Parity-Violation in the distribution of galaxies has been discovered!

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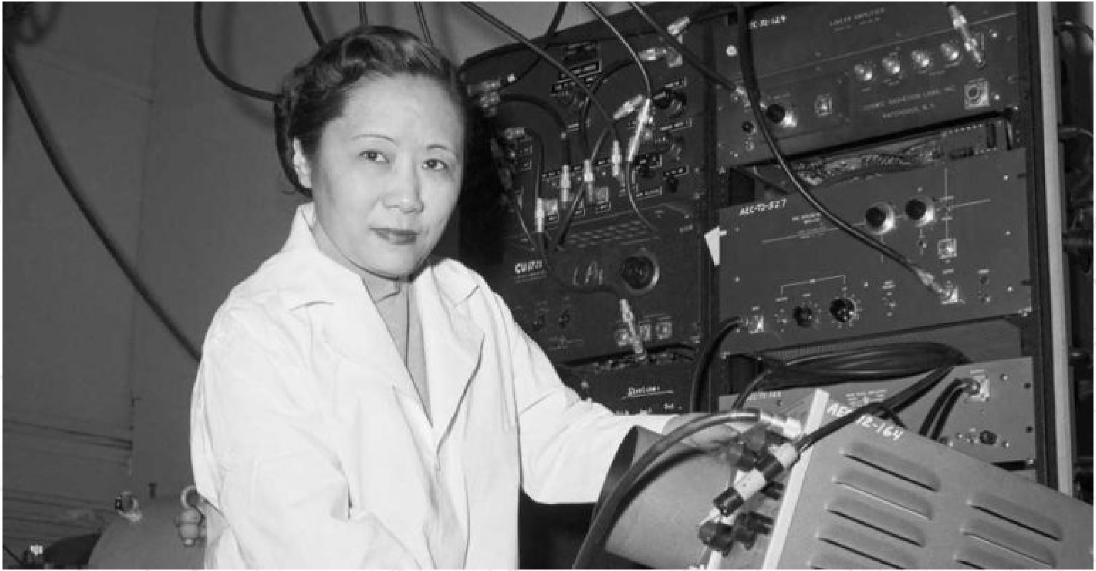
arXiv: 2206.03625, arXiv: 2206.04227

Astrophysics



Nuclear decay experiment undertaken by scientist Chien-Shiung Wu proved that parity is broken in nature.

The inflaton field

- The inflaton is a field that is supposed to have permeated space at or close to the moment the cosmos was born.
- The inflaton field was likewise repulsive, a churning, boiling medium where inflaton particles continuously bubbled up and vanished; for whatever short period it may have been, it would have caused our universe to swiftly expand to 100 trillion trillion times its original size.
- The inflaton field's quantum fluctuations of particles were all thrown into space, where they were frozen and transformed into changes in the density of matter.
- To create the galaxies and large-scale structure we observe today, the denser pockets kept gravitationally coalescing.

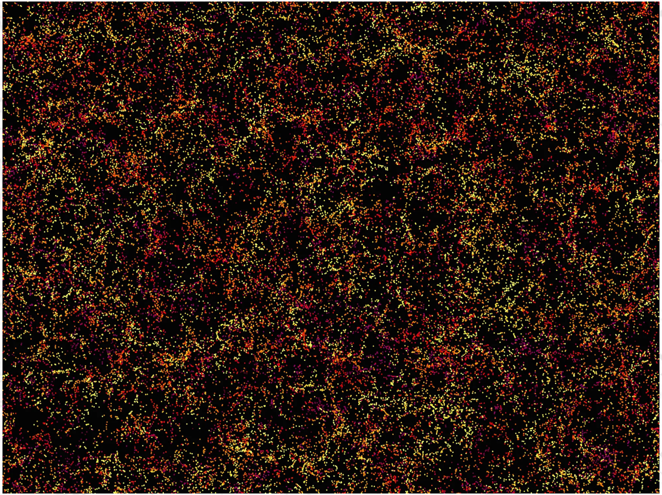
The inflaton field and Chern-Simons coupling

- What if there were other fields existing prior to this explosion?
- Right-handed and left-handed particles could have been created by the inflaton field interacting with another field. If the inflaton had formed particles with a preference for one handedness over the other, it might have handled right-handed particles differently than left-handed ones.
- There would have been an imbalance between left-handed and right-handed tetrahedral structures of galaxies as a result of this so-called Chern-Simons coupling, which would have given preference to one-handedness in the early quantum fluctuations.

Arthur Lue, Limin Wang, and Marc Kamionkowski
"Cosmological Signature of New Parity-Violating Interactions",
Phys. Rev. Lett. ***83****, 1506 (1999),*
arXiv:astro-ph/9812088,
doi:10.1103/PhysRevLett.83.1506

Parity-violating Chern-Simons interaction

- The gravitational field is one potential candidate for the extra field. In this case, the quantum units of gravity, gravitons, which would have emerged in the gravitational field during inflation, would interact with inflaton particles in a parity-violating Chern-Simons interaction.
- Such an interaction would have resulted in handedness in the early universe's density changes and, as a result, in the large-scale structure we see today.



The Sloan Digital Sky Survey and accompanying Baryon Oscillation Spectroscopic Survey tracked the locations of each dot in this image, which depicts around one-twentieth of the sky. The survey's 1 million galaxies were statistically analysed, and parity violation was discovered.

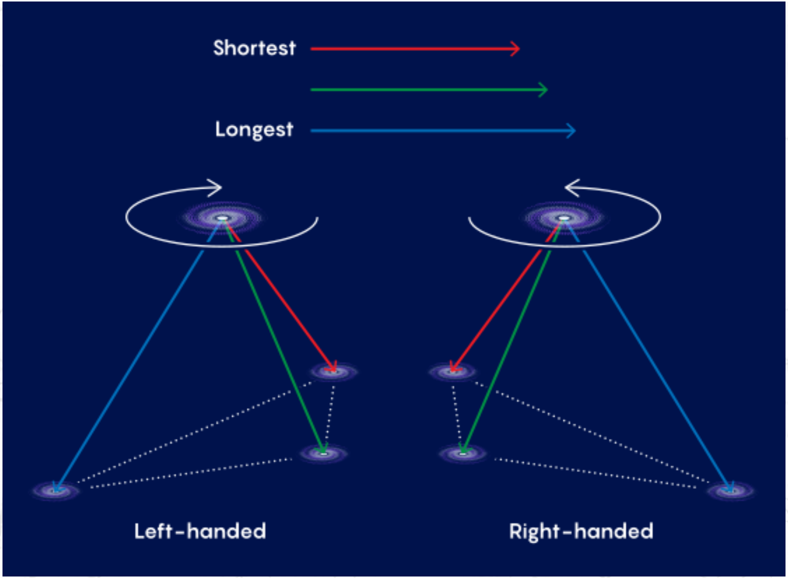
Chern-Simons gravity

- One of cosmology's greatest puzzles, why our universe includes more matter than antimatter, may be resolved via Chern-Simons gravity.
- It is possible that the Chern-Simons interaction produced a significant number of left-handed gravitons, favouring the production of left-handed matter over right-handed antimatter.

Stephon H. S. Alexander, Michael E. Peskin, and M. M. Sheikh-Jabbari "Leptogenesis from Gravity Waves in Models of Inflation", Phys. Rev. Lett. **96***, 081301 (2006), arXiv:hep-th/0403069, doi:0.1103/PhysRevLett.96.081301*

Tetrahedral arrangement of galaxies

- Studying the tetrahedral configurations of four galaxies is necessary to determine if the galaxy distribution respects or violates parity.
- The tetrahedron is the most basic three-dimensional shape; hence, only three-dimensional things have a chance of breaching parity.
- For the purpose of comparing the number of left-handed and right-handed galaxies in the sky, devise a method of determining the "handedness" of a tetrahedral arrangement of galaxies.
- A galaxy was chosen first, and the distances to three additional galaxies were examined.
- It referred to the tetrahedron as right-handed if the distances increased clockwise, like a right-handed screw. If the distances grew larger as you moved counterclockwise, it is left-handed.



The simplest shape with parity, or handedness, is the tetrahedron. When reflected in a mirror, it appears differently.

Collective tetrahedra

- You had to repeat the study for all the tetrahedra created from the database of one million galaxies in order to ascertain whether the cosmos as a whole has a preferred handedness.
- Such tetrahedra number nearly one trillion trillion, making handling them one at a time impossible.
- Instead of building one tetrahedron at a time and figuring out its parity, you might take each galaxy in turn and group all other galaxies based on how far away they are from it, forming layers similar to those found in an onion.
- It was possible to systematically assemble sets of three layers to create collective tetrahedra by representing the relative positions of galaxies in each layer in terms of spherical harmonics.

Comparing with simulated control

- Afterward, compare the outcomes to predictions based on parity-preserving physics.
- By replicating the evolution of the cosmos starting from minute, parity-preserving density fluctuations, false catalogues of galaxies were created and analysed.
- You could learn how the number of left- and right-handed tetrahedra randomly vary in comparison to a mirror-symmetric world through these mock catalogues.
- The imbalance between left- and right-handed tetrahedra was seven times larger than could be predicted from random chance and other conceivable sources of error, resulting in a parity violation at the 7σ level in the actual data.

Jiamin Hou, Zachary Slepian, Robert N. Cahn
"Measurement of Parity-Odd Modes in the Large-Scale 4-Point Correlation Function of SDSS BOSS DR12 CMASS and LOWZ Galaxies",
arXiv:2206.03625

Reduce the layers

- Reduce the number of layers used to group the galaxies, exclude several troublesome tetrahedra from the study, and reduce the parity violation to a more manageable 2.9σ.

H.E. Philcox
"Probing parity violation with the four-point correlation function of BOSS galaxies", Phys. Rev. D **106**, *063501 (2022),*
arXiv:2206.04227,
doi:10.1103/PhysRevD.106.063501

More statistics

- For instance, the current Dark Energy Spectroscopic Instrument survey has so far recorded 14 million galaxies and will eventually comprise more than 30 million. With much better statistics, it allows us to examine parity violations in much more detail.

Independent investigation of parity-violating physics in the early universe

- The cosmic microwave background's dappled pattern ought to have the same parity-violating correlations as the galaxies that later emerged.
- The stochastic gravitational wave backdrop is a pattern of gravitational waves that may have been produced during inflation. These left-handed or right-handed ripples in the fabric of space-time can be either, and in a parity-preserving world, they would have equal proportions of either.


Robert's Quartet, a tetrahedral grouping of galaxies.

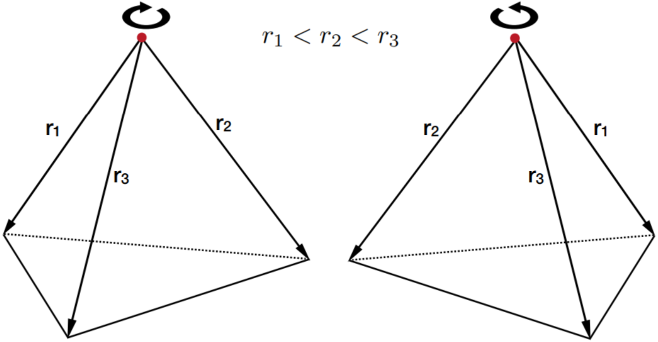


Figure 1. Parity transformation applied to a tetrahedron formed by a quartet of galaxies. Each vertex represents a galaxy. Choosing one galaxy (red dot) as our primary, the quartet is defined by the three vectors to the remaining vertices, $\mathbf{r}_1$, $\mathbf{r}_2$, and $\mathbf{r}_3$. For a quartet, the subscripts are fixed by requiring that $r_1 \leq r_2 \leq r_3$. When viewing the tetrahedron from the primary (red) looking down along each vector $\mathbf{r}_i$, the direction in which one reads going from smallest to largest side (r_1 to r_3) defines a handedness, either clockwise or counterclockwise. Here, the tetrahedron on the left, as viewed from the primary, is clockwise. Parity transformation in 3D is a reflection about a plane and then a 180° rotation about the vector perpendicular to that plane, and converts the clockwise tetrahedron at left to the counterclockwise one at right. When one averages over rotations, as in this work, only the mirroring matters.

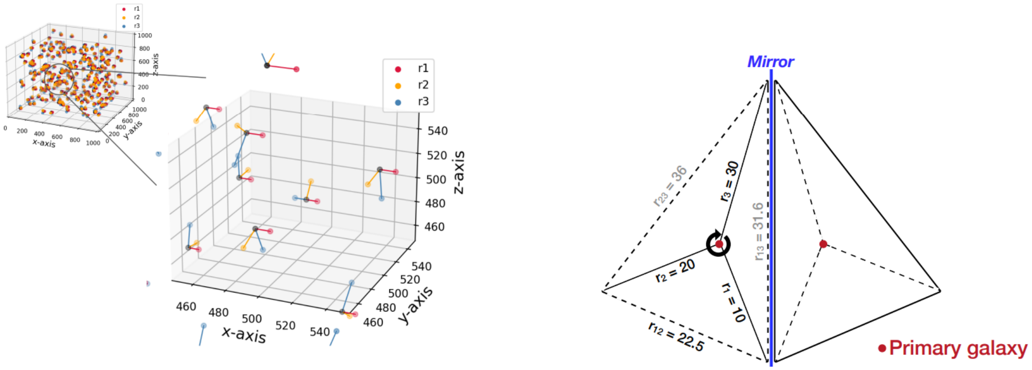


Figure 2. *Left:* A box with side length $L_{\rm box} = 1000h^{-1}$Mpc filled with tetrahedra (upper left, small panel). Each of them has a *unique* primary (black) from which the three sides with respective lengths $r_1 \sim 10h^{-1}$Mpc (red), $r_2 \sim 20h^{-1}$Mpc (yellow), and $r_3{\sim}30h^{-1}$Mpc (blue) extend. The larger panel on the left is a zoom-in on the full box to display the tetrahedra more clearly. *Right:* A sketch of a "clockwise" tetrahedron and its "counterclockwise" mirror image. The primary is in red. Our convention on clockwise and counterclockwise is detailed in Fig. 1. On the left, the red point is closer to us than all the others. Thus the tetrahedron on the left is clockwise, as looking down from the primary, we go clockwise as we move from the smallest side to the largest. On the right, the primary (in red) is behind the other galaxies, so looking down from it towards them will reverse the handedness. Thus the rightmost tetrahedron is counterclockwise as viewed from the primary.

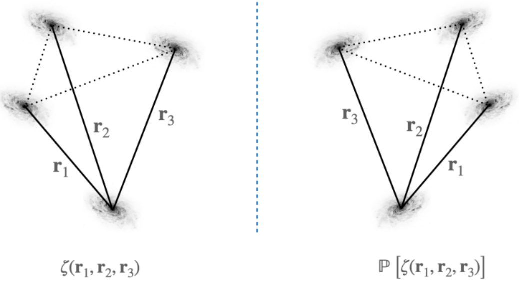


FIG. 1. Cartoon of the galaxy four-point correlation functions (4PCFs) considered in this work. In the left panel, we show the 4PCF, $\zeta(\boldsymbol{r}_1, \boldsymbol{r}_2, \boldsymbol{r}_3)$, which depends on the separation vectors of three secondary galaxies from a given primary. The right panel shows the parity-inverted 4PCF, $\mathbb{P}\left[\zeta(\boldsymbol{r}_1, \boldsymbol{r}_2, \boldsymbol{r}_3)\right]$, which corresponds to replacing $\boldsymbol{r}_i$ with $-\boldsymbol{r}_i$. Unlike for the 2PCF and 3PCF, the two configurations cannot be related by a rotation. The parity-even 4PCF is a sum of the two geometries (which have the same side-lengths and relative angles), whilst the parity-odd 4PCF is a difference. In this work, the 4PCF is given as a function of three lengths (r_1, r_2, and r_3) and three internal angles (fixing the angle of the $\boldsymbol{r}_i$ vectors with the respect to the primary galaxy). The latter are represented by their harmonic-space momenta, ℓ_1, ℓ_2 and ℓ_3, with odd-parity 4PCFs corresponding to odd $\ell_1 + \ell_2 + \ell_3$. Assuming standard ΛCDM physics, the two correlators shown in the figure should be equivalent, thus the expectation value of the parity-odd 4PCF is zero.