Piecing Together the Epoch of Reionization

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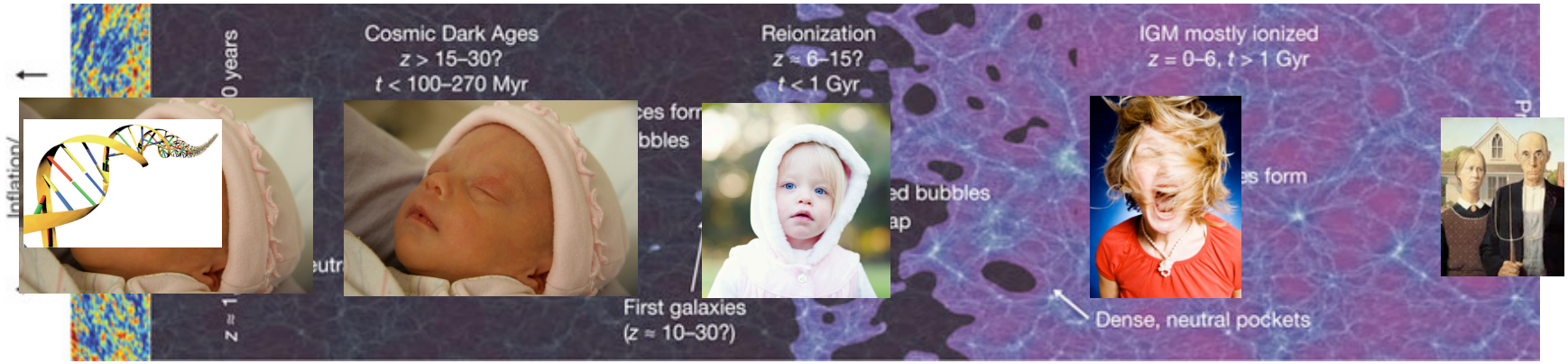
Outline

- *The Cosmic Dawn*
- *The Reionization Era(s): Introduction*
  - *Basic theoretical models*
  - *Existing Observational Constraints*
- *Next generation constraints*
  - *Analogs*
  - *Direct measures*
  - *Indirect measures*
- *Conclusions*

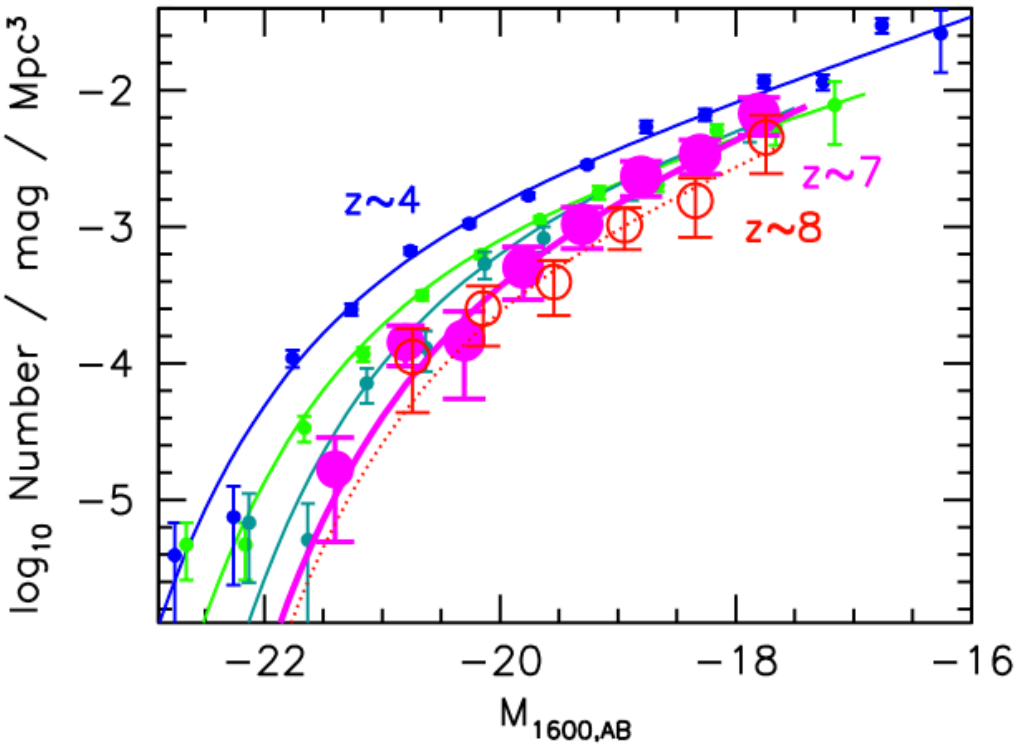
The Cosmic Dawn

- *The era of the first galaxies*
- *Birth of complexity*
- *Transition from exotic to normal*
- *Strongest interactions with their environment*



Robertson et al. 2010

Let's Find Some Galaxies!

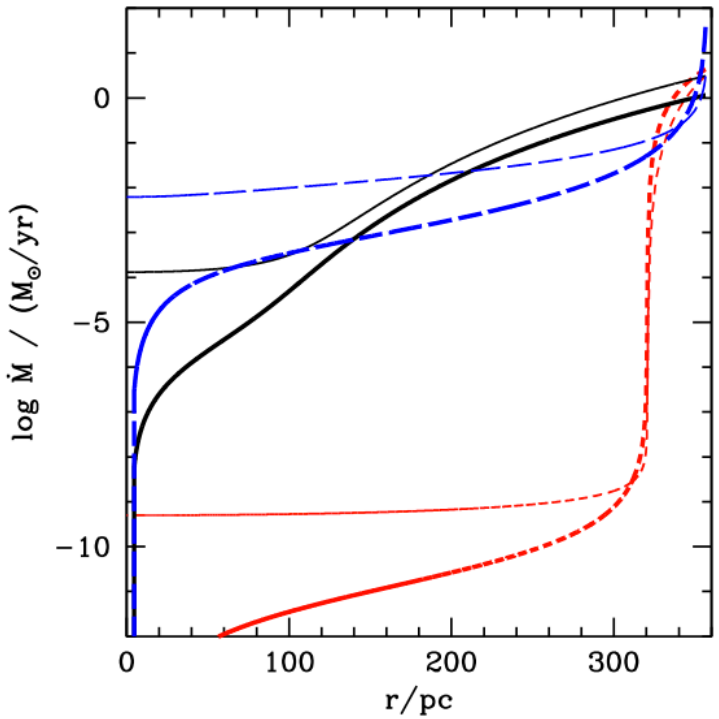


Bouwens et al. (2011)

Galaxy Surveys: What Do We Know?

- *How many bright galaxies there are*
- *The star formation rate in bright galaxies*
- *The stellar mass in bright galaxies*

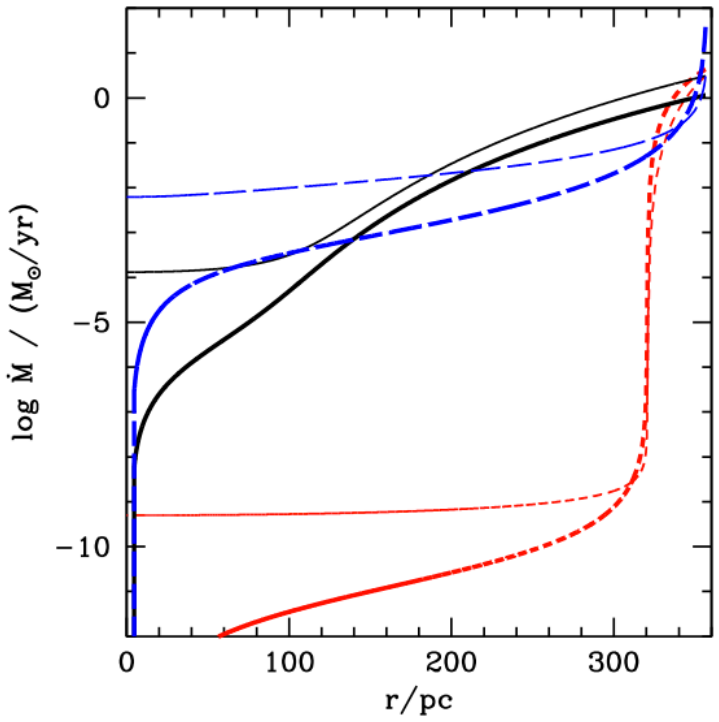
Modeling High-z Galaxies: First Steps



Munoz & Furlanetto (2012)

- *Basic picture (Thompson et al. 2005):*
  - *Disk supported by pressure generated by stars (radiation + supernovae)*
  - *Star formation occurs so as to maintain Q~1*
  - *Star formation consumes gas and ejects more (winds)*
  - *Leftover gas funneled into black hole*

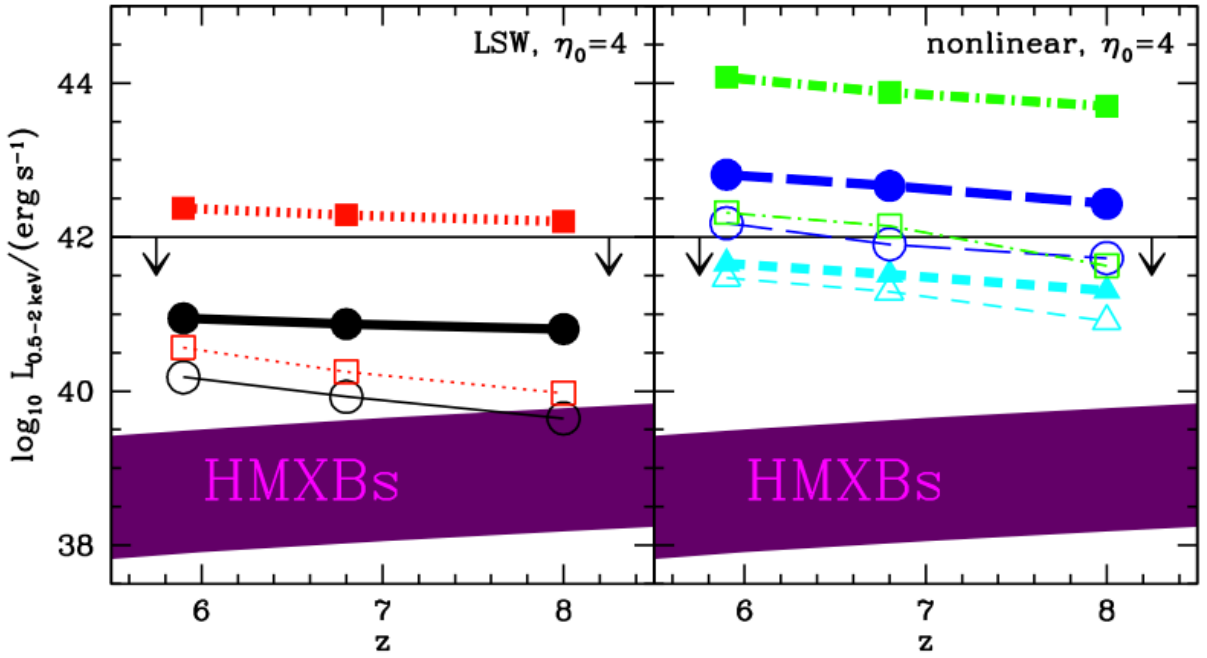
Modeling High-z Galaxies: First Steps



Munoz & Furlanetto (2012)

- *Thick: SFR*
- *Thin: Accretion rate*
- *Key parameter: speed of angular momentum transport*
  - *Red: α-disk*
  - *Black: spiral wave*
  - *Blue: shocked infall*

X-Rays from Distant Galaxies



- *Horizontal line: current observational limits (Cowie et al. 2012)*
- *Purple region: "natural" X-rays from star formation*
- *Lines: model predictions*

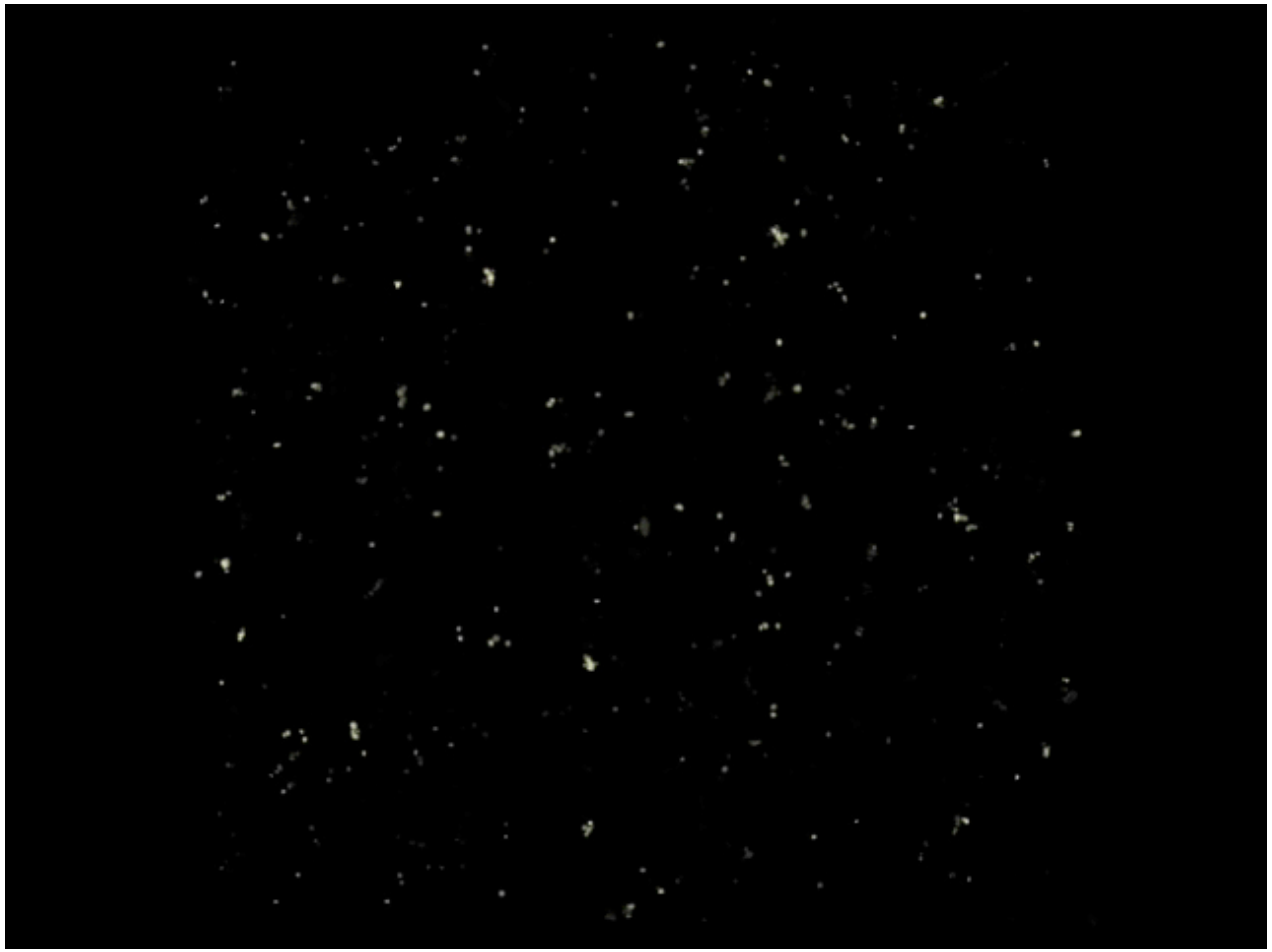
Galaxy Surveys: What Don't We Know?

- *Stellar parameters (age, metallicity, etc.)*
- *Halo mass*
- *Faint end of the luminosity function*
- *IMF*
- *Escape fraction*

Finding the First Galaxies, Indirectly

- *Light from the first galaxies affects the Universe around them*
- *Collective effects of many (tiny) galaxies can be enormous!*

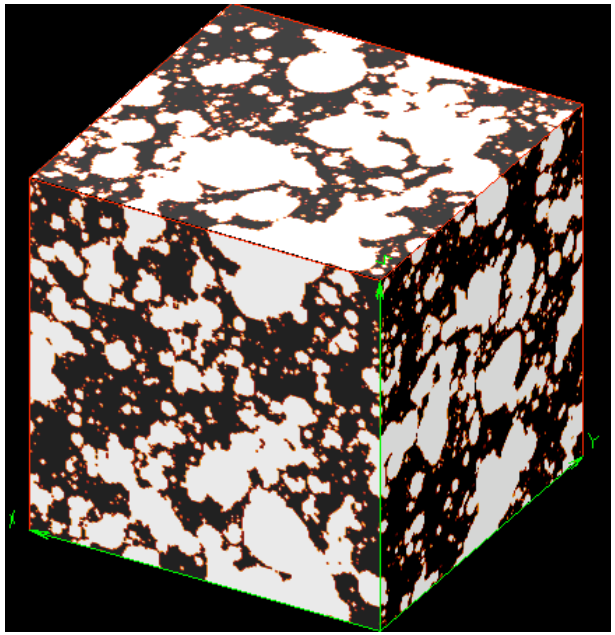
H I Reionization: The Movie



Alvarez, Kaehler, & Abel

The Reionization Process I

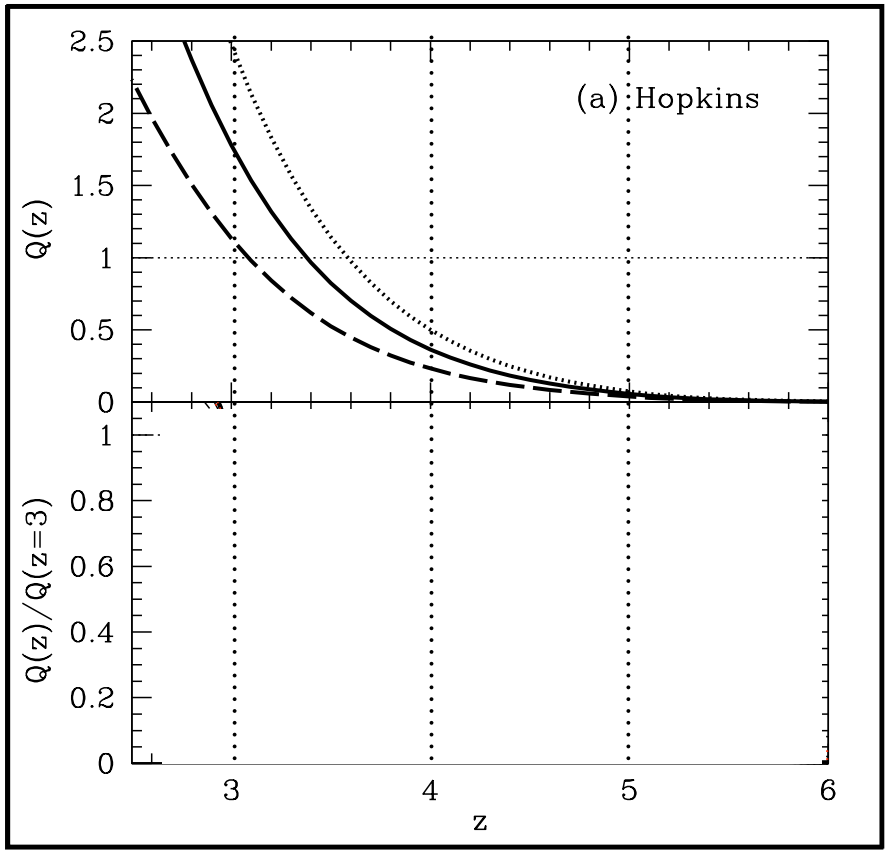
- *Limit #1: "Photon counting"*
- *Ionizing photons escape each source, and form ionized bubbles in IGM*
- *Bubbles grow and merge as more sources appear*



Mesinger & Furlanetto (2007)

When Was Reionization? (I)

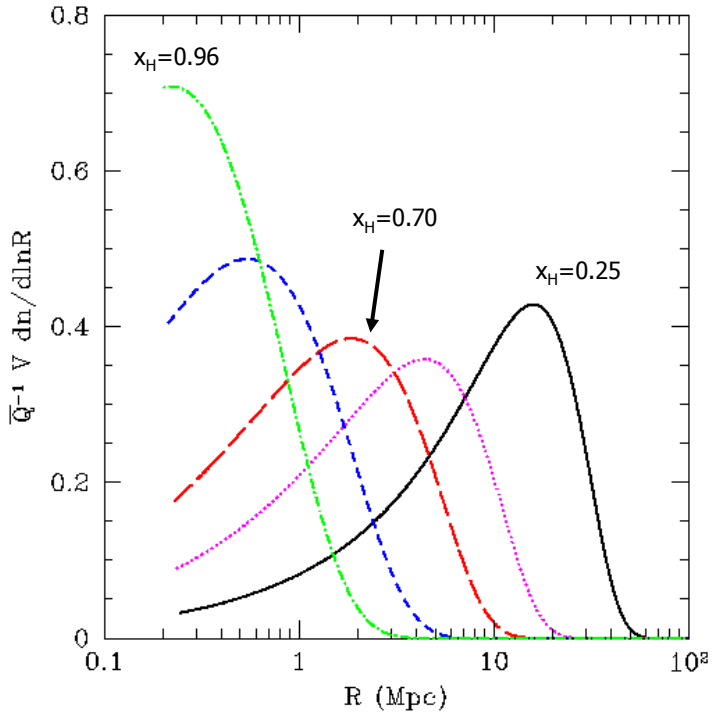
- *Ingredients: source luminosity function*
- *Poorly known for H I reionization, but well-known for He II!*
- *Quasars produce enough ionizing photons at z~3.6*



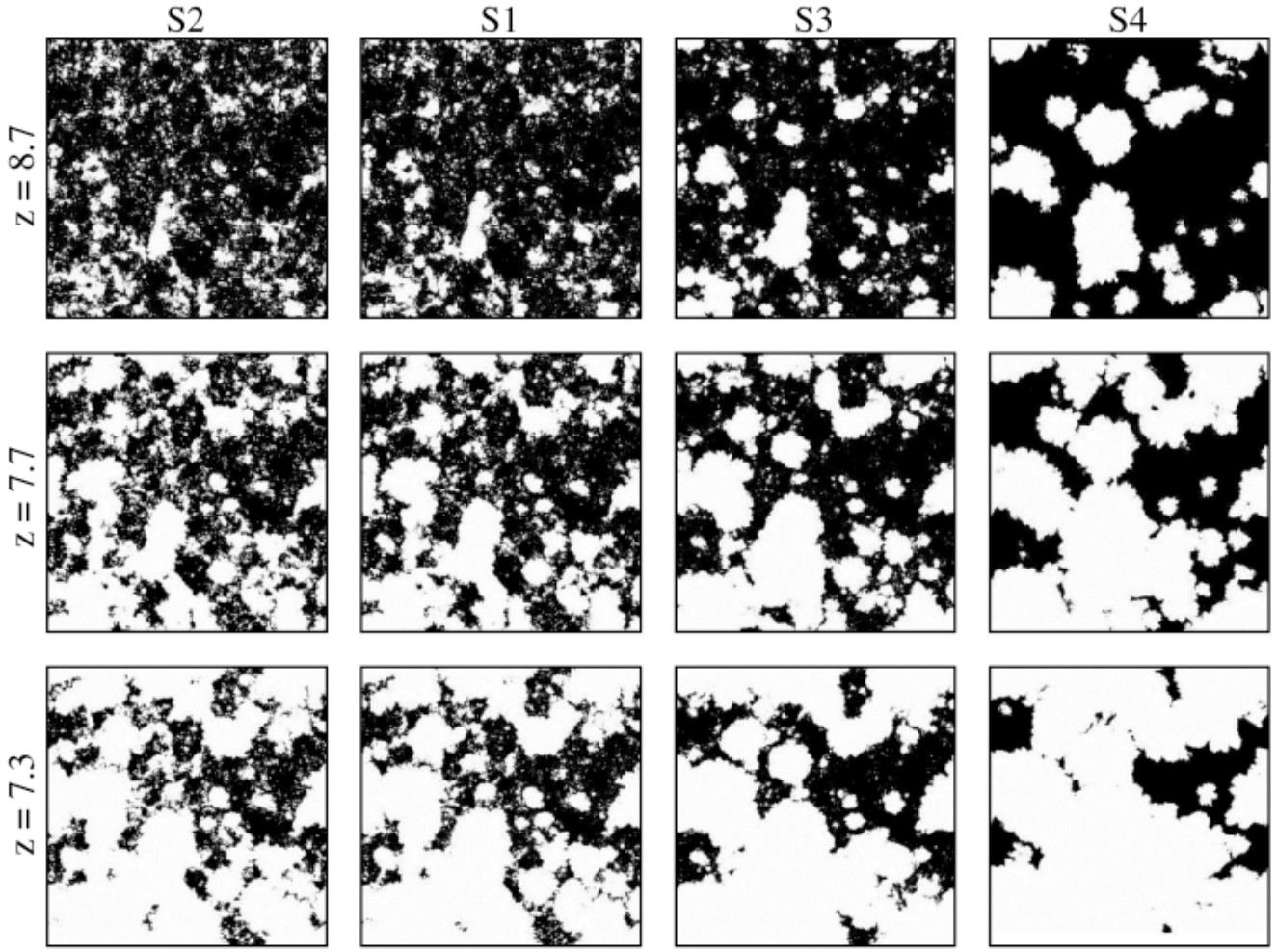
Furlanetto & Oh (2008)

Bubble Sizes: H I Reionization

- *Bubbles grow throughout reionization*
- *Driven by source clustering: massive halos, big bubbles*
- *LOTS of sources per bubble*

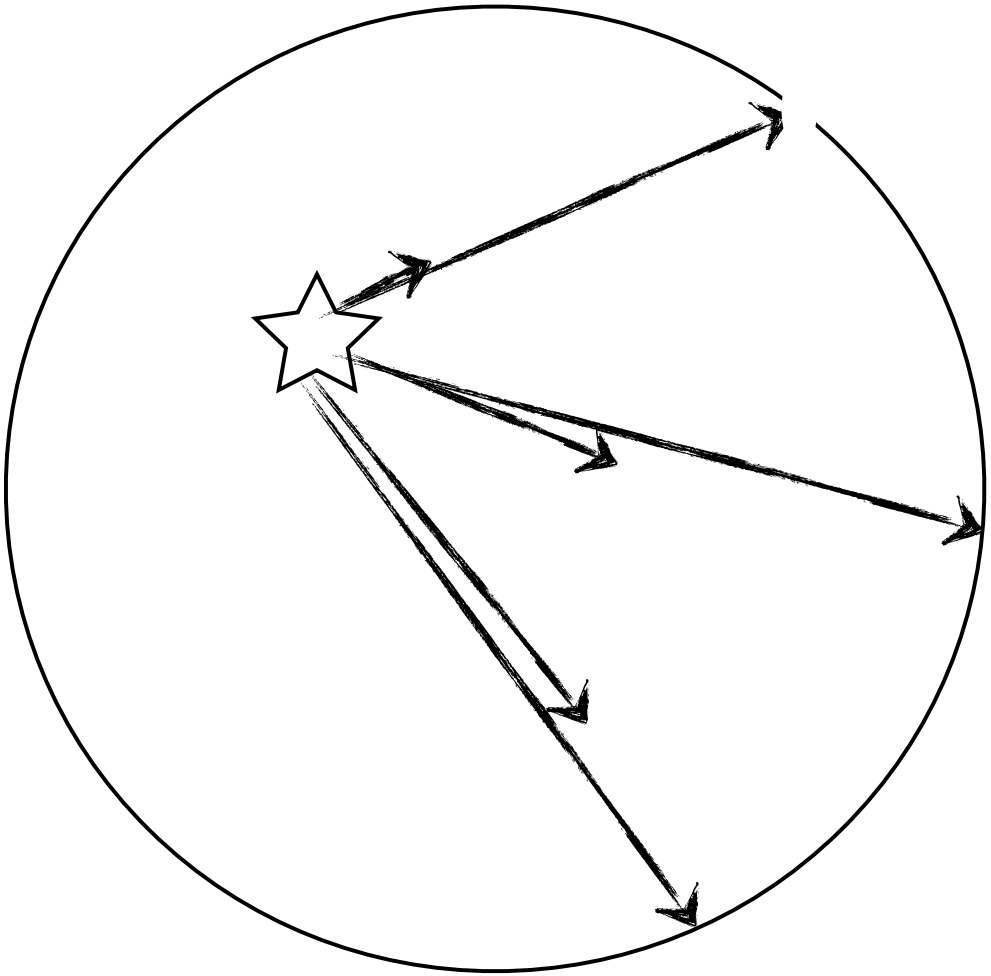


Reionization: Galaxy Populations



McQuinn et al. (2007); Furlanetto et al. (2004)

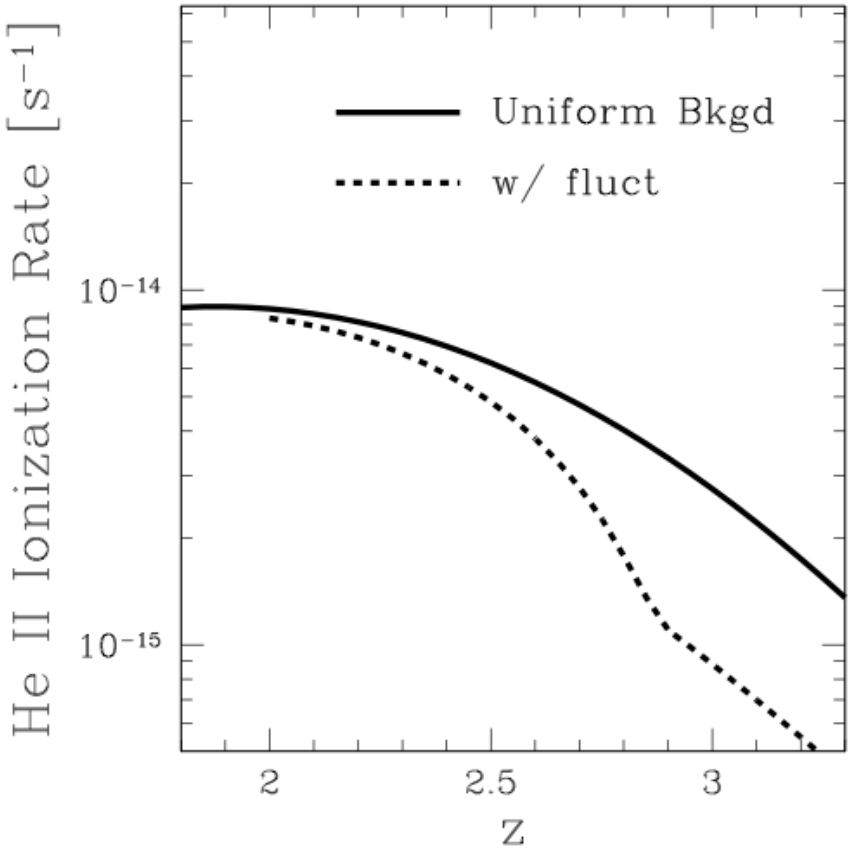
The Reionization Process II



- *Most recombinations are inside "Lyman-limit systems"*
- *Matters once (size of bubble) > (attenuation length)*
- *Controls post-reionization paths*

When Was Reionization? (II)

- *Ingredients: source luminosity function + clumping*
- *Recombinations occur in Lyman-α forest*
- *Again, well-measured at z~3 for He II reionization*



Davies & Furlanetto (in prep)

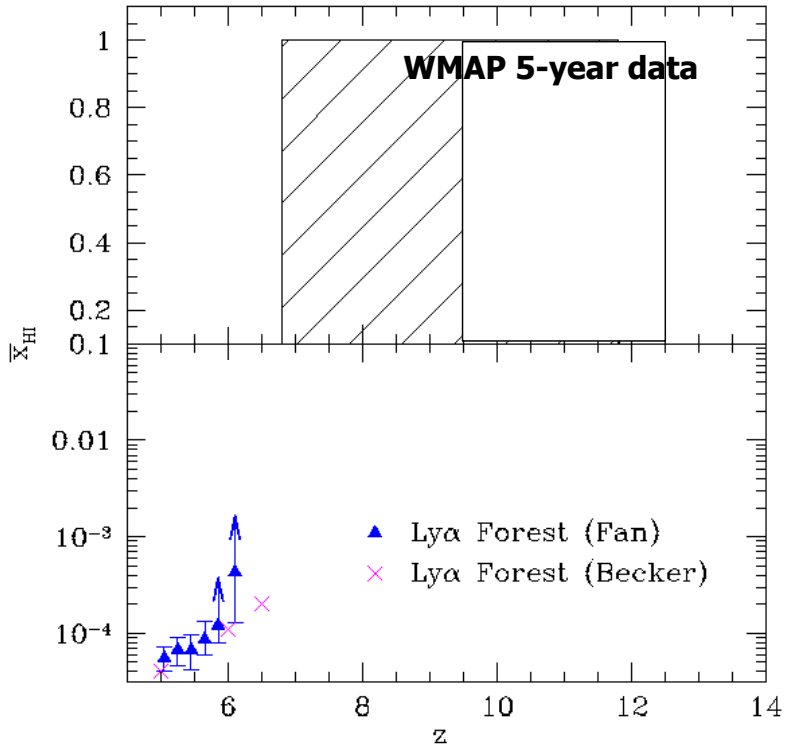
Reionization Models: The Ingredients

$$\Gamma x_n = \alpha(S,T) C \langle n_e \rangle$$

◦ *Source luminosity function (at all z)*	**He II**	**H I**
◦ *Mean free path and clumping (Lyman-α forest)*	**He II**	**H I**
◦ *The details*		
◦ *Spectrum*	**He II**	**H I**
◦ *Temperature*	**He II**	**H I**
◦ *Geometry of absorbers*	**He II**	**H I**
◦ *Environments of sources*	**He II**	**H I**
	Easy	**Hard** **Terrible**

Reionization: Existing Constraints

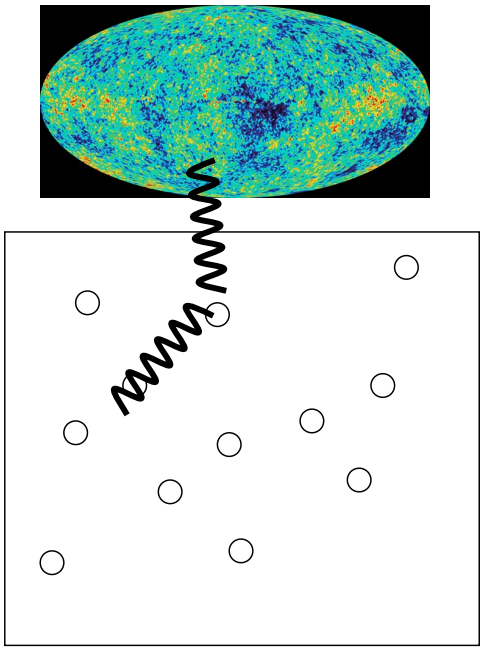
- *CMB Optical Depth*
- *Quasar Lines of Sight*



Furlanetto, Oh, & Briggs (2006)

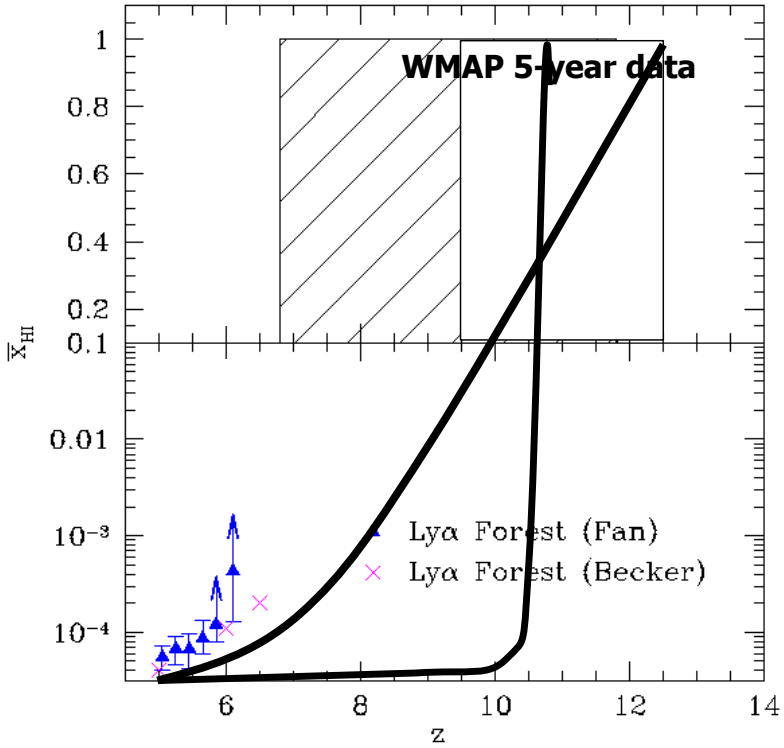
Reionization and the CMB

- *Free electrons can scatter CMB photons again!*
- *Smears out fluctuations*
- *Generates polarization*
- *Integral constraint*



Reionization: Existing Constraints

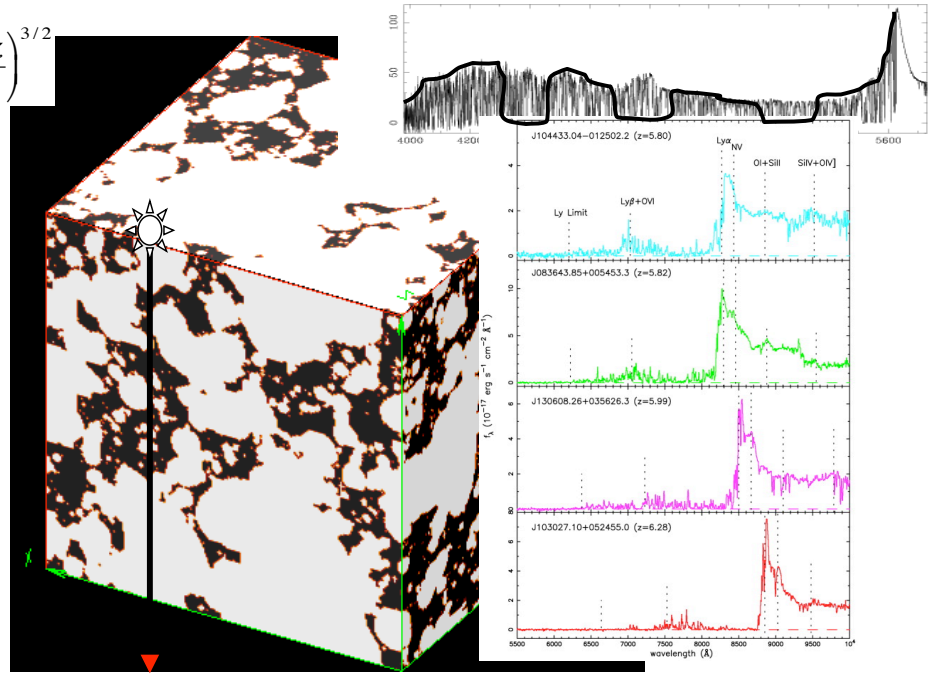
- *CMB Optical Depth*
  - *But just an integral constraint*



Furlanetto, Oh, & Briggs (2006)

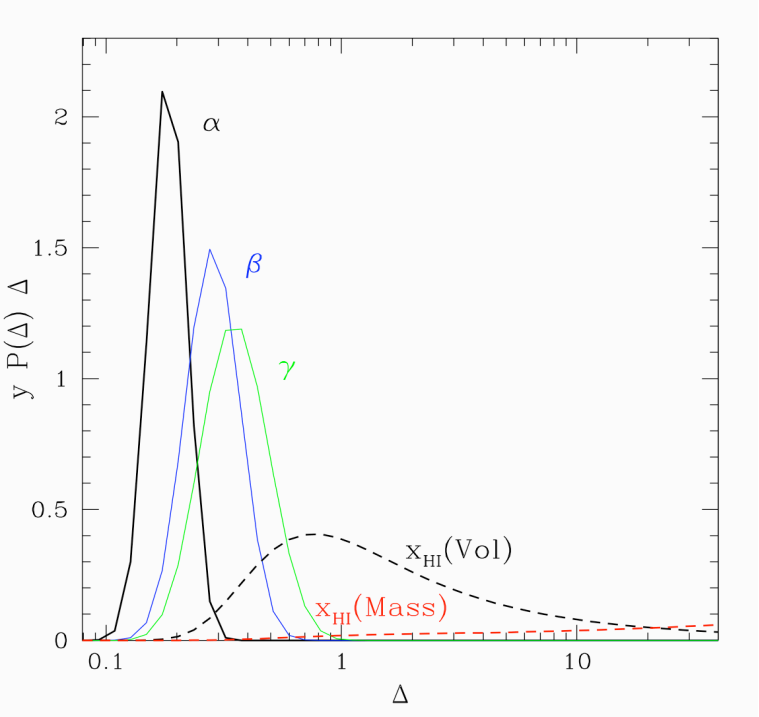
The Lyα Forest and Reionization

$$\tau_{GP} \approx 3\text{x}10^5 x_{\text{HI}} \left(\frac{1+z}{7}\right)^{3/2}$$



Fan et al. (2001)

The Biggest Problem: Extrapolation

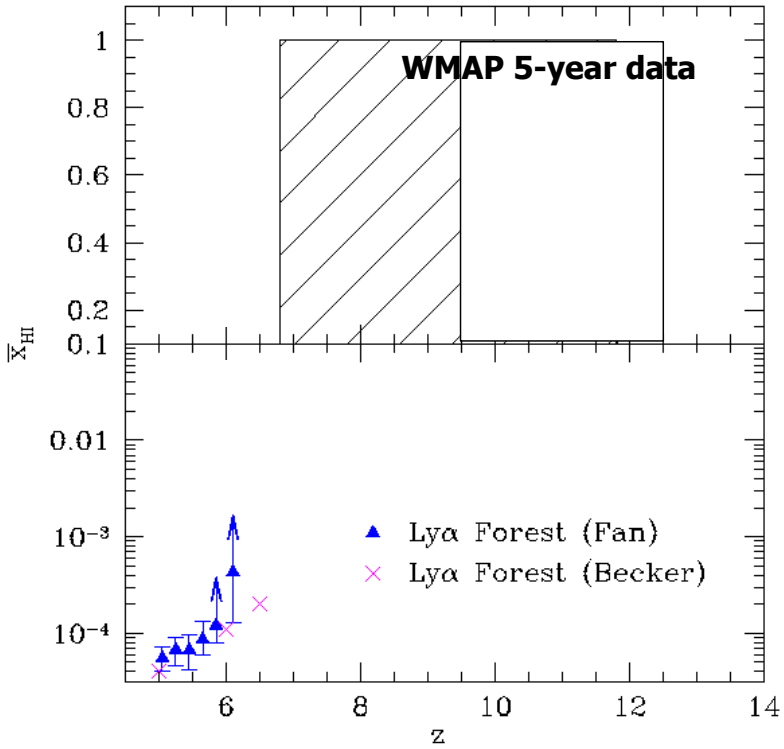


Oh & Furlanetto (2005)

- *Lyα is so optically thick that it probes only the tail of the IGM*
- *Higher-order transitions are better, but they have other difficulties*

Reionization: Existing Constraints

- *CMB Optical Depth*
  - *But only integrated constraint*
- *Quasar Lines of Sight*
  - *Suffers from saturation and rarity*



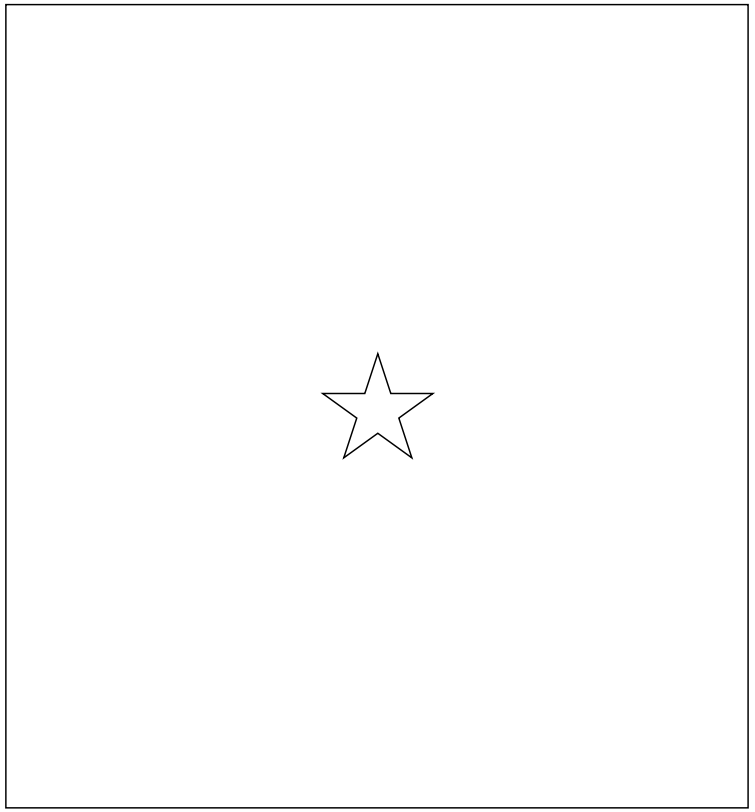
Furlanetto, Oh, & Briggs (2006)

How Can We Do Better???

New Approaches

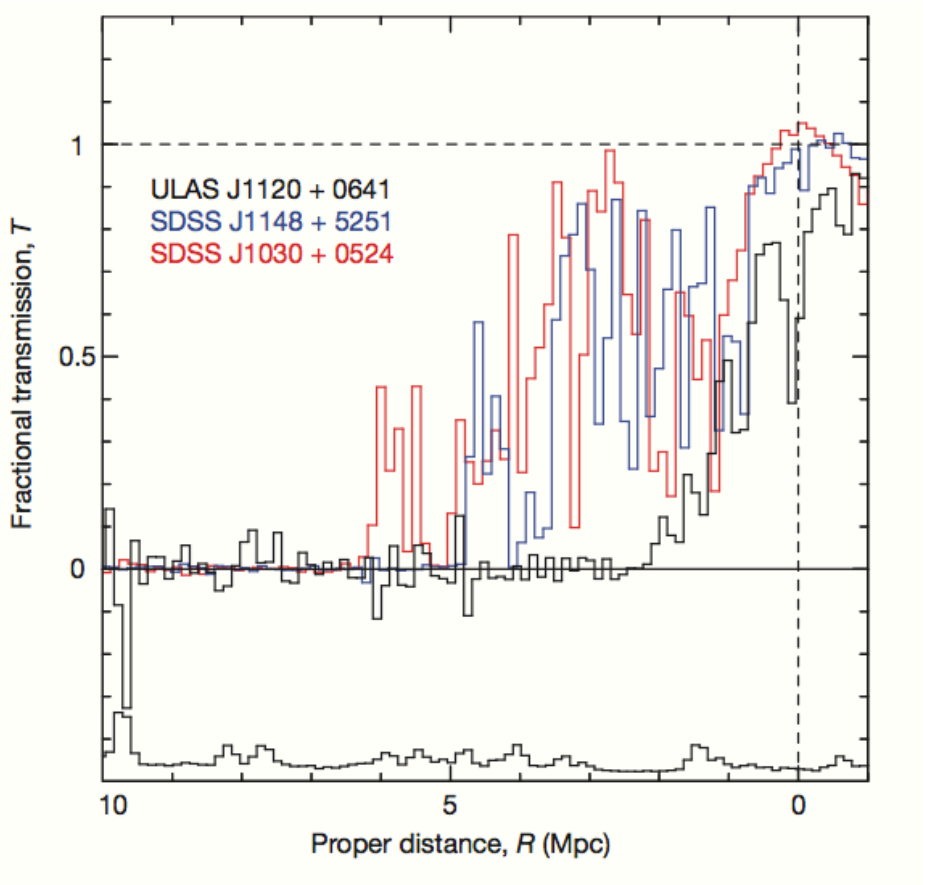
- *He II reionization as an analog*
- *Small-scale CMB anisotropies*
- *Quasar near zones*
- *Lyman-α emitters*
- *The Red Damping Wing*
- *The spin-flip background*
- *Diffuse line backgrounds*
- *Deeper galaxy surveys*

Ionized Bubbles Around Quasars



- *In a neutral Universe, smaller bubble if…*
  - *More neutral IGM*
  - *Younger quasar*
  - *Fewer intervening absorbers*

Quasar "Near-Zones"



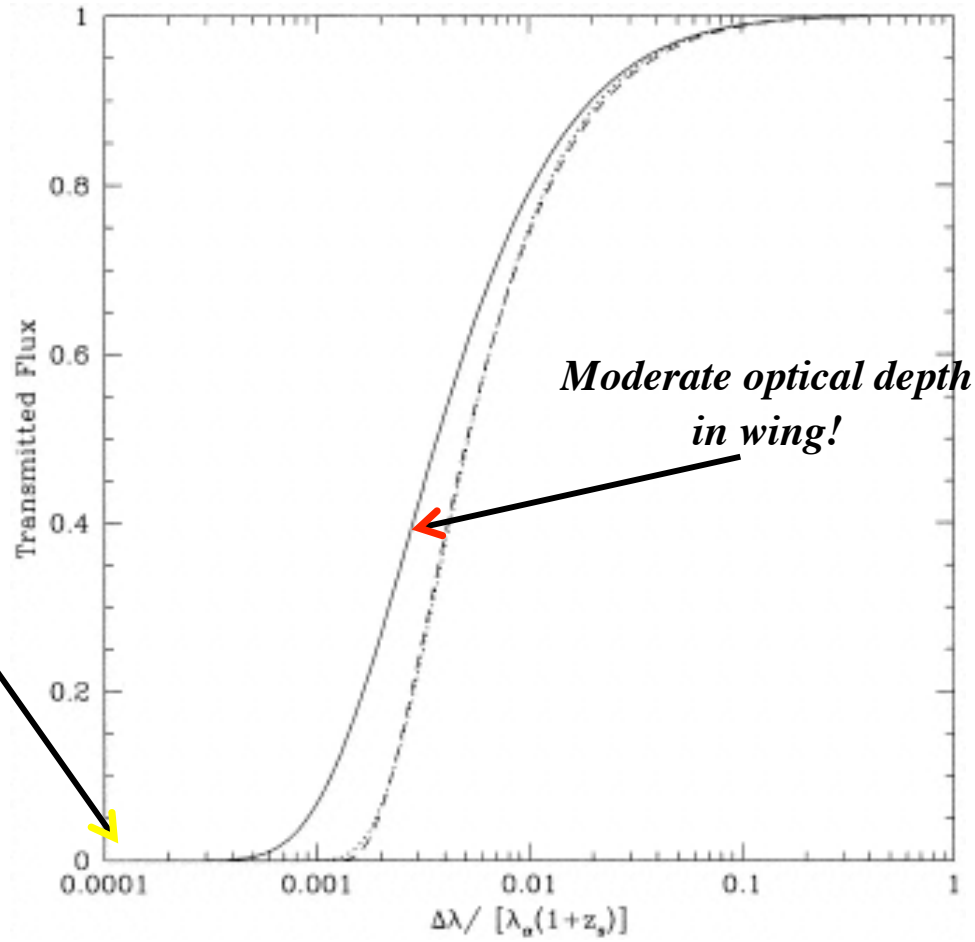
Mortlock et al. (2011)

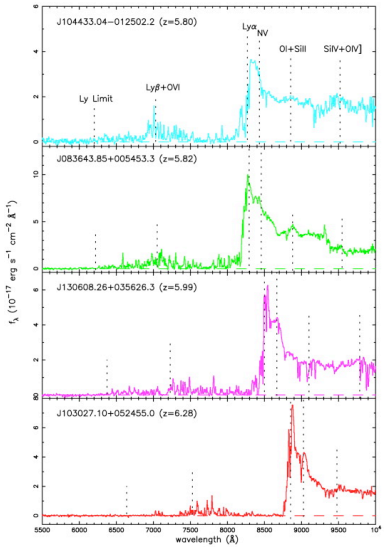
- *Near-zone from either...*
  - *Edge of H II region*
  - *OR just $1/r^2$ decline!*

The Forest Evolved: The Red Damping Wing

Enormous optical depth at line center

Moderate optical depth in wing!

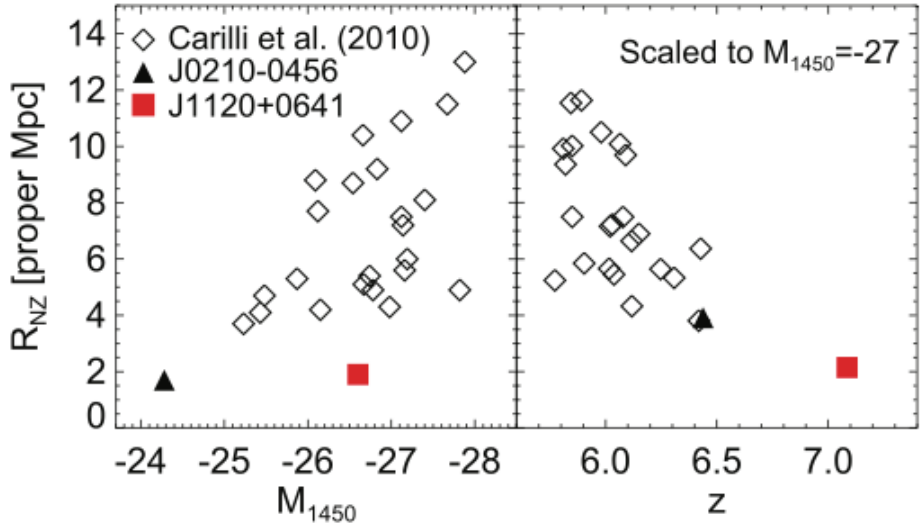




Miralda-Escude (1998)

Quasar "Near-Zones"

- *Size decreases as redshift increases*
- *Especially severe for z=7 object*
  - *Partly neutral medium?*
  - *Young quasar?*
  - *Intervening absorber?*

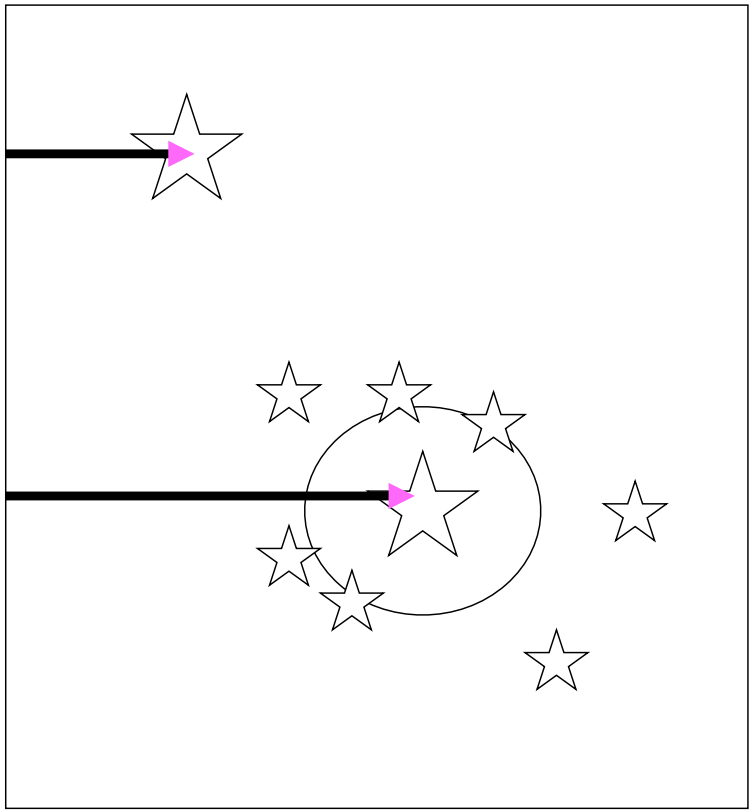


Bolton et al. (2011)

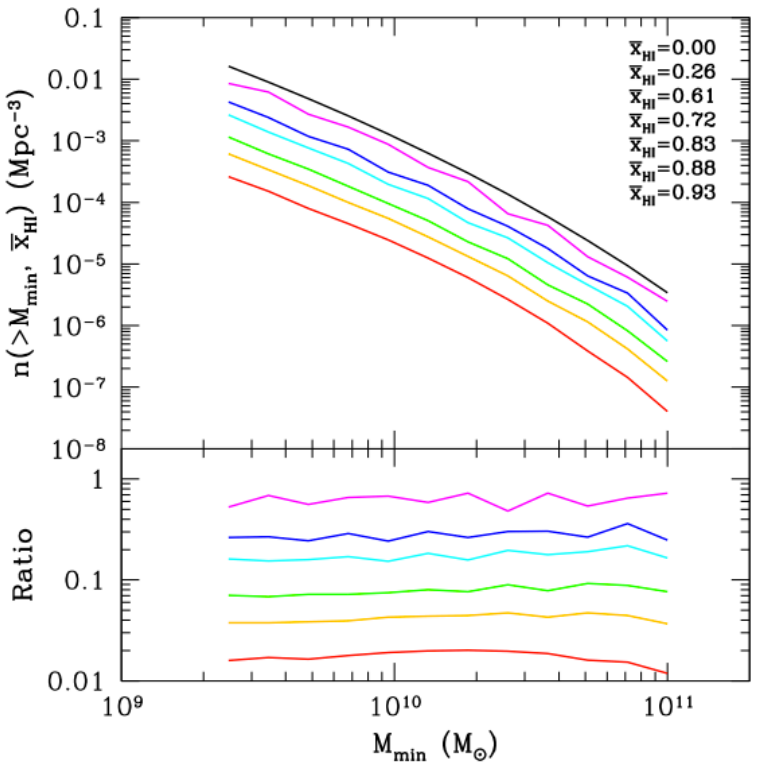
The Damping Wing and Galaxies

- *Lyman-α Galaxy Surveys*

$$\tau_{GP} \approx 3\text{x}10^{5}\, x_{\text{HI}} \left(\frac{1+z}{7}\right)^{3/2}$$



The Disappearance of Lyman-α Emitters

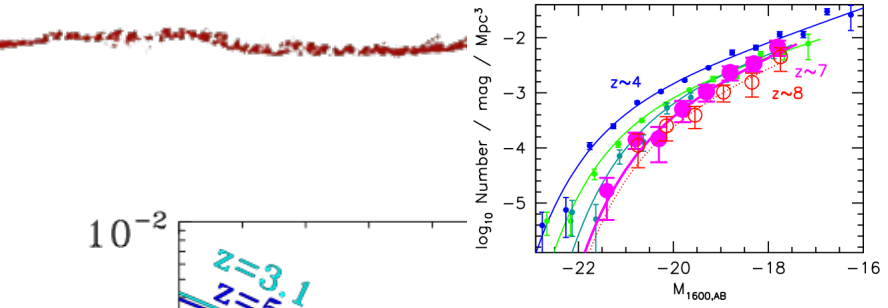


Mesinger & Furlanetto (2008)

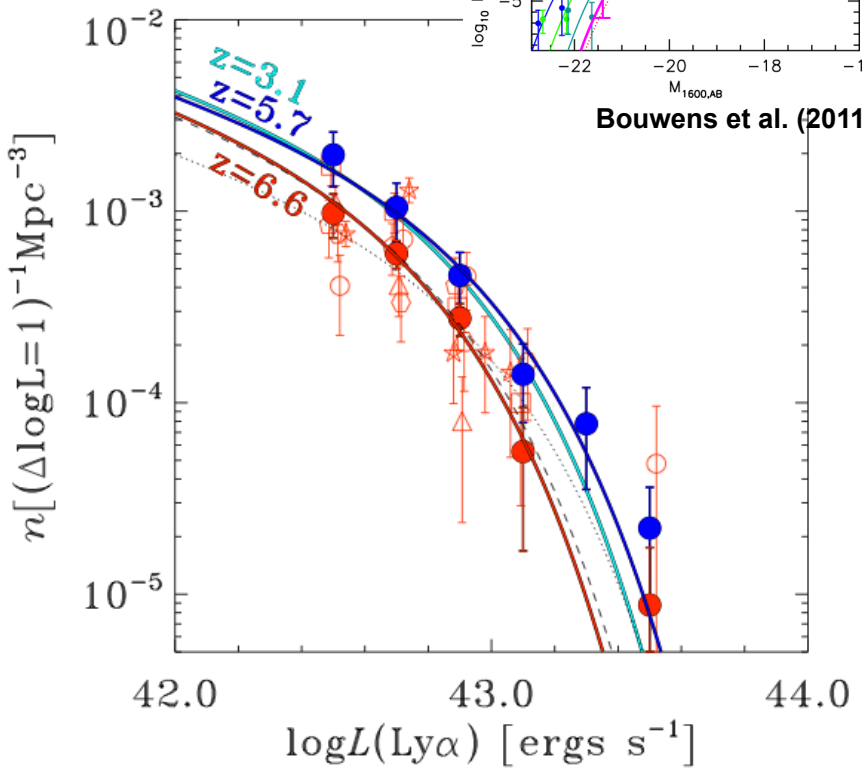
- *Number density declines when bubbles reach ~1 proper Mpc*
- *Occurs at x_{HI}~0.5*
- *Major uncertainty: winds*

The Disappearance of Lyman-α Emitters

- *LAE surveys show steady number density from z~3-6, then beginnings of a decline*
- *But LBGs also declining!*

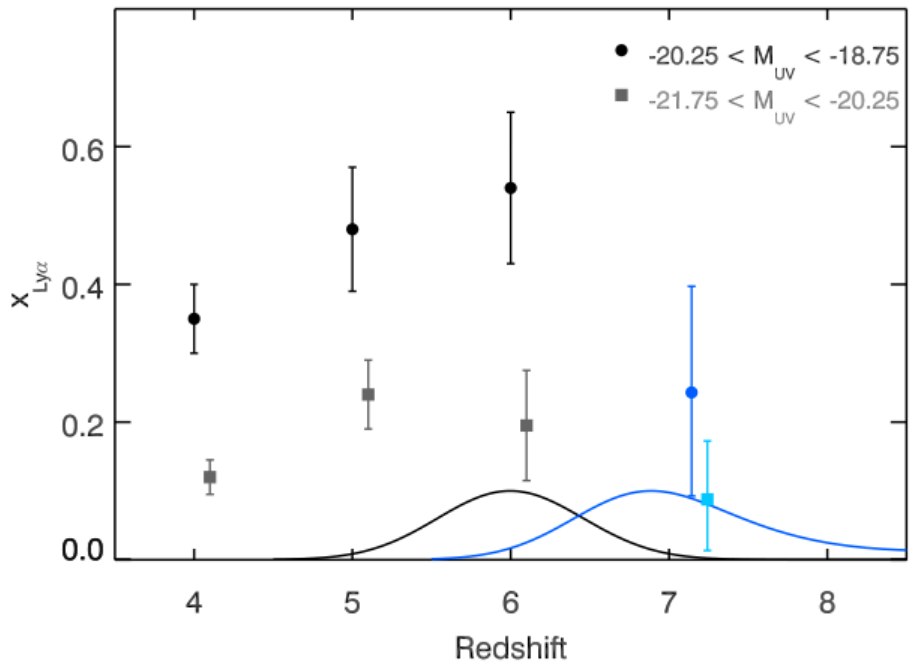


Bouwens et al. (2011)



Ouchi et al. (2010)

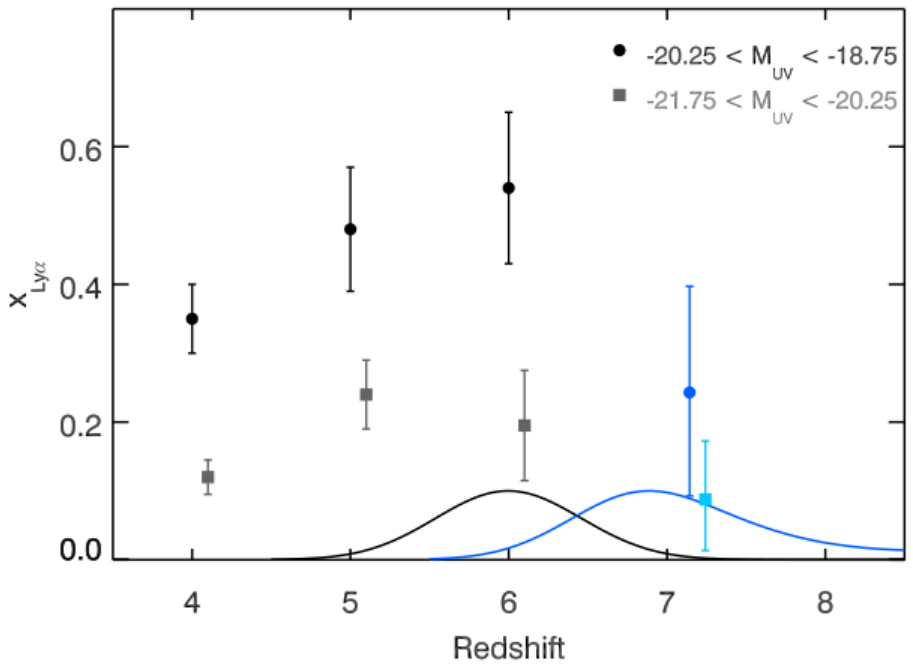
The Disappearance of Lyman-α Emitters



Schenker et al. (2011)

- *Spectroscopic followup of Lyman-break galaxies*
- *Measure evolution of fraction with strong Lyman-α emitters*
- *Three groups now finding a decline! (Schenker et al. 2011; Pentericci et al. 2011; Ono et al. 2011)*

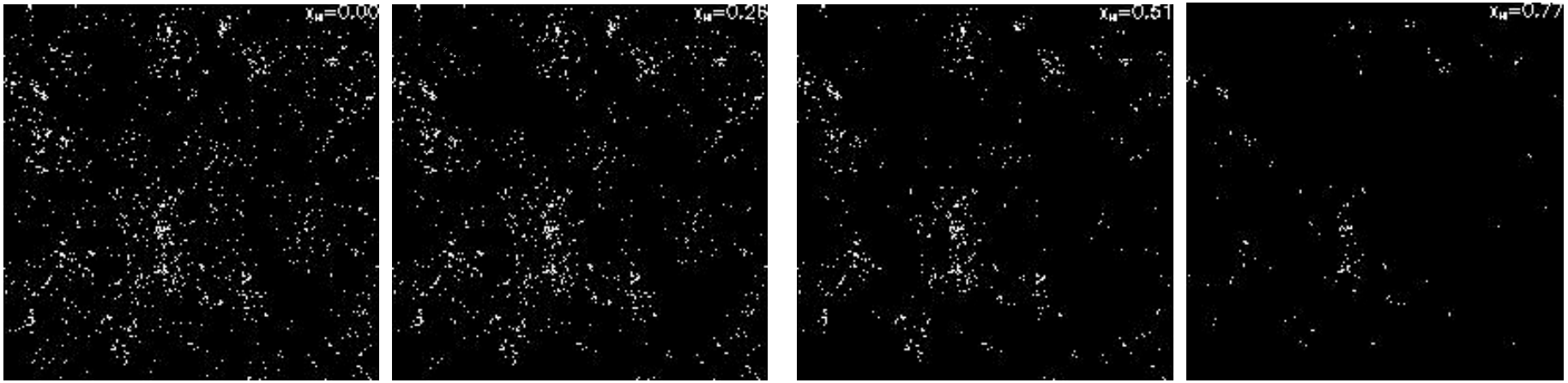
The Disappearance of Lyman-α Emitters



Schenker et al. (2011)

- *What does it mean?*
  - *Fast evolution in x_{HI}?*
  - *Reionization models wrong?*
  - *Reionization ends at z<6? (Mesinger 2011)*
  - *Strange selection?*
  - *Evolution in stellar populations?*

LAEs During Reionization

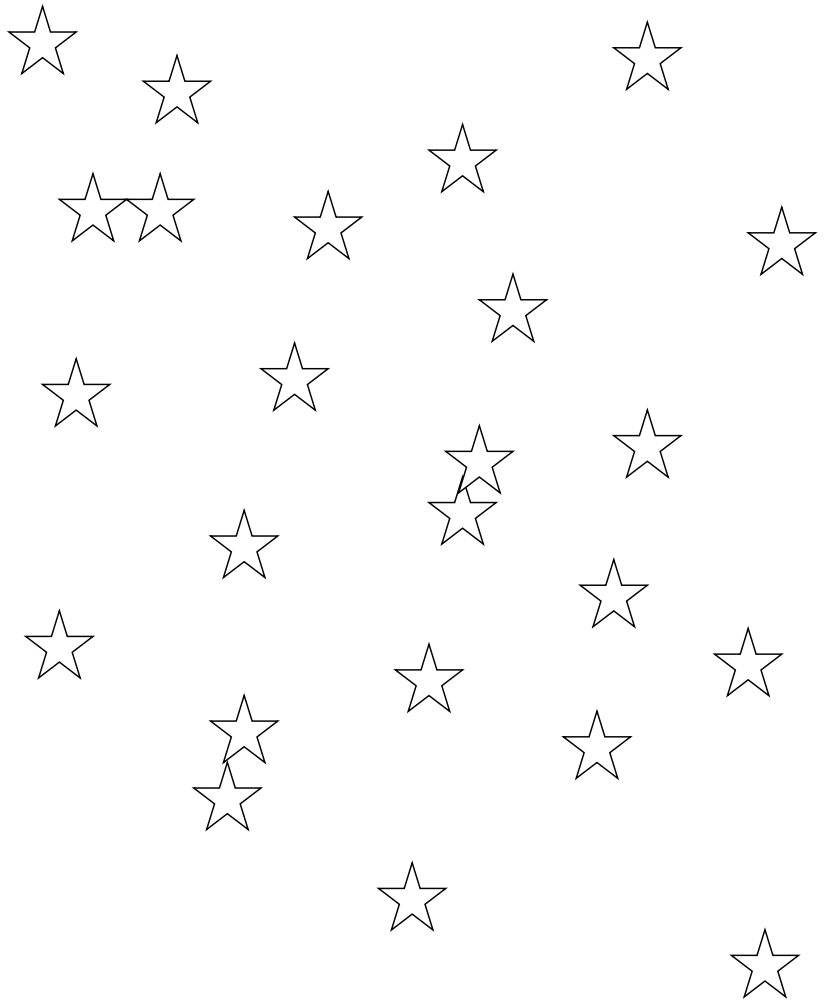


Mesinger & Furlanetto (2008)

- *z=9, R=125 observation, with M>1.7x10^{10} Msun*
- *Galaxies in small bubbles (underdense regions) masked out by absorption*

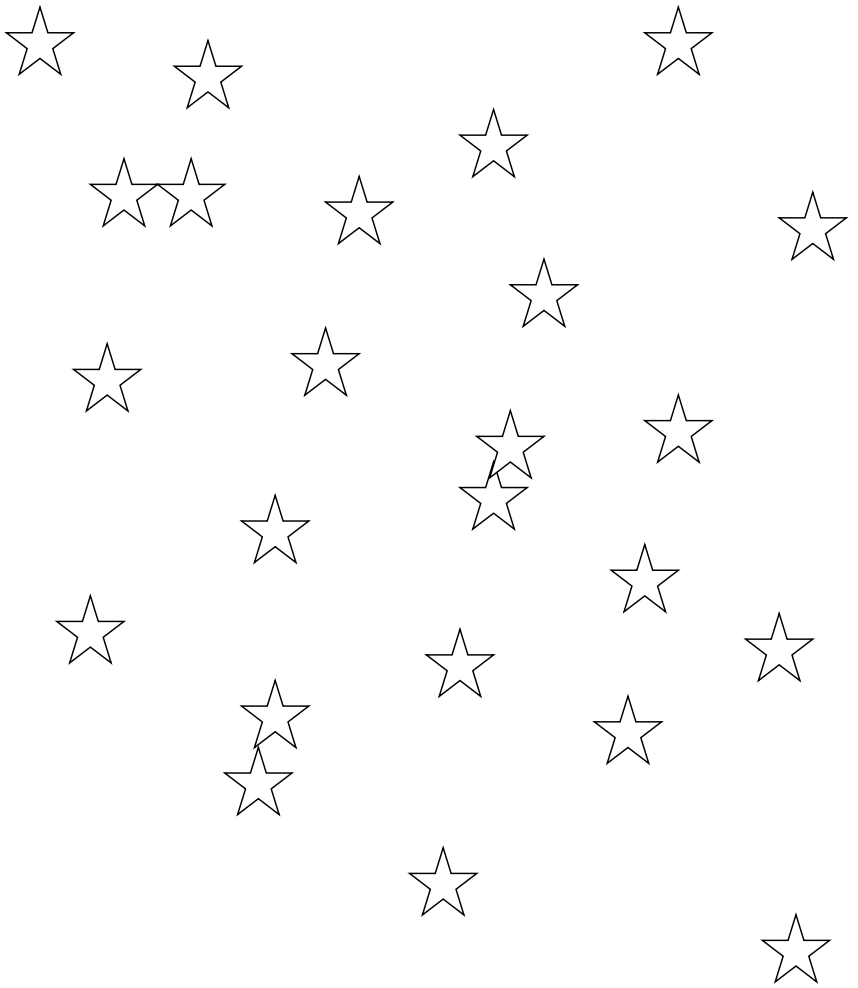
LAE Clustering During Reionization

- *Nearly randomly distributed galaxy population*
- *Small bubble: too much extinction, disappears*
- *Large bubble: galaxies visible to survey*



LAE Clustering During Reionization

- *Small bubble: too much extinction, disappears*
- *Large bubble: galaxies visible to survey*
- *Absorption selects large bubbles, which tend to surround clumps of galaxies*

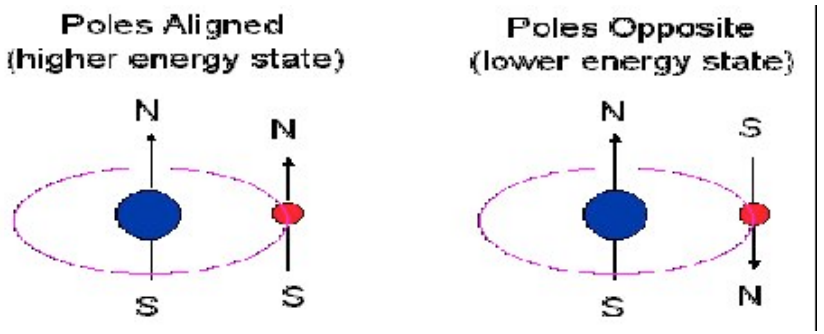


LAE Clustering During Reionization

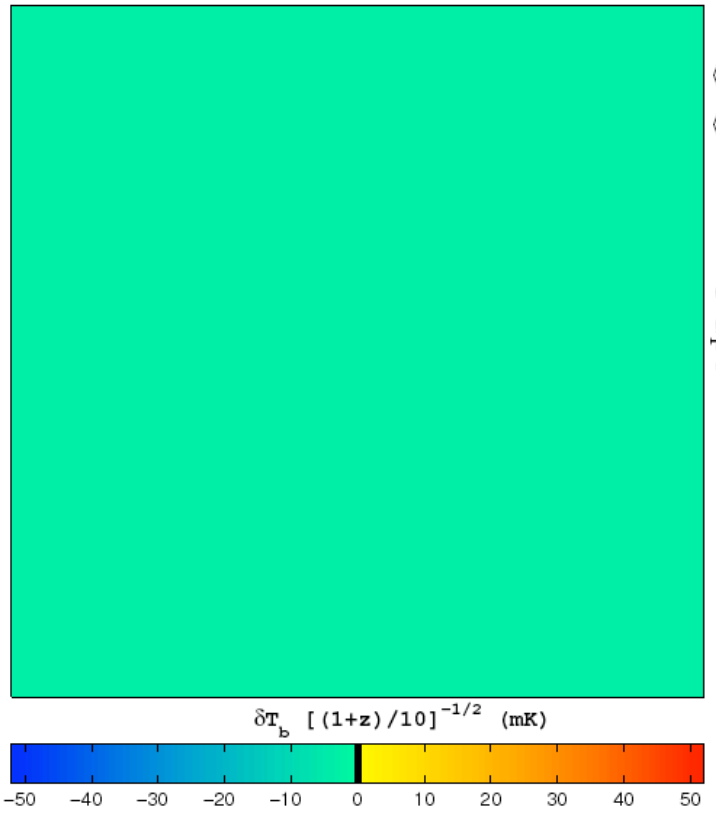
- *Small bubble: too much extinction, disappears*
- *Large bubble: galaxies visible to survey*
- *Absorption selects large bubbles, which tend to surround clumps of galaxies*
- *See Furlanetto et al. (2006), McQuinn et al. (2008), Mesinger & Furlanetto (2008)*

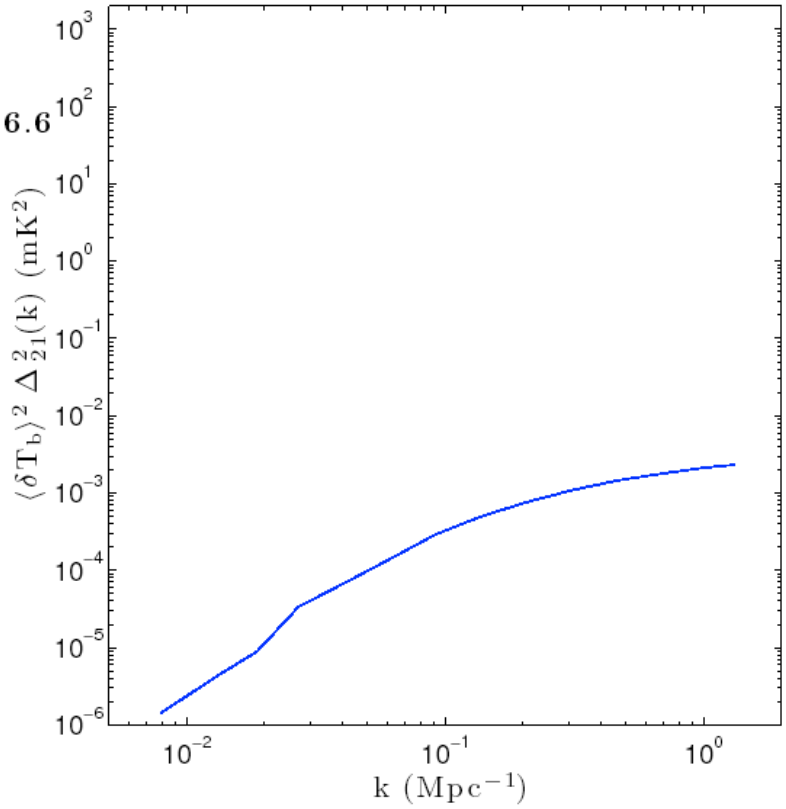
The Spin-Flip Transition

- *Protons and electrons both have spin and hence magnetic moments*
- *Produces 21 cm photons (ν~1.4 GHz)*



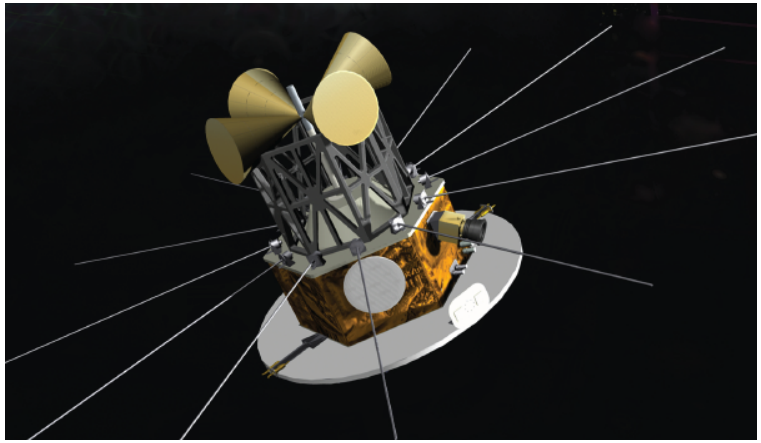
The Fluctuating Background

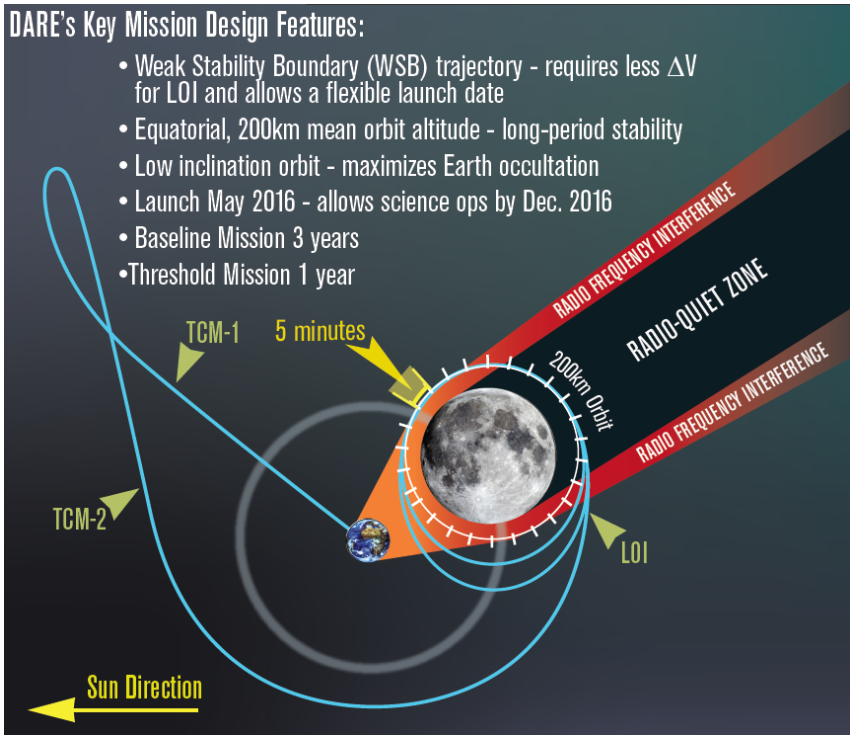




Mesinger, Furlanetto, & Cen (2010)

The Future: To the Moon!

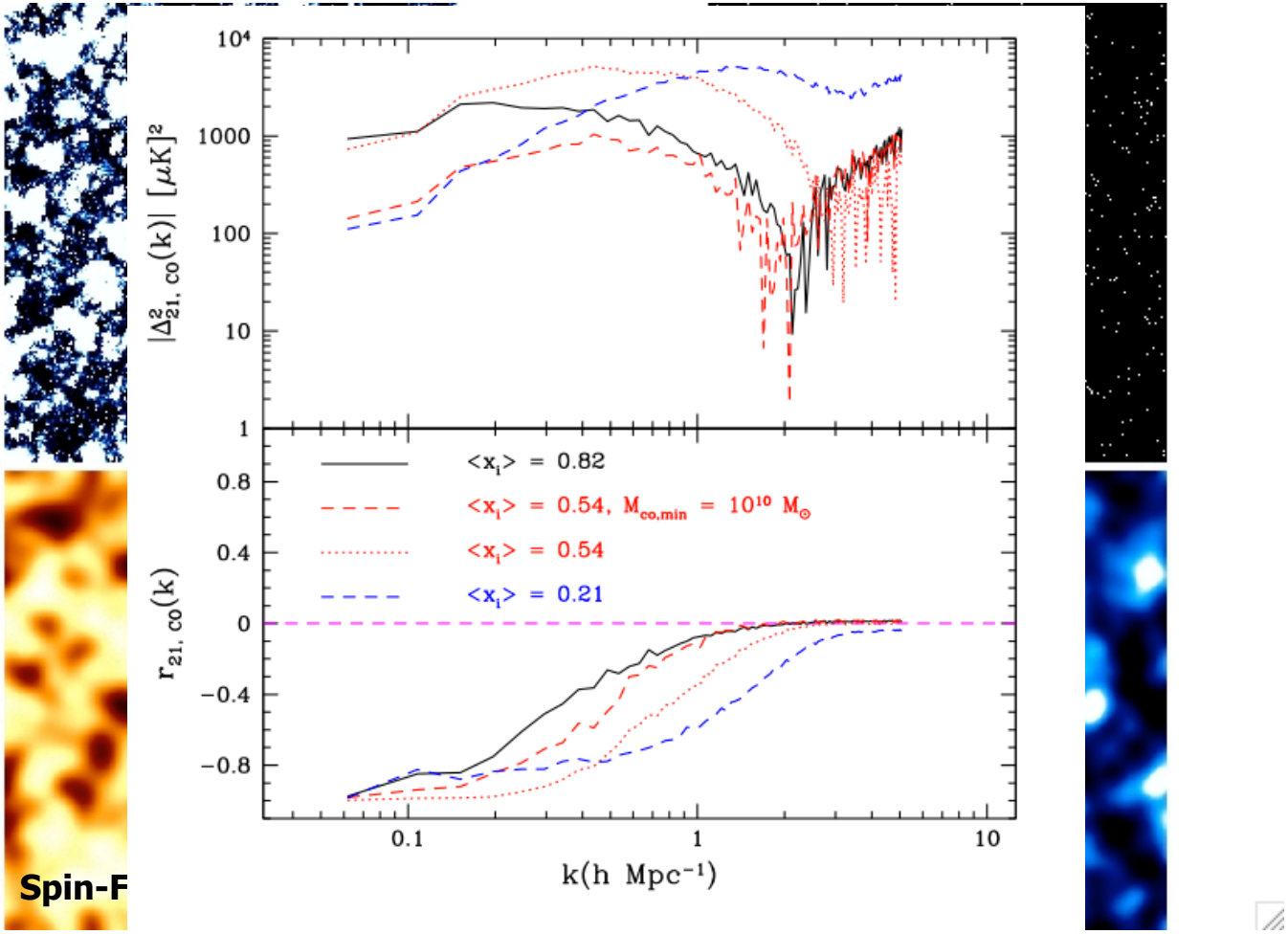




DARE

DARK AGES RADIO EXPLORER

Combining Measurements



Lidz et al. (2011)

Diffuse Line Backgrounds

- *CO transitions*
  - *Trace molecular star-forming gas*
  - *Multiple transitions mean easy identification*
- *C II or atomic lines*
  - *Trace cool, neutral gas (sort of)*
  - *Can be extremely luminous*
- *Lyman-α*
  - *Traces recombinations in ionized gas*
  - *Indirect tracer of high-mass star formation rate*

Observing Galaxies During Reionization

- *HST: UDF12 coming soon! (PI: Richard Ellis)*
  - *128 additional orbits*
  - *1 mag fainter at z=7, 2 at z=8 (key: steep faint end slope!)*
  - *Additional filter to quantify spectral shape (and stellar populations)*
  - *Additional filter to identify z~9-10 candidates*

Observing Galaxies During Reionization

- *Radio observatories*
  - *PdBI can place useful constraints on "normal" galaxies already, and detect massive quasar hosts (e.g., Maiolino et al. 2012)*
  - *ALMA will be much more sensitive!*
  - *EVLA can detect low-order CO as well*

Conclusions

- *The Cosmic Dawn is a key epoch in structure formation, and reionization is its hallmark event*
- *Current constraints are weak and confusing*
- *Battery of new techniques in the near future, studying the first galaxies both directly and indirectly*

Want To Know More?

The First Galaxies in the Universe

Abraham Loeb and Steven R. Furlanetto

- *Coming in late 2012 (or so) from Princeton University Press!*