

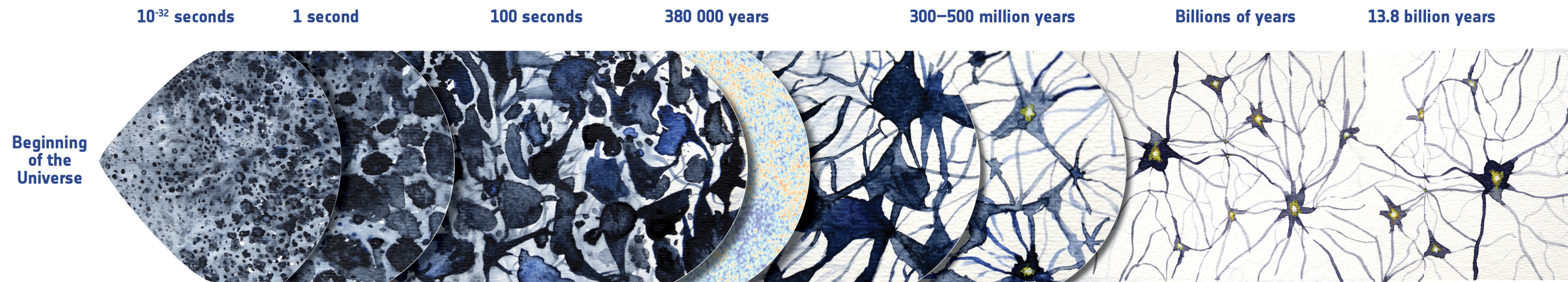
The background of the slide is a large, horizontally-oriented oval containing a Cosmic Microwave Background (CMB) fluctuation map. The map shows a complex, grainy pattern of colors representing temperature variations in the early universe. The colors range from blue (cooler) to red (warmer), with a prominent blue region on the right and a red region on the left. The overall texture is intricate and fractal-like.

# **CMB Physics: Theoretical Aspects**

**PUMA22: Probing the Universe with Multimessenger Astrophysics**

**Martina Gerbino (INFN Ferrara), Sestri Levante, 27 Sep 2022**

# What is the CMB?



Imprints of early Universe physics and effects of late-time evolution

The CMB is a comprehensive cosmological probe

**Inflation**  
Accelerated expansion of the Universe

**Formation of light and matter**

**Light and matter are coupled**

Dark matter evolves independently: it starts clumping and forming a web of structures

**Light and matter separate**

• Protons and electrons form atoms  
• Light starts travelling freely: it will become the Cosmic Microwave Background (CMB)

**Dark ages**

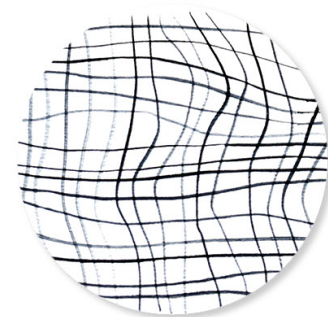
Atoms start feeling the gravity of the cosmic web of dark matter

**First stars**

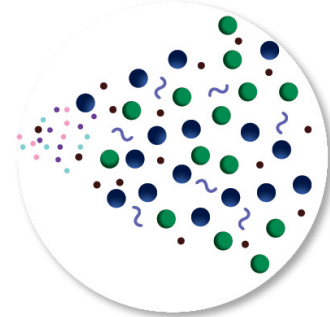
The first stars and galaxies form in the densest knots of the cosmic web

**Galaxy evolution**

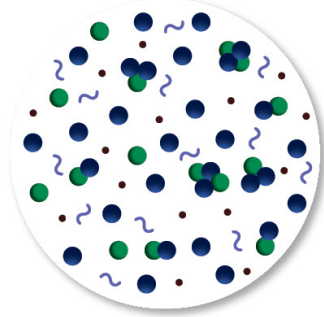
**The present Universe**



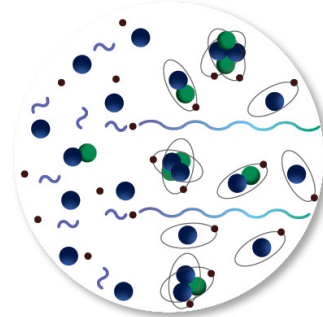
• *Tiny fluctuations: the seeds of future structures*  
• *Gravitational waves?*



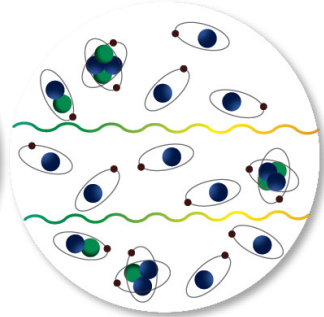
*Frequent collisions between normal matter and light*



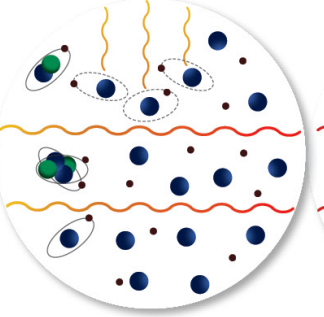
*As the Universe expands, particles collide less frequently*



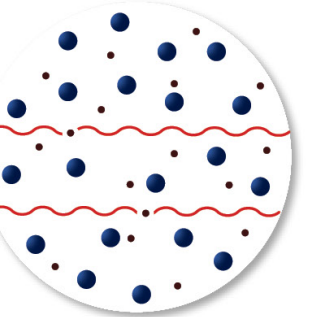
*Last scattering of light off electrons*  
→ **Polarisation**



*The Universe is dark as stars and galaxies are yet to form*



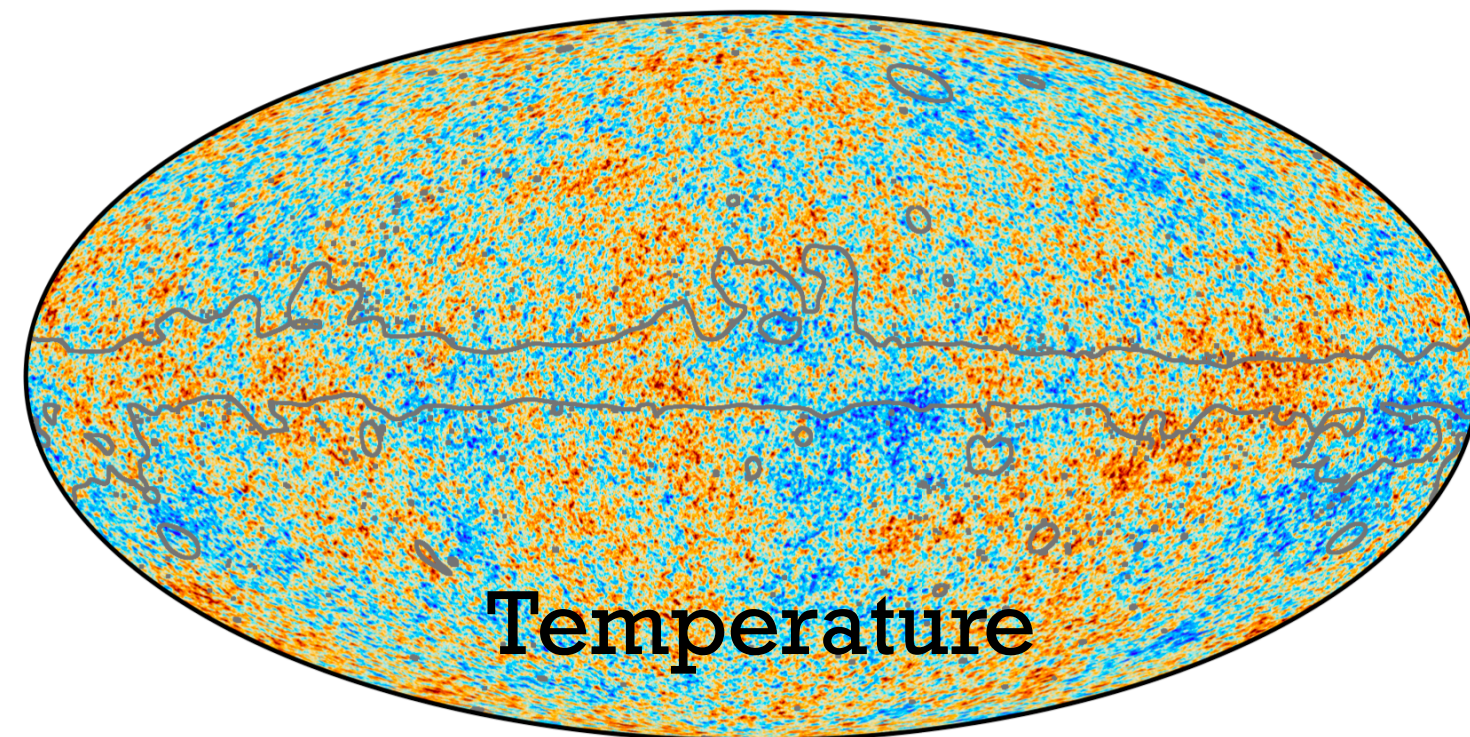
*Light from first stars and galaxies breaks atoms apart and "reionises" the Universe*



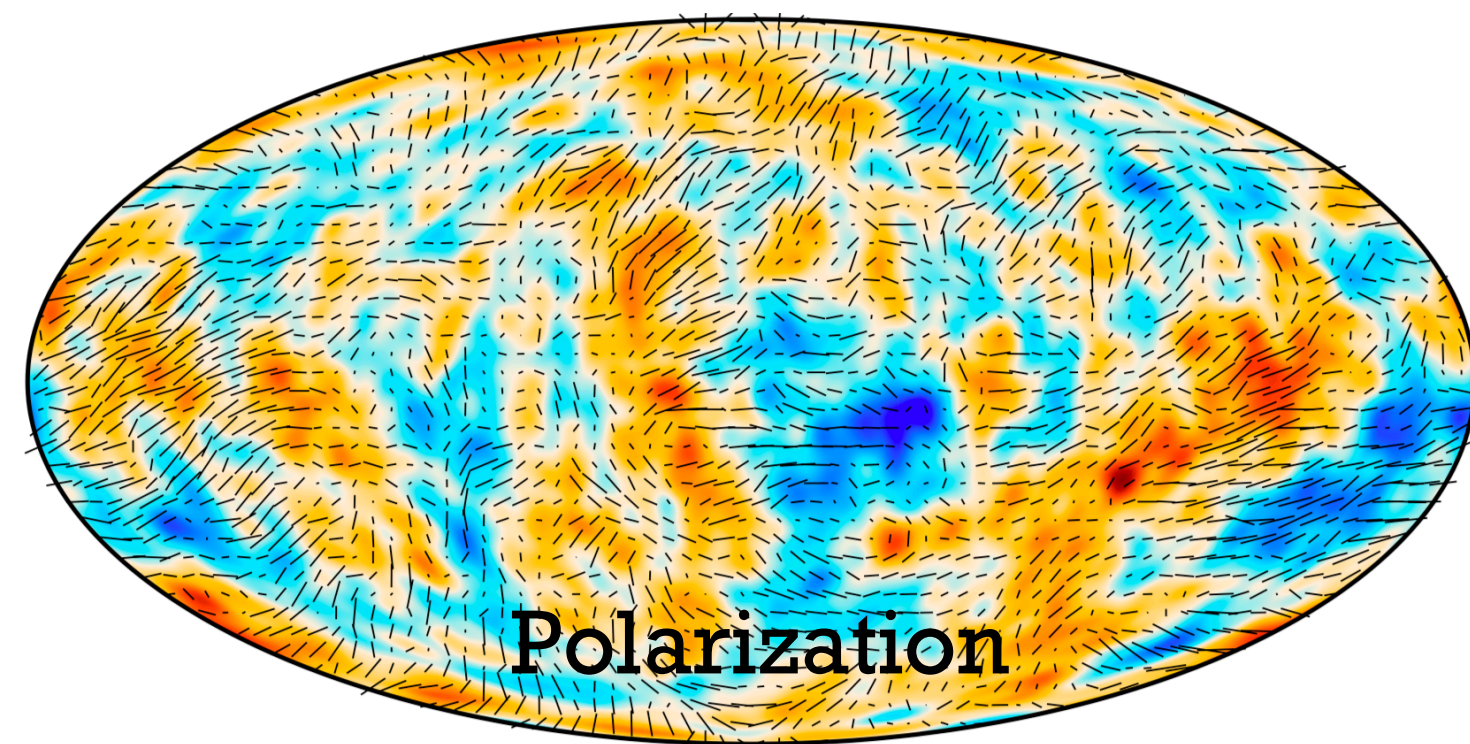
*Light can interact again with electrons*  
→ **Polarisation**

# Statistics of the CMB

$$\delta^X \sim \Delta^X \delta_{\mathcal{P}} \begin{matrix} \xrightarrow{\text{“Deterministic” evolution}} \\ \xrightarrow{\text{Stochastic primordial field}} \end{matrix}$$



-300 300  $\mu\text{K}$



| 0.41  $\mu\text{K}$  160  $\mu\text{K}$

Credit: ESA Planck

Primordial perturbations  
( $n_s, \bar{A}_s, r, n_t, \dots$ )

$$C_{\ell}^{xy} \propto \int d \ln k \mathcal{P}(k) \Delta_{\ell}^x(m_0, k) \Delta_{\ell}^{y*}(m_0, k)$$

$$\Delta_{\ell}^x(m_0, k) \propto \int d\eta \mathcal{S}(k, \eta) f(j_{\ell}[k(\eta_0, \eta)])$$

Transfer functions

Source function  
( $\tau, \text{obh2}, N_{\text{eff}}, \dots$ )
Projection  
( $\theta, \text{och2}, \text{oL}, \dots$ )

+ late-time effects due to interaction with LSS  
(gravitational lensing)

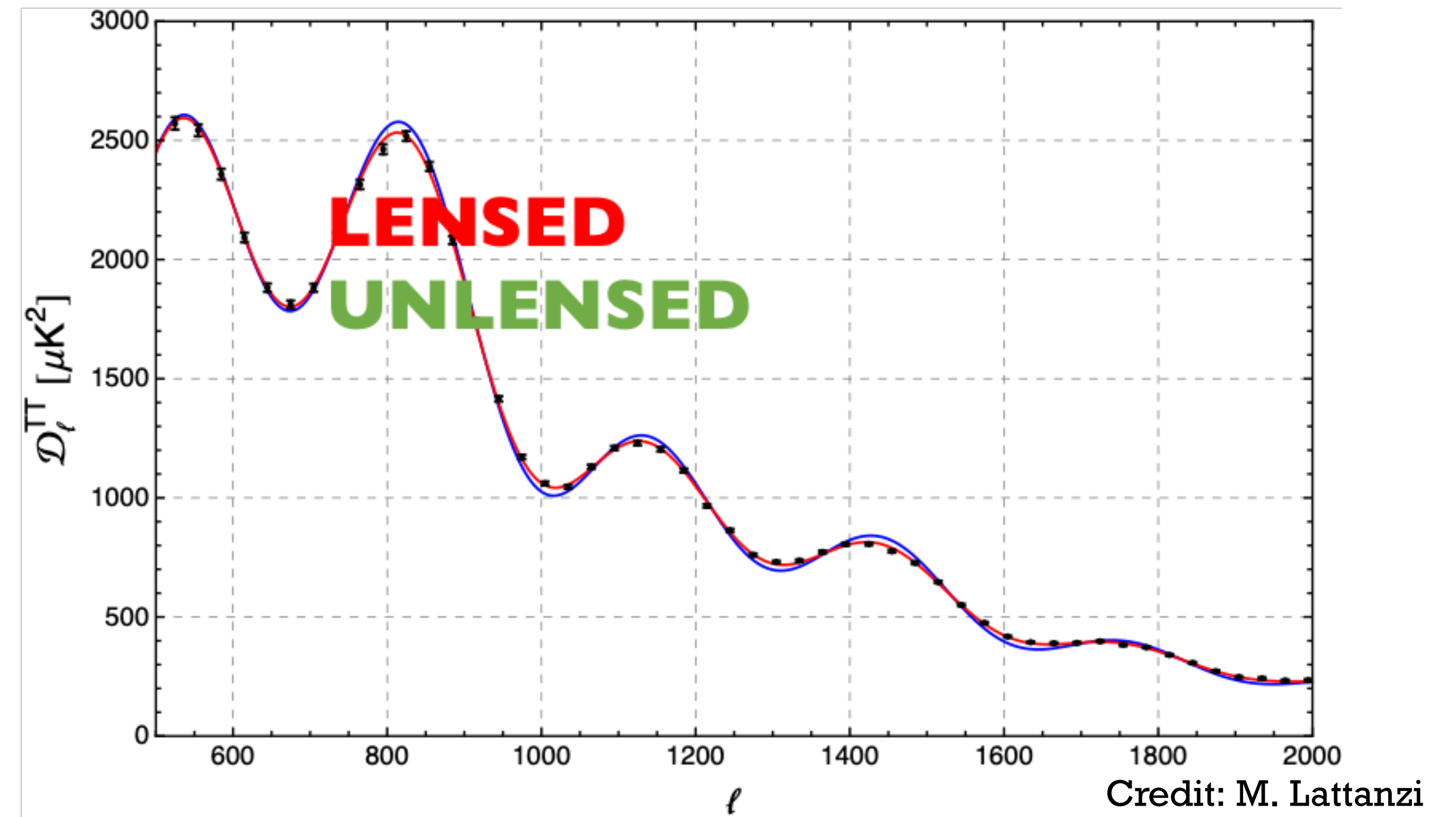
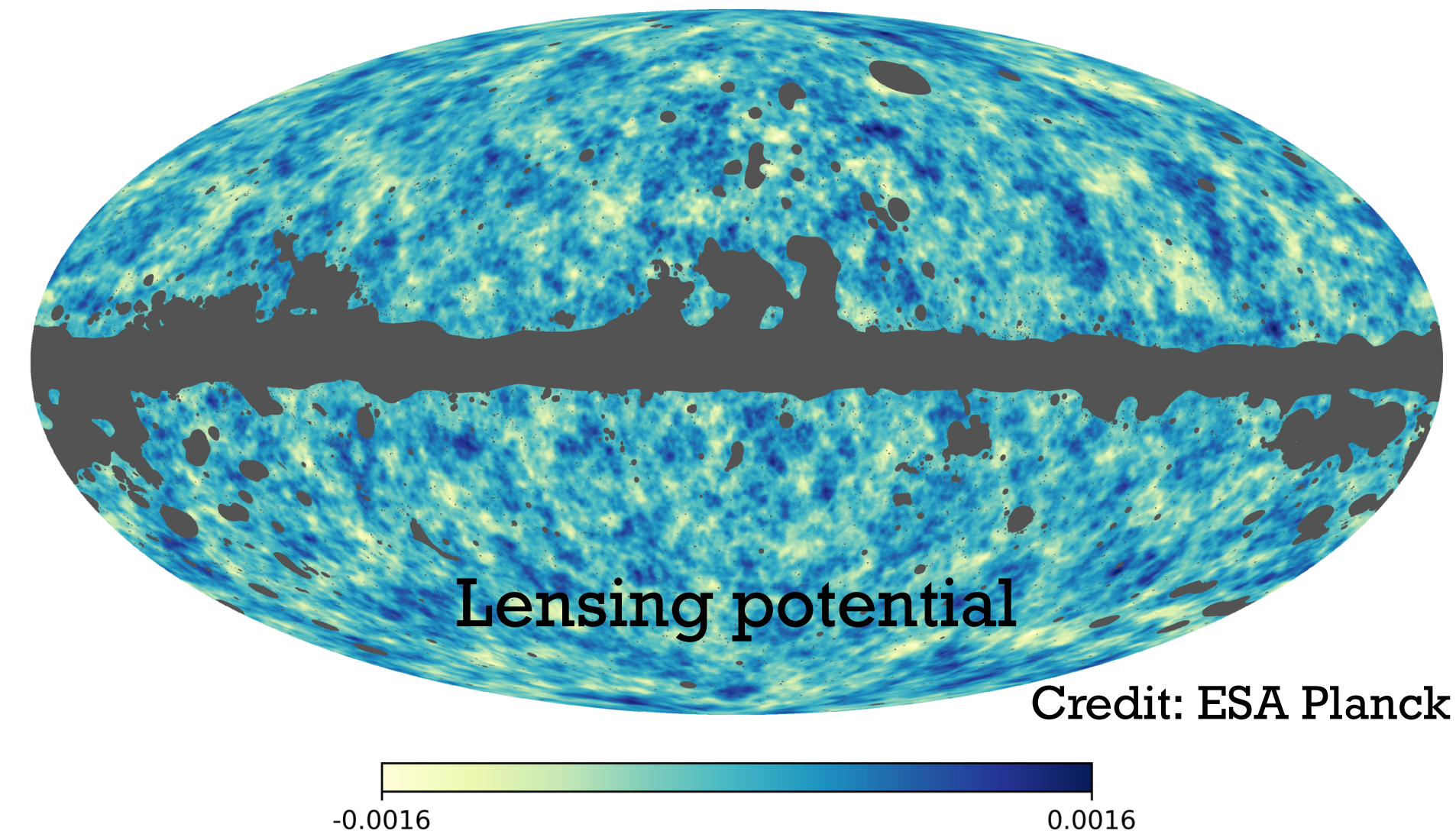
# Statistics of the CMB

Evolution of the large-scale structure affects statistics of the small scales

Fluctuations are “blurred”  
-> acoustic peaks are smoothed

Non-gaussian signal allows to reconstruct map of lensing field (depends on total matter)

Sensitivity to late-time physics (och2, Sumnu, oL, w, modified gravity, ...)



# Current measurements

CVL measurements in TT up to 2000 from Planck

Improved measurements in T and E  
down to arcmin scales from ACT&SPT

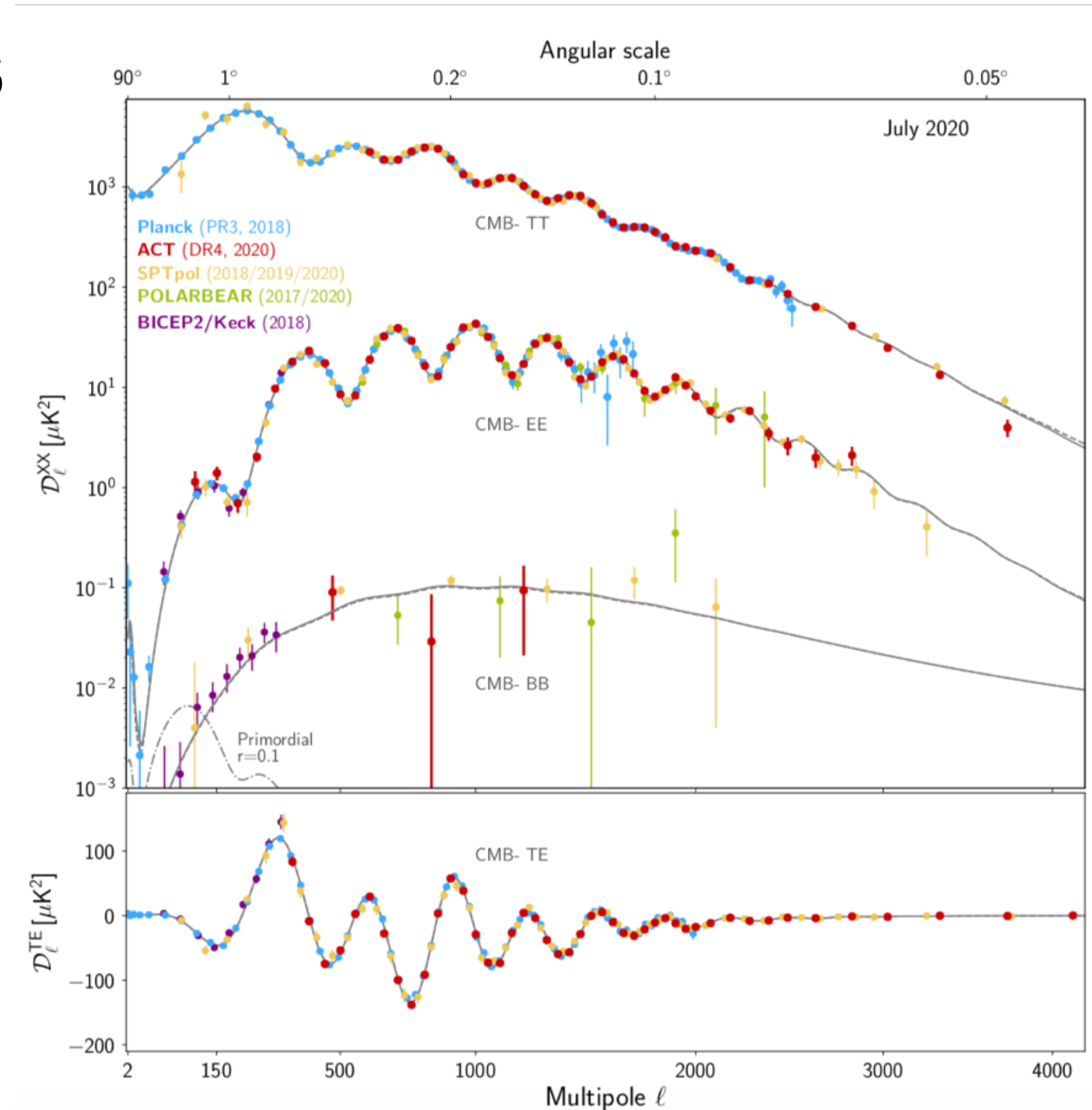
Measurements of degree and sub/degree scales in B  
from BK and Polarbear

Main cosmo params (but tau) constrained  
at sub/percent level

No clear evidence of deviation from LCDM

**BUT**

Many open questions in fundamental physics  
Many bounds to (hopefully) convert to constraints  
New routes to investigate  
Intriguing inconsistencies between experiments  
motivate next/generation surveys



ACT Coll., Aiola+, 2020

# Coming soon

Ground-based:  
Simons Observatory (first light 2023)  
CMB-S4 (start operation by 2030)  
Space mission:  
LiteBIRD (launch 2029)

Polarization and small scales  
Key areas for improvements

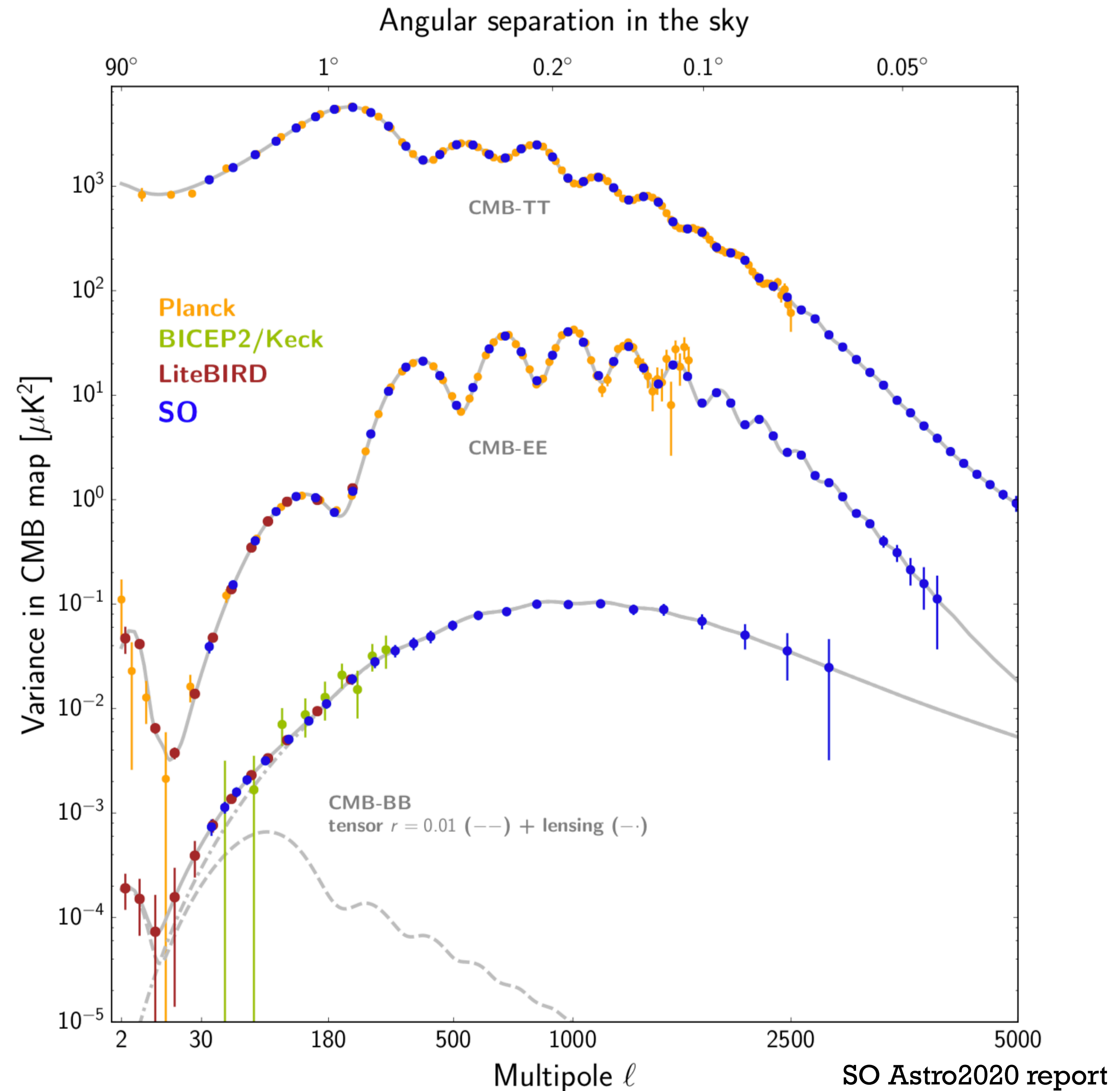
Wide range of science targets:

Early universe physics

Composition of the thermal plasma

Late/time evolution

Astrophysics



# Polarization and Neff

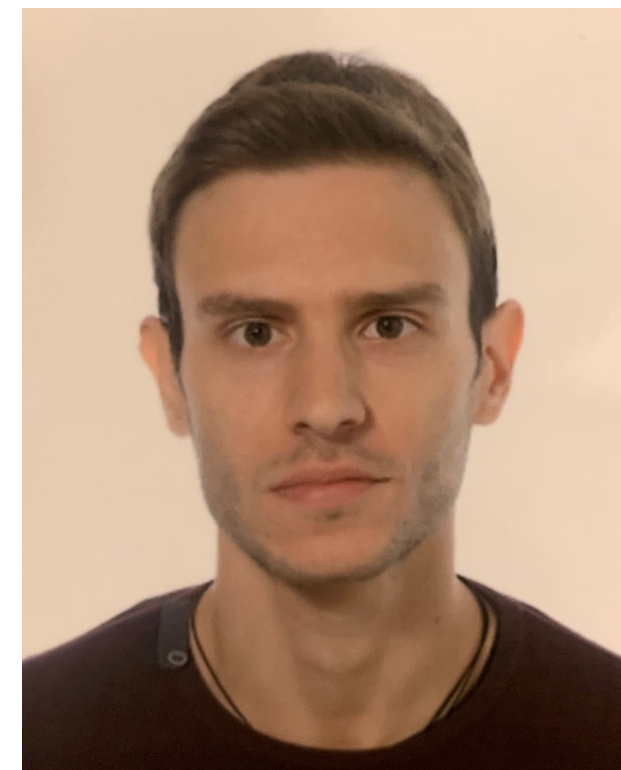
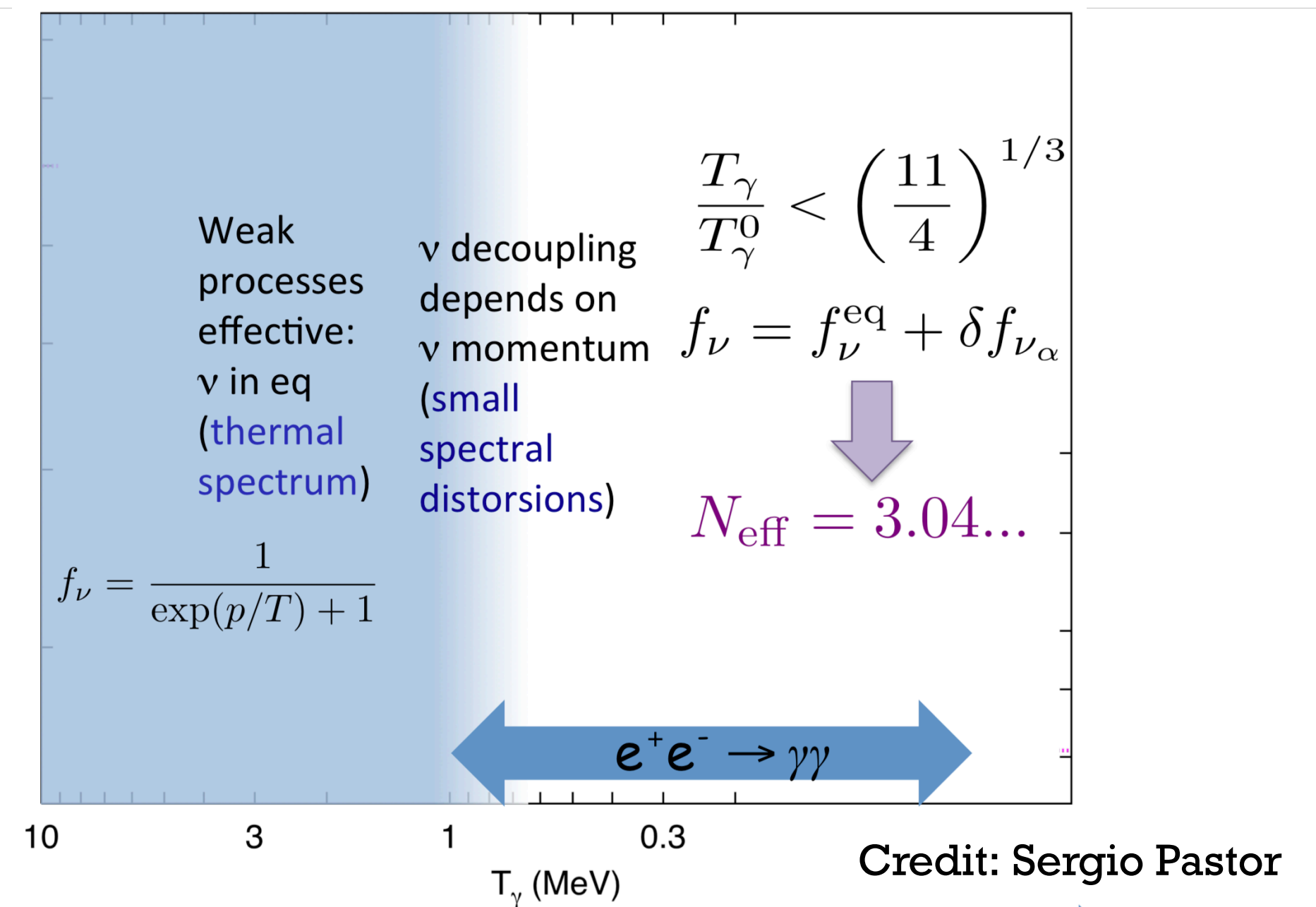
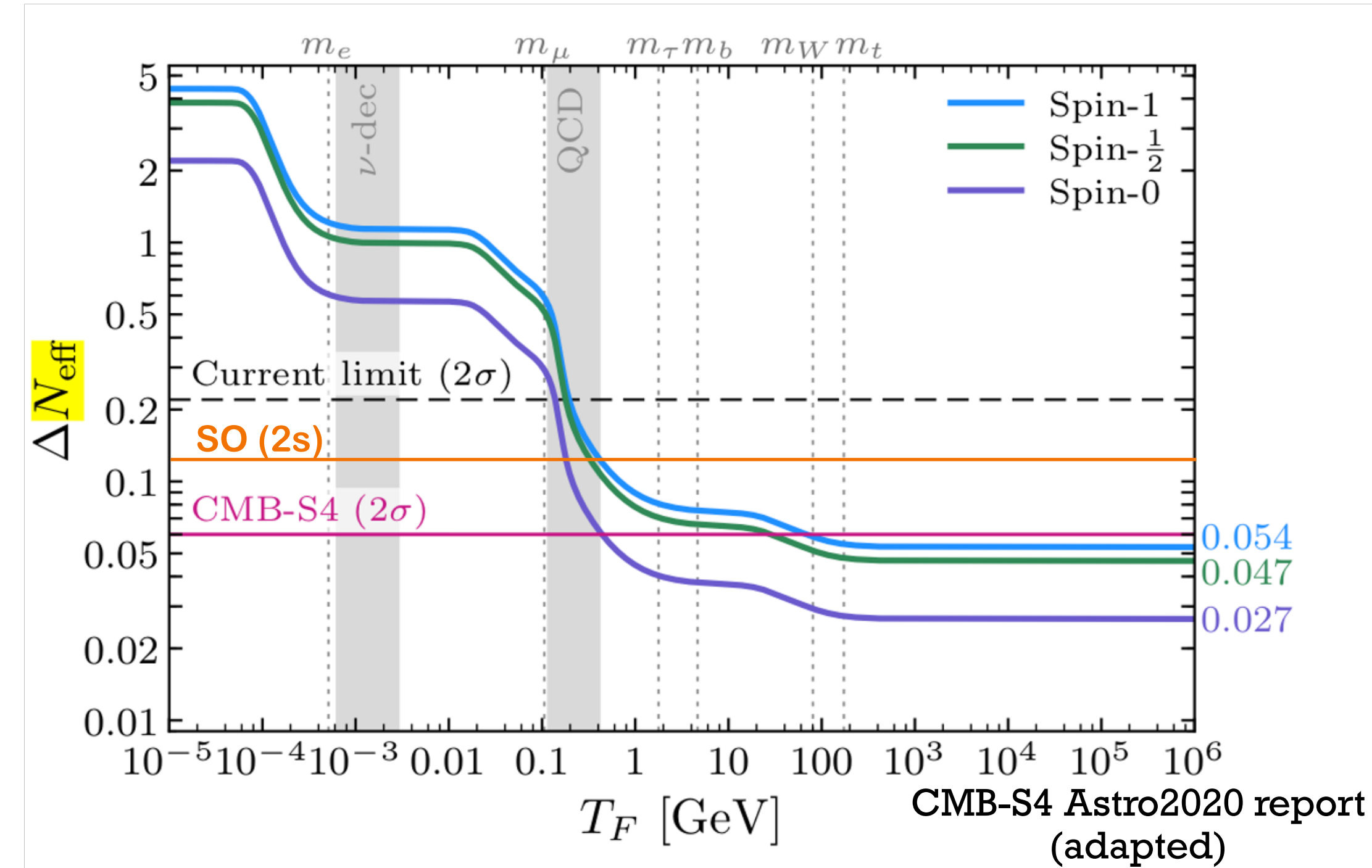
Polarization can help better constrain parameters

Sharper acoustic peaks in polarisation  
Improved sensitivity to Neff

Neff as a proxy for BSM properties of light relics

BSM neutrino properties  
Additional (thermal) relics -> axion properties!  
Non-standard thermal evolution

see Maria A. and Luca C. talks!



# Polarization and early Universe

Polarization can probe physics not visible in T

Deviations from standard EM  
(birefringence-like)

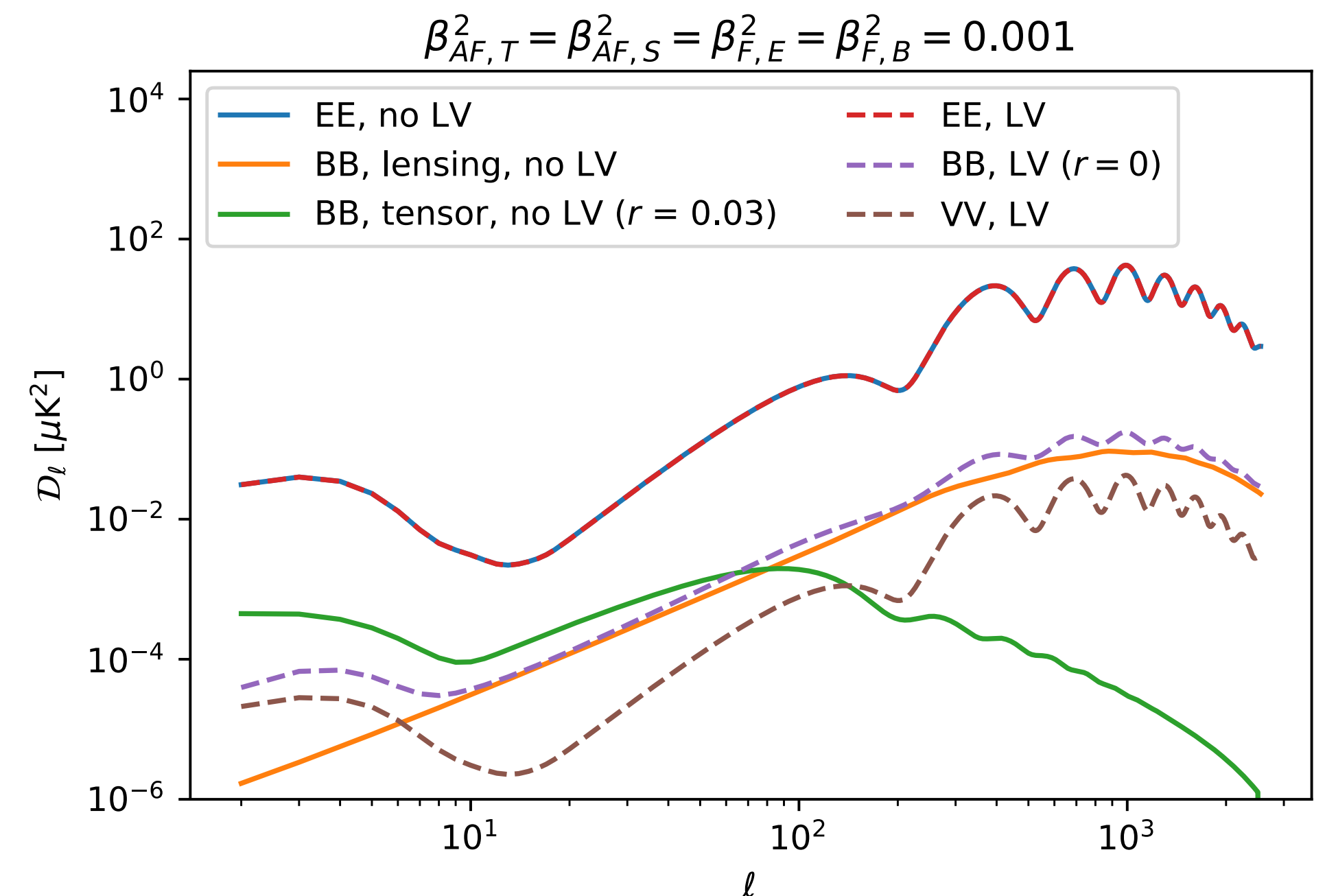
Order-of-magnitude improvement with current data

Promising prospects with future data  
including V-mode sensitivity

Minimal SM extension with Lorentz-violating EM

$$\mathcal{L} = \sqrt{-g} \left[ -\frac{1}{4} F_{\mu\nu} F^{\mu\nu} + \frac{1}{2} \varepsilon^{\alpha\beta\mu\nu} A_\beta (k_{AF})_\alpha F_{\mu\nu} - \frac{1}{4} (k_F)^{\alpha\beta\mu\nu} F_{\alpha\beta} F_{\mu\nu} \right]$$

mixes Q, U and V modes



Caloni, Giardiello+ (incl.MG), in prep.  
Lembo+, PRL 2021



L. Caloni

S. Giardiello

N. Raffuzzi

M. Lembo



# Small scales

Lensing of the CMB allows reconstruction of lensing potential

SZ effect allows mapping of clusters

Key tracers of matter field from CMB observations

Cross-correlation with LSS surveys

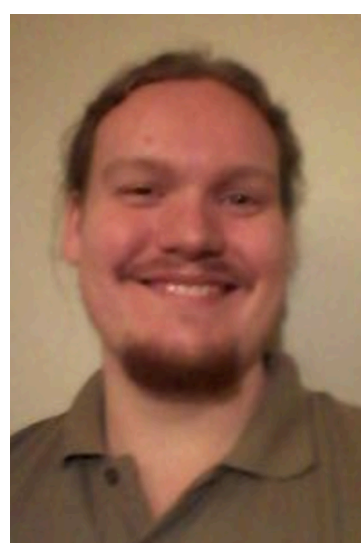
Impact of light yet massive relics  
(see talks by Maria and Luca)

Stability of dark matter

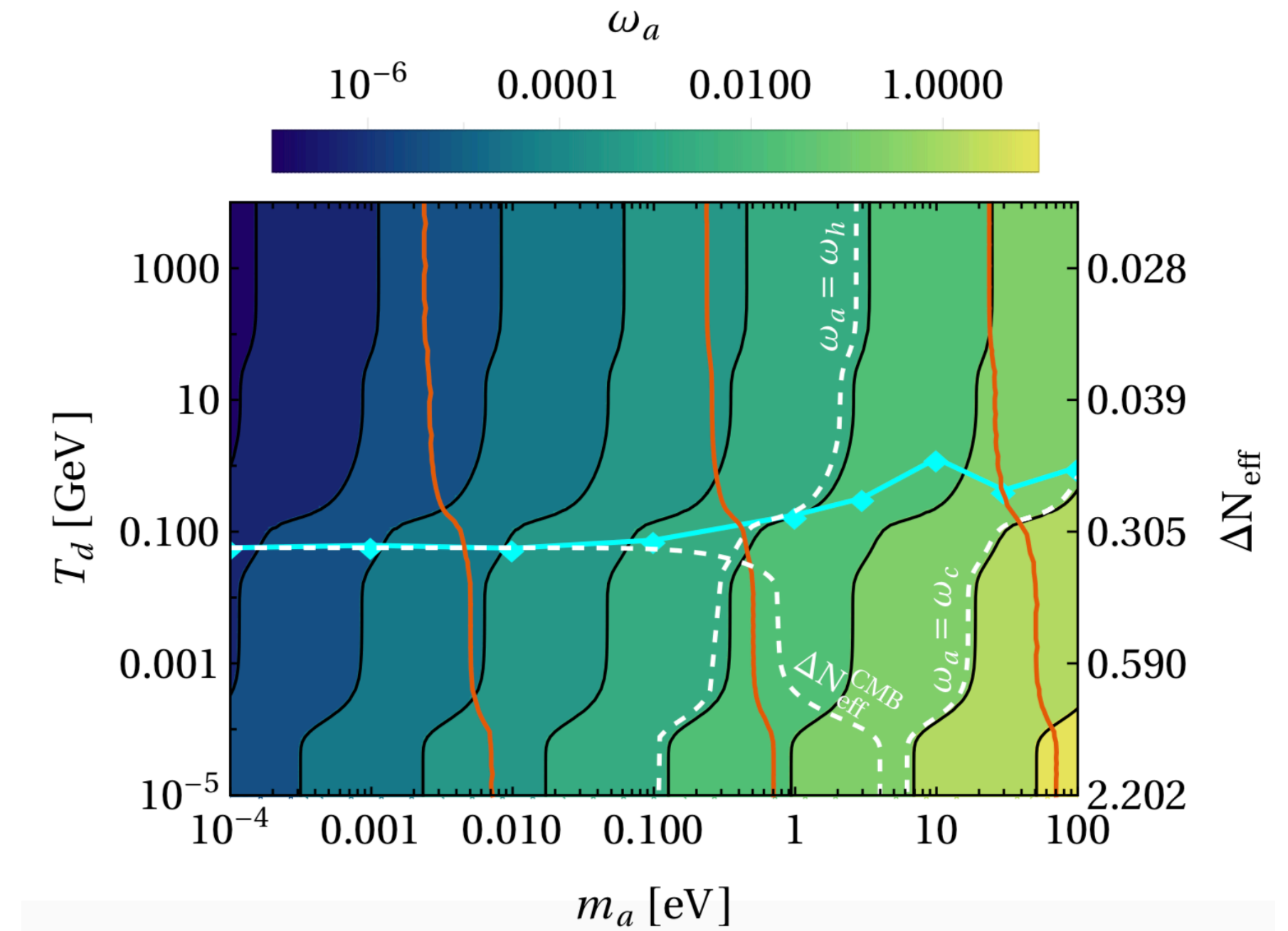
Handle to structure evolution



S. Alvi

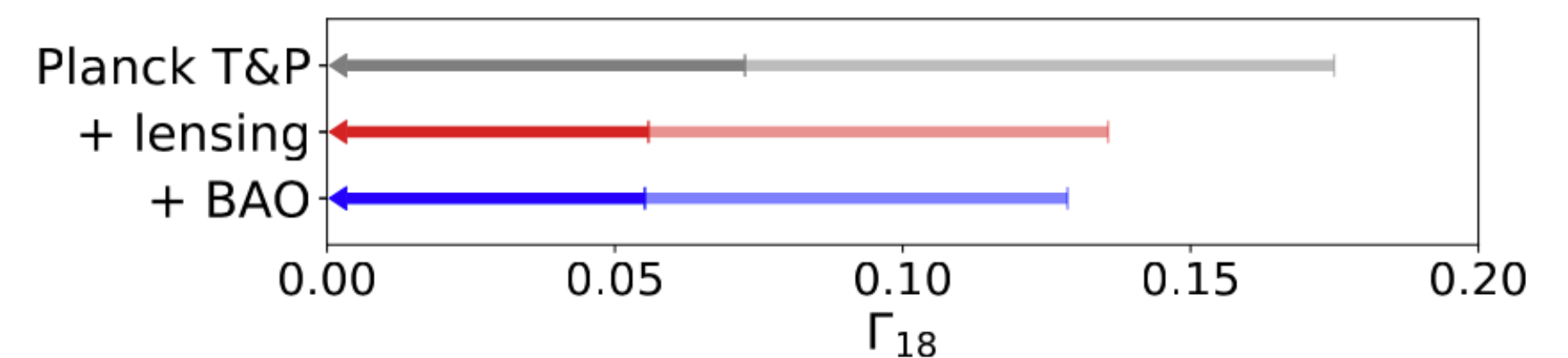


T. Brinckmann



Caloni, MG, Lattanzi, Visinelli, JCAP 2022

Dataset \ Parameter	$\Gamma_{18} = \Gamma_{\text{DCDM}}/10^{-18}\text{s}^{-1}$	$\tau_{\text{DCDM}}$ Gyr
Planck T&P	$< 0.175$	$> 181$
+ lensing	$< 0.136$	$> 234$
+ BAO	$< 0.129$	$> 246$



Alvi, Brinckmann, MG, Lattanzi, Pagano, arXiv:2205.05636

# Small scales

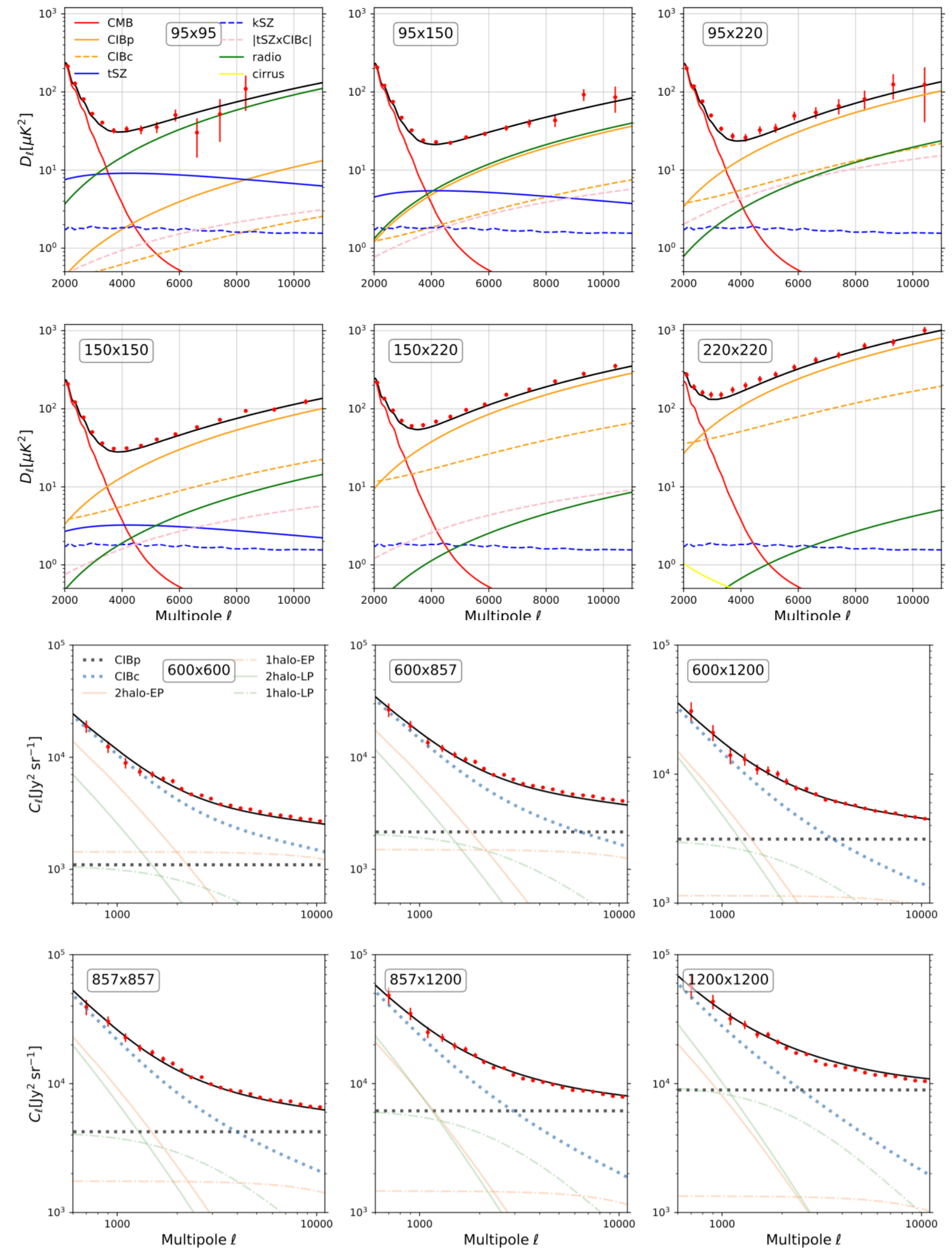
High-resolution, multi-frequency observations  
 -> enhanced sensitivity to astrophysical emissions

Foreground as astrophysical tools!

Possibility to constrain structure evolution  
 CIB -> dusty star-forming galaxies  
 tSZ, kSZ -> massive galaxy clusters



C. Chiochetta



Chiochetta PhD thesis,  
 advisors: L. Pagano, M. Negrello  
 in collab. with E. Calabrese, MG

# Conclusions

CMB measurements are a pillar of modern, precision cosmology

Wide range of information from fundamental physics to astrophysics

Complementarity with other searches (lab, astrophysics) -> multi-probe approach

Novel exciting results expected from next-gen surveys

Challenges ahead -> theory modelling, systematic effects, combined analyses

Voyage2050: “The Senior Committee recommend that ESA should develop a Large mission capable of deploying new instrumental techniques such as gravitational wave detectors or precision microwave spectrometers to explore the early Universe”

**THANKS FOR YOUR ATTENTION!**