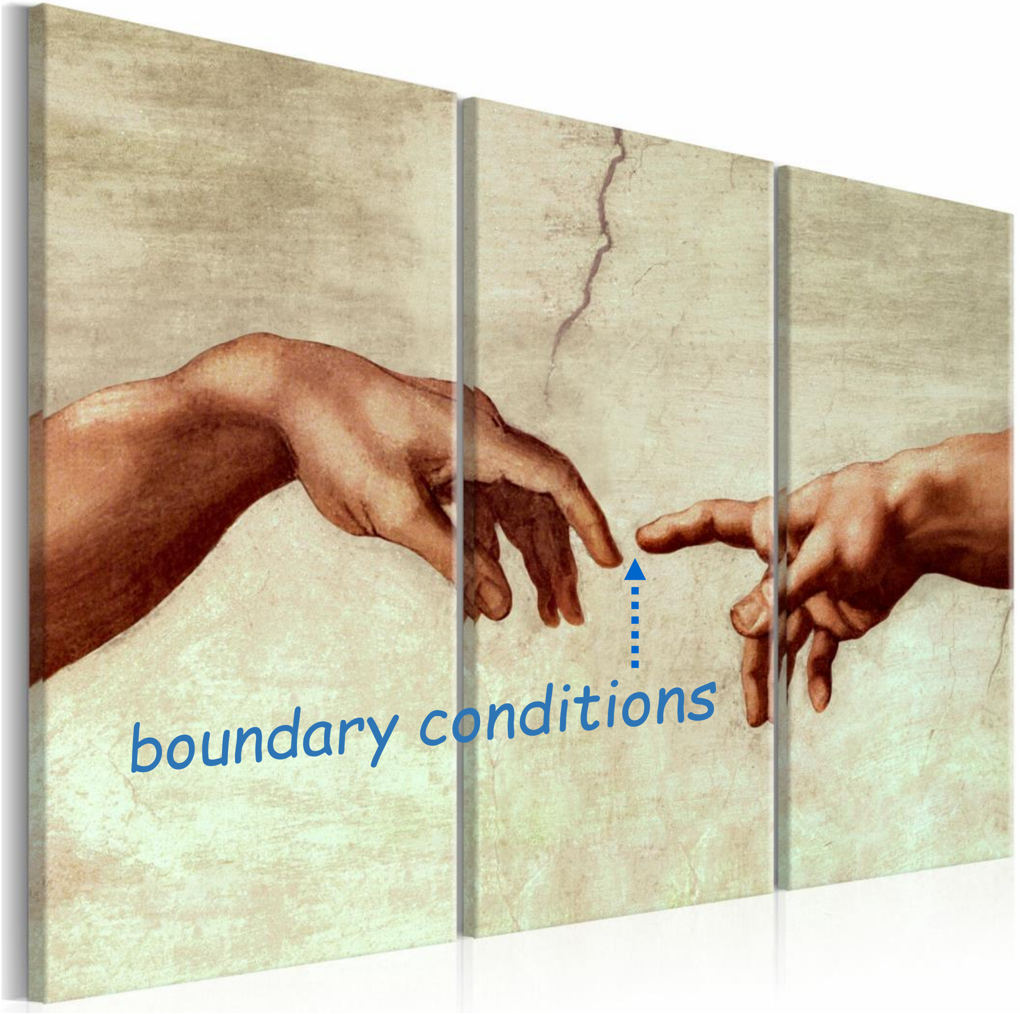
Probing the topology of the early universe using CMB temperature and polarization anisotropies



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CPAN days

Valencia 19-21 November, 2025

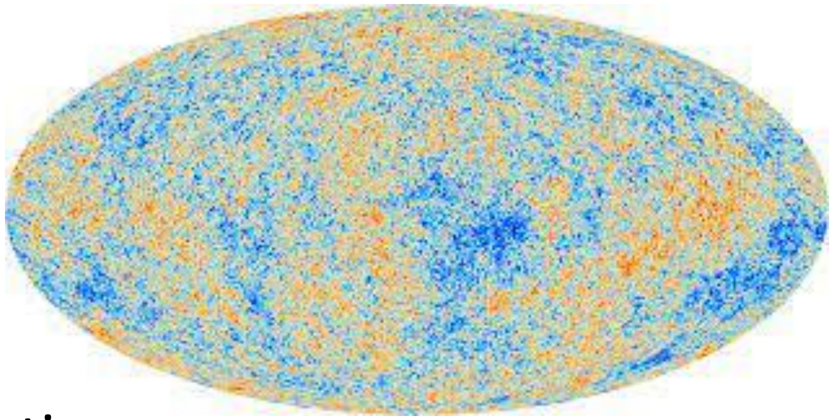
What we want

To explore the very early universe by studying the Cosmic Microwave Background (CMB)

searching for possible new physics at the GUT scale

More specifically

Temperature and polarization anisotropies stemming from



quantum perturbations of the *inflaton* field and *metric* fluctuations

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

How?

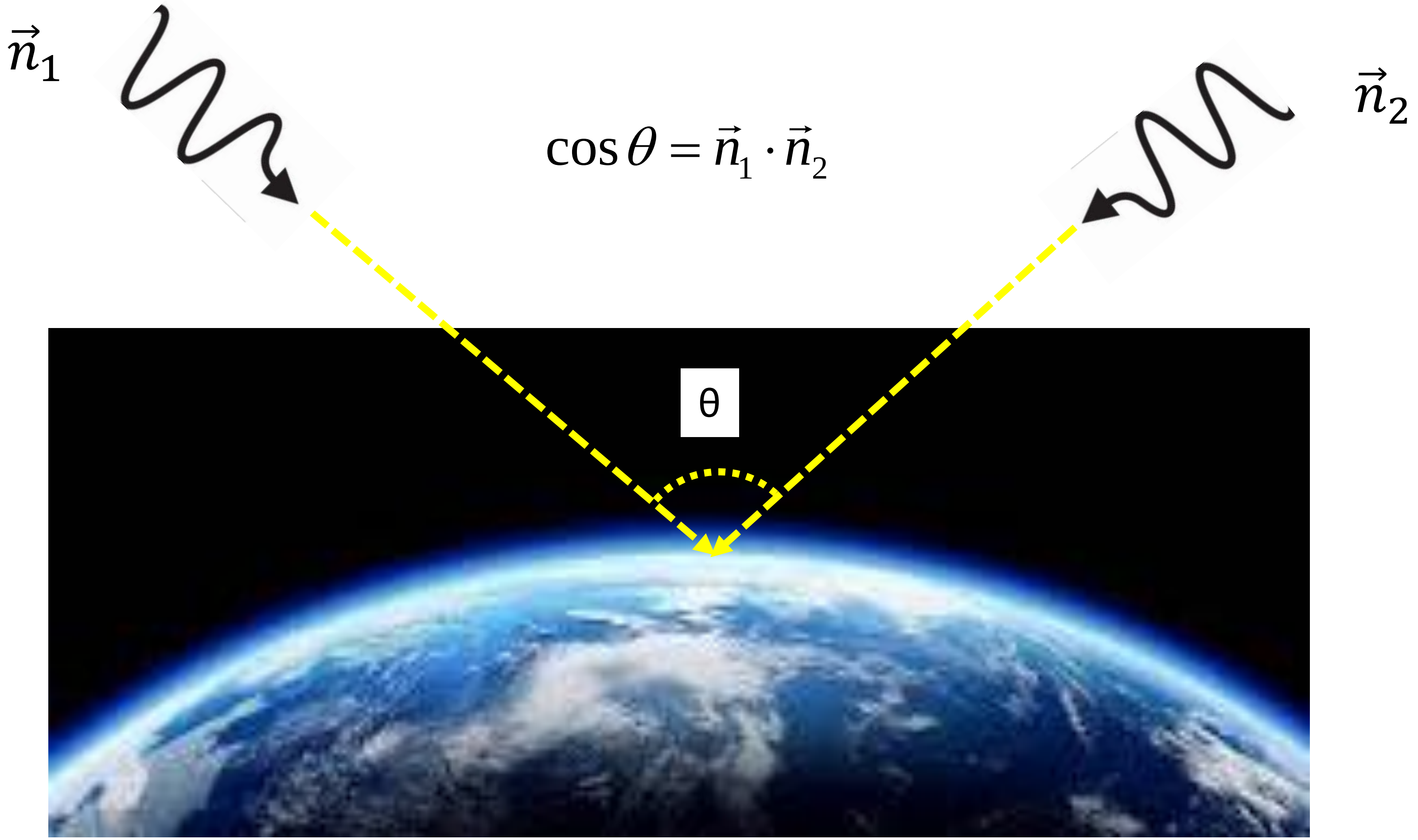
using the 2-point angular correlation function(s) focusing on large angles:

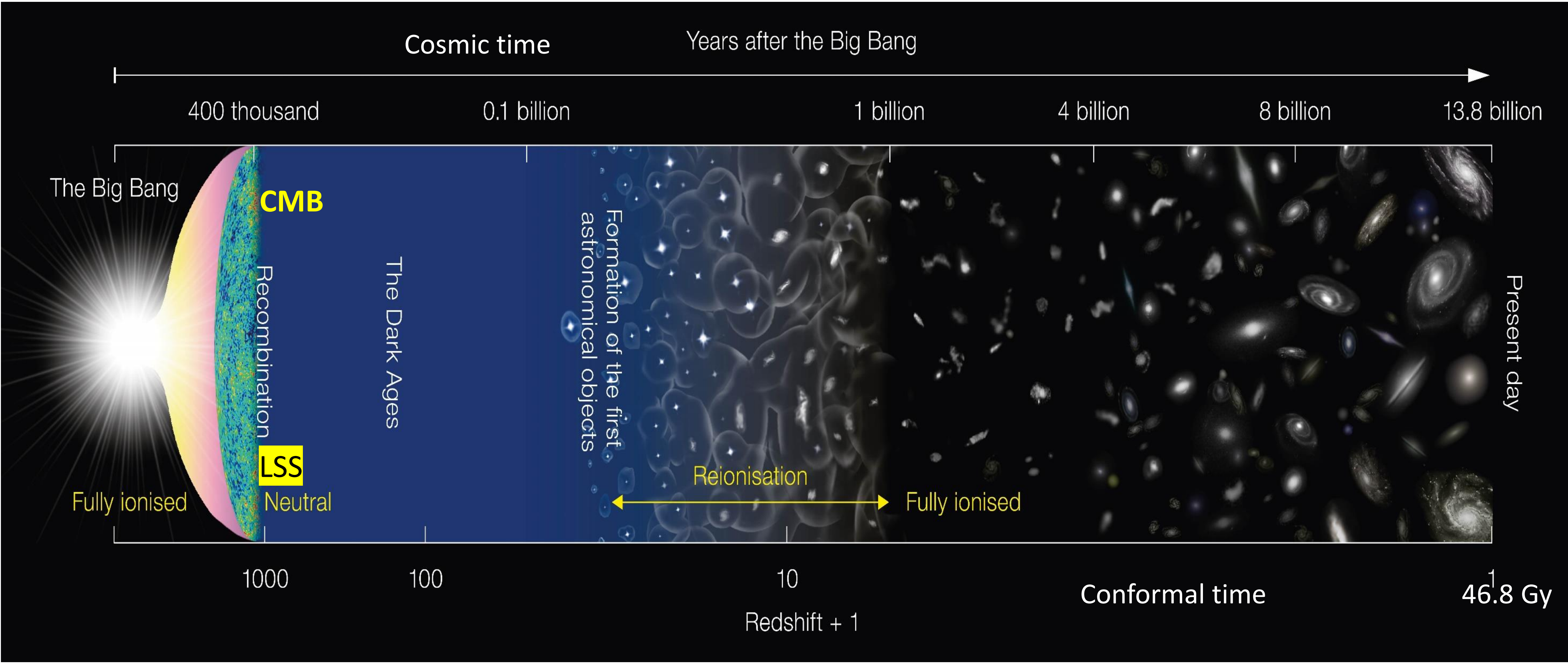
TT, EE and BB correlations

looking for possible parity breaking as a distinctive signature

CMB Temperature/Polarization angular correlations

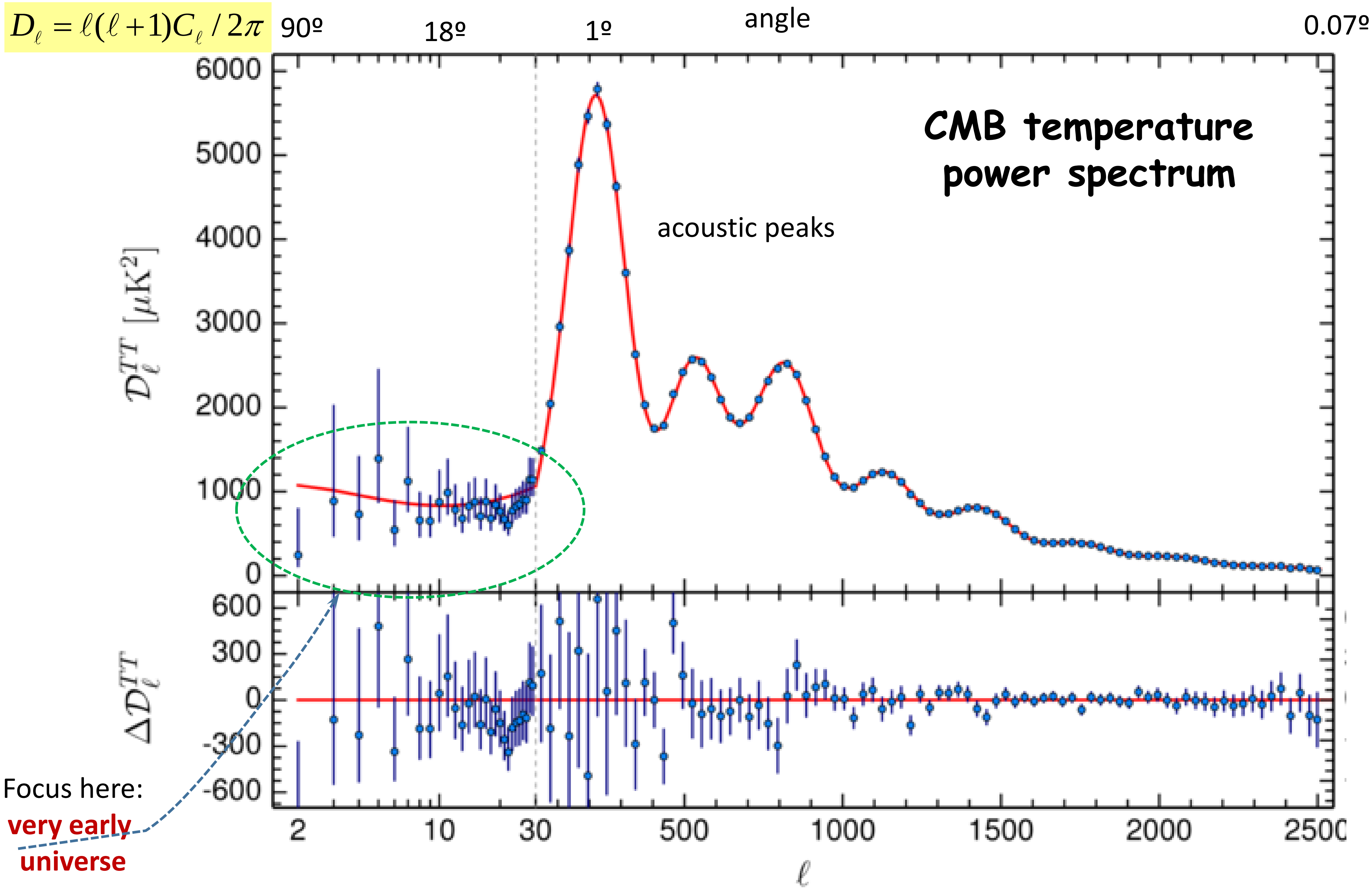
(at large angle)





radius of the observable (visible) universe today ≡ $r_d \approx 14.26$ Gpc = 46.5 Gly

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



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)

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

Legendre Polynomials

Sachs-Wolfe effect

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

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

spherical Bessel function

$$u = k\, r_d$$

k comoving momentum

r_d comoving distance to the LSS

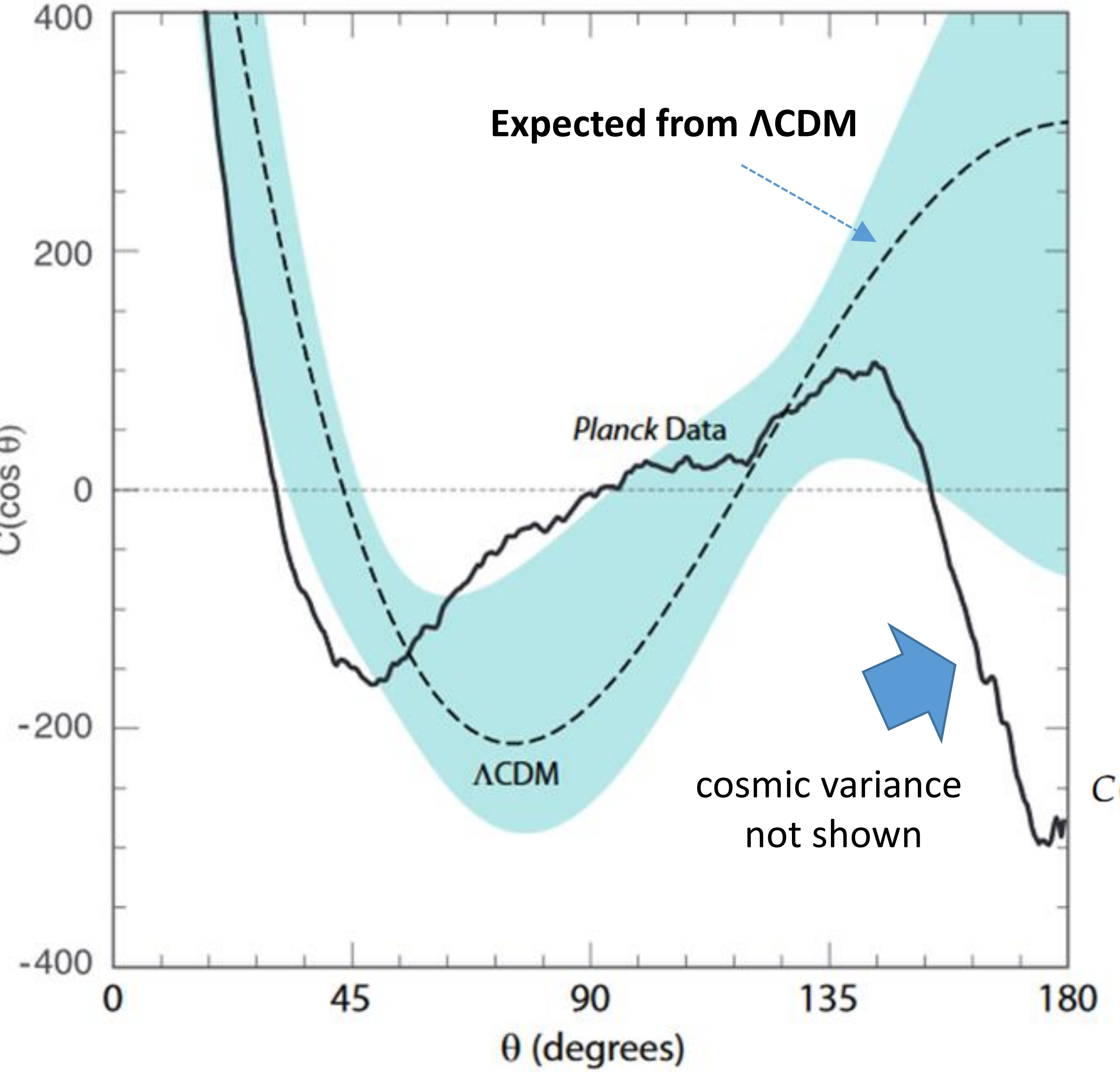
$$C_\ell = \frac{6}{\ell(\ell+1)} C_2 \quad \ell \le 30$$

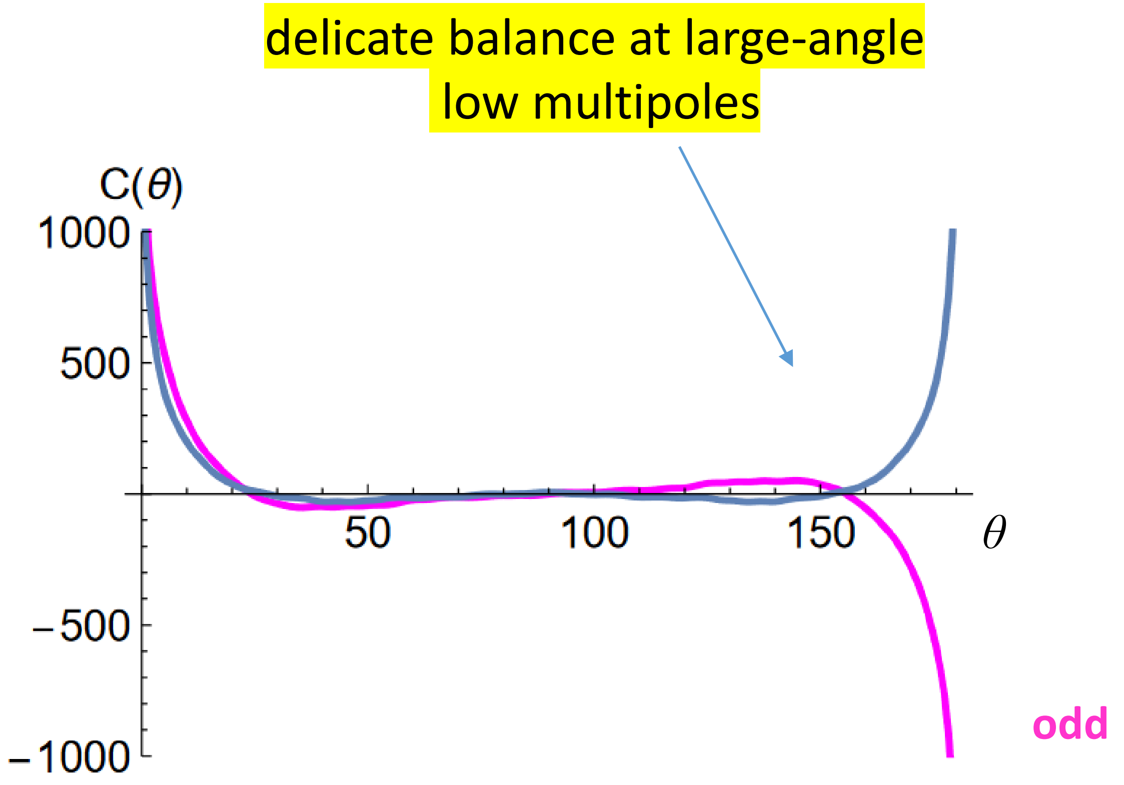
$$\ell(\ell+1)\, C_\ell = \text{constant}$$

Significant deviations at large angles !

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

Two-point correlation function of measured CMB temperature fluctuations from **Planck** dataset





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

upwards tail downwards tail

What next?

We will alter the initial parity balance in the multipole expansión

of the angular correlations function

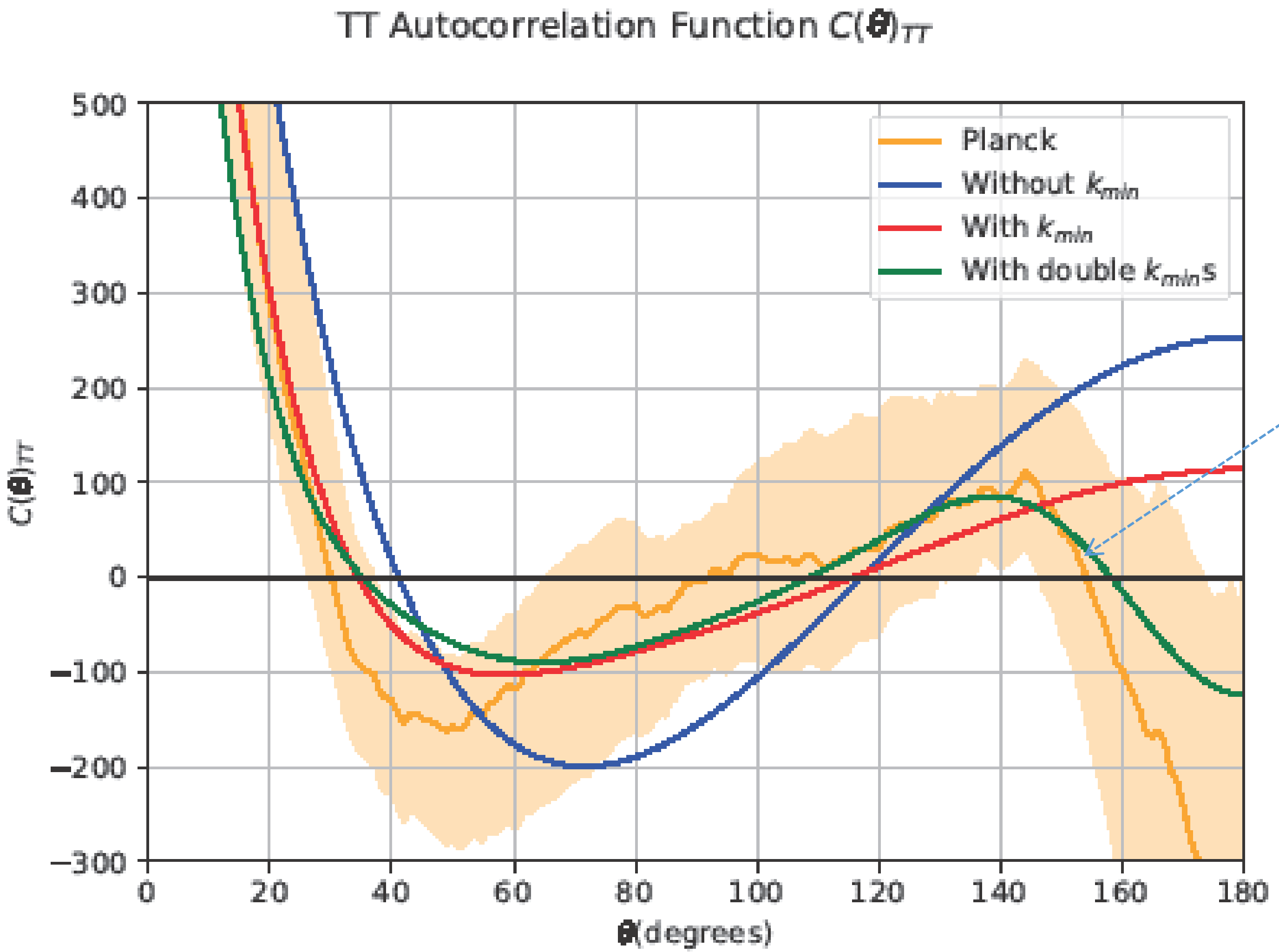
A doublet of infrared cutoffs (emerging from early universe topology)

to be introduced to the primordial scalar power spectrum

affecting differently odd and even multipoles

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]



clear improvement

χ^2 (reduced) ≈ 0.9

Scalar modes: Sachs-Wolfe effect

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

$\neq 0$

only scalar modes without tensor modes

M.A.S.L., Universe 8 (2022) 8, 396 [arXiv:2205.13257]

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

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

or equivalently

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

empirically motivated by our fits

and theoretically motivated

$$k_{\rm min}^{\rm odd} = 1.93 \pm 0.22 \times 10^{-4}\ {\rm Mpc}^{-1}\ ,\ k_{\rm min}^{\rm even} = 3.86 \pm 0.44 \times 10^{-4}\ {\rm Mpc}^{-1}$$

Several ways of breaking a symmetry of laws of nature to more or less extent are known:

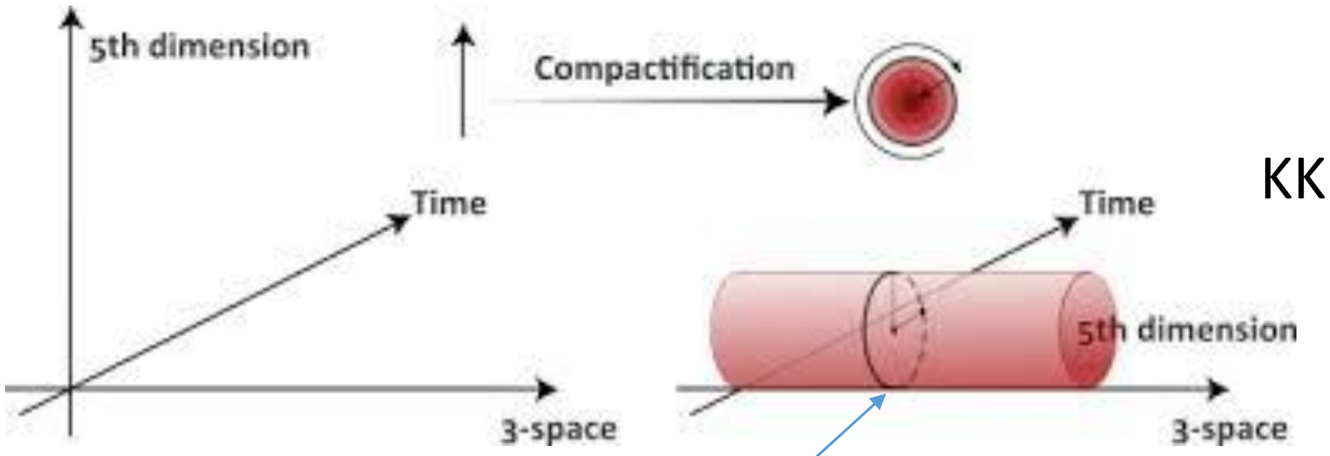
1) The Lagrangian is symmetric, but the vacuum (ground state) is not. It is generally known as Spontaneous Symmetry Breaking and the most celebrated example is the Higgs mechanism.

2) The Lagrangian itself contains terms that violate the symmetry. This is generally coined as Explicit Symmetry Breaking, e.g. adding a small mass term to a classically chiral-invariant theory.

3) The classical Lagrangian is symmetric under some continuous transformation, but the symmetry is broken by quantum effects in the quantization process. Awell-known example is the axial anomaly in the $\pi^0 \rightarrow \gamma\gamma$ decay

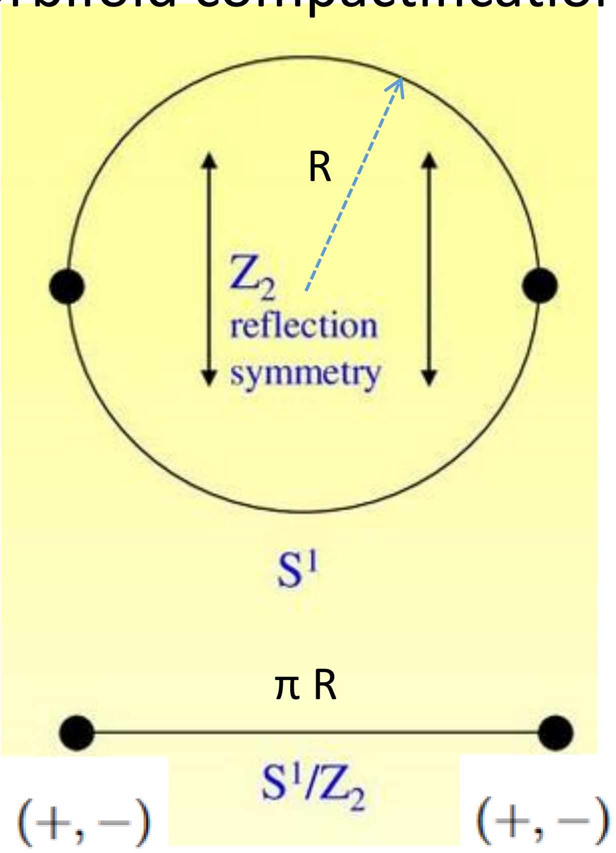
4) Geometric/Topology Symmetry Breaking, also known as the *Scherk–Schwarz* mechanism. The symmetry breaking comes from the topology or geometry of spacetime itself, not from the potential, the Lagrangian parameters, or quantum effects.

Topology in the early universe



KK extra dimension

Orbifold compactification



$$\Phi(x^\mu, z) = \phi(x^\mu)\, f(z)$$

$$\begin{aligned} \partial_z \Phi|_{z=z_0} &= 0 \text{ (Neumann, or } +) \\ \Phi(z_0) &= 0 \text{ (Dirichlet, or } -). \end{aligned}$$

Parity: $(+,+)$ and $(-,-)$ are *even*, and $(+,-)$ and $(-,+)$ are *odd.*

IR cutoffs provided by the masses of the lowest KK modes: $k_{\min}{}^{\text{odd}} = k_{\min}{}^{\text{even}}/2$

Assuming that $\Phi(x^\mu,z)$ is a scalar field in 5D, **the 4D field scalar *Φ(x^μ)* inherits the parity of *f(z)***

and the above ratio of cutoffs applies in the 4D world :

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

Robust prediction

Tensor modes are naturally born in a KK theory: spin-2 fields are unavoidably present containing a massless state identified with the graviton responsible for the 4D gravity plus a tower of KK states (KK-gravitons) whose low masses would again behave like infrared cutoffs on 4D fields.

Upon compactification and imposing the same boundary conditions on the fifth dimension one can show that for tensor modes again:

M.A. Sanchis-Lozano
Universe 8 (2025) 8, 396 [arXiv:2509.13257]

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

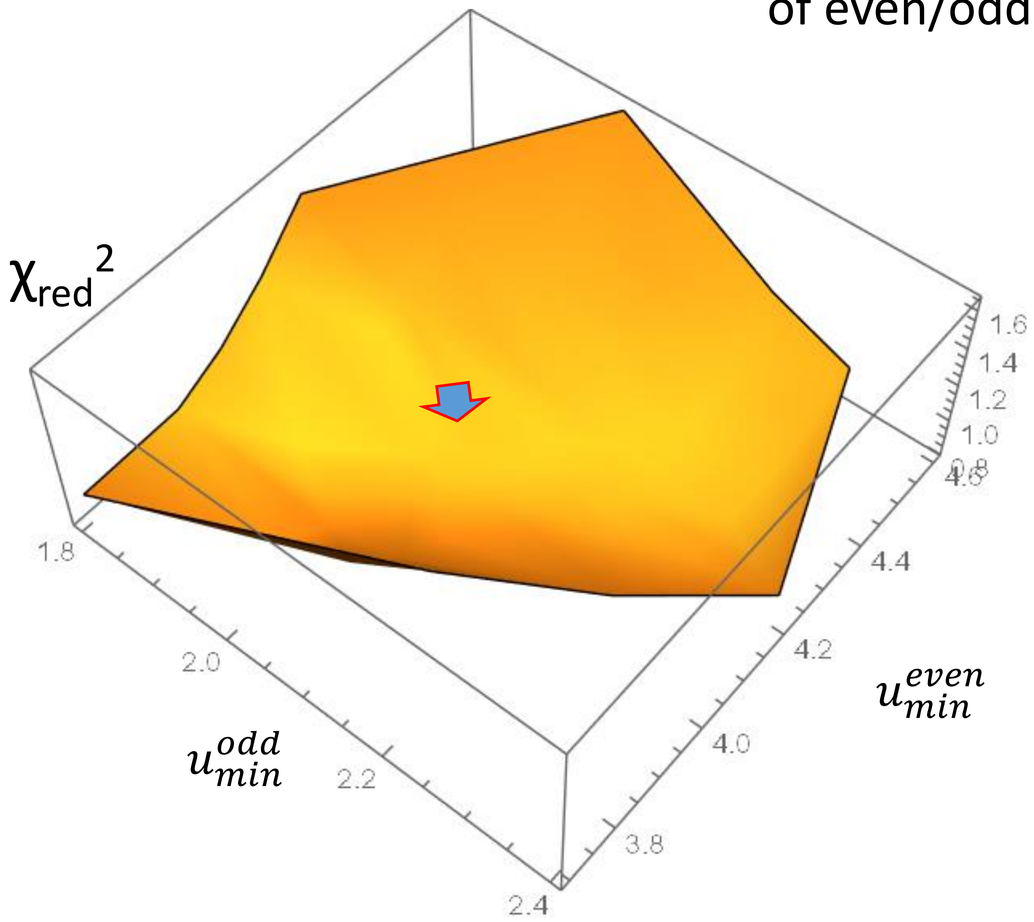
$$\frac{k_{\rm min}^{\rm even}}{k_{\rm min}^{\rm odd}} = 2 \quad \textbf{(tensor modes)}$$ Flat geometry

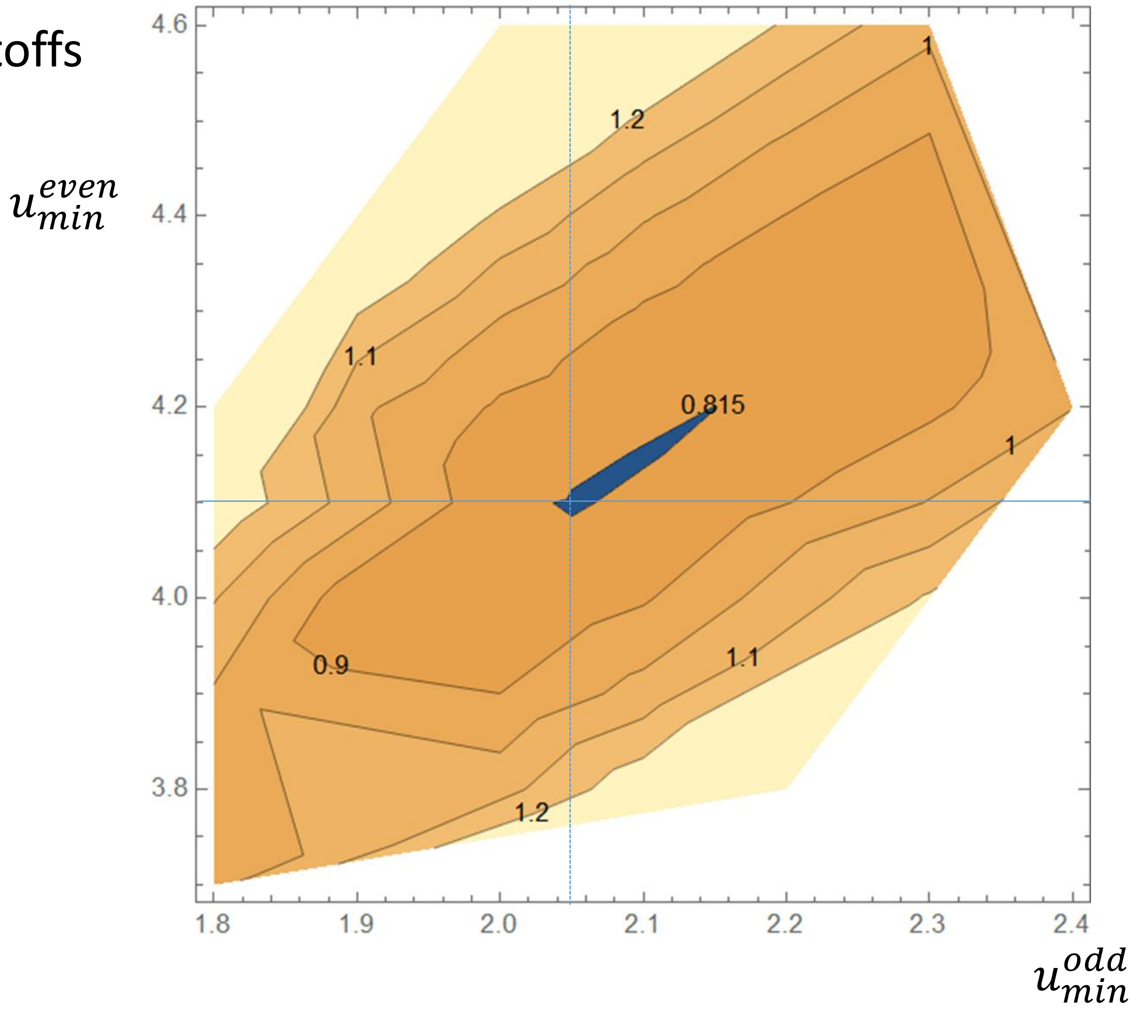
$$\frac{k_{\rm min}^{\rm even}}{k_{\rm min}^{\rm odd}} \gtrsim 2 \quad \textbf{(tensor modes)}$$ Warped geometry

$$C_{\ell_{\rm odd/even}}^{\rm TT}({\rm tensor}) = N^T \frac{(\ell+2)!}{(\ell-2)!} \int_{u_{\rm min}^{\rm odd/even}({\rm tensor})}^{\infty} du\, \frac{j_\ell^2(u)}{u^5}$$

extra contribution to TT correlations beyond scalar modes

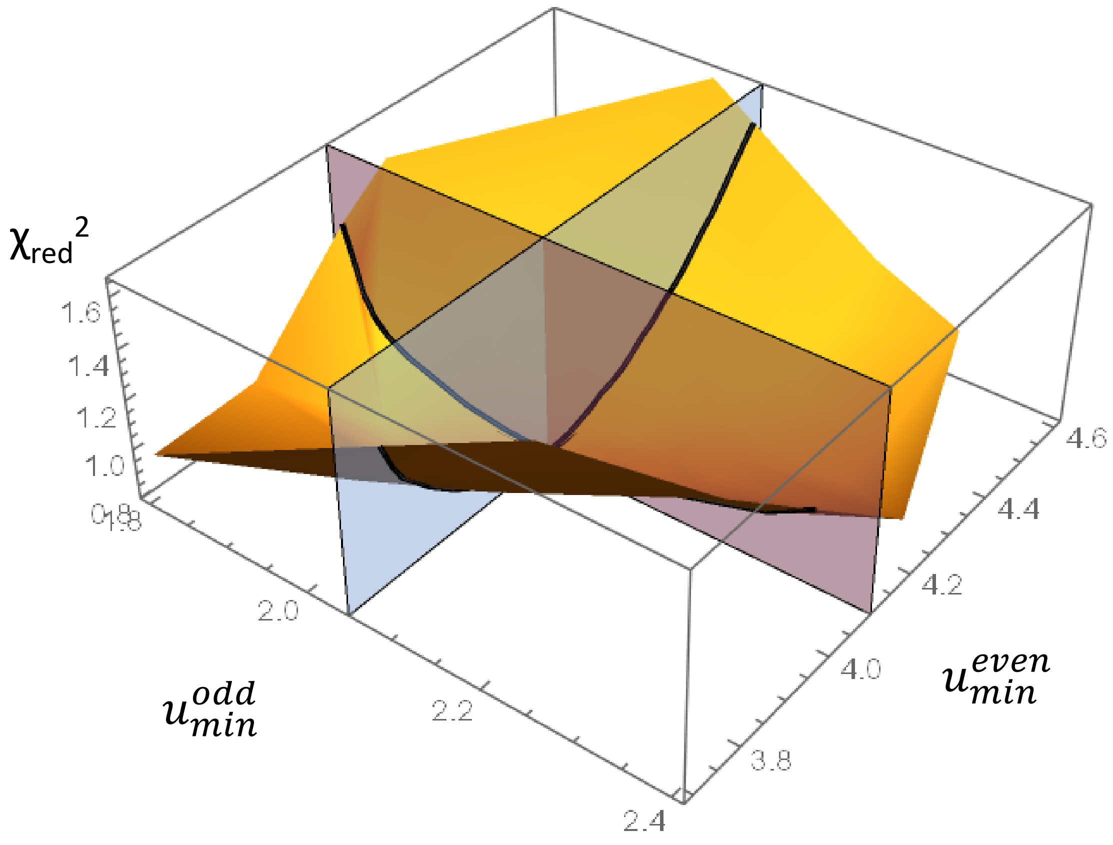
χ_{red}^2 as a function of even/odd infrared cutoffs

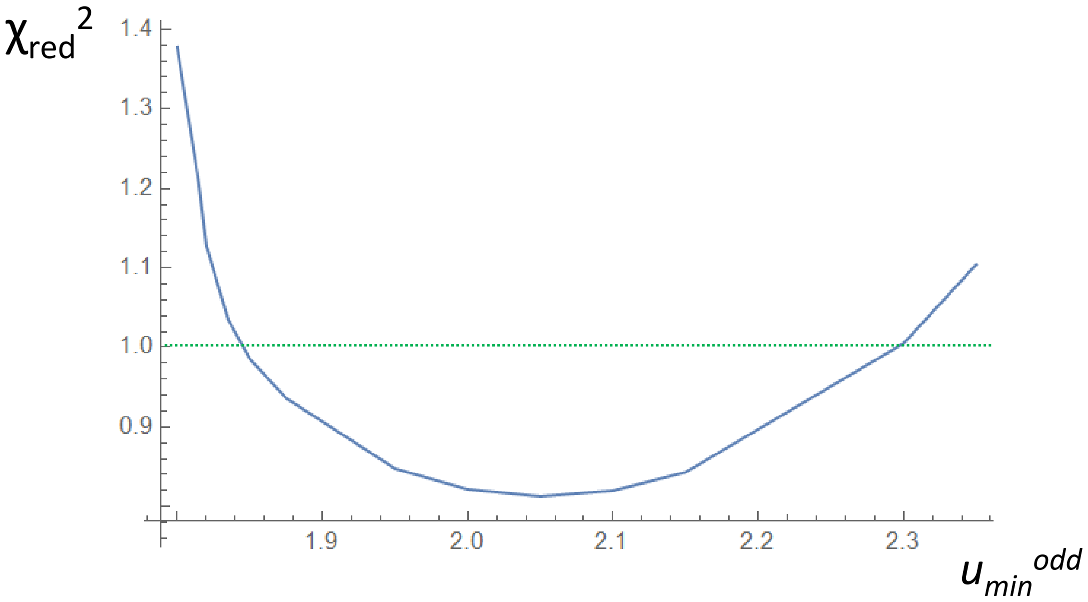


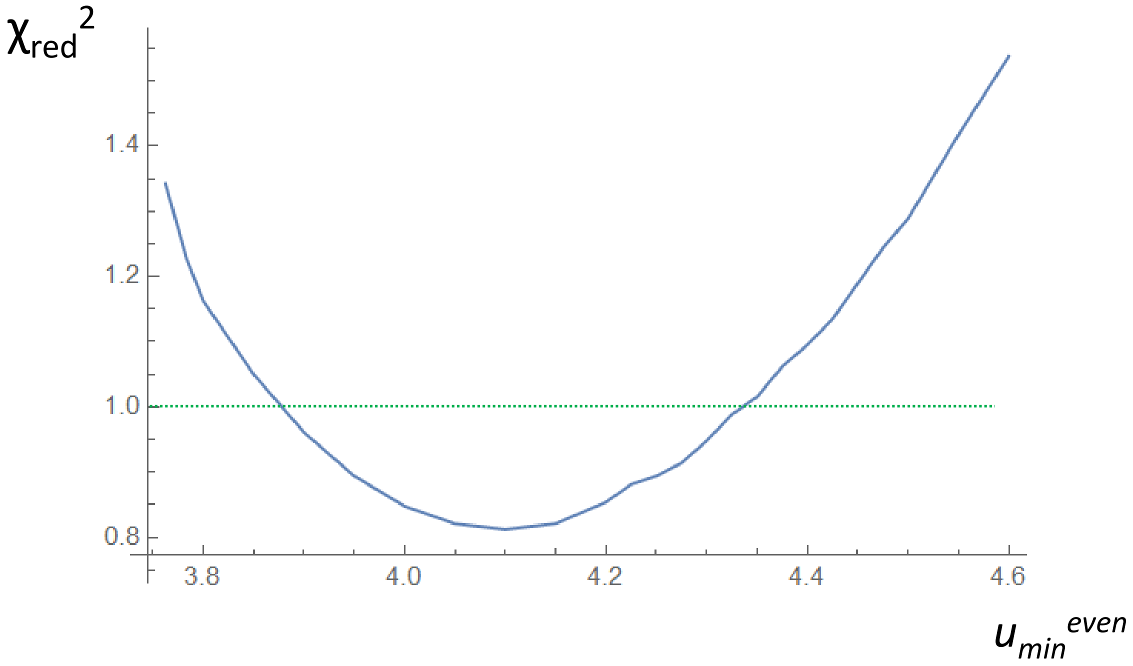


With a 0.05 pace for the scanning, *minimum* happens at (2.05,4.1) yielding χ^2(reduced) ≈ 0.81

PLOTS INCLUDING TENSOR MODES







Scalar modes

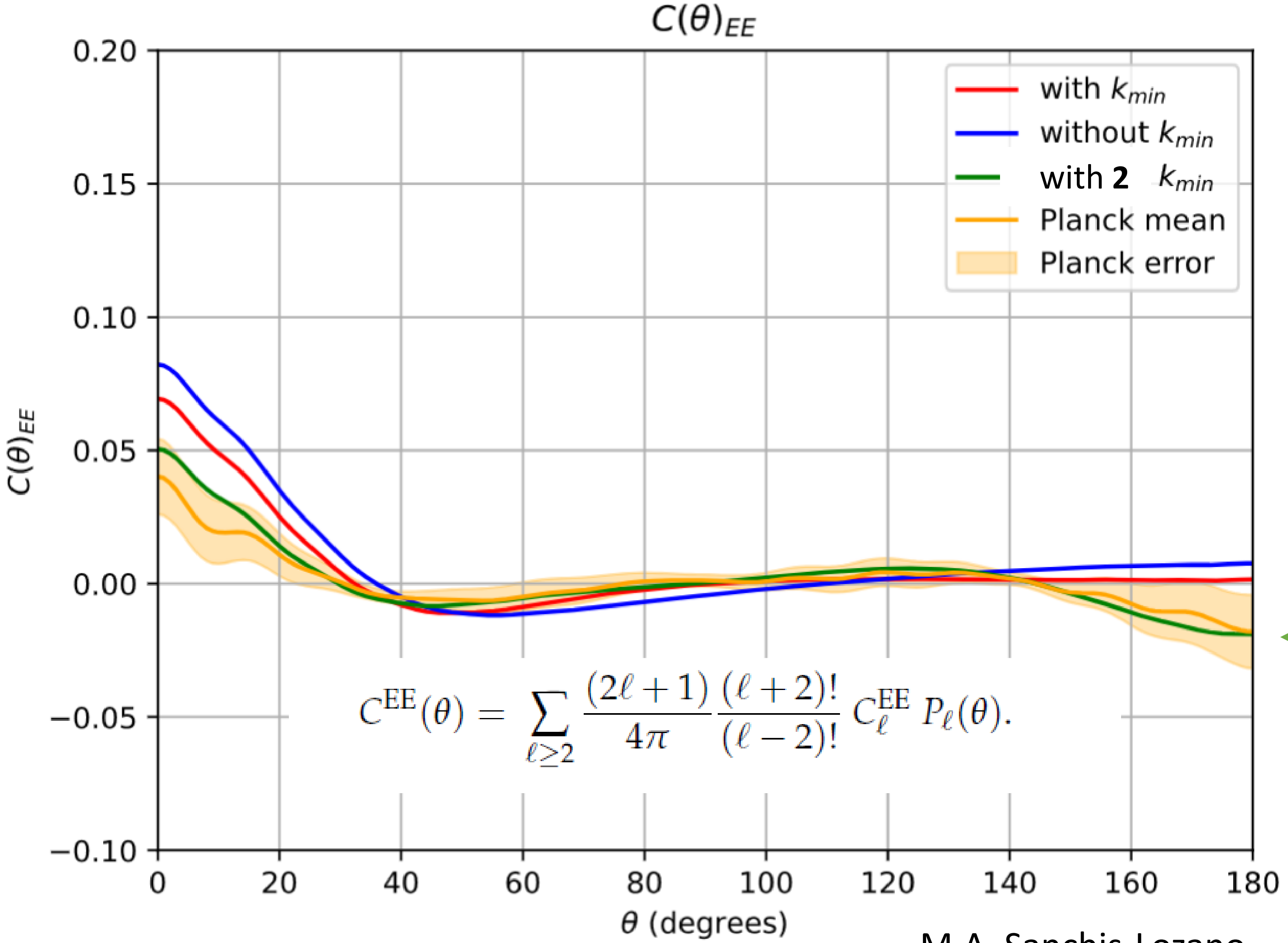
$$u_{min}^{odd} = 2.05_{-0.20}^{+0.25}$$

$$u_{min}^{even} = 4.10_{-0.20}^{+0.25}$$

Polarization study

E-mode 2-point (auto) correlation function

Planck data



$u_{min}^{odd}(scalar) = 2$

$u_{min}^{even}(scalar) = 4$

$u_{min}^{odd}(tensor) = 4$

$u_{min}^{even}(tensor) = 8$

negative correlations at large angle again

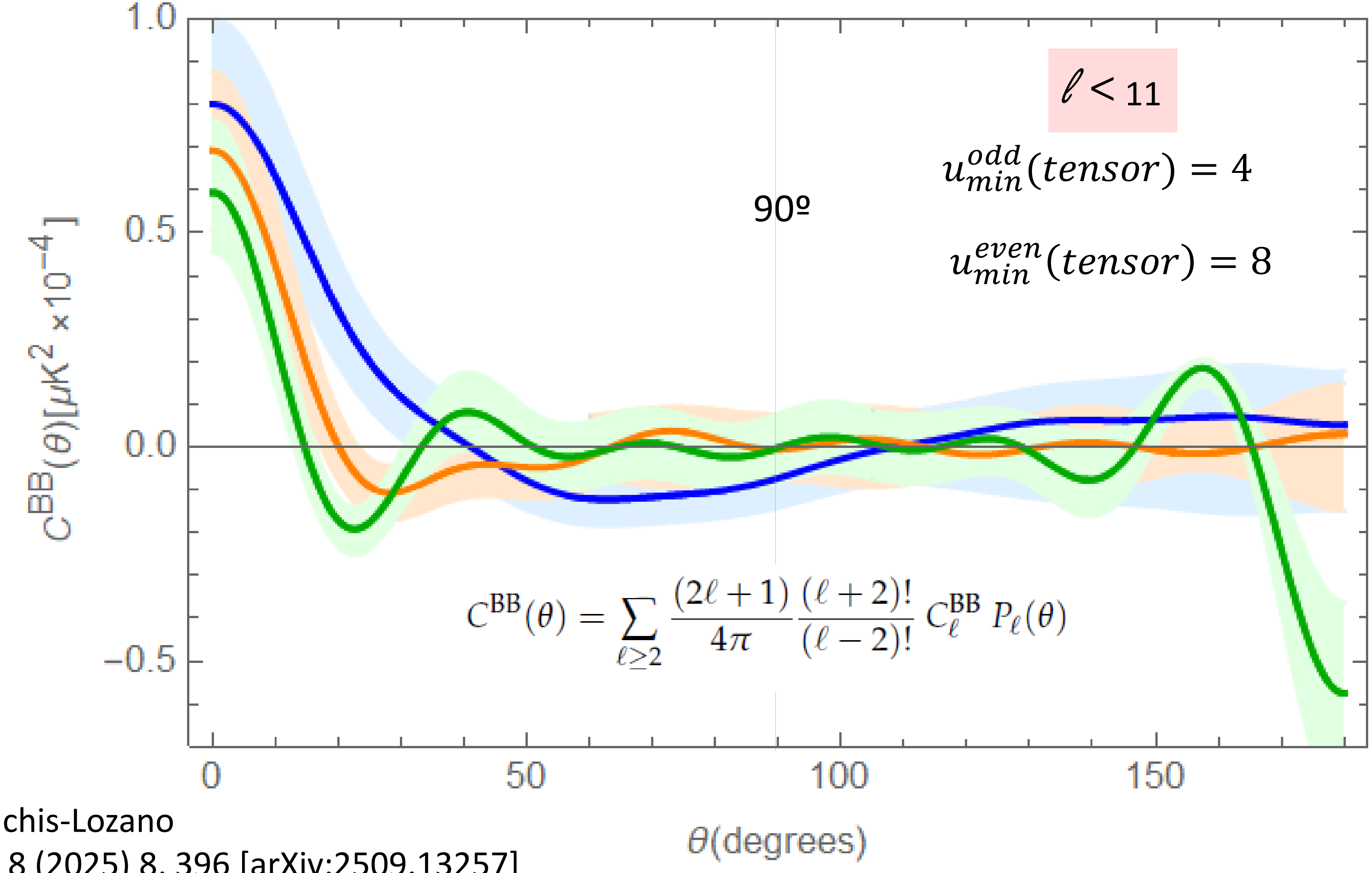
M.A. Sanchis-Lozano
Universe 8 (2025) 8, 396 [arXiv:2509.13257]

B-mode 2-point (auto)correlation function

Prediction

LITEbird

$r = 0.003$



negative correlations at large angle θ expected

M.A. Sanchis-Lozano
Universe 8 (2025) 8, 396 [arXiv:2509.13257]

Conclusions

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

1) In our approach the odd-parity preference (slightly breaking isotropy stemming from the cosmological principle) observed in angular correlations in the CMB by COBE, WMAP and *Planck* missions leads to two infrared cut-offs in the scalar power spectrum $\rightarrow \frac{u_{\min}^{\text{even}}}{u_{\min}^{\text{odd}}} = \frac{k_{\min}^{\text{even}}}{k_{\min}^{\text{odd}}} \approx 2$ and similarly for tensor modes

2) This phenomenological result is theoretically justified/motivated by assuming Dirichlet/Neumann BCs on a KK extra-dimension of the early universe (GUT epoch) affecting primordial scalar and tensor modes with observational consequences in our 4D universe as postulated in this work

3) Once primordial tensor modes are incorporated into the analysis of Planck data the goodness of fits to angular TT and TE correlations of the CMB improves significantly

4) Further studies (e.g.by LiteBIRD) using B-mode polarization of the CMB could be the smoking-gun of PWGs as well as underlying new physics beyond the Standard Model in PP and Cosmology, as postulated in this work

Final remarks

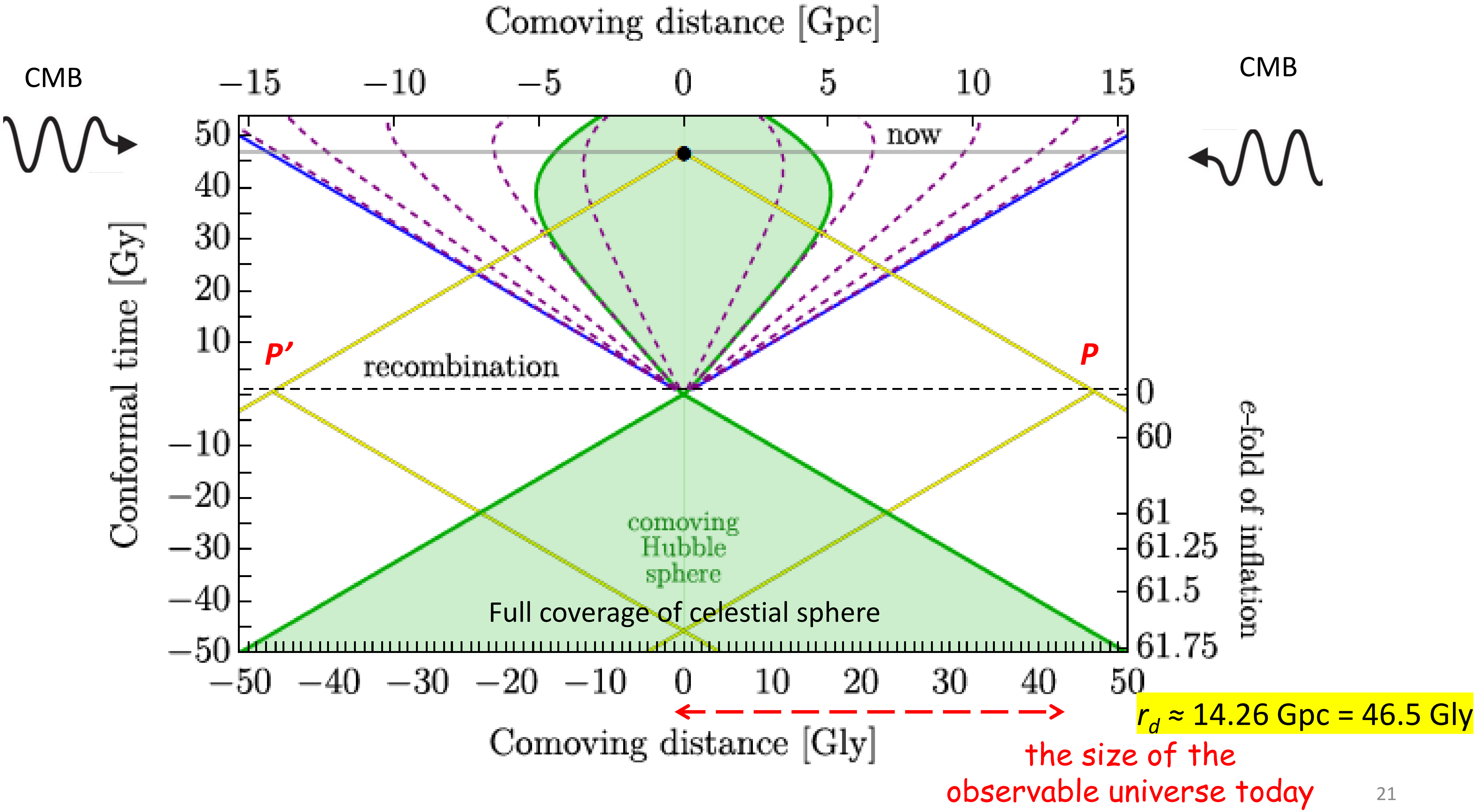
Deviations from theory and observations in angular correlations (odd-parity dominance) at large angular scales can be attributed to different sources: instrumental errors, foreground suppression, statistical fluke (cosmic variance)… and not due to an underlying cosmological origin

However, **a common tendency shown in both temperature and (E- and B-mode) polarization measurements would be a clear indication of a cosmological origin of odd-parity preference**.

THANKS!

BACK-UP

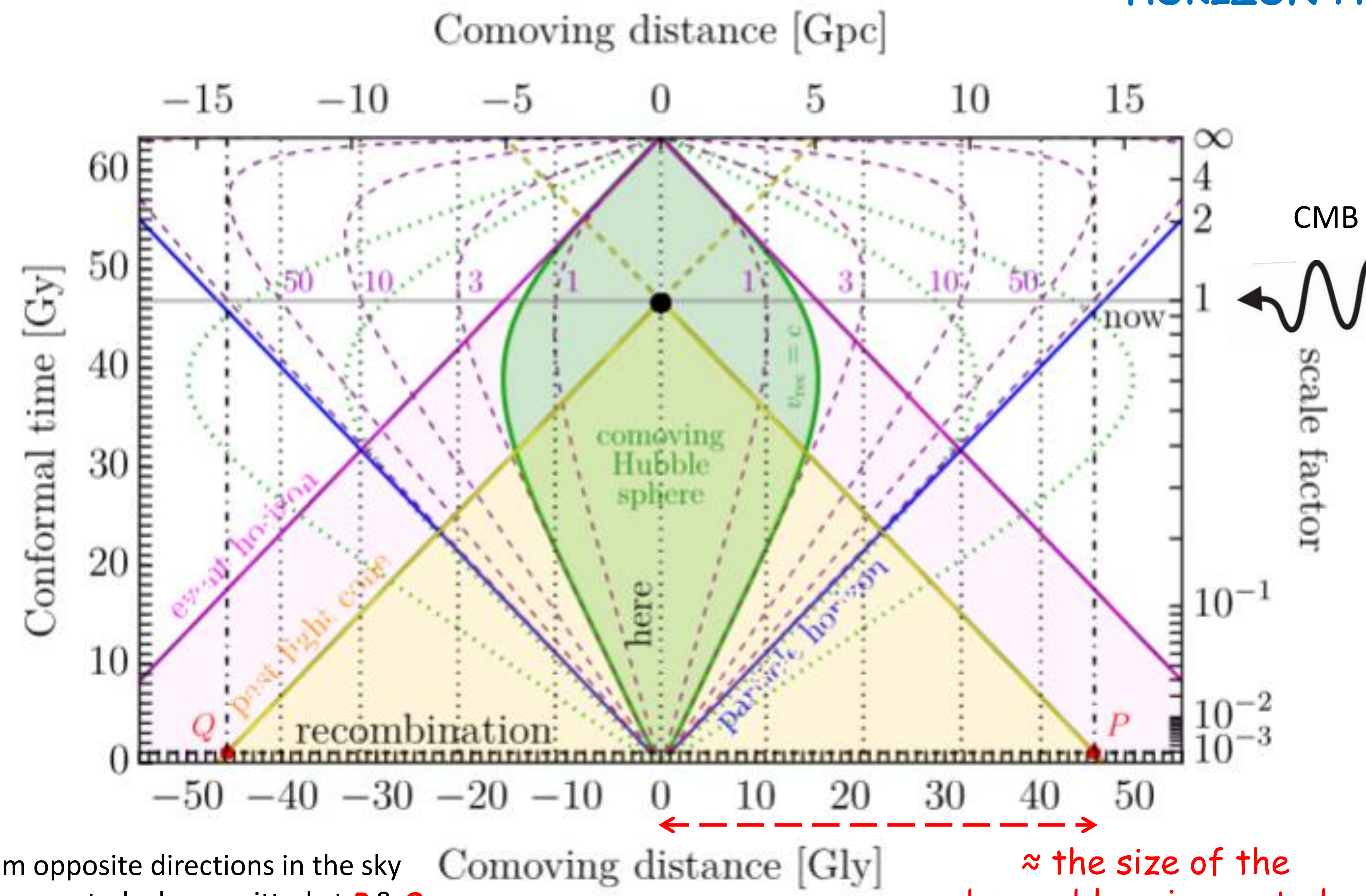
Solution to the horizon problem: inflationary epoch



HORIZON PROBLEM

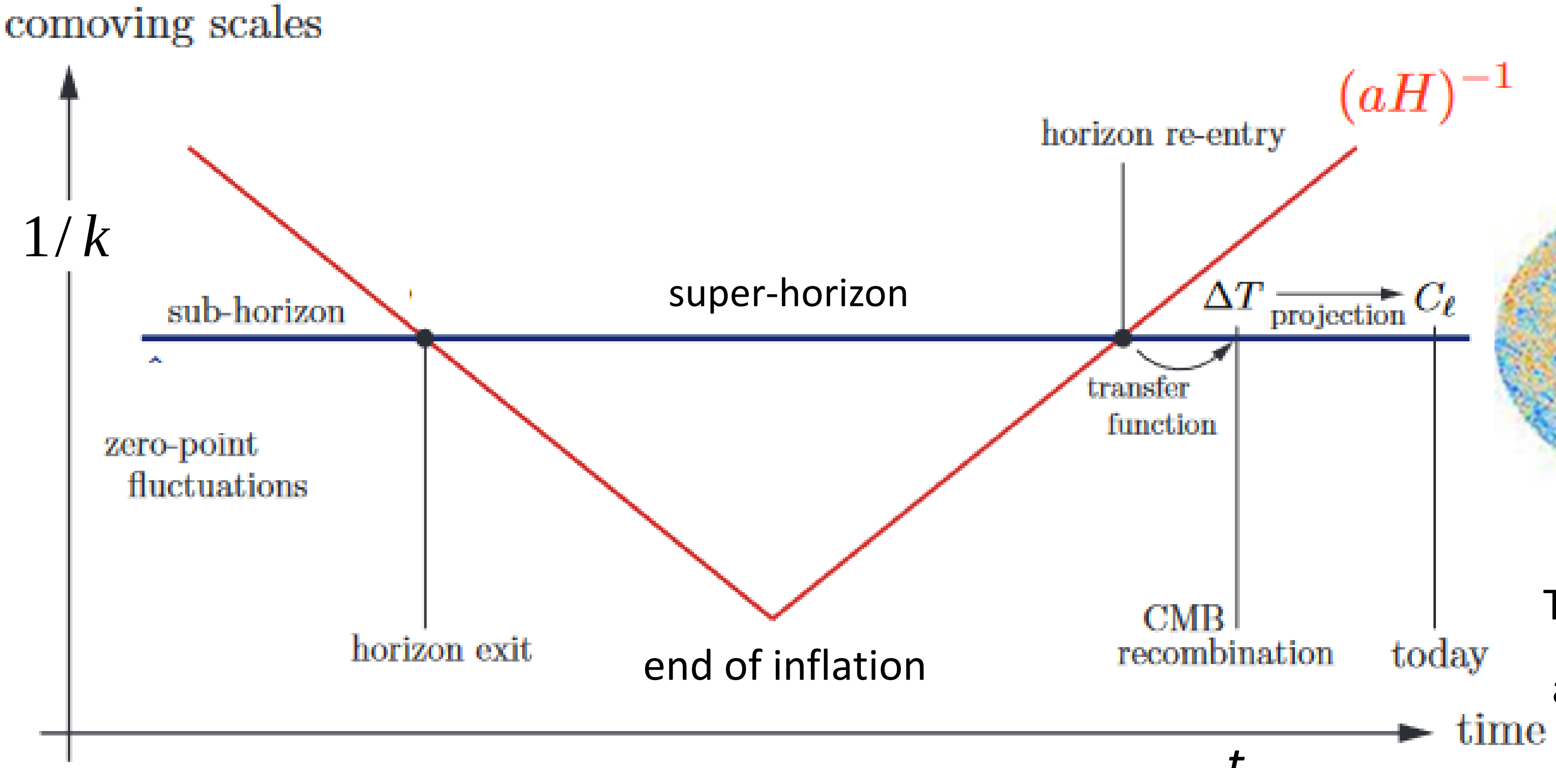
CMB

CMB



≈ the size of the observable universe today

CMB photons from opposite directions in the sky seem not causally connected when emitted at ***P*** & ***Q***



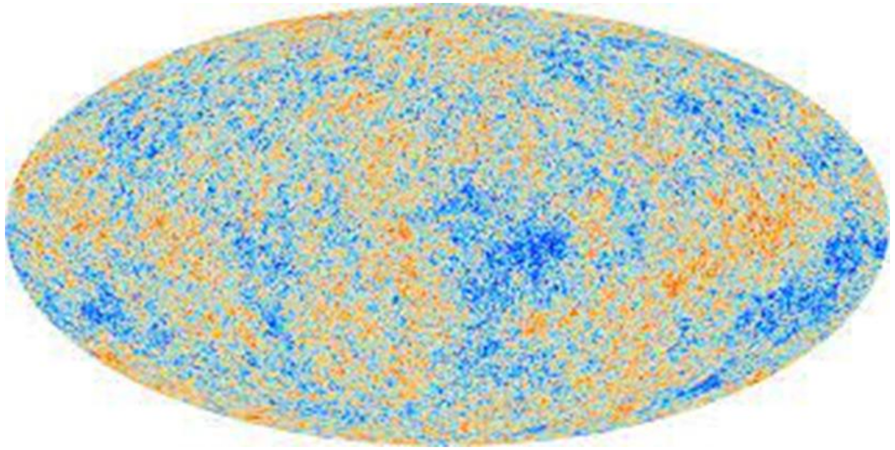
t_d

(decoupling/recombination)

zero-point quantum fluctuations of the inflaton field

Cosmic Microwave Background

CMB

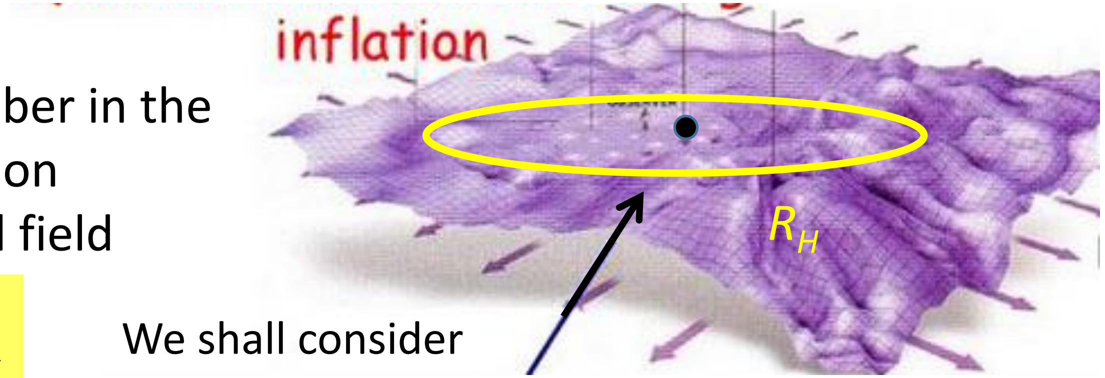


Temperature anisotropies from the sky as a snapshot of the early universe at the LSS and the seeds of the formation of the universe as seen today

k: comoving wavenumber in the Fourier expansion of the primordial field

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

a(now) = 1

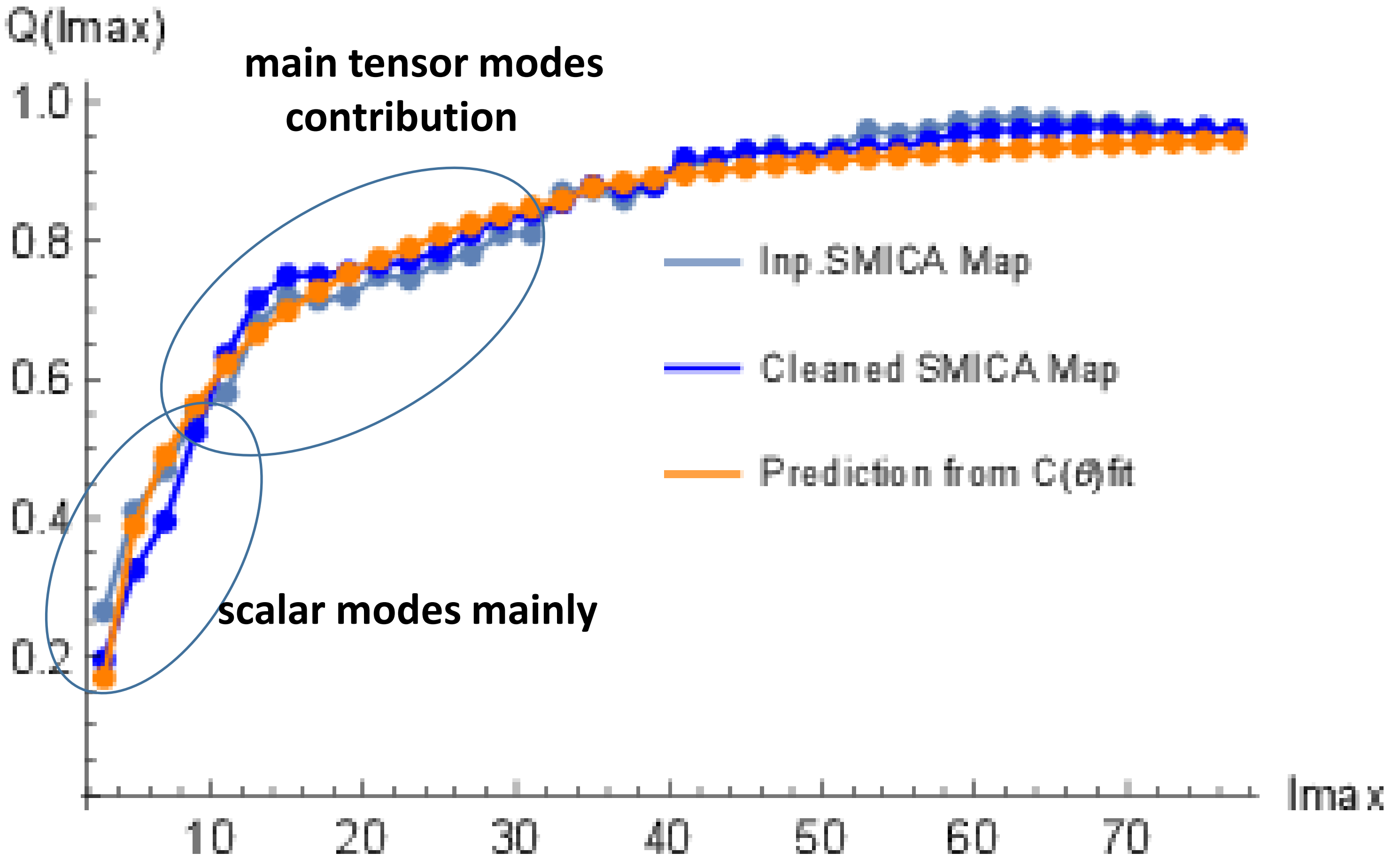


Inflation stretches physical scales out of the **physical** Hubble radius (in yellow) which remains fixed during inflation but later expands at different rates

We shall consider

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

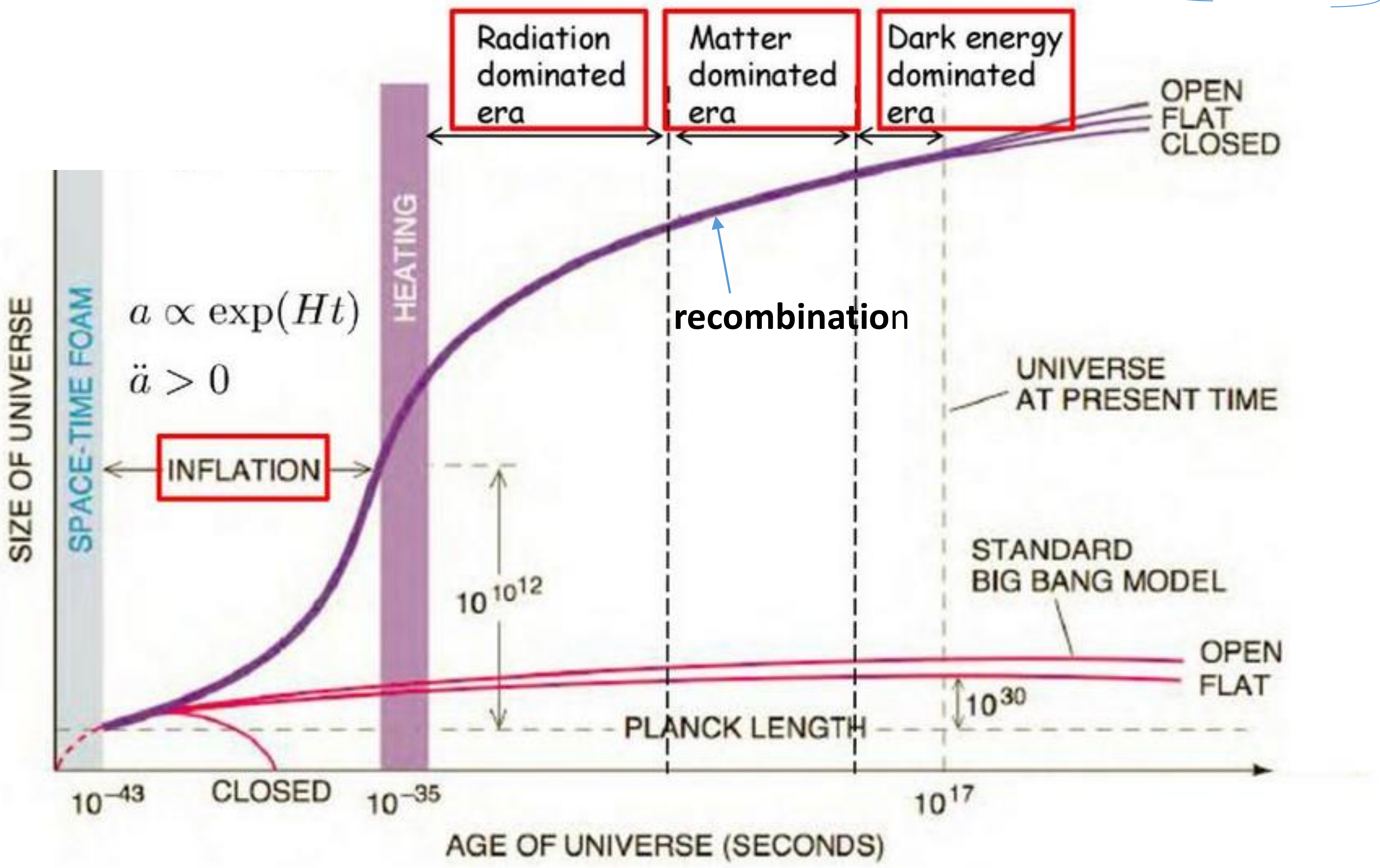
$$u^{even/odd}(T) = 2u^{\ even/odd}(S)$$



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



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

original proposal(s)

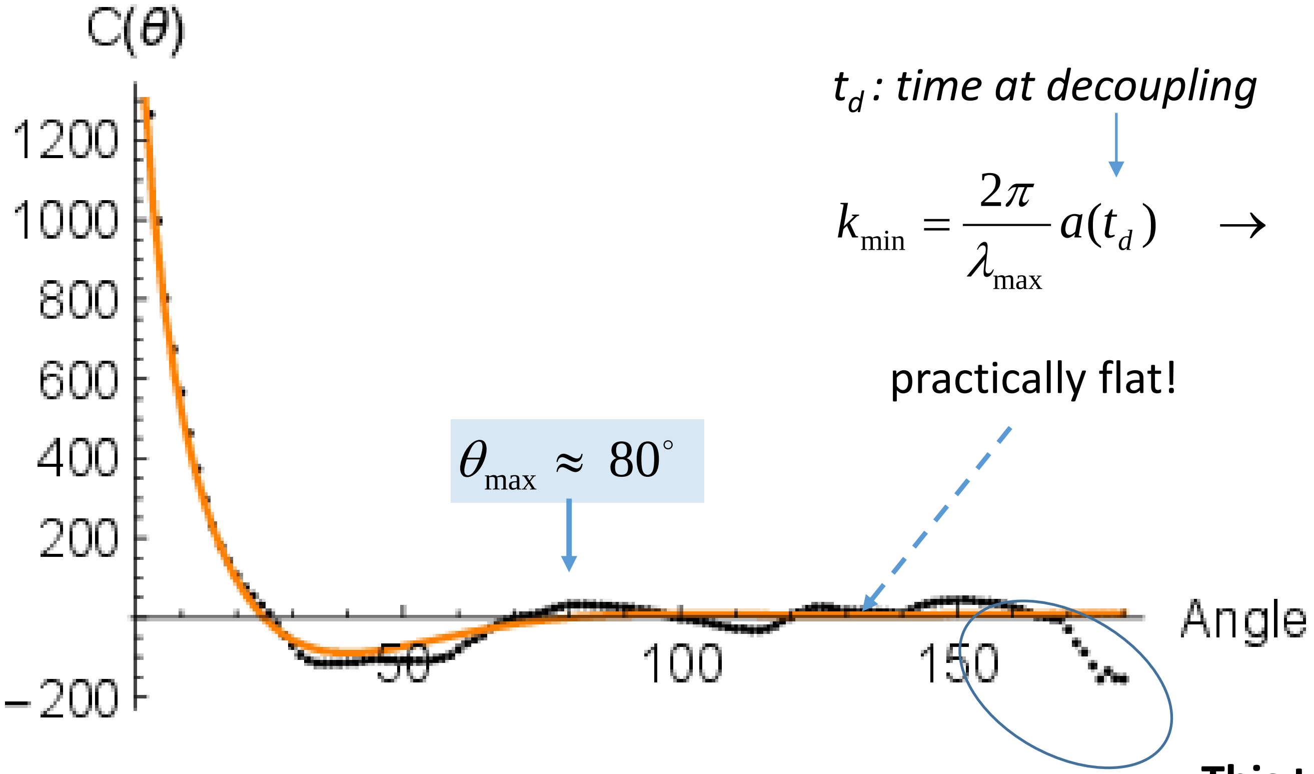
F. Melia & M. Lopez-Corredoira: arXiv: 1712.07847
Astronomy & Astrophysics, Volume 610 (2018) A87
Niarchu et al. PRD 69 (2004) 063515
Bridle et al. Mon. Not, R, Astron. Soc 342 (2003) 72-88

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

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

t_d : *time at decoupling* $\quad$ $r(t_d)$: *commoving distance to the LSS*

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



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

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

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

$$k_{min} \approx 3.3 \times 10^{-4}\ \mathrm{Mpc}^{-1}$$

This tail is not reproduced at all!

related to parity-imbalance

Obtained from a best fit to *Planck* datapoints

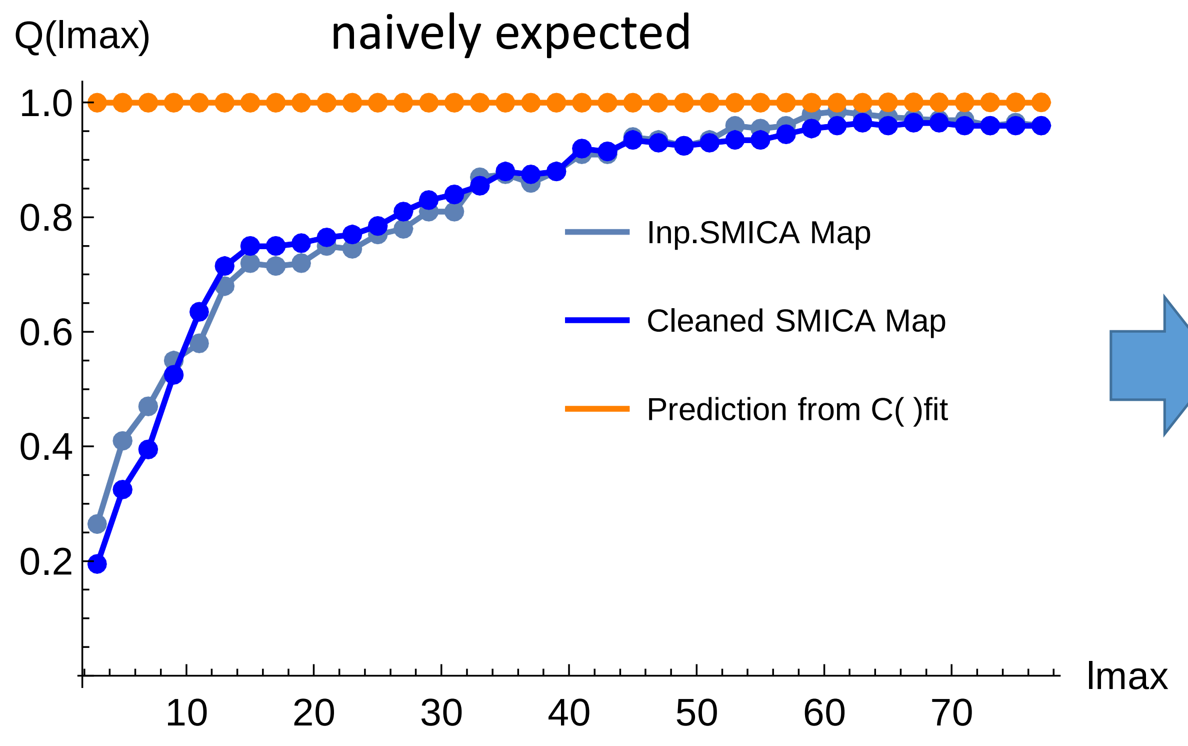
M.A.S.L, F.Melia, M.López-Corredoira and N.Sanchis-Gual
Astron.Astrophys. 660 (2022) A121 [arXiv:2202.10987]

Parity asymmetry statistic

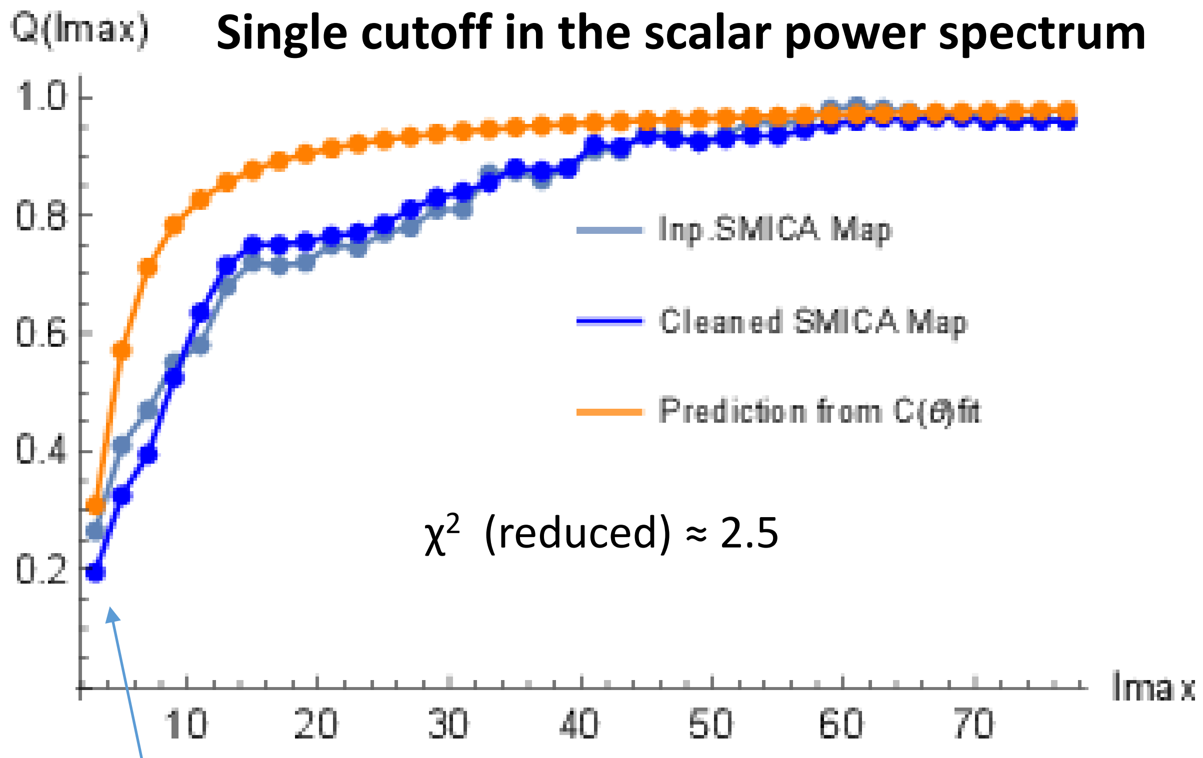
$$Q(\ell_{max}) = \frac{2}{\ell_{max}^{odd} - 1} \sum_{\ell=3}^{\ell_{max}^{odd}} \frac{D_{\ell-1}}{D_{\ell}}, \ \ell_{max} \geq 3 \quad \text{only odd integers}$$

Aluri & Jain, MNRAS 2012, 419, 3378

naively expected



Single cutoff in the scalar power spectrum



χ^2 (reduced) ≈ 2.5

Notice that adding an infrared cutoff (or more)

into the scalar power spectrum

breaks parity balance

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

Improvement but

not really satisfactory yet

Assuming a scalar field in 5D world, boundary Neumann/Dirichlet conditions from the KK extra dimension leads to a Dirac-like field in 4D which can be subject to periodicity/antiperiodicity boundary conditions on the early universe

Legendre polynomials in terms of cosine of angle θ and of half angle θ/2

$$
\begin{aligned}
P_1(\cos\theta) &= -1 + 2\cos^2(\theta/2) \\
P_2(\cos\theta) &= -0.5 + 1.5\cos^2(\theta) \\
P_3(\cos\theta) &= -1 + 0.75\cos^2(\theta/2) + 1.25\cos^2(3\theta/2) \\
P_4(\cos\theta) &= -0.7184 + 0.6249\cos^2(\theta) + 1.0937\cos^2(2\theta) \\
P_5(\cos\theta) &= -1 + 0.4687\cos^2(\theta/2) + 0.5469\cos^2(3\theta/2) + 0.9844\cos^2(5\theta/2)
\end{aligned}
$$

Alternative way

Legendre polynomials in terms of cosine of Chebyshev polynomials $T_n = \cos(n\theta)$

$$
\begin{aligned}
P_1(\cos\theta) &= T_1 \\
P_2(\cos\theta) &= 0.25 + 0.75T_2 \\
P_3(\cos\theta) &= 0.375T_1 + 0.625T_3 \\
P_4(\cos\theta) &= 0.1409 + 0.3124T_2 + 0.5468T_4
\end{aligned}
$$

Essential in our argument

TWO INFRARED CUT-OFFs

TWO different BOUNDARY CONDITIONS

in ordinary space from

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 condition the Fourier expansion reads

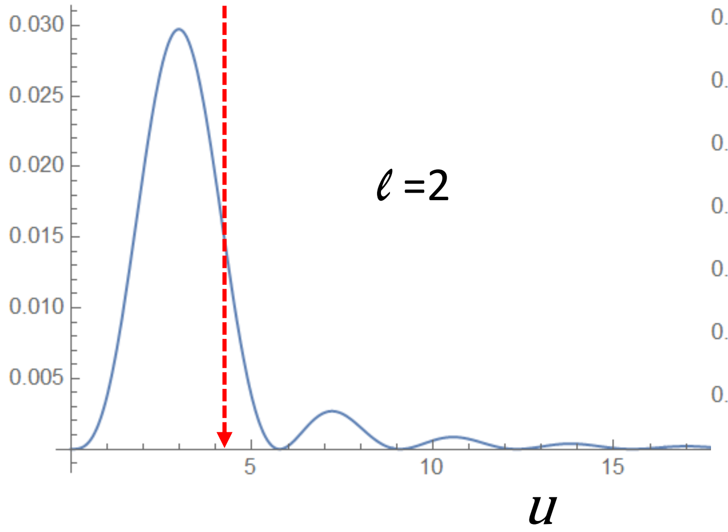
$$\psi(\varphi) = \sum_{n\in\mathcal{Z}^{+}+1/2} \alpha_n\, e^{in\varphi}\,,$$

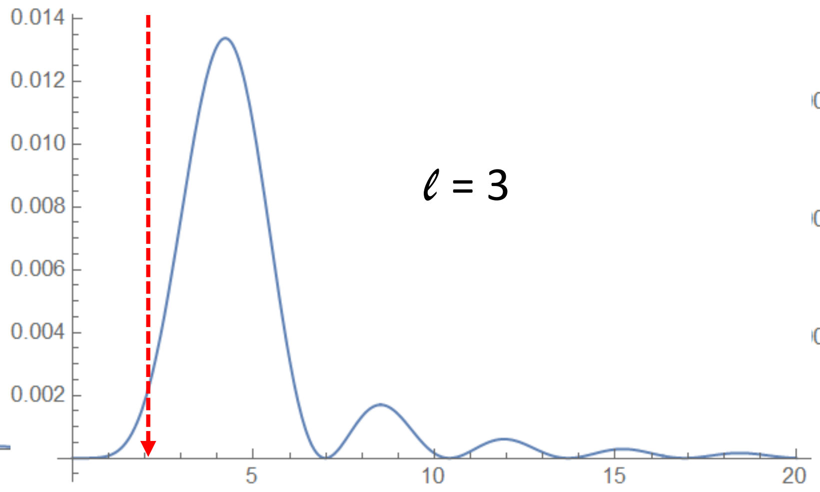
HALF-INTEGERS

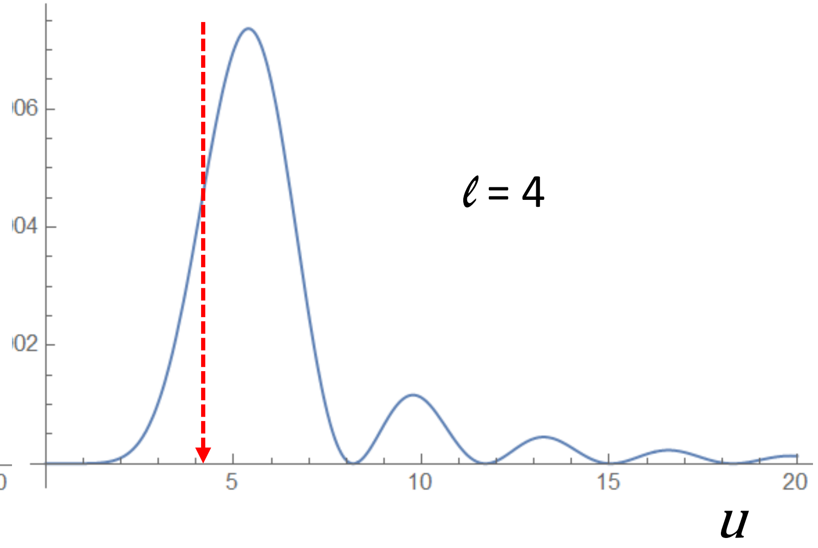
$$k_{\min}^{\text{odd}} = 2\pi a(t_d)/\lambda_{\max}^{\text{odd}}, \quad k_{\min}^{\text{even}} = 2\pi a(t_d)/\lambda_{\max}^{\text{even}}$$

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

comoving scales

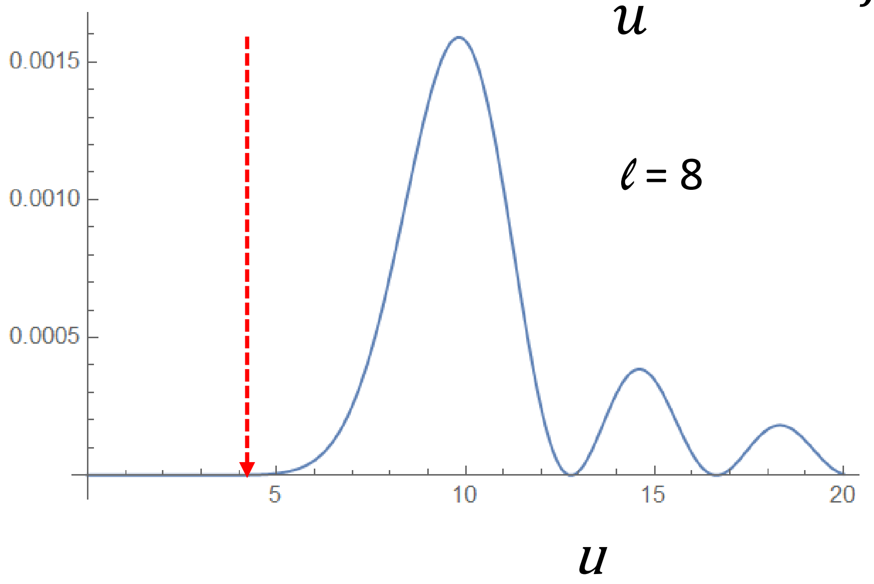




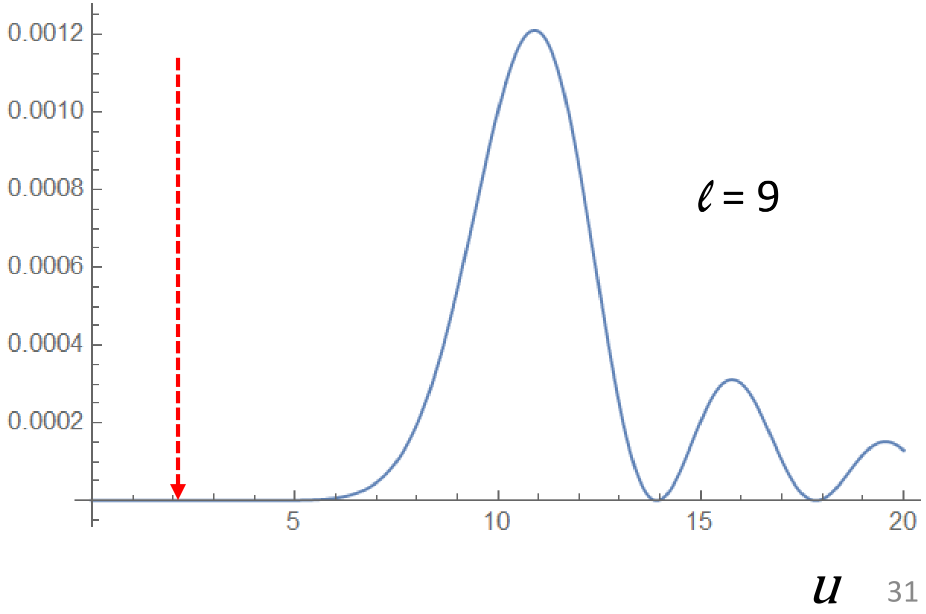


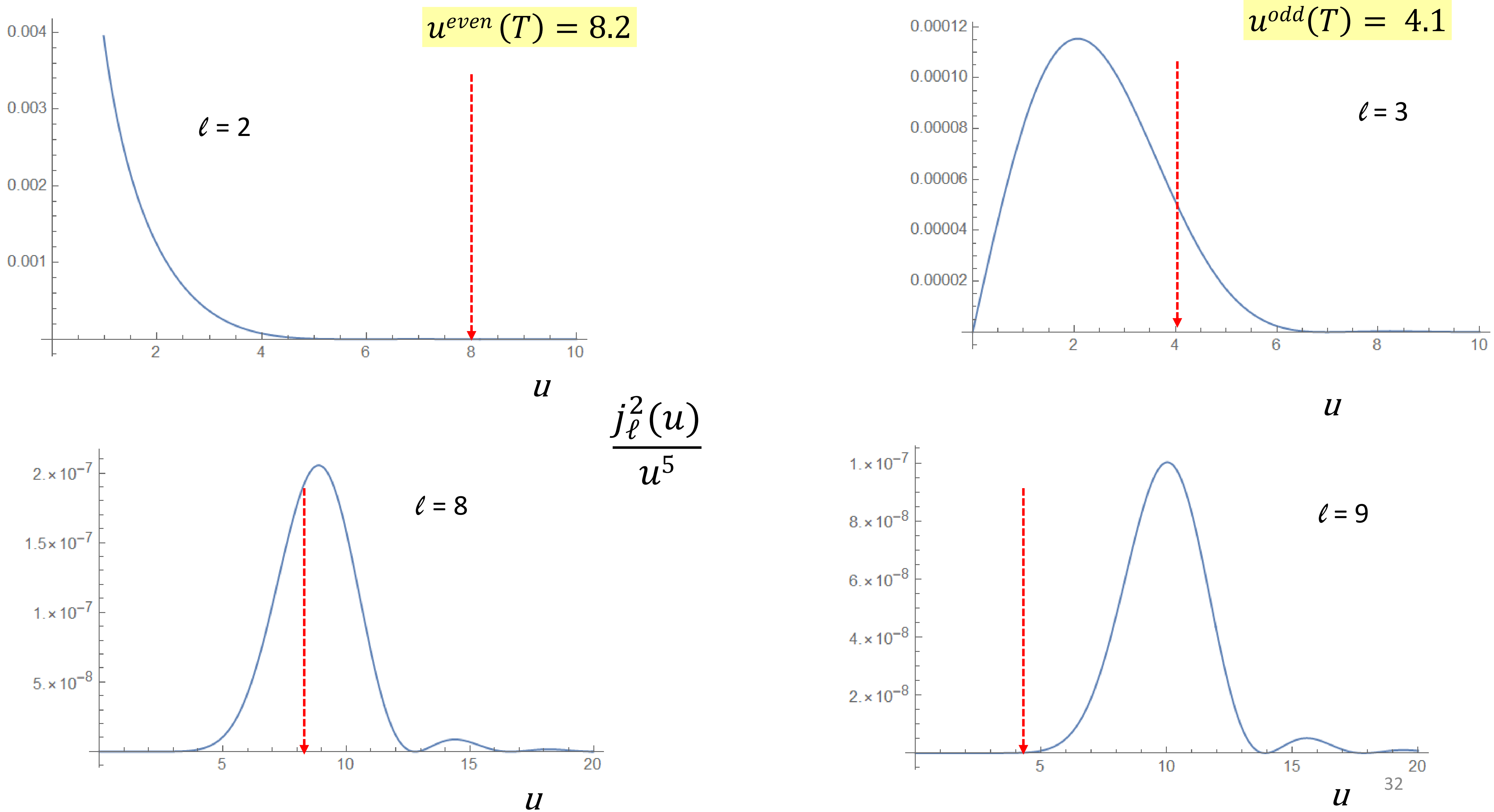
The first peak moves rightwards

$$\frac{j_\ell^2(u)}{u} \ as\ a\ function\ of\ u$$



Practically no effect





$u^{even}(T) = 8.2$
$\ell = 2$
$u^{odd}(T) = 4.1$
$\ell = 3$
$\frac{j_\ell^2(u)}{u^5}$
$\ell = 8$
$\ell = 9$
u

- Neumann–Neumann (+,+) with BCs: $\partial_y f_n(0) = 0,\ \partial_y f_n(L) = 0$.
  The set of solutions and allowed mass spectrum (including zero mode) can be written as

$$f_n(y) = \cos\left(\frac{2ny}{R}\right) = \cos\left(\frac{2n\pi y}{L}\right),\ m_n = \frac{2n}{R},\ n = 0, 1, 2, \cdots . \tag{16}$$

  Note that all modes are even under both $y \to -y$ and $y \to L - y$.
  The combined parity turns out to be *even*.

- Dirichlet–Dirichlet (−,−) with BCs: $f_n(0) = 0,\ f_n(L) = 0$.
  Solutions and mass spectrum (no zero mode):

$$f_n(y) = \sin\left(\frac{(2n+2)y}{R}\right) = \sin\left(\frac{(2n+2)\pi y}{L}\right),\ m_n = \frac{(2n+2)}{R}\ \ n = 0, 1, 2, \ldots . \tag{17}$$

  The combined parity is *even*.

- Neumann–Dirichlet (+,−) with BCs: $\partial_y f_n(0) = 0,\ f_n(L) = 0$.
  Solutions and mass spectrum (no zero mode):

$$f_n(y) = \cos\left(\frac{(2n+1)y}{R}\right) = \cos\left(\frac{(2n+1)\pi y}{L}\right),\ m_n = \frac{(2n+1)}{R},\ n = 0, 1, 2, \ldots . \tag{18}$$

  The combined parity is *odd*.

- Dirichlet–Neumann (−,+) with BCs: $f_n(0) = 0,\ \partial_y f_n(L) = 0$.
  Solutions and mass spectrum (no zero mode):

$$f_n(y) = \sin\left(\frac{(2n+1)y}{R}\right) = \sin\left(\frac{(2n+1)\pi y}{L}\right),\ m_n = \frac{(2n+1)}{R},\ n = 0, 1, 2, \ldots . \tag{19}$$

  The combined parity is *odd*.

In this way, the mass spectrum of scalar fields with BCs $(-,-)$ and $(-,+)$ can be related from Equations (17) and (19) as follows:

$$\boxed{\frac{m_n^{(-,-)}}{m_n^{(-,+)}} = \frac{2n+2}{2n+1},\ n = 0, 1, 2, \ldots .} \tag{20}$$