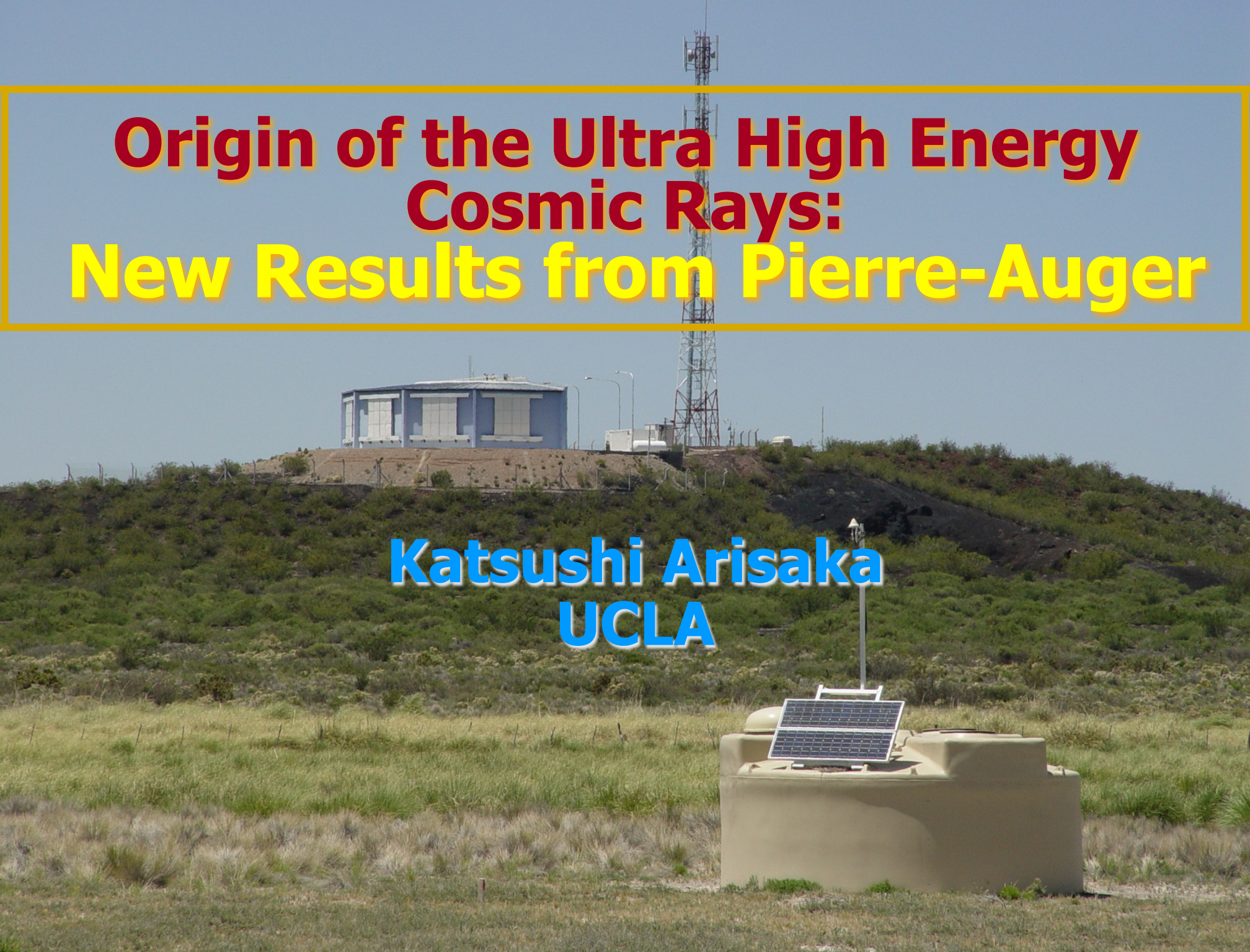


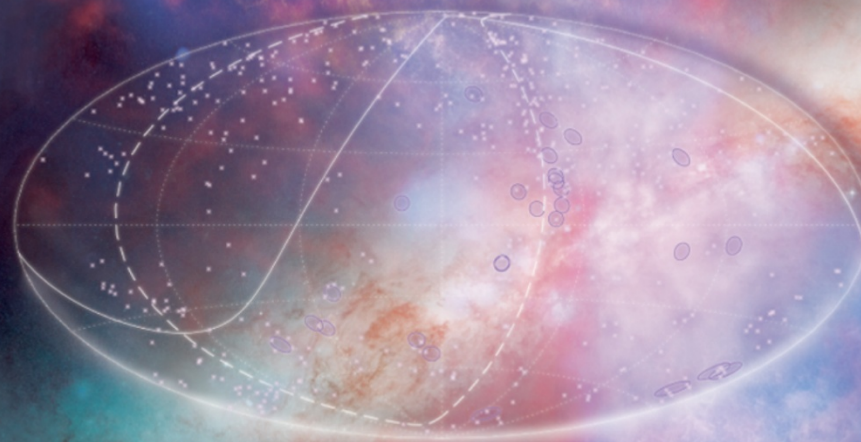
Origin of the Ultra High Energy Cosmic Rays: New Results from Pierre-Auger

Katsushi Arisaka
UCLA



Science

9 November 2007 | \$10



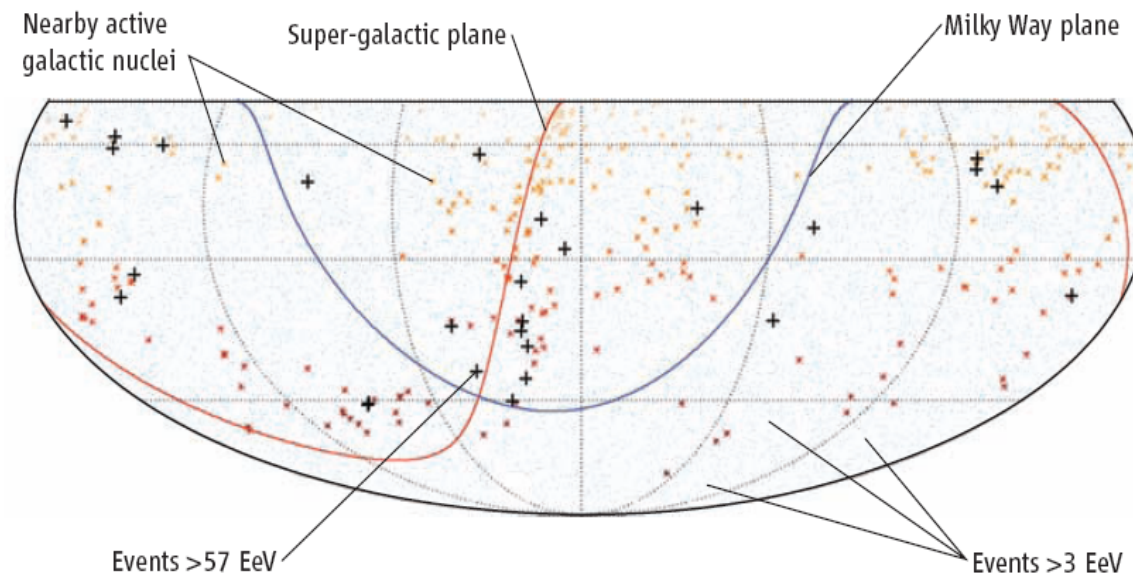
 AAAS

Correlation of the Highest-Energy Cosmic Rays with Nearby Extragalactic Objects

The Pierre Auger Collaboration*

AUTHORS' SUMMARY

Cosmic rays are particles and nuclei that bombard the Earth from space in all directions (1). A few have astounding energies—beyond 100 EeV (1 EeV = 1 exa-electron volt = 10^{18} eV)—orders of magnitude beyond even the future capabilities of any earthly particle accelerator. Such energies are so extreme that they could arise in only the most violent places in the universe. One possible location is within active galactic nuclei (AGN), galaxies hosting central black holes that feed



Sky map (2) showing cosmic rays detected by the Pierre Auger Observatory. Low-energy cosmic rays appear to originate from evenly distributed sources (blue dots), but the origins of the highest-energy events (crosses) correlate with the distribution of local matter as represented by nearby active galactic nuclei (red stars). Thus, active galactic nuclei are a likely source of these rare high-energy cosmic rays.

tens of EeV, the deflection is, however, small enough that the prospect of identifying possible sources becomes a reality.

Since 2004, the Auger Observatory has collected a million cosmic-ray events, and about 80 had energies exceeding 40 EeV, the energy at which we expect to begin to see the flux suppression of the GZK effect. First, we examined the data gathered before June 2006. We explored the amount of correlation between the arrival directions and the

Talk Outline

➤ Scientific Motivation

- *Top-down vs. Bottom-up*
- *Why is 10^{20} eV so special?*

➤ Pierre Auger Observatory

- *Previous Experiment – AGASA, HiRes*
- *Pierre Auger Detector*

➤ New Results

- *Energy Spectrum*
- *Any Top-down signal?*
- *Angular Distribution*

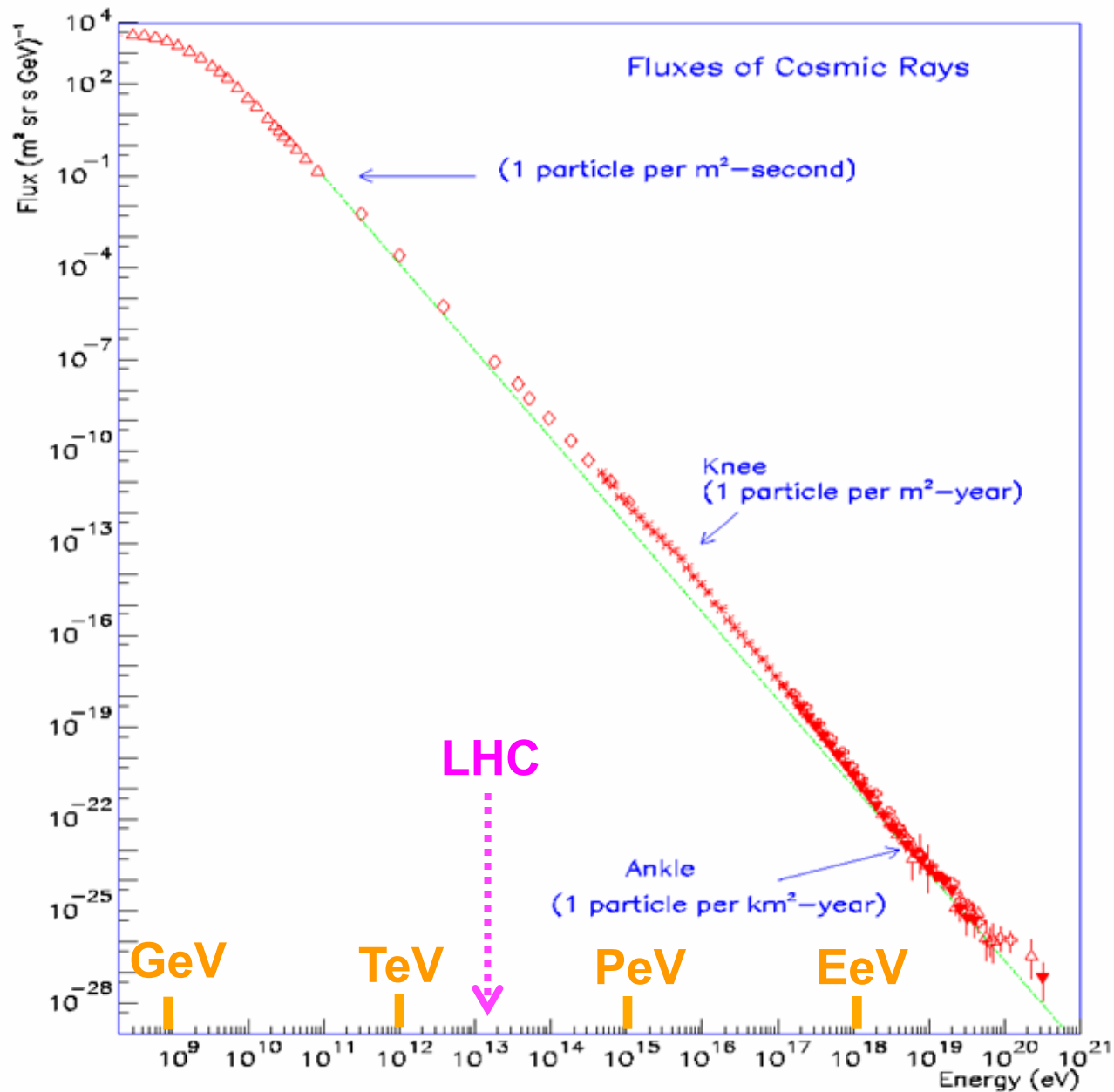
➤ Future Prospects

- *Are they irons?*
- *Auger-North*

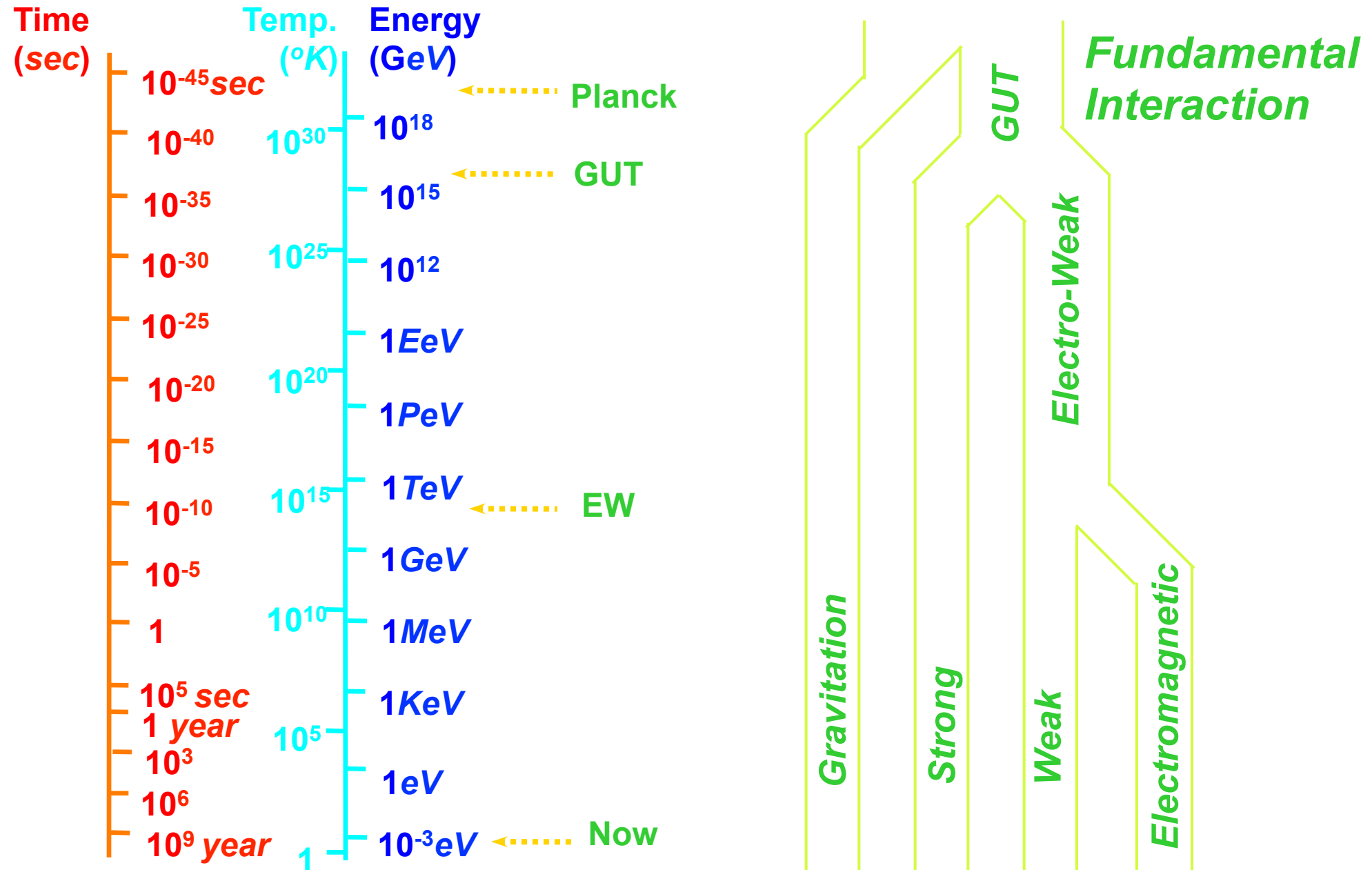
Scientific Motivation

Energy Spectrum of Cosmic Rays

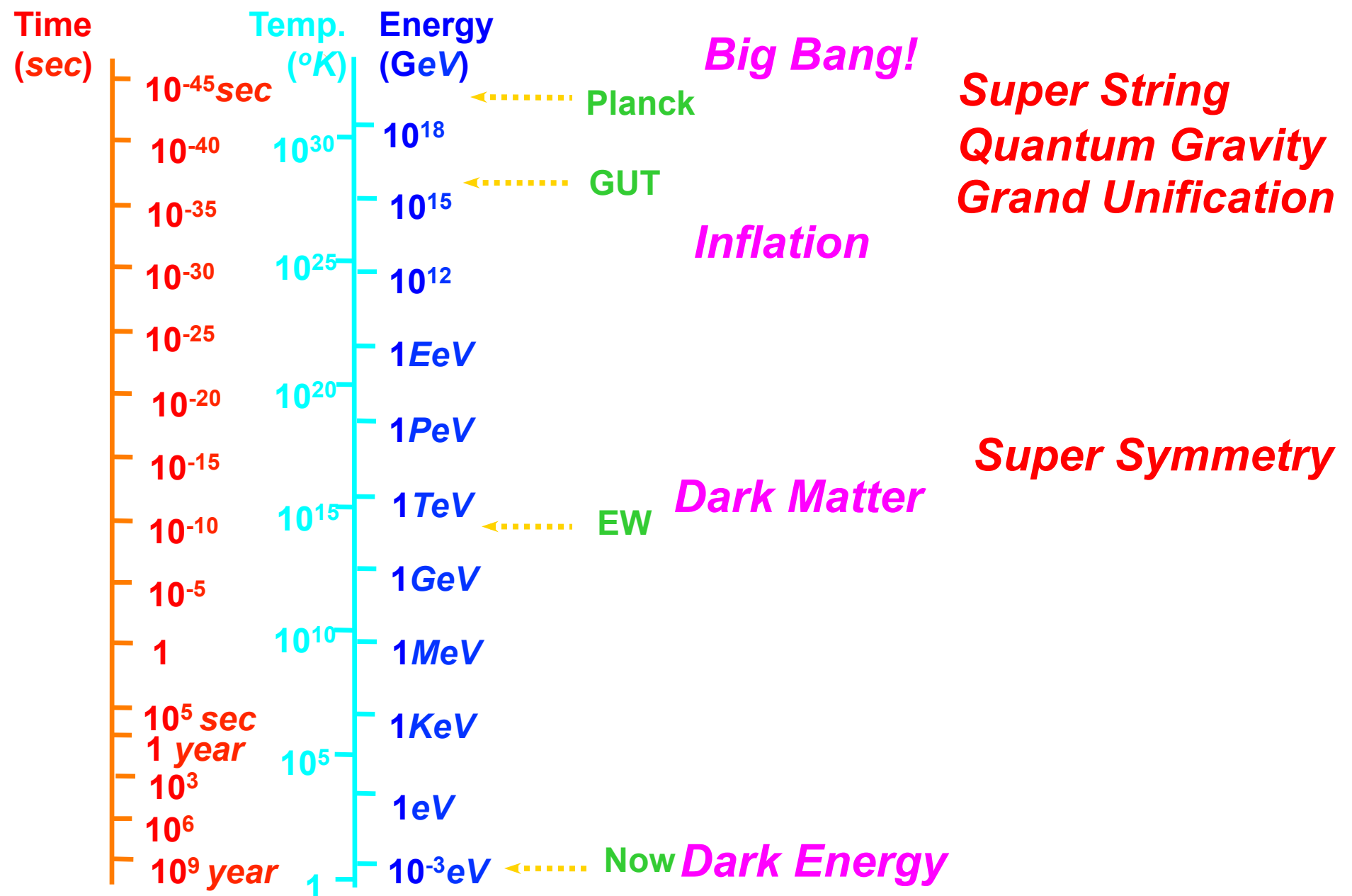
- Energy Spectrum
 $\sim E^{-3}$
- The spectrum extends beyond 10^{20} eV (=100 EeV).
- Beyond 10^{20} eV, Flux is only one particle per km^2 -century.



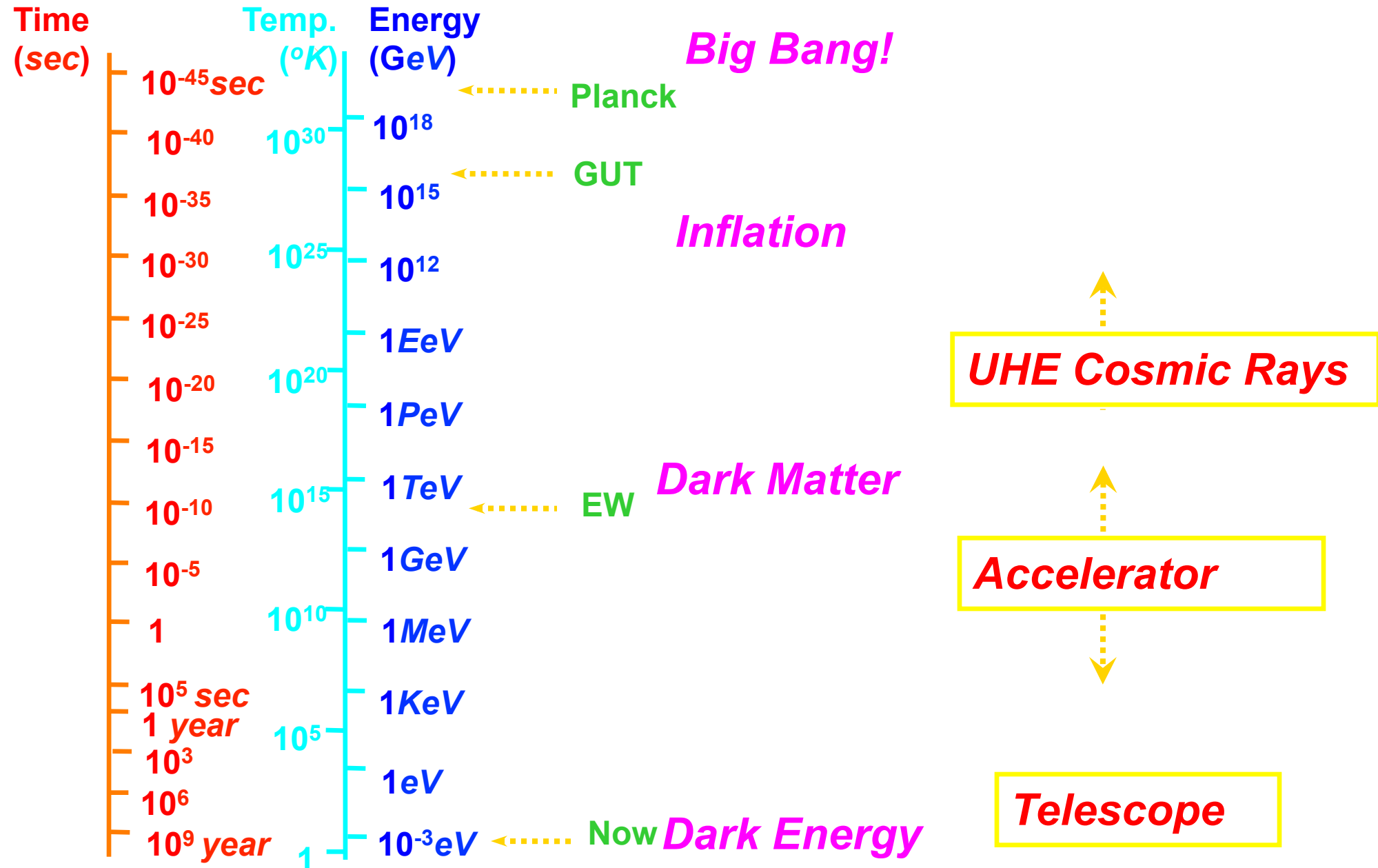
Particle Physics in Early Universe



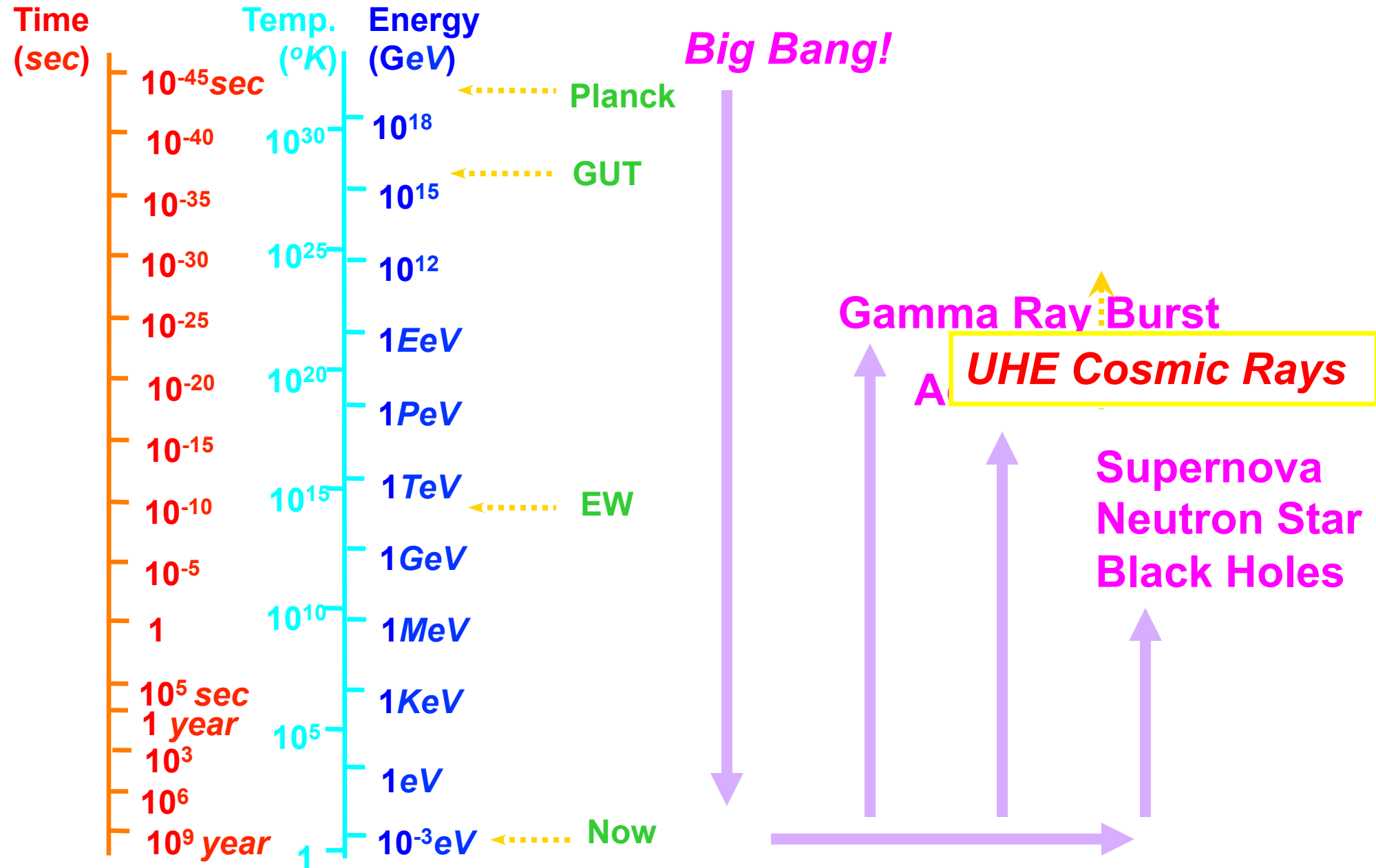
Particle Physics in Early Universe



Particle Physics in Early Universe



Top-down or Bottom-up?

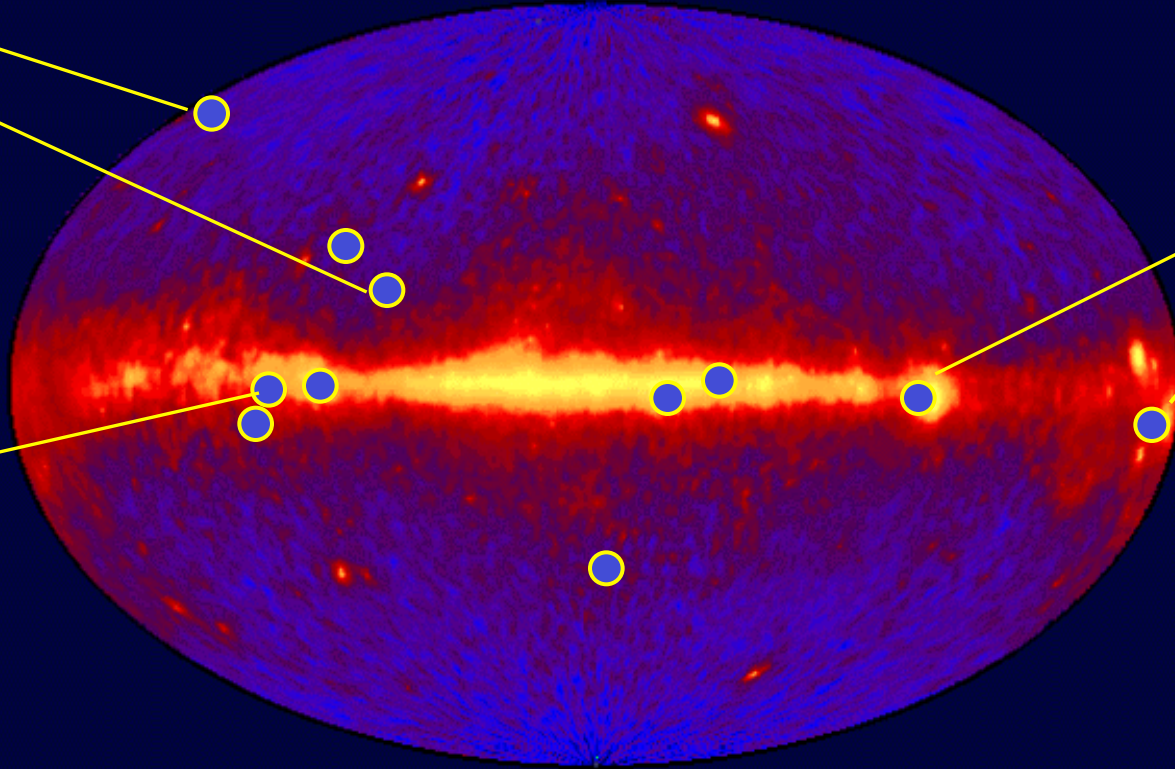


The Extreme Universe

AGN



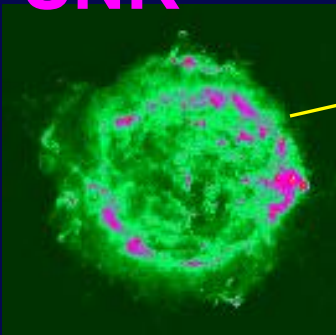
EGRET All-Sky Map Above 100 MeV



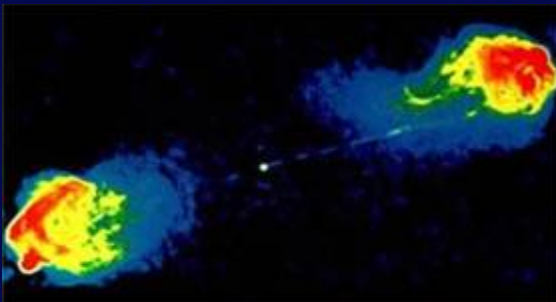
Pulsar



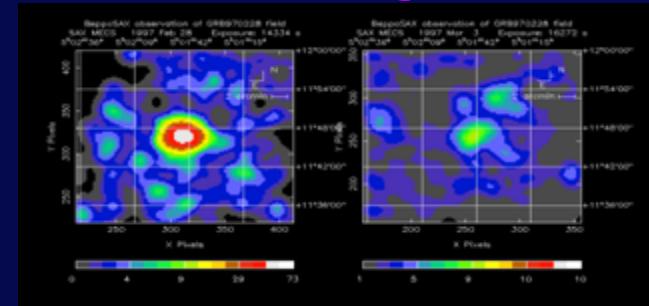
SNR



Radio Galaxy



GRB



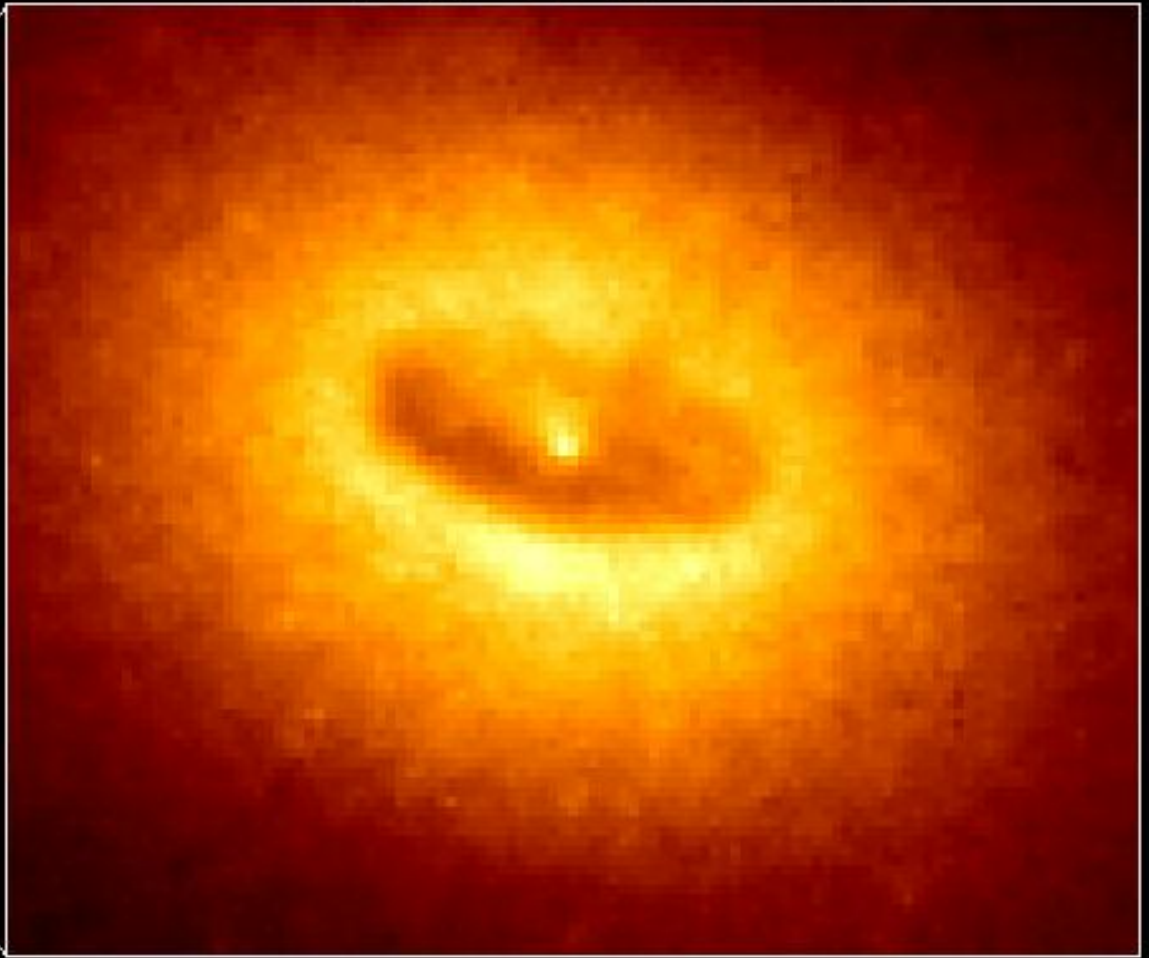
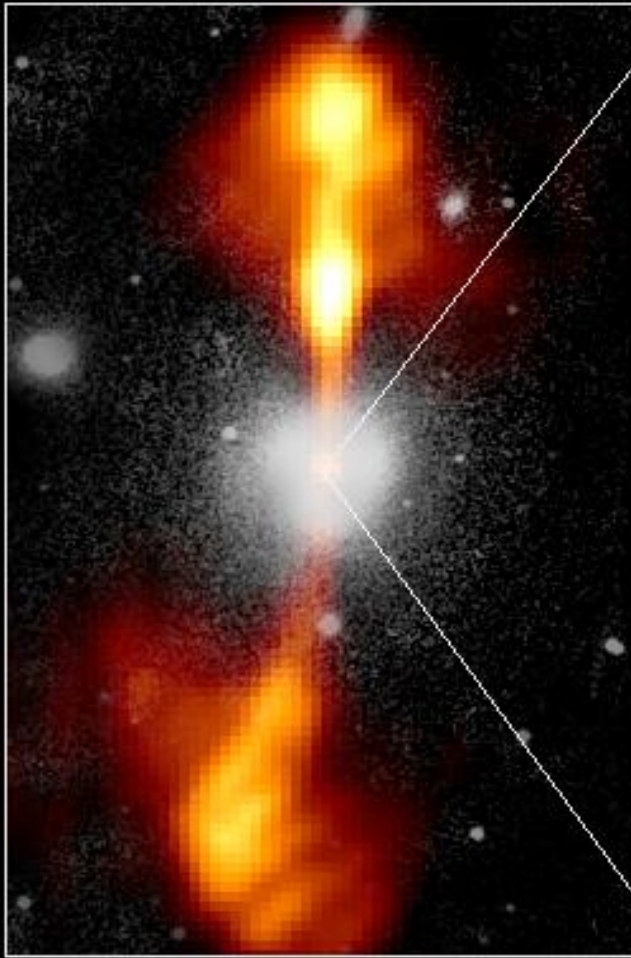
Core of Galaxy NGC 4261

Hubble Space Telescope

Wide Field / Planetary Camera

Ground-Based Optical/Radio Image

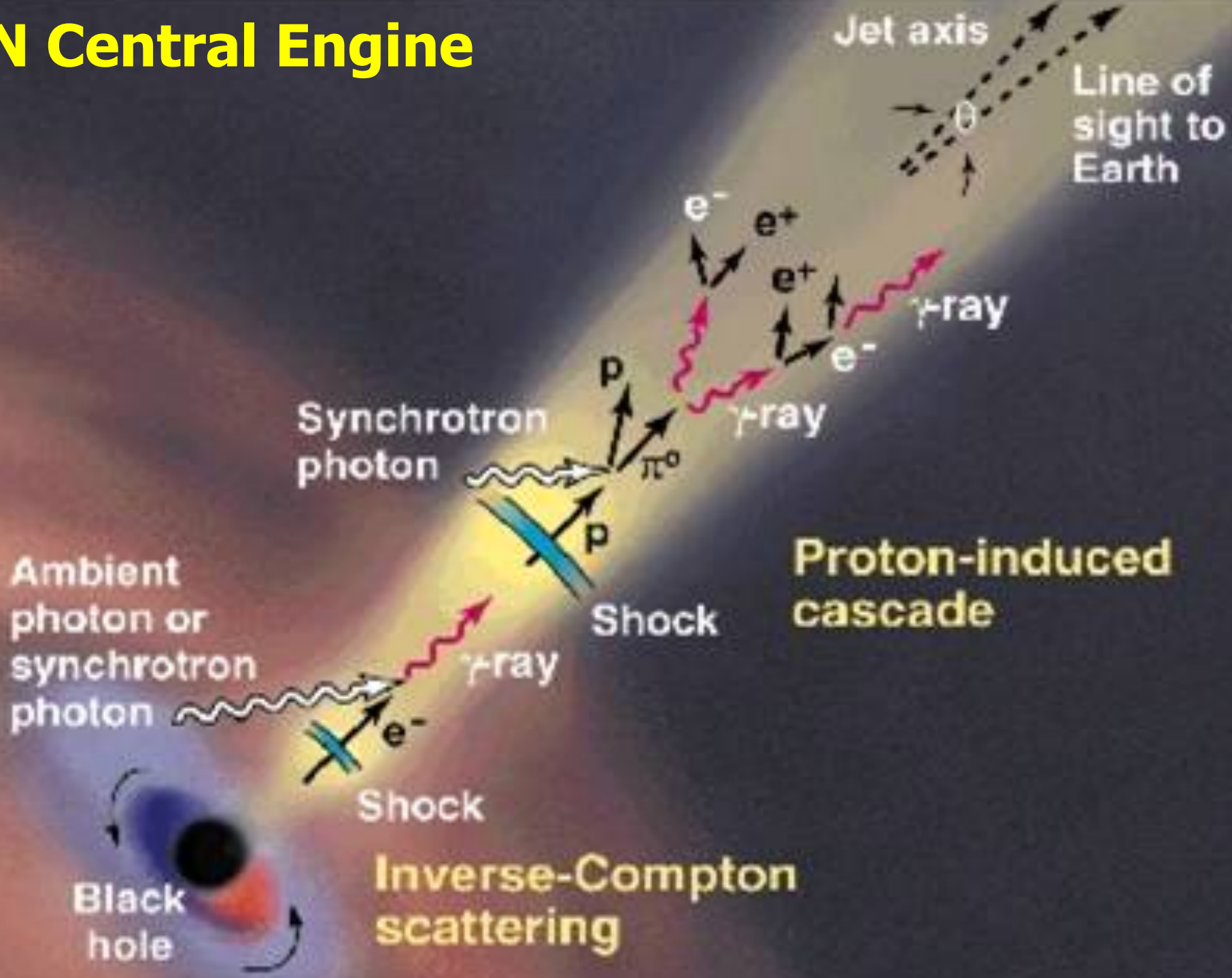
HST Image of a Gas and Dust Disk



380 Arc Seconds
88,000 LIGHT-YEARS

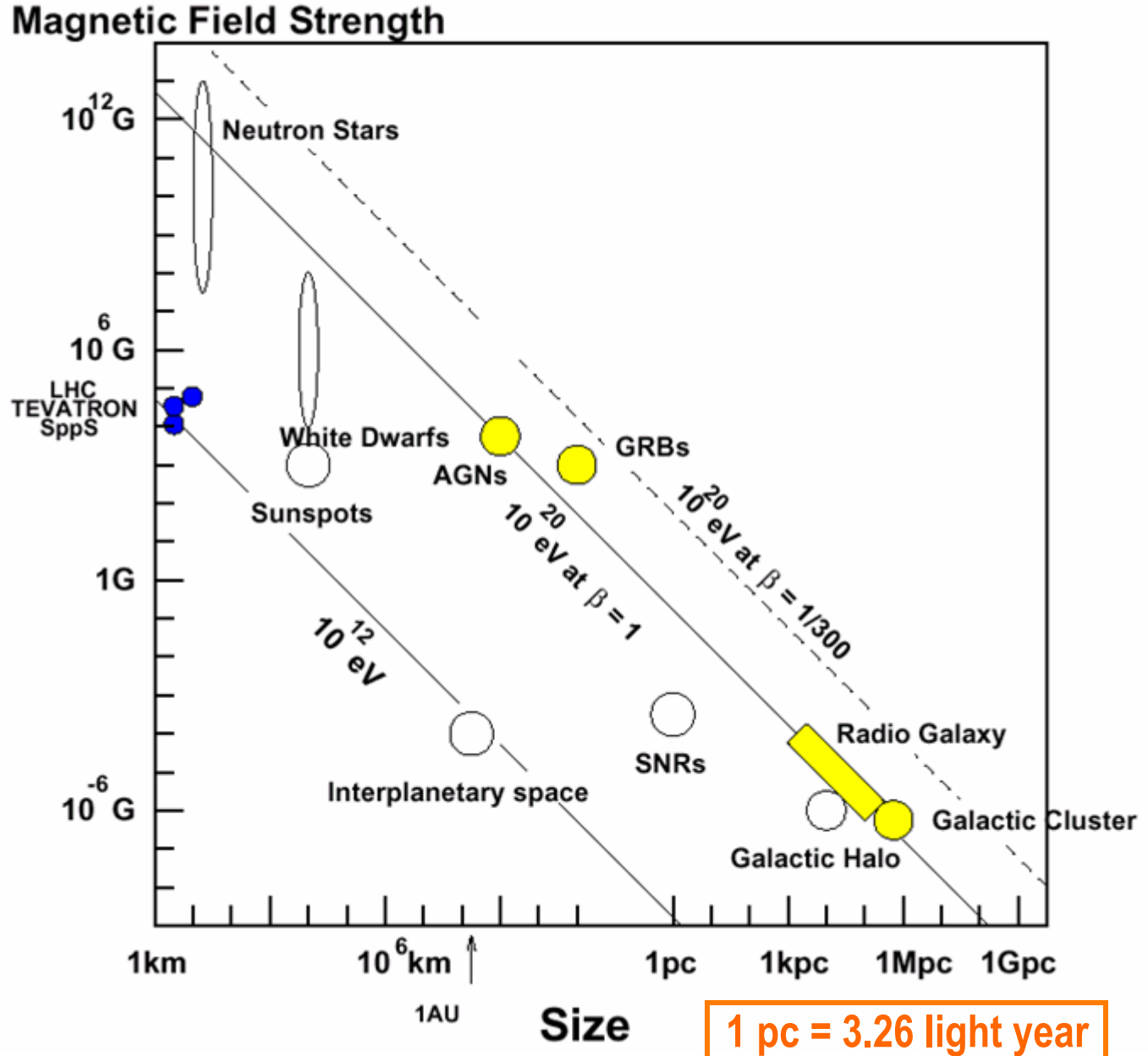
17 Arc Seconds
400 LIGHT-YEARS

AGN Central Engine

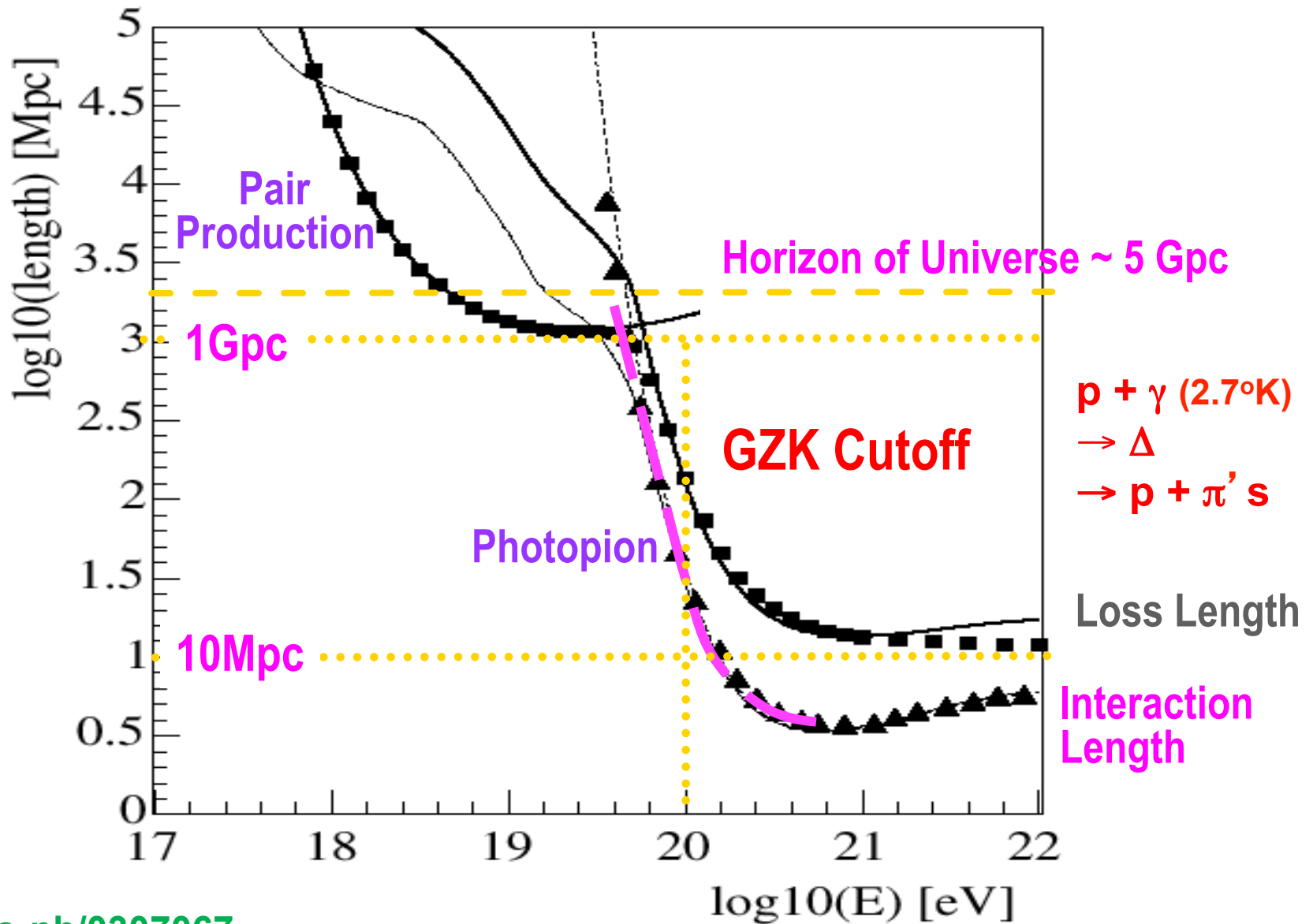


Possible Acceleration Sites

- Several possible accelerators in nature up to 10^{20} eV.
- Extremely difficult to accelerate above 10^{20} eV.



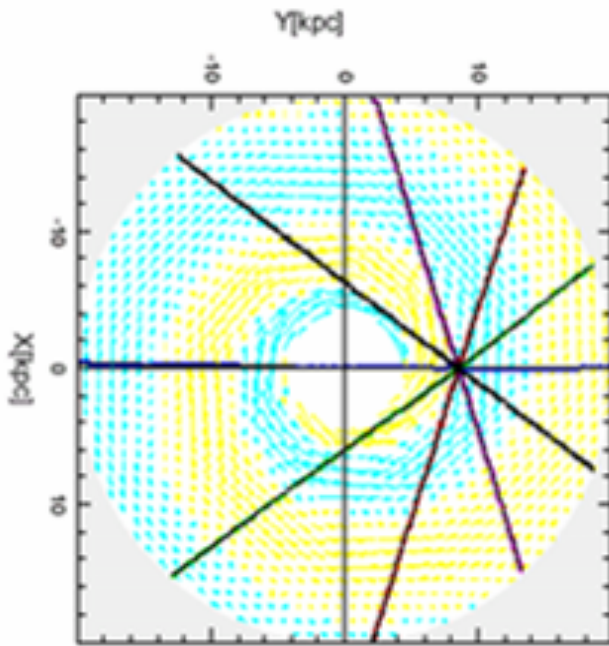
Interaction Length of UHE Protons



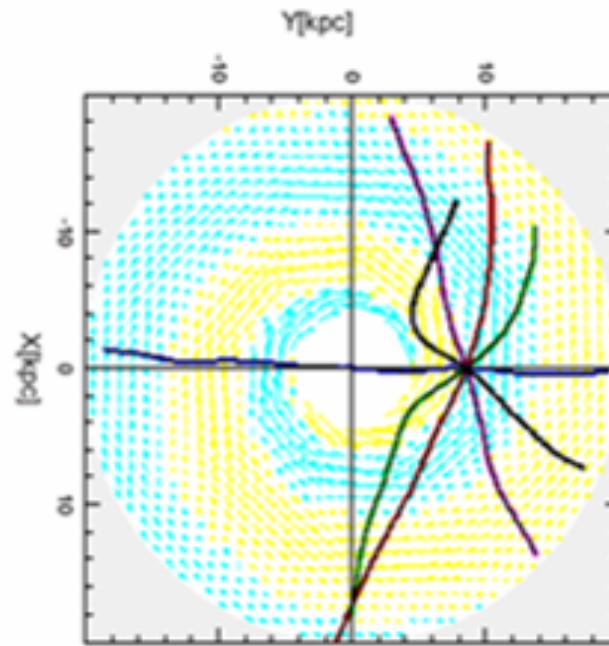
Blasi, astro-ph/0307067

Trajectory of Cosmic Ray Protons in the Galaxy

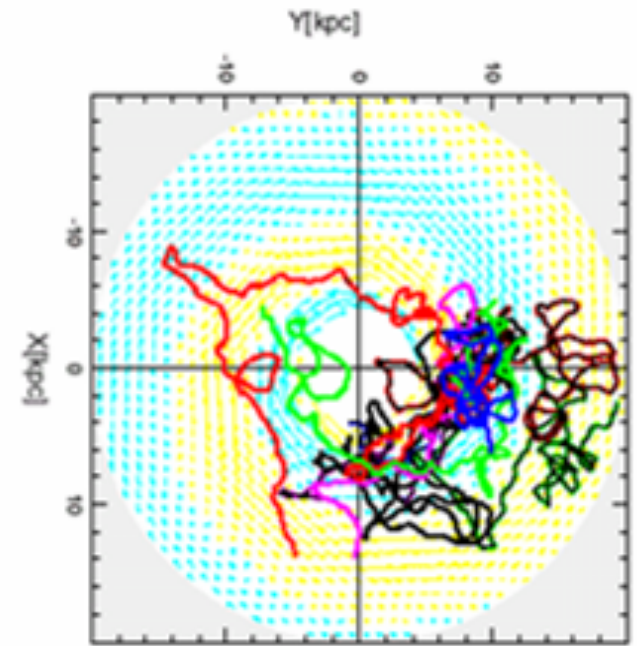
Magnetic Field in our Galaxy $\sim 2 \mu\text{G}$



$E=10^{20}\text{eV}$



$E=10^{19}\text{eV}$

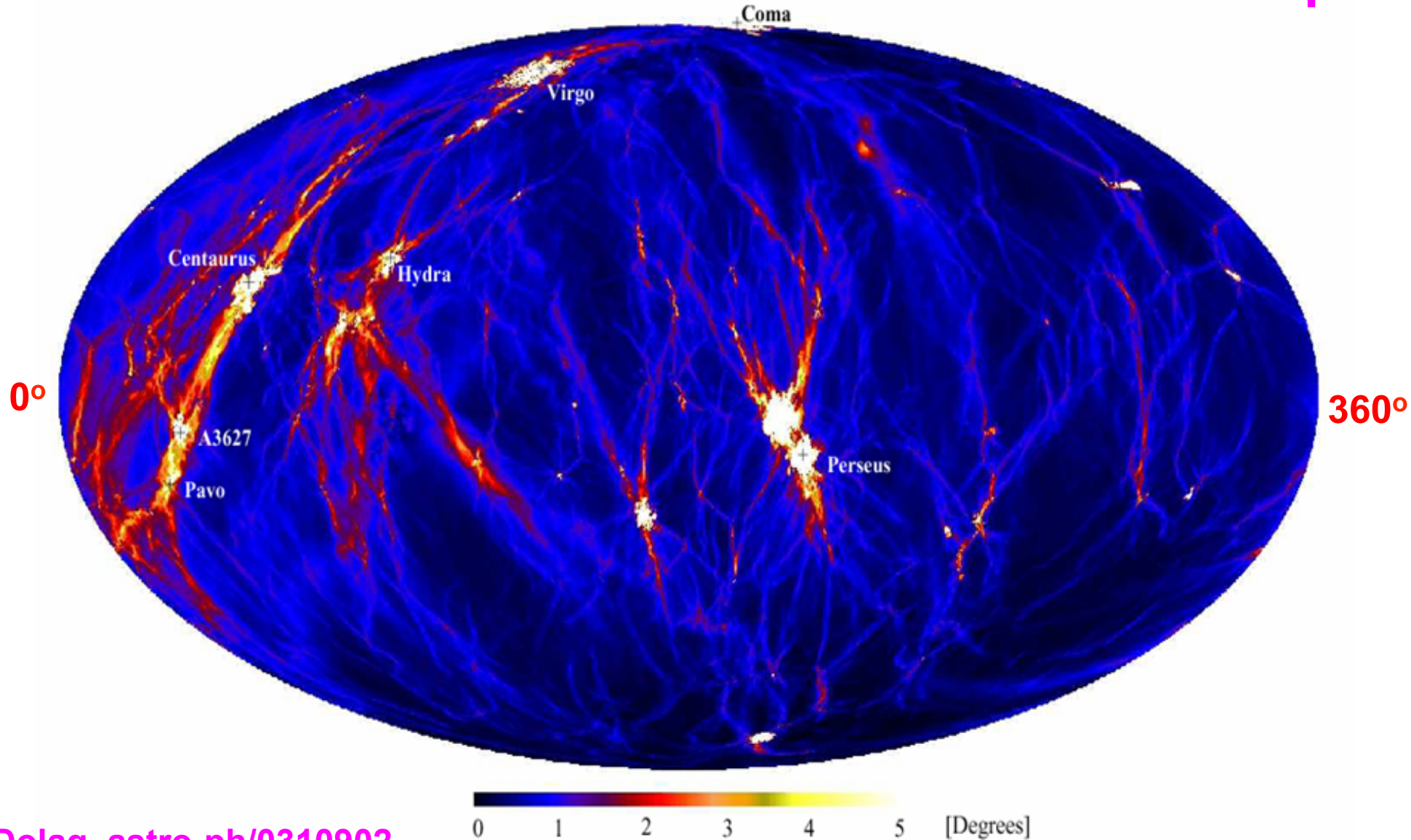


$E=10^{18}\text{eV}$

Deflection of Protons $>4 \times 10^{19} \text{ eV}$

Extra Galactic Magnetic Field $\sim 1 \text{ nG}$

$< 100 \text{ Mpc}$



Dolag, astro-ph/0310902

Why is 10^{20} eV so special?

- Nearly impossible to accelerate beyond 10^{20} eV by nature.



Top-down Mechanism?

- Protons cannot travel beyond ~ 50 Mpc at $E > 10^{20}$ eV due to interaction with CMB.

→ GZK Cut-off

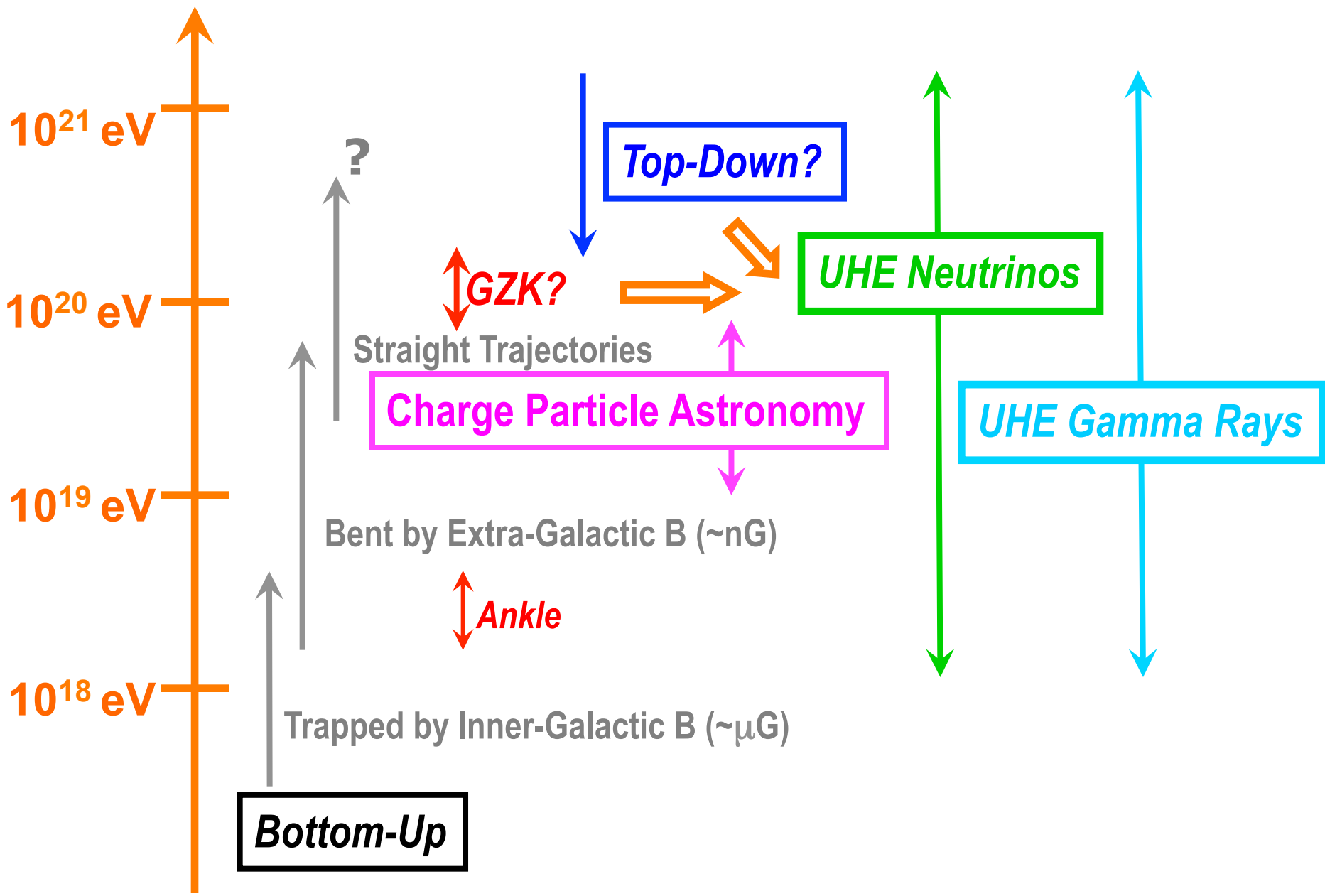


Violation of Special Relativity?

- Protons can travel straight at $E > \sim 4 \times 10^{19}$ eV.

→ Charged-Particle Astronomy

Rich Physics and Astronomy

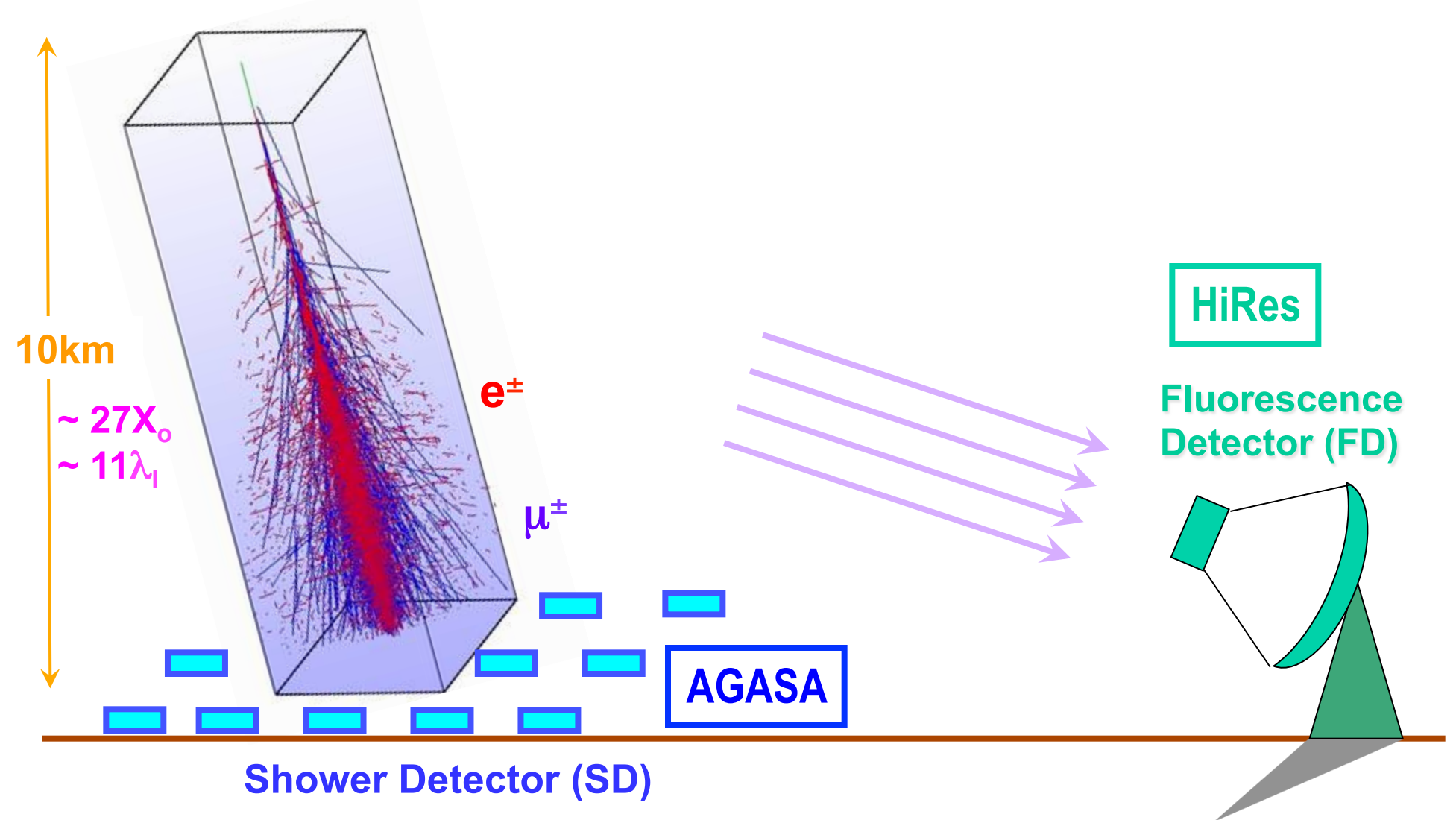


Past and Ongoing Experiments

- AGASA
- HiRes
- Pierre-Auger

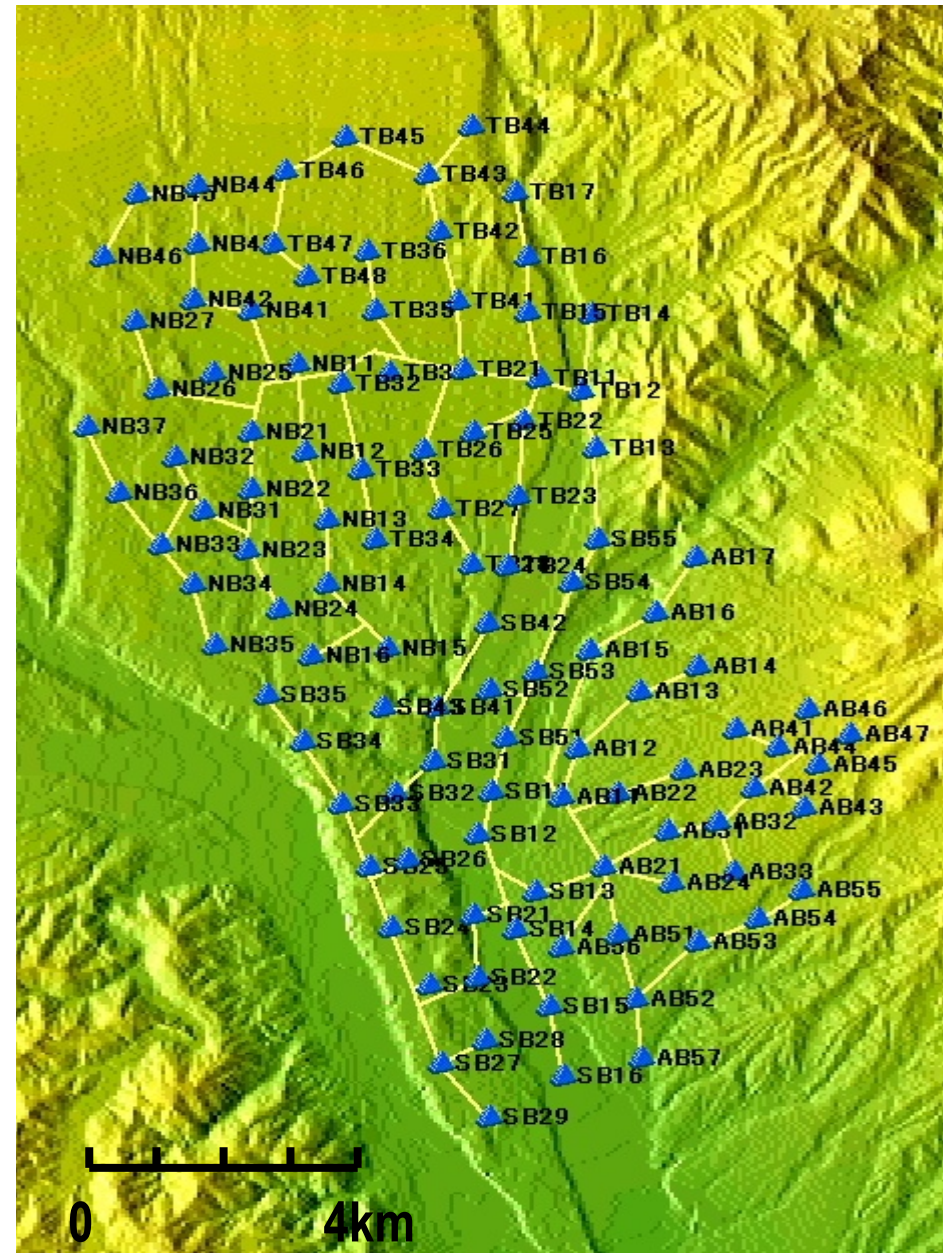
Detection Technique

MC Simulation of 10 EeV
(10^{19} eV) Proton Shower



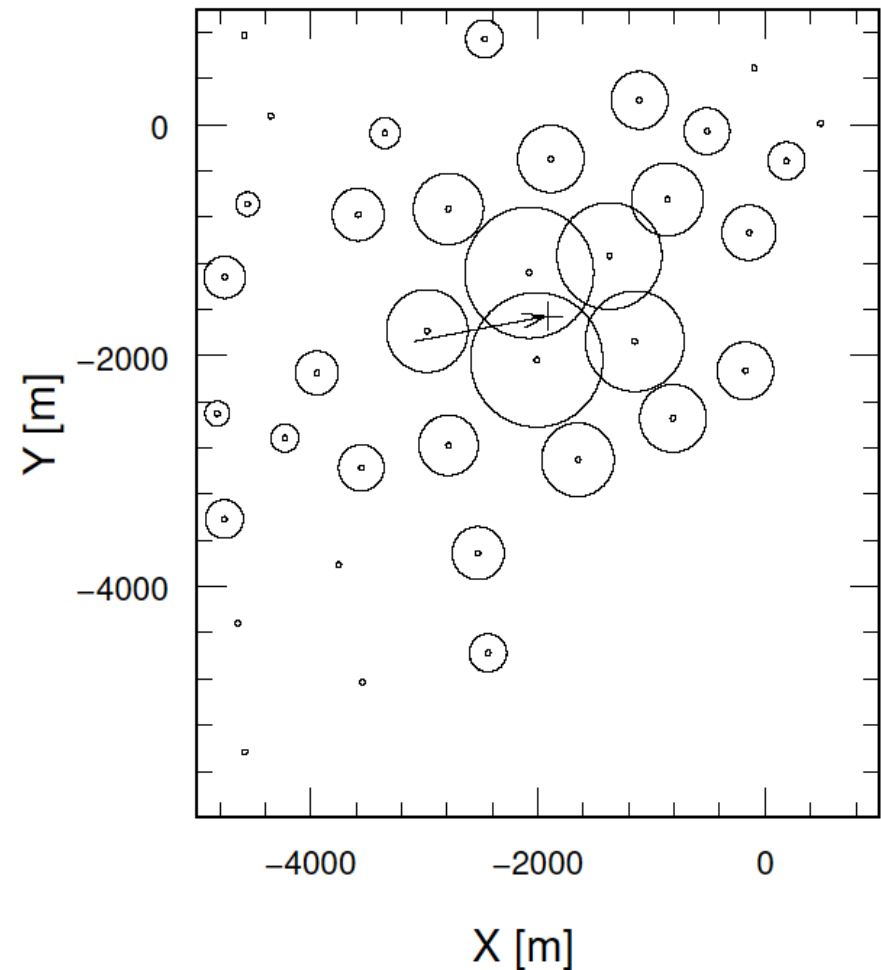
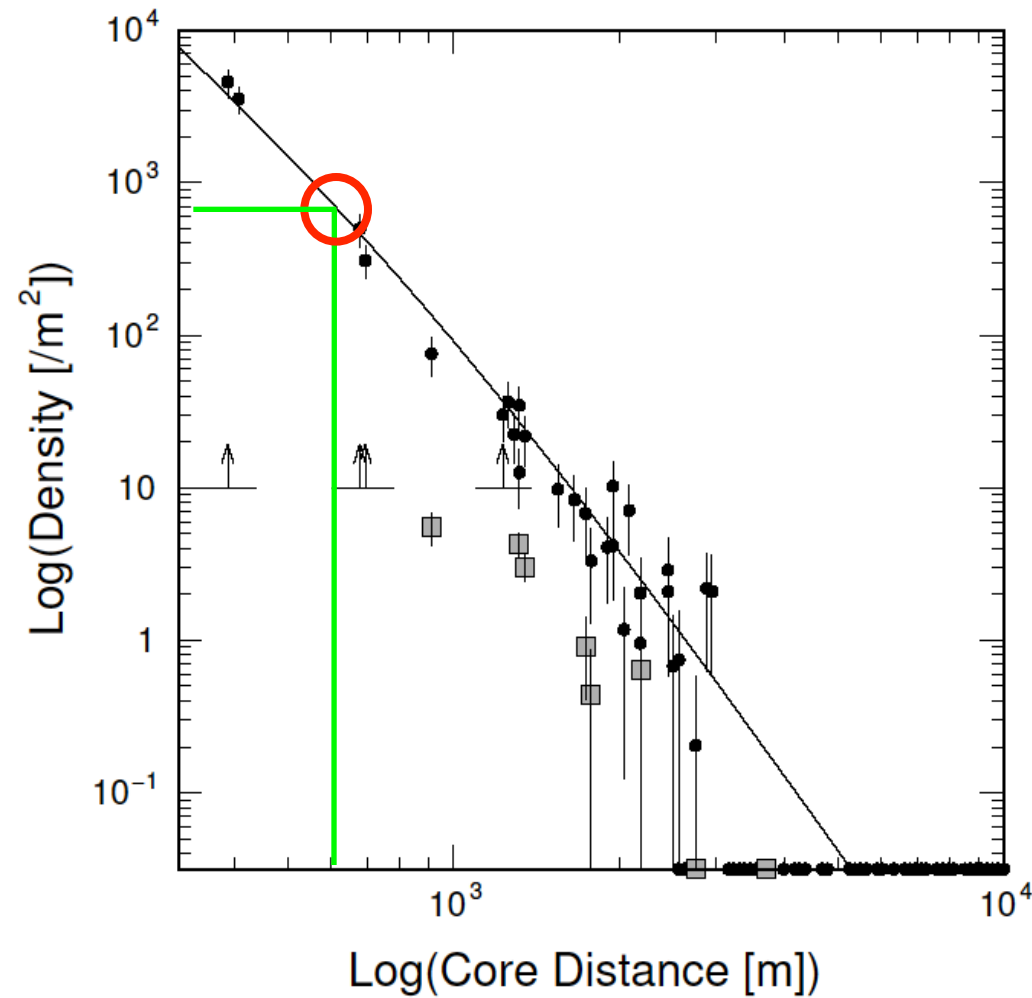
Akeno Giant Air Shower Array

- 111 Electron Detectors
 - 100 km²
- 27 Muon Detectors
- Operation 1991 - 2004

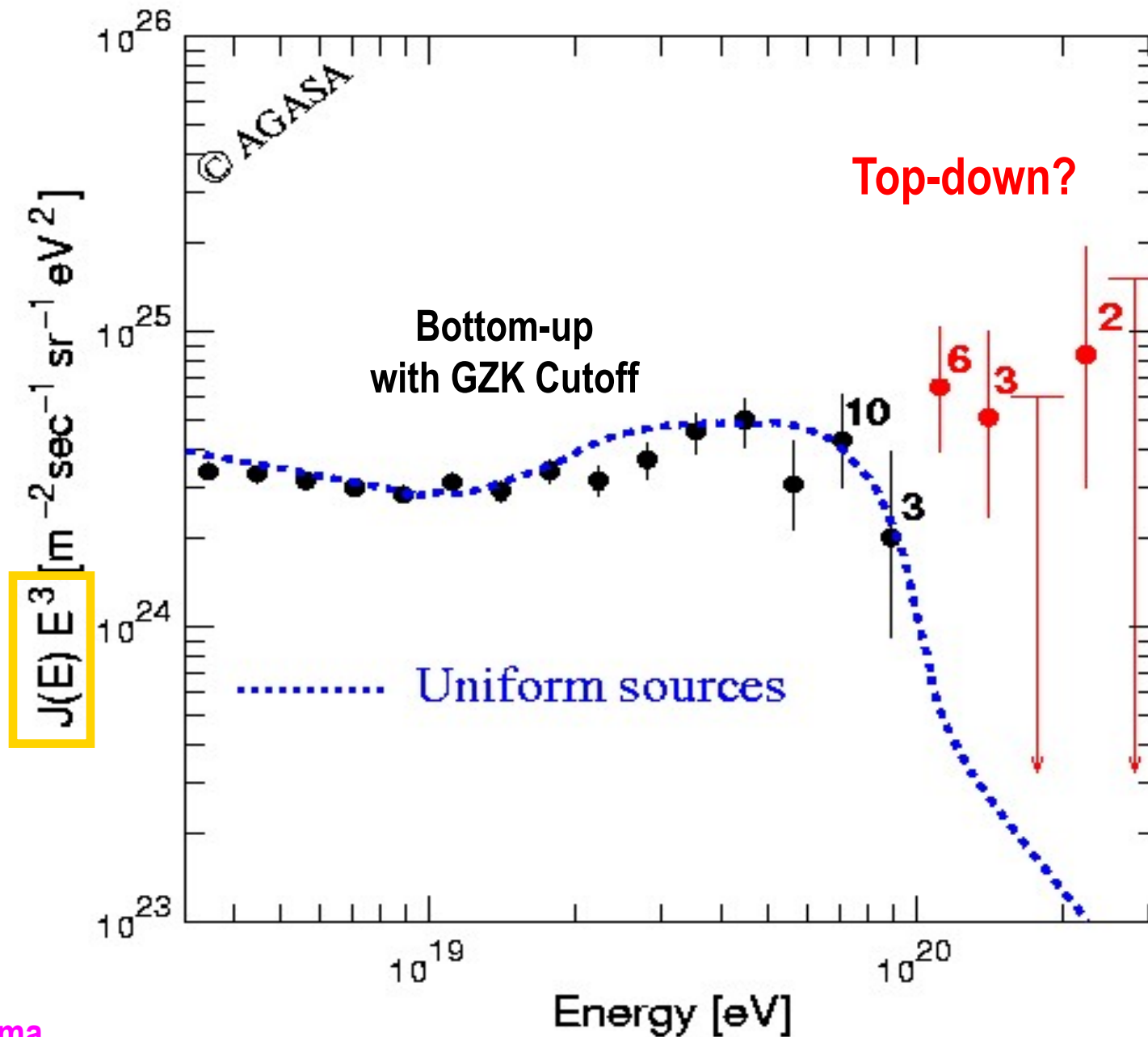


The Highest Energy Event by AGASA

2.5×10^{20} eV on 10 May 2001



Energy Spectrum by AGASA



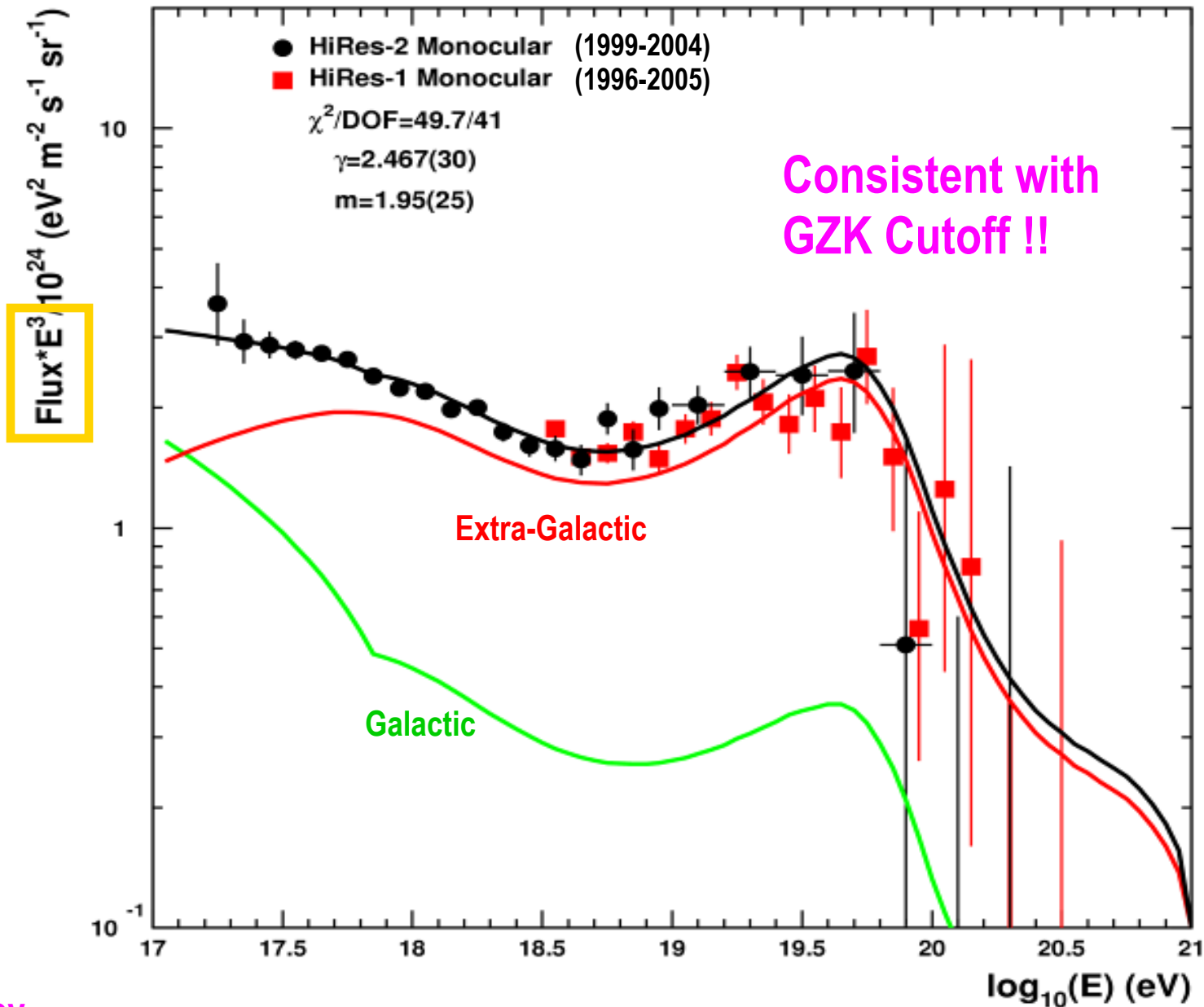
Two HiRes Detectors

- HiRes1: Atop Five Mile Hill
- 21 mirrors, 1 ring ($3^\circ < \text{altitude} < 17^\circ$).

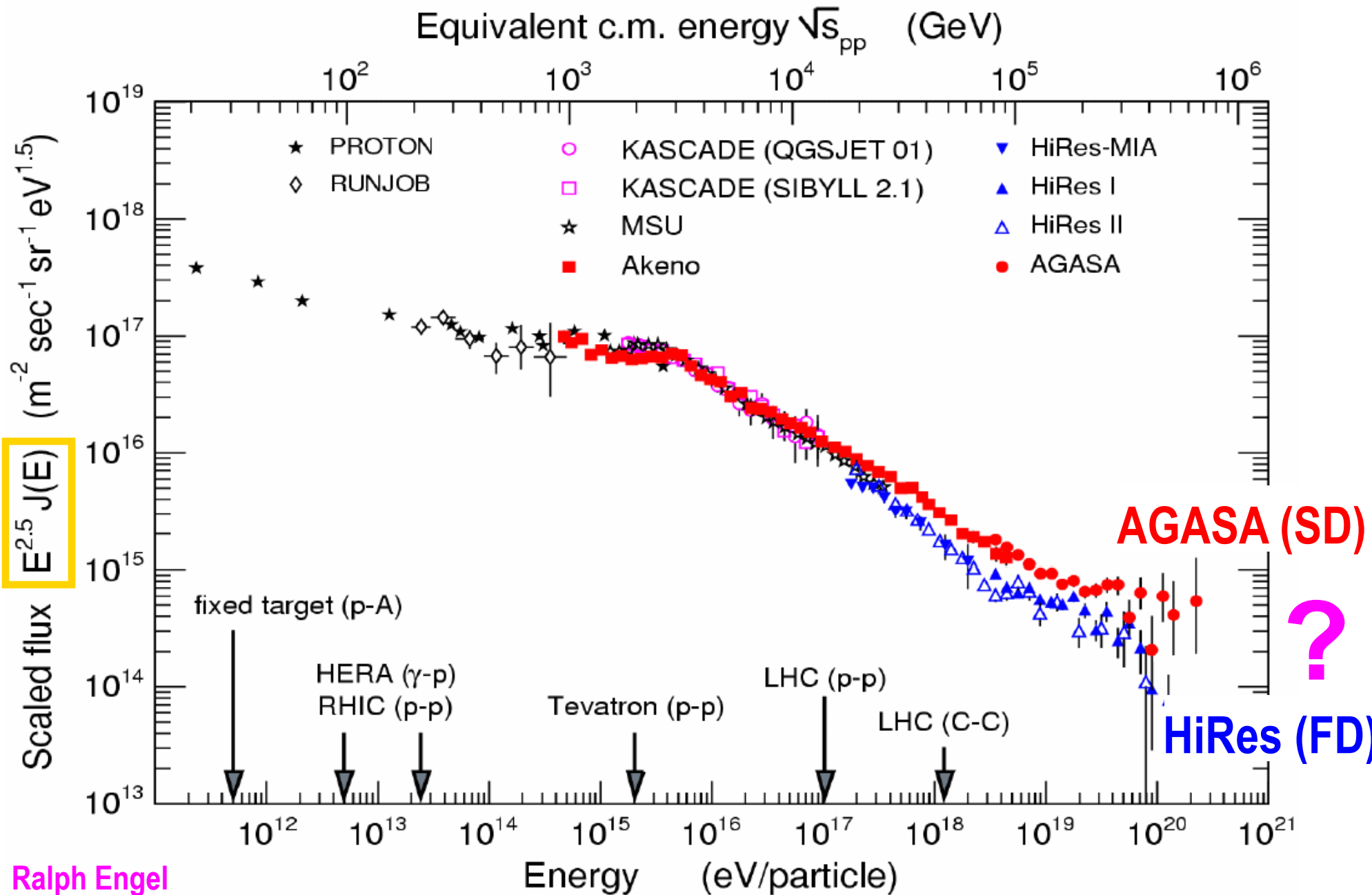


- HiRes2: Atop Camel's Back Ridge
- 12.6 km SW of HiRes1.
- 42 mirrors, 2 rings ($3^\circ < \text{altitude} < 31^\circ$).

Energy Spectrum by HiRes



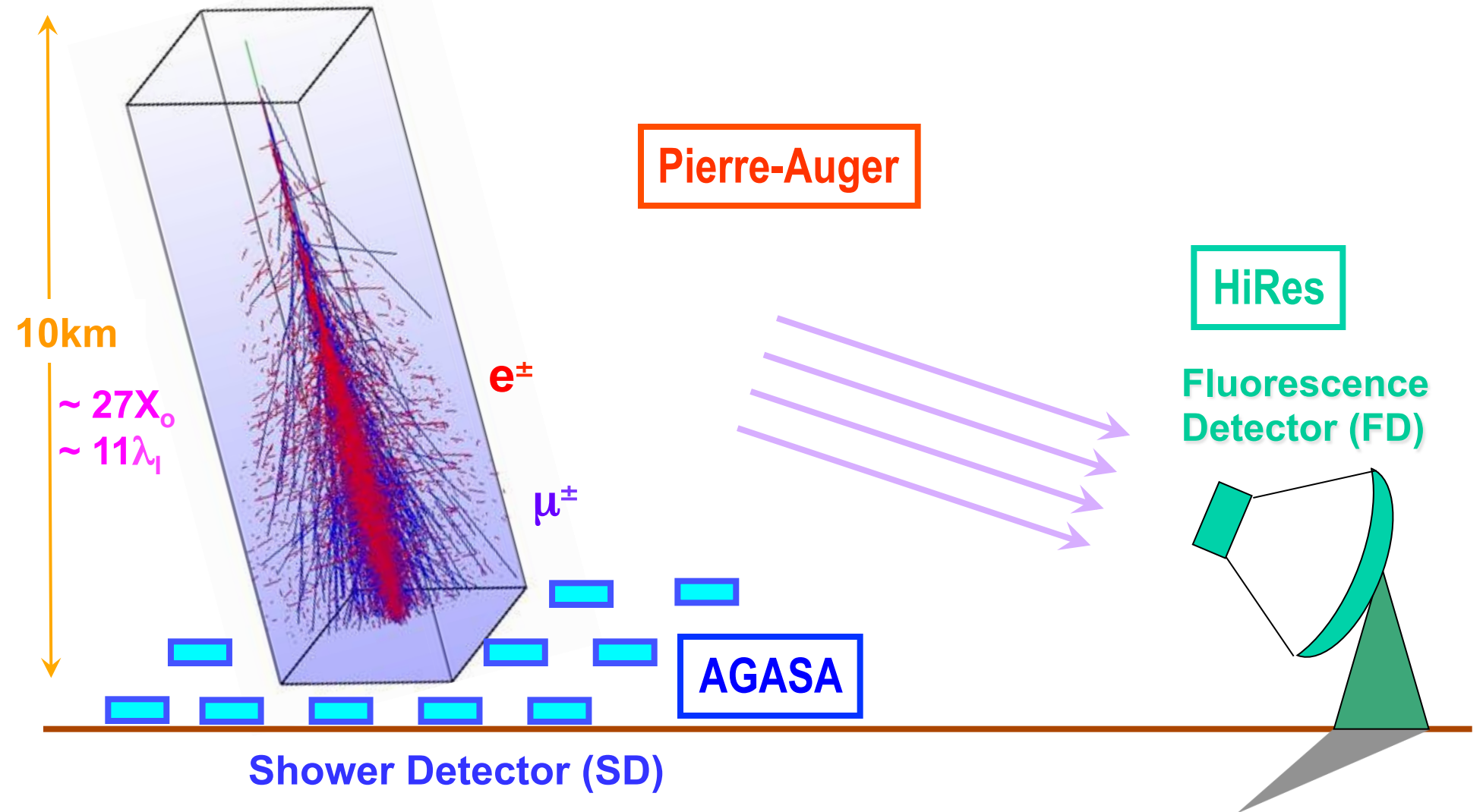
Energy Spectrum



Ralph Engel

Detection Technique

MC Simulation of
 10^{19} eV Proton Shower



SD vs. FD

- **SD (Shower Detector) - AGASA**
 - **Pros: Operational all the time**
 - **Cons: Sparse sampling at the tail of Shower**

- **FD (Fluorescence Detector) - HiRes**
 - **Pros: Totally calorimetric energy measurement**
 - **Cons: ~10% duty factor (only at moonless night)**

- ***Pierre-Auger utilizes both!***

Pierre Auger Collaboration

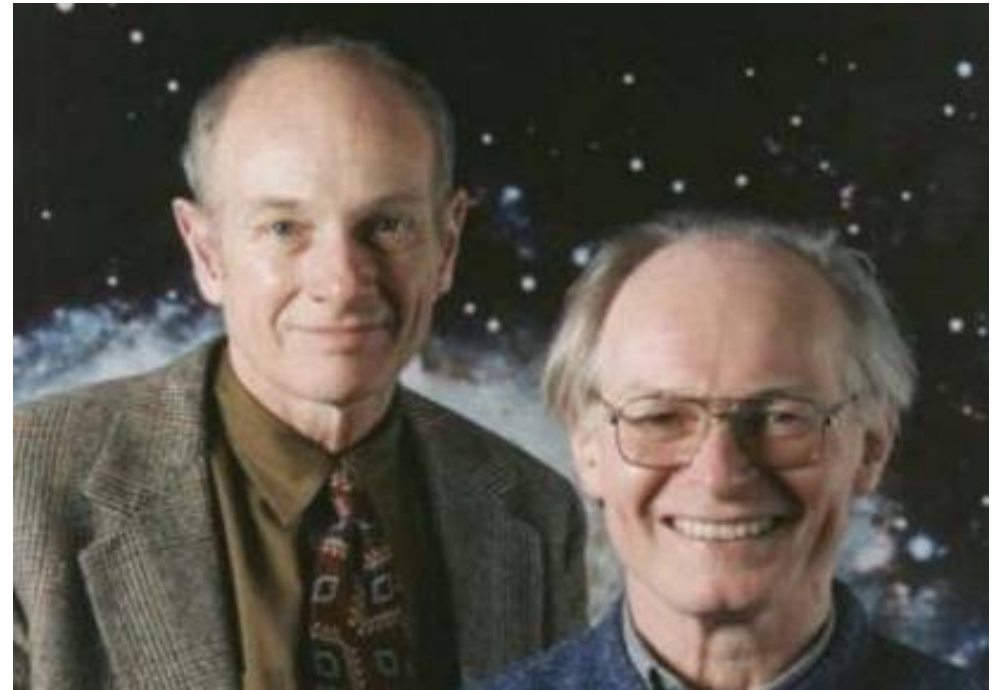
17 Countries
50 Institutions
~370 Scientists

Italy
Czech Republic
France
Germany
Poland
Slovenia
Spain
United Kingdom

Argentina
Australia
Brazil
Bolivia*
Mexico
USA
Vietnam*

**Associate Countries*

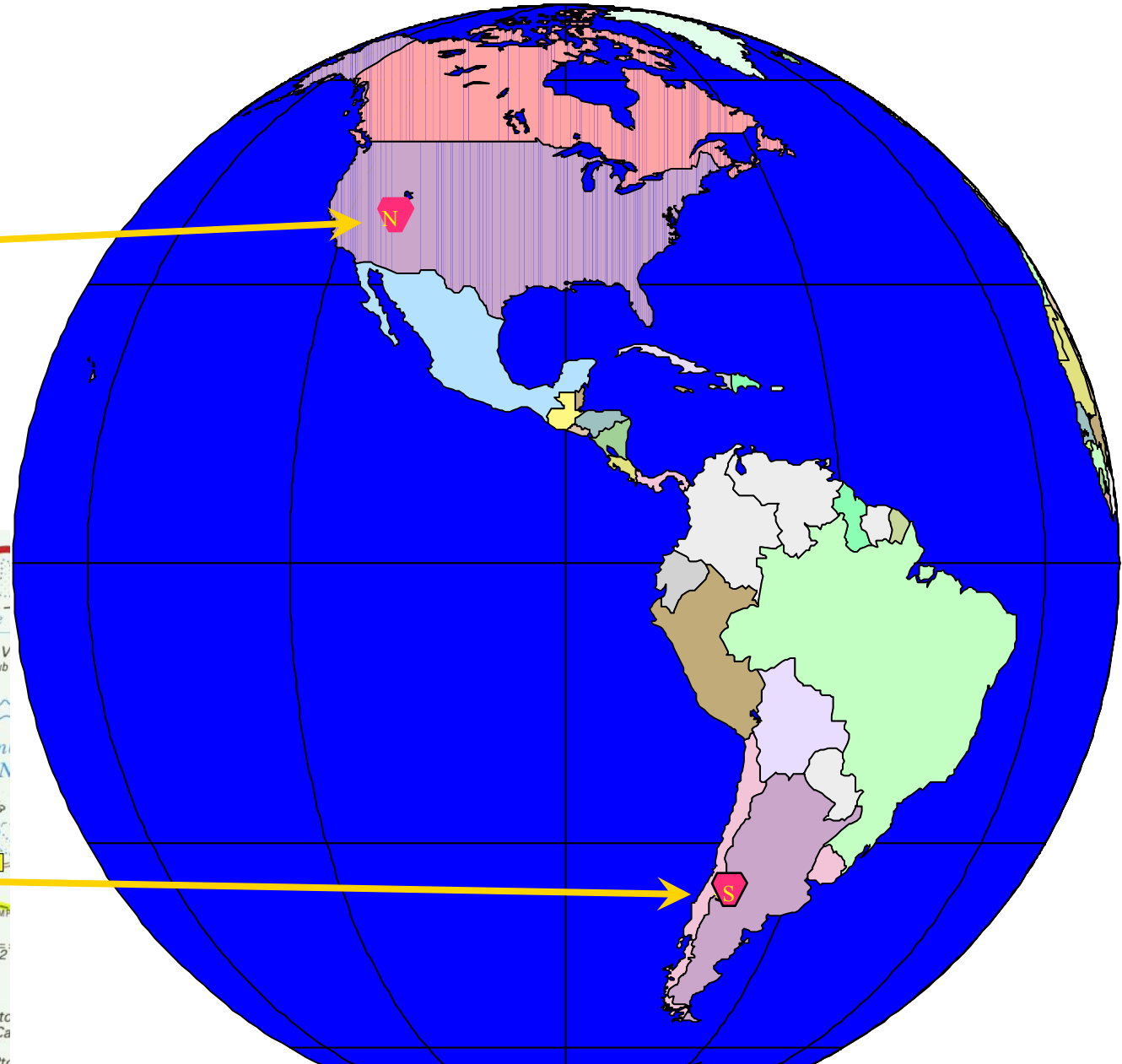
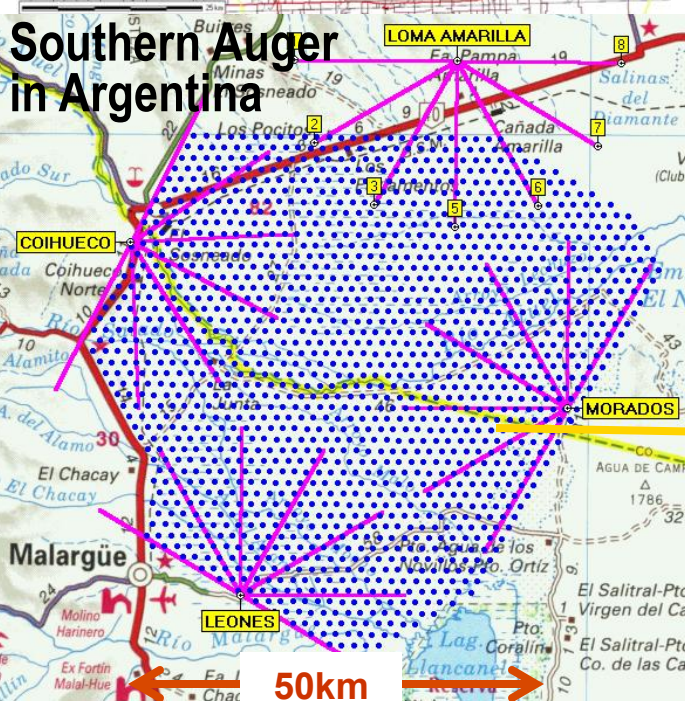
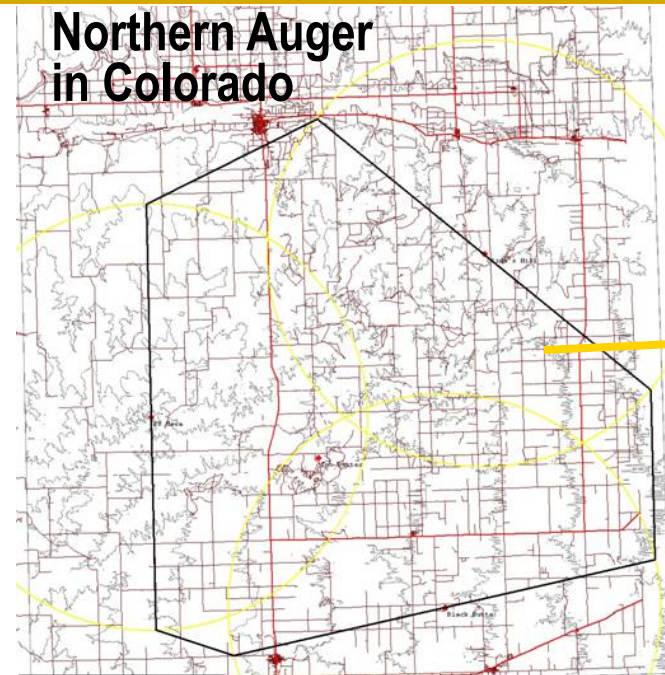
Founders



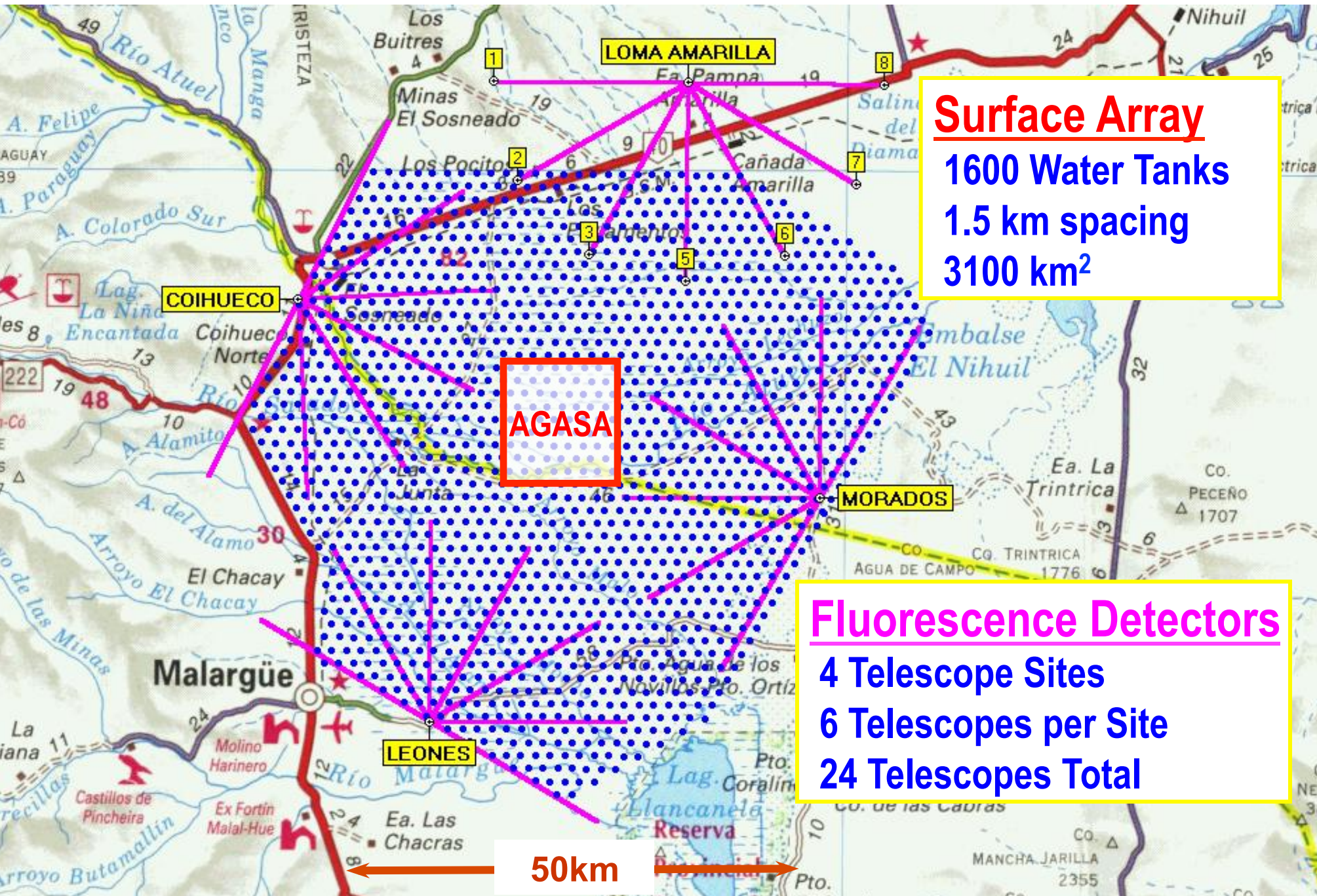
Jim Cronin

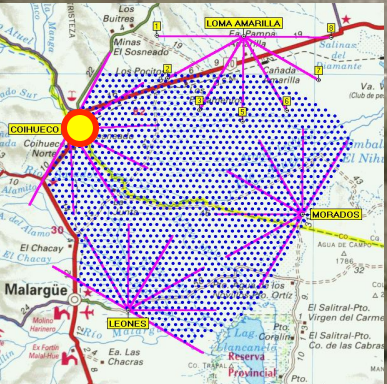
Alan Watson

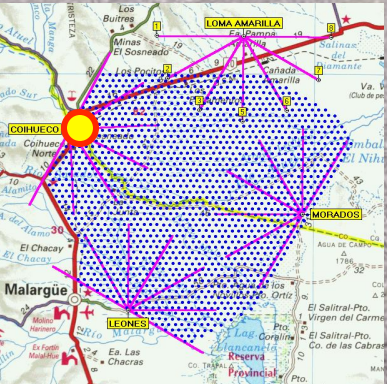
Pierre-Auger Observatory



Southern-Auger in Argentina







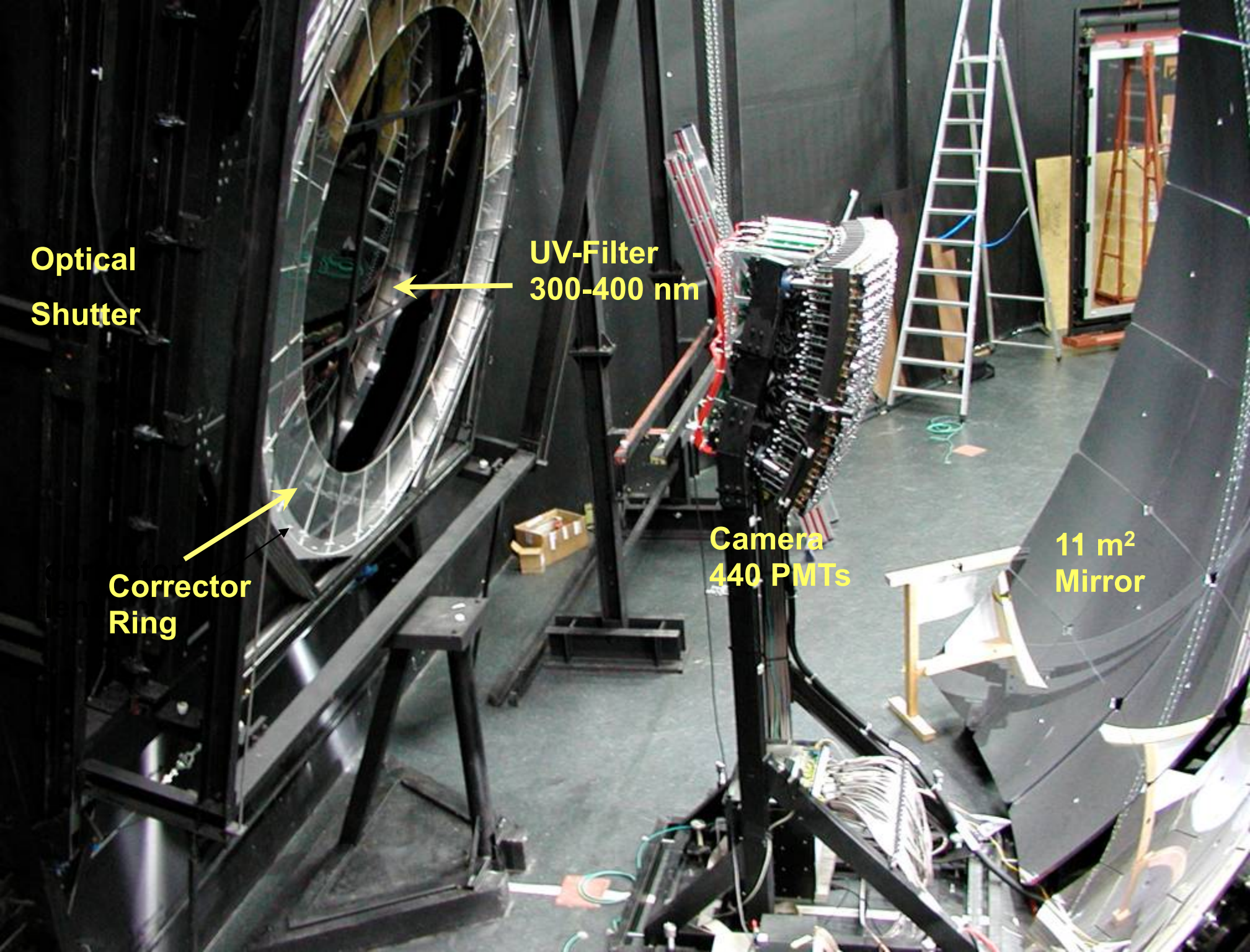
**Optical
Shutter**

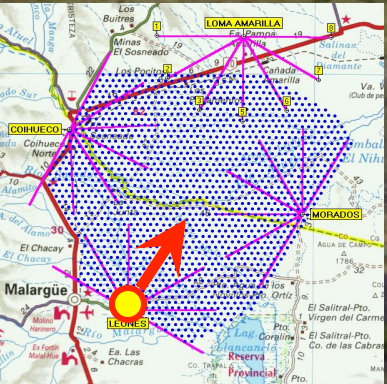
**UV-Filter
300-400 nm**

**Corrector
Ring**

**Camera
440 PMTs**

**11 m²
Mirror**





Tanks aligned seen from Los Leones



Real water tank under operation at Malargue

Communications antenna

GPS antenna

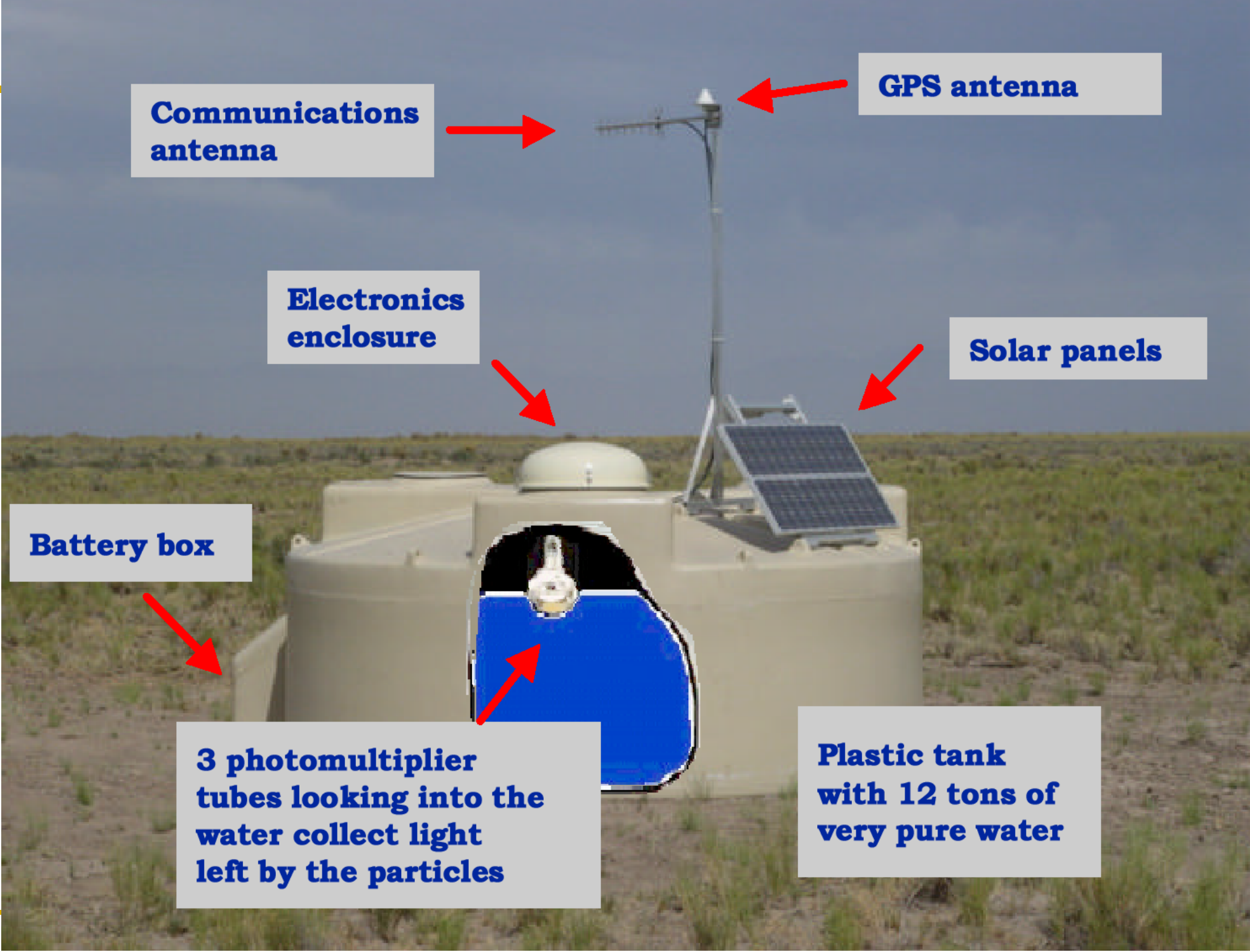
Electronics enclosure

Solar panels

Battery box

3 photomultiplier tubes looking into the water collect light left by the particles

Plastic tank with 12 tons of very pure water



Checking Electronics



Surface Detector inspection by residents of the Pampa



Don't get stuck!





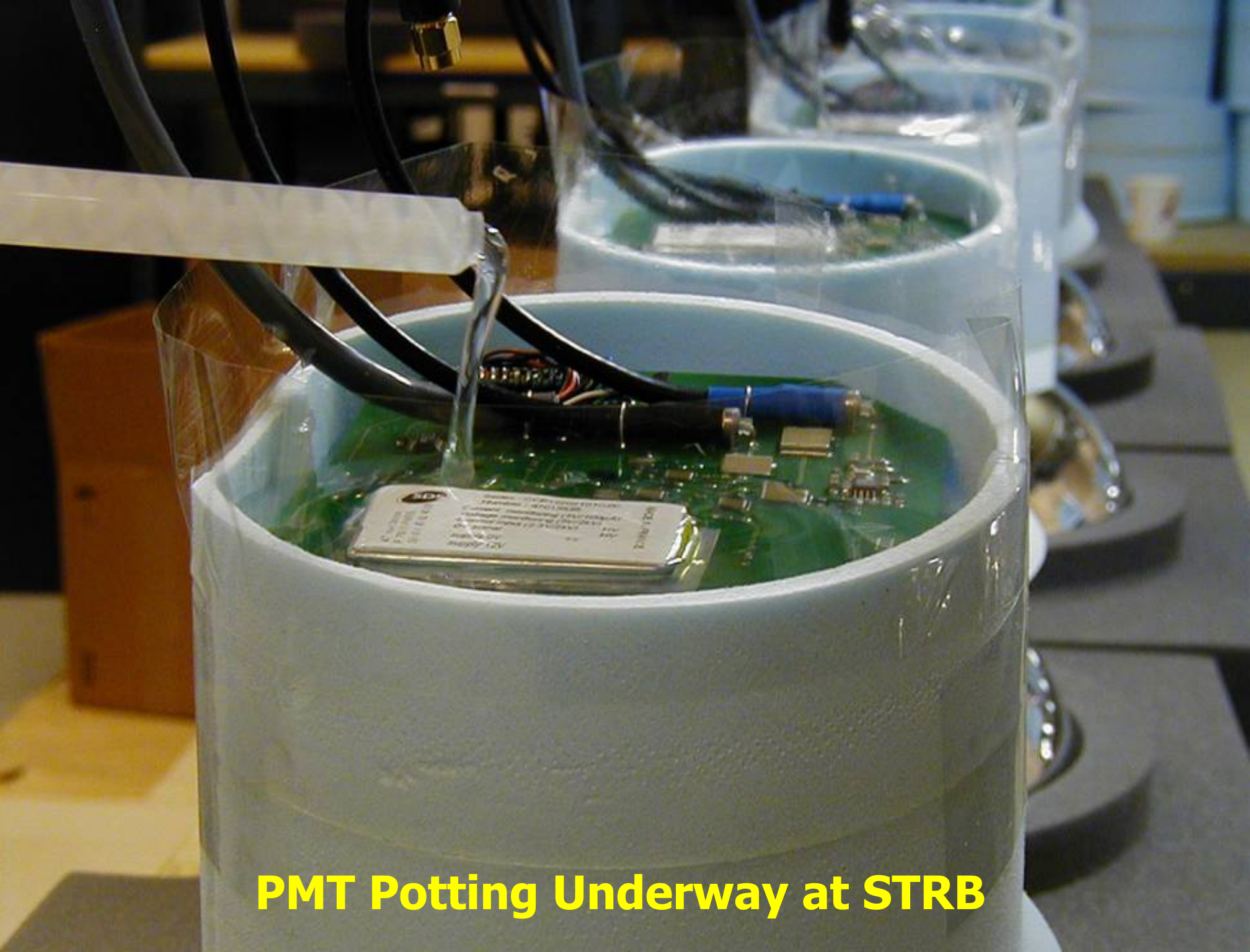
Beautiful Sunset on the Andes

UCLA Pierre-Auger Group

Name	Position	Responsibility	Active Year
Katsushi Arisaka	Professor	P.I.	1998 - present
William Slater	Professor	MC Simulation	1998 - 2006
Graciela Gelmini	Professor	Theory	2002 - present
Alex Kusenko	Professor	Theory	2002 - present
Matthew Malkan	Professor	AGN Astronomy	2007 - present
Arun Tripathi	Postdoc	Data analysis	1998 - 2006
Chris Jillings	Postdoc	PMT testing	1999 - 2002
Dmitry Semikoz	Postdoc	Theory	2002 - 2005
Oleg Kalashev	Postdoc	Theory	2005 - 2006
Tohru Ohnuki	PhD	Angular Distribution	2001 - 2006
David Barnhill	PhD	Photon limit	2001 - 2007
Joong Lee	PhD	Energy Spectrum	2002 - 2007
Matthew Healy	PhD	Mass Composition	2003 - present
Pedram Boghrat	UCLA Grad	Angular Distribution	2004 - 2007
Weichung Ooi	UCLA Grad	Angular Distribution	2004 - 2005
Artin Teymourian	UCLA Grad	Corellation with AGN	2006
Antoine Calvez	UCLA Grad (NSF REU)	Angular Distribution	2004 - 2005
Jacob Ribnik	UCLA undergrad	Compsition study, Dach job system	2004
Eitan Anzenber	From UCSC	Correlation with GRB with SWIFT data	2005
Adrian Cheng	UCLA undergrad	Search for Thread-like clustering	2005
Justin Young	UCLA undergrad	Neutrino detection	2005
Ryan Reece	NSF REU	Fluorescence Photon Yield	2005
Adam Lopez	UCLA CARE	Quantum Efficiency Measurement	2005
Daniel Maronde	UCLA undergrad	Collection Efficiency	2005
Alfonso Vergara	UCLA undergrad	Collection Efficiency	2005
Sourpouhi Bedikian	NSF REU	Correlation with AGN	2005
Joshua Moody	UCLA undergrad	Mass Composition study by Muon LDF	2006
Umi Yamamoto	From Tokyo	Correlation with AGN	2006
Tyler Dawson	UCLA undergrad	Catalog of Astronomical objects	2006
Brian Rothaug	UCLA undergrad	Catalog of Astronomical objects	2006
Min Lu	UCLA undergrad	Mass Composition study by Muon LDF	2006
and more before 2004....			

UCLA PMT Test Facility at STRB in Westwood





PMT Potting Underway at STRB

Malargüe PMT Test Facility



16 PMTs inspected by Arun



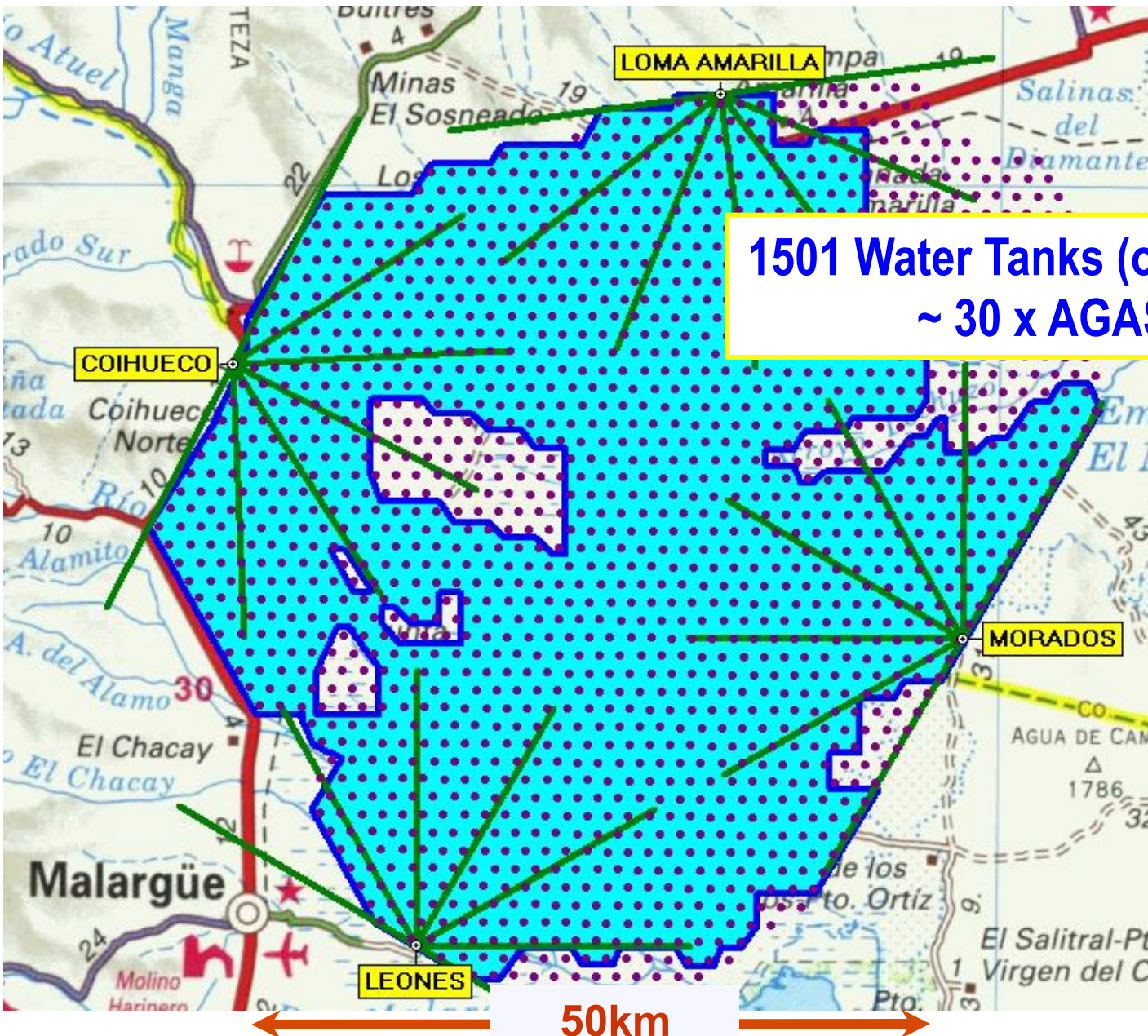
David in Control



PMTs Assembled by Tohru and Federico

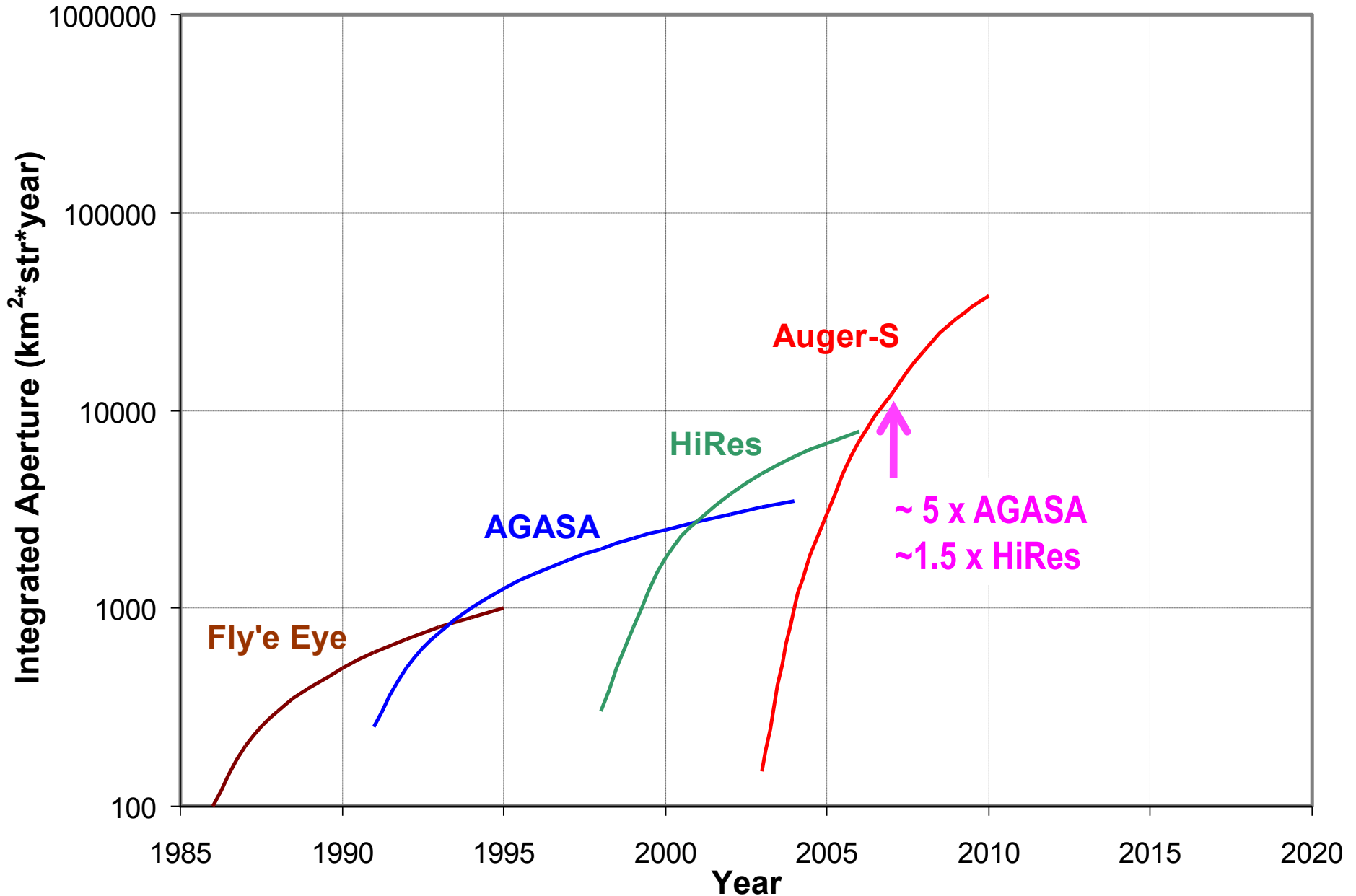


Southern Auger as of Nov. 2007



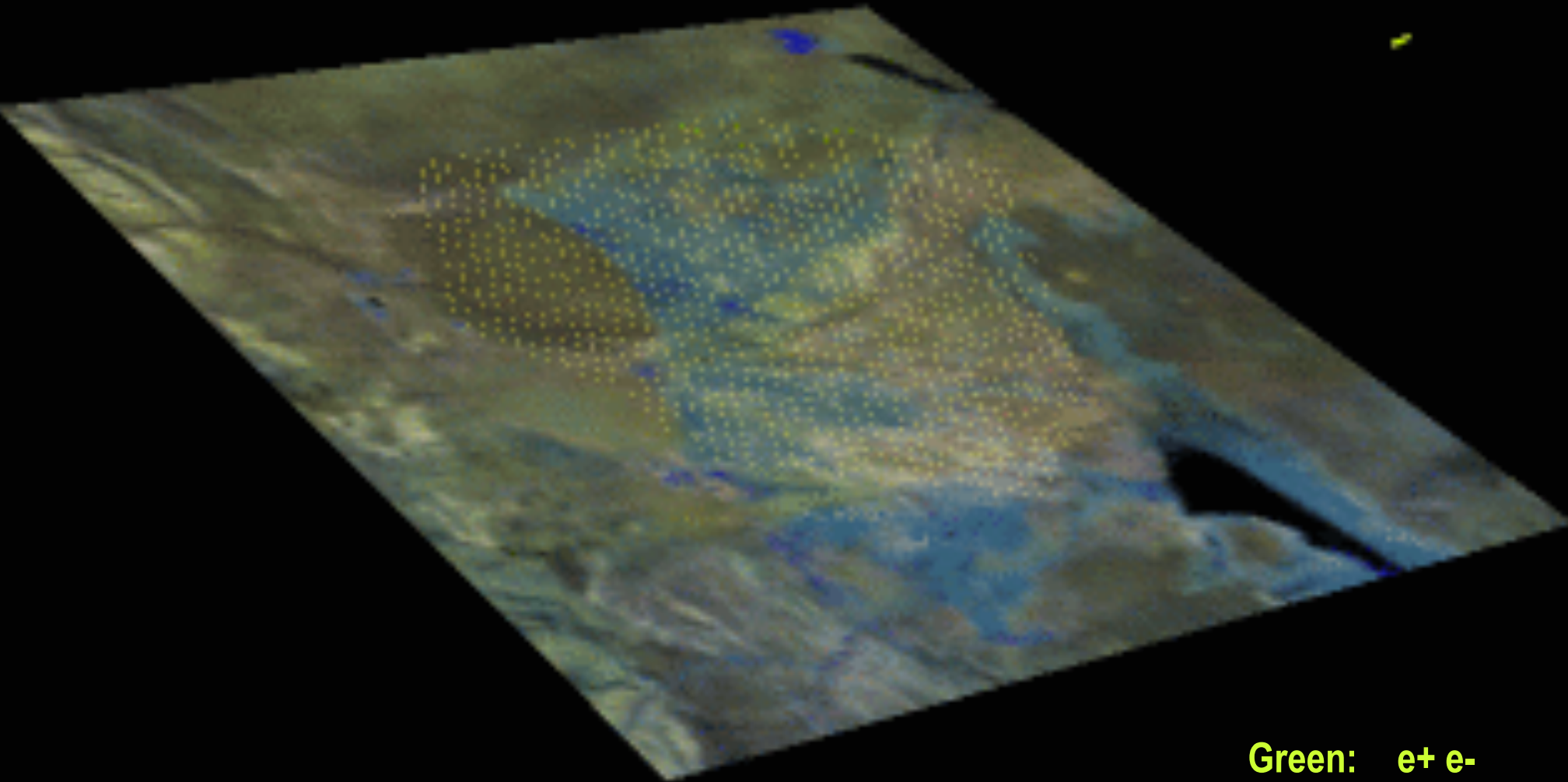
1501 Water Tanks (out of 1600)
~ 30 x AGASA

Comparison of Integrated Aperture



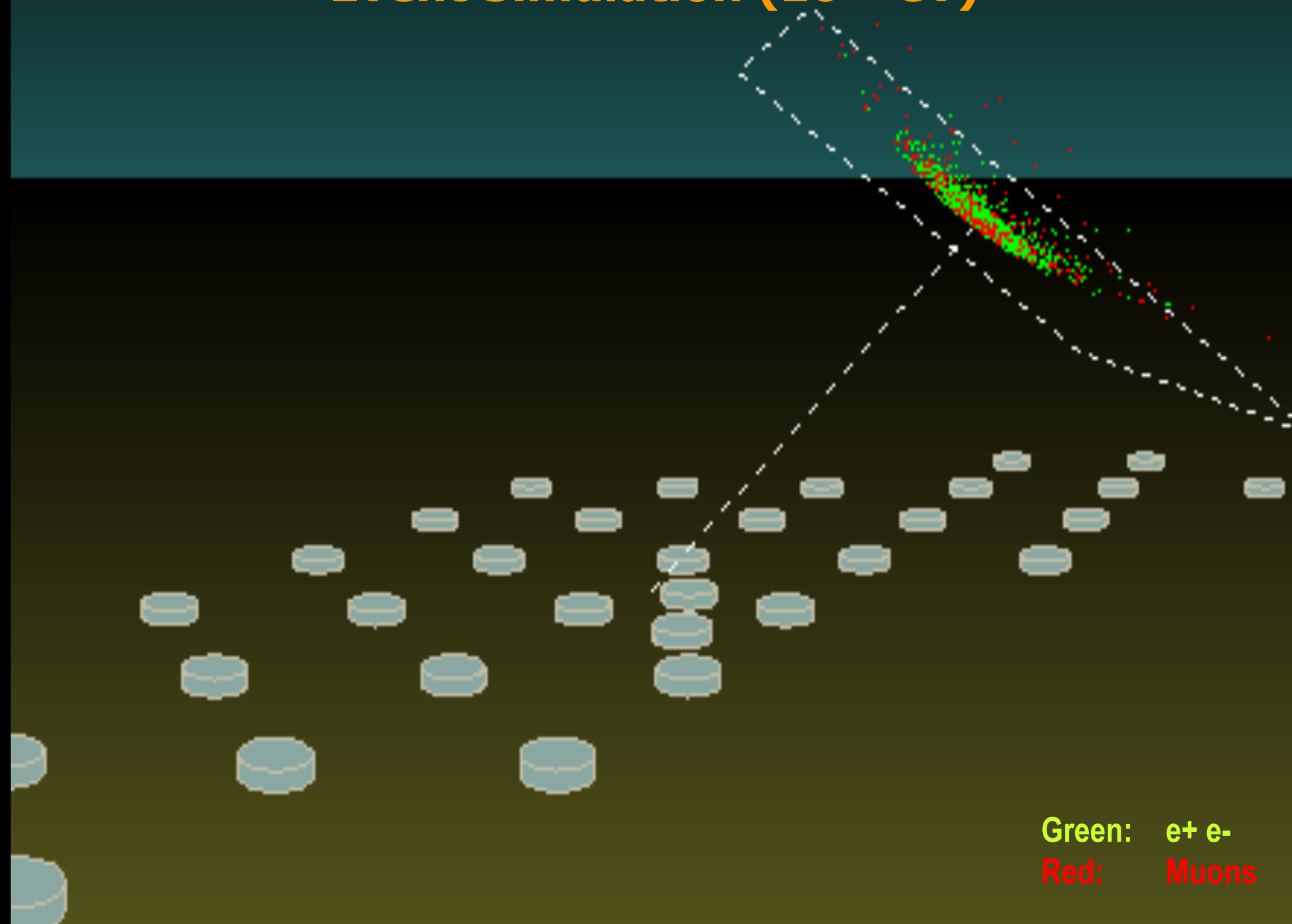
Energy Determination

Event Simulation (10^{19} eV)

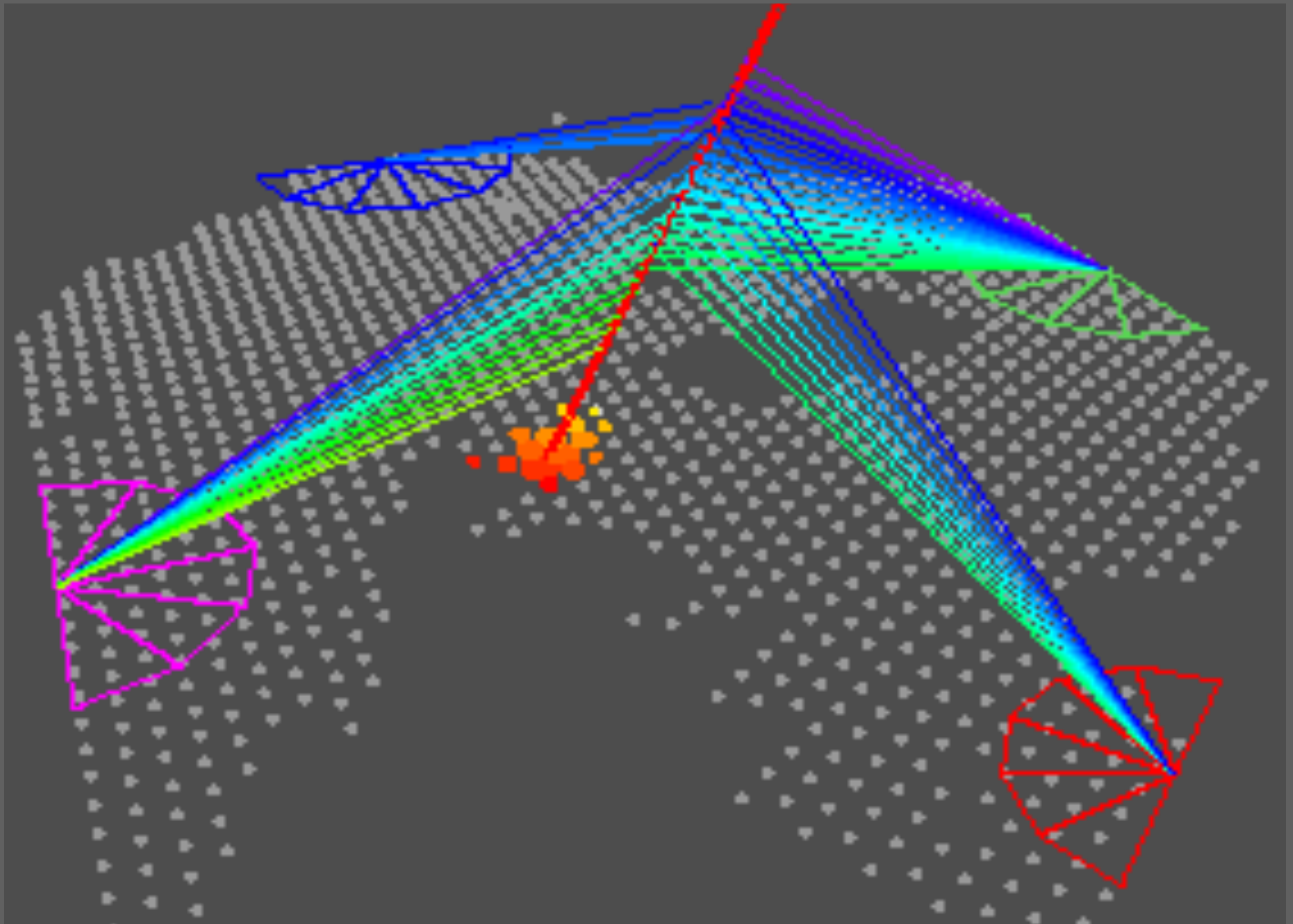


Green: $e^+ e^-$
Red: Muons

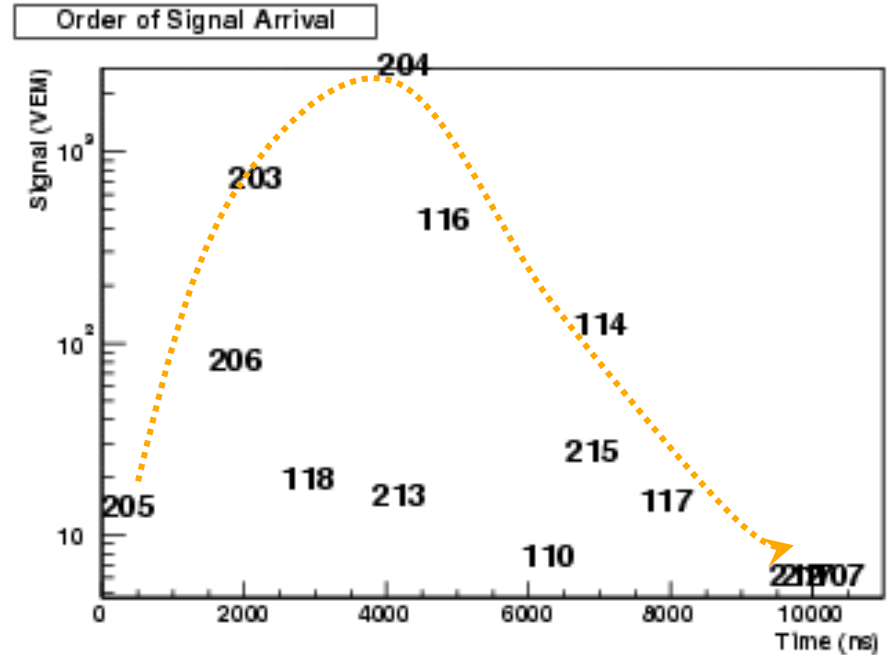
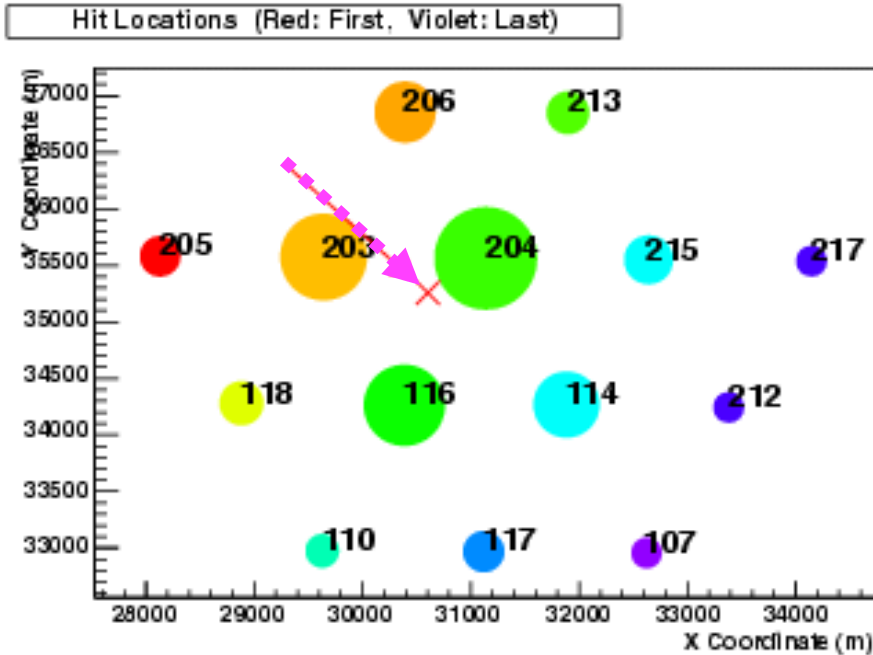
Event Simulation (10^{19} eV)



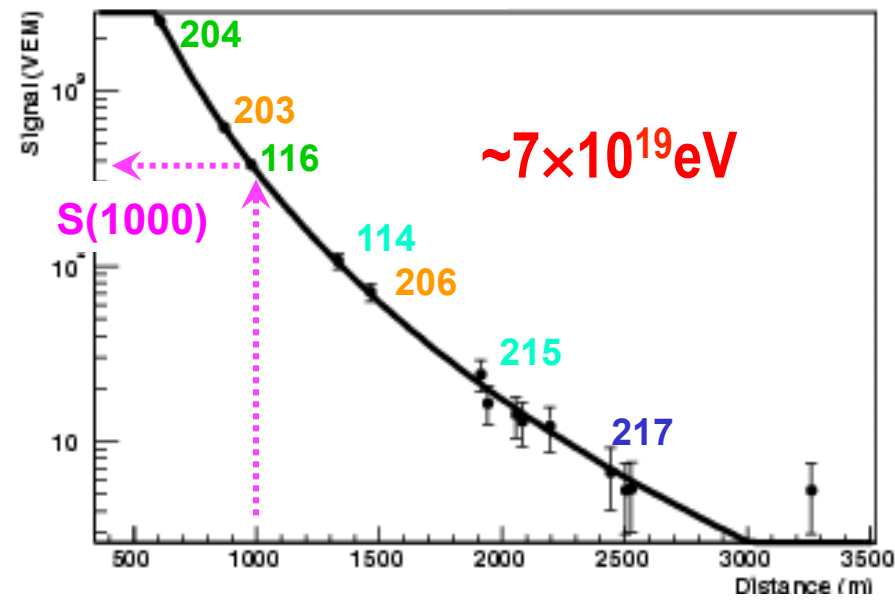
10^{19} eV event observed by all detectors



A Typical Event ("Young" Shower, Zenith $\sim 35^\circ$)



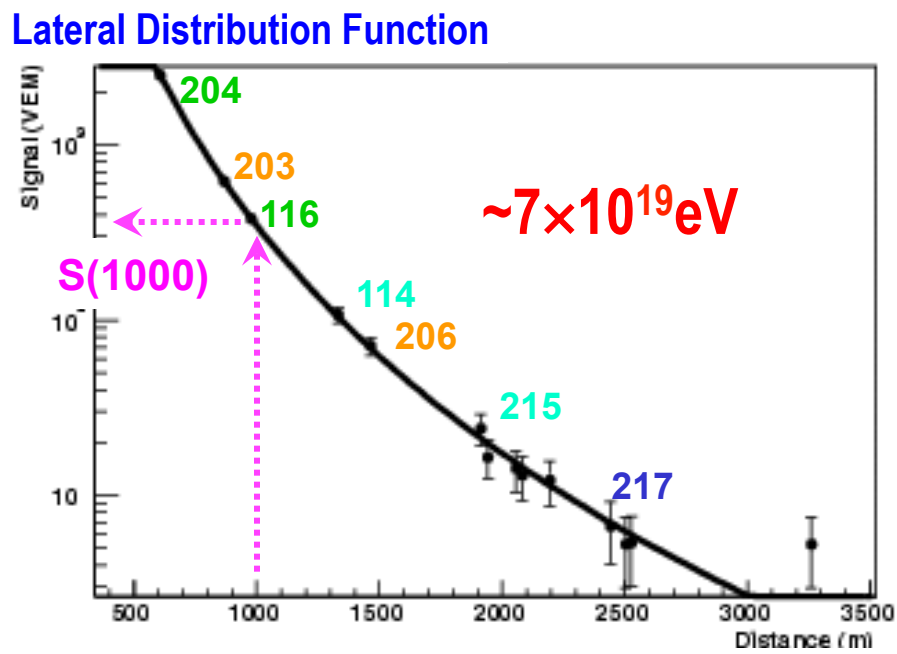
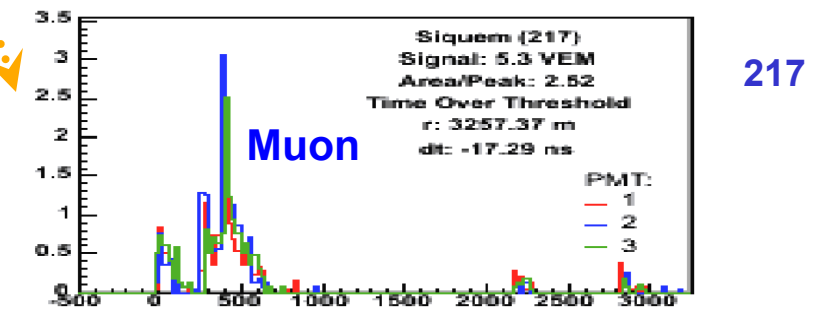
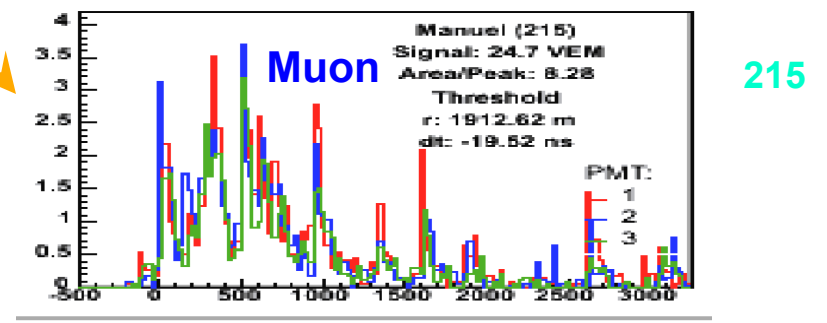
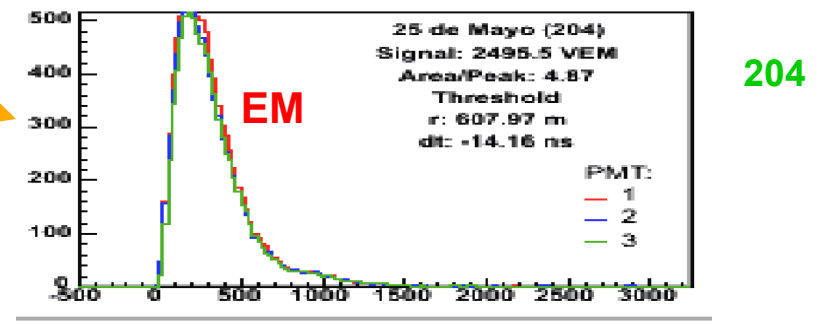
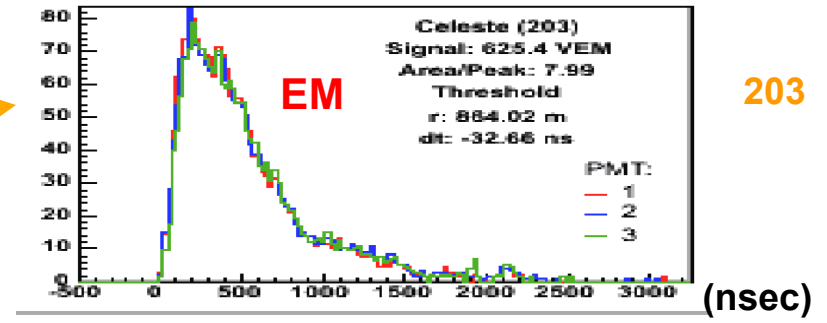
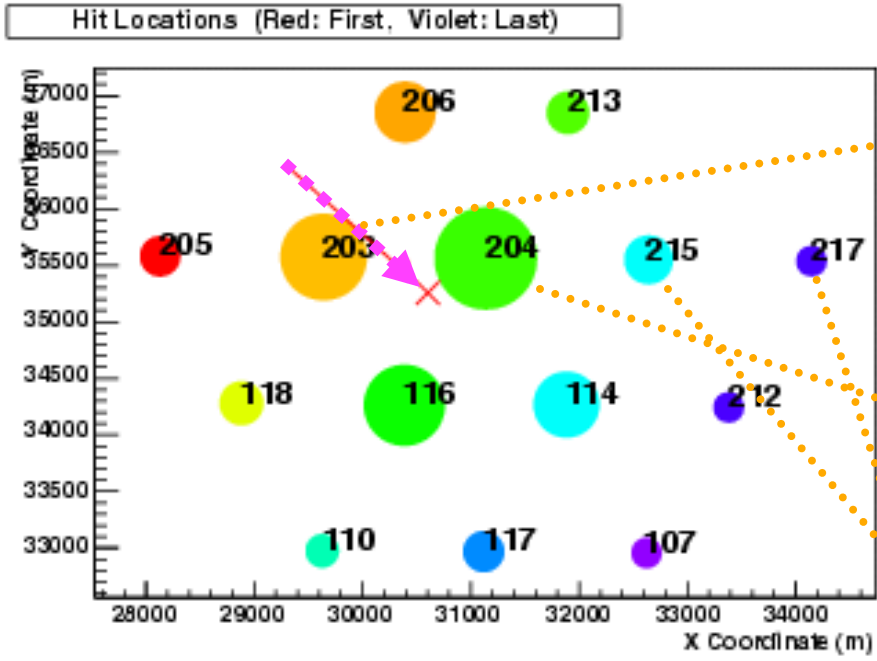
Lateral Distribution Function



$$S(r) = k \left(\frac{r}{700\text{m}} \right)^{-\beta} \left(1 + \frac{r}{700\text{m}} \right)^{-\beta}$$

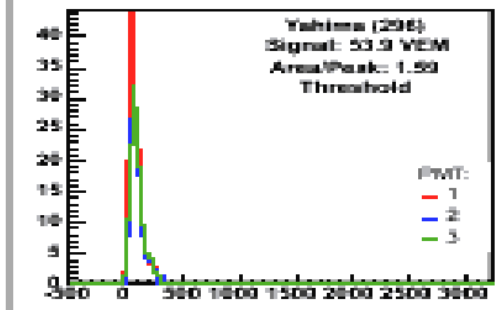
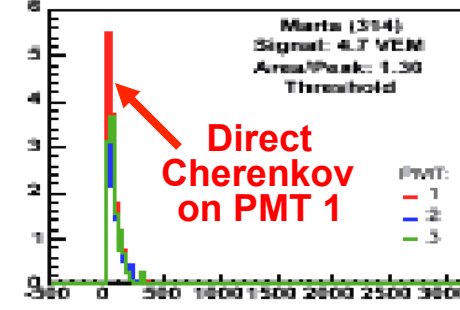
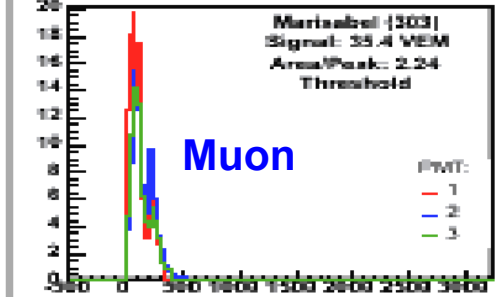
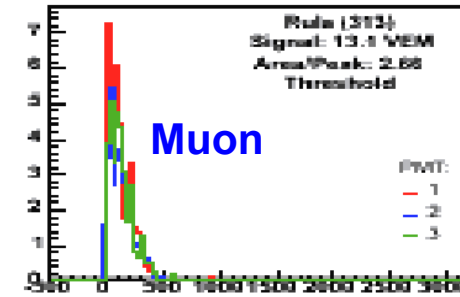
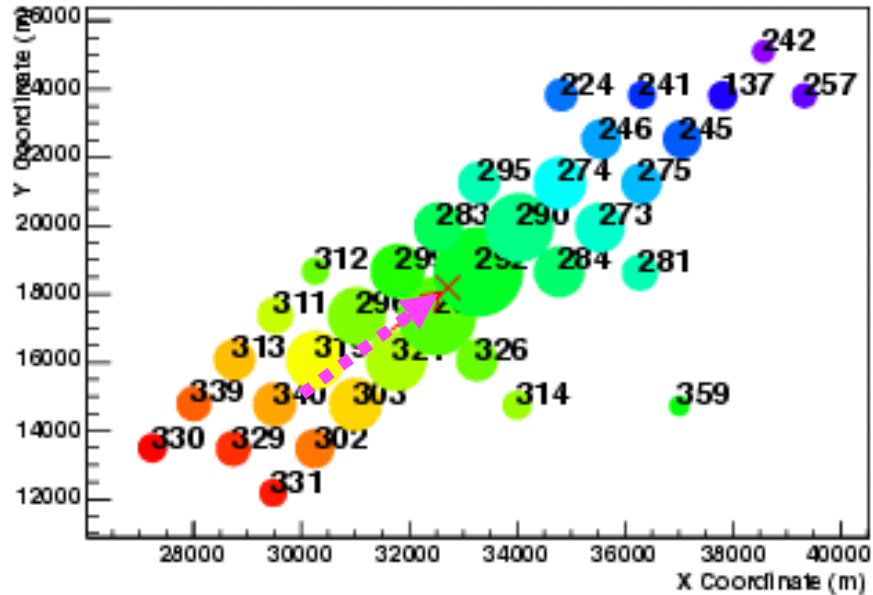
$$E = S(1000)^{1.05} \cdot f(\sec \theta)$$

A Typical Event ("Young" Shower, Zenith $\sim 35^\circ$)

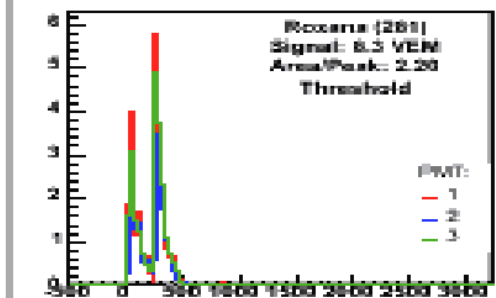
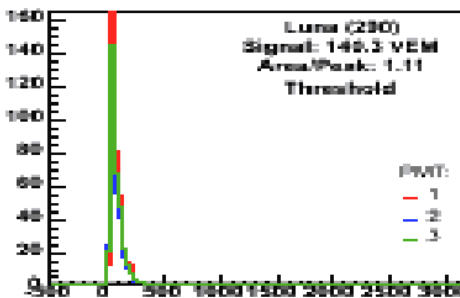
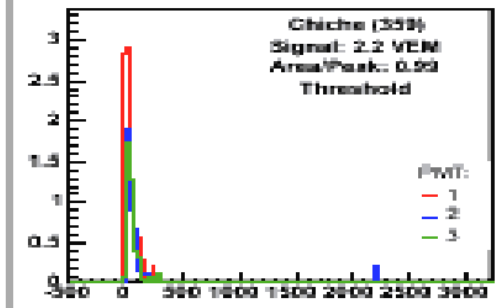
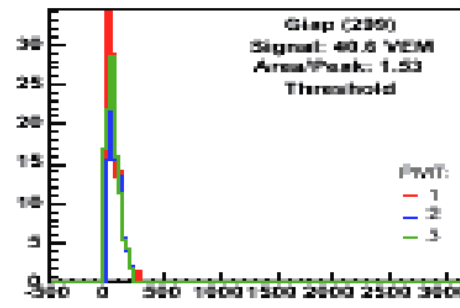
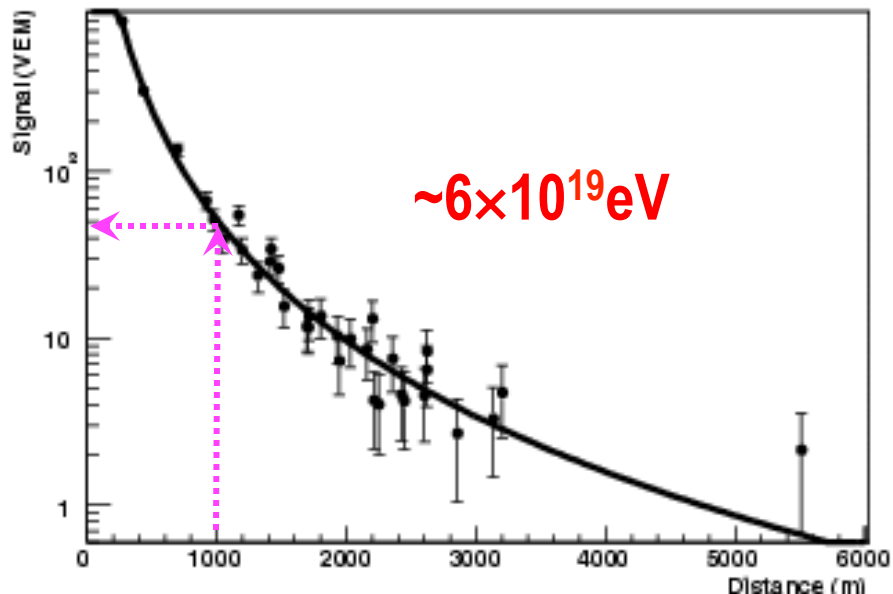


A Typical Inclined Event ("Old" Shower, Zenith $\sim 72^\circ$)

Hit Locations (Red: First, Violet: Last)

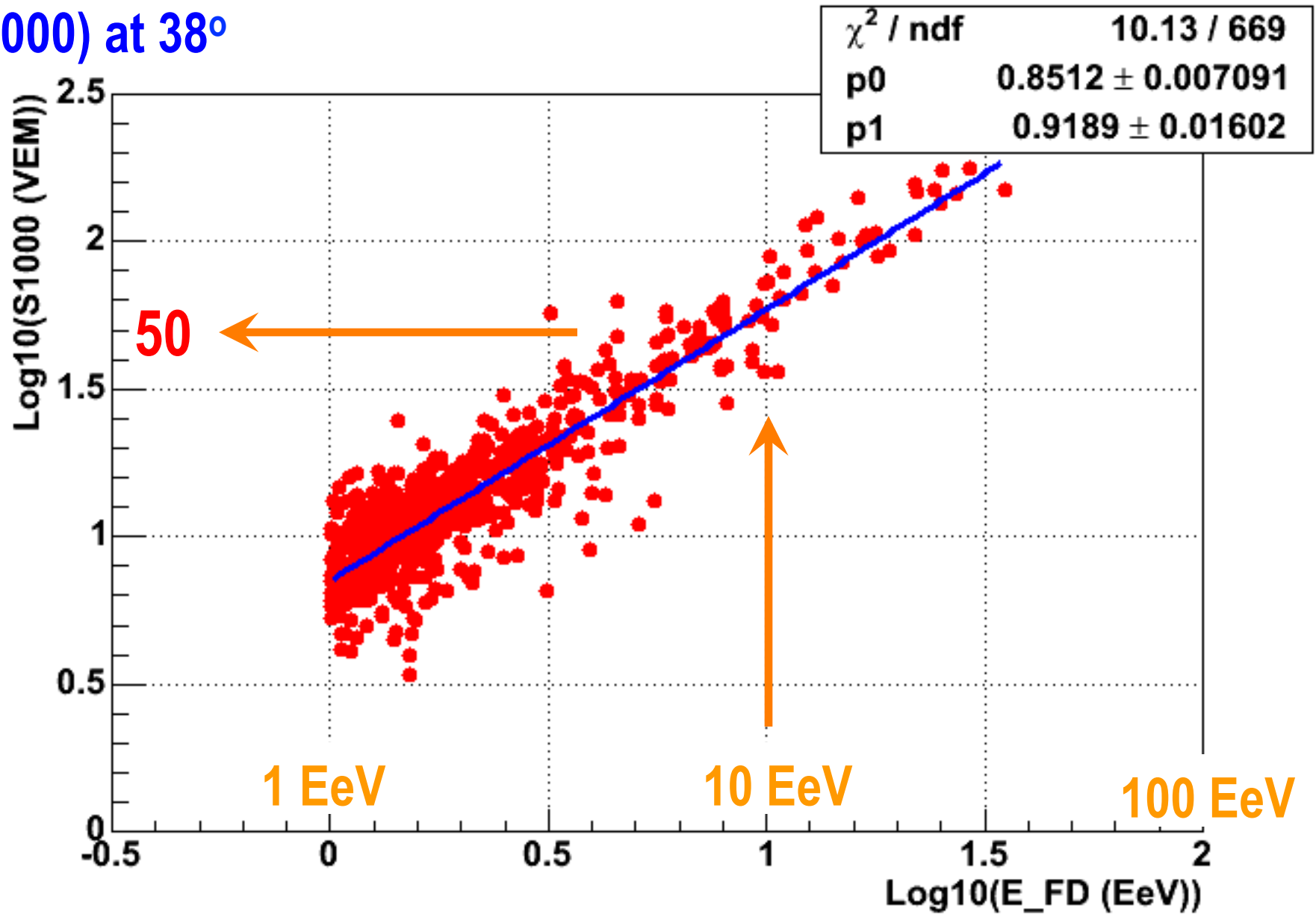


Lateral Distribution Function

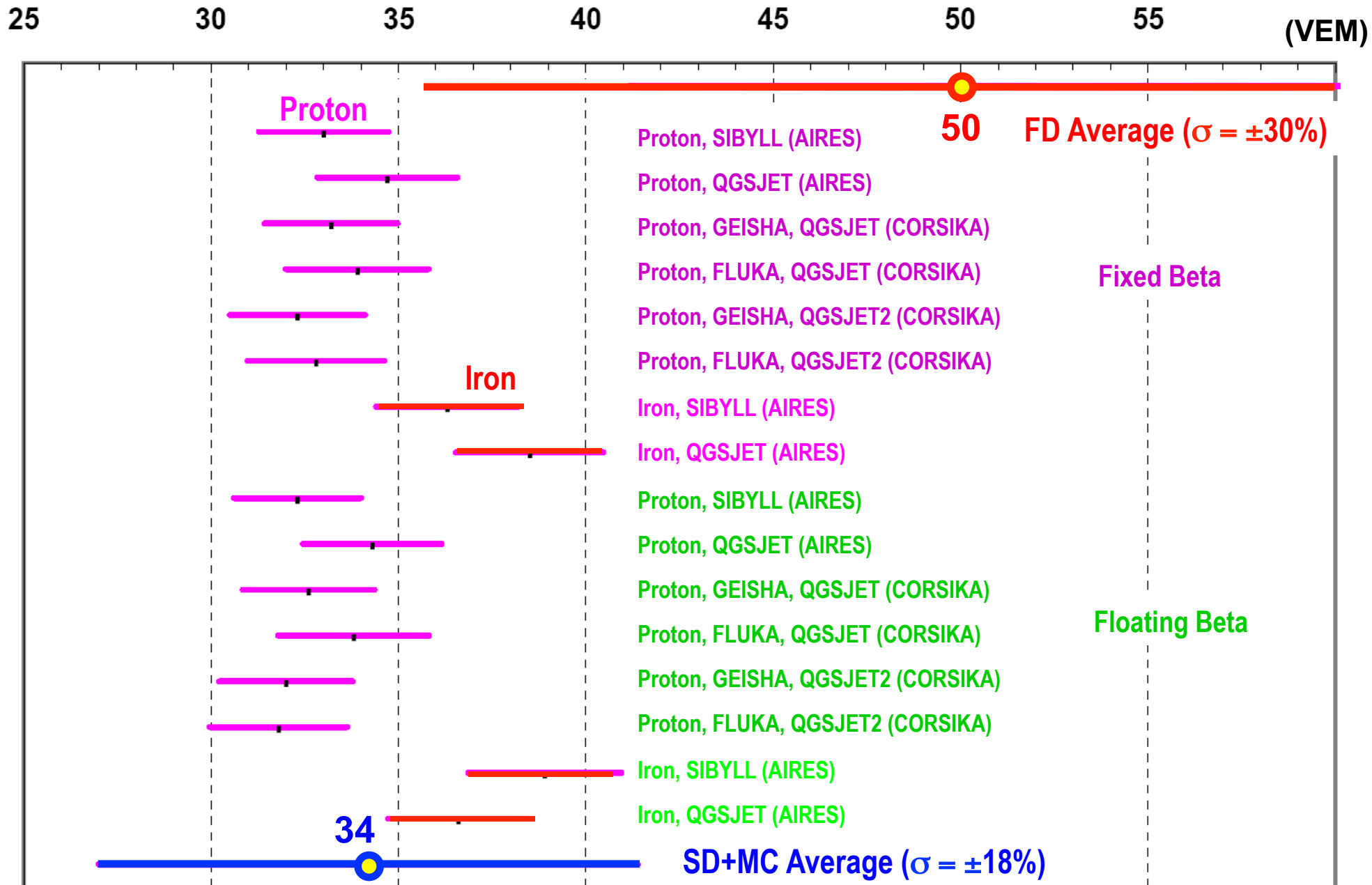


S(1000) at 38° vs. FD Energy

S(1000) at 38°

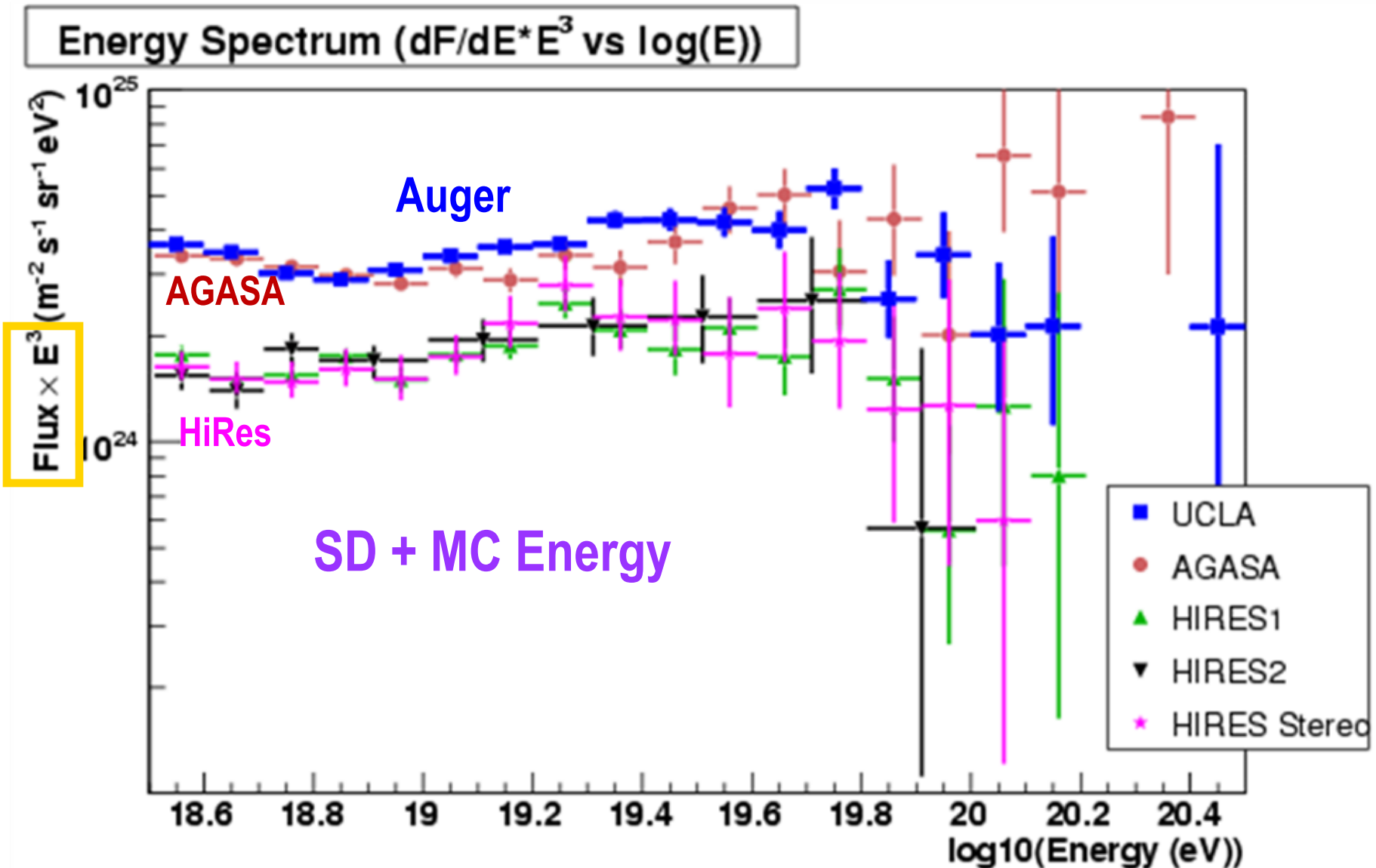


Summary of $S(1000)$ at 38° and 10 EeV

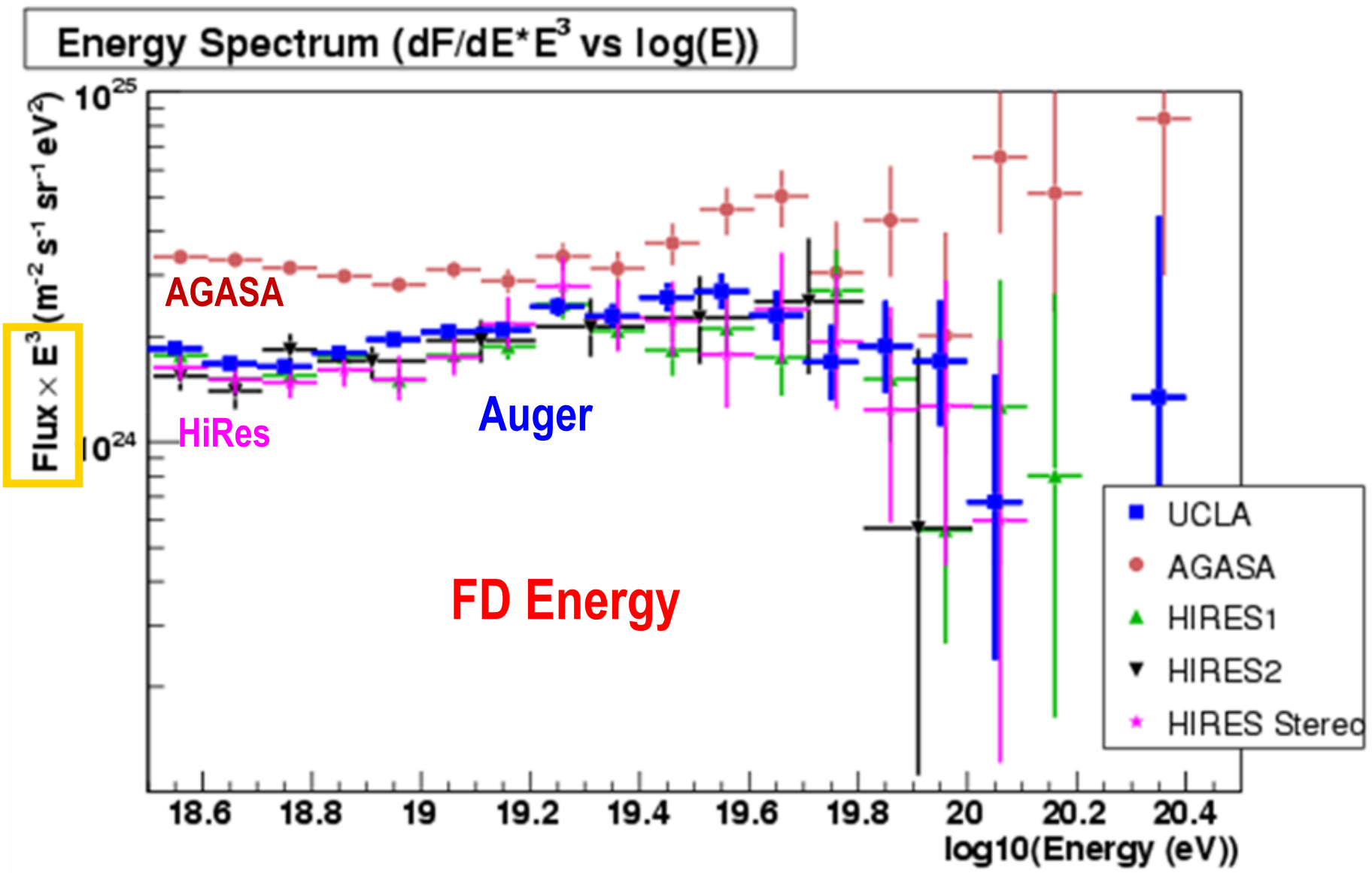


Energy Spectrums

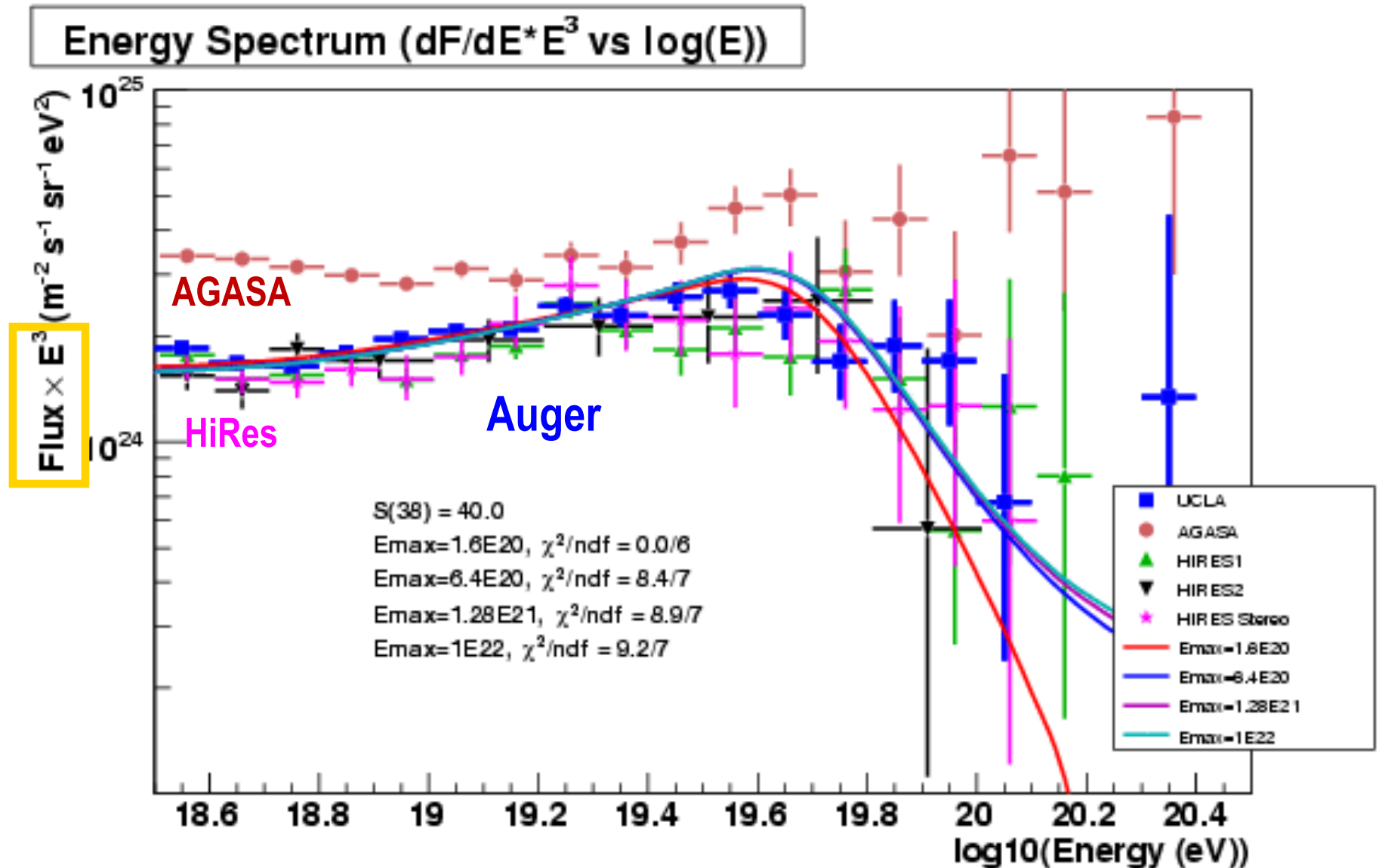
Energy Spectrum $\times E^3$ (SD+MC Energy)



Energy Spectrum $\times E^3$ (FD Energy)



Energy Spectrum $\times E^3$ (fit by proton injection)



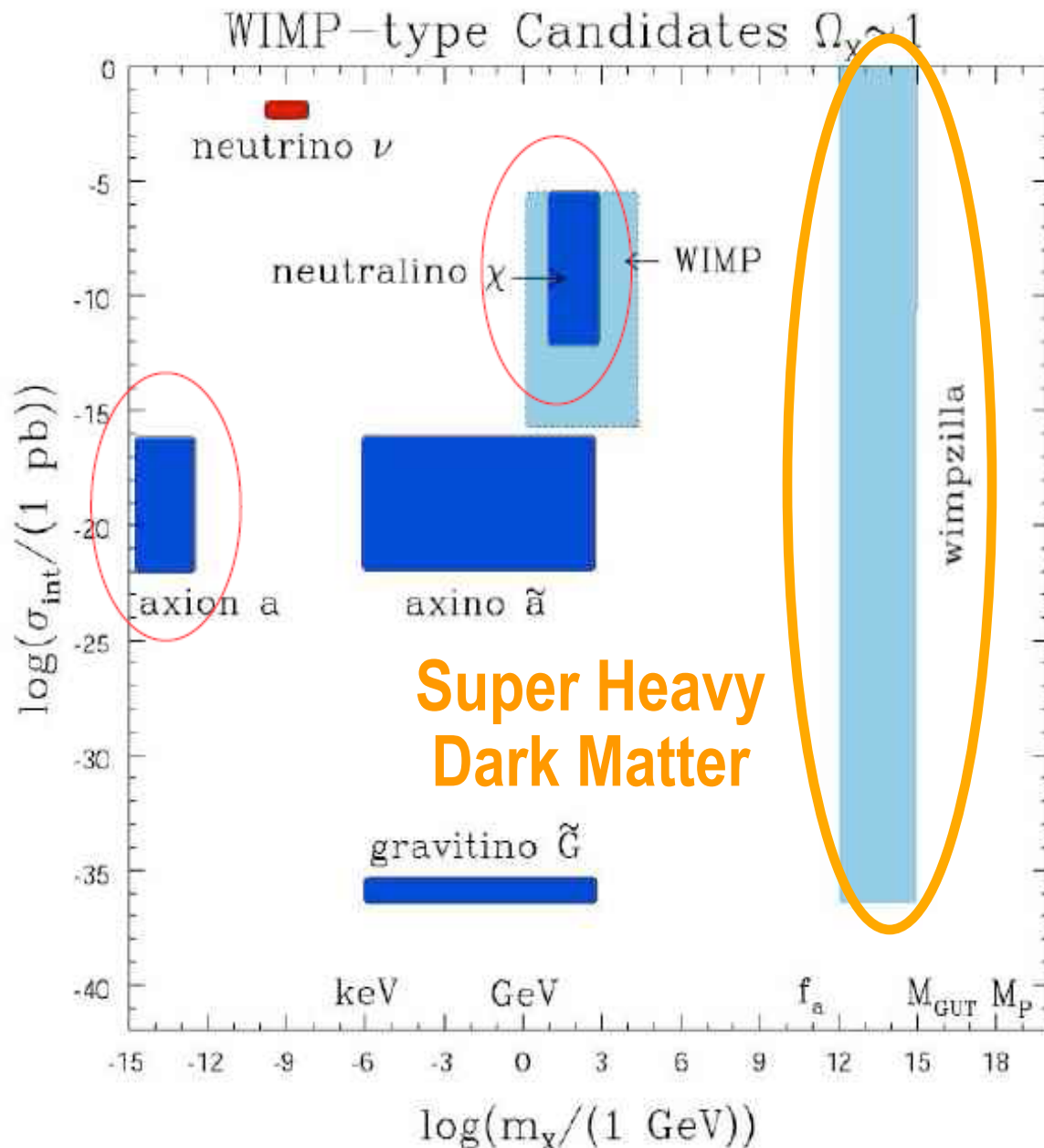
Arisaka, et al, astro-ph/0709.3390

Summary of Energy Spectrum

- Energy spectrum based on **SD+MC Energy** is similar to **AGASA**.
 - a hint of Super-GZK events?
 - but not as many as AGASA observed.
- Energy spectrum based on **FD Energy** is consistent with **HiRes**.
 - fits reasonably well with the GZK cutoff.
 - Injection spectrum of $1/E^{2.6}$.
- So far, the spectrum is consistent with **GZK Cutoff**.

Any Signal from Big Bang? Looking for UHE Photons

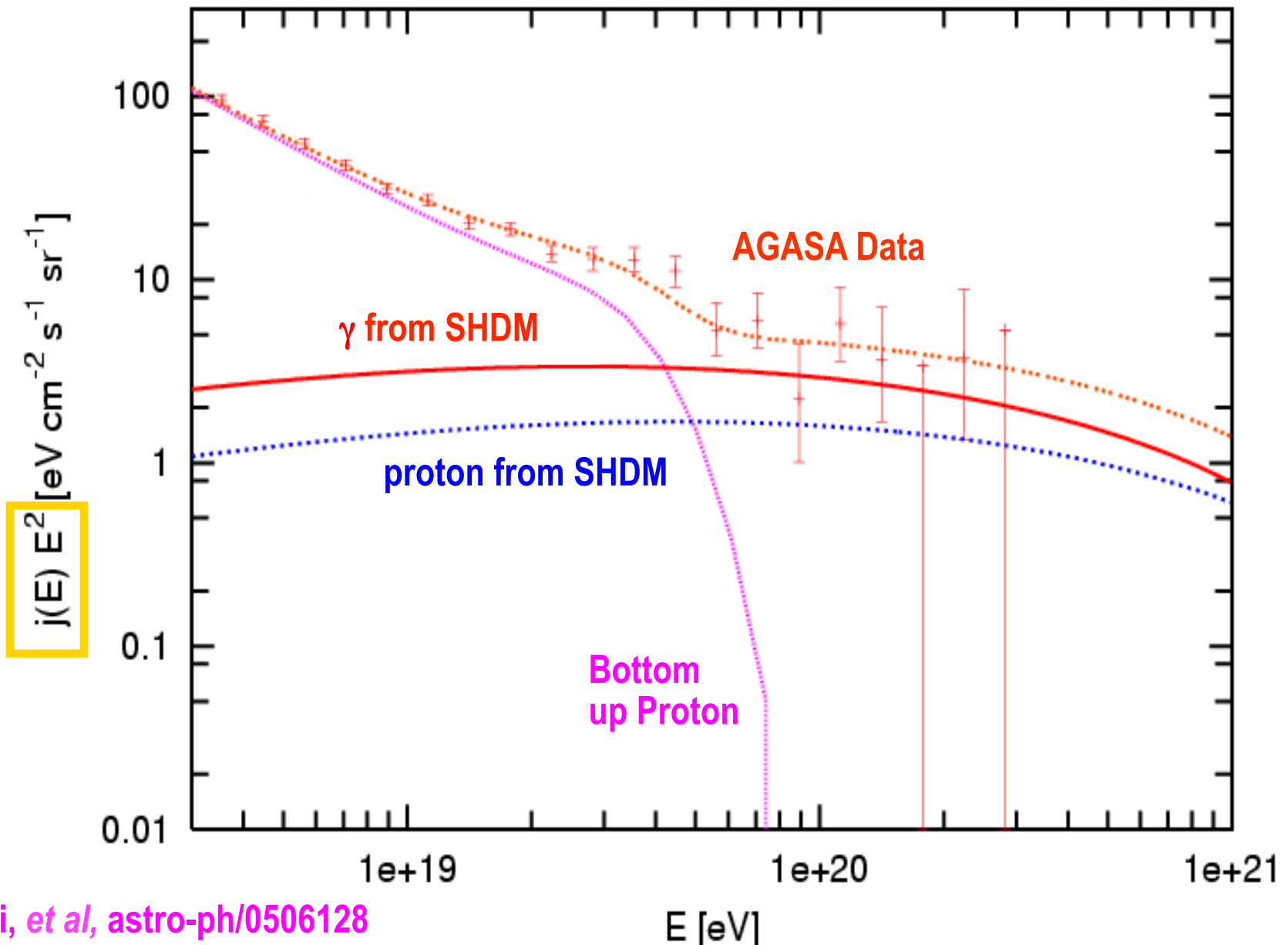
What is Dark Matter?



- neutrino ν – hot DM
- neutralino χ
- “generic” WIMP
- axion a
- axino \tilde{a}
- gravitino \tilde{G}
- wimpzilla,...

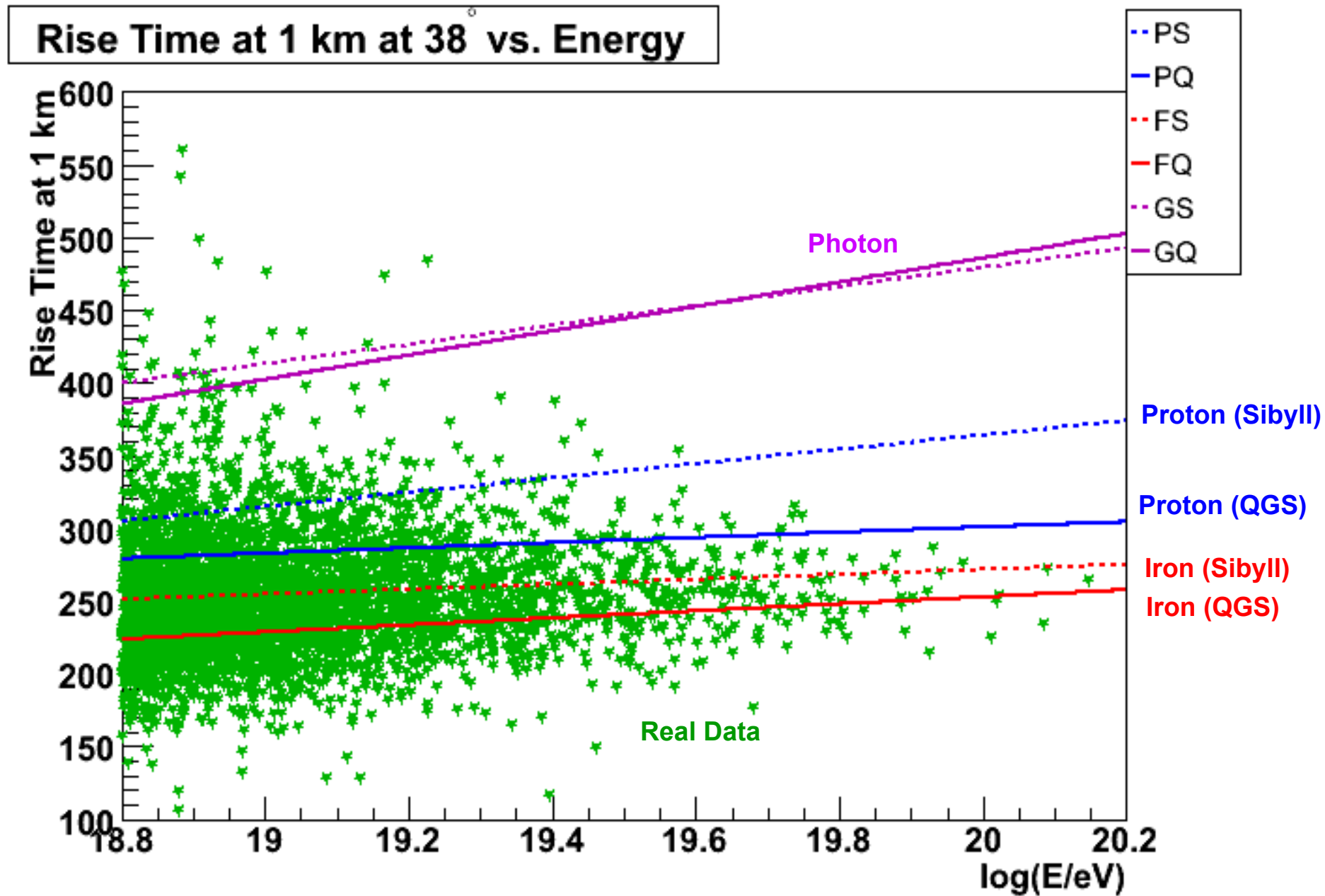
L. Roszkowski

Possibility of photons in AGASA data



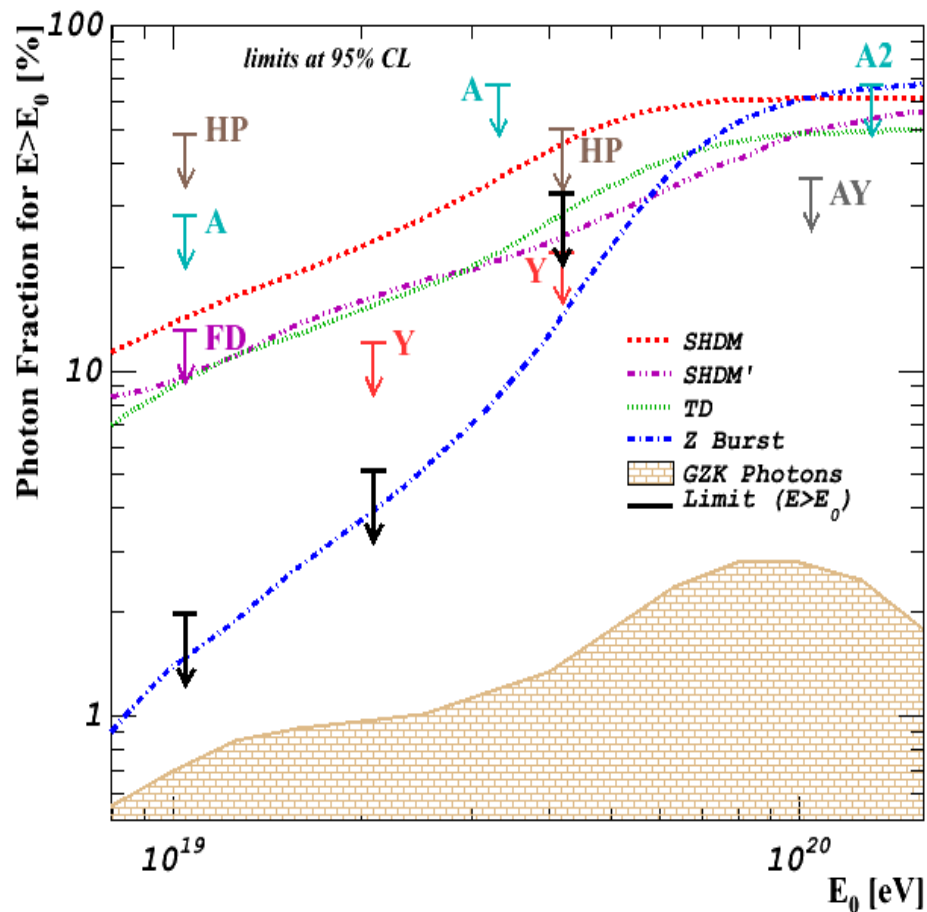
Gelmini, et al, astro-ph/0506128

Risetime vs. Log(E)

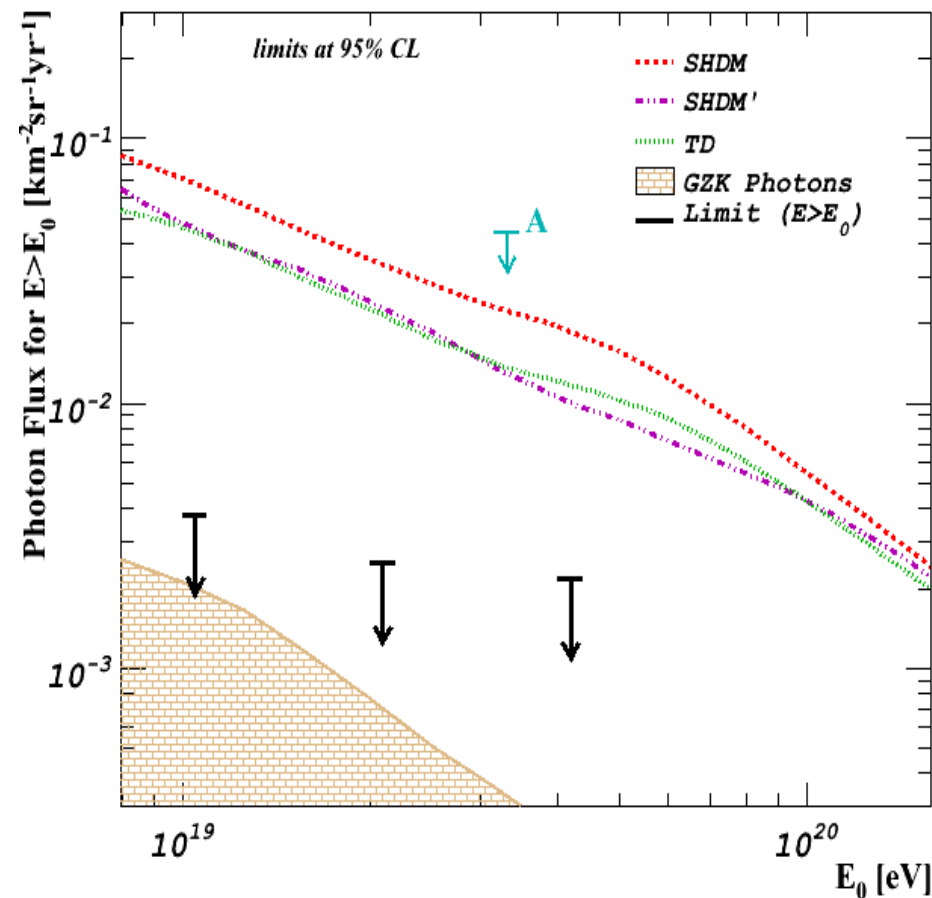


Photon Limit Results

Fraction Limit



Flux Limit

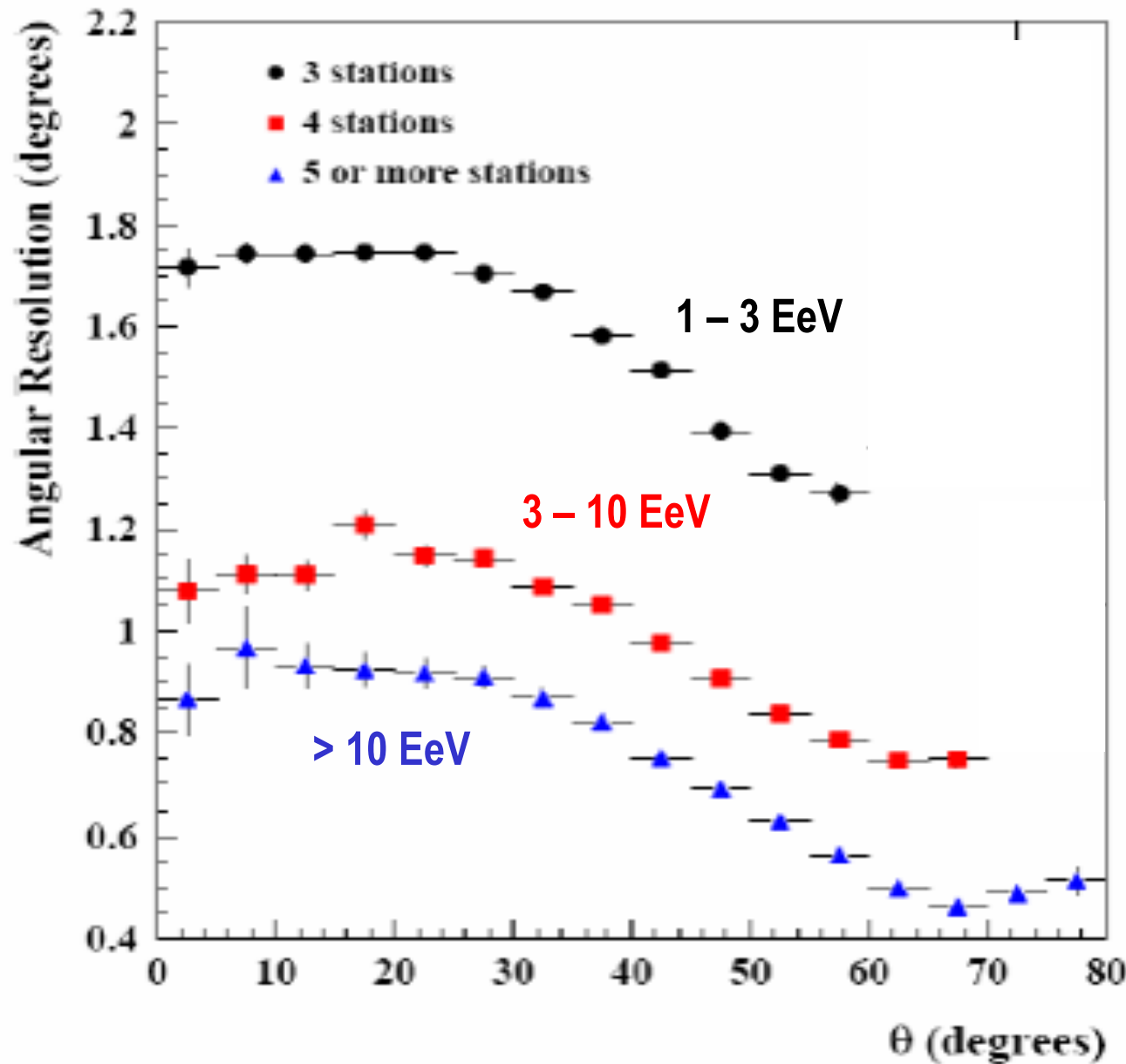


Summary of Photon Flux Limit

- **The combination of the following assumptions is disfavored.**
 - AGASA-like energy spectrum is correct.
 - There are extra Super-GZK events ($> 10^{20}$ eV).
 - These Super-GZK events are from the decay of Super Heavy Dark Matters.
- **Most likely**
 - No Top-down component, at least, majority of UHE cosmic rays are the Bottom-ups.

Angular Distributions

Angular Resolution of Auger SD



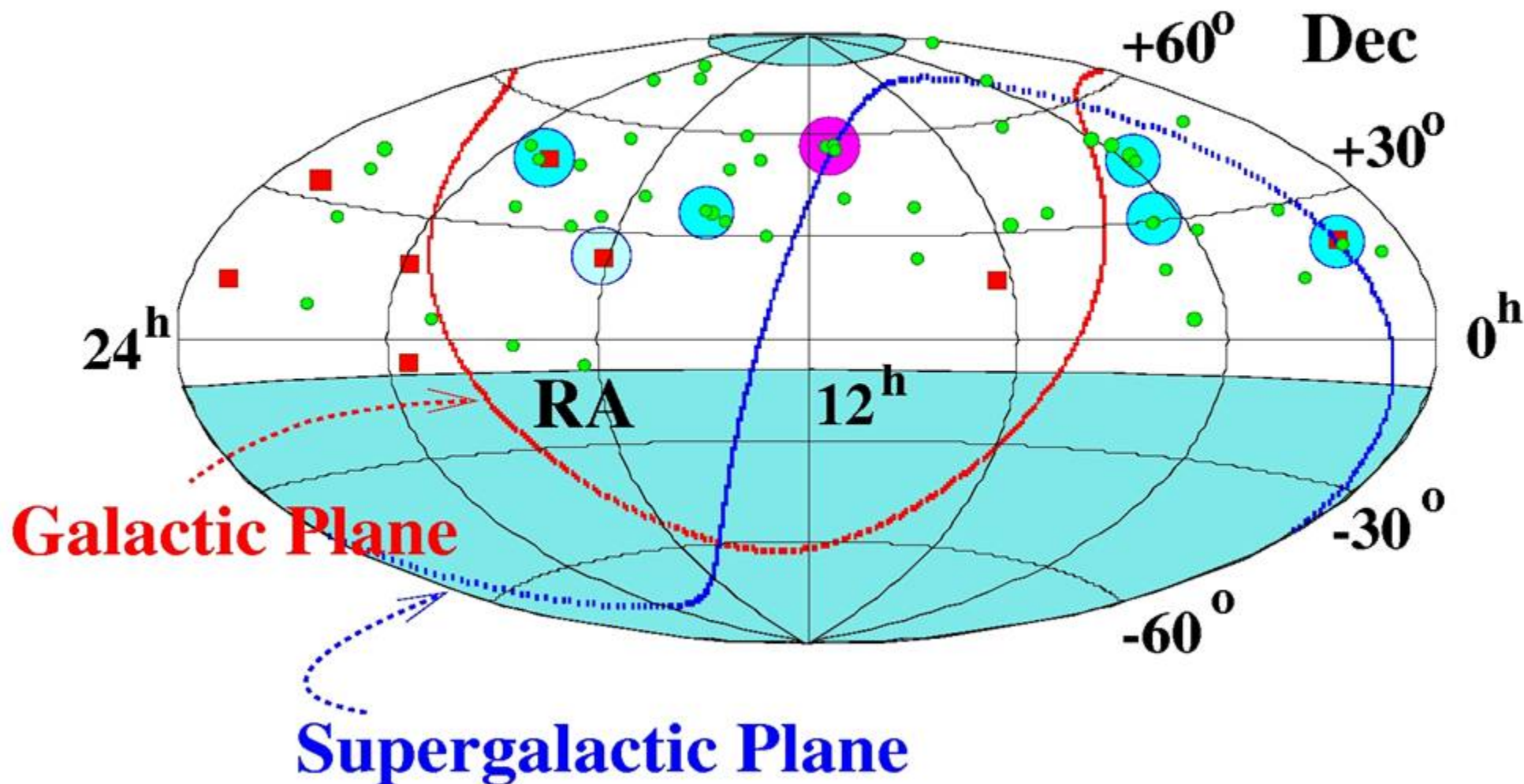
AGASA

HiRes (Stereo)

Clustering of UHECR (>40 EeV) by AGASA

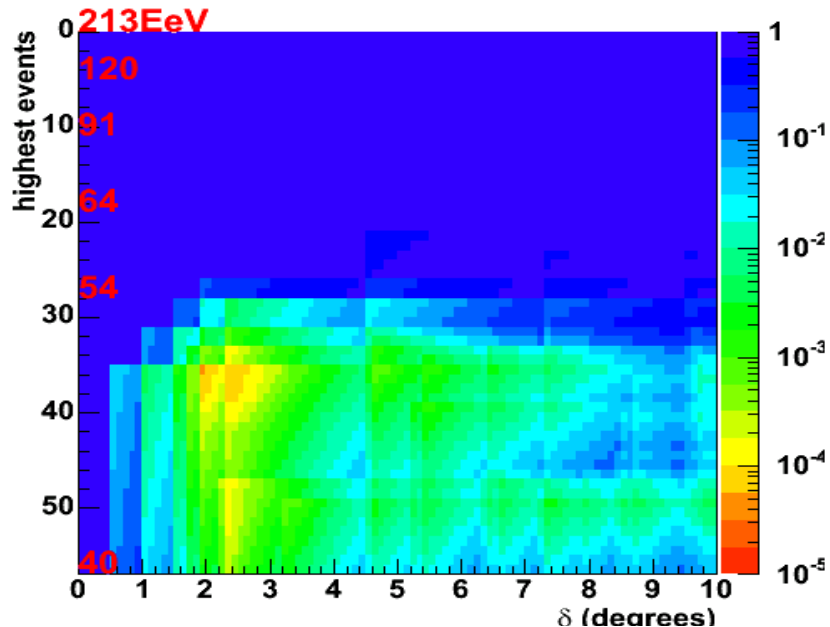
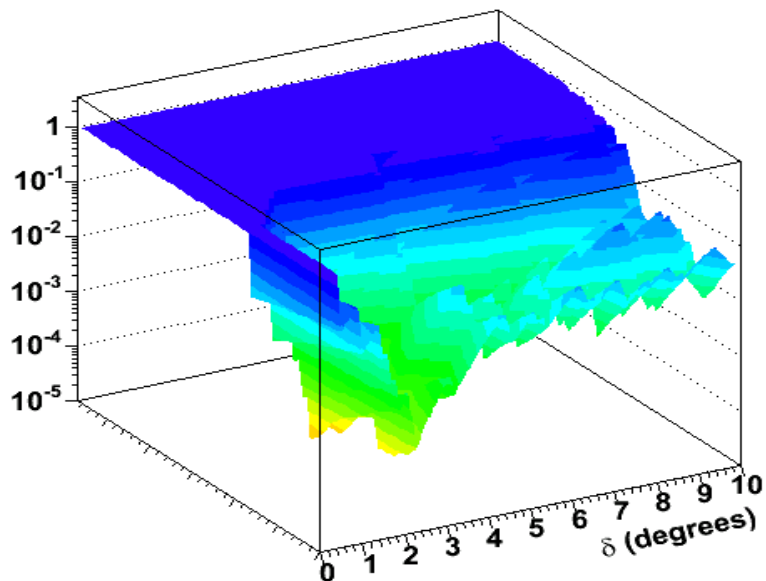
- 6 doublets and 1 triplet within 2.5° cone (out of 56 events)

Equatorial Coordinates

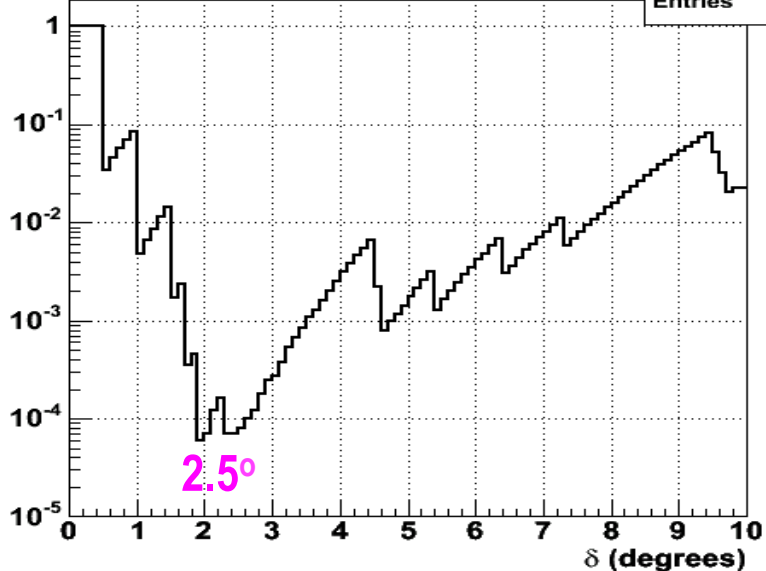


AGASA Auto-Correlation

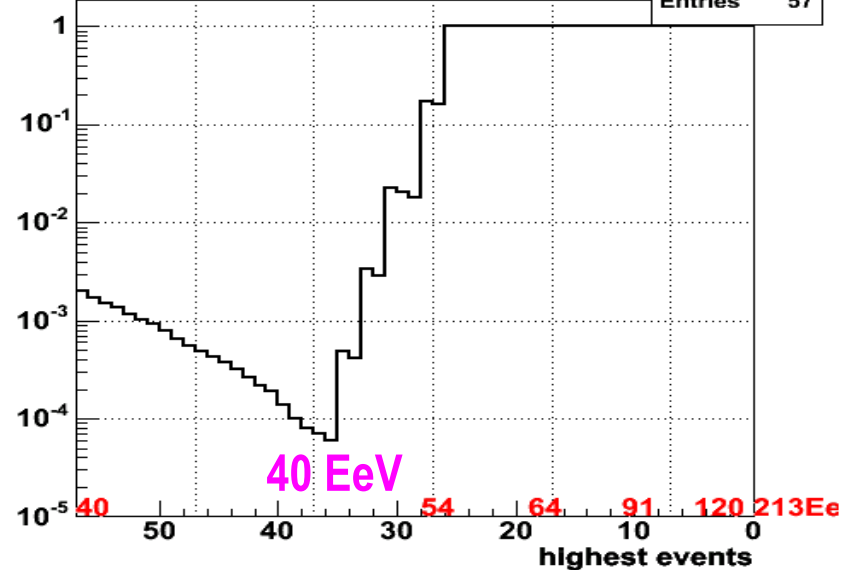
AUTOCORR_AGASA Correlation



AGASA Corr proj X



AGASA Corr proj Y



HiRes Correlation with BL Lacs

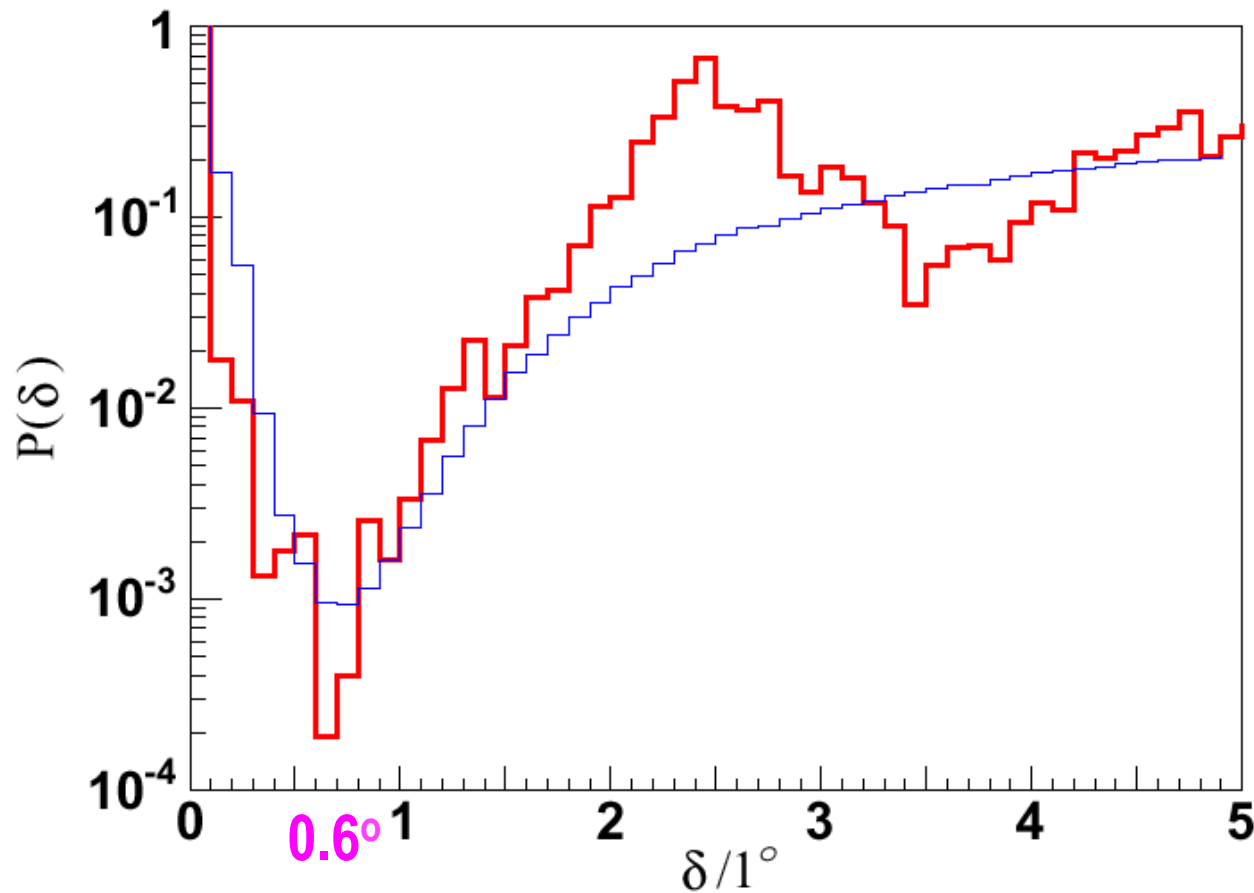
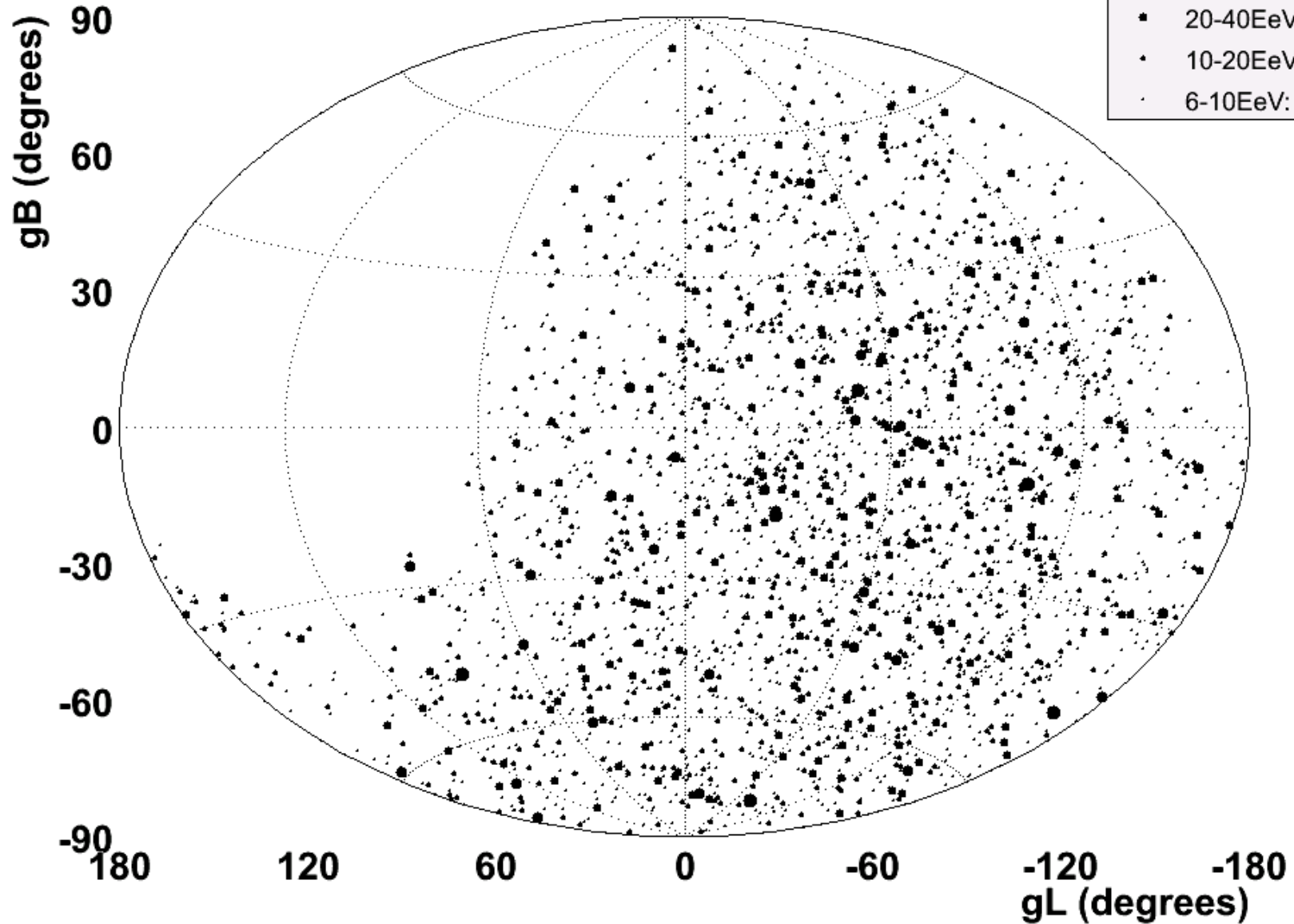


FIG. 3. $P(\delta)$ for the set of 156 BL Lacs and HiRes stereo events. The thick line shows data, the thin line shows $P_{\text{th}}(\delta)$ obtained in the Monte-Carlo simulations in which 9 events are from the BL Lac sources.

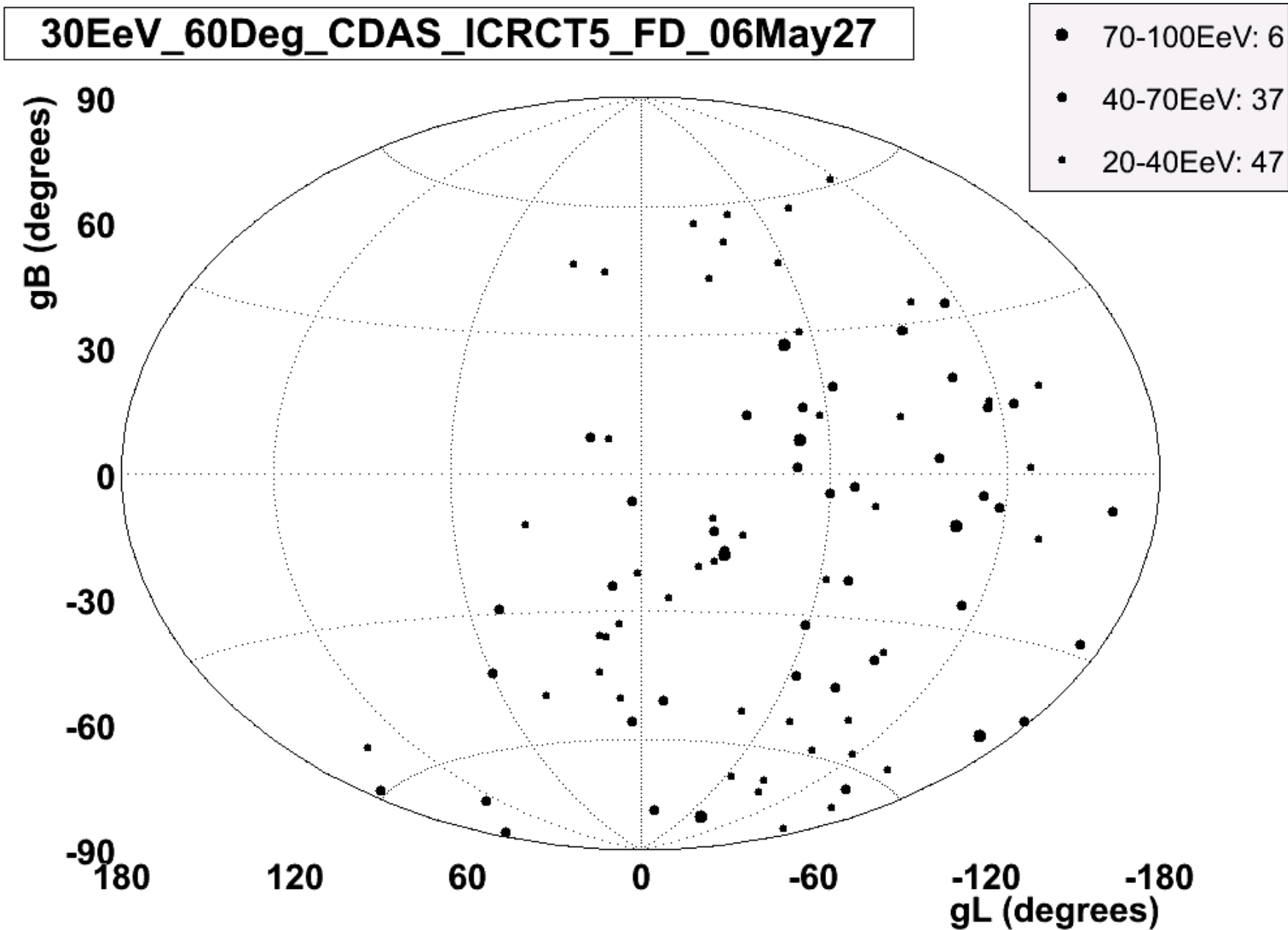
Sky Maps (>6 EeV, $< 75^\circ$)

6EeV_75Deg_CDAS_HEXT5_FD_06Aug31

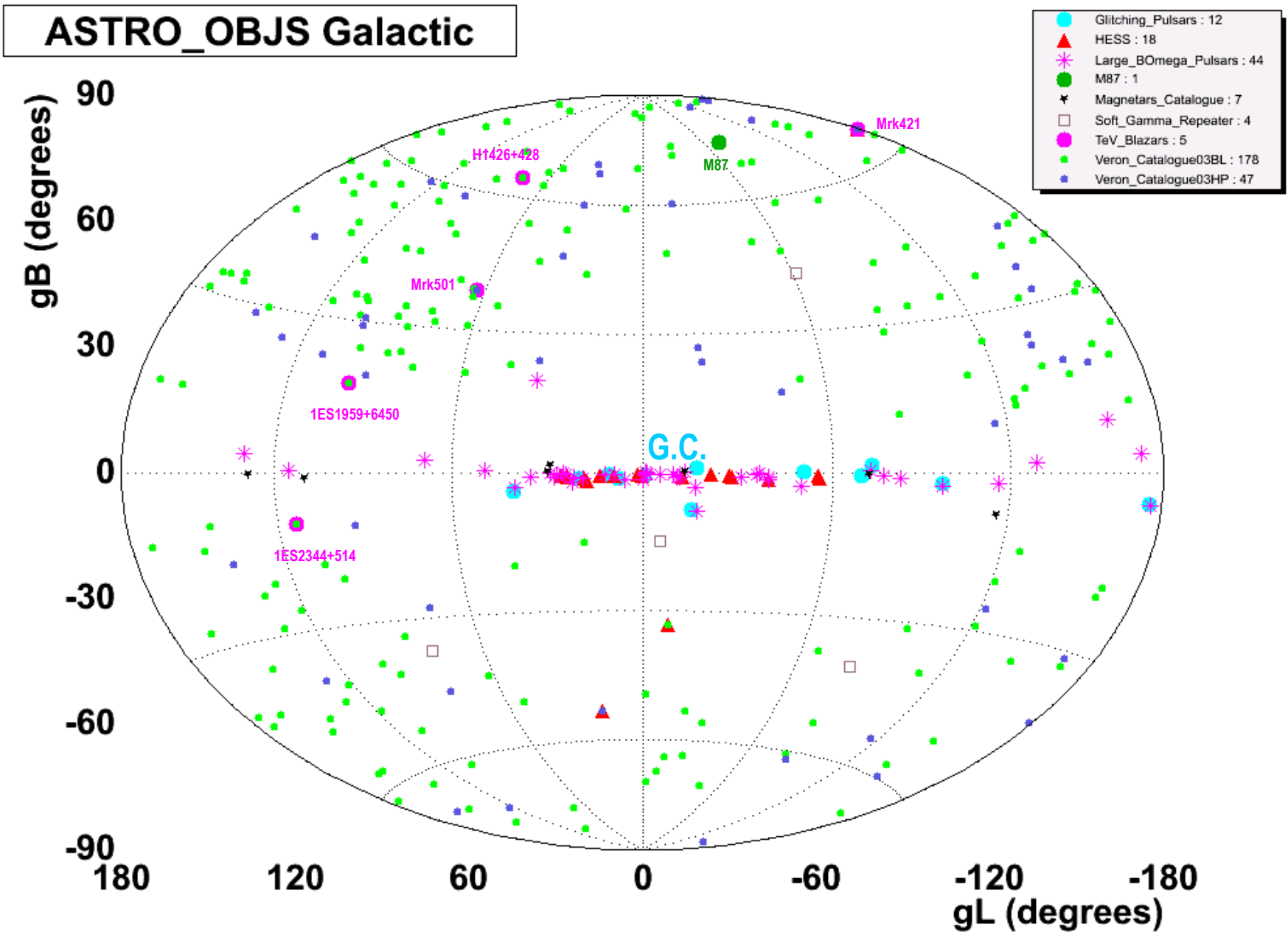
- 70-100EeV: 6
- 40-70EeV: 38
- 20-40EeV: 221
- ◆ 10-20EeV: 771
- 6-10EeV: 1599



Sky Maps (>30 EeV, $< 60^\circ$)

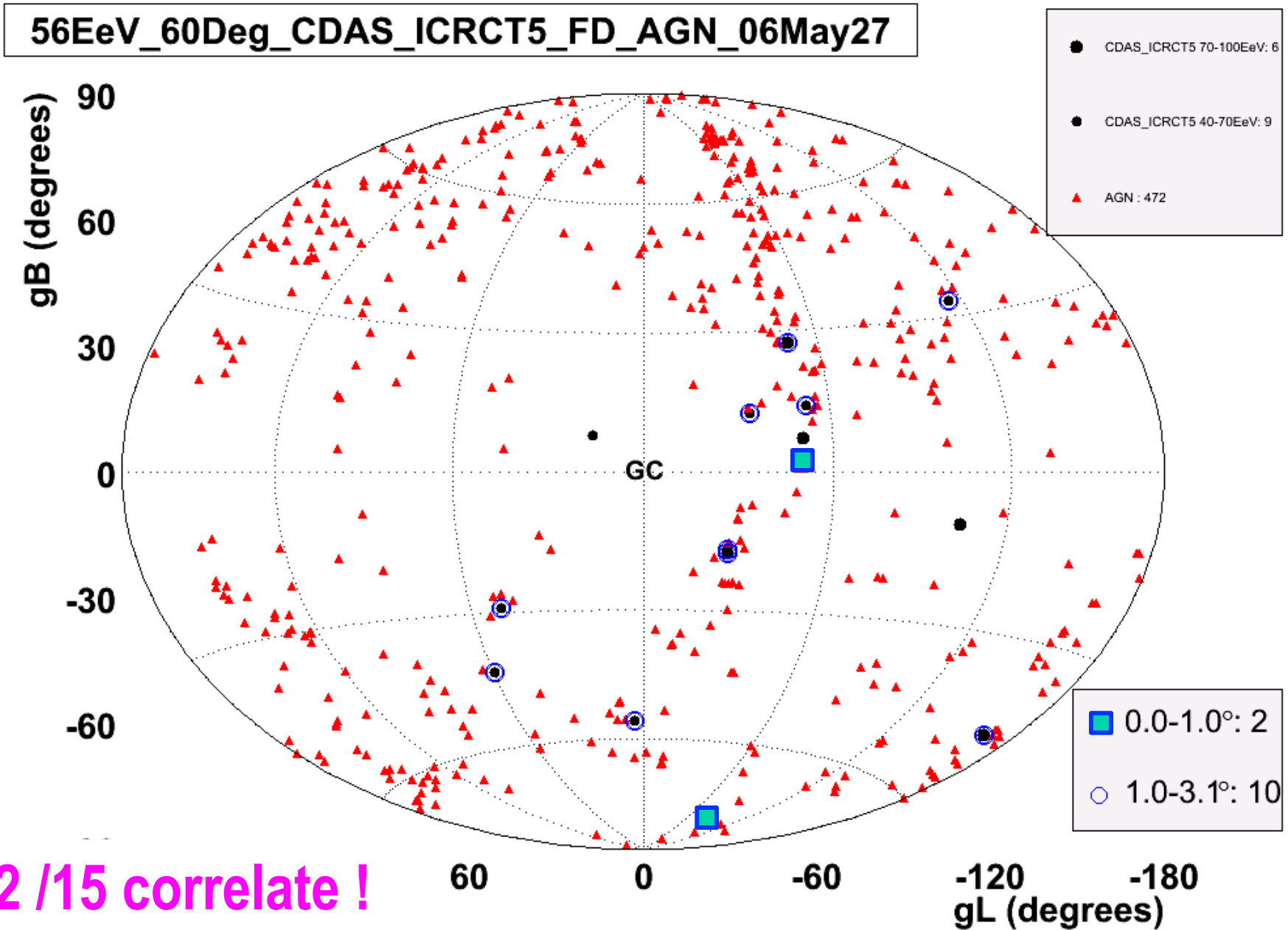


Sky Map of Astronomical Objects



**Then breaking news
from Argentina Group
in May, 2006**

AGN ($z < 0.018$) & Auger Events ($E > 56 \text{ EeV}$)



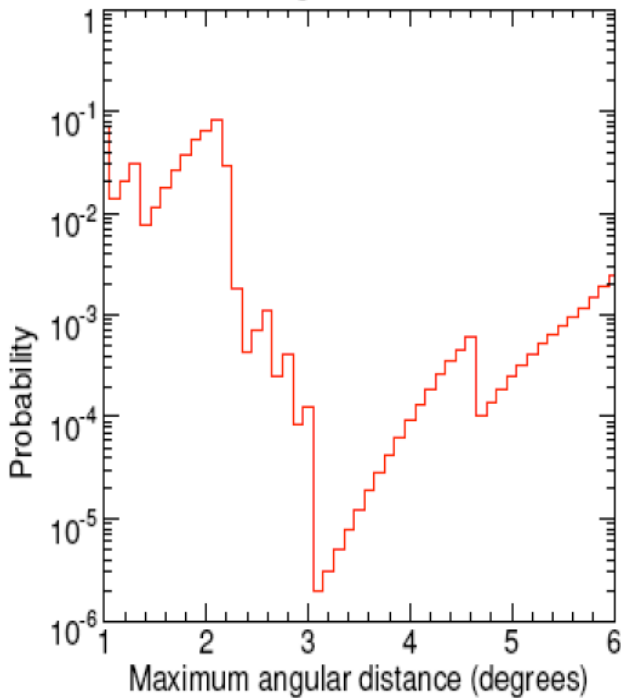
12 / 15 correlate !

AGN Correlation

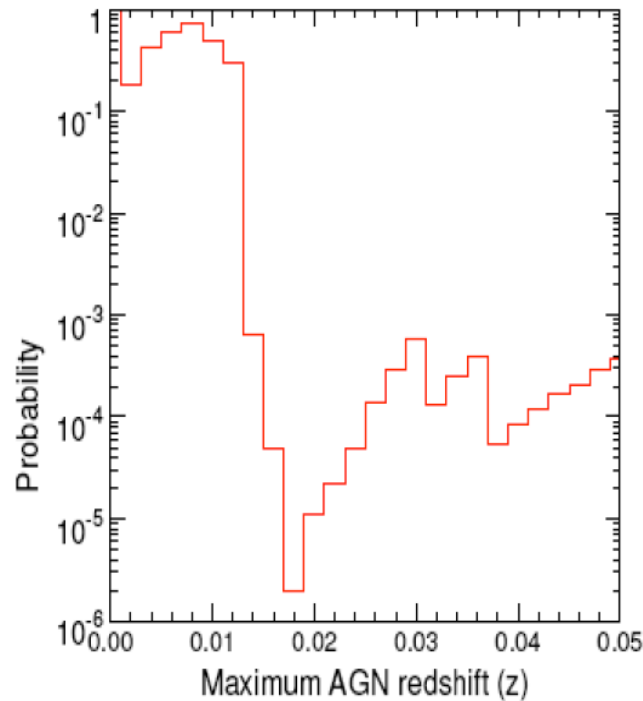
Significance is Maximum at

- Opening Angle $< 3.1^\circ$
- $z < 0.018$ (< 75 Mpc)
- $E > 56$ EeV

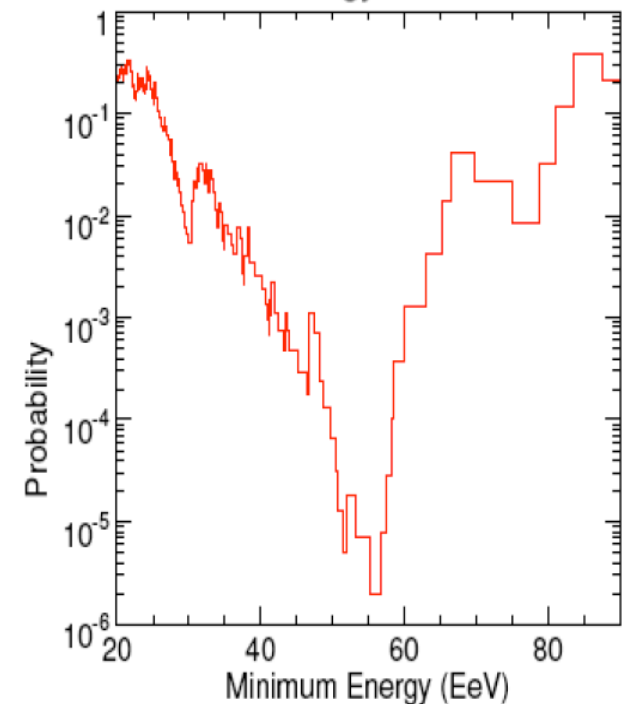
Angular Scan



Redshift Scan



Energy Scan



Argentina Group's Discovery

- **Veron-Cetty 12th edition catalog of AGN**
 - Total 85,221 quasars, 21,737 AGN, 1,122 BL Lac
 - Within 100 Mpc, 694 AGN, only 4 BL Lacs
 - Identified via optical observations, including recent SDSS
- **Correlation with cosmic rays maximized at**
 - $Z < 0.018$ (< 75 Mpc, 472 AGN)
 - $\theta < 3.1^\circ$
 - $E > 56$ EeV
- **Probability**
 - $p = 21\%$ for each correlation
 - **12 out of 15** UHECR correlate. (only expect 3.2 / 15)
 - $P \sim 10^{-6}$ but a posteriori

Independent Sequential Test

➤ June 2006

- Auger collaboration agreed to freeze the cuts and analysis procedure.
- Agreed to publish, once CL > 99% was realized for the new independent data set.

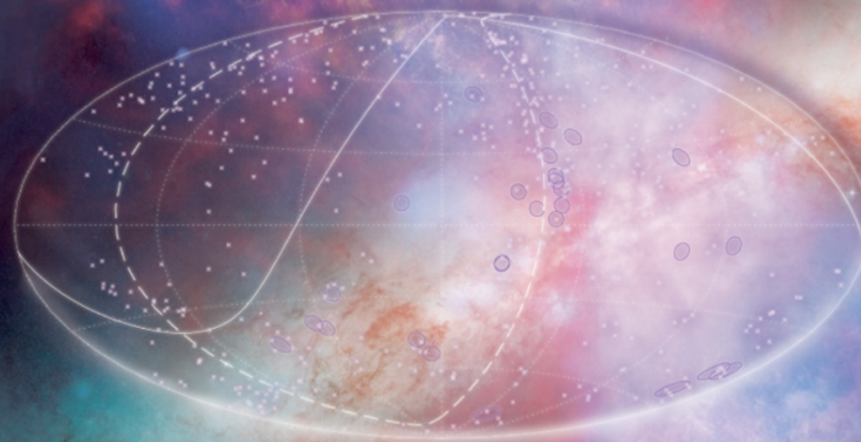
➤ August 31, 2007

- **8 / 13** new events correlated. (2.7 / 13 expected)
- A priori (unbiased) isotropic probability ~ **0.17%**
- This *a priori* analysis establishes the anisotropy of the UHE Cosmic Rays with at least 99% CL.

➤ Submitted a paper to “Science”

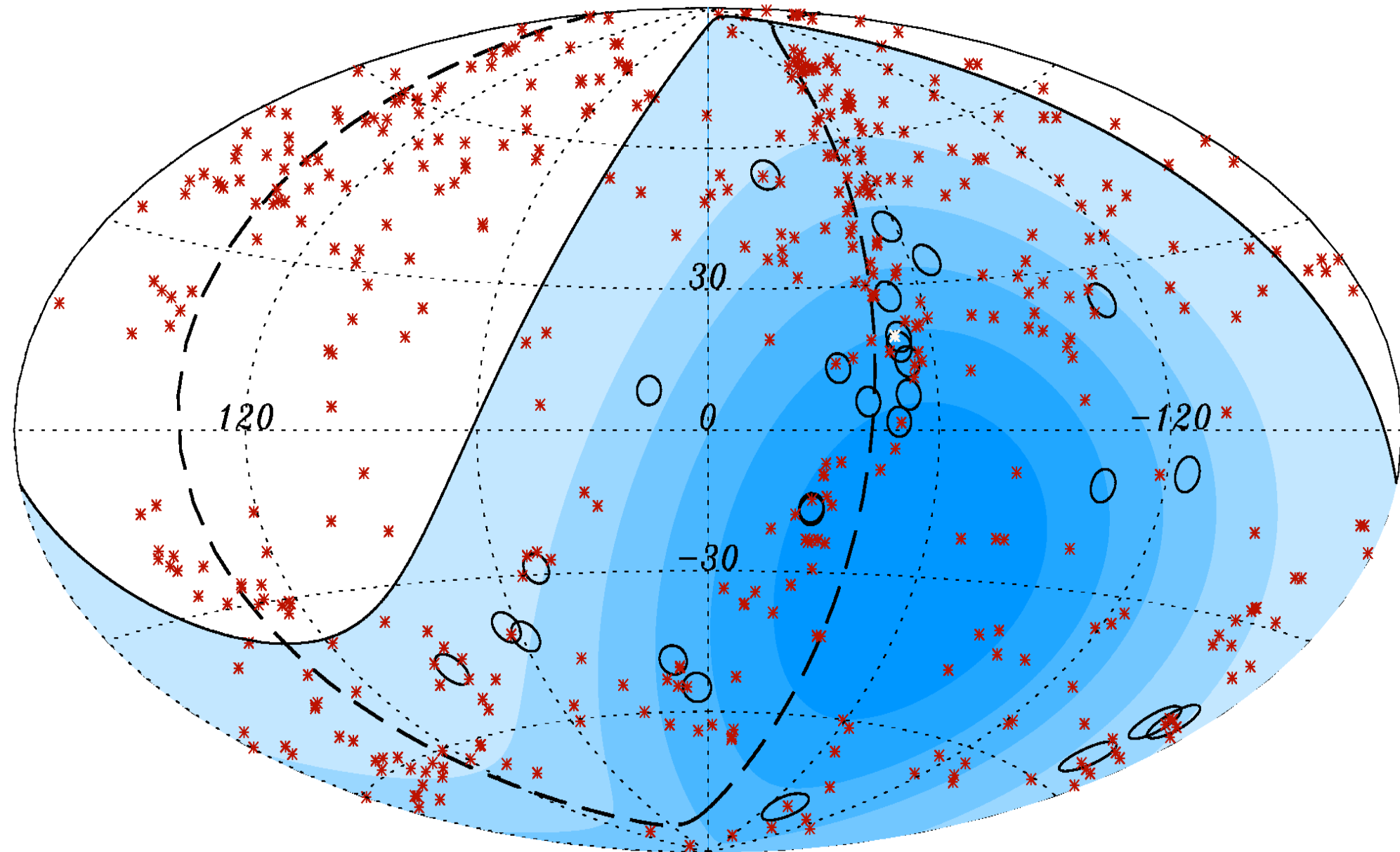
Science

9 November 2007 | \$10

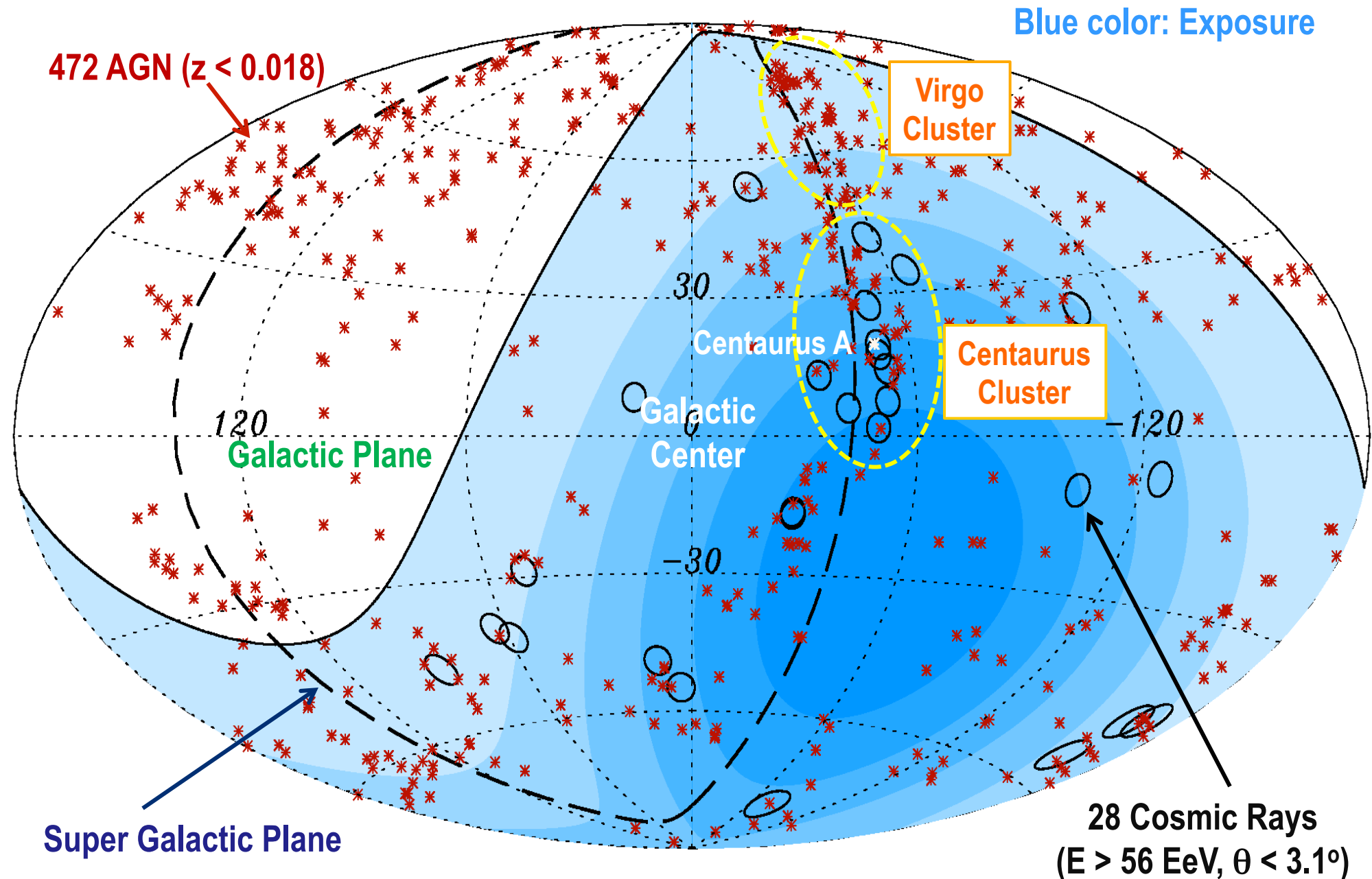


 AAAS

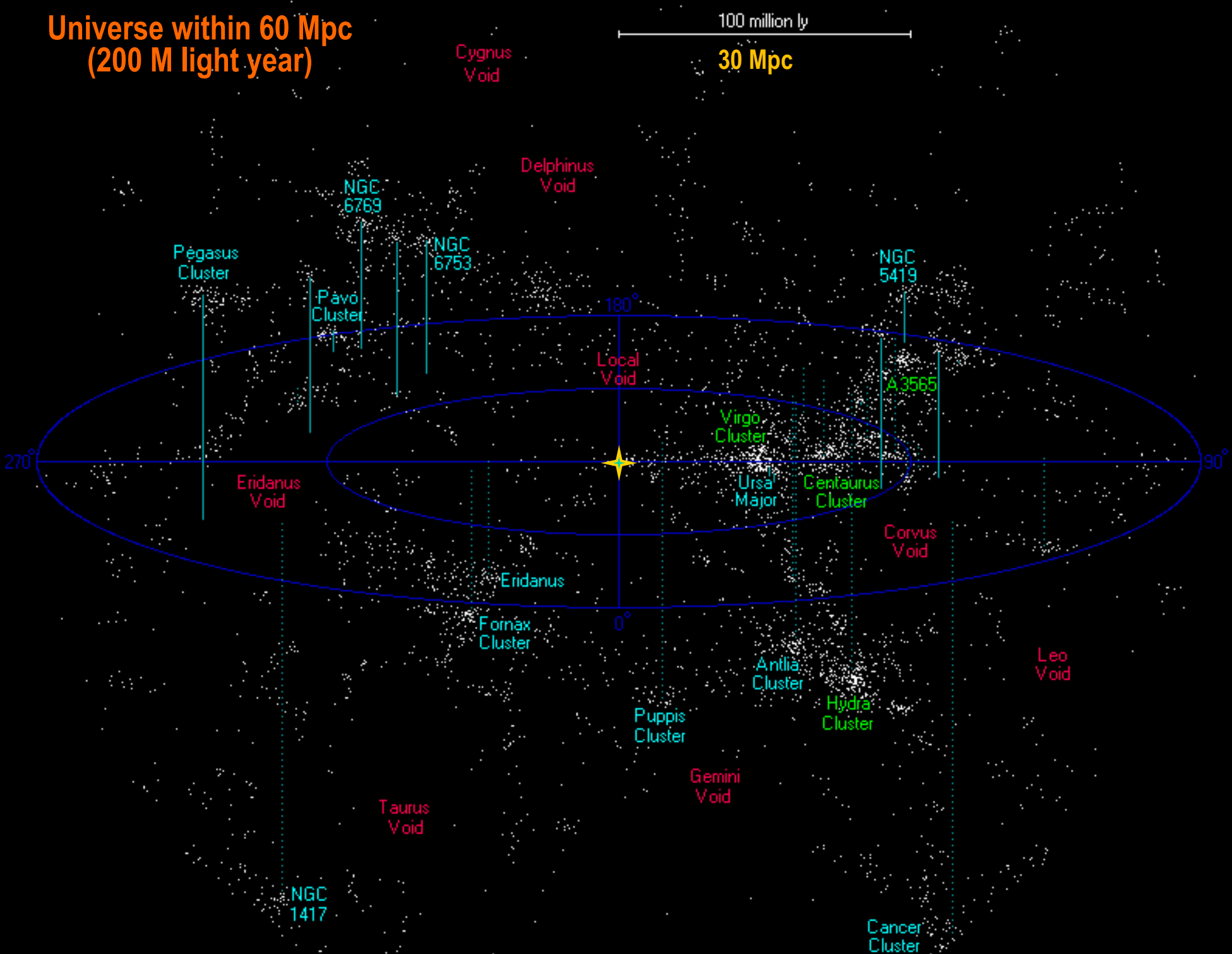
AGN Correlation in galactic coordinates



AGN Correlation in galactic coordinates

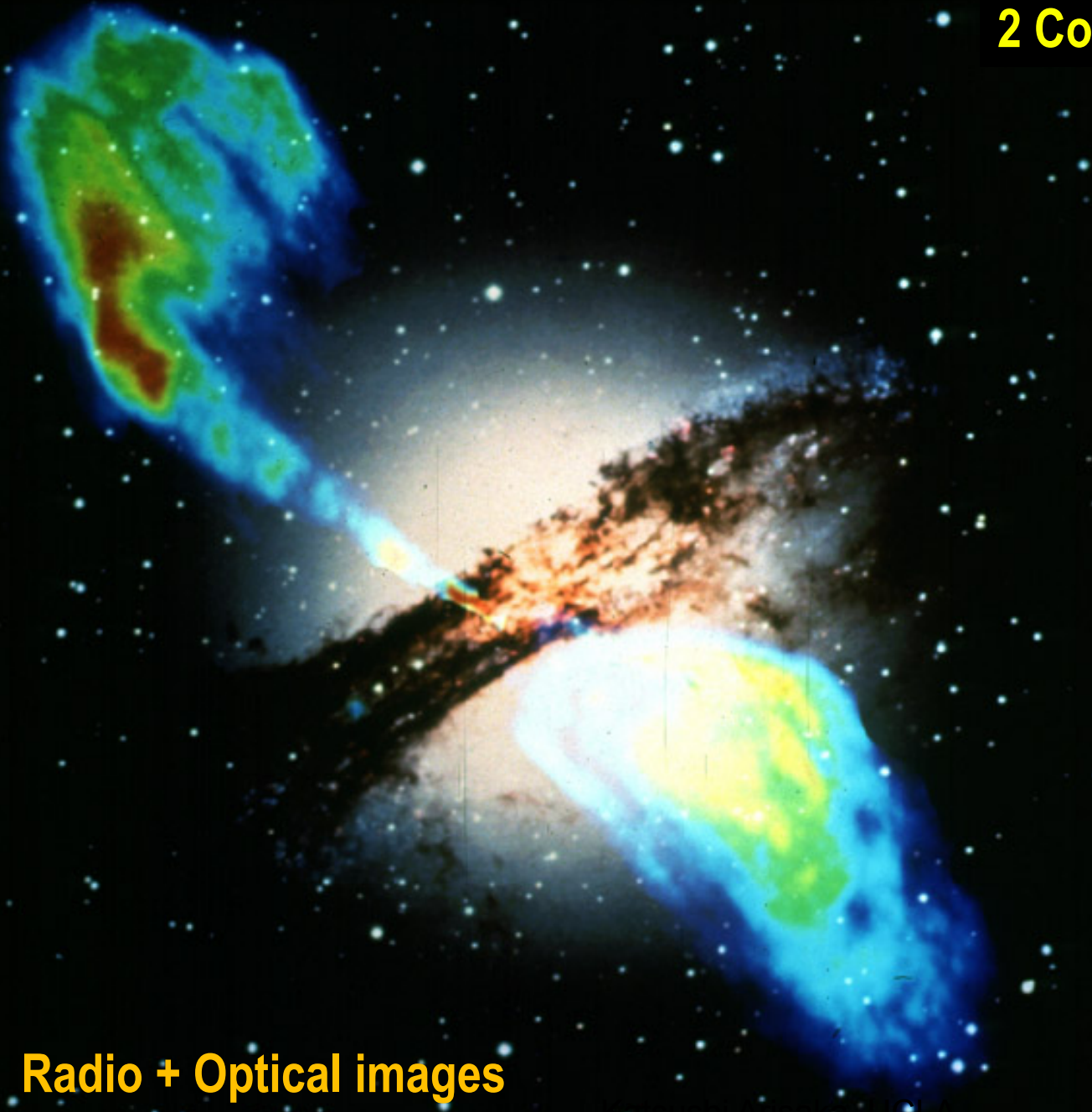


Universe within 60 Mpc (200 M light year)



Centaurus A (4 Mpc, 12 M light year)

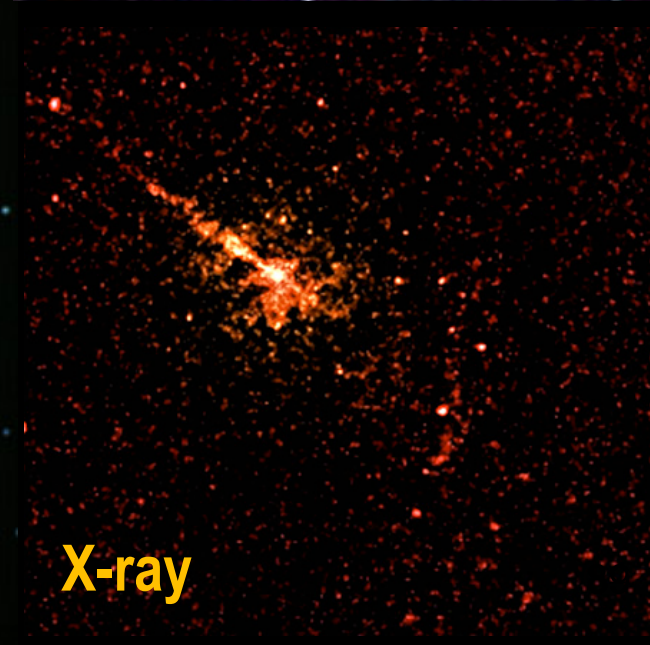
2 Cosmic Rays correlated.



Radio + Optical images

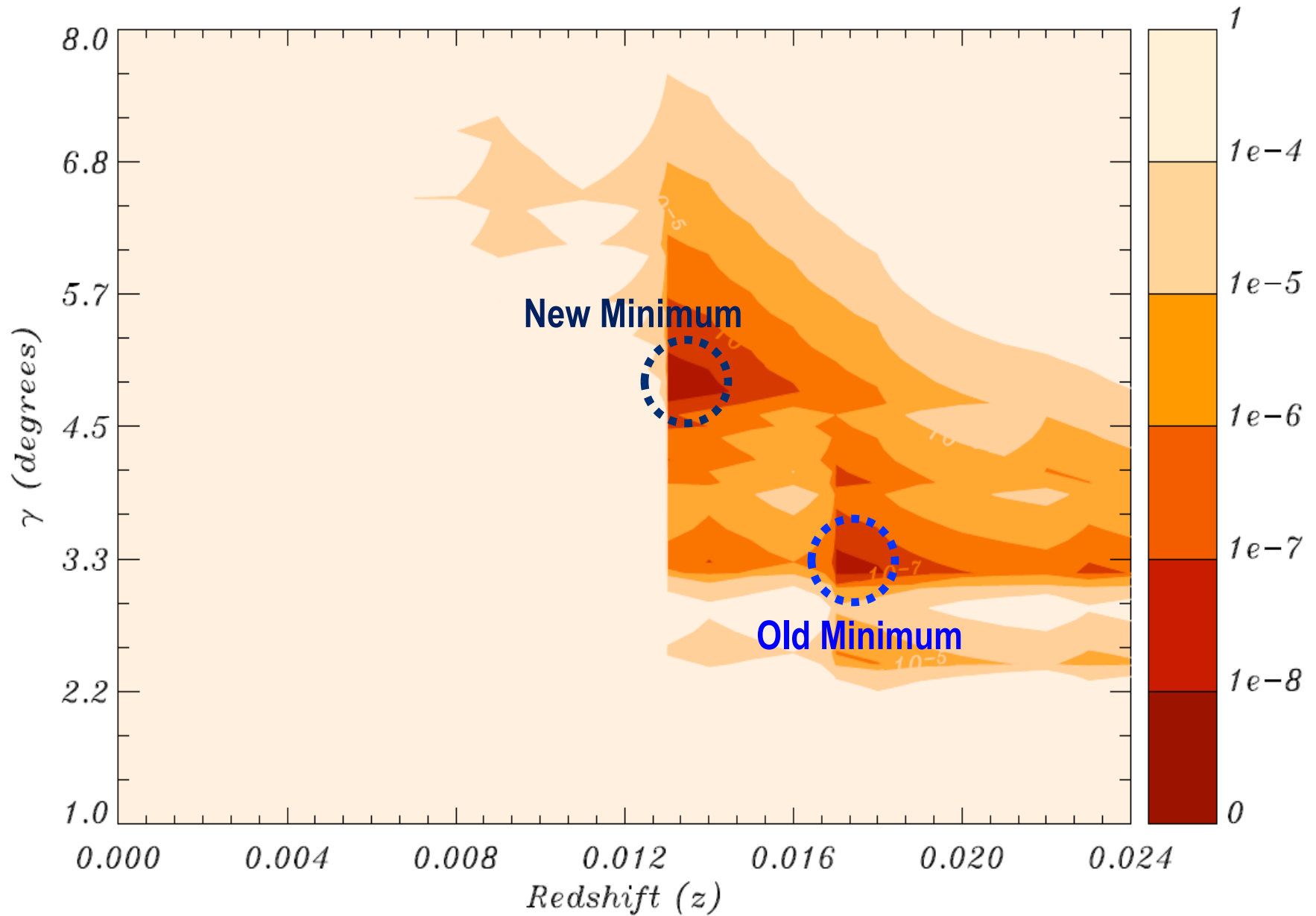


Infrared



X-ray

Scan over all the data ($E > 56 \text{ EeV}$)



Summary

- **Correlation with AGN established at >99% CL.**
 - $Z < 0.018$ (< 75 Mpc)
 - $\theta < 3 - 5^\circ$
 - $E \sim > 60$ EeV

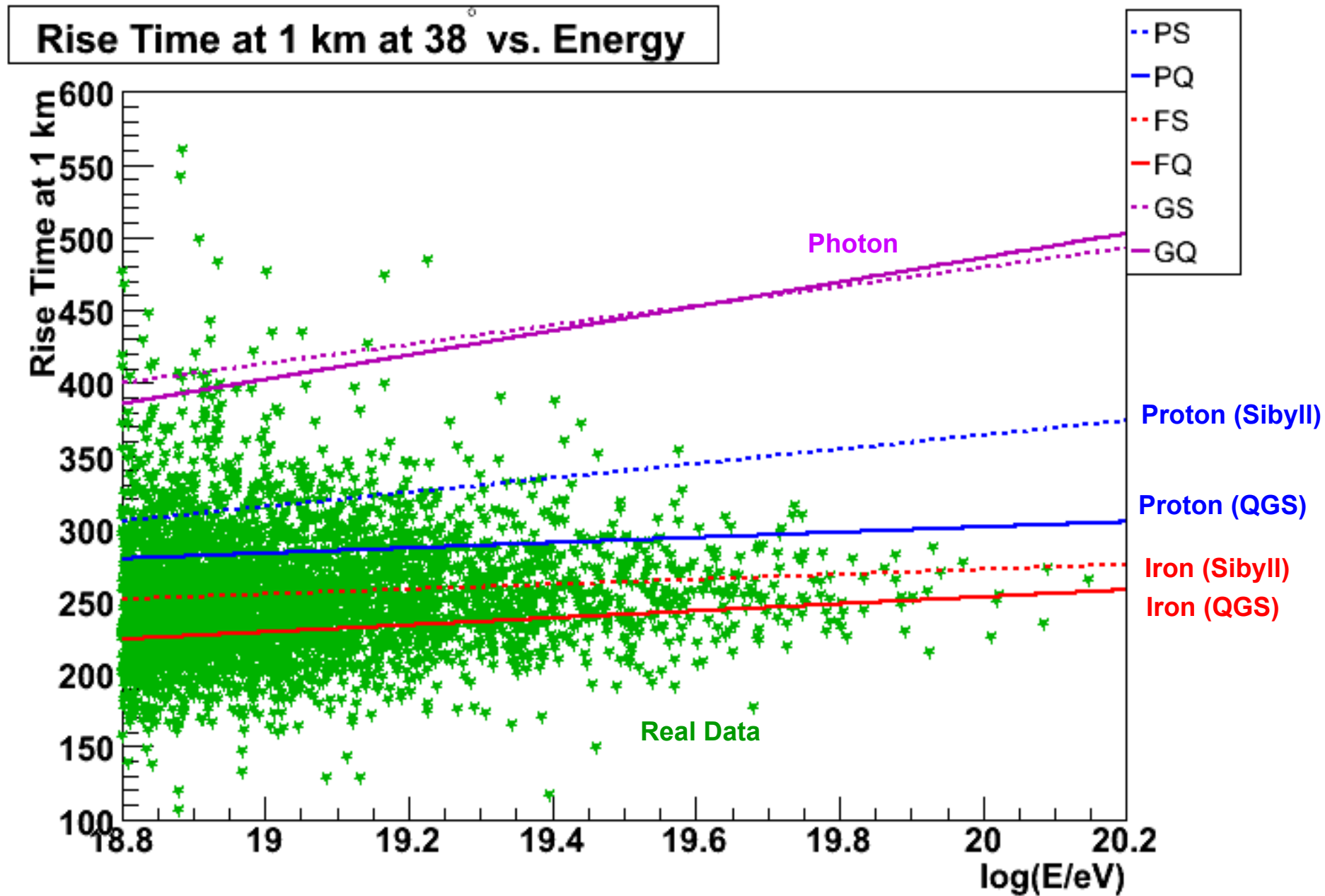
- **The first evidence of extra galactic origin of cosmic rays.**
 - It could be a correlation with Large Scale Structure (or other sources with similar distribution.)

- **Beginning of UHE Charged-particle Astronomy.**

**Are the protons or
heavy elements?**

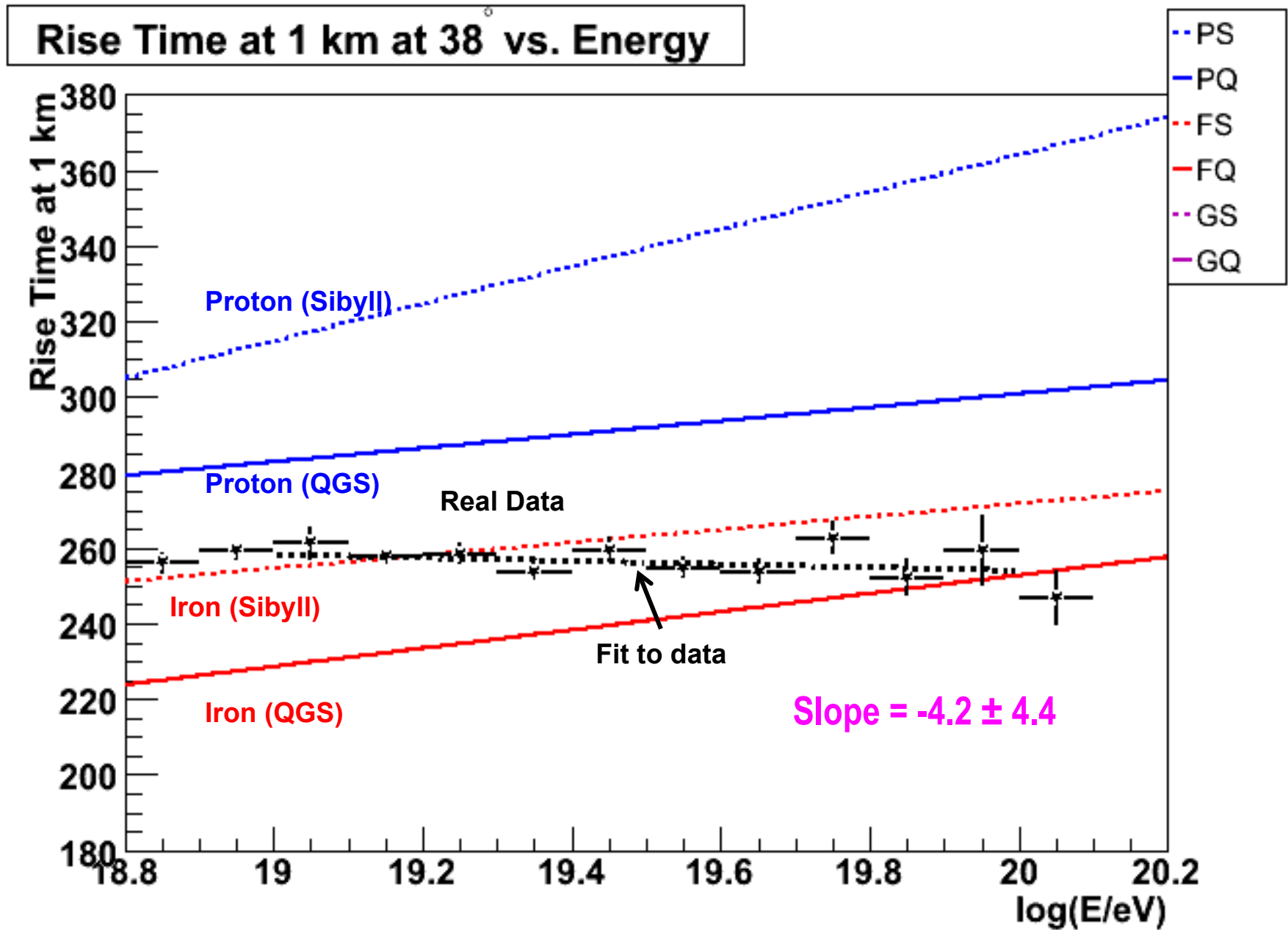
Risetime vs. Log(E)

Preliminary



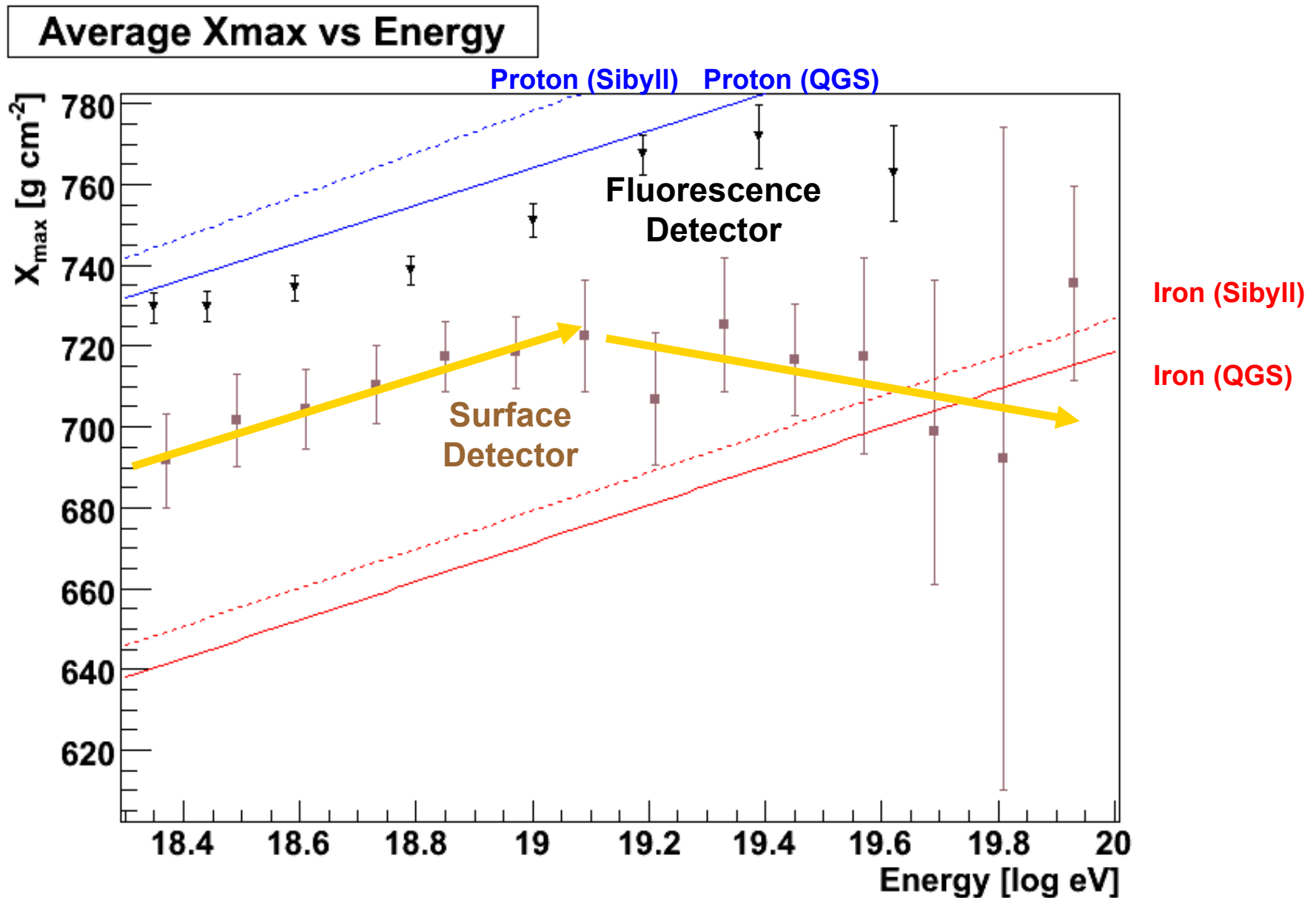
Risetime

Preliminary

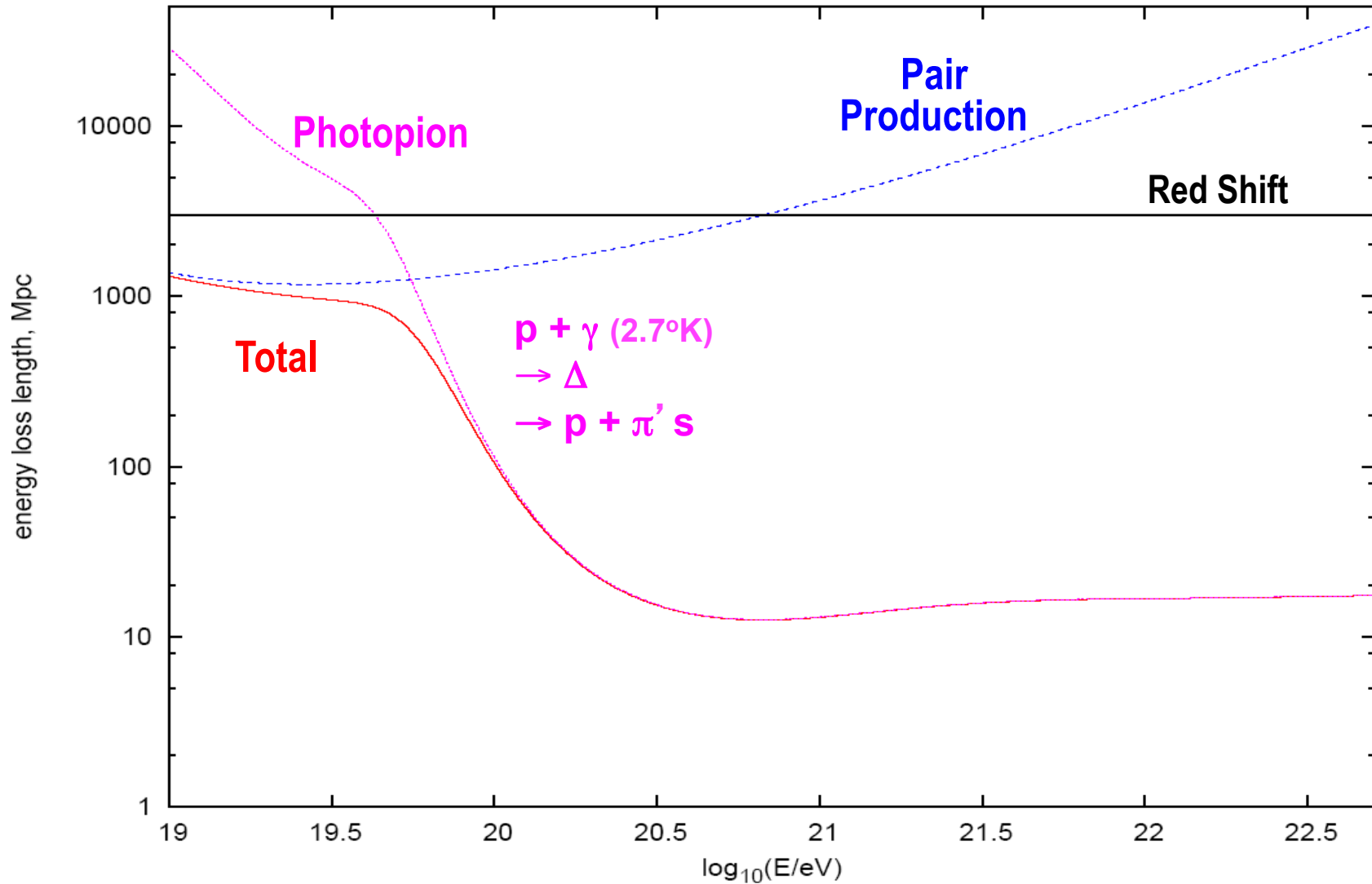


Elongation Rate

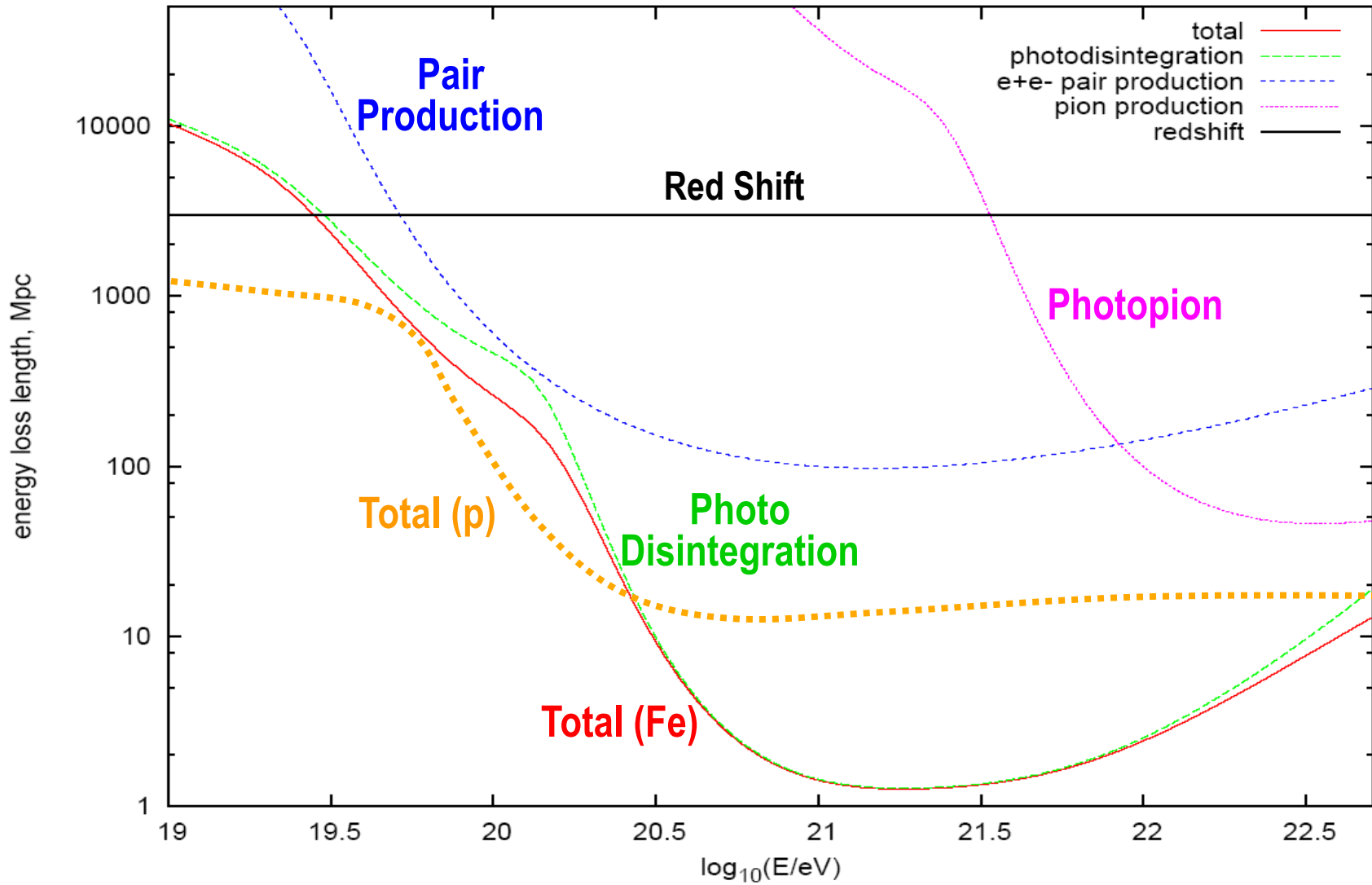
Preliminary



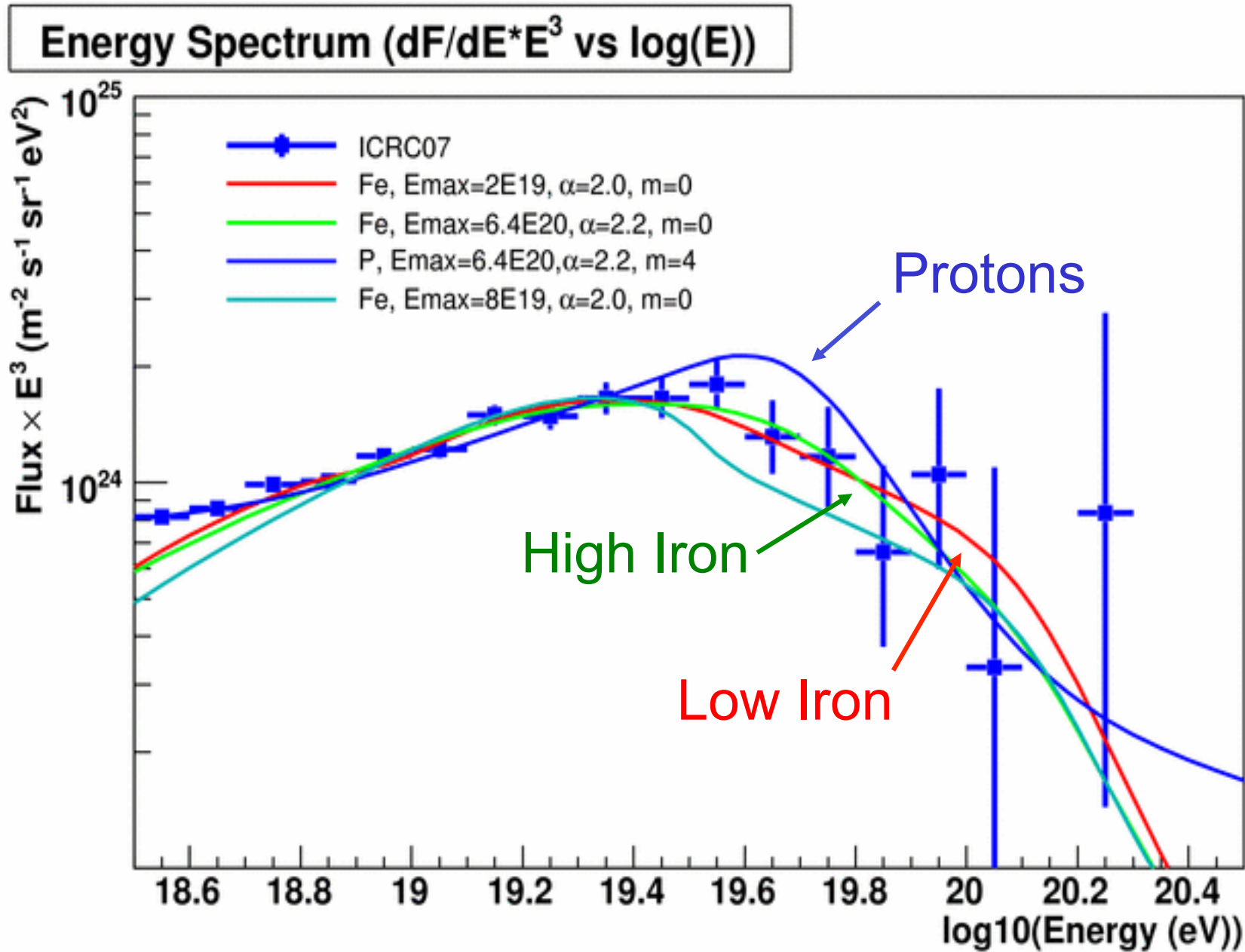
Energy Loss Length of Proton (UCLA Simulation)



Energy Loss Length of Fe (UCLA Simulation)



Fit to Spectrum



Auger-North

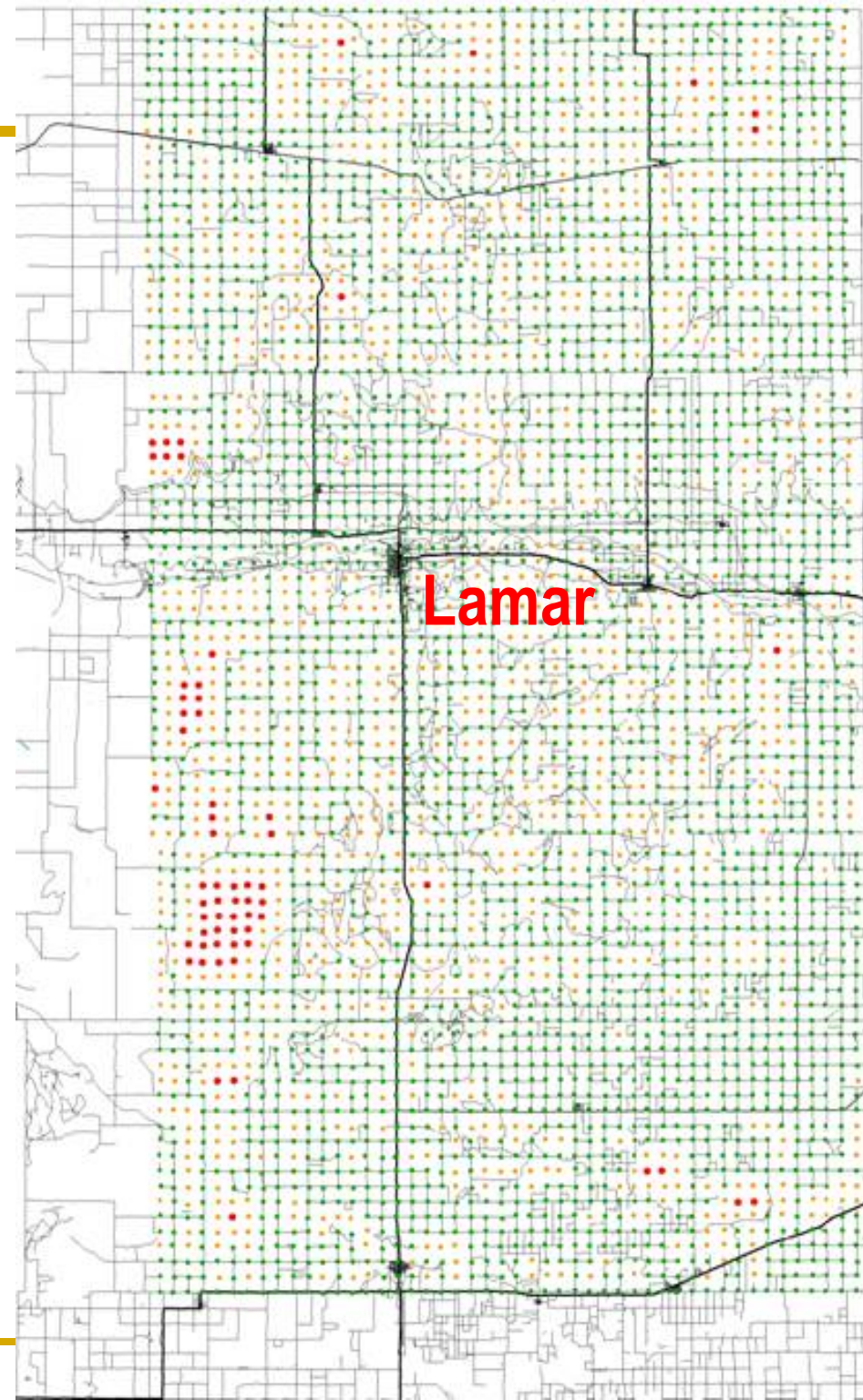
Auger-North in Colorado State



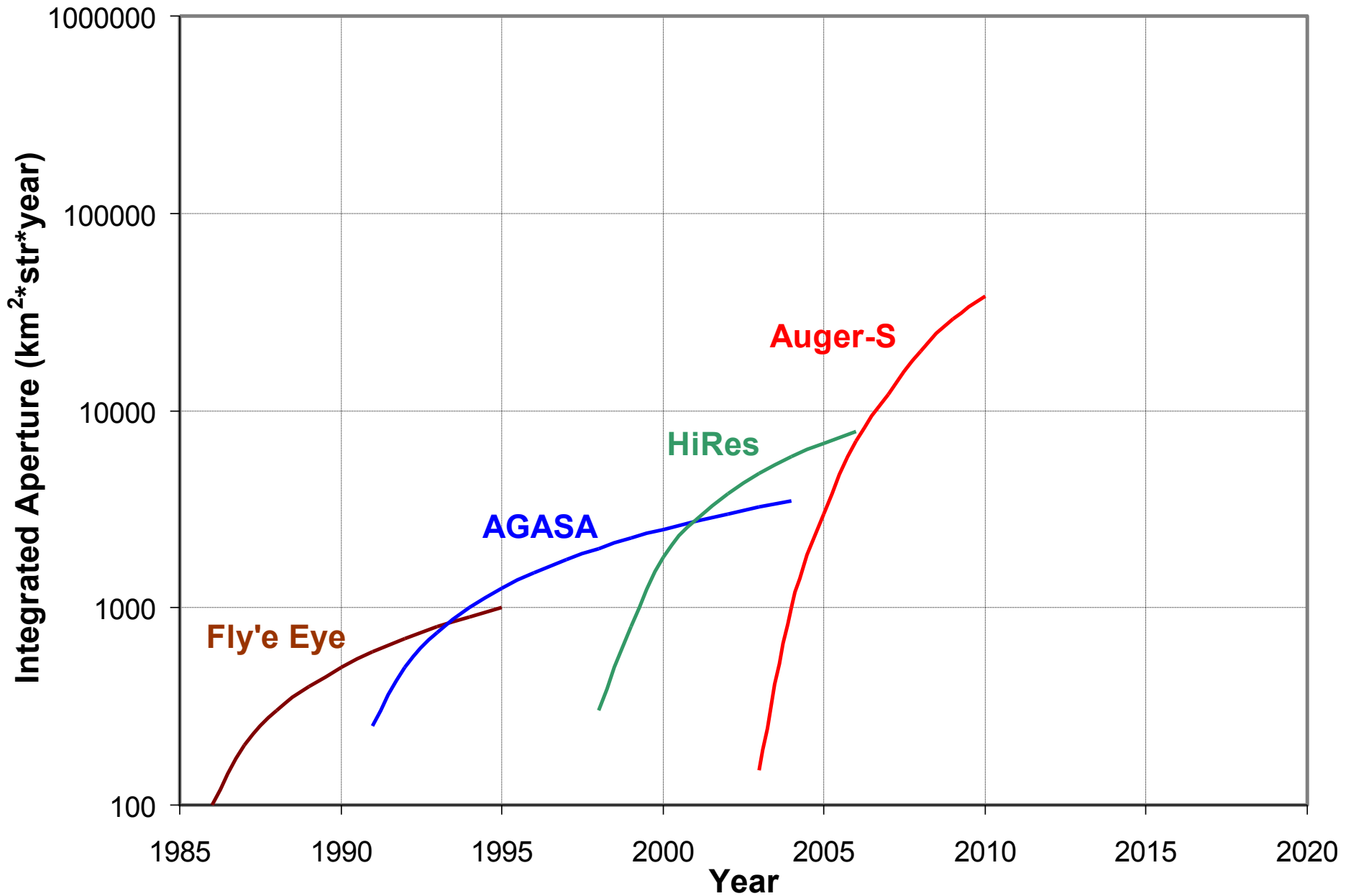
Auger
-North

Auger-North

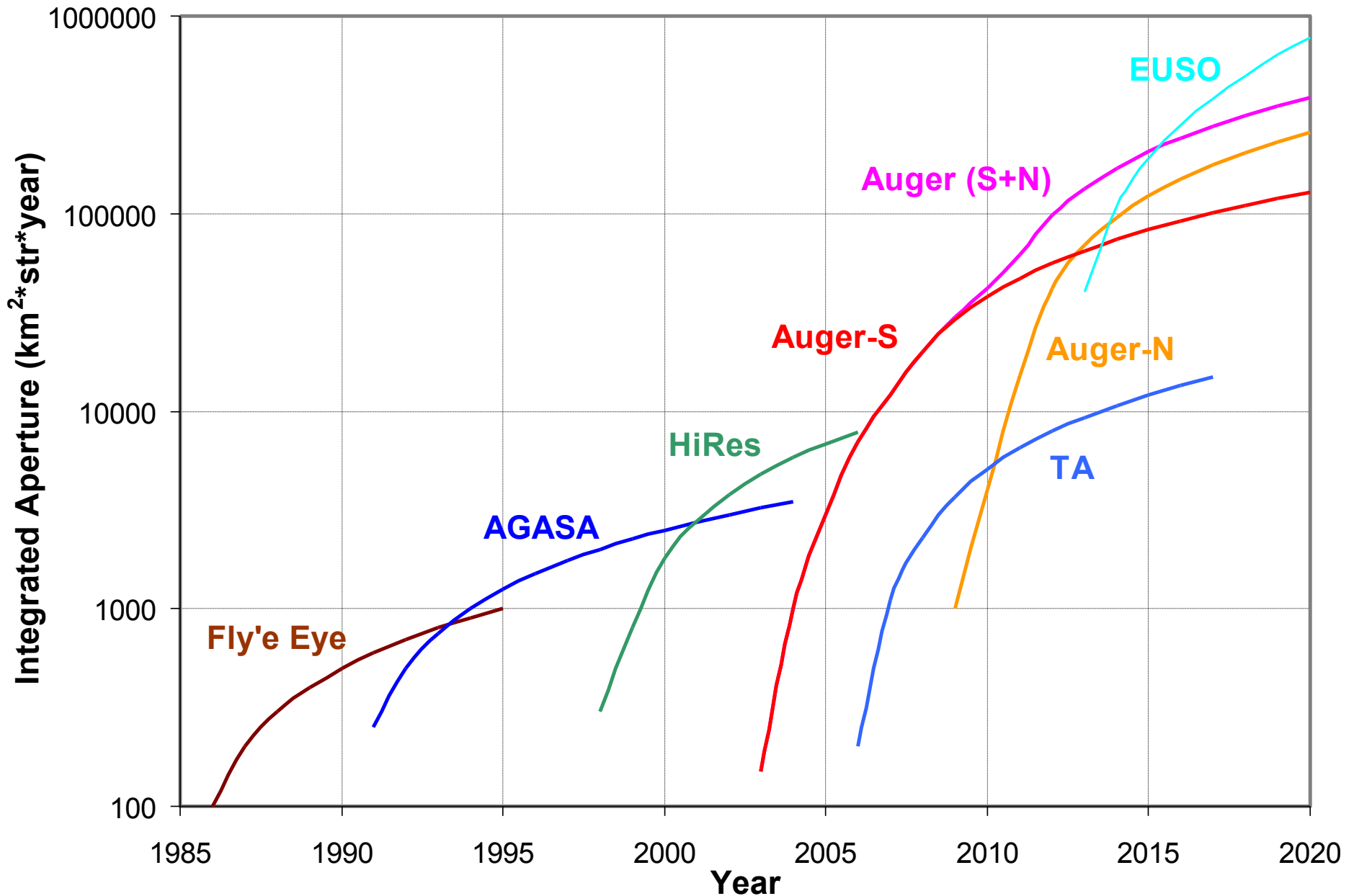
- **Total area: 10,000 km²**
 - **~3 x Auger-South**
- **4000 surface detector**
 - **1 mile (1.6 km) spacing**



Comparison of Integrated Aperture



Comparison of Integrated Aperture



Conclusions

- **The extra galactic origin of UHE cosmic rays has been established at 99% CL.**
 - Strong correlation with nearby AGN (< 80 Mpc)
 - Or something else which follows the super-galactic structure.
- **Birth of “UHE Charged Particle Astronomy”**
- **Need more investigation.**
 - Are they protons or heavy elements?
 - Who accelerates? What is the mechanism of acceleration?
 - Magnetic field effect: Our Galaxy or at the origin??
- **More statistics and experiments will follow.**
 - 5 x more data by 2012.
 - Auger-North (~ 3 x Auger-South), EUSO (~ 10 x Auger).

AGN Correlation in galactic coordinates

