First UV Sources and Their Impact on the IGM

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Sequence of Events

At z=1000 the Universe has cooled down to 3000 K. Hydrogen becomes neutral (“Recombination”).

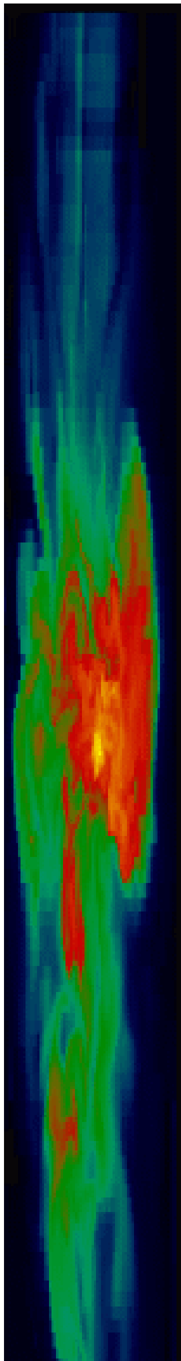
At z < 20 the first “PopIII” star (clusters)/small galaxies form.

At z ~ 6-15 these gradually photo-ionize the hydrogen in the IGM (“Reionization”).

At z<6 galaxies form most of their stars and grow by merging.

At z<1 massive galaxy clusters are assembled.

Which sources did reionize the universe ?

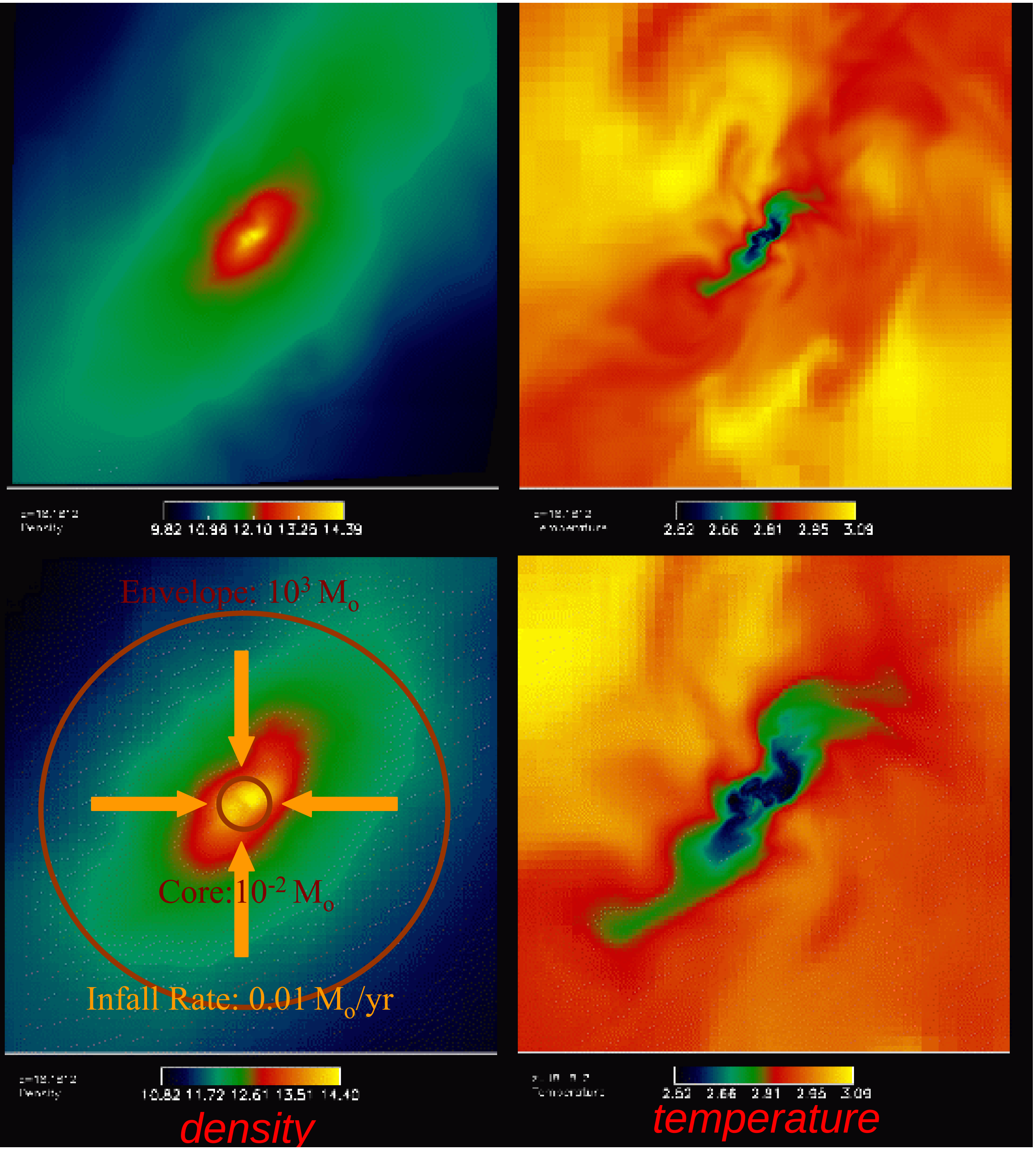


1400 AU:

forming
protostar

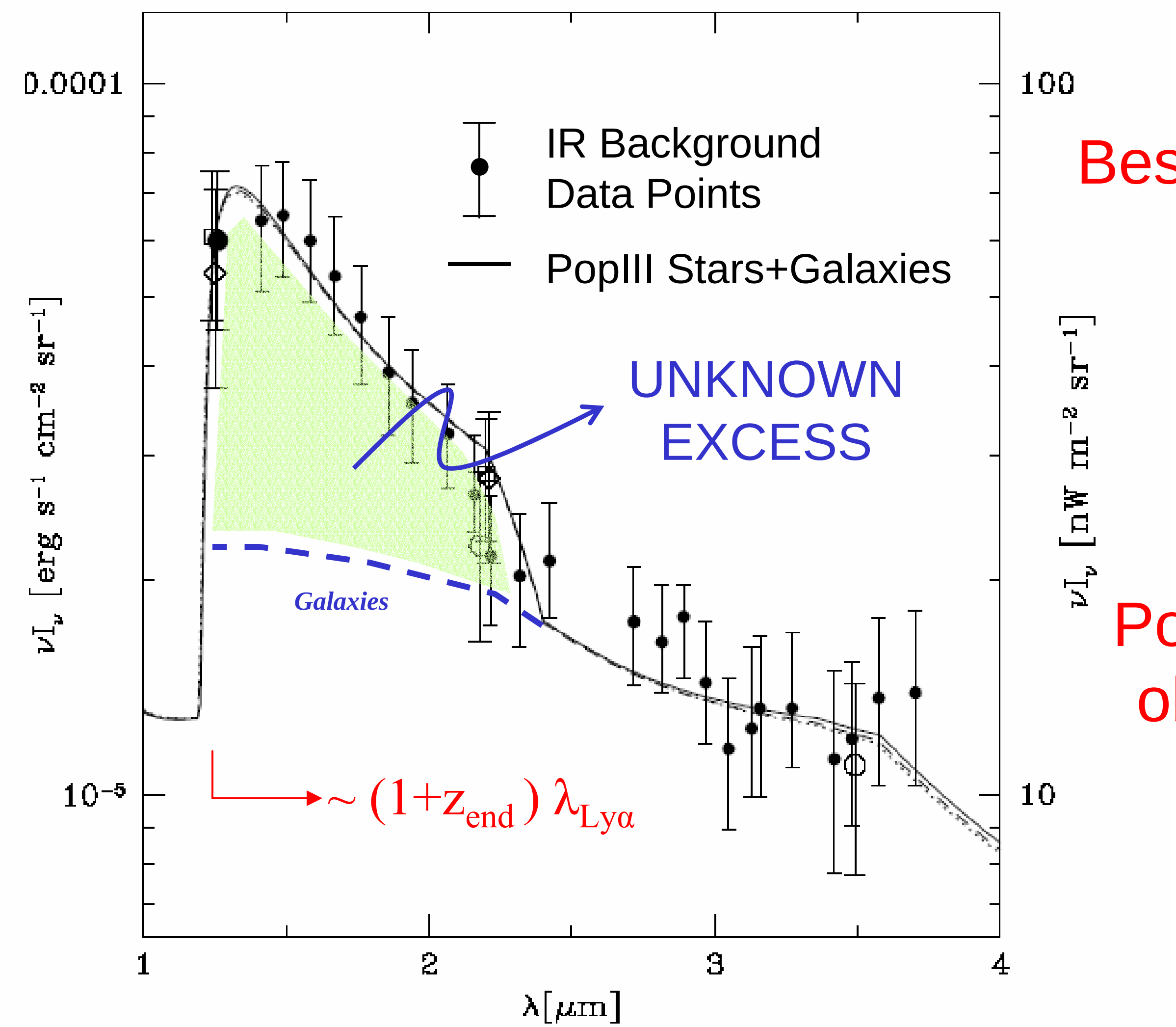
550 AU:

Tom Abel
Harvard Smithsonian CfA



First Stars and Near IR Background

Salvaterra & AF 2002; Santos et al 2002; Madau & Silk 2005



Best fit model to NIR data

$$z_{\rm end} = 8.8$$

$$f_\star \approx 30\%$$

Pop III stars can explain observed NIRB excess

if

VMS dominate IMF

Mapelli, Salvaterra & AF 2005

γ-ray constraints on the NIRB excess

TeV-GeV photons absorbed by optical/IR photons via $e^+ - e^-$ pair production.

The observed spectrum of blazars reproduced by convolving the unabsorbed spectrum (assumed to be a power-law) with the optical depth:

$$(dN/dE)_{abs} \propto e^{-\tau} E^{-\alpha}$$

$$\tau(E) = \int_0^{z_{em}} dz \frac{dl}{dz} \int_{-1}^{1} dx \frac{(1-x)}{2} \int_{\varepsilon_{th}}^{\infty} d\varepsilon \, n(\varepsilon) \sigma(\varepsilon, E, x)$$

σ peaks at $\lambda_{EBL} \sim 2.37\ (E/TeV)\ \mu m$.

First Stars and Near IR Background

Mapelli, Salvaterra & AF 2005

γ-ray constraints on the NIRB excess

■ CAT data

● HEGRA data

▲ Whipple data

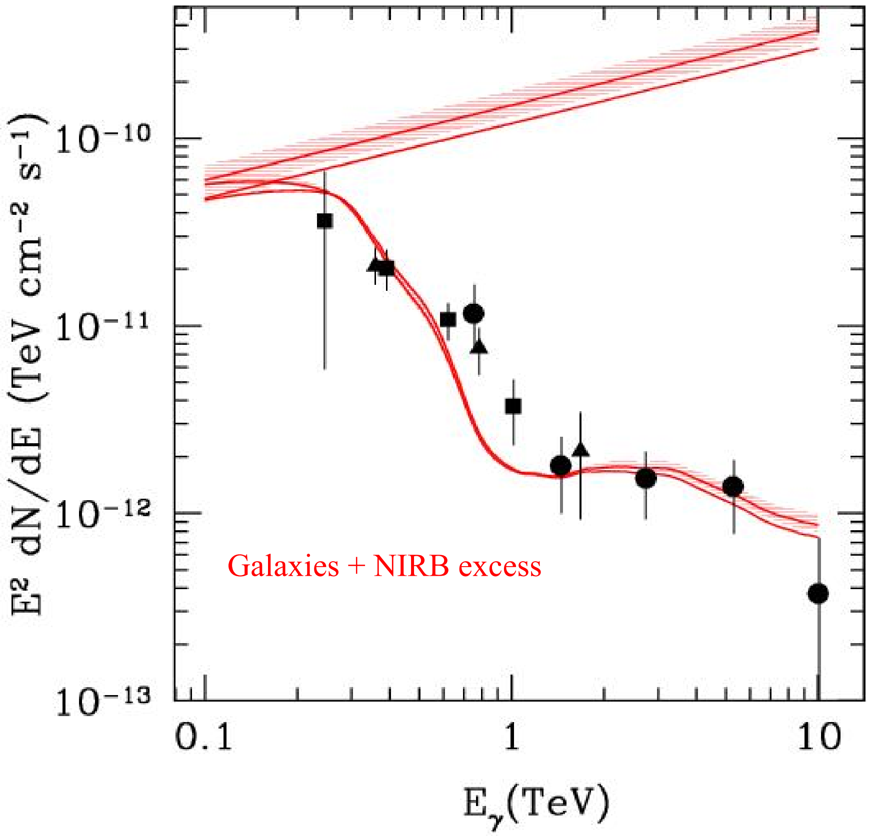
Blazar H1426+428 @ $z=0.129$ *(Aharonian et al. 2003)*

Background Light Model

OPTICAL– HDF counts

NIR – Matsumoto/DIRBE data

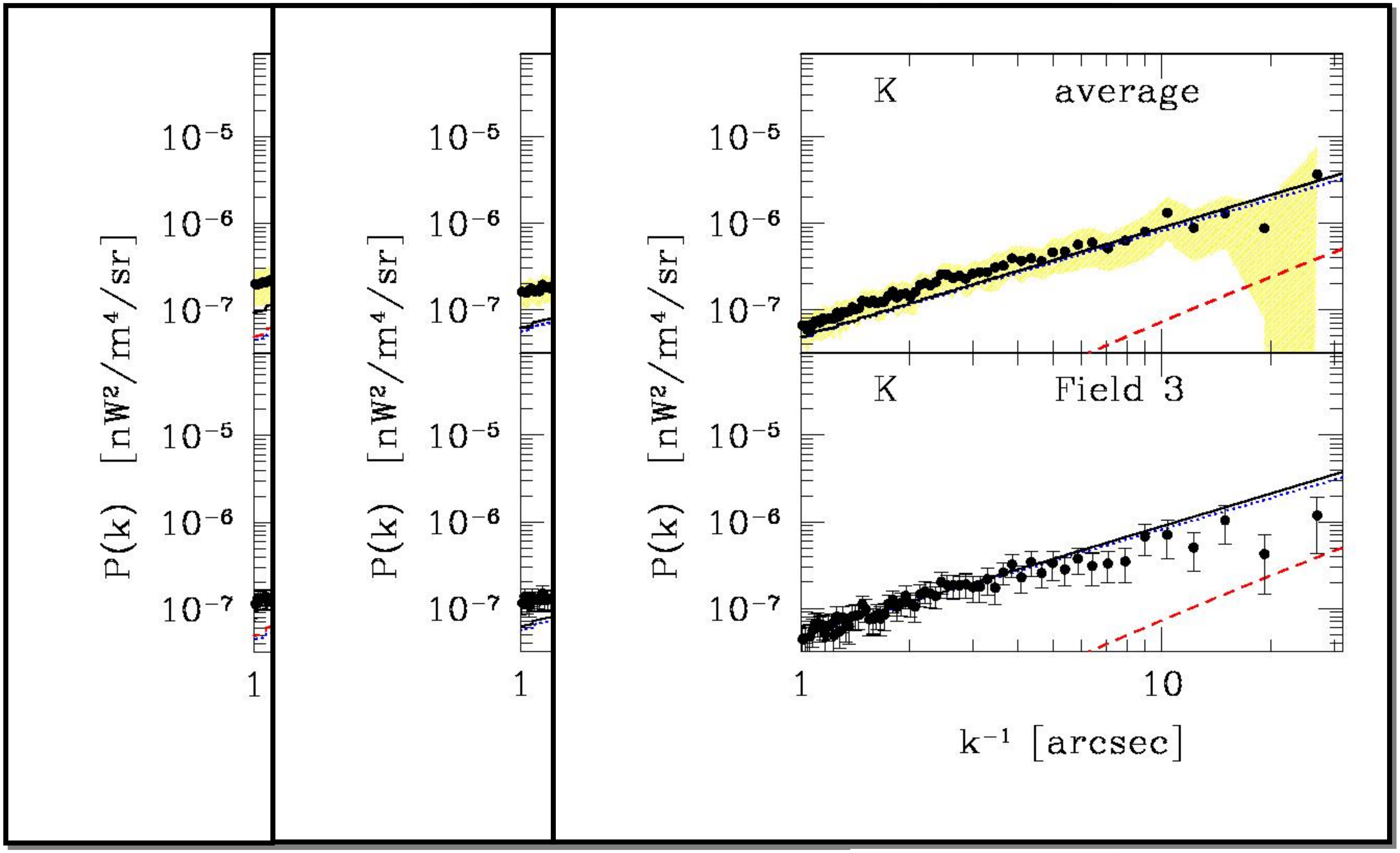
MIR – Totani & Takeuchi 2002



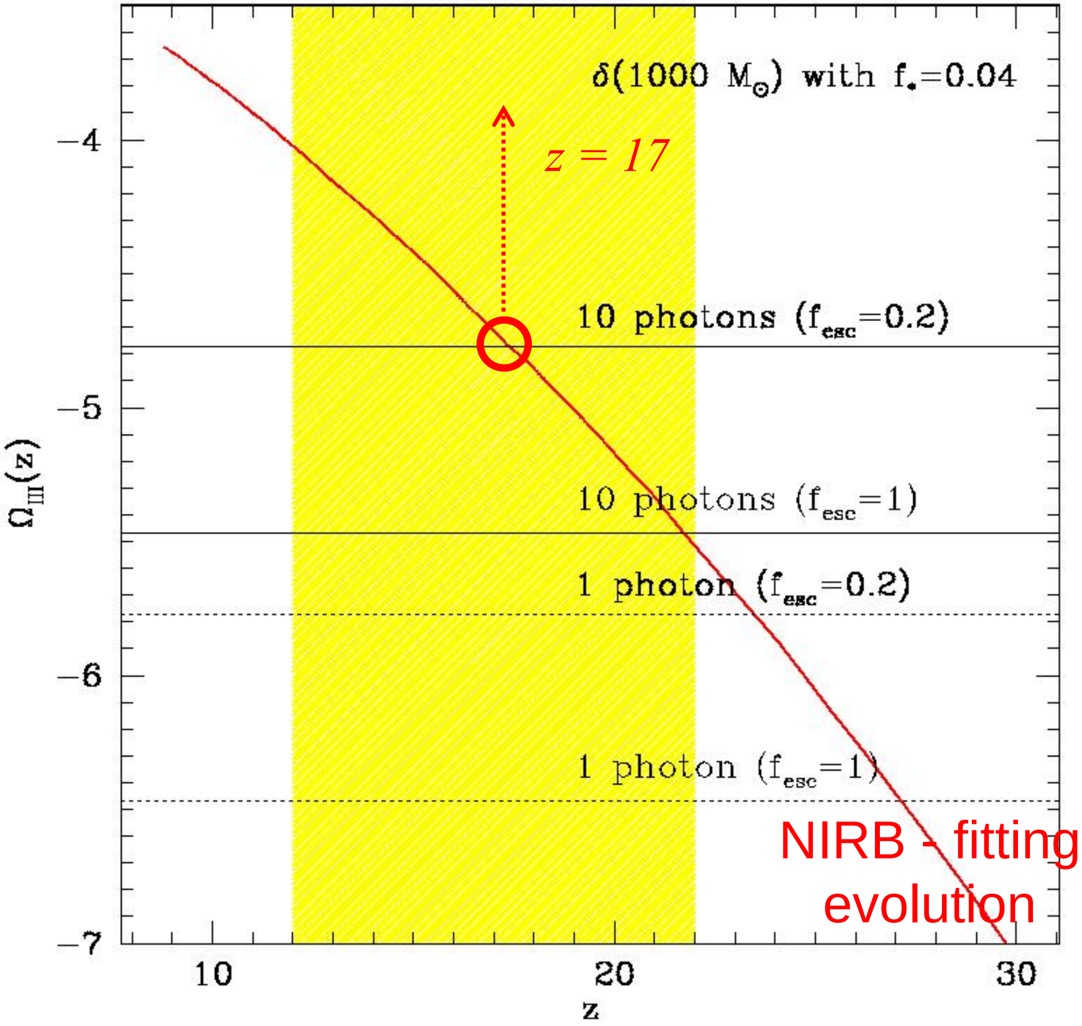
First Stars and Near IR Background

Magliocchetti, Salvaterra & AF 2003

NIRB fluctuations



Reionization by Very Massive Stars ?



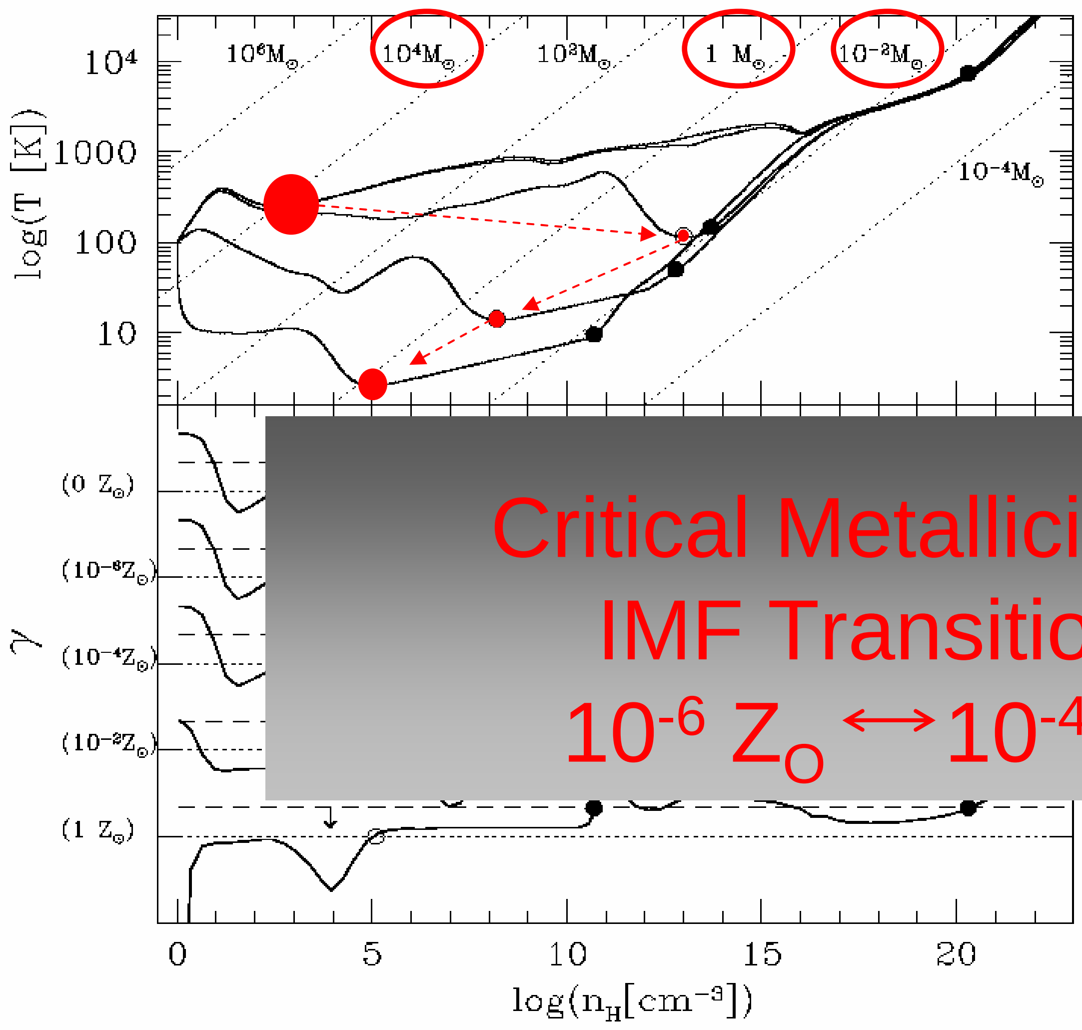
IMPLICATION

At z=0, ≈1/20 Ω_b in

IMBHs

Effects of Enrichment on the IMF of First Stars

Schneider, AF, Natarajan, Omukai 2002



Critical Metallicity for IMF Transition:
$10^{-6}\ Z_O \leftrightarrow 10^{-4}\ Z_O$

Chemical Network includes

H,D,He,C,O + Dust
55 species, 496 reactions

Additional Reionization sources

Additional Reionization Sources

Miniquasars

Cooray & Yoshida (2004) have speculated that accreting IMBHs, shining as miniquasars down to $z=9$, may contribute substantially to the reionization and NIRB

Miniquasars will contribute also to the Soft X-ray Background (SXRB;0.5-2 keV) that is now resolved to ~94% level (discrete sources at z<4, *Moretti et al. 2003*)

STRONG UPPER LIMIT

Unresolved fraction $< 1.23 \times 10^{-12}$ $erg\ s^{-1}\ cm^{-2}\ deg^{-2}$

Dijkstra et al. 2004

Additional Sources: Miniquasars

Salvaterra, Haardt & AF 2005

Spectral Properties

<u>TWO COMPONENT SPECTRUM</u>

Multi-Color Disk: L_{MCD}

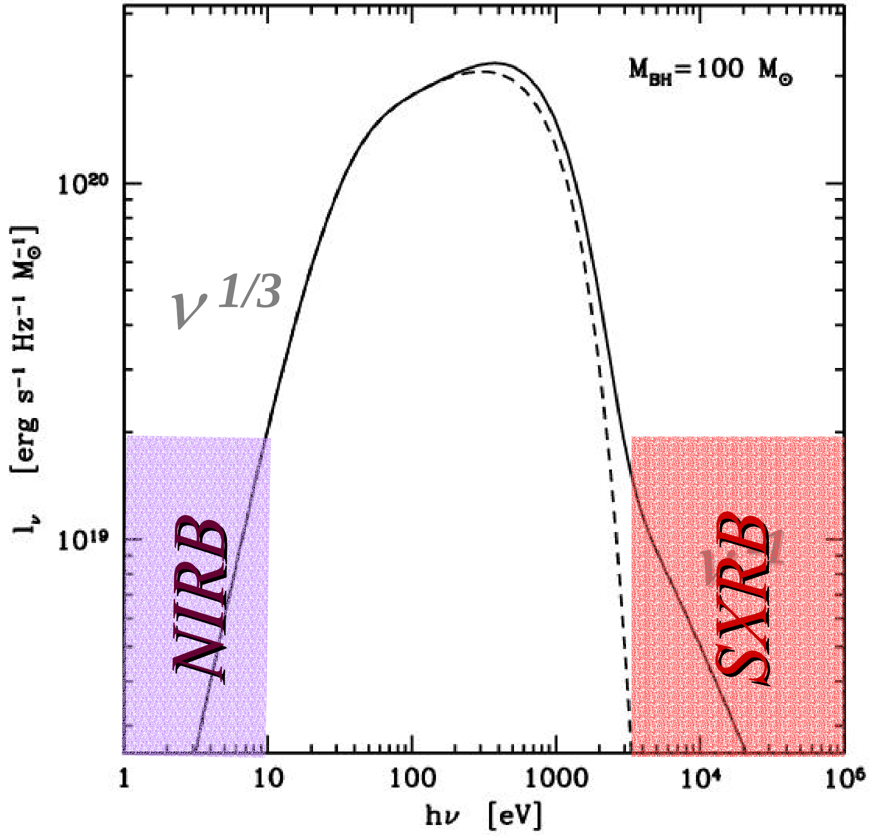
Multi-temperature BB accretion disk.
Spectrum peaked @ $E_{peak}=3kT_{max}$

Power Law: L_{PL}

$L_{\nu,PL} \propto \nu^{-1}$ for $E>E_{peak}$

IC scattering of thermal disk photons

$$\Phi = \frac{L_{PL}}{L_{MCD}} \approx 1 \quad \text{for ULX}$$

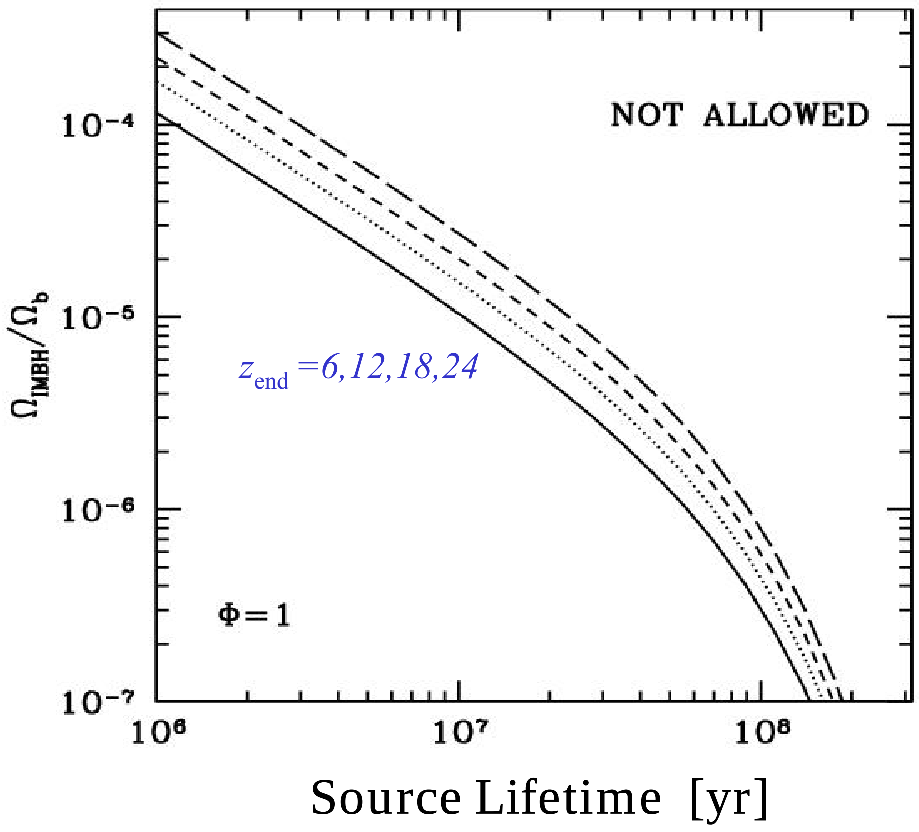


Additional Sources: Miniquasars

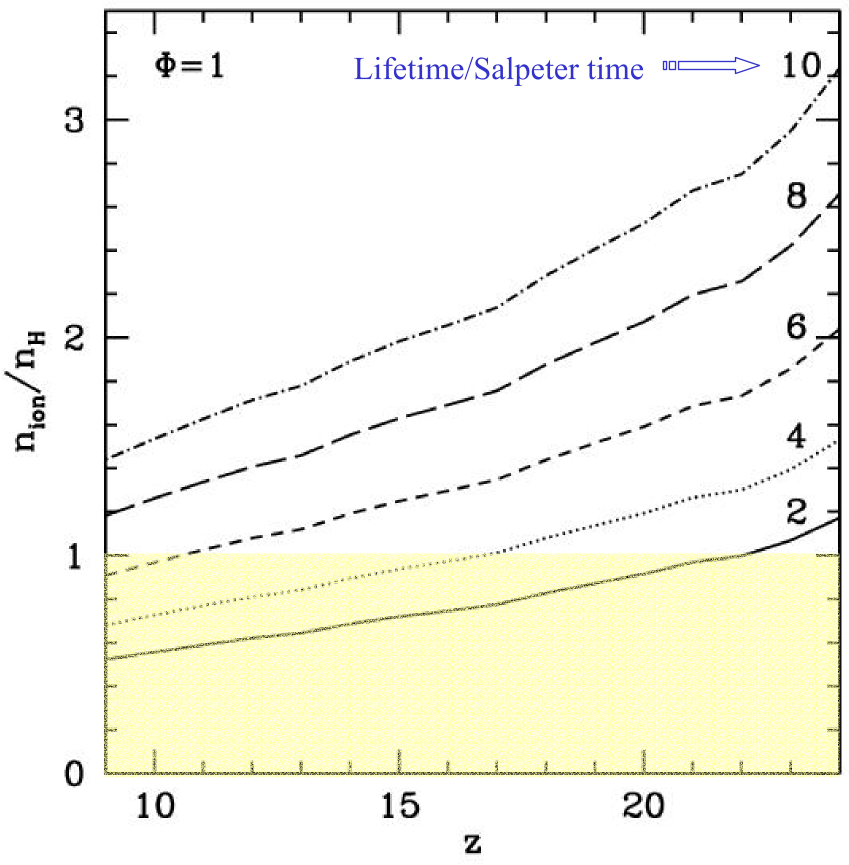
Salvaterra, Haardt & AF 2005

Constraints from SXRB

IMBH Abundance



Ionizing Photons from IMBHs



Additional Sources: Sterile Neutrinos

Mapelli & AF 2005

Radiative decay channel

$\nu_s \rightarrow \nu_a + e^+ + e^- \rightarrow \nu_a + \gamma$

$E_\gamma = ½\,(m_{\nu s}{}^2 - m_{\nu a}{}^2)/m_{\nu s}$

Typical sterile neutrino mass: ≈ few × keV

Pion decay channel

$\nu_s \rightarrow \pi + e^- \rightarrow \pi + e^- + \gamma_{\mathrm{CMB}}$

$E_e = ½\,(m_{\nu s} - m_\pi)$

Typical sterile neutrino mass: ≈ few × 100 MeV

Additional Sources: Sterile Neutrinos

Mapelli & AF 2005

Constraints from XRB

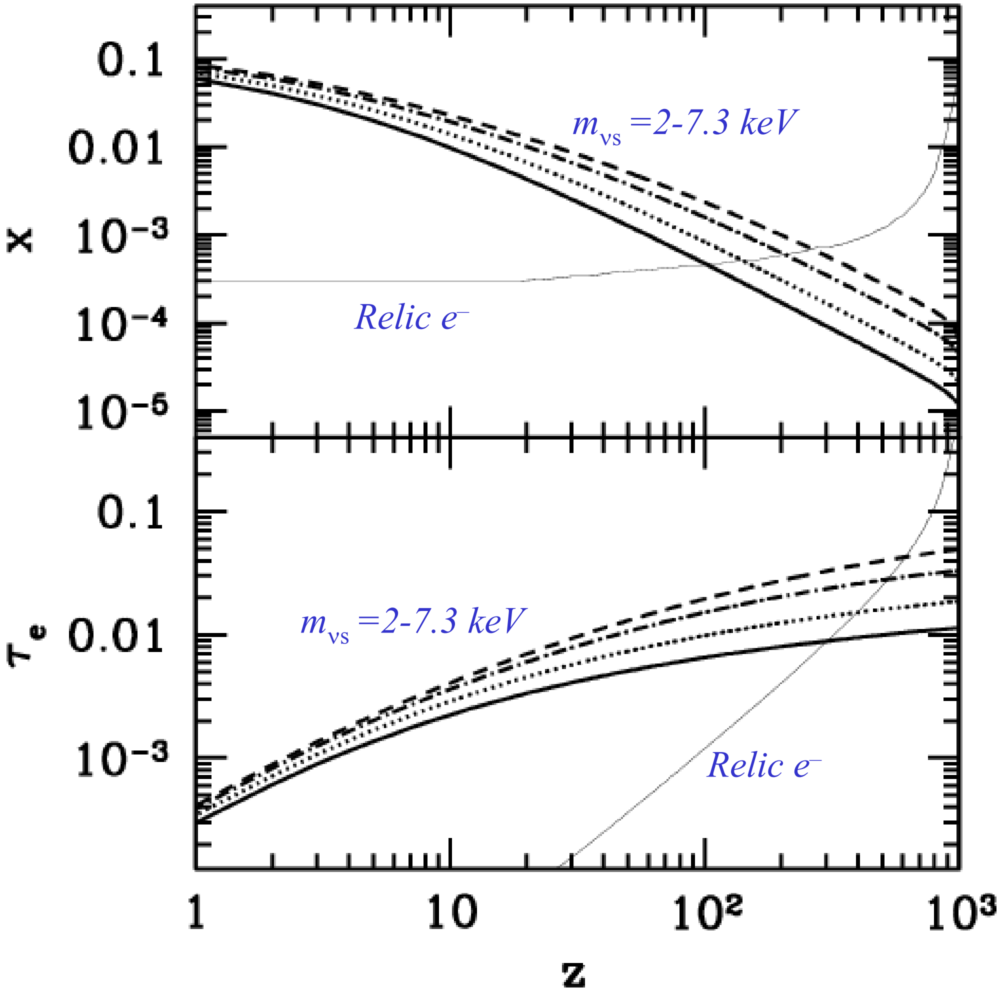
$m_{\nu s} < 7.3$ keV

Radiative decay

150 MeV $< m_{\nu s} <$ 500 MeV

Pion decay

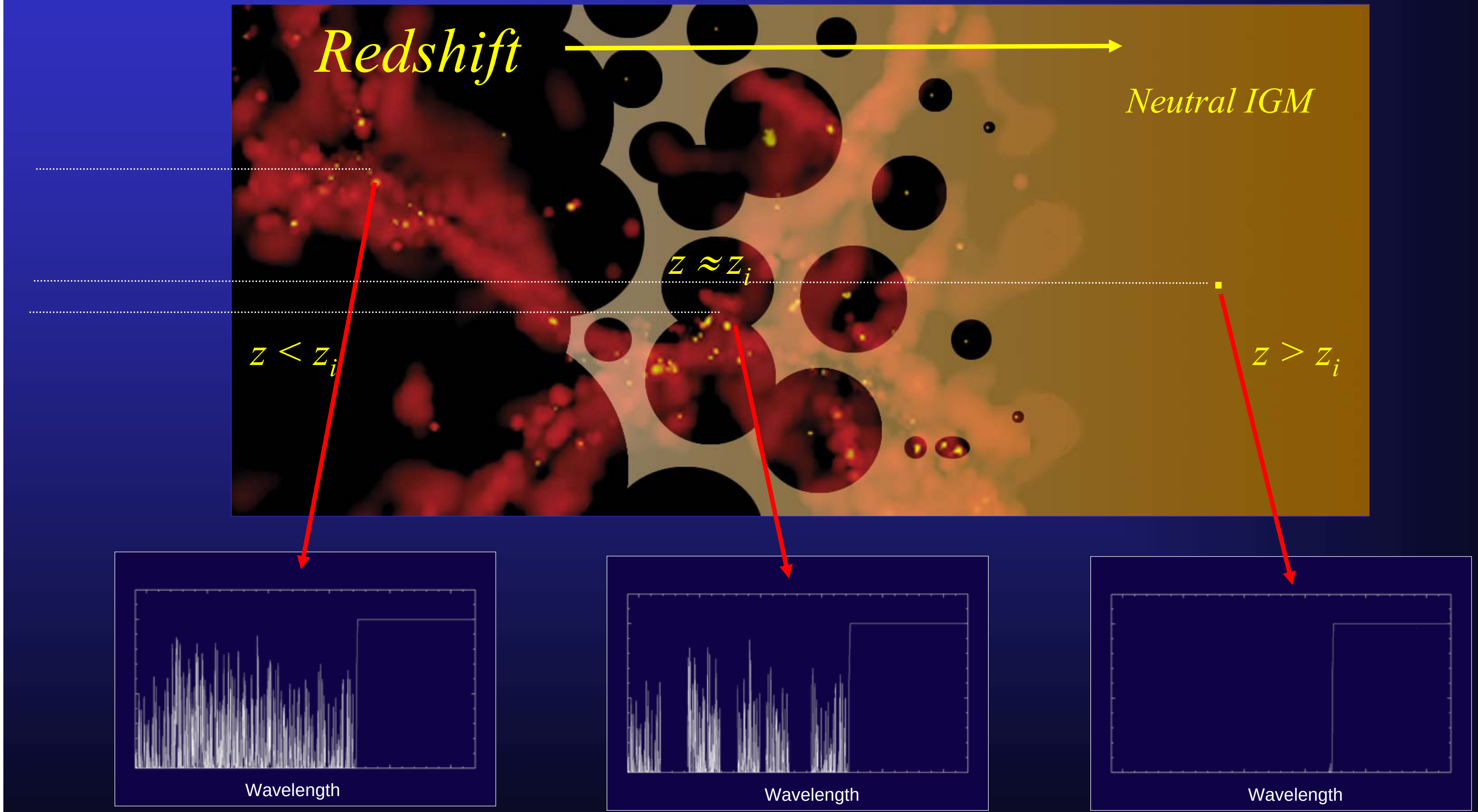
Reionization from Radiative Decays



EARLY OR LATE REIONIZATION ?

Reionization Tests

QSO absorption lines

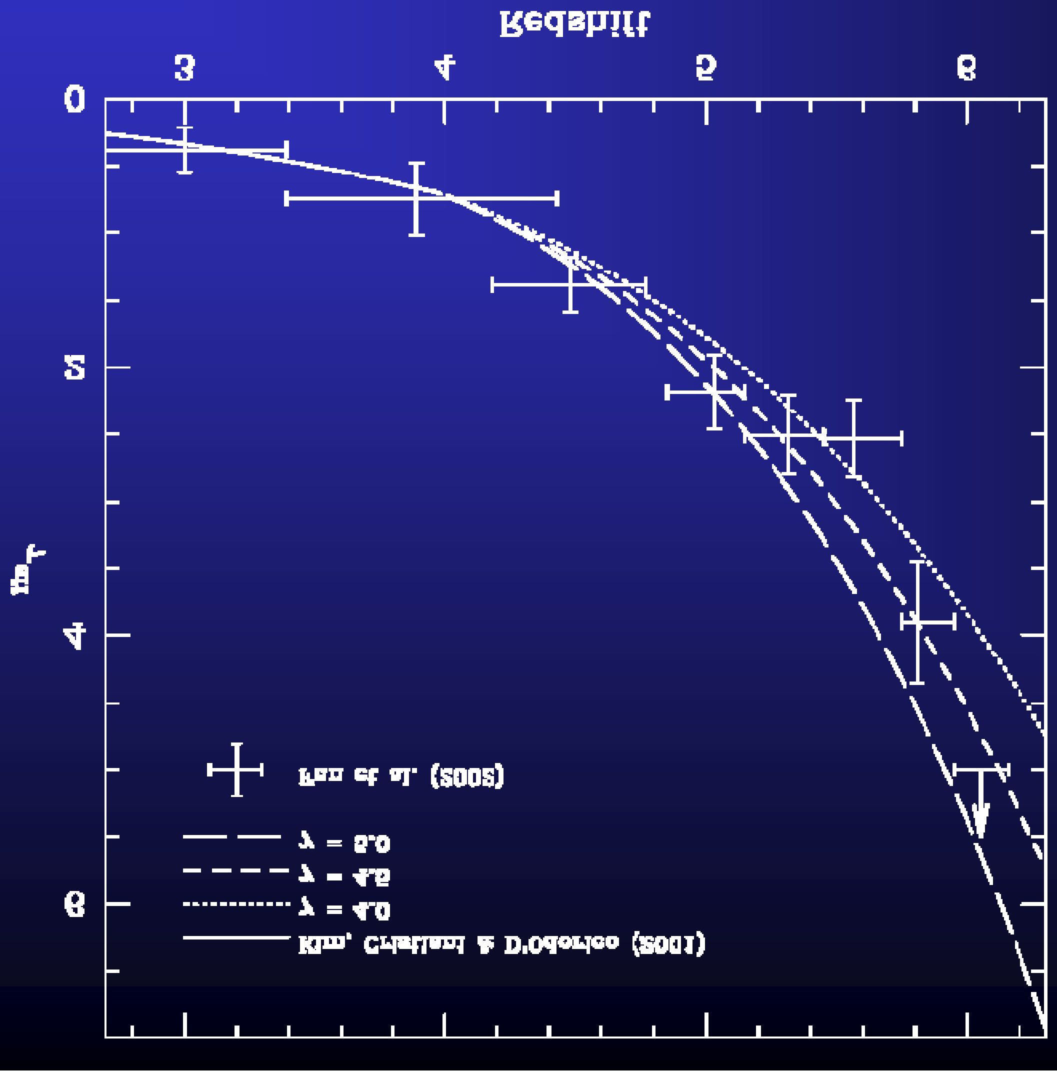


Lyman Forest Absorption

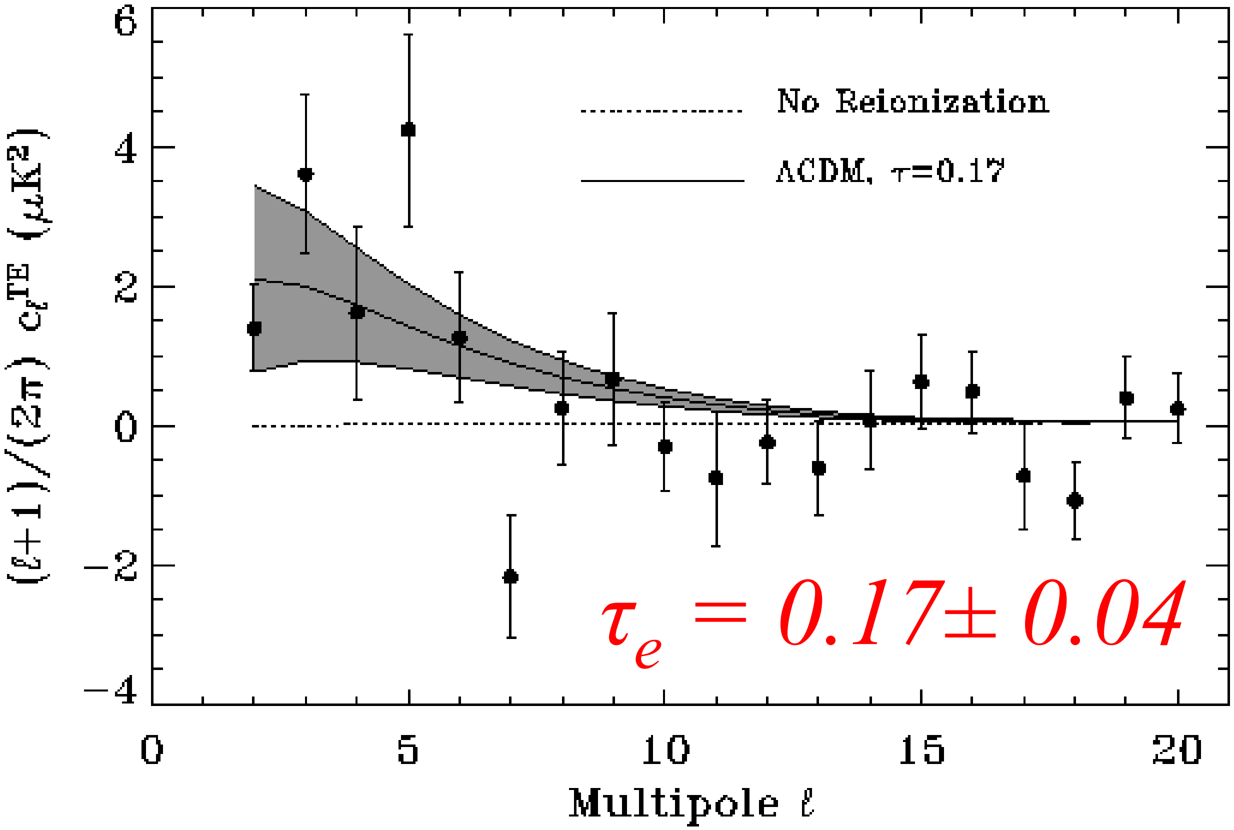
Patchy Absorption

Black Gunn-Peterson trough

Gunn-Peterson test: reionization at z ~ 6 ?



CMB/WMAP results: reionization at $z > 10$?



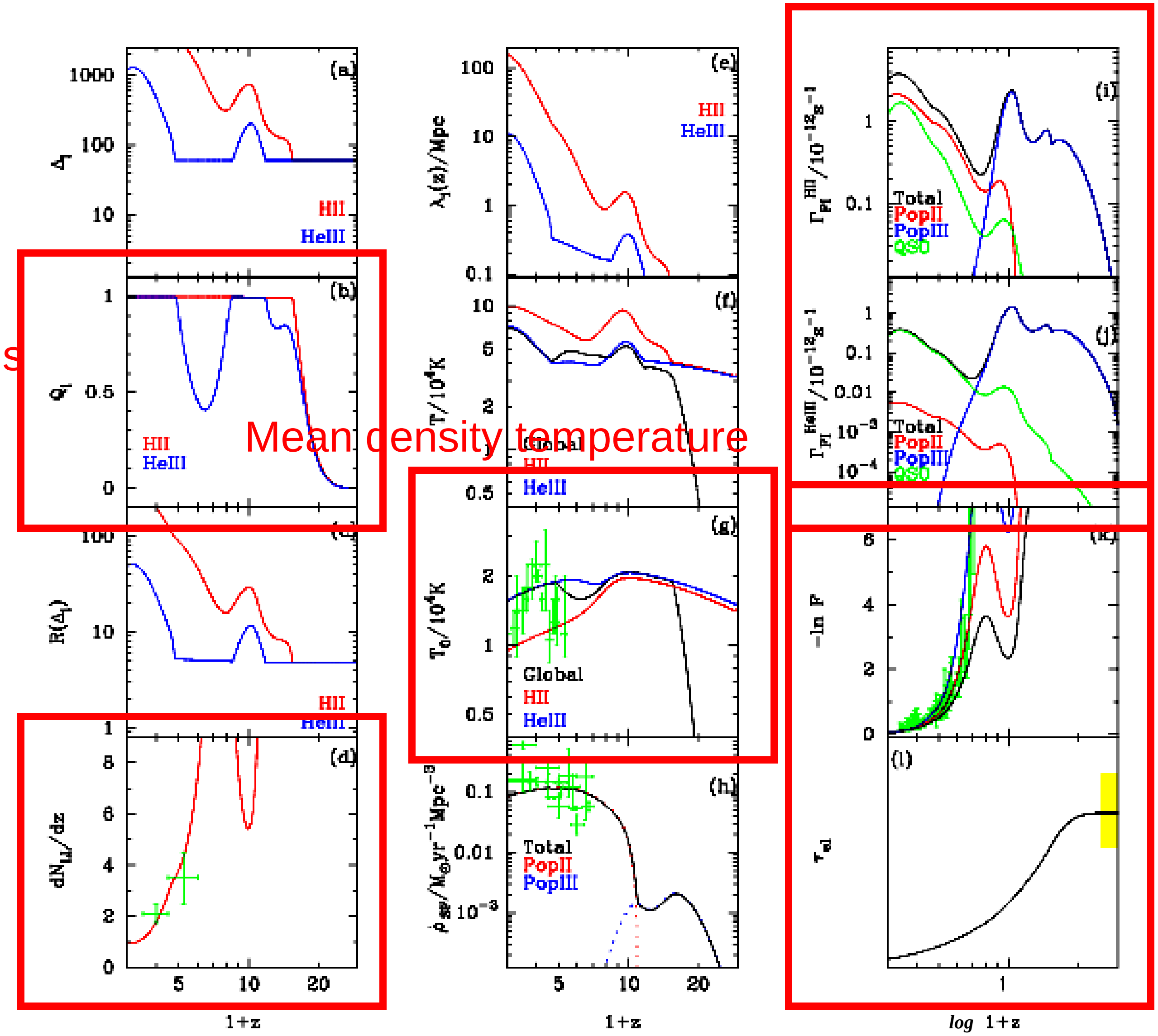
$$\tau_e = 0.17 \pm 0.04$$

Inhomogeneous Reionization

Choudhury & AF 2005

- ✓ Self-consistent treatment of the evolution of ionized regions and thermal history
- ✓ Follow evolution of neutral, HII and HeIII regions; treat IGM as multiphase gas
- ✓ Inhomogeneous density distribution: log-normal model
- ✓ Three sources of ionizing radiation:
  - PopIII stars: early redshifts, high mass, zero metallicity
  - PopII stars: Salpeter IMF, transition from PopIII @ $z < 9$
  - Quasars: significant @ $z < 6$, using σ-M_{BH} relation
- ✓ Radiative feedback suppressing SF in low-mass halos, set by:
  - Molecular cooling in neutral regions
  - Photoionization temperature in ionized regions

Model vs. experimental constraints



Ionized regions filling factor

Mean density temperature

LLS statistics

HI

Photo-rates

HeII

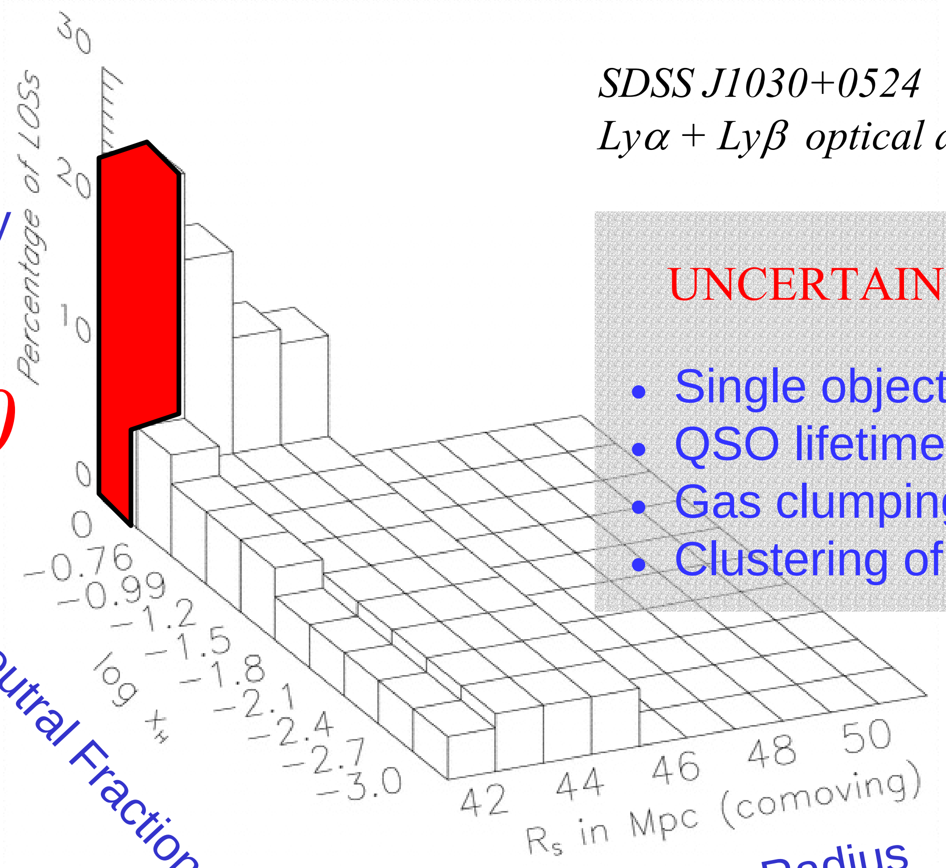
GP optical depth

e.s. optical depth

Inhomogeneous Reionization

Mesinger & Haiman 2004; Wyithe & Loeb 2004

A large neutral fraction at $z = 6.28$?



SDSS J1030+0524
Lyα + Lyβ optical depth fitting

LOS matching opacity

$x_H \geq 0.20$

Neutral Fraction

HII Region Radius

UNCERTAINTIES

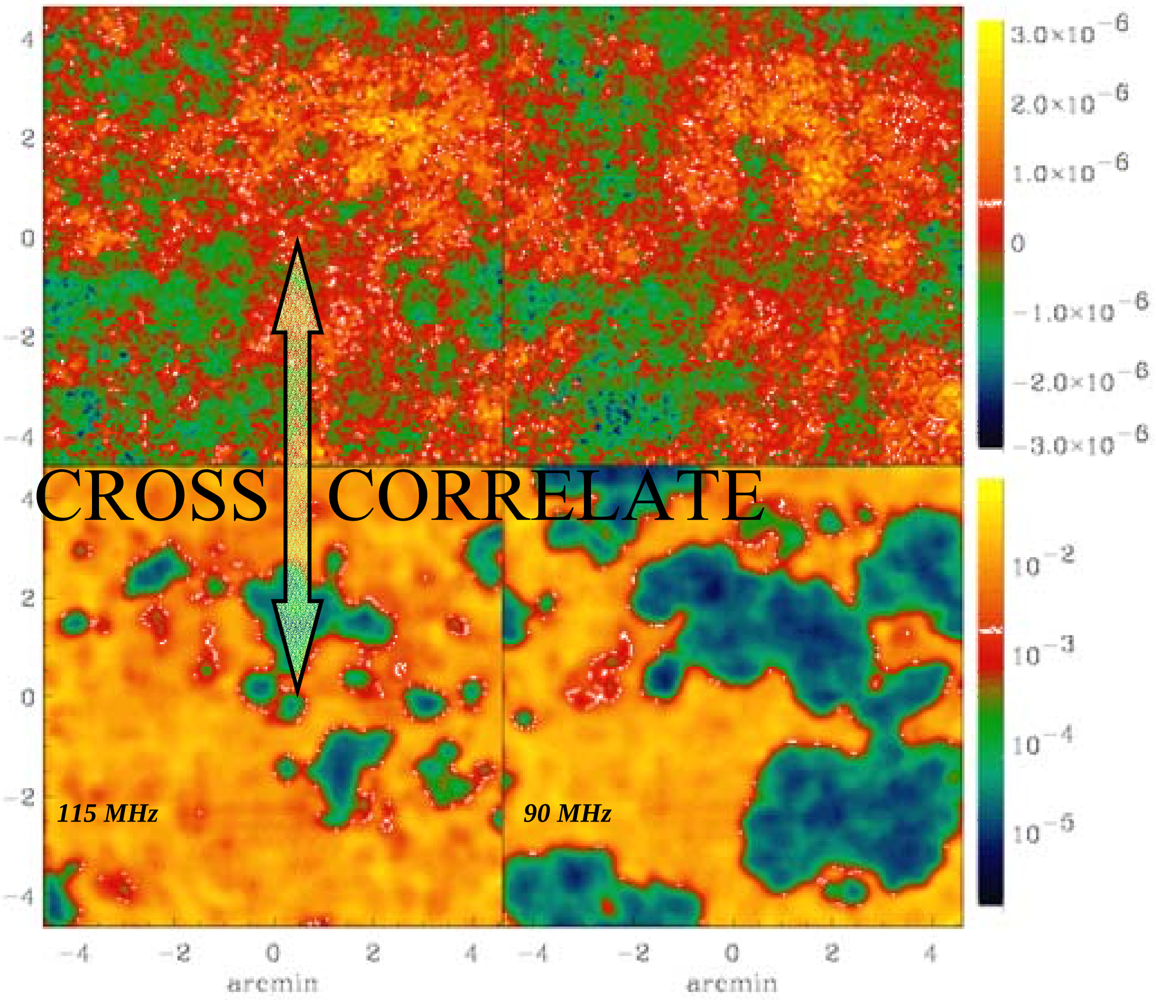
- Single object
- QSO lifetime and spectrum
- Gas clumping factor
- Clustering of sources

Inhomogeneous Reionization

Salvaterra, Ciardi, AF & Baccigalupi 2005

Additional hints from CMB+21cm line

late reionization early reionization



CROSS CORRELATE

$(\delta T/T_0)_{CMB}$

$(\delta T_b/T_0)_{21CM}$

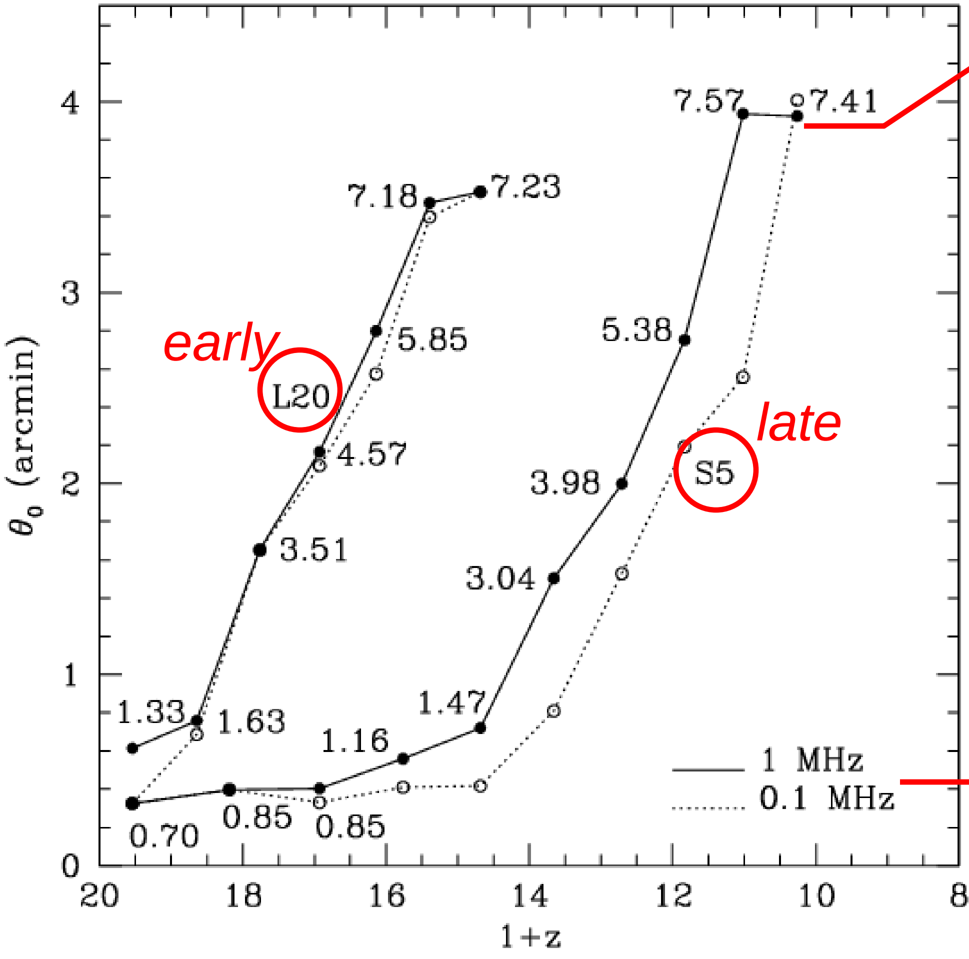
ALMA

LOFAR

Inhomogeneous Reionization

Salvaterra, Ciardi, AF & Baccigalupi 2005

HII regions: size evolution



Size of HII region (Mpc) from zero of correlation fct.

Bandwidth

Selected Summary

- Massive first stars likely responsible for NIRB excess can reionize the IGM at $z \approx 15$

- Reionization by miniquasars and neutrino decays strongly disfavored by XRB limits

- Early reionization not in contrast with any constraint from QSO absorption line data

- Reionizing (massive) stars produce a patchy IGM pollution to the critical metallicity

- Transition to normal stars occurs whenever/wherever $Z = Z_{crit} \sim 10^{-5} Z_{O}$

- A considerable fraction (5-10%) of baryons might be locked in IMBHs at $z=0$

Want to know more ?

THE END