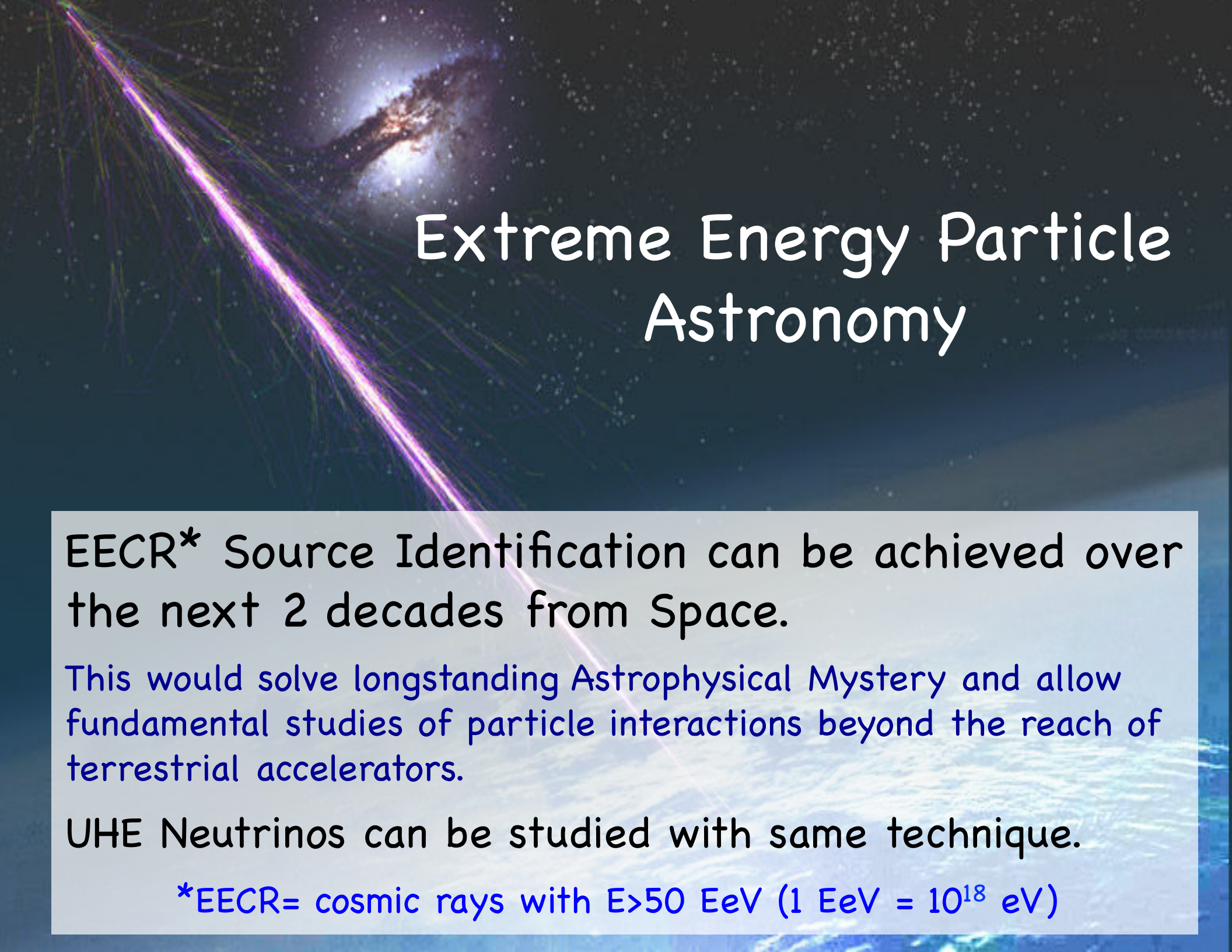


Extreme Energy Particle Astronomy

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A cosmic background image featuring a bright, glowing galaxy or nebula in the upper center, surrounded by a field of distant stars. A prominent, vibrant purple particle track, resembling a cosmic ray, streaks diagonally from the top left towards the bottom right, leaving a trail of smaller, fainter purple lines. The overall scene is set against a deep blue and black space background.

Extreme Energy Particle Astronomy

EECR* Source Identification can be achieved over the next 2 decades from Space.

This would solve longstanding Astrophysical Mystery and allow fundamental studies of particle interactions beyond the reach of terrestrial accelerators.

UHE Neutrinos can be studied with same technique.

*EECR= cosmic rays with $E > 50 \text{ EeV}$ ($1 \text{ EeV} = 10^{18} \text{ eV}$)

Particle Astronomy Begins

This Decade marks the beginning of Particle Astronomy
(ie, the identification of cosmic particle accelerators):

Anisotropies observed in Cosmic Ray distribution:

- Large Scale at Intermediate Energies (Milagro, Tibet, IceCube)
- Hints at Ultrahigh Energies (Pierre Auger, Telescope Array)

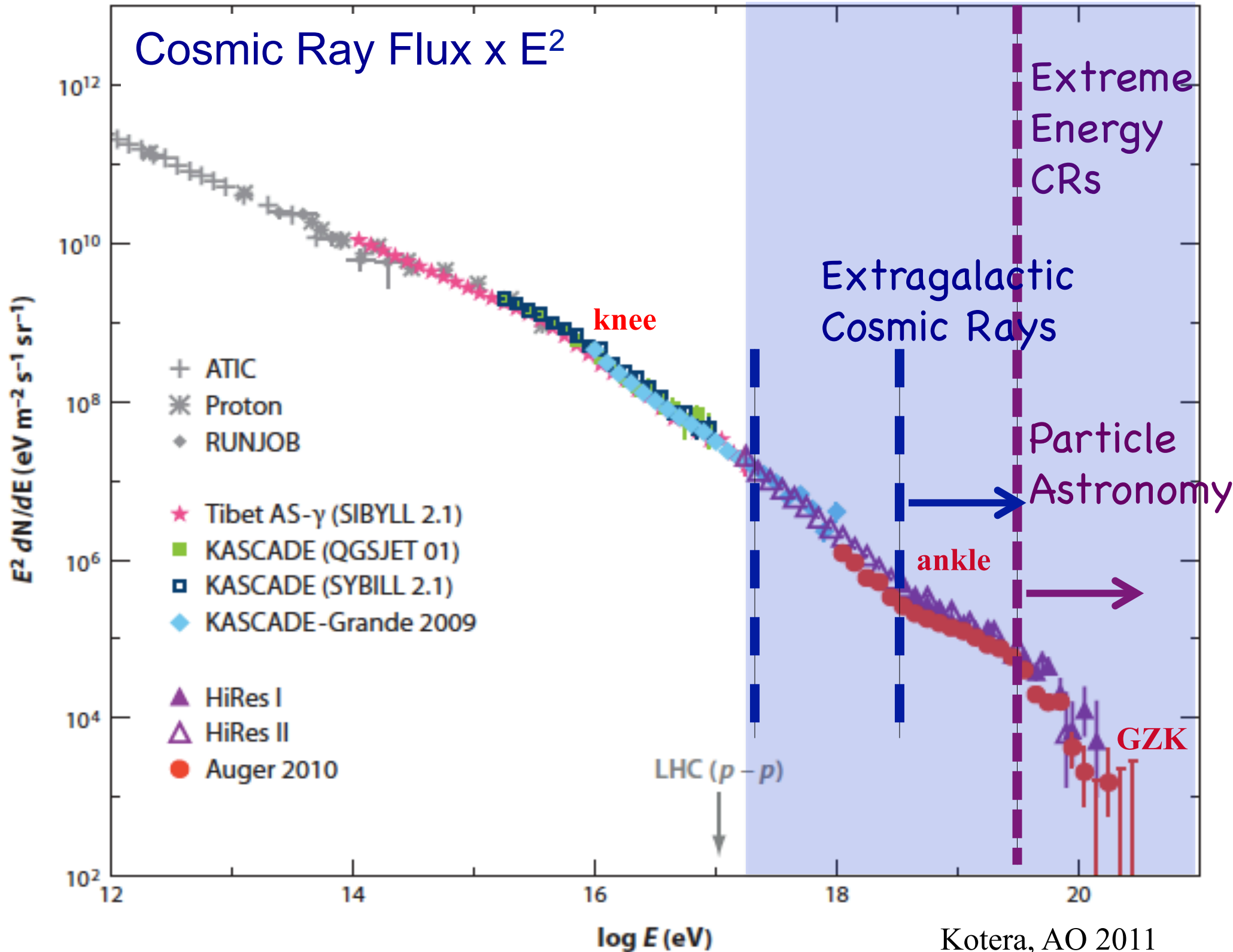
First π^0 decay signal identified (Fermi W44 & IC443, Feb'13)

PeV neutrinos first observed (IceCube, Apr'13)

Cosmic Magnetic Fields allow direct pointing above ~ 10 EeV (protons) and $Z \times 10$ EeV (nuclei w/ charge Z).

UHECRS are now known to be extragalactic above 1 EeV (protons) & 20 EeV (iron)

Cosmic Ray Flux x E^2



Extreme Energy Cosmic Rays

EECRs are observed up to $\sim 300 \text{ EeV} = 3 \cdot 10^{20} \text{ eV}$
($> 10^7 E_{\text{LHC}}$ equivalent to $\sim \text{PeV C.M.}$)

Their origin is unknown and observed energies challenge
ALL acceleration models

Among known cosmic photon accelerators only neutron stars, gamma-ray bursts, active galactic nuclei, and intergalactic medium shocks can contain these particles, requiring close to 100% efficient acceleration.

Need to observe many more EECRs to determine source.

Main Challenge: low flux $\sim 1 \text{ particle/km}^2/\text{century}$

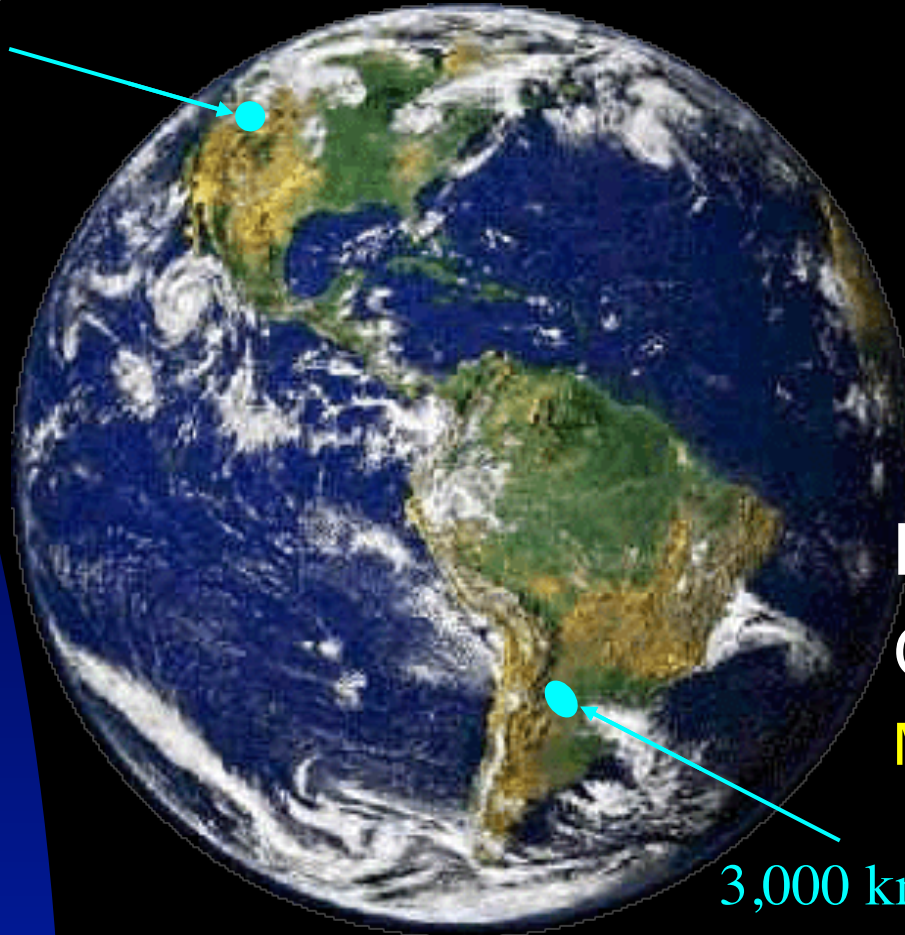
Space Observatories provide needed significant increase in statistics

Ultrahigh Energy Cosmic Rays Leading Observatories

Telescope Array

Utah, USA

760 km² array
3 fluorescence sites



Pierre Auger
Observatory
Mendoza, Argentina

3,000 km² array
4 fluorescence sites

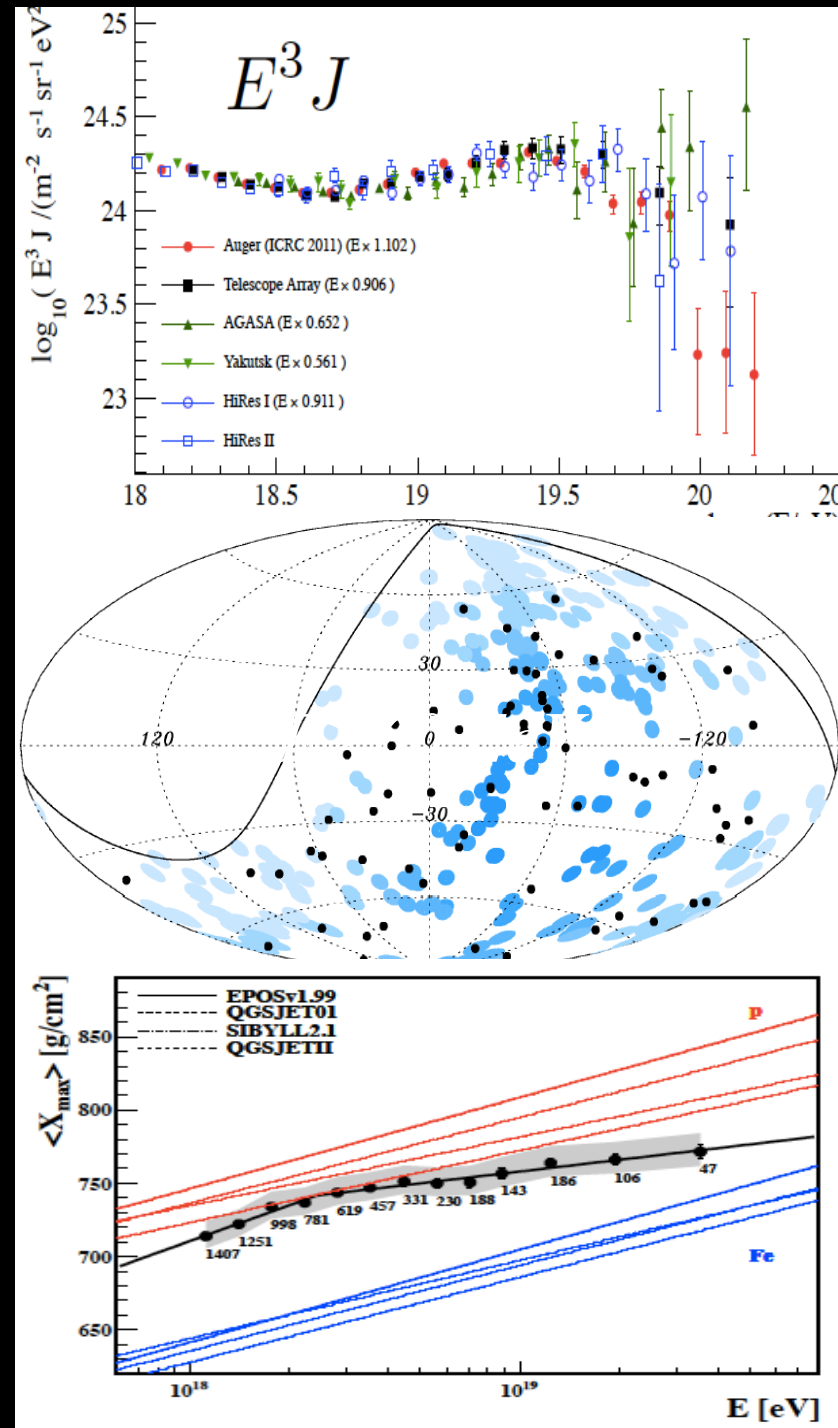
Ground UHECR Observations show:

Spectral feature > 40 EeV
due to CMB interactions?
(Greisen-Zatsepin-Kuzmin (GZK) effect?)
or due to E_{max} of sources?

$E > 60$ EeV – hints of anisotropy –
The start of Particle Astronomy?

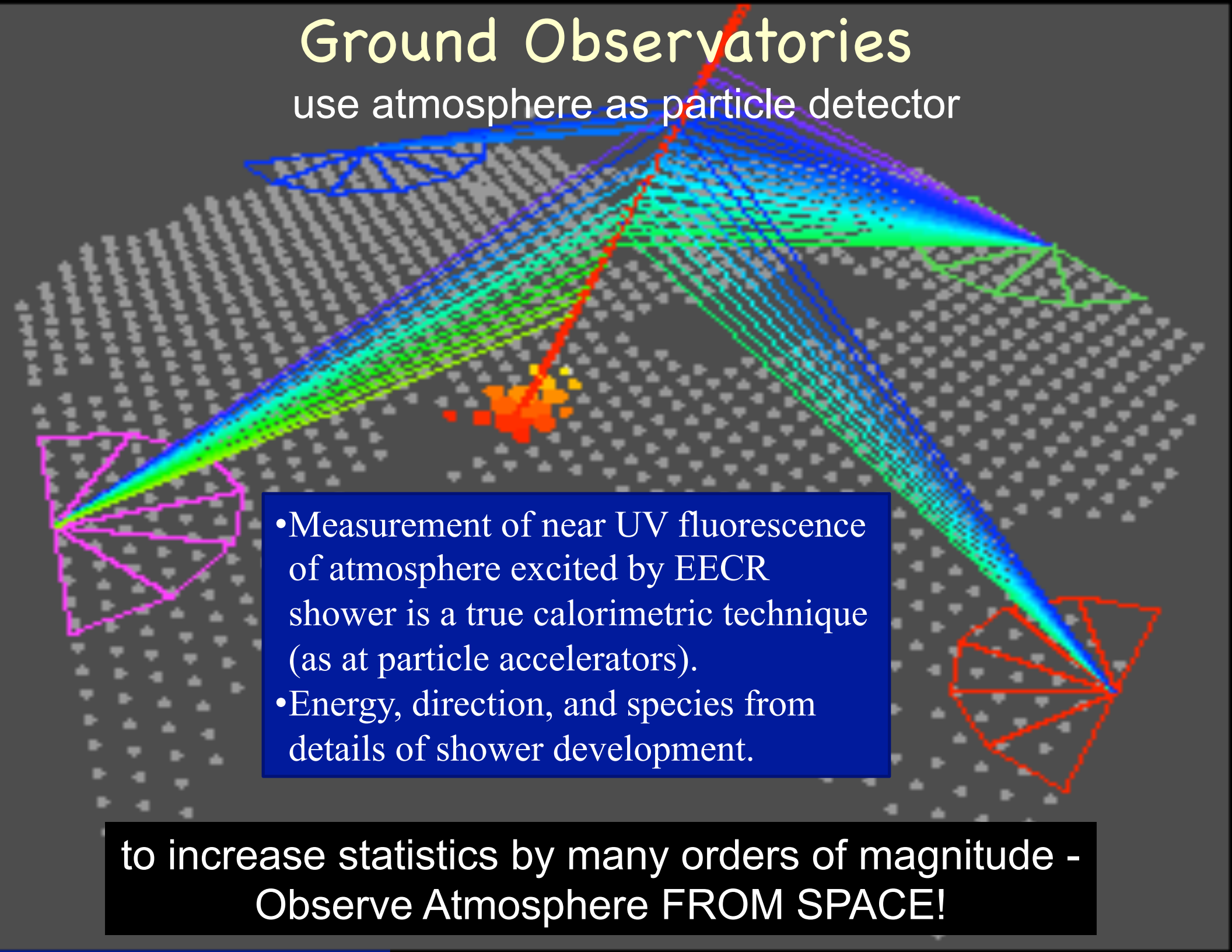
Composition: surprising change
toward heavier nuclei > 40 EeV?
or new Hadronic Interactions?

**Only ~ 1 event > 100 EeV/year
and ~ 30 events > 60 EeV/year**



Ground Observatories

use atmosphere as particle detector

- 
- A diagram illustrating an extensive air shower. A primary particle, represented by a red dot, enters the atmosphere from the top. It creates a cascade of secondary particles, shown as a fan of lines radiating outwards. The shower particles are depicted as a dense, multi-colored cloud (red, orange, yellow, green, blue) that expands as it moves downwards. The background is a dark gray grid of small white dots, representing the atmosphere. Several geometric shapes (triangles, quadrilaterals) are overlaid on the shower, likely representing detector footprints or measurement regions. A blue box contains text describing the measurement techniques.
- Measurement of near UV fluorescence of atmosphere excited by EECR shower is a true calorimetric technique (as at particle accelerators).
 - Energy, direction, and species from details of shower development.

to increase statistics by many orders of magnitude -
Observe Atmosphere FROM SPACE!

How many EECRs /yr?

Pierre Auger Obs. w/ 3,000 km²

~20 events > 60 EeV/ yr

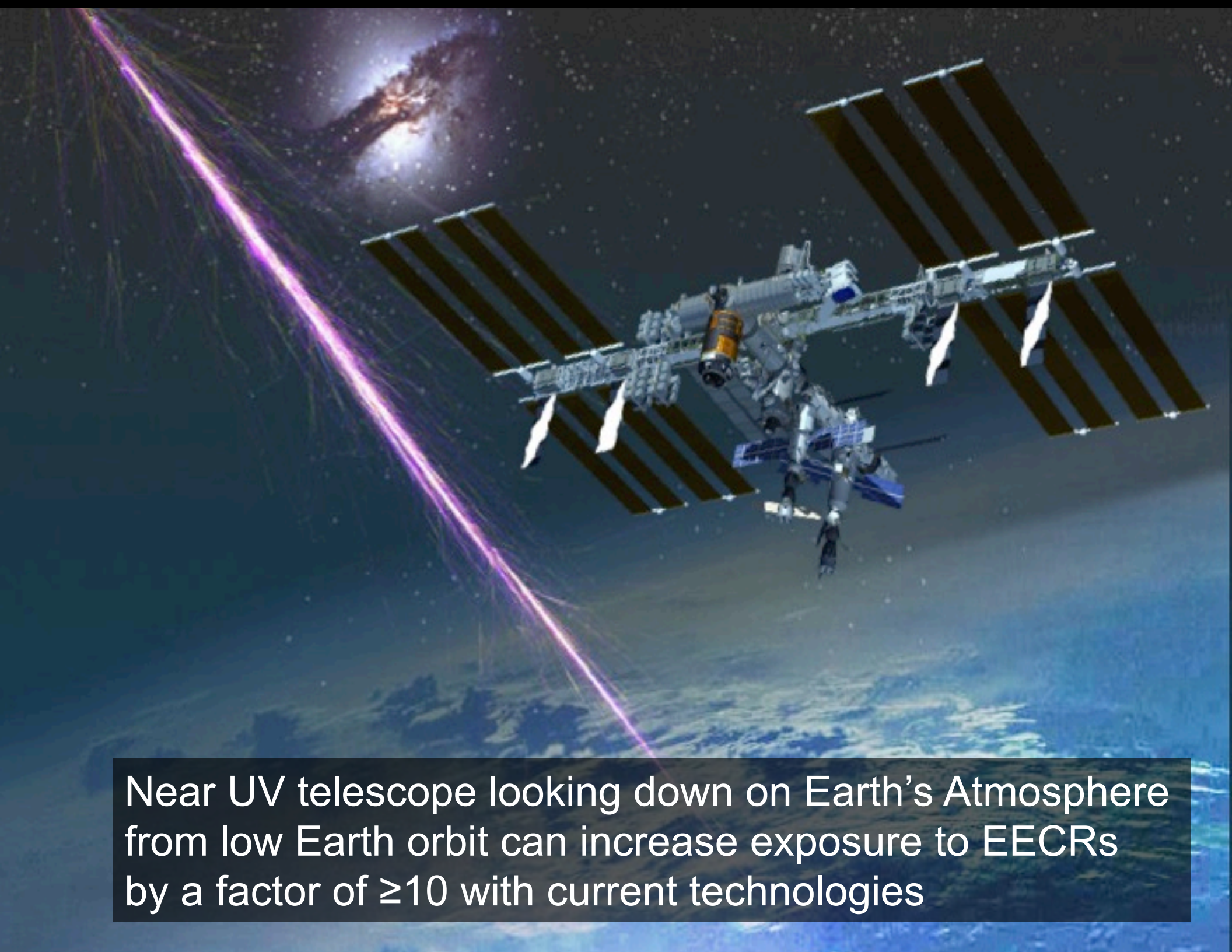
Telescope Array w/ 760 km²

~5 events > 60 EeV/ yr

TOTAL ~30 events/yr

**Earth Atmosphere receives
> 3 10⁶ events/yr!**





Near UV telescope looking down on Earth's Atmosphere from low Earth orbit can increase exposure to EECRs by a factor of ≥ 10 with current technologies

Huge Exposure Area

60 FOV from ISS

Tilt-mode ($\sim 7 \times 10^5 \text{ km}^2$)

Nadir-mode ($\sim 2 \times 10^5 \text{ km}^2$)

AGASA ($\sim 100 \text{ km}^2$)

Auger ($\sim 3000 \text{ km}^2$)

ISS (1min.)

100 x Area of Auger
10 % Duty Cycle
10 x Exposure

3000 Gton – for EHE neutrinos

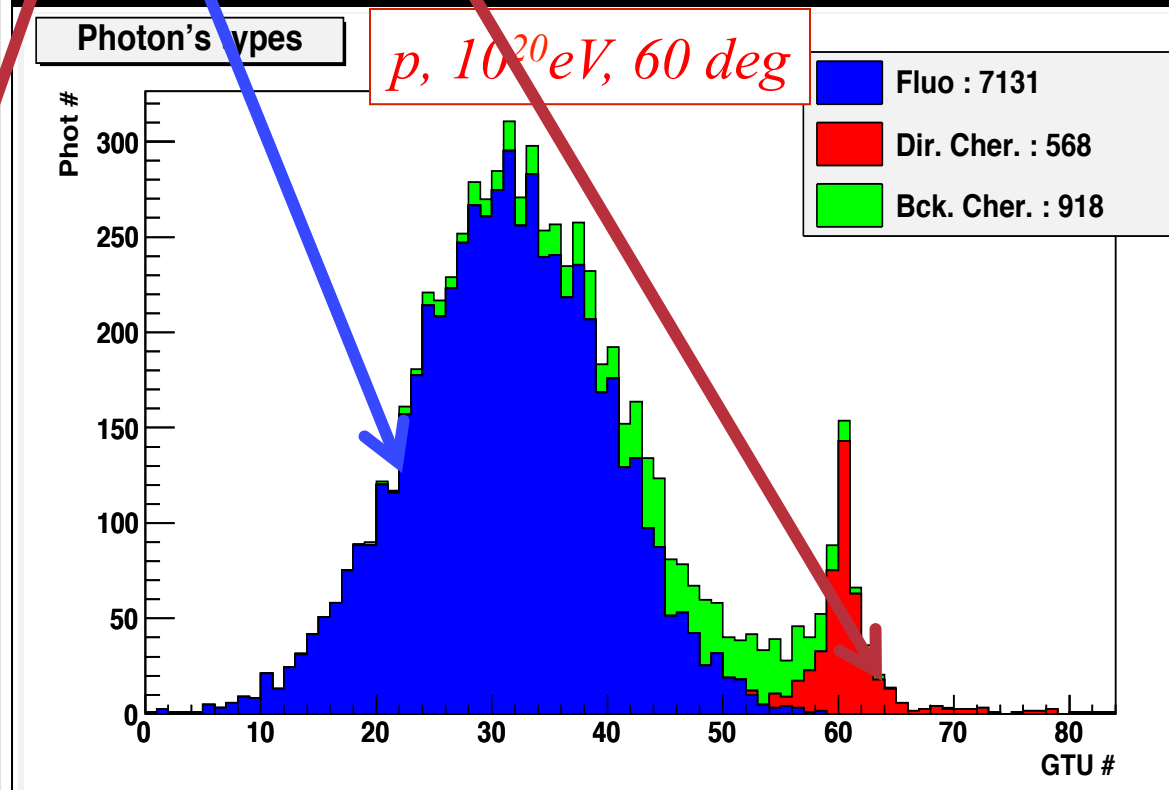
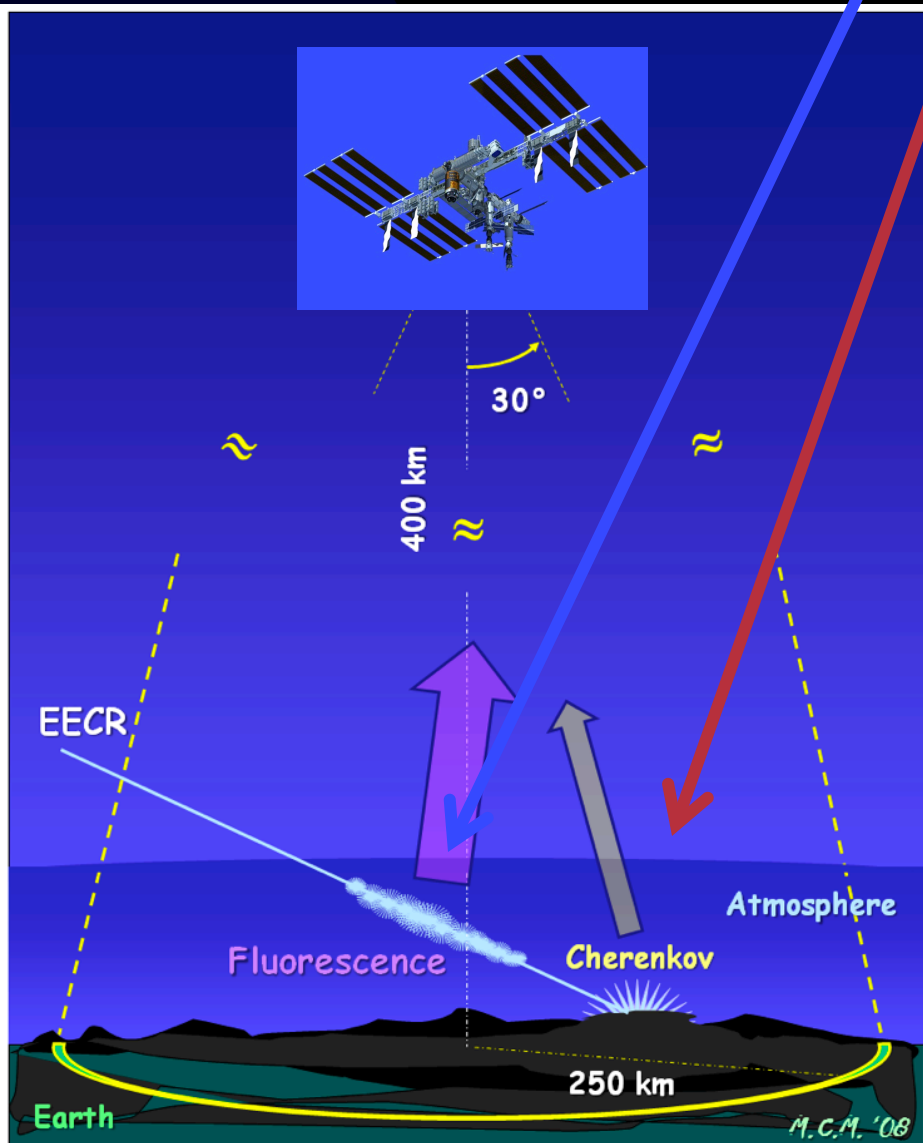
FAST Light SIGNAL

Duration 20 -150 μs (3 $\mu\text{s}/\text{km}$)

a) N_2 Fluorescence

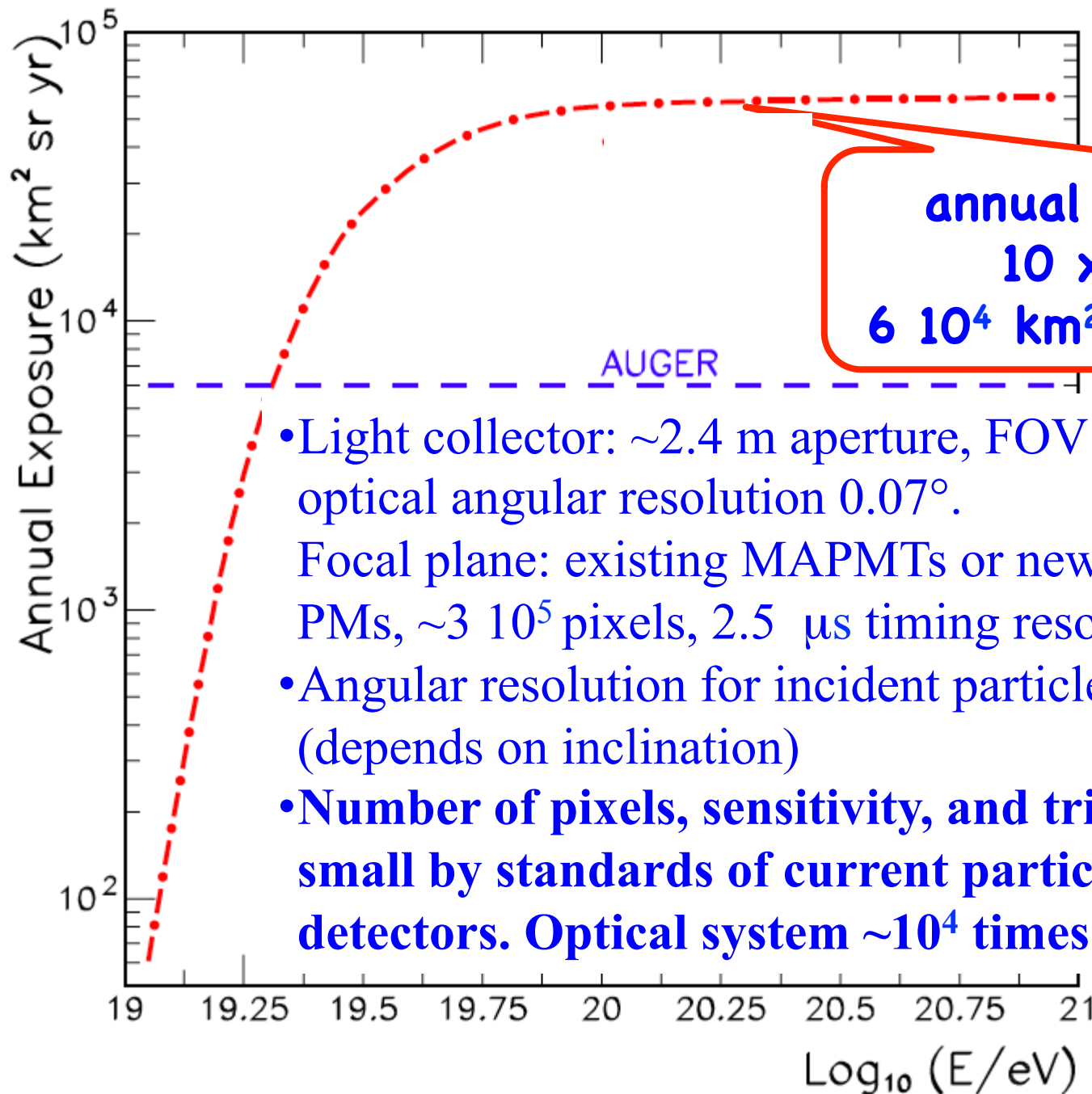
b) Scattered Cherenkov

c) Direct (diffusively reflected Cherenkov)



Background: $\sim 500 \text{ photons/m}^2 \text{ sr ns}$

60° FOV monocular refractor from the ISS

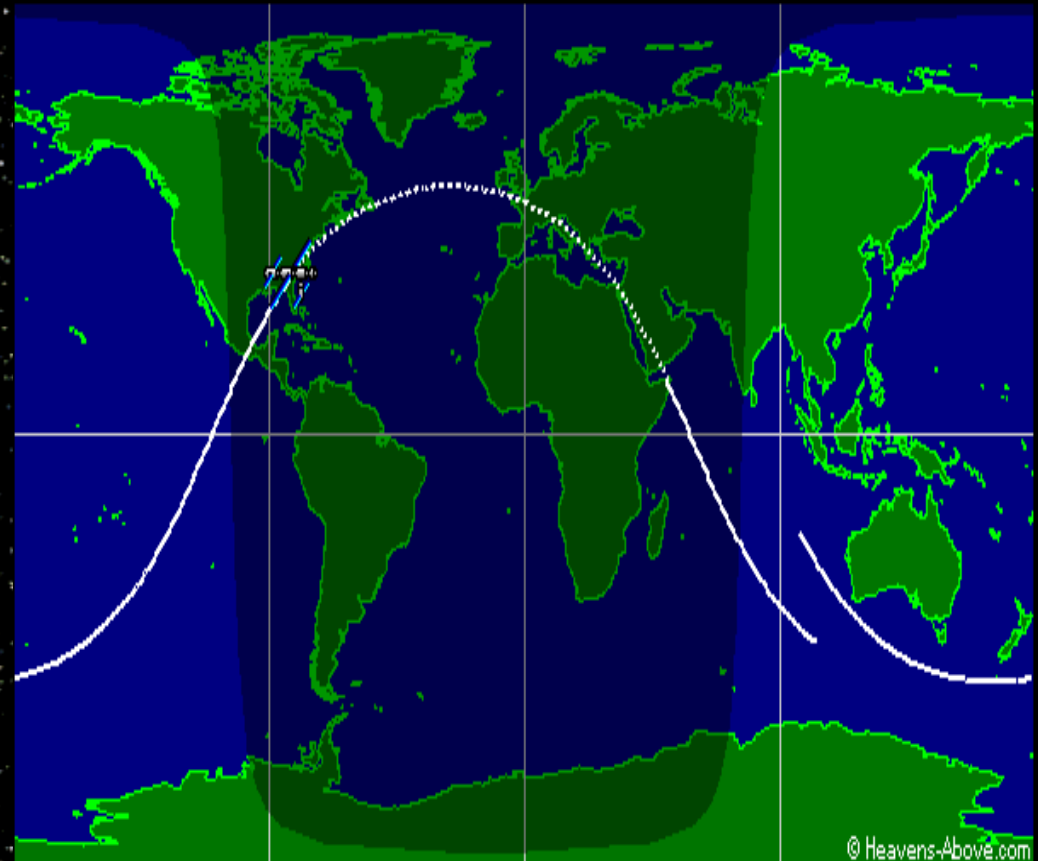


- Light collector: ~ 2.4 m aperture, FOV 60° half angle, optical angular resolution 0.07° .
Focal plane: existing MAPMTs or new UV solid-state PMs, $\sim 3 \cdot 10^5$ pixels, $2.5 \mu\text{s}$ timing resolution.
- Angular resolution for incident particle: few degrees (depends on inclination)
- **Number of pixels, sensitivity, and trigger selectivity small by standards of current particle collider detectors. Optical system $\sim 10^4$ times diffraction limit.**

Full Sky Coverage with nearly uniform exposure



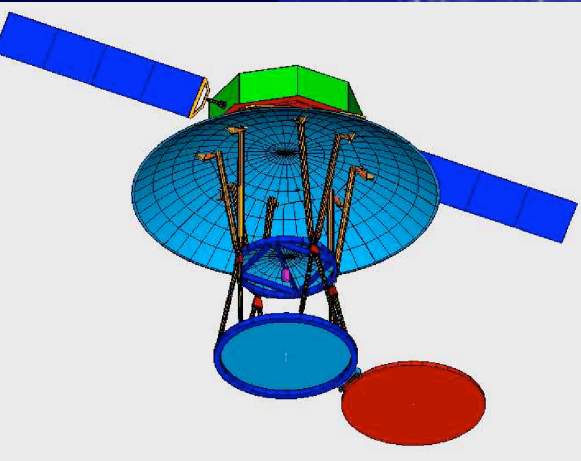
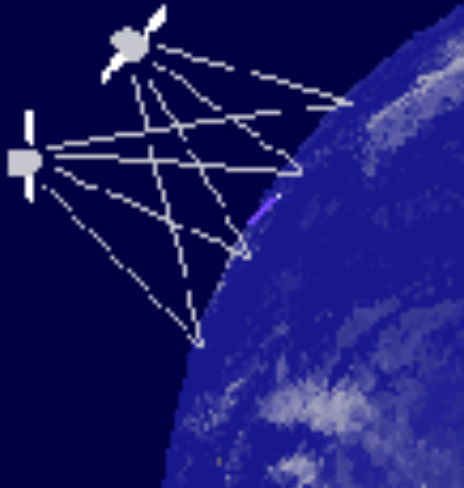
The ISS ORBIT



Inclination: 51.6°
Altitude: $\sim 400\text{km}$

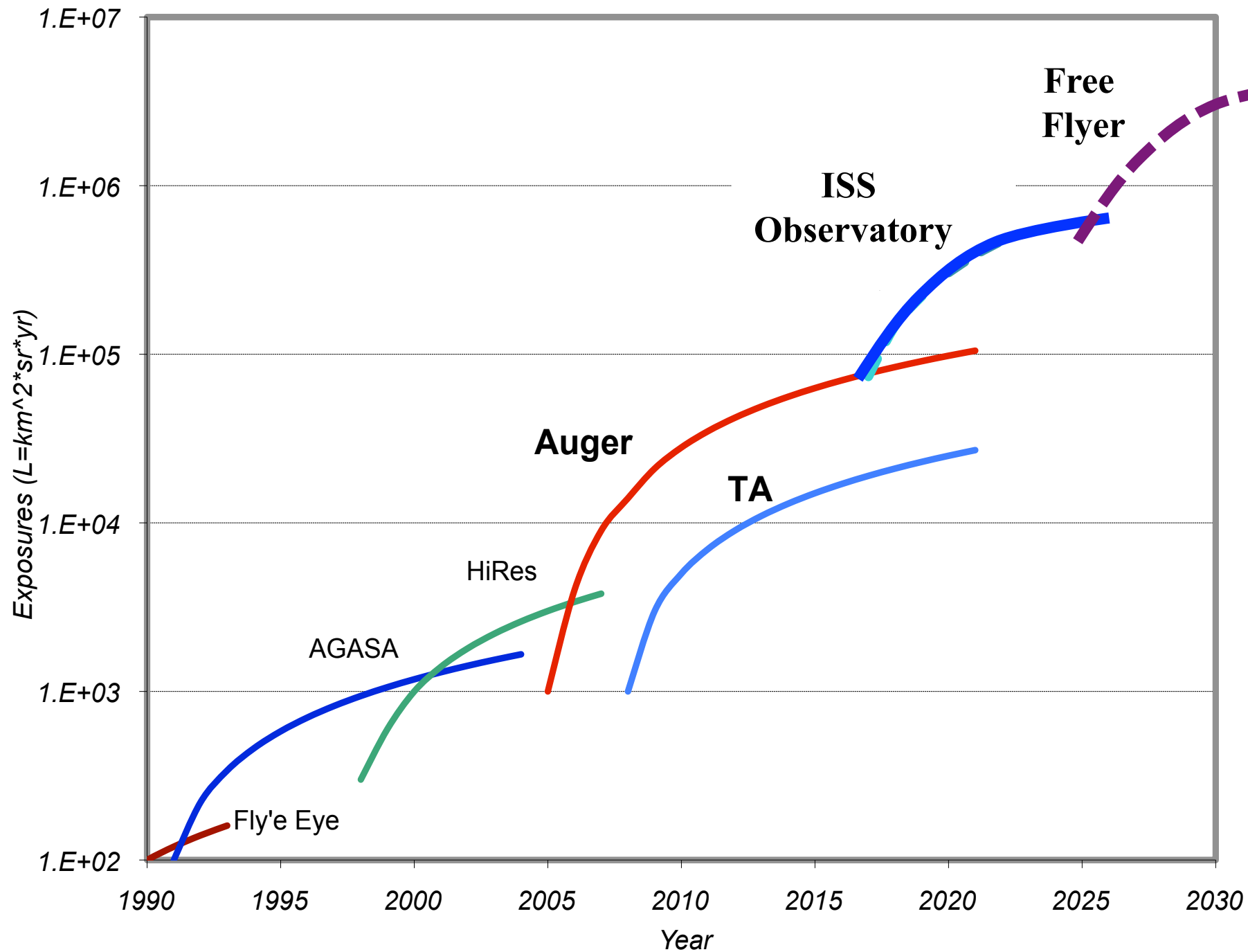
Next generation after ISS:

Co-orbiting Pair of Free Flyers



- Two satellites give Stereo View – improved particle angular resolution and energy resolution (atmospheric correction).
- 3 phase mission profile: 10° inclination orbit
 - 1) 1000 km, 20 km separation, 3 months – upward Ck light from v_t
 - 2) 1000 km, 600 km separation, ~ 2.5 yrs – highest energy EECR, $2 \cdot 10^{19}$ threshold
 - 3) 600 km, 500 km separation, remaining mission – 10^{19} threshold with reduced exposure
- Optional monocular mode – fault tolerance, increased aperture
- Light collector: Schmidt telescope (similar to asteroid finder), 7 m dia. mirror, ~ 3 m aperture, FOV 45° half angle, optical angular resolution 0.03° .
Focal plane: solid-state PMs, $5.5 \cdot 10^5$ pixels, 100 ns timing resolution (improved shower max resolution and monocular reconstruction).
- Angular resolution for incident particle: $\sim 1^\circ$
- Energy resolution $< 20\%$

Exposure History



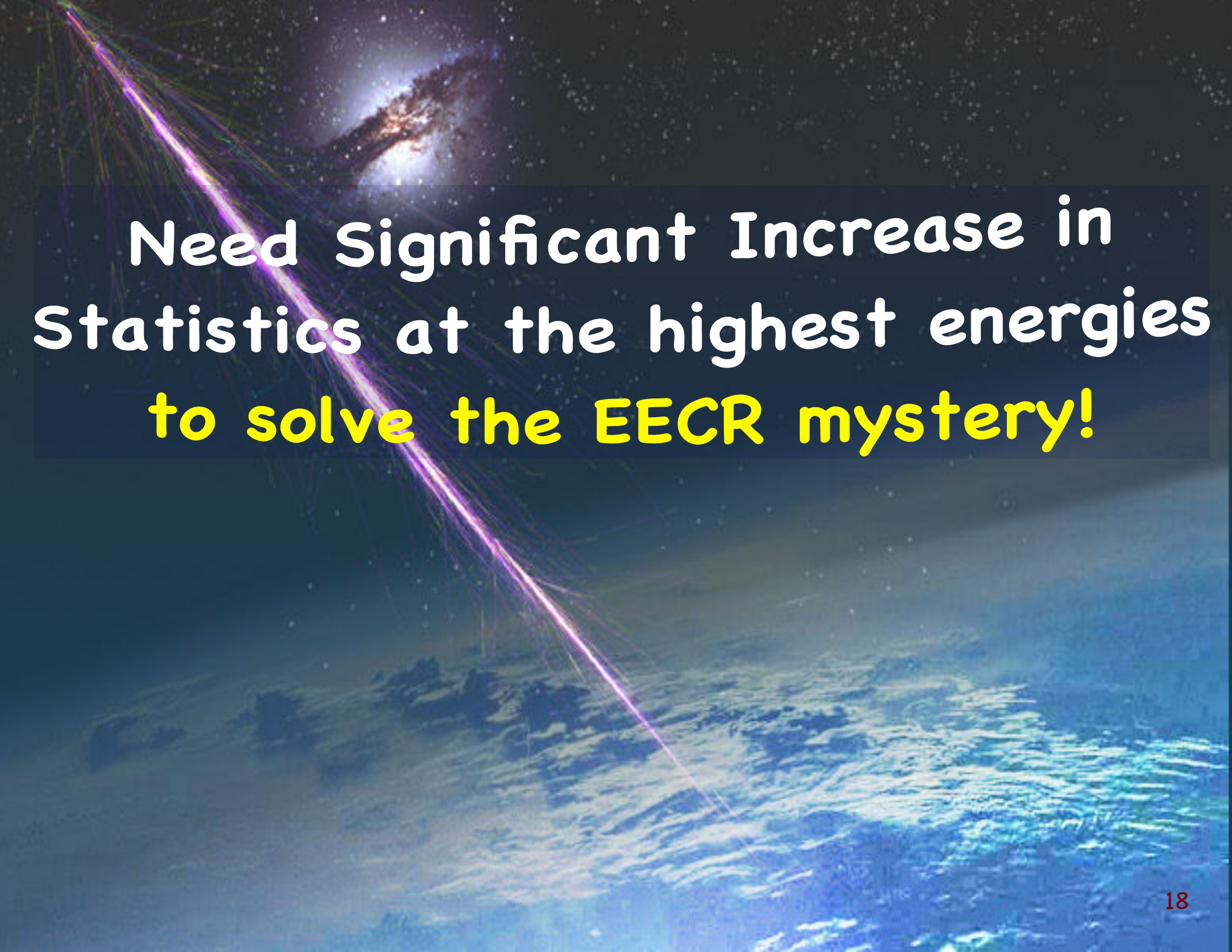
Same Technique can observe Cosmogenic (GZK) Neutrinos & Photons

$$p + \gamma_{cmb} \rightarrow \Delta^+ \rightarrow p + \pi^0 \rightarrow \gamma\gamma$$
$$\rightarrow n + \pi^+$$

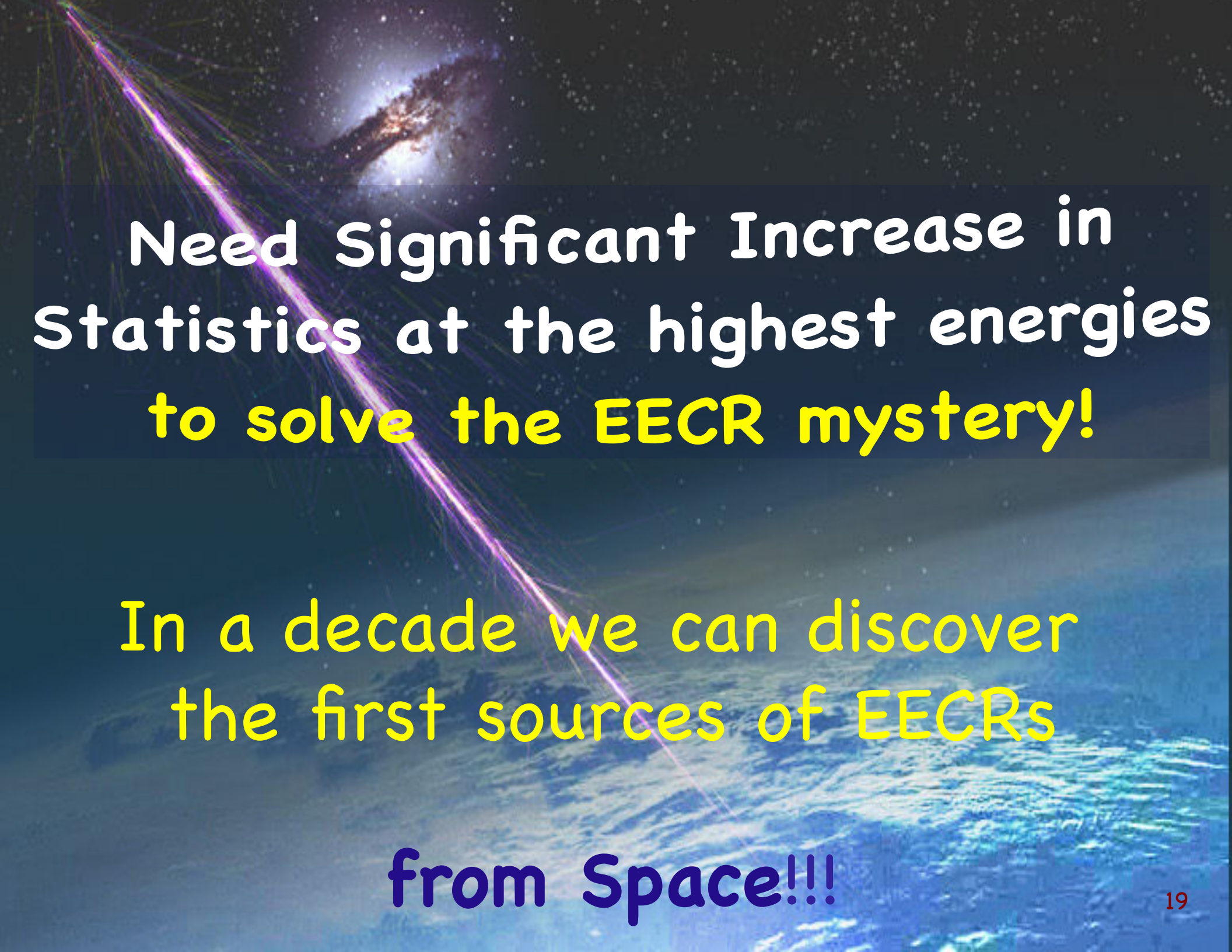
$$n \rightarrow p + e^- + \nu_e$$

$$\pi^+ \rightarrow \mu^+ + \nu_\mu$$

$$\mu^+ \rightarrow e^+ + \nu_e + \nu_\mu$$

A cosmic background image featuring a bright purple beam of light, possibly a gamma-ray burst or a high-energy particle beam, streaking diagonally across the frame. The beam originates from the top left and extends towards the bottom right. In the upper center, there is a bright, glowing nebula or galaxy core. The lower half of the image shows a view of Earth from space, with blue oceans and white clouds. The overall scene is set against a dark, star-filled sky.

**Need Significant Increase in
Statistics at the highest energies
to solve the EECR mystery!**

A cosmic background image featuring a bright, glowing galaxy in the upper center. A vibrant purple laser beam originates from the top left corner and extends diagonally across the frame, passing through the text. The background is filled with stars and a blueish-purple nebula at the bottom.

**Need Significant Increase in
Statistics at the highest energies
to solve the EECR mystery!**

**In a decade we can discover
the first sources of EECRs
from Space!!!**