Constraining Reionization with Lyman Alpha Emitters

Andrea Ferrara

Scuola Normale Superiore, Pisa
& IPMU, Tokyo

DAVID

The Dark Ages VIrtual Department

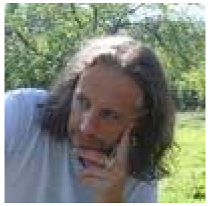
http://www.arcetri.astro.it/twiki/bin/view/DAVID/WebHome

S. Bianchi
INAF/Arcetri

B. Ciardi
MPA

P. Dayal
SISSA

C. Evoli
SISSA



A. Ferrara
SNS Pisa

S. Gallerani
OARoma

F. Iocco
IAP

F. Kitaura
SNS Pisa

M. Mapelli
ETH

A. Maselli
INAF/Arcetri

R. Salvaterra
INAF/Milano

S. Salvadori
SISSA

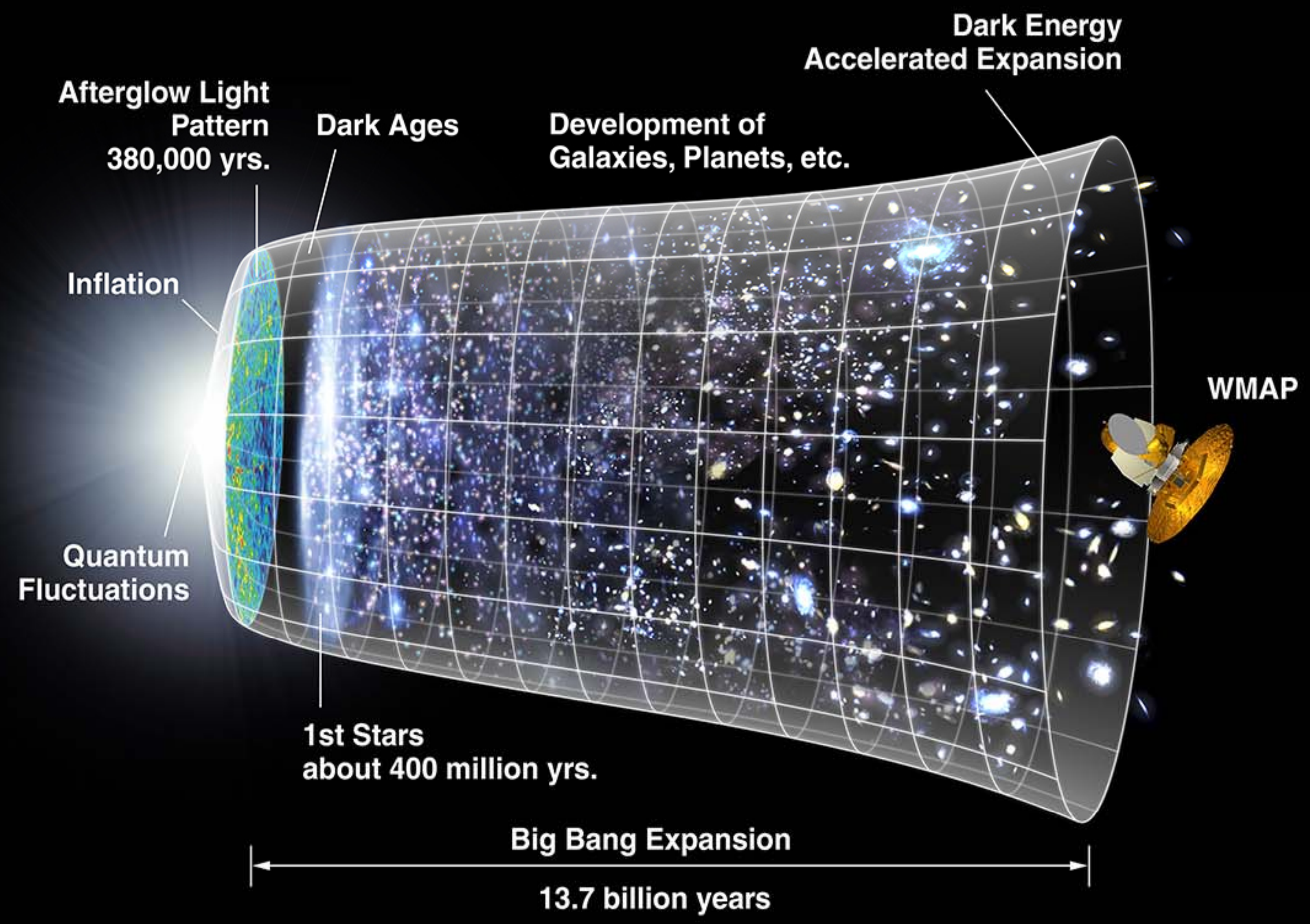
R. Schneider
INAF/Arcetri

L. Tornatore
INAF/Trieste

M. Valdes
IPMU

R. Valiante
Univ. Firenze

First Gyr



Dark Energy
Accelerated Expansion
Afterglow Light
Pattern
380,000 yrs.
Dark Ages
Development of
Galaxies, Planets, etc.
Inflation
WMAP
Quantum
Fluctuations
1st Stars
about 400 million yrs.
Big Bang Expansion
13.7 billion years

SOURCE LIST

- Stars: Pop II and/or (massive) Pop III

  In what proportion ? (4, 30, 100)$\times 10^3$ phot/baryon into stars

- Quasars

  Too rare, too late; key sources for HeII reionization

- Supernova explosions

  Filling factor too small; Compton-y limited

- Dark Matter: decays/annihilations

  Light particles (LDM, sterile neutrinos) can produce a $\tau_e < 0.01$
  Heavy particles (neutralinos, gravitinos) totally negligible

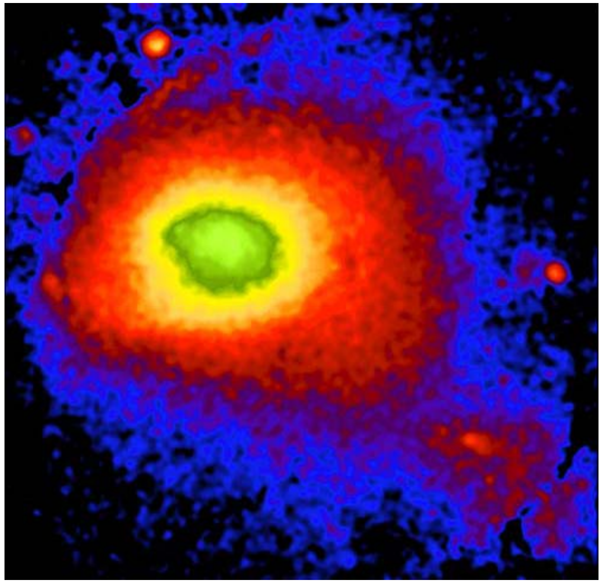
- Mini-quasars

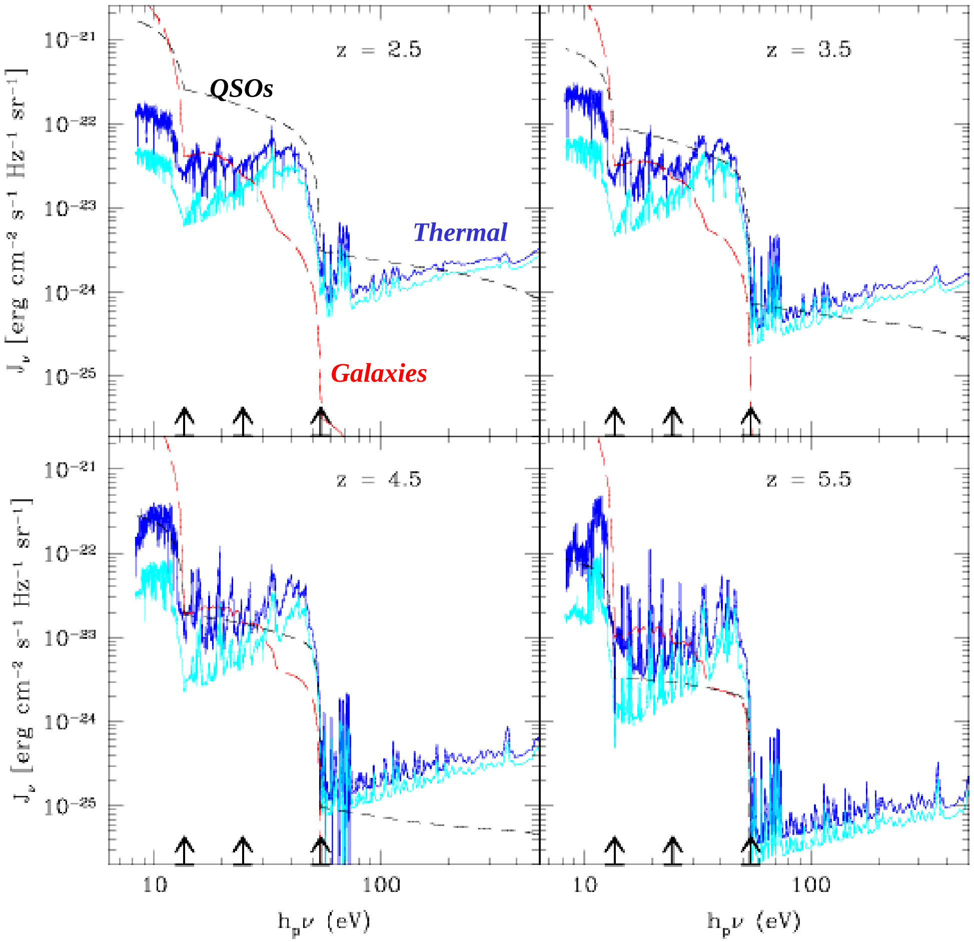
  Limited by unresolved SXRB
  Only 3 phot/baryon in IGM in 10 Salpeter times

- Structure formation

Miniati+2002

IONIZING PHOTONS FROM STRUCTURE FORMATION

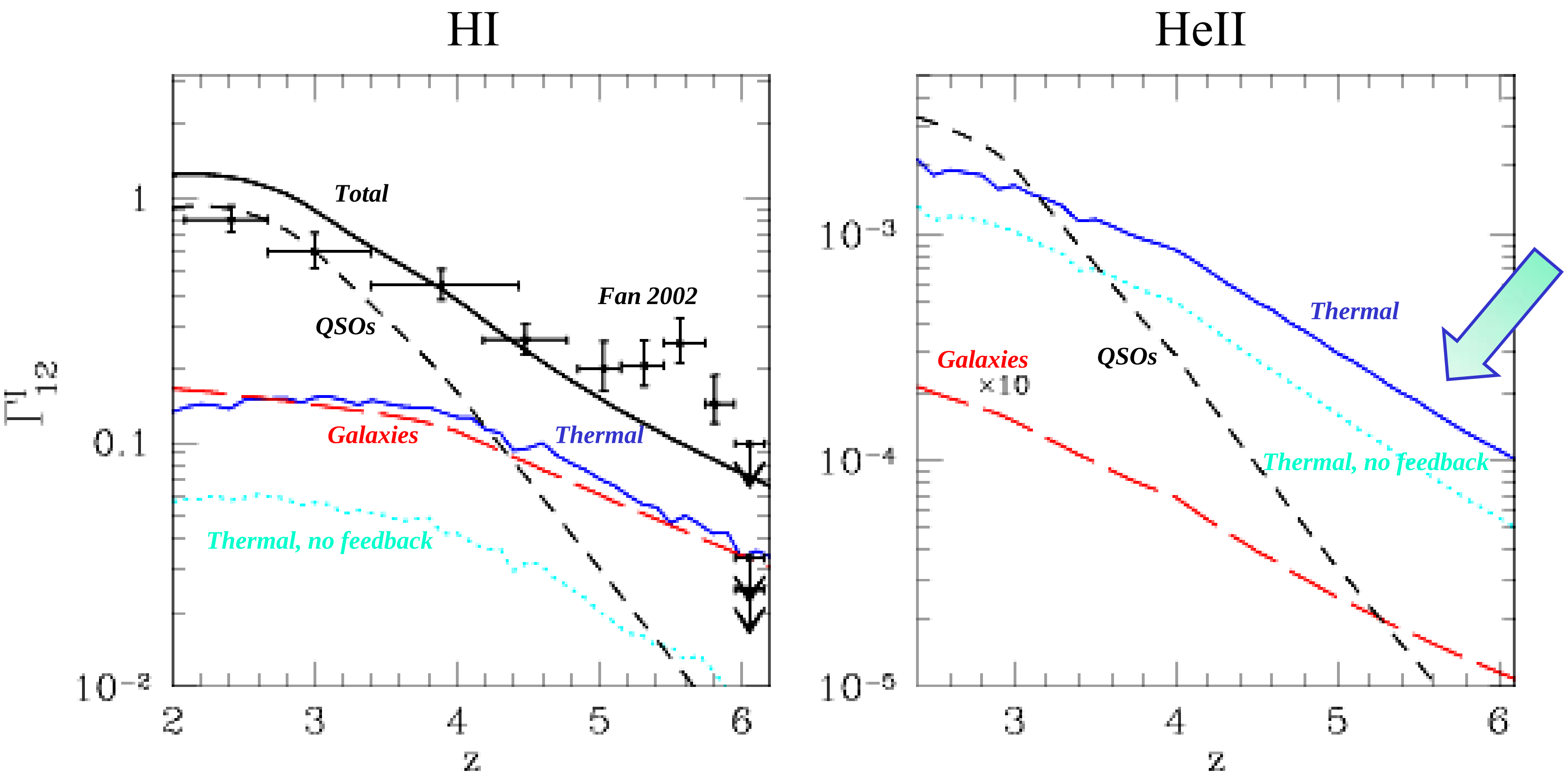




Mass range: log M = 11 – 13
Virial temperatures: log (T/K) ≥ 6
Bremsstrahlung + line emission
Escape fraction ≈ 1

Miniati+2002

IONIZATION FROM STRUCTURE FORMATION

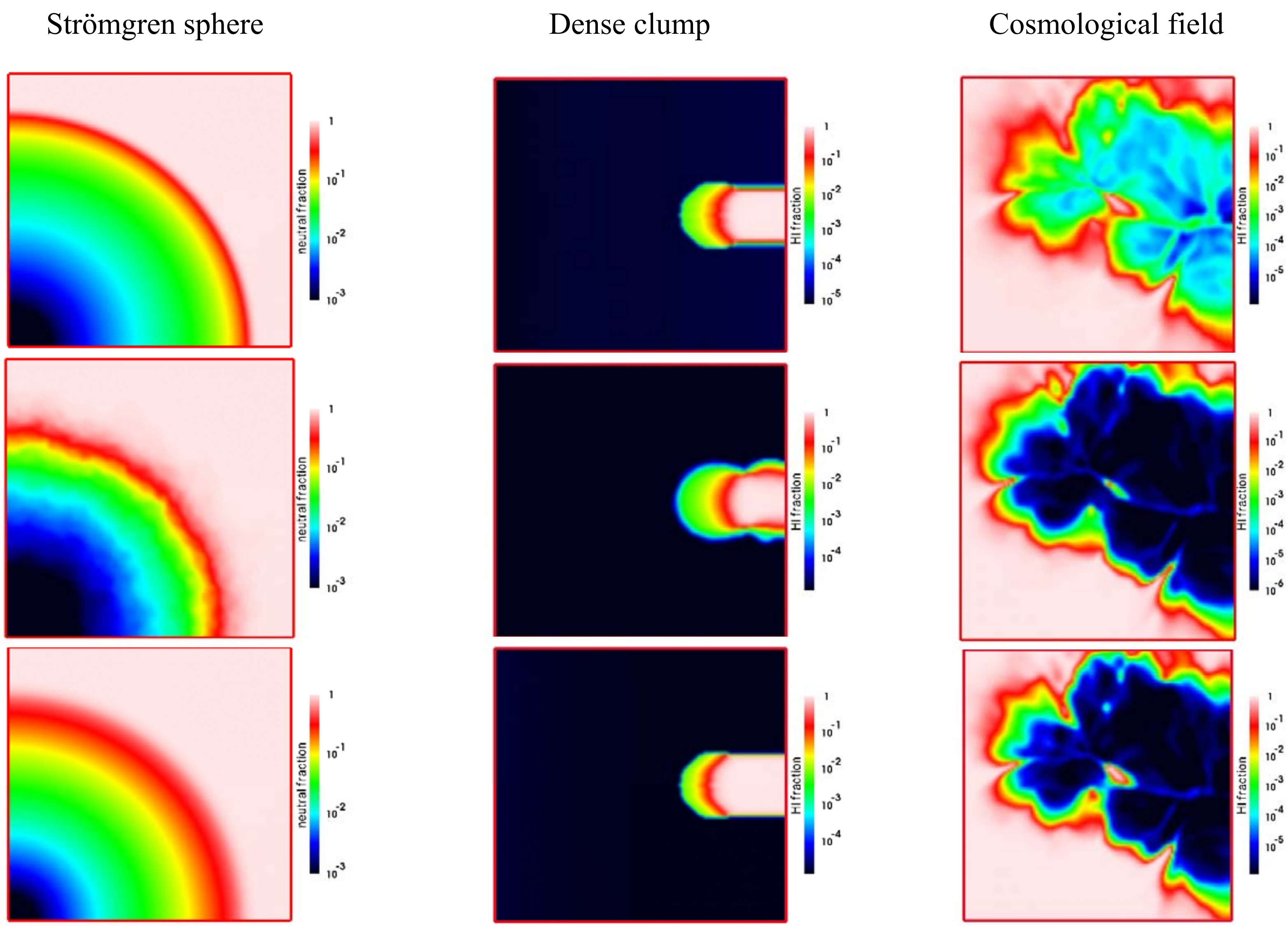


Photoionization rates

TSU³ CODE BENCHMARK

Iliev+2007

www.mpa-garching.mpg.de/**tsu3**/



EXPERIMENTAL CONSTRAINTS

- Lyα Gunn-Peterson opacity
- Electron scattering optical depth
- Lyβ Gunn-Peterson opacity
- UV Background intensity
- Redshift evolution of Lyman Limit Systems
- IGM Temperature evolution
- IGM Metallicity
- Cosmic star formation history
- High-z galaxy counts
- Near Infrared Background

Ciardi+2003, Choudhury & AF 2005, 2006, Trac & Cen 2007

MODEL FEATURES

✓ Self-consistent treatment of the evolution of ionized regions and thermal history

✓ Follow evolution of neutral, HII and HeIII regions

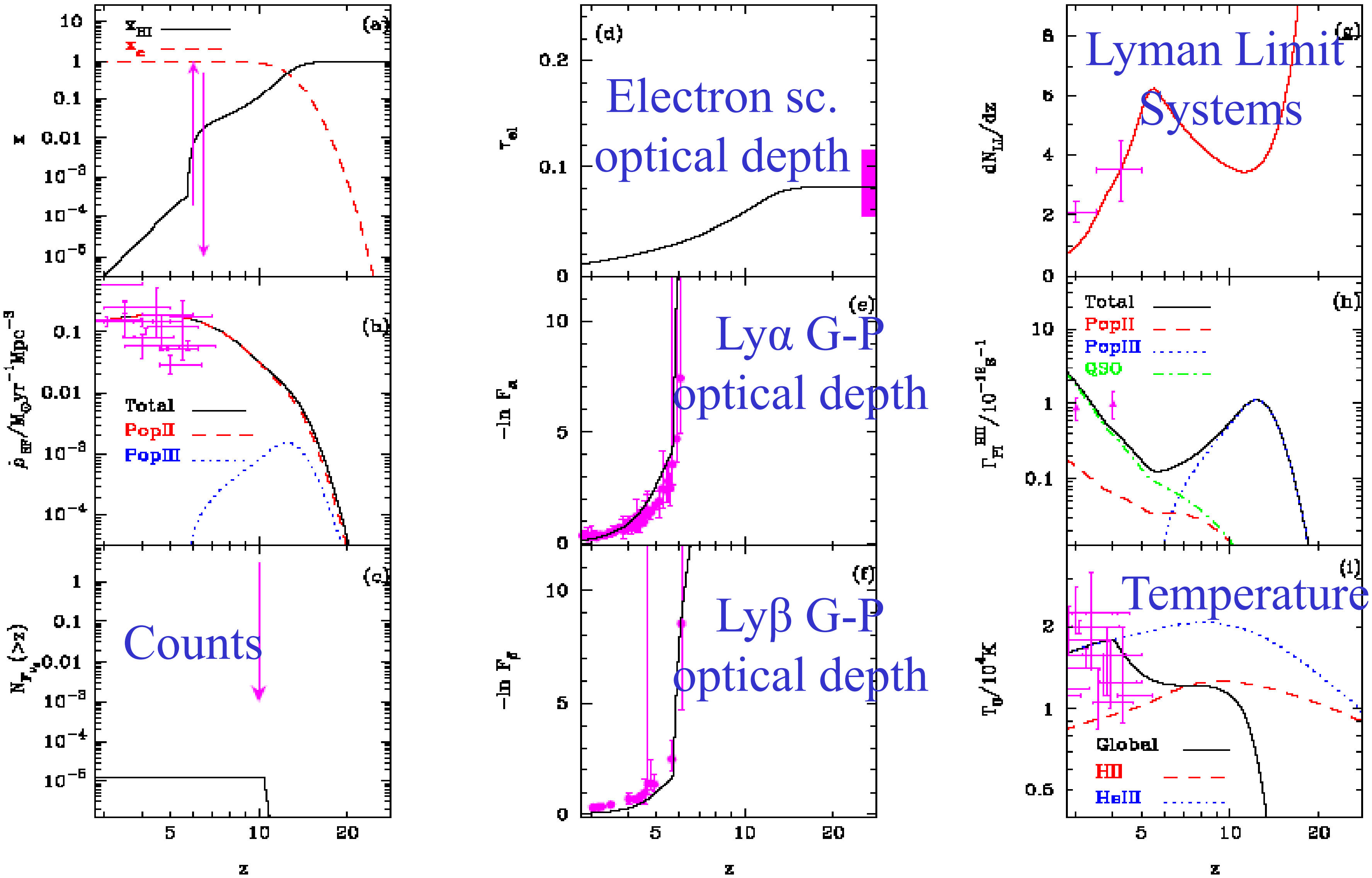
✓ Three sources of ionizing radiation:

- PopIII stars: early redshifts, Salpeter IMF, zero metallicity
- PopII stars: Salpeter IMF, PopIII-PopII transition included
- 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

Choudhury & AF 2005, 2006



Dayal+ 2009, Schaerer & de Barros 2009

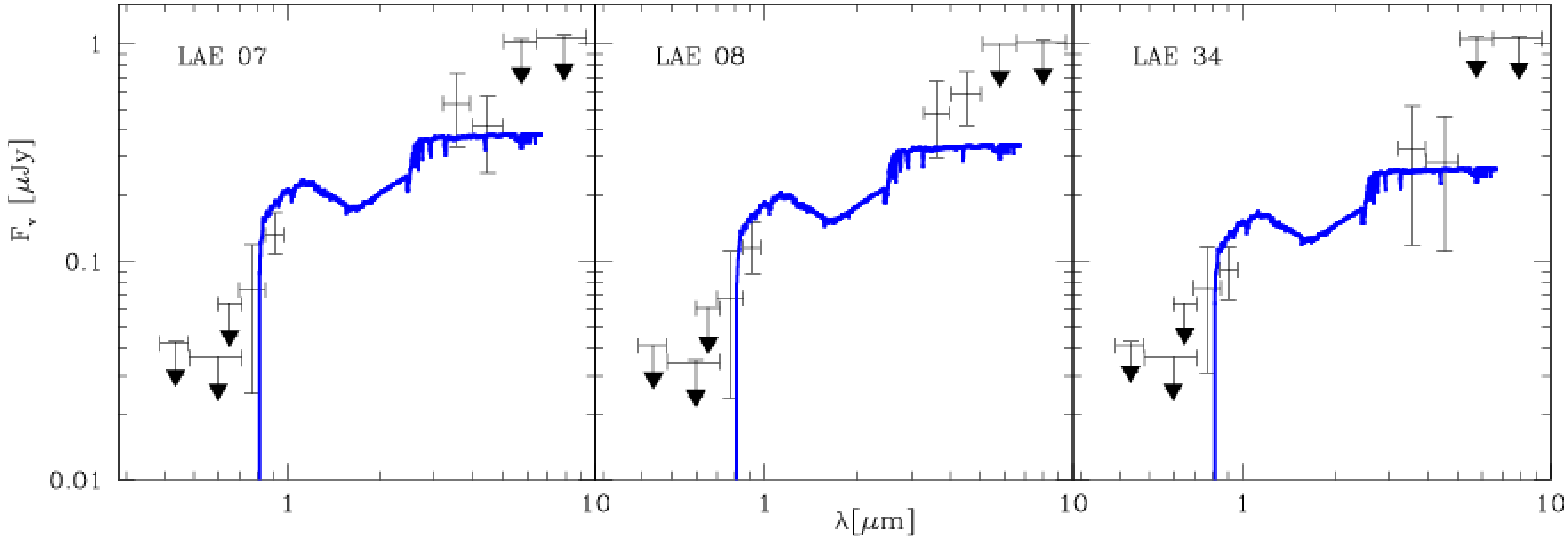
LAEs: STELLAR POPULATIONS

Age

$z \approx 5.7$

#LAE	t_* (Myr)	Z ($Z_\odot$)	$\dot{M}_*$ ($M_\odot yr^{-1}$)	E(B − V)
07	182	0.26	9.9	0.145
08	194	0.21	8.6	0.145
34	166	0.26	7.2	0.145

data: Lai+07



Dayal+ 2008, 2009

LAEs IONIZING POWER

@ $z = 6.6$

$$\log [Q_{LAE} / (s^{-1}\ Mpc^{-3})] = 49.32$$

$$\log [Q_{ion} / (s^{-1}\ Mpc^{-3})] = 51.54 + \log C_{30}$$

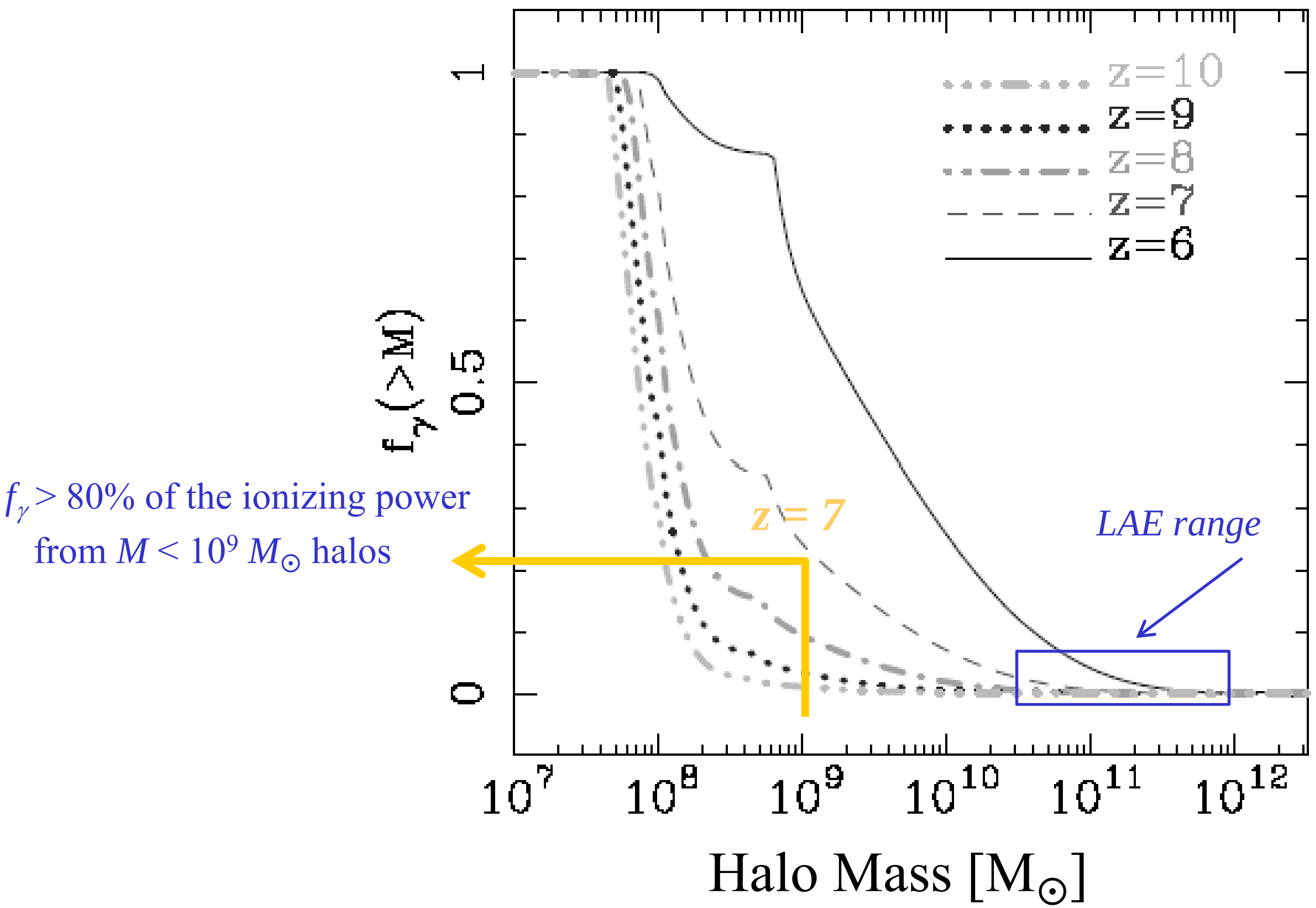
LAE contribute ≈ 1% of ionizing budget

Ages ≈ 150 Myr, star formation started at $z > 8$

PASSIVE REIONIZATION TRACERS

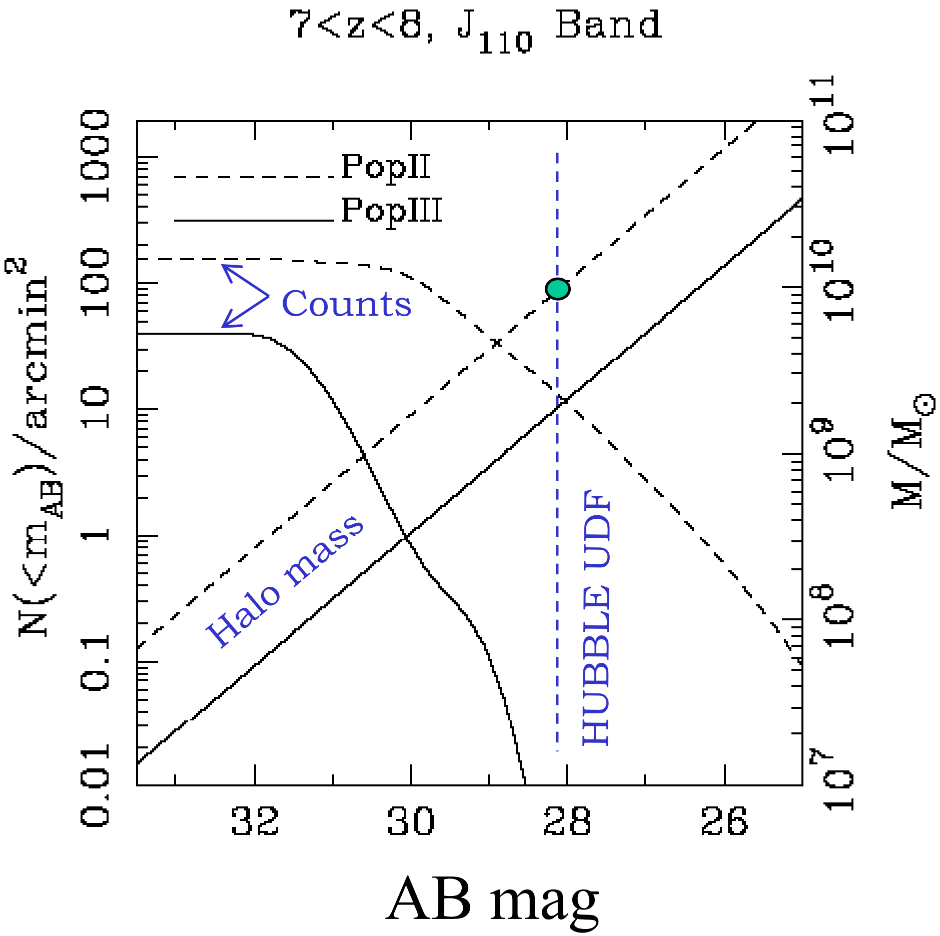
Choudhury & AF 2007

IONIZING PHOTON BUDGET



Choudhury & AF 2007

OBSERVING THE SOURCES

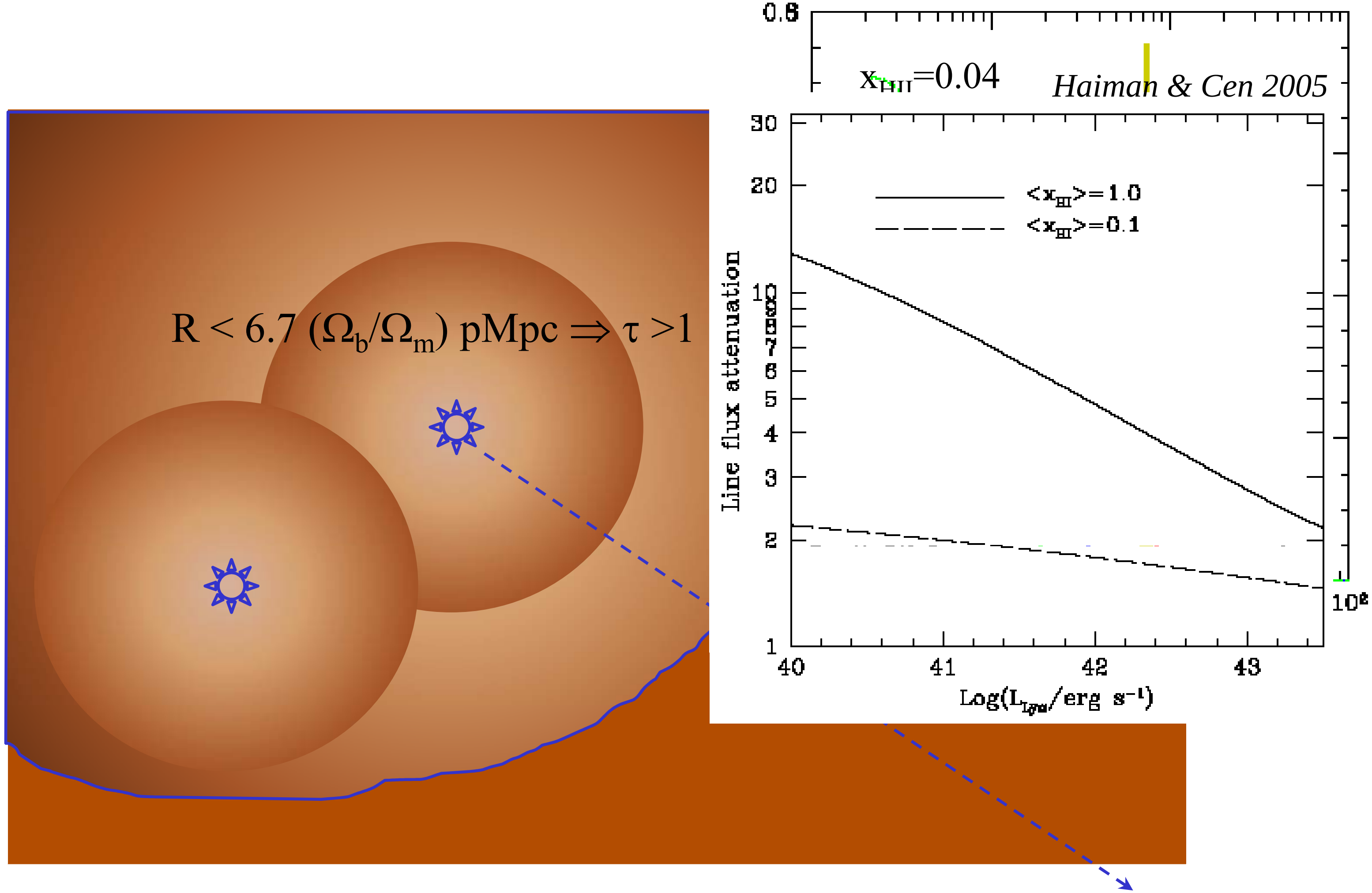


Current candidate high-z galaxies: $\leq 2\%$ of ionizing budget!

Santos 2004, Malhotra & Rhoads 2004, Gnedin & Prada 2004

BASIC IDEA

Furlanetto+2004, Salvaterra+2005

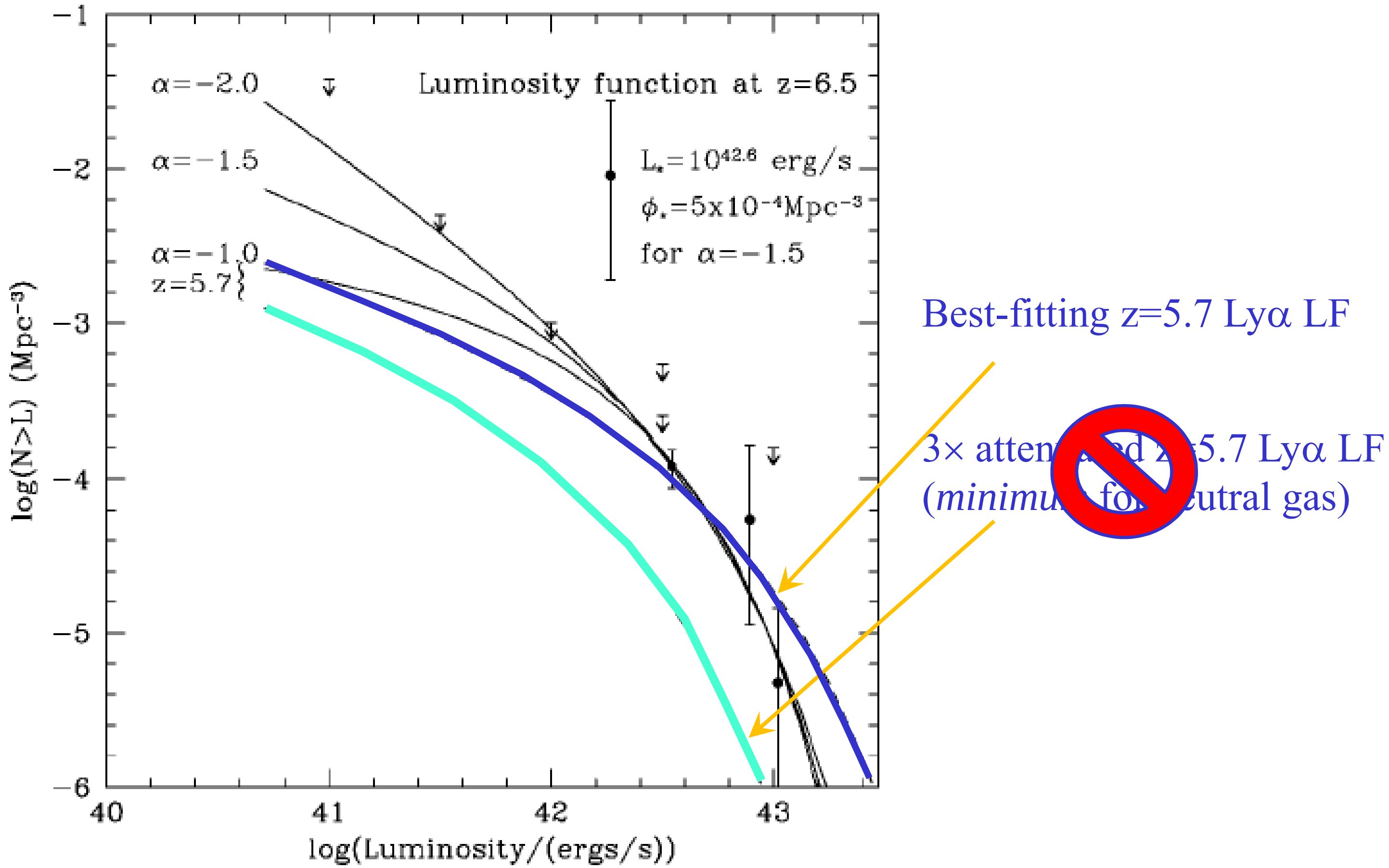


Malhotra & Rhoads 2004

USING THE LUMINOSITY FUNCTION

$x_{HI} < 0.3$

$z \approx 6.5$

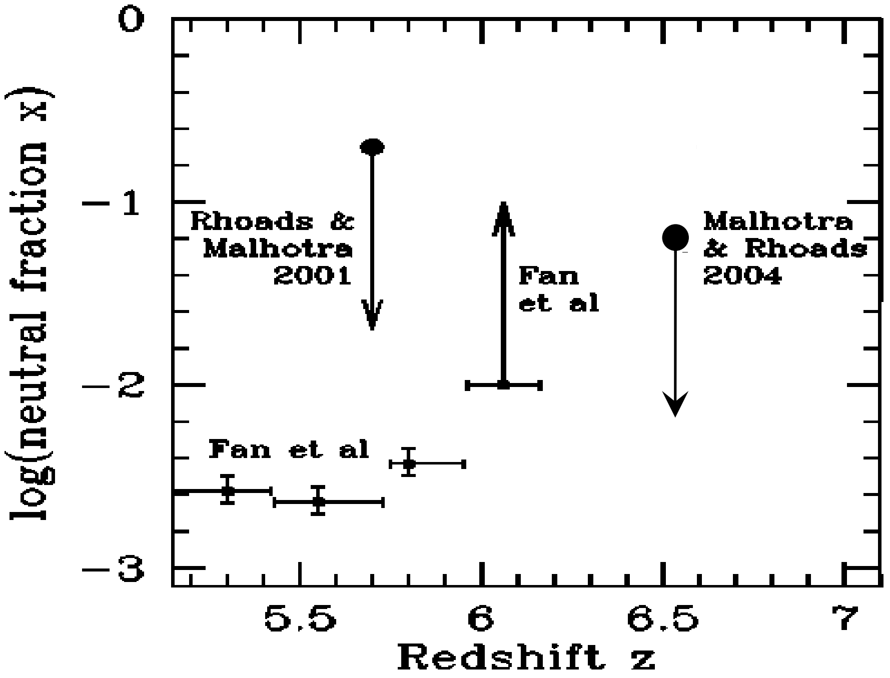


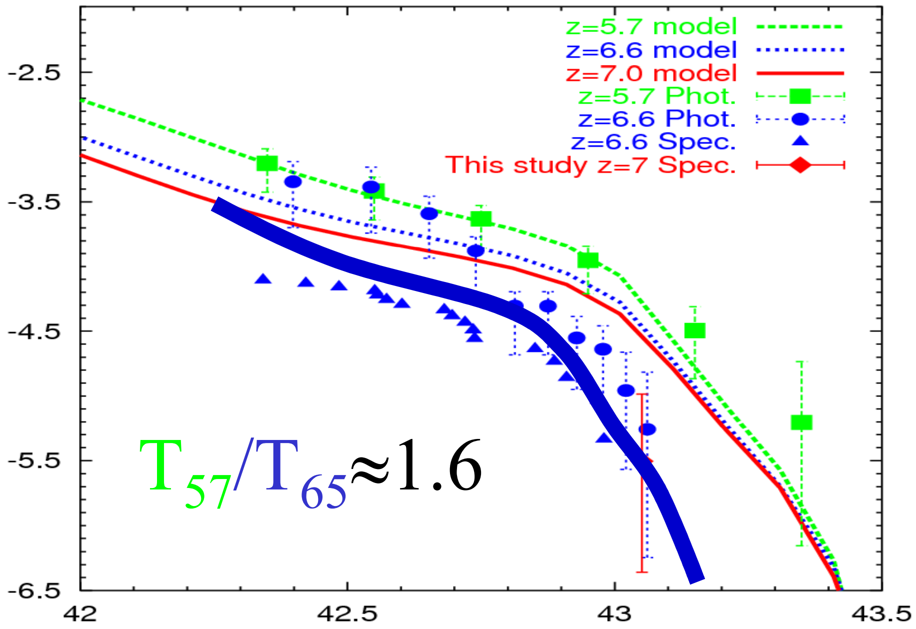
Kobayashi+2007

IS THE LF SHAPED BY REIONIZATION…

$x_{HI} < 0.3$

0.24 $< x_{HI} < 0.36$

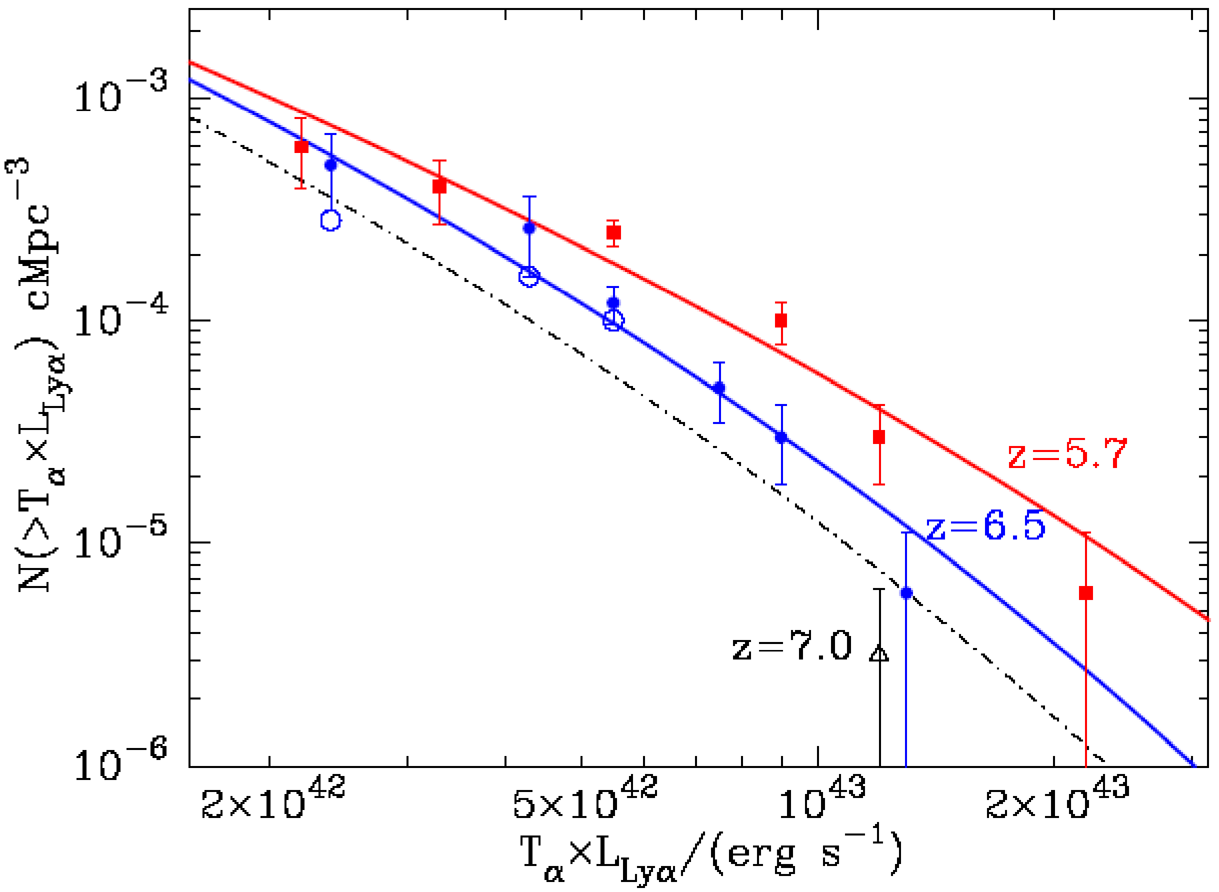




Dijkstra+2007

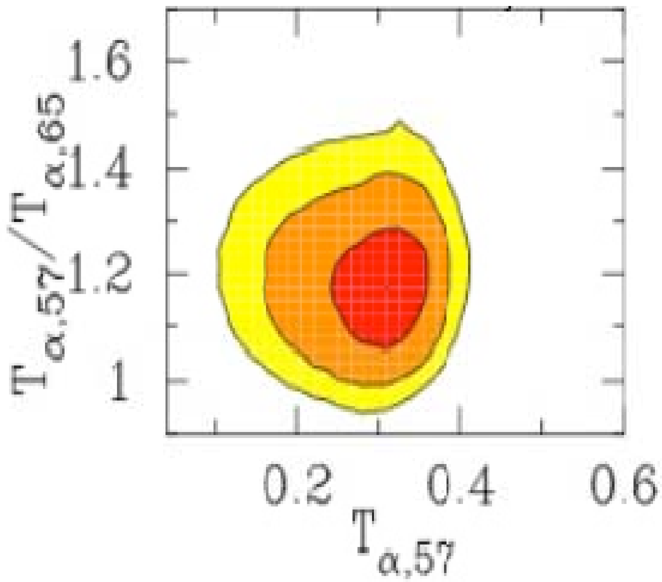
…. OR NOT ?

Pure halo mass function evolution



Dijkstra+2007

PROBABLY NOT !



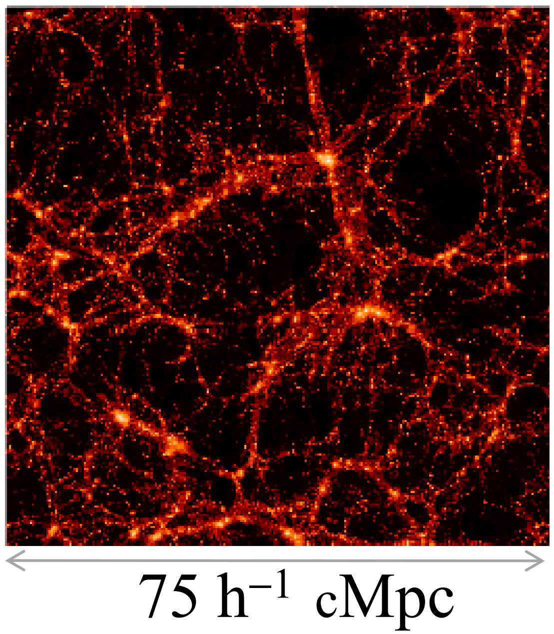
$$\frac{T_{57}}{T_{65}} = 1.2 \pm 0.1$$

The ~20% decrease of transmissivity from z=5.7 to z=6.5 is consistent with the IGM density evolution (~30%)

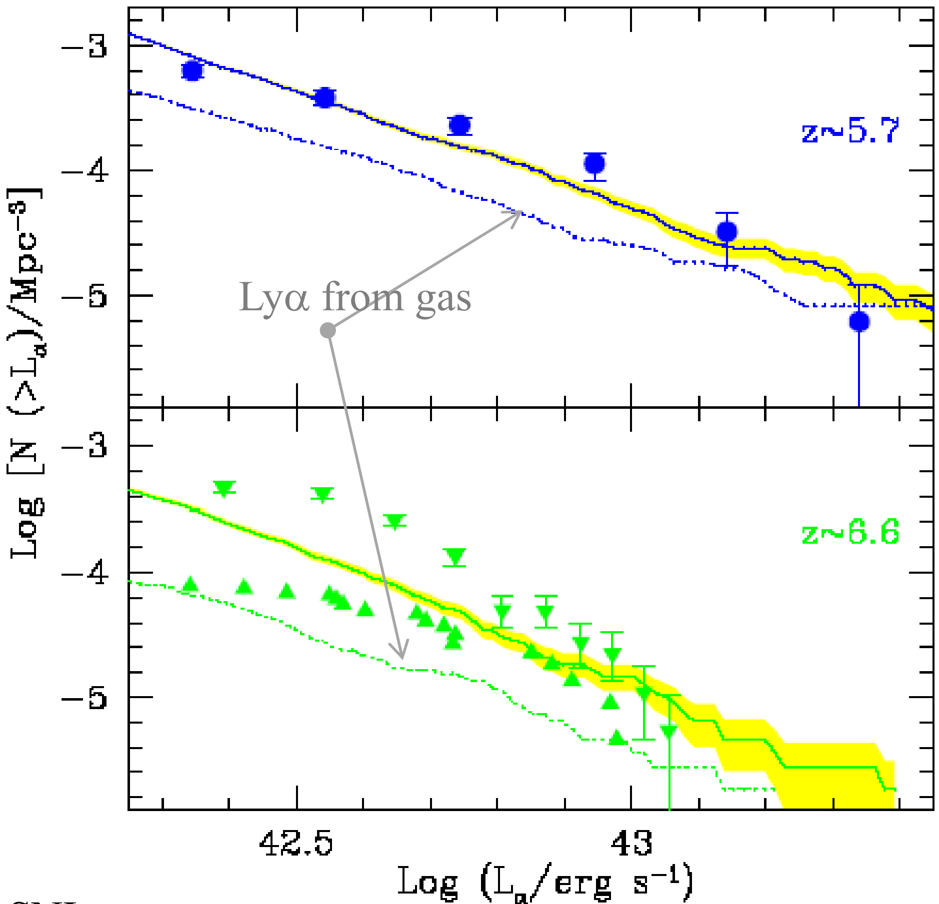
Early-sh reionization ?

Dayal+2008, Dayal & AF 2009

IS THE LF SHAPED BY DUST INSTEAD ?



Early reionization model



GADGET-2

$2\times(512)^3$ particles

$m_{dm} \approx 1.7\times10^8\ h^{-1}\ M_\odot$

Z-dependent cooling

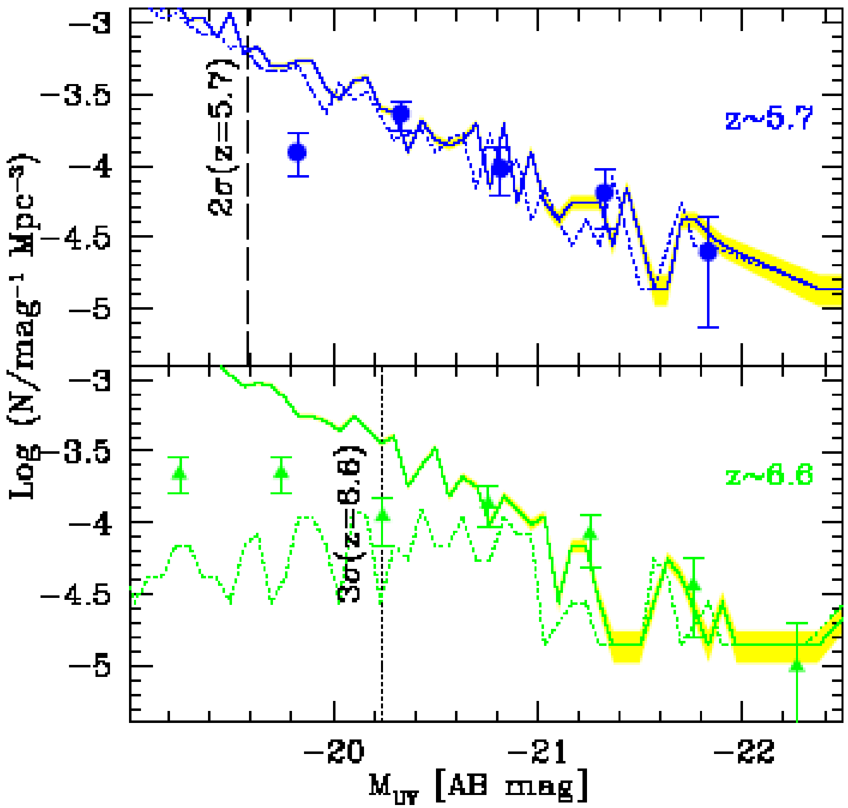
Feedback, metal enrichment by SNII & SNIa

Dust formation/destruction modelling

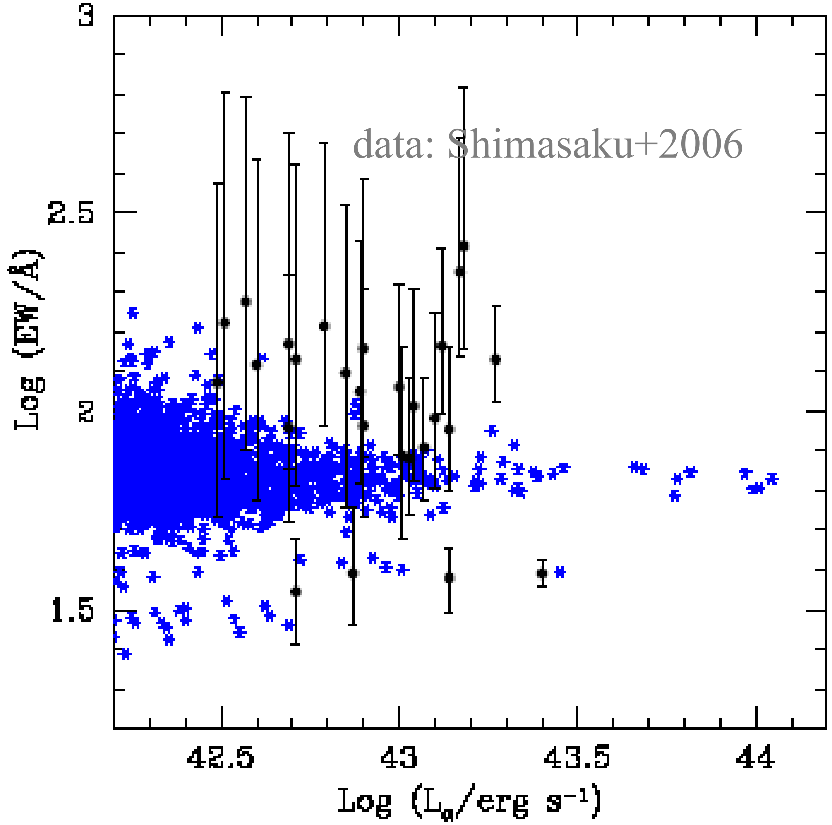
Dayal & AF 2009

MATCHING ALL OBSERVABLES

UV Luminosity Function



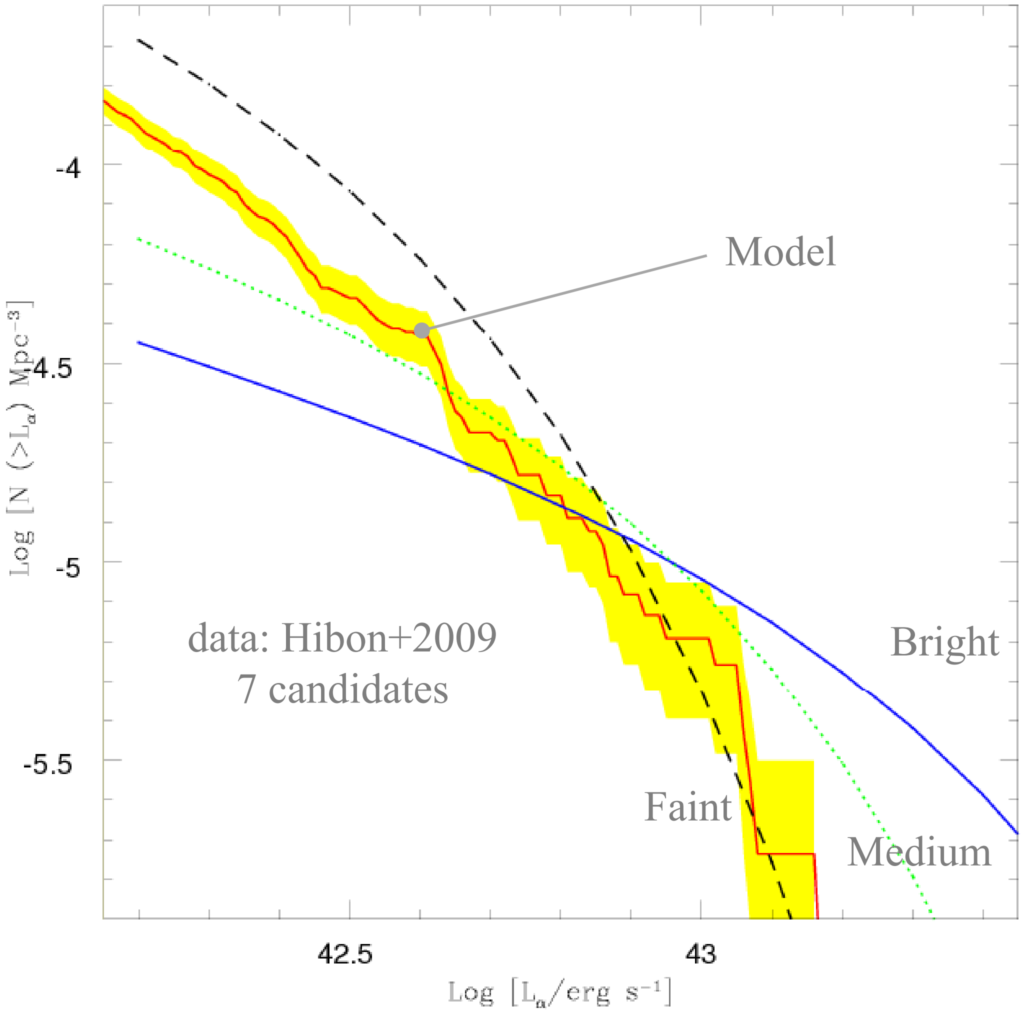
Lyα Equivalent Width



Dayal & AF 2009

HIGHER REDSHIFT: PREDICTIONS

z = 7.6



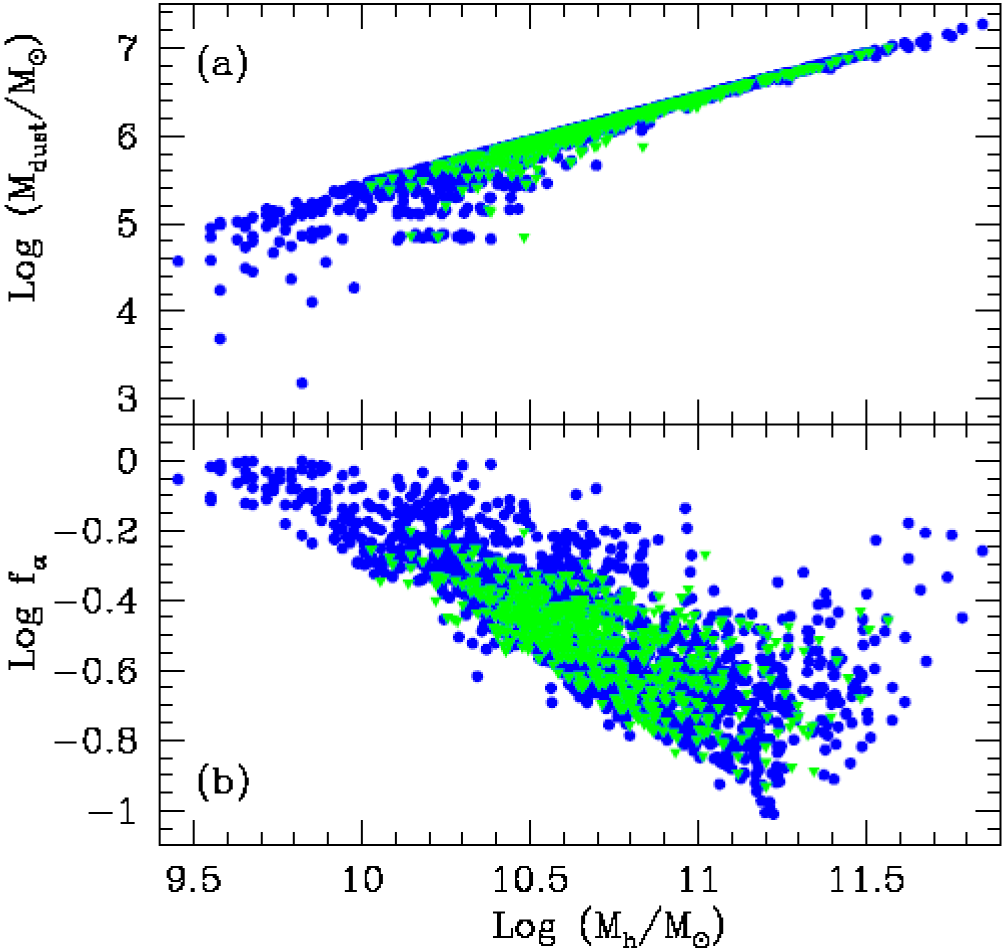
Dayal & AF 2009

IS THE LF SHAPED BY DUST INSTEAD ?

Dust mass

● $z = 5.7$
▲ $z = 6.6$

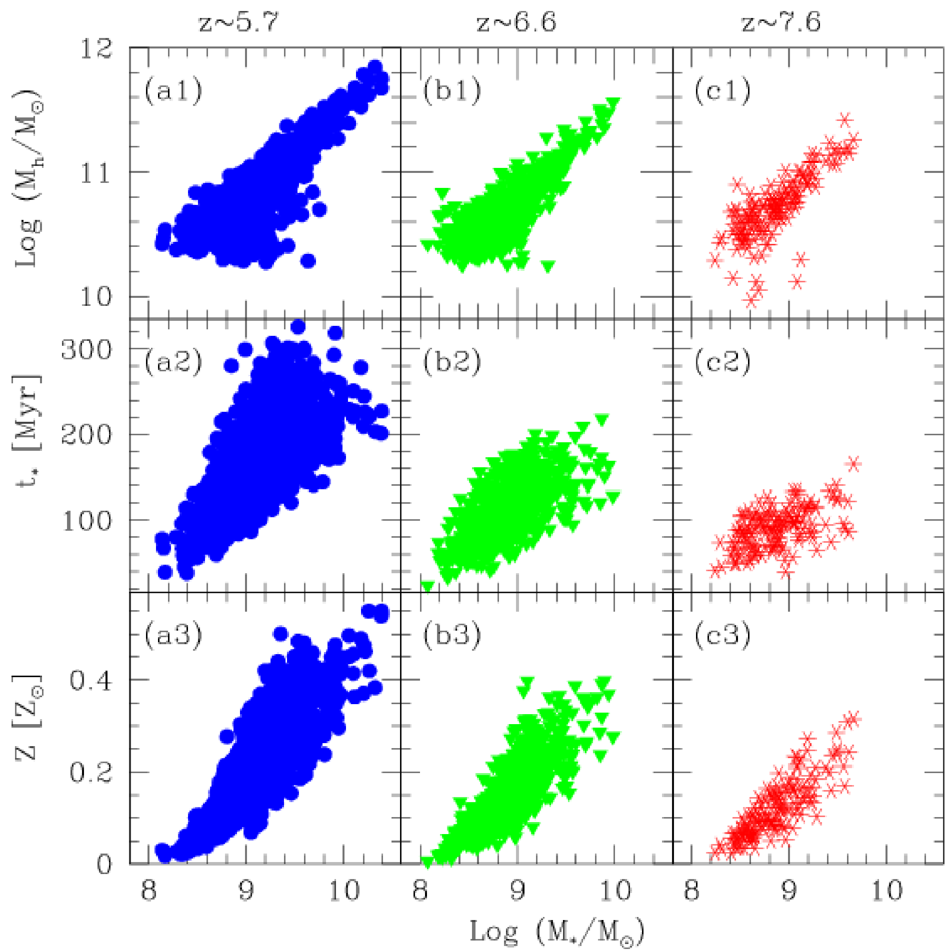
Lya escape fraction



Dayal+2008

WHAT ARE THEY?

Physical properties



Halo mass

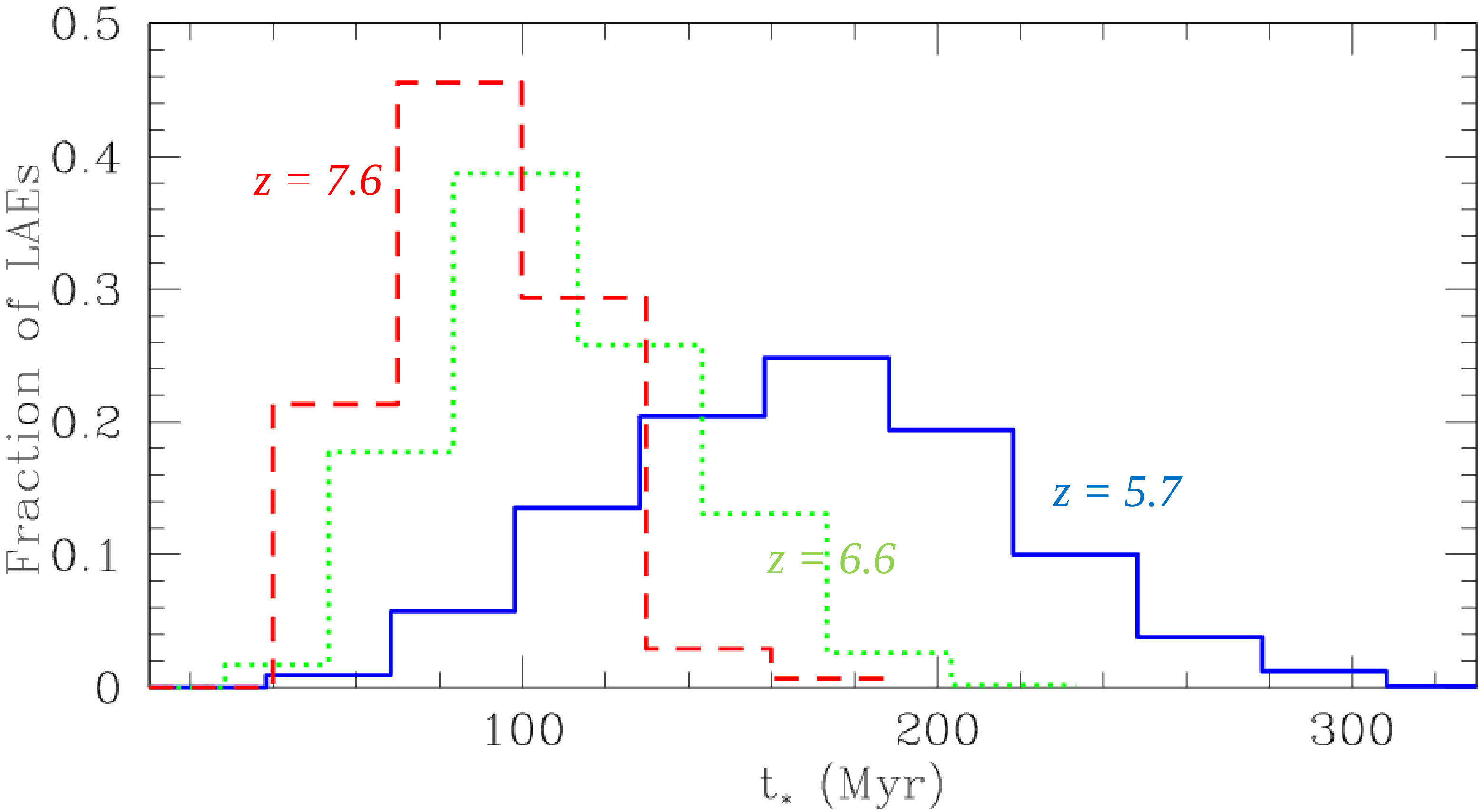
Stellar Age

Stellar Metallicity

Dayal+2008

WHAT ARE THEY?

Mass weighted stellar age distributions

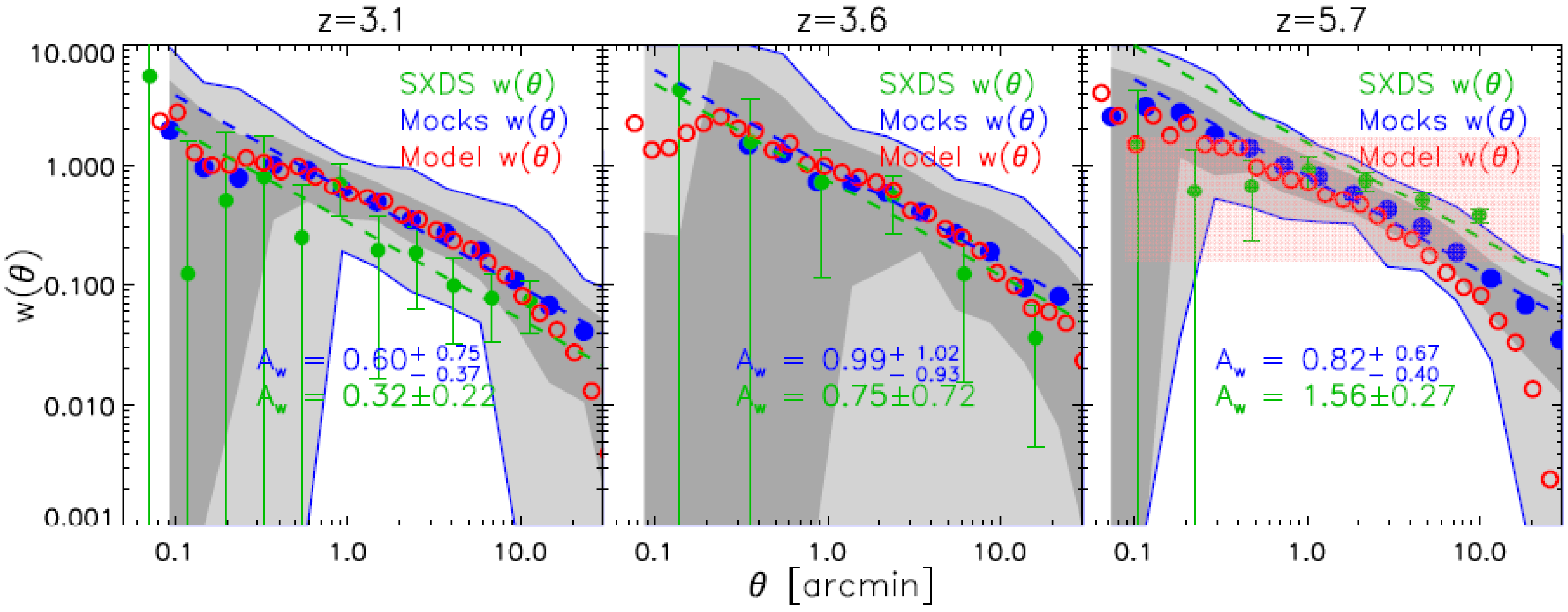


Nagamine+2008;Orsi+2009; Romero+2009

CLUSTERING: INTRINSIC

Angular correlation function

Discrepancy ?



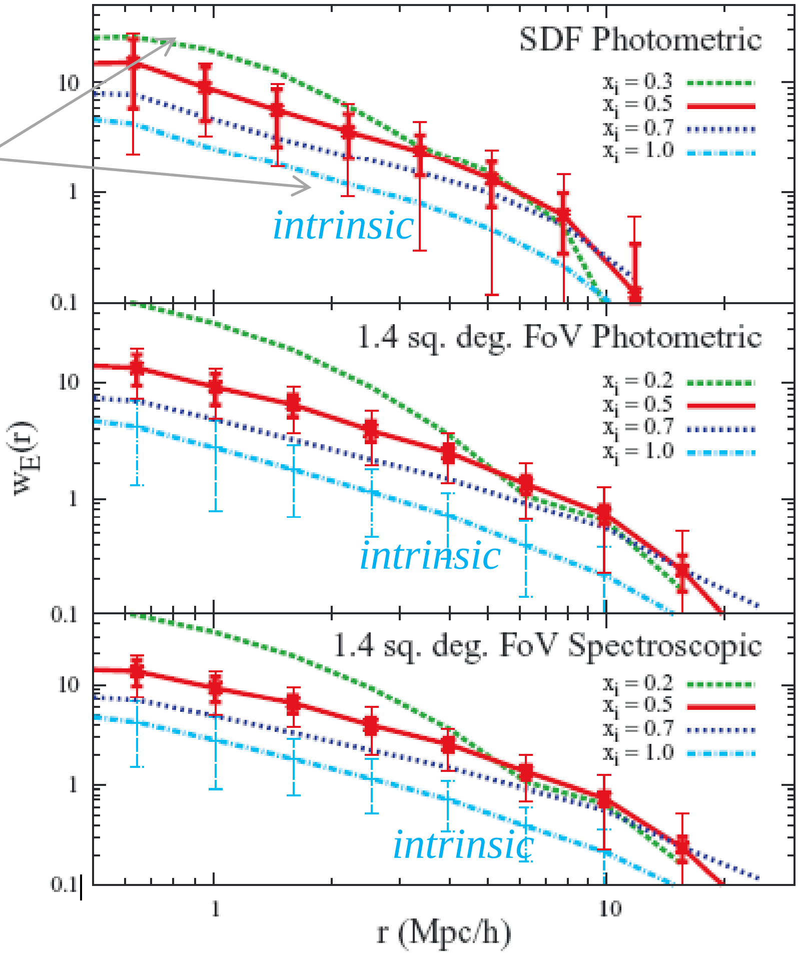
McQuinn+2008

CLUSTERING: REIONIZATION-INDUCED

Angular correlation function

Varying ionization fraction

$z = 6.6$



SDF
Sample: 58 LAEs

SXDF
Sample: 250 LAEs

SXDF
Sample: 190 LAEs

SUMMARY OF MAIN POINTS

- Stars dominate the reionization photon budget
- Reionization started by metal-free stars @ z=20; 90% complete @ z=8
- Early reionization ($z > 7$) not in contrast with any experimental data
- $f_\gamma > 80\%$ of the ionizing power at $z > 7$ from halos of $M < 10^9\ M_\odot$
- LAEs can produce only 1 % of ionizing budget at z=6.6: passive tracers
- Their LF and clustering properties suggest IGM already highly ionized up to z=6.6
- Stellar pops/ages indicate star formation started at z>8, i.e. Relatively evolved systems

Hirashita & AF 2002; Dayal & AF 2009

INCLUDING DUST

from simulations

production — *destruction* — *astration*

$$\frac{dM_{dust}}{dt} = y_d \gamma \dot{M}_* - \frac{M_{dust}}{\tau_{dest}} - \frac{M_{dust}}{M_{gas}} \dot{M}_*$$

continuum optical depth

$$\tau_c = \frac{3\Sigma_d}{4as}$$

continuum escape fraction

$$f_c = \frac{1 - e^{-\tau_c}}{\tau_c}$$

Lyα escape fraction

$$f_\alpha = q(A_\lambda, C)\, f_c$$

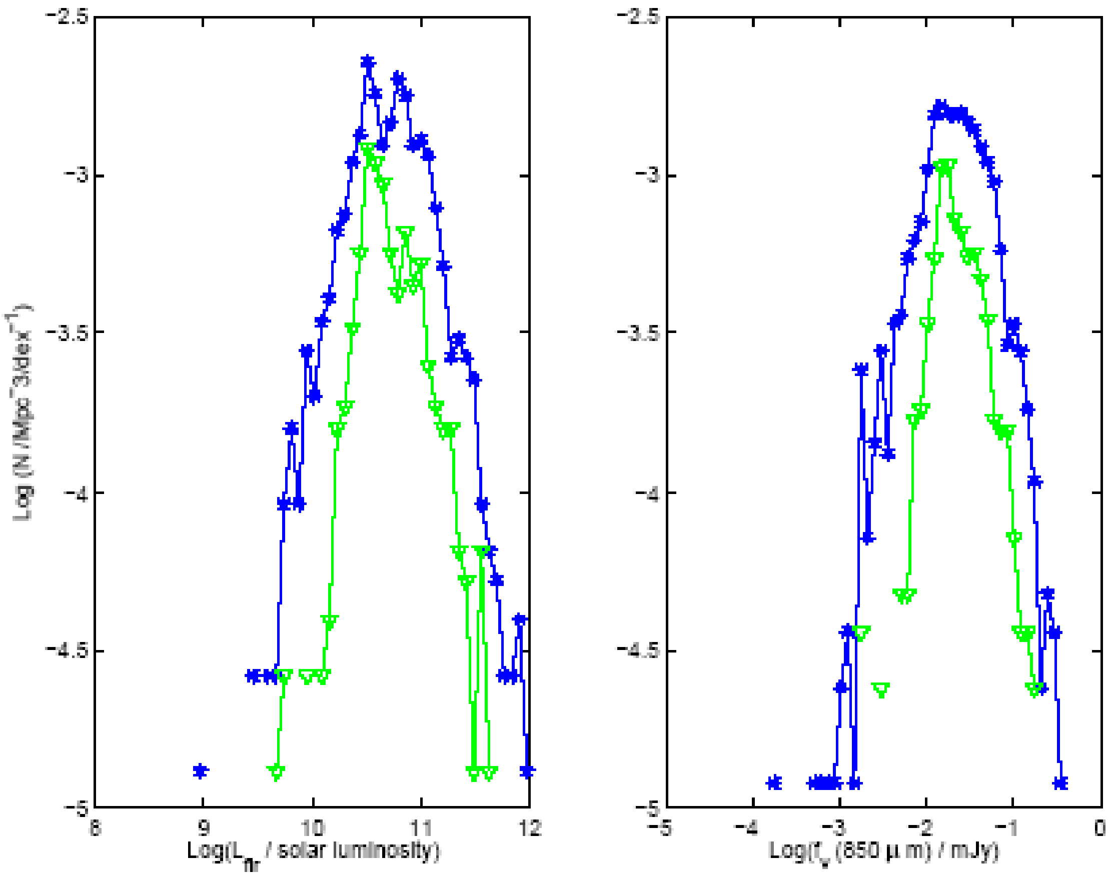
Lyα equivalent width

$$EW = EW^{int} \left(\frac{f_\alpha}{f_c} \right) T_\alpha$$

Finkelstein+09; Dayal+ in prep

MATCHING ALL OBSERVABLES

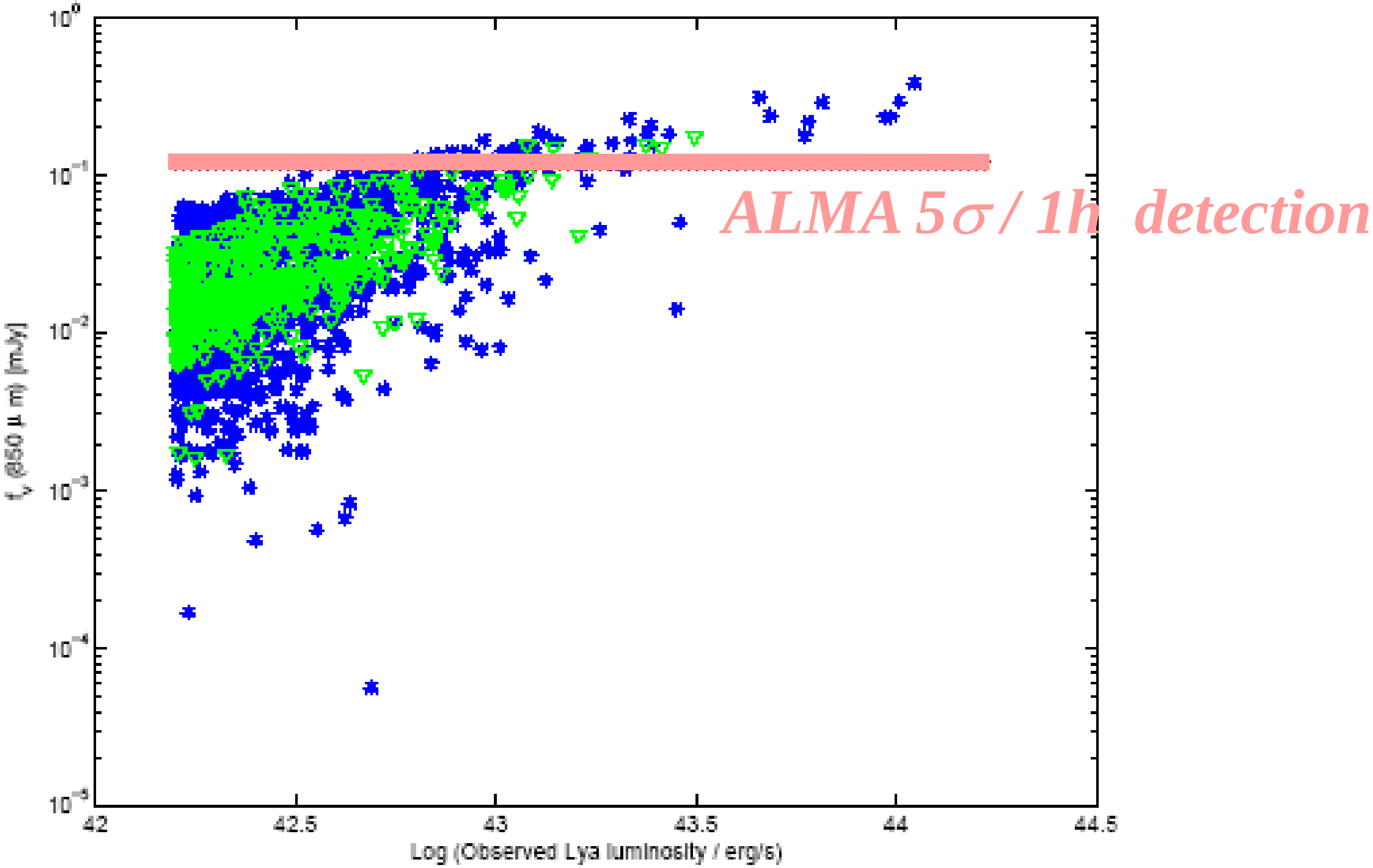
FIR Luminosity Function



Finkelstein+09; Dayal+ in prep

MATCHING ALL OBSERVABLES

Lyα - FIR Luminosity relation



● $z = 5.7$

▲ $z = 6.6$