Lyman series photons
(+ X-rays)
and the 21 cm signal

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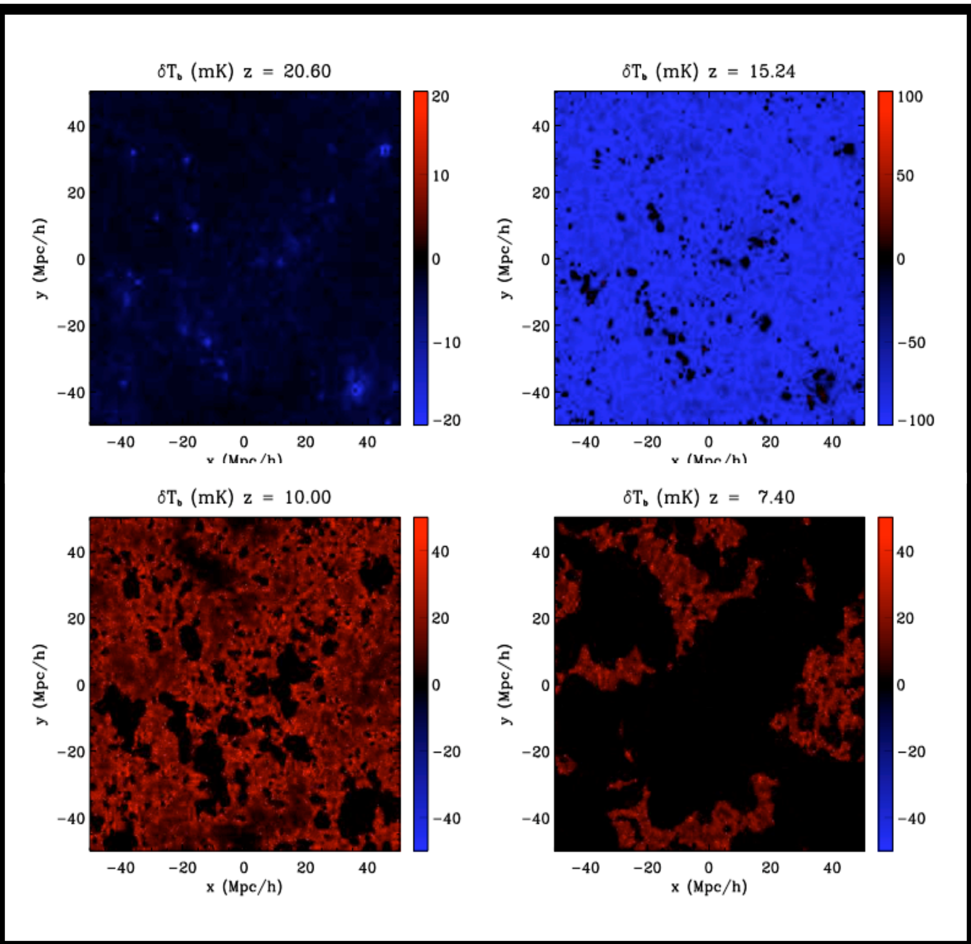
Overview



1. 21 cm basics
2. What effect do Lya and X-rays have on the 21cm signal?
3. How well do analytic models of the 21 cm signal match simulations?

21 cm basics

- HI hyperfine structure

n_1 $\uparrow\uparrow$

$1_1S_{1/2}$

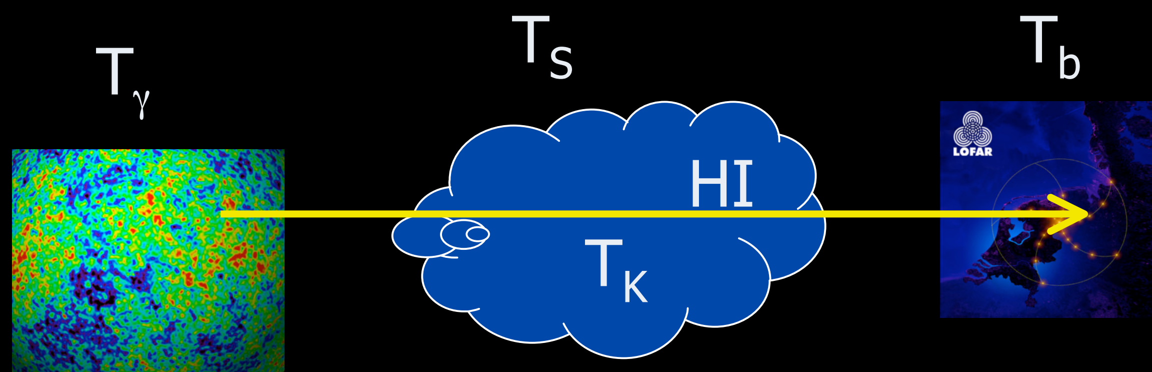
λ=21cm

$1_0S_{1/2}$

n_0 $\uparrow\downarrow$

$n_1/n_0 = 3\exp(-h\nu_{21cm}/kT_s)$

- Use CMB backlight to probe 21cm transition



z=13
f_{21cm}=1.4 GHz

z=0
f_{obs}=100 MHz

- 3D mapping of HI possible - angles + frequency
- 21 cm brightness temperature

$$T_b = 27 x_{\rm HI}(1+\delta_b)\left(\frac{T_S - T_\gamma}{T_S}\right)\left(\frac{1+z}{10}\right)^{1/2}\ {\rm mK}$$

- 21 cm spin temperature

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

- Coupling mechanisms:
  - Radiative transitions (CMB)
  - Collisions
  - Wouthuysen-Field

Wouthuysen-Field effect

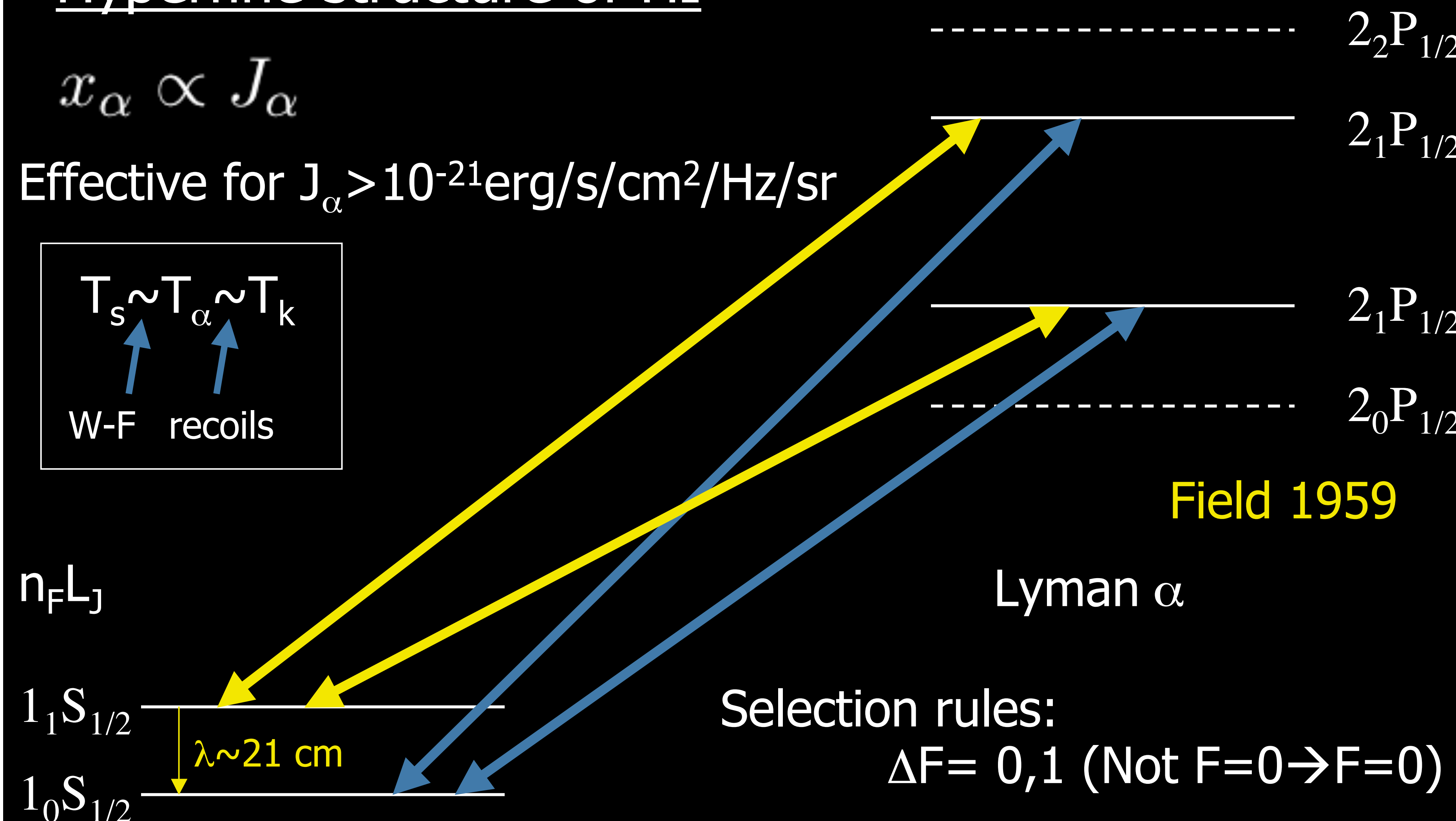
Hyperfine structure of HI

$$x_\alpha \propto J_\alpha$$

Effective for $J_\alpha > 10^{-21}$ erg/s/cm^2/Hz/sr

$T_s \sim T_\alpha \sim T_k$

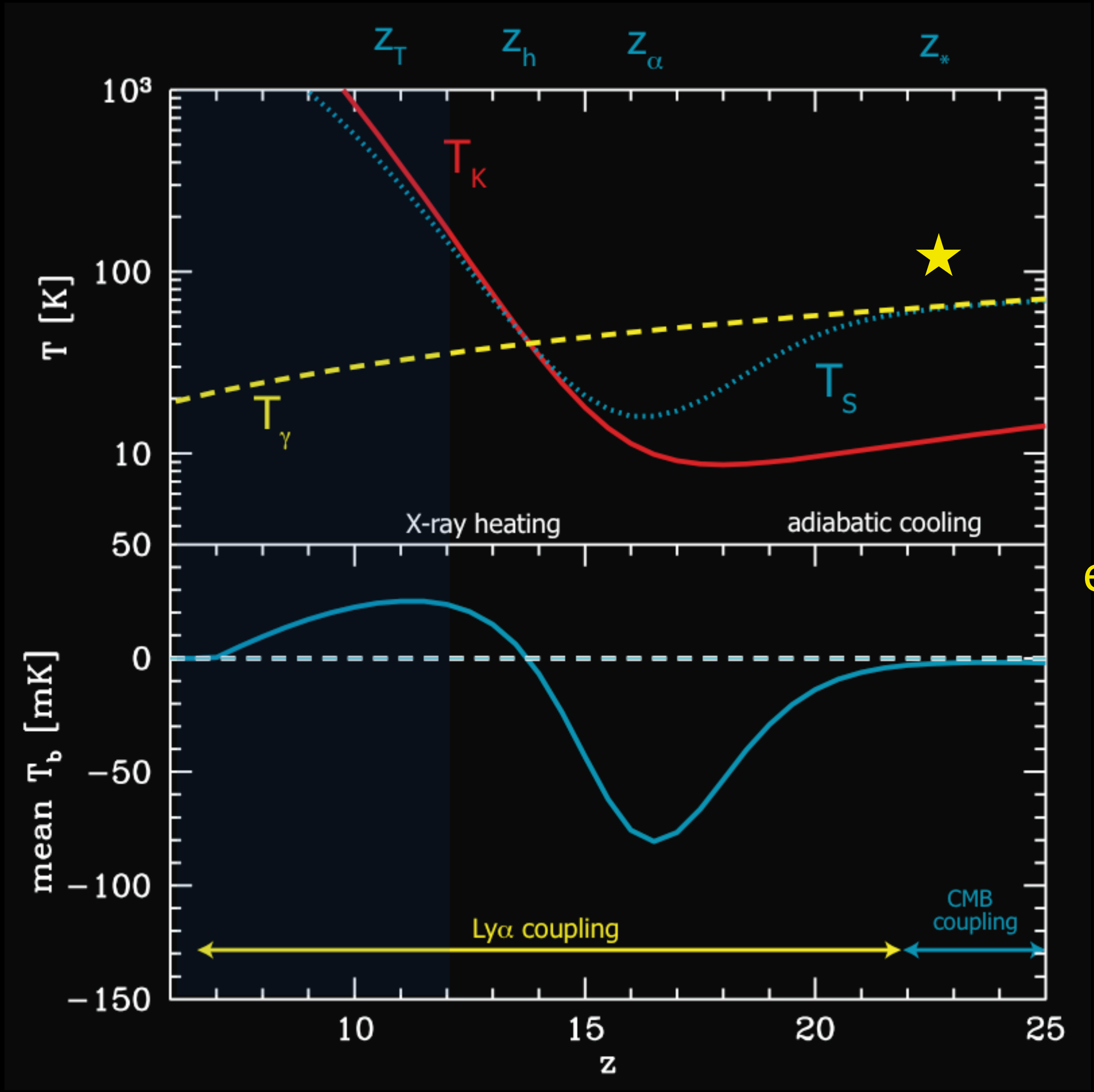
W-F recoils



Field 1959

Selection rules:
$\Delta F = 0,1$ (Not $F=0 \rightarrow F=0$)

Thermal History



e.g. Furlanetto 2006

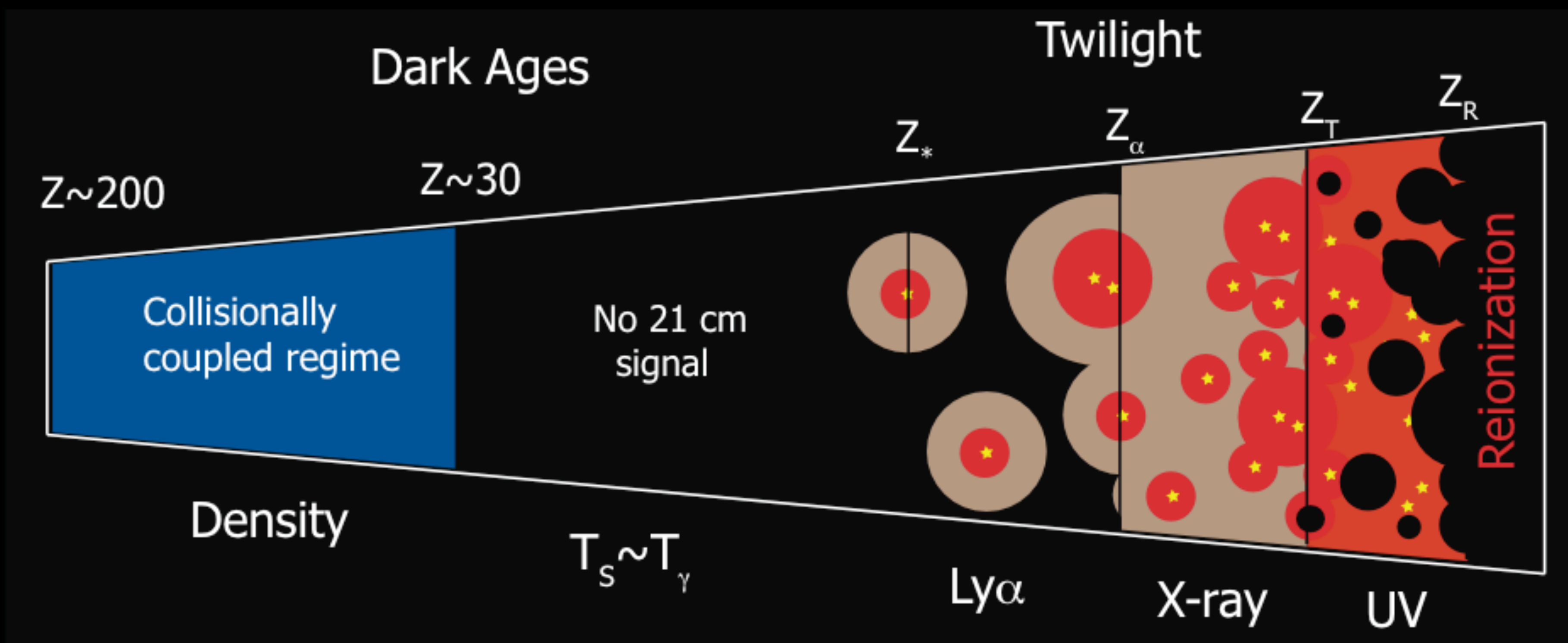
Measure with EDGES Bowman+ 2008

21 cm fluctuations

Brightness temperature | Baryon Density | Neutral fraction | Gas Temperature | W-F Coupling | Velocity gradient

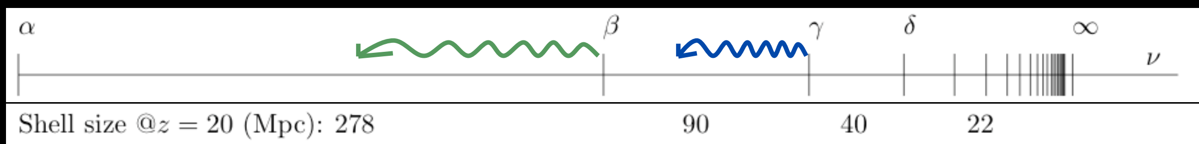
$$\delta_{T_b} = \beta\delta_b + \beta_x\delta_{x_{HI}} + \beta_T\delta_{T_k} + \beta_\alpha\delta_\alpha - \delta_{\partial v}$$

Cosmology | Reionization | X-ray sources | Lyα sources | Cosmology



Sources of radiation

Lya: Three contributions to Lyα flux:
continuum & injected from stars + x-ray



Lya heating typically small than that of X-rays

Barkana & Loeb 2005,
Pritchard & Furlanetto 2006
Hirata 2006

Chen & Miralde-Escude 2006
Chuzhoy & Shapiro 2006

X-ray: X-rays from mini-quasars, starburst galaxies, IC

X-ray photoionization leads to 2^{ry} ionization, heating, Lya

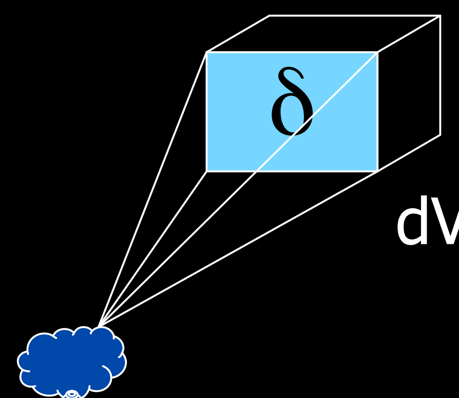
$$\lambda_X \approx 4.9 \bar{x}_{\rm HI}^{1/3} \left(\frac{1+z}{15}\right)^{-2} \left(\frac{E}{300\,{\rm eV}}\right)^{3} \text{Mpc}$$

Chen & Miralde-Escude 2006,
Pritchard & Furlanetto 2007,
Zaroubi+ (2007)
Pritchard & Loeb 2008

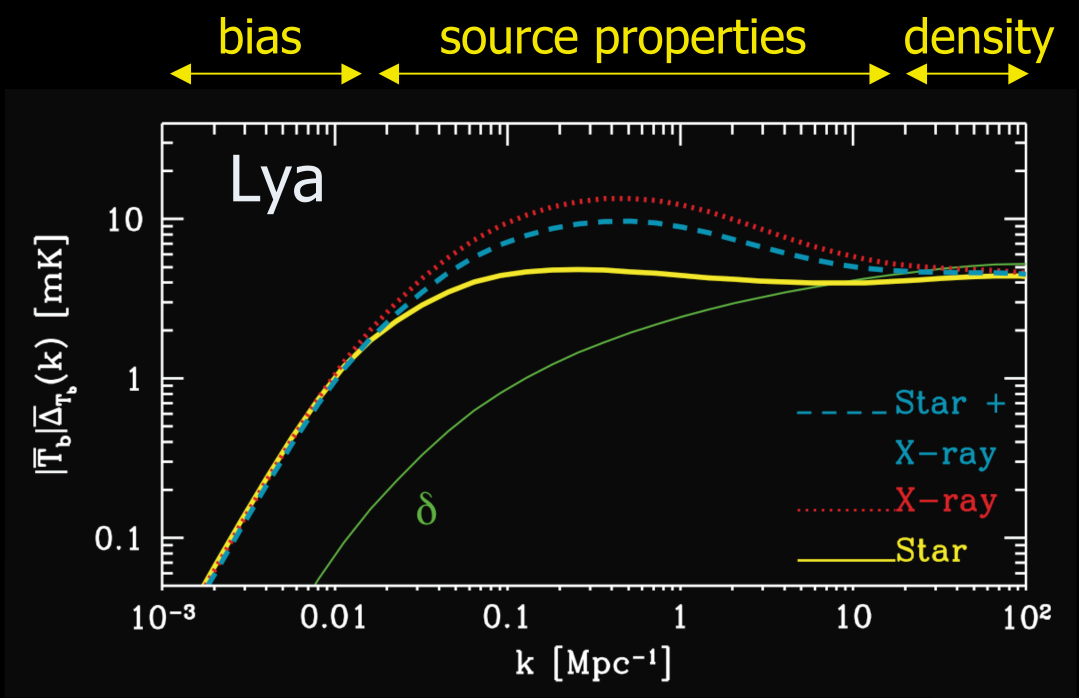
- Source properties very uncertain

Fluctuations:

- Despite long mfp significant fluctuations due to $1/r^2$ flux dependence and clustering of sources



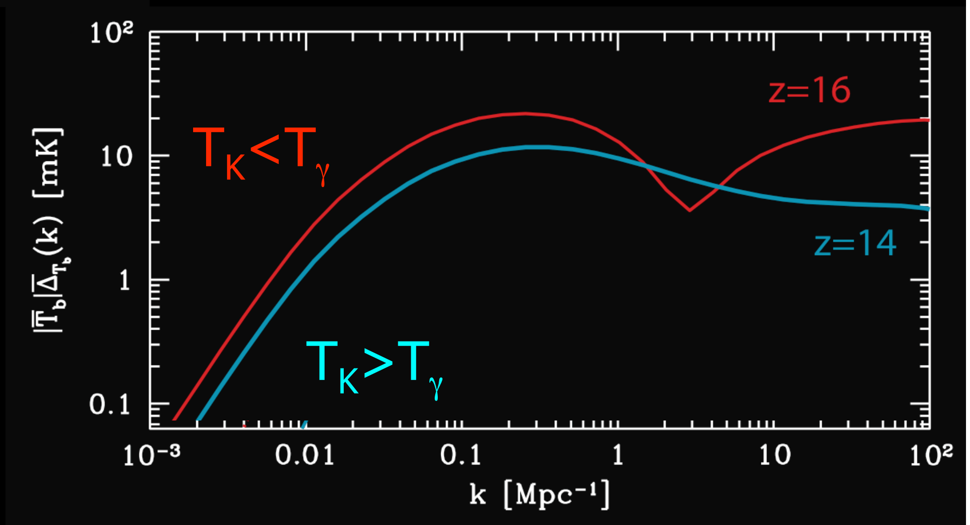
Power spectra



Barkana & Loeb 2004
Chuzhoy, Alvarez, & Shapiro 2006
Pritchard & Furlanetto 2007

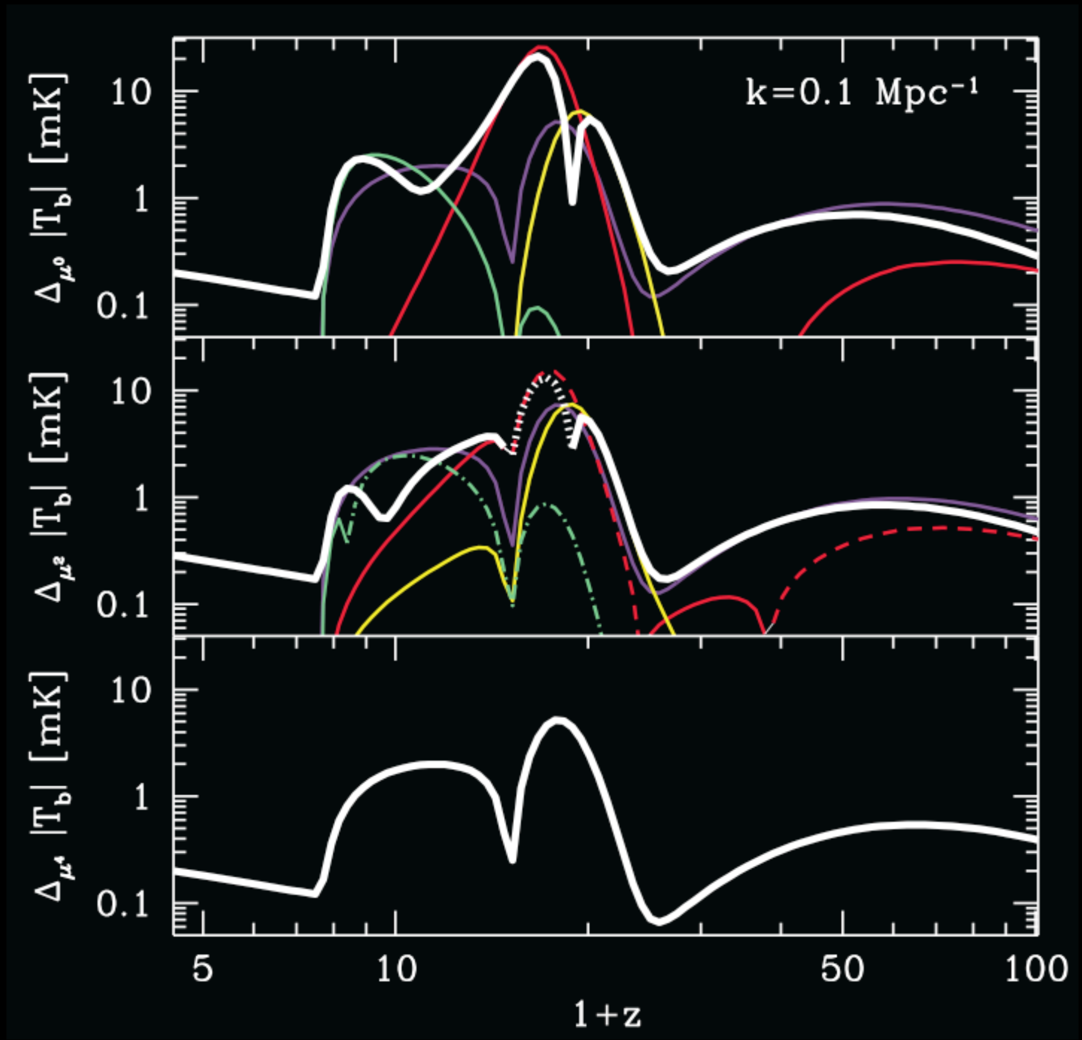
- Fluctuations in Lya or X-rays both add power on large scales
- Largest scales gives bias of sources
- Intermediate scales says something about sources
  e.g. stellar spectrum vs power law
- T fluctuations say something about thermal history

X-rays



Signal decomposition

Pritchard &
Loeb 2008



Full
Lya
T
x_i
density

Bharadwaj
& Ali 2004

Barkana &
Loeb 2005

Peculiar
velocities

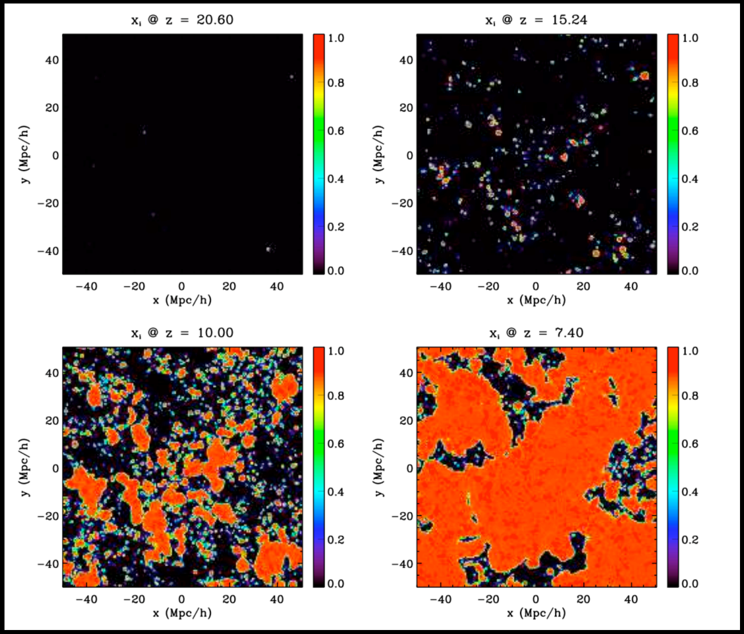
Angular separation by μ

$$\delta_{d_r v_r}(k) = -\mu^2 \delta \longrightarrow P_{T_b}(\mathbf{k}) = \mu^4 P_{\mu^4} + \mu^2 P_{\mu^2} + P_{\mu^0}$$

Reionization simulation

- Simulation techniques for reionization well developed
- Boxes well matched to typical bubble sizes ~1-10Mpc
- Including Lya and X-rays complicated by long mfp & need to track multiple frequencies and redshifting -> numerically expensive

(Baek+ 2009 - Included Lya radiative transfer into course 100 Mpc box, no X-rays)



L=100 Mpc/h
$N_{DM}=2880^3$
$M_{halo}=10^8$ Msol/h
RT on 360^3 grid

Resolves halos capable of atomic cooling

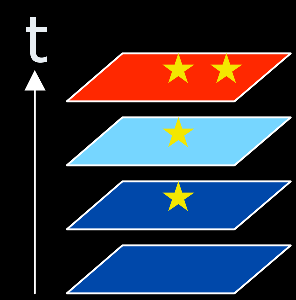
Shin+ 2007
Trac & Cen 2007
Santos+ 2008

Including other radiation fields

- Approach: Santos, Amblard, Pritchard, Trac, Cen, Cooray 2008
  - Implement semi-analytic procedure for fluxes using SFR from N-body simulation
  - Extract sources on time slices and integrate to get Lya & X-ray flux

$$J_{\rm X}(\boldsymbol{x},\ z,\ \nu) = \int d^3x' \frac{(1+z)^2}{4\pi|\boldsymbol{x}'|^2} \hat{\epsilon}_{\rm X}(\boldsymbol{x}+\boldsymbol{x}',\ \nu'_n,\ z') e^{-\tau(z,\nu,\boldsymbol{x},\boldsymbol{x}')}$$

$$\hat{\epsilon}_{\rm X}(\boldsymbol{x},\ z,\ \nu) = \hat{\epsilon}_{\rm X}(\nu)\left[\frac{\mathrm{SFRD}(\boldsymbol{x},\ z)}{M_\odot\ \mathrm{yr}^{-1}\ \mathrm{Mpc}^{-3}}\right]$$

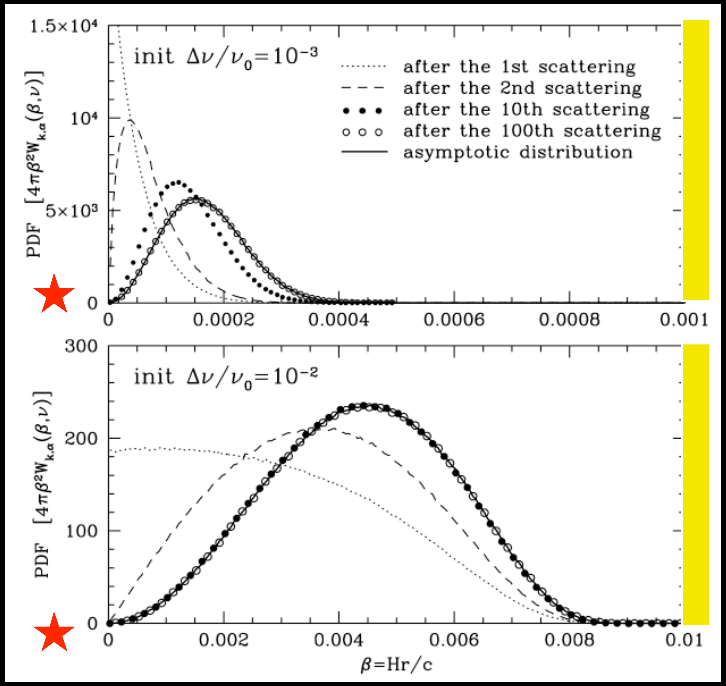


  - Convolution can be evaluated relatively quickly
  - Source parameters extrapolated from low z sources
    - Pop II + III stars -> reionization at z=6
    - X-ray emission from galaxies
  - Get coupling and heating from fluxes

STScI
MAR
2009

Simplifications

- Propagate in mean density IGM
  - Underestimates heating close to source & overestimates far away
- Propagate Lyman photons until redshift to line center

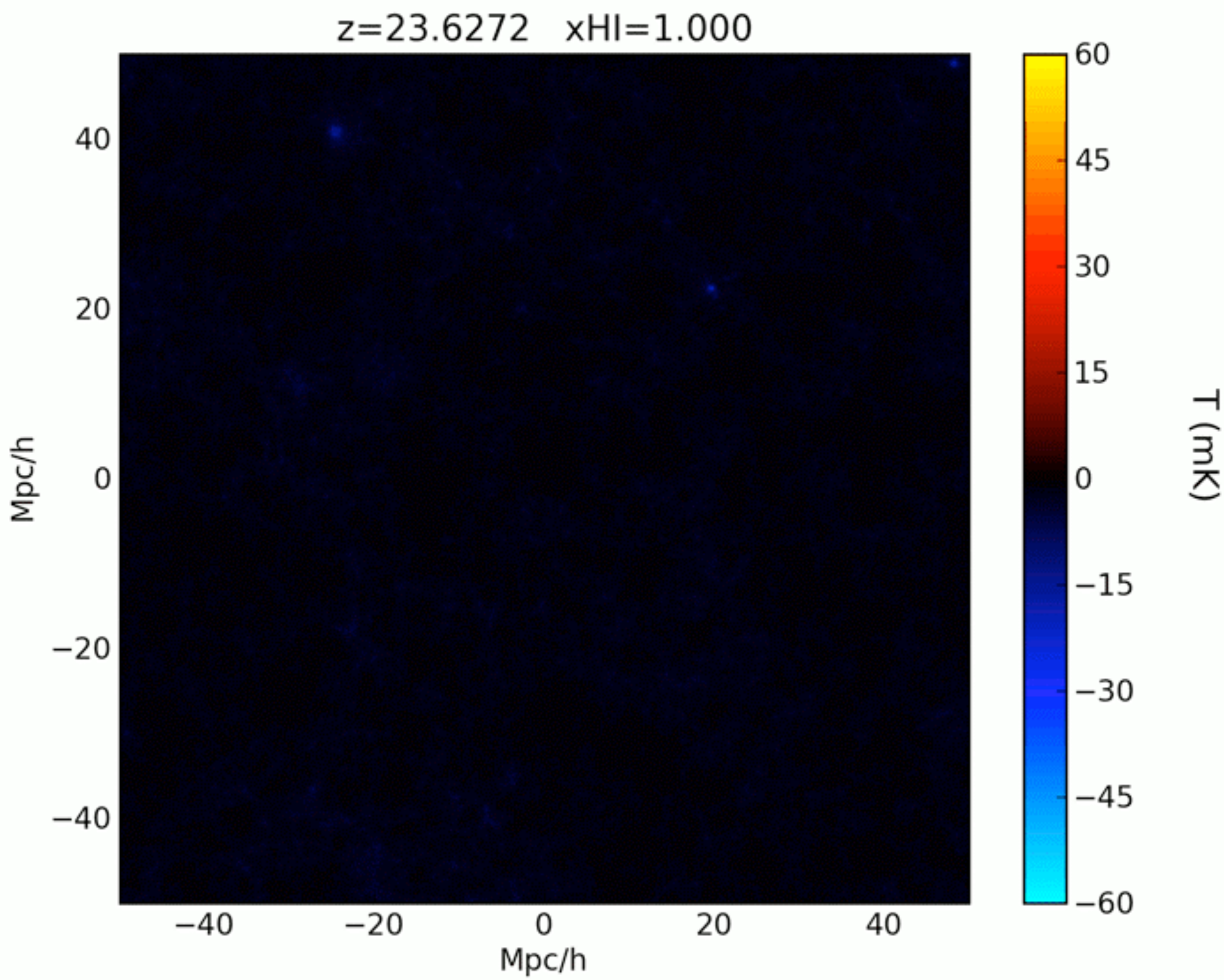


Scattering in wings tends to steepen radial dependence of flux

Semelin, Combes, Baek 2007
Chuzhoy & Zheng 2007
Naoz & Barkana 2007

- Both will tend to increase power on small scales
  - important for details, but not overall picture

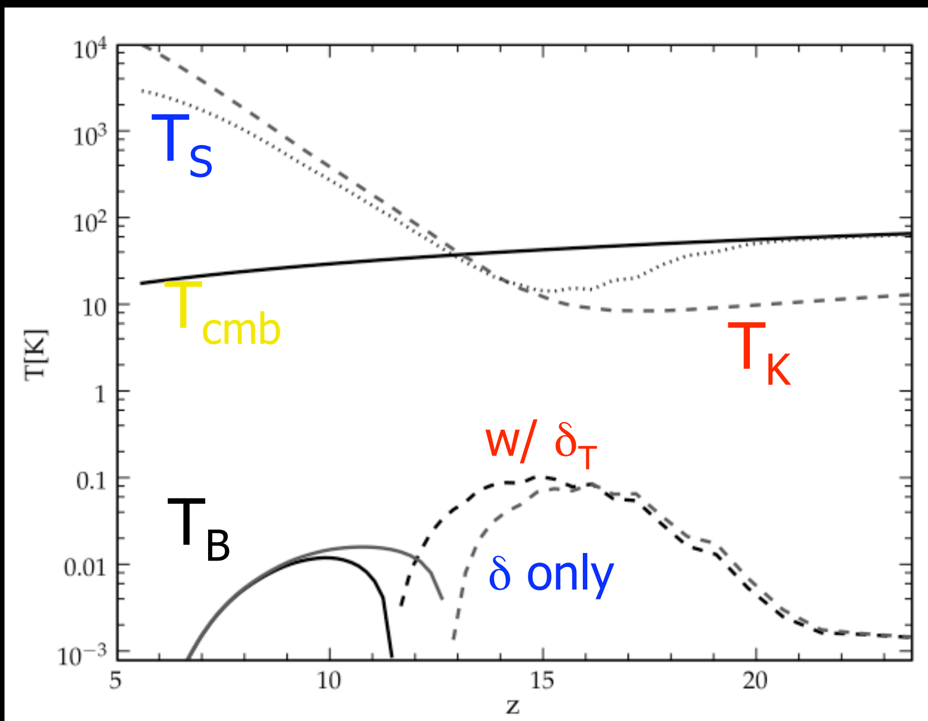
Full simulation



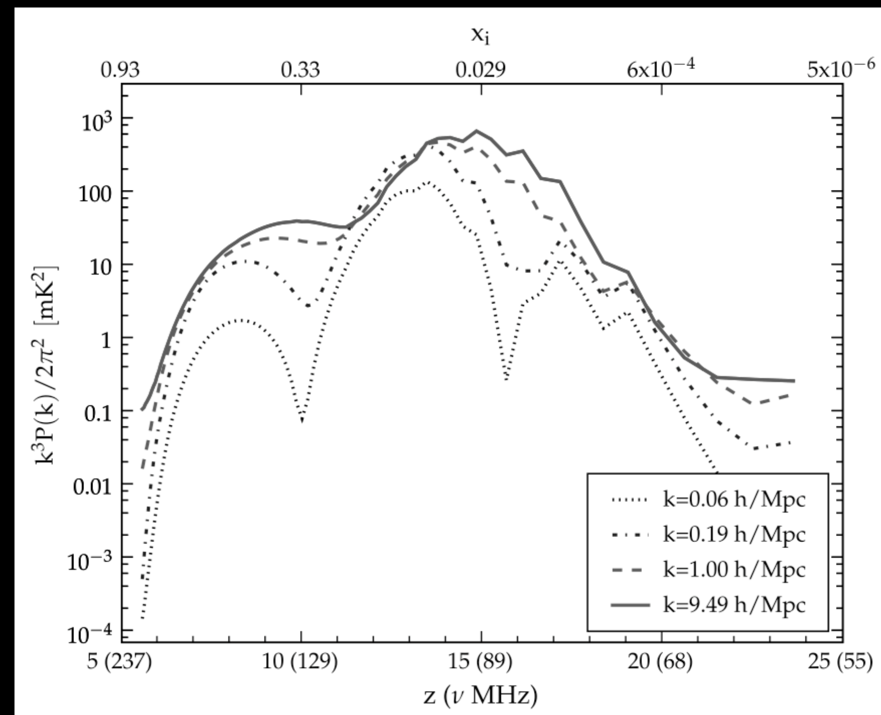
Movie courtesy of Mario Santos

Evolution of signal

Mean signal

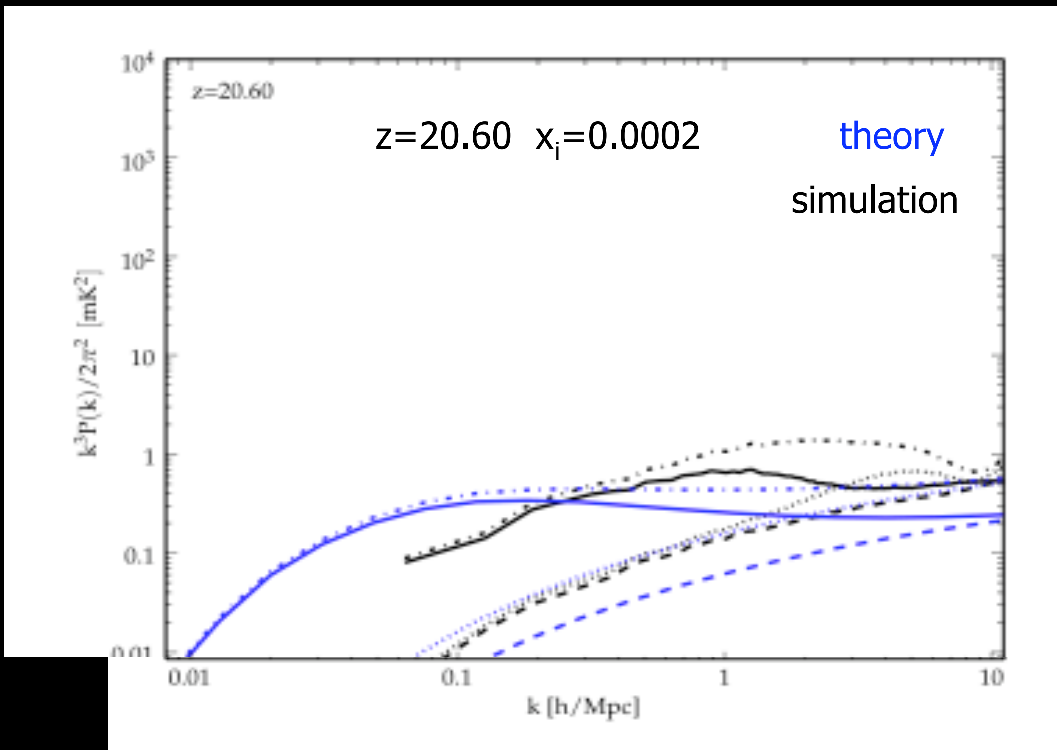


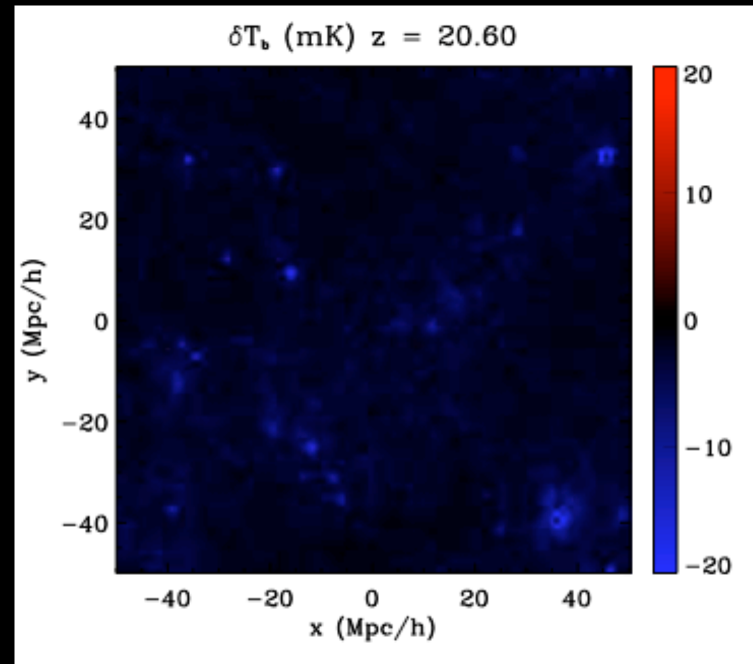
Power spectrum



- T fluctuations significantly shift mean T_B at moderate z
- Different fluctuations important at different times
- On smallest scales evolution mostly modulated by T_b

Lya

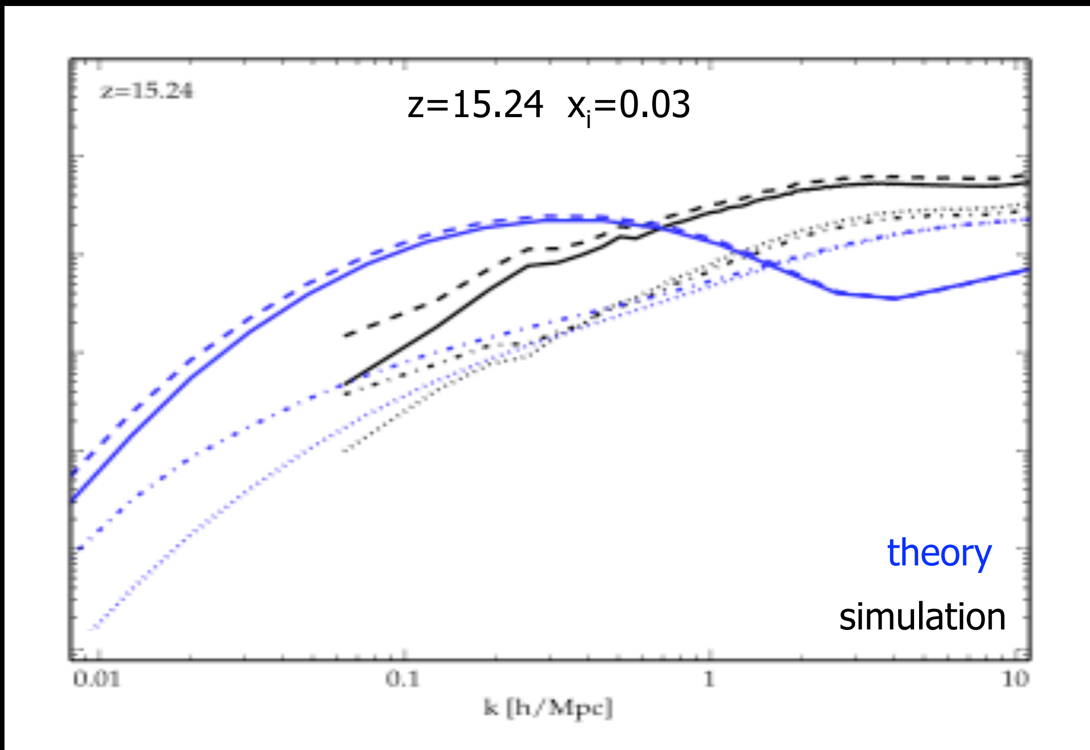


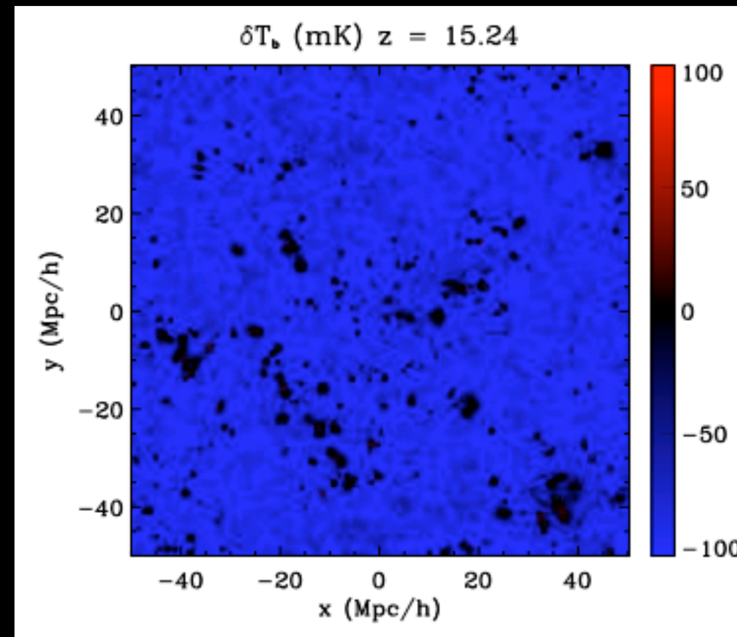


Dotted = δ+x_i Dot-dashed = +Lya
Dashed = +X-ray Solid= All

- Analytic model underestimates SFR slightly
  -> less Lya -> weaker signal
- In both cases Lya fluctuations flatten P(k)

Lya/T





Dotted = $\delta + x_i$ Dot-dashed = +Lya
Dashed = +X-ray Solid= All

- Lya fluctuations match well
- T fluctuations disagree somewhat
  - -> cross correlation between T and density too strong on small scales in analytic model
- Modeling needs improvement

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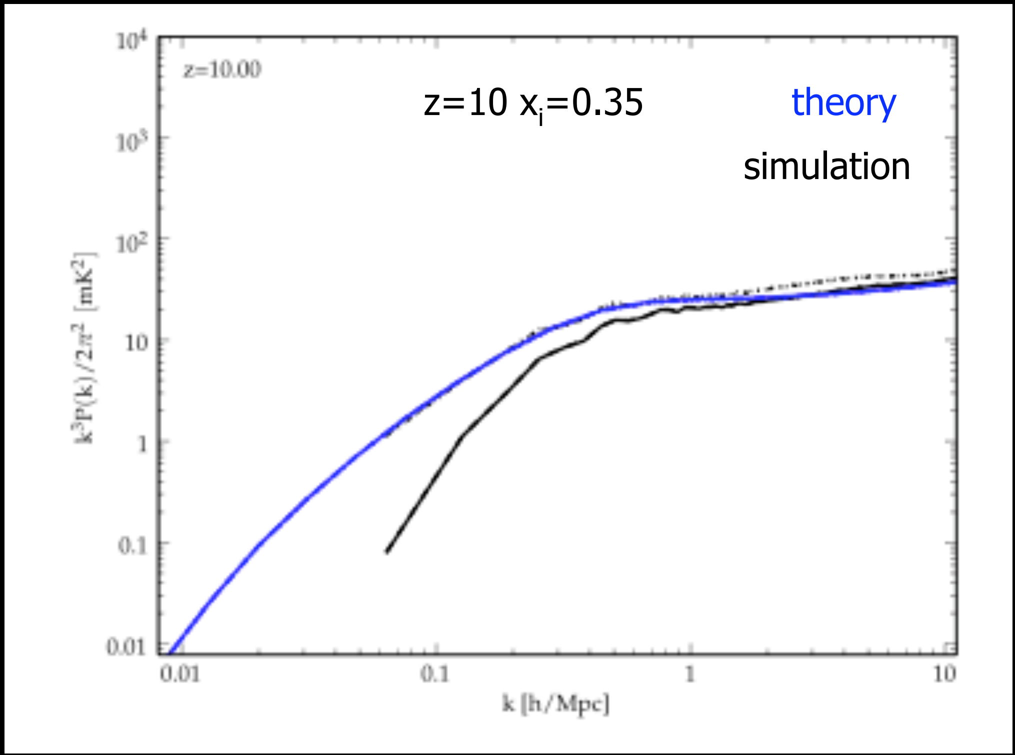
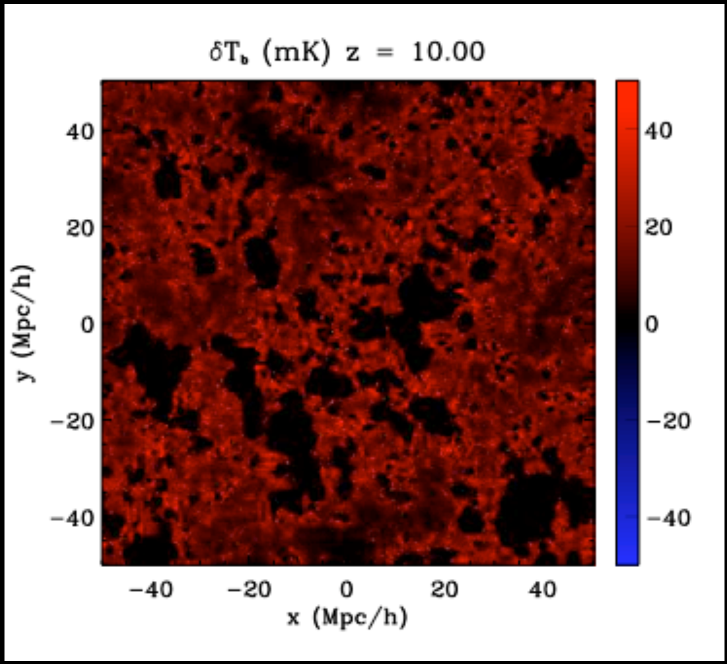
2009

Temperature



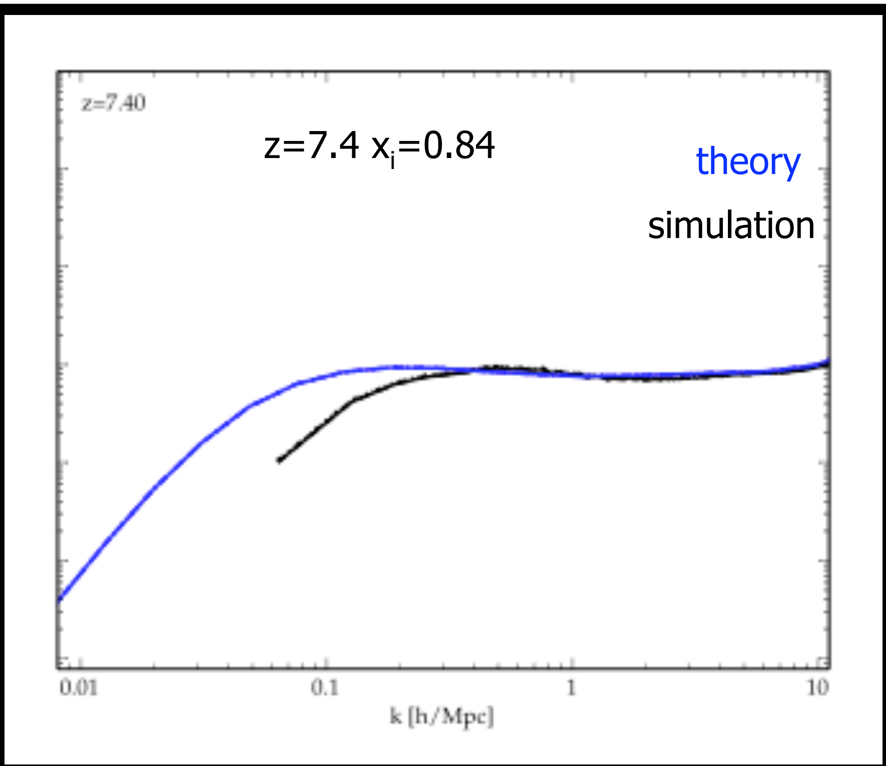


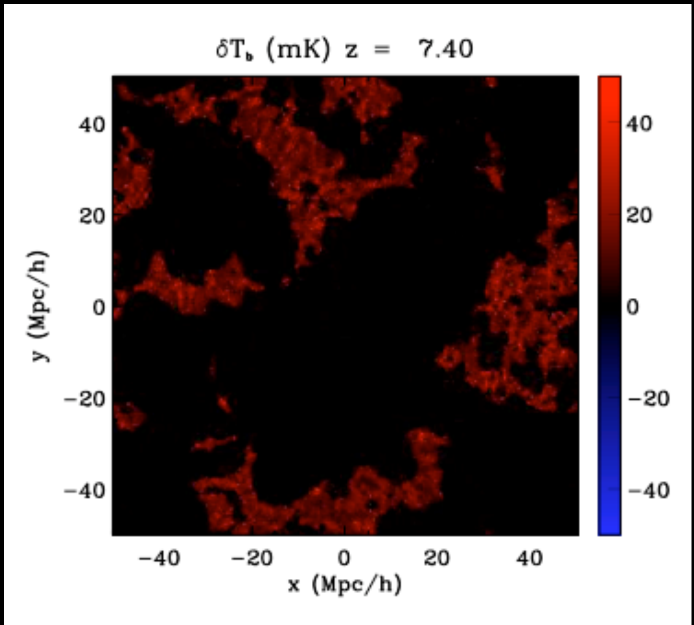
Dotted = $\delta + x_i$ Dot-dashed = +Lya
Dashed = +X-ray Solid= All

- Ionization fluctuations agree very well with FZH model
- Temperature fluctuations more important in simulation
  -> large scales still close to CMB temperature
  -> contributes with opposite sign to ionization so power reduced
  (hottest regions ionized)

Furlanetto, Zaldarriaga, Hernquist 2004

Ionization





Dotted = $\delta+x_i$ Dot-dashed = +Lya
Dashed = +X-ray Solid= All

- Good agreement except on largest scales
- Bubble size comparable to box size -> problems
- Echoes previous comparisons of FZH model for ionization

Zahn+ 2007

Conclusions

- Have told a simple story, but large uncertainties with sources

- Learn about sources during/preceding reionization from fluctuations in Lya and X-ray flux from details of power spectra
  - -> constrain faint population of early sources
  - -> thermal history

- Results suggest weak separation of different fluctuations
  - -> details parameter dependant

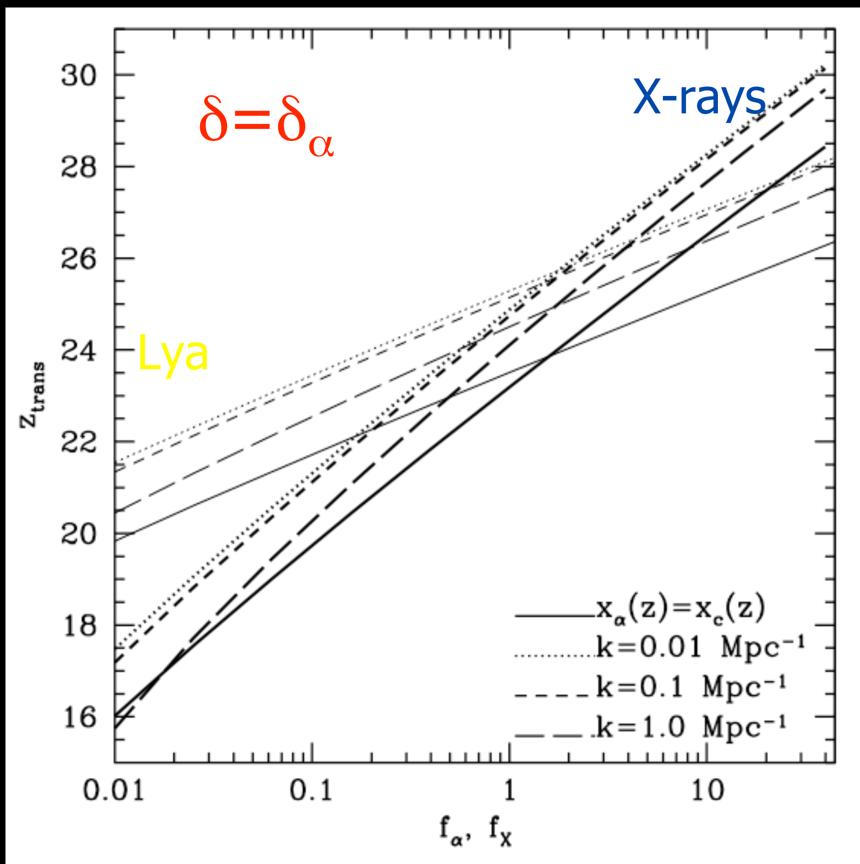
- Temperature fluctuations can be important at even low neutral fractions -> may need both Lya heating & X-ray heating

- Theory and simulation agrees reasonably well
  - -> fast method for including relevant physics in simple way
  - -> need for RT of Lya and X-rays in cosmological simulations
  - -> analytic calculations valuable for fast exploration of parameters

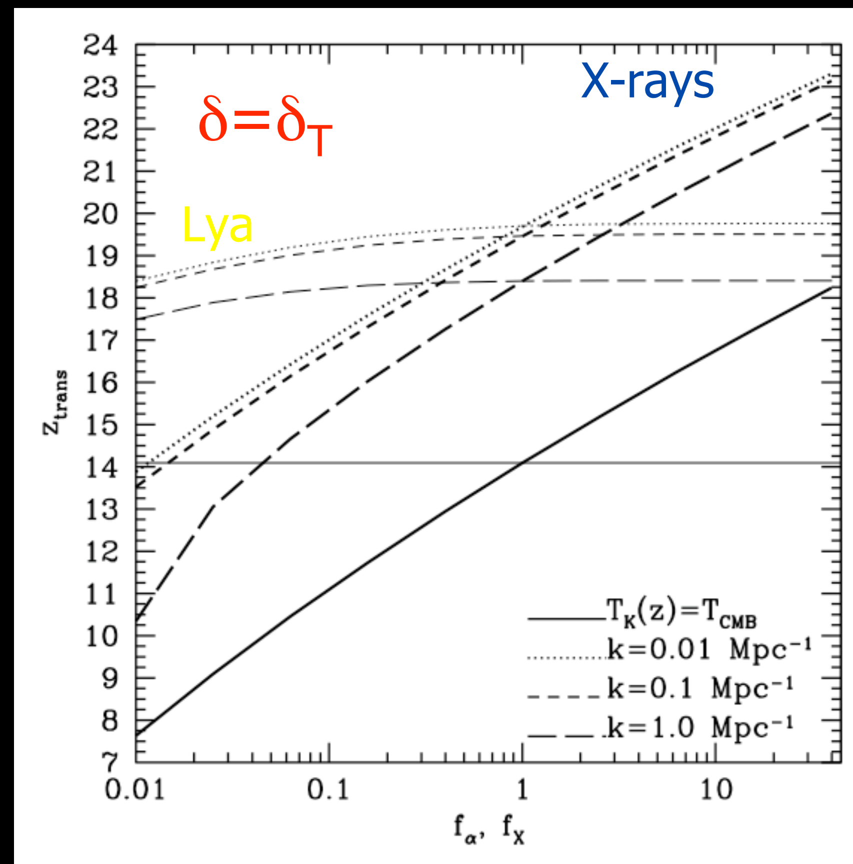
- Using 21 cm fluctuations to understand early stages of reionization requires understanding contribution of Lya and X-rays

Transition redshifts

Lya



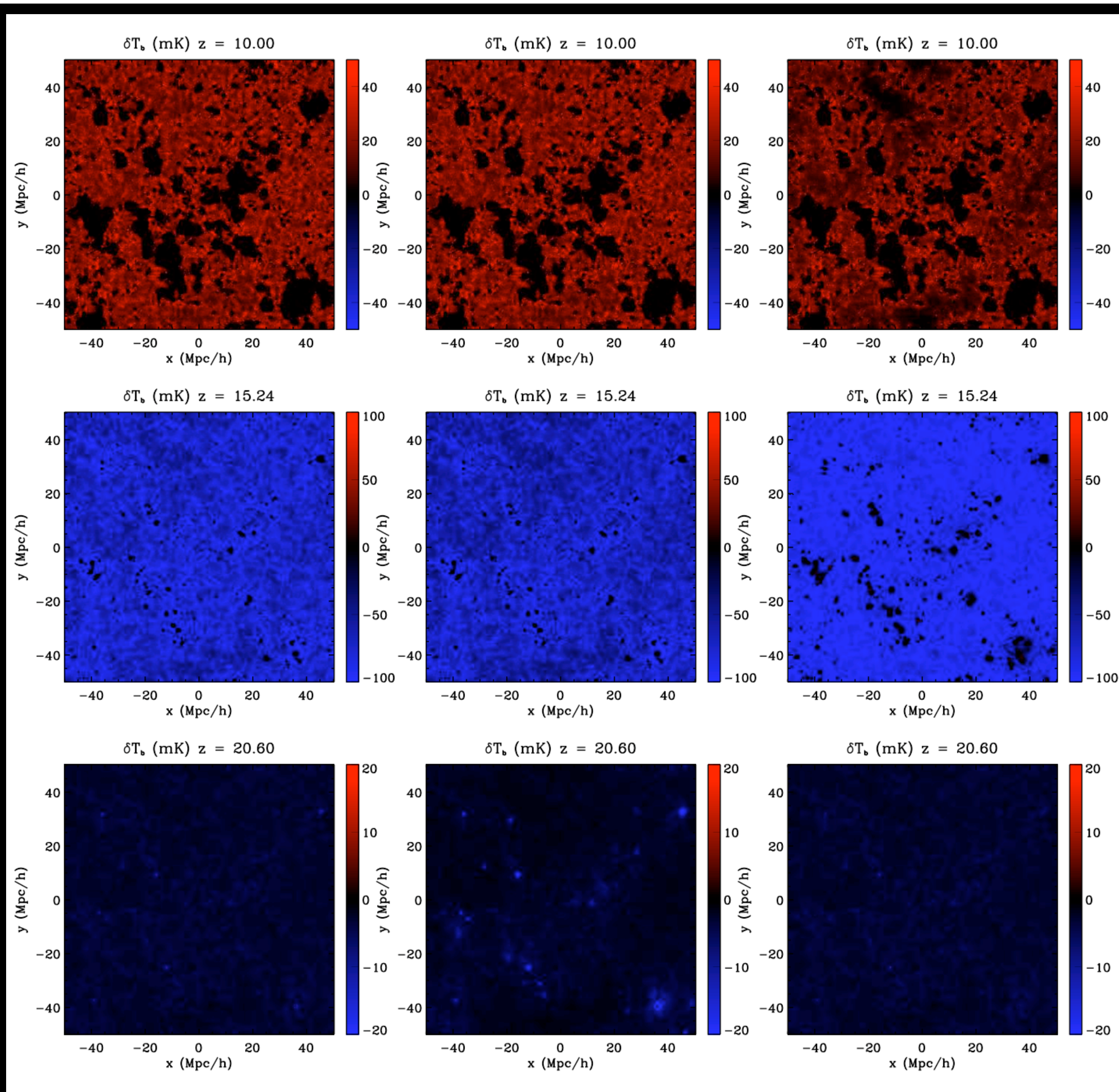
Temperature



- Onset of Lya fluctuations less parameter dependent
- Lya coupling precedes heating same for fluctuations
- X-rays couple & Lya photons heat (if no X-rays)

Pritchard & Loeb 2008

Comparison of Fluctuations

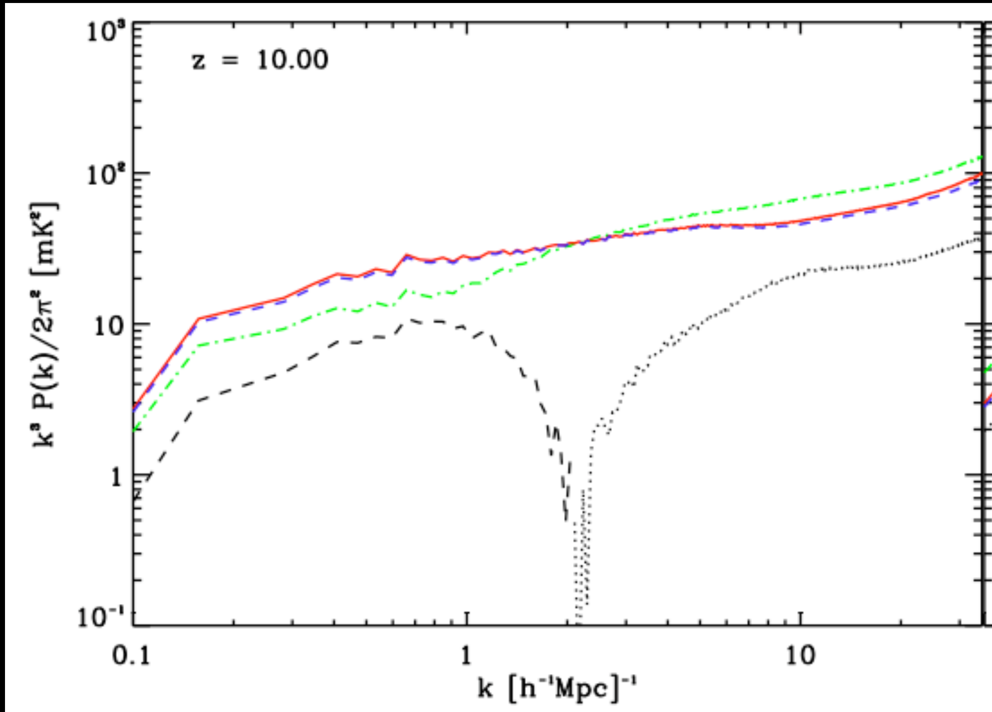


uniform Lya X-ray

Higher order terms

- Ionization fluctuations are not small $\delta X_H \sim 1$
- Higher order (in X) terms modify P21 on all scales
  - important to include in modeling

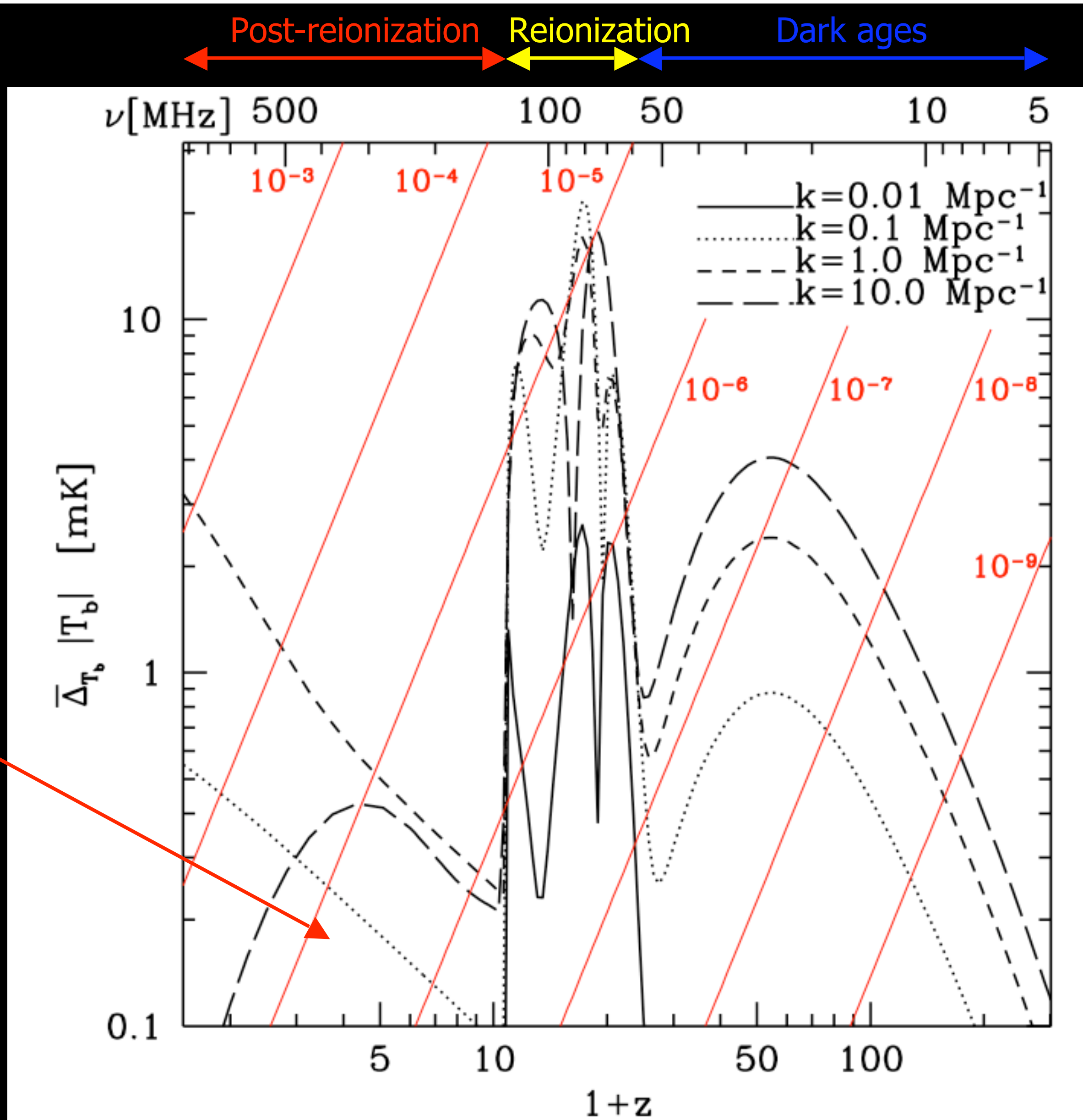
$$P_{21}(k) = T_c^2 \left[\bar{f}_{\rm HI}^2 P_{\delta,\delta}(k) + P_{x_i,x_i}(k) - 2\bar{f}_{\rm HI} P_{x_i,\delta}(k) + 2P_{x_i\delta,x_i}(k) - 2\bar{f}_{\rm HI} P_{x_i\delta,\delta}(k) + P_{x_i\delta,x_i\delta}(k) \right] ,$$



Green=full
Dashed = h.o.t.
Solid=standard

Lidz+ 2007
Santos+ 2008

Temporal evolution



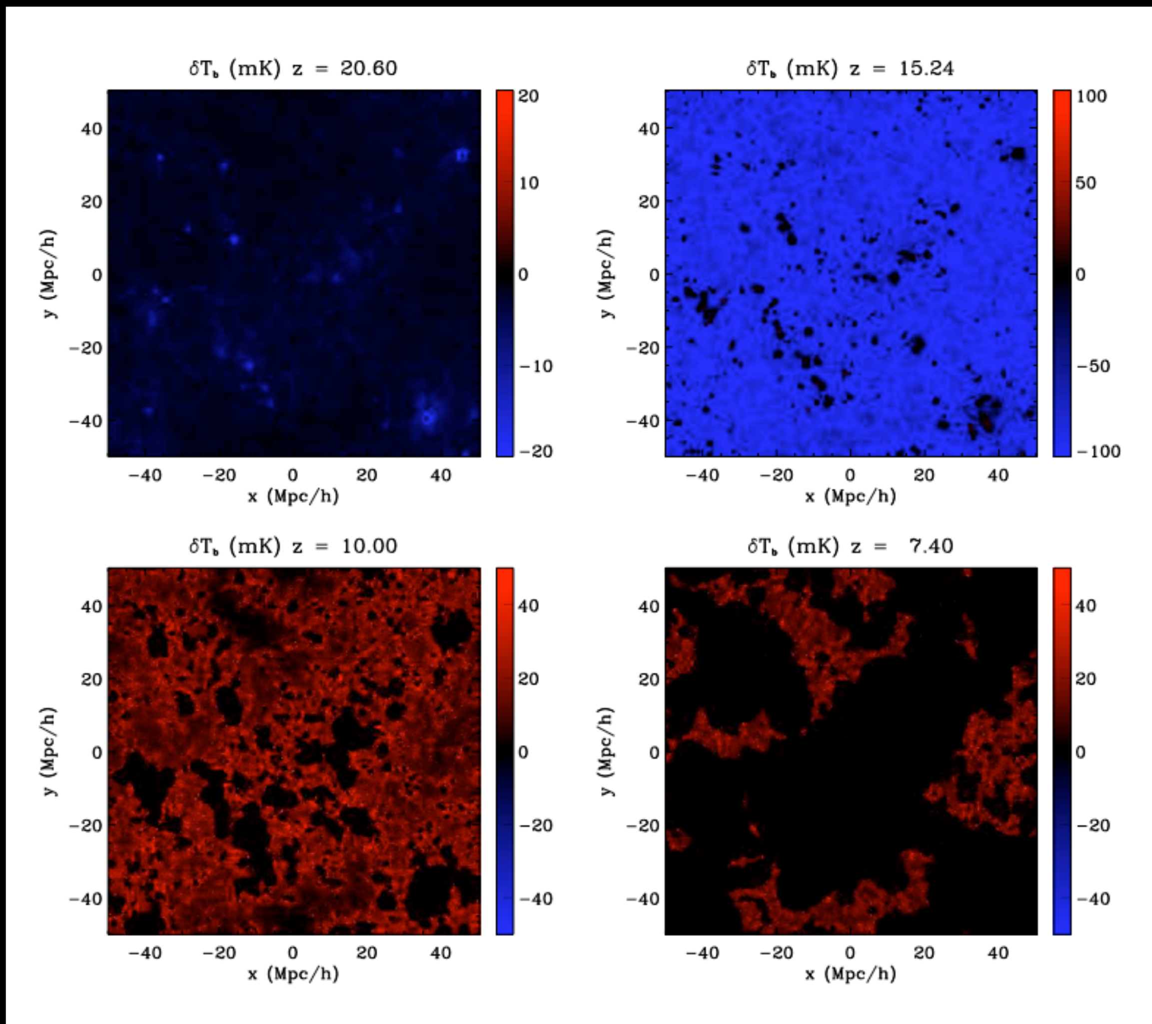
Signal from dense neutral clumps at low z

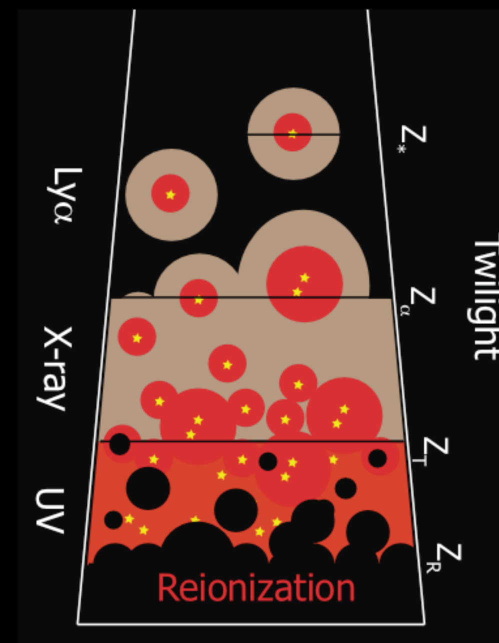
Chang et al. 2007
Wythe & Loeb 2007

Pritchard & Loeb 2008

Simulation + Lya +X-rays

$$\delta_{T_b} = \beta\delta + \beta_x\delta_{x_{HI}} + \boxed{\beta_T\delta_{T_k} + \beta_\alpha\delta_\alpha} - \delta_{\partial v}$$





Lya & T fluctuations can be important

Santos, Amblard, JRP, Trac, Cen, Cooray 2008