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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Photon scattering rate

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

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

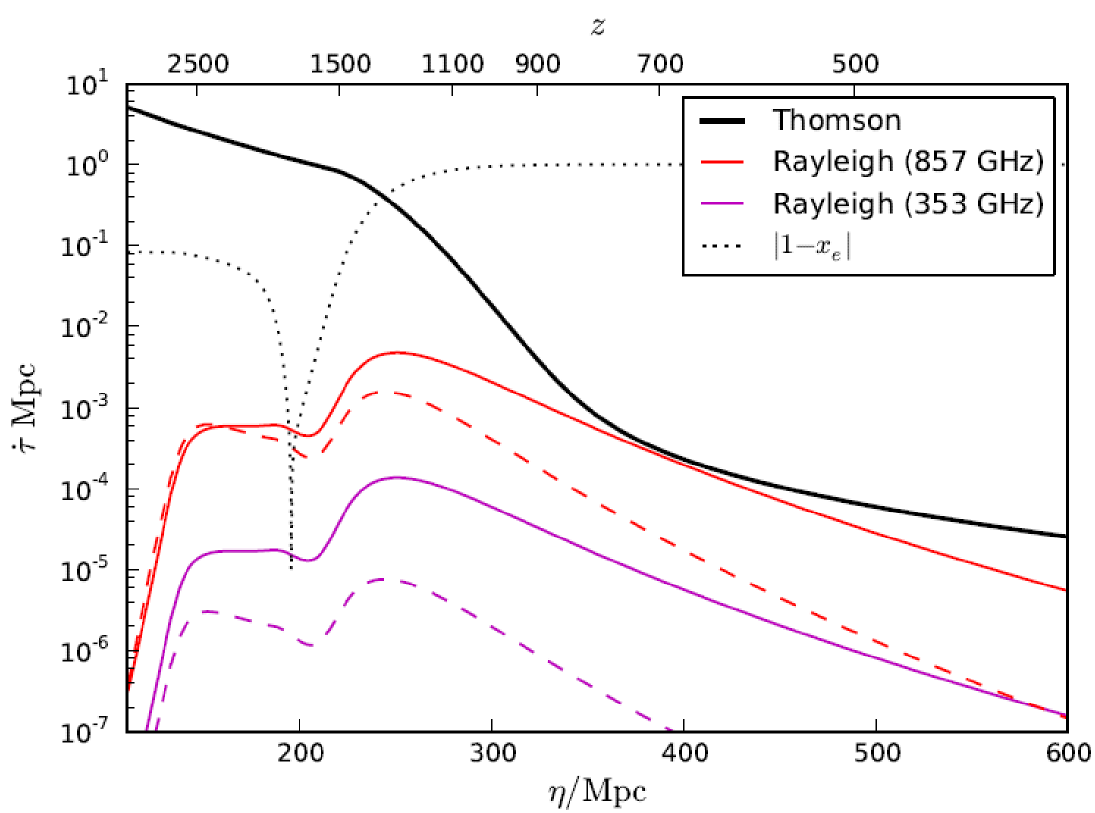
$$\nu_{\rm eff} \equiv \sqrt{\frac{8}{9}}\, c\, R_A \approx 3.1 \times 10^6 \,\text{GHz} \quad , R_{He} \approx 0.1$$

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

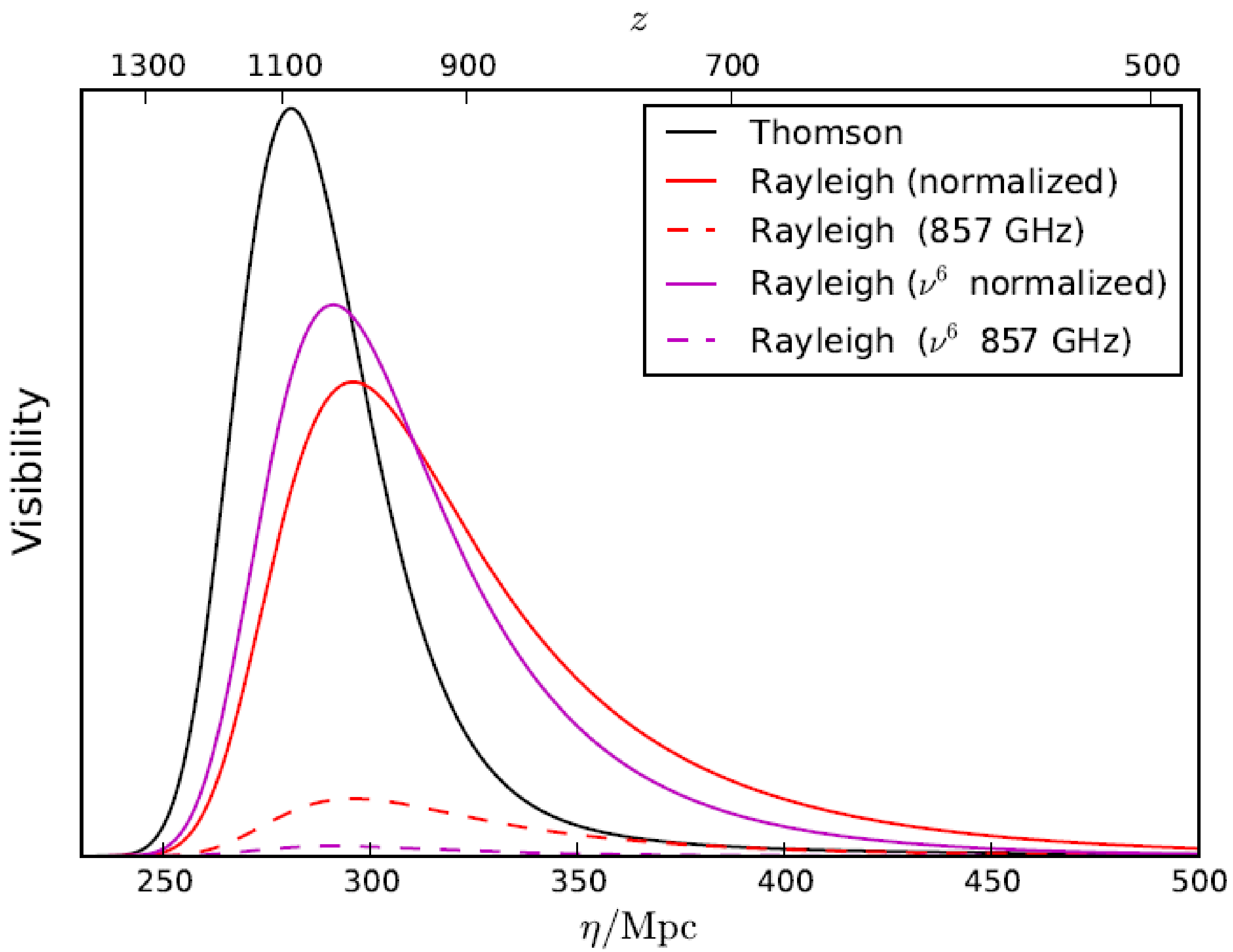
$$\dot{\tau} = \Gamma/(1+z)$$

Rayleigh only negligible compared to Thomson for

$$n_H \left(\frac{(1+z)\nu_{\rm obs}}{3\times 10^6 \,\text{GHz}}\right)^4 \ll n_e$$



Visibility

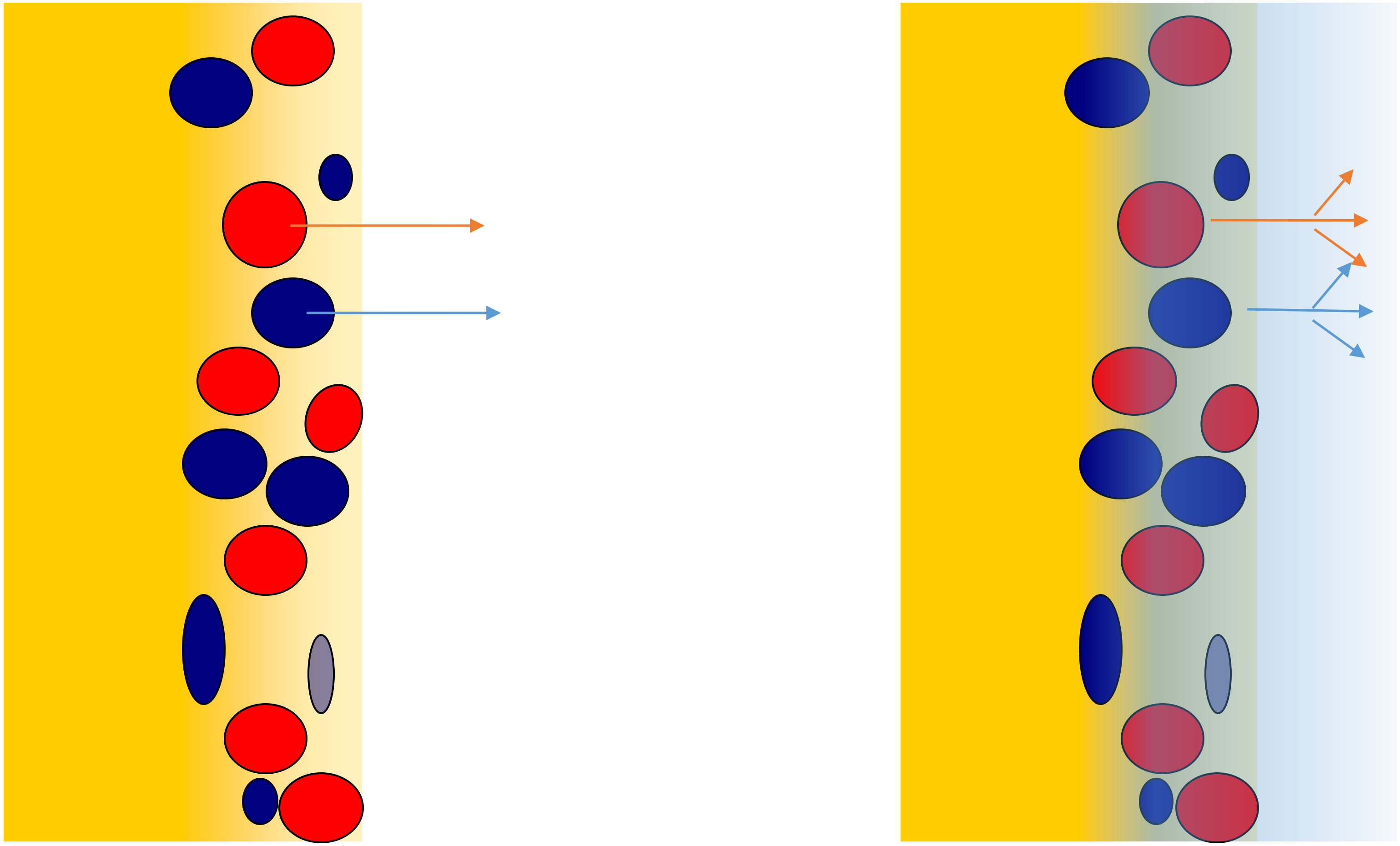


z
1300
1100
900
700
500
Thomson
Rayleigh (normalized)
Rayleigh (857 GHz)
Rayleigh (ν^6 normalized)
Rayleigh (ν^6 857 GHz)
Visibility
250
300
350
400
450
500
η/Mpc

Small-scale CMB

Primary signal

Primary + Rayleigh signal



Rayleigh temperature power spectrum

$$(\text{Primary+Rayleigh})^2 = \text{Primary}^2 + 2\ \text{Primary} \times \text{Rayleigh}\ + \text{Rayleigh}^2$$

Small-scales: main effect is percent-level additional damping

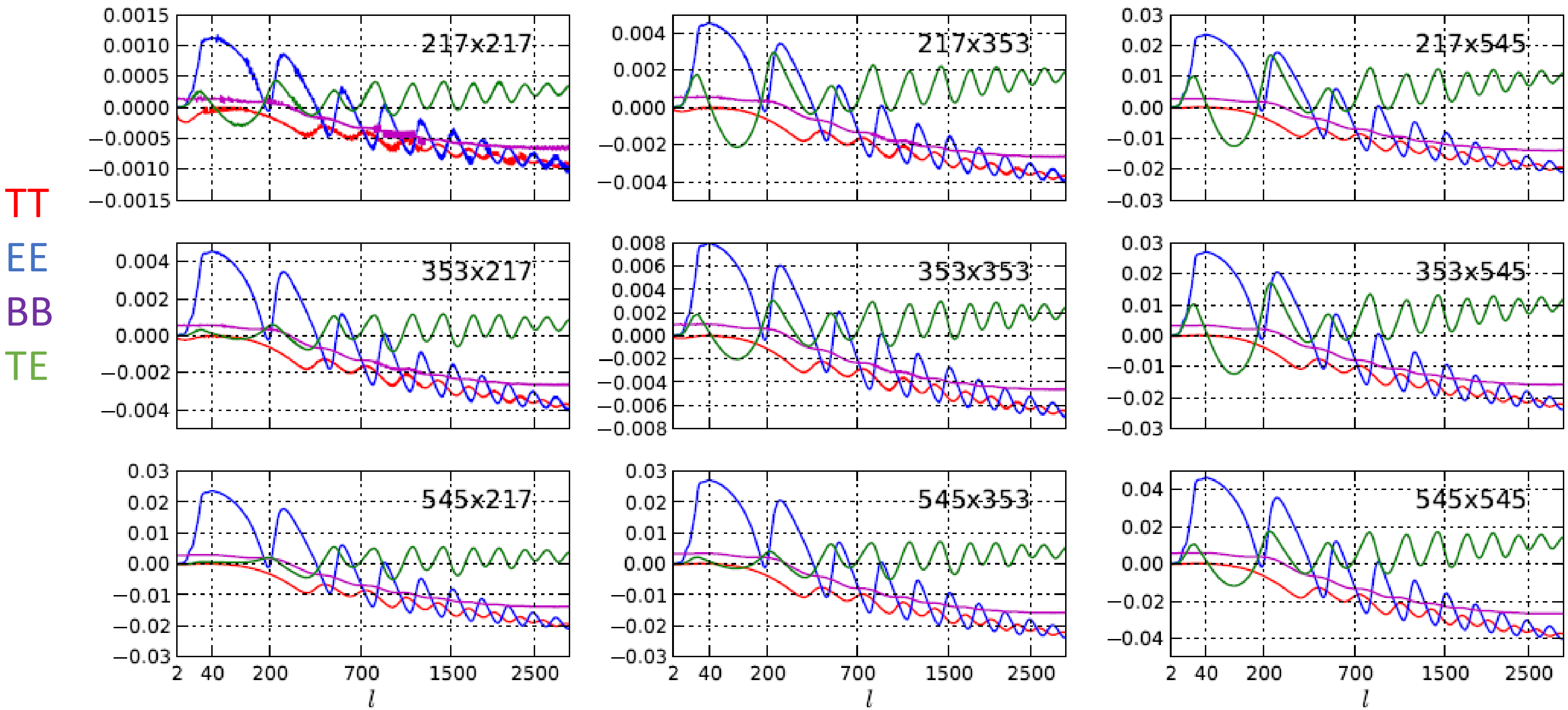


FIG. 5: Fractional difference between the lensed scalar CMB power spectra $C_l^{X_i Y_j}$ for observed frequencies 217, 353 and 545 GHz, compared to the primary (low-frequency) power spectra. Each plot shows the fractional difference $\Delta C_l / C_l$ for temperature (red), E-polarization (blue) and B-polarization (magenta), and $\Delta C_l^{TE} / \sqrt{C_l^{EE} C_l^{TT}}$ for the T-E cross-correlation spectra (green). Each plot is a different pair of frequencies, and the results above and below the diagonal are the same except for the $C_l^{T_i E_j}$ correlation (green) which is not symmetric. Note that a small fractional difference does not necessarily mean that the signal is unobservable, since detectability is only limited by noise (and foregrounds); conversely a relatively large fractional difference in the polarization is not observable unless the noise is low enough.

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)

Sachs-Wolfe

Doppler

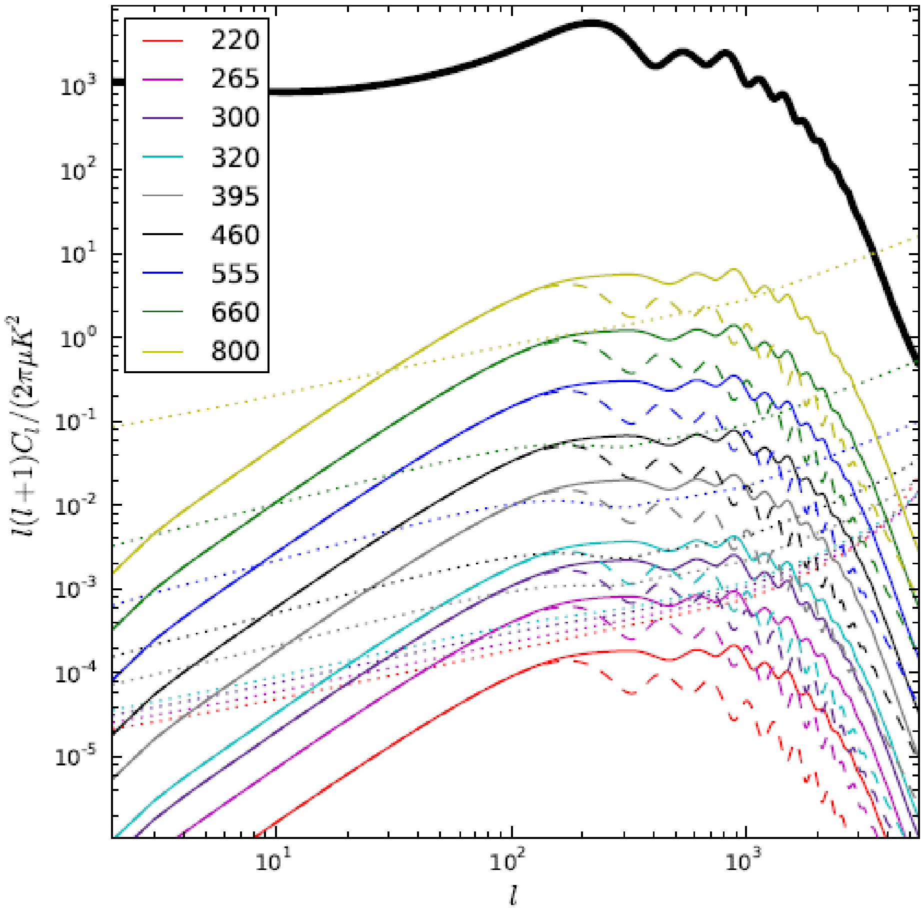
ISW

➡ 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!

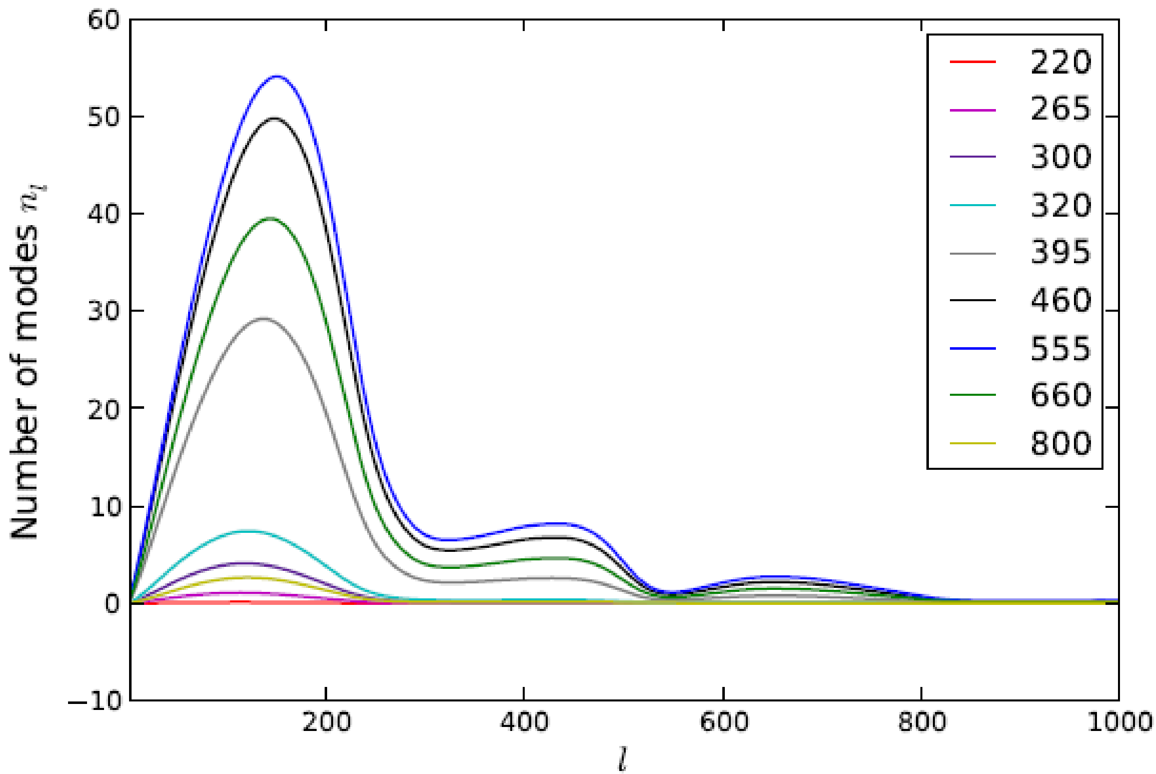
BUT: signal highly correlated to primary on small scales; need the uncorrelated part



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



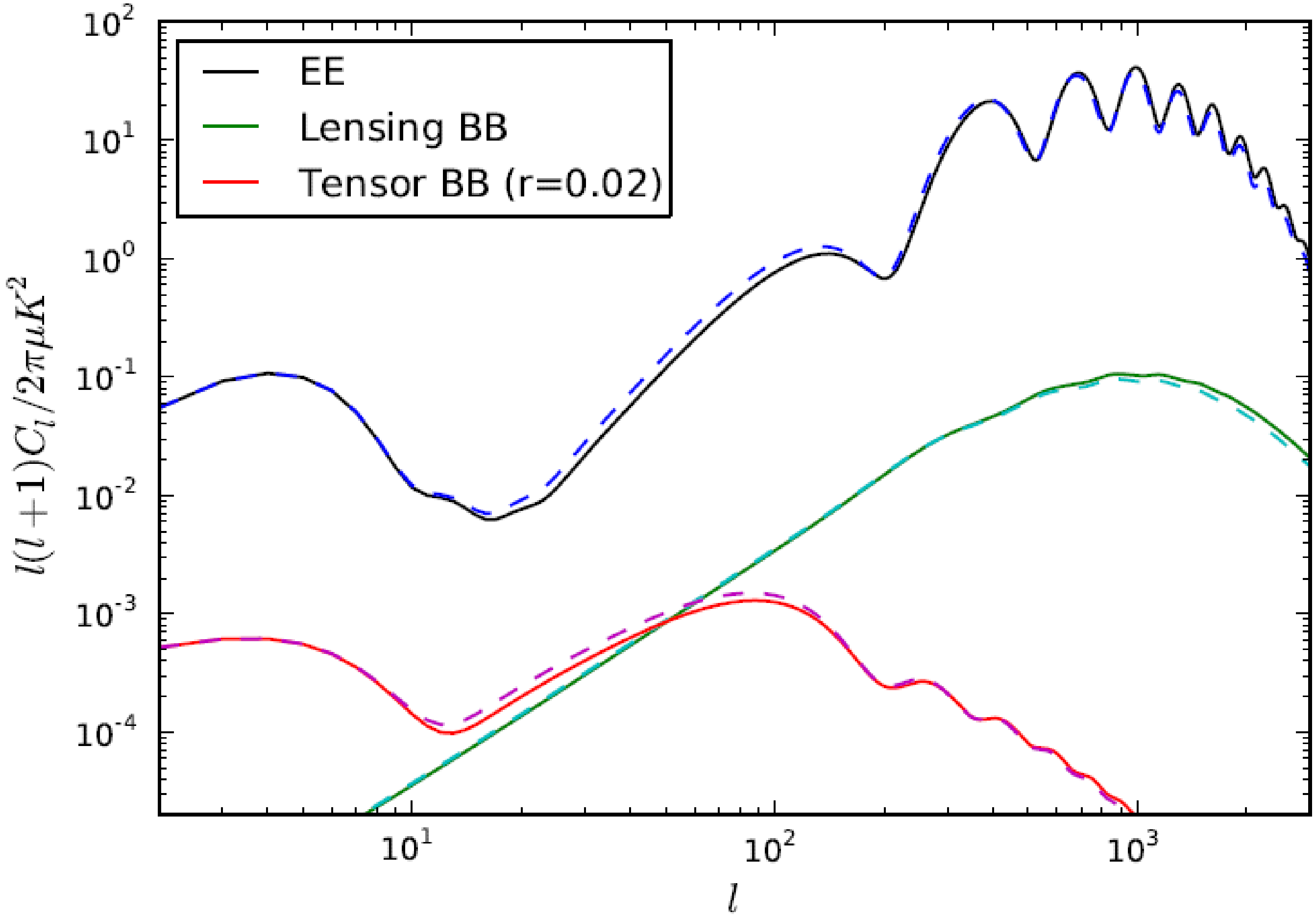
New modes almost all in the $l \leq 500$ temperature signal: total $\approx 10\ 000$ extra modes

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

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

Rayleigh polarization power spectra

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

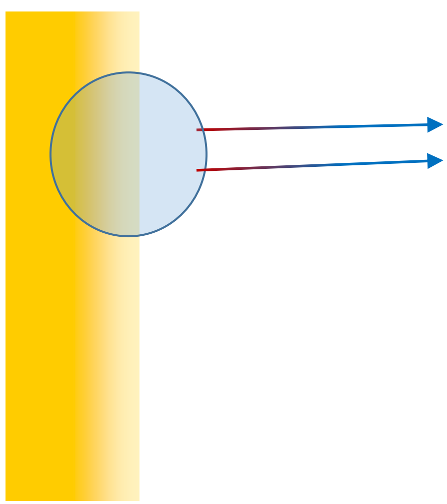


Large-scale polarization from scattering into the line of sight ⇒ polarized CMB sky is blue

but same quadrupole, so highly correlated to primary

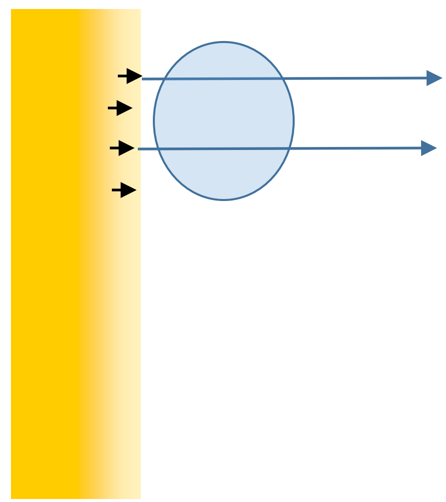
Three nearly-independent perturbation modes being probed on intermediate scales

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



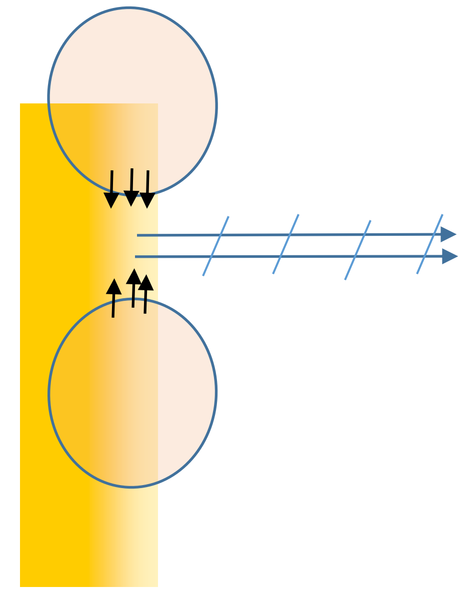
Primary

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



Rayleigh, Primary

Polarization from quadrupole scattering

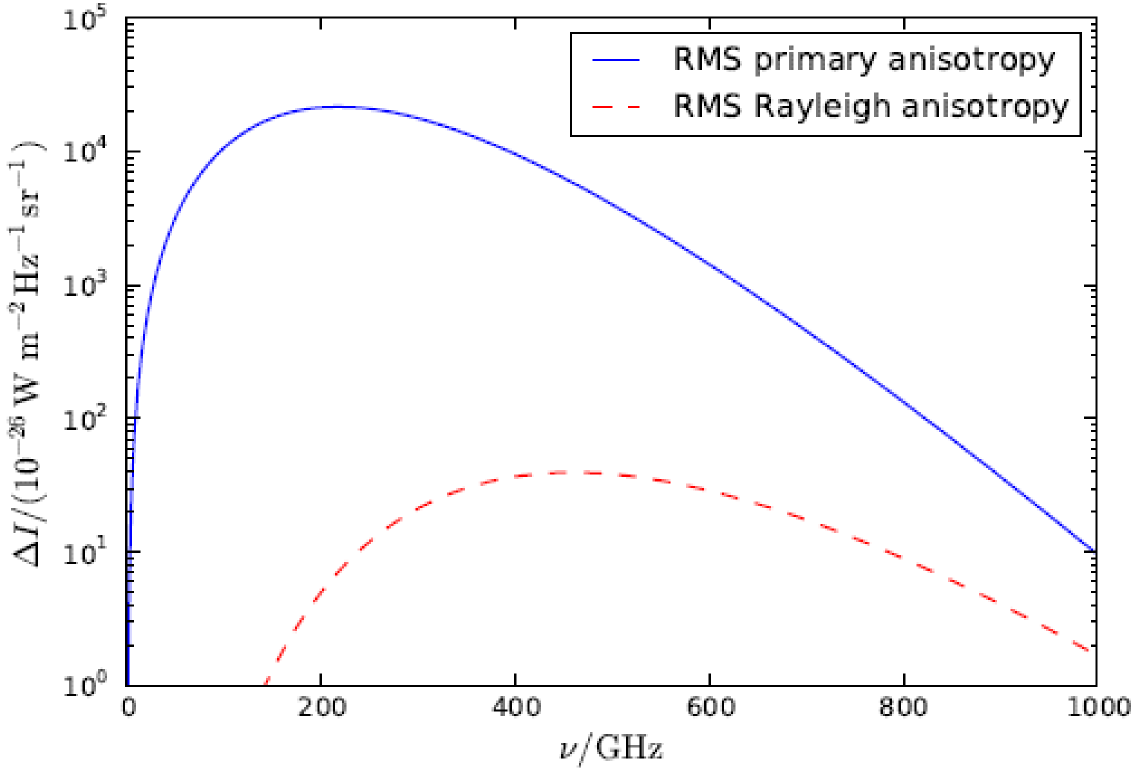


Rayleigh, Primary

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

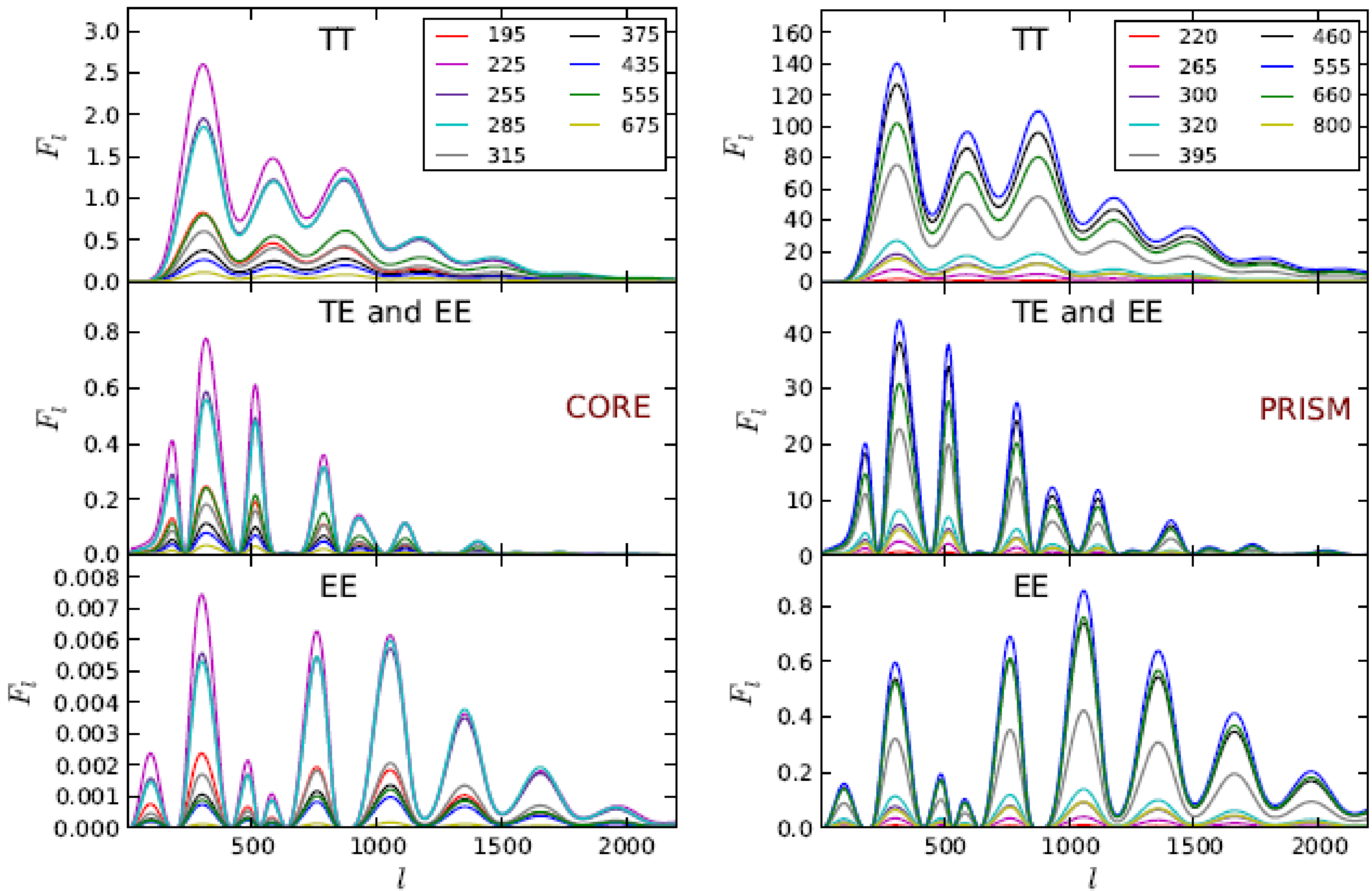


Need sensitivity at $200\mathrm{GHz} \leq \nu \leq 800\mathrm{GHz}$

(+probably higher for foreground separation efficiency; very hard above 350GHz from ground)

Fisher signal per frequency channel

(assuming no foreground separation uncertainty)



Conclusions

Is it worth measuring?

- Sure-fire signal, probably only marginally detectable with Planck if at all
- Very hard to measure from ground-based CMB (with $\nu <\sim 300\mathrm{Ghz}$)
- Check on understanding of recombination (and hence all parameter inferences)
- 'easy' robust detection of correlated signal by low-high frequency correlation
- Up to 10,000 new inflation modes on quite large scales (anomalies?)
- Similar fractional effect on polarization signal
- *Not optional* (need to model for high frequency T,Q,U to do other science)

But:

- Most of the signal is highly correlated to primary and accurately predicted
  (cool to measure correlated signal, but fundamentally nothing new)

- Fractional increase in information from new modes is small
  (and requires closer to PRISM than CORE sensitivities at $\nu \sim 500\mathrm{GHz}$)

- Can systematics/foregrounds be low enough to measure new modes?

To do well: good sensitivity at 300 Ghz $< \nu <$ 700 GHz + good foreground separation