Theoretical and Observational Insights into Reionization and the Dark Ages

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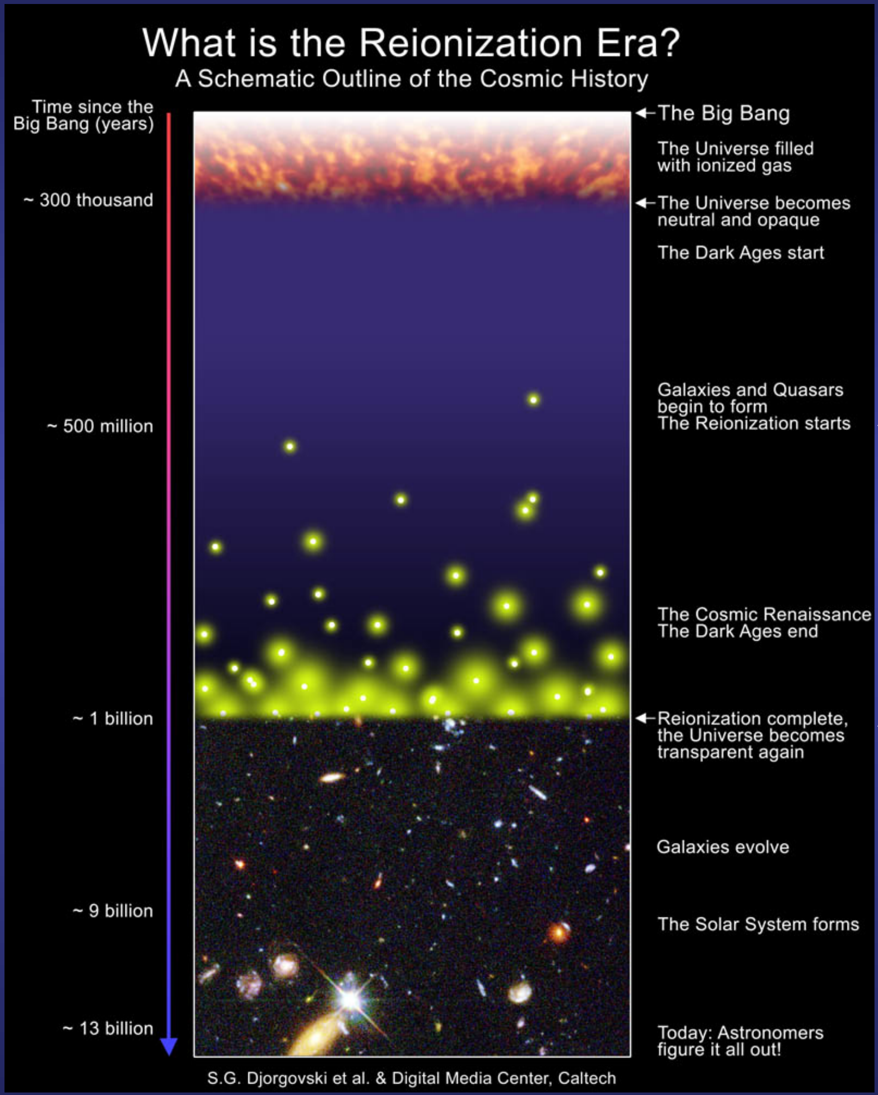
Cosmic Dawn



z ~ 1100

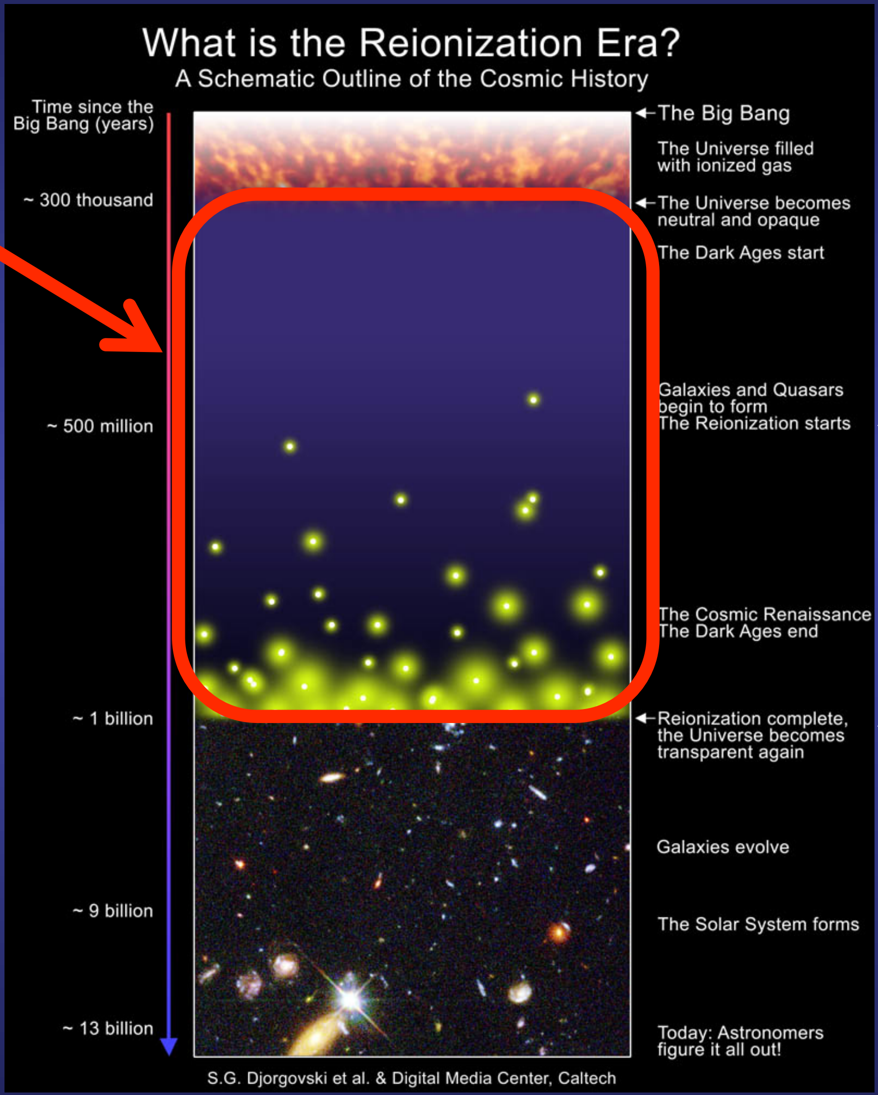
z ~ 30 ??

z ~ 6 ???

z = 0

Cosmic Dawn

80% of the observable Universe!



z ~ 30 ??

z ~ 6 ???

Who cares?

- Bulk of our light cone
- Only practical way of studying the high-z galaxy population
- One of the two important phase transitions. Affected the vast majority of baryons.
- Impact resonated even to present day, e.g. abundance of dwarf galaxies
- Testbed for exciting early Universe physics
- Practical: many billions of $ and € devoted to studying these epochs
- Freekin’ cool! Undiscovered final frontier!

Outline

- *Once upon a time…* the story of the dawn of our galactic ancestors and reionization: *a theorist's perspective*
  - Early stages; first stars and feedback
  - Middle stages; ionizing sources
  - Late stages; ionizing sinks
- Observational constraints; high-z QSOs:
  - Early (mis)-interpretations
  - Model-independent and model-dependent constraints
- 21cm cosmology and astrophysics
- Efficient semi-numerical simulations DexM and 21cm*FAST*

Early stages of reionization

-Hierarchal structure formation means that the first astrophysical objects were likely hosted by "minihalos" ($T_{VIR}<10^4$ K), with baryons accreting via the H_2 cooling channel.

- Without metals to aid in cooling and fragmentation, the first generations of stars were likely massive ($M\sim100M_{sun}$), short-lived PopIII stars (Abel+2002; Bromm+2002; Yoshida+2008).

- Such giants would have very different ionizing properties than "regular" PopII stars: a factor of ~10 increase in ionizing photons per baryon; harder spectra (e.g. Schaerer 2002, 2003)

-What was their IMF and formation efficiency? requires costly exploration of parameter space (e.g. Turk+2009; Grief+2011; Prieto+2011)

-What were their fates? requires detailed stellar modeling (e.g. Heger+ 2003)

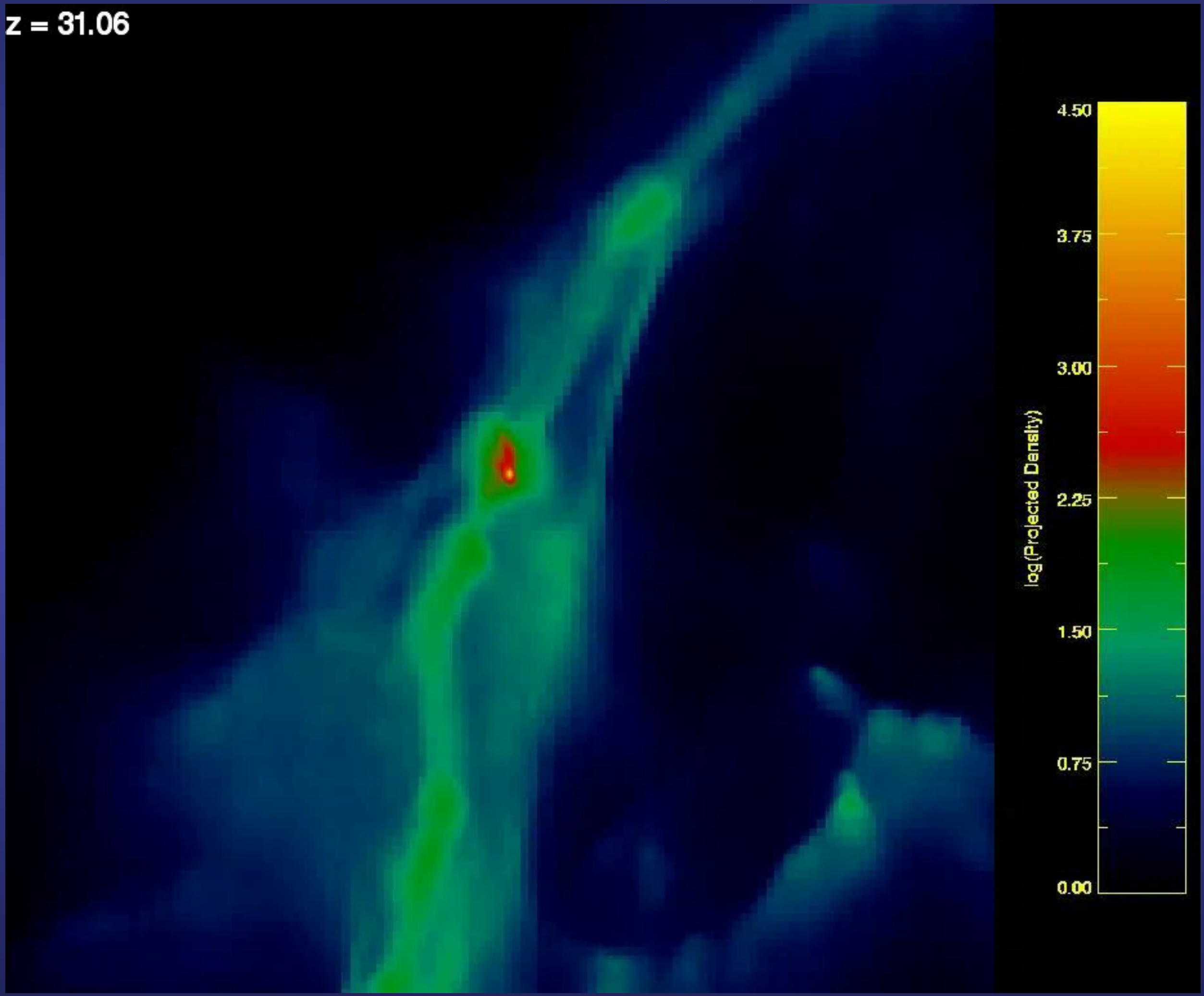
Early stages, continued…

-How did they affect future star formation? Very sensitive to feedback mechanisms:

1. Mechanical– SNe can blow out the gas from the host minihalo (e.g. Whalen+2008; Wise & Abel 2007)

Early stages, continued…

Wise & Abel (2007)



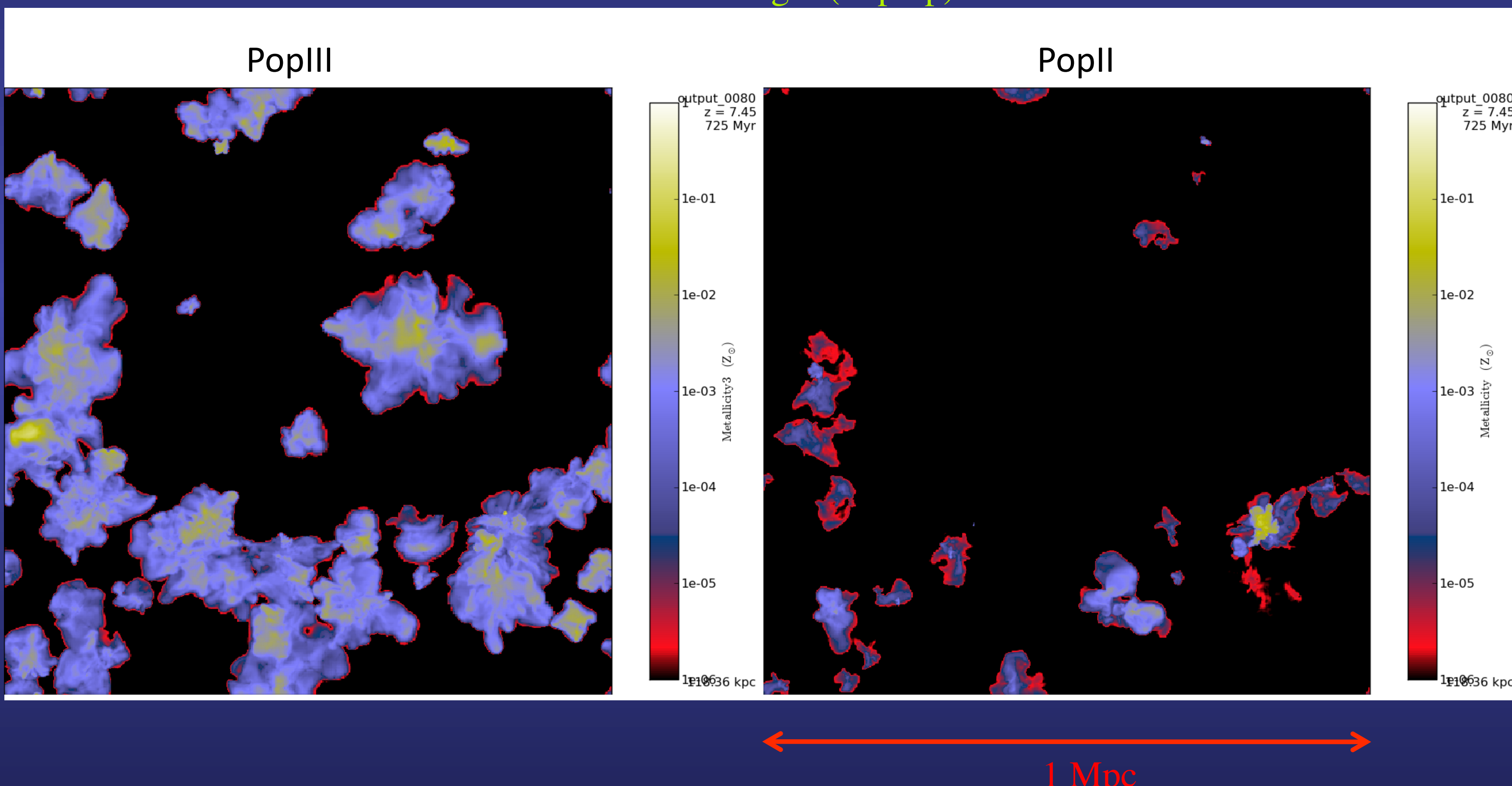
Early stages, continued…

-How did they affect future star formation? Very sensitive to feedback mechanisms:

1. Mechanical– SNe can blow out the gas from the host minihalo (e.g. Whalen+2008; Wise & Abel 2007)
2. Chemical – the evolution in the IMF depends on metal enrichment and ionization history (Tan & McKee 2008; Smith+2009; Schneider & Omukai 2009; Grief+2010). It's important to try to model the enrichment on "large" scales to capture the PopIII → PopII transition (e.g. Tornatore+2007; Wise & Mesinger *in-prep*).

Early stages, continued…

Wise & Mesinger (in prep)



Early stages, continued…

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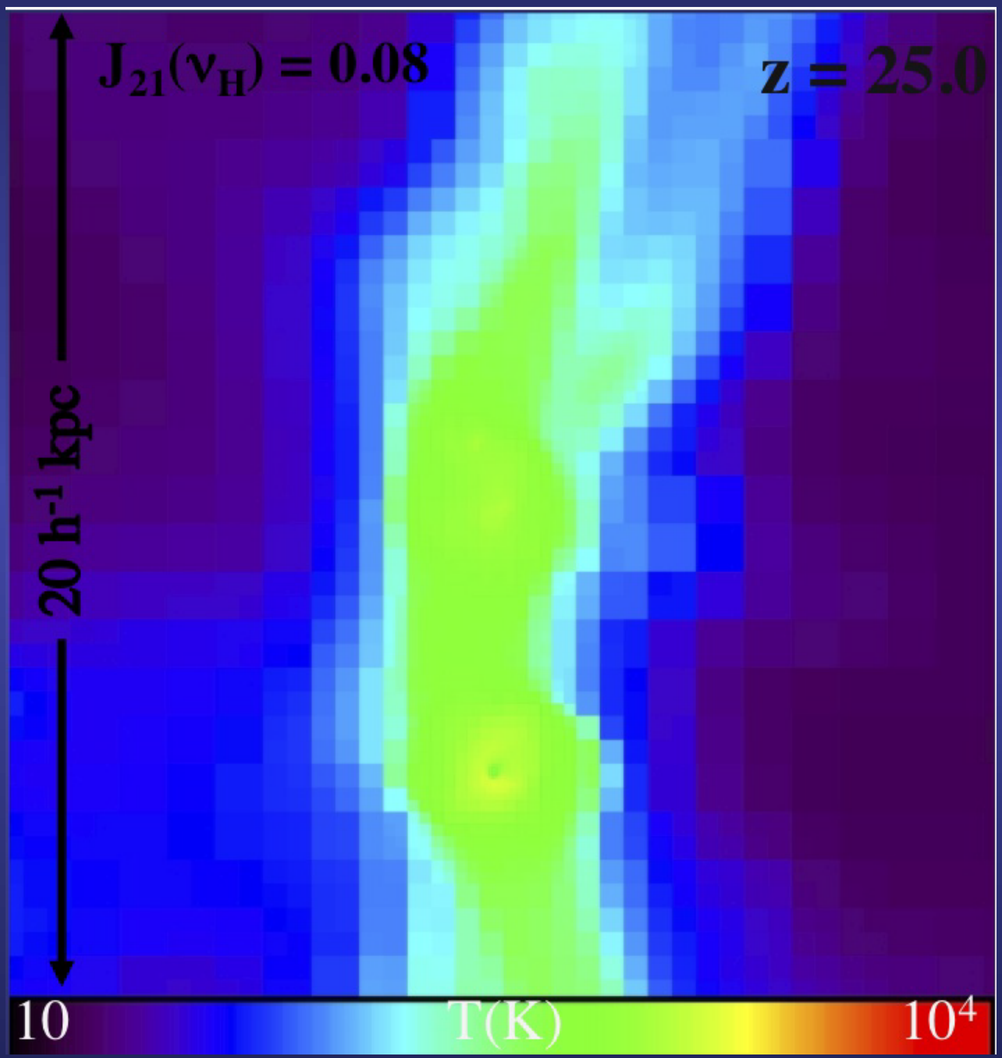
3. Radiative – X-rays (Kuhlen & Madau 2005); transient UV (Oh & Haiman 2003; Mesinger, Bryan & Haiman 2006, 2009; Wise & Abel 2007; Whalen+2008); LW (Machacek +2001,2003; Yoshida+2003); Combination (Mesinger, Bryan & Haiman 2006, 2009; Wise & Abel 2007)

 *positive (e^- catalyzes H_2 formation/cooling channel)*

 *negative (LW radiation disassociates H_2; radiative heating can photoevaporate small halos)*

Early stages, continued…



Mesinger, Bryan, Haiman (2006)

Advanced stages of reionization

- Eventually atomically-cooled halos ($T_{VIR}>10^4$ K) dominate the ionizing photon budget.
- HII regions grow to be ~ tens of comoving Mpc in size → >10000 times the volumes of the AMR simulations shown before!
- This means:
  - more approximate/empirical prescriptions
  - ignore (or add "by-hand") photon sinks
  - ignore minihalos
  - even if you ignore minihalos, simulations are limited to ~100Mpc
- Even with this, we don't know how to populate our DM halos with luminous matter…

Philosophy… how to approach the problem

Strategy #1:

bottom-up approach

scale

Seminumerical Simulations
or Analytic Estimates

↑

Seminumerical Simulations or
lower resolution large-scale numerical simulations

↑

Hydrodynamical Numerical Simulations (+RT)

Philosophy… how to approach the problem

Strategy #2:

Large scales/analytic models to generate ***general, robust*** *claims (true for large swaths of parameter space)*

make predictions & match observations (caution: interpretation is difficult; watch out for degeneracies..)

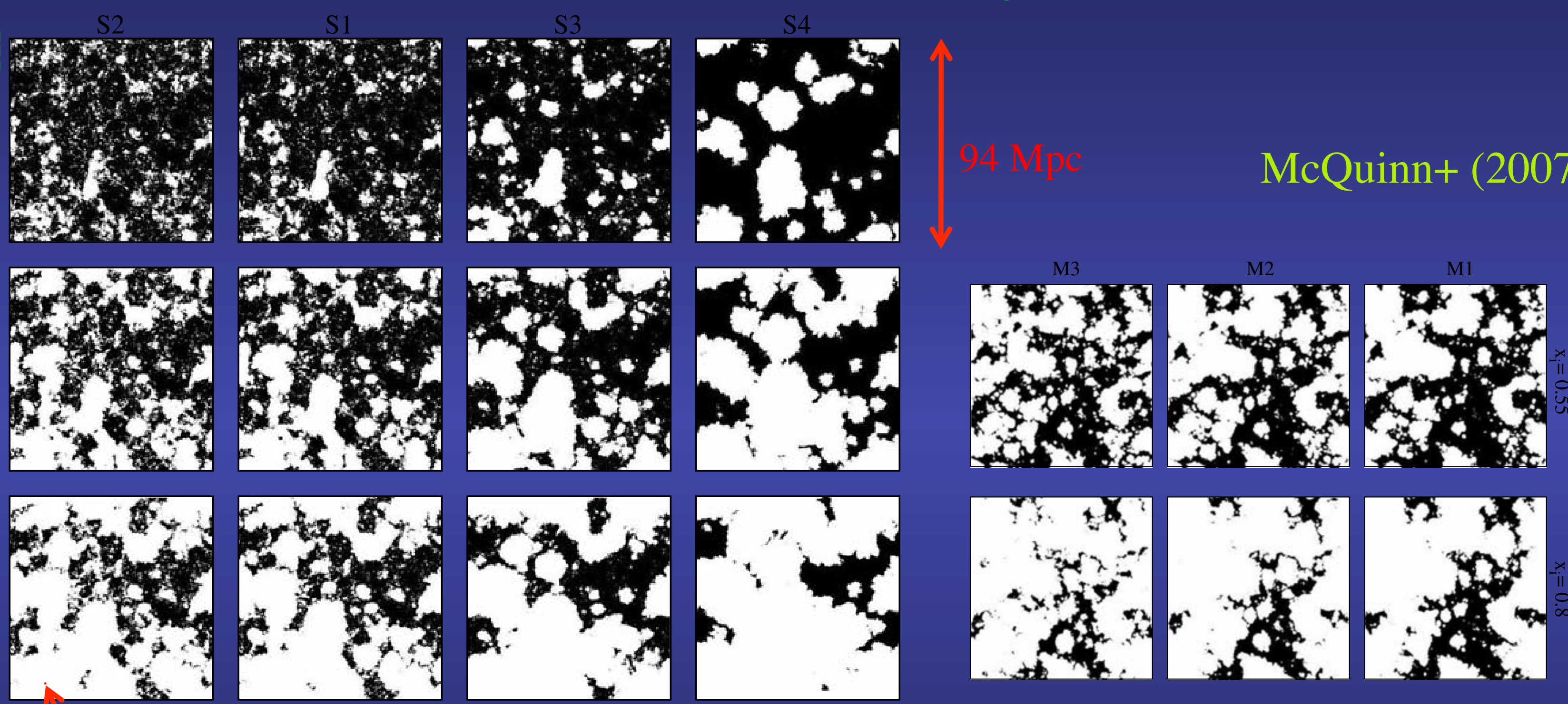
Can be used to simplify the problem:

- radiative feedback is not so important (e.g. Mesinger & Dijkstra 2008)
- HII morphology not sensitive to *z*, when normalized to same $\langle x_{HI} \rangle$ (Furlanetto +2004; McQuinn+ 2007)
- *sources* are more important than *sinks* in setting HII morphology (Furlanetto+2004; McQuinn+ 2007)

e.g.: ionization morphology parameter study

various models →

redshift or x_{HI} ↓



McQuinn+ (2007)

sources

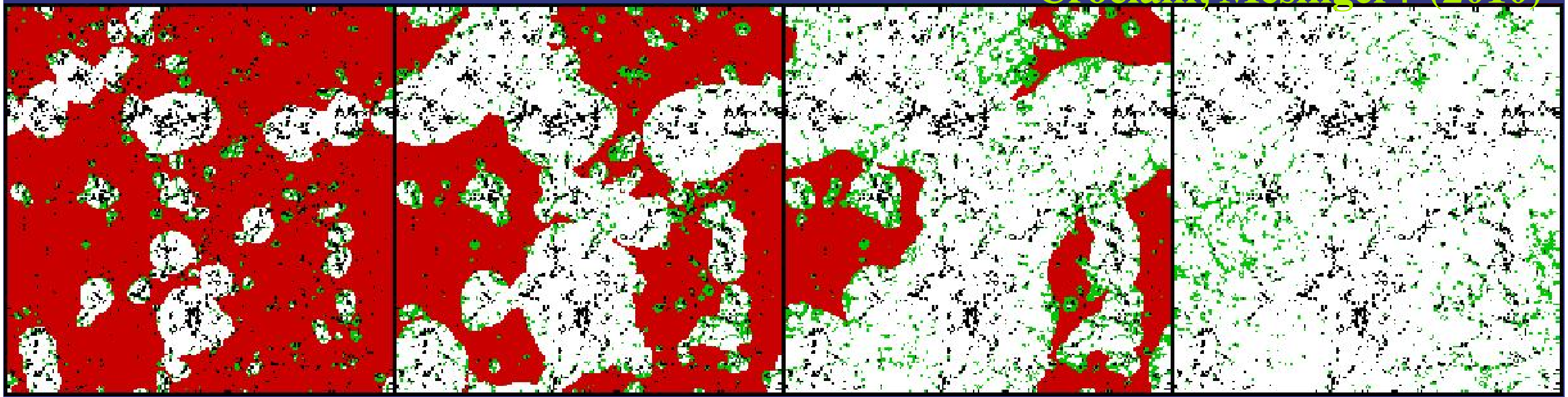
sinks

"early reionization" box size

Final stages of reionization…sinks

-photon sinks (Lyman limit absorption systems) regulate the progress of reionization once the HII regions grow to be larger than the mean free path through them (e.g. Mesinger & Dijkstra 2008; Furlanetto & Mesinger 2009).

Crociani, Mesinger+ (2010)



x_{HI}=0.72 x_{HI}=0.45 x_{HI}=0.45 x_{HI}=0

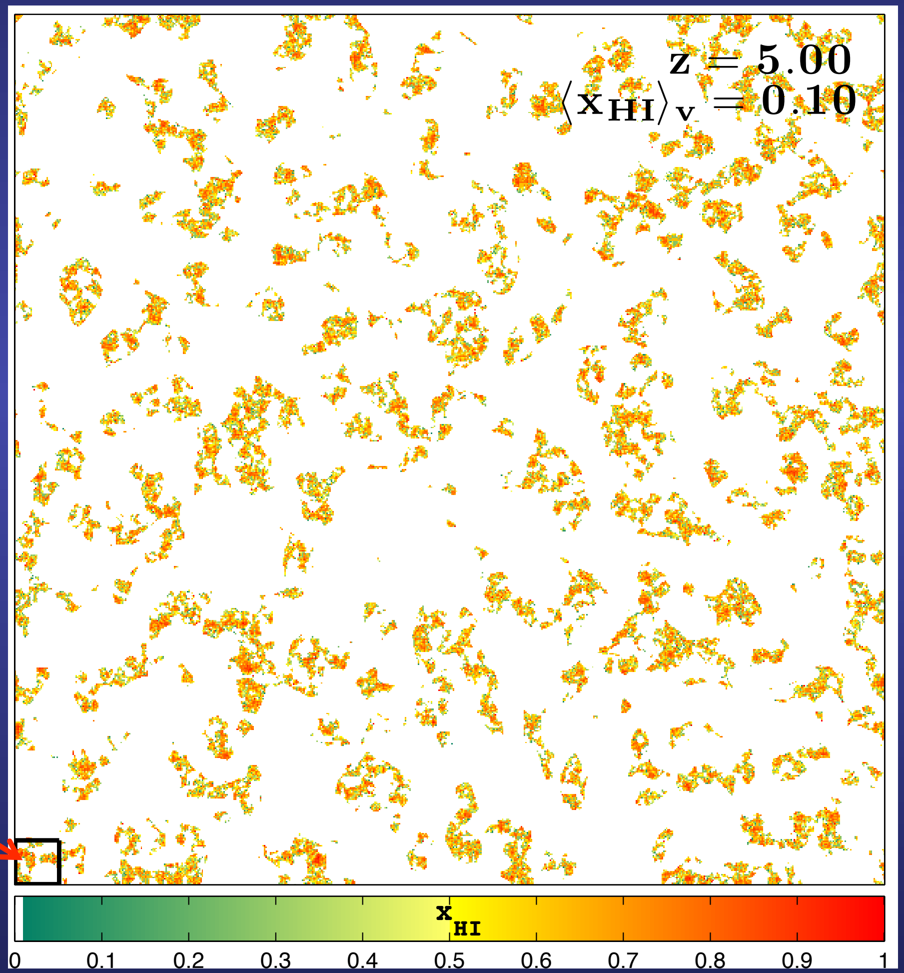
-final overlap stages could be delayed until absorbers are photoevaporated or remaining neutral islands ionized from the inside → slow and gradual evolution of Γ (Furlanetto & Mesinger 2009)

-strong 21cm signal from absorbers?

- -yes (Choudhury+2010)
- -probably not (Lidz+ 2008; Crociani, Mesinger+ 2010)

And again we need even larger boxes..

Mesinger (2010)



2 Gpc

"middle reionization" box size

Can’t we place constraints using existing observations??

Very difficult… Current observations are sparse and open to many interpretations.

Current Reionization Constraints at z~6-7

Caution:

- WMAP $\tau_e \sim 0.087 \pm 0.017$ reionization z~11?
  Dunkely+2009

- *integrated measurement*

- *Lyα forest in GP troughs of SDSS QSOs*
  Fan et al. 2006: $x_{HI} \geq 10^{-3}$ and accelerated τ_{GP} evolution
  Becker et al. 2007: no accelerated evolution

- can't predict what the gas is doing even in the ionized IGM (analytical density models; differences sensitive to low τ)
-density field scatter (Lidz+ 2007)
-extrapolation sensitive to continuum fitting
-rise in τ does not directly translate to rise in x_{HI} (Furlanetto & Mesinger 2009)

- *Size of Proximity Region: $x_{HI} \geq 0.1$*
  Wyithe & Loeb 2004; Wyithe+ 2004
  Evolution in size (Fan et al. 2006): $x_{HI} \sim 10^{-3}$

-extremely model-dependent
-cannot directly read size or evolution of proximity region from spectra! (Mesinger+ 2004; Mesinger & Haiman 2004; Bolton & Haehnelt 2007ab; Maselli+ 2006, 2007)

Current Reionization Constraints at z~6-7, *cont*.

Caution:

- No evolution in Lyα emitter (LAE) LF
  - In isolation: $x_{HI} < 0.3$ (e.g. Malhotra & Rhoads 2004)
  - Clustered: $x_{HI} < 0.5$ (Furlanetto+ 2006)
- Some evolution in LAE LF (Kashikawa+ 2006)
- LAE clustering $x_{HI} < 0.5$ (McQuinn+ 2007)

-L <--> M unknown
-very model dependent
-drop due to density and halo evolution? (Dijkstra et al. 2007)
-reionization signature should be a flat suppression (Furlanetto+ 2006; McQuinn+ 2007; Mesinger & Furlanetto 2008a)
-Iliev+ 2008 disagree with impact on clustering

- *Lack of Lyα damping wing in z=6.3 GRB*
  Totani+ 2006 $x_{HI} < 0.2$

-no statistical significance (McQuinn et al. 2008; Mesinger & Furlanetto 2008b)

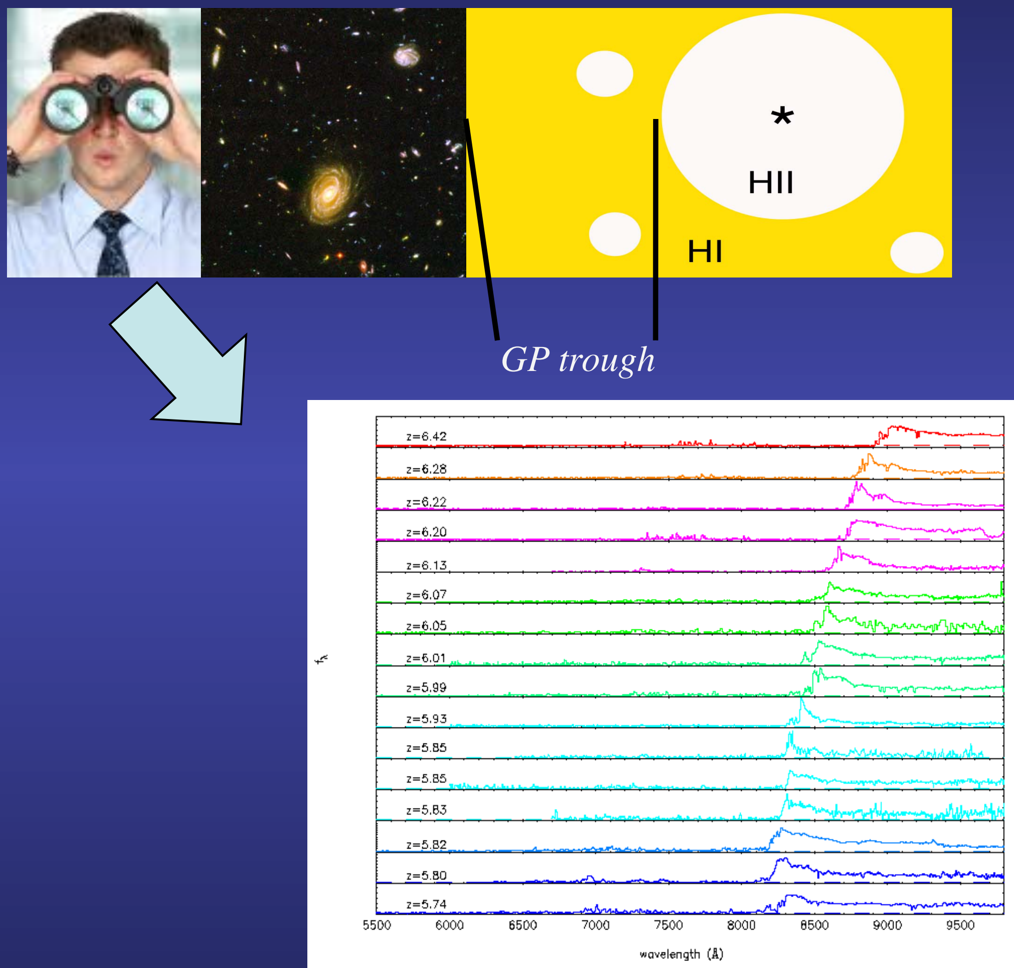
- *Detection of Lyα damping wing in QSOs*

Sharp decline in flux (Mesinger & Haiman 2004) $x_{HI} > 0.2$
Modeling Lyα forest in proximity region
(Mesinger & Haiman 2007) $x_{HI} > 0.03$

- 2 sightlines
- patchy reionization likely degrades confidence contours (Mesinger & Furlanetto 2008b)

e.g. High-z Quasars

e.g. White+ (2003)

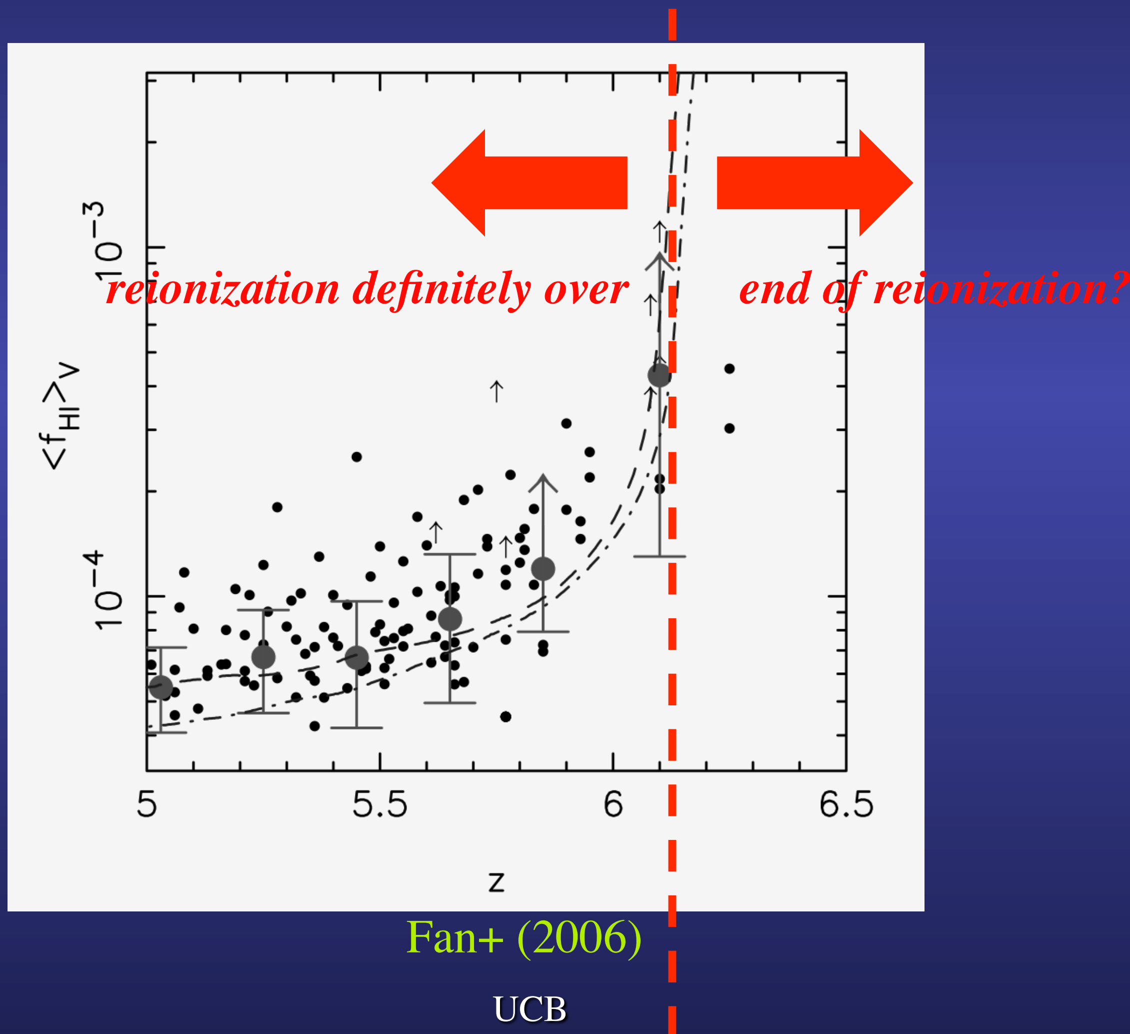


Lyα is sensitive to $x_{HI} < 10^{-4}$

Fan+ (2006)

e.g. High-z Quasars

observed flux → IGM neutral fraction



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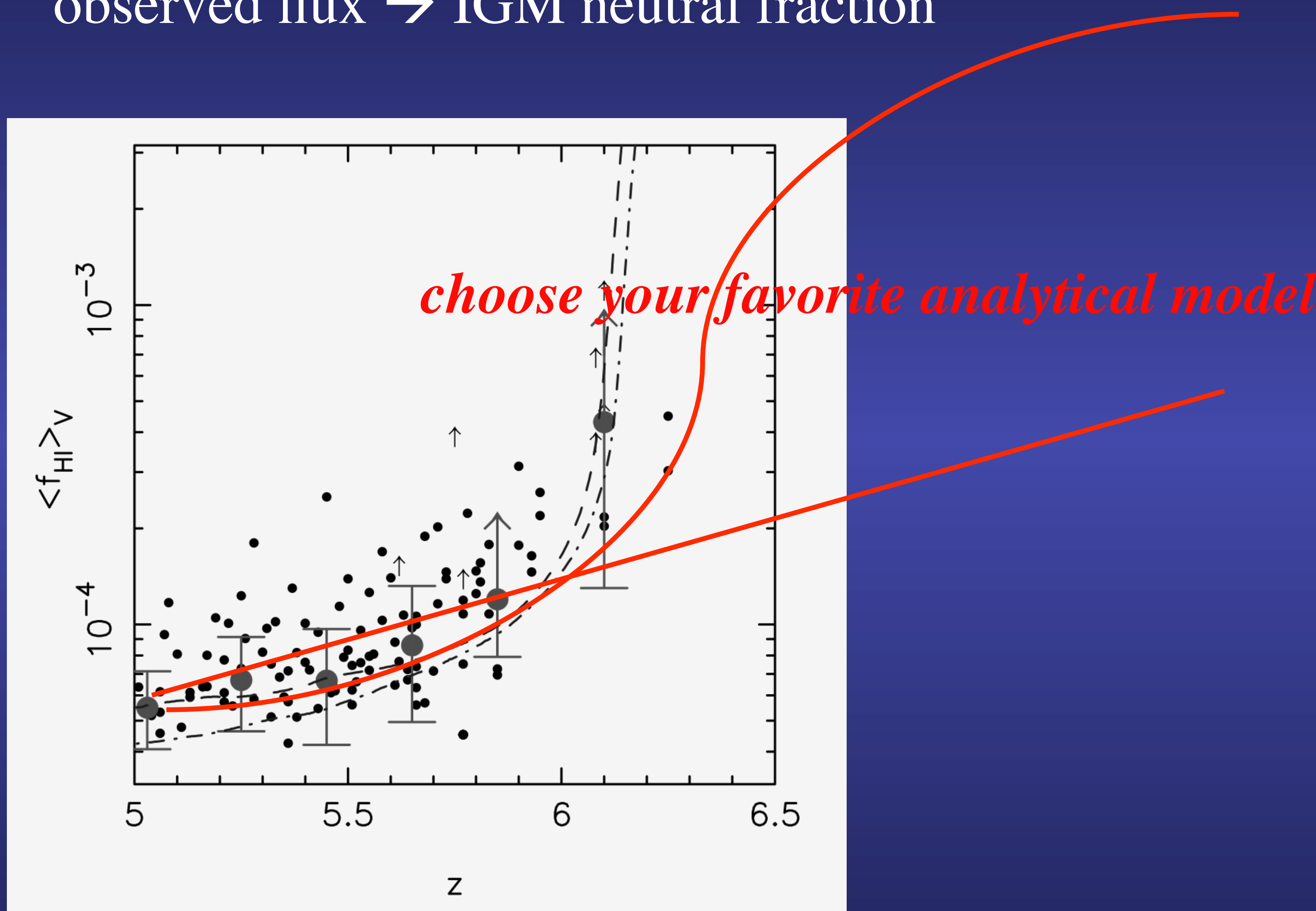


Fan+ (2006)

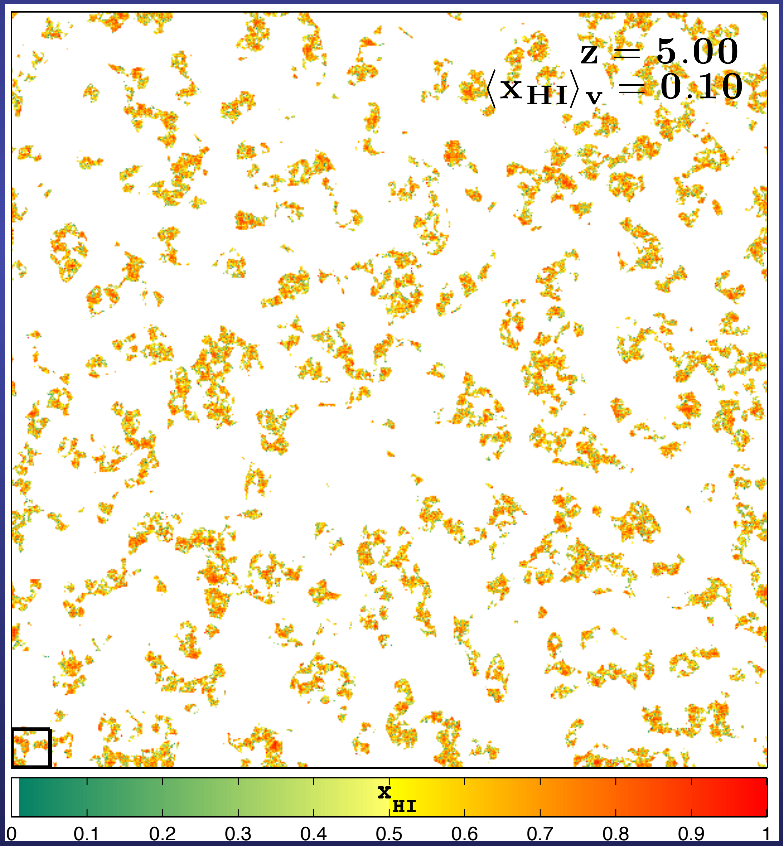
Now lets go back and think about z<6

observed flux $\overset{?}{\rightarrow}$ IGM neutral fraction

a-priory assumes reionization is over through a uniform ionization rate!

Reionization is VERY inhomogeneous!

2 Gpc



much of the spectra pass just through the ionized IGM!

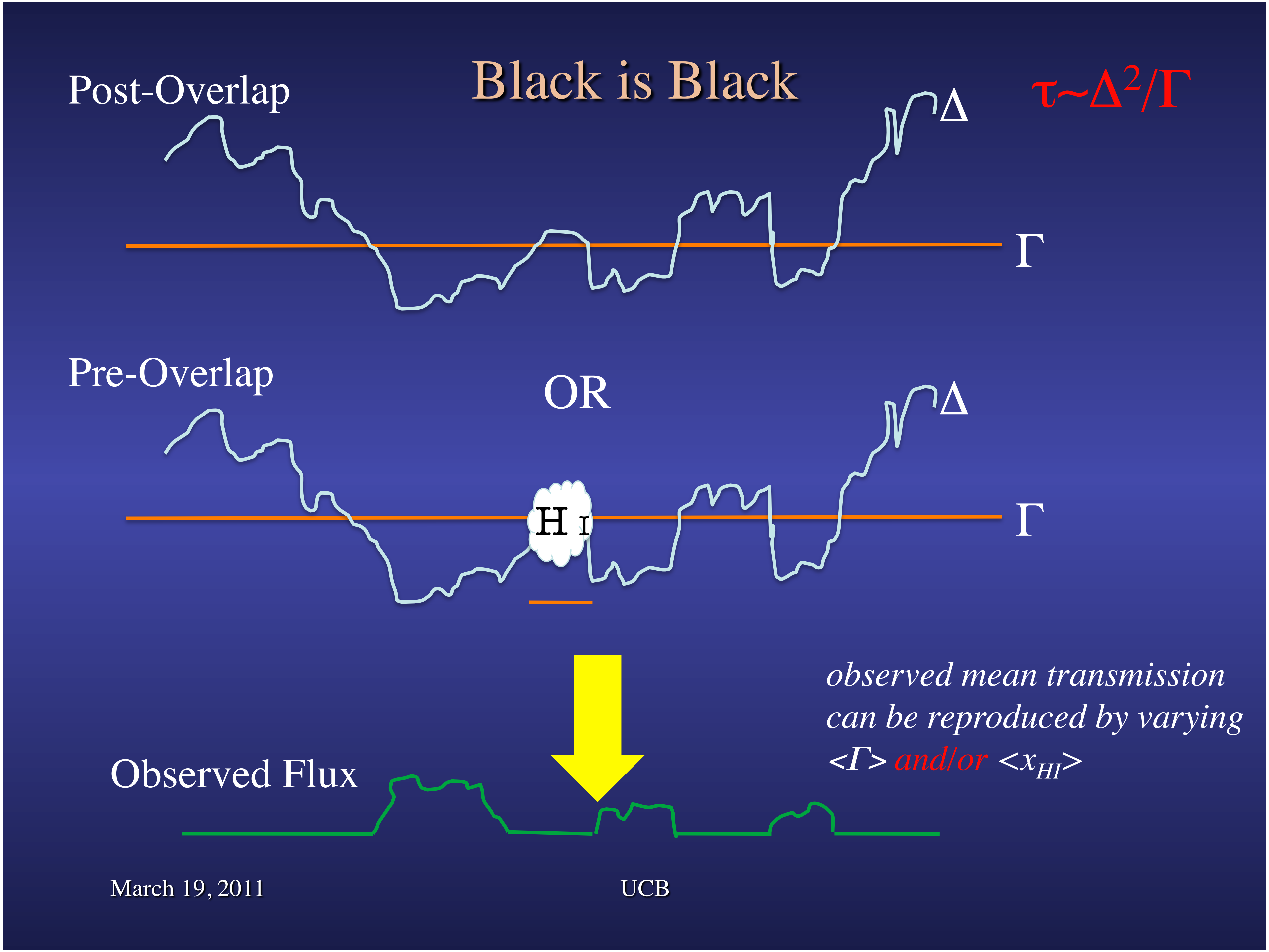
Mesinger (2010)
see also Lidz+(2007)

Black is Black

$\tau \sim \Delta^2/\Gamma$

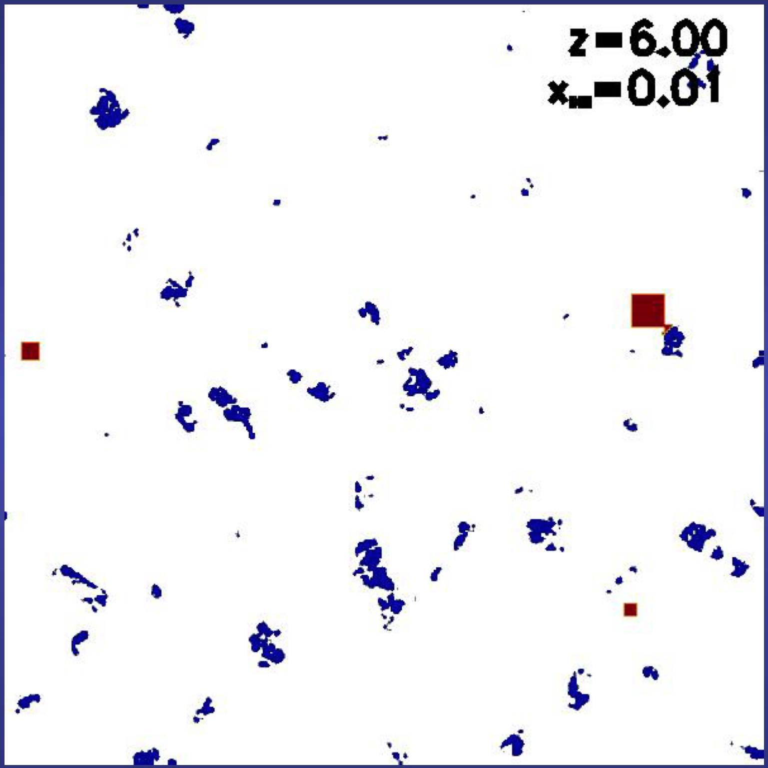
Post-Overlap

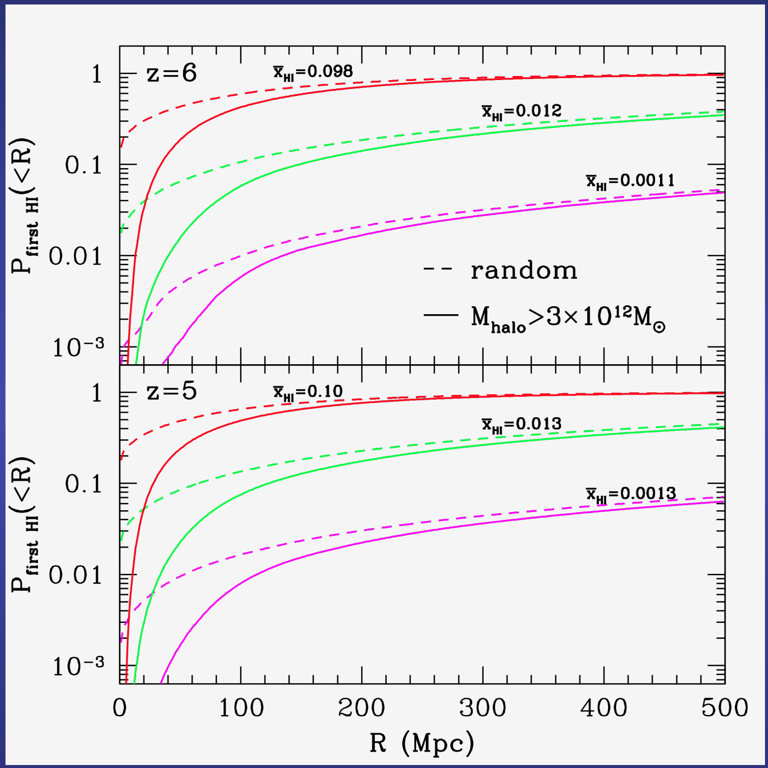
Observed Flux



Black is Black
Post-Overlap
τ~Δ²/Γ
Δ
Γ
Pre-Overlap
OR
Δ
H I
Γ
Observed Flux
observed mean transmission
can be reproduced by varying
<Γ> and/or <x_HI>
March 19, 2011
UCB

Another complication:
QSO bias with respect to the ionization field



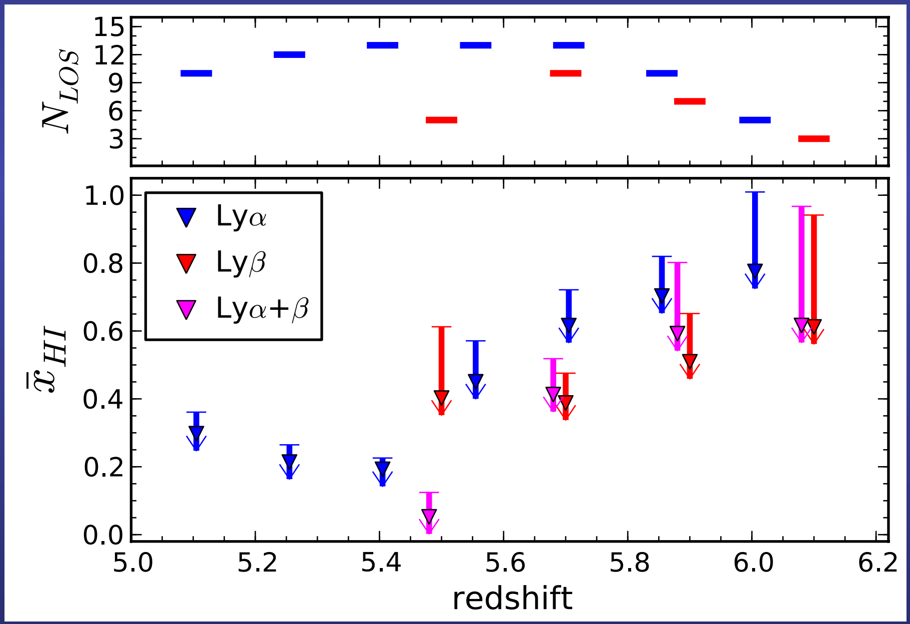


Mesinger (2010)

So what are the actual observational constraints??

-simplest, model-independent upper limit comes from the "dark fraction"
-it is an upper limit since you are also counting the absorption inside the ionized IGM

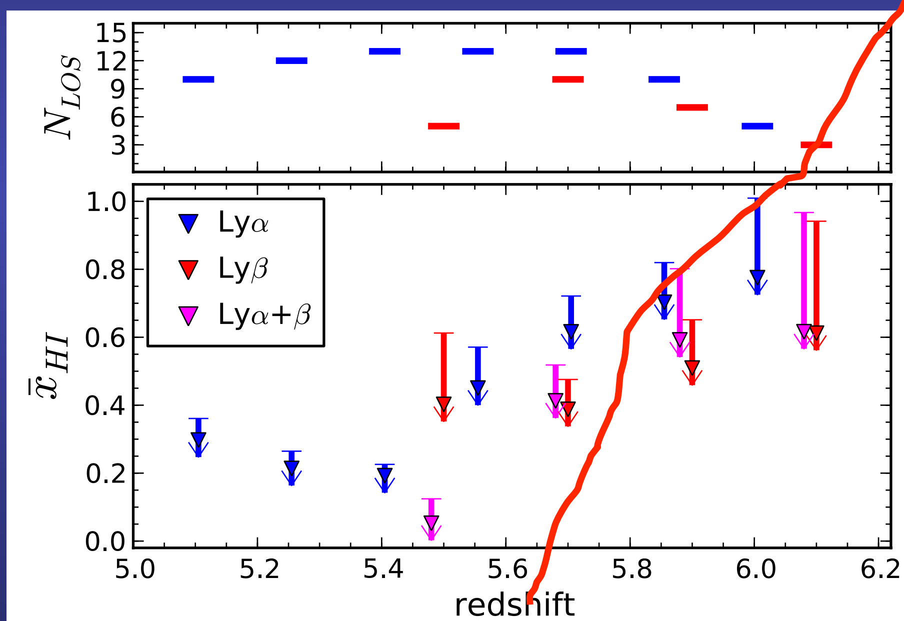
McGreer, Mesinger, Fan (2011)

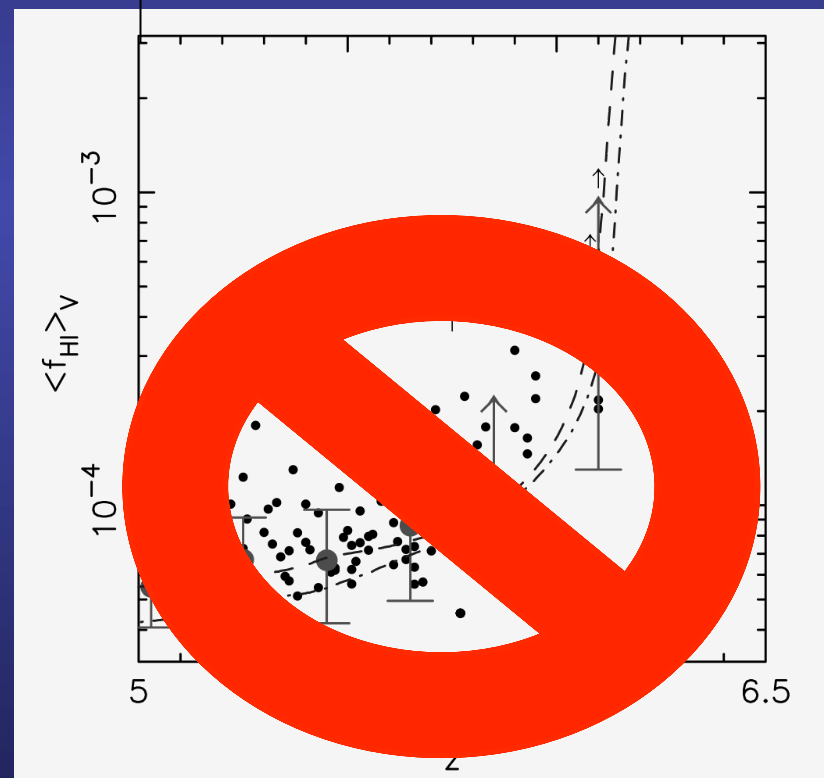


The more we learn, the less we know…

choose your favorite analytical model

McGreer, Mesinger, Fan (2011)

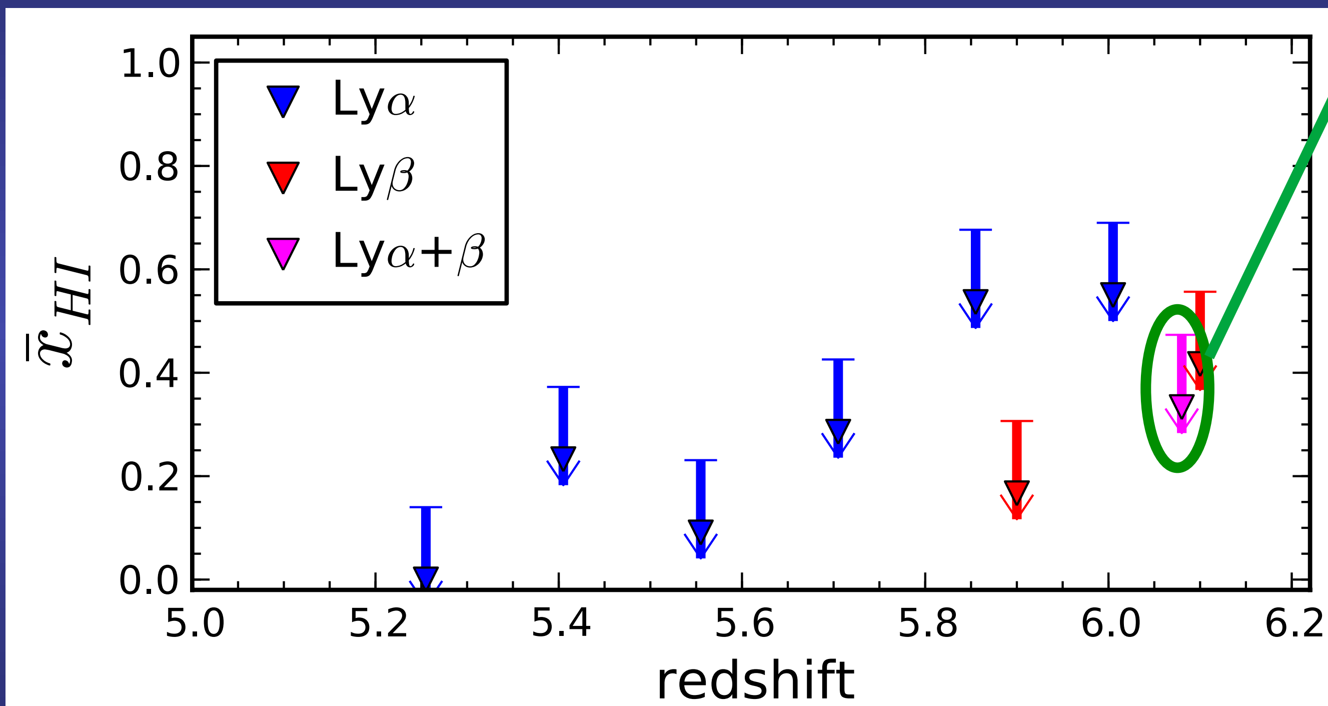




Two deepest spectra:
Most robust upper limit on $\langle x_{HI} \rangle$ at z~6!

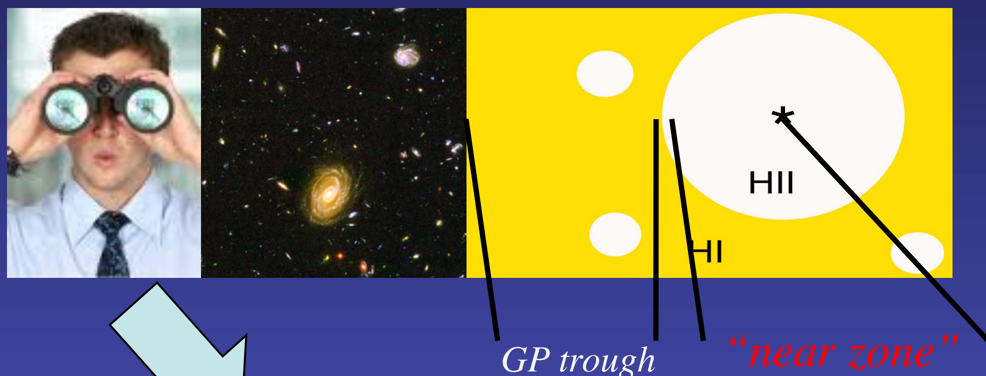
$\langle x_{HI} \rangle_V < 0.5$

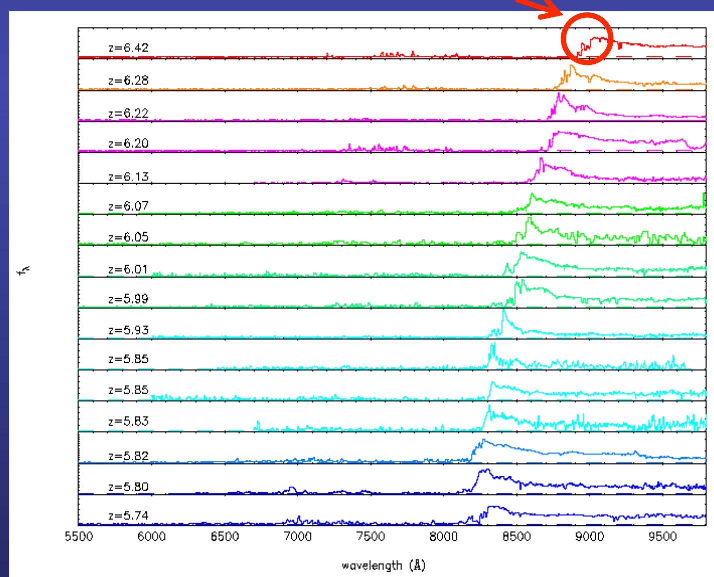
McGreer, Mesinger, Fan (2011)



cosmic variance error bars are conservatively estimated from the models of Mesinger (2010)

Now let's try to get get creative and do some modeling



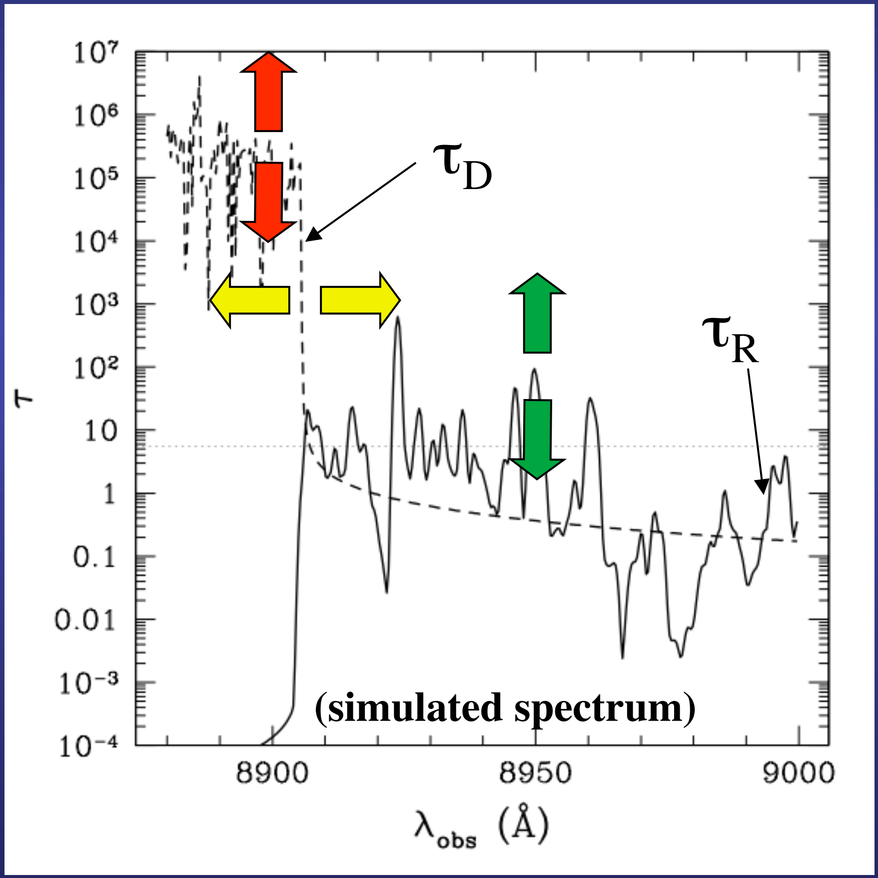


Lyα is sensitive to $x_{HI} < 10^{-4}$

Fan+ (2006)

Model the flux distributions in the near zone

Model spectra using LOSs from hydro simulations (Cen et al. 2003)



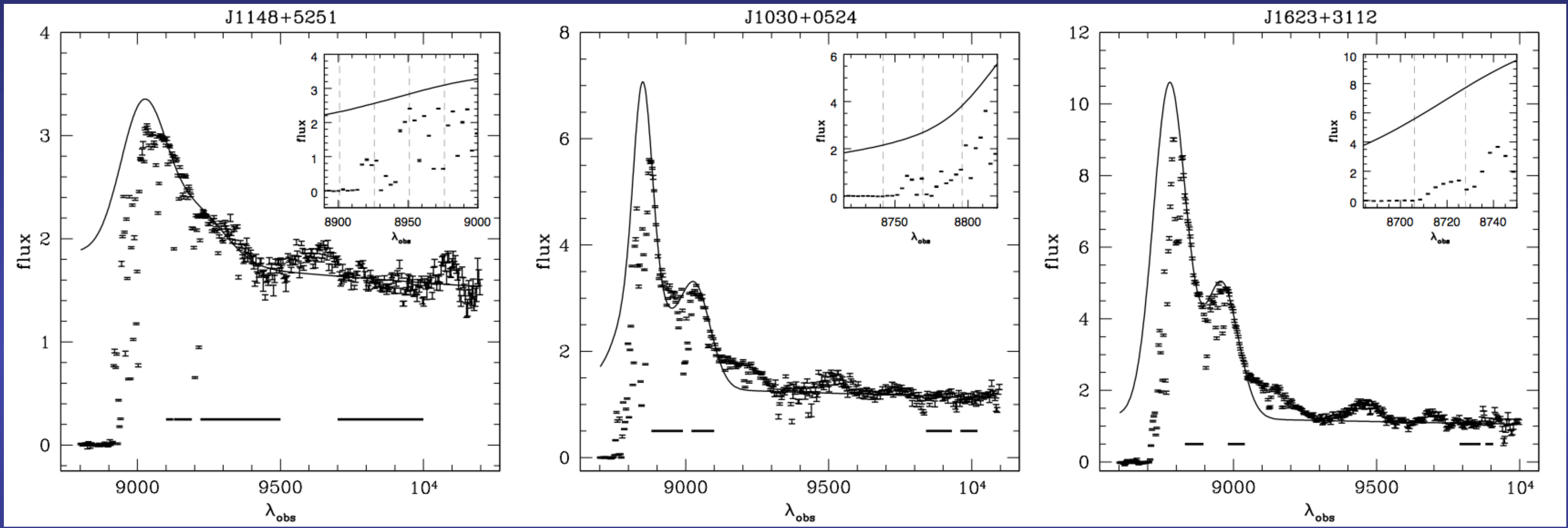
Free Parameters:

- IGM neutral fraction, x_{HI}
- distance to HII region edge, R_S
- QSO's ionizing luminosity, L_ν

Important to keep parameters free and treat each spectrum independently

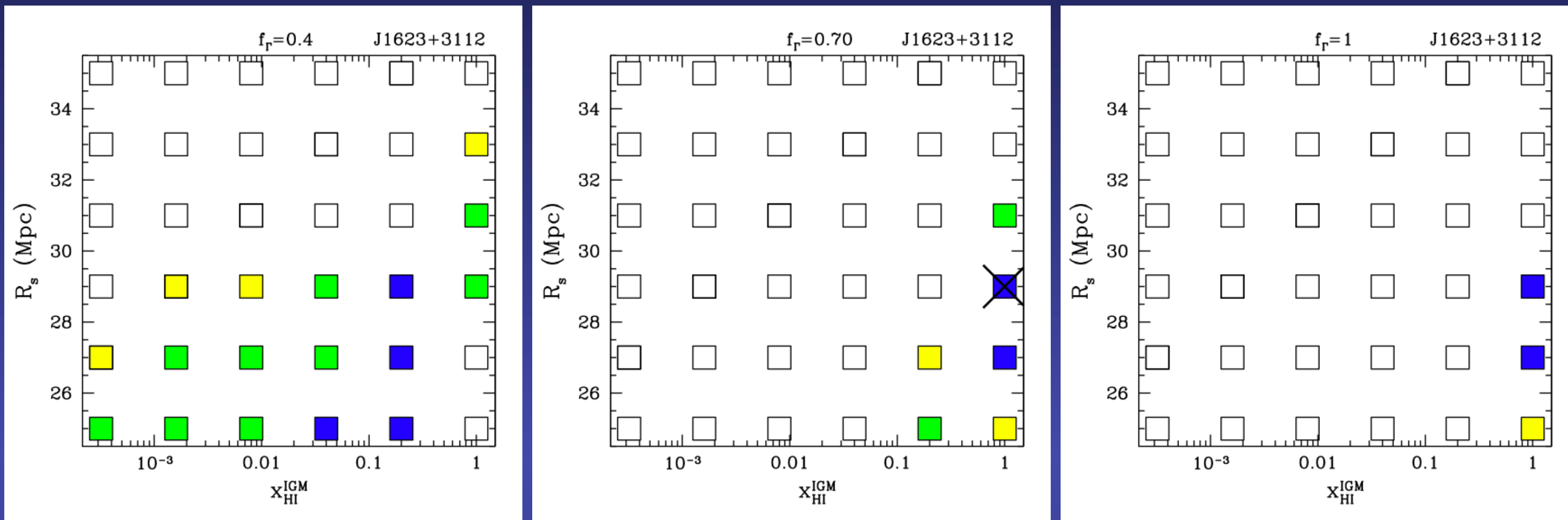
Fitting QSO Intrinsic Emission

Mesinger & Haiman (2007)



double Gaussian for Lyα + single Gaussian for Nv + power law continuum

e.g. J1623+3112, z = 6.22



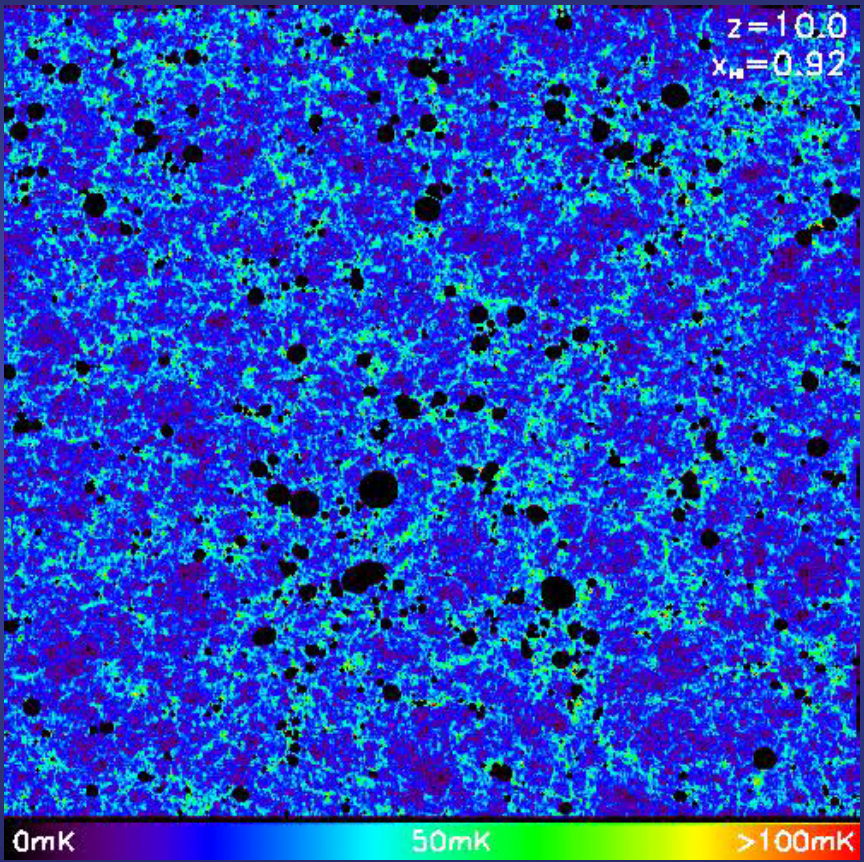
Peak likelihood of 39% occurs at $(R_S, x_{HI}, N_{ph}) = (29\ \mathrm{Mpc}, 1.0, 0.7\mathrm{x}10^{57}\mathrm{s}^{-1})$

- $25\ \mathrm{Mpc} \leq R_S \leq 29\ \mathrm{Mpc}$
- $0.033 \leq x_{HI}$
- $0.5\mathrm{x}10^{57}\mathrm{s}^{-1} \leq N_{ph} \leq 1.7\mathrm{x}10^{57}\mathrm{s}^{-1}$

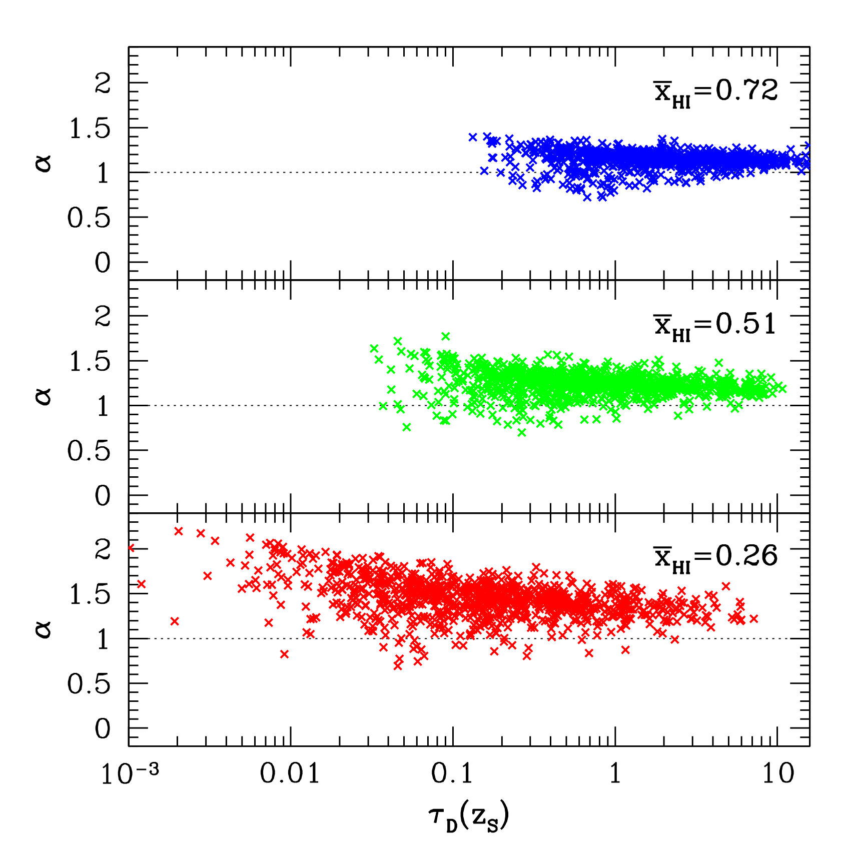
But again, reionization is patchy!

→ scatter and bias in the damping wing profile

profile is steeper, more DLA-like



http://www.astro.princeton.edu/~mesinger/DexM



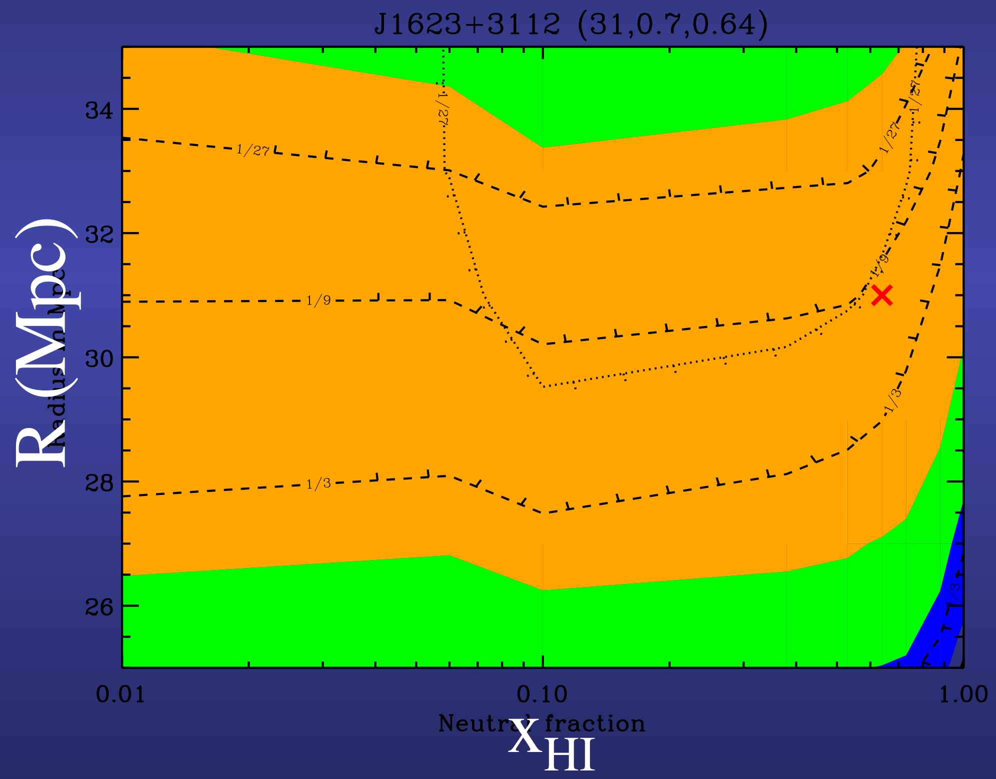
Mesinger & Furlanetto (2008)

see also McQuinn+(2008) for explicit application to GRBs

Re-analysis with patchy reionization

include patchy reionization LOSs from DexM (*http://www.astro.princeton.edu/~mesinger/DexM*)

no priors on the size of the HII region



Schroeder, Mesinger, Haiman (in-prep)

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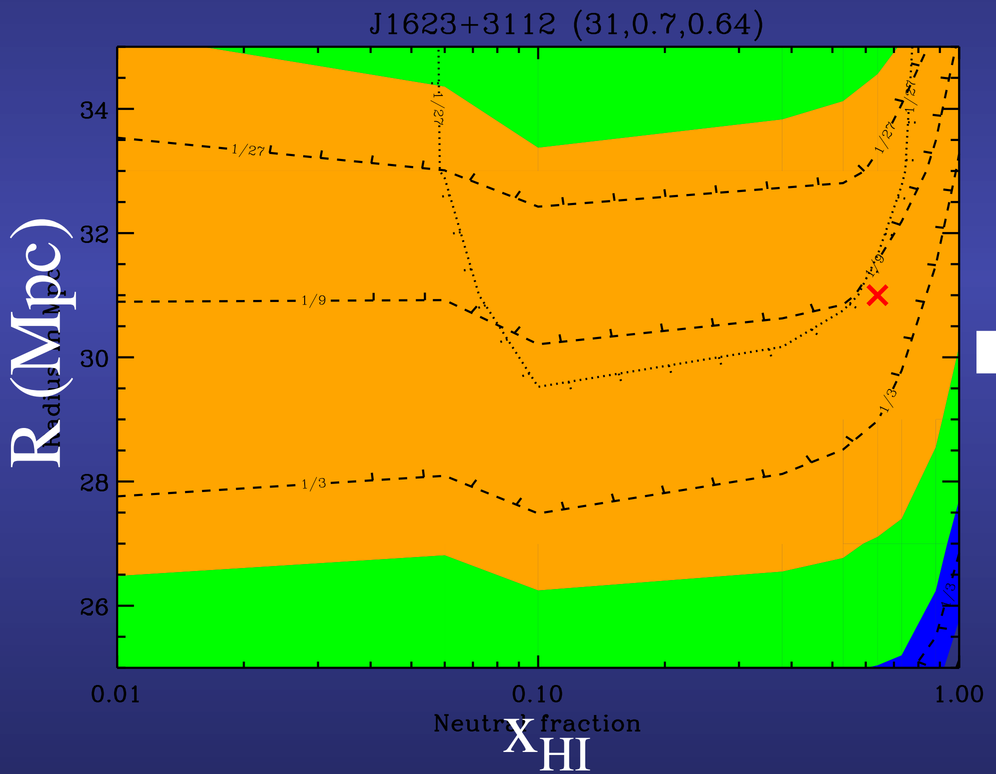
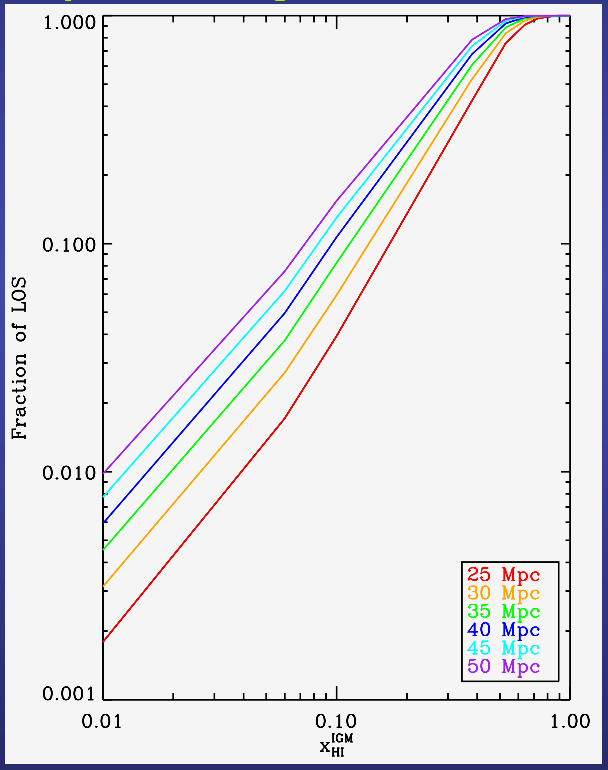


Schroeder, Mesinger, Haiman (in-prep)

priors on HII region size
(from Mesinger 2010)



+ =

Re-analysis with patchy reionization

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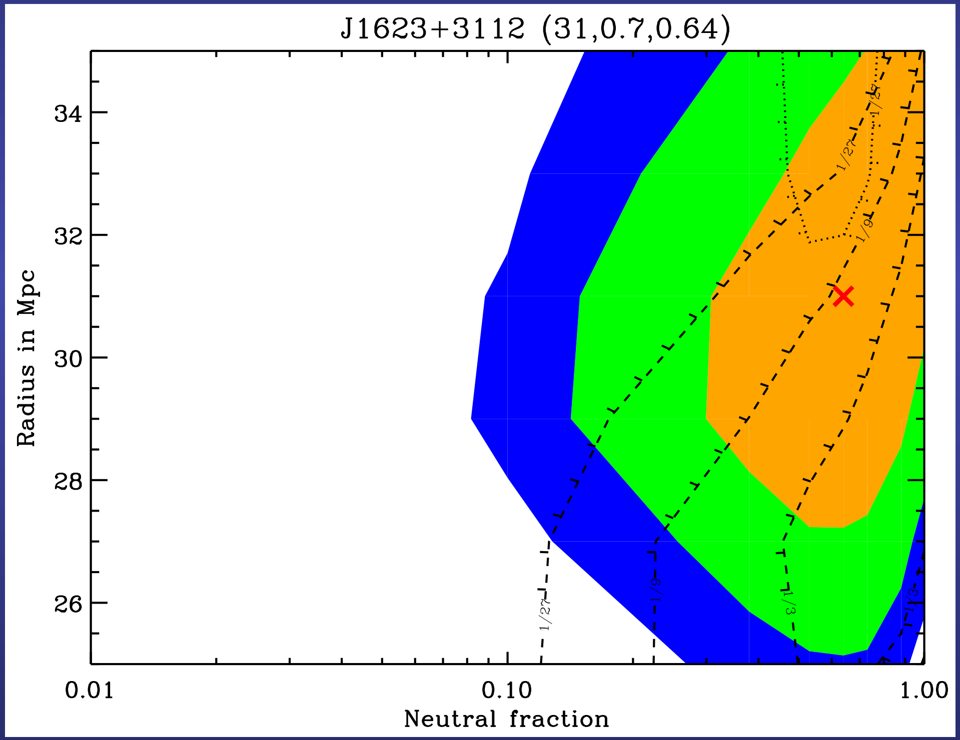
with priors on the size of the HII region



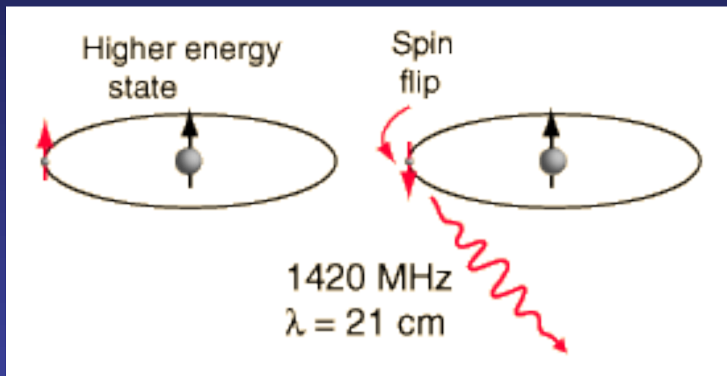
Schroeder, Mesinger, Haiman (in-prep)

- *Strong damping wing is preferred in 2 out of 3 QSOs*
- *However, prior probabilities must be used to rule out isolated HI patches in highly ionized IGM or DLAs*
- *There is no evidence of DLAs however in HIRES spectra (Becker, private com.)*

Coming soon: a direct probe of the astrophysical bounty of reionization and the dark ages:

21cm!

21 cm line from neutral hydrogen

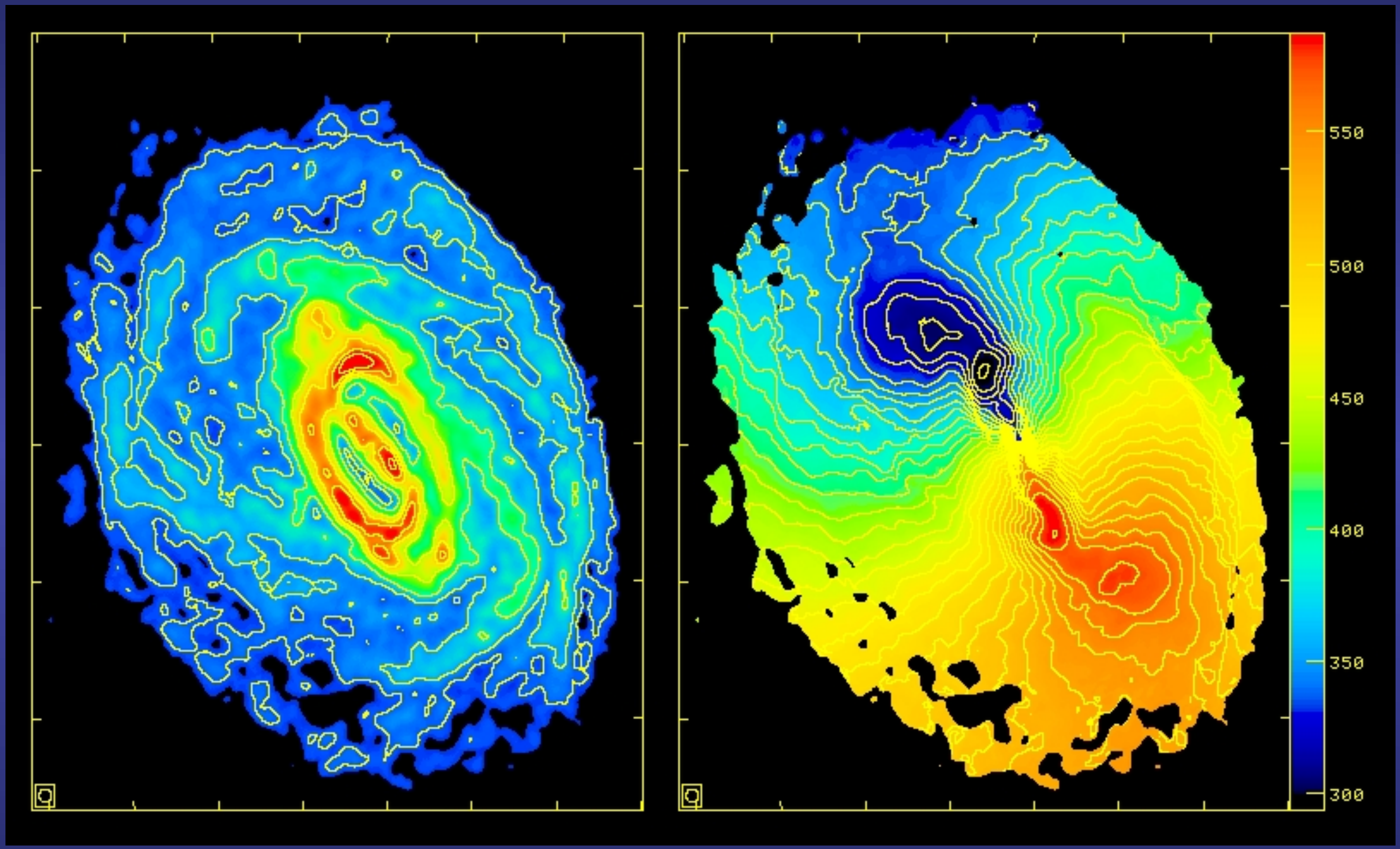


Hyperfine transition in the ground state of neutral hydrogen produces 21cm line.

2. In discussion with H.C. van de Hulst, at the reception on the occasion of Oort's quadrennial jubilee as a staff member of Leiden Observatory, 1964.

Predicted by van den Hulst when Oort told him to find unknown radio lines to study our galaxy

Now widely used to map the HI content of nearby galaxies



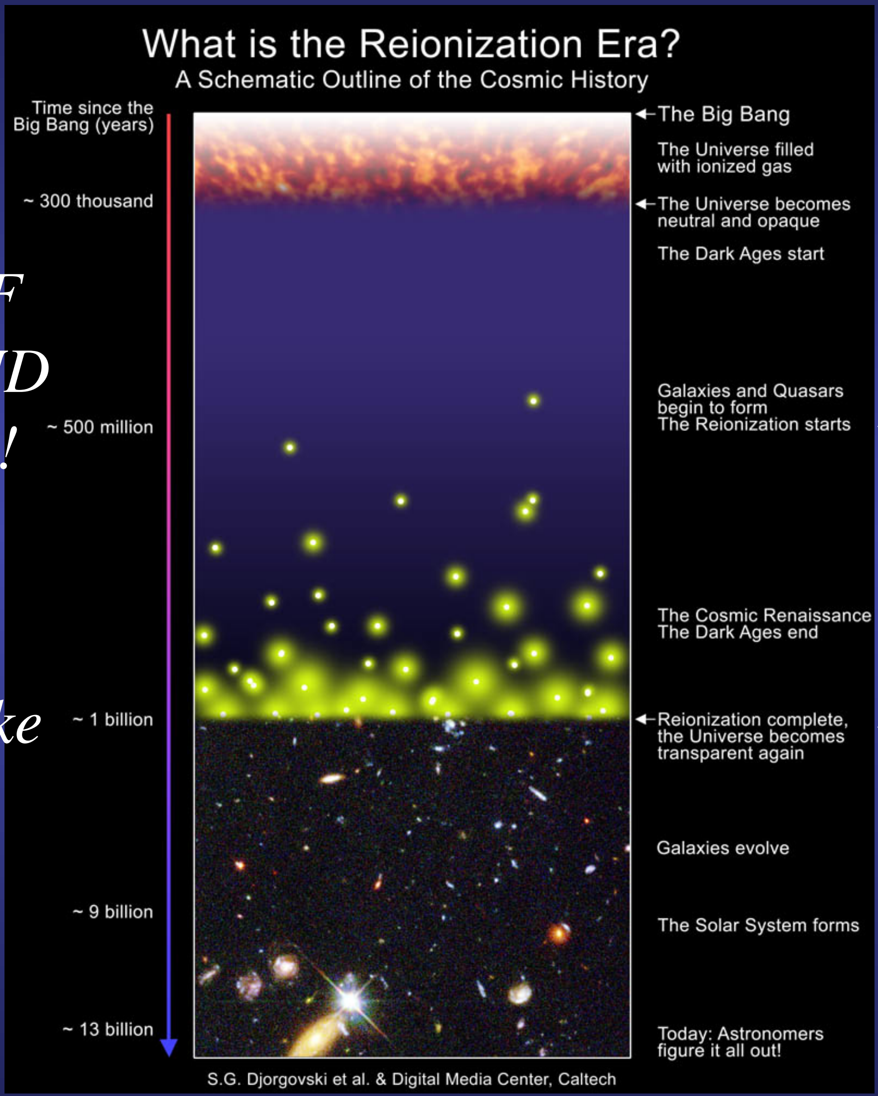
Circinus Galaxy

ATCA HI image by B. Koribalski (ATNF, CSIRO), K. Jones, M. Elmouttie (University of Queensland) and R. Haynes (ATNF, CSIRO).

Once upon a time, HI was much more abundant

DIRECT PROBE OF REIONIZATION AND THE DARK AGES!!!

Does not saturate like Lyman transitions!



z ~ 30 ?

z ~ 6 ???

Cosmological 21cm Signal

$$\delta T_b(\nu) \approx 27 x_{HI} (1+\delta_{nl}) \left(\frac{H}{dv_r/dr + H}\right) \left(1 - \frac{T_\gamma}{T_S}\right) \left(\frac{1+z}{10}\frac{0.15}{\Omega_M h^2}\right)^{1/2} \left(\frac{\Omega_b h^2}{0.023}\right) \text{mK}$$

spin temperature

LOS velocity gradient

neutral fraction

gas density

Cosmological 21cm Signal

$$\delta T_b(\nu) \approx 27 x_{\mathrm{HI}}(1+\delta_{\mathrm{nl}})\left(\frac{H}{dv_r/dr + H}\right)\left(1-\frac{T_\gamma}{T_S}\right)\left(\frac{1+z}{10}\frac{0.15}{\Omega_M h^2}\right)^{1/2}\left(\frac{\Omega_b h^2}{0.023}\right) \mathrm{mK}$$

Powerful probe:

Cosmology

&

Astrophysics

Has something everyone can enjoy!
The trick is to disentangle the components.

Cosmological 21cm Signal

$$\delta T_b(\nu) \approx 27 x_{HI}(1+\delta_{nl})\left(\frac{H}{dv_r/dr + H}\right)\left(1 - \frac{T_\gamma}{T_S}\right)\left(\frac{1+z}{10}\frac{0.15}{\Omega_M h^2}\right)^{1/2}\left(\frac{\Omega_b h^2}{0.023}\right) \mathrm{mK}$$

spin temperature

defined in terms of the ratio of the number densities of electrons occupying the two hyperfine levels:

$$n_1/n_0 = 3\, e^{-0.068\ \mathrm{K}/T_s}$$

Spin Temperature

$$\delta T_b(\nu) \approx 27 x_{HI}(1+\delta_{nl})\left(\frac{H}{dv_r/dr + H}\right)\left(1 - \frac{T_\gamma}{T_S}\right)\left(\frac{1+z}{10}\frac{0.15}{\Omega_M h^2}\right)^{1/2}\left(\frac{\Omega_b h^2}{0.023}\right) \text{mK}$$

spin temperature:

$$T_S^{-1} = \frac{T_\gamma^{-1} + x_\alpha T_\alpha^{-1} + x_c T_K^{-1}}{1 + x_\alpha + x_c}$$

T_γ – temperature of the CMB
T_K – gas kinetic temperature
T_α – color temperature ~ T_K

the spin temperature interpolates between T_γ and T_K

The spin temperature interpolates between T_γ and T_K

$$T_S^{-1} = \frac{T_\gamma^{-1} + x_\alpha T_\alpha^{-1} + x_c T_K^{-1}}{1 + x_\alpha + x_c}$$

two coupling coefficients:

$$x_c = \frac{0.0628\ \mathrm{K}}{A_{10} T_\gamma} \left[n_{\mathrm{HI}} \kappa_{1-0}^{\mathrm{HH}}(T_{\mathrm{K}}) + n_e \kappa_{1-0}^{\mathrm{eH}}(T_{\mathrm{K}}) + n_{\mathrm{p}} \kappa_{1-0}^{\mathrm{pH}}(T_{\mathrm{K}}) \right]$$

collisional coupling

requires high densities
effective in the IGM at z>40

$$x_\alpha = 1.7 \times 10^{11} (1+z)^{-1} S_\alpha J_\alpha$$

Wouthuysen-Field (WF)

uses the Lyα background
effective soon after the first sources ignite

The spin temperature approaches the kinetic temperature if either coefficient is high. Otherwise, the spin temperature approaches the CMB temperature: NO SIGNAL!

What do the temperatures do?

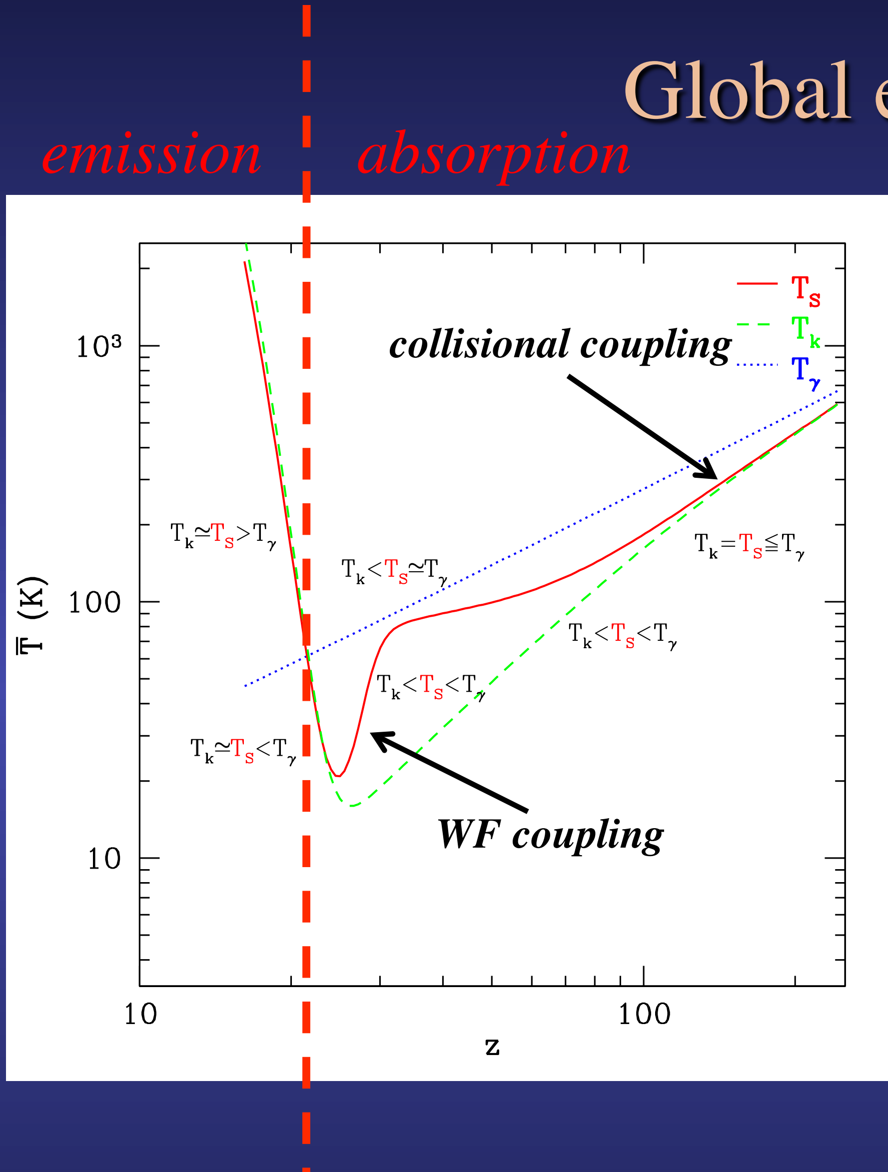
T_γ – CMB temperature decreases as (1+z)

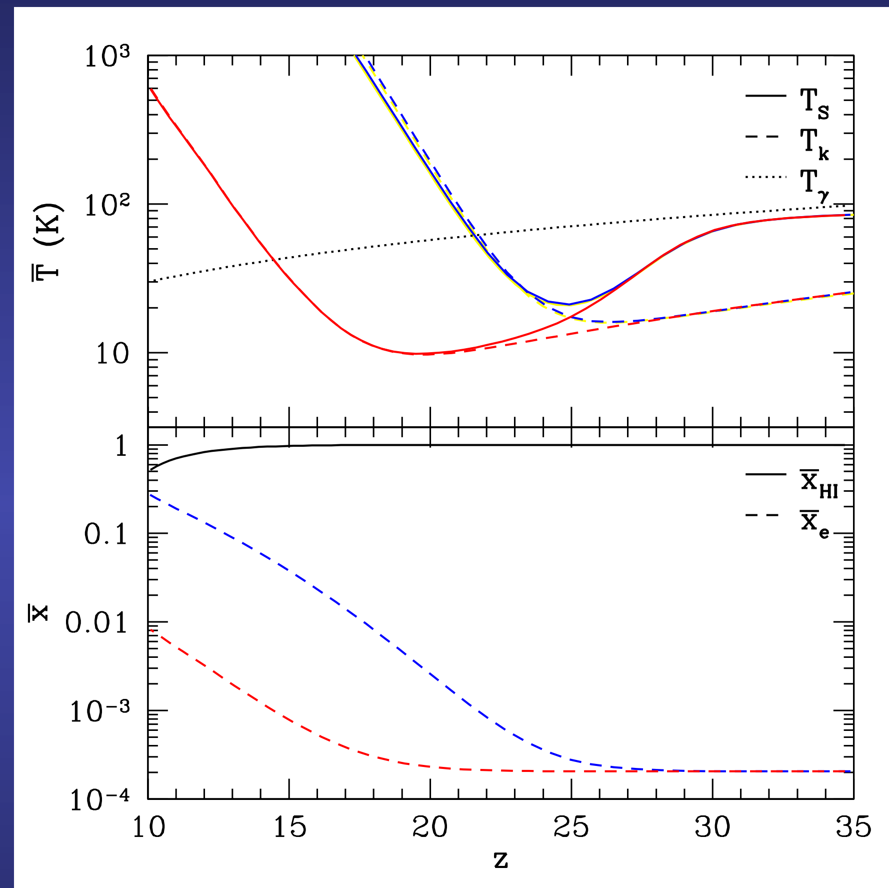
T_K – coupled to the CMB at high z ~>250. Then after decoupling adiabatically cools as $\sim(1+z)^2$. When first astrophysical sources ignite, they heat the IGM through their X-rays.

Other sources of heating:

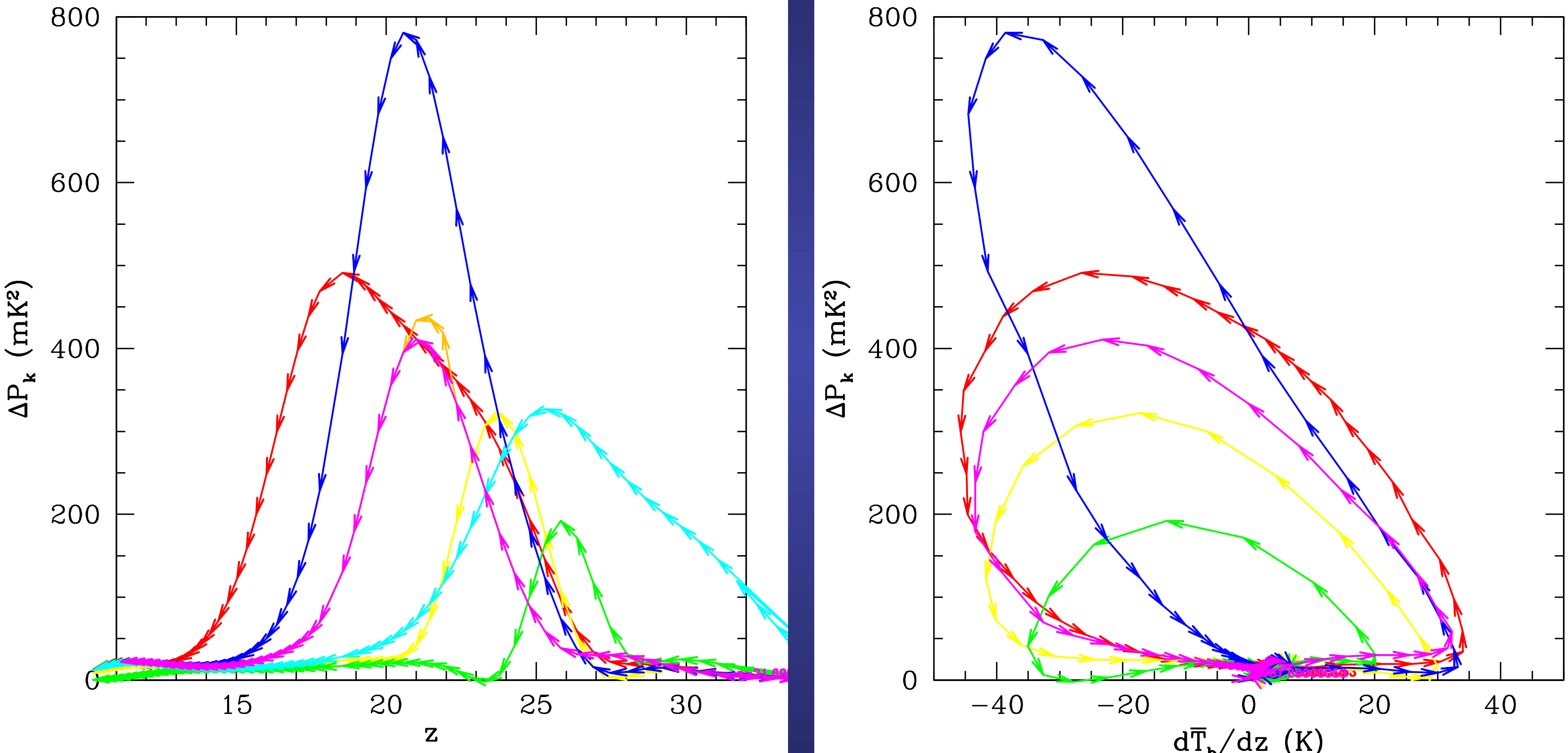
- *Compton* (high-z; included in 21cmFAST v1.0)
- *Lyα heating* (probably negligible: Chen & Miralda-Escude 2004, Rybicki 2006, Furlanetto & Pritchard 2006)
- *Shock heating* (not at strong at high-z in the IGM, e.g. Furlanetto & Loeb 2004, Kuhlen+2006; subdominant to X-ray heating for fiducial models, though see Gnedin & Shaver 2004)
- *DM annihilation* (likely minor, e.g. Mapelli et al. 2006, Furlanetto+ 2006, Ripamonti+2007, Valdes+ 2007, though depends on halo profiles and clumping., e.g. Chuzhoy 2008)

Global evolution

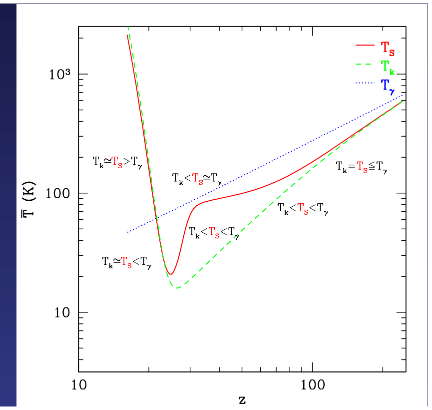




X-Ray Heating Astrophysical Parameter Space

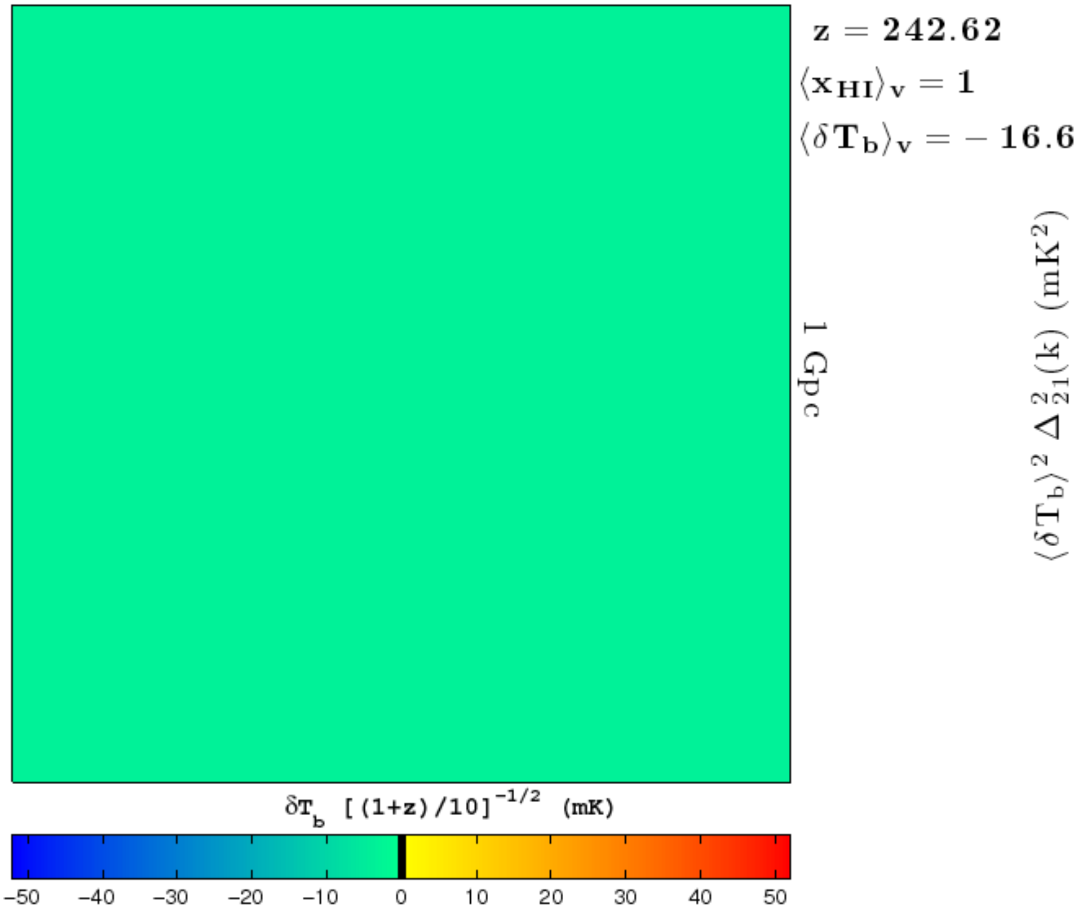


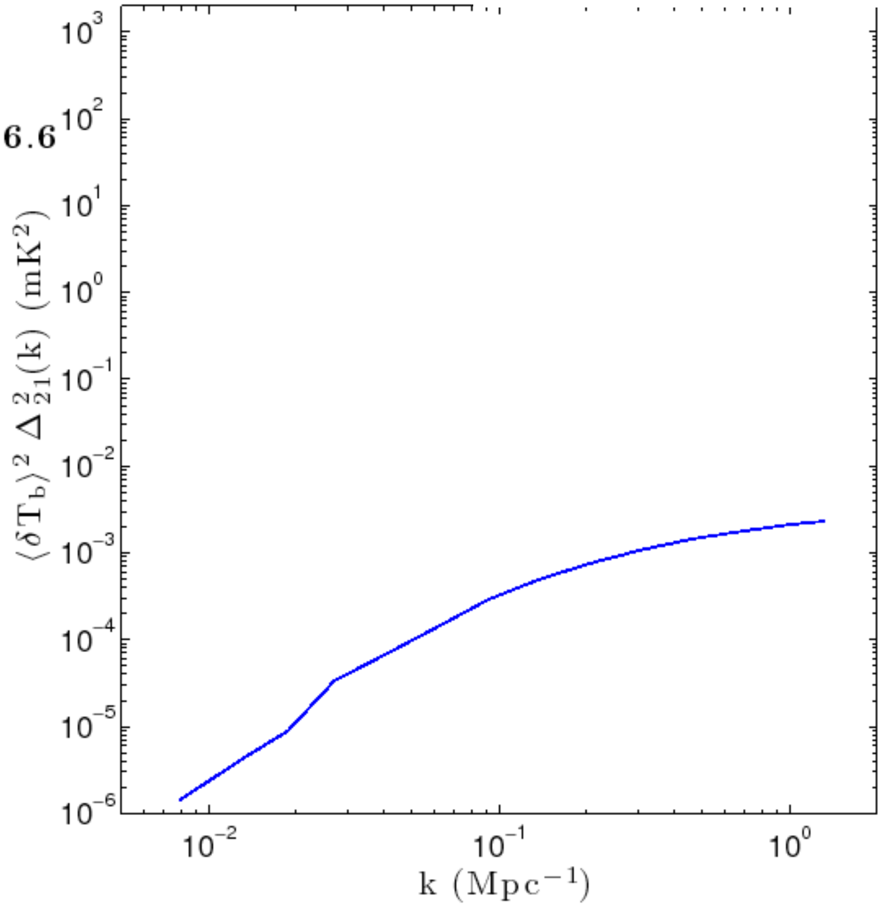
Mesinger & Santos, in prep.



http://www.astro.princeton.edu/~mesinger/21cm_Movie.html

Mesinger+ (2010)





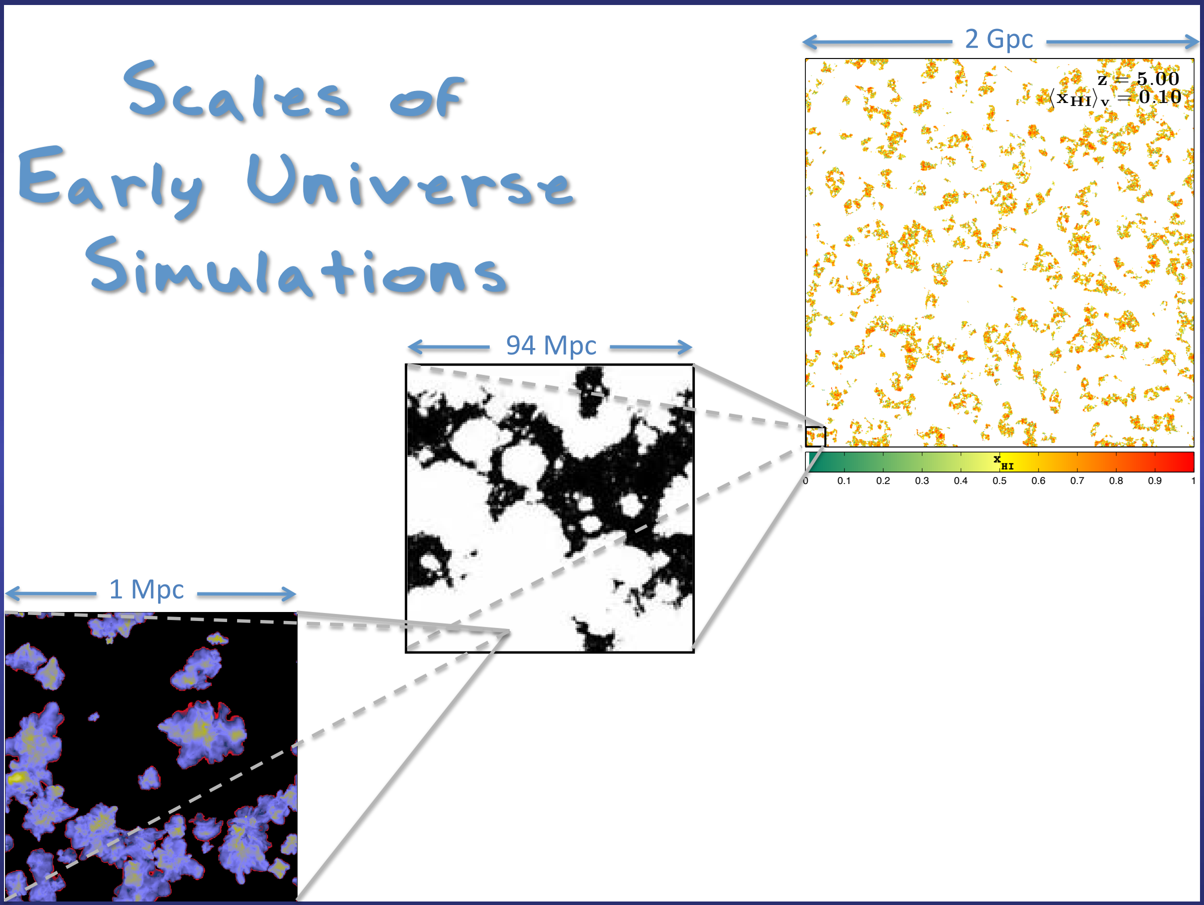
The Future for the Dark Ages is Bright!

(sorry for the pun…)

- 21cm tomography: GMRT, MWA, PAPER, LOFAR, 2nd generation: SKA, LUNAR
- High-redshift IR spectra: JWST, TMT, GMT, E-ELT
- wide-field LAE surveys: Subaru HyperSupremeCam
- E-mode CMB by Planck
- kSZ from patchy reionization: SPT, ACT
- 1 of 3 main science objectives stressed by the Decadal Survey of the US National Academies

We need efficient tools to interpret observations!

Challenges: (i) *parameter space; (ii) dynamic range*



use the right tool for each task!

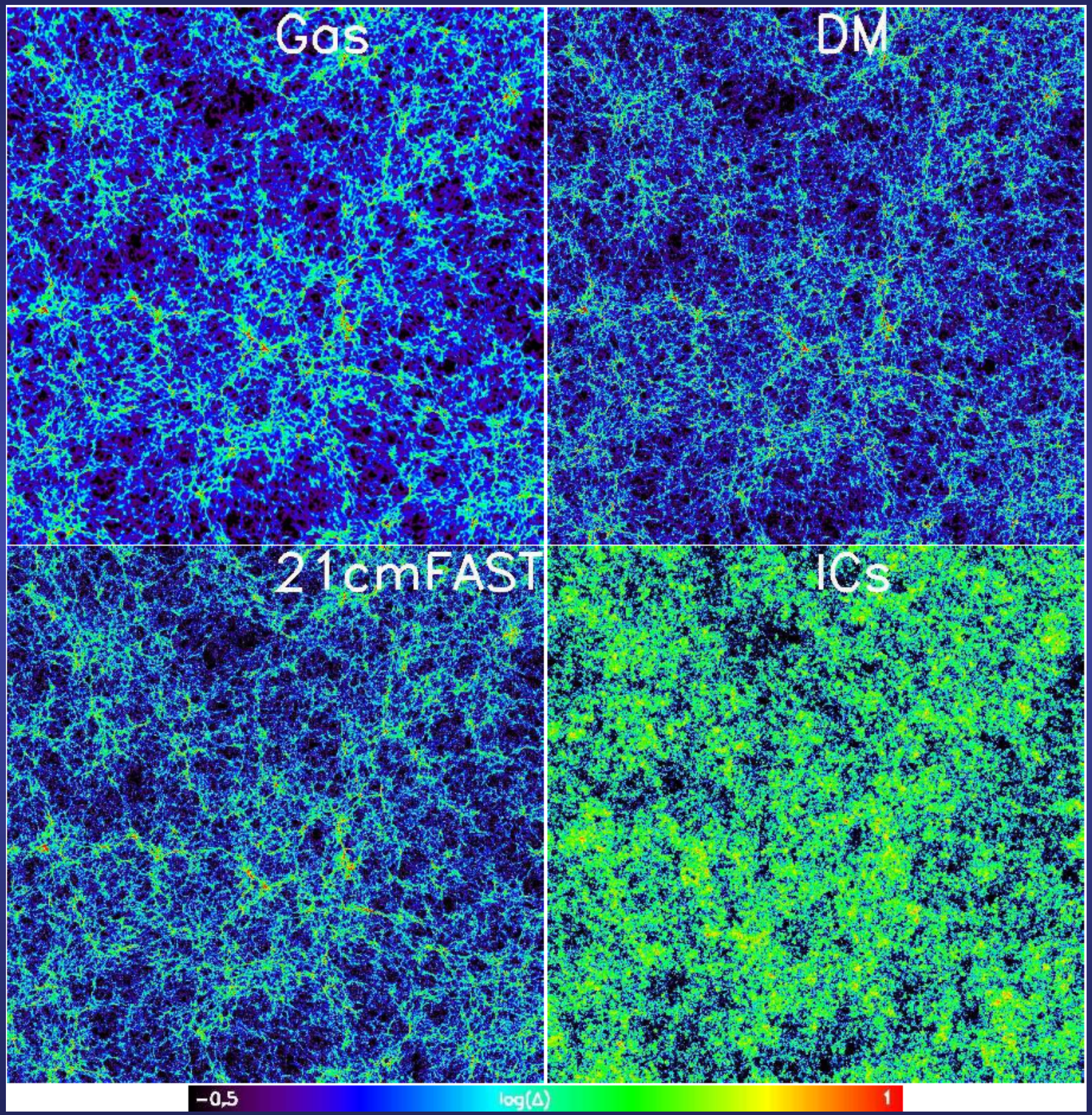
“Semi-numeric” simulations DexM & 21cmFAST

http://www.astro.princeton.edu/~mesinger/Sim

- More approximate physics than “numeric” simulations but much faster! ~ minutes on a single CPU
- Combines perturbation theory and excursion set formalism
- Tested extensively against numerical simulations, with great agreement well into the quasi-linear regime
- publicly available!

e.g. Density Fields

z=7

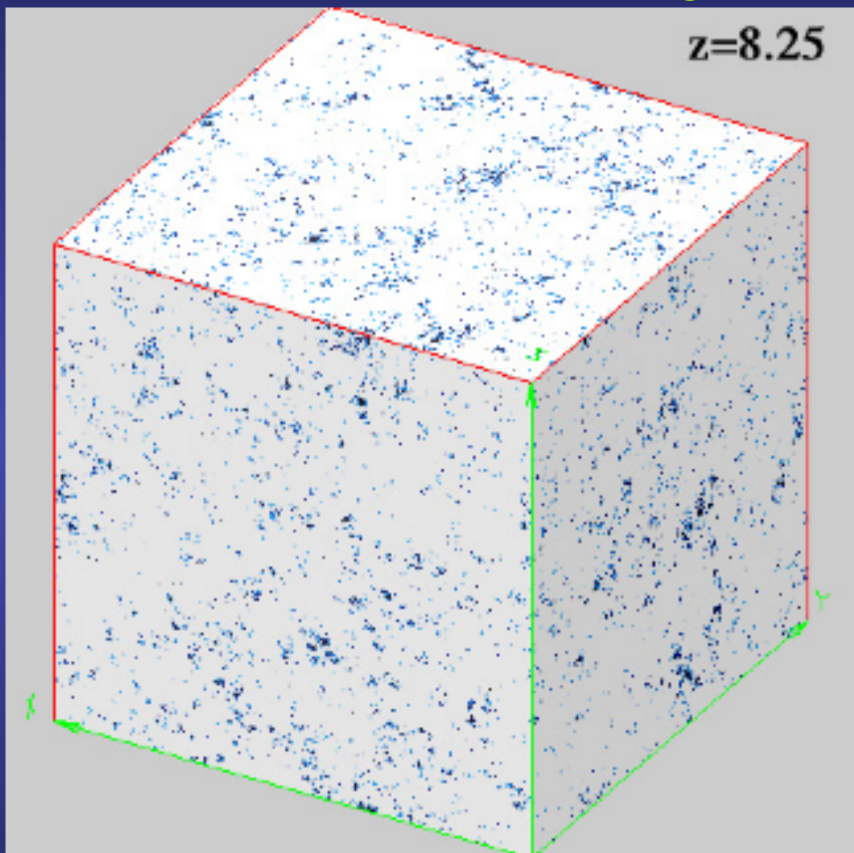


0.19 Mpc cells

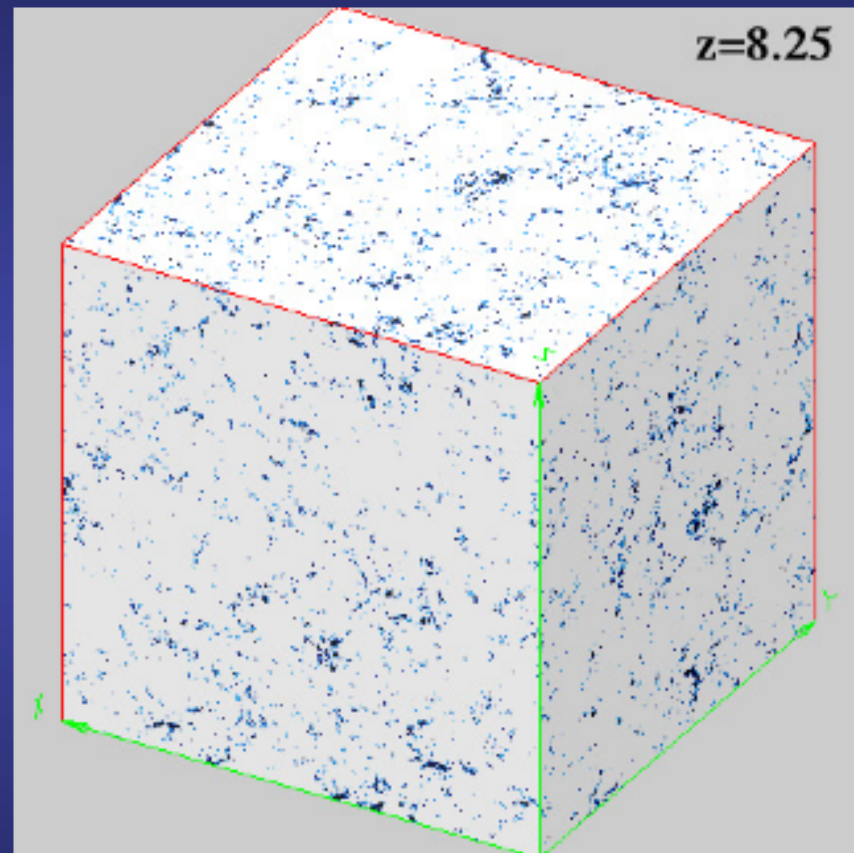
143 Mpc

Halo Fields (DexM)

Mesinger & Furlanetto (2007)

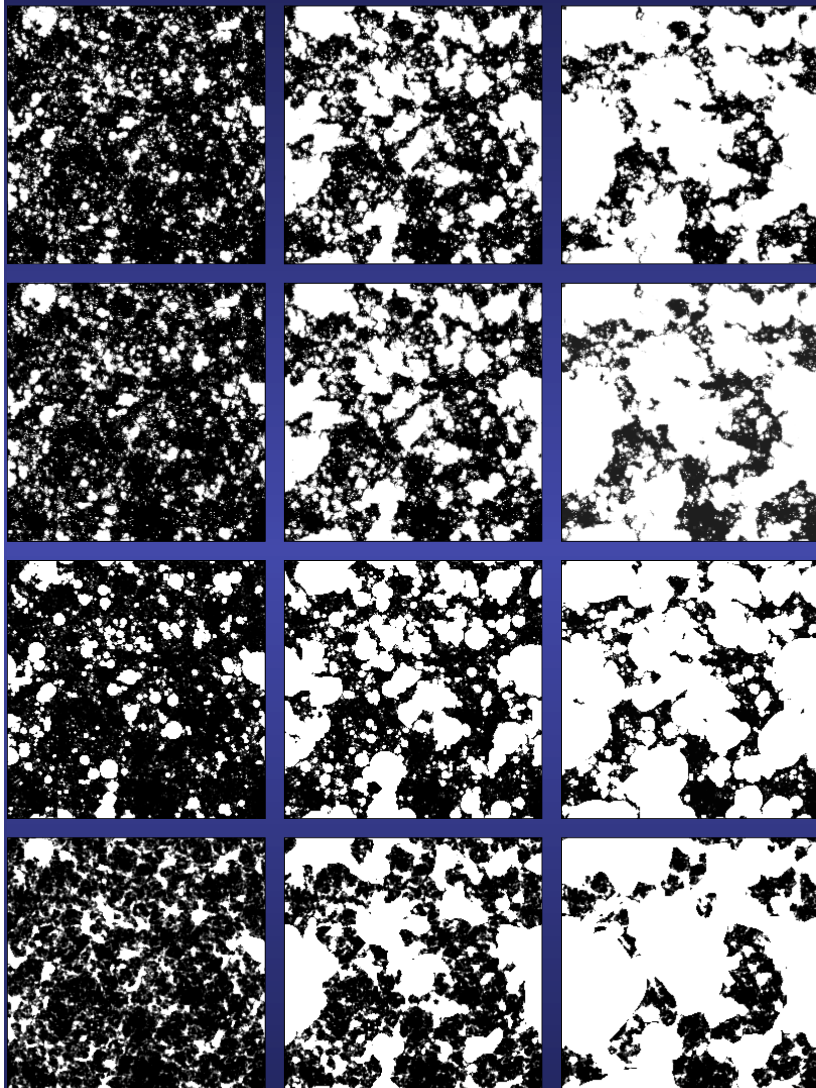


without adjusting halo locations



with adjusting halo locations

Ionization Fields



McQuinn+ (2007)

Trac & Cen (2007)

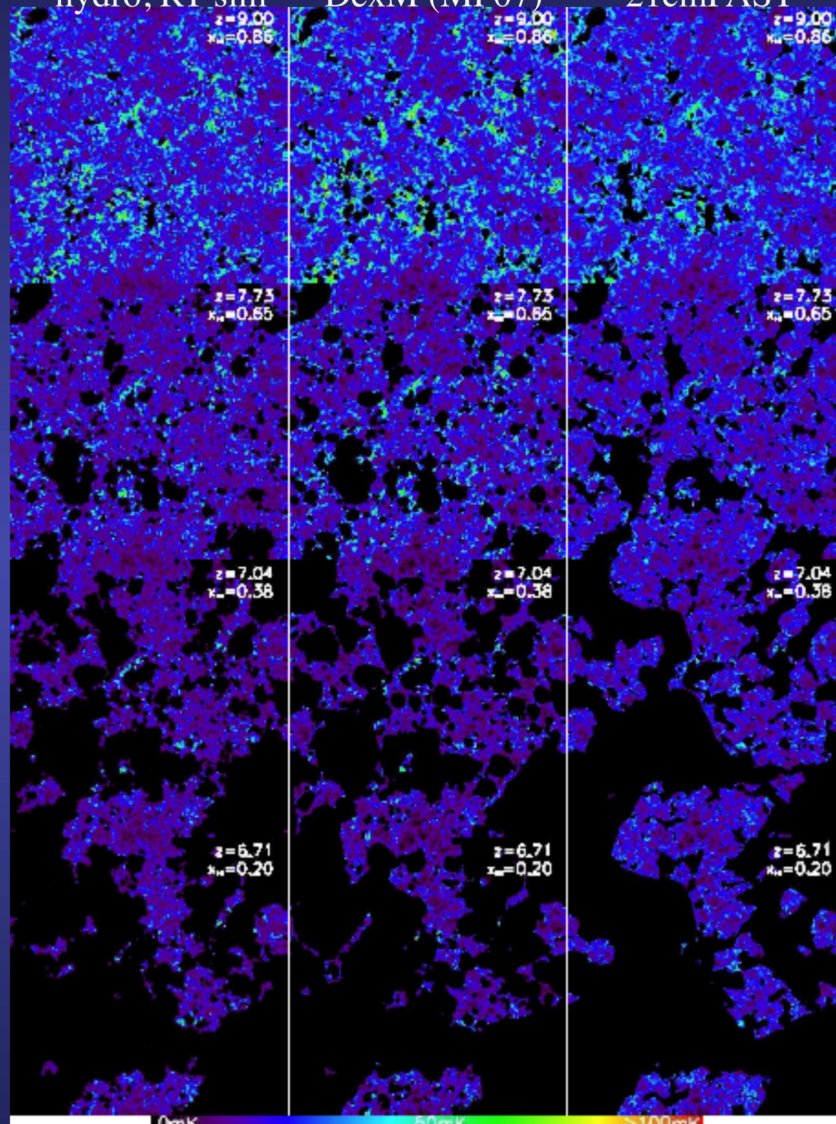
DexM (Mesinger & Furlanetto; 2007)

21cmFAST (Mesinger, Furlanetto, Cen 2010)

Zahn+ (2010)

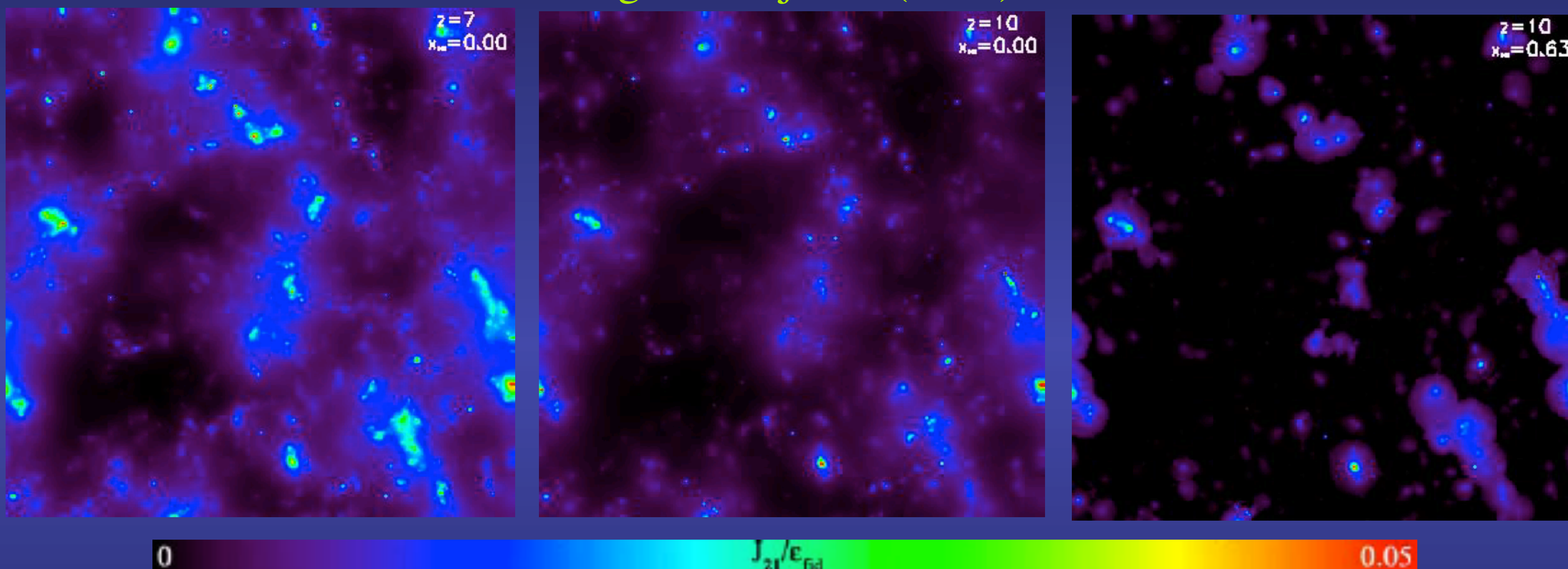
21cm Fields ($T_s \gg T_\gamma$)

hydro, RT sim DexM (MF07) 21cmFAST



Ionizing UV Flux Fields

Mesinger & Dijkstra (2008)



$$\text{flux} \propto \sum L(M_{halo})/r^2 \, e^{-r/\lambda_{mfp}}$$

Get onboard!

http://www.astro.princeton.edu/~mesinger/Sim

Conclusions

- Astrophysical milestones such as reionization are likely the only practical way of observing the primordial zoo of astrophysical objects in the near future, and they provide an exciting testbed of early Universe physics
- Reionization is likely extended, going through various stages
- Early interpretation of quasar spectra assumed a homogeneous reionization; a model-independent estimate yields $x_{HI} \lesssim 0.5$
- Stronger lower limits can be obtained by modeling the transmission in the quasar 'near zone'
- Cosmological 21cm signal is very rich in information, containing both cosmological and astrophysical components
- The range of scales and unknown parameter space is enormous!
- We need efficient modeling tools to make sense of the upcoming observations: 21cmFAST and DexM
- We are living in exciting times!