Searching for primordial gravitational waves in angular correlations of the CMB

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Based on:

M.A. Sanchis-Lozano, F. Melia, M. López-Corredoira and N. Sanchis-Gual
Astron.Astrophys. 660 (2022) A121 [arXiv:2202.10987]

M.A. Sanchis-Lozano
Universe 8 (2022) 8, 396 [arXiv:2205.13257]

M.A. Sanchis-Lozano and V. Sanz,
Phys.Rev. D 109 (2024) 6, 063529 [arXiv:2312.02740]

Starting point

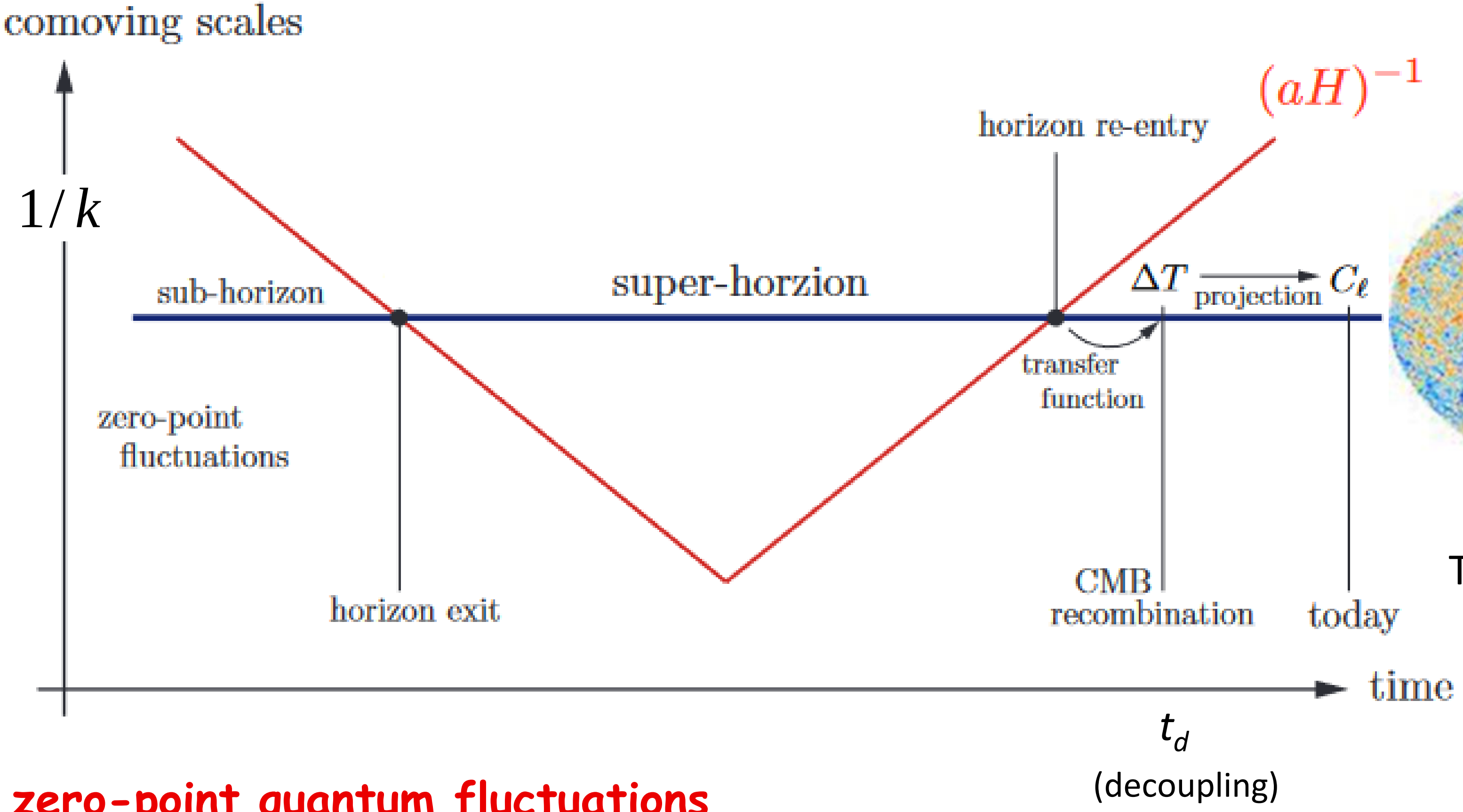
In an inflationary scenario, primordial **density inhomogeneities** due to unavoidable **quantum fluctuations of the inflaton field**, are the seed of later **primary (temperature) CMB anisotropies**, as well as of the large scale structure of our observable universe today.

Commonly, temperature anisotropies are mainly attributed to the **scalar modes** of the inflaton field, while **tensor modes** are expected to contribute to a **quite lesser extent**, hardly distinguishable from the former.

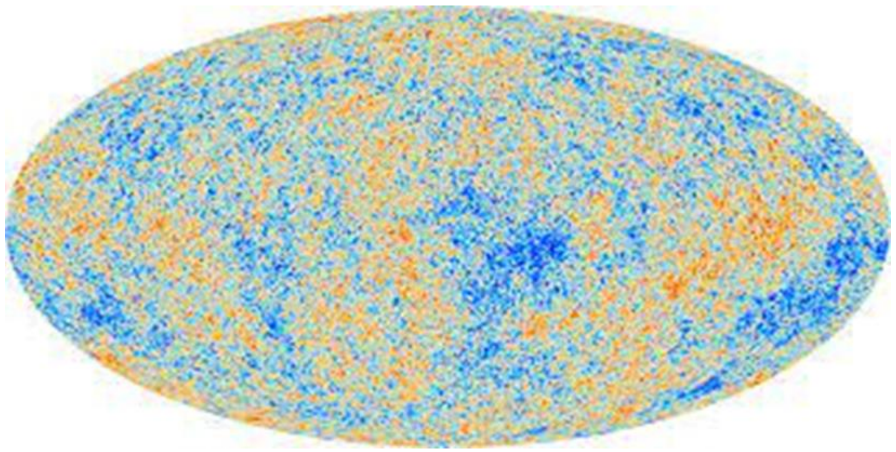
Hence, common wisdom dictates that **polarization of the CMB remains as the main hope to detect primordial gravitational waves** produced in the very early universe as only tensor modes -and not scalar modes- can produce B-modes of polarization.

Here we **first** focus on the expected small but maybe observational effect of **the tensor modes on the CMB temperature correlations especially at large angle (low multipoles)**, **as a way of searching for PGW.**

At the end we examine the effect of **tensor modes on the quadrupole and octupole** contributions to the **BB power spectrum** of the CMB



Cosmic Microwave Background
CMB



Temperature anisotropies from the sky

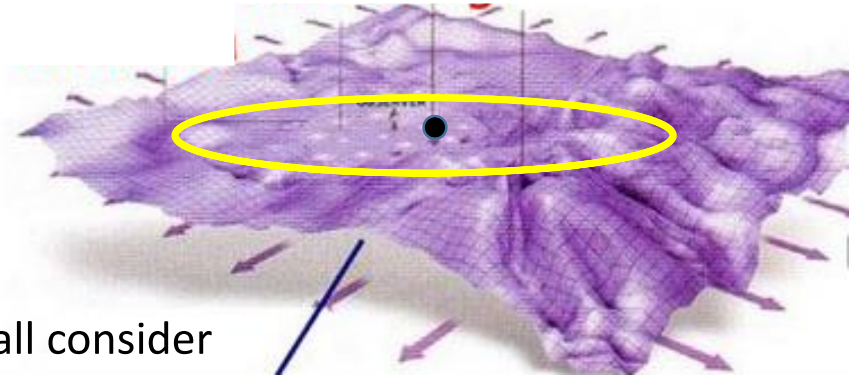
as a snapshot of the early universe

and the seeds of the formation

of LSS of the universe today

zero-point quantum fluctuations

of the inflaton field



k: comoving wavenumber
of the Fourier expansion

$$\frac{k}{a} = \frac{2\pi}{\lambda_k} \quad \text{physical}$$

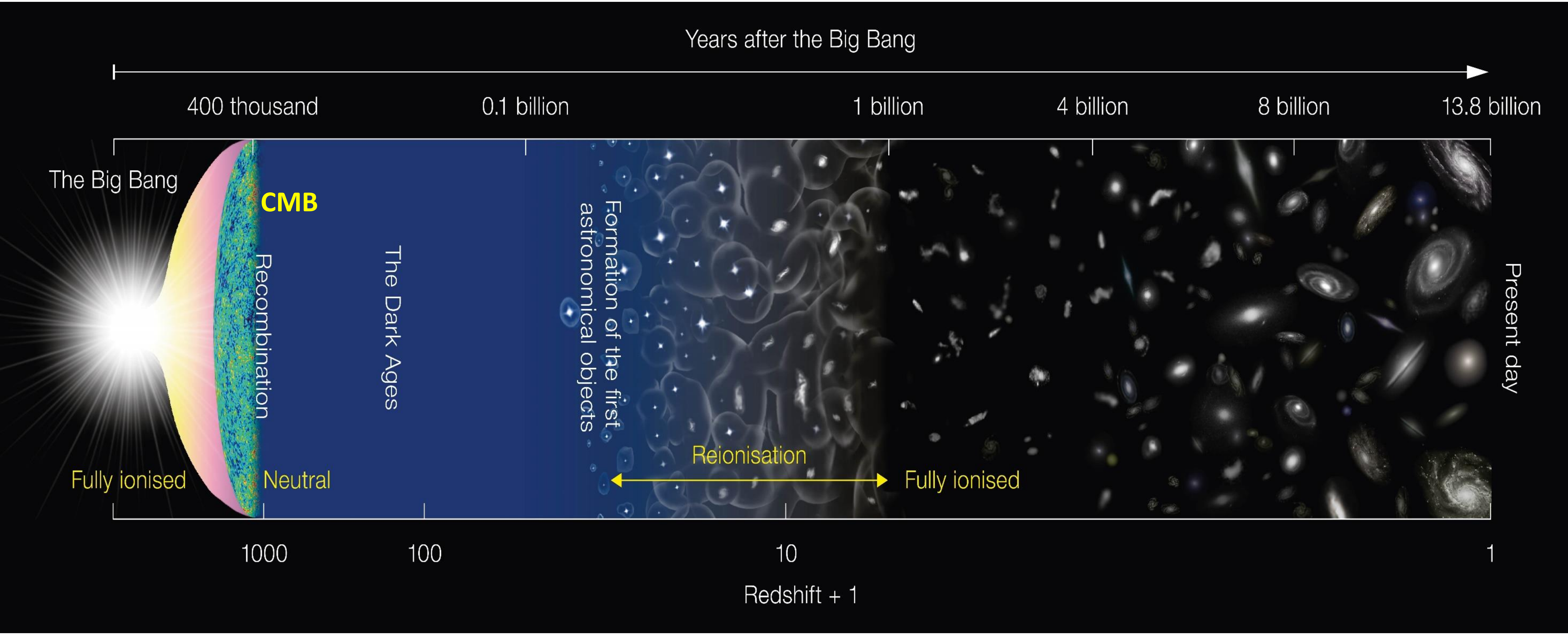
Inflation stretches physical scales

out the Hubble radius (in yellow)

which remains fixed during inflation

We shall consider

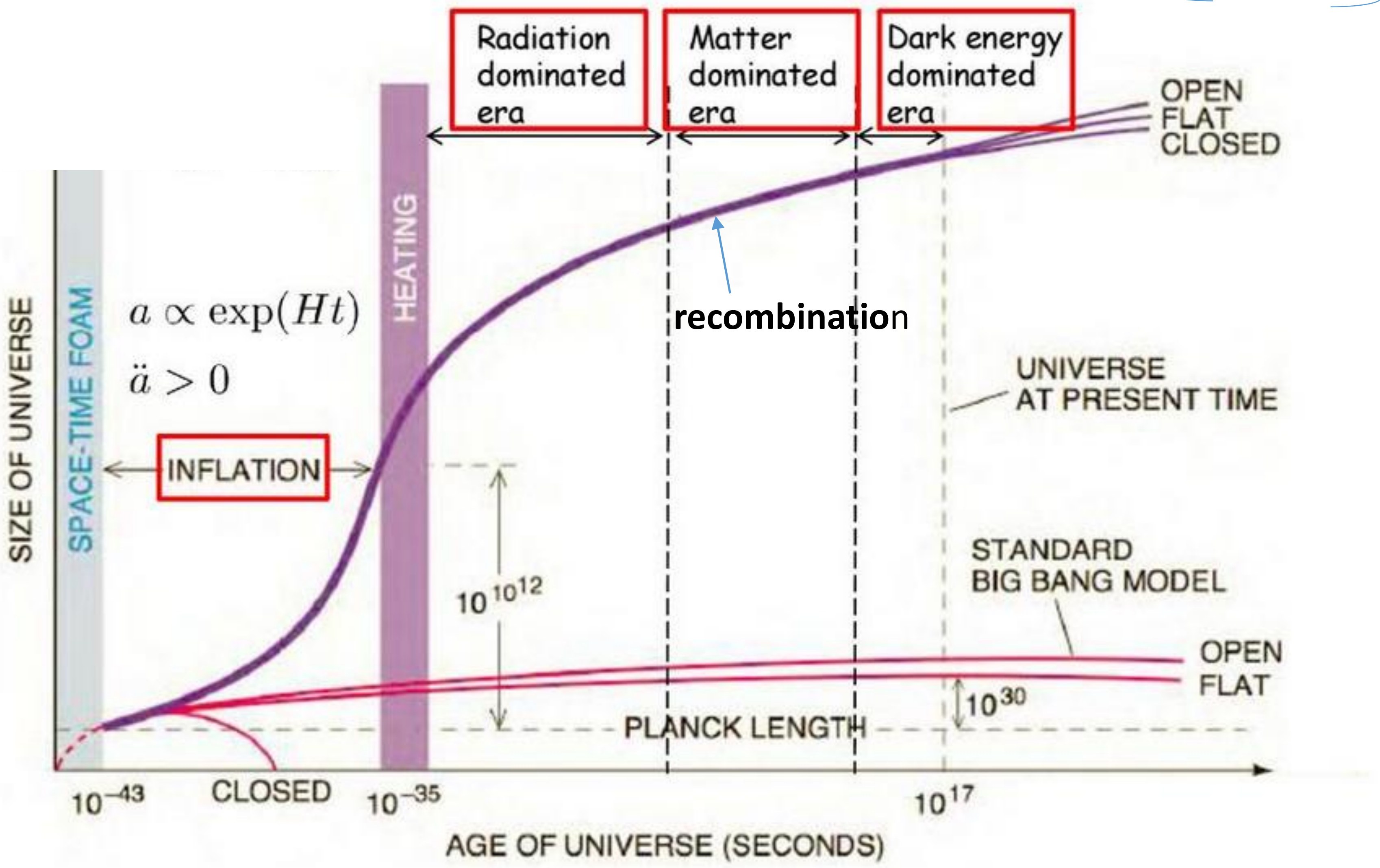
scalar and **tensor modes** (→ primordial gravitational waves)



Years after the Big Bang
400 thousand
0.1 billion
1 billion
4 billion
8 billion
13.8 billion
The Big Bang
CMB
Recombination
The Dark Ages
Formation of the first astronomical objects
Present day
Fully ionised
Neutral
Reionisation
Fully ionised
1000
100
10
1
Redshift + 1

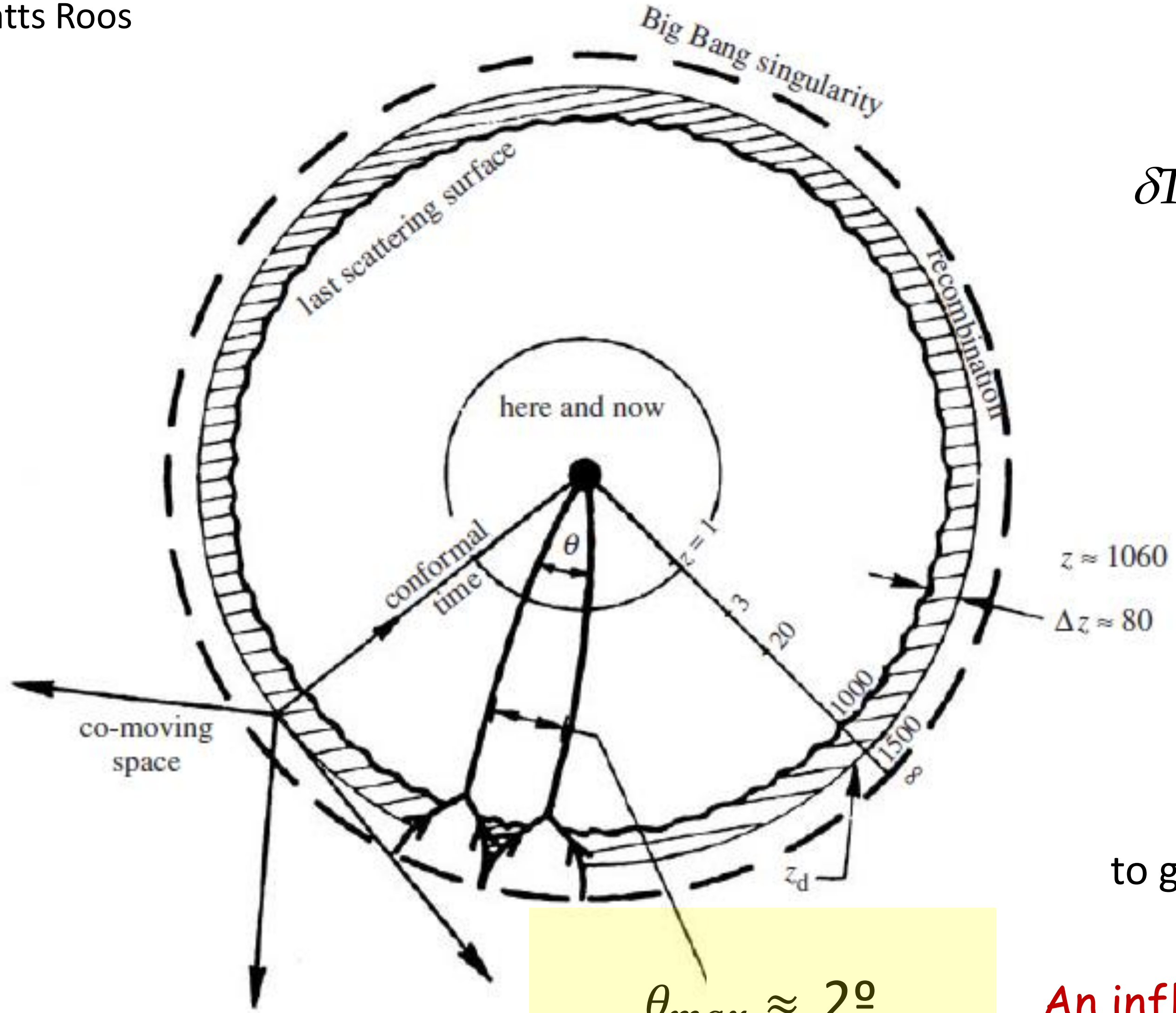
Inflation is a phase of accelerated expansion taking place in the very early Universe. It solves the fine tuning puzzles of the standard model of cosmology

horizon, flatness, monopole problems



Cosmic Microwave Background: maximum angular correlation

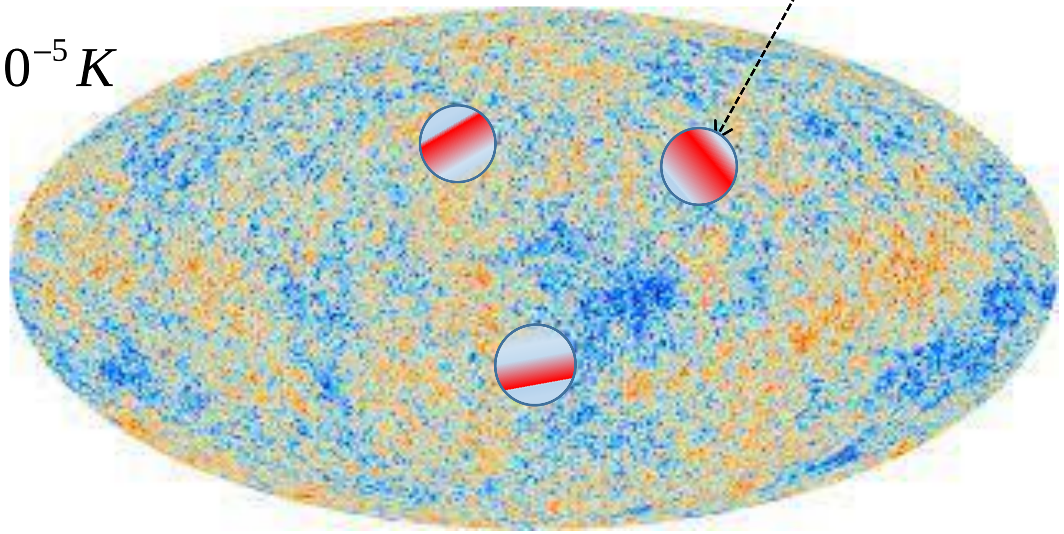
Image from: *Introduction to Cosmology*
Matts Roos



$\theta_{max} \approx 2^{\circ}$

expected “pixel” size of temperature anisotropies in the CMB **without inflation**

$\delta T \approx 10^{-5} K$



Horizon problem

N-point angular correlation functions provide a tool

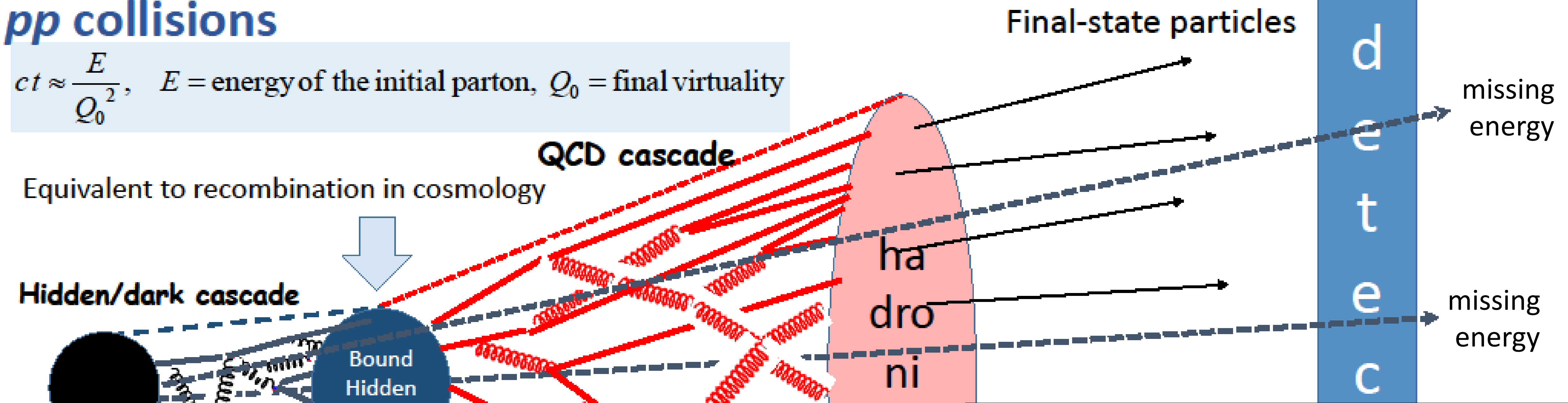
to get rich information from the original temperature rawdata

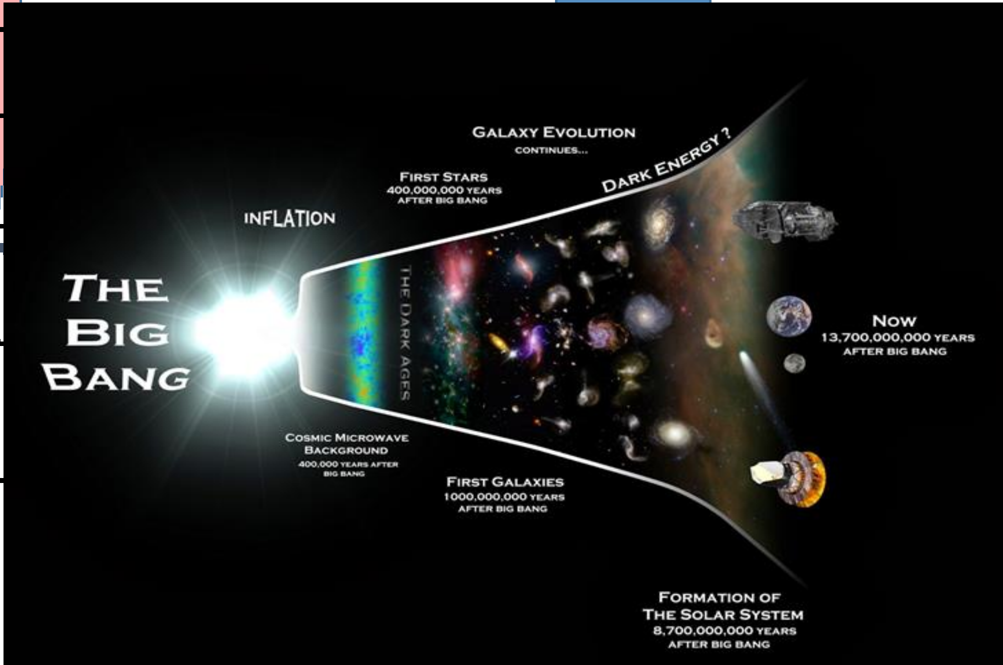
An inflationary epoch in the very early universe is required

Analogy with high-energy collisions ("artistic" view)

pp collisions

$ct \approx \frac{E}{Q_0^2}$, E = energy of the initial parton, Q_0 = final virtuality





Not to scale

M.A.S.L. and E. Sarkisyan-Grinbaum
Phys.Rev.D 102 (2020) 3, 035013 arXiv:2006.06569

Correlation function vs power spectrum

The information contained in the **angular power spectrum** is basically the same as in the **correlation function** but the latter highlights the behaviour at large angles (small ℓ)

$$C(\cos\theta) \equiv \langle \delta T(\vec{n}_1)\, \delta T(\vec{n}_2) \rangle = \frac{1}{4\pi} \sum_{\ell=2}^{\infty} (2\ell+1)\, C_\ell\, P_\ell(\cos\theta)$$

$$\cos\theta = \vec{n}_1 \cdot \vec{n}_2$$

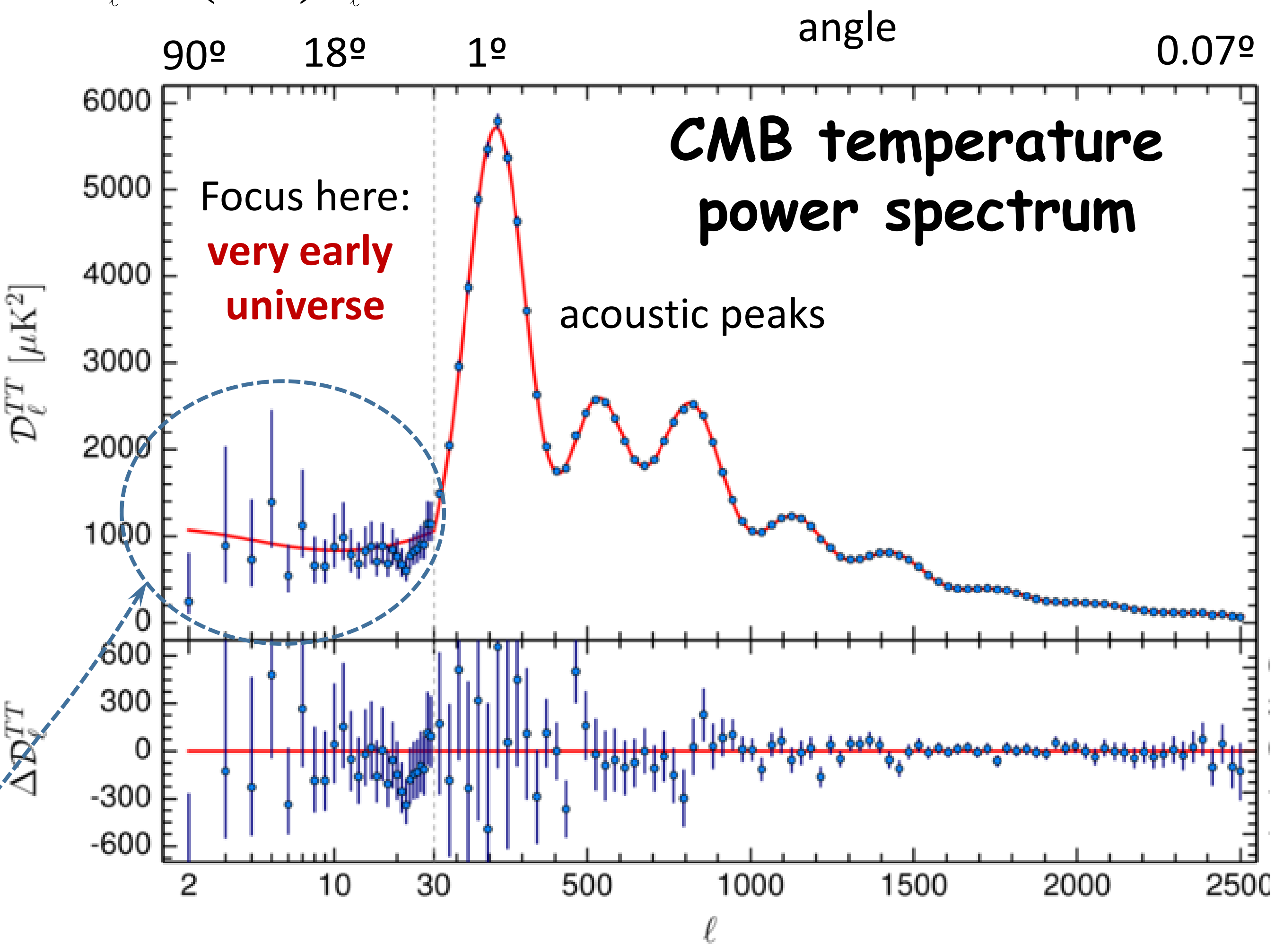
Power-law spectrum and assuming $n_s \approx 1$

$$C_\ell \propto \int_0^\infty dk\; k^{n_s-2} j_\ell^2(k r(t_d)) \;\propto \int_0^\infty \frac{j_\ell^2(u)}{u}\, du$$

Spherical Bessel function $\qquad u = k r_d$

r_d comoving distance to LSS

$$D_\ell = \ell(\ell+1) C_\ell / 2\pi$$



$$C_\ell = \frac{6}{\ell(\ell+1)} C_2 \qquad \ell \leq 30$$

Sachs-Wolfe plateau

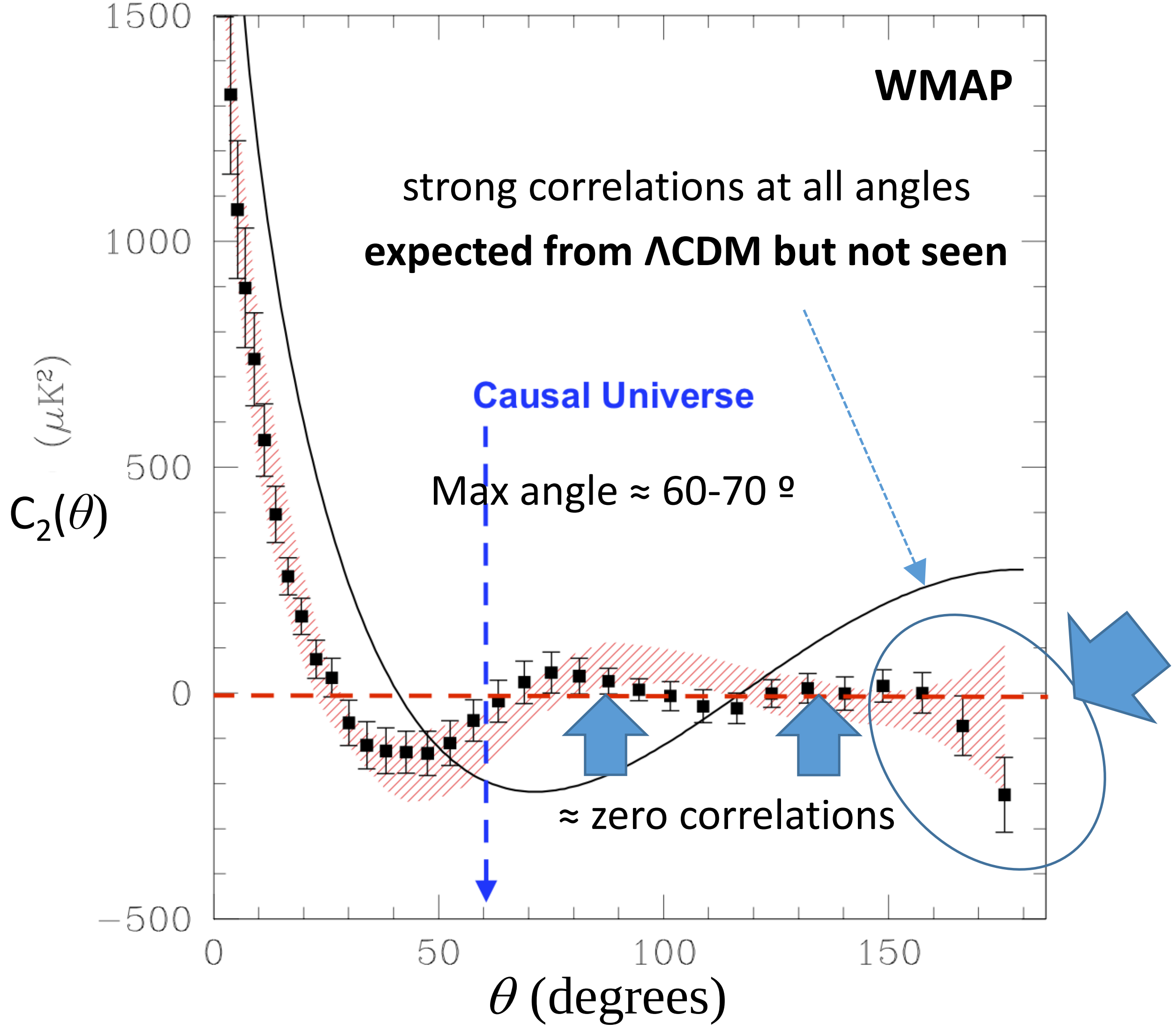
$$\ell(\ell+1)\, C_\ell = \text{constant}$$

Significant deviations!

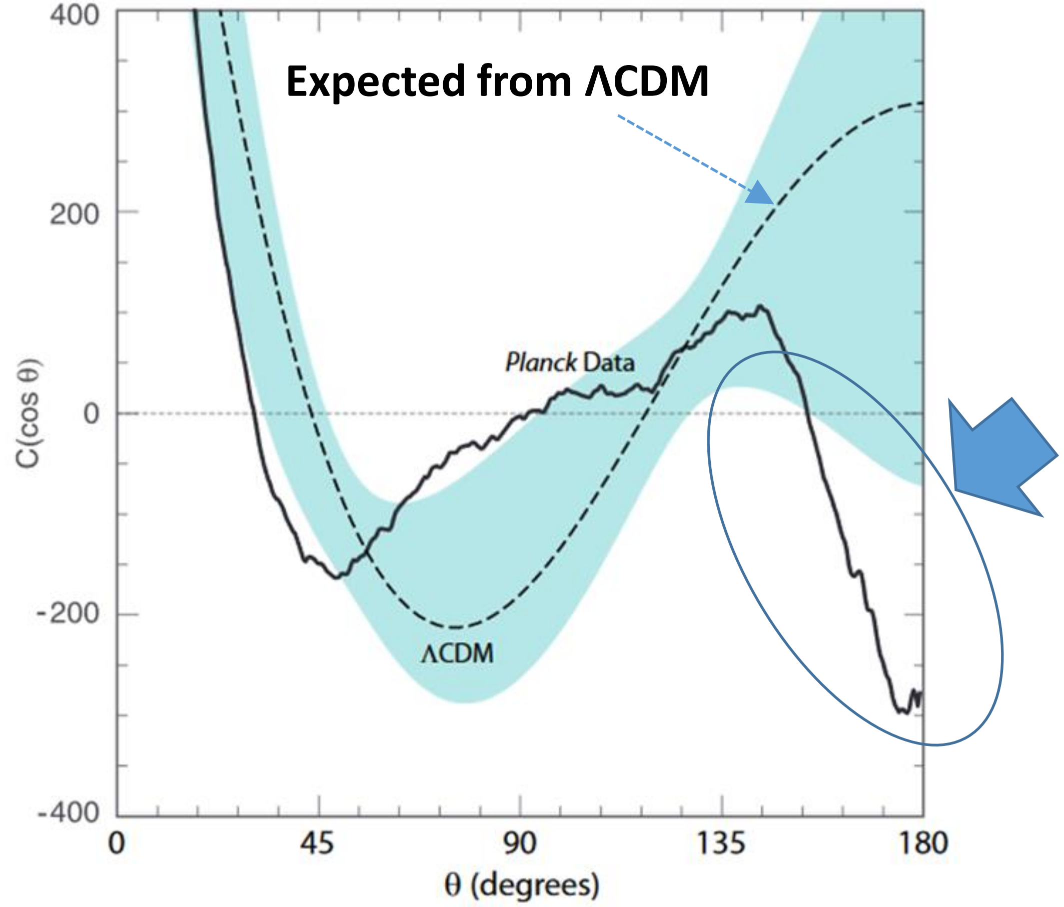
the lower limit of the integral will be soon modified becoming different from zero!!!

Unexpected **lack of large angle** (> 60-70º) **2-point correlations** in the CMB observed by COBE, WMAP & Planck mission

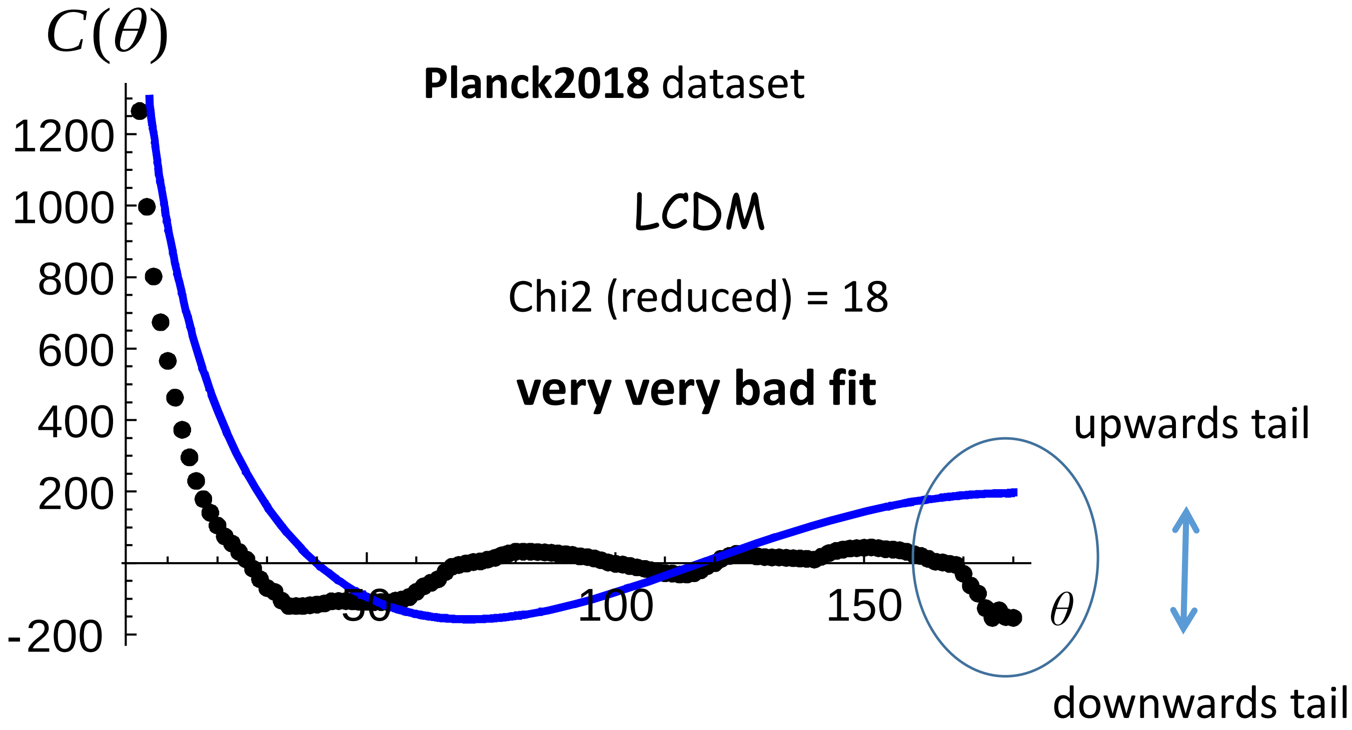
HOWEVER

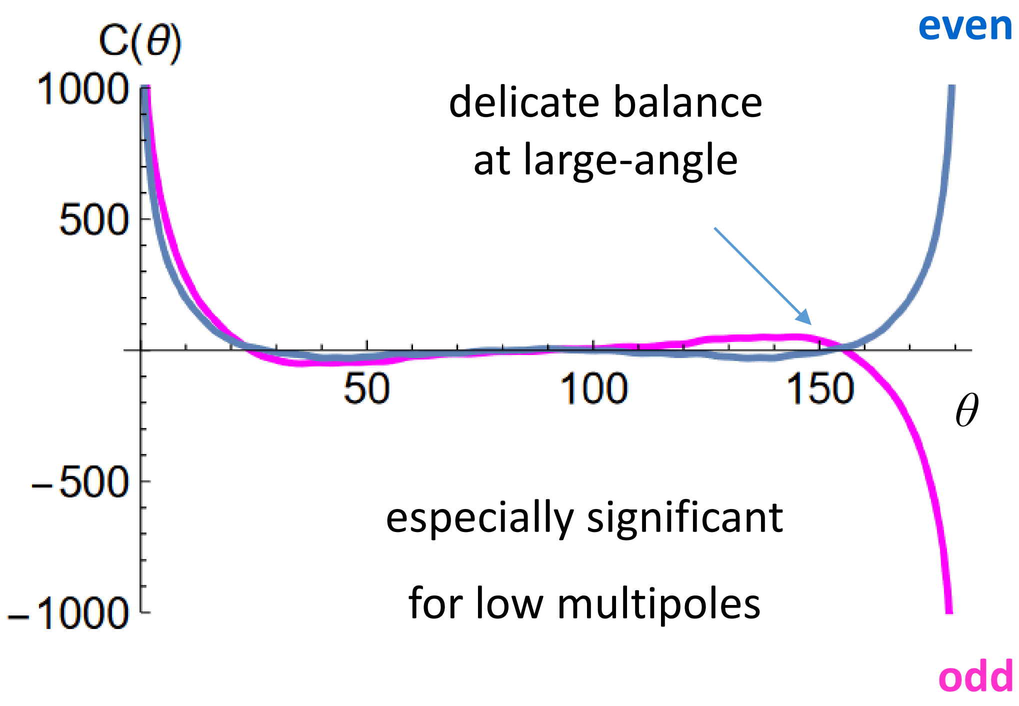


Two-point correlation function of measured CMB temperature fluctuations in **Planck2015** dataset



Next let us examine 2-point correlations in more detail using Planck 2018 data





An (even small) odd-even **imbalance** in the Legendre polynomials leads at large angles to

upwards tail (**even-parity dominance**)

downwards tail (**odd-parity dominance**)

$$C(\theta) = C_{\rm even}(\theta) + C_{\rm odd}(\theta) = \frac{1}{4\pi}\sum_{\ell_{\rm even}}(2\ell+1)\,C_\ell\,P_\ell(\cos\theta) + \frac{1}{4\pi}\sum_{\ell_{\rm odd}}(2\ell+1)\,C_\ell\,P_\ell(\cos\theta).$$

Introducing a single infrared cutoff k_{min} into the scalar power spectrum

original proposal

Melia & Lopez-Corredoira: arXiv: 1712.07847

Astronomy & Astrophysics, Volume 610 (2018) A87

$$C_\ell \propto \int_{k_{\min}}^{\infty} dk\, k^{n_s-2} j_\ell^2\big(kr(t_d)\big) \propto \int_{u_{\min}}^{\infty} \frac{j_\ell^2(u)}{u}\, du$$

$$\text{If } k_{\min} = 0 \rightarrow C_\ell \propto \frac{1}{\ell(\ell+1)} \quad \ell \leq 20$$

t_d time at decoupling

$r(t_d)$: commoving distance to the LSS

$$k_{\min} = \frac{2\pi}{\lambda_{\max}} a(t_d) \rightarrow u_{\min} = \frac{2\pi}{\lambda_{\max}} a(t_d)\, r(t_d) \rightarrow \theta_{\max} = \frac{2\pi}{u_{\min}} \rightarrow u_{\min} \neq 0$$

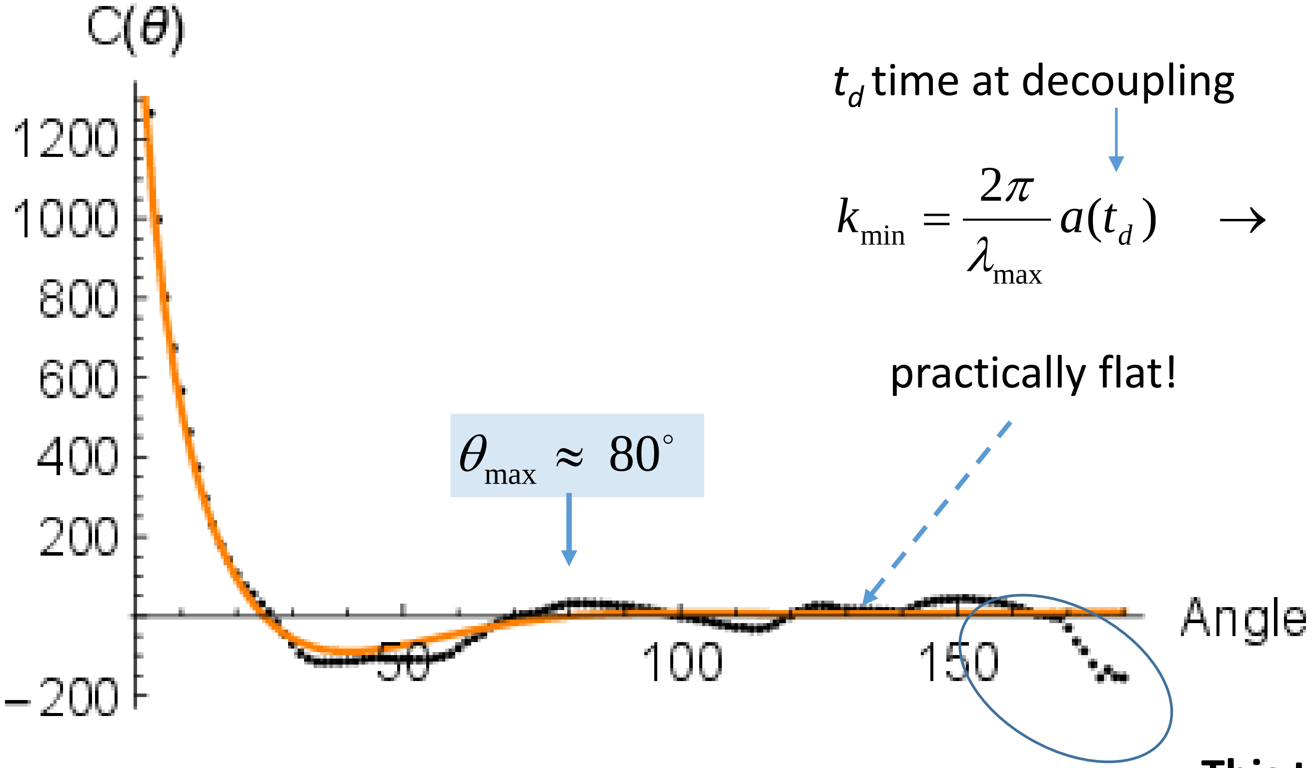
$$k_{\min} = \frac{u_{\min}}{r(t_d)}$$

$$u_{\min} = 4.5 \pm 0.5$$

$$\theta_{\max} \approx 80^\circ$$

$$k_{\min} \approx 3\times10^{-4}\,\text{Mpc}^{-1}$$

Obtained from a best fit to Planck datapoints



M.A.S.L, F.Melia, M.López-Corredoira and N.Sanchis-Gual
Astron.Astrophys. 660 (2022) A121 [arXiv:2202.10987]

This tail is not reproduced at all!

related to parity-imbalance

Is our Universe (parity) odd?

Nature is parity violating e.g. in the electroweak sector

of the Standard Model of particles and interactions

We restrict our discussion to the question of a **possible odd-even parity imbalance** in the

2-point angular correlation function of the CMB

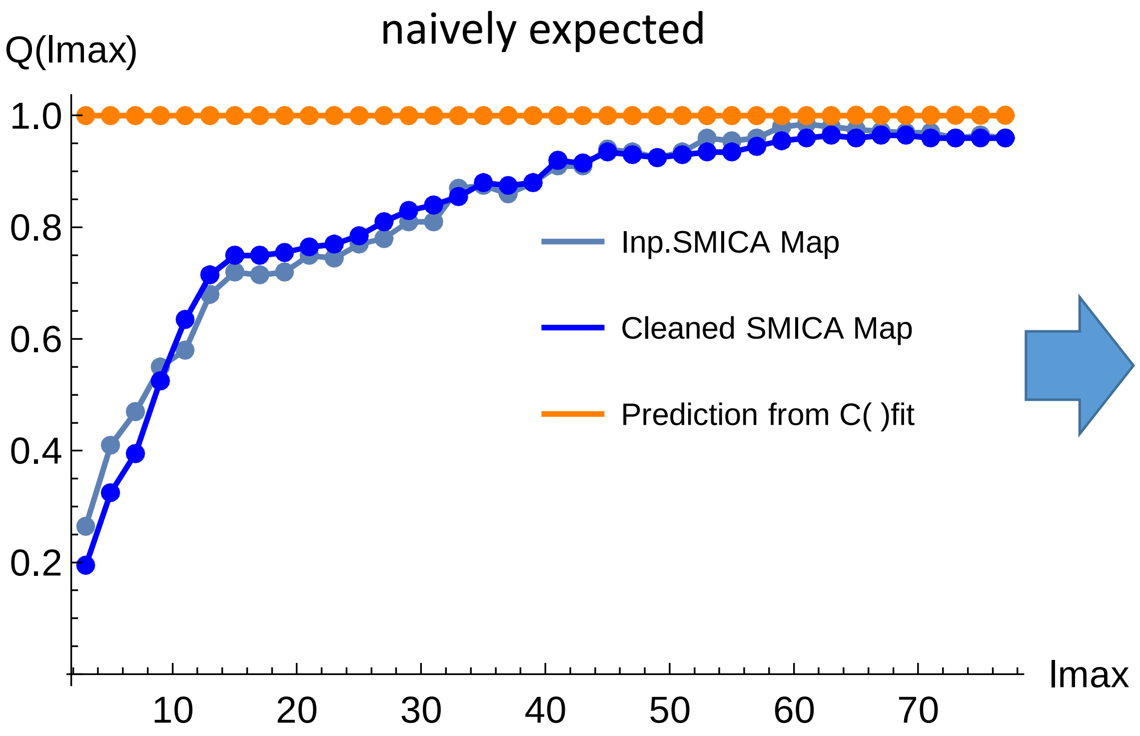
$$C(\cos\theta) \equiv \langle \delta T(\vec{n}_1)\, \delta T(\vec{n}_2) \rangle = \frac{1}{4\pi} \sum_{\ell=2}^{\infty} (2\ell+1)\, C_\ell\, P_\ell(\cos\theta)$$

determined using a cosmological model + fit to data

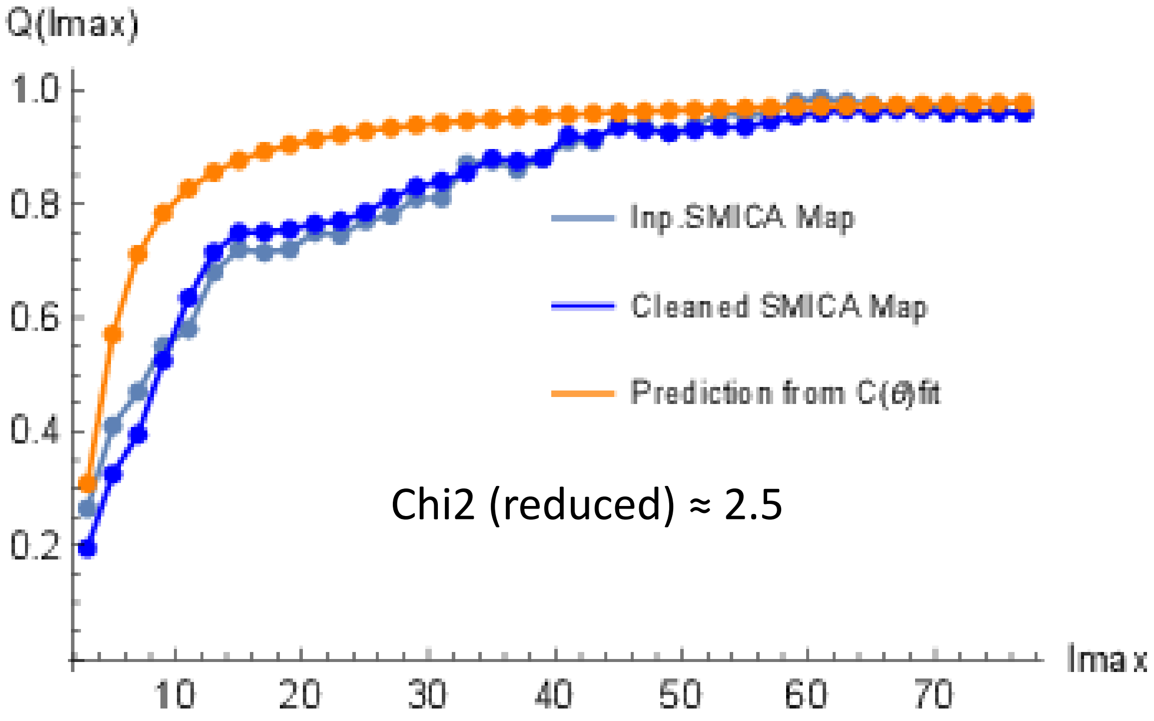
There are other anomalies/tensions of the Cosmological SM not considered in this talk

Parity asymmetry statistic

$$Q(\ell_{\max}) = \frac{2}{\ell_{\max}^{odd} - 1} \sum_{\ell=3}^{\ell_{\max}^{odd}} \frac{D_{\ell-1}}{D_\ell}, \; \ell_{\max} \geq 3 \quad \text{only odd integers}$$



Aluri & Jain, MNRAS 2012, 419, 3378



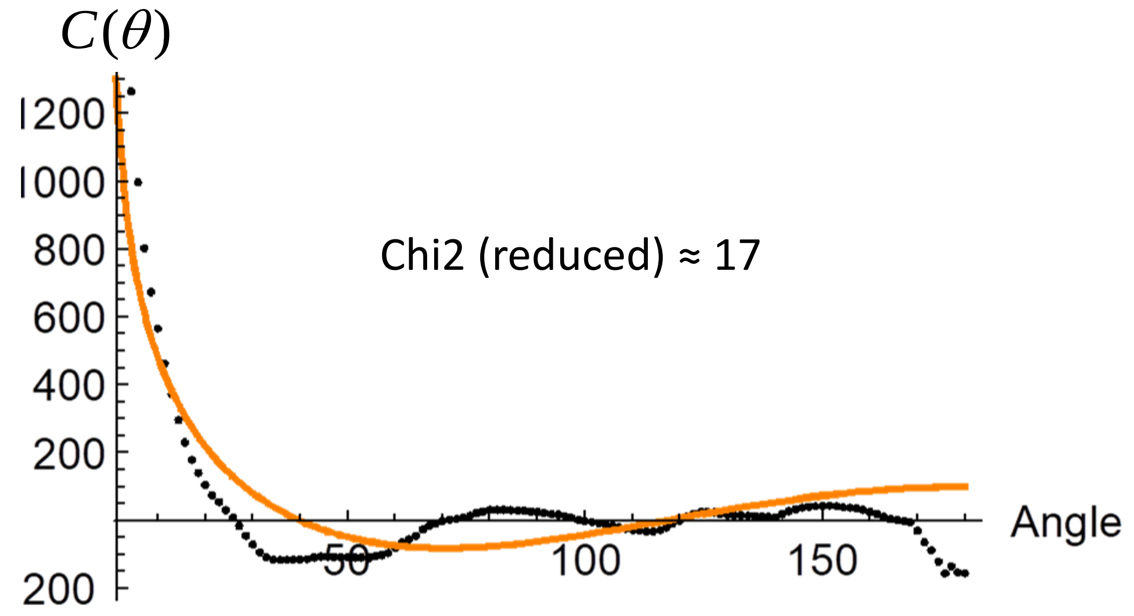
Notice that adding an infrared cutoff

into the scalar power spectrum

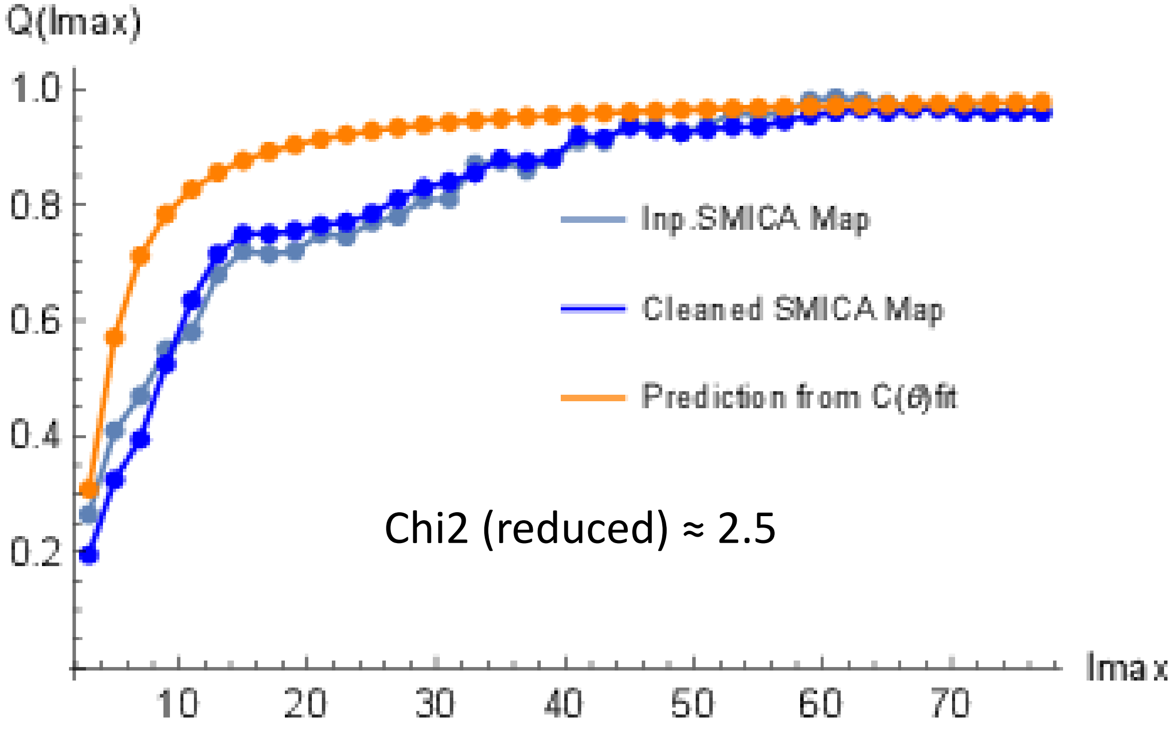
breaks parity balance

Improvement but

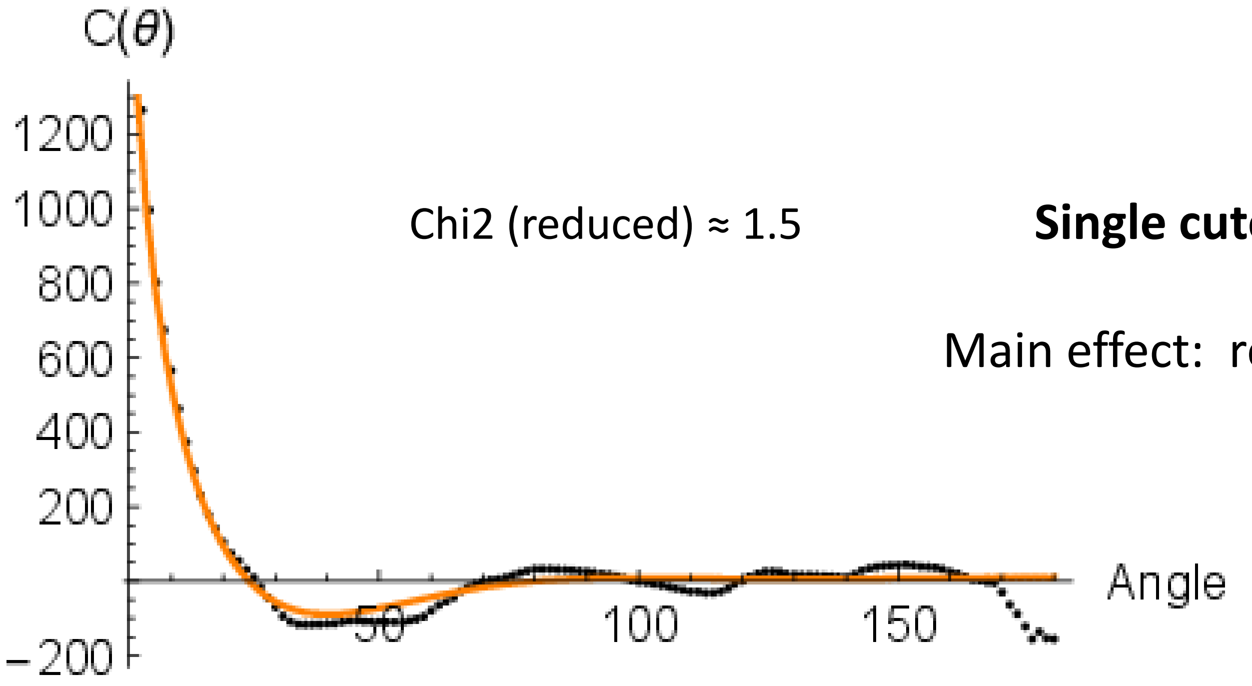
not really satisfactory yet



Chi2 (reduced) ≈ 17



Chi2 (reduced) ≈ 2.5



Chi2 (reduced) ≈ 1.5

Single cutoff in the scalar power spectrum

Main effect: reducing the quadrupole contribution
(like in an ellipsoidal universe)

rather modest improvements!

Next step: **two infrared cutoffs** instead of one

in the primordial power spectrum

affecting odd and even multipoles, respectively

M.A. Sanchis-Lozano, *Universe* 8 (2022) 8, 396 [arXiv:2205.13257]

M.A. Sanchis-Lozano and V. Sanz, *Phys.Rev.* D 109 (2024) 6, 063529 [arXiv:2312.02740]

Assumption of a KK extra-dimension in the very early universe (GUT era) leads yo a set of two infrared cutoffs for both scalar and tensor modes

Dirichlet and Neumann boundary conditions when applied on an extra spatial dimension: lead to the following ratio of infrared cutoffs in the scalar and tensor power spectra

$$\frac{u_{\rm min}^{\rm even}}{u_{\rm min}^{\rm odd}} = \frac{k_{\rm min}^{\rm even}}{k_{\rm min}^{\rm odd}} = 2$$

"magic number"

for both scalar & tensor modes with $u^{even/odd}(T) = 2u^{\,even/odd}(S)$

$k_{\rm min}{}^{\rm even/odd} \approx$ few $10^{-4}\,{\rm Mpc}^{-1} \rightarrow$ $k_{\rm min}{}^{\rm even/odd}/{\rm a}(t_{\rm extra}) \approx 10^{14\text{-}16}\,{\rm GeV}$

physical

$$C(\theta) = C_{\rm even}(\theta) + C_{\rm odd}(\theta) = \frac{1}{4\pi}\sum_{\ell_{\rm even}}(2\ell+1)\,C_\ell\,P_\ell(\cos\theta) + \frac{1}{4\pi}\sum_{\ell_{\rm odd}}(2\ell+1)\,C_\ell\,P_\ell(\cos\theta).$$

Temperature scalar multipole coefficients

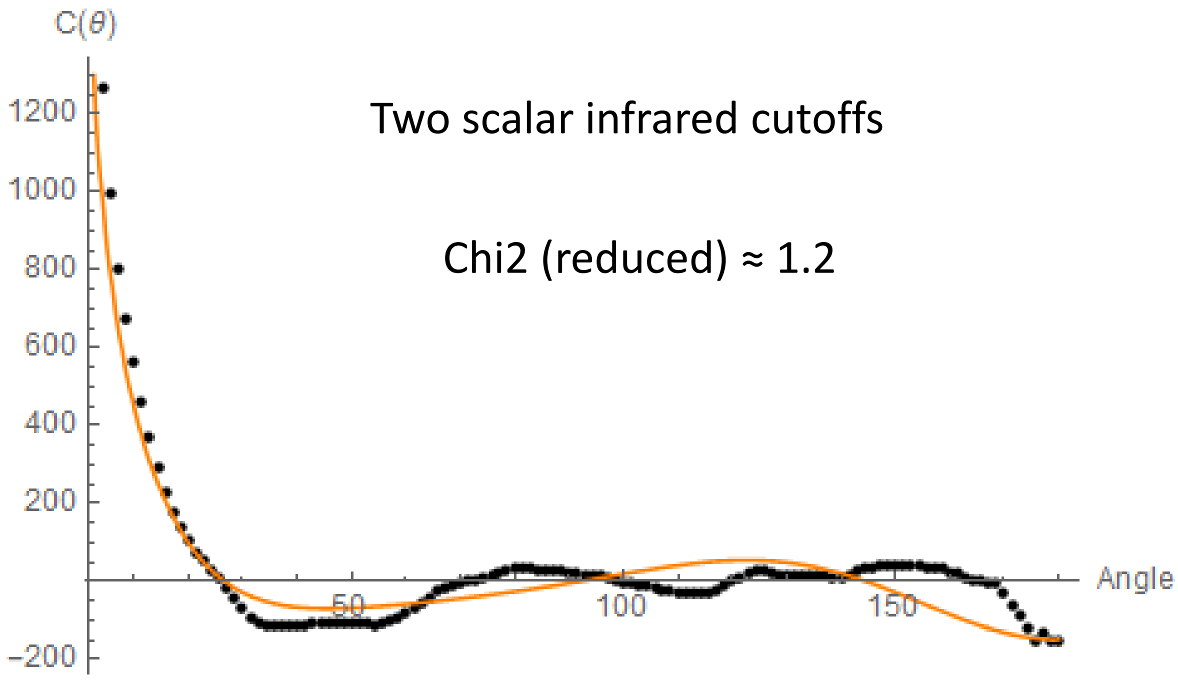
$$C_{\ell_{\rm even/odd}} = N\int_{u_{\rm min}^{\rm even/odd}}^{\infty} du\,\frac{j_\ell^2(u)}{u}$$

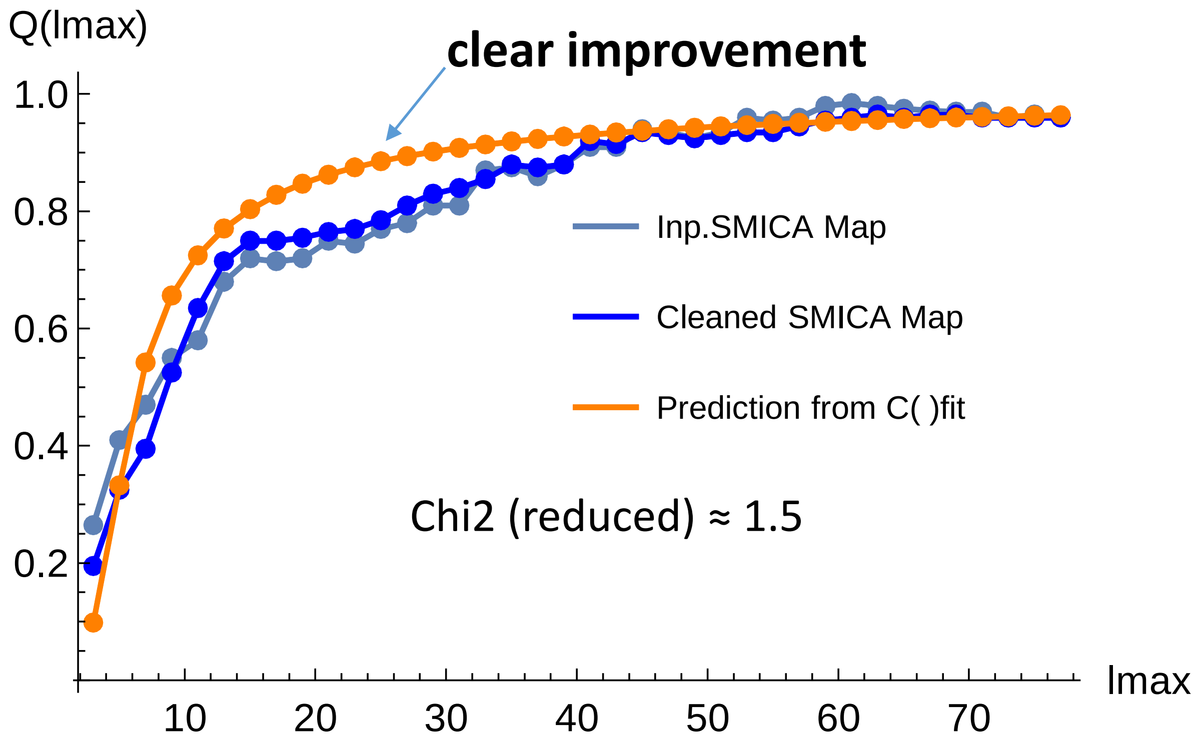
$$u_{\rm min}^{even} = 2\,u_{\rm min}^{odd}$$

oboe

"cosmic duetto"

clarinet





M.A. Sanchis-Lozano, *Universe* 8 (2022) 8, 396, 2205.13257

$$u_{\rm min}^{\rm odd} = 2.67 \pm 0.31 \ \ ; \ \ u_{\rm min}^{\rm even} = 5.34 \pm 0.62 \, .$$

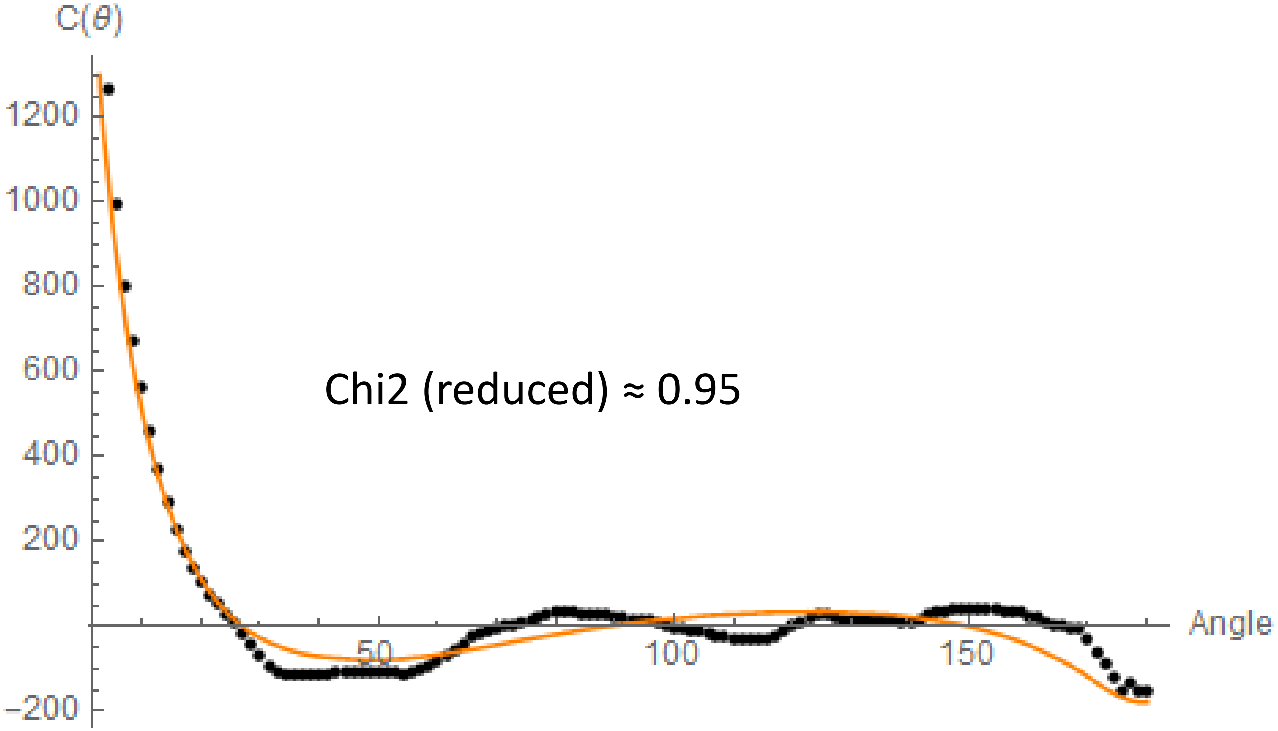
$$C_{\ell_{\rm even/odd}} = N \int_{u_{\rm min}^{\rm even/odd}}^{\infty} du \, \frac{j_\ell^2(u)}{u}$$

$$\frac{u_{\rm min}^{\rm even}}{u_{\rm min}^{\rm odd}} = \frac{k_{\rm min}^{\rm even}}{k_{\rm min}^{\rm odd}} = \mathbf{2}$$

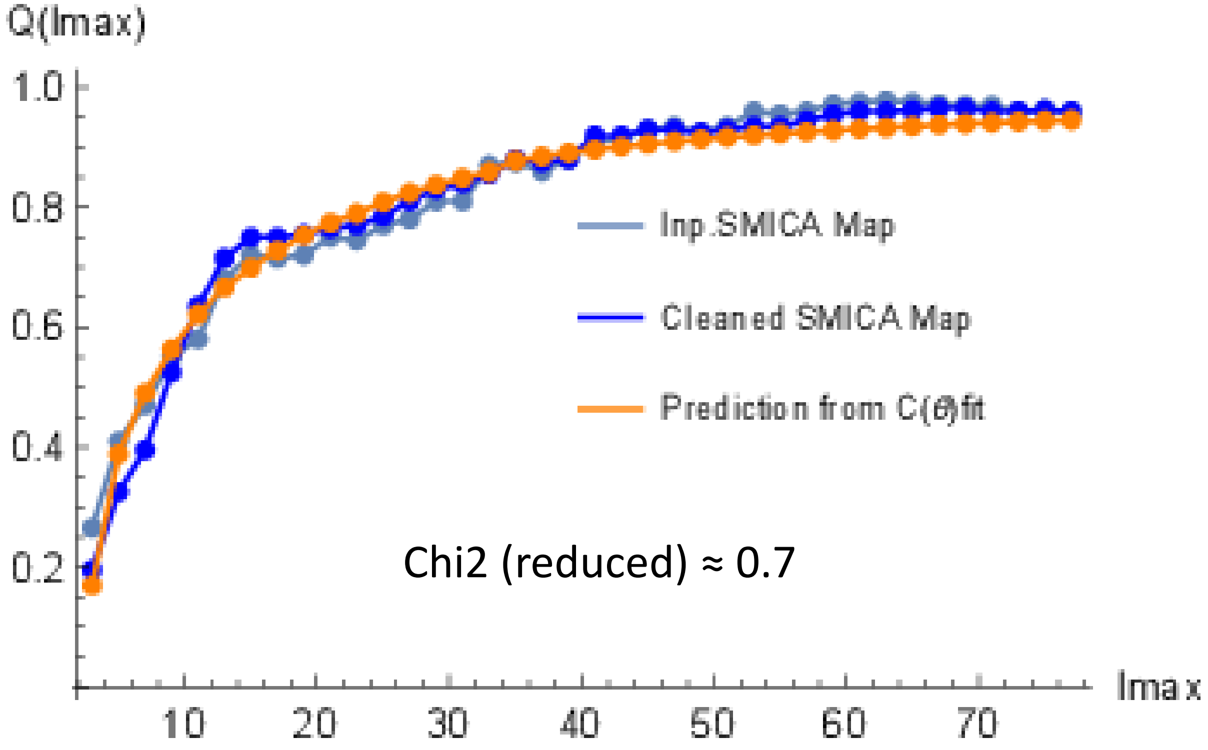
Scalar modes: Sachs-Wolfe effect

(remains fixed in our fits)

Including Primordial Gravitational Waves



Chi2 (reduced) ≈ 0.95



Chi2 (reduced) ≈ 0.7

remember: $uev^{en/odd}(T) = 2u^{\,even/odd}(S)$

Tensor mode multipole coefficients

$$C^{\mathrm{T}}_{\ell_{even/odd}} = N^T\ (\ell-1)\ell(\ell+1)(\ell+2)\ \int_{u_{min}^{even/odd}(T)}^{\infty} du\ \frac{j_\ell^2(u)}{u^5}$$

only one extra fit parameter: N^T !

constrained by the tensor-to-scalar ratio *r*

Mukhanov, V. F. , Physical Foundations of Cosmology; Cambridge University Press: Cambridge, UK, 2005.

Excellent fits!

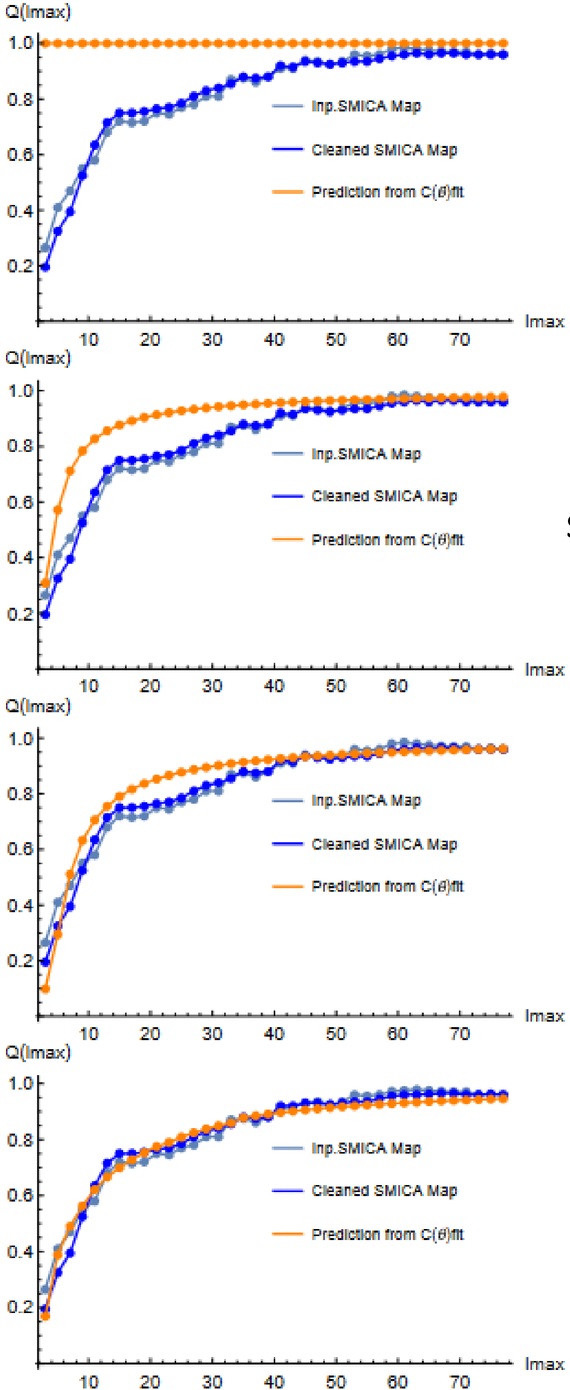
overview

scalar modes only

no cutoff

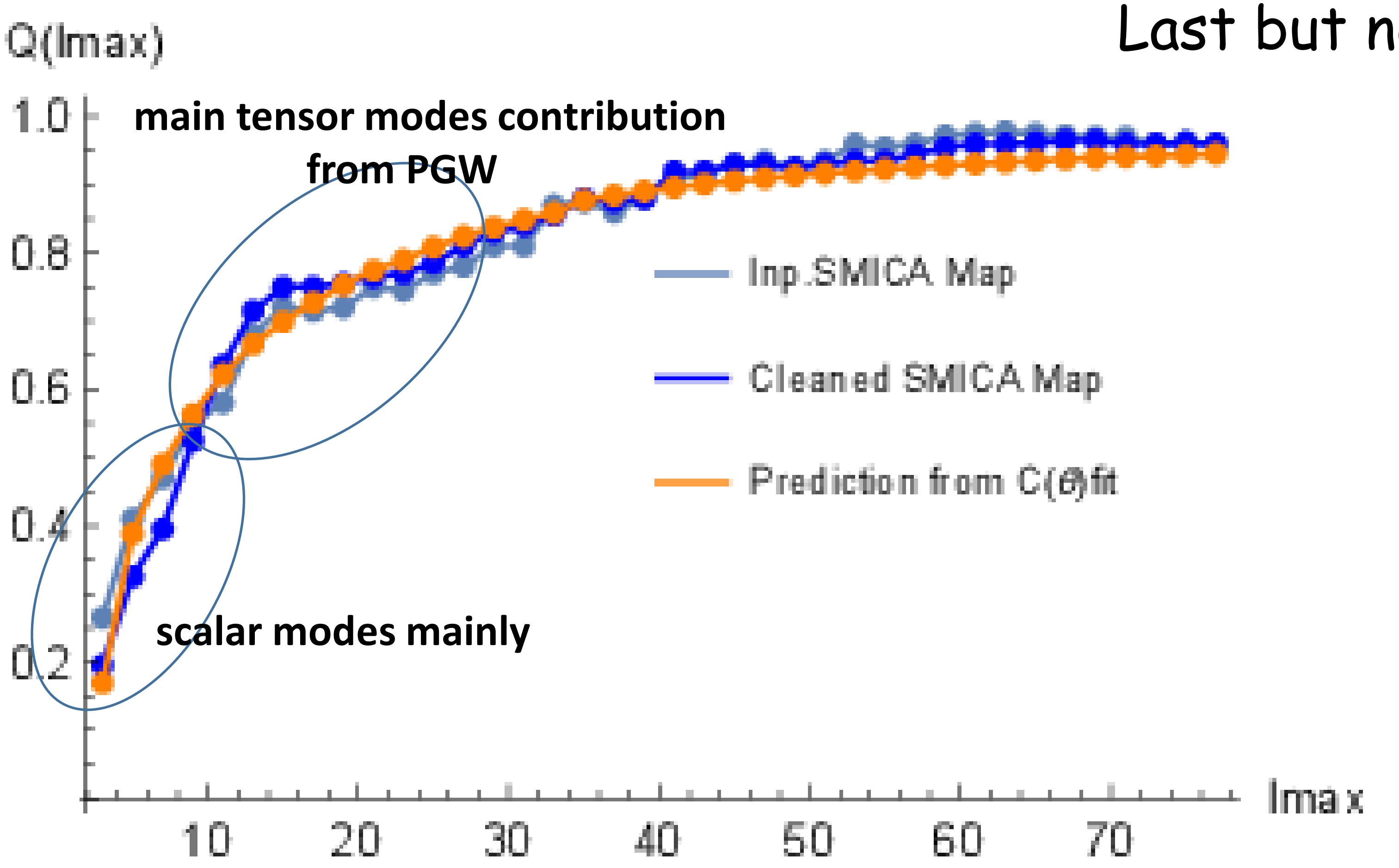
single scalar cutoff

two scalar cutoffs



+ tensor modes

Last but not least remark



Note that the effect of a lower cut-off u_{min} becomes noticeable at $\ell \gtrsim u_{min}$

Final remark:
the observed parity imbalance in angular correlations can be associated with the detection of PGW

Checking some inflation parameters obtained from our fits:

$$r \approx 0.68 \left\langle \frac{C_\ell^T}{C_\ell^S} \right\rangle_{10 \le \ell \le 30} \approx 0.027 \pm 0.007$$

Ratio of tensor-to-scalar power spectra

Uncertainties due to theoretical approximations and modelling dependence are not included

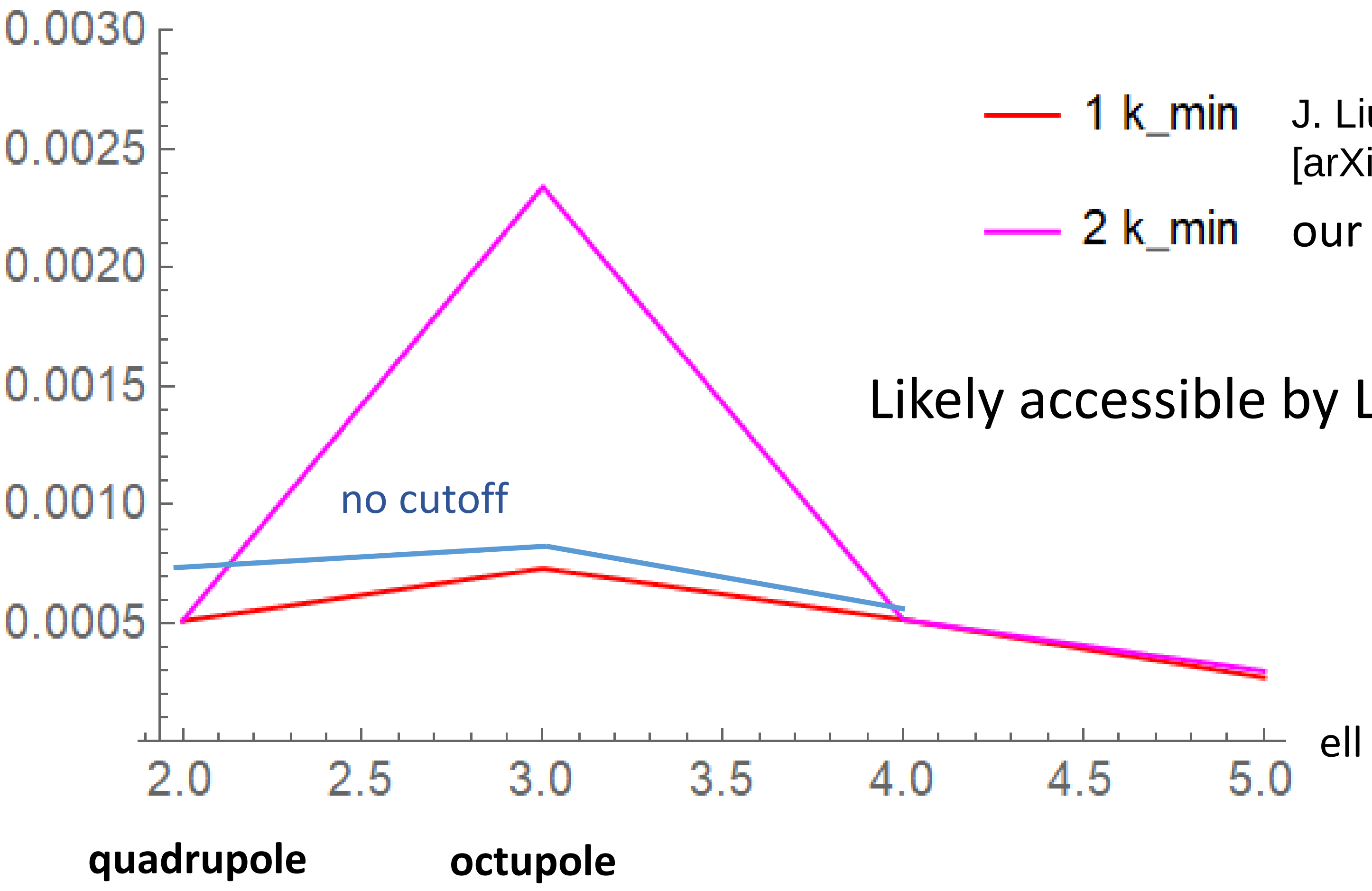
consistency relation:

$$r = 16\varepsilon \quad \rightarrow \quad \varepsilon \approx 0.0017$$

BB correlations

Very preliminary

$D_{\ell\ell}{}^{BB} = (1/2\pi)\, \ell\, (\ell+1)\, C_{\ell\ell}{}^{BB}\, (\mu K^2)$



J. Liu and F. Melia, *Phys.Lett.B* 853 (2024) 138645 [arXiv:2404.08170]

our result

Likely accessible by LiteBIRD misión!

Conclusions

Anomalies/tensions from astrophysical/cosmological data somewhat question the Standard Cosmological Model

In our approach the odd-parity preference (ultimately breaking isotropy from the cosmological principle)

observed in angular correlations of CMB by COBE, WMAP and *Planck* missions leads to two infrared cut-offs

in the scalar power spectrum $\rightarrow \frac{u_{\min}^{\text{even}}}{u_{\min}^{\text{odd}}} = \frac{k_{\min}^{\text{even}}}{k_{\min}^{\text{odd}}} \approx 2$

This phenomenological result can be theoretically motivated by Dirichlet/Neumann boundary conditions

imposed on a KK extra-dimension of the early universe affecting primordial scalar and tensor modes

Once primordial tensor modes from PGW are incorporated into the analysis of the temperature correlations

the fits of the correlation function $C(\vartheta)$ and the statistic $Q(\ell_{\max})$ improve significantly

Further checks using polarization of the CMB should be applied, e.g. looking at the ratio of

quadrupole and octupole modes in the BB power spectrum might be a clear signal of PWG

Muito obrigado/many thanks!!!

BACK-UP

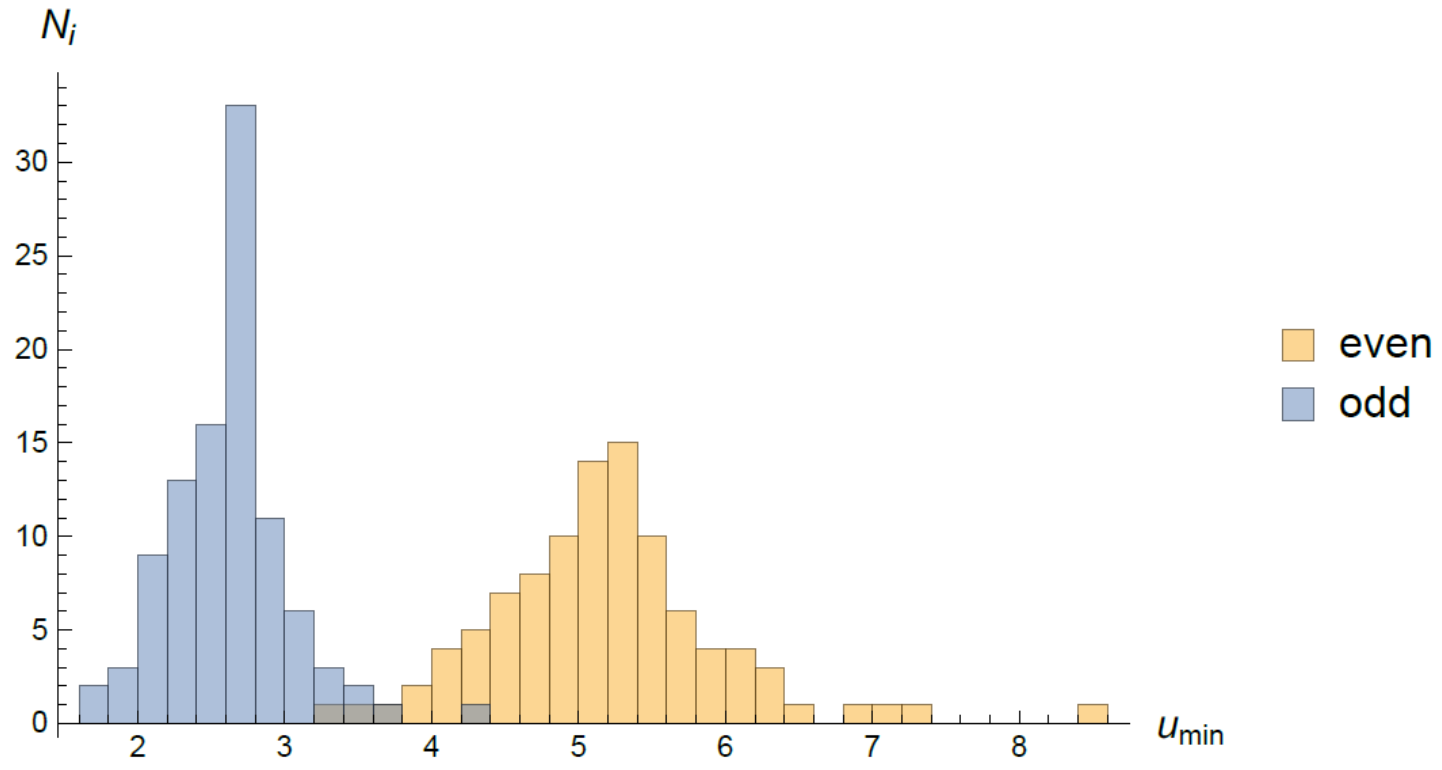


Figure 4. Histogram of $u^{\text{odd}}_{\min,i}$ (**left**) and $u^{\text{even}}_{\min,i}$ (**right**), both showing approximate Gaussian shapes. Let us point out that the condition $u^{\text{even}}_{\min,i} = 2u^{\text{odd}}_{\min,i}$ was required throughout the data analysis.

TWO INFRARED CUT-OFFs

TWO different BOUNDARY CONDITIONS

based on causality

Periodic and **antiperiodic** boundary conditions

$$\psi(\varphi+2\pi) = \psi(\varphi) \qquad \lambda_{\max}^{even} = 2\pi R_h$$

$$\psi(\varphi+2\pi) = -\psi(\varphi) \rightarrow \psi(\varphi+4\pi) = \psi(\varphi) \qquad \lambda_{\max}^{even} = 4\pi R_h$$

The angular Fourier expansion of $\psi(\varphi)$ for the periodic condition reads:

$$\psi(\varphi) = \sum_{n\in\mathcal{Z}} \alpha_n e^{in\varphi}$$

INTEGERS

For the antiperiodic conditions, the Fourier expansion reads

$$\psi(\varphi) = \sum_{n\in\mathcal{Z}^+ + 1/2} \alpha_n e^{in\varphi},$$

HALF-INTEGERS

$$k_{\min}^{odd} = 2\pi a(t_d)/\lambda_{\max}^{odd}, \quad k_{\min}^{even} = 2\pi a(t_d)/\lambda_{\max}^{even}$$

$$\frac{u_{\min}^{even}}{u_{\min}^{odd}} = \frac{k_{\min}^{even}}{k_{\min}^{odd}} = 2$$

comoving scales

The angular Fourier expansion of $\psi(\varphi)$ for the periodic condition reads:

$$\psi(\varphi) = \sum_{n \in \mathcal{Z}} \alpha_n \, e^{in\varphi} \tag{15}$$

and for a real function,

$$\psi(\varphi) = 2 \sum_{n \in \mathcal{Z}^+} \text{Re}\, \alpha_n \, e^{in\varphi} \,, \tag{16}$$

so that only cos $(n\varphi)$ terms appear in the Fourier expansion.

Let us define now a correlation function as in [36]

$$\int_0^{2\pi} \psi(\varphi) \, \psi(\varphi + \Delta\varphi) \, \frac{d\varphi}{2\pi} \,. \tag{17}$$

For random Gaussian Fourier coefficients, if we define $\theta = \Delta\varphi/2$, one finds

$$C(\Delta\varphi) = 2 \sum_{n \in \mathcal{Z}^+} C_n \cos(n\Delta\varphi) \to C(\theta) = 4 \sum_{n \in \mathcal{Z}^+} C_n \cos^2(n\theta) - 2 \,, \tag{18}$$

with $C_n = \langle \alpha_n \alpha_n^* \rangle$ and $\theta \in [0, \pi]$ to be identified with the angle appearing as the argument of the two-point correlation function $C(\theta)$.

For the antiperiodic conditions, the Fourier expansion reads

$$\psi(\varphi) = \sum_{n \in \mathcal{Z}^+ + 1/2} \alpha_n \, e^{in\varphi} \,, \tag{19}$$

which guarantees that it changes sign when $\varphi \to \varphi + 2\pi$. Therefore,

$$C(\theta) = 4 \sum_{n \in \mathcal{Z}^+ + 1/2} C_n \cos^2(n\theta) - 2. \tag{20}$$