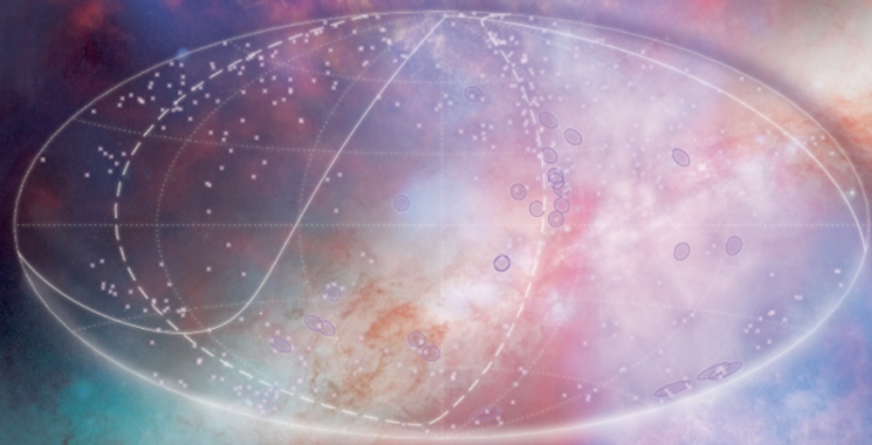
Origin of the Most Energetic Particles in the Universe:
New Results from Pierre-Auger

Katsushi Arisaka
UCLA

9 November 2007 | $10

Science



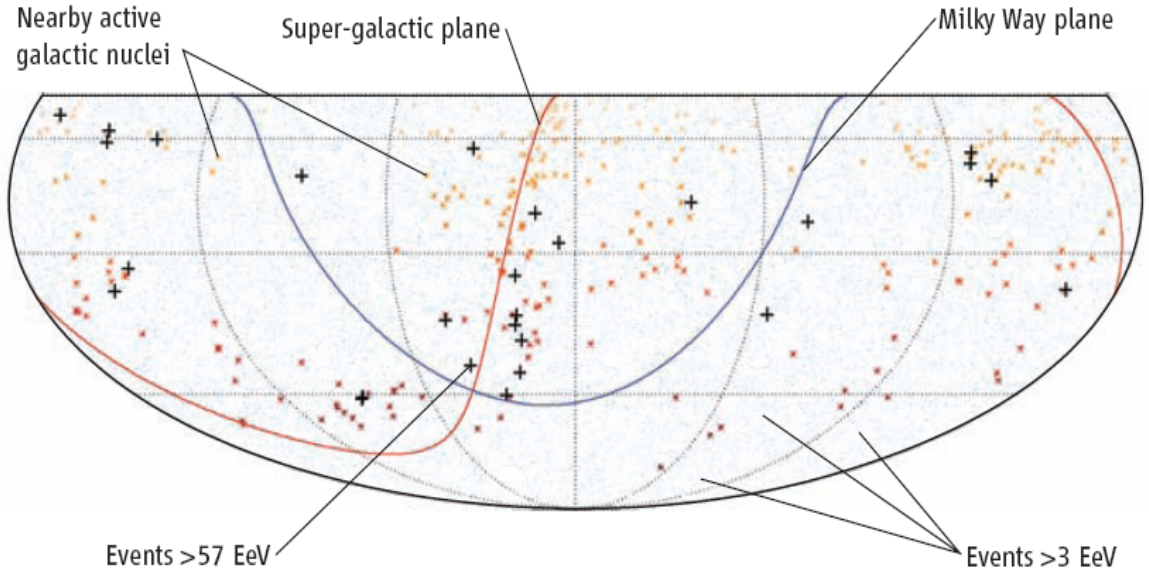
AAAS

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



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

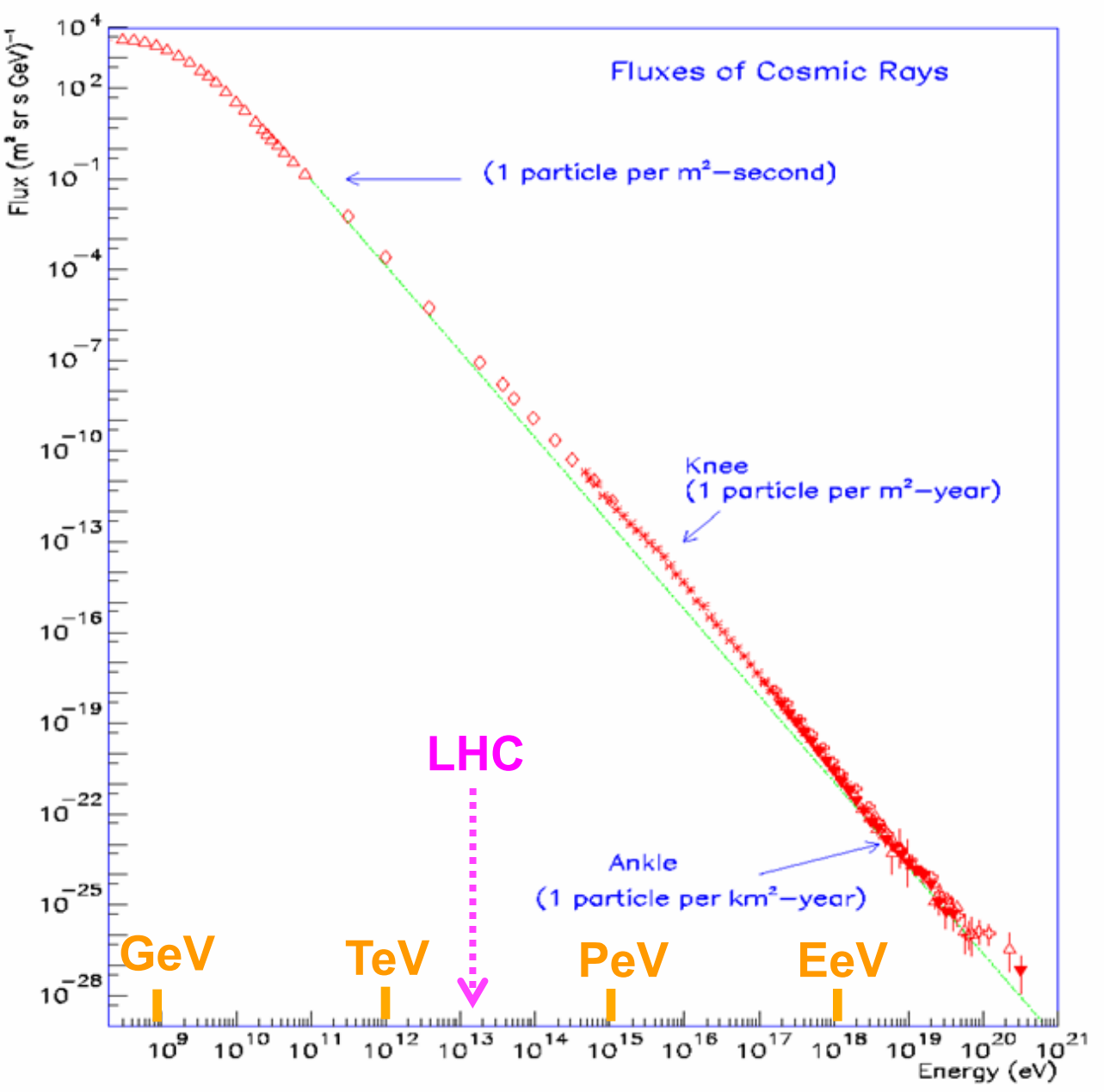
Talk Outline

- **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*

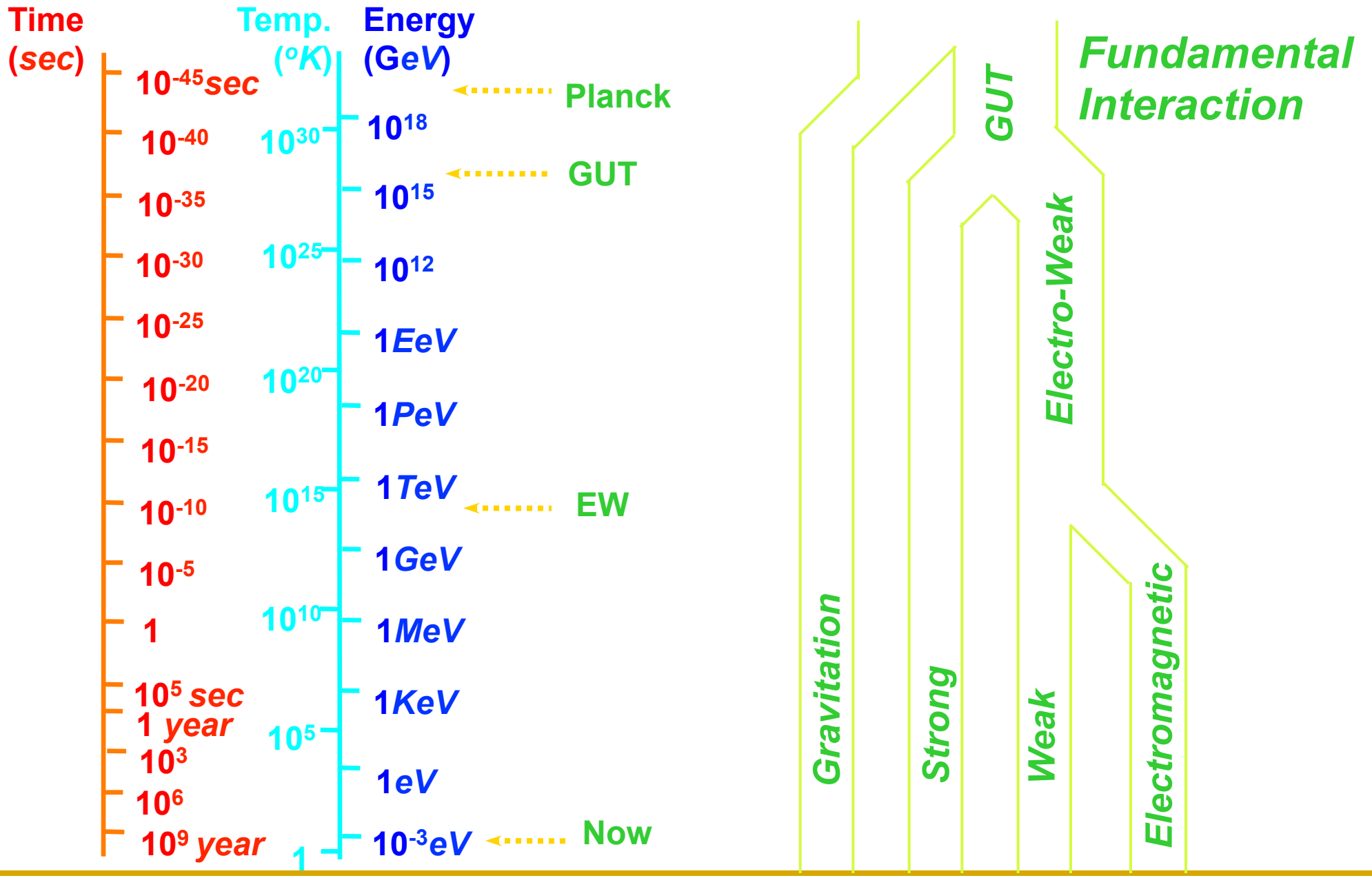
Scientific Motivation

Energy Spectrum of Cosmic Rays

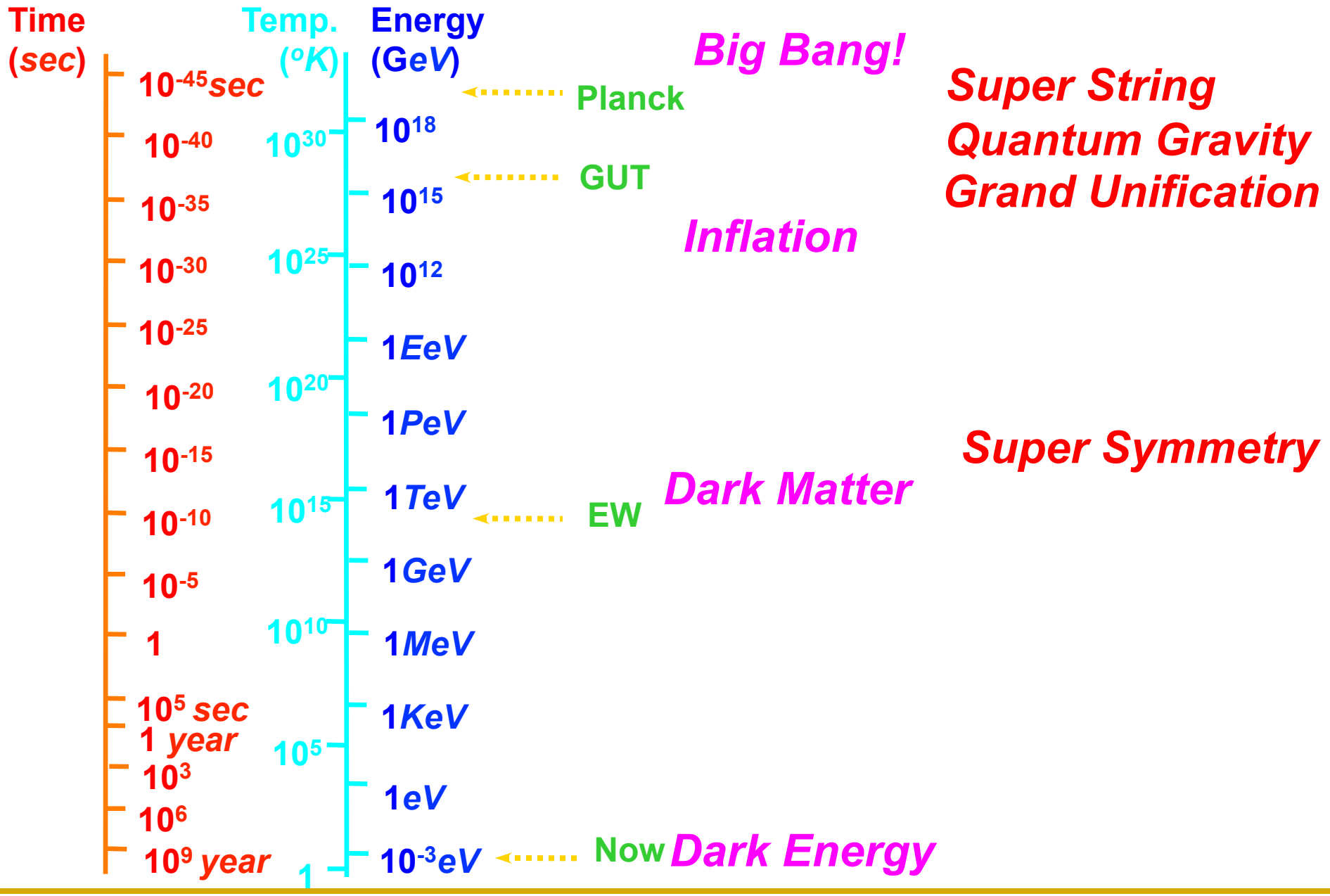
- Energy Spectrum ~ E^{-3}
- The spectrum extends beyond 10^{20} eV (=100 EeV).
- Beyond 10^{20} eV, Flux is only one particle per km^2-century.



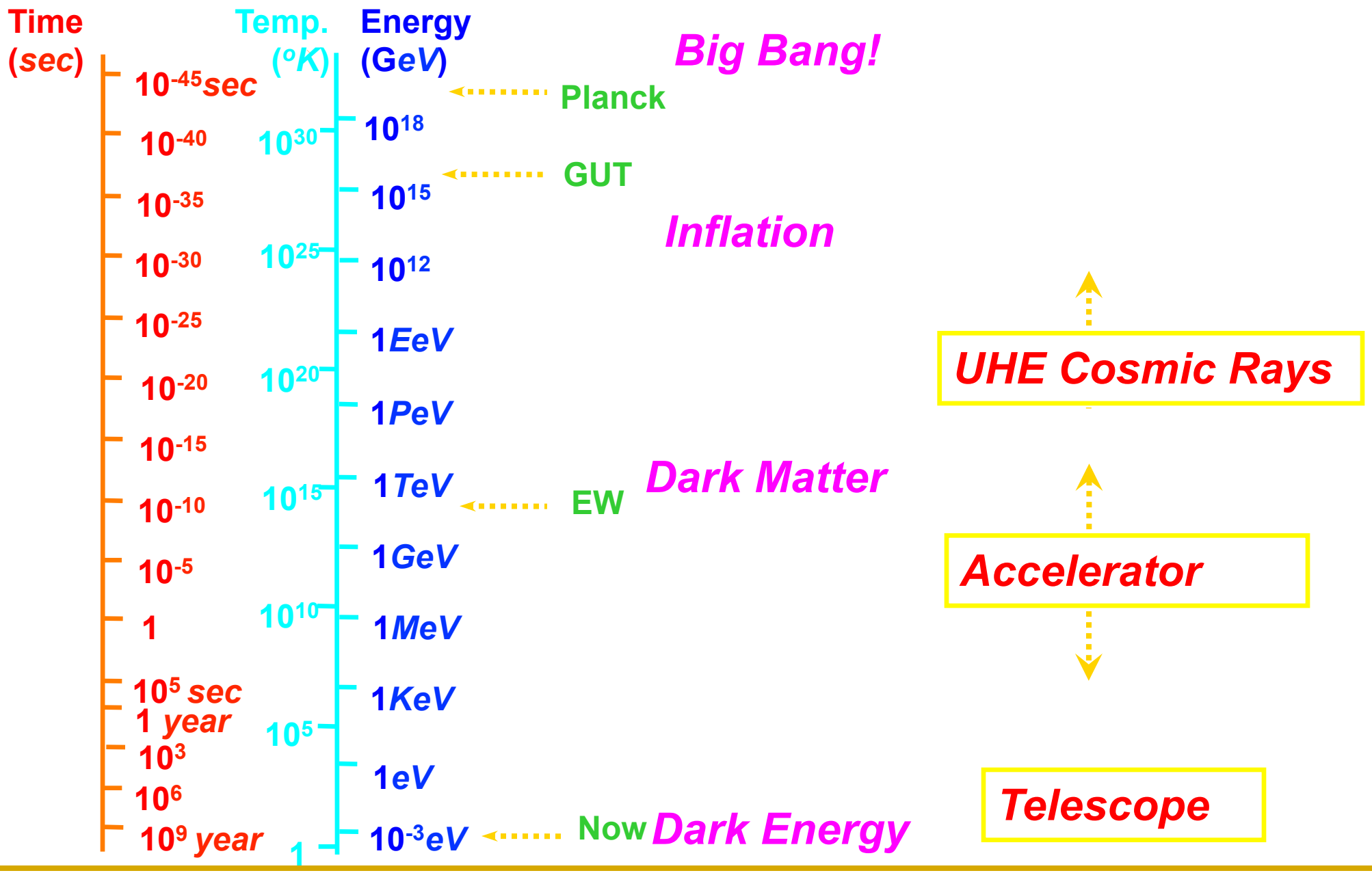
Particle Physics in Early Universe



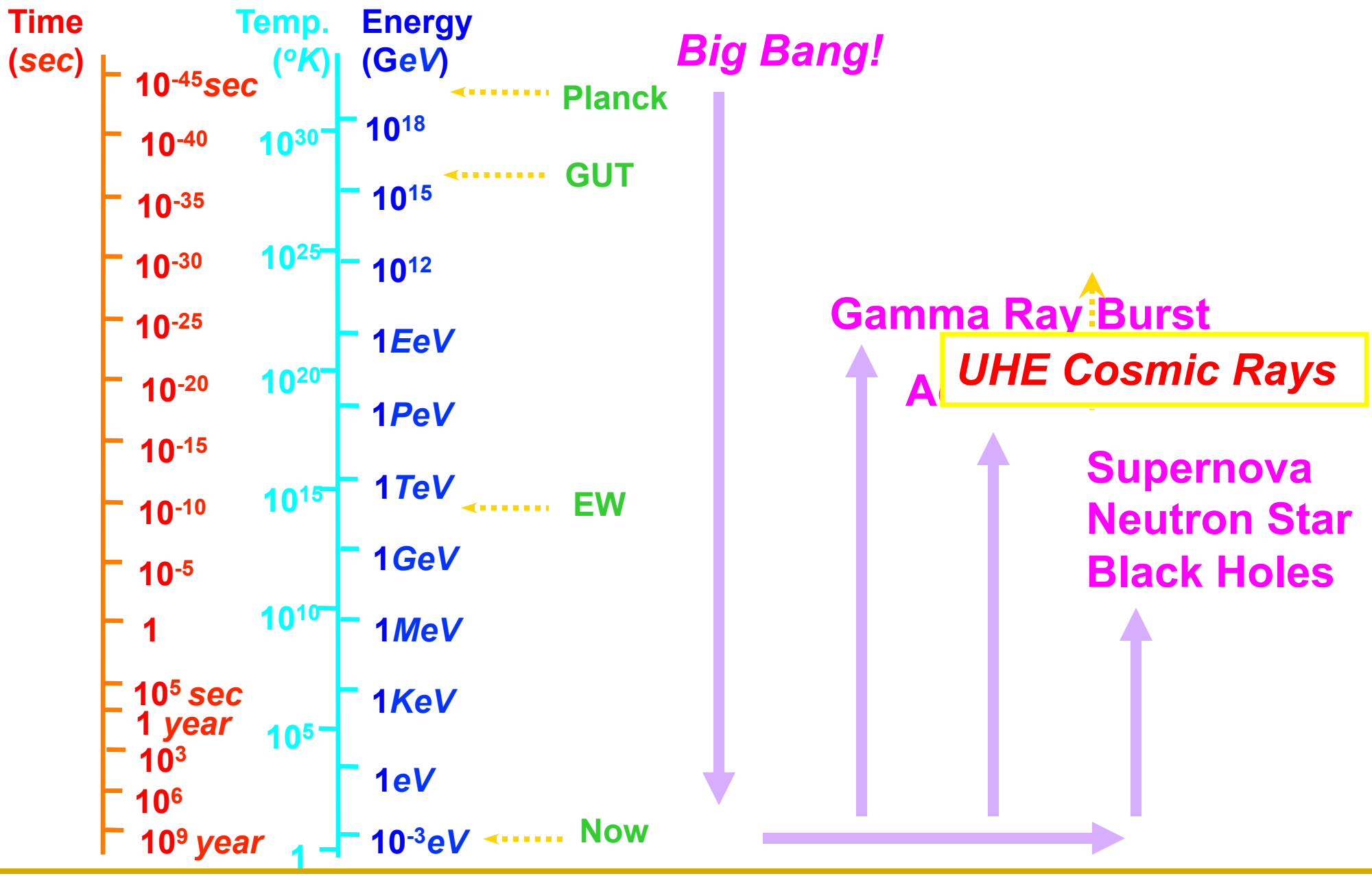
Particle Physics in Early Universe



Particle Physics in Early Universe



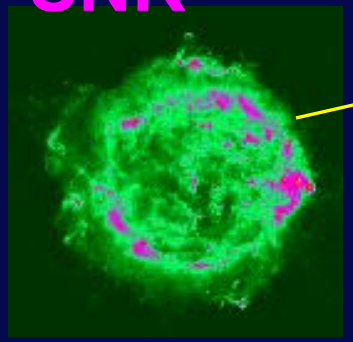
Top-down or Bottom-up?

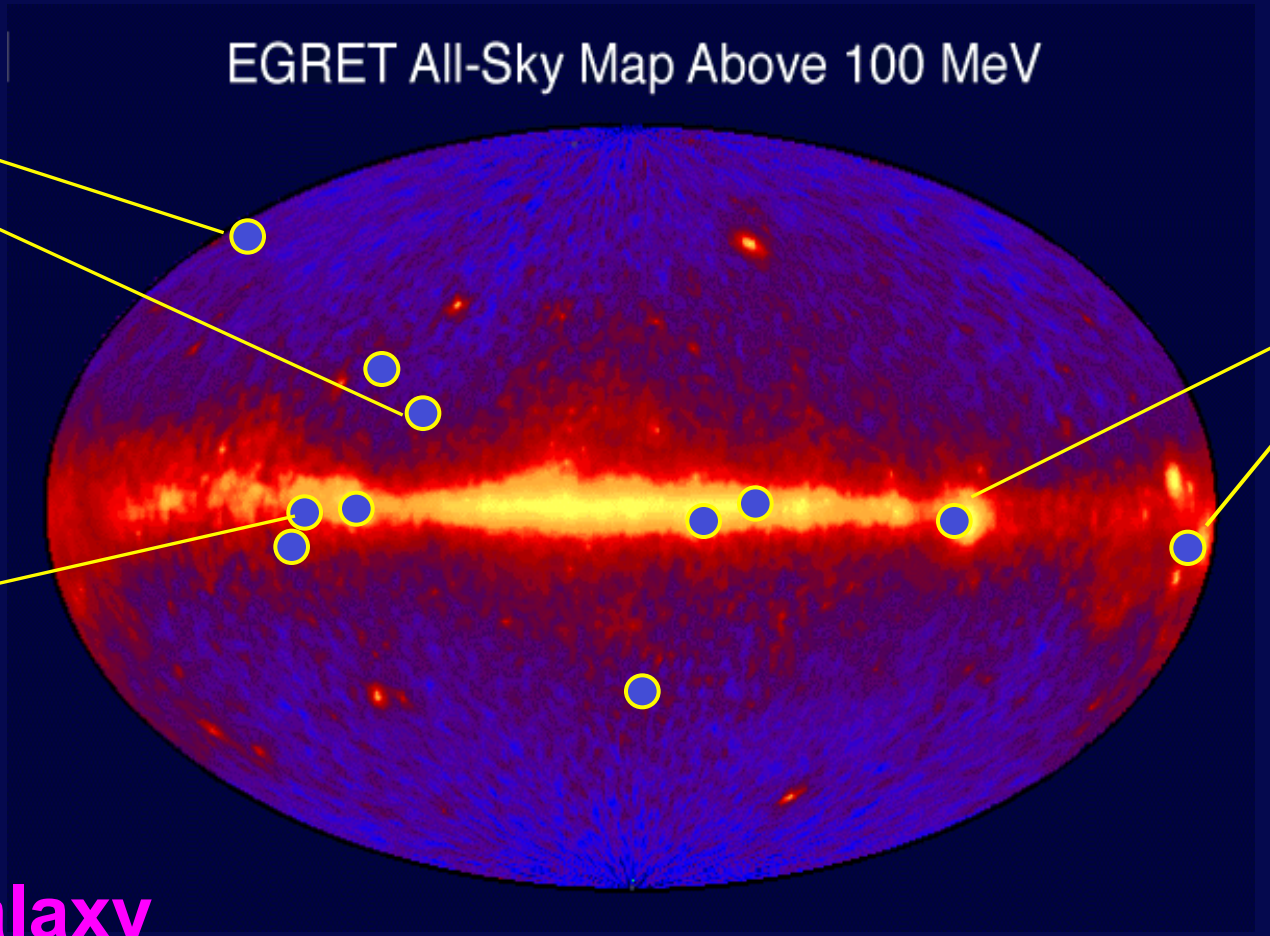


The Extreme Universe

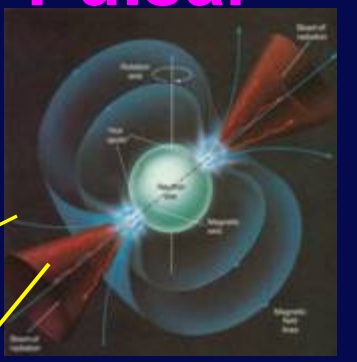
AGN

SNR

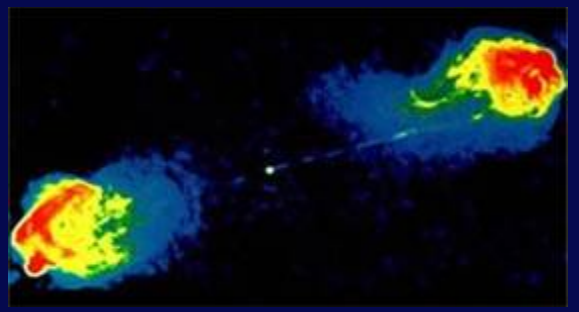




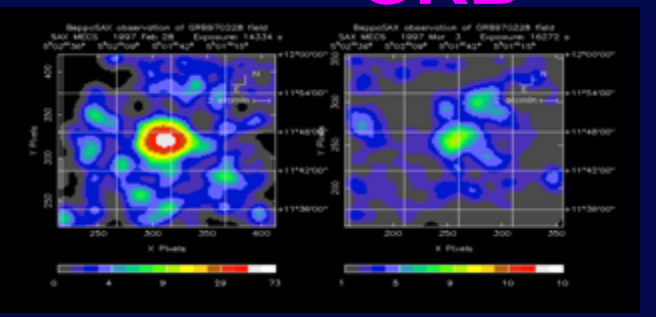
Pulsar



Radio Galaxy



GRB



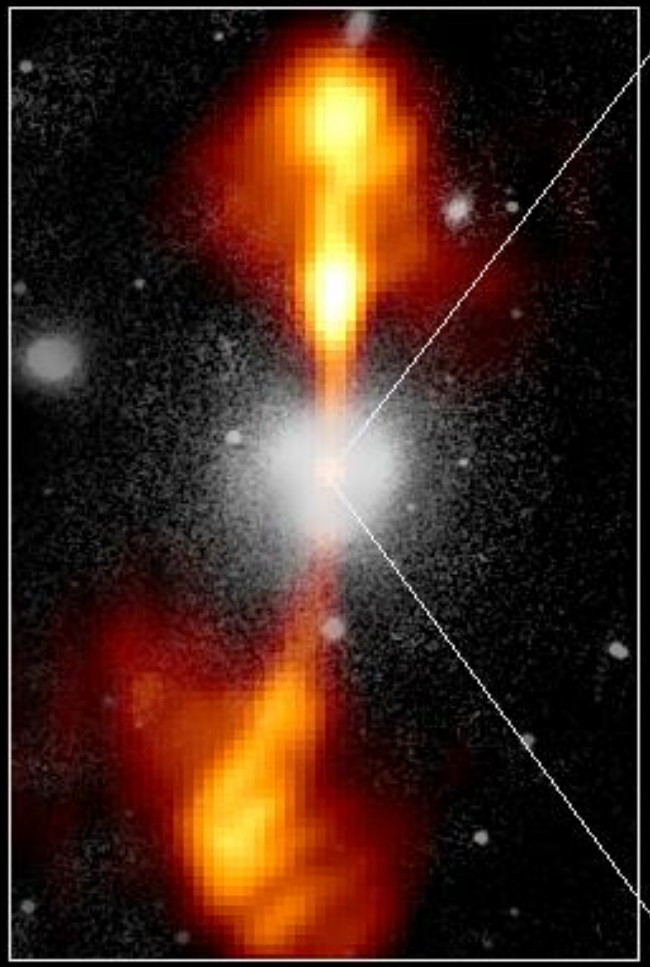
By Rene Ong

Core of Galaxy NGC 4261

Hubble Space Telescope

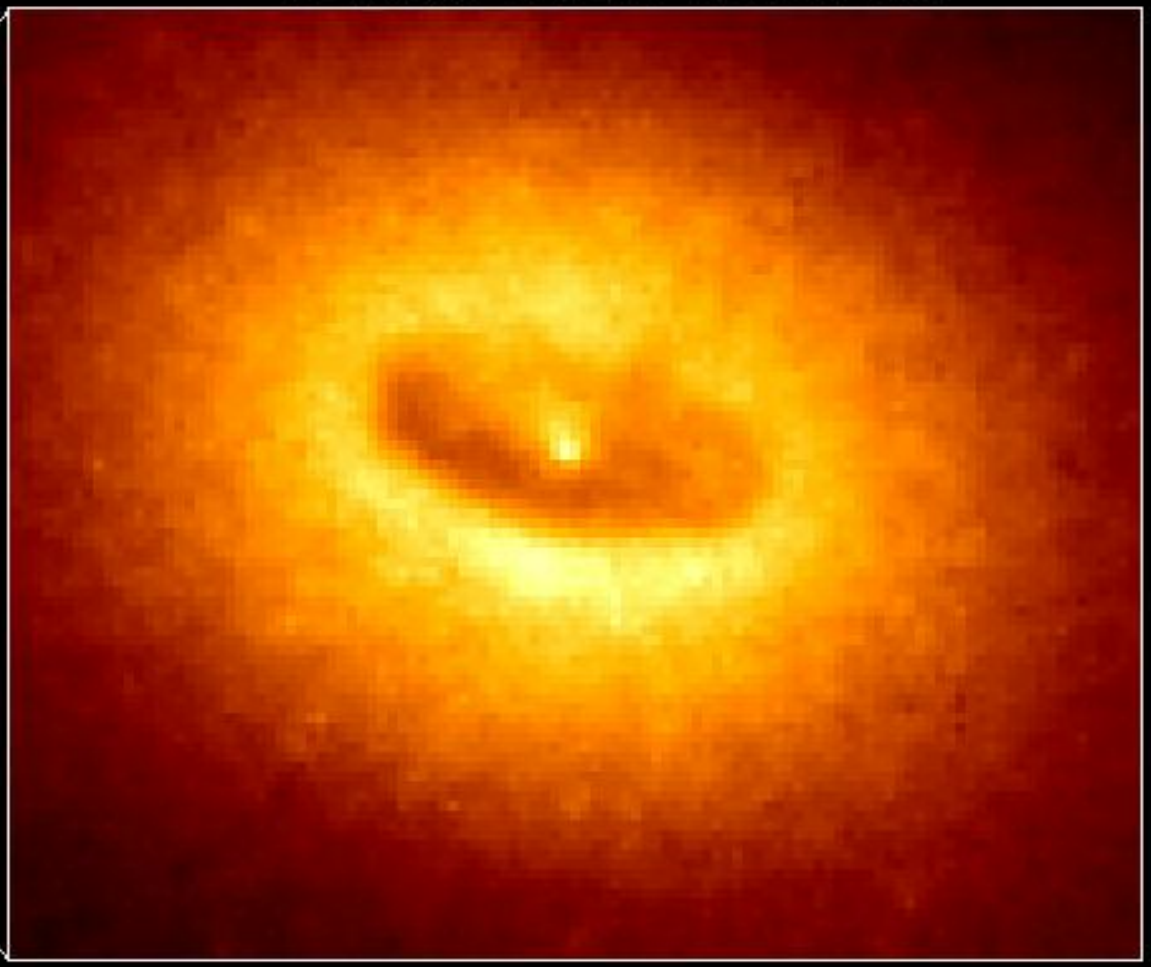
Wide Field / Planetary Camera

Ground-Based Optical/Radio Image



380 Arc Seconds
88,000 LIGHT-YEARS

HST Image of a Gas and Dust Disk

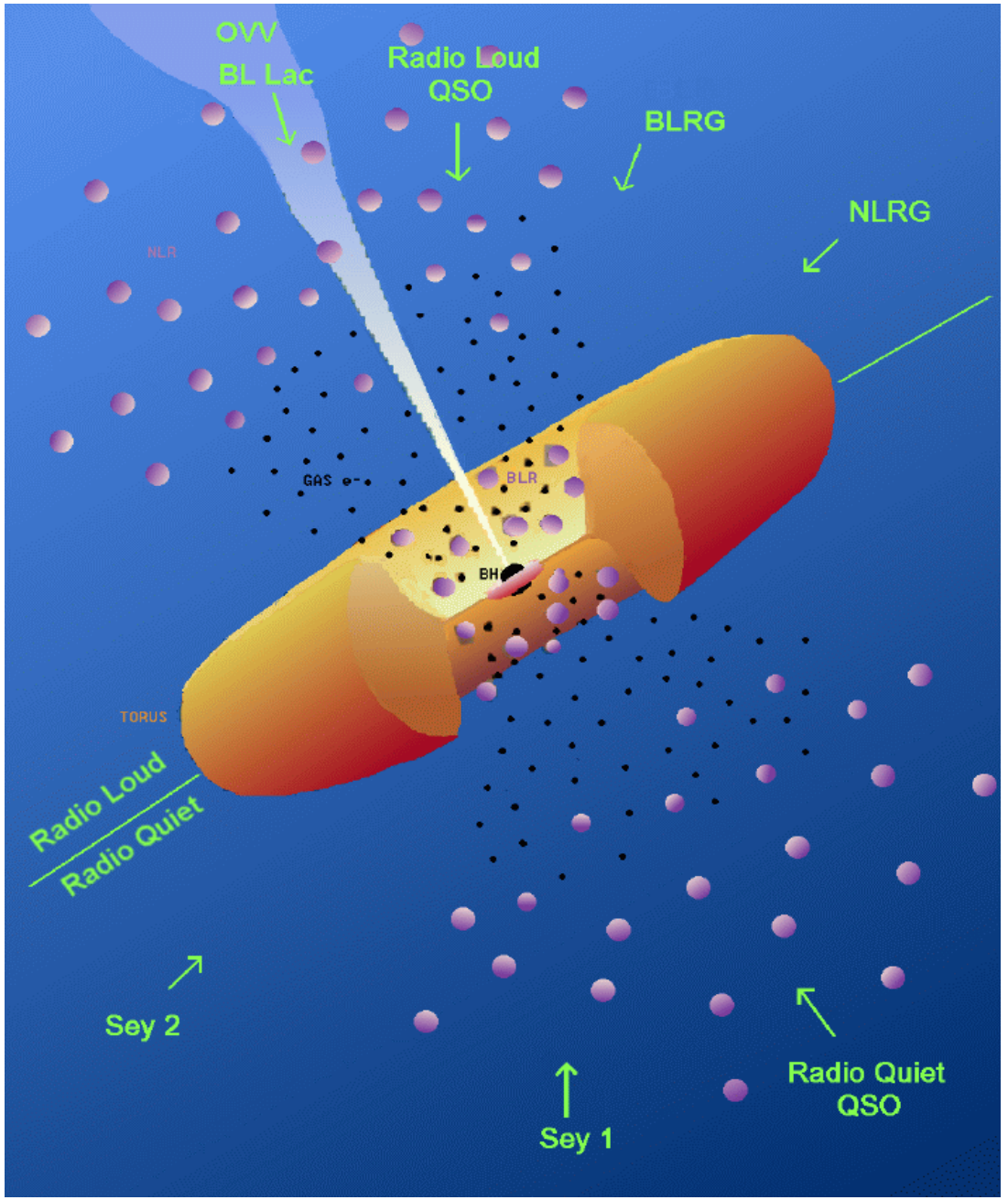


1.7 Arc Seconds
400 LIGHT-YEARS

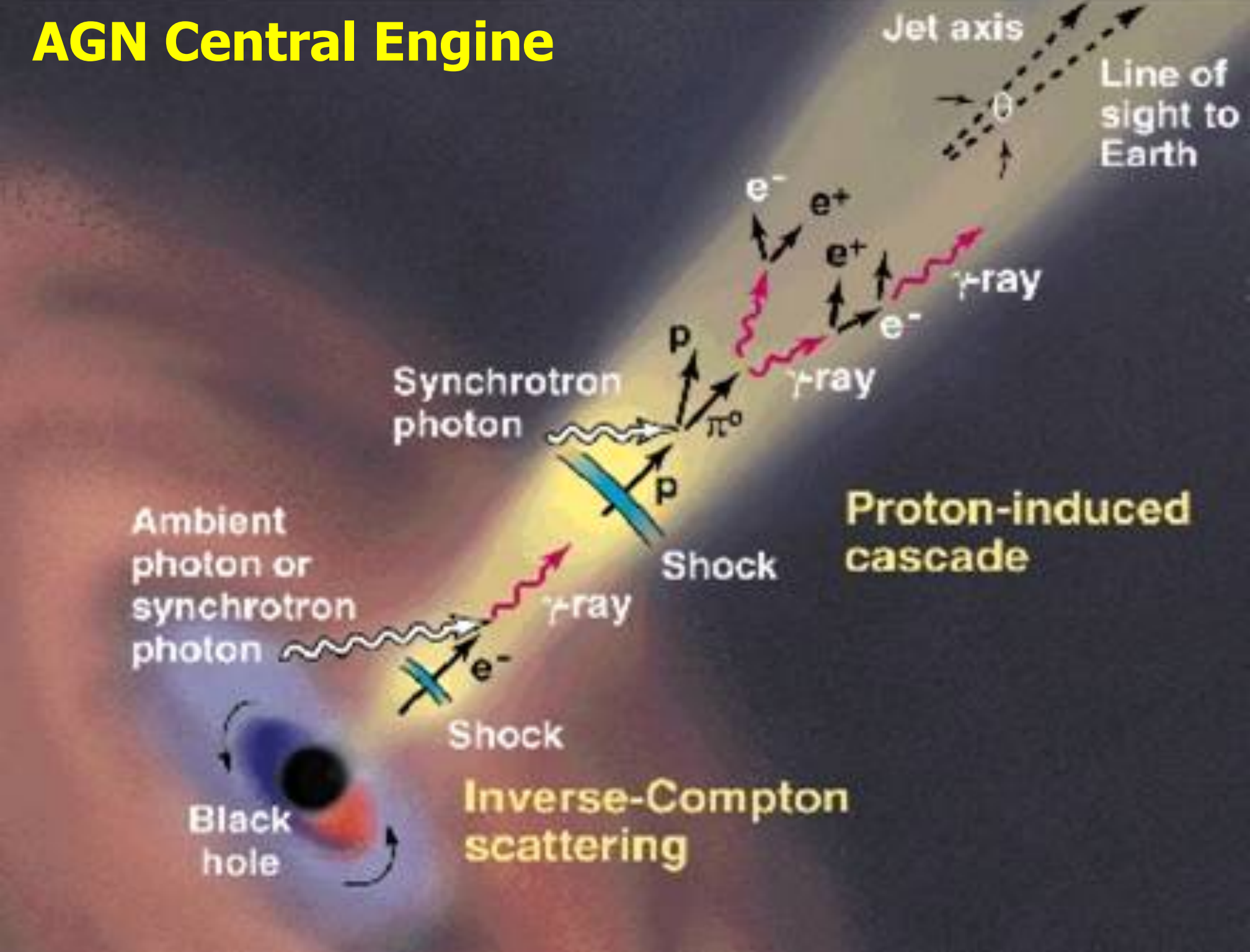
Various AGN

Various classes of AGN are thought to be Super-Massive Black Holes viewed from different angles.

Energetic ones are thought to emit jets and called Blazars (BL Lac is a subcategory)

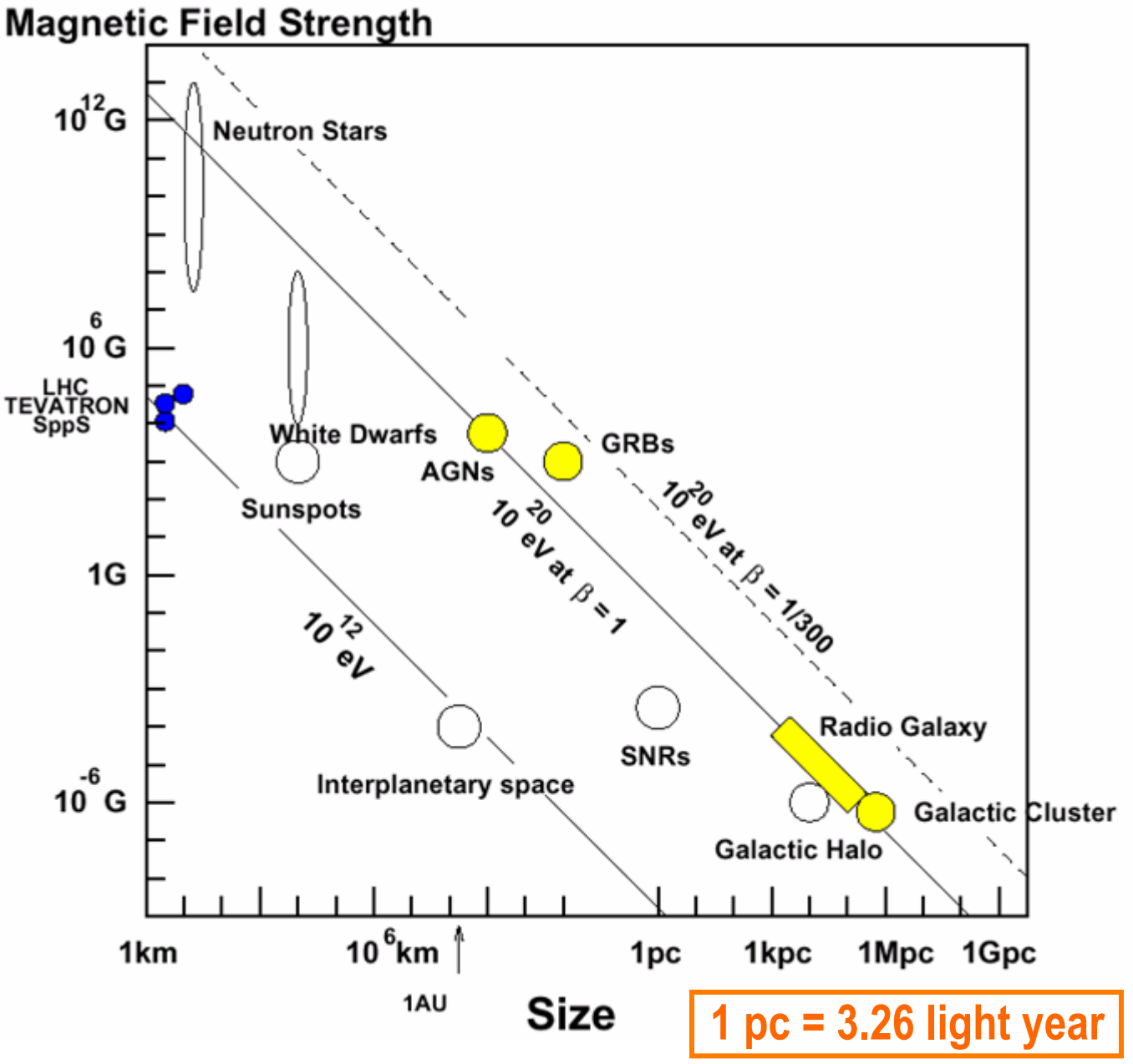


AGN Central Engine

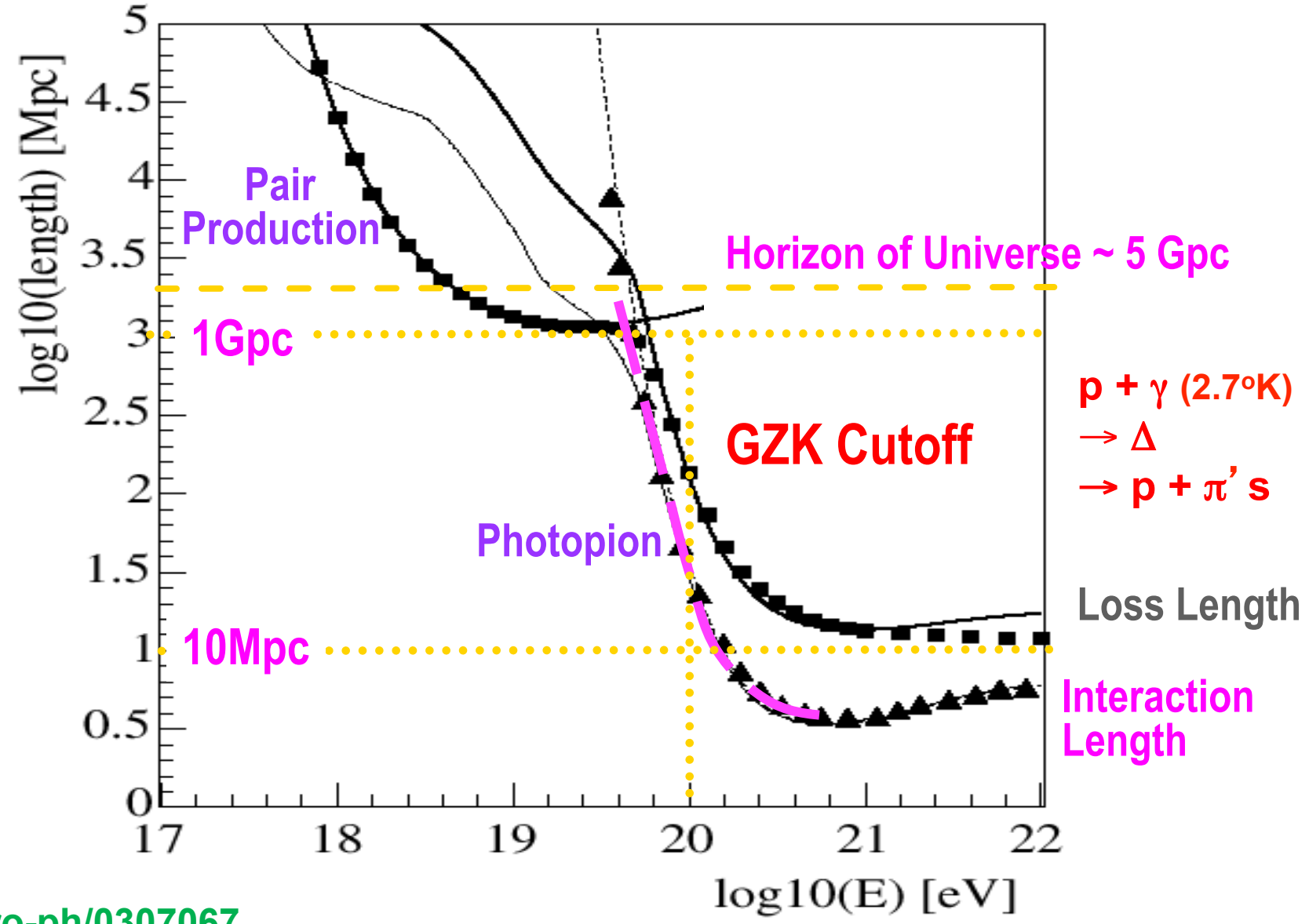


Possible Acceleration Sites

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



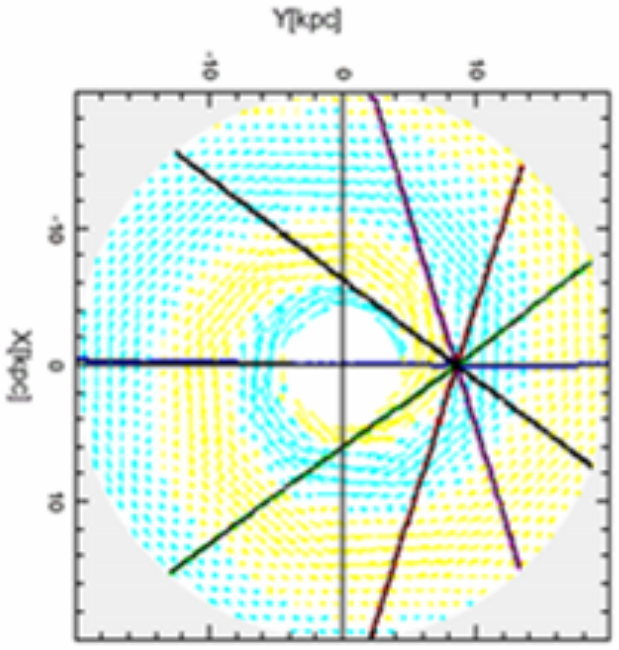
Interaction Length of UHE Protons

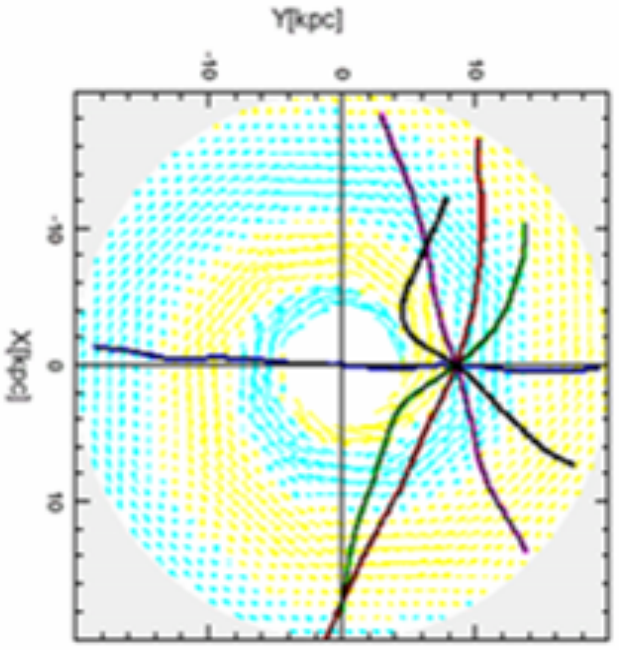


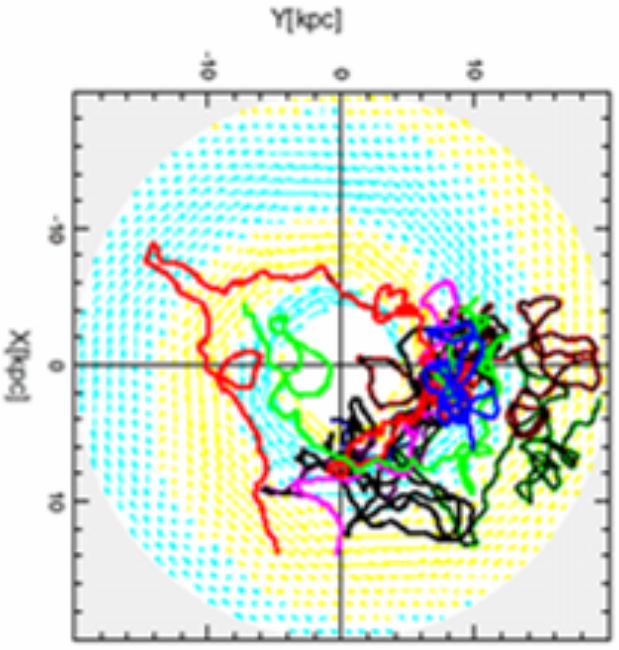
Blasi, astro-ph/0307067

Trajectory of Cosmic Ray Protons in the Galaxy

Magnetic Field in our Galaxy ~ 2 μG





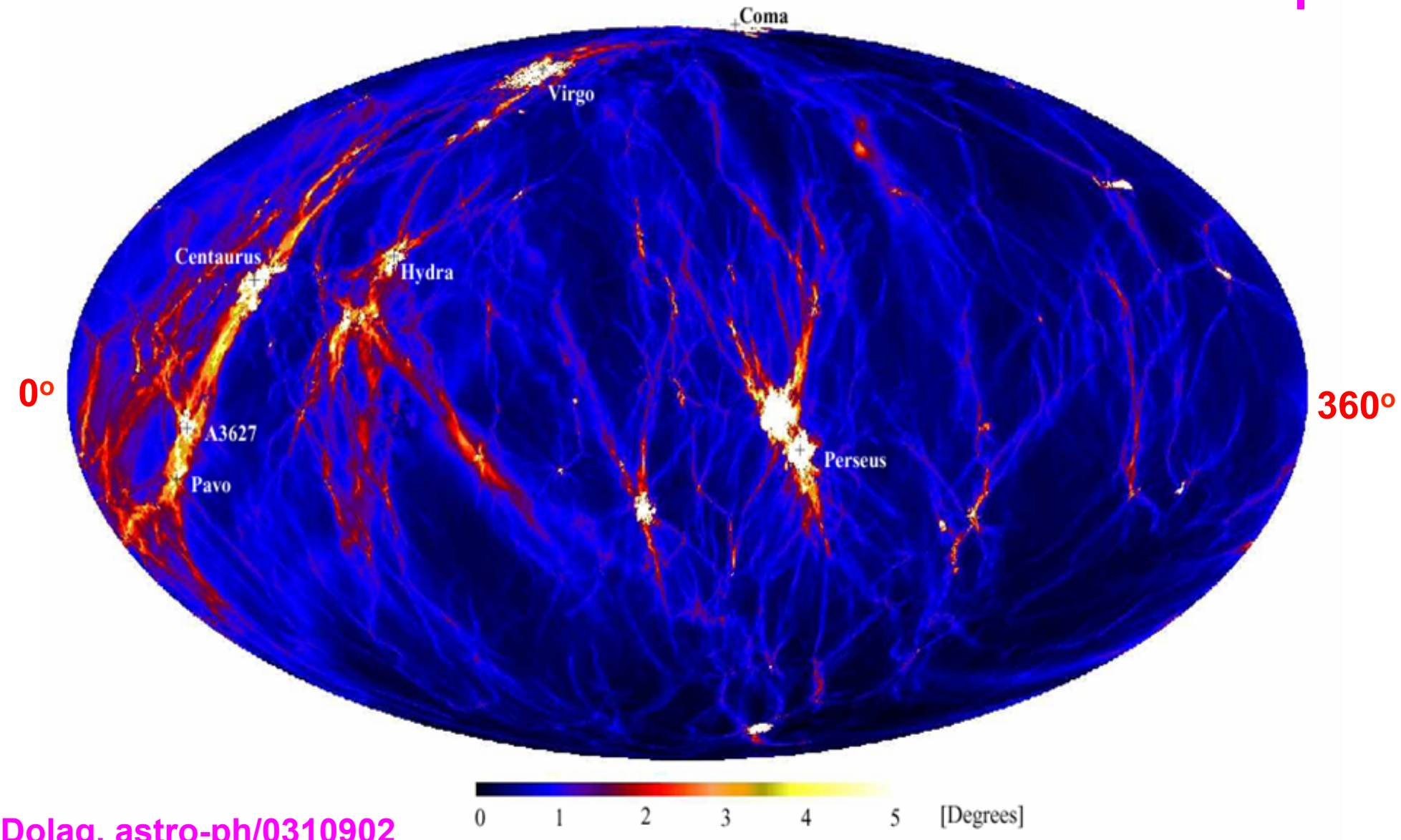


$E=10^{20}eV$ $E=10^{19}eV$ $E=10^{18}eV$

Deflection of Protons >4×10^{19}eV

Extra Galactic Magnetic Field ~ 1 nG

< 100 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

  →

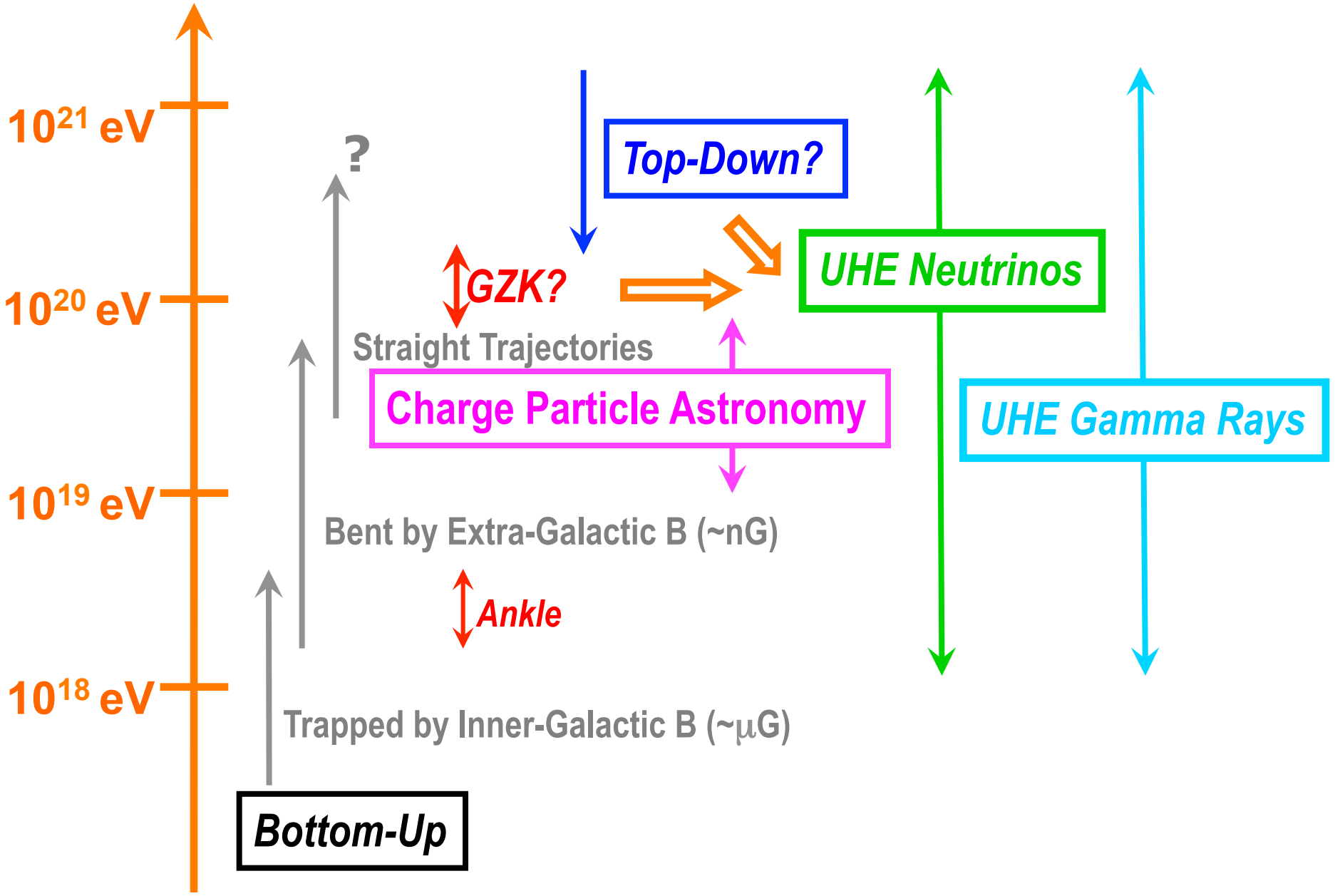
  Violation of Special Relativity?

- Protons can travel straight at E > ~4×10^{19} eV.

  → Charged-Particle Astronomy

  → New Window of Extreme

Rich Physics and Astronomy

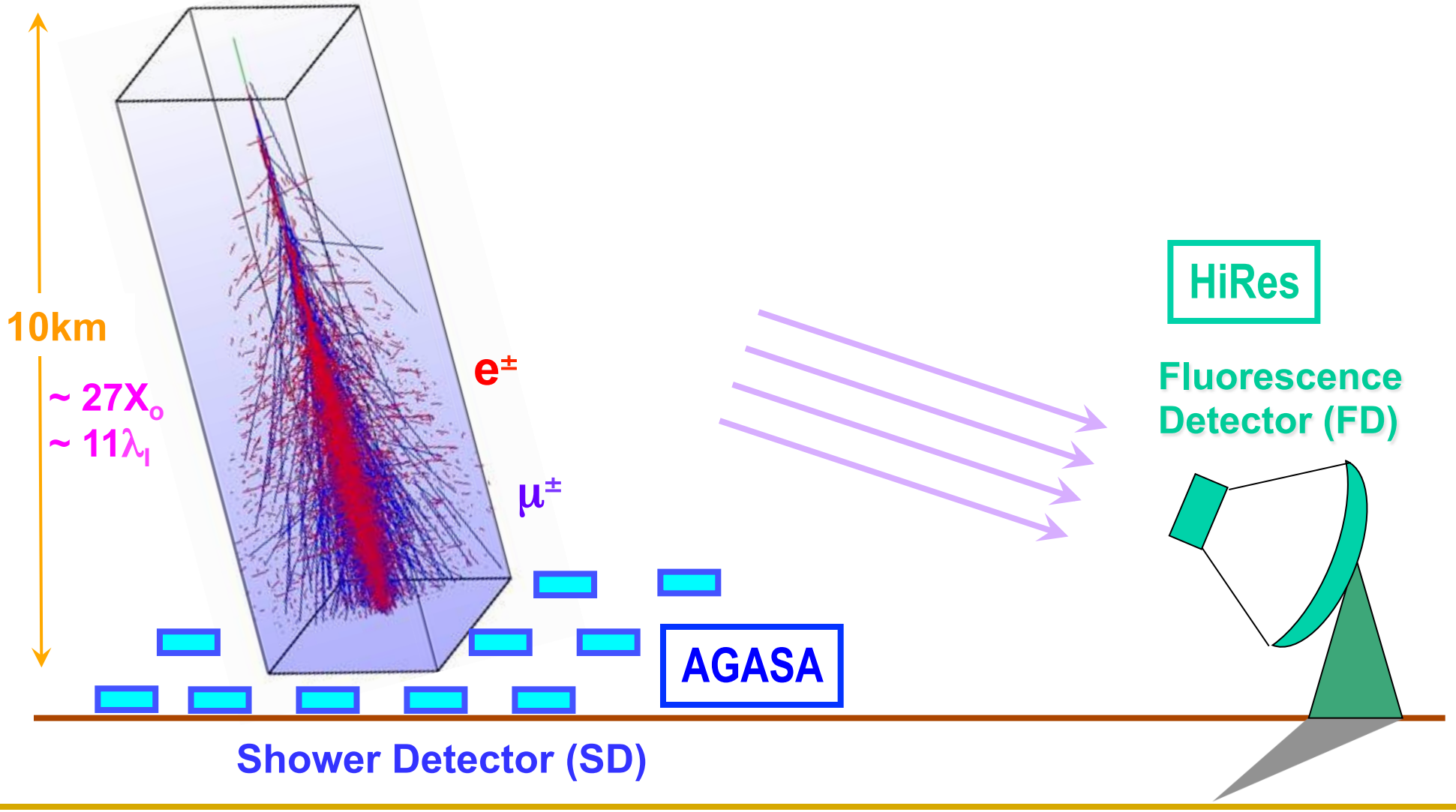


Past and Ongoing Experiments

- AGASA
- HiRes
- Pierre-Auger

Detection Technique

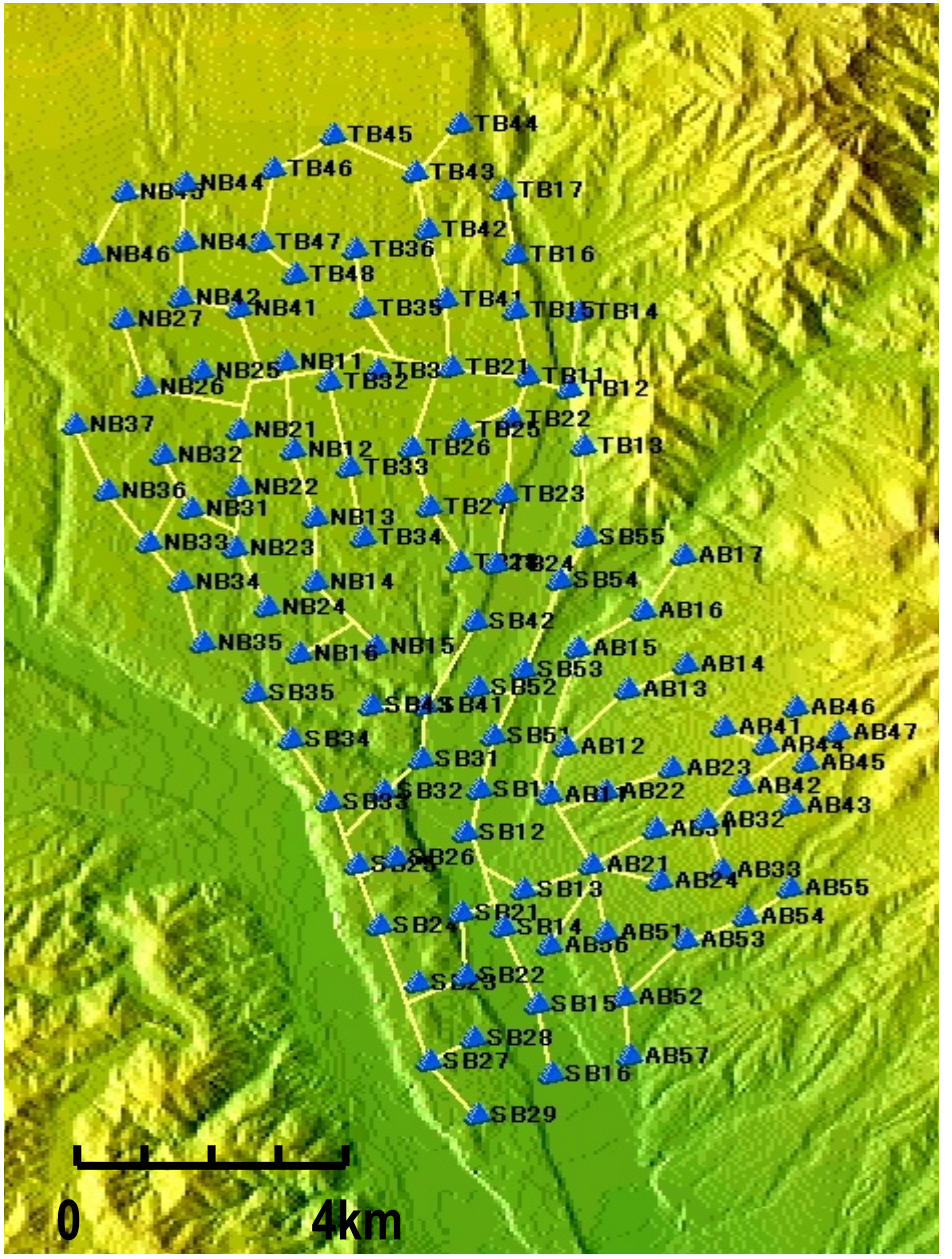
MC Simulation of 10 EeV (10^{19}eV) Proton Shower



Akeno Giant Air Shower Array

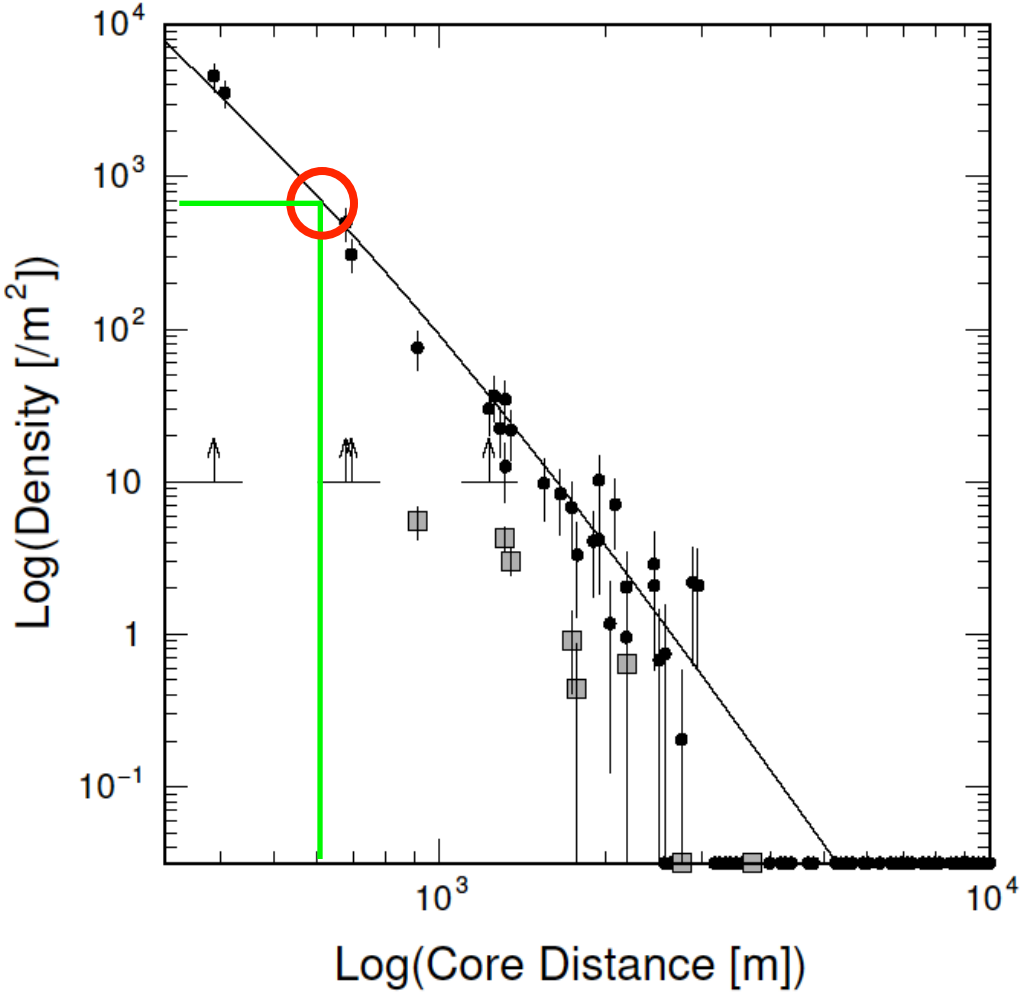
- 111 Electron Detectors
  - 100 km^2
- 27 Muon Detectors
- Operation 1991 - 2004

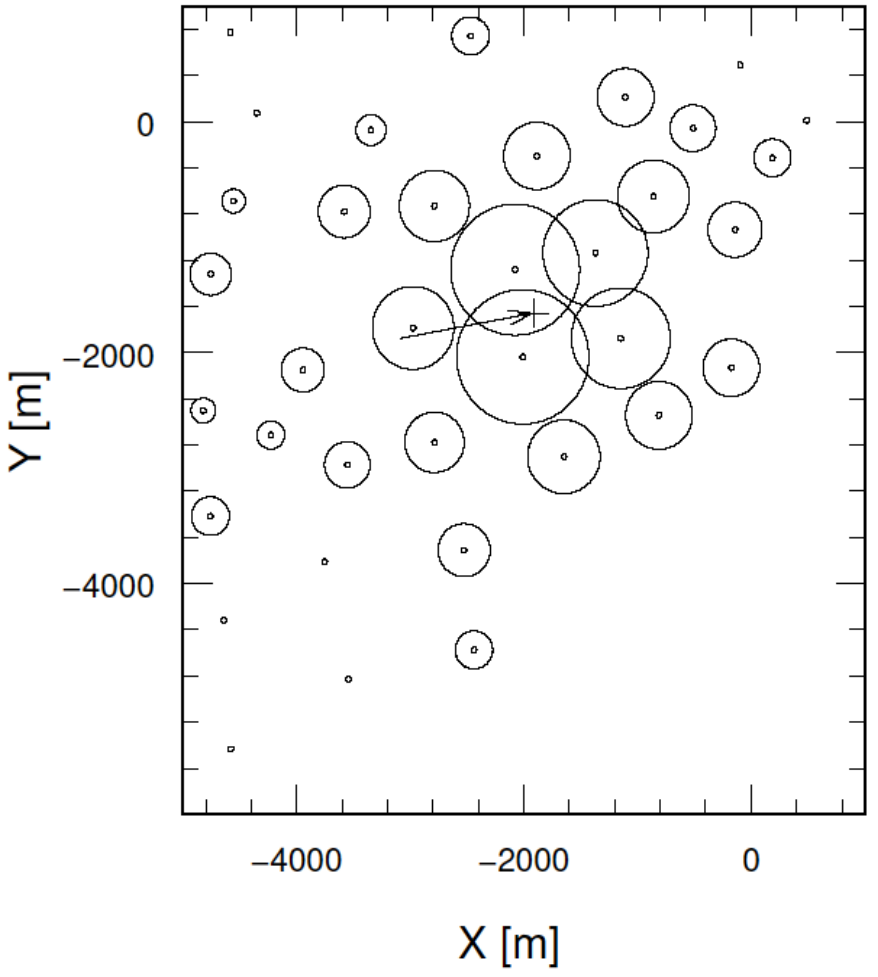
M. Teshima



The Highest Energy Event by AGASA

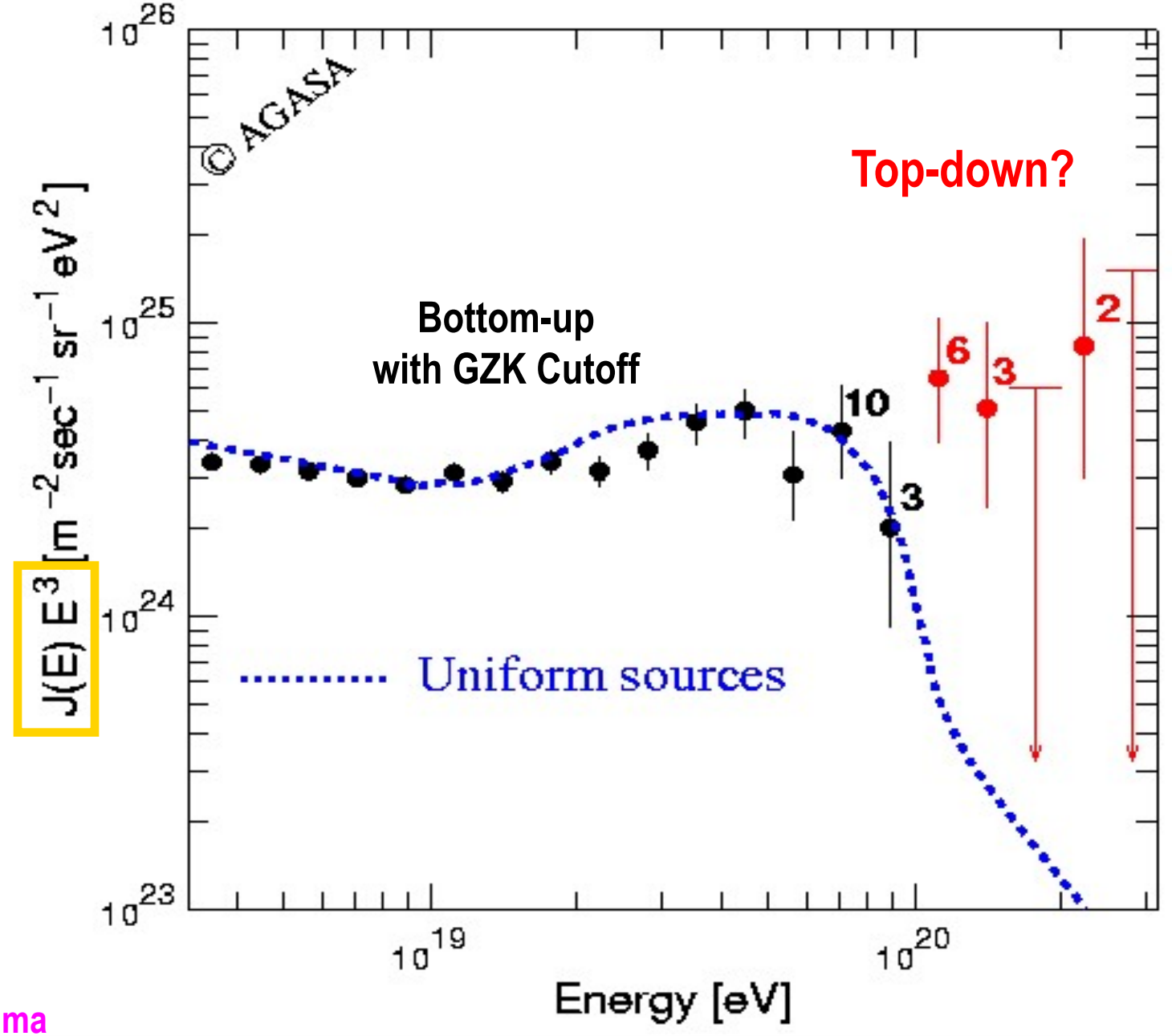
2.5 x10^{20}eV on 10 May 2001





M. Teshima

Energy Spectrum by AGASA



M. Teshima

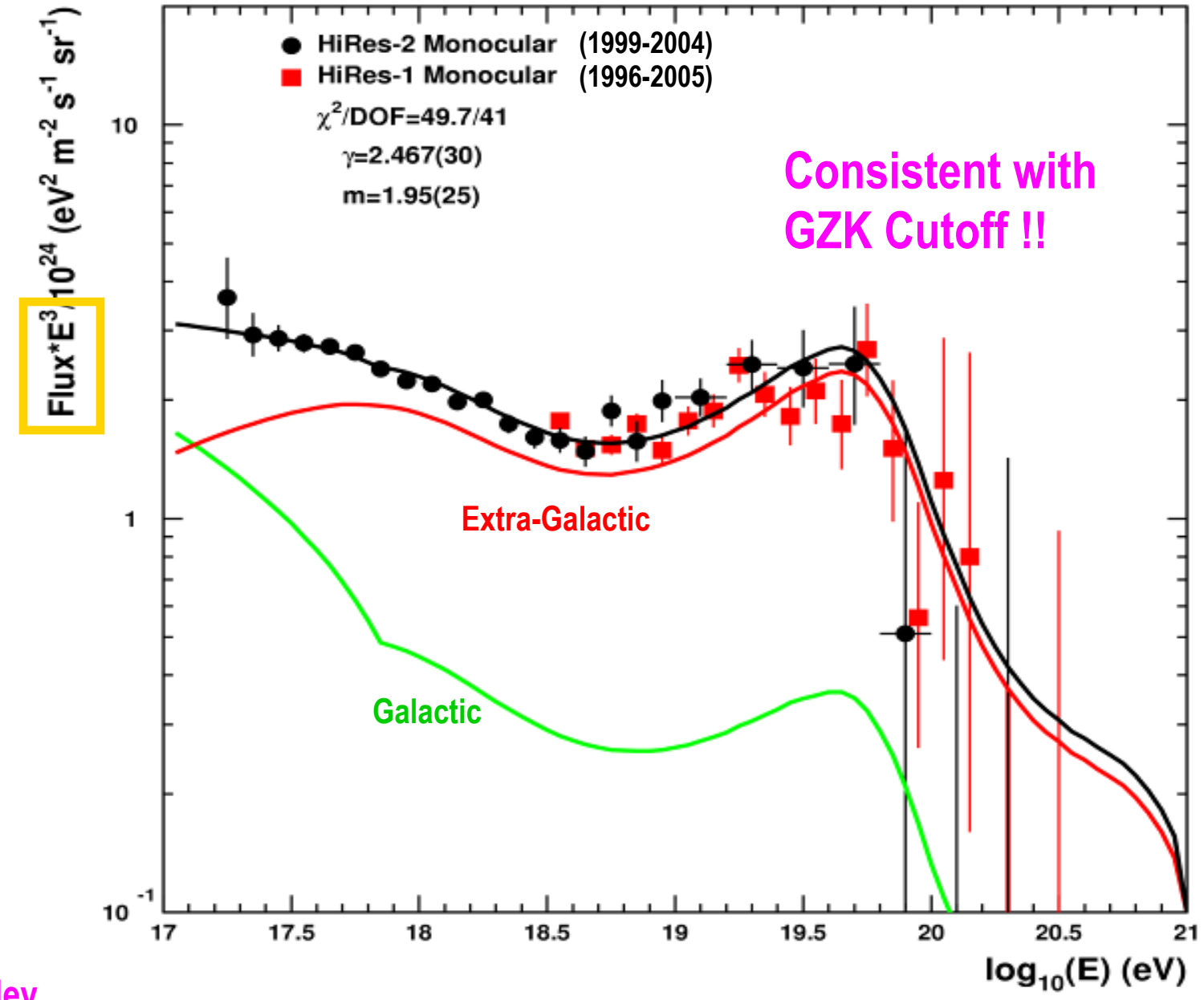
Two HiRes Detectors

- HiRes1: Atop Five Mile Hill
- 21 mirrors, 1 ring (3°<altitude<17°).

- HiRes2: Atop Camel's Back Ridge
- 12.6 km SW of HiRes1.
- 42 mirrors, 2 rings (3°<altitude<31°).

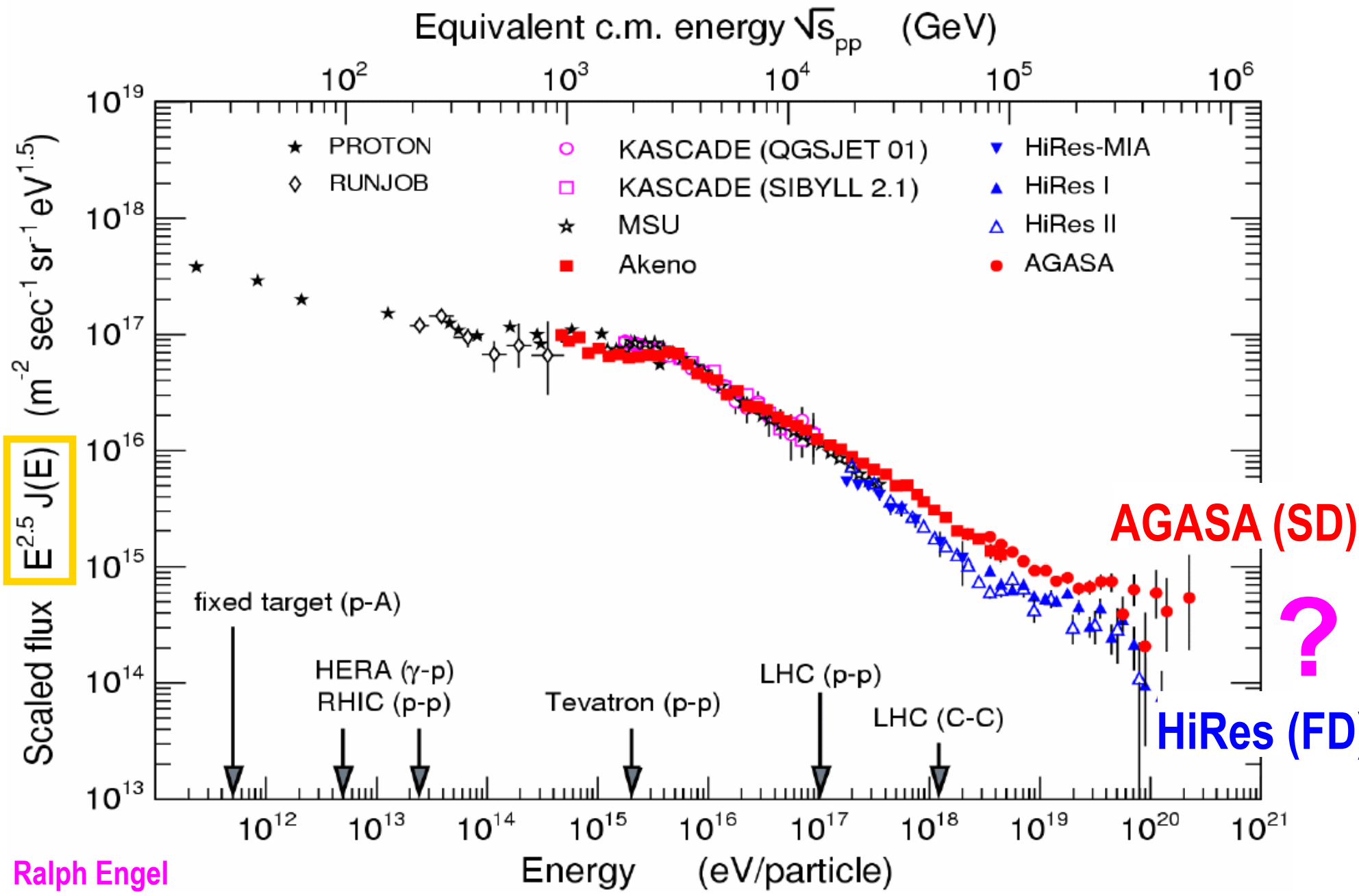
G. Thomson

Energy Spectrum by HiRes



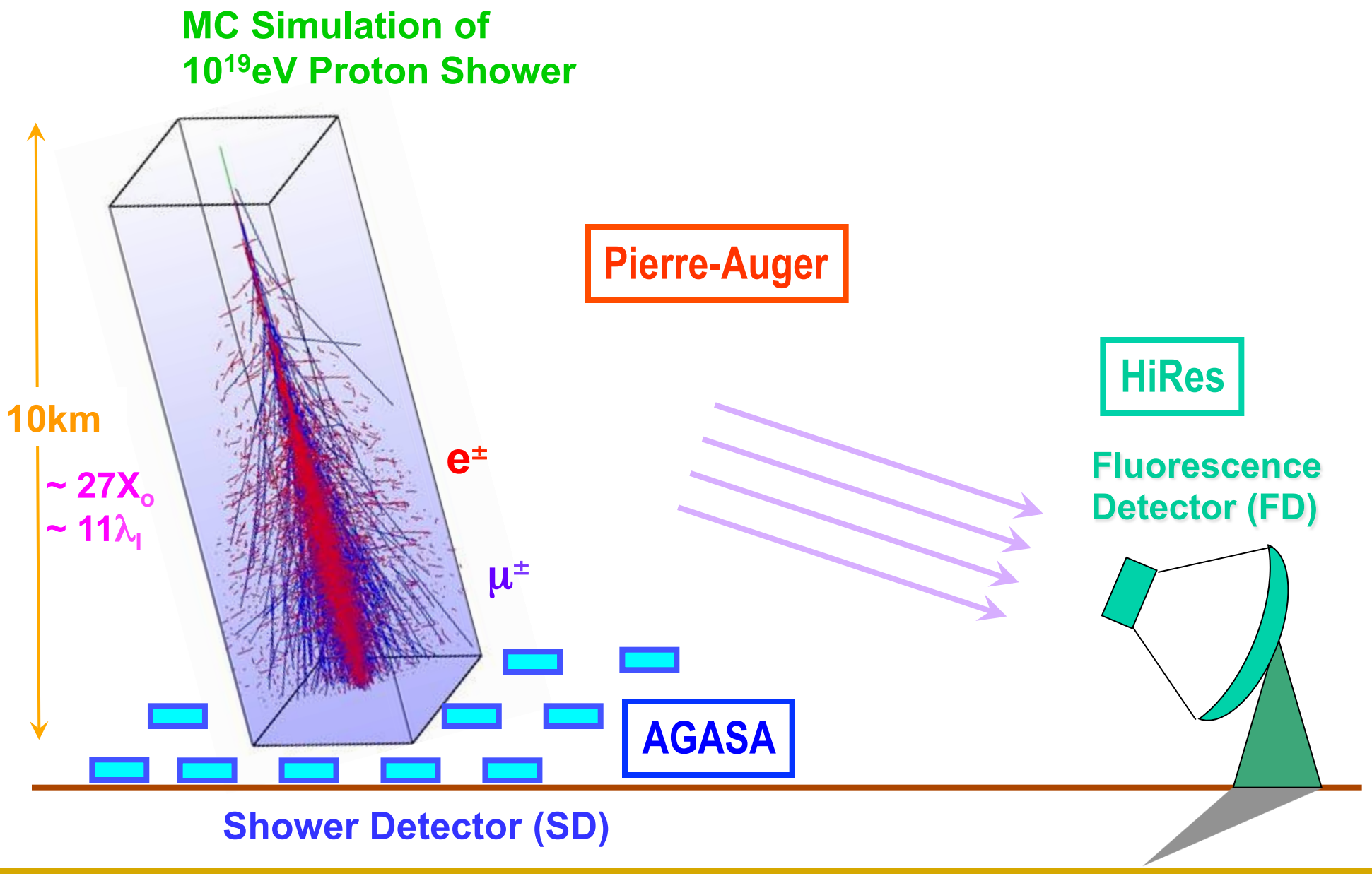
C. Finley

Energy Spectrum



Ralph Engel

Detection Technique



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

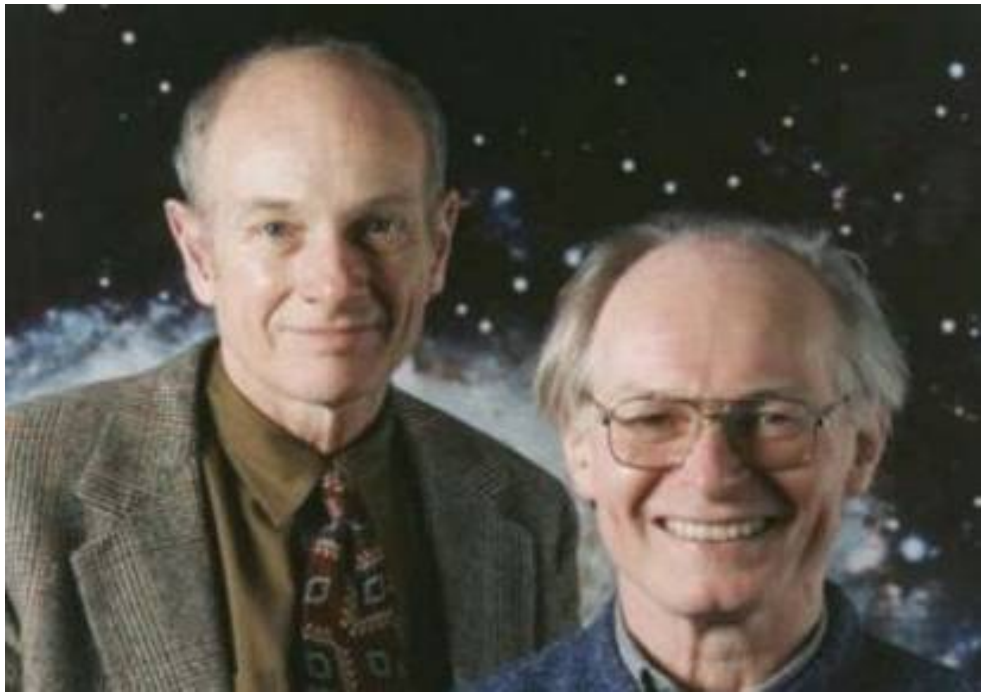
17 Countries
50 Institutions
~370 Scientists

Italy
Czech Republic
France
Germany
Poland
Slovenia
Spain
United Kingdom

Argentina
Australia
Brazil
Bolivia*
Mexico
USA
Vietnam*

**Associate Countries*

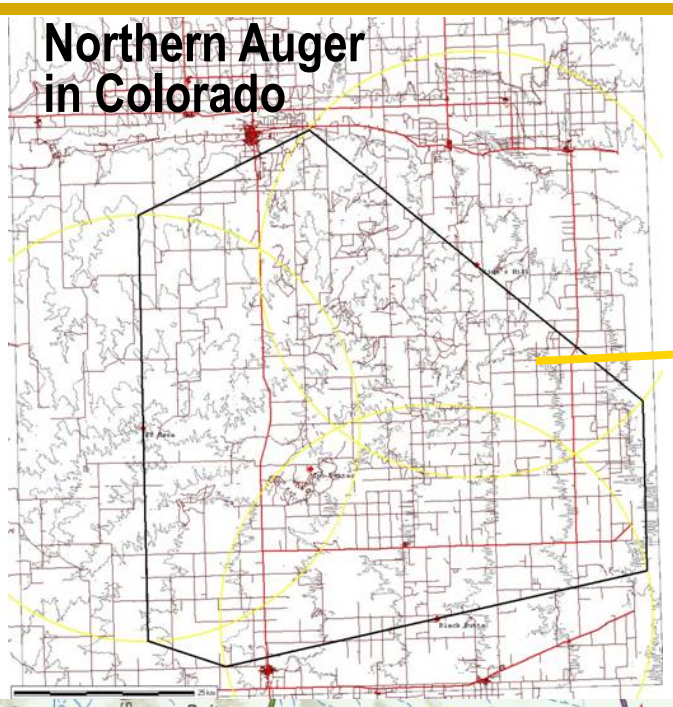
Founders

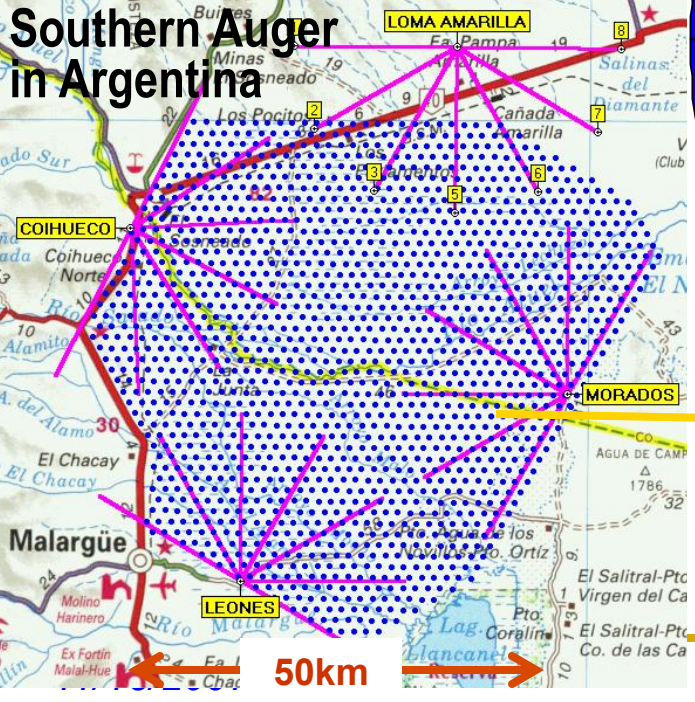


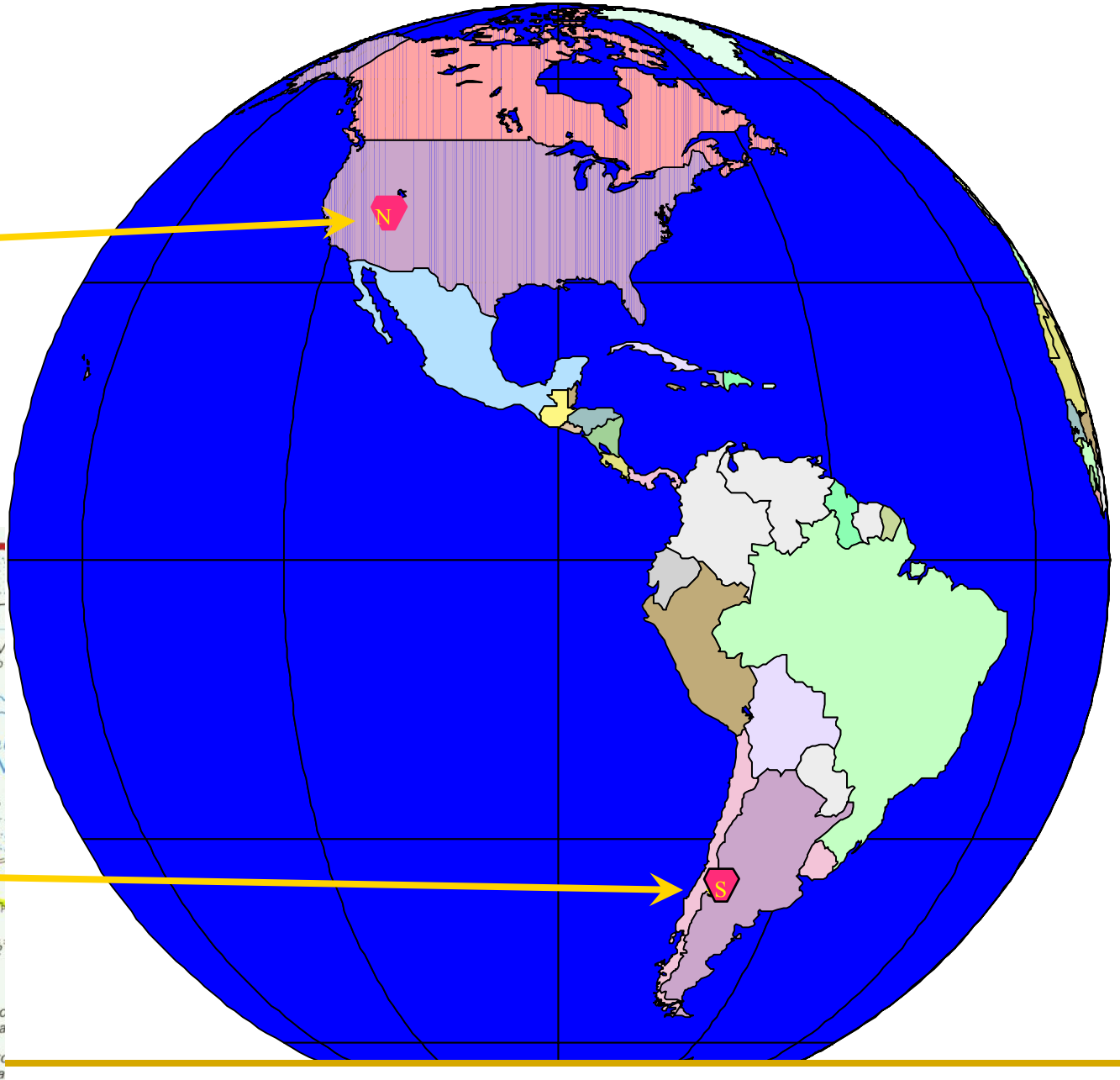
Jim Cronin

Alan Watson

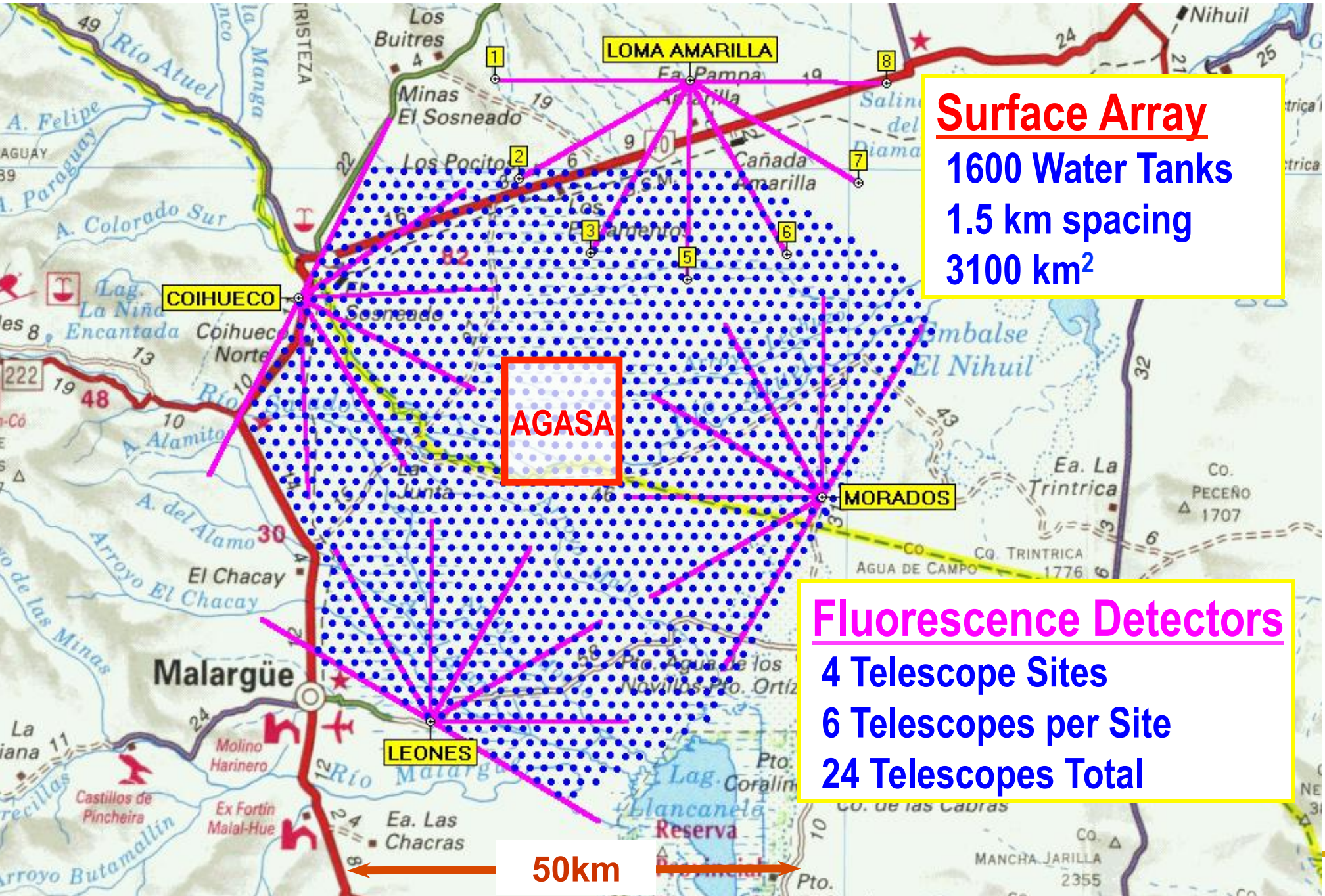
Pierre-Auger Observatory







Southern-Auger in Argentina




LOMA AMARILLA
COIHUECO
MORADOS
Malargüe
LEONES
Los Buitres
Minas El Sosneado
Los Coquitos
Cañada Amarilla
Coihueco Norte
El Chacay
Ea. Las Chacras
Reserva Provincial
El Salitral-Pto. Virgen del Carmen
El Salitral-Pto. Co. de las Cabras
Pto. Corolino


LOMA AMARILLA
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El Chacay
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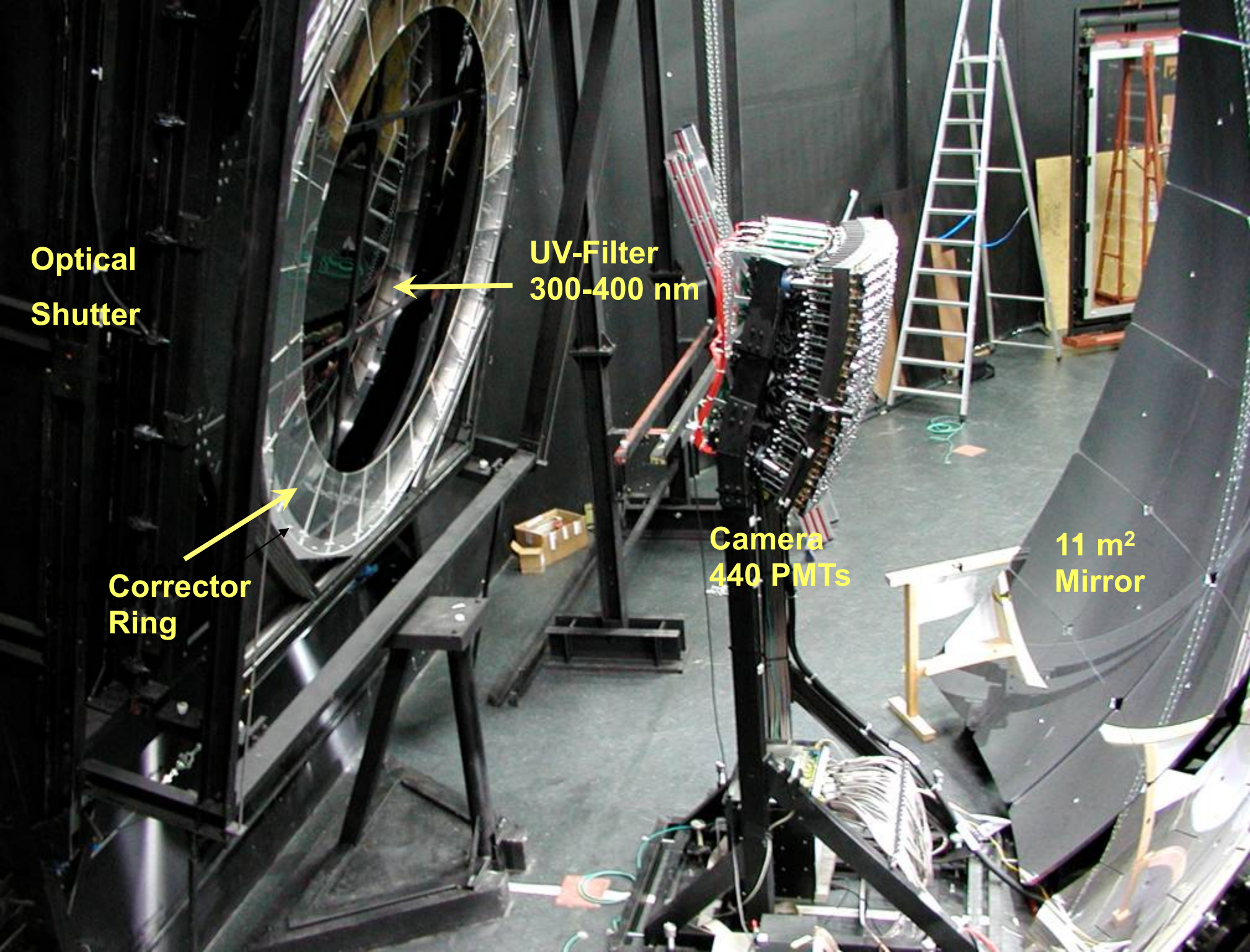
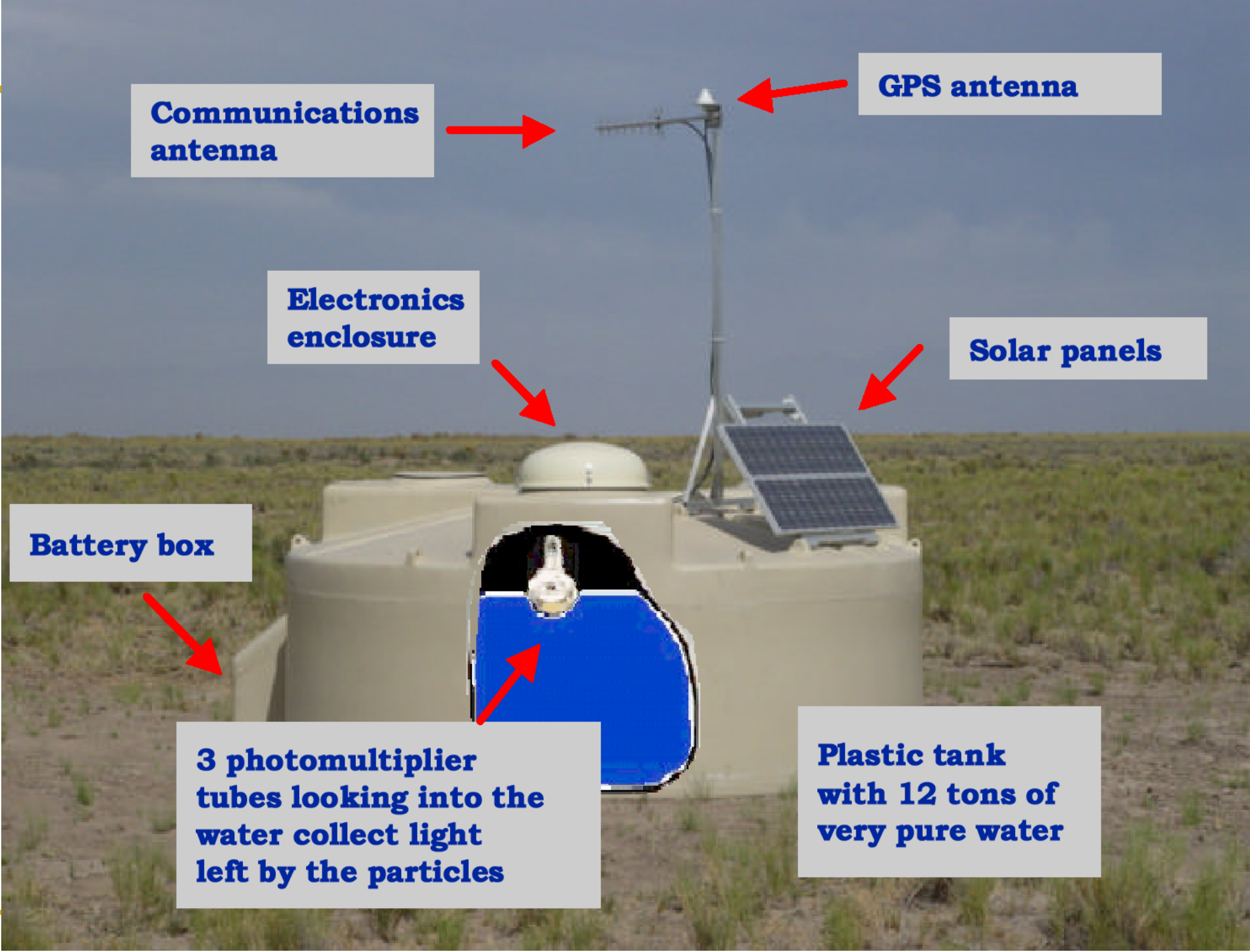
El Salitral-Pto. Co. de las Cabras
Pto. Corolina
Salinas del Diamante


Optical
Shutter
UV-Filter
300-400 nm
Corrector
Ring
Camera
440 PMTs
11 m²
Mirror

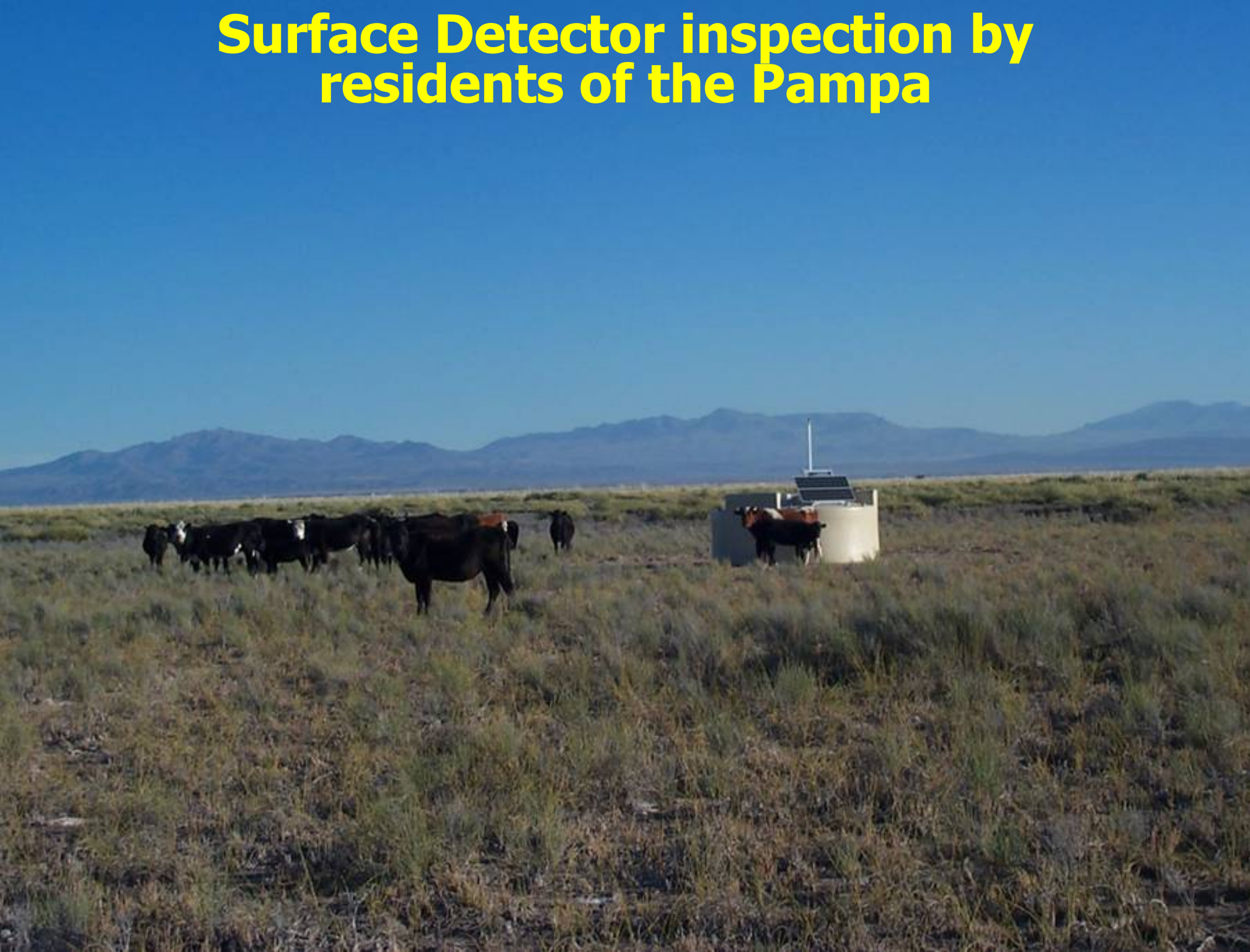
Tanks aligned seen from Los Leones

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

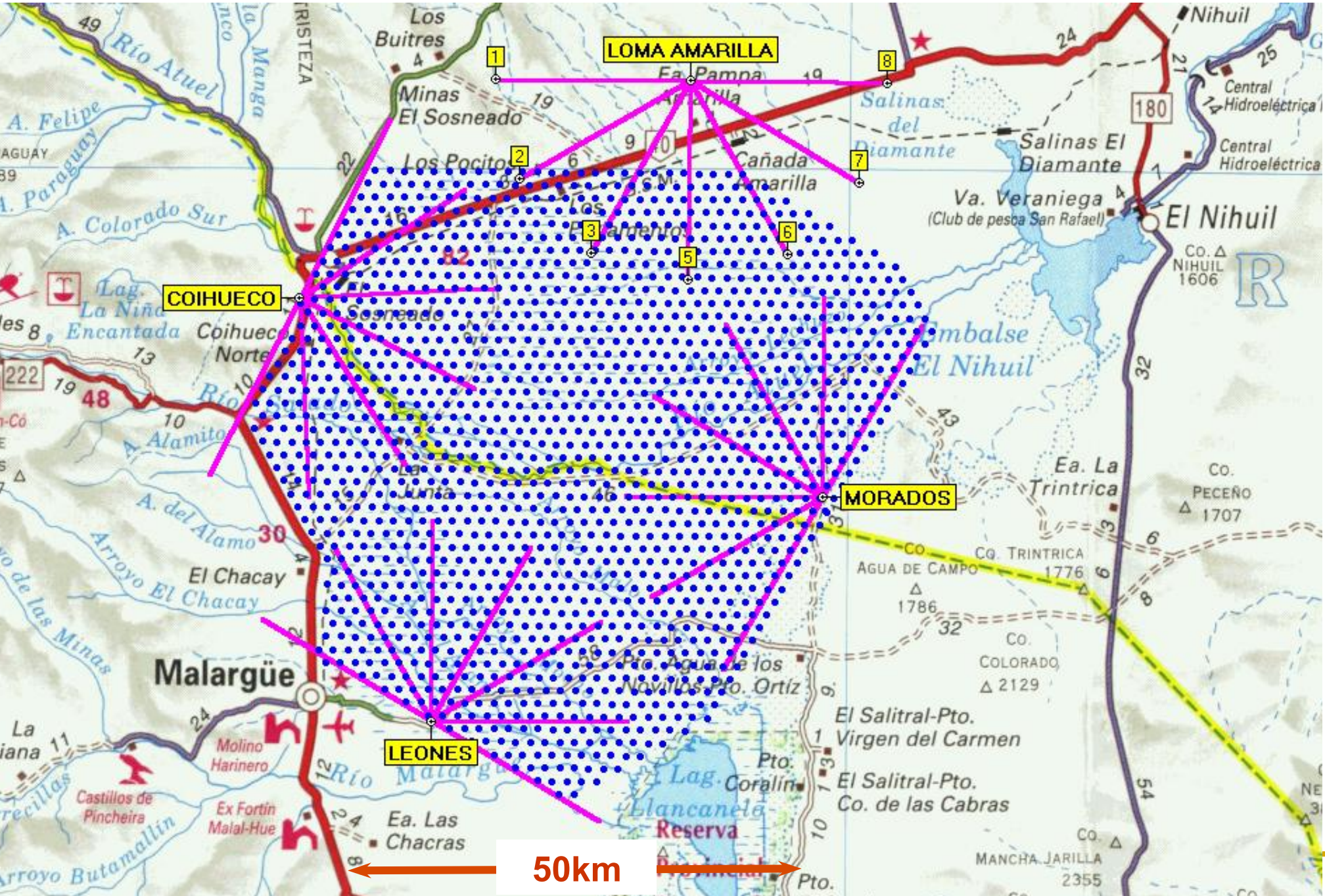


Don’t get stuck!

Beautiful Sunset on the Andes

Lively Life in Malargue

Southern-Auger in Argentina



Entrance of City of Malargue


Auger Office Building

Center of City


Annual Festival


05
MOTOKA
YAMAHA
133


Regalería
Summer
EQUIPOS DE MUSICA - REGALOS
JUGUETES - BAZAR - HERRAMIENTAS
ARMERIA Y PESCA
ARTICULOS DE LIBRERIA
LAPICES
CARPETAS
CUADERNOS
CARTUCHERAS
HOJAS
minutas
PESCA
OBSERVATORIO DE RAYOS COSMICOS PIERRE AUGER
Malargüe, Provincia de Mendoza, Argentina
PIERRE AUGER OBSERVATORY
PIERRE AUGER OBSERVATORY


Visiting a local high school…
Exposition of the World Culture

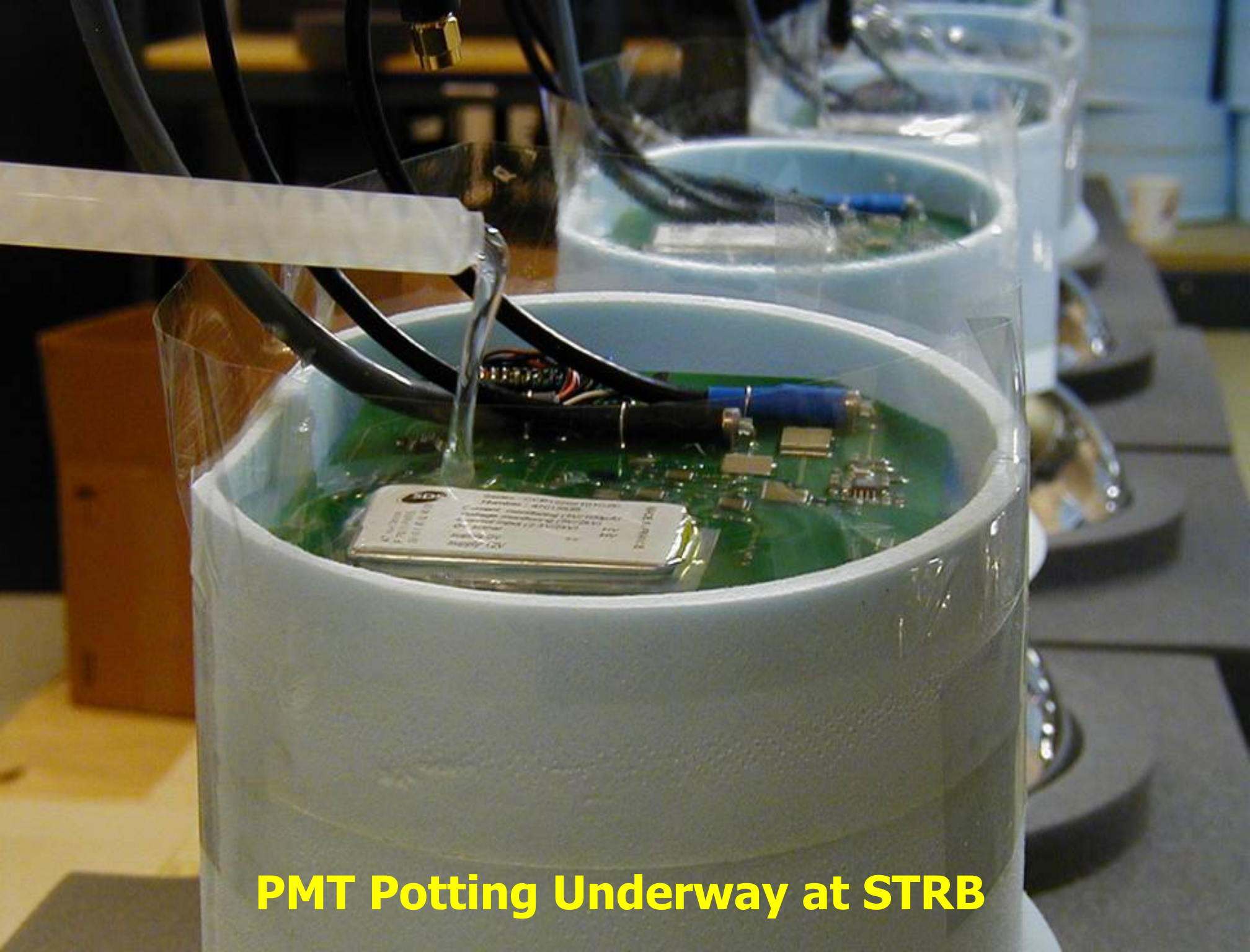

ARGENTINA
BOLIVIA
JAPON
Japon

UCLA Contributions

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….			

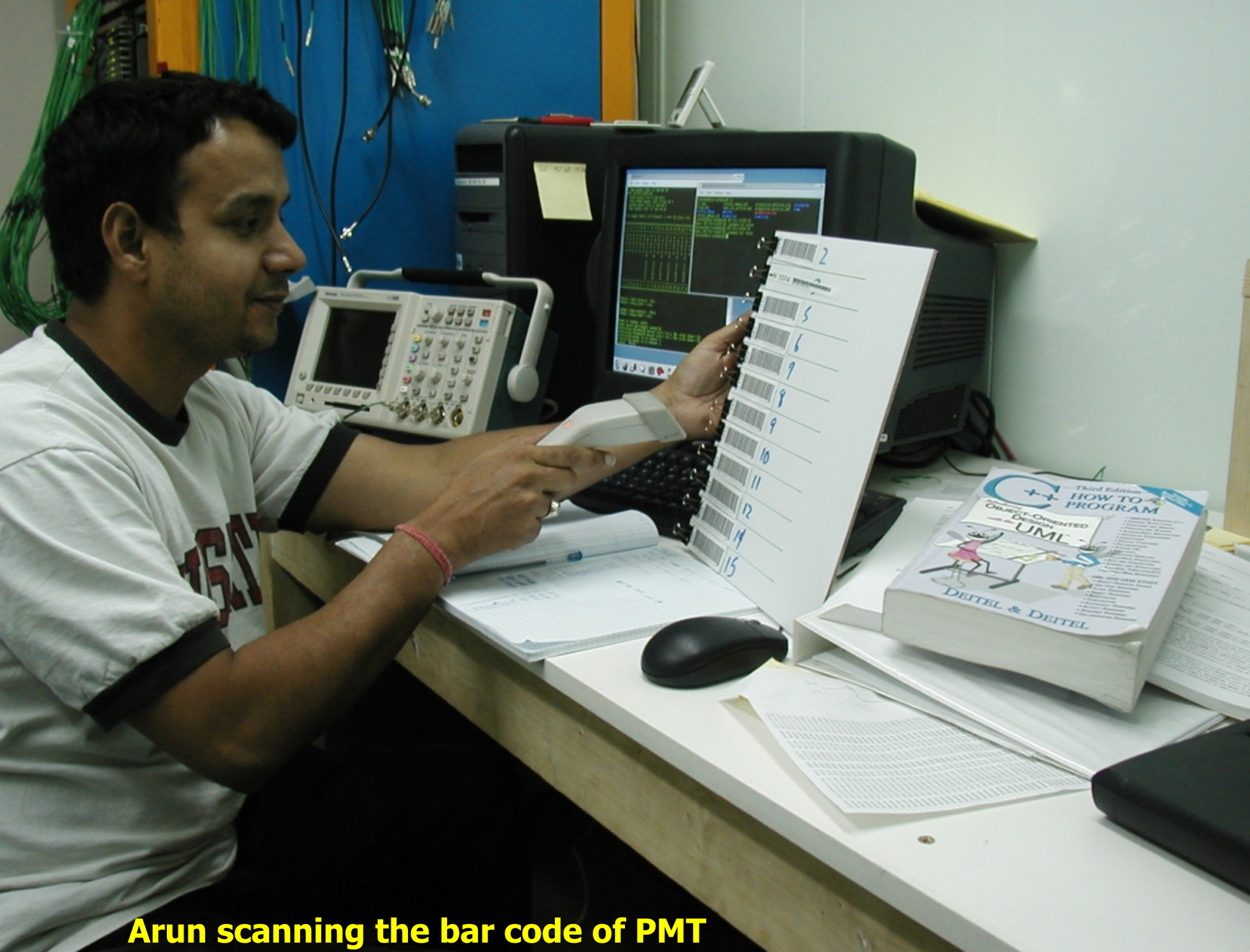
UCLA PMT Test Facility at STRB in Westwood



PMT Potting Underway at STRB

Malargüe PMT Test Facility

16 PMTs inspected by Arun



Arun scanning the bar code of PMT

David in Control

PMTs Assembled by Tohru and Federico

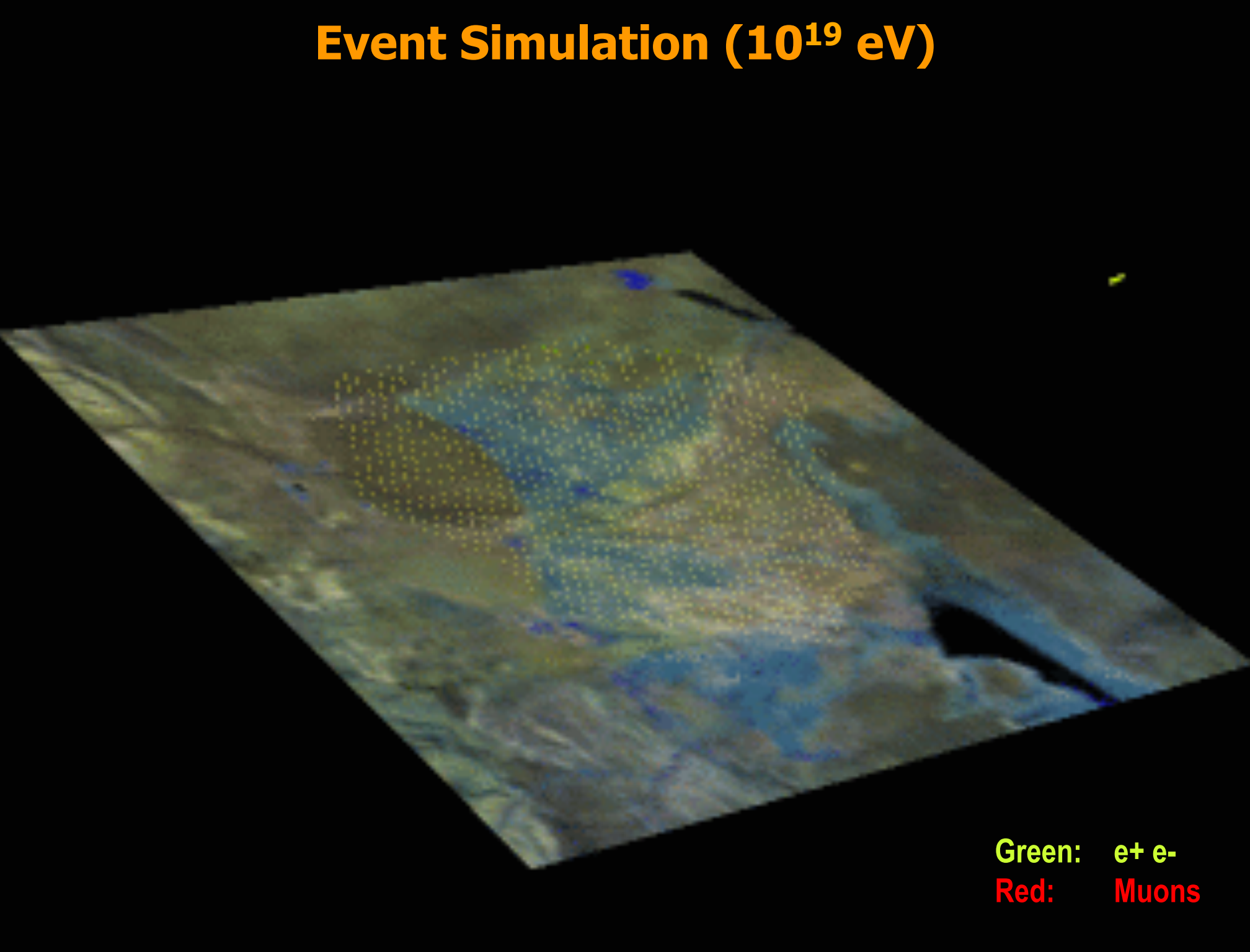
Barbeque Party at UCLA Lab at Malargüe


Federico
Coca-Cola

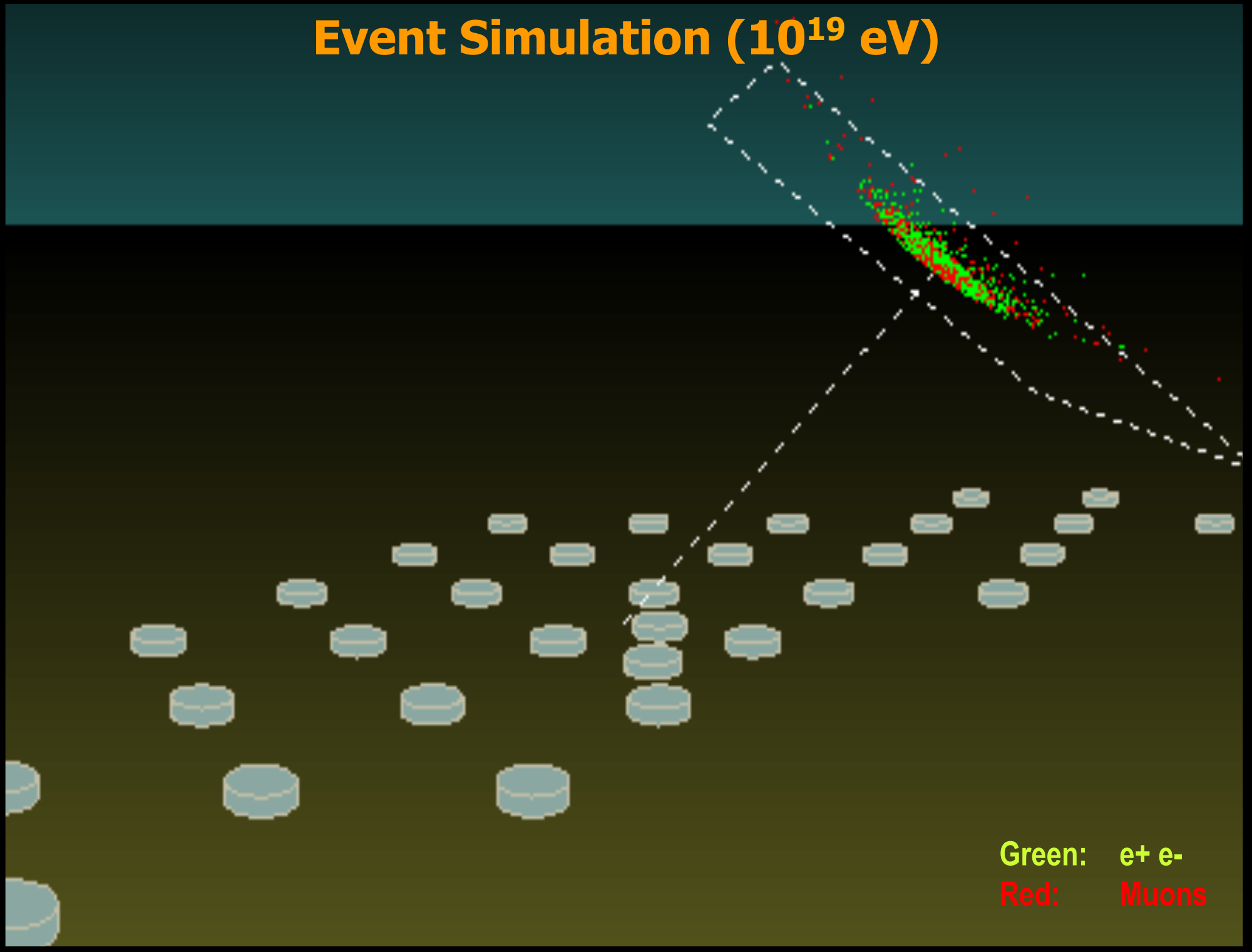
UCLA Contributions

- **Detector Construction** — 1999 - 2004
  - Development of new PMT
  - Testing of all PMT
- **Data Taking and Calibration** — 2003 - 2006
  - Detector calibration
  - Monitoring the long term stability
- **Software Development** — 2004 - 2007
  - Detector simulation
  - Standard software package (DPA)
- **Physics Analyses** — 2004 – Now
  - Energy Spectrum
  - Composition
  - Angular Distribution

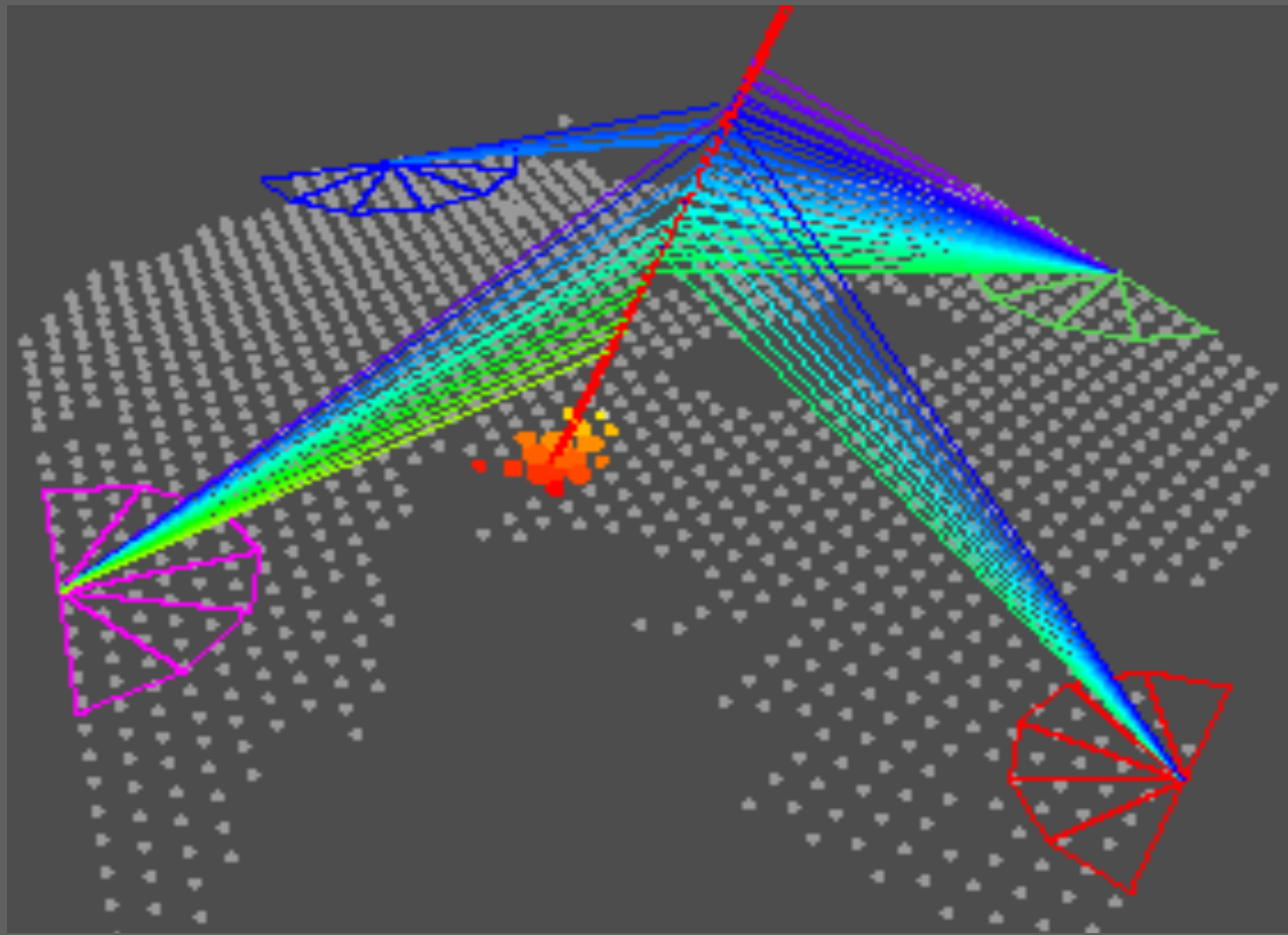
Event Simulation (10^{19} eV)



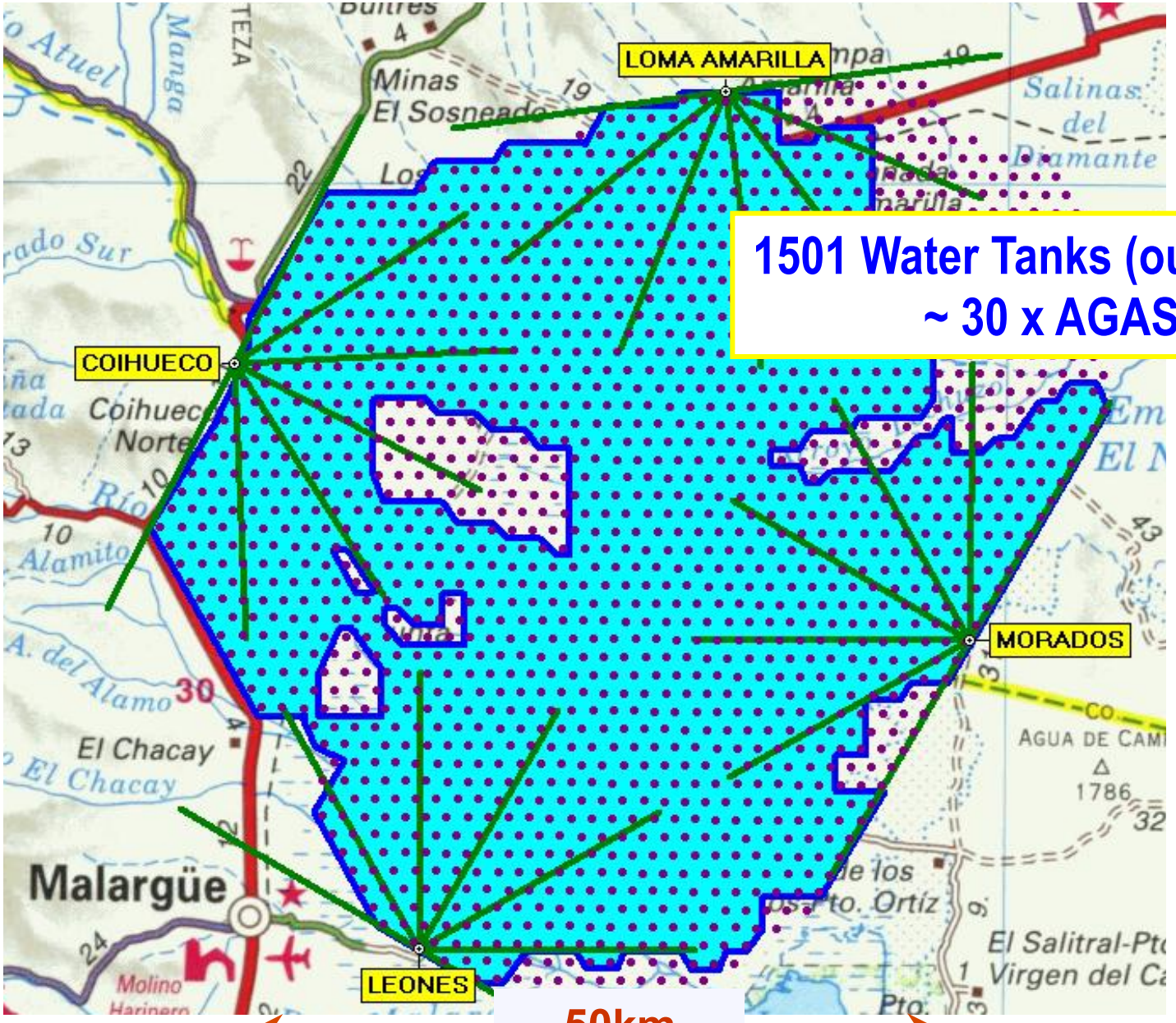
Event Simulation (10^{19} eV)



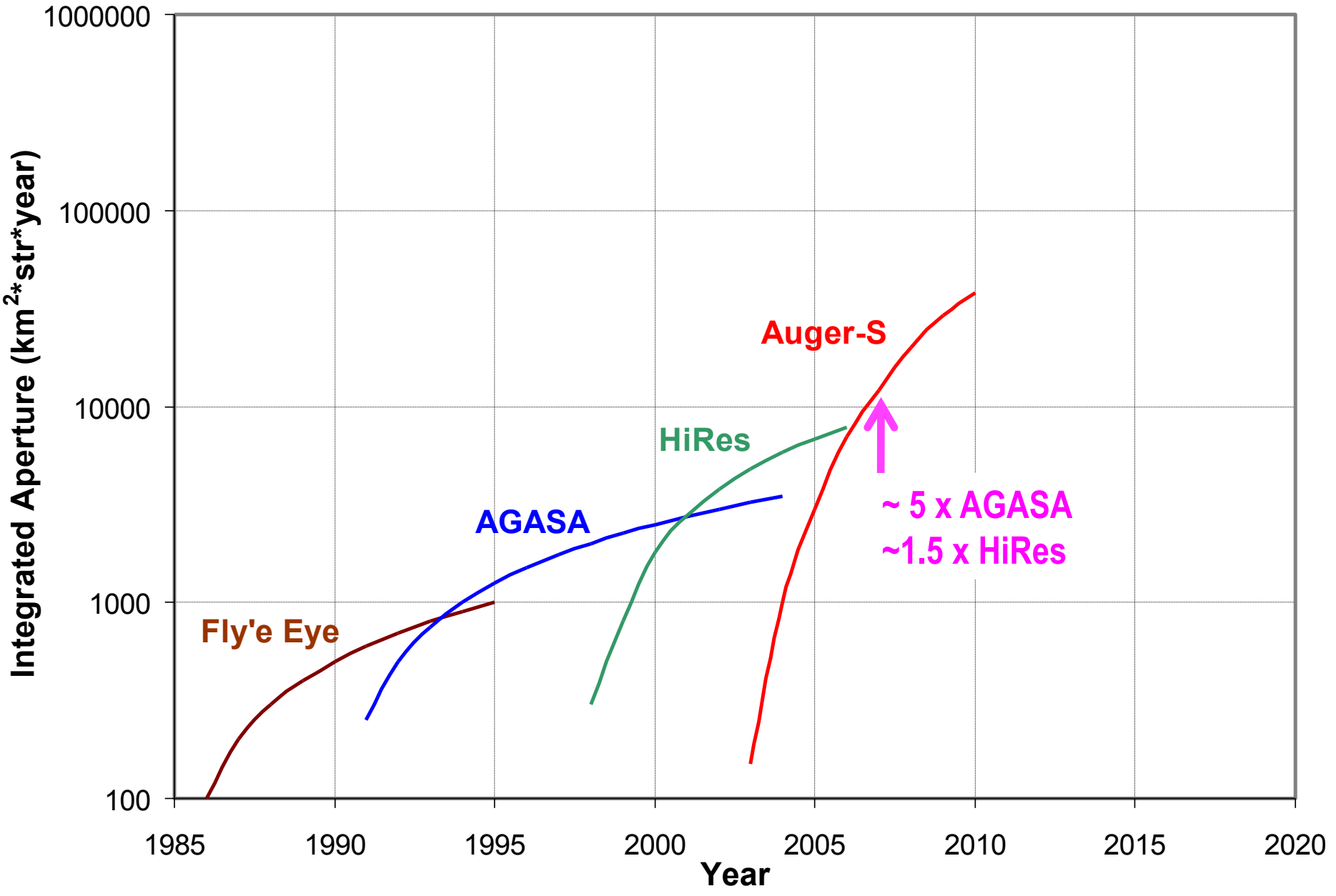
10^{19} eV event observed by all detectors



Southern Auger as of Nov. 2007



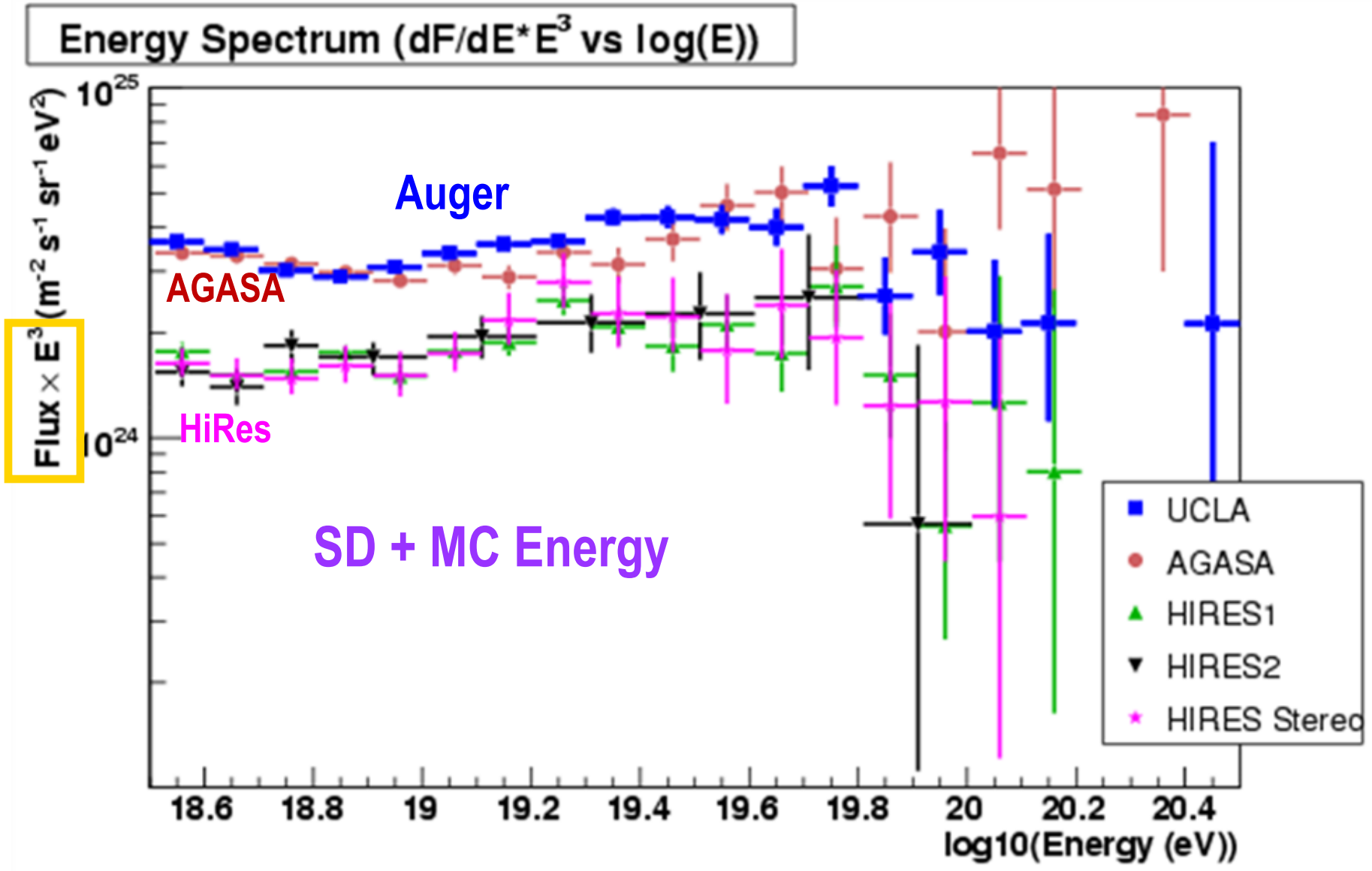
Comparison of Integrated Aperture



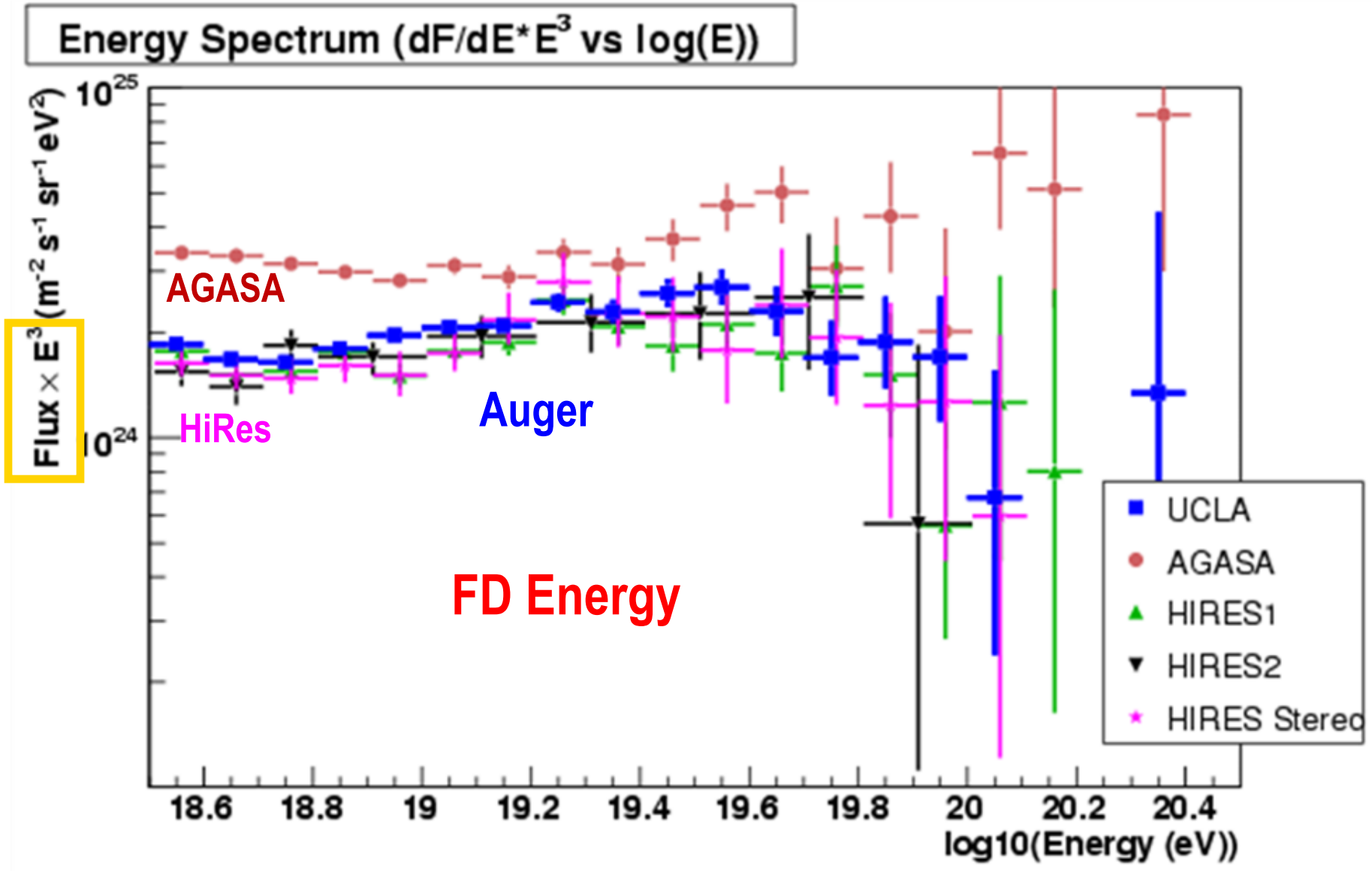
Energy Spectrums

- Arun Tripathi
- Joong Lee (PhD)
- Oleg Kalashev

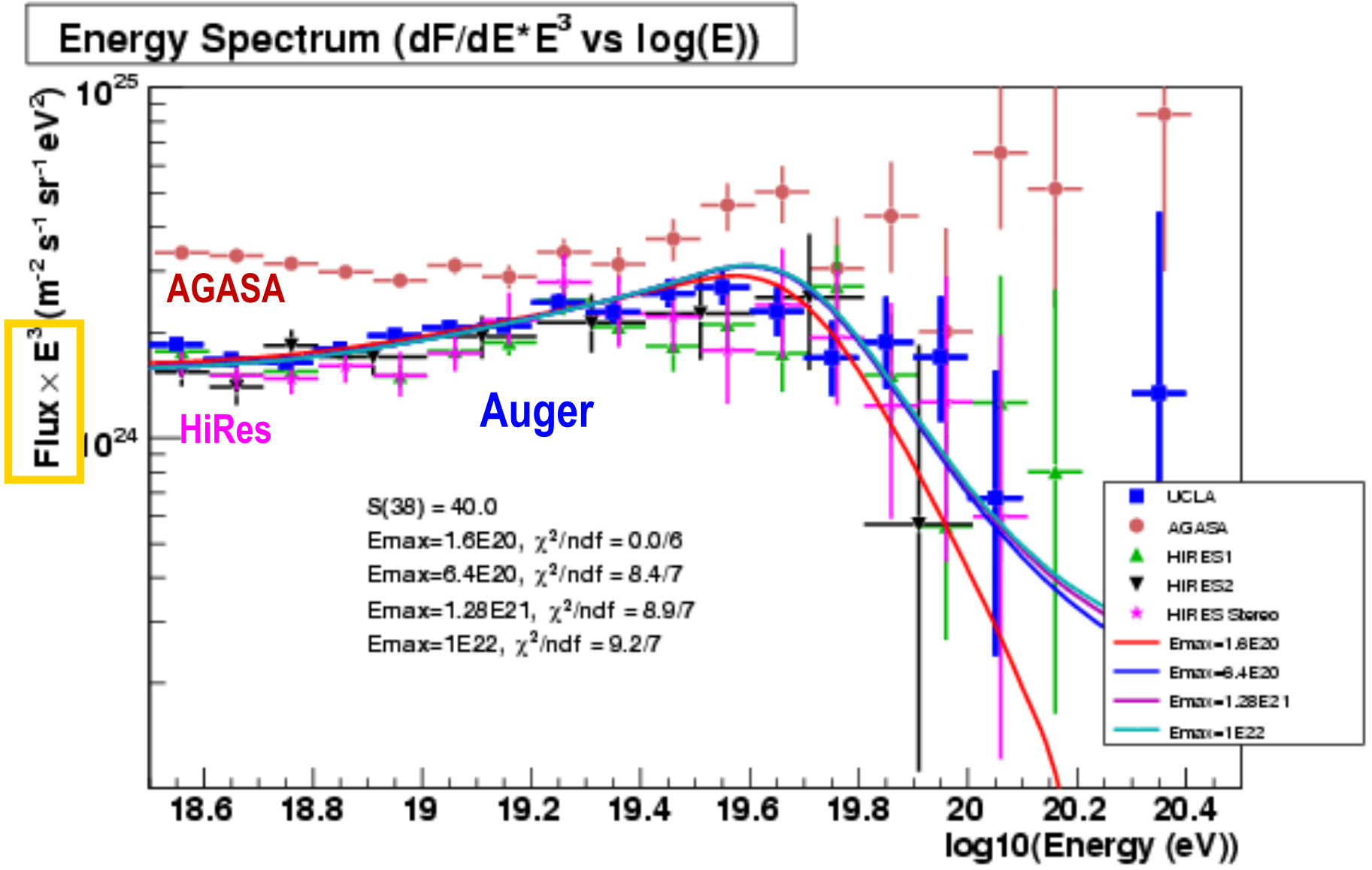
Energy Spectrum × E^3 (SD+MC Energy)



Energy Spectrum × E^3 (FD Energy)



Energy Spectrum × E^3 (fit by proton injection)



Arisaka, *et al*, astro-ph/0709.3390

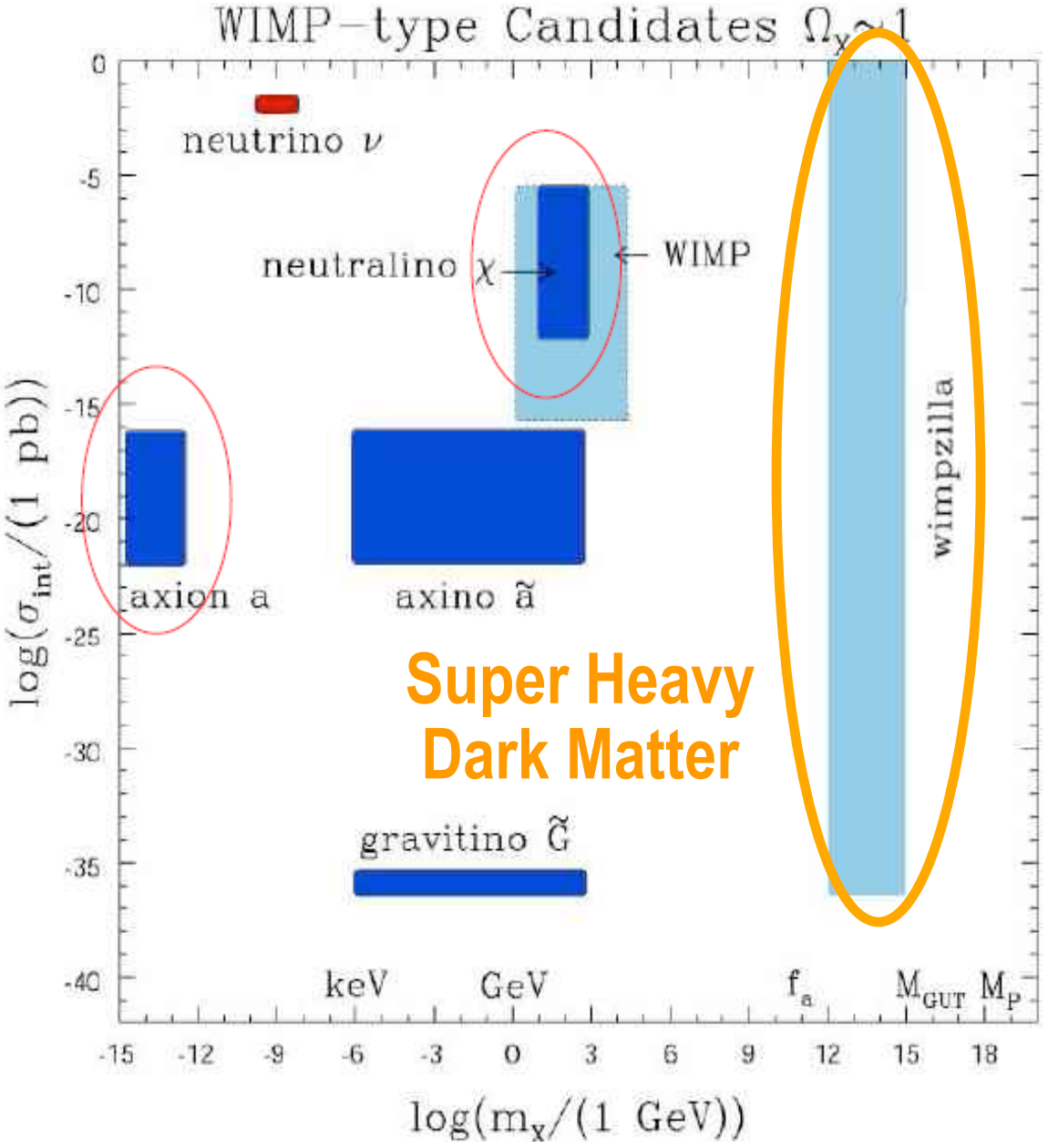
Summary of Energy Spectrum

- 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

- David Barnhill (PhD)
- Graciela Gelmini

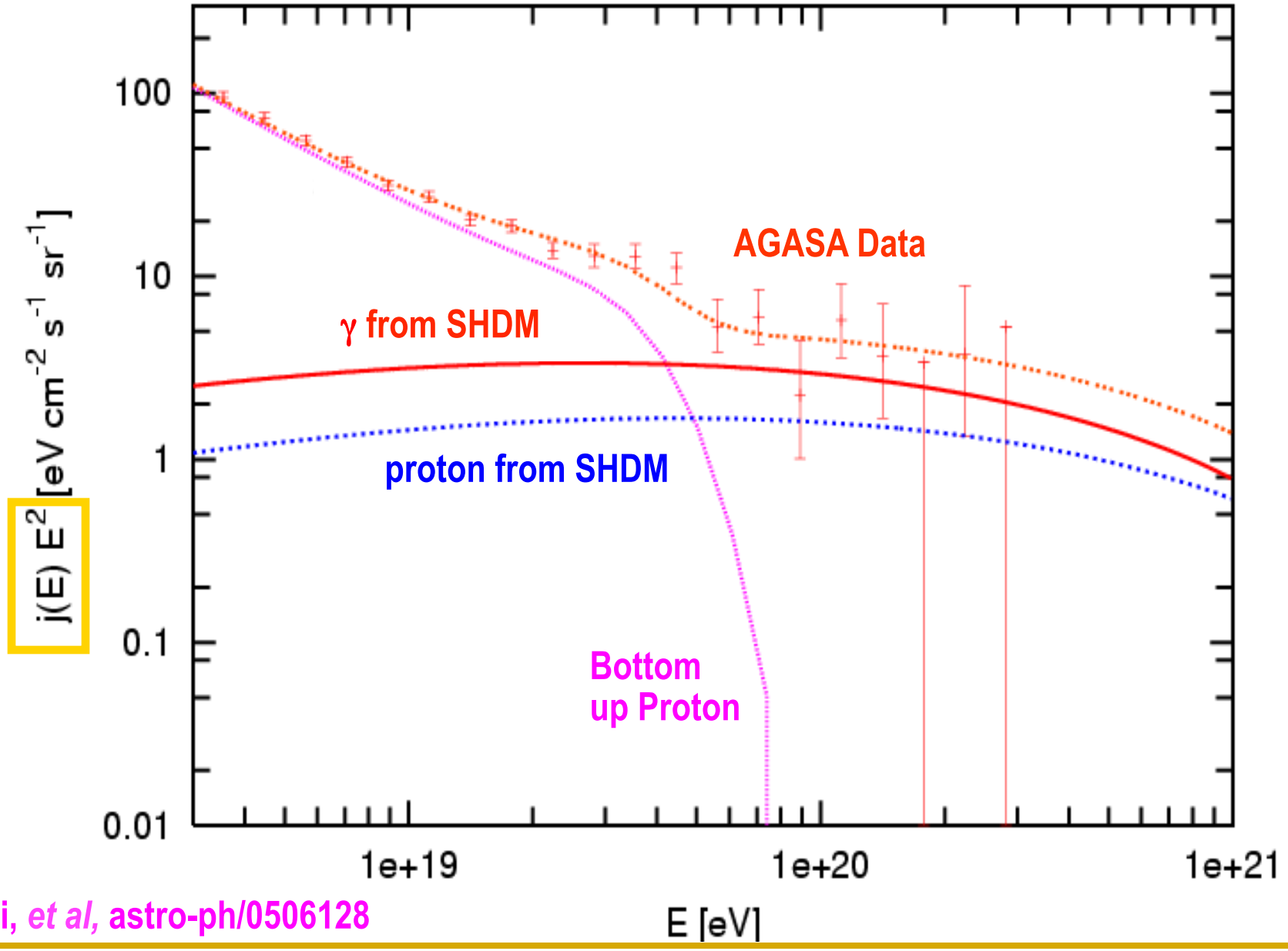
What is Dark Matter?



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

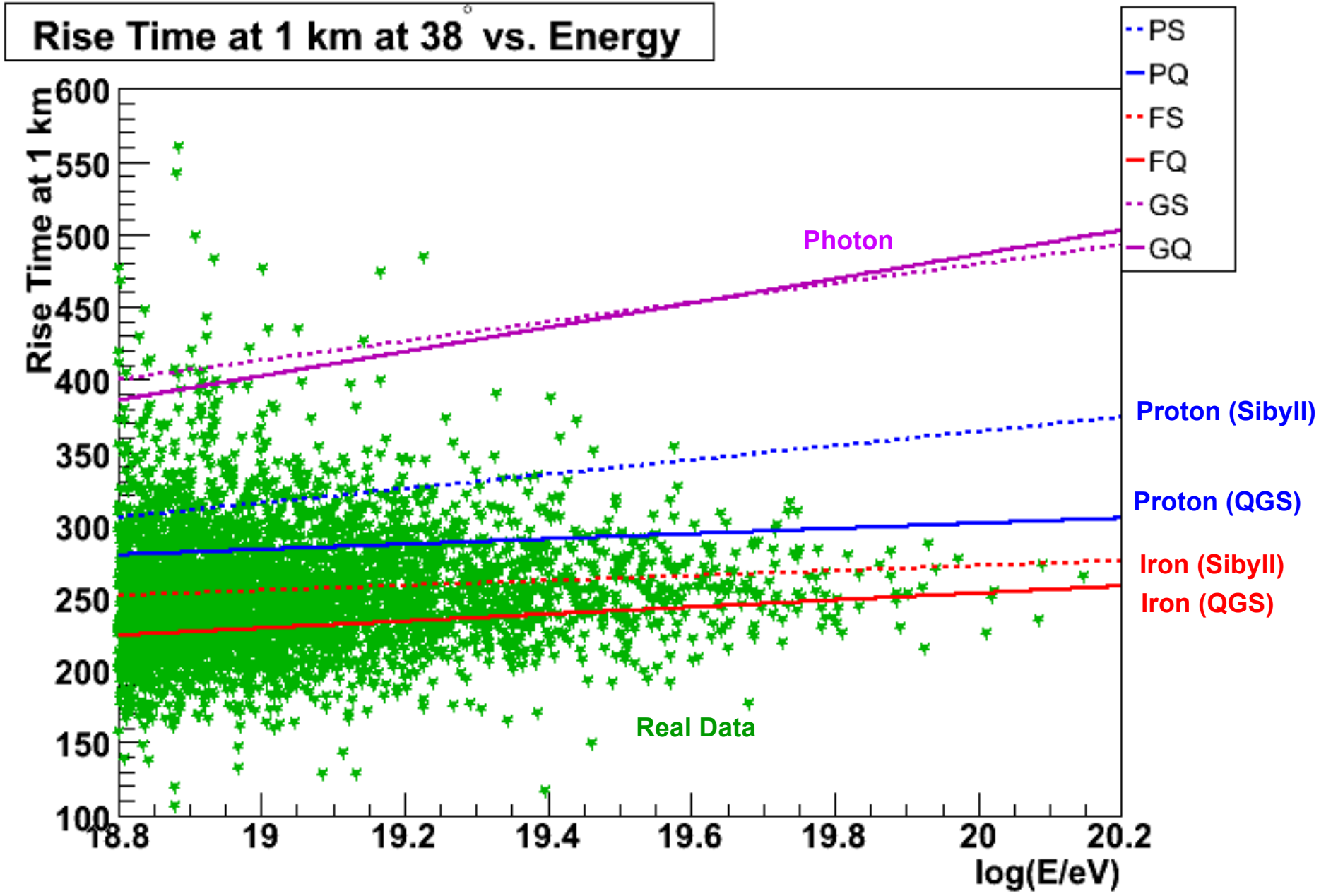
L. Roszkowski

Possibility of photons in AGASA data



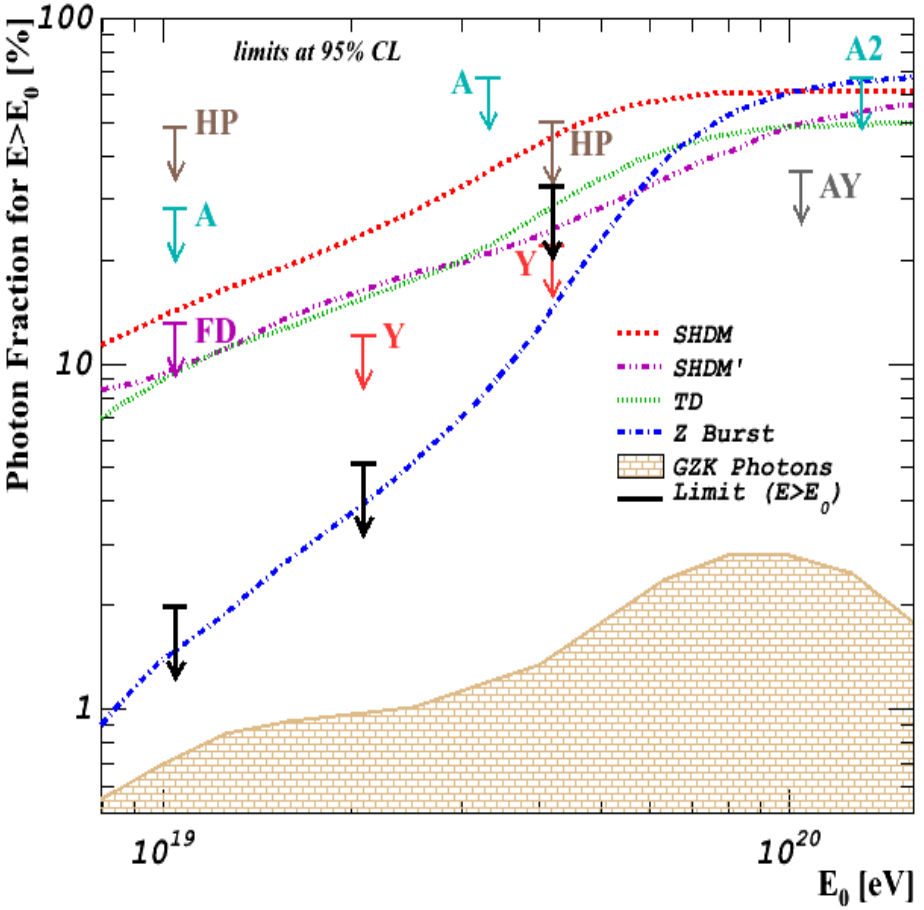
Gelmini, *et al*, astro-ph/0506128

Risetime vs. Log(E)

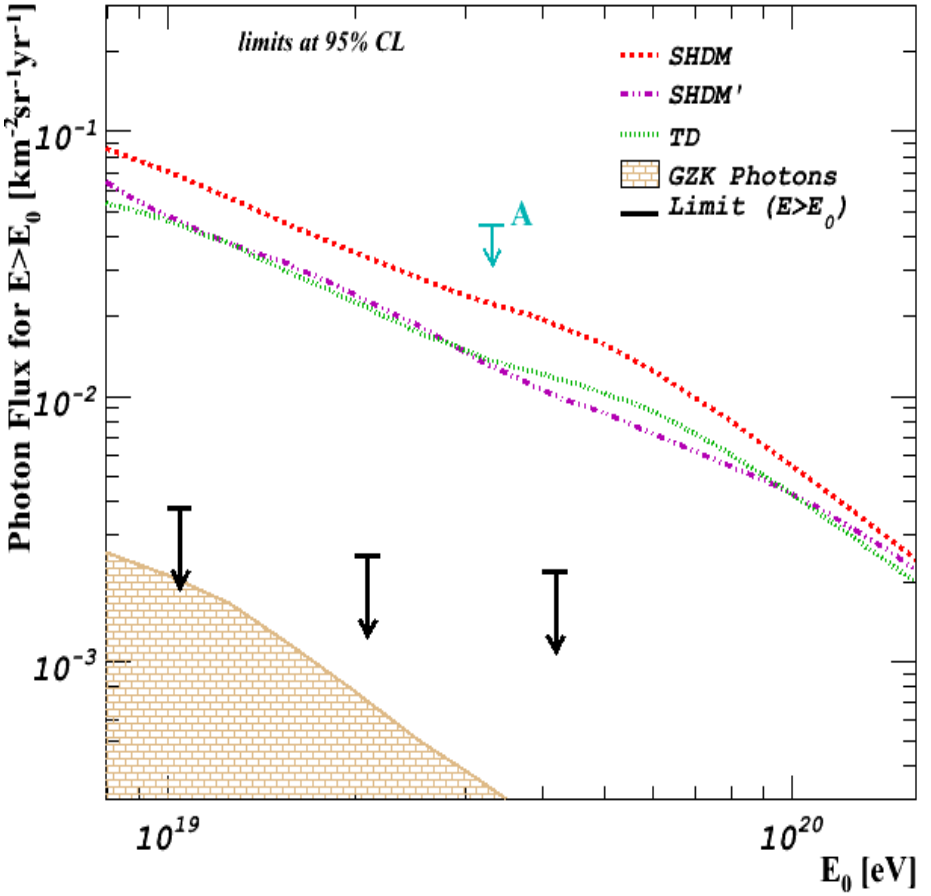


Photon Limit Results

Fraction Limit



Flux Limit



Summary of Photon Flux Limit

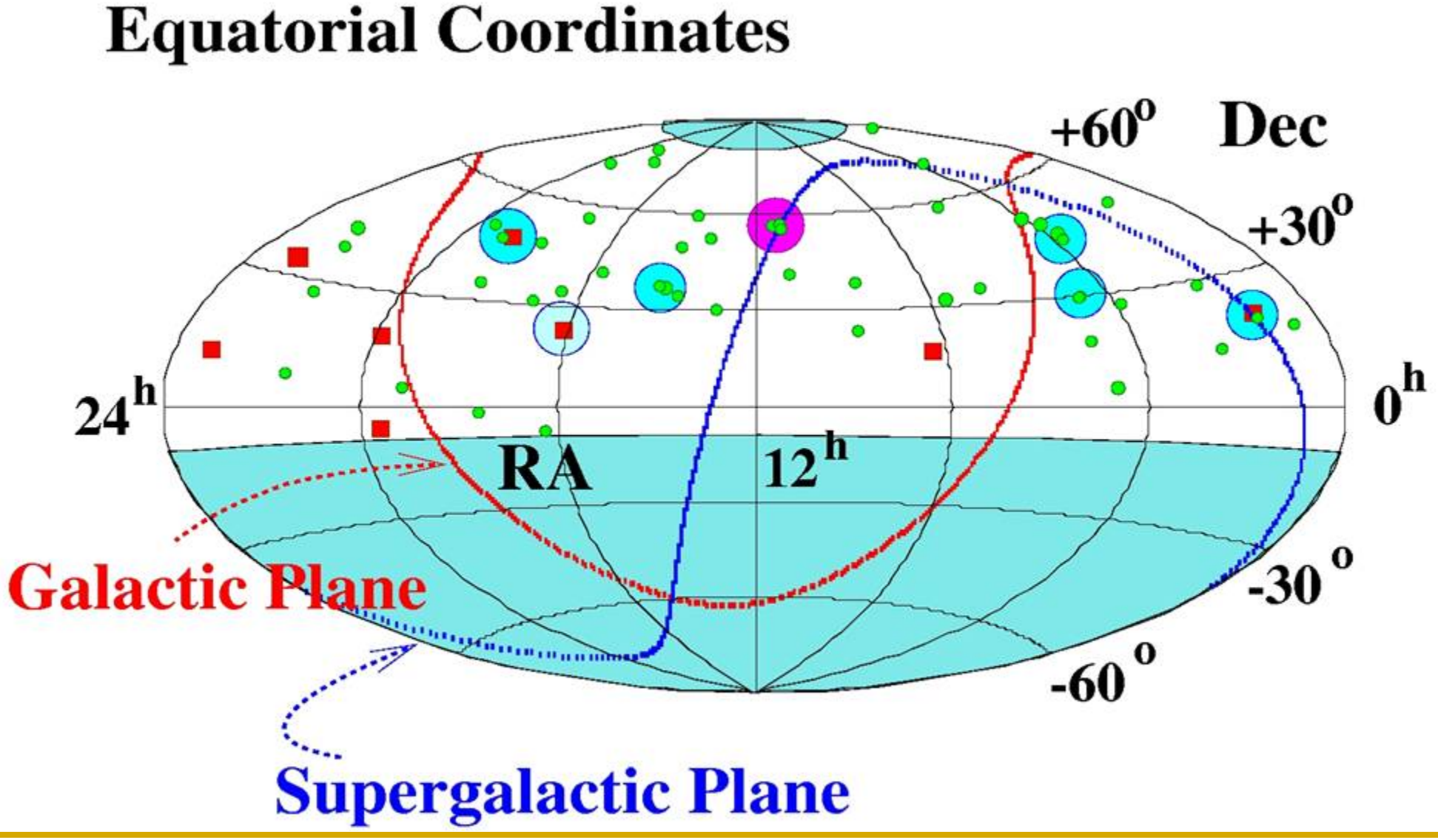
- **The combination of the following assumptions is disfavored.**
  - **AGASA-like energy spectrum is correct.**
  - **There are extra Super-GZK events (> 10^{20} eV).**
  - **These Super-GZK events are from the decay of Super Heavy Dark Matters.**
- **Most likely**
  - **No Top-down component, at least,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

Angular Distributions

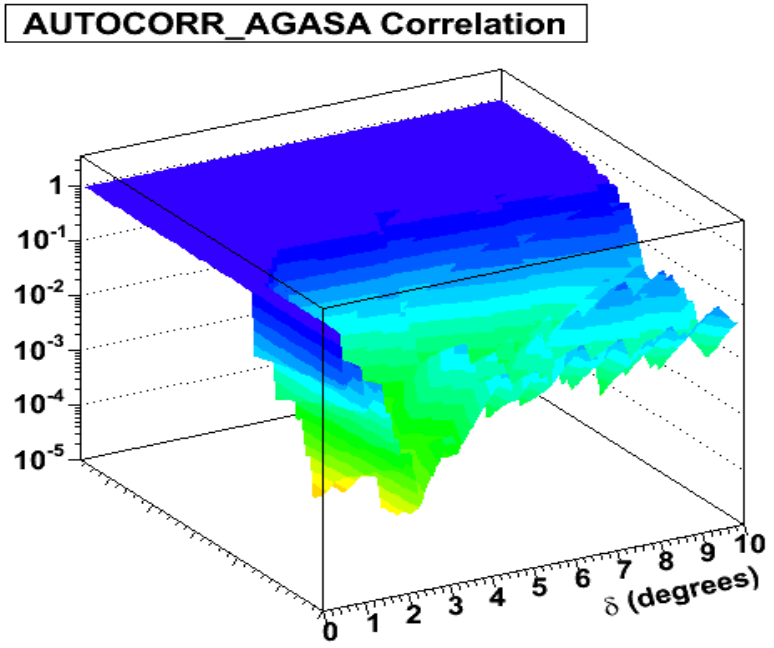
- Tohru Ohnuki (PhD)
- Pedram Boghrat
- Antoine Calvez
- Artin Teymourian

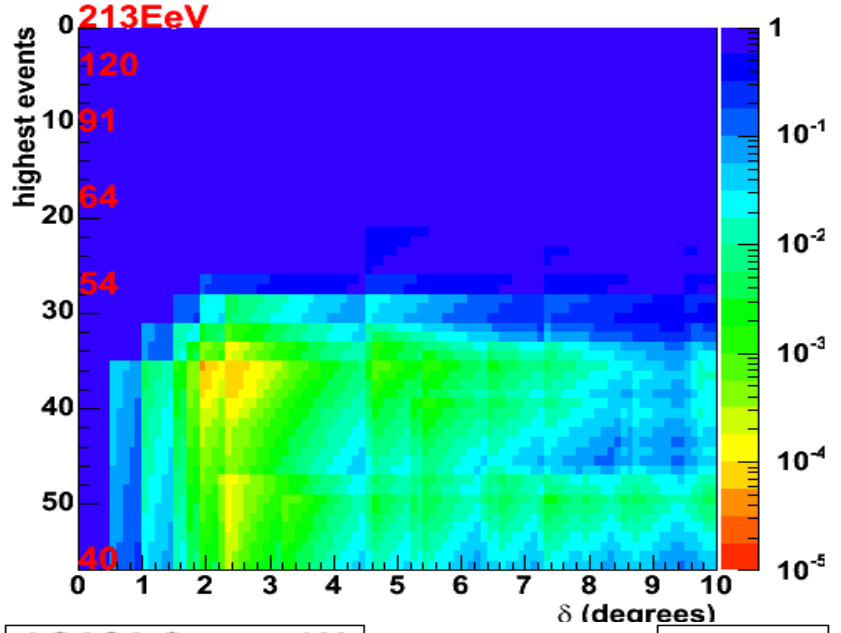
Clustering of UHECR (>40 EeV) by AGASA

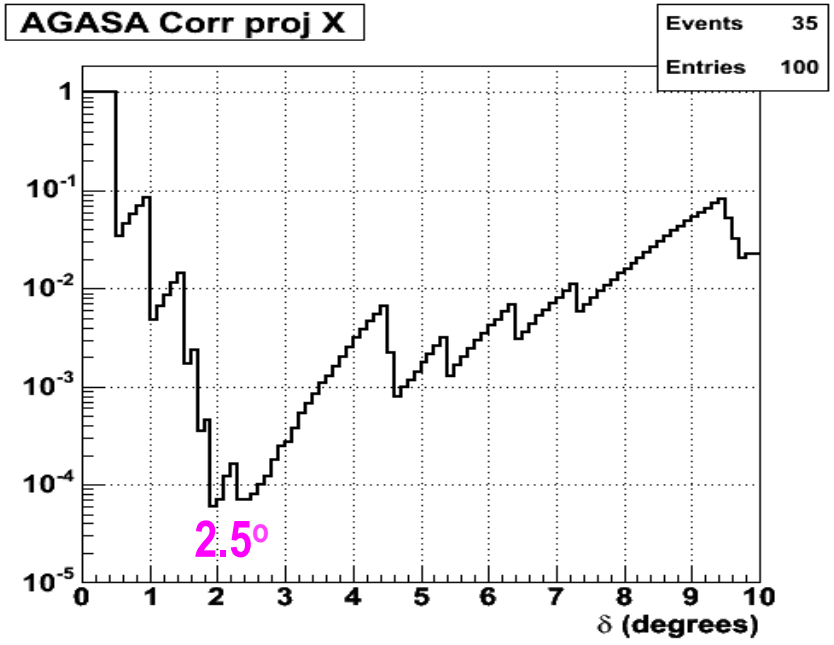
- 6 doublets and 1 triplet within 2.5° cone (out of 56 events)

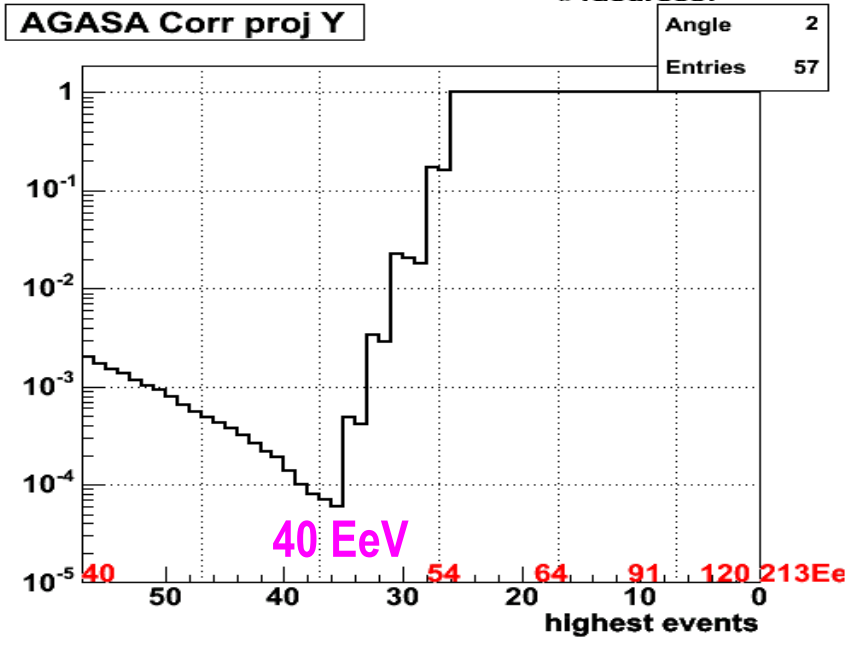


AGASA Auto-Correlation









HiRes Correlation with BL Lacs

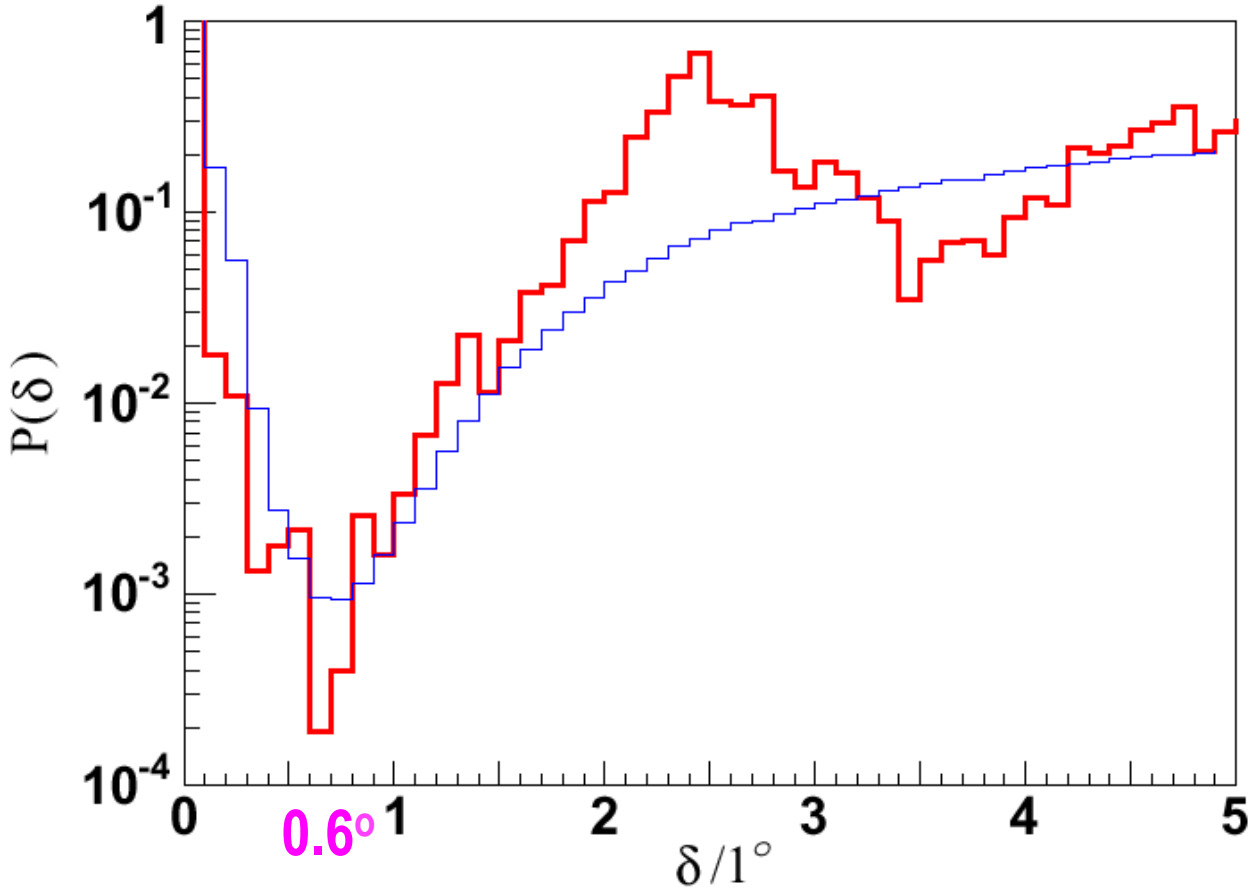
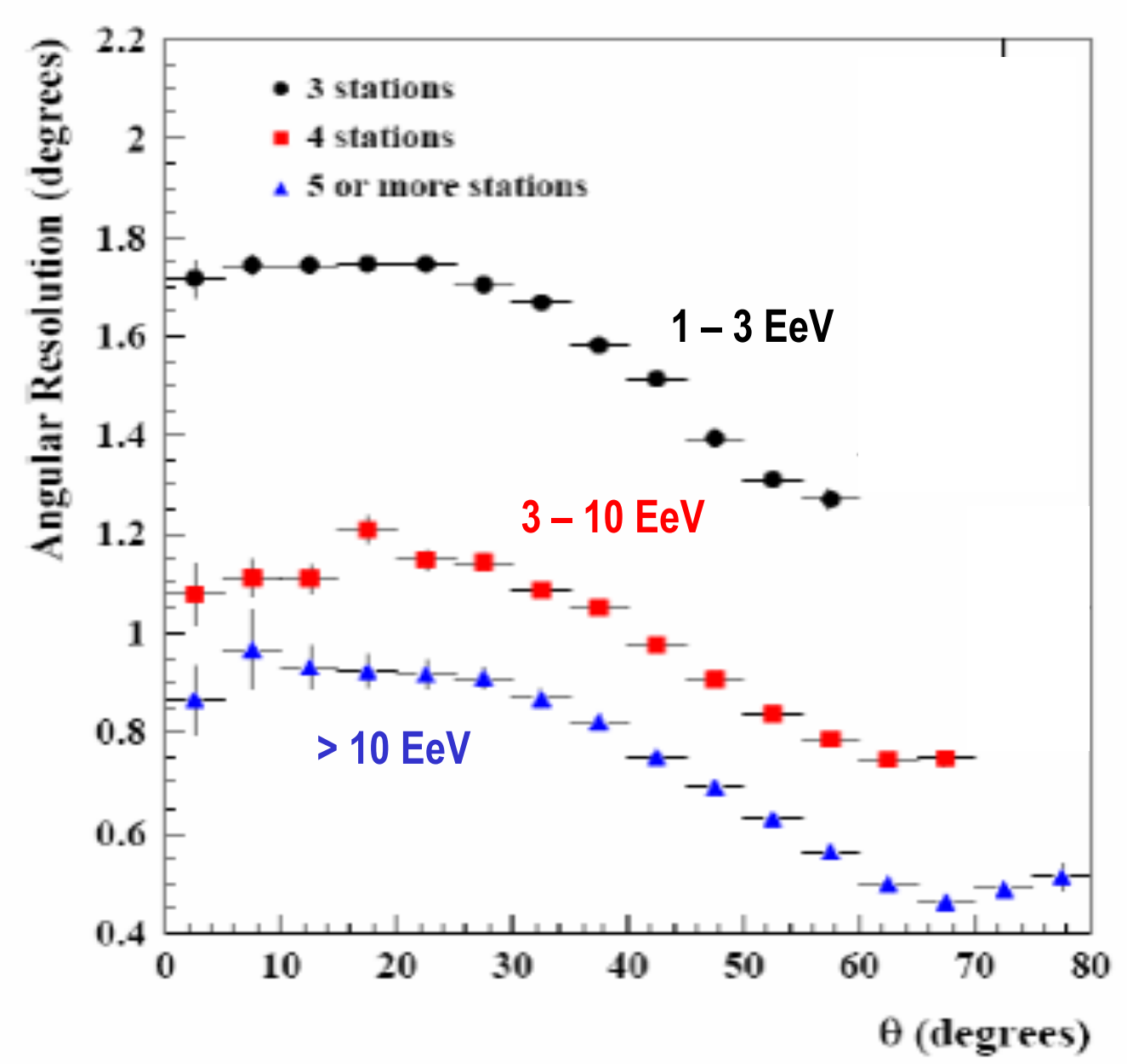


FIG. 3. $P(\delta)$ for the set of 156 BL Lacs and HiRes stereo events. The thick line shows data, the thin line shows $P_{\rm th}(\delta)$ obtained in the Monte-Carlo simulations in which 9 events are from the BL Lac sources.

Gorbunov et al., astro-ph 0406654

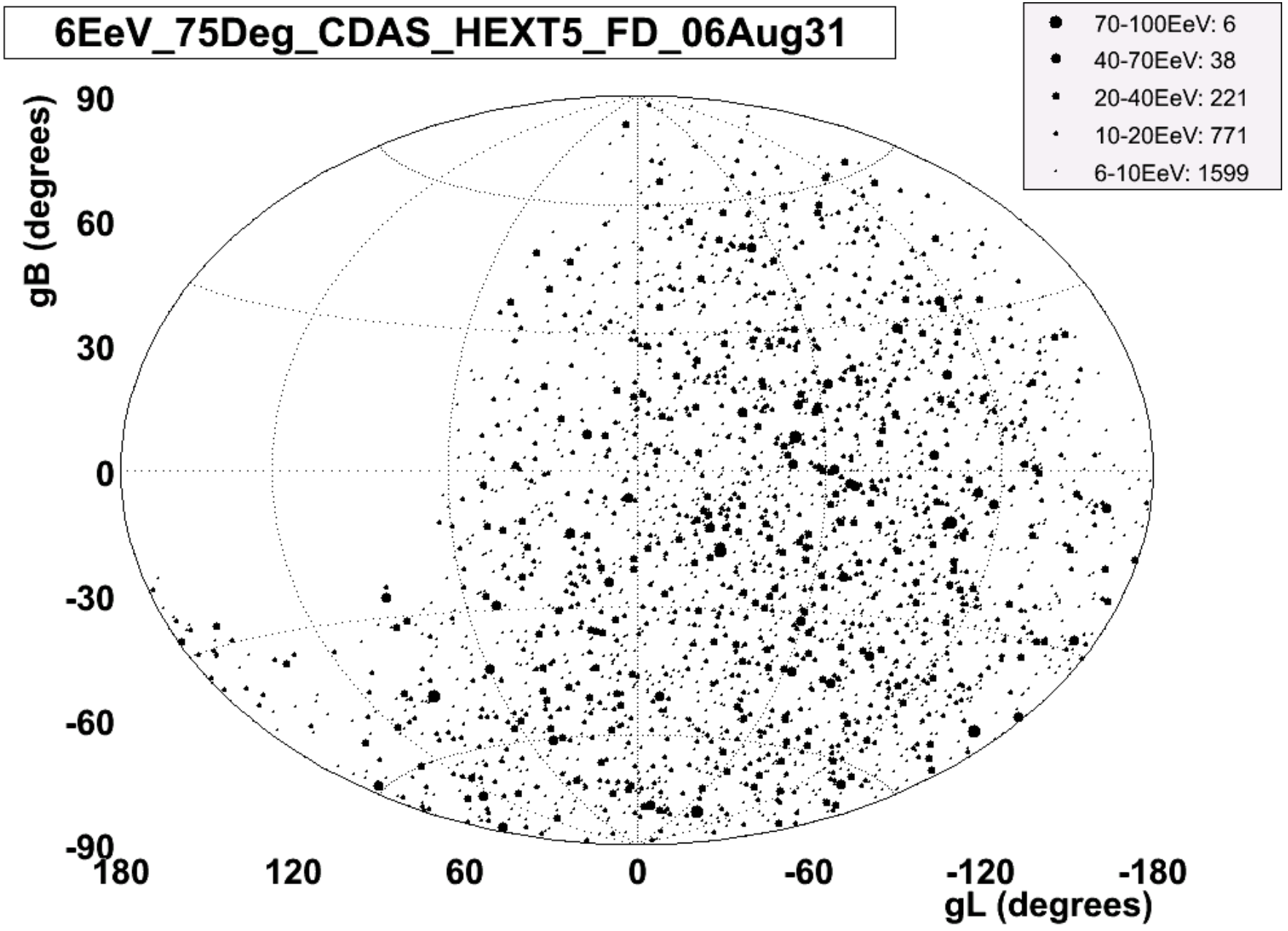
Angular Resolution of Auger SD



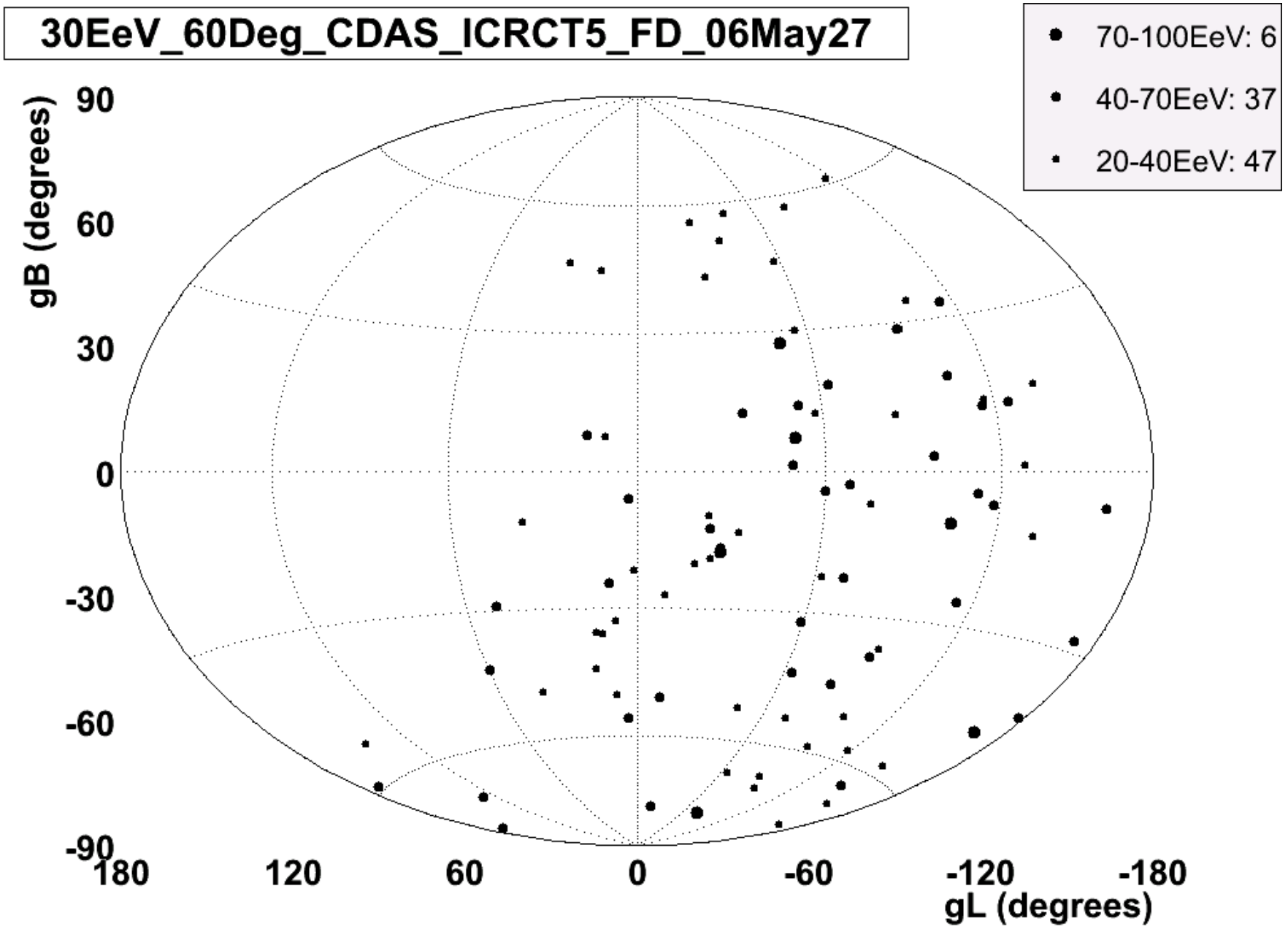
AGASA

HiRes (Stereo)

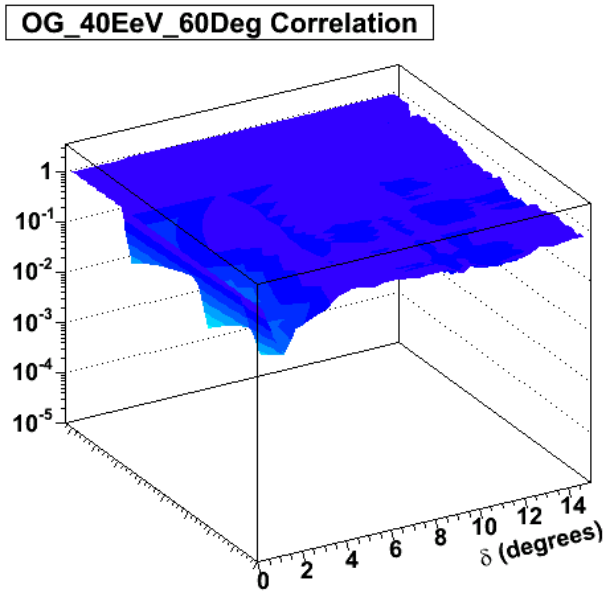
Sky Maps (>6 EeV, < 75º)

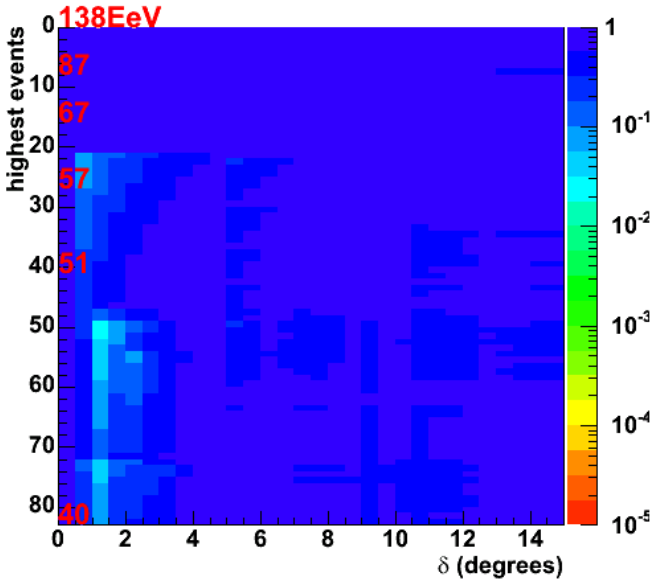


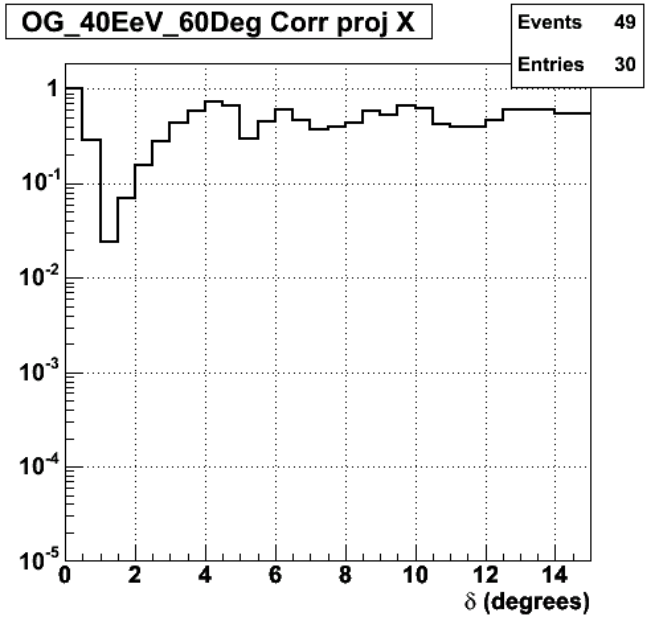
Sky Maps (>30 EeV, < 60°)

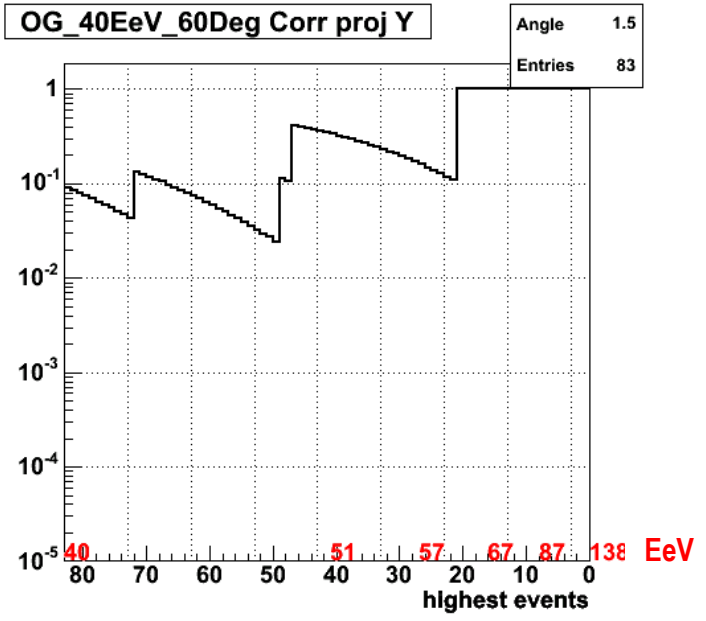


Auger Auto-correlation (>40 EeV, < 60°)

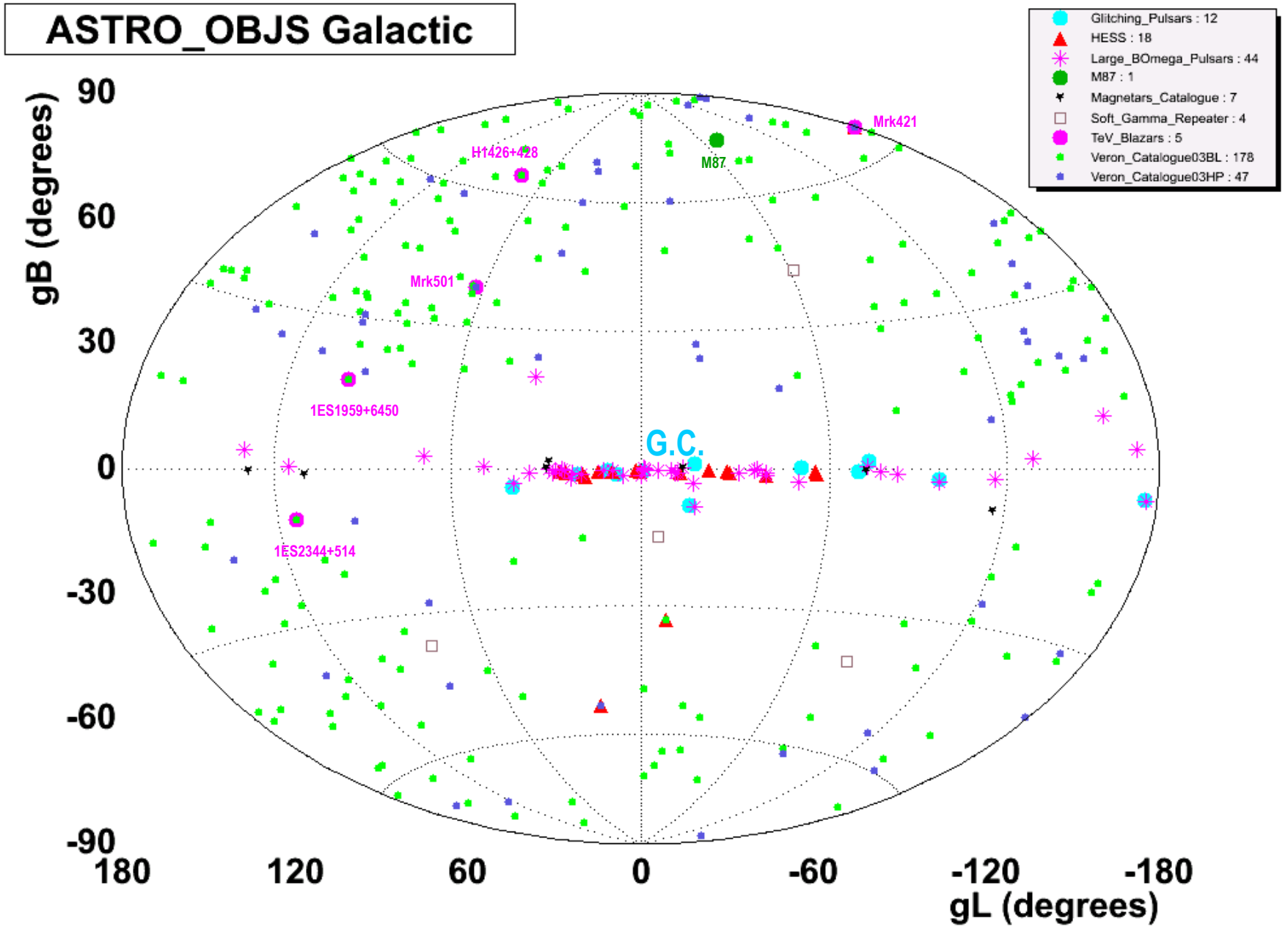






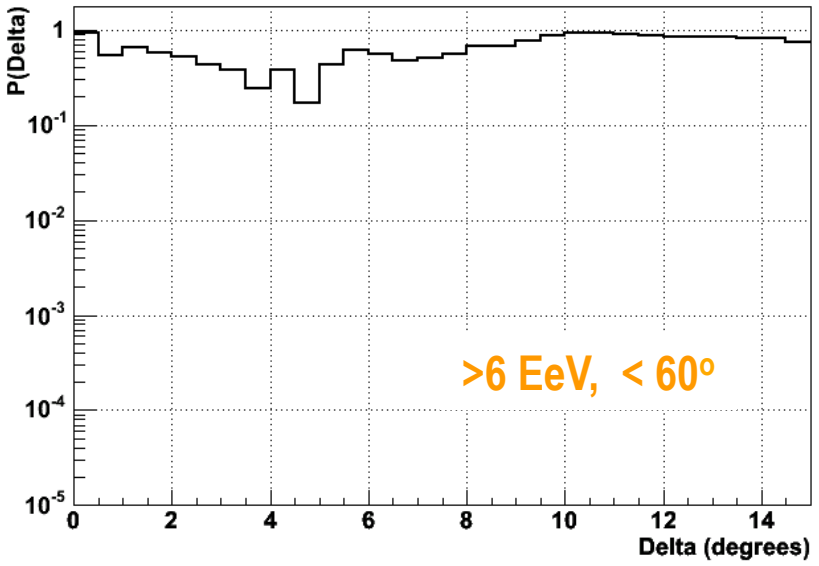


Sky Map of Astronomical Objects

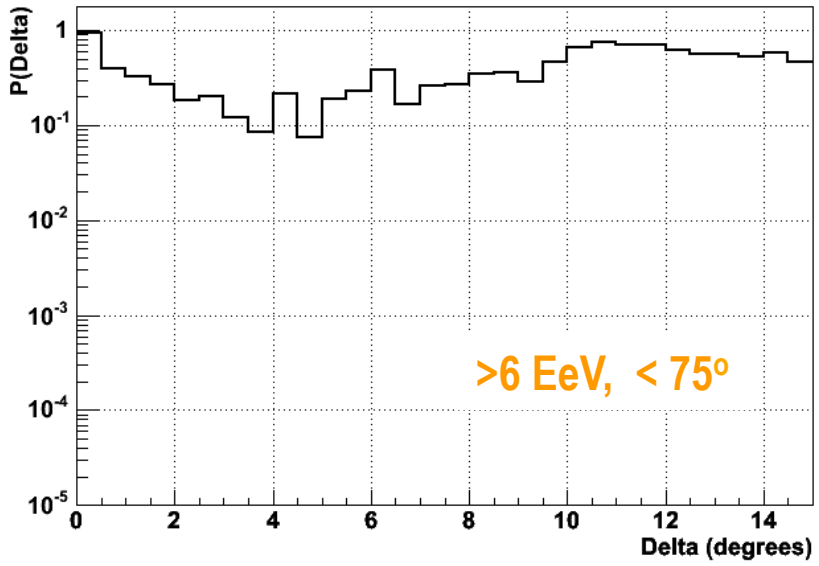


Auger – BL Lac Correlation

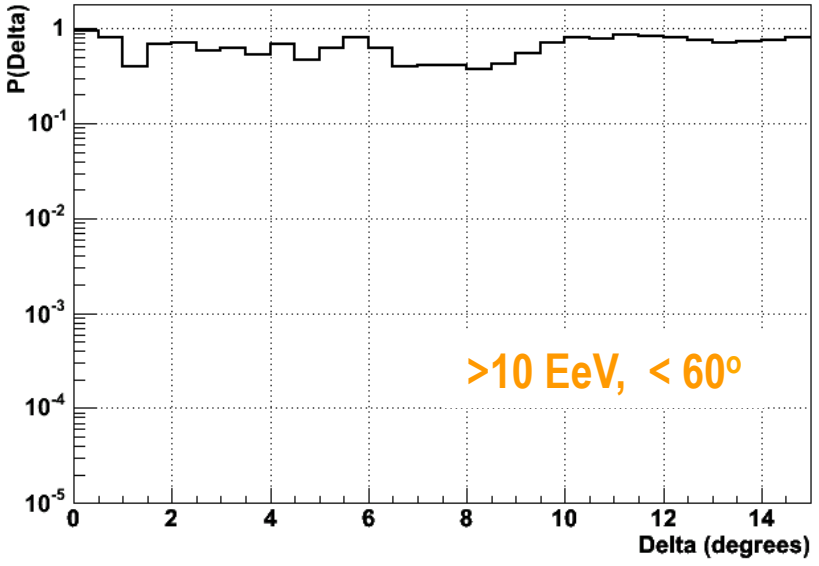
OG_6EeV_60Deg_VERON03BLHP



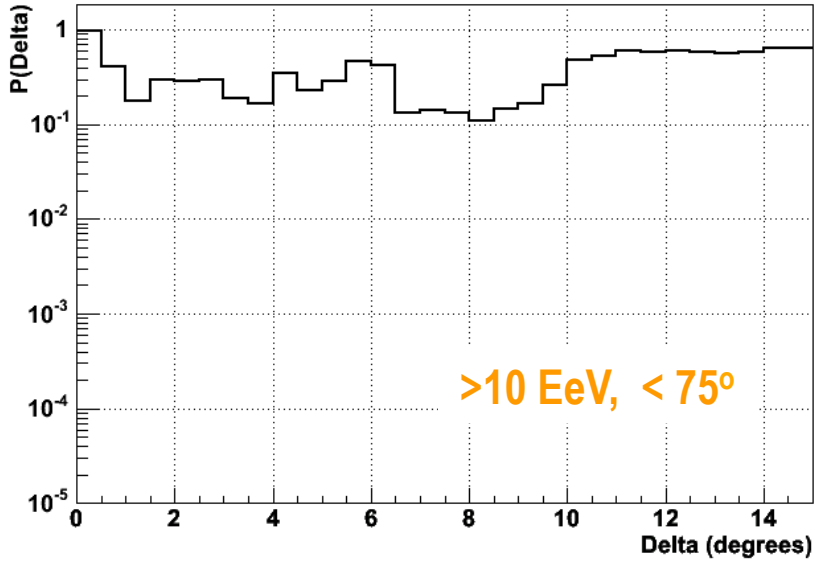
OG_6EeV_75Deg_VERON03BLHP



OG_10EeV_60Deg_VERON03BLHP

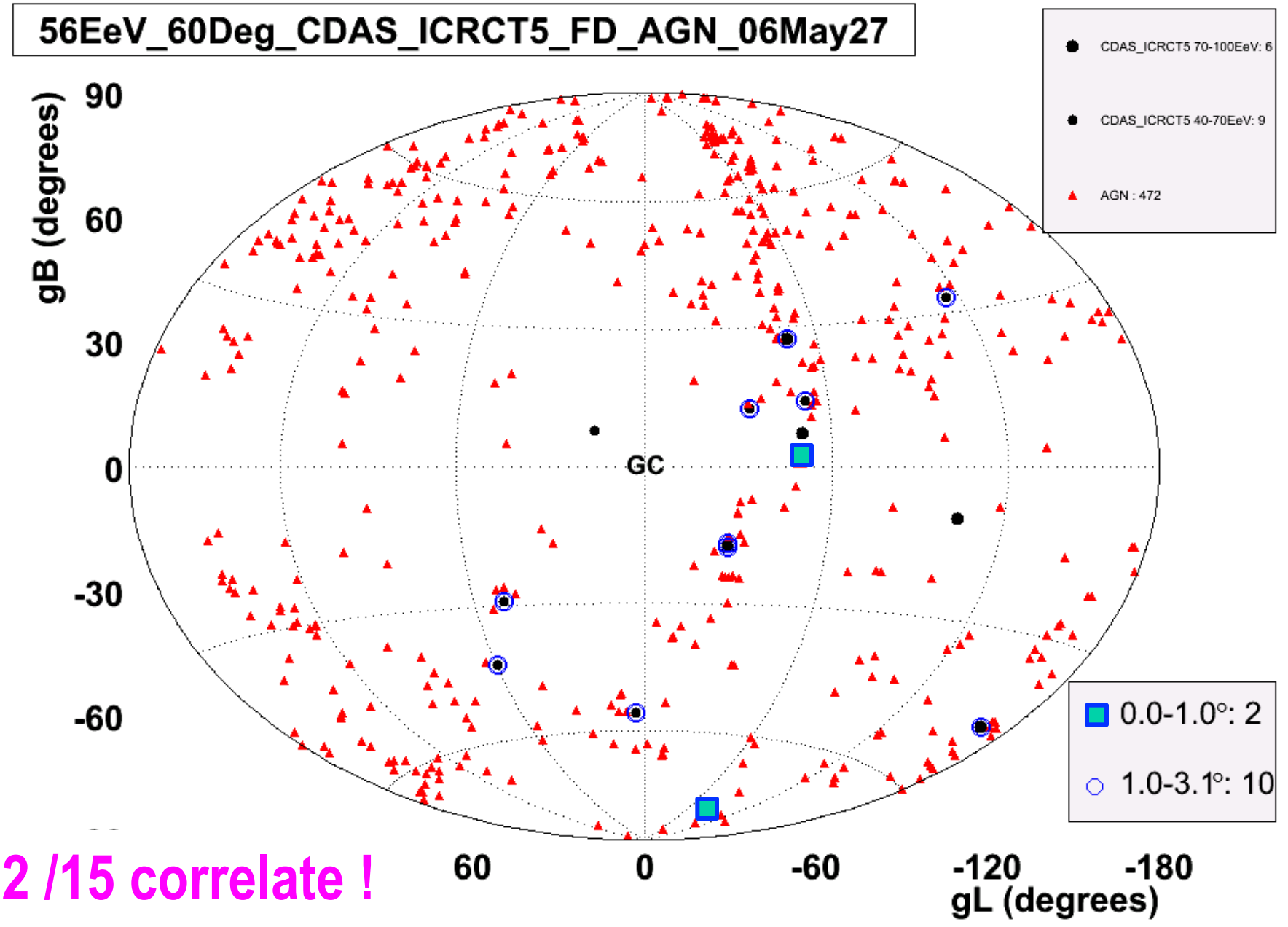


OG_10EeV_75Deg_VERON03BLHP



Then breaking news from Argentina Group in May, 2006

AGN (z <0.018) & Auger Events (E > 56 EeV)

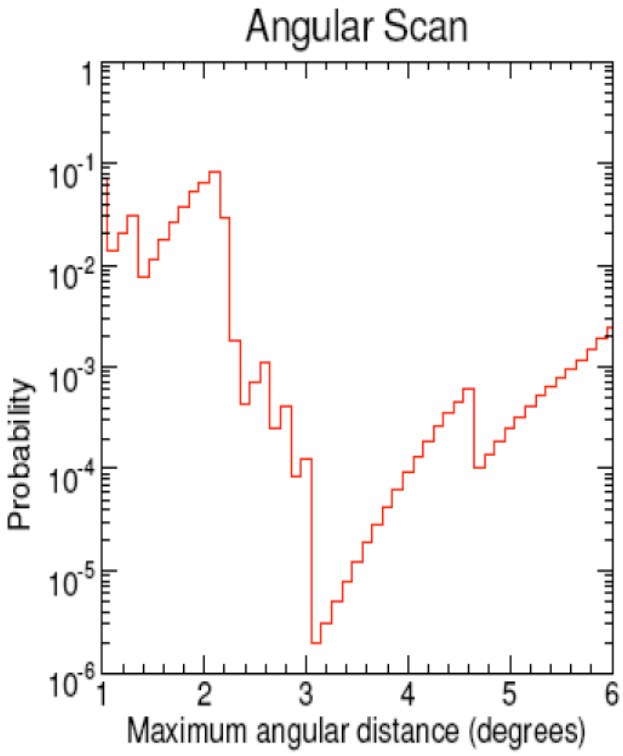


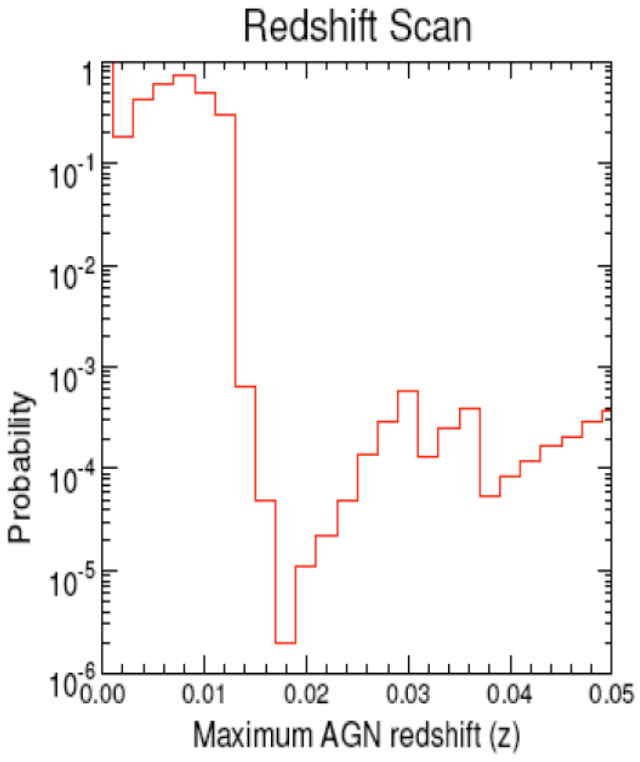
12 /15 correlate !

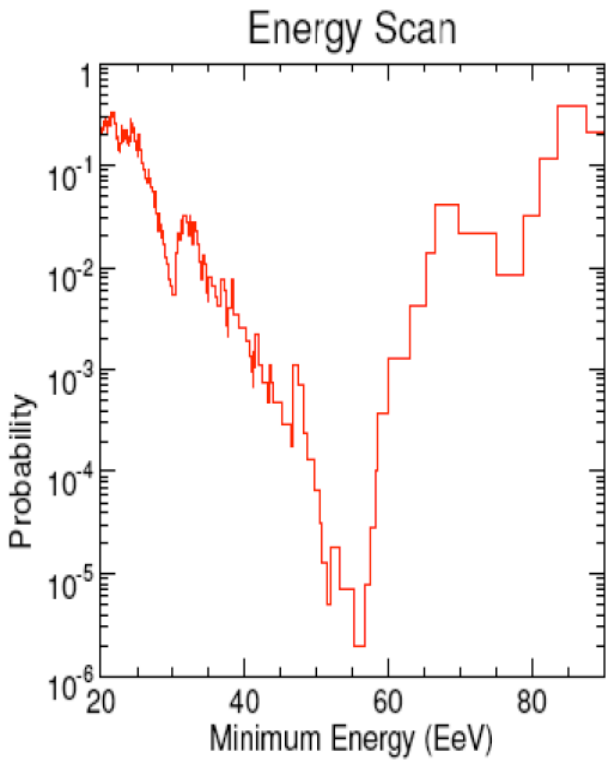
AGN Correlation

Significance is Maximum at

- Opening Angle < 3.1°
- z < 0.018 (< 75 Mpc)
- E > 56 EeV







Argentina Group's Discovery

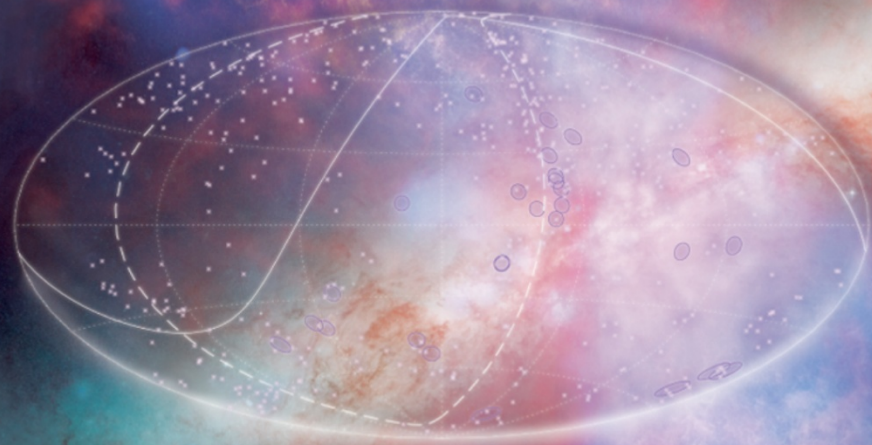
- **Veron-Cetty 12th edition catalog of AGN**
  - Total 85,221 quasars, 21,737 AGN, 1,122 BL Lac
  - Within 100 Mpc, 694 AGN, only 4 BL Lacs
  - Identified via optical observations, including recent SDSS
- **Correlation with cosmic rays maximized at**
  - $Z < 0.018$ (< 75 Mpc, 472 AGN)
  - $\theta < 3.1°$
  - $E > 56$ 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"**

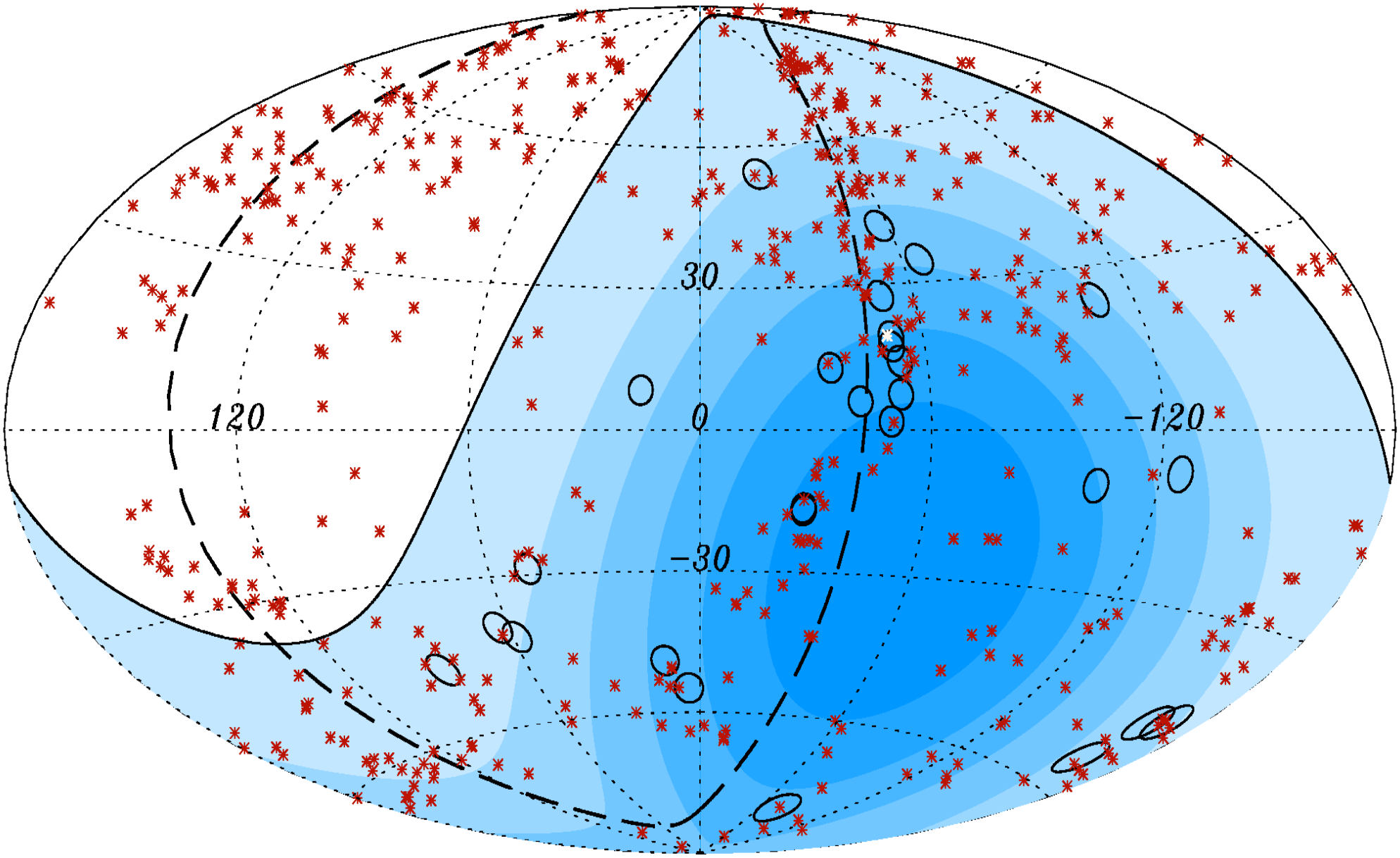
9 November 2007 | $10

Science

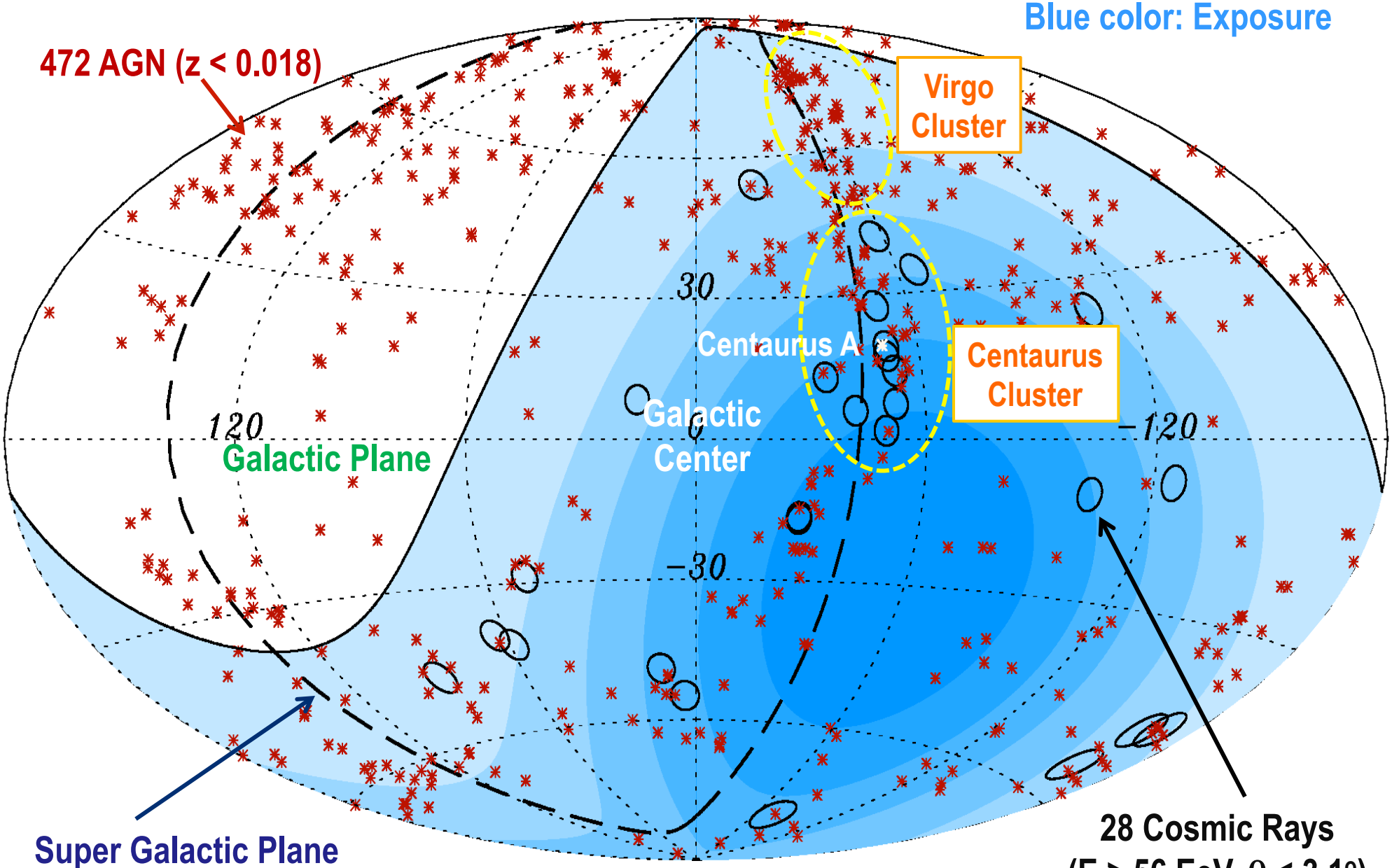


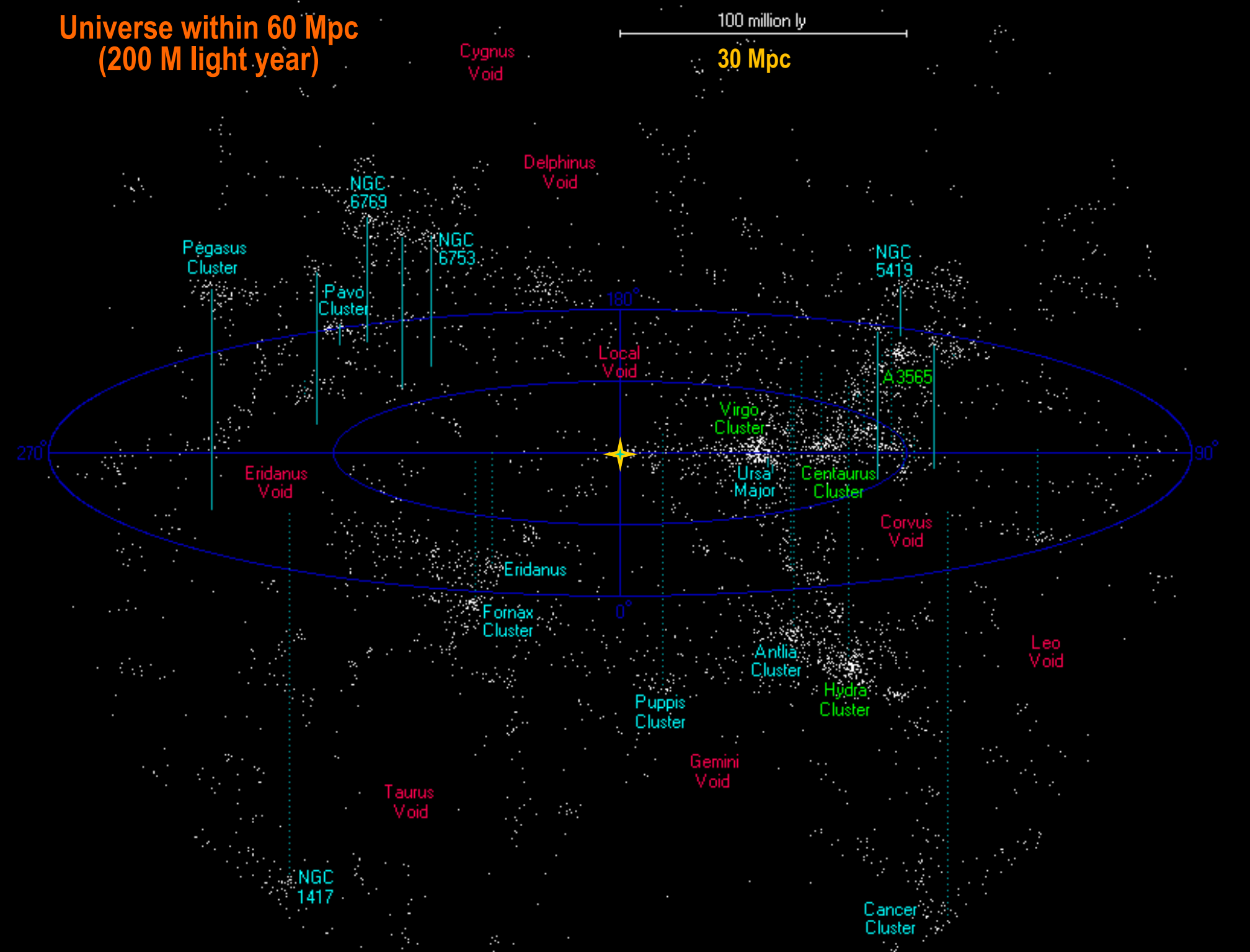
AAAS

AGN Correlation in galactic coordinates



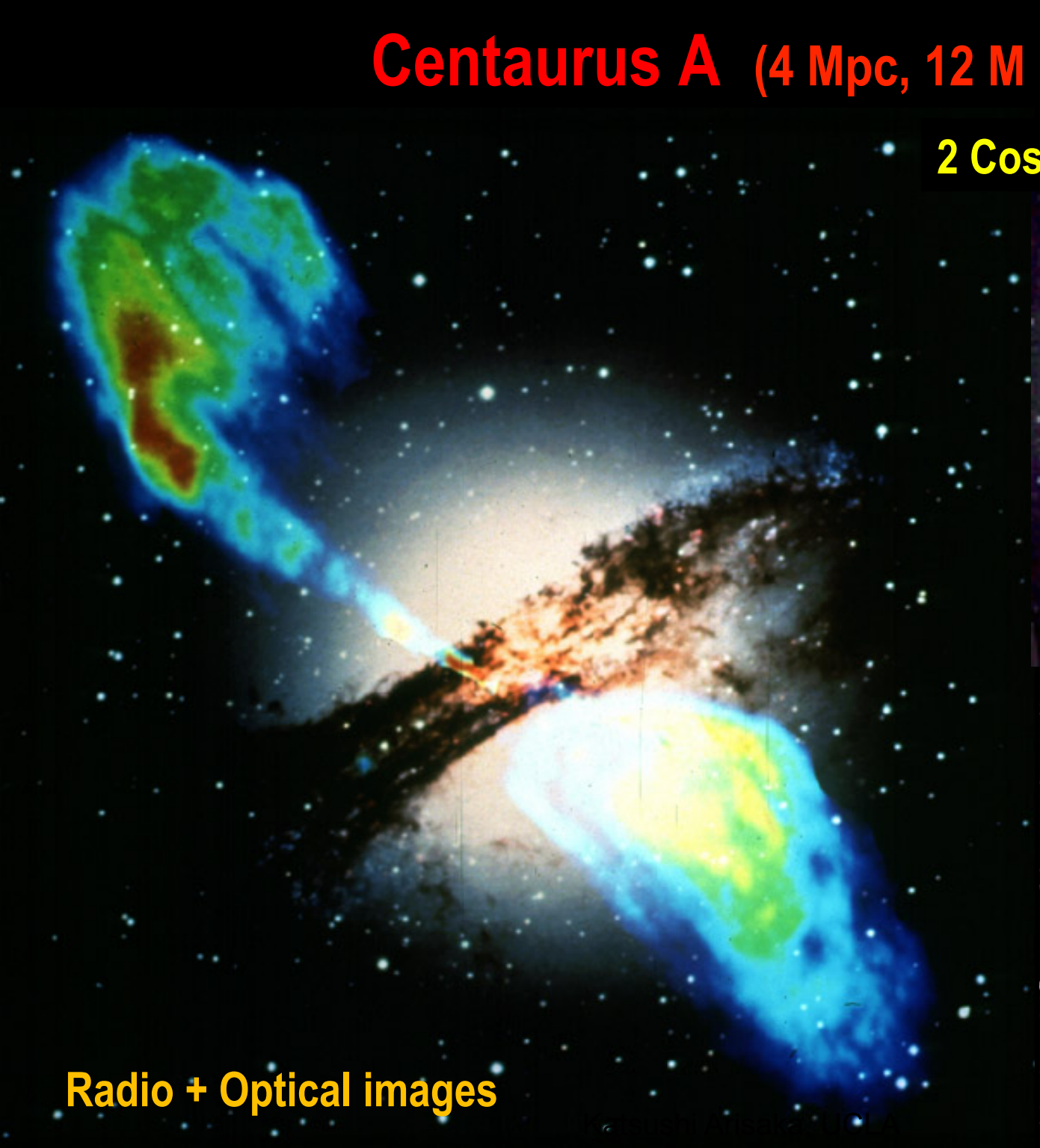
AGN Correlation in galactic coordinates




Universe within 60 Mpc
(200 M light year)
100 million ly
30 Mpc
Cygnus
Void
Delphinus
Void
NGC
6769
NGC
6753
Pegasus
Cluster
Pavo
Cluster
NGC
5419
180°
Local
Void
A3565
Virgo
Cluster
270°
90°
Eridanus
Void
Ursa
Major
Centaurus
Cluster
Corvus
Void
Eridanus
0°
Fornax
Cluster
Antlia
Cluster
Leo
Void
Hydra
Cluster
Puppis
Cluster
Gemini
Void
Taurus
Void
NGC
1417
Cancer
Cluster

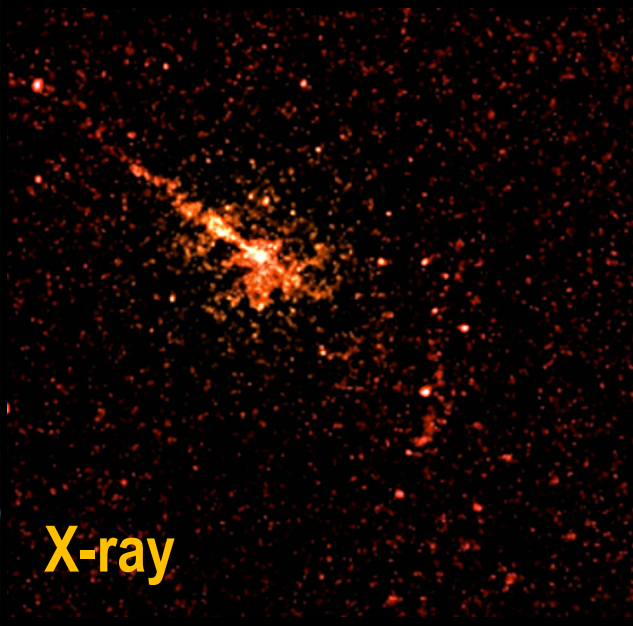
Centaurus A (4 Mpc, 12 M light year)

2 Cosmic Rays correlated.



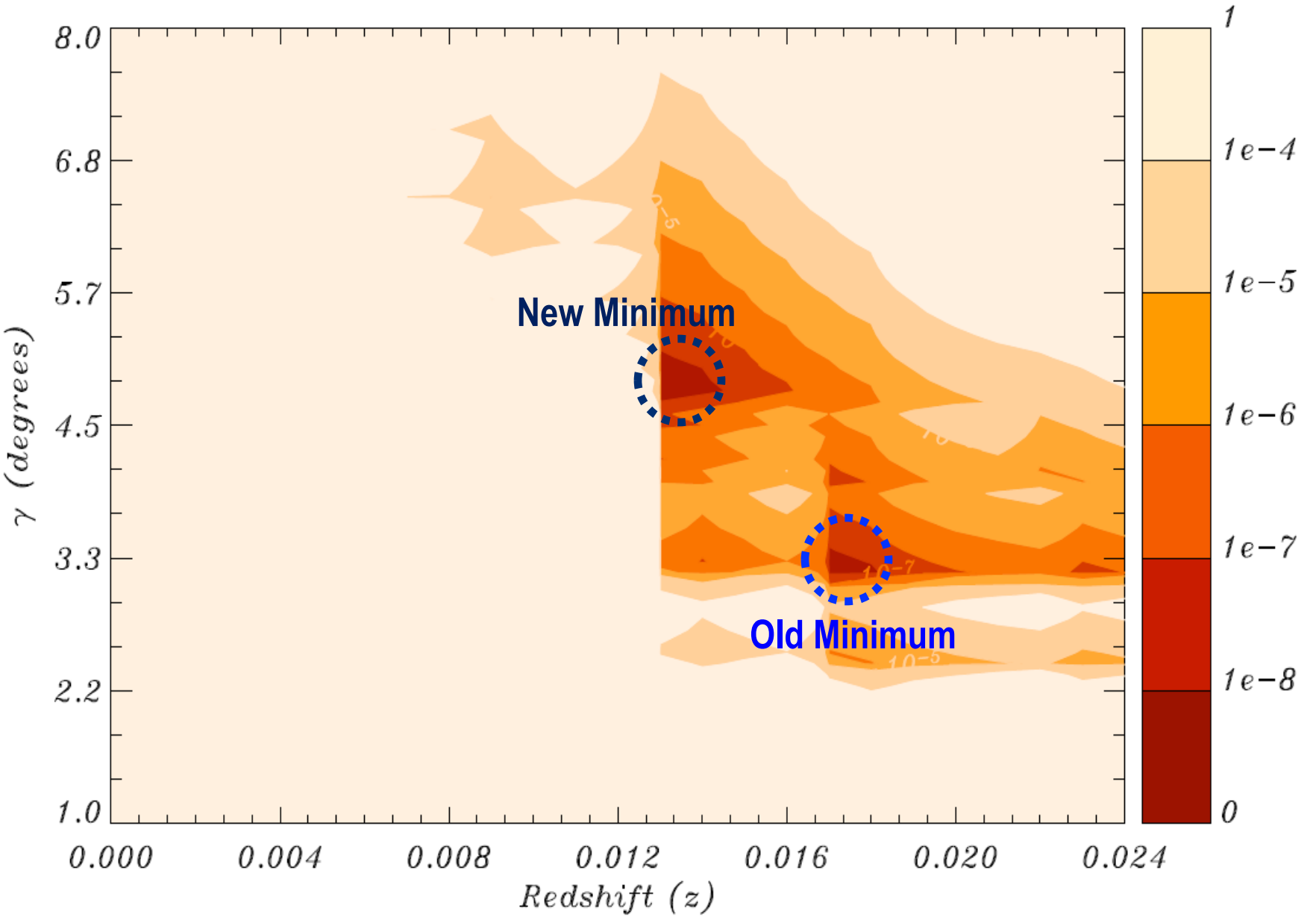
Radio + Optical images

Infrared



X-ray

Scan over all the data (E > 56 EeV)



Summary

- **Correlation with AGN established at >99% CL.**
  - **Z < 0.018 (< 75 Mpc)**
  - **θ < 3 - 5°**
  - **E ~> 60 EeV**

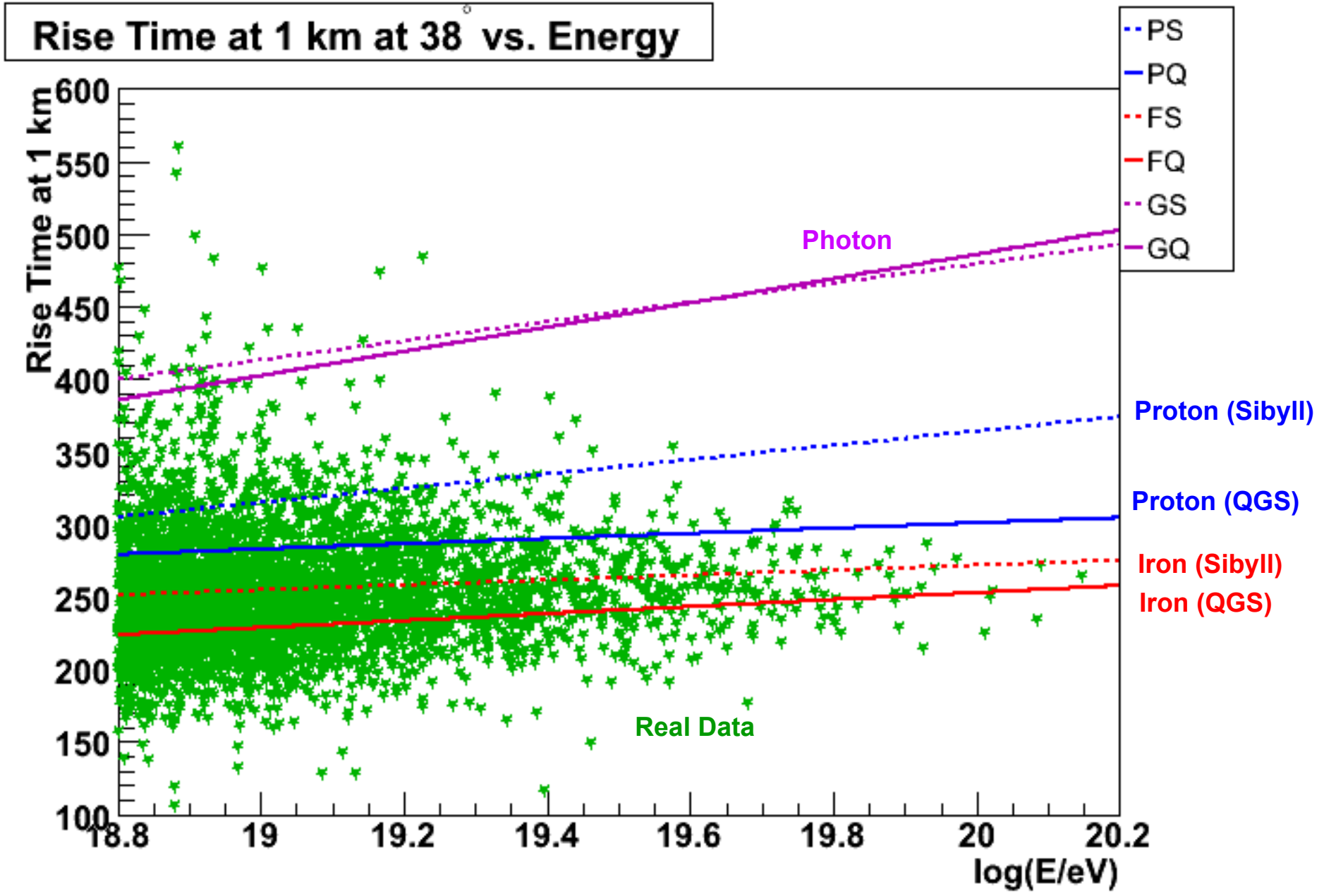
- **The first evidence of extra galactic origin of cosmic rays.**
  - **It could be a correlation with Large Scale Structure (or other sources with similar distribution.)**

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

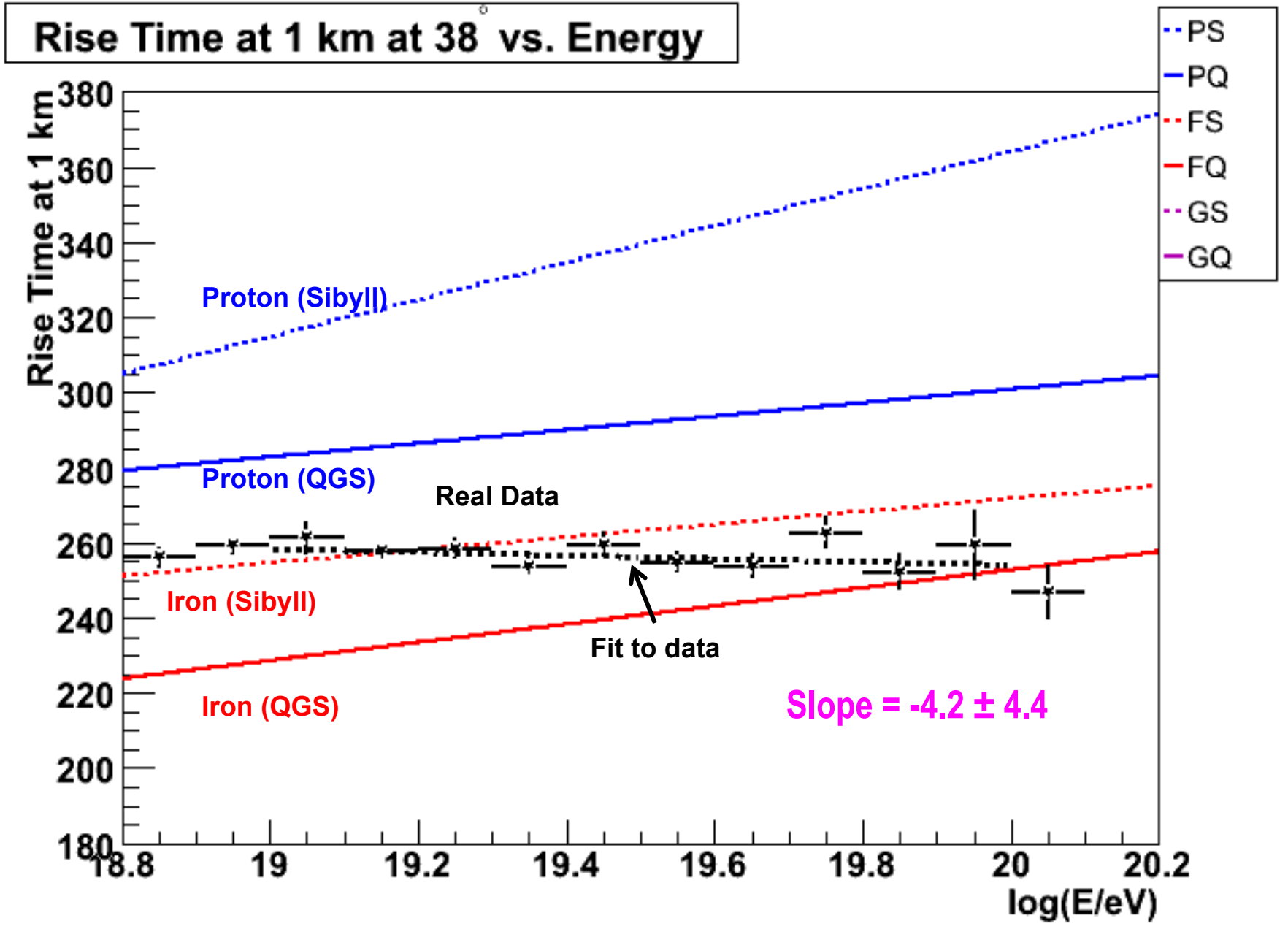
Are the protons or heavy elements?

- Matt Healy (PhD)
- David Barnhill

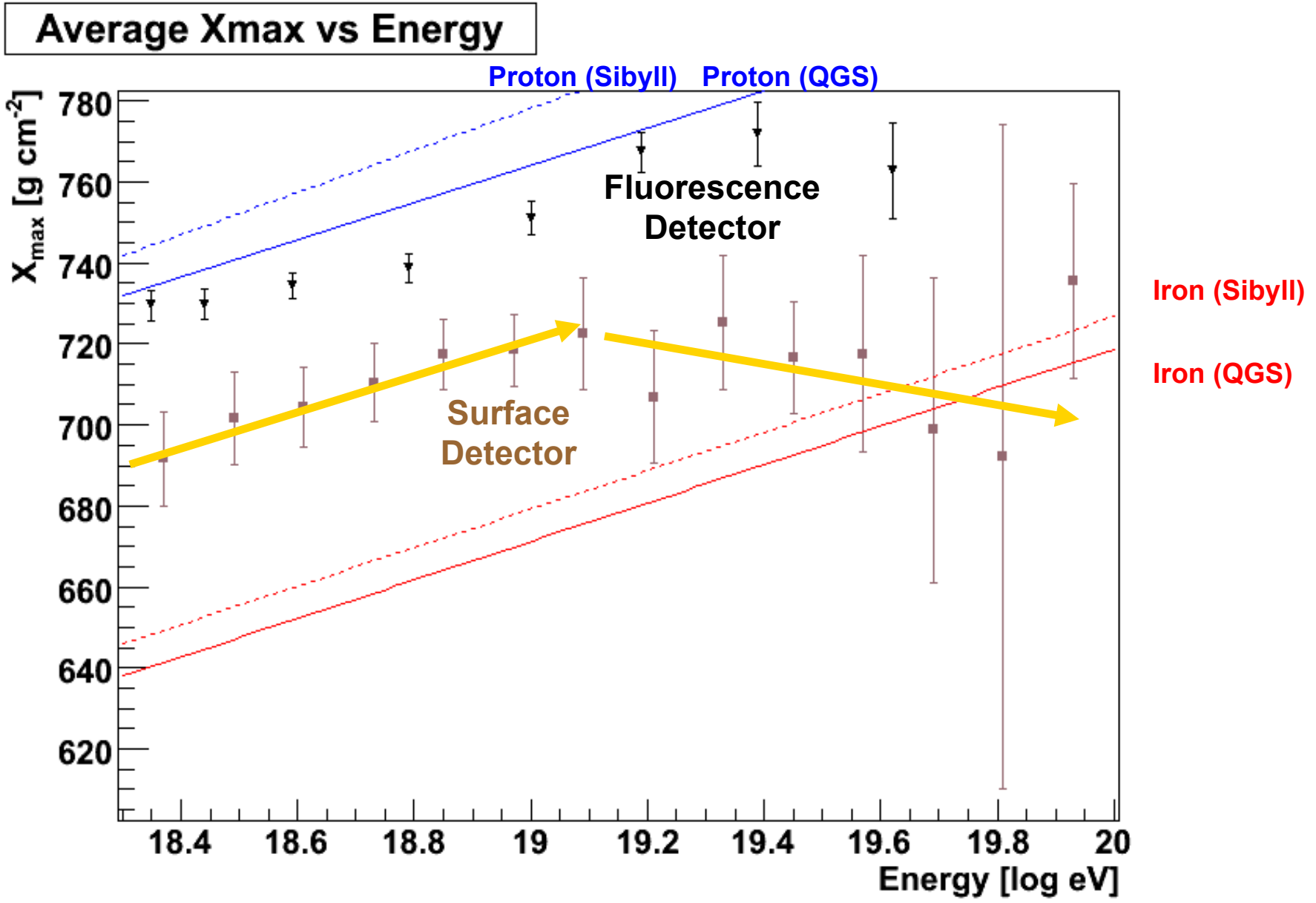
Risetime vs. Log(E)



Risetime


Rise Time at 1 km at 38° vs. Energy
Rise Time at 1 km
380
360
340
320
300
280
260
240
220
200
180
18.8
19
19.2
19.4
19.6
19.8
20
20.2
log(E/eV)
PS
PQ
FS
FQ
GS
GQ
Proton (Sibyll)
Proton (QGS)
Real Data
Iron (Sibyll)
Fit to data
Iron (QGS)
Slope = -4.2 ± 4.4

Elongation Rate (Preliminary)



Another Talk Next Week

- **High Energy Seminar**
  - **Wednesday, November 21**
  - **Knudsen 4-134**

"What are these UHE Cosmic Rays?"

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).

Special thanks to all my collaborators at UCLA!

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….			

AGN Correlation in galactic coordinates