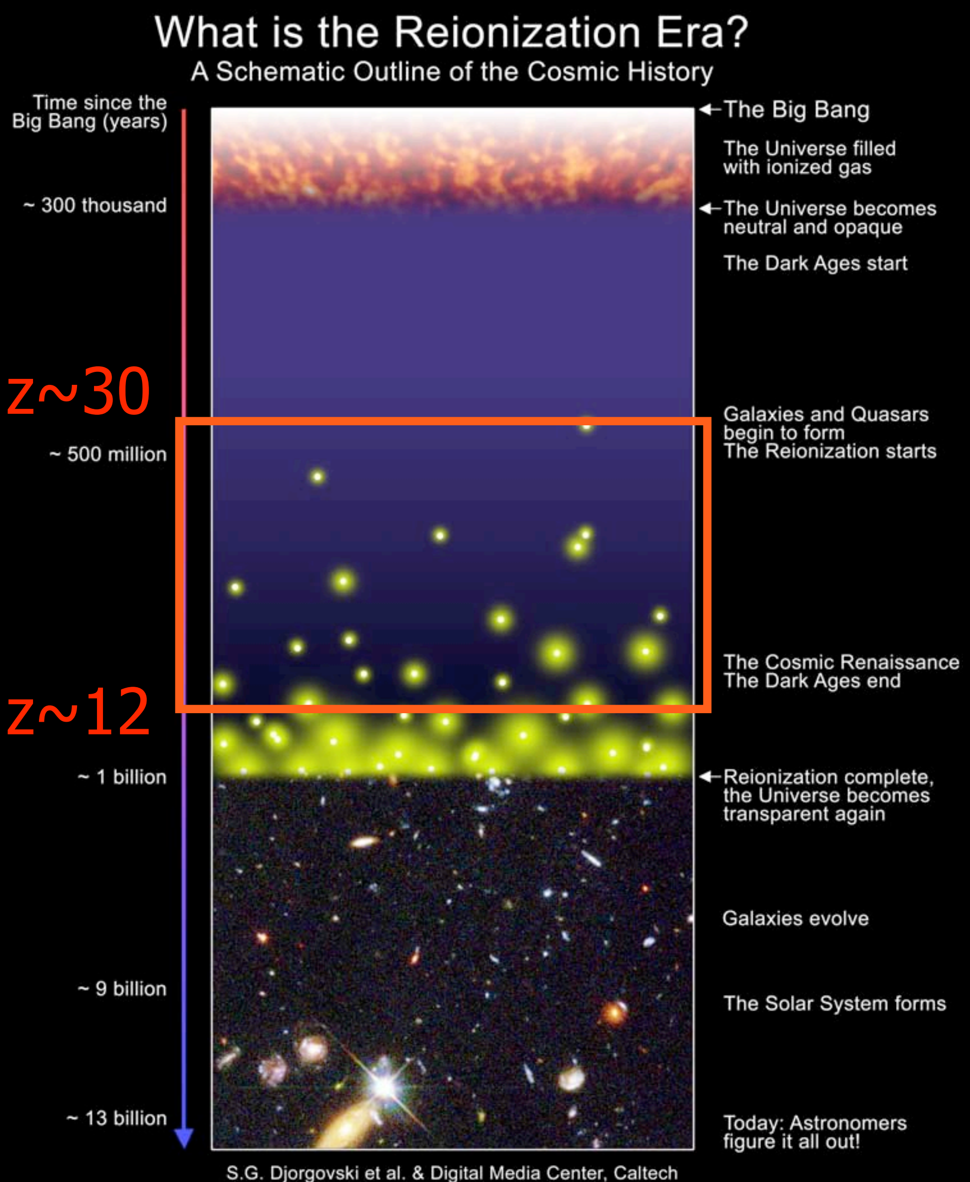
Radiation backgrounds from the first sources and the redshifted 21 cm line

Jonathan Pritchard
(Caltech)

Collaborators: Steve Furlanetto (Yale)

Advisor: Marc Kamionkowski (Caltech)

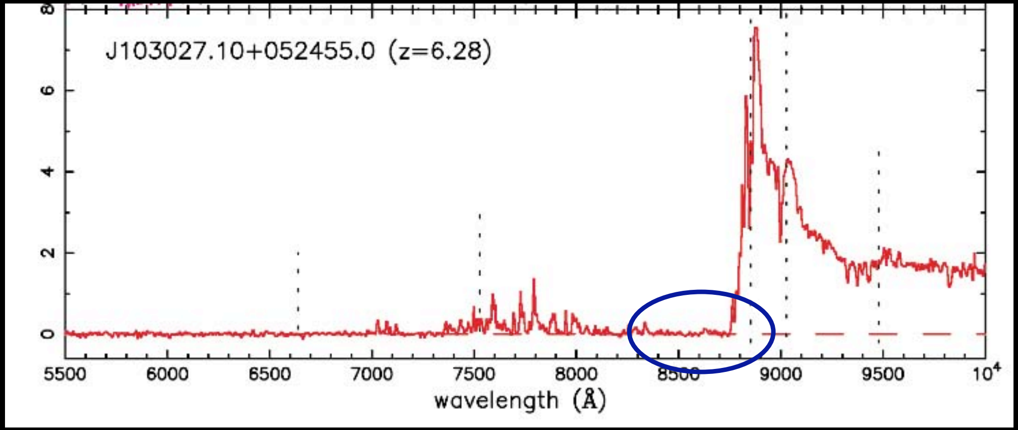
Overview



- 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)
- Observational prospects

Ionization history

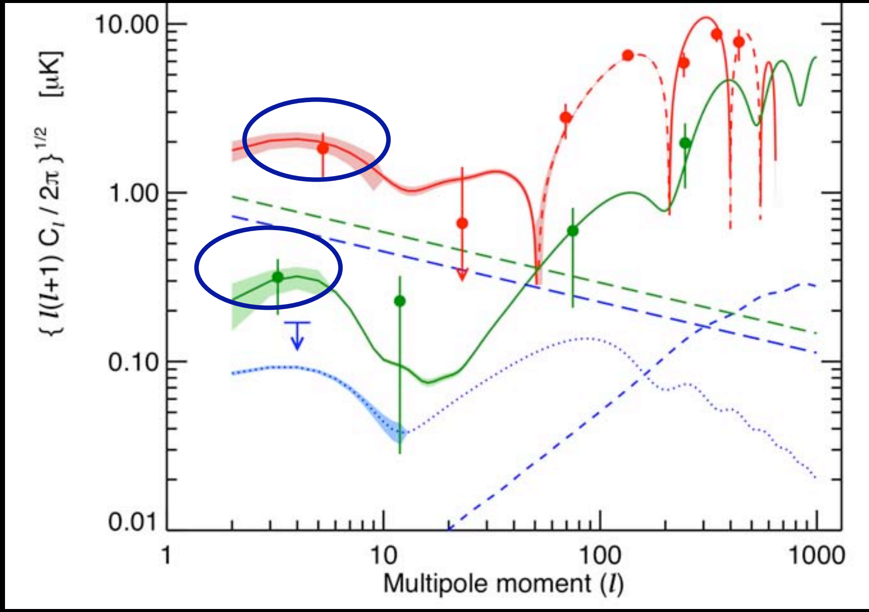
- Gunn-Peterson Trough



Becker et al. 2005

- Universe ionized below z~6, some neutral HI at higher z
- black is black

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

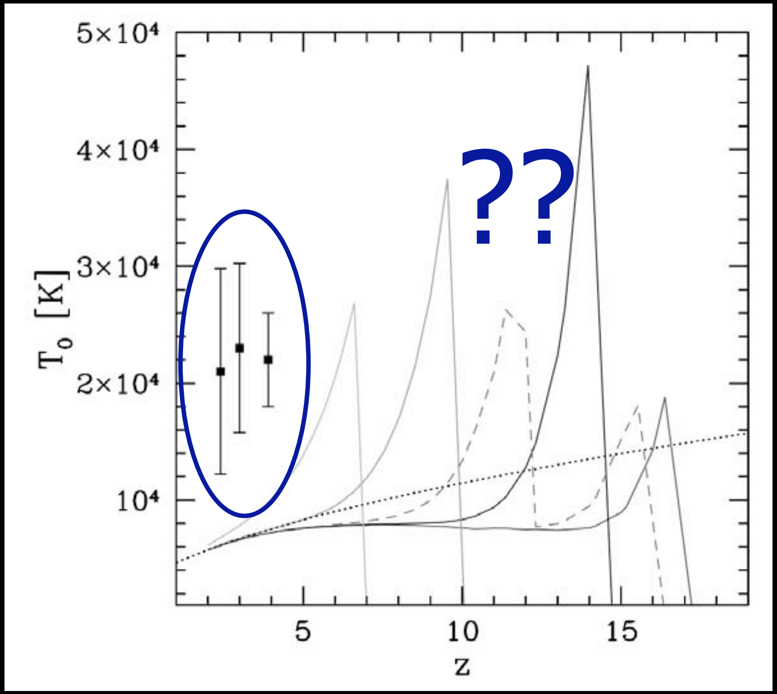


Page et al. 2006

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

Thermal history

- Lyα forest



Zaldarriaga, Hui, & Tegmark 2001

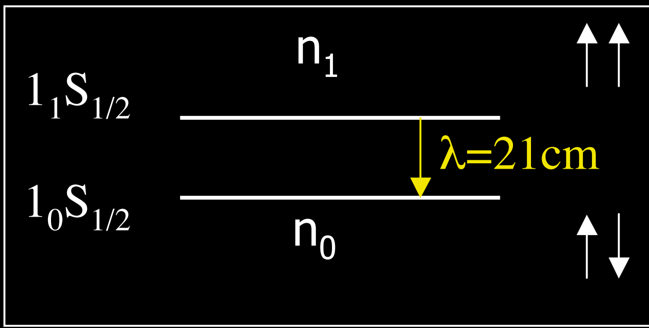
Hui & Haiman 2003

- 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

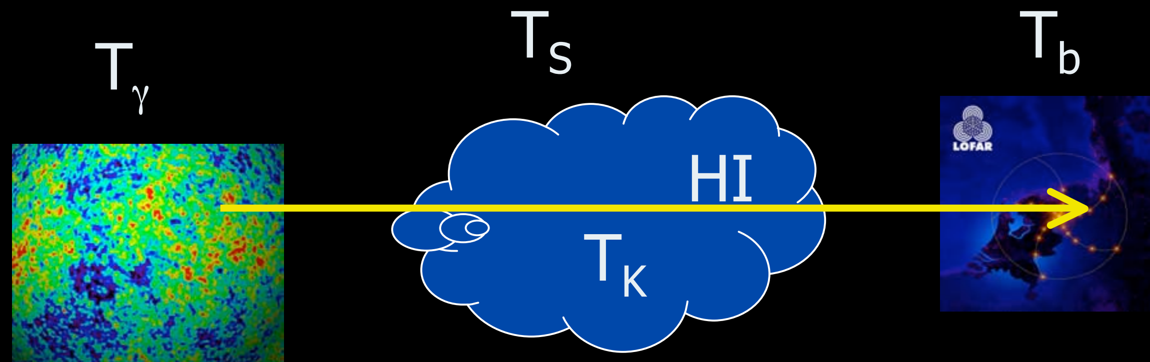
21 cm basics

- HI hyperfine structure



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

- Use CMB backlight to probe 21cm transition



z=13
f_{21cm}=1.4 GHz

z=0
f_{obs}=100 MHz

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

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

- 21 cm spin temperature

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

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

Wouthysen-Field effect

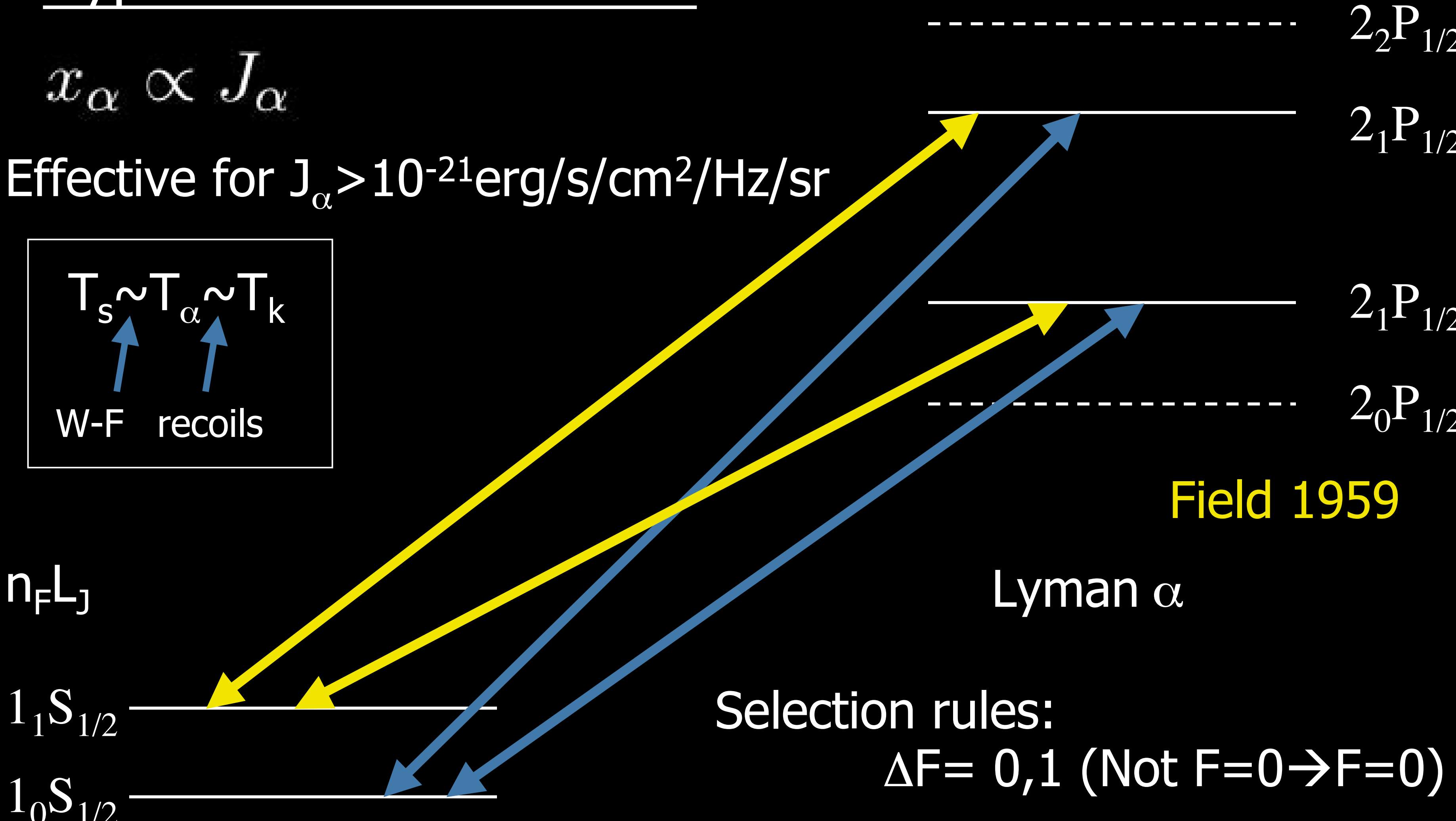
Hyperfine structure of HI

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

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

$T_s \sim T_\alpha \sim T_k$

W-F recoils



Field 1959

Lyman α

Selection rules:

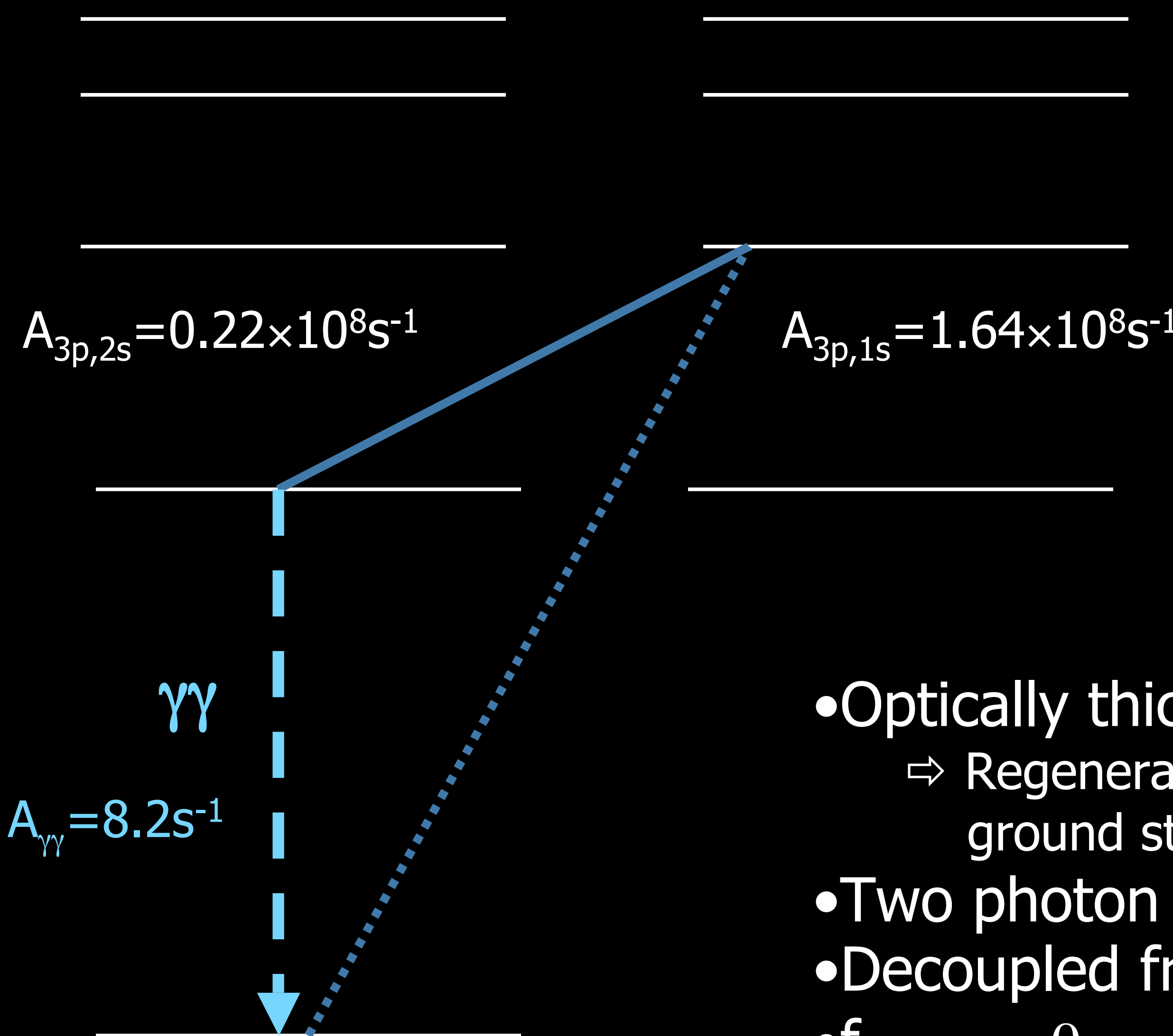
$\Delta F = 0,1$ (Not $F=0 \rightarrow F=0$)

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…

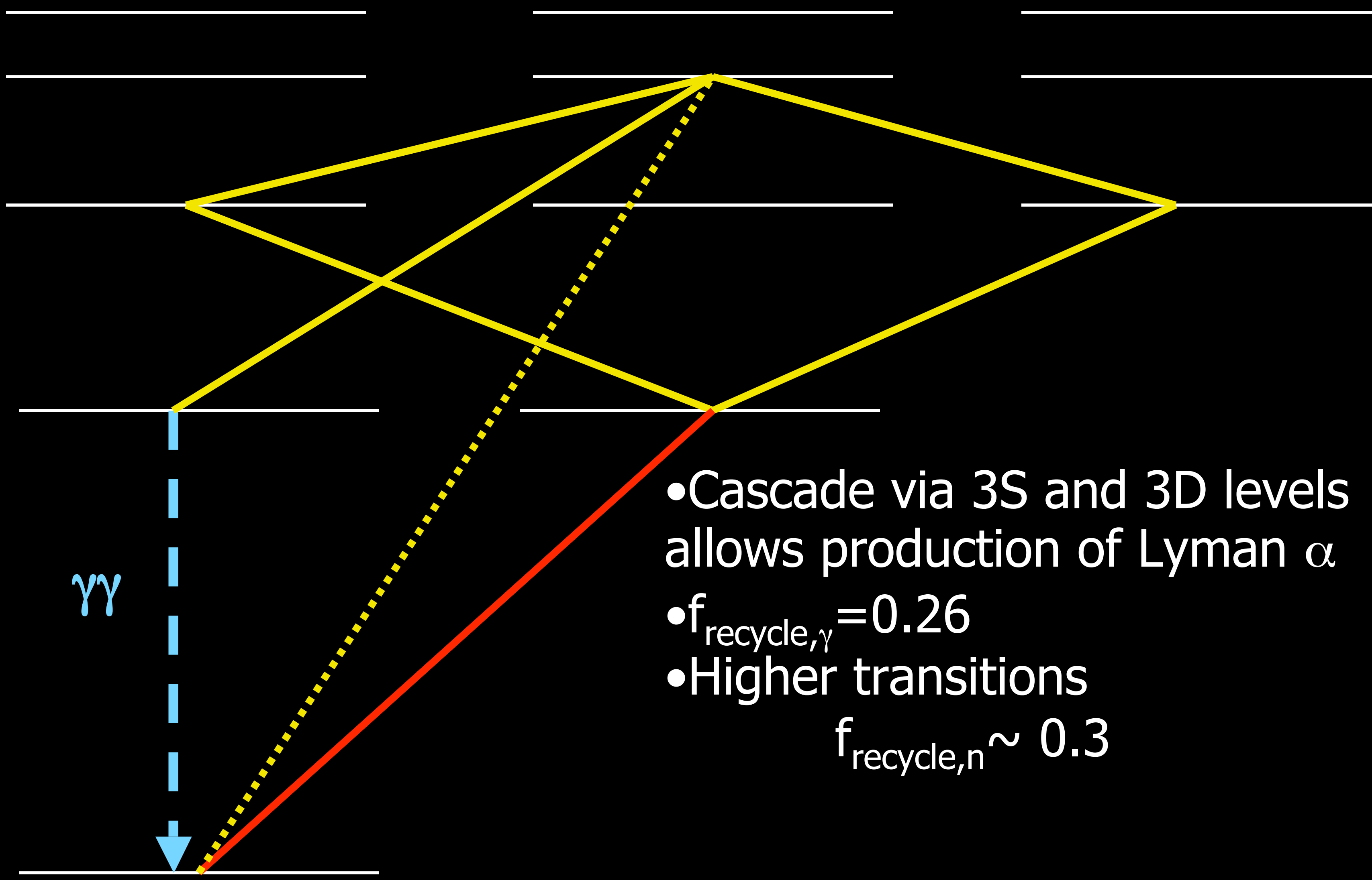
Pritchard & Furlanetto 2006 | Hirata 2006

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

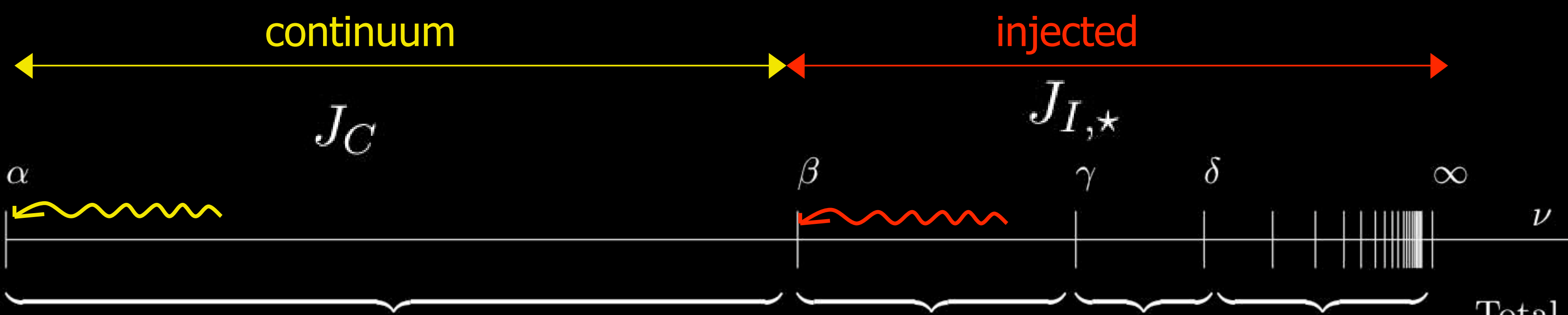


- Cascade via 3S and 3D levels allows production of Lyman α
- $f_{recycle,\gamma}$=0.26
- Higher transitions

  $f_{recycle,n} \sim 0.3$

Lyman alpha flux

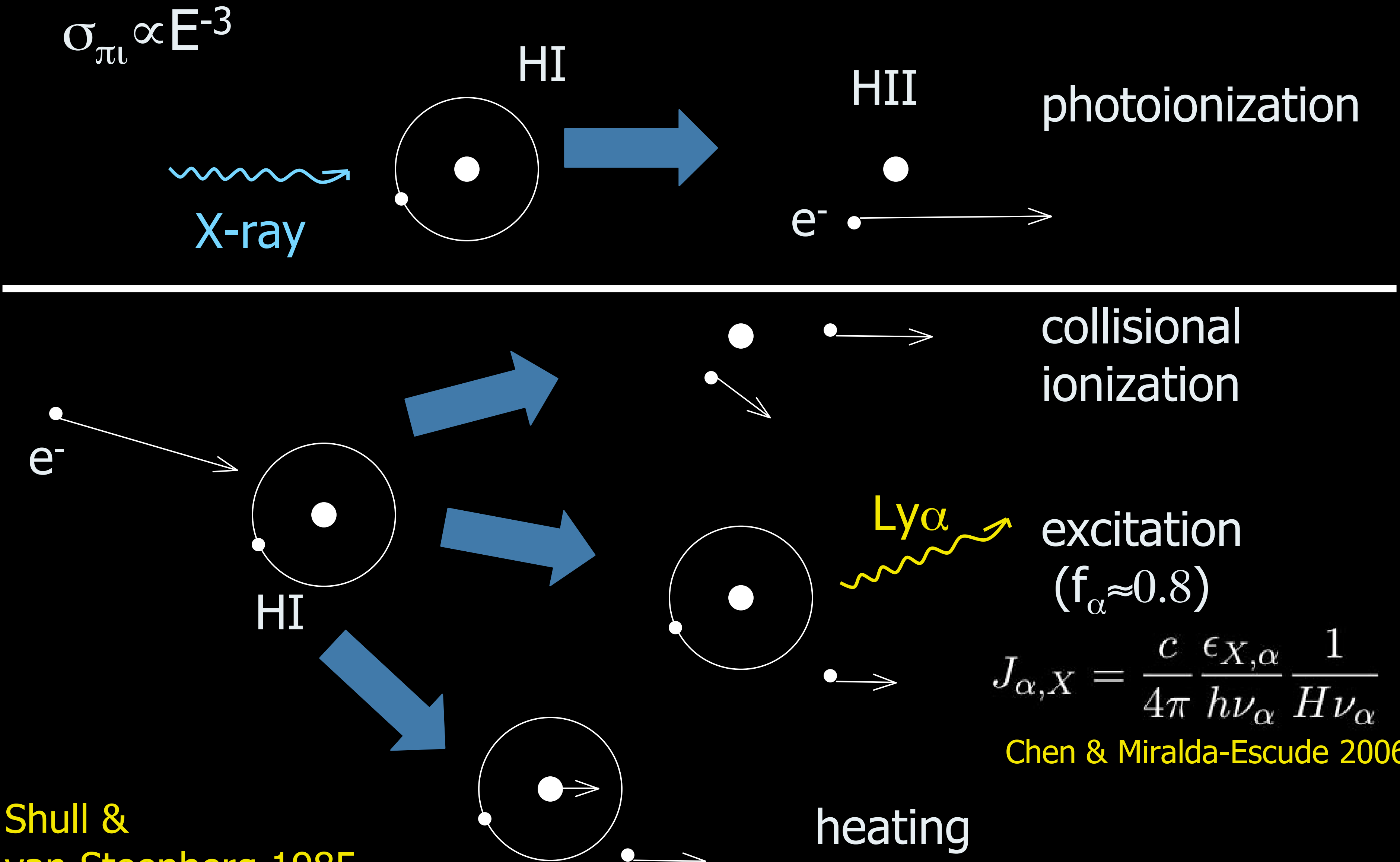
- Stellar contribution



					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 X-rays…

X-rays and Lyα production



$$J_{\alpha,X} = \frac{c}{4\pi}\frac{\epsilon_{X,\alpha}}{h\nu_\alpha}\frac{1}{H\nu_\alpha}$$

Chen & Miralda-Escude 2006

Shull &
van Steenberg 1985

Experimental efforts

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

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

PAST/21CMA: China
Freq: 70-200 MHz

$(f_{21cm}=1.4\ \text{GHz})$

SKA: S Africa/Australia
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

Global history

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

Furlanetto 2006

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

$\frac{\mathrm{d}x_i}{\mathrm{d}t} =$ UV ionization + recombination — HII regions

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

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

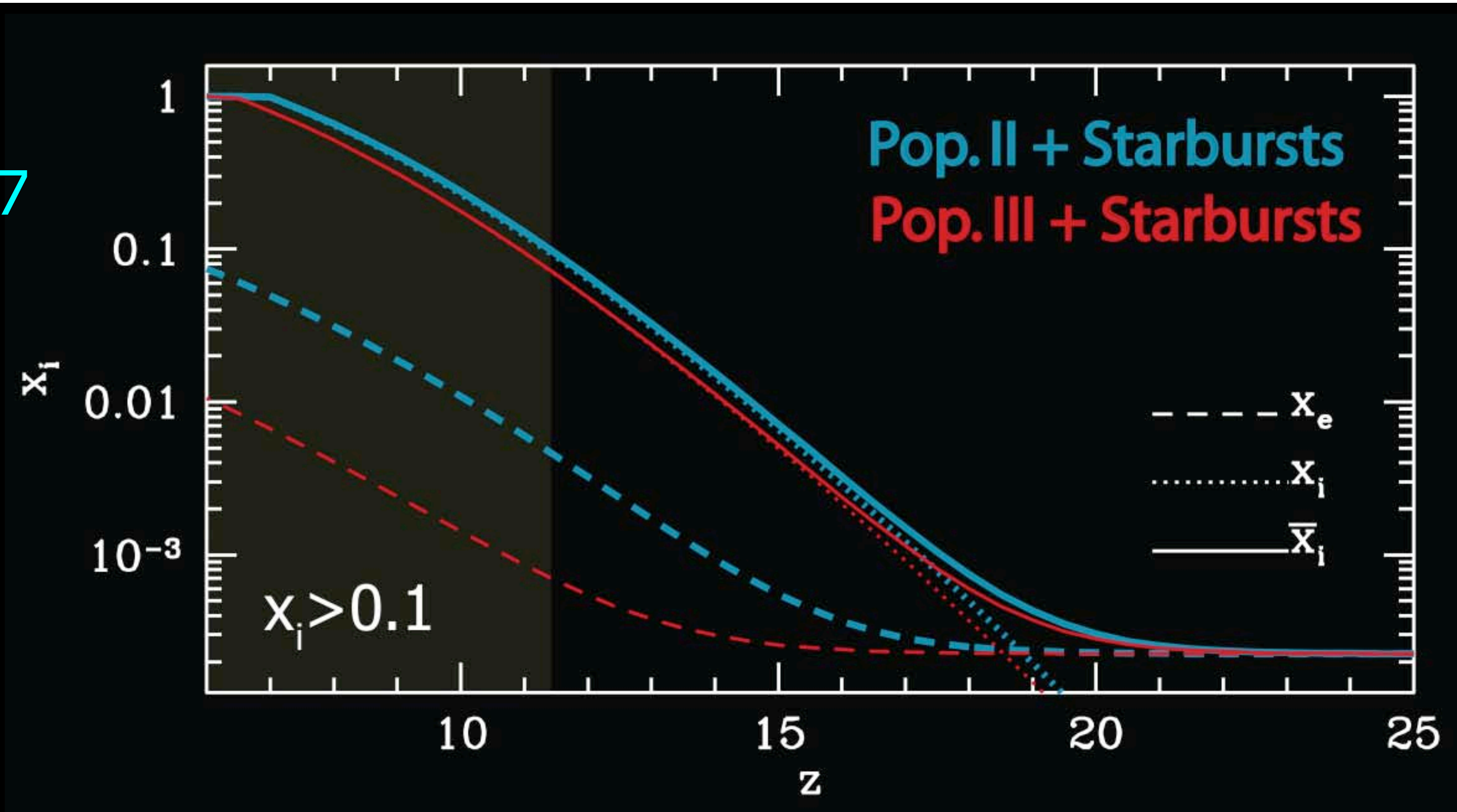
continuum injected

Lyα flux

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

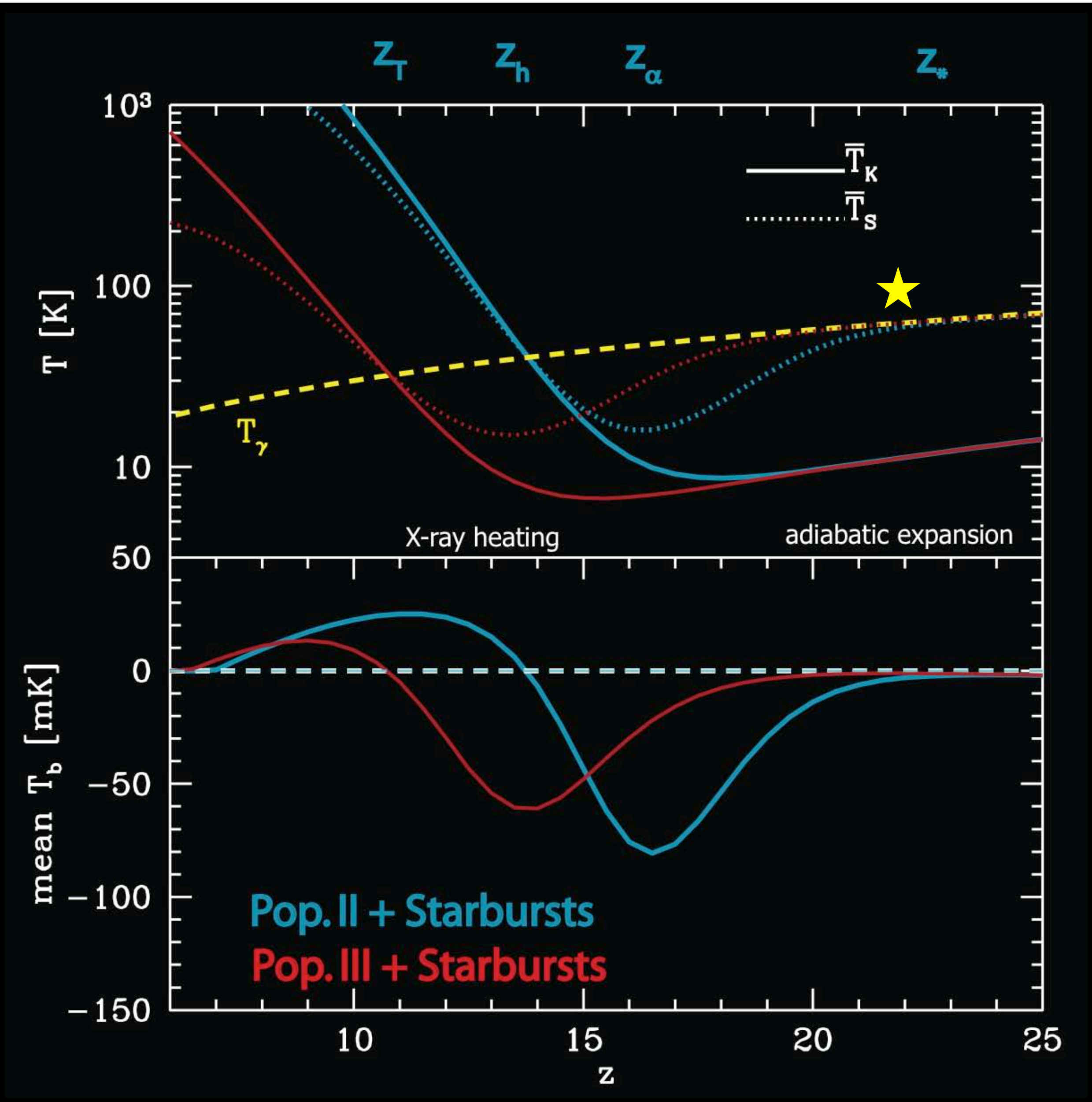
Ionization history

$z_R \sim 7$
$\tau \sim 0.07$



- Models differ by factor ~10 in X-ray/Lyα per ionizing photon
- Reionization well underway at z<12

Thermal history

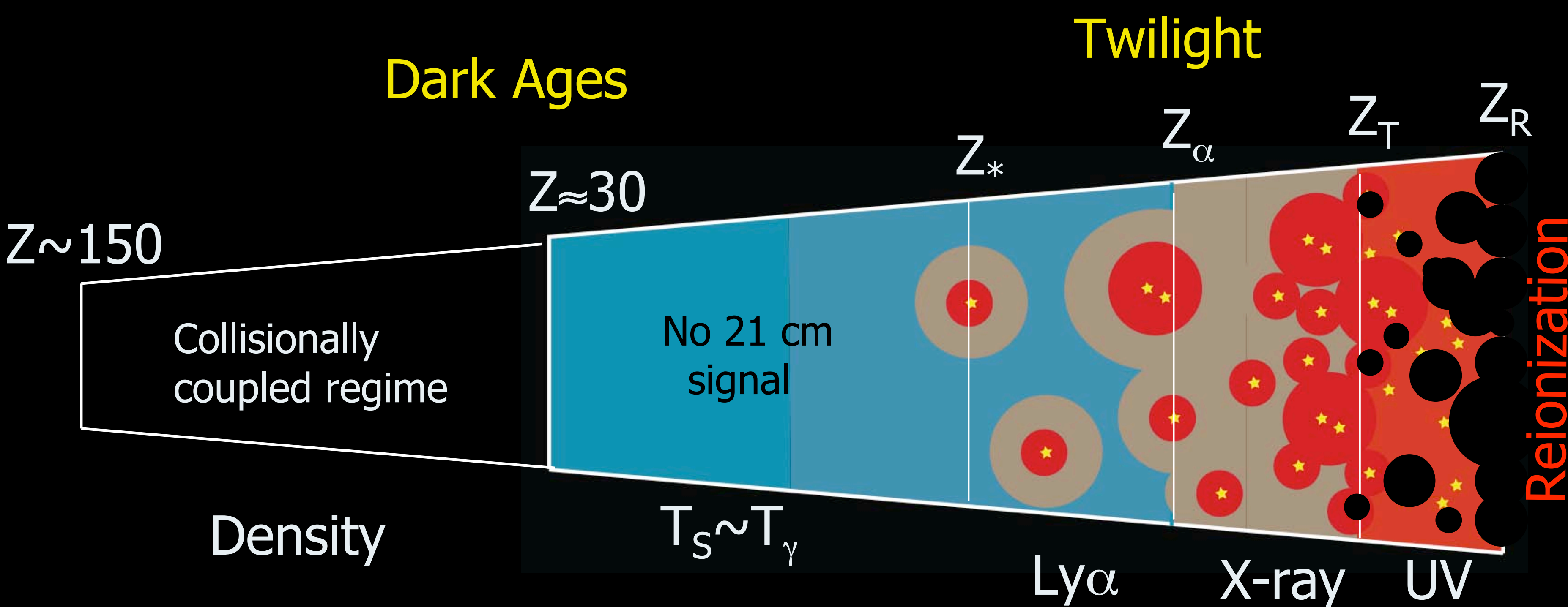


21 cm fluctuations

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

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

Cosmology	Reionization	X-ray sources	Lyα sources	Cosmology



Angular separation?

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

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

- 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

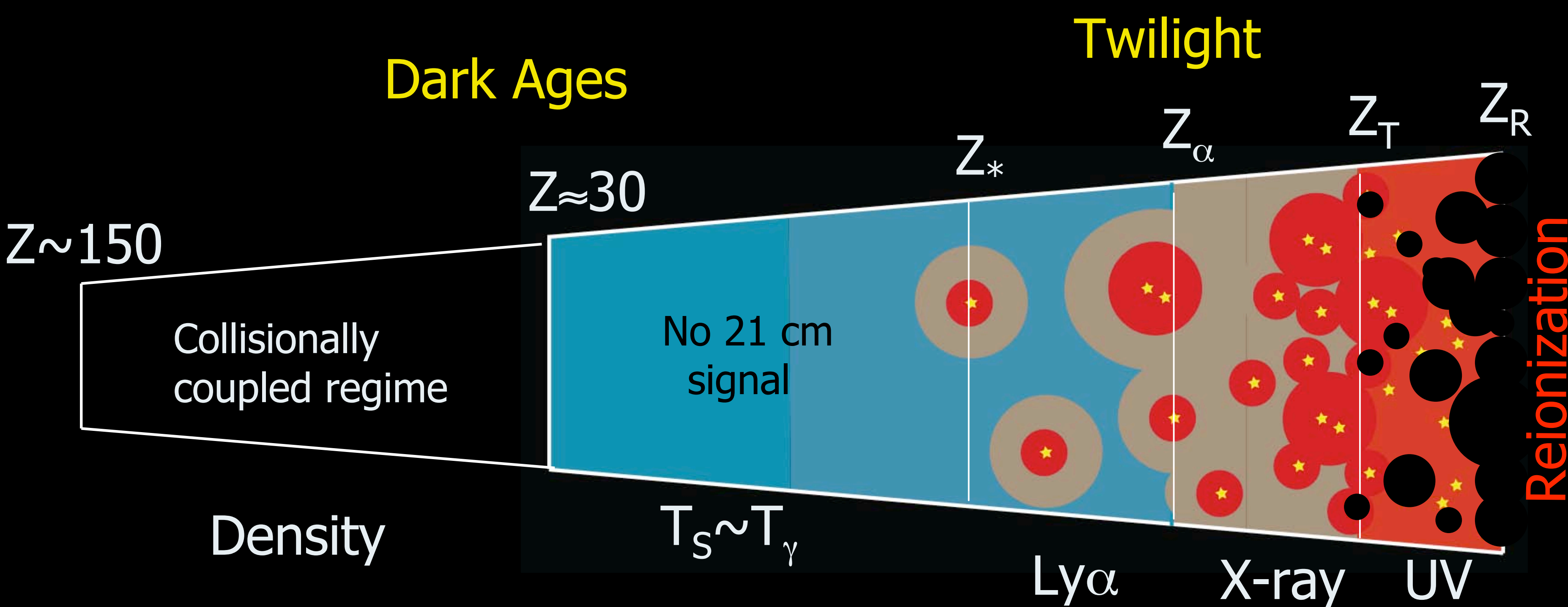
- Initial observations will average over angle to improve S/N

21 cm fluctuations

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

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

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



Reionization

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

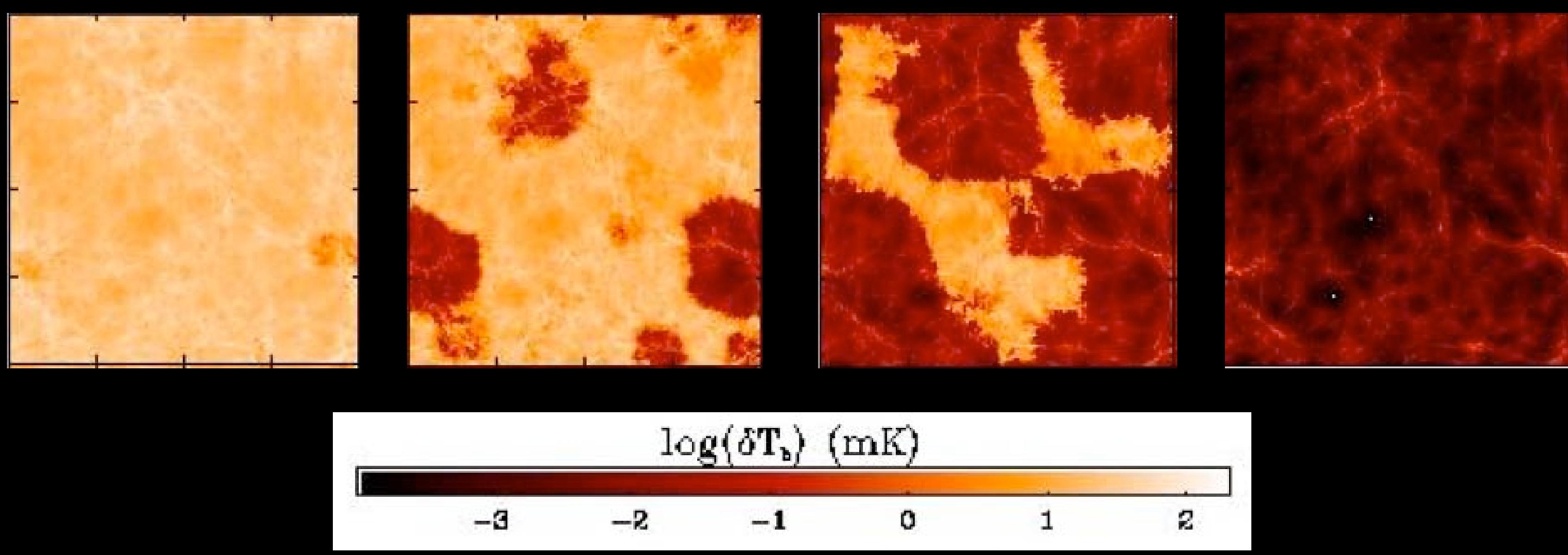
$$\delta_{T_b} = \beta\delta + \boxed{\beta_x \delta_{x_{HI}}} + \cancel{\beta_T \delta_{T_k}} + \cancel{\beta_\alpha \delta_\alpha} - \delta_{\partial v}$$

HII regions large

IGM hot $T_K >> T_\gamma$

Lyα coupling saturated

Z=12.1 | Z=9.2 | Z=8.3 | Z=7.6



Furlanetto, Sokasian, Hernquist 2003

21 cm fluctuations: Lyα

Density	Neutral fraction	Gas Temperature	W-F Coupling	Velocity gradient

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

IGM still mostly neutral

-negligible heating of IGM
-tracks density

Lyα flux varies

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

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

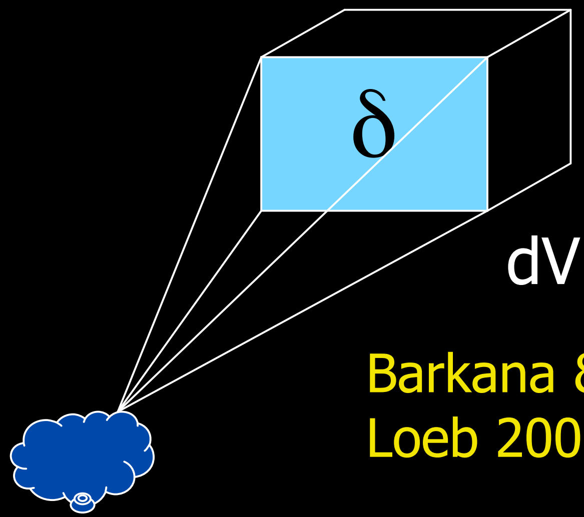
$$\boxed{x_\alpha \propto J_\alpha}$$

- 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



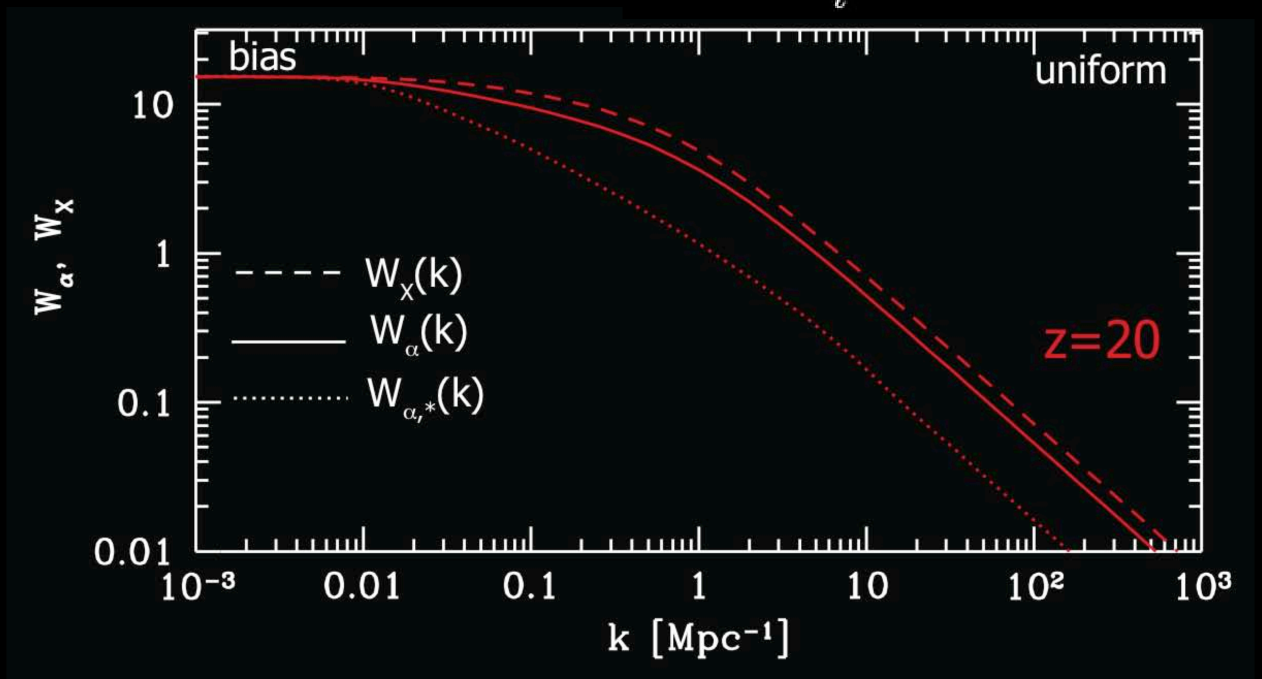
Barkana & Loeb 2005

- Fluctuations in flux from source clustering, $1/r^2$ law, optical depth,…
- 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

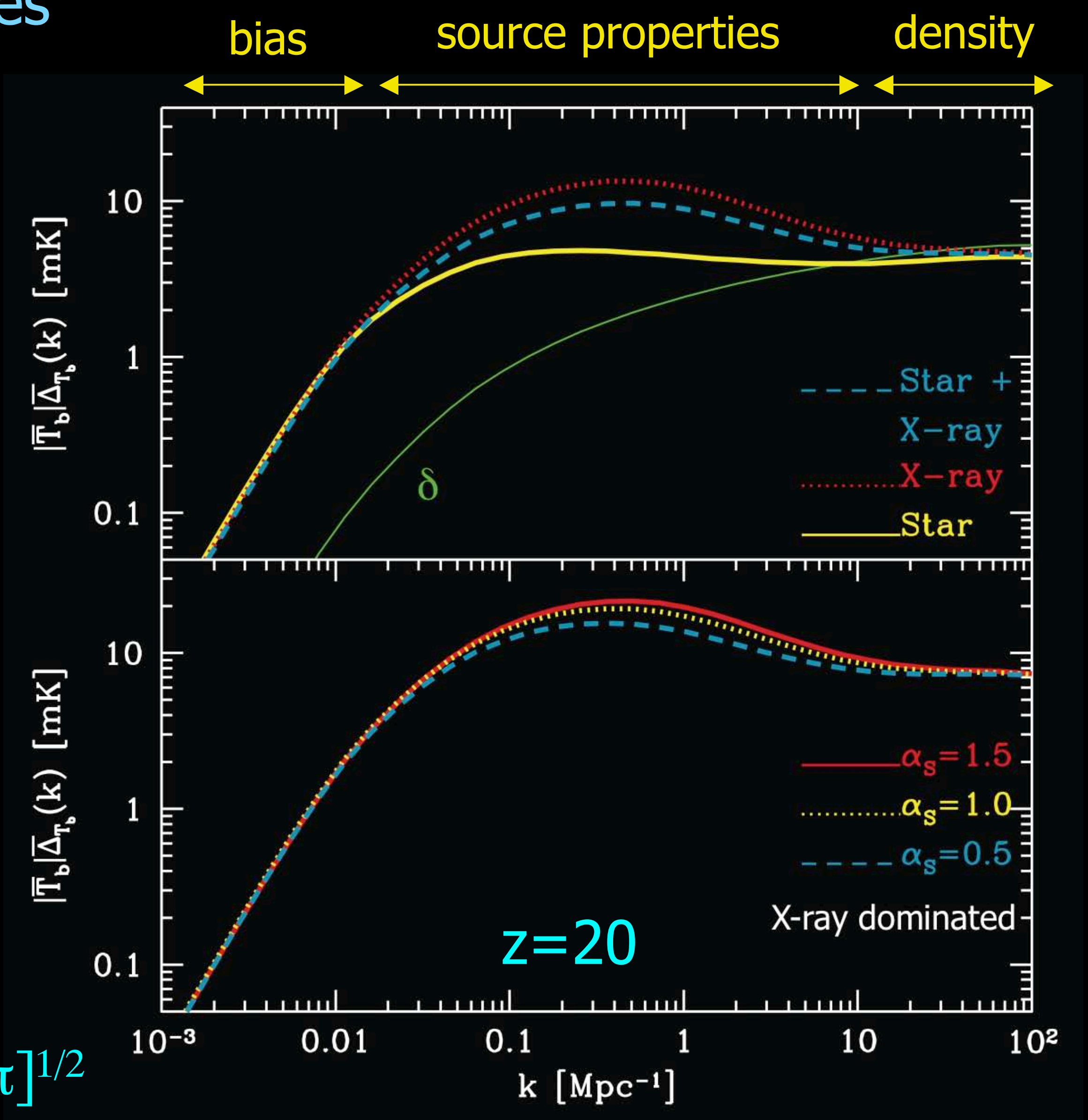
δ_α dominates

Sources

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

Spectra

α_S



Chuzhoy, Alvarez, & Shapiro 2006

Pritchard & Furlanetto 2006

$\Delta=[k^3P(k)/2\pi]^{1/2}$

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

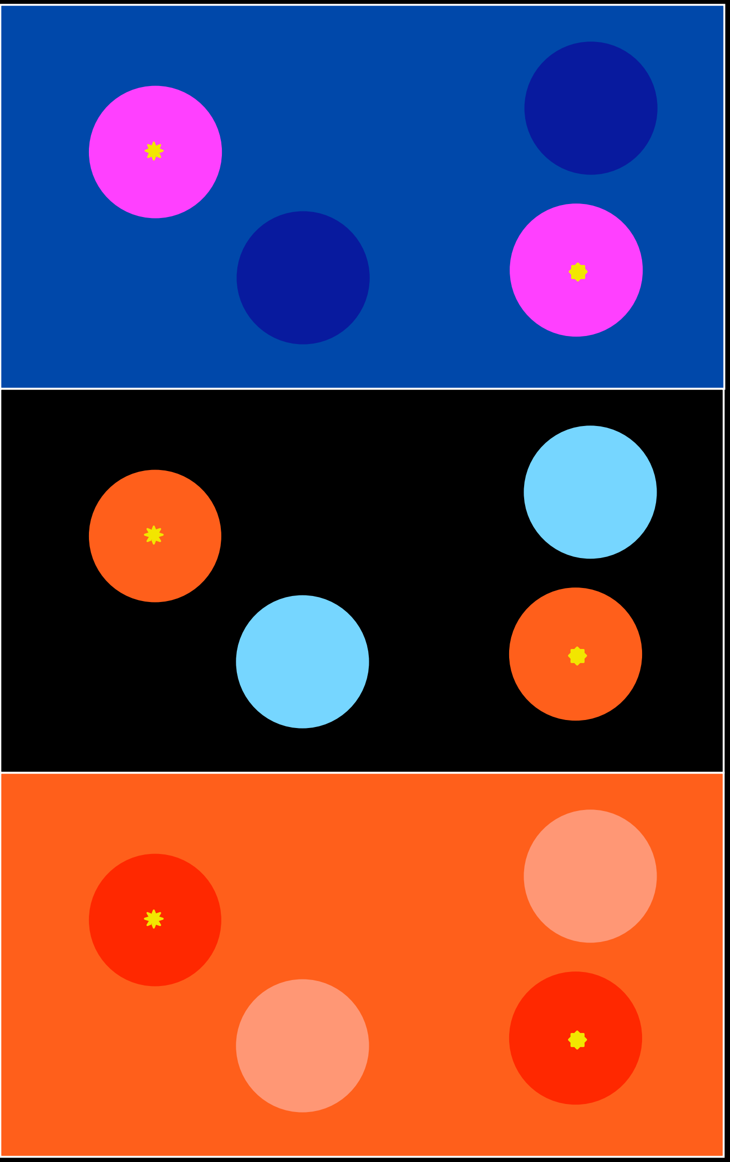
$$\beta_T \approx \frac{T_\gamma}{T_K - T_\gamma}$$

- 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

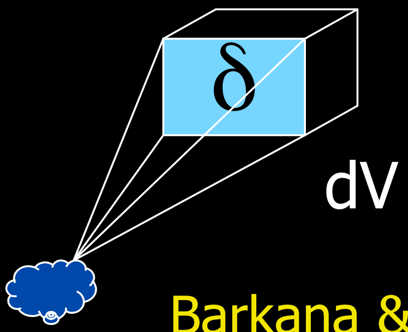
$T_S \sim T_K > T_\gamma$
$T_b > 0$ (emission)
Hotter region = stronger emission
$\beta_T > 0$

X-ray heating

- X-rays provide dominant heating source in early universe (shocks possibly important very early on)
- X-ray heating often 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
- X-ray flux -> heating rate -> temperature



Barkana & Loeb 2005

$$\delta_T = g_T(k,z)\delta$$

adiabatic index -1

Growth of fluctuations

expansion X-rays Compton

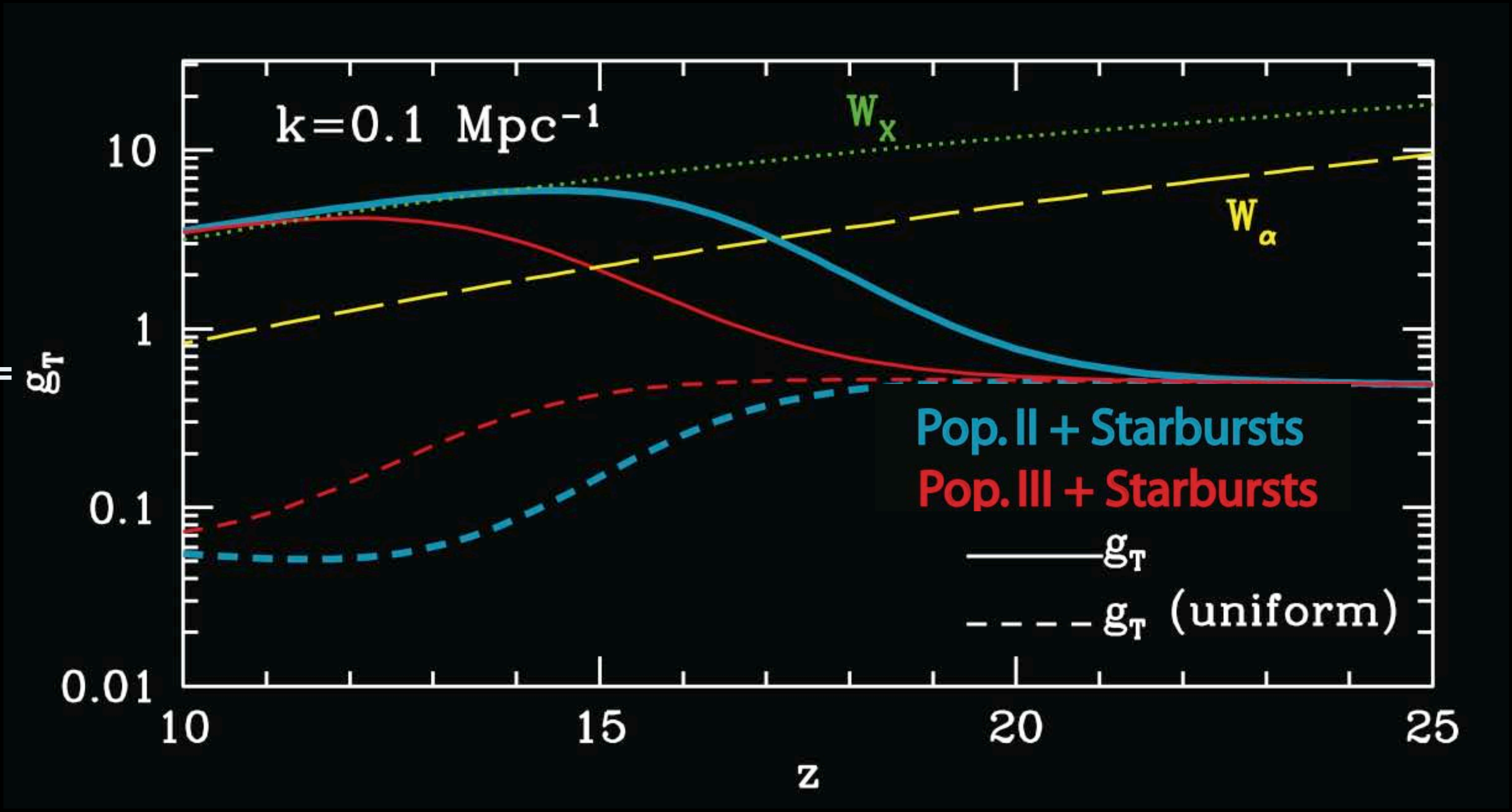
$$\frac{\mathrm{d}g_T}{\mathrm{d}z} = \left(\frac{g_T - 2/3}{1+z}\right) - Q_X(z)[W_X(k) - g_T] - Q_C(z)g_T$$

temperature fluctuations

Heating fluctuations

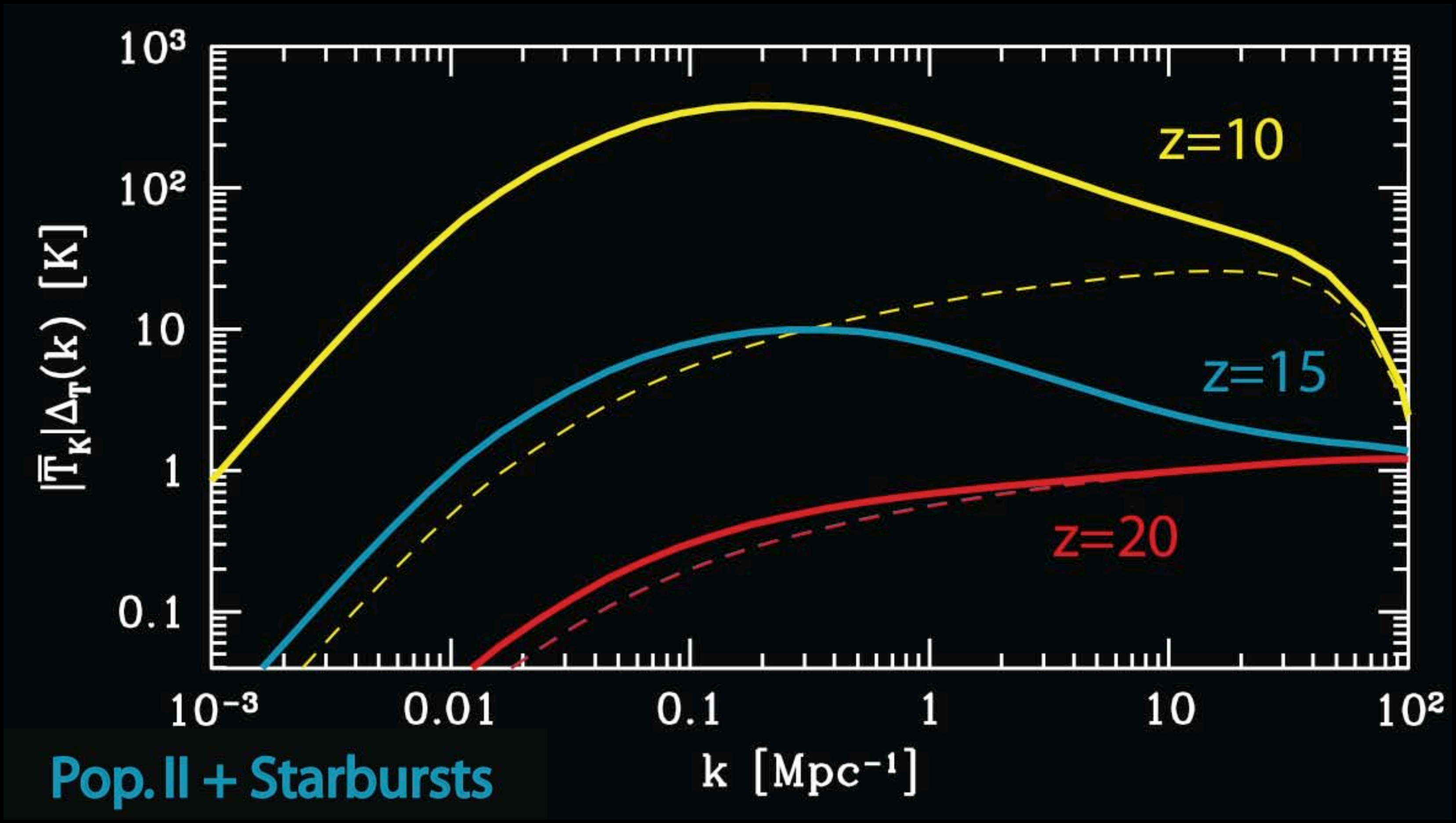
Fractional heating per Hubble time at z

$\delta_T / \delta = g_T$



T_K fluctuations

- Fluctuations in gas temperature can be substantial
- Amplitude of fluctuations contains information about IGM thermal history



Indications of T_K

- Constrain heating transition

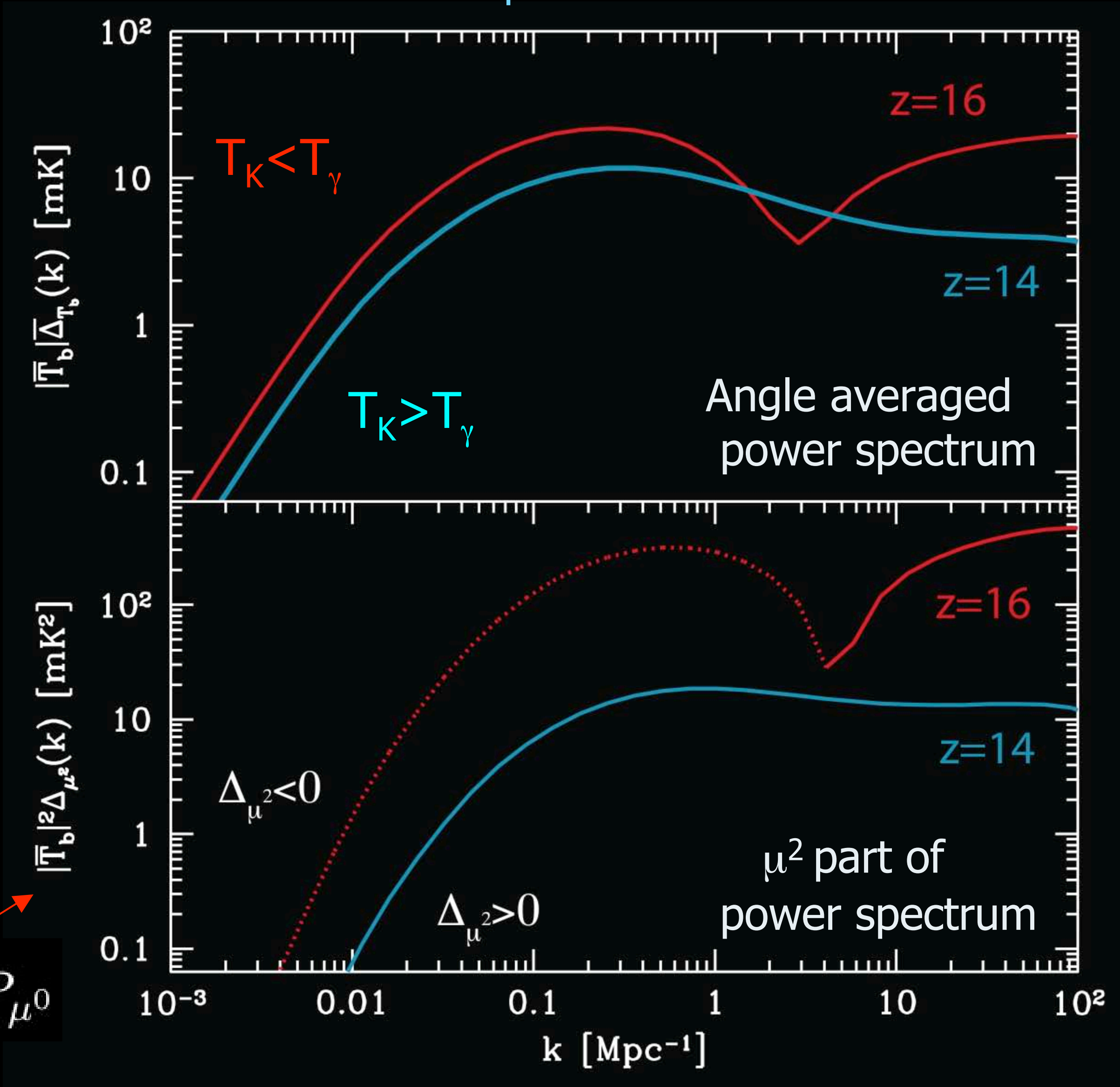
$$\delta_{T_b} \approx \delta + \beta_T \delta_{T_k}$$

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

- $\Delta_{\mu^2} < 0$ on large scales indicates $T_K < T_\gamma$ (but can have $P_{\delta x} < 0$)

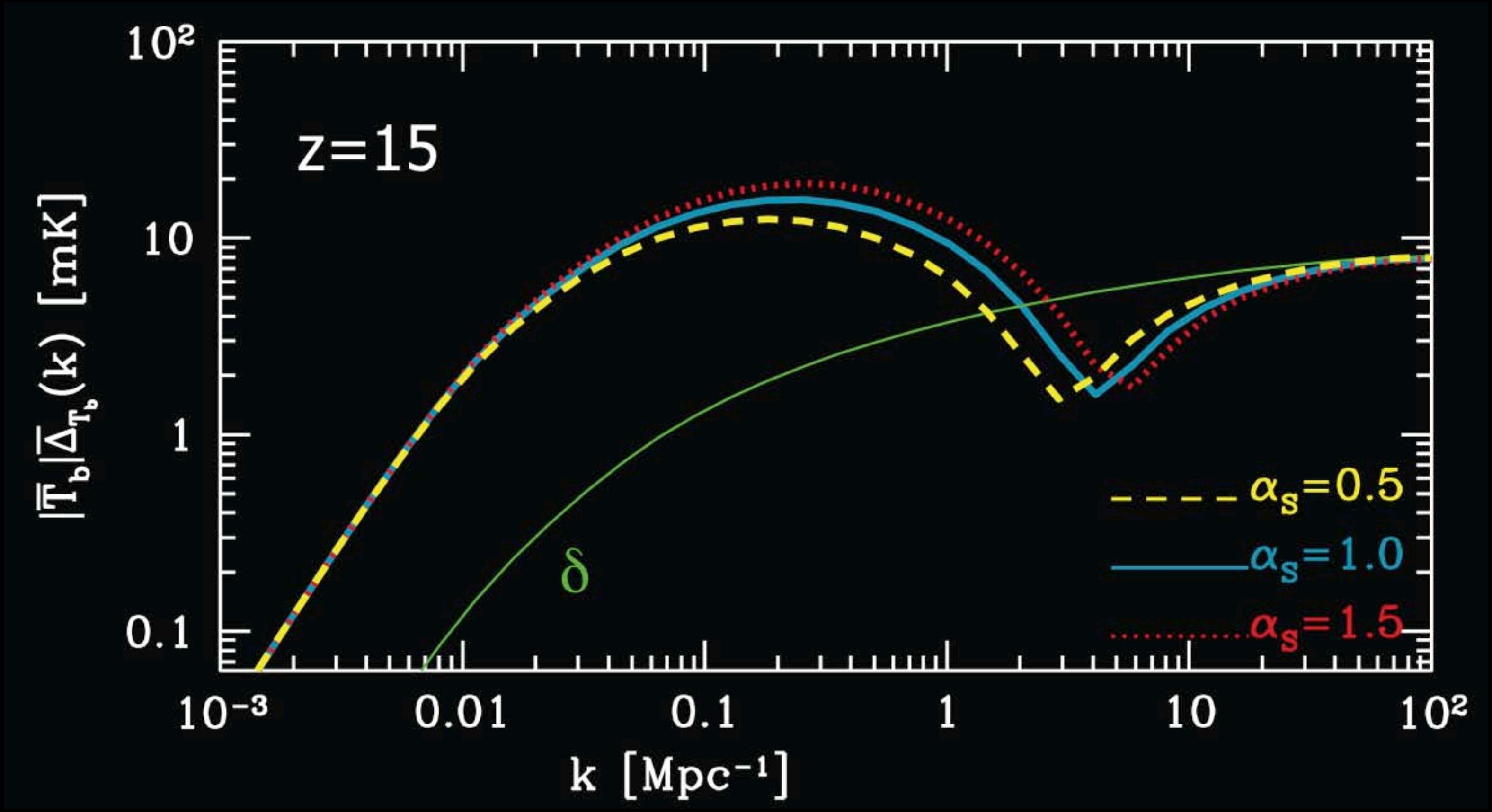
$$P_{T_b}(\mathbf{k}) = \mu^4 P_{\mu^4} + \mu^2 P_{\mu^2} + P_{\mu^0}$$

δ_T dominates



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

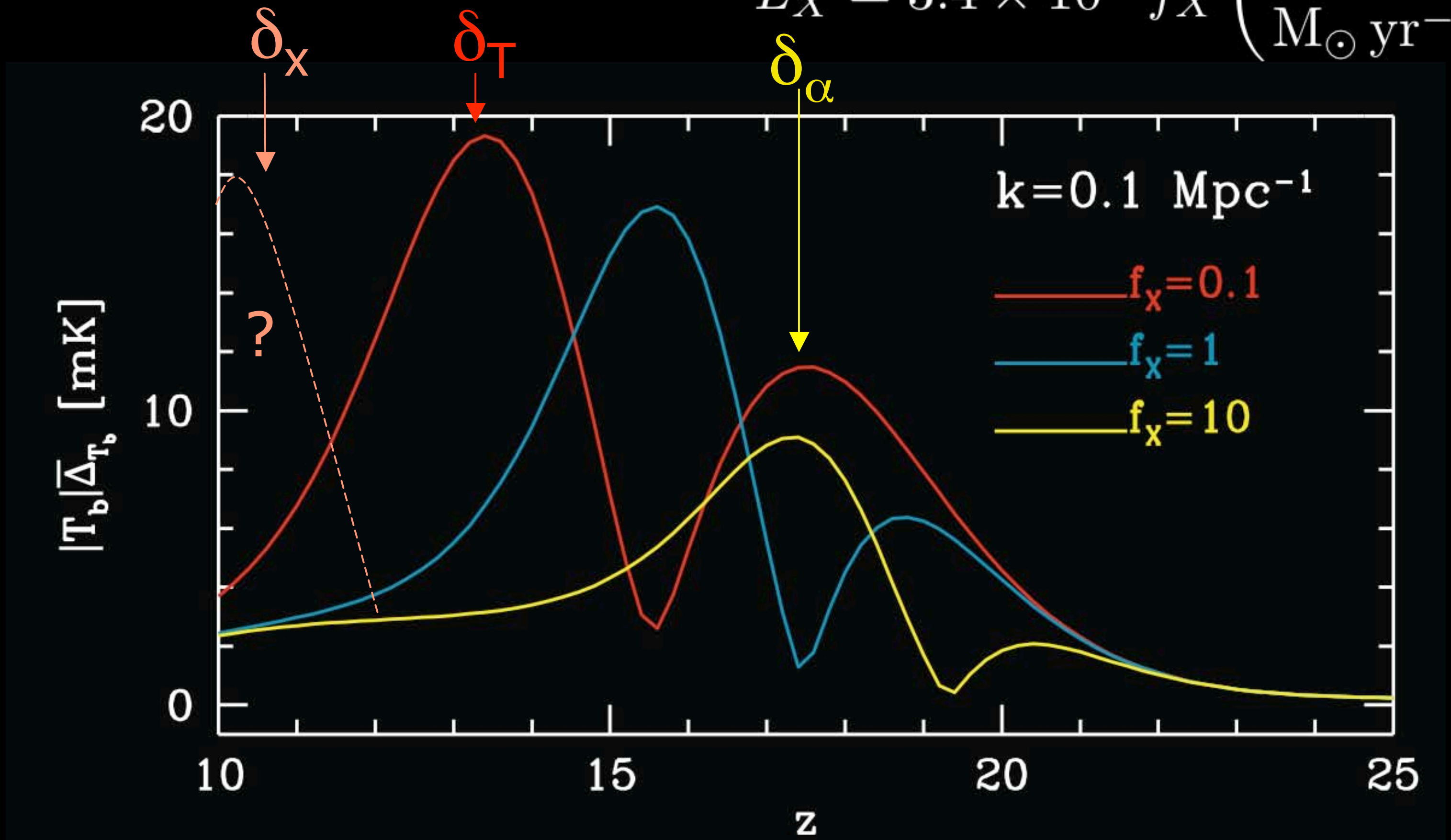


X-ray background?

- X-ray background at high z is poorly constrained

Extrapolating low-z X-ray:IR correlation gives: Glover & Brand 2003

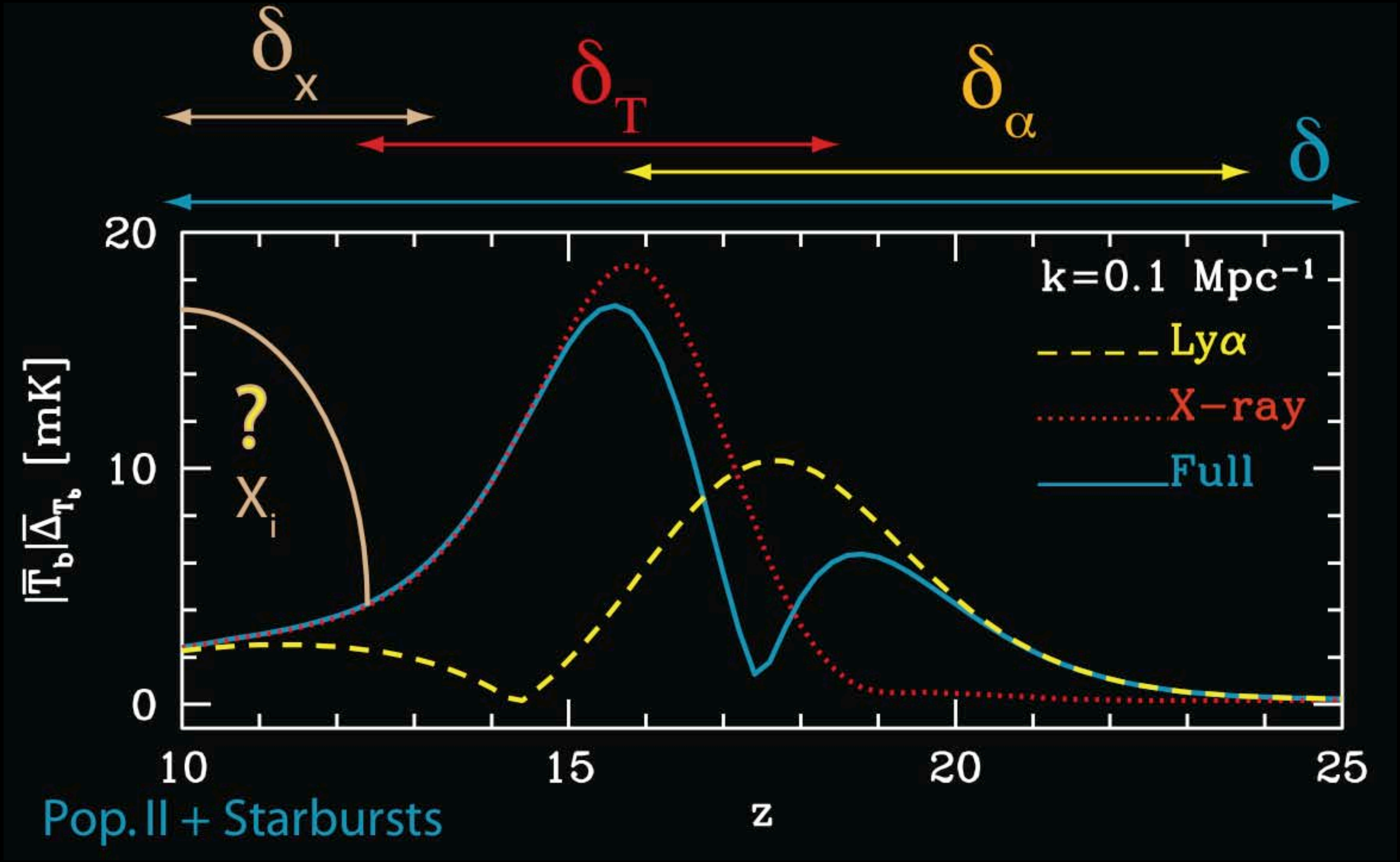
$$L_X = 3.4 \times 10^{40} f_X \left(\frac{\mathrm{SFR}}{\mathrm{M_\odot\,yr^{-1}}} \right) \mathrm{erg\,s^{-1}}$$



•1st Experiments might see T_K fluctuations if heating late

21 cm fluctuations: z

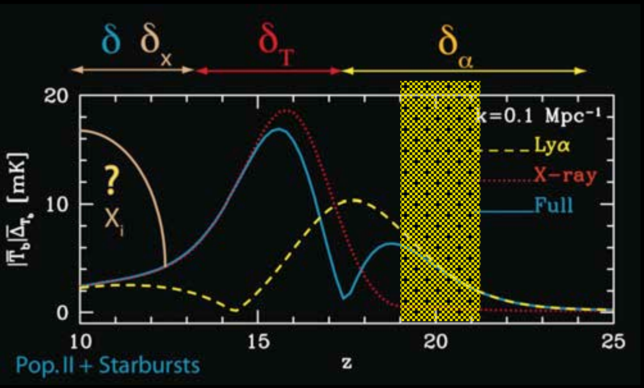
$$\delta_{T_b} = \beta\delta + \beta_x\delta_{x_{HI}} + \beta_T\delta_{T_k} + \beta_\alpha\delta_\alpha - \delta_{\partial v}$$



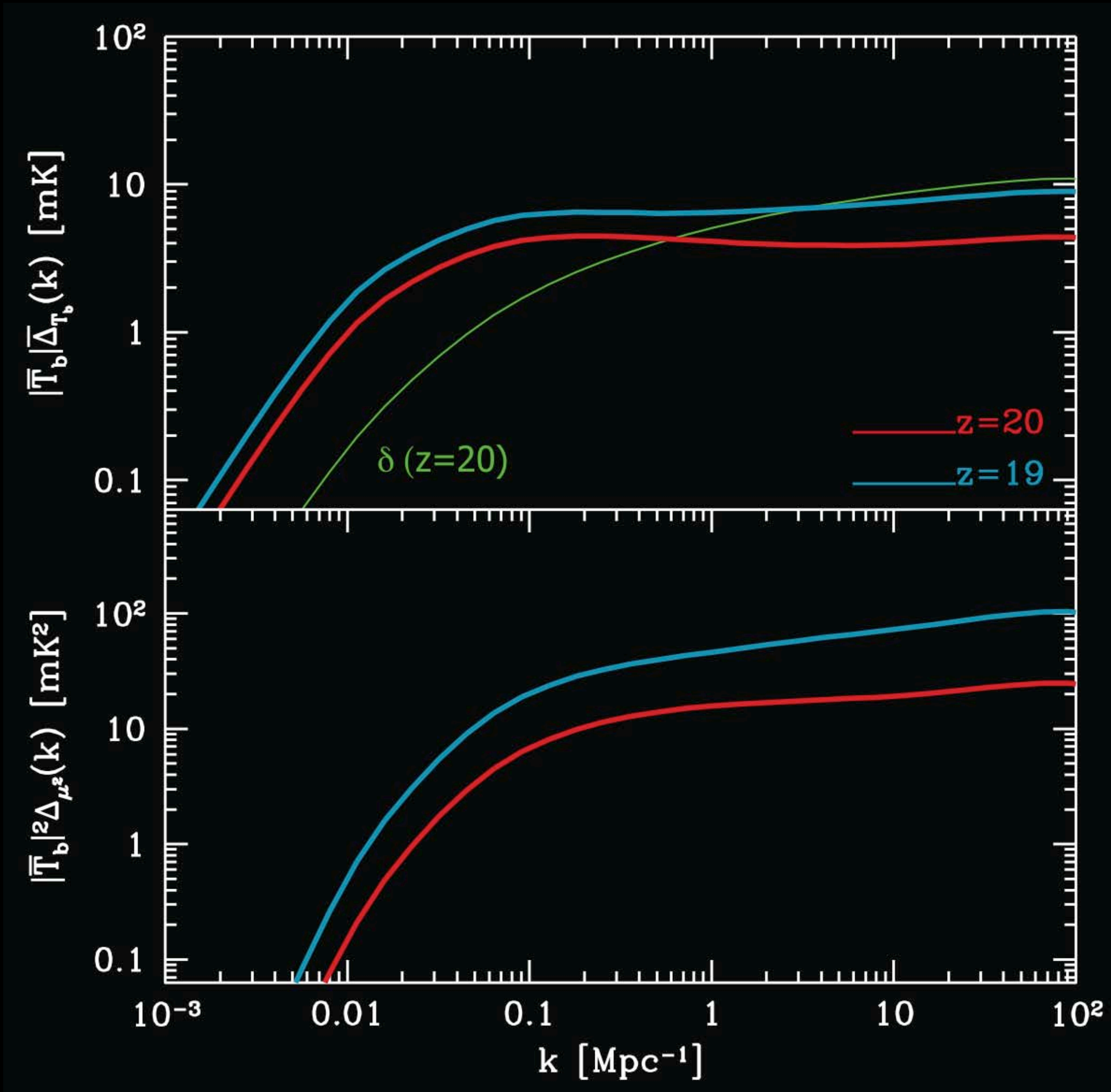
- Exact form very model dependent

Redshift slices: Lyα

z=19-20

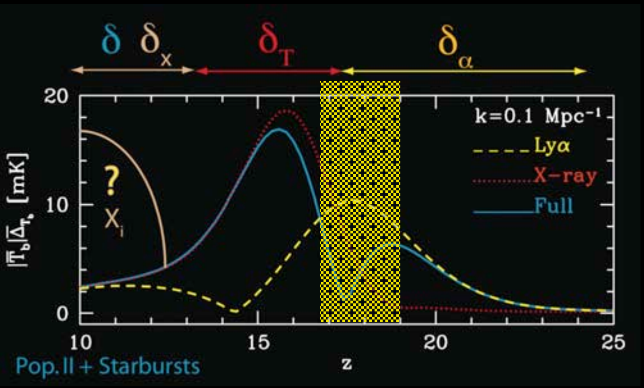


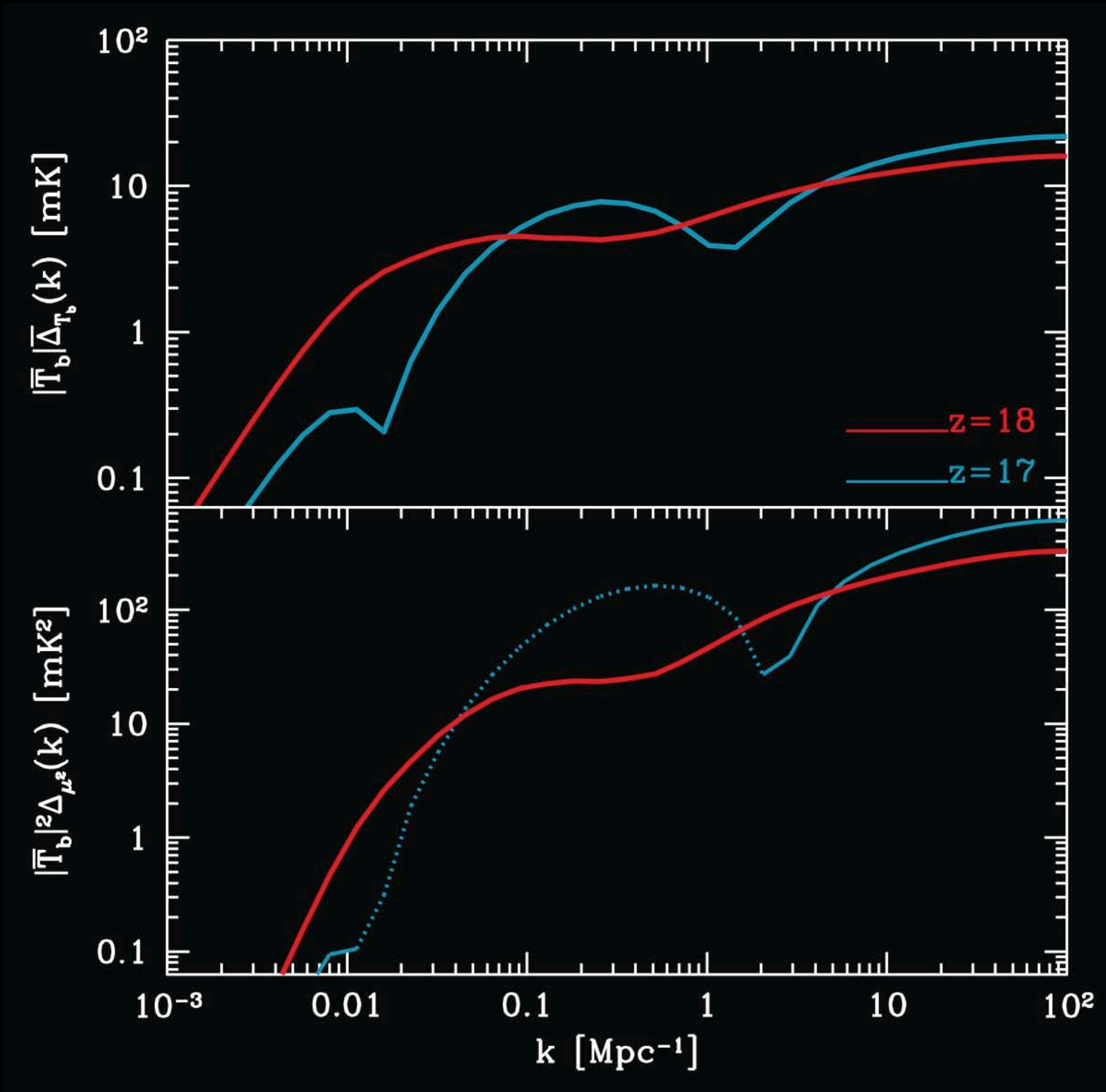
- Pure Lyα fluctuations



Redshift slices: Lyα/T

z=17-18



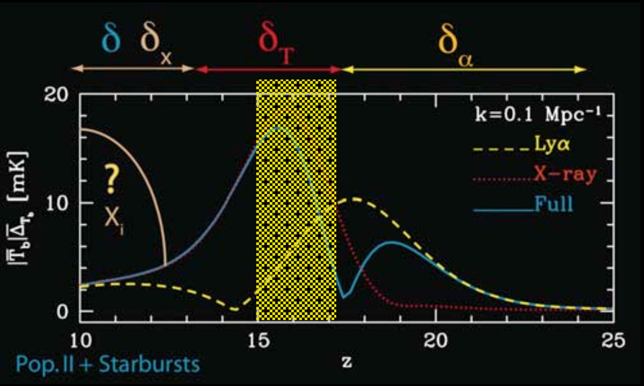


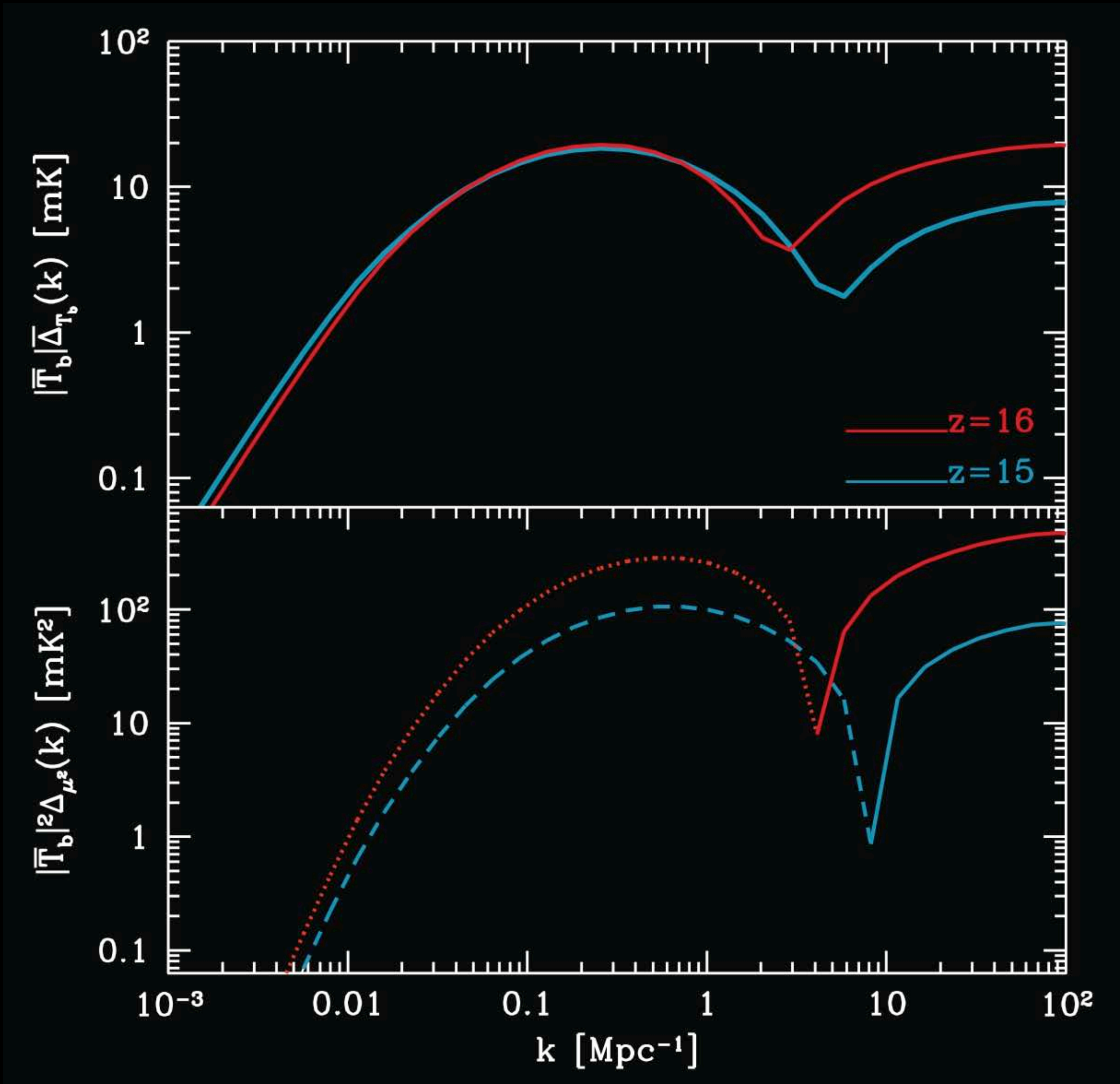
- Growing T fluctuations lead first to dip in Δ_{Tb} then to double peak structure

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

Redshift slices: T

z=15-16

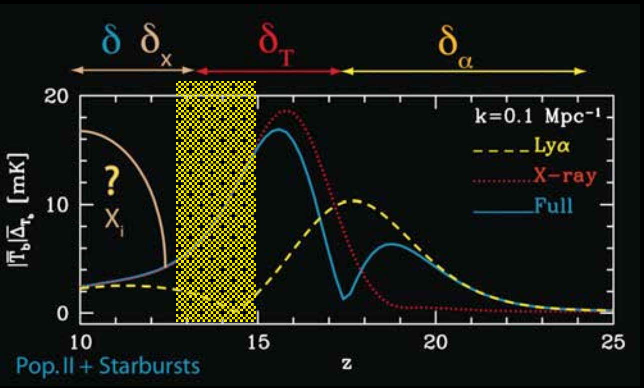




- T fluctuations dominate over Lyα
- Clear peak-trough structure visible
- $\Delta_{\mu^2}<0$ on large scales indicates $T_K<T_\gamma$

Redshift slices: T/δ

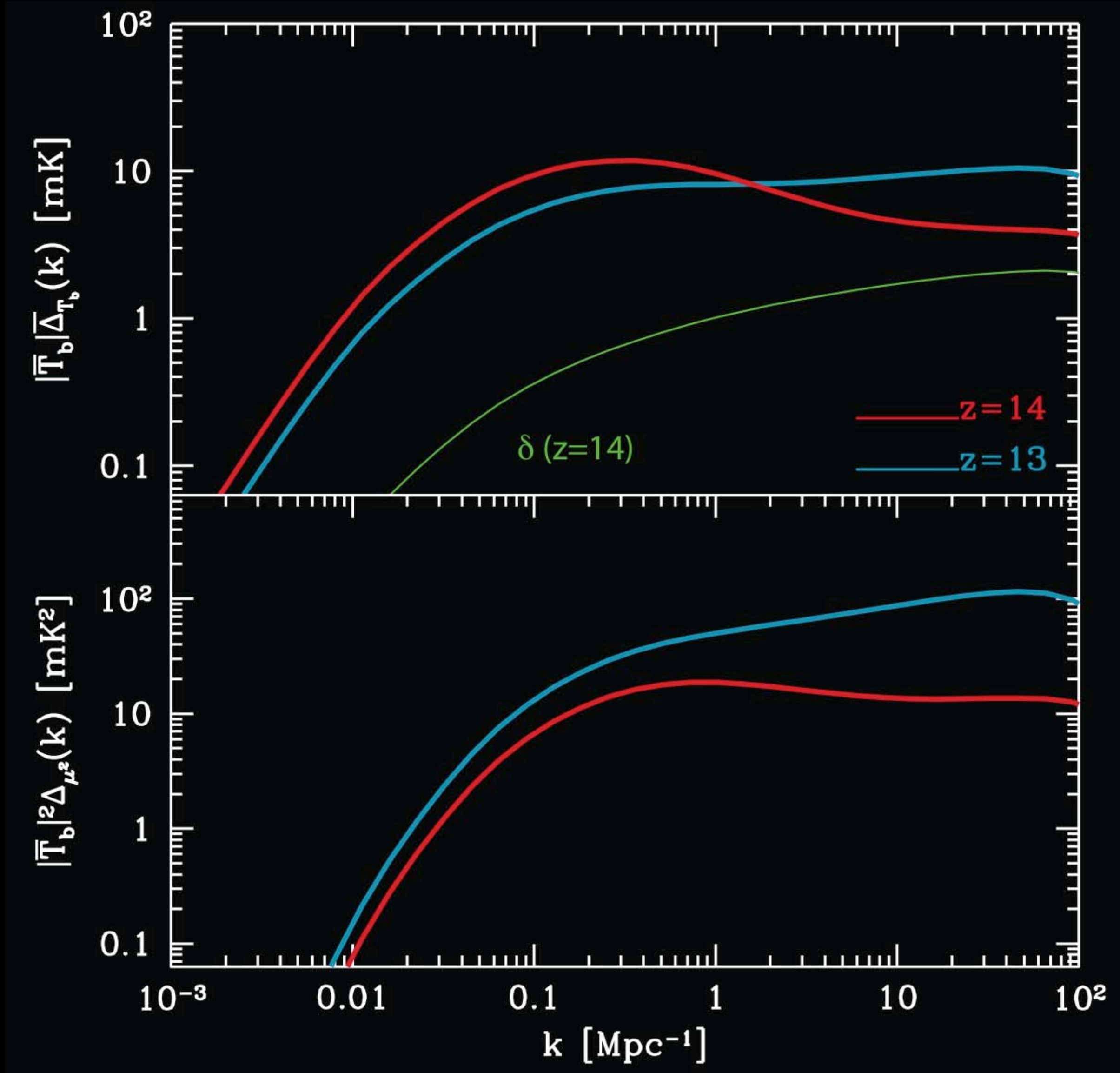
z=13-14



- 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

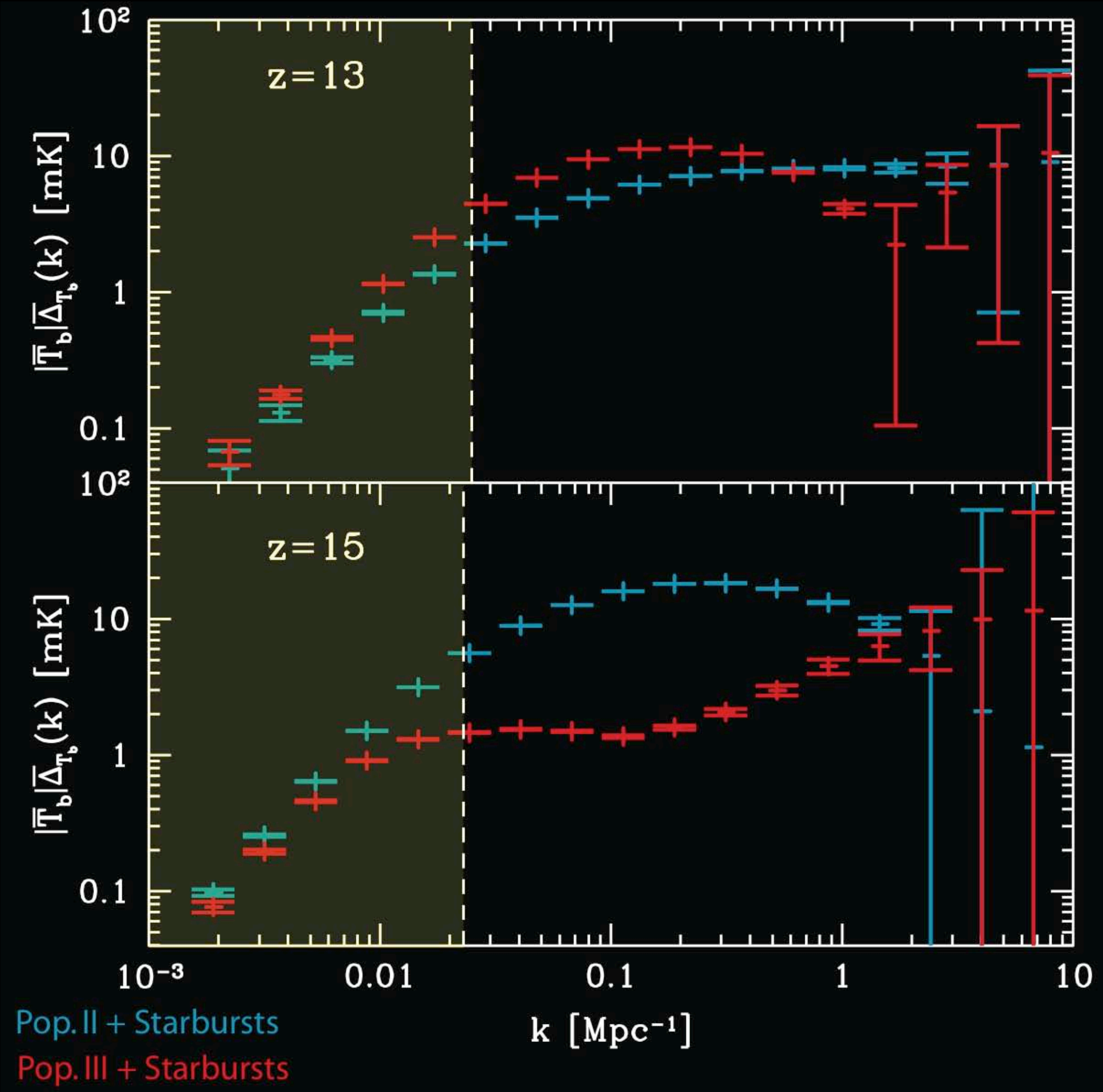


Observations

- Need SKA to probe these brightness fluctuations
- Observe scales k=0.025-2 Mpc^{-1}
- Easily distinguish two models
- Probably won't see trough :(

foregrounds

poor angular resolution



Conclusions

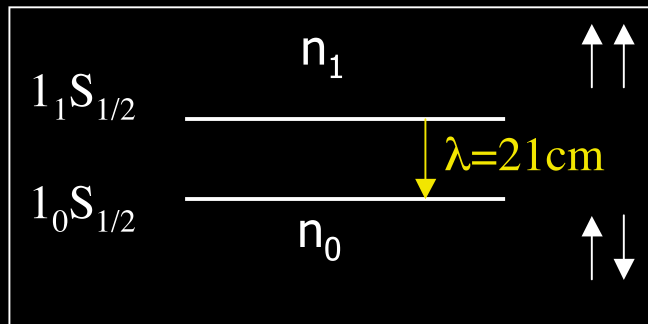
- 21 cm fluctuations potentially contain much information about the first sources
  - Bias
  - X-ray background
  - X-ray source spectrum
  - IGM temperature evolution
  - Star formation rate
- Lyα and X-ray backgrounds may be probed by future 21 cm observations
- Foregrounds pose a challenging problem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

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

Extra Slides

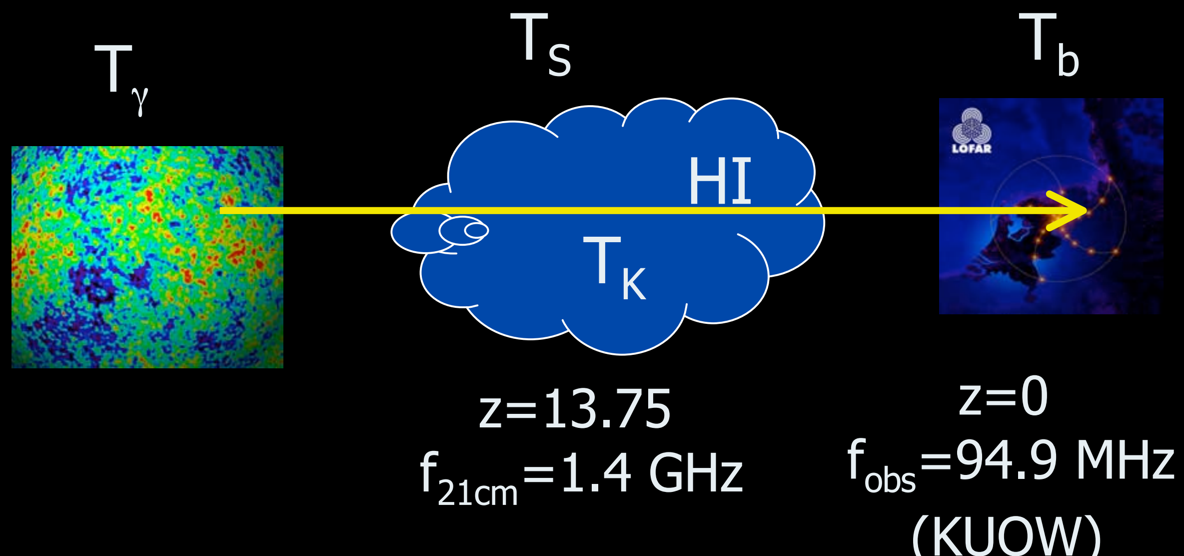
21 cm basics

- HI hyperfine structure



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

- Use CMB backlight to probe 21cm transition



- 3D mapping of HI possible - angles + frequency

21 cm basics

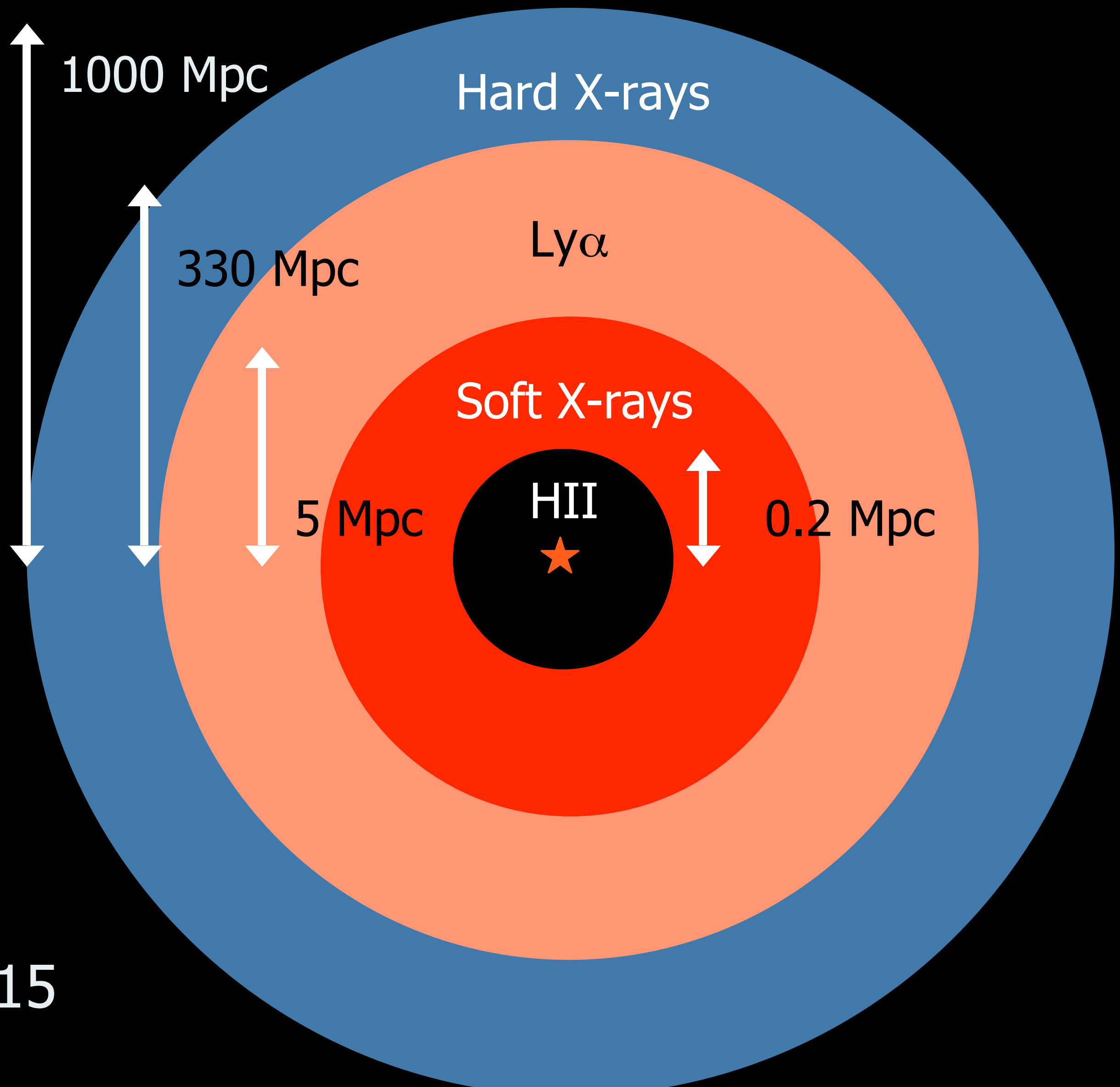
- 21 cm brightness temperature

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

- 21 cm spin temperature

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

The first sources



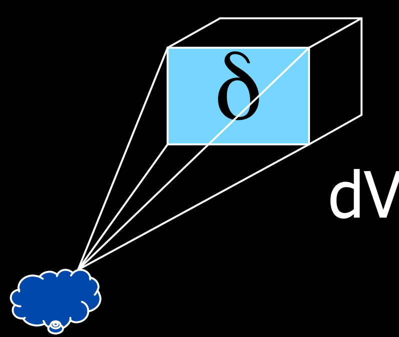
$z=15$

X-ray heating

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

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

- 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

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

temperature fluctuations

Heating fluctuations

Fractional heating per Hubble time at z