No cubic pattern in public Auger cosmic-ray directions, at a sensitivity that sees only large ones

A preregistered search for a lattice imprint on the public Pierre Auger arrival directions at five energy cuts, with exposure-keeping scrambles and planted patterns

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Version 1.0, 9 November 2026. Finding F344 in the findings ledger. Honest null (tier D).

Abstract

If space were a fine cubic grid, the highest-energy cosmic rays could arrive in a pattern aligned with its axes, a signature Beane, Davoudi and Savage proposed in 2012. We searched the public Pierre Auger Observatory data for such a pattern with a method fixed in advance. The data are the 25,086 main-array events in the public 10 percent sample and the catalogue of the highest-energy events, cut at 8, 16, 32, 40 and 78 EeV. For each cut we fitted a cube-symmetric pattern over 400 orientations and compared the best fit with skies whose right ascensions were scrambled, which keeps the detector's exposure. No cut shows a cubic pattern: raw p values run from 0.19 to 0.85, and all five read 0.85 after the Benjamini-Hochberg correction. The search could only have seen a strong pattern: at 8 EeV it reaches power 0.9 at a planted strength of 0.2, and at 32 EeV it reaches power 0.97 only at strength 1.0, where the sky along the cube axes is twice the average. The highest-energy event, 166 EeV, bounds the lattice spacing below 3.7e-27 m, an inverse spacing of 5.3e10 GeV, which is 0.53 of the 1e11 GeV bound of Beane and colleagues. This is a null whose value lies in stating how weak it is.

1 What this means for a reader

The public share of the Auger data is small enough that only a large cubic imprint on the arrival directions would have shown up. So the result rules out a strong pattern and says nothing about a subtle one. Anyone citing public cosmic-ray data for or against a grid-like universe should quote the planted sensitivity beside the p value, and the full Auger dataset would do much better than the public share.

2 Introduction

Lattice calculations in particle physics put space and time on a grid. Beane, Davoudi and Savage [2] asked what an observer inside such a calculation could detect if the universe itself were computed on a grid with some lattice spacing. Their abstract reports that the most stringent bound on the inverse spacing, about 1e11 GeV, comes from the high-energy end of the cosmic-ray spectrum, and their published account predicts that the highest-energy cosmic rays would show the cube symmetry of the grid in their arrival directions.

The particles that could carry that signature are the ultra-high-energy cosmic rays, with energies of many EeV. The Pierre Auger Observatory records them with an array of ground detectors. The Auger Collaboration reported in 2017 a large-scale anisotropy above 8 EeV, a dipole of about 6.5 percent amplitude in 3e4 events, which it reads as evidence that these particles come from outside our galaxy [3]. Since 2021 the collaboration has published 10 percent of its cosmic-ray events, with a catalogue of the highest-energy events added in 2023 [1].

We asked whether the public arrival directions carry a cubic pattern, and what the most energetic event says about the spacing. The decision it informed was how to describe public cosmic-ray data in any work of ours

on discretised space: as evidence, or as a weak test. Our searches found the proposal above and the Auger anisotropy results and no published cubic search on the open data; that is what the searches returned, and it does not show that none exists.



Figure 1. Robert P. Traxler, Fig. II, "A sectional side and edge view of the Sun with Mercury Venus Earth and Mars", from The Principles of Mechanics as Applied to the Solar System (San Francisco, 1889) [5]. Above, the inner planets on a grid of radial force lines and rings with a marked line of attraction; below, the Sun's equatorial plane drawn as swirling streams. Traxler drew his plates to argue for a repelling force from the Sun, his own theory in 1889, which physics did not adopt. The plate draws a grid laid over space, the kind of structure this test looks for. Public domain; scan from the Internet Archive, University of California Libraries.

3 Preregistration and design

The preregistration and the forecast file were written and hash-locked on 31 October 2026, before the run. They name the baseline (an isotropic sky at the data's declinations), the planted answer (a cubic pattern at random orientation), the control (right-ascension scrambles), the outlier checks (the top 3 events and the region around Centaurus A, with and without), the assumption changed (the energy cut and the Centaurus A exclusion), and the kill condition.

The kill condition, fixed in advance: if the cubic search gives a corrected p below 0.01, the lattice reading must still survive the Centaurus A exclusion and a second energy cut, or it dies. Each forecast and condition became a rule set whose pass or fail is a verdict read off by code.

4 Data and provenance

The data are the Pierre Auger Observatory Open Data release of 2024 [1], Zenodo record 10488964, licensed CC BY-SA 4.0, fetched on 31 October 2026. We read the event summaries of the main surface array, vertical and inclined showers together with duplicates removed, which gave 25,086 events with direction and energy. This public sample is 10 percent of the recorded events. We also read the catalogue of the highest-energy surface-array events, 109 events with a top energy of 166 EeV. We report statistics only.

The cuts at 8, 16 and 32 EeV use the event summaries, and the cuts at 40 and 78 EeV use the catalogue. Table 1 gives the count at each cut.

5 Methods

The pattern

For an arrival direction written as a unit vector with components x, y, z, the cubic harmonic is

$$C = x^4 + y^4 + z^4 - 0.6 \tag{1}$$

The constant 0.6 is its average over the sphere, so C averages to zero on an isotropic sky. It is largest, 0.4, along the six axes of the cube and smallest along the eight diagonals. A grid in space need not line up with our coordinates, so the pattern was rotated through 400 random orientations R.

The statistic

A ground array does not watch the whole sky evenly: its exposure depends strongly on declination. The baseline sky was therefore built from 60,000 directions with uniform right ascension and declinations drawn from the data. For orientation R, let μ_R and s_R be the mean and standard deviation of C on this baseline, and m_R its mean over the N real events. The standardised excess is

$$Z_R = \frac{|m_R - \mu_R|}{s_R/\sqrt{N}} \tag{2}$$

and the statistic T is the largest Z_R over the 400 orientations. For cuts with 500 events or fewer, the baseline declinations were drawn from the 8 EeV events.

The null and the correction

Each p value comes from a right-ascension scramble: each event keeps its declination and gets a random right ascension, which keeps the exposure and removes any pattern. The statistic was recomputed on 300 scrambled skies, and

$$p = \frac{k + 1}{n + 1} \tag{3}$$

with k the number of scrambles at or above the real T and n the number of scrambles. The five p values were corrected with the Benjamini-Hochberg correction [4]: with the raw values sorted so that p_i is the ith smallest of $M = 5$,

$$q_i = \frac{M p_i}{i} \tag{4}$$

and each corrected value is the smallest q_j at its own rank or above.

Planted patterns

A planted sky keeps the real events' declinations and draws right ascensions from a density proportional to

$$1 + \frac{\varepsilon C}{0.4} \tag{5}$$

at one random orientation, so that the sky along the cube axes is 1 + ε times the average. The detection power at strength ε is the share of planted skies whose statistic exceeds the 95th percentile of scrambled skies. At 32 EeV the threshold came from 200 scrambles and each strength had 30 planted skies; at 8 EeV, 60 scrambles and 10 planted skies.

The kinematic reading

On a grid of spacing a, a particle cannot have a wavelength much shorter than the grid. In the simple picture used here, a particle of energy E_{top} could not propagate unless

$$a < \frac{\pi Q}{E_{top}} \tag{6}$$

where Q = 1.973e-16 GeV m is the reduced Planck constant times the speed of light. The inverse spacing in energy units is E_{top}/π.

6 Controls and planted checks

The right-ascension scramble is the null for every p value. As a separate control at 32 EeV, 200 scrambled skies gave a mean statistic of 2.32 and a 95th percentile of 3.27; the real statistic, 1.69, sat well inside them (p value from draws 0.87).

The planted check measured the search's power at each strength. Figure 3 and Table 2 give the result. The planted powers are coarse: each is a share of 30 or of 10 trials.

The outlier checks removed the 28 events at 32 EeV within 27 degrees of Centaurus A, and separately the 3 highest-energy events, and recomputed the p value with 200 scrambles each.

7 Results

No cut shows a cubic pattern: raw p values run from 0.19 to 0.85, and all five read 0.85 after the Benjamini-Hochberg correction. Table 1 and Figure 2 give the values.

Table 1. The cubic search at each energy cut. Raw p from 300 scrambles; corrected p by Benjamini-Hochberg over the five cuts.

Cut	Events	Statistic T	Raw p	Corrected p
8 EeV	3,111	2.74	0.19	0.85
16 EeV	793	1.91	0.68	0.85
32 EeV	155	1.69	0.85	0.85
40 EeV	109	2.80	0.55	0.85
78 EeV	101	2.79	0.61	0.85

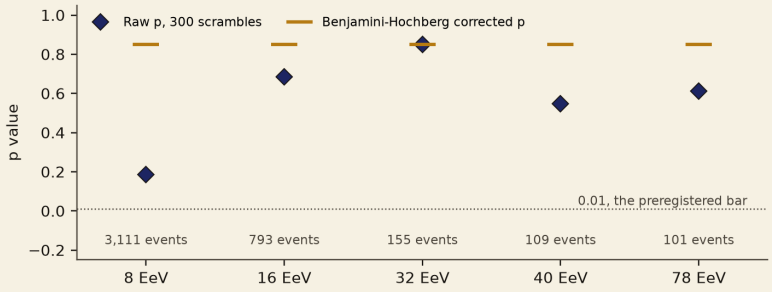


Figure 2. Raw and corrected p values at each energy cut, with the number of events. The preregistered bar of 0.01 is the dotted line. Drawn from the run's result file.

Removing the 28 events near Centaurus A or the 3 highest-energy events leaves no pattern at 32 EeV: p 0.38 and 0.71.

The search could only have seen a strong pattern: at 8 EeV it reaches power 0.9 at a planted strength of 0.2, and at 32 EeV it reaches power 0.97 only at strength 1.0, where the sky along the cube axes is twice the average.

Table 2. Detection power against planted strength. Each power is a share of 30 planted skies at 32 EeV and of 10 at 8 EeV.

Planted strength	Power at 32 EeV	Power at 8 EeV
0.05	not run	0.10
0.1	0.03	0.30
0.2	0.20	0.90
0.3	0.27	not run
0.5	0.40	not run
0.8	0.80	not run
1.0	0.97	not run

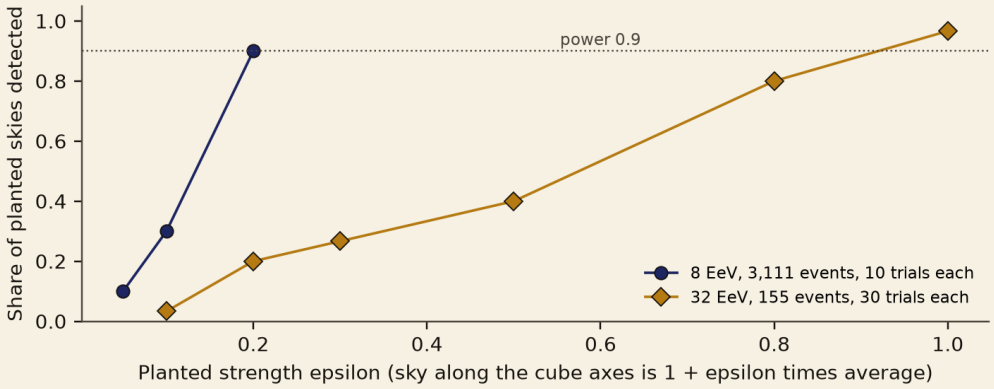


Figure 3. Detection power against planted strength at the 8 and 32 EeV cuts. Drawn from the run's result file.

The highest-energy event, 166 EeV, bounds the lattice spacing below 3.7e-27 m, an inverse spacing of 5.3e10 GeV, which is 0.53 of the 1e11 GeV bound of Beane and colleagues. The 1e11 GeV figure was entered from memory before the run; the abstract of Beane and colleagues [2], read for this paper, gives the same value.

The study also ran a toy model of waves on a cubic grid, to check the dispersion a lattice would cause. Along an axis, the phase speed falls short of the continuum value by $(ka)^2/24$, with k the wavenumber, within 0.8 percent for ka up to 0.8. The group speed falls short by $(ka)^2/8$, within 1.3 percent; our forecast had given it the phase speed's coefficient, and that forecast missed. Along a diagonal, waves run faster than along an axis by $(ka)^2/48$, within 1.2 percent, and the model sets the highest energy along a diagonal at $\sqrt{3}$, 1.73, times that along an axis, from the grid's geometry. This direction dependence is what would imprint a cube on arrival directions.

Table 3 sets the forecasts written before the run against the outcomes.
The event forecast was made from memory of the full dataset; the public release holds a tenth of it.

8 Discussion

The search found nothing, and the planted skies say how little that means. At 32 EeV, the highest cut with event-level data, only 155 events are public, and the search needs a pattern that doubles the flux along the cube axes before it sees one reliably. At 8 EeV the sample is twenty times larger and the threshold falls to a 20 percent modulation, but at that energy the particles are bent strongly by galactic magnetic fields, which would

Table 3. Forecasts fixed before the run against what it gave.

Quantity	Forecast	Outcome
Events above 32 EeV	about 2,600	155
Cubic search, no pattern	p above 0.05, probability 0.9	all raw p 0.19 or above
Strength for power 0.9	about 0.12, band 0.05 to 0.3	0.2 at 8 EeV; about 1.0 at 32 EeV
Kinematic reading against 1e11 GeV	within a factor of 3	0.53
Group speed on axis	deficit $(ka)^2/24$ within 1 percent	deficit $(ka)^2/8$
Axis minus diagonal	$(ka)^2/48$ within 5 percent	within 1.2 percent
Highest energy, diagonal over axis	square root of 3	1.73, set by the model

smear a pattern made at the source.

For scale, the dipole the Auger Collaboration measured above 8 EeV with its full data has an amplitude of about 6.5 percent [3]. A cubic pattern of that size would be far below what our search can see in the public share. The kinematic reading lands within a factor of 2 of the published bound because both rest on the same top energy and the same simple argument; it adds a check of arithmetic and no new information.

The result therefore excludes a large cubic imprint on the public arrival directions and nothing smaller. The same method on the full Auger data would set a stronger limit.

9 Limitations

- Only the public 10 percent of events was available, which is the main reason the sensitivity is low.
- Cosmic rays at these energies are bent by galactic and intergalactic magnetic fields, and we did not model that; a lattice pattern at the source could be smeared before arrival.
- Only a cubic pattern was tested. Other grid symmetries and other signatures of a lattice were not.
- The scramble also removes the known dipole from the null skies. With partial sky coverage a dipole is not exactly independent of a cubic pattern, so a dipole could raise the statistic slightly; we did not test this.
- The planted powers rest on 30 or 10 trials per strength and are coarse.
- The 1e11 GeV bound was entered from memory and agrees with the abstract read for this paper; the full paper was not read.
- Scoring was by our own code and was not blind.

10 Verified

Verified: on 9 November 2026 the 25,086 events read, the catalogue count and top energy, the counts, statistics and raw p values at each cut, the corrected value of 0.85, the Centaurus A and top-3 p values with the 28 events removed, every planted power and the 32 EeV threshold, the scramble control's mean, percentile and p, the spacing bound, the inverse spacing and the 0.53 ratio, the lattice dispersion errors and the three verdicts were re-read from the run's result file. They match the findings ledger. The data source and licence were read from the download's source record. The preregistration's SHA-256 matches the hash recorded in the result file and in the lock file. Both figures were drawn by a script that reads only that result file. The study was not re-run for this paper. The literature was found by searches run on 9 November 2026 and read at the level of abstracts, publisher pages and search summaries; the full texts were not read. The Benjamini and Hochberg paper is cited for the method only and was not searched or read for this paper.

11 Corrections

- 31 October 2026: a review of our ledger noted that the public 10 percent of the data gives 155 events at 32 EeV and low power, with planted power needing strength 1.0 there. The claim was narrowed to a large

pattern, as here.

- 9 November 2026: first published version.

12 Reproduction

- Data: the Pierre Auger Observatory Open Data release 2024, Zenodo record 10488964 (CC BY-SA 4.0): the surface-array event summaries and the highest-energy catalogue.
- Cut at 8, 16 and 32 EeV in the summaries and at 40 and 78 EeV in the catalogue.
- For each cut, compute eq. 2 over 400 random orientations of eq. 1 against an exposure-matched baseline, keep the largest, and compute eq. 3 from 300 right-ascension scrambles. Correct with eq. 4.
- Plant eq. 5 at a random orientation into skies with the real declinations to measure power. Remove the events near Centaurus A and the top 3 events and recompute.
- Apply eq. 6 to the top energy.
- Preregistration SHA-256: 1b0153b42a6fffc2789b98f6f2bd9774da4c0da48bda7e22e51266e9bd5f0f29. Plan SHA-256: 6785b5da63d8a3597424d3b4d72015ad4bf66979959f281bb55fda7df057548b. Run 20261031T211927Z.
- Cost: the analysis took about 138 s and the scramble control about 3 s on one desktop CPU.

13 Appendix A. The preregistered verdicts

Each verdict is a set of rules written before the run. A verdict passes only when every rule holds. Values are read from the run's result file.

Table 4. Preregistered verdicts and the rules that decided each one.

Verdict	Deciding rule	Value	Holds
Cubic pattern absent	smallest corrected p above 0.01	0.85	yes
Planted power	power at strength 1.0, 32 EeV, at least 0.9	0.97	yes
Kinematic reading	ratio to 1e11 GeV between 0.33 and 3	0.53	yes

14 Glossary

Each term is defined where it is first used in the text. The same definitions, with the field each comes from and what each excludes, are collected here.

- **lattice spacing**. The distance between neighbouring points of a grid on which space is modelled; on a grid, waves shorter than about twice the spacing cannot exist and the speed of a wave depends on its direction. Field: lattice field theory. Excludes the Planck length, which is a scale built from constants and not a measured grid.
- **ultra-high-energy cosmic ray**. A charged particle from space, a proton or heavier nucleus, arriving with an energy above about 1e18 electronvolts; it is recorded through the shower of secondary particles it makes in the atmosphere. Field: astroparticle physics. Excludes photons and neutrinos, and the far more common cosmic rays of lower energy.
- **EeV**. An exaelectronvolt, 1e18 electronvolts, or 1e9 GeV, carried by a single particle. Field: physics (units). Excludes the total energy of the shower in a detector, which is spread over many secondary particles.
- **preregistration**. A dated written plan for a study, fixed and hash-locked before any result is seen: the question, the data, the statistic, the controls, the forecasts and the kill conditions. Field: research method (metascience). Excludes a plan revised after looking at the outcome, and a protocol written only for the record after the run.
- **control**. A version of the data with the structure under test removed (for example shuffled or pooled), scored

the same way as the real data, so the real score has something to beat. Field: statistics and experimental design. Excludes a comparison with a different dataset or with a published number.

- **kill condition**. A rule written in the preregistration that, when met, decides against the claim with no room for judgement after the run. Field: research method (our usage, after Popper's falsification). Excludes reasons found after the run for setting a result aside.
- **verdict**. The pass or fail of one preregistered rule set against the run's numbers, read off by code. Field: research method (our usage). Excludes an interpretation written after reading the numbers.
- **cubic harmonic**. The simplest pattern on a sphere with the symmetry of a cube: here x^4 + y^4 + z^4 minus its average, largest along the six cube axes and smallest along the eight diagonals. Field: mathematics (spherical harmonics) and crystallography. Excludes a dipole, a single hot spot, or any pattern that a rotation of the cube by a right angle would change.
- **exposure**. How much of each part of the sky a detector watched over time; a ground array sees some declinations far more than others, so an isotropic sky still looks uneven in its data. Field: astroparticle physics. Excludes the number of events, which is exposure times the true flux.
- **right-ascension scramble**. A control sky made by keeping each event's declination and giving it a random right ascension; the Earth's rotation makes a ground array's exposure nearly even in right ascension, so the scramble keeps the exposure and removes any pattern. Field: astroparticle physics (anisotropy searches). Excludes a fully random sky, which would ignore the detector's exposure.
- **Benjamini-Hochberg correction**. A rule that raises a set of p values to control the expected share of false discoveries among the tests called significant; the smallest raw p is multiplied by the number of tests and larger ones by less. Field: statistics (multiple testing). Excludes an uncorrected p value read on its own when several tests were run.
- **detection power**. The share of planted skies, each with a pattern of known strength, in which the search finds the pattern at its preregistered threshold. Field: statistics. Excludes the chance that a pattern exists in the real sky.
- **p value (from draws)**. The share of control draws scoring at or above the real score, with one added to the count and to the number of draws, so it is never zero. Field: statistics. Excludes a p value from a textbook formula that assumes a distribution.
- **planted check**. Data built so that the right answer is known, run through the same analysis before the real data, to show that the analysis can see the effect when it is there. Field: research method; called a positive control in experimental science. Excludes any check made on the real data, which cannot show what the analysis misses.
- **findings ledger**. The append-only, dated list of every result we have recorded, numbered F1, F2 and on; corrections are added as new dated lines and old entries are never rewritten. Field: our records. Excludes a curated list of successes.

15 References

[1] Pierre Auger Collaboration. Auger Open Data release 2024. Zenodo record 10488964. doi:10.5281/zenodo.10488964. Licence CC BY-SA 4.0. Described in: Pierre Auger Collaboration (2024). The Pierre Auger Observatory open data. The European Physical Journal C. doi:10.1140/epjc/s10052-024-13560-5. arXiv:2309.16294

[2] Beane, S. R., Davoudi, Z. and Savage, M. J. (2014). Constraints on the universe as a numerical simulation. The European Physical Journal A. doi:10.1140/epja/i2014-14148-0. arXiv:1210.1847

[3] Pierre Auger Collaboration (2017). Observation of a large-scale anisotropy in the arrival directions of cosmic rays above 8 x 10^18 eV. Science 357, 1266-1270. doi:10.1126/science.aan4338. arXiv:1709.07321

[4] Benjamini, Y. and Hochberg, Y. (1995). Controlling the false discovery rate: a practical and powerful approach to multiple testing. Journal of the Royal Statistical Society, Series B 57, 289-300.

[5] Traxler, R. P. (1889). The Principles of Mechanics as Applied to the Solar System. San Francisco: C. A. Murdock and Co. Internet Archive item principlesofmech00traxiala.