Symmetry in the Early Universe: Searcing For Parity Violation

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Outline

- Discrete Symmetry (C, P, T, CP, CPT) in Particle Physics (in particular in the Standard Model): A Historical Perspective
- Discrete Symmetries in the Universe
  - Parity and the CMB Power Spectrum
  - Parity and the 3d Density Field
  - Parity and the CMB Bispectrum
  - Constructing an Efficient Estimator
- Conclusions

Symmetry in Physics

- Homogeneity and isotropy of spacetime
- Lorentz invariance
- Charge conjugation
- Parity
- Time reversal: arrow of time
- Electromagnetism and U(1)
- $SU(2)_{isospin}$, the eightfold way
- Yang-Mills: $SU(2)_L$, $U(1)_Y$, $SU(3)_{color}$, $SU(5)$?, ...
- Gravity as a gauge symmetry (general covariance)
- Supersymmetry
- ....

In the absence of evidence to the contrary, physicists (in particular theorists) have tended to presume that Nature is as symmetric as possible, and experiment often has proven a universe less symmetric than it would be if designed by theorists.

PARITY AND CP IN THE STANDARD MODEL

1956 — $\theta - \tau$ puzzle - charged kaon decay

$\theta \to 2\pi$, $\tau \to 3\pi$; therefore, they must be different particles having different masses and lifetimes. But as data got better, the differences in measured masses and measured lifetimes became implausibly small.

PHYSICAL REVIEW VOLUME 104, NUMBER 1 OCTOBER 1, 1956

Question of Parity Conservation in Weak Interactions*

T. D. LEE, *Columbia University, New York, New York*

AND

C. N. YANG,† *Brookhaven National Laboratory, Upton, New York*

(Received June 22, 1956)

The question of parity conservation in β decays and in hyperon and meson decays is examined. Possible experiments are suggested which might test parity conservation in these interactions.

RECENT experimental data indicate closely identical masses[1] and lifetimes[2] of the $\theta^+(\equiv K_{\pi 2}^+)$ and the $\tau^+(\equiv K_{\pi 3}^+)$ mesons. On the other hand, analyses[3] of the decay products of τ^+ strongly suggest on the grounds of angular momentum and parity conservation that the τ^+ and θ^+ are not the same particle. This poses a rather puzzling situation that has been extensively discussed.[4]

One way out of the difficulty is to assume that parity is not strictly conserved, so that θ^+ and τ^+ are two different decay modes of the same particle, which necessarily has a single mass value and a single lifetime. We wish to analyze this possibility in the present paper against the background of the existing experimental evidence of parity conservation. It will become clear that existing experiments do indicate parity conserva-

PRESENT EXPERIMENTAL LIMIT ON PARITY NONCONSERVATION

If parity is not strictly conserved, all atomic and nuclear states become mixtures consisting mainly of the state they are usually assigned, together with small percentages of states possessing the opposite parity. The fractional weight of the latter will be called $\mathfrak{F}^2$. It is a quantity that characterizes the degree of violation of parity conservation.

The existence of parity selection rules which work well in atomic and nuclear physics is a clear indication that the degree of mixing, $\mathfrak{F}^2$, cannot be large. From such considerations one can impose the limit $\mathfrak{F}^2 \lesssim (r/\lambda)^2$, which for atomic spectroscopy is, in most cases, $\sim 10^{-6}$. In general a less accurate limit obtains for nuclear spectroscopy.

1957

Experimental Test of Parity Conservation in Beta Decay*

C. S. Wu, *Columbia University, New York, New York*

AND

E. Ambler, R. W. Hayward, D. D. Hoppes, and R. P. Hudson, *National Bureau of Standards, Washington, D. C.*

(Received January 15, 1957)

In a recent paper[1] on the question of parity in weak interactions, Lee and Yang critically surveyed the experimental information concerning this question and reached the conclusion that there is no existing evidence either to support or to refute parity conservation in weak interactions. They proposed a number of experiments on beta decays and hyperon and meson decays which would provide the necessary evidence for parity conservation or nonconservation. In beta decay, one could measure the angular distribution of the electrons coming from beta decays of polarized nuclei. If an asymmetry in the distribution between θ and $180°-\theta$ (where θ is the angle between the orientation of the parent nuclei and the momentum of the electrons) is observed, it provides unequivocal proof that parity is not conserved in beta decay. This asymmetry effect has been observed in the case of oriented Co^{60}.

It has been known for some time that Co^{60} nuclei can be polarized by the Rose-Gorter method in cerium magnesium (cobalt) nitrate, and the degree of polarization detected by measuring the anisotropy of the succeeding gamma rays.[2] To apply this technique to the present problem, two major difficulties had to be over-

sotropy alone provides a reliable measure of nuclear polarization. Specimens were made by taking good single crystals of cerium magnesium nitrate and growing on the upper surface only an additional crystalline layer containing Co^{60}. One might point out here that since the allowed beta decay of Co^{60} involves a change of spin of

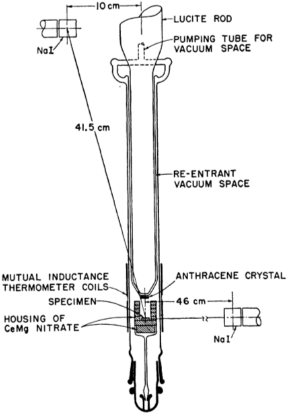
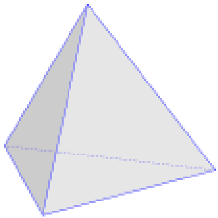


Fig. 1. Schematic drawing of the lower part of the cryostat.

Lee-Yang Nobel Prize (1957).

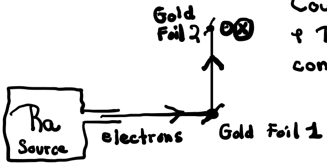
A non-planar tetrahedron whose sides are numbered (or of unequal length) defines a chirality. It cannot be rotated into its mirror image. A tetrahedron is defined by 3 linearly-independent (nonplanar) vectors, or four momenta satisfying $\sum_{i=1} \mathbf{p}_i = 0$.



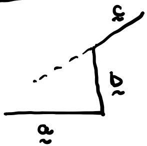
$\mathbf{a} \cdot (\mathbf{b} \times \mathbf{c})$ violates parity (or defines a chirality) if non-zero.
Spin (or any other "axial vector") may be thought of as a pair of polar vectors (sort of defining a plane) $[\mathbf{S} = \mathbf{x} \times \mathbf{p}]$.

Cox (1928) and Chase (1930)

Forgotten Discovery of Parity Violation in Observation of β-ray Helicity in Radium Decay



Counts Up & Down are compared



$$\underset{\sim}{a}^2 = \underset{\sim}{b}^2 = \underset{\sim}{c}^2 = 1$$

$$\underset{\sim}{a}\cdot\underset{\sim}{b} = \underset{\sim}{b}\cdot\underset{\sim}{c} = \underset{\sim}{c}\cdot\underset{\sim}{a} = 0$$

But

$$\mathrm{sgn}\left[\underset{\sim}{a}\cdot(\underset{\sim}{b}\times c)\right]$$

has two choices.

Recall the Dirac equation was discovered only in 1928.

Modern Interpretation

Mott scattering (relativistic Coloumb scattering of a spin-$\frac{1}{2}$ particle off a pointlike spin-0 particle or external potential)

$(\underset{\sim}{\Omega}_i \times \underset{\sim}{\Omega}_f) \cdot \underset{\sim}{\sigma}$ spin-orbit relativistic contribution

1st scatter converts electron helicity into linear polarization

$\perp$ component respects P

$\parallel$ component violates P

2nd scatter measures linear polarization

★★ Much easier than Wu, Ambler et al. experiment

No cryogenics

Refs. Allan Franklin, *Neglect of Experiment*, CUP (1986)

R.T. Cox et al., Proc. Nat. Academie of Sciences 14 (1928) 544-9

C. Chase, Phys. Rev. 36 (1930) 1060

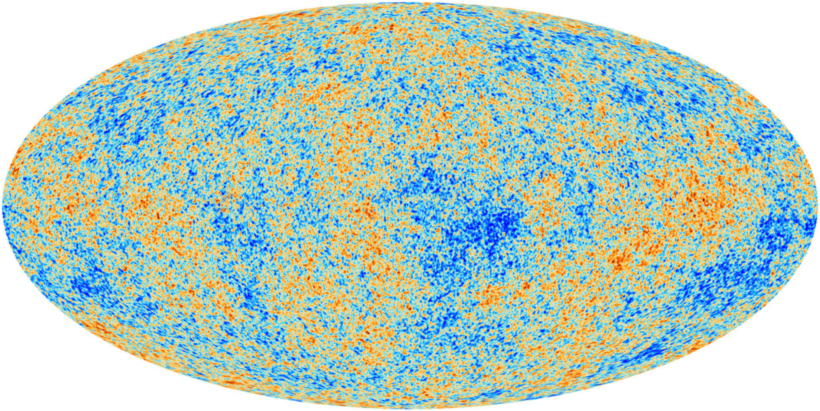
L. Grodzins, Proc. Nat. Acad. 45 (1959) 399

Reflections on the CP Violationi Discovery

Physics as a science has made incredible progress because of the delicate interplay between theory and experiment. Astonishing predictions based on theories devised to account for known phenomena have been confirmed by experiment. Experiments probing previously unexplored areas often reveal physical effects which are completely unanticipated by theoretical conjecture.

—Val Fitch, 1980 Nobel Lecture

PARITY AND CP IN THE UNIVERSE

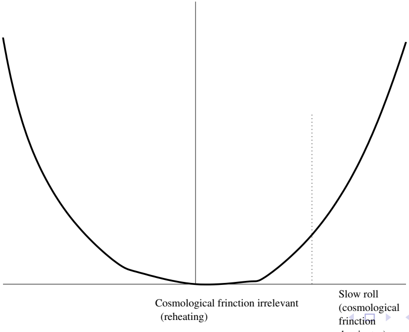


Some references

- M Kamionkowski, T Souradeep "Odd-parity cosmic microwave background bispectrum," Physical Review D, 2011 (arXiv:1010.4304)
- Maresuke Shiraishi, Michele Liguori, James R. Fergusson, "General parity-odd CMB bispectrum estimation," JCAP 05 (2014) 008 arXiv:1403.4222 [astro-ph.CO]
- Lots of theory papers with specific models....
- MB (in preparation - bispectrum method paper). Application to Planck maps next.
- EB and TB Power spectrum birefrigence: claim. Eskit and Komatsu, PRD 106 (2022à 063503 Rotation by $\beta = 0.342^\circ \pm 0.094^\circ$ parity violation claim.
- Papers on density 4pt function in 3D. O. Philcox, PRD 106 (2022) 063501 [2.9σ] Hou, Slepian and Chan, MNRAS 522 (2023) 5701 [Parity violation claim at 3.1σ and 7.1σ]

In the beginning there was a scalar field that dominated the universe. Everything came from this scalar field and there was nothing without the scalar field. The quantum fluctuations of this field (that is, those of the vacuum) generated small fluctuations that advanced or retarded the instant of re-heating. These were the seeds of the large-scale structure.

$$\ddot{\phi} + 3H\dot{\phi} = -V_{,\phi}$$



Searching for Parity Violation in the Power Spectrum (aka 2-point function)

Under P, T and E are polar whereas B is axial. Thus under P

$$c_\ell^{AA} \rightarrow +c_\ell^{AA}, \text{for} \quad A = T, E, B$$

$$c_\ell^{TE} \rightarrow +c_\ell^{TE}$$

But

$$c_\ell^{TB} \rightarrow -c_\ell^{TB}$$

$$c_\ell^{EB} \rightarrow -c_\ell^{EB}$$

Much work has already carried out using this approach, but difficult in the absence of a primordial B mode signal.

A frequency-independent circular birefringence in the propagation of the photons from the surface of last scatter to us today would mimic the same effect.

Extremely accurate absolute calibration of detector orientations is required for this kind of measurement.

Planck 2013 Results. XXIV. Constraints on primordial non-Gaussianity

Planck Collaboration: P. A. R. Ade, N. Aghanim, C. Armitage-Caplan, M. Arnaud, M. Ashdown, F. Atrio-Barandela, J. Aumont, C. Baccigalupi, A. J. Banday, R. B. Barreiro, J. G. Bartlett, N. Bartolo, E. Battaner, K. Benabed, A. Benoît, A. Benoit-Lévy, J.-P. Bernard, M. Bersanelli, P. Bielewicz, J. Bobin, J. J. Bock, A. Bonaldi, L. Bonavera, J. R. Bond, J. Borrill, F. R. Bouchet, M. Bridges, M. Bucher, C. Burigana, R. C. Butler, J.-F. Cardoso, A. Catalano, A. Challinor, A. Chamballu, L.-Y Chiang, H. C. Chiang, P. R. Christensen, S. Church, D. L. Clements, S. Colombi, L. P. L. Colombo, F. Couchot, A. Coulais, B. P. Crill, A. Curto, F. Cuttaia, R. D. Davies, R. J. Davis, P. de Bernardis, A. de Rosa, G. de Zotti, J. Delabrouille, J.-M. Delouis, F.-X. Désert, J. M. Diego, H. Dole, S. Donzelli, et al. (175 additional authors not shown) (Submitted on 20 Mar 2013)

The Planck nominal mission cosmic microwave background (CMB) maps yield unprecedented constraints on primordial non-Gaussianity (NG). Using three optimal bispectrum estimators, separable template-fitting (KSW), binned, and modal, we obtain consistent values for the primordial local, equilateral, and orthogonal bispectrum amplitudes, quoting as our final result $f_{NL}^{local} = 2.7 \pm 5.8$, $f_{NL}^{equil} = -42 \pm 75$, and $f_{NL}^{ortho} = -25 \pm 39$ (68% CL statistical); and we find the integrated Sachs-Wolfe lensing bispectrum expected in the ΛCDM scenario. The results are based on comprehensive cross-validation of these estimators on Gaussian and non-Gaussian simulations, are stable across component separation techniques, pass an extensive suite of tests, and are confirmed by skew-C_l, wavelet bispectrum and Minkowski functional estimators. Beyond estimates of individual shape amplitudes, we present model-independent, three-dimensional reconstructions of the Planck CMB bispectrum and thus derive constraints on early-Universe scenarios that generate primordial NG, including general single-field models of inflation, excited initial states (non-Bunch-Davies vacua), and directionally-dependent vector models. We provide an initial survey of scale-dependent feature and resonance models. These results bound both general single-field and multi-field model parameter ranges, such as the speed of sound, $c_s \geq 0.02 (95\% CL)$, in an effective field theory parametrization, and the curvaton decay fraction $r_D \geq 0.15 (95\% CL)$. The Planck data put severe pressure on ekpyrotic/cyclic scenarios. The amplitude of the four-point function in the local model $\tau_{NL} < 2800 (95\% CL)$. Taken together, these constraints represent the highest precision tests to date of physical mechanisms for the origin of cosmic structure.

Defining the Reduced Power Spectrum (assuming statistical isotropy)

$$B^{ABC}(\ell_1, \ell_2, \ell_3) = \sum_{m_1, m_2, m_3} \begin{pmatrix} \ell_1 & \ell_2 & \ell_3 \\ m_1 & m_2 & m_3 \end{pmatrix} a^A_{\ell_1 m_1} a^B_{\ell_2 m_2} a^C_{\ell_3 m_3}$$

where $A, B, C = T, E, B$.

Planck Bispectral Analysis (2013, 2015, 2018)

The official Planck non-Gaussianity analysis used three estimators:

1. The KSW estimator
2. The modal estimator
3. The binned bispectrum estimator

Of these three, the first two require a template for the pattern of expected pattern of bispectral non-Gaussianity. More precisely, one postulates an Ansatz of the form:

$$B(\ell_1, \ell_2, \ell_3) = f_{NL} B_{f_{NL}=1}(\ell_1, \ell_2, \ell_3)$$

and confidence limits (or a posterior distribution) is obtained for the scalar parameter f_{NL}.
Only estimator (3) is capable of detecting and characterizing a serendipitous signal for which there is no predicted template. Originally, the motivation was to characterize the bispectral non-Gaussianity of the foregrounds, for which a theoretical prediction was (and still is) altogether lacking. This was expected to be important for exploring whether a signal arose from inadequate foreground cleaning.

Binned bispectrum estimator

$$B^{ABC}(\ell_1, \ell_2, \ell_3) = \sum_{m_1, m_2, m_3} \begin{pmatrix} \ell_1 & \ell_2 & \ell_3 \\ m_1 & m_2 & m_3 \end{pmatrix} a^A_{\ell_1 m_1} a^B_{\ell_2 m_2} a^C_{\ell_3 m_3}$$

where $A, B, C = T, E, B$.

Gaunt Integral

$$\int_{S^2} d\hat{\mathbf{\Omega}}\ Y_{l_1 m_1}(\hat{\mathbf{\Omega}})\ Y_{l_2 m_2}(\hat{\mathbf{\Omega}})\ Y_{l_3 m_3}(\hat{\mathbf{\Omega}})$$
$$= \sqrt{4\pi(2\ell_1+1)(2\ell_2+1)(2\ell_3+1)} \begin{pmatrix} \ell_1 & \ell_2 & \ell_3 \\ 0 & 0 & 0 \end{pmatrix} \begin{pmatrix} \ell_1 & \ell_2 & \ell_3 \\ m_1 & m_2 & m_3 \end{pmatrix}$$

With coarse-graining in ℓ

$$B_{binned}([lmin_1, lmax_1]; [lmin_2, lmax_2]; [lmin_3, lmax_3])$$
$$= \int_{S^2} d\hat{\mathbf{\Omega}}\ T_{[lmin_1, lmax_1]}(\hat{\mathbf{\Omega}})\ T_{[lmin_2, lmax_2]}(\hat{\mathbf{\Omega}})\ T_{[lmin_3, lmax_3]}(\hat{\mathbf{\Omega}})$$

From Planck NG (2015)

Planck Collaboration: *Planck* 2015 Results. Constraints on primordial NG

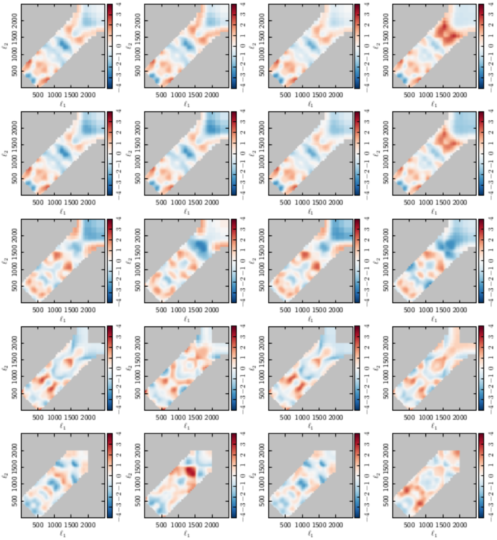


Fig. 8. Smoothed binned signal-to-noise bispectrum $\mathcal{B}$ for the *Planck* 2015 cleaned sky map, as determined with the binned estimator, as a function of ℓ_1 and ℓ_2 for a fixed ℓ_3-bin [518, 548]. From left to right results are shown for the four component separation methods `SMICA`, `SEVEM`, `NILC`, and `Commander`. From top to bottom are shown: *TTT*, *TTT* cleaned from radio and CIB point sources; *T2E*, *TE2*; and *EEE*. The colour range is in signal-to-noise from −4 to +4. The light grey regions are where the bispectrum is not defined, either because it is outside the triangle inequality or because of the cut $\ell^E_{max} = 2000$.

Symmetry properties of the Wigner 3j-symbols

$$\begin{pmatrix} \ell_{\pi(1)} & \ell_{\pi(2)} & \ell_{\pi(3)} \\ m_{\pi(1)} & m_{\pi(2)} & m_{\pi(3)} \end{pmatrix} = (1)^{\ell_1+\ell_2+\ell_3} \begin{pmatrix} \ell_1 & \ell_2 & \ell_3 \\ m_1 & m_2 & m_3 \end{pmatrix}$$

Planck papers focus almost exclusively on the even-parity sector of the bispectrum. Here is investigate how to explore efficiently the other parity-violating sector.

A Parity-Violating Version of the Gaunt Integral

For $f, g, h \in C^\infty(S^2)$, we define the triple product

$$\{f, g, h\} = \int_{S^2} f(\mathbf{d}g \wedge \mathbf{d}h) = -\int_{S^2} f(\mathbf{d}h \wedge \mathbf{d}g) = -\{f, h, g\}$$

This definition is based on the Cartan exterior differential calculus and thus (unlike the Gaunt integral) does not rely on an metric structure (or even volume 2-form) on the sphere.

$$0 = \int_{S^2} (\mathbf{d}(fg)) \wedge \mathbf{d}h) = \int_{S^2} f(\mathbf{d}g) \wedge \mathbf{d}h) + \int_{S^2} g(\mathbf{d}f) \wedge \mathbf{d}h)$$

Thus $\{f, g, h\} = -\{g, f, h\}$ and $\{\cdot, \cdot, \cdot\}$ is anti-symmetric in all pairs of indices.

Computing the parity-violating reduced bispectrum of a full sky map using $\{\cdot,\cdot,\cdot\}$

Thus when $(-)^{\ell_1+\ell_2+\ell_3} = -1$, the reduced bispectrum

$$B^{TTT}(\ell_1,\ell_2,\ell_3) = \int_{S^2} \mathcal{F}_{\ell_1} T(\hat{\mathbf{\Omega}})[\mathbf{d}\mathcal{F}_{\ell_2} T(\hat{\mathbf{\Omega}})] \wedge [\mathbf{d}\mathcal{F}_{\ell_3} T(\hat{\mathbf{\Omega}})]$$

Here $\mathcal{F}_\ell : C^\infty(S^2) \to C^\infty(S^2)$ is the filter operator defined as

$$(\mathcal{F}_\ell f)(\hat{\mathbf{\Omega}}) = \sum_{m=-\ell}^{+\ell} Y_{\ell m}(\hat{\mathbf{\Omega}}) \int d\hat{\mathbf{\Omega}}' Y^*_{\ell m}(\hat{\mathbf{\Omega}}') f(\hat{\mathbf{\Omega}}')$$

In this way we can completely avoid using Wigner 3j symbols in the actual computations involving sky maps.
Of course, $\Delta\ell = 1$ is the finest possible spectral resolution possible, which is limited by the area of the celestial sphere (i.e., 4π) a number that has absolutely nothing to do with primordial CMB physics.

We may rewrite our "coordinate-free" expression as

$$
\begin{aligned}
\{f,g,h\} &= \int d\Omega\ f(\Omega)\ \hat{\mathbf{r}}\cdot\Big[\big(\boldsymbol{\nabla} g(\Omega)\big)\times\big(\boldsymbol{\nabla} h(\Omega)\big)\Big] \\
&= \int d\Omega\ f(\Omega)\ \Bigg[\quad \hat{\mathbf{r}}_{\,0}(\Omega)\,[\nabla_{+1} g(\Omega)\ \nabla_{-1} h(\Omega) - \nabla_{-1} g(\Omega)\ \nabla_{+1} h(\Omega)] \\
&\qquad + \hat{\mathbf{r}}_{+1}(\Omega)\,[\nabla_{-1} g(\Omega)\ \nabla_{\,0} h(\Omega) - \nabla_{\,0} g(\Omega)\ \nabla_{-1} h(\Omega)] \\
&\qquad + \hat{\mathbf{r}}_{-1}(\Omega)\,[\nabla_{\,0} g(\Omega)\ \nabla_{+1} h(\Omega) - \nabla_{+1} g(\Omega)\ \nabla_{\,0} h(\Omega)]\Bigg]
\end{aligned}
\tag{1}
$$

where we use the unit vectors

$$
\hat{\mathbf{e}}_{\pm1} = \mp\frac{\hat{\mathbf{e}}_x \pm i\hat{\mathbf{e}}_y}{\sqrt{2}}, \qquad \hat{\mathbf{e}}_0 = \hat{\mathbf{e}}_z, \tag{2}
$$

for which

$$
\begin{aligned}
\hat{\mathbf{e}}_{\pm1}\times\hat{\mathbf{e}}_{\mp1} &= \pm i\ \hat{\mathbf{e}}_0, \\
\hat{\mathbf{e}}_{\pm1}\times\hat{\mathbf{e}}_0 &= \pm i\ \hat{\mathbf{e}}_{\pm1}.
\end{aligned}
\tag{3}
$$

The relation

$$
\hat{\mathbf{r}}\cdot\big[(\nabla g)\times(\nabla h)\big] = \hat{\mathbf{r}}\cdot\big[(\mathbf{L}g)\times(\mathbf{L}h)\big] \tag{4}
$$

allows us to rewrite using the angular momentum operator rather than the gradient on the sphere.

We thus obtain

$$\begin{aligned}
\{f, g, h\} &= \int d\Omega\ f(\Omega)\ \hat{\mathbf{r}} \cdot \left[(\mathbf{L}g) \times (\mathbf{L}h)\right] \\
&= \int d\Omega\ f(\Omega)\ \begin{vmatrix} \hat{r}_{-1}(\Omega) & \hat{r}_0(\Omega) & \hat{r}_{+1}(\Omega) \\ L_{-1}g(\Omega) & L_0 g(\Omega) & L_{+1}g(\Omega) \\ L_{-1}h(\Omega) & L_0 h(\Omega) & L_{+1}h(\Omega) \end{vmatrix} \\
&= \int d\Omega\ f(\Omega)\ \begin{vmatrix} \hat{Y}_{1,-1}(\Omega) & \hat{Y}_{1,0}(\Omega) & \hat{Y}_{1,+1}(\Omega) \\ L_{-1}g(\Omega) & L_0 g(\Omega) & L_{+1}g(\Omega) \\ L_{-1}h(\Omega) & L_0 h(\Omega) & L_{+1}h(\Omega) \end{vmatrix}
\end{aligned} \tag{5}$$

For the spherical harmonics

$$\begin{aligned}
&\{Y_{l_A,m_A}, Y_{l_B,m_B}, Y_{l_C,m_C},\} \\
&= \int d\Omega\ Y_{l_A,m_A}(\Omega)\ \begin{vmatrix} \hat{Y}_{1,-1}(\Omega) & \hat{Y}_{1,0}(\Omega) & \hat{Y}_{1,+1}(\Omega) \\ L_{-1}Y_{l_B,m_B}(\Omega) & L_0 Y_{l_B,m_B}(\Omega) & L_{+1}Y_{l_B,m_B}(\Omega) \\ L_{-1}Y_{l_C,m_C}(\Omega) & L_0 Y_{l_C,m_C}(\Omega) & L_{+1}Y_{l_C,m_C}(\Omega) \end{vmatrix}
\end{aligned} \tag{6}$$

which is the sum of six generalized Gaunt integrals, which can be readily evaluated by fusing the first two factors of each terms to obtain a Gaunt integral involving three spherical harmonics.

Parity violation in $\langle TTT \rangle$ (and $\langle TTE \rangle$ and $\langle TEE \rangle$)

1. With the parity-odd sector we can hope to discover P violation in the new physics with simply the T maps (and E maps).
2. $r \neq 0$ is not required for finding parity violation in the CMB

What about this counter-argument?

In the flat-sky approximation at least, we can image the last scattering surface to be observed from both sides. If we imagine an observer at the mirror image of ourselves, would not this observer see the negative of our odd-parity bispectrum?

The person putting forward this argument would say we need 3d observables with

$$\mathbf{k}_1 + \mathbf{k}_2 + \mathbf{k}_3 + \mathbf{k}_4 = 0.$$

with $\mathbf{k}_1, \mathbf{k}_2, \mathbf{k}_3, \mathbf{k}_4$ *and non-planar.*

Is there anything wrong with the above argument?
Can TTT arise from scalar fluctuations (the purely adiabatic mode)?

Why the previous argument is not correct

- The Sachs-Wolfe formula contains a Doppler term, which changes sign under the spatial inversion envisaged in the previous transparency. Thus the normal vector to the LSS enters into the observed anisotropies. Gradients normal to the LSS thus enter creating non-planar tetrahedra.
- We want to derive parity violation from a 3-dimensional theory. With more than one scalar field parity violating planar configurations exist and these can be generated by higher-dimensional operators. Moreover fields with spin (eg vector and tensor field) naturally violate planarity.

Conclusions

- Testing discrete symmetries has played a crucial role in the road to the Standard Model of Particle Physics. It remains to be seen whether the New Physics in the Very Early Universe that generated the primordial cosmological perturbations respects P (and CP). This is a question that should be resolved by observations.
- In principle considerable scope remains for discovering parity violation in the T and E Planck maps (work in progress) and new data will provide even better opportunities. Detecting the B mode at large S/N is not needed when one goes beyond the power spectrum.
- Higher-order (trispectrum and beyond) and 3d data (from the SKA and galaxy surveys) are another place to look for parity violation. Some interesting claims, as well as birefringence.
- For estimator here, biases and leakages resulting from a masked sky must be dealth with (by MC simulation) as was done for the even parity estimator.
- The fact that the popular models almost all conserve P gives the mistaken impression that P violation is a long shot. Sensitive probes analyzing the data in a model independent way are needed.