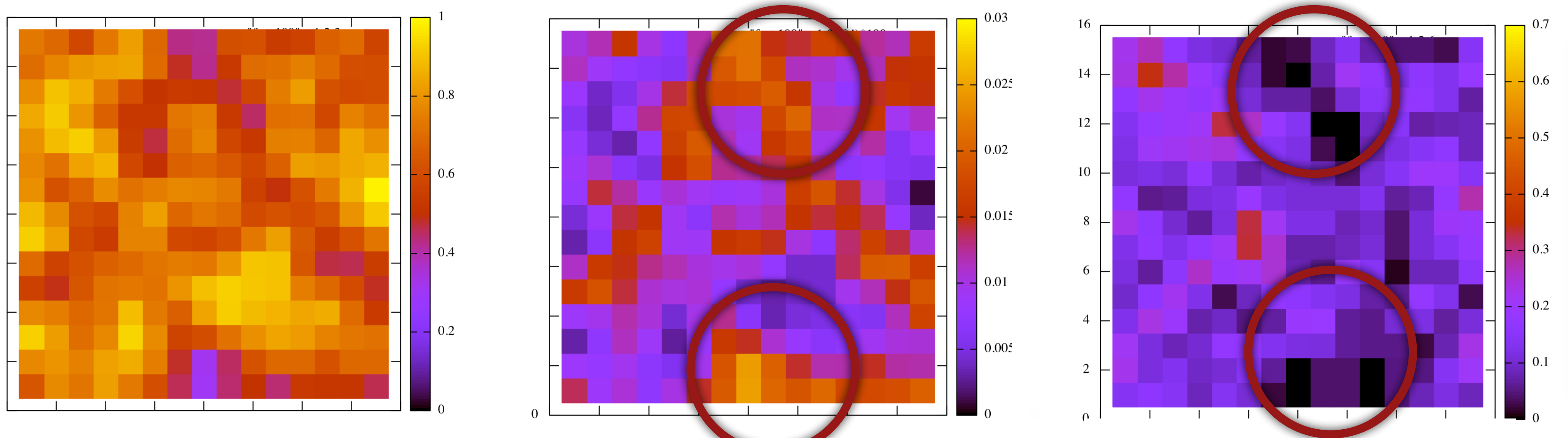
160Mpc

- 21cm signal map (that will be obtained by the SKA phase 2) well correlates with the true HI map.

Obtaining the map of HI fraction

(Coarse-grained cell size is set to be 10Mpc) @z=7.3

ionization degree $1-x_{HI}$ (answer) | HI 21cm signal differential T_b [K] | $f_{Ly\alpha}=n_{LAE}/n_{all,gal}$



160Mpc | 160Mpc | 160Mpc

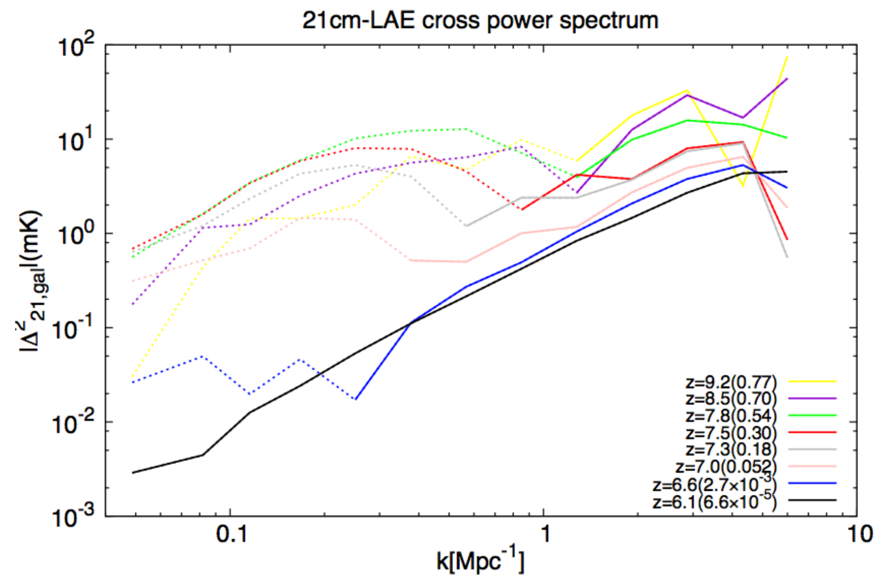
- 21cm signal map (that will be obtained by the SKA-2) well correlates with the true HI map.

- Local f_{Lya} seems to correlate inversely with 21cm signal.

=> Will be a nice cross-check for HI mapping

21cm-LAE cross correlation

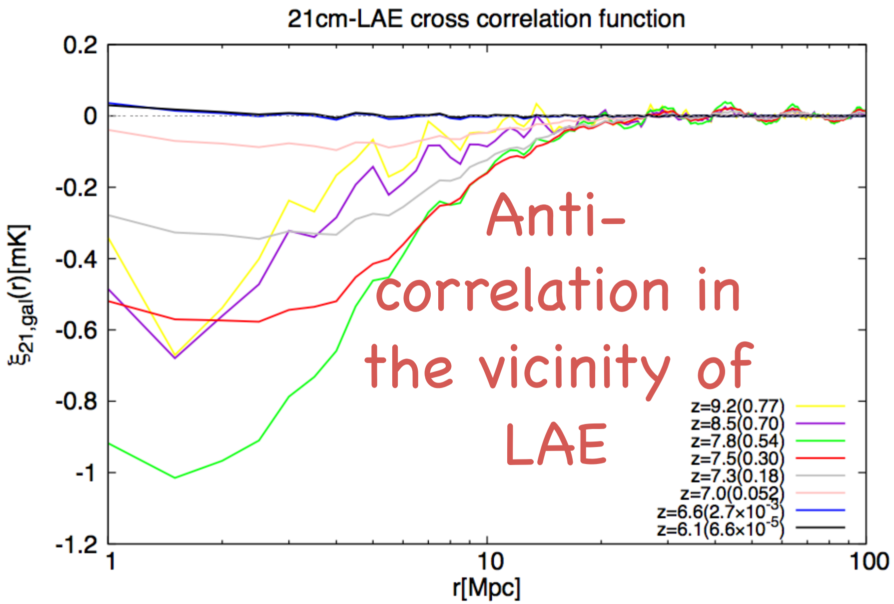
Preliminary results (by K. Kubota, & S. Yoshiura)



21cm-LAE cross power spectrum

$$\langle \tilde{\delta}_{21}(\mathbf{k_1})\tilde{\delta}_{\rm gal}(\mathbf{k_2})\rangle \equiv (2\pi)^3\delta_D(\mathbf{k_1}+\mathbf{k_2})P_{21,\rm gal}(\mathbf{k_1})$$

$$\Delta^2_{21,\rm gal}(k) = \frac{k^3}{2\pi^2}P_{21,\rm gal}(k)$$



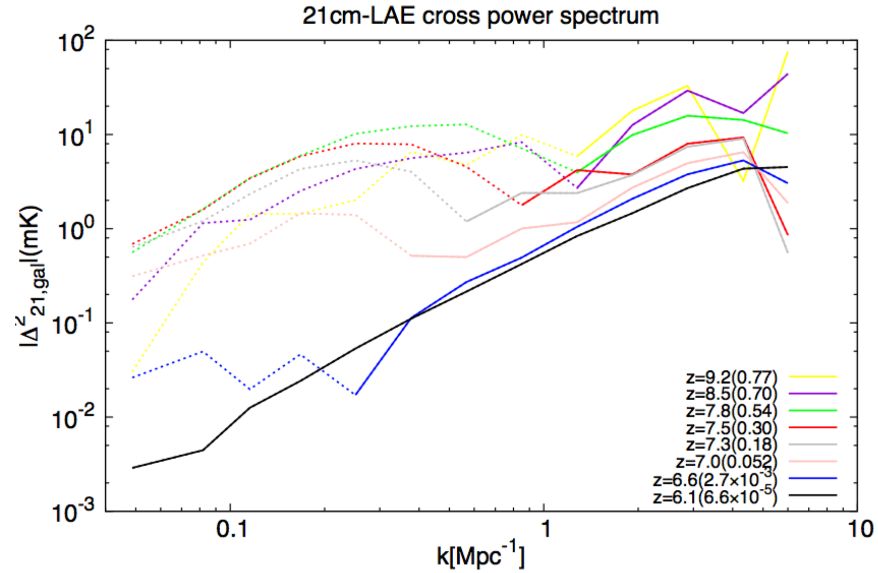
21cm-LAE cross correlation function

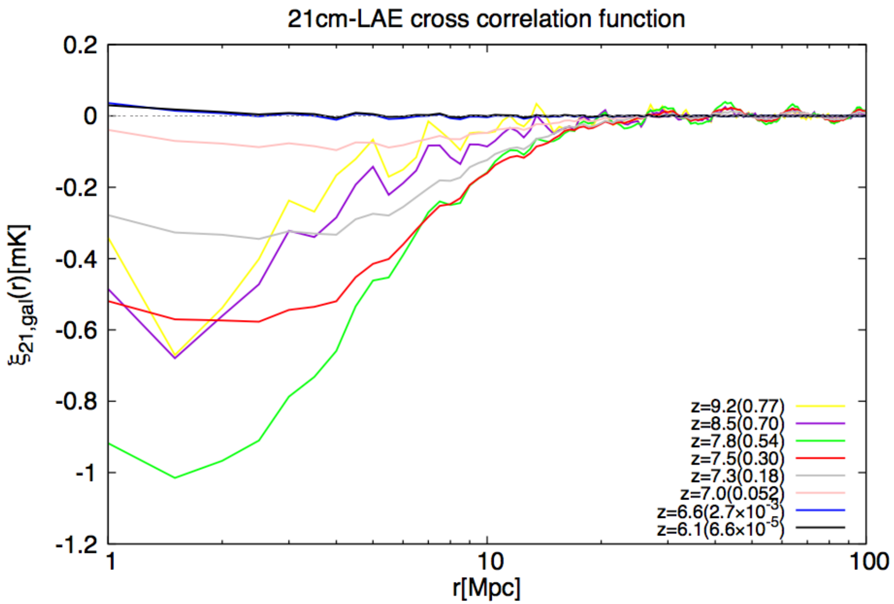
$$\xi_{21,\rm gal}(r) = \frac{1}{(2\pi)^3}\int P_{21,\rm gal}(k)\frac{\sin(kr)}{kr}4\pi k^2 dk$$

see also e.g., Lidz+09, Park+13, Hutter +16, Sobacchi+16,

21cm-LAE cross correlation

Galaxy dominant Scenario





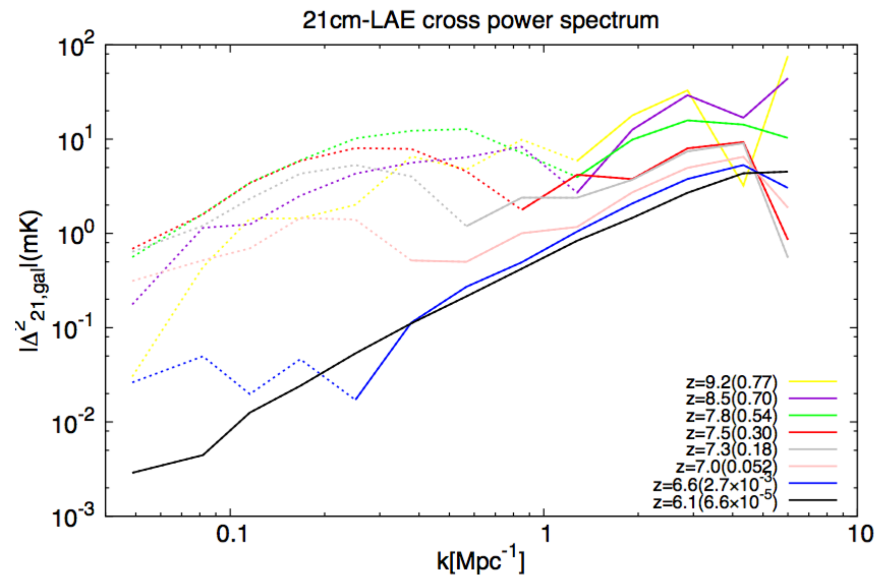
AGN dominant Scenario?

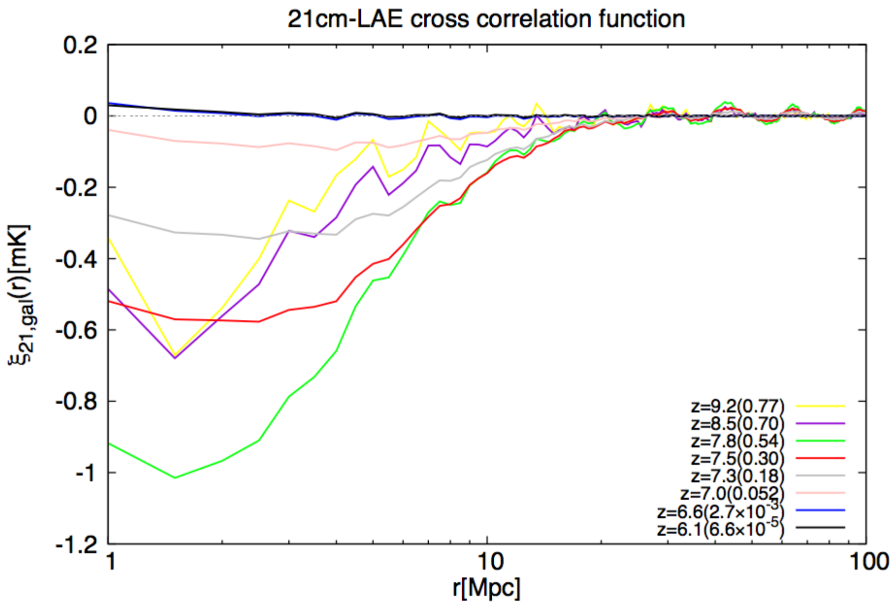
?

?

21cm-LAE cross correlation

Galaxy dominant Scenario





AGN dominant Scenario?

?

* Feasibility study for MWA-Subaru observation. (by K. Kubota)

* If AGNs largely contribute to reionization, how is its impact imprinted on the cross-correlation function?

?

Summary

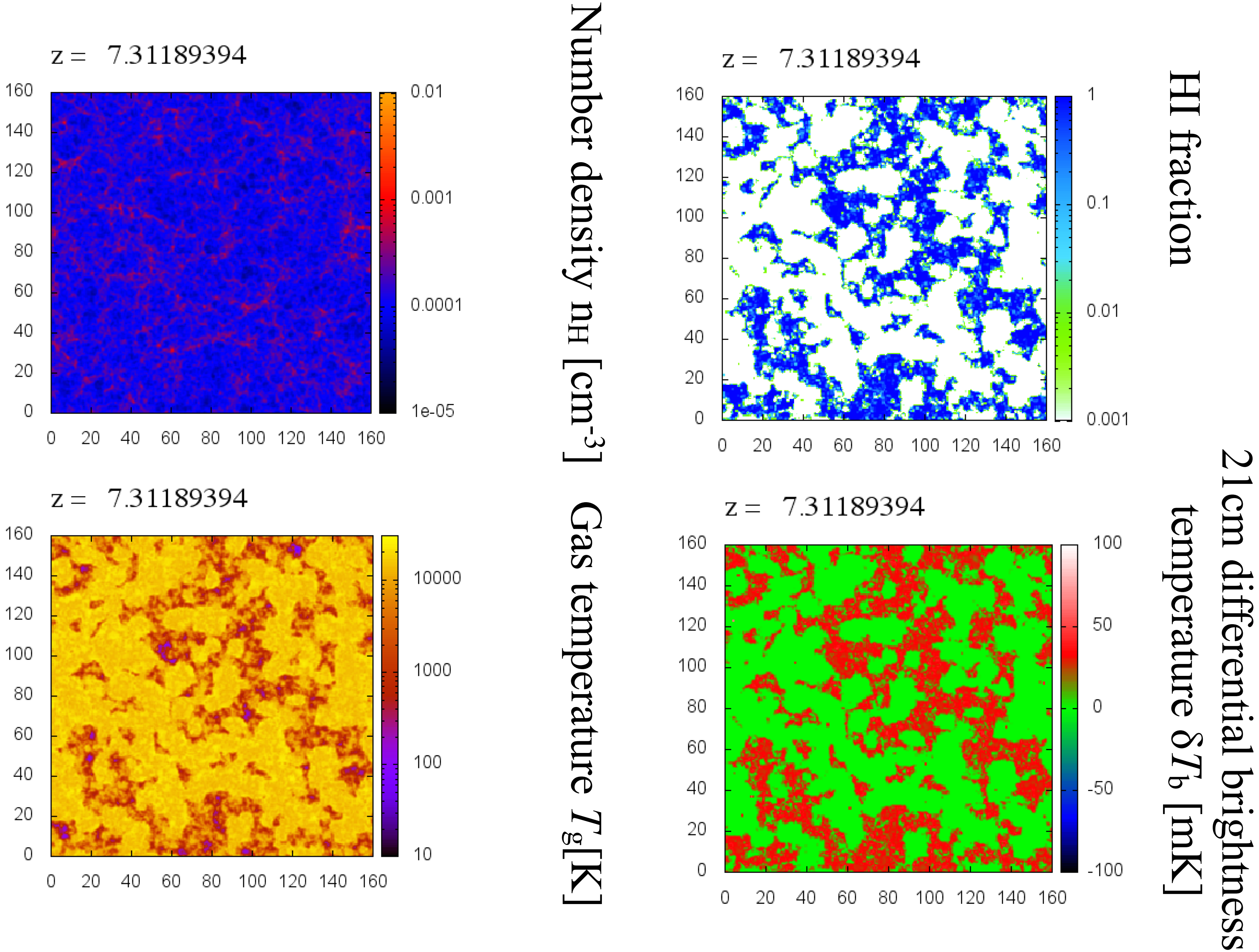
- Constructed the models of galaxies and IGM that include feedback effects.
- Our simulation with the models well reproduces observations (reionization and LAEs).
- Synergy with Subaru will provide fruitful information on the reionization process.

Future Work

- Implement X-ray model (Yoshiura,KH+) in the RT simulation
  => Create 21cm-LAEs cross-correlation templates for various situations
- Synergy SKA(21cm) + Subaru(LAE) + WFIRST(LBGs, AGNs)
  (discussions with Masami Ouchi & Takahiro Sumi)
  => cross-correlations 21cm & (LAE/LBG/AGN),

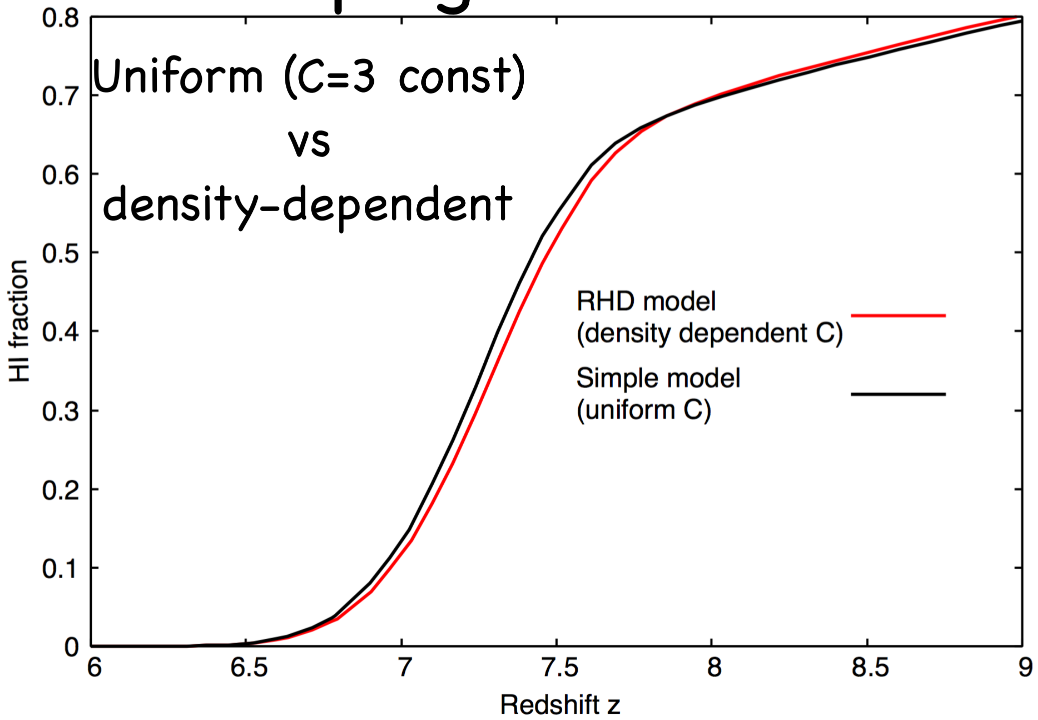
backup slides

Snapshot @ z=7.3



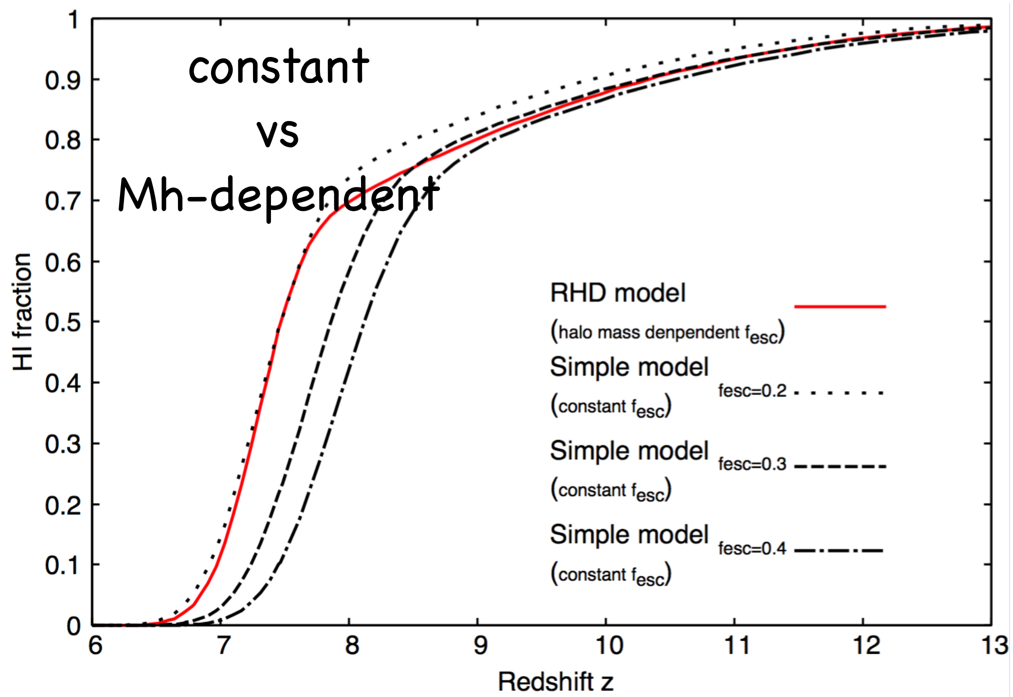
Comparison : RHD model vs. Simple model

Clumping factor model



- With our C model, reionization proceeds slowly at earlier stages.
- Then catch up later.

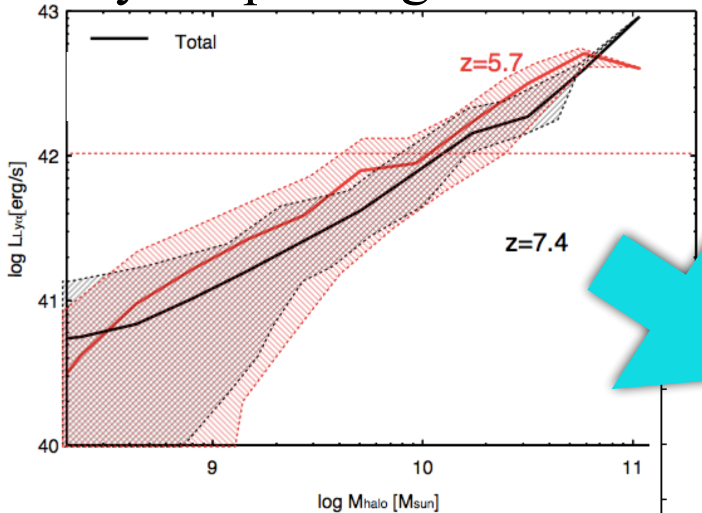
Galaxy model



- With our f_{esc} model, the averaged f_{esc} evolves from 0.3 to 0.2. Since less massive galaxies with high f_{esc} are dominant at higher redshifts.
- Thus, it becomes extended reionization history.

Modeling LAEs

Lyα depending on Mhalo



Intrinsic Lya luminosity

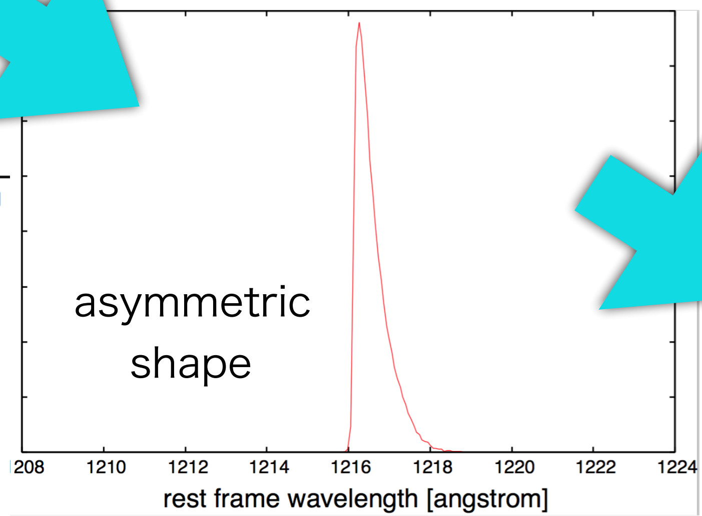
via recombination + collisional excitation

Ly α escape fraction

$f_{\alpha\,esc}$=30%

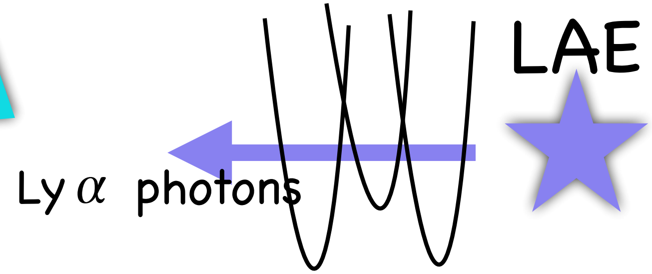
(e.g., Yajima et al. 2015)

Lyα profile



Lya radiative transfer in simplified model : $N_{HI}=10^{19}cm^{-2}$, v_outflow=150 km/s

Lyα attenuation by the IGM



Evaluate the transmission rate, by performing ray-tracing along the line of sight through the simulated IGM in the Hubble flow

Key Quantities for understanding Reionization

Ionizing photon emissivity vs. recombination rate (e.g., Madau+99)

$$\dot{N}_{\rm ion} > \alpha_{\rm B}(T)\langle n_{\rm e} n_{\rm HII}\rangle \approx \alpha_{\rm B}(T)\langle n_{\rm HII}^2\rangle = \alpha_{\rm B}(T)\langle n_{\rm HII}\rangle^2 C_{\rm HII}$$

$\alpha_{\rm B}$:recombination rate

$$C \equiv \frac{< n^2 >}{< n >^2}$$ Clumping factor

Key Quantities are:

1) Intergalactic medium (IGM) clumping factor

2) Number of ionizing sources (including faint galaxies)

3) Ionizing photon emissivity per one ionizing source (closely related to SFR, escape fraction f_{esc})

IMPORTANT:

These quantities are severely affected by radiative feedback.

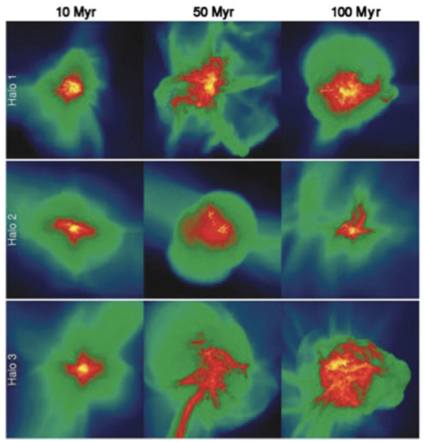
UV feedback on galaxies and IGM

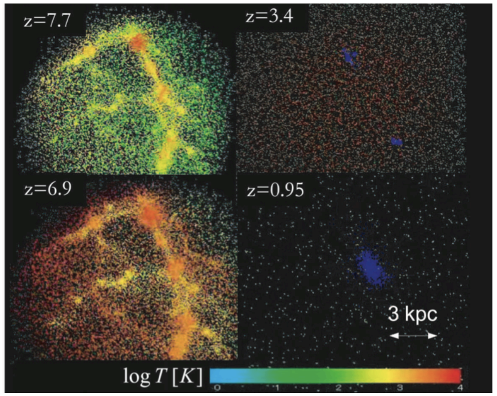
Photoionization: Heating gas up to ~10^4K

Photodissociation: Decreasing coolants.

on Galaxies

Internal (from stars) and external radiation affects SFR and escape fraction (e.g., Susa Umemura 04 Wise & Cen 09, Umemura, KH +12, KH, Semelin 2013).



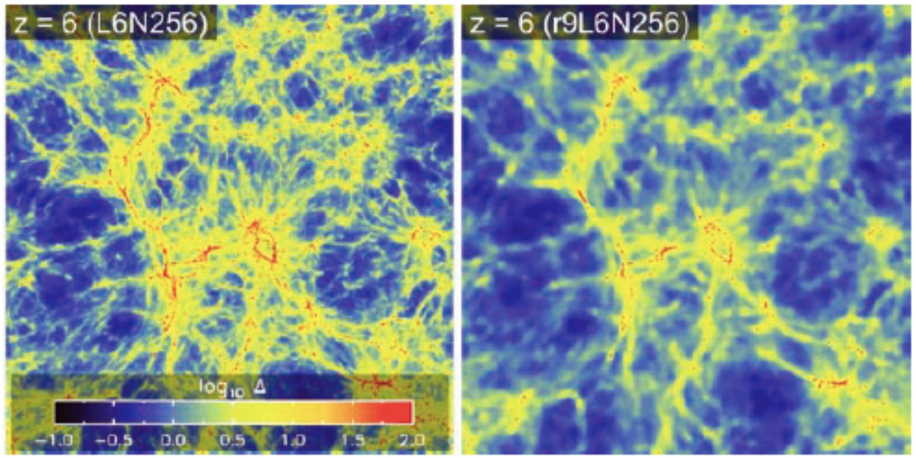


=> Reduce the number of galaxies during the EoR (e.g., Finlator+13, Wise+14)

on IGM

Uniform heating case

w/o photoheating   w/ photoheating

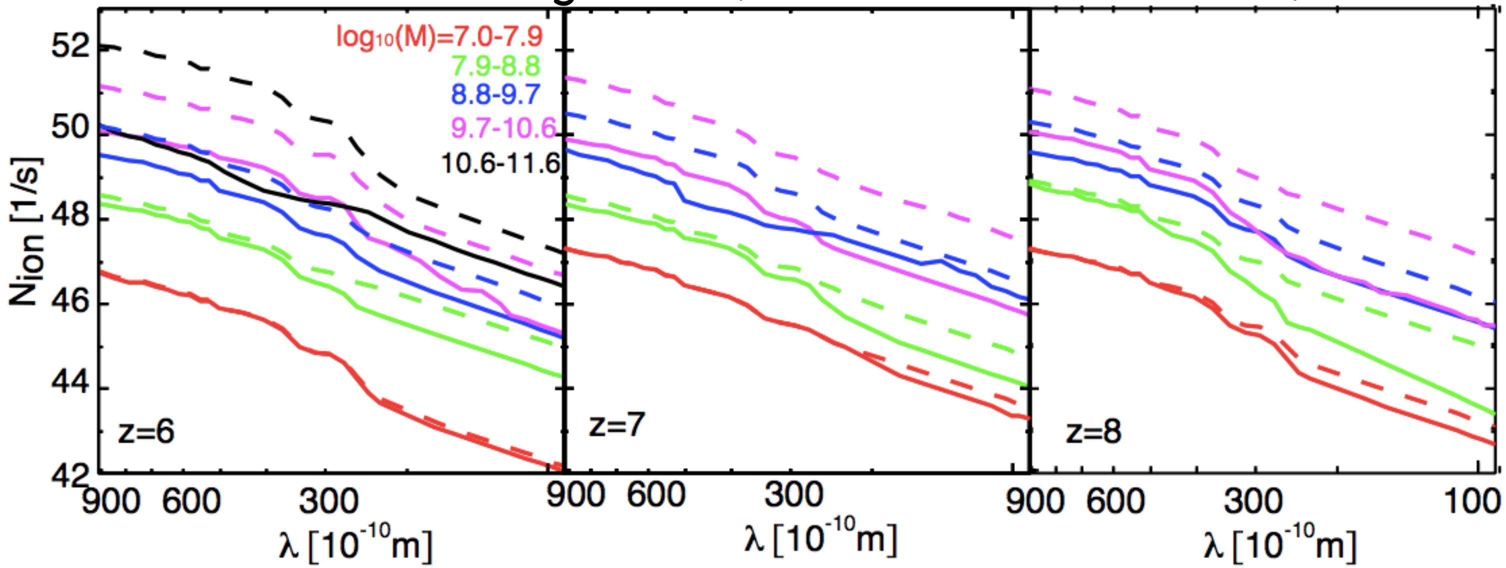


Clumping factor is decreased by photoheating (e.g., Pawlik+ 09)

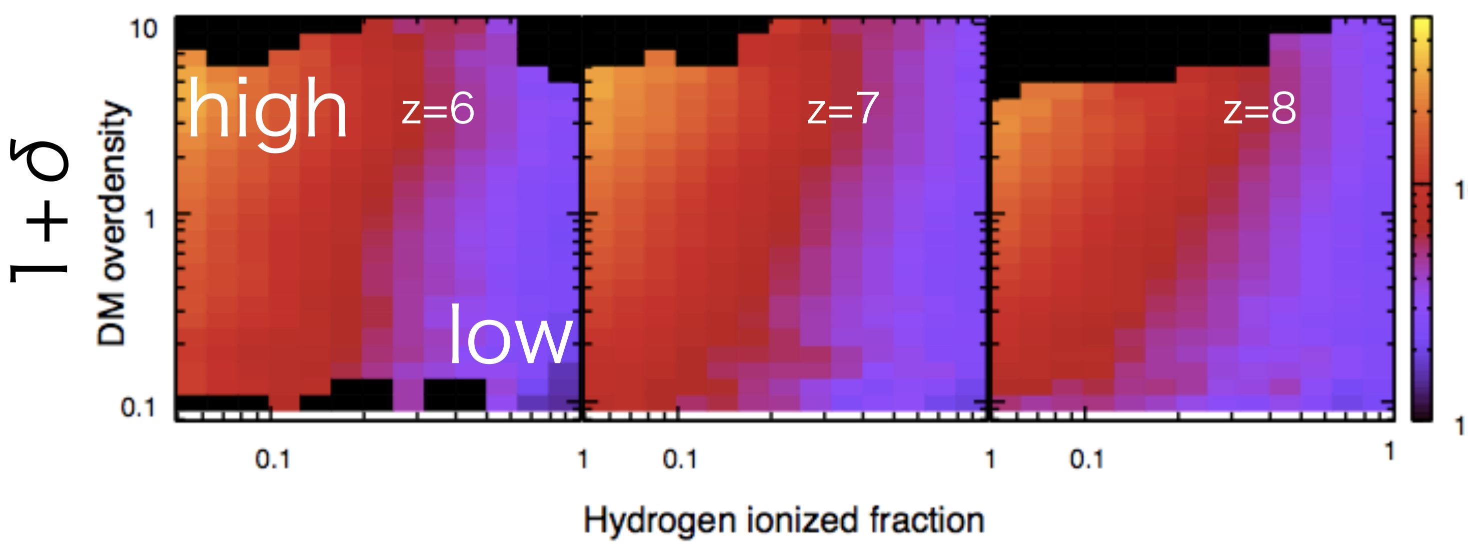
=> averaged clumping factor corresponds to ~2-4.

Models of Galaxies and Clumping factor

SEDs of simulated galaxies(KH+ 16, arXiv:1603.01961)



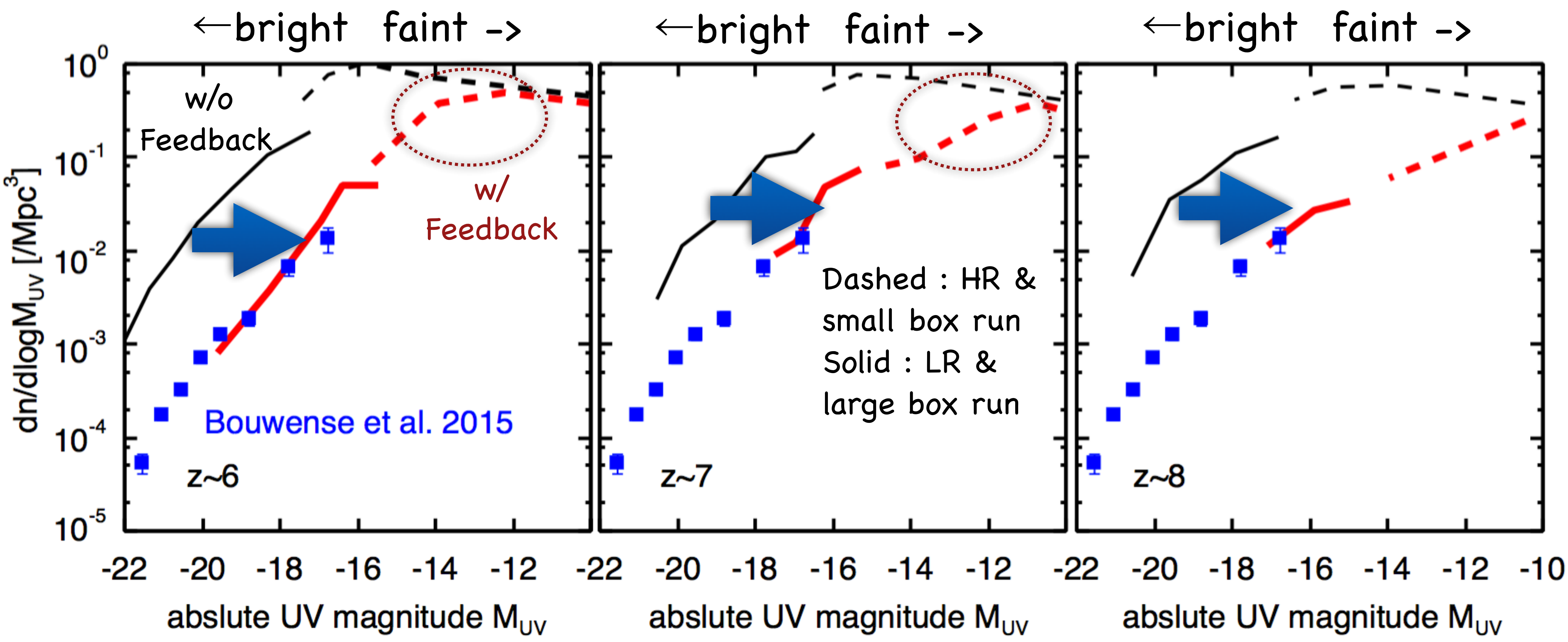
Feedback regulated SFR + Escape fraction = Halo mass-dependent SED.



Make a look -up table of clumping factor as a function of local density and ionization degree.

Clumping factor decreases with increasing local ionization degree and decreasing local density.

UV(1500Å) Luminosity Function (LF): Sim. vs. Obs.



- Feedback effects suppress SF activities.
- Simulated UVLFs are consistent with observed LFs. (Hence consistent cosmic star formation density.)
- Predict flattening of faint-end LF at M_{UV} -13 ~ -14.