Northern Auger - Frequently Asked Questions

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1. General Questions

Q1-a) What is the ultimate goal of the Pierre-Auger Observatory?

The Pierre-Auger observatory is not merely a traditional cosmic ray experiment, but it is an astronomical observatory, carefully optimized and designed to open the entirely new world of the "Charged Particle Astronomy". Its goal is to explore the untouched territory of the "Highest Energy Universe".

Our universe itself continues to offer wonderful natural laboratories whose extreme conditions are unparalleled by anything within the terrestrial environment. The "Highest Energy Universe" broadly includes the beginning of the Universe (i.e. the Big Bang) and the extreme conditions realized by the compact objects (Neutron Stars, Black Holes etc.) as well as the most energetic phenomena in nature such as Active Galactic Nuclei (AGN) and Gamma Ray Bursts (GRB). Energy conditions in such places are so extreme that the physics laws behind their mechanism have not even been established yet, indicating the possibility of totally new physics principles beyond the standard model of particle physics and/or cosmology.

As evidenced by the 2002 Nobel Prize in Physics, awarded to the pioneers of X-ray Astronomy and Neutrino Astronomy, every time in history that a new type of "cosmic messenger" was detected, our knowledge of the Universe itself and the fundamental physics laws governing it have been advanced a step higher. For this very reason, there have been tremendous attempts to explore the Universe by all possible types of cosmic messengers, such as Cosmic Microwave Background (CMB), Gamma rays, and gravitational waves.

Ultra high-energy cosmic rays (UHECR) form one such kind of messenger whose origin is not known yet, but whose existence has been firmly established by previous experiments. What is so remarkable is their energy. Simply put, the observed energy level of $\sim 10^{20}$eV has absolutely no comparison in nature; the next highest energy phenomenon is $\sim 10^{14}$eV gamma rays from AGN (i.e. millions of times lower than the UHECR). What puzzles us most is the fact that the origin of cosmic messengers with such extreme energy is still neither identified nor explained by any known laws of physics. The Pierre-Auger Observatory was originally designed and proposed precisely to seek to answer this fundamental question.

Q1-b) How can the Pierre-Auger address particularly these scientific questions?

Since it was originally proposed in 1997, the Pierre-Auger Observatory was designed and is being constructed to satisfy the following criteria, and they have never been changed as of today.

- Uniform full sky coverage by two identical detectors at two locations, one in Southern hemisphere and the other in Northern hemisphere.

- ~3,000km^2 aperture per site, which is at least an order of magnitude larger than previous experiments (such as AGASA and HiRes)
- Hybrid detector, consisting of ground air-shower array and air fluorescence telescopes for the highest quality measurement of three-dimensional shower profile measurement, providing superior energy, angular and composition resolutions.
- 100% detection efficiency above 10^{19}eV.

Above 10^{19}eV, we expect more than 5,000 events of UHECR every year to be observed by the ground array, and 10% of them are hybrid observations together with atmospheric Fluorescence signals. Such high statistics, high quality measurements by the observatory will allow us to identify the origin of UHECR for the first time in 90 years of history of cosmic rays.

We should also note that, unlike the detection of gravitational waves, high-energy neutrinos or proton decays, high statistics signals are 100% guaranteed. Thus there is no risk factor in UHECR detection by the Pierre-Auger. This experiment is not limited by backgrounds nor by statistics of signals.

Q1-c) Is the observatory well optimized to achieve its scientific goal? Is it cost effective?

Is it indeed optimized to achieve the scientific objectives in the most cost effective way. To begin with, the observatory design was carefully optimized by considering two factors.

- Ability to overcome the limitations of prior experiments: Basically they were statistically limited, technically neither advanced nor sophisticated, and the sky coverage was only partial.
- Ability to distinguish theoretical models and to identify the true origin and the fundamental mechanism behind UHECR.

The identical twin observatories, one in South and the other in North are the most essential concept to achieve the scientific goal. For the highest energy side of UHECR (above GZK cutoff of ~5×10^{19}eV) where statistics is so challenging, the ground array will assure high statistics observations with completely uniform all-sky coverage.

For the energy region between the Ankle (~5×10^{18}eV) and the GZK cutoff, where the statistics is not so demanding but the quality of observation (such as angular resolution, energy resolution and composition measurements) becomes critical, the Hybrid observation will provide the highest quality. There is a good possibility that the UHECR events in this energy regime are affected by inter-galactic magnetic fields. Thus all sky coverage is, again, the absolute necessity to untangle such an effect. More detailed answers are given in (Q2-a) – (Q2-e).

Q1-d) Does the wider community confer high priority on this science?

Yes, it is strongly endorsed and supported by wide community of high energy physics, astronomy and cosmology.

For example, the recent report by the Committee on Physics of the Universe, chaired by Michael Turner specifically recommends this science. This so-called “Turner report” is entitled *“Connecting Quarks with the Cosmos: Eleven Science Questions for the New Century.”* Among the eleven questions, the number five is stated *“How do cosmic accelerators work and what are they accelerating?”* It continues as follows:

“Physicists have detected an amazing variety of energetic phenomena in the universe, including beams of particles of unexpectedly high energy but of unknown origin. In laboratory accelerators, we can produce beams of energetic particles, but the energy of these cosmic beams far exceeds any energies produced on Earth.”

In executive summary, it lists seven specific recommendations. At the number five, it recommends to *“Determine the origin of the highest energy gamma rays, neutrinos and cosmic rays. The Committee supports the broad approach already in place, and recommends that the United States ensure the timely completion and operation of the Southern Auger array.”* It continues as follows:

“The highest-energy particles accessible to us are produced by natural accelerators throughout the universe and arrive on Earth as high-energy gamma rays, neutrinos and cosmic rays. A full understanding of how these particles are produced and accelerated could shed light on the unification of Nature’s forces. The Southern Auger array in Argentina is crucial to solving the mystery of the highest energy cosmic rays.”

The other example is the latest HEPAP sub-panel report. Although it was primarily written to endorse the Next Linear Collider, the report did state the importance of the research in highest-energy cosmic rays in “Appendix A: Roadmap for Particle Physics”. In section “A.7.2 Highest-Energy Cosmic Rays”, the Auger Observatory and funding for North are mentioned as shown below:

“The Pierre Auger Observatory consists of a large array of charged particle detectors and several wide-angle atmospheric fluorescence detectors. Its goal is to probe the origins of the highest-energy cosmic rays through measurements of their energy spectra, anisotropies, and compositions. The southern hemisphere observatory is currently under construction in Argentina by an international collaboration from more than thirty countries. A decision will be taken during the next few years on whether to proceed with the northern observatory. The U.S. contribution to the northern hemisphere Auger observatory would be about $25M. Planning efforts are underway for other ultra high-energy cosmic ray instruments on earth and in space. These efforts may request partial funding from the U.S. high-energy physics program.”

It is fair to say that these two reports present a consensus of today's community of high energy physics, particle astrophysics and cosmology. The wide community is waiting for us to complete the Southern Observatory, and to proceed with the Northern one, which together will allow us to solve one of the largest mysteries in Nature.

Q1-e) Why is it timely?

The observation of the extreme Universe is not an easy task by any means; we must explore possibilities of detecting all kinds of cosmic messengers. Such a grand effort, "Multi-messenger exploration of the extreme Universe", has indeed already begun:

- VERITAS (and many others) will soon explore the various sources of 50GeV-100TeV gamma rays. GLAST will map the entire sky by detecting 0.1~100GeV gamma rays. Swift will detect far more Gamma Ray Bursts than any previous experiments. All of them will come true in the next 10 years.
- High energy neutrino observatories, such as AMANDA/ICECUBE (as well as ANTARES/NESTOR) will explore the new world of the extreme universe by detecting neutrinos.
- Gravitational waves will soon be detected by LIGO/VIRGO, and eventually by space-based LISA.

These areas are well funded, and have already proceeded into major construction. It may be worth mentioning that all three areas have been awarded commitments for nearly a half billion dollars over the next ten years. No one denies that UHECR, as cosmic messengers from the extreme Universe, are as important as the other messengers listed above. Not only that, but we are sure they exist, and we know exactly how to detect them. We therefore argue that similar funding at the hundred-million dollar level is well justified.

It is also worth mentioning the difference in funding sources. For the high energy neutrino and gravitational wave observatories, the US and Europe are supporting their own projects; ICECUBE and LIGO receive U.S. support while there is European funding support for ANTARES/NESTOR and VIRGO. These detectors, being in different continental locations, scientifically complement each other. In the case of UHECR observatories, the Southern Auger in Argentina, and the Northern Auger would act in the same fashion. However, there is a significant difference since in the case of the Pierre-Auger, both observatories will be funded by the international collaboration jointly.

In conclusion, it is not only timely but critical to fund and complete the entire Pierre-Auger Observatory now, when the observation of the other messengers will come to reality. Now is timelier than ever from this point of view.

Q1-f) Is there any other fundamental discovery we can expect?

Yes. In addition to UHCER, ultra high-energy neutrinos or gamma rays can be detected if they exist as predicted by many theoretical models.

Generally speaking, most of so-called "Top-down" models produce abundant UHE neutrinos or gamma rays above GZK cutoff energy. In particular, neutrinos will not be affected by CMB (unlike hadrons or gammas). The Pierre-Auger Observatory covers 3,000 km^2 of (~10m water equivalent) atmosphere per site, whose total volume far exceeds a cubic kilometer of water or ice. Detection of deeply-penetrating, nearly horizontal air showers will provide unmistakable evidence of UHE neutrinos. Needless to say, such a discovery would dramatically change our view of "the Highest Energy Universe" more than any other observation.

2. Why Northern-Auger?

Q2-a) Why do you really need all sky coverage? Should not you be able to achieve the scientific goal with only the Southern Auger?

Uniform all-sky coverage is the single most powerful tool needed to investigate the origin of the UHECR. Without it, the possible scientific achievements of the Observatory would be severely compromised.

There are three fundamental reasons.

- As evidenced by the all sky maps of COBE, EGRET, BETSE etc., only uniform coverage of the entire sky provides a global picture of source distribution by means of spherical harmonic analysis (which will reveal the existence of dipole moment, quad-pole moment etc.).
- An excess of large structures, such as the galactic plane, galactic halo, and the Local Super-cluster, can be studied without making assumptions about the blind area.
- From clustering, point sources can be identified and studied in far more systematic ways than in the case of partial sky coverage. Traditional astronomers build telescopes in both Southern and Northern hemispheres for this obvious reason.

Almost a century has passed since the first discovery of cosmic rays by Victor Hess. During these years, detectors became larger and larger, and the observed energy scale became higher and higher to the level of 10^{20}eV. However, there has been no effort to build the identical observatories in North and South. When the observed highest energy was below 10^{18} eV, this was reasonable, because the directional information of cosmic rays under 10^{18}eV is believed to be lost due to Galactic magnetic fields of microgauss order.

Today we have reached the point where the observable energy is becoming high enough (>>10^{18} eV) that these charged particles can travel to us essentially without deflection. Correspondingly, the necessity of all sky coverage is clearly justified by the same essential reason that astronomers build telescopes on both hemispheres.

Q2-b) Show a physics example in which the Southern-Auger by itself is not adequate but all-sky coverage with both Southern- and Northern-Auger can provide an answer.

One of the clean examples is the case of the "Top-down", where the origin of UHECR is in the super heavy relic particles trapped in the Galactic Halo as Cold Dark Matter. Observing the 5-10% excess dipole moment toward the center of our Galaxy can identify such an origin. Without uniform all-sky coverage, this observation is impossible.

In the "Bottom-up" case, natural accelerators (Zevatrons) are likely to be distributed outside the Milky Way Galaxy. They could be within the GZK sphere (<50 Mpc) in the case no GZK cutoff, or they could be located at cosmological distances consistently with a GZK cutoff. Since we already know that the distribution of matter within the GZK sphere is rather irregular, a systematic study of the entire sky will unambiguously distinguish these two cases. On the other hand, partial sky coverage by the Southern Observatory alone would severely compromise such a study.

Lastly, AGASA has reported finding of six doublets and one triplet above $4\text{x}10^{19}$eV within a 2^{o} angular bin (corresponding to detector resolution.) What if the Southern Auger does not see any such clustering? Unless the same Northern sky is viewed by the Northern Auger, we can not verify whether AGASA is correct or not in this claim!

Q2-c) Why do you really need the Hybrid Detector for Northern Auger? Should not the Ground Array be adequate?

Answering this question is not so simple, compared to the previous one. The Hybrid Mode can certainly offer higher quality measurements in terms of energy, angular and composition resolutions. However, the loss of statistical power by a factor of ten (over the ground array only) must be taken into account.

The Super-GZK events (i.e. UHECR above $\sim 5\text{x}10^{19}$eV) are statistically very limited so that a factor of ten fewer events would be disadvantageous. Nevertheless, even a handful of "gold-plated" hybrid events could be critical in identifying their composition, which in turn could well be the only clue to their origin.

The real gain from the superior quality of the Hybrid will stand out as the inferior statistical power becomes less important. That is the case for events between the Ankle and the GZK cutoff, where the systematic uncertainty becomes a dominant factor. At energies above the Ankle, bending in the Galactic Magnetic field finally becomes small enough for cosmic rays to reach us from outer space, but not small enough to be totally neglected. To associate multiple events with a certain source location, momentum analysis together with composition measurement (i.e. rigidity analysis) becomes of particular importance. The hybrid mode offers far better angular resolution ($\sim 0.4^{o}$ compared to $\sim 1^{o}$ for the Ground array by itself) together with superior composition measurement.

Q2-d) Show an example of physics case, which the Ground Array by itself can not explain but the Northern-Auger Hybrid Detector can answer.

The best example is the case where the external magnetic field is such that the bending angles of UHECR are comparable to, or somewhat smaller than, the angular resolution of the "Ground Array only" observatory. In this case, momentum analysis is impossible without the Hybrid observation. With the superior angular resolution of the "Hybrid" observatory, the correlation between direction and energy, together with an independent composition measurement, will reveal a complete solution including the particle species as well as the magnitude and direction of the inter-Galactic magnetic fields. This will really be the beginning of the "Charged Particle Astronomy".

We should note here that such a momentum analysis may be possible *only* in the Northern hemisphere, where most of the detector aperture faces toward the outside of the Galactic plane, where the effective magnetic field is expected to be uniform. (This was first pointed by M. Teshima, and he indeed tried to apply the resulting methodology in AGASA data analysis with modest success.)

Q2-e) Why do you really need 3,000 km^2 for each site? What is wrong with half that size? Or 3/4 size?

Needless to say, the larger the better, if the budget is unlimited. Therefore a more practical question is, what cost can be justified for the Pierre-Auger Observatory? As we pointed out in (Q1-e), in comparison with the high energy neutrino observatory, ICECUBE, and the gravitational wave observatory, LIGO, it is our strong belief that a funding level of $100M to the UHECR observatory is not only well justified but rather modest from the view point of purely scientific significance.

The total budget of the full size (i.e. 3,000 km^2) observatory per site is estimated to be $50M. Thus the entire observatory (North & South) would cost $100M, of which it can be argued that the US should fund half as the host country of the Northern Observatory.

A significantly lower funding level than this estimate obviously means smaller detectors than 3,000 km^2 per site. This detector size was derived to ensure a tenfold increase in statistics compared with the previous experiments such as AGASA and HiRes. Considering the fact that AGASA and HiRes disagree on their energy flux measurement, anything smaller than 3,000 km^2 may not be able to resolve this discrepancy.

We should also point out that detector cost is not proportional to detector size since there are substantial (say $10 million) infrastructure costs. A half size detector would not cut the cost by half, it would compromise the scientific objectives.

3. Why now?

Q3-a) What is new in UHECR observations since the submission of the original proposal of Pierre-Auger in 1997?

Two major ongoing experiments, AGASA and HiRes have published their latest results in 2002. To summarize the present situation, AGASA claims to see a spectrum continuing above 10^{20}eV as of now containing eight events which would mean there is no GZK cutoff. In the same energy regime, HiRes claims to observe a clear GZK cutoff.

AGASA has ~250 km^2str of aperture above 10^{19} eV, and it has accumulated 10 years of data for the latest publication. The AGASA group reported the following findings:

- Energy spectrum above 10^{19}eV is consistent with a simple power law of $E^{-2.7}$, which extends as high as $3x10^{20}$eV.
- Above ~10^{19}eV, the large-scale angular distribution is consistent with isotropy.
- Above $4x10^{19}$eV, six doublets and one triplet were observed within 2^o angular bins. The statistical significance was estimated to be 5σ.

HiRes-Mono has ~10,000 km^2str aperture (at 10^{20}eV) with 10% duty factor. After two years of operation (i.e. equivalent to ~8 years of AGASA), they reported the following.

- Energy spectrum clearly shows the GZK cutoff around $10^{19.8}$ eV, and there are only two events above 10^{20}eV.
- The flux is almost a factor of two lower than AGASA (which can be explained by 20% difference of the absolute energy scale).

At a glance, the discrepancy between AGASA and HiRes appears very significant. However, once the energy scale of one experiment is shifted by 20% (to match their overall flux below the GZK cutoff), the disagreement in the number of events above 10^{20}eV becomes only a 2.5σ effect, not significant enough to conclude that there is a contradiction.

Obviously, a definite resolution of this discrepancy will come from the Pierre-Auger, where a Hybrid, high statistics observation can answer the questions of both the absolute energy scale and the possible spectrum distortion by one type of detection technique.

Q3-b) It appears that recent results from AGASA and HiRes are inconsistent. If HiRes is correct, there may be no interesting physics to study beyond the GZK cut off.

We argue that such an attitude is wrong and that there are deeper scientific issues at stake. The importance of UHECR observations and especially the elucidation of their origin will not be impacted regardless of whether the GZK cutoff exists or not.

The GZK cutoff (or spectrum change around GZK cutoff energy) is a generic feature in all cases of a cosmological origin of UHECR. As far as the messengers are hadrons, the GZK cutoff is unavoidable for any type of "Bottom-up" model which all assume uniform distribution of "Zevatrons" over the entire Universe.

If AGASA is correct and there is no GZK cutoff, it suggests three possibilities:

- The origins are "Top-down" and they are locally (<50Mpc) distributed, or
- Messengers are not hadrons, but neutrinos (or other type of weakly interacting particles) which can travel cosmological distances, or
- Lorentz invariance is violated.

Any of the above clearly would be a remarkable discovery. However, we should also be aware of the fact that the Super-GZK events by AGASA are consistent with an isotropic distribution, which suggests a cosmological origin, but that is inconsistent with failure to see a GZK cutoff.

One way to escape this inconsistency, suggested by G. Sigl, is the following idea:

- Origins are within the Local Super-cluster (<50Mpc), and
- There is strong (~0.5μG) magnetic field in the Local Super-cluster, which very much destroys directional information, resulting in an isotropic distribution.
- Such a magnetic field can also create clustering as a consequence of magnetic lensing.

To really distinguish the above four cases, an analysis of multi-pole moments with all-sky coverage becomes the most critical issue (as already mentioned in (Q2-b)). It is arguably the only way to untangle the puzzle presented by AGASA data.

On the other hand, if HiRes is correct, the existence of the GZK cutoff would imply two consequences:

- Origins are cosmologically distributed, and
- Messengers are hadrons.

Such a situation is not exotic, but it would exclude various "Top-down" models. An obvious consequence is that it will be the beginning of "Charged Particle Astronomy" above the Ankle. Then "Astronomy" will always require all-sky coverage. And furthermore, "Hybrid" observation is highly desirable for momentum analysis (as mentioned in (Q2-d)).

In conclusion, we are convinced that the necessity of all-sky coverage by essentially identical observatories in northern and southern hemispheres is actually increased due to the confusing situation between AGASA and HiRes.

Q3-c) Why don't you wait until initial physics results are obtained from the Southern Auger?

It is true that Southern Auger is likely to tell us whether AGASA is correct or HiRes is correct. However, that will not end the investigation: it will either signal the beginning of a new world of 'Top-down" physics of the Early Universe, or else the beginning of the field of "Charged Particle Astronomy" as mentioned in (Q3-b). In either case, we are surely in a win-win situation.

Therefore, there is absolutely no reason to wait for physics results from the Southern Auger before constructing the Northern Auger. The necessity of Northern Auger will not be diminished or reduced; instead it is decoupled from whether AGASA is right or HiRes is right, and it is also decoupled from the anticipated findings of the Southern Auger.

It is our opinion that the Northern Auger should be constructed in the time frame of the Southern Auger so as to maximize the physics outcome from the total Observatory as quickly as possible. The statistics from the North and South should be matched to achieve truly uniform sky coverage. Any delay of Northern construction will reduce the significance of the Southern Observatory.

Q3-d) What is the current status of other ongoing and future experiments such as AGASA, HiRes, TA and EUSO? Is the Northern-Auger competitive and timely?

Yes. It is very much so. Proposed construction of Pierre-Auger Observatories, both in South and North, are very timely and they fit very well in the long range plan, including the future space based programs such as EUSO and OWL.

For comparison, Table 1 below summarizes these experiments. AGASA has already accumulated 10 years of data; thus additional years will not dramatically improve its statistics. After some unfortunate difficulty of accessing the sites, HiRes has established partially-remote stable data taking. However, it has not demonstrated the expected aperture size for the stereo view yet. In the table, HiRes-Mono aperture is listed (together with expected resolution of stereo-view).

To compare the accumulated sensitivity, the integrated aperture (in units of $km^2 \times str \times year$) of each experiment is plotted below in Figure 1 as a function of calendar year. Even if HiRes stereo aperture turns out be as large as the mono aperture, once the Southern-Auger starts full construction this year, our statistics will catch up and exceed the HiRes integrated aperture in 2004. Together with the Northern Observatory, the Pierre-Auger project is going to accumulate ten times the entire HiRes statistics by year 2010 (assuming HiRes stops operation around 2006. By that time, the integrated statistics will exceed the expected annual output of EUSO. Considering the high price and precarious future (given the recent shuttle tragedy) of space-based experiments, Pierre-Auger is the most cost effective way to achieve scientific objectives.

Exper-iment	Method	Covered Area	Duty Factor	Effective Aperture	Energy Thres.	Energy Resol.	Angle Resol.	Cost	Start Year
Unit		*km*^{2}	%	*km*^{2}*str*	*eV*	%	Deg.	$M	-
Fly's Eye	FD	300	10	100	~10^{17}	~20	~2°	0.5	1986
AGASA	SD	100	100	250	~3×10^{18}	~20	~2°	1	1992
HiRes	FD	10,000	10	1,000	~3×10^{18}	~10	~0.5°	5	1999
Pierre-Auger (South)	SD	3,000	100	7,000	~10^{19}	~10	~1°	50	2005
	Hybrid	3,000	10	700	~3×10^{18}	~5	~0.4°		
(South + North)	SD	6,000	100	14,000	~10^{19}	~10	~1°	100	2007
	Hybrid	6,000	10	1,400	~3×10^{18}	~5	~0.4°		
EUSO	FD	500,000	10	50,000	~5×10^{19}	~30	~2°	~250	~2010
OWL	FD	5,000,000	10	500,000	~10^{20}	~30	~2°	?	>2015

Table 1 Comparison between past, ongoing and future UHECR experiments. Effective aperture, energy resolution and angular resolution are given at E= 10^{20}eV.

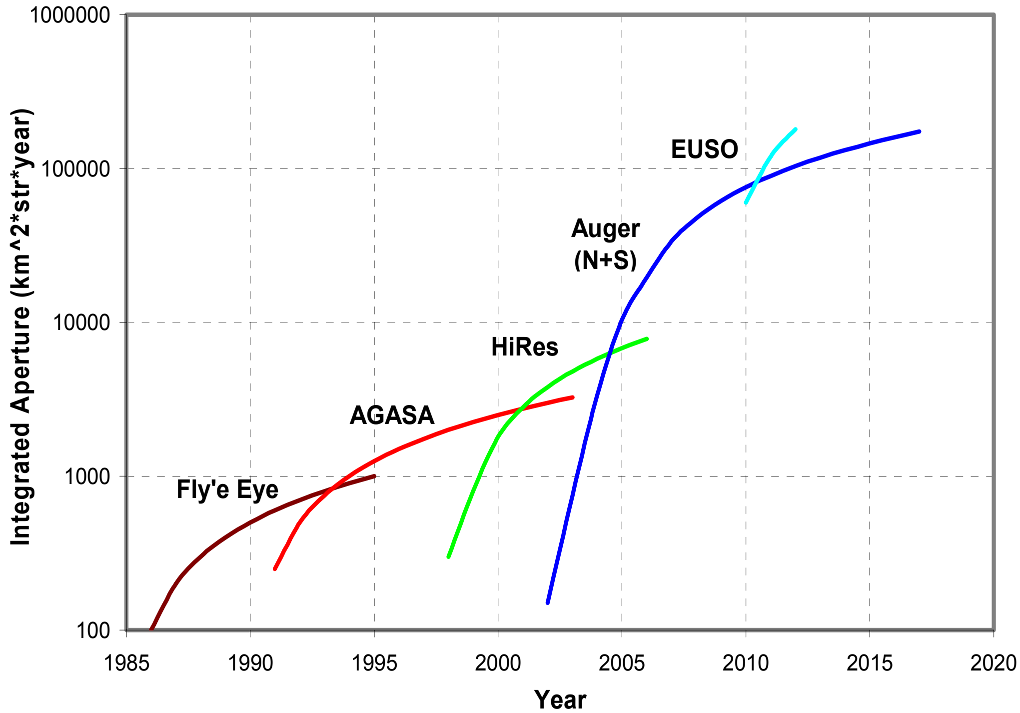

Figure 1 Integrated aperture of past, ongoing, future UHECR experiments in unit of km^2 × str × year.