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Probing Dark Energy through Euclid Cross-Correlation Analysis

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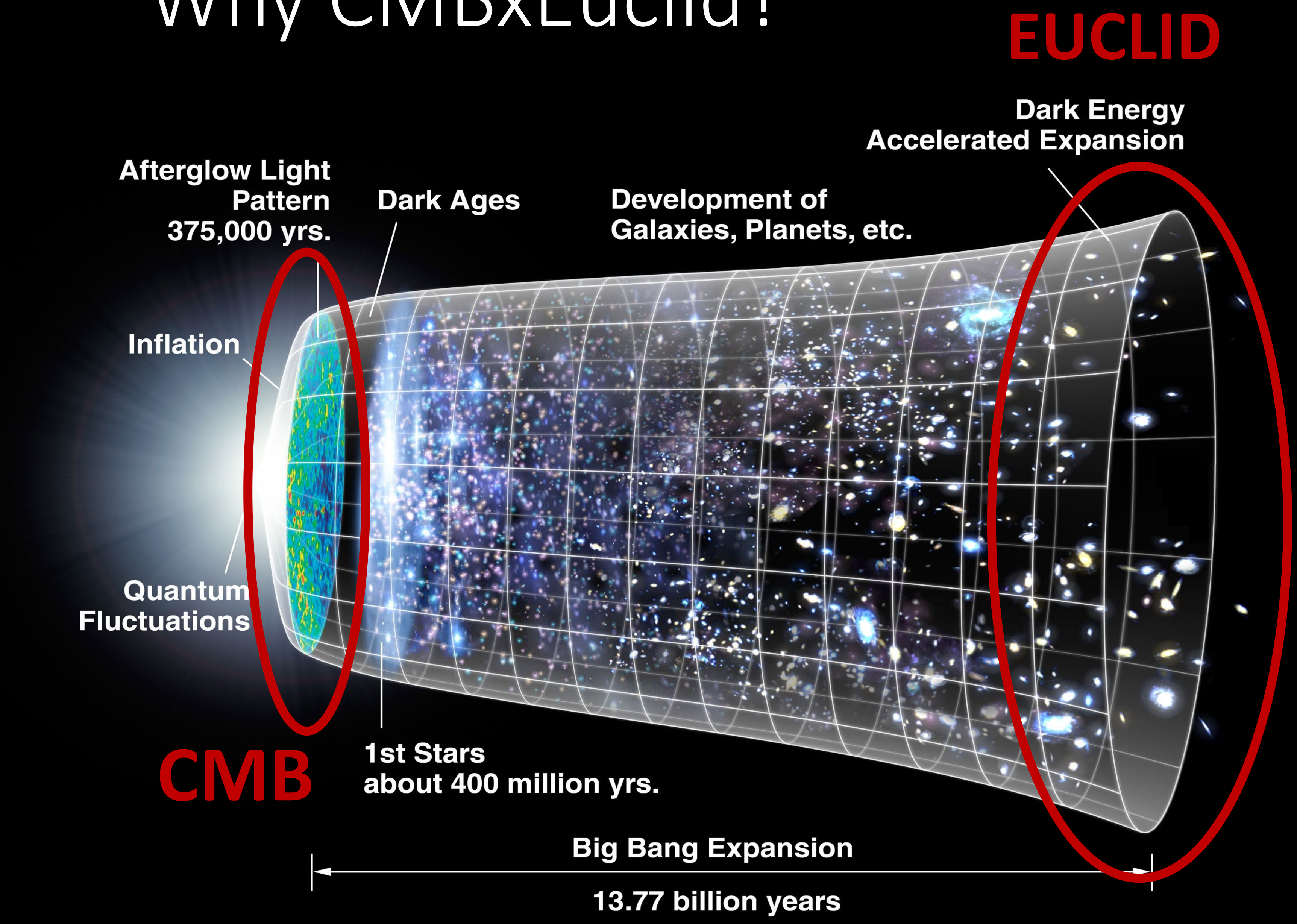
Motivations

1. The **Euclid** experiment will allow us to derive constraints on **cosmological parameters** through **cross-correlation** measurements between the Cosmic Microwave Background (**CMB**) and Large Scale Structure (**LSS**).
2. The idea is to **estimate** the **LSS-CMB signal** by exploiting **needlet** functions in order to **detect** the late Integrated Sachs-Wolfe (**iSW**) effect and constraint cosmological parameters.

Why CMBxEuclid?

- **Euclid** will probe the **late time Universe**, targeting the **growth** and **evolution** of the **large-scale structures** and the **late time evolution**, through the Galaxy Clustering (**GC**) and Weak Lensing (**WL**) measurements;
- **CMB** probes the **early Universe** through the **fluctuations** of the temperature and polarization field. The most accurate measurements come from the Planck satellite;
- At **late times**, CMB photons **interact** with LSS (e.g. **gravitational lensing**, **secondary anisotropy**) affecting the temperature and polarization power spectrum.

Why CMBxEuclid?



With the combination of Euclid and CMB probes we can cover nearly the entire history of the Universe

Why CMBxEuclid?

1. CMB and LSS are both **tracers** of the matter distribution but at **very different stages** of the Universe history;
2. The **EuclidxCMB** terms provide **additional cosmological information** at late time, possibly increasing the constraints on some cosmological parameters;
3. The cross-correlation analysis can **reduce the impact of correlation** between different cosmological and nuisance parameters and **of experimental systematics**.

Why CMBxEuclid?

- Within the Euclid collaboration, the CMBX Science Working Group is the one focused in this joint analysis (reference arXiv:2106.08346v2);
- Two main probes:
  - **CMB temperature-galaxy number counts (TG)** cross correlation, sensitive to the nature of dark energy through the iSW effect;
  - **CMB lensing-galaxy number counts (ϕG)** cross correlation, contains information about the growth of structures;

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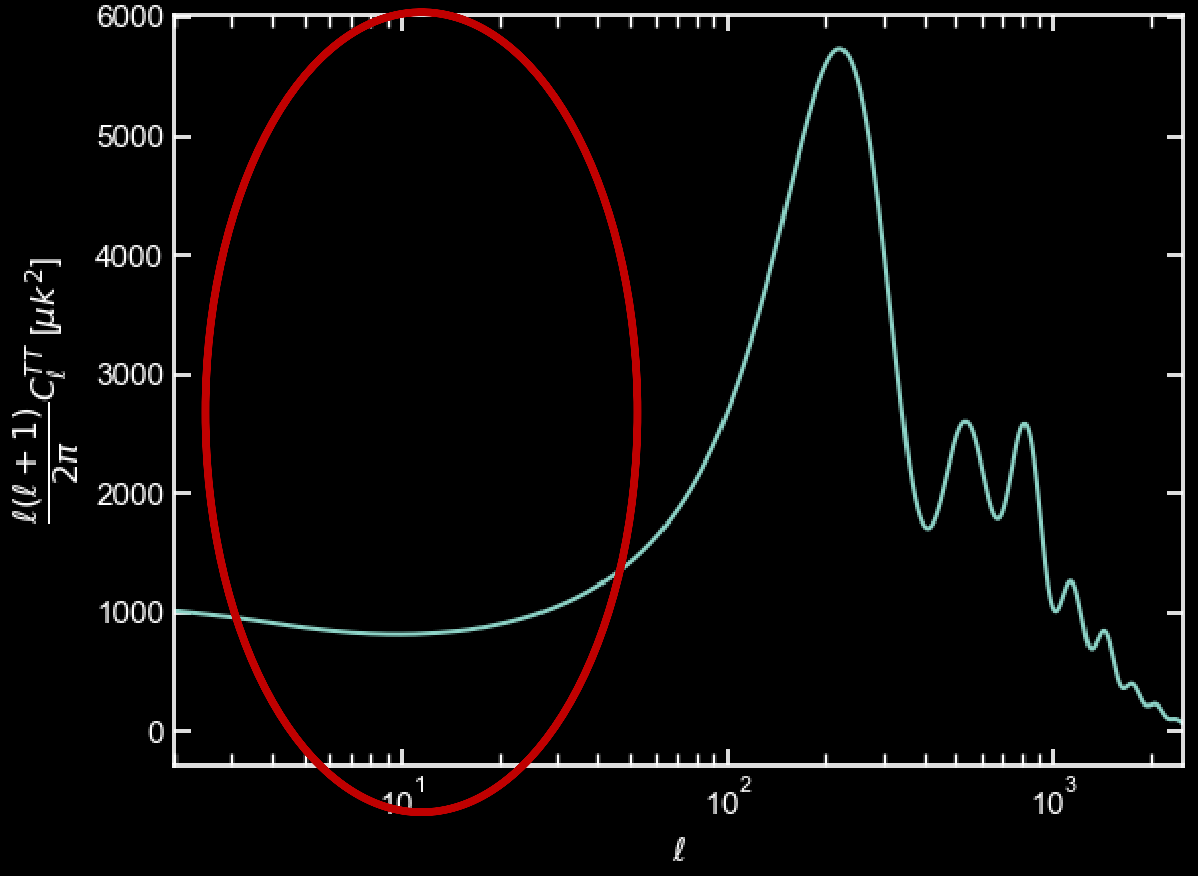
Integrated Sachs-Wolfe effect

- The iSW is sensitive to the **late time** Universe **acceleration** and so to the **Dark Energy parameters**.
- The iSW is due to the **interaction** between CMB photons and time evolving gravitational potential wells;

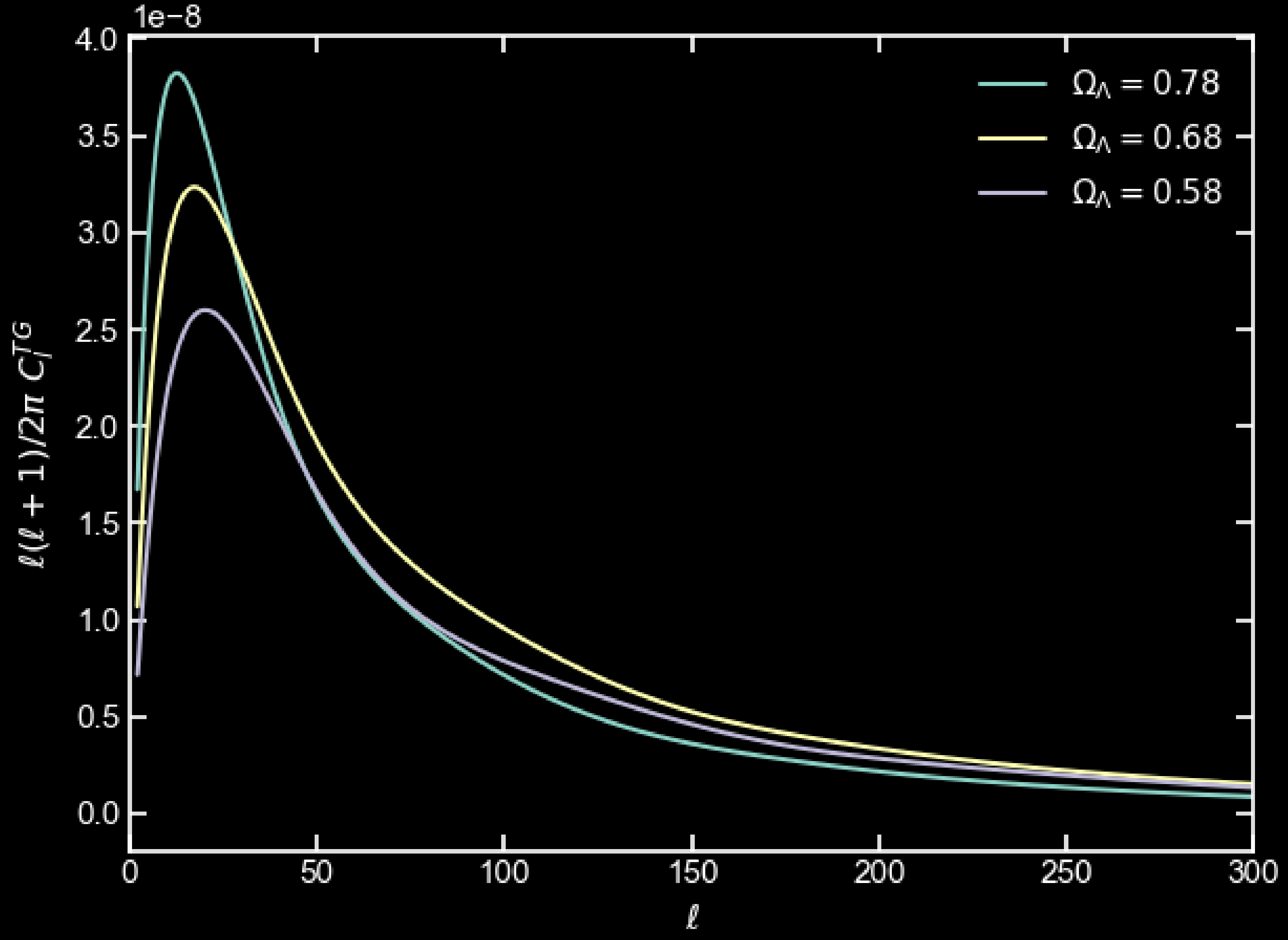


CMB temperature cross correlation with LSS

- iSW anisotropies are **subdominant** with respect to primary anisotropy (before recombination) and the CMB in dominated by **noise**;
- One of the most direct ways to detect this effect it to **cross-correlate** CMB anisotropises with **distribution** of **galaxies** at low ℓ;
- The angular power spectrum in the harmonics space C_ℓ^{TG} is the most common **observable**.

CMB temperature cross correlation with LSS

- Cross-correlation angular power spectrum at low ℓ is dependent on **cosmological parameters** Ω_Λ;
- Ω_Λ changes the **amplitude** of the power spectrum;

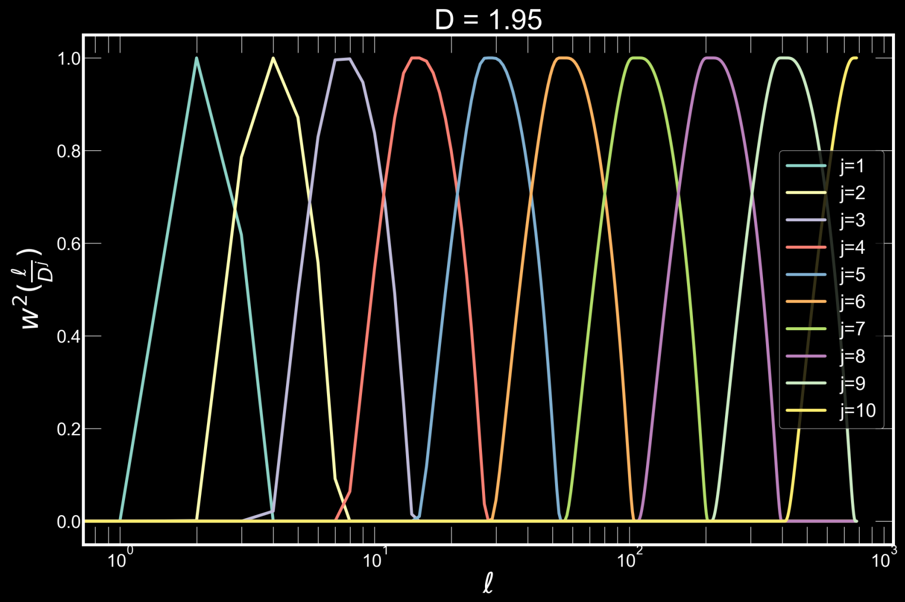


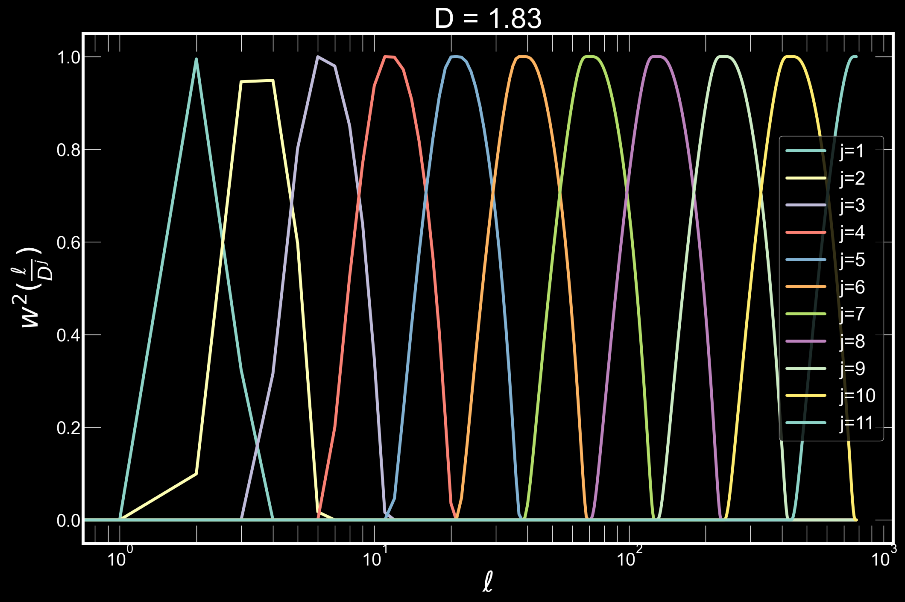
Other estimators?

- Harmonic estimator exploits **orthogonal** properties in harmonic space;
- It possesses the **minimum** variance in case of no mask, spatially uniform noise;
- Building new **estimators** to deal with a more **realistic** scenario.

Needlets

- Needlets are a kind of **spherical wavelet**;
- Needlets are a **convolution** of spherical **harmonics** and a suitably chosen **window function**;
- Needlets are **localized** both on **real** space and on **harmonic** space;
- This is an advantage when analyzing maps with **incomplete data** (e.g. masked observations, incomplete sky coverage)
- Needlets are useful for **testing** the presence of **systematics**.

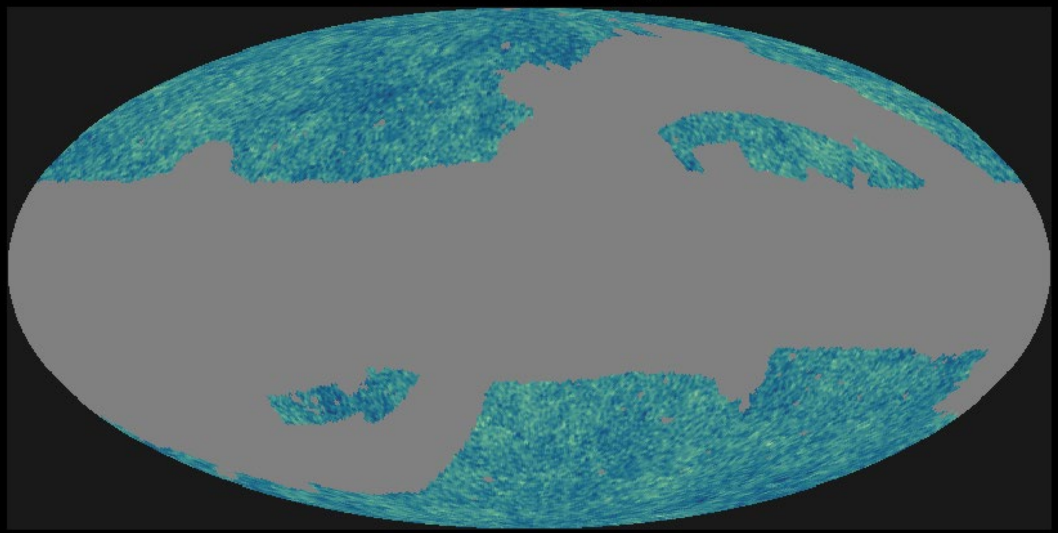


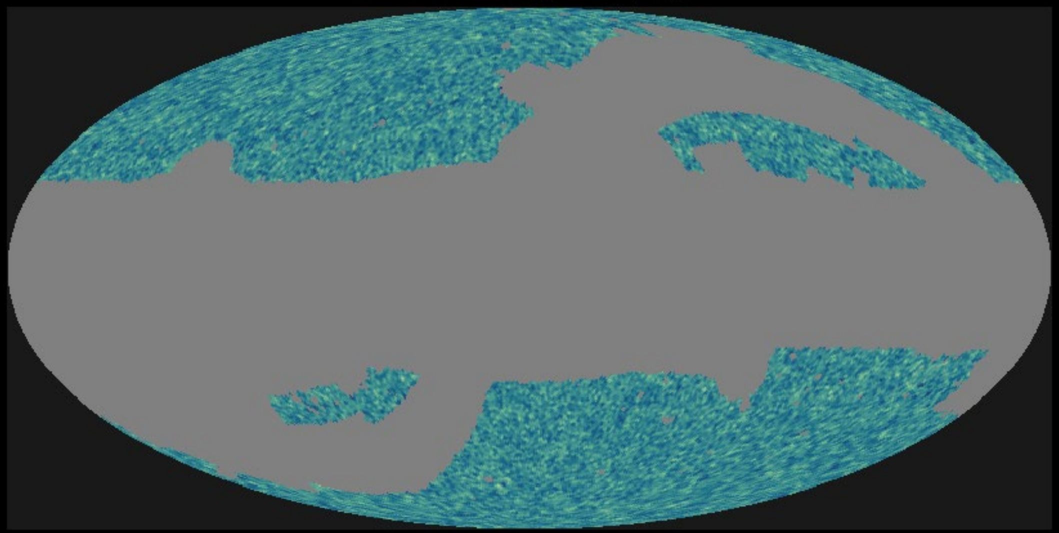


Needlets cross power spectrum from Euclid simulations

- Analysis of 1000 **simulated 2D maps** of the **correlated** CMB temperature anisotropies and galaxy distributions provided by the CMBX SWG (non-tomographic case);
- Each maps is **Gaussian distributed** around mean equal to zero and variance equal to the theoretical power spectra $\boldsymbol{C_\ell}$.
- Cosmological model: **ΛCDM** with the cosmological parameters fixed by the recipe for the **Euclid forecast** (reference arXiv:1910.09273).
- Contribution of the **shot noise** from the predicted number of galaxies Euclid will observe (**30 galaxies/arcmin**^2)

Needlets cross power spectrum from Euclid simulations

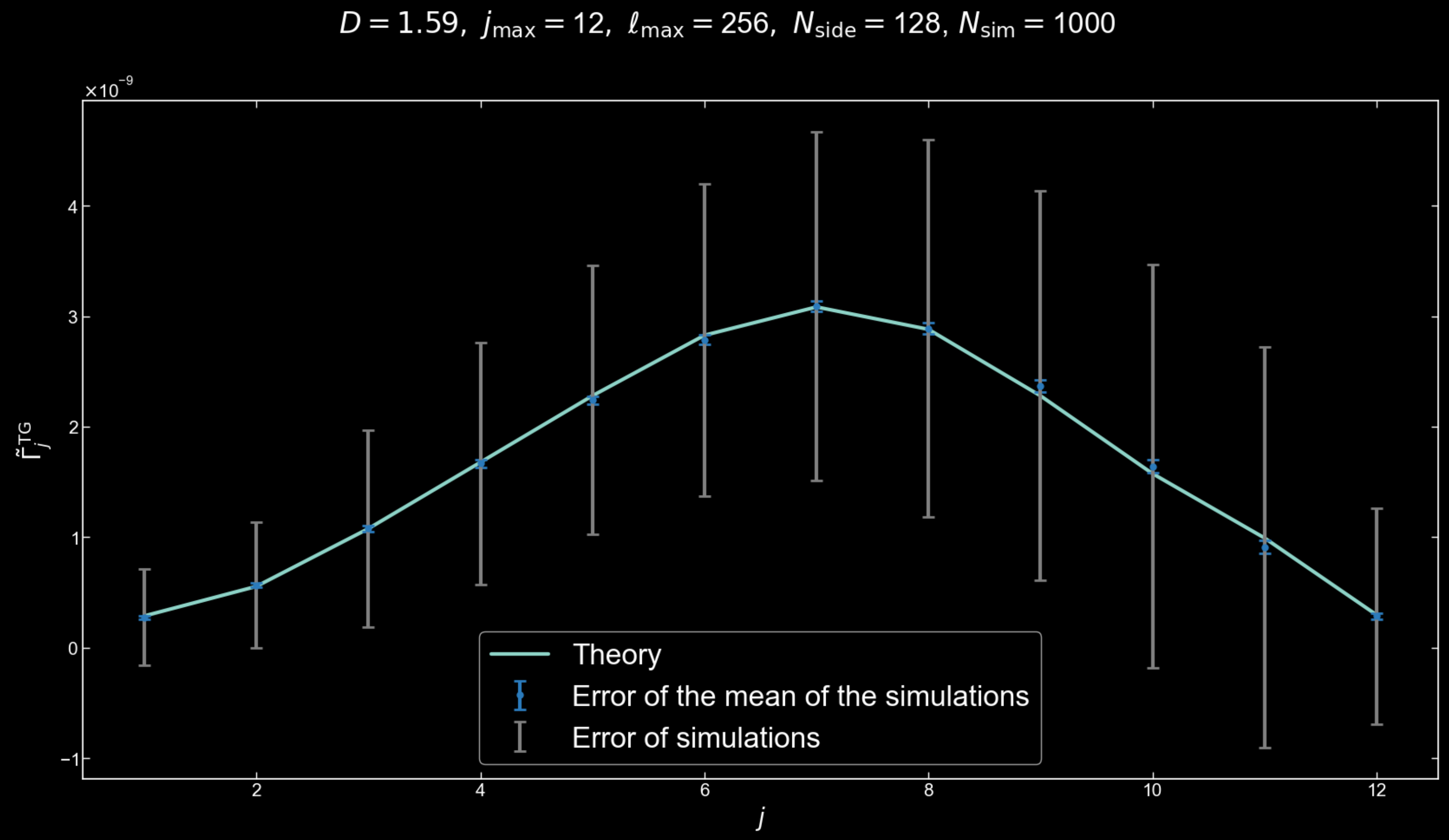




Exp. Value: $\left\langle \hat{\boldsymbol{\Gamma}}_j^{TG} \right\rangle$

Variance: $\left(\Delta\Gamma_j^{TG}\right)^2$

Needlets – CMBxG power spectrum from Euclid simulations

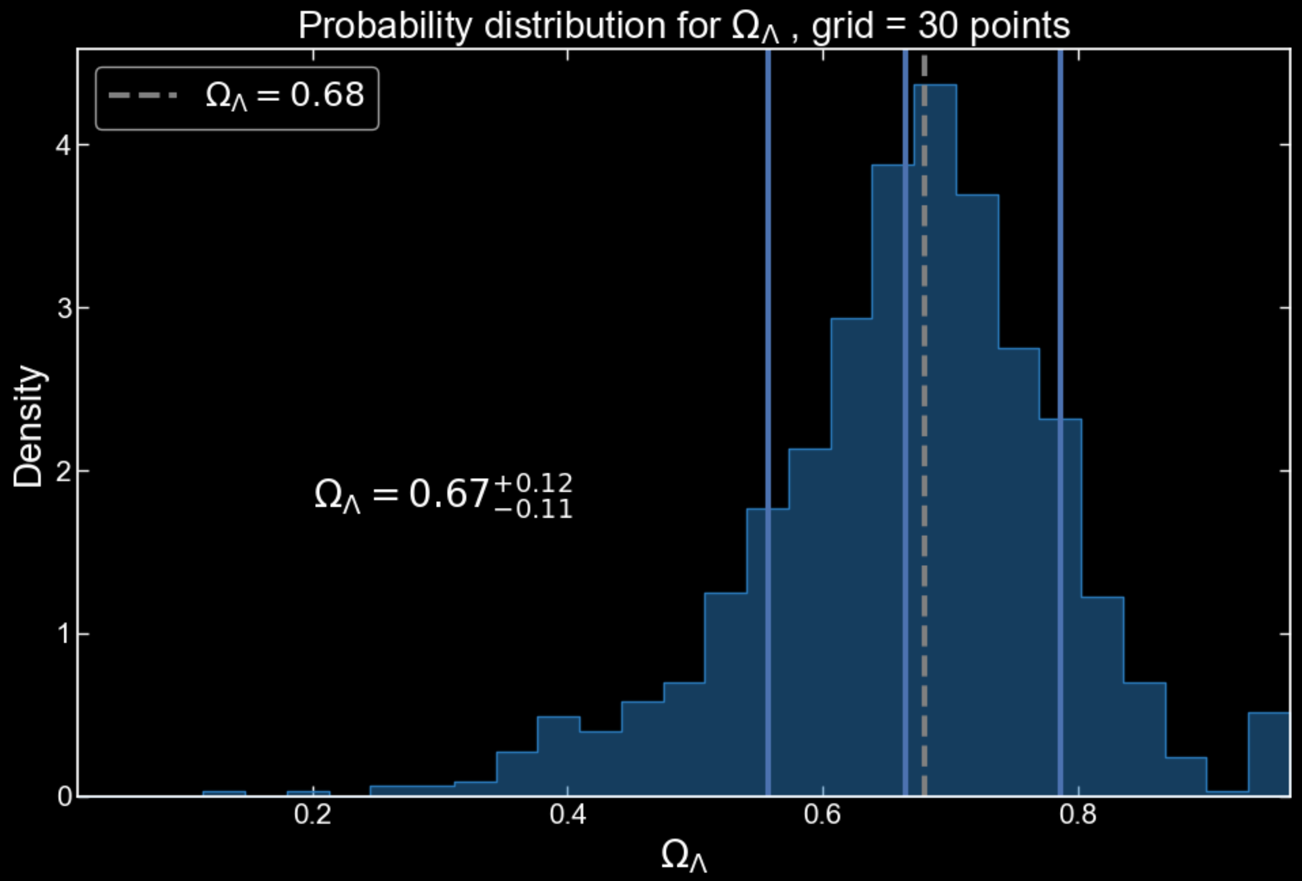


Needlets – Dark Energy parameter estimation

- We produced a **grid** of spectra for 30 different values of $\boldsymbol{\Omega_\Lambda}$, $\boldsymbol{\Gamma_j^{TG,\Omega_\Lambda}}$;
- In each point we evaluated a Gaussian **likelihood** for each realizations, with mean equal to $\Gamma_j^{TG,\Omega_\Lambda}$ in that point and covariance from the simulations;
- We drew the histogram of the **best-fit values** from all the simulations;
- We calculated the **mean** and **Confidence Interval at 68% Confidence Level** of the distribution.

Needlets – Dark Energy parameter estimation

- We recovered the fiducial value for Ω_Λ within 1σ.
- **Next step**: including the tomographic case, realistic noise and … analysing the **real data**!



What about neutrinos?

What about neutrinos?

- The standard ΛCDM model predicts **three neutrino species**, approximated as **two massless states** and a **single massive neutrino** of mass $\boldsymbol{m_\nu = 0.06}$ **eV**, in the **normal mass hierarchy** scenario (reference arXiv:1807.06209).
- Two main contributions to C_ℓ^{TG} from massive neutrinos:
  - **Suppression** of the power at **small scales** due to **the free-streaming** (slowing down structure formation);
  - **Enhancement** of the **iSW** effect at **high redshift** and **small scales**, because massive neutrinos change the behaviour of the growth factor.

What about neutrinos?

- iSW alone is **not able to constraint neutrinos' mass**: one must add the cross-correlation probes to CMB and LSS probes;
- Forecasting results for **EuclidxCMB** analysis for **extended model** ΛCDM + $\{N_{eff}, \sum m_\nu\}$ in reference arXiv:2106.05267 by means of **Fisher analysis**;
- They found that including the **TG and ϕG cross-correlation** terms to the CMB and Euclid probes can reduce the uncertainties on the neutrino mass up to $\sim \mathbf{40\%}$.

What about neutrinos?

DISCLAIMER

These are forecasts: do not rely on realistic simulations of the experiments and do not include realistic systematic/experimental effects!

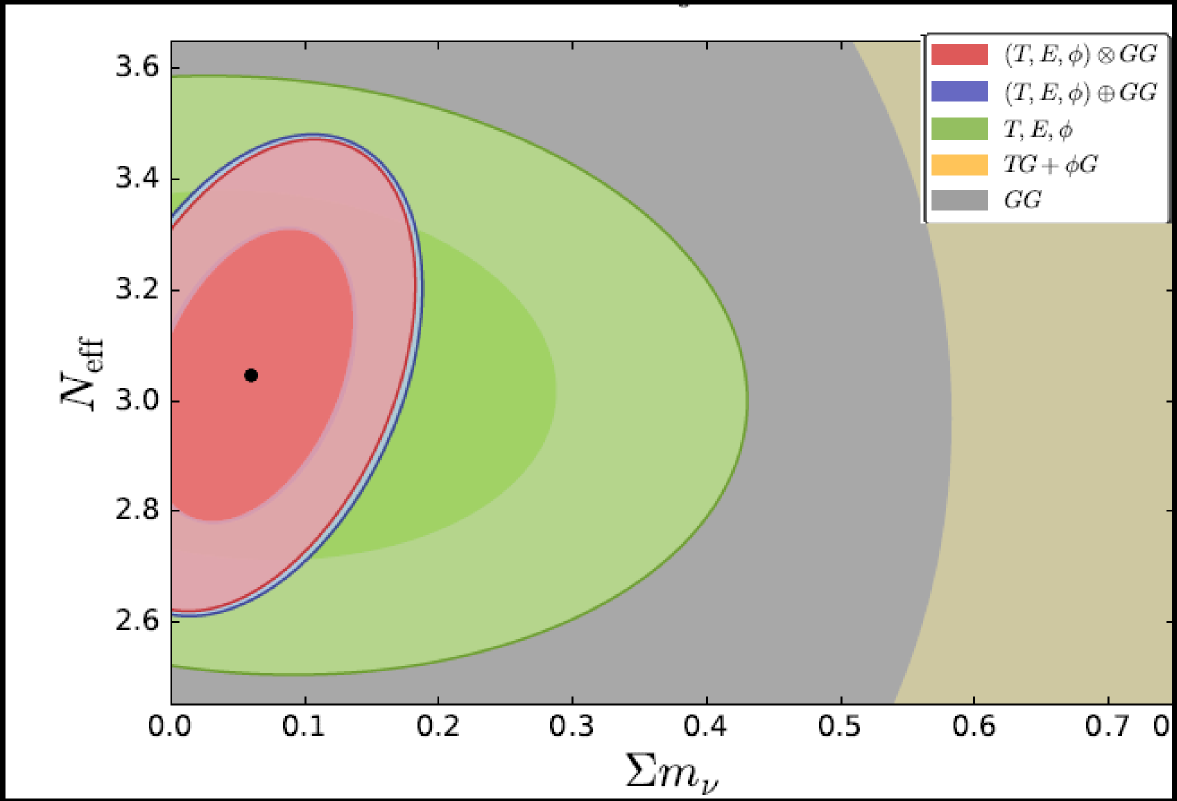
These kind of analysis are meant to understand which kind of physics we can address.

- nd

Euclid probes can reduce the uncertainties on the neutrino mass up to ~ 40%.

Forecast on neutrino mass

- Marginalized 68% and 95% 2D confidence regions for the **constraints from CMB, GC and cross-correlation independently and jointly** for the extension ΛCDM+$\{N_{eff}, \sum m_\nu\}$
- All the other parameters of the model are fixed except for N_{eff} and $\sum m_\nu$;



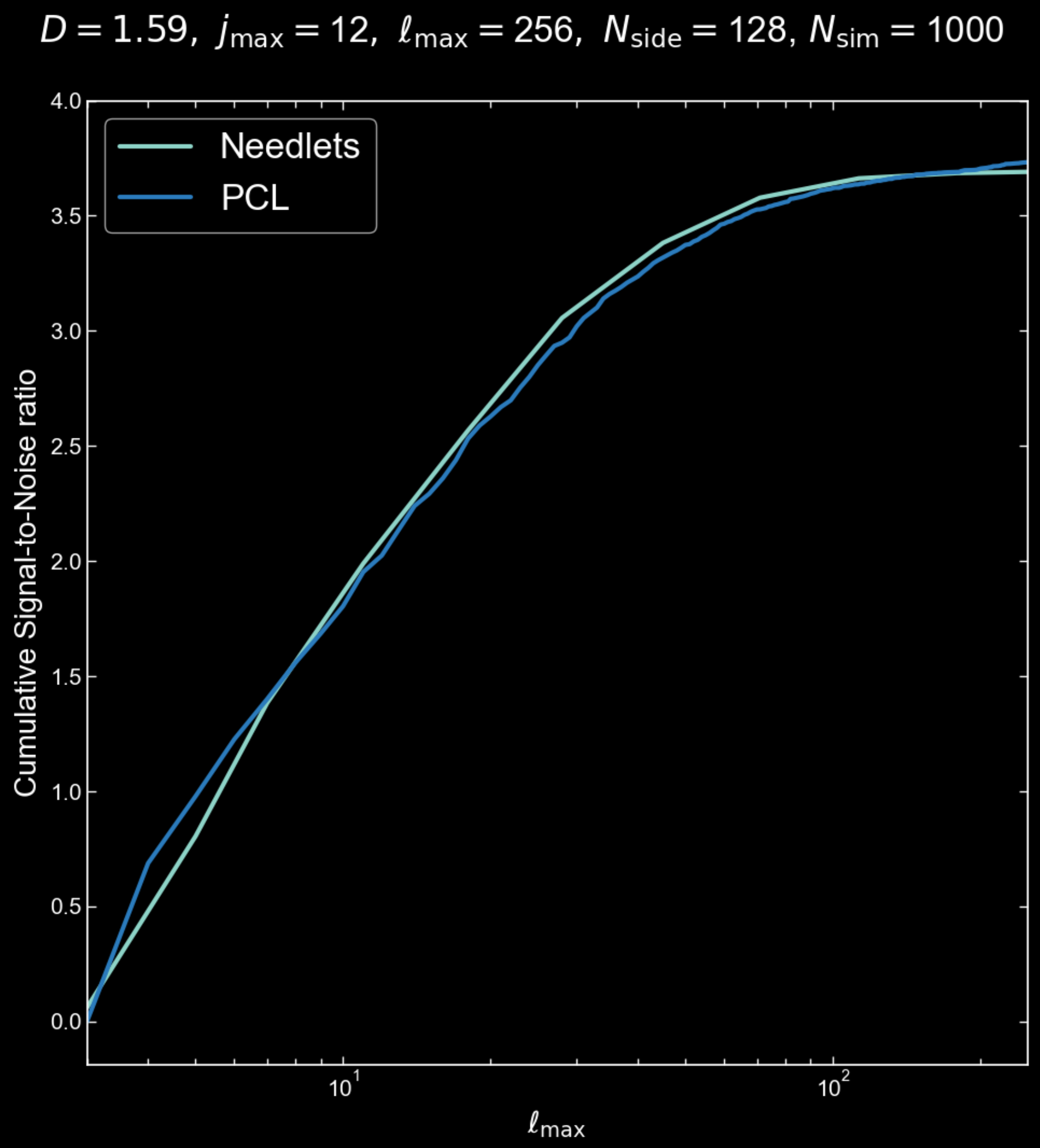
arXiv:2106.05267

Thank you for the attention!

Backup

Signal-to-Noise analysis

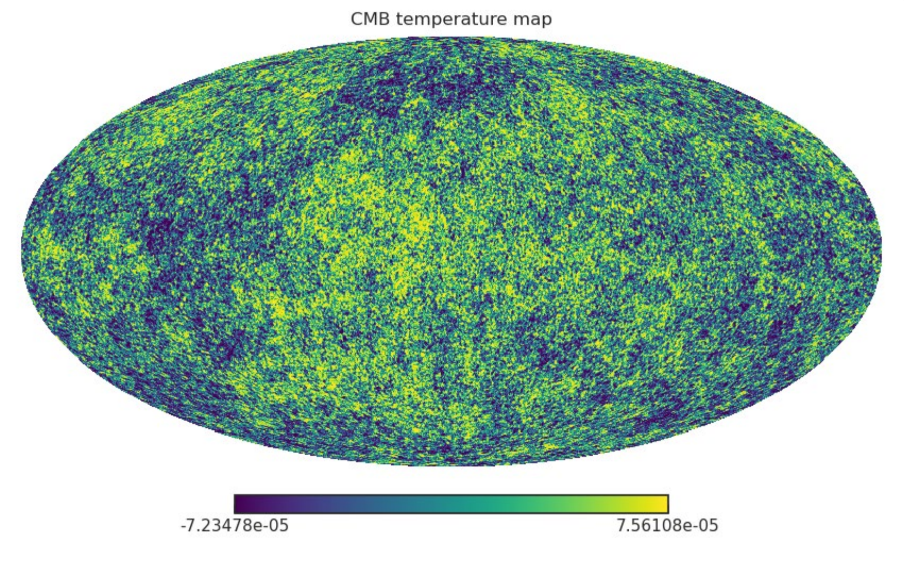
- $\left(\frac{S}{N}\right)_j^2 = \frac{\left(\widehat{\Gamma}_j^{TG}\right)^2}{\left(\Delta\Gamma_j^{TG}\right)^2}$
- Summing over all the maximum multipole of the analysis to obtain the **cumulative S/N**;
- Most iSW signal up to $\ell_{max} \lesssim \mathbf{100}$;
- Same performance of the **needlets** and the standard **harmonic** estimators;

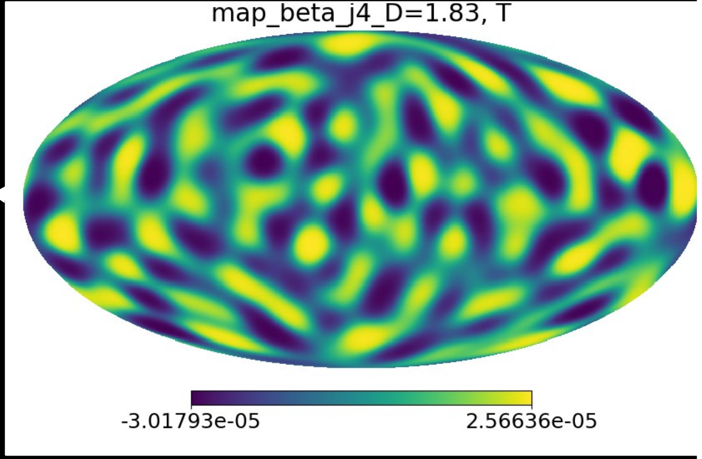


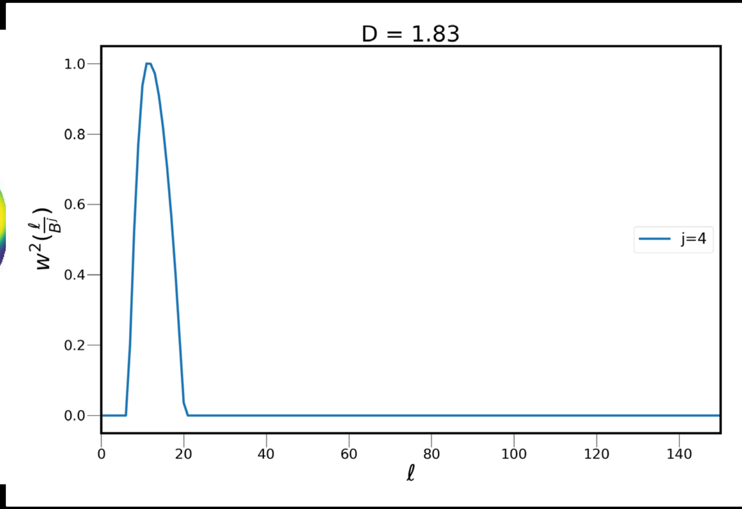
Needlets cross power spectrum from Euclid simulations

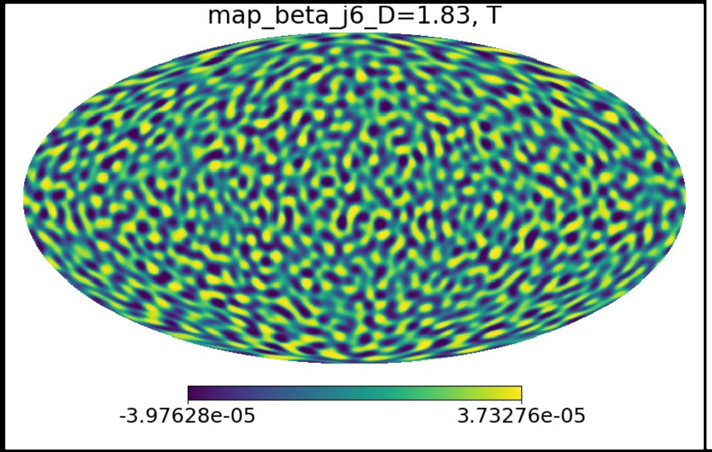
- We apply to both maps the **combination** of the **Planck mask** for the CMB sky and a **realistic mask for** the **Euclid** survey. The total fraction of the sky observed is $\boldsymbol{f_{sky}} \sim \mathbf{36\%}$;
- Extraction of the **needlet-based** cross-correlation power spectrum $\widehat{\boldsymbol{\Gamma}}_{\boldsymbol{j}}^{\boldsymbol{TG}}$ from maps;
- Computation of the **covariance** matrix from simulations;
- Comparison with the **theoretical prediction** for the expected value Γ_j^{TG} and the variance $\left(\Delta\Gamma_j^{TG}\right)^2$.

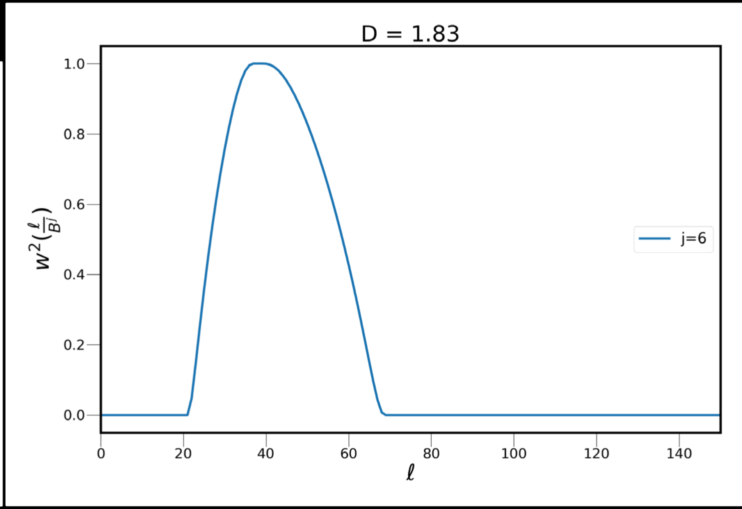
Analysis with needlets



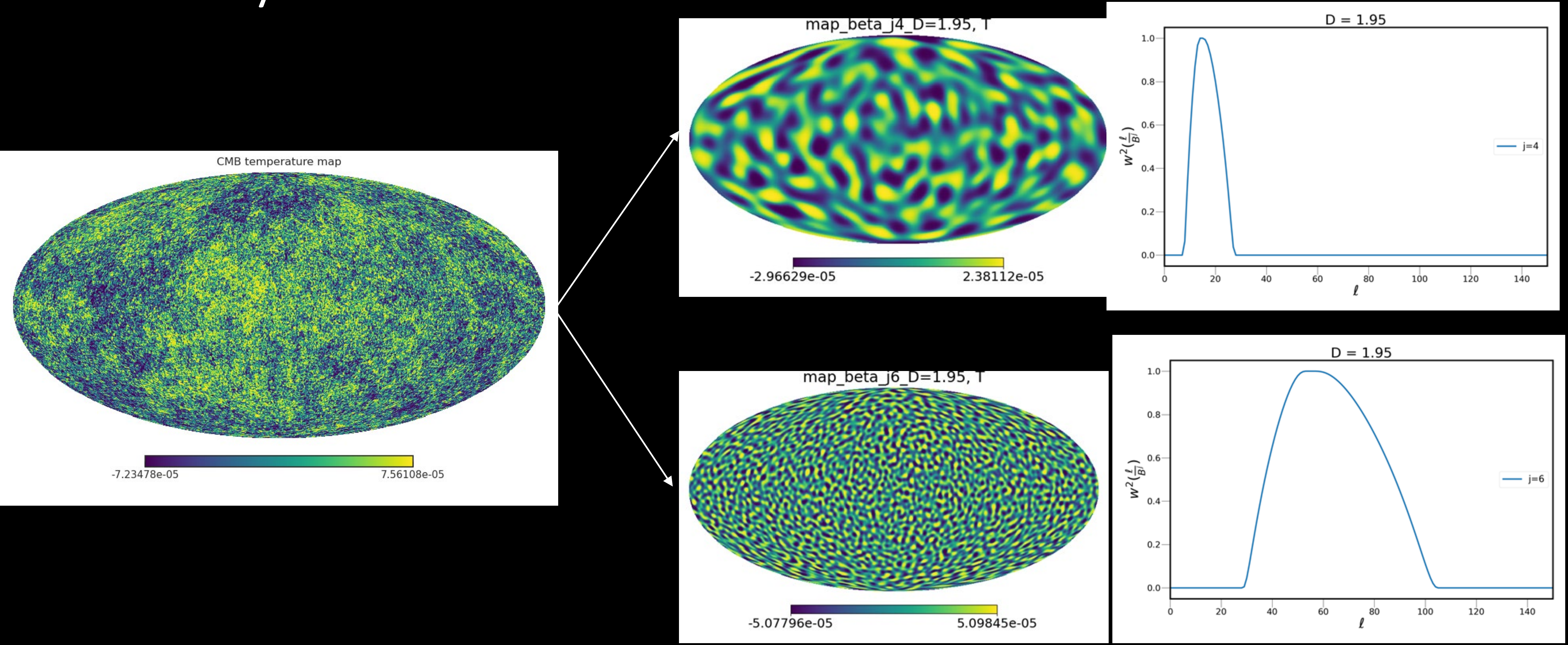








Analysis with needlets



Why CMBxEuclid?

- Ratio between the sigma before and after adding the cross-correlation between all the CMB probes (T and ϕ) to the Euclid probes ($GC_s, GC_{ph}, WL, GC_{ph} + WL$);
- Improvement on the bias parameters: galaxy bias and intrinsic alignment parameters
- Improvement in ΛCDM parameters and in extended models (especially $w_0 w_a$CDM)

	$\Omega_{b,0}$	$\Omega_{m,0}$	n_s	h	σ_8	τ	w_0	w_a	$\Omega_{DE,0}$	γ	b_1	b_2	b_3	b_4	b_5	b_6	b_7	b_8	b_9	b_{10}	A_{IA}	η_{IA}	β_{IA}
Optimistic Euclid + S4, flat ΛCDM	6.7	1.2	1.6	1.6	1.3	3.9					1.2	1.2	1.2	1.2	1.2	1.2	1.2	1.2	1.2	1.2	1.0	1.0	1.0
non-flat ΛCDM	5.0	1.6	1.5	1.6	1.4	1.4			5.5		1.4	1.7	1.9	1.9	2.0	2.0	2.1	2.3	2.5	2.6	1.0	1.0	1.0
flat $w_0 w_a$CDM	5.3	2.2	2.0	1.2	2.0	2.8	1.9	1.7			1.1	1.4	1.5	1.6	1.6	1.7	1.7	1.8	1.8	1.9	1.0	1.0	1.0
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flat $w_0 w_a \gamma$CDM	6.1	2.5	2.2	1.3	2.1	2.8	1.8	1.6		1.6	1.0	1.3	1.5	1.6	1.7	1.8	1.9	2.0	2.2	2.1	1.0	1.0	1.0
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arXiv:2106.08346v2

Late ISW

- The late ISW occurs at late times, $z \lesssim 1$
- It is restricted to extremely large scale $l \lesssim 30$
- It depends on the cosmological parameters related to the Dark Energy
- The most direct way to detect this effect it to cross correlate CMB photons with the Large Scale Structure (LSS) at low redshifts.
- Galaxies and clusters are tracers of the dark matter overdensity δ_m related to the evolution of the gravitational potential Ψ trough the Poisson equation:

$$\nabla^2\Psi = 4\pi G a^2 \rho_m \delta_m(\vec{x}, a)$$

Integrated Sachs-Wolfe effect

$$\Theta_\ell^{ISW} = -2\int_0^{\eta_0} d\eta\, e^{-\tau}\psi'(k,\eta) j_\ell[k(\eta_0-\eta)]$$

- The ISW is due to the evolution of the gravitational potential Ψ after recombination;
- The ISW at late time is due to the decay of gravitational potential. This gives rise to temperature anisotropy in the CMB spectrum during the era of transition between a matter dominated universe to a dark energy dominated one;
- ISW happens at $z \lesssim 1$ and it is restricted to extremely large scale $l \lesssim 30$;
- It depends on the cosmological parameters related to the Dark Energy.

Research activity - Needlets

- I am currently working on a needlet-based estimator of the cross-correlation power spectrum between CMB photons and LSS;
- Needlets are a form of spherical wavelet widely study for data analysis of power spectra. Wavelets are useful to handle with rapidly changeable signals;

$$\psi_{jk}(\hat{\mathrm{n}}) = \sqrt{\lambda_{jk}} \sum_{\ell=[B^{j-1}]}^{[B^{j+1}]} b\left(\frac{\ell}{B^j}\right) \sum_{m=-\ell}^{\ell} Y^*_{\ell m}(\hat{\mathrm{n}}) Y_{\ell m}(\xi_{jk})$$

- The parameter B defines the localization in the harmonic space, since $\ell \in \left[B^{j-1}, B^{j+1}\right]$, and in the real spaces;
- Needlets-based estimator:

$$\beta_{jk} = \sqrt{\lambda_{jk}} \sum_{\ell=[B^{j-1}]}^{[B^{j+1}]} b\left(\frac{\ell}{B^j}\right) \sum_{m=-\ell}^{\ell} x_{\ell m} Y_{\ell m}(\xi_{jk})$$

$$\hat{\beta}_j^{XY} = \frac{1}{N_{\mathrm{pix}}} \sum_k \beta^X_{jk} \beta^Y_{jk}$$

- Mean and variance:

$$\langle \hat{\beta}_j^{XY} \rangle \equiv \beta_j^{XY} = \sum_\ell \frac{2\ell+1}{4\pi} b^2\left(\frac{\ell}{B^j}\right) C_\ell^{XY}$$

$$(\Delta\beta_j^{XY})^2 \equiv \mathrm{Var}[\hat{\beta}_j^{XY}] = \sum_\ell \frac{2\ell+1}{16\pi^2} b^4\left(\frac{\ell}{B^j}\right) \left[(C_\ell^{XY})^2 + C_\ell^{XX} C_\ell^{YY}\right]$$

- Covariance:

$$\mathrm{Cov}_{jj'} \equiv \mathrm{Cov}[\hat{\beta}_j, \hat{\beta}_{j'}] = \langle (\hat{\beta}_j - \langle \hat{\beta}_j \rangle_{\mathrm{MC}})(\hat{\beta}_{j'} - \langle \hat{\beta}_{j'} \rangle_{\mathrm{MC}}) \rangle_{\mathrm{MC}}$$