New Insights Into Cosmic Reionization

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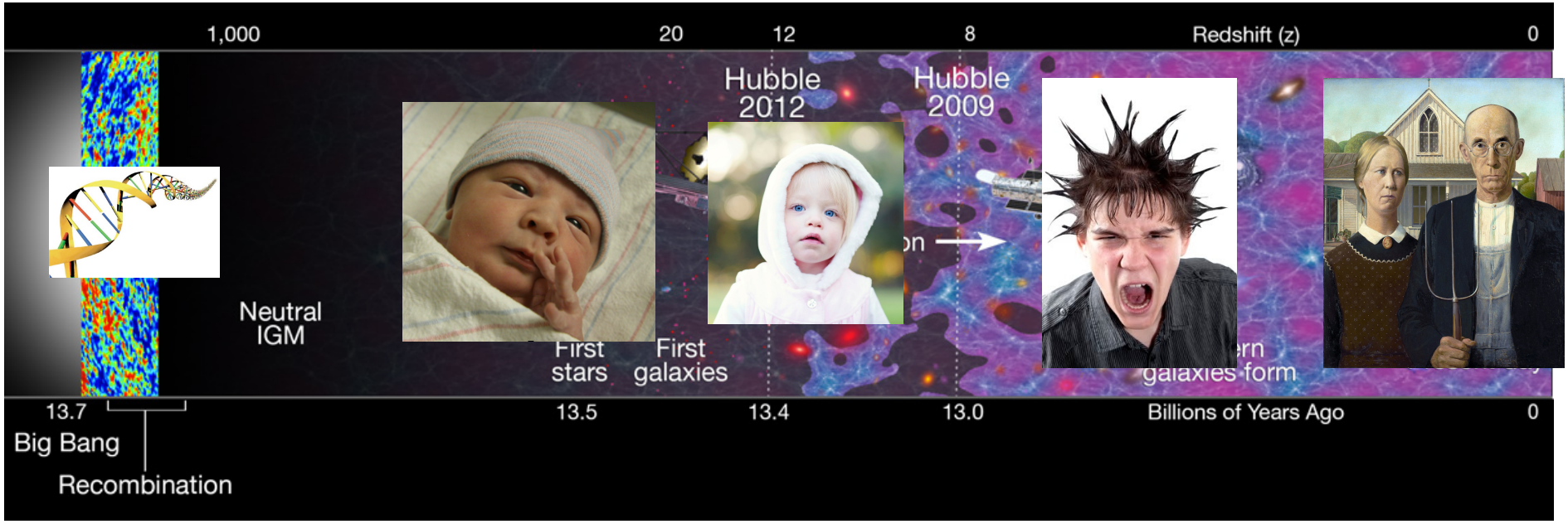
UCLA
March 7, 2016

Outline

- *Introduction*
- *How do galaxies evolve during the Cosmic Dawn?*
- *How do we model reionization?*
- *How can we observe reionization directly?*

The “Cosmic Dawn”



How did reionization unfold?

Alvarez, Kahler, & Abel

Why Should You Care? (I)

- *The third (and last) time all the baryons in the universe did the same thing at the same time*

Why Should You Care? (II)

- *Global phase transition*
  - *Easier to observe than tiny galaxies!*

Why Should You Care? (III)

- *Reionization also* ***heats*** *the intergalactic medium*
- *Affects fuel for future generations of galaxy formation*

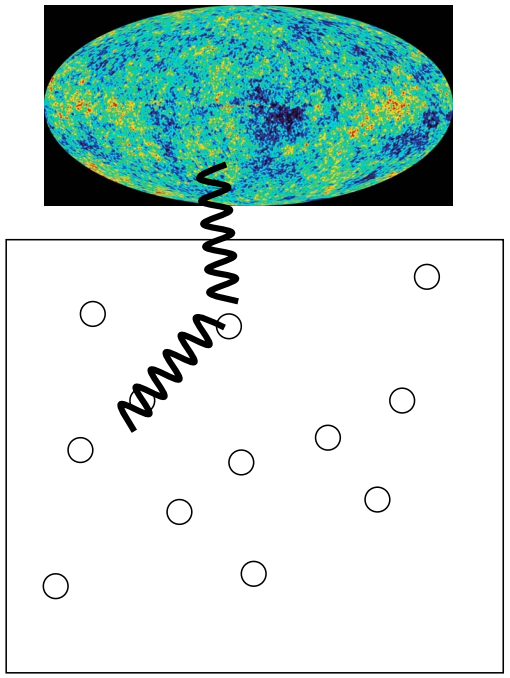
$$H + \gamma \rightarrow H + e^-$$

Why Should You Care? (IV)

- *The history of the Milky Way*
  - *What were the Milky Way's first progenitors like?*
  - *How did reionization influence the structure of our Galaxy?*
- *Many of the smallest and oldest of the Milky Way's neighbors are mysterious…can reionization explain this?*

Reionization Measurements So Far

- *Must end by z~6 because we see highly-ionized medium*
- *CMB Polarization*
  - *Current best measurement from Planck Collaboration (2015): **τ=0.066 +- 0.012** (corresponds to instantaneous reionization at **z~7-11**)*



How do galaxies evolve during the Cosmic Dawn?

The UDF12 Campaign

- *128 HST orbits in UltraDeep Field (~4 days)*
- *Completed summer-fall 2012*

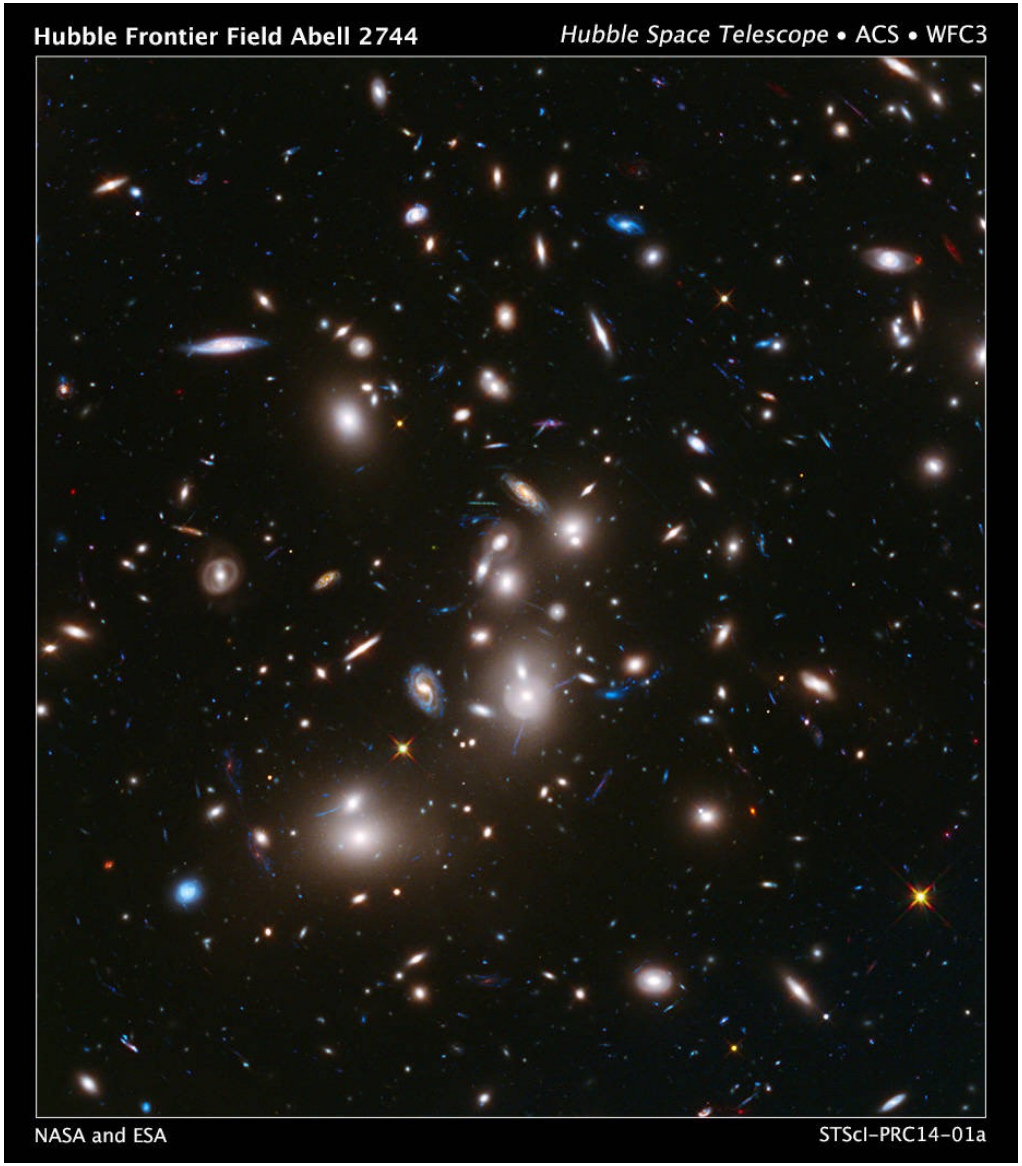
- **PI:** Richard Ellis
- **Collaborators:** Matt Schenker (Caltech), Brant Robertson, Dan Stark (Arizona), Steve Furlanetto (UCLA), Jim Dunlop, Ross McLure (Edinburgh), Yoshiaki Ono, Masami Ouchi (Tokyo), Stephane Charlot (IAP)

When did reionization occur?

How many galaxies are out there?

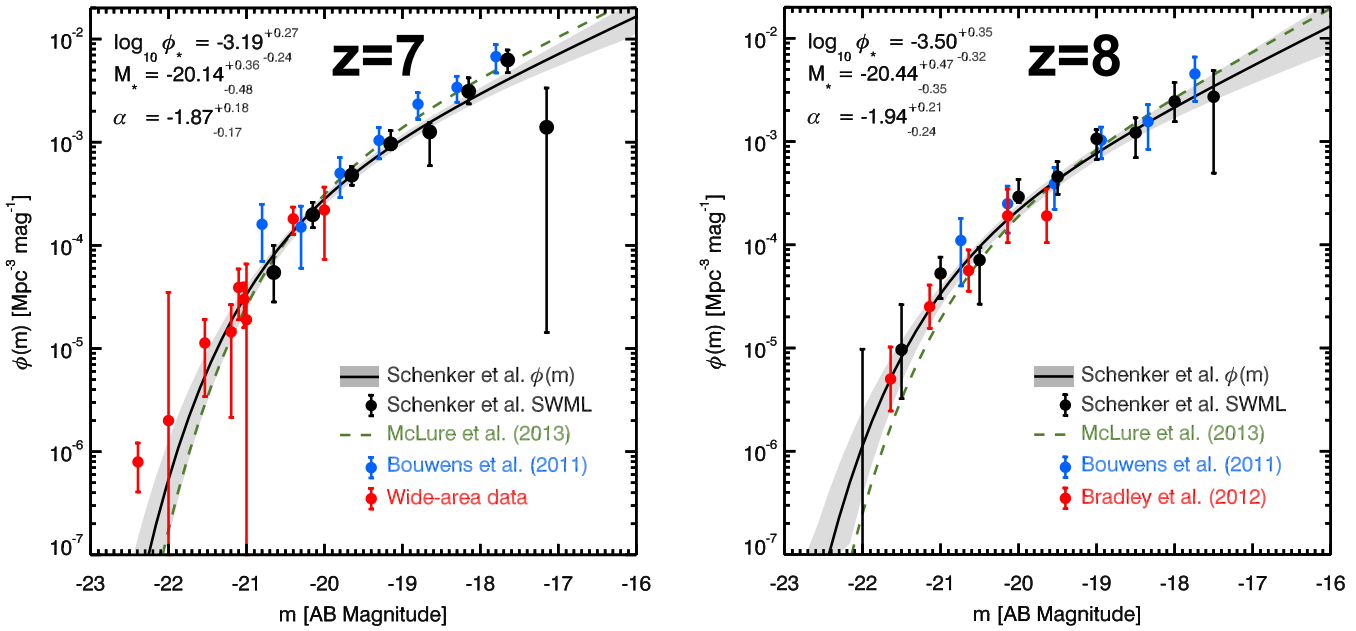
What sorts of stars live inside them?

Hubble Frontier Fields



- *Ongoing project to observe 12 massive galaxy clusters with HST*
- *Very deep observations + gravitational lensing means probing faintest galaxies!*

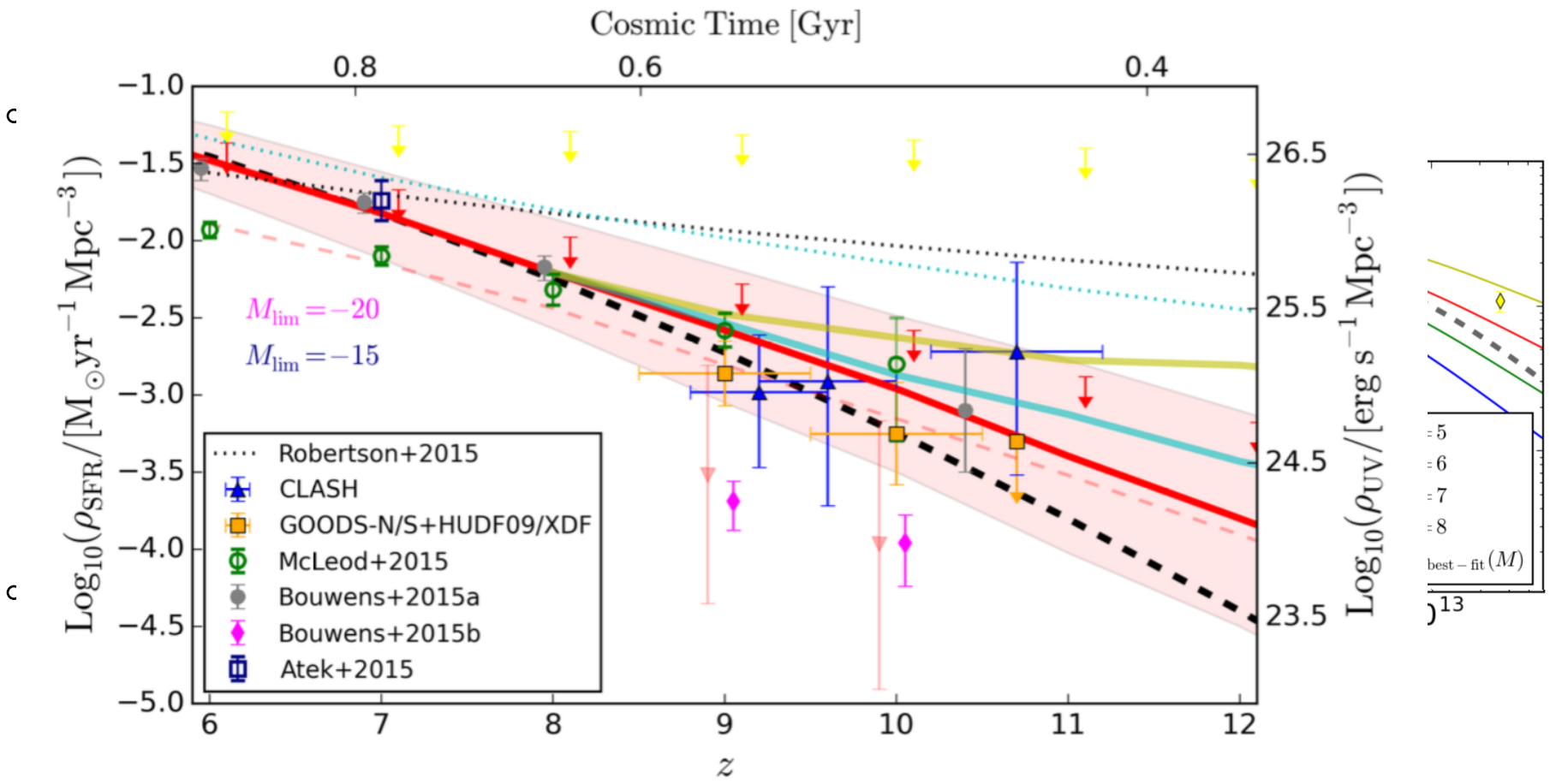
The Observed Luminosity Function



Robertson et al. (2013)

- *Galaxy luminosity functions well-measured, to about L*, at z<8*
- *Deeper measurements from gravitational lensing (e.g. Atek et al. 2015)*
- *Now seeing ~10s of galaxies at z>9 as well*

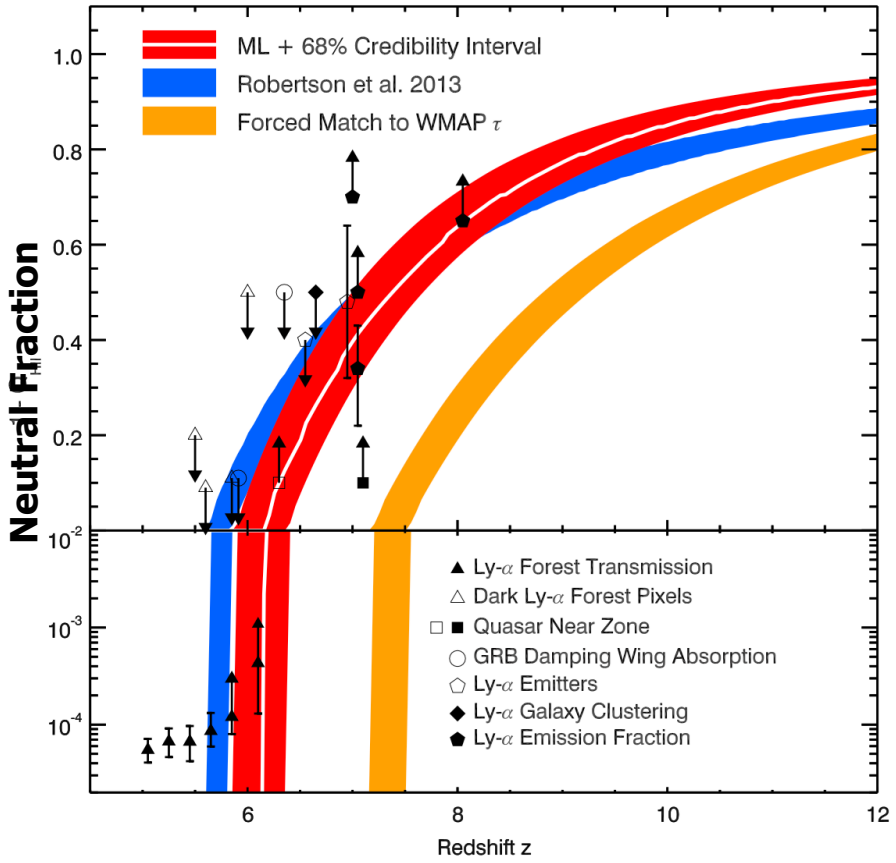
Abundance Matching of High-z Galaxies



Sun & Furlanetto (2016)

Constraints on Reionization

- *Can model reionization history from galaxy observations, with many assumptions*
  - *How many faint galaxies?*
  - *How do galaxies evolve at early times?*
  - *Escape fraction of ionizing photons!*
- *Lots of other model-dependent astrophysical constraints*

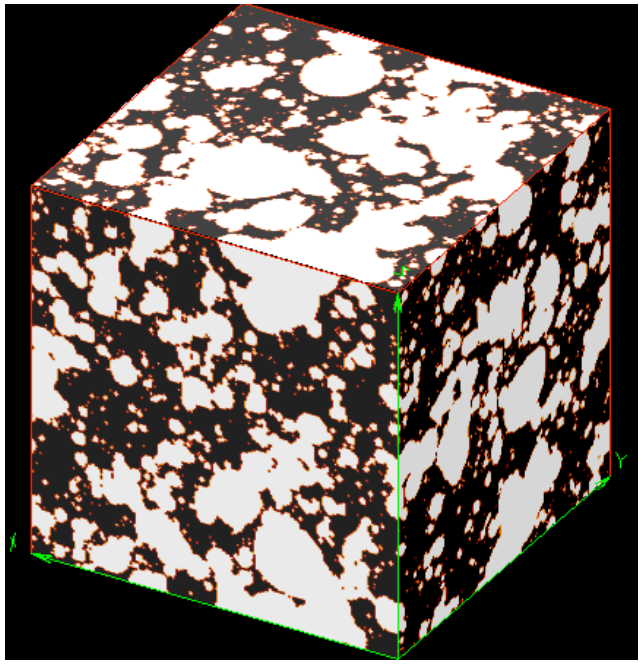


Robertson et al. (2015)

How do we model reionization?

The Reionization Process

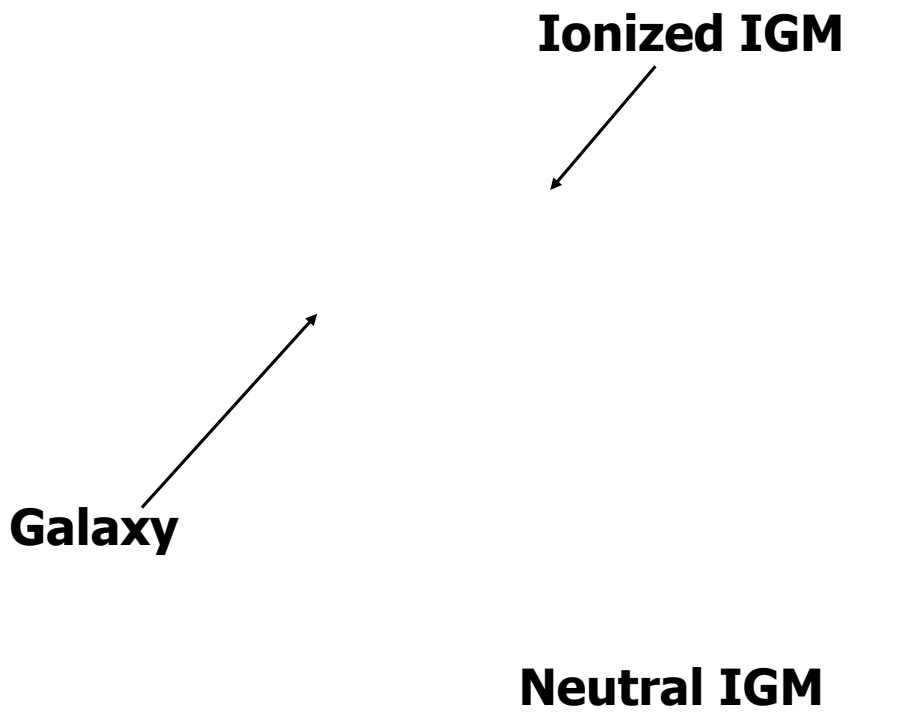
- *Goal: a simple model for the morphology of the ionized gas*
  - *Assume we know galaxy distribution*



Mesinger & Furlanetto (2007)

A Simple Model of Reionization

- *Compare (# ionizing photons) to (# atoms)*
- *First ionized bubble is easy...*
- *But what if that bubble overlaps another galaxy?*
  - *Early galaxies are highly clustered and bubbles are big!*



Furlanetto et al. (2004)

A Simple Model of Reionization

- *Compare (# ionizing photons) to (# atoms)*
- *Work from large to small scales:*
  - *Automatically includes overlap!*

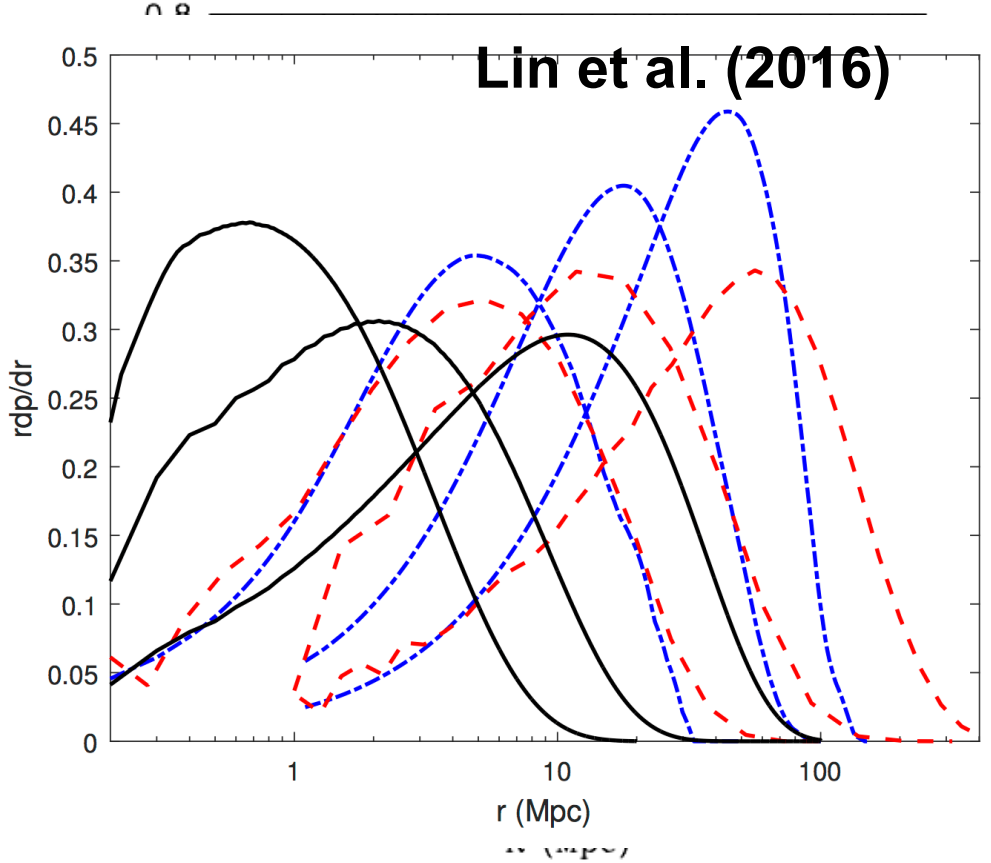
Furlanetto et al. (2004)

"Semi-numerical" models: DexM, 21cmFAST, etc.

A simple model of reionization

- *Provides analytic predictions for sizes of these bubbles (a "bubble mass function")*
- *…but they're WRONG!*

Furlanetto, Zaldarriaga, & Hernquist (2004)



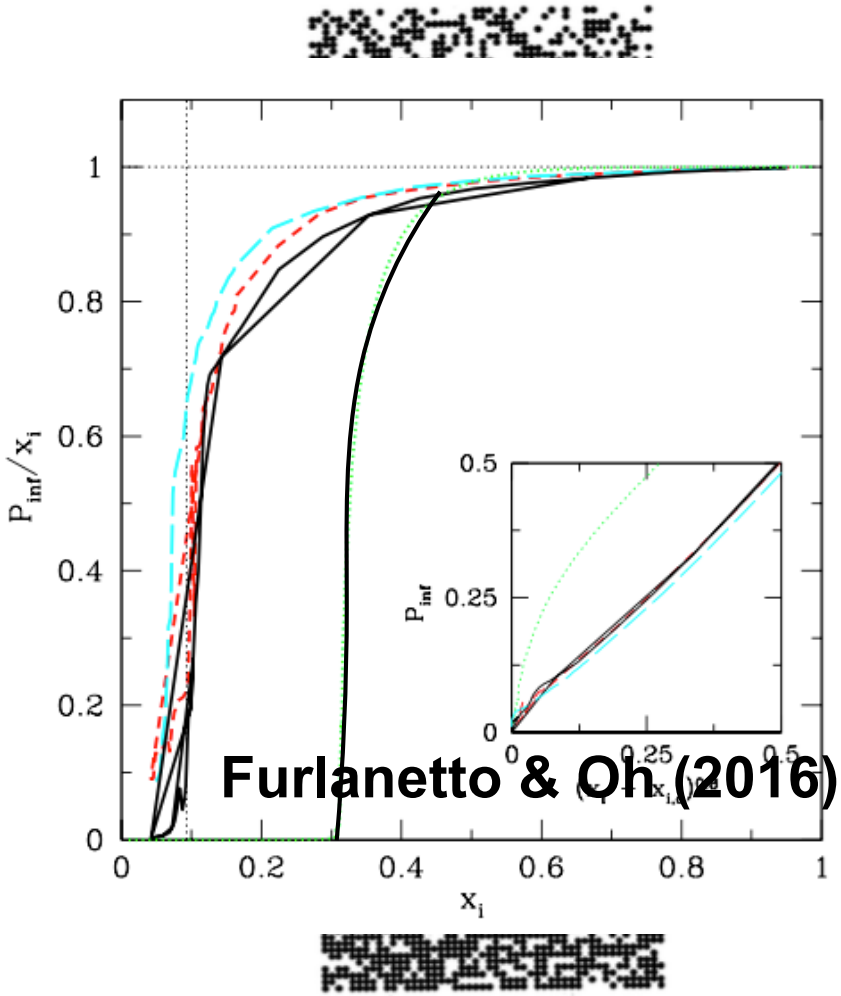
Reionization and Percolation Theory

- ***Percolation theory*** *is the study of the structures formed by random processes filling a space*
- *Extensively studied by mathematicians, geologists, and condensed matter physicists*

Isichenko (1992)

Reionization and Percolation

- *Some key results*
  - ***Percolating cluster!*** *A unique infinite region appears at a well-defined (but lattice-dependent) threshold*

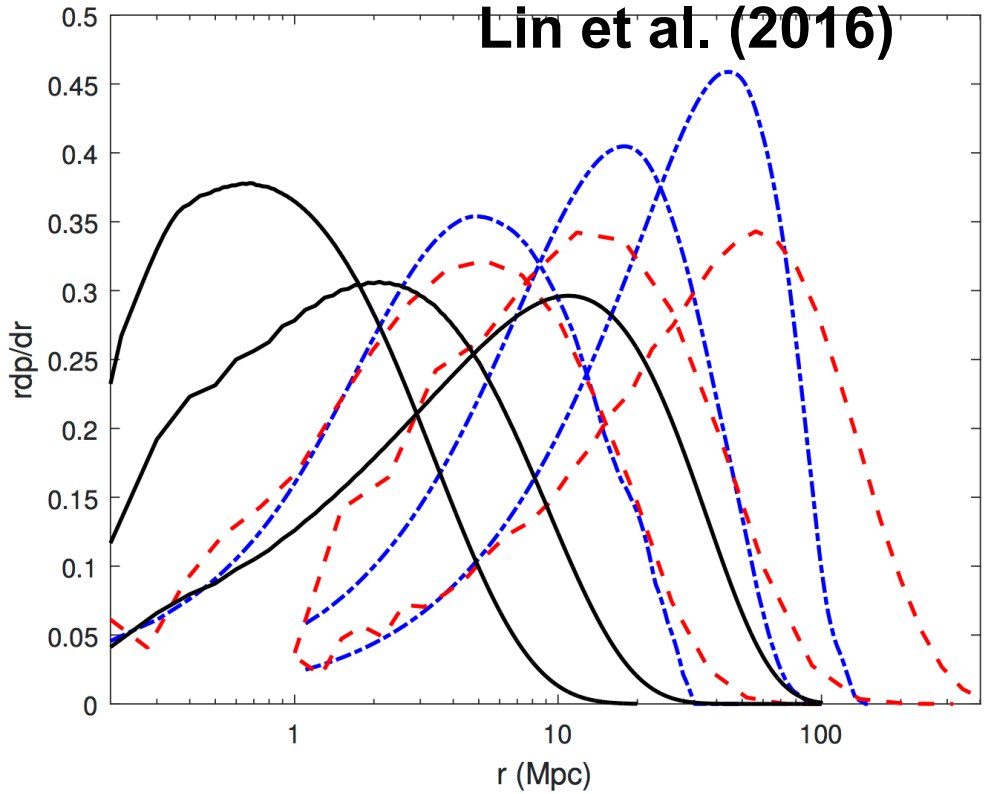


Furlanetto & Oh (2016)

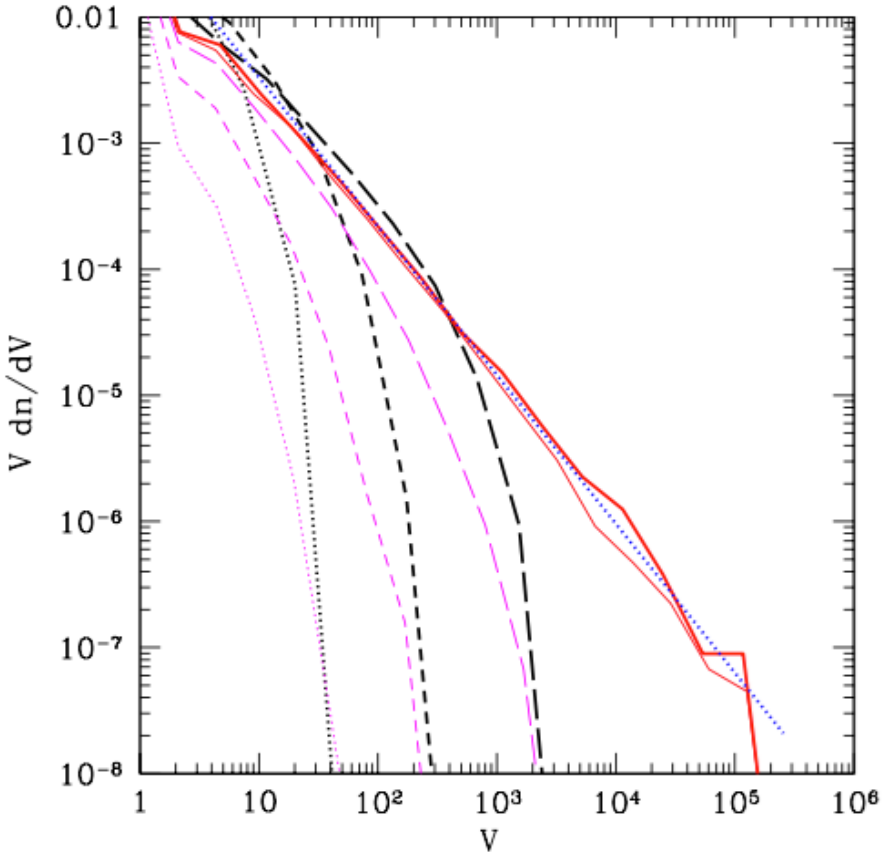
Isichenko (1992)

Reionization and Percolation

- *Some key results*



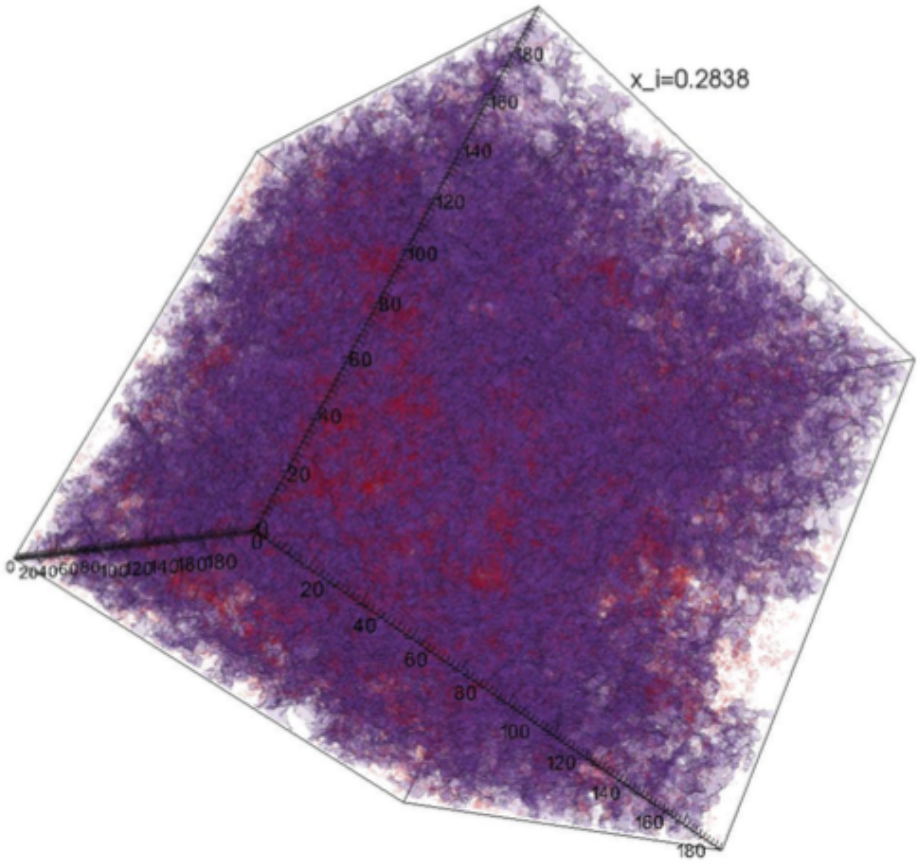
structures are fractal



Furlanetto & Oh (2016)

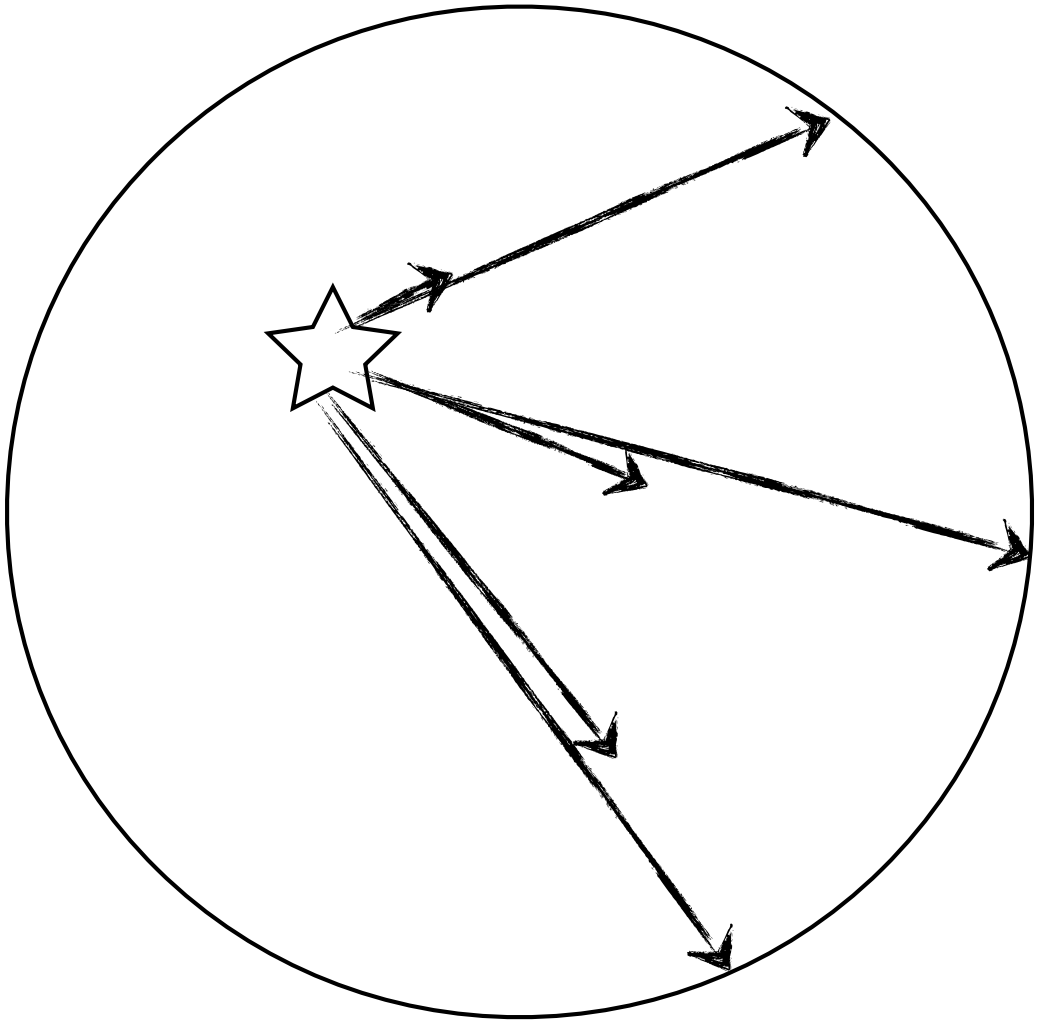
Reionization and Percolation

- *Reionization is a percolation process with (almost) all of the expected properties!*
- *Blue: percolating cluster ($x_{i,c}$=0.088)*
- *Red: other ionized regions*



Furlanetto & Oh (2016)

How did reionization end?

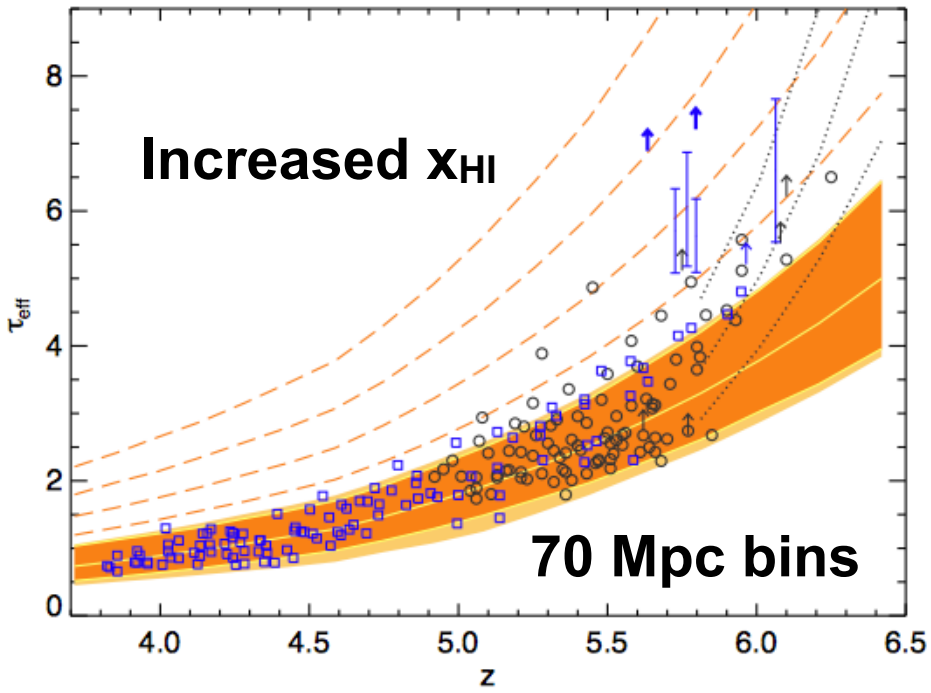


Furlanetto & Oh (2005)

- *End of reionization controlled by recombining clumps*
- *Modeling dense blobs in IGM is extremely difficult!*
  - *Direct observations at relevant cosmic times are impossible*

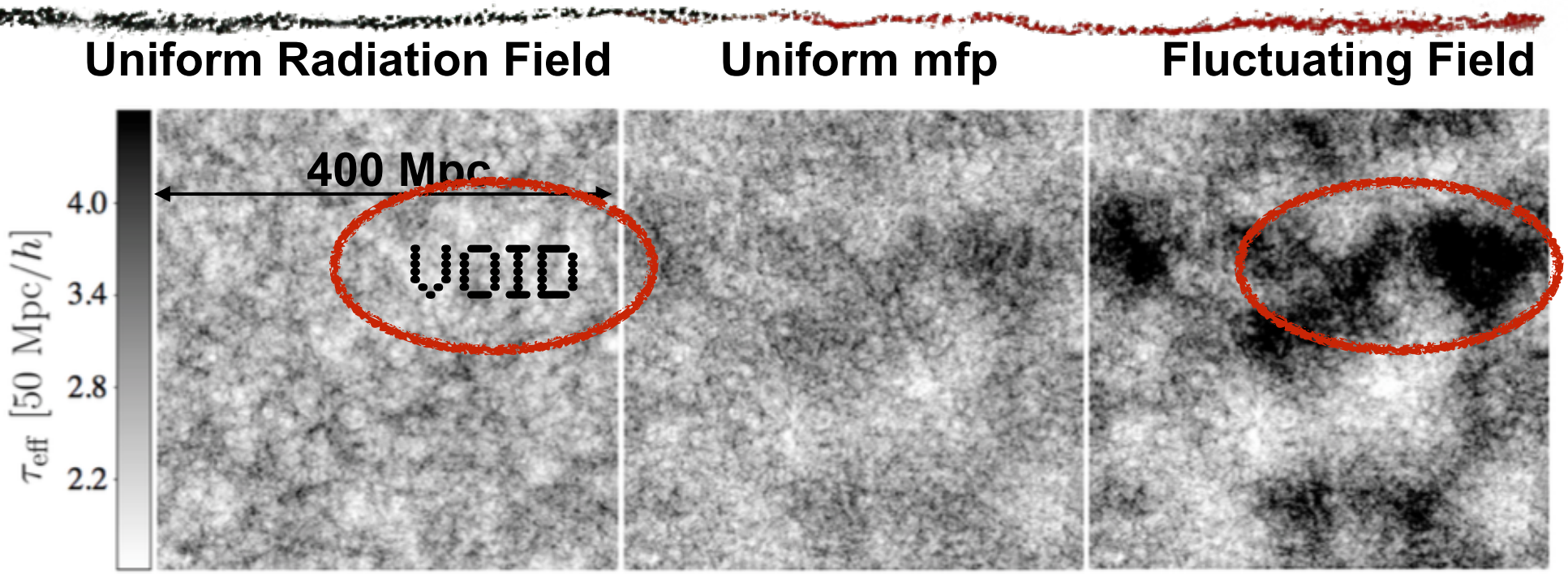
Fluctuations After Reionization

- *Bright quasars allow us to measure relic neutral gas after reionization along the line of sight*
- *Recent observations show substantial fluctuations on very large scales*
- *NOT consistent with standard models just after reionization!*



Becker et al. (2015)

Fluctuations After Reionization



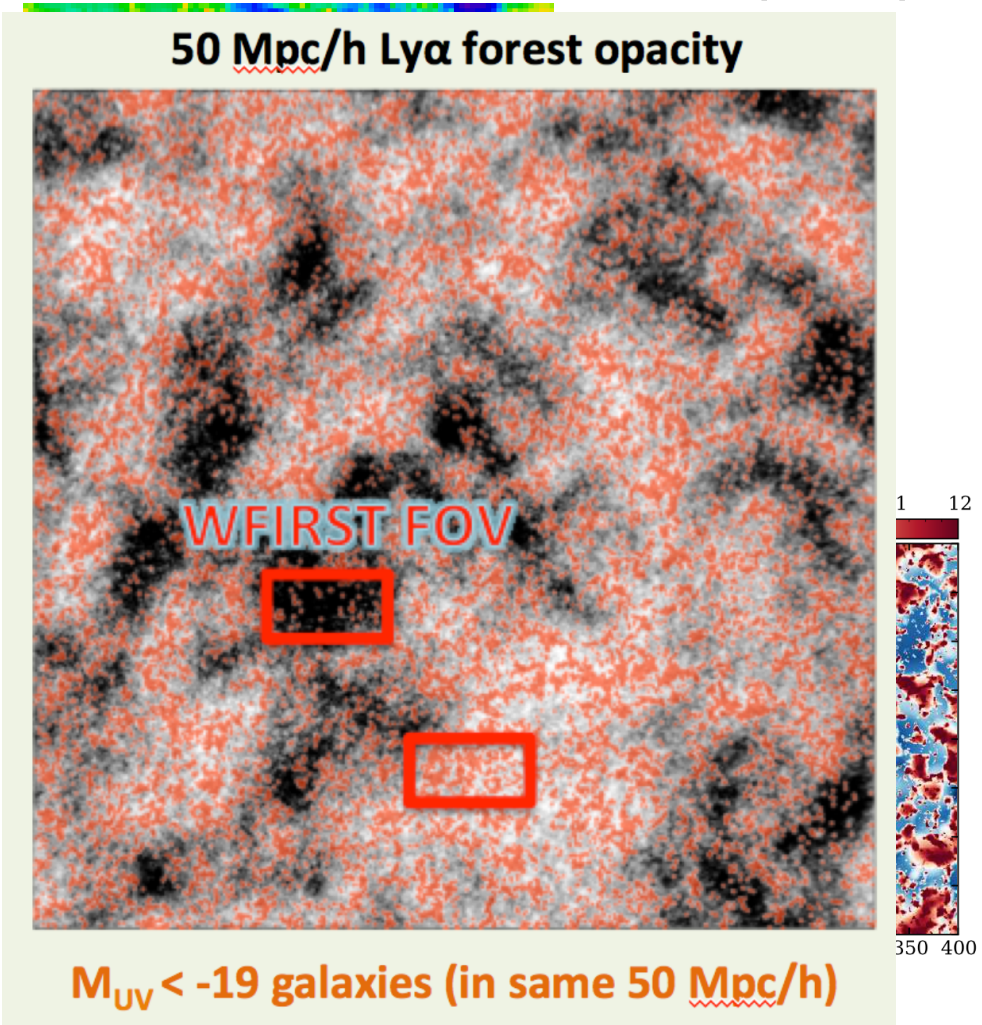
Davies & Furlanetto (2016)

- *Uniform background: densest regions are most opaque*
- *Fluctuating mfp: voids are more opaque*

Competing Theories!

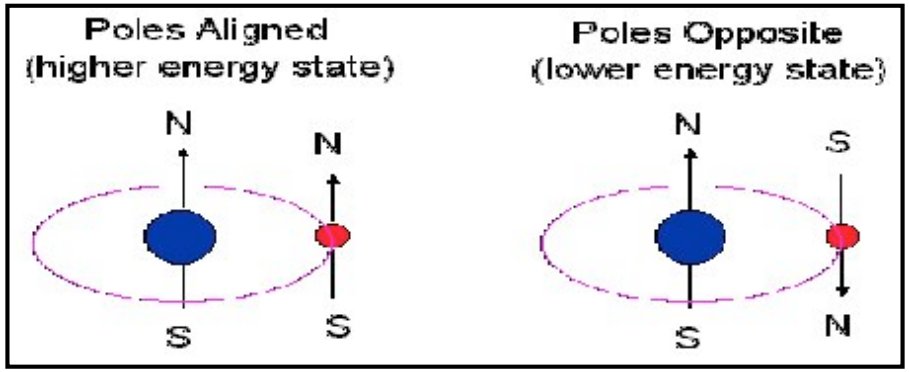
- *Alternative: heating from reionization causes fluctuations*
- *These two models make OPPOSITE predictions for high-τ environments!*

Davies & Furlanetto (2016)



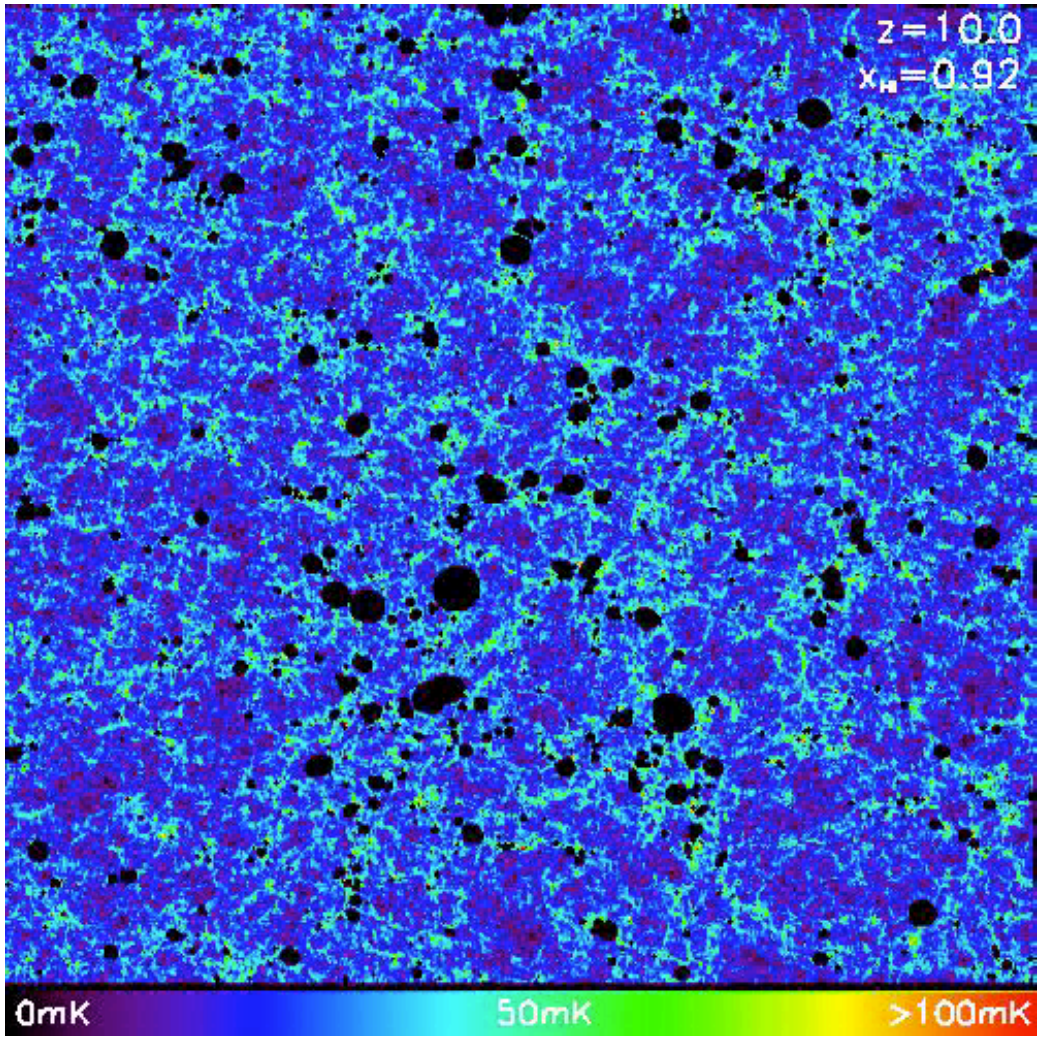
D'Aloisio, McQuinn, & Trac (2015)

How can we observe reionization?



The 21-cm line

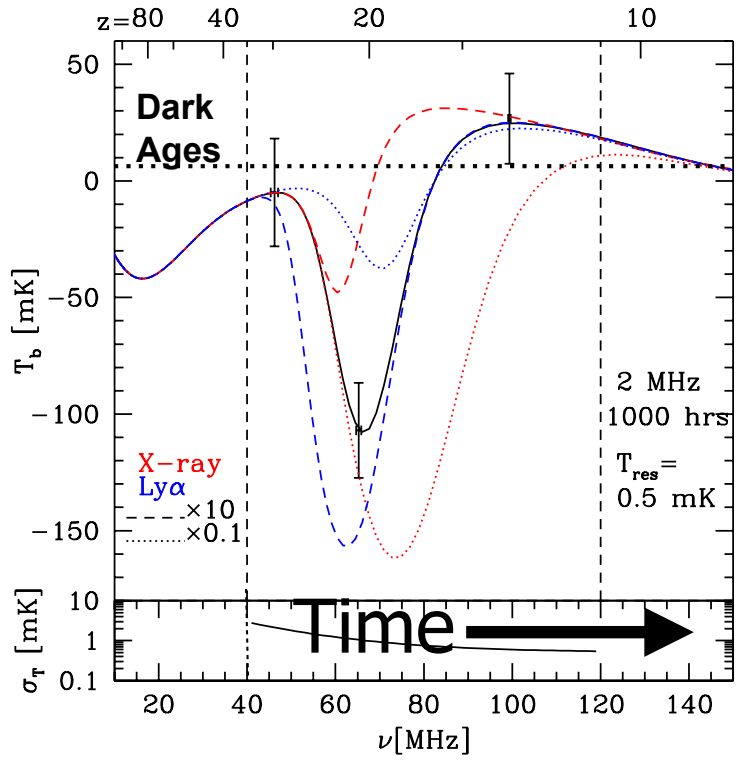
- *Spectral line measures entire history*
- *Directly measures intergalactic gas*
- *Weak absorption*



Mesinger & Furlanetto

How does the spin-flip background teach us about source populations?

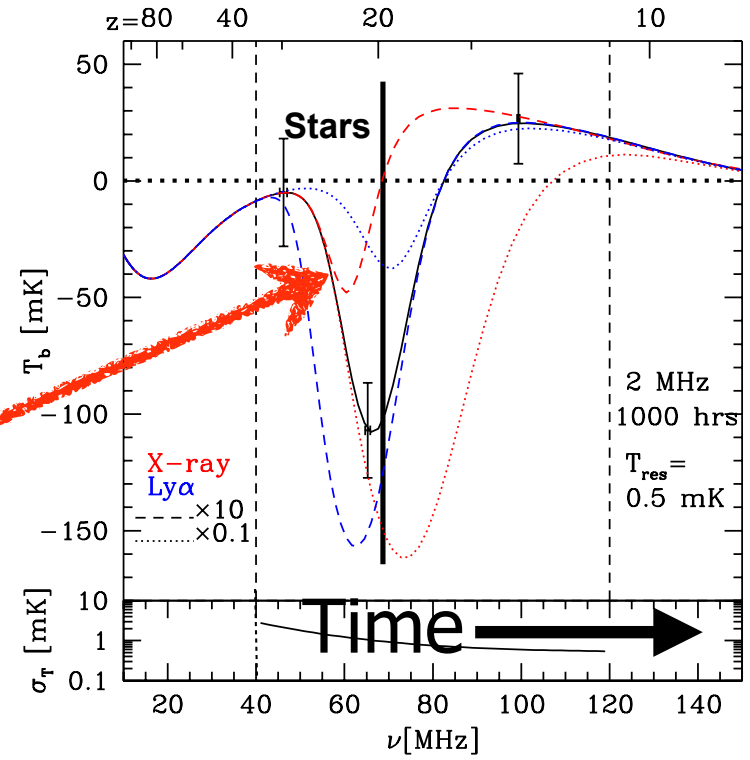
- *Four Phases to the spin-flip background*
  - *Dark Ages (potential probe of exotic physics)*



J. Pritchard

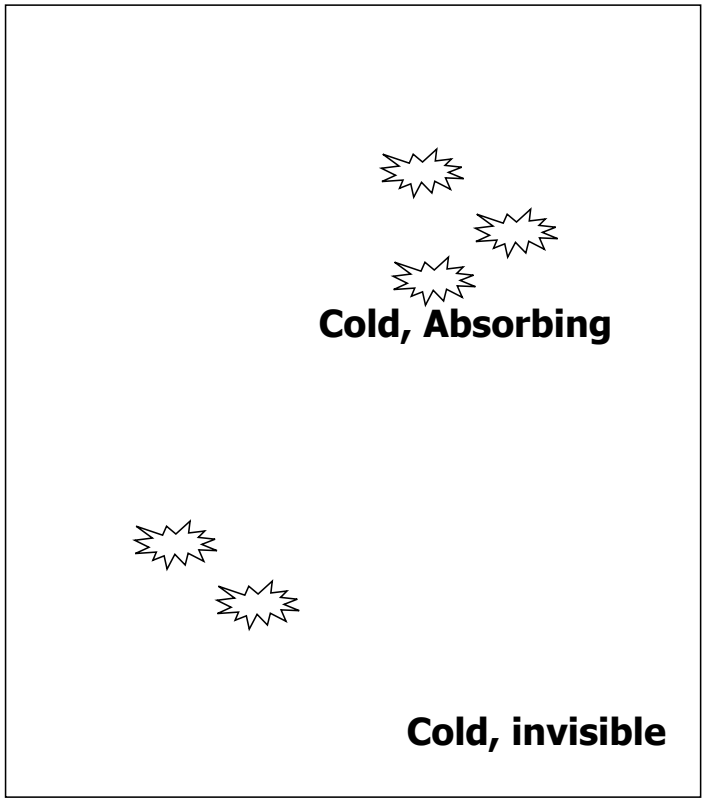
How does the spin-flip background teach us about source populations?

- *Four Phases to the spin-flip background*
  - *Dark Ages*
  - *First Stars*



J. Pritchard

The First Stars: Lyα Fluctuations



- *Strong absorption near first galaxies*
- *Eventually saturates*

Barkana & Loeb 2004, Pritchard & Furlanetto 2006, Mesinger et al. 2011

How does the spin-flip background teach us about source populations?

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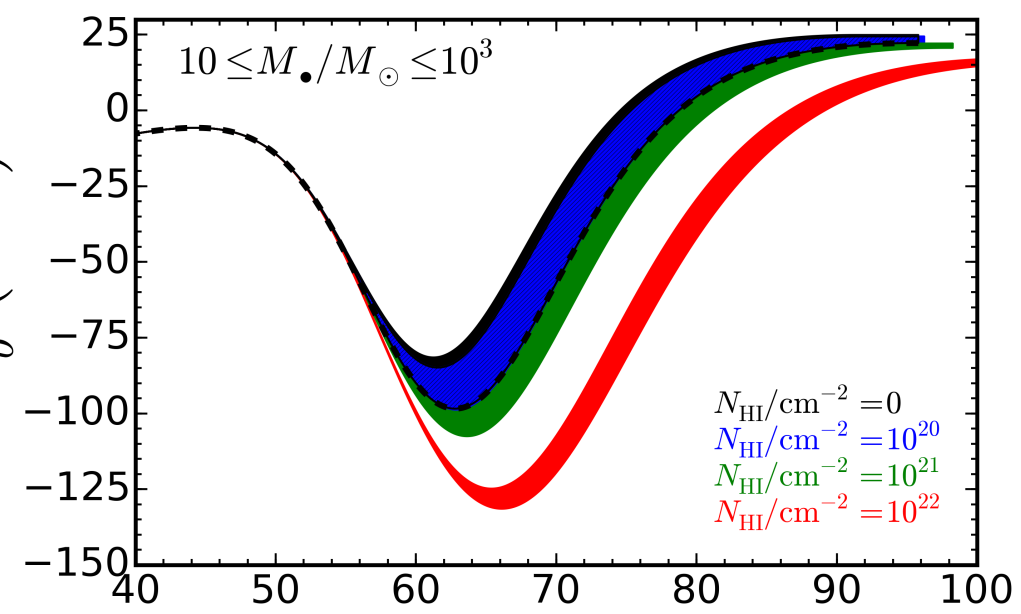
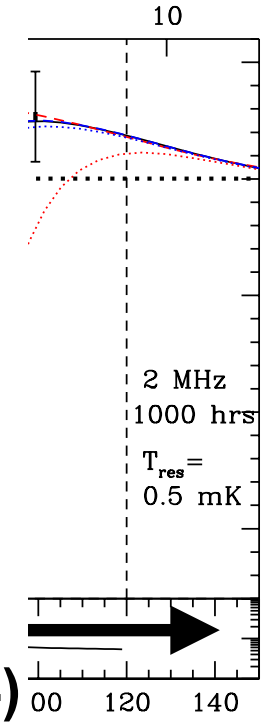
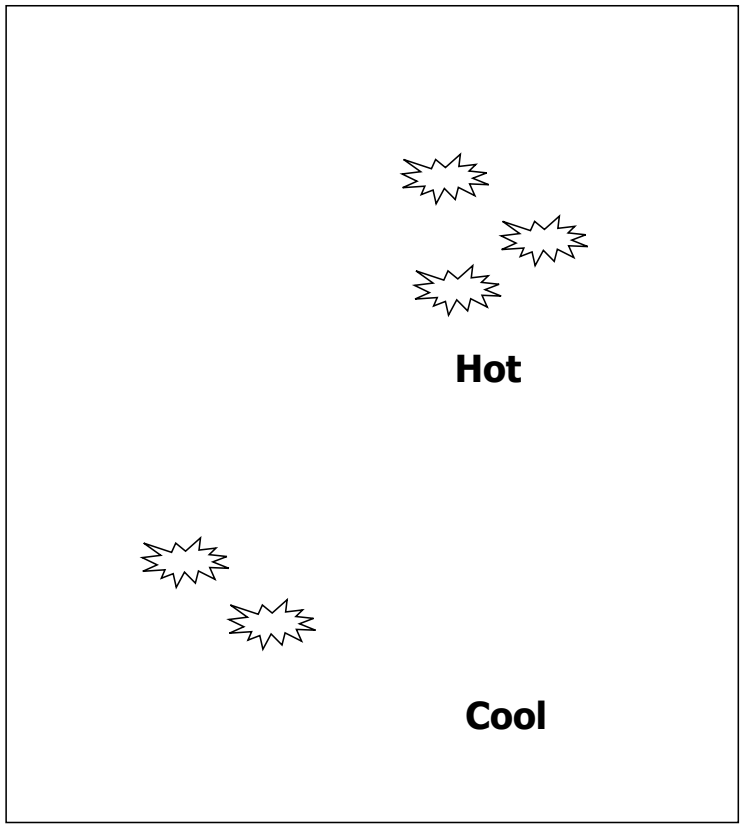


Mirocha (2014)



J. Pritchard

The First Black Holes

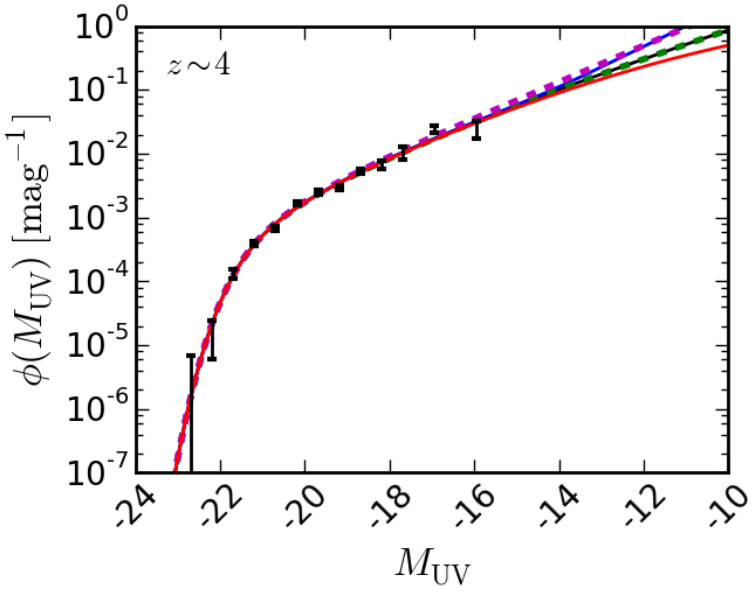


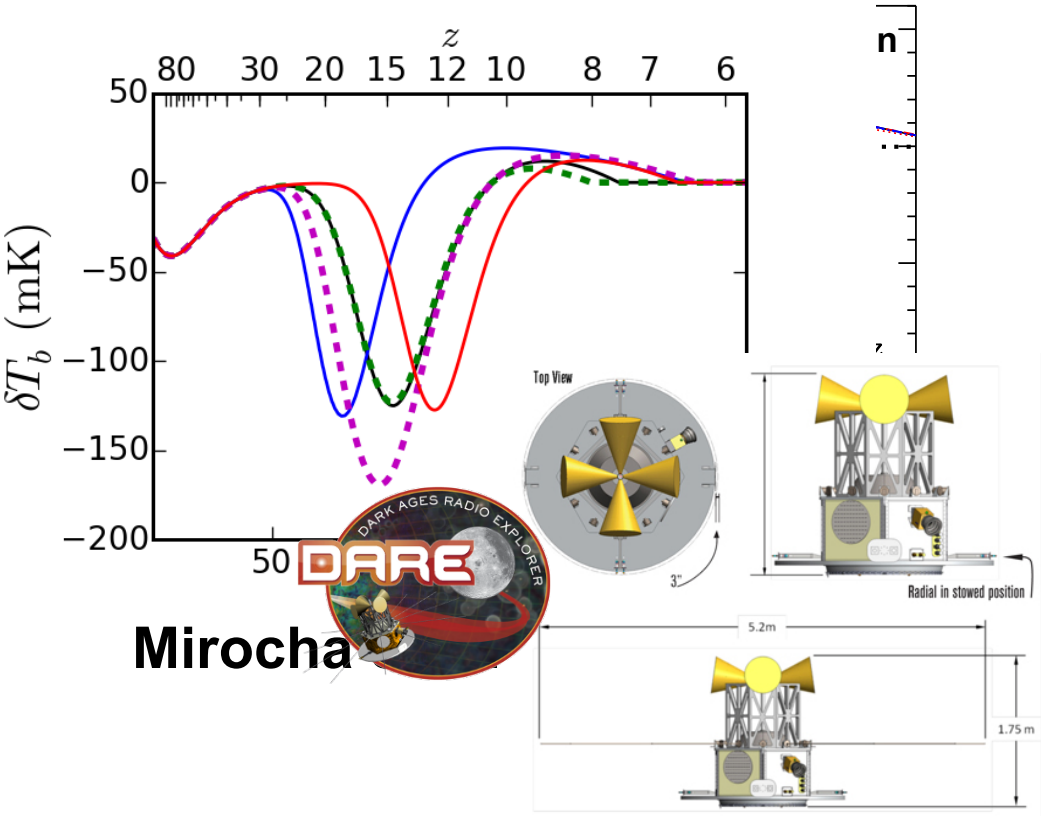
- *X-ray photons heat gas around first black holes*
  - *Supernovae*
  - *Stellar remnants*
  - *Quasars*
- *Hot IGM near them, cool IGM elsewhere*

Pritchard & Furlanetto 2007, Chuzhoy et al. 2007, Chen & Miralda-Escude 2008, Santos et al. 2009, Mesinger, Furlanetto, & Cen 2011, Baek et al. 2010

How does the spin-flip background teach us about source populations?

- *Four Phases to the*





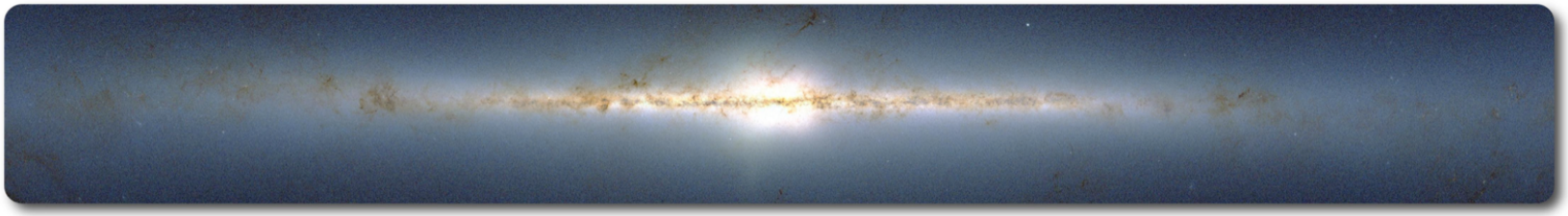
- *Reionization*

Mirocha

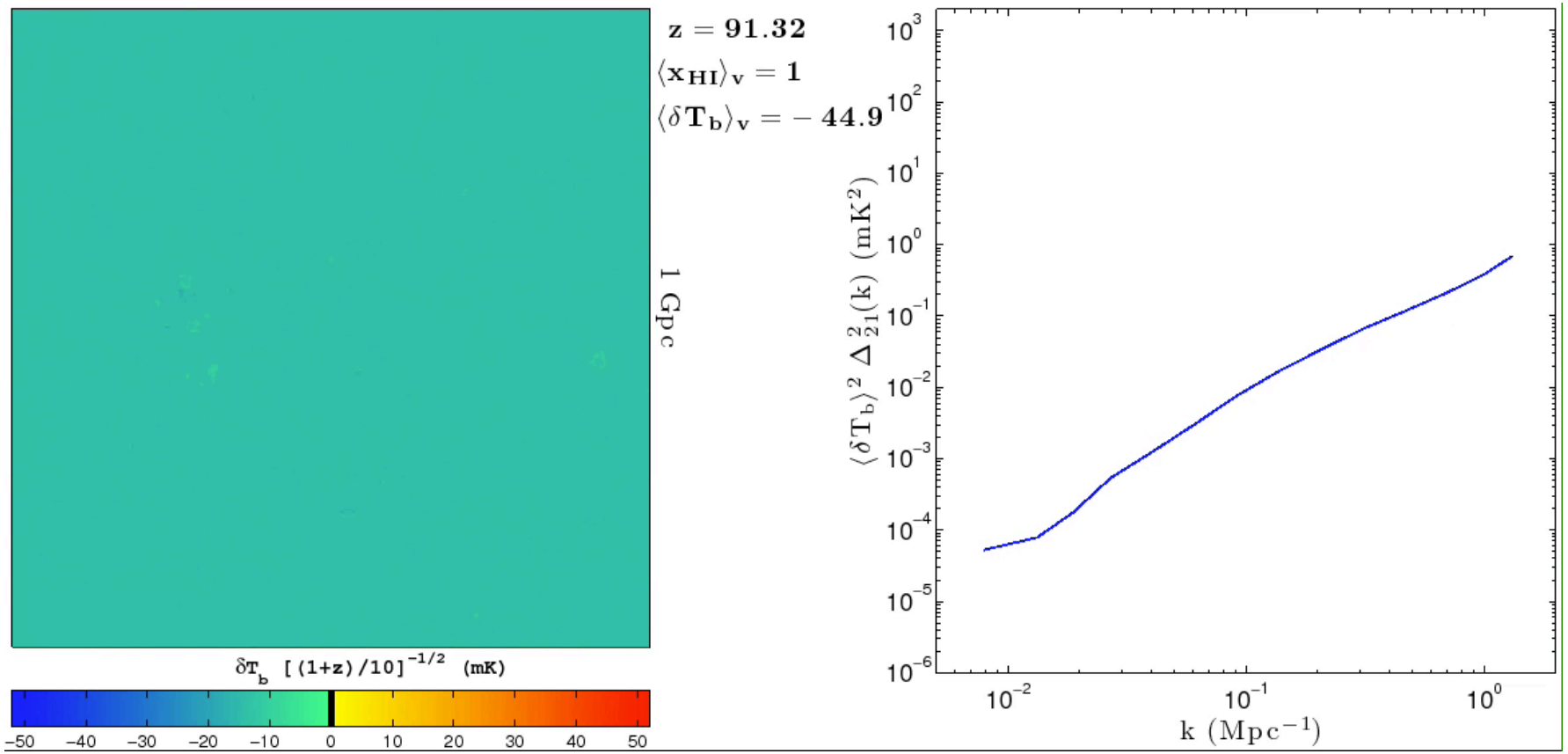
+ EDGES, LEDA, SCI-HI

But can we see it?

- *Terrestrial foregrounds*
- *Ionosphere*
- *Astrophysical foregrounds*

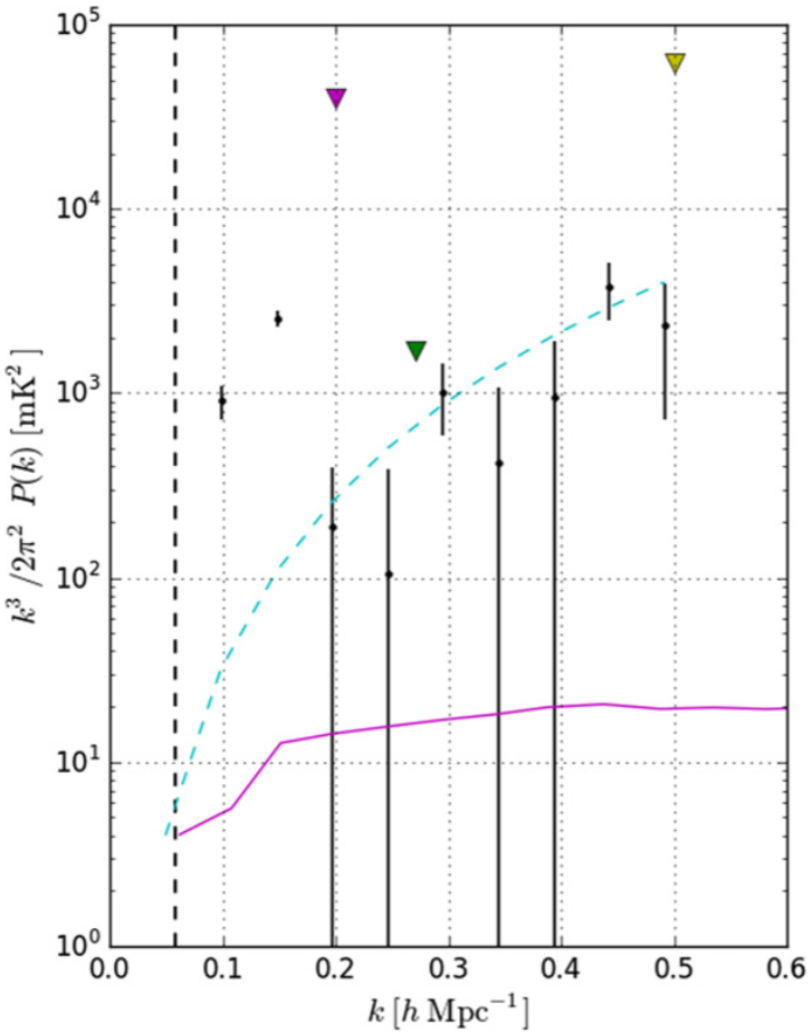


The 21-cm Background



Mesinger, Furlanetto, & Cen (2011)

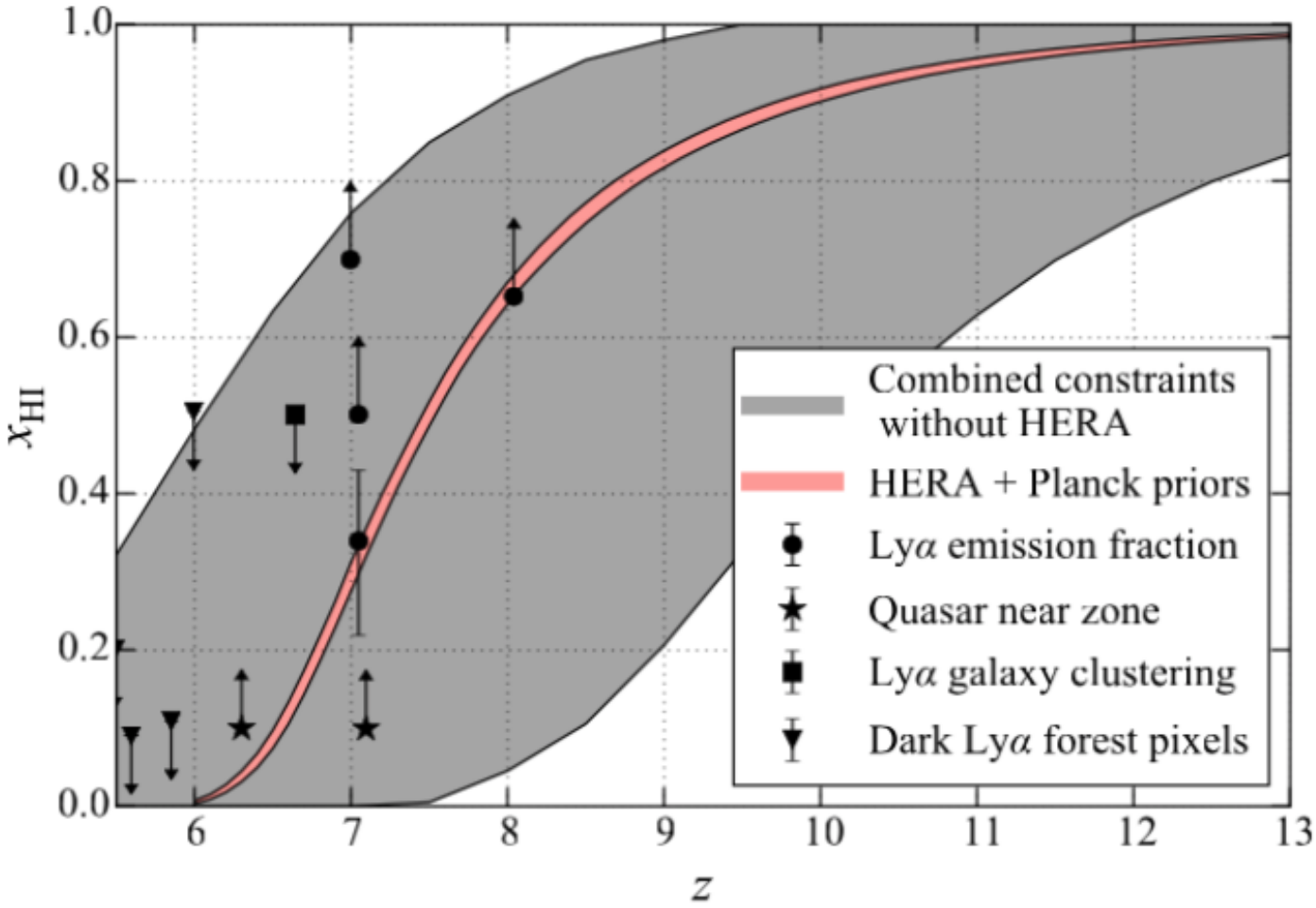
The Story So Far



Ali et al. (2015)

- *Four active observatories: LOFAR, GMRT, MWA, PAPER*
- *Best constraints so far from PAPER*
- *Rule out cold IGM at z~8 (Pober et al. 2015)*

The Hydrogen Epoch of Reionization Array



Onward!

- *Galaxy evolution at these times is still poorly understood*
  - *Basic expectations seem reasonable*
  - *Hints (perhaps!) of some changes, but nothing dramatic*
- *The process of reionization can be modeled well…*
  - *But its underlying structure is just beginning to be explored*
- *The end of reionization is being probed but is poorly understood*
  - *(Finally!) hints of progress*
- *We hope for measurements of the spin-flip line SOON*