Extreme Energy Particle Astronomy

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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 EeV (1 EeV = 10^{18} 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:

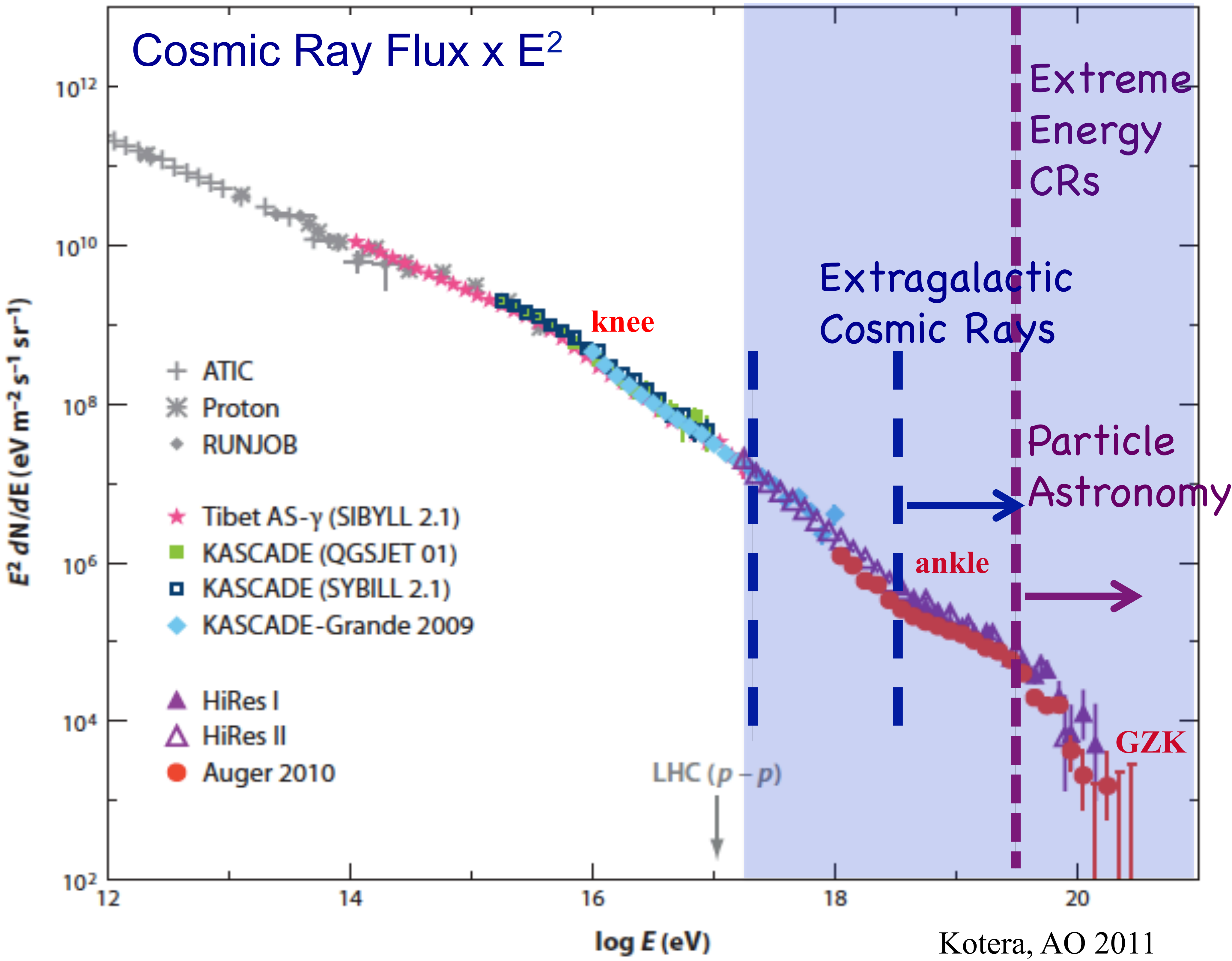
- Large Scale at Intermediate Energies (Milagro, Tibet, IceCube)
- Hints at Ultrahigh Energies (Pierre Auger, Telescope Array)

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 x 10 EeV (nuclei w/ charge Z).

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



Kotera, AO 2011

Extreme Energy Cosmic Rays

EECRs are observed up to ~ 300 EeV = 3 10^{20} eV
(> 10^{7} E_{LHC} equivalent to ~ 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 ~ 1 particle/km^2/century

Space Observatories provide needed significant increase in statistics

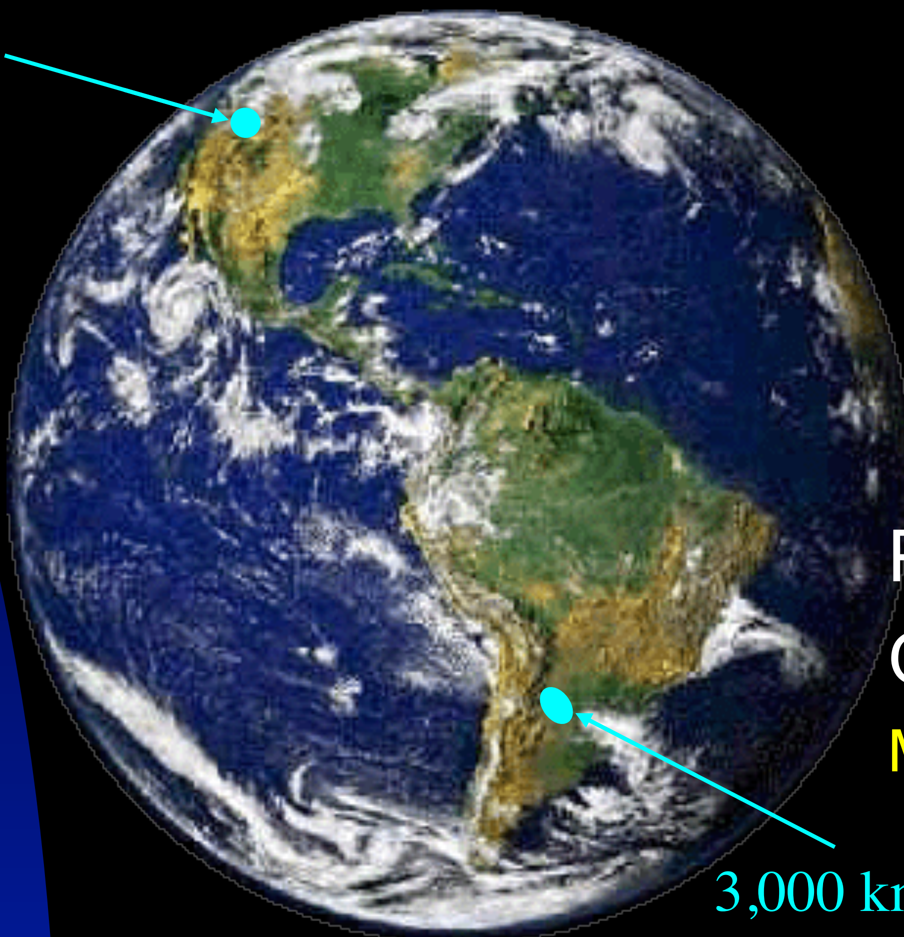
Ultrahigh Energy Cosmic Rays Leading Observatories

Telescope Array

Utah, USA

760 km^2 array

3 fluorescence sites



Pierre Auger Observatory

Mendoza, Argentina

3,000 km^2 array

4 fluorescence sites

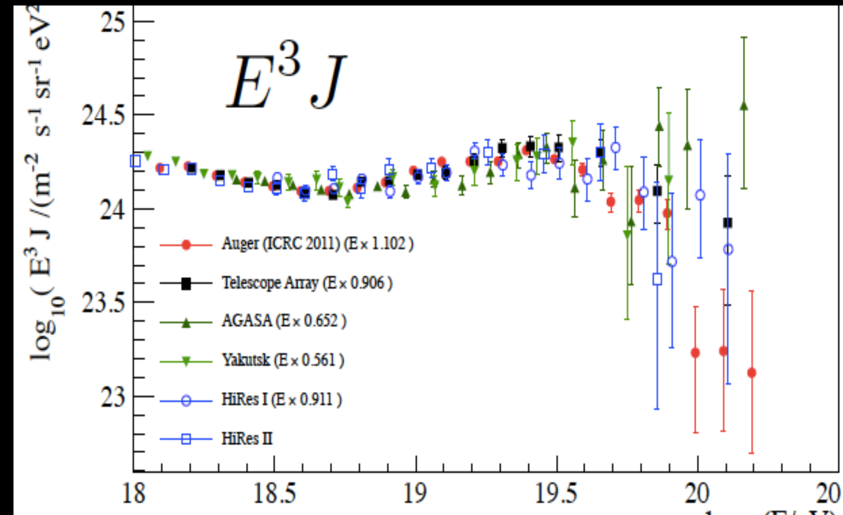
Ground UHECR Observations show:

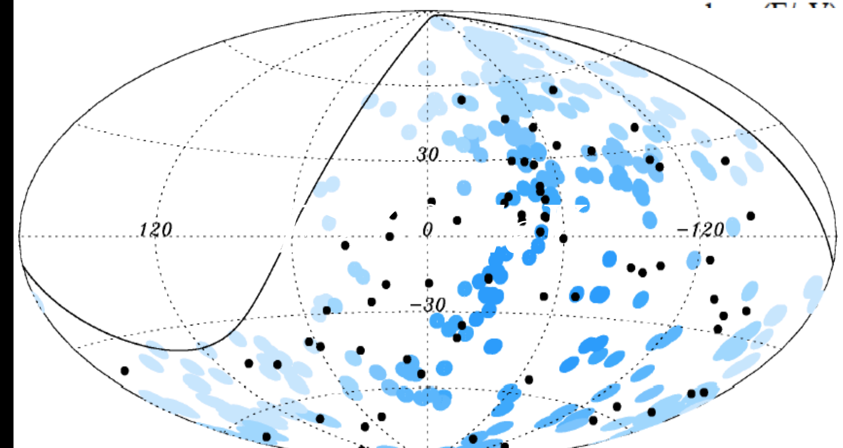
Spectral feature > 40 EeV
due to CMB interactions?
(Greisen-Zatsepin-Kuzmin (GZK) effect?)
or due to E_{max} of sources?

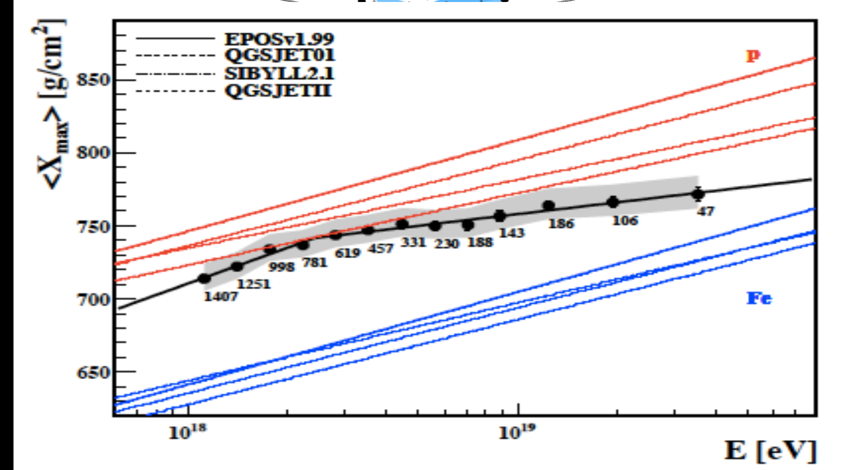
E > 60 EeV – hints of anisotropy –
The start of Particle Astronomy?

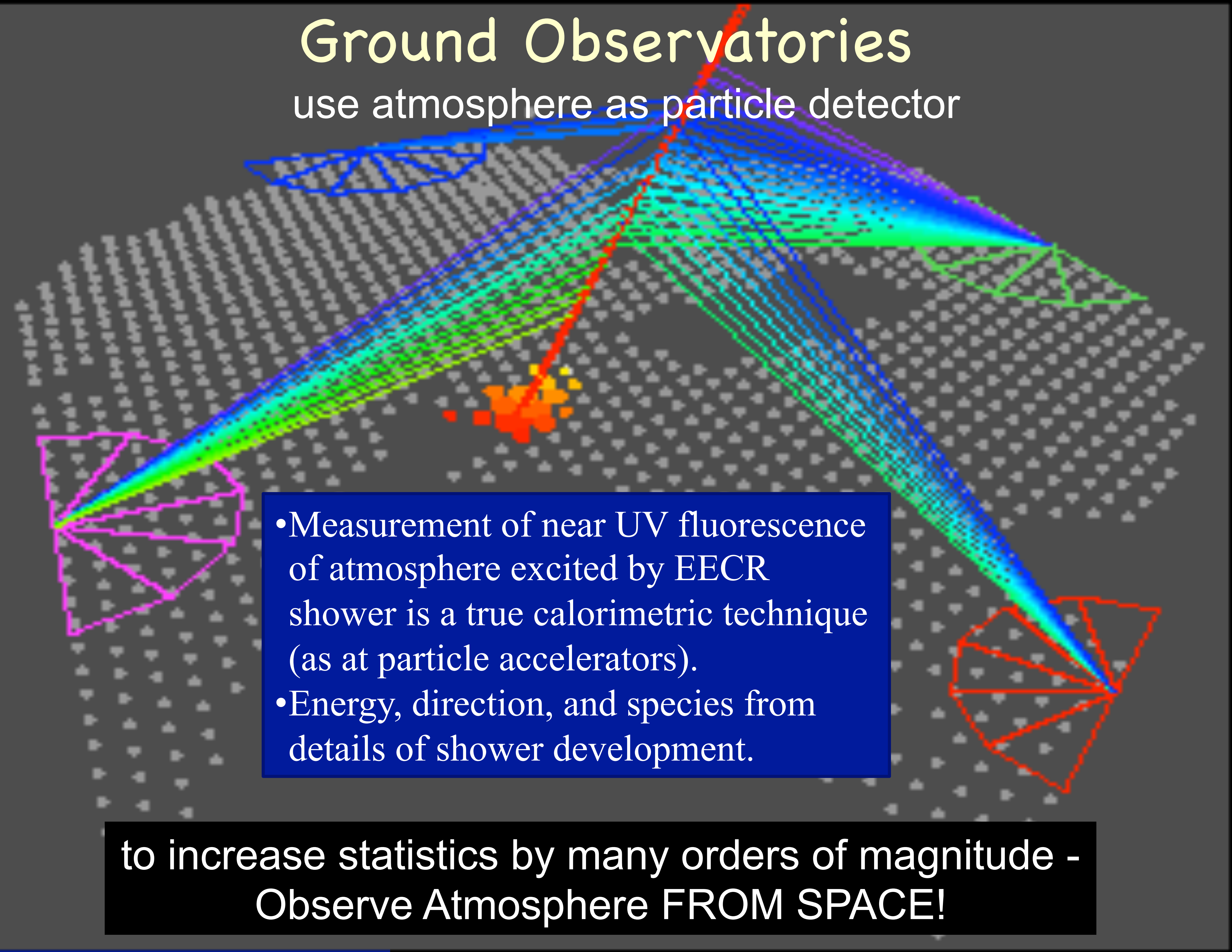
Composition: suprising change
toward heavier nuclei > 40 EeV?
or new Hadronic Interactions?

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








Ground Observatories
use atmosphere as particle detector
•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 km^2

~20 events > 60 EeV/ yr

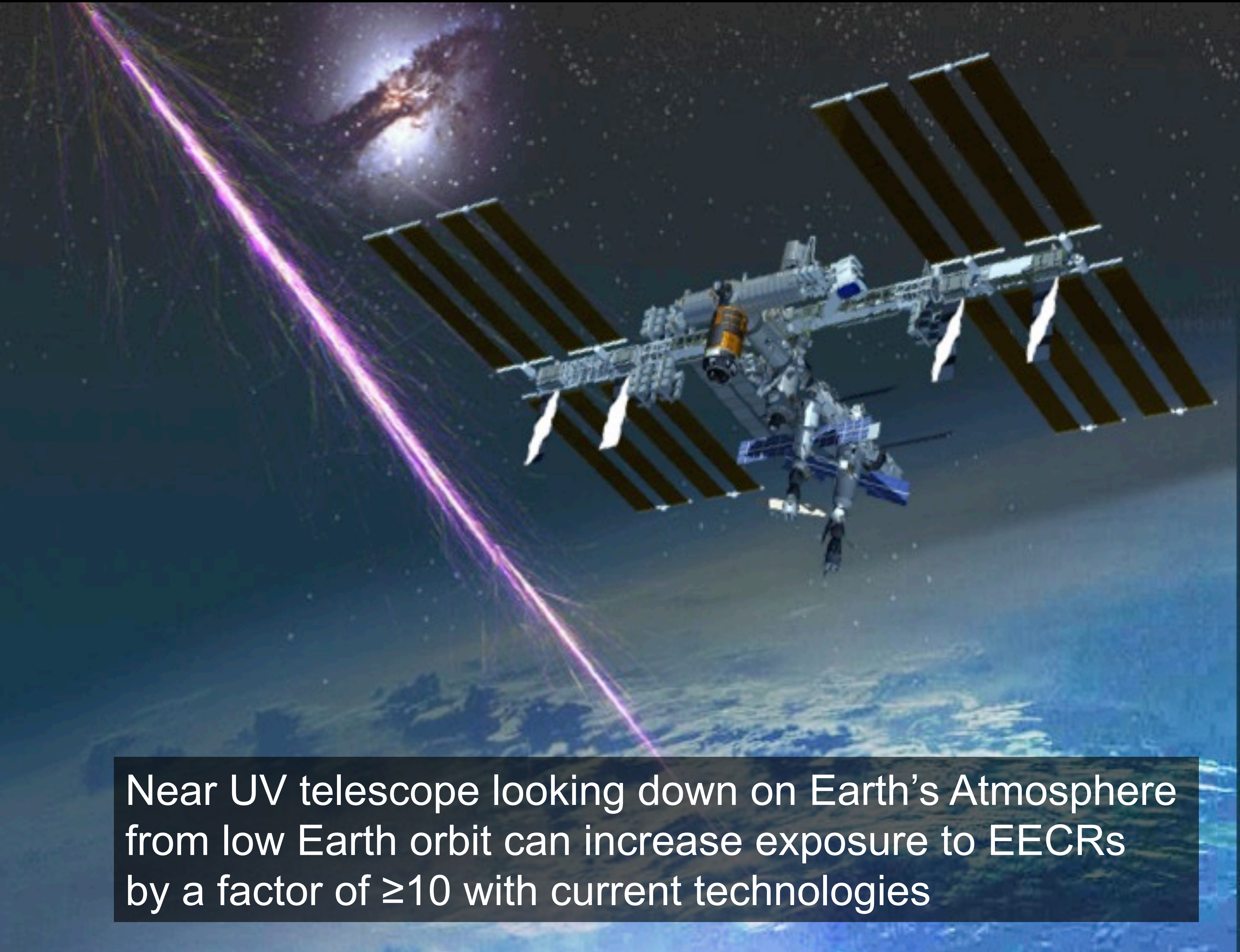
Telescope Array w/ 760 km^2

~5 events > 60 EeV/ yr

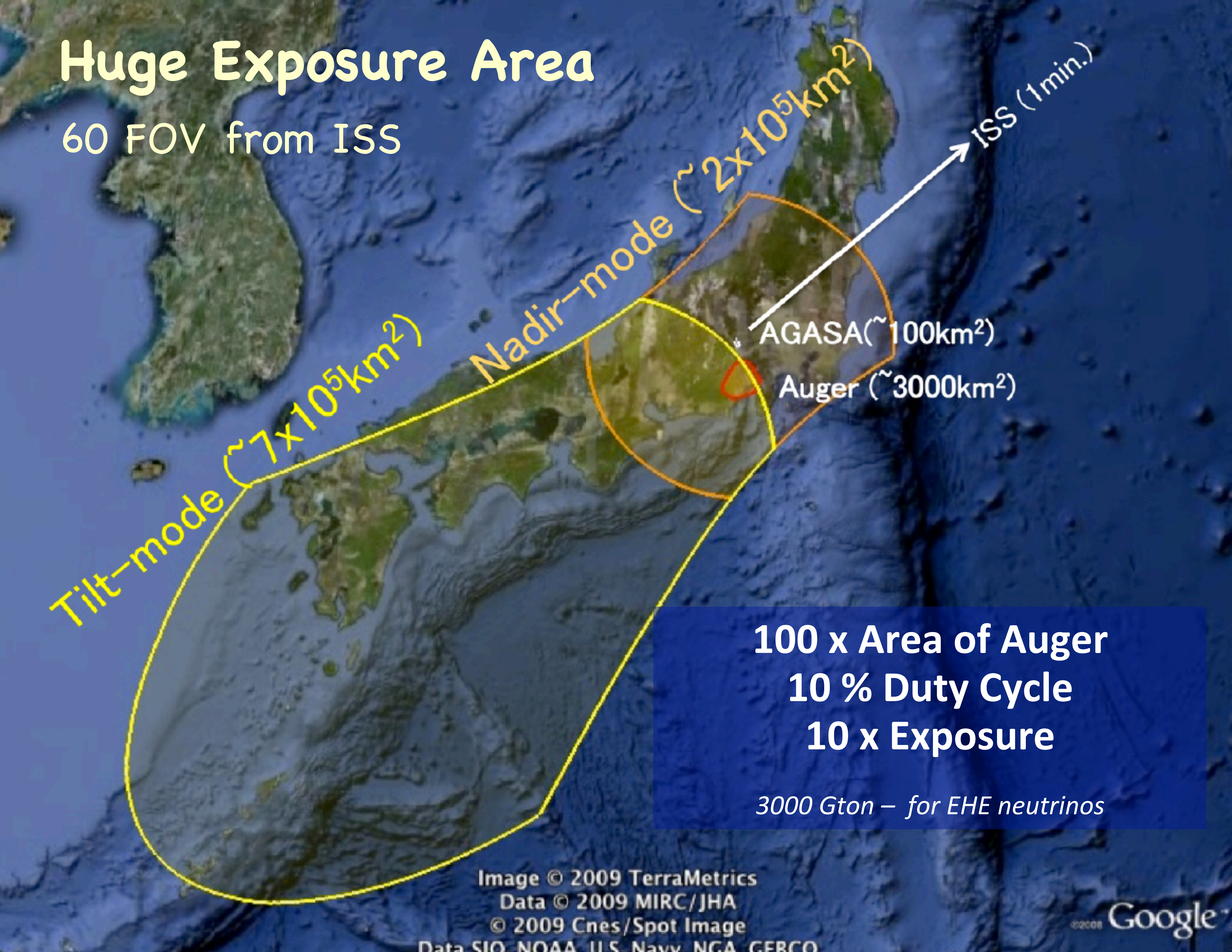
TOTAL ~30 events/yr

Earth Atmosphere receives

> 3 10^6 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
Nadir-mode (~2x10^5km^2)
ISS (1min.)
AGASA(~100km^2)
Auger (~3000km^2)
Tilt-mode (~7x10^5km^2)
100 x Area of Auger
10 % Duty Cycle
10 x Exposure
3000 Gton – for EHE neutrinos
Image © 2009 TerraMetrics
Data © 2009 MIRC/JHA
© 2009 Cnes/Spot Image
Google

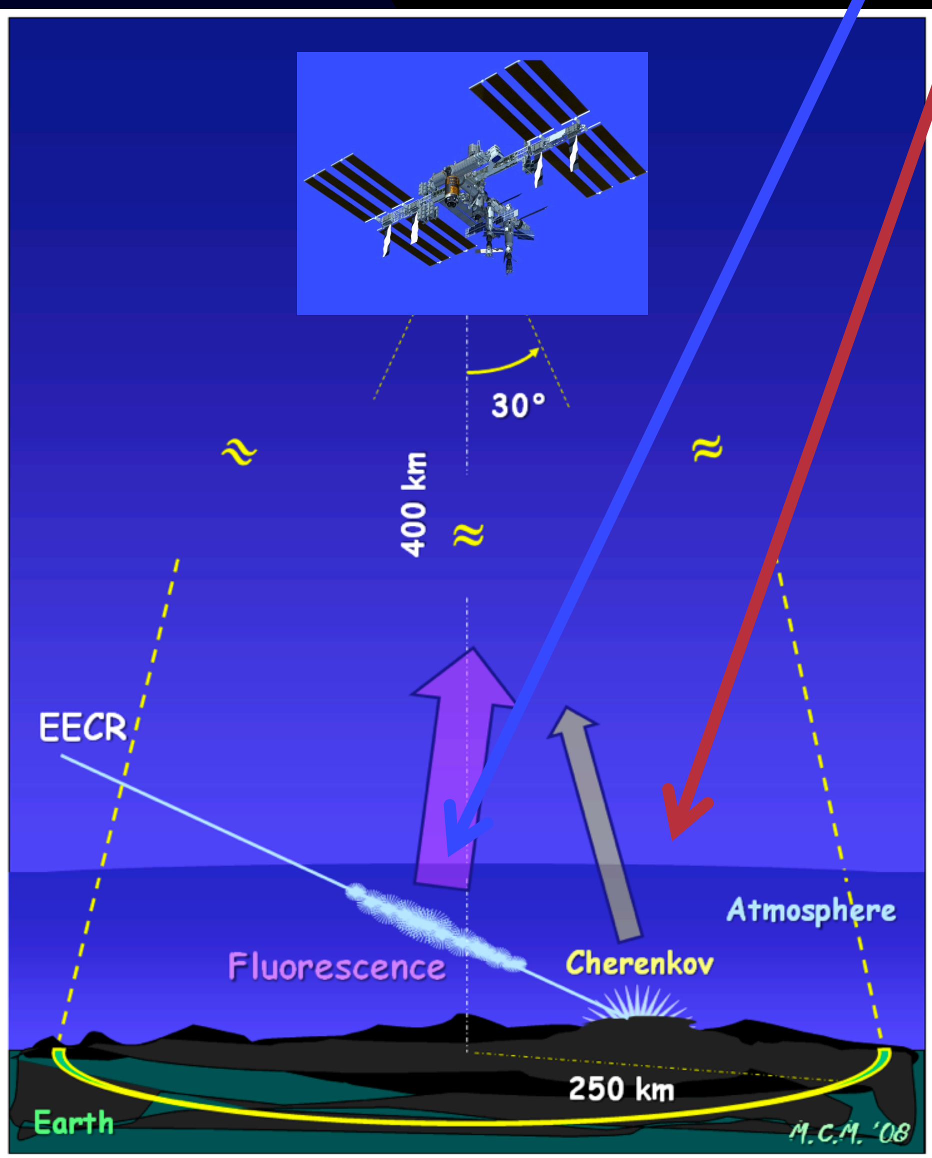
FAST Light SIGNAL

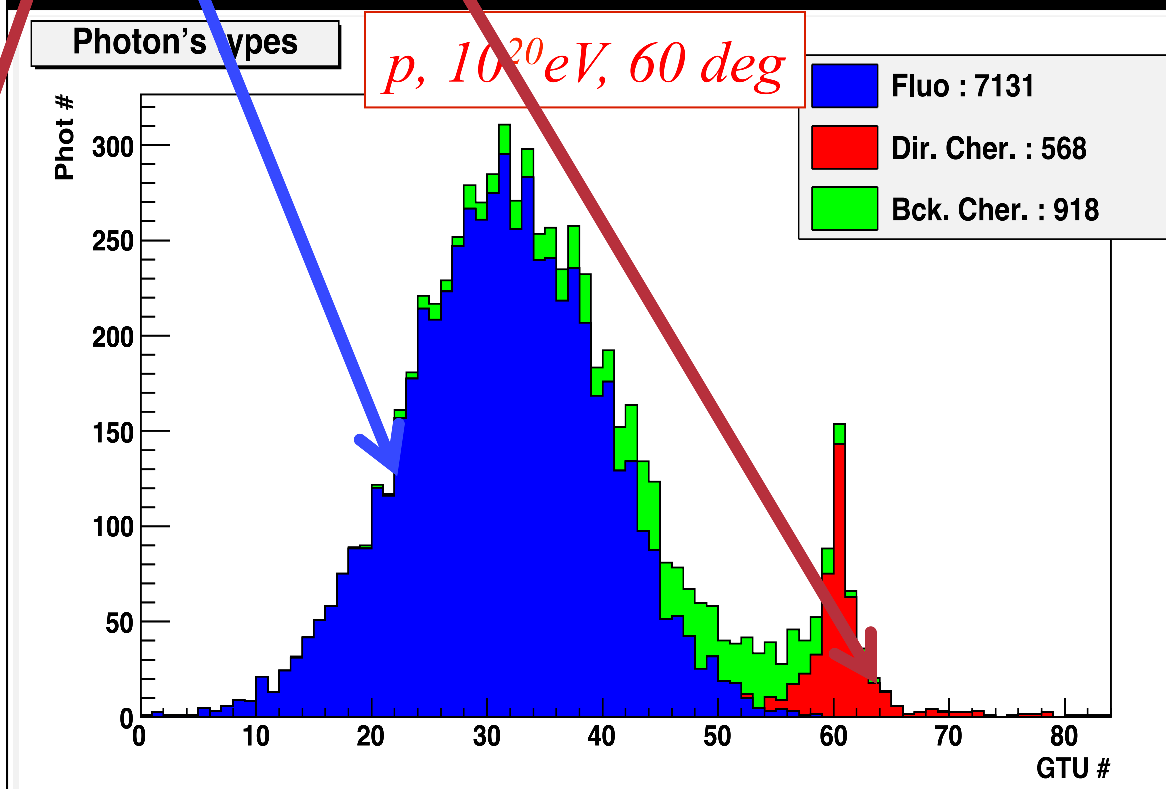
Duration 20 -150 μs (3 μs/km)

a) N_2 Fluorescence

b) Scattered Cherenkov

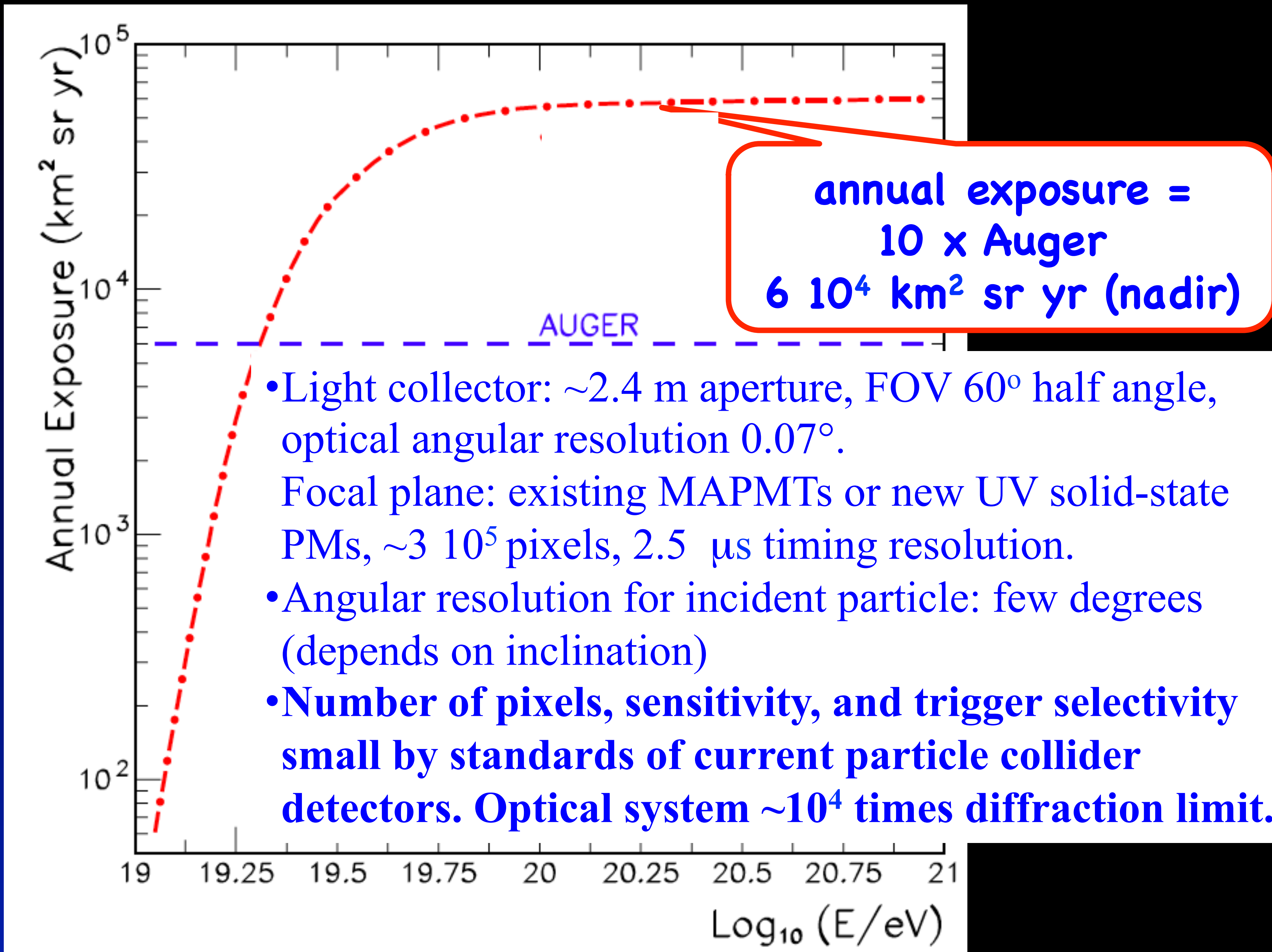
c) Direct (diffusively reflected Cherenkov)





Background: ~500 photons /m^2 sr ns

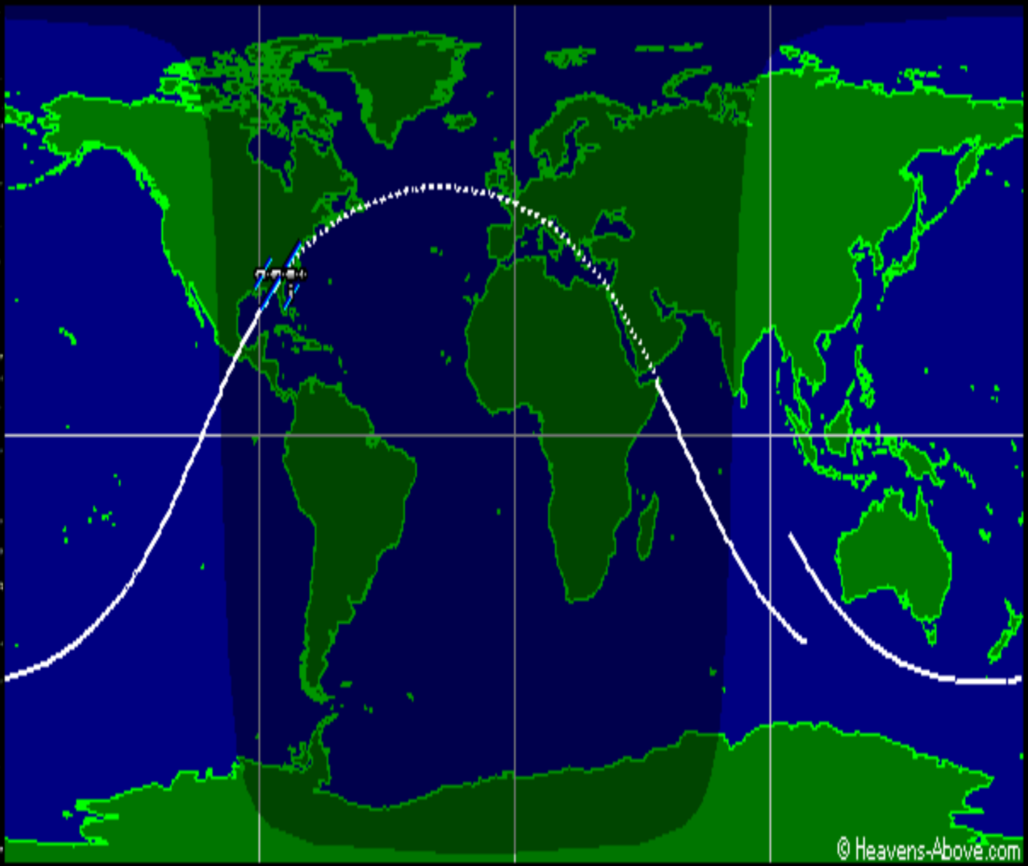
60º FOV monocular refractor from the ISS



- Light collector: ~2.4 m aperture, FOV 60º half angle, optical angular resolution 0.07°.
  Focal plane: existing MAPMTs or new UV solid-state PMs, ~3 10^5 pixels, 2.5 μs 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 ~10^4 times diffraction limit.**

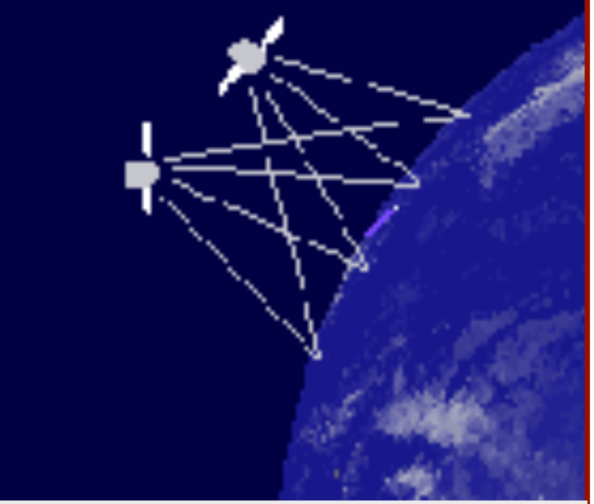
Full Sky Coverage
with nearly uniform exposure

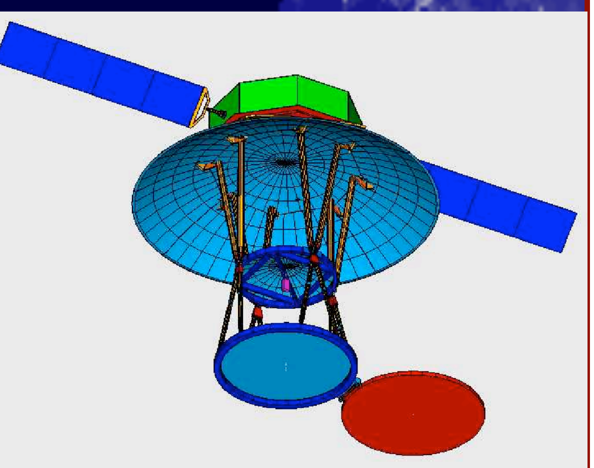
The ISS ORBIT



Inclination: 51.6°
Altitude: ~400km

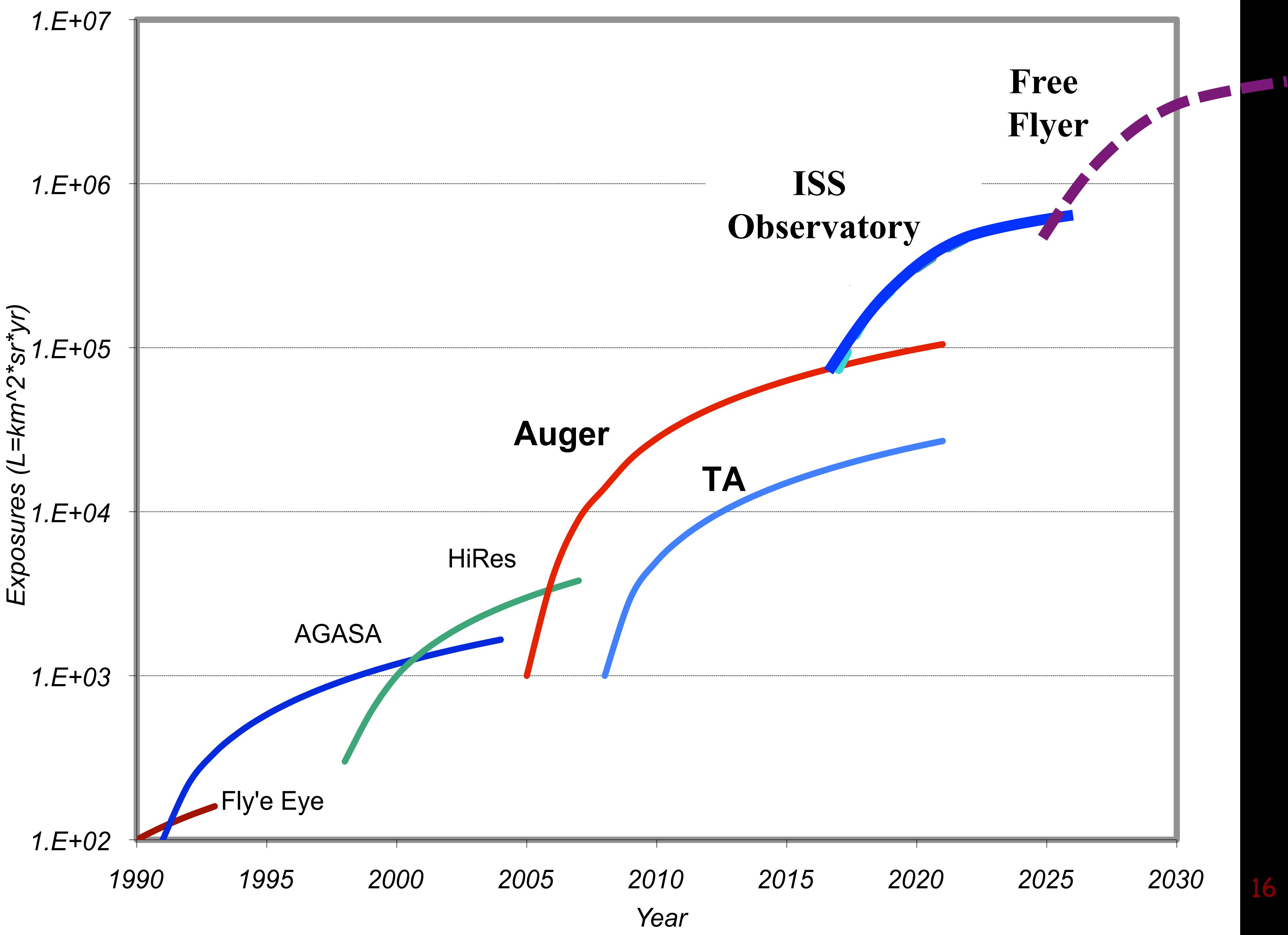
Next generation after ISS: Co-orbiting Pair of Free Flyers





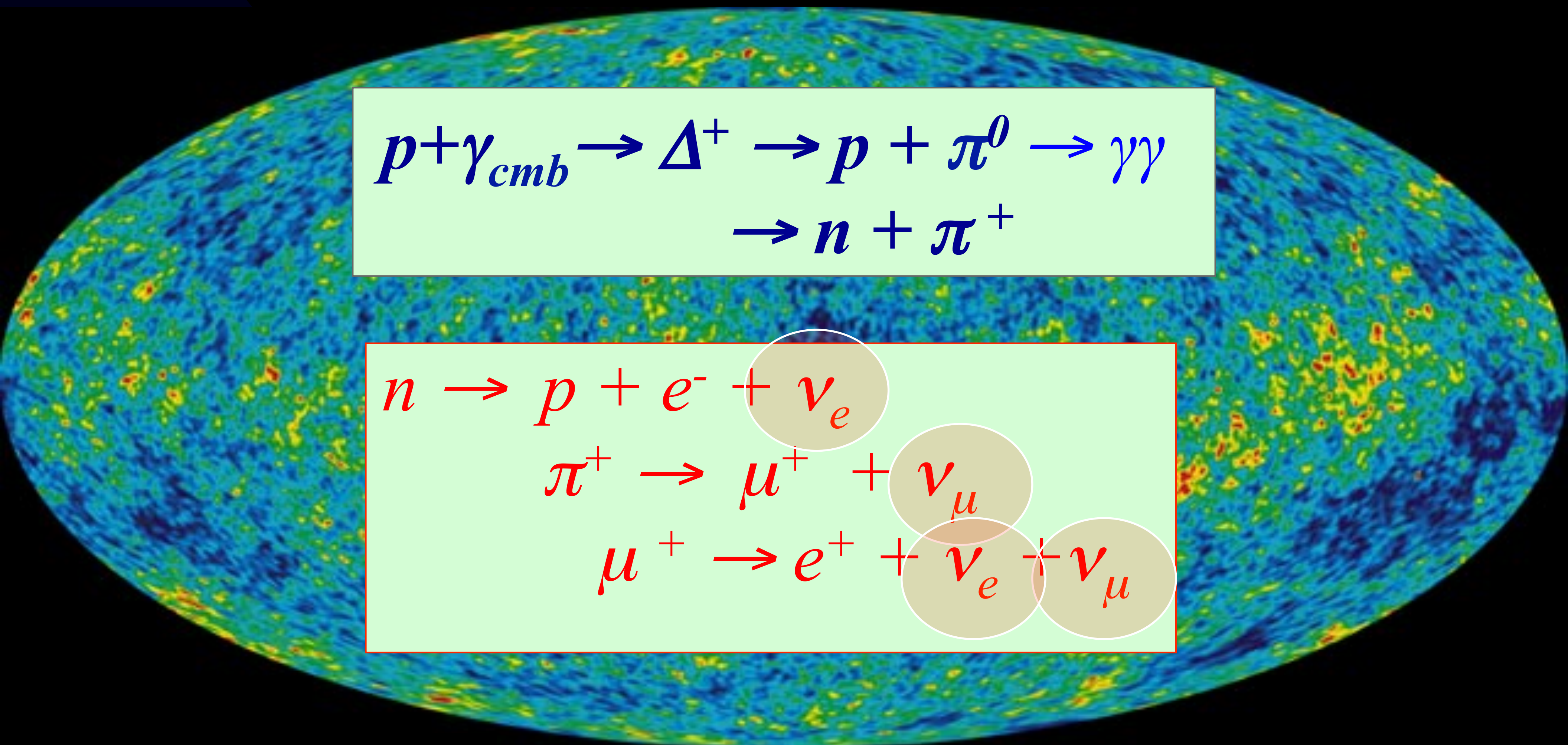
- Two satellites give Stereo View – improved particle angular resolution and energy resolution (atmospheric correction).
- 3 phase mission profile: 10° inclination orbit
  1) 1000 km, 20 km separation, 3 months – upward Ck light from ν_τ
  2) 1000 km, 600 km separation, ~2.5 yrs – highest energy EECR, $2\ 10^{19}$ 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, $5.5\ 10^5$ pixels, 100 ns timing resolution (improved shower max resolution and monocular reconstruction).
- Angular resolution for incident particle: ~1°
- Energy resolution <20%

Exposure History



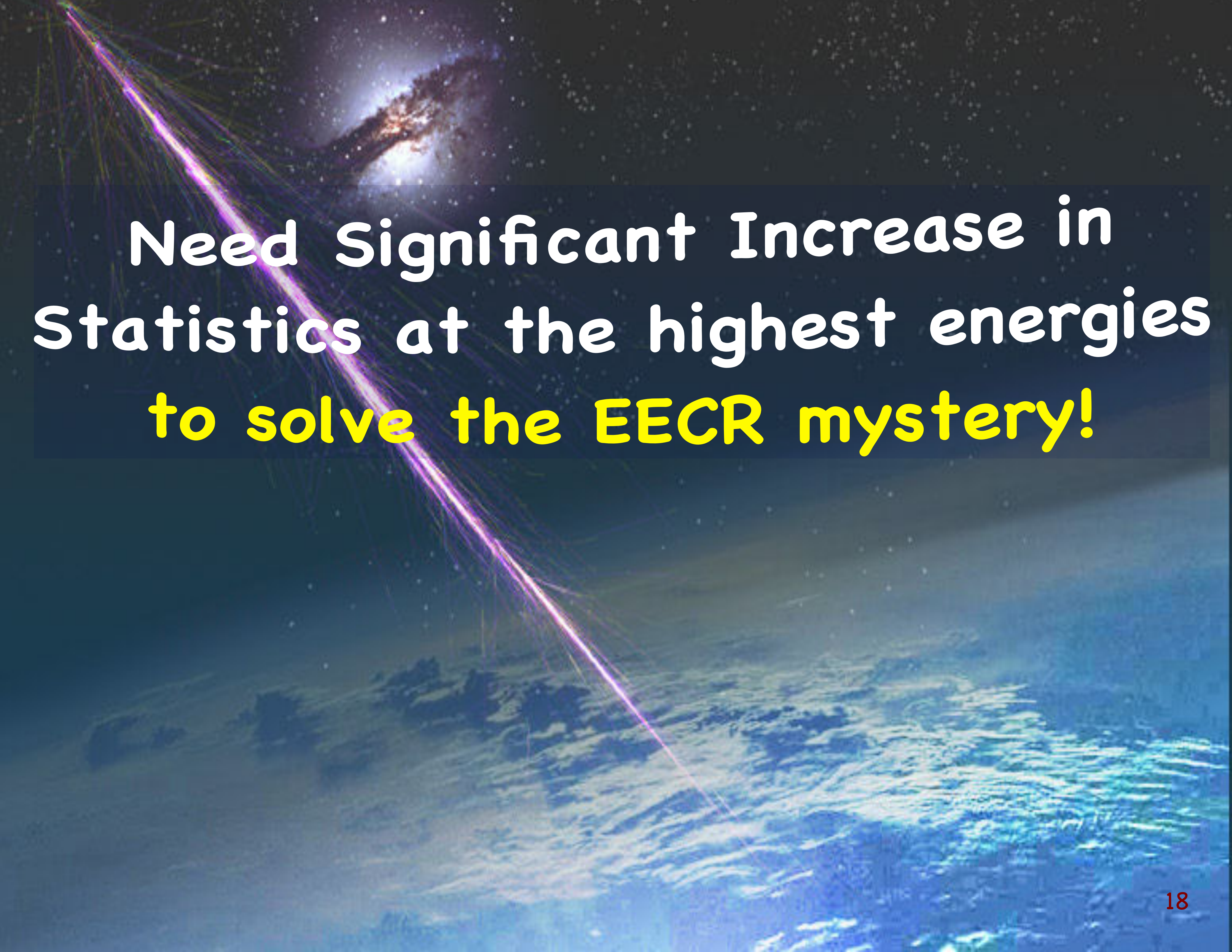
Same Technique can observe

Cosmogenic (GZK) Neutrinos & Photons



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

$$n \rightarrow p + e^{-} + \nu_e$$
$$\pi^{+} \rightarrow \mu^{+} + \nu_\mu$$
$$\mu^{+} \rightarrow e^{+} + \nu_e + \nu_\mu$$



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

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In a decade we can discover the first sources of EECRs

from Space!!!