arXiv:2606.09491v1

Spectral distortion anisotropies from photon to dark photon conversions

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CMB Spectral Distortions

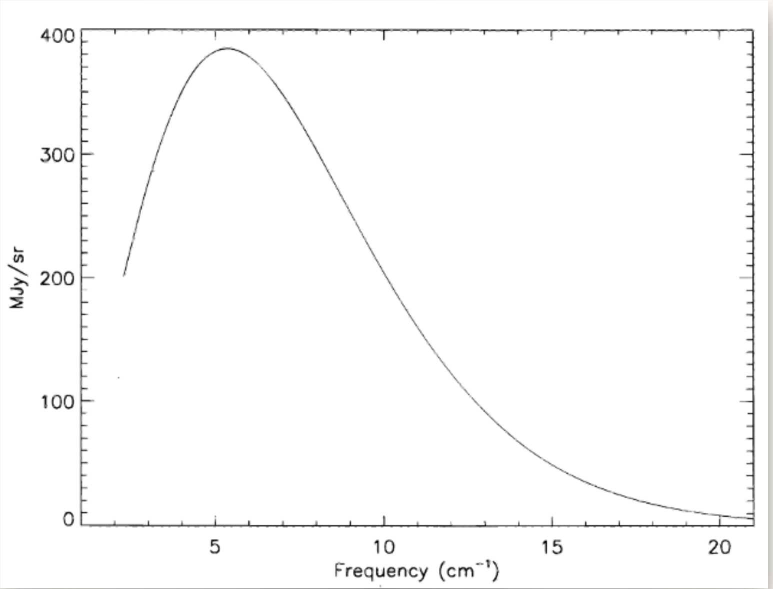
COBE/FIRAS observations:

- The CMB photons follow a blackbody distribution with

$$T_0 = 2.725 \pm 0.001\mathrm{K}$$

- Departures from a perfect blackbody are present, with an upper limit: $$\frac{\Delta I}{I} \leq 10^{-5}$$

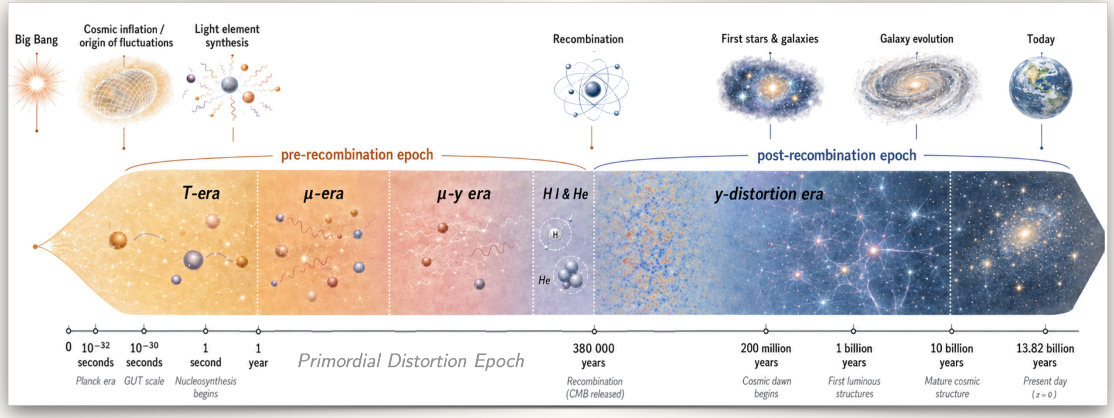
Fixsen et al., 1996



They contain fundamental information on the thermal history of the early Universe

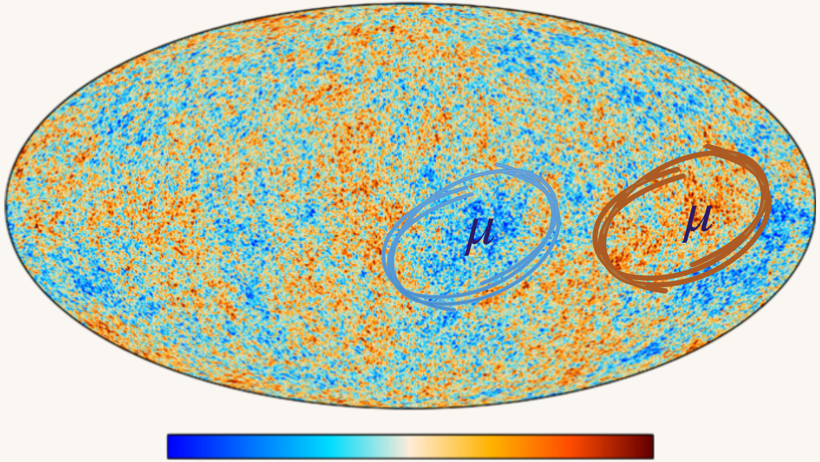
How are they generated?

- Energy injections and production of energetic particles at early times
- Compton scattering (CS), Double Compton scattering (DC) and Breemstrahlung (BR) tend to thermalise the spectrum
- If it fully thermalises we get a temperature shift G(x) with amplitude $\theta = \Delta T/T$



Credit: Dr. Bryce Cyr

Let's go anisotropic



Solving for all k modes is computationally challenging!!

- SDs can also provide space-dependent information
- Caused by anisotropic heating (e.g. SZ effect) and evolution
- Extension of the temperature anisotropies formalism

A new spectral basis

The problem simplifies if we define a new analytical basis to parametrise spectral distortions:

$$G(x) = \hat{O}_x n_{\rm bb} = \frac{xe^x}{(e^x-1)^2}, \qquad M(x) = G(x)\left[\frac{1}{\beta_M} - \frac{1}{x}\right], \qquad Y(x) = G(x)\left[\frac{e^x+1}{e^x-1} - 4\right],$$

Temperature shift

μ-distortion

y-distortion

$$Y_k = (1/4)^k \hat{O}_x^k Y \qquad \hat{O}_x = -x\partial_x \qquad x = \frac{h\nu}{kT}$$

Boost operator

Dimensionless frequency variable

$$\boxed{\Delta n = \mathbf{B}\cdot\mathbf{y}, \qquad \mathbf{B} = (G, Y_0, Y_1, \ldots, Y_N, M)^T, \qquad \mathbf{y} = (\Theta, y_0, y_1, \ldots, y_N, \mu)^T}$$

Standard Photon Hierarchy

$$\frac{\partial \Theta^{(1)}}{\partial t} + \frac{c\,\hat{\gamma}}{a} \cdot \nabla \Theta^{(1)} + \frac{\partial \Phi^{(1)}}{\partial t} + \frac{c\,\hat{\gamma}}{a} \cdot \nabla \Psi^{(1)} = \dot{\tau}\left[\Theta_0^{(1)} + \frac{1}{10}\Theta_2^{(1)} - \Theta^{(1)} + \beta^{(1)}\chi\right]$$

Free streaming

Doppler and
potential driving

Thomson collision term

Need to solve $\mathcal{O}(30)$ coupled ODE for $\sim 10^2 - 10^3$ values in *k*

If we include the frequency evolution we have $\mathcal{O}(10^4)$ coupled ODE for $\sim 10^2 - 10^3$ values in *k*

The Frequency Hierachy (FH) Treatment

$$\frac{\partial \mathbf{y}_0^{(0)}}{\partial \eta} = \tau' \theta_z \left[M_K y_0^{(0)} + D_0^{(0)} \right] + \frac{\mathbf{Q}'^{(0)}}{4} + \mathbf{S}_0'^{(0)},$$

$$\frac{\partial \mathbf{y}_0^{(1)}}{\partial \eta} = -k\, \mathbf{y}_1^{(1)} - \frac{\partial \Phi^{(1)}}{\partial \eta} b_0^{(0)} + \frac{\mathbf{Q}'^{(1)}}{4} + \Theta_0^{(1)} + \mathbf{C}_0^{(0)} + \mathbf{S}_0'^{(1)}$$

$$+\tau' \theta_z \left\{ M_\mathrm{T} \mathbf{y}_0^{(1)} + \left[(\delta_\mathrm{b}^{(1)} + \Theta_0^{(1)} + \Psi^{(1)})\, M_\mathrm{T} + \Theta_0^{(1)} M_\mathrm{BK} \right] \mathbf{y}_0^{(0)} \right\}$$

$$\frac{\partial \mathbf{y}_1^{(1)}}{\partial \eta} = k \left(\frac{1}{3} \mathbf{y}_0 - \frac{2}{3} \mathbf{y}_2 \right) + \frac{k}{3} \Psi^{(1)} b_0^{(0)} - \tau' \left[\mathbf{y}_1^{(1)} - \frac{\beta^{(1)}}{3} b_0^{(0)} \right] + \mathbf{S}_1'^{(1)},$$

$$\frac{\partial \mathbf{y}_2^{(1)}}{\partial \eta} = k \left(\frac{2}{5} \mathbf{y}_1^{(1)} - \frac{3}{5} \mathbf{y}_3^{(1)} \right) - \frac{9}{10} \tau' \mathbf{y}_2^{(1)} + \mathbf{S}_2'^{(1)},$$

$$\frac{\partial \mathbf{y}_{\ell \geq 3}^{(1)}}{\partial \eta} = k \left(\frac{\ell}{2\ell + 1} \mathbf{y}_{\ell-1}^{(1)} - \frac{\ell + 1}{2\ell + 1} \mathbf{y}_{\ell+1}^{(1)} \right) - \tau' \mathbf{y}_\ell^{(1)} + \mathbf{S}_\ell'^{(1)}.$$

Thermalisation terms perform a rotation under energy conservation, mixing the spectral components!!

Chluba, Kite & Ravenni, 2022, paper I, arXiv:2210.09327
Chluba, Ravenni & Kite, 2022, paper II, arXiv:2210.15308
Kite, Ravenni & Chluba, 2022, paper III, arXiv:2212.02817
Chluba, SE, Daman & Vasil, 2026, arXiv:2602.14963v1

The Dark Photon

- Gauge boson of a minimal U(1) extension of the Standard Model of particle physics
- Resonant conversion into photons is expected for $m_d \approx m_\gamma(z_{\rm con})$ in the plasma, in analogy to neutrino oscillations
- The conversion probability near the resonance is related to the conversion parameter

Dark Photon Mass

Mixing parameter

Plasma frequency

$$\gamma_{\rm con}(\epsilon, m_d) = \frac{\pi m_d^2 \epsilon^2}{T_{\rm CMB}(z) H(z)(1+z)} \left| \frac{1}{\omega_{\rm pl}^2} \frac{d\omega_{\rm pl}^2}{dz} \right|^{-1} \Bigg|_{z=z_{\rm con}} \equiv \frac{\pi m_d^2 \epsilon^2}{T_{\rm CMB}(z) H(z)(1+z)\lambda(z)} \Bigg|_{z=z_{\rm con}}$$

Perturbed Source Terms

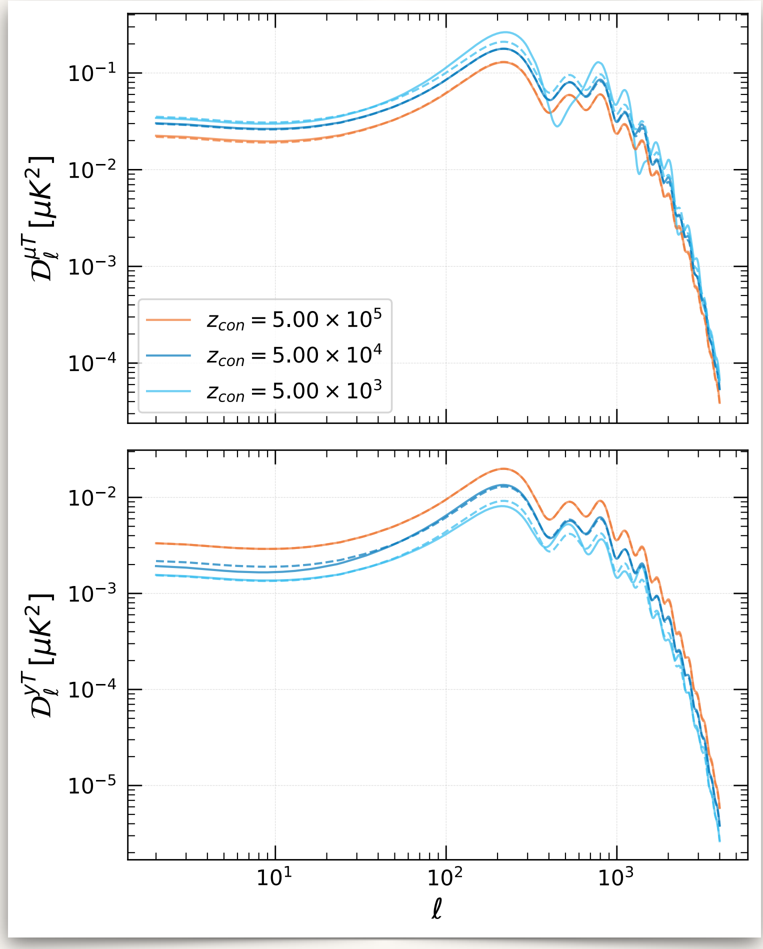
Final source terms as implemented into CosmoTherm after including perturbations in local quantities:

$$\frac{\mathrm{d}S^{(0)}(z,x)}{\mathrm{d}z} \equiv \gamma_{\rm con}^{(0)}\,\delta\!\left(z - z_{\rm con}^{(0)}\right) S_{\rm d}(x),$$

$$\frac{\mathrm{d}S^{(1)}(z,\boldsymbol{r},\hat{\boldsymbol{\gamma}},x)}{\mathrm{d}z} \equiv \gamma_{\rm con}^{(0)}\,\delta\!\left(z - z_{\rm con}^{(0)}\right) \left\{ \left[\frac{\gamma_{\rm con}^{(1)}}{\gamma_{\rm con}^{(0)}} + \Psi^{(1)}\right] S_{\rm d}(x) + \Theta^{(1)}\Delta S_{\rm d}(x) \right\}$$

The Power Spectrum

- Important to compare with experimental data from existing experiments
- Rich time-dependent peak structure at small scale
- μT dominates over yT
- Good agreement with stationary solutions

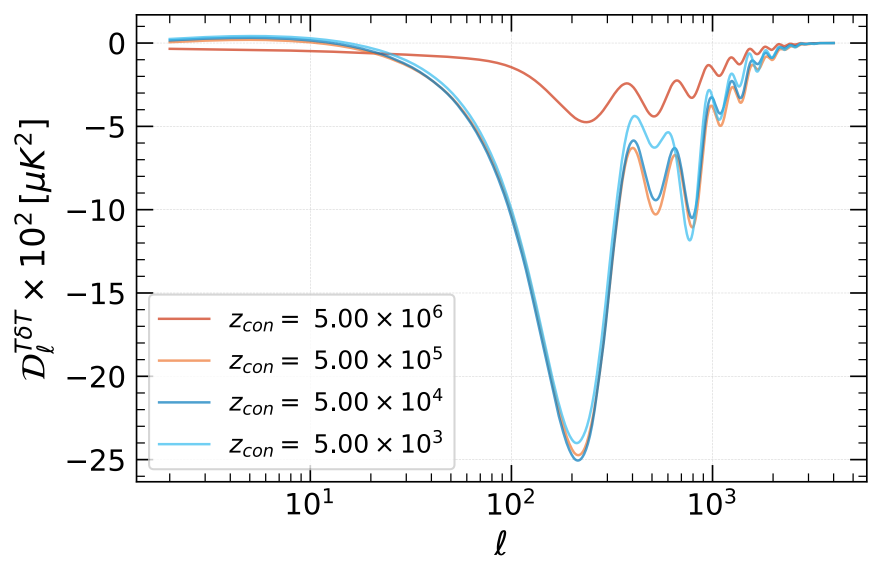


Temperature corrections

- We evolve the corrections to the standard temperature independently[1]

$$\delta\Theta^{(1)} = \Theta^{(1),\mathrm{full}} - \Theta^{(1)}$$

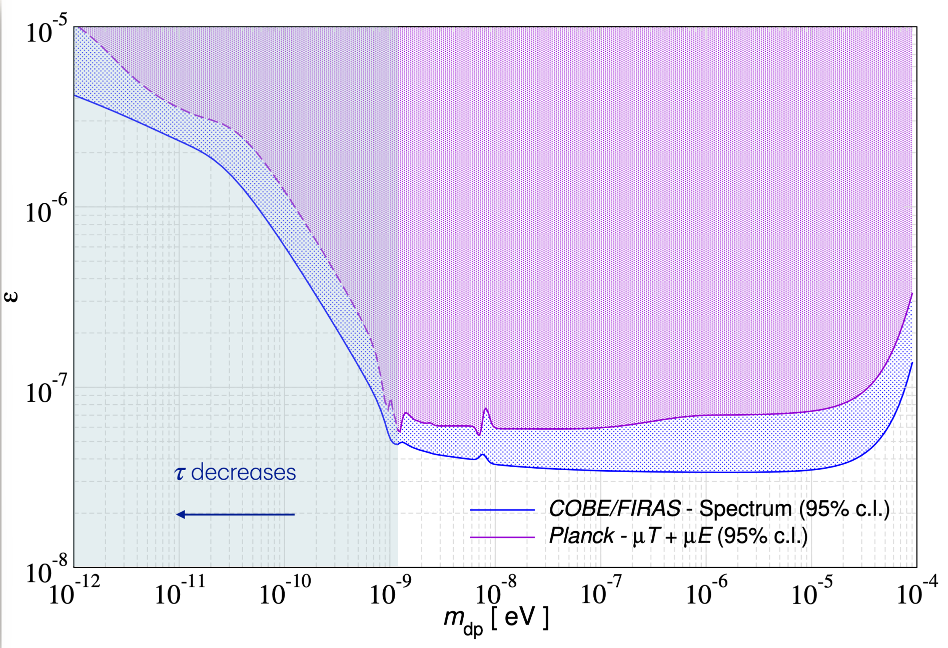
- Early conversions provide information even when SDs are fully thermalised
- Iso-curvature type perturbations (to be studied further)
- Dark photons perturbations are not included at the moment



1. Chluba, SE, Daman & Vasil, 2026, arXiv:2602.14963v1

Preliminary Constraints

- Comparing cross-power spectra with existing limits from *Planck* on μT and μE
- Results for $z_{con} \gtrsim 200$, with some care after recombination for numerical convergence
- Estimated limits are only marginally weaker than those from *COBE/FIRAS* (independent)



Conclusions and Future Work

- SDs anisotropies are now tractable and can open the path to novel information on Early Universe processes (e.g. Dark photons)
- Computed power spectra can be used to improve constraints using data from existing experiments (Planck, ACT, SPT) and combining them with the monopole
- Temperature corrections present an isocurvature type pattern that deserves further attention
- Implementing a hierarchy for dark photons distortions could have an impact on the temperature spectrum