

Descending from on high: Lyman series cascades and spin-kinetic temperature coupling in the 21cm line

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Overview

- 21cm studies provide a way of probing the first galaxies (**Barkana & Loeb 2004**)
- Fluctuations in the Lyman α flux lead to 21cm fluctuations via the Wouthysen-Field effect
- Previous calculations have assumed all photons emitted between Lyman β and Lyman limit are converted into Lyman α photons
- Quantum selection rules mean that some photons will be lost due to the $2S \rightarrow 1S$ two photon decay
- Here consider atomic physics to calculate the details of the cascade process and illustrate the effect on the 21cm power spectra

21cm Basics

- Observe difference of spin temperature against CMB temperature

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

$$\frac{1_1 S_{1/2}}{1_0 S_{1/2}} = \frac{n_1}{n_0} \quad n_1/n_0 = 3 \exp(-h\nu_{10}/kT_s)$$

- Spin temperature determined by radiative, collisional x_c and Wouthysen-Field x_α coupling
- Fluctuations: density, Lyman α flux, x_{HI} , velocity gradient

$$\delta_{T_b} = \beta\delta + \frac{x_\alpha}{\tilde{x}_{tot}} \delta_{x_\alpha} + \cancel{\delta_{x_{HI}}} - \delta_{d_r v_r}$$

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

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 2004

Wouthysen-Field Effect

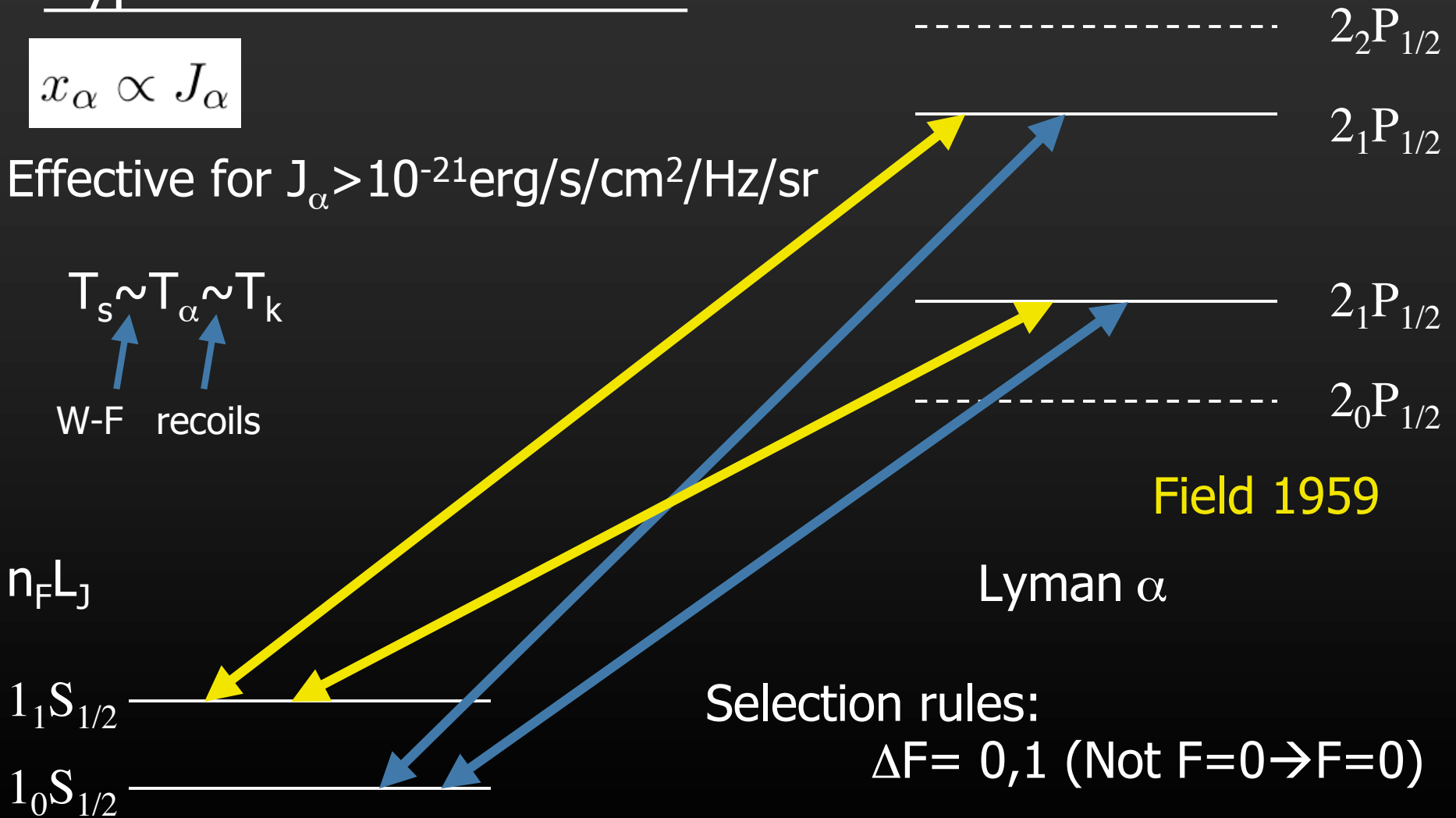
Hyperfine structure of HI

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

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

$$T_s \sim T_{\alpha} \sim T_k$$

↑ ↑
W-F recoils



Field 1959

Lyman α

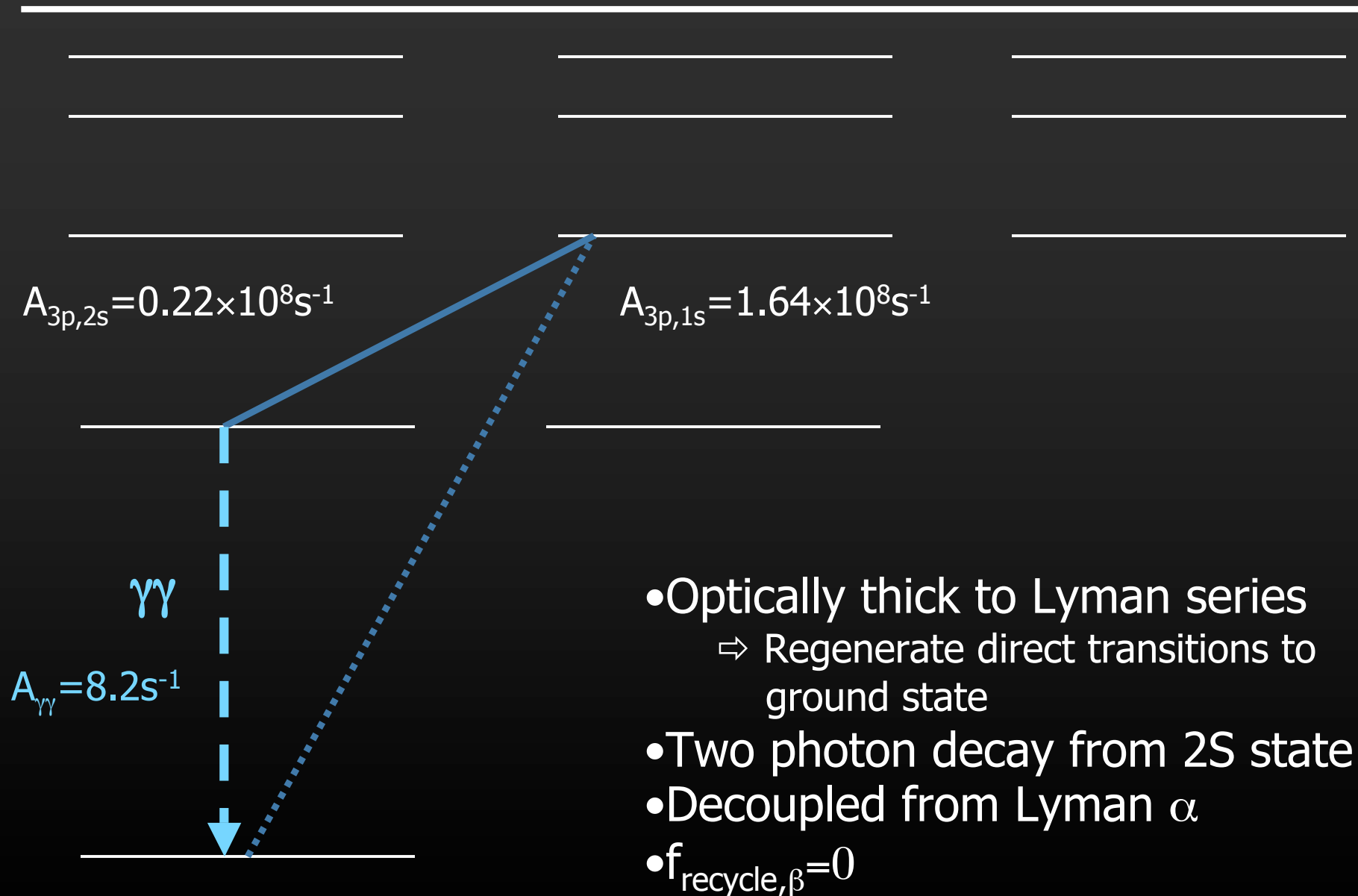
Selection rules:

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

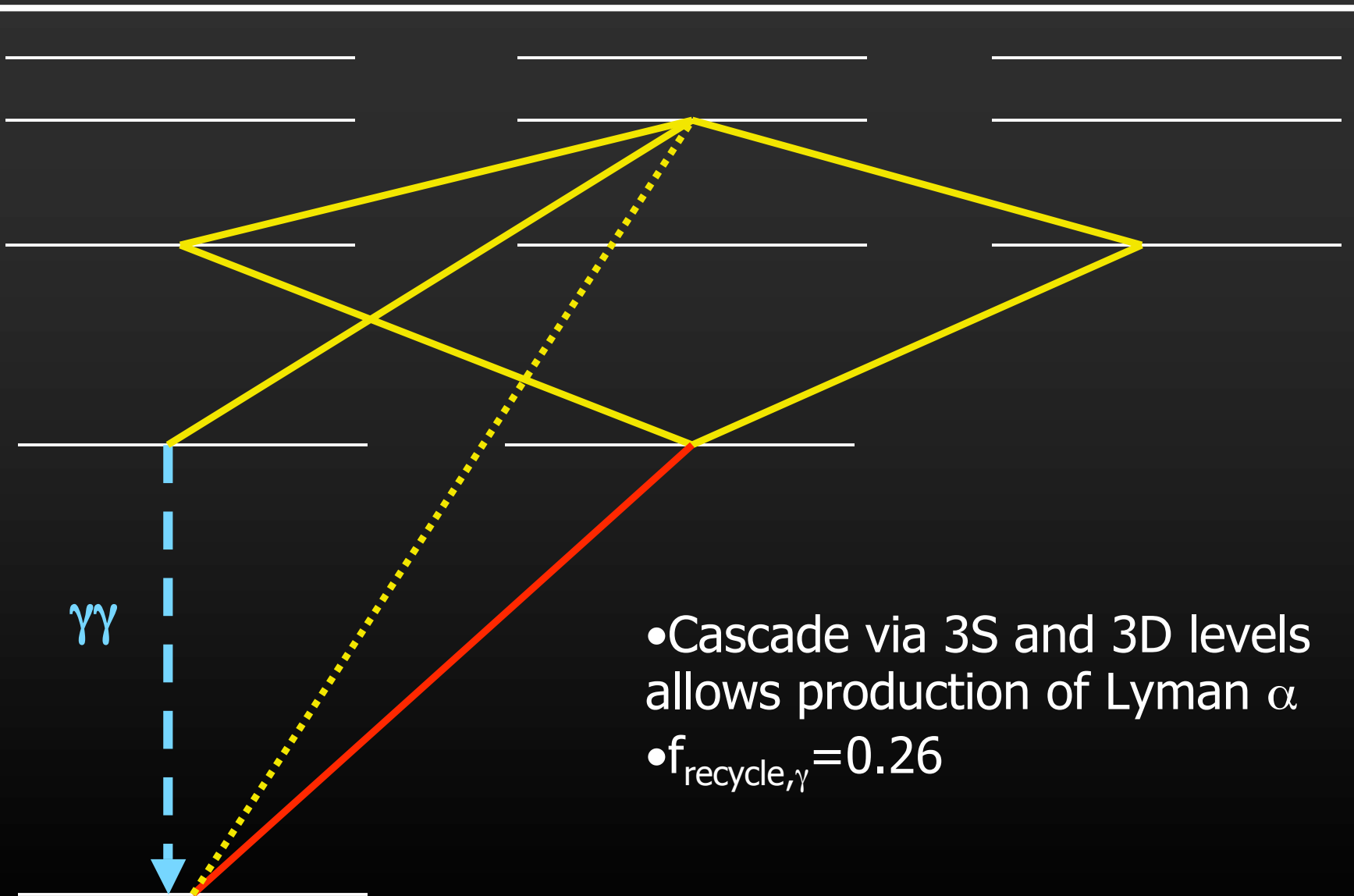
Higher Lyman Series

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

Lyman β

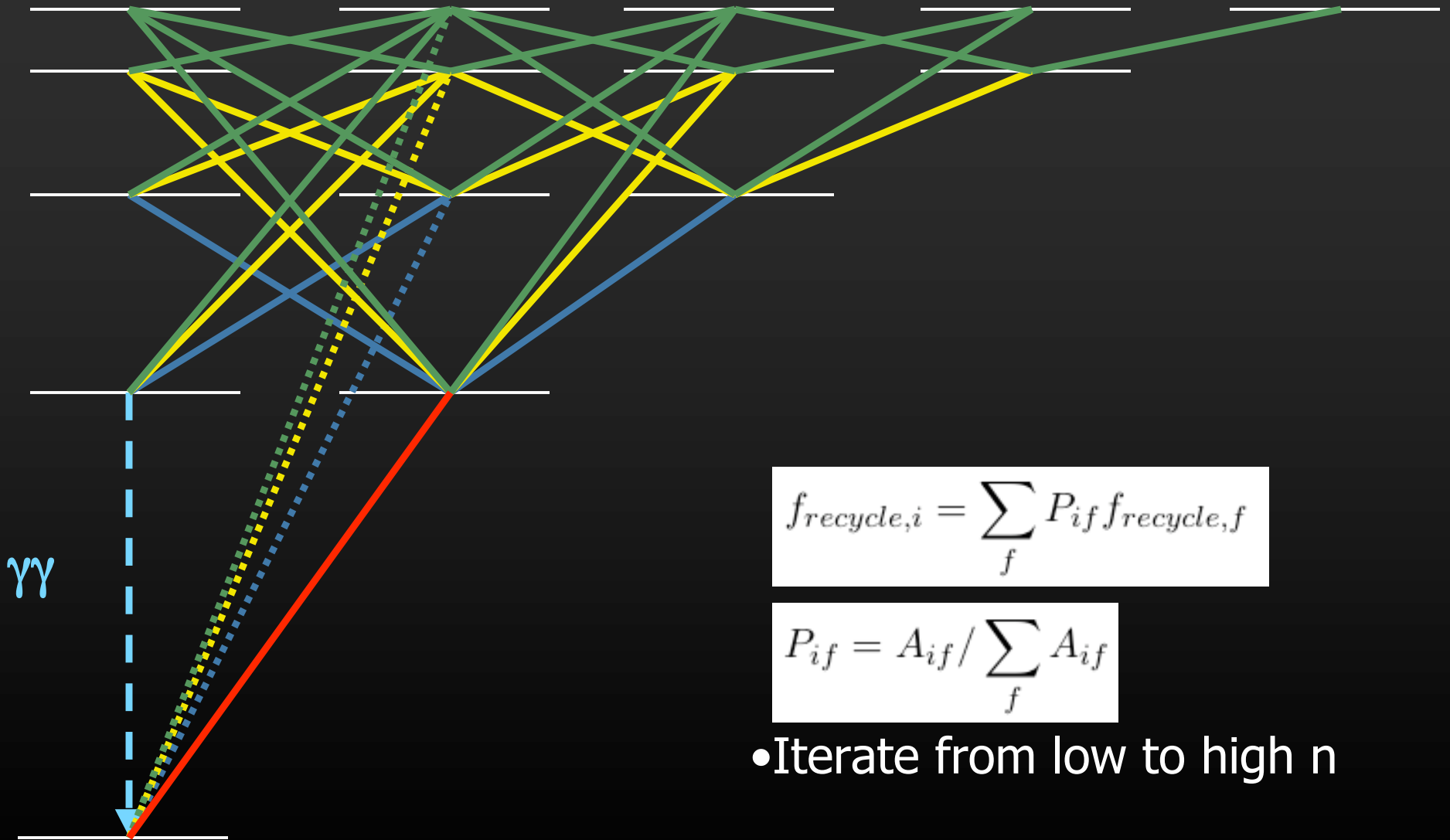


Lyman γ



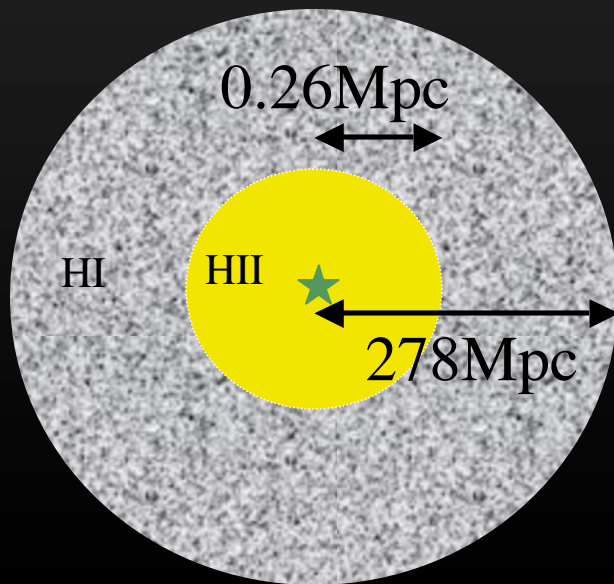
- Cascade via 3S and 3D levels allows production of Lyman α
- $f_{\text{recycle},\gamma} = 0.26$

Calculating Recycling Fractions



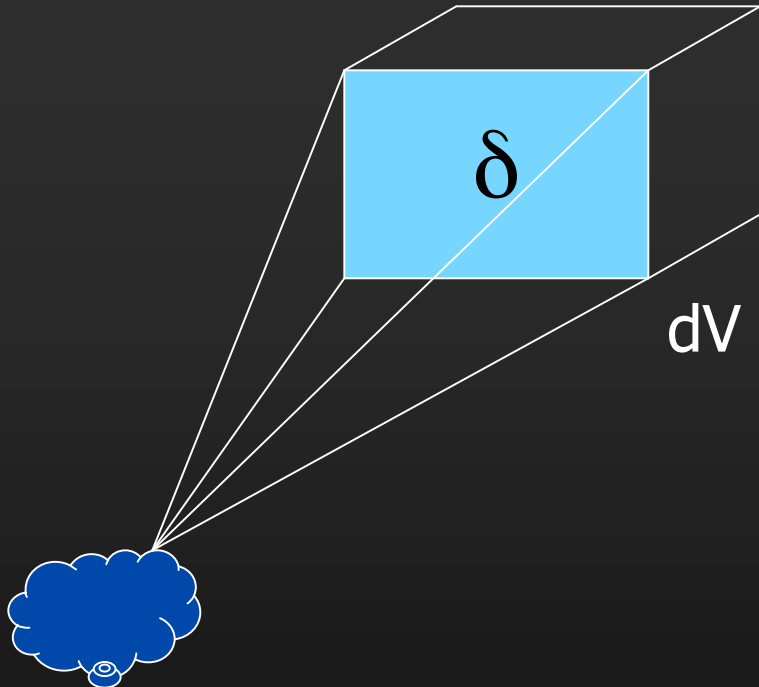
Lyman Series Cascades

	α	β	γ	δ	∞	ν
No. Photons: (pop III)	2670	965	451	810		<u>Total</u> 4896
f_{recycle} :	1.0	0	0.26	0.35		0.62
Ly α Contribution:	2670	0	118	268		3056
Shell size @ $z = 20$ (Mpc):	278	90	40	22		



- Photons redshift until they hit Lyman series resonance
- $\sim 62\%$ emitted photons recycled into Lyman α
- Contribution limited to scales within Lyman α range and outside HII region of galaxy $\Rightarrow n_{\text{max}} = 23$

Origin of Density Fluctuations



- Overdense region modifies observed flux from region dV

$$dA \rightarrow \left(1 + \frac{2}{3}\delta\right)dA$$

$$n \rightarrow (1 + b(z)\delta)n$$

$$dz \rightarrow (1 + \delta_{d_r v_r})dz$$

Barkana & Loeb 2004

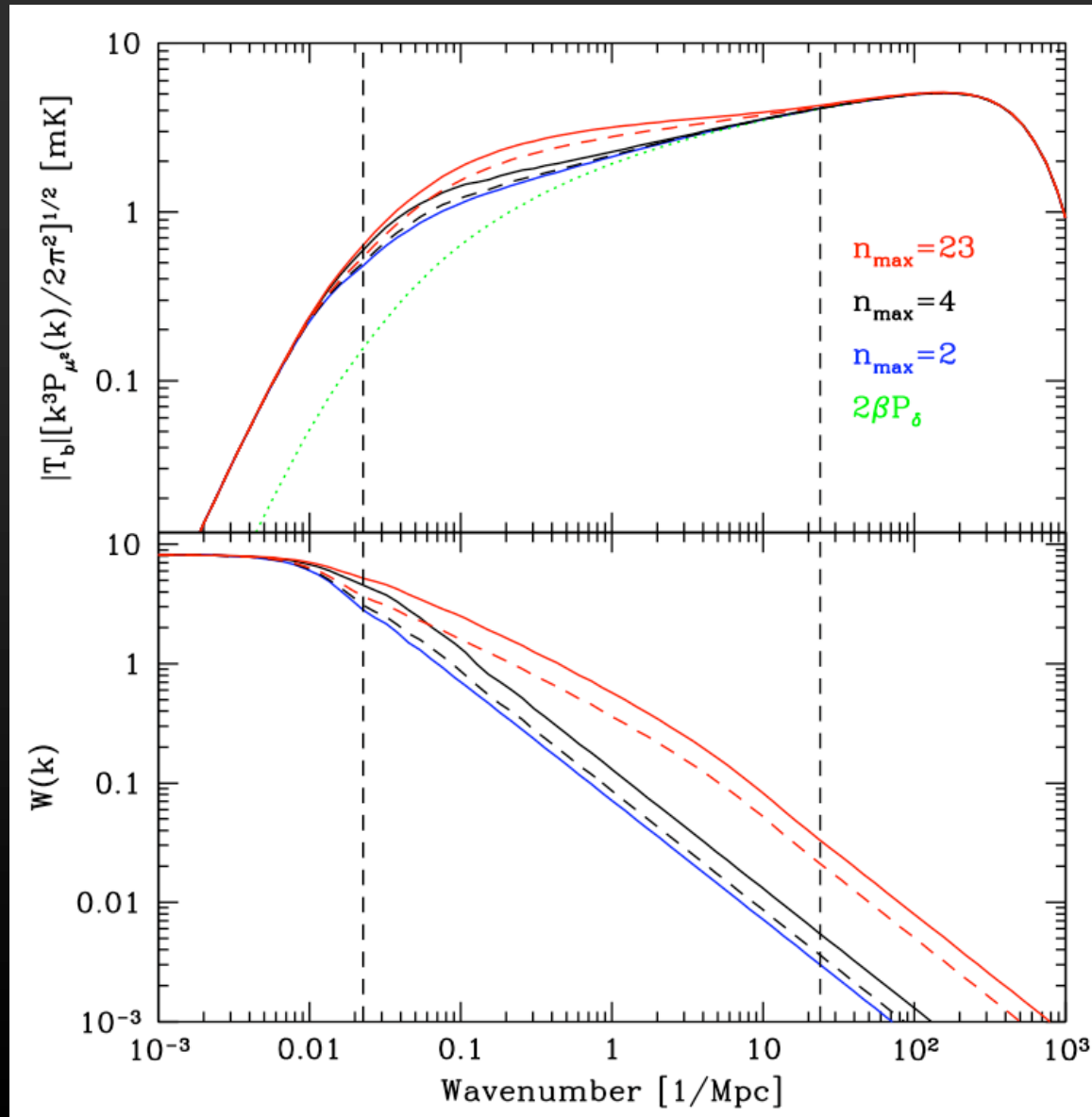
- Relate Ly α fluctuations to overdensities

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

- Extract power spectrum

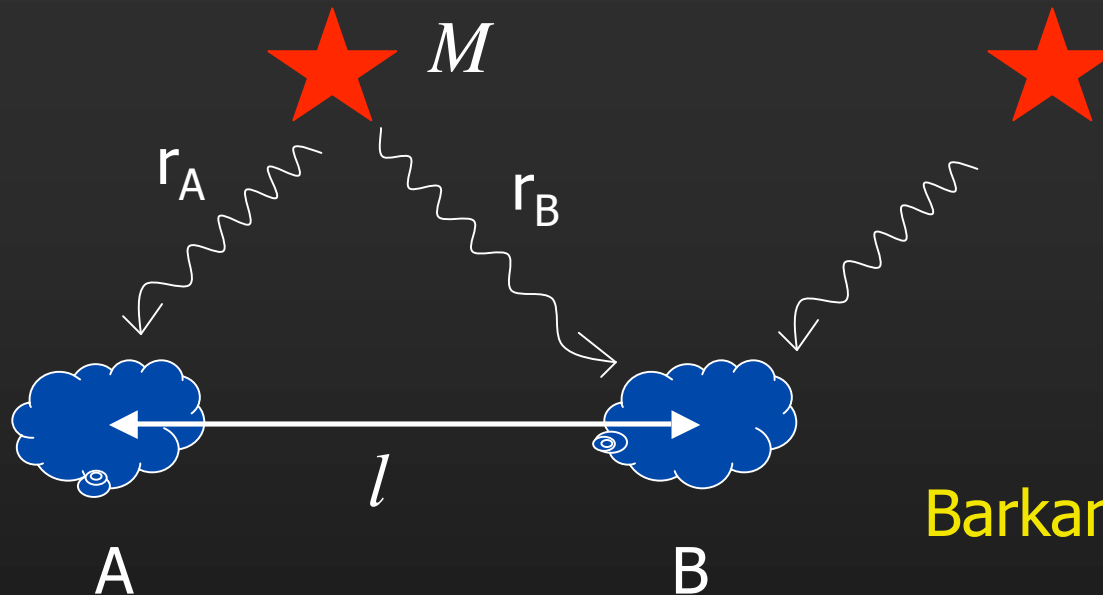
$$P_{\mu^2}(k) = 2P_\delta(k) \left[\beta + \frac{x_\alpha}{\tilde{x}_{tot}} W(k) \right]$$

Density Fluctuations



- Excess power on scales less than 24 Mpc^{-1}
- Recover shape of matter power spectrum on small scales
- Cutoffs from width of 21cm line and pressure support on small scales
- Fluctuation \propto flux
 \Rightarrow Reduction ~ 0.65

Origin of Poisson Fluctuations



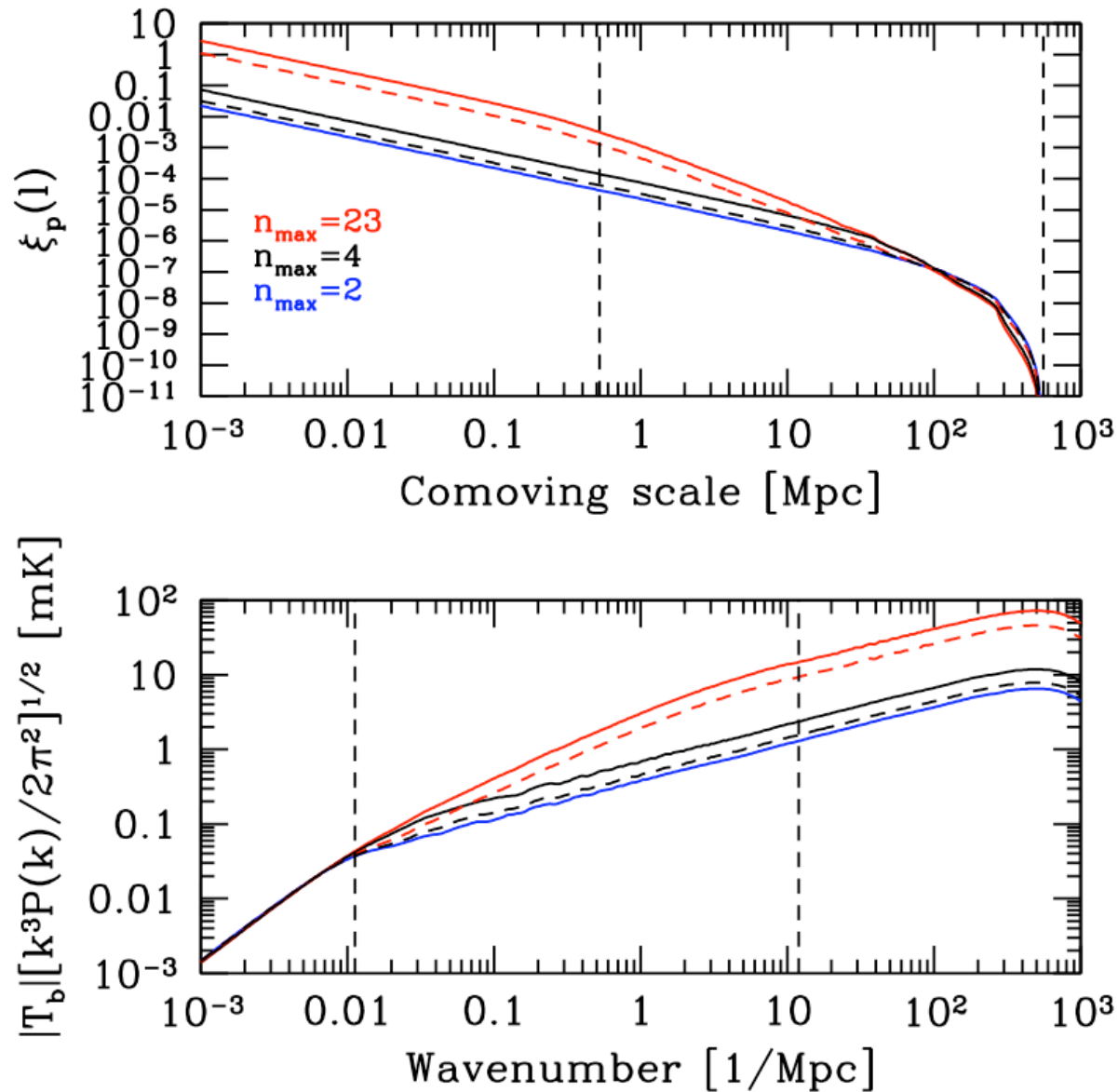
Barkana & Loeb 2004

- Fluctuations independent of density perturbations

$$P_{un-\delta}(k) \equiv P_{\mu^0} - \frac{P_{\mu^2}^2}{4P_{\mu^4}} = \left(\frac{x_{\alpha}}{\tilde{x}_{tot}} \right)^2 \left(P_{\alpha} - \frac{P_{\delta-\alpha}^2}{P_{\delta}} \right)$$

- Small number statistics
- Different regions see some of the same sources though at different times in their evolution

Poisson Fluctuations



- Higher Lyman transitions increase correlation on small scales

- No correlation on scales larger than twice Ly α range

- Excess power in wavenumbers larger than 0.01 Mpc^{-1}

- Fluctuation $\propto \text{flux}^2$
 \Rightarrow Reduction ~ 0.4

Conclusions

- Including correct atomic physics is important for extracting astrophysical information from 21cm fluctuations
- Cascade generated Lyman α photons increase the theoretical signal, but not as much as has previously been thought
- $\sim 62\%$ emitted Lyman series photons recycled into Lyman α
- Recycling fractions are straightforward to calculate and should be included in future work on this topic
- Basic atomic physics encoded in characteristic scales