Title: The Epoch of Reionization and the Lyman-alpha Forest

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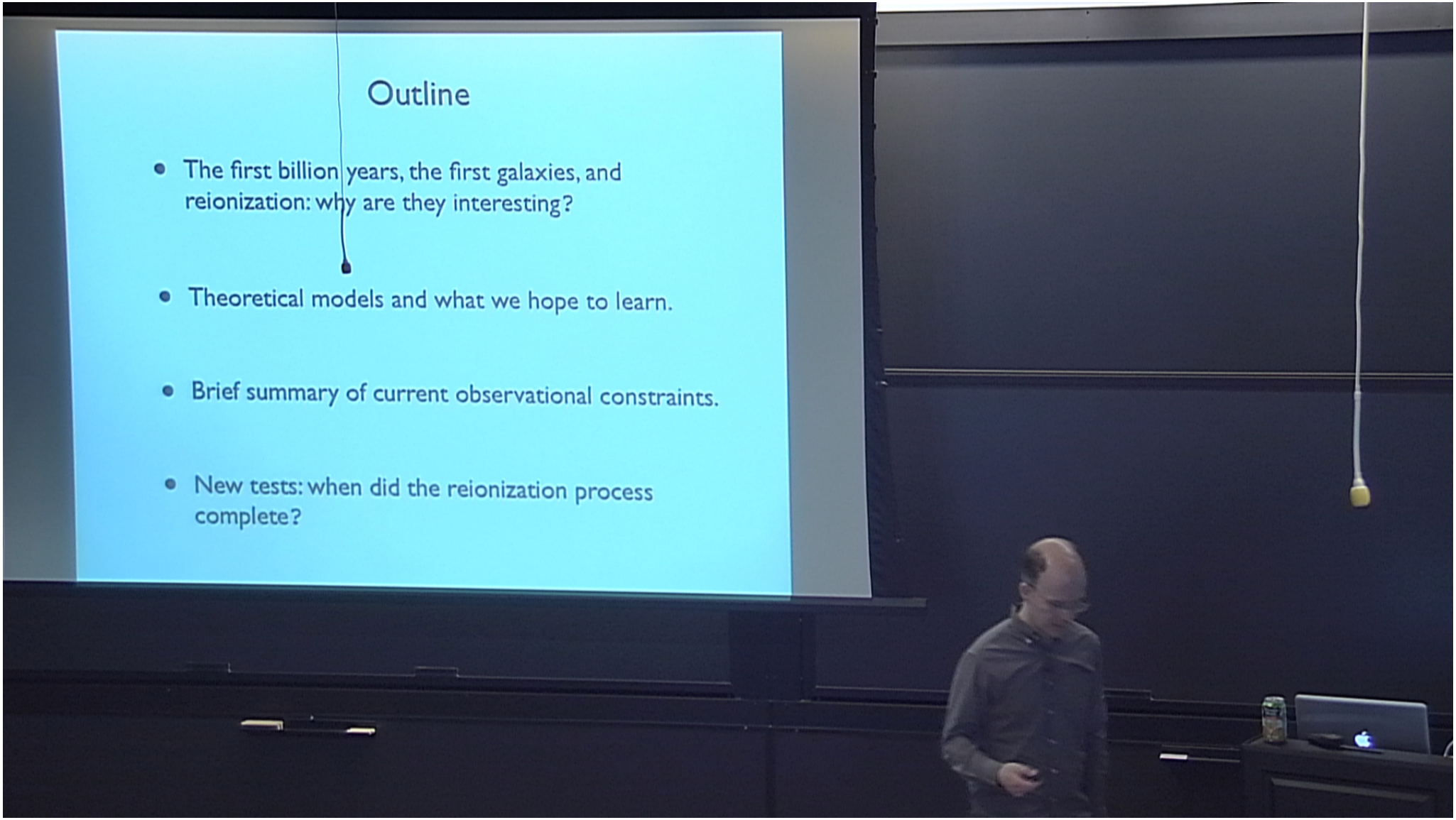
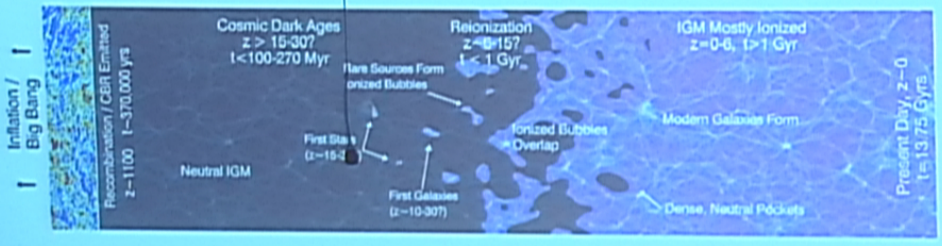
Abstract: An exciting and largely unexplored frontier in observational and theoretical cosmology is to understand the properties of the universe between 400,000 years and one billion years after the big bang. Notably, the first galaxies formed in this time period, perhaps a few hundred million years after the big bang. These galaxies strongly influenced the gas in their surroundings as well as the formation of subsequent generations of galaxies. The early galaxies emitted ultraviolet light and ionized "bubbles" of hydrogen gas around them. These ionized bubbles grew, merged, and eventually filled the entire volume of the universe with ionized hydrogen in a process known as reionization. Understanding this process will constrain the properties of the first luminous sources, and fill in a significant gap in our story of structure formation, whereby the universe transitions from simple initial conditions to its present day complexity. I will briefly summarize current observational constraints and describe some new ideas for better determining when the reionization process completed using existing Lyman-alpha forest data.

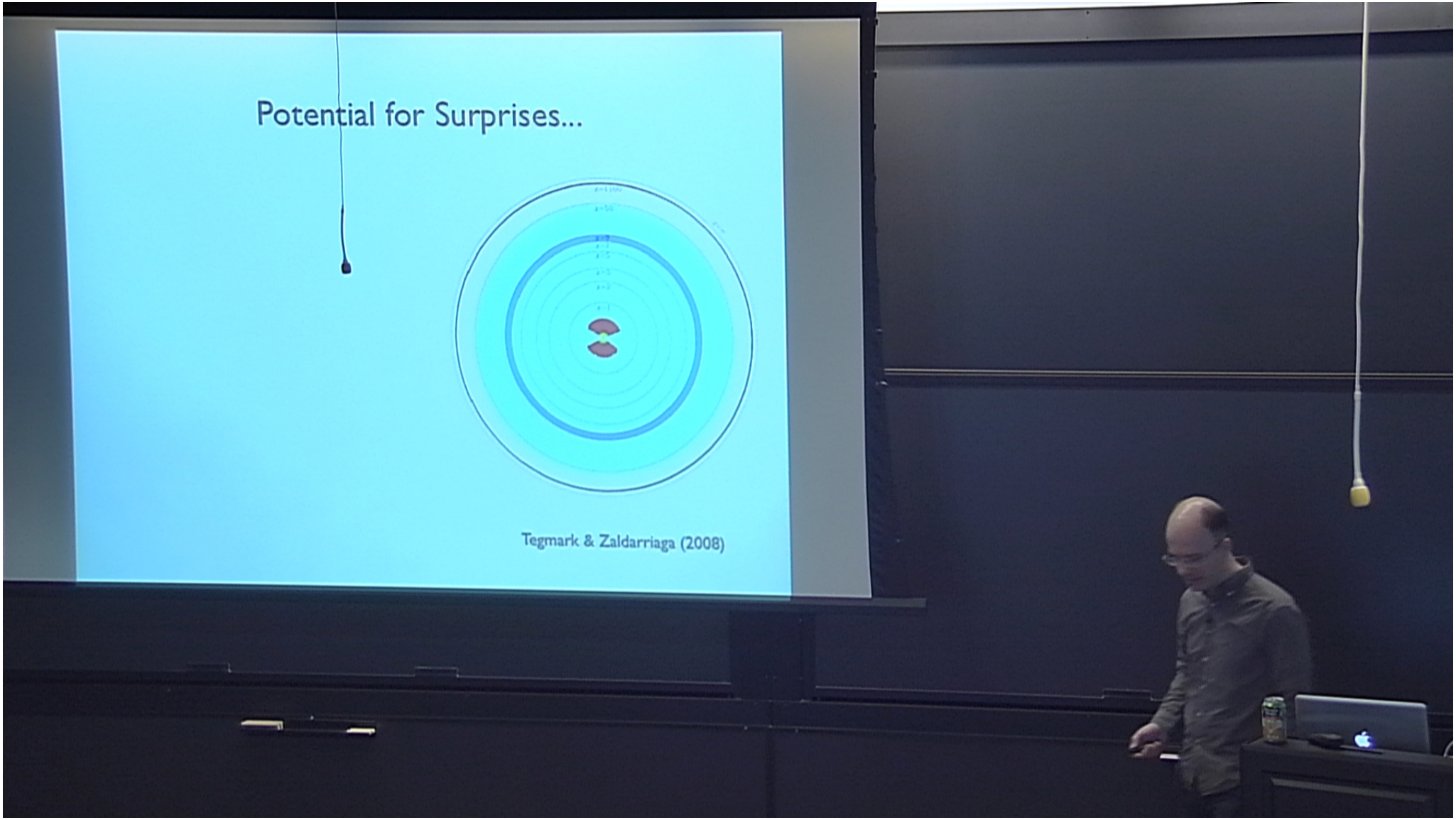

Outline
The first billion years, the first galaxies, and reionization: why are they interesting?
Theoretical models and what we hope to learn.
Brief summary of current observational constraints.
New tests: when did the reionization process complete?

First Luminous Sources

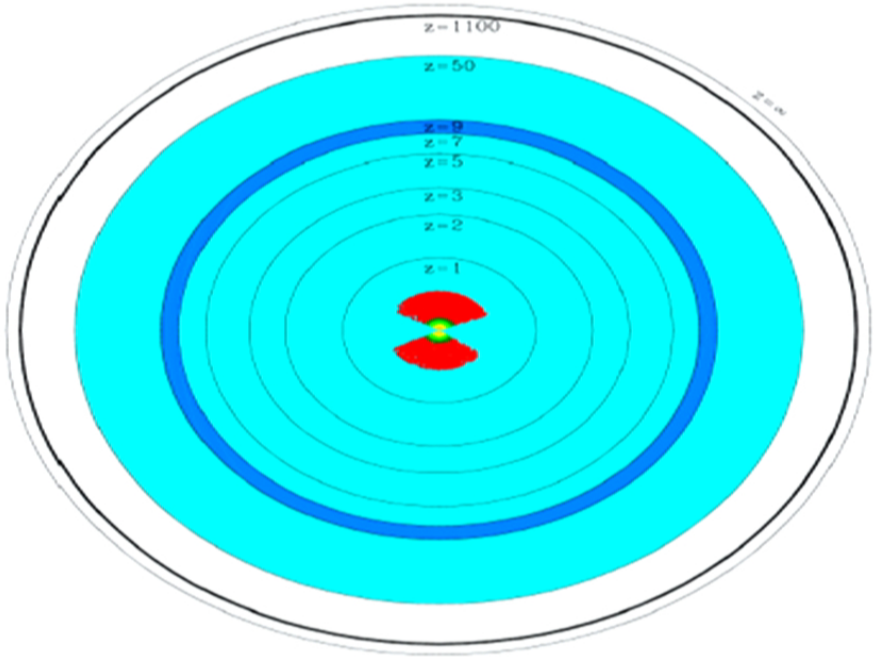


Robertson+ 10

- Mostly unexplored era: t~400,000 years - 1 billion years.
- First stars, galaxies, and accreting black holes formed.
- *Dramatically* impacted gas around them ("Reionization"), and impacted subsequent galaxy formation.

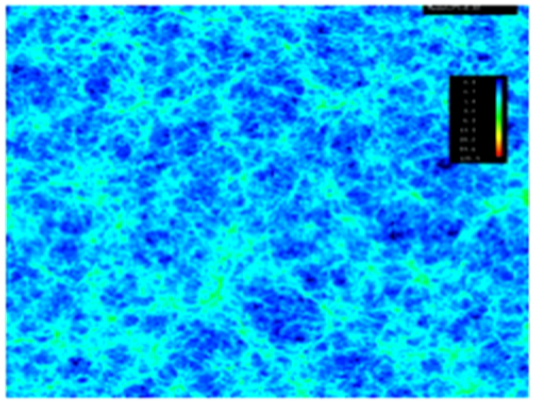

Potential for Surprises...
Tegmark & Zaldarriaga (2008)

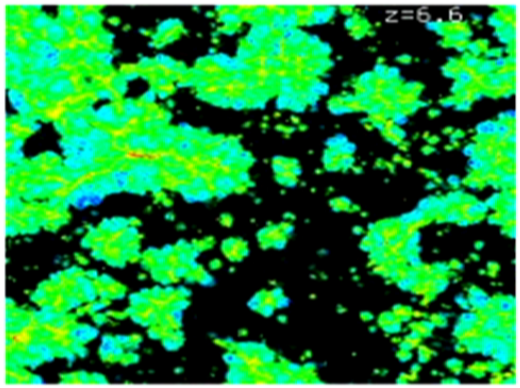
Potential for Surprises...



Tegmark & Zaldarriaga (2008)

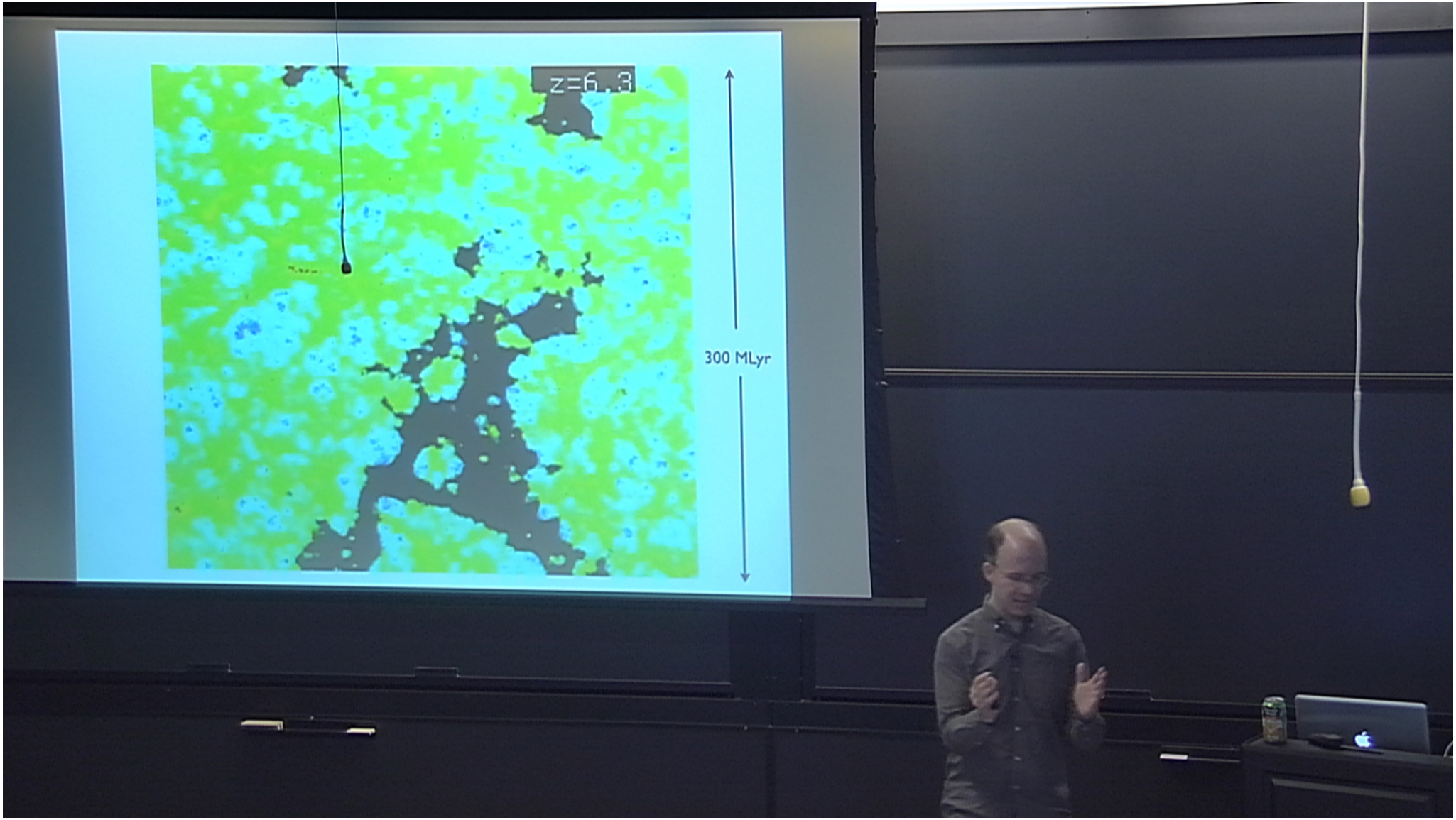
Simulating Hydrogen Reionization

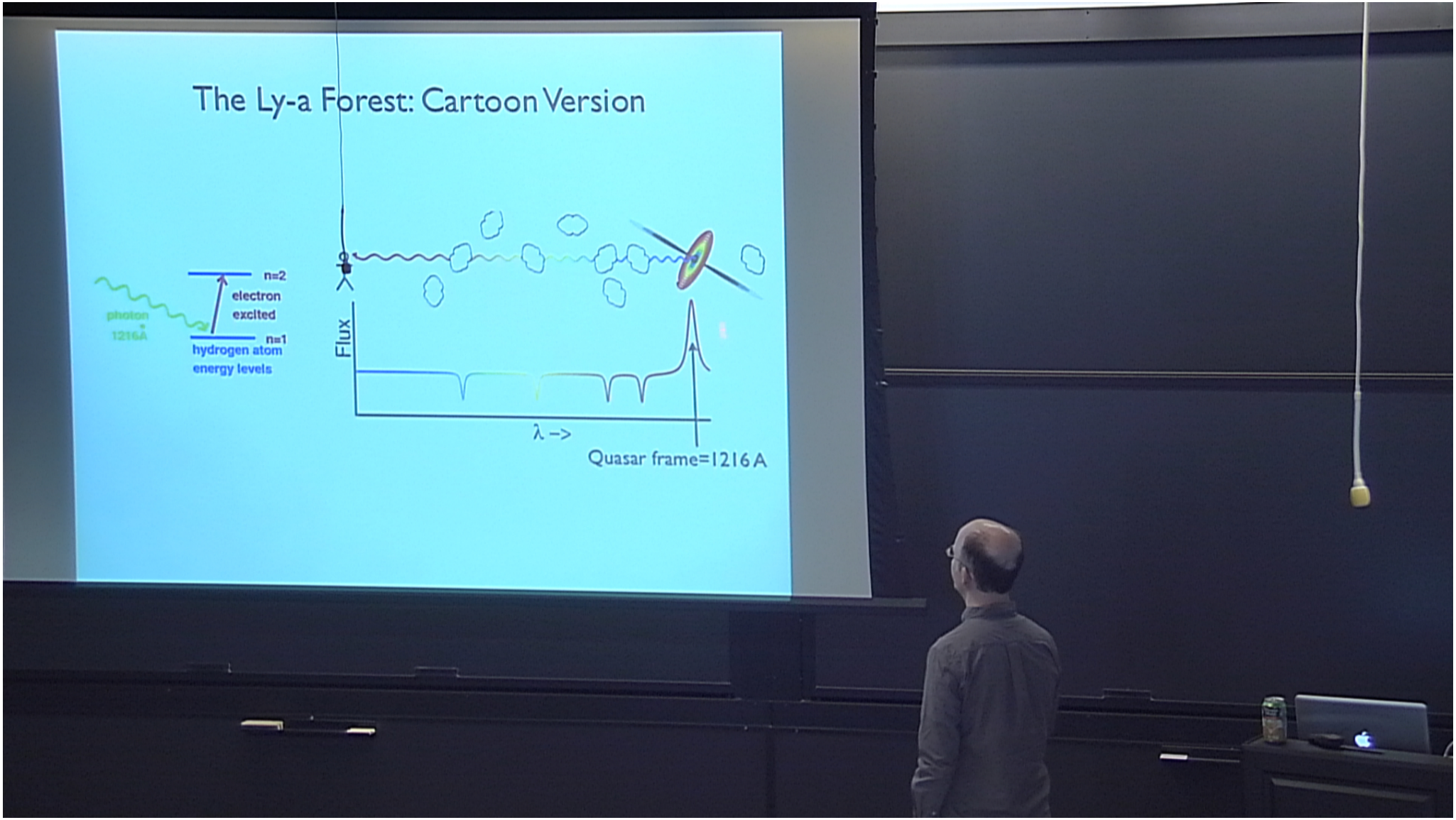


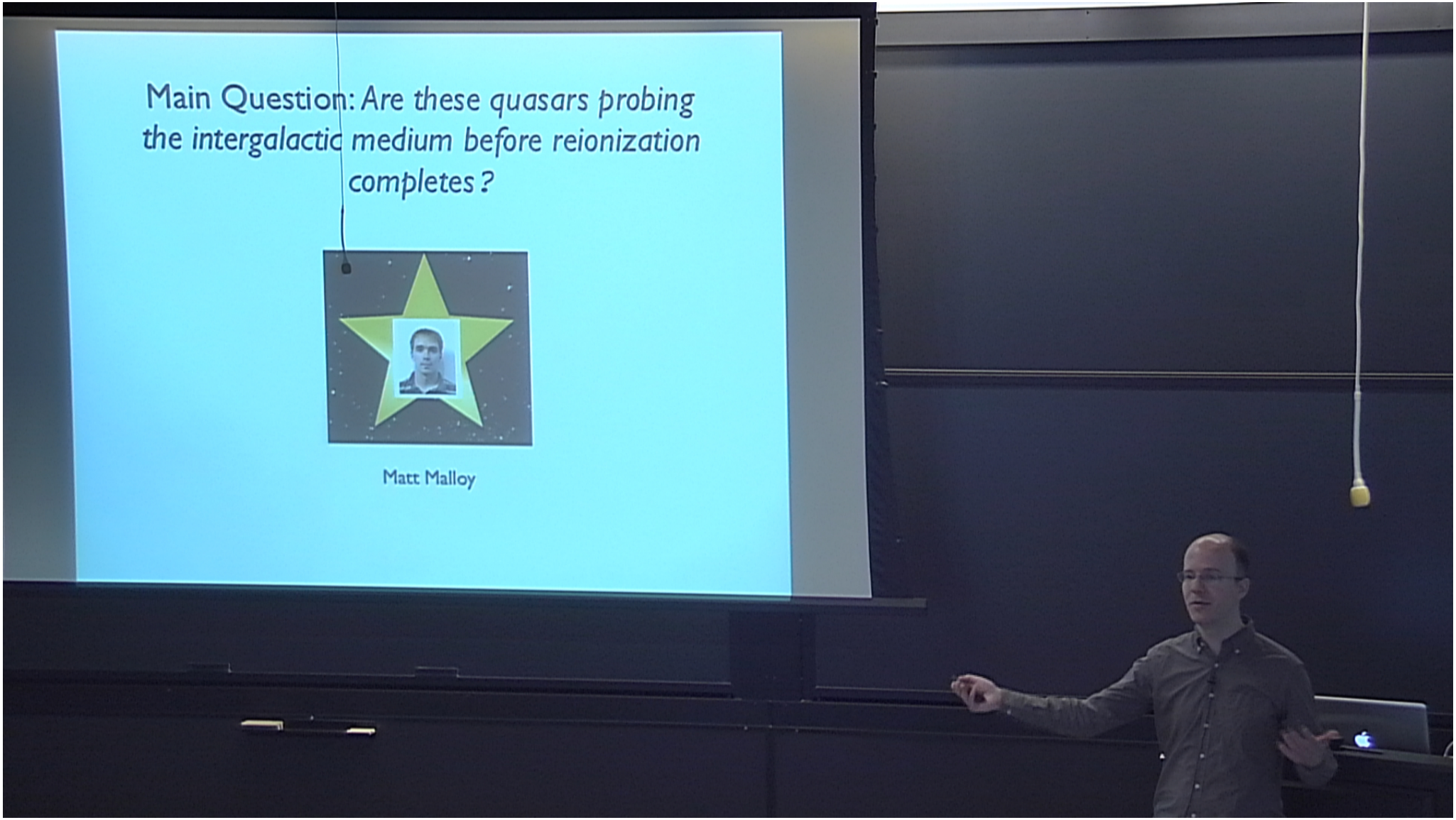


- Large volume to sample large ionized regions. (Capture scales that are today 300-600 Million light years.)
- 1024^3 tracer particles to resolve small mass galaxies.
- Prescriptions to connect simulated dark matter halos with galaxies. Subgrid models for "sinks" of ionizing photons.
- Ray tracing scheme for calculating radiative transfer.

McQuinn, AL,+ 2007


z=6.3
300 MLyr

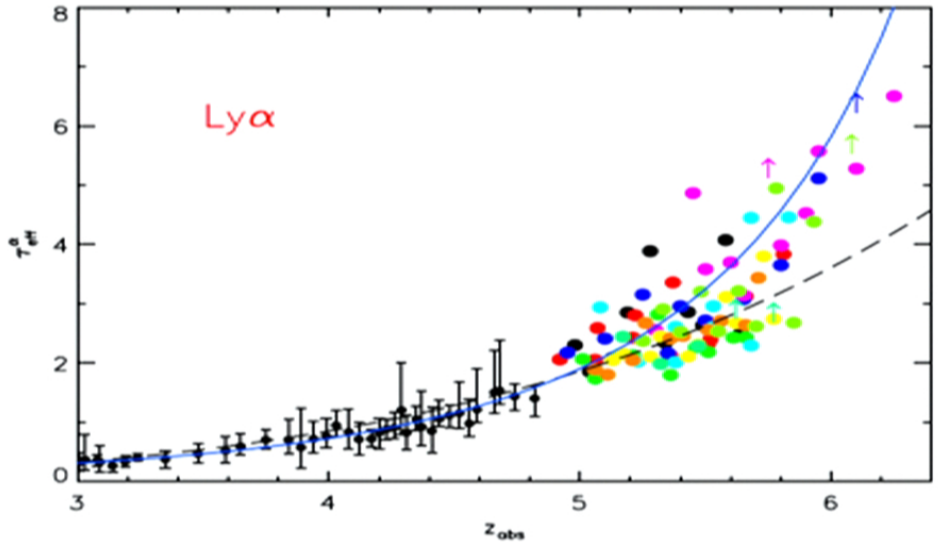

The Ly-a Forest: Cartoon Version
photon
1216A
n=2
electron
excited
n=1
hydrogen atom
energy levels
Flux
λ ->
Quasar frame=1216 A


Main Question: Are these quasars probing the intergalactic medium before reionization completes?
Matt Malloy

Interpretation?

$$\tau_{\mathrm{GP},\alpha} = 3.7 \times 10^5 \left[\frac{X_{HI}}{1}\right] \left[\frac{1+\delta}{1}\right] \left[\frac{1+z}{7}\right]^{3/2}$$

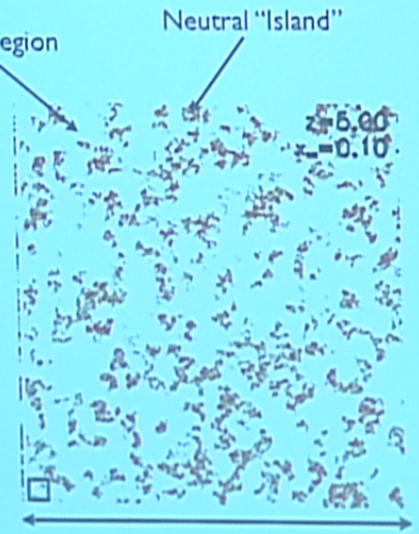
- A neutral fraction of $>\sim 10^{-4}$ is sufficient to give complete absorption in Ly-a.
- When forest is completely absorbed (z>6), we can't tell how neutral it is.
- Often claimed: Transmission below z<6 implies reionization is definitely complete by z<6.

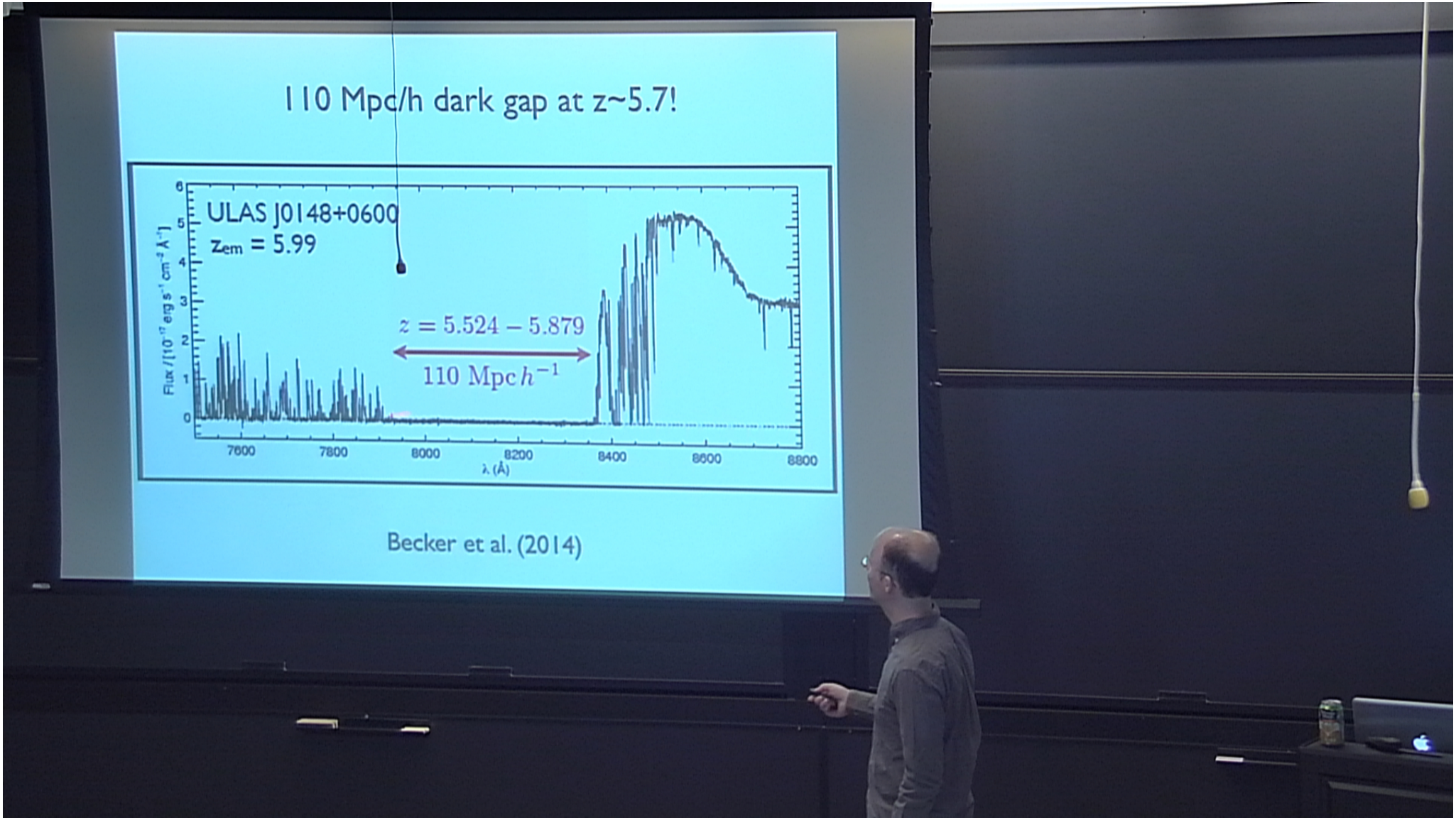


Becker et al. (2007)

Reionization is Inhomogeneous....

- Highly ionized bubbles may allow transmission, even when some regions are significantly neutral.
- May have transmission through forest even *before reionization completes.*

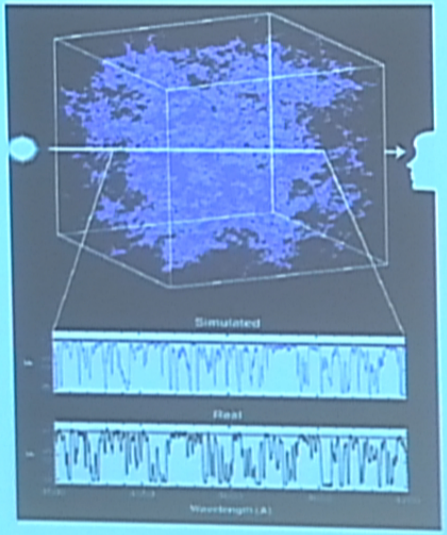



110 Mpc/h dark gap at z~5.7!
ULAS J0148+0600
zem = 5.99
$z = 5.524 - 5.879$
$110\ \mathrm{Mpc}\,h^{-1}$
Flux / [10^-17 erg s^-1 cm^-2 Å^-1]
λ (Å)
Becker et al. (2014)

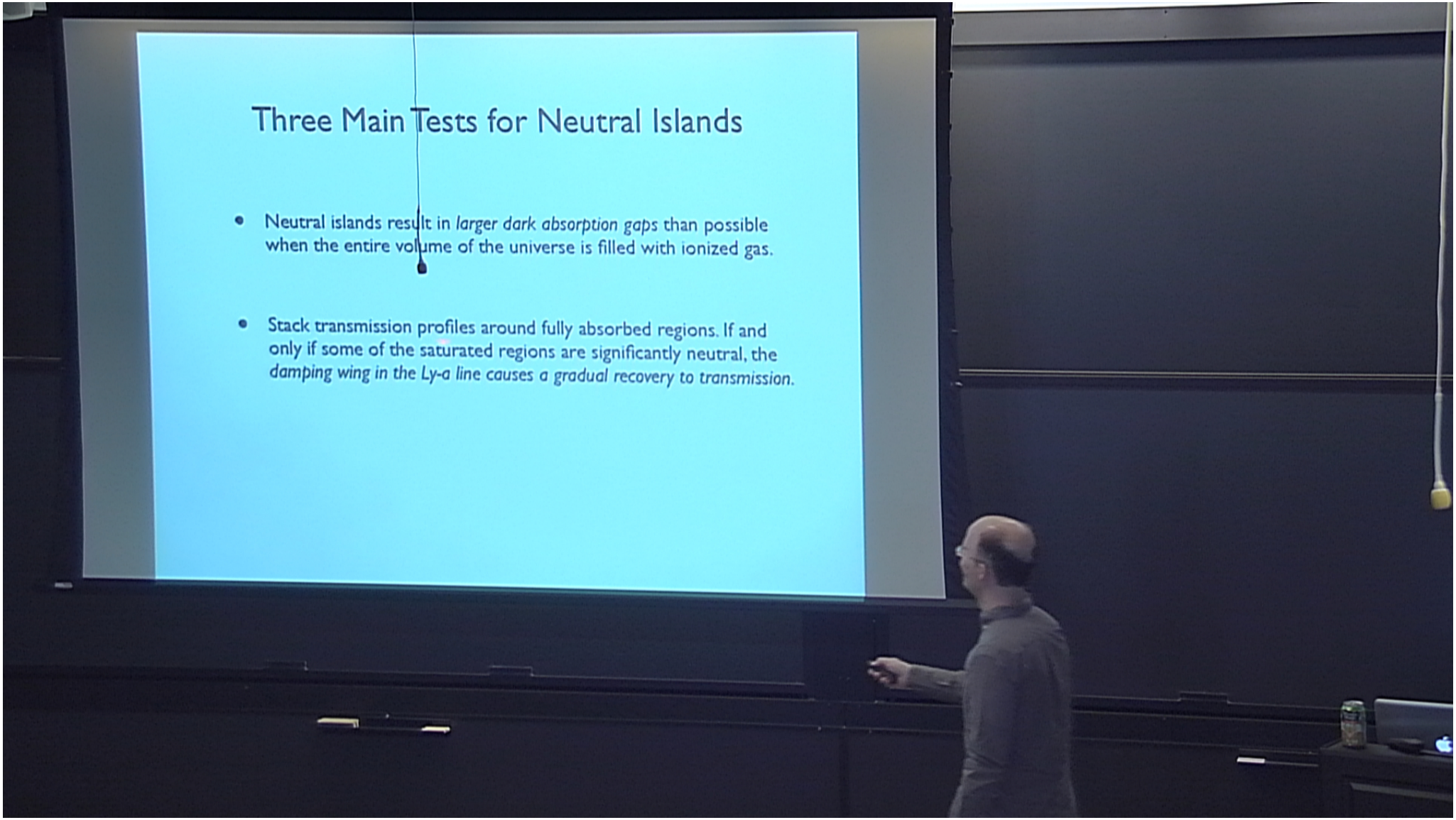
Simulating the Ly-a Forest

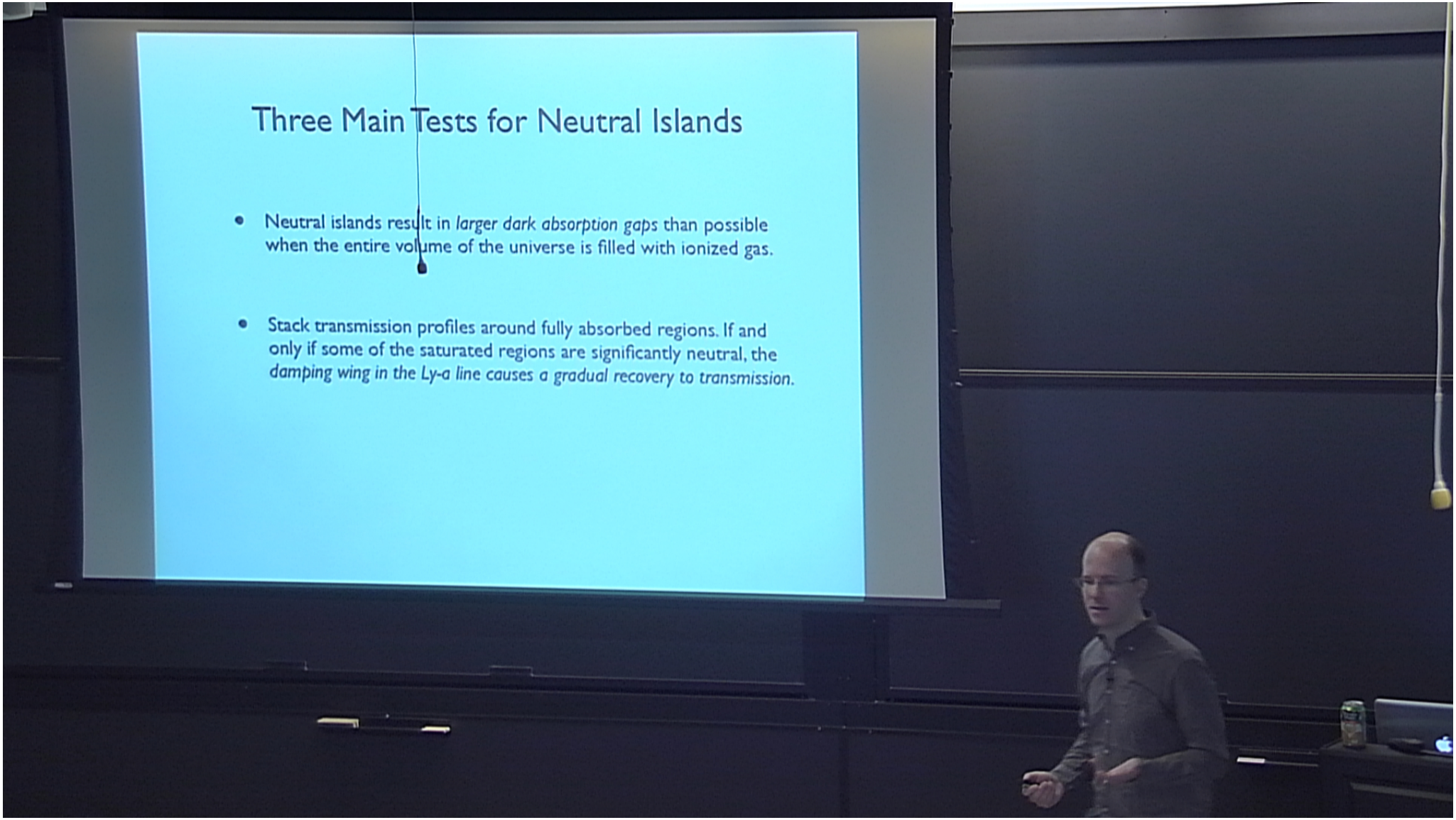
- Make mock quasar spectra by shooting lines of sight through cosmological simulation boxes.

- Compare statistics of simulated and real spectra.



Faucher-Giguere, AL, & Hernquist
Science 2008


Three Main Tests for Neutral Islands
• Neutral islands result in *larger dark absorption gaps* than possible when the entire volume of the universe is filled with ionized gas.
• Stack transmission profiles around fully absorbed regions. If and only if some of the saturated regions are significantly neutral, the *damping wing in the Ly-α line causes a gradual recovery to transmission.*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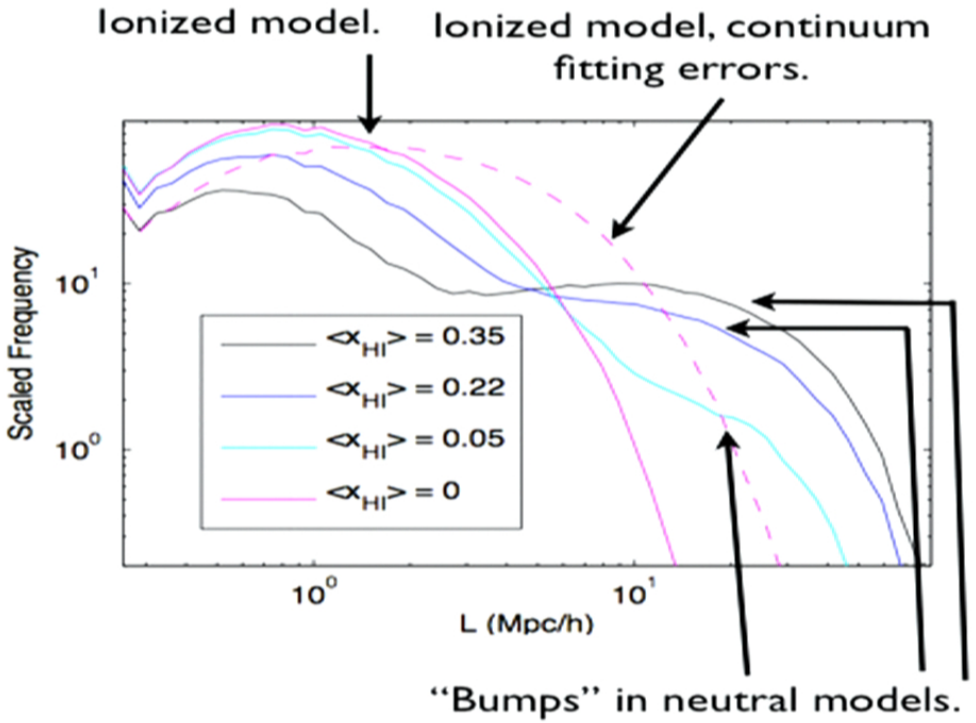
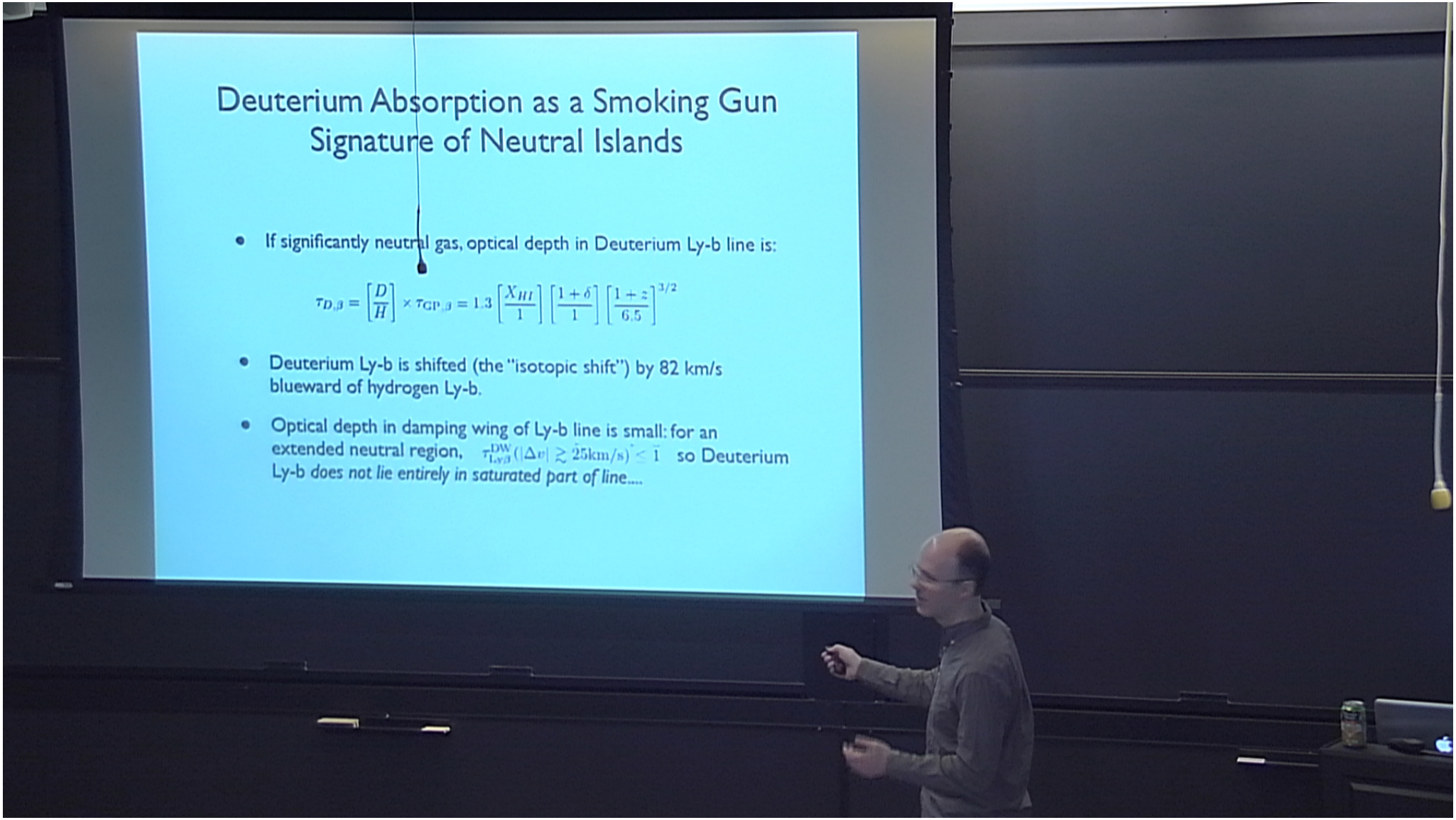
Distribution of Dark Gaps

- Simulated size distribution of dark gaps.
- Neutral regions imprint a large-scale bump in this distribution, making it bi-modal.

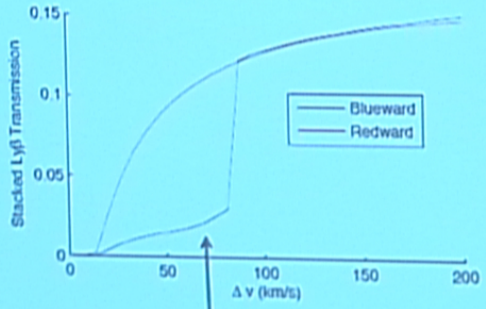


Malloy & Lidz (2014)


Deuterium Absorption as a Smoking Gun Signature of Neutral Islands
If significantly neutral gas, optical depth in Deuterium Ly-b line is:
$\tau_{D,\beta} = \left[\frac{D}{H}\right] \times \tau_{GP,\beta} = 1.3 \left[\frac{X_{HI}}{1}\right] \left[\frac{1+\delta}{1}\right] \left[\frac{1+z}{6.5}\right]^{3/2}$
Deuterium Ly-b is shifted (the "isotopic shift") by 82 km/s blueward of hydrogen Ly-b.
Optical depth in damping wing of Ly-b line is small: for an extended neutral region, $\tau^{DW}_{Ly\beta}(|\Delta v| \gtrsim 25\mathrm{km/s}) \lesssim 1$ so Deuterium Ly-b does not lie entirely in saturated part of line....

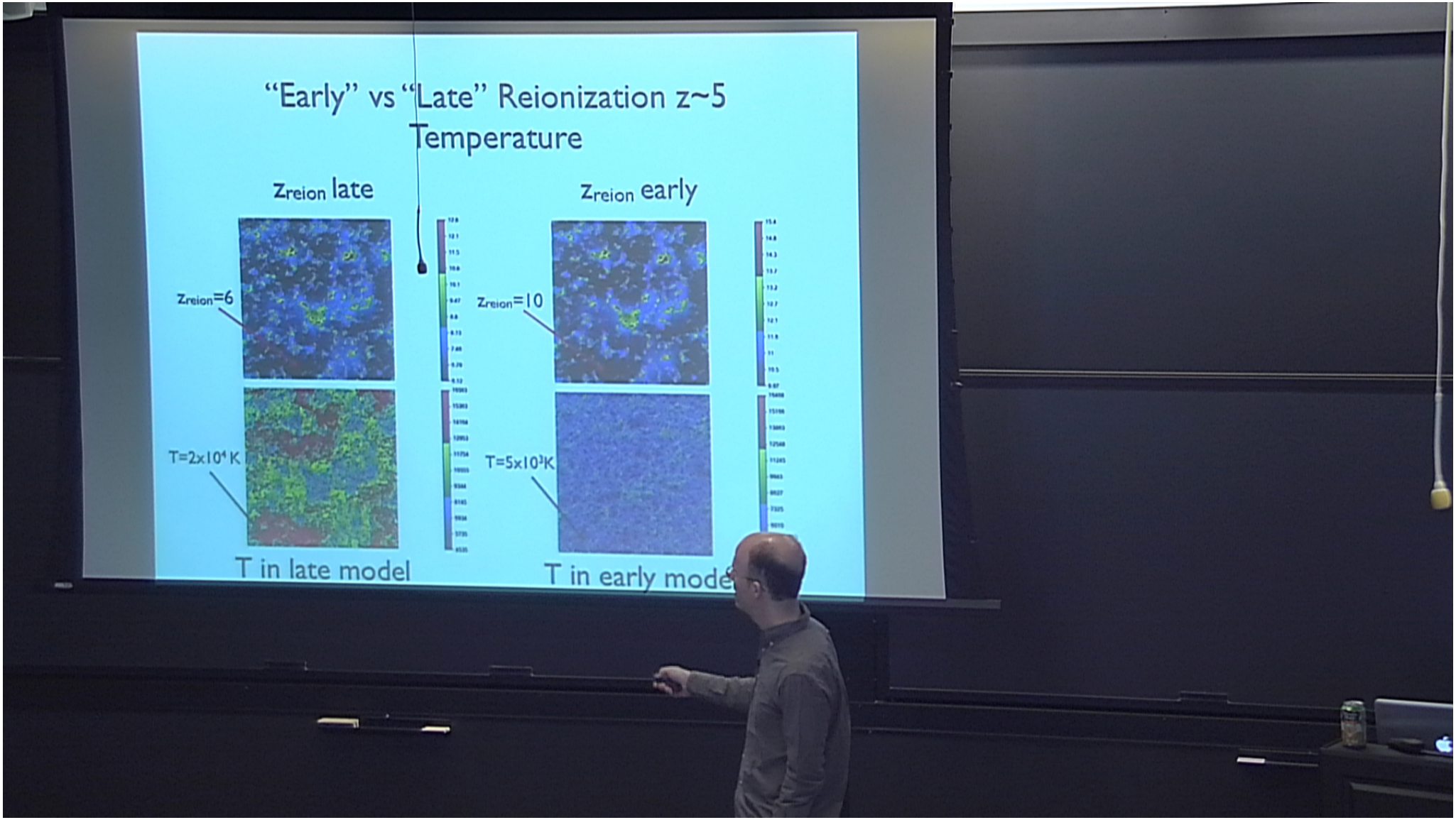
Deuterium Ly-b feature: idealized case

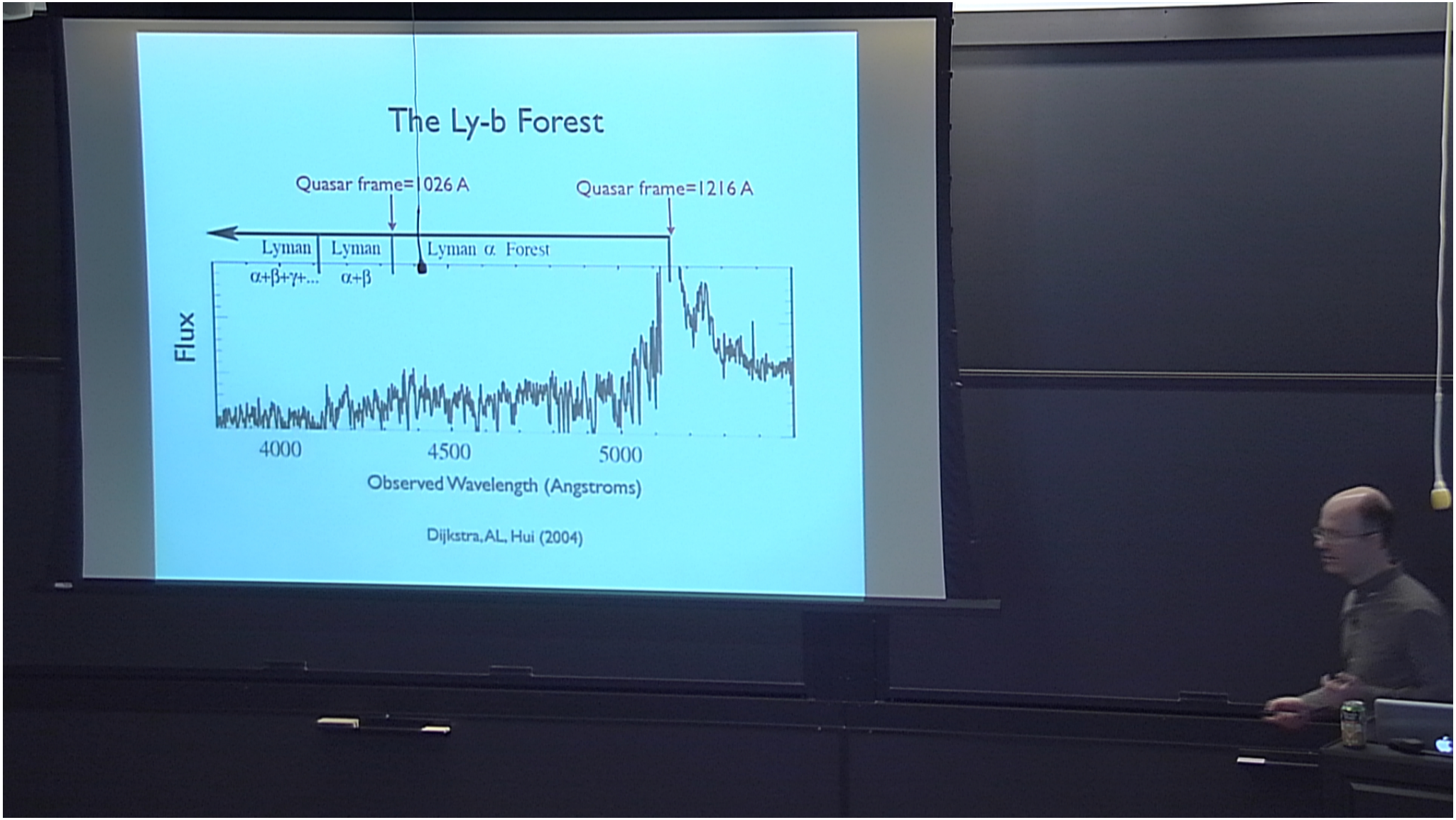
- Idealized stacking of isolated, mean density neutral regions...
- Deuterium Ly-b produces slight excess on blue side of saturated neutral regions compared to red side. Out to 82 km/s. (Blue/red asymmetry...)
- Only present if significantly neutral regions remain.



Excess from Deuterium Ly-b

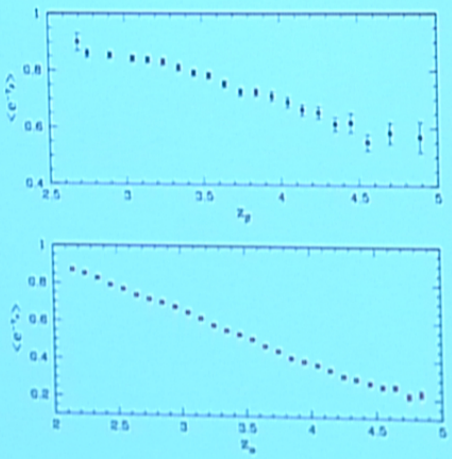
Malloy & Lidz (2014)


"Early" vs "Late" Reionization z~5
Temperature
Zreion late
Zreion early
Zreion=6
Zreion=10
T=2x10⁴ K
T=5x10³K
T in late model
T in early mode


The Ly-b Forest
Quasar frame=1026 A
Quasar frame=1216 A
Lyman
Lyman
Lyman α Forest
α+β+γ+...
α+β
Flux
4000
4500
5000
Observed Wavelength (Angstroms)
Dijkstra, AL, Hui (2004)

Measurement in progress….

- 60 high resolution spectra from Keck/Magellan.
- 100,000 quasar spectra from SDSS/BOSS. Basic method developed by Bernardi et al. (2002).
- We will use this to constrain trend of temperature with density.

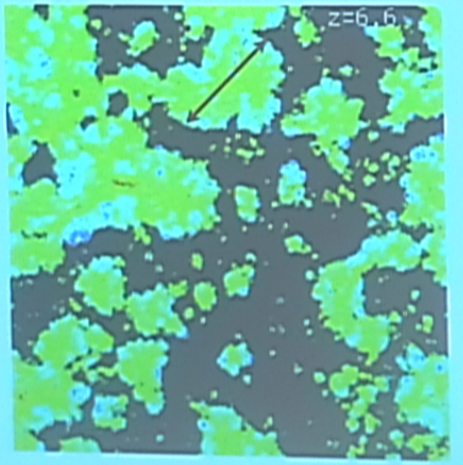


Preliminary!

Passaglia, AL+ (in prep)

But how about the bubble sizes?

- How do we get this from observations?

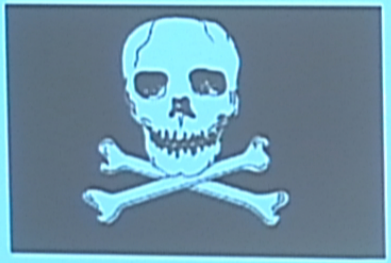


300 Million light years

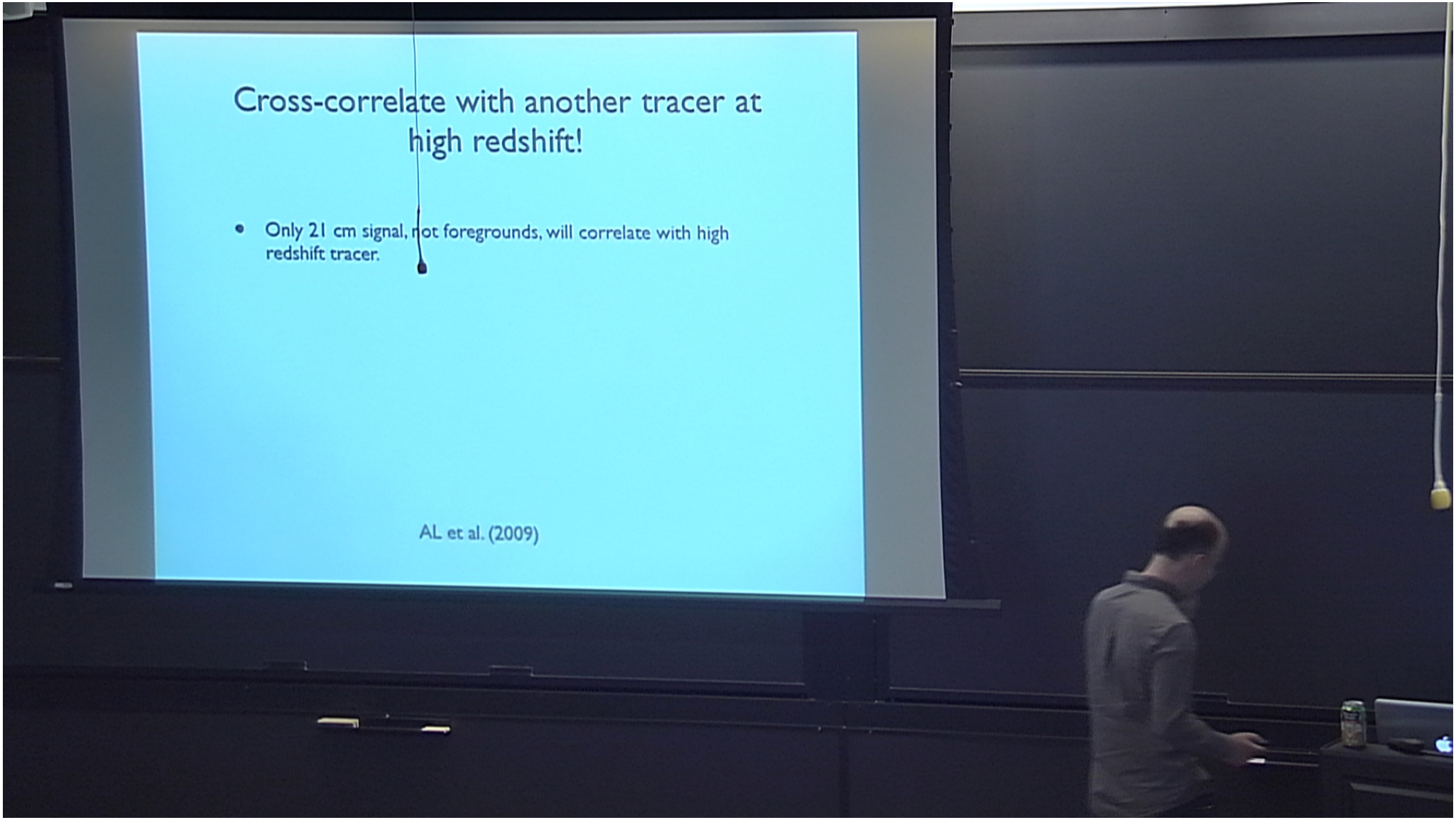
McQuinn, AL+ (2007)

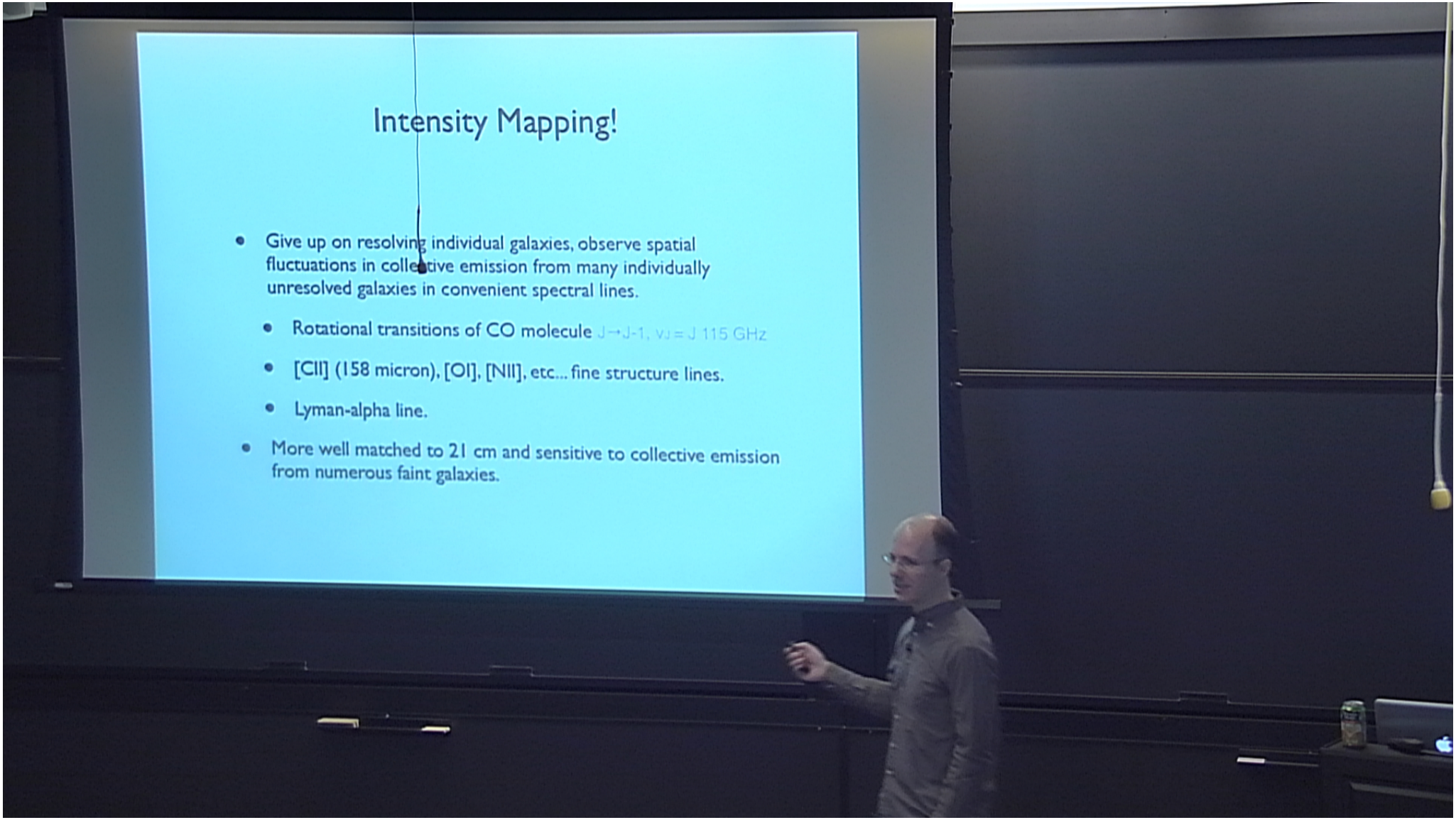
Foregrounds!

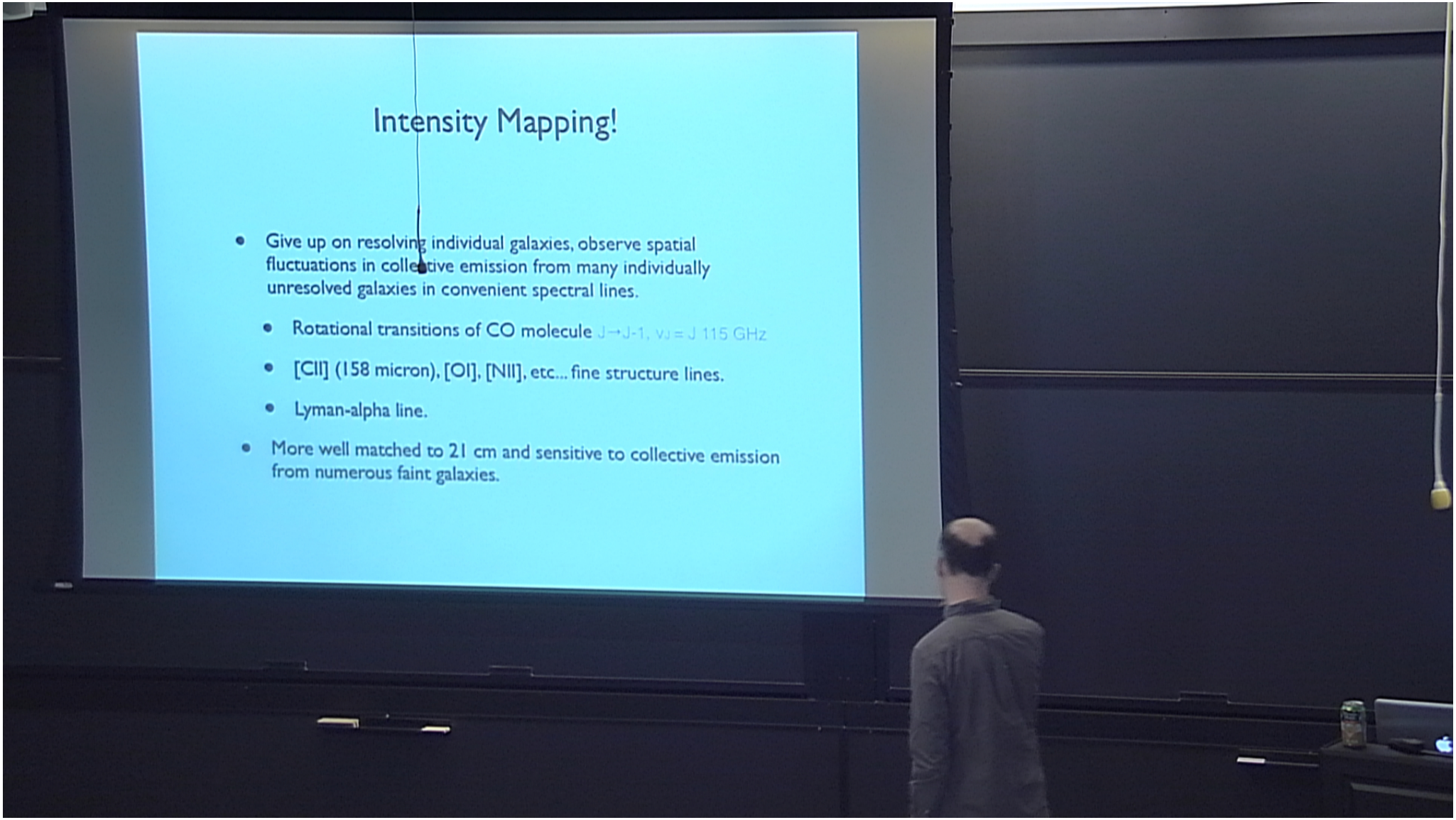
- ~Four orders of magnitude larger than signal!



How do we convince ourselves an initial detected signal is real and not residual foregrounds?


Cross-correlate with another tracer at high redshift!
Only 21 cm signal, not foregrounds, will correlate with high redshift tracer.
AL et al. (2009)


Intensity Mapping!
Give up on resolving individual galaxies, observe spatial fluctuations in collective emission from many individually unresolved galaxies in convenient spectral lines.
Rotational transitions of CO molecule J→J-1, νJ = J 115 GHz
[CII] (158 micron), [OI], [NII], etc... fine structure lines.
Lyman-alpha line.
More well matched to 21 cm and sensitive to collective emission from numerous faint galaxies.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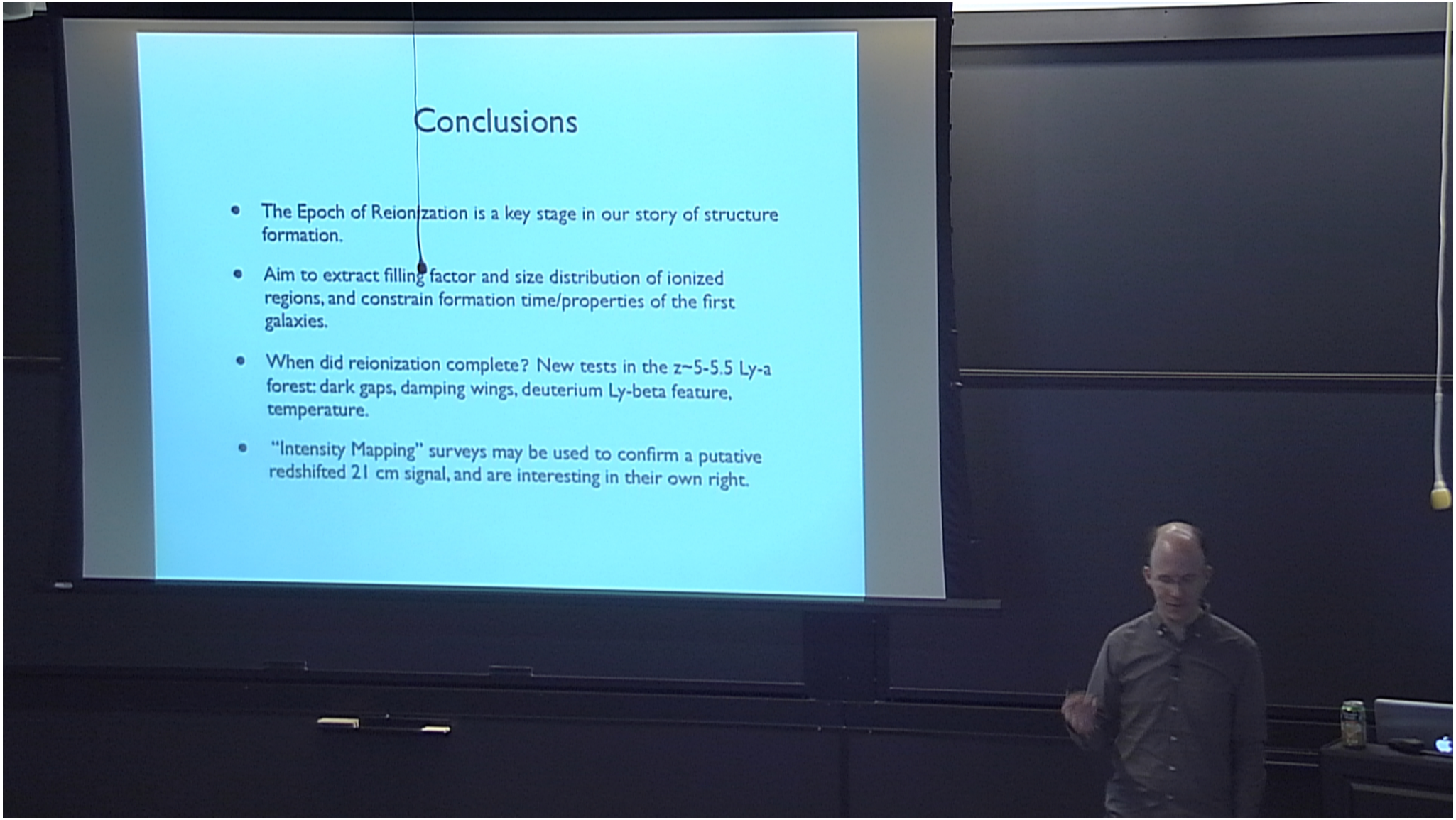
Conclusions
The Epoch of Reionization is a key stage in our story of structure formation.
Aim to extract filling factor and size distribution of ionized regions, and constrain formation time/properties of the first galaxies.
When did reionization complete? New tests in the z~5-5.5 Ly-a forest: dark gaps, damping wings, deuterium Ly-beta feature, temperature.
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