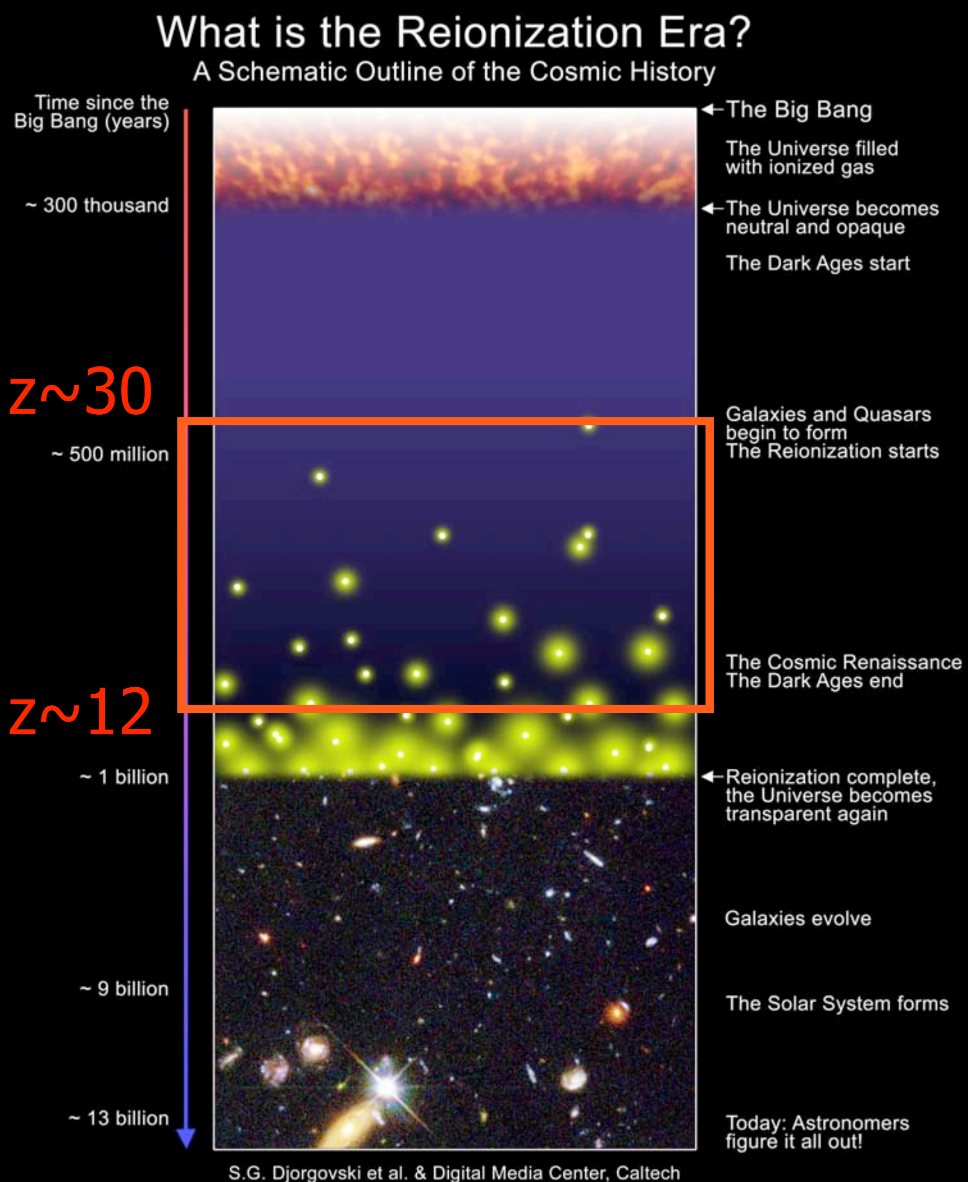
Radiation backgrounds from the first sources and the redshifted 21 cm line

Jonathan Pritchard
(Caltech)

Collaborators: Steve Furlanetto (Yale)

Advisor: Marc Kamionkowski (Caltech)

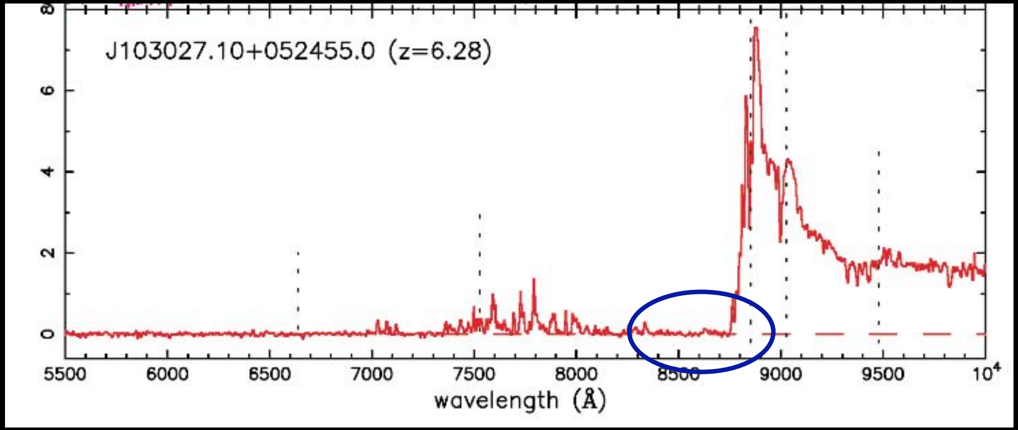
Overview



- Evolution of 21 cm signal
- Detecting the first stars through 21 cm fluctuations (Lyα)
- Inhomogeneous X-ray heating and gas temperature fluctuations (X-ray)
- Observational prospects

Ionization history

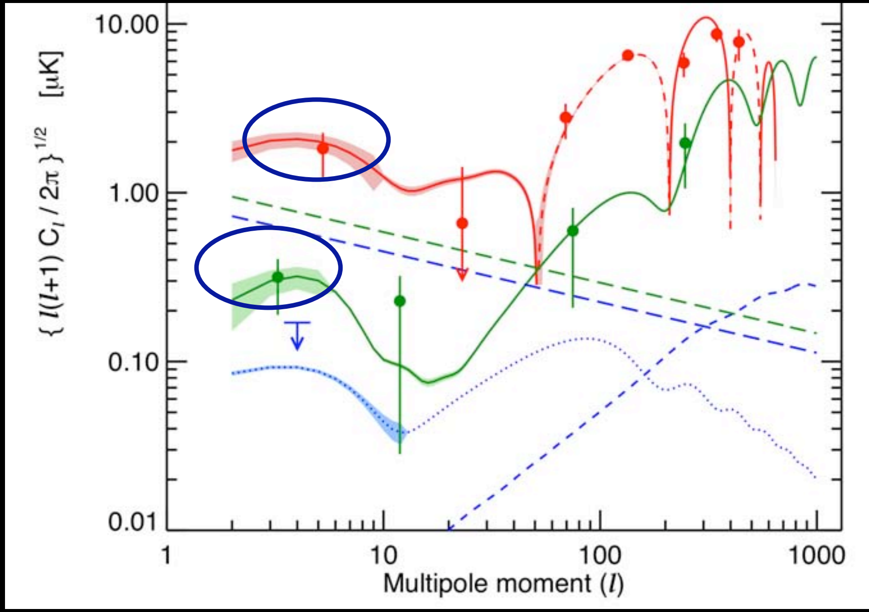
- Gunn-Peterson Trough



Becker et al. 2005

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

- WMAP3 measurement of $\tau\sim0.09$ (down from $\tau\sim0.17$)

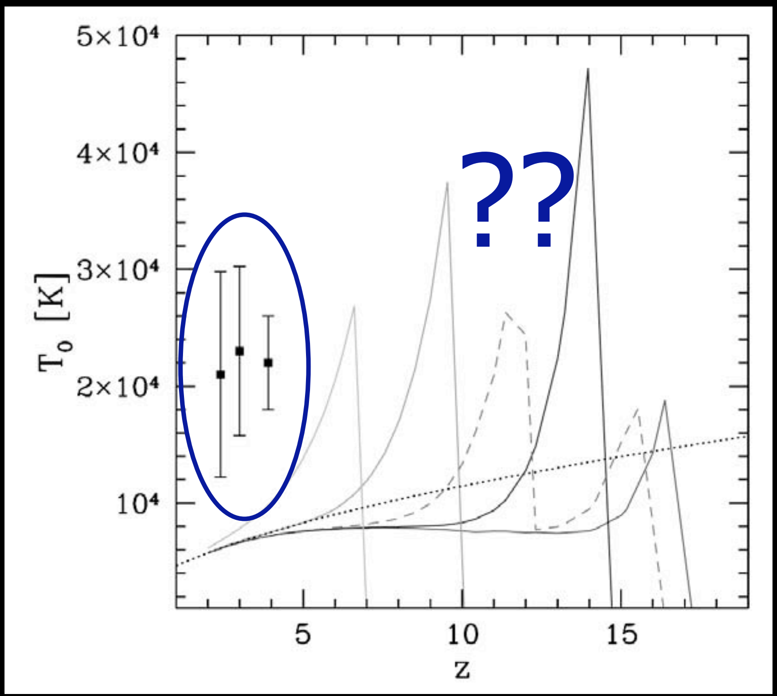


Page et al. 2006

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

Thermal history

- Lyα forest



Zaldarriaga, Hui, & Tegmark 2001

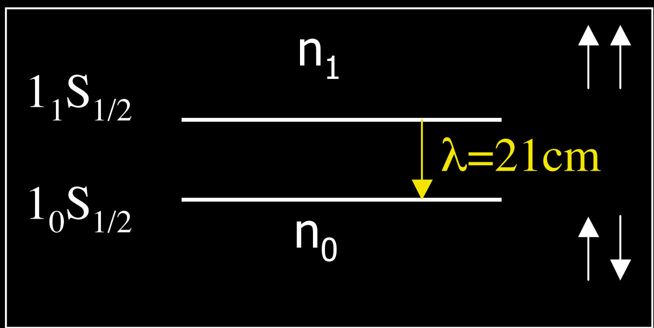
Hui & Haiman 2003

- 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

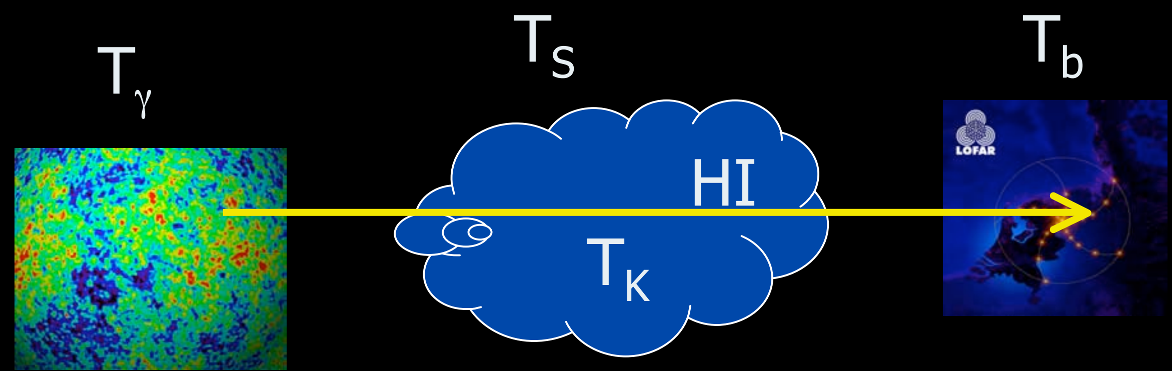
21 cm basics

- 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

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

- 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

Wouthysen-Field effect

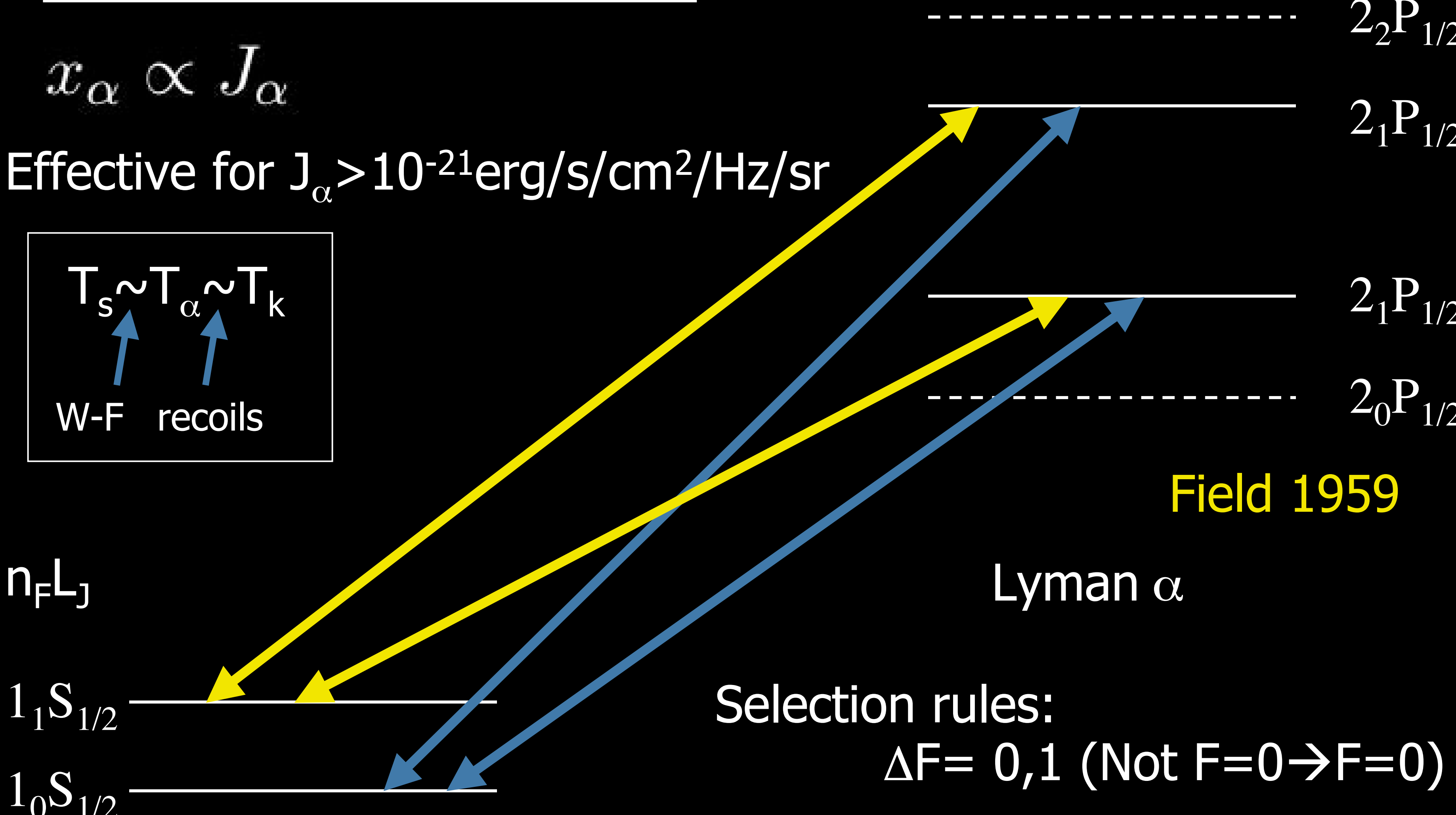
Hyperfine structure of HI

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

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 $F=0 \rightarrow F=0$)

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

PAPER: UCB ?

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

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

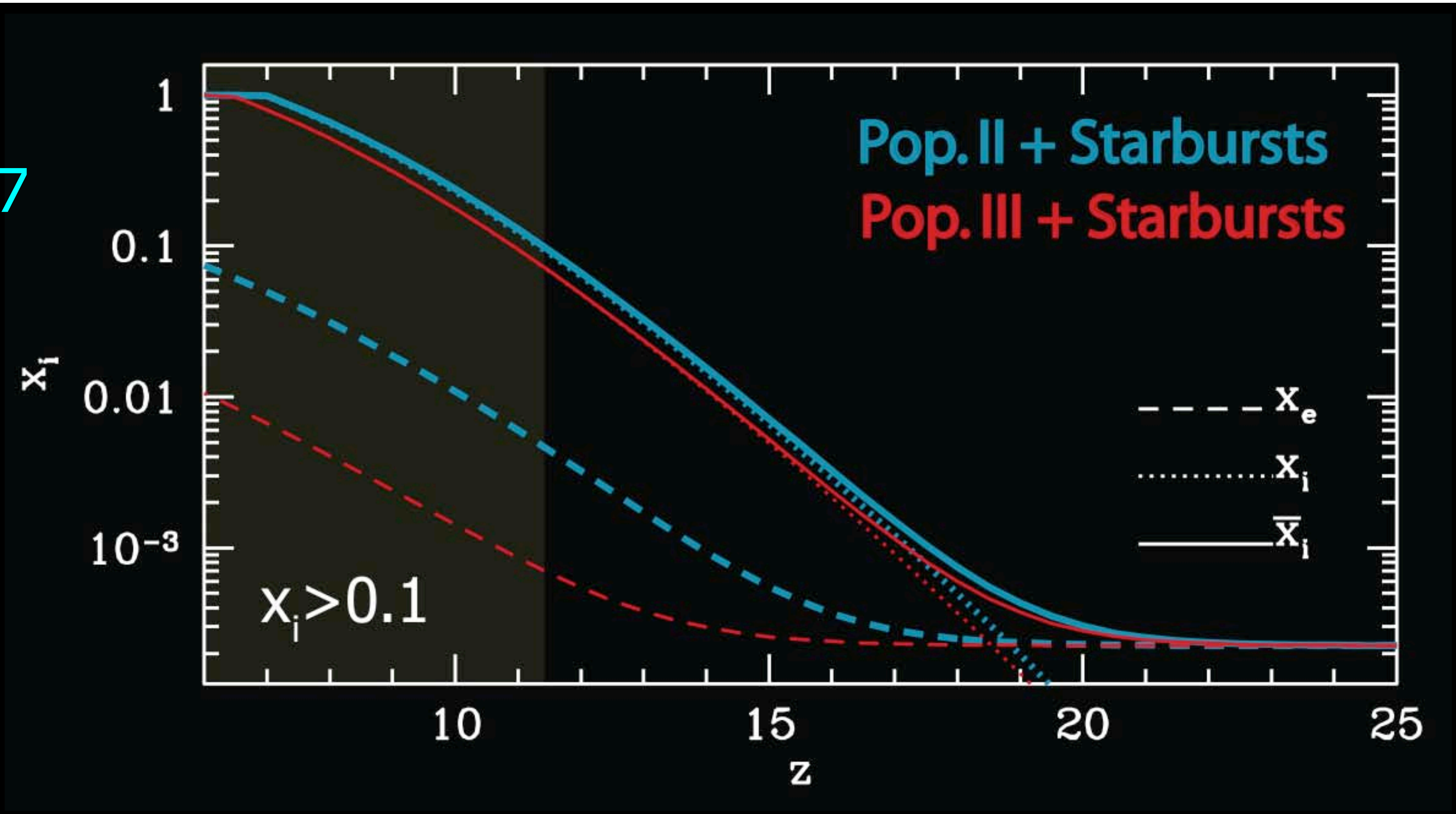
$$J_\alpha = J_C + J_{I,\star} + J_{I,X}$$ — Lyα flux

continuum injected

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

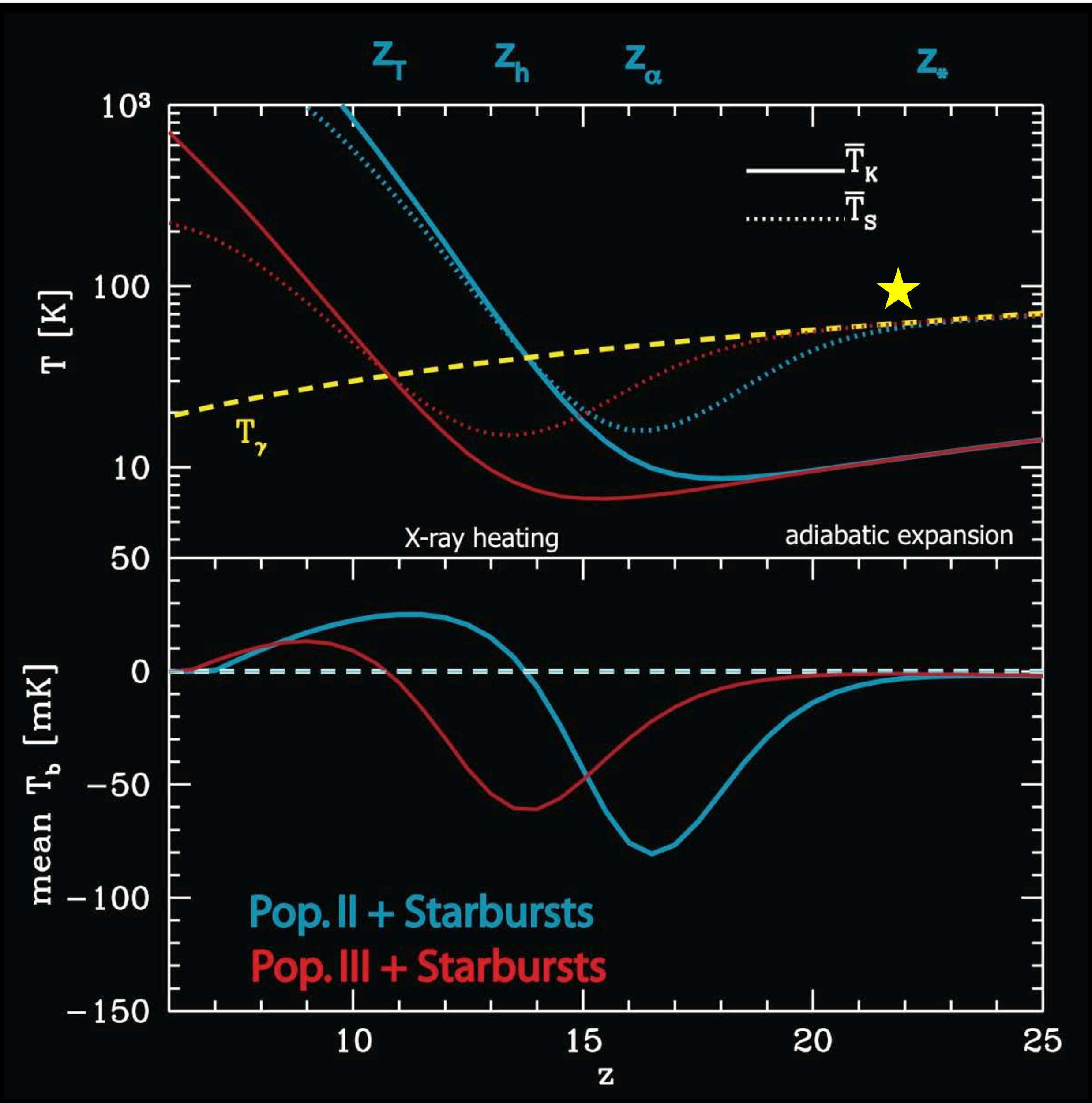
Ionization history

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



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

Thermal history

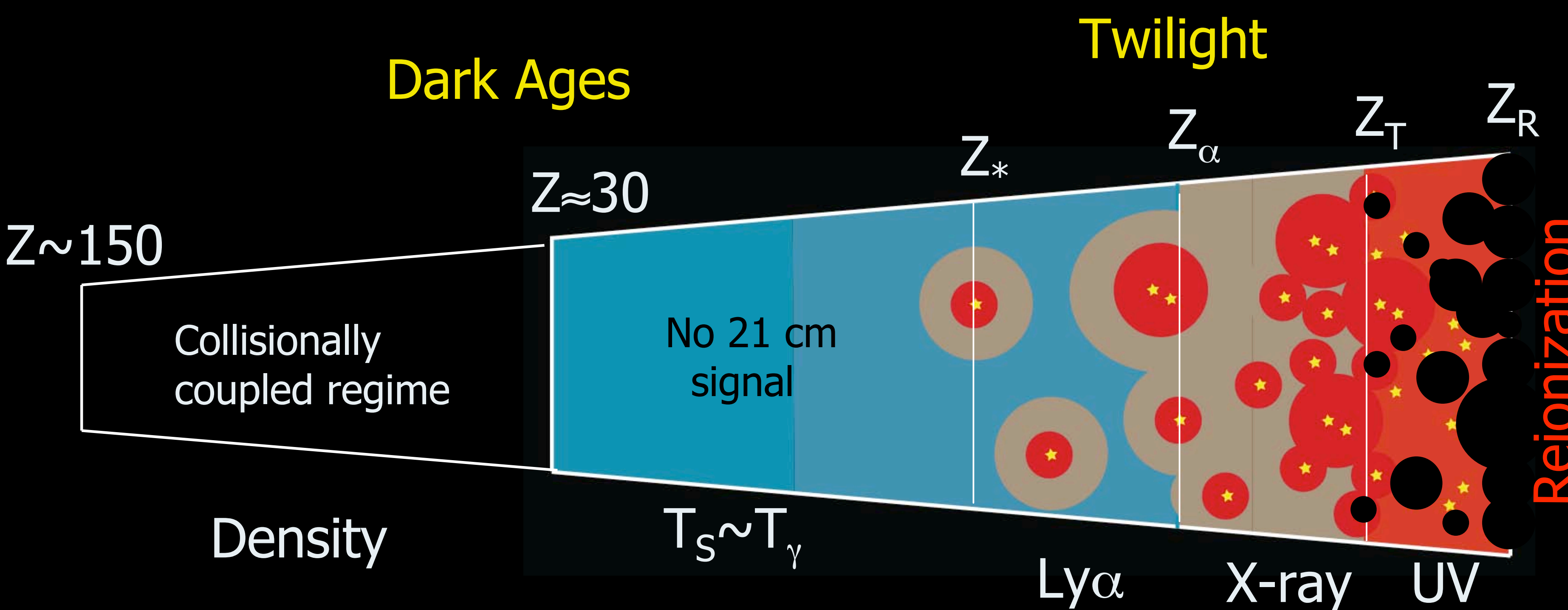


21 cm fluctuations

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

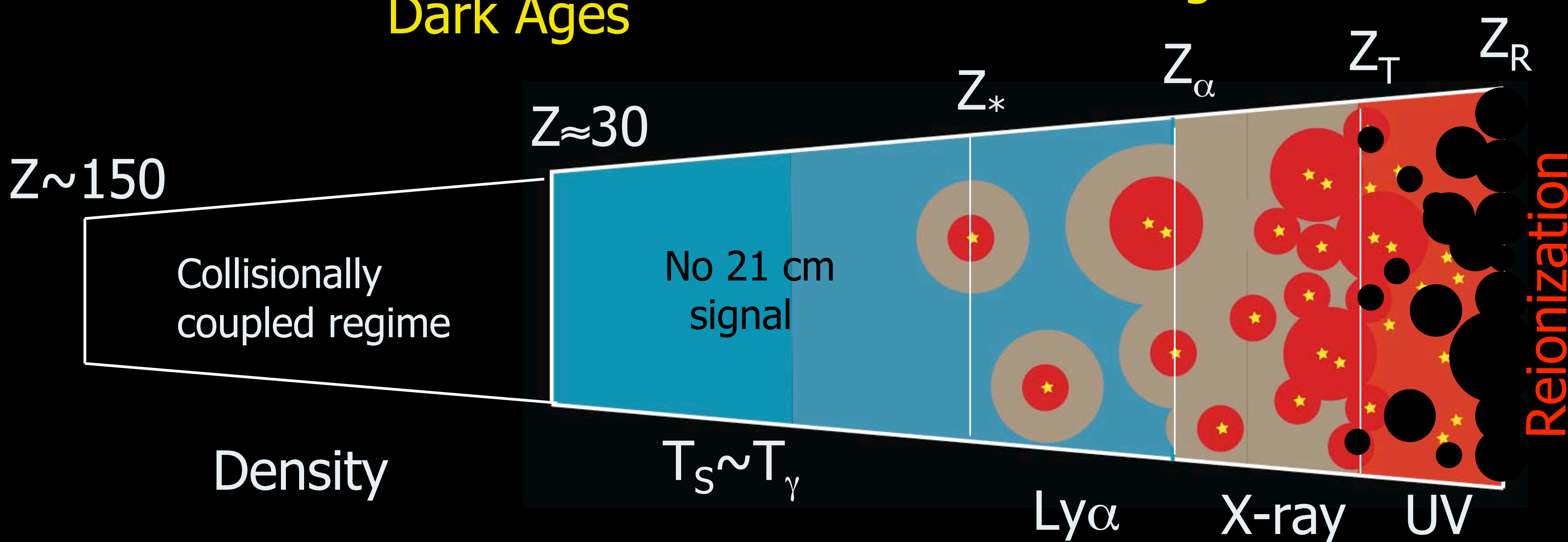
Brightness temperature	Baryon Density	Neutral fraction	Gas Temperature	W-F Coupling	Velocity gradient

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

Cosmology	Reionization	X-ray sources	Lyα sources	Cosmology

Twilight

Dark Ages



21 cm fluctuations: Lyα

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

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

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

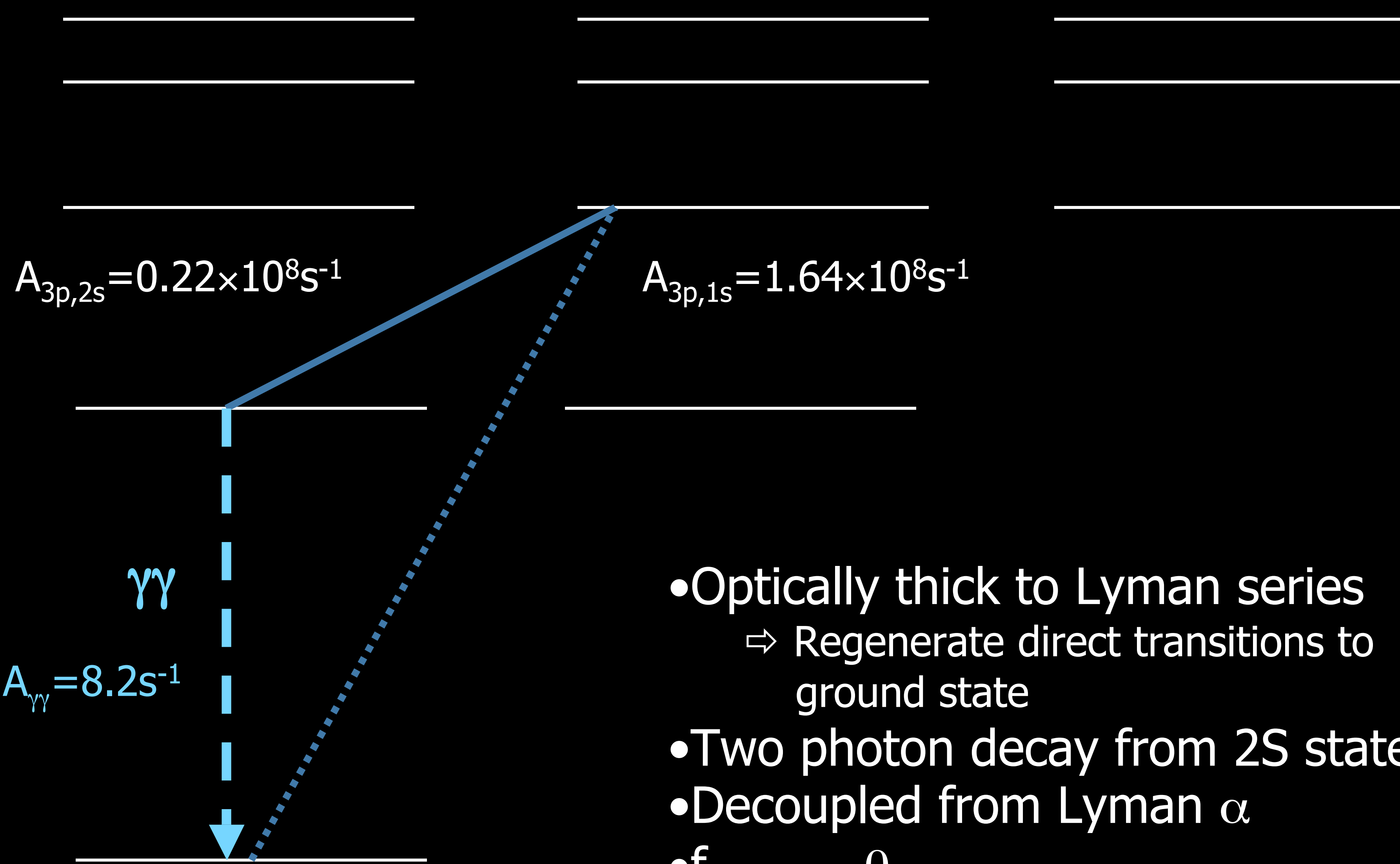
Chen & Miralda-Escude 2006

Higher Lyman series

- Two possible contributions from Ly n photons
  - 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…

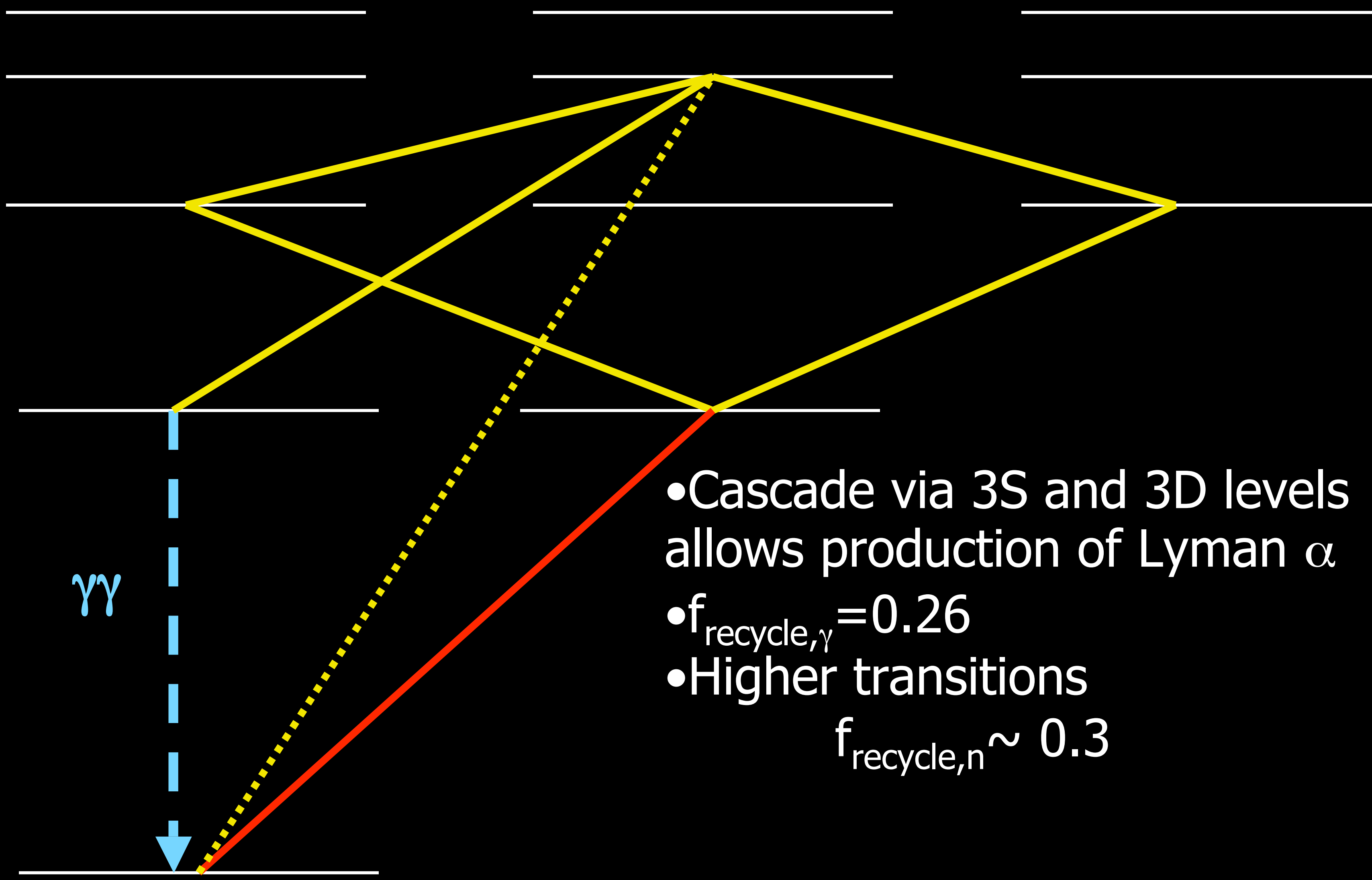
Pritchard & Furlanetto 2006 Hirata 2006

Lyman β



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

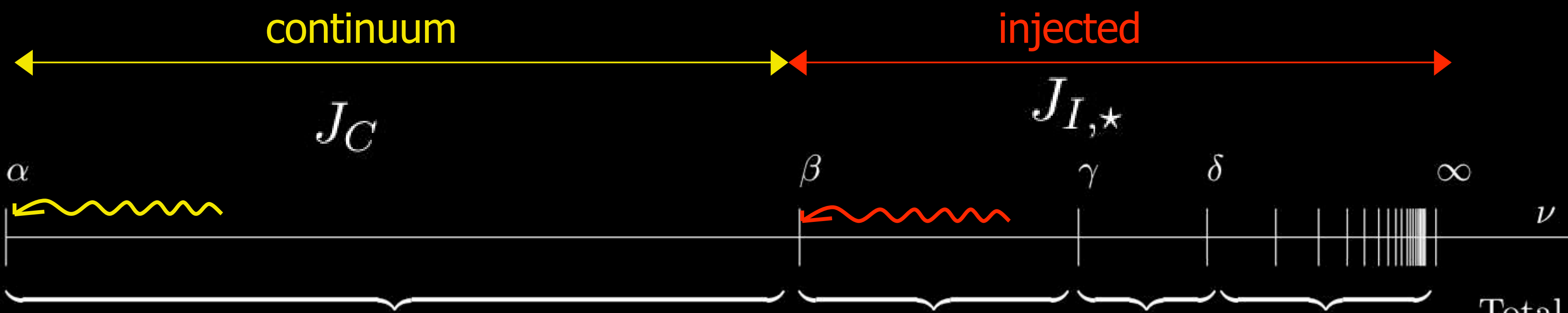
Lyman γ



- 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

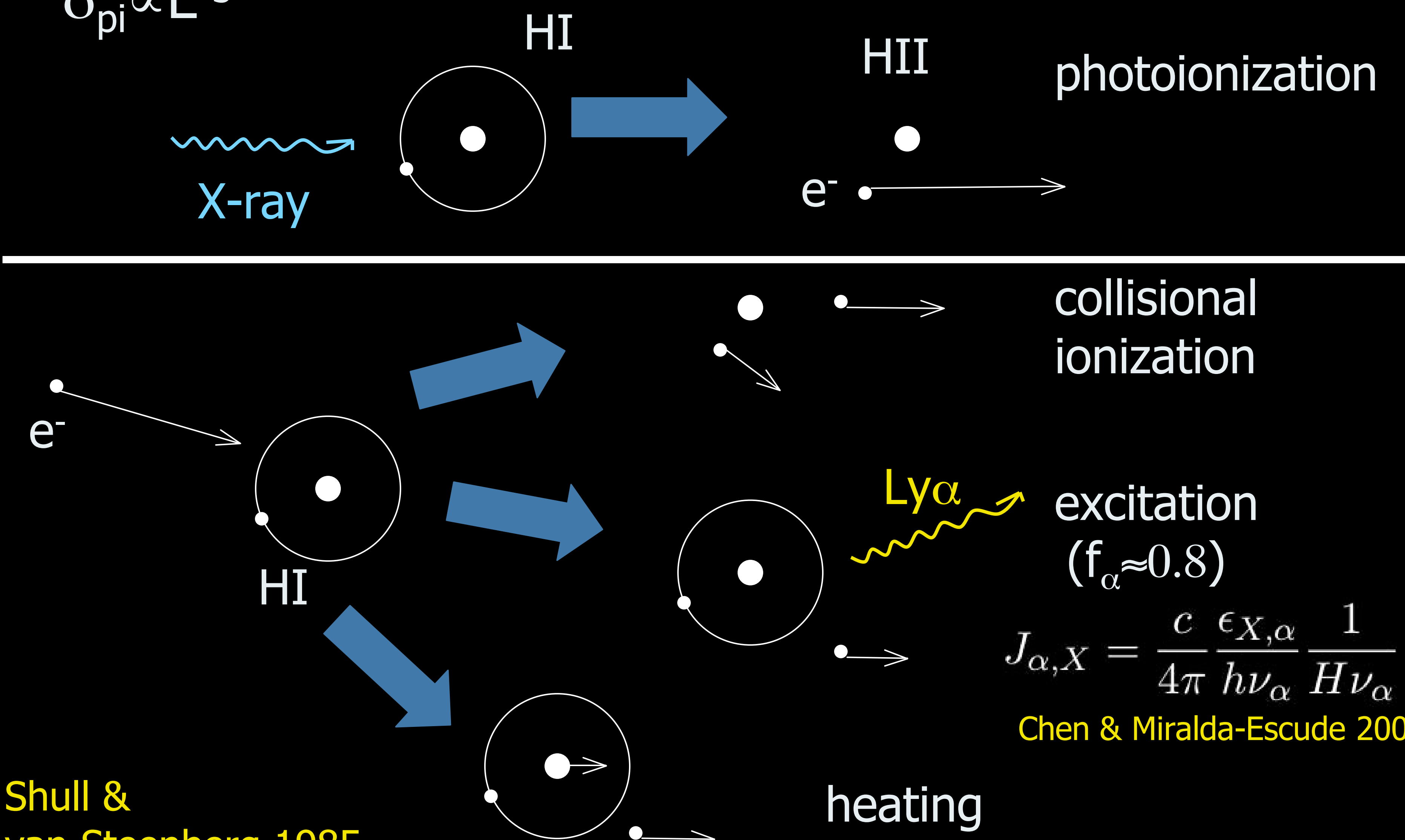


					Total
No. Photons: (pop III)	2670	965	451	810	4896
$f_{recycle}$:	1.0	0	0.26	0.35	0.62
Lyα Contribution:	2670	0	118	268	3056
Shell size @$z = 20$ (Mpc):	278	90	40	22	

- also a contribution from X-rays…

X-rays and Lyα production

$\sigma_{pi} \propto E^{-3}$

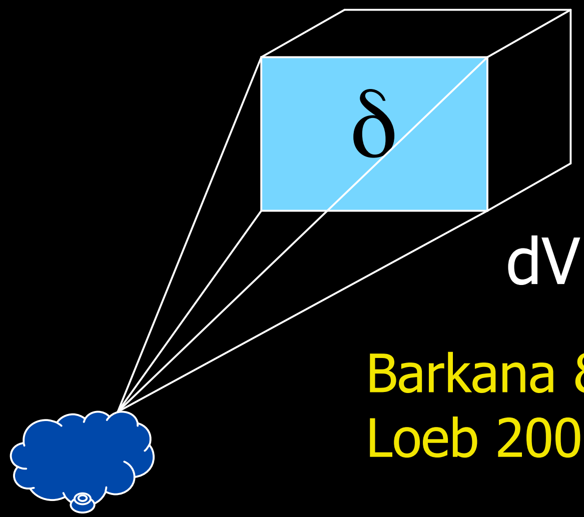


$$J_{\alpha,X} = \frac{c}{4\pi}\frac{\epsilon_{X,\alpha}}{h\nu_\alpha}\frac{1}{H\nu_\alpha}$$

Chen & Miralda-Escude 2006

Shull &
van Steenberg 1985

Fluctuations from the first stars



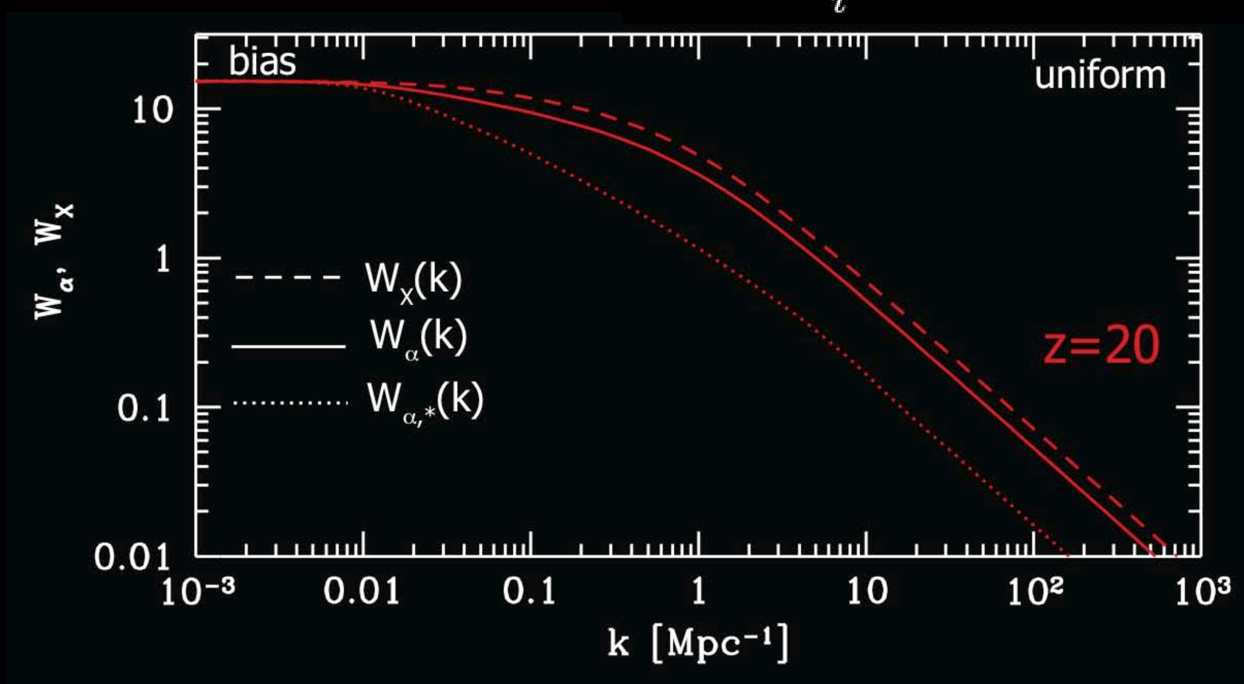
Barkana & Loeb 2005

- 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

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



TAC
Nov 2006

Determining the first sources

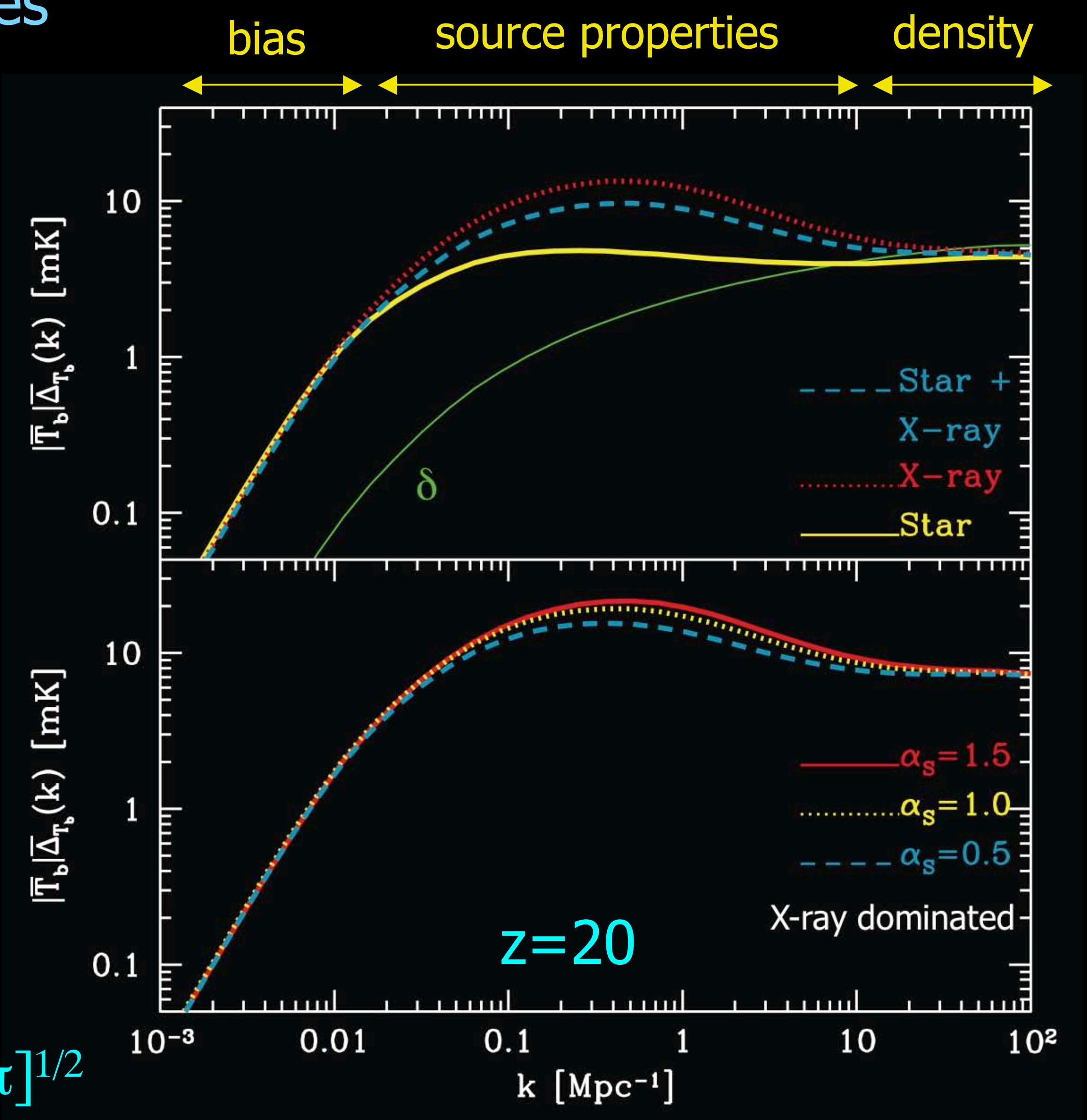
δ_α dominates

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

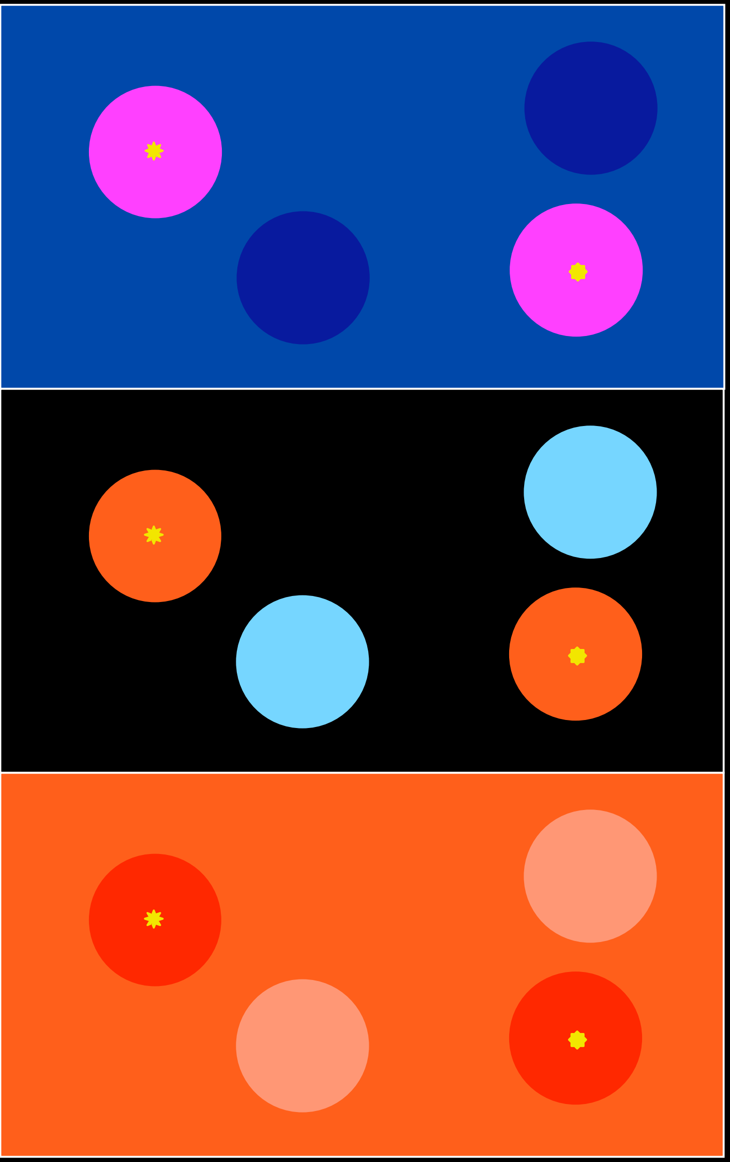
$$\beta_T \approx \frac{T_\gamma}{T_K - T_\gamma}$$

- 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

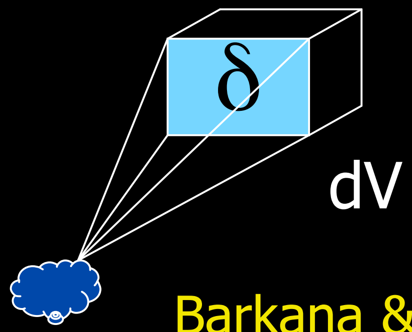
$T_S \sim T_K > T_\gamma$
$T_b > 0$ (emission)
Hotter region = stronger emission
$\beta_T > 0$

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

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

- Simplistic, fluctuations may lead to observable 21cm signal
- 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

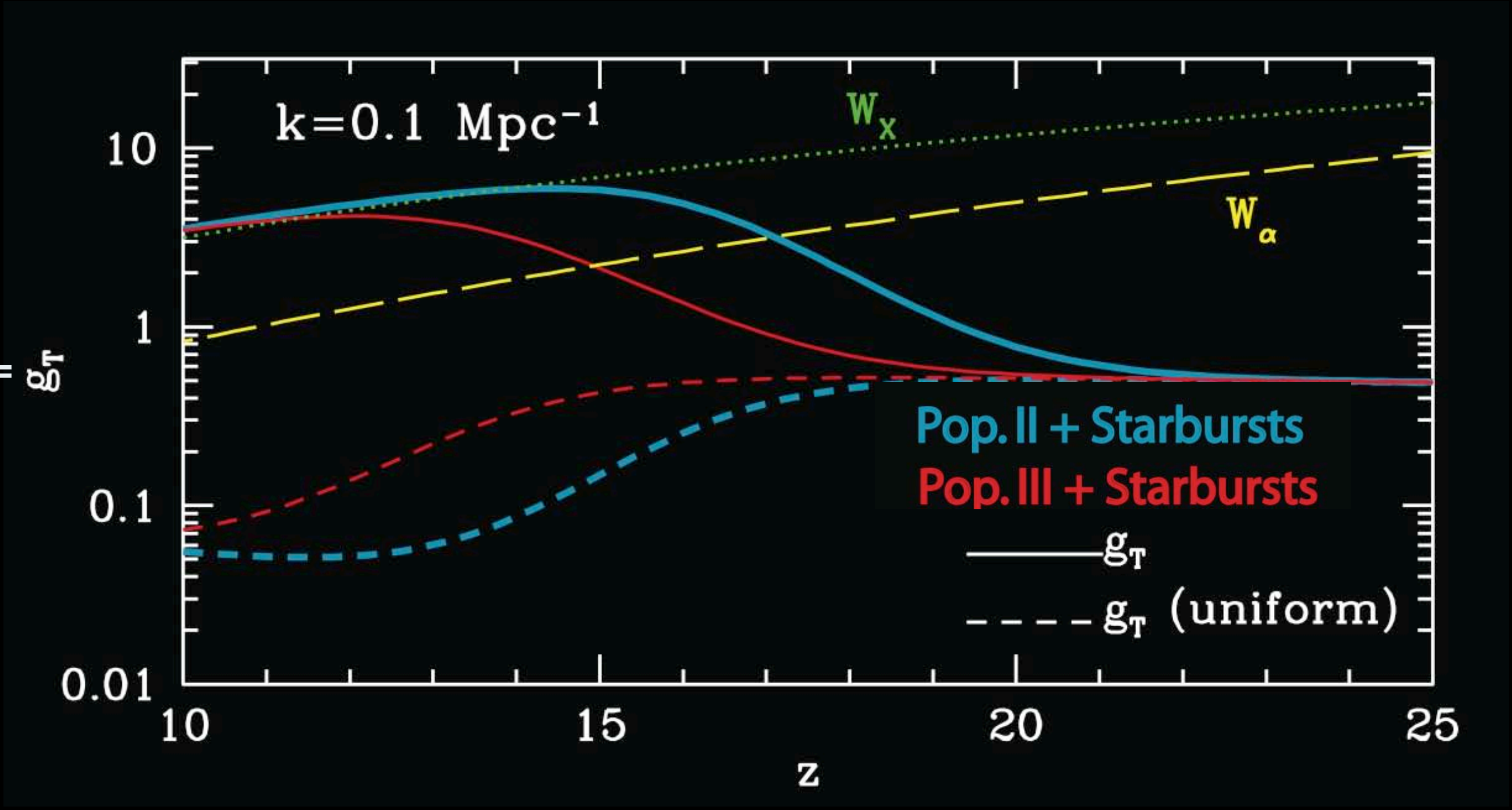
$$\frac{\mathrm{d}g_T}{\mathrm{d}z} = \left(\frac{g_T - 2/3}{1+z}\right) - Q_X(z)[W_X(k) - g_T] - Q_C(z)g_T$$

temperature fluctuations

Heating fluctuations

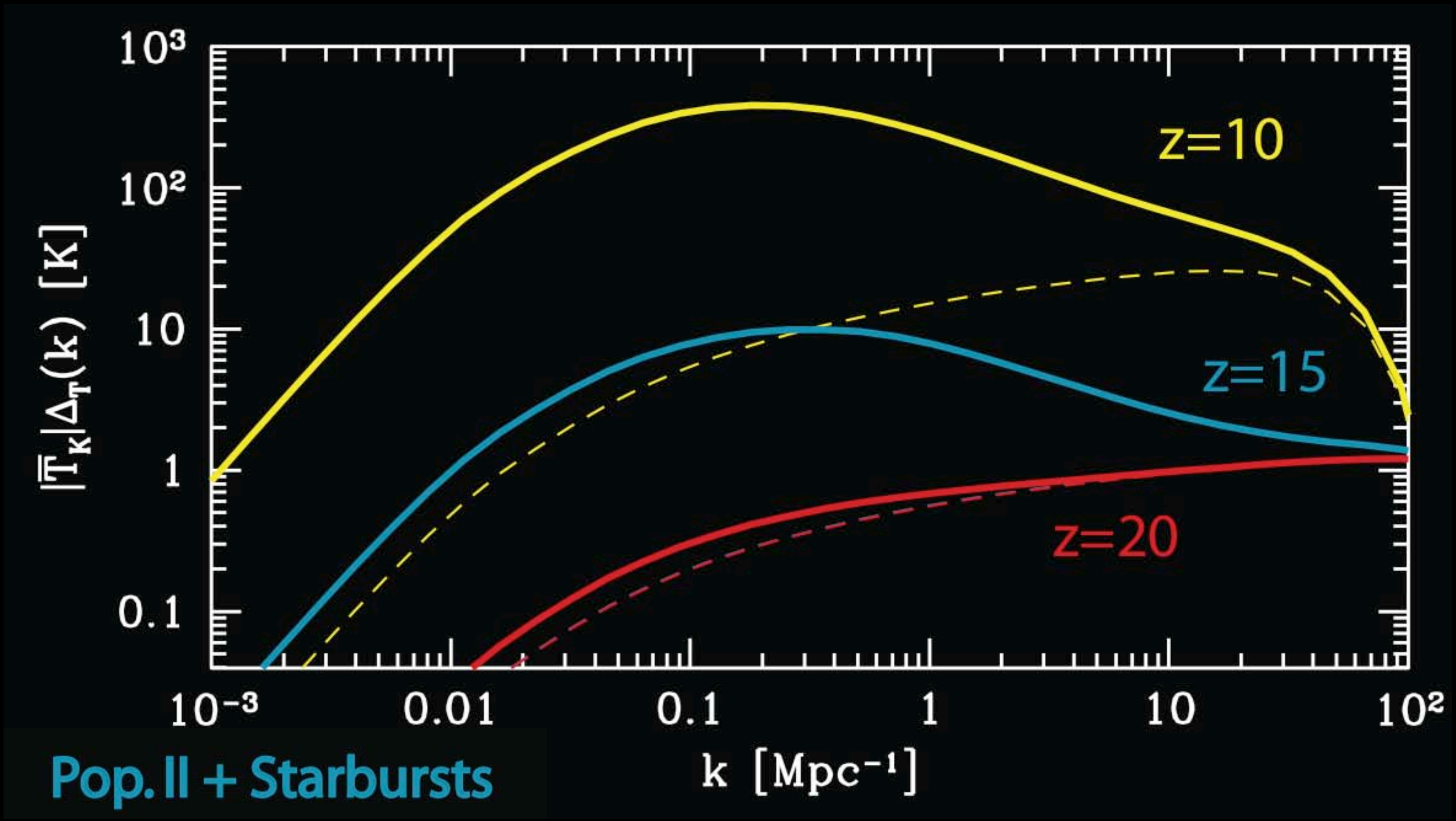
Fractional heating per Hubble time at z

$\delta_T / \delta = g_T$



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

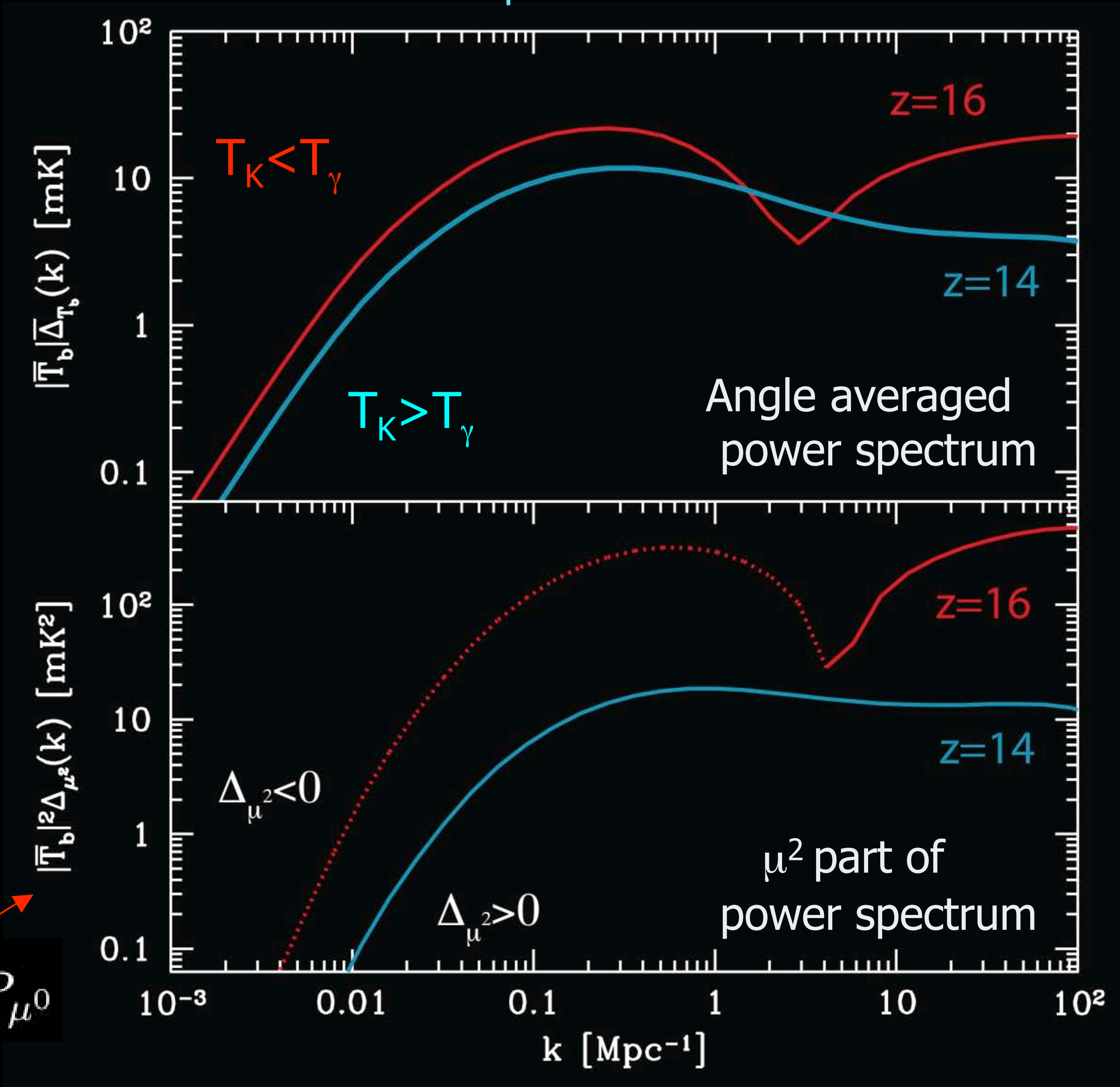
$$\delta_{T_b} \approx \delta + \beta_T \delta_{T_k}$$

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

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

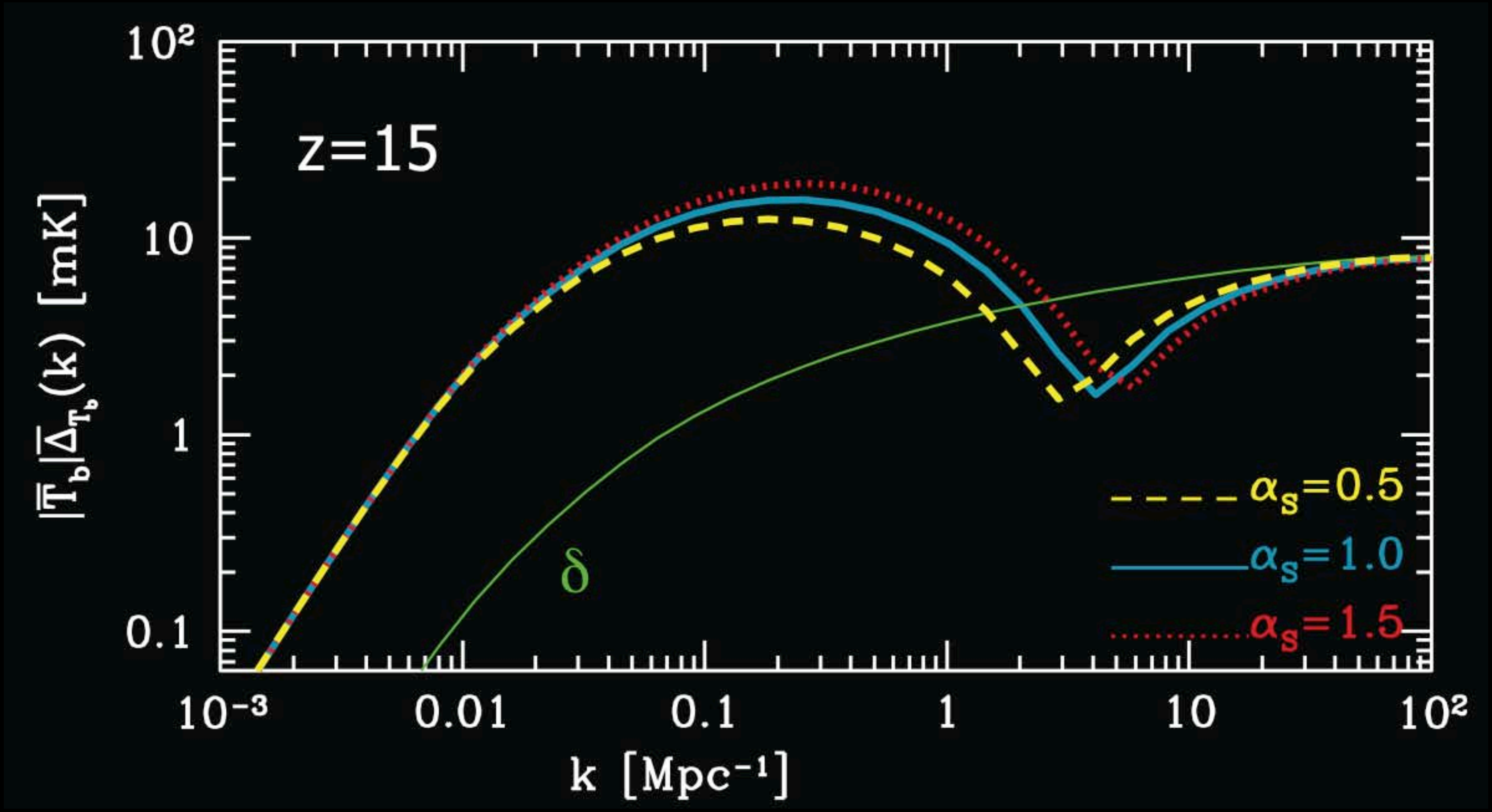
$$P_{T_b}(\mathbf{k}) = \mu^4 P_{\mu^4} + \mu^2 P_{\mu^2} + P_{\mu^0}$$

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

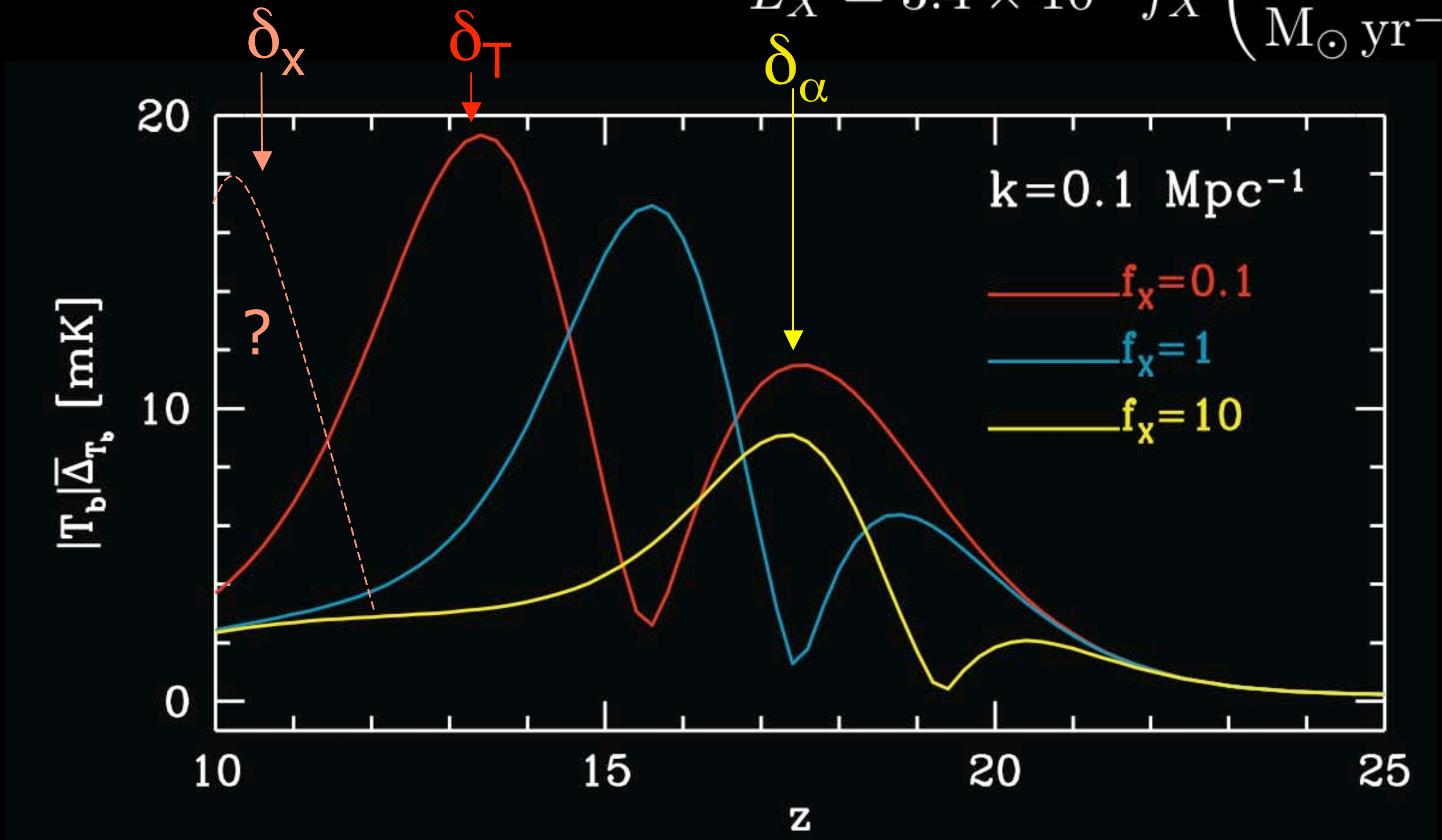


X-ray background?

- 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

Cosmology?

Density	Neutral fraction	Gas Temperature	W-F Coupling	Velocity gradient

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

HII regions still small

IGM hot $T_K >> T_\gamma$

Lyα coupling saturated

TABLE 2
ERRORS ON COSMOLOGICAL PARAMETER ESTIMATES WHEN DENSITY FLUCTUATIONS DOMINATE THE 21CM SIGNAL FOR TWO YEAR OBSERVATIONS WITH 21 CM INTERFEROMETERS AND IN COMBINATION WITH CURRENT CMB OBSERVATIONS (CCMB) AND WITH PLANCK.[a]

	τ	Ω_w	w	$\Omega_m h^2$	$\Omega_b h^2$	n_s	$\delta_H \times 10^5$ [b]	α_s	Ω_ν	$\bar{x}_H$
	0.1	0.7	-1.0	0.14	0.022	1.0	3.91	0.0	0.0	1.0
LOFAR	-	0.09	-	0.14	0.04	0.14	3.9	-	-	-
MWA	-	0.10	-	0.13	0.03	0.13	3.9	-	-	-
MWA5000	-	0.007	-	0.011	0.003	0.03	0.31	0.012	0.008	-
SKA	-	0.005	-	0.011	0.003	0.06	0.42	0.017	0.016	-
SKA[c]	-	0.14	-	0.051	0.003	0.07	2.4	0.020	0.09	-
SKA*	-	0.005	-	0.009	0.002	0.04	0.26	0.011	0.009	-
MWA50K*	-	0.002	-	0.005	0.001	0.01	0.11	0.004	0.003	-
CCMB	0.060	0.084	-	0.017	0.0014	0.072	0.29	0.039	0.12	-
CCMB+ LOFAR	0.058	0.058	-	0.011	0.0012	0.031	0.22	0.025	0.03	0.2
CCMB+ MWA	0.057	0.058	-	0.011	0.0012	0.033	0.22	0.025	0.02	0.2
CCMB+ MWA5000	0.049	0.007	-	0.003	0.0009	0.013	0.18	0.006	0.005	0.06
CCMB + SKA	0.049	0.005	-	0.003	0.0009	0.014	0.18	0.005	0.007	0.06
Planck	0.0050	0.029	0.09	0.0023	0.00018	0.0047	0.026	0.008	0.010	-
Planck +MWA5000	0.0046	0.019	0.07	0.0011	0.00013	0.0034	0.018	0.004	0.003	0.05
Planck + SKA	0.0046	0.022	0.08	0.0009	0.00013	0.0034	0.018	0.003	0.004	0.06
Planck + SKA*	0.0046	0.018	0.07	0.0009	0.00013	0.0033	0.018	0.003	0.004	0.05
Planck + MWA50K*	0.0045	0.008	0.03	0.0004	0.00010	0.0029	0.015	0.002	0.001	0.02

<- Optimistic

improve n_s and Ω_ν most

McQuinn et al. 2006

Reionization

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

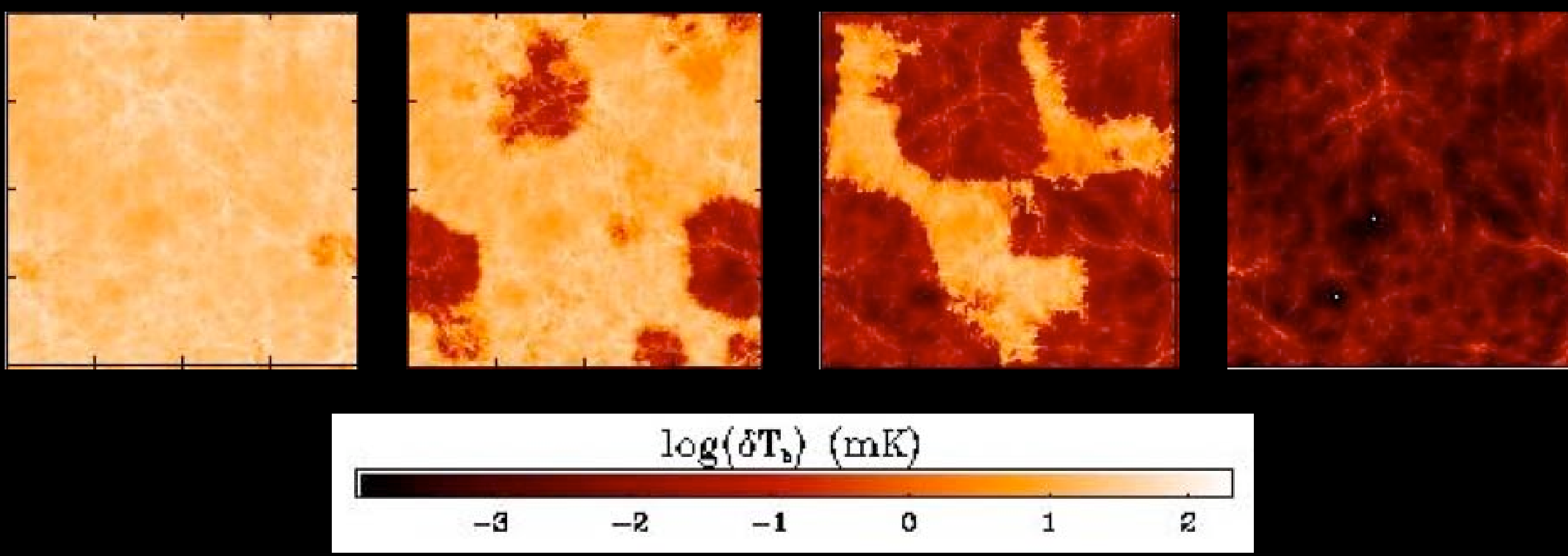
$$\delta_{T_b} = \beta\delta + \boxed{\beta_x \delta_{x_{HI}}} + \cancel{\beta_T \delta_{T_k}} + \cancel{\beta_\alpha \delta_\alpha} - \delta_{\partial v}$$

HII regions large

IGM hot $T_K >> T_\gamma$

Lyα coupling saturated

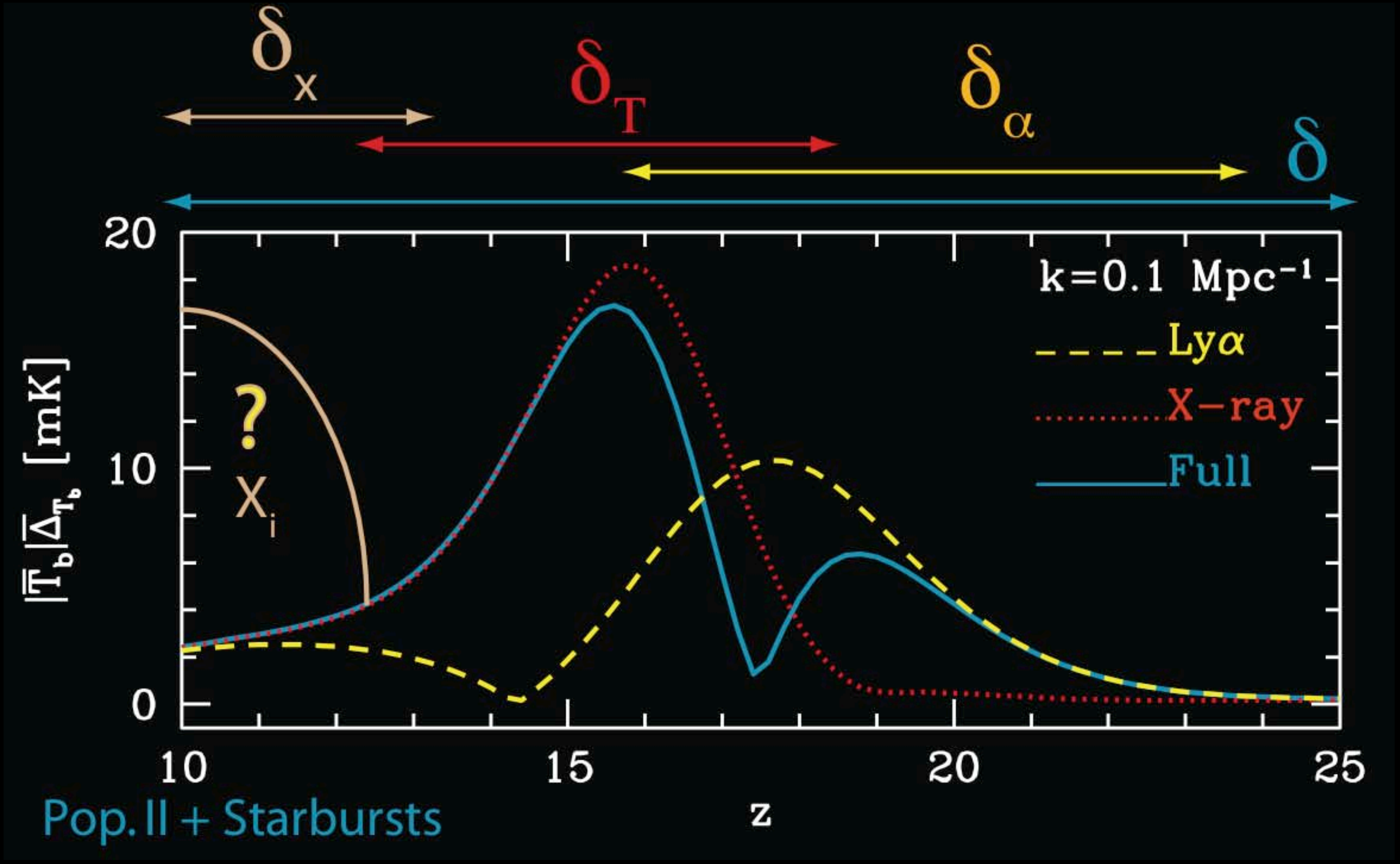
Z=12.1 | Z=9.2 | Z=8.3 | Z=7.6



Furlanetto, Sokasian, Hernquist 2003

21 cm fluctuations: z

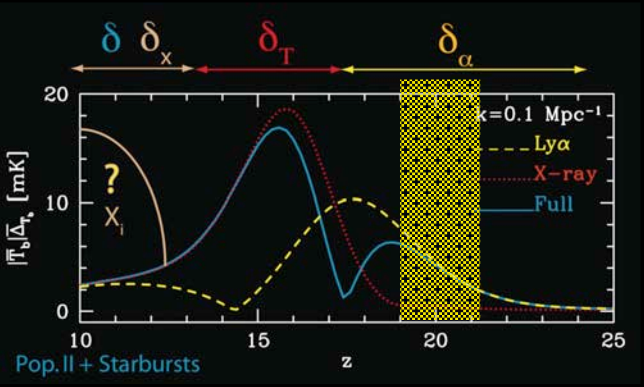
$$\delta_{T_b} = \beta\delta + \beta_x\delta_{x_{HI}} + \beta_T\delta_{T_k} + \beta_\alpha\delta_\alpha - \delta_{\partial v}$$



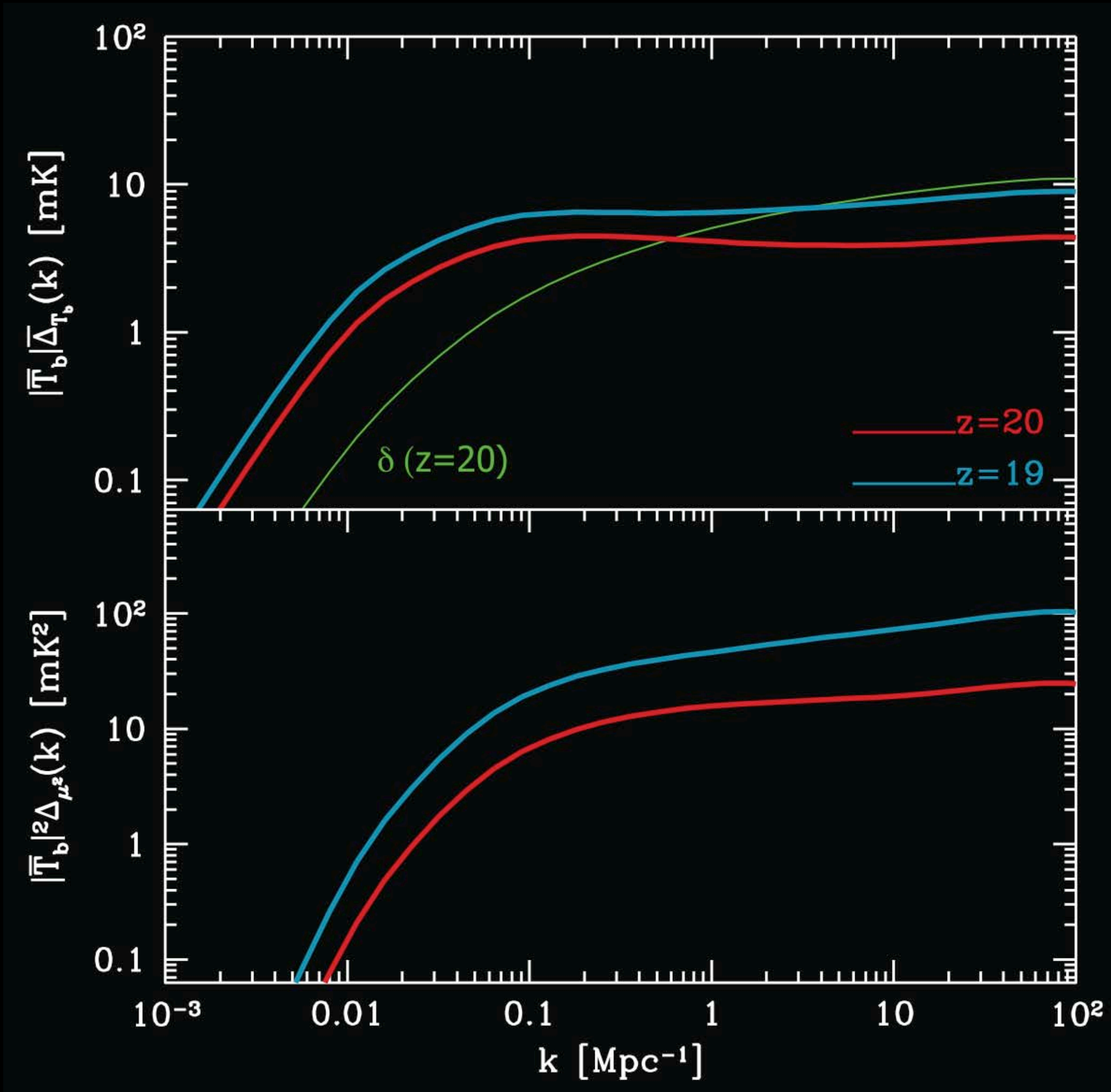
- Exact form very model dependent

Redshift slices: Lyα

z=19-20

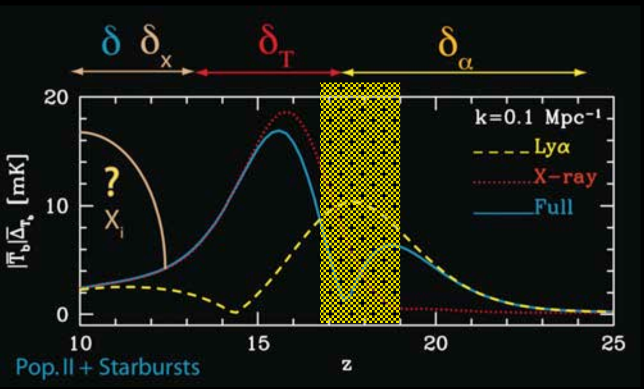


•Pure Lyα fluctuations



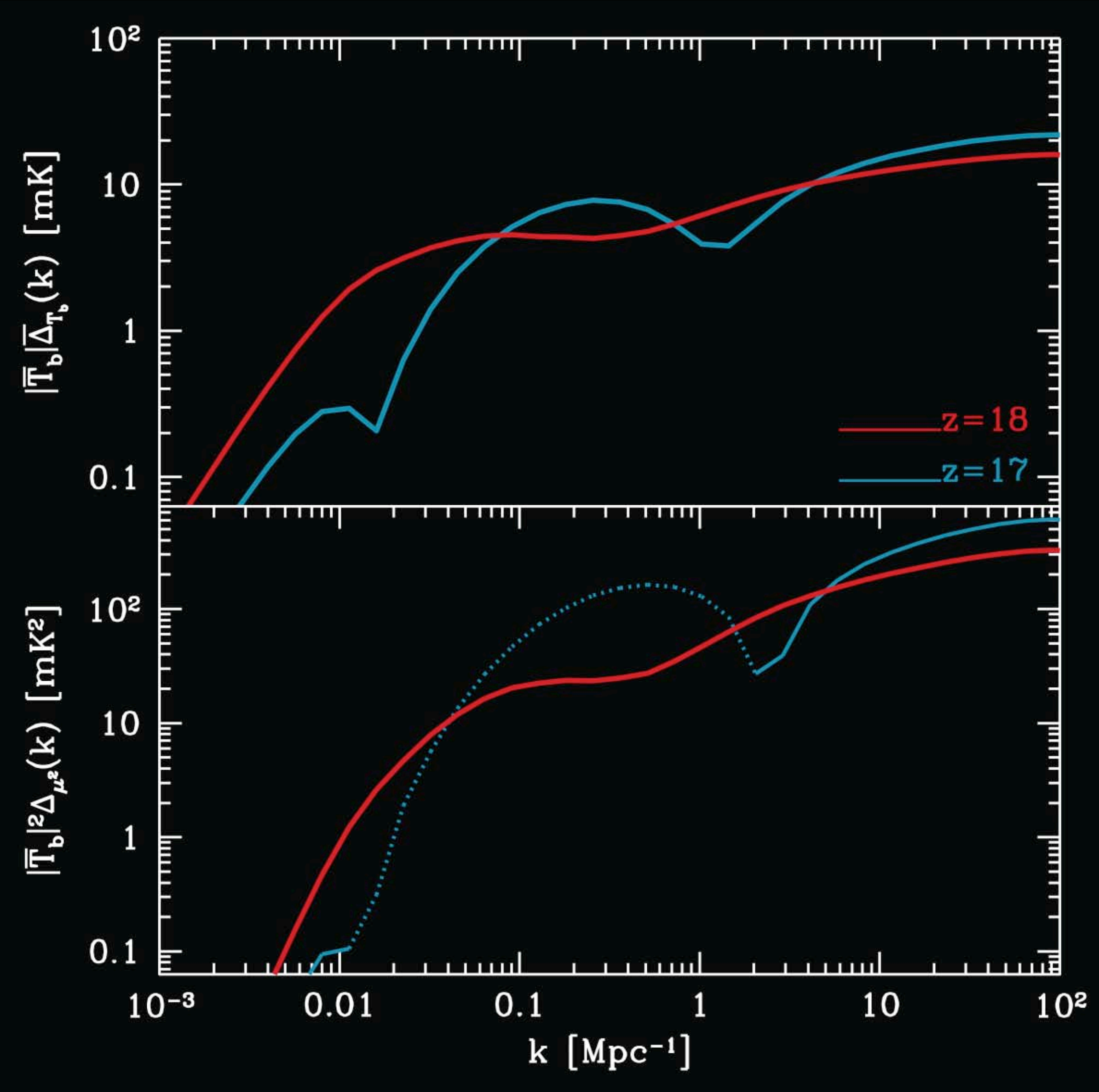
Redshift slices: Lyα/T

z=17-18



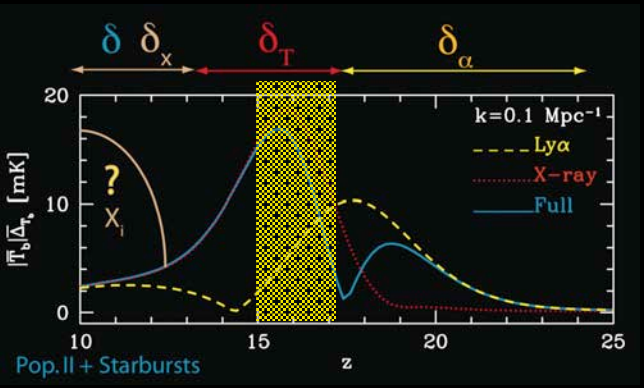
- Growing T fluctuations lead first to dip in Δ_{Tb} then to double peak structure

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

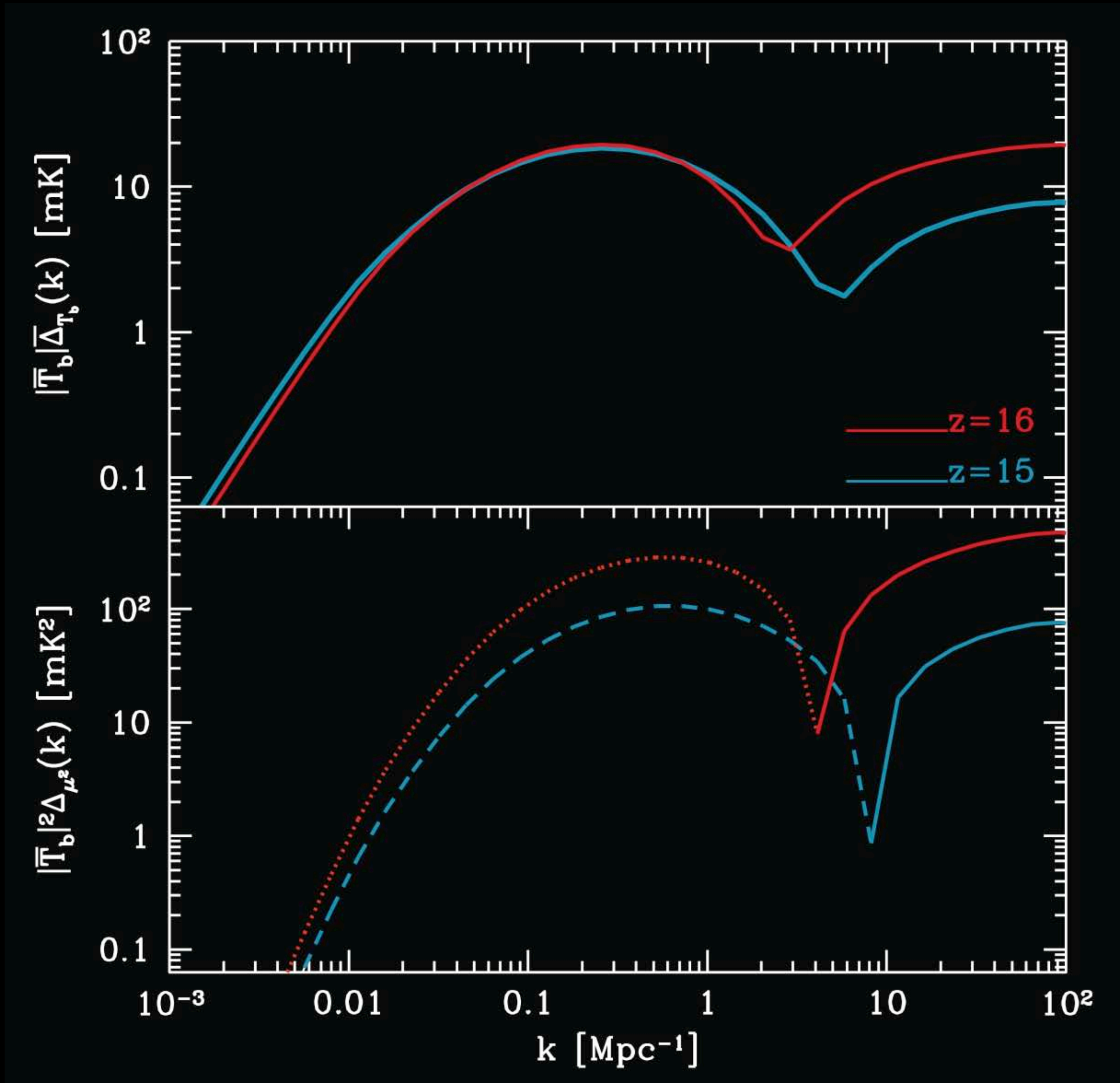


Redshift slices: T

z=15-16

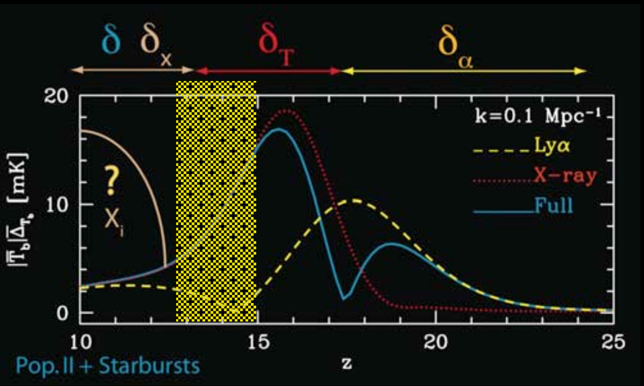


- T fluctuations dominate over Lyα
- Clear peak-trough structure visible
- Δ_{μ^2} <0 on large scales indicates $T_K<T_\gamma$

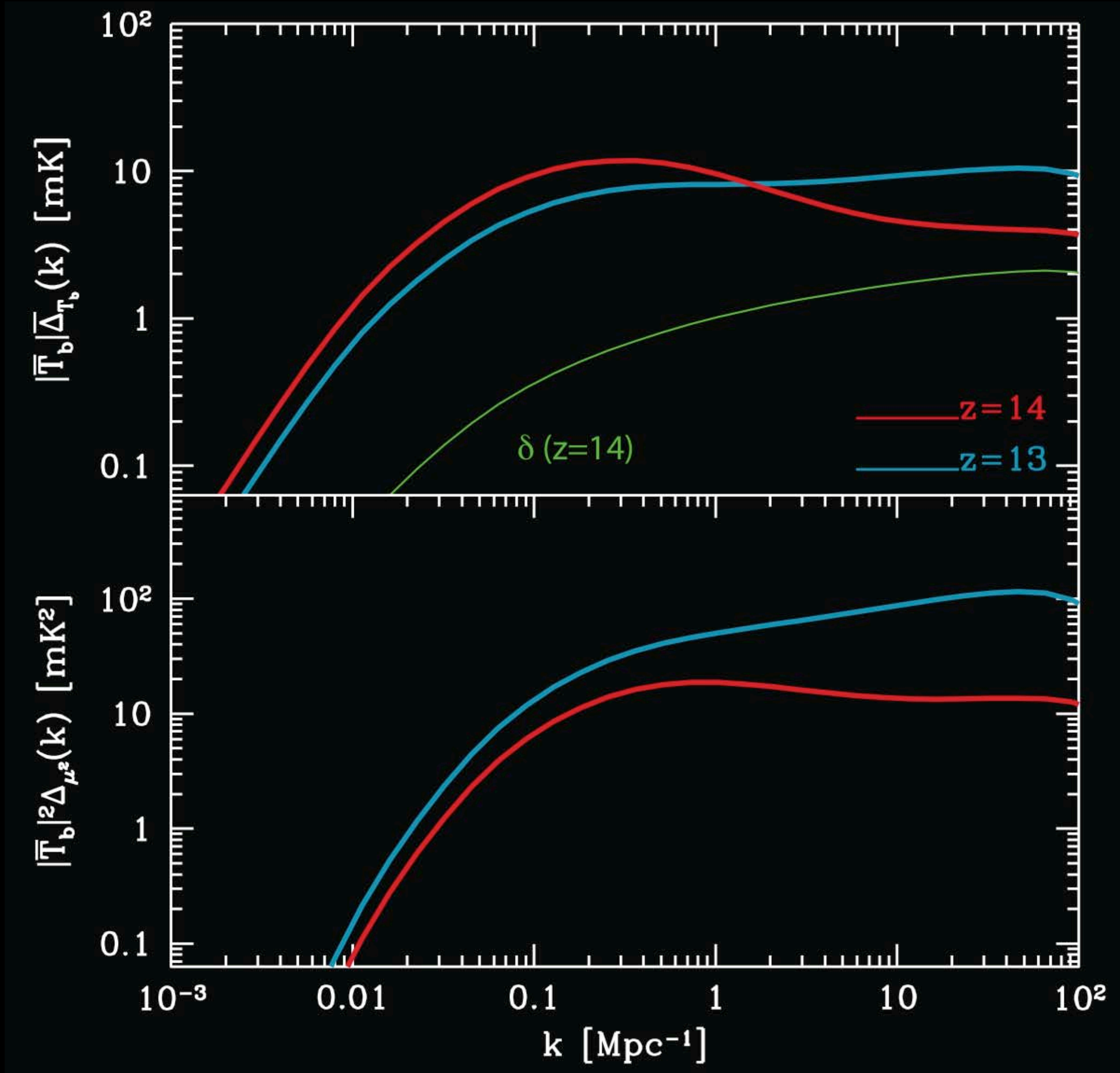


Redshift slices: T/δ

z=13-14

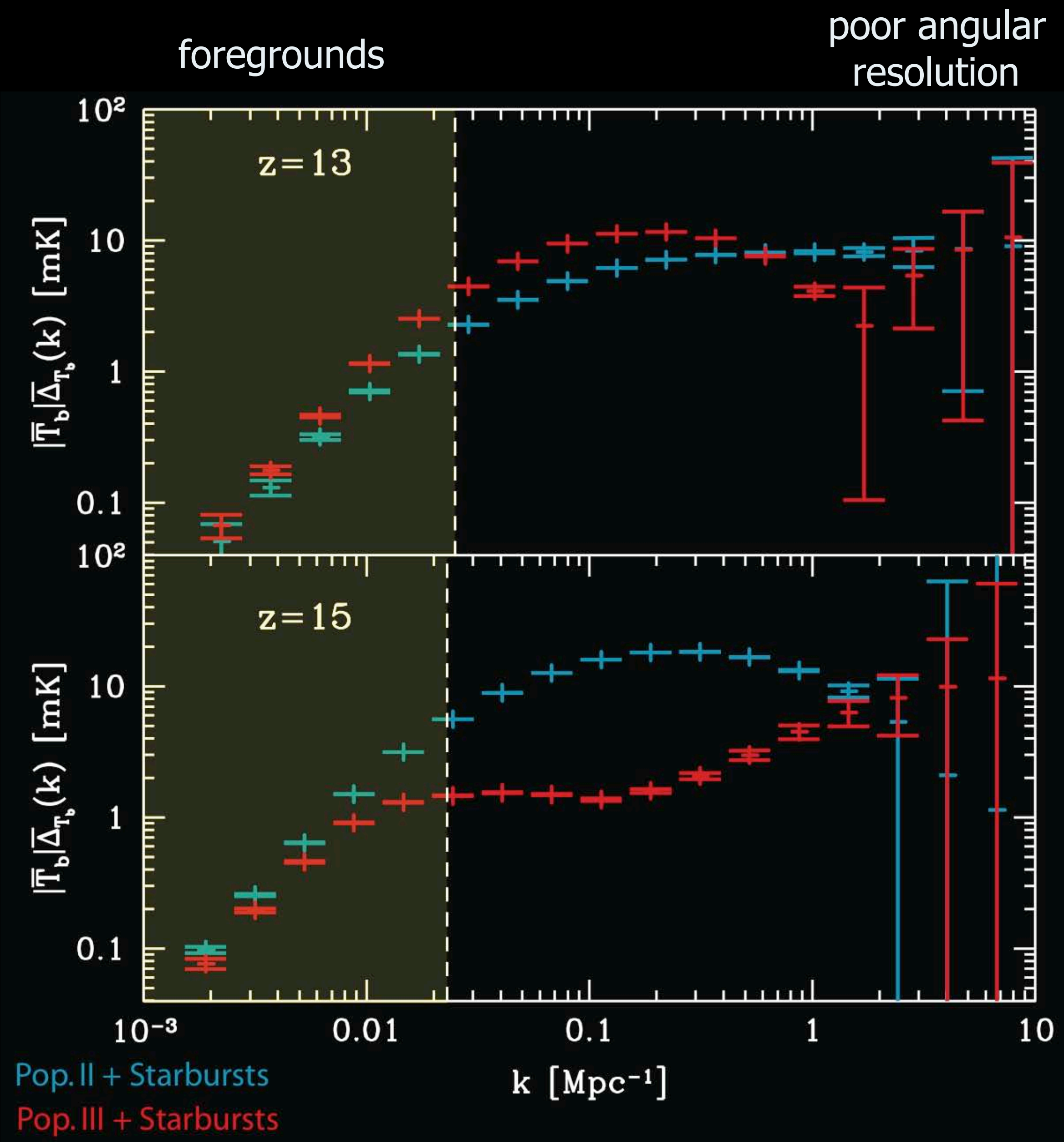


- After $T_K > T_\gamma$, the trough disappears
- As heating continues T fluctuations die out
- X_i fluctuations will start to become important at lower z



Observations

- Need SKA to probe these brightness fluctuations
- Observe scales k=0.025-2 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
- Challenge may be to separate out information
- Foregrounds pose a challenging problem at high z
- Will be important to include spin temperature fluctuations in future simulations
- Many model uncertainties - X-ray reionization?

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