The challenging tail of the Cosmic Ray Spectrum

Enrique Zas
University of Santiago de Compostela
Alicante Marzo 2004

Today's Summary:

- Cosmic rays → General overview
- High energy tail → Motivation
- Air showers → The techniques
- The data → Facts and fiction
- The challenge → Present and future

Tomorrow: Composition and neutrinos

Earth bombarded with particles

more

particles	mostly from	seen up to
ν	sun	E> 10^{10} eV
p He nuc (cr)	galactic	E> 10^{20} eV
γ (astronomy)	agn	E> 10^{13} eV
e^- e^+ $\bar{p}$ ...	cr interactions	E> 10^{11} eV

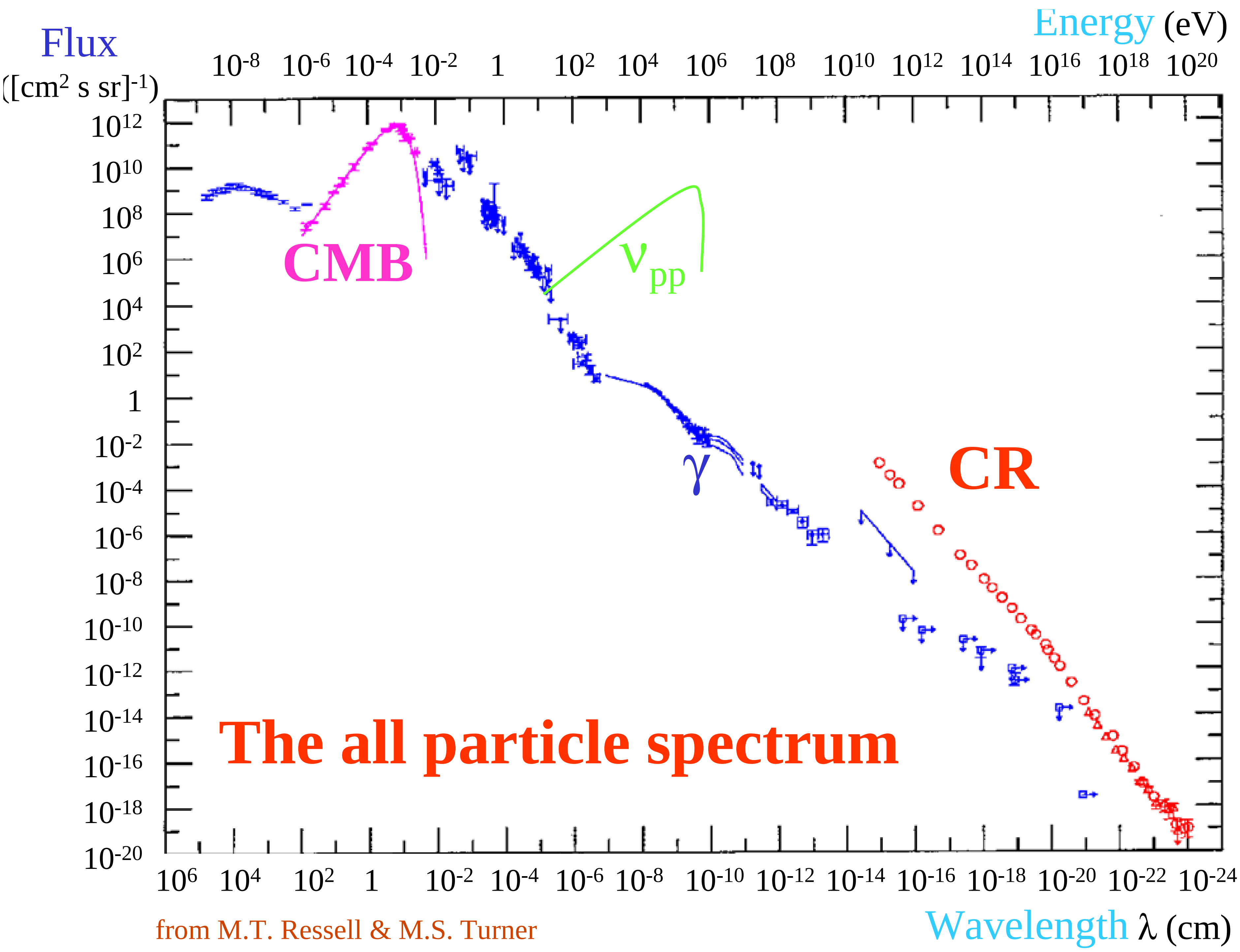
less

Fluxes are related at Production, Transport & Detection

Earth bombarded with particles

particles	mostly from	seen up to
• ν	sun	E> 10^{10} eV
• p He nuc (cr)	galactic	E> 10^{20} eV
• γ (astronomy)	agn	E> 10^{13} eV
• e^- e^+ $\bar{p}$ ...	cr interactions	E> 10^{11} eV

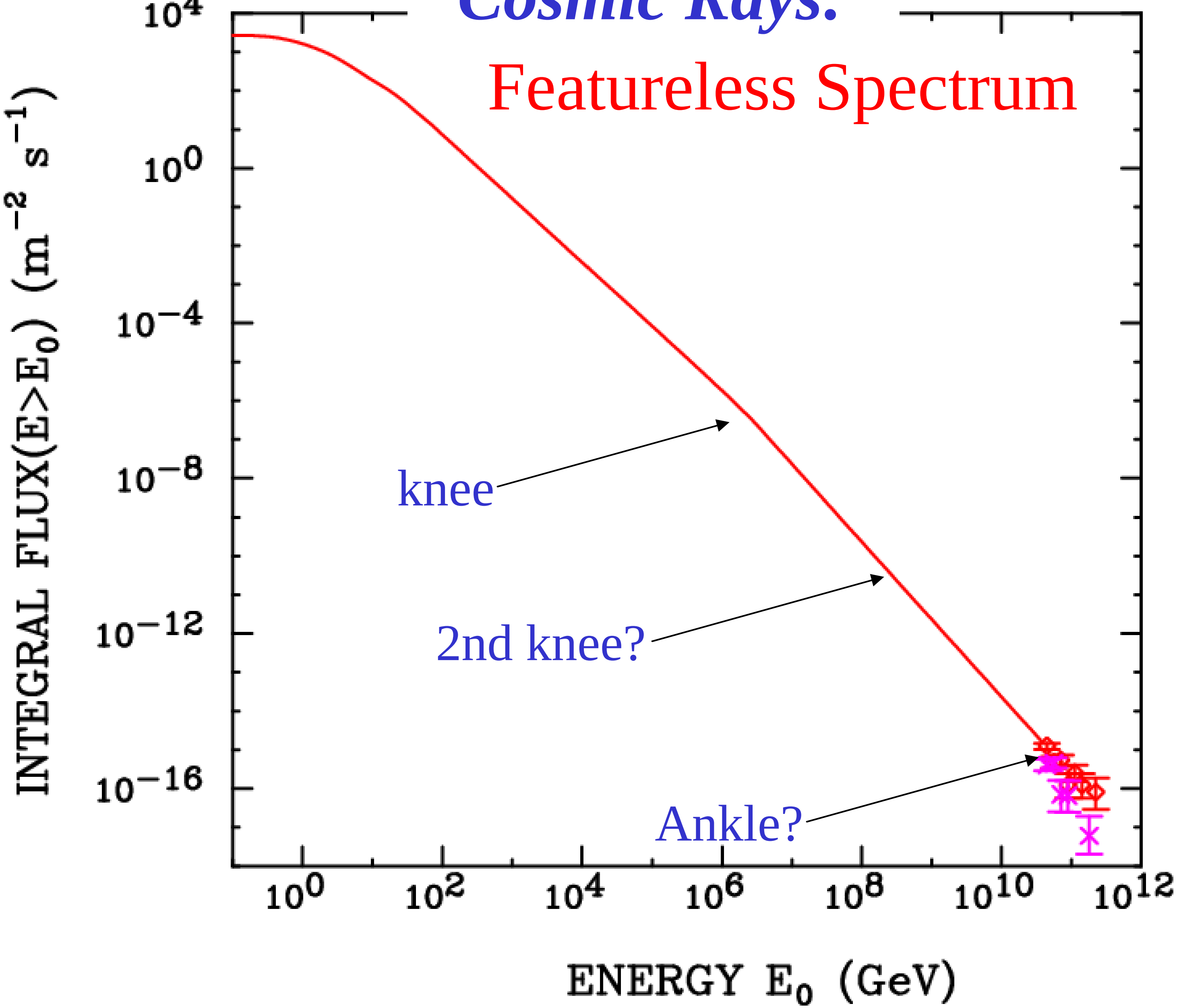
Term: *Cosmic rays* → **Millikan (Leeds 1926)**

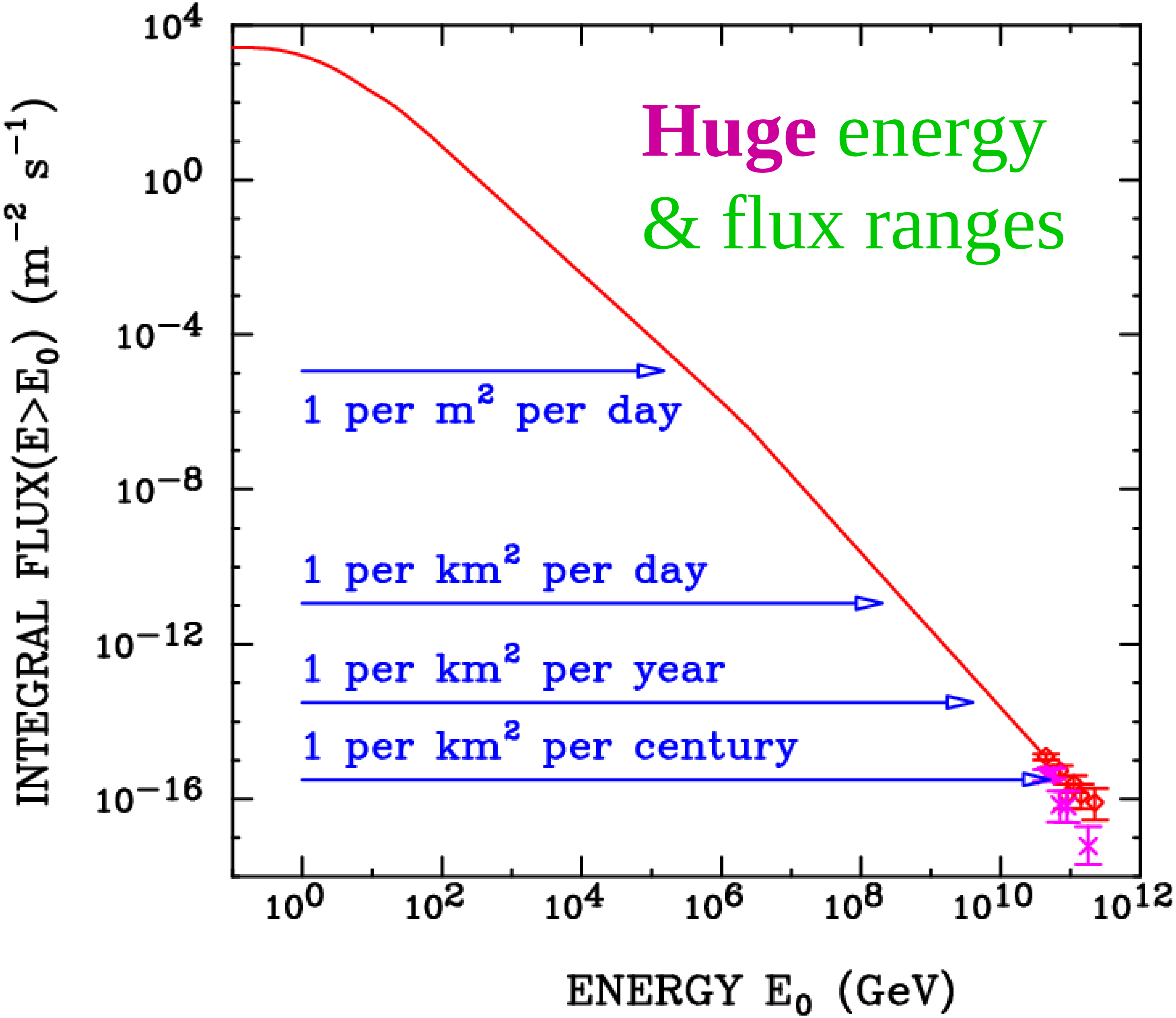


Flux ([cm² s sr]⁻¹)
Energy (eV)
Wavelength λ (cm)
CMB
ν pp
γ
CR
The all particle spectrum
from M.T. Ressell & M.S. Turner

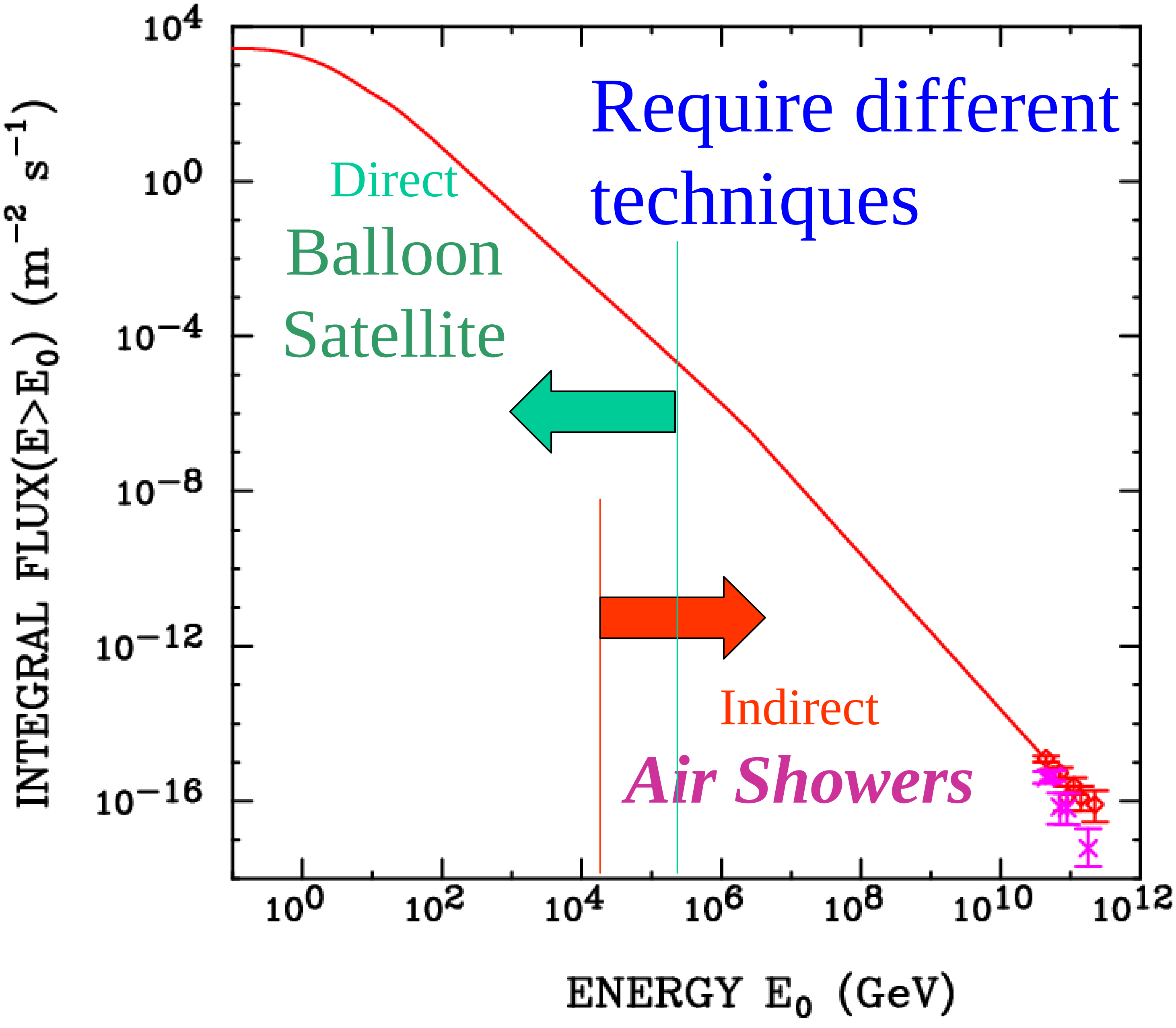
Cosmic Rays:

Featureless Spectrum



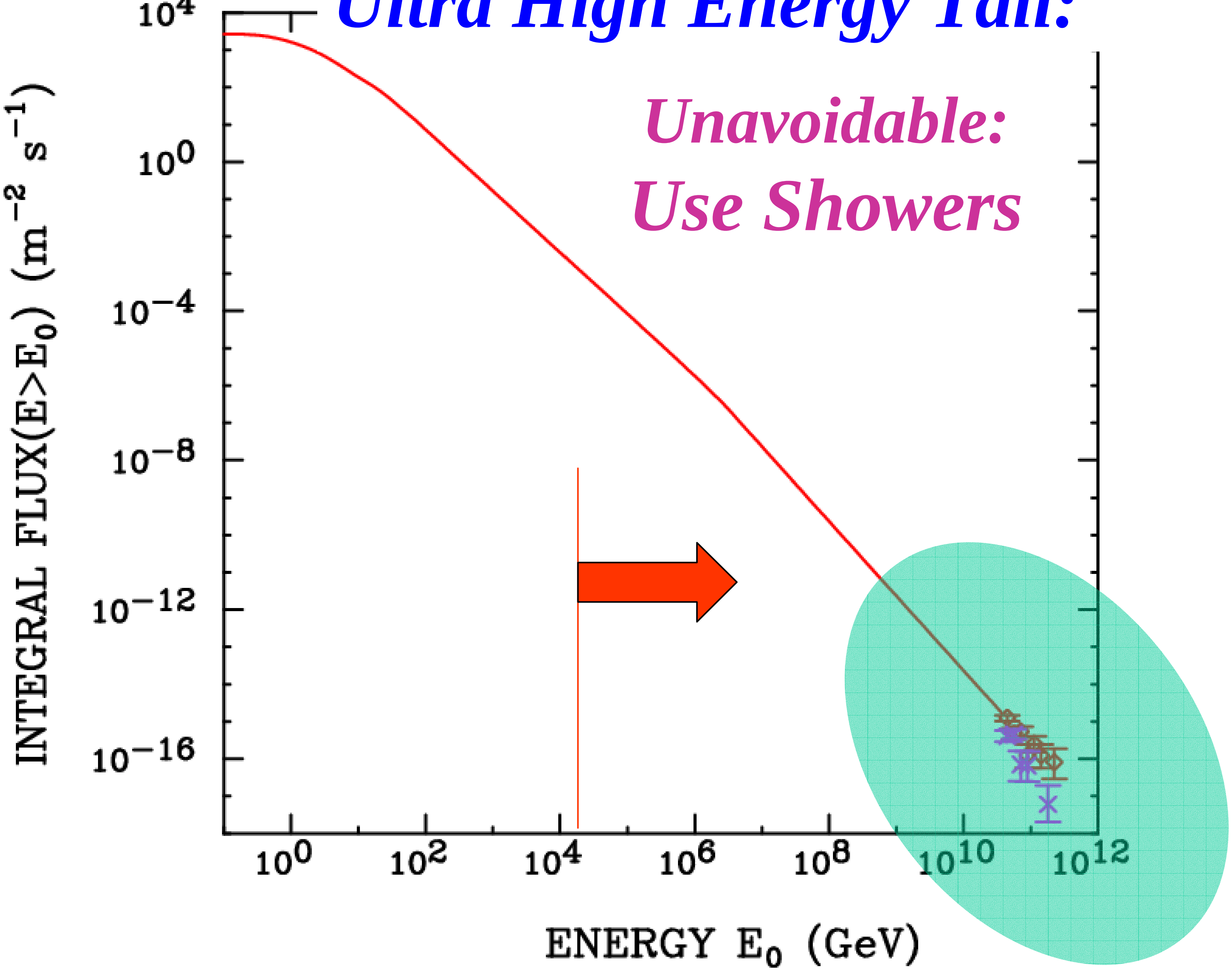


Huge energy
& flux ranges
1 per m² per day
1 per km² per day
1 per km² per year
1 per km² per century
INTEGRAL FLUX(E>E0) (m⁻² s⁻¹)
ENERGY E0 (GeV)
10^4
10^0
10^-4
10^-8
10^-12
10^-16
10^0
10^2
10^4
10^6
10^8
10^10
10^12



Require different techniques
Direct
Balloon
Satellite
Indirect
Air Showers
INTEGRAL FLUX(E>E0) (m−2 s−1)
ENERGY E0 (GeV)
10^4
10^0
10^−4
10^−8
10^−12
10^−16
10^0
10^2
10^4
10^6
10^8
10^10
10^12

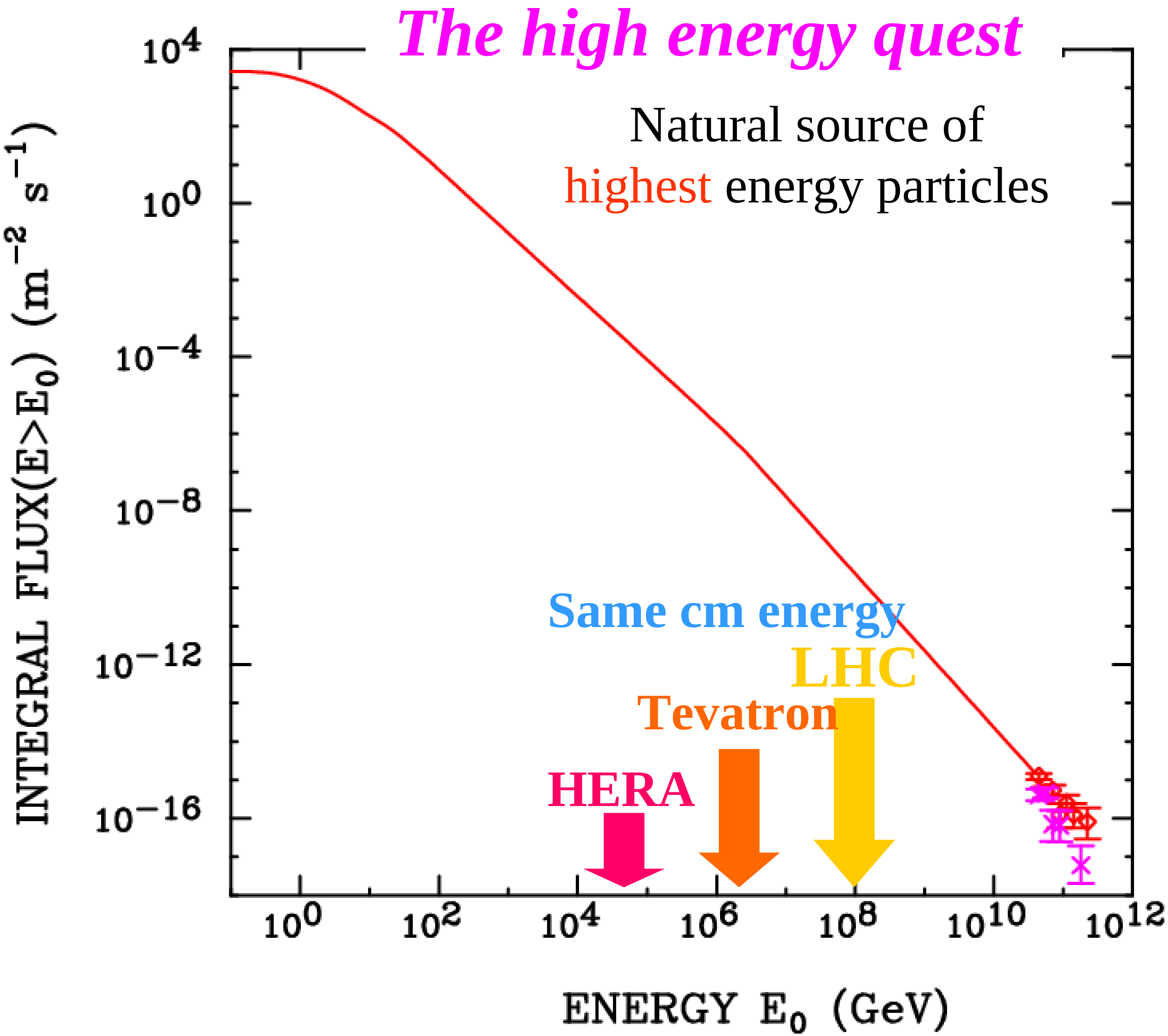
Ultra High Energy Tail:



Ultra High E ⇨ 2-fold motivation

- Particle Physics
  - Test interactions at (always) highest energies
  - Test forward region
- Astrophysics
  - Unresolved puzzle
  - Posibility to do astronomy

    learn about B fields



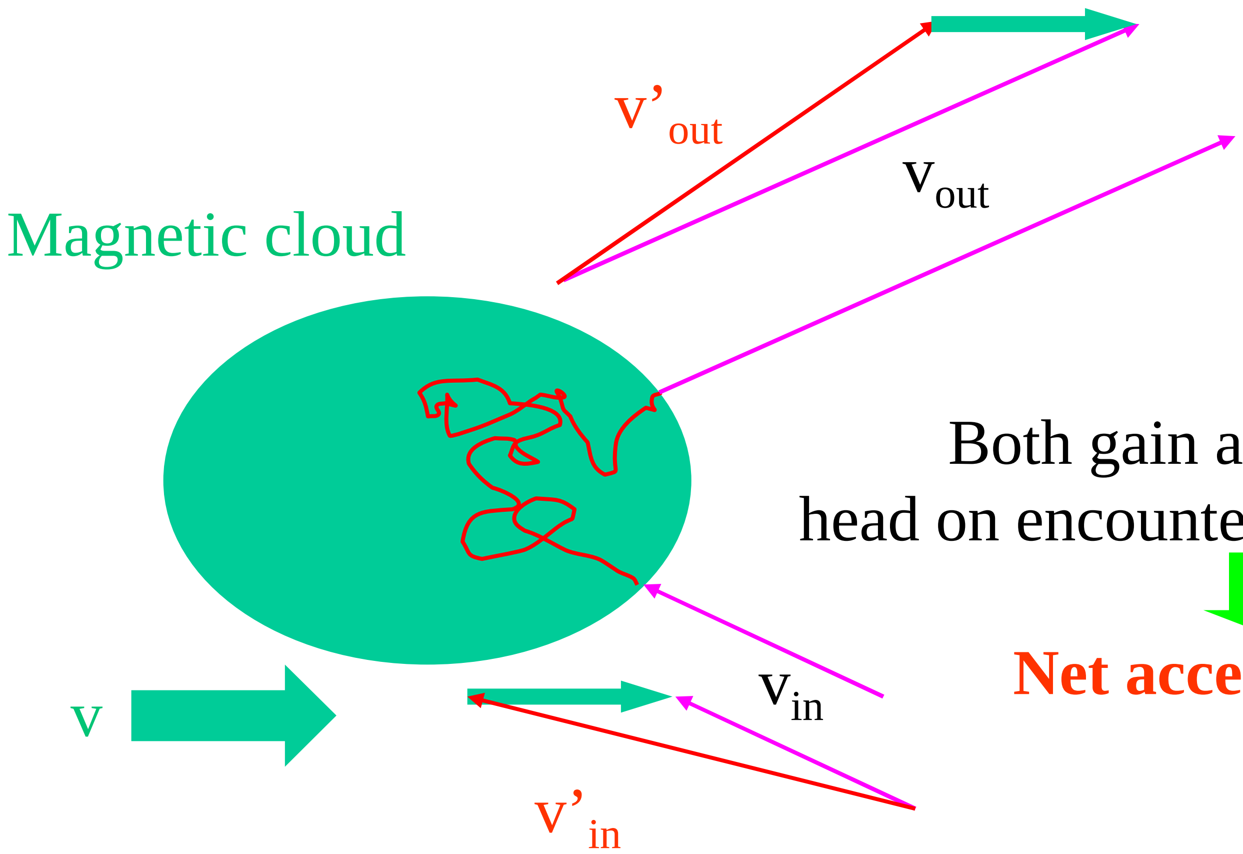
The high energy quest
Natural source of
highest energy particles
Same cm energy
LHC
Tevatron
HERA
INTEGRAL FLUX(E>E0) (m−2 s−1)
10^4
10^0
10^−4
10^−8
10^−12
10^−16
10^0
10^2
10^4
10^6
10^8
10^10
10^12
ENERGY E0 (GeV)

The Mystery Tail

- Limitations of acceleration (Fermi)
  - Extreme sources [B field and Size]
- Implications of interactions
  - CMB ⇒ GZK cutoff
  - B fields ⇒ directionality & clustering

  none established so far

Acceleration (Fermi 1949):



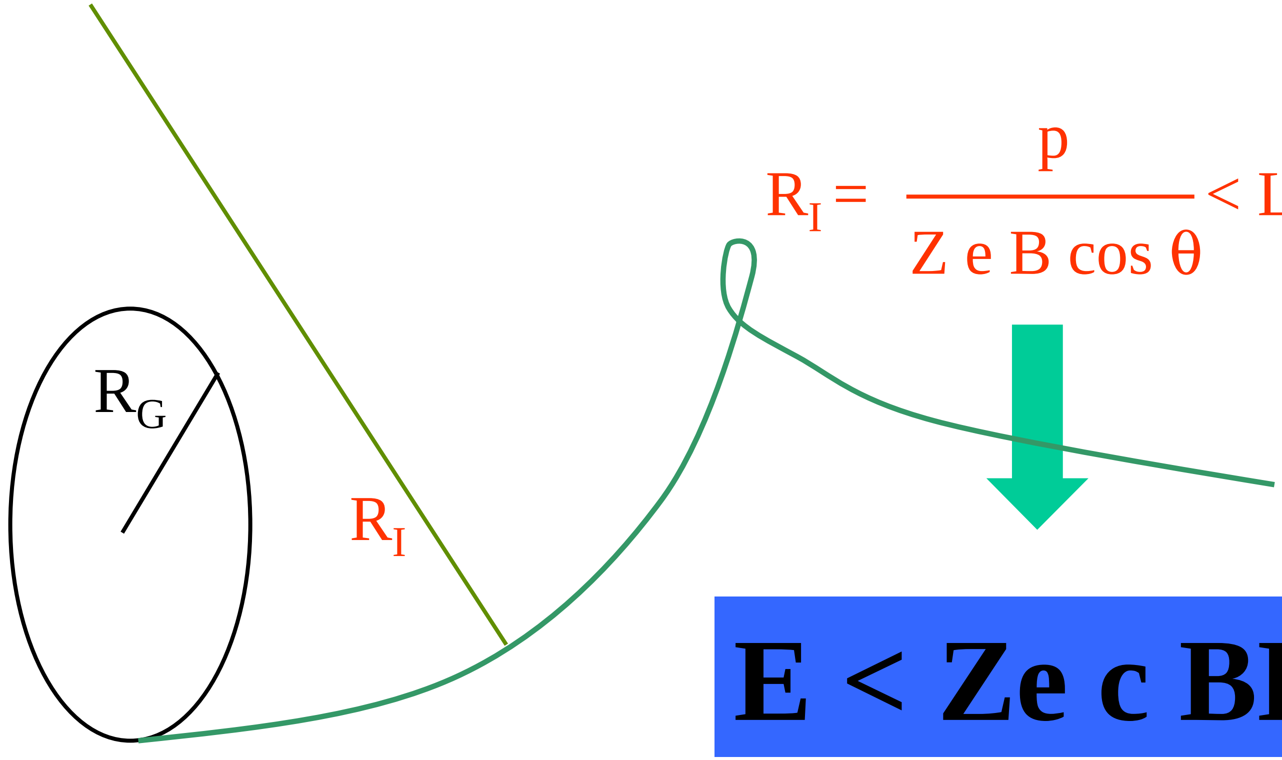
Both gain and loss but
head on encounters more frequent

Net acceleration

$$\frac{\Delta E}{E} = \frac{4\,v^2}{3\,c^2}$$

Spectrum $\alpha\ E^{-\gamma}$ (γ=2.2-2.7)

Acceleration size (L) **MUST EXCEED** radius (R_I)

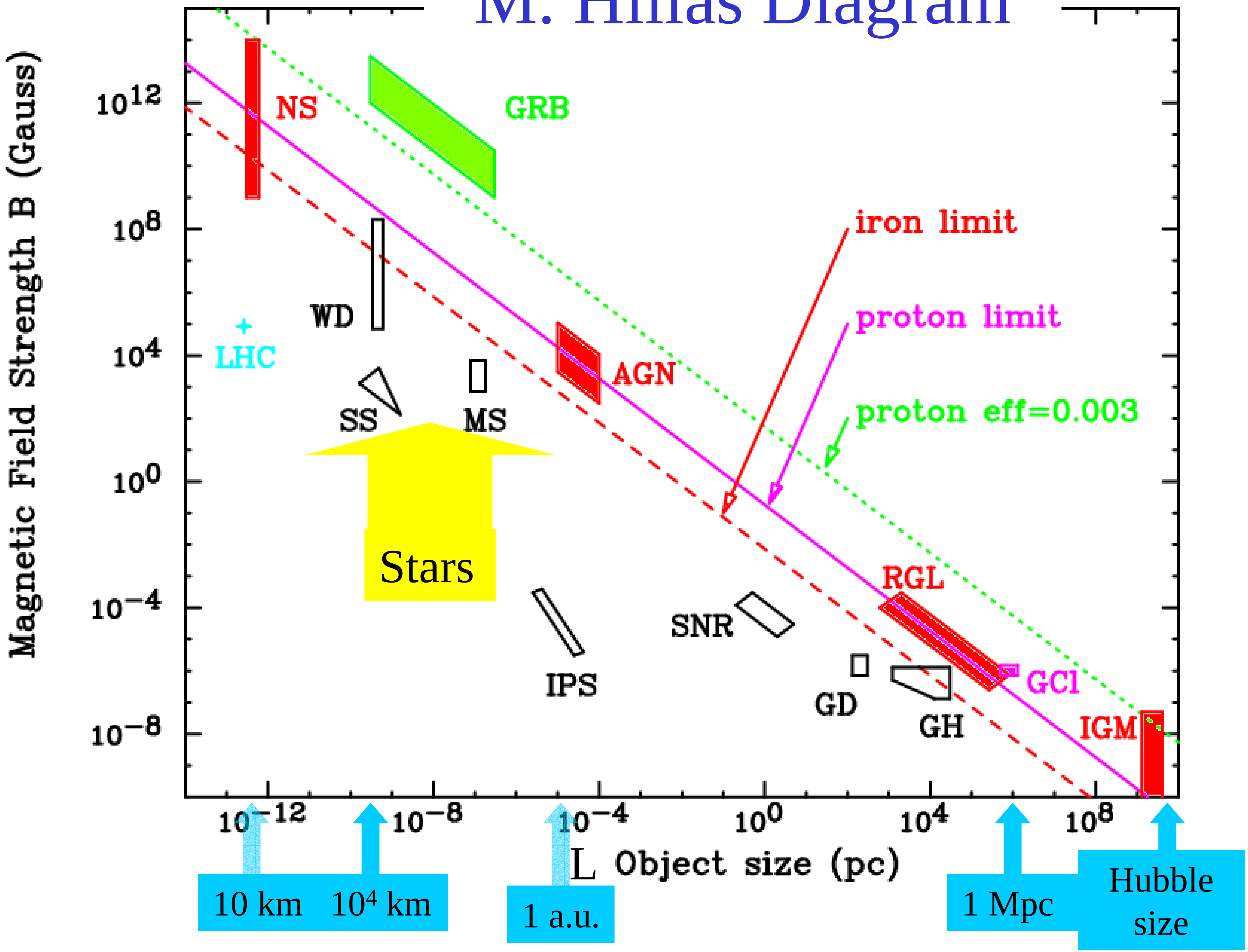


$$R_I = \frac{p}{Z\,e\,B\cos\theta} < L$$

$$\mathbf{E < Ze\;c\;BL}$$

Diffusive propagation in accelerating region

M. Hillas Diagram



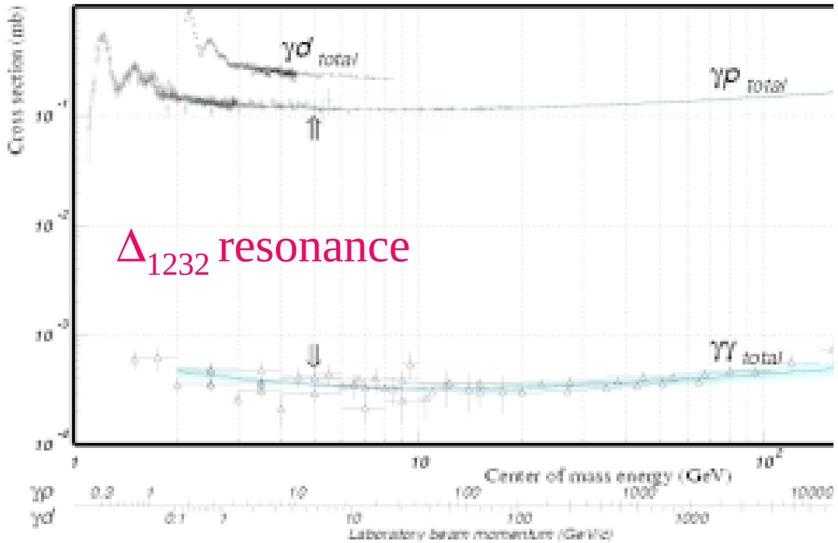
The Greisen-Zatsepin-Kuzmin cutoff

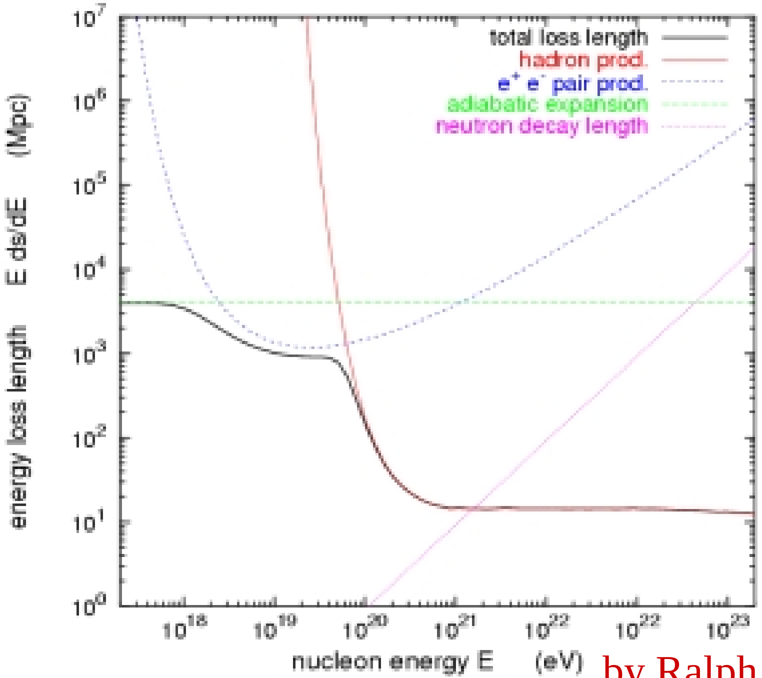
$p+\gamma_{CMB} \rightarrow n\,\pi^+$

$\quad \hookrightarrow \nu_\mu\,\mu^+$

$p+\gamma_{CMB} \rightarrow p\,\pi^0$

$\quad \hookrightarrow \gamma\gamma$





by Ralph Engel

Pair production lower threshold

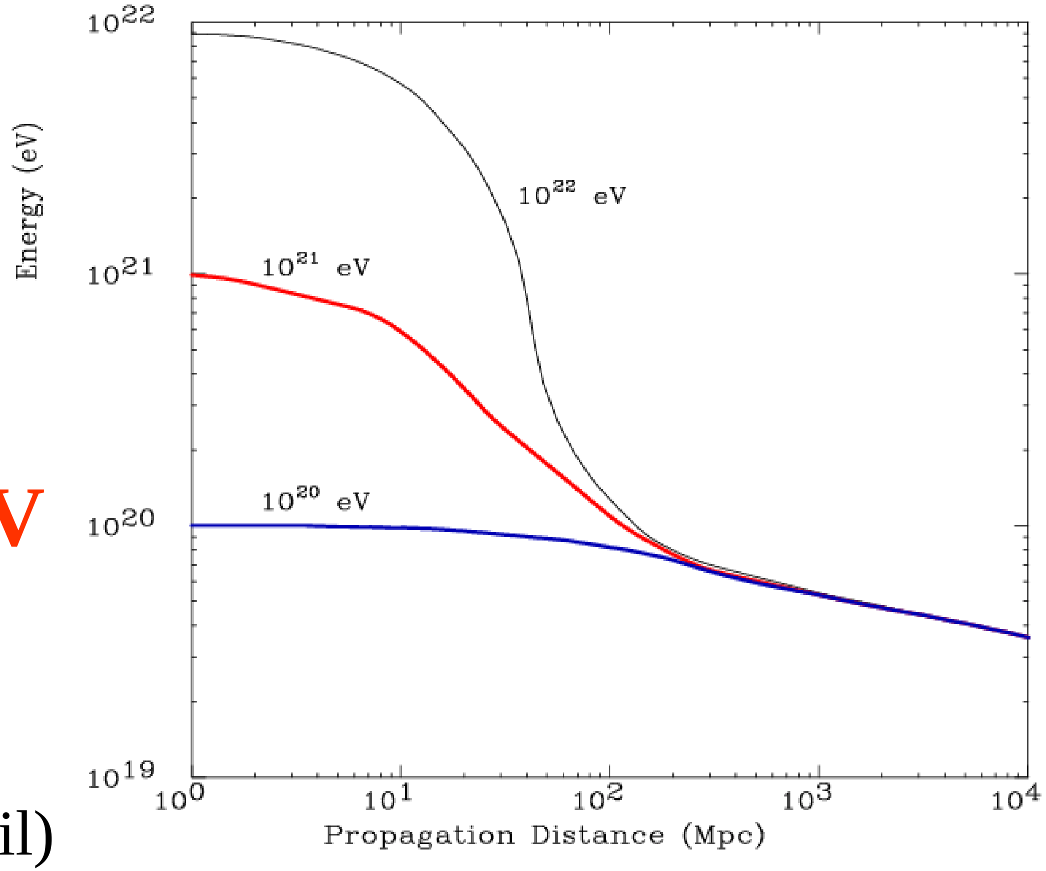
lower cross section

Expect Structure at a well defined energy

Threshold for

ε_γ= 3 [2.73] 8.62 10^{-5} eV

$$E_p = \frac{(2m_p+m_\pi)m_\pi}{4\,\varepsilon_\gamma} = \mathbf{10^{20}\ eV}$$

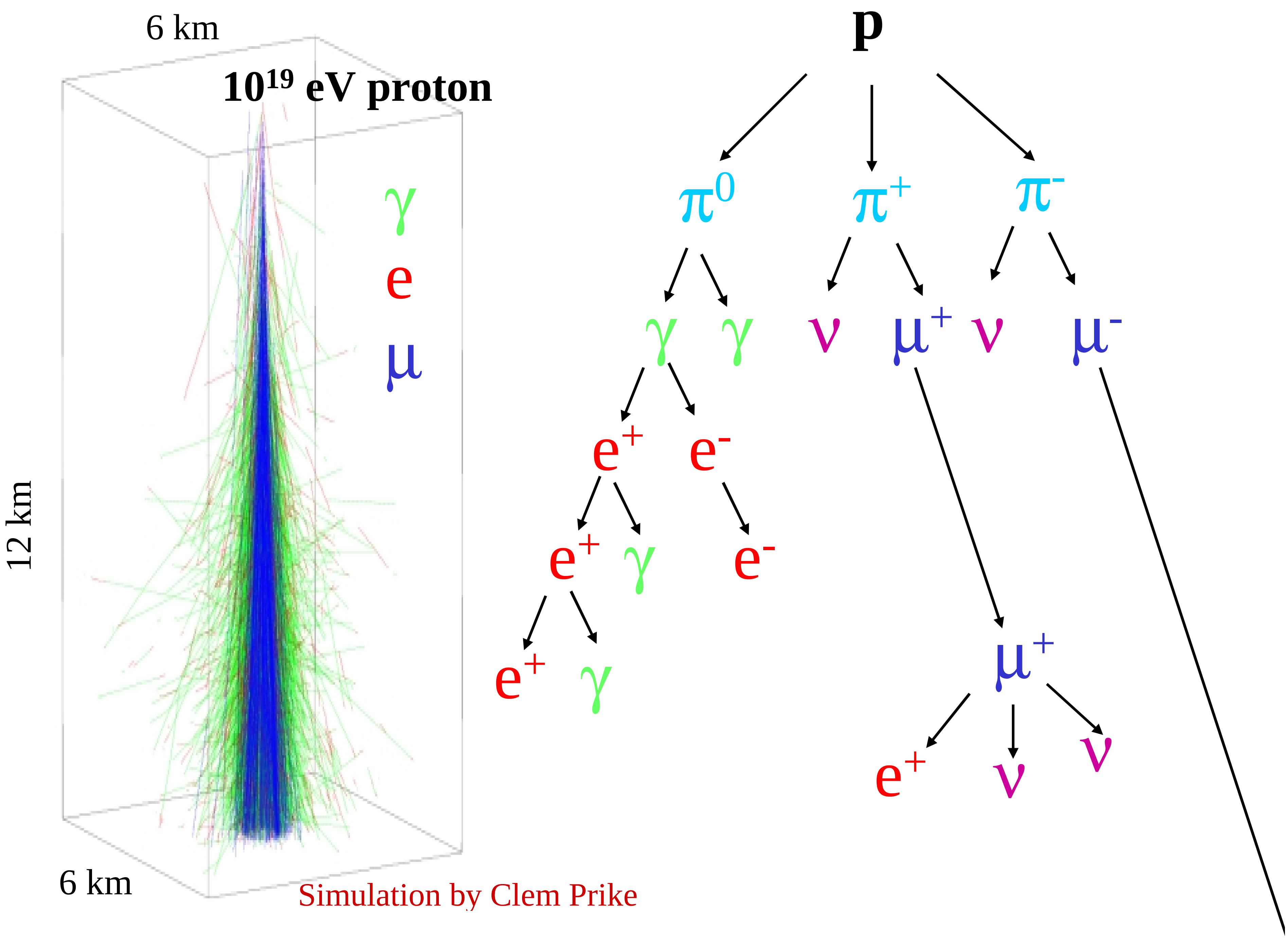


GZK starts earlier (Wien tail)

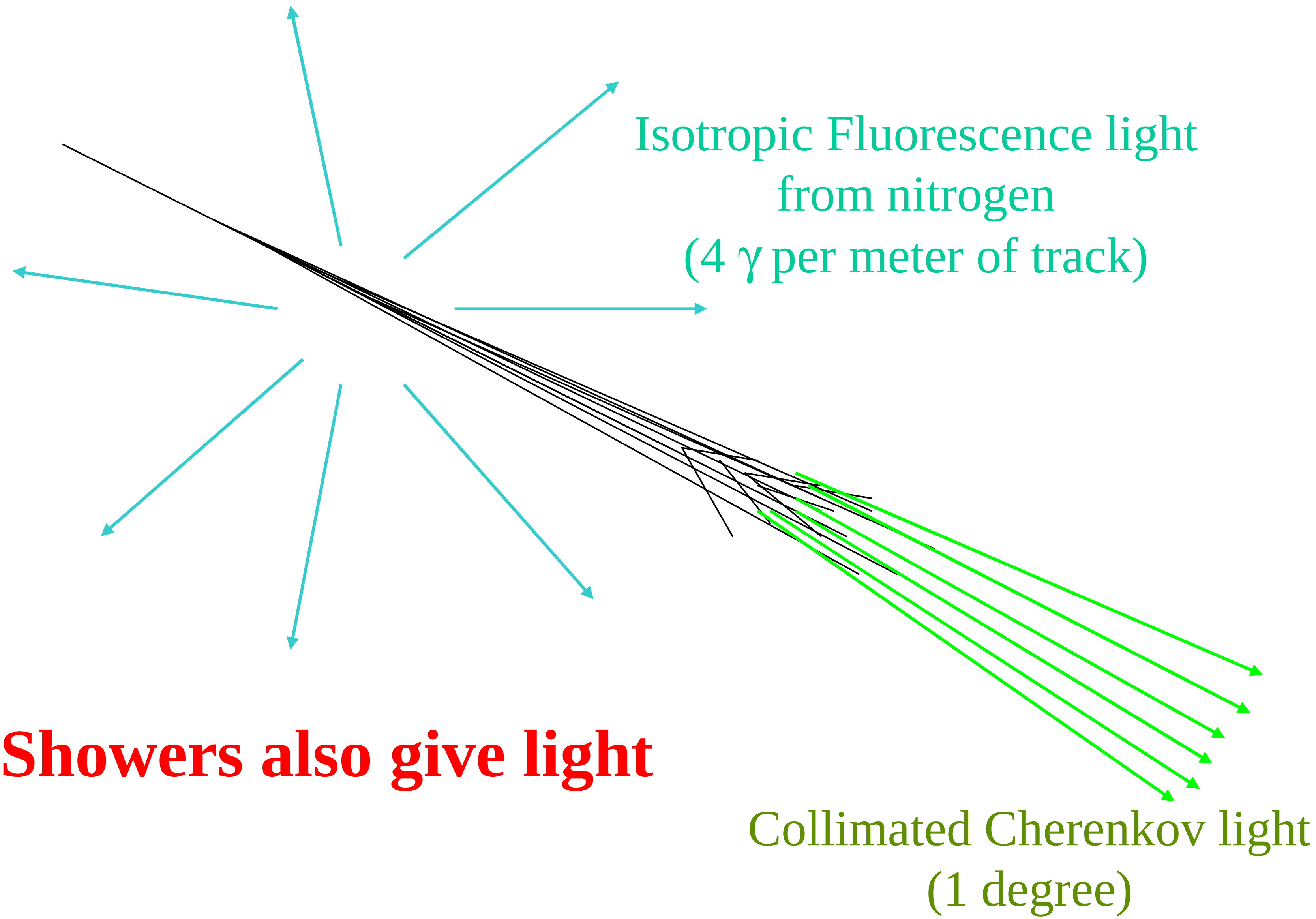
We have only detected Extensive Air Showers

spread over several km

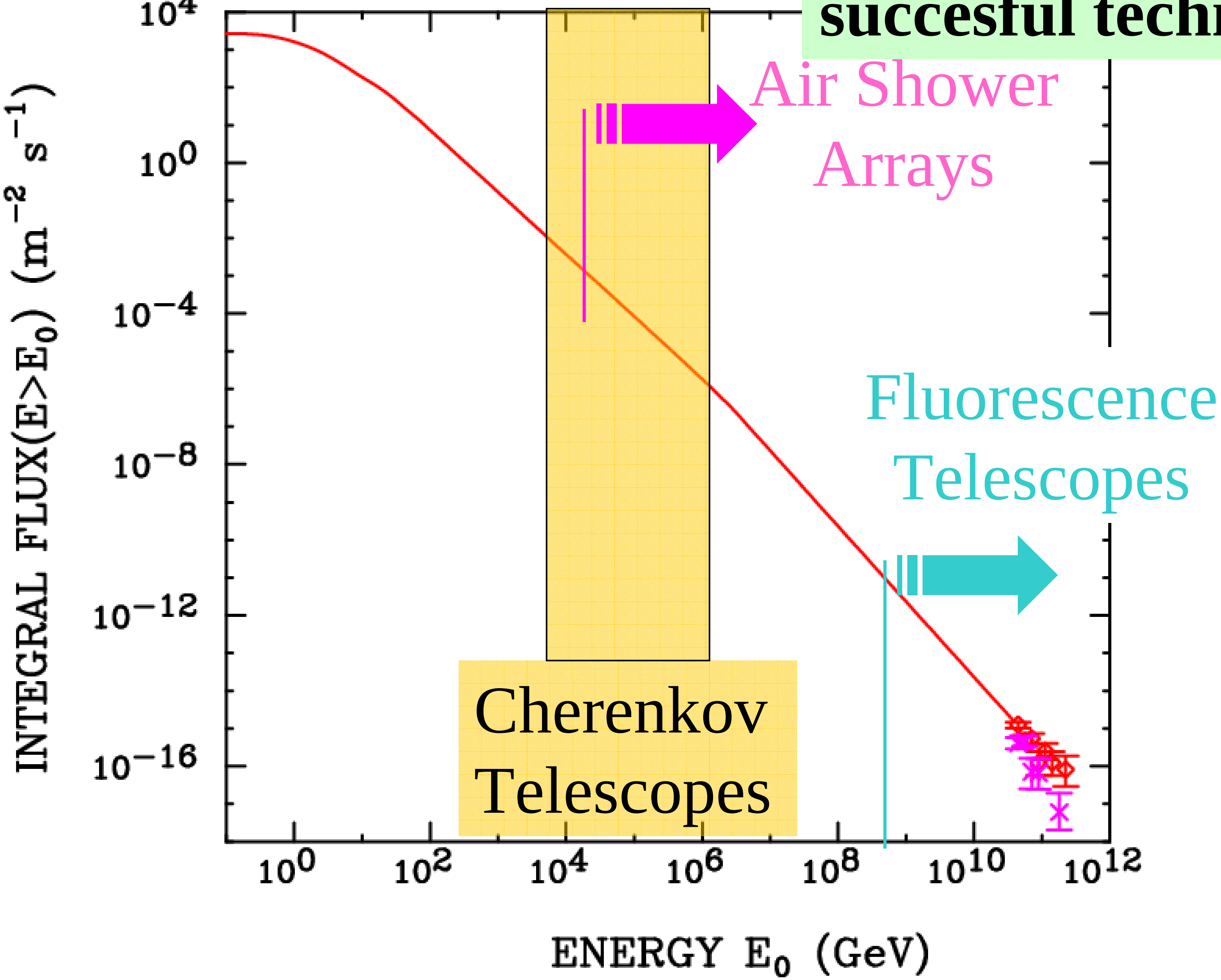
The atmosphere is (part of) our detector


6 km
10^{19} eV proton
γ
e
μ
12 km
6 km
p
π^0 π^+ π^-
γ γ ν μ^+ ν μ^-
e^+ e^-
e^+ γ e^-
e^+ γ
μ^+
e^+ ν ν
Simulation by Clem Prike

Showers also give light



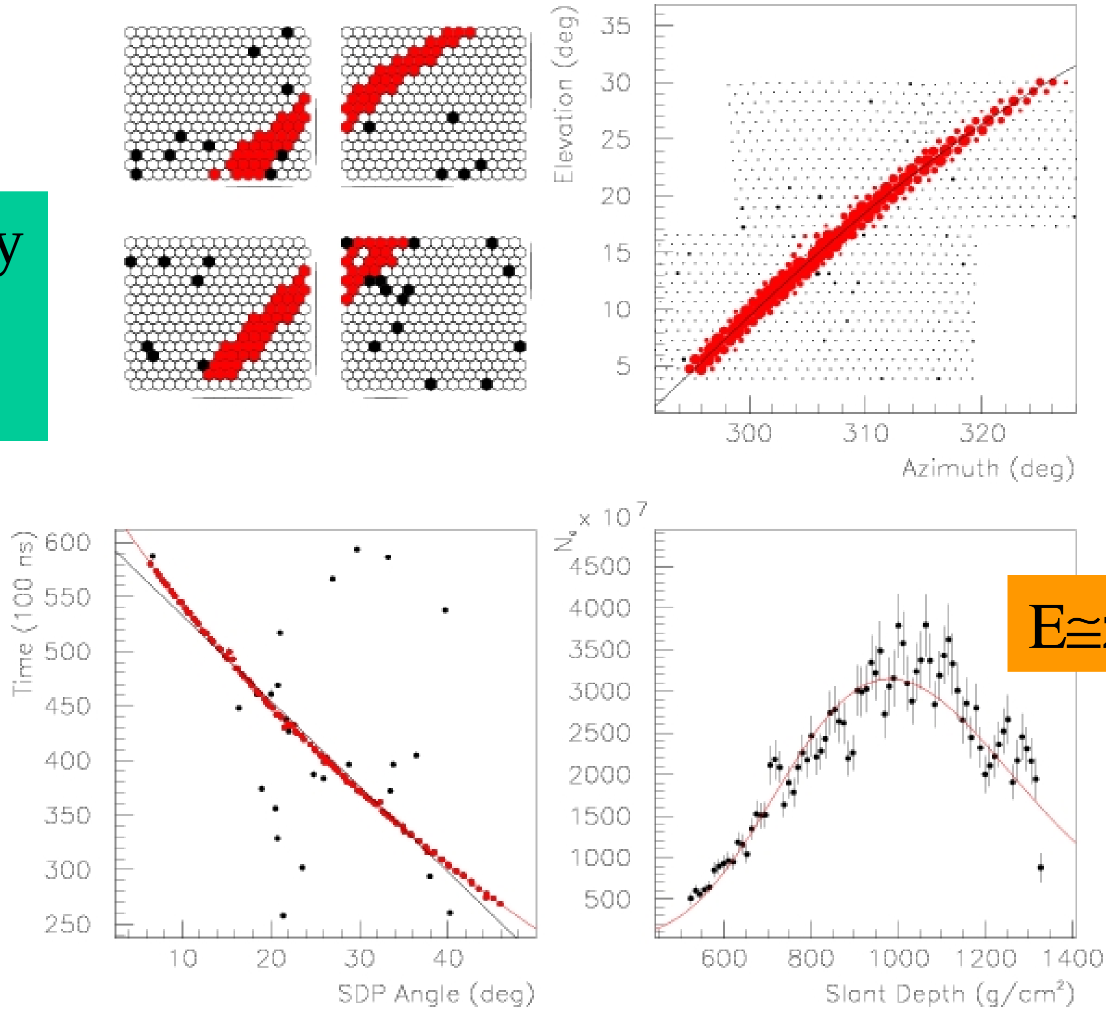
UHECR: Only Two succesful techniques



The Fluorescence Technique

Geometry & Timing

noise direction



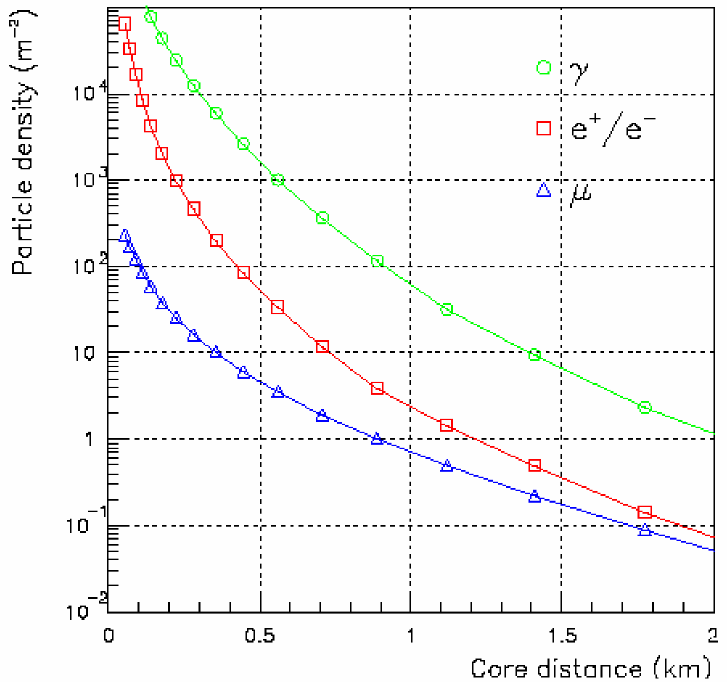
Energy:

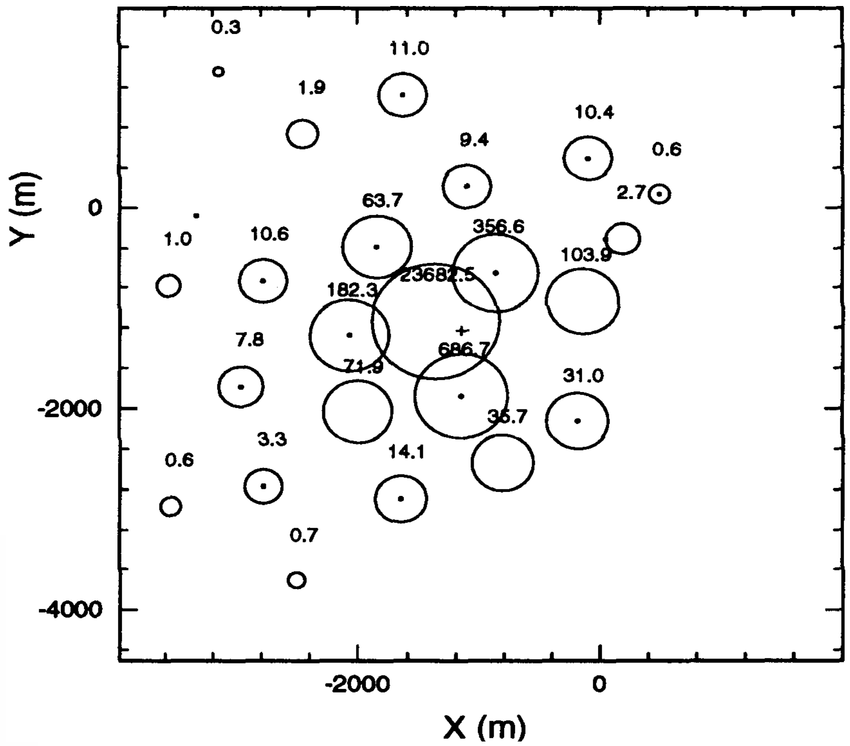
"Calorimetric"

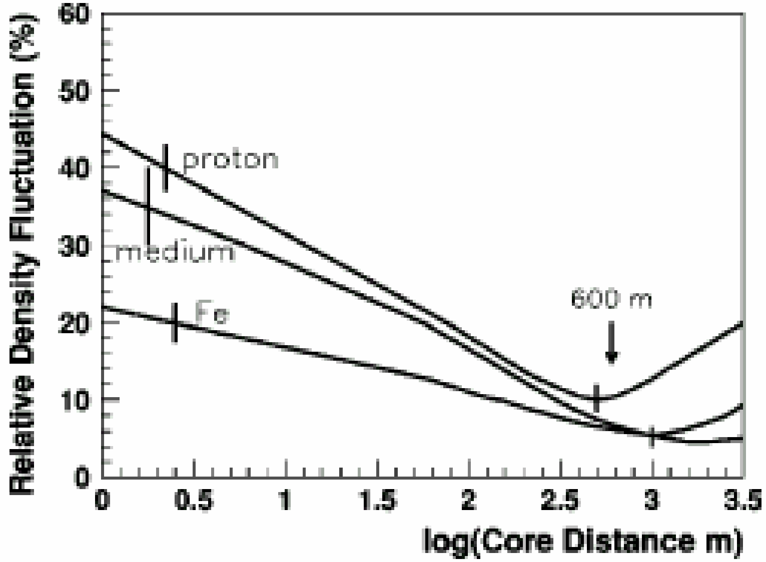
$$E \cong 2.19\ \mathrm{MeV} \int N_e(x)\,dx$$

C.Song et al., Astropart. Phys. 14, 7 (2000)

The particle array Technique

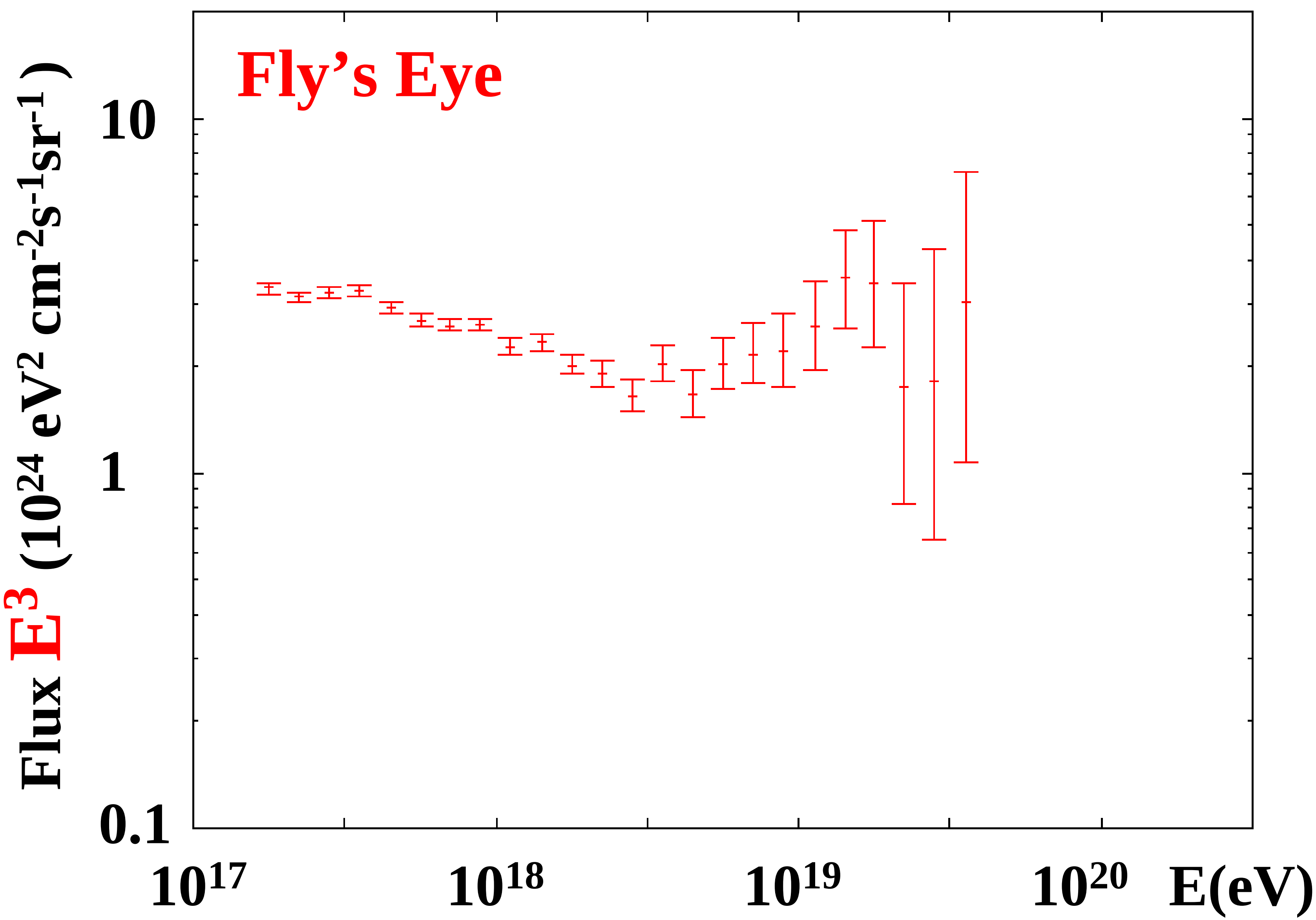


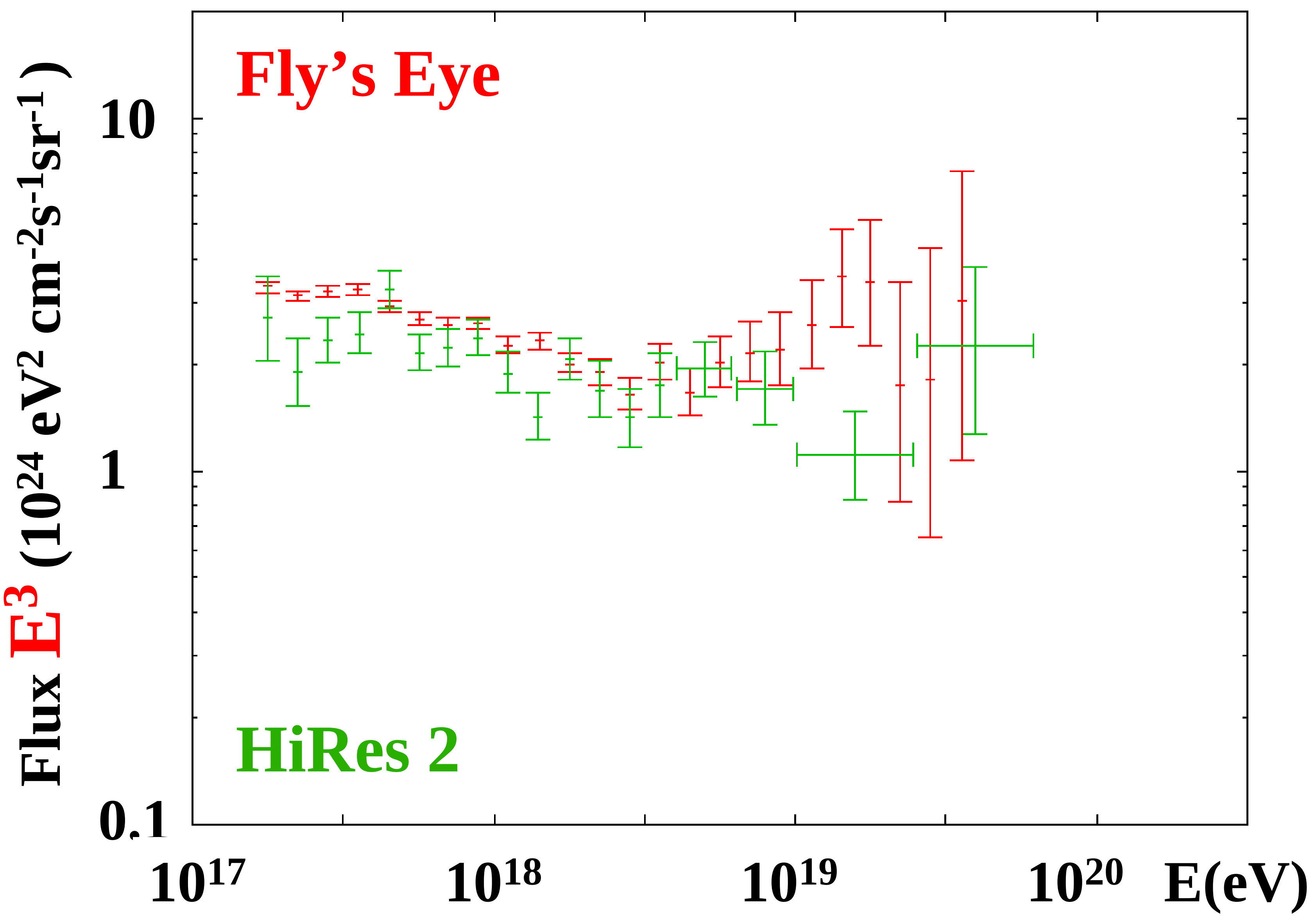




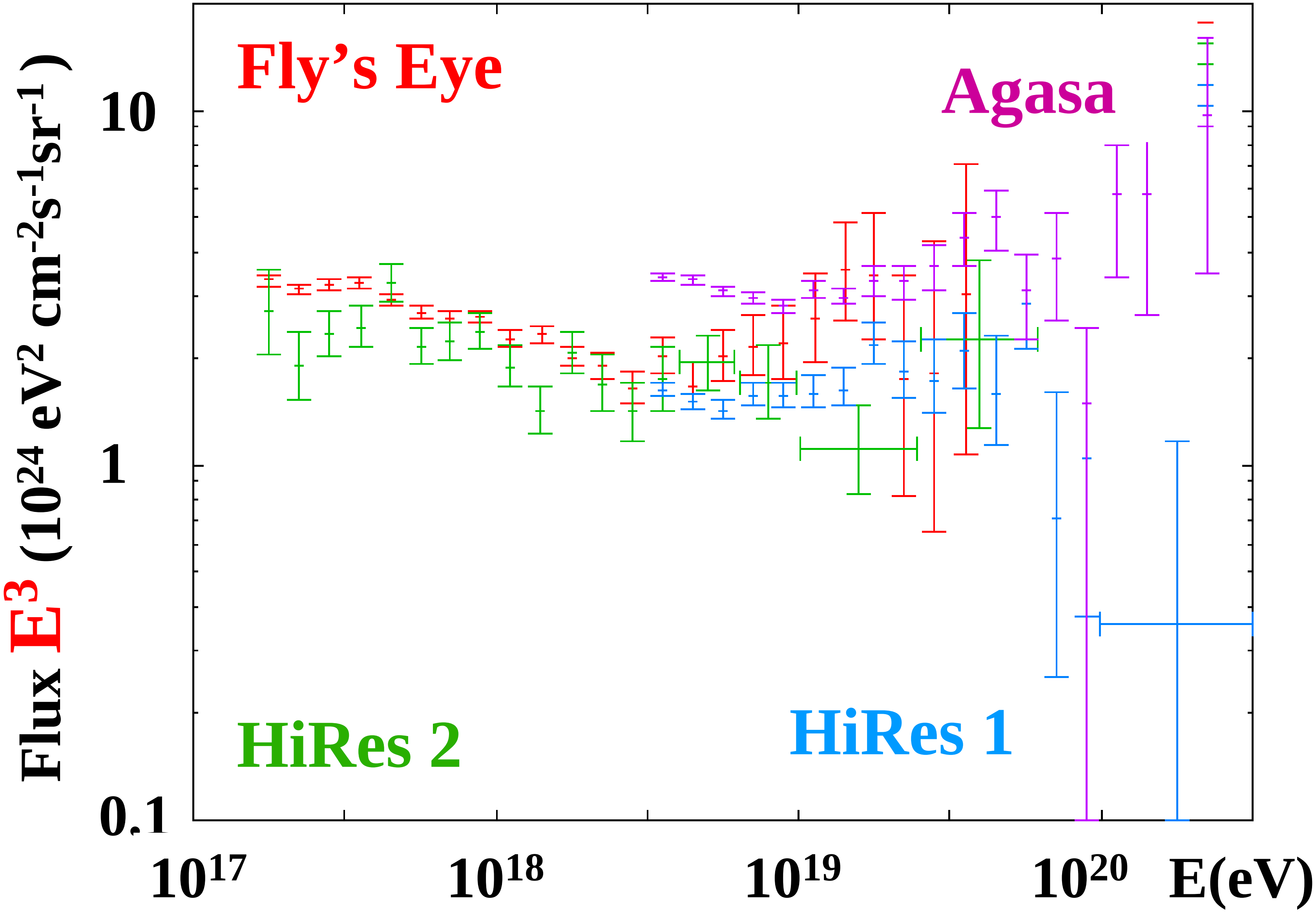
E~ρ(600 m) [ρ(1000 m)]

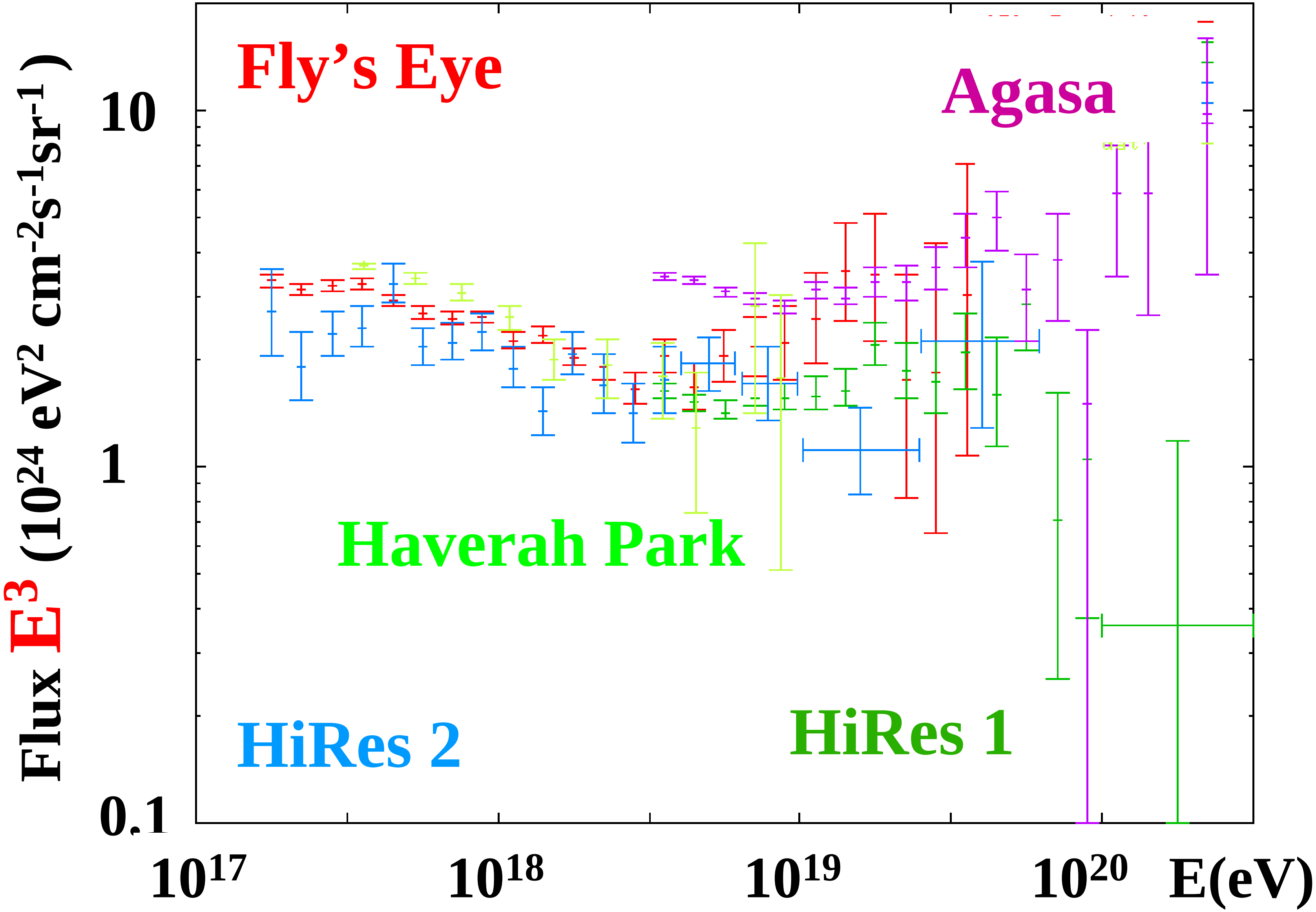
The Ultra High Energy data:





Fly's Eye
HiRes 2
Flux E3 (10^24 eV^2 cm^-2 s^-1 sr^-1)
10
1
0.1
10^17
10^18
10^19
10^20
E(eV)


Fly's Eye
Agasa
HiRes 2
HiRes 1
Flux E3 (10^24 eV^2 cm^-2 s^-1 sr^-1)
10
1
0.1
10^17
10^18
10^19
10^20
E(eV)



Fly's Eye
Agasa
Haverah Park
HiRes 2
HiRes 1
Flux E3 (10^24 eV^2 cm^-2 s^-1 sr^-1)
10
1
0.1
10^17
10^18
10^19
10^20
E(eV)

Disagreement between data

(Exagerated by E^3 presentation)

- Fluorescence data
  - Suggests GZK cutoff
  - No clustering evidence
- Array data
  - No GZK cutoff seen
  - Marginal clustering?

Both techniques:

Depend on Simulation

& Int models

but

–Detect events above 10^{20} eV

–Agree at UHE at the 2-σ level

Two methods at competiton?

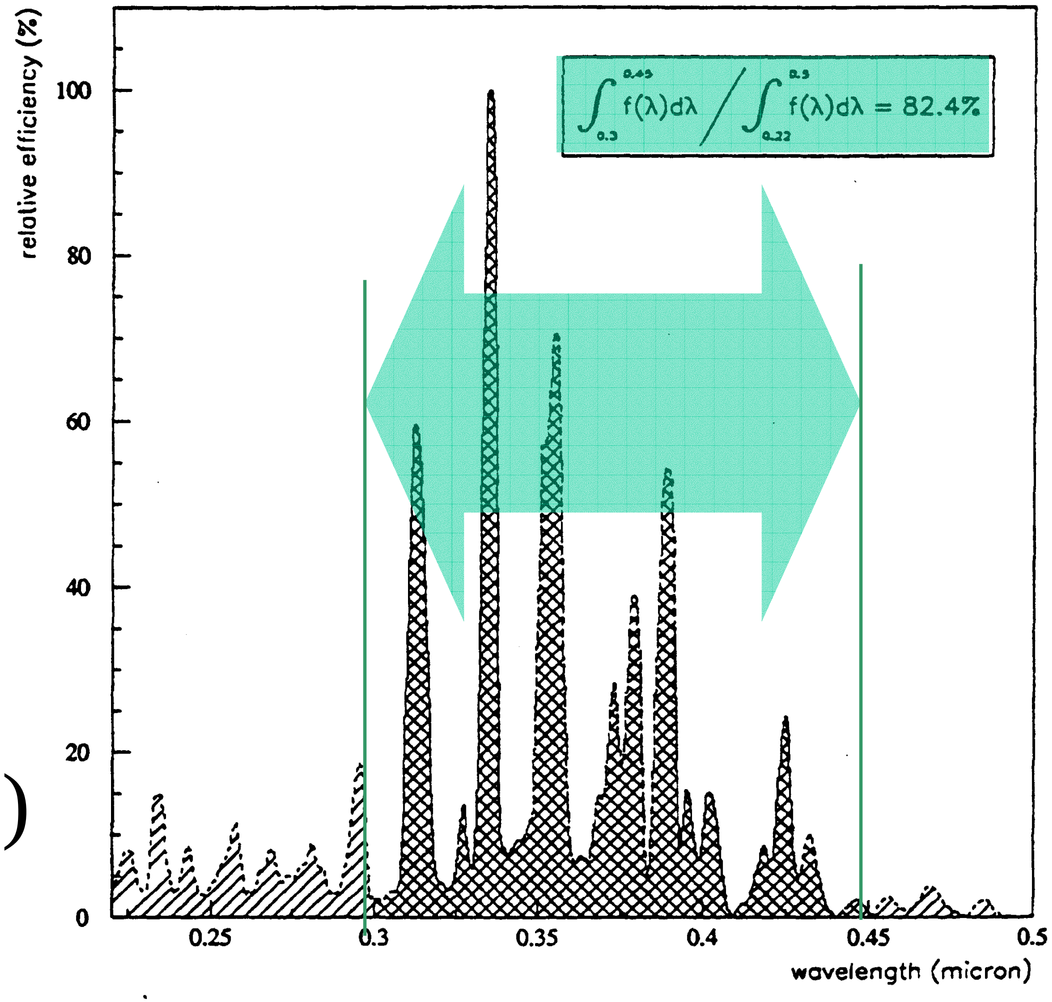
- Flourescence
  - Calorimetric E
  - Acceptance(E)
  - Corrections(t)
    - Absorption
    - Cherenkov
  - Fluor yield(T,p)
- EAS arrays
  - 1 layer calorim
  - Geometric Acc
  - Corrections
    - Fluctuations
    - Sampling

The fluorescence technique is less established

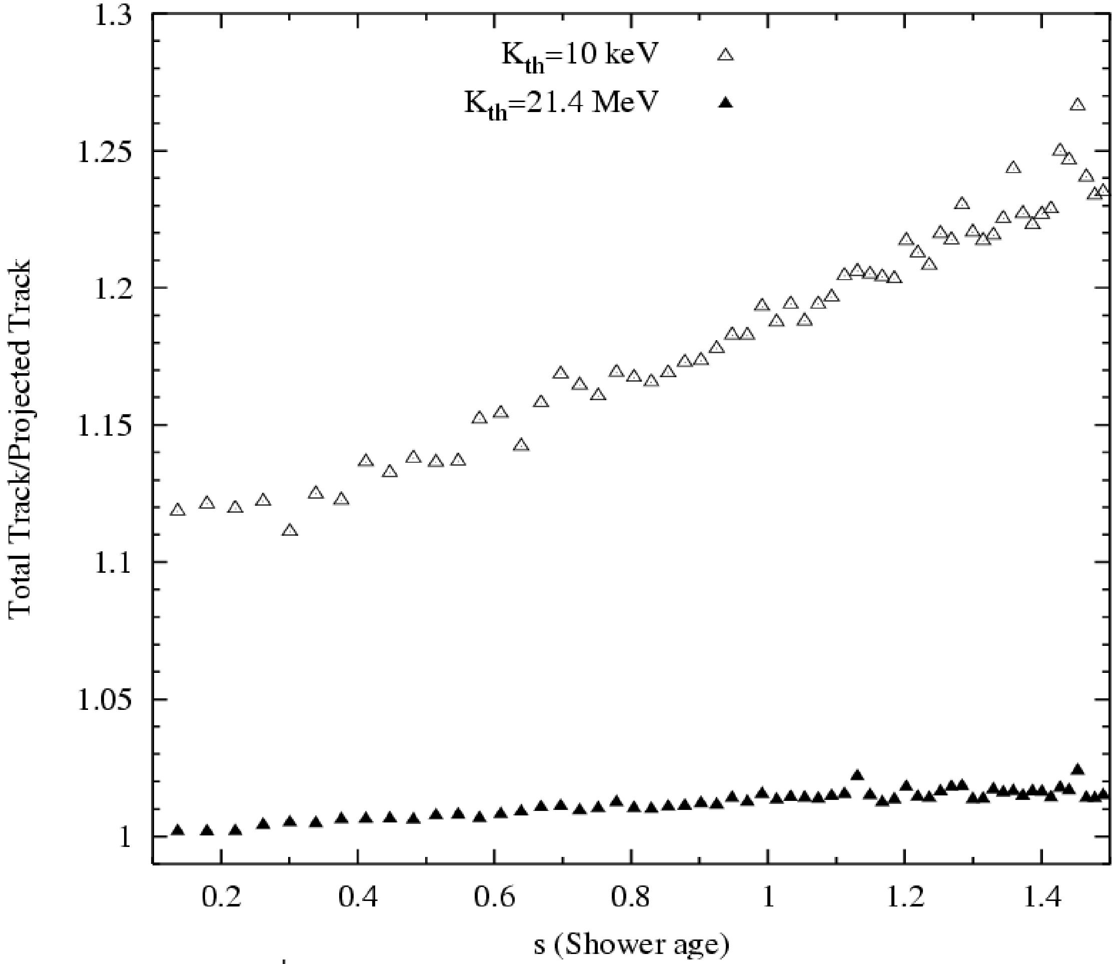
Fluorescence Yield:

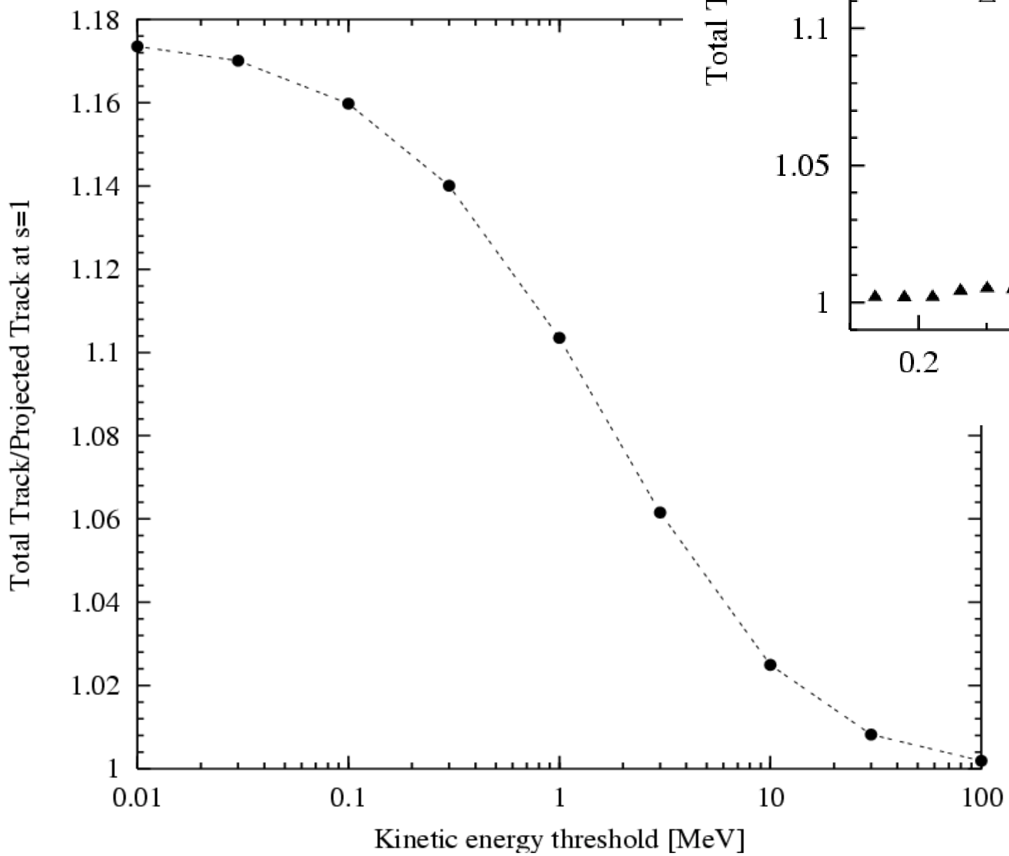
Bunner (1964)

Kakimoto (1992)



Corrections due to lateral spread

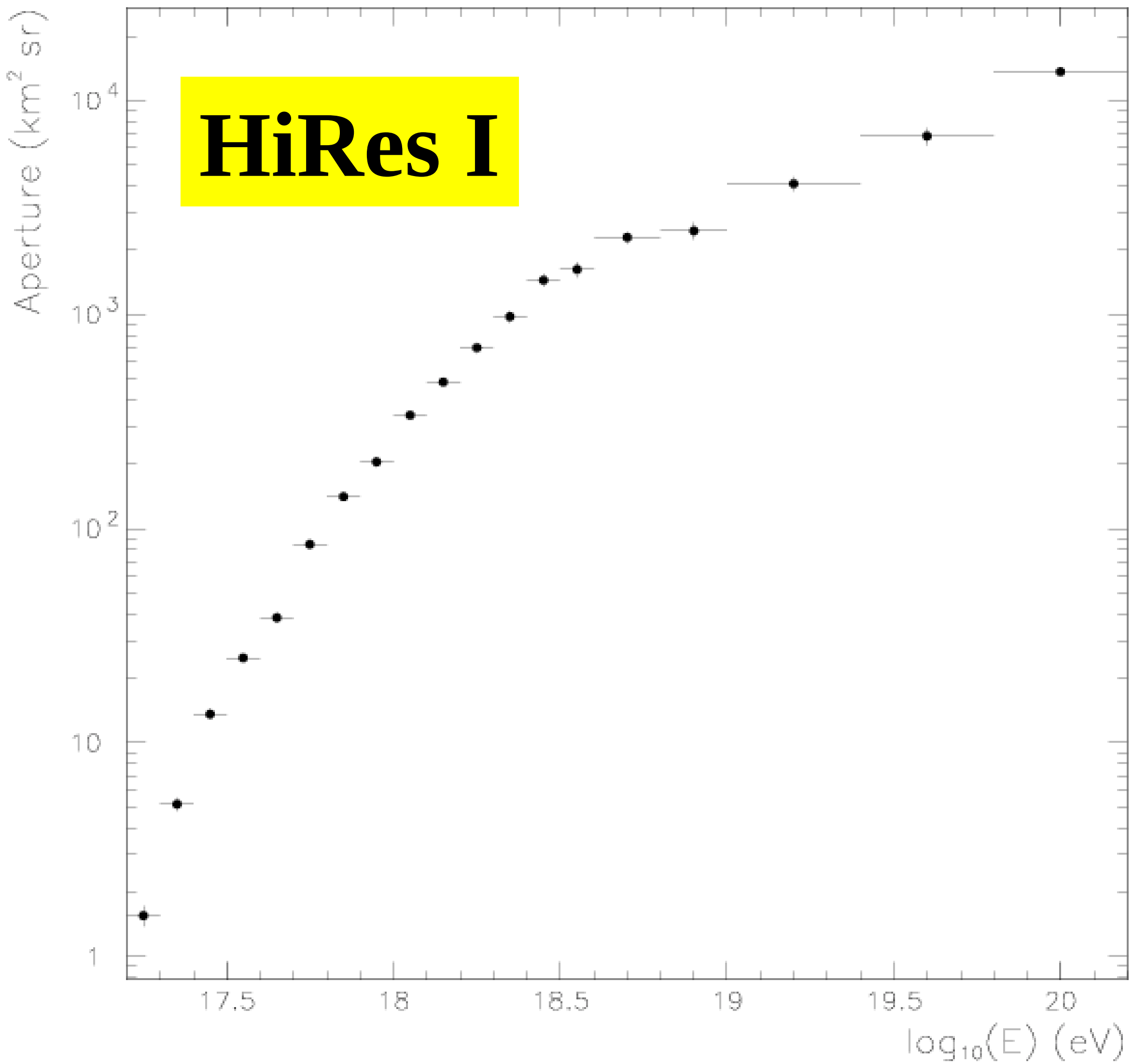




Alvarez Muñiz, Marques, Vazquez &E.Z.
PRD (2004)

Fluorescence exposure grows with Energy

Uncertainty also grows with Energy



Understanding the disagreement

- Statistical fluctuations (2-σ level discrepancies)
  - Shower to shower
  - Sampling
- Calibration problems
  - Attenuation (Mie scattering-aerosol)
  - Fluorescence yield
- Unknown systematics
  - Fluorescence exposure uncertainty grows with energy
  - A 25% systematic in the energy solves the problem
  - Systematics in the simulations
- Flux differences between exposure regions
  - TStanev astro-ph/0303123

Need more statistics and better accuracy

The experimental challenge:

- **Very large Acceptance**
- **Improved resolution**
- **Control systematic uncertainties**

The present solution:

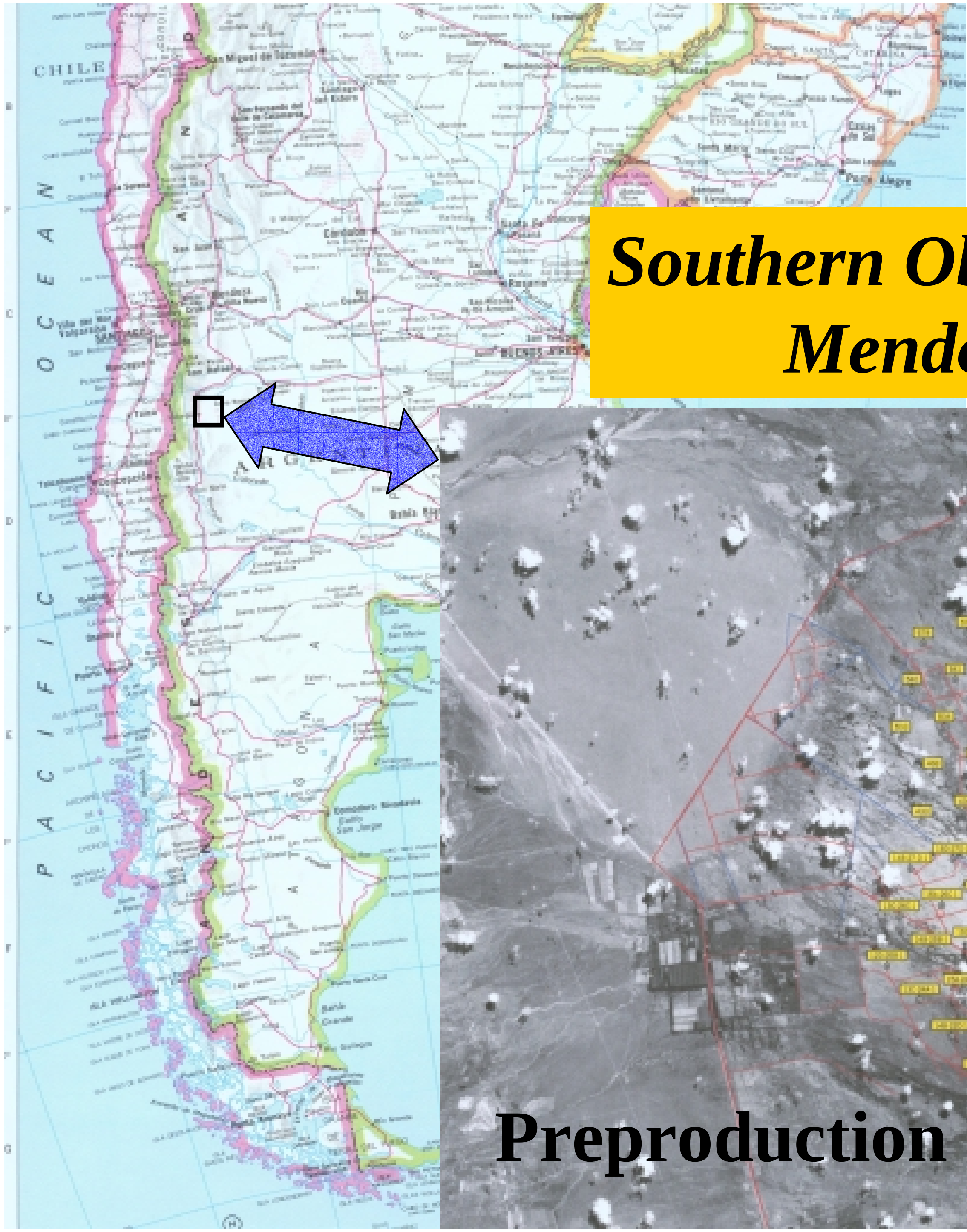
The Auger Observatories

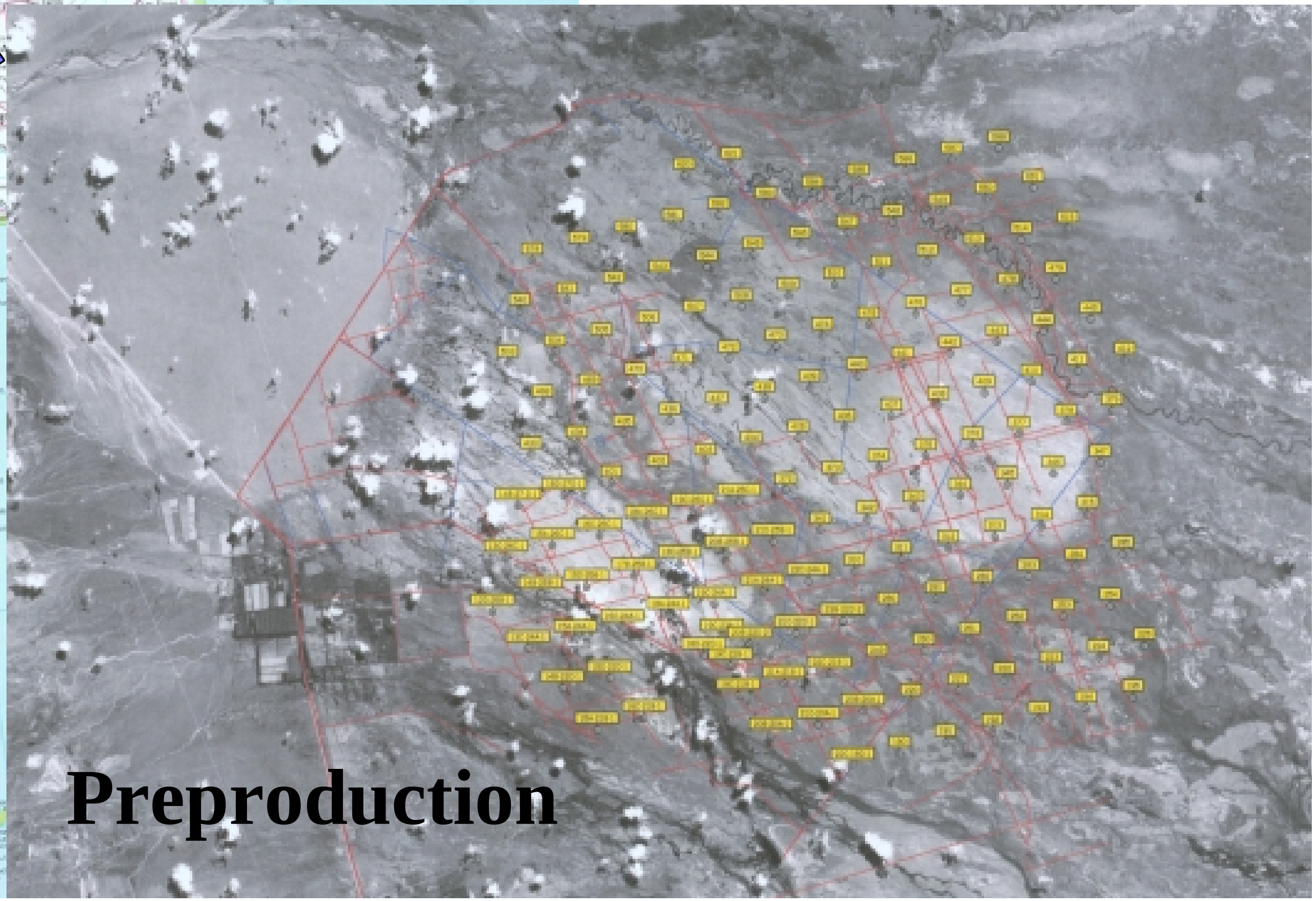
In each Hemisphere

- 3000 km^2 EAS array
- 4 Fluorescence eyes
- Hybrid detector

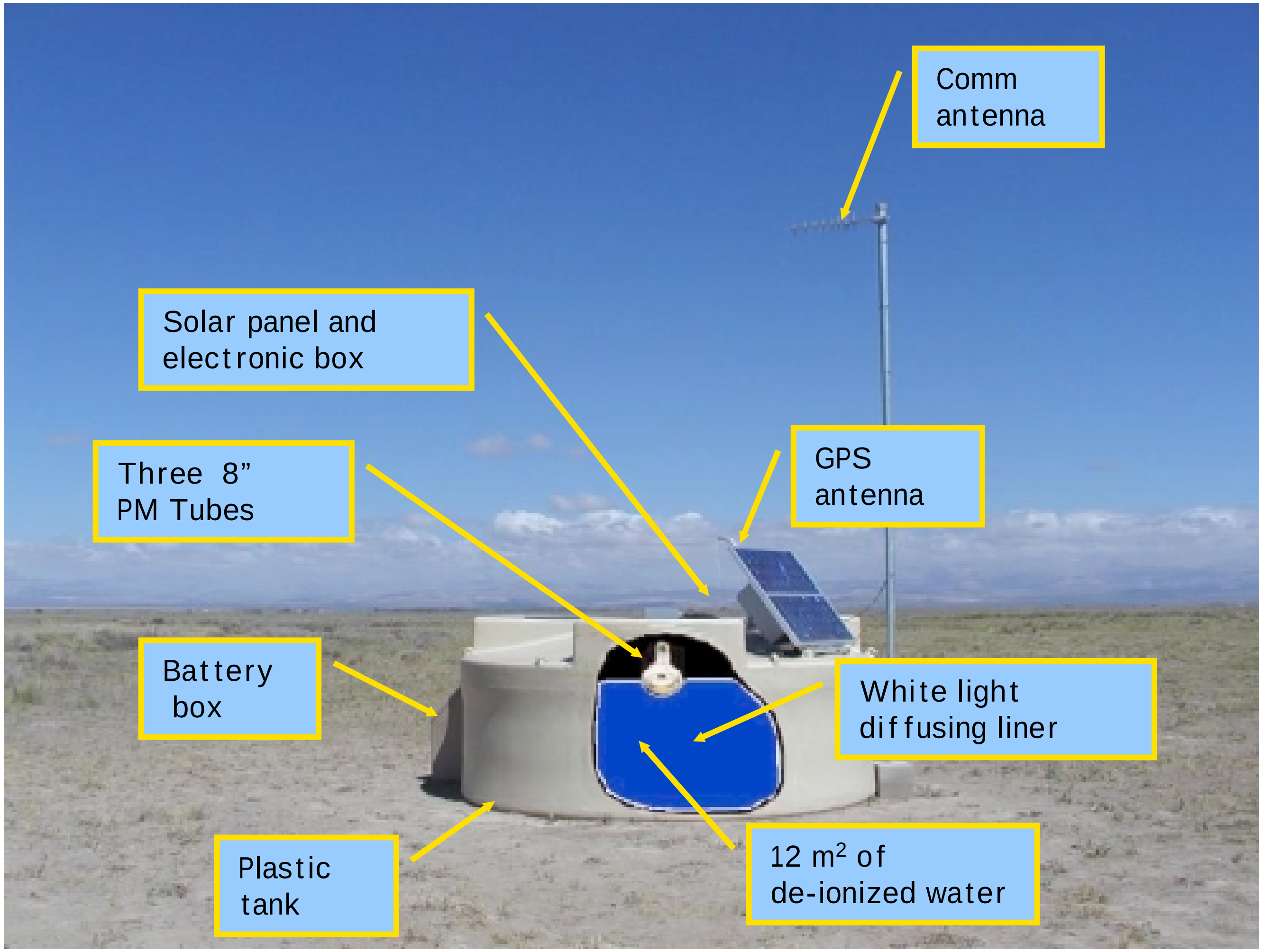
AUGER

Southern Observatory: Malargüe Mendoza (Argentina)

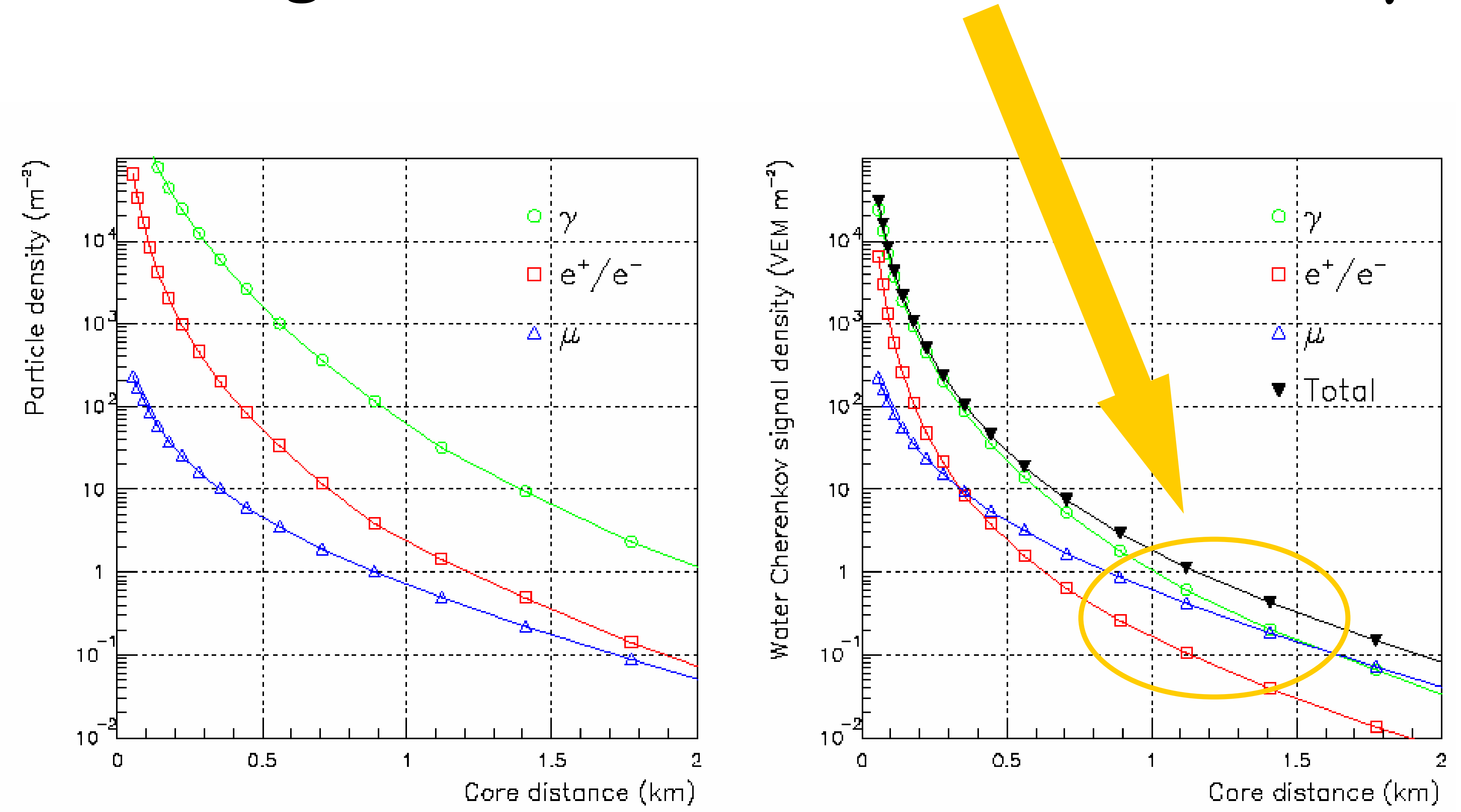


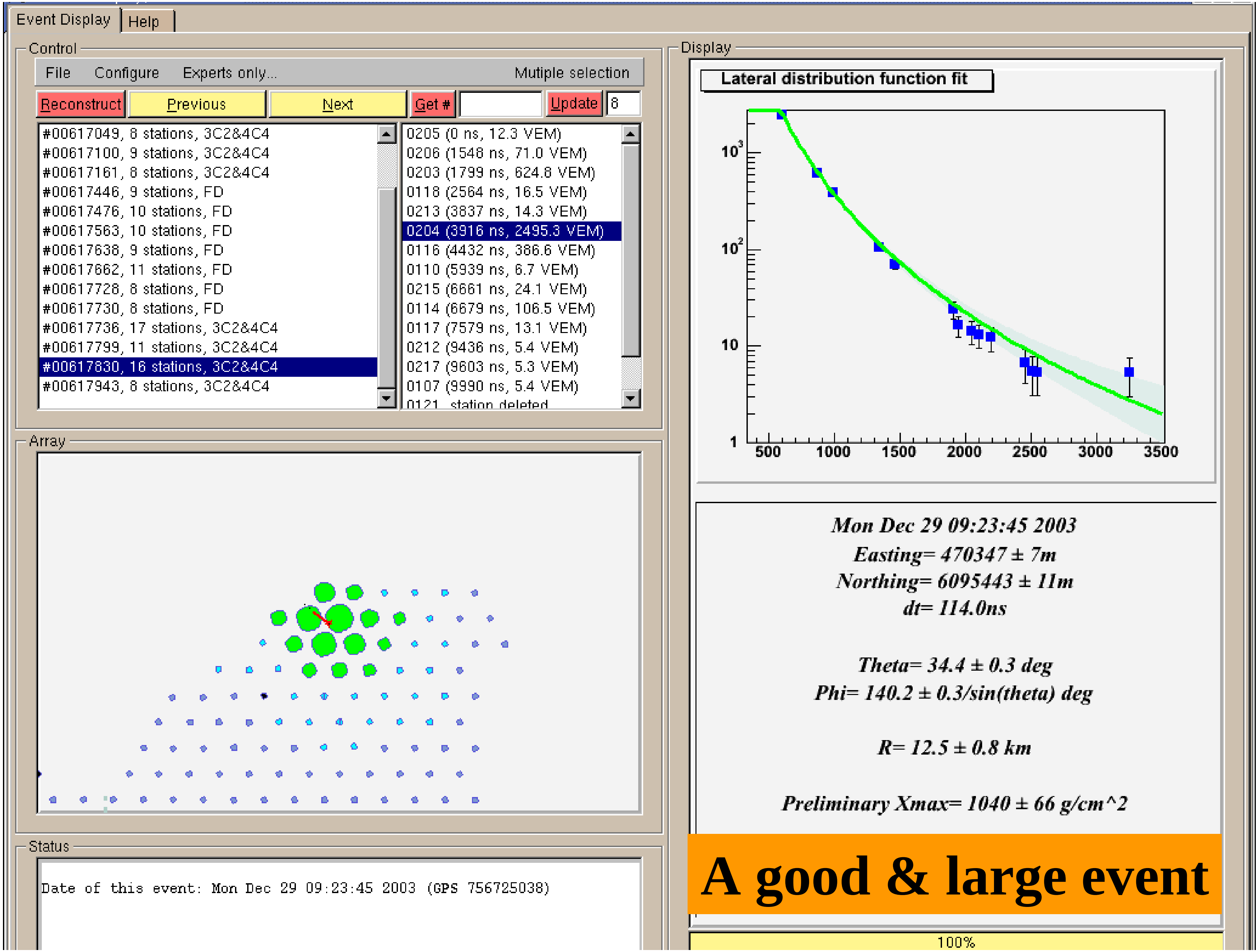


Auger Surface Detectors



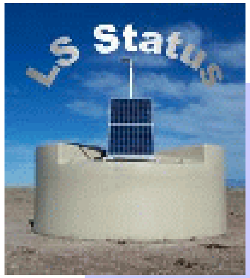
Tank signal due to muons similar to e and γ





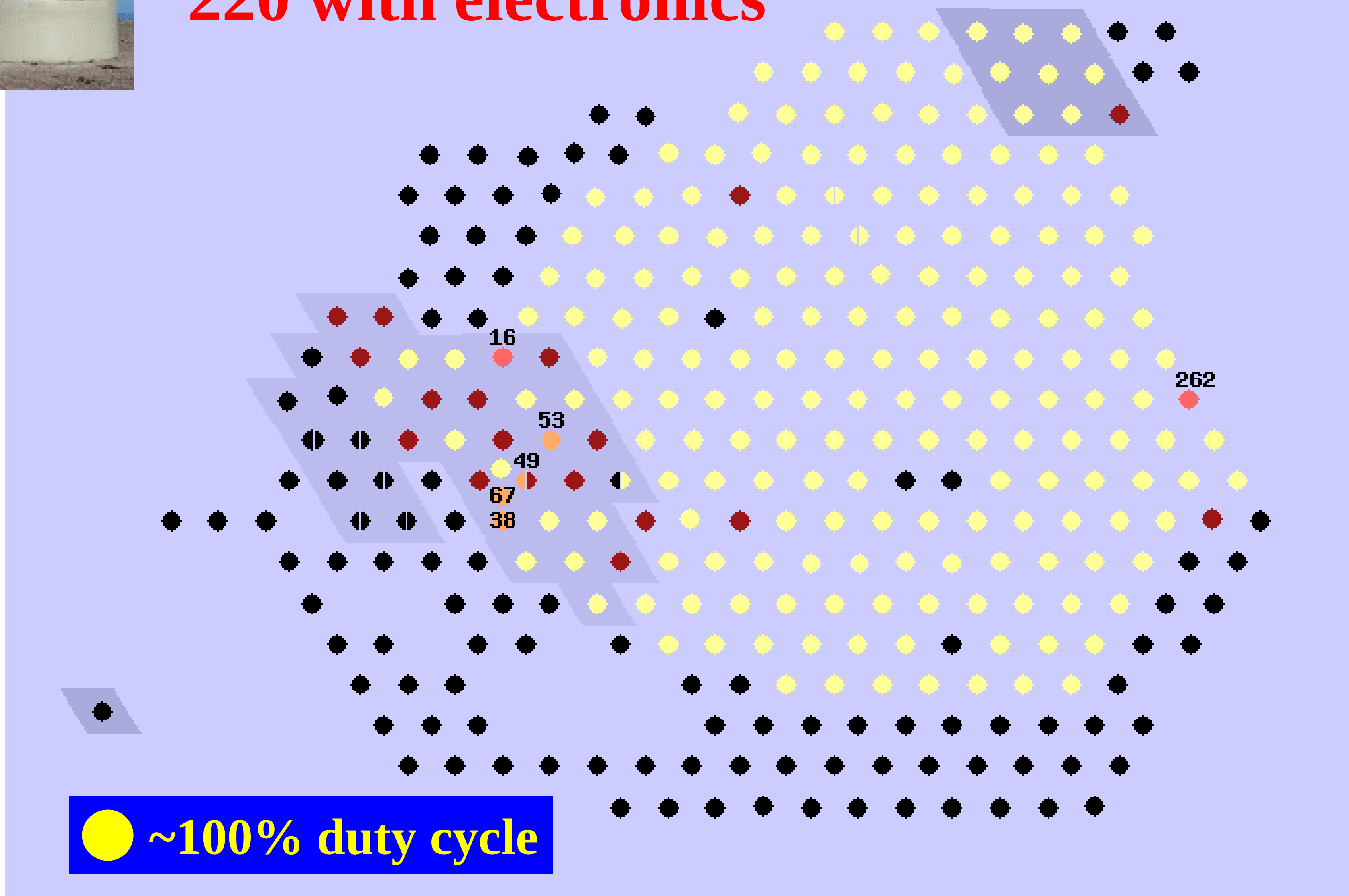
A good & large event

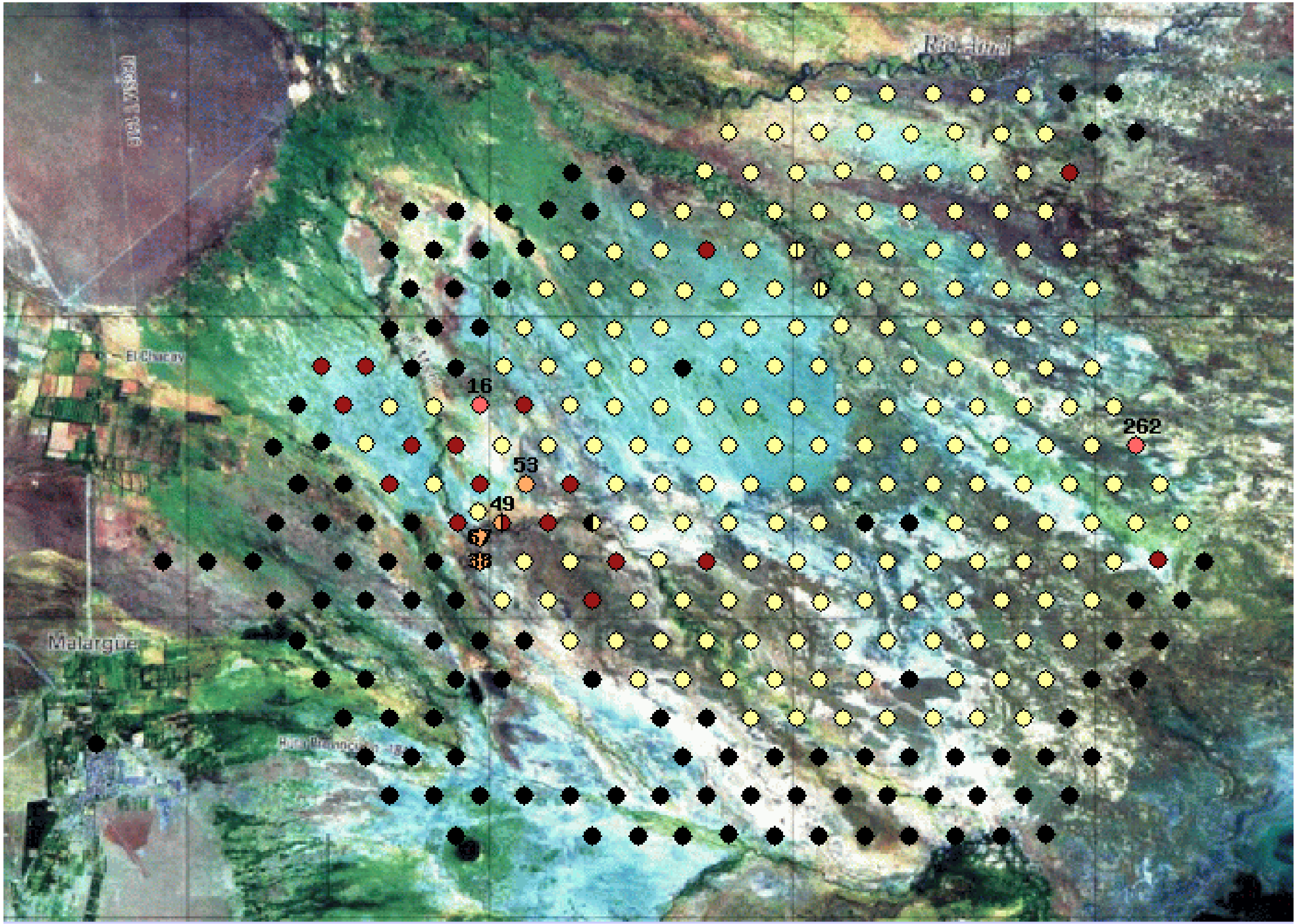
Array status 25th of February 2004



337 tanks deployed **End 2005**

220 with electronics



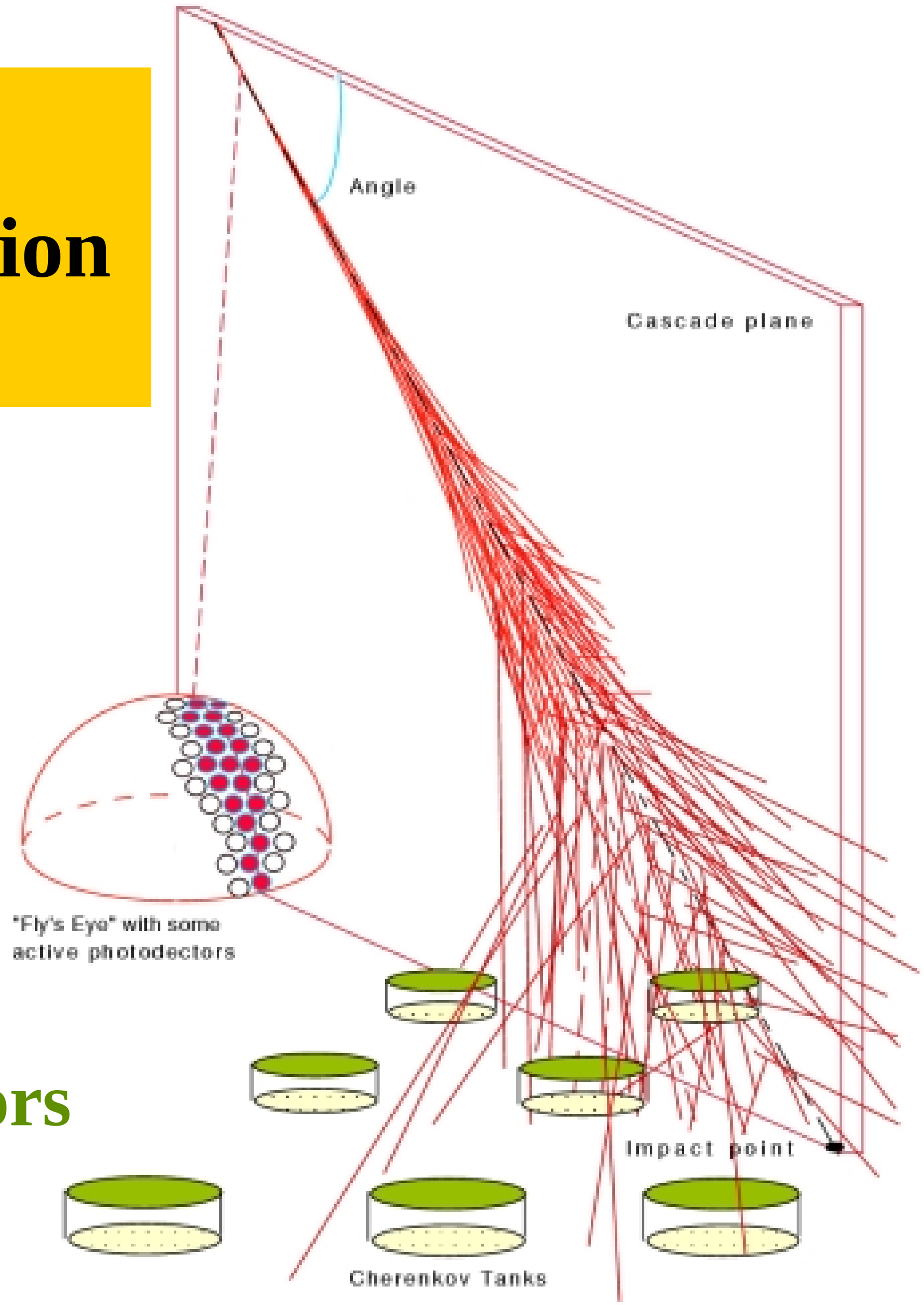


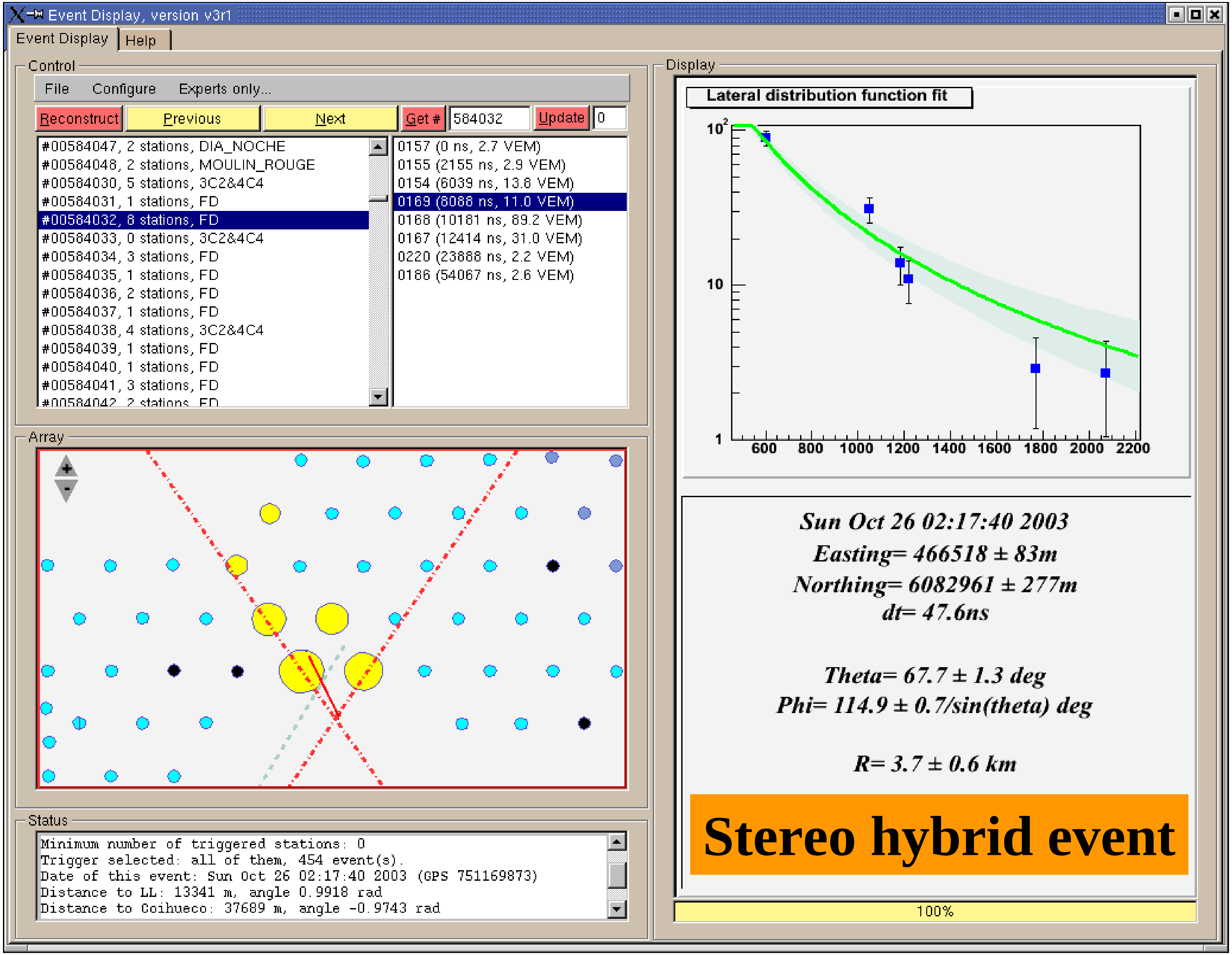
Malargüe
El Chacay
16
53
49
262

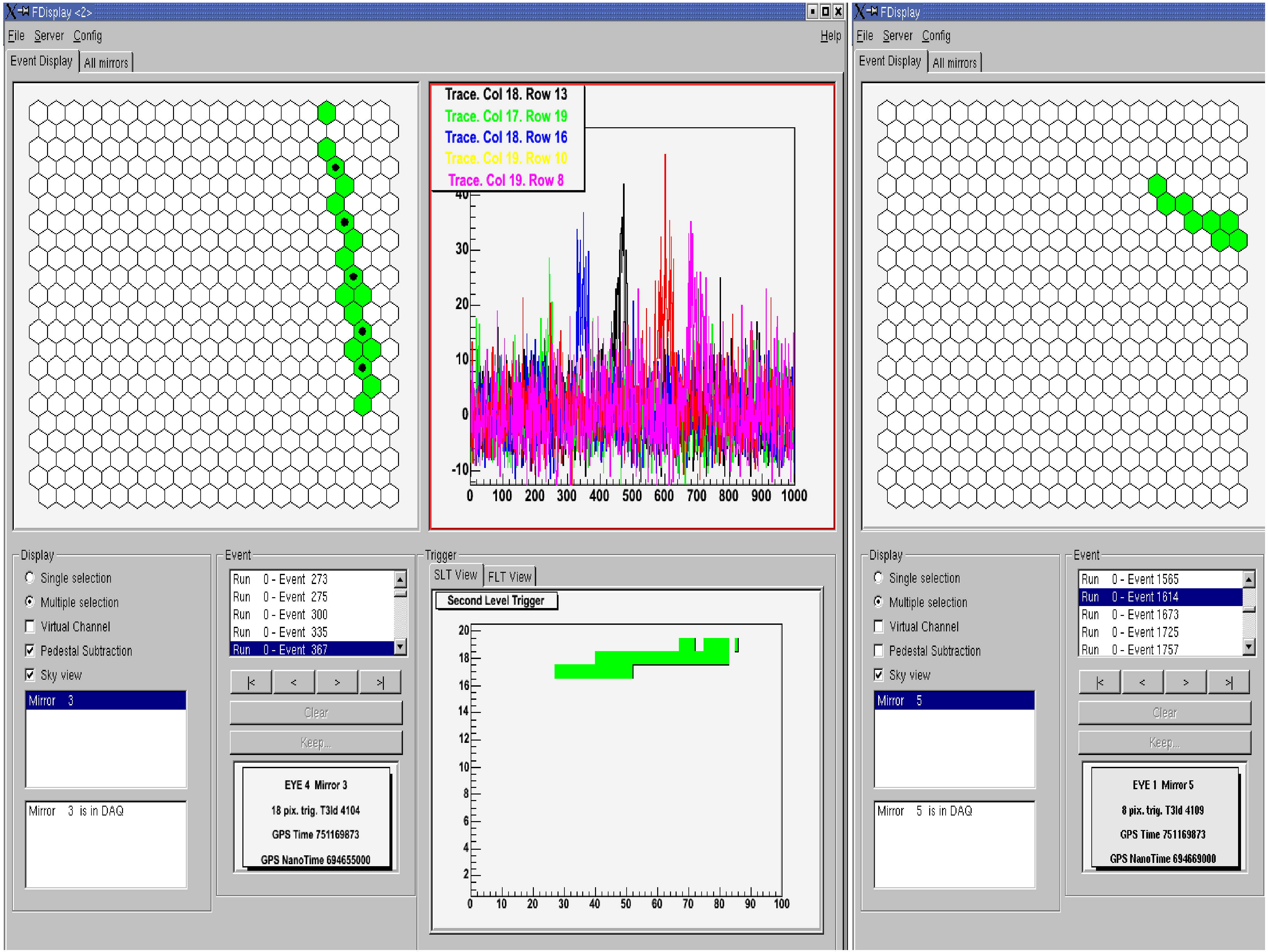
Hybrid:
Improve θ φ reconstruction using impact point

Fluorescence Telescopes

Arrays of particle detectors




Event Display, version v3r1
Event Display
Help
Control
File
Configure
Experts only...
Reconstruct
Previous
Next
Get #
584032
Update
0
#00584047, 2 stations, DIA_NOCHE
#00584048, 2 stations, MOULIN_ROUGE
#00584030, 5 stations, 3C2&4C4
#00584031, 1 stations, FD
#00584032, 8 stations, FD
#00584033, 0 stations, 3C2&4C4
#00584034, 3 stations, FD
#00584035, 1 stations, FD
#00584036, 2 stations, FD
#00584037, 1 stations, FD
#00584038, 4 stations, 3C2&4C4
#00584039, 1 stations, FD
#00584040, 1 stations, FD
#00584041, 3 stations, FD
0157 (0 ns, 2.7 VEM)
0155 (2155 ns, 2.9 VEM)
0154 (6039 ns, 13.8 VEM)
0169 (8088 ns, 11.0 VEM)
0168 (10181 ns, 89.2 VEM)
0167 (12414 ns, 31.0 VEM)
0220 (23888 ns, 2.2 VEM)
0186 (54067 ns, 2.6 VEM)
Array
Status
Minimum number of triggered stations: 0
Trigger selected: all of them, 454 event(s).
Date of this event: Sun Oct 26 02:17:40 2003 (GPS 751169873)
Distance to LL: 13341 m, angle 0.9918 rad
Distance to Coihueco: 37689 m, angle -0.9743 rad
Display
Lateral distribution function fit
10^2
10
1
600
800
1000
1200
1400
1600
1800
2000
2200
Sun Oct 26 02:17:40 2003
Easting= 466518 ± 83m
Northing= 6082961 ± 277m
dt= 47.6ns
Theta= 67.7 ± 1.3 deg
Phi= 114.9 ± 0.7/sin(theta) deg
R= 3.7 ± 0.6 km
Stereo hybrid event
100%


FDisplay <2>
File Server Config
Help
Event Display
All mirrors
Trace. Col 18. Row 13
Trace. Col 17. Row 19
Trace. Col 18. Row 16
Trace. Col 19. Row 10
Trace. Col 19. Row 8
Display
Single selection
Multiple selection
Virtual Channel
Pedestal Subtraction
Sky view
Mirror 3
Mirror 3 is in DAQ
Event
Run 0 - Event 273
Run 0 - Event 275
Run 0 - Event 300
Run 0 - Event 335
Run 0 - Event 367
Clear
Keep...
EYE 4 Mirror 3
18 pix. trig. T3Id 4104
GPS Time 751169873
GPS NanoTime 694655000
Trigger
SLT View
FLT View
Second Level Trigger
FDisplay
File Server Config
Event Display
All mirrors
Display
Single selection
Multiple selection
Virtual Channel
Pedestal Subtraction
Sky view
Mirror 5
Mirror 5 is in DAQ
Event
Run 0 - Event 1565
Run 0 - Event 1614
Run 0 - Event 1673
Run 0 - Event 1725
Run 0 - Event 1757
Clear
Keep...
EYE 1 Mirror 5
8 pix. trig. T3Id 4109
GPS Time 751169873
GPS NanoTime 694669000

The future solution:

Satellite observations

Fluorescence: EUSO (KLYPVE)

- **300000 km^2 area**
- **Cosmic Rays and nuetrinos**

Needs fluorescence calibration (Auger)

Radio: moon or planets as targets

- **Cosmic Rays and nuetrinos**

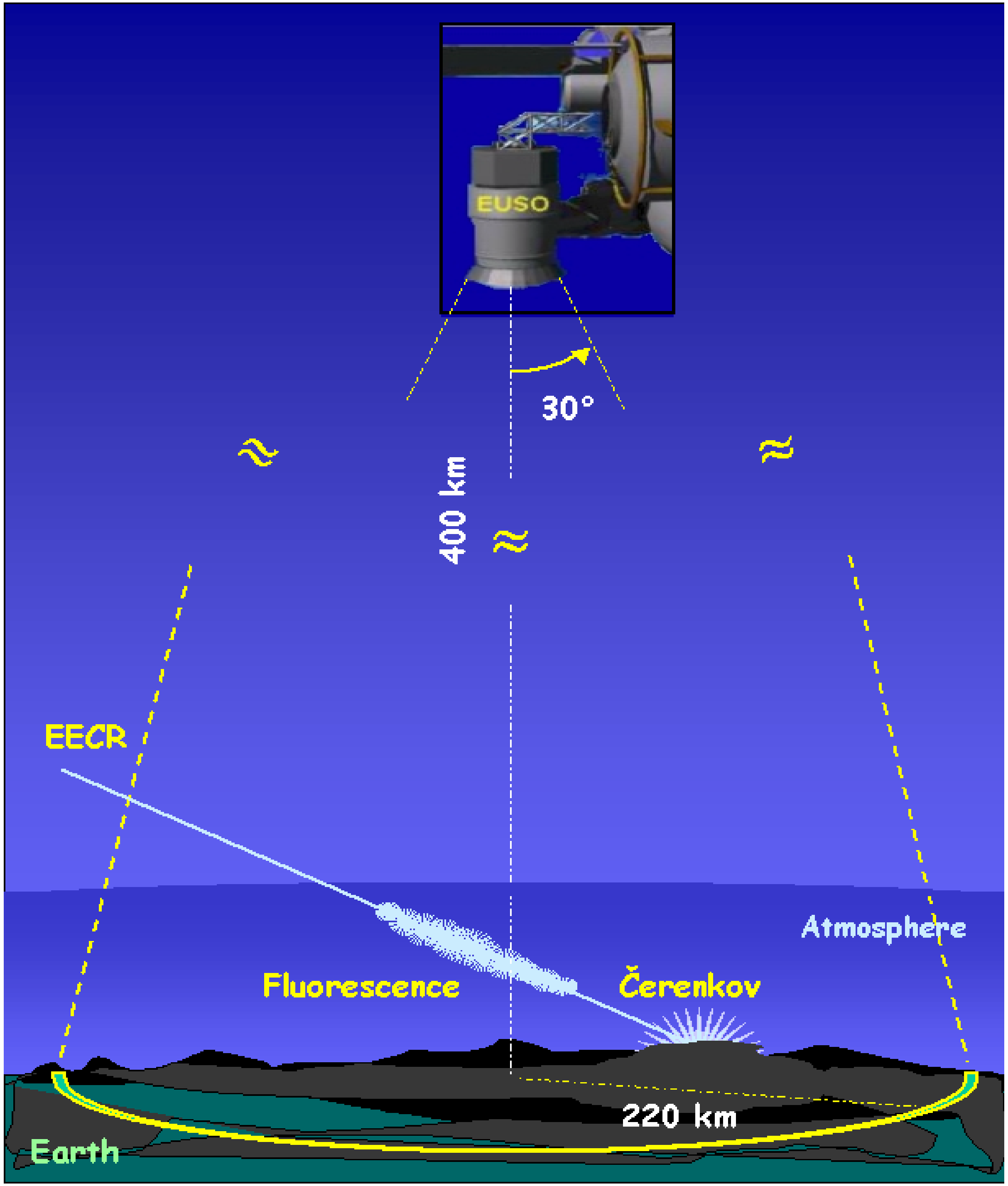
Needs radio calibration (EUSO?)

The EUSO concept

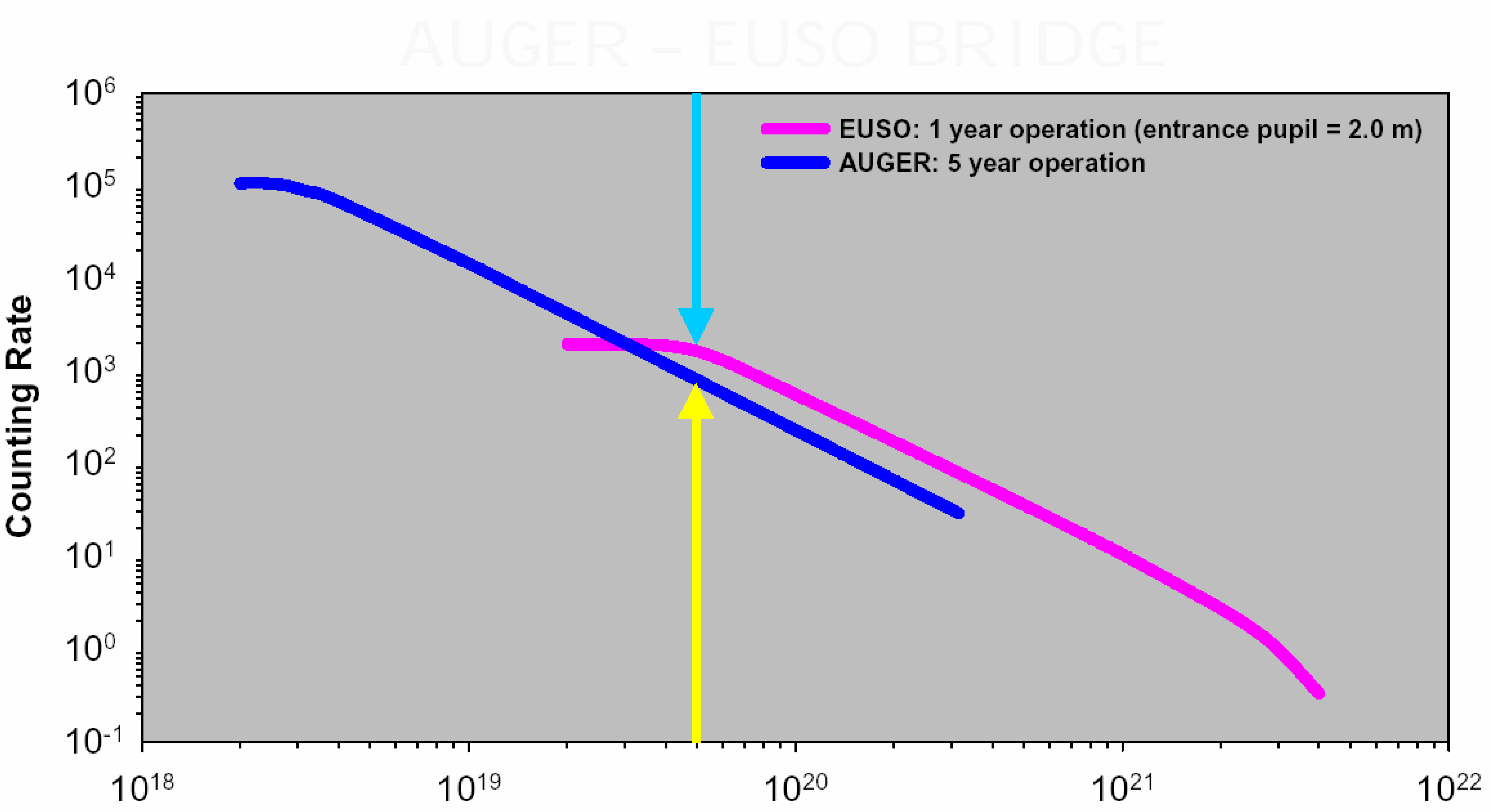
2010-2012

150000 km^2
10% duty cycle

From M.Pimenta



Calibration with Auger



From M.Pimenta