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 <u>all</u> 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->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

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

$1_1S_{1/2}$ ———— n_1

$1_0S_{1/2}$ ———— n_0

$n_1/n_0 = 3\exp(-h\nu_{10}/kT_s)$

- 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

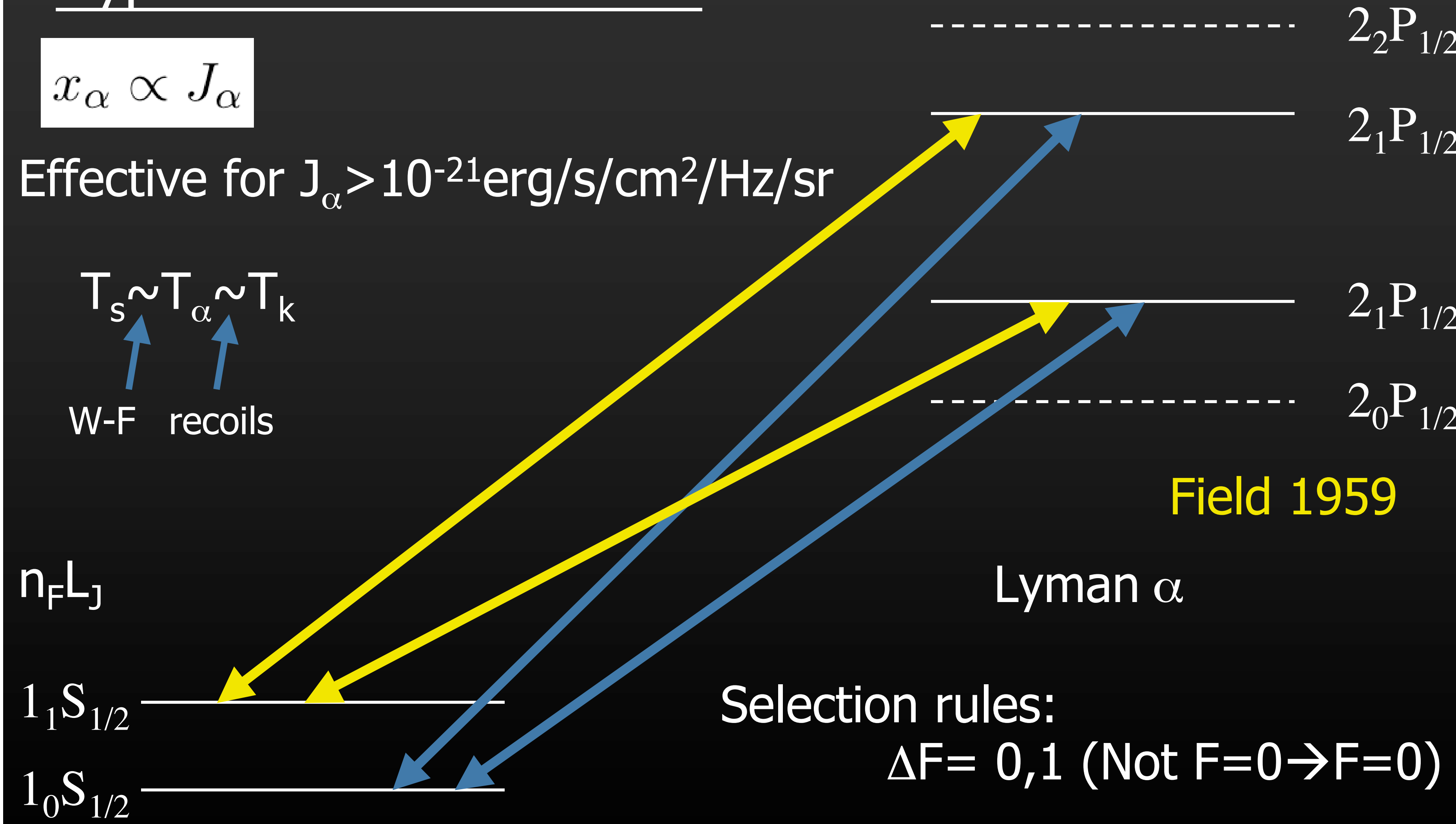
Hyperfine structure of HI

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

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

$T_s \sim T_\alpha \sim T_k$

W-F recoils



Field 1959

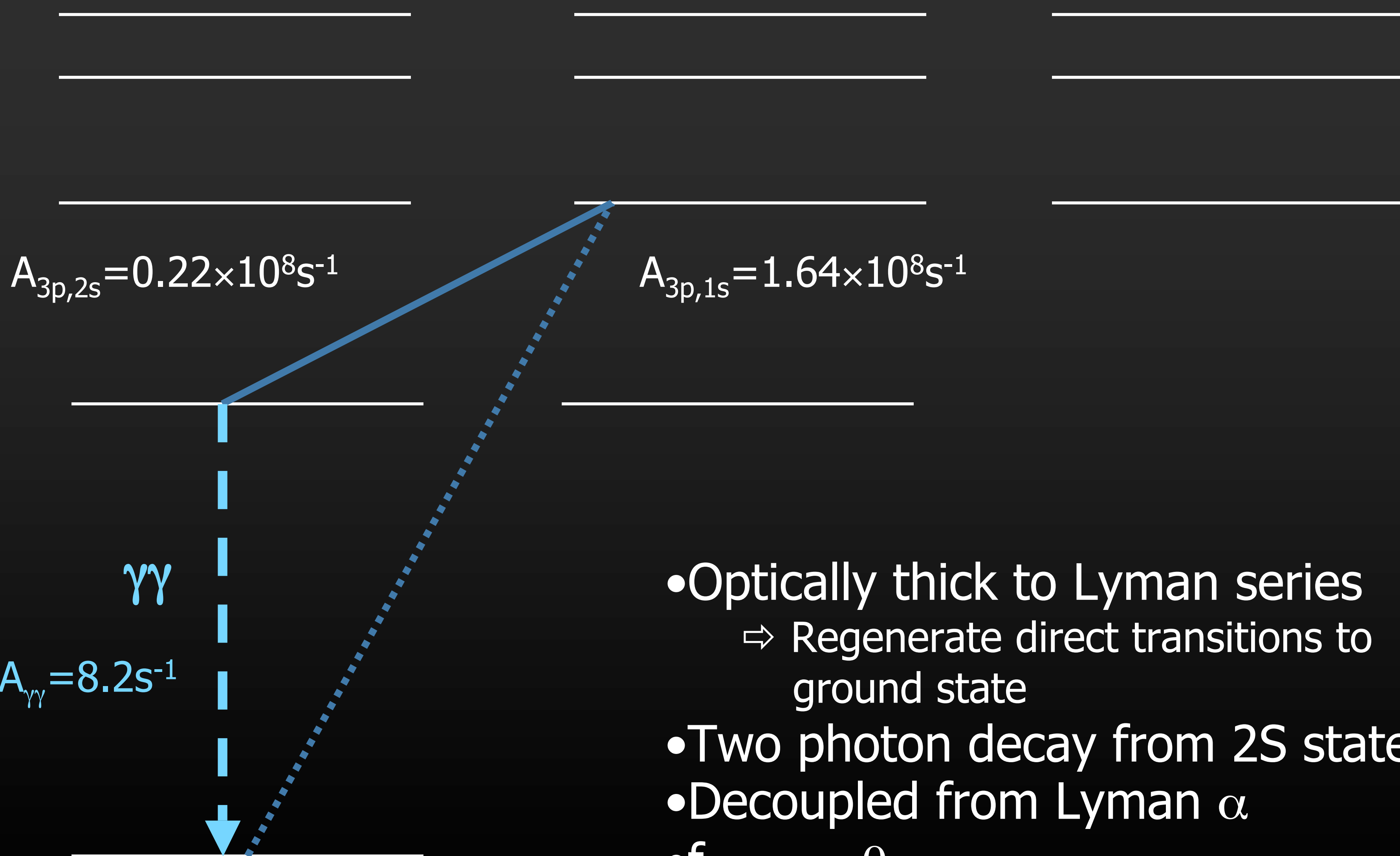
Selection rules:

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

Higher Lyman Series

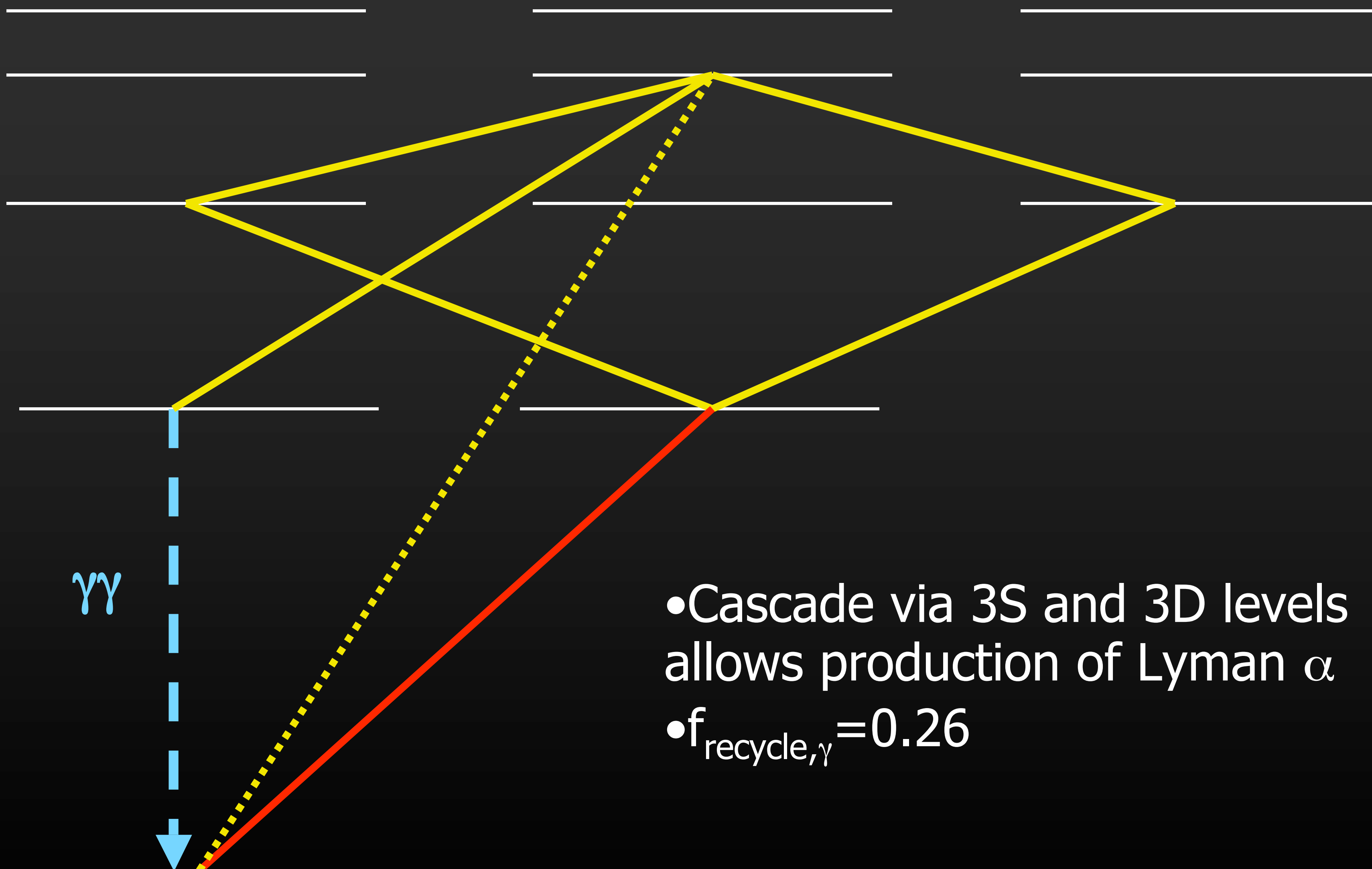
- Two possible contributions
  - Direct pumping: Analogy of the W-F effect
  - Cascade: Excited state decays through cascade to generate Lyα
- Direct pumping is suppressed by the possibility of conversion into lower energy photons
  - Ly α scatters ~10^6 times before redshifting through resonance
  -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

Lyman β



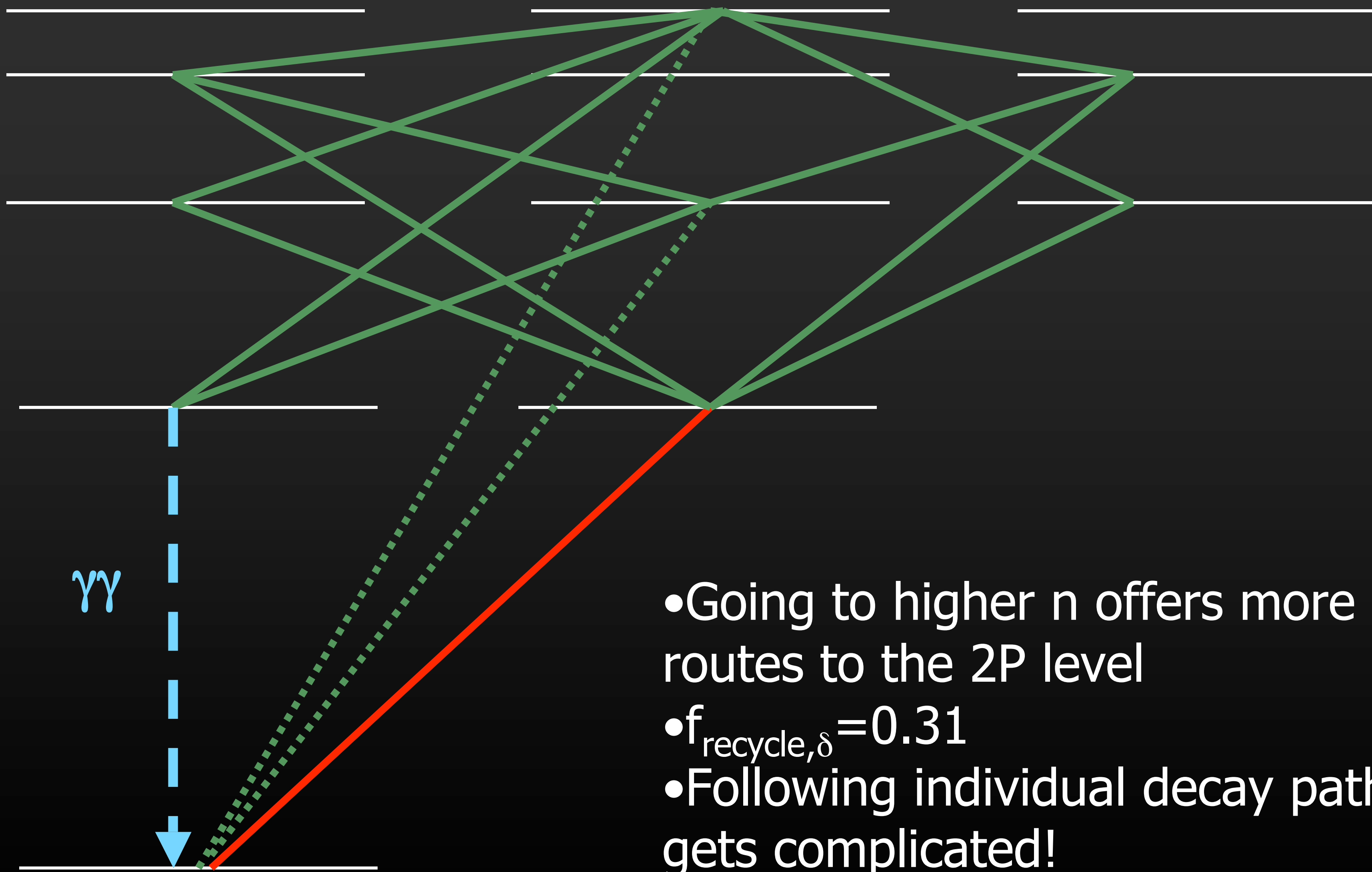
- Optically thick to Lyman series
  - ⇨ Regenerate direct transitions to ground state
- Two photon decay from 2S state
- Decoupled from Lyman α
- $f_{recycle,\beta}=0$

Lyman γ



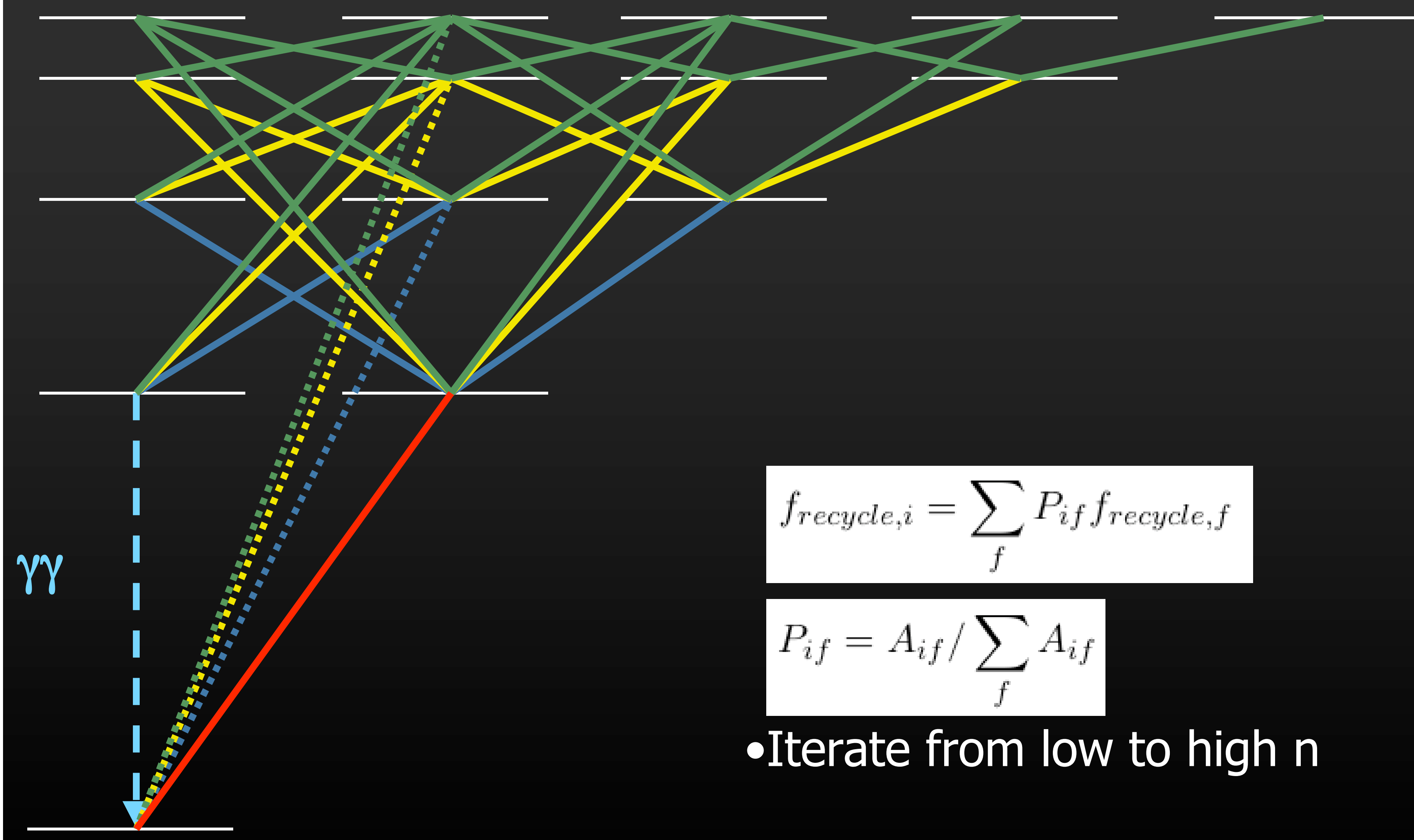
- Cascade via 3S and 3D levels allows production of Lyman α
- $f_{recycle,\gamma}=0.26$

Lyman δ



- Going to higher n offers more routes to the 2P level
- $f_{recycle,\delta}$=0.31
- Following individual decay paths gets complicated!

Calculating Recycling Fractions

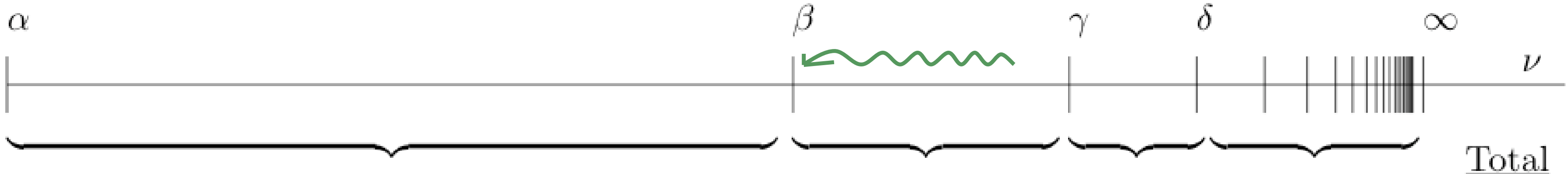


$$f_{recycle,i} = \sum_f P_{if} f_{recycle,f}$$

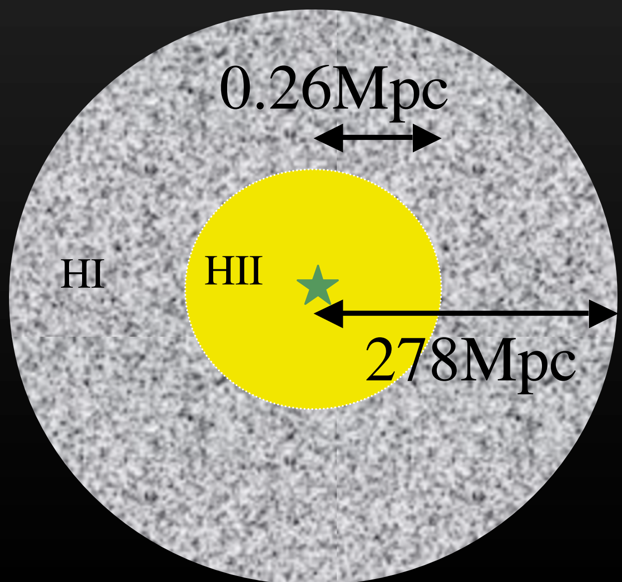
$$P_{if} = A_{if} / \sum_f A_{if}$$

- Iterate from low to high n

Lyman Series Cascades

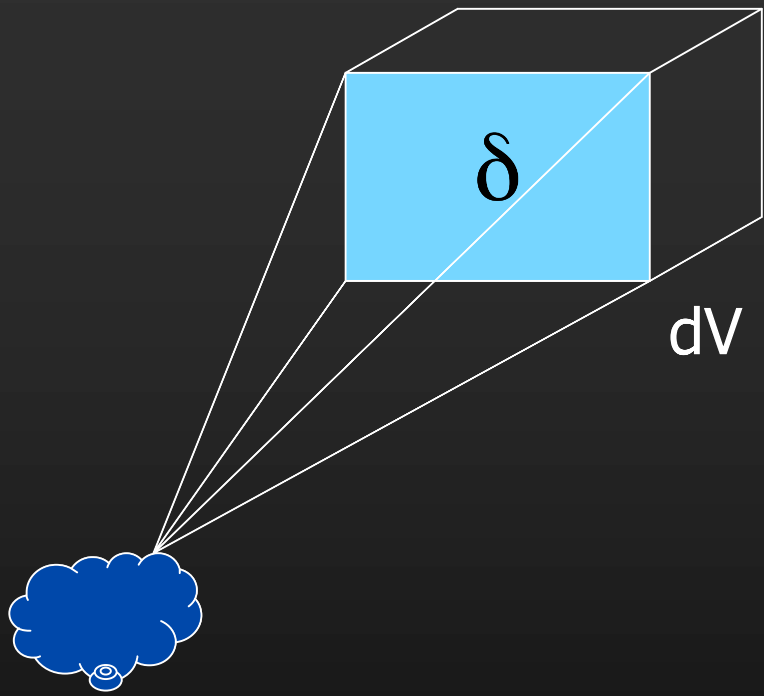


					Total
No. Photons: (pop III)	2670	965	451	810	4896
$f_{recycle}$:	1.0	0	0.26	0.35	0.62
Lyα Contribution:	2670	0	118	268	3056
Shell size @$z = 20$ (Mpc):	278	90	40	22	



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

Origin of Density Fluctuations



- Overdense region modifies observed flux from region dV

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

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

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

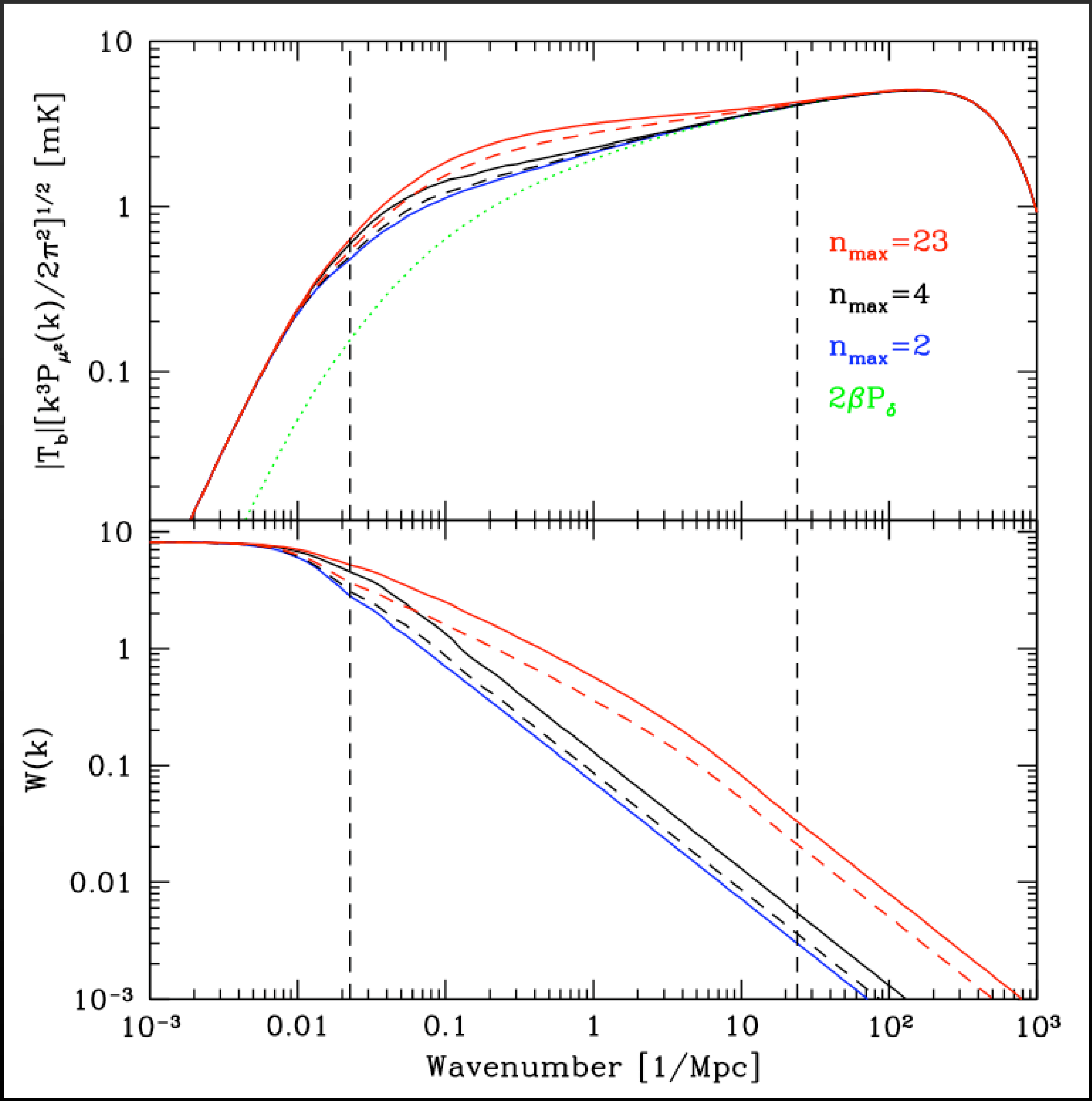
Barkana & Loeb 2004

- Relate Ly α fluctuations to overdensities $\delta_{x_\alpha}(\mathbf{k}) = W(k)\delta(\mathbf{k})$

- Extract power spectrum

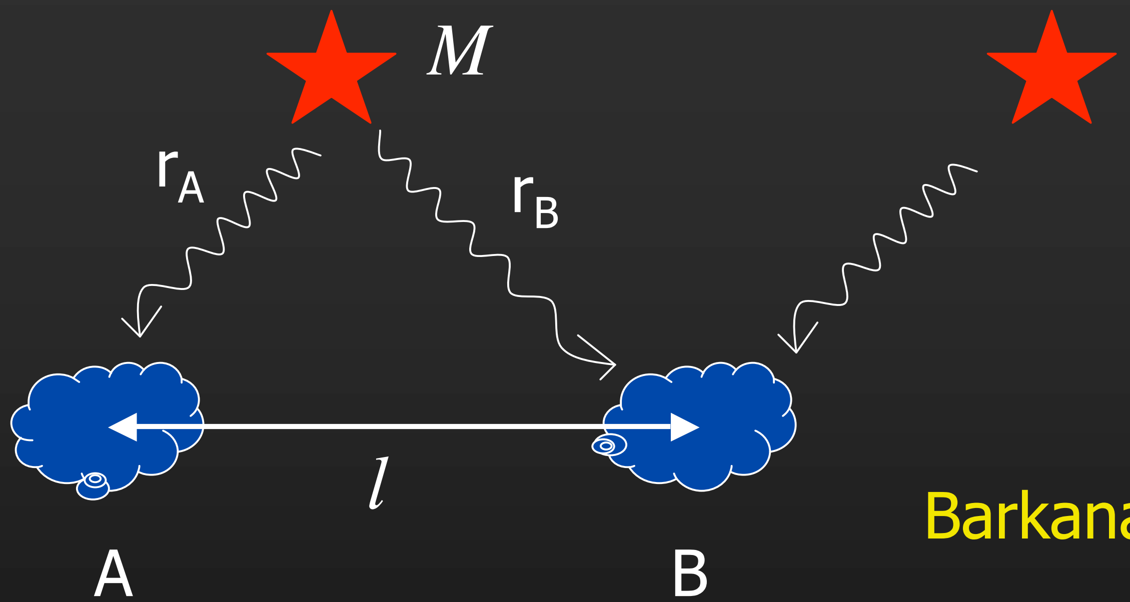
$$P_{\mu^2}(k) = 2P_\delta(k)\left[\beta + \frac{x_\alpha}{\tilde{x}_{tot}} W(k)\right]$$

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 ∝ flux
  ⇨ Reduction ~ 0.65

Origin of Poisson Fluctuations



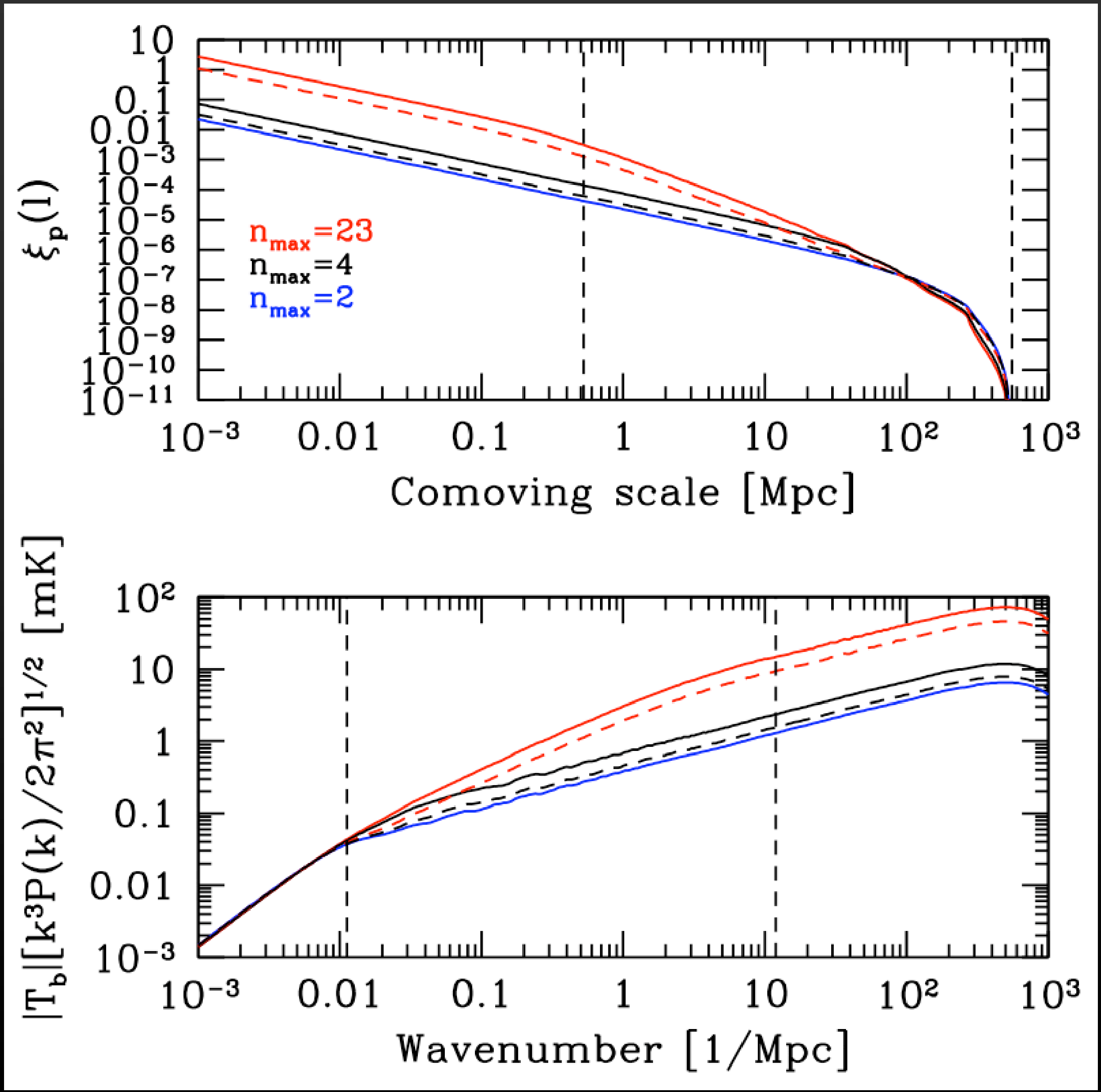
Barkana & Loeb 2004

- 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 $\propto$ flux^2
  ⇨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
- ~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