Very Large Space Optics for an Investigation of the Extreme Universe

Presented by Jim Adams
for the Super EUSO Collaboration*

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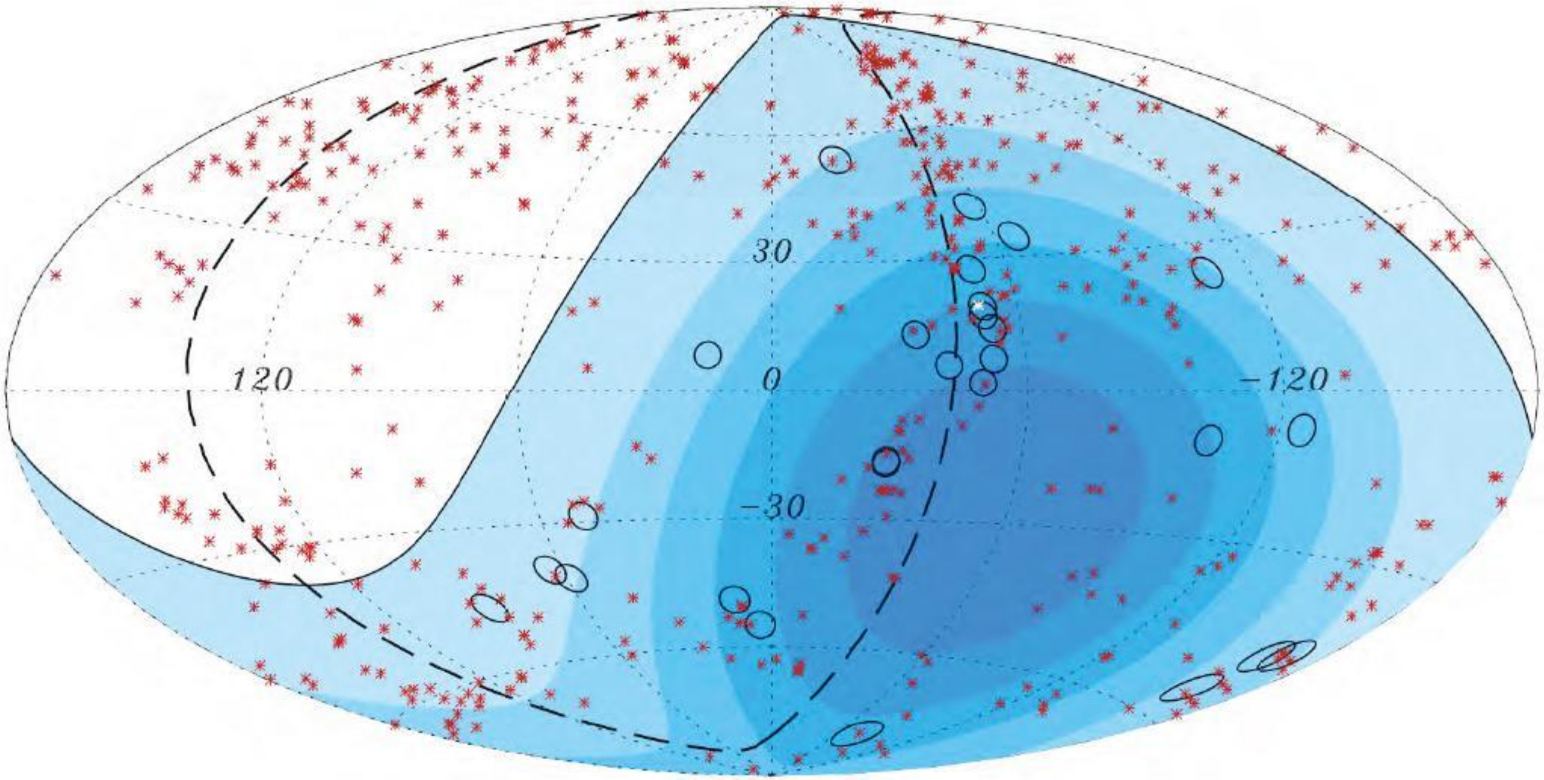
Auger main anisotropy result



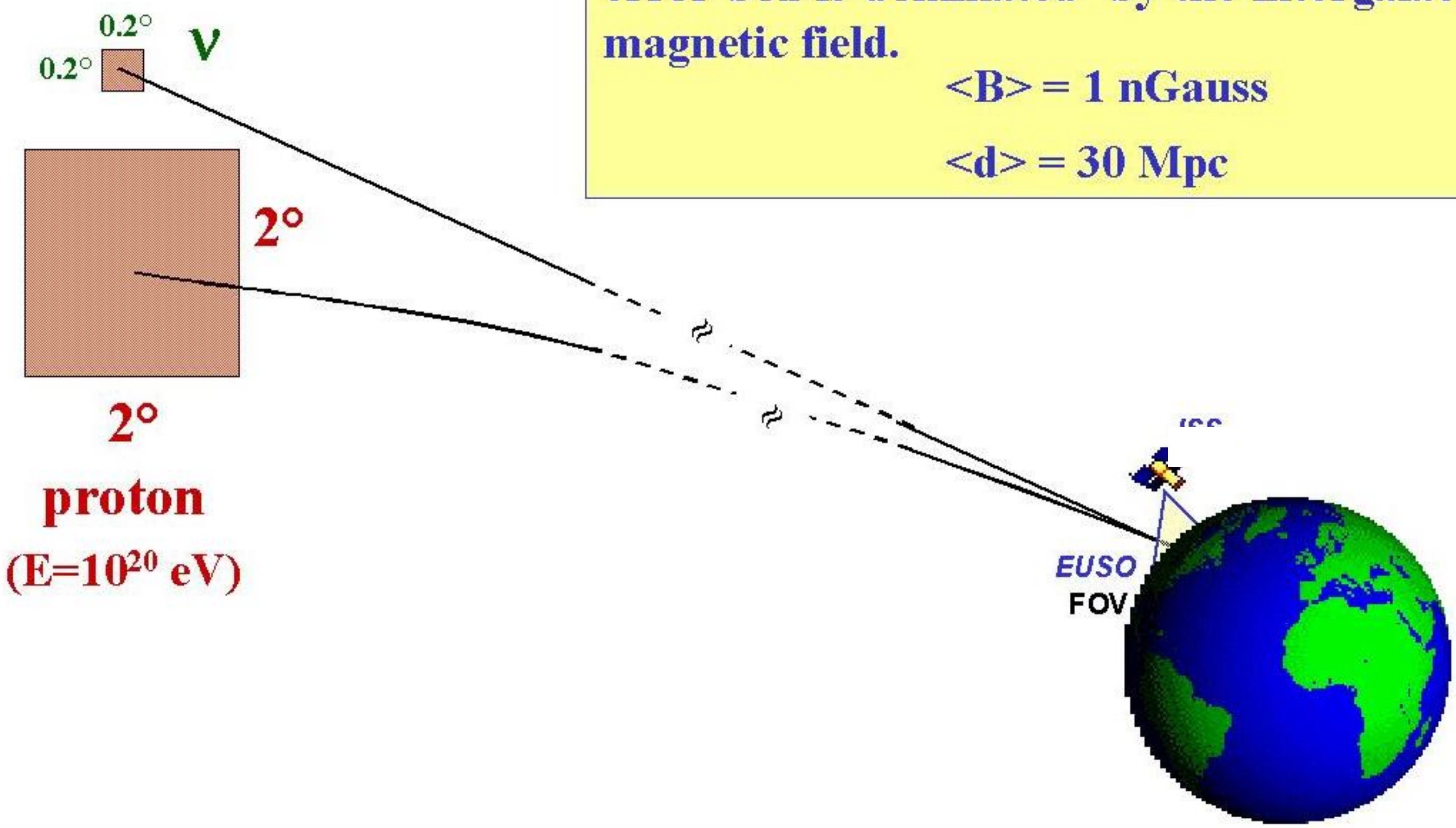
○ (cosmic rays); X (active galactic nuclei); blue shading (exposure)

Event Arrival Direction Reconstruction

Neutrino error box is limited only by the EUSO angular resolution while the proton error box is dominated by the intergalactic magnetic field.

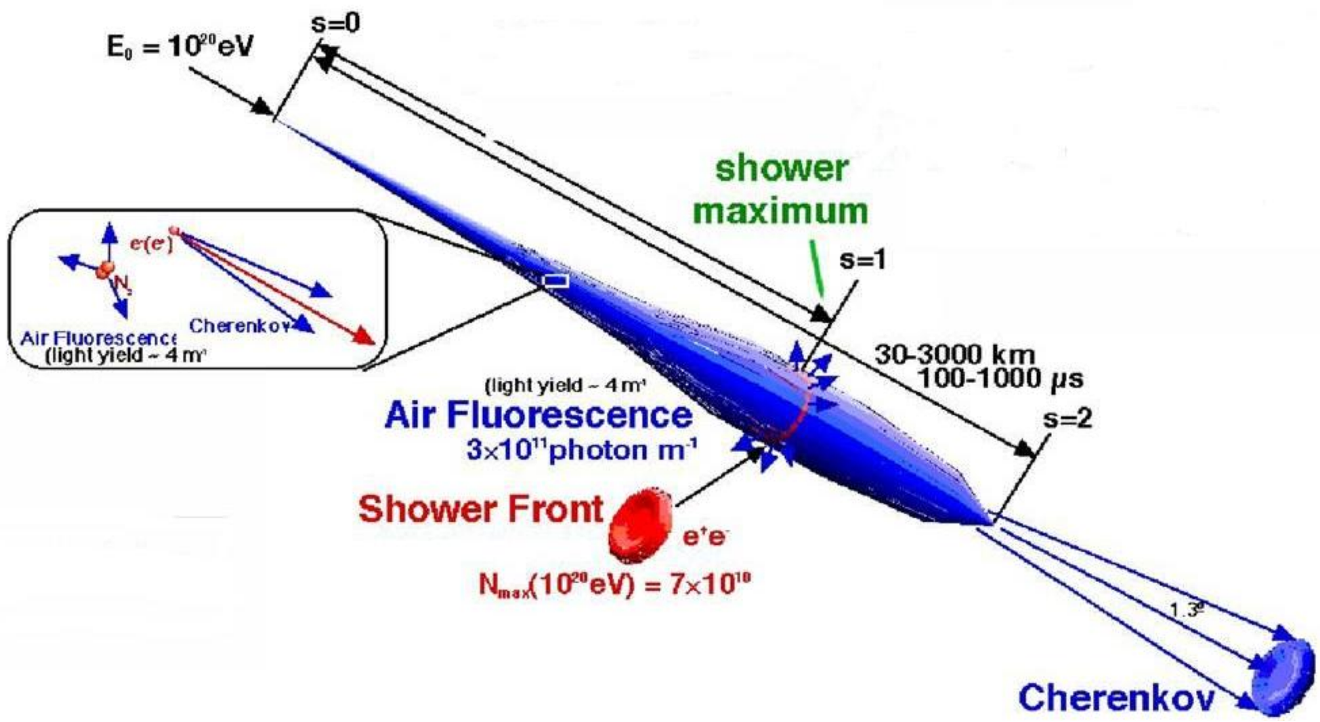
$\langle B \rangle = 1$ nGauss

$\langle d \rangle = 30$ Mpc

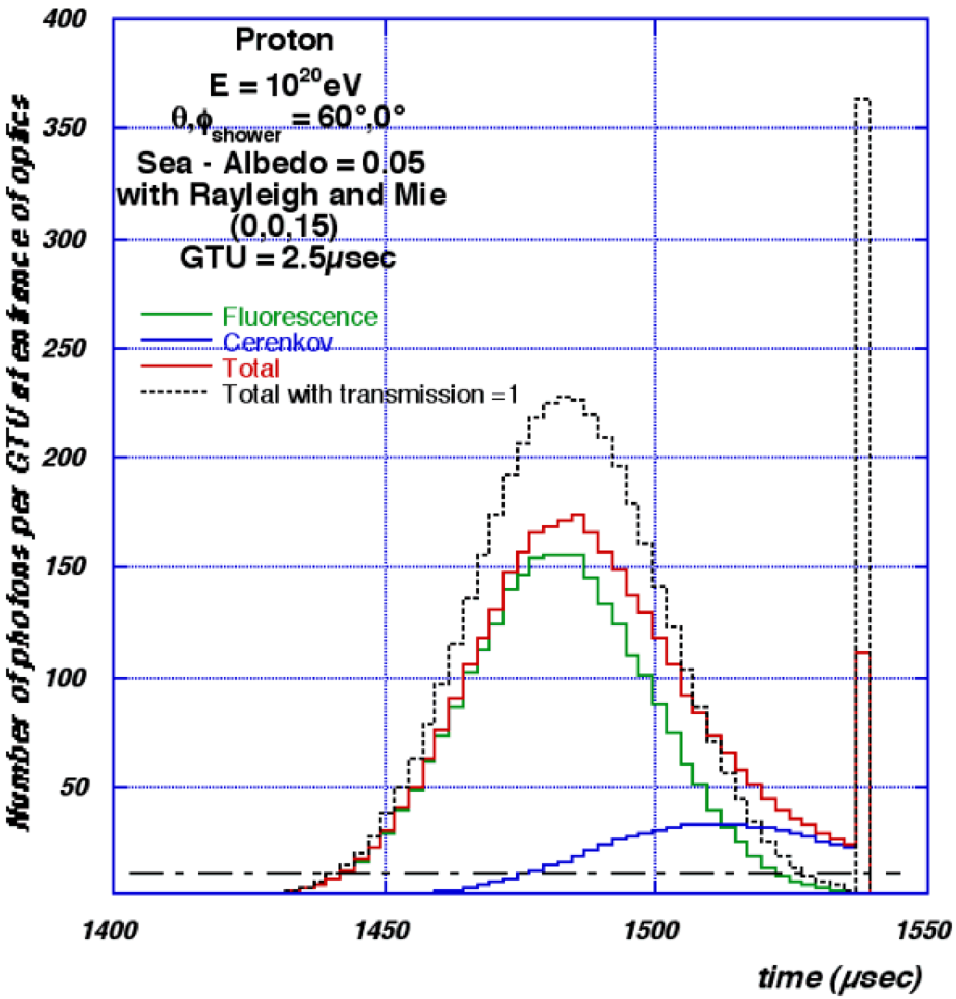


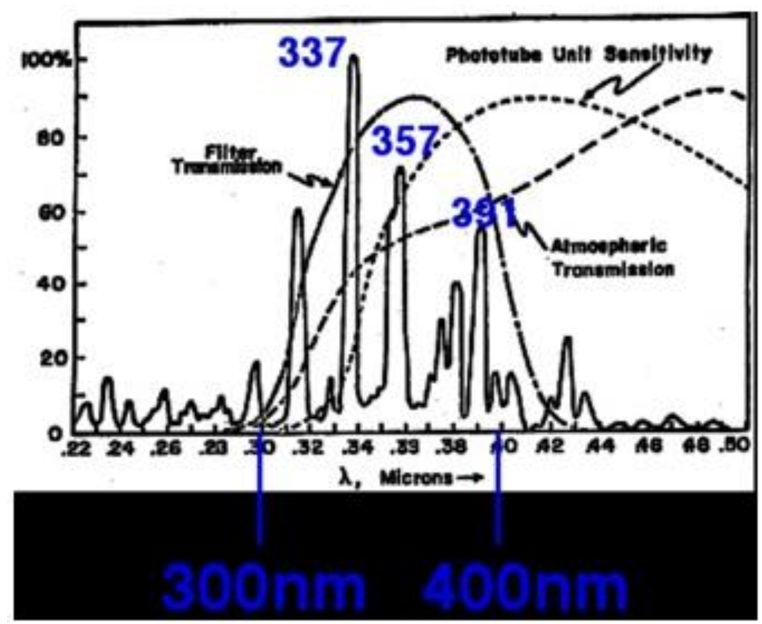
Extreme Energy Cosmic Rays (EECRs)

- Energies extending to at least 50 Joules/particle
- Fluxes of 1 particle/(km^2 $*$ century)



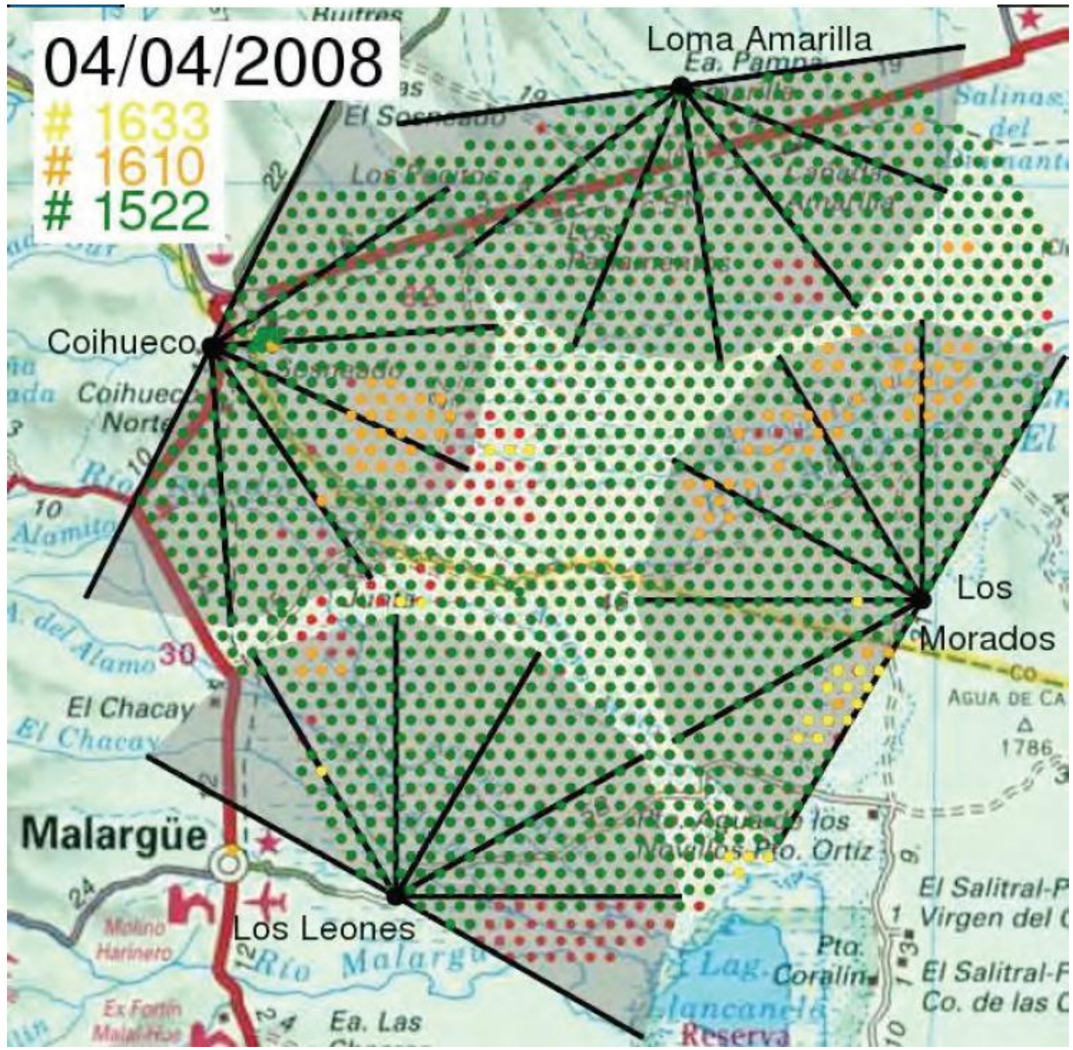
Shower Time Profile



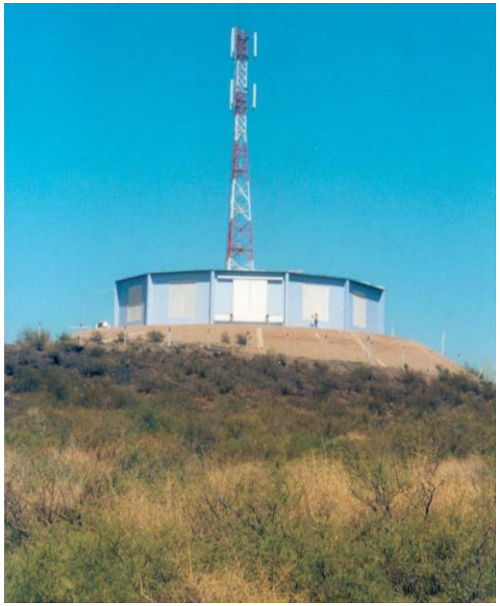


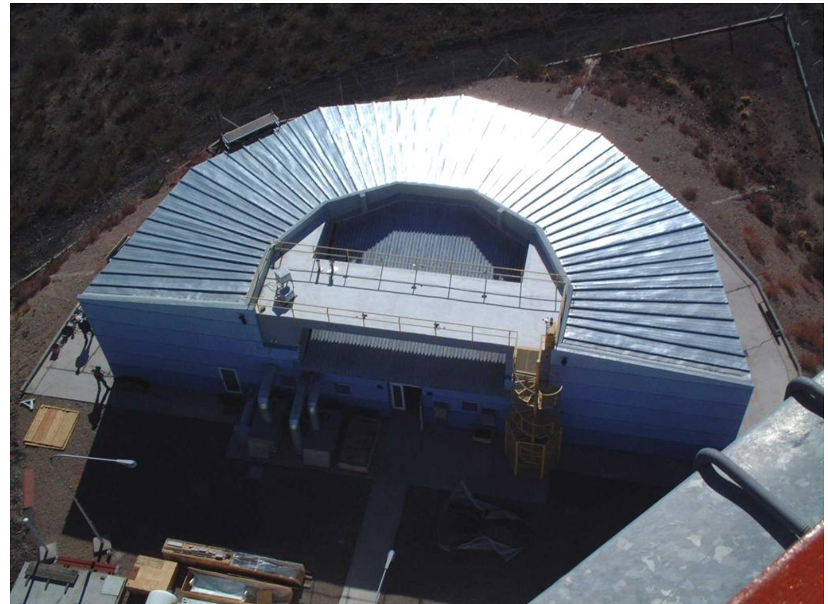
Hybrid Ground-based Array

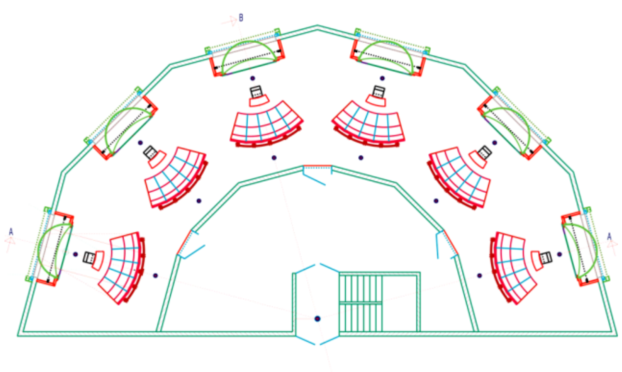
PIERRE
AUGER
OBSERVATORY

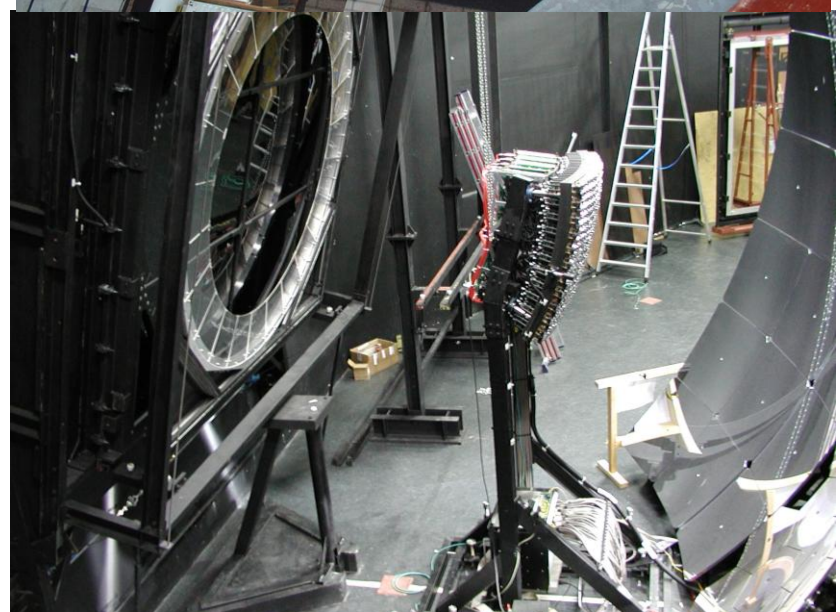


Fluorescence Detector

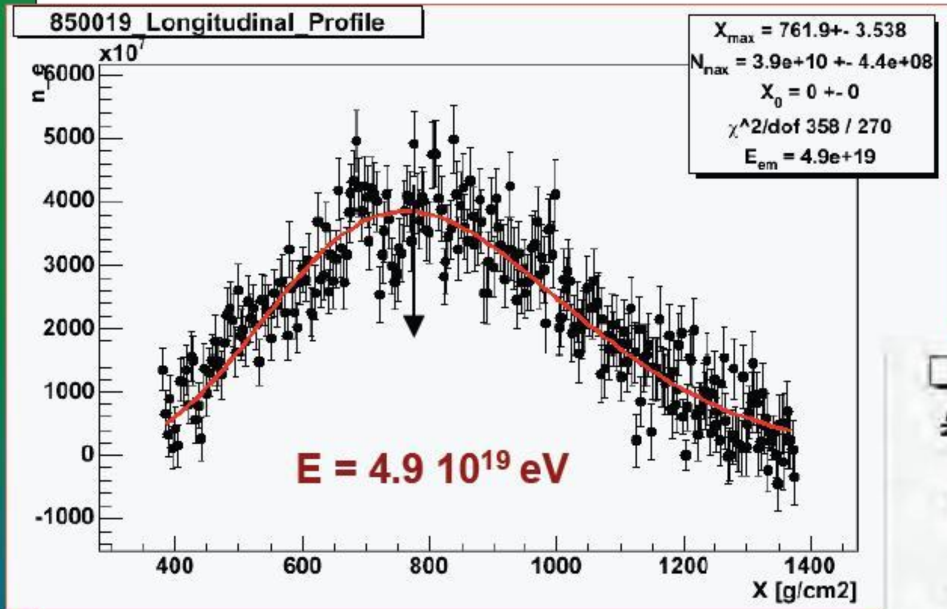


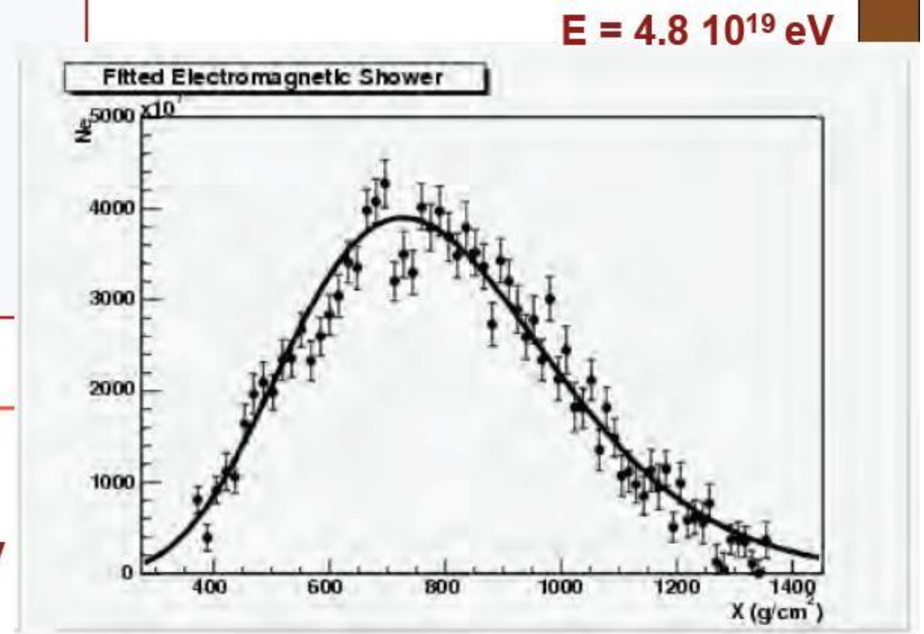


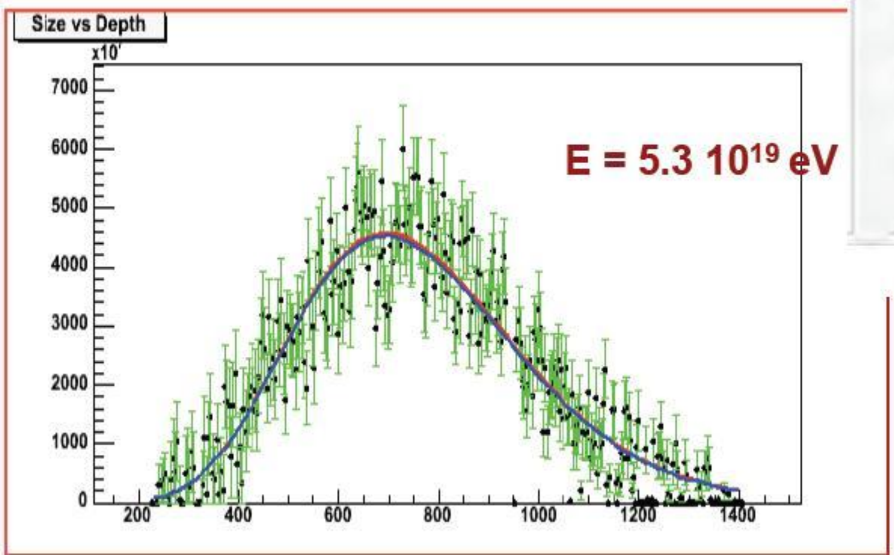




Independent analyses of stereo events

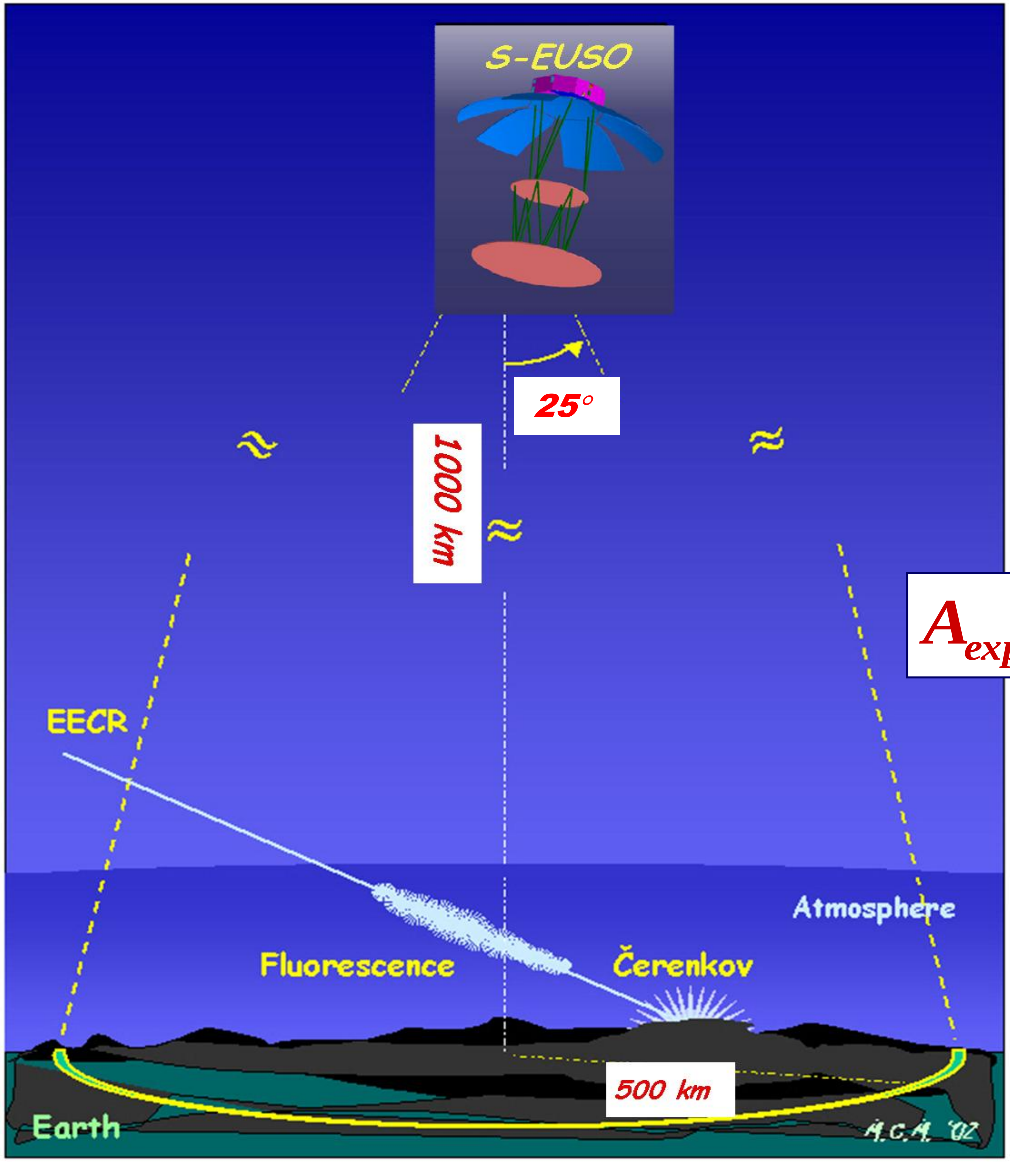






E_{em} calculated by fitting a GH profile and integrating

Super-EUSO



•Free Flyer

- Variable orbit 1000 km
- $\boxed{A_{aper}^{inst} \approx 2.4 \times 10^6\ \ km^2 \cdot sr}$
- $\boxed{Life \approx 5\,yr}$

$\boxed{\eta_{cycle} \approx 10 \div 20\,\%}$

$$\boxed{A_{exp} \approx (1.2-2.4)\times 10^6\,km^2 sr\ \ yr}$$

Tilted mode

(? $\boxed{A_{exp} \rightarrow 10^7\ L}$

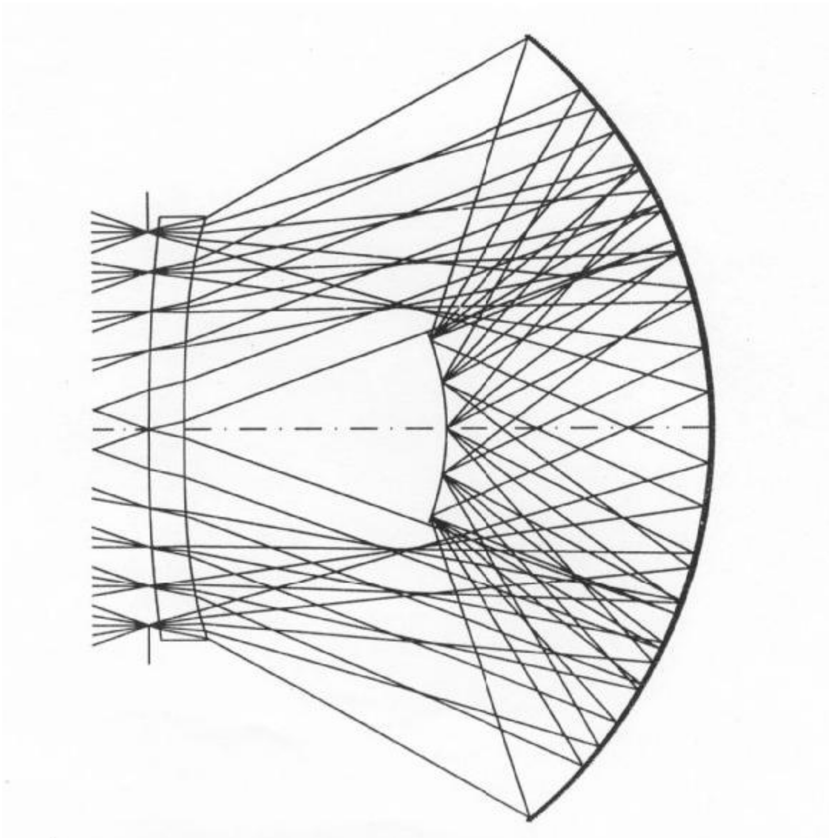
Super EUSO Instrument Requirements

- Very large wide-angle telescope with high optical throughput and ~1 milliradian angular resolution
- High efficiency pixelated photo-detectors with single photon sensitivity
  - Photomultiplier tubes with ultra-bialkali photocathodes or
  - Silicon photomultipliers
- Optics Design Options
  - Reflective optics:
    - Schmidt or Maksutov optics
      - Convex focal surface
  - Refractive optics (the JEM-EUSO concept)
    - Very large and light-weight Fresnel lenses
    - Diffractive lens for chromatic correction
  - Antireflective coatings needed in either case

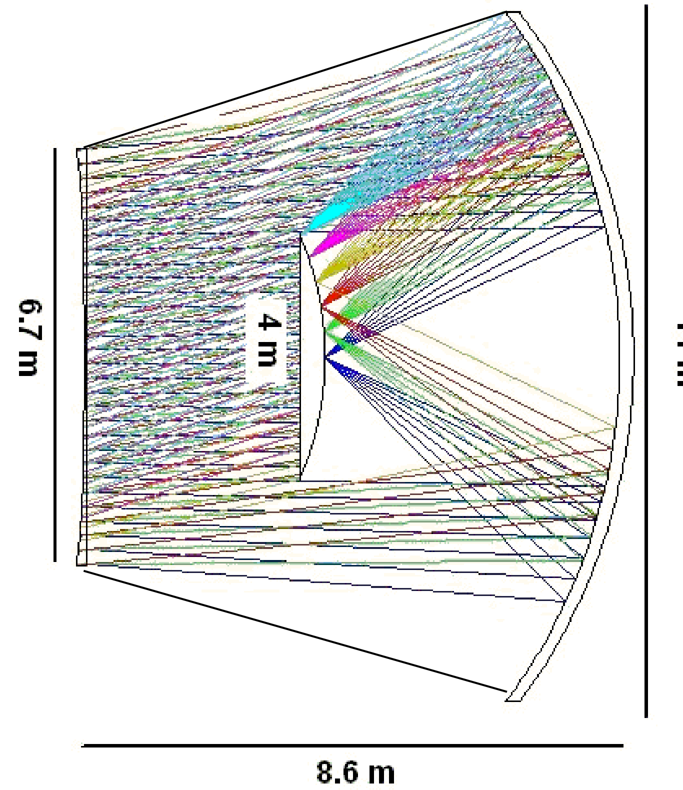
Photomultiplier Tubes

- Hamamatsu Ultra-Bialkali photocathodes
  - 40-45% Q.E. from 330-400 nm
  - Off the shelf (Hamamatsu)
  - Large inter-tube gaps on a convex surface
- Back-illuminated Silicon Photomultipliers
  - 90% Q.E. from 330-400 nm
  - Requires cooling
  - Developmental (Siemens)
  - Small inter-device gaps on a convex surface

Optics Design Concepts

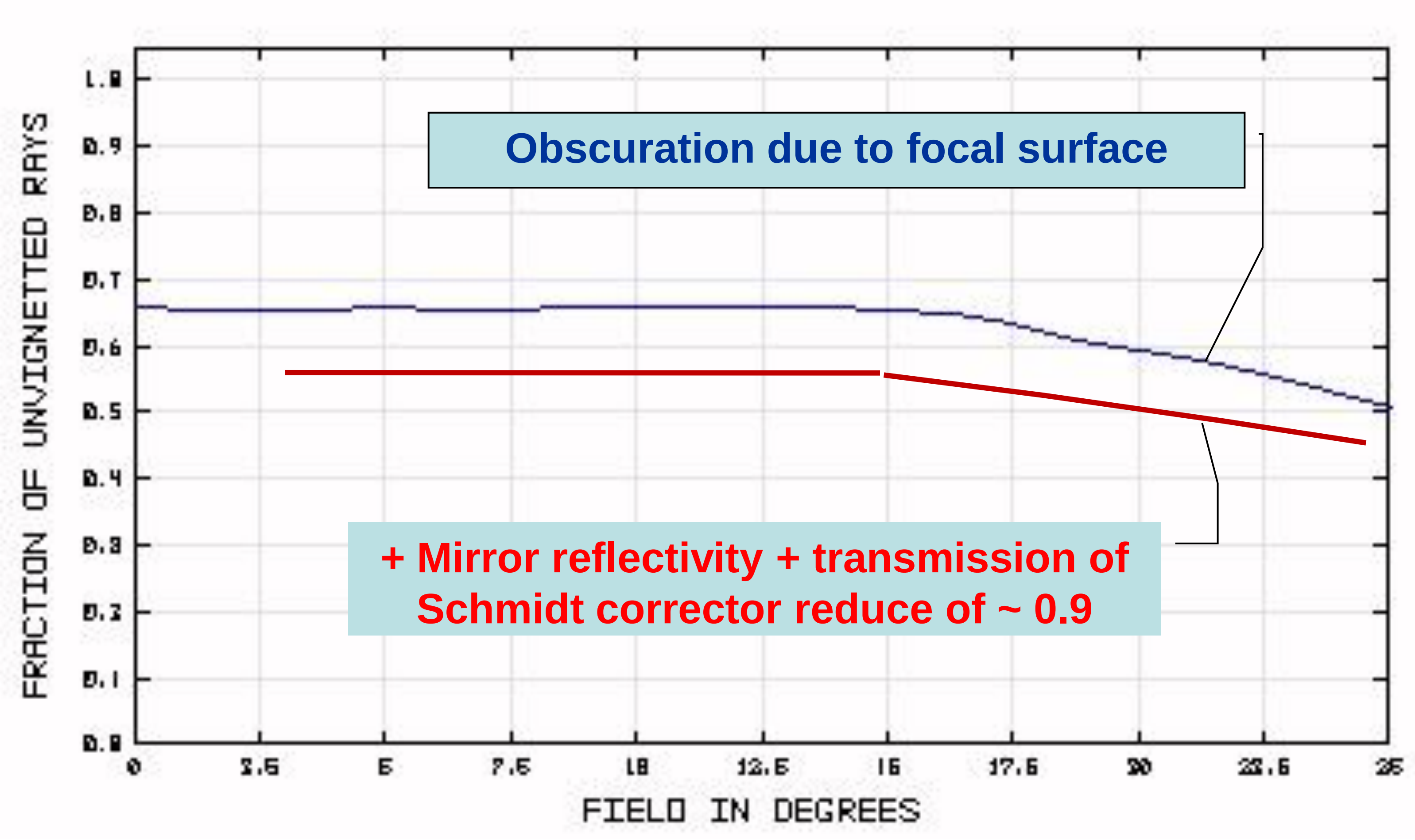


Maksutov optical design with an f/# of 0.66, CAO at UAH, Huntsville



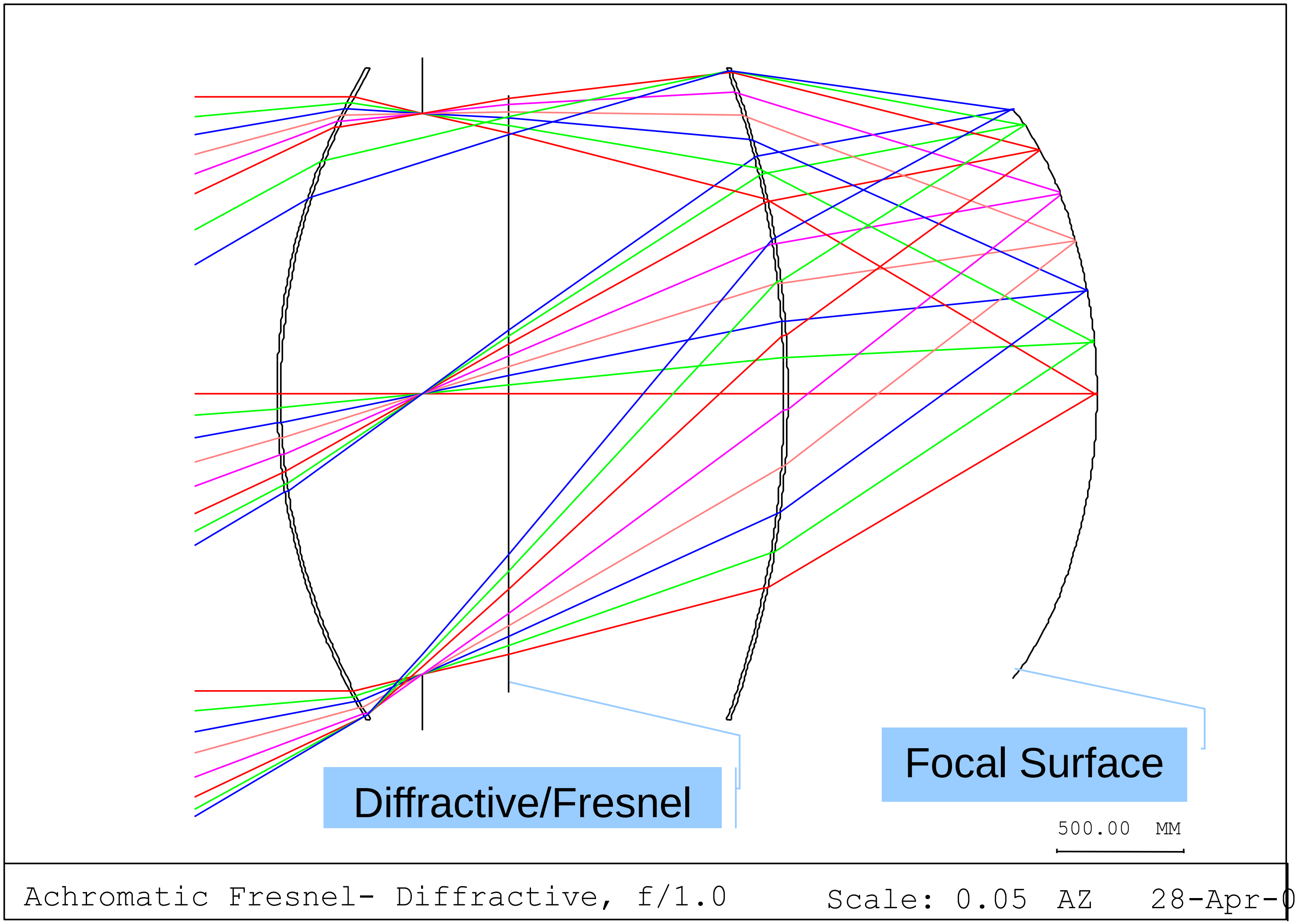
Schmidt design with an f/# of 0.7 and a 50° field of view, CNR- INOA, Firenze

Optics Throughput



Filters not considered so far!!

Refractive Optics



Throughput is less than with reflective systems

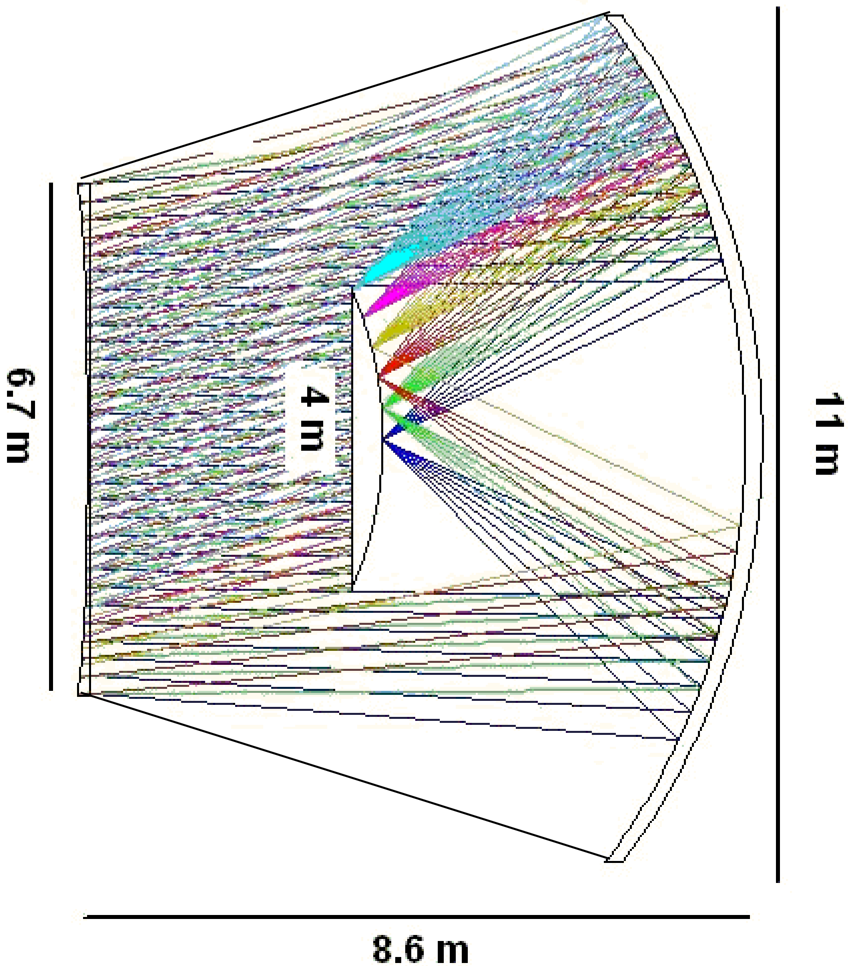
Shower Imaging and Reconstruction

Super-EUSO functions like a high-speed and wide angle video camera

- Frame rate: ~3 μsec/frame
- Pixel Size: 4×4 mm^2 on the focal surface or 1×1 km^2 on Earth
- Reconstruction in $1 \times 1 \times 1$ km^3 voxels
- Arrival direction reconstruction to <0.2°
- Energy reconstructed from fitted intensity at shower maximum

For those events with a detected Cherenkov reflection at a known altitude:

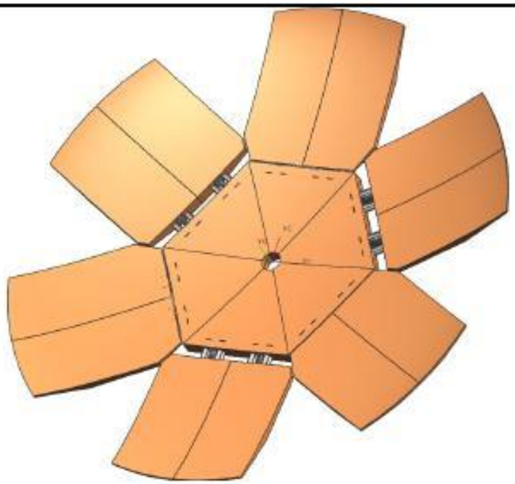
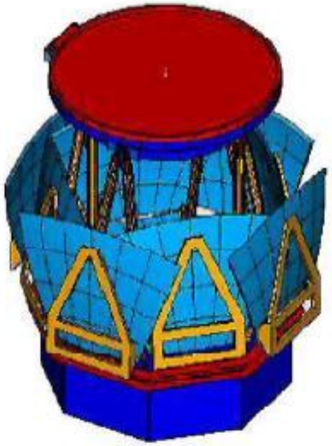
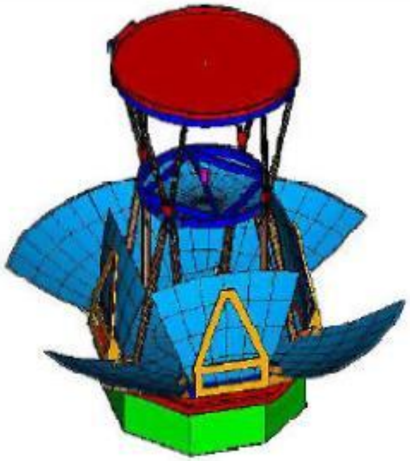
- Shower profile versus atmospheric depth will be reconstructed.



Optics Manufacturing Requirements

- Surface Roughness
  - 20 nm RMS on refractive elements
  - 5 nm RMS on reflective elements
- Tilt errors
  - <0.5 milliradian
- Anti-reflective Coatings on refractive elements
  - >90% transmission in the 330-400 nm band

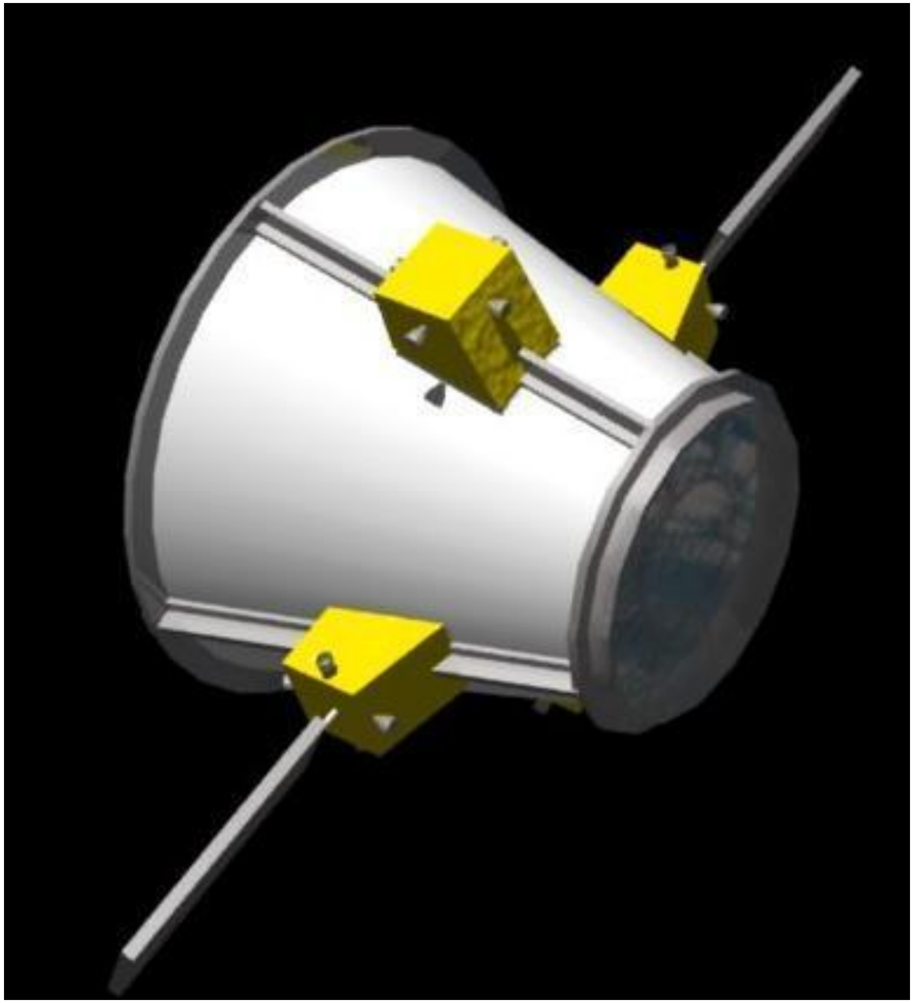
Super EUSO Spacecraft Concepts

		
• Figure 2 – Concept scheme of the optics deployment (Carlo Gavazzi Space).	• Figure 3 – The folded structure (from the OWL concept study, NASA, [10]).	• Figure 4 - The un-folded structure (from the OWL concept study, NASA, [10]).

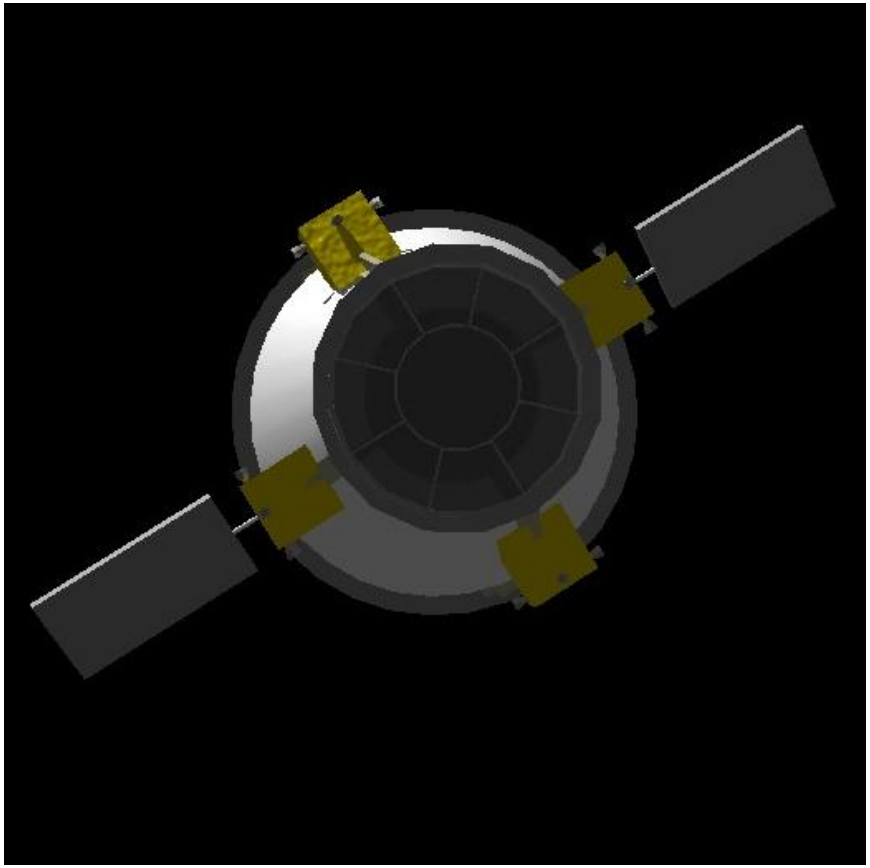
These folding concepts were developed to fit Super-EUSO into an existing faring.

ARES V Option

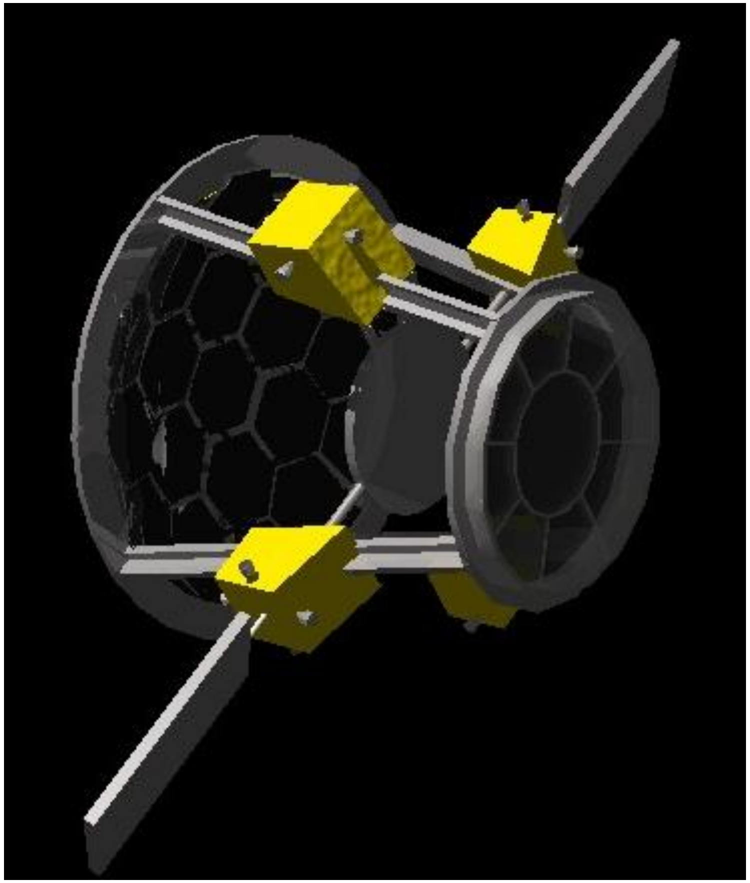
- Launch Super EUSO as a rigid unit
  - Spherical mirror constructed from regular hexagonal zones
  - Segmented corrector plate in the style of a lighthouse lens



Notional Design



Segmented Corrector Plate



Mirror constructed from hexagonal spherical segments

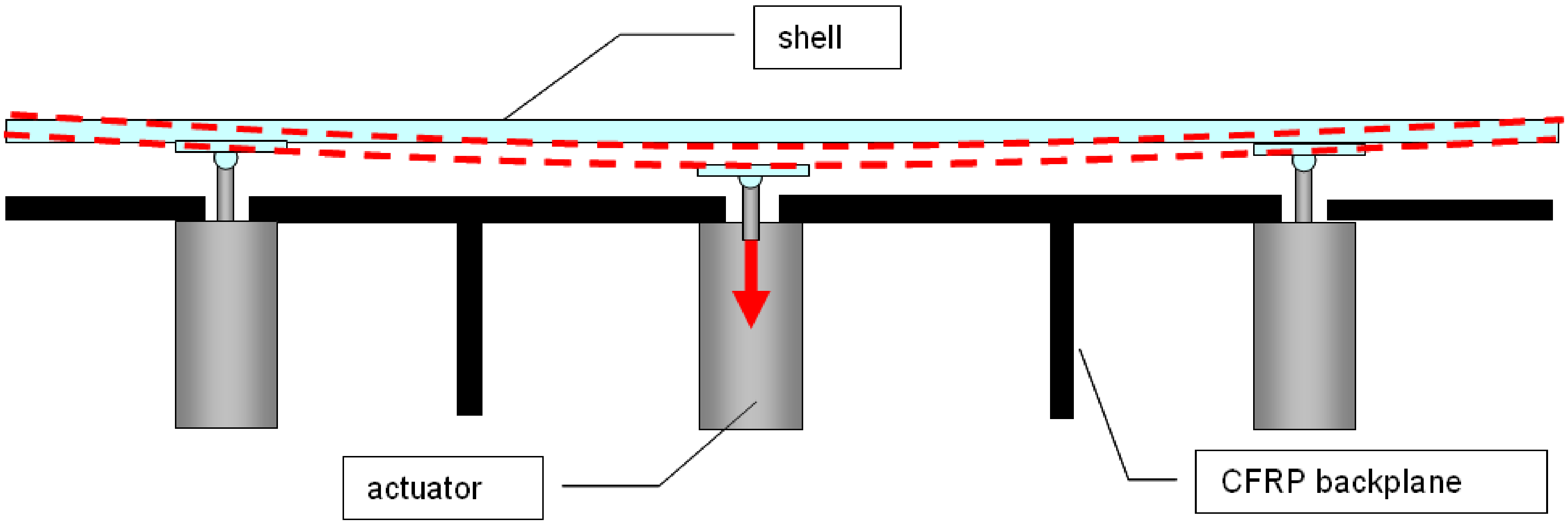
Summary

- Super EUSO is needed to find out how the most energetic cosmic accelerators work and what they are accelerating?
- The Super-EUSO instrument must be a very large high-speed and wide-angle video camera in space.
- We are open to suggestions for improvements in design and also concepts for manufacturing such an instrument.

The End

Active Mirror Control: How it works

A polished thin glass surface is coupled to a stiff lightweight support structure through an array of actuators, adjusted on a wave-front reference



Any deformation of the support is compensated by the actuators

The actuators can also be used for in-orbit alignment and optimization

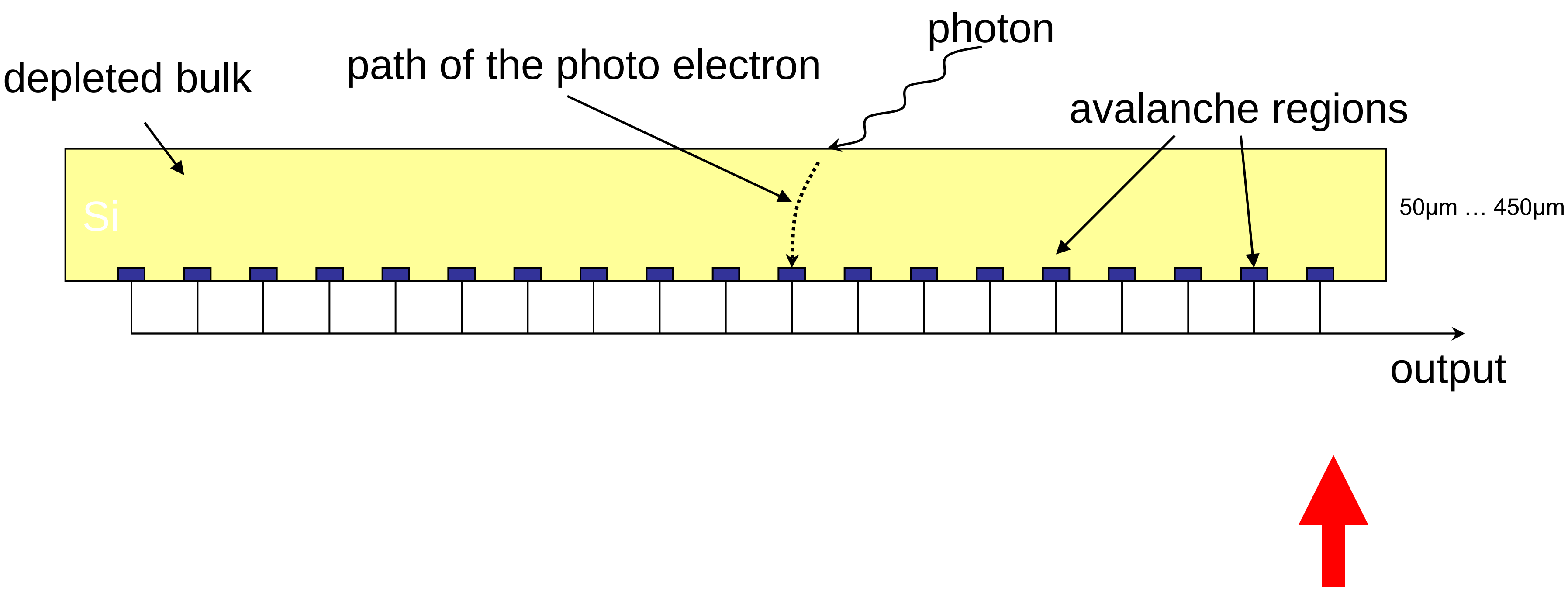
From the CNR- INOA National Institute of Applied Optics - Firenze

Back-illuminated Silicon PMT
(under development at MPI, Munchen)

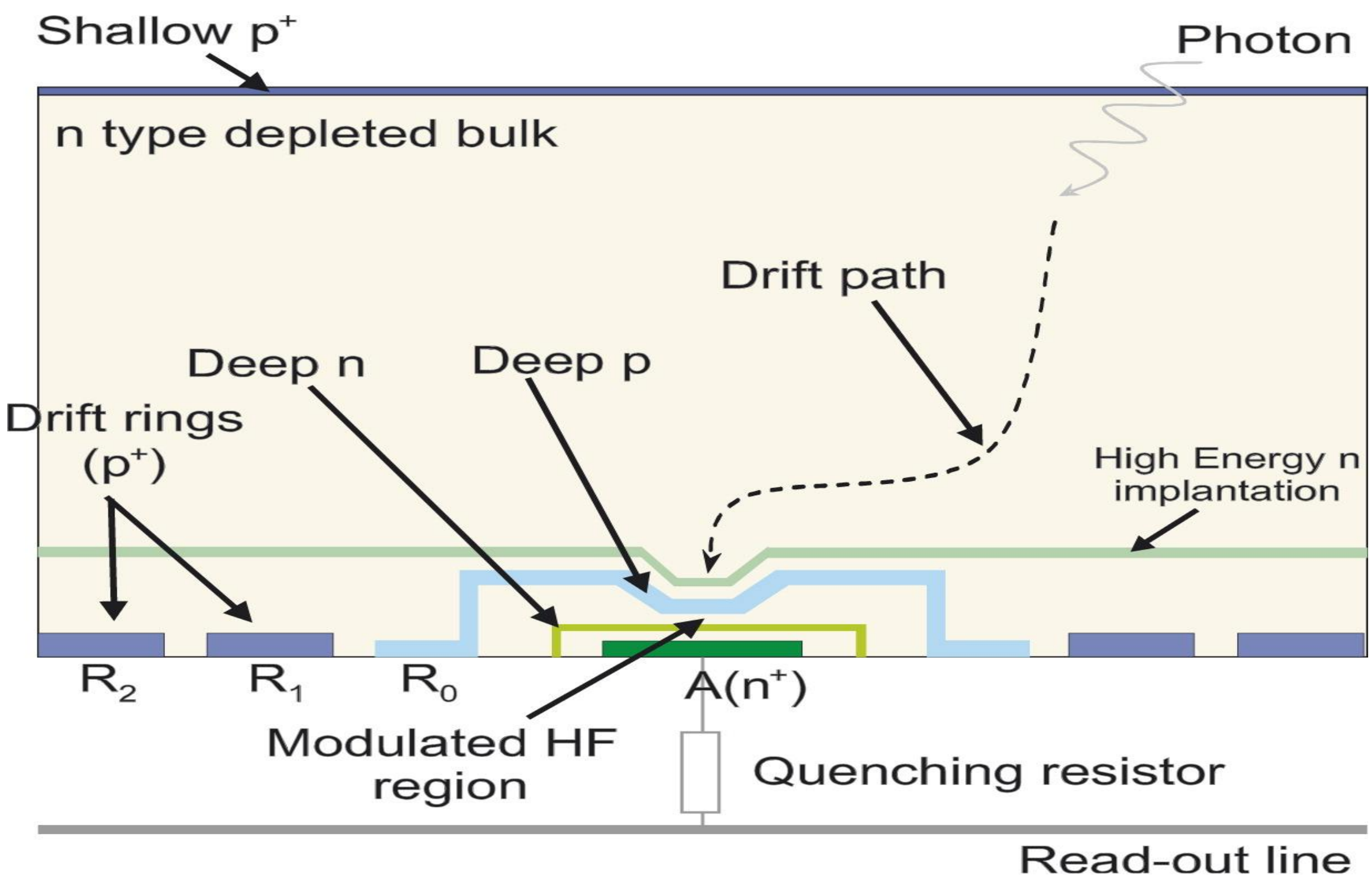
- Quenched avalanche photodiode array
- Back-illuminated, promising up to 90% photon detection efficiency
- ~10^6 internal gain
- Thin device allows high fill factor on convex focal surface
- Light weight

Back-illuminated PMT

BID SiPM – combined principle of avalanche photodiode and drift diode



Zoom to a single cell



G. Lutz et al., IEEE Trans. Nuc. Sci., 52, (2005) 1156-1159.
G. Lutz et al., Proc. Int. Con. New Dev. Photodet, Beaune 2005, to be published in NIM A.

Advantages and Disadvantages

Advantages:

- Unstructured thin entrance window
- 100% fill factor
- High conversion efficiency (especially at short wavelength)
- Lateral drift field focuses electrons into high field region
- High Geiger efficiency (always electrons trigger breakdown)
- Small diode capacitance (short recovery, reduced x-talk)

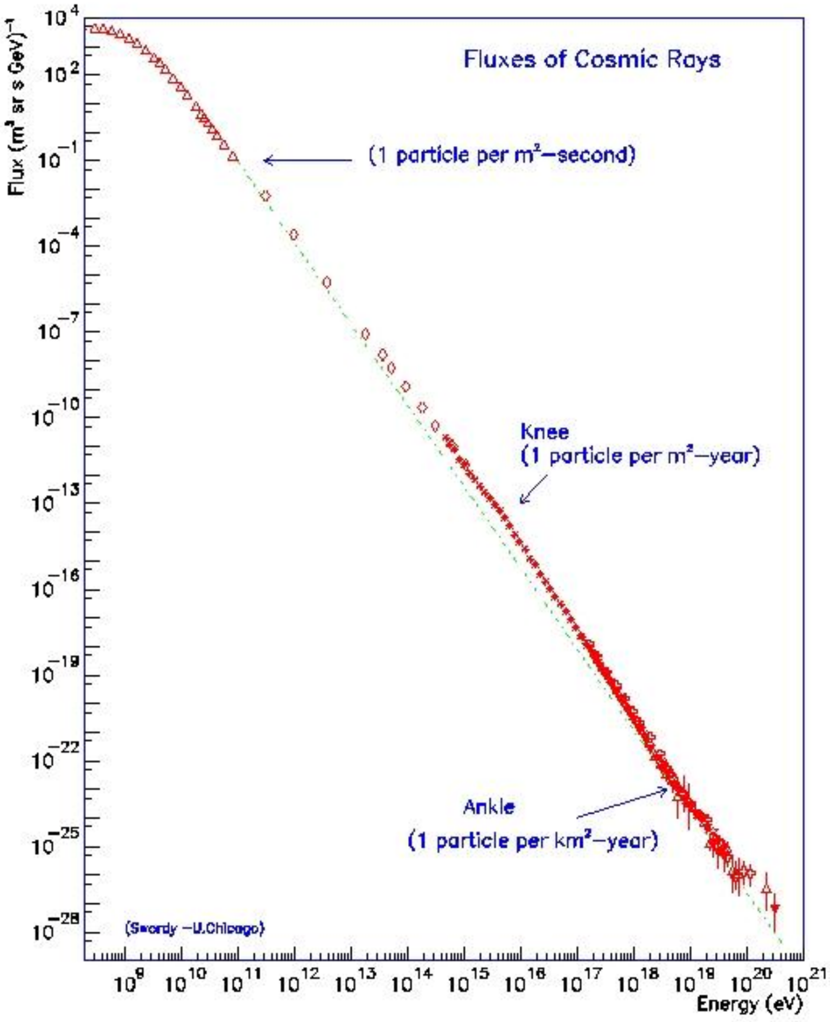
Disadvantages:

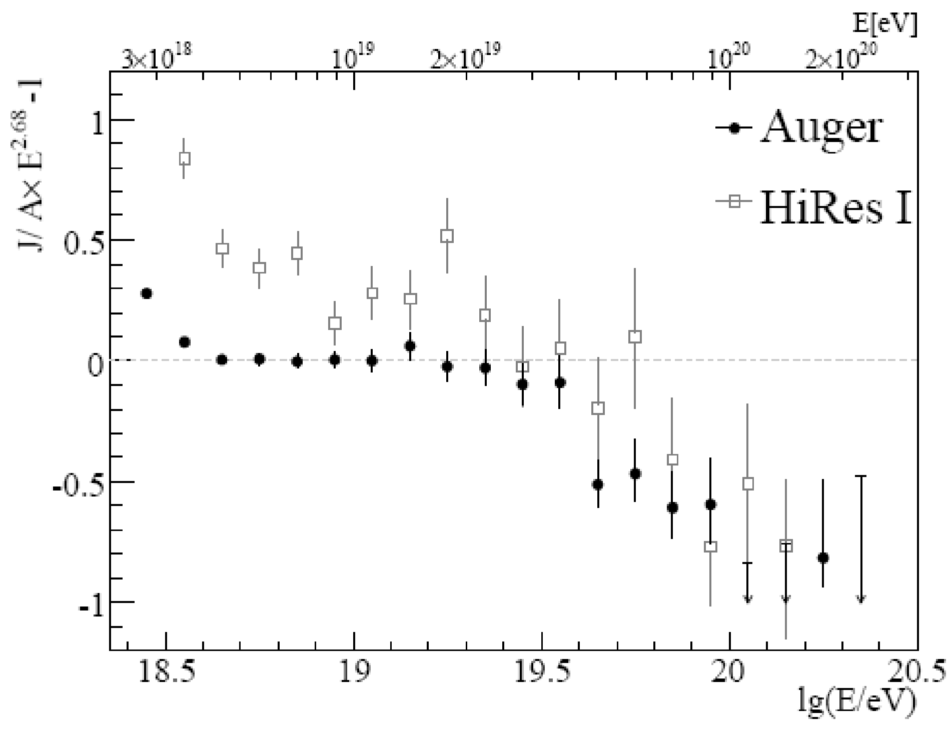
- Large volume for thermal generated currents (→increased dark rate), May need:
  - Cooling
  - Thinning (< 50 μm instead of 450 μm)
- Large volume for internal photon conversion (→increases x-talk), May need:
  - Lower gain (small diode capacitance helps)
  - Thinning (< 50 μm instead of 450 μm)

Technology Development Required

- Optics (ESA assessment, TRL 2)
  - Composite mirrors this large have never been made before.
  - Lenses this large have never been made before.
- Photo-Detectors (ESA assessment, TRL 2)
  - Back-illuminated Silicon PMT not demonstrated
  - High background noise in current Silicon PMTs
  - Cooling the focal surface appears to be challenging
- Front-end Electronics (ESA assessment, TRL 3)
  - 10^6 channels are required

Cosmic Ray Spectrum

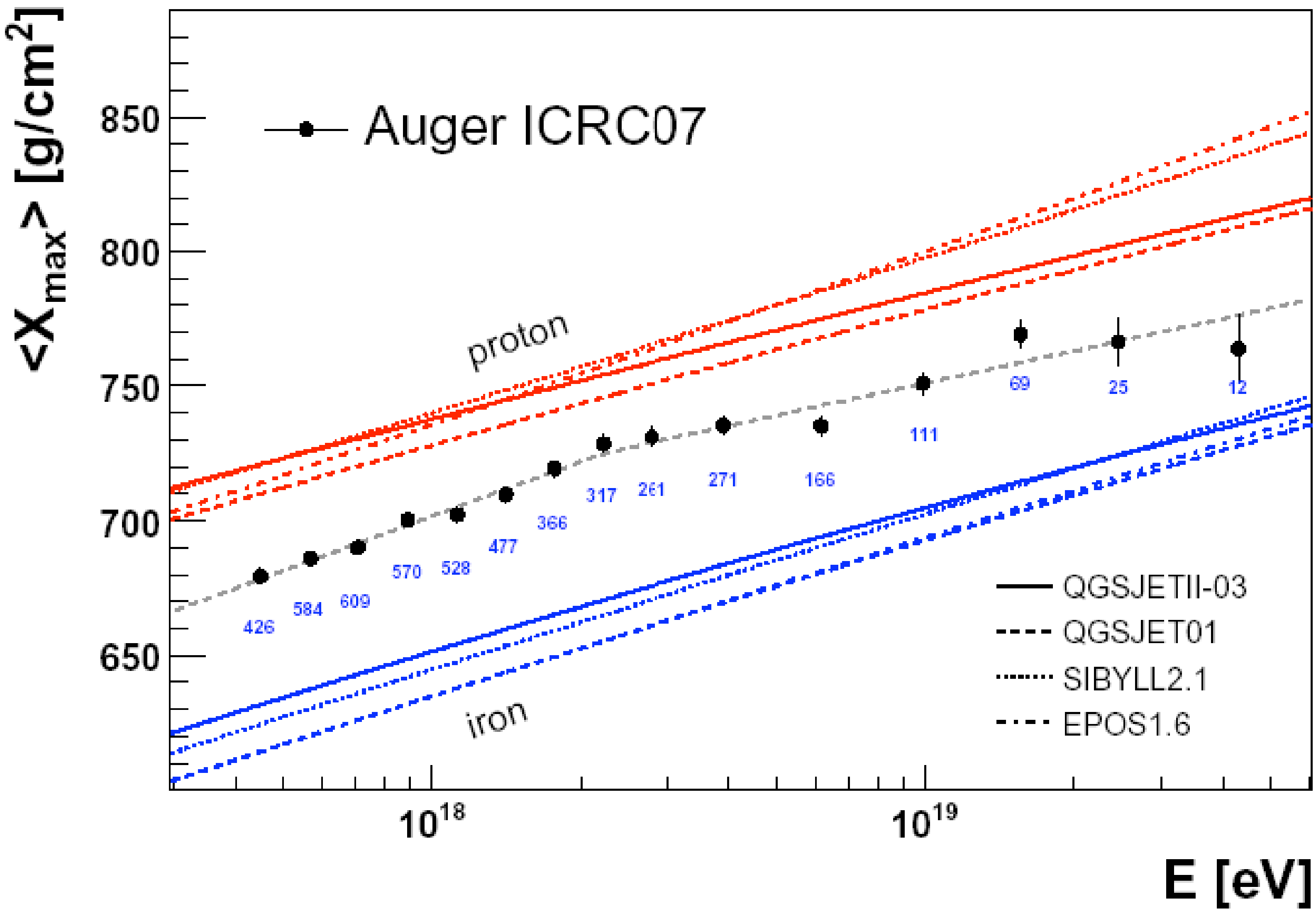




J. Abraham et al., Phys. Rev. Lett. 100, 211101 (2008)

http://astroparticle.uchicago.edu/cosmic_ray_spectrum_picture.htm

Composition



Griesen-Zatsepin-Kuzmin Effect

The GZK suppression and Horizon:

The reaction $N + \gamma \rightarrow N + \pi$, (where N represents an EECR nucleon, γ represents a cosmic microwave background photon and π represents a pi-meson) gives the energy attenuation factor, $e^{-x/(27\mathrm{Mpc})}$ at 10^{20} eV, leading to an effective range (Horizon) of up to ~100 Mpc. This effect appears for E > 5×10^{19} eV

- The horizon is ~1000 Mpc at 5×10^{19} eV
- This horizon moves nearer at higher energies

(Greisen K., 1966; Zatsepin G.T. & Kuzmin V.A., 1966)

Suppression of Nuclei

Photodisintegration Cutoff

- For $E>1\times10^{20}$eV/particle
- Distance>100 Mpc
- Photodisintegration of EECR nuclei primarily on the 3°K CMB
  - Note that disintegration shifts the energy scale, i.e.

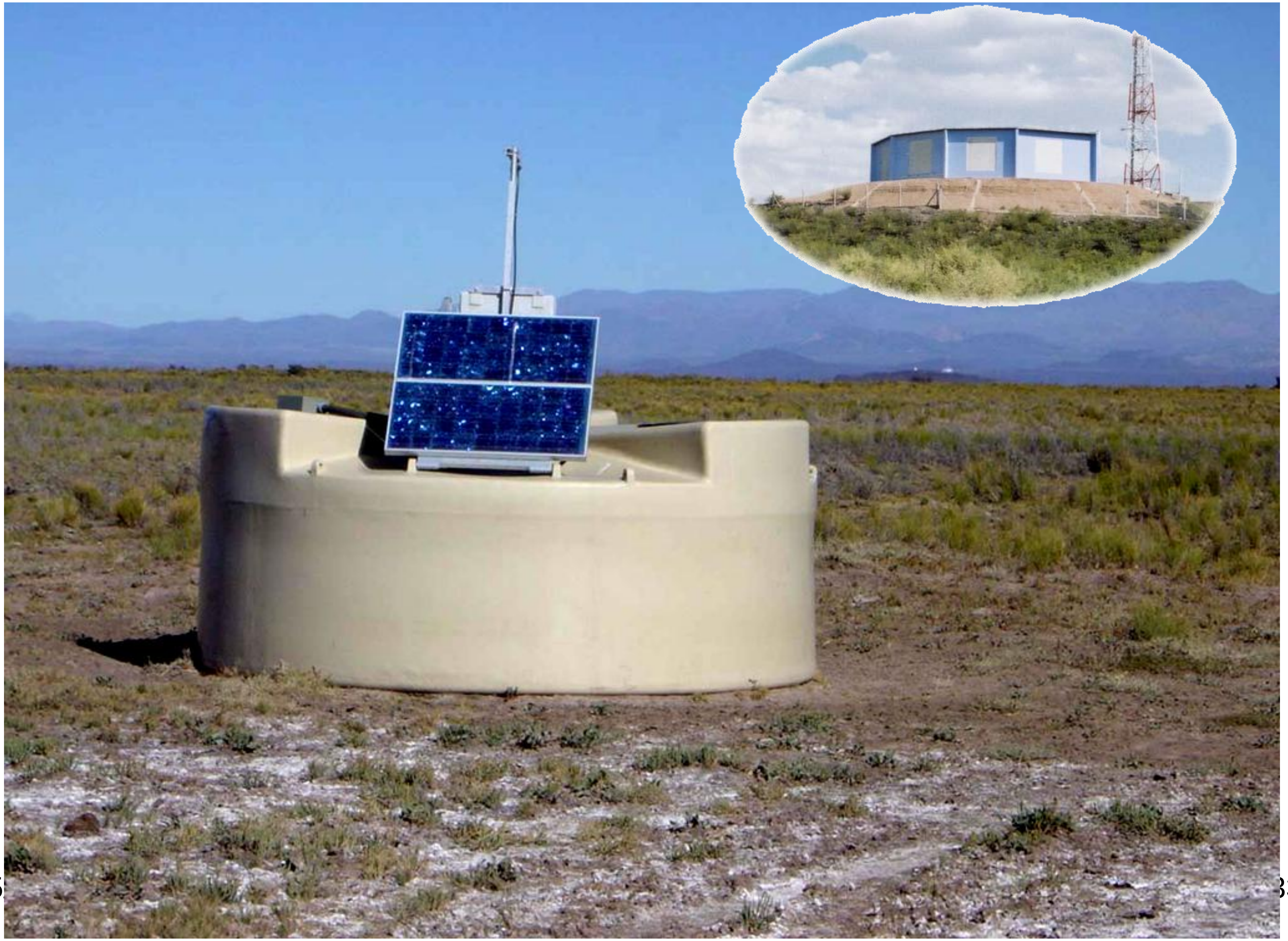
    $^4He \Rightarrow 2p + 2n$ so if $E_{He} = 1\times10^{20}$ then $E_n = 2.5 \times10^{19}$

(Stecker & Salamon, 1999)

EECR Detection

- EECRs must be detected by remotely sensing their interaction with the atmosphere
- Two methods are possible
  - Detection of charged particles at the Earth's surface
  - Detection of atmospheric fluorescence

Water Tank and Fluorescence Detector



The Pierre Auger Observatory

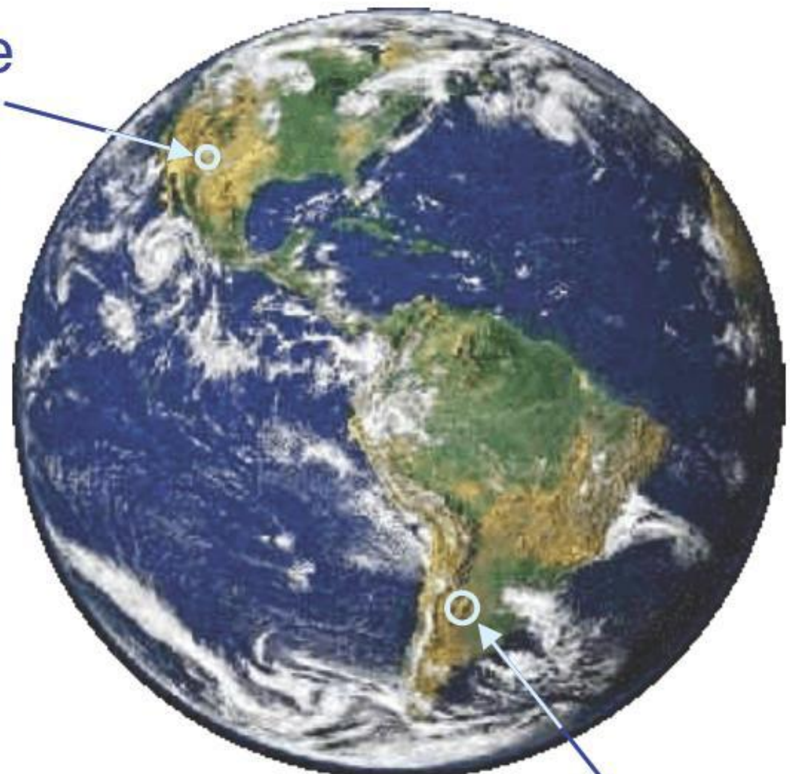
Northern site

20 000 km^2

(still to be funded)

63 Institutions

369 Scientists



- *Participating Countries*

- Argentina
- Australia
- Brazil
- Czech Republic
- France (+ Vietnam)
- Germany
- Italy
- Mexico (+ Bolivia)
- Netherlands
- Poland
- Portugal
- Slovenia
- Spain
- United Kingdom
- USA

3 000 km^2

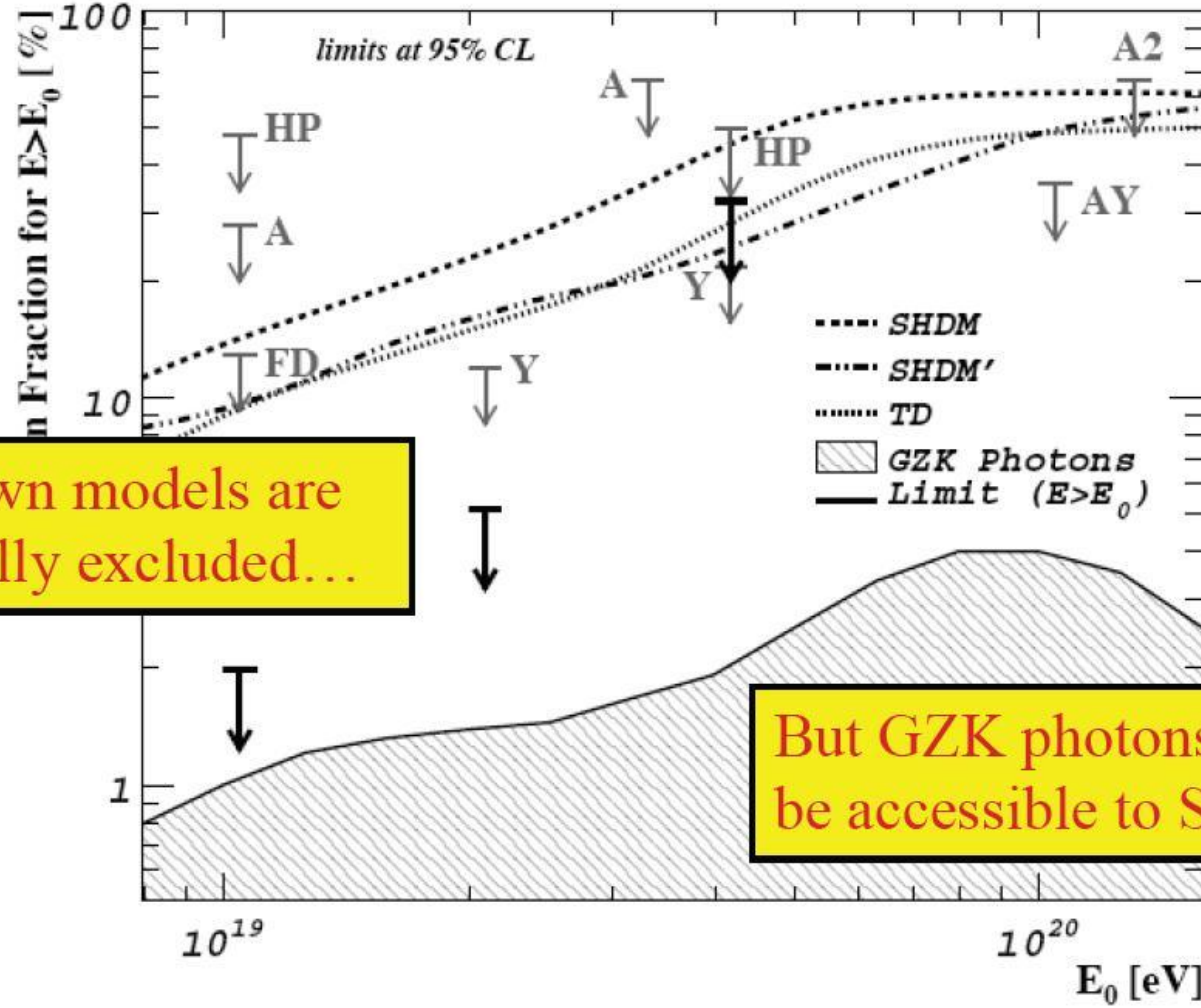
Southern site

Results from Present Experiments

- EECR spectrum (already presented) shows evidence for the GZK effect.
- The AUGER composition results (already shown) show a mix of protons and nuclei, in agreement with Fly's Eye and HiRes.
- Strong limit on photon flux
- Upper limit on neutrino flux
- Super GZK anisotropy found

Photon flux limit

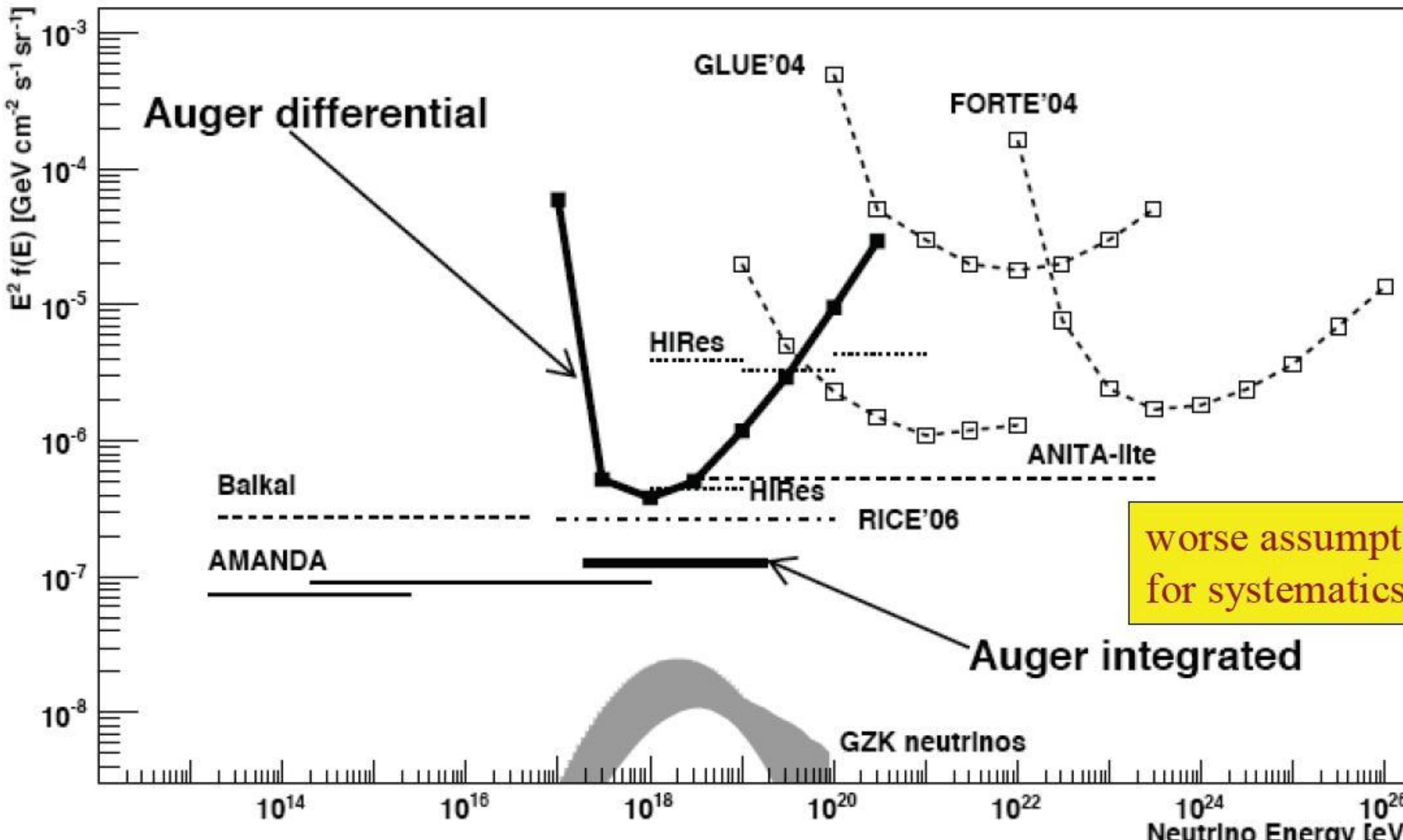
astro-ph/0712.1147



Top-down models are essentially excluded…

But GZK photons should be accessible to S-EUSO!

Auger upper limit on HE neutrinos



worse assumptions for systematics

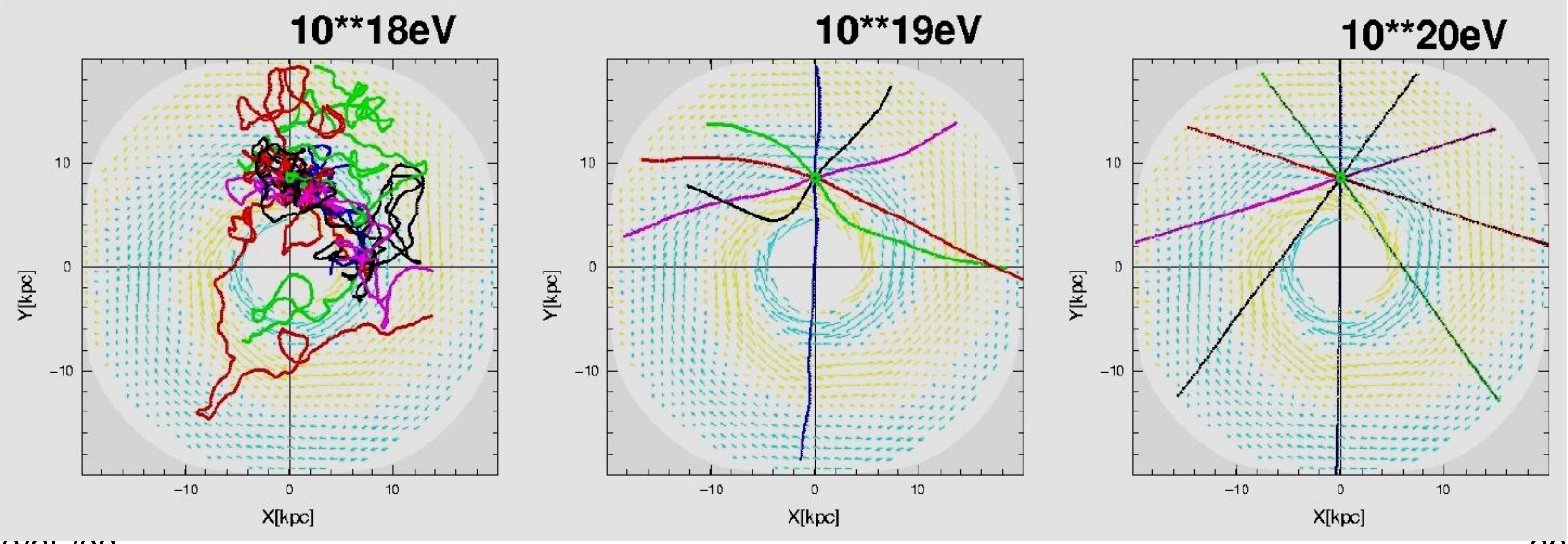
90% confidence level (1 neutrino flavor)

Super GZK Anisotropy

- $E > 5.6 \times 10^{19}$ eV/particle
- Sample of 27 events
- Compared to AGN map from the catalog of Véron-Cetty / Véron, 12th Edition, 2006
- Result: At a 99% CL, the excess seen in the original data set was not a random fluctuation from an otherwise isotropic cosmic ray distribution

Magnetic Field Deflection

- Galactic and extragalactic magnetic fields can create dispersion in the arrival directions of EECRs
- Little is known of the extragalactic field and the random part of the Galactic field
- But the dispersion should lessen at higher energies



What are the implications?

- EECR astronomy is possible!
- Many EECR sources within 1000 Mpc
- By using a higher energy threshold:
  - The GZK horizon is much closer
    - Fewer sources
  - Magnetic-field-induced dispersion is less
- Top-down EECR sources are unlikely
- Neutrino Astronomy may be possible

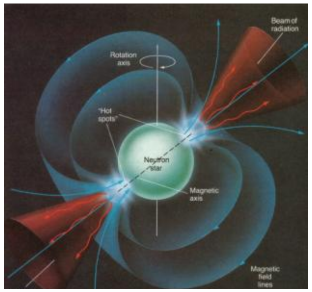
How to Proceed?

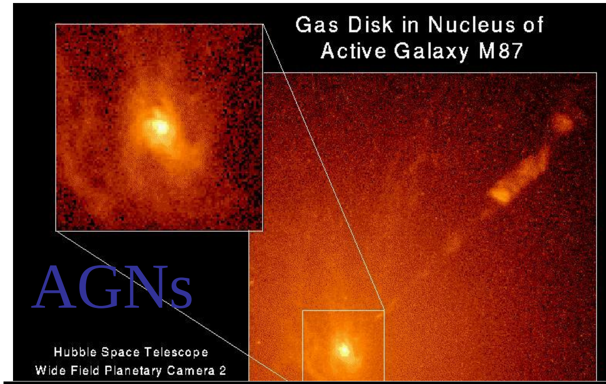
- An instrument with a much larger collecting power is needed
- Monitoring large areas of the Earth's atmosphere is best done from space
- Space-based instrument concepts
  - Orbiting Wide-angle Light-collector (OWL)
    - Subject of a NASA-sponsored Concept Study
  - Extreme Universe Space Observatory (EUSO)
    - Selected by NASA for flight before the Columbia Accident
    - Selected for Phase A/B study by JAXA
  - Super-EUSO free flyer
    - Selected by ESA for advanced technology development

Super EUSO Objectives

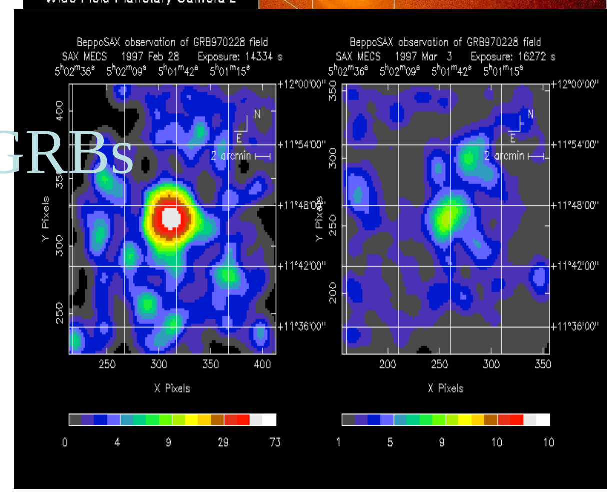
- How does the cosmic-ray spectrum continue beyond the existing data?
  - Is there a maximum energy?
  - Do we see changes in the spectrum above the observed energy range?
- Which are the point sources responsible for the anisotropy and the correlation with the matter distribution in the local universe observed by Auger in the southern hemisphere and possibly observed in the Northern Hemisphere by AGASA?
  - Can we identify the sources and study their spectra?
- Do the UHECP consist of protons, nuclei, photons, neutrinos, and/or exotic particles not yet discovered?
- What is the neutrino flux at UH Energies?
  - What is the flux of “cosmogenic” neutrinos?
- Are there point sources of neutrinos?
  - Are active galactic nuclei (AGN) or gamma-ray bursts (GRBs) copious sources of neutrinos?
  - Are there other sources?
- What is the gamma-ray flux at extreme energies?
  - Does it exhibit any predicted quantum gravity effects?
- Which is the flux ratio between downward and upward/skimming showers induced by neutrinos?

EECR Source Candidates



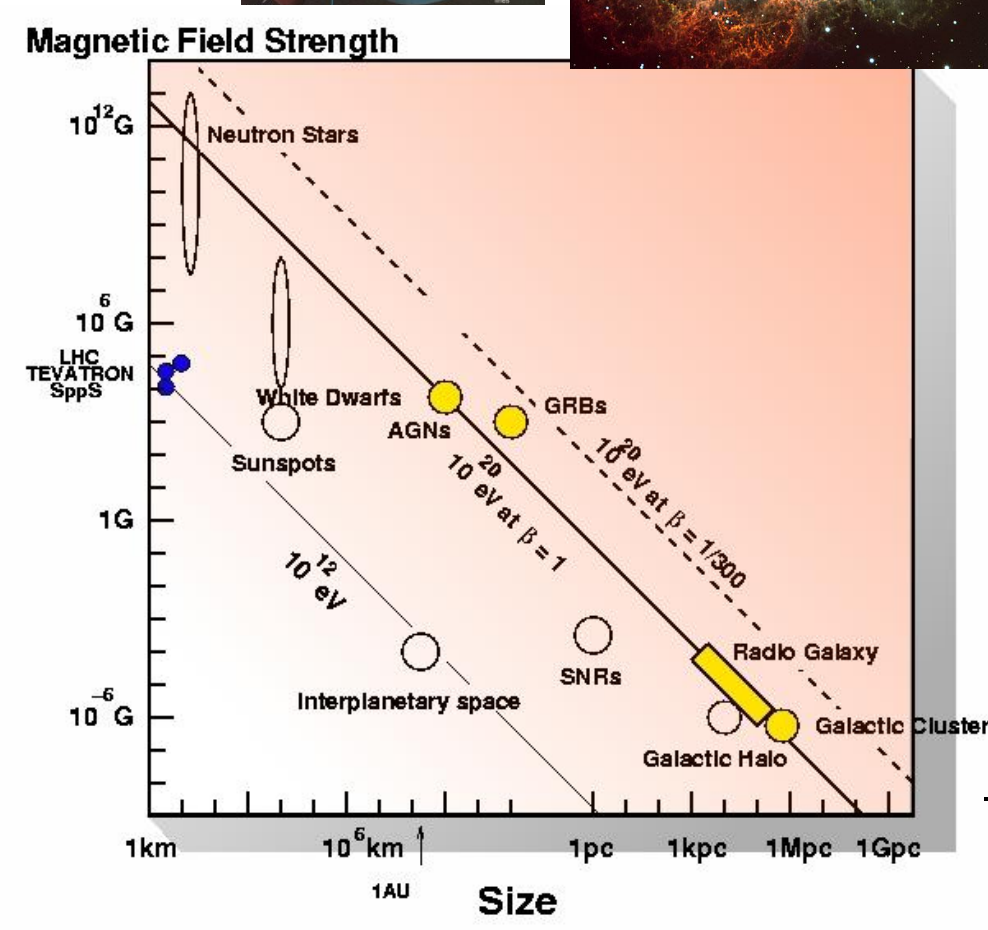


AGNs



GRBs

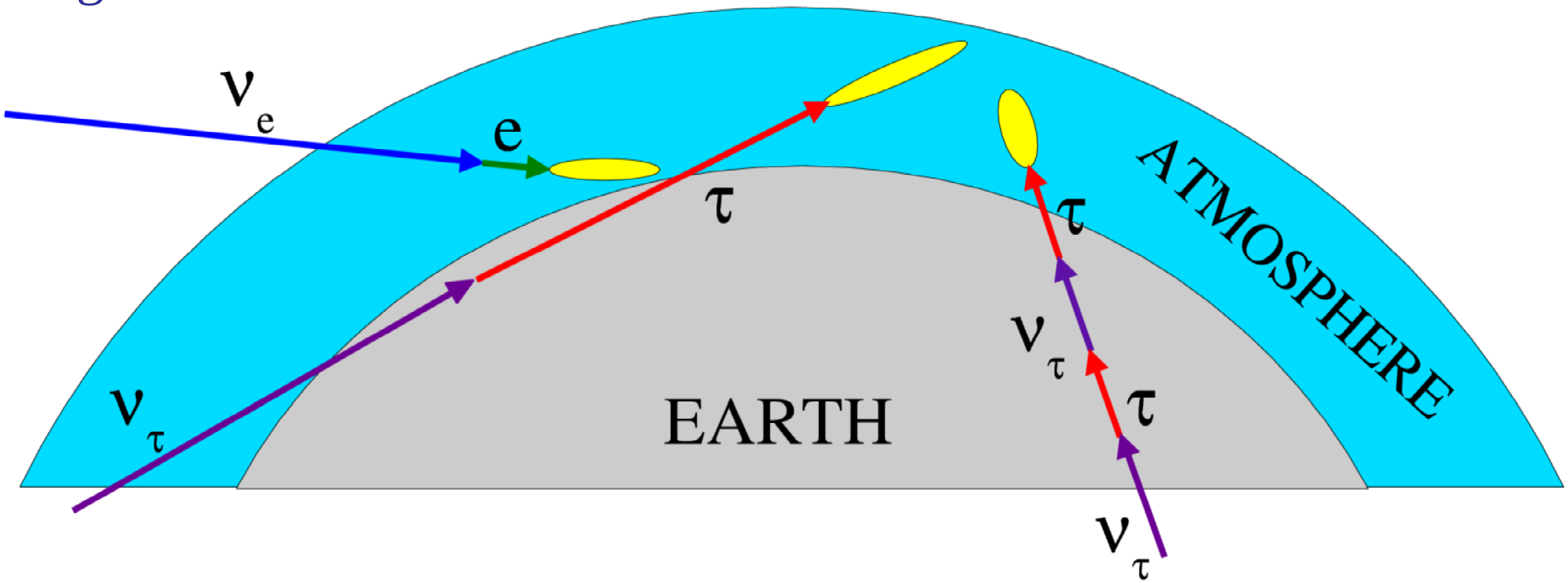
Radio Galaxy Lobes



Taken from (Hillas, 1984)

Possible Neutrino Measurements

Opening the Channel of Extreme Energy Neutrino Astronomy: The universe is transparent to extreme energy neutrinos so distant sources might be seen.



Measurement of the Neutrino Cross Sections at 10^{19} eV can probe "color glass condensate" phase of QCD

Anchordoqui et al., 2006

Neutrino Cross Sections can be measured from the ratio of Horizontal to Upward showers

Palomarez-Ruiz, Irimia and Weiler, 2006

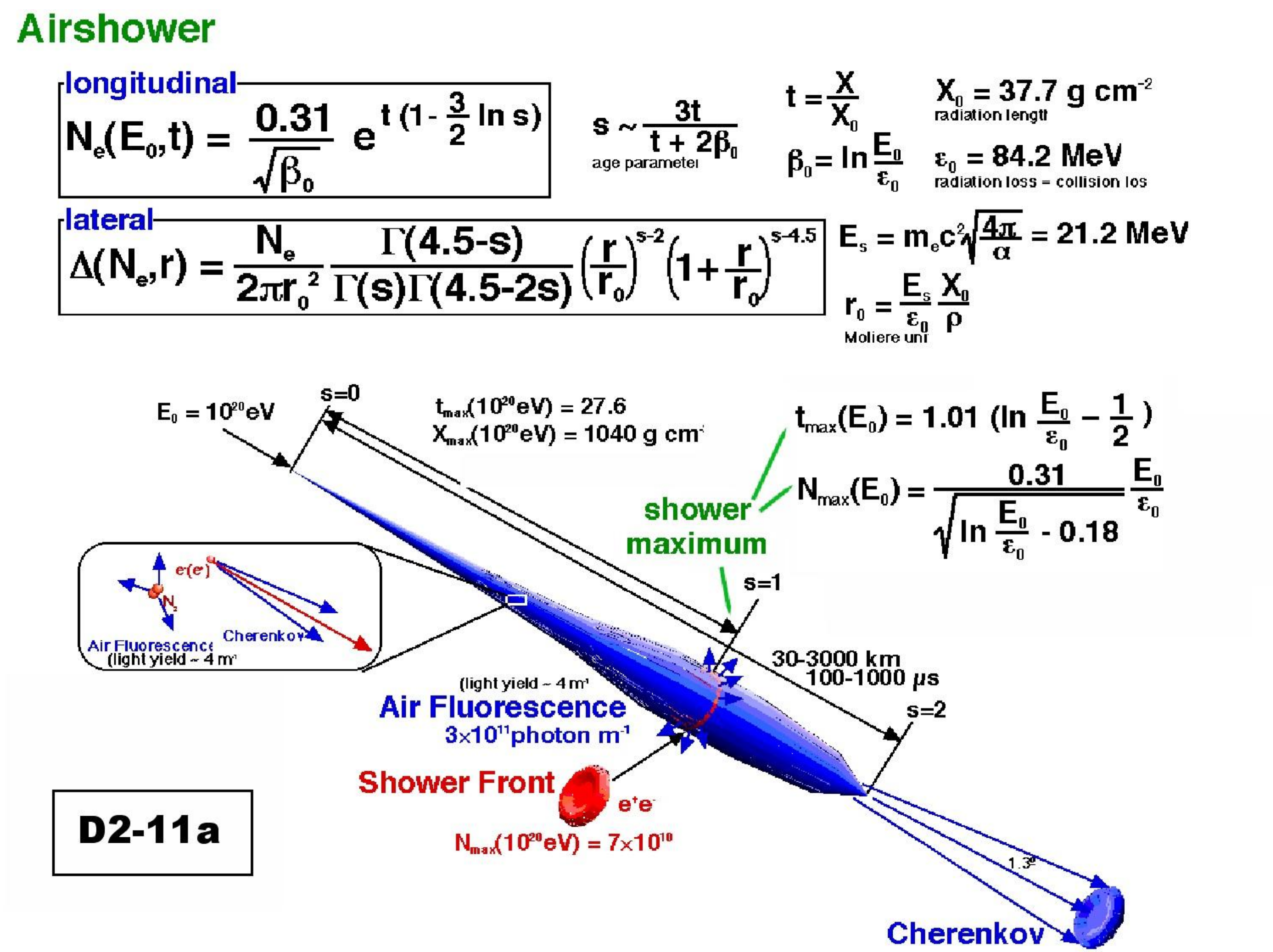
Theoretical Questions

- What processes and what astronomical objects can generate particles with these extreme energies?
- Must we postulate topological defects and/or supermassive relic particles to explain the observations?
  - With special decay modes that produce few γ-rays
- Is special relativity valid at extreme energies?
- Are the UHECRs a window to new physics at the TeV–PeV mass energy scale?
- Can we measure Neutrino Cross sections?

Relevance to NASA's mission

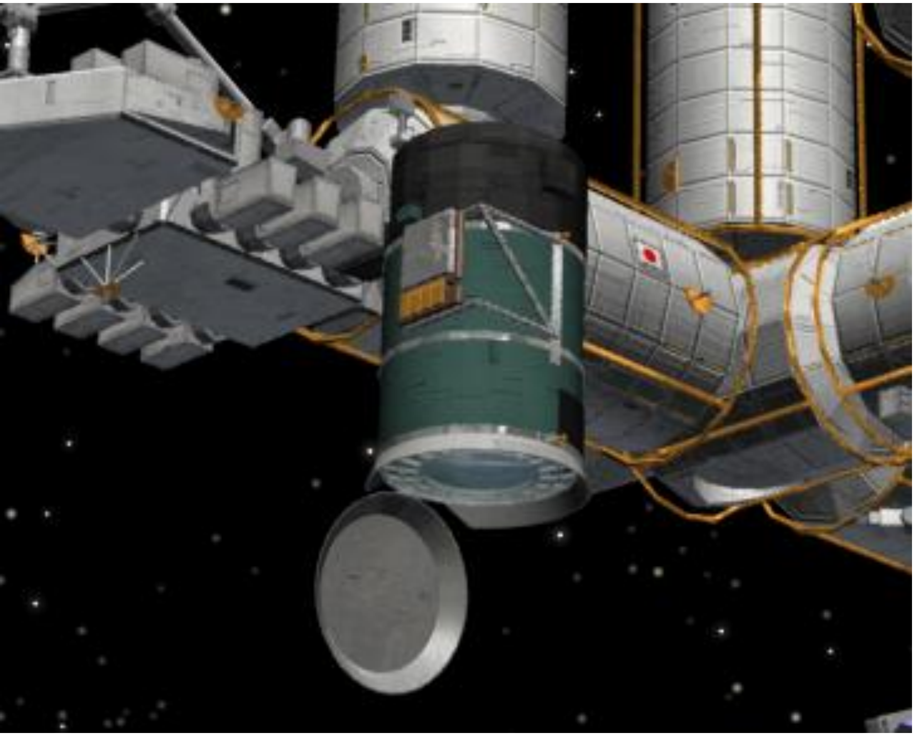
- NASA's Space Enterprise Strategy (2003) Goal
  - Explore the behavior of matter in extreme astrophysical environments including disks, cosmic jets and the sources of gamma-ray bursts and cosmic rays.
- The Physics of the Universe (2004) - Eleven Science Questions for the New Century
  - Question 6: How Do Cosmic Accelerators Work and What Are They Accelerating?
- The Science Program for NASA's Astronomy and Physics Division (2006)
  - "At still higher energies, we detect cosmic rays that cannot be confined by the magnetic fields of our Galaxy and probably come from great distances. Although ground-based observatories are currently used to detect huge showers of particles produced by these very energetic particles, space instruments looking back down on the Earth would be more effective, creating a detector as wide as the entire Earth."

Detecting Cosmic Rays from Space

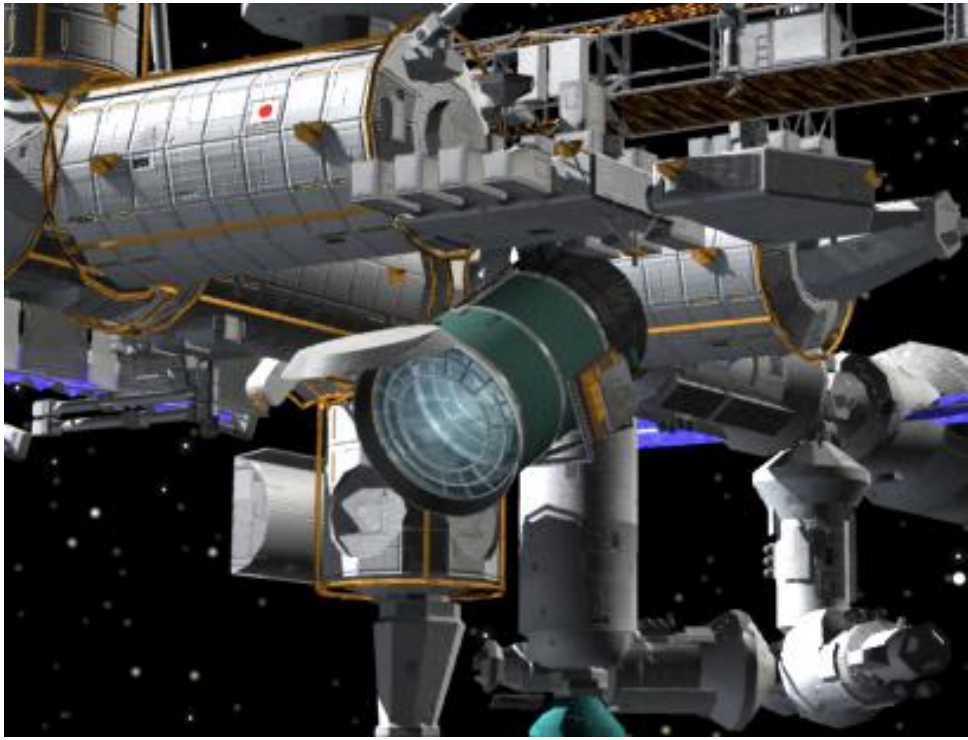


JEM-EUSO on the ISS

JEM-EUSO Telescope is being planned for deployment on the Exposure Facility of Japanese Experiment Module (JEM/EF) of ISS in about 2013



Vertical Mode



Tilted Mode