An Overview of Cosmological Reionization

Steven Furlanetto
UCLA
February 13, 2012

Outline

- *Theoretical models of reionization*

  - *"Photon-counting" and the emissivity*

  - *Recombinations and clumping*

- *Observations of reionization: What we "know"*

- *Photoheating*

  - *Potential measurements*

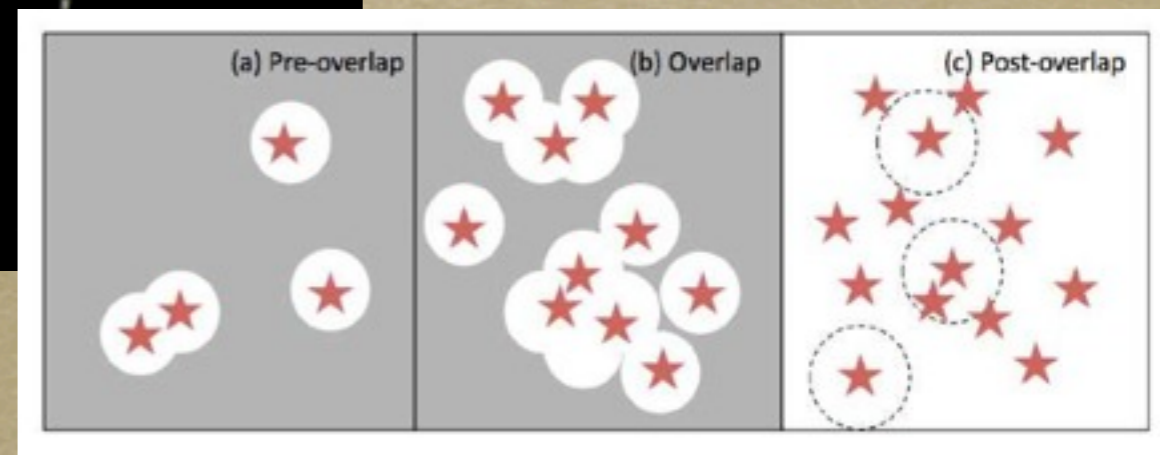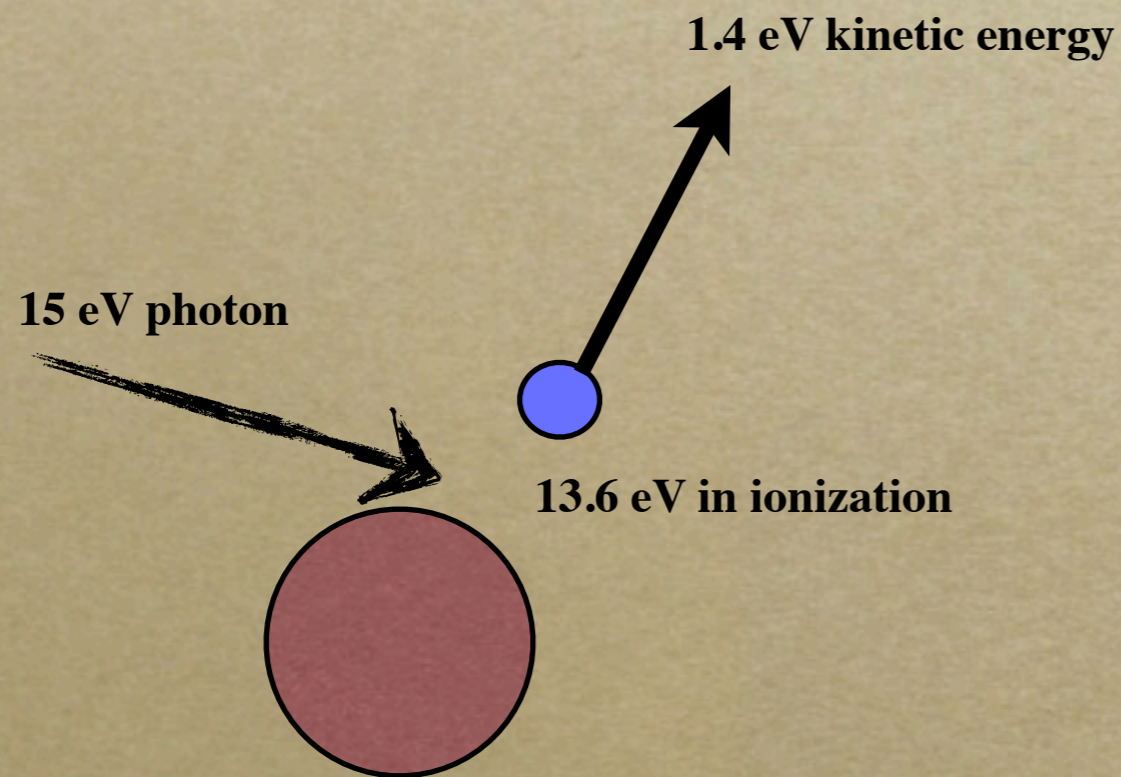 - *Some implications*

H I Reionization: The Movie


M. Alvarez

H I Reionization: The Movie

M. Alvarez

(a) Pre-overlap (b) Overlap (c) Post-overlap

Photoheating During Reionization

1.4 eV kinetic energy

15 eV photon

13.6 eV in ionization

- *Each ionization deposits several eV in IGM*

- *Expect >10,000 K heating during reionization*

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*
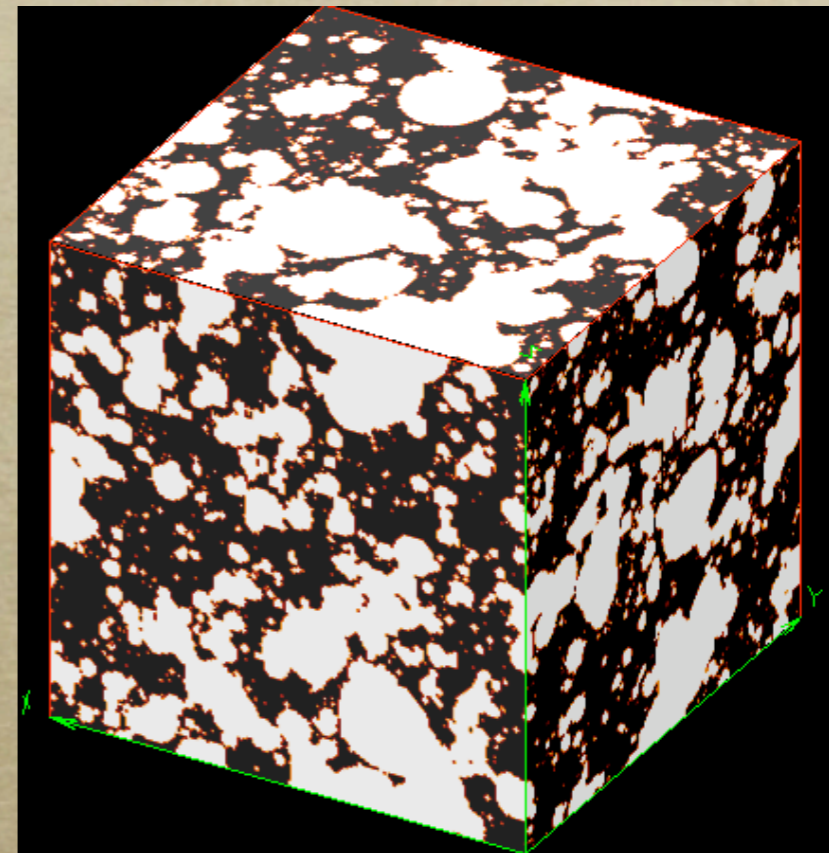
Mesinger & Furlanetto (2007)

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*
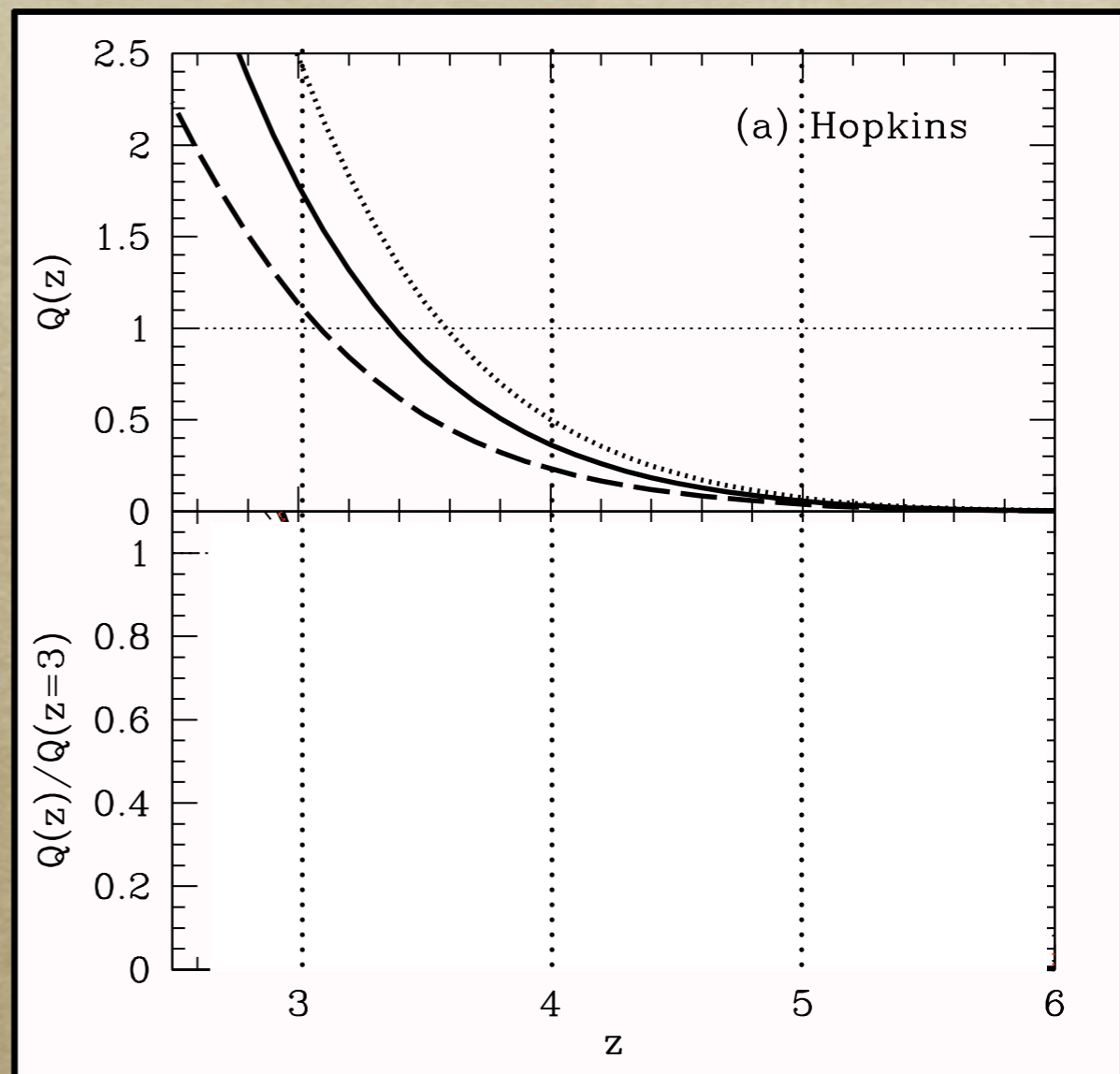
Furlanetto & Oh (2008)
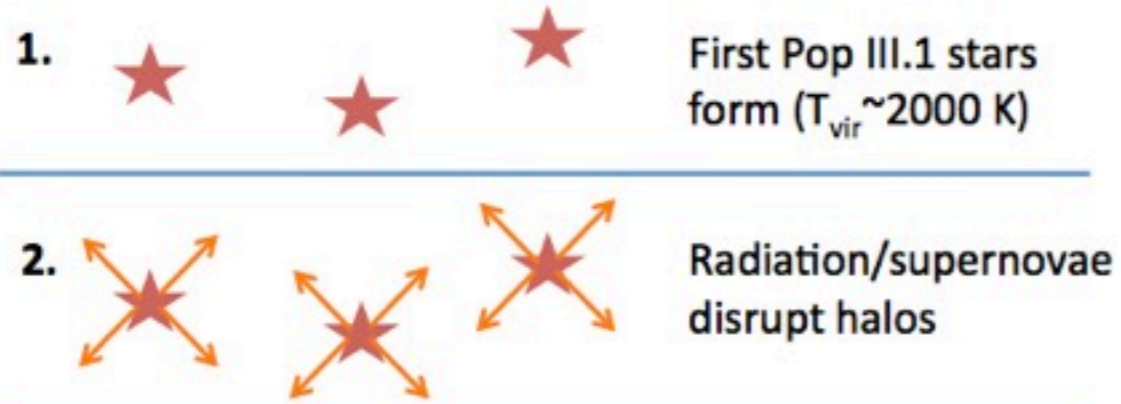
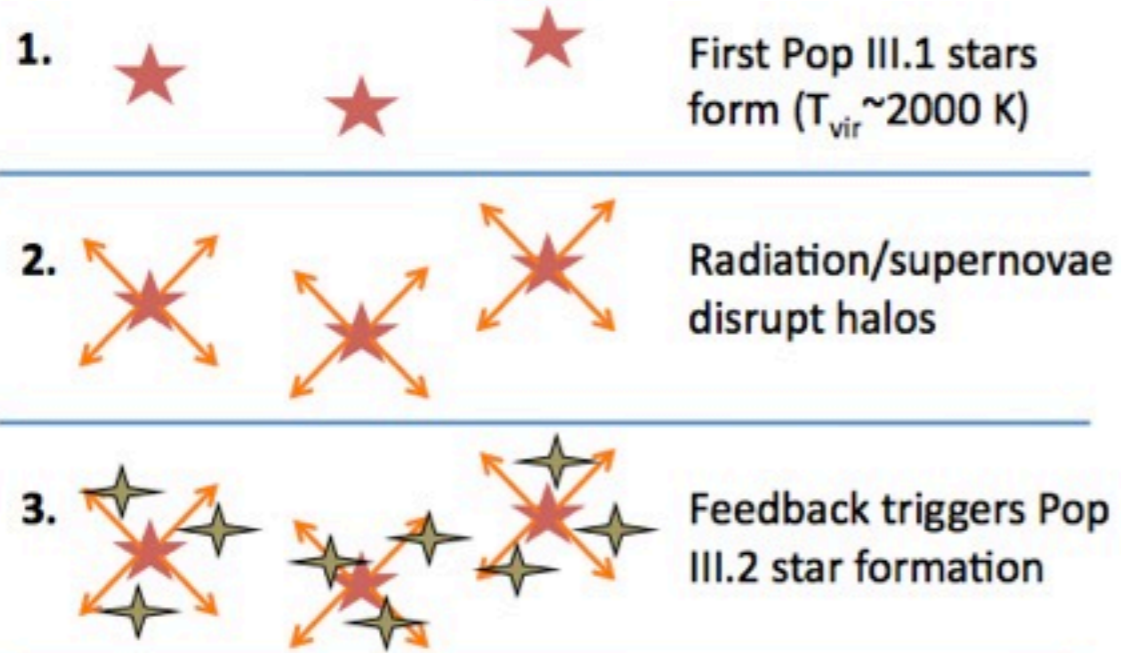# What's So Hard About the Emissivity?
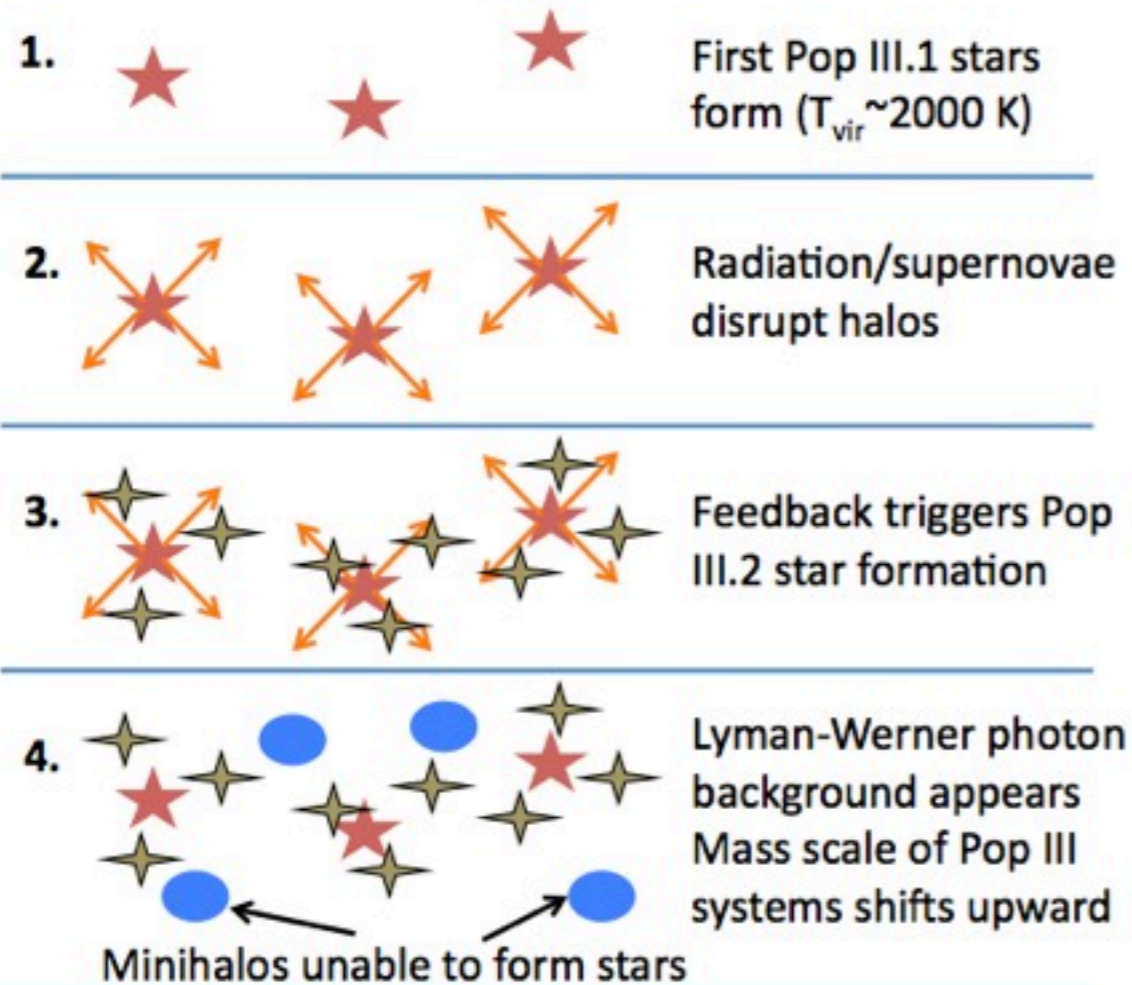
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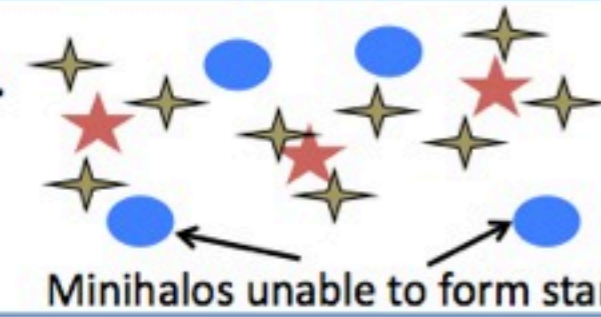
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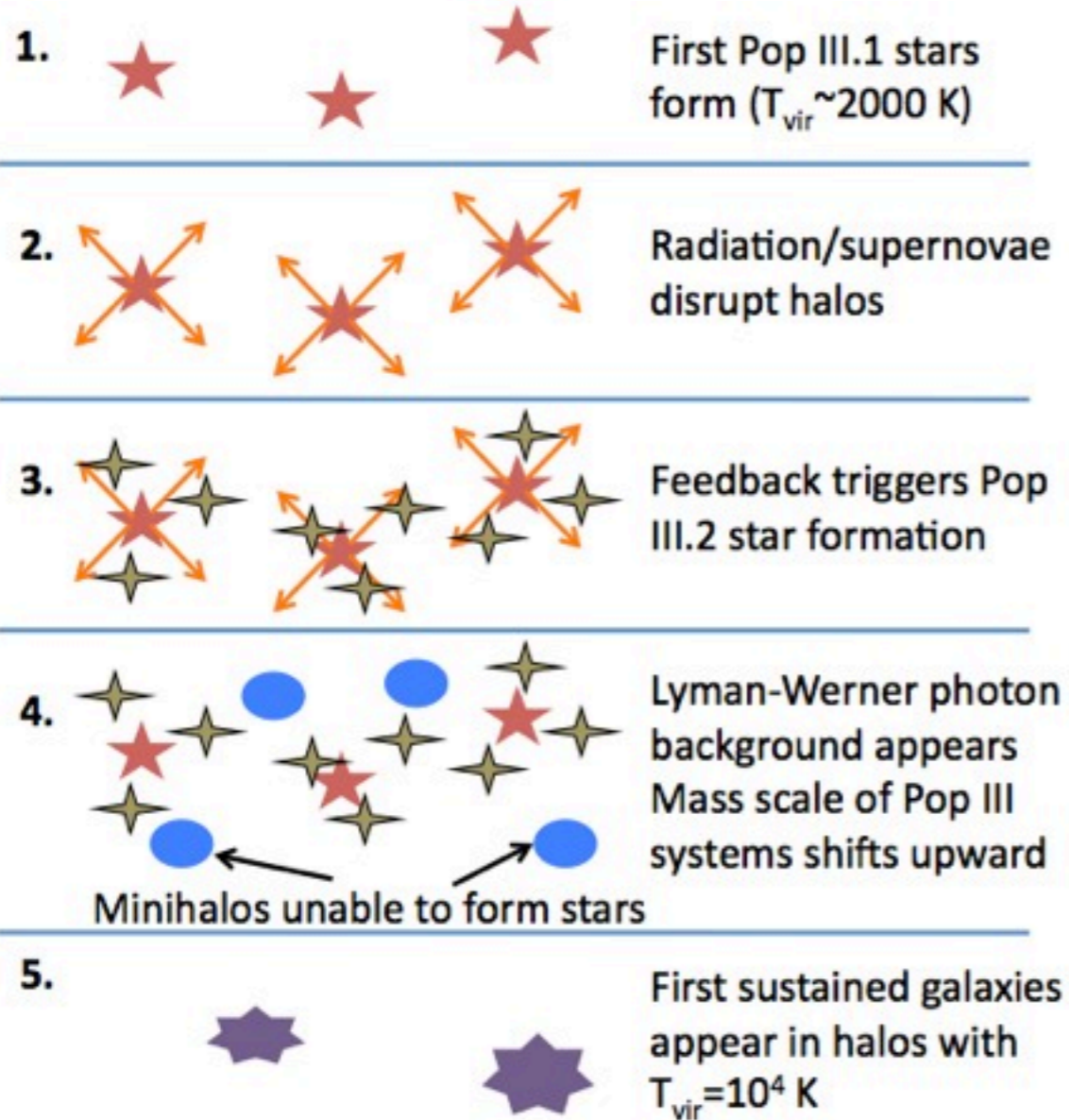   Mass scale of Pop III systems shifts upward

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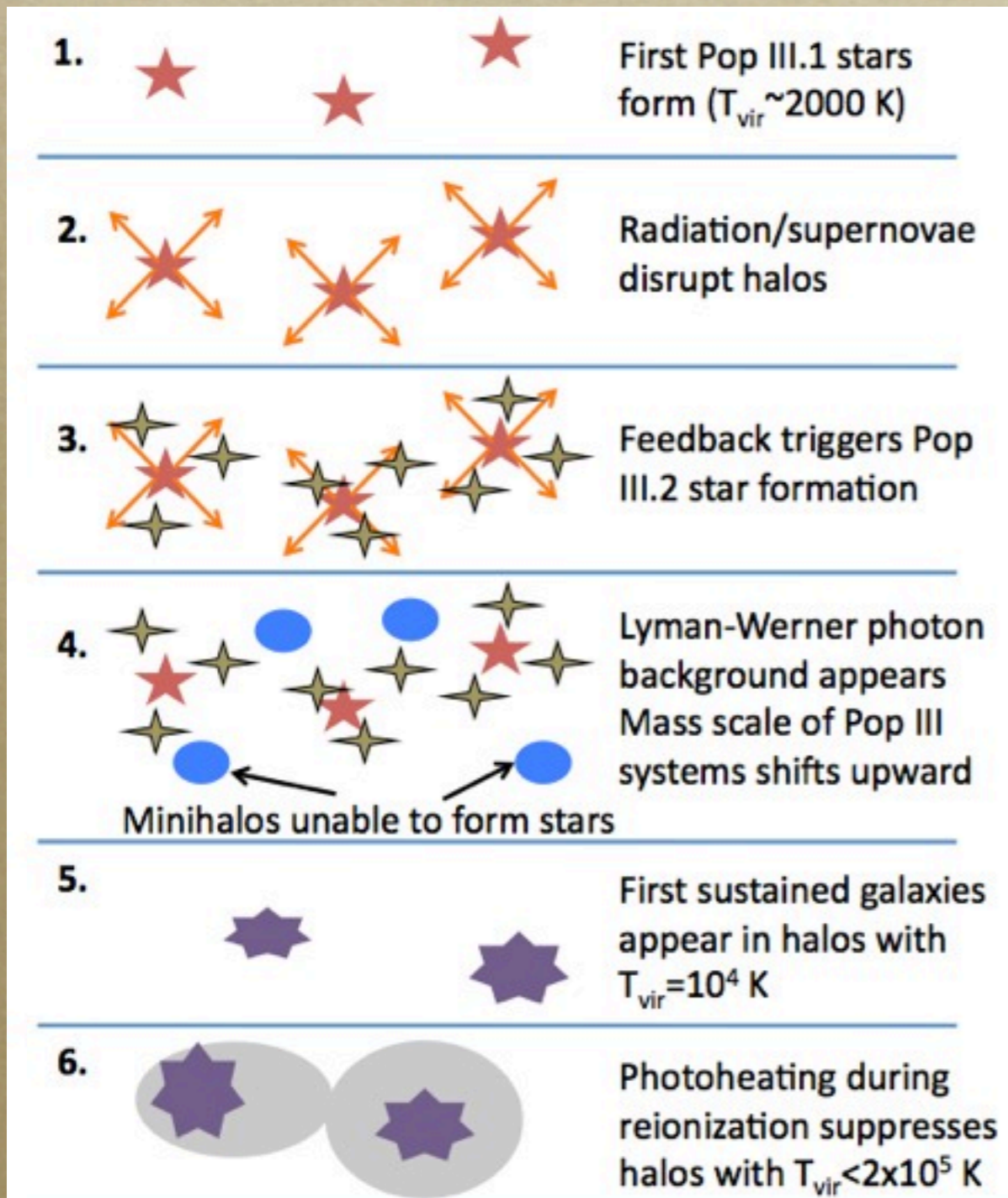

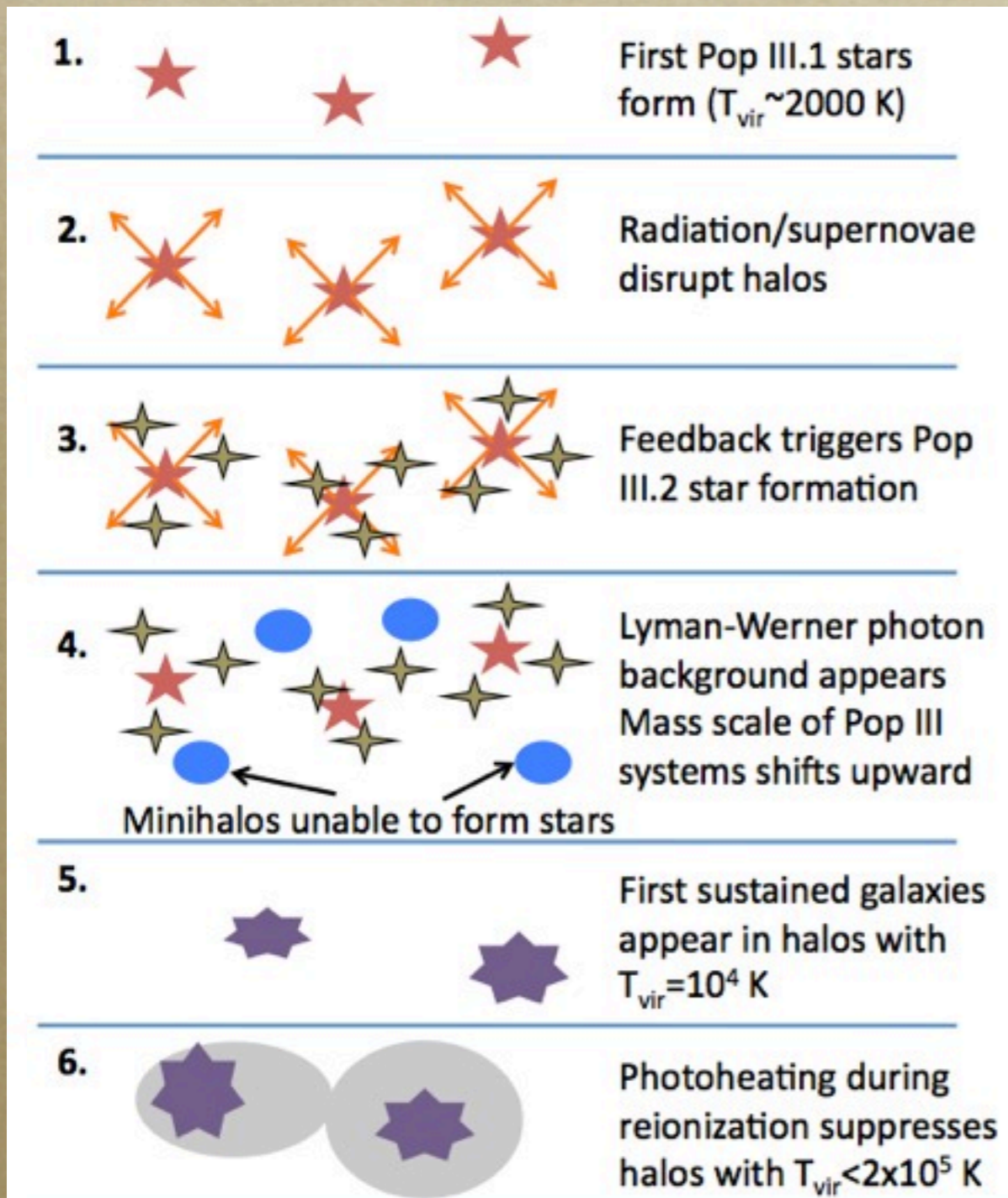1. First Pop III.1 stars form ($T_{vir} \sim 2000$ K)

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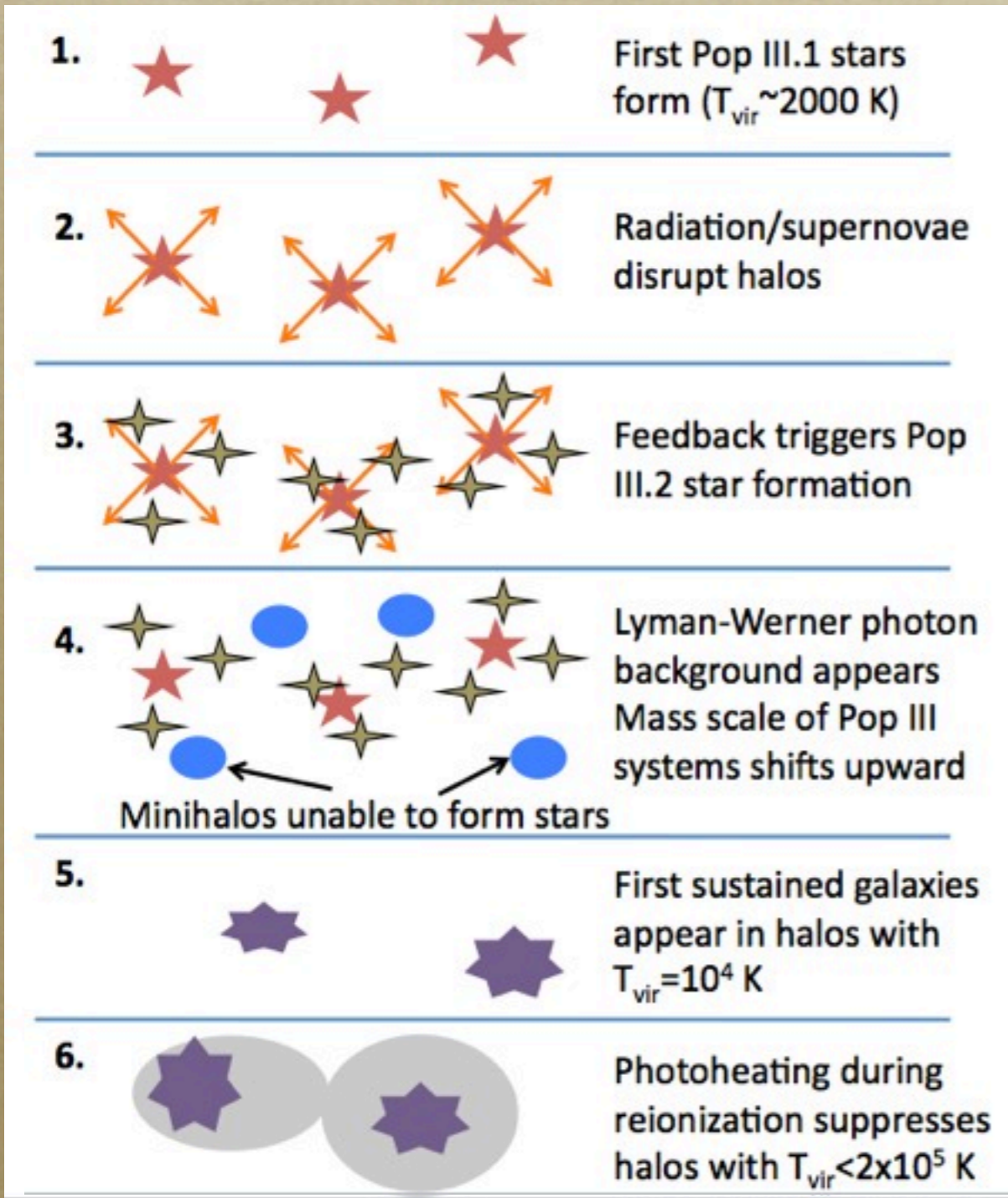
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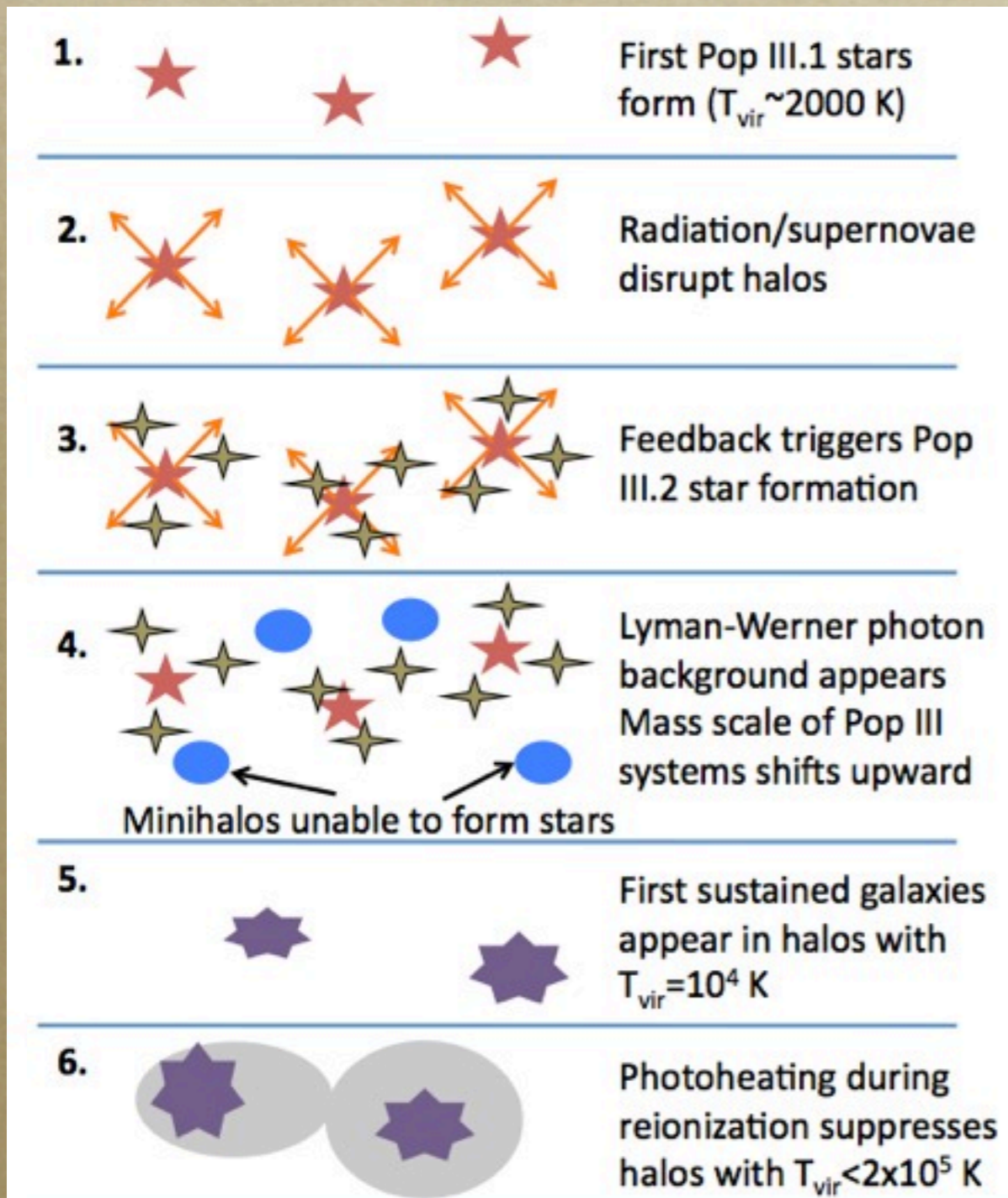
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7

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  - *Escape fraction of UV photons*

Modeling High-z Galaxies

- *Basic Picture: Gas inflow balanced by star formation and winds*

- *Comparison to observed luminosity function depends on:*

  - *Accretion rate*

  - *Wind loading*

  - *Dust*
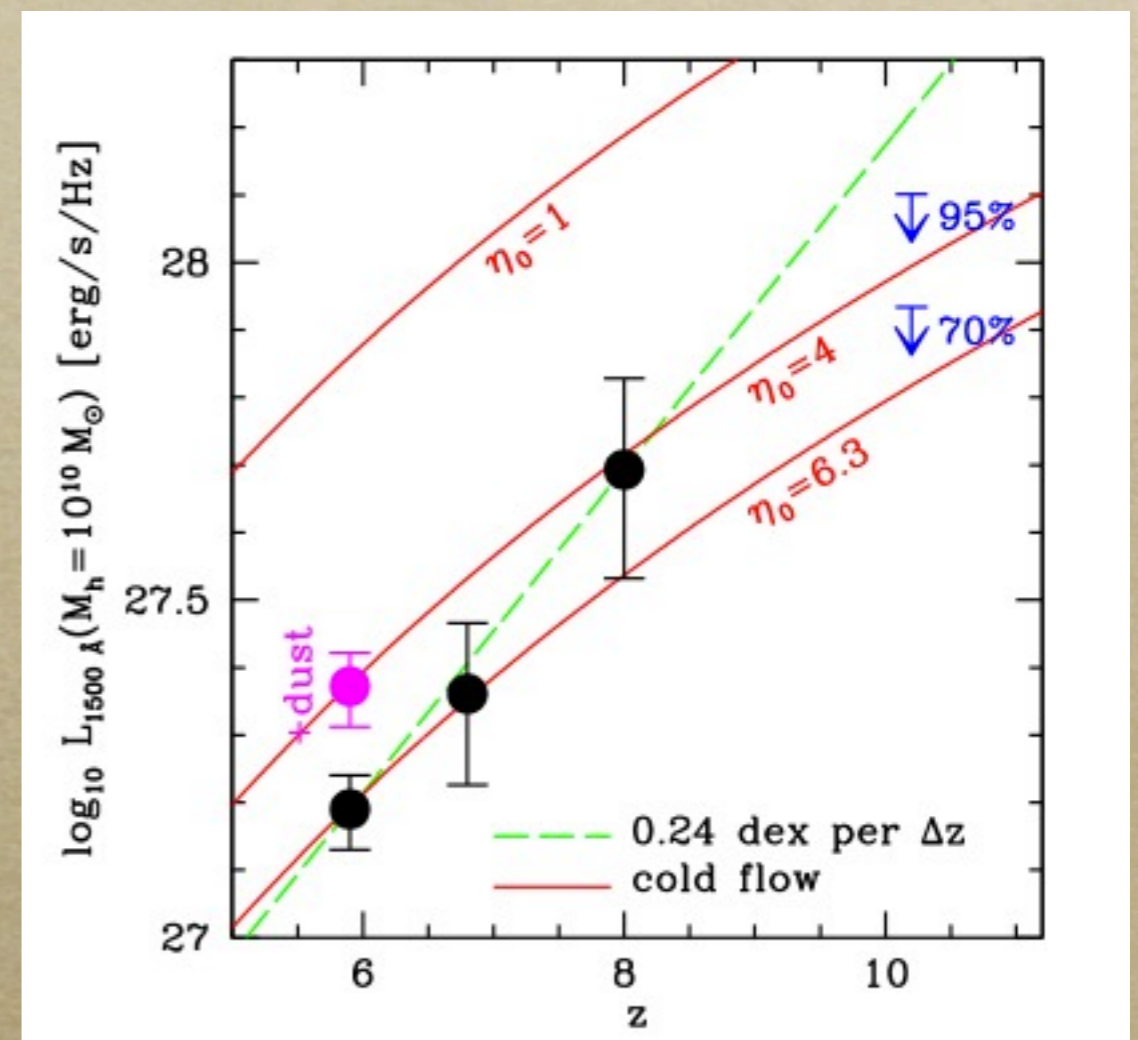
Munoz (2012)

Modeling High-z Galaxies

Thin: Gas accretion rate
Thick: SFR

m=0.2
β=0.01
α=0.3

log Ṁ, SFR [M⊙/yr]

r/pc
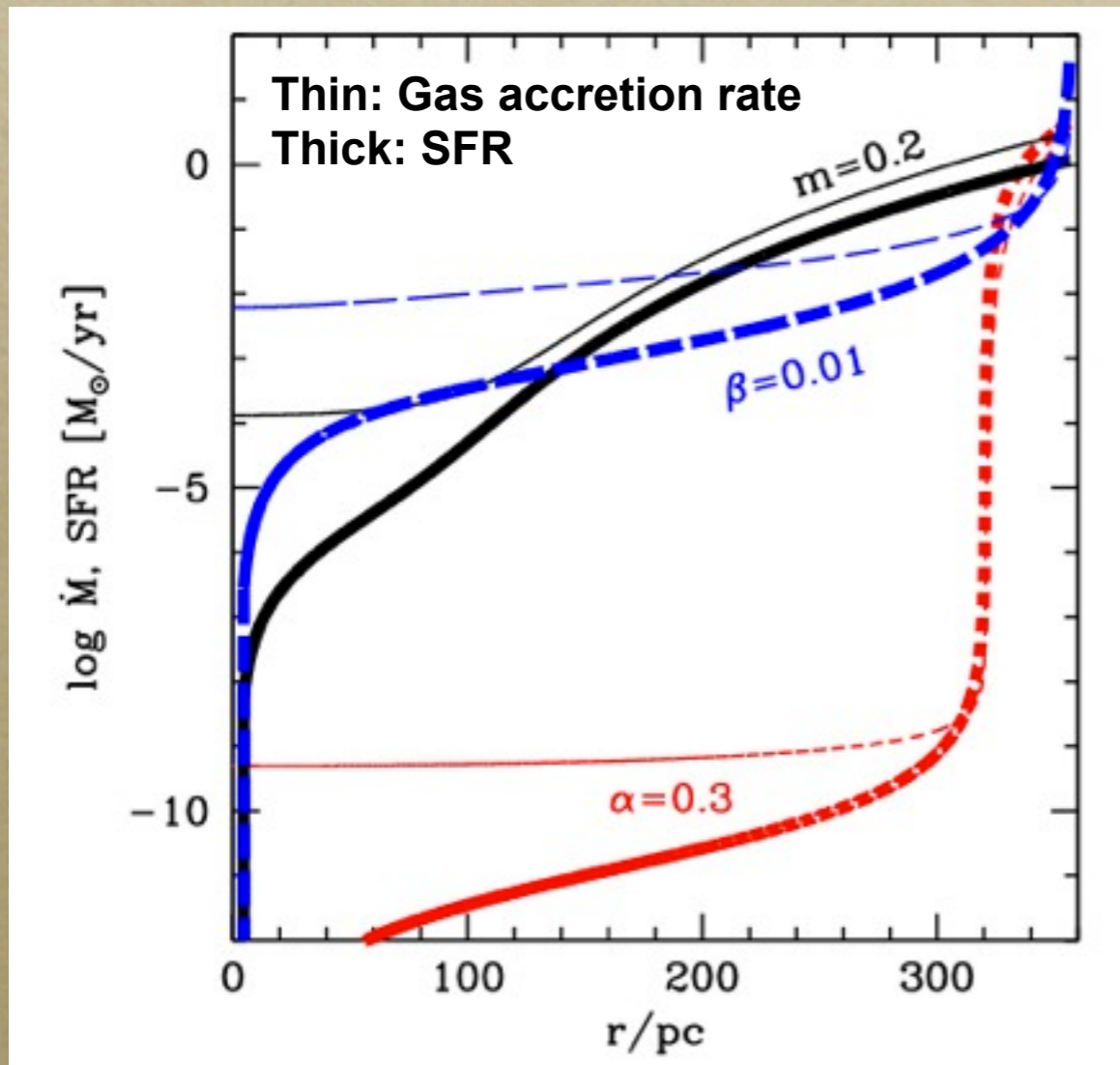
Munoz & Furlanetto (2012)

- *Basic picture*
  - *Star formation when Toomre Q~1*
  - *Leftover gas forms BH*
- *Key parameter: rate of gas transport through disk*

Photon Counting

- *Assume galaxies have fixed ionizing efficiency*
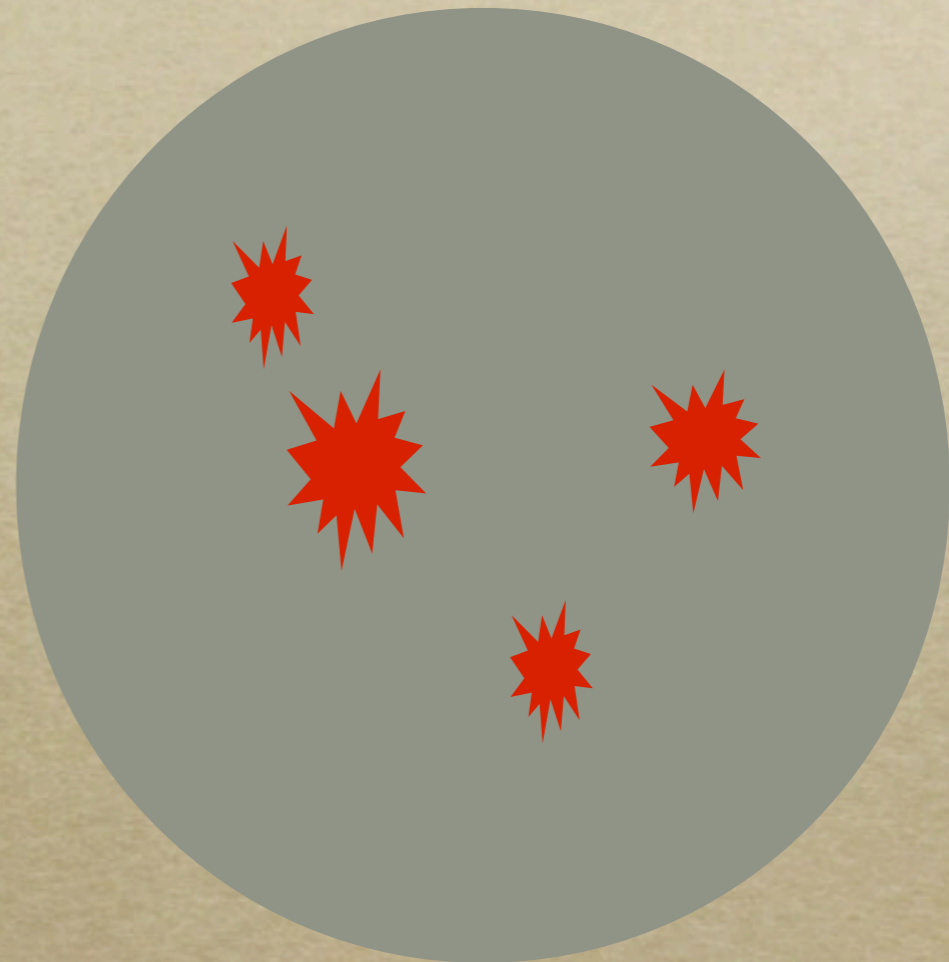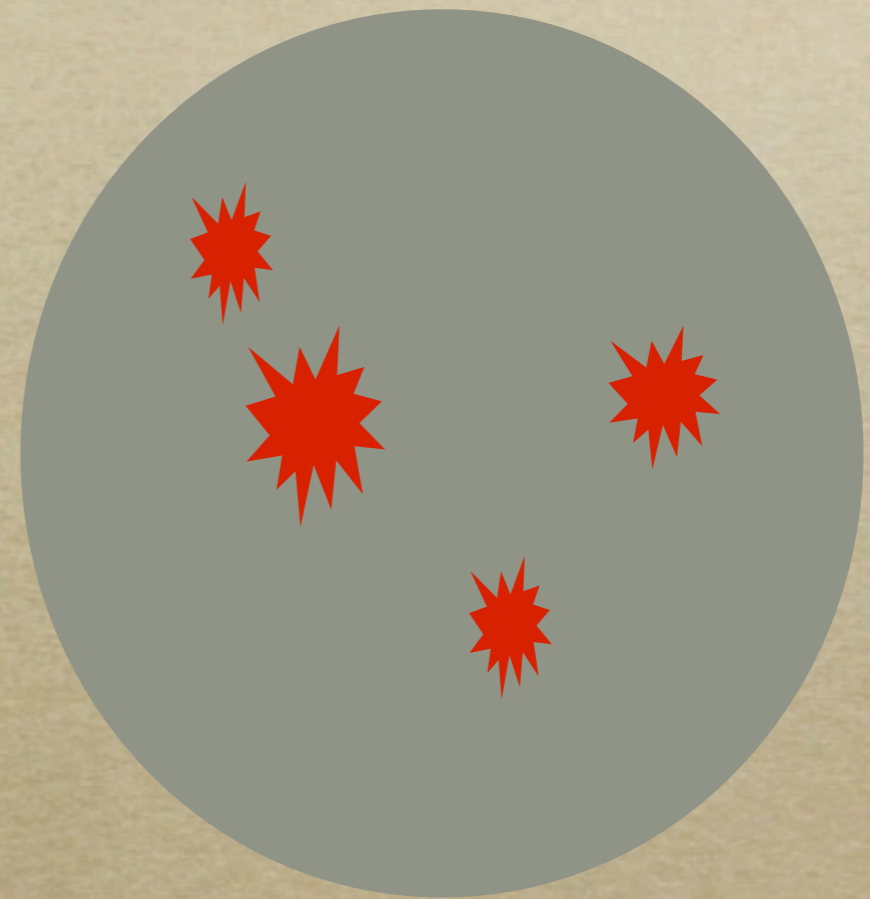- *Isolated galaxies generate HII regions*
- *Clustered galaxies work together*

Ionized IGM

Galaxy

Neutral IGM

# Photon Counting

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Bubble Sizes: H I Reionization

- *Bubbles grow throughout reionization*

- *Driven by source clustering: massive halos, big bubbles*

- *LOTS of sources per bubble*
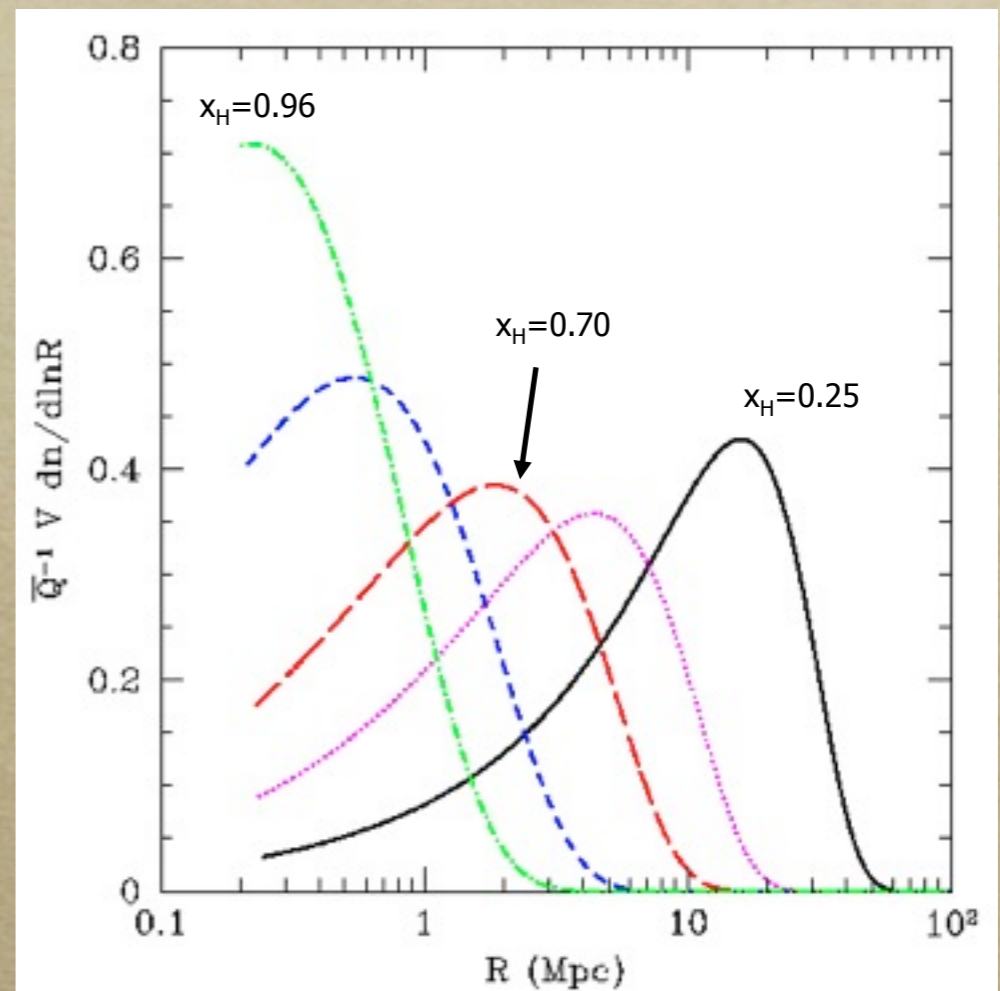
Reionization: Galaxy Populations
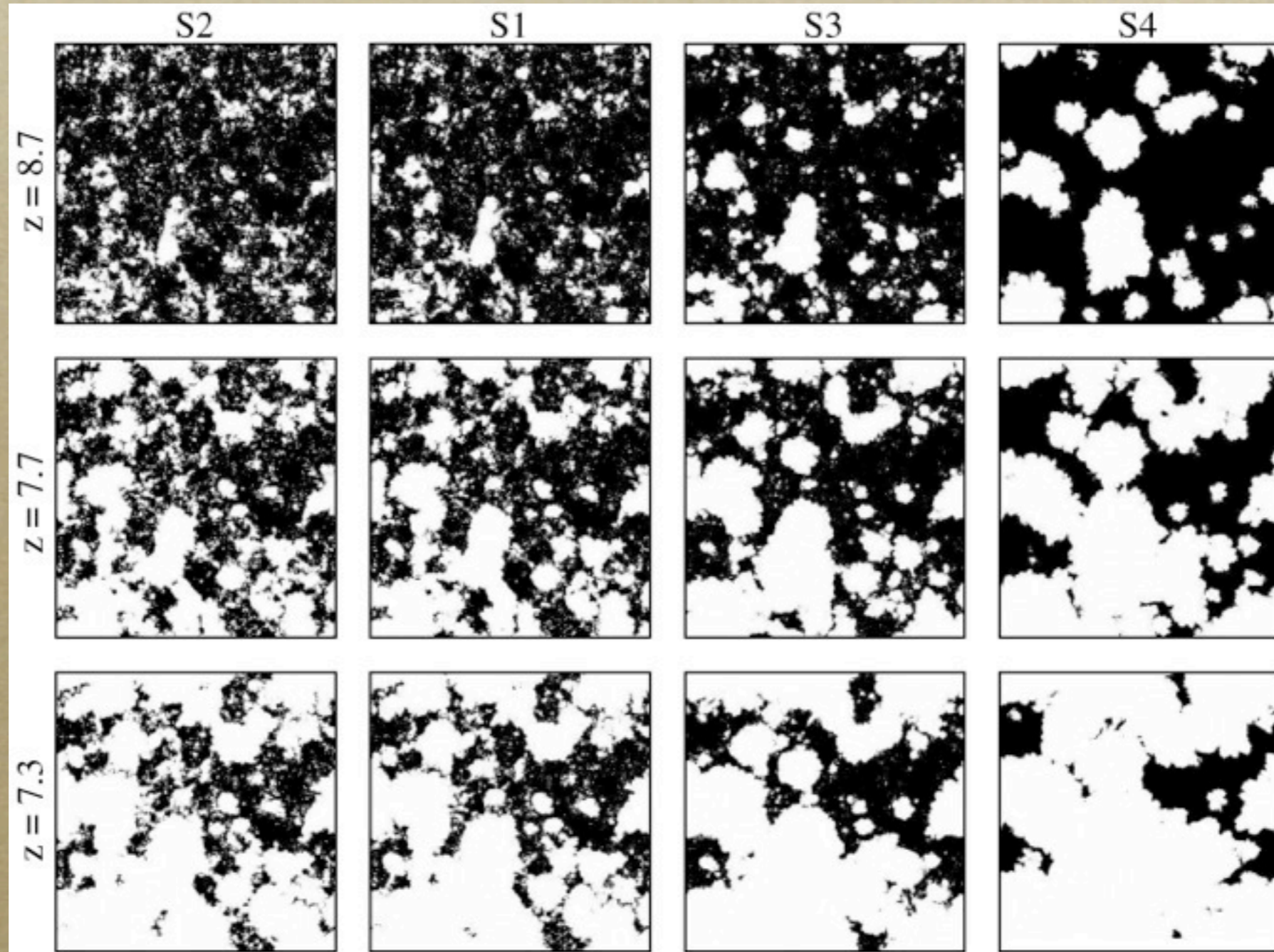
McQuinn et al. (2007); Furlanetto et al. (2004)

When Was Reionization? (Ia)

- *Precise timing depends on recombination rate*

- *Parameterized crudely by "clumping factor:" enhancement relative to uniform IGM from clumping:*

  - $C = \langle n^2 \rangle / \langle n \rangle^2$
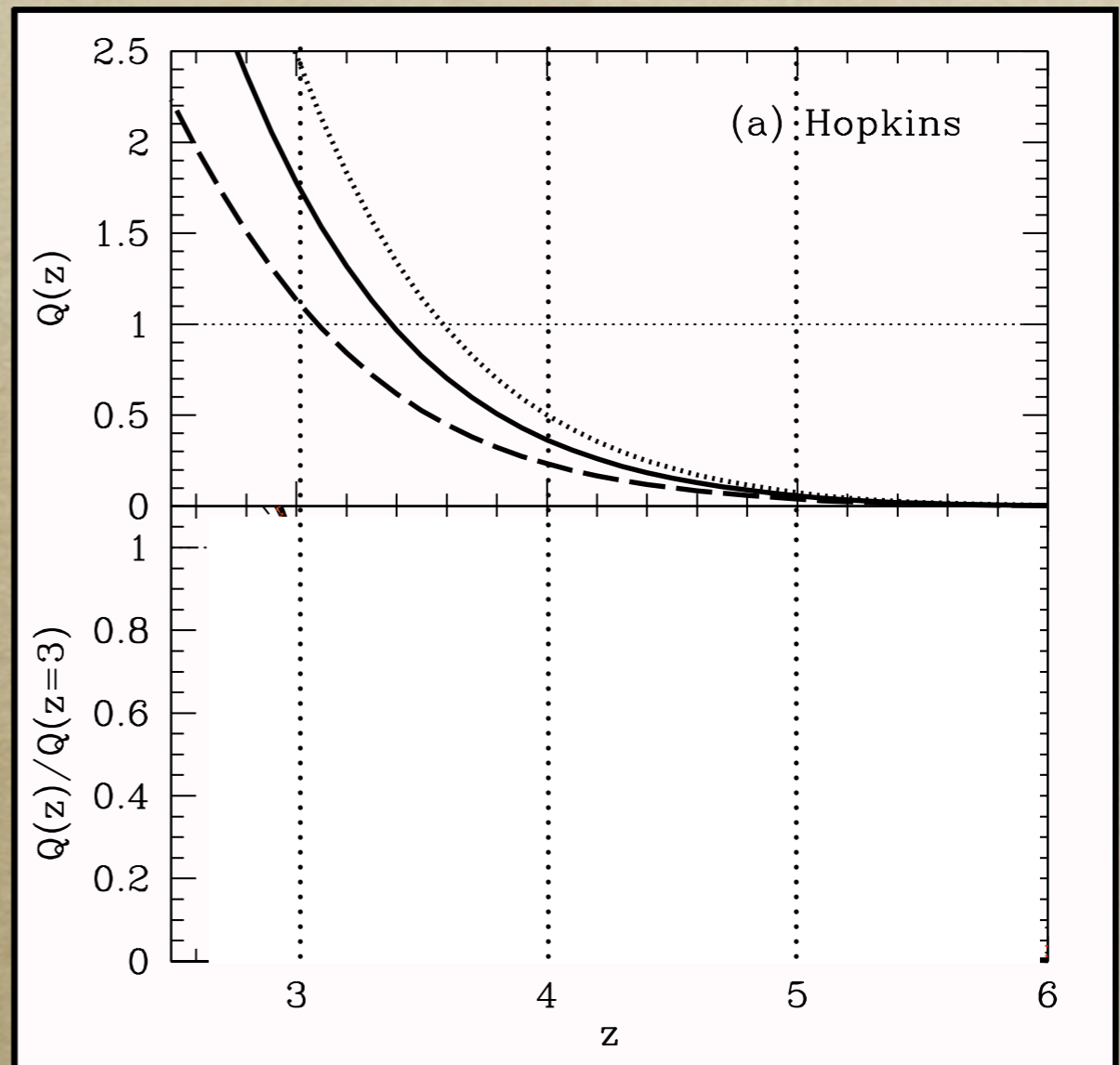
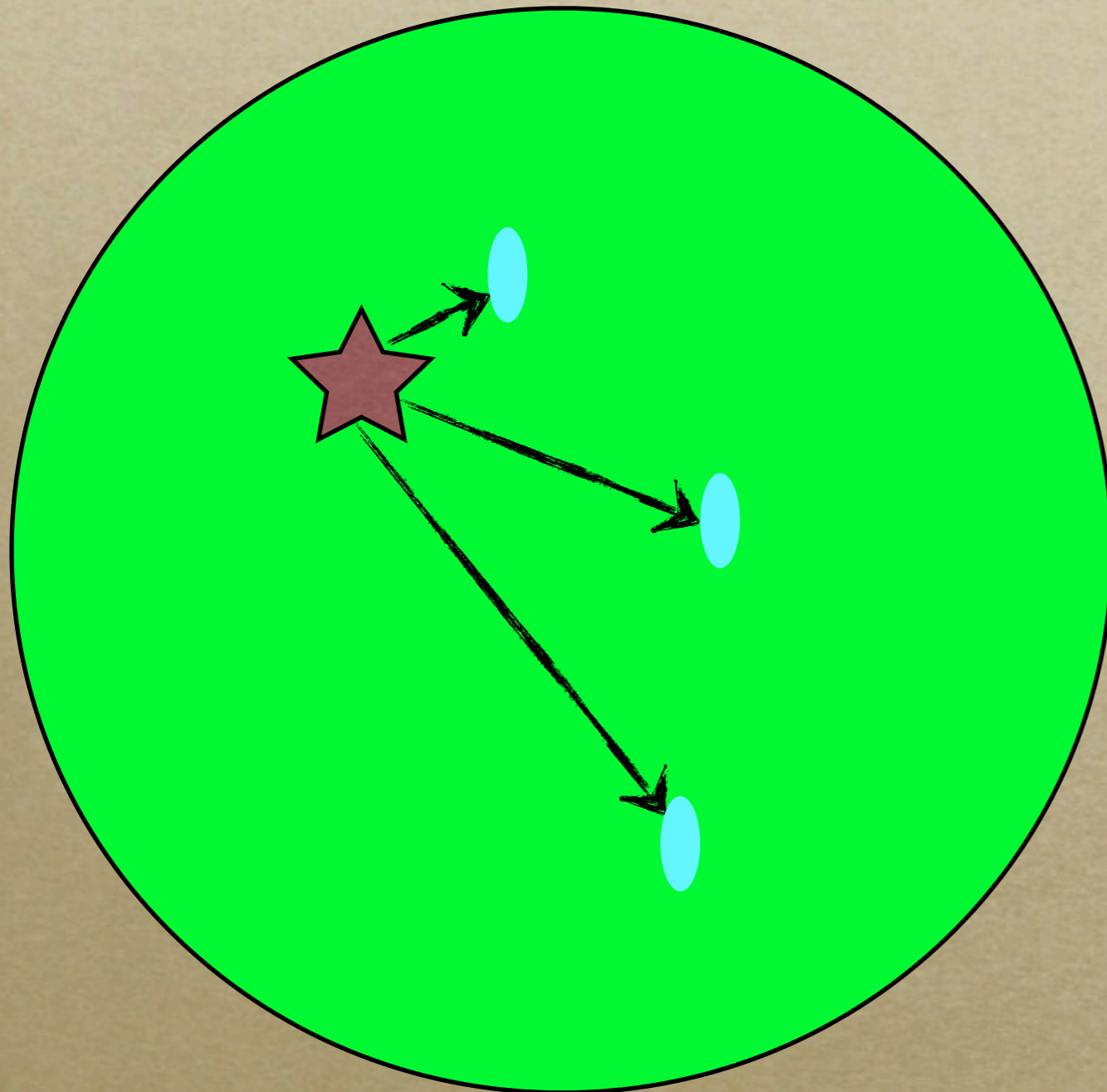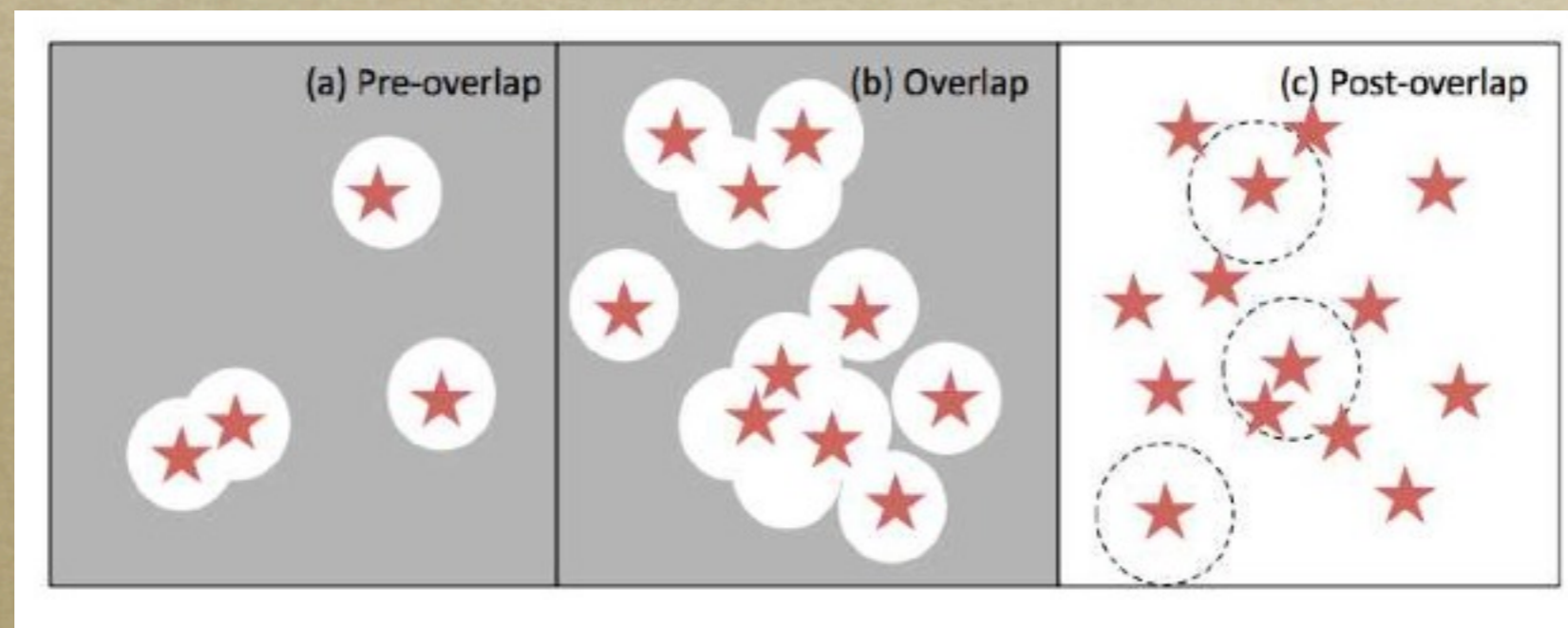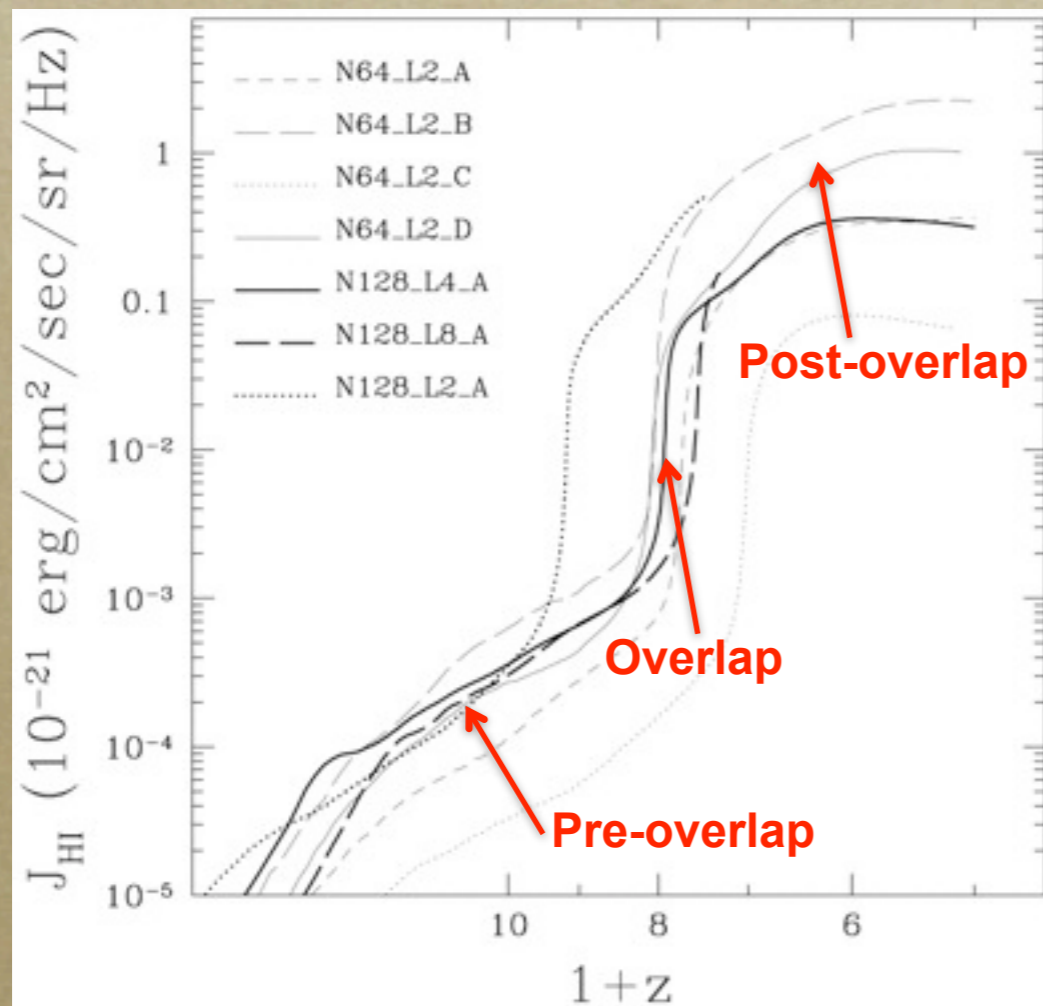**Furlanetto & Oh (2008)**

The Reionization Process II
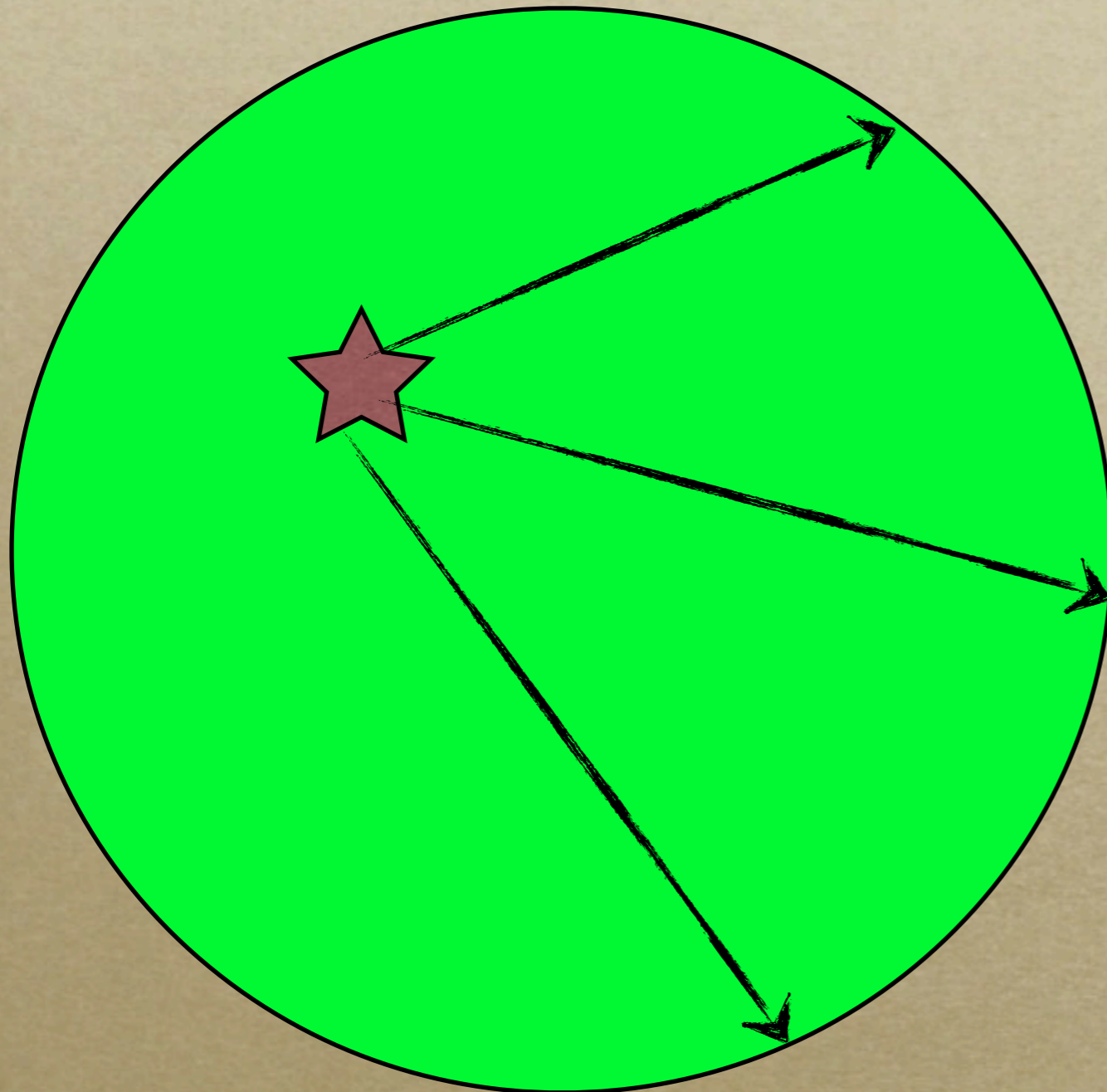
- *Most recombinations are inside "Lyman-limit systems"*

- *Matters once (size of bubble) > (attenuation length)*

- *Controls post-reionization paths*

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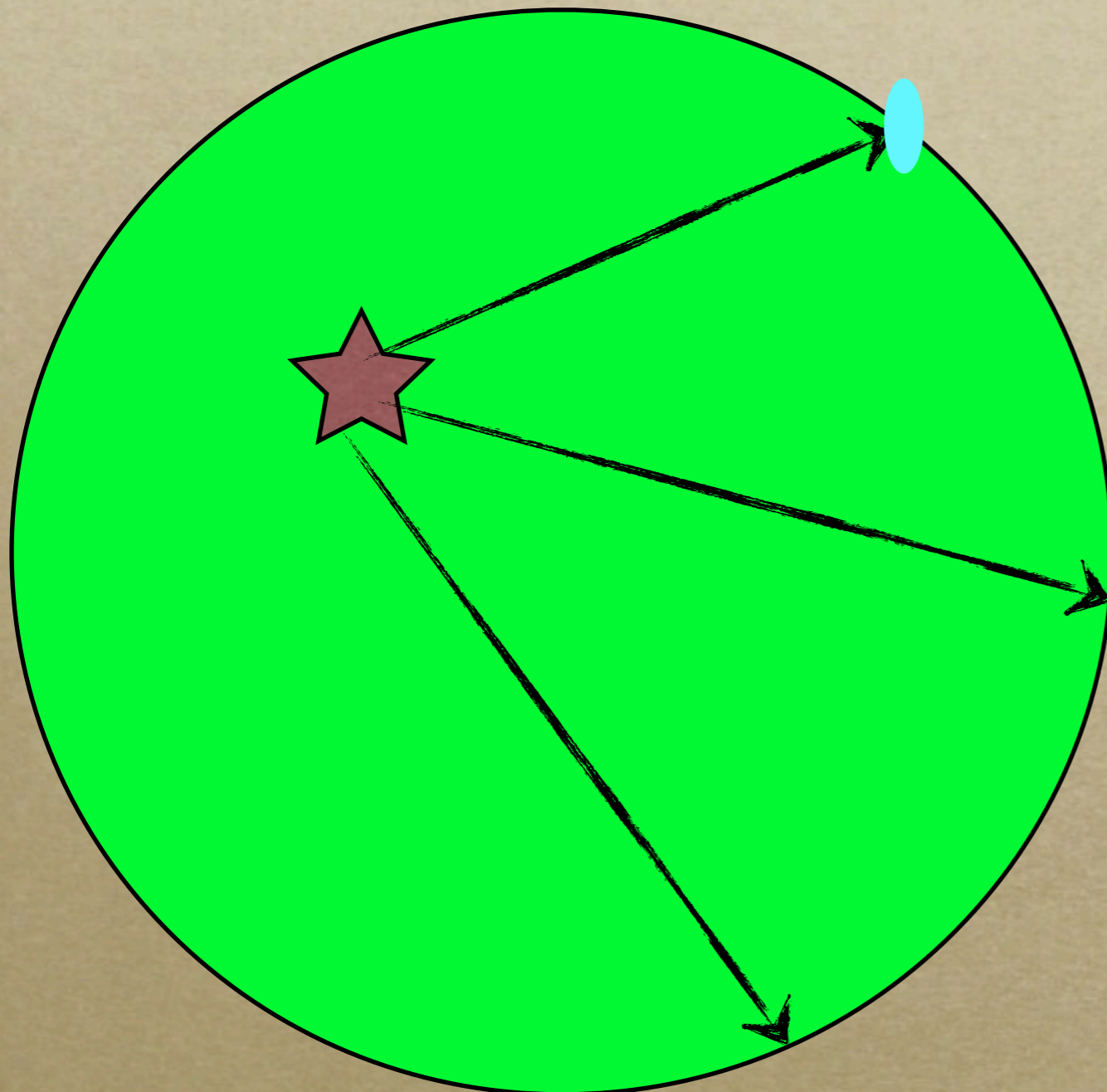
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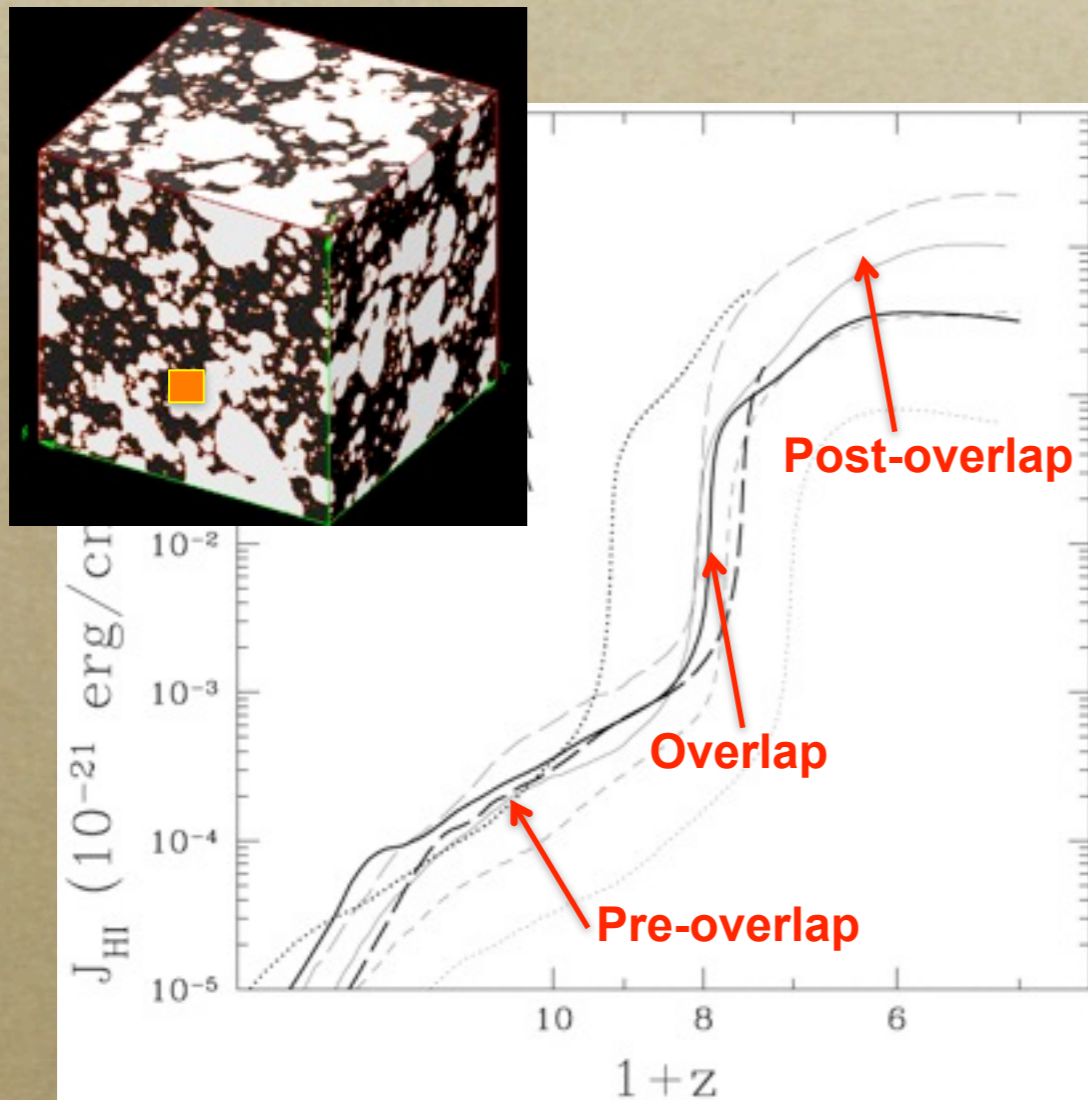- *Controls post-reionization paths*
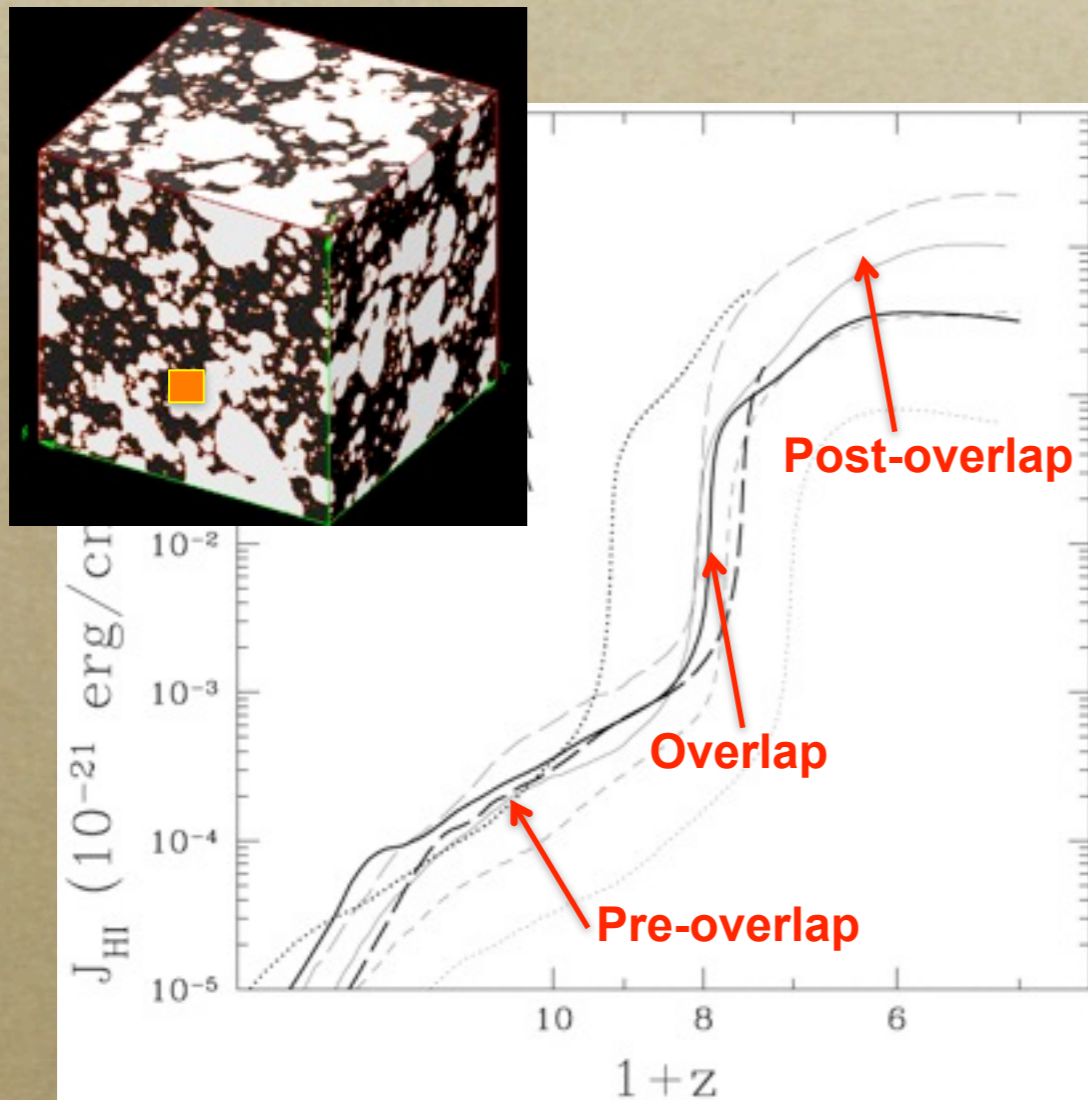
The Phases of Reionization

The Meaning of Overlap
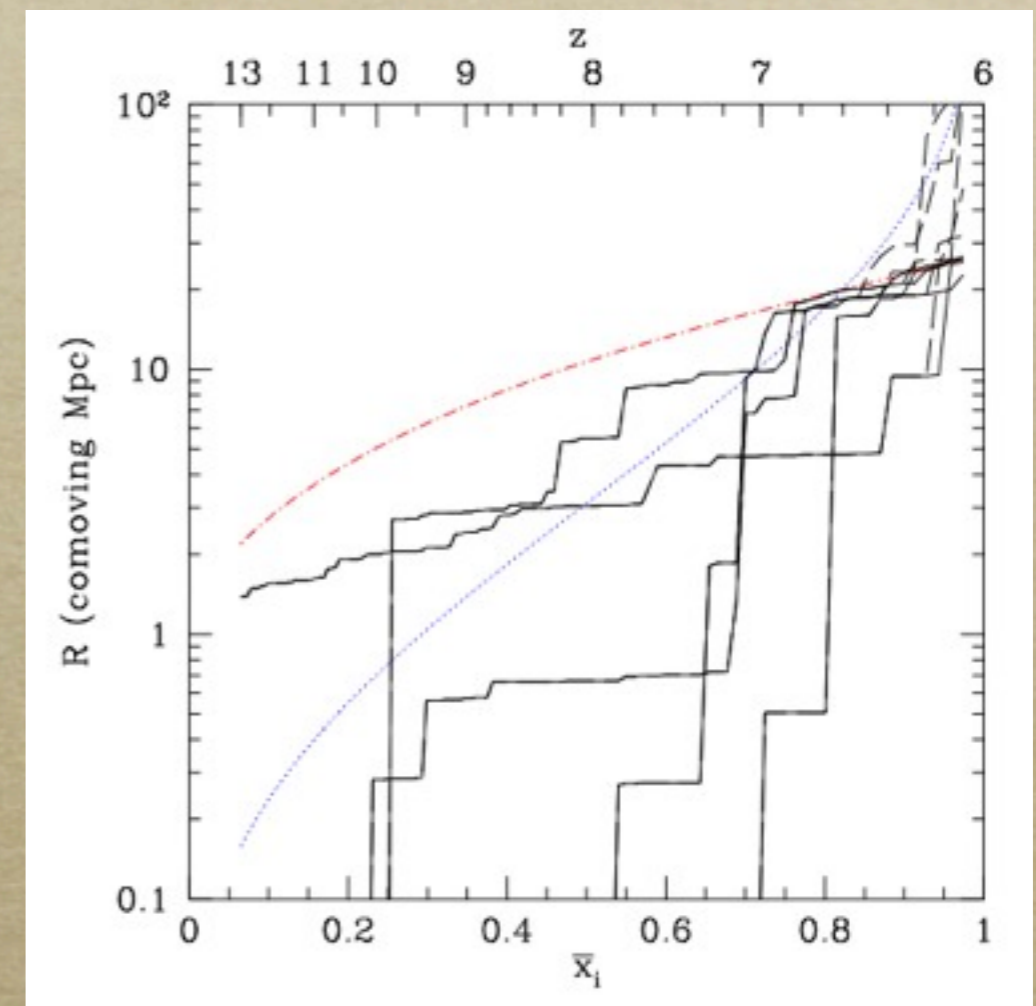

Gnedin (2000)

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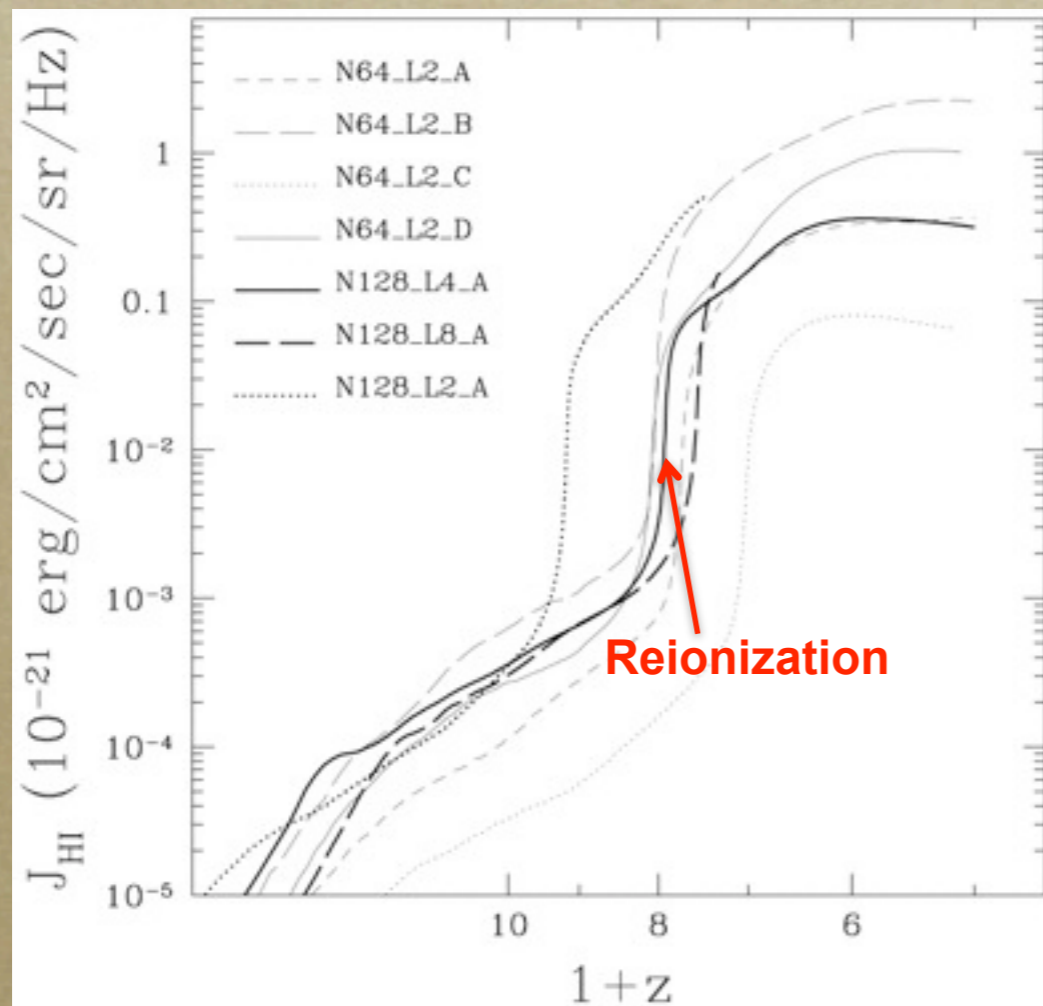
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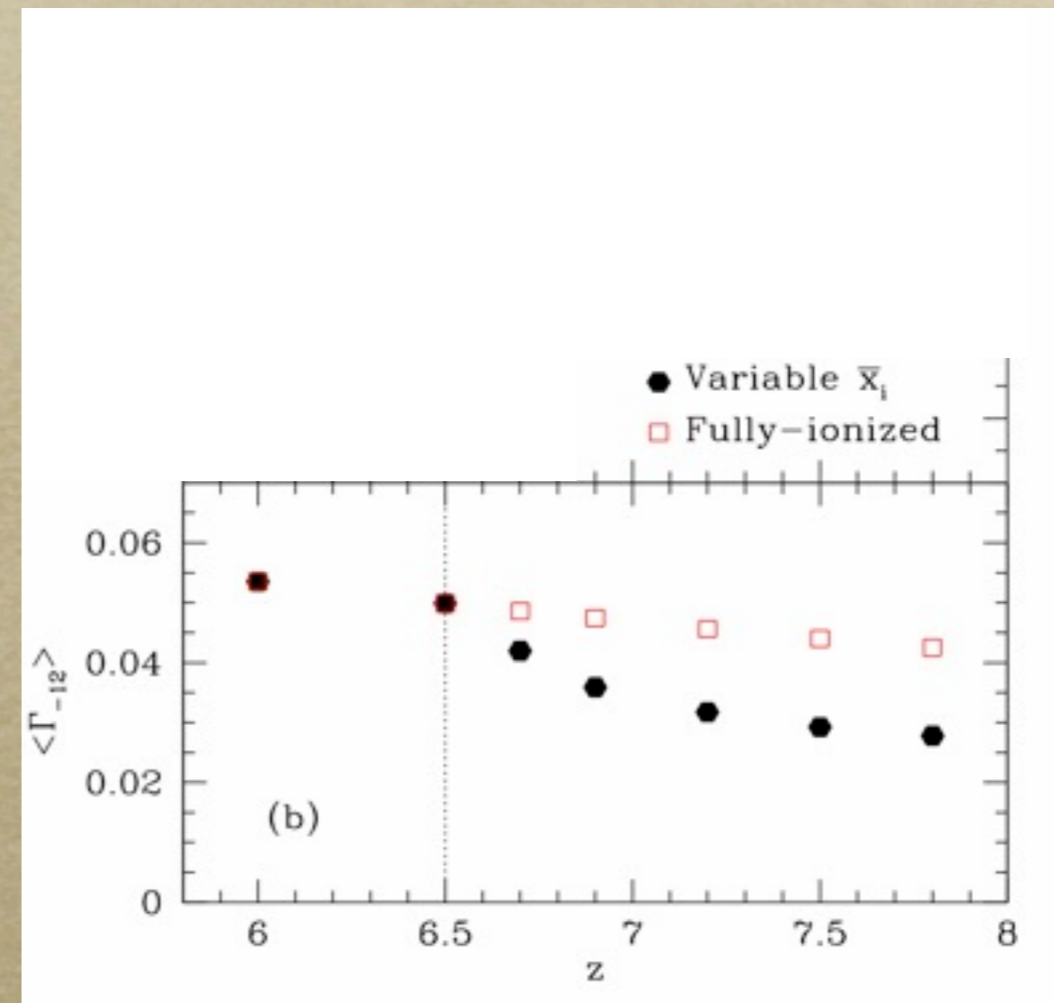

Gnedin (2000)

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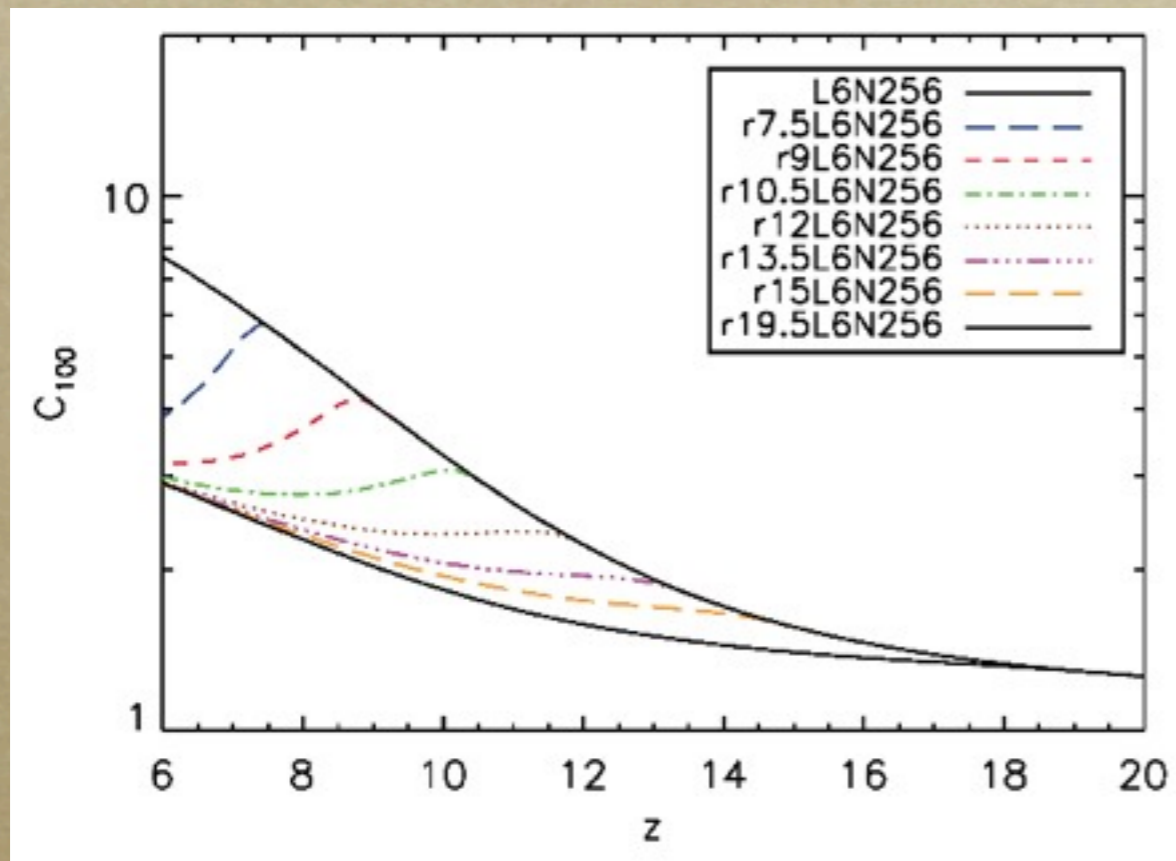

Reionization

Gnedin (2000)

Furlanetto & Mesinger (2008)

The Hidden Underworld of Clumping
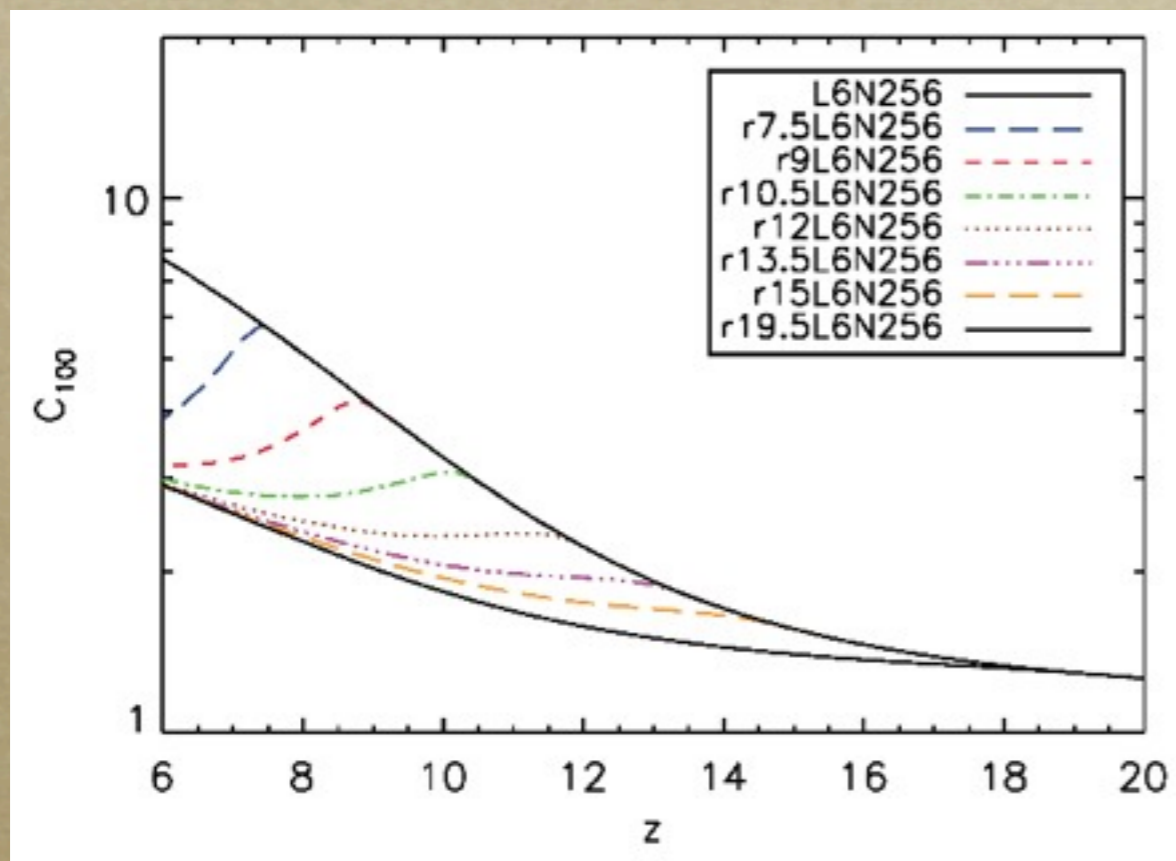
○ *Clumping depends on…*

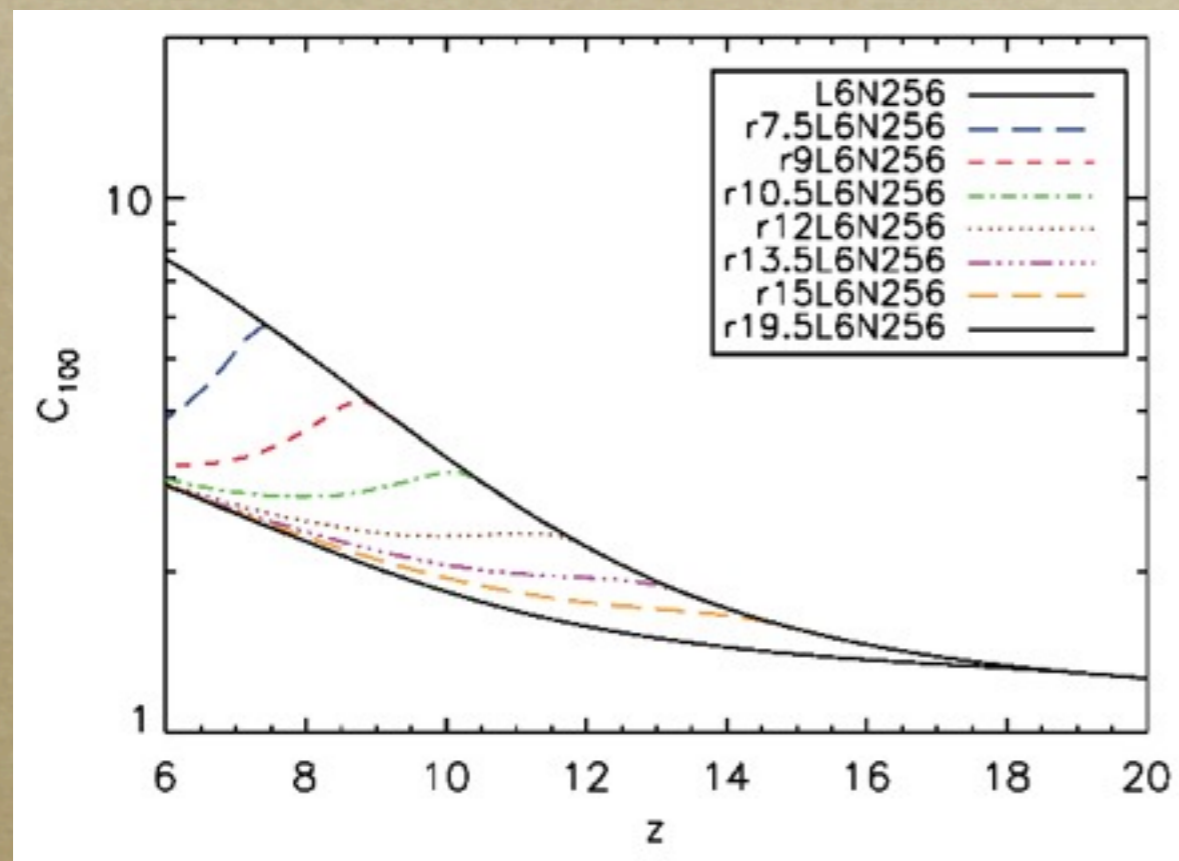

Pawlik et al. (2009)

The Hidden Underworld of Clumping

Clumping depends on…

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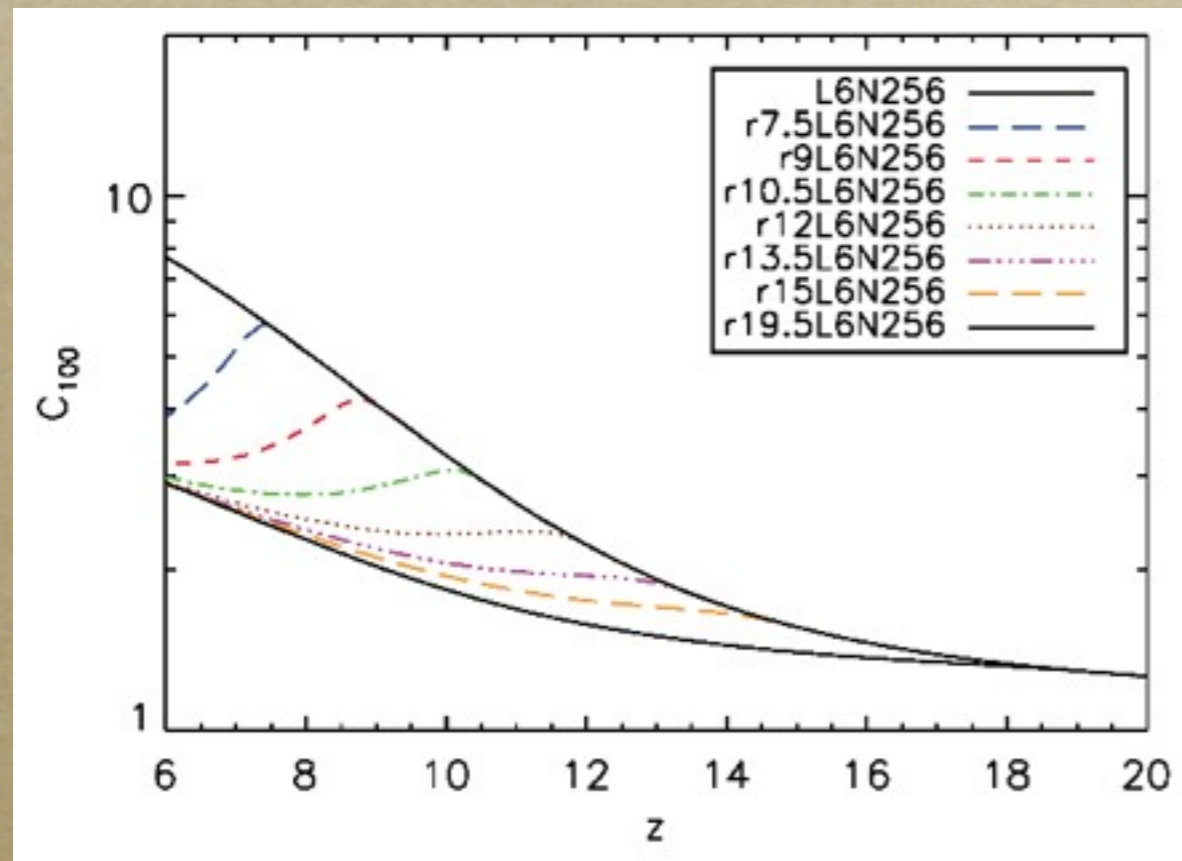
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- *Clumping depends on…*

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The Hidden Underworld of Clumping

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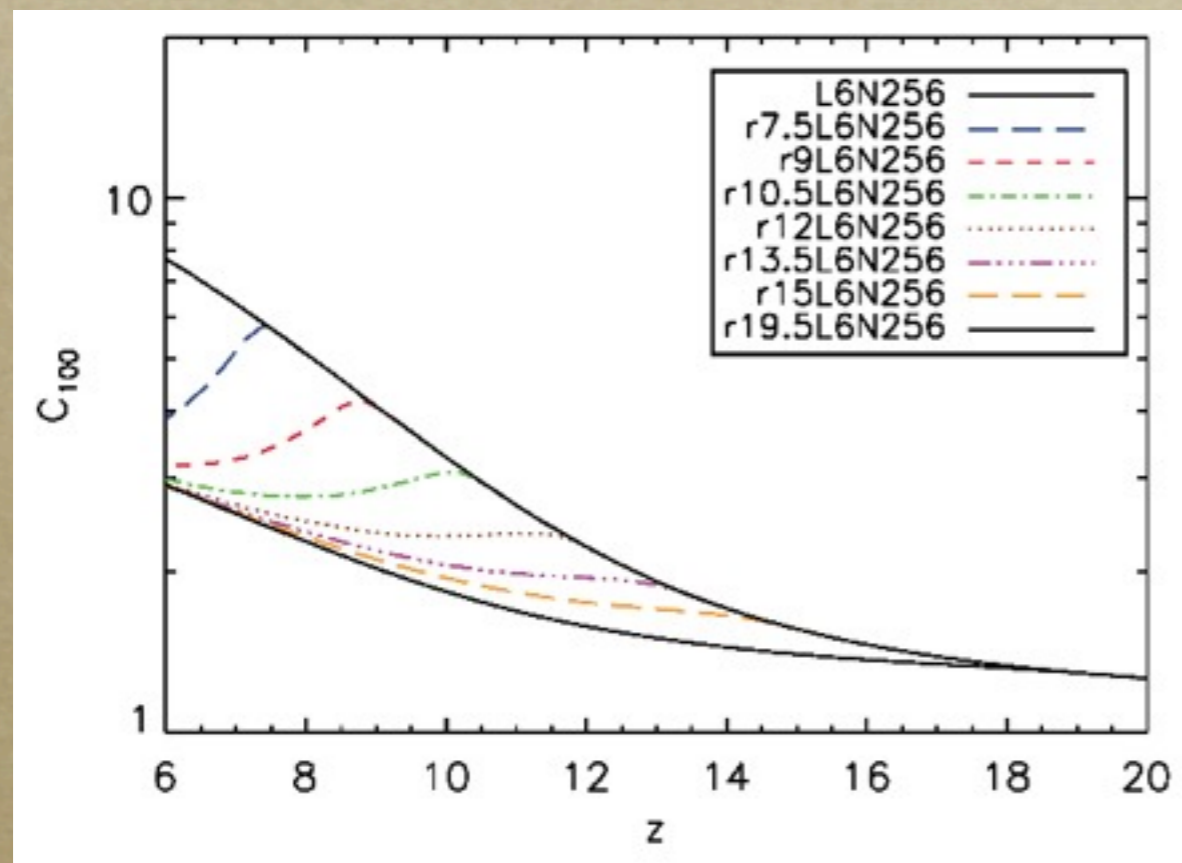
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The Hidden Underworld of Clumping

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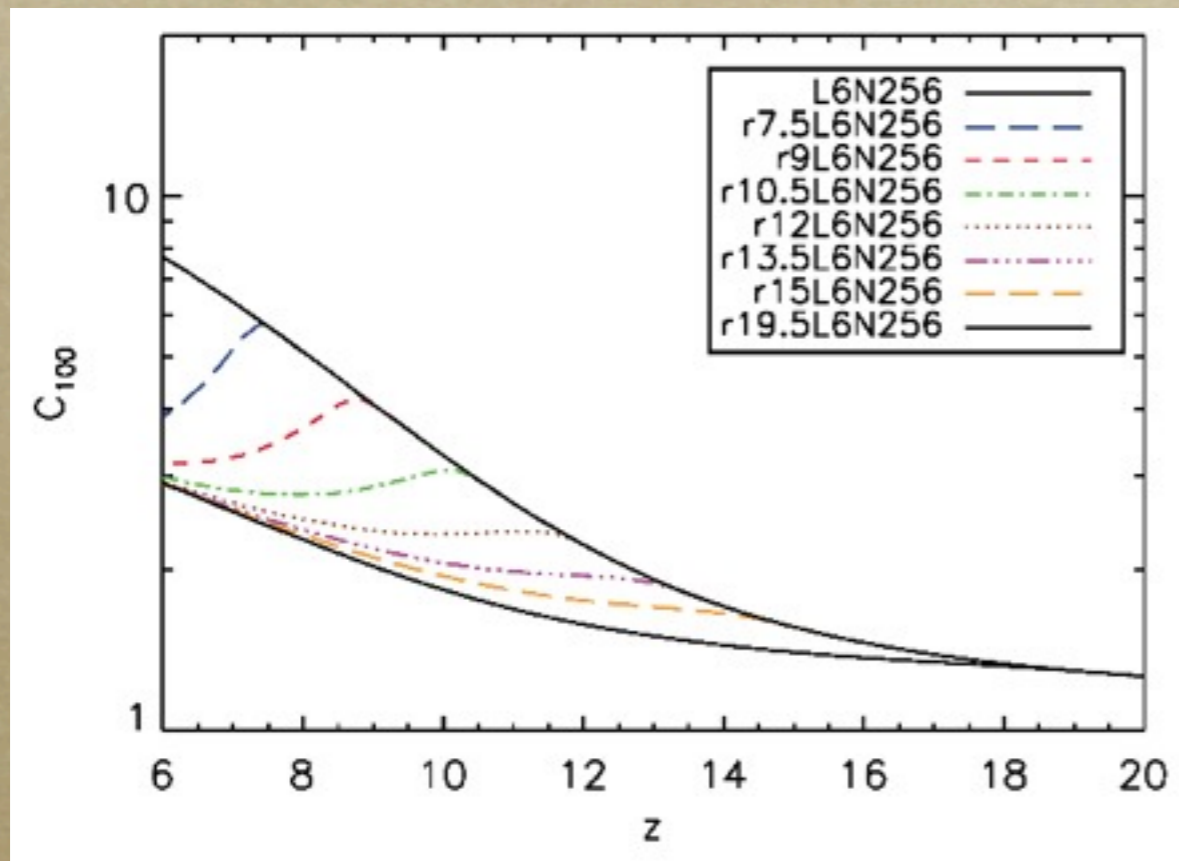
  - *Escape fraction*

  - *Morphology of reionization*

- *But regardless of all these factors: IT IS NOT 30!!!!!*

Observing Reionization

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

Securely Known Facts About Reionization

○ *The Universe is now highly ionized and has been since z>5*

Securely Known Facts About Reionization

- *The Universe is now highly ionized and has been since z>5*

- *It didn't used to be so*

Hints About Reionization

○ *The Universe was highly-ionized to z~6.2*

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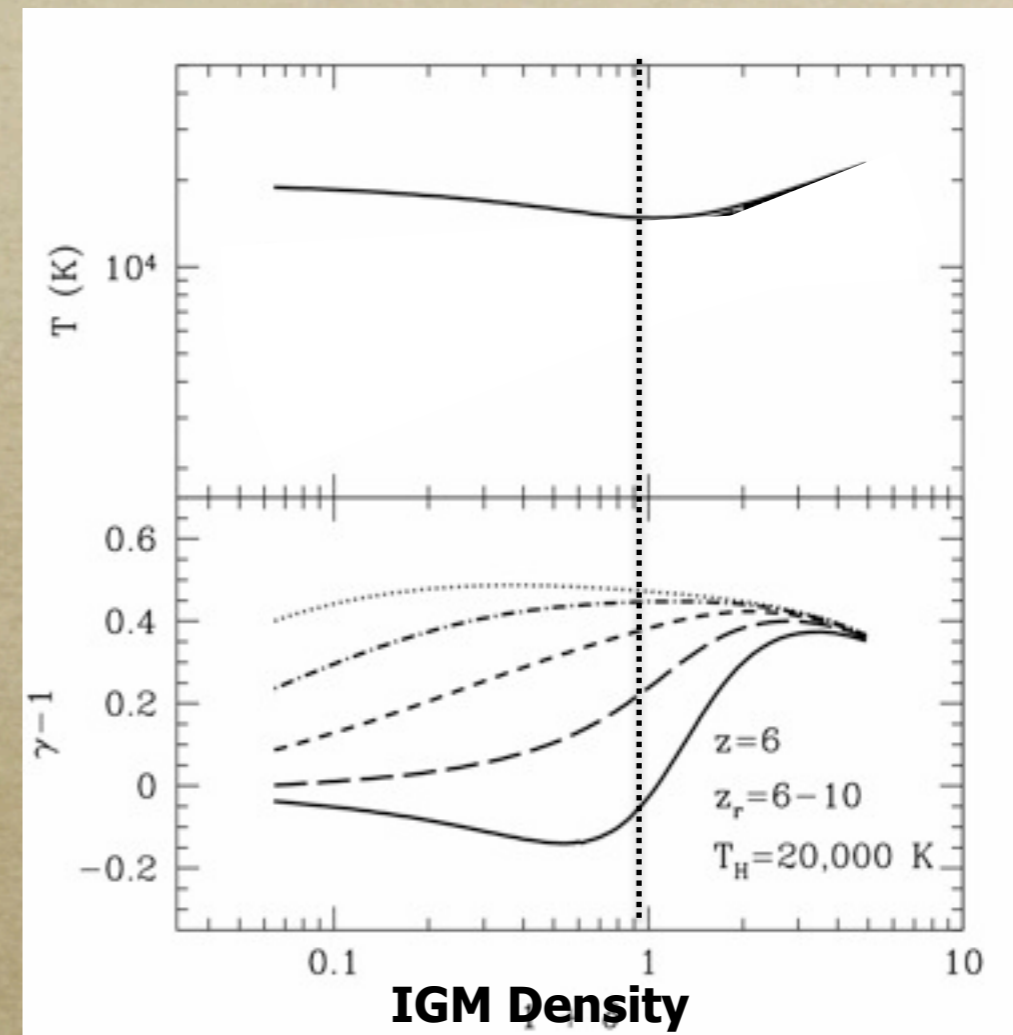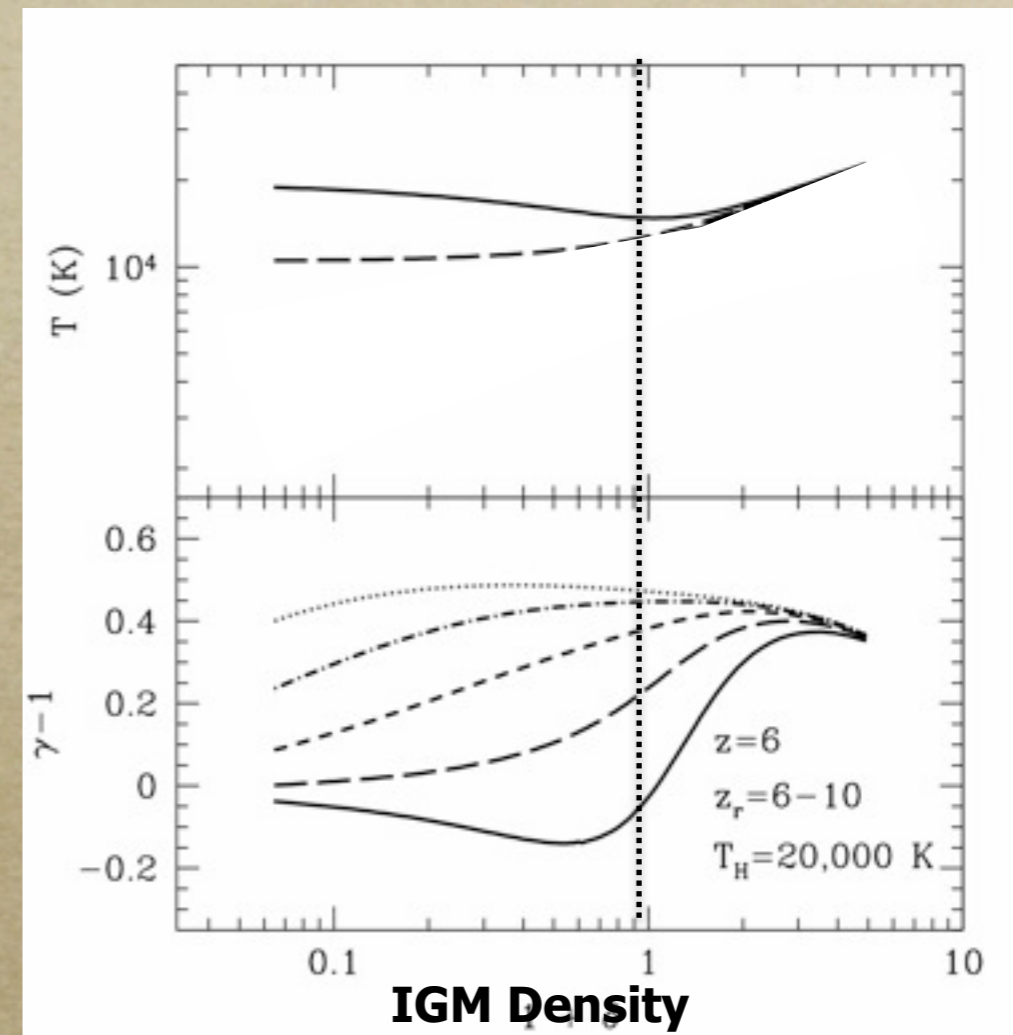
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Hints About Reionization

- *The Universe was highly-ionized to z~6.2*

- *The Universe was substantially neutral (x_{HI}>0.2) at z~7*

- *The Universe was mostly ionized at z~10*

- *Star-forming galaxies (but not the ones we can see now) are responsible for this reionization*
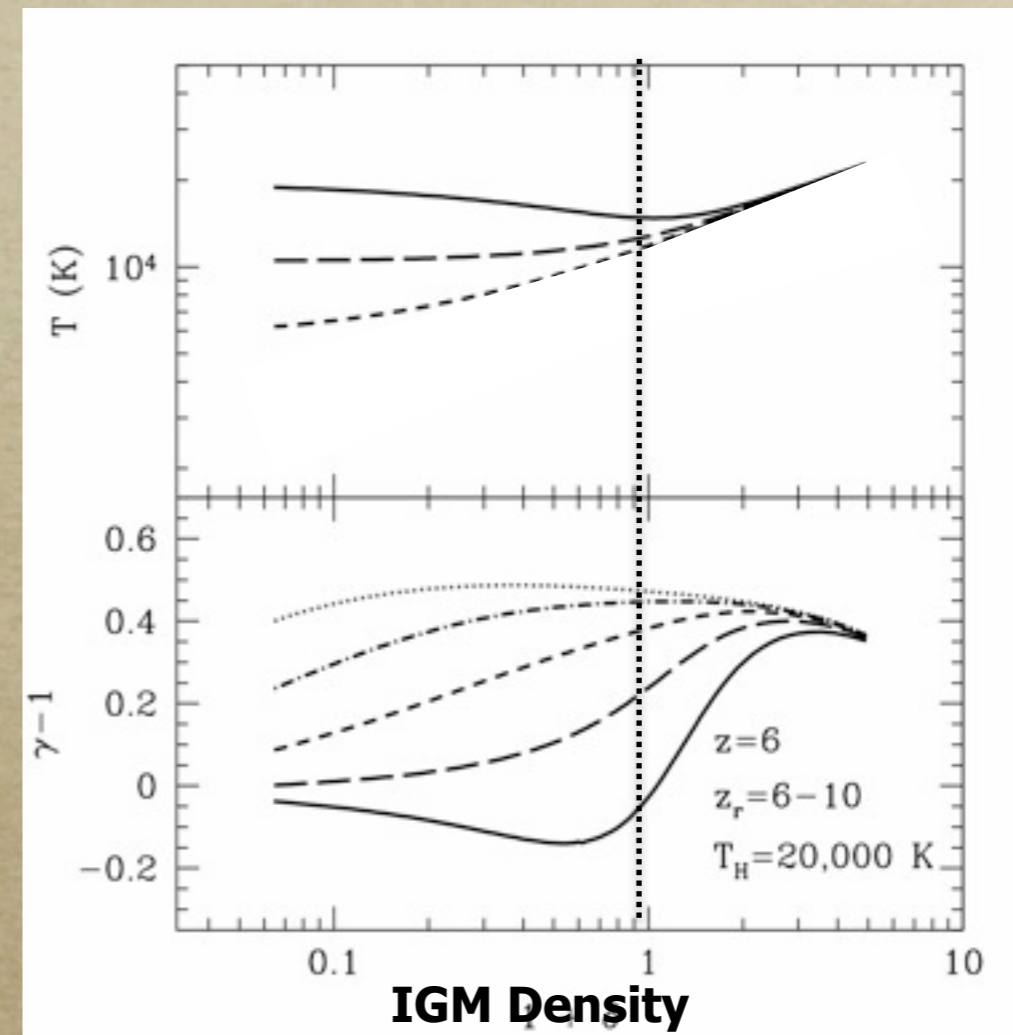
Photoheating During Reionization

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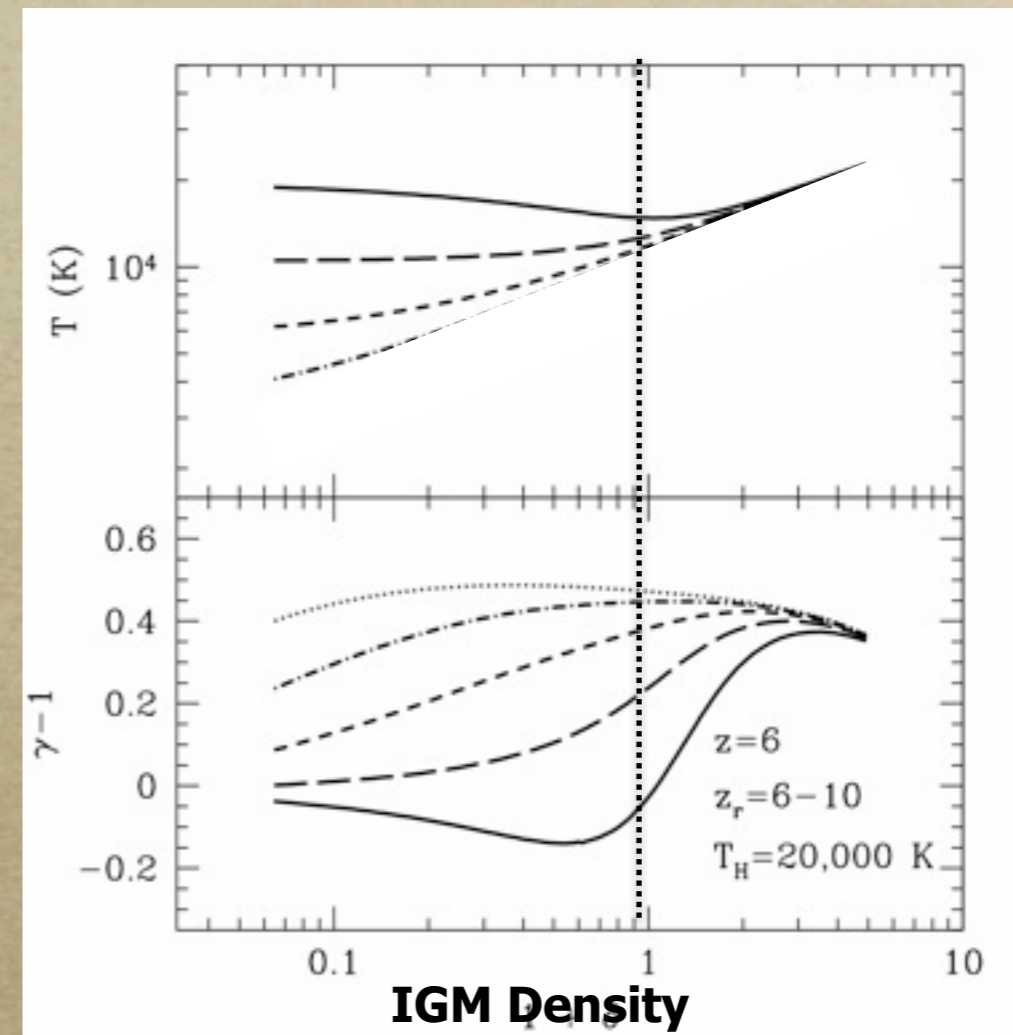

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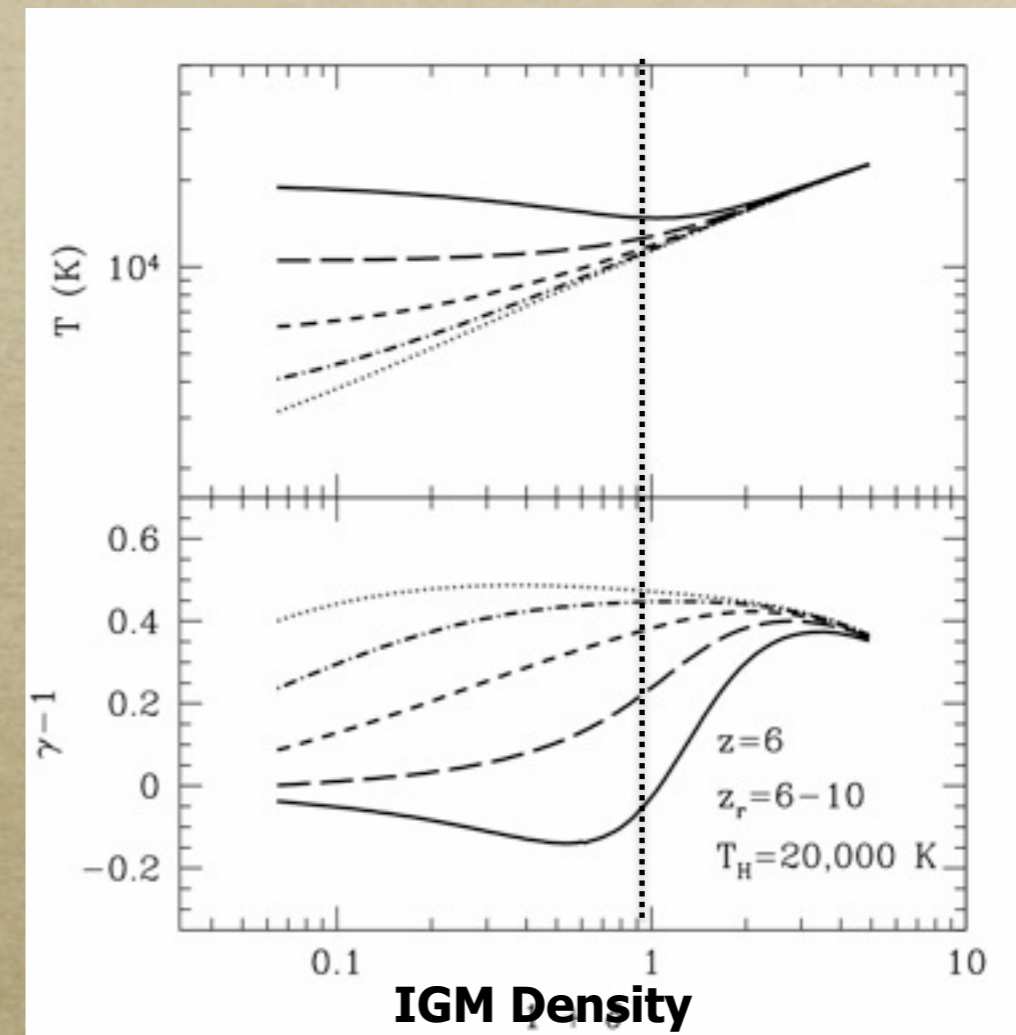
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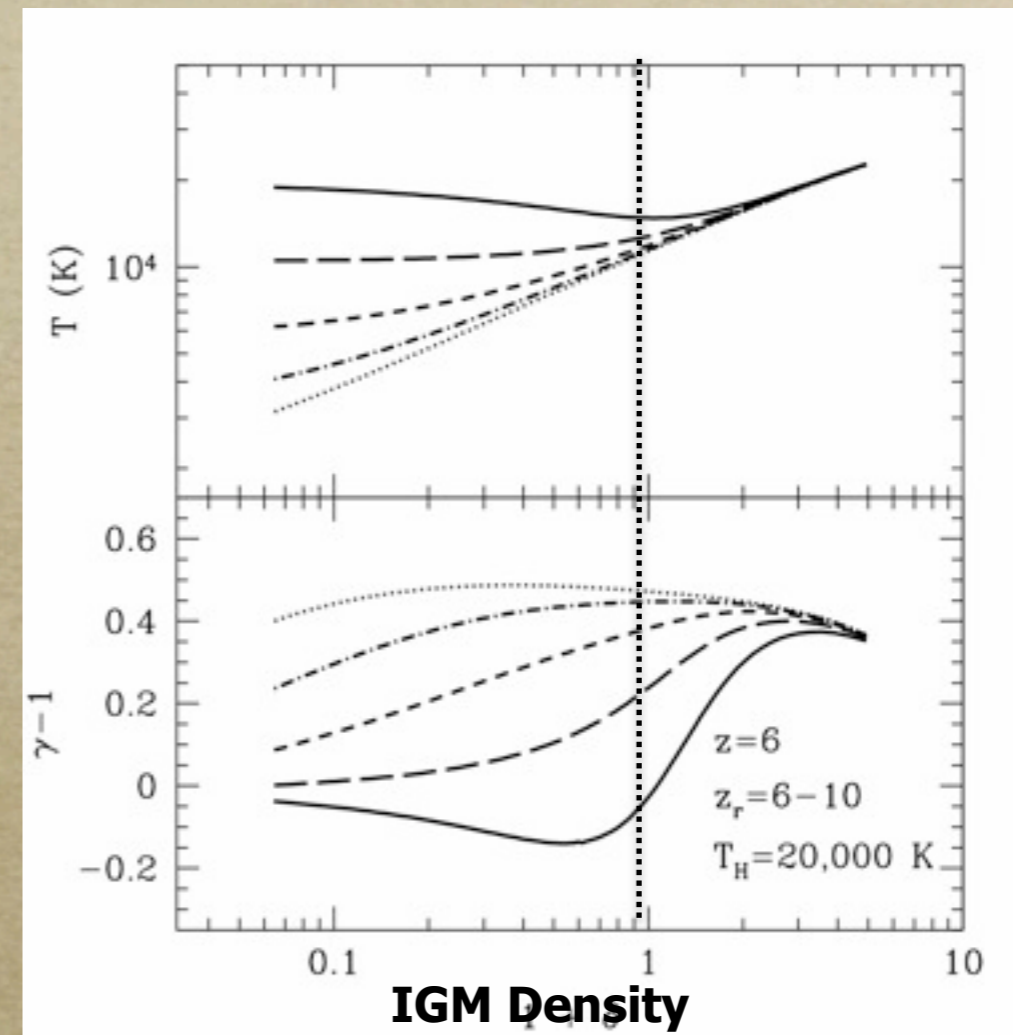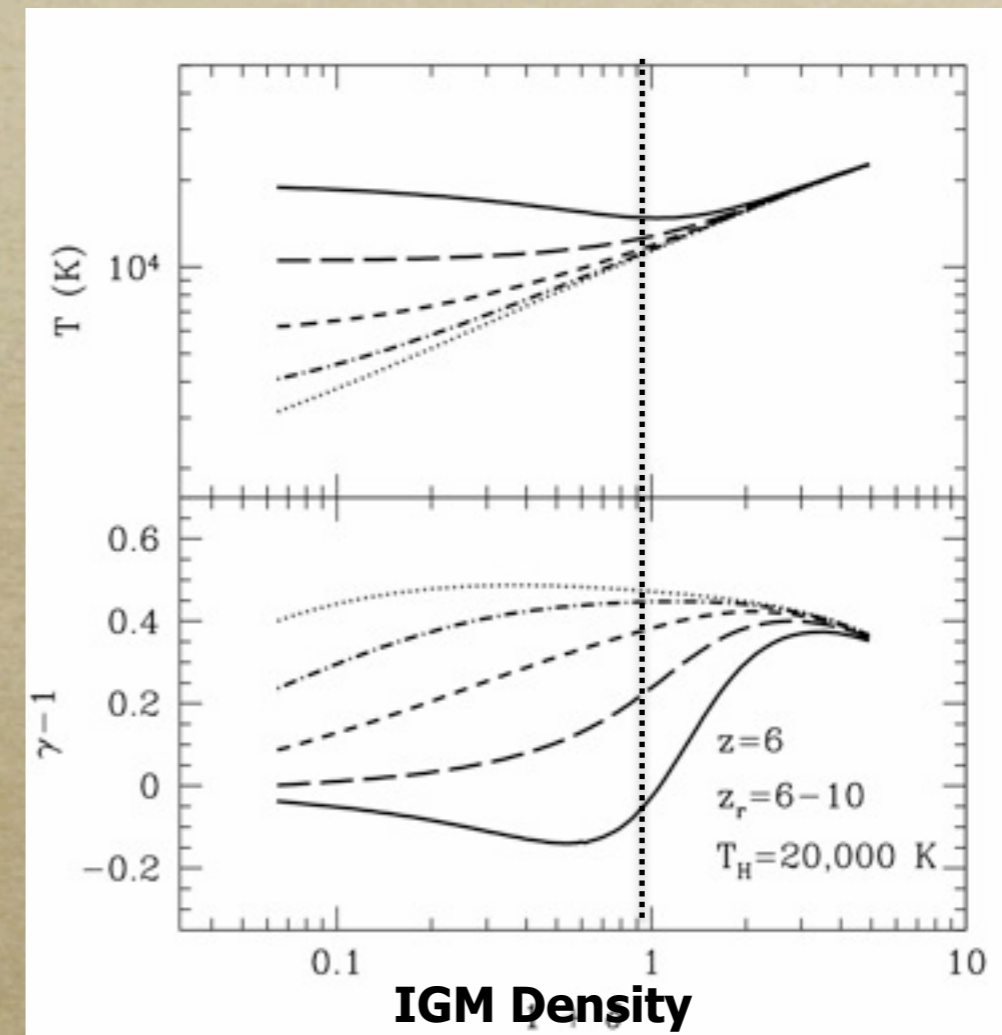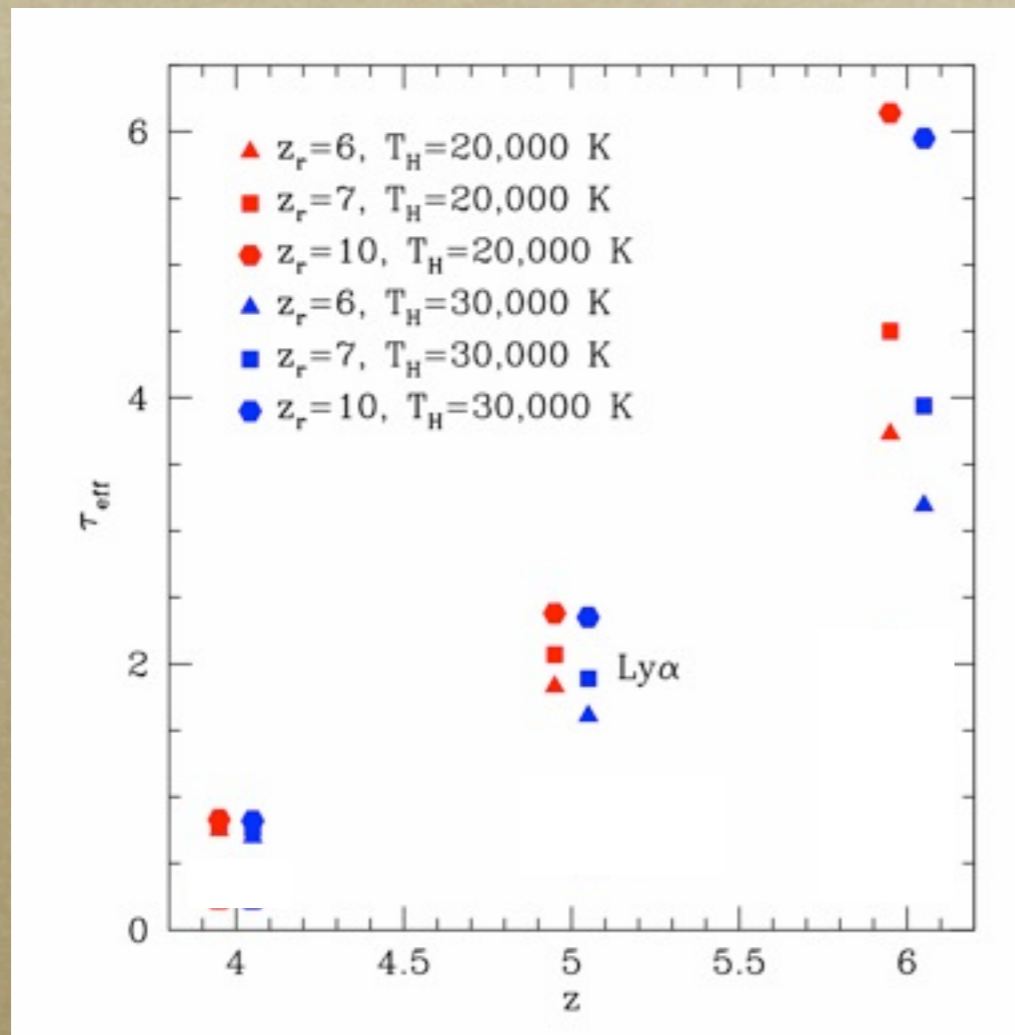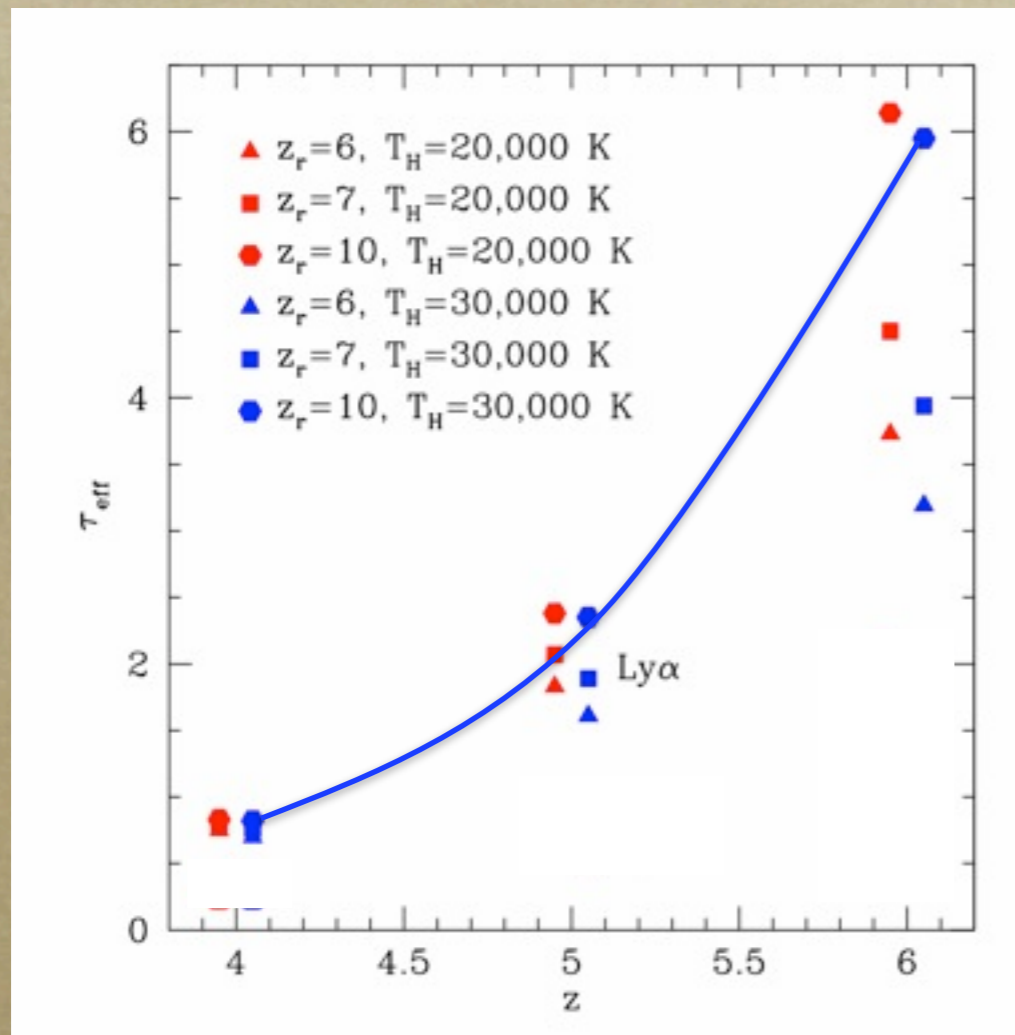
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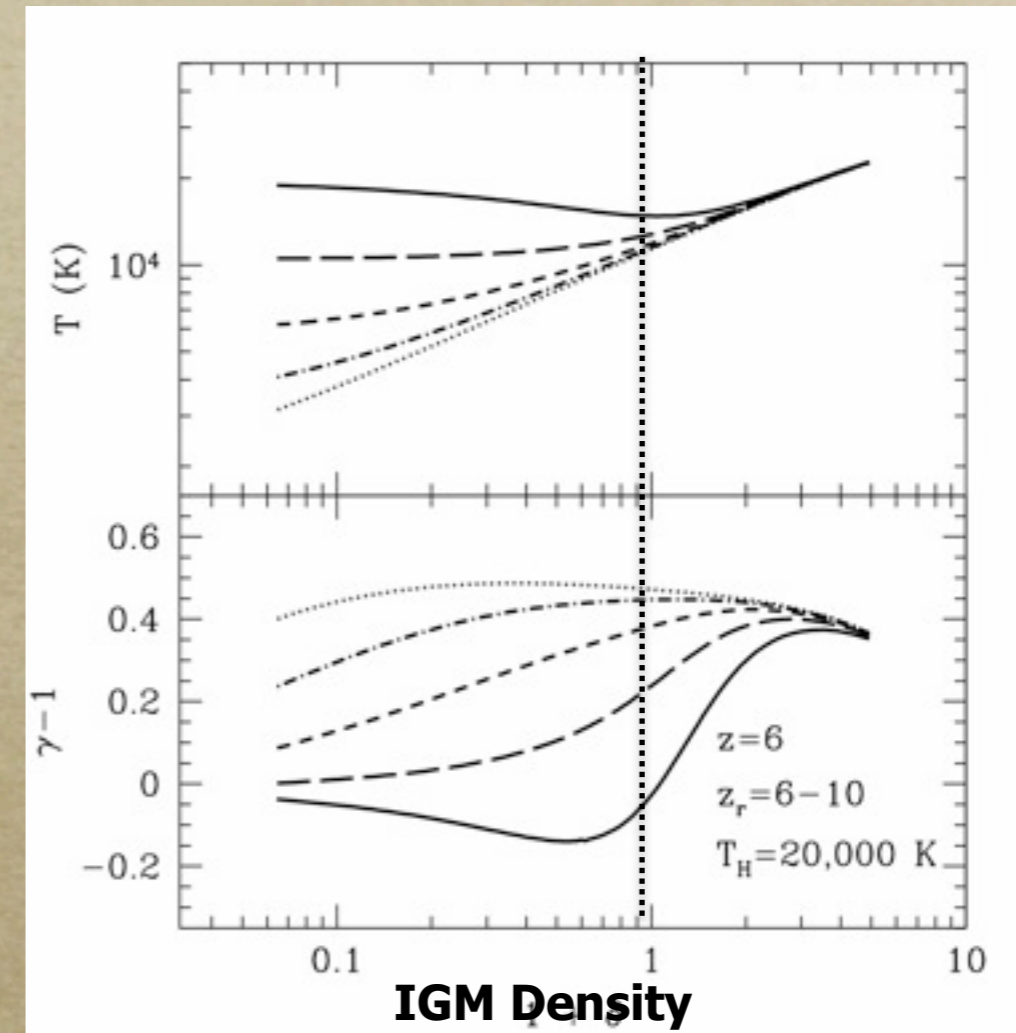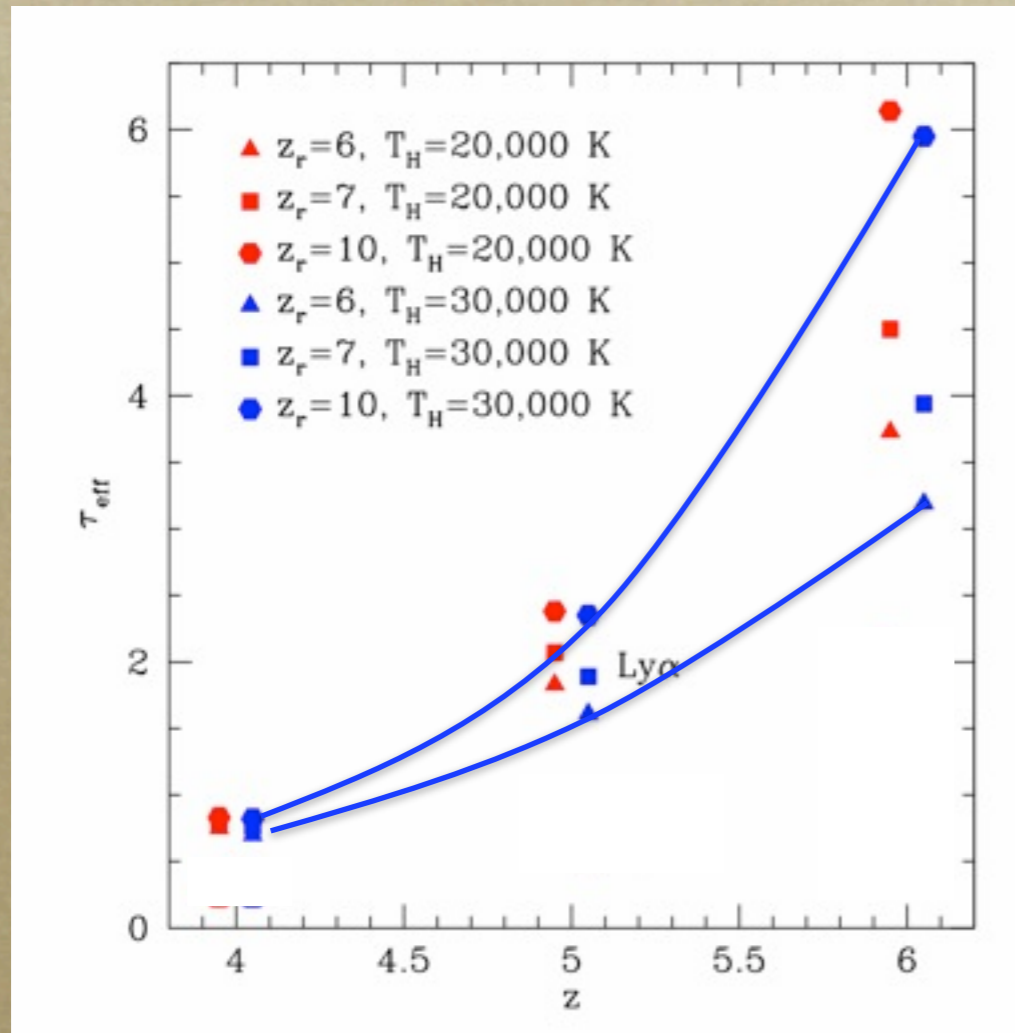
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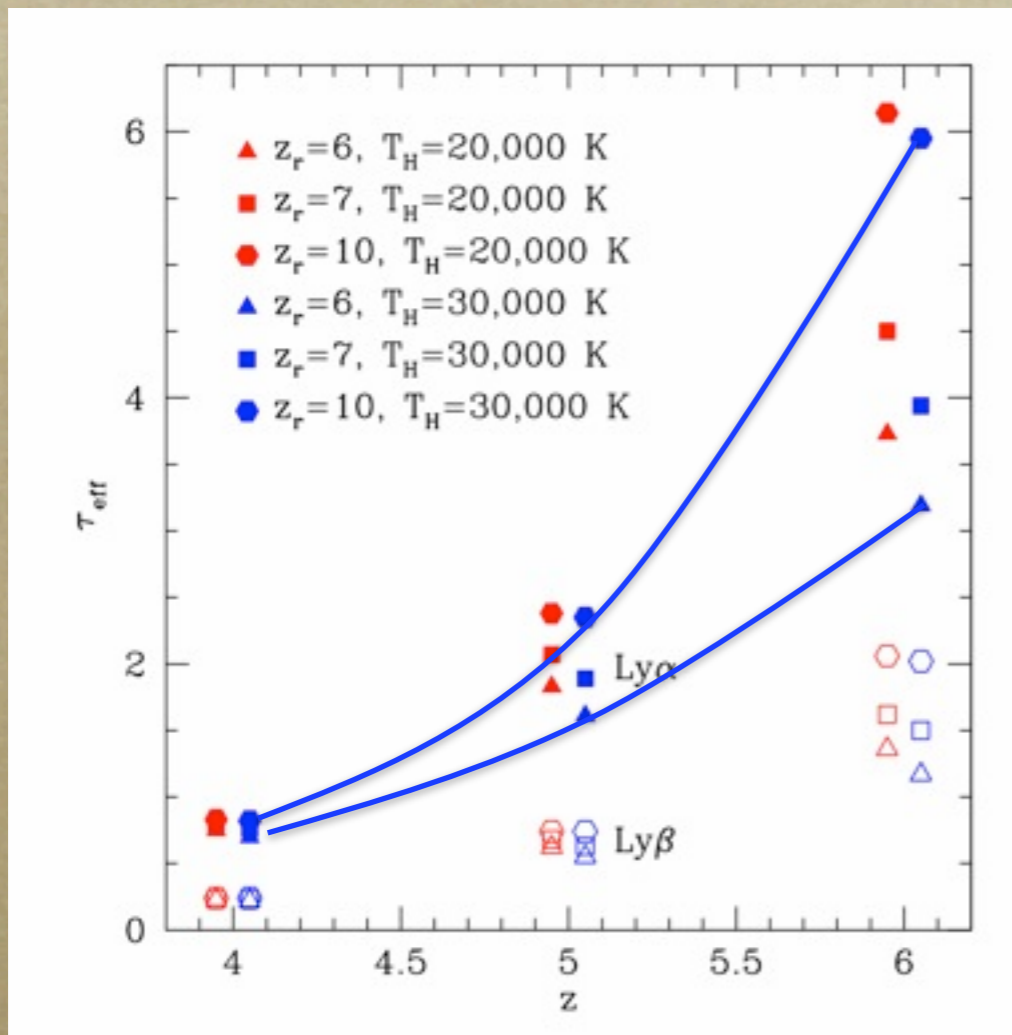
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The Hidden Underworld of Photoheating

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- *Increased IGM temperature (thus pressure) prevents accretion, via Jeans (or filter) mass*
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- *AND, it depends on...*
  - *Self-shielding*
  - *Recombinations and cooling*
  - *Amplitude and spectrum of ionizing background*

The Hidden Underworld of Photoheating

- *Increased IGM temperature (thus pressure) prevents accretion, via Jeans (or filter) mass*
  - *Ignore if halo lies above IGM Jeans mass (~10^{10} Msun)*
  - *Completely dominates if halo lies below halo Jeans mass (~10^9 Msun)*
- *AND, it depends on…*
  - *Self-shielding*
  - *Recombinations and cooling*
  - *Amplitude and spectrum of ionizing background*
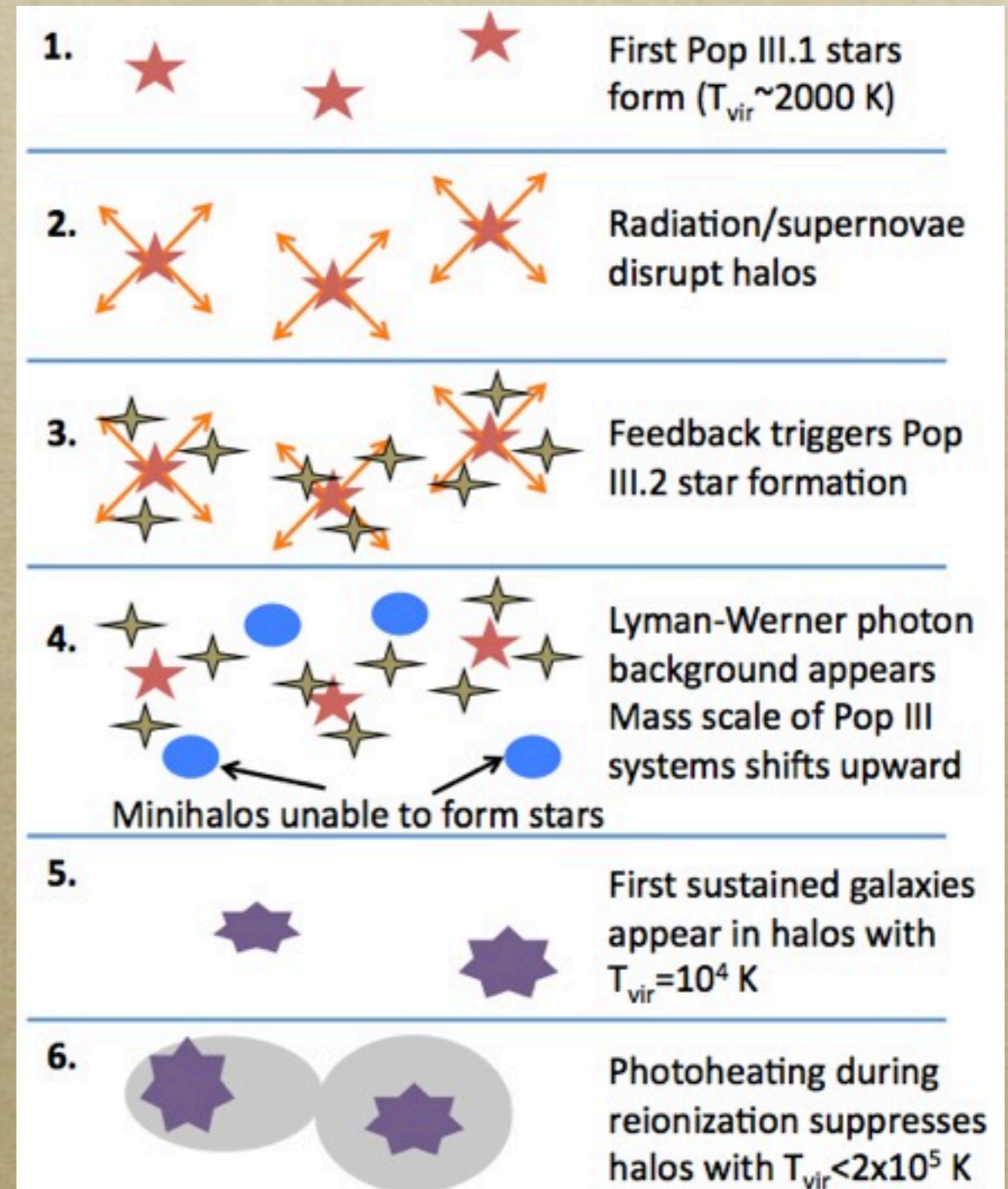 - *Timing of accretion v. heating*

The Hidden Underworld of Photoheating

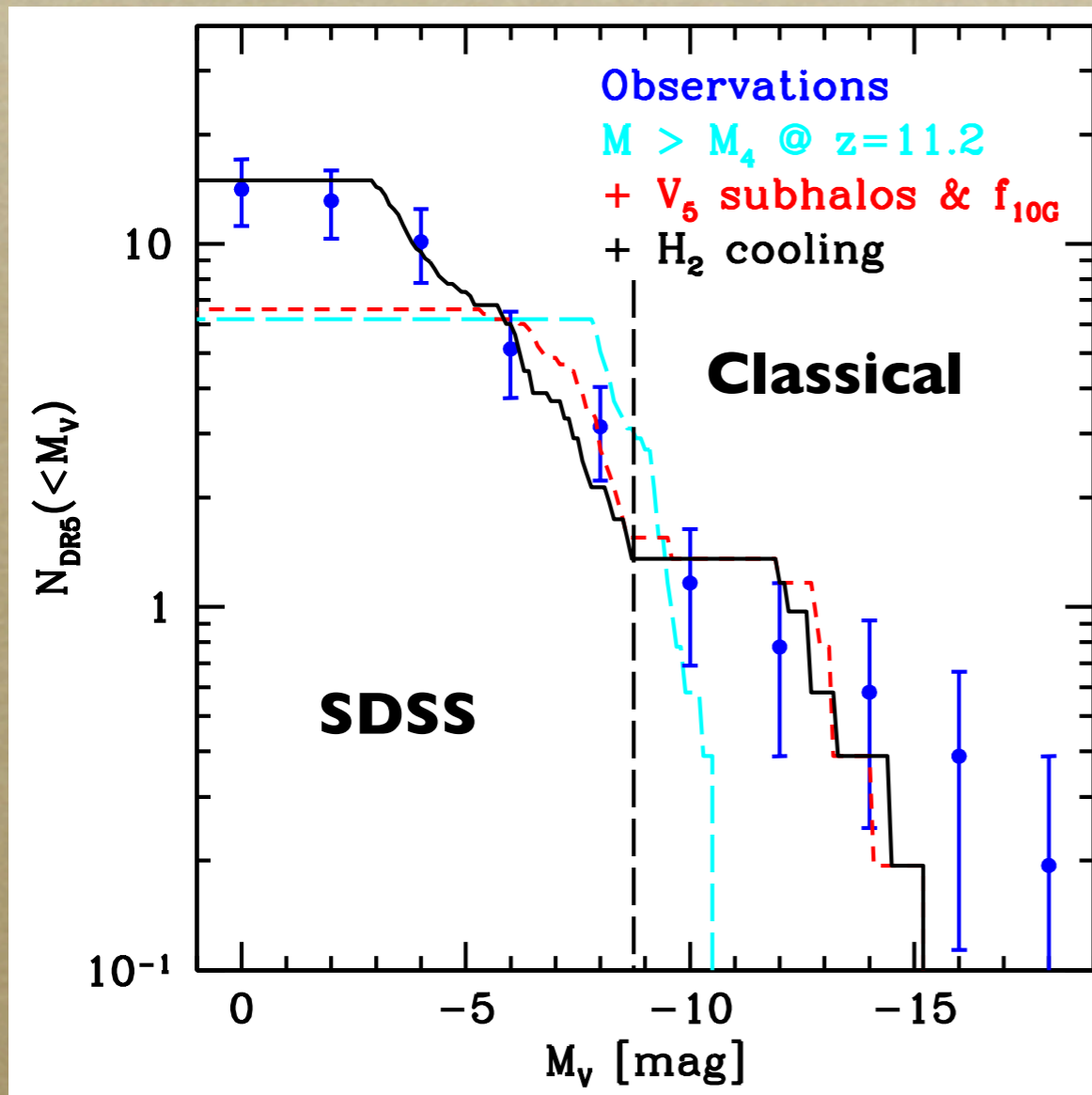- *Increased IGM temperature (thus pressure) prevents accretion, via Jeans (or filter) mass*
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  - *Amplitude and spectrum of ionizing background*
  - *Timing of accretion v. heating*
  - *"Pre-heating"*

But Reionization Is Only One Piece…

○ *Every transition is potentially crucial!*

1. First Pop III.1 stars form ($T_{vir} \sim 2000$ K)

2. Radiation/supernovae disrupt halos

3. Feedback triggers Pop III.2 star formation

4. Lyman-Werner photon background appears
   Mass scale of Pop III systems shifts upward
   Minihalos unable to form stars

5. First sustained galaxies appear in halos with $T_{vir} = 10^4$ K

6. Photoheating during reionization suppresses halos with $T_{vir} < 2 \times 10^5$ K

Dwarf Galaxies and First Stars

Munoz et al. (2009)

- *Different luminosities constrain different processes*

  - *large L (classical): $T_{vir} > 10^5$ K*

  - *-5 > M_V > -9 (SDSS): HI cooling before z_{rei}*

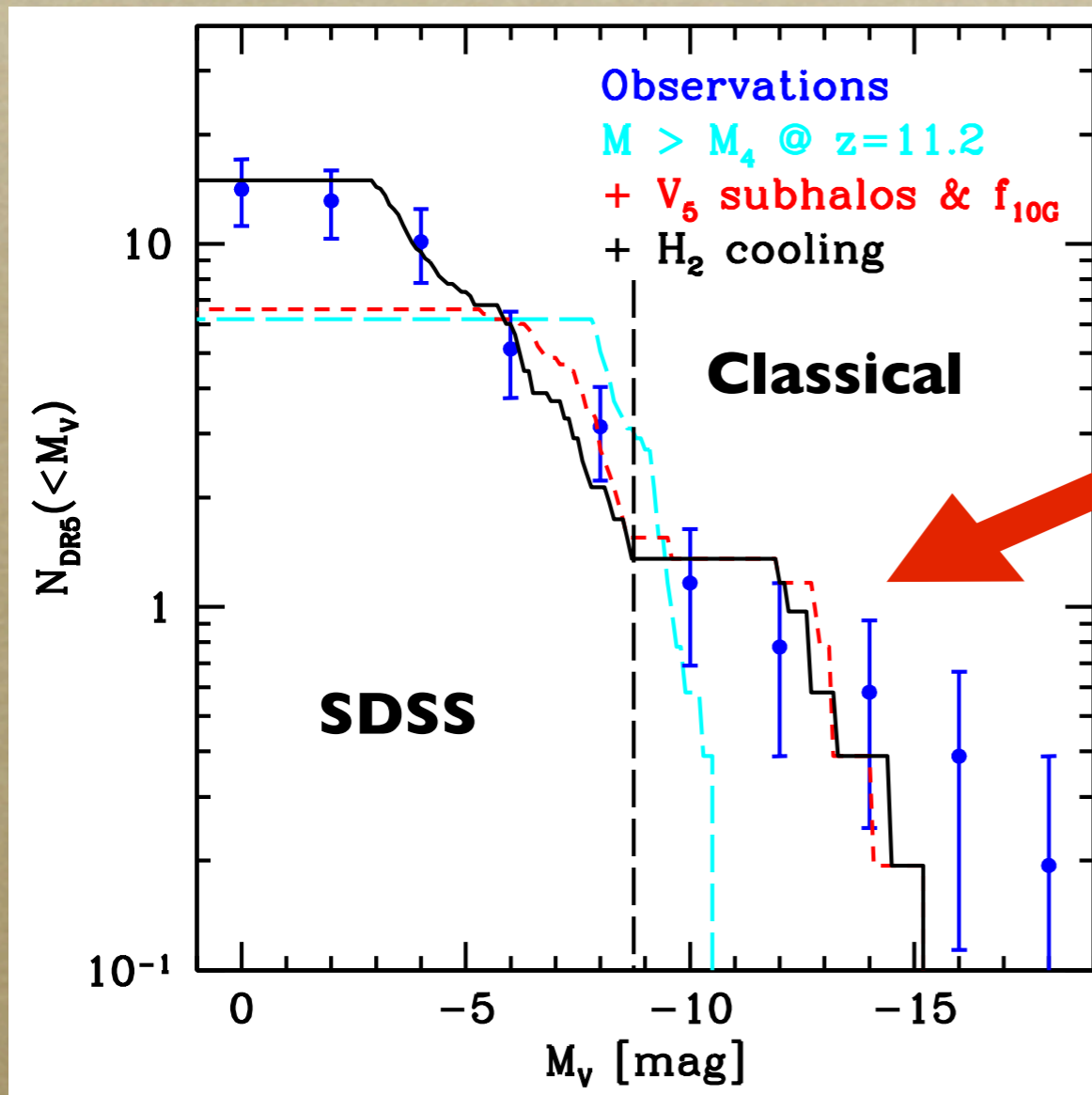 - *M_V > -5 (SDSS): H_2 cooled stars*

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Dwarf Galaxies and First Stars
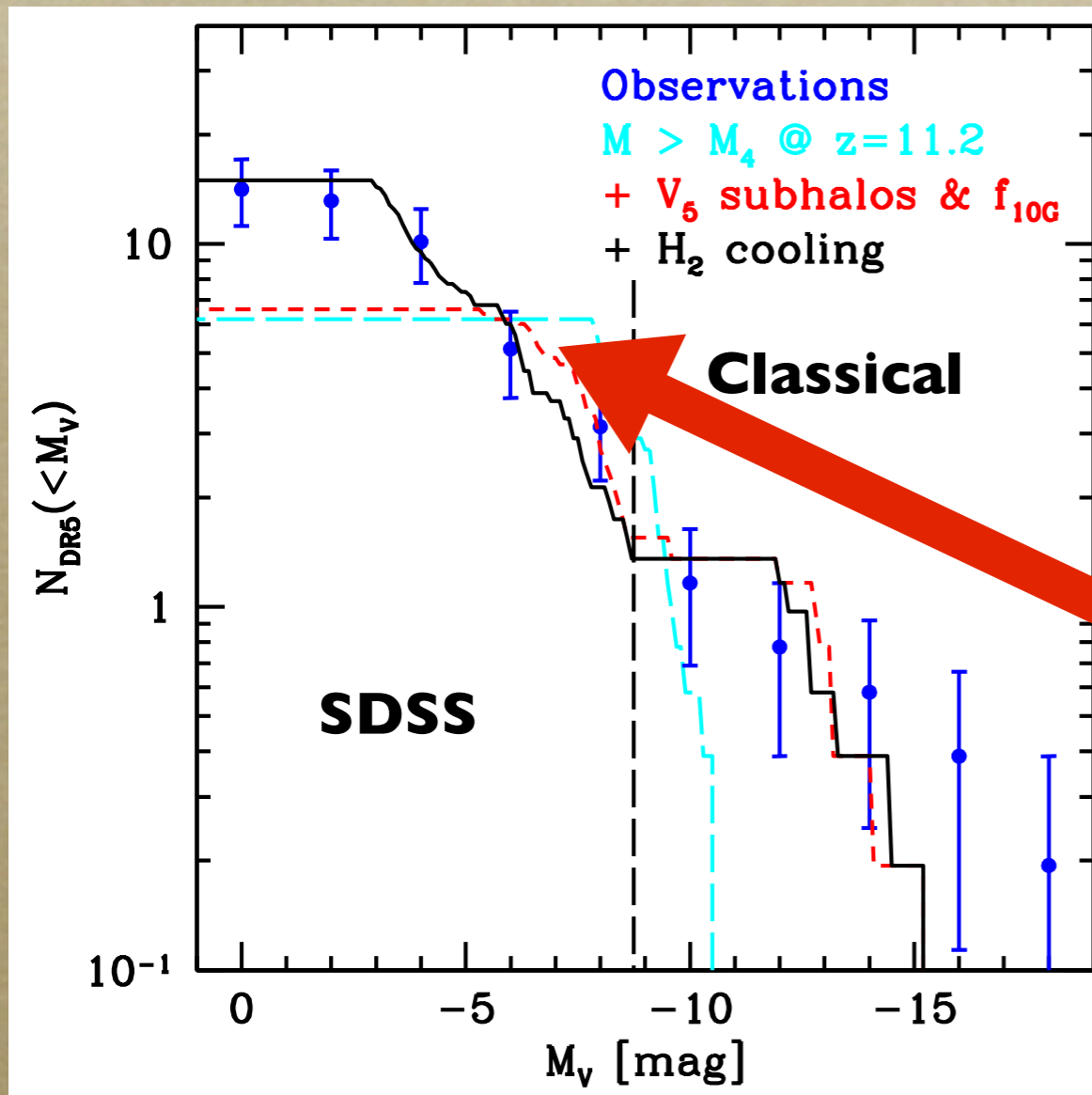

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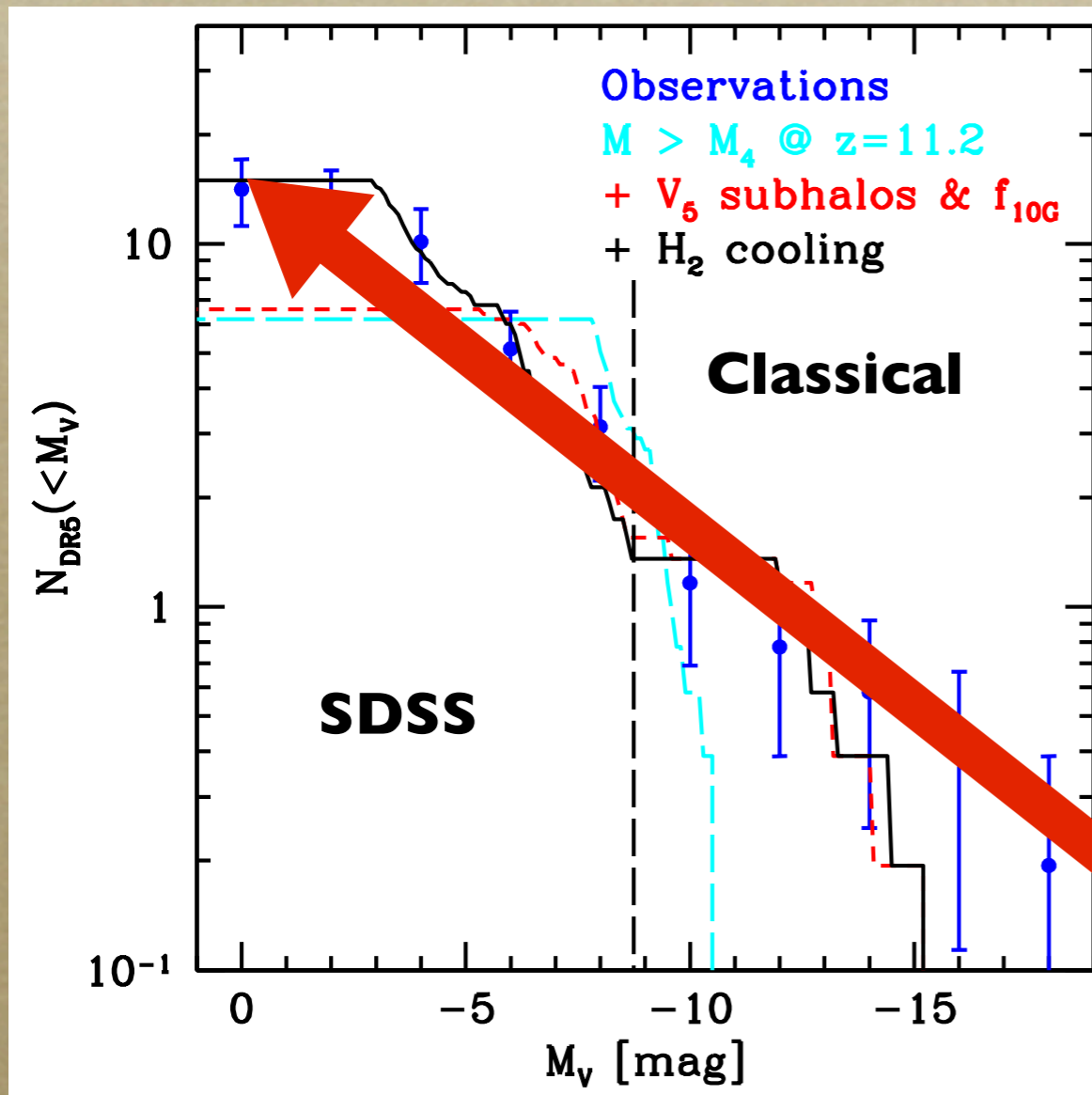 - *M_V > -5 (SDSS): H_2 cooled stars*

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Conclusions

- *The timing of reionization is extremely difficult to predict*

- *The early phases of reionization can be reasonably well-understood*

- *The late phases of reionization are more difficult*

- *Reionization is highly spatially inhomogeneous*

- *Photoheating may leave interesting observable signatures, but its effects on galaxies are poorly understood*

Want To Know More?

The First Galaxies in the Universe

Abraham Loeb and Steven R. Furlanetto

○ *Coming in January 2013 (or so) from Princeton University Press!*