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Non-Gaussian extrema counts for CMB maps

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In the context of the geometrical analysis of weakly non-Gaussian cosmic microwave background maps, the 2D differential extrema counts as functions of the excursion set threshold is derived from the full moments expansion of the joint probability distribution of an isotropic random field, its gradient, and invariants of the Hessian. Analytic expressions for these counts are given to second order in the non-Gaussian correction, while a Monte Carlo method to compute them to arbitrary order is presented. Matching count statistics to these estimators is illustrated on fiducial non-Gaussian Planck data.

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Random fields are ubiquitous phenomena in physics appearing in areas ranging from turbulence to the landscape of string theories. In cosmology, the sky-maps of the polarized cosmic microwave background (CMB) radiation—a focal topic of current research—is a prime example of such 2D random fields. Modern view of the cosmos, developed primarily through statistical analysis of these fields, points to a Universe that is statistically homogeneous and isotropic with a hierarchy of structures arising from small Gaussian fluctuations of quantum origin. While the Gaussian limit provides the fundamental starting point in the study of random fields [1–3], non-Gaussian features of the CMB fields are of great interest. Indeed, CMB inherits a high level of Gaussianity from initial fluctuations, but small non-Gaussian deviations may provide a unique window into the details of processes in the early Universe. The search for the best methods to analyze non-Gaussian random fields is ongoing.

In Ref. [4] the general invariant based formalism for computing topological and geometrical characteristics of non-Gaussian fields was presented. The general formulas for the Euler characteristics to all orders has been derived, which encompasses the well-known first correction [5] and which was later confirmed to the next order by [6]. We now focus on the statistics of the density of extremal points that follows directly from the formalism of [4]. Extrema counts is an example of the real space statistical measures that can be used to detect non-Gaussianity and place the limits on the cosmological models that give rise to it in a way complimentary to the spectral techniques (see e.g. [7]). The goal of this paper is to provide an explicit recipe on how to use this formalism in practice on idealized 2D CMB Planck-like data.

I. EXTREMA COUNTS

Extrema counts, especially that of the maxima of the field, have long application to cosmology (see e.g. [3]); however, theoretical developments have been mostly

restricted to the Gaussian fields. The statistics of extrema counts, as well as of the Euler number, requires the knowledge of the one-point joint probability distribution function (JPDF) $P(x, x_i, x_{ij})$ of the field x , its first, x_i , and second, x_{ij} , derivatives [8]. Extrema density is an intrinsically isotropic statistics given by [1,9]

$$\frac{\partial n_{\text{ext}}}{\partial x} = \int d^3x_{ij} P(x, x_i = 0, x_{ij}) |x_{ij}|. \quad (1)$$

Under the condition of statistical isotropy of the field, the essential form for the JPDF is therefore given in terms of the rotation invariants— x itself, the square of the magnitude of the gradient $q^2 \equiv x_1^2 + x_2^2$, and the two invariants $J_1 \equiv \lambda_1 + \lambda_2$, $J_2 \equiv (\lambda_1 - \lambda_2)^2$ of the Hessian matrix x_{ij} (where λ_i are the eigenvalues of the Hessian). Introducing $\zeta = (x + \gamma J_1)/\sqrt{1 - \gamma^2}$ (where the spectral parameter $\gamma = -\langle x J_1 \rangle$ characterizes the shape of the underlying power spectrum), leads to the following JPDF for the Gaussian 2D field:

$$G_{2D} = \frac{1}{2\pi} \exp \left[-\frac{1}{2}\zeta^2 - q^2 - \frac{1}{2}J_1^2 - J_2 \right]. \quad (2)$$

The invariant form for the extrema counts

$$\frac{\partial n_{\text{ext}}}{\partial x} = \int \frac{dJ_1 dJ_2}{8\pi^2 \sqrt{1 - \gamma^2}} \exp \left[-\frac{1}{2}\zeta^2 - \frac{1}{2}J_1^2 - J_2 \right] |J_1^2 - J_2|$$

then readily recovers the classical results [1,3,9] when the limits of integration that define the extrema type are implemented, namely, $J_1 \in [-\infty, 0]$, $J_2 \in [0, J_1^2]$ for maxima, $J_1 \in [0, \infty]$, $J_2 \in [0, J_1^2]$ for minima, and $J_1 \in [-\infty, \infty], J_2 \in [J_1^2, \infty]$ for saddle points.

In [4] we have observed that for non-Gaussian JPDF the invariant approach immediately suggests a Gram-Charlier expansion in terms of the orthogonal polynomials defined by the kernel G_{2D} . Since ζ , q^2 , J_1 , and J_2 are uncorrelated variables in the Gaussian limit, the resulting expansion is

$$P_{2D}(\zeta, q^2, J_1, J_2) = G_{2D} \left[1 + \sum_{n=3}^{\infty} \sum_{i,j,k,l=0}^{i+2j+k+2l=n} \frac{(-1)^{j+l}}{i!j!k!l!} \langle \zeta^i q^{2j} J_1^k J_2^l \rangle_{\text{GC}} H_i(\zeta) L_j(q^2) H_k(J_1) L_l(J_2) \right], \quad (3)$$

where terms are sorted in the order of the field power n and $\sum_{i,j,k,l=0}^{i+2j+k+2l=n}$ stands for summation over all combinations of non-negative i, j, k, l such that $i + 2j + k + 2l$ adds to the order of the expansion term n . H_i are (*probabilists'*) Hermite and L_j are Laguerre polynomials.

The Gram-Charlier coefficients, $\langle \zeta^i q^{2j} J_1^k J_2^l \rangle_{\text{GC}} \equiv (-1)^{j+l} j!l! \langle H_i(\zeta) L_j(q^2) H_k(J_1) L_l(J_2) \rangle_m$ that appear in the expansion can be related to the more familiar cumulants of the field and its derivatives (we use $\langle \rangle_m$ for statistical moments while reserving $\langle \rangle$ for statistical cumulants), actually being identical to them for the first three orders $n = 3, 4, 5$. See Ref. [10] for lookup tables of the relationship between Gram-Charlier cumulants and statistical cumulants. As an illustration, one sixth-order nontrivial cumulant would be $\langle J_1^3 J_2 \zeta \rangle_{\text{CG}} = \langle J_1^3 J_2 \zeta \rangle + \langle J_1^3 \rangle \langle J_2 \zeta \rangle + 3 \langle J_1 J_2 \rangle \langle J_1^2 \zeta \rangle$. It is prudent to stress that the Gram-Charlier series expansion is distinct from the perturbative expansions. For instance, while the linear Edgeworth or f_{NL} expansion match solely to the first-order $n = 3$ Gram-Charlier coefficients, quadratic terms require knowledge of the Gram-Charlier terms to $n = 6$, while the cubic ones to $n = 9$.

Integrals over J_1 and J_2 for extremal points can be carried out analytically even for the general expression (3).

Different types of critical points can be evaluated separately by restraining the integration domain in the $J_1 - J_2$ plane to ensure the appropriate signs for the eigenvalues.

The effect of the non-Gaussian cubic correction on the total number of the extrema of different types is given by

$$\begin{aligned} n_{\text{max/min}} &= \frac{1}{8\sqrt{3}\pi R_*^2} \pm \frac{18\langle q^2 J_1 \rangle - 5\langle J_1^3 \rangle + 6\langle J_1 J_2 \rangle}{54\pi\sqrt{2\pi}R_*^2}, \\ n_{\text{sad}} &= \frac{1}{4\sqrt{3}\pi R_*^2}, \end{aligned} \quad (4)$$

where we have restored (see note [11]) the dimensional scaling with $R_* = \sigma_1/\sigma_2$, the characteristic separation scale between extrema. The total number of saddles, as well as of all the extremal points, $n_{\text{max}} + n_{\text{min}} + n_{\text{sad}}$, are preserved in the first-order (the latter following for the former, as topological considerations imply $n_{\text{max}} - n_{\text{sad}} + n_{\text{min}} = \text{const}$), but the symmetry between the minima and the maxima is broken.

The differential number counts with respect to the excursion threshold ν are given by

$$\begin{aligned} \frac{\partial n_{\text{max/min}}}{\partial \nu} &= \frac{1}{\sqrt{2\pi}R_*^2} \exp\left(-\frac{\nu^2}{2}\right) \left[1 \pm \text{erf}\left(\frac{\gamma\nu}{\sqrt{2(1-\gamma^2)}}\right) \right] K_1(\nu, \gamma) \pm \frac{1}{\sqrt{2\pi(1-\gamma^2)}R_*^2} \exp\left(-\frac{\nu^2}{2(1-\gamma^2)}\right) K_3(\nu, \gamma) \\ &+ \frac{\sqrt{3}}{\sqrt{2\pi(3-2\gamma^2)}R_*^2} \exp\left(-\frac{3\nu^2}{6-4\gamma^2}\right) \left[1 \pm \text{erf}\left(\frac{\gamma\nu}{\sqrt{2(1-\gamma^2)(3-2\gamma^2)}}\right) \right] K_2(\nu, \gamma), \end{aligned} \quad (5)$$

$$\frac{\partial n_{\text{sad}}}{\partial \nu} = \frac{2\sqrt{3}}{\sqrt{2\pi(3-2\gamma^2)}R_*^2} \exp\left(-\frac{3\nu^2}{6-4\gamma^2}\right) K_2(\nu, \gamma), \quad (6)$$

where K_1, K_2, K_3 are polynomials with coefficients expressed in terms of the cumulants. Here we give explicit expressions for the first non-Gaussian order, while the next order can be found at [10].

The term $K_1(\nu, \gamma)$ has a special role determining the Euler number $\chi(\nu)$ via $\partial\chi/\partial\nu = \partial/\partial\nu(n_{\text{max}} + n_{\text{min}} - n_{\text{sad}}) = \sqrt{2/\pi}R_*^{-2} \exp(-\nu^2/2)K_1(\nu, \gamma)$. As such, its full expansion has been given in [4], Eq. (7), and confirmed to the second order in [6]. To the leading non-Gaussian order

$$K_1 = \frac{\gamma^2}{8\pi} \left[H_2(\nu) + \left(\frac{2}{\gamma} \langle q^2 J_1 \rangle + \frac{1}{\gamma^2} \langle x J_1^2 \rangle - \frac{1}{\gamma^2} \langle x J_2 \rangle \right) H_1(\nu) - \left(\langle x q^2 \rangle + \frac{1}{\gamma} \langle x^2 J_1 \rangle \right) H_3(\nu) + \frac{1}{6} \langle x^3 \rangle H_5(\nu) \right]. \quad (7)$$

Introducing scaled Hermite polynomials $\mathcal{H}_n^\pm(\nu, \sigma) \equiv \sigma^{\pm n} H_n(\nu/\sigma)$, the polynomial $K_2(\nu, \gamma)$, the only one that determines the distribution of saddle points, can be written as

$$K_2 = \frac{1}{8\pi\sqrt{3}} \left[1 - \left(\langle xq^2 \rangle + \frac{1}{3} \langle xJ_1^2 \rangle - \frac{4}{3} \langle xJ_2 \rangle + \frac{2}{3} \gamma \langle q^2 J_1 \rangle + \frac{2}{9} \gamma \langle J_1^3 \rangle - \frac{2}{3} \gamma \langle J_1 J_2 \rangle \right) \mathcal{H}_1^-(\nu, \sqrt{1 - 2/3\gamma^2}) \right. \\ \left. + \frac{1}{6} \left(\langle x^3 \rangle + 2\gamma \langle x^2 J_1 \rangle + \frac{4}{3} \gamma^2 \langle xJ_1^2 \rangle + \frac{2}{3} \gamma^2 \langle xJ_2 \rangle + \frac{8}{27} \gamma^3 \langle J_1^3 \rangle + \frac{4}{9} \gamma^3 \langle J_1 J_2 \rangle \right) \mathcal{H}_3^-(\nu, \sqrt{1 - 2/3\gamma^2}) \right]. \quad (8)$$

The remaining term $K_3(\nu, \gamma)$ is the most complicated one. It is expressed as the expansion in $\mathcal{H}_n^+(\nu, \sqrt{1 - \gamma^2})$:

$$K_3 = \frac{(1 - \gamma^2)}{2(2\pi)^{3/2}(3 - 2\gamma^2)^3} \left[\gamma(3 - 2\gamma^2)^3 \mathcal{H}_1^+(\nu, \sqrt{1 - \gamma^2}) + \left(\frac{1}{2} \gamma^3 (1 + \gamma^2 - 26\gamma^4 + 28\gamma^6 - 8\gamma^8) \langle x^3 \rangle \right. \right. \\ \left. - \gamma^4 (26 - 28\gamma^2 + 8\gamma^4) \langle x^2 J_1 \rangle + \gamma(1 - \gamma^2)(1 + 2\gamma^2)(3 - 2\gamma^2)^2 \langle xq^2 \rangle - \gamma(24 - 26\gamma^2 + 8\gamma^4) \langle xJ_1^2 \rangle \right. \\ \left. + \gamma(15 - 23\gamma^2 + 8\gamma^4) \langle xJ_2 \rangle + 4(1 - \gamma^2)(3 - 2\gamma^2)^2 \langle q^2 J_1 \rangle - (10 - 12\gamma^2 + 4\gamma^4) \langle J_1^3 \rangle + 6(1 - \gamma^2)(2 - \gamma^2) \langle J_1 J_2 \rangle \right) \\ - \frac{1}{6} (\gamma(27 + 36\gamma^2 - 224\gamma^4 + 192\gamma^6 - 48\gamma^8) \langle x^3 \rangle + (108 - 324\gamma^2 + 216\gamma^4 - 48\gamma^6) \langle x^2 J_1 \rangle \\ \left. + 6\gamma(3 - 2\gamma^2)^3 \langle xq^2 \rangle - 36\gamma \langle xJ_1^2 \rangle - 18\gamma \langle xJ_2 \rangle - 8\gamma^2 \langle J_1^3 \rangle - 12\gamma^2 \langle J_1 J_2 \rangle) \mathcal{H}_2^+(\nu, \sqrt{1 - \gamma^2}) \right]. \quad (9)$$

Equations (5) and (6) (together with the next order expansion available online) are the main theoretical result of this paper.

II. IMPLEMENTATION

Evaluating these estimators requires computing the cumulants appearing in Eqs. (7)–(9). In non-Gaussian models where the field is represented by the functional of a Gaussian field this may be possible directly, while in general, as shown in [6], such cumulants can be found as weighted marginals of the underlying bispectrum (to third order), trispectrum (to fourth order), etc. On a sphere, the high-order marginals are particularly cumbersome and time consuming to compute, as they also involve the contractions of $n - j$ Wigner symbols. Here we suggest a different route, based on the assumption that scientists interested in fitting extrema counts to non-Gaussian maps are typically in a position to generate realizations of such maps. In that case, it becomes relatively straightforward to draw samples of such maps, and estimate the corresponding cumulants. The HEALPIX [12] library provides in fact a direct estimate of the derivatives of such maps up to second order, which is all that is required to compute the cumulants of the JPDF.

As an illustration, let us generate sets of parameterized non-Gaussian maps using the package SKY-NG-SIM [13] of HEALPIX. In this so-called harmonic model, the PDF of the pixel temperature T is given by $\exp(-T^2/2\sigma_0^2) |\sum_{i=0}^n \alpha_i C_i H_i(T/\sigma_0)|^2$, where C_i are normalization constants. In this paper, we use NSIDE=2048, $\ell_{\max} = 4096$, $n = 2$, $\sigma_0 = 1$ and vary α_1 and α_2 . We also consider the second option of SKY-NG-SIM, which produces non-Gaussian field as even power, β of unit variance zero mean Gaussian fields. For each set of maps, we compute its derivatives, and arithmetically

average the corresponding cumulants, using a code, MAP2CUM, relying on the HEALPIX routine ALM2MAP_DER. Invariant variables J_1 and J_2 on a sphere are defined via the mixed tensor of covariant derivatives $J_1 = x_{;i}^{,i}$ and $J_2 = J_1^2 - 4|x_{;i}^{,j}|$. The differential counts are then evaluated for a range of threshold, $\nu \in [-5, 5]$. For each of these maps, the number of extrema is computed by the procedure MAP2EXT that implements the following algorithm: for every pixel a segment of quadratic surface is fit in the tangent plane based on the temperature values at the pixel of origin and its HEALPIX neighbors. The position of the extremum of this quadratic, its height, and its Hessian are computed. The extremum is counted into the tally of the type determined by its Hessian if its position falls within the original pixel. Several additional checks are performed to preclude registering extrema in the neighboring pixels and minimize missing extrema due to jumps in the fit parameters as region shifts to the next pixel. Masks are treated by not considering pixels next to the mask boundary. Pixel-pixel noise covariance can be included while doing the local fit. On noise-free maps the procedure performs with better than 1% accuracy when the map is smoothed with a Gaussian filter with FWHM exceeding six pixels. Both MAP2CUM and MAP2EXT are available upon request. Figure 1 illustrates the very good agreement between the theoretical expectation of the differential number counts and the low-frequency ν dependency of the measured ones for both the harmonic and the power-law models.

We have also successfully explored an alternative numerical procedure based on Monte Carlo (see e.g. [11]) evaluation of the integral (1) over the distribution function. This procedure is likely to be more practical for expansion beyond the fourth order for 2D topological invariants. Starting from Eq. (3), we reexpress both the polynomials

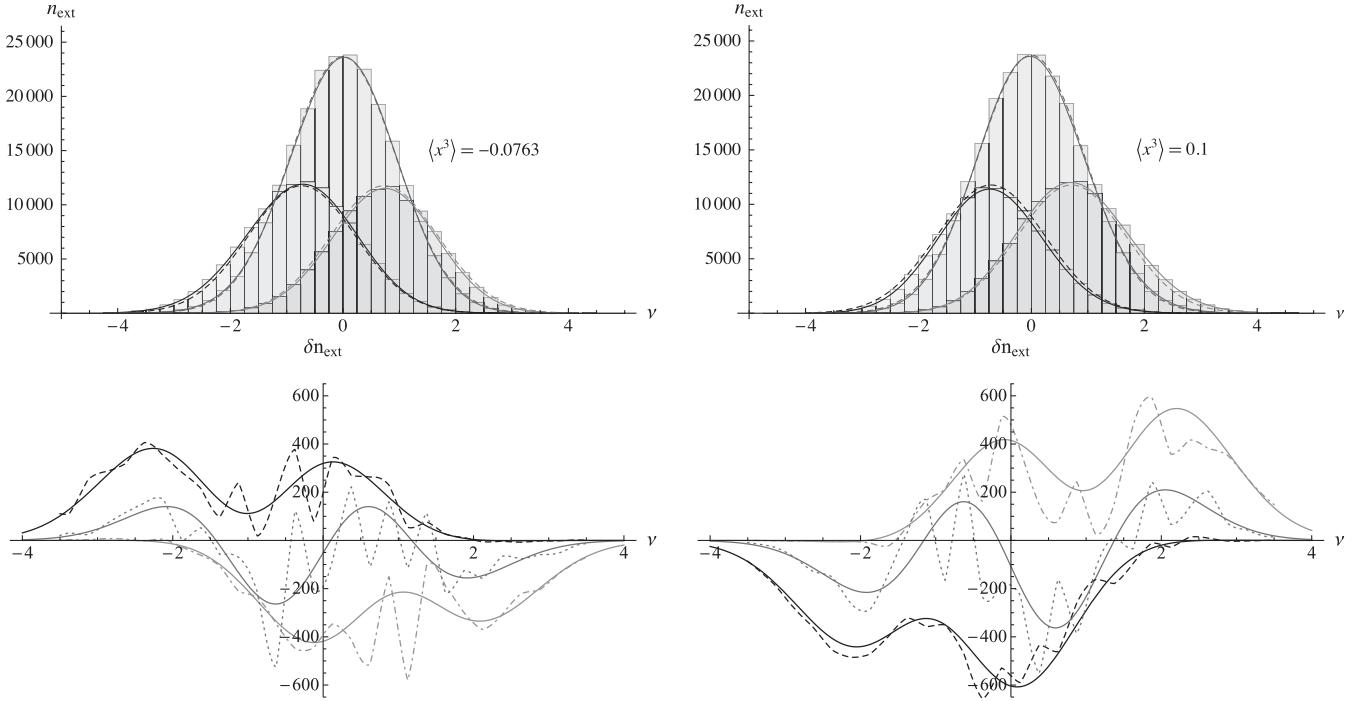


FIG. 1. (Top) Predicted (solid line) number of maxima (right), saddle (middle), and minima (left) in $\Delta\nu = 0.25$ bins as a function of the threshold, ν , on top of the measured count from a single realization full-sky NSIDE=2048 HEALPIX map (histogram). The temperature field is smoothed with the Gaussian filter of 10 arcmin FWHM, resulting in $R_* \approx 5.5 \text{ arcmin} \approx 3 \text{ pixels}$. The dashed line corresponds to the Gaussian prediction. The left panel corresponds to the harmonic oscillator model of non-Gaussianity with $\alpha_1 = 0.6$, $\alpha_2 = 0.6$ (for which $\langle x^3 \rangle = -0.07$), while the right panel corresponds to the power-law non-Gaussianity with $\beta = 2$ (for which $\langle x^3 \rangle = 0.1$). (Bottom) Departure from Gaussianity for the two models as predicted (solid line) and measured (dashed line) for maxima (light grey), minima (dark grey), and saddle points (grey). Note that the corrections of Eqs. (5) and (6) (solid line) give a very accurate match to the low-frequency ν behavior of the measured PDF. As is seen, different models of non-Gaussianity can be distinguished by their effects on extrema.

in J_1 , J_2 , ζ , and q^2 and G_{2D} in terms of the six field variables, (x, x_i, x_{ij}) . It is then straightforward to draw large sets of random number triplets x_{11}, x_{22}, x_{12} satisfying the Gaussian marginal distribution $G_\nu(x_{11}, x_{12}, x_{22}|x = \nu, x_1 = x_2 = 0)$. The integrand then consists of the correction to the JPDF in Eq. (3) times $|J_1^2 - J_2|/4$. Each triplet element constitutes a Hessian matrix and is sorted to contribute to either minima, saddle, or maxima count based on the signs of its eigenvalues. The sum of the integrand over all triplets yields a Monte Carlo estimate of $\partial n_{\text{ext}}/\partial \nu$.

We note that all of the presented analysis allows for straightforward generalization to 3D (notably the Monte Carlo method), as shown in [14], to describe the large scale distribution (LSS) of matter. Indeed in this context, the gravitational instability that nonlinearly maps

the initial Gaussian inhomogeneities in matter density into the LSS induces strong non-Gaussian features culminating in the formation of collapsed, self-gravitating objects such as galaxies and clusters of galaxies.

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