The Beginning and Ending Stages of Cosmic Reionization

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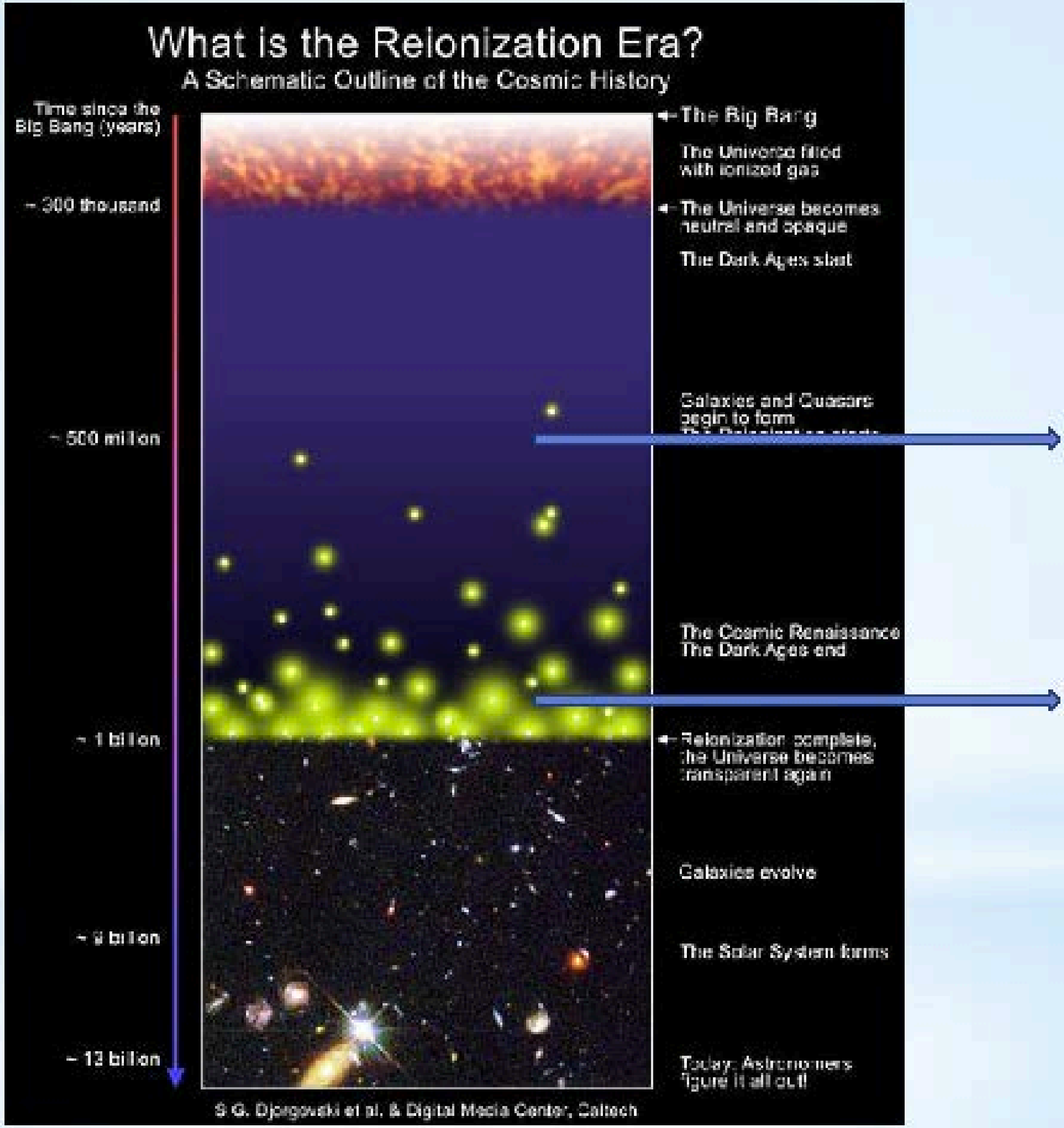
Yue et al., 2013b, MNRAS 433, 1556
Yue et al., 2014, MNRAS 440, 1263
Xu et al., 2014, ApJ, 781, 97

Outline

- Cosmic reionization
- The missing source for the near-infrared background (NIRB) fluctuations on large scales
- The direct collapse black hole (DCBH) interpretation
- The DCBH formation during the early EoR

After the brief DCBH era…

- The island model for the late EoR
    - The excursion set theory
    - The bubbles-in-island effect
    - The ionizing background
    - The percolation criterion and the neutral islands statistics
- Summary

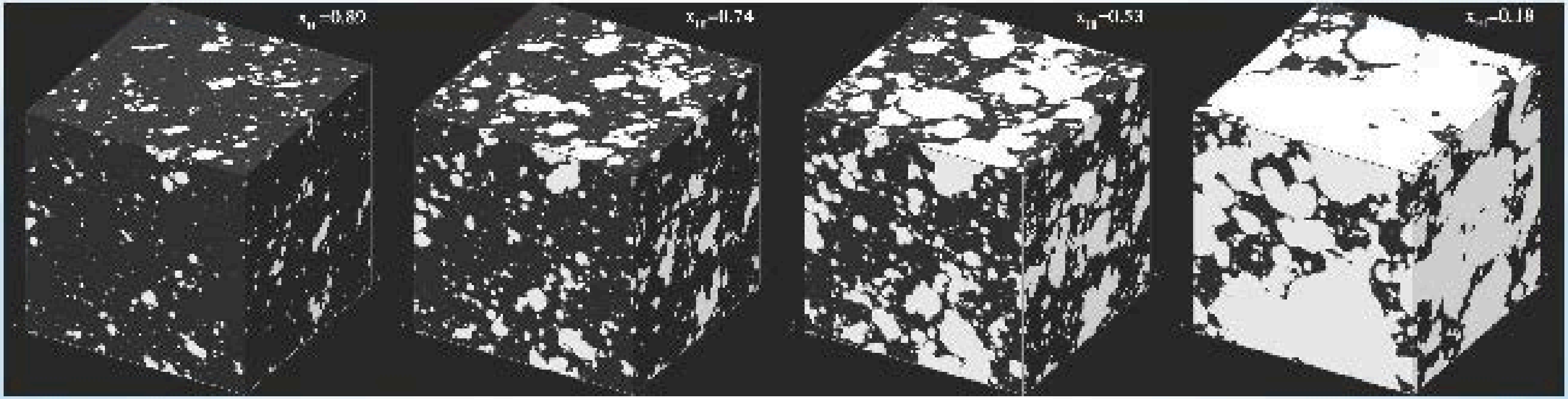


DCBHs

Neutral Islands

Theoretical works on reionization

* Simulations: e.g. Battaglia+2013; Ciardi+2012; Iliev+2012
* Analytical models: e.g. Furlanetto+2004 ("bubble model")
* Semi-numerical simulations: e.g. Mesinger & Furlanetto 2007; Alvarez+2009



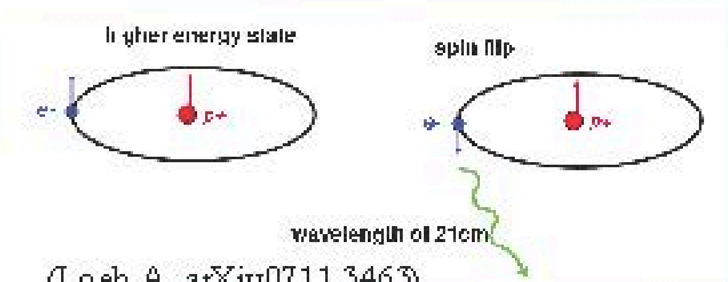
(From Mesinger & Furlanetto 2007 ApJ, 669, 663)

Probes of cosmic reionization

* The polarization data of CMB from PLANCK → z ~ 11.1 (Planck Collaboration 2013);
* The Gunn-Peterson tests → very nearly complete at z ~ 6 (Fan et al. 2006);
* High redshift galaxy surveys (e.g. Lehnert+2010);
* The kSZ effect (e.g. Zahn et al. 2012);
* The 21cm probe of HI.

  EDGES, PAPER, GMRT, LWA, MWA,

  LOFAR, 21CMA, HERA, SKA



(Loeb A. arXiv0711.3463)

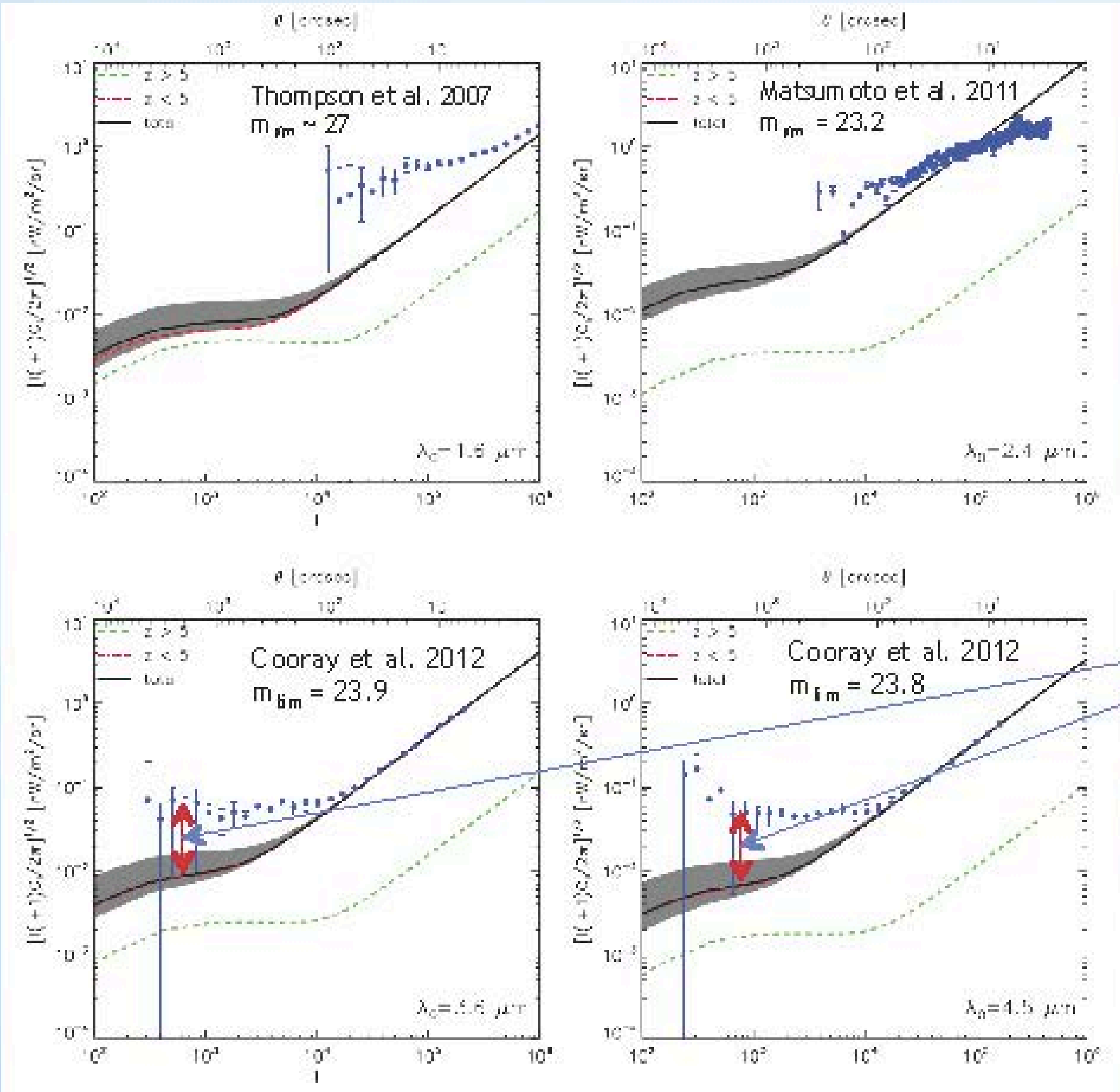
The Near-Infrared Background
from the Epoch of Reionization (EoR)

* ***Near-infrared:***
  * wavelength range: ~ 0.7 – 8 μm
  * for galaxies with $z > \sim 6$, the bulk of the emission is redshifted into near-infrared band
* ***Background:***
  * most of galaxies that contribute to reionization are below the limiting magnitude
  * their cumulative radiation forms a background
* The NIRB as a probe to the first galaxies and black holes.

The Near-Infrared Sky

* Foreground (zodiacal light, strongest, ~10^4 times the signal, but smooth at the observed sky region)
* + possible light from stars/ISM in our Milky Way
* + bright galaxies (point sources)
* + ***faint galaxies, first stars… (of interests)***

The angular fluctuations of source-subtracted NIRB



The contribution from low-z galaxies
- Helgason et al. (2012)
The contribution from high-z galaxies
- Yue et al. (2013a)

Unknown sources?

The Clues

* Cluster on large scales
* Faint (at least >~ 25 at 3.6 and 4.5 μm, >~ 29 - 30 at the H-band)
* Negligible contribution to reionization, i.e. $f_{esc} \sim 0$
* Be consistent with the constraints on the CXB level

➤ *One possible explanation: diffuse intrahalo light of galaxies at z ~ 1 – 4 (Cooray et al. 2012a, Nature, 490, 514)*

Compton-thick, intermediate-mass black holes

- ✓ Sufficiently intense Lyman-Werner (LW) radiation → H2 cooling is quenched
- ✓ Pristine gas in halos with $T_{vir} \geq 10^4$ K → atomic H cooling sustain an almost isothermal collapse preventing gas fragmentation into smaller sub-units.
- ➔ Rapid (≈1 *Myr*) formation of a direct collapse black hole (DCBH) of mass 10^{4-6} *M*sun (Bromm & Loeb 2003; Begelman et al. 2006; Lodato & Natarajan 2006; Regan & Haehnelt 2009 ……).

As the gas continues to fall onto the BH …

➔ ***probably Compton-thick!***

Spectrum of a Compton-thick accreting BH

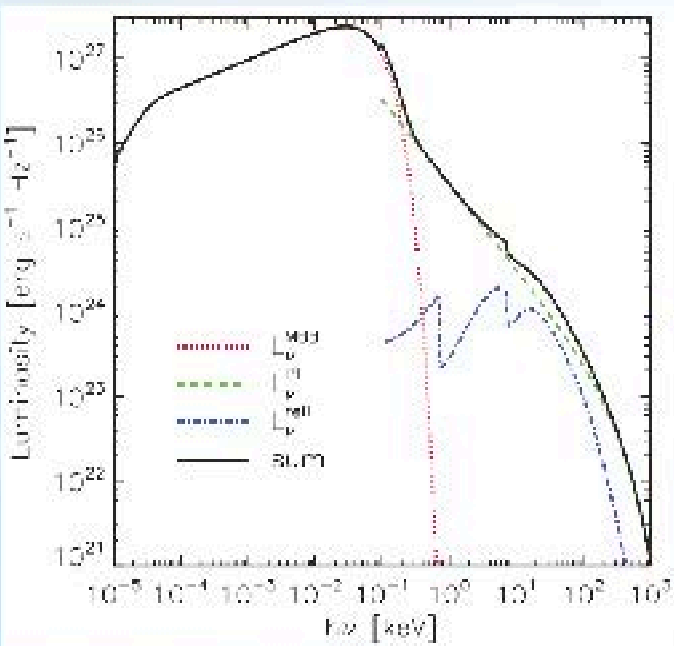
* The primary spectrum
* The emergent spectrum

$$L_\nu = L_\nu^{\mathrm{MBB}} + L_\nu^{\mathrm{PL}} + L_\nu^{\mathrm{refl}},$$

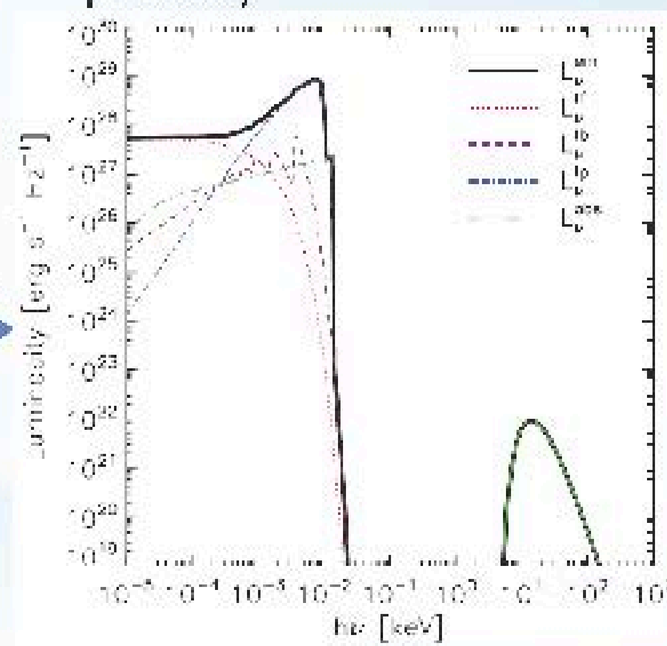
absorption

scattering

'nebular emission' (free-free, free-bound, two-photon)



a massive accreting envelope



$M_{\mathrm{BH}} = 10^6$ Msun and $N_H = 1.5 \times 10^{25}$ cm^{-2}

NIRB and CXB fluctuations from DCBHs

* The emissivity:

$$\epsilon_\nu(z) = \frac{1}{4\pi}\int_{z_{\rm start}}^{z} L_\nu^{\rm em}(M')\frac{{\rm d}n_{\rm BH}}{{\rm d}z'}(z'){\rm d}z',$$

* The BH power spectrum:

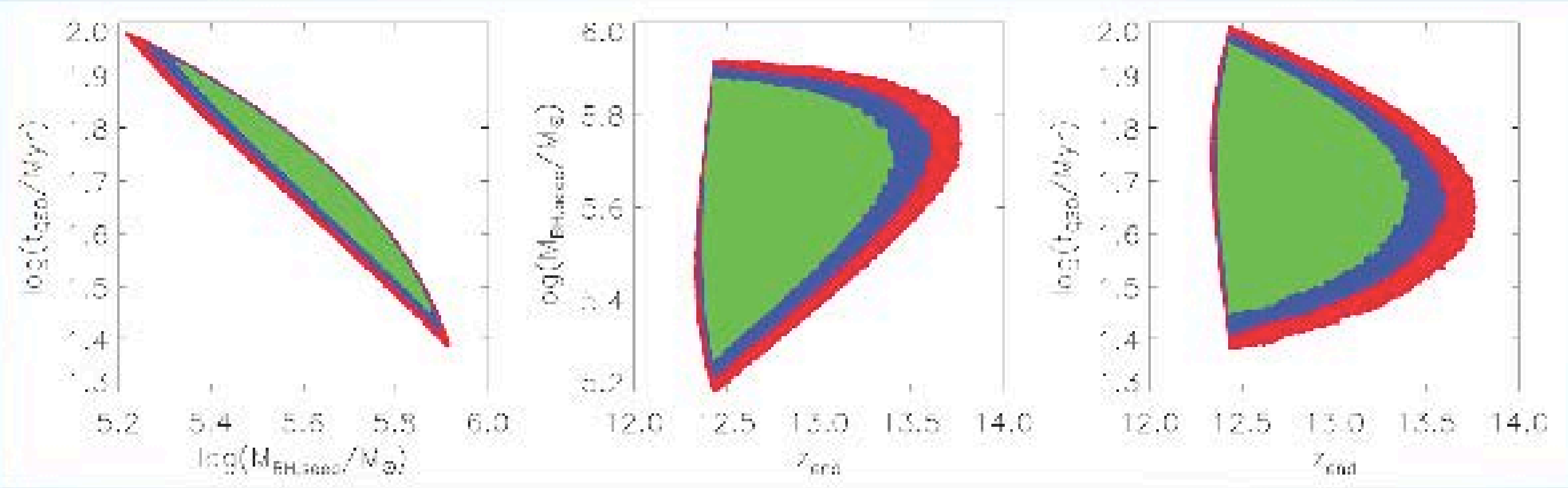
$$P_{\rm BH}(k,z) \approx P(k,z)b_{\rm eff}^2(z),$$

* The angular power spectrum:

$$C_l^{\rm NIRB} = \int_{z_{\rm end}}^{z_{\rm start}} {\rm d}z \frac{[\nu\epsilon_\nu(z){\rm e}^{-\tau(\nu_0,z)}]^2}{H(z)r^2(z)(1+z)^4} P_{\rm BH}(z),$$

Fitting the NIRB fluctuation data

- *Model parameters:*
  - $M_{BH,seed}$, t_{QSO}, z_{end}, N_H (the NIRB is very insensitive to NH once the BH is Compton-thick, but the CXB level is sensitive to it)
- Limits:
  - Apparent magnitude m > 30 at the H-band of *HST*/WFC3
  - m > 27 at 3.6 and 4.5 μm band of *Spitzer*/IRAC

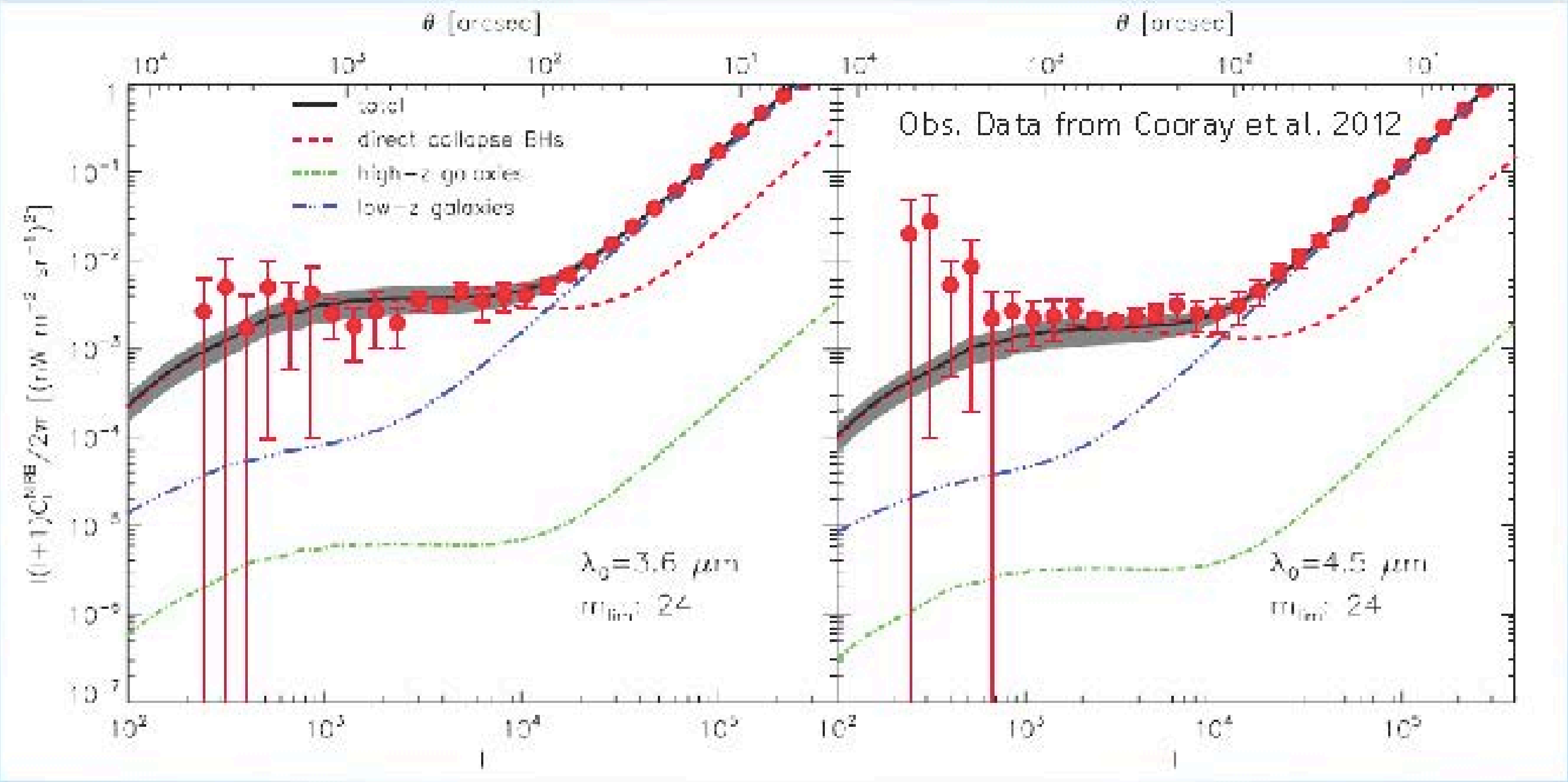


Best fitting parameters: $M_{BH,seed}$: $10^{5.85}$ Msun, t_{QSO}: $10^{1.48}$ Myr, z_{end}: 12.44

The predicted source-subtracted NIRB spectrum

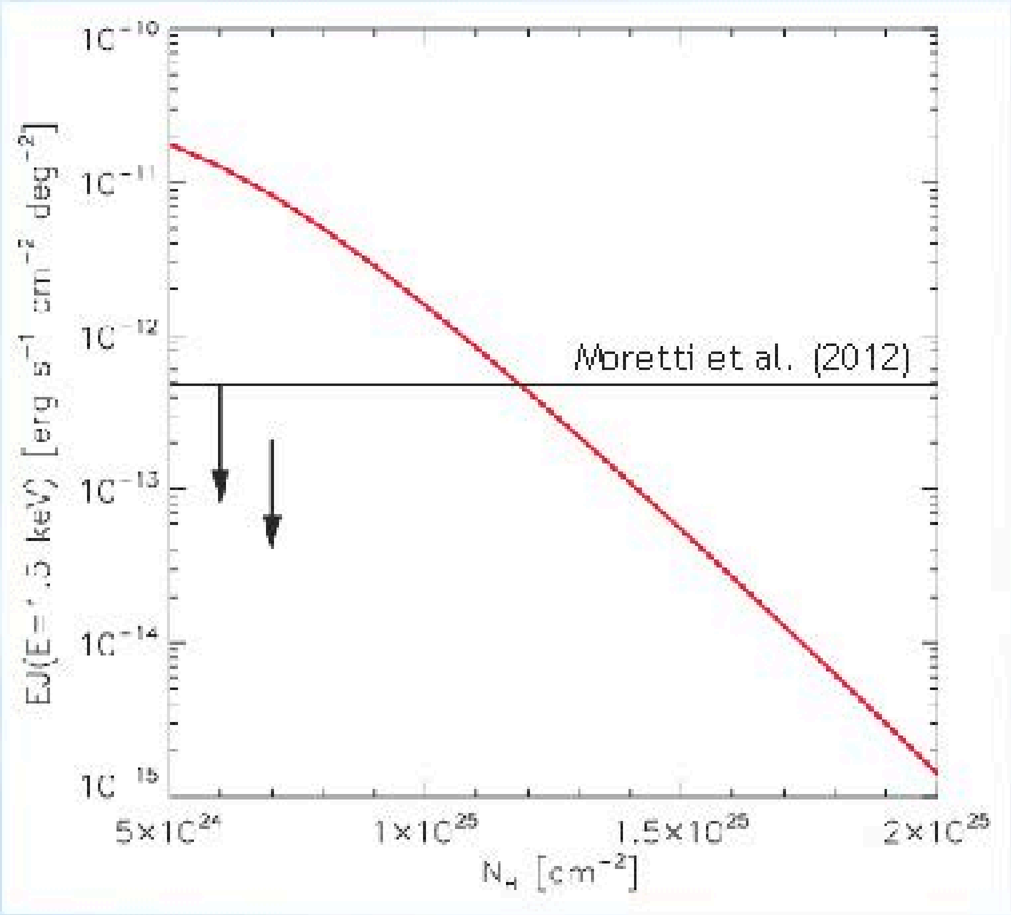
Faint galaxies at z > 5: Yue et al. 2013a

Faint galaxies at z < 5: Helgason et al. 2012



Best fitting parameters: $M_{BH,seed}$: $10^{5.85}$ Msun, t_{QSO}: $10^{1.48}$ Myr, z_{end}: 12.44

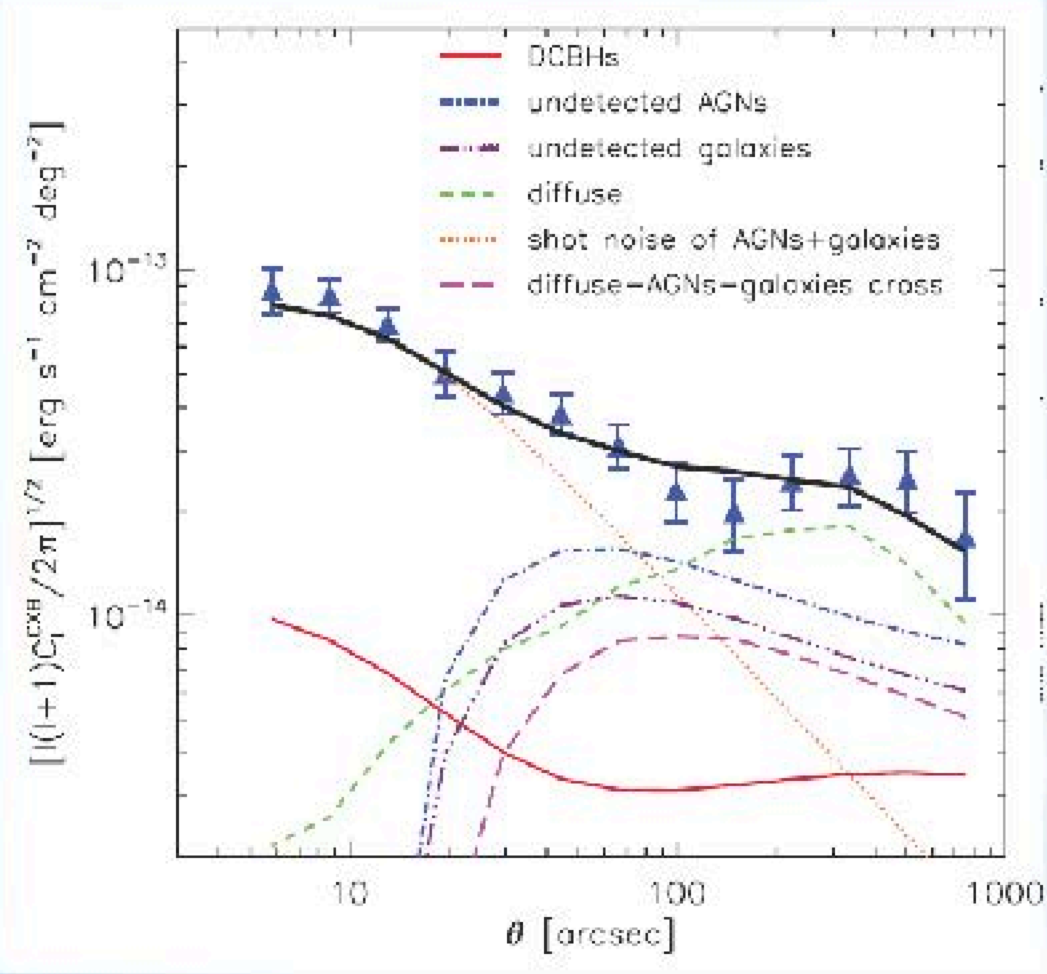
Constraints on the N_H by CXB level



* The DCBH contribution to the unresolved CXB for the best fitting parameters

→ N_H > $1.2-1.3\times10^{25}$ cm^{-2} is required (Compton-thick)

The angular power spectrum of the CXB

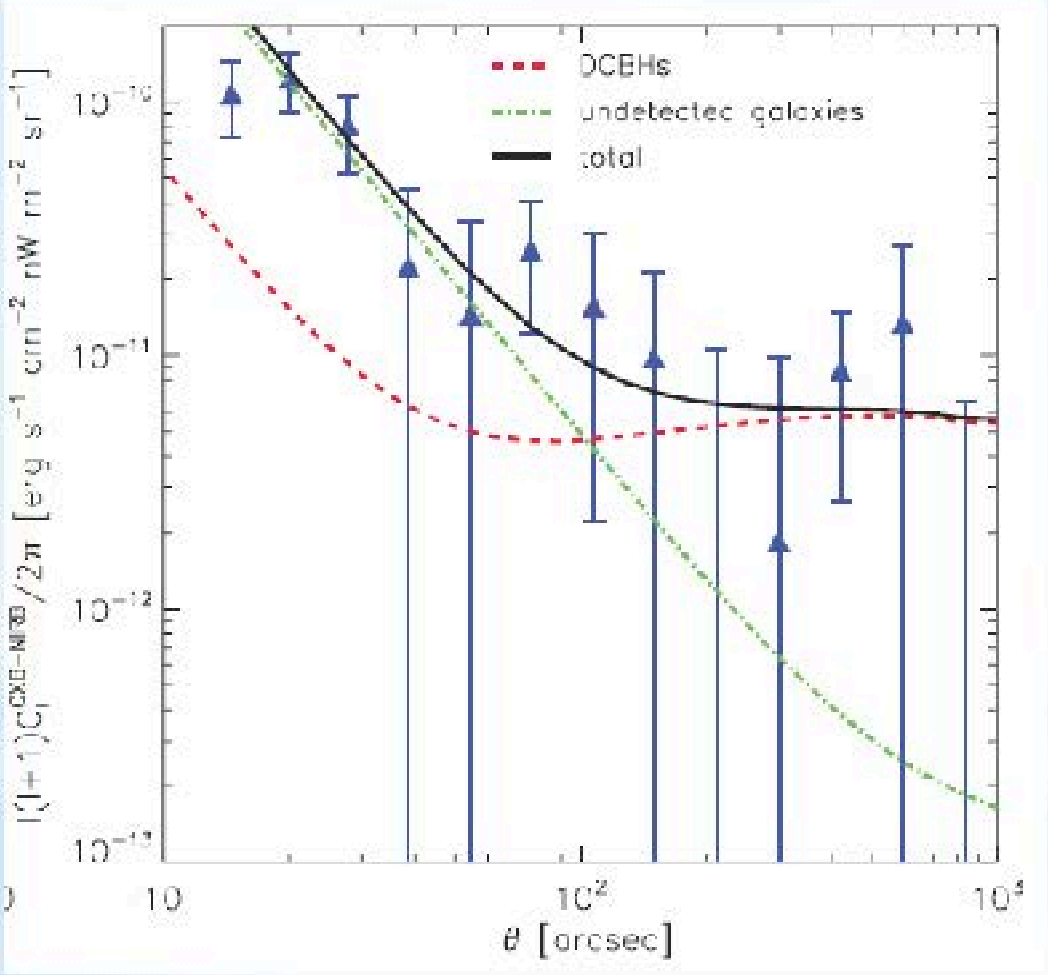


$N_H = 1.5\times10^{25}$ cm^{-2}

Data and other contributions from Cappelluti et al. 2012

- **The contribution of DCBHs to CXB fluctuations is negligible with respect the other sources at all angular scales.**

CXB (0.5-2.0 keV)-NIRB(4.5μm) cross-correlation



$N_H = 1.5\times10^{25}$ cm^{-2}

Data from Cappelluti et al. 2013

- Undetected low-z galaxies dominates at small scales (<100 arcsec) (shot noise)
- DCBHs dominate at large scales (>100 arcsec)

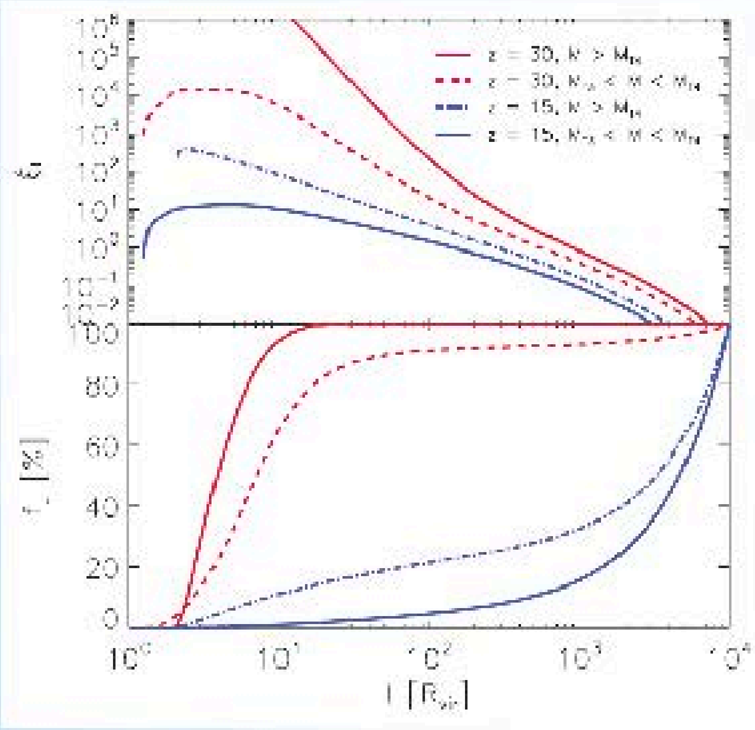
(unknown source reported by Helgason et al. 2014)

The DCBH formation history

* At the early EoR, galaxies were rare but highly clustered, and they triggered the formation of the earliest DCBHs.
* Once the first DCBHs formed, they emit much more LW photons than galaxies
* They then trigger a runaway process of further DCBH formation, producing a sudden rise in their cosmic mass density.
* The formation is quenched by reionizaition after z ~13

Various feedbacks

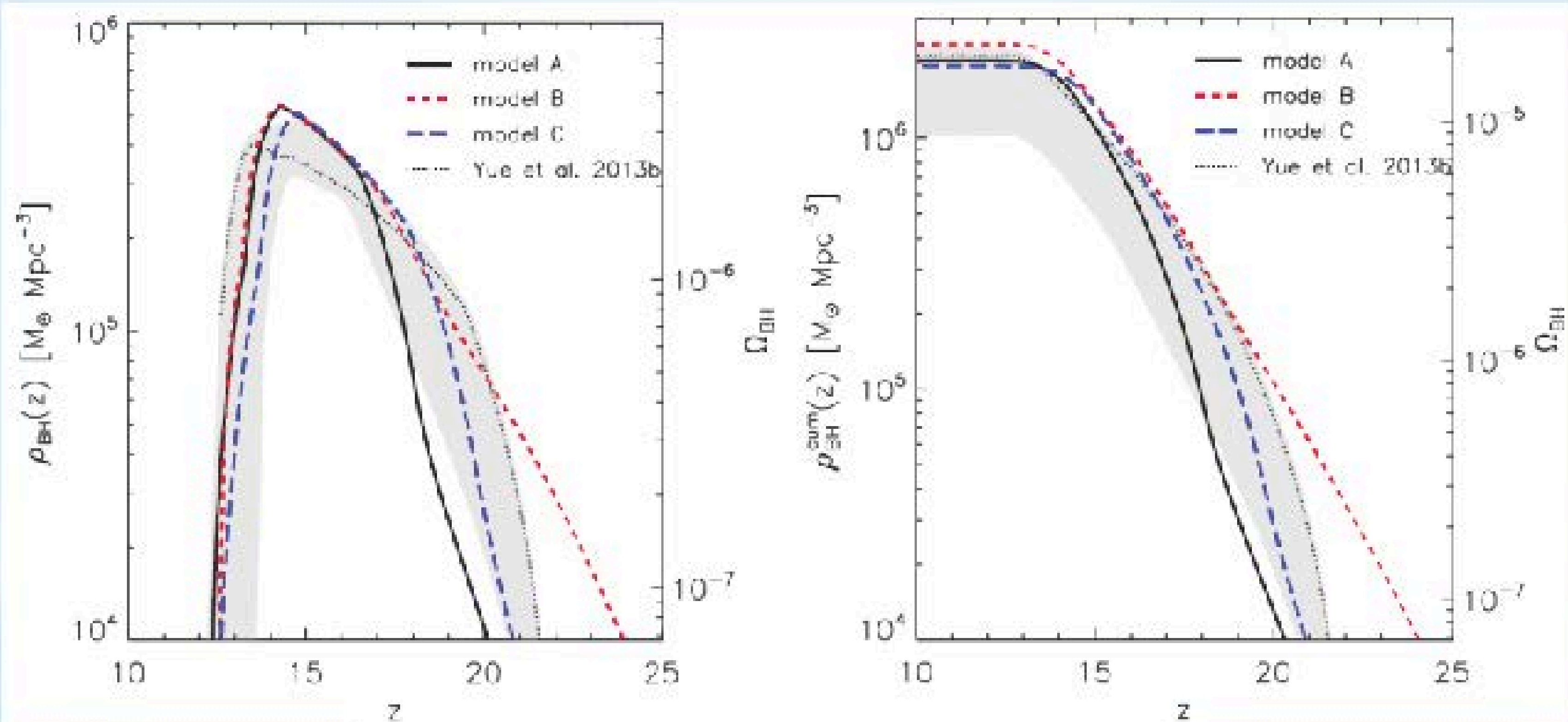
* Positive feedback:
  * Strong clustering
  * High LW luminosity of DCBHs themselves



* Negative feedbacks:
  * Genetic enrichment
  * Wind enrichment
  * Photo-evaporation by reionization
* The DCBH formation rate:

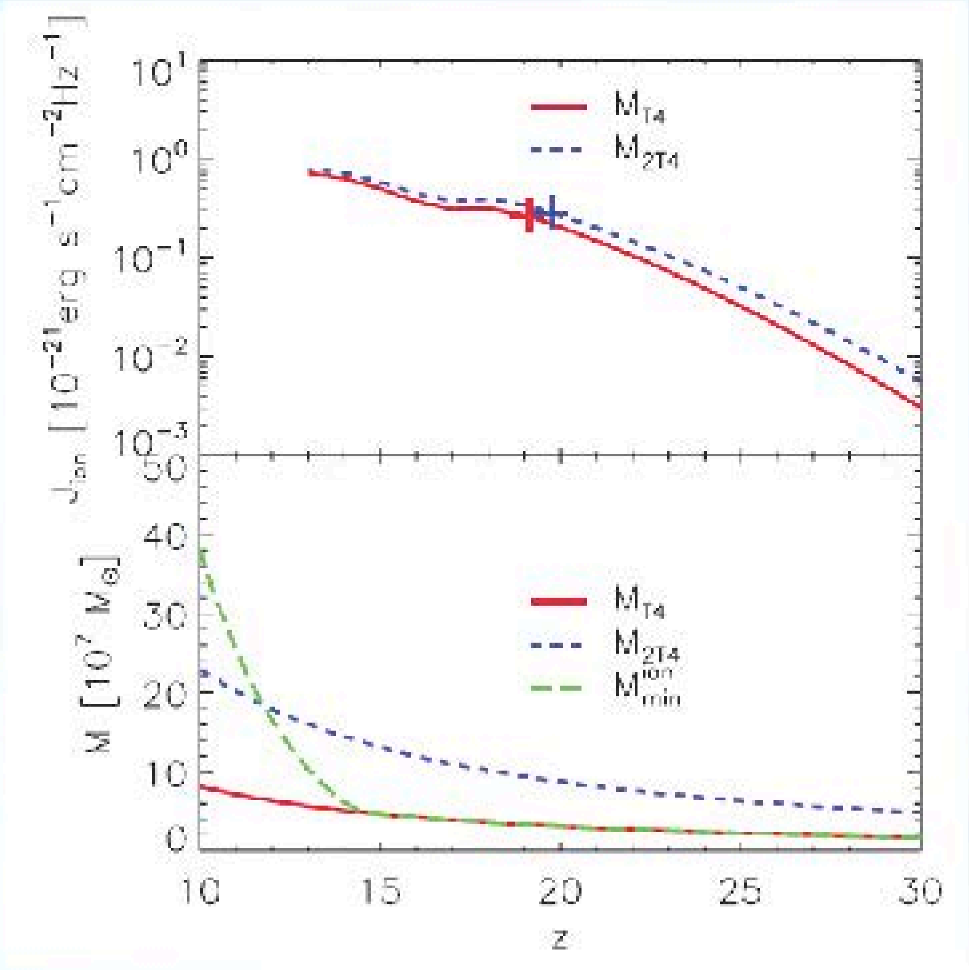
$$\frac{\mathrm{d}n_{\mathrm{BH}}}{\mathrm{d}z}(z) = [1 - p_{\mathrm{g}}(M'_{\mathrm{T4}}, z')]\,p_{\mathrm{l-w}}(M'_{\mathrm{T4}}, z')$$
$$\times \int_{M_{\mathrm{T4}}}^{M_{2\mathrm{T4}}} \mathrm{d}M\, \frac{\mathrm{d}n}{\mathrm{d}M}(z) \frac{\mathrm{d}P}{\mathrm{d}z'}(z', M'_{\mathrm{T4}}|M, z) \frac{\mathrm{d}z'}{\mathrm{d}z}.$$

The DCBH abundance



Model	J_{LW}^{crit}	l_{min}	f_{ion}	Genetic enrichment
A	50	1	0.2	Yes
B	150	1	0.3	No
C	30	2	0.3	Yes

The role of photo-evaporation



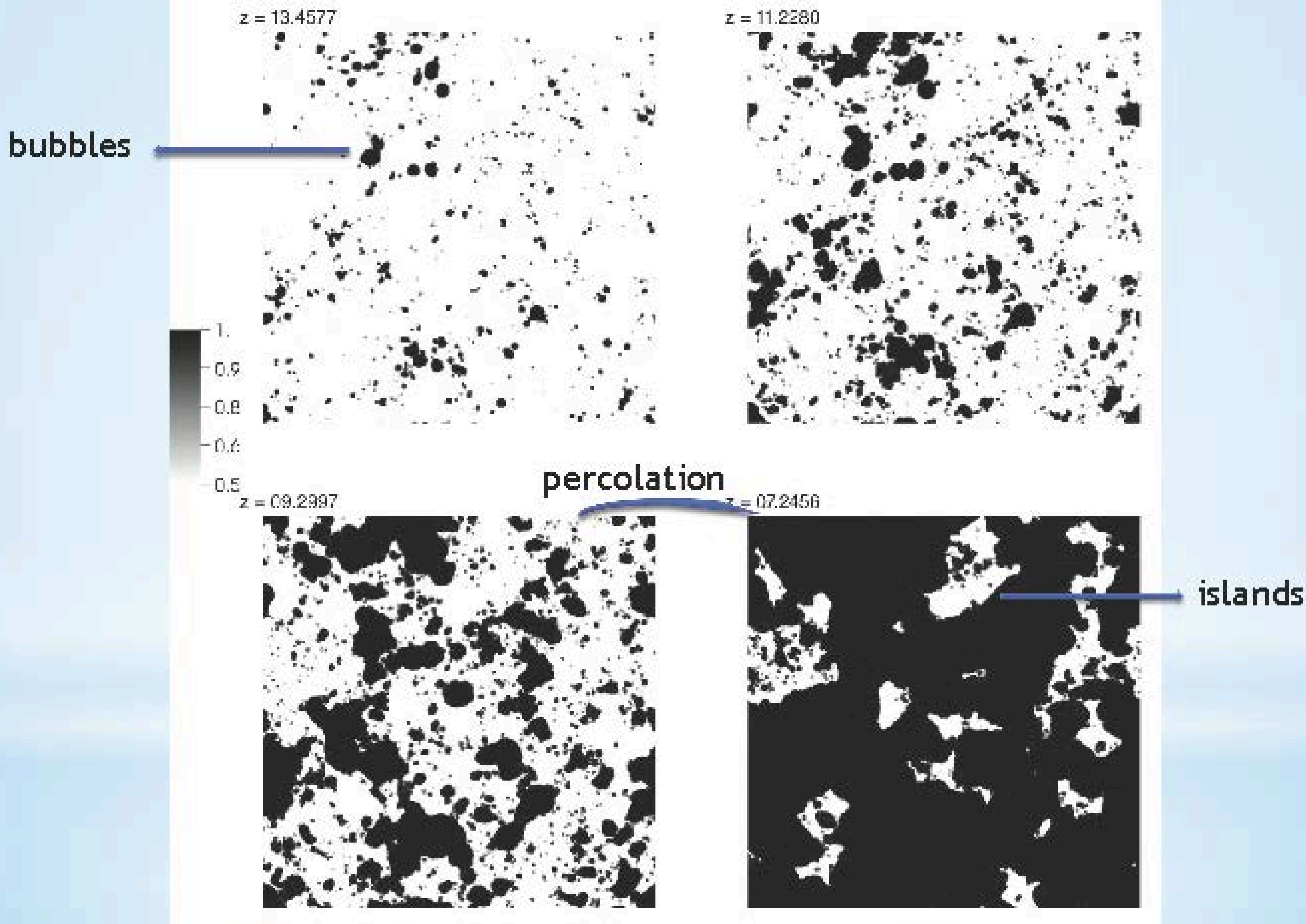
- Clustering of M_{T4} halos
- The DCBH era ends at z ~ 13.
- leaves behind a large number of 'fossil' DCBH seeds ($\Omega_{BH} \sim 10^{-5}$).

The DCBHs play no active role in driving reionization.

But reionization ends the DCBH era.

↓

The epoch of reionization



Shin, Trac & Cen, 2008ApJ...681..756S

Analytical models of reionization

* Early stage – the "bubble model" (Furlanetto et al. 2004)

  -- growing ionized bubbles

* Late stage – the "island model"

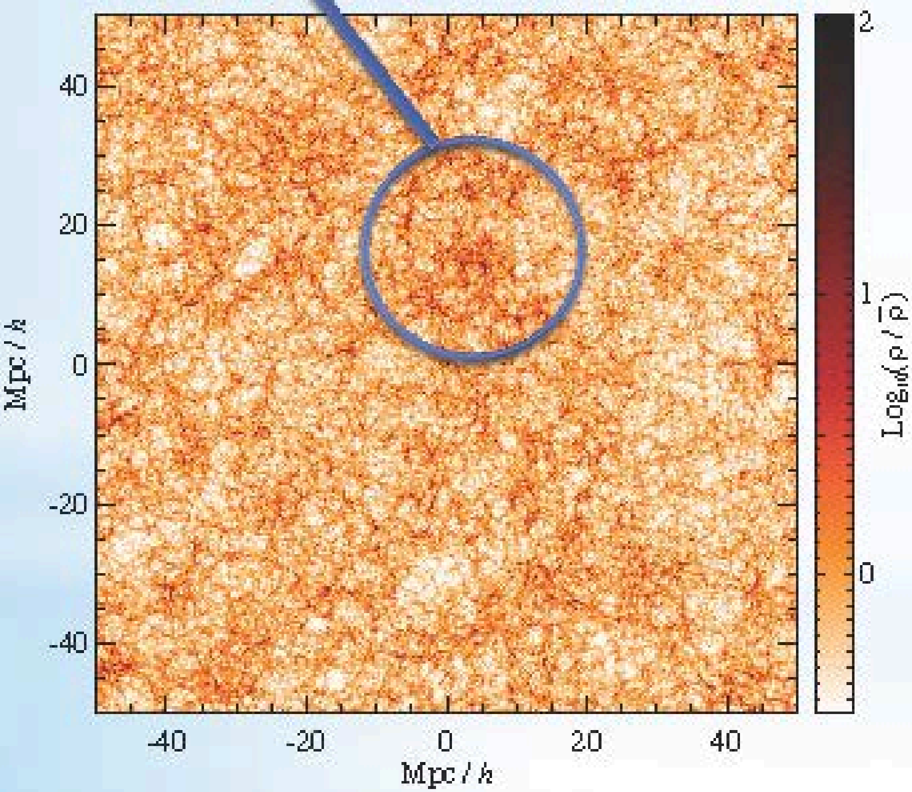
  -- shrinking neutral islands

→ ***Both based on the excursion set theory***

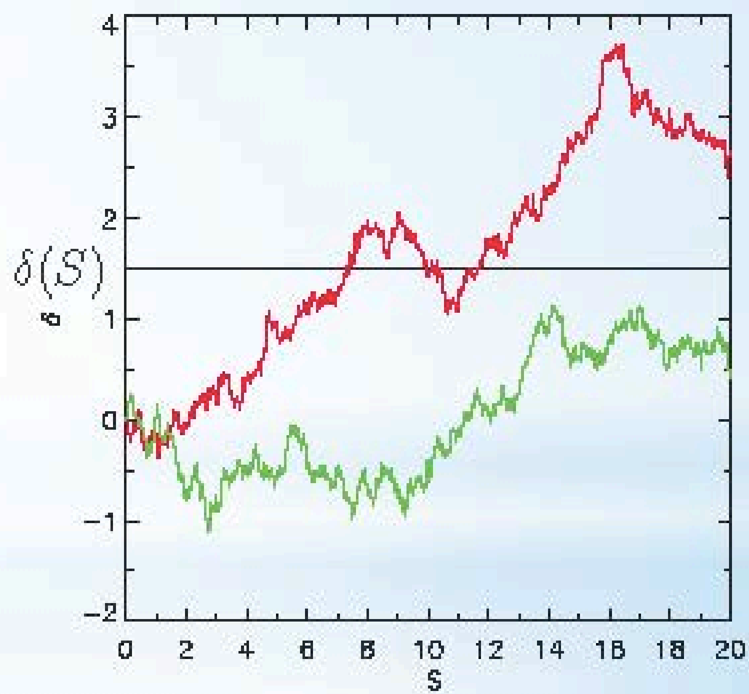
The Excursion Set Theory of Halo Model

(Bond et al. 1991, Lacey & Cole 1993)

$$\delta(\vec{x}; R) \equiv [\rho(\vec{x}) - \rho_{\rm M}]/\rho_{\rm M}.$$



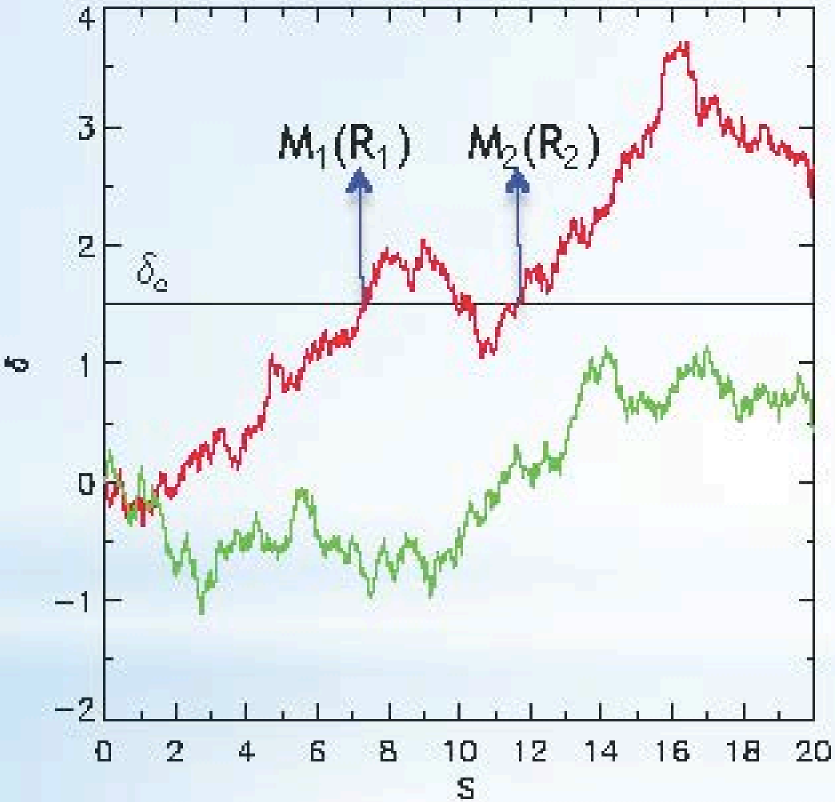
- **k-space top-hat window function**



$$S \equiv \sigma^2(R)$$

The Excursion Set Theory of Halo Model

(Bond et al. 1991, Lacey & Cole 1993)

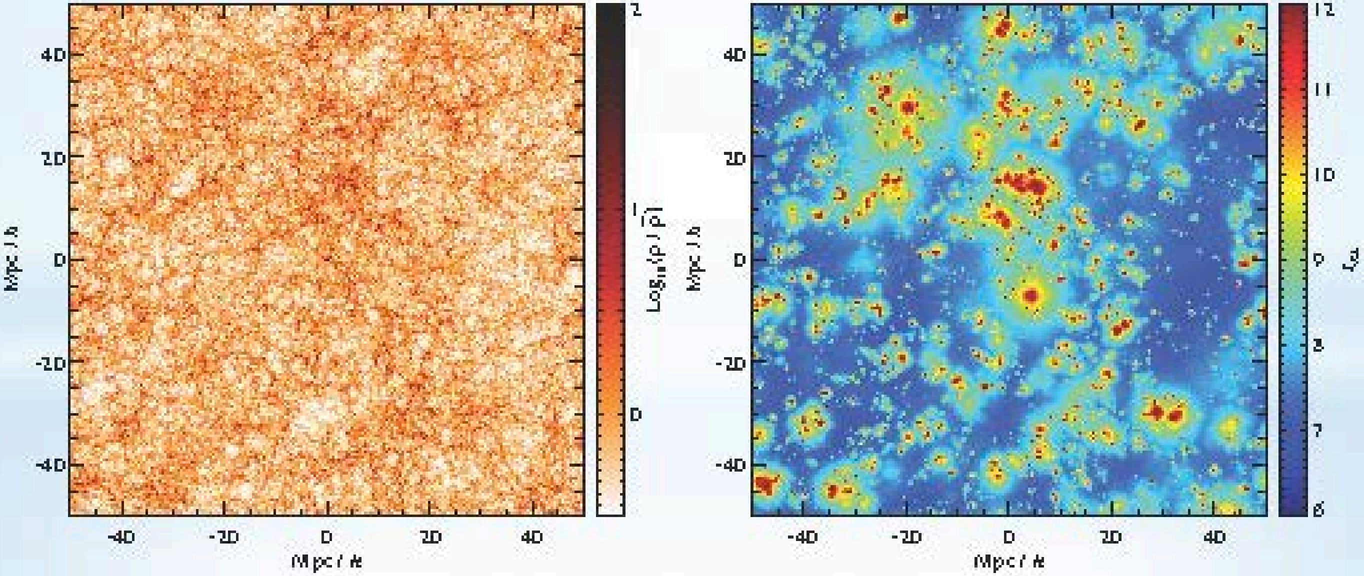


- *The cloud-in-cloud problem*

- **Solving a diffusion equation →** *"first-crossing distribution"* **→ halo mass function**

Why excursion set theory?

→ ***The reionization field follows the density field on large scales (Battaglia et al. 2013)***



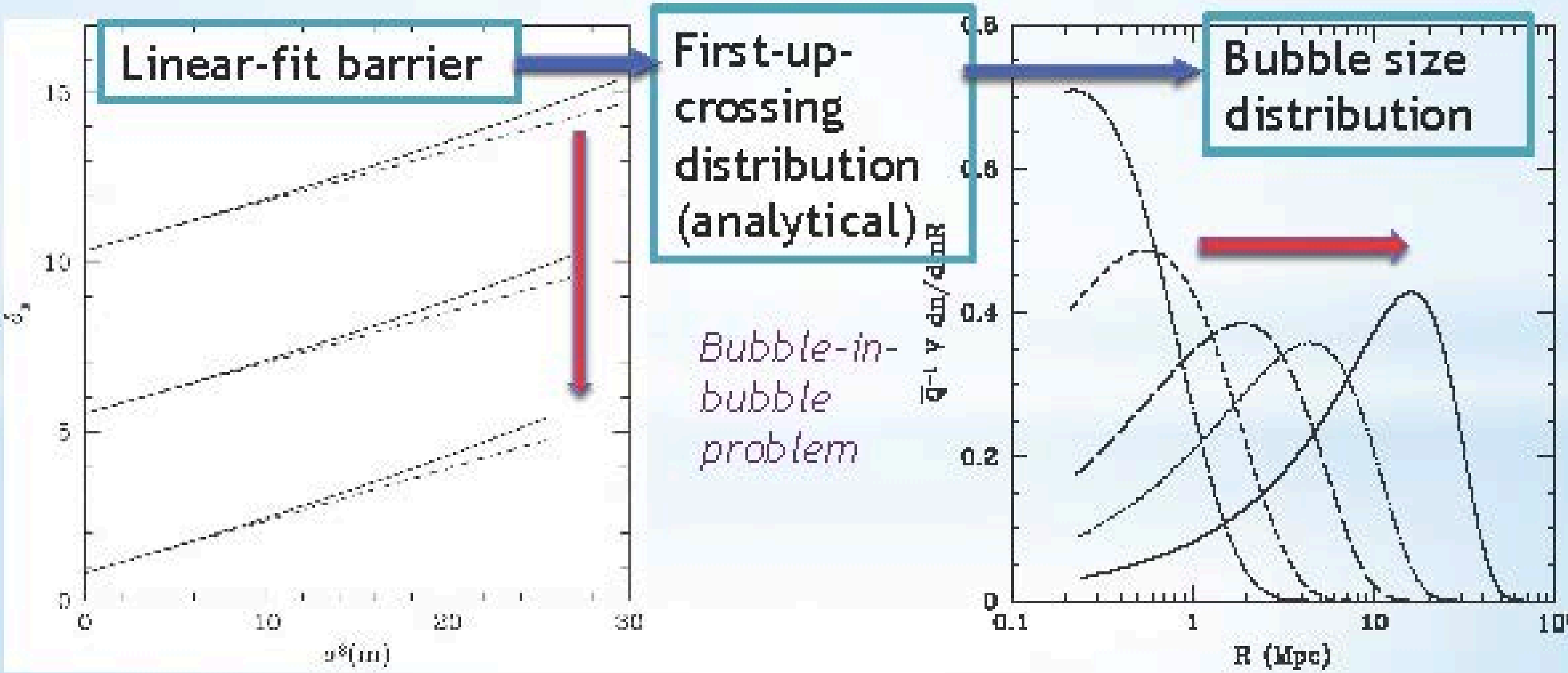
(From Battaglia et al. 2013 ApJ, 776, 81)

The Excursion Set Approach for ionized bubbles – The bubble model of reionization

(Furlanetto et al. 2004)

- Relate the ionization field to the initial density field
- Ask whether an isolated region of mass *M* can be fully self-ionized.

$$f_{coll} > f_x - \zeta^{-1}. \;\longrightarrow\; \delta_m > \delta_x(m, z) \quad \delta_c(z) \quad \sqrt{2}K(\zeta)[\sigma^2_{min} \quad \sigma^2(m)]^{1/2}$$



However, after percolation…

1. The isolated and spherical assumption for the ionized bubbles breaks down

   ➔ the neutral islands are more isolated

2. The existence of an ionizing background

   ➔ the shape of barriers could be changed

   (the linear fit may not apply)

The island model

It would be relatively easier for the upcoming instruments to probe the signal at the late reionization stages.

The Island Model

- Negative island barrier ("inside-out" reionization)
- Island mass scales are identified by ***first-down-crossings*** through the island barrier (but not the "never-up-crossing" distribution).
- With the inclusion of an ionizing background, the condition of keeping from being ionized:

$$\xi f_{\rm coll}(\delta_{\rm M}; M, z) + \frac{\Omega_m}{\Omega_b} \frac{N_{\rm back} m_{\rm H}}{M X_{\rm H}(1 + \bar{n}_{\rm rec})} < 1,$$

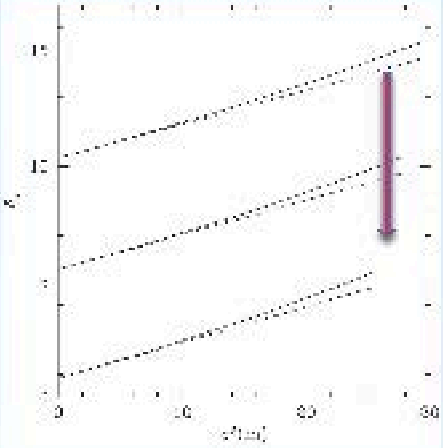
→ The island barrier:

$$\delta_{\rm M} < \delta_{\rm I}(M, z) \equiv \delta_c(z) - \sqrt{2[S_{\rm max} - S(M)]}\,{\rm erfc}^{-1}\left[K(M, z)\right],$$

$$K(M, z) = \xi^{-1}\left[1 - N_{\rm back}(1 + \bar{n}_{\rm rec})^{-1} \frac{m_{\rm H}}{M(\Omega_b/\Omega_m) X_{\rm H}}\right].$$

the integral number of background ionizing photons consumed by an island during the time interval between the setup of an ionizing background and the redshift under consideration.

The Island Model



* Define the ***"background onset time"*** as the time at which the barrier curve passes through the origin point on the δ − S plane

$$\delta_{\rm I}(S=0; z=z_{\rm back}) = \delta_c(z_{\rm back}) - \sqrt{2\,S_{\rm max}(z_{\rm back})}\,{\rm erfc}^{-1}(\xi^{-1}) = 0.$$

* We take $\{f_{\rm esc}, f_*, N_{\gamma/{\rm H}}, \bar{n}_{\rm rec}\} = \{0.2, 0.1, 4000, 1\}$ as the fiducial set of parameters, so that $\xi = 40$ and $z_{\rm back} = 8.6$.

* Solving for the first-down-crossing distribution (Zhang & Hui 2006):

(the "island-in-island" problem is naturally solved)

$$f_{\rm I}(S_{\rm I}) = -g_1(S_{\rm I}) - \int_0^{S_{\rm I}} {\rm d}S' f_{\rm I}(S') \left[g_2(S_{\rm I}, S')\right],$$

$$g_1(S_{\rm I}) = \left[\frac{\delta_{\rm I}(S_{\rm I})}{S_{\rm I}} - 2\frac{{\rm d}\delta_{\rm I}}{{\rm d}S_{\rm I}}\right] P_0[\delta_{\rm I}(S_{\rm I}), S_{\rm I}], \quad P_0(\delta, S) = \frac{1}{\sqrt{2\pi S}} \exp\left(-\frac{\delta^2}{2S}\right)$$

$$g_2(S_{\rm I}, S') = \left[2\frac{{\rm d}\delta_{\rm I}}{{\rm d}S_{\rm I}} - \frac{\delta_{\rm I}(S_{\rm I}) - \delta_{\rm I}(S')}{S_{\rm I} - S'}\right] P_0[\delta_{\rm I}(S_{\rm I}) - \delta_{\rm I}(S'), S_{\rm I} - S'],$$

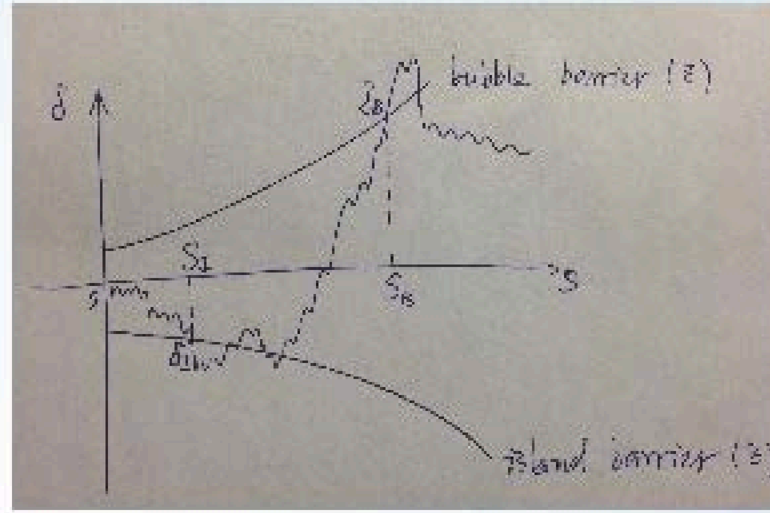
* The mass function of islands:

$$\frac{{\rm d}n}{{\rm d}\ln M_{\rm I}}(M_{\rm I}, z) = \bar{\rho}_{\rm m,0} f_{\rm I}(S_{\rm I}, z) \left|\frac{{\rm d}S_{\rm I}}{{\rm d}M_{\rm I}}\right|$$

* The volume fraction of neutral regions:

$$Q_{\rm V}^{\rm I} = \int {\rm d}M_{\rm I} \frac{{\rm d}n}{{\rm d}M_{\rm I}} V(M_{\rm I}).$$

The bubbles-in-island effect



* Solving for a two-barrier problem:

1 - The first down-crossing distribution of random walks w.r.t. ***island barrier***:

$$f_{\mathrm{I}}(S_{\mathrm{I}}, z)$$

2 - The conditional first up-crossing distribution w.r.t. ***bubble barrier***: $f_{\mathrm{B}}[S_{\mathrm{B}}, \delta_{\mathrm{B}} | S_{\mathrm{I}}, \delta_{\mathrm{I}}]$

* The effective bubble barrier:

$$\delta'_{\mathrm{B}} = \delta_{\mathrm{B}}(S + S_{\mathrm{I}}) - \delta_{\mathrm{I}}(S_{\mathrm{I}}) \qquad \text{where } S = S_{\mathrm{B}} - S_{\mathrm{I}}.$$

The bubbles-in-island effect

* The bubbles-in-island fraction:

$$q_{\rm B}(S_{\rm I},\delta_{\rm I};z) = \int_{S_{\rm I}}^{S_{\rm max}(\xi M_{\rm min})} [1+\delta_{\rm I}\,D(z)]\; f_{\rm B}[S_{\rm B},\delta_{\rm B}|S_{\rm I},\delta_{\rm I}]\,{\rm d}S_{\rm B}.$$

* The neutral island mass function:

$$\frac{dn}{dM}(M,z) = \frac{dn}{dM_{\rm I}}\frac{dM_{\rm I}}{dM} = \frac{\bar{\rho}_{\rm m,0}}{M_{\rm I}} f_{\rm I}(S_{\rm I},z)\left|\frac{dS_{\rm I}}{dM_{\rm I}}\right|\frac{dM_{\rm I}}{dM}.$$

$$M = M_{\rm I}(S_{\rm I})\,[1-q_{\rm B}(S_{\rm I},\delta_{\rm I};z)]$$

The ionizing background

* Considering the effect of ***Lyman limit systems*** on the mean free path of ionizing photons, the comoving number density of background ionizing photons is

$$n_\gamma(z) = \int_z \bar{n}_{\rm H} \left| \frac{{\rm d} f_{\rm coll}(z')}{{\rm d}z'} \right| f_* N_{\gamma/{\rm H}} f_{\rm esc} \exp\left[-\frac{l(z,z')}{\lambda_{\rm mfp}(z)} \right] {\rm d}z',$$

* With the MHR00 model for the volume-weighted density distribution of the IGM (Miralda-Escude et al. 2000),

$$P_V(\Delta)\, d\Delta = A_0 \exp\left[-\frac{(\Delta^{-2/3} - C_0)^2}{2\,(2\delta_0/3)^2} \right] \Delta^{-\beta}\, d\Delta$$

the mean free path of ionizing photons can be written as

$$\lambda_{\rm mfp} = \frac{\lambda_0}{[1 - F_V(\Delta_{\rm crit})]^{2/3}},$$

The ionizing background

* The critical relative density for a clump to self-shield

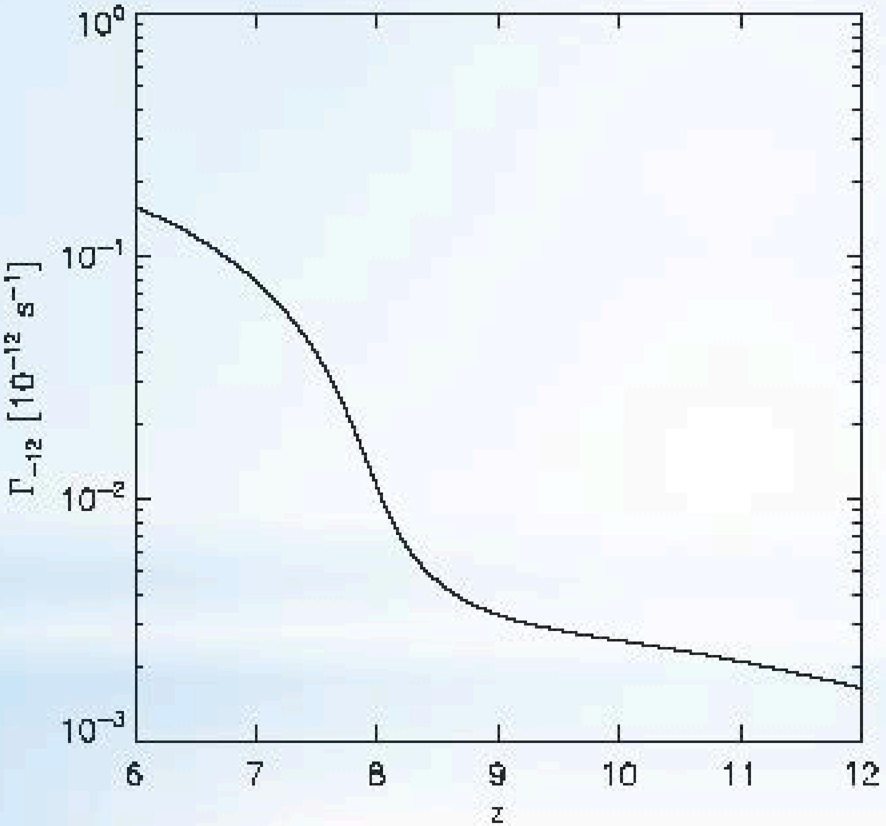
$$\Delta_{\rm crit} = 36\,\Gamma_{-12}^{2/3}\,T_4^{2/15}\left(\frac{\mu}{0.61}\right)^{1/3}\left(\frac{f_e}{1.08}\right)^{-2/3}\left(\frac{1+z}{8}\right)^{-3}$$

* The HI photoionization rate Γ_{HI} is related to the total number density of ionizing photons n_γ by

$$\Gamma_{\rm HI} = \int \frac{{\rm d}n_\gamma}{{\rm d}\nu}\,(1+z)^3\,c\,\sigma_\nu\,{\rm d}\nu,$$

* Scaling the hydrogen photoionization rate to be $\Gamma_{HI} = 10^{-12.8}\ s^{-1}$ at redshift 6, as suggested by recent measurements from the Ly-α forest (Wyithe & Bolton 2011; Calverley et al. 2011)

The ionizing background



* Consistent with our definition of the "background onset time"

The island-γS model

* We assume that the photons consumed by an island at any instant is proportional to its surface area, then

$$N_{\rm back} = \int F(z)\, \Sigma_{\rm I}(t)\, {\rm d}t, \qquad F(z) = n_\gamma(z)(1+z)^3\, c/4.$$

* For a spherical island,

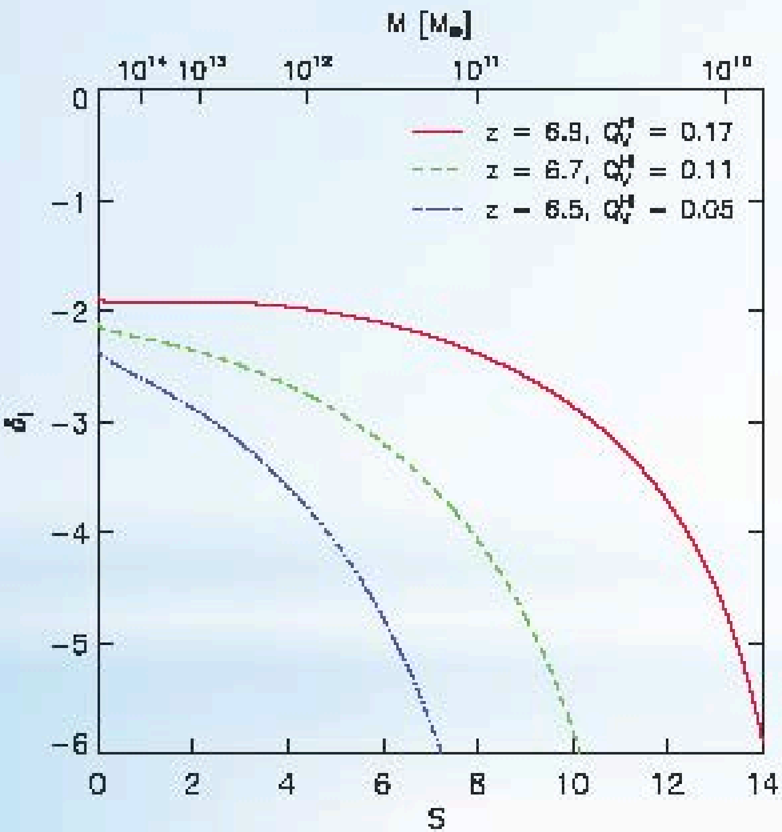
$$n_{\rm H}(R)(1+\bar{n}_{\rm rec})\, 4\pi R^2\, (-{\rm d}R) = F(z)\, \frac{4\pi R^2}{(1+z)^2}\, {\rm d}t,$$

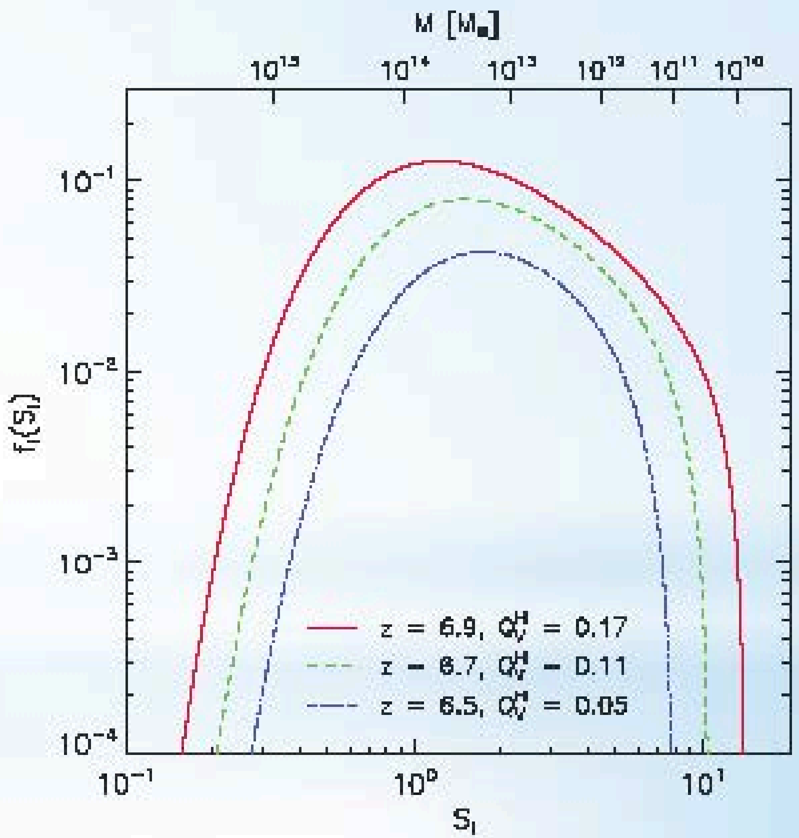
$$\Delta R \equiv R_i - R_f = \int_z^{z_{\rm back}} \frac{F(z)}{\bar{n}_{\rm H}(1+\bar{n}_{\rm rec})}\, \frac{{\rm d}z}{H(z)(1+z)^3},$$

* The total number of background ionizing photons consumed is

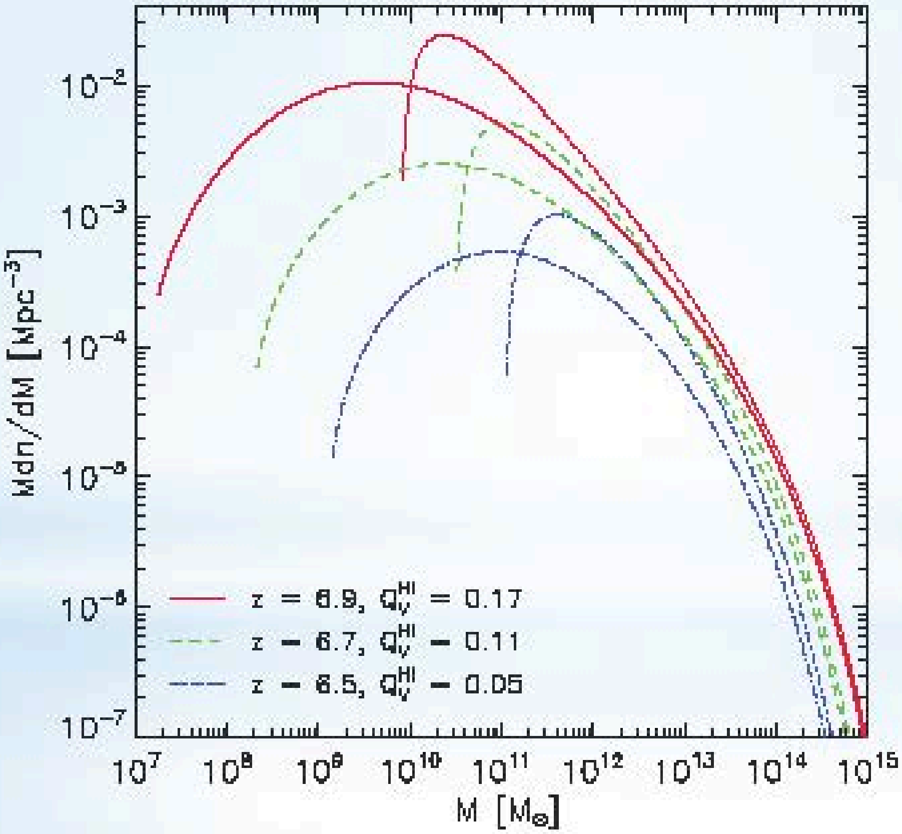
$$N_{\rm back} = \frac{4\pi}{3}\, (R_i^3 - R_f^3)\, \bar{n}_{\rm H}(1+\bar{n}_{\rm rec}),$$

The island-vS model
– the island barrier and first down-crossing distribution





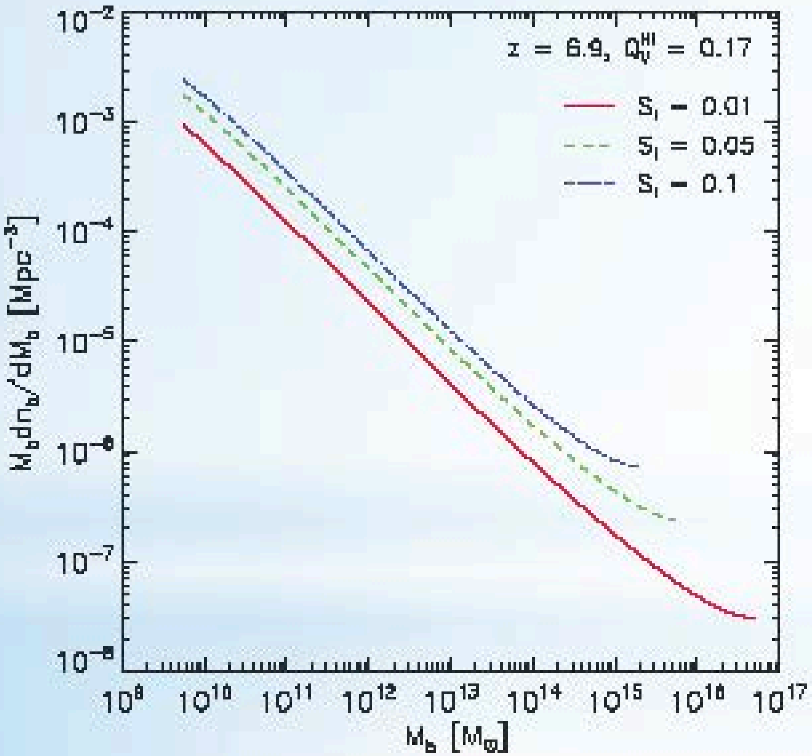
The island-vS model
- the host island mass function

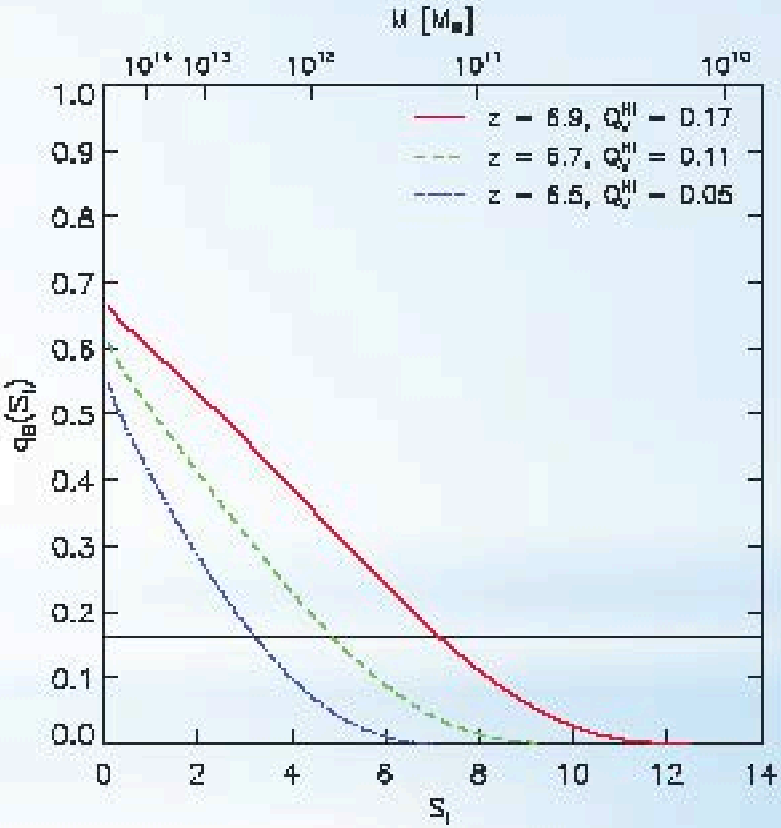


- The shrinking hosts

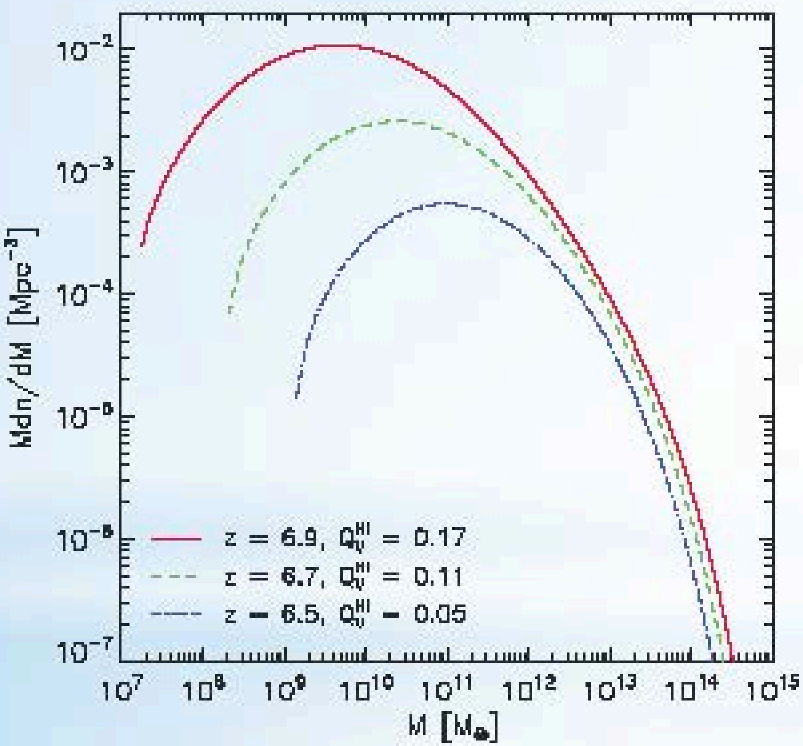
$$\frac{M_f}{M_i} = (1 - \frac{\Delta R}{R_i})^3$$

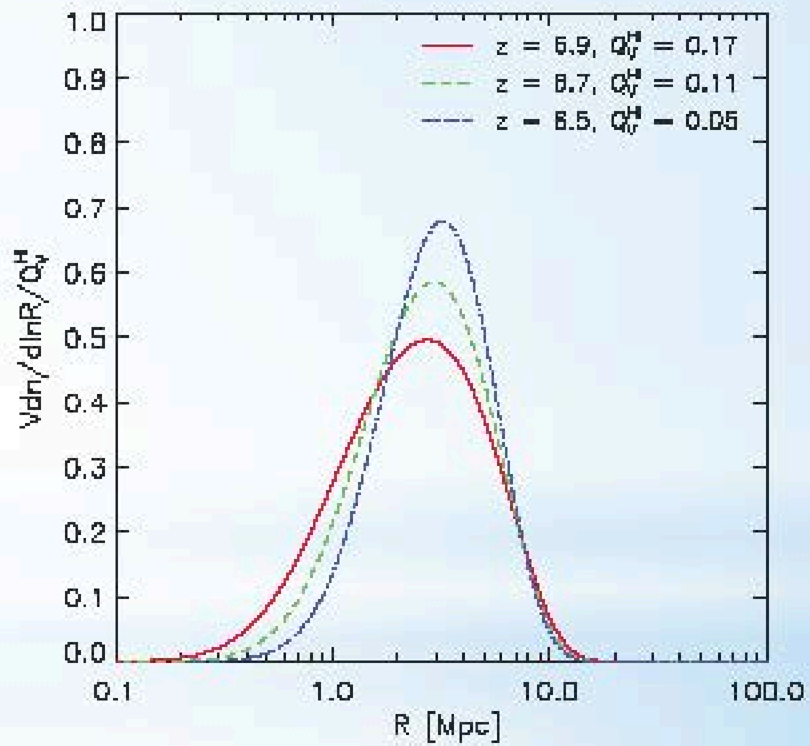
The island-vS model
- the bubbles-in-island



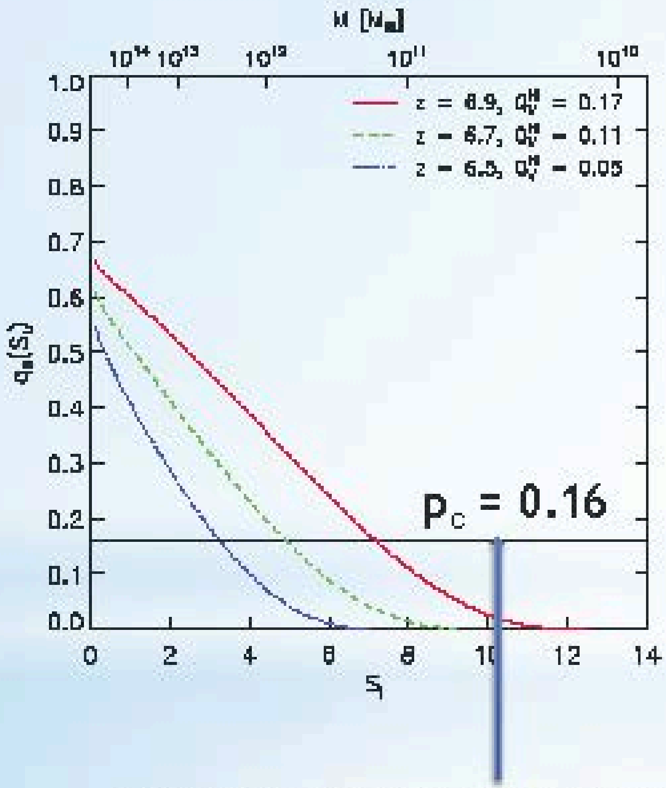


The island-νS model
- the mass function and size distribution





The problem of large bubbles-in-island fraction



for Gaussian random fields

* Host islands → overestimate the neutral fraction
* Neutral islands → not the real image
* Difficult to visually identify the host islands
* Break down of bubble model inside islands

The role of percolation threshold p_c

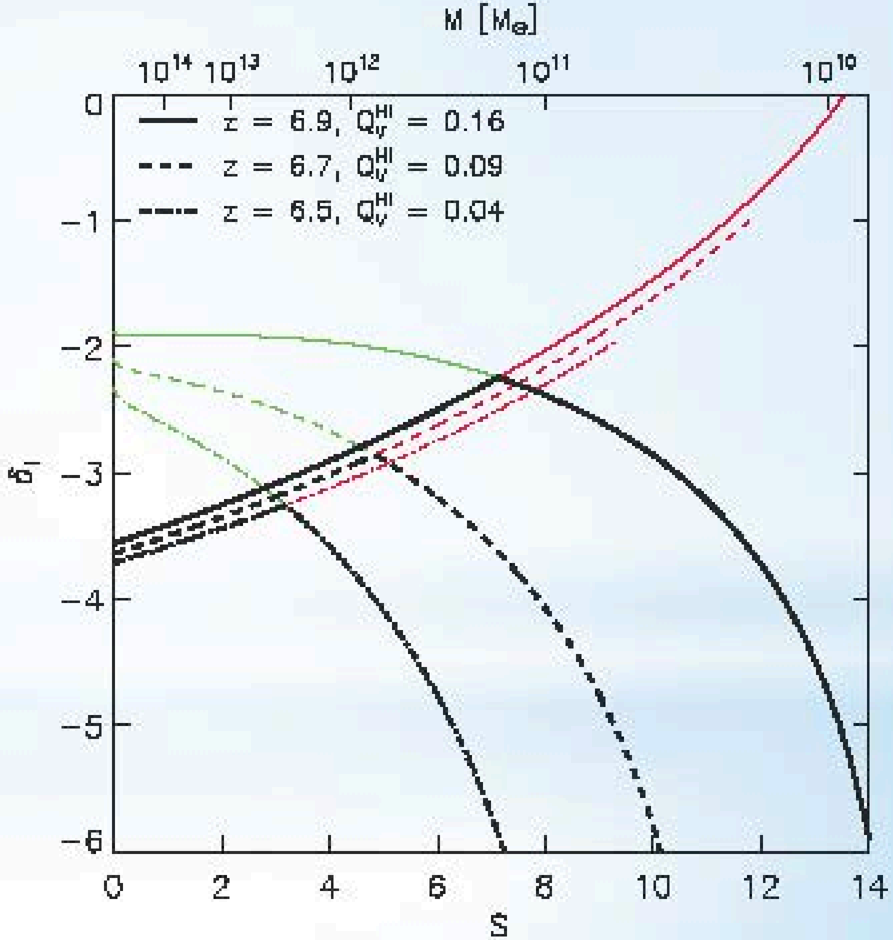
* The bubble model regime: $z > z_{Bp}$ ($x_{HII} < p_c$)
* The island model regime: $z < z_{Ip}$ ($x_{HI} < p_c$)
* The background onset redshift: $z_{Bp} > z_{back} > z_{Ip}$
* The definition of bona fide neutral islands: $q_B < p_c$

The percolation criterion

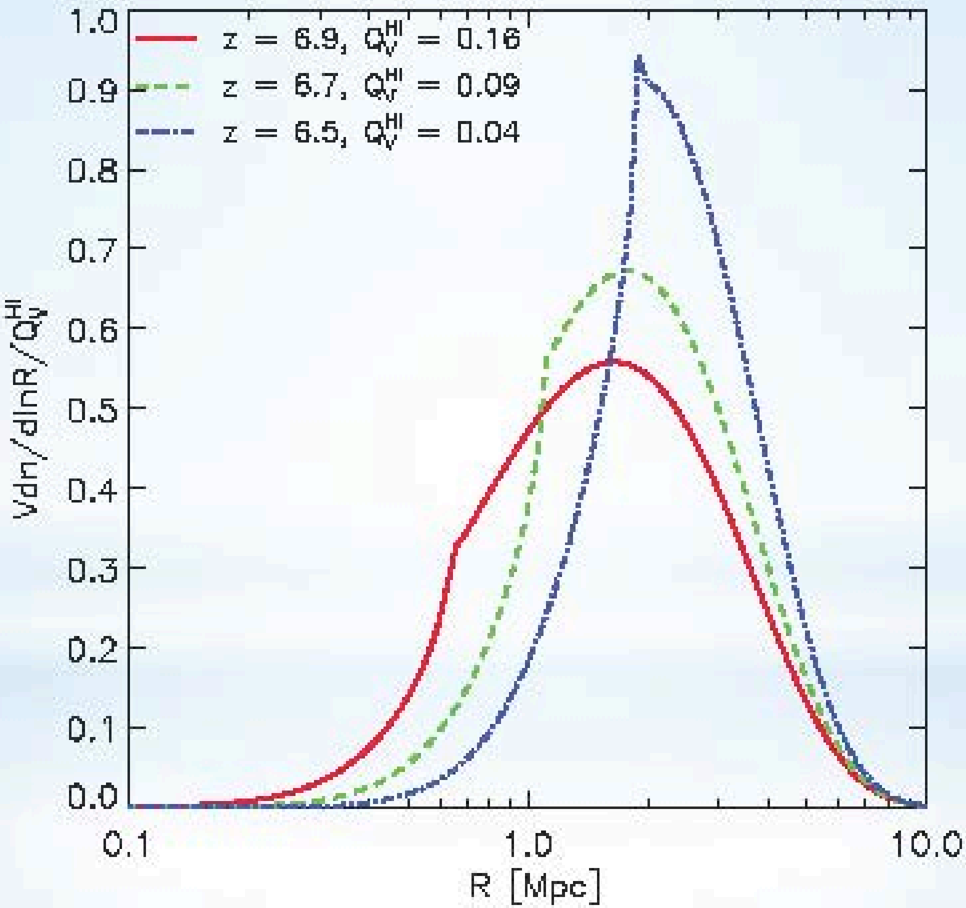
* The additional barrier is obtained by solving

  $q_B(S_I, \delta_I; z) < p_c$

* p_c = 0.16 for Gaussian random fields



Results
- the size distribution with p_c cutoff



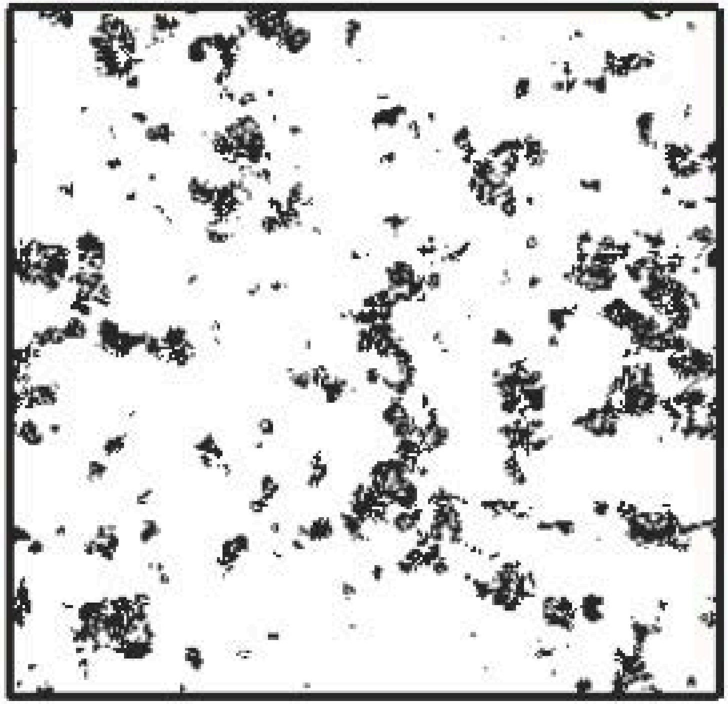
Summary

* It is challenging to explain the measured level of NIRB fluctuations, the source-subtracted signal is >10 times higher than expected from distant galaxies below the detection limit.
* We propose that the Compton-thick, intermediate-mass BHs formed through direct collapse are possible sources.
* This model predicts the NIRB angular power spectrum and the NIRB-CXB cross-correlation agrees well with observations.
* DCBHs themselves are bright at the LW band, they can trigger the formation of more other DCBHs, and a runaway formation process is ignited.
* This process is quenched by the reionization after z ~ 13.

Summary

* An analytical model of neutral islands during the late EoR based on the excursion set theory.
  * An island barrier on the density contrast for the islands to remain neutral, with the inclusion of an ionizing background.
  * An island was identified when the random walk first-down-crosses the island barrier.
  * We took into account the effect of bubbles-in-island by computing the conditional first up-crossing distribution.
  * An semi-empirical way to determine the intensity of the ionizing background self-consistently.
  * A percolation criterion was applied to find bona fide neutral islands
* The size distribution of neutral islands shows a peak indicating a characteristic scale of the islands, and it does not change much with redshift.

THANK YOU!



512 Mpc, 1024^3

low redshift faint galaxies (z<5)

* Helgason et al. 2012:
  * get the number count of galaxies in multiband observations of LFs
  * extrapolate to faint magnitude
  * reconstruct the NIRB fluctuations
  * galaxies clustering is from the halo model

high redshift faint galaxies (z>5)

* Yue et al. 2013:
  * reionization (the escape fraction, Mitra et al. 2012,2013)
  * observed LFs
  * simulations (Salvaterra et al. 2011)

-- 10 h^{-1}Mpc, including gas dynamics, radiative cooling, supernova explosion, photoionization and heating, and a detailed treatment of chemical enrichment.

-- agree well with the observed LF!

A toy model - island-Y

- The ionizing photons permeated through the neutral islands with a uniform density (X-rays)
  - Extremely large mean free path
  - Neglecting the absorption by dense clumps

- The averaged number density of the background ionizing photons

$$n_\gamma = \bar{n}_{\rm H} \, f_{\rm coll}(z) \, f_\star \, N_{\gamma/{\rm H}} \, f_{\rm esc} - (1 - Q_{\rm V}^{\rm I}) \, \bar{n}_{\rm H} \, (1 + \bar{n}_{\rm rec}),$$

A toy model - island-V

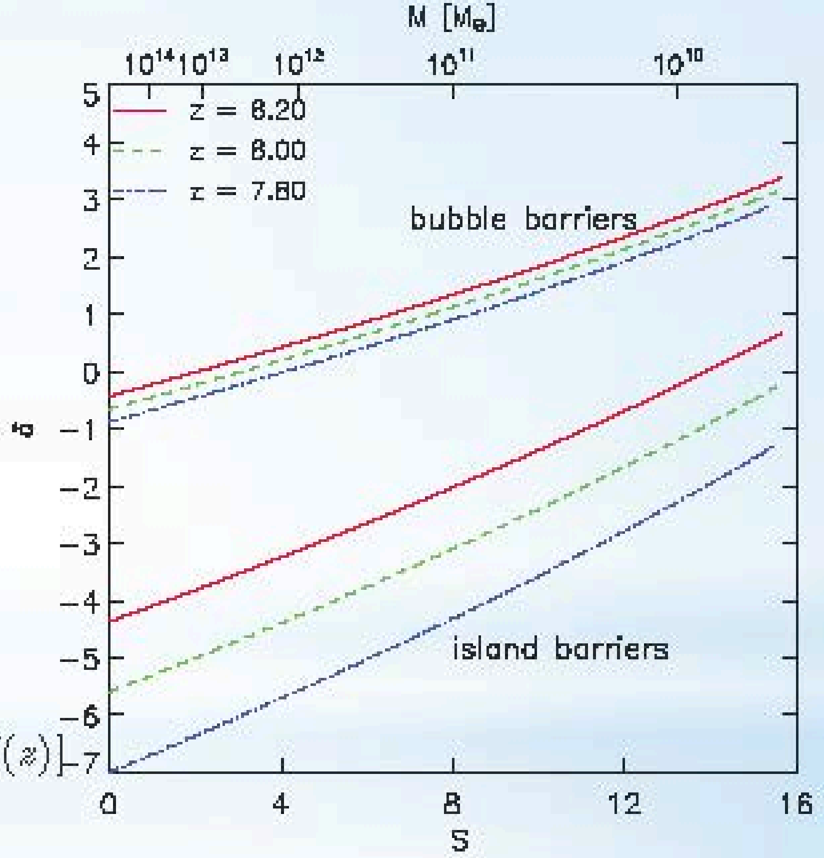
$$\delta_M < \delta_I(M,z) \equiv \delta_c(z) - \sqrt{2[S_{max} - S(M)]}\,\mathrm{erfc}^{-1}[K(M,z)],$$

$$K(M,z) = \xi^{-1}\left[1 - N_{back}(1+\bar{n}_{rec})^{-1}\frac{m_H}{M(\Omega_b/\Omega_m)X_H}\right].$$

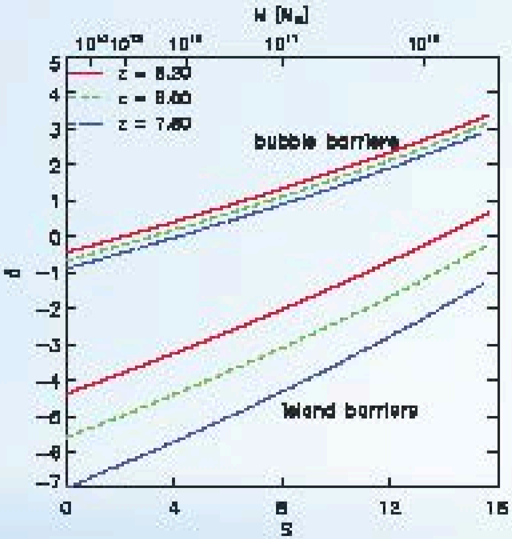
- N_{back} proportional to V

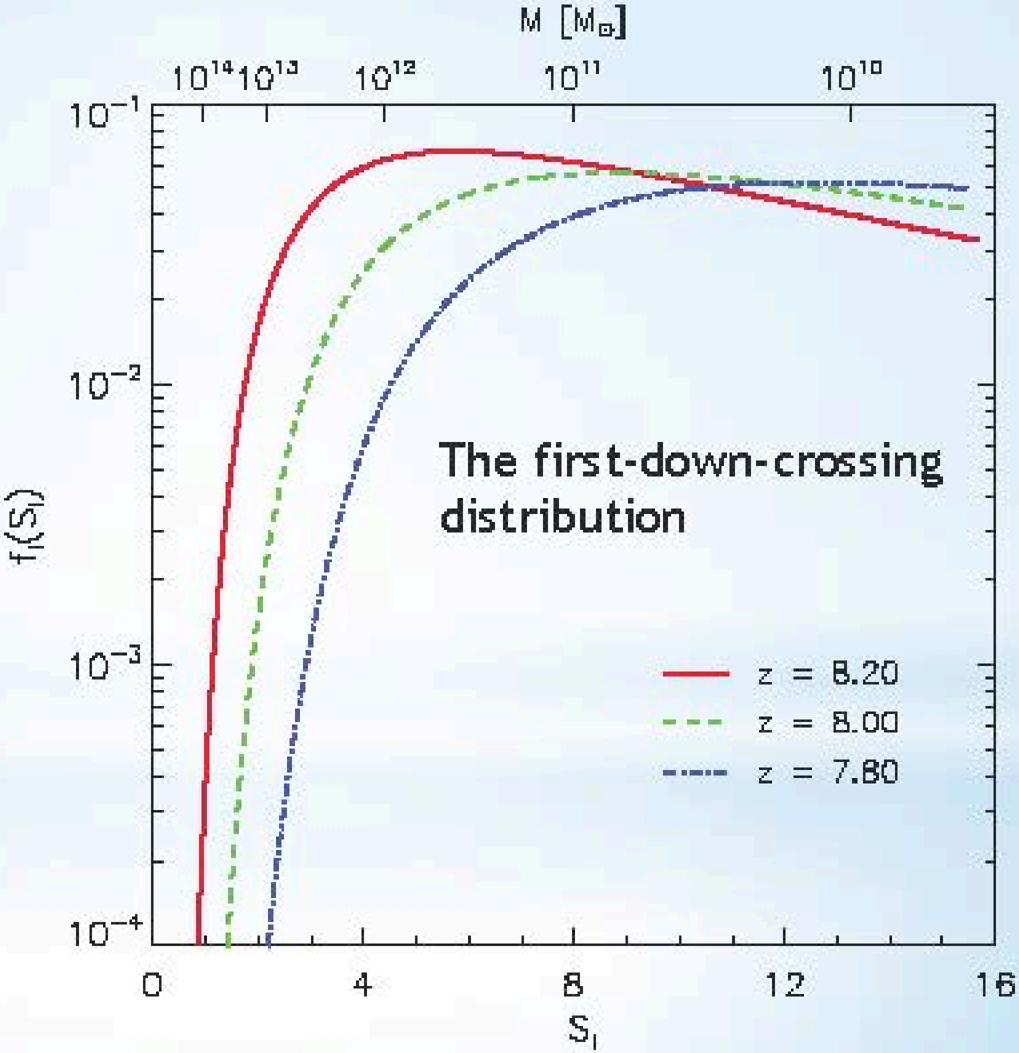
$$N_{back}/M = n_\gamma/\bar{\rho}_m$$

$$\delta_I(M,z) = \delta_c(z) - \sqrt{2\left[S_{max} - S(M)\right]}\,\mathrm{erfc}^{-1}\left[K(z)\right]$$



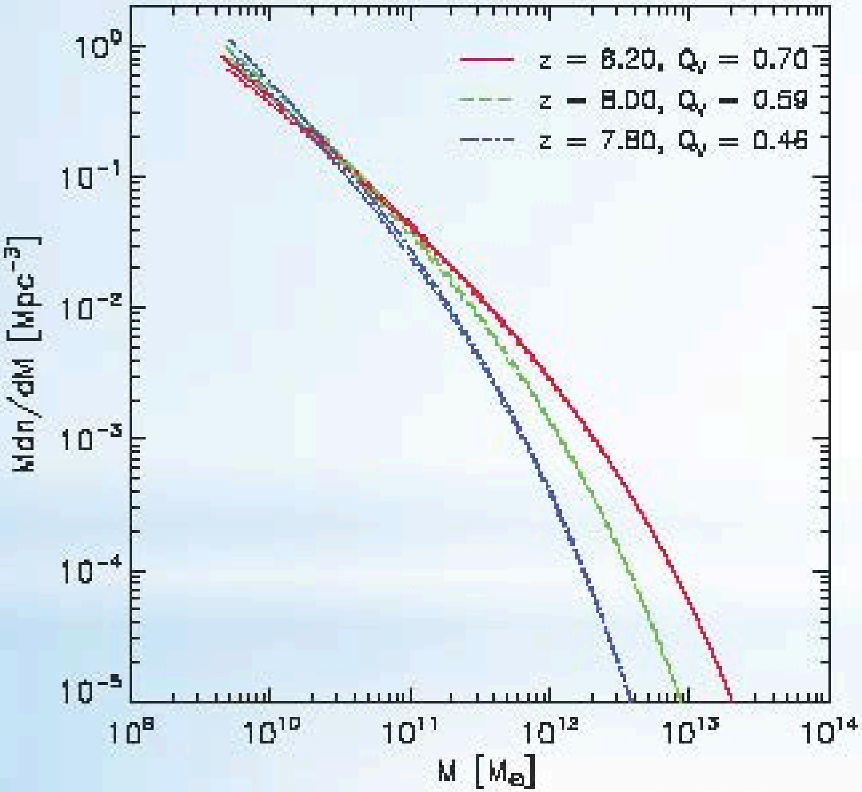
A toy model - island-V





A toy model - island-V

Mass function of islands



Size distribution of islands