Rayleigh scattering:

blue sky thinking for future CMB observations

arXiv:1307.8148; previous work: Takahara et al. 91, Yu, et al. astro-ph/0103149

http://en.wikipedia.org/wiki/Rayleigh_scattering

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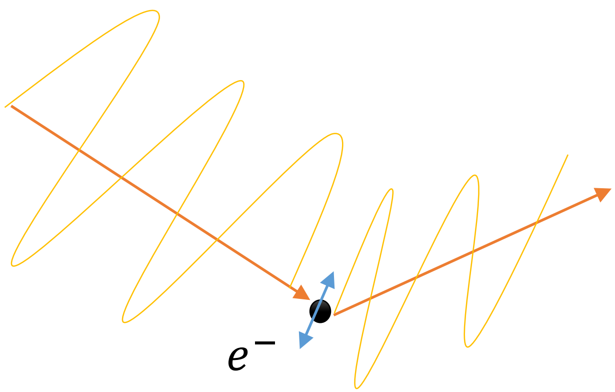
Classical dipole scattering

Oscillating dipole $\boldsymbol{p} = p_0 \sin(\omega t)\,\hat{\boldsymbol{z}} \Rightarrow$ radiated power $\propto \omega^4 p_0^2 \sin^2\theta\, \mathrm{d}\Omega$

Thomson Scattering

$$m_e \ddot{z} = -eE_z \sin\omega t$$
$$\Rightarrow \boldsymbol{p} = \frac{-e^2 E_z}{m_e \omega^2} \sin\omega t\ \hat{\boldsymbol{z}}$$



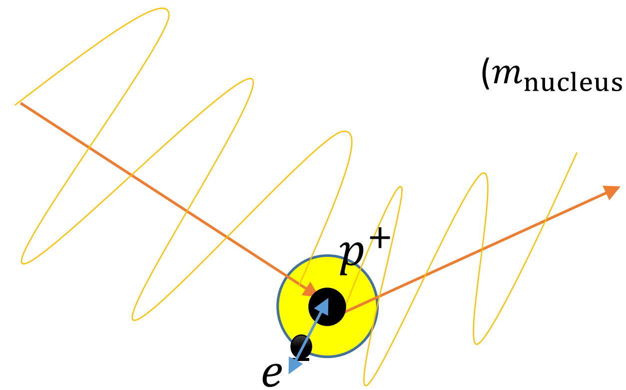
Frequency independent
Given by fundamental constants:

$$\sigma_T = \frac{8\pi}{3}\left(\frac{e^2}{4\pi\epsilon_0 m_e c^2}\right)^2$$

Rayleigh Scattering

$$m_e \ddot{z} = -eE_z \sin\omega t - m_e \omega_0 z$$
$$\Rightarrow \boldsymbol{p} = \frac{-e^2 E_z}{m_e(\omega^2 - \omega_0^2)} \sin\omega t\ \hat{\boldsymbol{z}}$$

$(m_{\text{nucleus}} \gg m_e)$



Frequency dependent
Depends on natural frequency ω_0 of target

$$\sigma_R \approx \frac{\omega^4}{\omega_0^4} \sigma_T \qquad (\omega \ll \omega_0)$$

http://farside.ph.utexas.edu/teaching/em/lectures/node95.html

Photon scattering rate

Total cross section ≈ $$\Gamma(\nu) = n_e\sigma_T + \sigma_R(\nu)\left[n_H + R_{He}n_{He}\right]$$

$$\sigma_R(\nu) = \left[\left(\frac{\nu}{\nu_{\rm eff}}\right)^4 + \frac{638}{243}\left(\frac{\nu}{\nu_{\rm eff}}\right)^6 + \frac{1626820991}{136048896}\left(\frac{\nu}{\nu_{\rm eff}}\right)^8 + \dots\right]\sigma_T$$

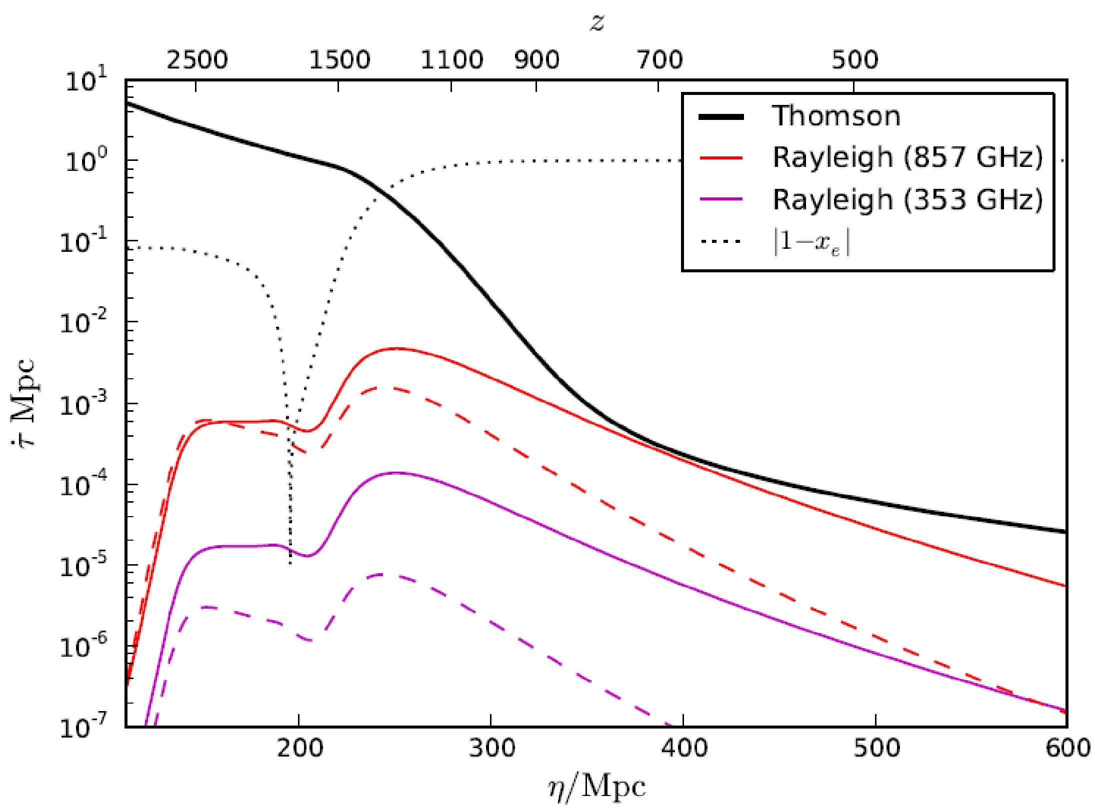
$$\nu_{\rm eff} \equiv \sqrt{\frac{8}{9}}\,c\,R_A \approx 3.1\times 10^6\,\text{GHz} \quad , R_{He} \approx 0.1$$

(Lee 2005: Non-relativistic quantum calculation, for energies well below Lyman-alpha)

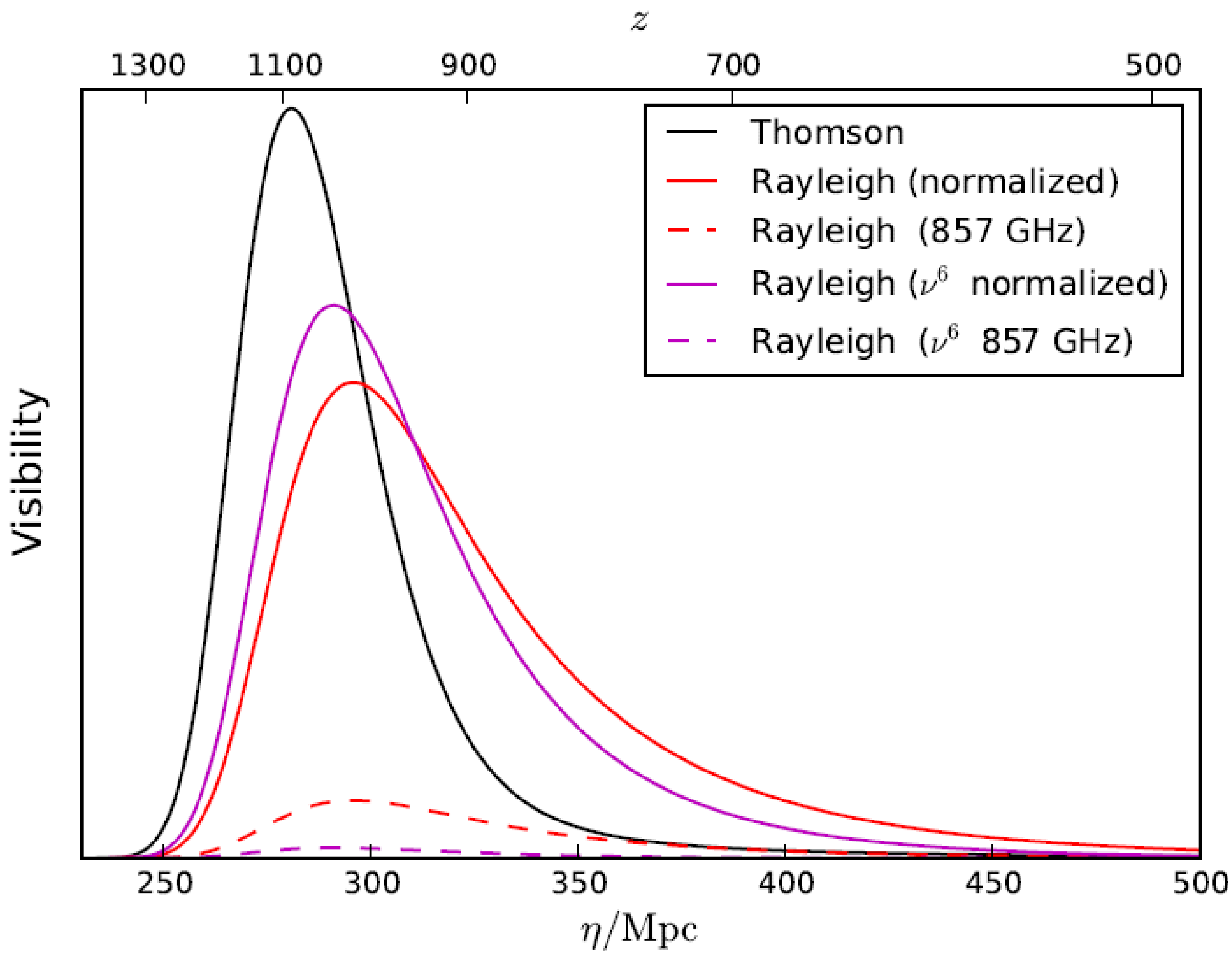
$$\dot\tau = \Gamma/(1+z)$$

Rayleigh only negligible compared to Thomson for

$$n_H\left(\frac{(1+z)\nu_{\rm obs}}{3\times10^6\,\text{GHz}}\right)^4 \ll n_e$$



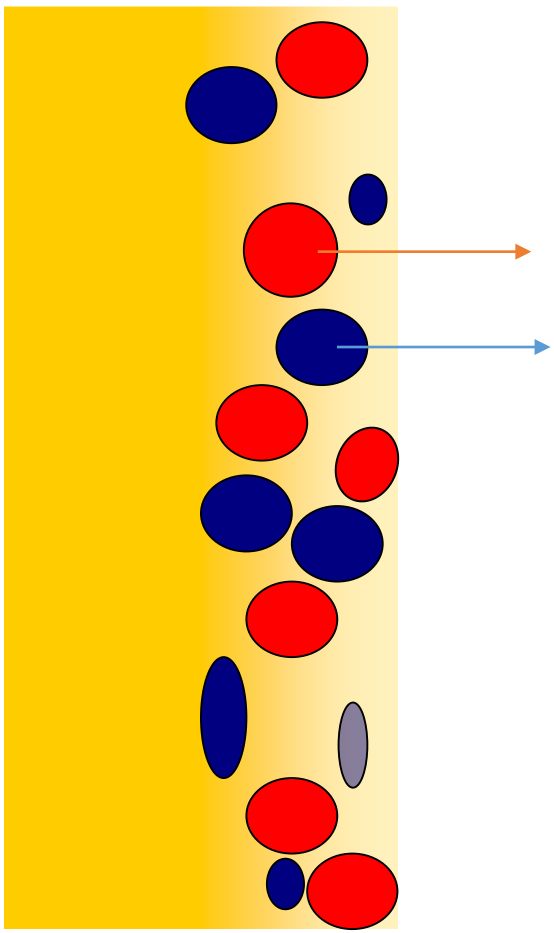
Visibility



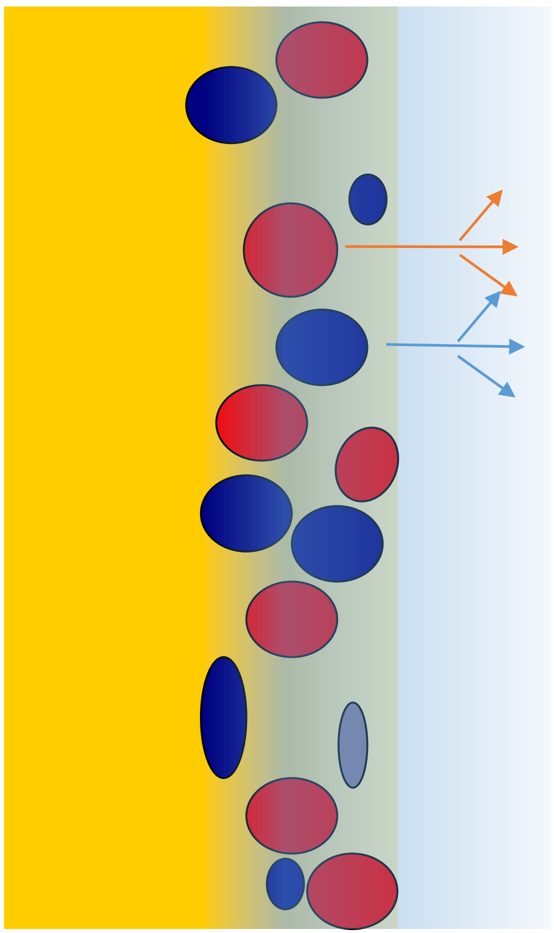
z
1300
1100
900
700
500
Thomson
Rayleigh (normalized)
Rayleigh (857 GHz)
Rayleigh (ν^6 normalized)
Rayleigh (ν^6 857 GHz)
Visibility
250
300
350
400
450
500
η/Mpc

Small-scale CMB

Primary signal



Primary + Rayleigh signal



Rayleigh difference signal: (photons scattered in to line of sight) – (scattered out)

$$\sim \tau_R \, \Delta T$$

Small-scale CMB cont.

Hot spots are red, cold spots are blue

Polarization is scattered and is red too

Rayleigh signal highly correlated to primary. Several percent effect at high frequencies. 'Easily' detectable in future missions (potentially even 5σ with Planck)

Note: multiple frequencies ⇒ no cosmic variance from primary CMB (difference = Rayleigh+Forgrounds+Noise)

⇒ Test of expansion and ionization history at recombination

Large-scale CMB temperature

Rayleigh signal only generated by sub-horizon scattering
(no Rayleigh monopole background to distort by anisotropic photon redshifting)

$$\frac{\Delta T_0}{T}(\hat{\mathrm{n}}) = \frac{\Delta_\gamma(\eta_*)}{4} + \underbrace{\Psi(\eta_*) - \Psi_0}_{\text{Sachs-Wolfe}} + \underbrace{\hat{\mathrm{n}} \cdot (\mathrm{v}_o - \mathrm{v})}_{\text{Doppler}} + \underbrace{\int_{\eta_*}^{\eta_0} d\eta (\Psi' + \Phi')}_{\text{ISW}}$$

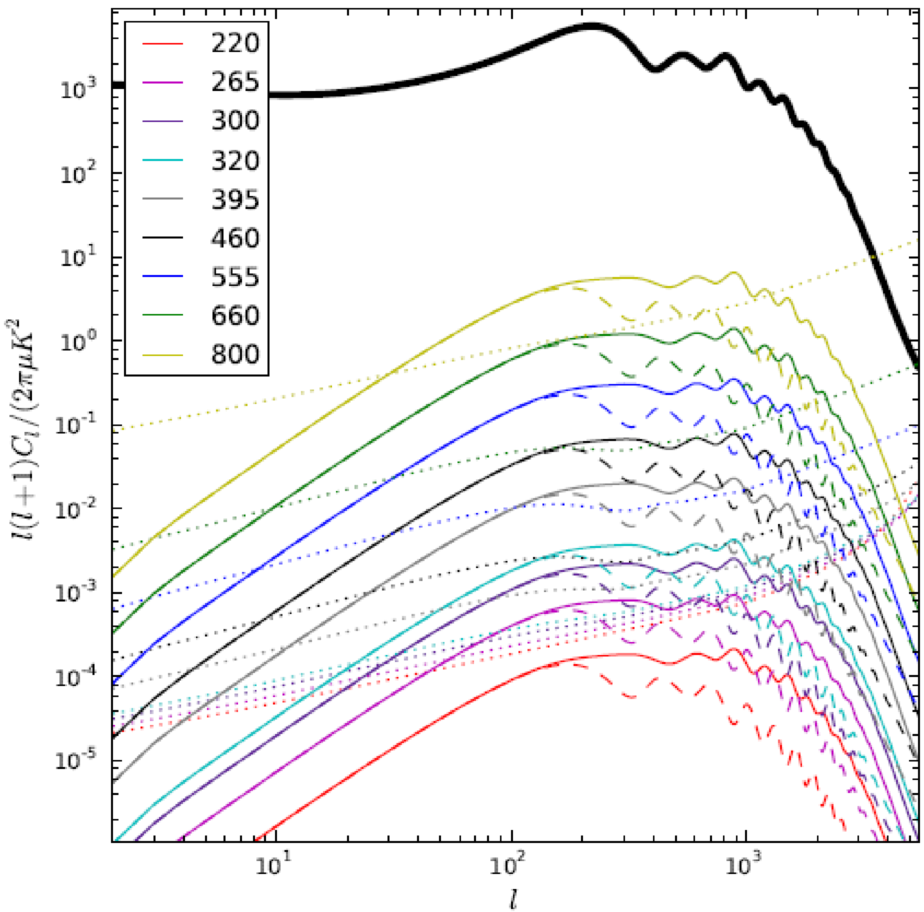
Temperature
perturbation at
recombination
(Newtonian Gauge)

Rayleigh scattering probes Doppler terms independently of SW/ISW

Measure new primordial modes with Rayleigh× Rayleigh spectrum?

In principle could double number of modes compared to T+E!

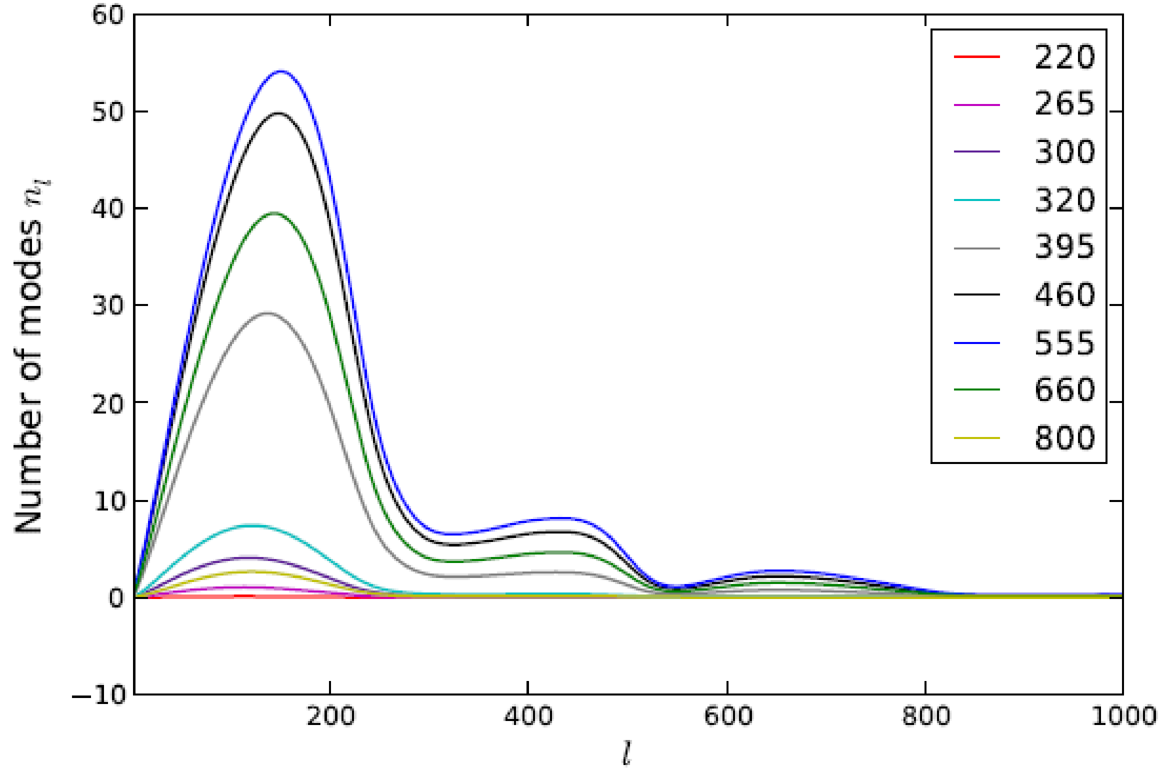
BUT: signal highly correlated to primary on small scales; need the uncorrelated part



Solid: Rayleigh× Rayleigh total; Dashed: uncorrelated part; Dots: error per $\frac{\Delta l}{l} = 10$ bin a from PRISM

Number of new modes with PRISM

Define $n_l \equiv (2l+1) f_{\rm sky} \mathrm{Tr}\left[\left([\boldsymbol{C}_l + \boldsymbol{N}_l]^{-1} \boldsymbol{C}_l \right)^2 \right]$



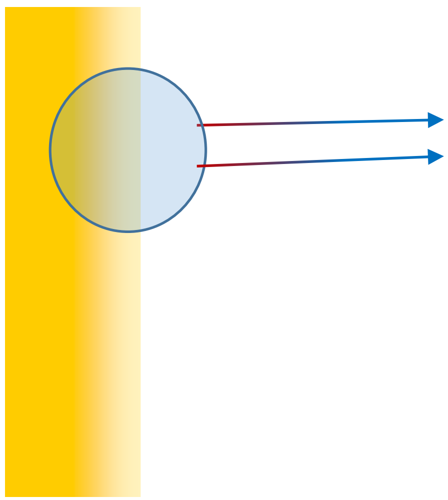
New modes almost all in the $l \leq 500$ temperature signal: total $\approx 10\,000$ extra modes

More horizon-scale information (disentangle Doppler and Sachs-Wolfe terms)

Would need much higher sensitivity to get more modes from polarization/high l

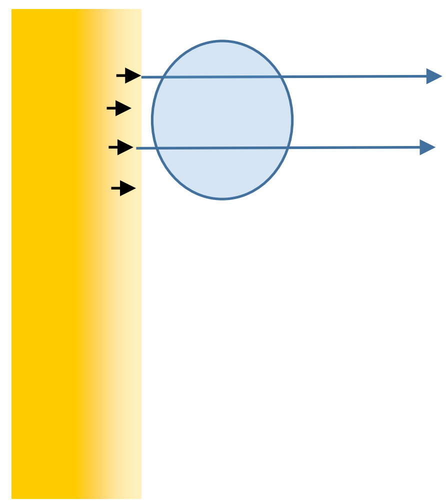
Three nearly-independent perturbation modes being probed

$\frac{\Delta T}{T} + \Phi + \mathrm{ISW}$
(anisotropic redshifting to constant temperature recombination surface)



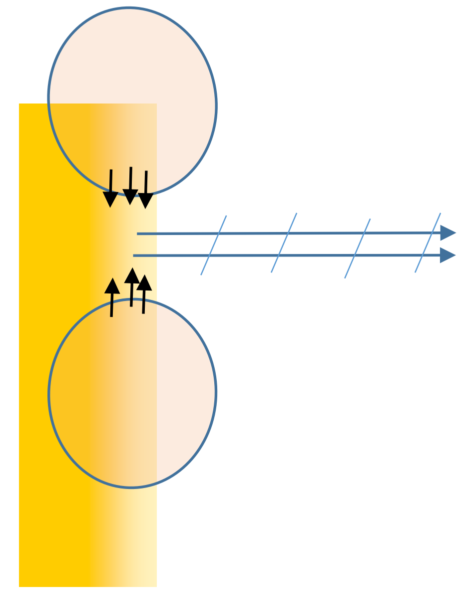
Primary

$\hat{\mathrm{n}} \cdot \mathrm{v_b}$: Doppler



Rayleigh, Primary

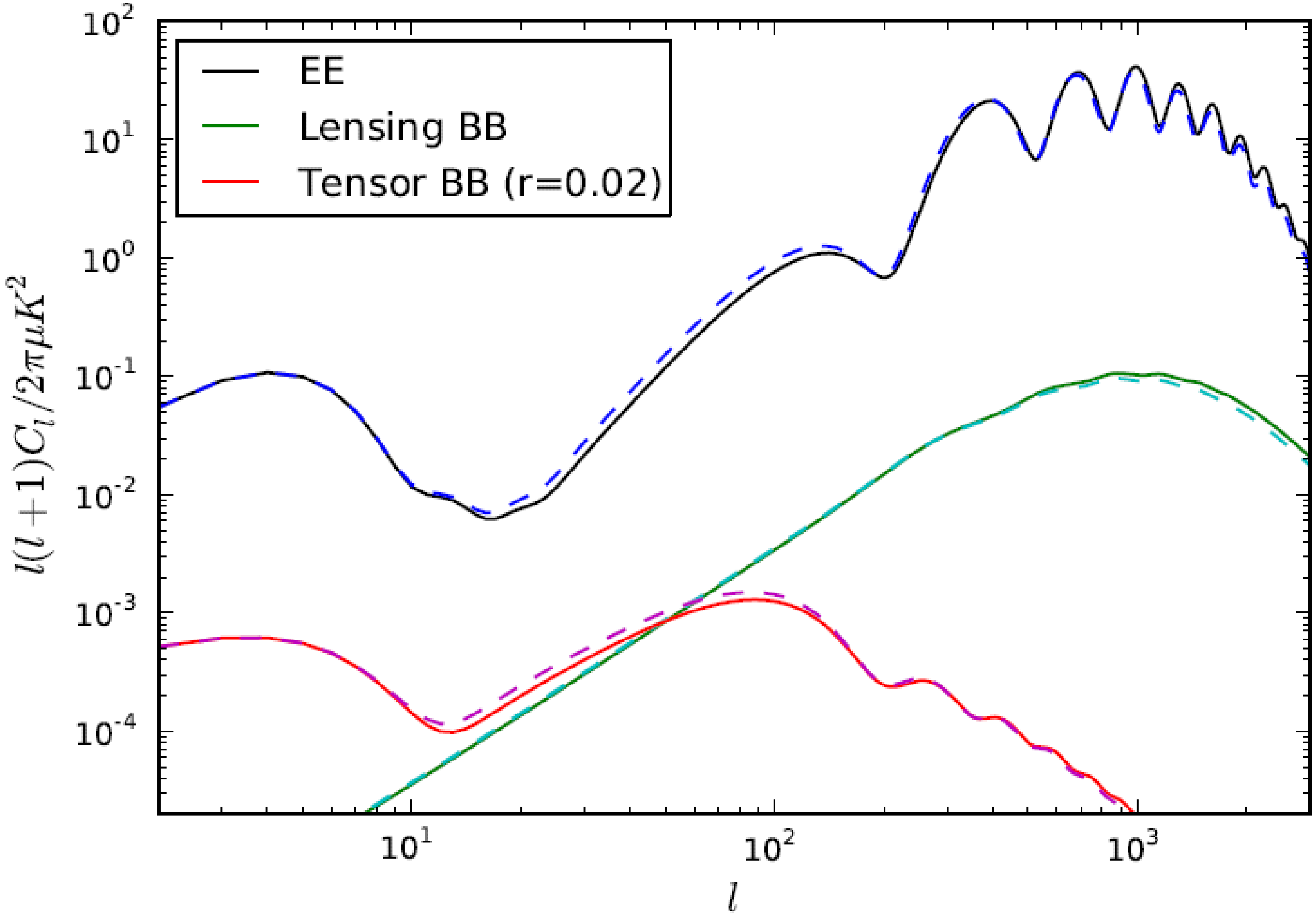
Polarization from quadrupole scattering



Rayleigh, Primary

Rayleigh polarization power spectra

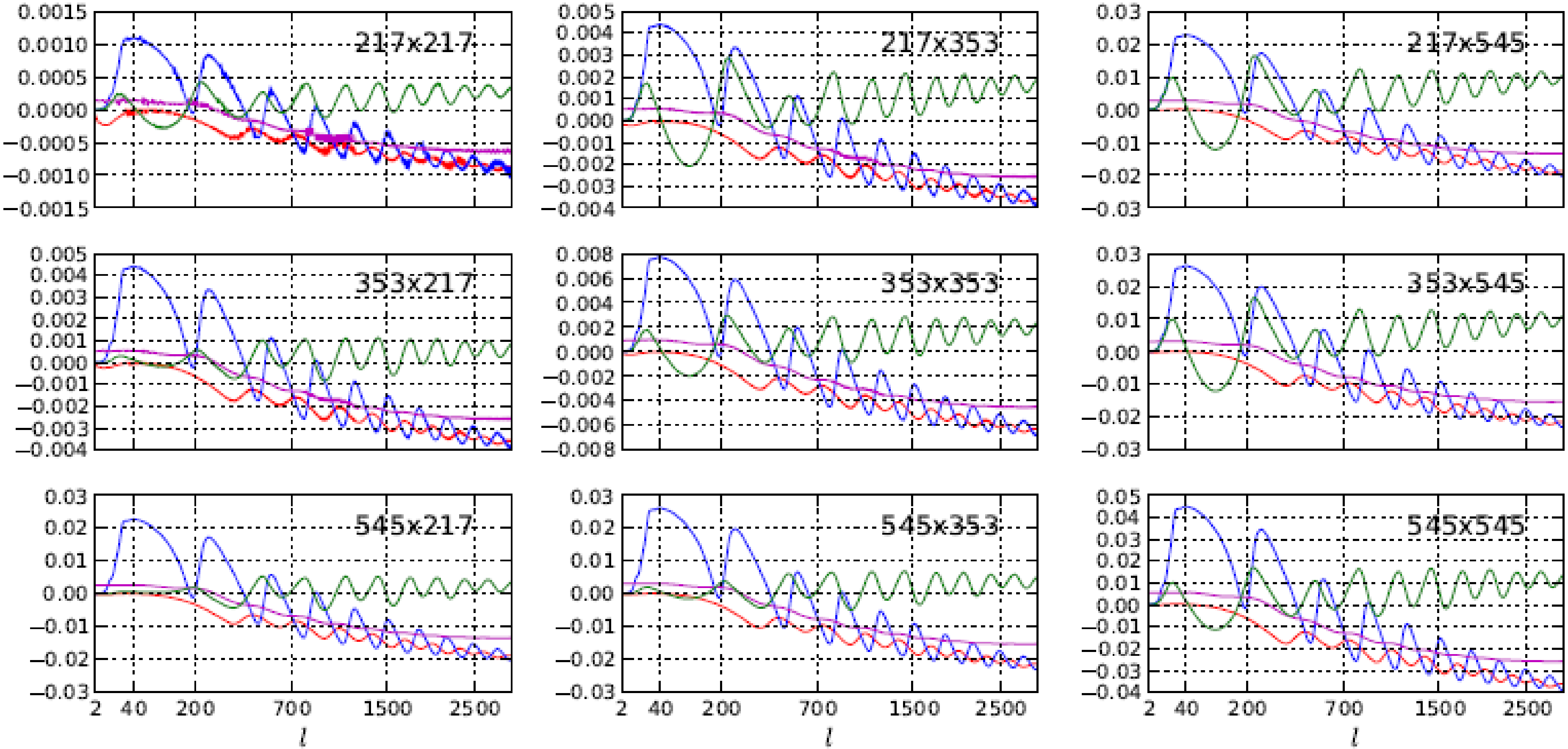
Solid: primary　　　　　Dashed: primary + Rayleigh (857GHz)



Large-scale polarization from scattering into the line of sight ⇒ polarized CMB sky is blue

but same quadrupole, so highly correlated to primary

Fractional total C_L differences at realistic frequencies



TT, **EE**, **BB**: $\frac{\Delta C_l}{C_l}$

TE: $\frac{\Delta C_l^{TE}}{\sqrt{C_l^{EE} C_l^{TT}}}$

Conclusions

- Significant Rayleigh signal at $\nu \geq 200$ GHz; several percent on T, E at $\nu \geq 500$GHz
- Strongly correlated to primary signal on small scales (mostly damping)
  – robust detection via cross-correlation?
- Powerful test of recombination physics/expansion
- Boosts large-scale polarization (except B modes from lensing)
- Multi-tracer probe of last-scattering
  - limited by noise/foregrounds, not cosmic variance
- May be able to provide additional primordial information (10,000+ modes)
  - mostly horizon-scale T modes at recombination from Doppler signal
  - degree scales, could measure with low-res FTS in space (a la Pixie)?

Question:

How well can foregrounds be removed/how large is uncorrelated foreground noise? (CIB, dust..)

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Rayleigh scattering: blue sky thinking for future CMB observations

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Abstract. Rayleigh scattering from neutral hydrogen during and shortly after recombination causes the CMB anisotropies to be significantly frequency dependent at high frequencies. This may be detectable with *Planck*, and would be a strong signal in any future space-based CMB missions. The later peak of the Rayleigh visibility compared to Thomson scattering gives an increased large-scale CMB polarization signal that is a greater than 4% effect for observed frequencies $\nu \gtrsim 500$GHz. There is a similar magnitude suppression on small scales from additional damping. Due to strong correlation between the Rayleigh and primary signal, measurement of the Rayleigh component is limited by noise and foregrounds, not cosmic variance of the primary CMB, and should observable over a wide range of angular scales at frequencies $200\text{GHz} \lesssim \nu \lesssim 800\text{GHz}$. I give new numerical calculations of the temperature and polarization power spectra, and show that future CMB missions could measure the temperature Rayleigh cross-spectrum at high precision, detect the polarization from Rayleigh scattering, and also accurately determine the cross-spectra between the Rayleigh temperature signal and primary polarization. The Rayleigh scattering signal may provide a powerful consistency check on recombination physics. In principle it can be used to measure additional horizon-scale primordial perturbation modes at recombination, and distinguish a significant tensor mode B-polarization signal from gravitational lensing at the power spectrum level.

Keywords: CMBR theory, CMBR polarisation, CMBR experiments, recombination

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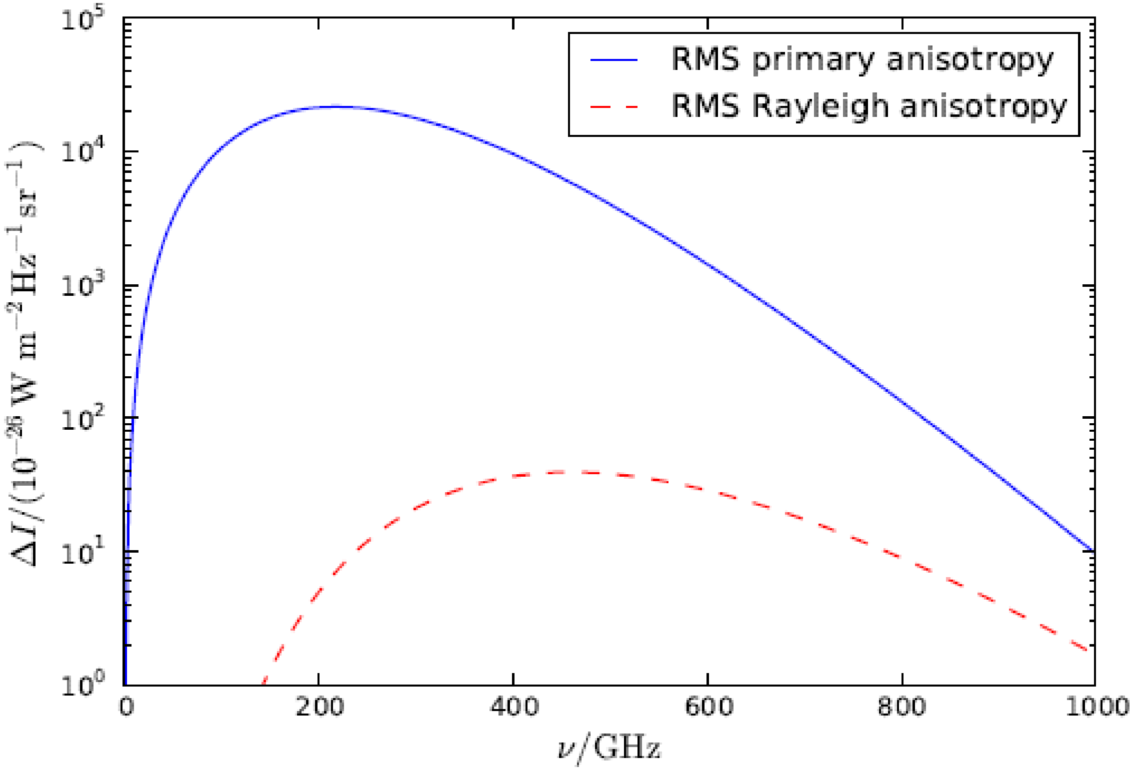
Expected signal as function of frequency

Zero order: uniform blackbody not affected by Rayleigh scattering (elastic scattering, photons conserved)

1st order: anisotropies modified, no longer frequency independent



May be detectable signal at $200\mathrm{GHz} \leq \nu \leq 800\mathrm{GHz}$