Radiation backgrounds from the first sources and the redshifted 21 cm line

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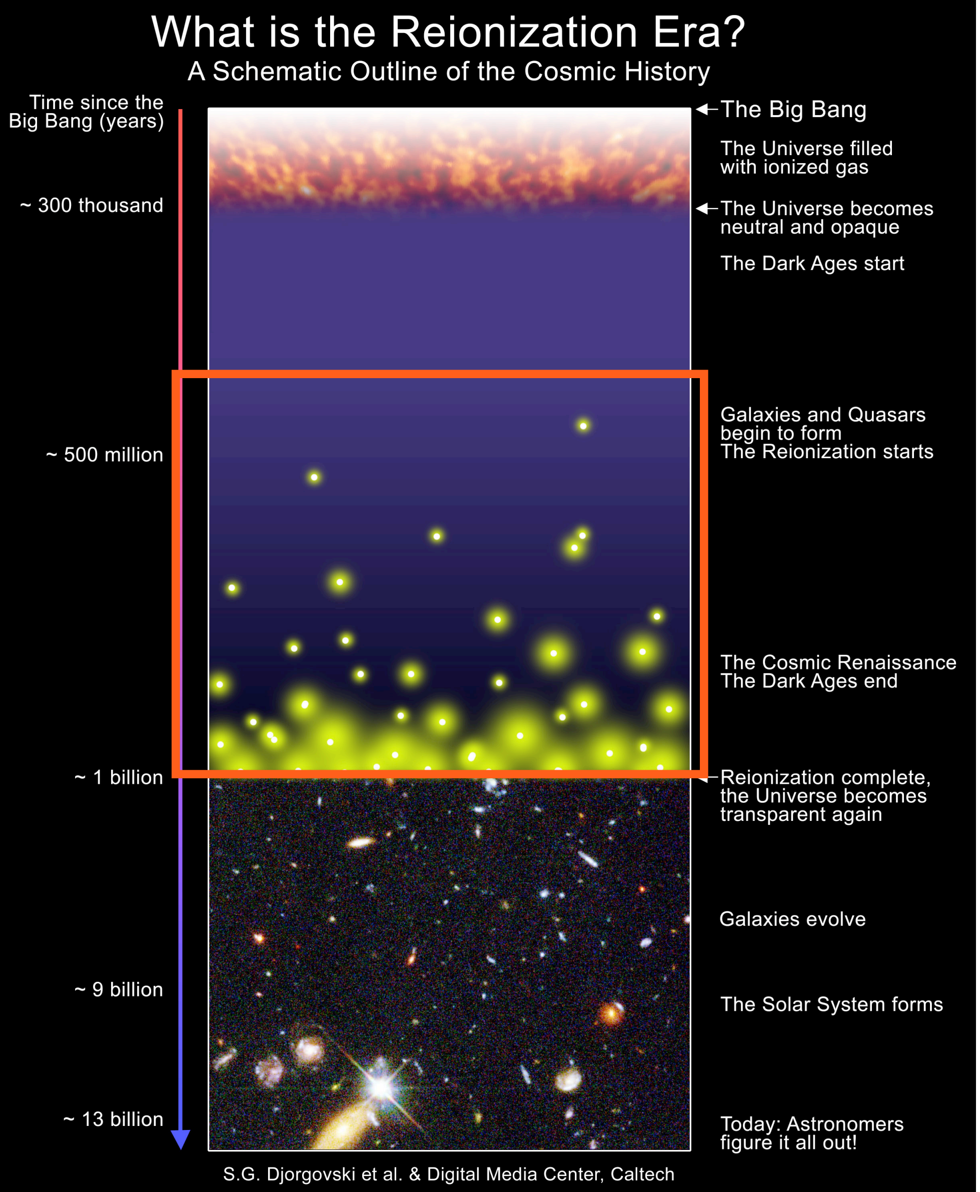
astro-ph/0508381

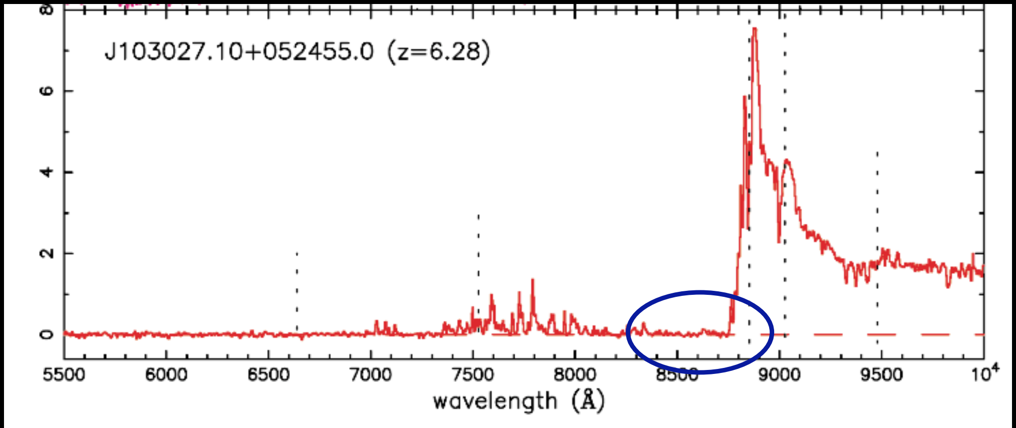
Overview

- 21 cm physics
- Atomic cascades and the Wouthysen-Field Effect
- Detecting the first stars through 21 cm fluctuations (Lyα)
- Inhomogeneous X-ray heating and gas temperature fluctuations (X-ray)



Ionization history

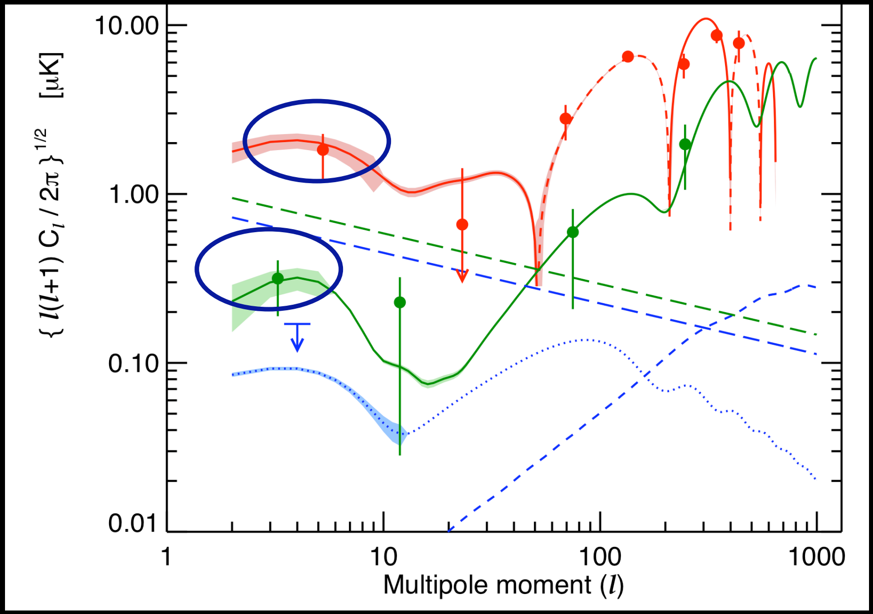
- Gunn-Peterson Trough



Becker et al. 2005

- Universe ionized below z~6, approaching neutral at higher z

- WMAP3 measurement of τ~0.09 (down from τ~0.17)

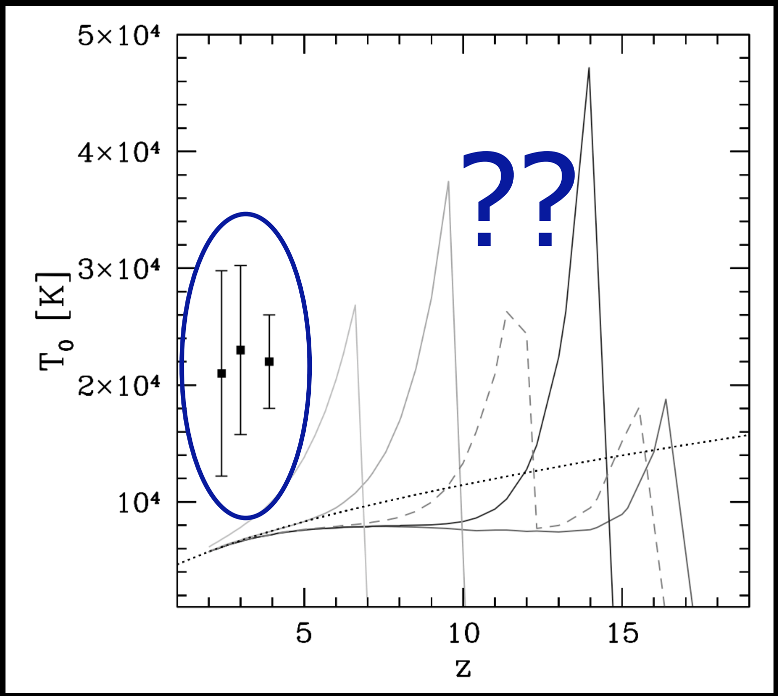


Page et al. 2006

- Integral constraint on ionization history
- Better TE measurements + EE observations

Thermal history

- Lya forest



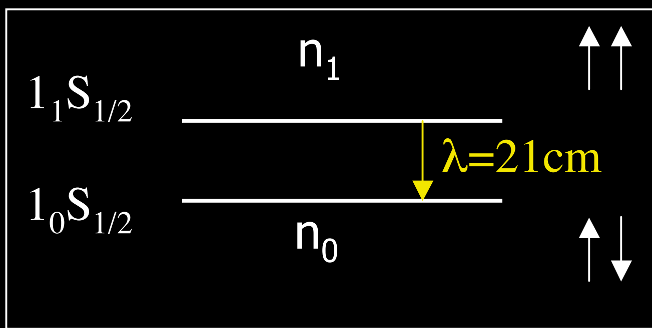
Hui & Haiman 2003

- IGM retains short term memory of reionization - suggests z_R<10
- Photoionization heating erases memory of thermal history before reionization

- CMB temperature
  - Knowing T_{CMB}=2.726 K and assuming thermal coupling by Compton scattering followed by adiabatic expansion allows informed guess of high z temperature evolution

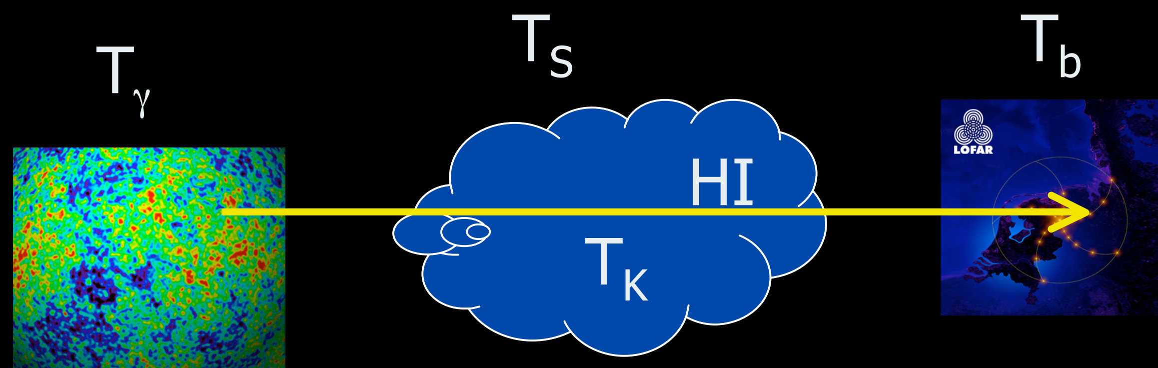
21 cm basics

- HI hyperfine structure



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

- Use CMB backlight to probe 21cm transition



z=13.75
f_{21cm}=1.4 GHz

z=0
f_{obs}=94.9 MHz
(KUOW)

- 3D tomography possible - angles + frequency

- 21 cm brightness temperature

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

- 21 cm spin temperature

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

Wouthysen-Field effect

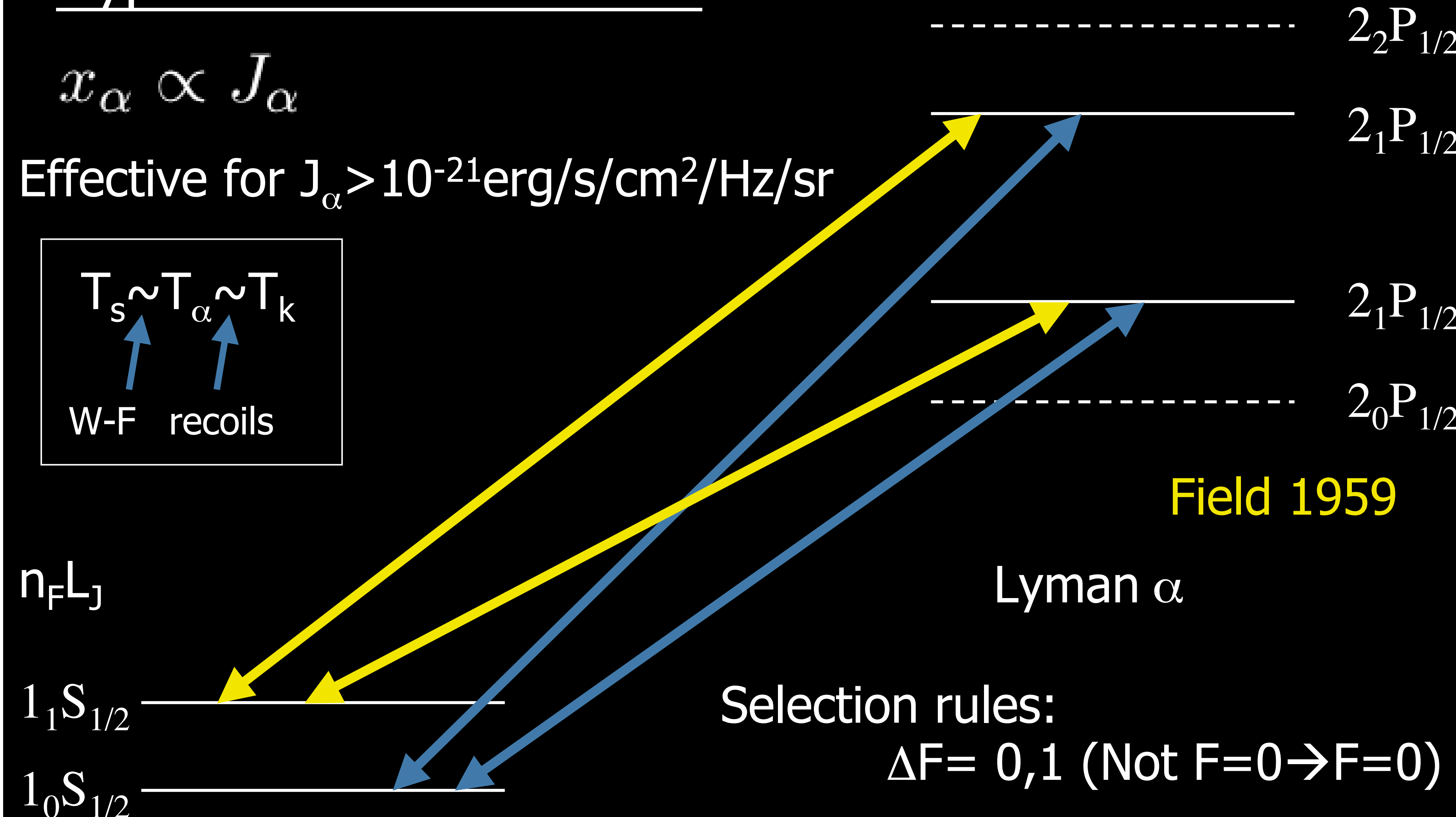
Hyperfine structure of HI

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

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

$T_s \sim T_\alpha \sim T_k$

W-F recoils



Selection rules:

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

Higher Lyman series

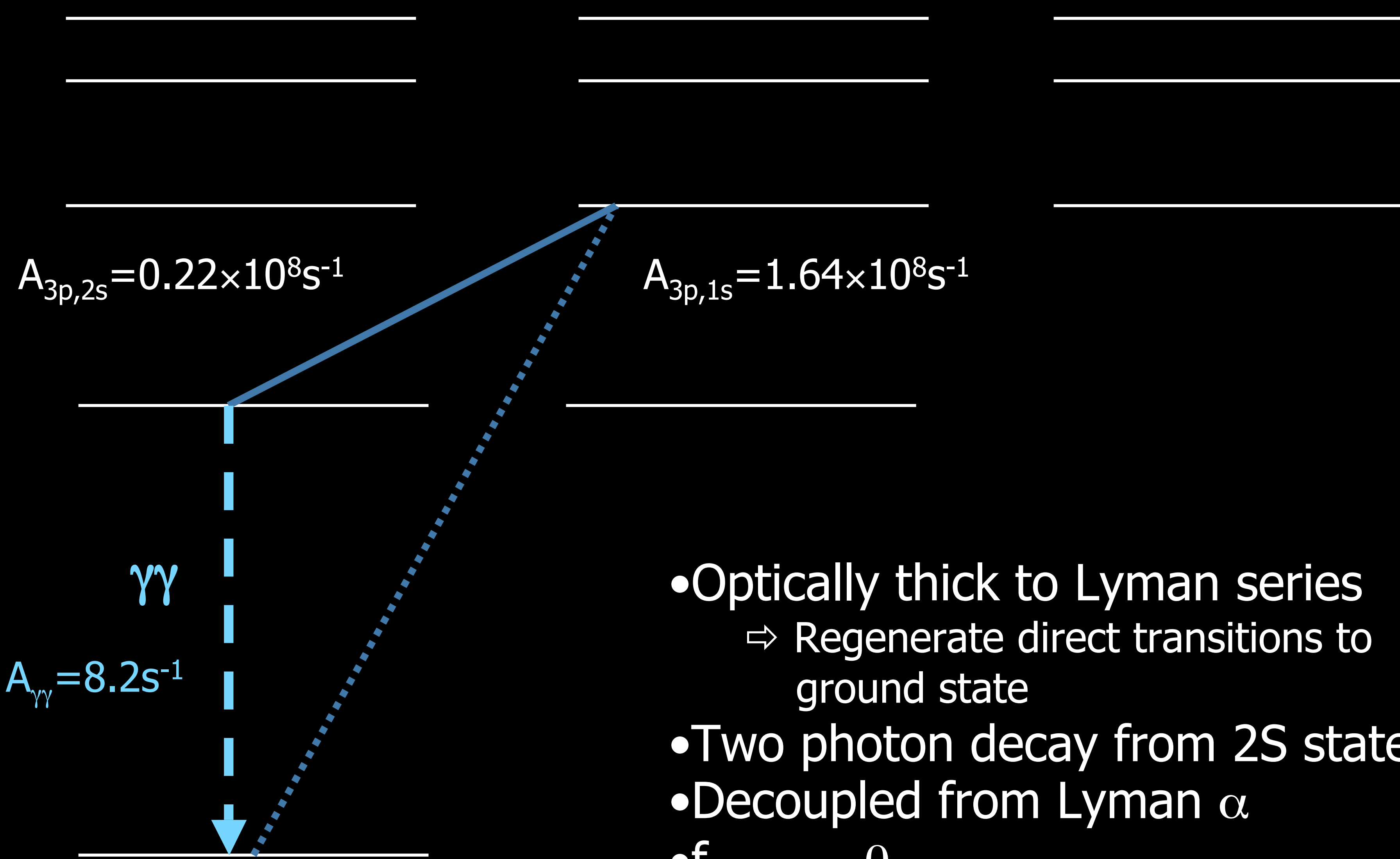
- Two possible contributions
  - Direct pumping: Analogy of the W-F effect
  - Cascade: Excited state decays through cascade to generate Lyα
- Direct pumping is suppressed by the possibility of conversion into lower energy photons
  - Ly α scatters ~10^6 times before redshifting through resonance
  - Ly n scatters ~$1/P_{abs}$~10 times before converting

  ⇨ Direct pumping is not significant
- Cascades end through generation of Ly α or through a two photon decay
  - Use basic atomic physics to calculate fraction recycled into Ly α
  - Discuss this process in the next few slides…

Pritchard & Furlanetto 2006

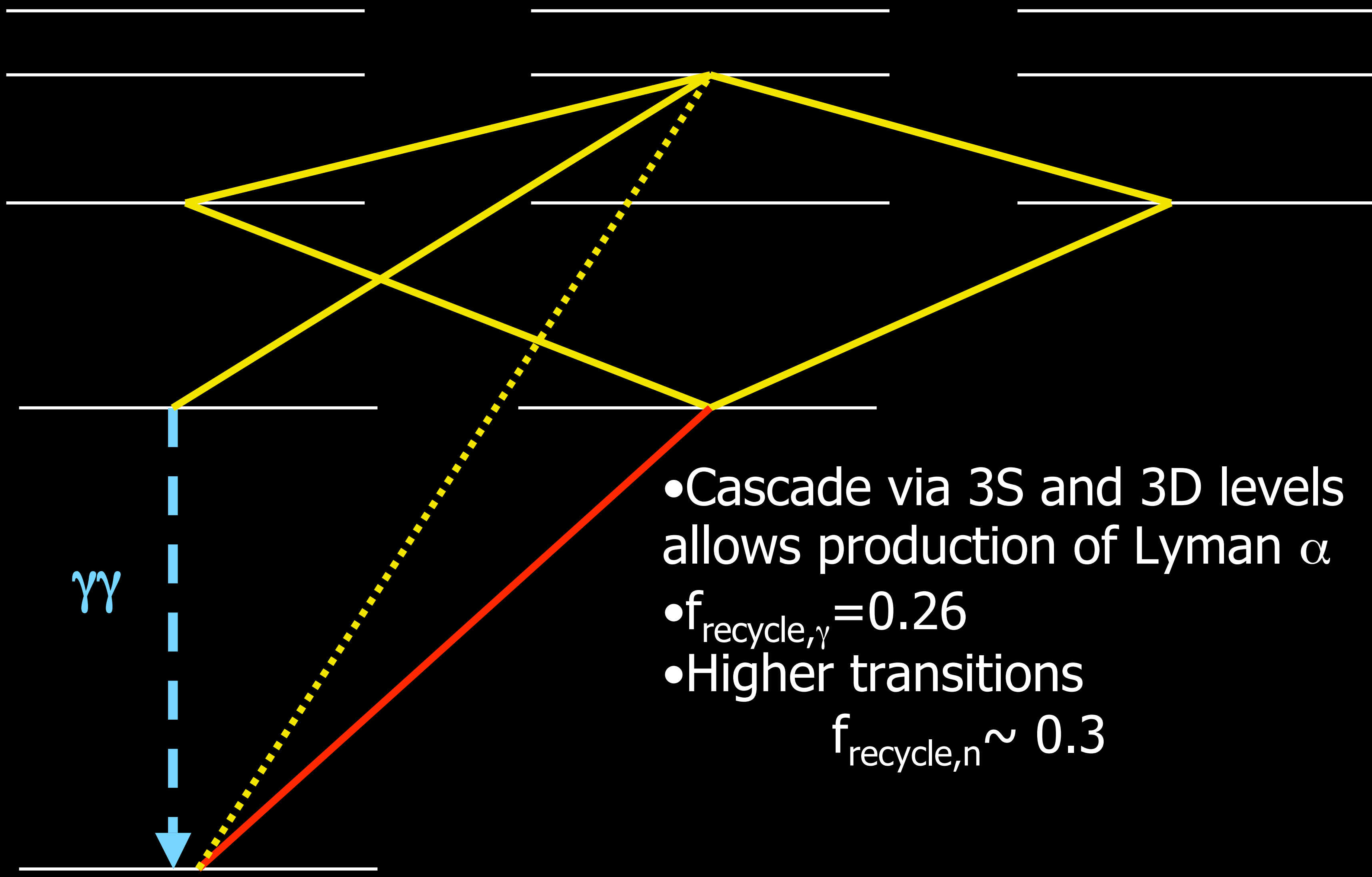
Hirata 2006

Lyman β



- Optically thick to Lyman series
  - ⇨ Regenerate direct transitions to ground state
- Two photon decay from 2S state
- Decoupled from Lyman α
- $f_{recycle,\beta}=0$

Lyman γ

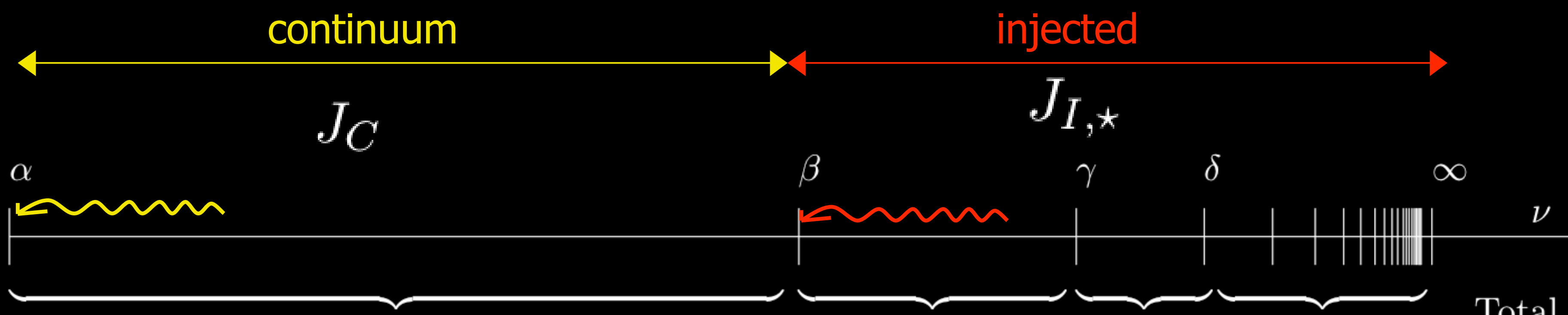


- Cascade via 3S and 3D levels allows production of Lyman α
- $f_{recycle,\gamma}=0.26$
- Higher transitions

  $f_{recycle,n} \sim 0.3$

Lyman alpha flux

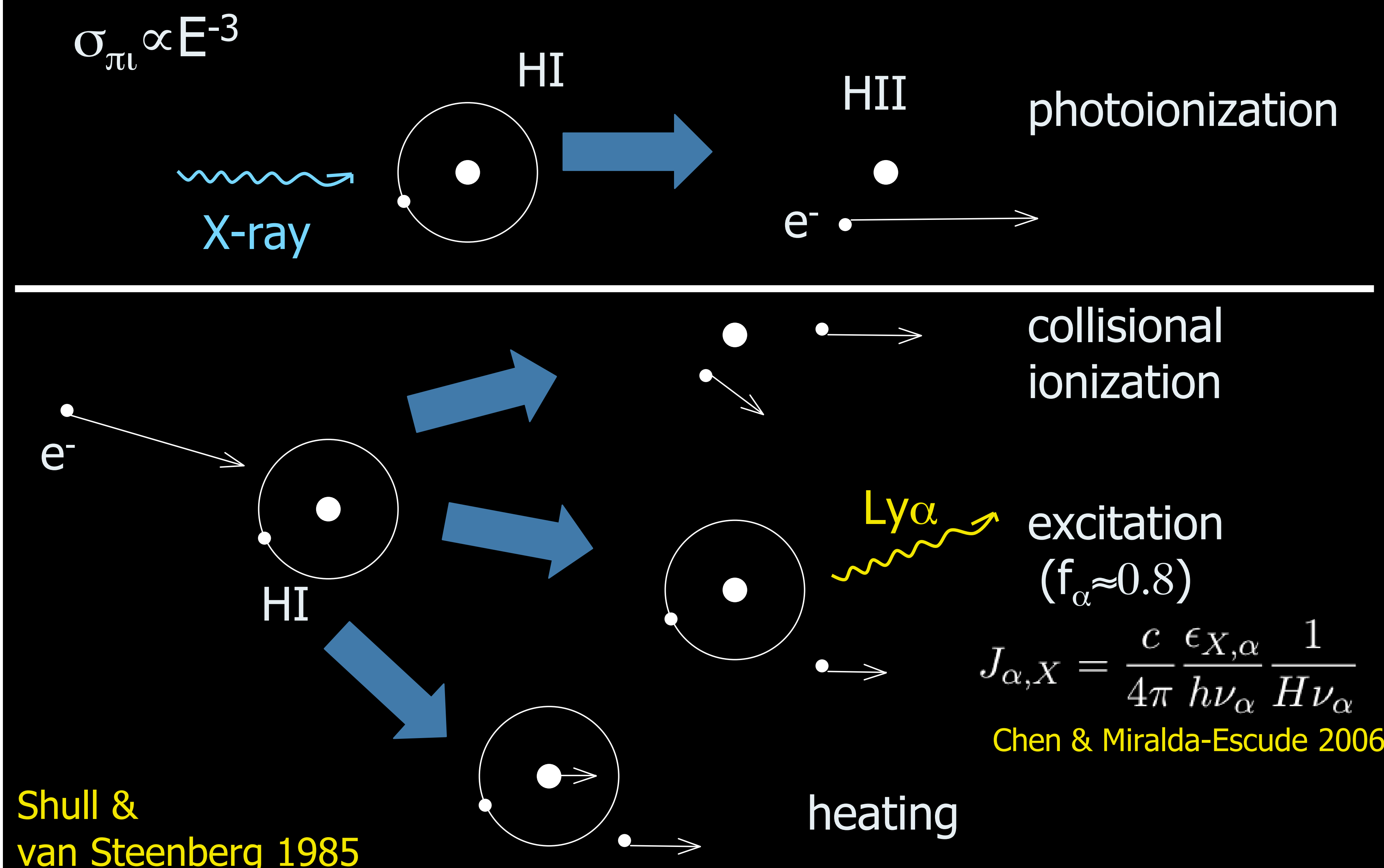
- Stellar contribution



					Total
No. Photons: (pop III)	2670	965	451	810	4896
$f_{recycle}$:	1.0	0	0.26	0.35	0.62
Lyα Contribution:	2670	0	118	268	3056
Shell size @$z = 20$ (Mpc):	278	90	40	22	

- also a contribution from any X-rays…

X-rays and Lya production



Experimental efforts

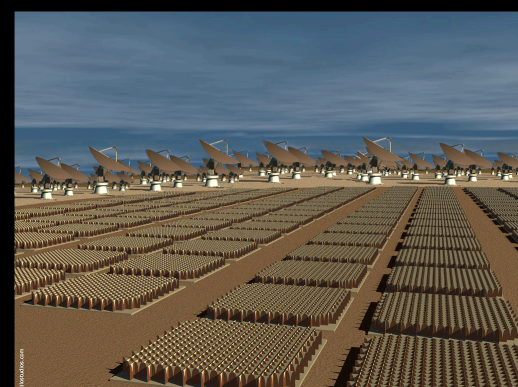
LOFAR: Netherlands
Freq: 120-240 MHz
Baselines: 100m-100km

MWA: Australia
Freq: 80-300 MHz
Baselines: 10m-1.5km

PAST: China
Freq: 70-200 MHz

(f_{21cm}=1.4 GHz)

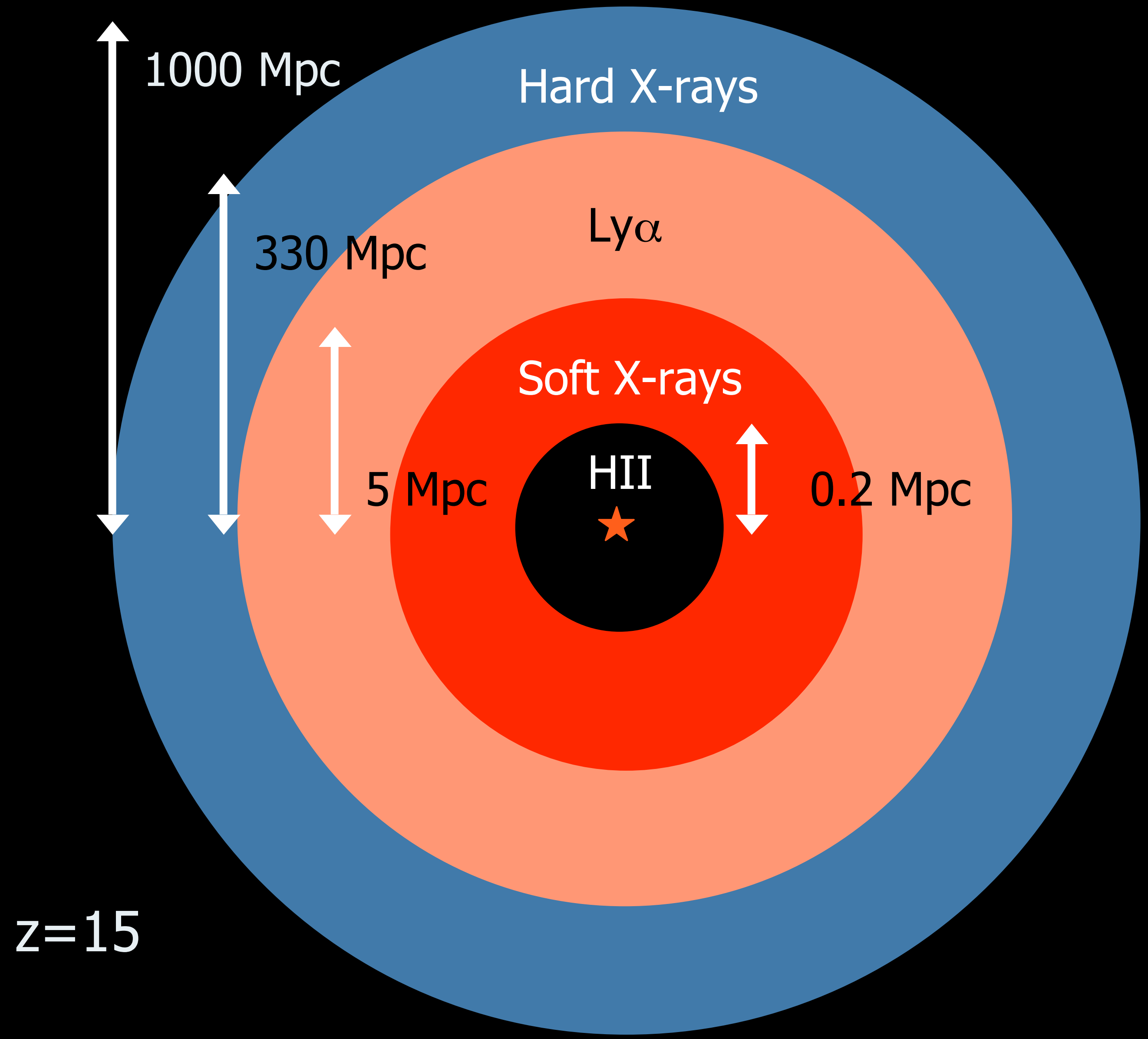
SKA: ???
Freq: 60 MHz-35 GHz
Baselines: 20m-3000km



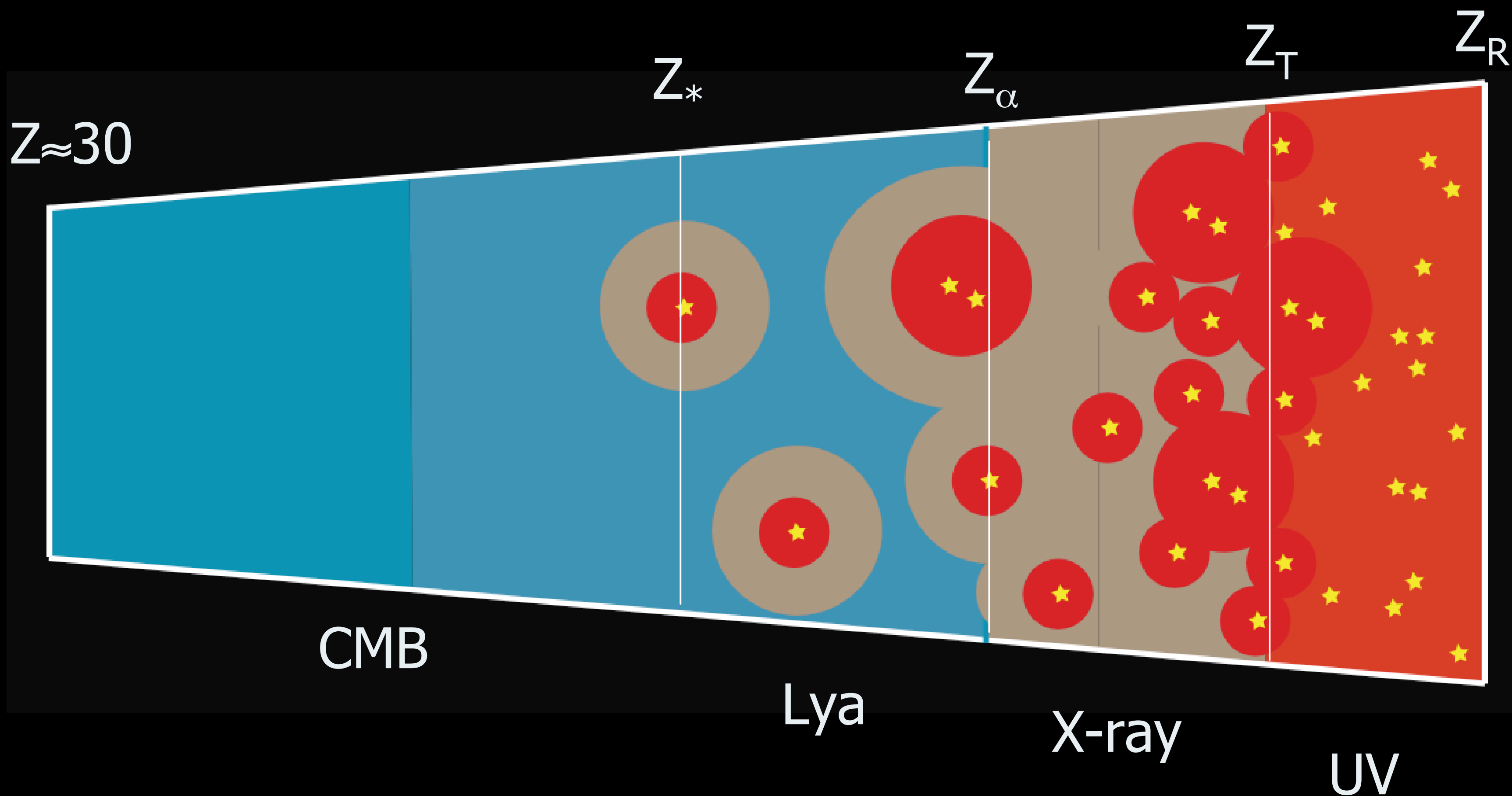
Foregrounds

- Many foregrounds
  - Galactic synchrotron (especially polarized component)
  - Radio Frequency Interference (RFI)
    e.g. radio, cell phones, digital radio
  - Radio recombination lines
  - Radio point sources
- Foregrounds dwarf signal:
  foregrounds ~1000s K vs 10s mK signal
- Strong frequency dependence $T_{sky} \propto \nu^{-2.6}$
- Foreground removal exploits smoothness in frequency and spatial symmetries

The first sources



Cosmological context



- Three main regimes for 21 cm signal
- Each probes different radiation field

Global history

$$\boxed{T_b = T_b(x_{\rm HI},\, T_K,\, J_\alpha,\, n_H)}$$

Furlanetto 2006

$$\frac{\mathrm{d}T_K}{\mathrm{d}t} = \text{Adiabatic expansion} + \text{X-ray heating} + \text{Compton heating}$$

Heating

$$\frac{\mathrm{d}x_i}{\mathrm{d}t} = \text{UV ionization} + \text{recombination}$$

HII regions

$$\frac{\mathrm{d}x_e}{\mathrm{d}t} = \text{X-ray ionization} + \text{recombination}$$

IGM

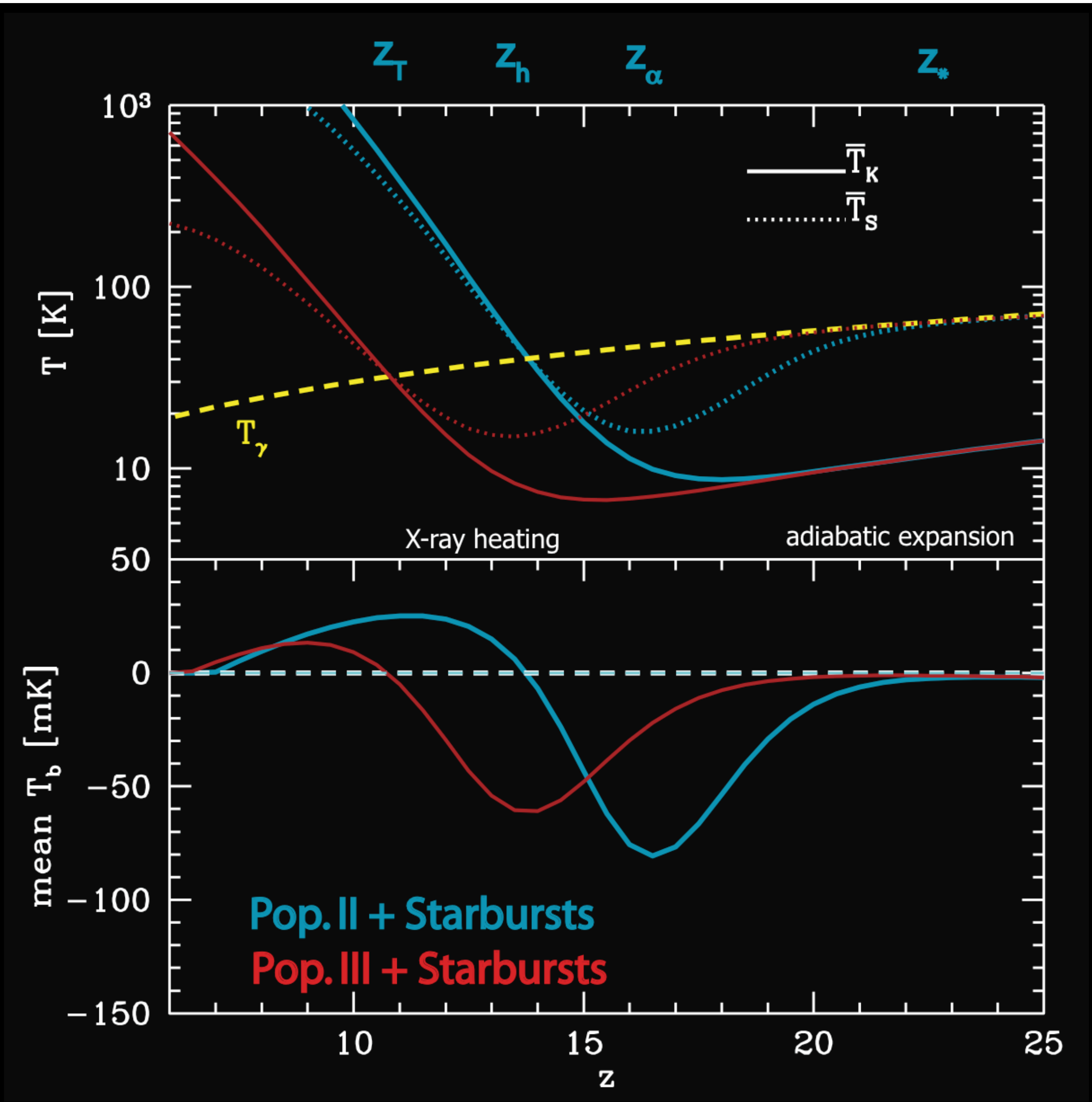
$$J_\alpha = J_C + J_{I,\star} + J_{I,X}$$

continuum injected

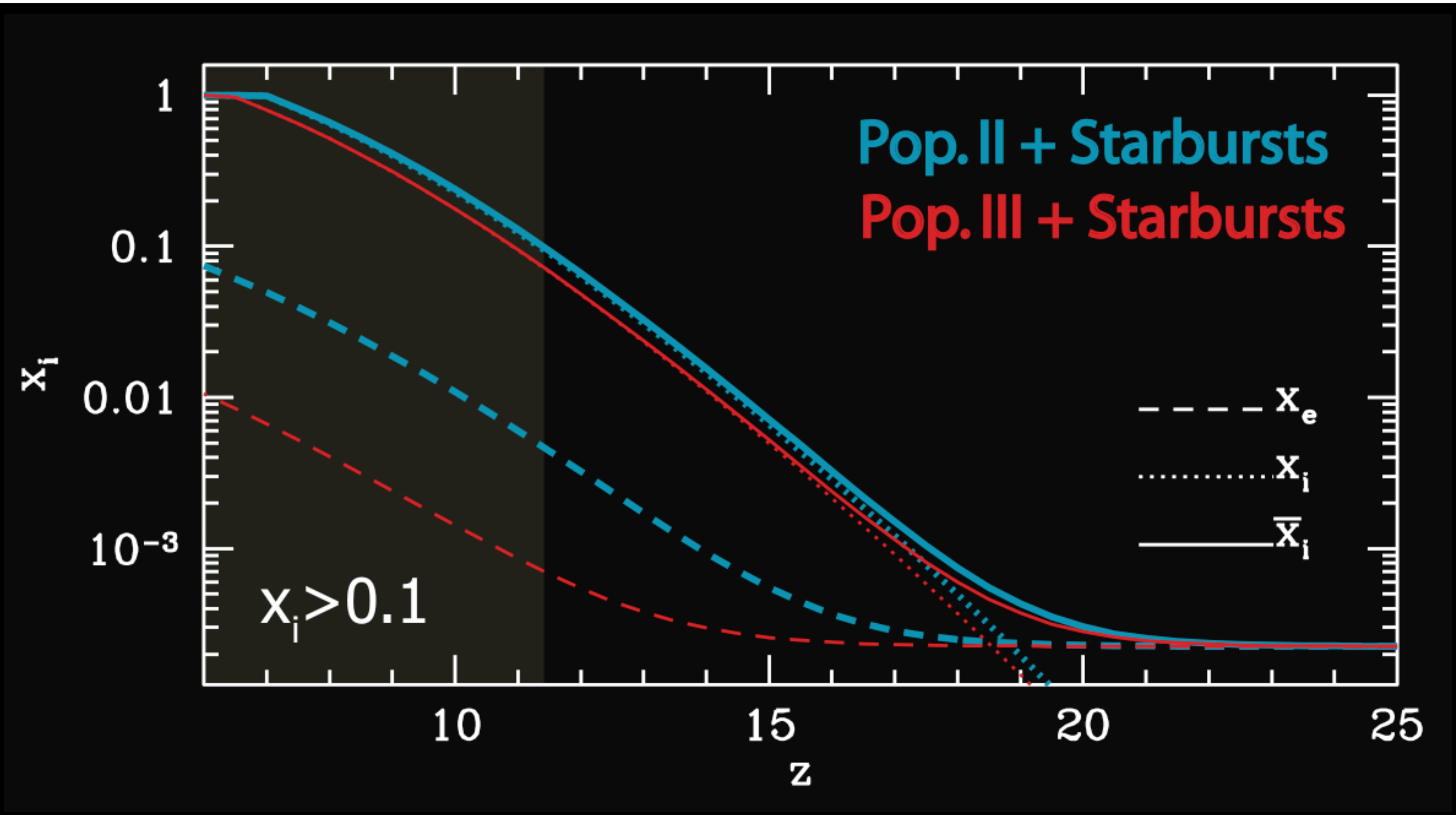
Lyα flux

- Sources: Pop. II & Pop. III stars (UV+Lya)
  Starburst galaxies, SNR, mini-quasar (X-ray)
- Source luminosity tracks star formation rate

Thermal history



Ionization history



•Ionization fluctuations relevant for z<12, not so important above that redshift. Furlanetto, Zaldarriaga, Hernquist 2004

•We'll restrict to fluctuations at z>13

21 cm fluctuations

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

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

Radiation background probed:	UV	X-ray	Lya

- In linear theory, peculiar velocities correlate with overdensities

$$\delta_{d_r v_r}(k) = -\mu^2 \delta$$

Bharadwaj & Ali 2004

- Anisotropy of velocity gradient term allows angular separation

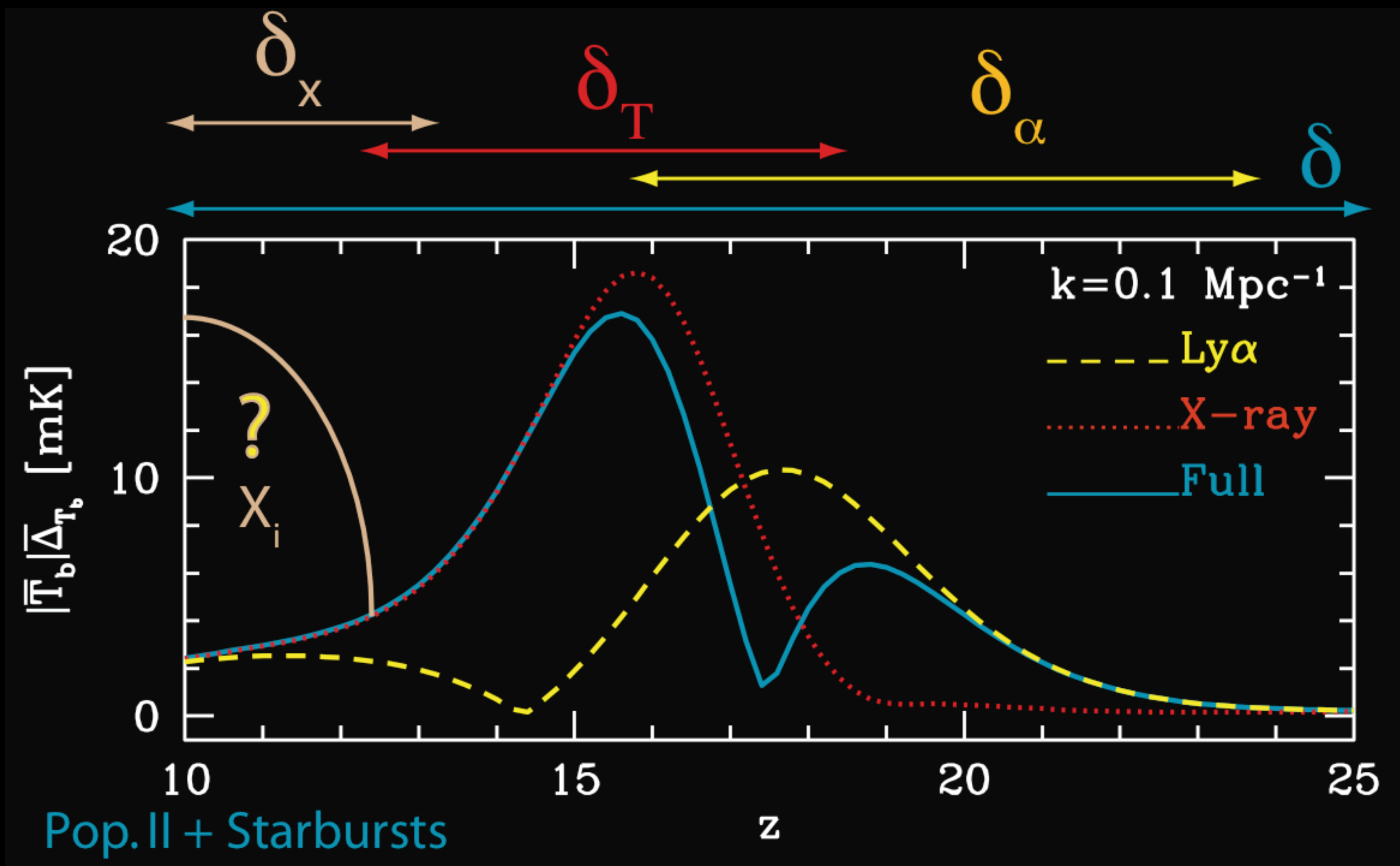
$$P_{T_b}(\mathbf{k}) = \mu^4 P_{\mu^4} + \mu^2 P_{\mu^2} + P_{\mu^0}$$

Barkana & Loeb 2005

- Initial observations will average over angle to improve S/N

21 cm fluctuations: z

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



•Exact form very model dependent

21 cm fluctuations: Lyα

Density	Neutral fraction	Gas Temperature	W-F Coupling	Velocity gradient

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

IGM still mostly neutral

negligible heating of IGM

Lya flux varies

- Lyα fluctuations unimportant after coupling saturates (x_α>>1)

$$\beta_\alpha \approx \frac{1}{1+x_\alpha}$$

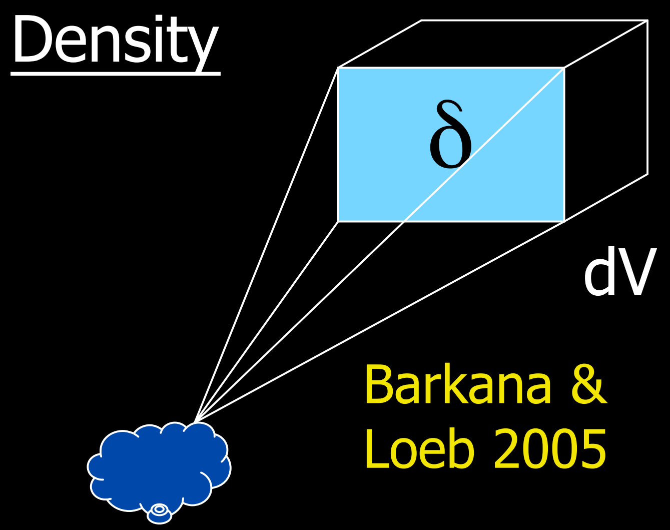
$$\boxed{x_\alpha \propto J_\alpha}$$

- Three contributions to Lyα flux:
  1. Stellar photons redshifting into Lyα resonance
  2. Stellar photons redshifting into higher Lyman resonances
  3. X-ray photoelectron excitation of HI

Chen & Miralda-Escude 2004

Chen & Miralda-Escude 2006

Fluctuations from the first stars



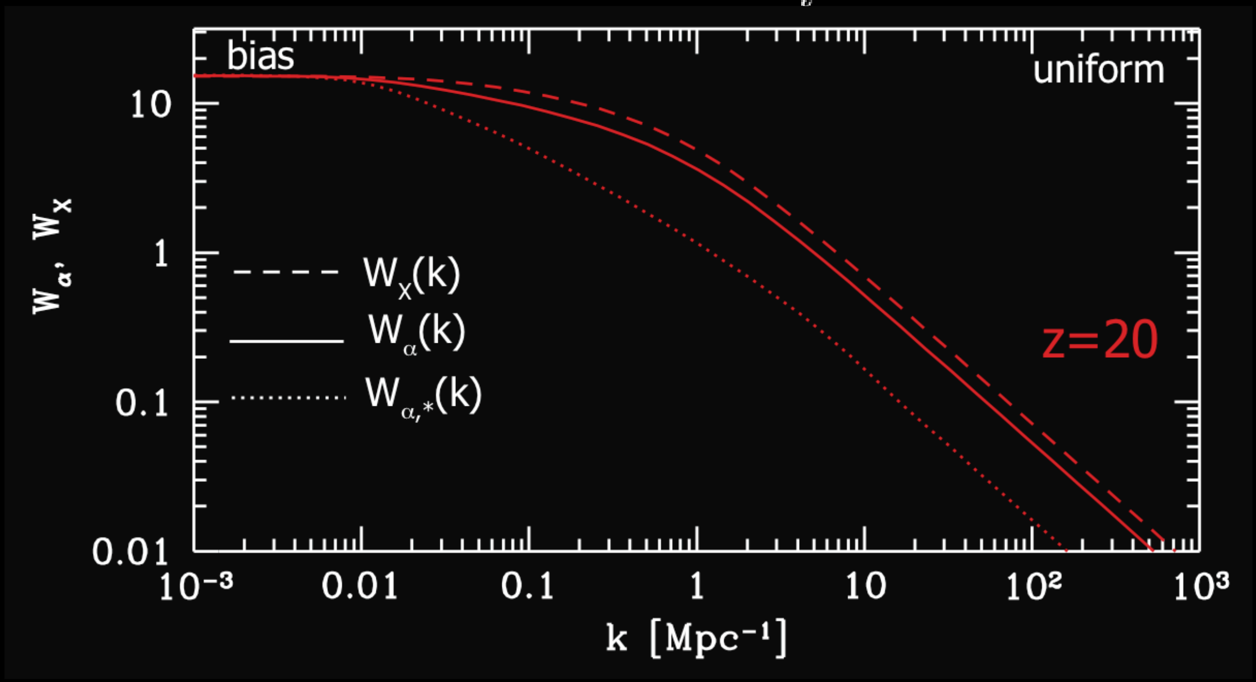
Barkana & Loeb 2005

- Overdense region modifies observed flux from region dV
- Relate Lyα fluctuations to overdensities

$$\delta_{x_\alpha}(\mathbf{k}) = W(k)\delta(\mathbf{k})$$

- W(k) is a weighted average

$$W_\alpha = \sum_i W_{\alpha,i}(J_{\alpha,i}/J_\alpha)$$



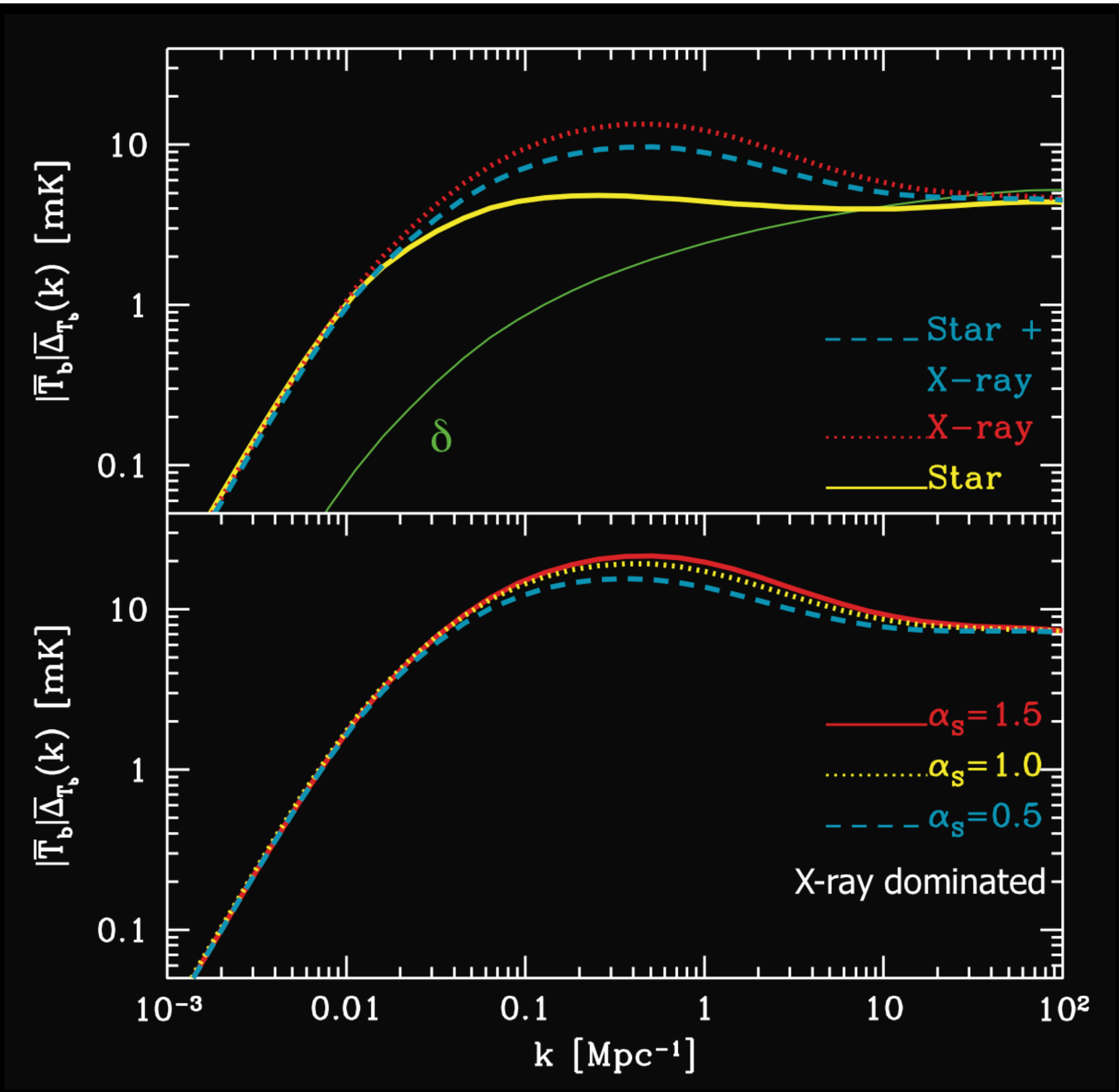
Determining the first sources

Sources

$J_{\alpha,*}$ vs $J_{\alpha,X}$

Spectra

α_S



Chuzhoy & Shapiro 2006

Summary: Lyα

- Including correct atomic physics is important for extracting astrophysical information from 21cm fluctuations
- Lyα fluctuations dominate 21 cm signal at high z
- Can be used to determine major source of Lya photons
- Intermediate scales give information on X-ray spectrum
- Constrain bias of sources at high z
- Probe early star formation
- Poisson fluctuations may also be interesting

21cm fluctuations: T_K

Density	Neutral fraction	Gas Temperature	W-F Coupling	Velocity gradient

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

IGM still mostly neutral

density + x-rays

coupling saturated

- In contrast to the other coefficients β_T can be negative

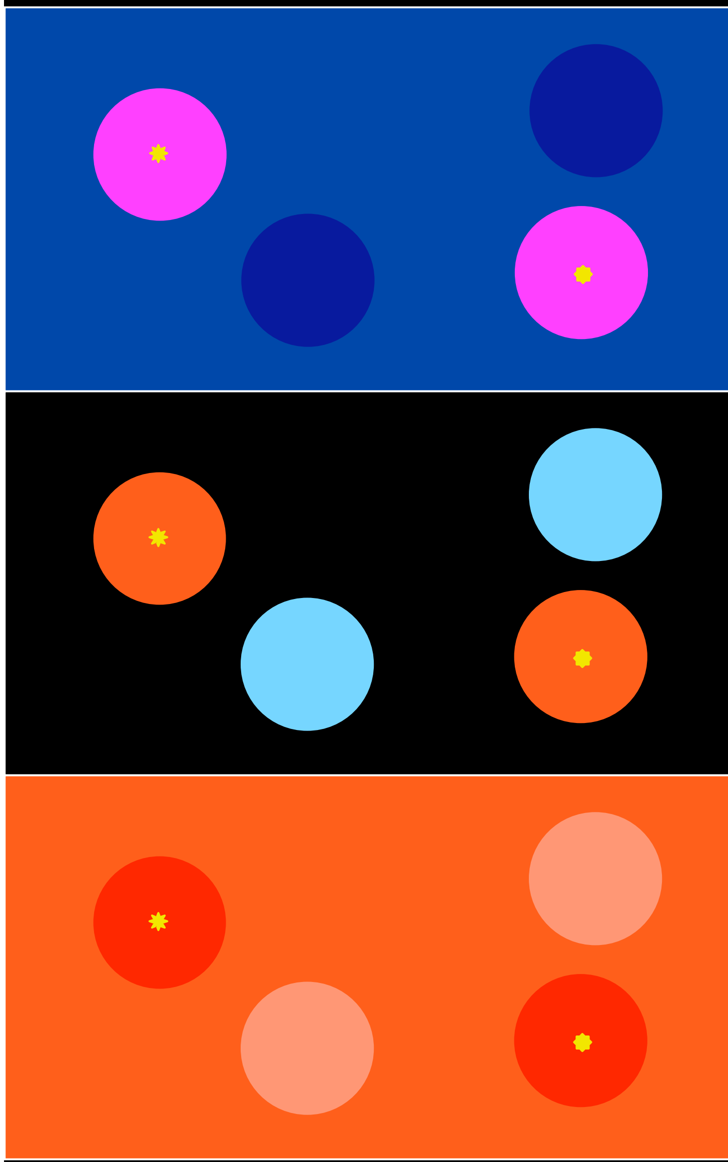
$$\beta_T \approx \frac{T_\gamma}{T_K - T_\gamma}$$

- Sign of β_T constrains IGM temperature

Pritchard & Furlanetto 2006

Temperature fluctuations

$$T_B = \tau \left(\frac{T_s - T_\gamma}{1+z} \right)$$



$T_S \sim T_K < T_\gamma$
$T_b < 0$ (absorption)
Hotter region = weaker absorption
$\beta_T < 0$

$T_S \sim T_K \sim T_\gamma$
$T_b \sim 0$
21cm signal dominated by temperature fluctuations

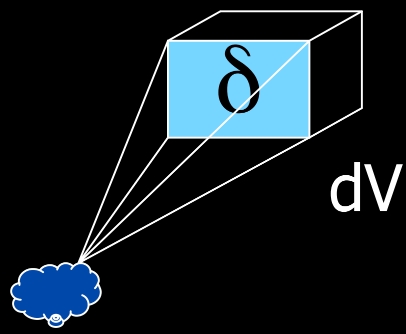
$T_S \sim T_K > T_\gamma$
$T_b > 0$ (emission)
Hotter region = stronger emission
$\beta_T > 0$

X-ray heating

- X-rays provide dominant heating source in early universe (shocks possibly important very early on)
- X-ray heating usually assumed to be uniform as X-rays have long mean free path

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

- Simplistic, fluctuations may lead to observable 21cm signal
- $$J_X \xrightarrow{\text{photo-ionization}} \Lambda_X \xrightarrow{\text{time integral}} T_K$$
- Fluctuations in J_X arise in same way as J_α
- $$\delta_T = g_T(k,z)\delta$$



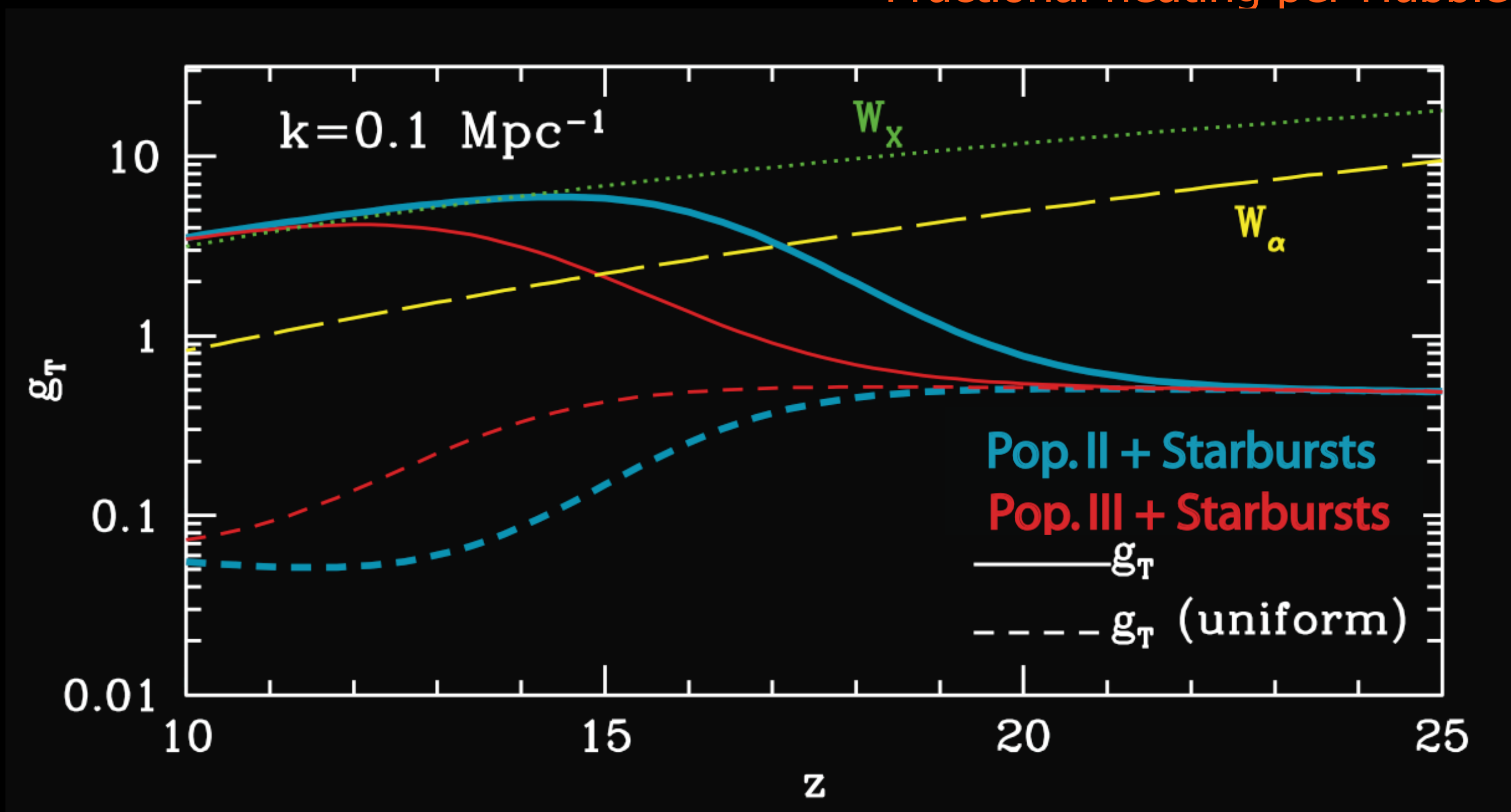
Growth of fluctuations

expansion X-rays Compton

$$\frac{\mathrm{d}g_T}{\mathrm{d}z} = \left(\frac{g_T - 2/3}{1+z}\right) - Q_X(z)[W_X(k) - g_T] - Q_C(z)g_T$$

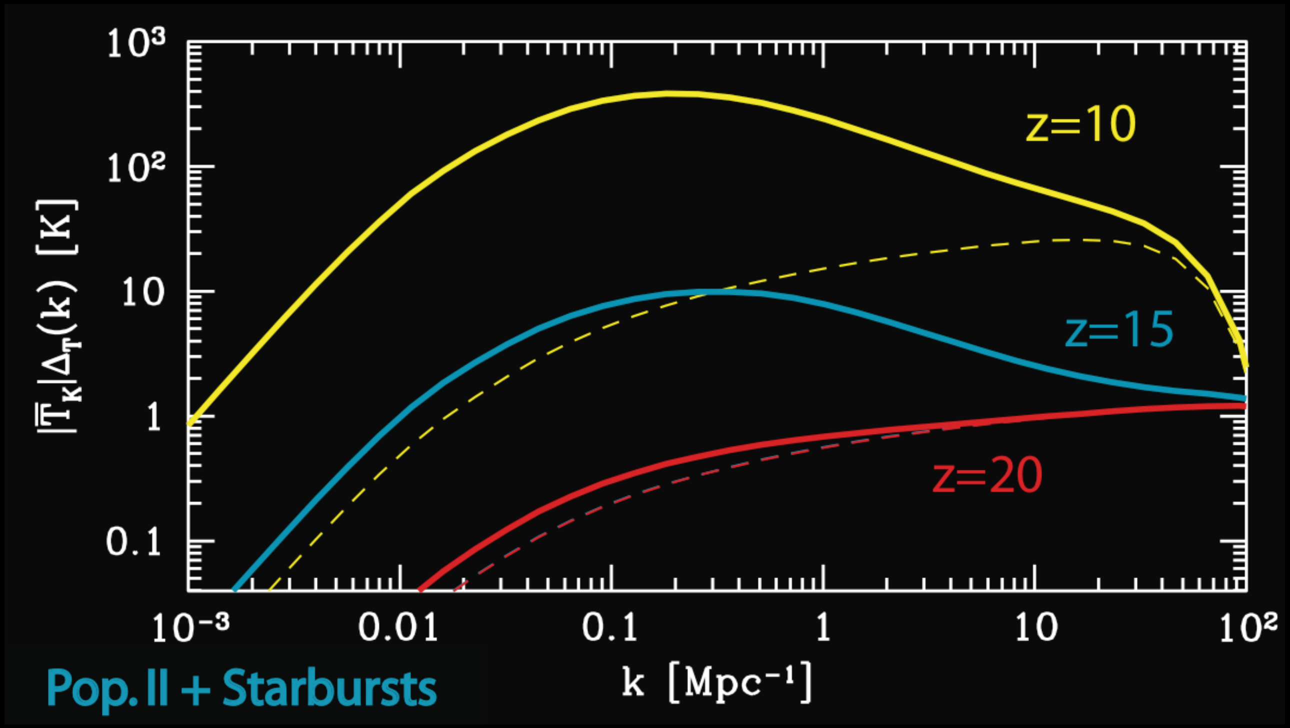
Heating fluctuations

Fractional heating per Hubble time at z



T_K fluctuations

- Fluctuations in gas temperature can be substantial
- Uniform heating washes out fluctuation on small scales
- Inhomogeneous heating amplifies fluctuation on large scales
- Amplitude of fluctuations contains information about IGM thermal history



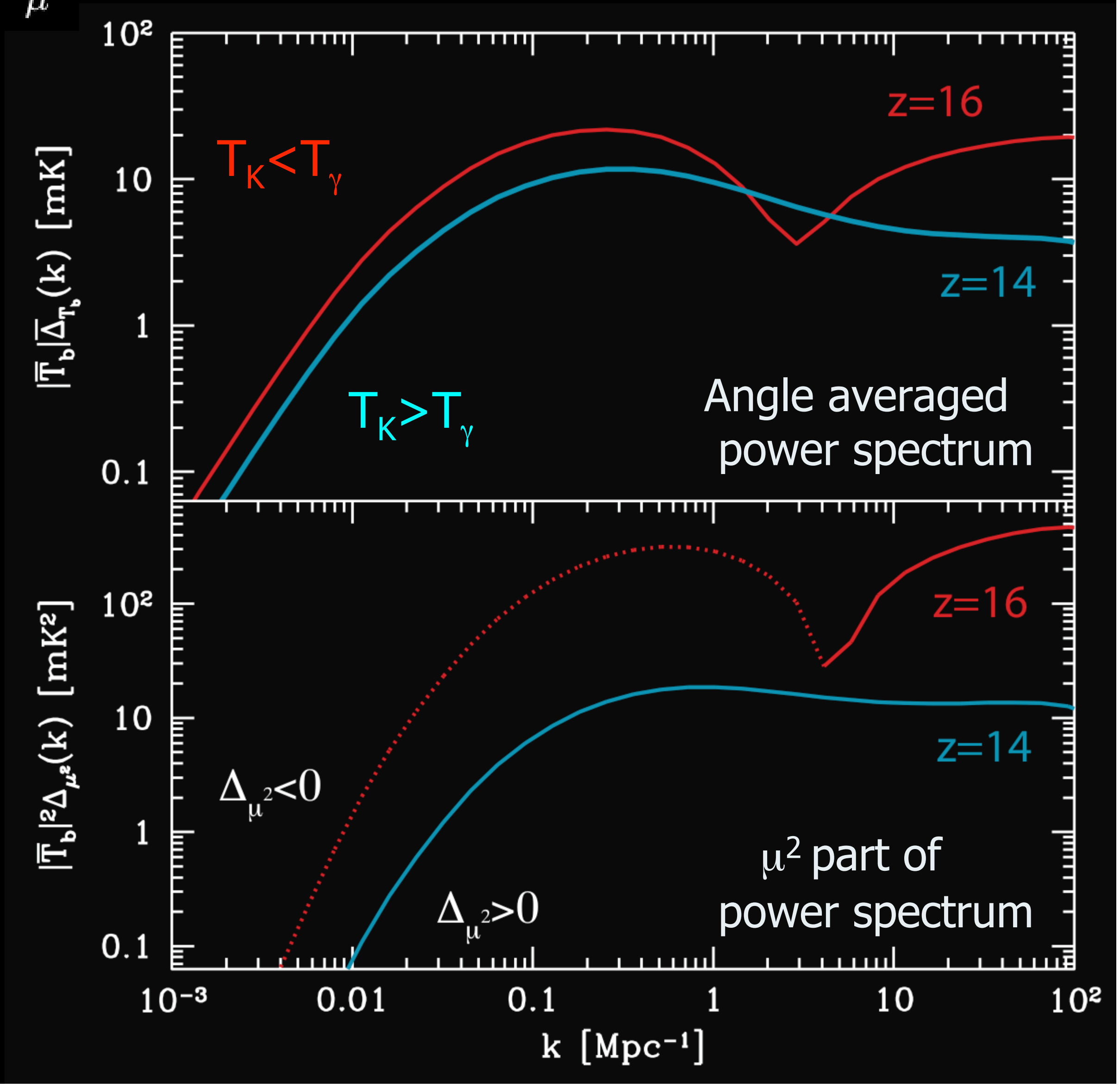
Indications of T_K

$$P_{T_b}(\mathbf{k}) = \mu^4 P_{\mu^4} + \mu^2 P_{\mu^2} + P_{\mu^0}$$

- When $T_K<T_\gamma$ very different form from Lyα

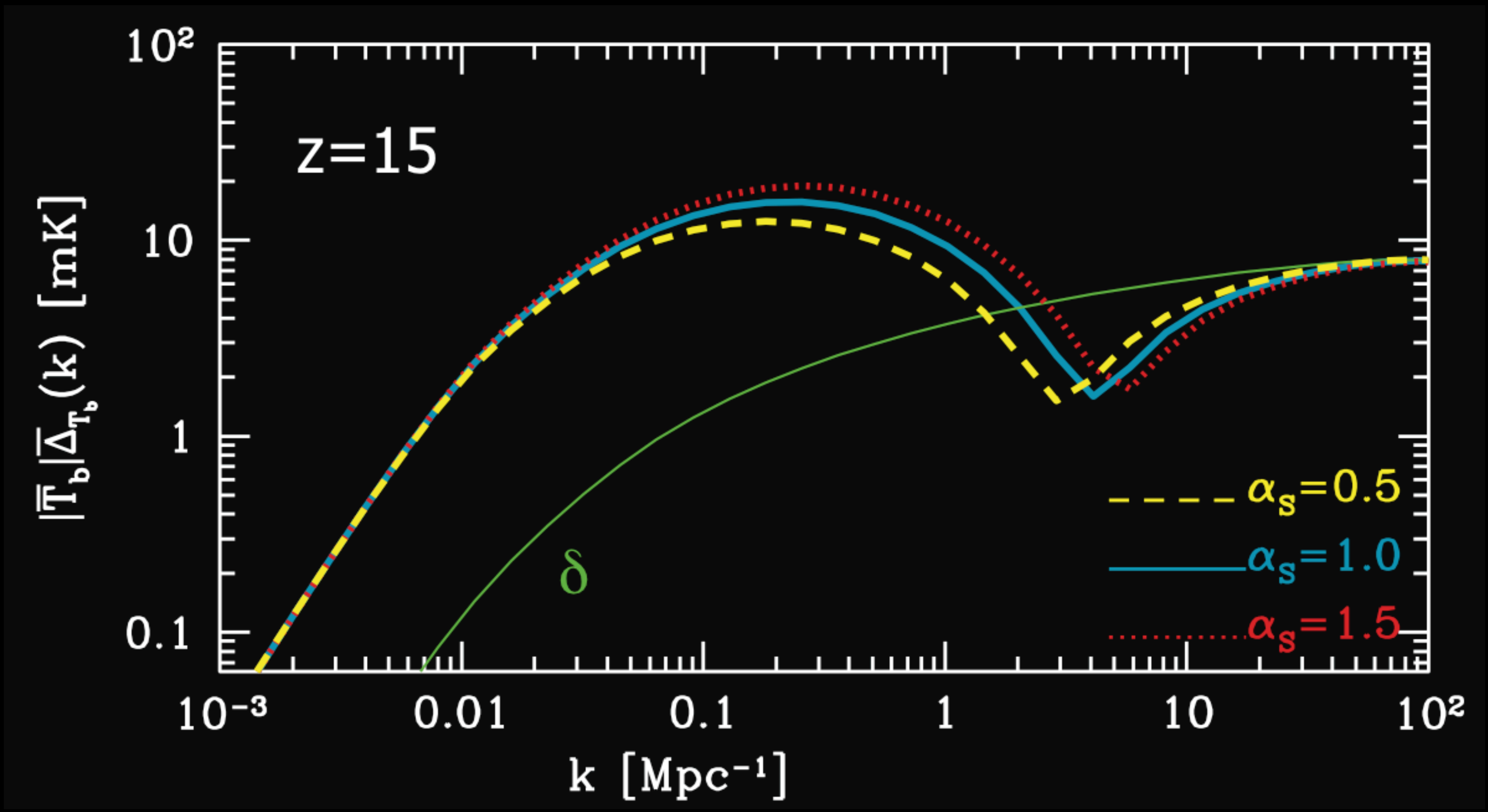
- Δ_{μ^2} can be negative which is clear indication of $\beta_T <0$ (trough)

- Existence of features will help constrain astrophysical parameters



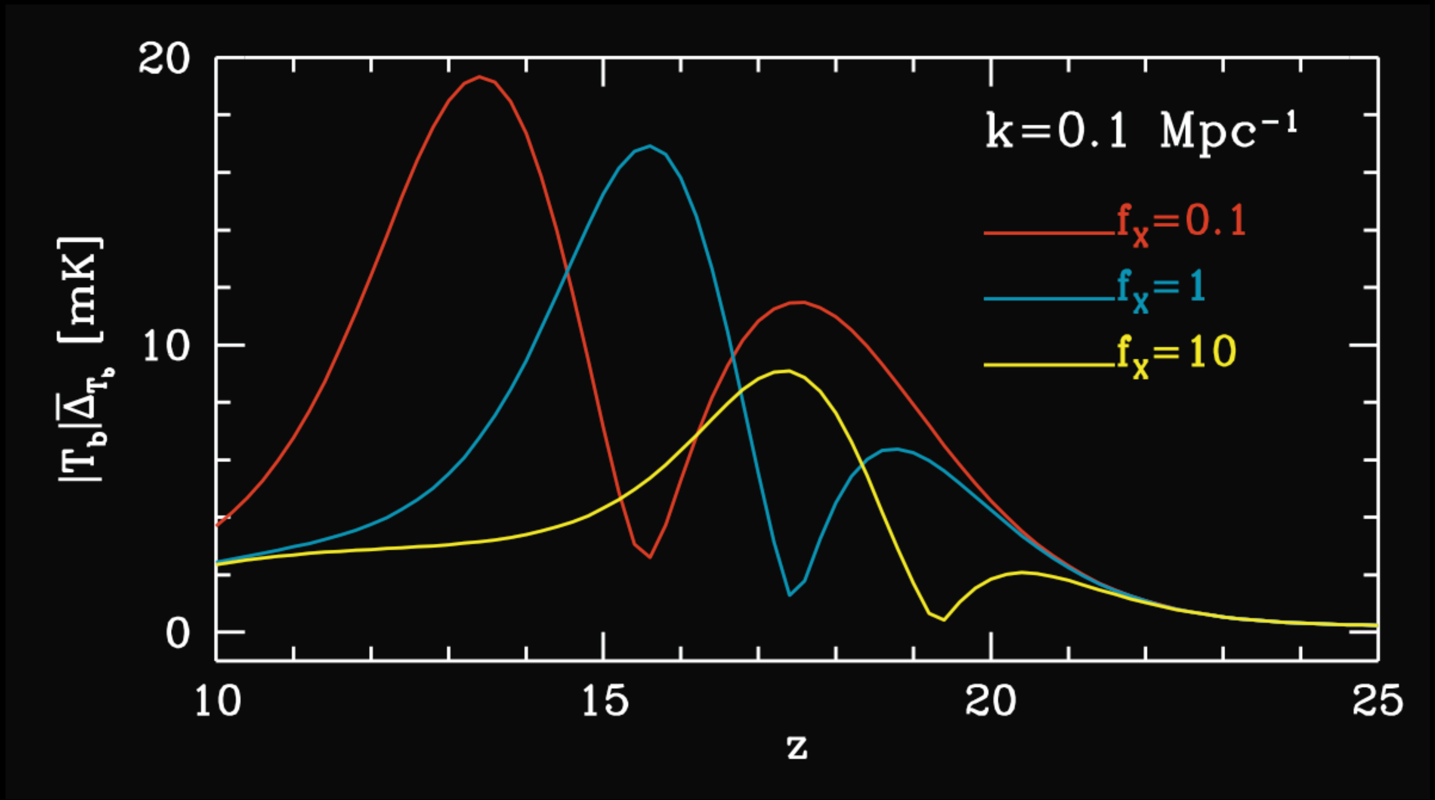
X-ray source spectra

- Sensitivity to α_S through peak amplitude and shape
- Also through position of trough
- Effect comes from fraction of soft X-rays



X-ray background?

- X-ray background at high z is poorly constrained
- Decreasing f_X helps separates different fluctuations
- Also changes shape of Lyα power spectrum
- If heating is late might see temperature fluctuations with first 21 cm experiments

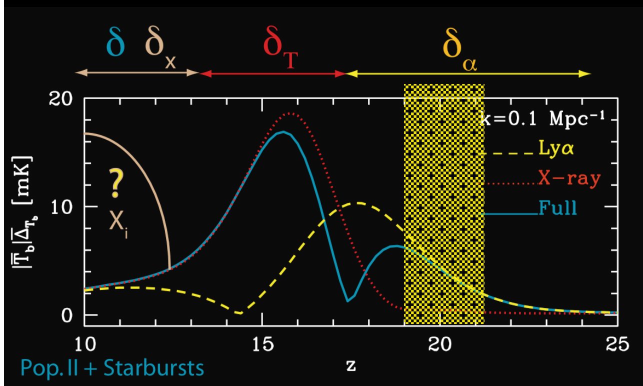


Summary: T_K

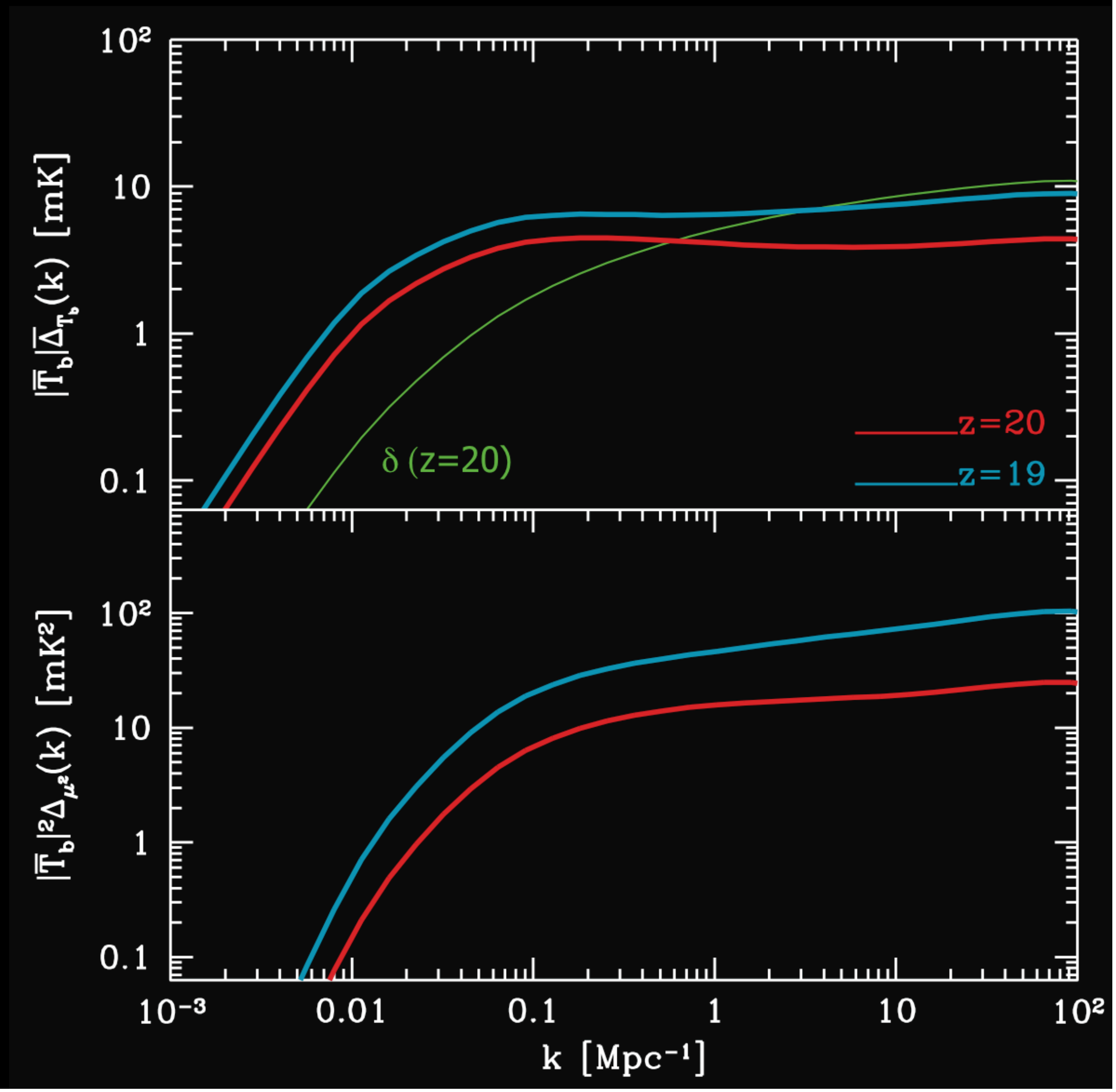
- Inhomogeneous X-ray heating leads to significant fluctuations in gas temperature
- Temperature fluctuations track heating rate fluctuations, but lag somewhat behind
- Gas temperature fluctuations contain information about the thermal evolution of the IGM before reionization
- $\beta_T<0$ leads to interesting peak-trough structure
- Structure will assist astrophysical parameter estimation
- 21cm observations at high-z may constrain spectrum and luminosity of X-ray sources

Redshift slices: Lyα

z=19-20

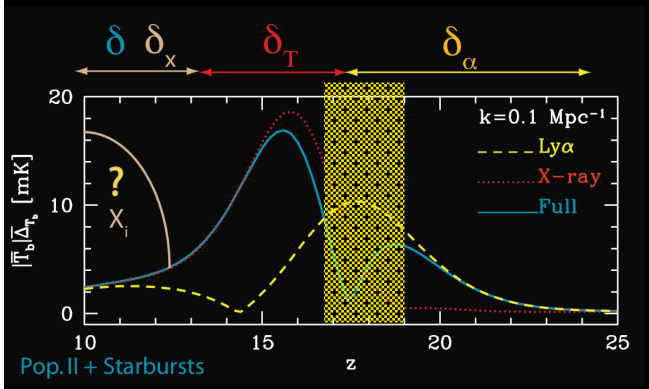


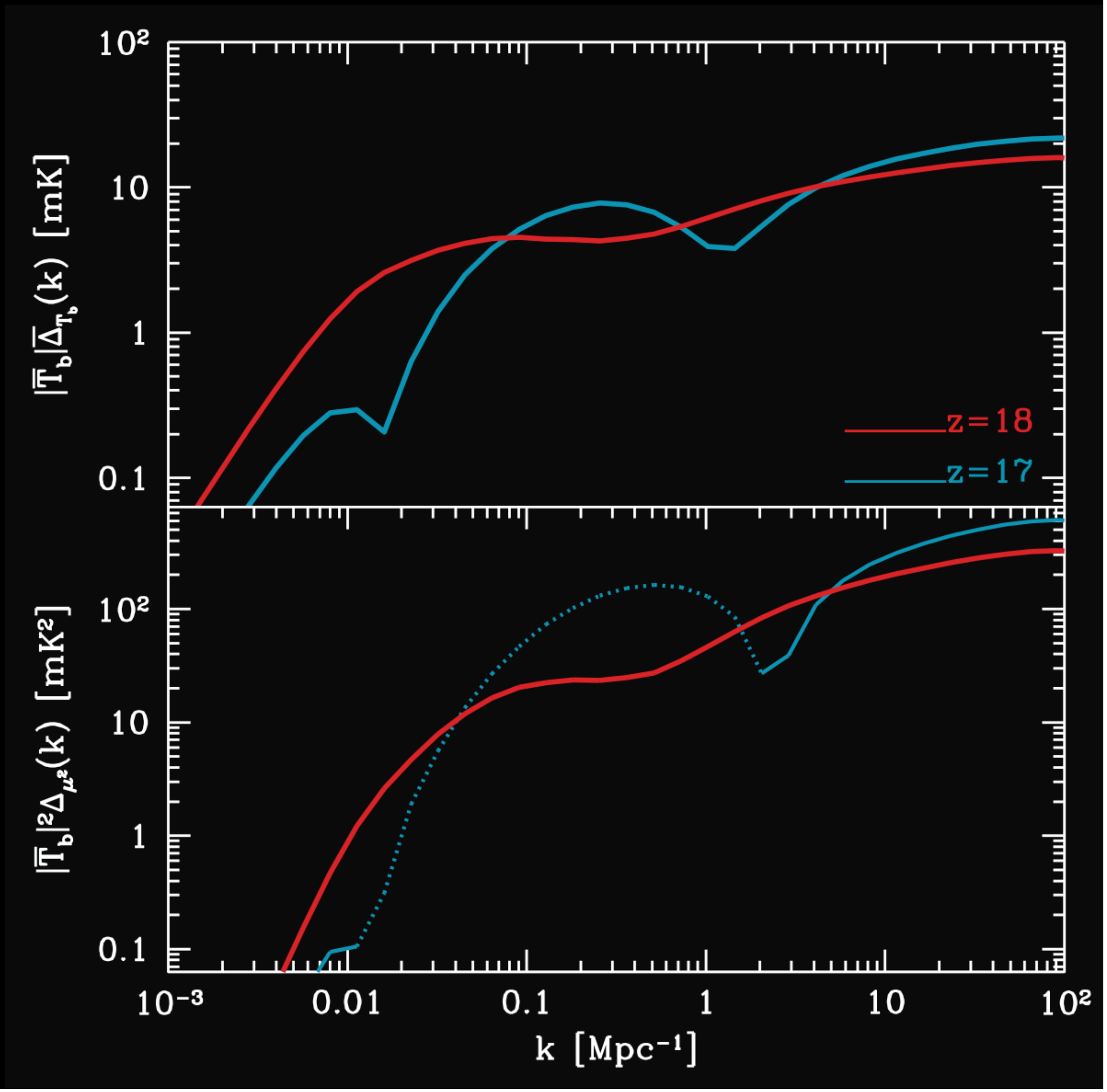
- Pure Lyα fluctuations



Redshift slices: Lyα/T

z=17-18



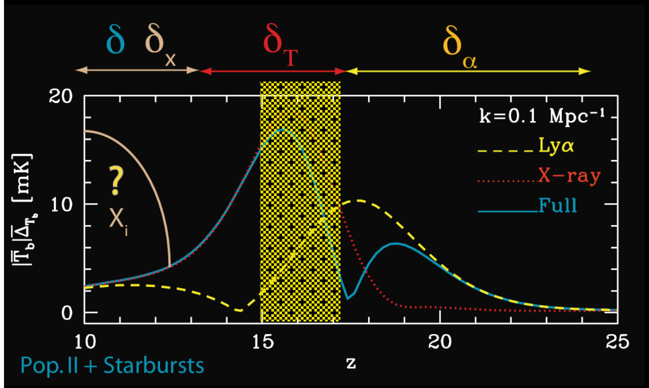


- Growing T fluctuations lead first to dip in Δ_{Tb} then to double peak structure

- Double peak requires T and Lyα fluctuations to have different scale dependence

Redshift slices: T

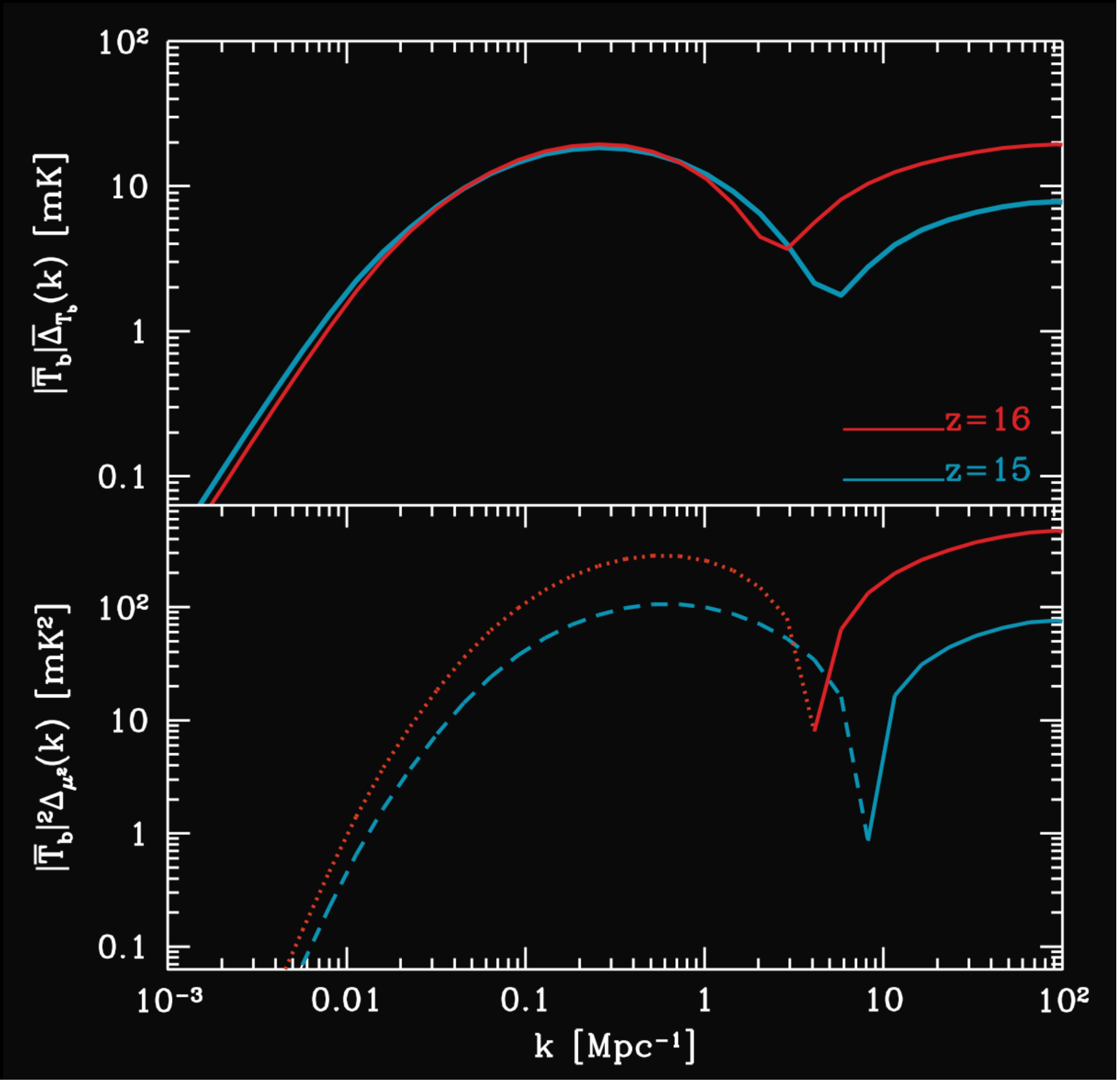
z=15-16



- T fluctuations dominate over Lyα

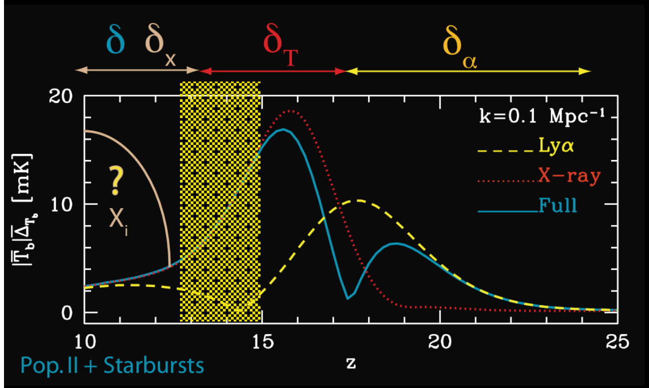
- Clear peak-trough structure visible

- Δ_{μ^2} <0 on large scales indicates $T_K<T_\gamma$



Redshift slices: T/δ

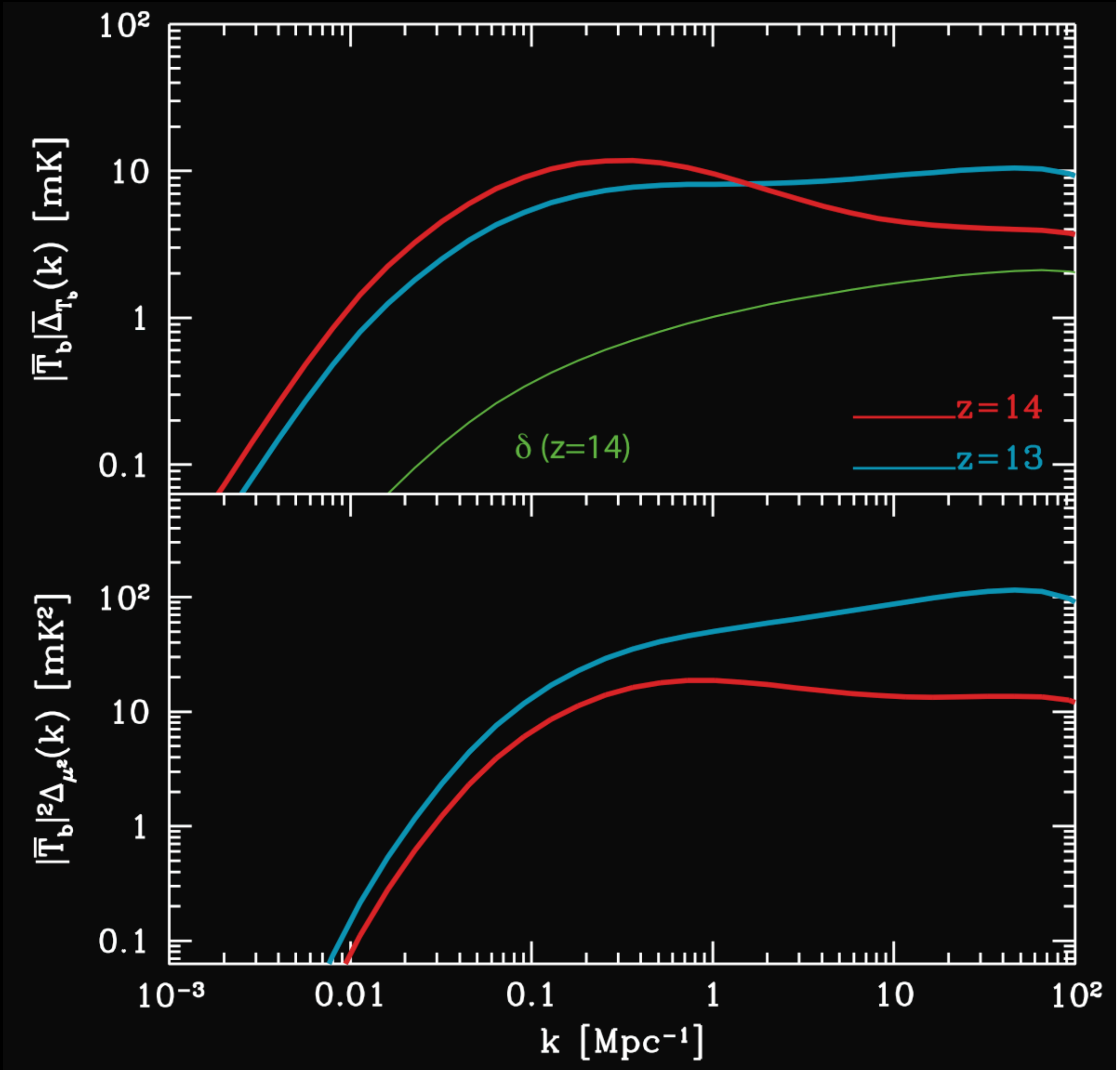
z=13-14



- After $T_K > T_\gamma$, the trough disappears

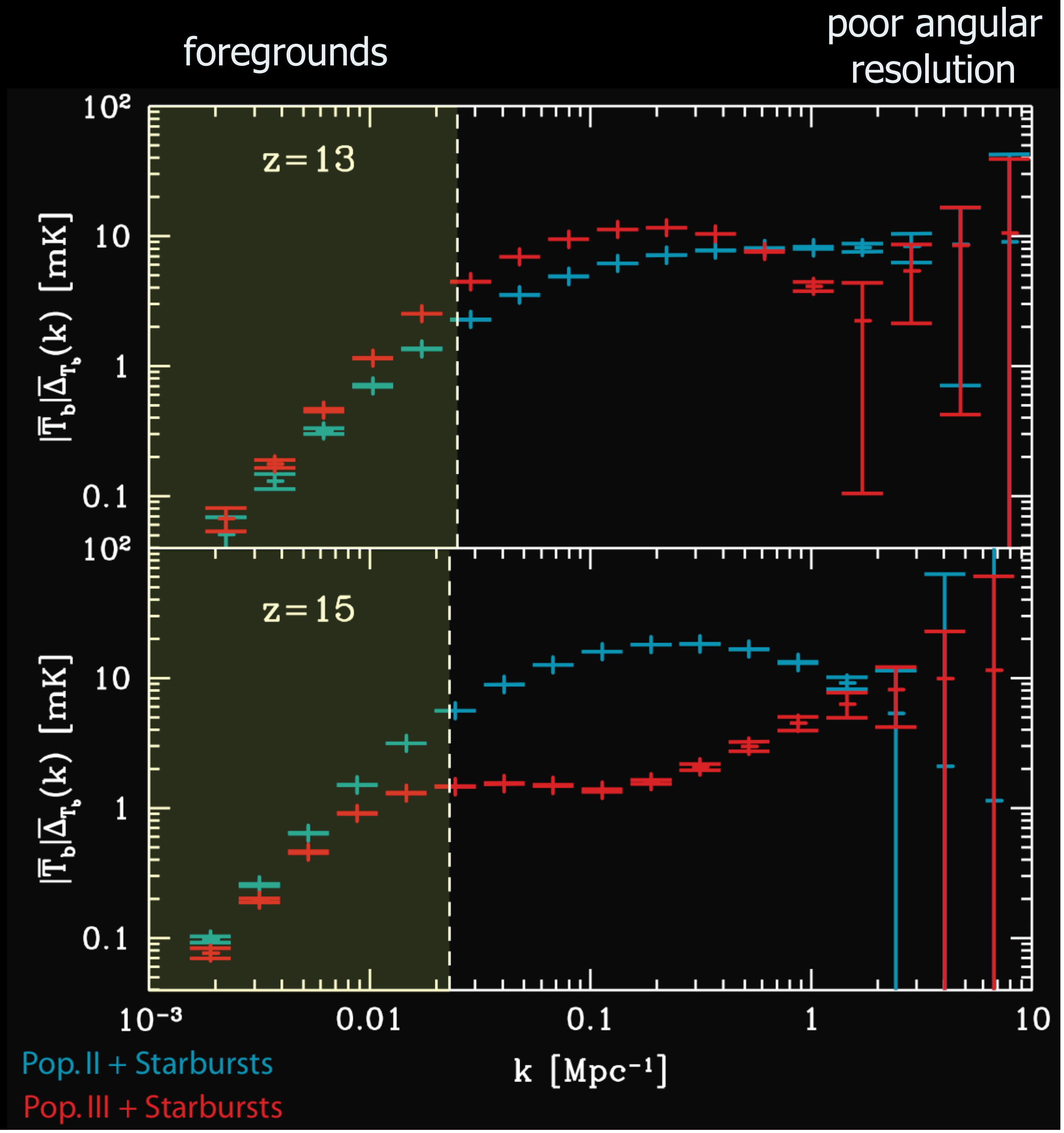
- As heating continues T fluctuations die out

- X_i fluctuations will start to become important at lower z



Observations

- Need SKA to probe these brightness fluctuations
- Observe scales $k=0.025\text{-}3\ \mathrm{Mpc}^{-1}$
- Easily distinguish two models
- Probably won't see trough :(



Conclusions

- 21 cm fluctuations potentially contain much information about the first sources
  - Bias
  - X-ray background
  - X-ray source spectrum
  - IGM temperature evolution
  - Star formation rate
- Lyα and X-ray backgrounds may be probed by future 21 cm observations
- Foregrounds pose a challenging problem at high z
- SKA needed to observe the fluctuations described here

For more details see astro-ph/0607234 & astro-ph/0508381

The end