Cosmology with Rayleigh scattering

Beyond primary CMB with the next generation of surveys

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Based on arXiv:2008.xxxxx, to be submitted by the release of this recording.

Outline :

- Motivations
- Distortions induced by Rayleigh scattering
- Detectability with the next generation of CMB surveys
- Impact on cosmological parameters estimation

With the next generation of CMB surveys promising to be Cosmic Variance limited up to $\ell \sim 5000$, there is a strong need to look beyond the primary CMB signal to further constrain ΛCDM and its extensions.

- Spectral distortions
- Secondary anisotropies : CMB lensing, tSZ, kSZ, patchy reionisation
- **Rayleigh Scattering !**

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What is Rayleigh scattering ?

The recombination history is usually told as follows :

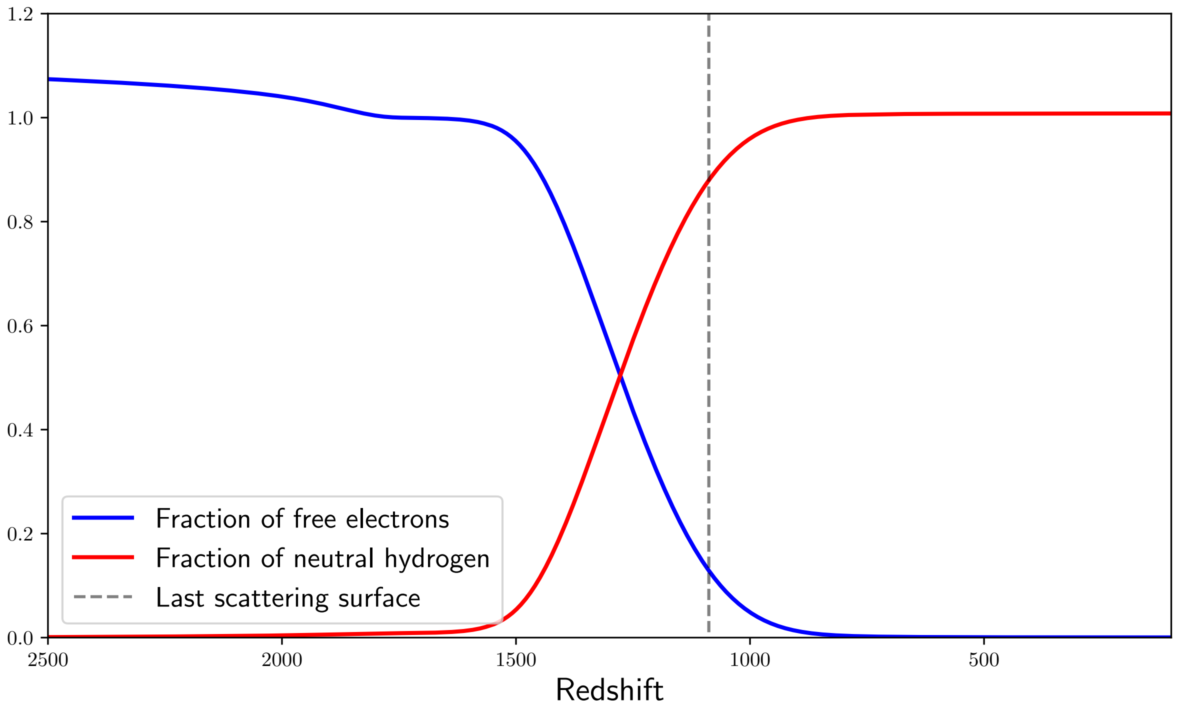
- The primordial plasma consists in protons and free electrons (mainly),
- Photons are kept in equilibrium by Thomson scattering,
- As the universe expands, less and less and free electrons,
- Finally, one last scattering event.

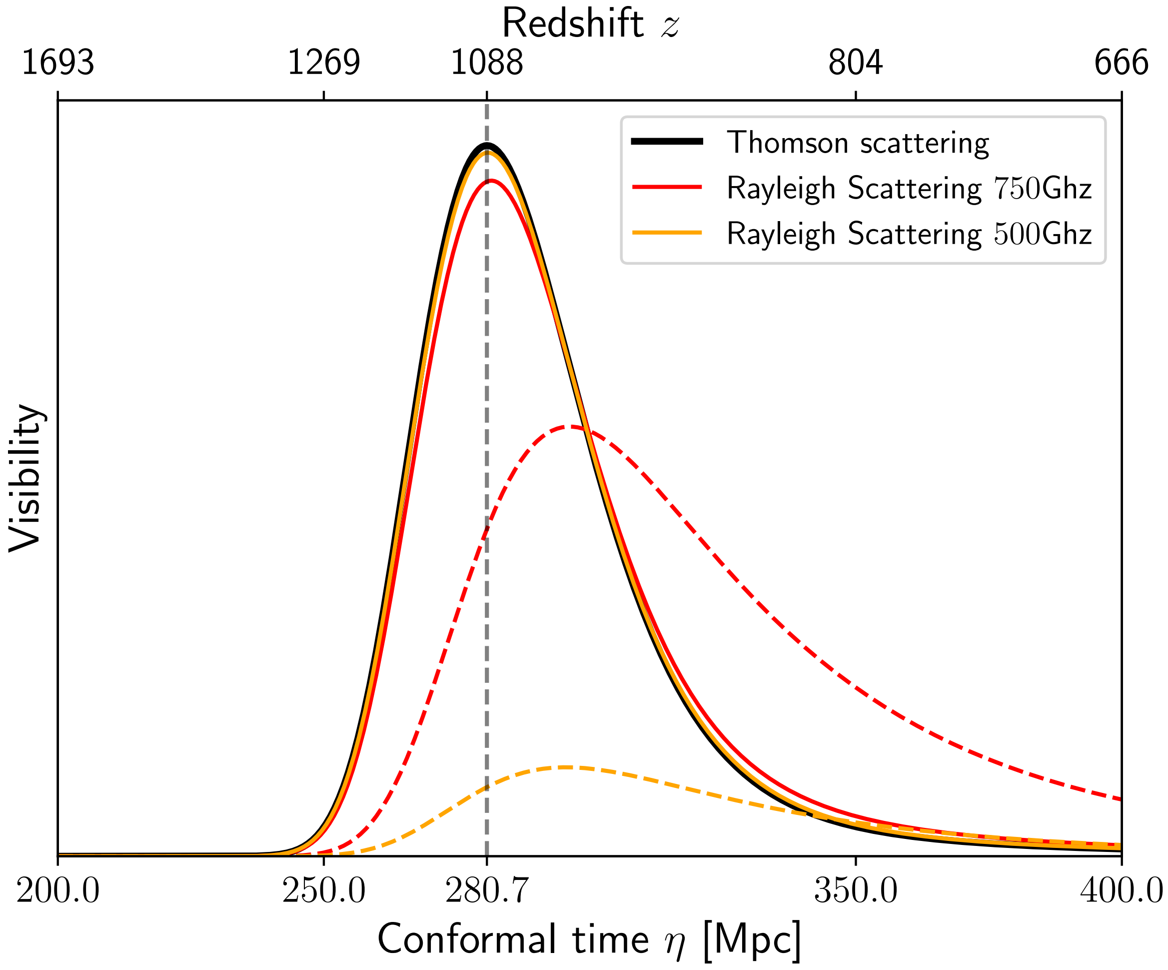
What is Rayleigh scattering ?

However, photons may also scatter off **neutral species** formed during recombination :

- **Rayleigh scattering** by Hydrogen and Helium atoms,
- Strong frequency dependence : $\sigma_R(\nu) \propto \sigma_T \nu^4$ (to lowest order)
- As the universe expands, neutral species are diluted $\propto a^{-3}$ and photons redshifted $\propto a^{-1}$,

Cosmology with Rayleigh scattering





Rayleigh scattering increases the comoving opacity of the plasma and makes it frequency dependent :

$$\dot{\tau} = a n_e \sigma_T \;\rightarrow\; \dot{\tau}(\nu) = a n_e \sigma_T + a[n_H + 0.1 \cdot n_{He}]\sigma_R(\nu)$$

This leads to :

- A damping of small scales anisotropies both in temperature and E-mode polarization.
- On large angular scales, the shift of the last scattering surface towards lower redshifts, where the local quadrupole is larger, boosts the large scales E-mode signal.
- A shift in the location of the acoustic peaks, both in temperature and E-mode polarization spectra.

Rayleigh scattering effects at frequencies below ~ 700 GHz can be modelled as a linear distortion to the primary CMB :

$$a_{\ell m}^{X}(\nu) = a_{\ell m}^{X,CMB} + \left(\frac{\nu}{\nu_0}\right)^4 \Delta a_{\ell m}^{X,4} + +\mathcal{O}\left(\left(\frac{\nu}{\nu_0}\right)^6\right)$$, with $X = T, E, B$

[Lewis 2013 :1307.8148]

The power spectrum reads :

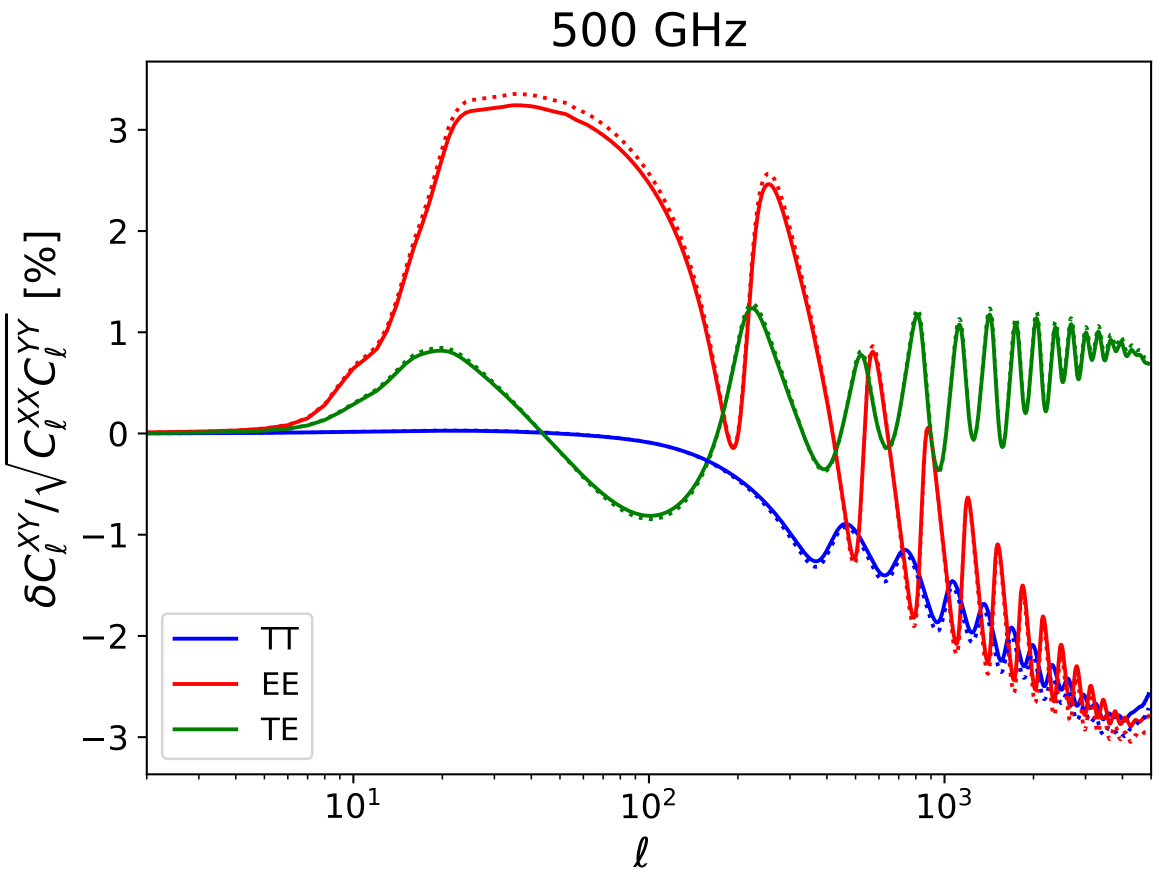
$$C_\ell^{XY}(\nu_1,\nu_2) = C_\ell^{XY,CMB} + \left(\frac{1}{\nu_0}\right)^4 \left[\nu_1^4 C_\ell^{X\Delta Y,4} + \nu_2^4 C_\ell^{\Delta X,4Y}\right] + \left(\frac{\nu_1\nu_2}{\nu_0^2}\right)^4 C_\ell^{\Delta X,4\Delta Y,4} + \ldots$$

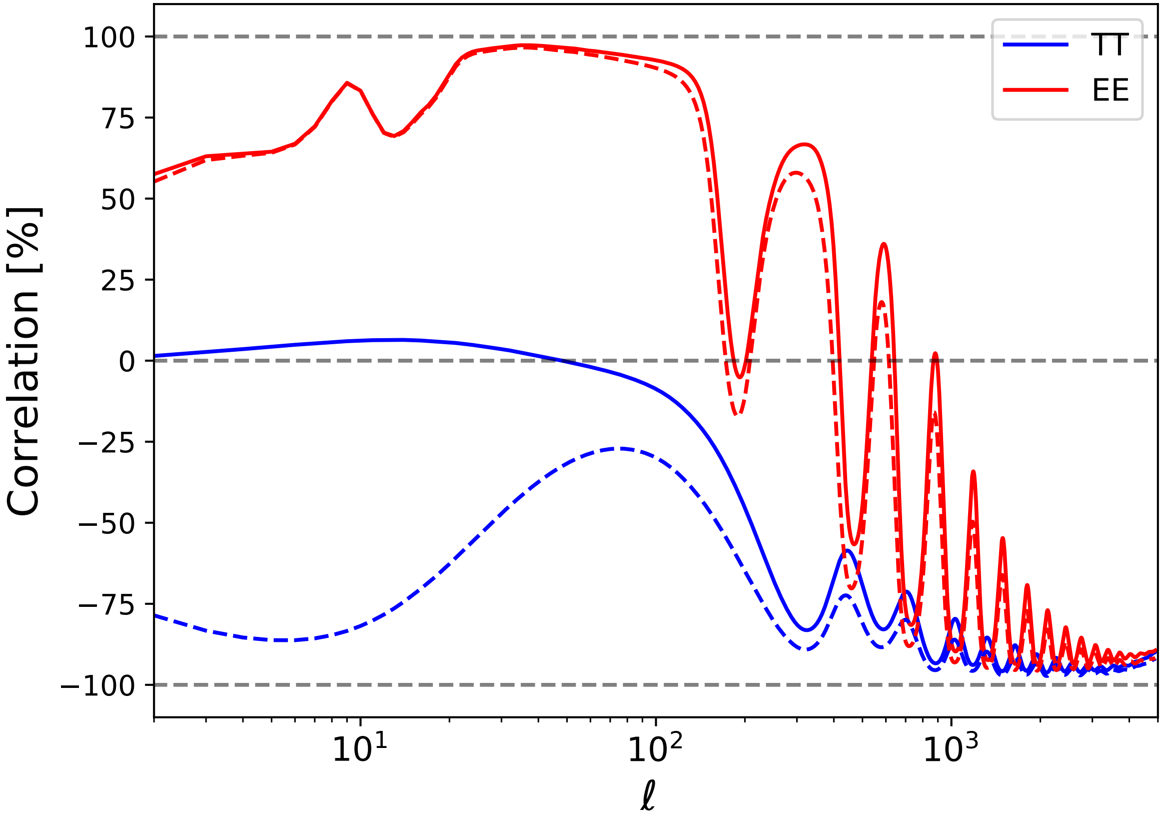
Primary CMB

ν^4 cross spectra

ν^4 auto spectra

Cosmology with Rayleigh scattering





What is Rayleigh scattering ?

- Scattering of CMB photons by neutral species right after recombination,
- Increases the comoving opacity in a frequency dependent way,
- Distortions can be modelled linearly at the multipole level,
- Produces a signal that is small (~3% at 500GHz) and highly correlated to the primary CMB.

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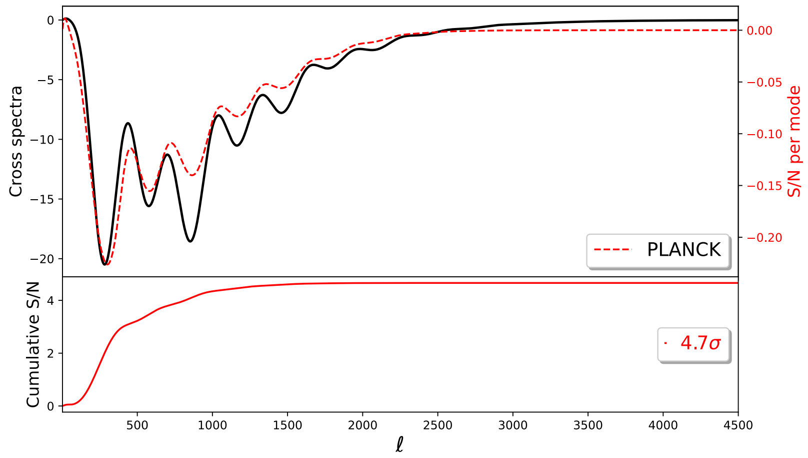
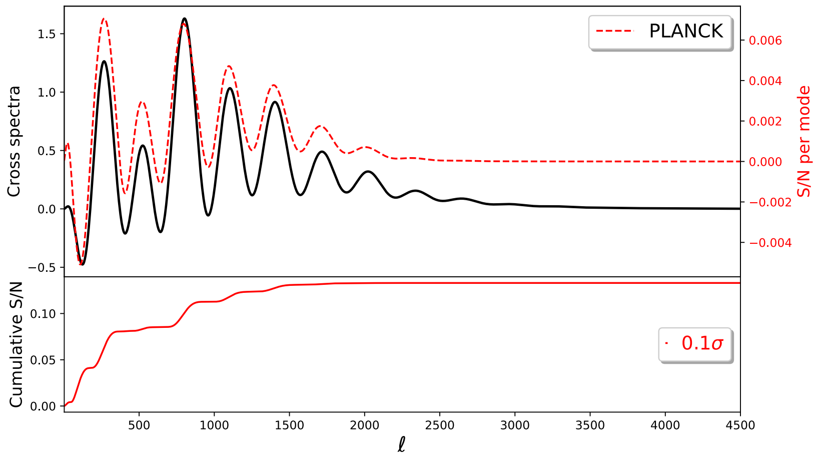
Cosmology with Rayleigh scattering

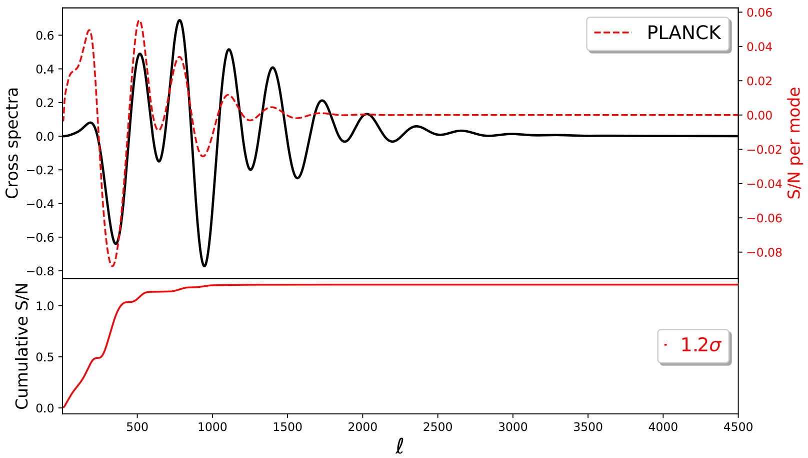
Primary T x RS T spectrum



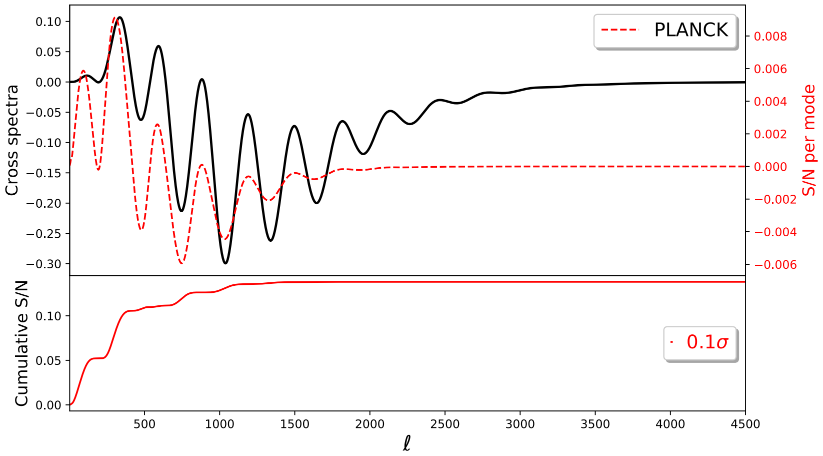
Primary T x RS E spectrum



Primary E x RS T spectrum



Primary E x RS E spectrum

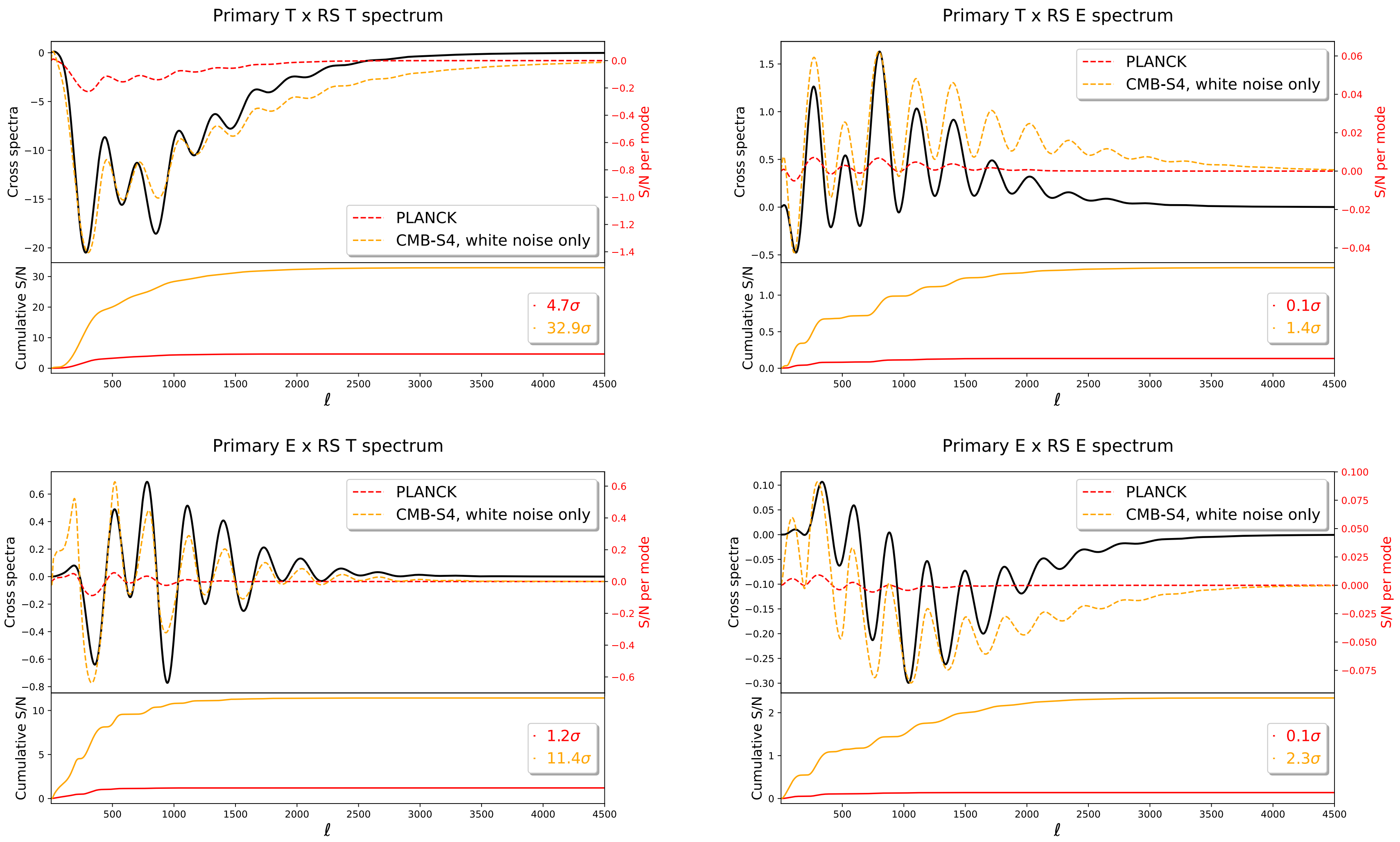


PLANCK only

Most of the constraining power comes from temperature large scales $\ell < 1000$.

Almost no contribution from the polarized Rayleigh scattering signal.

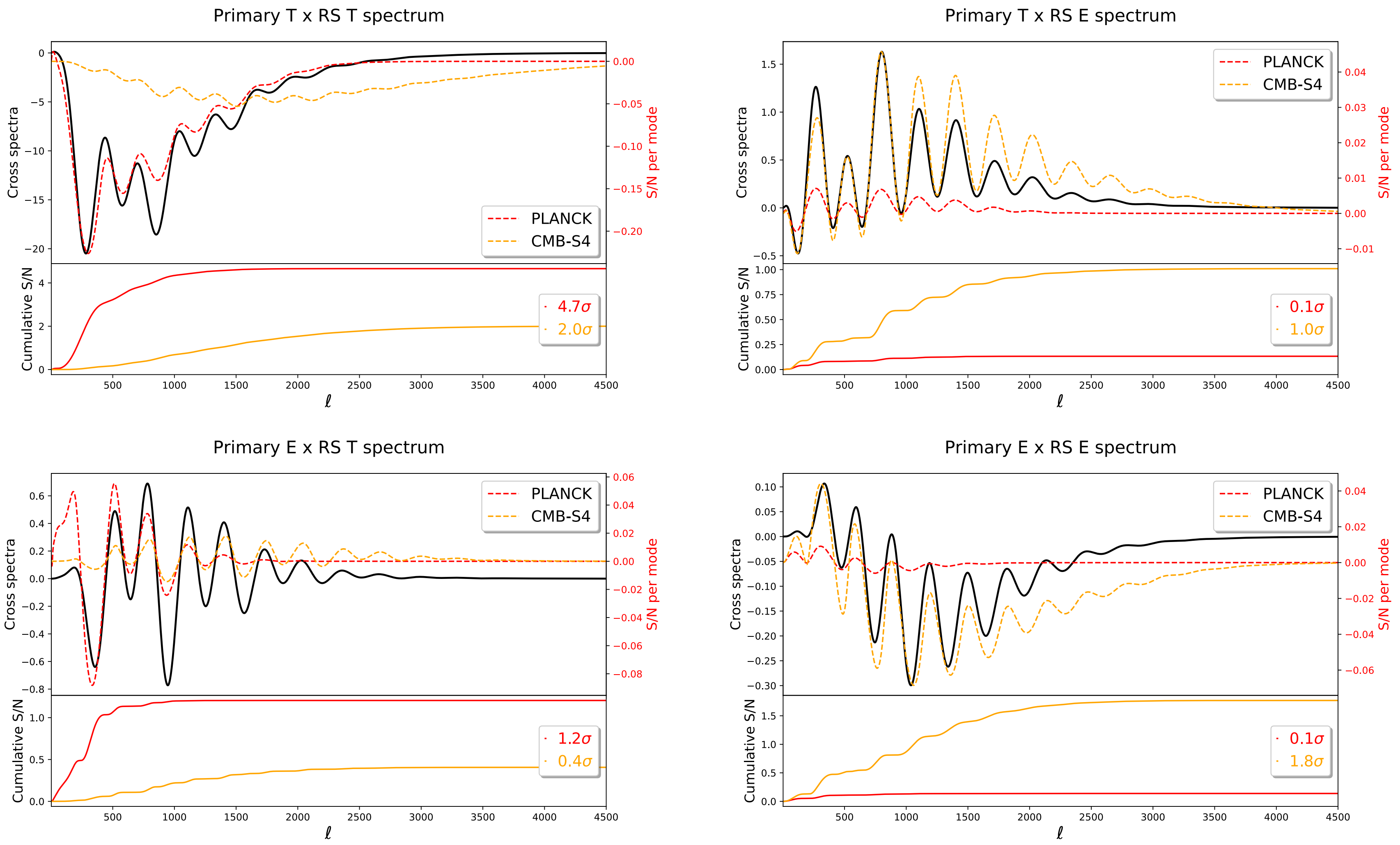
Cosmology with Rayleigh scattering



CMB-S4 white noise only

Most of the constraining power still comes from temperature large scales $\ell < 2000$. Which will be impacted by atmospheric noise.

Cosmology with Rayleigh scattering



CMB-S4

Since temperature channels are the most impacted by atmospheric noise, most of the constraining power comes from polarized channels.

Improvements in detector noise in the polarized channels will directly result in improvements in constraints on Rayleigh scattering.

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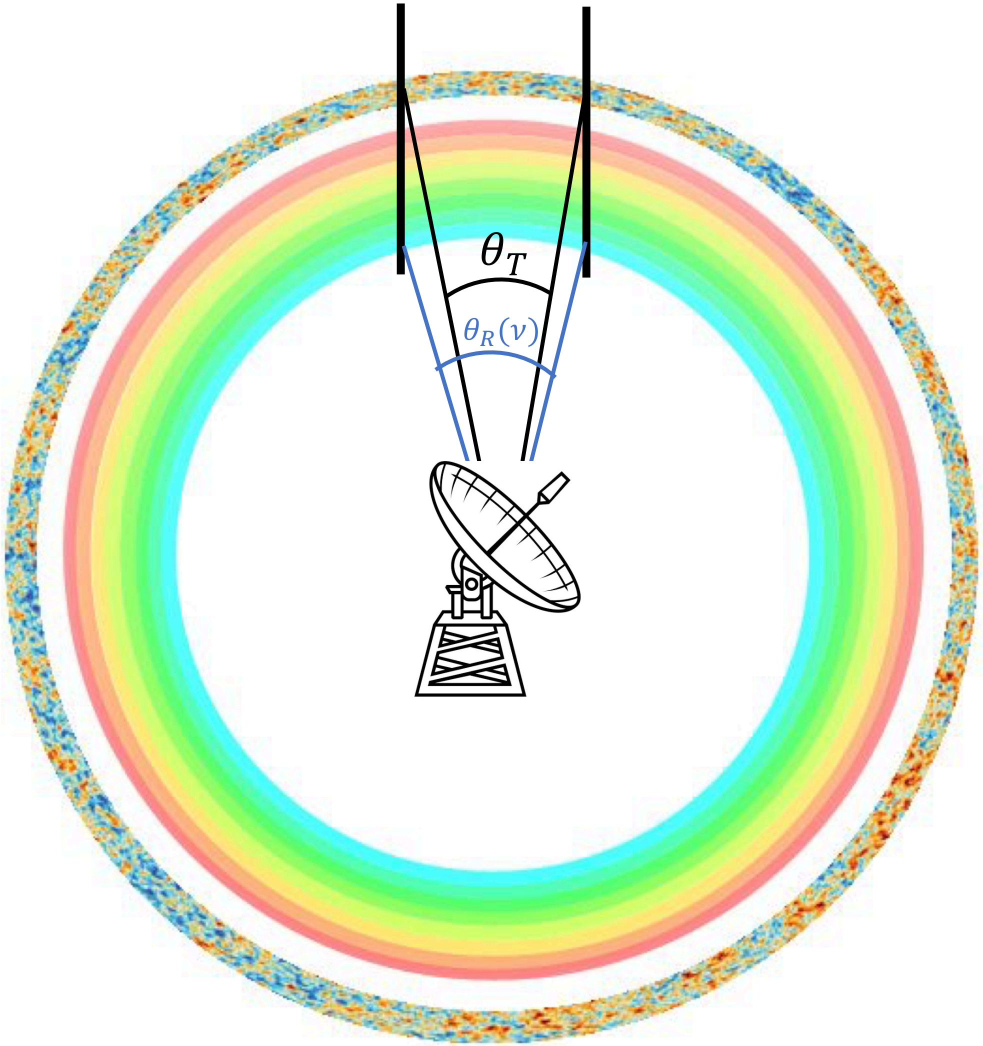

Courtesy of Joel Meyers.

- Rayleigh scattering amplitude directly probes Helium fraction : $\boldsymbol{Y_{He}}$
- Rayleigh scattering produces different last scattering surface and fluctuation spectrum at each frequency.
- Fixed length scales appear at different angular scales for primary and Rayleigh scattered components of the CMB.
- Ratio of these angular scales helps constraining parameters.
- $\boldsymbol{\theta_S, \Omega_c h^2, N_{eff}}$ are improved.

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Cosmology with Rayleigh scattering

		$\Omega_b h^2$	$\Omega_c h^2$	H_0[km/s/Mpc]	$10^9 A_s$	n_s	τ
Reference case	PICO no Rayleigh	2.30×10^{-5}	2.30×10^{-4}	8.78×10^{-2}	6.48×10^{-3}	1.27×10^{-3}	1.77×10^{-3}
	PICO with Rayleigh	1.91×10^{-5}	2.14×10^{-4}	7.85×10^{-2}	6.07×10^{-3}	1.17×10^{-3}	1.67×10^{-3}
	Improvement	16.98%	6.92%	10.52%	6.36%	7.61%	5.51%
	Primary-only CVL	7.94×10^{-6}	1.61×10^{-4}	6.06×10^{-2}	5.21×10^{-3}	7.02×10^{-4}	1.43×10^{-3}
With DESI BAO	PICO no Rayleigh	2.30×10^{-5}	1.91×10^{-4}	7.29×10^{-2}	5.87×10^{-3}	1.21×10^{-3}	1.56×10^{-3}
	PICO with Rayleigh	1.90×10^{-5}	1.82×10^{-4}	6.66×10^{-2}	5.60×10^{-3}	1.10×10^{-3}	1.50×10^{-3}
	Improvement	17.51%	4.73%	8.62%	4.64%	8.80%	3.52%
	Primary-only CVL	7.89×10^{-6}	1.45×10^{-4}	5.45×10^{-2}	4.81×10^{-3}	6.67×10^{-4}	1.31×10^{-3}
With unlensed spectra	PICO no Rayleigh	1.98×10^{-5}	2.31×10^{-4}	8.59×10^{-2}	6.52×10^{-3}	1.23×10^{-3}	1.73×10^{-3}
	PICO with Rayleigh	1.71×10^{-5}	2.15×10^{-4}	7.77×10^{-2}	6.12×10^{-3}	1.12×10^{-3}	1.65×10^{-3}
	Improvement	13.76%	6.85%	9.57%	6.15%	8.31%	4.96%
	Primary-only CVL	6.62×10^{-6}	1.48×10^{-4}	5.38×10^{-2}	5.02×10^{-3}	6.51×10^{-4}	1.35×10^{-3}
Not including $C_\ell^{\phi\phi}$	PICO no Rayleigh	2.39×10^{-5}	2.83×10^{-4}	1.08×10^{-1}	6.62×10^{-3}	1.40×10^{-3}	1.77×10^{-3}
	PICO with Rayleigh	1.93×10^{-5}	2.48×10^{-4}	9.09×10^{-2}	6.34×10^{-3}	1.31×10^{-3}	1.68×10^{-3}
	Improvement	19.29%	12.28%	16.11%	4.24%	6.69%	5.28%
	Primary-only CVL	1.02×10^{-5}	1.75×10^{-4}	6.57×10^{-2}	5.35×10^{-3}	9.88×10^{-4}	1.45×10^{-3}

PICO-like experiment ***[arXiv:1902.10541]***

$\ell_{max} = 5000, Y_{He}$ fixed

More details in ***arXiv:2008.xxxxx***

		N_{eff}	$\sum m_\nu$[meV]
Reference case	PICO no Rayleigh	3.06×10^{-2}	35.9
	PICO with Rayleigh	2.81×10^{-2}	16.7
	Improvement	8.21%	53.55%
	Primary-only CVL	9.68×10^{-3}	21.0
With DESI BAO	PICO no Rayleigh	2.85×10^{-2}	11.5
	PICO with Rayleigh	2.63×10^{-2}	10.1
	Improvement	7.72%	11.85%
	Primary-only CVL	9.47×10^{-3}	9.70
With unlensed spectra	PICO no Rayleigh	2.41×10^{-2}	33.8
	PICO with Rayleigh	2.28×10^{-2}	16.4
	Improvement	5.15%	51.48%
	Primary-only CVL	8.04×10^{-3}	17.3
Not including $C_\ell^{\phi\phi}$	PICO no Rayleigh	3.50×10^{-2}	37.8
	PICO with Rayleigh	3.04×10^{-2}	17.4
	Improvement	13.05%	53.84%
	Primary-only CVL	1.46×10^{-2}	26.3

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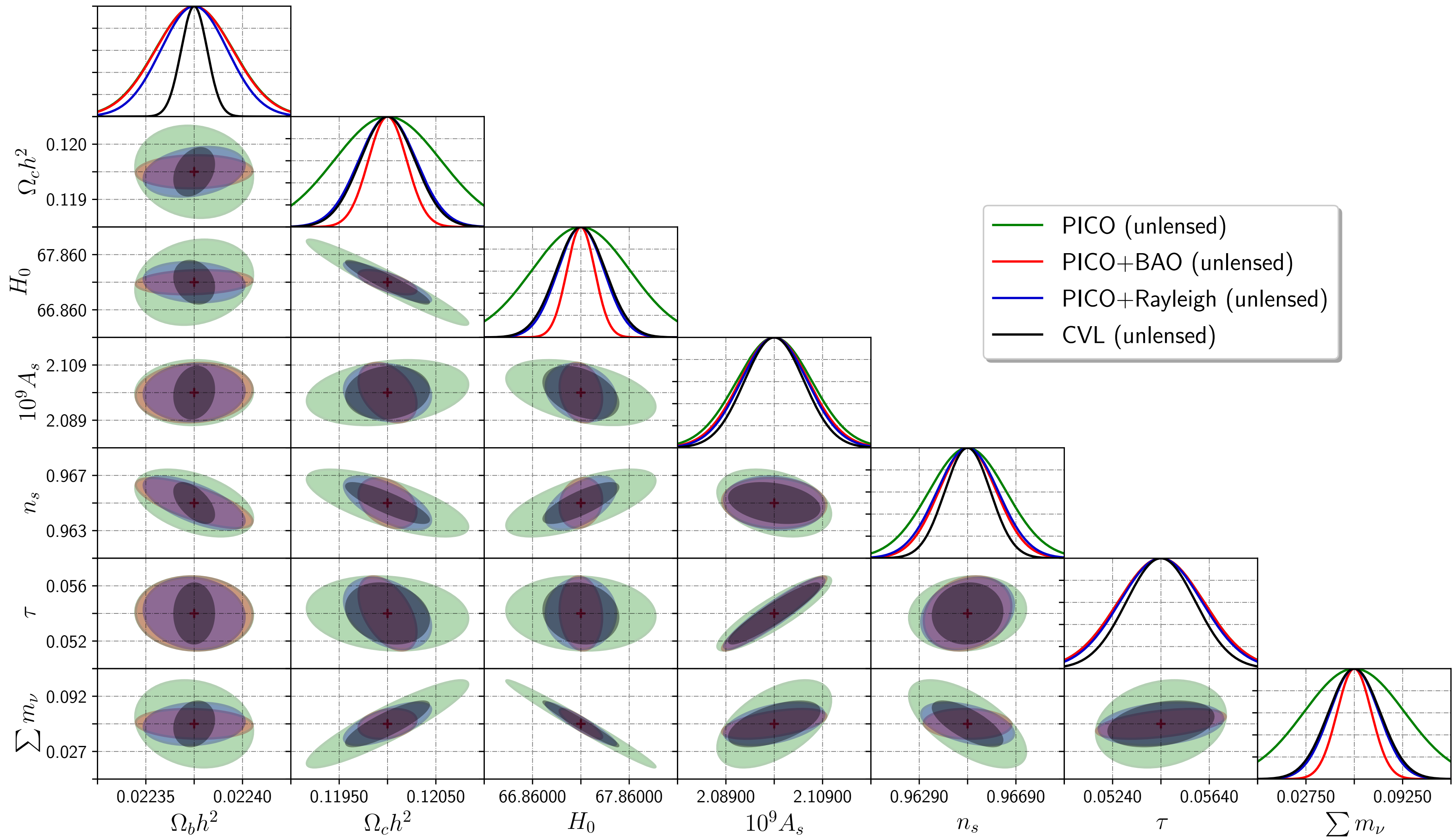

Cosmology with Rayleigh scattering

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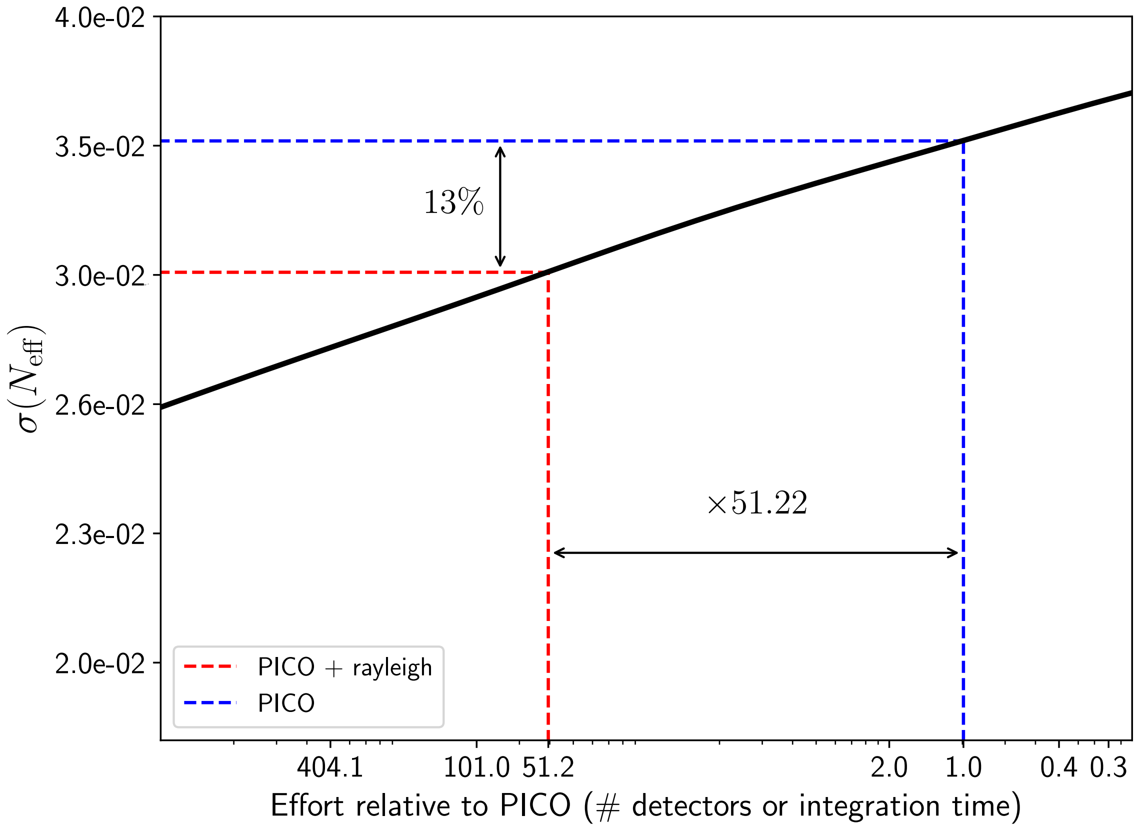

A modest 13% improvements on N_{eff}, would require 50 times more effort without Rayleigh scattering.

This holds for a 5' beam experiment (space-based), using lensed spectra up to ℓ_{max} = 5000 and not including $C_\ell^{\phi\phi}$.

In all this work we have neglected foregrounds contamination. Several aspects of Rayleigh scattering signal will play in our favour when looking for it :

- It has a strong and unique scaling with frequency which make it suitable for blind methods such as **Internal Linear Combination (ILC).**

- Its correlation with the primary CMB means would require to be dealt with by using a **constrained-ILC.**

- Rayleigh scattering signal is well understood and modelled which make it usable in **parametric component separation** codes.

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Conclusion

- Rayleigh Scattering is a weak yet robustly predicted signal in the sky .
- Its first detection could be achieved with the next generation of CMB surveys.
- Future space missions will use this signal to further constrain ΛCDM and its extension
- Component separation will play a crucial role in a first detection.

Thank you very much for your attention !

(Have a look on the arxiv for our paper on Rayleigh scattering !)