Cosmology with Rayleigh scattering of the CMB

Looking beyond the primary CMB

Benjamin Beringue - APC, CNRS - CMB France #6 - December 2024

Science from the large scale cosmic microwave background polarization structure

Rayleigh scattering of the CMB

Outline

- What is Rayleigh scattering of the CMB ?
- How can this effect be modelled ?
- Can we detect it with upcoming surveys ?
- Does it help constraining cosmology ?

What is Rayleigh scattering ?

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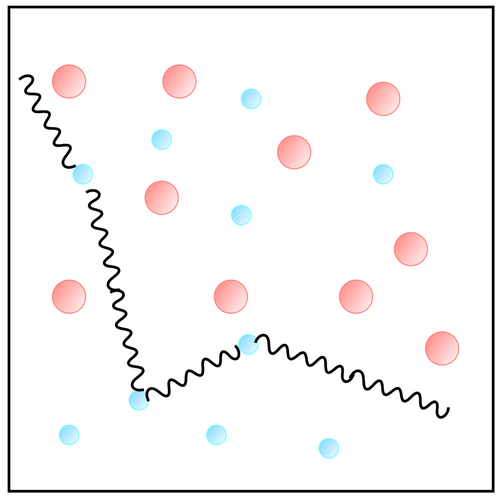
Lyman series frequencies and oscillator strength

Rayleigh scattering is frequency dependent !!

What is Rayleigh scattering ?

Around recombination



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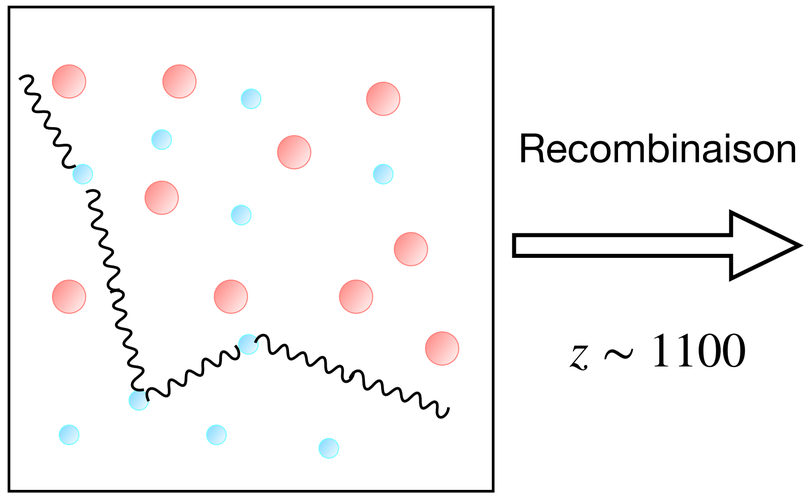

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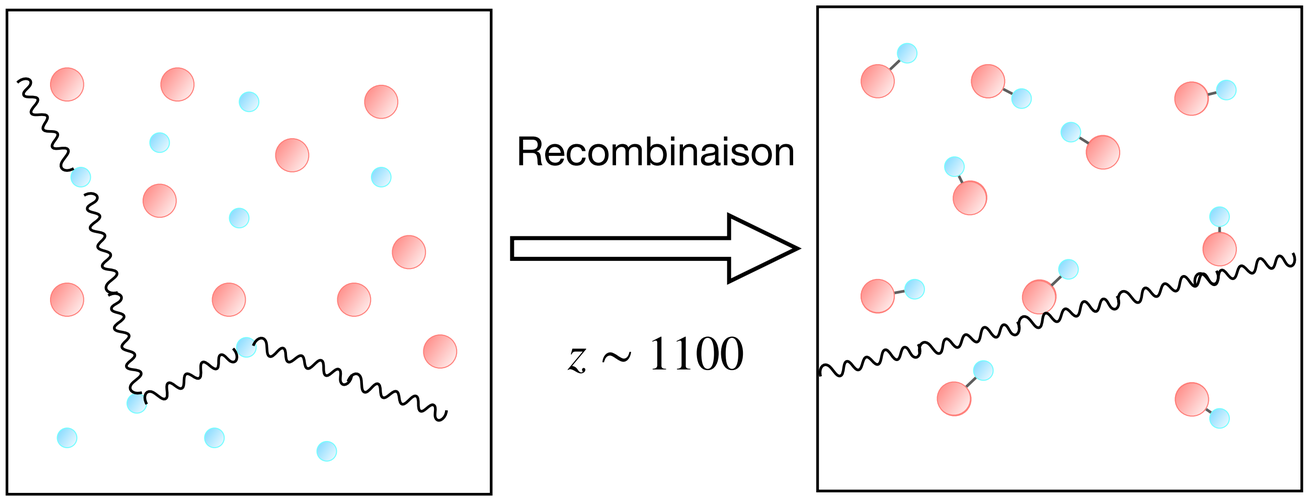

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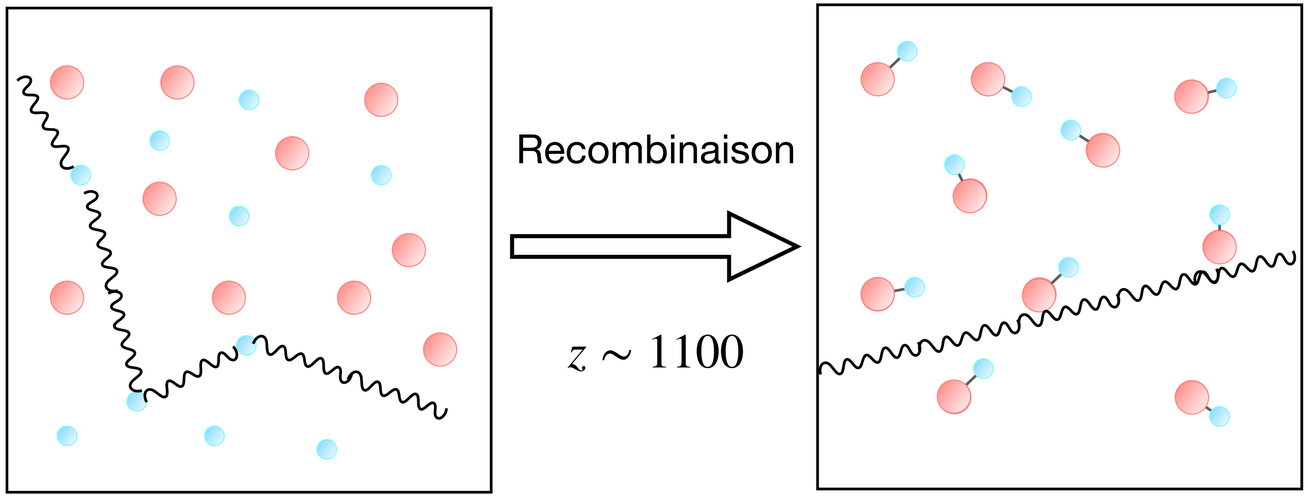

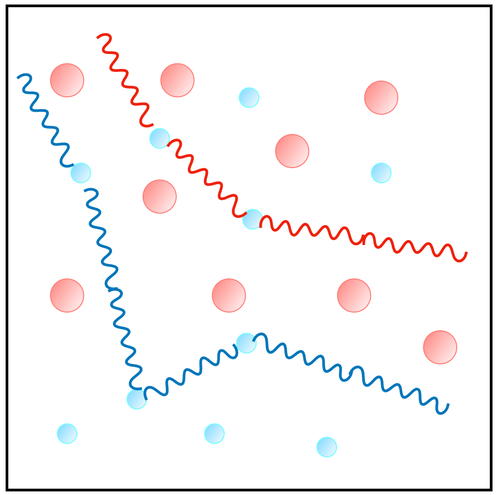

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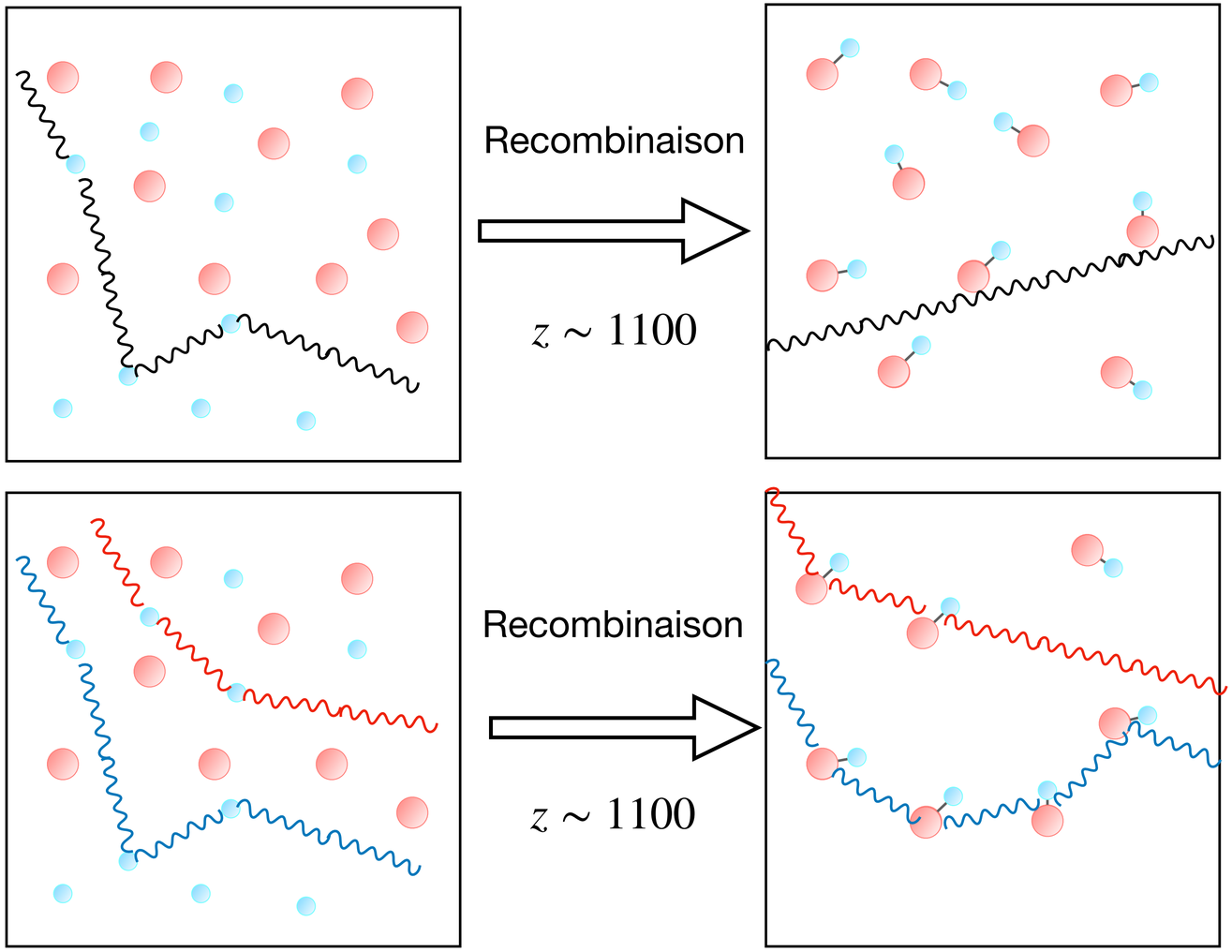

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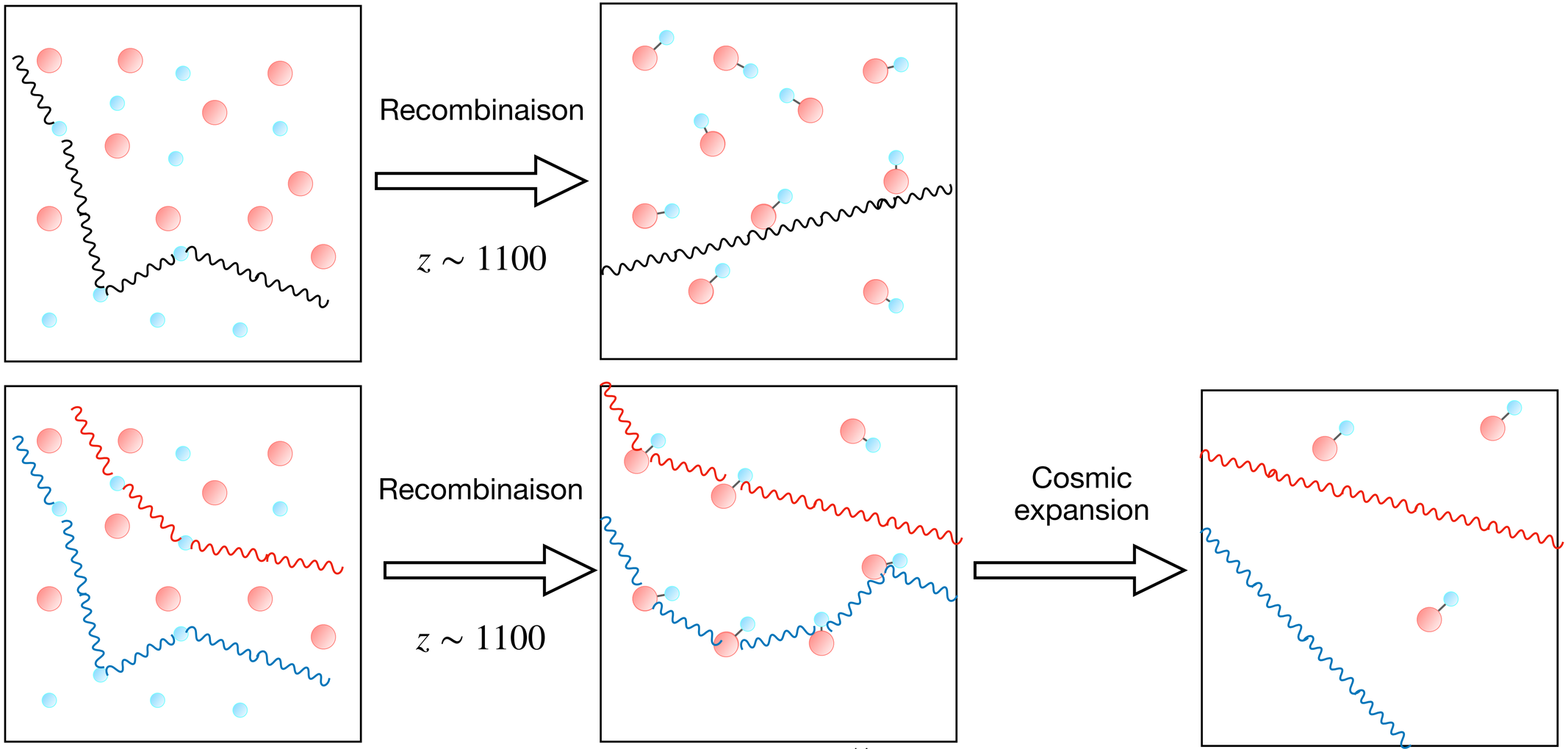

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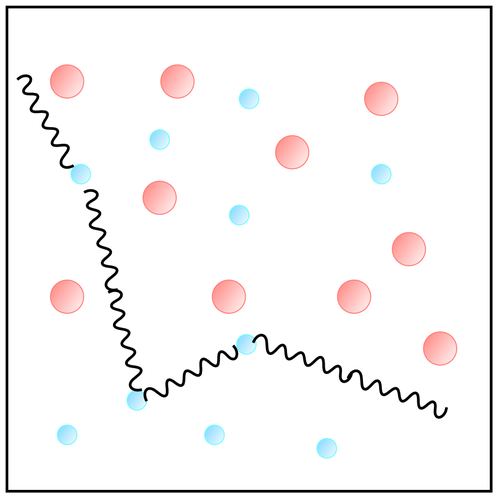
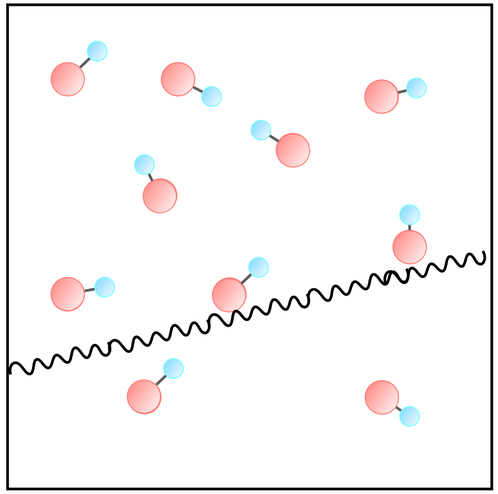


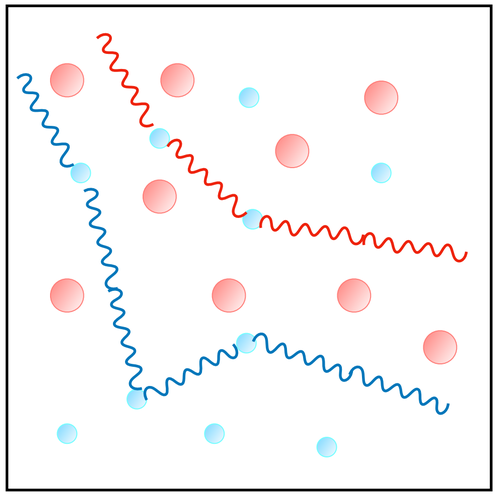
Recombinaison

$z \sim 1100$



$$\sigma_R(\nu) \approx \sigma_T \left[\left(\frac{\nu}{\nu_{\text{eff}}} \right)^4 + \alpha \left(\frac{\nu}{\nu_{\text{eff}}} \right)^6 + \beta \left(\frac{\nu}{\nu_{\text{eff}}} \right)^8 + \dots \right]$$

[Lewis 16, Yu et al. 01]



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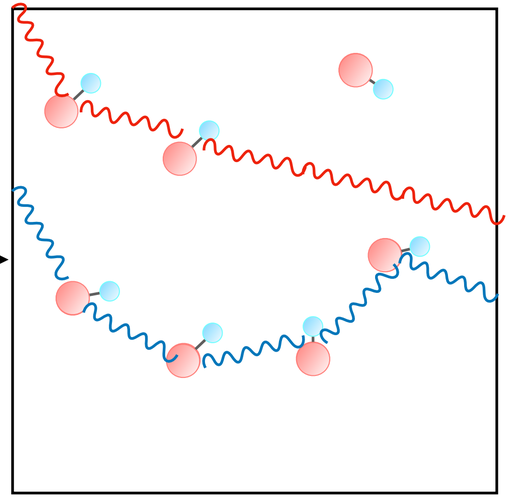
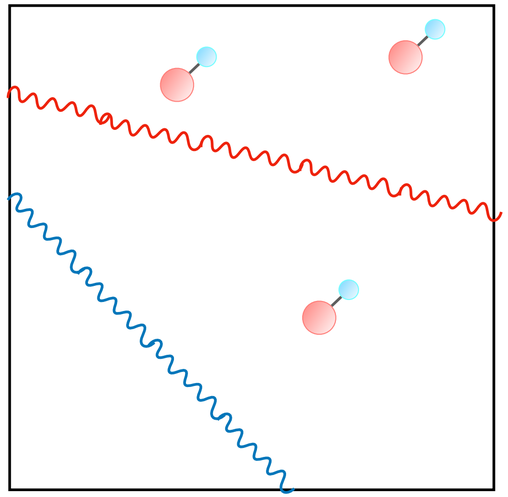


Cosmic expansion



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$$\dot{\tau} = a n_e \sigma_T \rightarrow \dot{\tau}(\nu) = a n_e \sigma_T + a \left[n_{\mathrm{H}} + 0.1 n_{\mathrm{He}} \right] \sigma_R(\nu)$$

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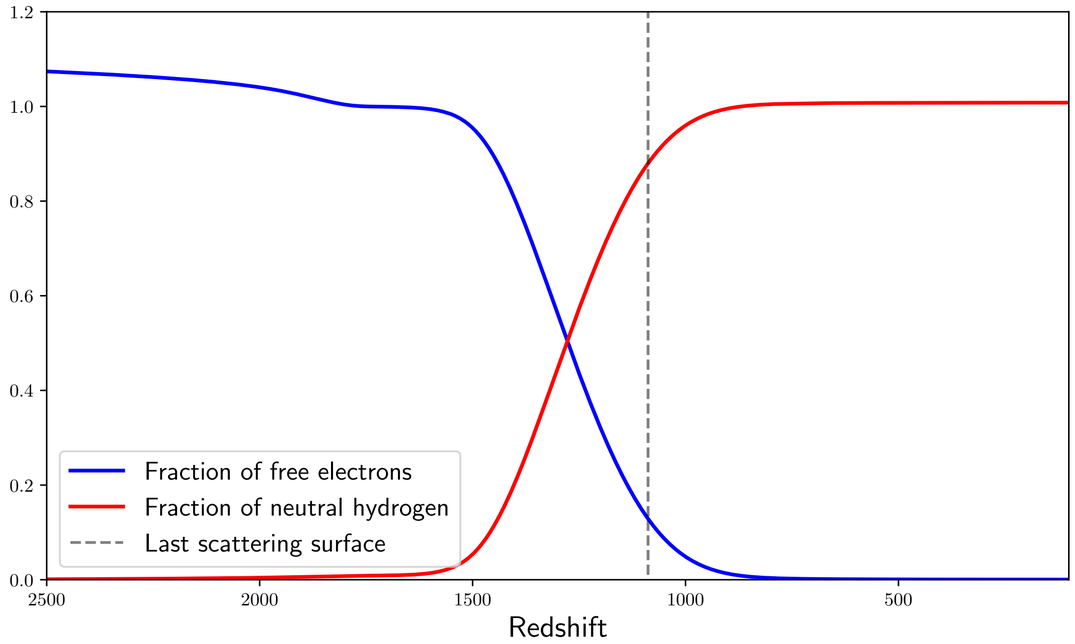

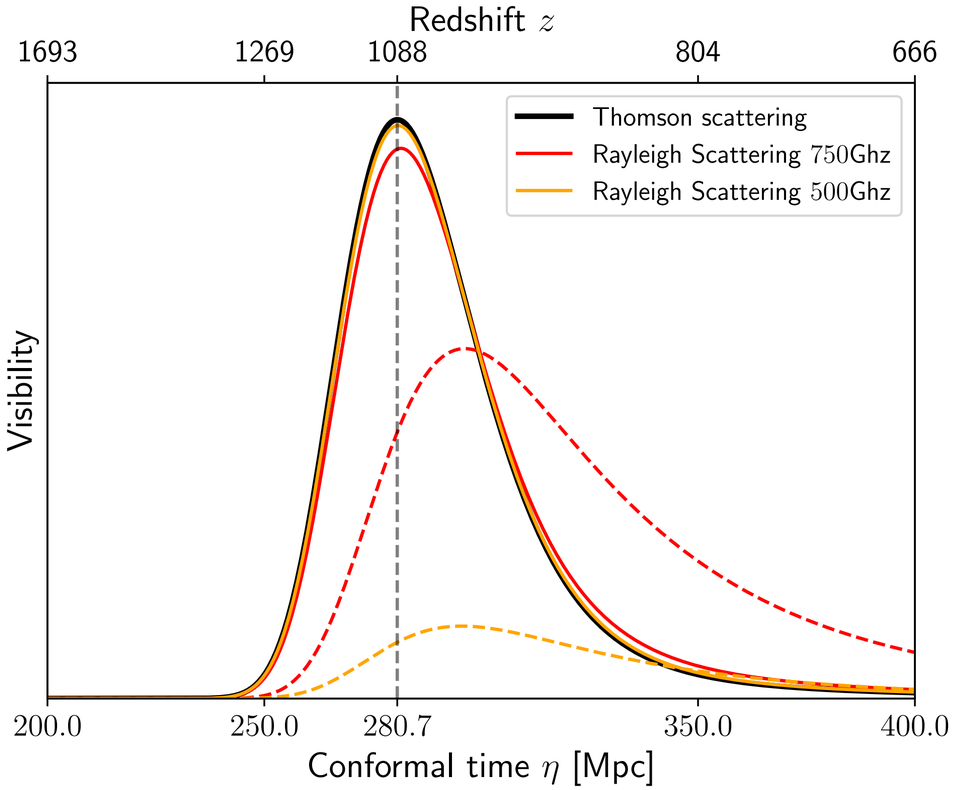

[BB, Meerburg, Meyers and Battaglia 21]

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This leads to:

- An increase of Silk damping on small scales.
- A boost on large scales in polarisation, due to the visibility function being shifted towards low redshift where the local quadrupole is larger.
- A shift in the location of the acoustic peaks

[BB et al 21, Lewis 16, Yu et al 01]

How can this be modelled ?

At the power-spectrum level

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The power spectra read:

$$C^{XY}_\ell(\nu_1,\nu_2) = C^{XY,\mathrm{CMB}}_\ell + \frac{1}{\nu_0^4}\left(\nu_1^4 C^{XY_4}_\ell + \nu_2^4 C^{X_4Y}_\ell\right) + \left(\frac{\nu_1\nu_2}{\nu_0^2}\right)^4 C^{X_4Y_4}_\ell + \cdots$$

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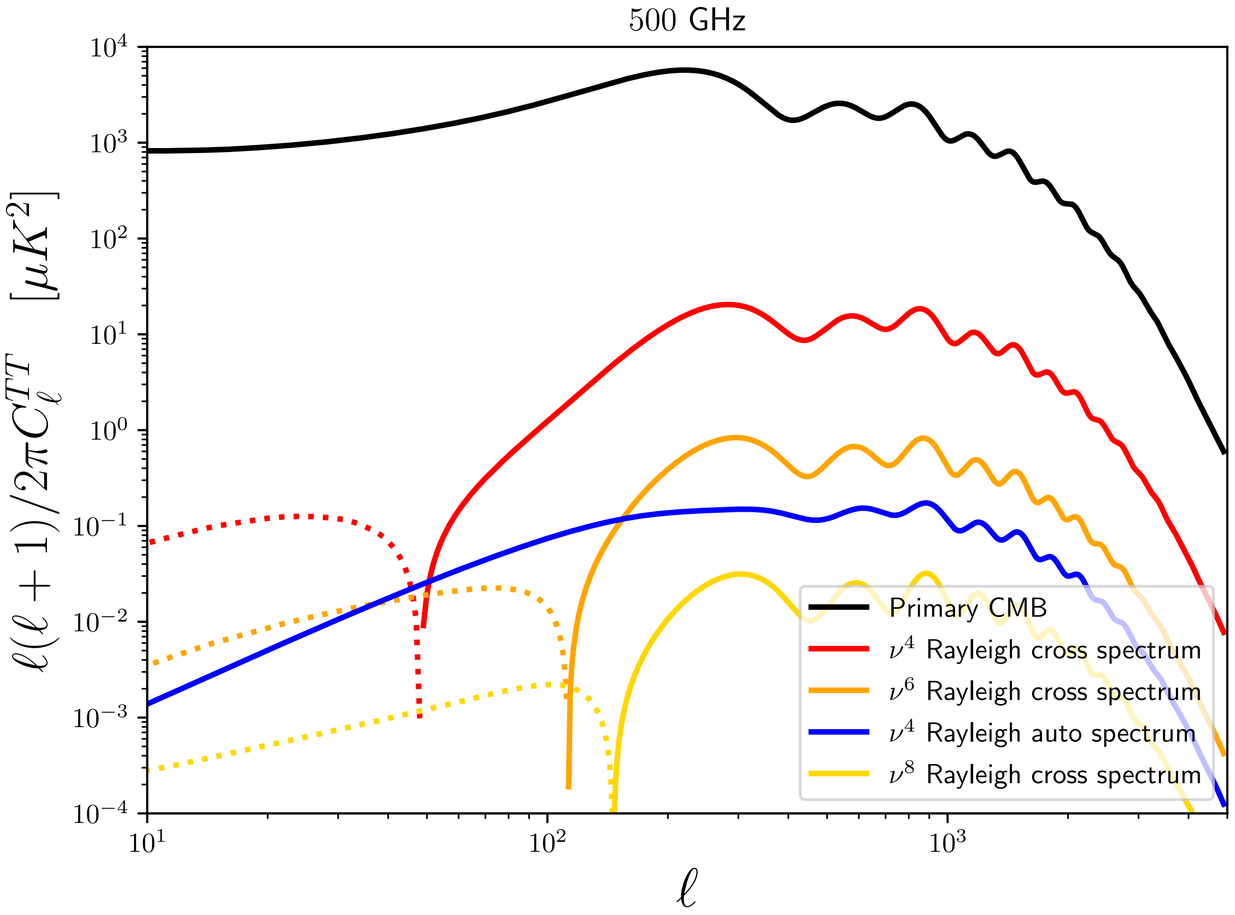

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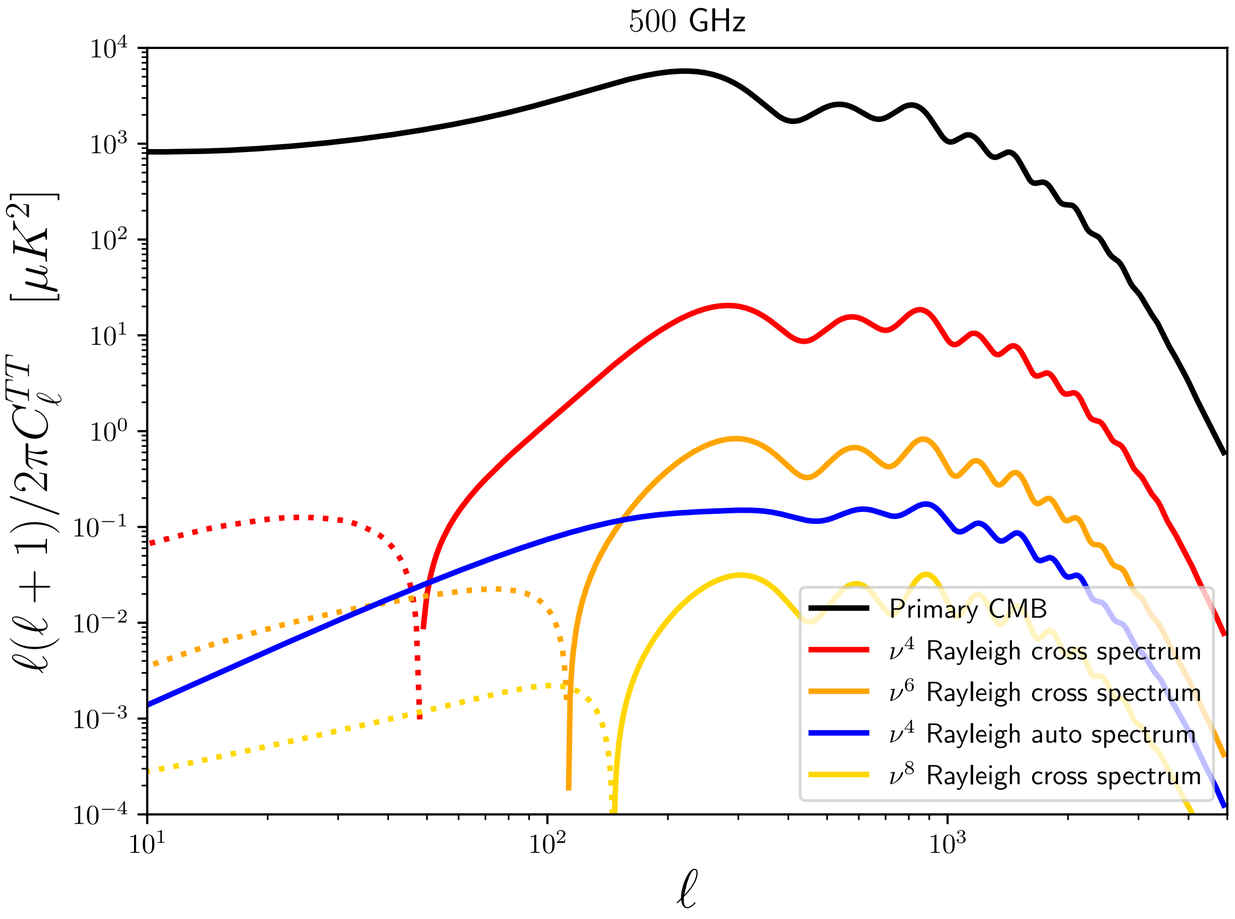

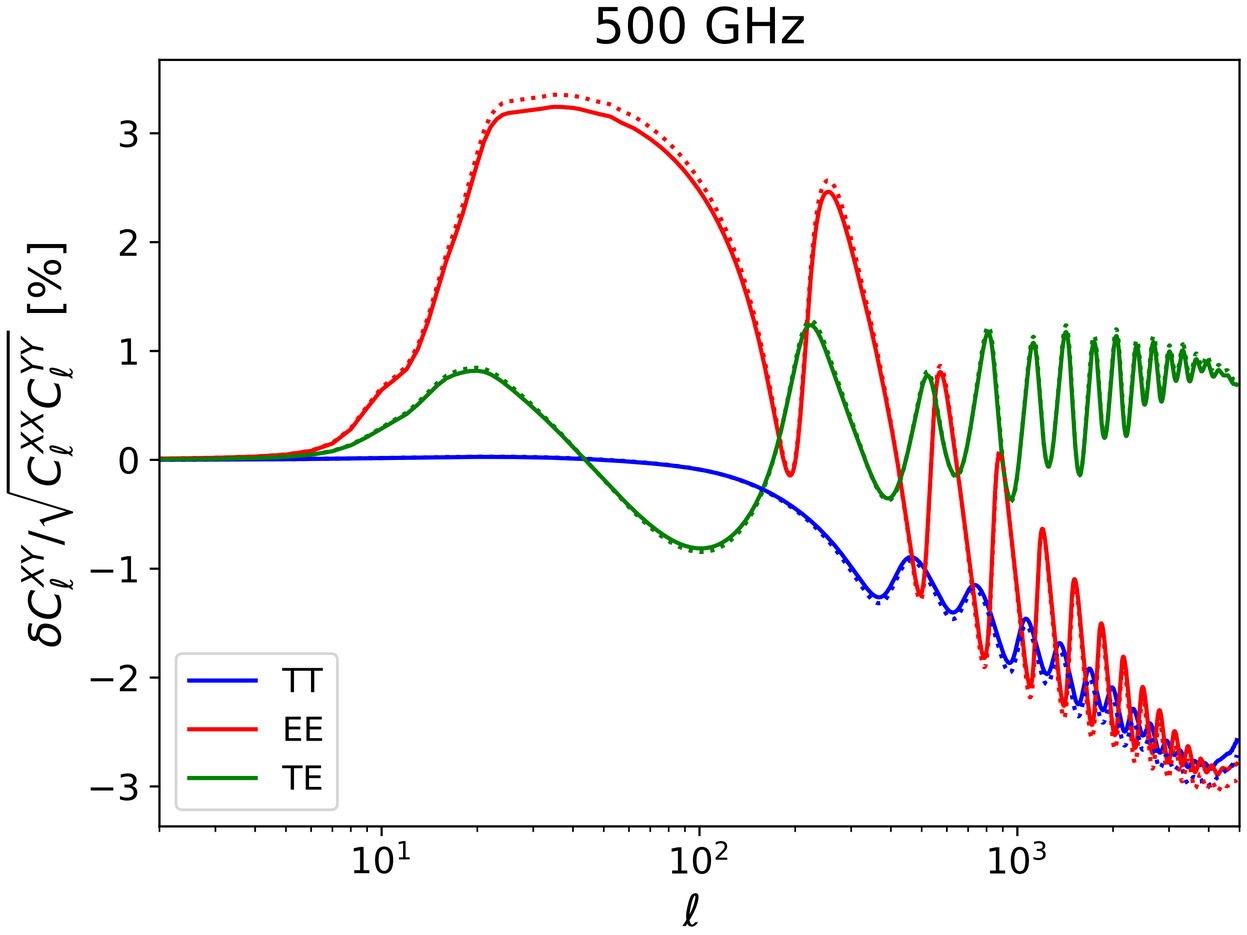

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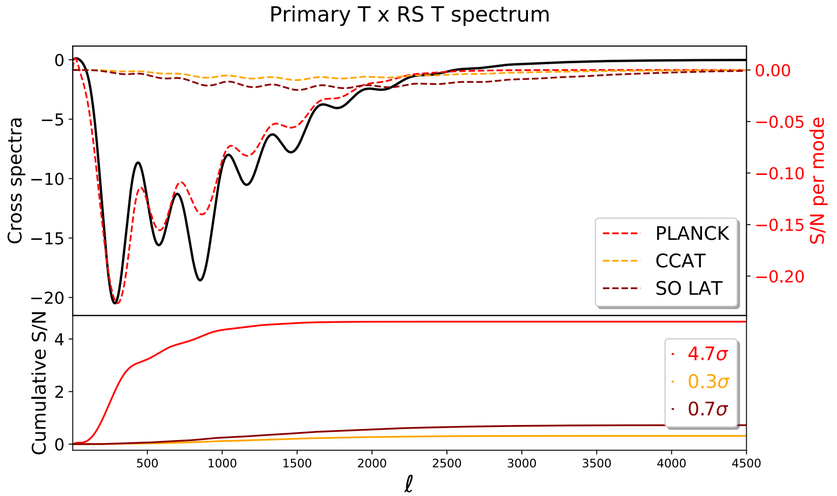
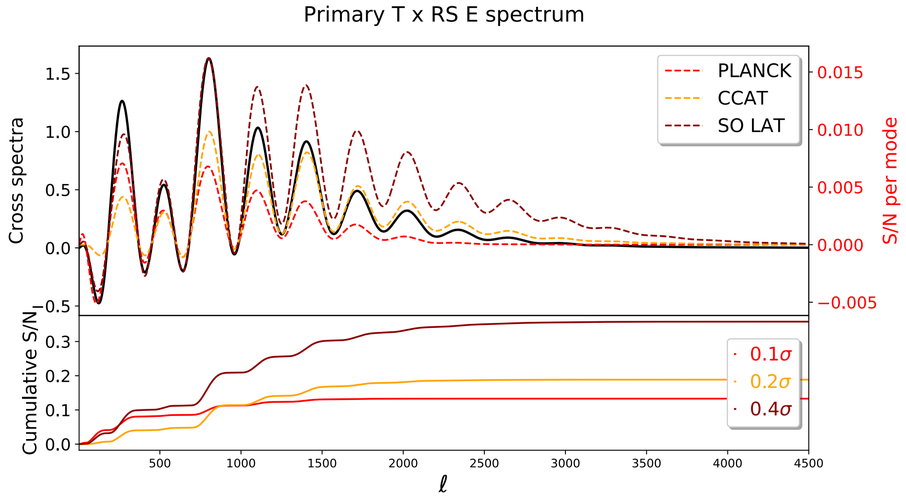
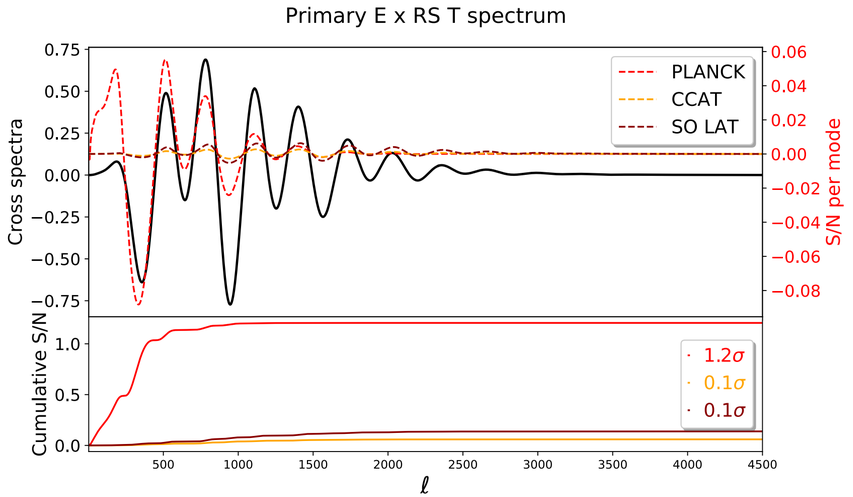
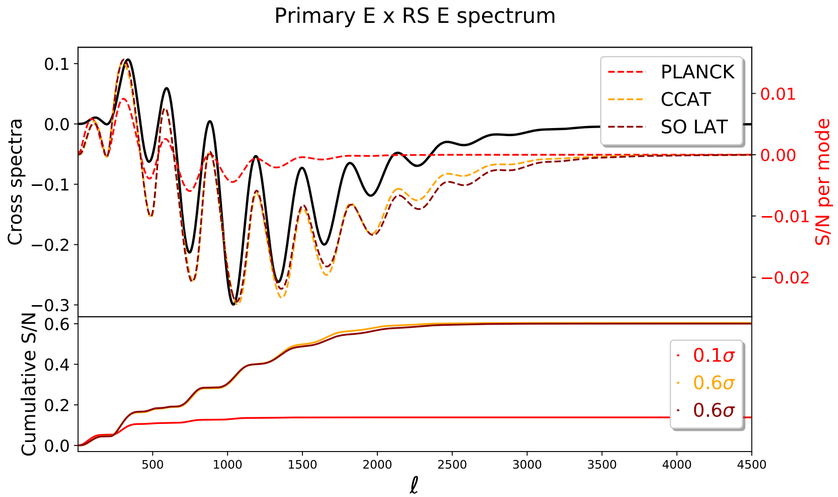
Can we detect it with upcoming surveys ?

Planck, SO, CCAT









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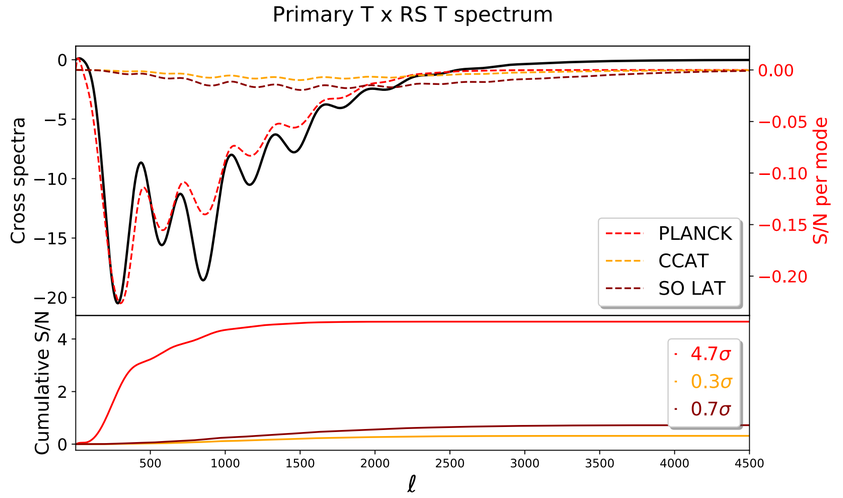

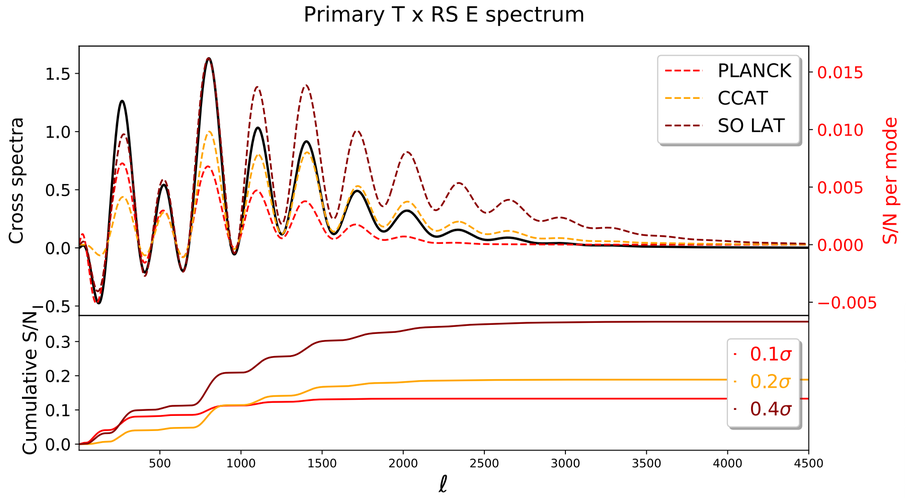

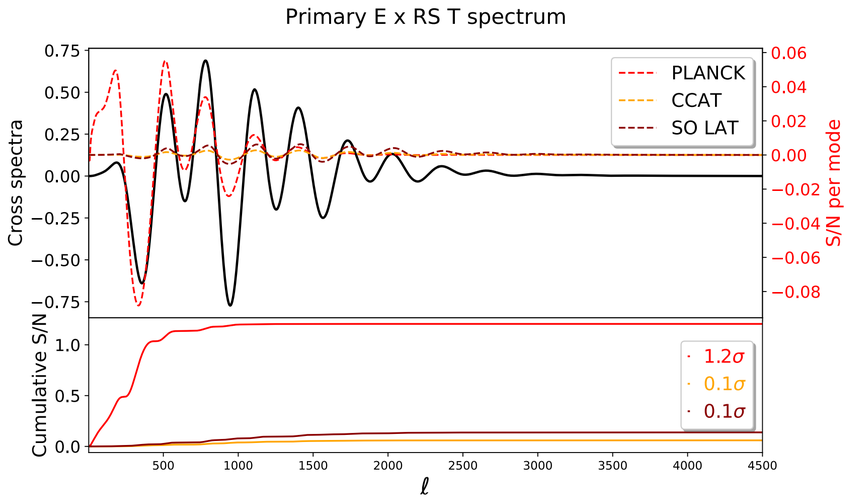

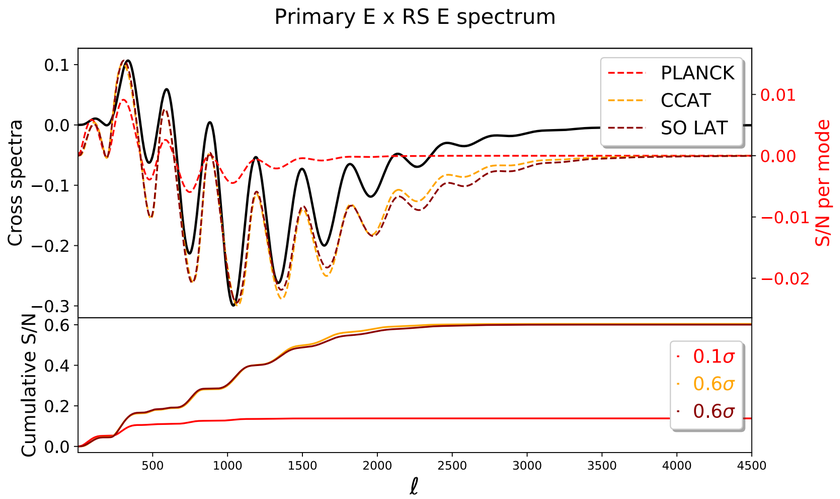

	Planck	SO LAT	CCAT-prime
$T_{\rm CMB} \times T_{\rm RS}$	4.7	0.7	0.3
$E_{\rm CMB} \times E_{\rm RS}$	0.1	0.6	0.6
$T_{\rm CMB} \times E_{\rm RS}$	0.1	0.4	0.2
$E_{\rm CMB} \times T_{\rm RS}$	1.2	0.1	0.1

[BB, Meerburg, Meyers and Battaglia 21]

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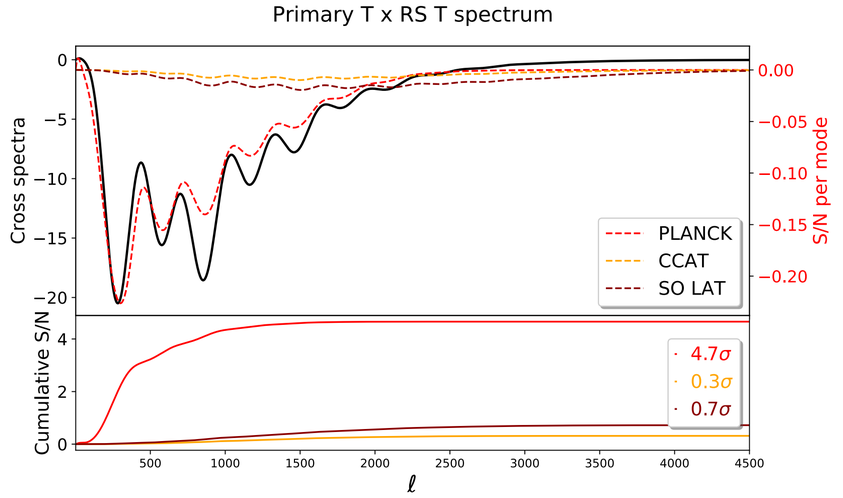

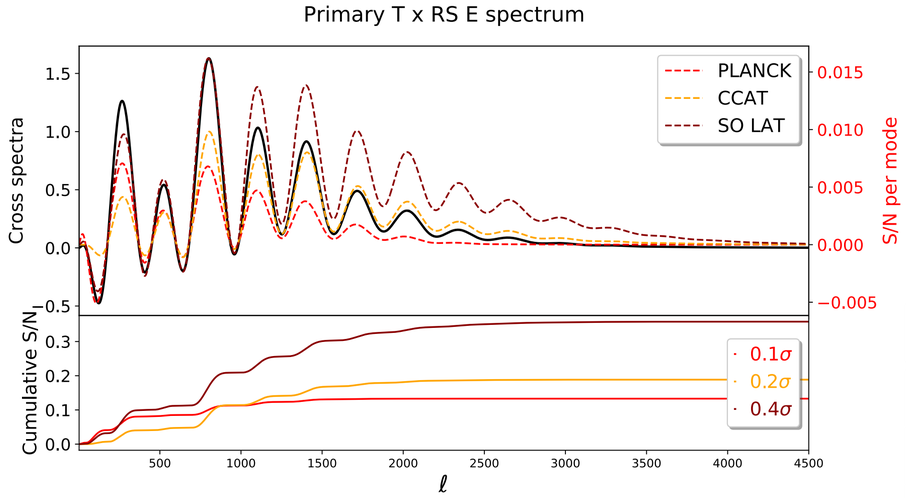

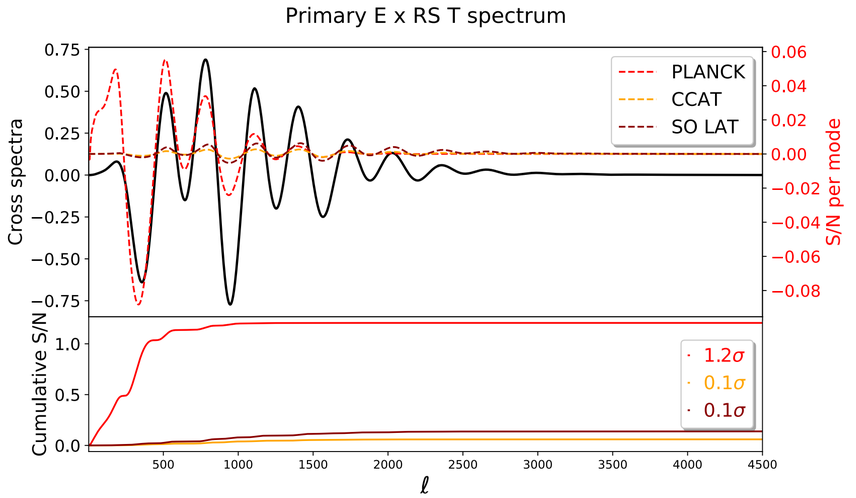

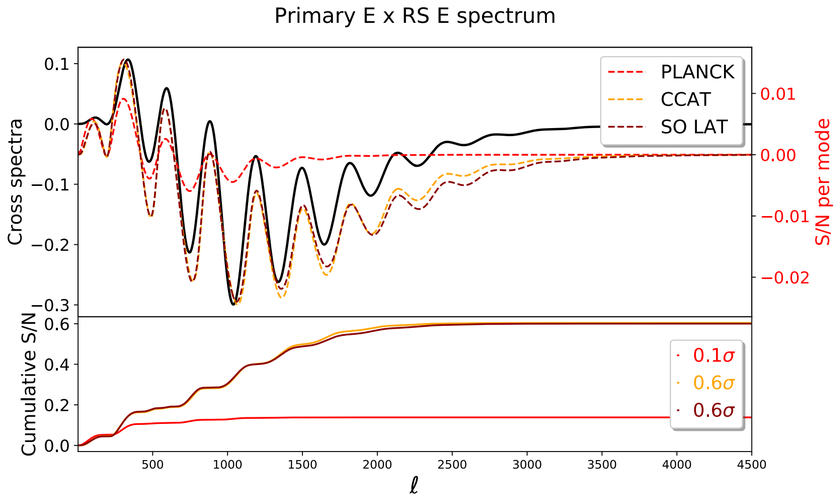

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$\sim 5.2\sigma$

[BB, Meerburg, Meyers and Battaglia 21]

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Upcoming surveys

	Planck	SO LAT	CCAT-prime	CCAT-prime : $\ell_{\rm knee}/2$	CCAT-prime : $2 \times N_{\rm det}$	CMB-S4	LiteBIRD	PICO
$T_{\rm CMB} \times T_{\rm RS}$	4.7	0.7	0.3	1.2	0.3	2.0	25	715
$E_{\rm CMB} \times E_{\rm RS}$	0.1	0.6	0.6	0.7	0.9	1.8	1.4	45
$T_{\rm CMB} \times E_{\rm RS}$	0.1	0.4	0.2	0.4	0.3	1.0	0.9	30
$E_{\rm CMB} \times T_{\rm RS}$	1.2	0.1	0.1	0.2	0.1	0.4	10	195

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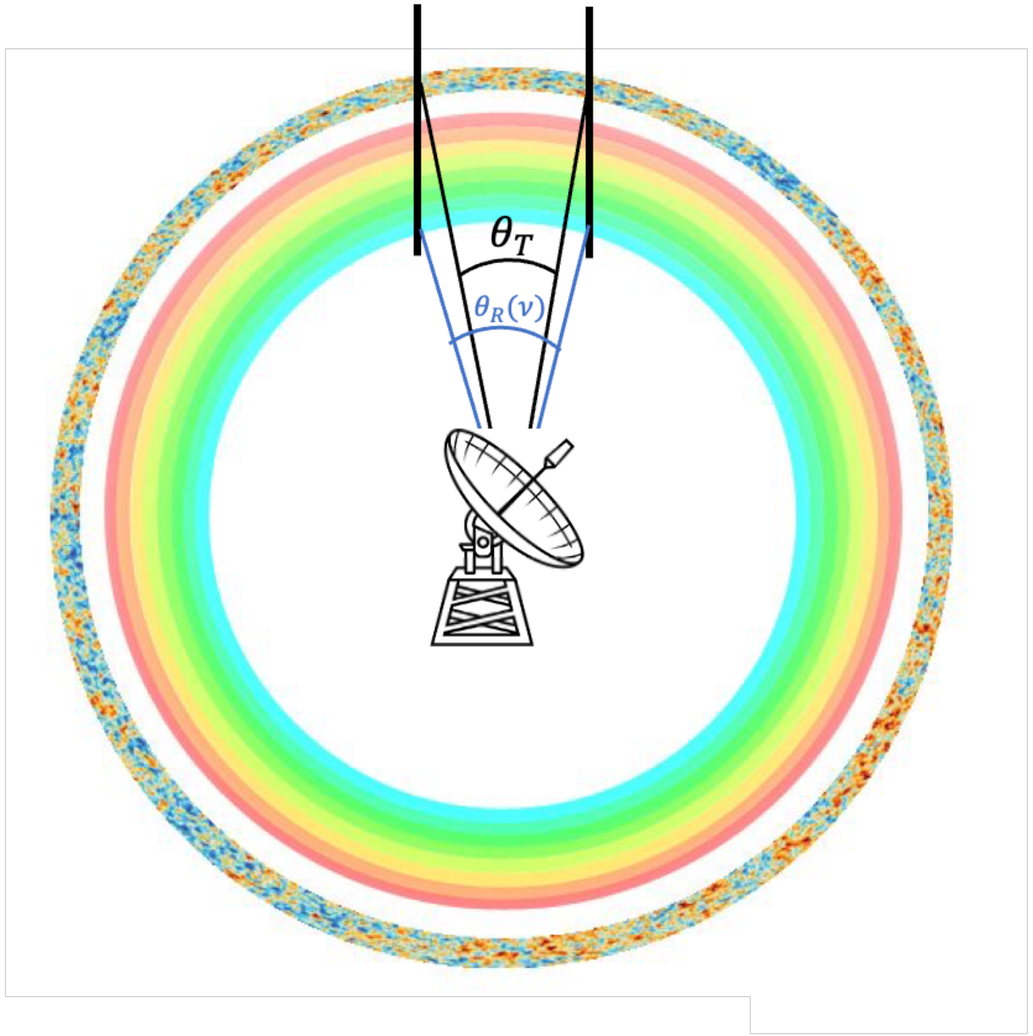
Forecasts after component separation (cILC) including extragalactic foregrounds

	SNR			
Configuration	TT	TE	ET	EE
CCATp+SO+*Planck*	1.1	0.3	0.3	0.6
LiteBIRD	1.9	0.1	0.9	0.2
LiteBIRD+CCATp+*Planck*	2.2	0.2	0.9	0.4
PICO	85	17	43	26

[Zhu, BB et al 23]

Does it help constraining cosmology?



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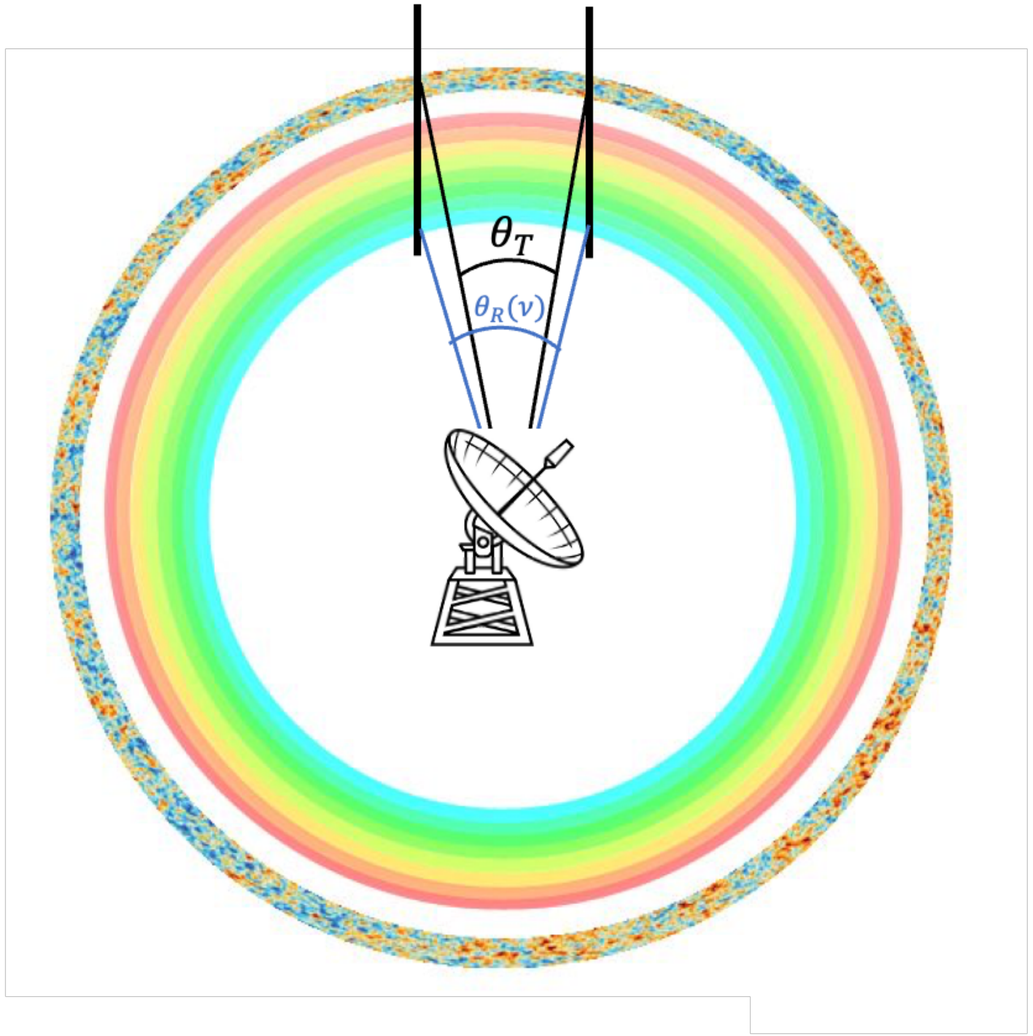

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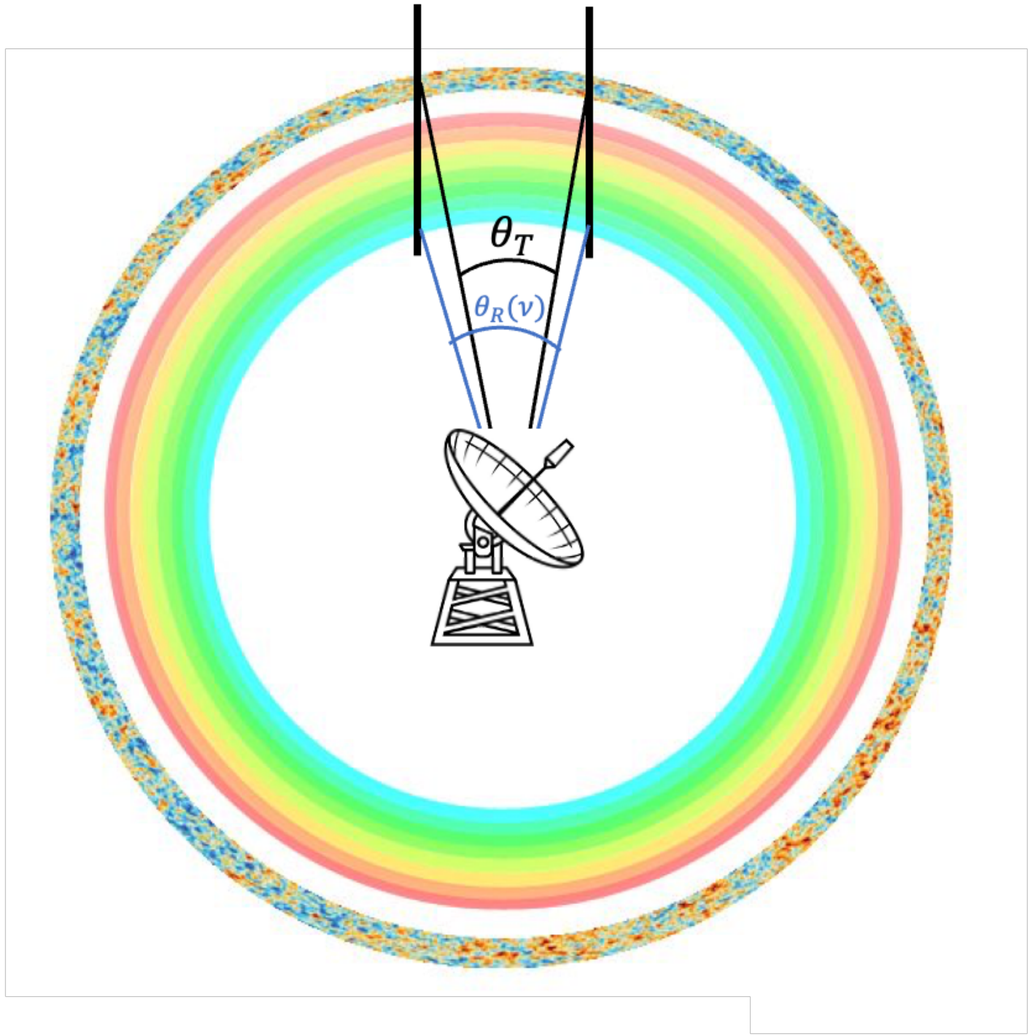

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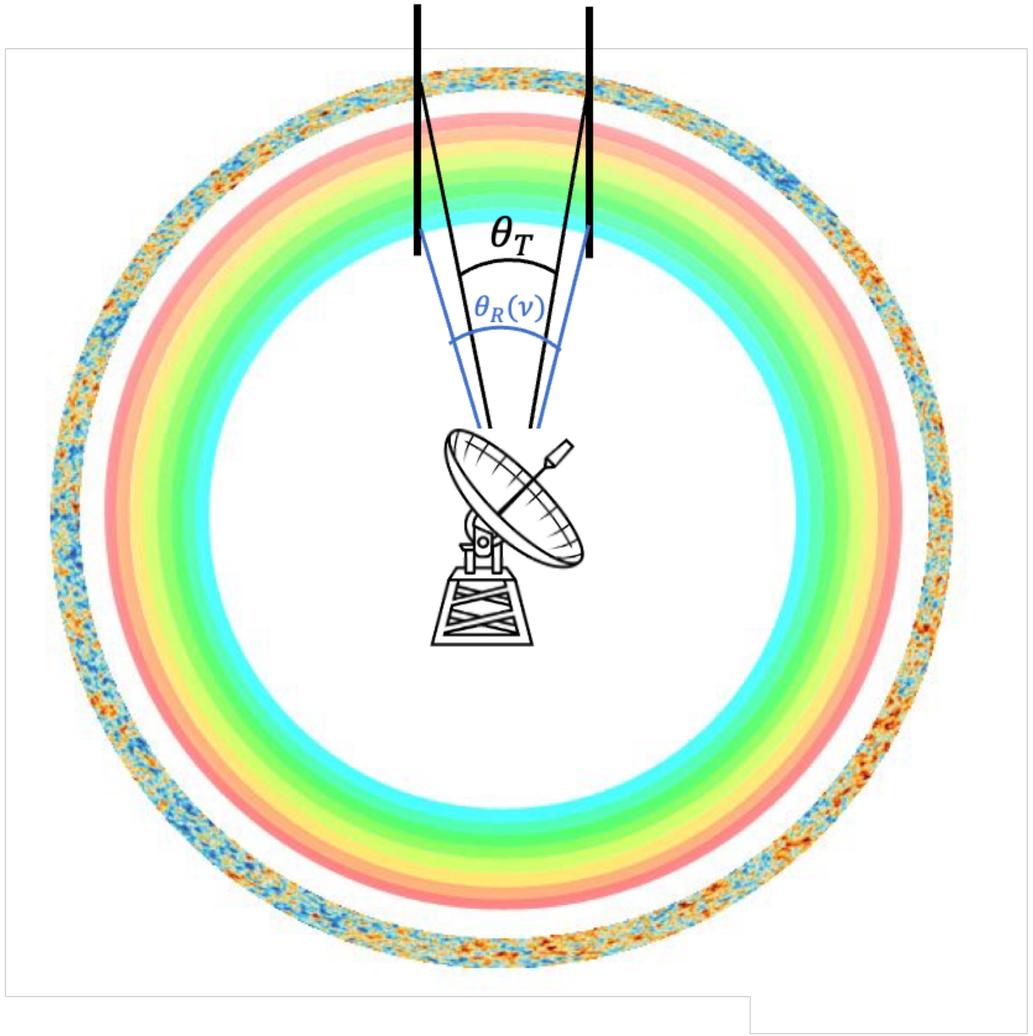

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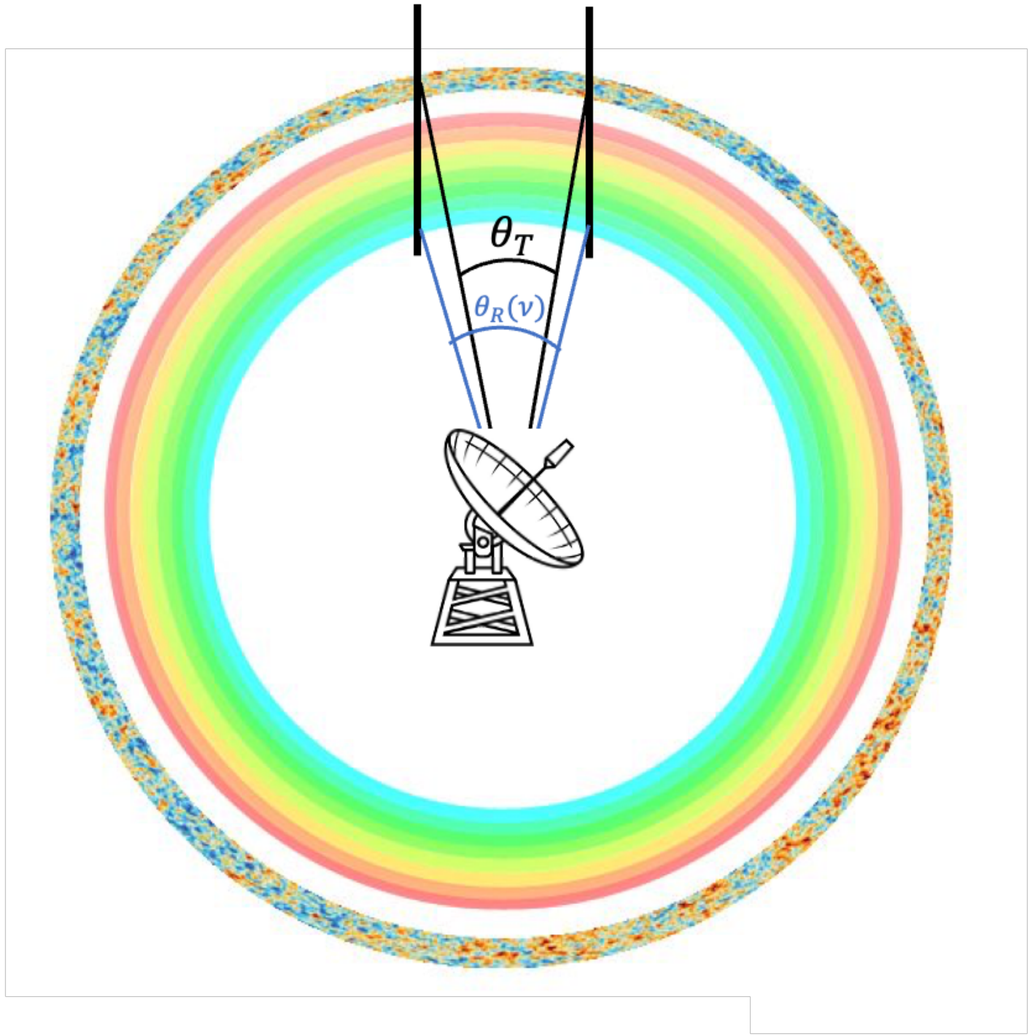

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- Rayleigh scattering produces different last scattering surface and fluctuation spectrum at every frequencies.
- Fixed length scales appear at different angular scales for primary and Rayeligh scatters components.
- Ratio of these angular scales helps constraining parameters.

Does it helps constraining cosmology ?

PICO forecasts

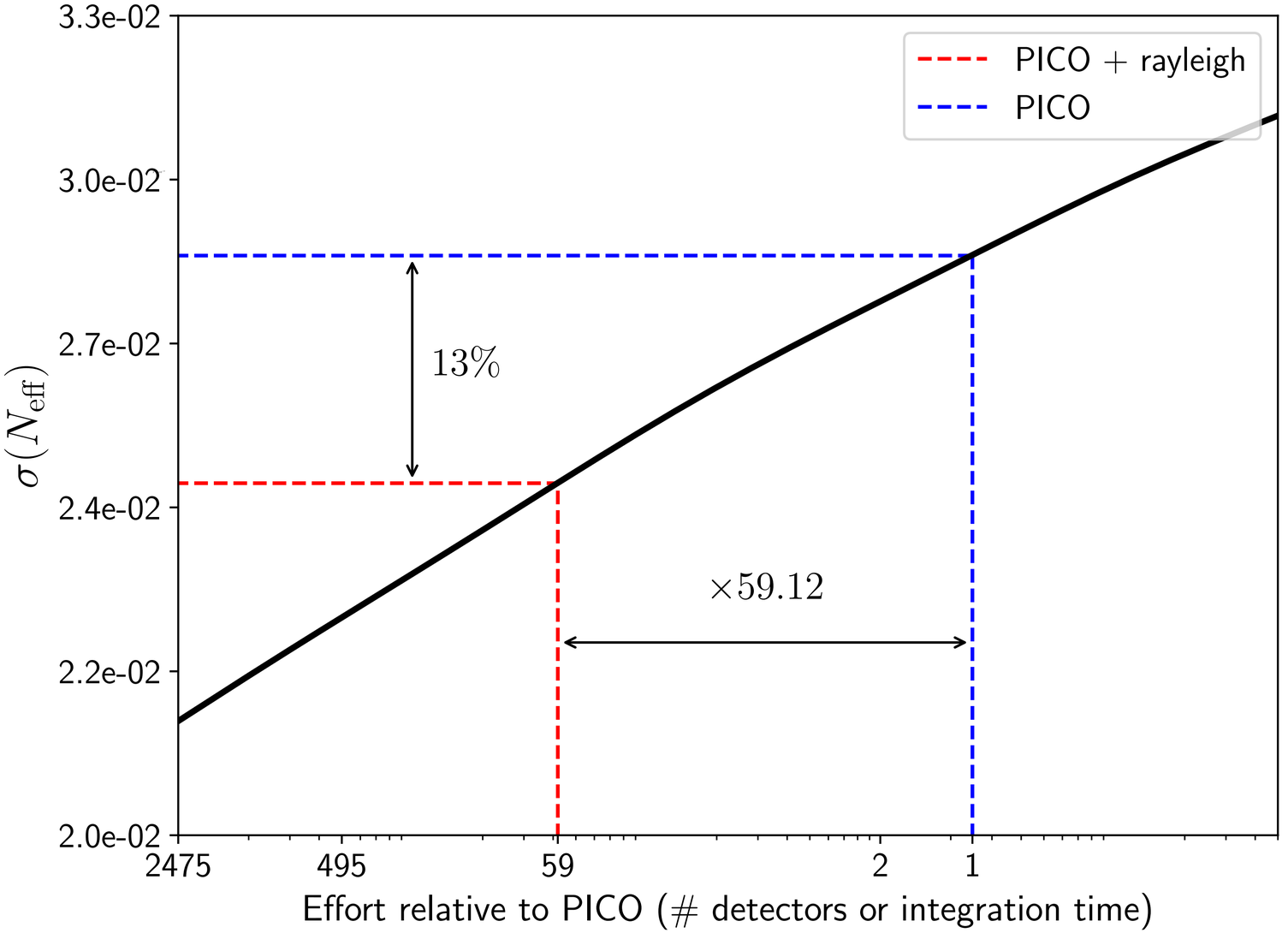
[BB, Meerburg, Meyers and Battaglia 21]

		$\Omega_b h^2$	$\Omega_c h^2$	$H_0[\mathrm{km/s/Mpc}]$	$10^9 A_s$	n_s	τ
TTTEEE	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}
TTTEEE + lensing	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}
TTTEEE + lensing + BBN	PICO no Rayleigh	2.31×10^{-5}	2.30×10^{-4}	8.79×10^{-2}	6.49×10^{-3}	1.26×10^{-3}	1.77×10^{-3}
	PICO with Rayleigh	1.92×10^{-5}	2.14×10^{-4}	7.85×10^{-2}	6.07×10^{-3}	1.17×10^{-3}	1.67×10^{-3}
	Improvement	16.84%	7.07%	10.71%	6.45%	7.54%	5.62%
	Primary-only CVL	8.00×10^{-6}	1.61×10^{-4}	6.07×10^{-2}	5.22×10^{-3}	7.01×10^{-4}	1.44×10^{-3}
TTTEEE + lensing + BBN + 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}

Does it helps constraining cosmology ?

PICO forecasts

[BB, Meerburg, Meyers and Battaglia 21]



What next ?

- M1 Student Andrea Landais (now M2 NPAC) has worked (a lot) to include Raleigh scattering in latest CAMB version.

- Allow for eg. EDE forecasts, easier integration with multifrequencies likelihoods, non-parametric recombination history.

- Trying different component separation methods: parametric, SMICA on future SO and CCAT data.

Thank you !

PyRayTE (Soon)

- Yu et al 2001
- Alipour et al 2015
- Lewis 2016
- **Beringue et al 2021**
- **Coulton et al 2021**
- **Zhu et al 2023**
- Dibert et al 2023