宇宙再電離:最新観測からの制限

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初代星・初代銀河形成研究会
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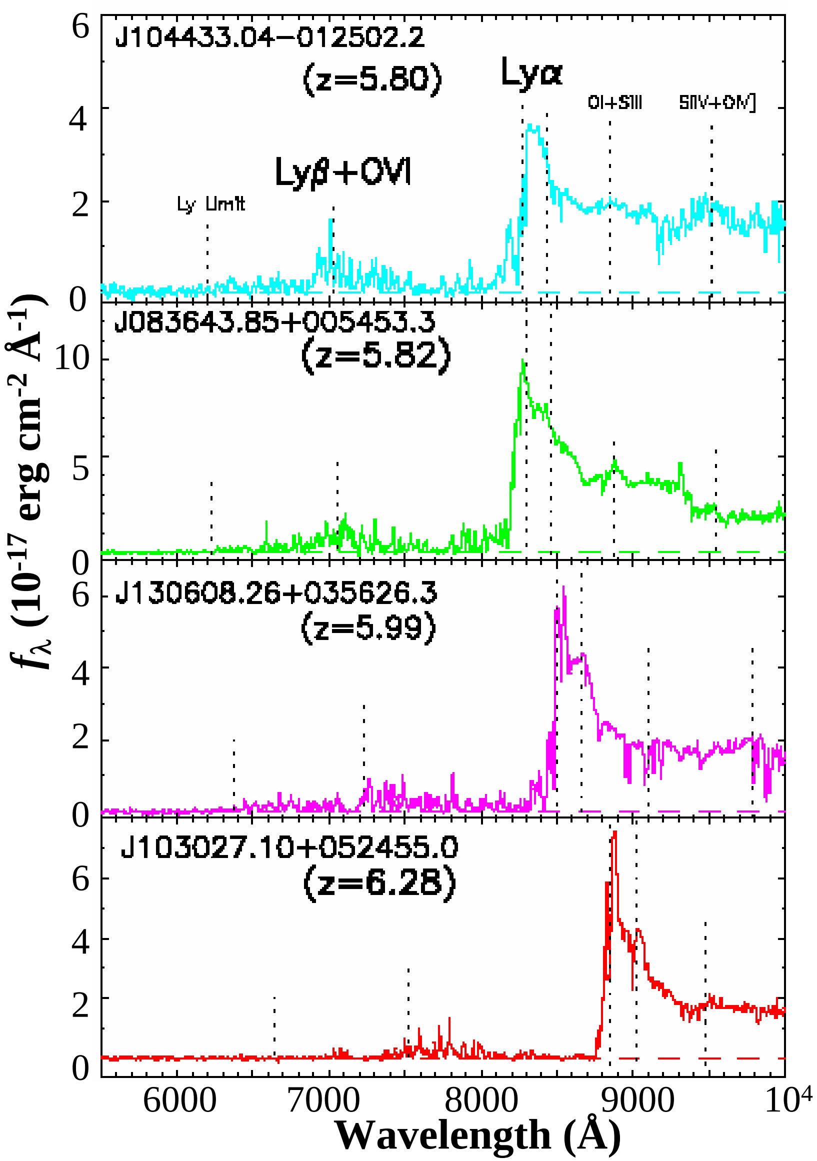
   (Hirose, Umemura 2006)

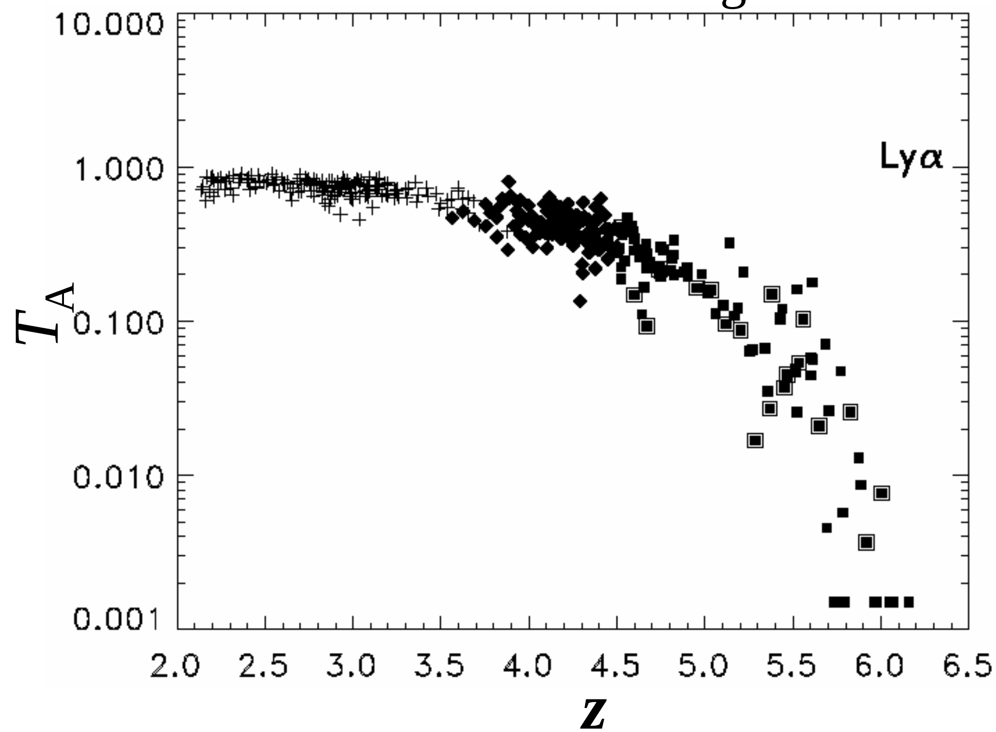
Transmitted Fraction at High z

Becker et al. 2001



$$T_A \equiv \langle f_\lambda / f_{\rm cont} \rangle$$

Songaila 2004



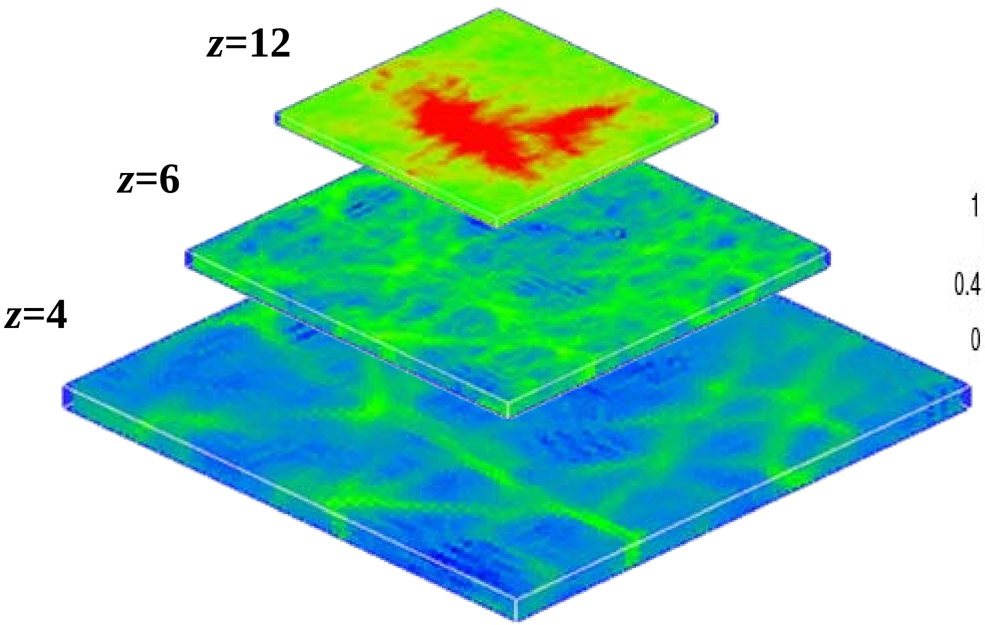
宇宙再電離3次元輻射輸送計算

ΛCDM

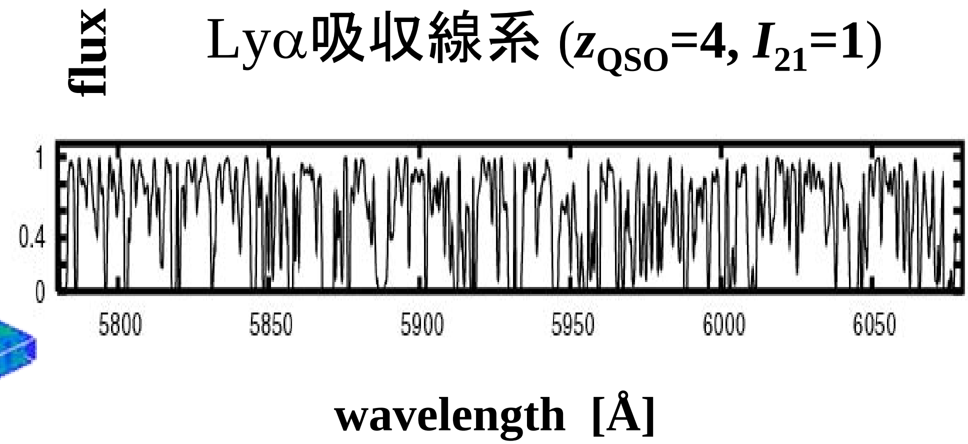
$\Omega_m=0.3, \Omega_\Lambda=0.7, \Omega_b h^2=0.02, H_0=70\text{km s}^{-1}\text{ Mpc}^{-1}$

UVB Intensity:

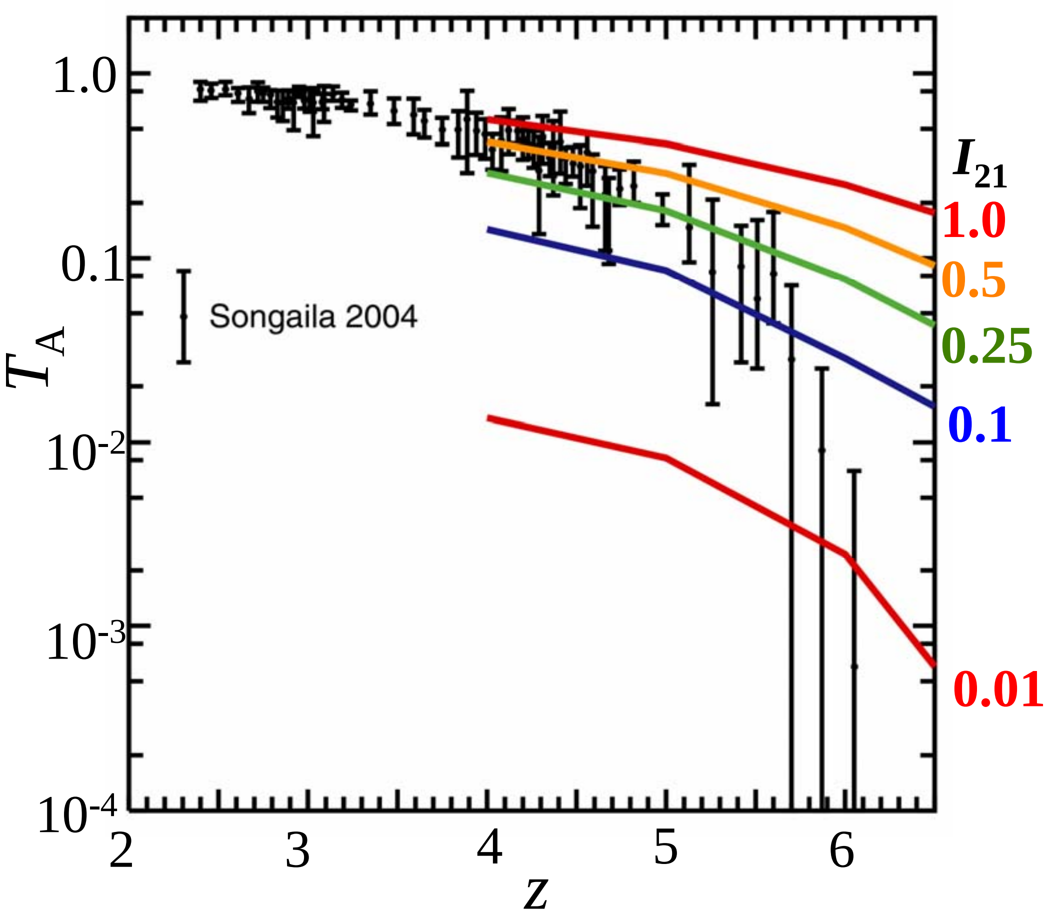
$I_0=I_{21}\,10^{-21}(\nu/\nu_L)^{-1}$ erg s^{-1} cm^{-2} Hz^{-1} str^{-1}



Lyα吸収線系 (z_{QSO}=4, I_{21}=1)



UVB Intensity への制限



at $4 \leq z < 5$

$0.25 \leq I_{21} \leq 1$

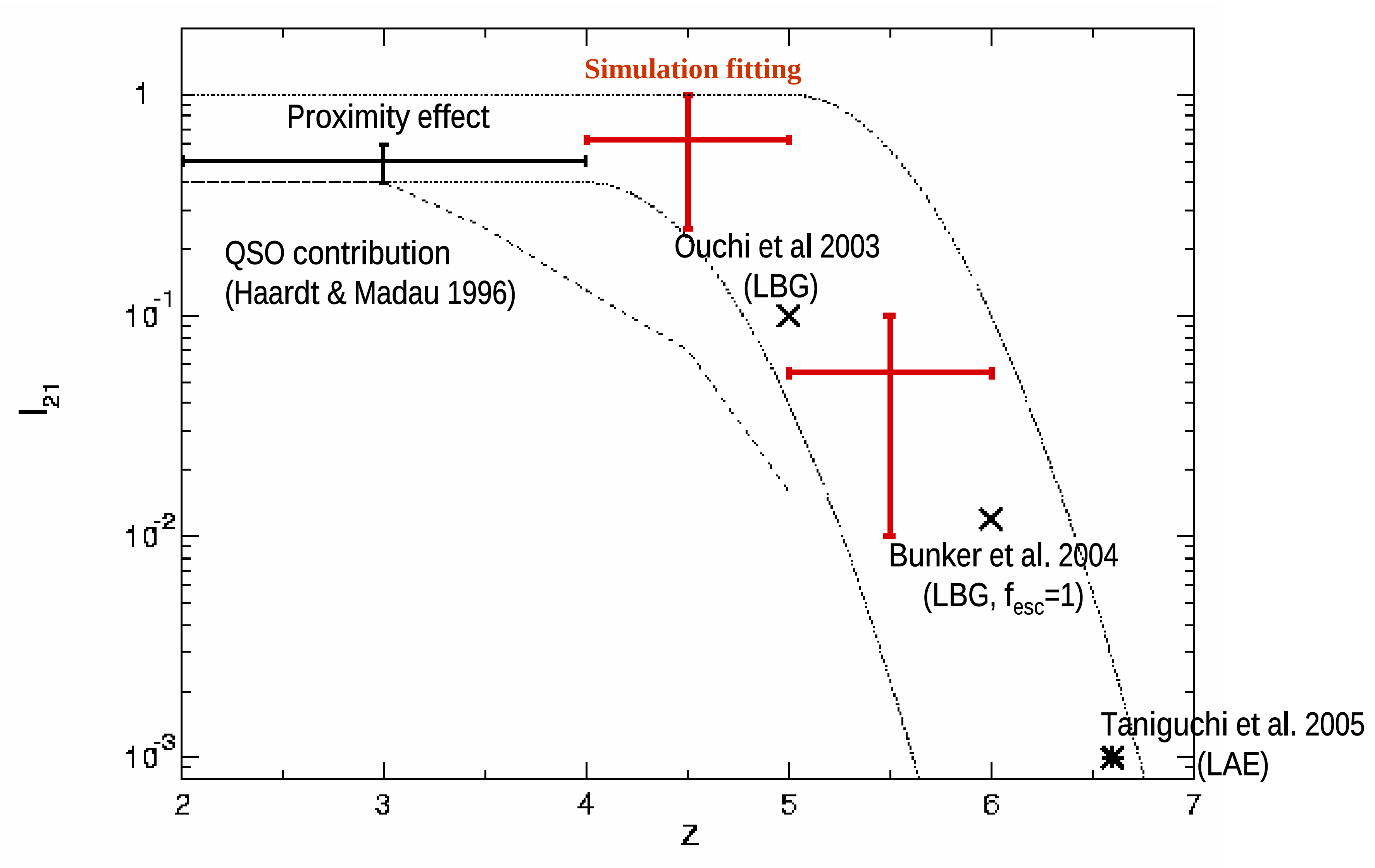
at $5 \leq z \leq 6$

$0.01 \leq I_{21} \leq 0.1$

Constraints on UV Background Radiation at 3<z<7

Hiroi, Umemura, Nakamoto, 2006 in prep

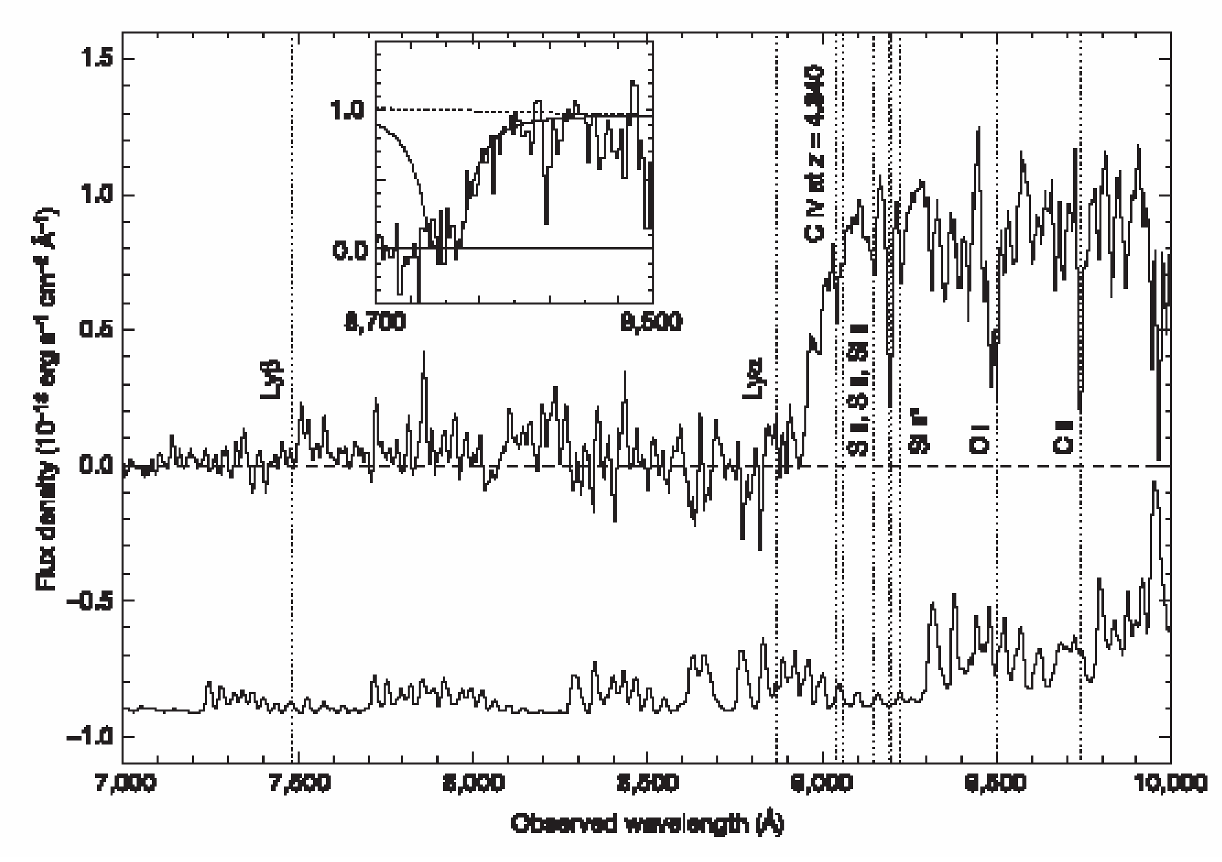
$$I_0 = I_{21}\ 10^{-21} (\nu / \nu_L)^{-1}\ \text{erg s}^{-1}\ \text{cm}^{-2}\ \text{Hz}^{-1}\ \text{str}^{-1}$$



GRB 050904 (z=6.295)

Kawai et al. 2006, Nature, 440, 184
Totani, et al. 2006, PASJ, 58, 485-498

$$X_{\rm HI} = 0.00 \pm 0.17 \text{ (<0.6 at 95\%CL)}$$



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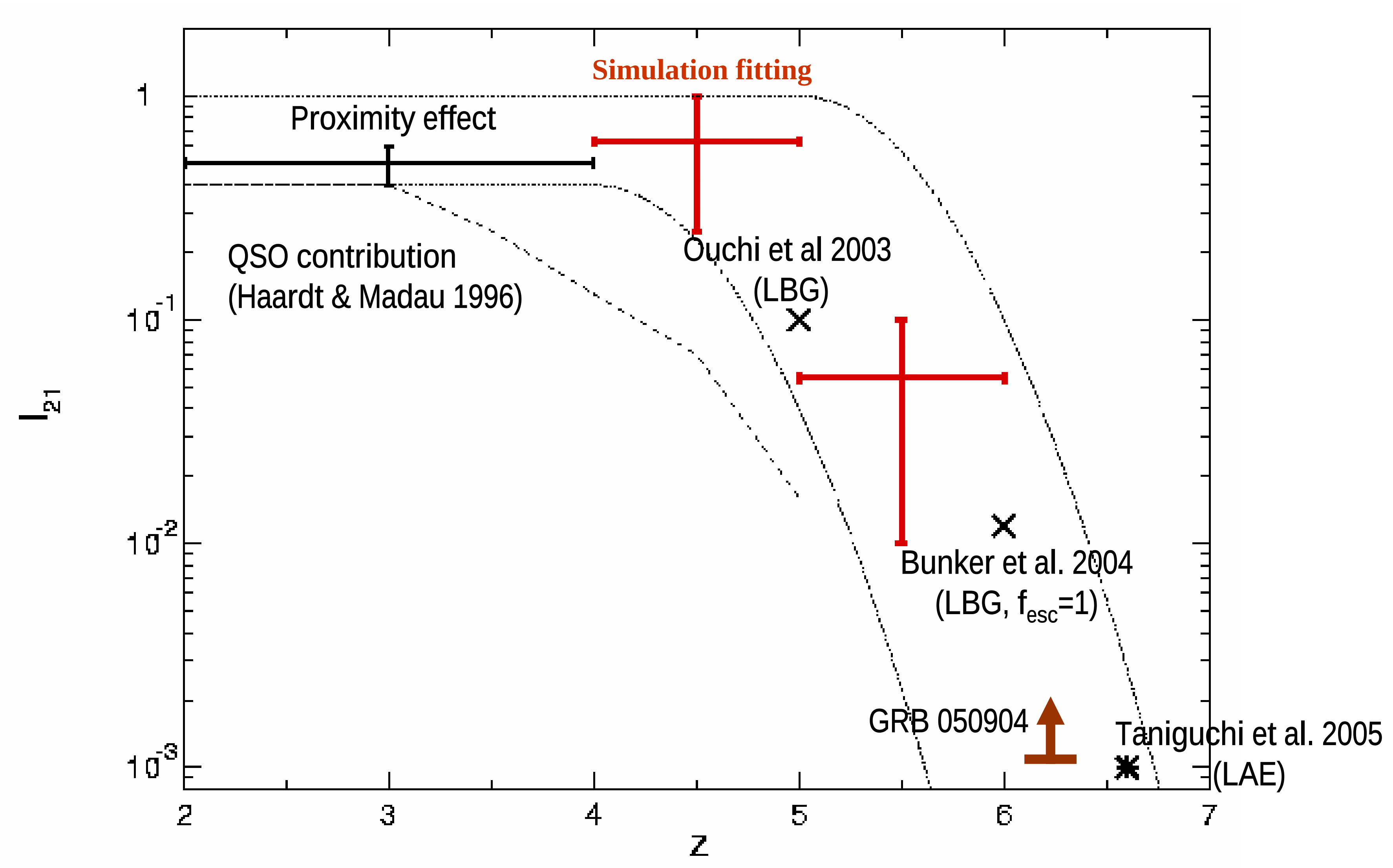


WMAP Tree Year Results
&
Reionization of the Universe

$\Omega_{tot} = 1.00$

$\Omega_{\Lambda 0} = 0.72$

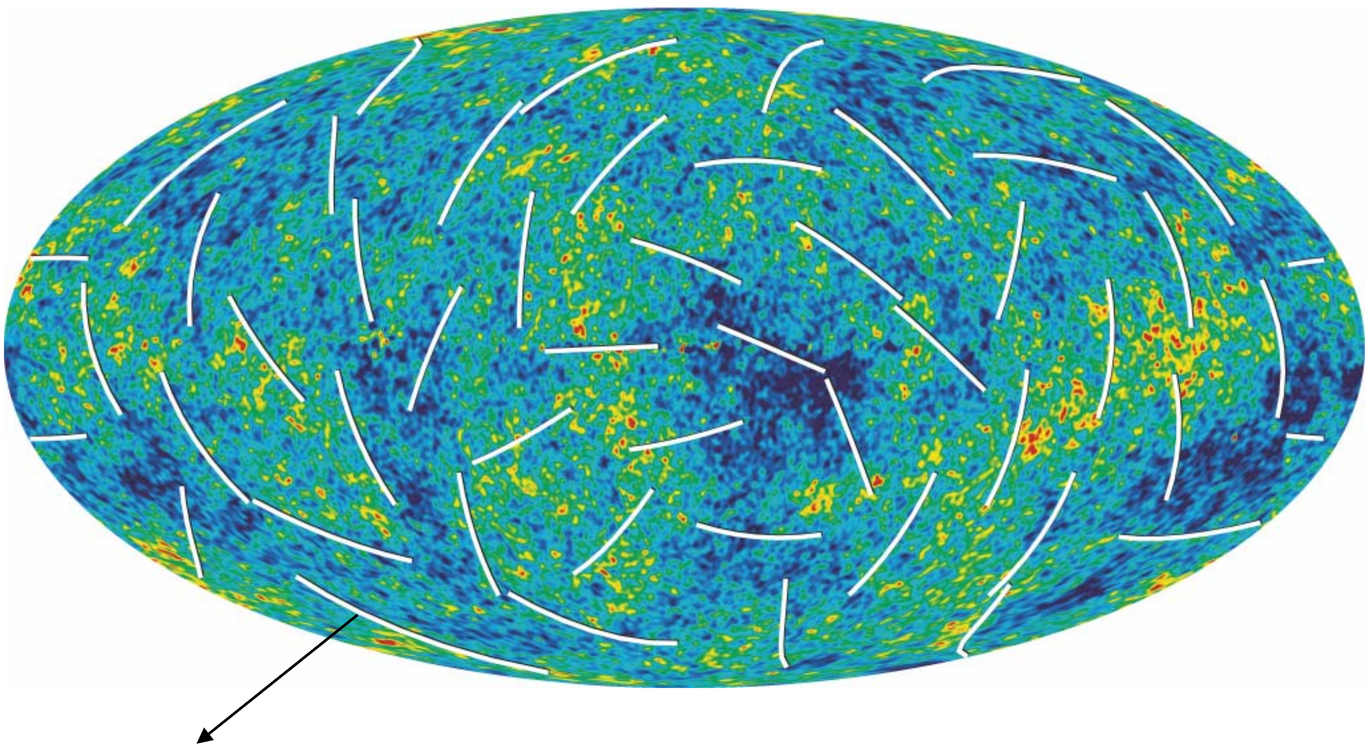
$\Omega_{\mathrm{CDM}} h_0^2 = 0.127$

$\Omega_b h_0^2 = 0.0223$

$\sigma_8 = 0.74$

$n = 0.951$

$h_0 = 0.73$



polarization pattern

$$\tau_e = 0.09 \pm 0.03$$

$$\Downarrow$$

$$z_{\mathrm{reion}} = 8.6 - 13.6$$

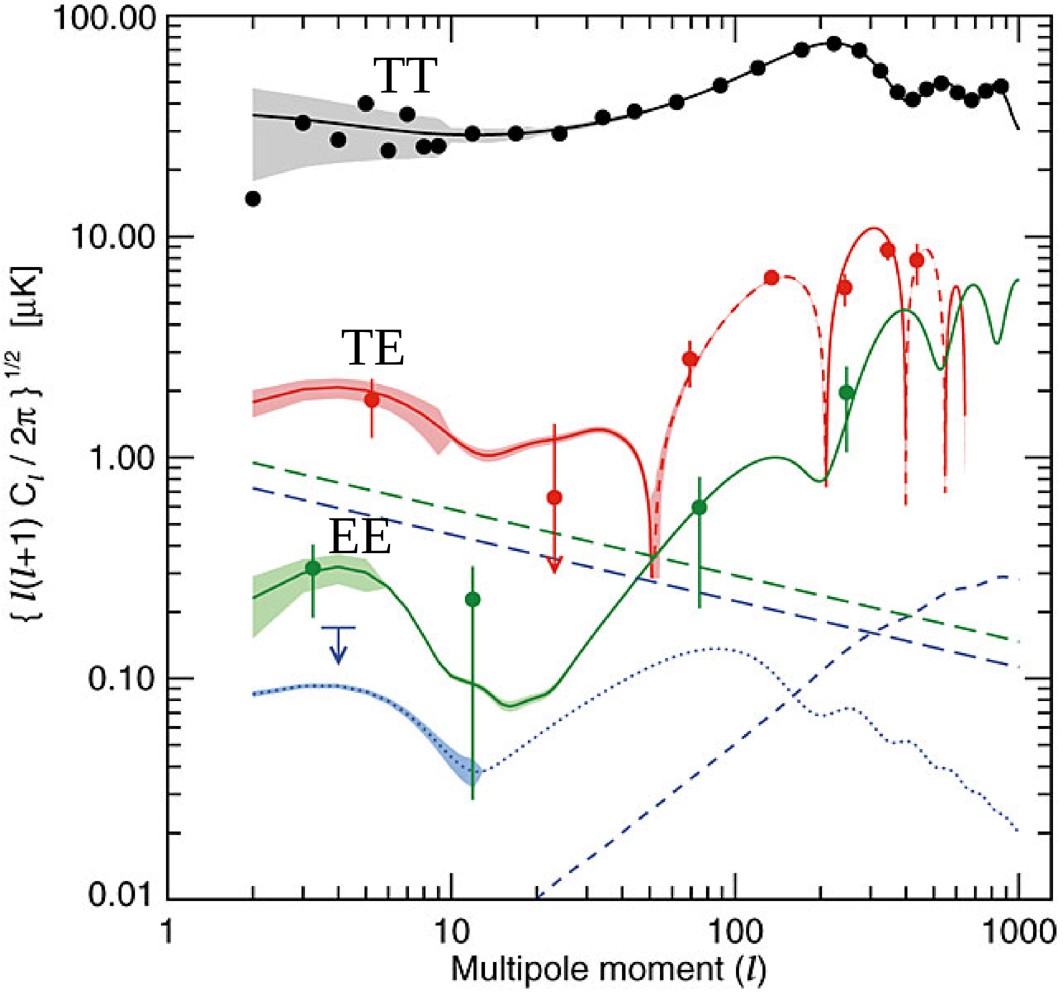


FIG. 25.— Plots of signal for TT (black), TE (red), EE (green) for the best fit model. The dashed line for TE indicates areas of anticorrelation. The cosmic variance is shown as a light swath around each model. It is binned in ℓ in the same way as the data. Thus, its variations reflect transitions between ℓ bin sizes. All error bars include the signal times noise term. The ℓ at which each point is plotted is found from the weighted mean of the data comprising the bin. This is most conspicuous for EE where the data are divided into bins of $2 \leq \ell \leq 5$, $6 \leq \ell \leq 49$, $50 \leq \ell \leq 199$, and $200 \leq \ell \leq 799$. The lowest ℓ point shows the cleaned QV data, the next shows the cleaned QVW data, and the last two show the pre-cleaned QVW data. There is possibly residual foreground contamination in the second point because our model is not so effective in this range as discussed in the text. For BB (blue dots), we show a model with $r = 0.3$. It is dotted to indicate that at this time *WMAP* only limits the signal. We show the 1σ limit of 0.17 μK for the weighted average of $\ell = 2 - 10$. The BB lensing signal is shown as a blue dashed line. The foreground model (Equation 25) for synchrotron plus dust emission is shown as straight dashed lines with green for EE and blue for BB. Both are evaluated at $\nu = 65$ GHz. Recall that this is an average level and does not emphasize the ℓs where the emission is low.

Sources for Early Reionization

<u>PopIII stars</u>

Cen 2003; Ciardi, Ferrara & White 2003; Somerville & Livio 2003; Fukugita & Kawasaki 2003; Wyithe & Loeb 2003; Sokasian et al. 2004; Ricotti & Ostriker 2004

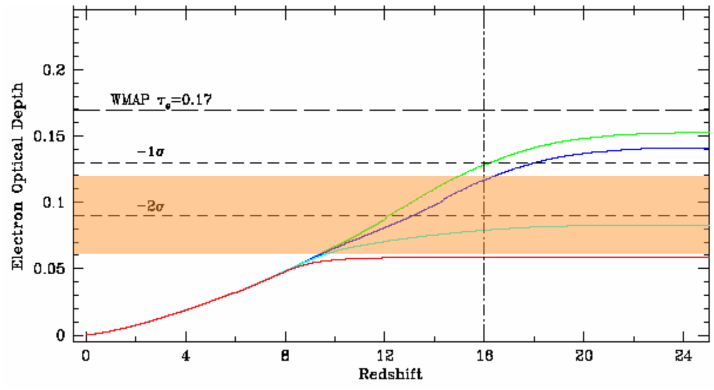
$\tau_e < 0.15$

cf **WMAP 1st year $\tau_e = 0.17 \pm 0.04$**

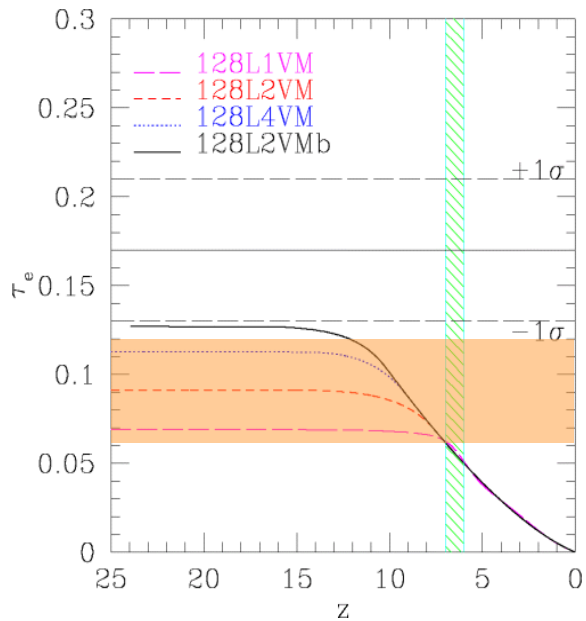
WMAP Three year $\tau_e = 0.09 \pm 0.03$

<u>Pop III BH / Mini-quasar</u>

Gnedin, Ostriker & Rees 1995
Madau et al. 2004
Ricotti & Ostriker 2004

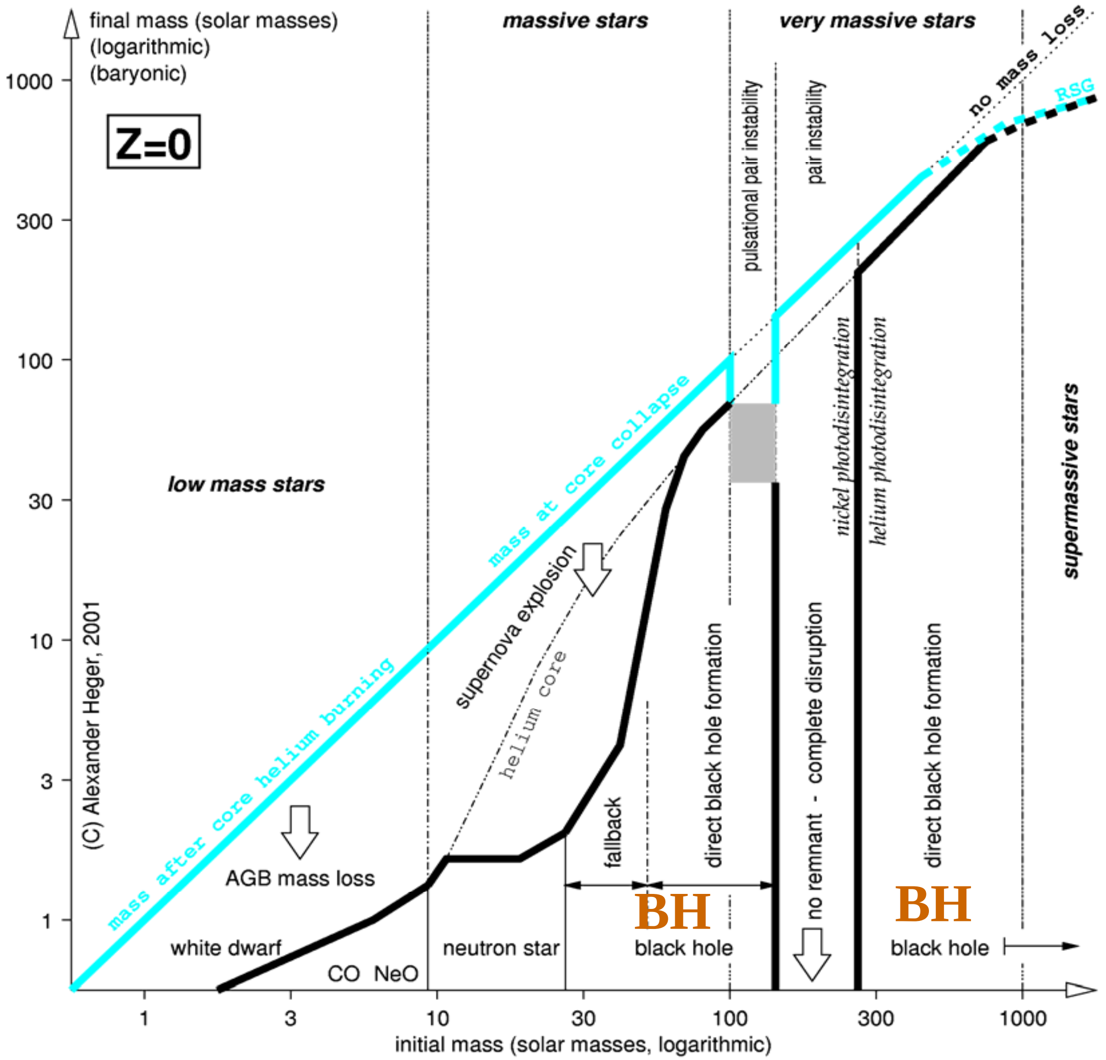


Sokasian et al. 2004, MNRAS, 350, 47



Ricotti & Ostriker 2004, MNRAS, 350, 539

Pop III BHs



Heger & Woosley 2002, ApJ, 567, 532

Observational Constraints for Pop III BHs

Integration of QSO LF

$$\Omega_{BH}(\text{QSO}) \approx 1.8 \times 10^{-6}$$ (Yu & Tremaine 2002, MNRAS, 335, 965)

$$\Omega_{BH}(\text{QSO}) \approx (2.4 - 4.8) \times 10^{-6}$$ (Marconi et al. 2004, MNRAS, 351, 169)

SMBH-bulge mass relation at z=0

$$\Omega_{BH}(\text{bulge}) \approx 2.1 \times 10^{-6}$$

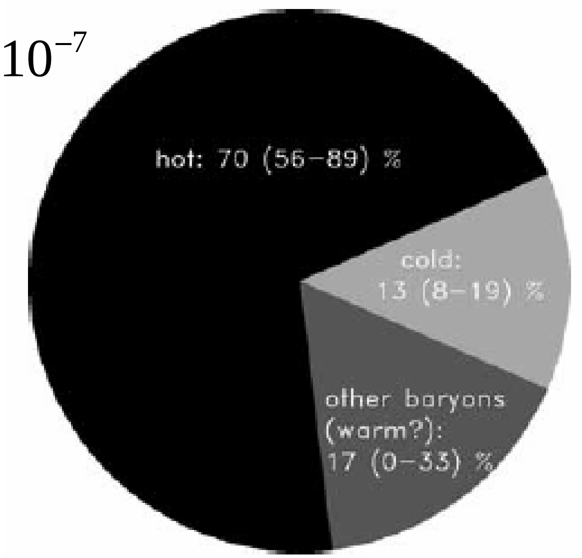
$$\Rightarrow \Omega_{BH}(\text{Pop III}) \approx \Omega_{BH}(\text{bulge}) - \Omega_{BH}(\text{QSO}) < 3 \times 10^{-7}$$

BHs in halos

$$\Omega_{BH}(\text{Pop III}) < \Omega_{MACHO} \approx 0.001$$

Missing baryons

$$\Omega_{BH}(\text{Pop III}) \text{ d } 0.01$$



Cluster baryonic pie
Ettori 2003

Accretion Flows

$$L = \eta \dot{m} \dot{M}_{\rm crit} c^2, \ \dot{M}_{\rm crit} = 10 L_E / c^2 = 10 \cdot \frac{4\pi G c m_p M}{\sigma_T c^2}$$

① Sub-Eddington: RIAF (Radiatively Inefficient Accretion Flow)

higher energy photons (strong X-ray)

$$\dot{m} \equiv \frac{\dot{M}}{\dot{M}_{\rm crit}} \ll 1 \quad \Rightarrow \quad \eta \approx 0.1\dot{m}$$

② Eddington: Standard Disk

lower energy photons

$$\dot{m} \equiv \frac{\dot{M}}{\dot{M}_{\rm crit}} \approx 1 \quad \Rightarrow \quad \eta \approx 0.1$$

③ Super-Eddington: Slim Disk (Photon trapping)

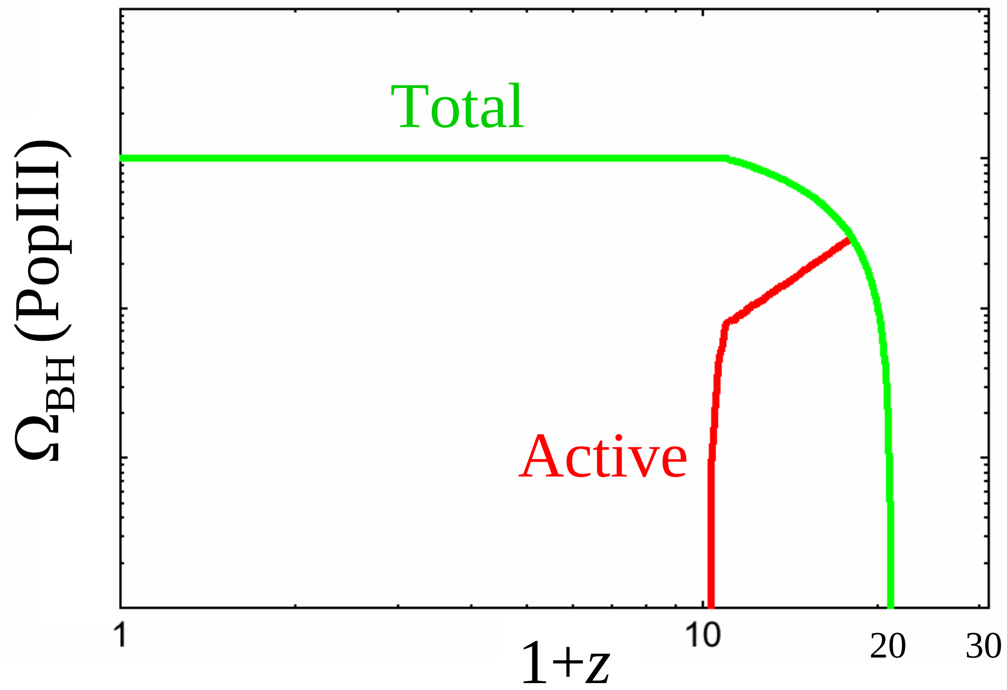
lower energy photons

$$\dot{m} \equiv \frac{\dot{M}}{\dot{M}_{\rm crit}} > 1 \quad \Rightarrow \quad \eta \approx 0.1\dot{m}^{-1/2}$$

モデル

Eddington time:
$$t_E \equiv \frac{M}{\dot{M}_{crit}} = 4.53\times10^7\left(\frac{\eta}{0.1}\right)[\mathrm{yr}]$$

z_{min}<z<z_{max} の間にPopIII BHが誕生し，
Eddington time で死んでいく。



スペクトル

$$\varepsilon_\nu(z) = A\nu^{-1}$$

Eddington luminosity density：

$$L_E = \frac{4\pi G c m_p}{\sigma_T} 10\eta\dot{m}\Omega_{BH}\rho_c \quad [\mathrm{erg/s/cm^3}]$$

$$L_E = \int_{\nu_{min}}^{\nu_{max}} \varepsilon_\nu(z)d\nu = A\ln\left(\frac{\nu_{max}}{\nu_{min}}\right) \quad \nu_{min} = 1\mathrm{eV} \quad \nu_{max} = 1\mathrm{keV}$$

$\eta = 0.1$, $\dot{m} = 1$ → Eddington (Standard disk)

Cosmological Radiative Transfer

$$\left(\frac{\partial}{\partial t} - \nu H \frac{\partial}{\partial \nu}\right) J = -3HJ - ckJ + \frac{c}{4\pi}\varepsilon$$

$$J(\nu_0, z_0) = \frac{1}{4\pi}\int_{z_0}^{\infty} dz \frac{dl}{dz}\frac{(1+z_0)^3}{(1+z)^3}\varepsilon(\nu, z)\exp(-\tau(\nu_0, z_0, z)) \quad \mathrm{erg/s/Hz/cm^2/str}$$

$$\tau(\nu_0, z_0, z) = \int_{z}^{z_0} \chi_{HI}(z')n(z')\sigma_{HI}(\nu)\frac{dl}{dz'}dz'$$

$$\sigma_{HI} = 6.3\times 10^{18}\left(\frac{\nu_L}{\nu}\right)^3 \quad [\mathrm{cm}^2]$$

・銀河間ガスは水素原子のみから成るとする

・水素原子は一様に分布するとする

H : ハッブル定数

k : 吸収係数 [cm^{-1}]

ε: emissivity [$\mathrm{erg/s/cm^3/Hz}$]

$\nu_L = 3.3\times 10^{15}$: Lyman limit 振動数

$\chi_{HI}(z)$: 中性水素割合

$n(z)$:水素原子数密度

$$\frac{d\chi_{HI}}{dt} = -\Gamma^{\gamma}\chi_{HI} + \alpha_B(T)(1-\chi_{HI})^2 n(z)$$: 電離方程式

$$\Gamma^{\gamma}(z_0) = 4\pi\int_{\nu_L}^{\infty}\frac{J(\nu_0, z_0)}{h\nu_0}\sigma_{HI}d\nu_0 \quad [1/\mathrm{s}]$$: photoionization rate

$\alpha_B(T)$: 再結合率 [$\mathrm{cm^3\,s^{-1}}$] （ T=10^4 K ）

宇宙論パラメータ

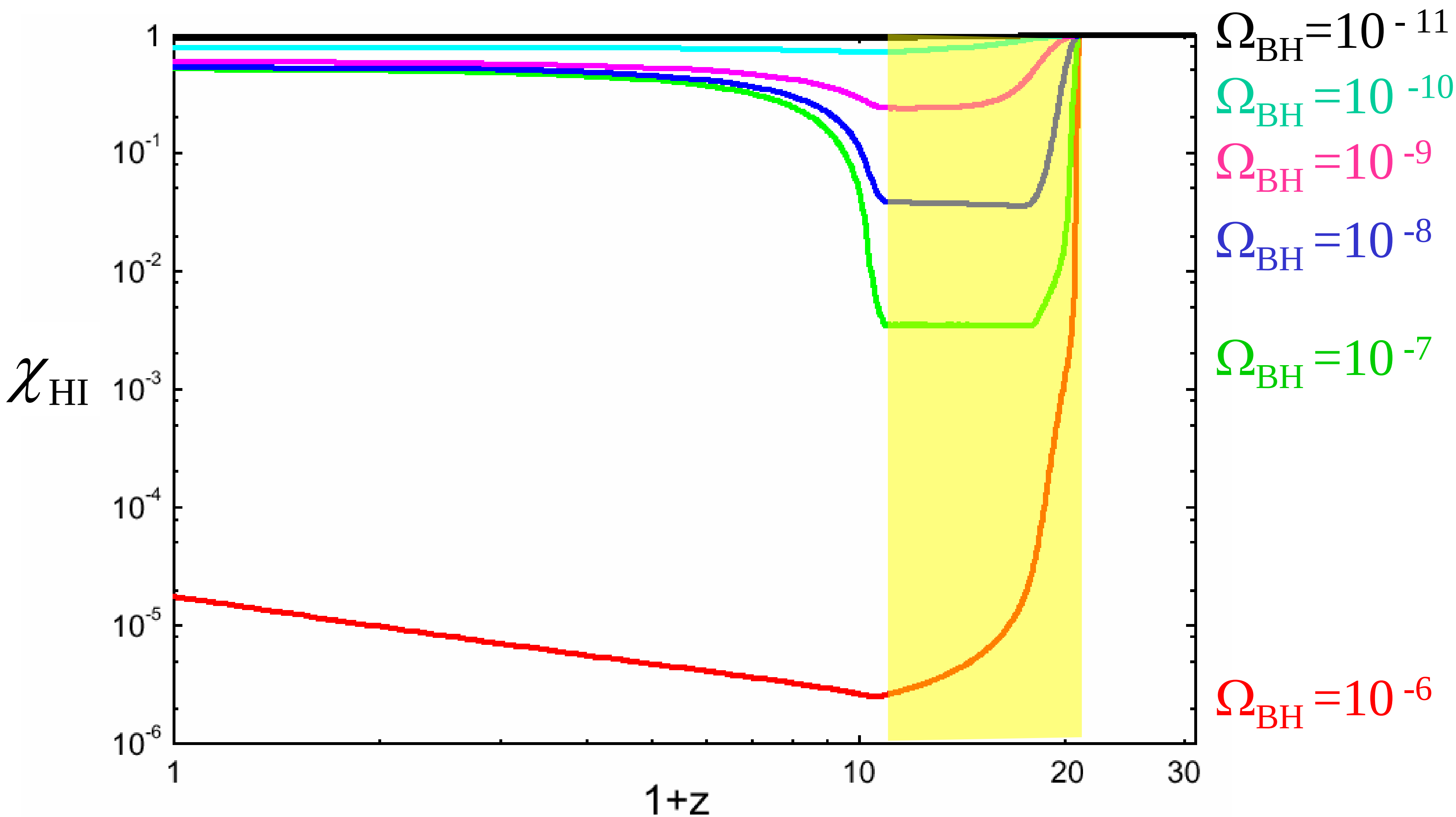
$\Omega_0 = 0.3$

$\Omega_{\Lambda 0} = 0.7$

$\mathrm{H}_0 = 70$ km/s/Mpc

Ionization History

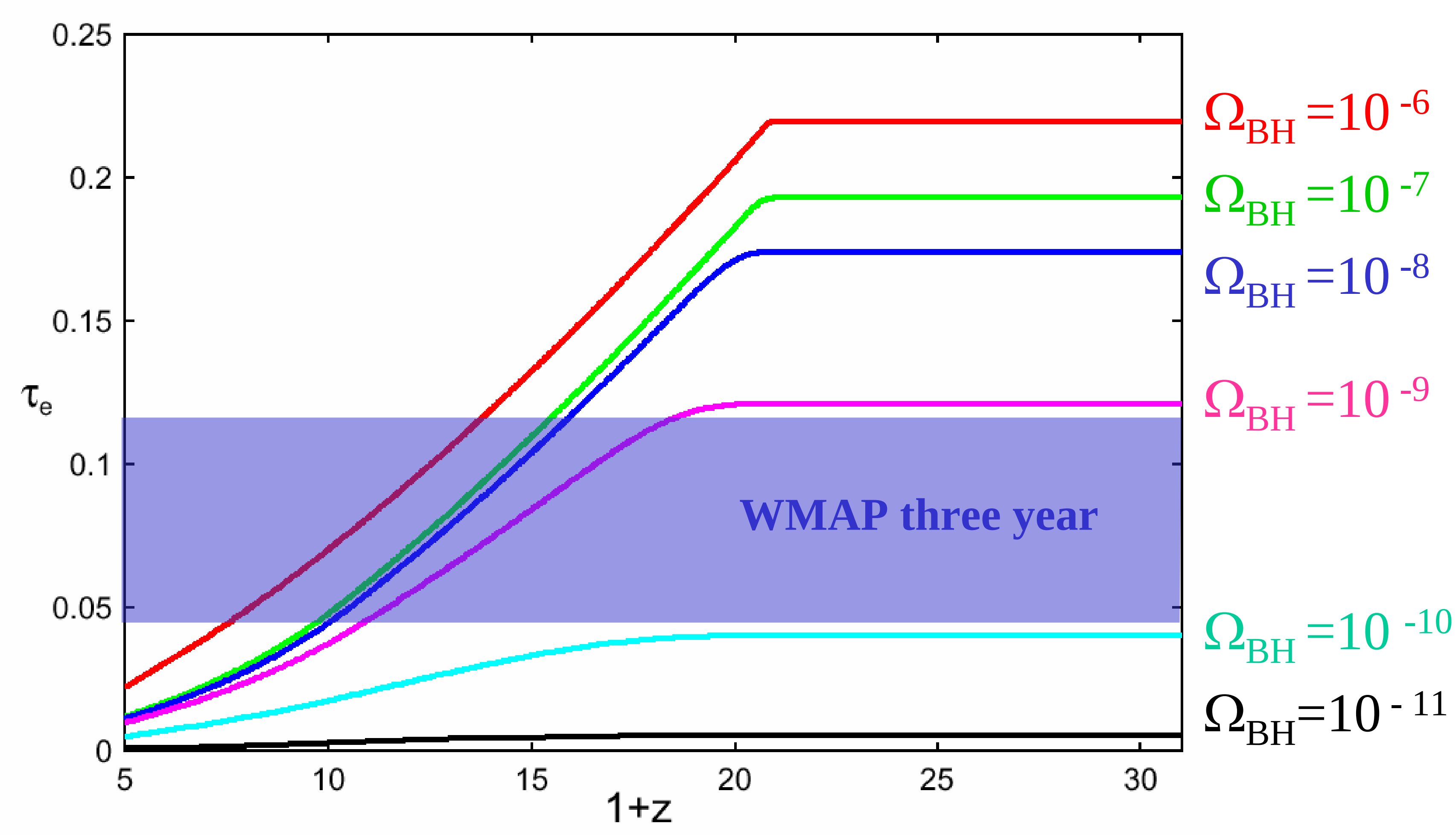
$\eta = 0.1$, $\dot{m} = 1$, $f_{esc} = 1$, $z_{max} = 20$, $z_{min} = 10$



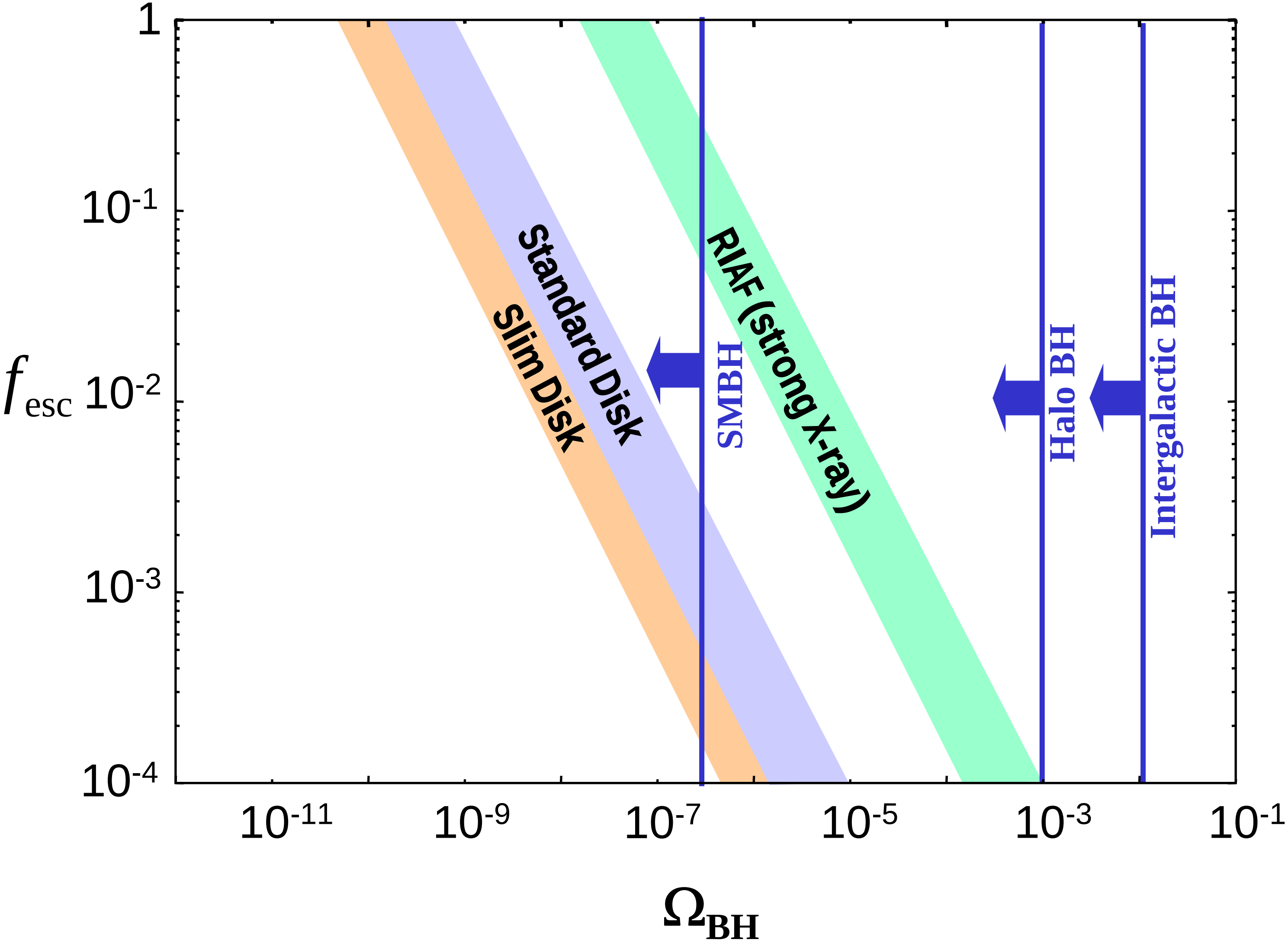
Thomson optical depth

$$\tau_e = \int (1 - \chi_{HI}) n(z) \sigma_T \frac{dl}{dz} dz$$

$$\eta = 0.1 \ , \ \dot{m} = 1 \ , \ f_{esc} = 1 \ , \ z_{max} = 20 \ , \ z_{min} = 10$$



Ω_{BH} (Pop III)に対する制限



WMAP Three year による Ω_{BH} (Pop III)への制限

- Standard Accretion Disk & Slim Disk

$$3 \times 10^{-11} < \Omega_{\rm BH} f_{\rm esc} < 8.6 \times 10^{-10} \quad (10 < z < 20)$$

$$f_{\rm BH}(\rm PopIII) = \Omega_{\rm BH}(\rm PopIII) / \Omega_b$$ として

$$10^{-9} f_{\rm esc}^{-1} \ \mathrm{d} \ f_{\rm BH}(\rm PopIII) \ \mathrm{d} \ 10^{-8} f_{\rm esc}^{-1}$$

- RIAF

$$1.6 \times 10^{-8} < \Omega_{\rm BH} f_{\rm esc} < 8.6 \times 10^{-8}$$

(too strong X-ray background ?)

f_{BH} (Pop III)について

assump 1: mass fraction of Pop III halos f **(halo) ≈** 10^{-1}**-**10^{-2}

assump 2: 1 Pop III star/halo f **(Pop III) ≈**$10^{3}M_{\odot}/10^{5}M_{\odot}=10^{-2}$

assump 3: BH fraction in Pop III stars f **(BH) ≈**10^{-1}

f_{BH} (Pop III) ≈ 10^{-4}-10^{-5}

ॐ f_{esc_4} ≏10^{-}

Conclusions

1. IGM HI吸収 vs UVB強度変化
(Hiroi, Umemura, Nakamoto 2006)
① High-z QSO
② GRB 050904 (z=6.295)
⇒ High-z UVB強度はLAEとconsistent

2. WMAP 3Year vs Pop III BH Density
(Hirose, Umemura 2006)
⇒ PopIII BH はかなり少ない（？）
Accretion rate が非常に小さい（？）

Thank you