Candidacy Talk

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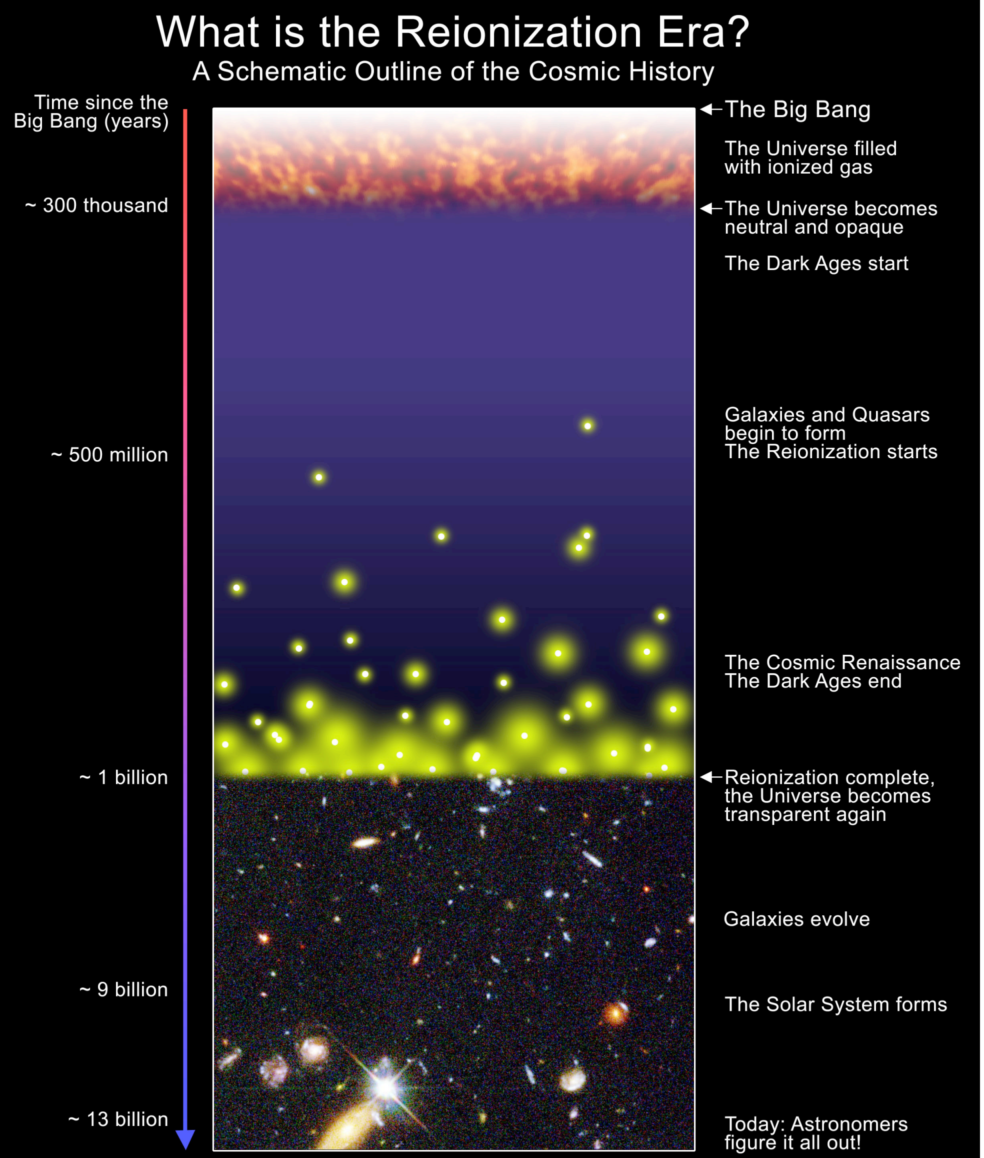
Overview

- Tensor modes and the CMB
- Spin-kinetic temperature coupling in the 21 cm line
- Imprints of reionization in the galaxy power spectrum
- Future work



S.G. Djorgovski et al. & Digital Media Center, Caltech

Cosmic microwave background fluctuations from gravitational waves: An analytic approach

Jonathan Pritchard
Marc Kamionkowski
(Caltech)

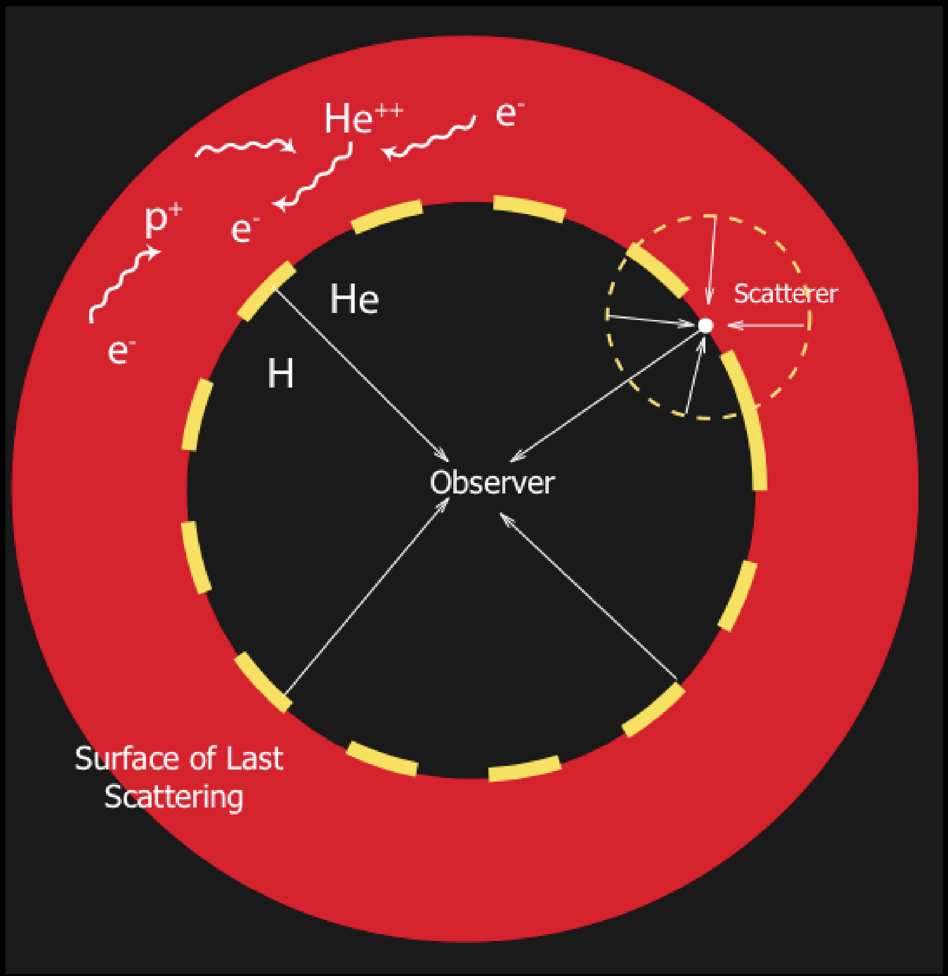
Annals of Physics 318 (2005) 2-36

Overview

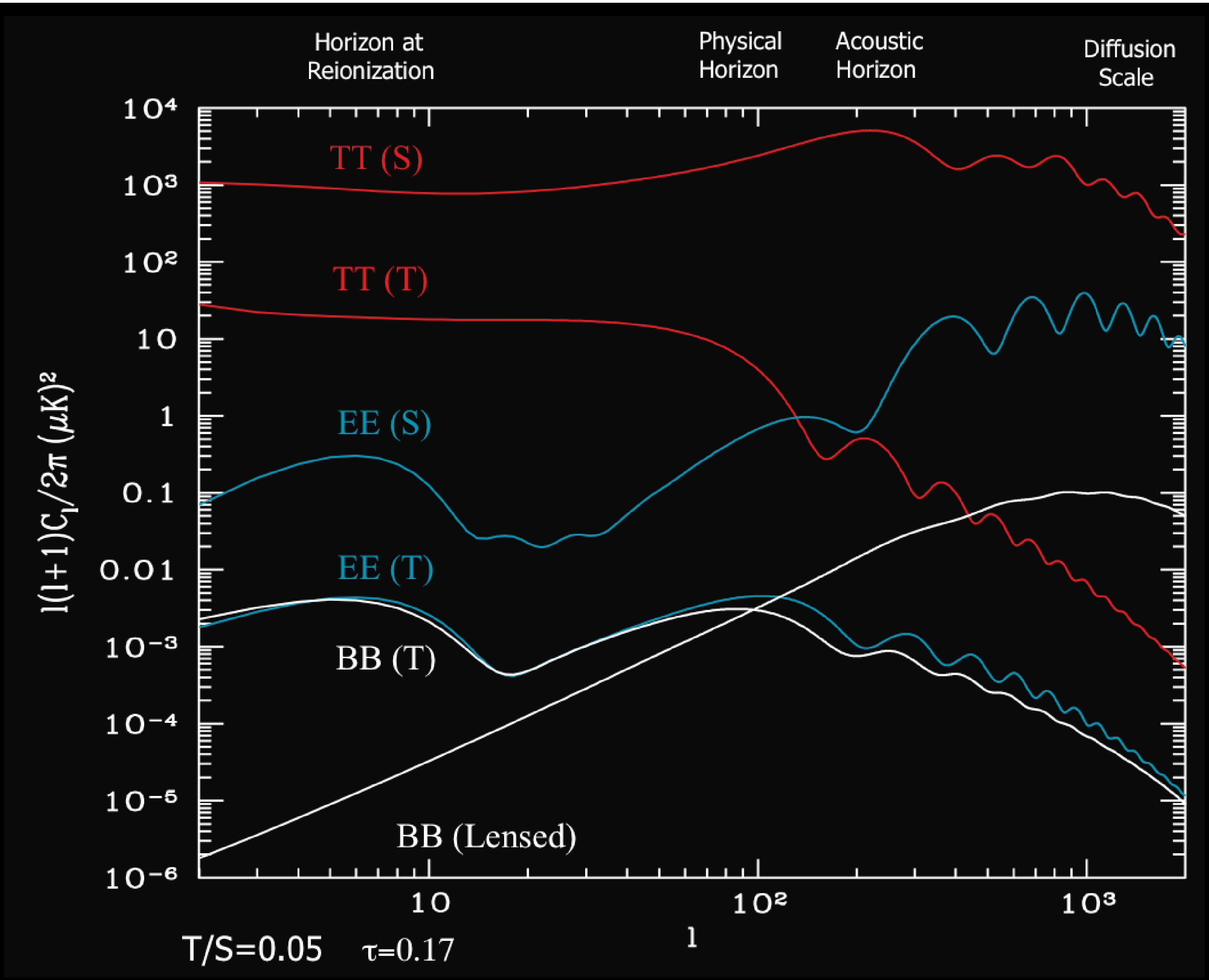
- Gravitational waves produced during inflation provide a possible probe of the very early universe.
- Much experimental interest in detecting the B mode polarisation signal.
- Analytic understanding of the form of the power spectrum is useful in providing intuition.
- Will describe the various elements that go into calculating the tensor power spectra and describe useful analytic approximations.
- Hope to bring out the physics behind the maths.

The Cosmic Microwave Background

- Mechanical coupling of baryons and photons via Thompson scattering ends with recombination
- Photons scatter for last time then free-stream to observer
- CMB contains frozen snapshot of perturbations at surface of last scattering

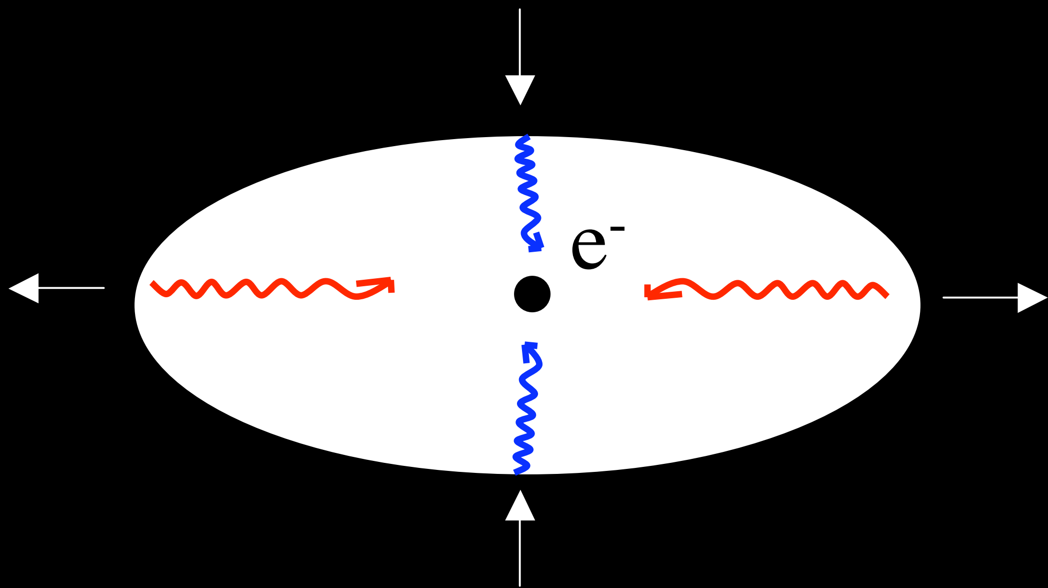


Power Spectra



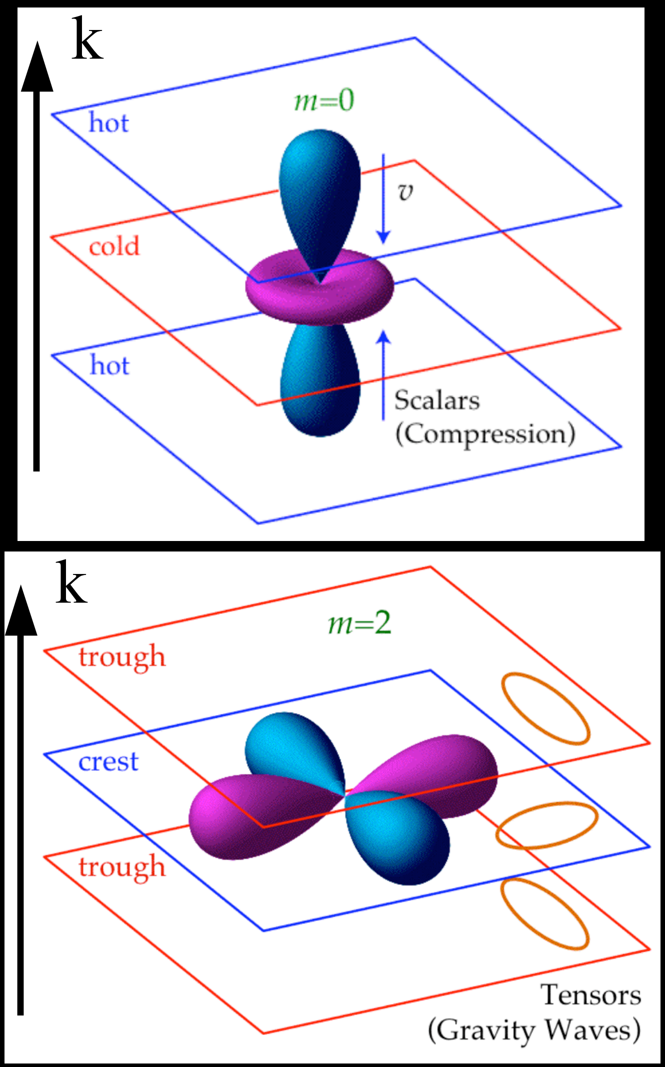
Temperature Anisotropies

- Local distortion of space generates temperature quadrupole



- Decay of gravitational waves after horizon entry leads to net increase in temperature
"Integrated Sachs-Wolfe Effect" (ISW)

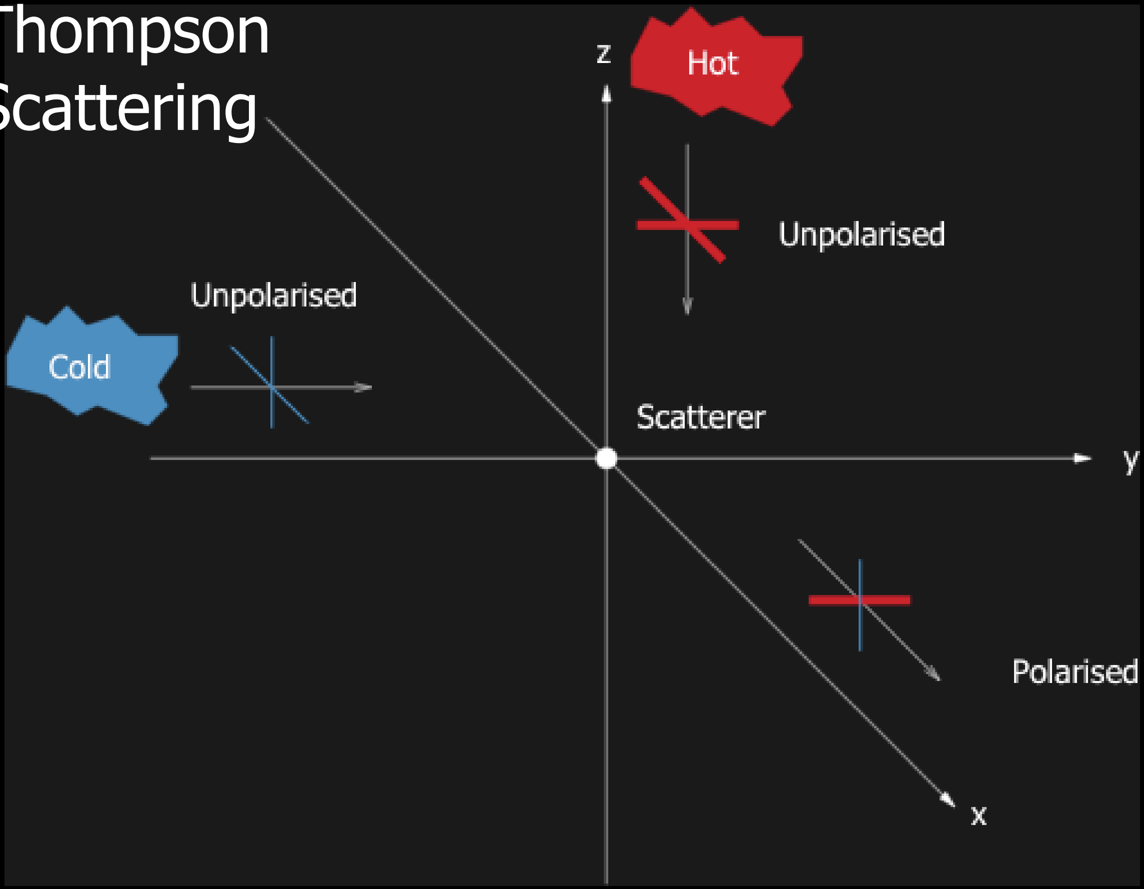
- L=2 quadrupoles



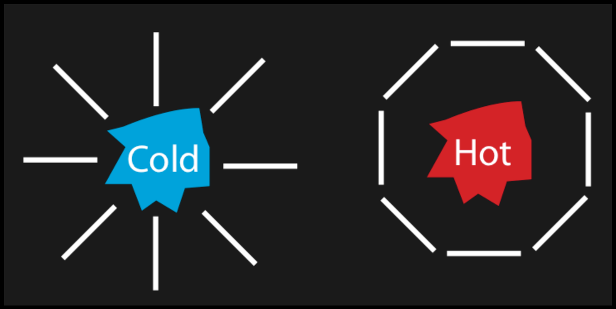
Hu & White 1997

Polarisation of the CMB

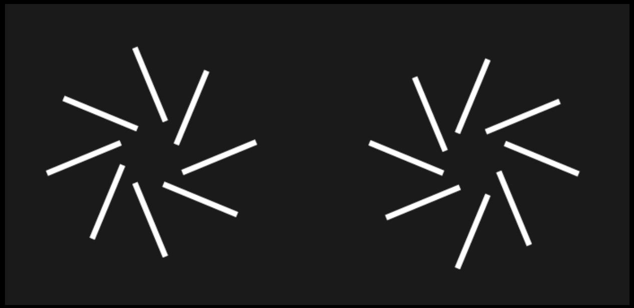
Thompson Scattering



E mode (Grad)



B mode (Curl)



•Tensor quadrupole doesn't show axial symmetry -> B mode polarisation

Kamionkowski, Kosowsky & Stebbins 1997

Zaldarriaga & Seljak 1997

Line of Sight Formalism

Inflation Anisotropies

$$C_l^{XX'} = (4\pi)^2 \int k^2 dk\, P_h(k) \Delta_{Xl}(k) \Delta_{X'l}(k)$$

X=(T,E,B)

$$\Delta_{Xl}(k) = \int_0^{\tau_0} d\tau\, S_X(k,\tau) P_{Xl}(k[\tau_0 - \tau])$$

Sources Projection

- Sources

$$S_T(k,\tau) = -\dot{h}e^{-\kappa} + g\Psi$$

$$S_P(k,\tau) = -g\Psi$$

- Boltzmann Equations - dynamics

$$\dot{\tilde{\Delta}}_T + ik\mu\tilde{\Delta}_T = -\dot{h} - \dot{\kappa}[\tilde{\Delta}_T - \Psi]$$

$$\dot{\tilde{\Delta}}_P + ik\mu\tilde{\Delta}_P = -\dot{\kappa}[\tilde{\Delta}_P + \Psi]$$

$$\Psi \equiv \left[\frac{1}{10}\tilde{\Delta}_{T0} + \frac{1}{7}\tilde{\Delta}_{T2} + \frac{3}{70}\tilde{\Delta}_{T4} - \frac{3}{5}\tilde{\Delta}_{P0} + \frac{6}{7}\tilde{\Delta}_{P2} - \frac{3}{70}\tilde{\Delta}_{P4}\right]$$

- Gravitational Waves

$$\ddot{h}_{ij} + 2\frac{\dot{a}}{a}\dot{h}_{ij} + k^2 h_{ij} = 16\pi G a^2 \pi_{ij}.$$

- Ionization history

$$g(\tau) = \dot{\kappa}e^{-\kappa} \qquad \dot{\kappa} = a n_e x_e \sigma_T$$

- Inflation - initial conditions

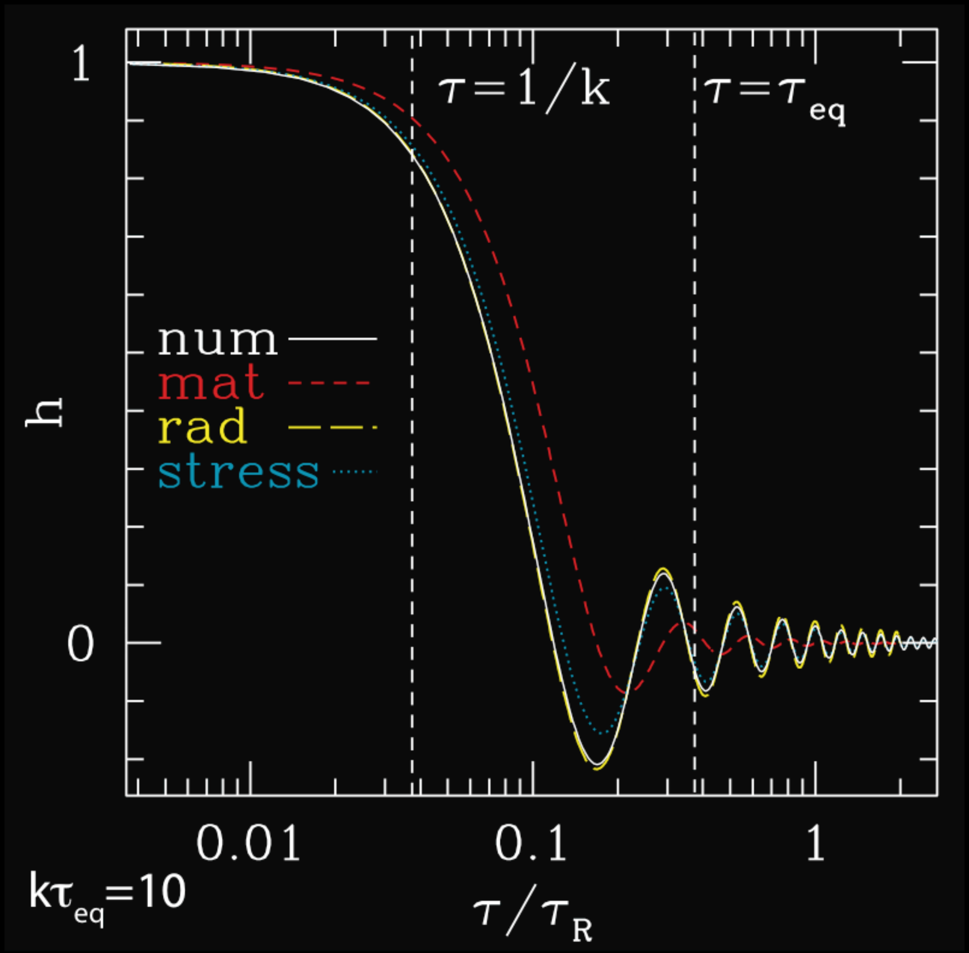
$$P_h(k) = \left.\frac{32\pi G H^2}{(2\pi)^3 k^3}\right|_{aH=k} \approx A_T k^{n_T - 3}$$

Polnarev 1985 Seljak & Zaldarriaga 1997

Gravitational Waves

$$\ddot{h}_{ij} + 2\frac{\dot{a}}{a}\dot{h}_{ij} + k^2 h_{ij} = 16\pi G a^2 \pi_{ij}.$$

anisotropic stress ← Freestreaming relativistic particles e.g. neutrinos



- Modes enter horizon and decay
- Background energy content affects phase at SLS
- Anisotropic stress damps amplitude by ~0.8 Weinberg 2003

$$h(k,\tau) \approx A_T \frac{\sin(k\tau + \phi_0)}{a(\tau)}$$

Sources

$$S_T(k,\tau) = -\dot{h}e^{-\kappa} + g\Psi$$

ISW — integrated along LoS

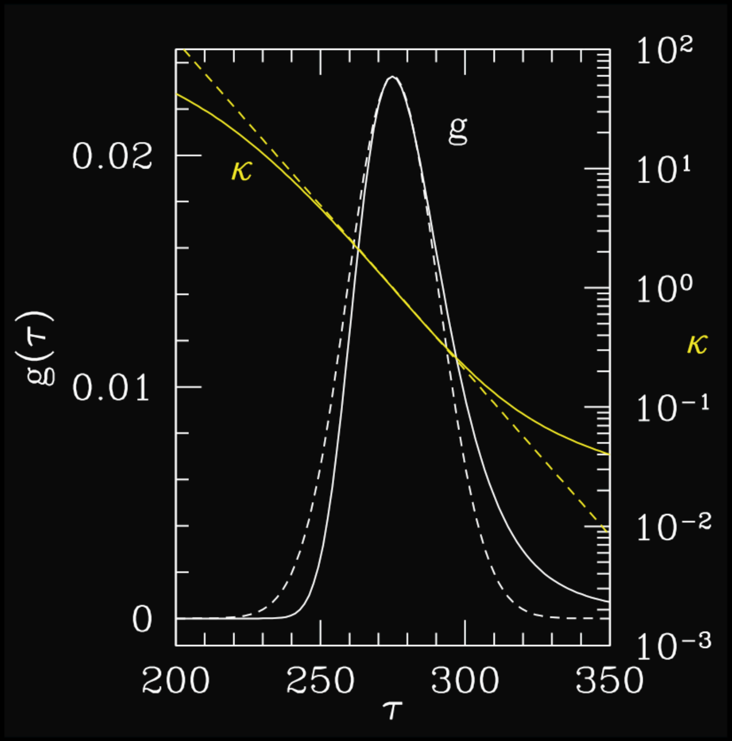
scattering — localised to SLS

$$S_P(k,\tau) = -g\Psi$$

scattering

localised to SLS

- Visibility function is narrow and centered at the time of recombination



$$g(\tau) = \dot{\kappa}e^{-\kappa}$$

- Thompson scattering: T->P & P->T

$$\Psi \equiv \left[\frac{1}{10}\tilde{\Delta}_{T0} + \frac{1}{7}\tilde{\Delta}_{T2} + \frac{3}{70}\tilde{\Delta}_{T4} - \frac{3}{5}\tilde{\Delta}_{P0} + \frac{6}{7}\tilde{\Delta}_{P2} - \frac{3}{70}\tilde{\Delta}_{P4}\right]$$

Tight Coupling

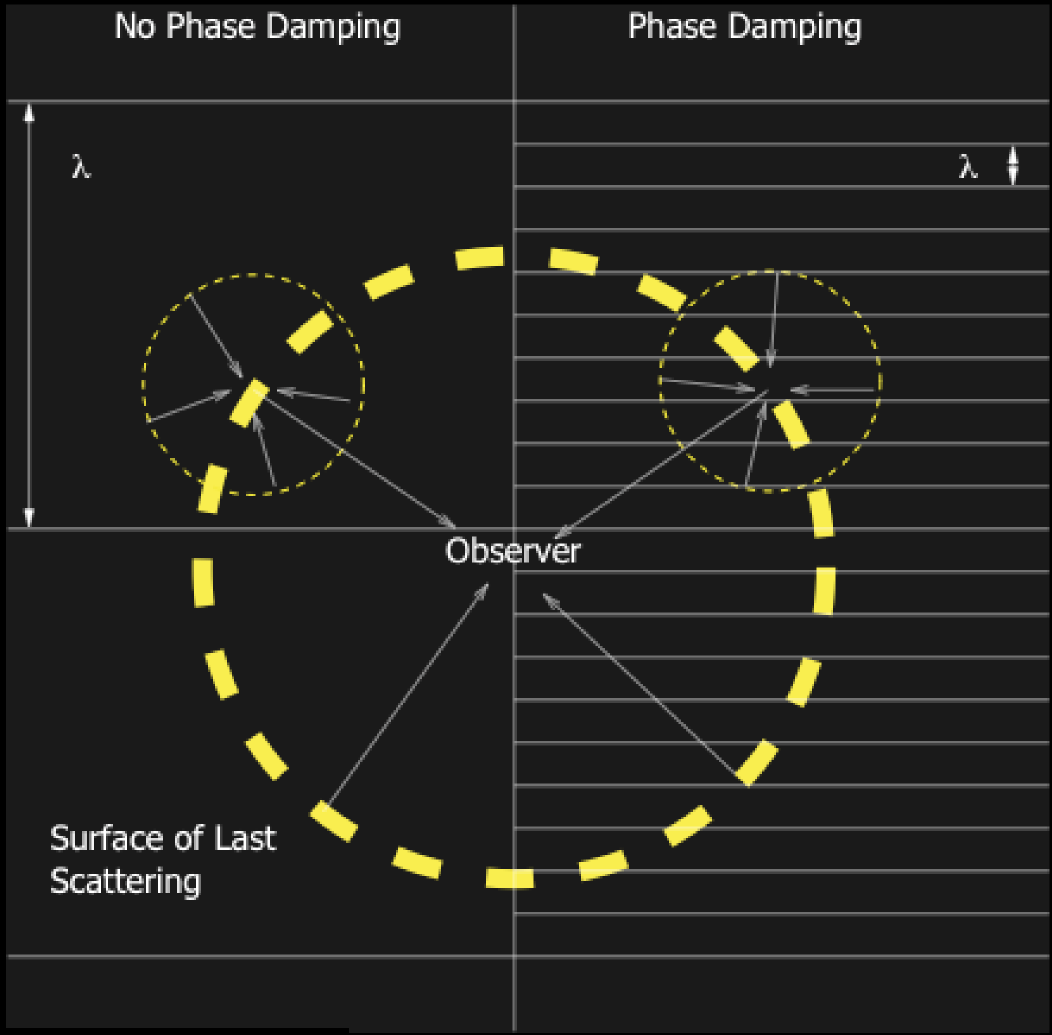
- Rapid Thompson scattering couples baryons and photons and prevents the growth of anisotropy
- Recombination -> increasing m.f.p. -> anisotropy grows
- Use large optical depth to simplify Boltzmann equations

$$\dot{\Psi} + \frac{3}{10}\dot{\kappa}\Psi = -\frac{\dot{h}}{10}.$$

•If gravitational wave driving term varies slowly over the SLS, i.e. $k\Delta\tau_R$<<1, then

$$\underbrace{\Psi \propto \dot{h}(\tau_R)}_{\text{driving term}}\underbrace{\Delta\tau_R}_{\text{width of SLS}}$$

Phase Damping

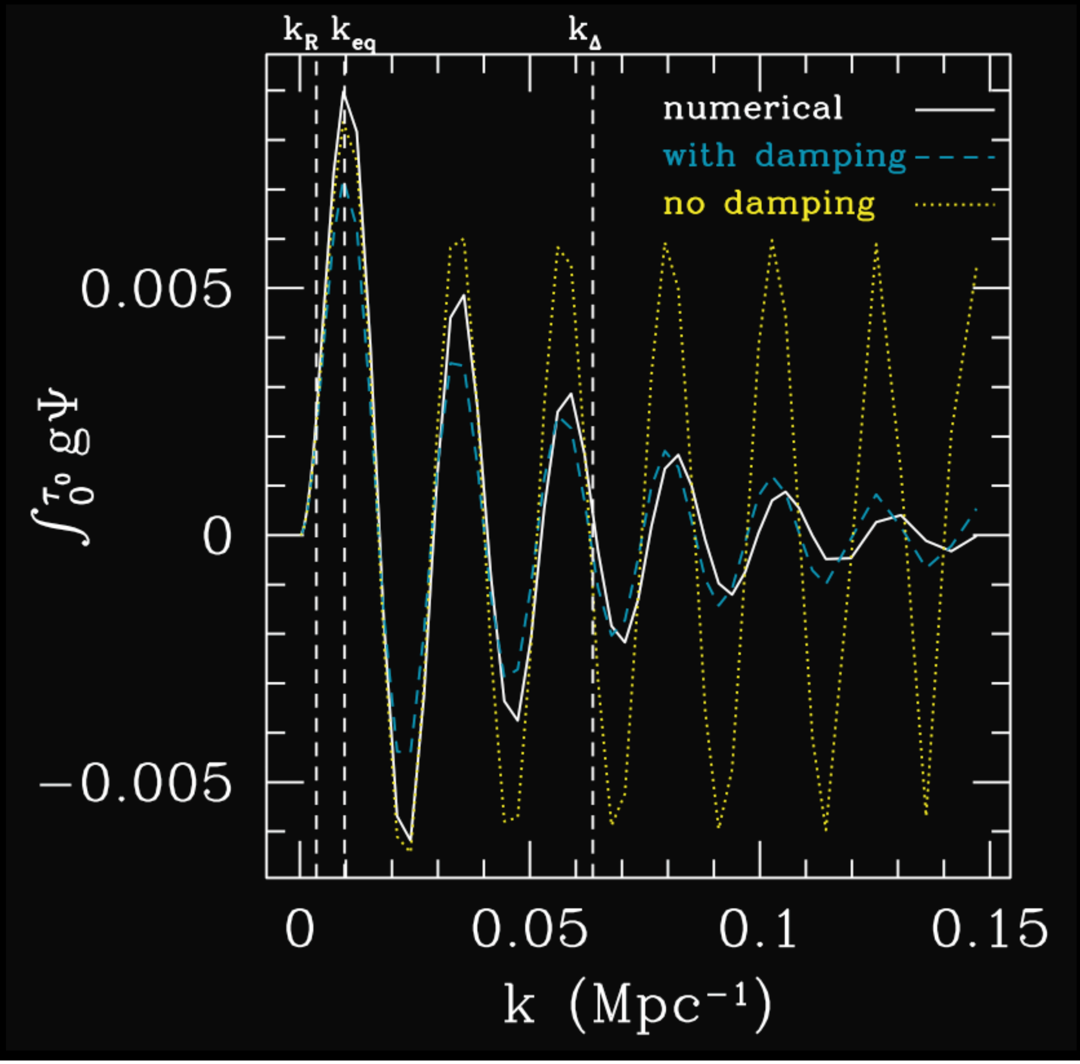


- On smaller scales, finite size of SLS becomes important
- Different regions contribute with different phases
- Exponentially suppresses power on small scales

$$\langle \dot{h}(\tau) \rangle = \int_0^{\tau_0} d\tau\, g(\tau) \dot{h}(\tau) \approx \dot{h}(\tau_R) e^{-(k\Delta\tau_R)^2/2}$$

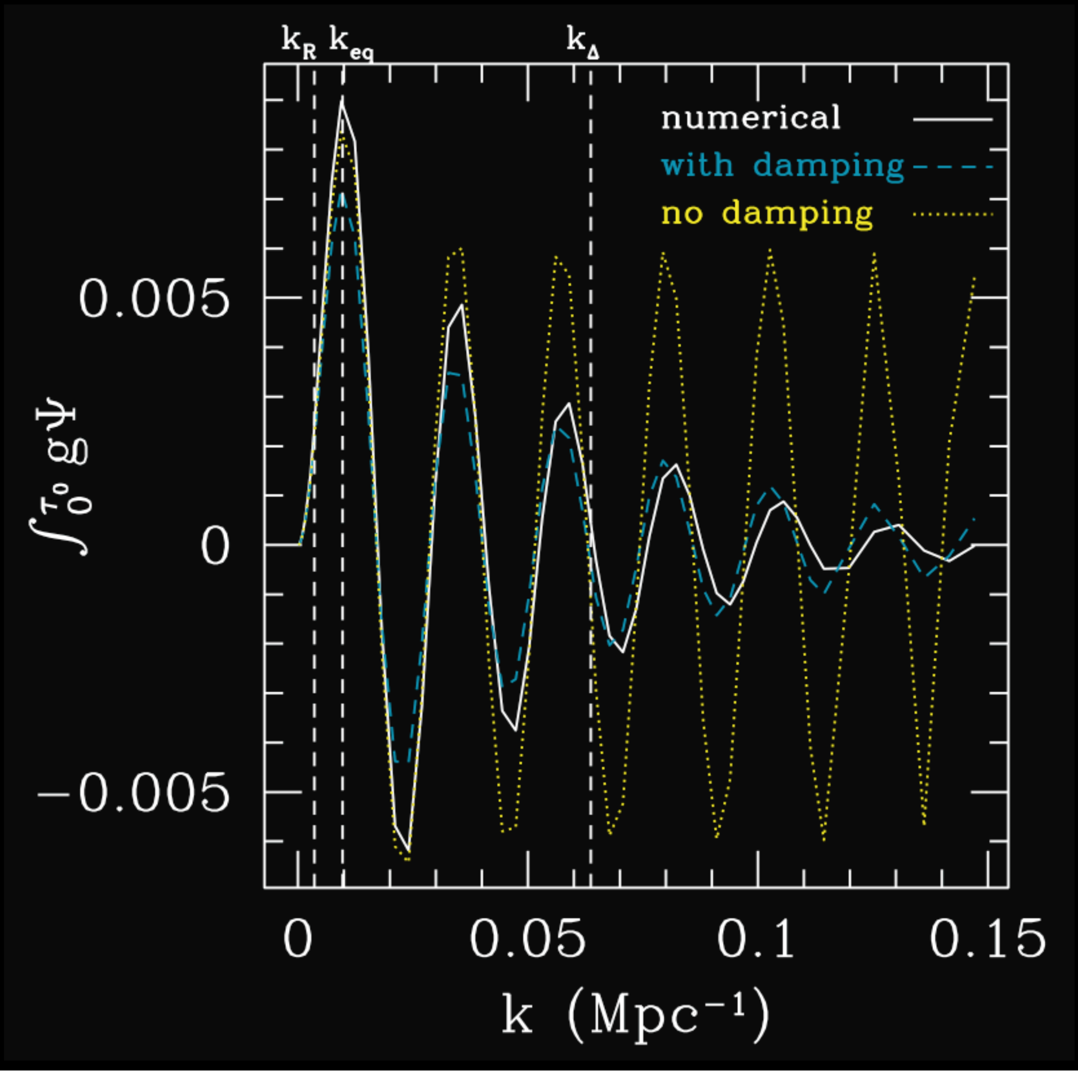
Source Evolution

$$\Delta_{Xl}(k) \approx P_{Xl}(k[\tau_0 - \tau_R]) \int_0^{\tau_0} d\tau \, g(\tau)\Psi(k,\tau)$$

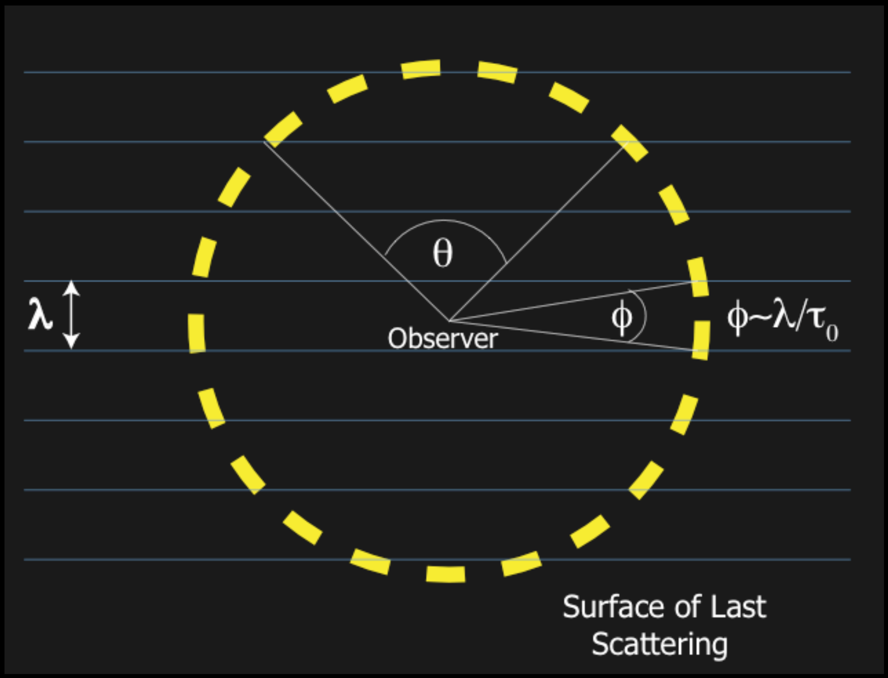


Source Evolution

$$\Delta_{Xl} \approx P_{Xl}[k(\tau_0 - \tau_R)]\dot{h}(\tau_R)\Delta\tau_R e^{-(k\Delta\tau_R)^2/2}\left(\frac{1}{7}\log\frac{10}{3}\right)$$

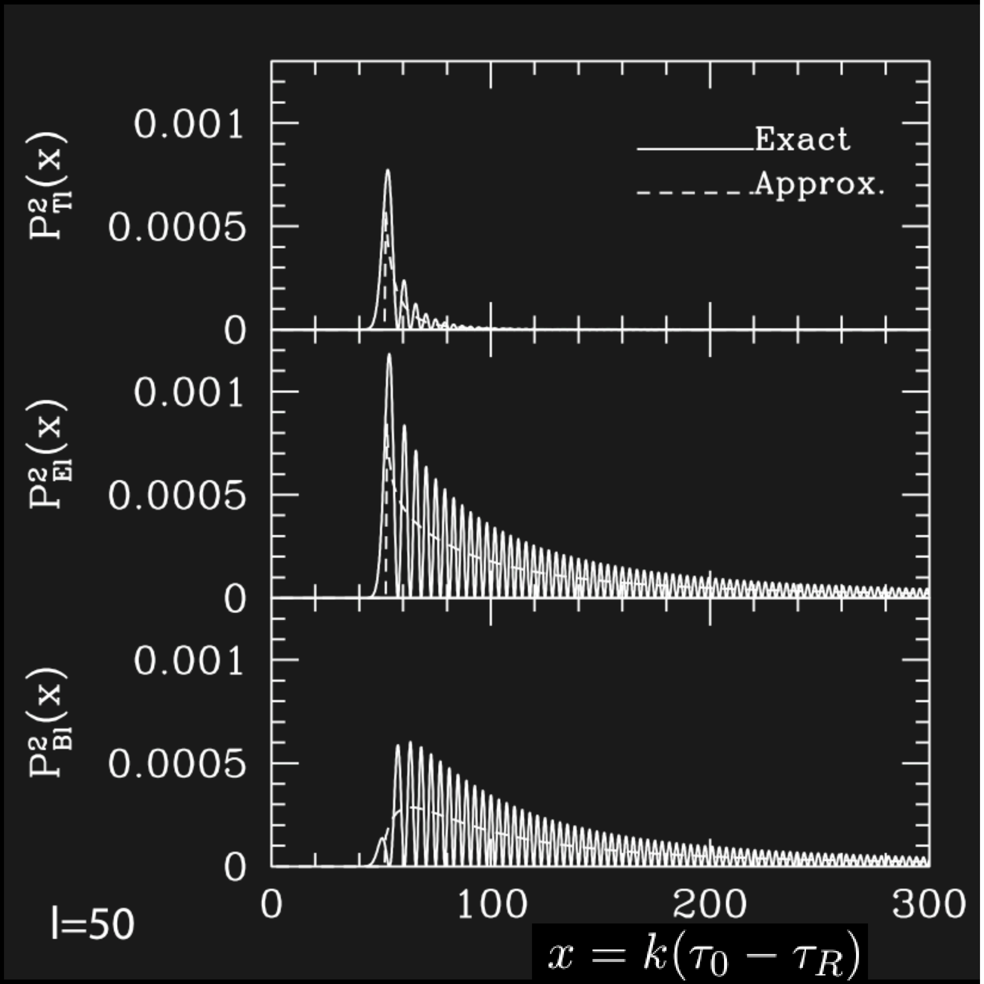


Projection I



Peak l~k(lookback time)

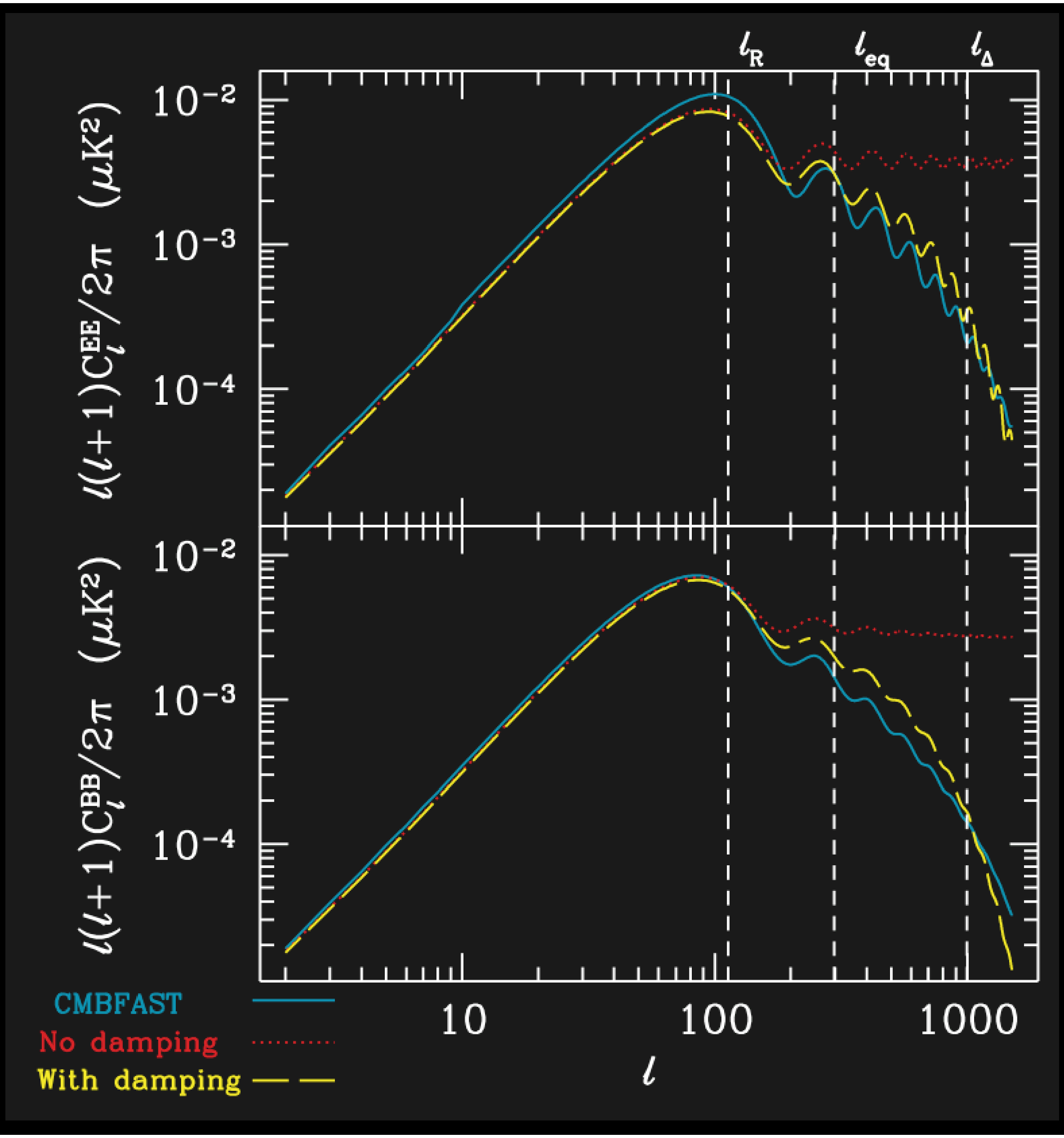
peak at x~l



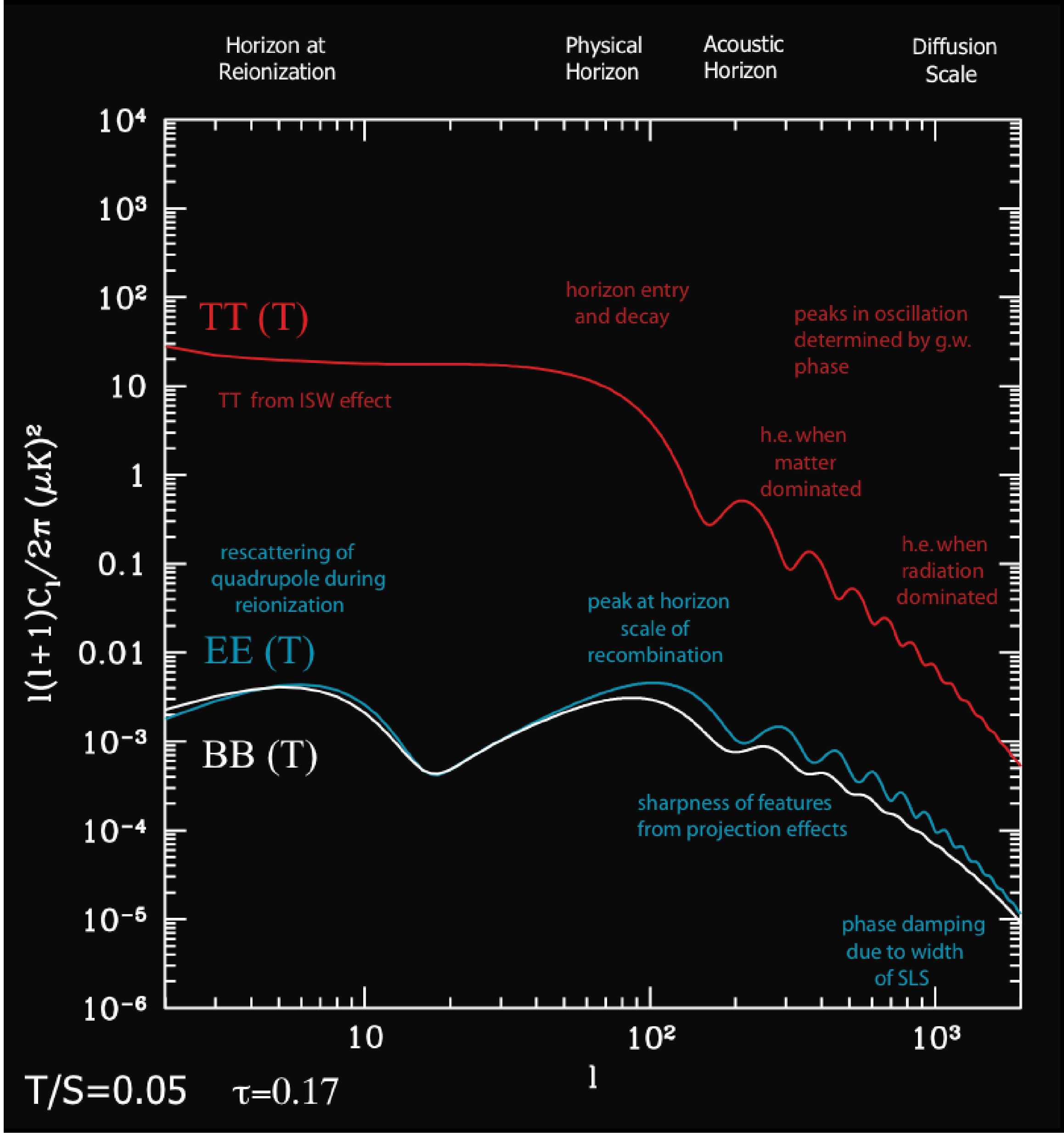
- Approximate using Debye's formula for spherical bessel function when x>l

Debye 1909

Analytical Model



Conclusions z=1100



- Phase damping important for understanding decline in power on small scales
- Projection determines form of the polarisation power spectrum
- Inclusion of anisotropic stress suppresses tensor power by ~0.64 on small scales
- Approximations reproduce shape of power spectrum with reasonable accuracy

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

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Steve Furlanetto
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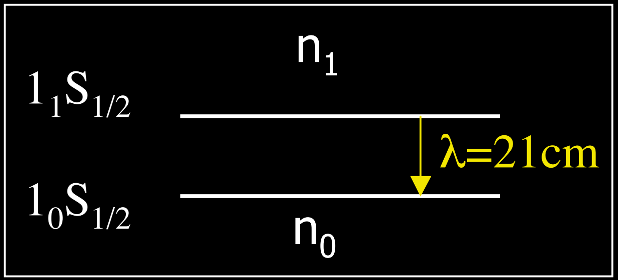
astro-ph/0508381
submitted to MNRAS

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

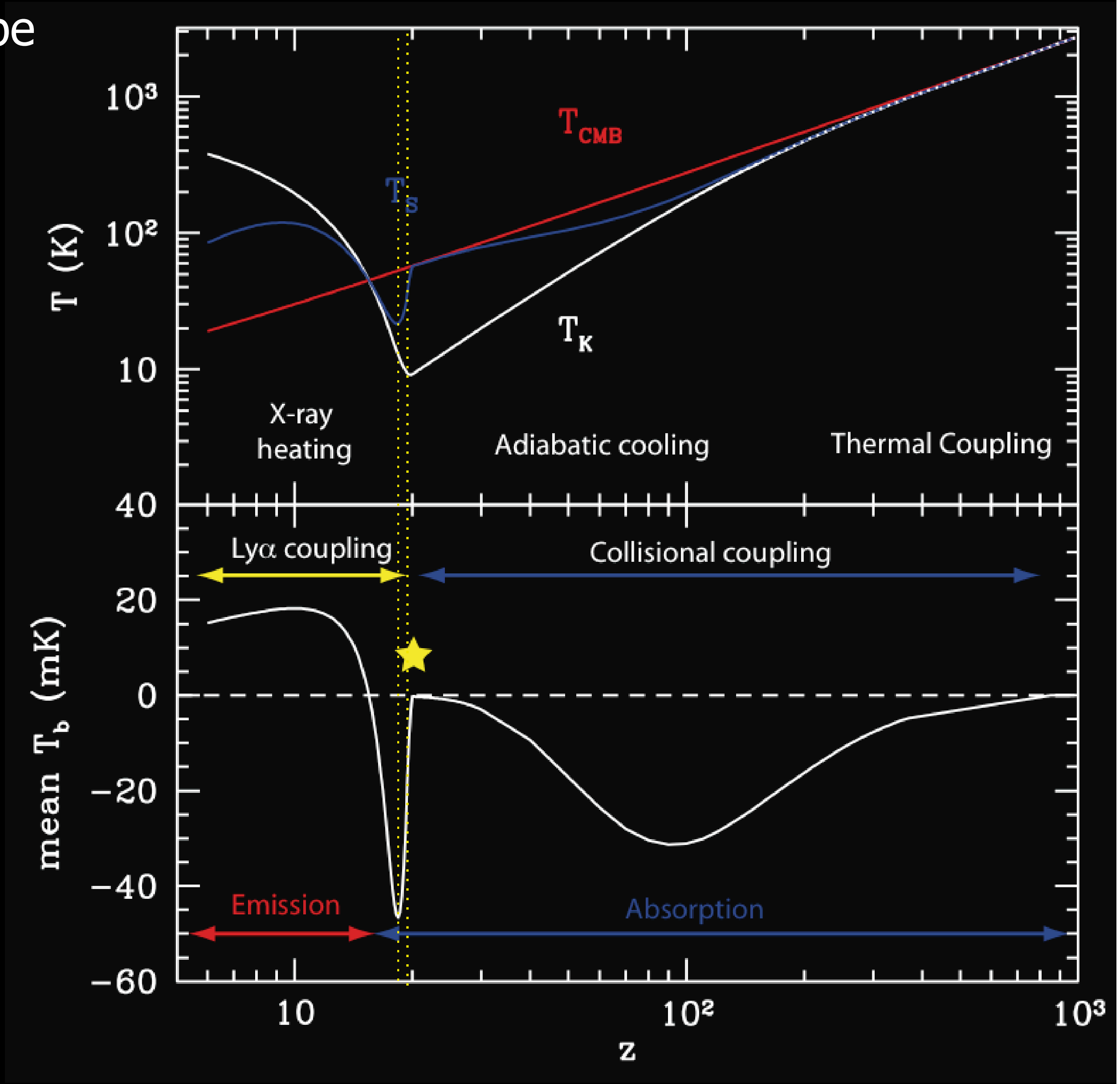
Thermal History

- Use CMB backlight to probe 21cm transition
- HI hyperfine structure



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

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



21cm Fluctuations

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

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

from density inhomogeneities

flux variations

IGM still mostly neutral

- 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 2004

Experimental Efforts

- Three main experiments: PAST (NW China), LOFAR (NL) and MWA (SW Australia)
- Large radio arrays using interferometry
- Foregrounds!

MWA: (f_{21cm}=1.4 GHz)
Freq: 80-300 MHz
Baselines: 10m-1.5km

LOFAR:
Freq: 30-240 MHz
Baselines: 100m-100km
~14000 antennae

The old: large dishes

The new: small dipoles

… & long baselines

Wouthysen-Field Effect

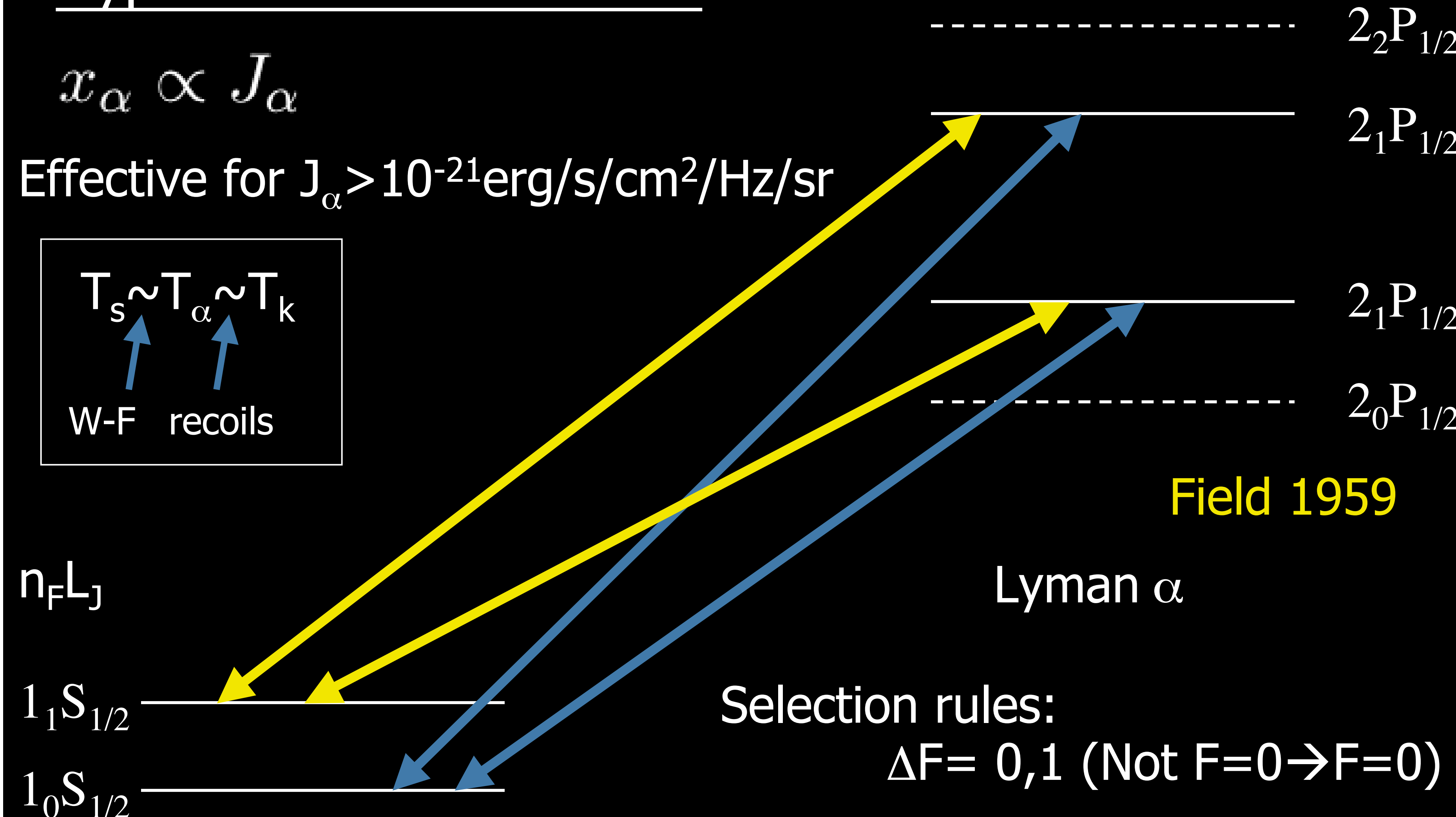
Hyperfine structure of HI

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

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:

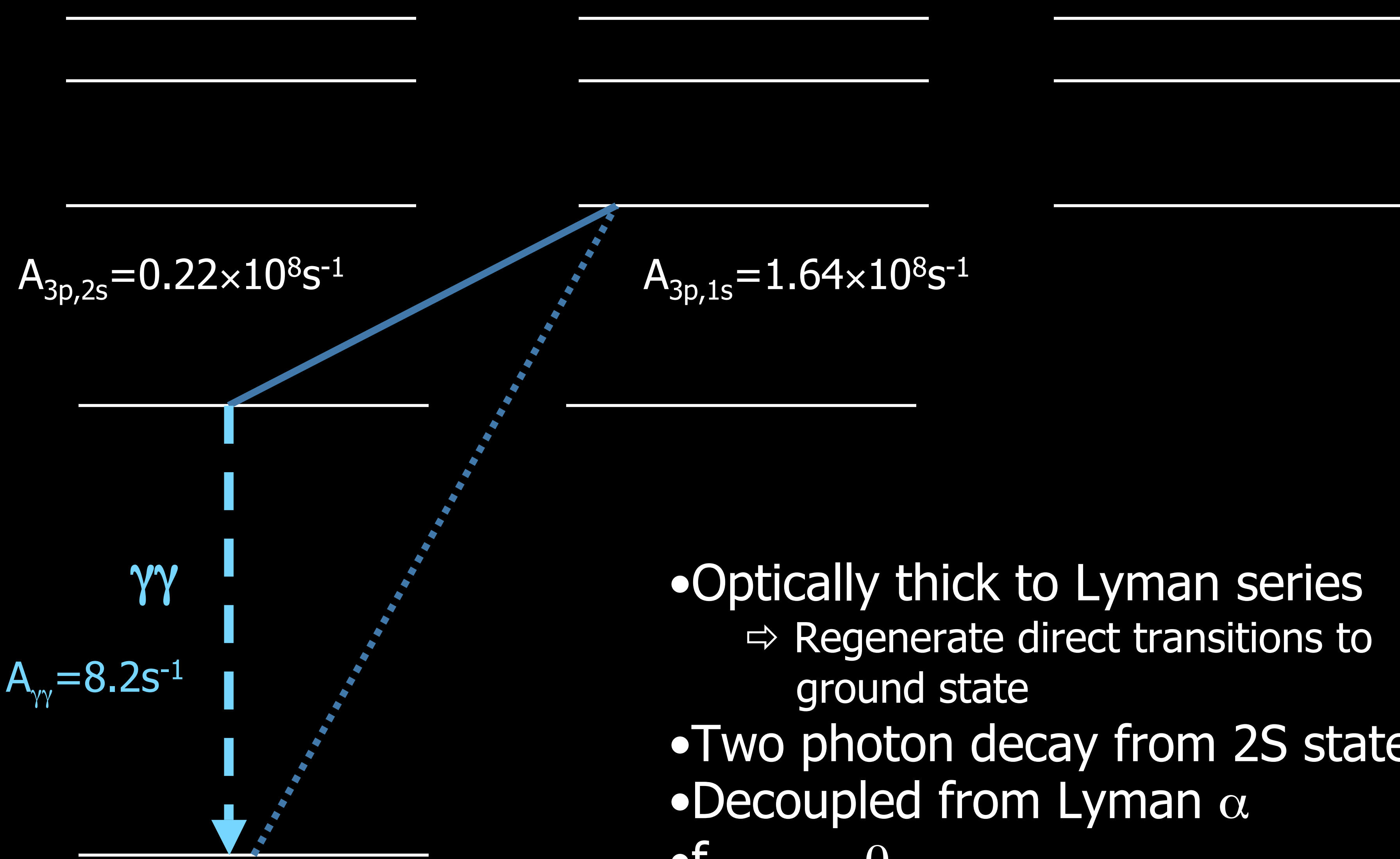
$\Delta F = 0,1$ (Not $F=0 \rightarrow F=0$)

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…

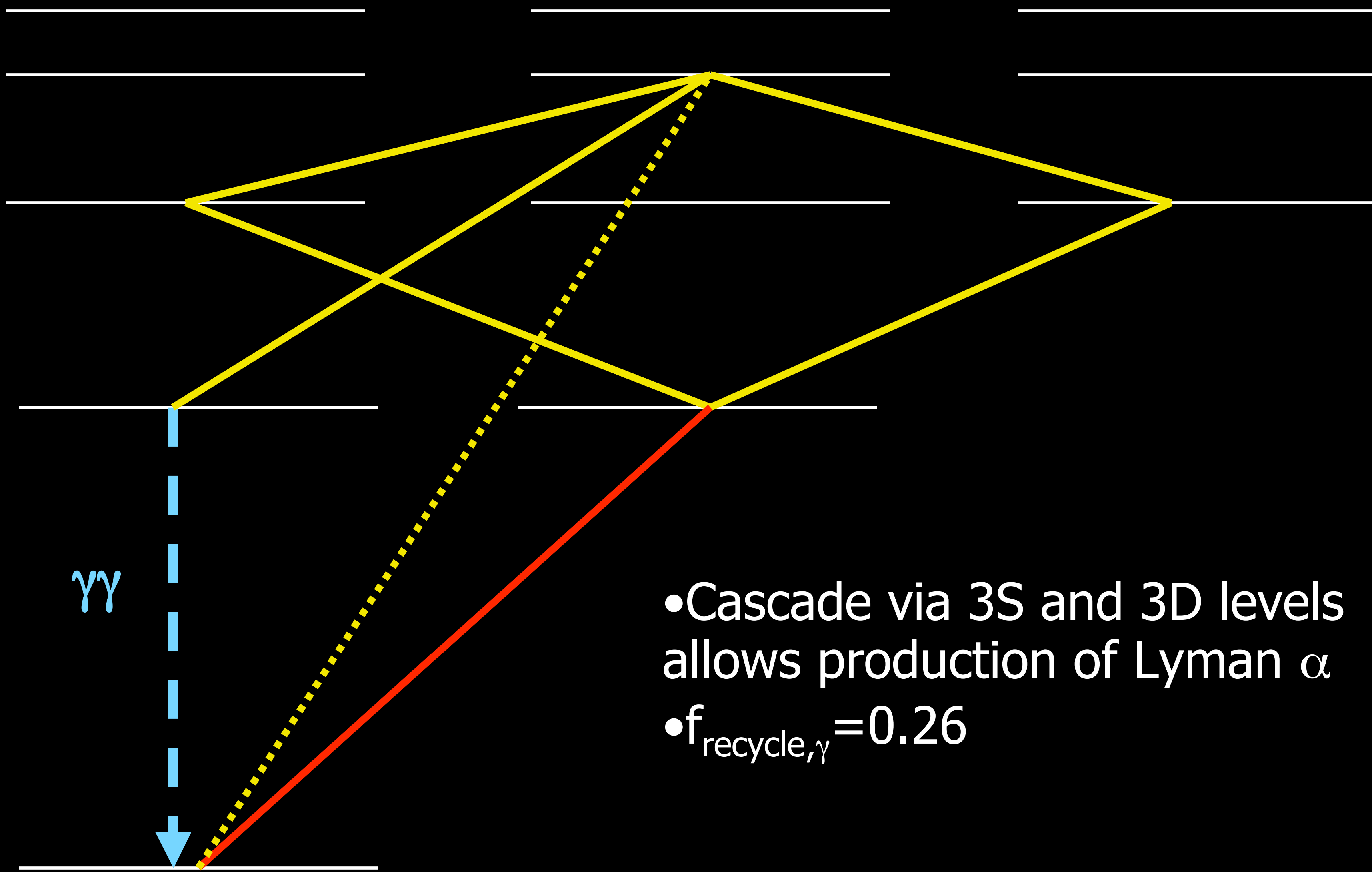
Hirata 2005

Lyman β



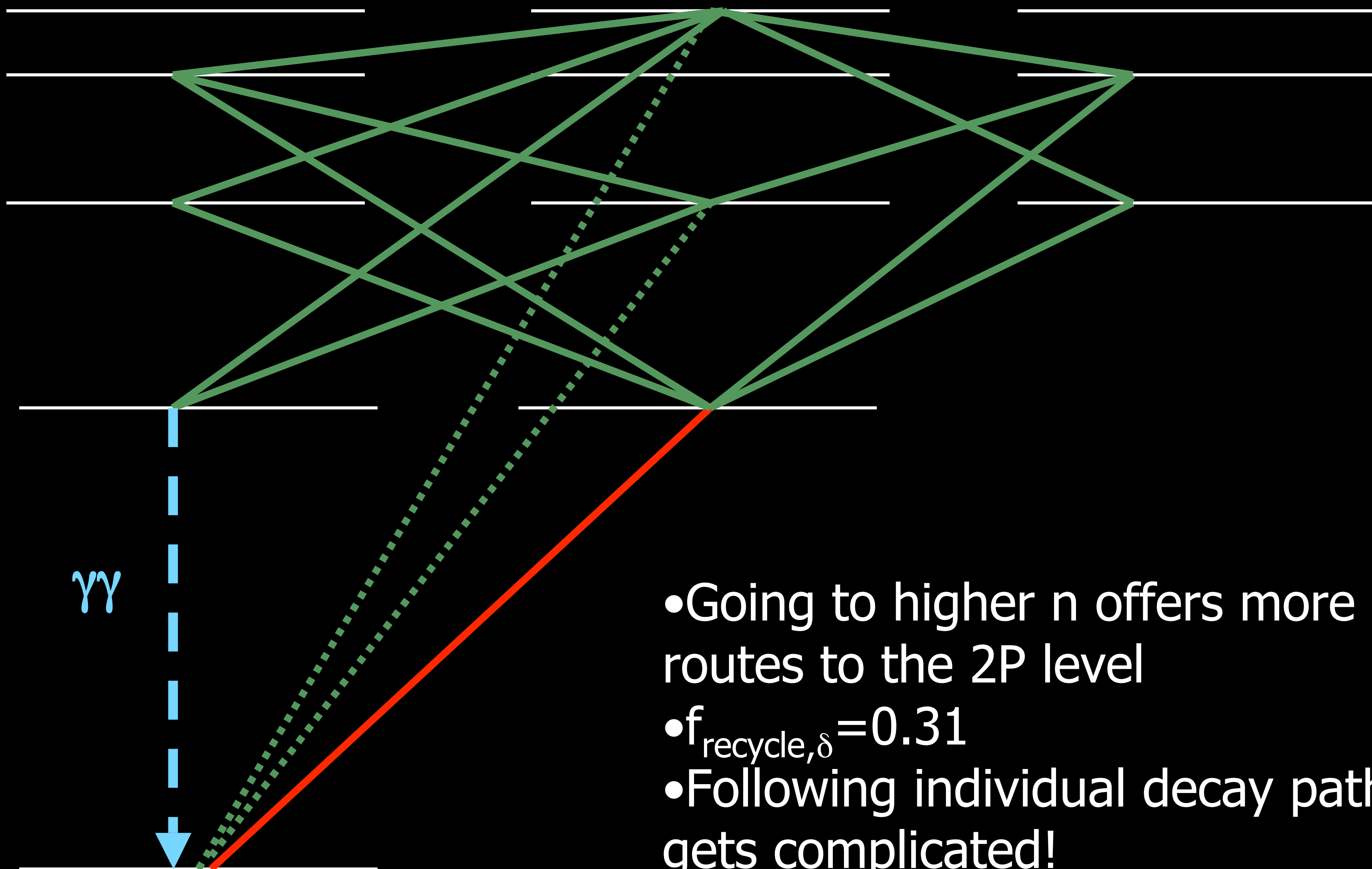
- Optically thick to Lyman series
  - ⇨ Regenerate direct transitions to ground state
- Two photon decay from 2S state
- Decoupled from Lyman α
- $f_{recycle,\beta}=0$

Lyman γ



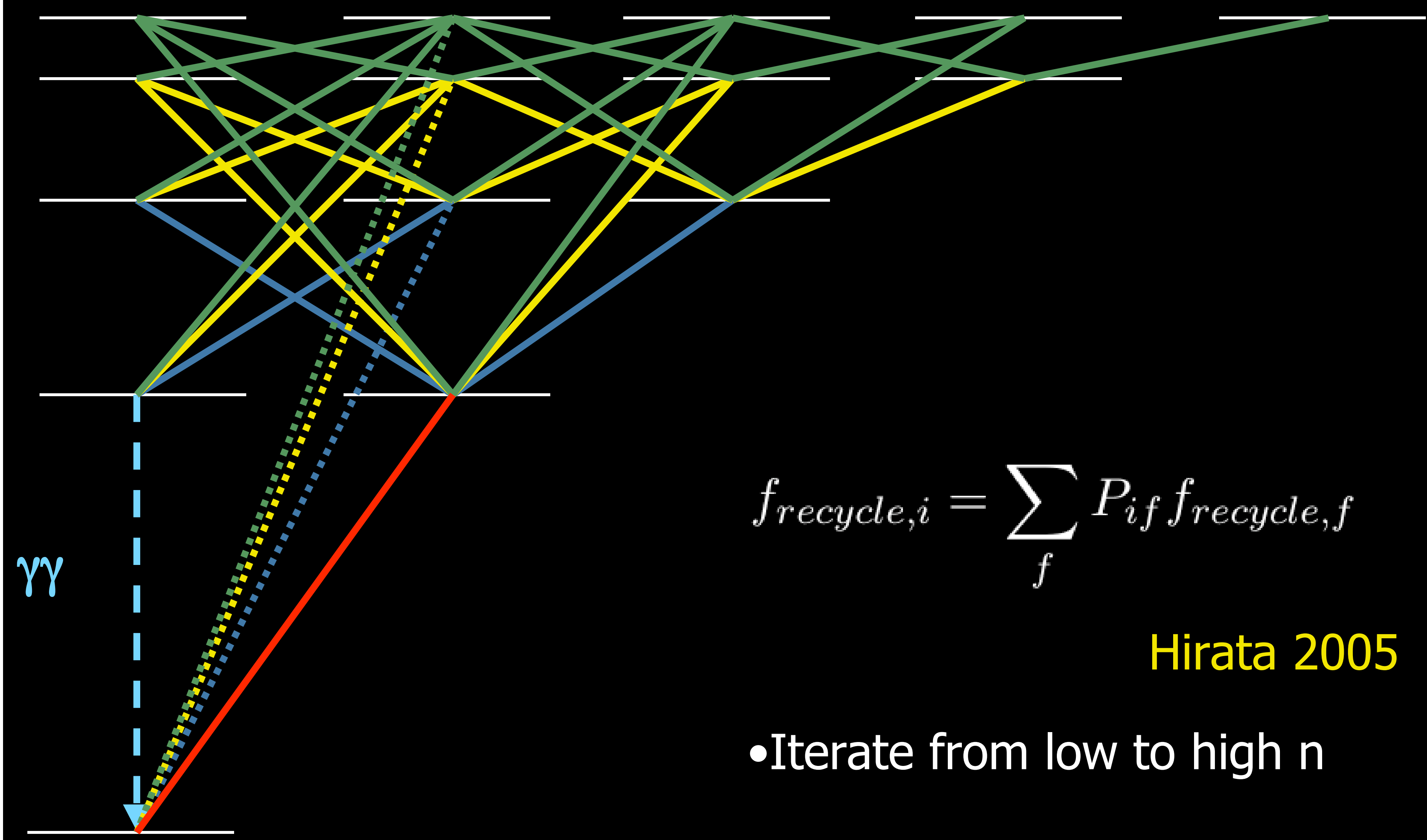
- Cascade via 3S and 3D levels allows production of Lyman α
- $f_{recycle,\gamma}$=0.26

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

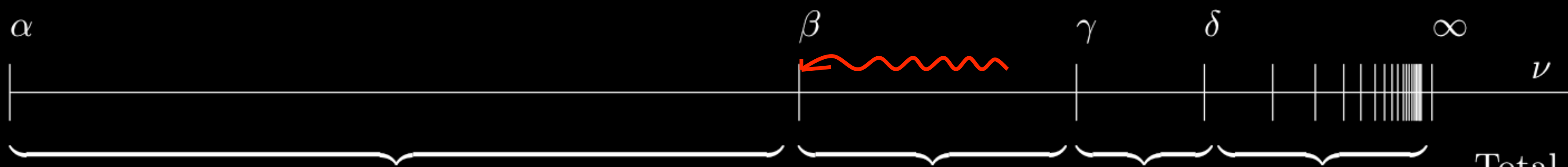


$$f_{recycle,i} = \sum_f P_{if} f_{recycle,f}$$

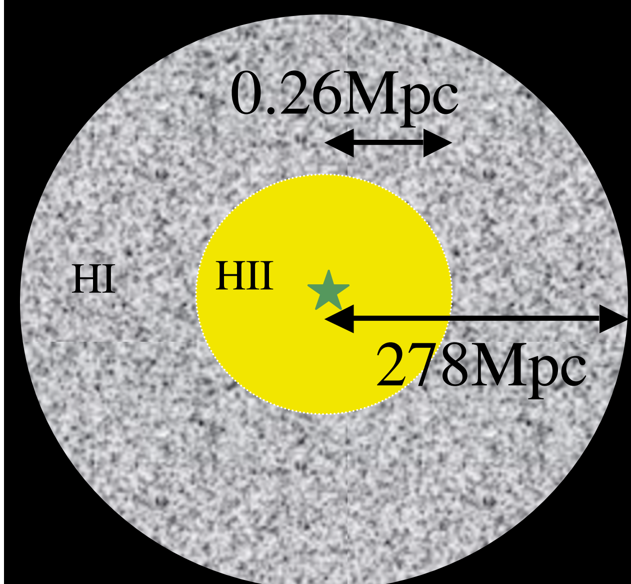
Hirata 2005

- Iterate from low to high n

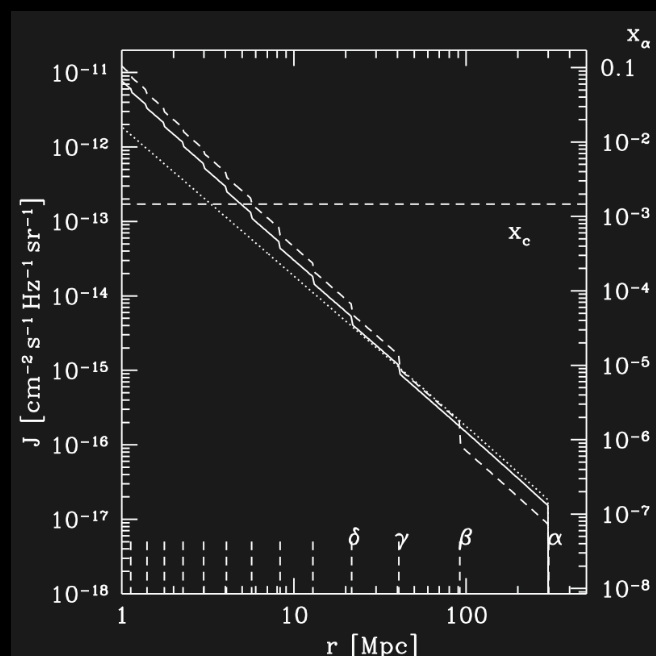
Lyman Series Cascades



					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	



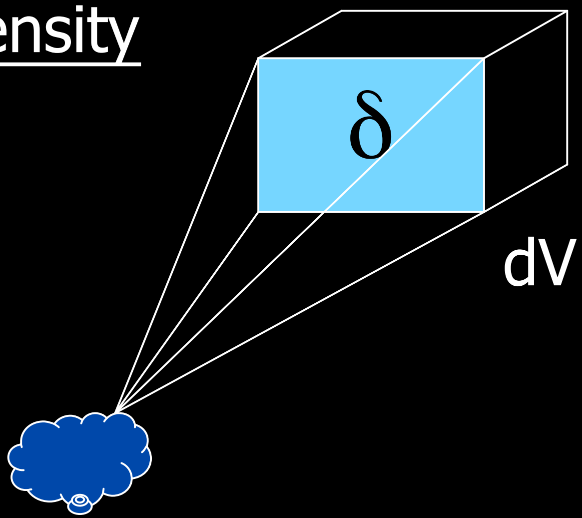
n_{max}=23



- ~62% emitted photons recycled into Lyα
- Lyα flux profile is steepened

Fluctuations from the first stars

Density



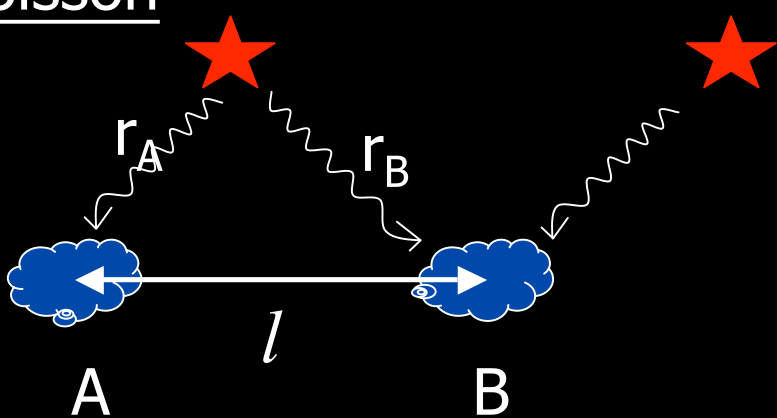
- Overdense region modifies observed flux from region dV
- Relate Ly α fluctuations to overdensities

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

- Probe using separation of powers

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

Poisson

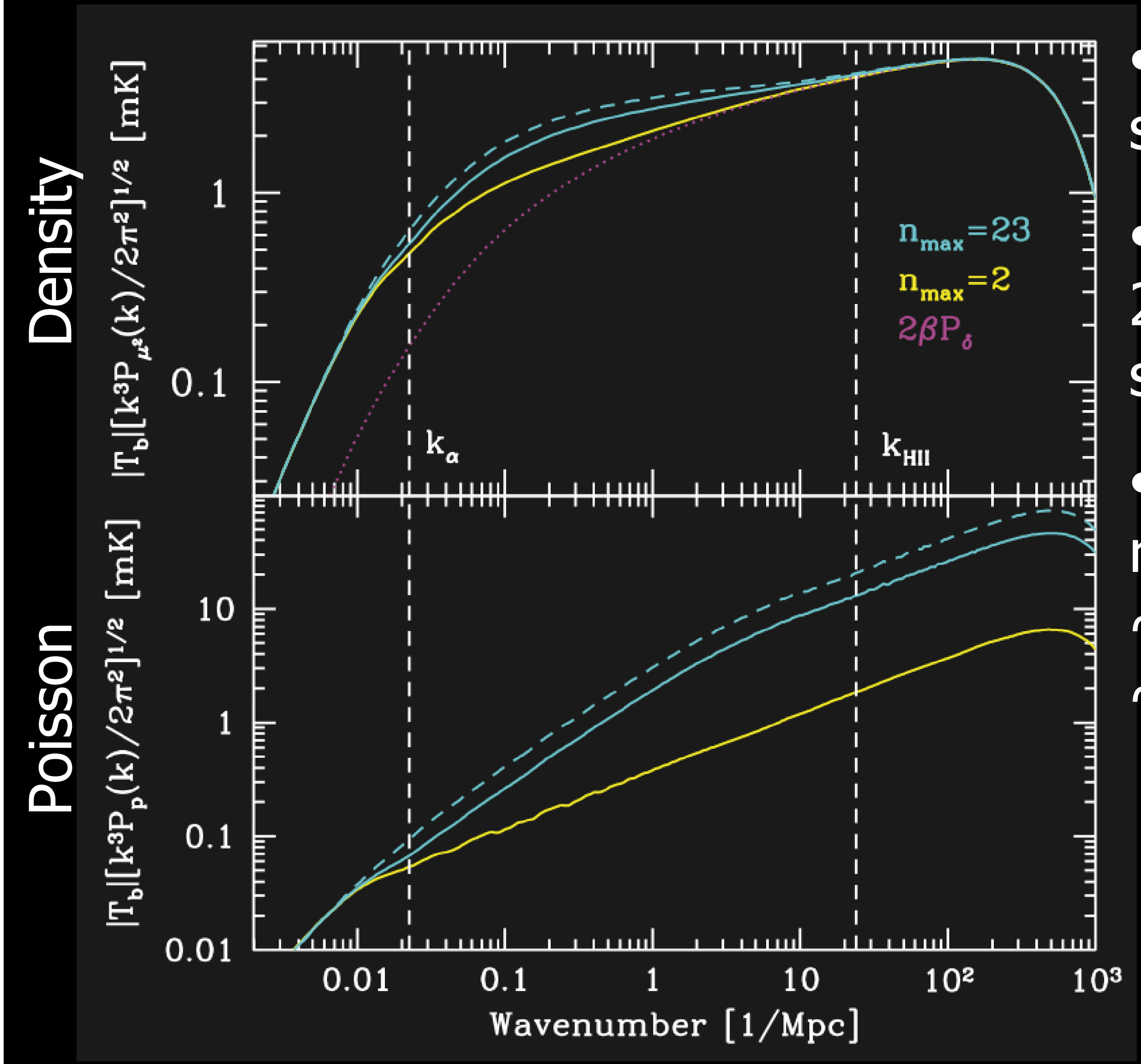


- Fluctuations independent of density perturbations
- Small number statistics
- Different regions see some of the same sources though at different times in their evolution

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

Barkana & Loeb 2004

Fluctuation Power Spectra



- Excess power probes star formation rate
- Cutoffs from width of 21cm line and pressure support on small scales
- Correct atomic physics reduces power by ~0.65 (density) ~0.42 (poisson)

Conclusions z=20

- 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
- 21cm signal can, in principle, be used to probe early star formation

Imprints of reionization in the galaxy power spectrum

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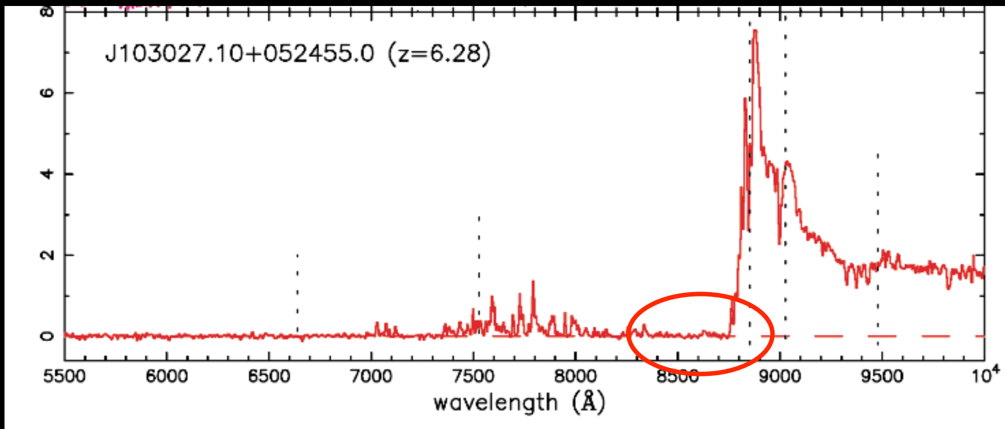
Work in progress…

Overview

- Formation of the first galaxies changes the IGM affecting the formation of further galaxies
- The galaxy power spectrum may retain an imprint from the effect of ionized regions on galaxy formation
- Use simple model in lieu of detailed physics
- Use the Fisher Matrix formalism to probe this imprint
- Consider effect on determination of cosmological and dark energy parameters

Evidence for Reionization

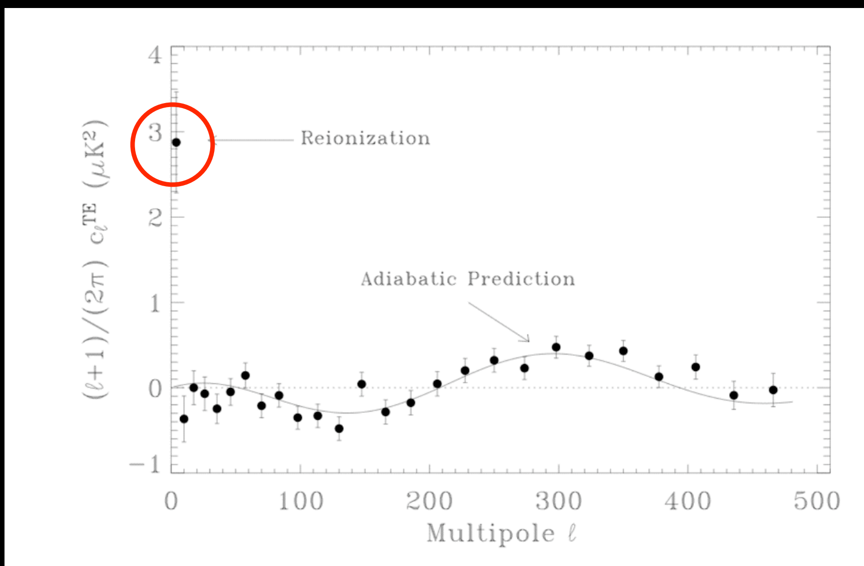
- Gunn-Peterson Trough



Becker et al. 2005

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

- WMAP measurement of τ~0.17

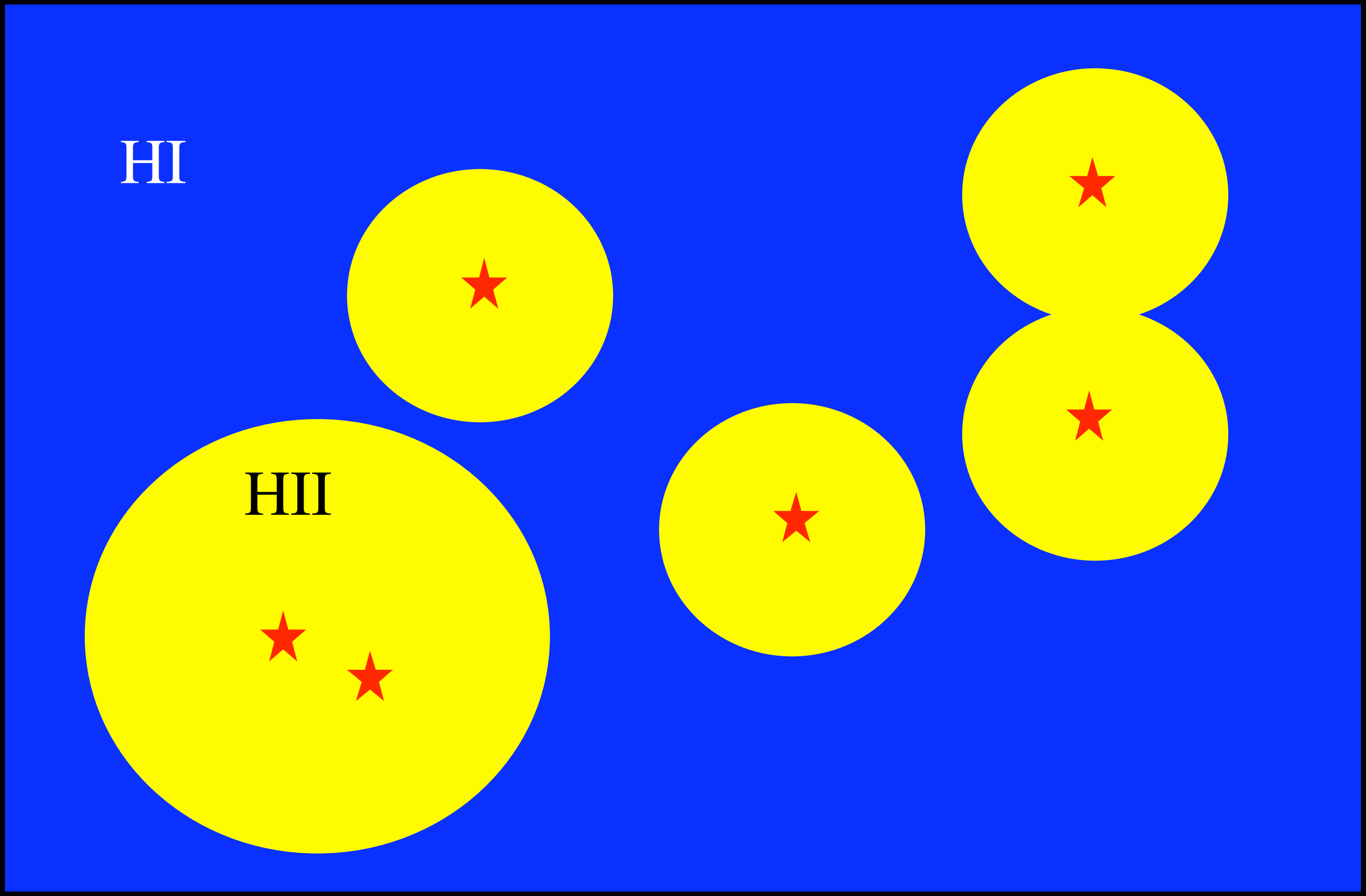


Kogut et al. 2003

•Need early star formation to match large optical depth

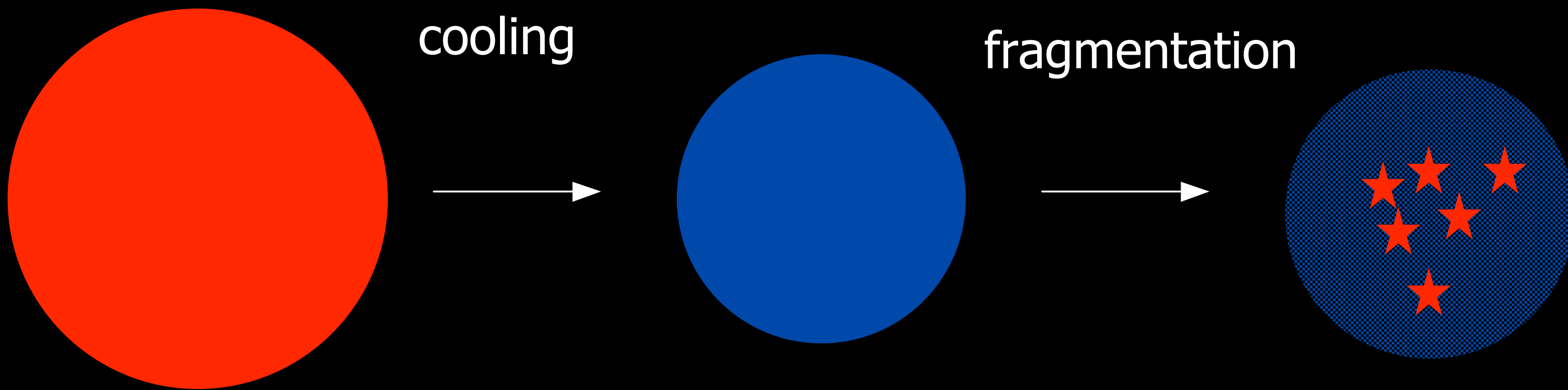
•Integral constraint on ionization history

Patchy Reionization



- Ionizing flux from stars creates HII bubbles around galaxies
- Eventually bubbles overlap and reionization completes

Galaxy formation and feedback



- To get star formation need gas cloud to cool and fragment

$$t_{cool} < t_{dyn} < t_{hubble}$$

- Feedback from first stars complicates matters:

-radiation, winds, metal pollution

- Here ignore the details and parameterise our ignorance

$$n_{\rm gal}(x) = \bar{n}\left[1 + b\delta(x) + \epsilon_b f(x)\right]$$

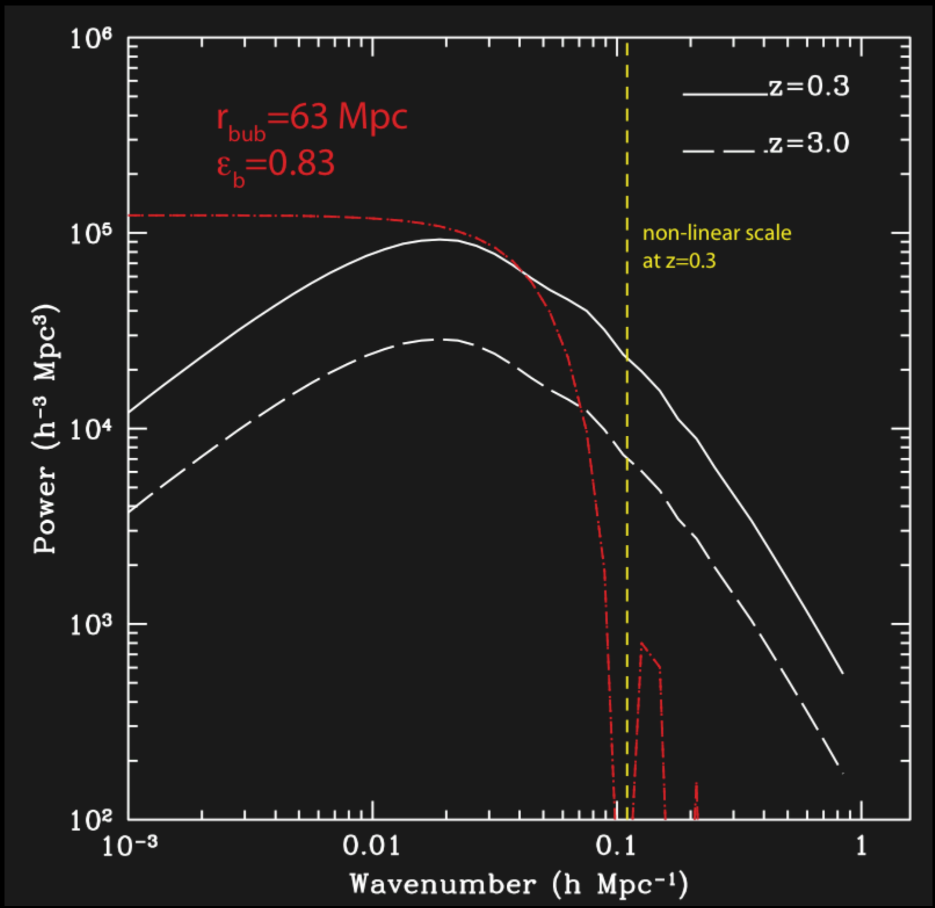
bias

ionized fraction

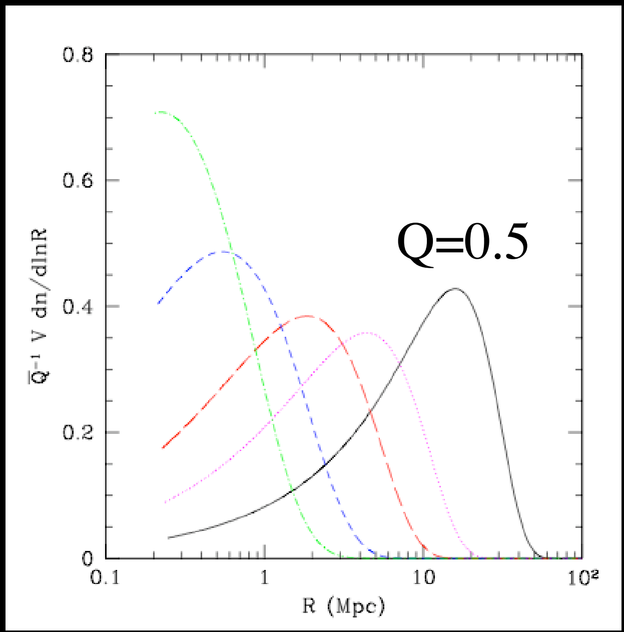
Bubble Model

- Halo model approach to bubble power spectrum + single bubble size

$$P^{1b}(k) = \epsilon_b^2 \bar{Q} V_{bub} |u(k|R_b)|^2$$



- Bubble sizes? - Unclear
- R~10Mpc



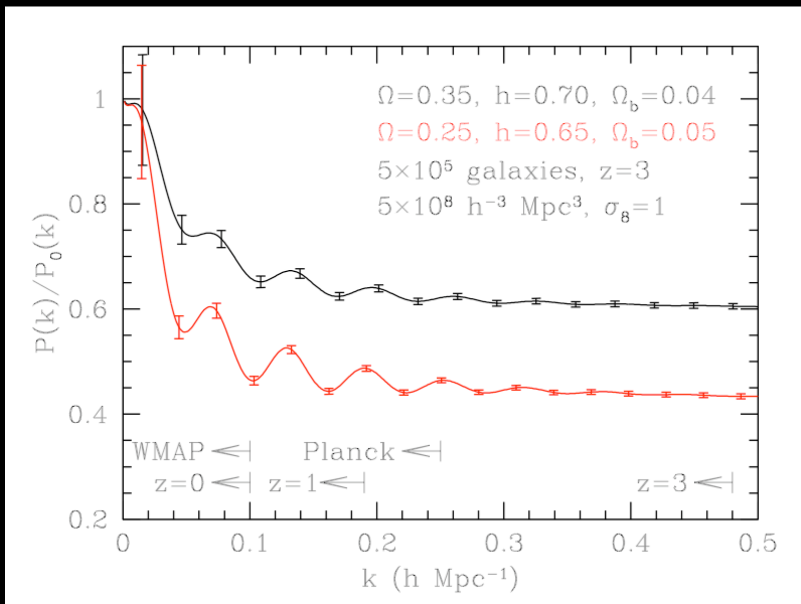
Furlanetto, Zaldarriaga, Hernquist 2004

- R~60Mpc

Wyithe and Loeb 2005

Probing Dark Energy

Baryon Oscillations



•Same acoustic oscillations as seen in the CMB

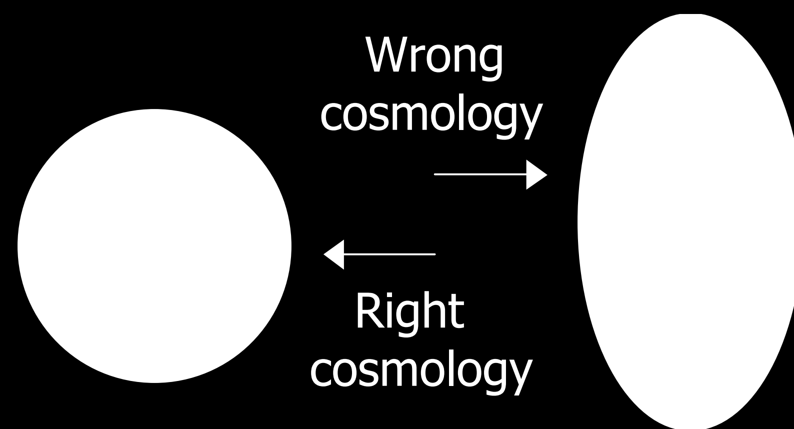
•Constrains angular diameter distance D_A

Seo & Eisenstein 2005

Alcock-Paczynski Effect

Observe Infer

$$(\Delta\theta, \Delta z) \rightarrow (r_\perp, r_{||})$$



•Using wrong cosmology to reconstruct coordinate distances breaks spatial isotropy

•Constrains HD_A

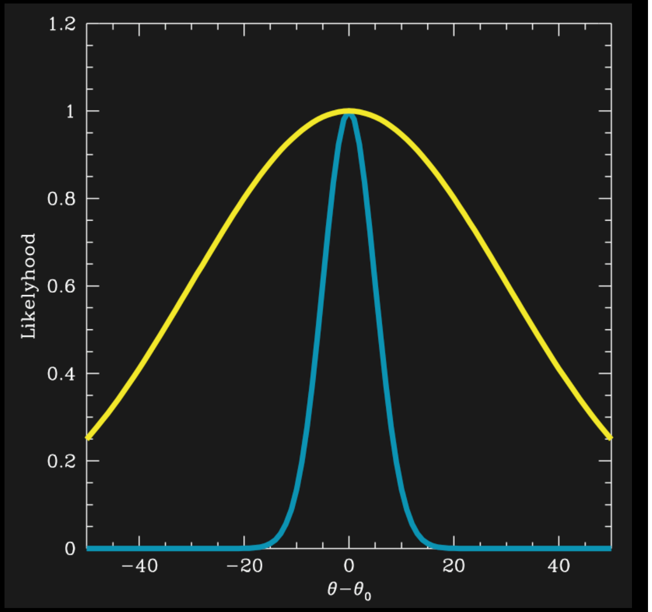
Alcock & Paczynski 1979

The Fisher Matrix

- Estimate curvature of likelihood

$$F_{\alpha\beta} = -\left\langle \frac{\partial^2 \log L}{\partial\theta_\alpha \partial\theta_\beta} \right\rangle .$$

Fisher 1935



- Likelihood describes distribution of model parameters
- Cramer-Rao inequality: $\sigma_\alpha \geq \sqrt{(F^{-1})_{\alpha\alpha}}$
- Depends only on theoretical model and experimental specifications

$$F_{\alpha\beta}^{CMB} = \sum_\ell \sum_{X,Y} \frac{\partial C_\ell^X}{\partial\theta_\alpha} (\mathrm{Cov}_\ell)^{-1}_{\mathrm{XY}} \frac{\partial C_\ell^Y}{\partial\theta_\alpha}$$

$$F_{\alpha\beta}^{gal} = \int_{k_{\min}}^{k_{\max}} \frac{d^3k}{(2\pi)^3} \frac{\partial \ln P(k)}{\partial\theta_\alpha} \frac{V_{\mathrm{eff}}(k)}{2} \frac{\partial \ln P(k)}{\partial\theta_\beta}$$

Tegmark 1997

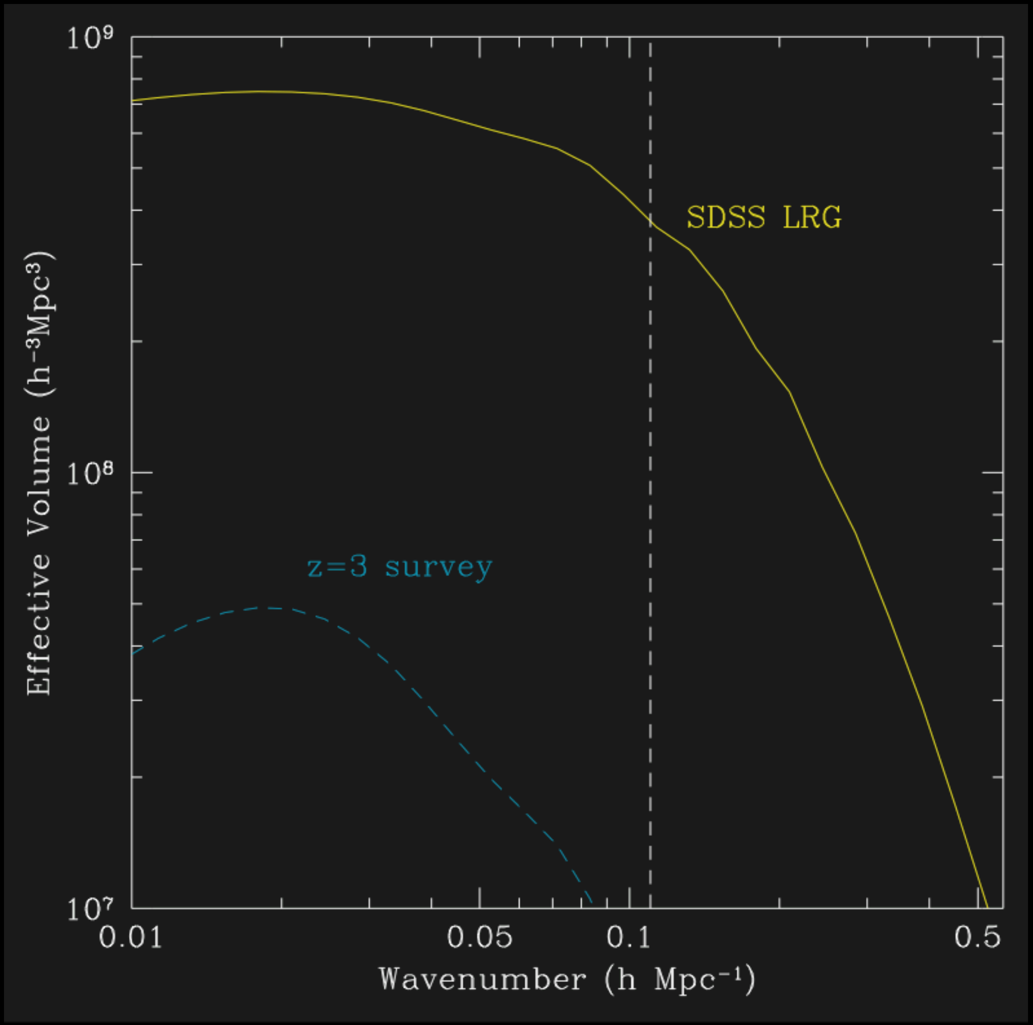
Galaxy Surveys

SDSS LRG

- $z \sim 0.3$
- Luminous Red Galaxies
- $n \sim 10^{-4}\,(h^{-1}\mathrm{Mpc})^{-3}$
- $V_{survey}=1.0\,(h^{-1}\mathrm{Gpc})^3$

Survey 2

- $z \sim 3.0$
- Lyman Break Galaxies
- $n \sim 10^{-3}\,(h^{-1}\mathrm{Mpc})^{-3}$
- $V_{survey}=0.5\,(h^{-1}\mathrm{Gpc})^3$



$$V_{\mathrm{eff}}(k,\mu) = \int \left[\frac{n(r)P(k,\mu)}{n(r)P(k,\mu)+1} \right]^2 V_{\mathrm{survey}}$$

Approach Summary

AP Effect — Linear Growth — Bias and Redshift distortion — Density fluctuations — Bubbles

$$P_{\rm obs}(k,\mu) = \frac{D_A^2(z)H^{\rm tr}(z)}{D_A^{\rm tr\,2}(z)H(z)}\left[\left[\frac{G(z)}{G(z=0)}\right]^2 b^2(1+\beta[\mu^{\rm tr}]^2)^2 P_\delta(k^{\rm tr}) + P_{\rm bub}(k^{\rm tr})\right] + P_{\rm shot}.$$

+

$$F_{\alpha\beta} = -\left\langle \frac{\partial^2 \log L}{\partial\theta_\alpha \partial\theta_\beta} \right\rangle.$$

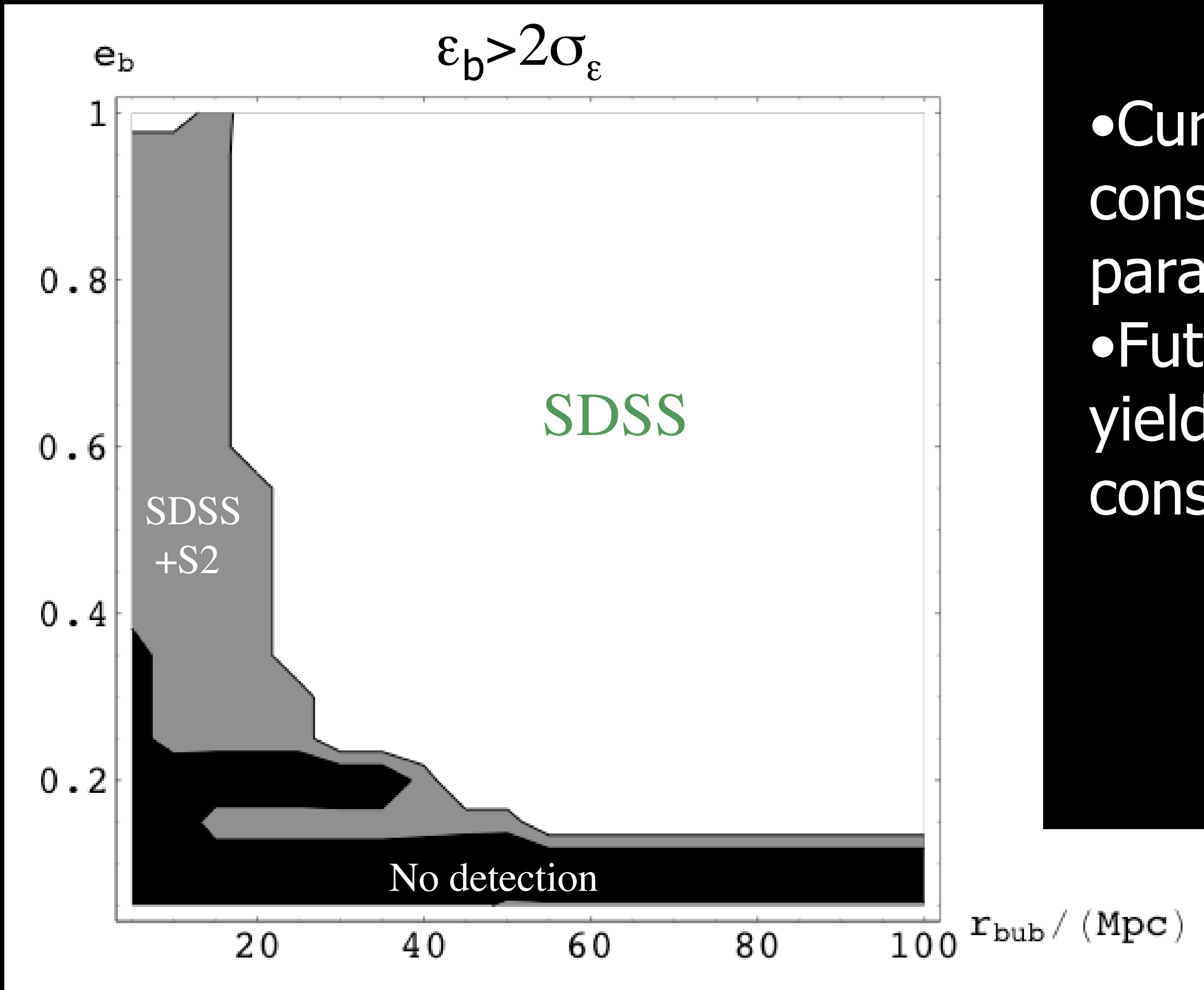
& Galaxy + CMB experiment specifications

->

Uncertainties on cosmological and bubble model parameters

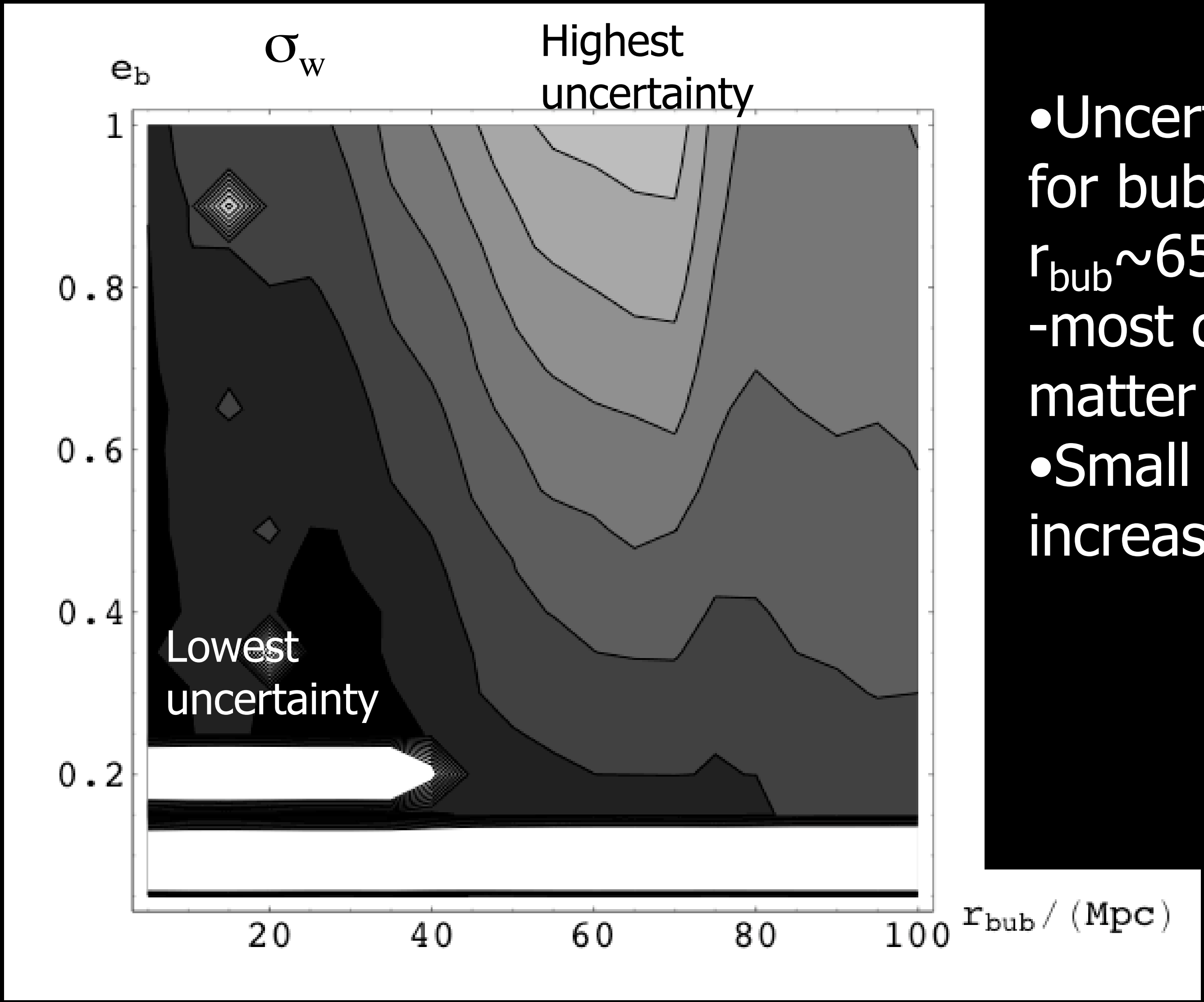
- Use these to probe effect of bubbles on galaxy power spectrum

Possibilities for Detection



- Current surveys barely constrain most relevant parameter region
- Future surveys may yield interesting constraints

Dark Energy Uncertainties



- Uncertainties increased for bubbles with r_{bub}~65Mpc
  - -most degenerate with matter power spectrum
- Small effect ~30% increase at most

Conclusions z=3

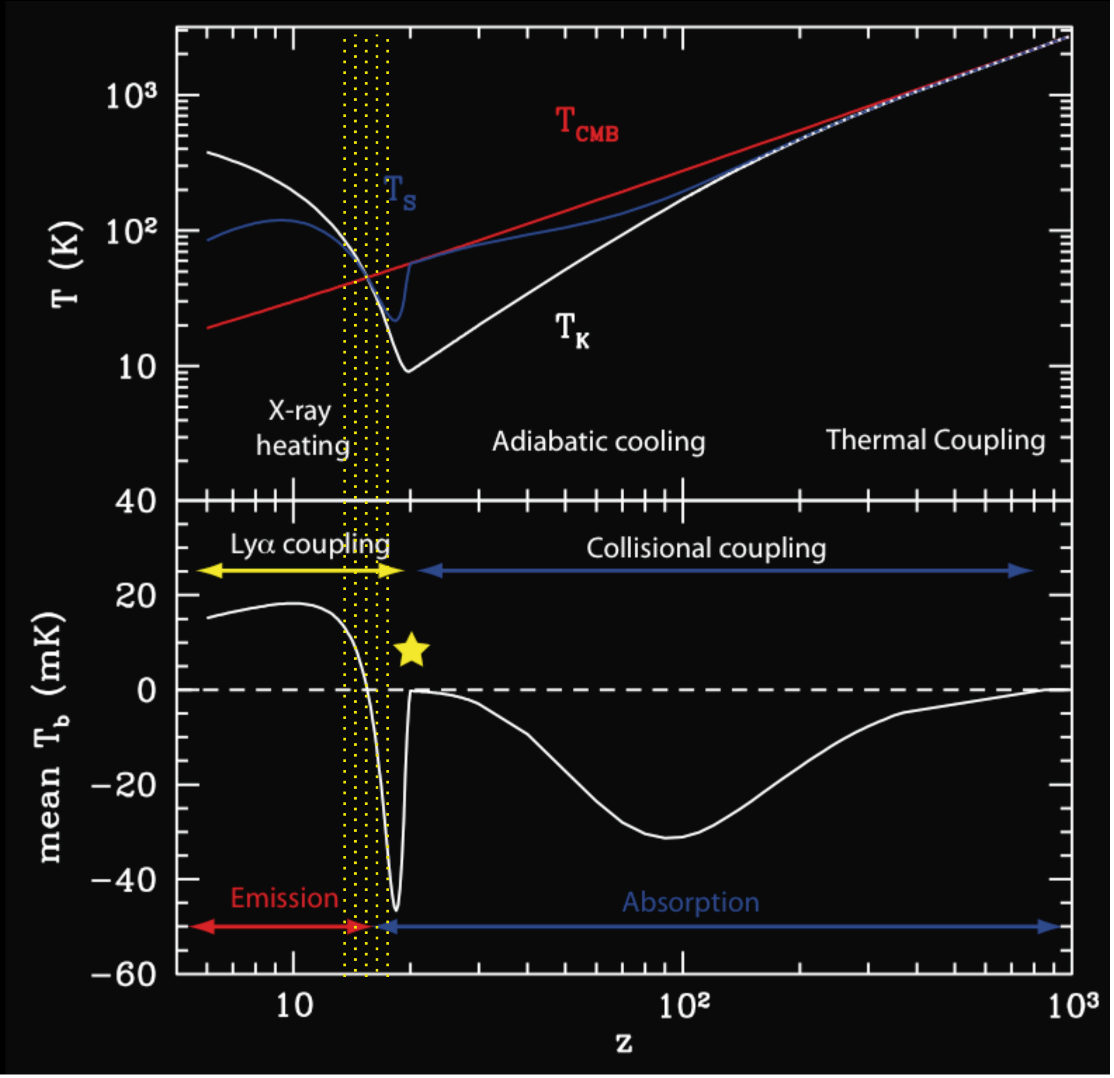
- Future galaxy surveys should be able to place interesting constraints on the effect of ionization regions on galaxy formation
- Bubbles shouldn’t provide a major source of noise when attempting to constrain dark energy parameters
- Some numerical issues need to be addressed
- Need to explore different shapes for bubble power spectrum
- Have explored statistical errors from including bubbles, but there will be a systematic change in maximum likelihood parameters as well. How can this be quantified?
- Toy model used - would be nice to make a connection to the underlying physics e.g. Babich & Loeb 2005

Inhomogeneous X-ray Heating

Jonathan Pritchard
Steve Furlanetto
(Caltech)
Proposed work…

Inhomogeneous X-ray heating

- X-rays are responsible for heating the IGM above the CMB temperature
- Heating usually assumed to be uniform
- Simplistic, fluctuations may lead to observable 21cm signal
- Analogous to Lyα fluctuations



Calculation

- Model star formation to calculate X-ray flux variation (Barkana & Loeb 2005)
- Convert X-ray flux to temperature perturbations (Shull & Van Steenberg 1985)
- Calculate resulting 21cm T_b signal
- Compare with temperature variation from overdense regions e.g. from photo-ionization equilibrium (Nasser 2005)

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

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

Density + x-ray

Lyα coupling saturated

IGM still mostly neutral

Future work z=0

- Inhomogeneous X-ray heating as a source of 21 cm brightness temperature fluctuations
- Graduate June 2007!