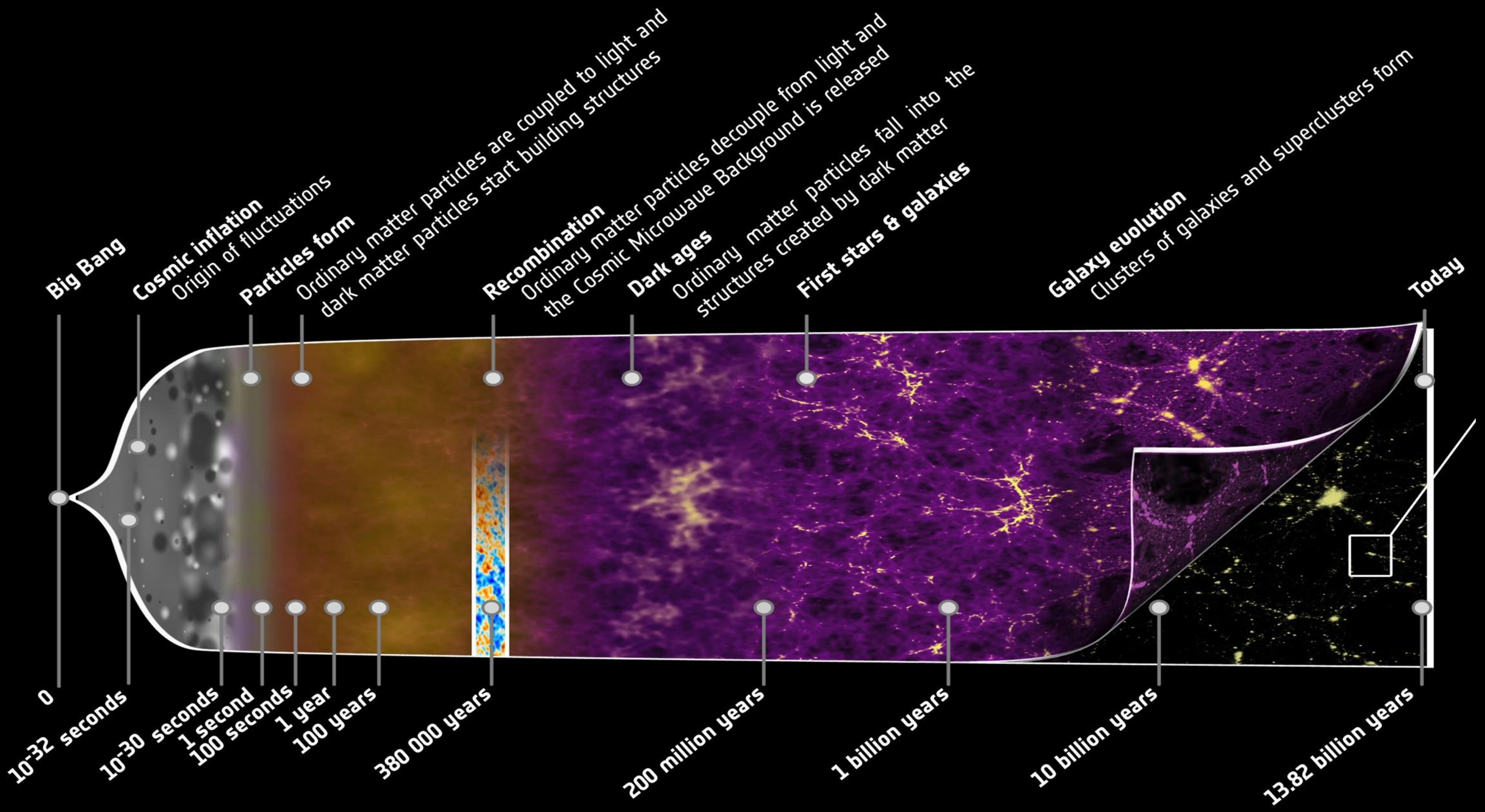
Illuminating the Universe with the Cosmic Microwave Background

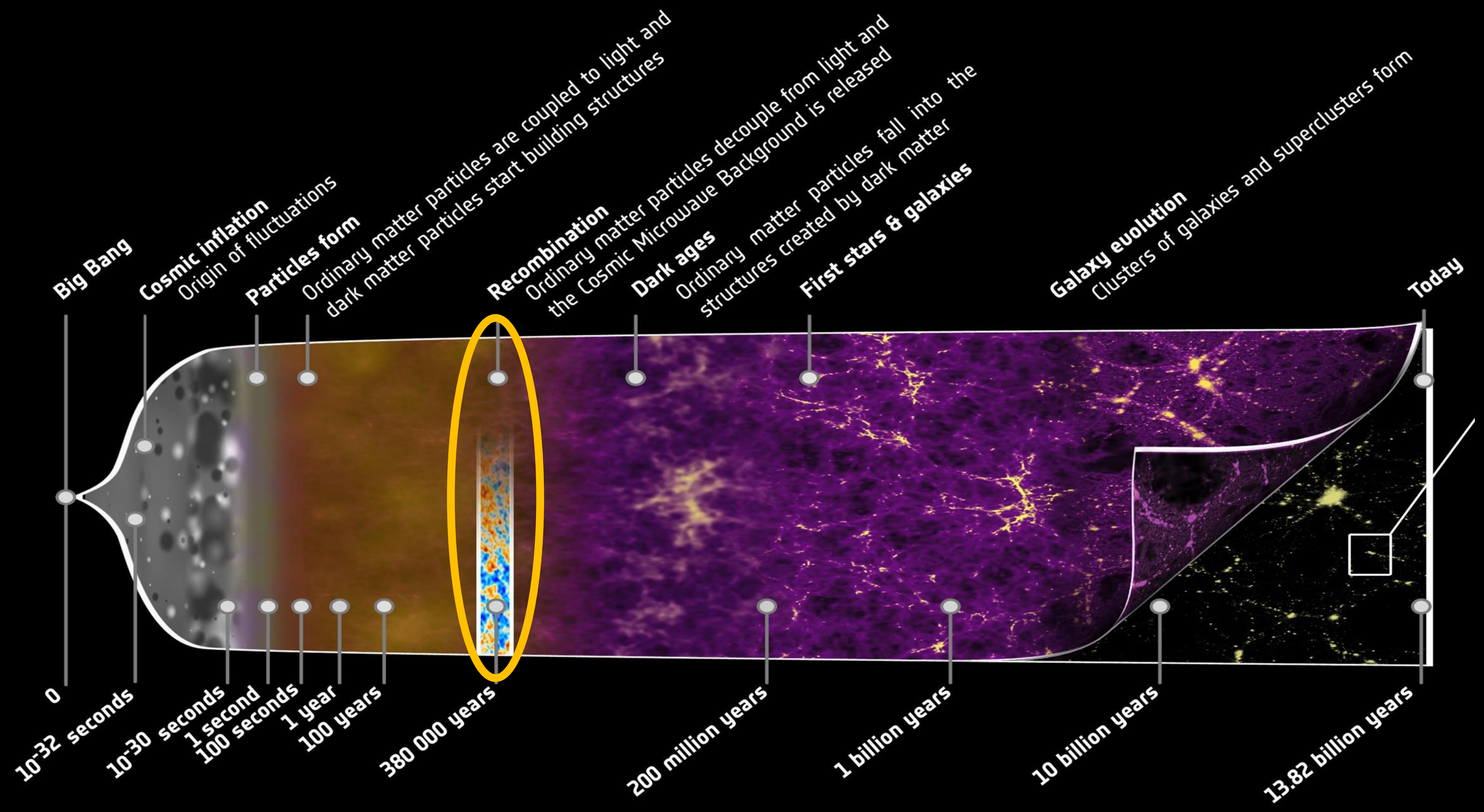
Marina Migliaccio
Università di Roma "Tor Vergata"

marina.migliaccio@roma2.infn.it

Genova, 2 April 2025

the History of the Universe as we know it

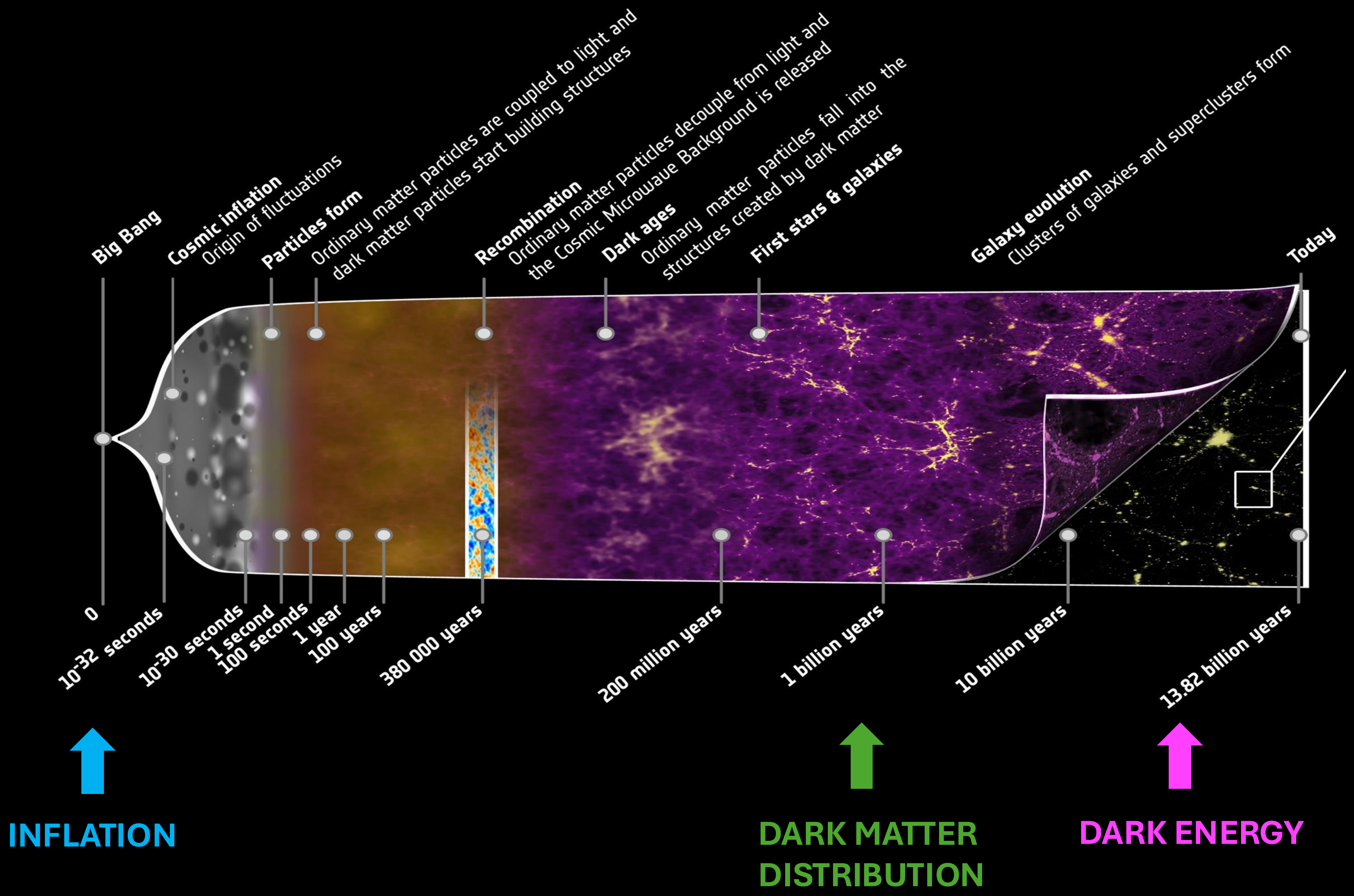




Cosmic Microwave Background radiation is released

Most ancient light and a unique picture of the early-Universe

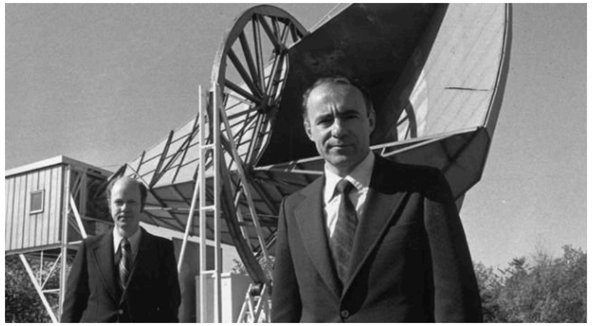
Photons propagate across the Universe "almost" unimpeded, can interact with structures gravitationally or by scattering

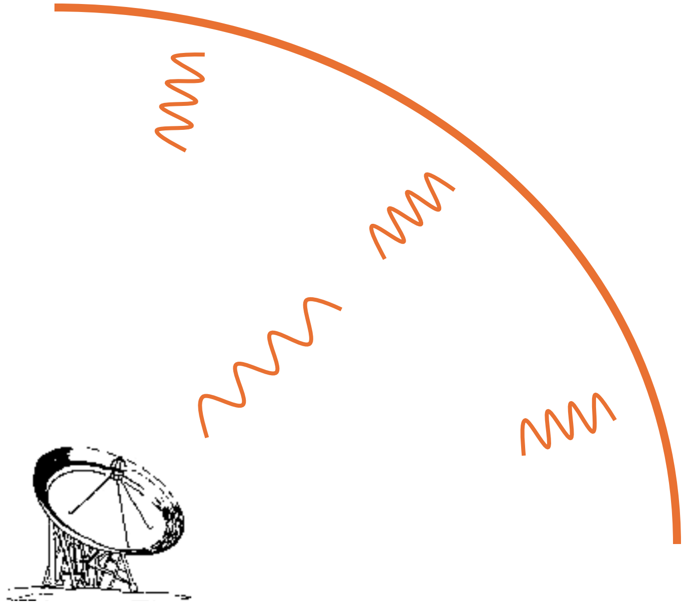

Big Bang
Cosmic inflation
Origin of fluctuations
Particles form
Ordinary matter particles are coupled to light and dark matter particles start building structures
Recombination
Ordinary matter particles decouple from light and the Cosmic Microwave Background is released
Dark ages
Ordinary matter particles fall into the structures created by dark matter
First stars & galaxies
Galaxy evolution
Clusters of galaxies and superclusters form
Today
0
10-32 seconds
10-30 seconds
1 second
100 seconds
1 year
100 years
380 000 years
200 million years
1 billion years
10 billion years
13.82 billion years
INFLATION
DARK MATTER DISTRIBUTION
DARK ENERGY

Cosmic Microwave Background

COBE (1989-1993)
G. Smoot & J. Mather

1964 Discovery
A. Penzias & R. Wilson



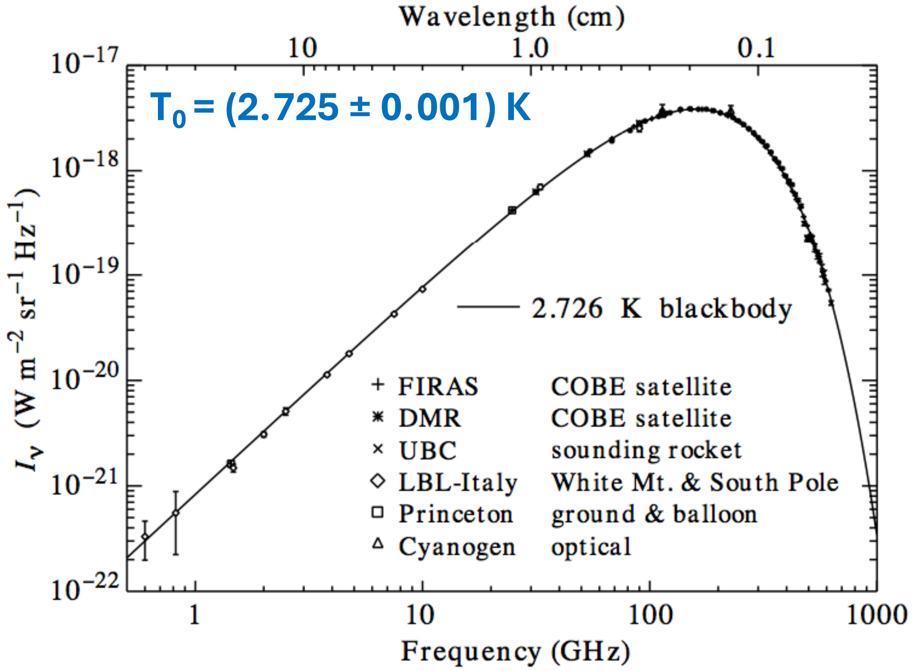


3 K ← **3000 K**

13.8 Gyr **380000 yr**

z = 0 **z = 1100**

The most precise black-body in nature



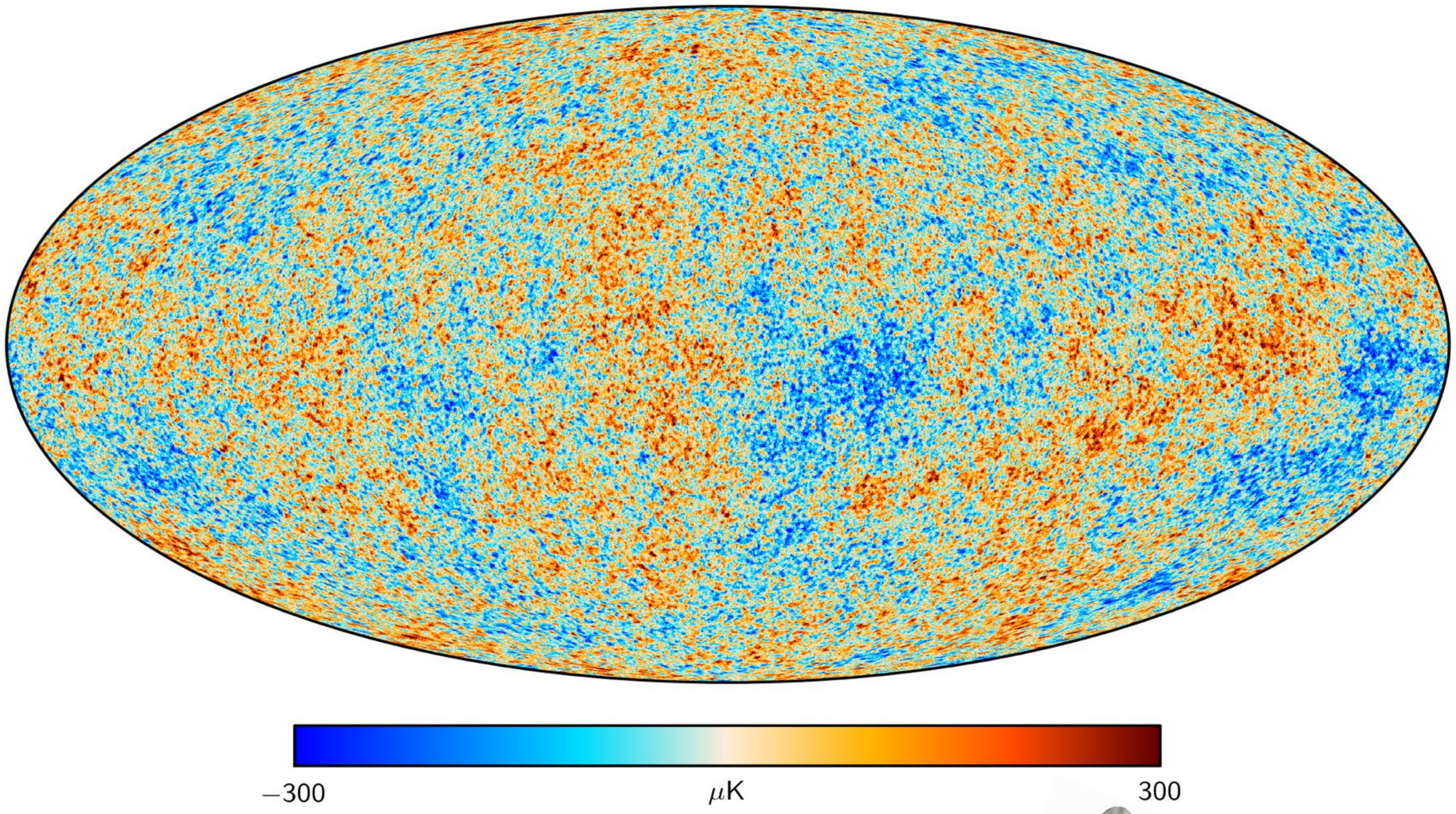
Active experimental campaign from the ground, stratospheric balloons, and space.

Temperature anisotropies

The *ultimate* measurement of the CMB temperature anisotropy field.

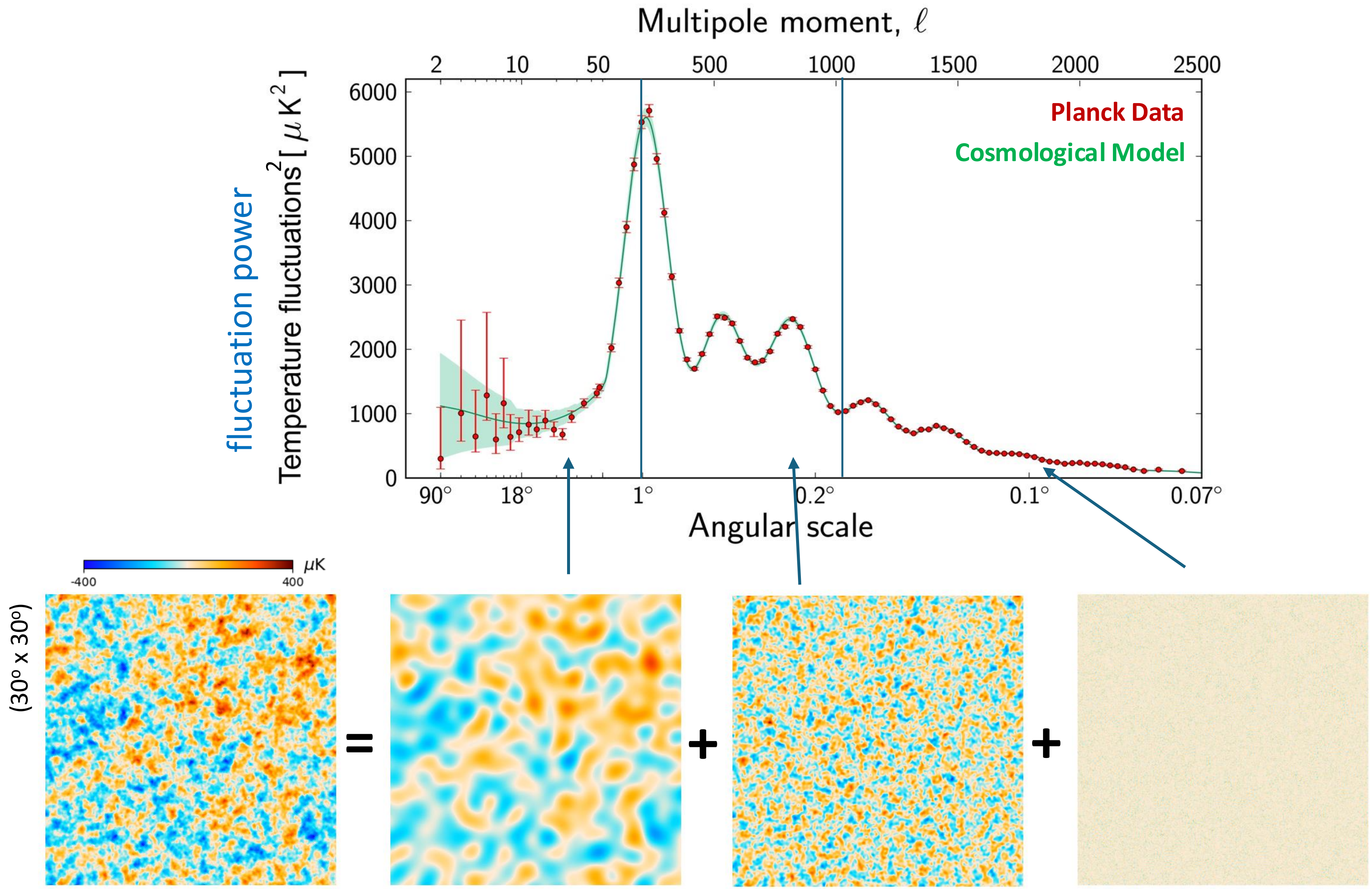
Tracing the density fluctuations in the primordial plasma from which all the structures formed.

$\frac{\Delta T}{T} \sim 10^{-5}$



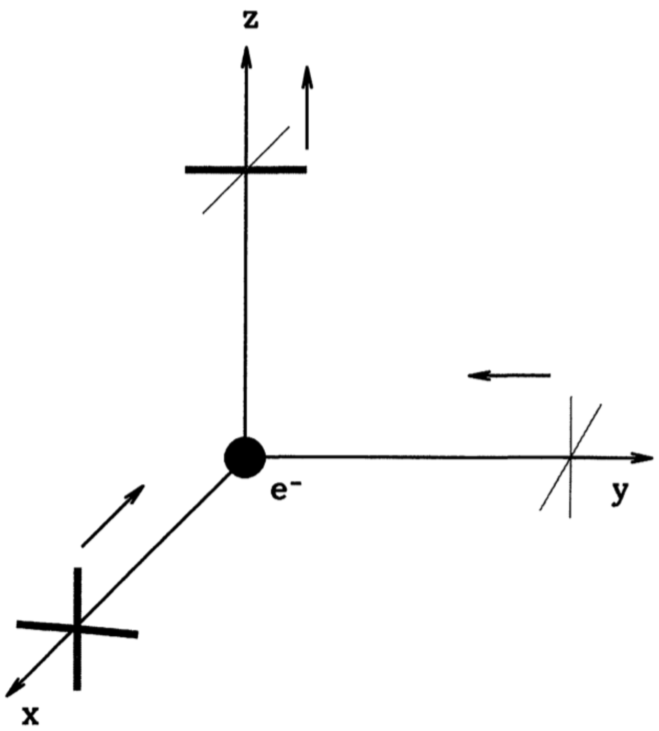
Planck Collaboration 2018

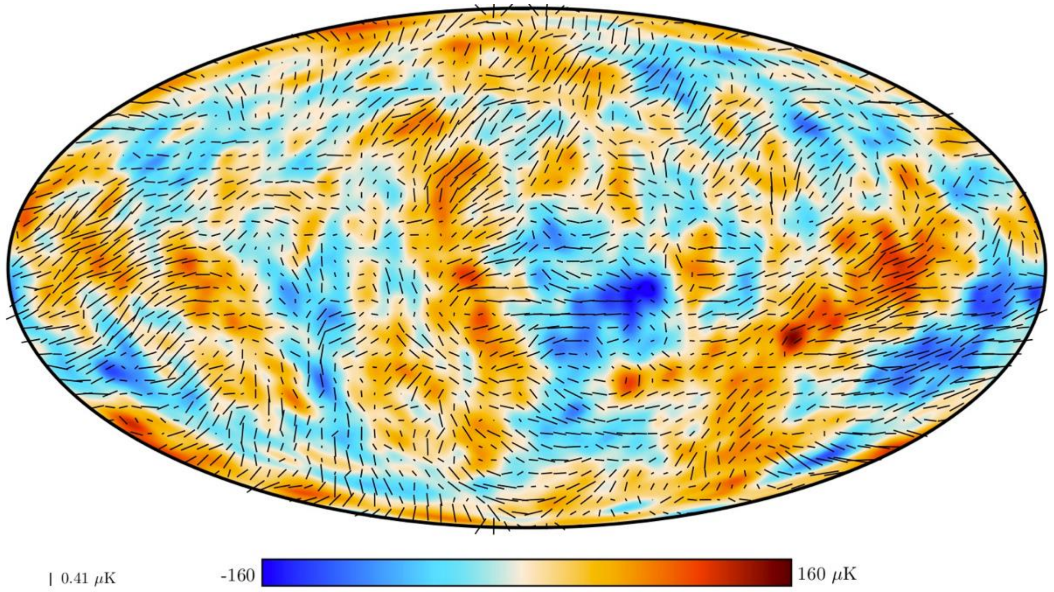
Temperature anisotropies



Polarization

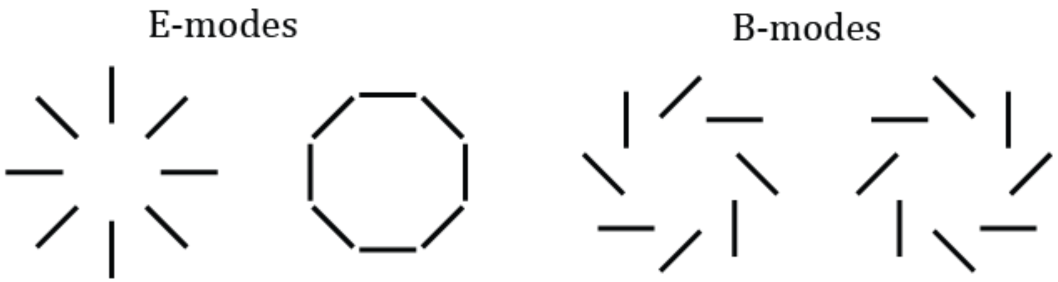
Linear polarization is generated by Thomson scattering of a radiation field with quadrupolar anisotropy



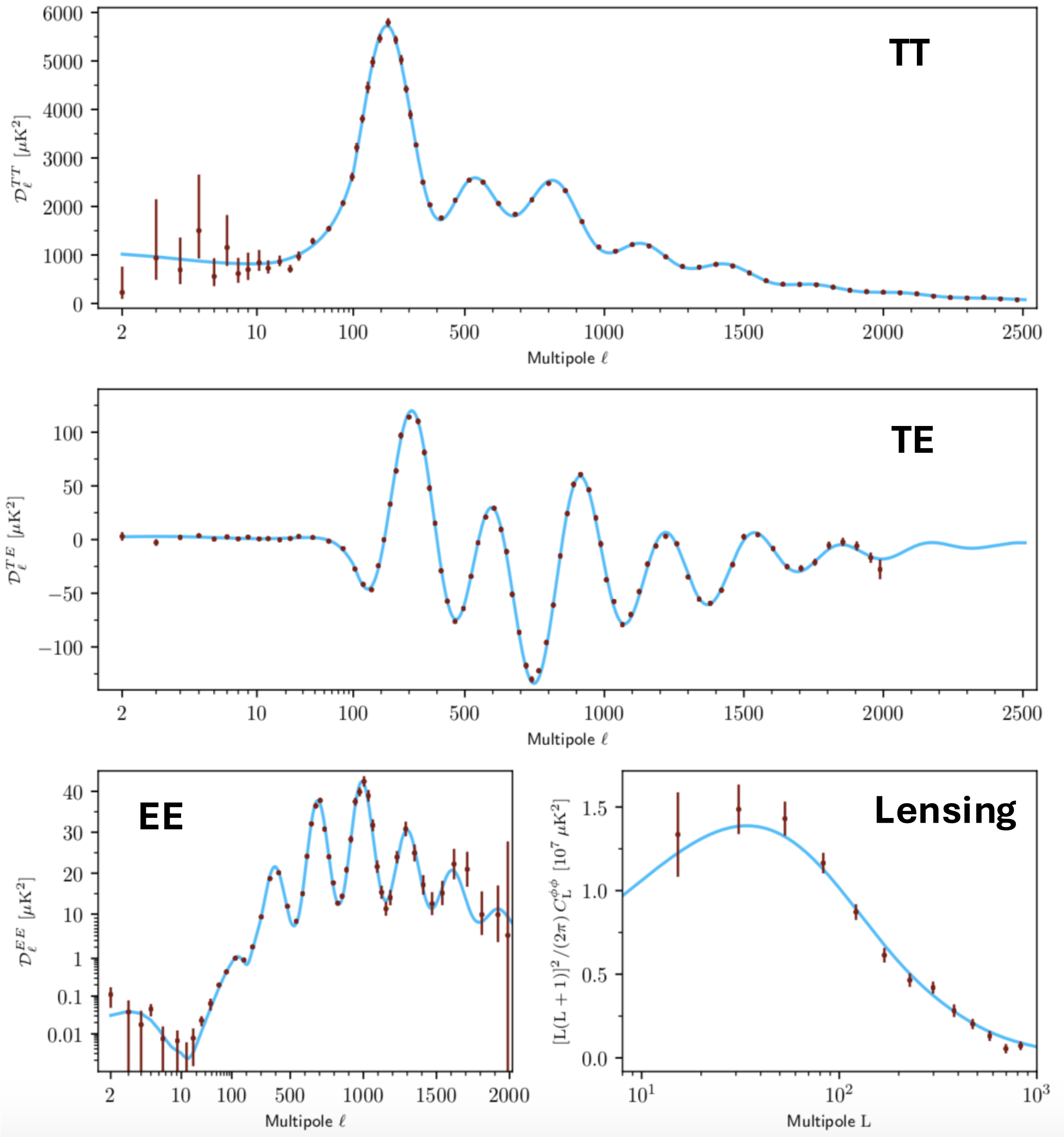


Planck Collaboration 2018

- (Q,U) Stokes parameters are coordinate dependent.
- Decompose the 2D polarization field in:
  - **E-modes (grad-like)**: generated by scalar and tensor perturbations
  - **B-modes (curl-like)**: scalar perturbations have no handiness → generated by tensor perturbations = gravitational waves



PLANCK LEGACY



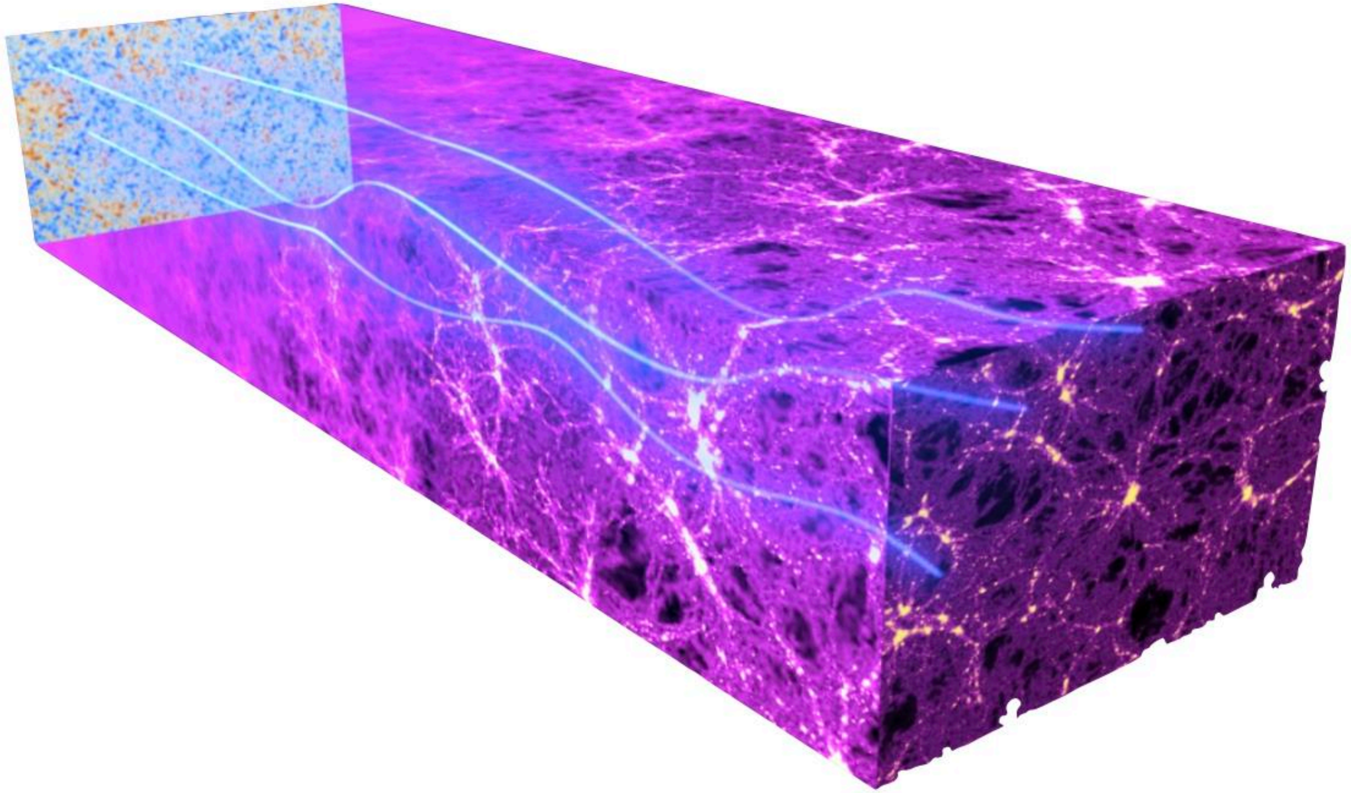
Gravitational Lensing

Deflection of the CMB photons trajectory induced by the large-scale structure gravitational field.

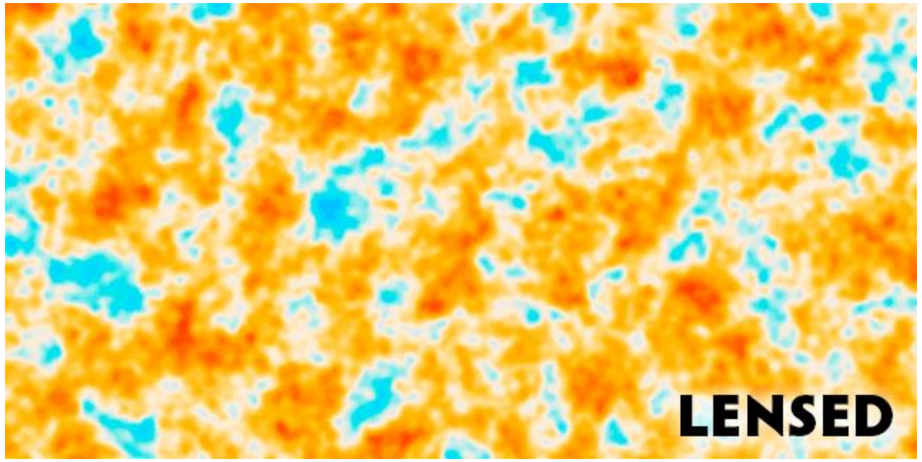
A subtle effect that can be measured statistically with high angular resolution, low-noise observations.

CMB temperature fluctuations are remapped by the deflection angle.

$$T(\hat{n}) \rightarrow T(\hat{n} + \hat{d})$$



$$\hat{d} = -2 \int d\chi \frac{\chi^* - \chi}{\chi^* \chi} \nabla \Psi(\chi \hat{n}, \eta_0 - \chi)$$

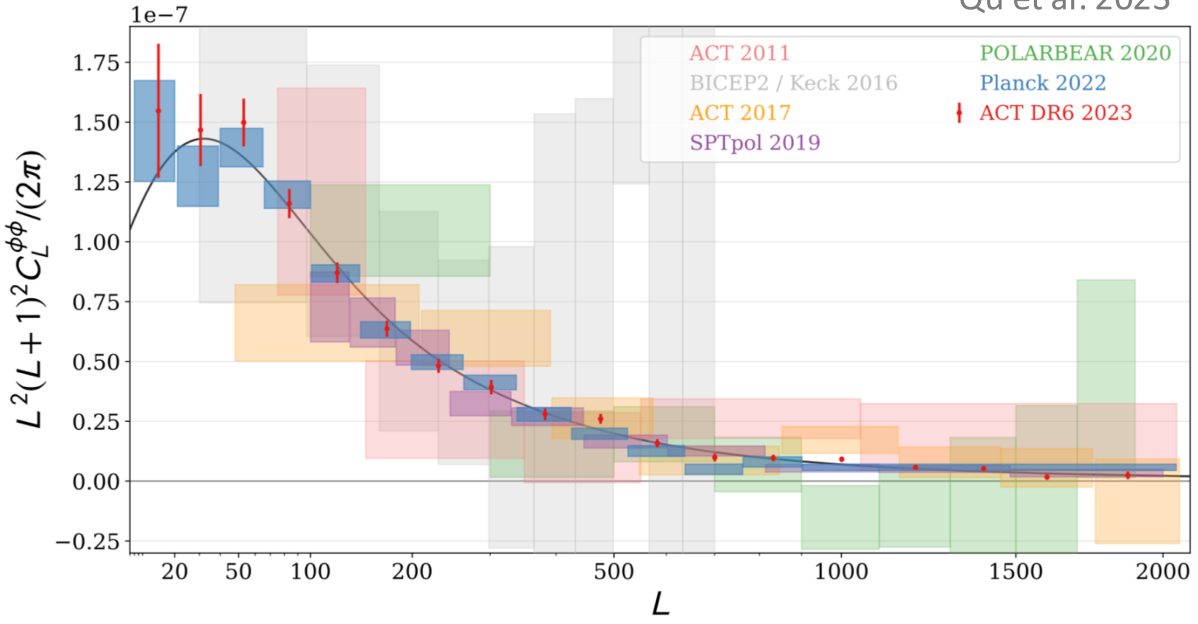


Gravitational Lensing

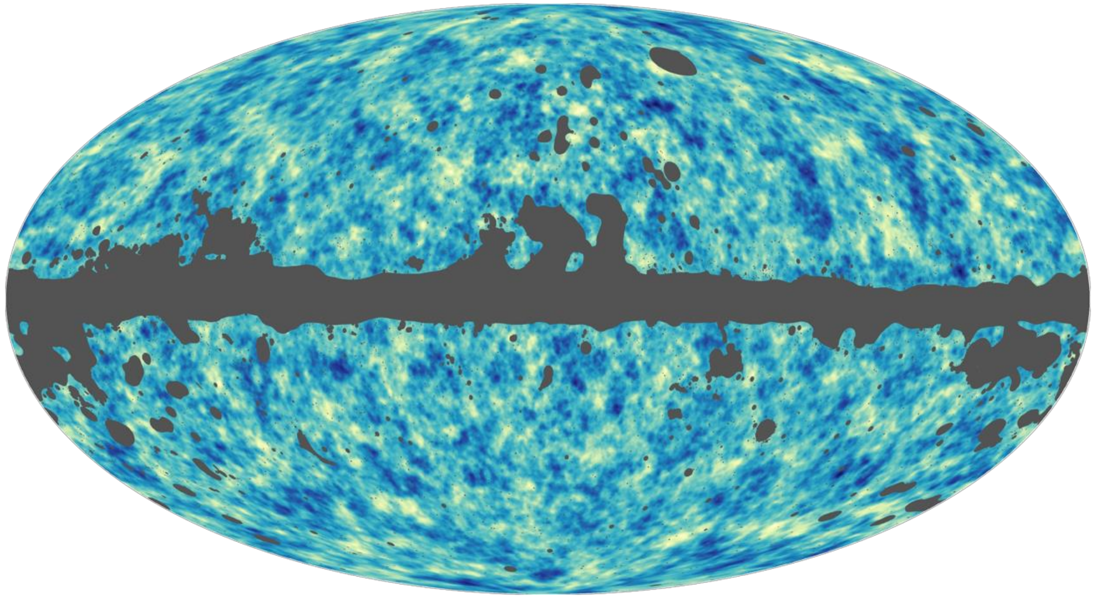
Main impact on CMB observables

- Smooths peaks and troughs in the CMB power spectra
- Induces non-Gaussianities
- Generates a B-mode polarization from E-modes

Qu et al. 2023



Map of the mass distribution in the Universe integrated along the line of sight



Planck Collaboration 2018

Sensitive to late-time expansion, geometry, and clustering of matter

PLANCK LEGACY

- Spatially-flat expanding Universe.
- Dynamics are described by General Relativity.
- Constituents are cold dark matter, dark energy (cosmological constant Λ), baryons and radiation (photons + 3 neutrino species).
- The primordial seeds of cosmic structures are Gaussian distributed, almost scale-invariant fluctuations as predicted by inflation.
- No deviations to the standard ΛCDM model are favored.
- Concordance with BBN, BAO, RSD, SNIa.
- Mild tension with some weak lensing surveys on clustering.
- Disagreement with local measurements of the Hubble constant.

Planck 2018 results. I.

Parameter	*Planck* alone
$\Omega_b h^2$	0.02237 ± 0.00015
$\Omega_c h^2$	0.1200 ± 0.0012
$100\theta_{MC}$	1.04092 ± 0.00031
τ	0.0544 ± 0.0073
$\ln(10^{10} A_s)$	3.044 ± 0.014
n_s	0.9649 ± 0.0042
H_0	67.36 ± 0.54
Ω_Λ	0.6847 ± 0.0073
Ω_m	0.3153 ± 0.0073
$\Omega_m h^2$	0.1430 ± 0.0011
$\Omega_m h^3$	0.09633 ± 0.00030
σ_8	0.8111 ± 0.0060
$\sigma_8(\Omega_m/0.3)^{0.5}$	0.832 ± 0.013
z_{re}	7.67 ± 0.73
Age [Gyr]	13.797 ± 0.023
r_* [Mpc]	144.43 ± 0.26
$100\theta_*$	1.04110 ± 0.00031
r_{drag} [Mpc]	147.09 ± 0.26
z_{eq}	3402 ± 26
k_{eq} [Mpc^{-1}]	0.010384 ± 0.000081
Ω_K	-0.0096 ± 0.0061
Σm_ν [eV]	< 0.241
N_{eff}	$2.89^{+0.36}_{-0.38}$
$r_{0.002}$	< 0.101

68% limits
base ΛCDM model

95% limits
extended models

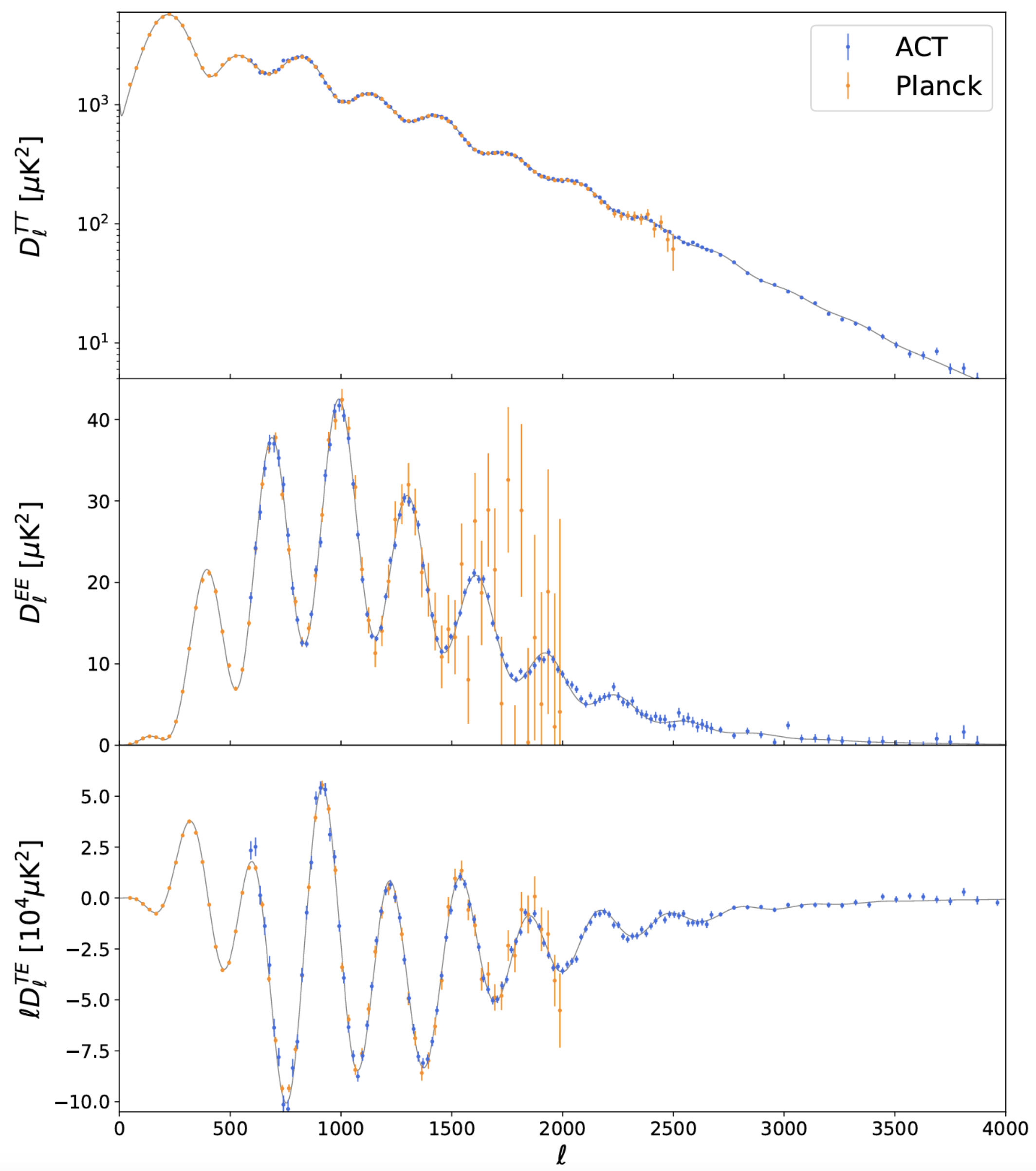
Atacama Cosmology Telescope
March 2025

(Louis et al. 2025 & Calabrese et al. 2025)

No statistically significant preference for departures from the baseline ΛCDM model.

Mentioning just a result

- $H_0 = 66.11 \pm 0.79$ km/s/Mpc



* partial list

Upcoming experiments will be targeting

→ Polarization

→ Secondary Anisotropies

CMB Polarization: the hunt for primordial B-modes

B-modes from primordial Gravitational Waves

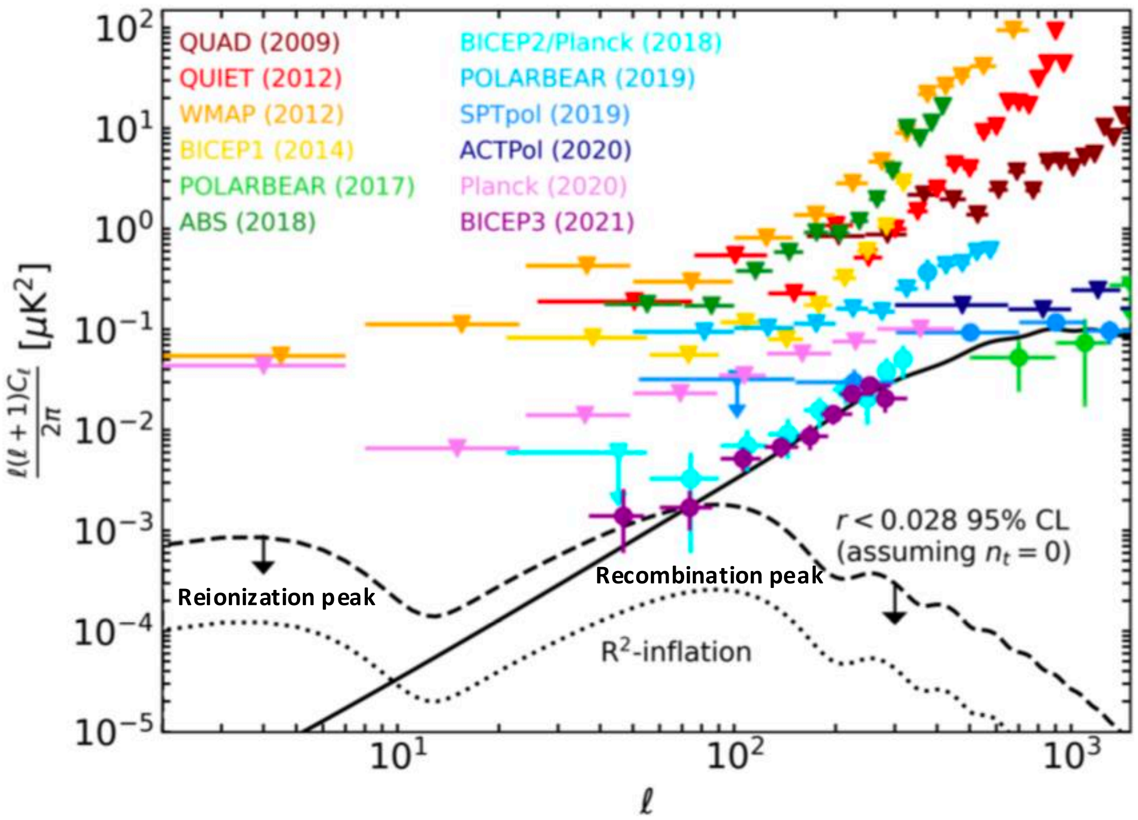
- Provide direct evidence for cosmic inflation
- Insight into the quantum nature of gravity
- Knowledge on when inflation happened and its energy scale

$$V^{1/4} \sim 10^{16} \times \left(\frac{r}{0.01}\right)^{1/4} GeV$$

$r =$ tensor-to-scalar ratio

- Making a discovery or ruling out well-motivated inflationary models

B-mode power spectrum



Galloni el at. (MM) 2023

$r < 0.028$ 95% CL

Planck PR4 + BICEP/Keck 2018 + LIGO/Virgo 2021

CMB Polarization: the hunt for primordial B-modes

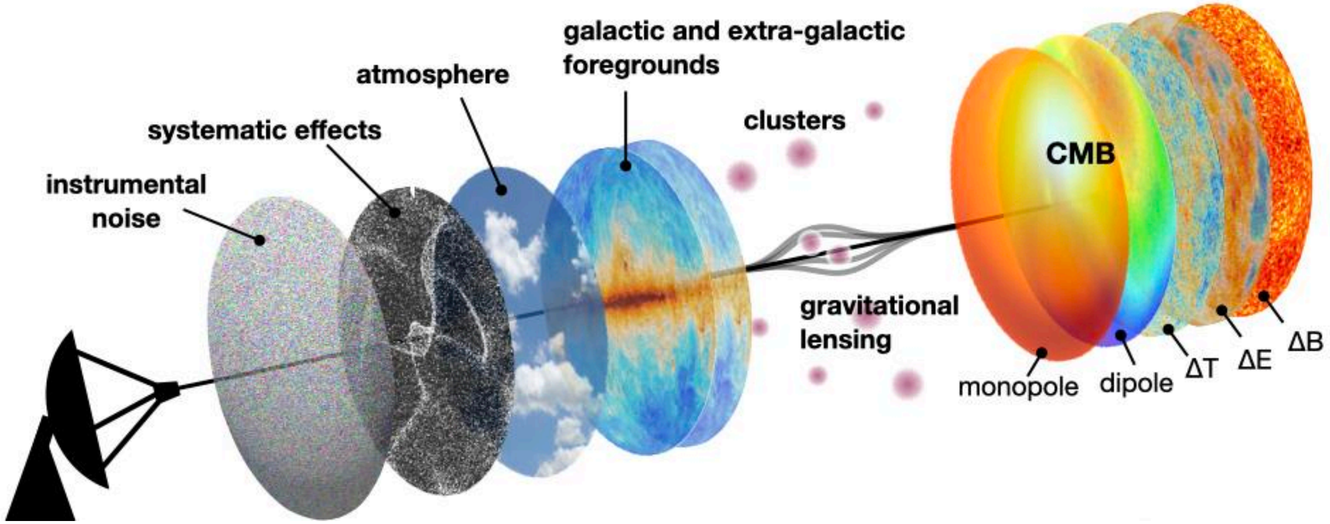
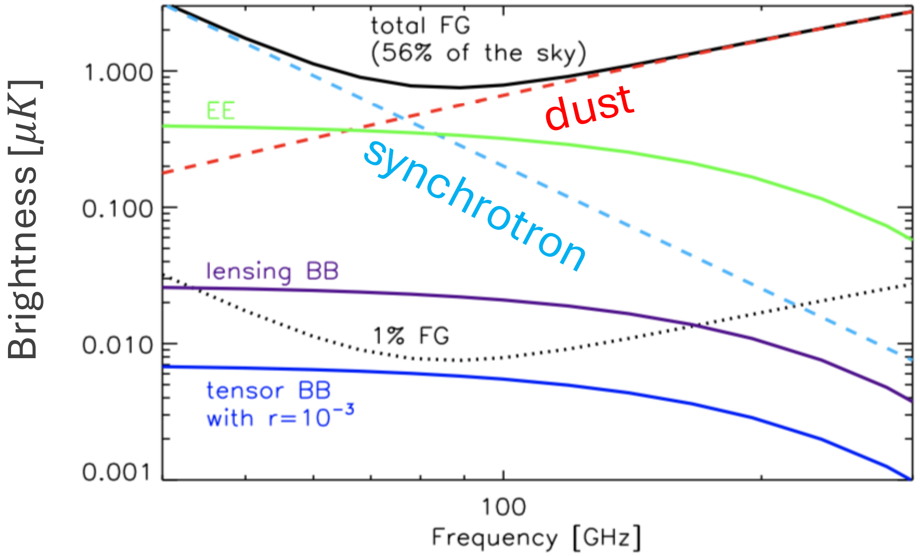


Image Credit: J. Errard

LiteBIRD Coll. BAAS (2019)



CMB Polarization: the hunt for primordial B-modes

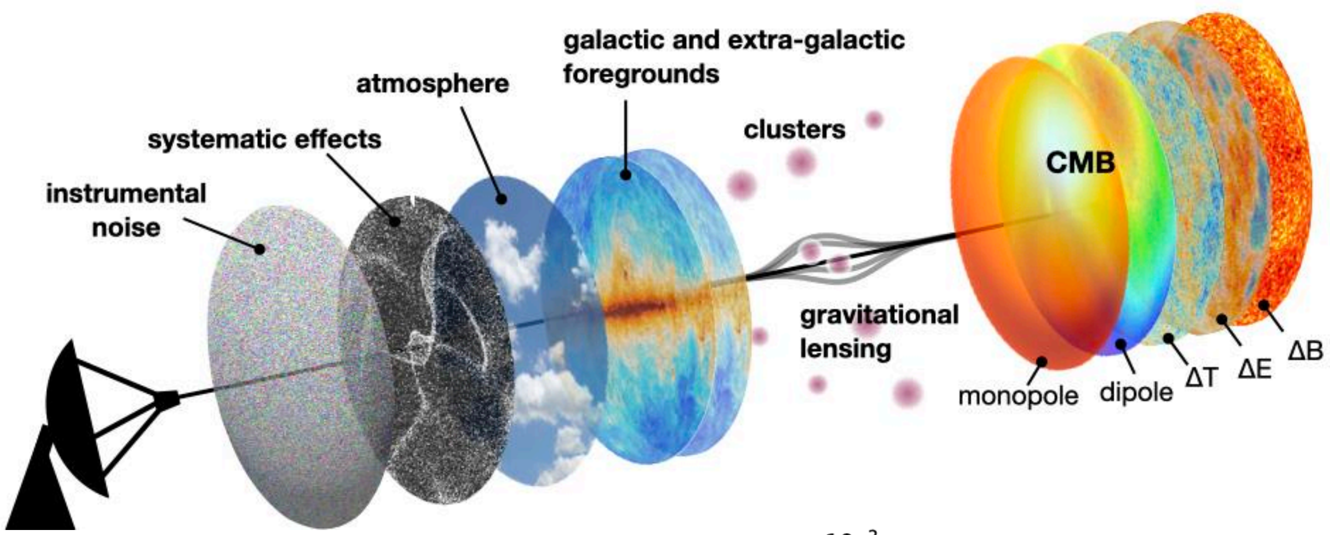
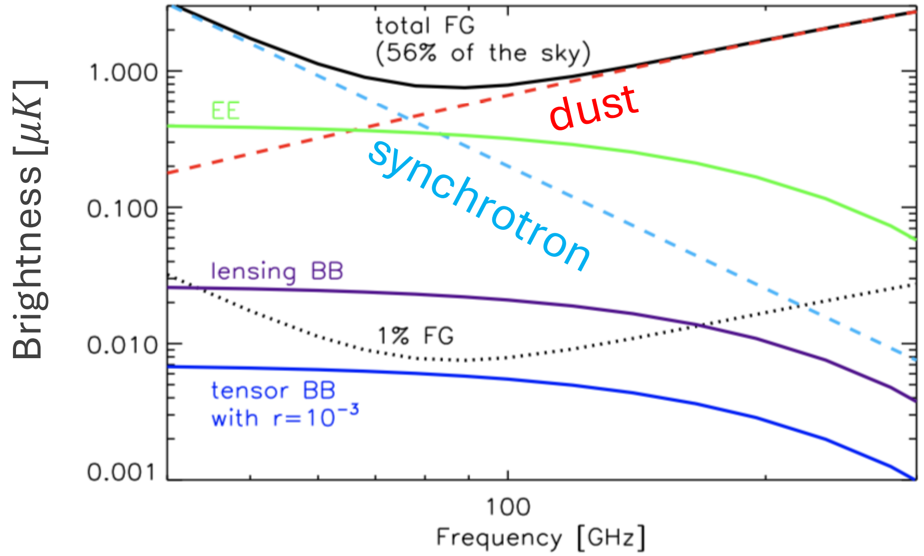
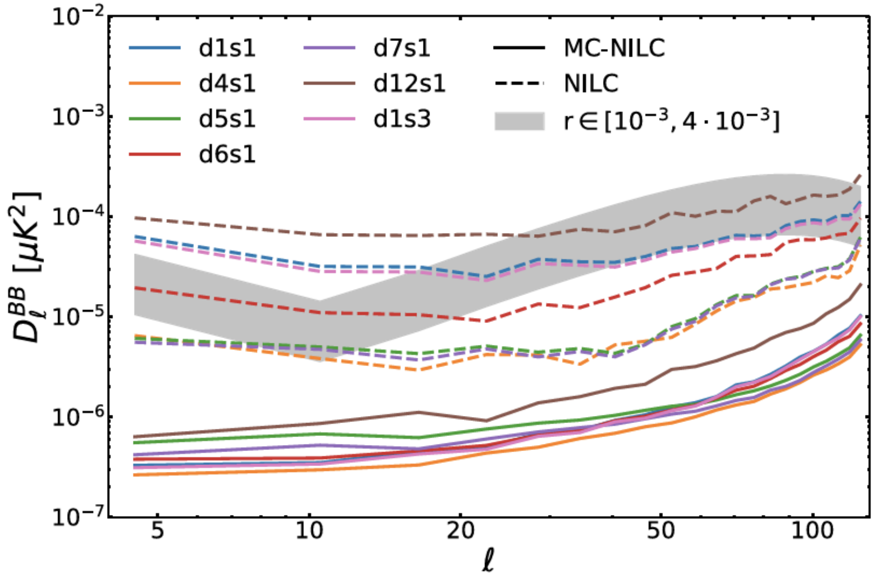


Image Credit: J. Errard

LiteBIRD Coll. BAAS (2019)



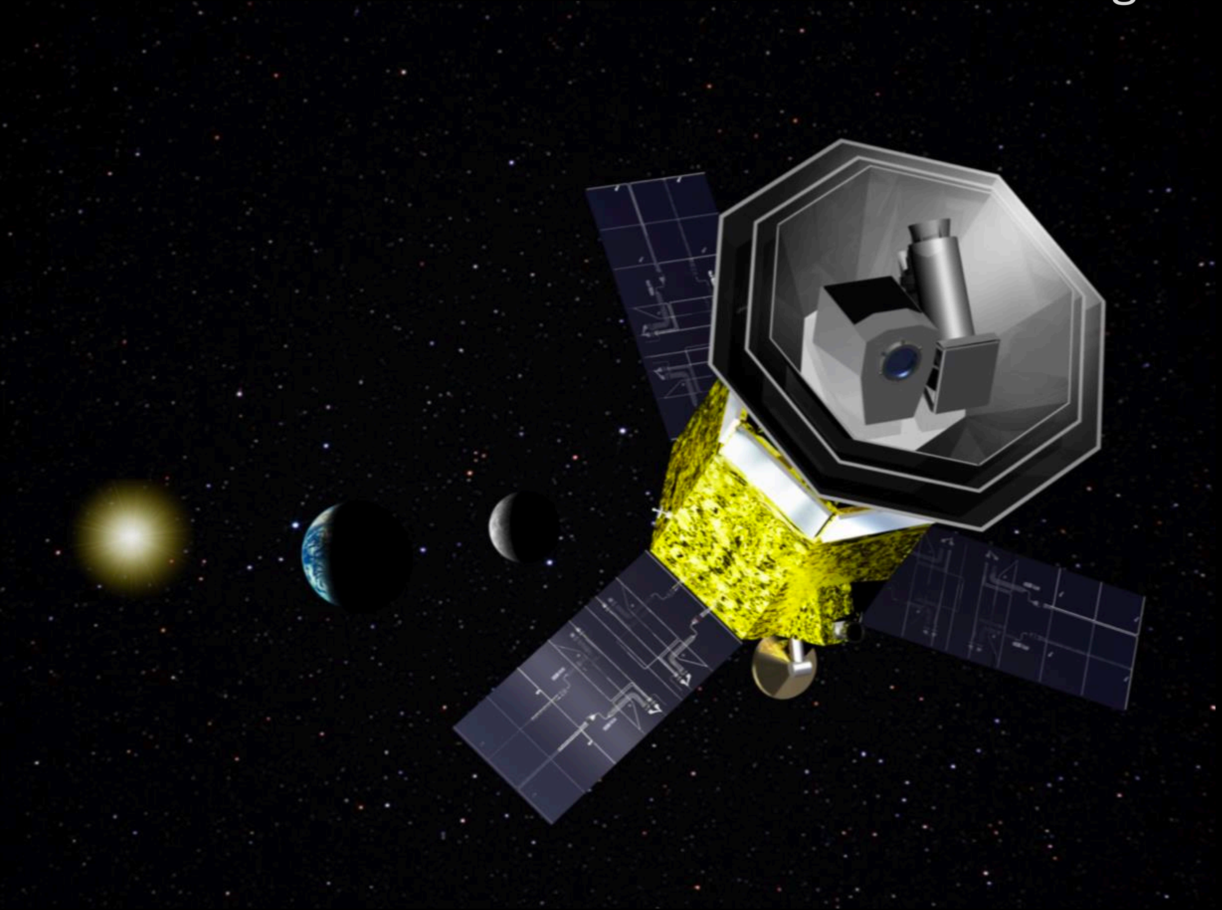


Need for advanced component separation techniques

Carones, MM et al. 2023a
Carones, MM et al. 2023b

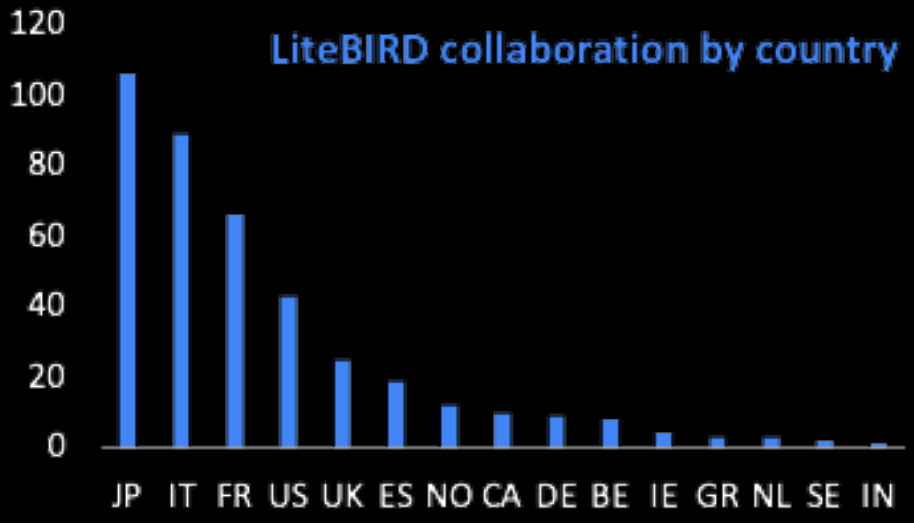
LiteBIRD

Lite (light) satellite for the studies of **B**-mode polarization and **I**nflation from cosmic background **R**adiation **D**etection



At least 50x improvement over current constraints

- For r = 0, total uncertainty of $\delta r < 0.001$
- For r = 0.01, 5σ detection of the reionization ($2 < \ell < 10$) and recombination ($11 < \ell < 200$) peaks independently

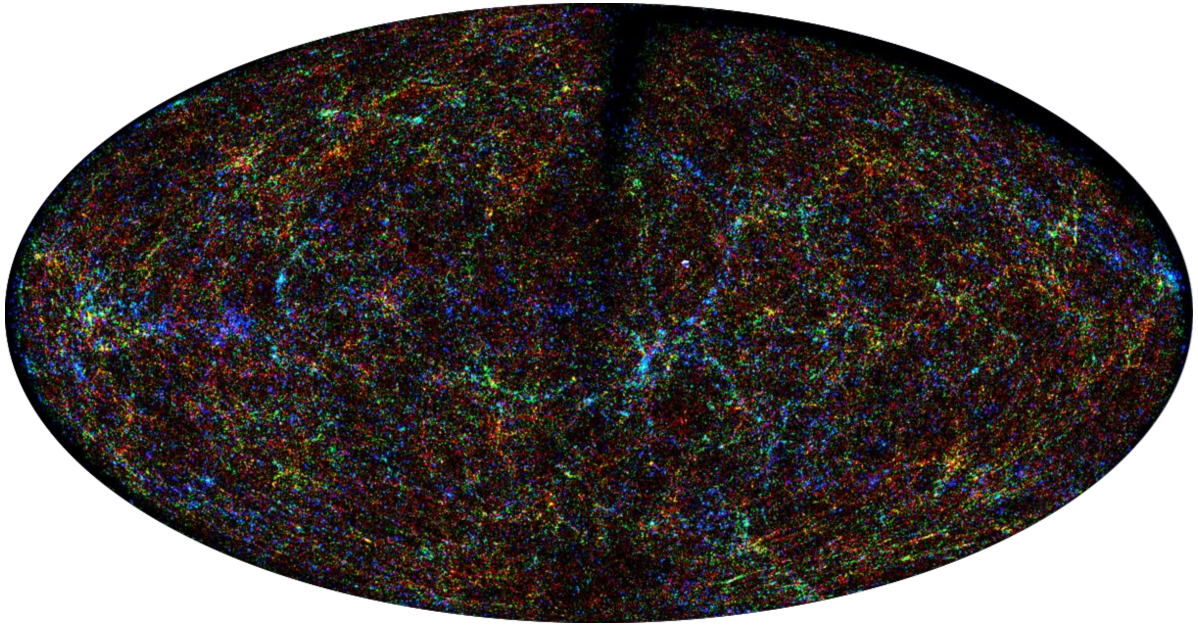


Will deliver much more than r !

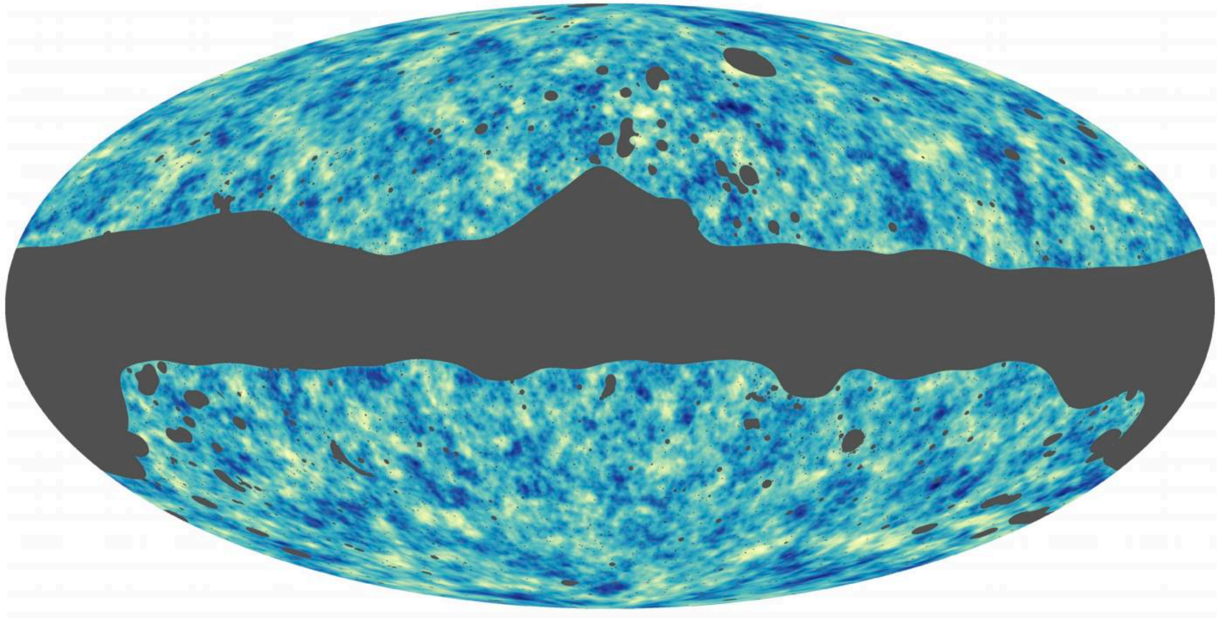
Probing Cosmic Inflation with LiteBIRD (arXiv:2202.02773)


* partial list
CMB
QUIJOTE
esa
planck
SPT
BICEP / KECK
ACT
QUBIC
LSPE
Large Scale Polarization Explorer
SIMONS
OBSERVATORY
LiteBIRD
CMB-S4
Next Generation CMB Experiment
TODAY
LSS
DARK ENERGY
SURVEY
SDSS
DARK ENERGY SPECTROSCOPIC INSTRUMENT
esa
euclid
SPHEREx
VERA C. RUBIN
OBSERVATORY
SKA
SQUARE KILOMETRE ARRAY
WST
NANCY GRACE
ROMAN
SPACE TELESCOPE

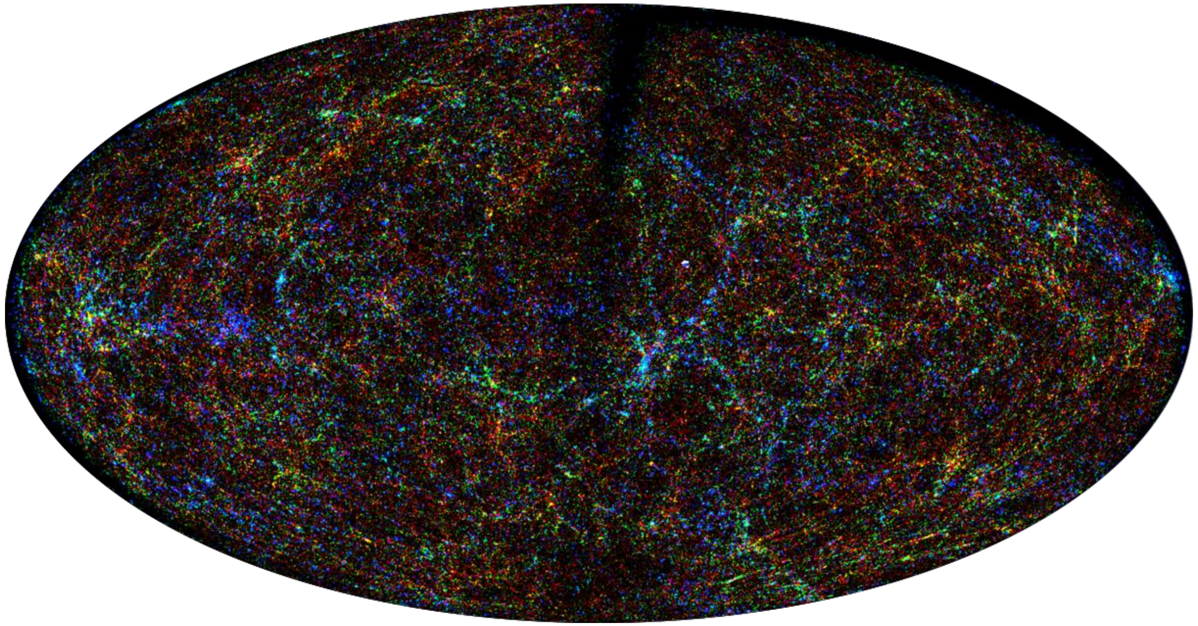
Galaxies are sparse tracers of the large-scale distribution of dark matter in the Universe



Map of the mass distribution in the Universe integrated along the line of sight



Galaxies are sparse tracers of the large-scale distribution of dark matter in the Universe



⇒ CMB lensing and other luminous tracers must be correlated !

Cross-correlation with CMB lensing

Now detected from radio frequencies to γ-rays

{Planck, ACT, SPT, POLARBEAR}

$\times$

{SDSS, CFHTLenS, DES, KIDS, *Herschel*-ATLAS, SuperCOSMOS, Hyper-Supreme CAM, WISE, LOFAR, 2MASS, FERMI, EMU, …}

- Powerful confirmation of General Relativity on cosmological scales.
- Novel estimators for late-time expansion and clustering of matter.
- Break degeneracy between cosmological and astrophysical parameters.
- Maximise the return of information in constraining the cosmological parameters.
- Robustness to poorly known astrophysical and instrumental systematic effects that affect each probe separately.

Cross-correlation with CMB lensing

Theoretical Predictions

$$C_\ell^{\kappa G} = \frac{2}{\pi} \int_0^\infty dz\, W^\kappa(z) \int_0^\infty dz'\, W^G(z') \int_0^\infty dk\; k^2\; j_\ell[k\,\chi(z)]\, j_\ell[k\,\chi(z')]\, P(k, z, z')$$

CMB Lensing Kernel for a flat Universe

$$W^\kappa = \frac{3\;\Omega_m}{2}\;\frac{H_0^2}{H(z)}\;(1+z)\;\chi(z)\;\frac{\chi(z_*) - \chi(z)}{\chi(z_*)}$$

Galaxy Kernel

$$W^G = b(z)\;N(z)$$

Cross-correlation with CMB lensing

Theoretical Predictions

$$C_\ell^{\kappa G} = \frac{2}{\pi} \int_0^\infty dz\, W^\kappa(z) \int_0^\infty dz'\, W^G(z') \int_0^\infty dk\, k^2\, j_\ell[k\,\chi(z)]\, j_\ell[k\,\chi(z')]\, P(k, z, z')$$

CMB Lensing Kernel for a flat Universe

$$W^\kappa = \frac{3\,\Omega_m}{2} \frac{H_0^2}{H(z)} (1+z)\,\chi(z)\, \frac{\chi(z_*) - \chi(z)}{\chi(z_*)}$$

Galaxy Kernel

$$W^G = b(z)\,N(z)$$

Abundance of galaxies is not well known at high-redshift.

Cross-correlation with CMB lensing

Theoretical Predictions

$$C_\ell^{\kappa G} = \frac{2}{\pi}\int_0^\infty dz\, W^\kappa(z) \int_0^\infty dz'\, W^G(z') \int_0^\infty dk\, k^2\, j_\ell[k\,\chi(z)]\, j_\ell[k\,\chi(z')]\, P(k,z,z')$$

CMB Lensing Kernel for a flat Universe

$$W^\kappa = \frac{3\,\Omega_m}{2}\,\frac{H_0^2}{H(z)}\,(1+z)\,\chi(z)\,\frac{\chi(z_*)-\chi(z)}{\chi(z_*)}$$

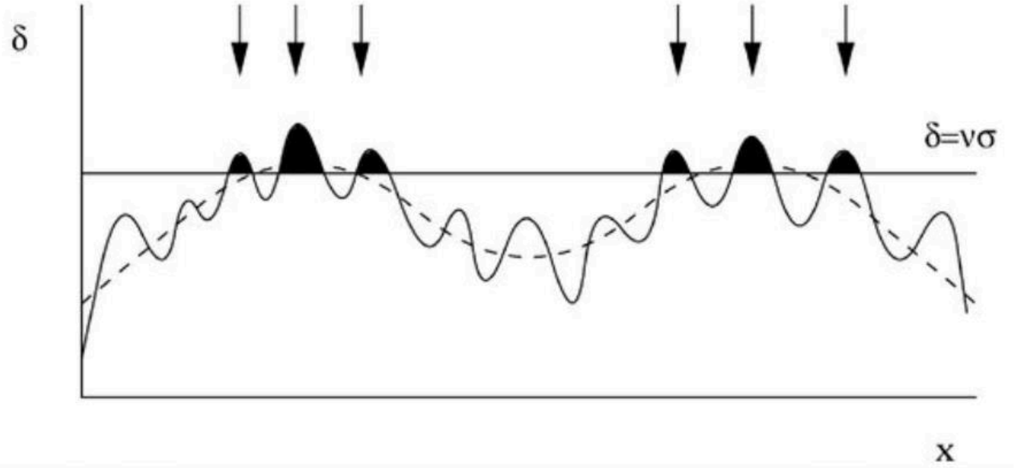
Galaxy Kernel

$$W^G = b(z)\,N(z)$$

Abundance of galaxies is not well known at high-redshift.

Galaxy Bias

$$C^{gg} = b^2 C^{mm}$$



Cross-correlation with CMB lensing

Theoretical Predictions

$$C_\ell^{\kappa G} = \frac{2}{\pi}\int_0^\infty dz\, W^\kappa(z) \int_0^\infty dz'\, W^G(z') \int_0^\infty dk\, k^2\, j_\ell[k\,\chi(z)]\, j_\ell[k\,\chi(z')]\, P(k, z, z')$$

CMB Lensing Kernel for a flat Universe

$$W^\kappa = \frac{3\,\Omega_m}{2}\,\frac{H_0^2}{H(z)}\,(1+z)\,\chi(z)\,\frac{\chi(z_*) - \chi(z)}{\chi(z_*)}$$

Unbiased tracer of the mass distribution along the line of sight.

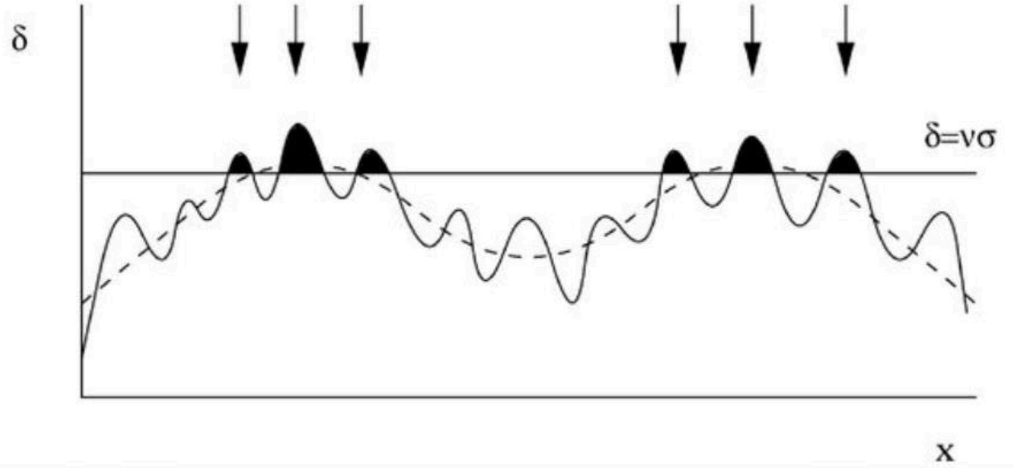
Galaxy Kernel

$$W^G = b(z)\,N(z)$$

Abundance of galaxies is not well known at high-redshift.

Galaxy Bias

$$C^{gg} = b^2 C^{mm}$$



Cross-correlation with CMB lensing

Combining gg and κg is very effective in breaking degeneracies between cosmological parameters and astrophysical parameters

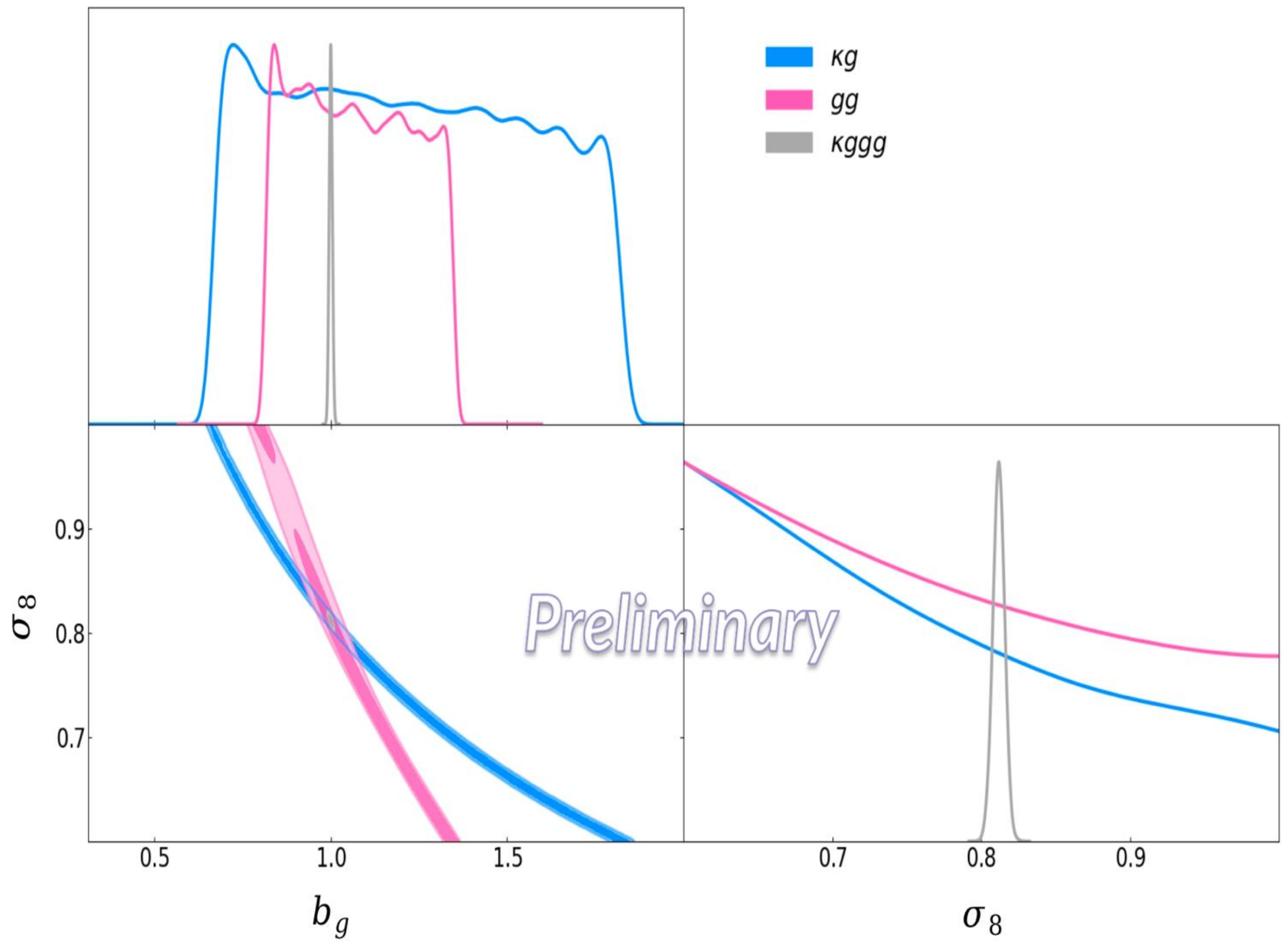
$$C_\ell^{gg} \propto b_g^2 \sigma_8^2$$
$$C_\ell^{\kappa g} \propto b_g \sigma_8^2$$

Constraining

→ **Late-time expansion** and **clustering of matter**

→ **Properties of the sources** (abundance, bias, evolution with time, …)

Simulated
Square Kilometre Array × Simons Observatory



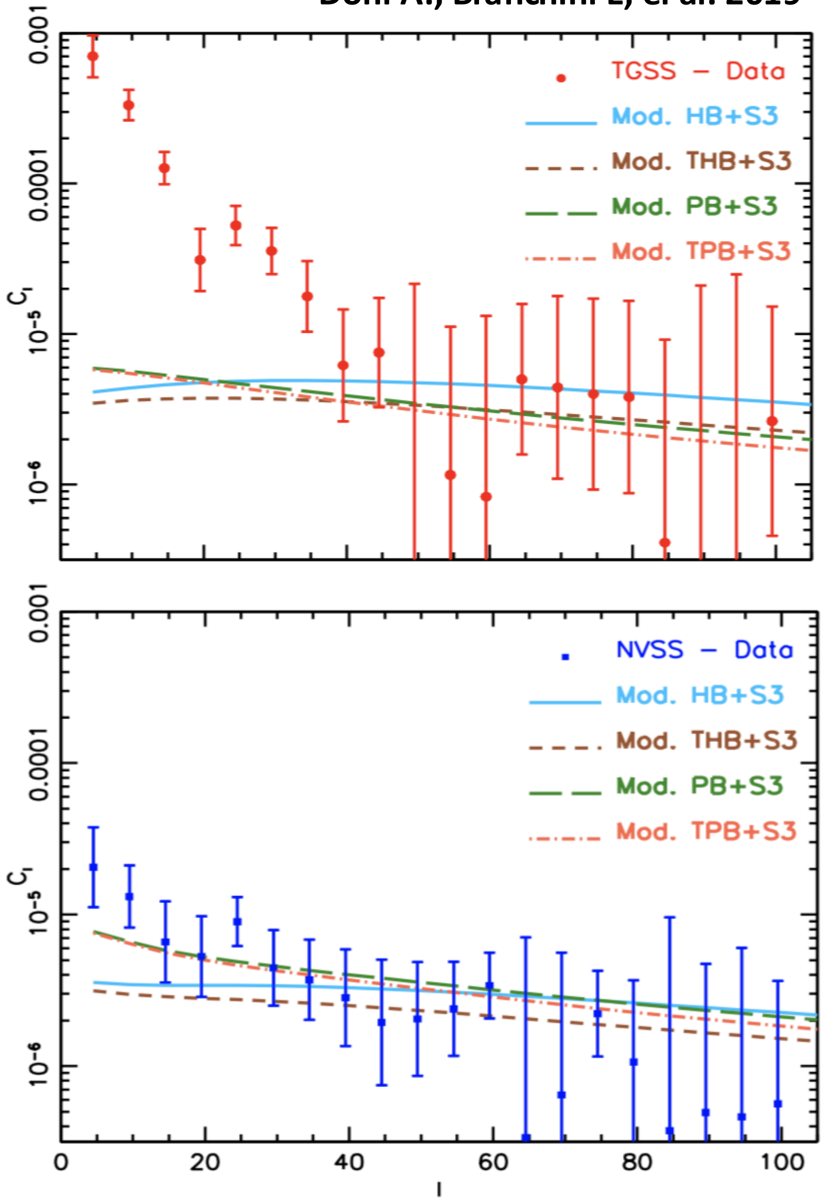
Cross-correlating CMB lensing with radio sources

Anomalously large signal detected at large scales in the clustering of TGSS radio sources:

- Failure of the standard cosmological model?
- Mismodelling of source properties?
- Uncorrected systematic effects in the data?

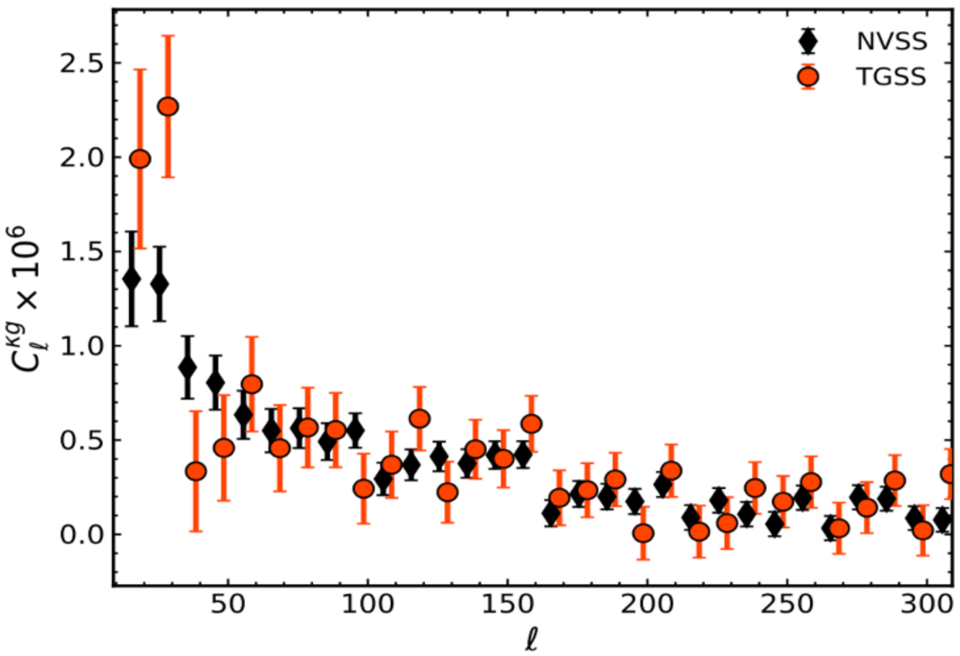
Our proposal
→ Use the cross-correlation with Planck CMB lensing to investigate the origin of the signal excess

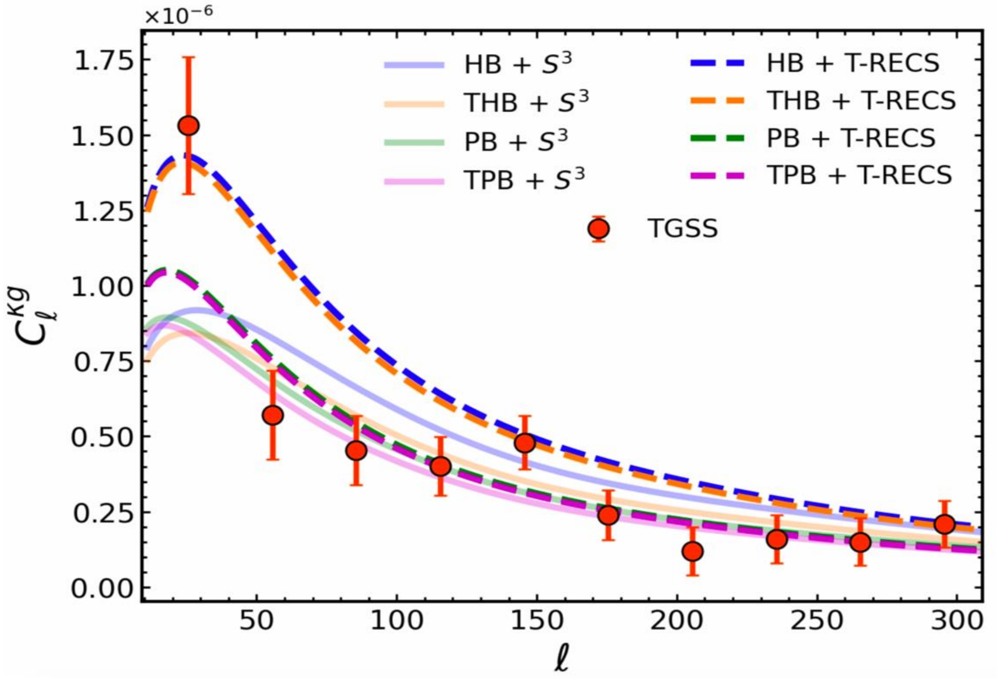
Dolfi A., Branchini E, el al. 2019



Cross-correlating CMB lensing with radio sources

Piccirilli G., MM, Branchini E., Dolfi A. (2023)





- **First measurement of the cross-correlation between Planck CMB lensing convergence and TGSS sources** (12σ detection)
- In the cross spectrum κg, the excess power with respect to NVSS is significantly reduced → **Supports the hypothesis of a systematic origin**

- **Models do not reproduce the radio sources clustering signal at large scales.**
- **Future data (SKA and its precursors) and models of radio sources properties will allow to better answer these questions.**

euclid consortium

esa

European Space Agency

Launched in July 2023

Visible to Near-Infrared (with spectroscopy) space telescope operating in L2

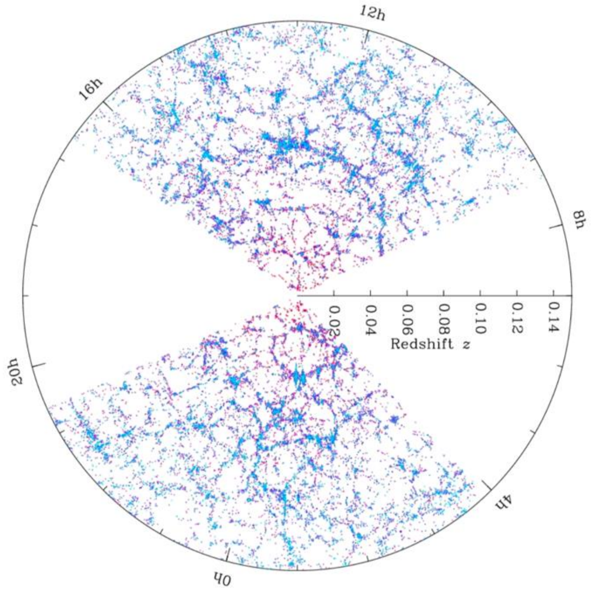
Map position, distance and shape of billions of galaxies out to 10 billion light years $z{\sim}2$ across > 1/3 of the sky

Euclid Mission Primary Objective: The Dark Universe

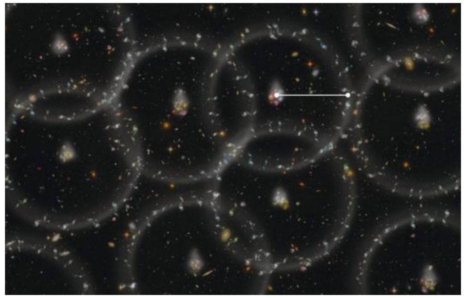
Understand the origin of the Universe's accelerated expansion

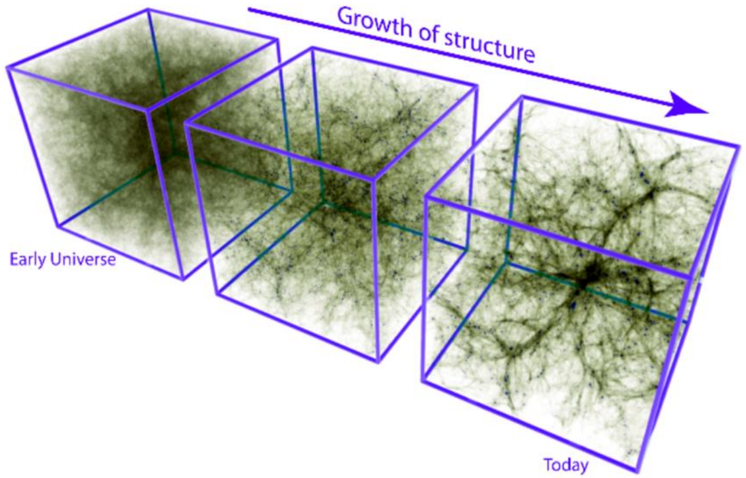
Probe the properties and nature of Dark Energy, Dark Matter, and Gravity by tracing their observational effects

Galaxy Clustering

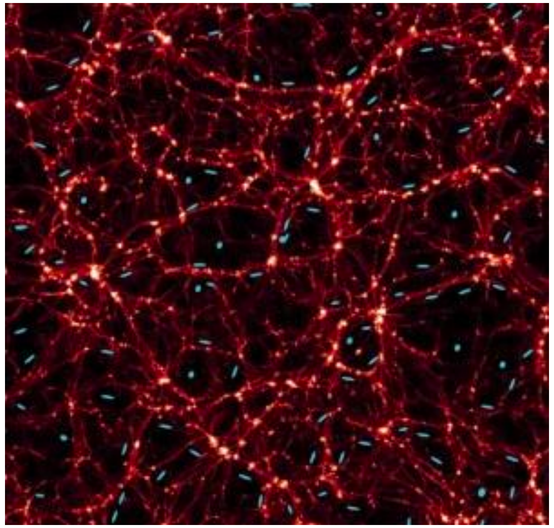


Expansion History





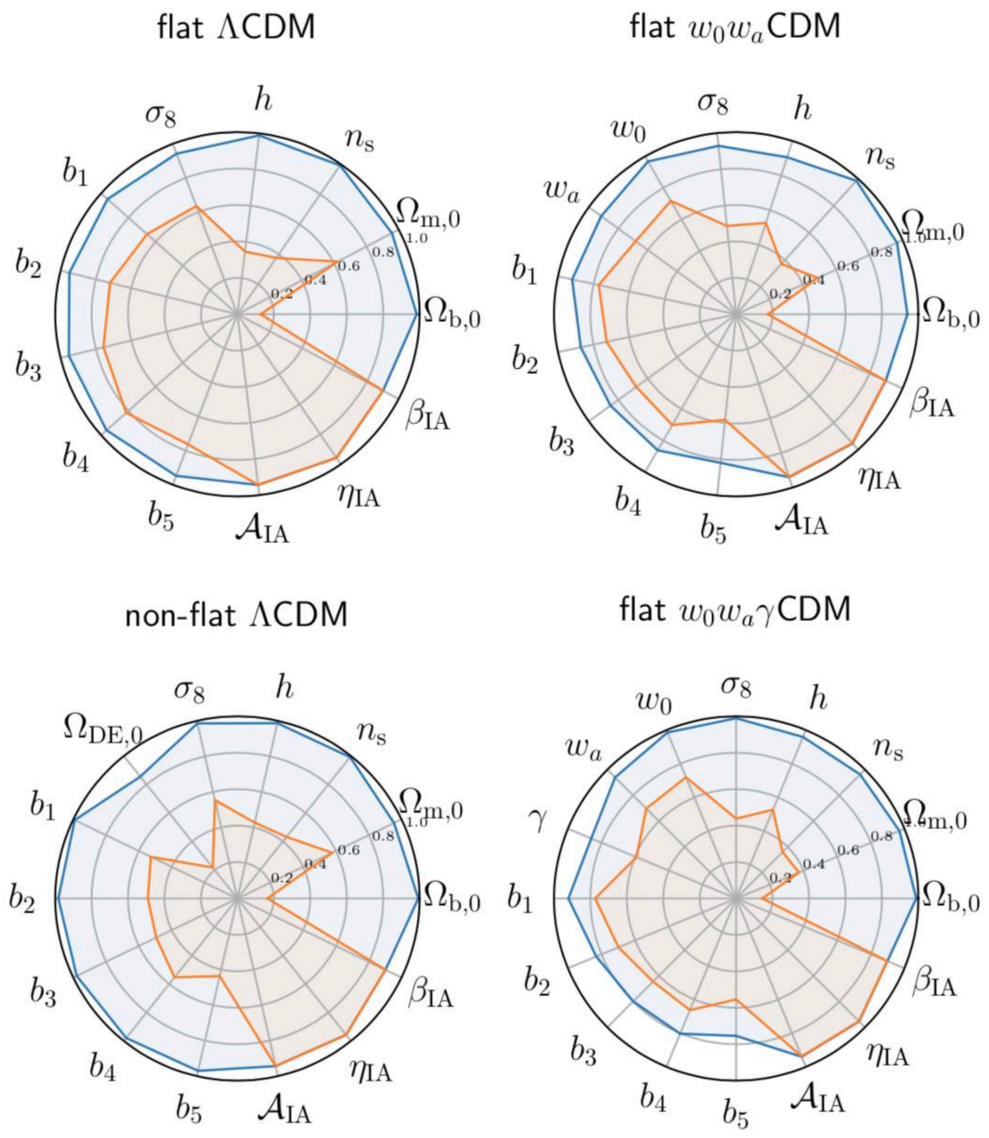
Weak Lensing



At least 2 independent and complementary probes to unsure control of systematic residuals to an unprecedented level of accuracy

Euclid preparation

XV. Forecasting cosmological constraints for the *Euclid* and CMB joint analysis



There is a dedicated CMBX Science Working Group

COMBINATION of Euclid data with CMB measurements will provide the largest lever arm of epochs, ranging from recombination to structure formation and the late-time accelerated expansion of the Universe.

Up to 3x - 10x improvement on ΛCDM and extended model parameters wrt to Euclid alone

Ilic et al. (MM) 2022

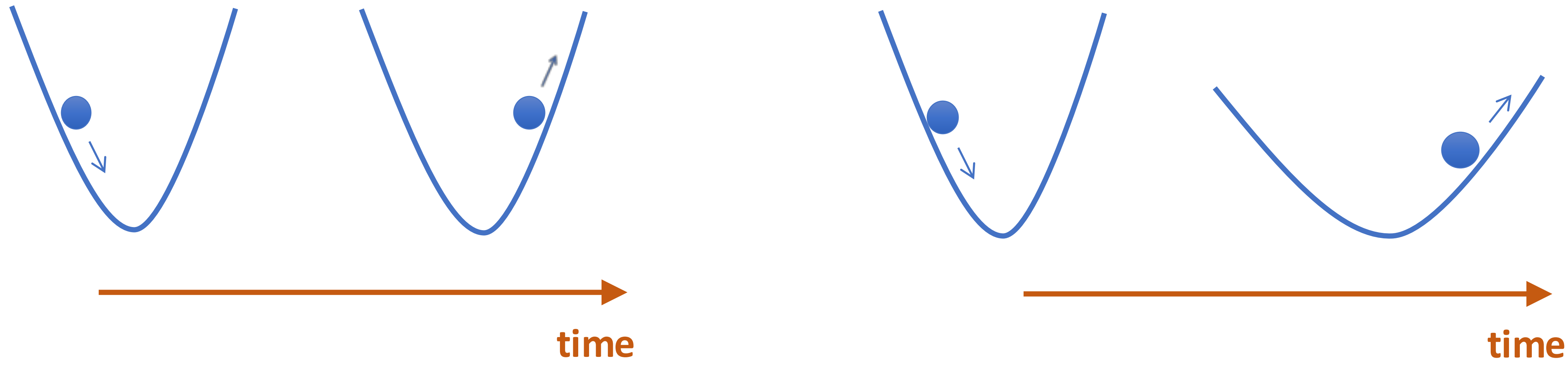
Fig. 6. Ratio of predicted 1σ uncertainties (see end of Sect. 5.2) showing how constraints are tightened after adding CMB lensing (blue) or all CMB probes (orange) when compared to the *Euclid*-only constraints (black outer rim), assuming a pessimistic *Euclid* scenario and SO-like CMB data, for four selected cosmological models (*from top to bottom, left to right*: flat ΛCDM; flat w_0 w_aCDM; non-flat ΛCDM; and flat w_0 w_a γCDM).

Late-time Integrated Sachs-Wolfe Effect

Gravitational Redshift: A photon gains energy when falling into a potential well (*blueshift*), while it loses energy climbing out (*redshift*).

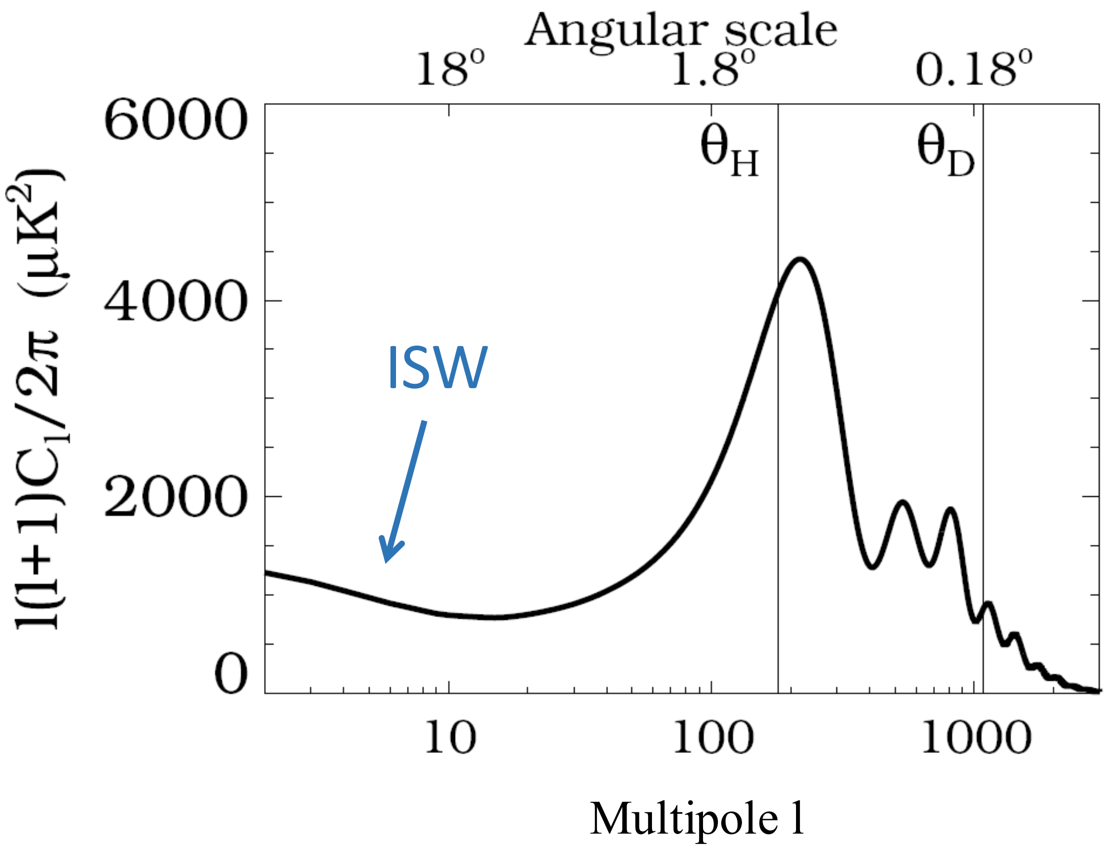
ISW effect: time-varying gravitational potentials along the photon path induce CMB temperature fluctuations (Sachs & Wolfe 1967).

- In a CDM Universe, there is an exact compensation between decay rate due to expansion and growth rate of the density perturbations → linear gravitational potentials stay constant ($\dot{\Phi} = 0$)
- The effect is a **manifestation of the late-time accelerated expansion** ($\dot{\Phi} \neq 0$), induced by Dark Energy, Modified Gravity, or of deviations from flat-ΛCDM perturbation growth (e.g. curvature, DM interactions, massive neutrinos)



Late-time Integrated Sachs-Wolfe Effect

$$\delta_T(\mathbf{n}_2) = \frac{T(\mathbf{n}_2) - \bar{T}}{\bar{T}} = -2 \int e^{-\tau(z)} \frac{d\Phi}{dz}(\mathbf{n}_2, z) dz$$



Cannot be directly detected in the pattern of CMB temperature anisotropies because of cosmic variance

Late-time Integrated Sachs-Wolfe Effect

$$\delta_T(\mathbf{n}_2) = \frac{T(\mathbf{n}_2) - \bar{T}}{\bar{T}} = -2 \int e^{-\tau(z)} \frac{d\Phi}{dz}(\mathbf{n}_2, z) dz$$

$$\delta_g(\mathbf{n}_1) = \frac{N_g(\mathbf{n}_1) - \bar{N}_g}{\bar{N}_g} = \int b(z) \frac{dN}{dz}(z) \delta_m(\mathbf{n}_1, z) dz$$

δ_m related to Φ via the Poisson equation

Late-time Integrated Sachs-Wolfe Effect

$$\delta_T(\mathbf{n}_2) = \frac{T(\mathbf{n}_2) - \bar{T}}{\bar{T}} = -2\int e^{-\tau(z)}\frac{d\Phi}{dz}(\mathbf{n}_2, z)dz$$

$$\delta_g(\mathbf{n}_1) = \frac{N_g(\mathbf{n}_1) - \bar{N}_g}{\bar{N}_g} = \int b(z)\frac{dN}{dz}(z)\delta_m(\mathbf{n}_1, z)dz$$

δ_m related to Φ via the Poisson equation

→ **ISW effect can only be measured by cross-correlating CMB temperature anisotropies with tracers of the large-scale structure** (Crittenden & Turok, 1996)

$$C^{\mathrm{Tg}}(\vartheta) = \left\langle \delta_T(\mathbf{n}_1)\delta_g(\mathbf{n}_2) \right\rangle$$

Firstly, detected by Boughn & Crittenden in 2004 , since then measured at increasing significance (for a review Planck 2013 results. XIX)

Late-time Integrated Sachs-Wolfe Effect

$$\delta_T(\mathbf{n}_2) = \frac{T(\mathbf{n}_2) - \bar{T}}{\bar{T}} = -2\int e^{-\tau(z)}\frac{d\Phi}{dz}(\mathbf{n}_2, z)dz$$

$$\delta_g(\mathbf{n}_1) = \frac{N_g(\mathbf{n}_1) - \bar{N}_g}{\bar{N}_g} = \int b(z)\frac{dN}{dz}(z)\delta_m(\mathbf{n}_1, z)dz$$

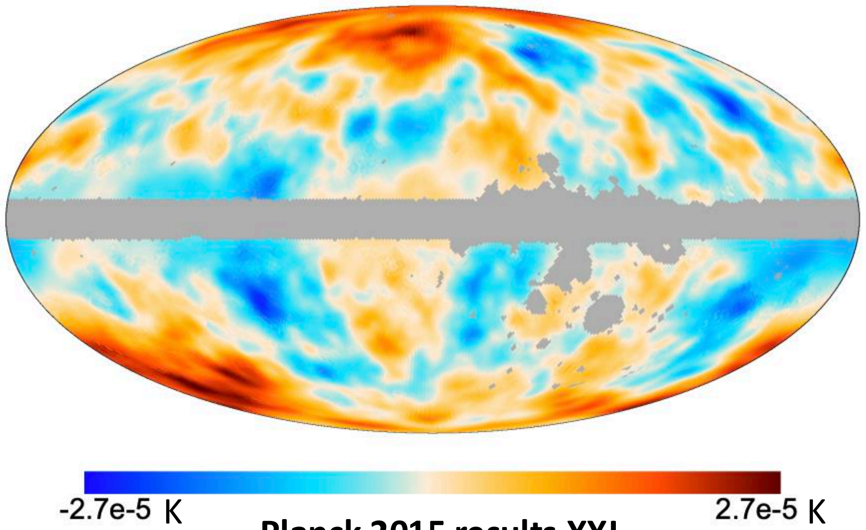
δ_m related to Φ via the Poisson equation

→ **ISW effect can only be measured by cross-correlating CMB temperature anisotropies with tracers of the large-scale structure** (Crittenden & Turok, 1996)

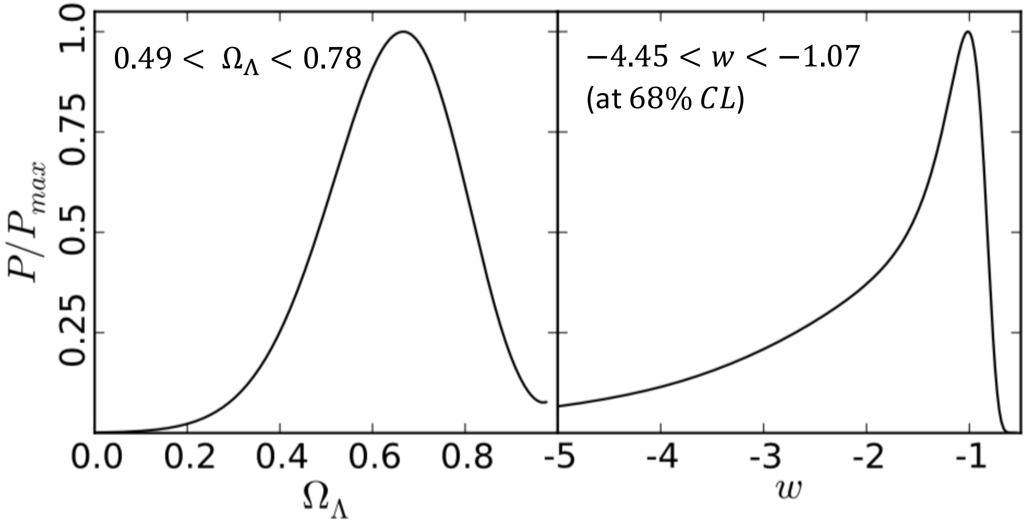
$$C^{\mathrm{Tg}}(\vartheta) = \left\langle \delta_T(\mathbf{n}_1)\delta_g(\mathbf{n}_2)\right\rangle$$

Firstly, detected by Boughn & Crittenden in 2004 , since then measured at increasing significance (for a review Planck 2013 results. XIX)

ISW MAP

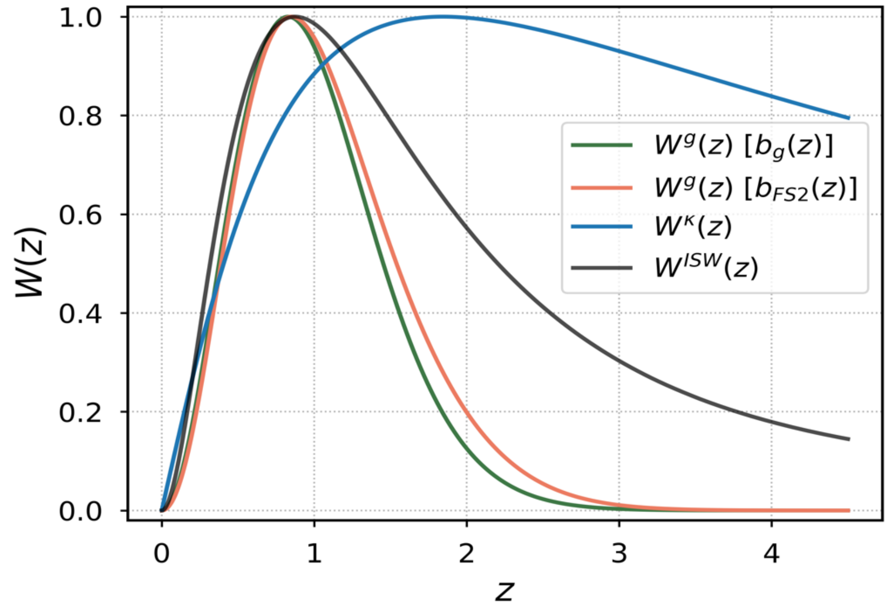


Planck 2015 results XXI



Late-time Integrated Sachs-Wolfe Effect

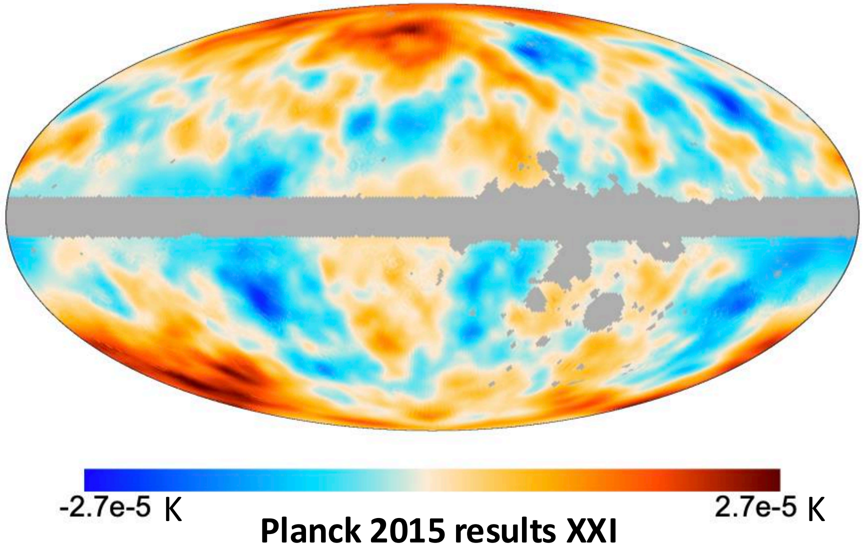
With **Euclid** × **Planck** TG expected to be measured with S/N ≃ 4 reaching S/N ≃ 4.6 with LiteBIRD including polarization data



Optimal extraction of the iSW signal with Euclid:

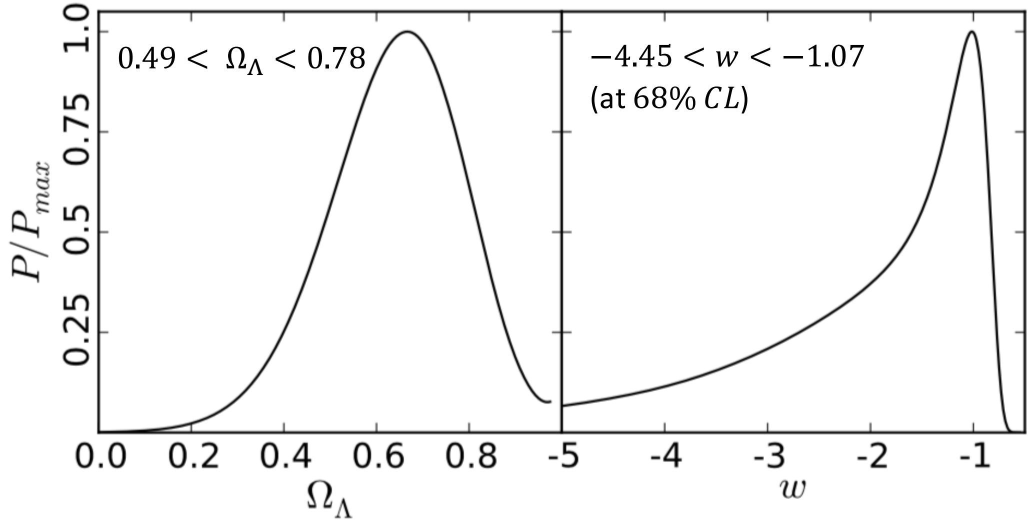
- large number of galaxies
- wide coverage in sky area and redshift
- high-degree of correlation
- tomographic information

ISW MAP



Planck 2015 results XXI

Dark Energy density parameter **Dark Energy equation of state**



Primordial Non-Gaussianity with CMB cross-correlations

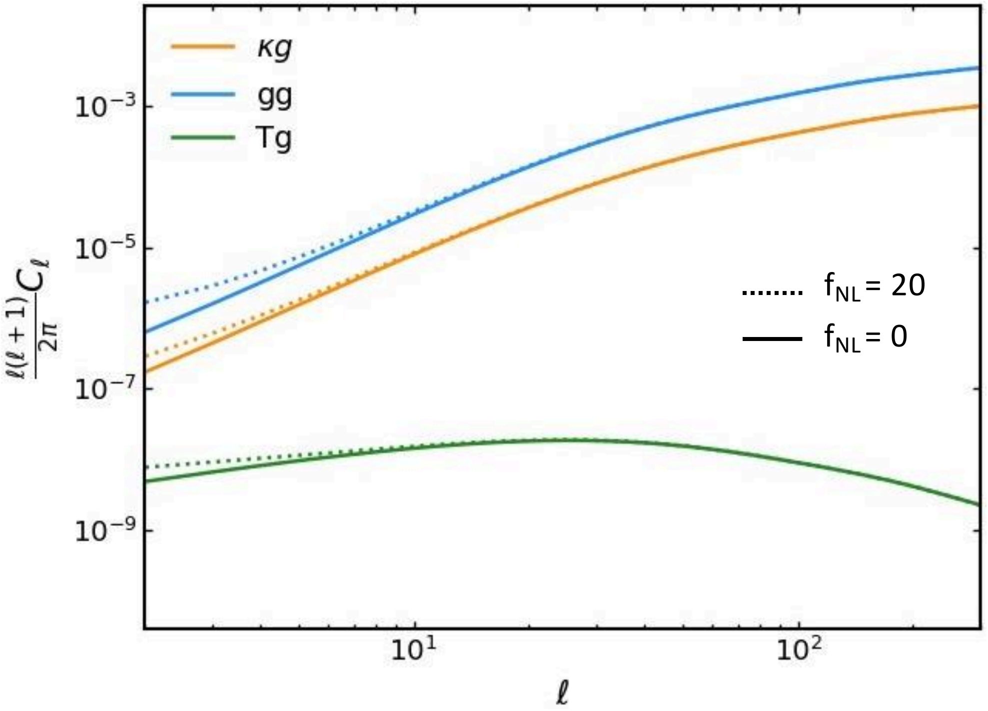
- Inflationary models predict different levels of deviations from Gaussianity in the distribution of density fluctuations.
- Local type non-Gaussianity introduces correlations between short-scale modes (which form halos) and long-scale modes in the primordial potential, parameterized with the amplitude f_{NL}

→ **Scale-dependent galaxy bias**

$$b(z) \rightarrow b(z)\,[1 + f_{NL}\,\beta(k,z)]$$

- From Planck $f_{NL} = 0.9 \pm 5.1$ bispectrum of the anisotropy fields
- Using $b(k,z)$ From BOSS $f_{NL} = -12 \pm 21$ and DESI quasars $f_{NL} = -18 \pm 28$
- Large-angular scales in galaxy clustering are difficult to map and more affected by systematic effects → **importance of κG and TG**

Credit: G. Piccirilli

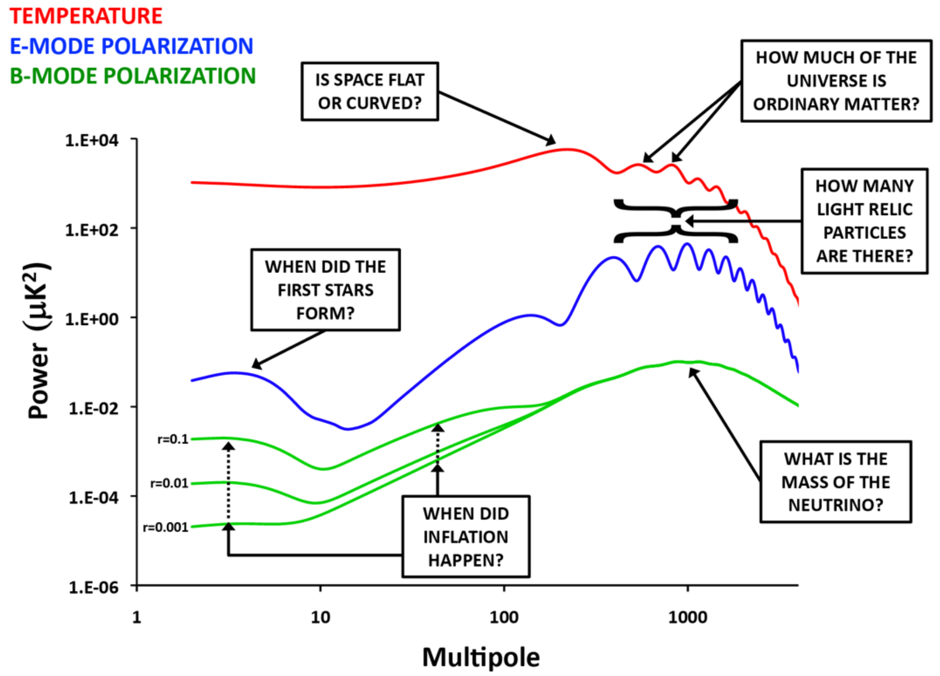


- **LiteBIRD will be unique in mapping the large angular scales** → $\sigma(f_{NL}) \sim 40$ with only κG (Lonappan et al. (MM) 2024), improved constraints from LiteBIRD+Planck with κG, TG, GG in prep.

Future of CMB Cosmology

- ✓ CMB has played a crucial role in shaping the ΛCDM model.
- ✓ It will remain an extremely active field in the coming decades (polarization, secondary anisotropies, spectral distortions, ...)
- ✓ CMB cross-correlations are booming:
  transitioning from the detection regime to powerful cosmological probe.

- **Origin of the universe**
- **Dark Matter**
- **Dark Energy, Modified Gravity and Growth of Structures**
- **Reionization and First Sources**
- **Astrophysics** (Galactic Science, Feedback and inter-galactic medium, Dusty star-forming galaxies)



Credit: Snowmass2021 Cosmic Frontier: CMB Measurements White Paper