

Title: The Origin of the Highest Energy Particles

Date: Jan 09, 2008 02:00 PM

URL: <http://pirsa.org/08010000>

Abstract: After almost a century of observations, the ultra-high energy sky has finally displayed an anisotropic distribution. A significant correlation between the arrival directions of ultra-high cosmic rays measured by the Pierre Auger Observatory and the distribution of nearby active galactic nuclei signals the dawn of particle astronomy. These historic results have important implications to both astrophysics and particle physics.



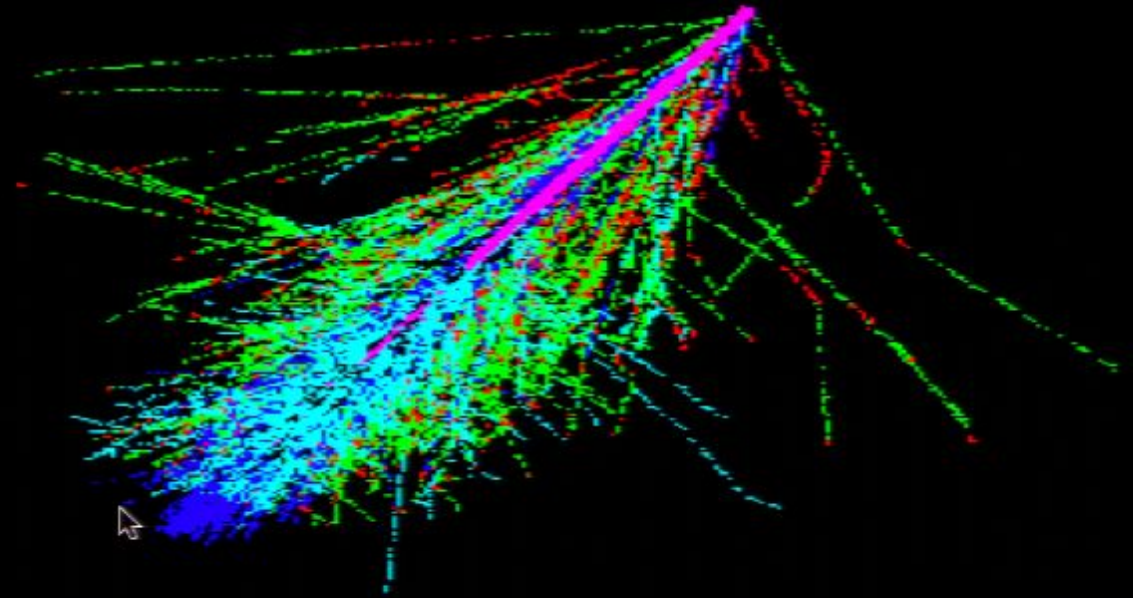
PIERRE
AUGER
OBSERVATORY

The Origin of Highest Energy Particles

Angela V. Olinto

APC Paris Diderot

The University of Chicago

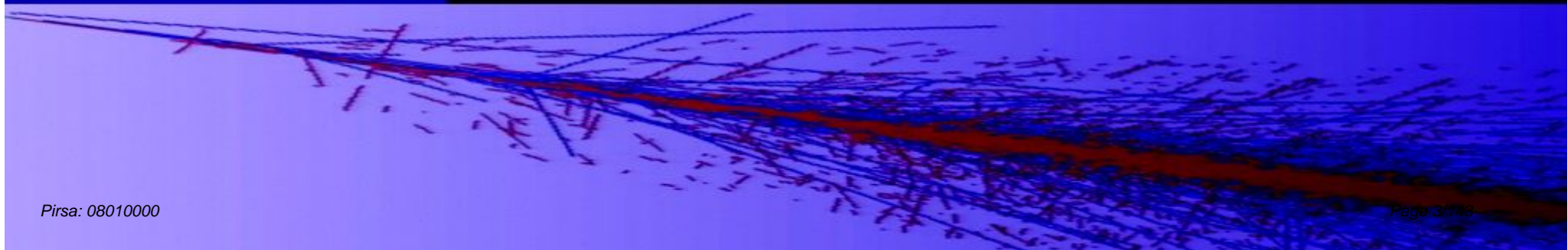
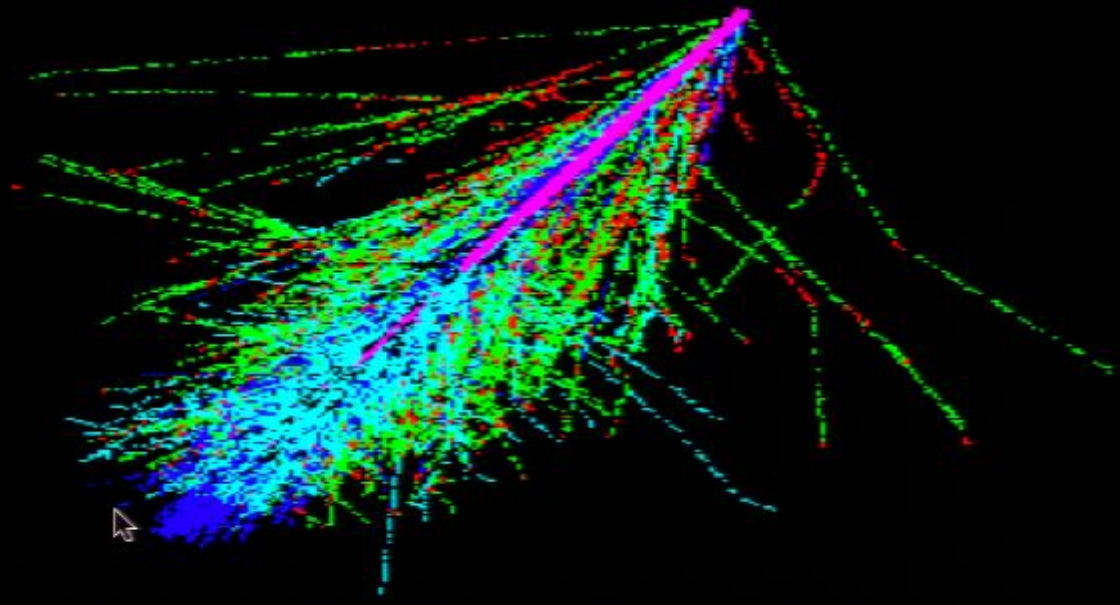




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UGER
SERVATORY

The Origin of Highest Energy Particles

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The New Era of Particle Astronomy

is just beginning...

*The Pierre Auger Observatory
finds correlation between
Ultra High Energy Cosmic Rays
and
Active Galactic Nuclei (AGN)*



Plan

High Energy cosmic rays

Pierre Auger Observatory

Recent Results



Implications & Future

High Energy Cosmic Rays



Birth of Particle Physics & Particle Astrophysics

Study of
cosmic rays

1953

1932 Positron

1936 Muon

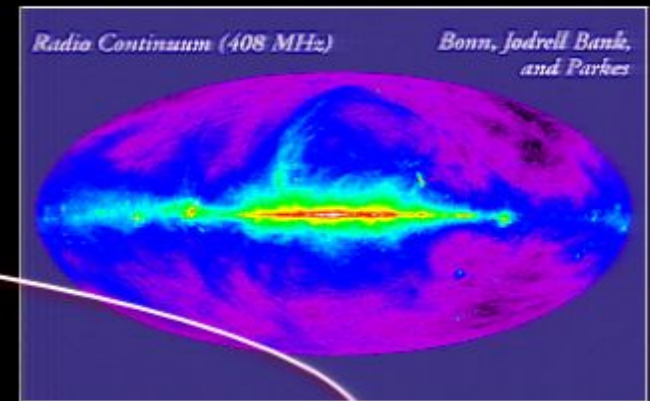
1947 Pions : π^0 , π^+ , π^-

1949 Kaons (K)

1949 Lambda (Λ)

1952 Xi (Ξ)

1953 Sigma (Σ)



astrophysics

particle physics

High Energy Cosmic Rays

OBSERVABLES:

Spectrum

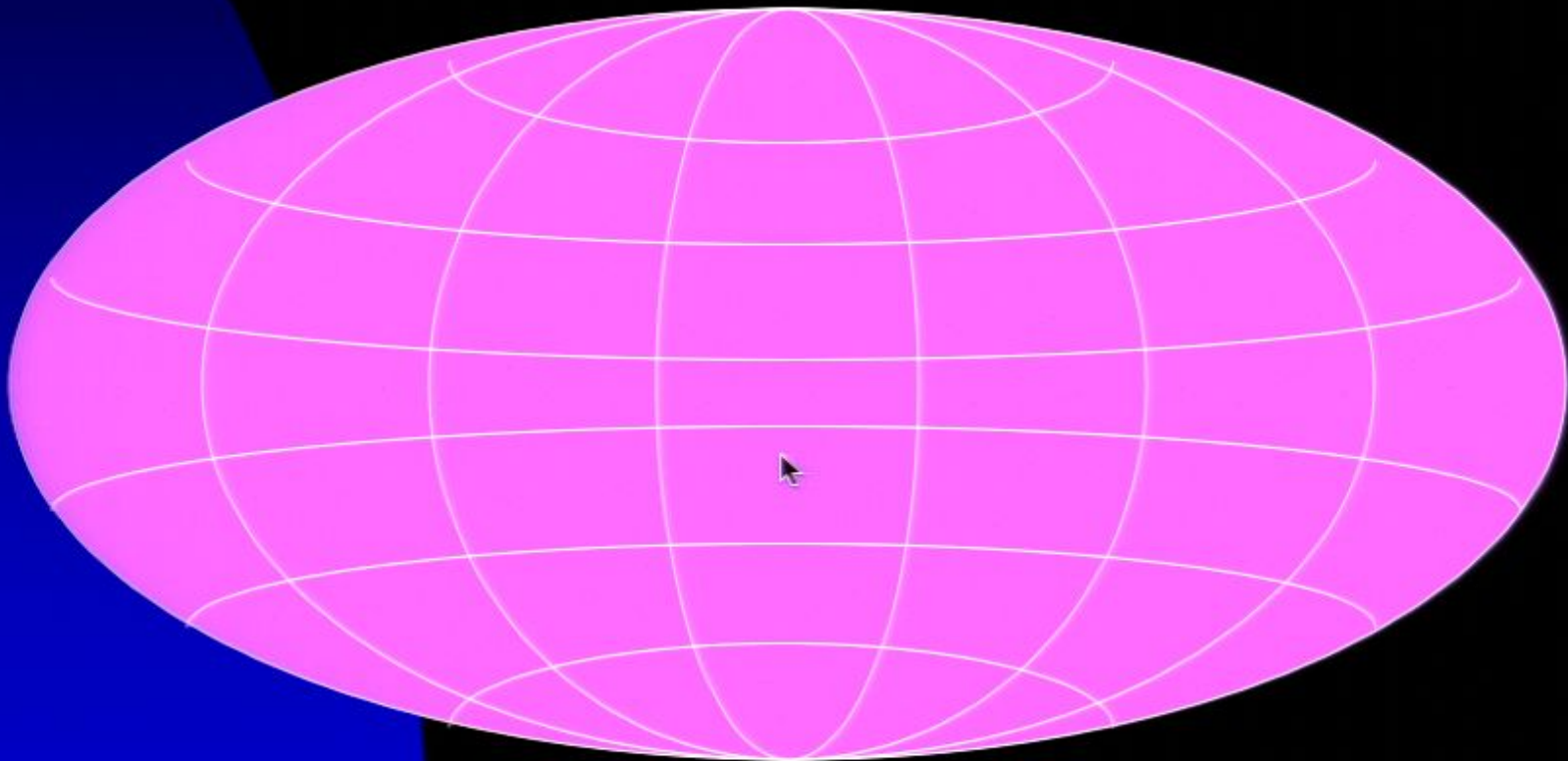
Composition

Sky Distribution



CR arrival directions

Isotropic!



High Energy Cosmic Rays

OBSERVABLES:

Spectrum

Composition

Sky Distribution



Cosmic Ray Spectrum

non-thermal
Phenomena

Extreme
Accelerators

$E_{\text{max}} > 10^{20}$ eV

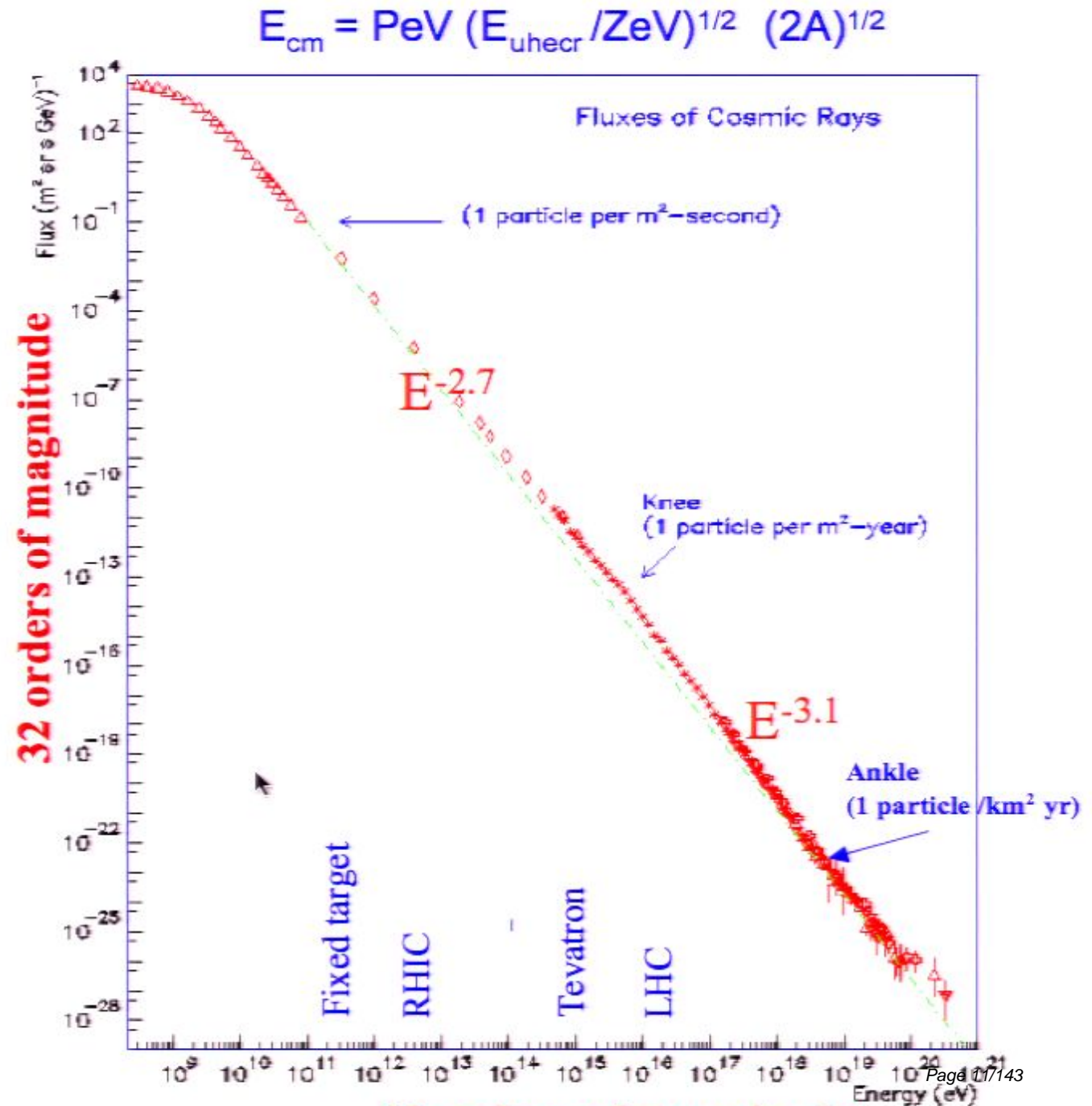
Features:

Knee, ankle, GZK cutoff

accelerators

propagation

interactions



Cosmic Ray Spectrum

non-thermal Phenomena

Extreme Accelerators

$E_{\text{max}} > 10^{20}$ eV

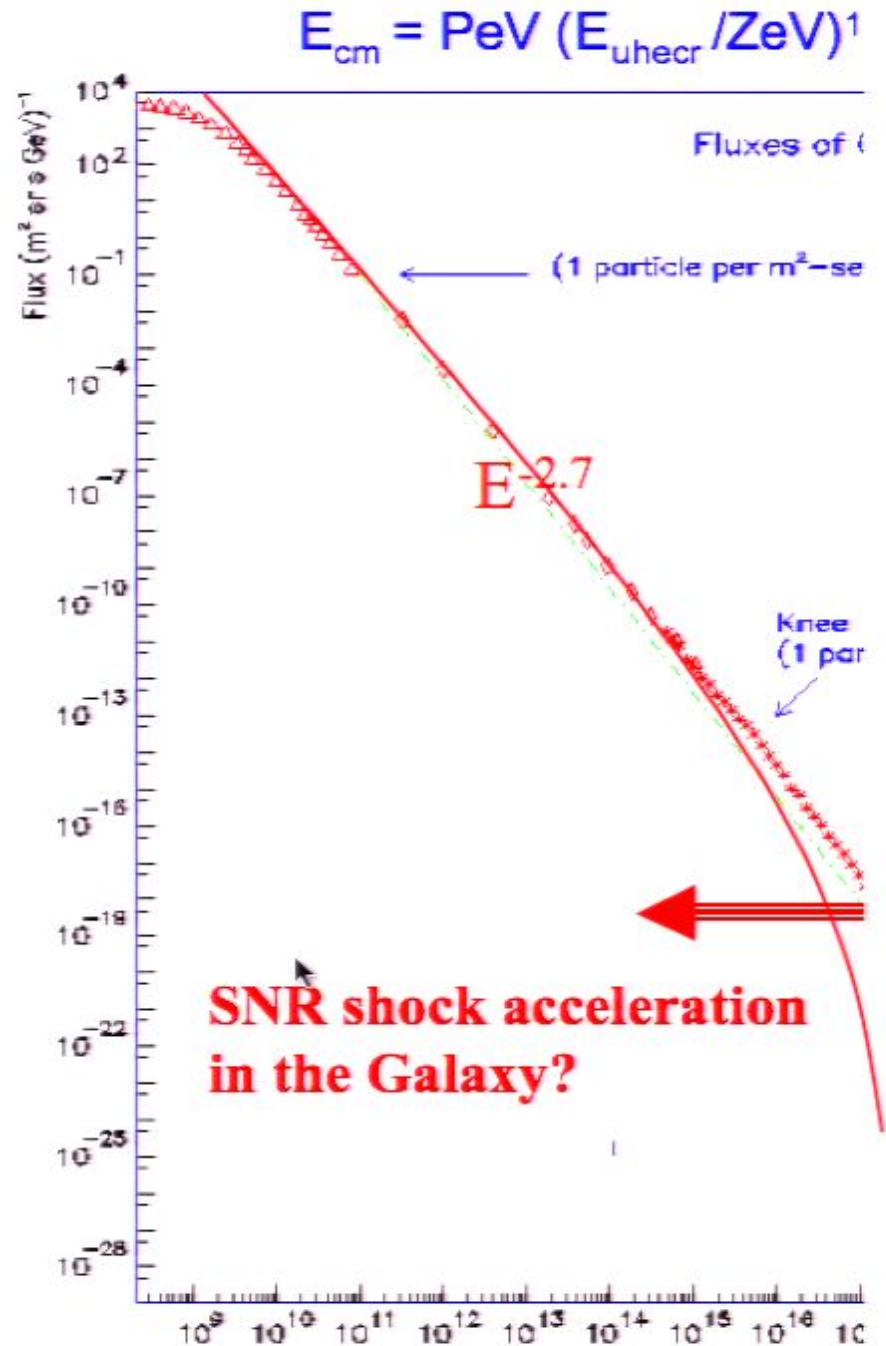
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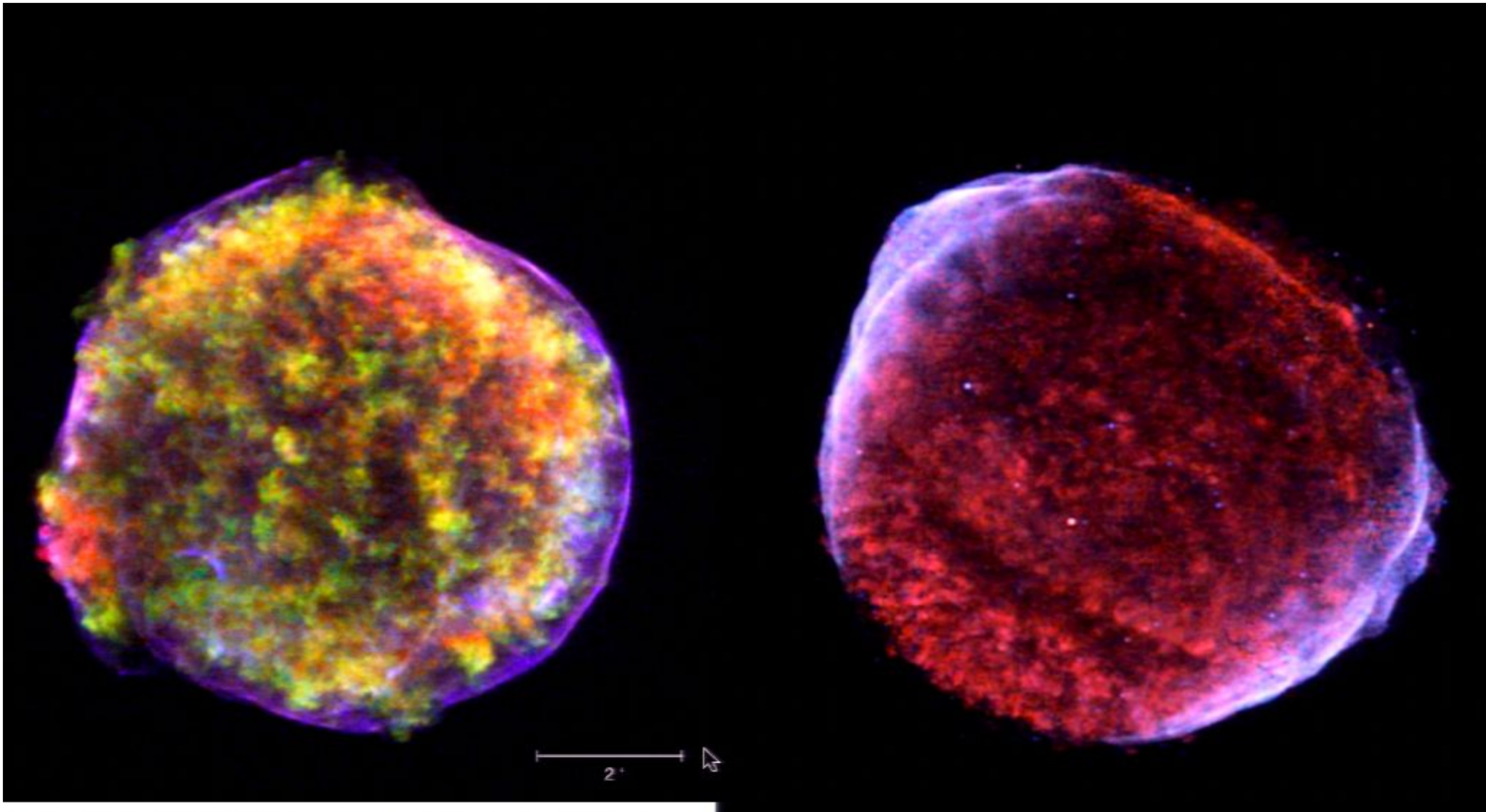
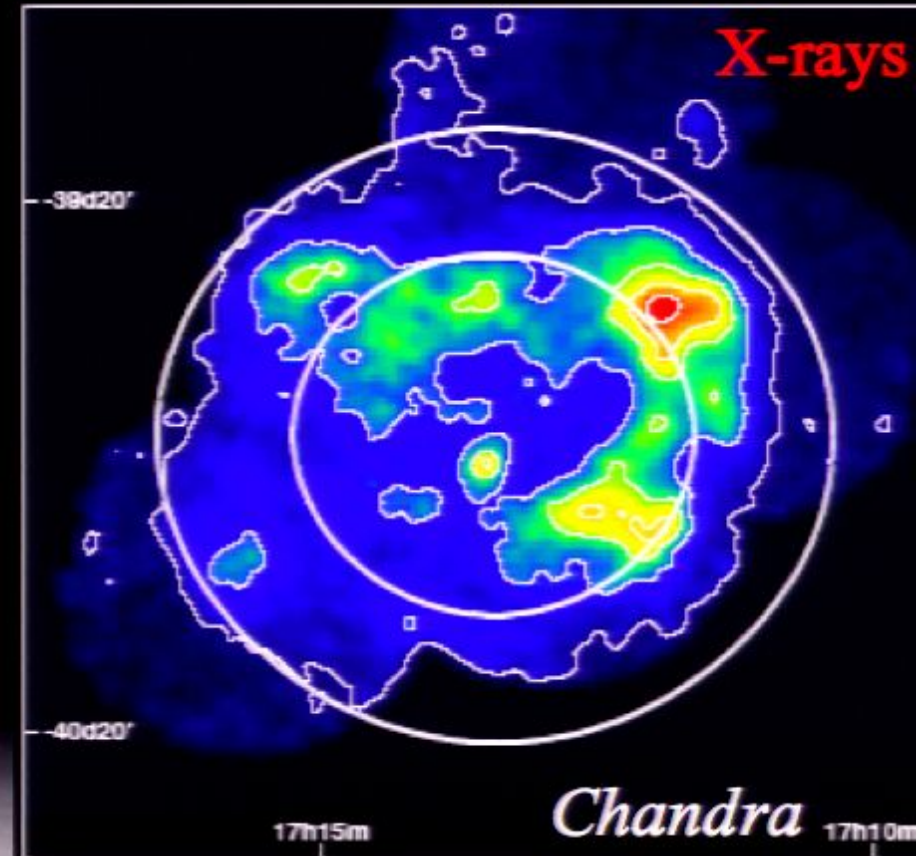
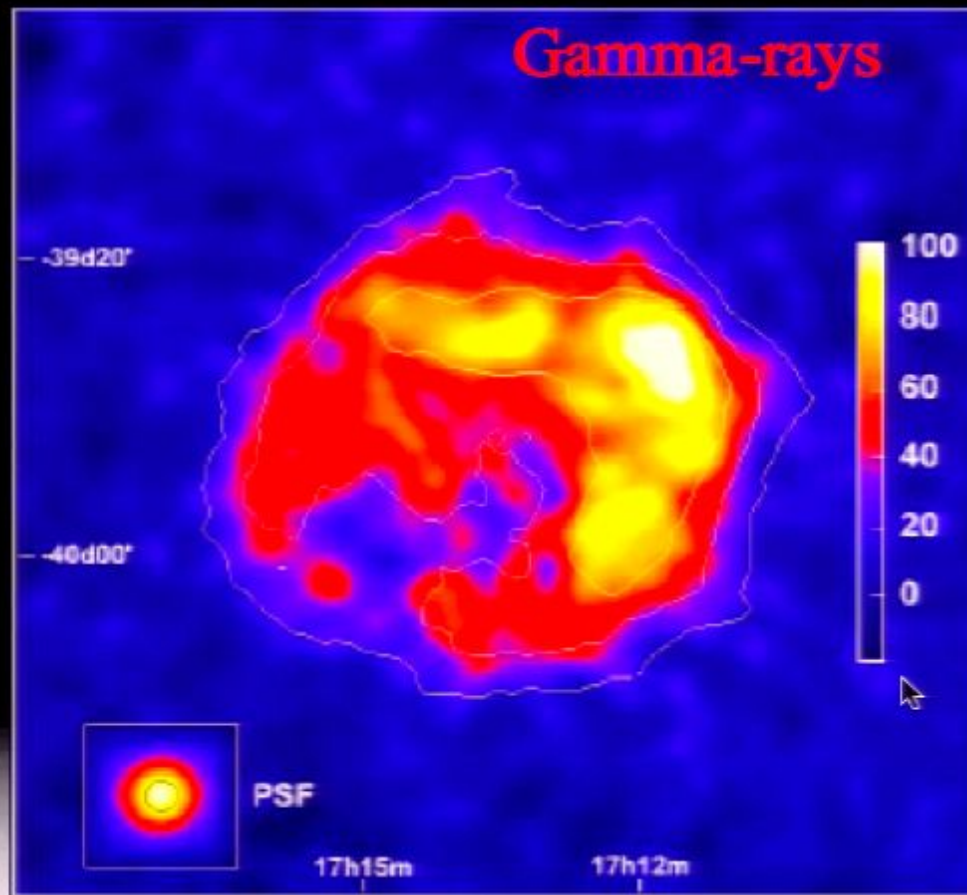


Fig. 3. 2005 CHANDRA image of Tycho's SNR, from chandra.nasa.gov. The outer thin surface is synchrotron radiation from highly relativistic electrons accelerated at the outer shock. Behind this is a highly turbulent region, presumably formed by Rayleigh-Taylor instability at the contact discontinuity. Acknowledgement to NASA/CXC/SAO.

Fig. 4. CHANDRA image of SNR1006, from Chandra.nasa.gov. Synchrotron radiation from ultra-relativistic electrons occurs in two 'polar cap' regions, probably where the external magnetic field is nearly perpendicular to the outer surface. Acknowledgement to NASA/CXC/SAO.

HESS - TeV γ 's ! smoking guns of CR acceleration?

RX J1713 - 20 σ



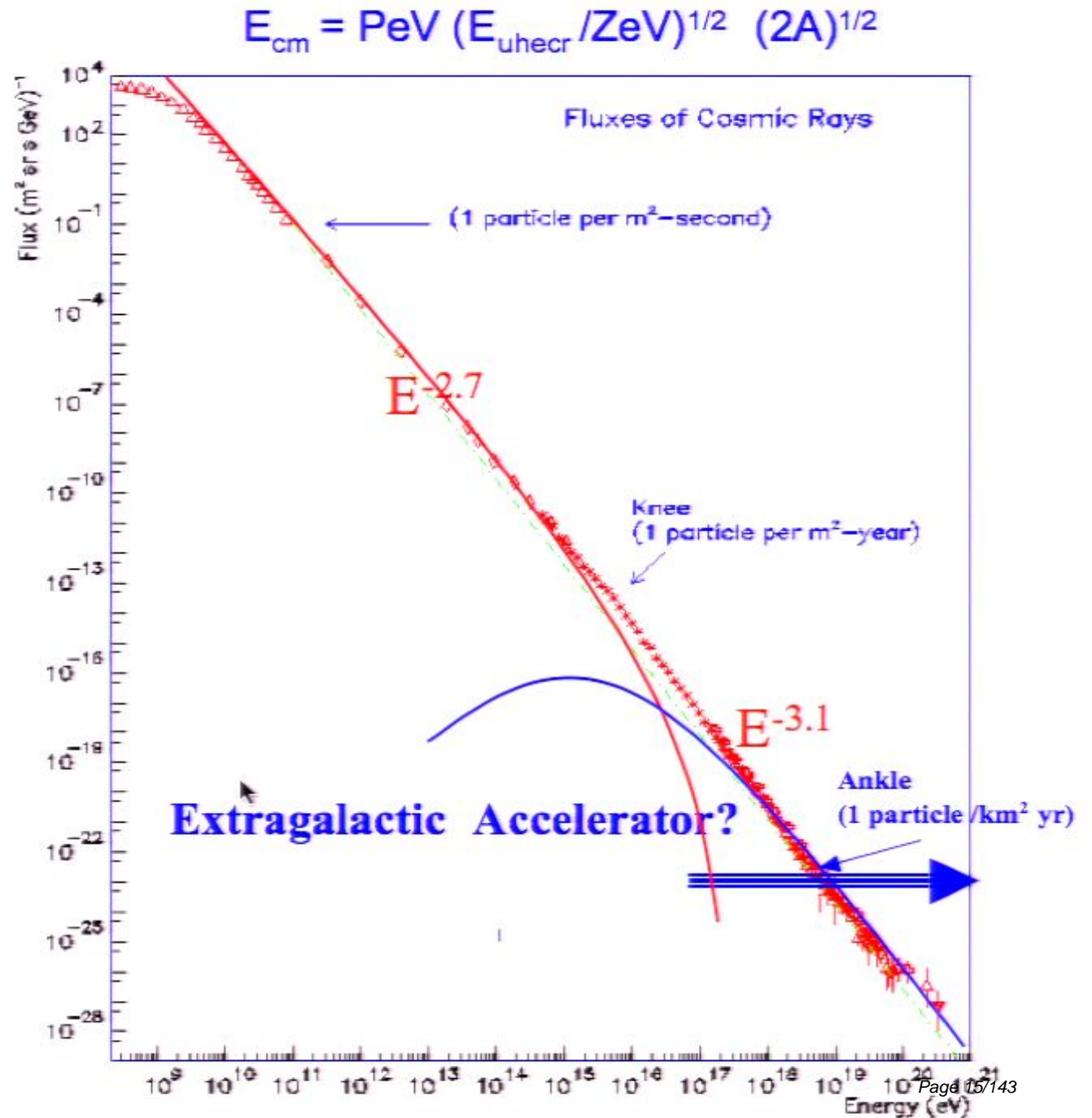
Cosmic Ray Spectrum

non-thermal Phenomena

Extreme Accelerators
 $E_{\text{max}} > 10^{20}$ eV

Features:

Knee, ankle, GZK cutoff
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Ultra High Energy Cosmic Ray Accelerators?

Galaxy Jets from Black Holes?



Gamma Ray Bursts?

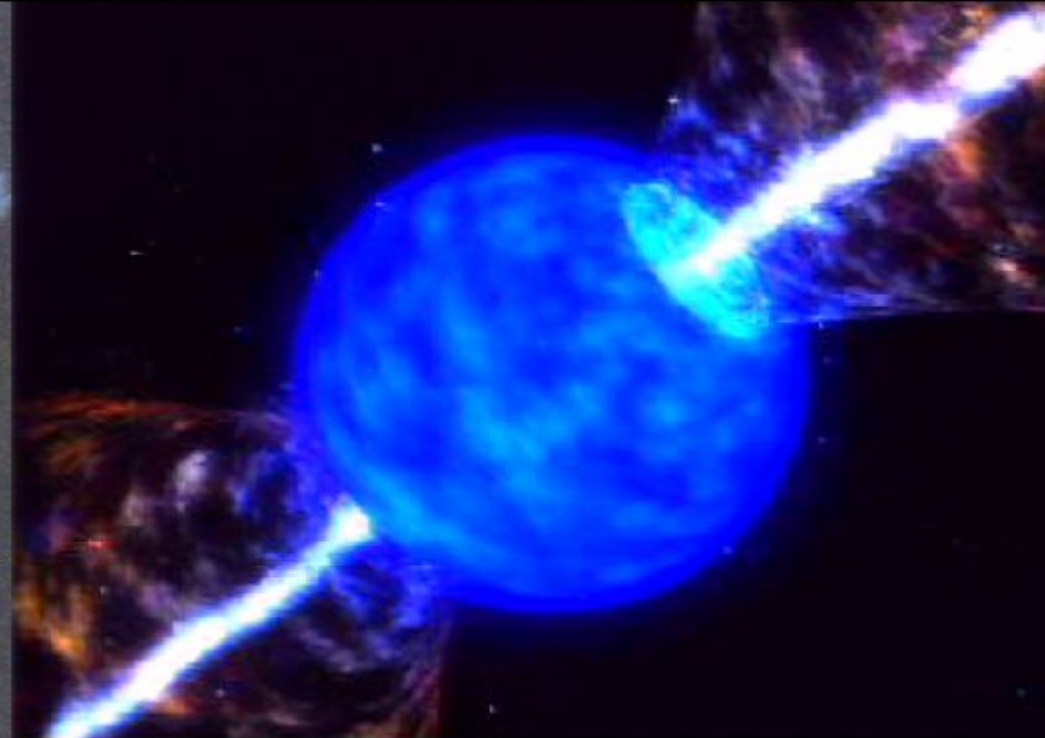


Neutron Stars? Magnetars?

Ultra High Energy Cosmic Ray Accelerators?

Galaxy Jets from Black Holes?

Gamma Ray Bursts?

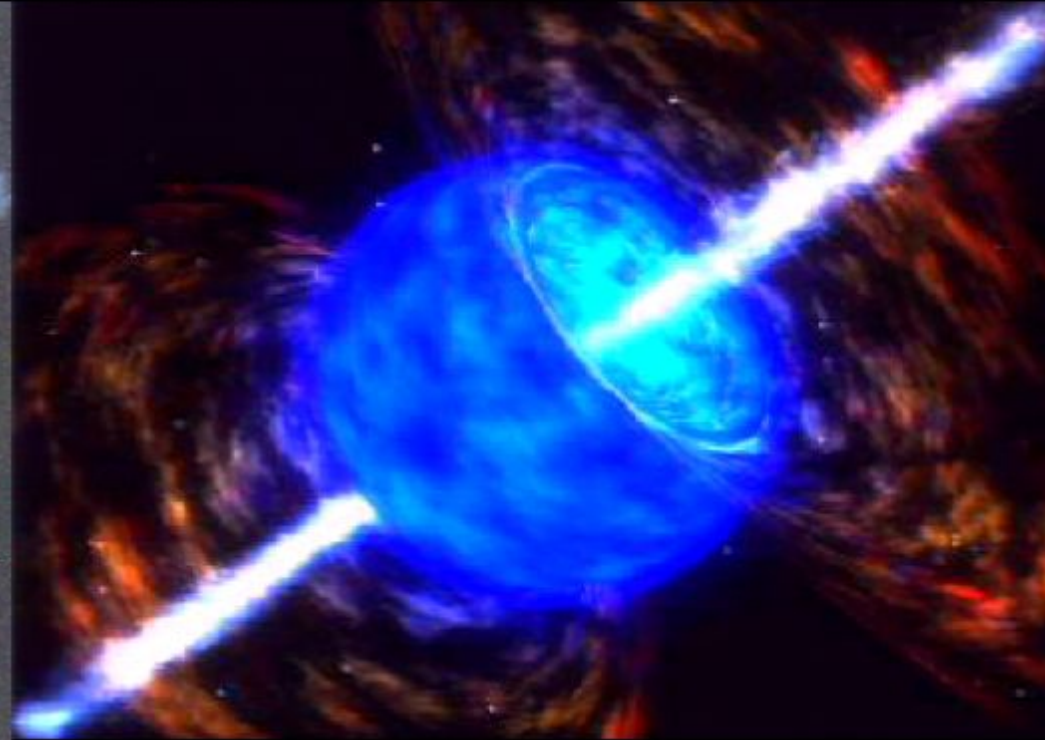


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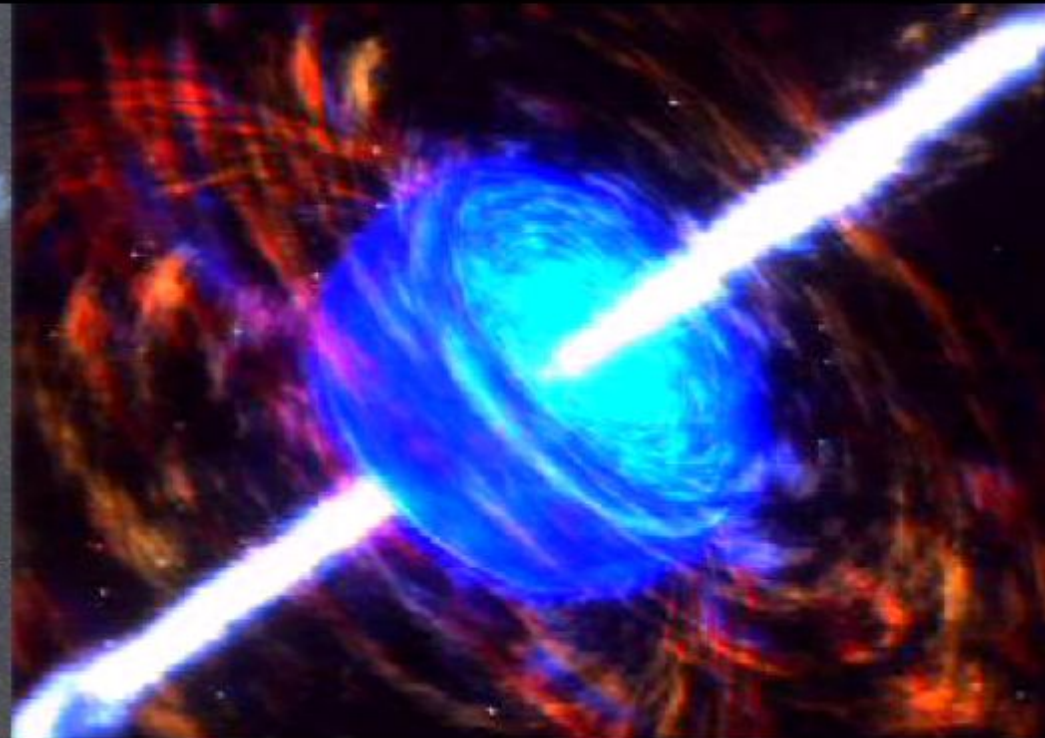


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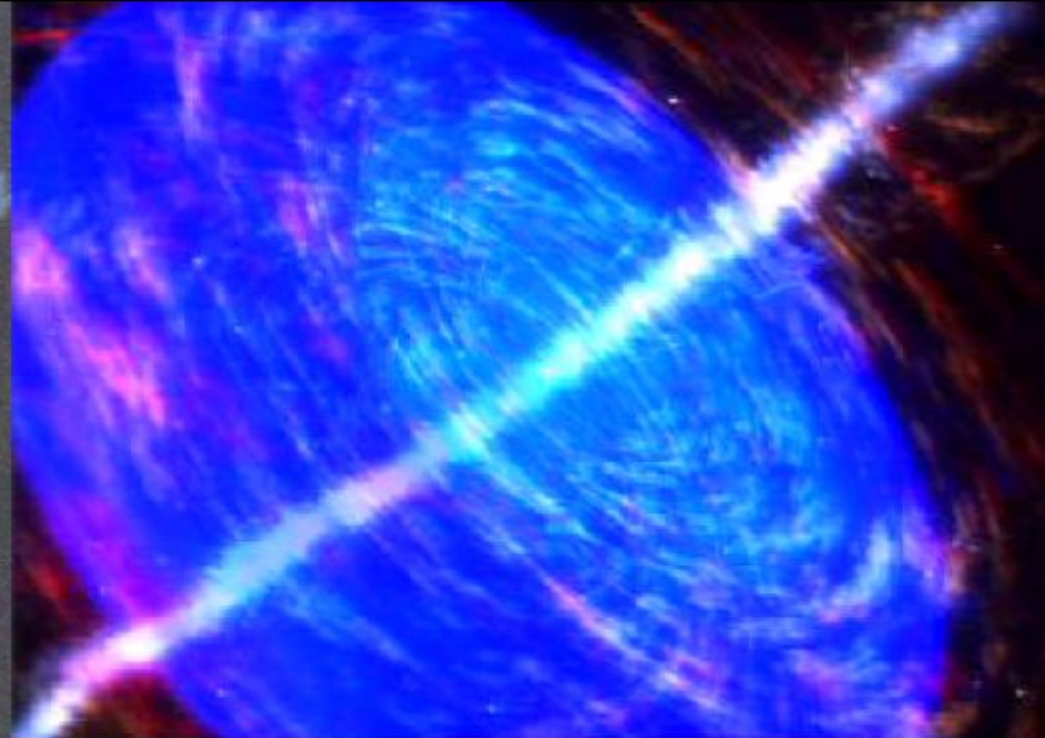
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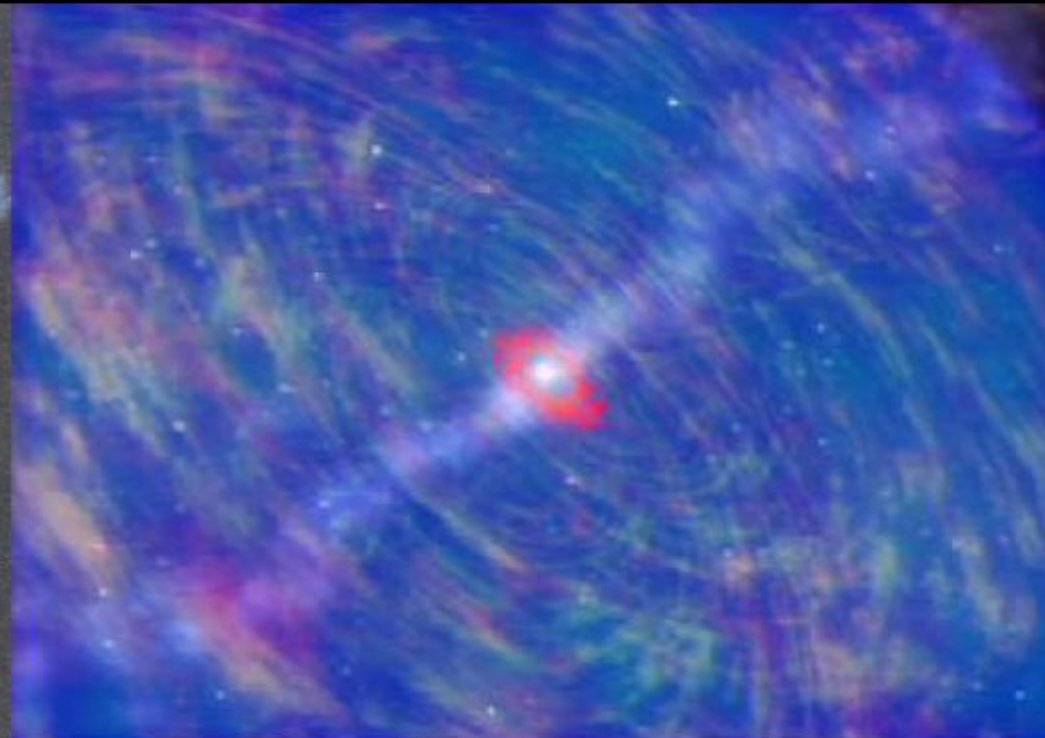


Neutron Stars? Magnetars?

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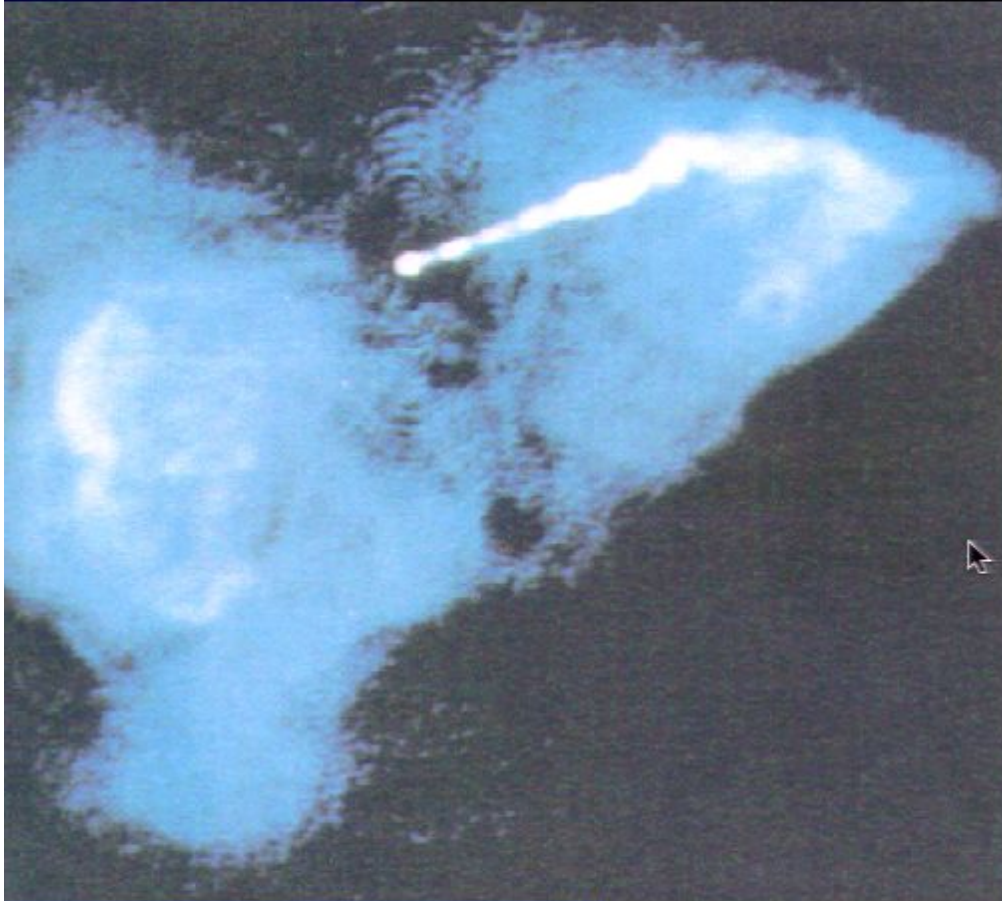
Gamma Ray Bursts?



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Gamma Ray Bursts?



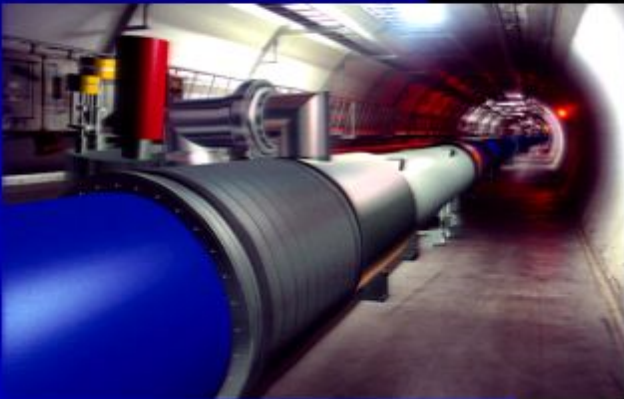
Neutron Stars? Magnetars?

Challenging Accelerators

LHC magnetic field,
radius = 6×10^7 km (Sun/Mercury distance)

acceleration time = 815 years

ILC electric field,
radius = 1.5×10^9 km (Saturn)

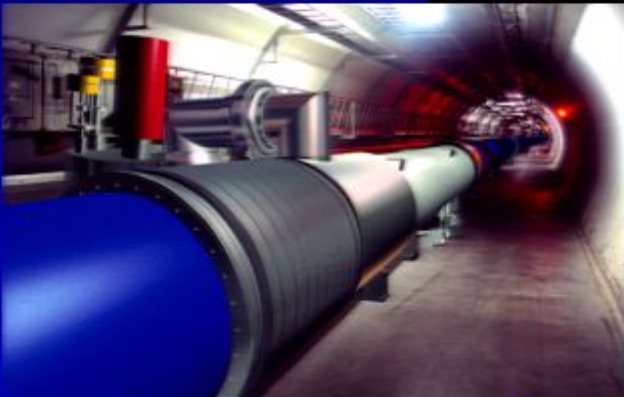


Challenging Accelerators

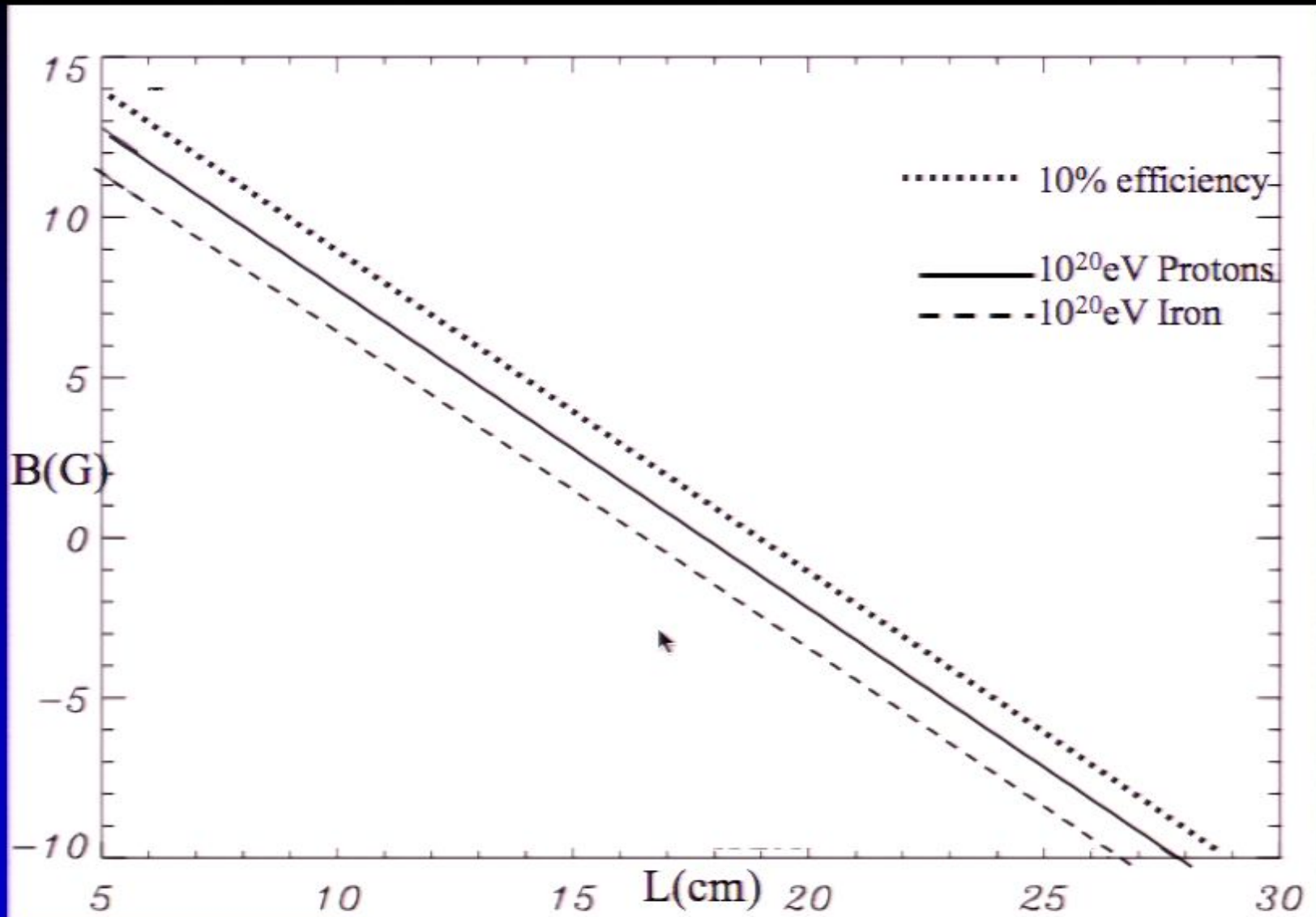
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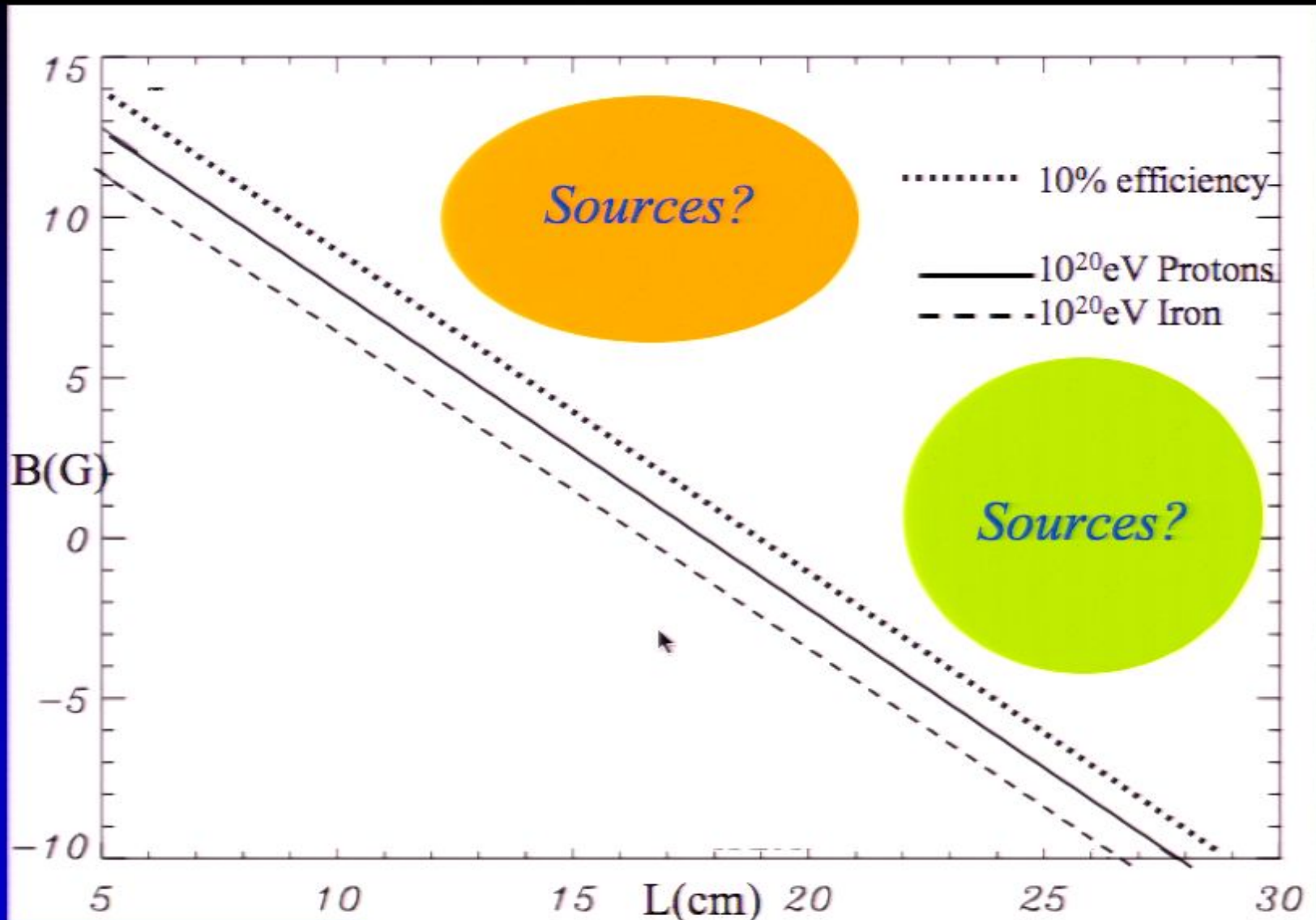
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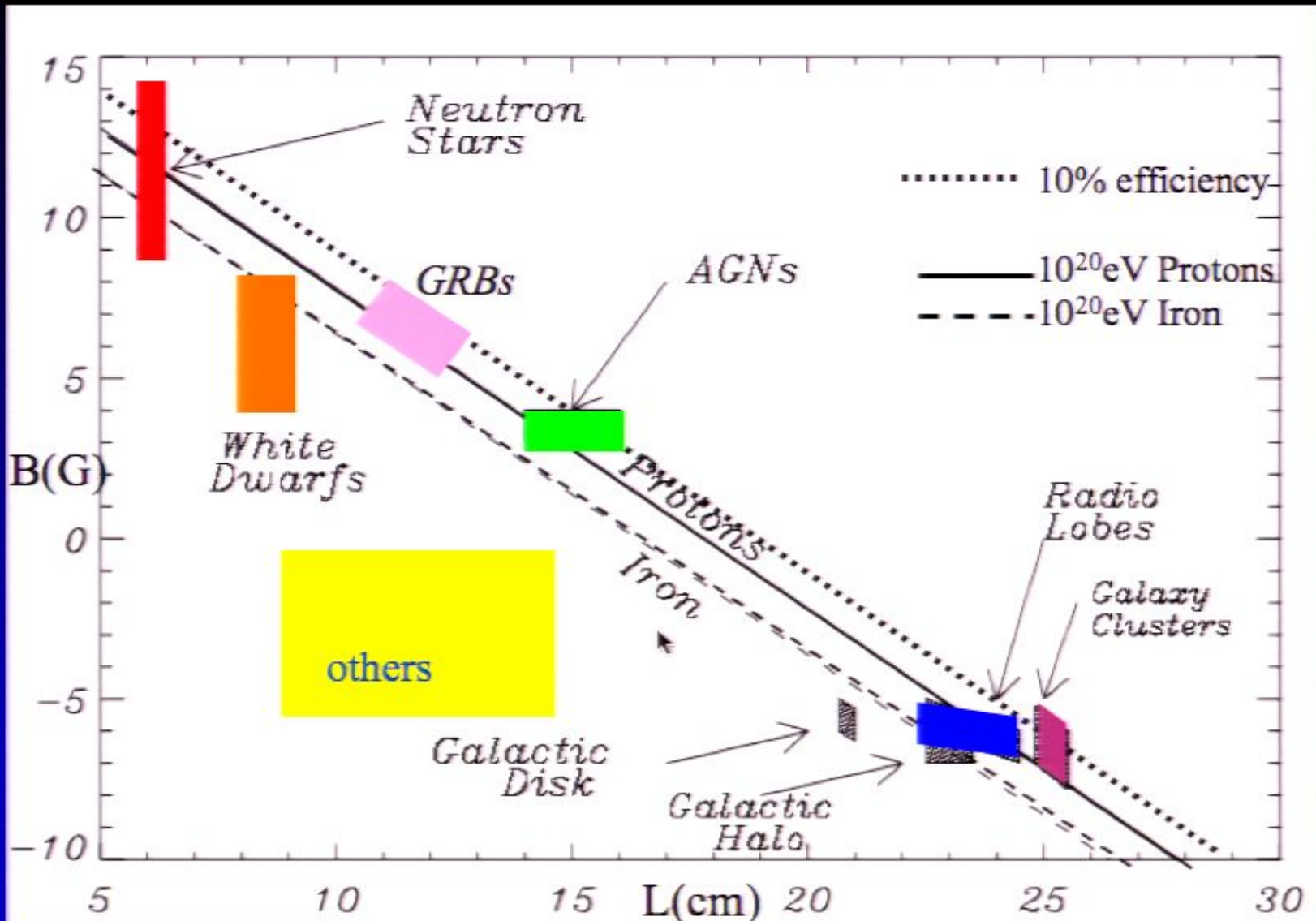
$$E = ZeBL$$



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$$E = ZeBL$$



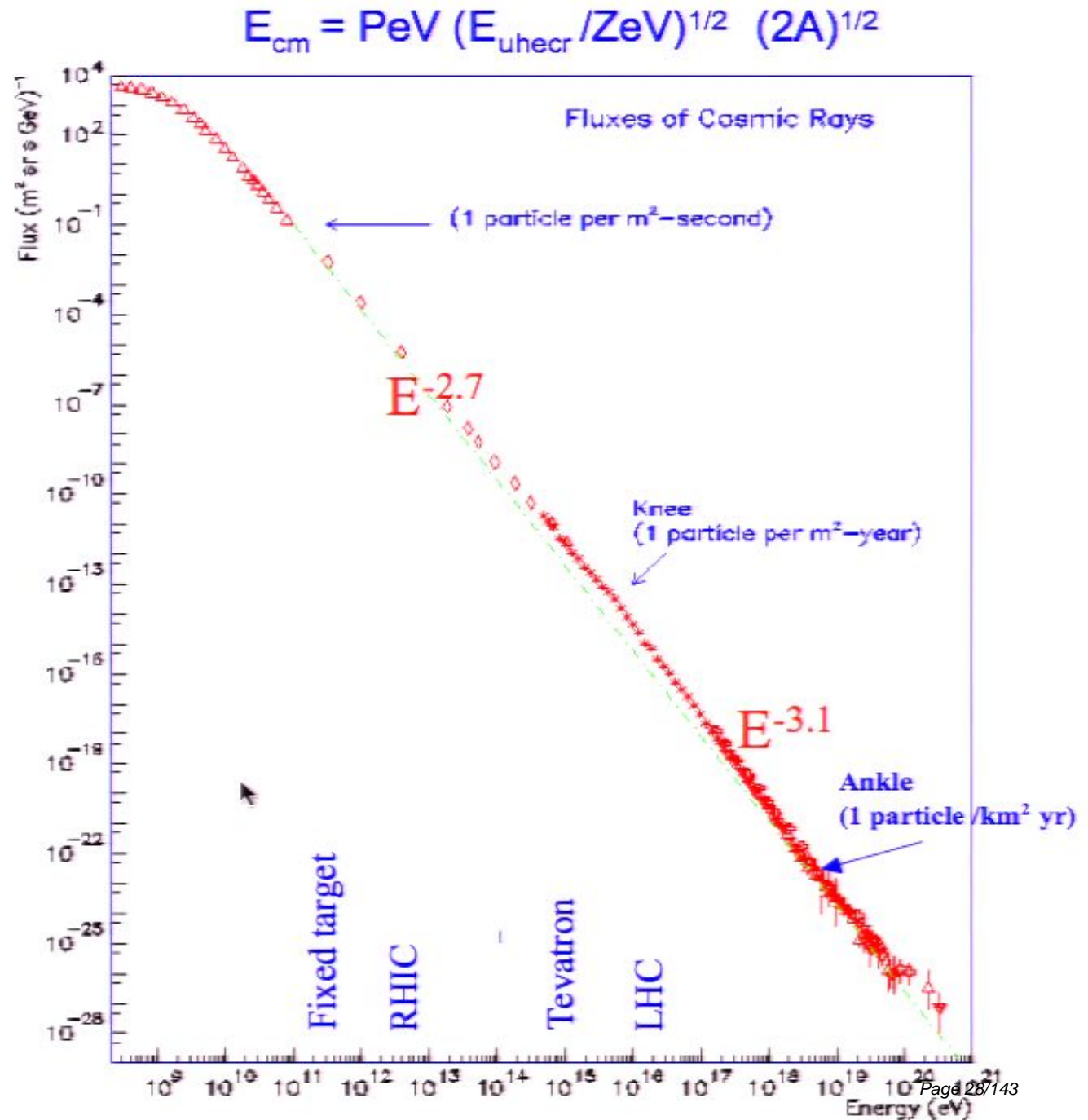
Cosmic Ray Spectrum

non-thermal
Phenomena

Extreme
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Features:
Knee, ankle, GZK
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interactions

Pirsa: 08010000

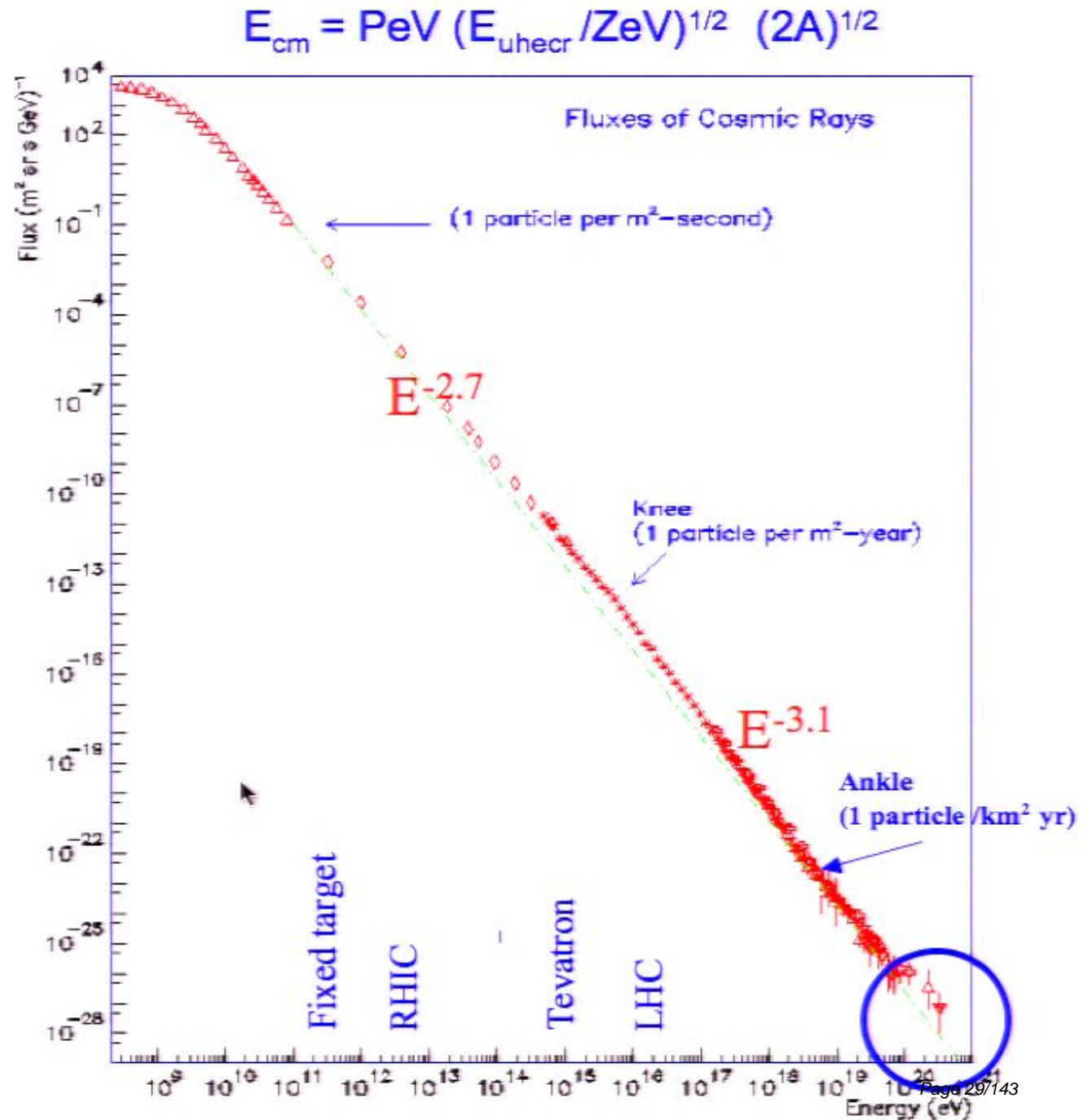


Cosmic Ray Spectrum

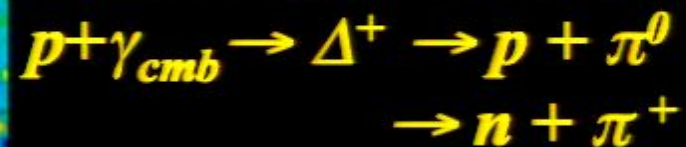
non-thermal
Phenomena

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Cosmologically Meaningful Termination



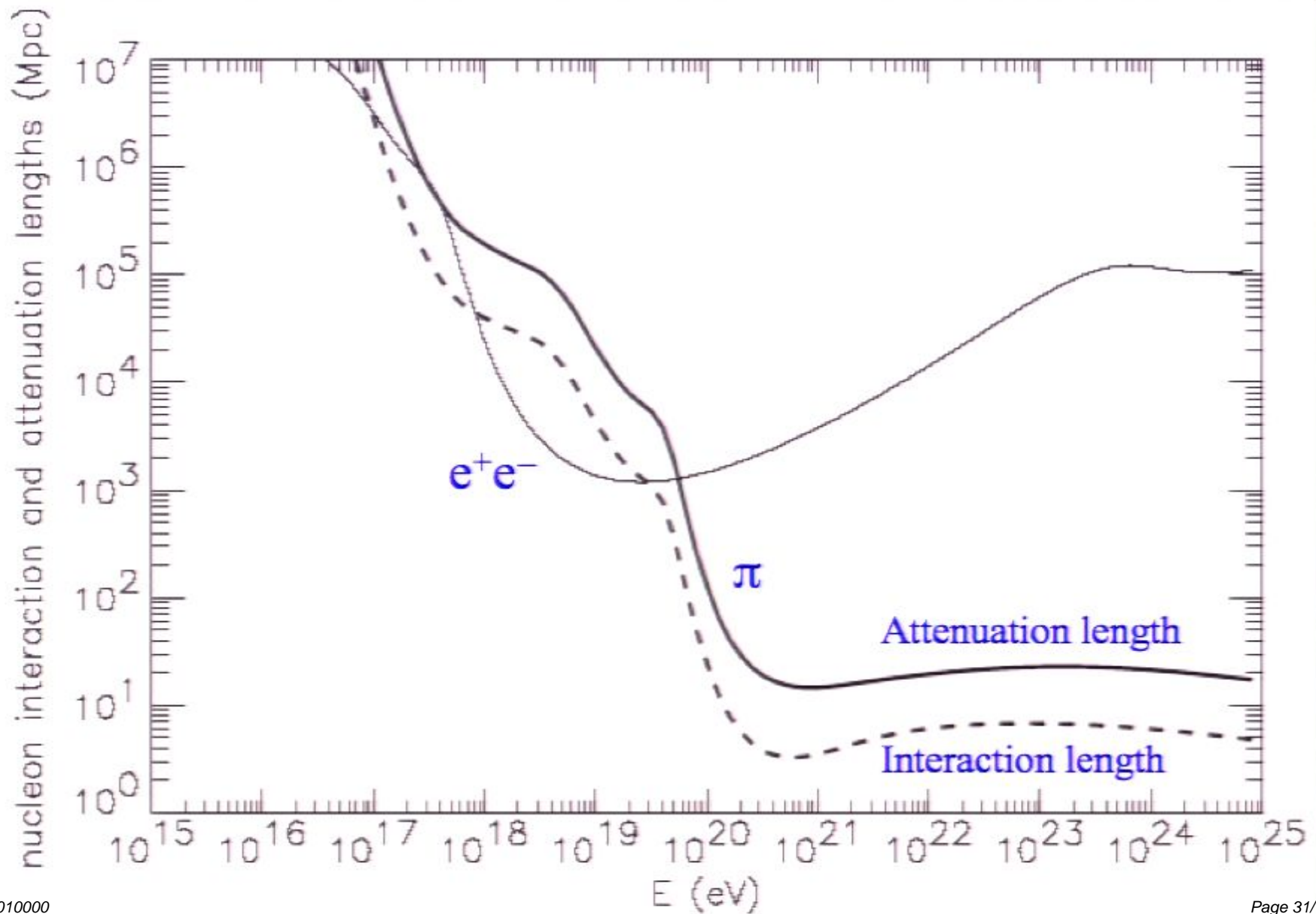
Proton Horizon
 10^{20} eV

ZK Cutoff

Greisen, Zatsepin, Kuzmin 1966

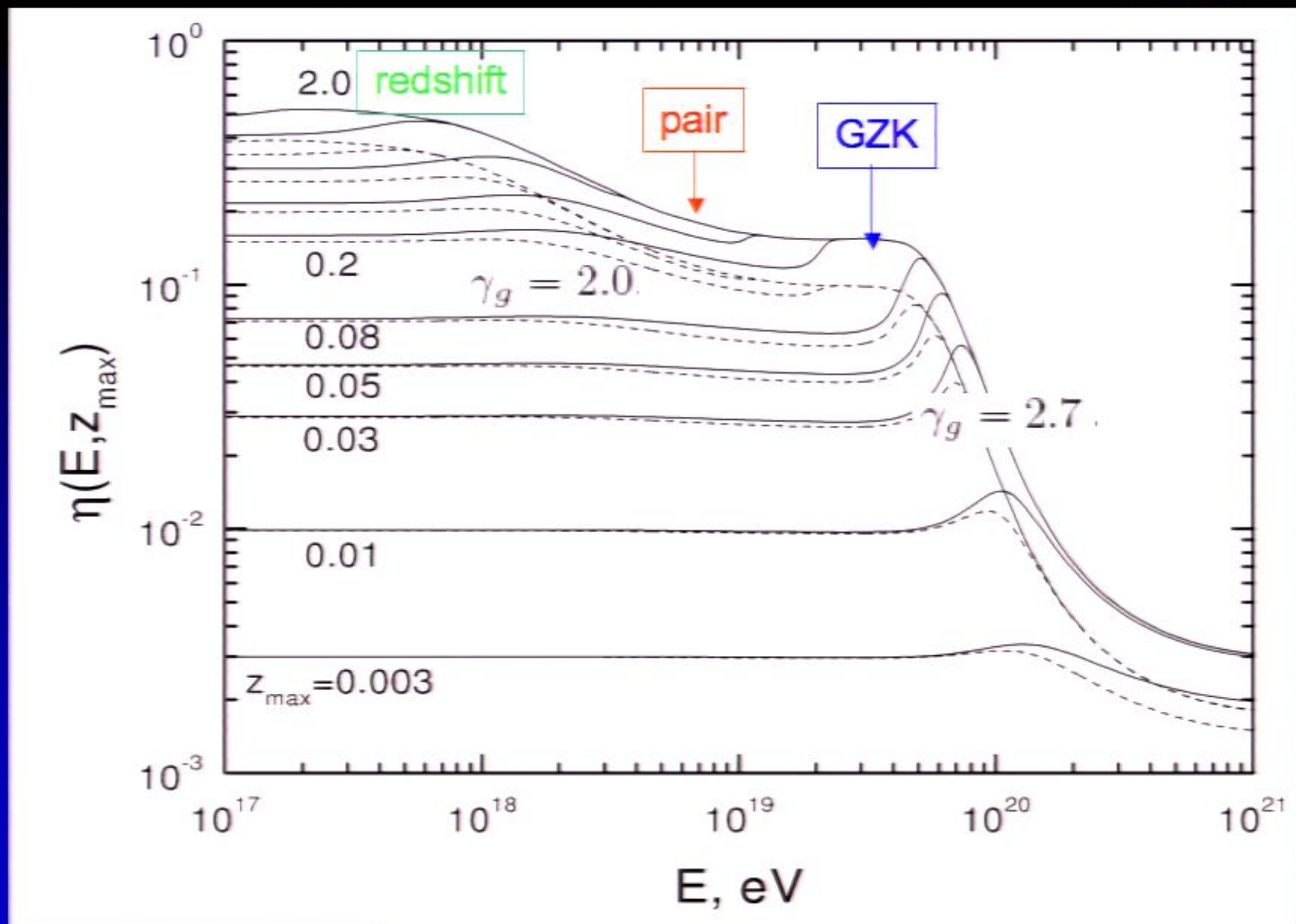
Pisa: 03010000

Attenuation length



Energy loss Features for protons

Berezinsky et al. 03



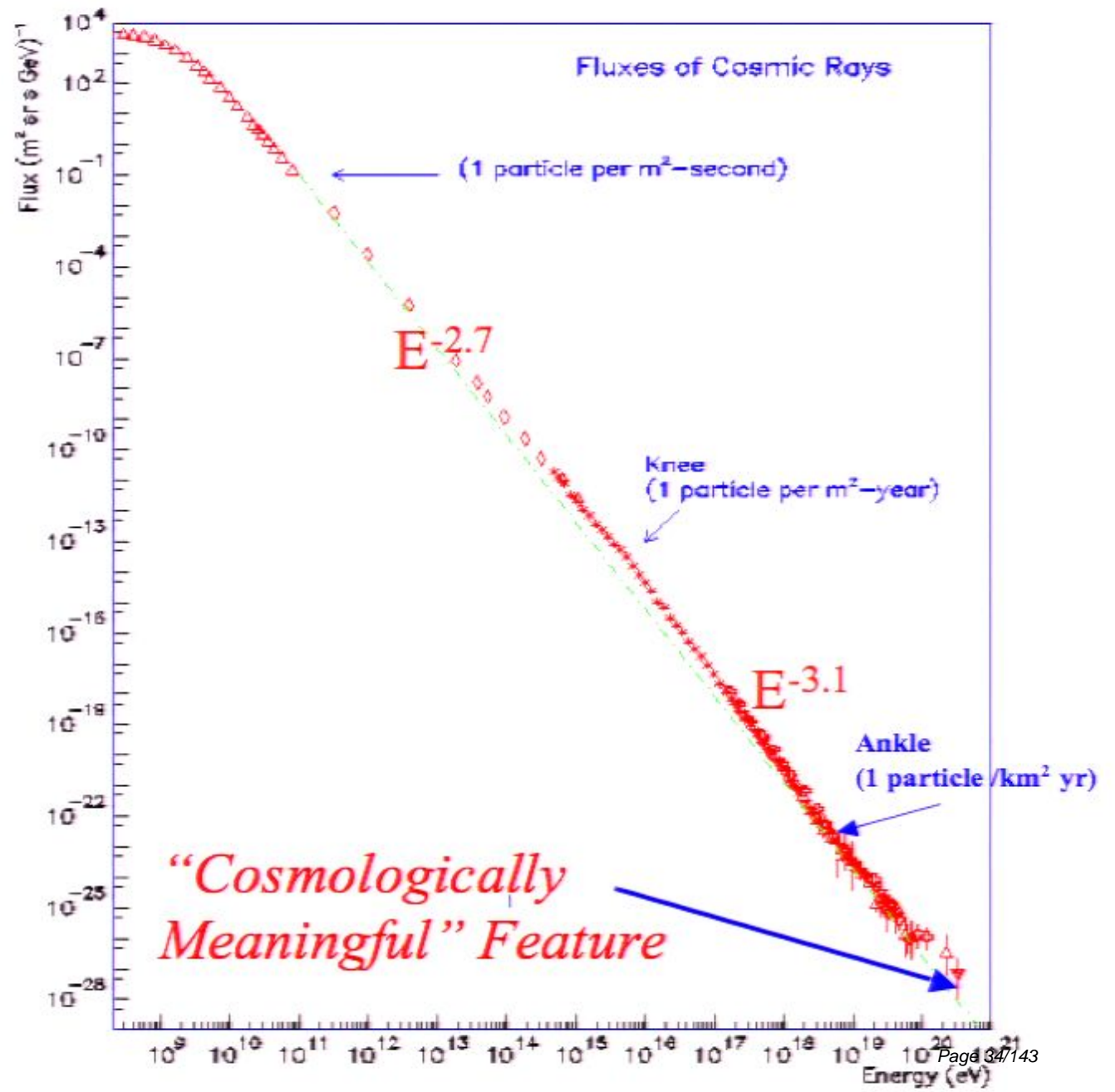
GZK Effect

Spectral Feature

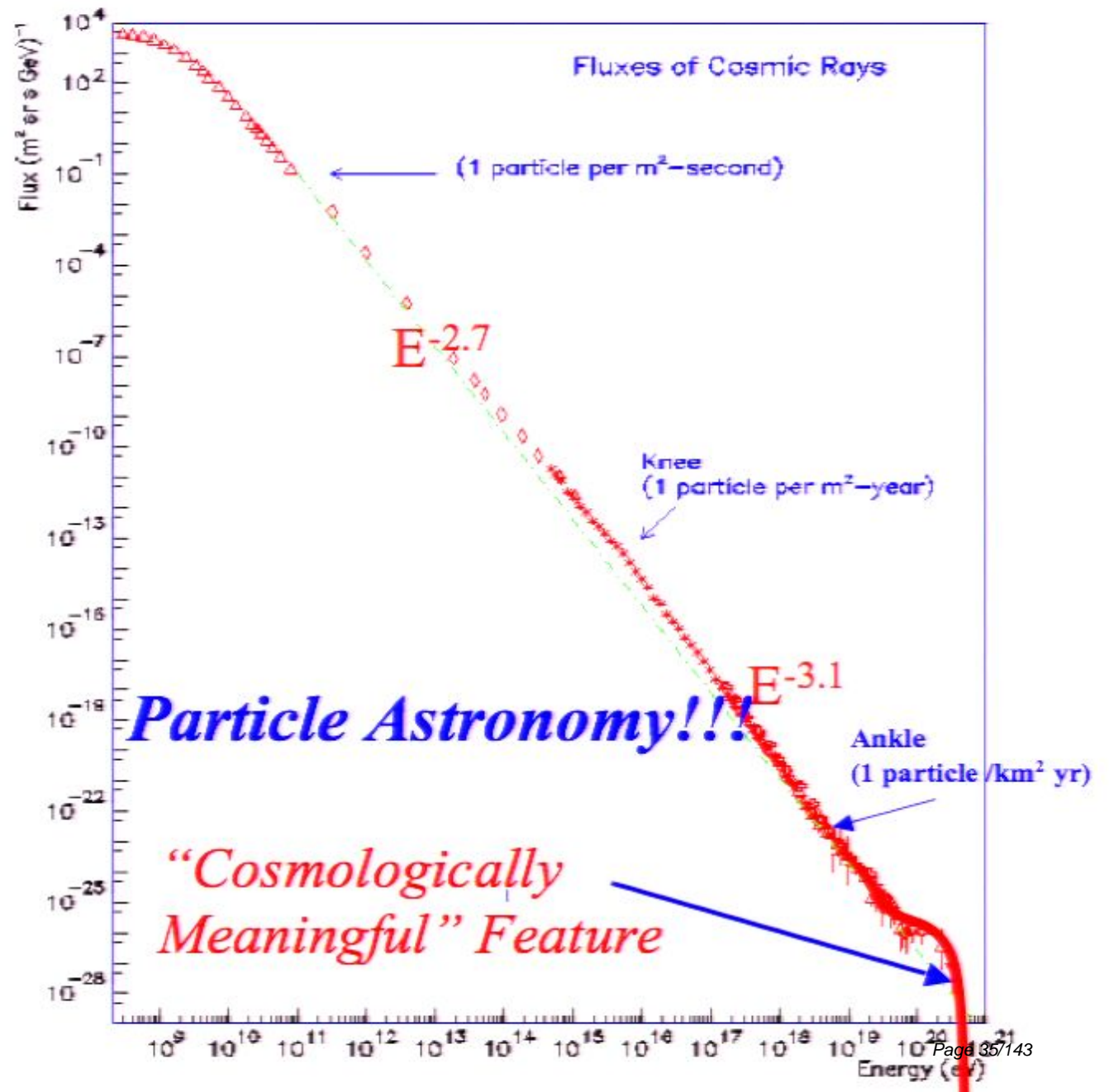
+

Anisotropies in Sky Distribution

Cosmic Ray Spectrum

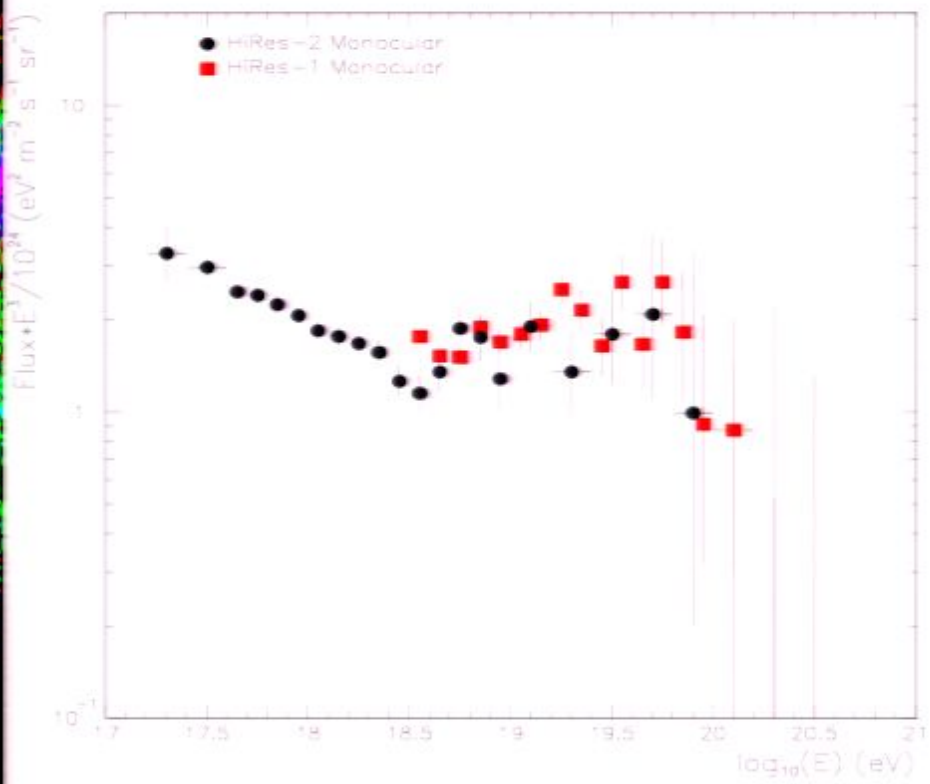
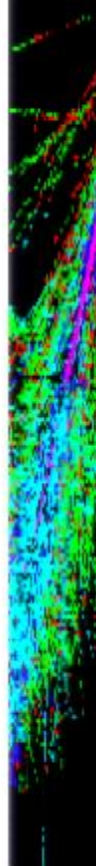
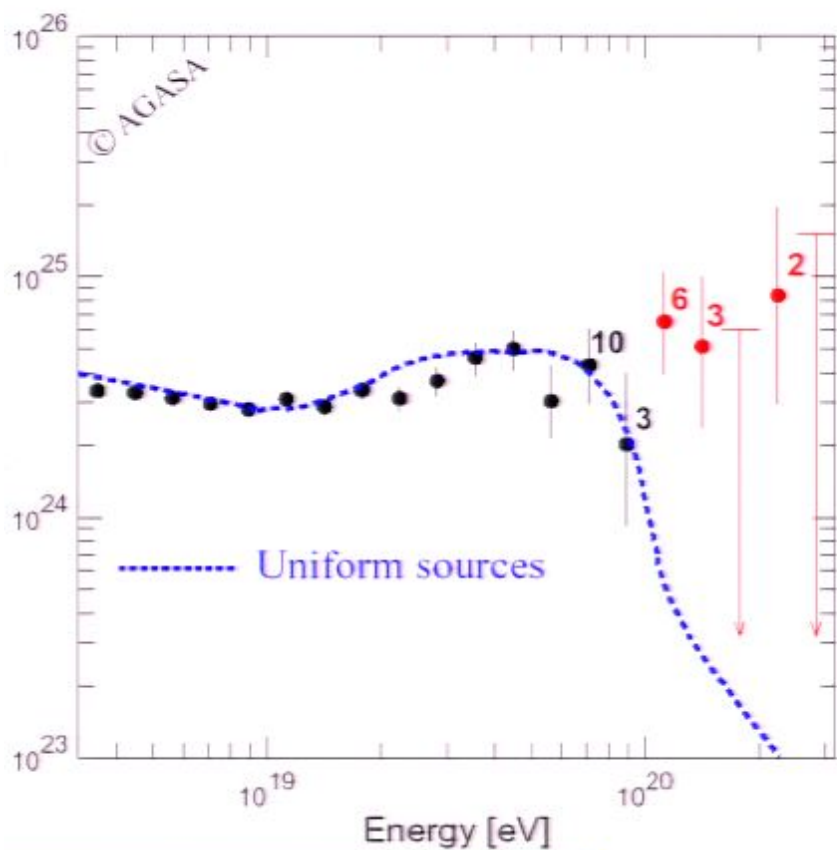


Cosmic Ray Spectrum



AGASA

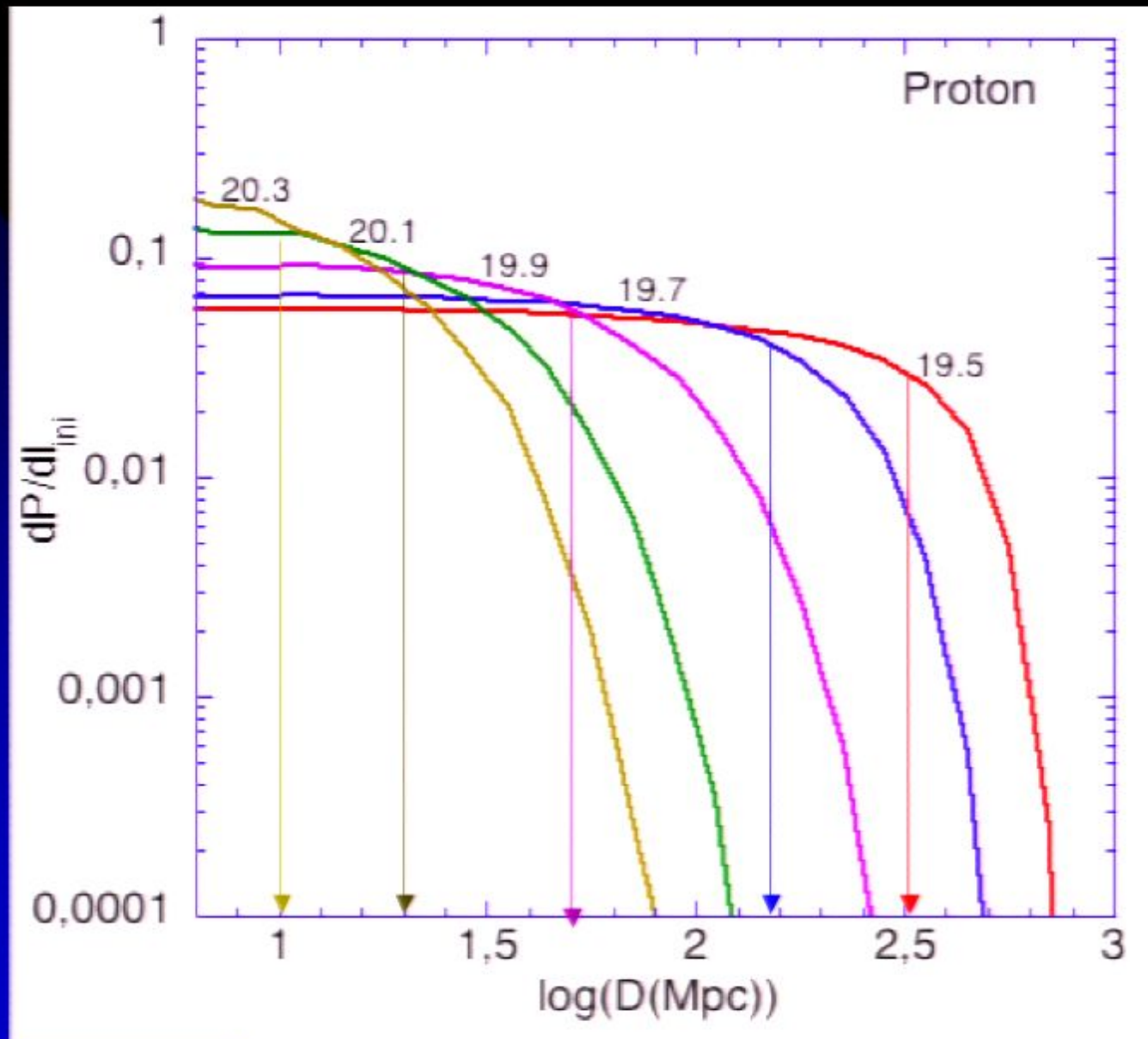
High Resolution Fly's Eye



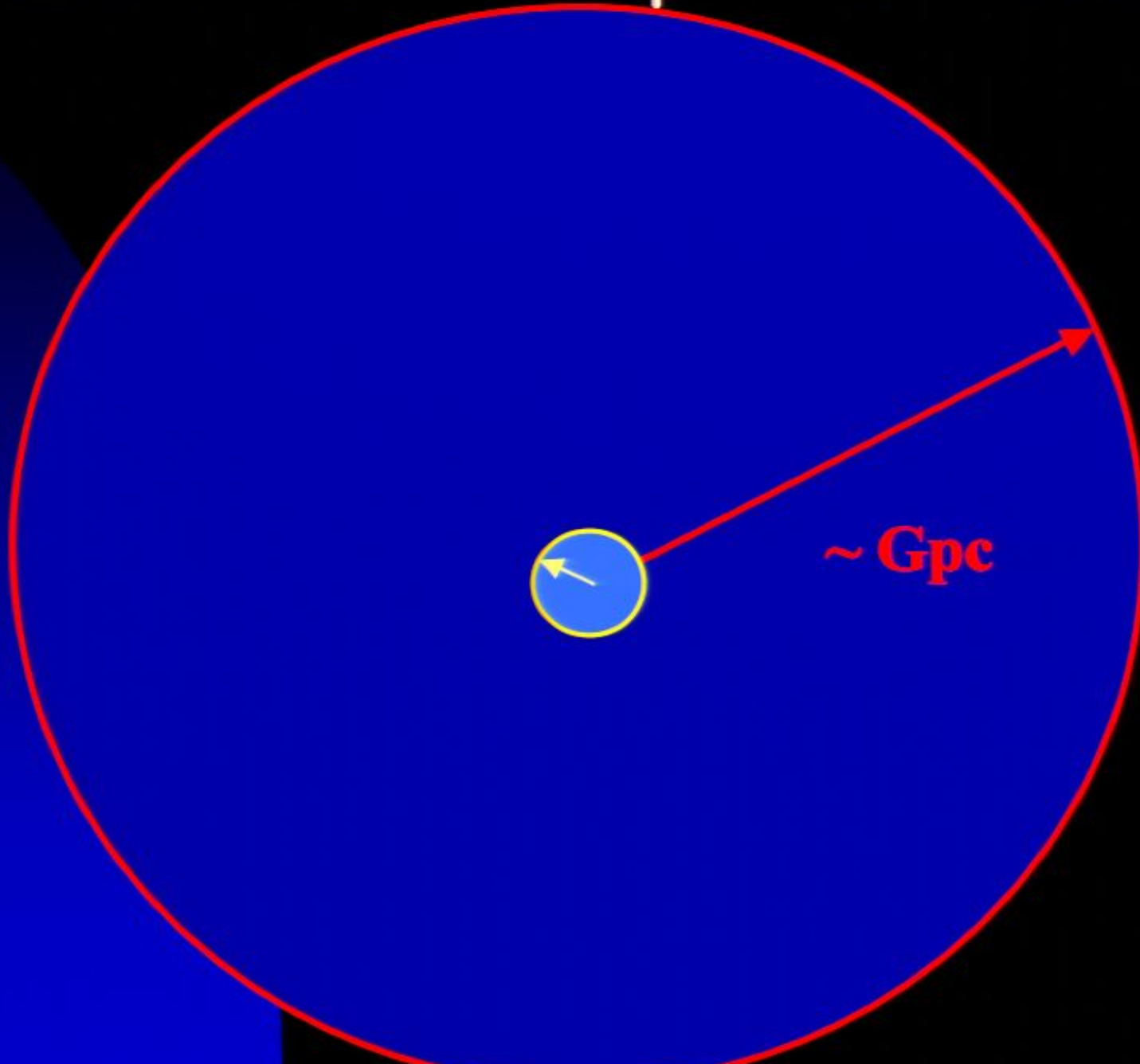
No GZK cutoff

Consistent w/ GZK cutoff

Horizon- observed Protons



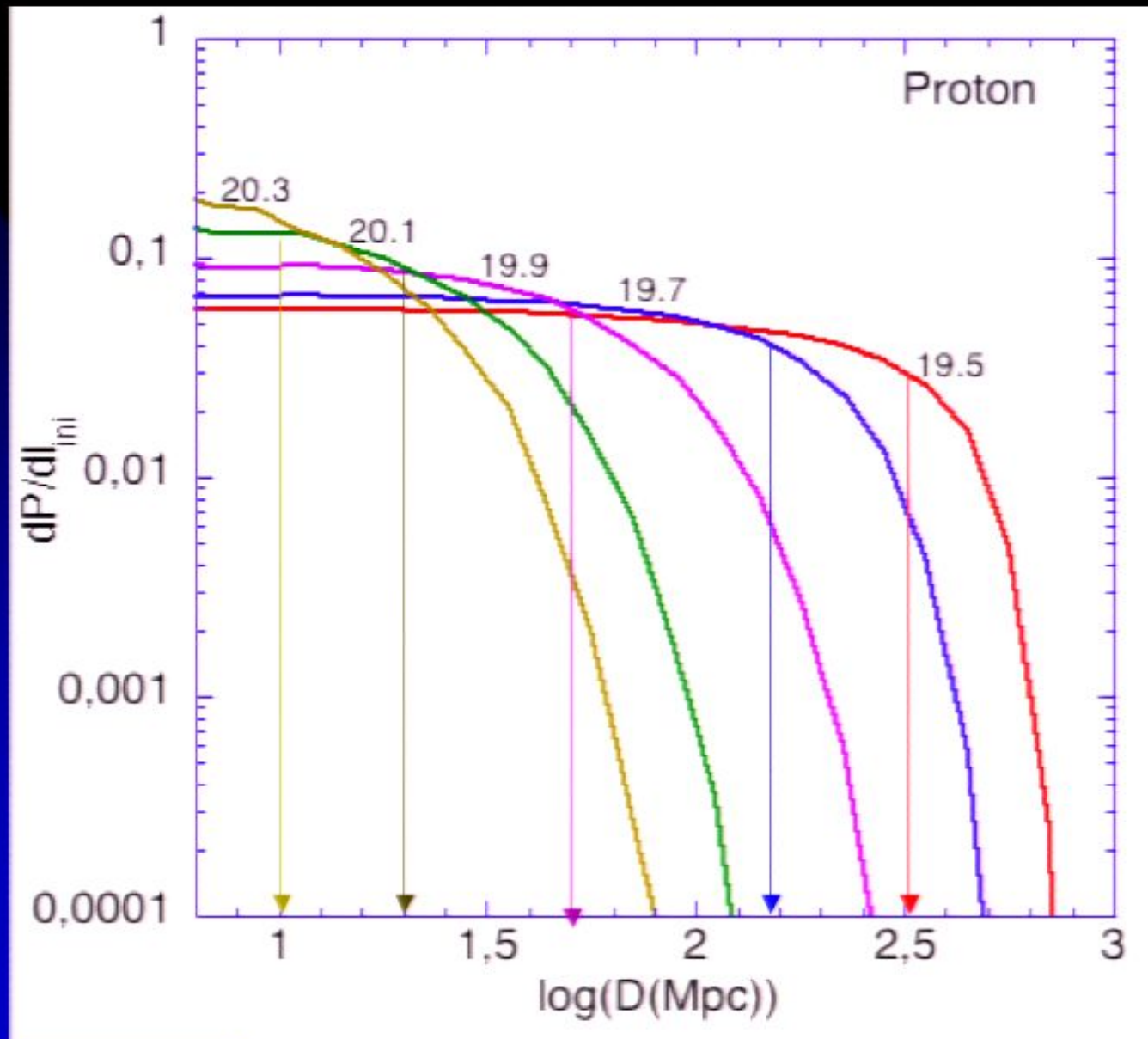
Horizon of $10^{20.5}$ eV proton ~ 100 Mpc



THE SLOAN GREAT WALL

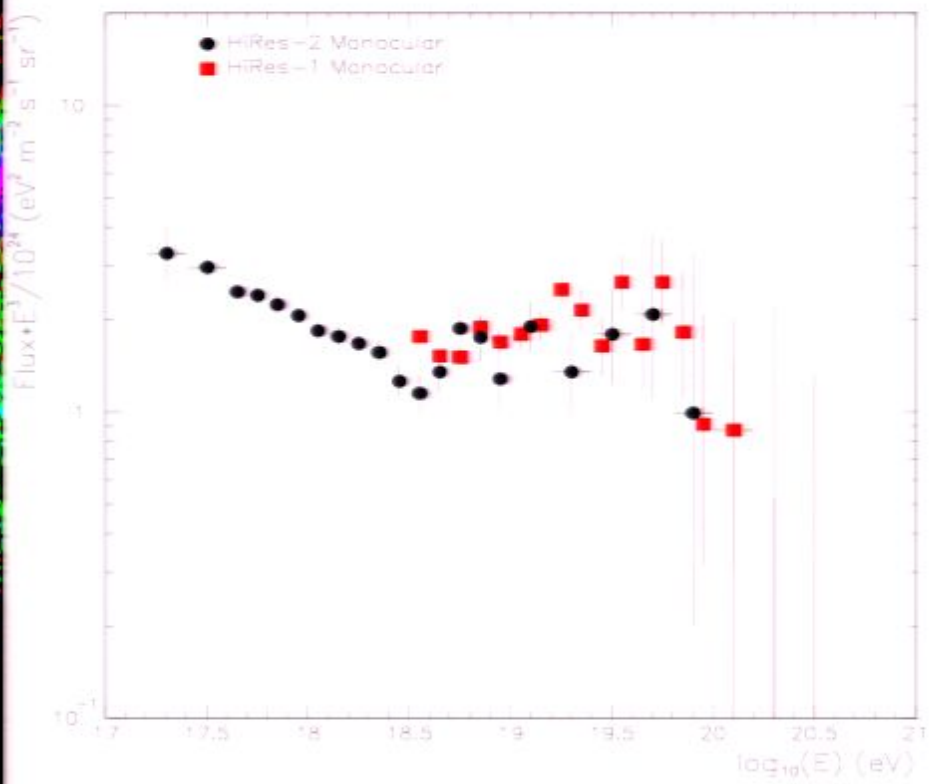
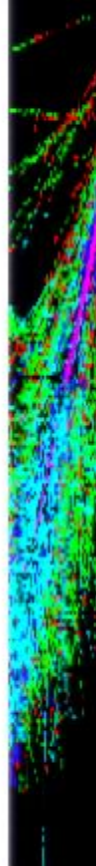
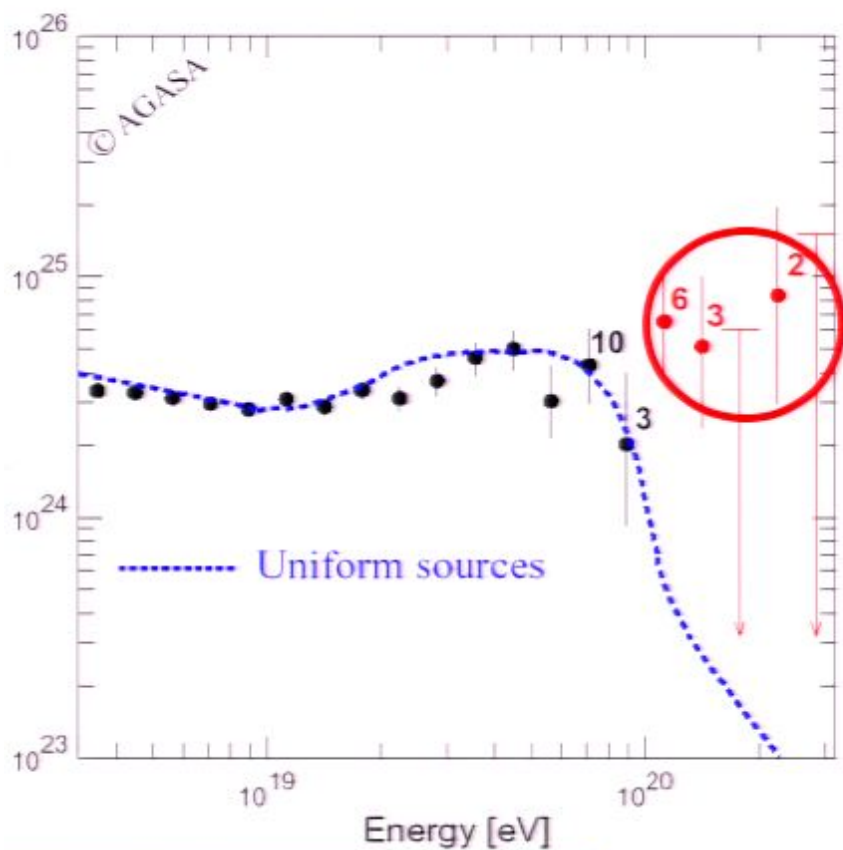


Horizon- observed Protons



AGASA

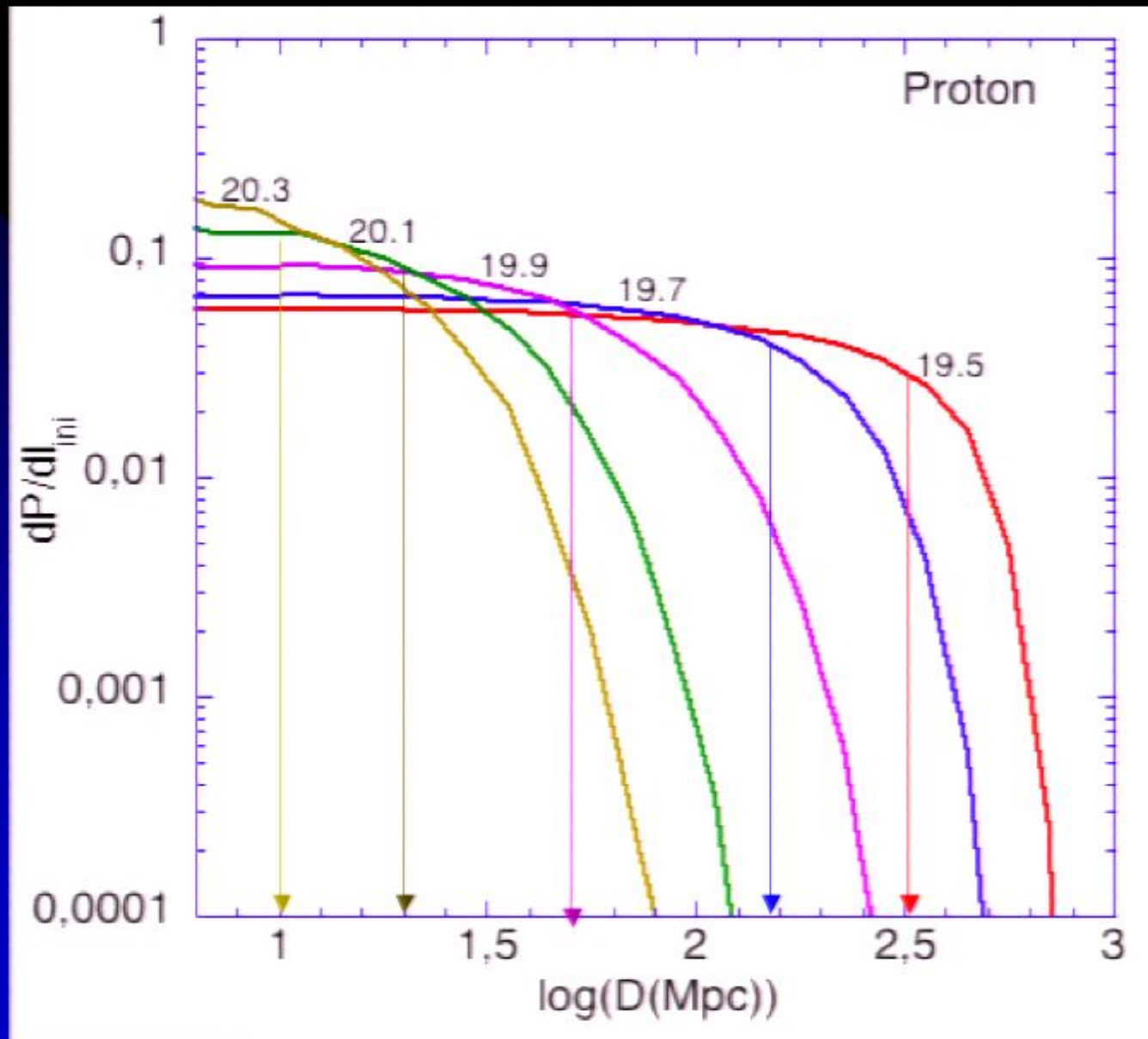
High Resolution Fly's Eye



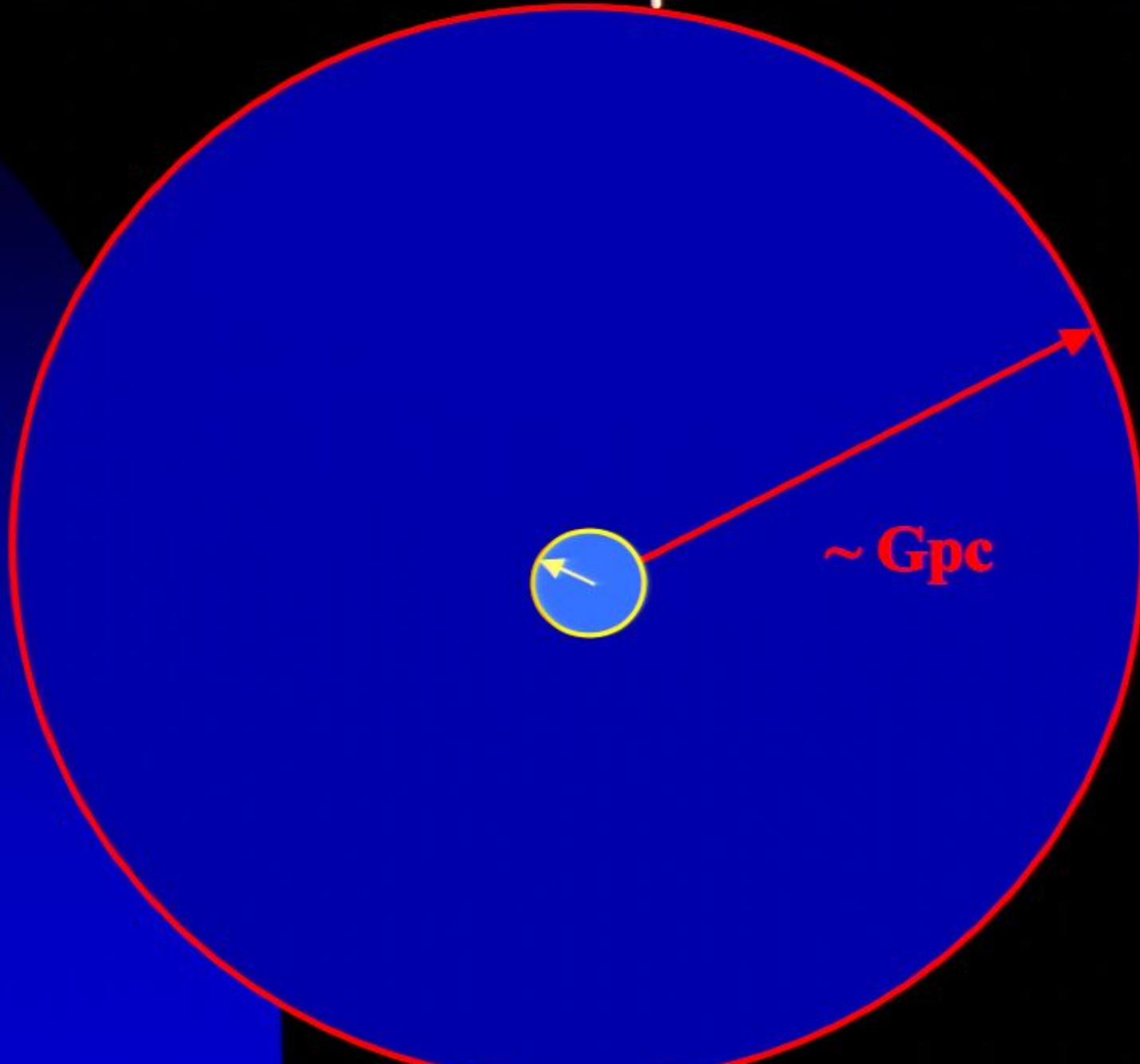
No GZK cutoff

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Horizon of $10^{20.5}$ eV proton ~ 100 Mpc



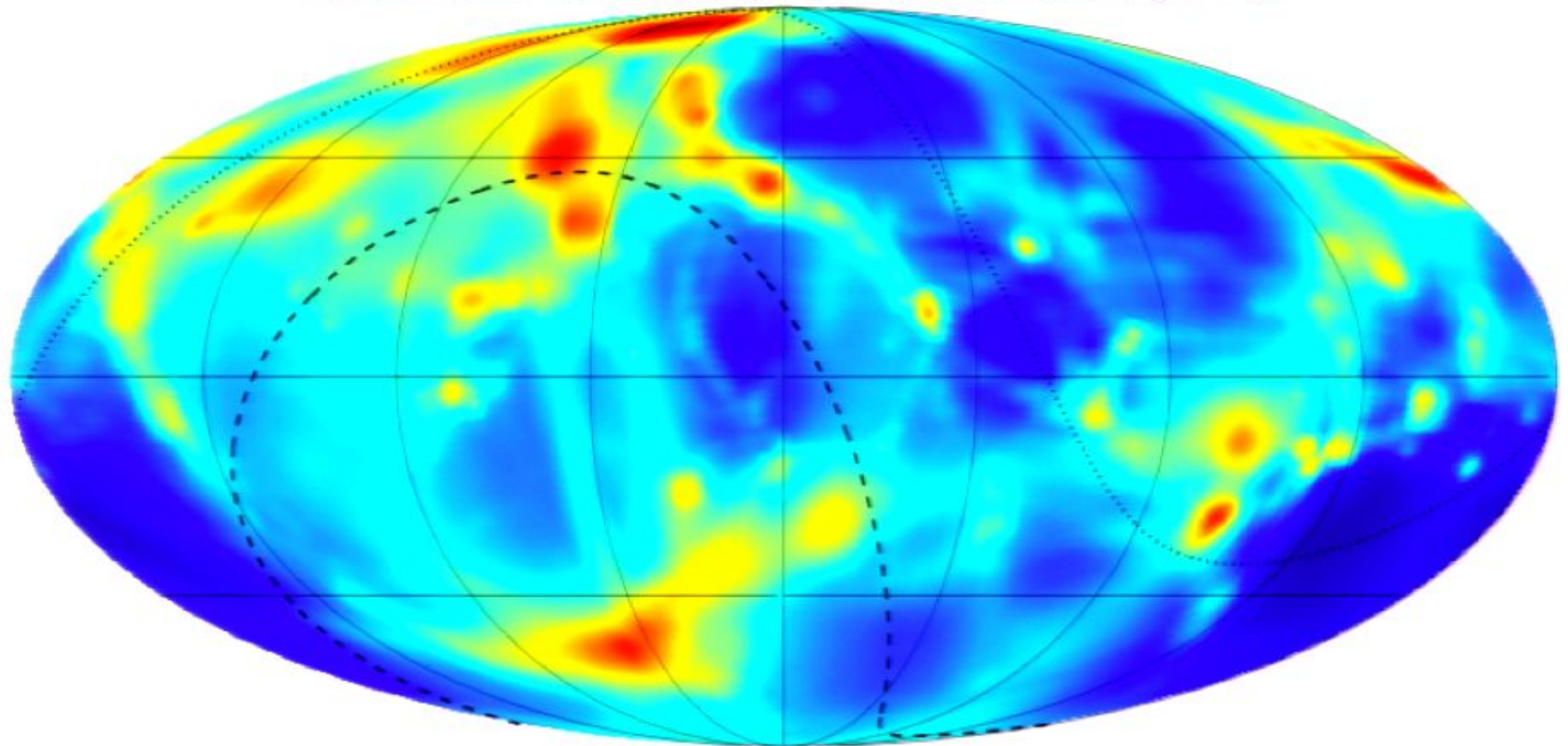
THE SLOAN GREAT WALL



Protons with $> 10^{20.5}$ eV

$E_{\text{proton}} > 10^{20.5}$ eV

Exclusion zones: South (dotted), North (dashed), assuming $\theta < 60^\circ$



-2.2  0.0 Log ()

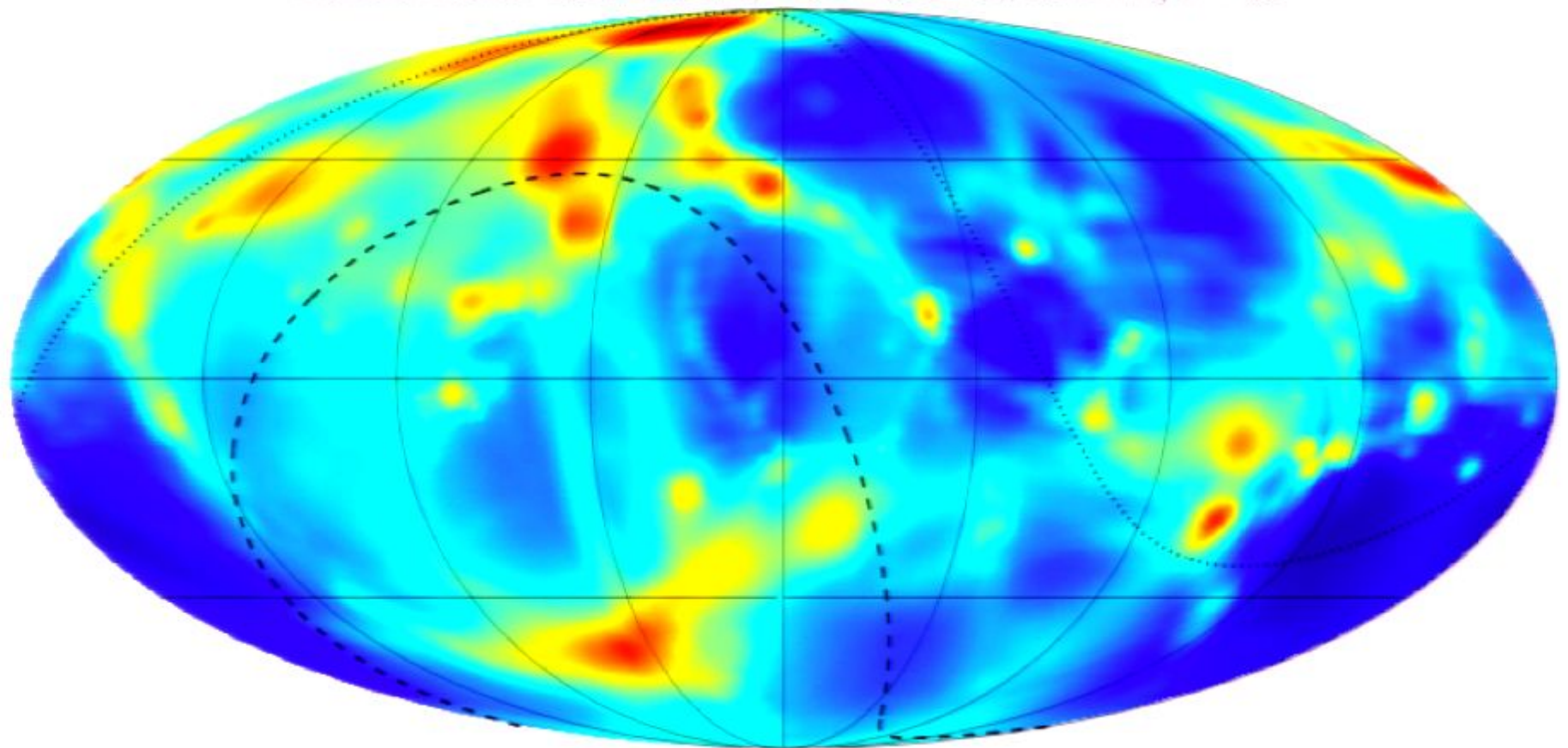
THE SLOAN GREAT WALL



Protons with $> 10^{20.5}$ eV

$E_{\text{proton}} > 10^{20.5}$ eV

Exclusion zones South (dotted), North (dashed), assuming $\theta = 60^\circ$

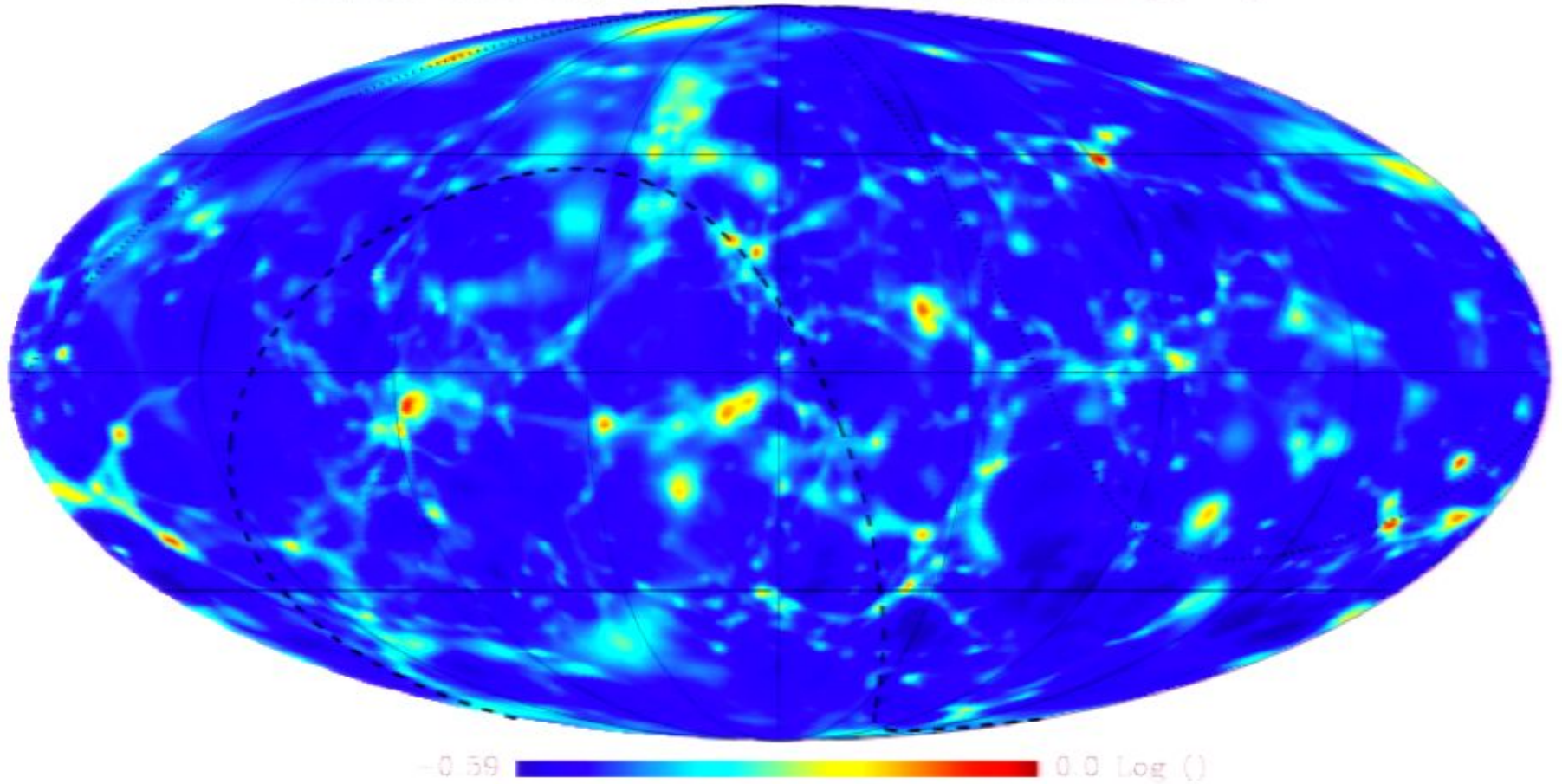


-3.2  0.0 log ()

Protons with $> 10^{19.5}$ eV

$E_{\text{proton}} > 10^{19.5}$ eV

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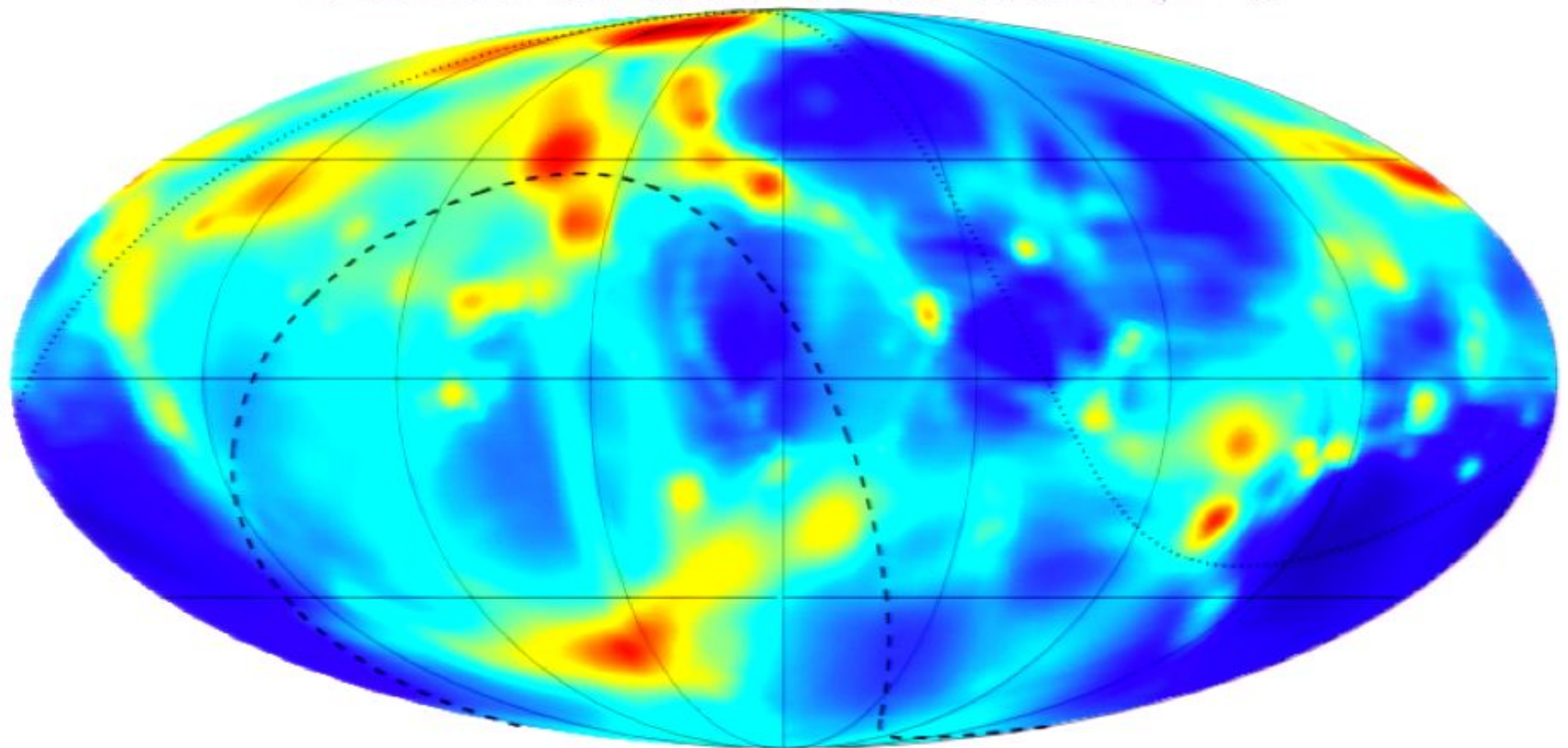


-0.59  0.0 Log ()

Protons with $> 10^{20.5}$ eV

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Exclusion zones: South (dotted), North (dashed), assuming $\theta < 60^\circ$

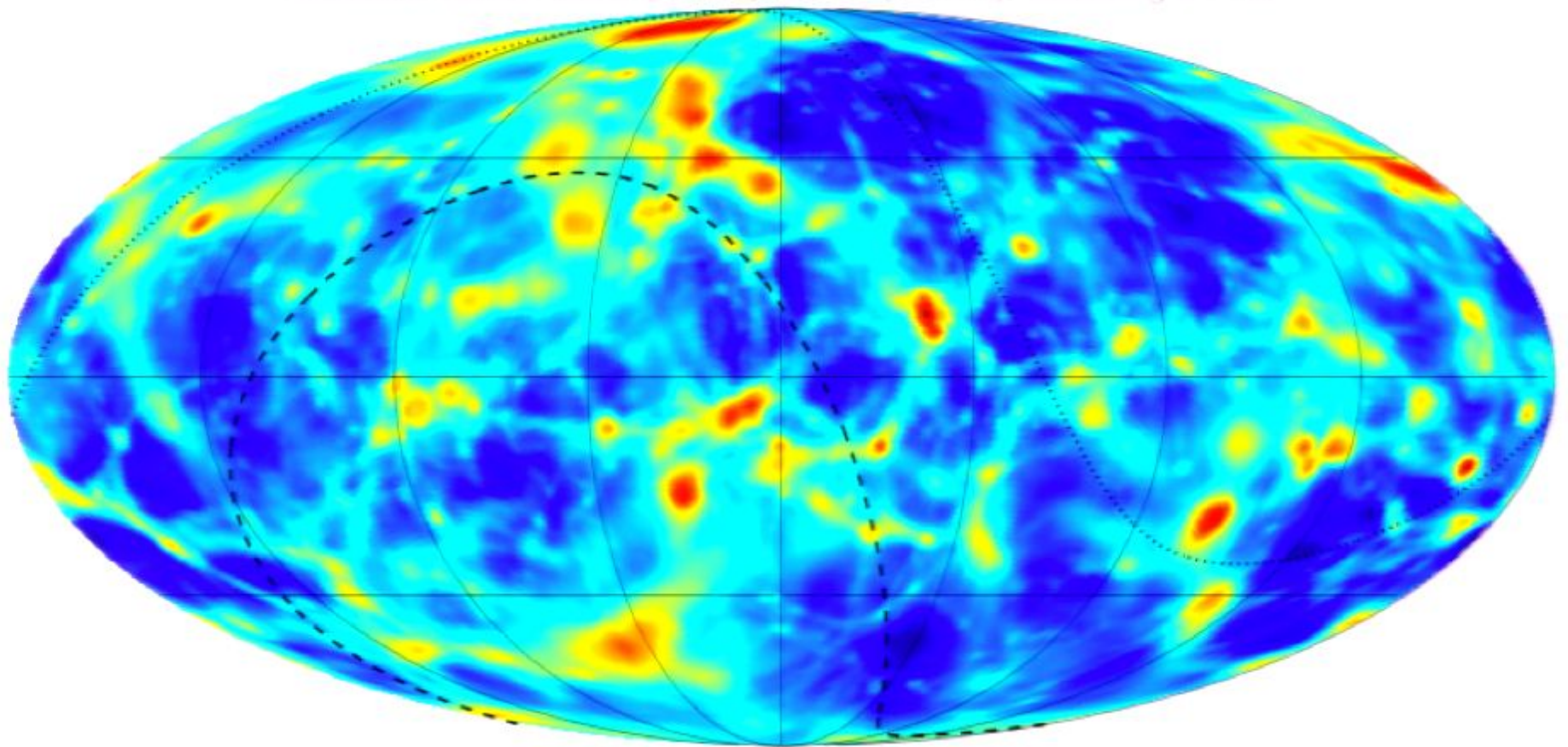


-3.2  0.0 Log ()

Protons with $> 10^{20}$ eV

$E_{\text{proton}} > 10^{20}$ eV

Exclusion zones South (dotted), North (dashed), assuming $\theta < 60^\circ$

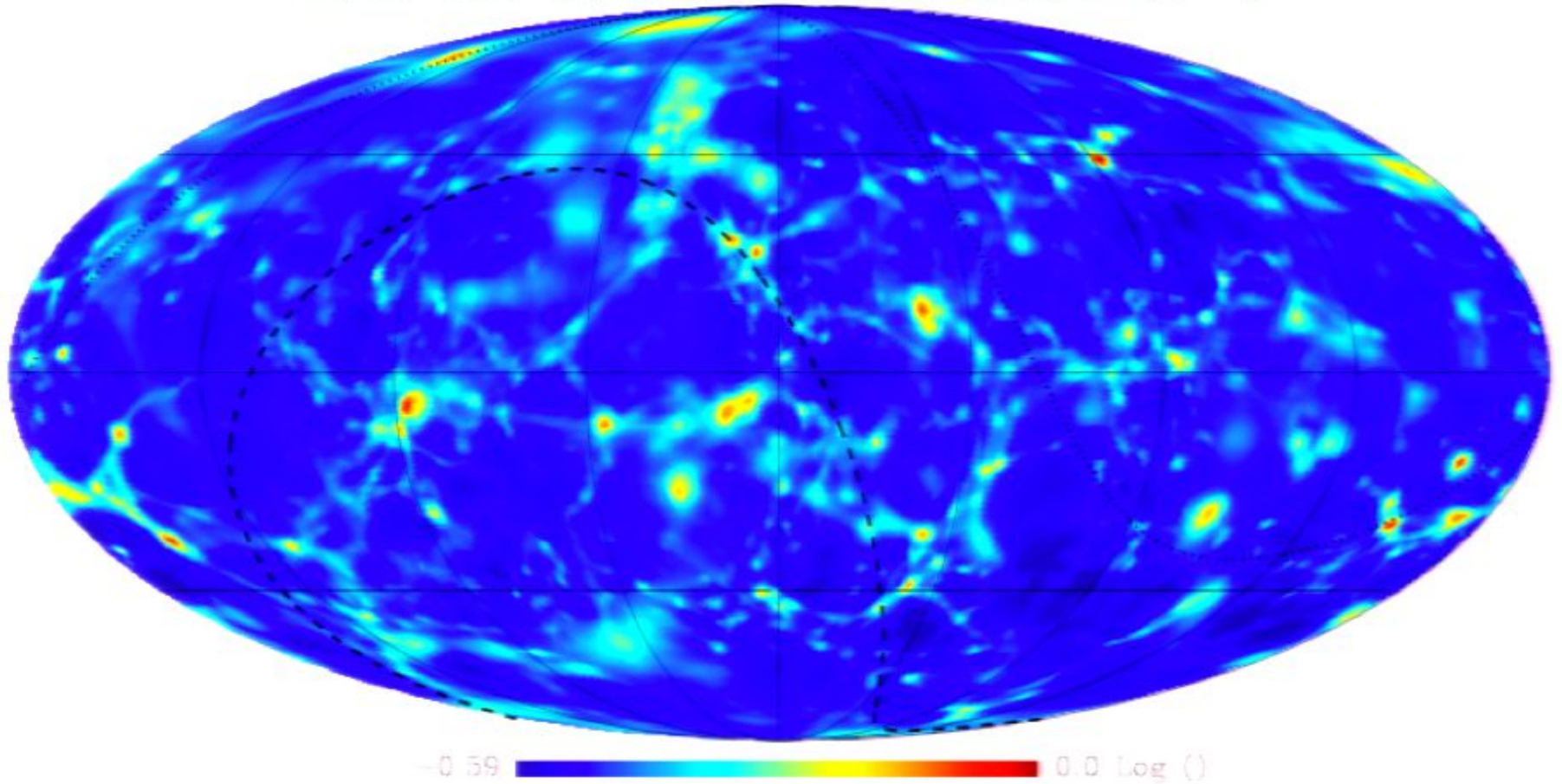


-1.7  0.0 Log ()

Protons with $> 10^{19.5}$ eV

$E_{\text{proton}} > 10^{19.5}$ eV

Exclusion zones: South (dotted), North (dashed), assuming $\theta < 60^\circ$

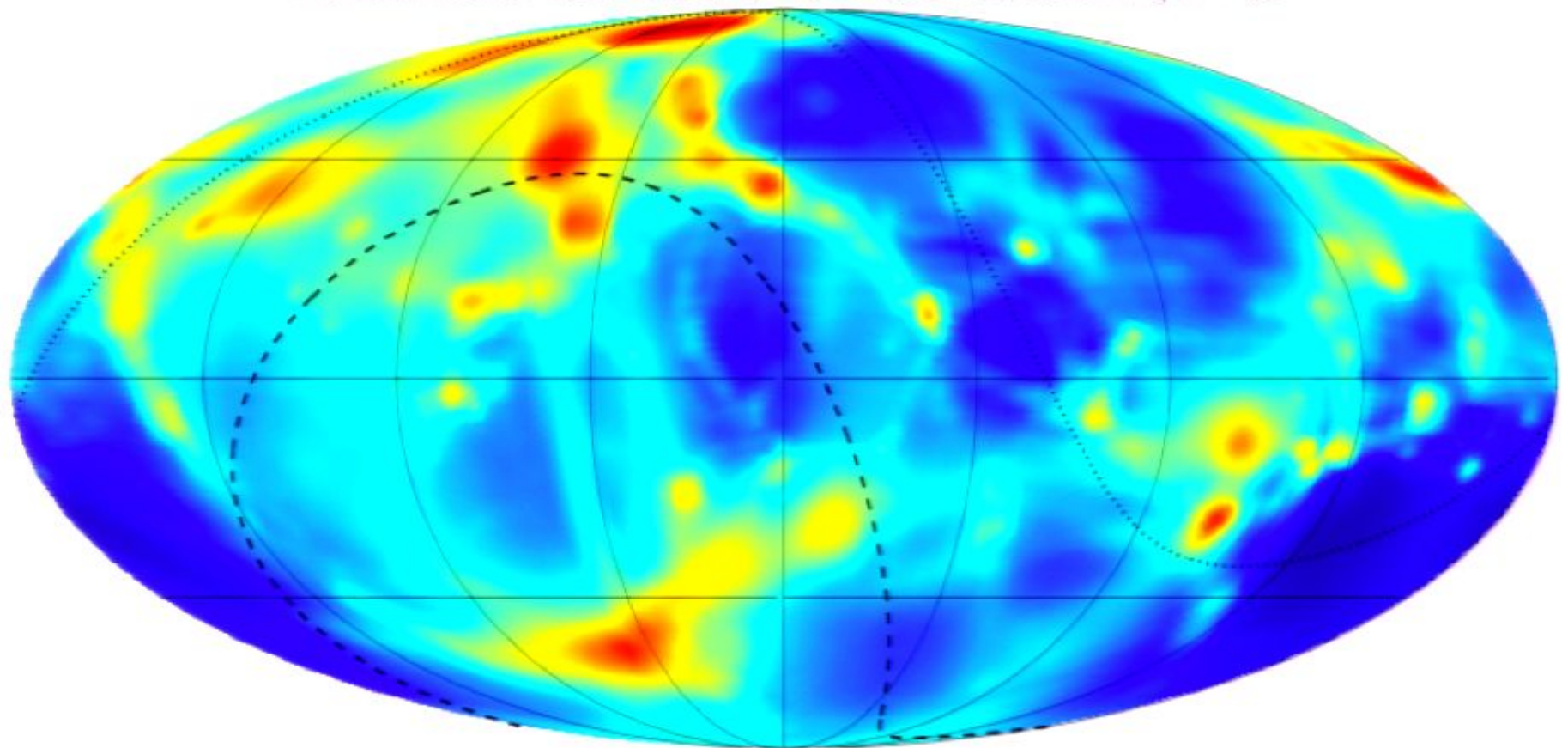


-0.59  0.0 Log ()

Protons with $> 10^{20.5}$ eV

$E_{\text{proton}} > 10^{20.5}$ eV

Exclusion zones South (dotted), North (dashed), assuming $\theta < 60^\circ$



-3.2  0.0 Log ()

Charged Particle Astronomy

Window of opportunity

10^{19} to 10^{21} eV

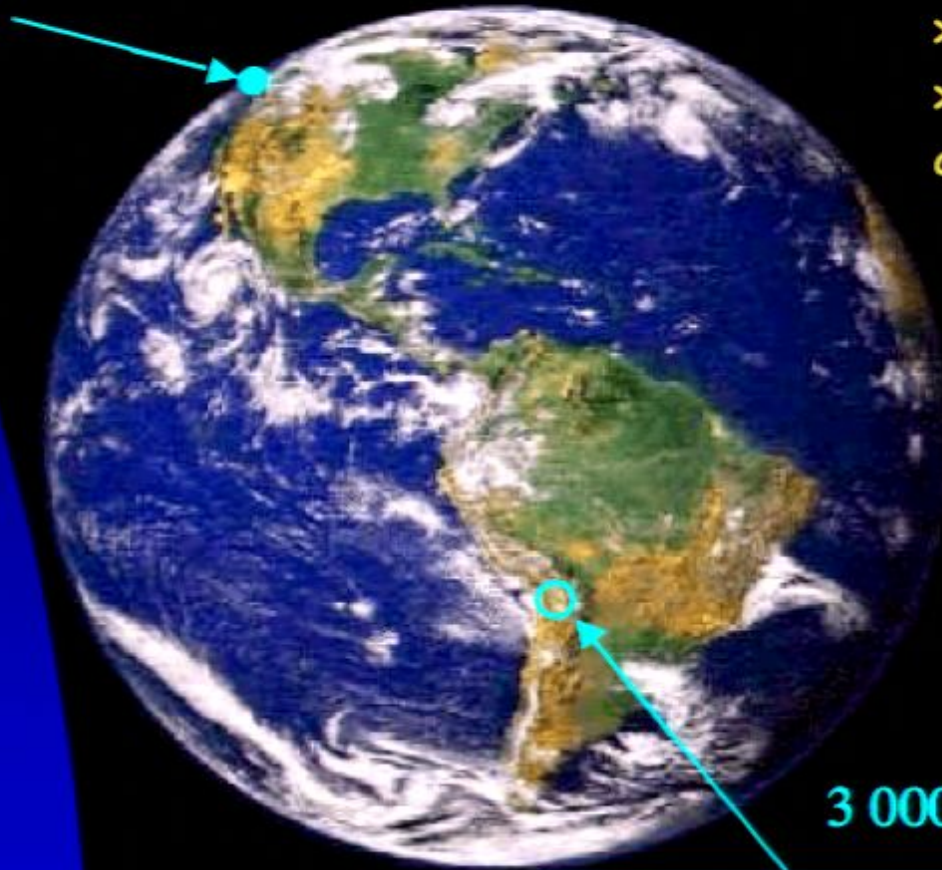
Maximize the Statistics in this window



The Pierre Auger Observatory

The Pierre Auger Observatory of Ultra-High Energy Cosmic Rays

Northern site
10 000 km²



> 300 PhD scientists from
> 70 Institutions
and 17 countries

Argentina

Australia

Brasil

Bolivia*

Czech Republic

France

Germany

Italy

Mexico

Netherlands

Poland

Portugal

Slovenia

Spain

UK

USA

Vietnam*

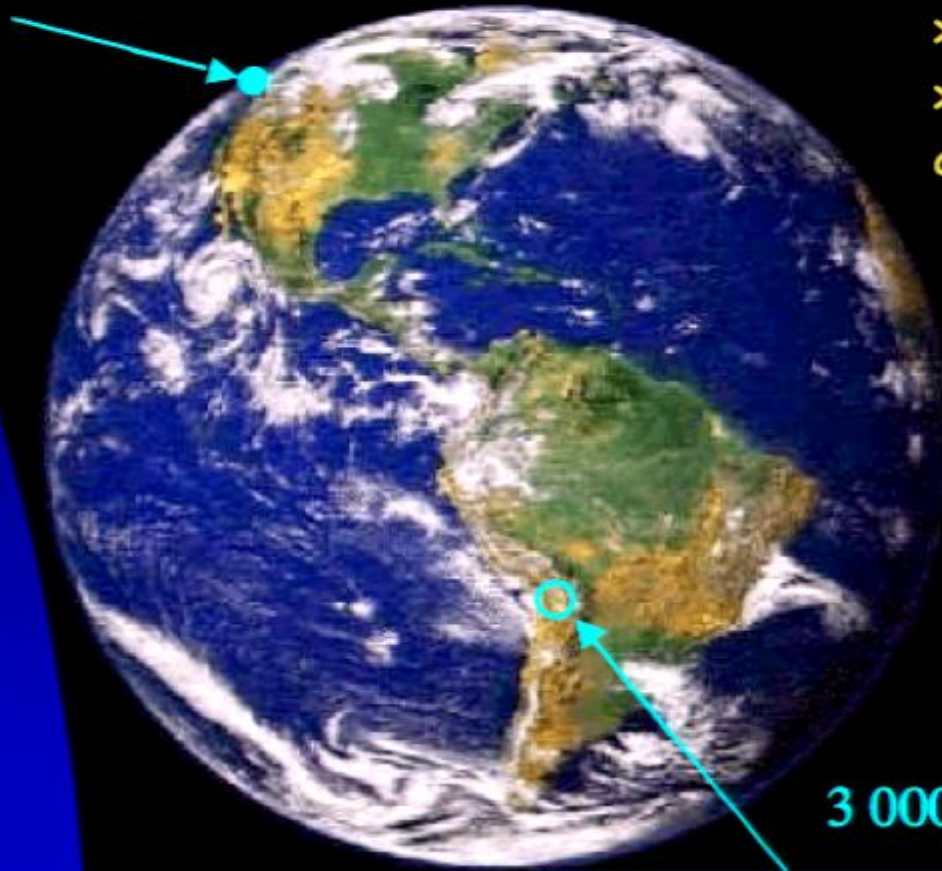
3 000 km²

Southern site

The Pierre Auger Observatory

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Northern site
10 000 km²



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Slovenia
Spain
UK
USA
Vietnam*

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Southern site

Pierre Auger Colaboration Meeting

Malargüe, Argentina

March 15-19, 2006

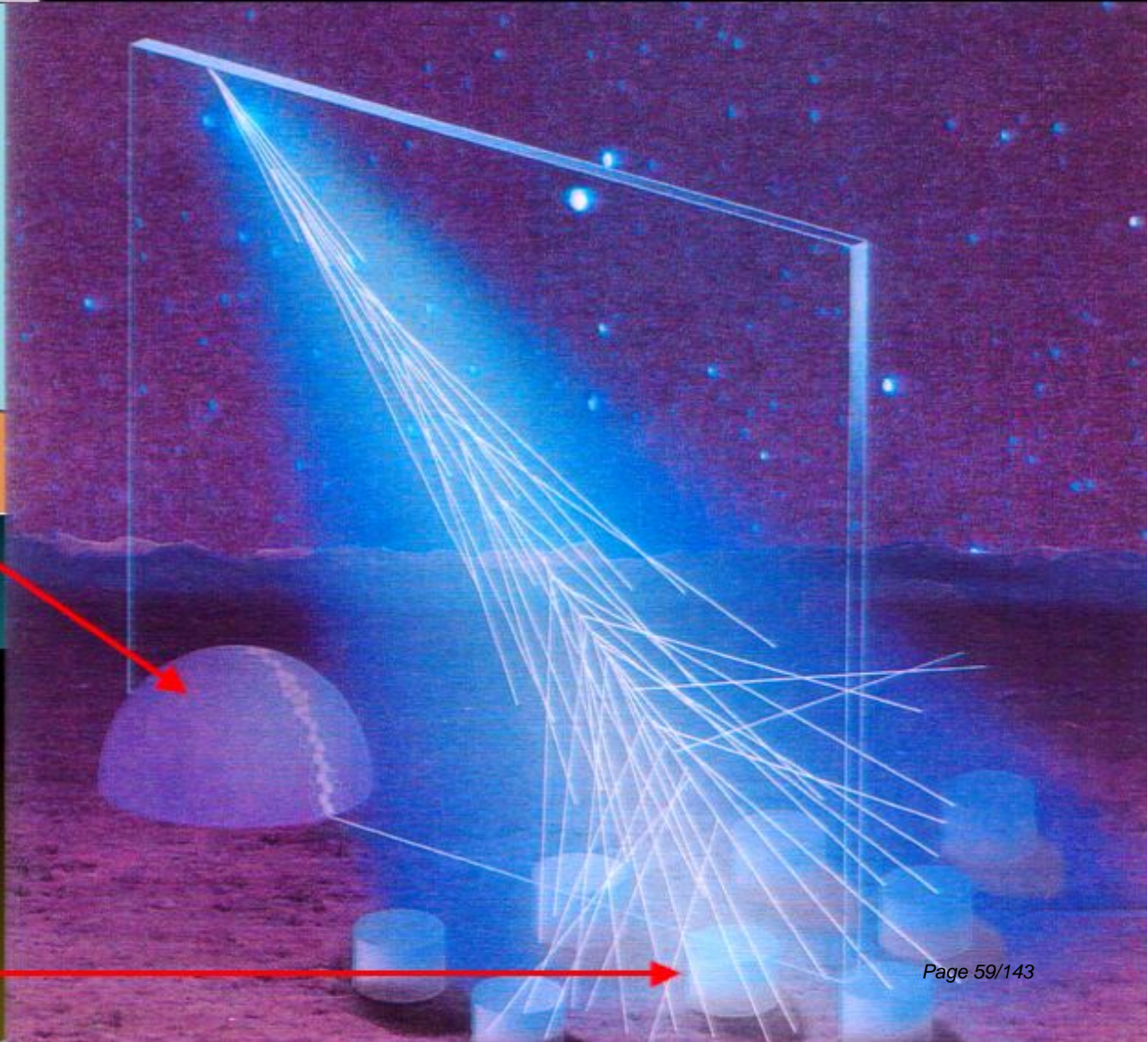
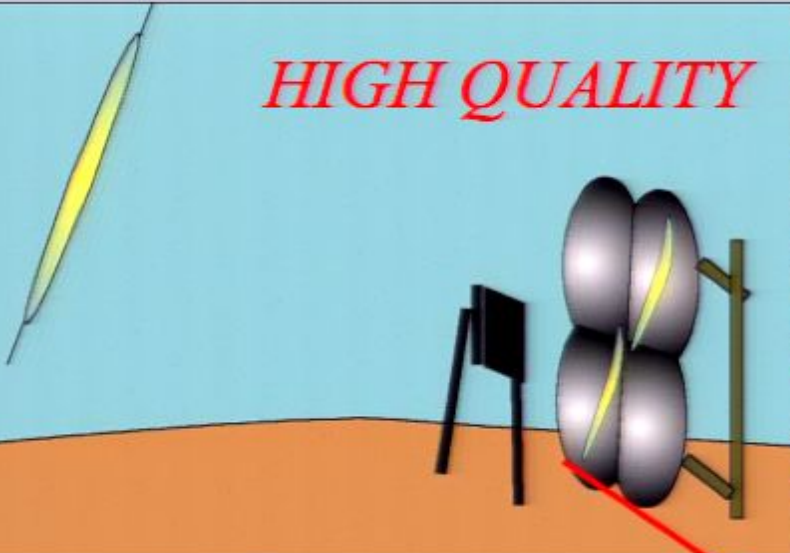


PIERRE
AUGER
OBSERVATORY



The First Hybrid UHECR Observatory

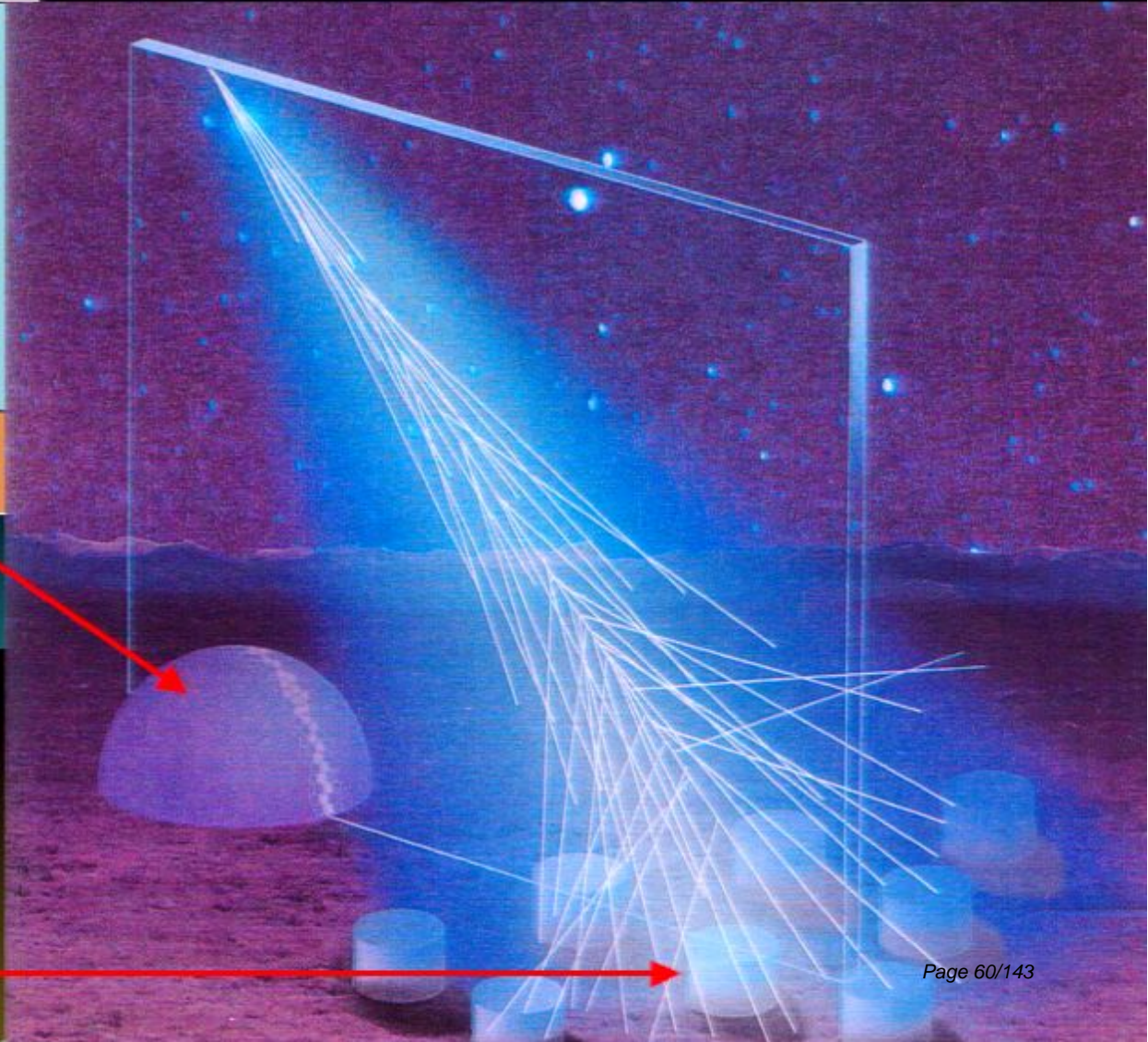
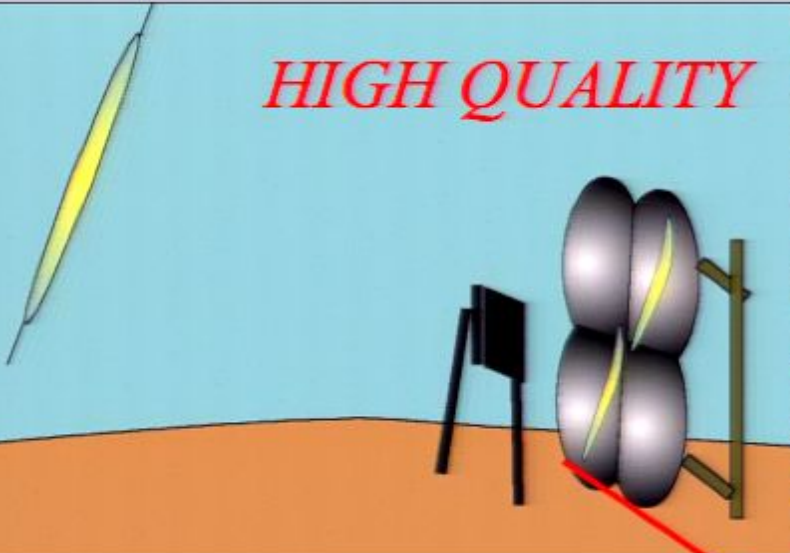
HIGH QUALITY



LARGE QUANTITY

The First Hybrid UHECR Observatory

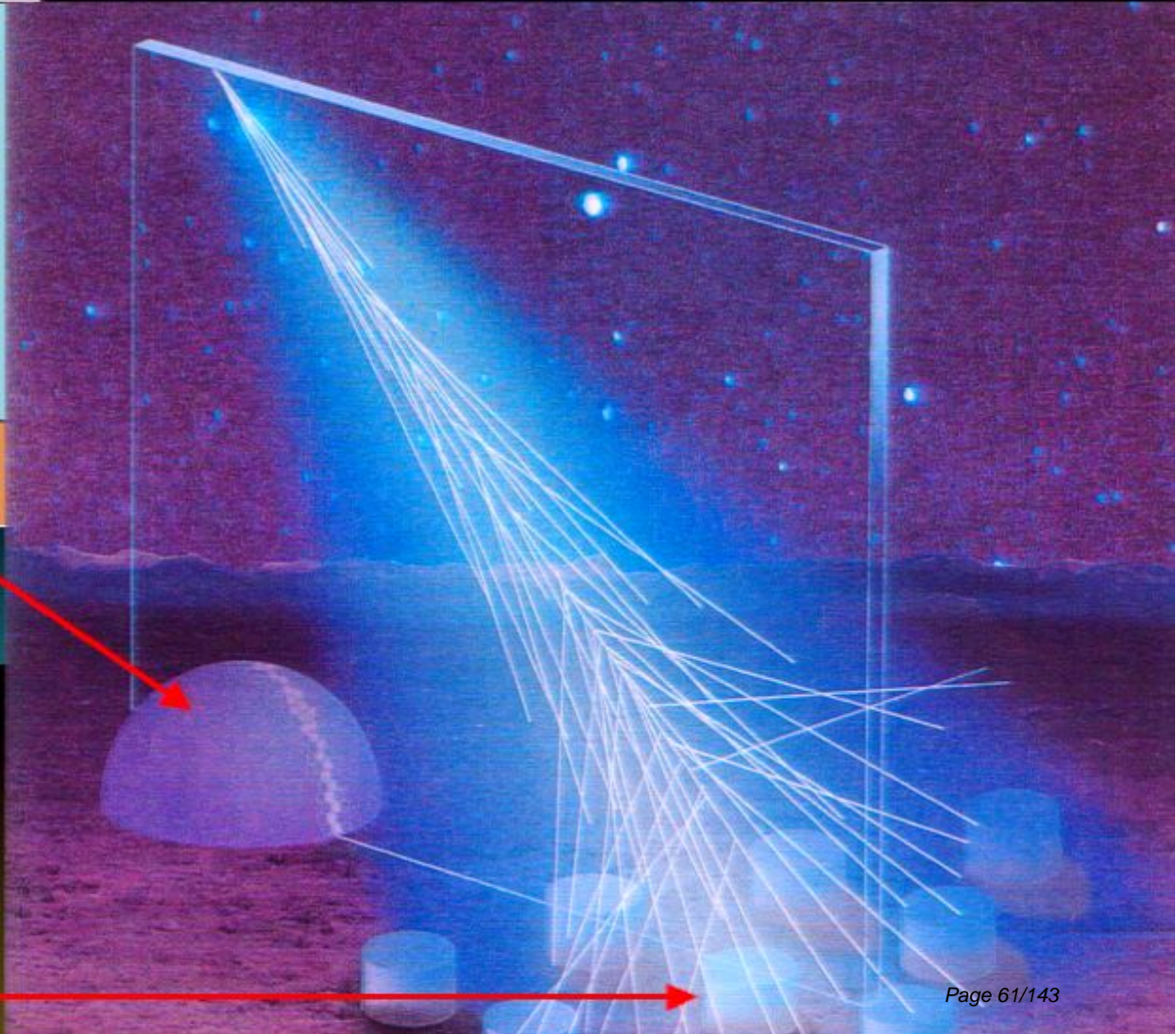
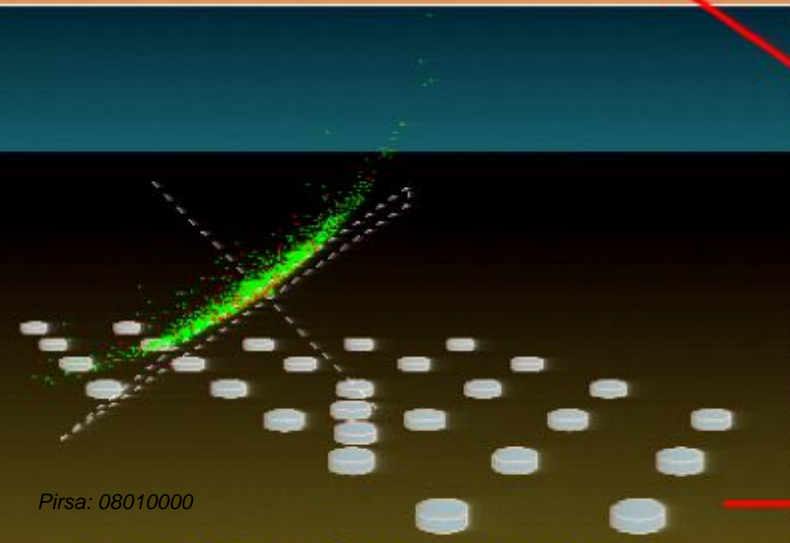
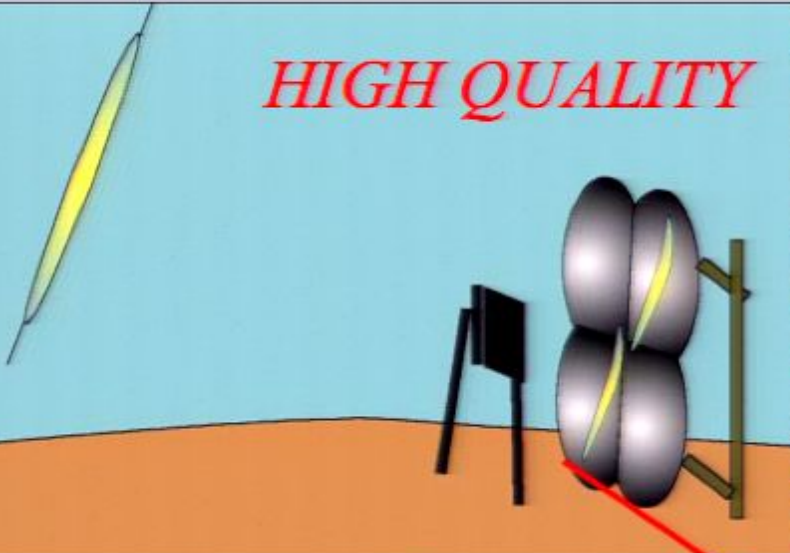
HIGH QUALITY



LARGE QUANTITY

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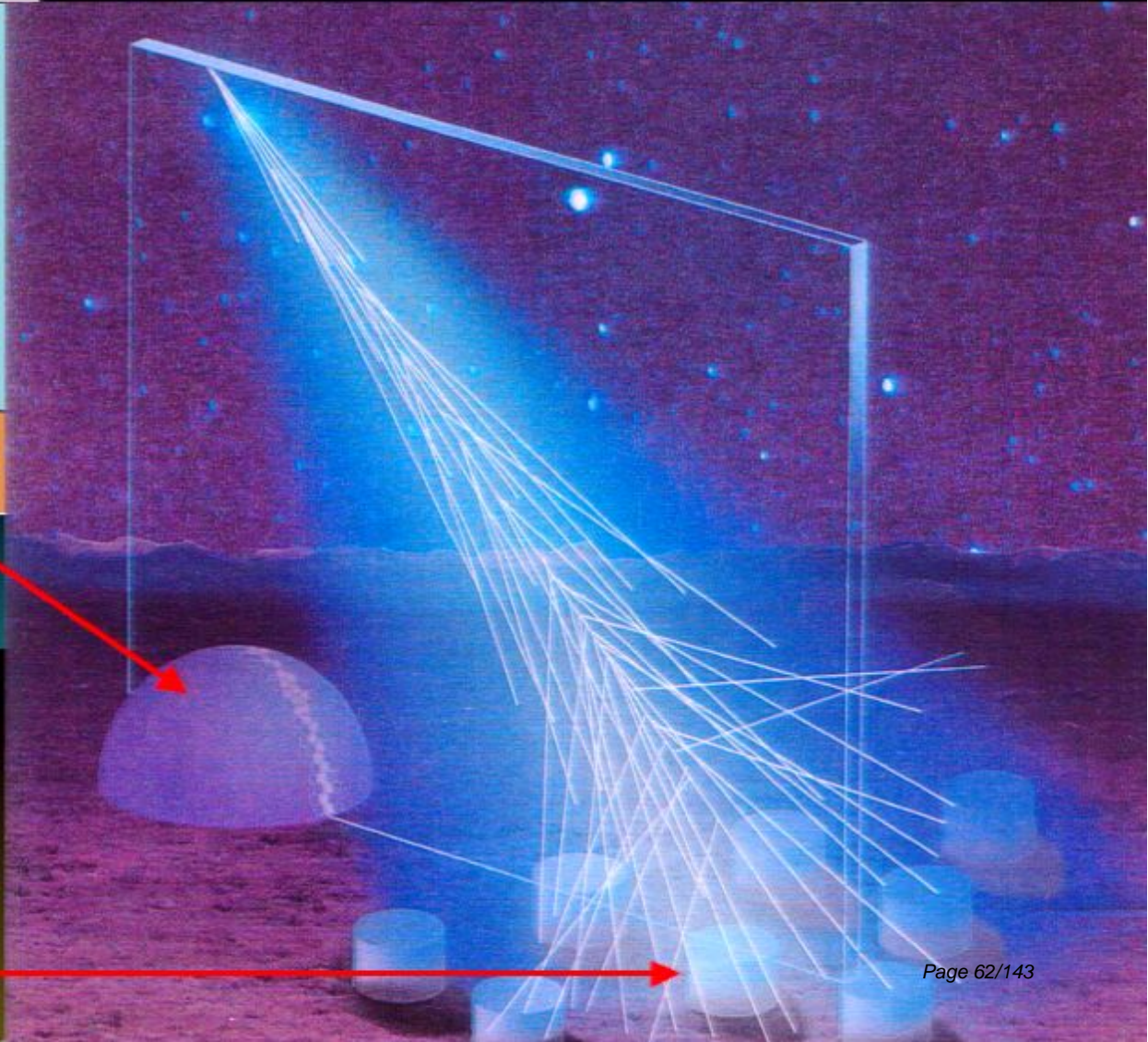
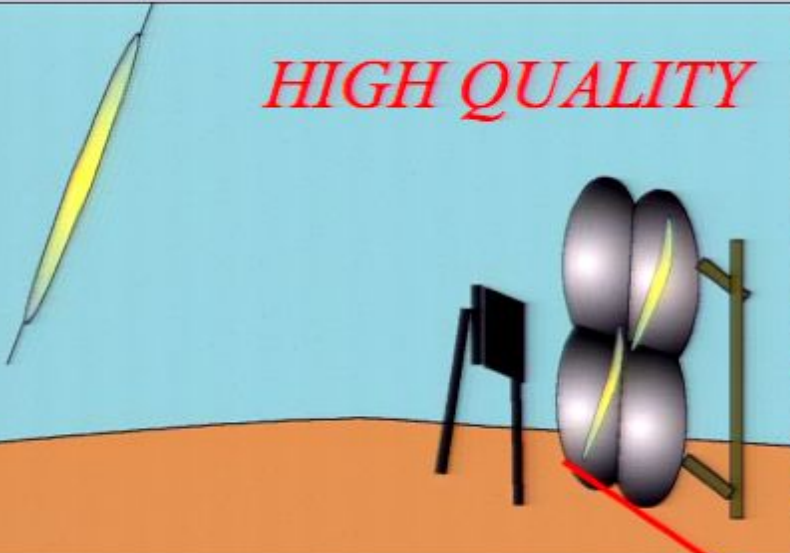
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LARGE QUANTITY

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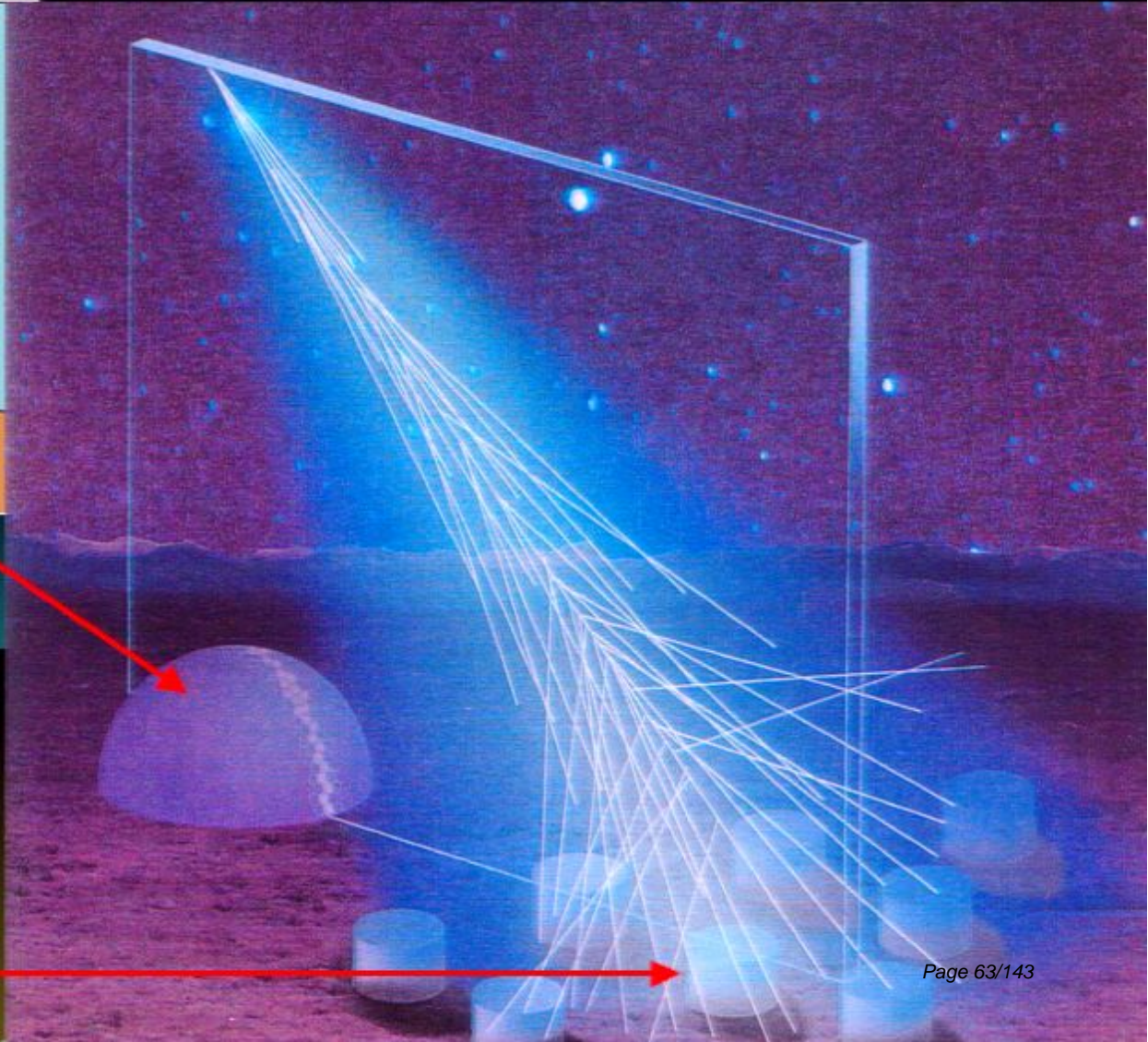
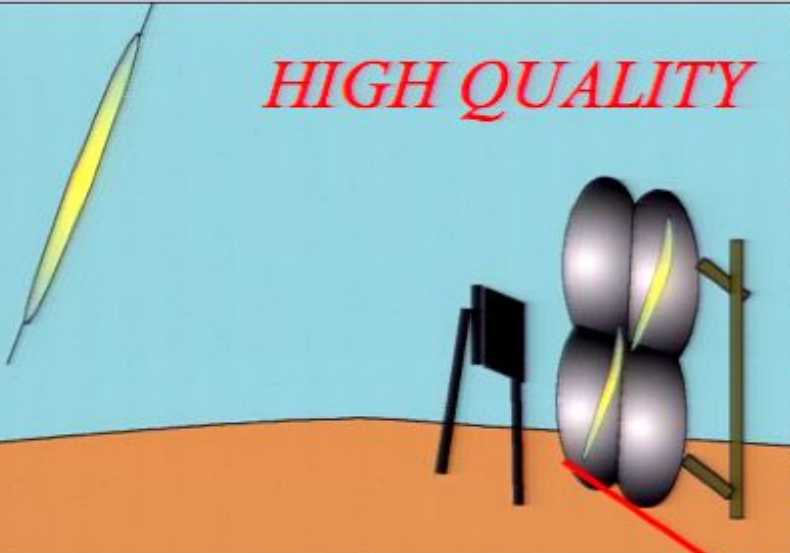
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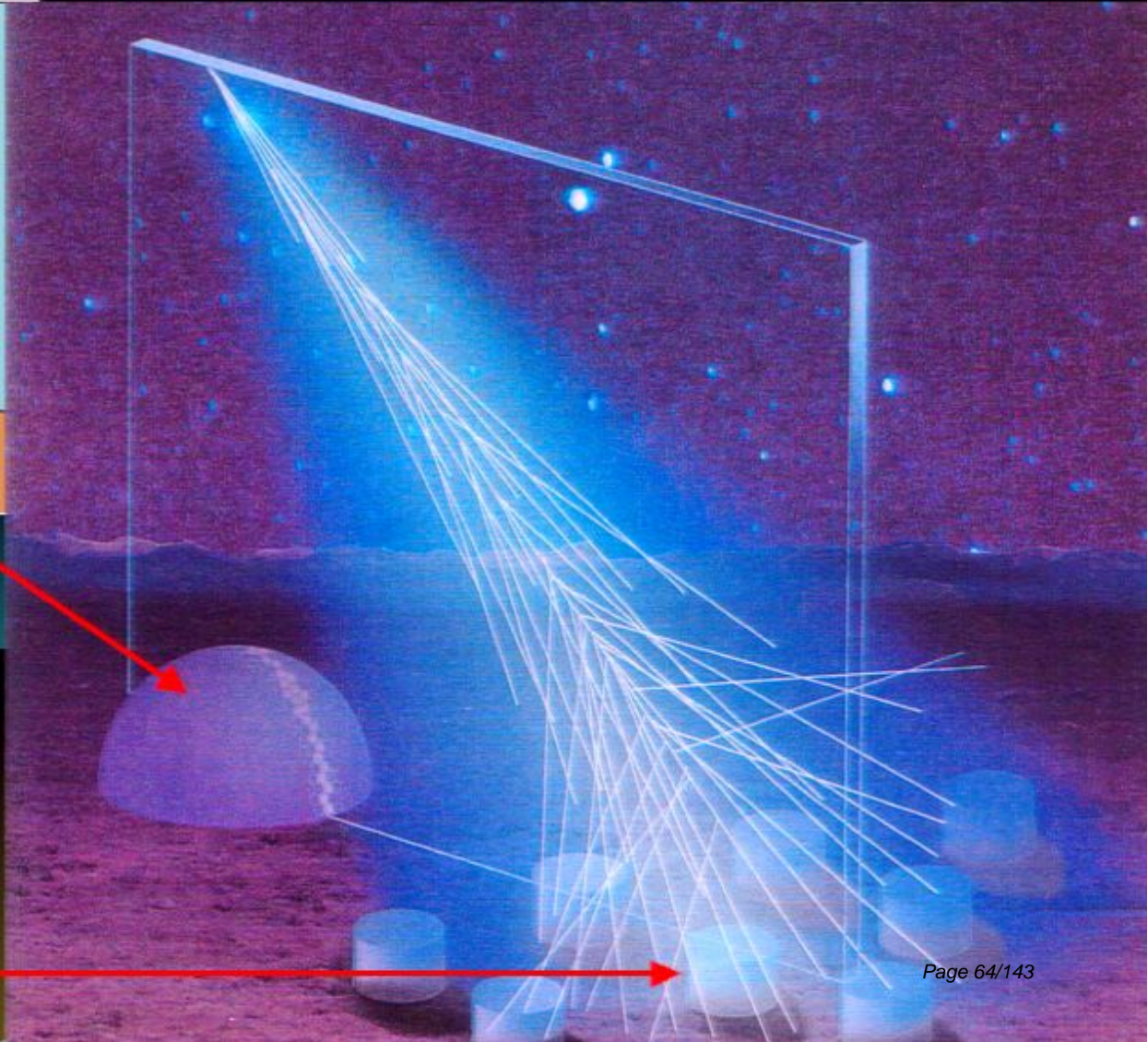
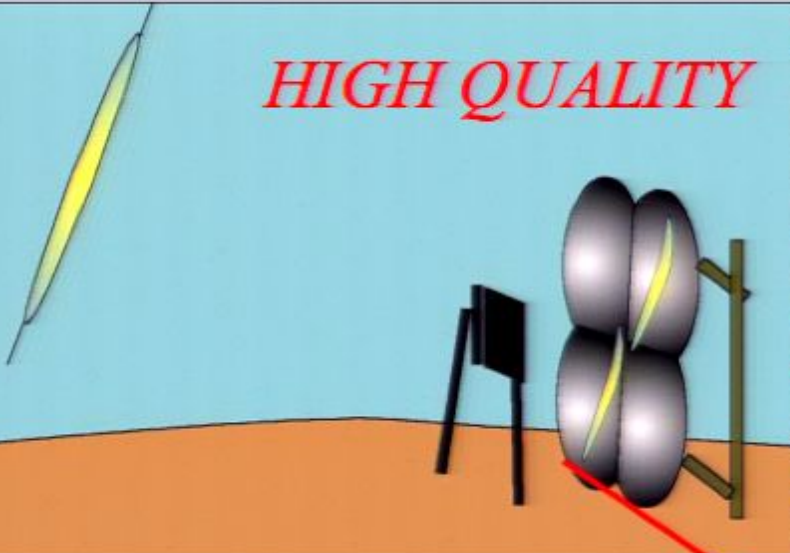
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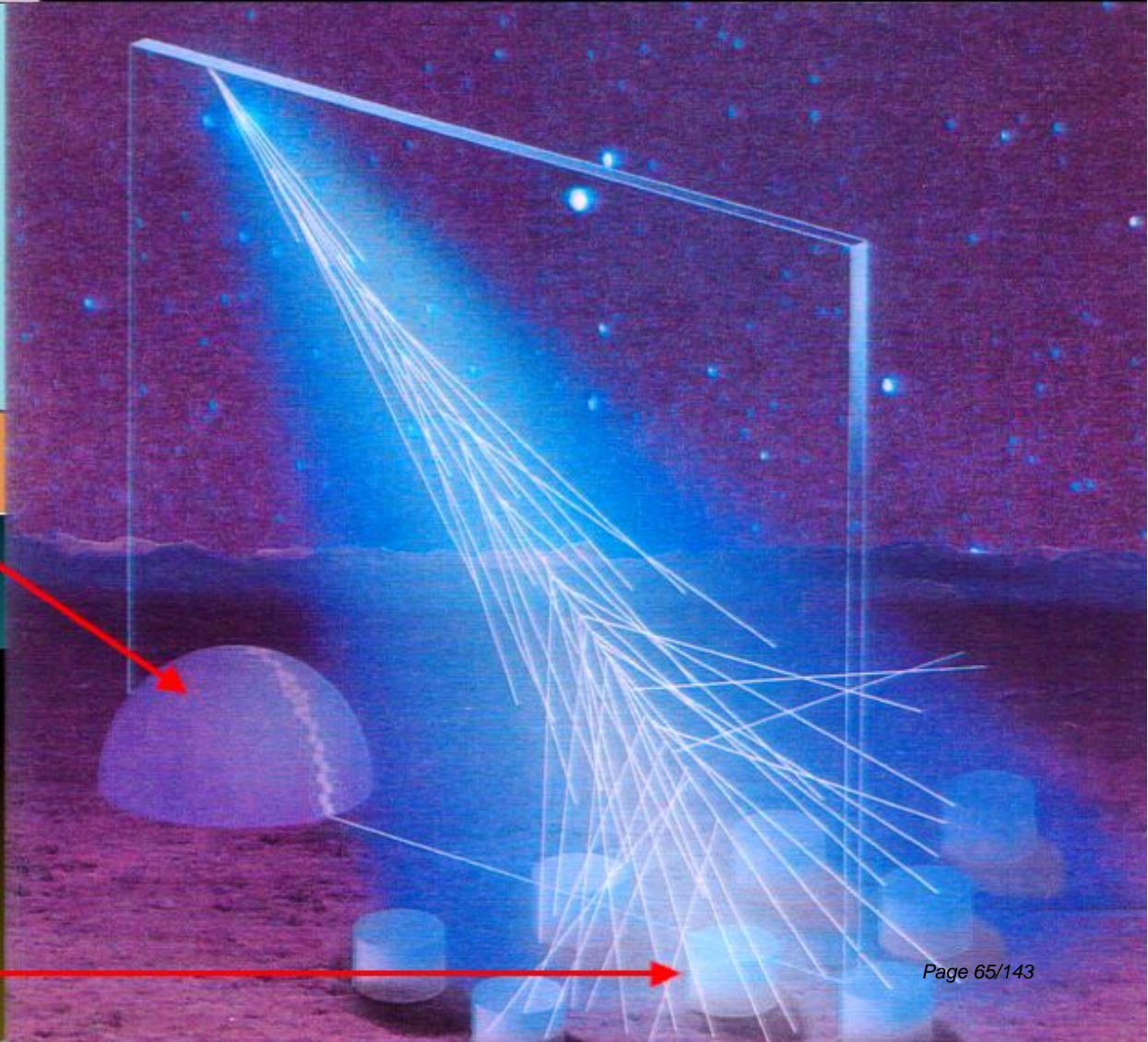
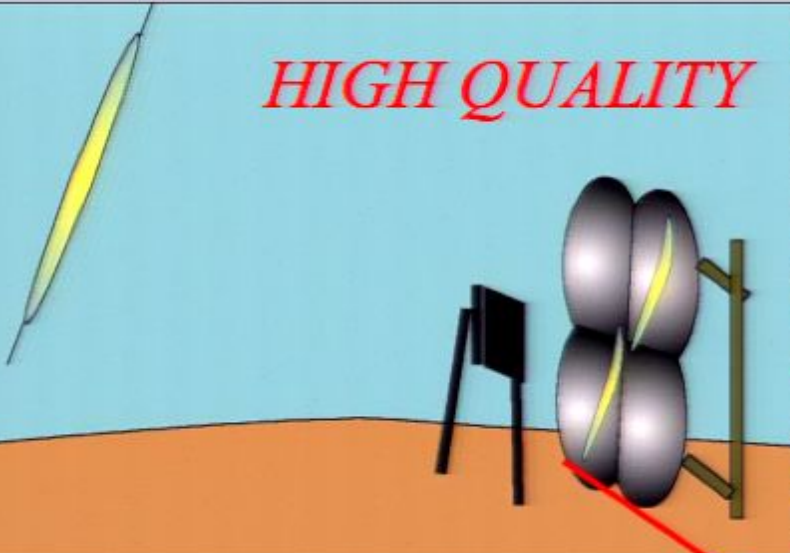
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LARGE QUANTITY

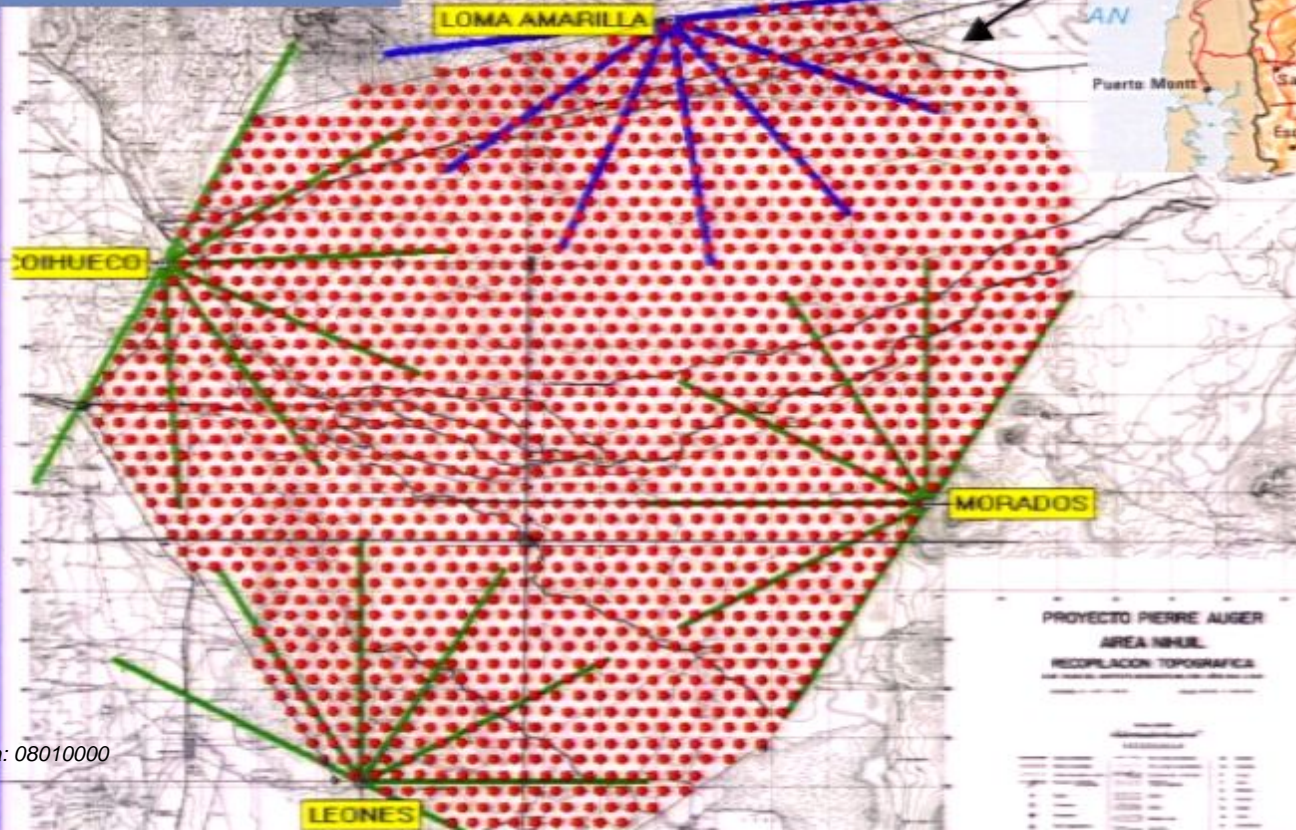
The First Hybrid UHECR Observatory

HIGH QUALITY



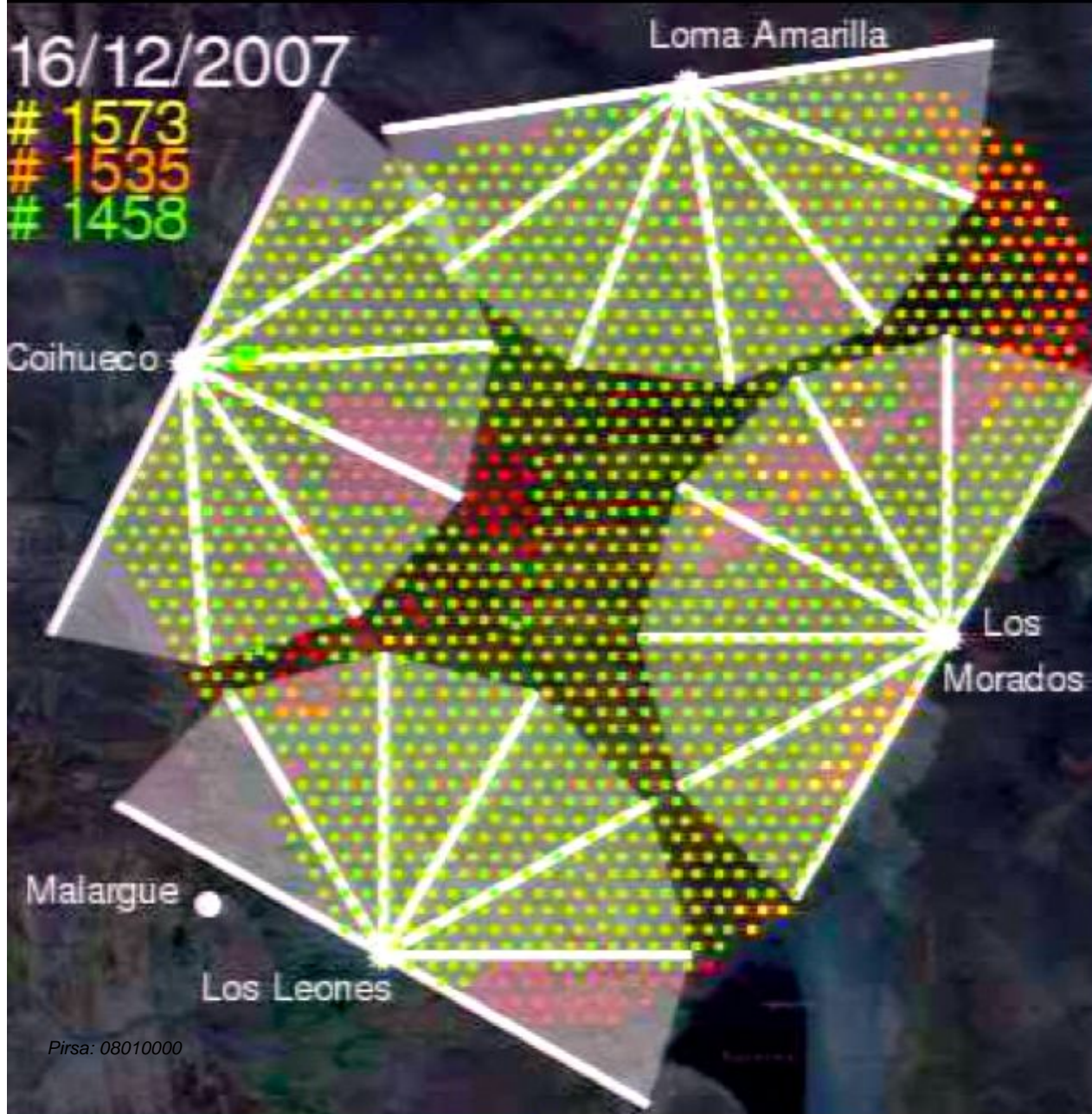
LARGE QUANTITY

Auger South



*1600 tanks in a
3,000 km²
Surface Array
4 Fluorescence
Detector Sites*

The Surface Detector Array



The Surface Detector Array



1573 deployed
1535 filled
1458 taking data
of the
1600 tanks, 3,000km²

1600 surface detectors



tanks aligned seen from Los Leones



Auger SD station Cherenkov water tank



tanks aligned seen from Los Leones

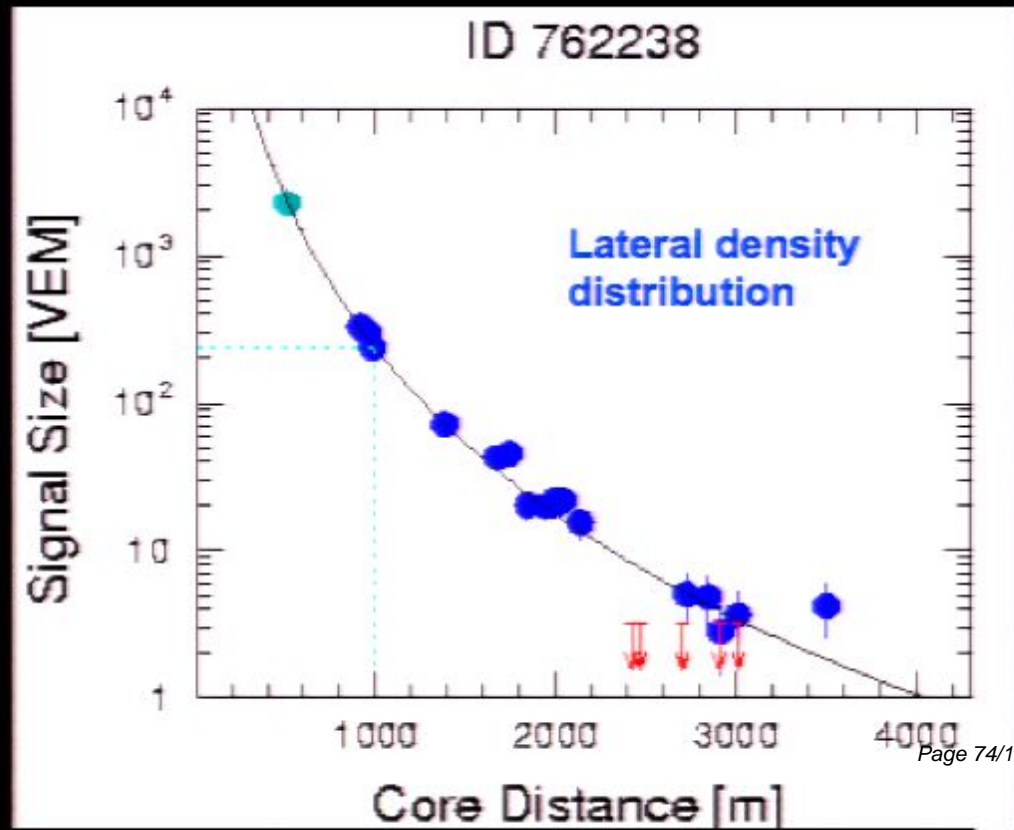
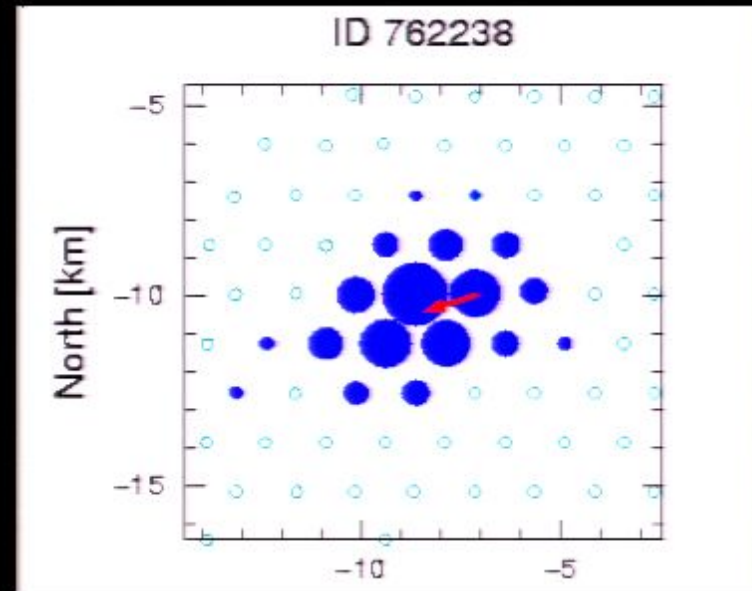
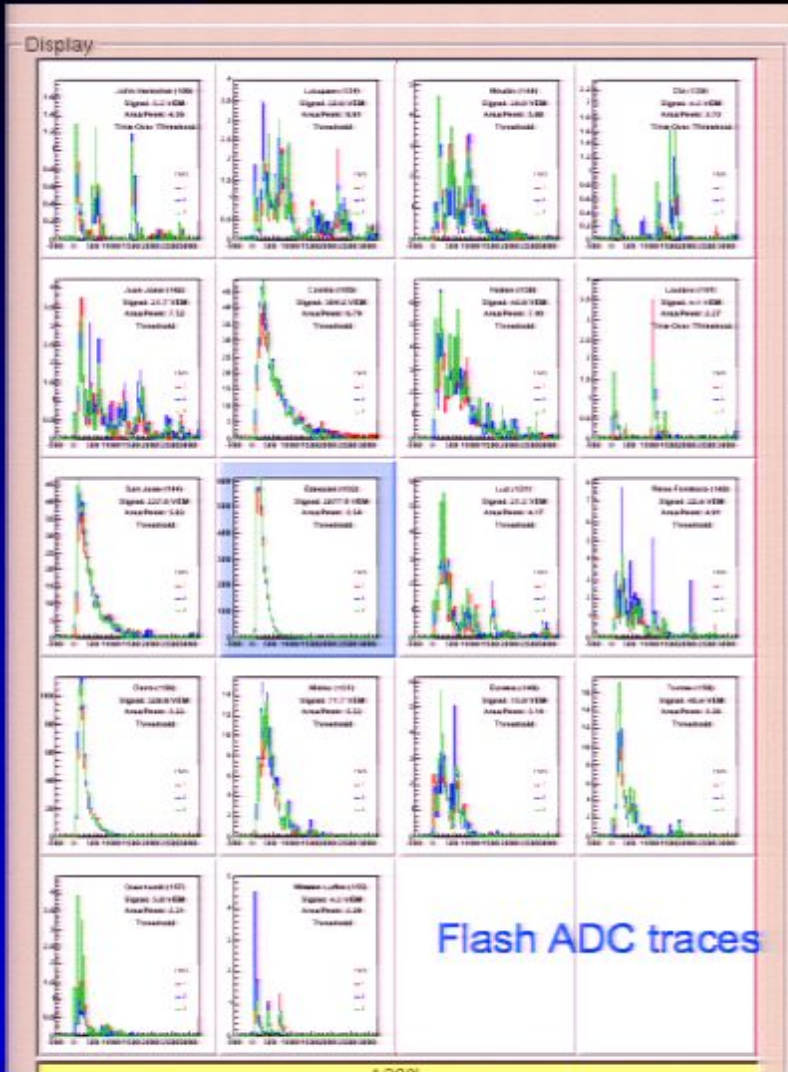


Auger SD station Cherenkov water tank



Example Event 1

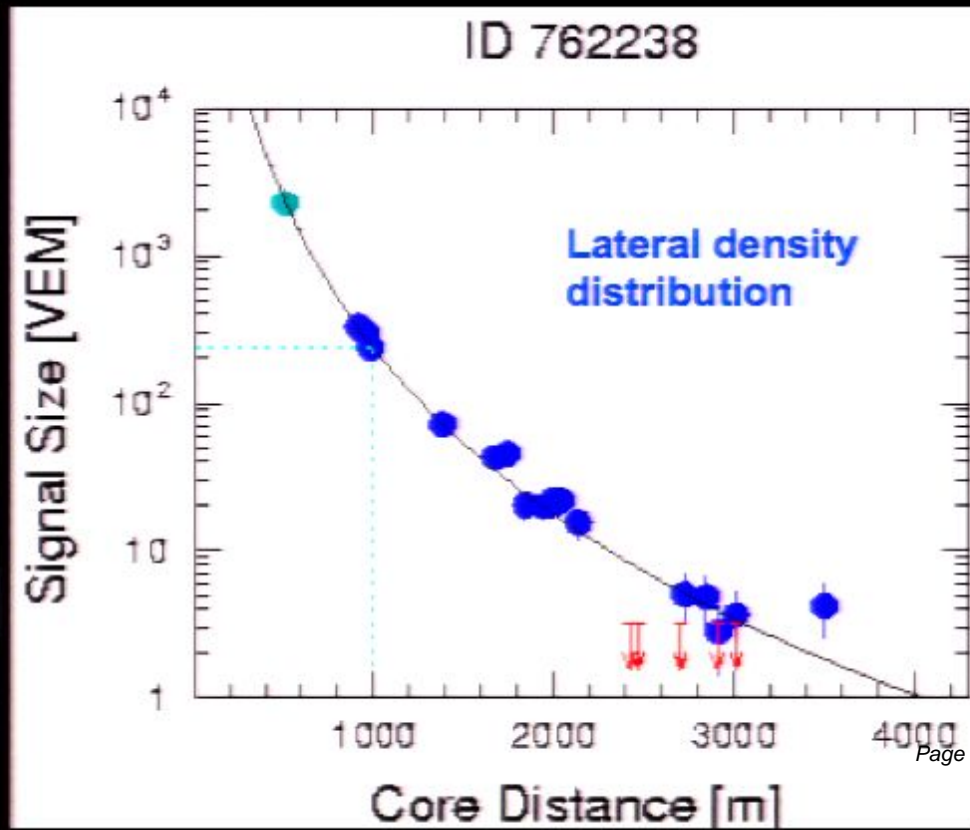
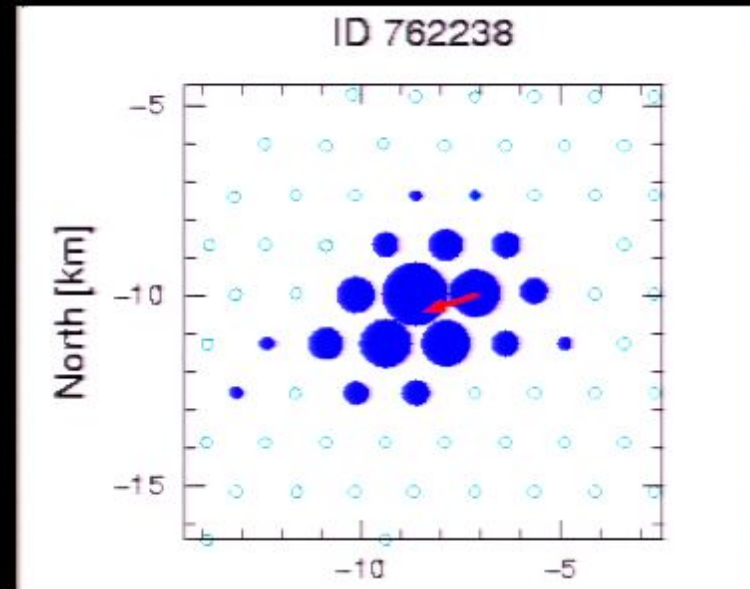
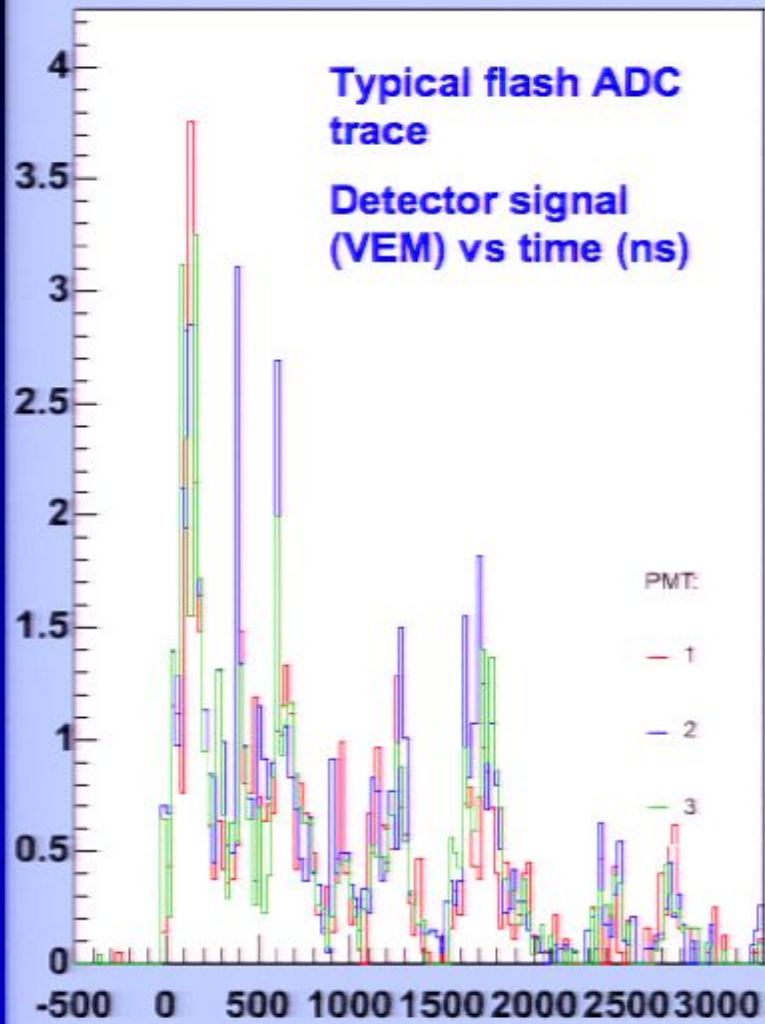
A moderate angle event 762238
Zenith angle $\sim 48^\circ$, Energy ~ 70 EeV



Example Event 1

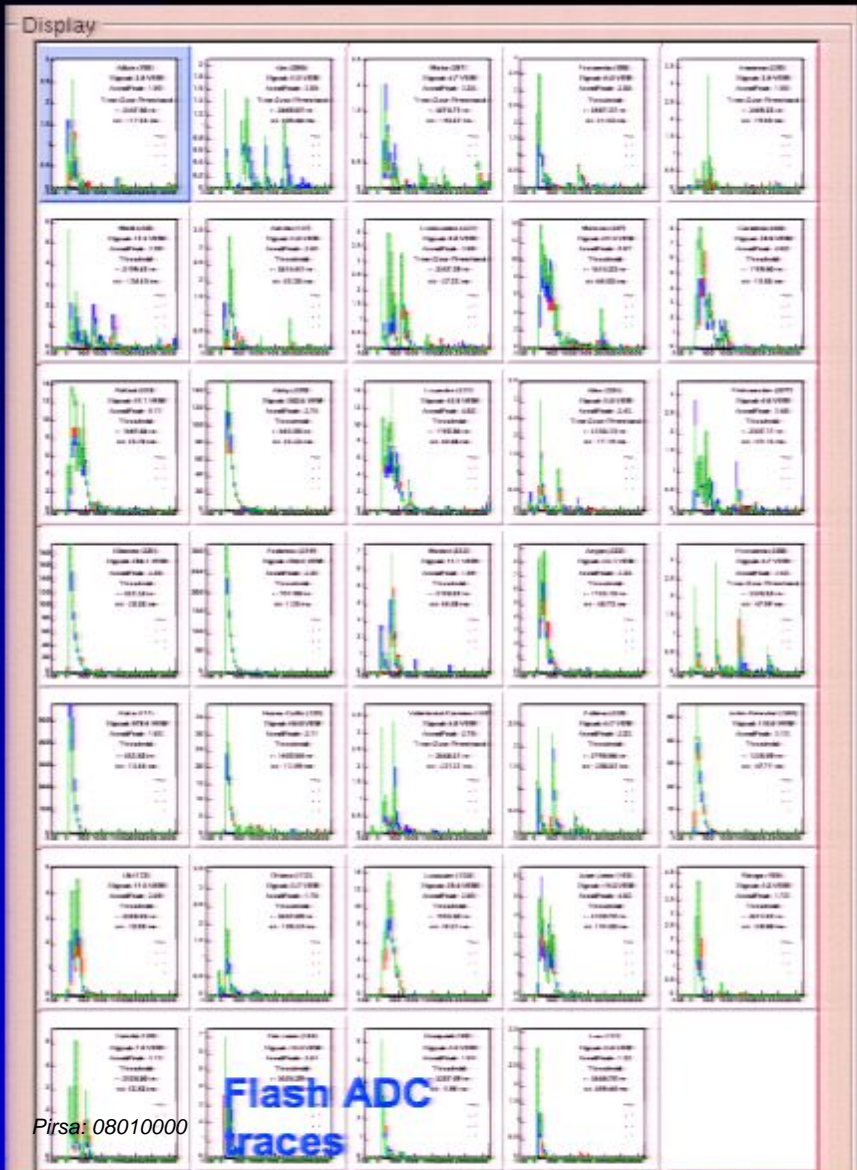
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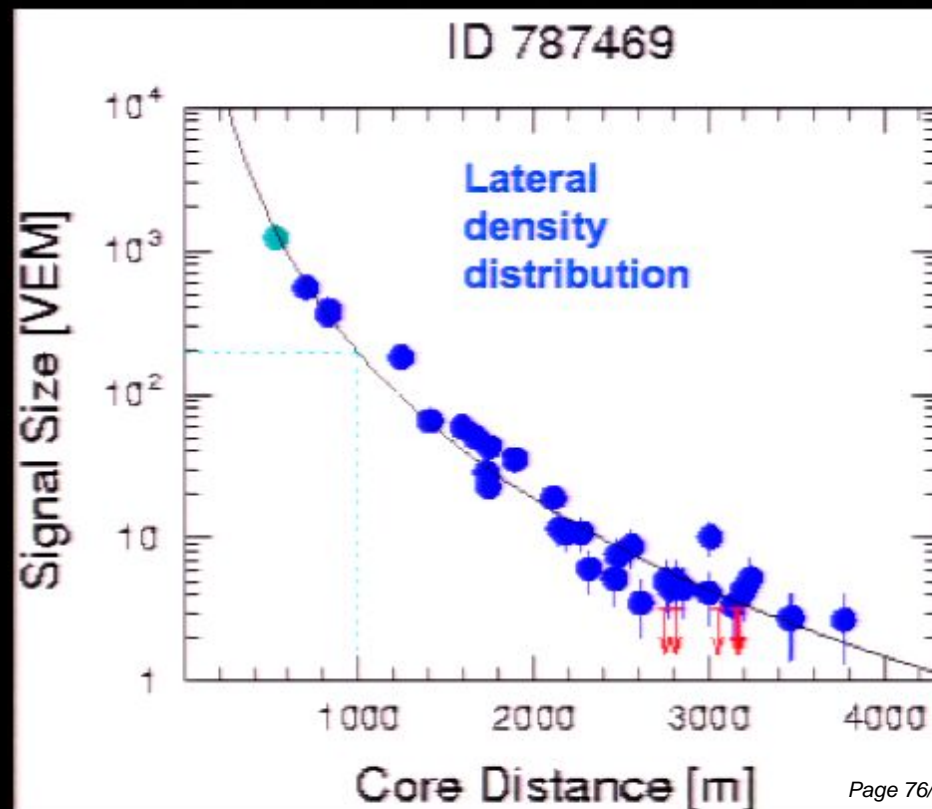
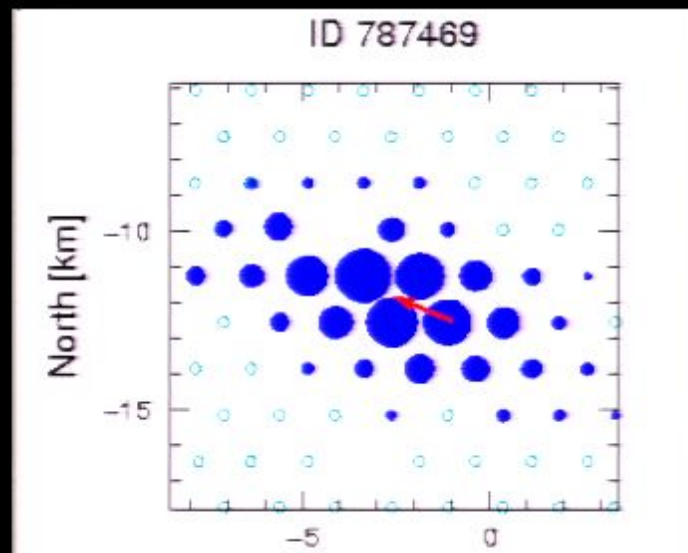


Example Event 2

A high zenith angle event - 787469
Zenith angle $\sim 60^\circ$, Energy ~ 86 EeV



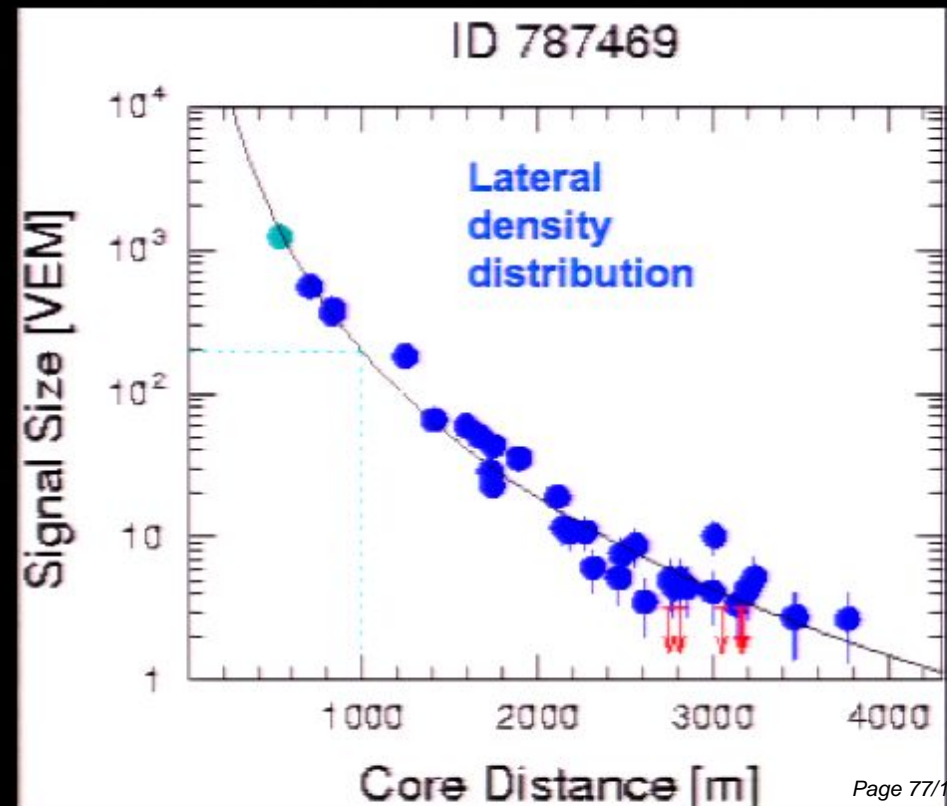
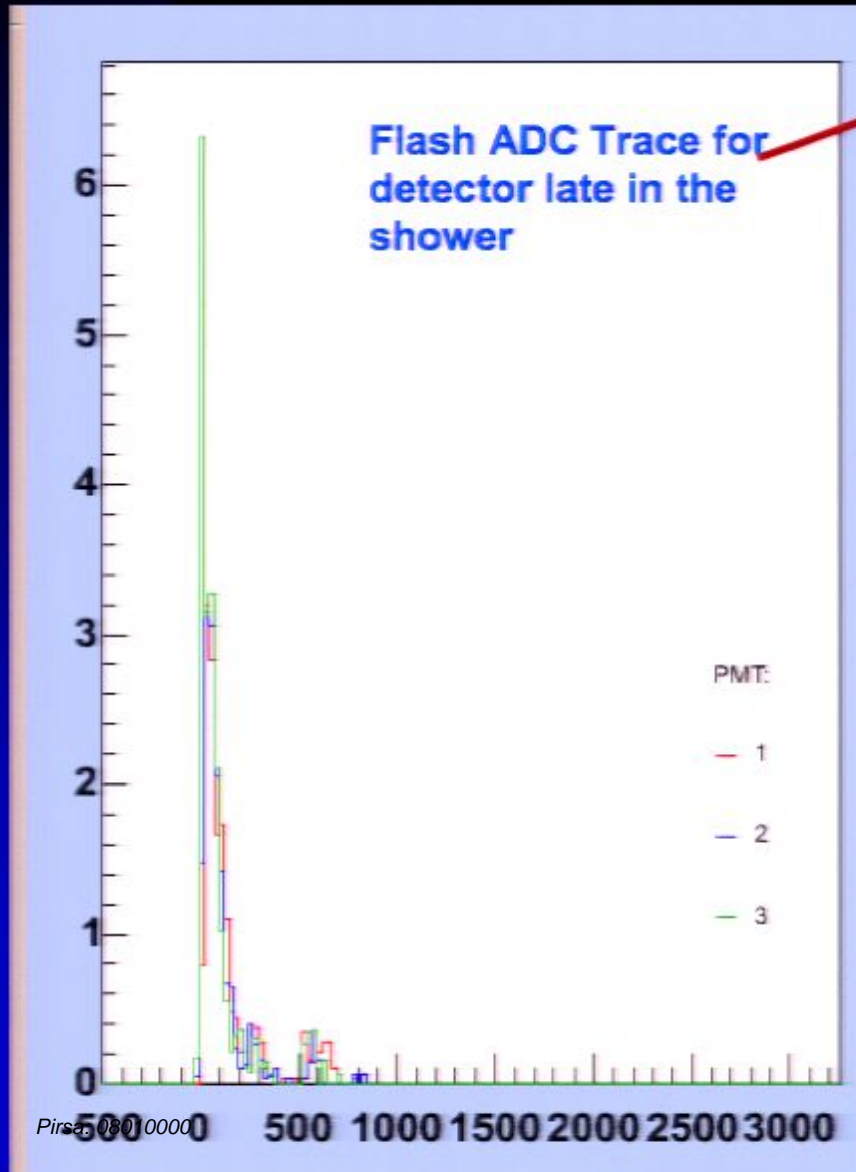
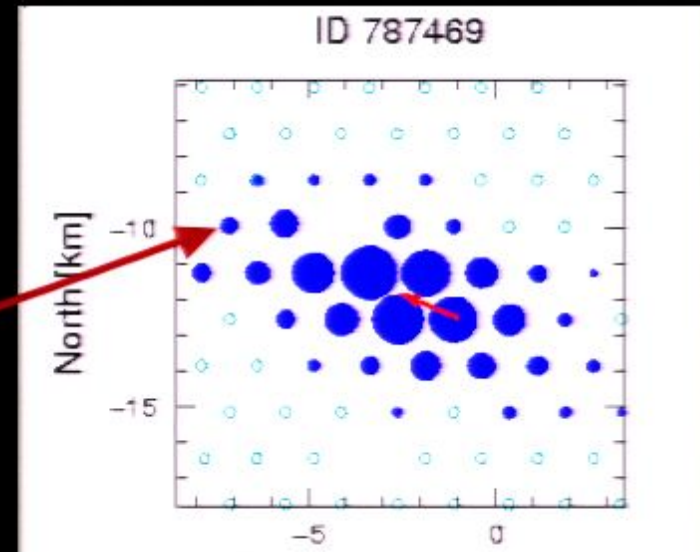
Pirsa: 08010000



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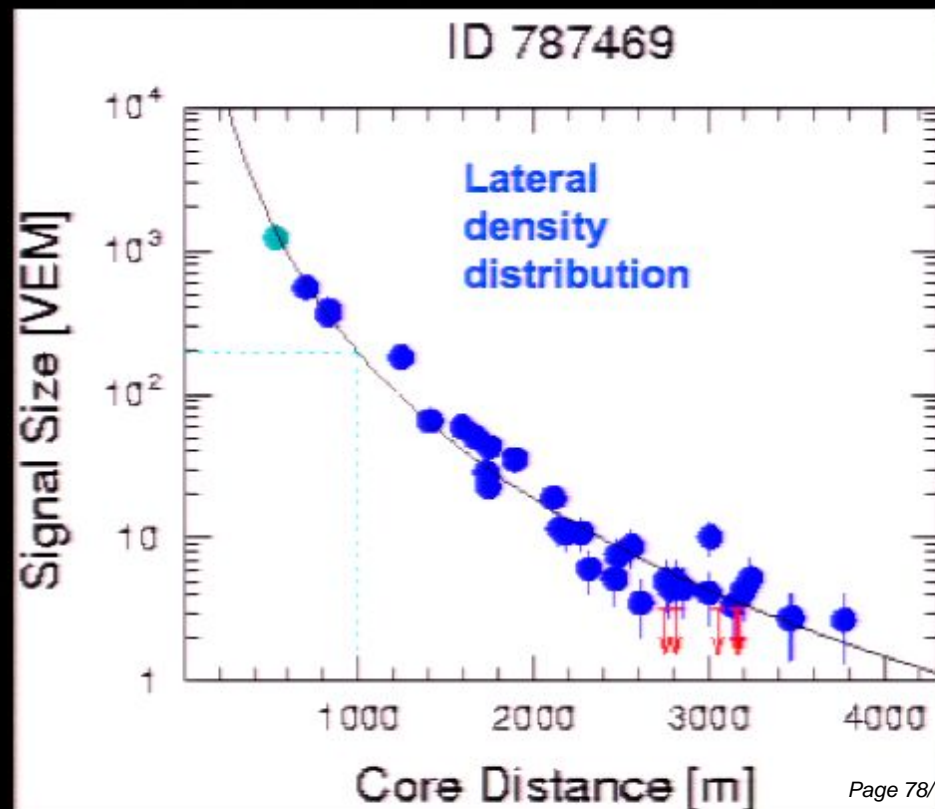
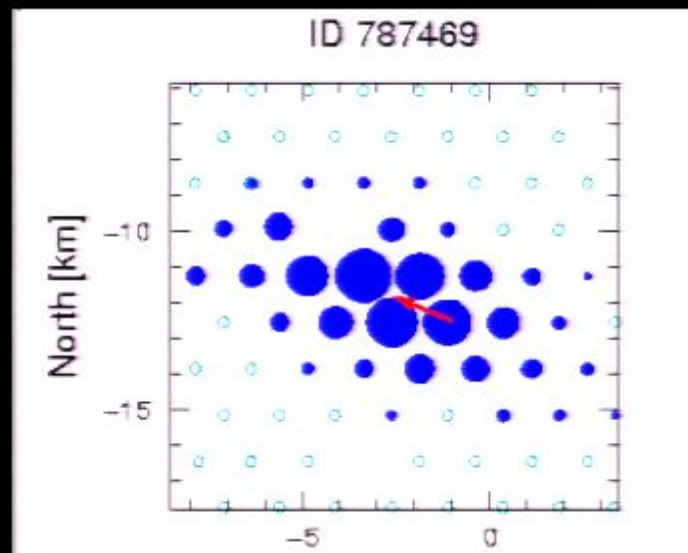
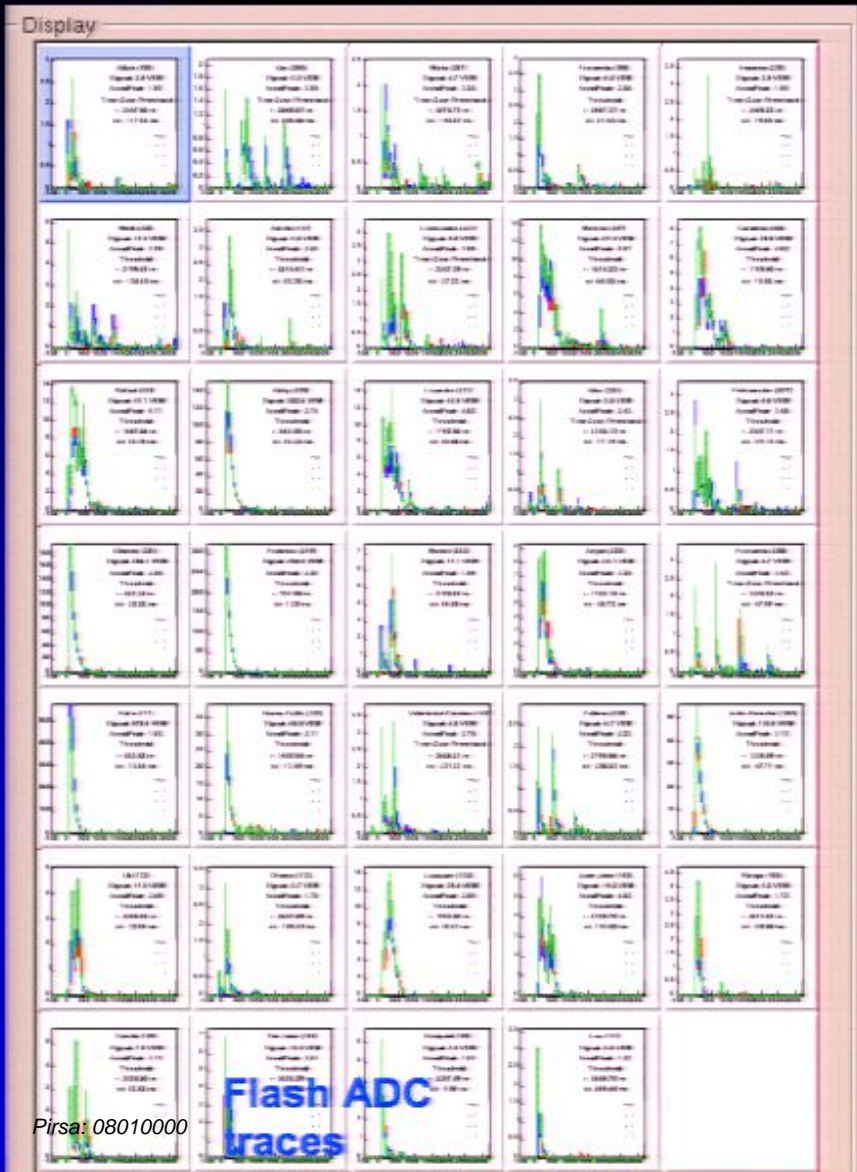
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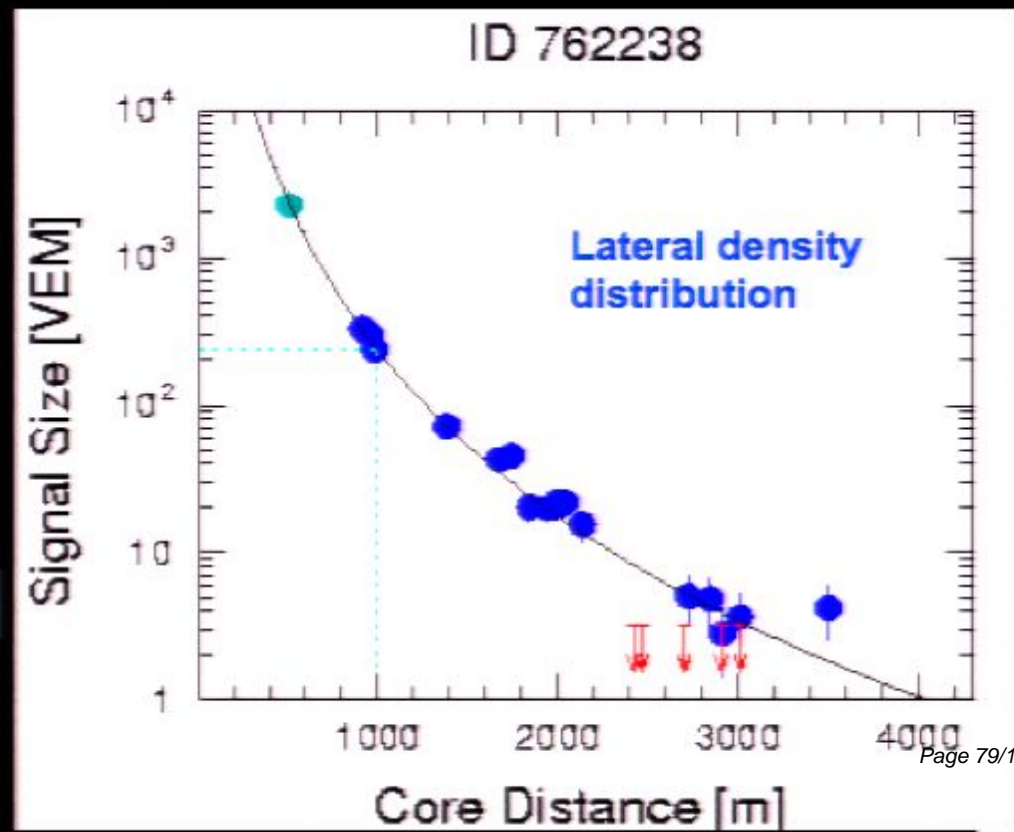
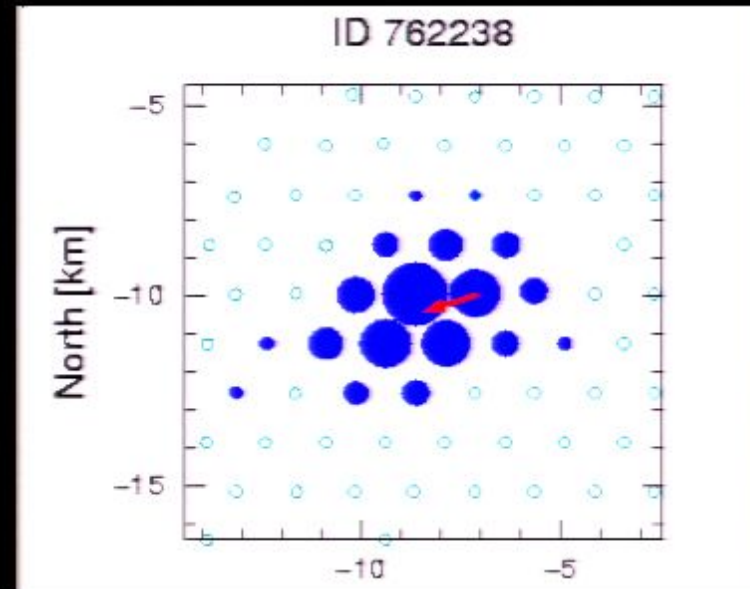
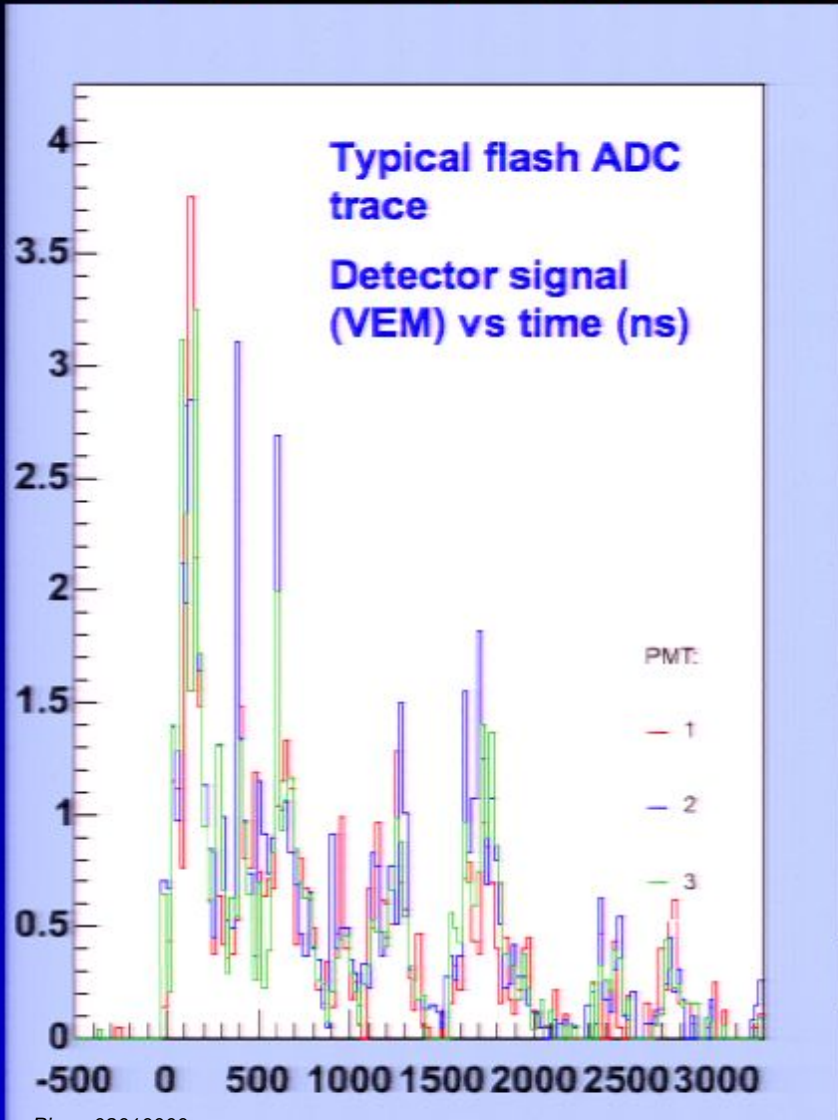
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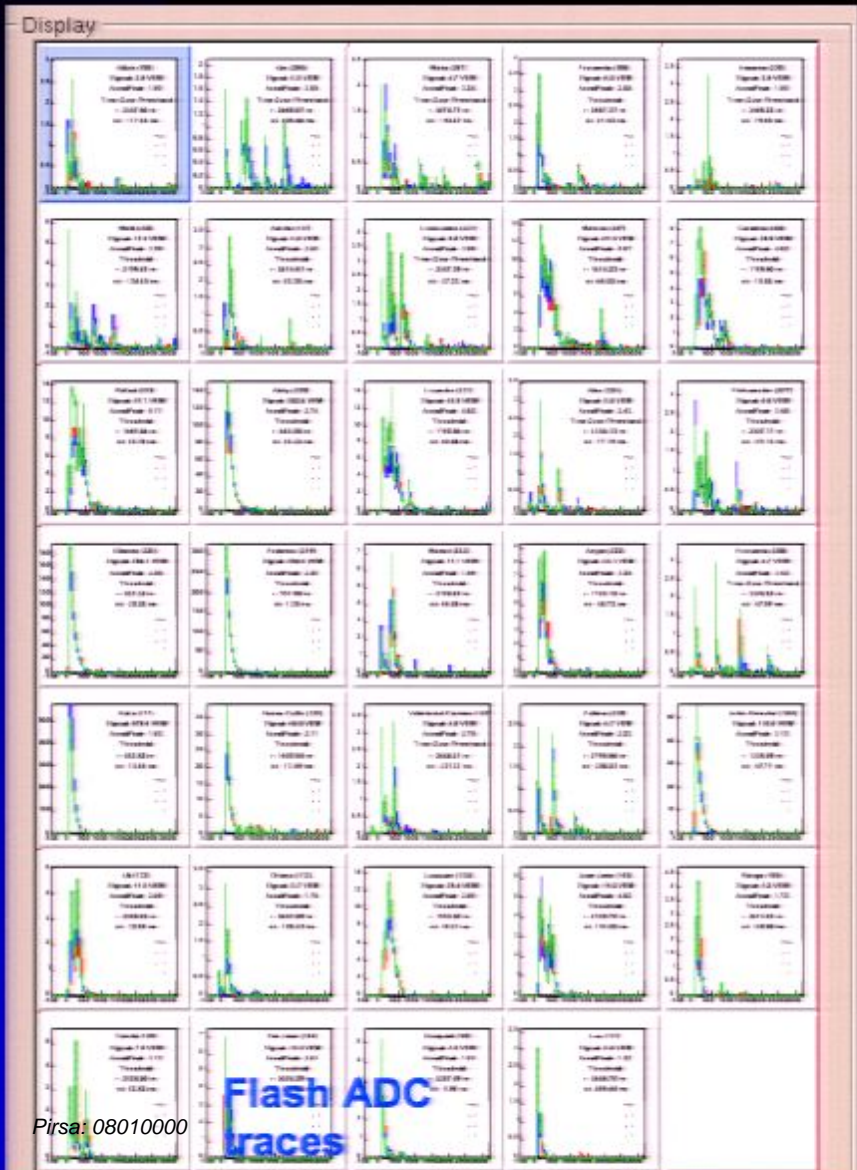
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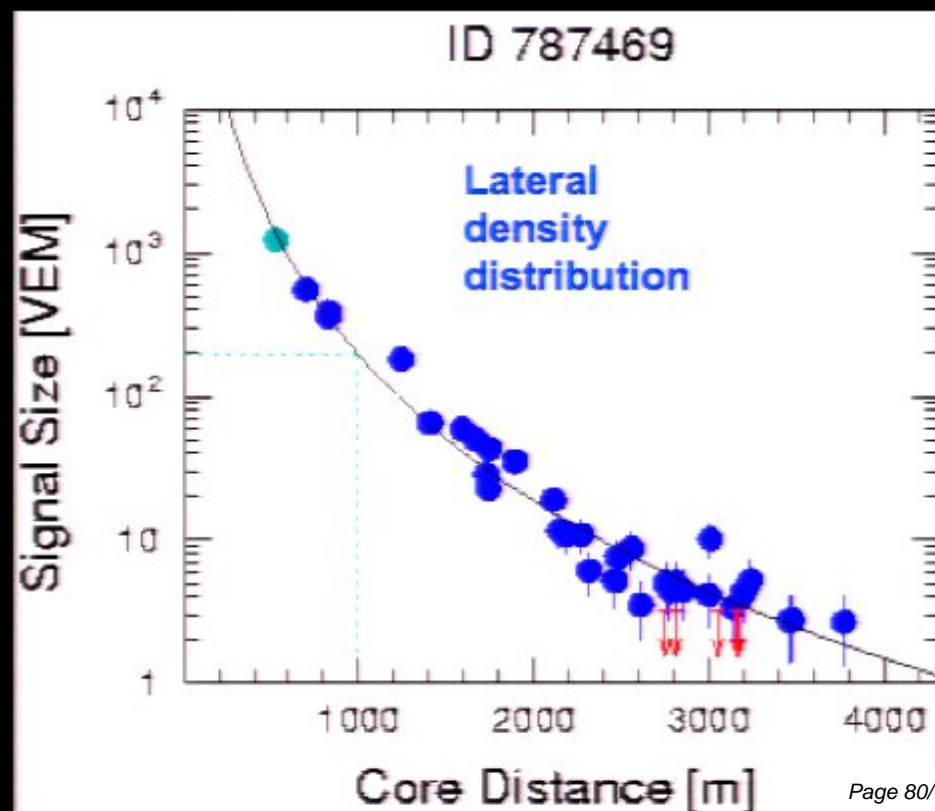
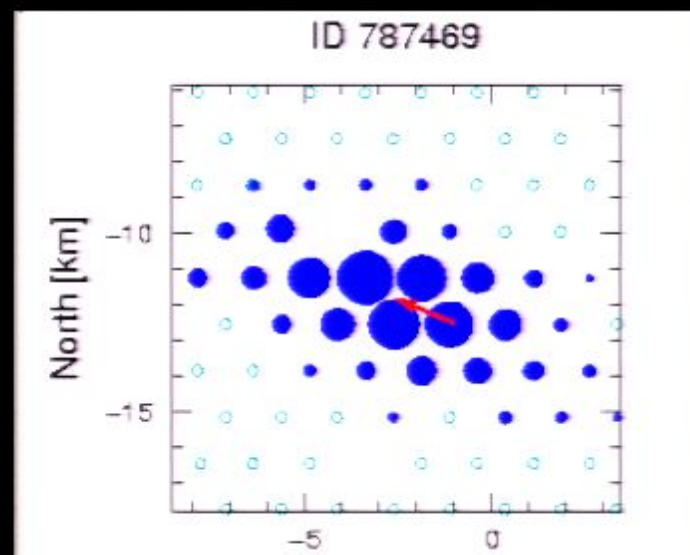


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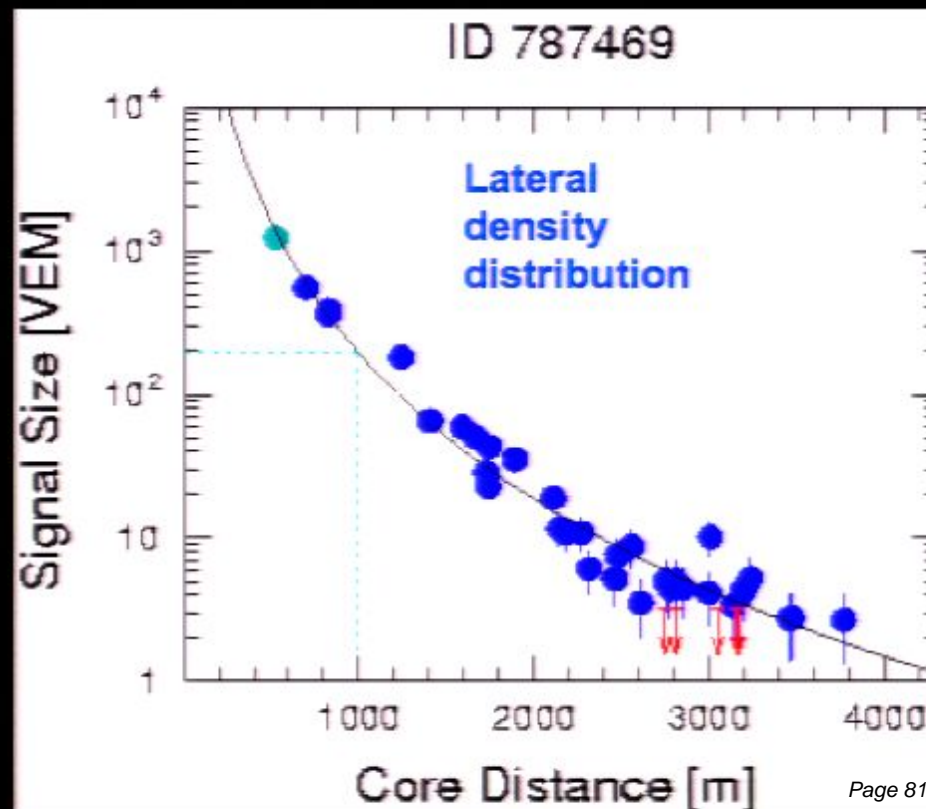
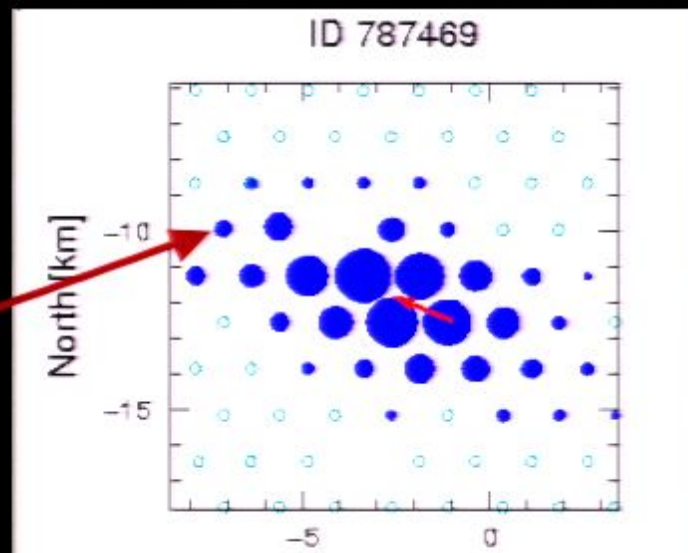
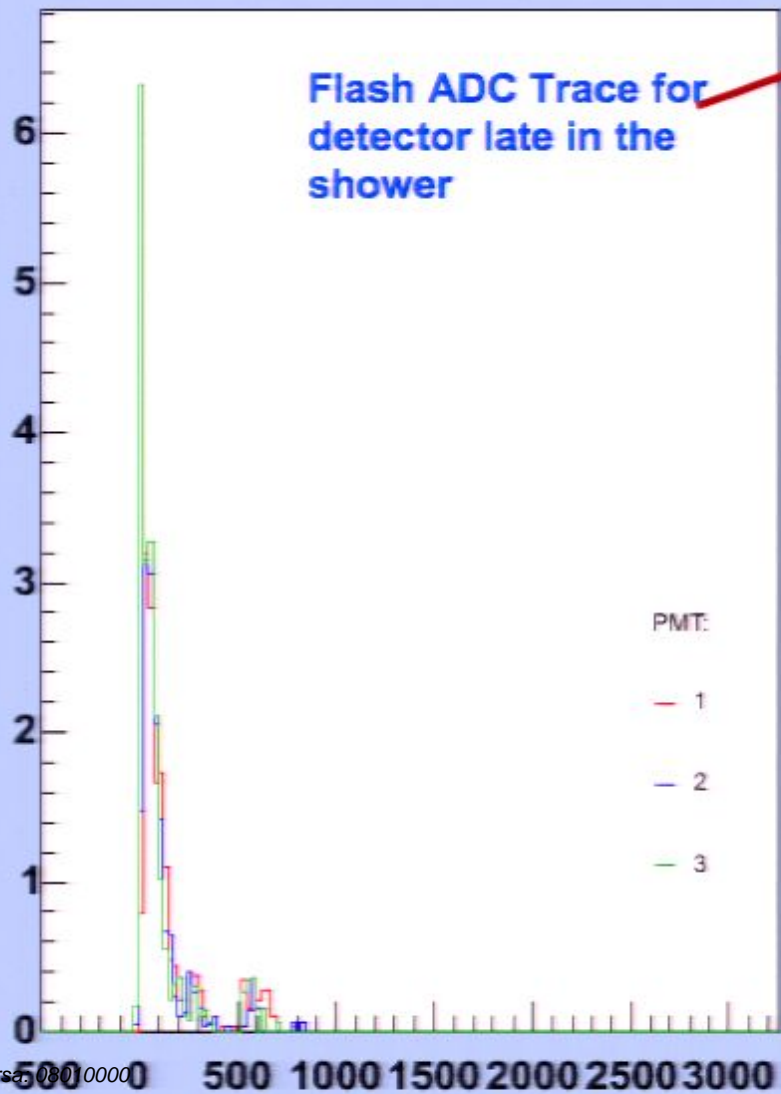
Pirsa: 08010000



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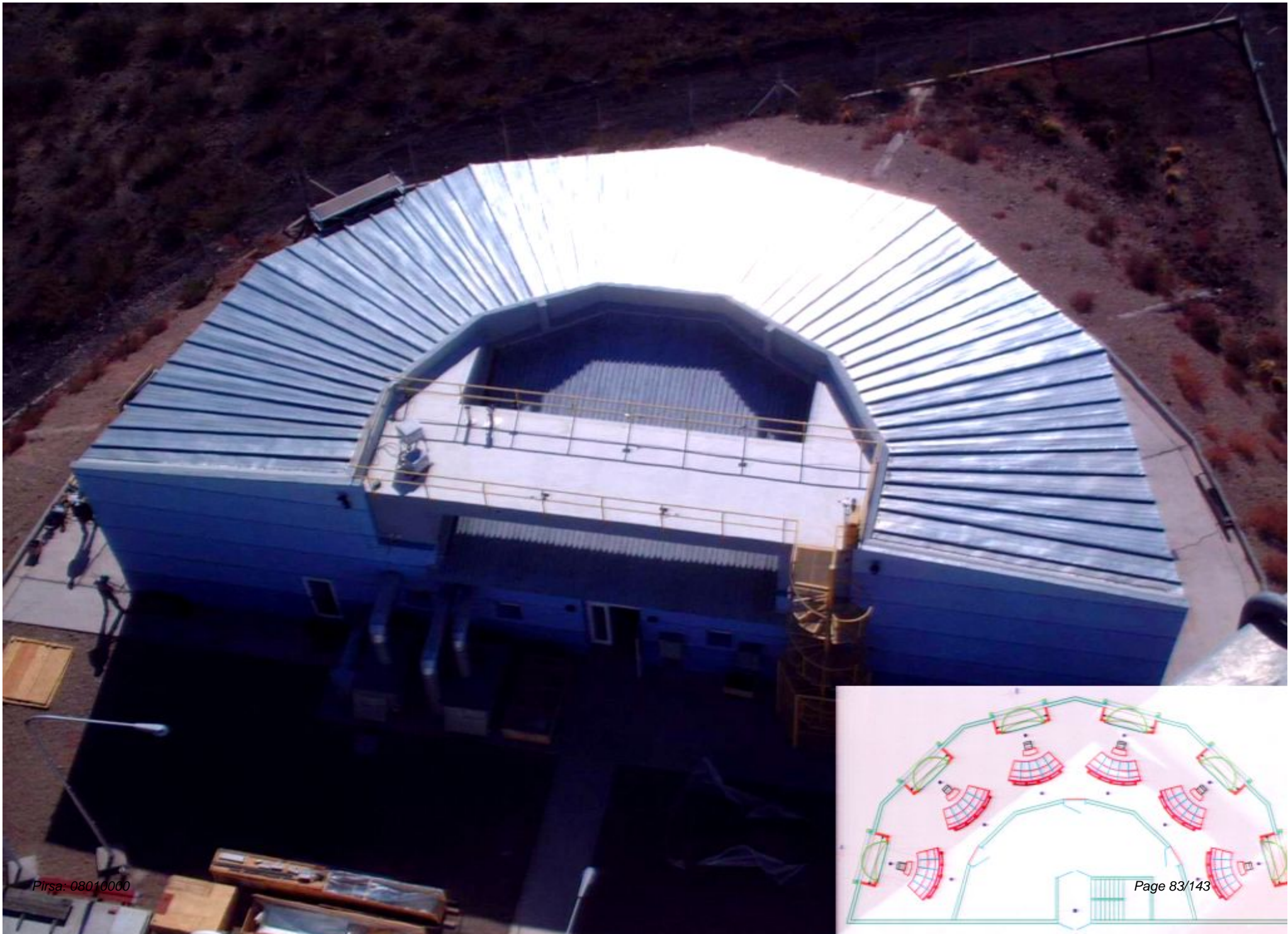
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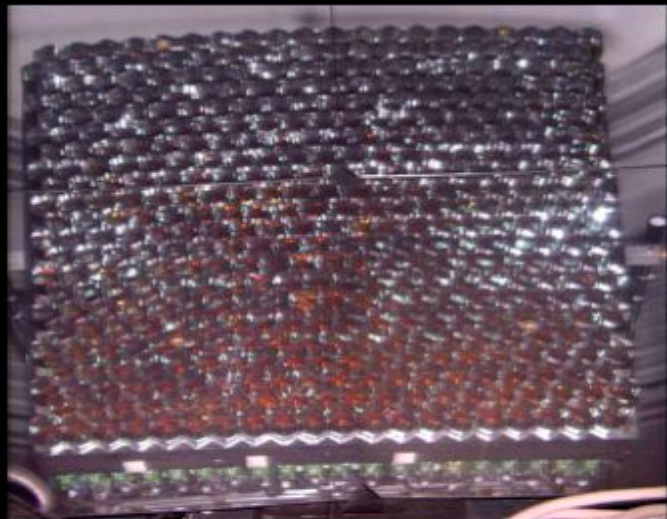
view of Los Leones Fluorescence





**corrector lens
(aperture x2)**

**segmented
spherical
mirror**



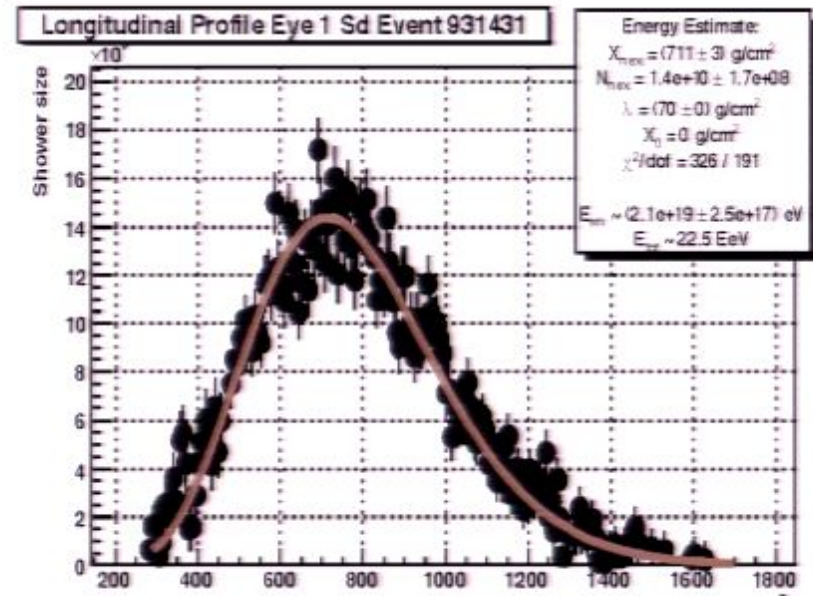
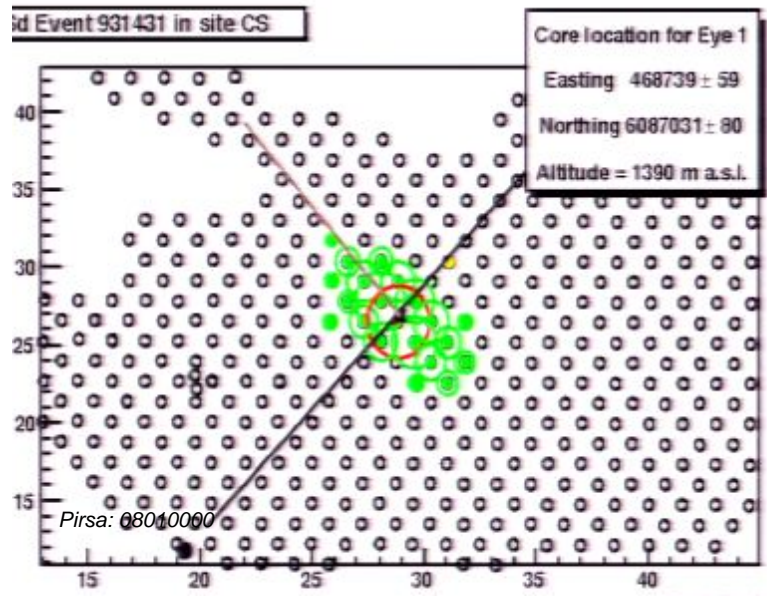
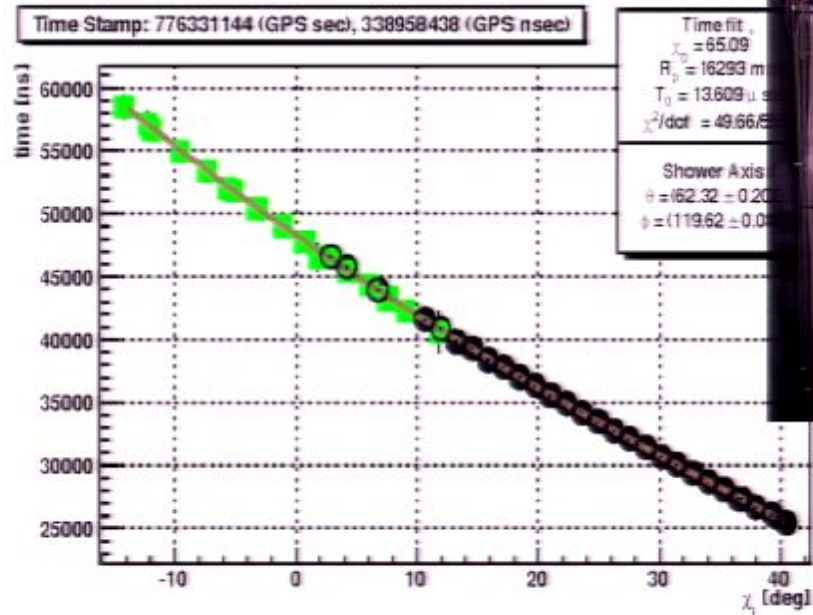
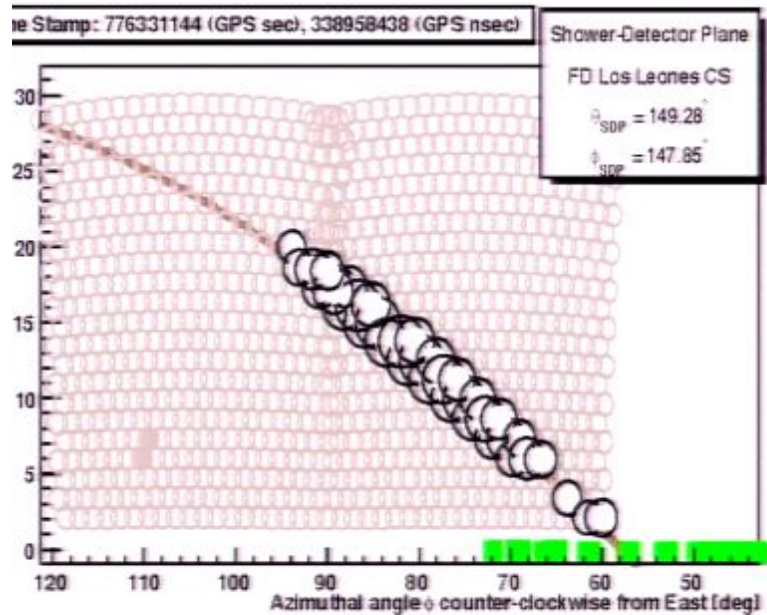
440 PMT camera 1.5° per pixel

**box
pass
curtain**

4 times 6 telescopes overlooking the site

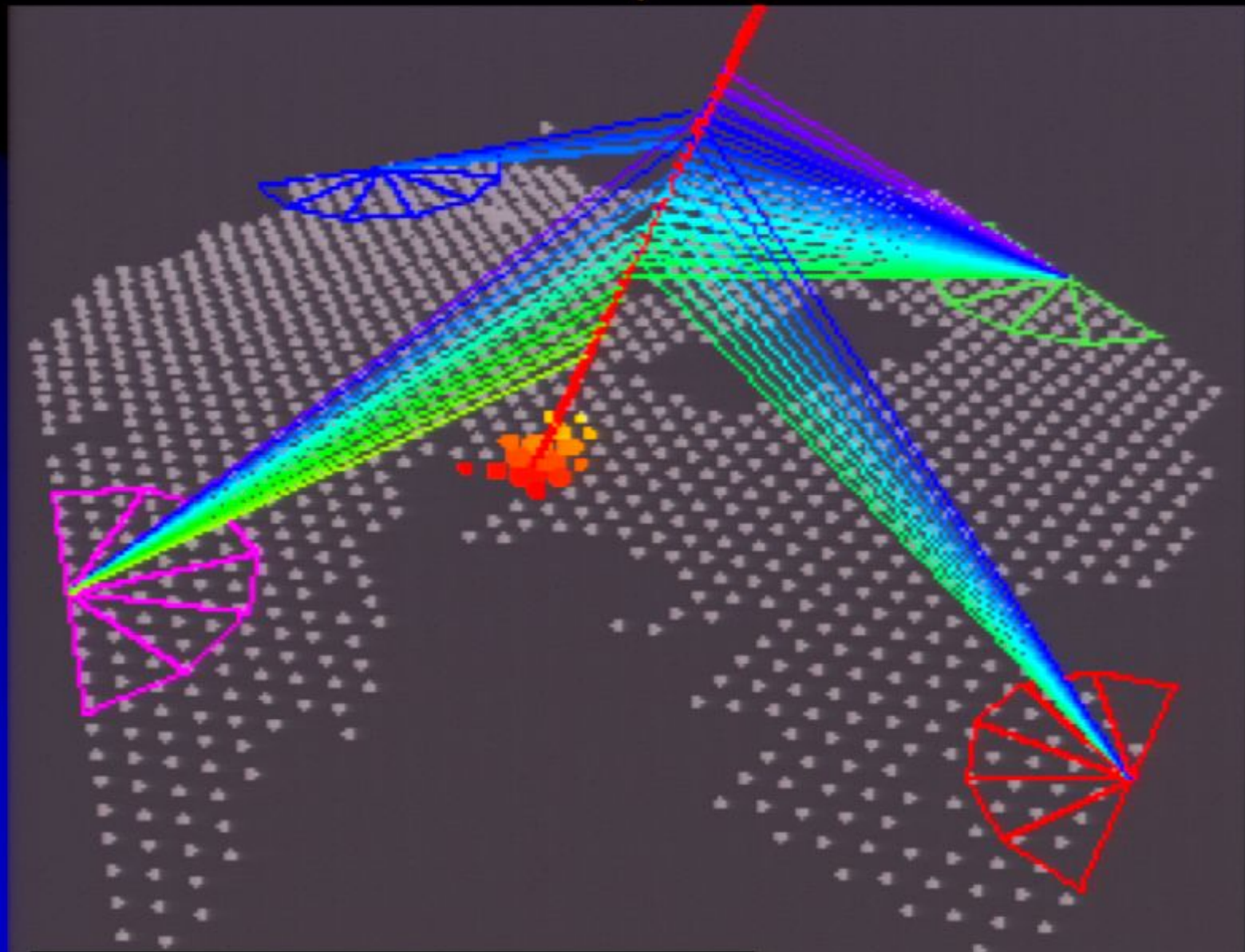


A Hybrid Event



1st - 4 Fold Hybrid Event

1st - 4 Fold Hybrid Event



20 May 2007 E ~ 10¹⁹ eV

Hybrid Era

| | HYBRID | SD only | FD only |
|---------------------------|------------------|------------------|------------------|
| Energy | A & M indep | depend | independ |
| Aperture | E, A, M indep | independ | depend |
| Angular Resolution | $\sim 0.2^\circ$ | $\sim 1-2^\circ$ | $\sim 3-5^\circ$ |

E= energy, A= mass, M = hadronic model

Goals of the Auger Observatory

***** Determine the Origin of UHECRs *****

Energy Spectrum

Composition

Arrival Direction Distribution

Goals of the Auger Observatory

***** Determine the Origin of UHECRs *****

Energy Spectrum

features? ankle, GZK; injection? Propagation?

Composition

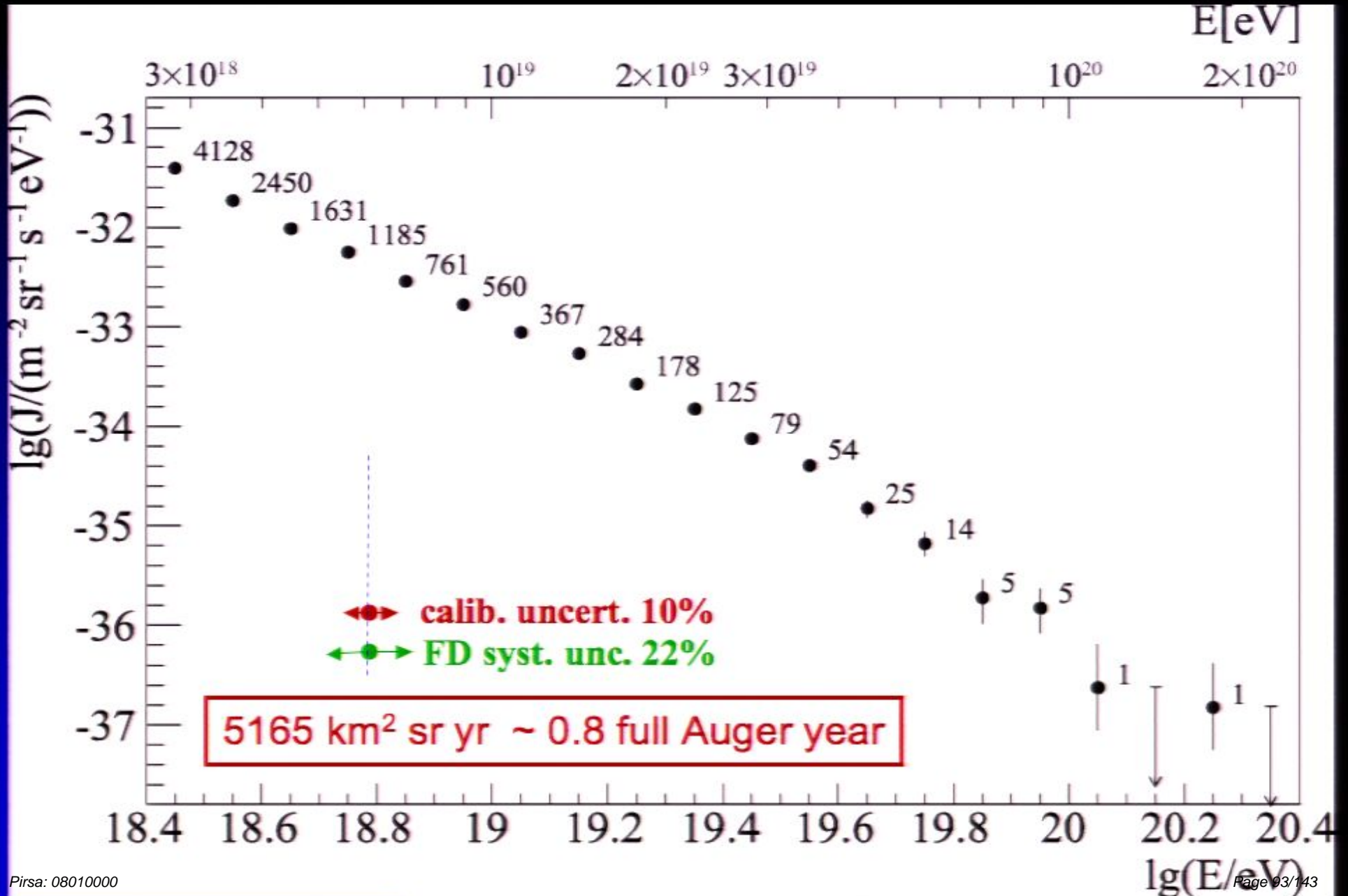
protons, nuclei, photons, neutrinos

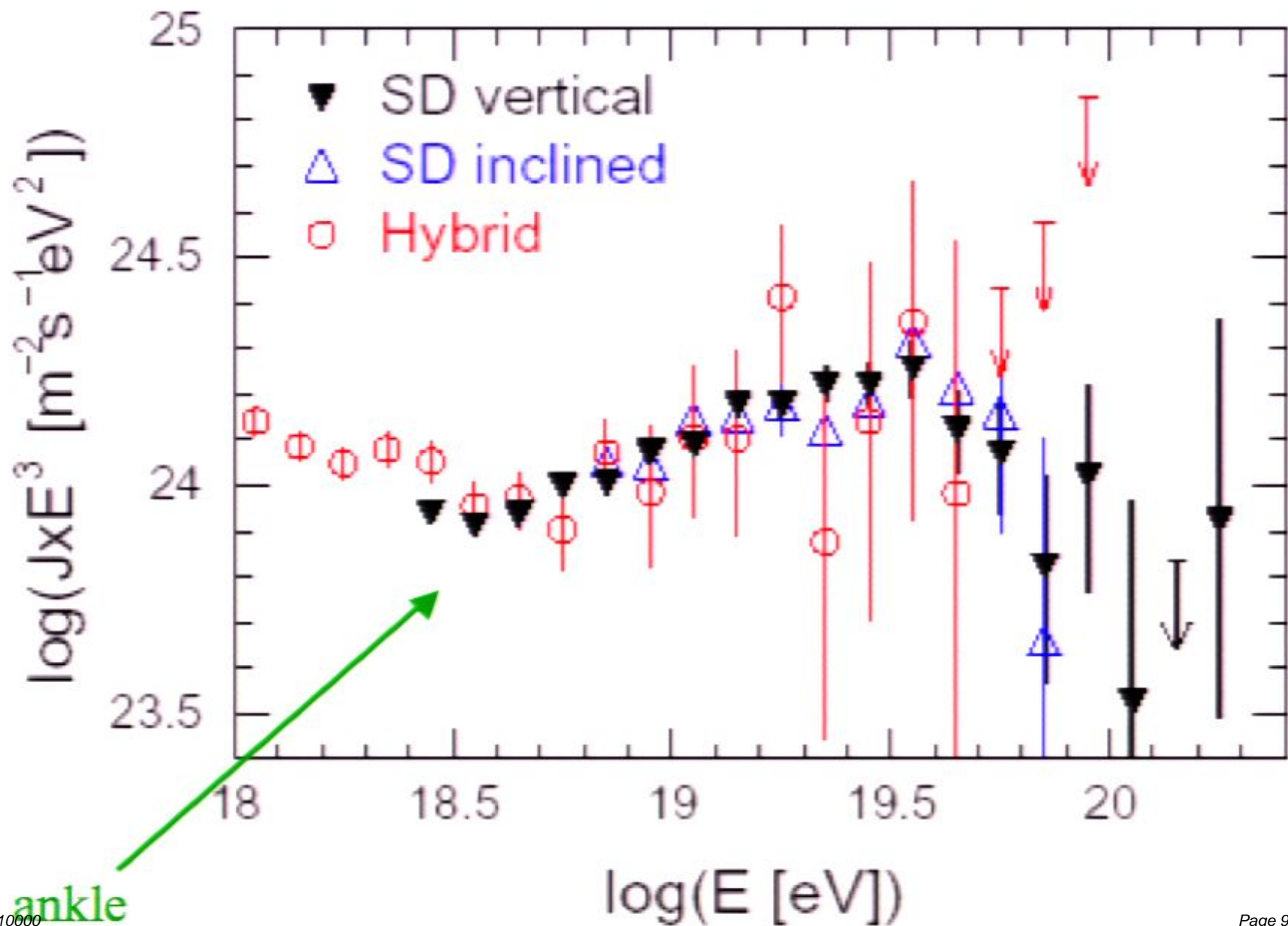
Arrival Direction Distribution

anisotropies?

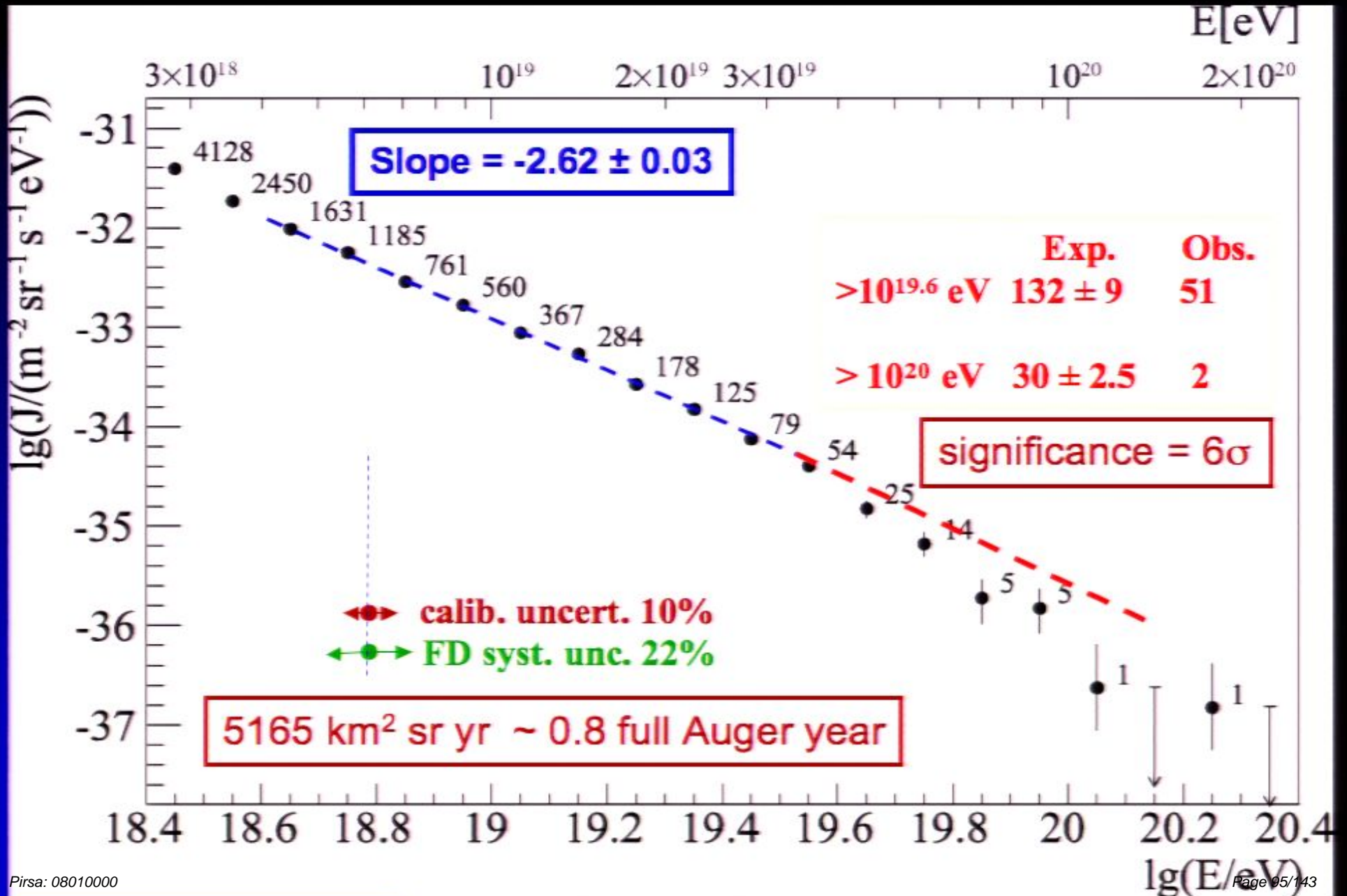
Recent Results

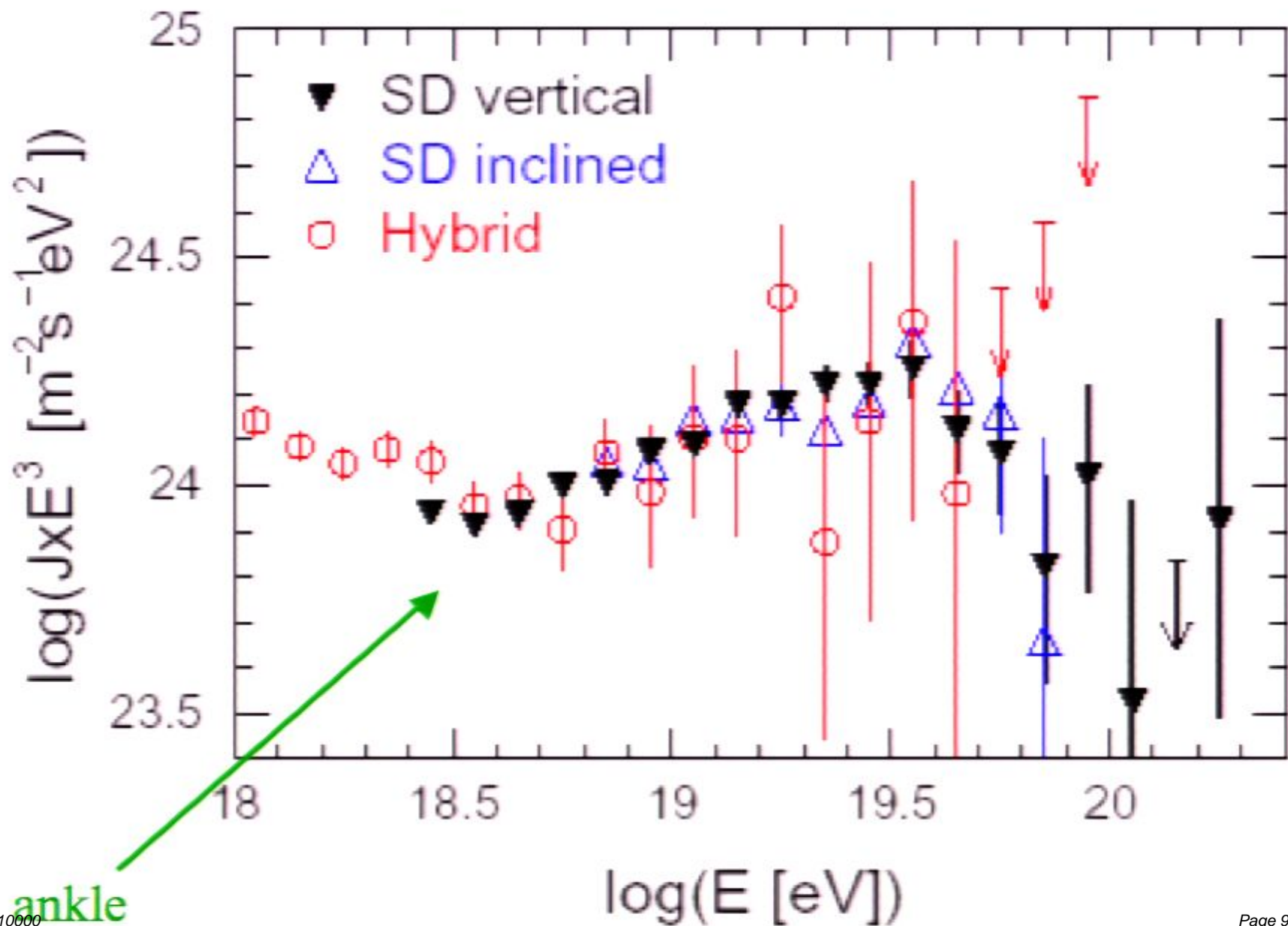
Energy spectrum from SD showers with $\theta \leq 60^\circ$





Energy spectrum from SD showers with $\theta \leq 60^\circ$





Spectrum facts

There is an ankle

→ How to interpret it?

Galactic/Extragalactic transition?

or

Spectral feature from pair-production
energy losses of pure-proton UHECRs?

→ analyse composition!

There is a “cut-off”

→ How to interpret it?

GZK suppression?

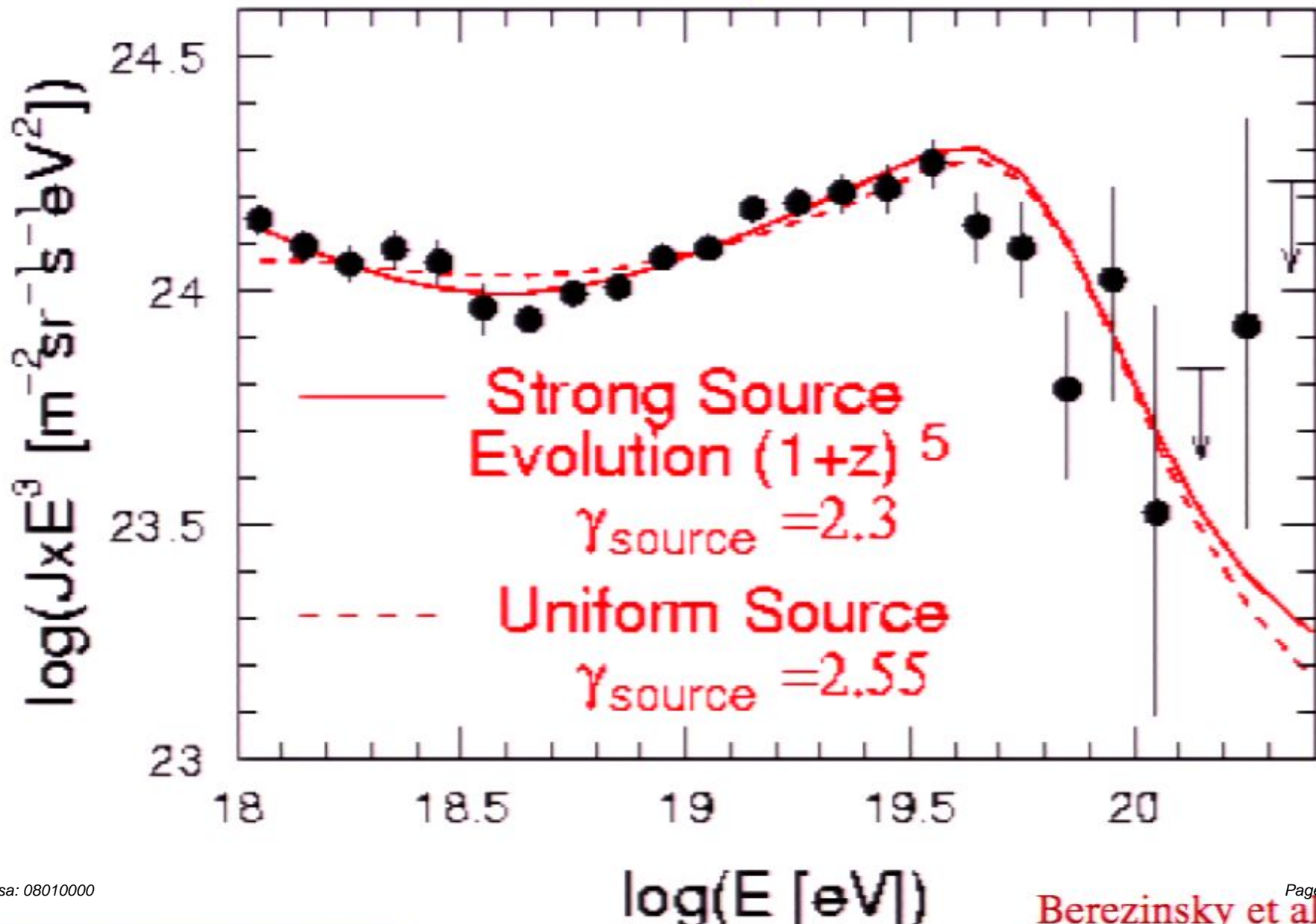
or

Limit of the acceleration process?

E_{\max}

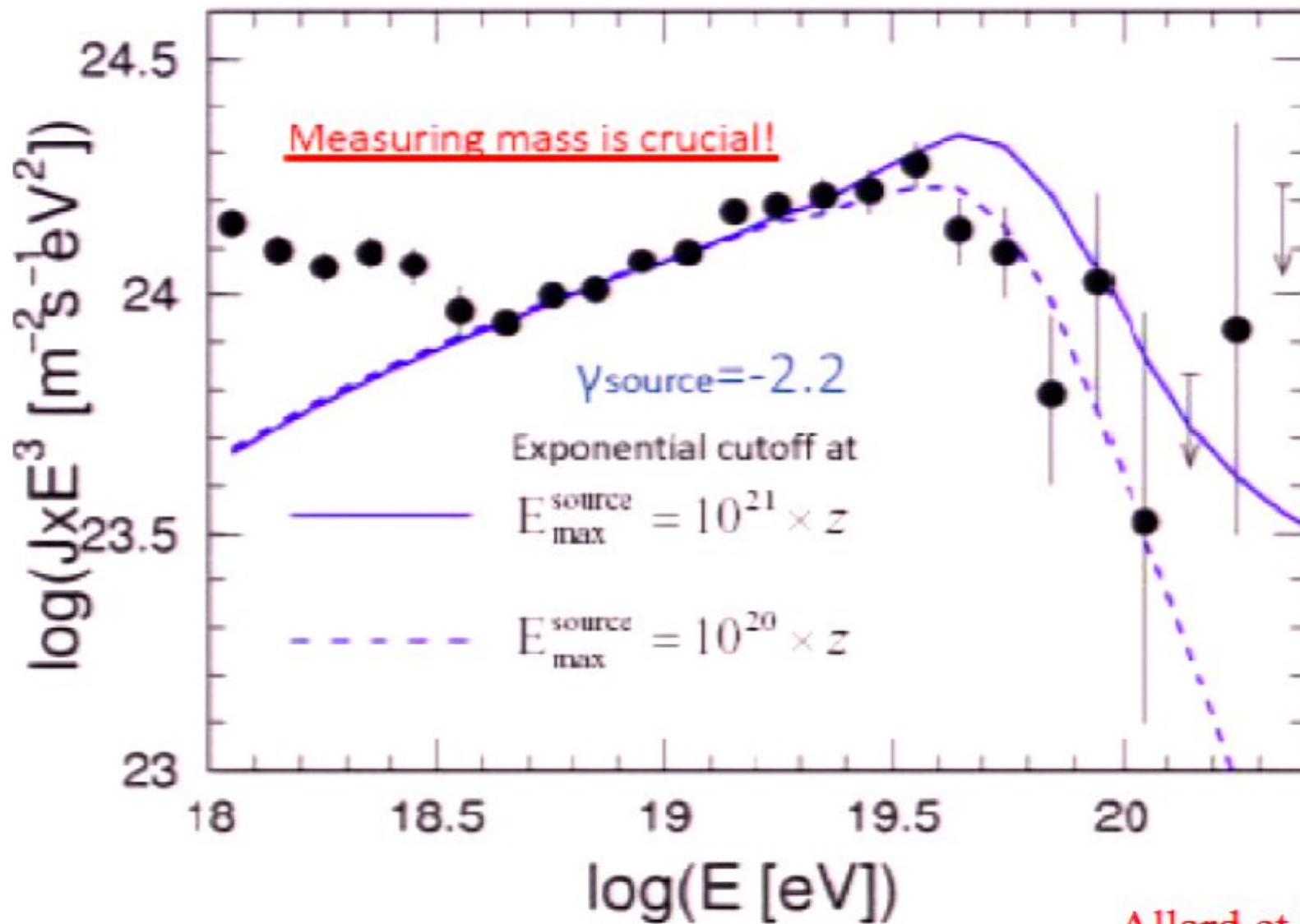
→ analyse arrival directions!

Ankle as Pure Proton e^+e^- dip



Nucleus Model

CR abundance is same as low energy Galactic components



Allard et al.

Goals of the Auger Observatory

***** Determine the Origin of UHECRs *****

Energy Spectrum

features? ankle, GZK; injection? Propagation?

Composition

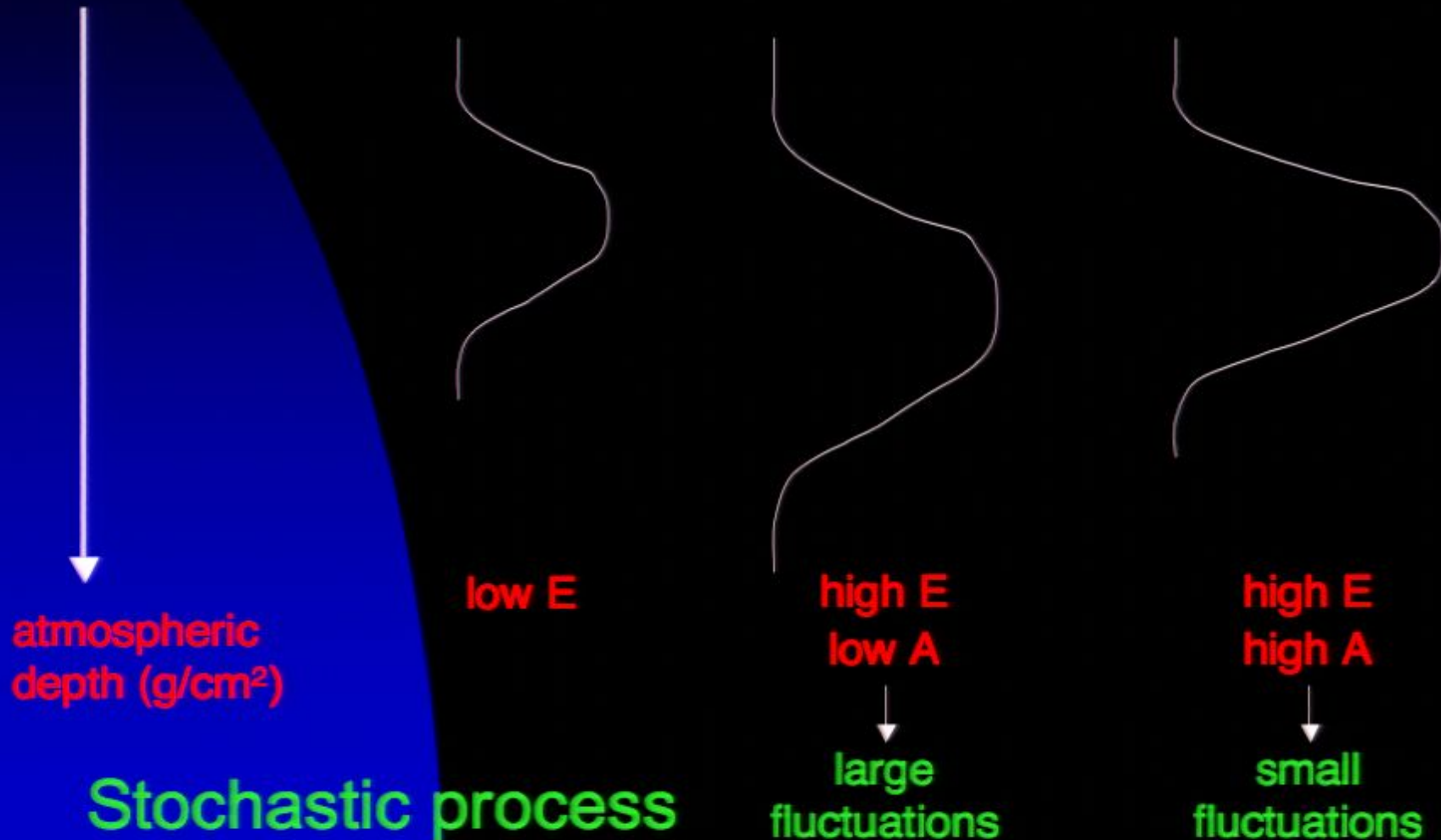
protons, nuclei, photons, neutrinos

Arrival Direction Distribution

anisotropies?

Composition-sensitive observables

Depth of shower maximum development: X_{\max}



Goals of the Auger Observatory

***** Determine the Origin of UHECRs *****

Energy Spectrum

features? ankle, GZK; injection? Propagation?

Composition

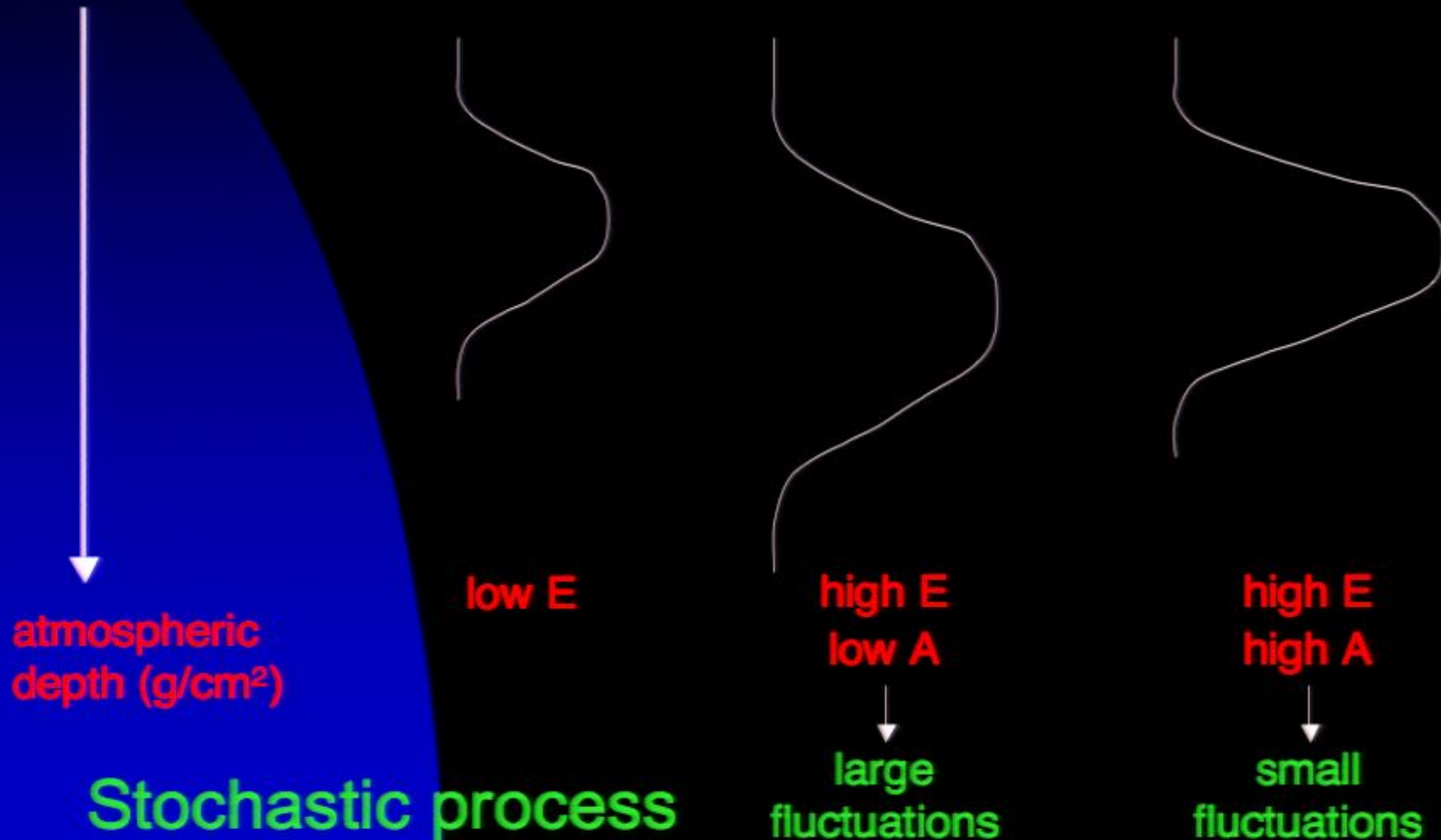
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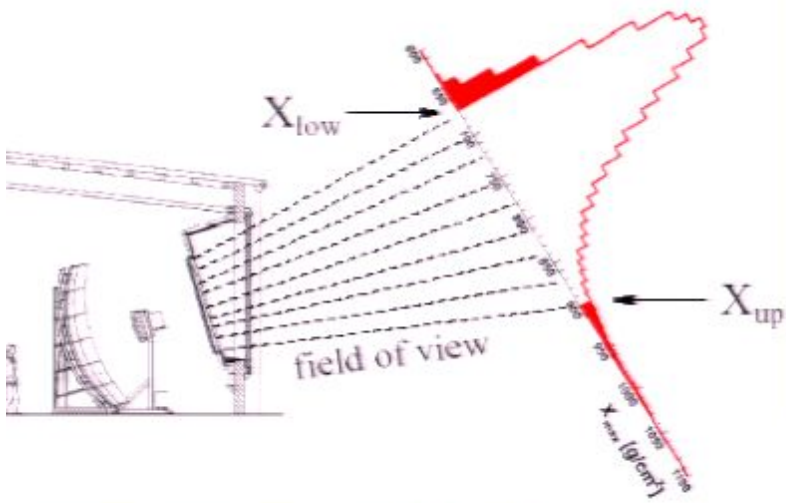
Arrival Direction Distribution

anisotropies?

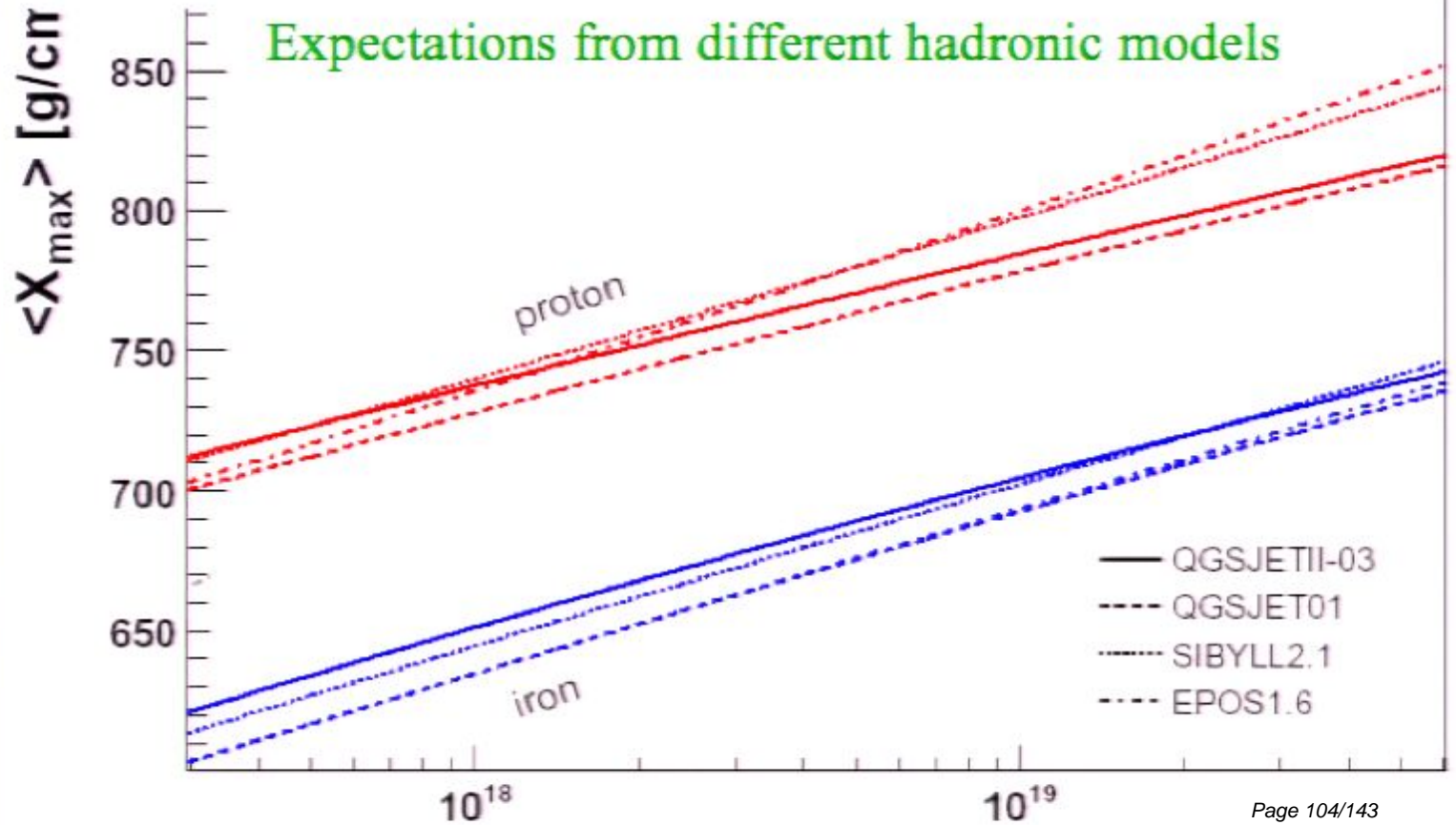
Composition-sensitive observables

Depth of shower maximum development: X_{\max}





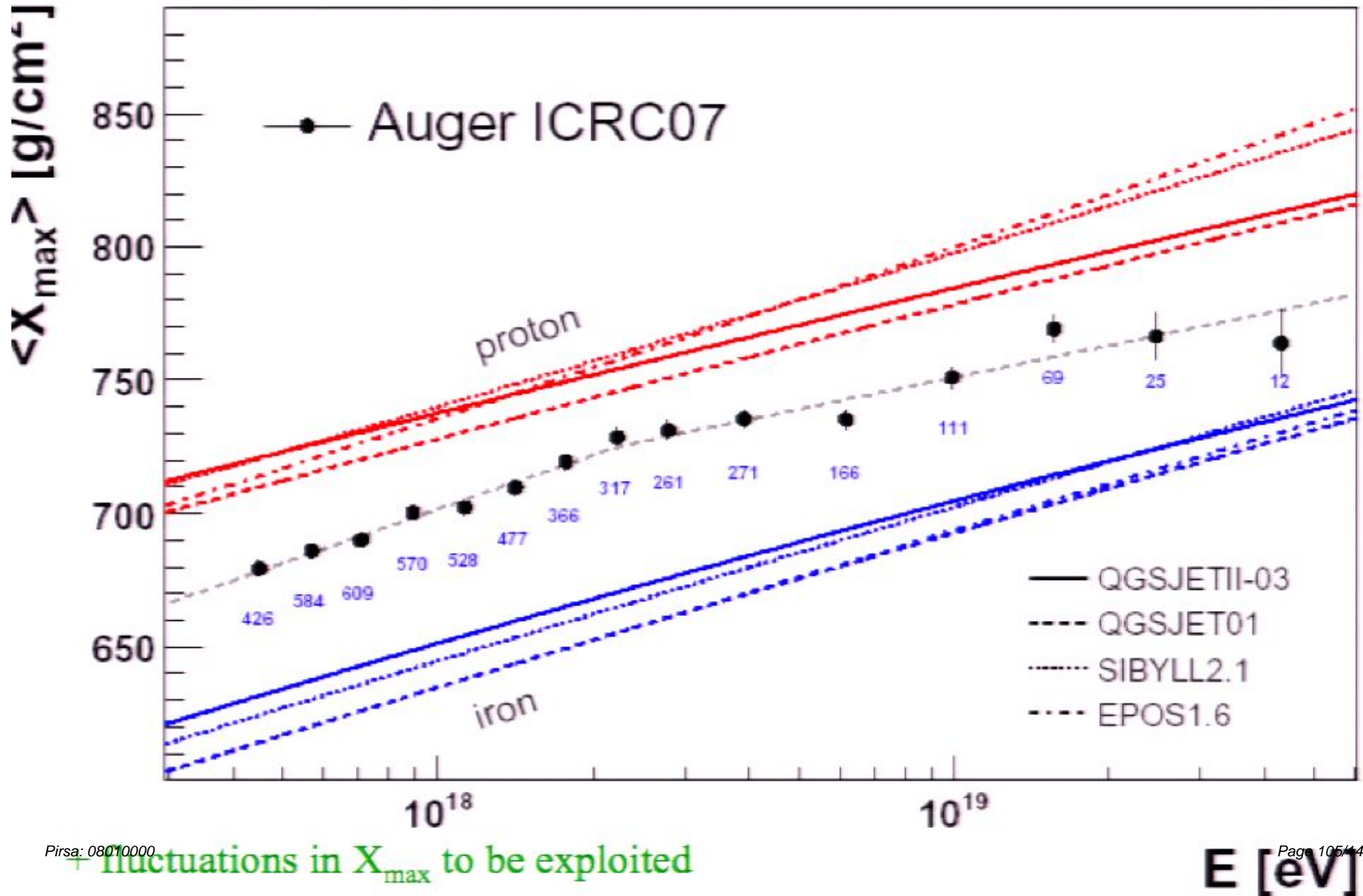
**Composition observable:
shower maximum**



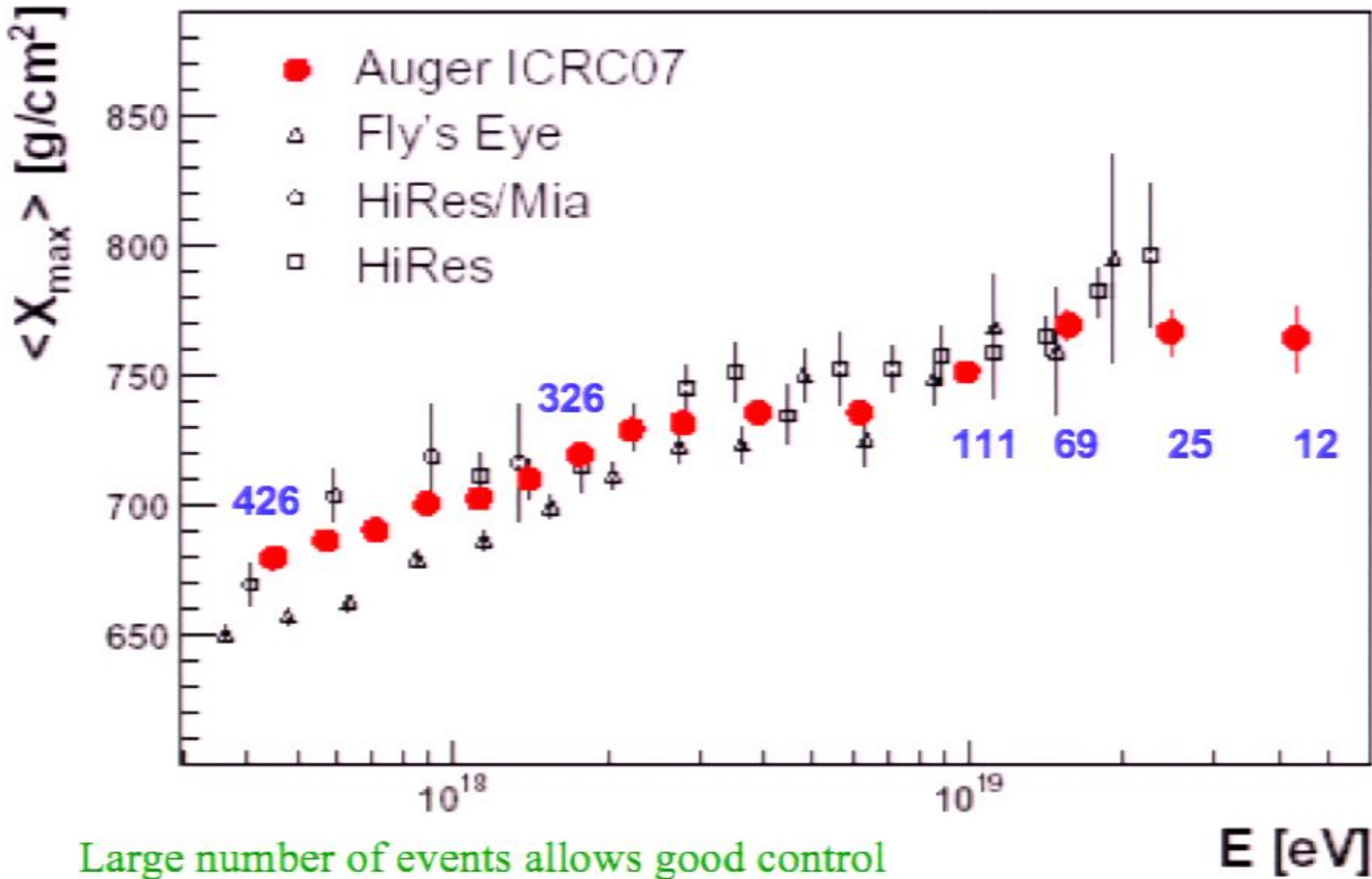
+ fluctuations in X_{max} smaller for heavier nuclei

E [eV]

Shower maximum over 2 decades in E



Comparison with previous studies



Large number of events allows good control
and understanding of systematics

Photon limit

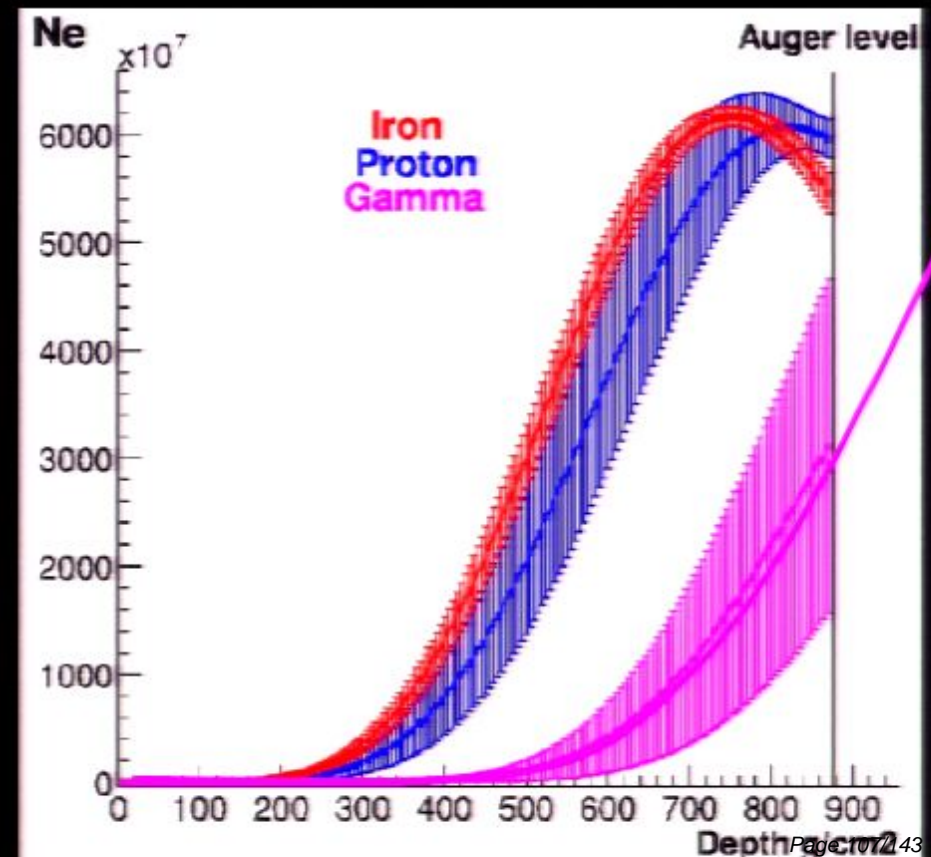
Top-down models predict large UHE photon flux

SHDM models: decay of super-heavy dark matter accumulated in Galactic halo

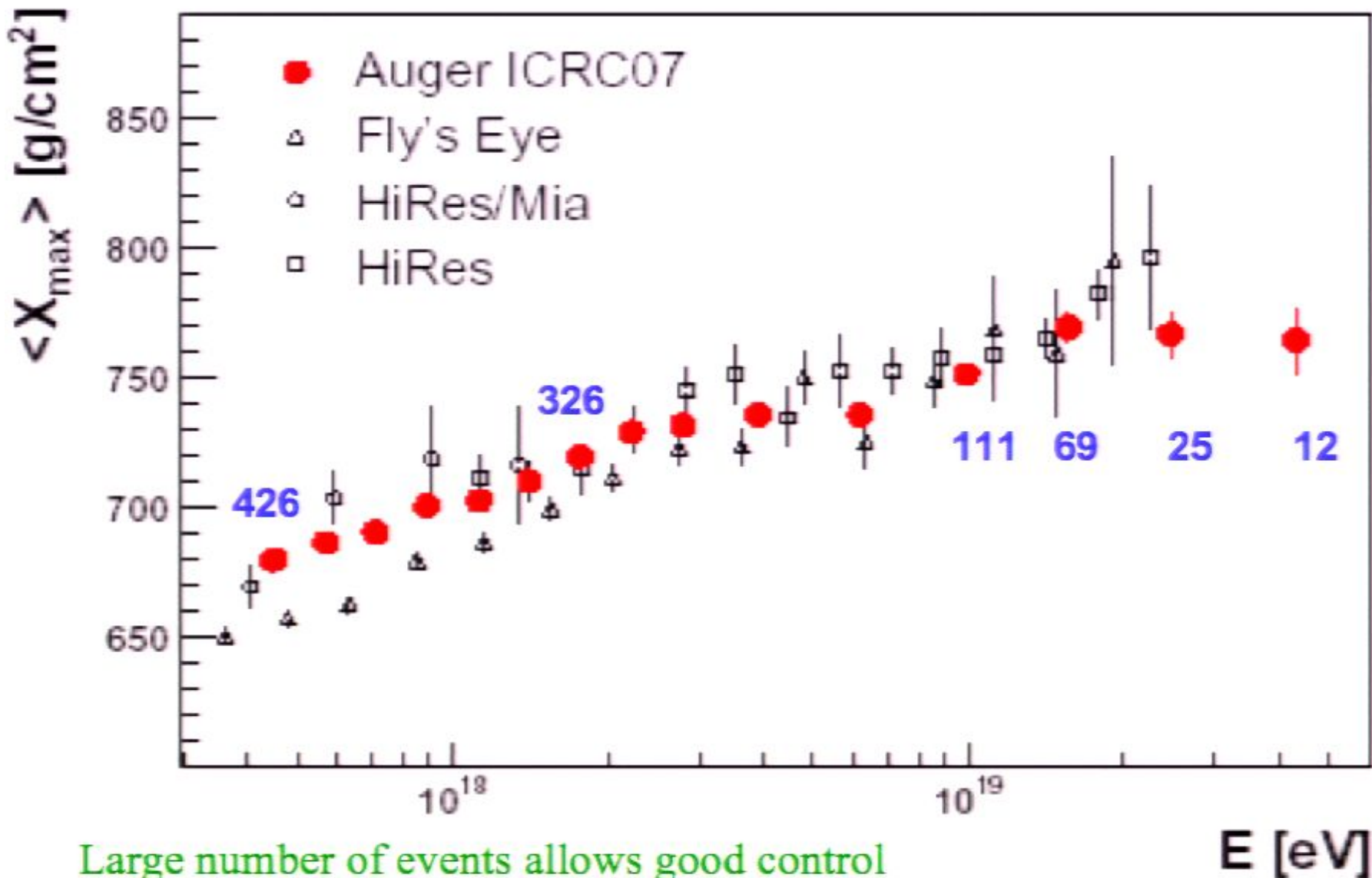
TD models: supermassive particle decay from topological defect interaction or annihilation

Photon-induced showers look very different

Showers at $E = 10^{19}$ eV, $\theta = 0^\circ$:

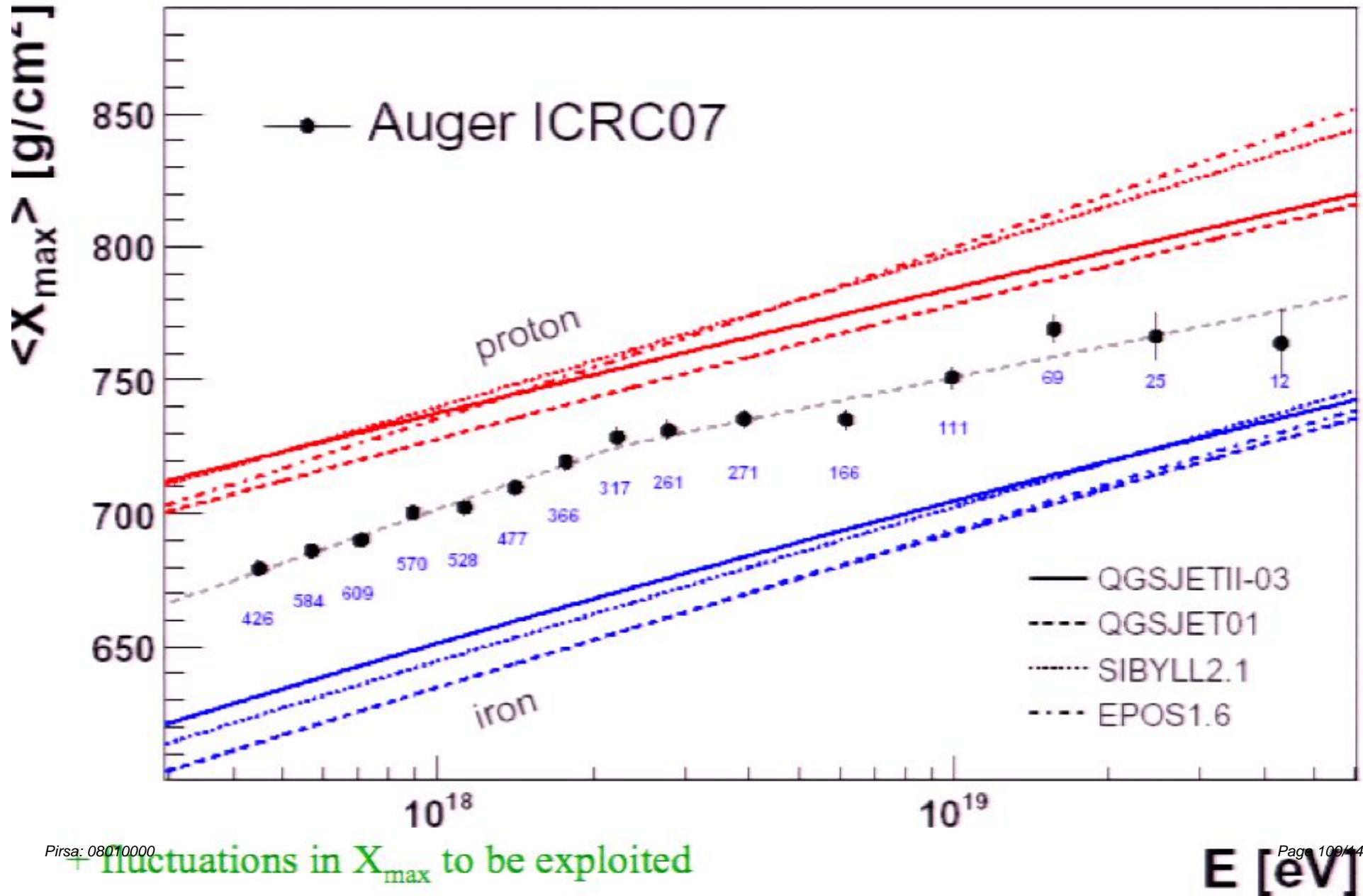


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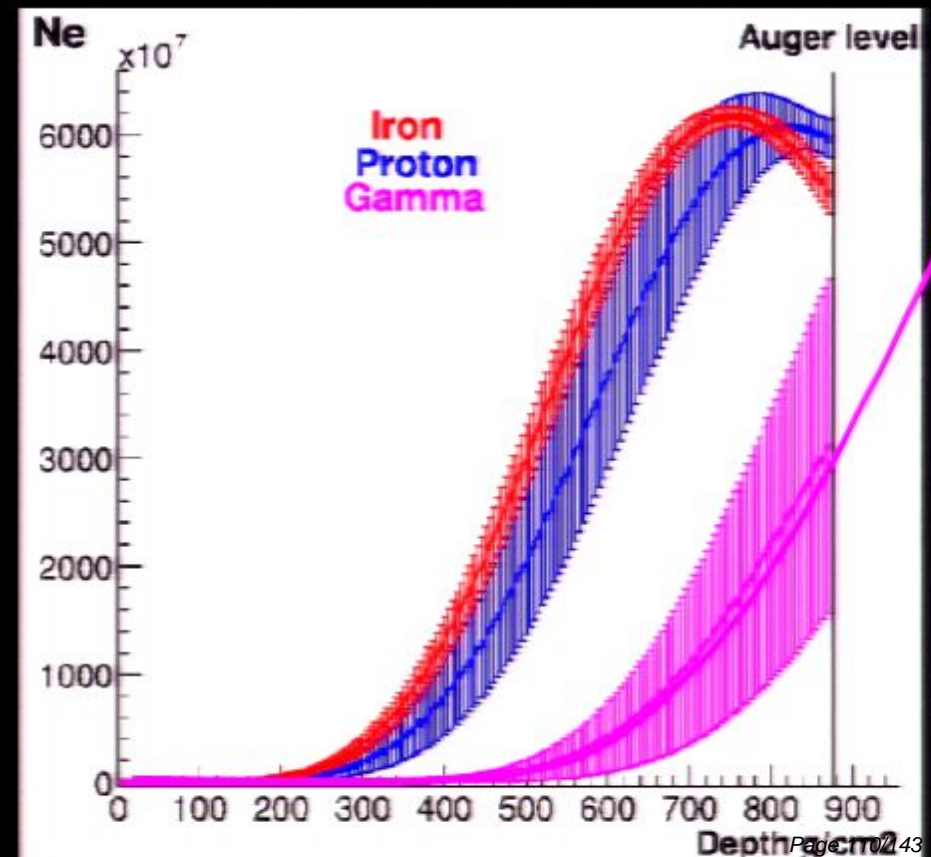
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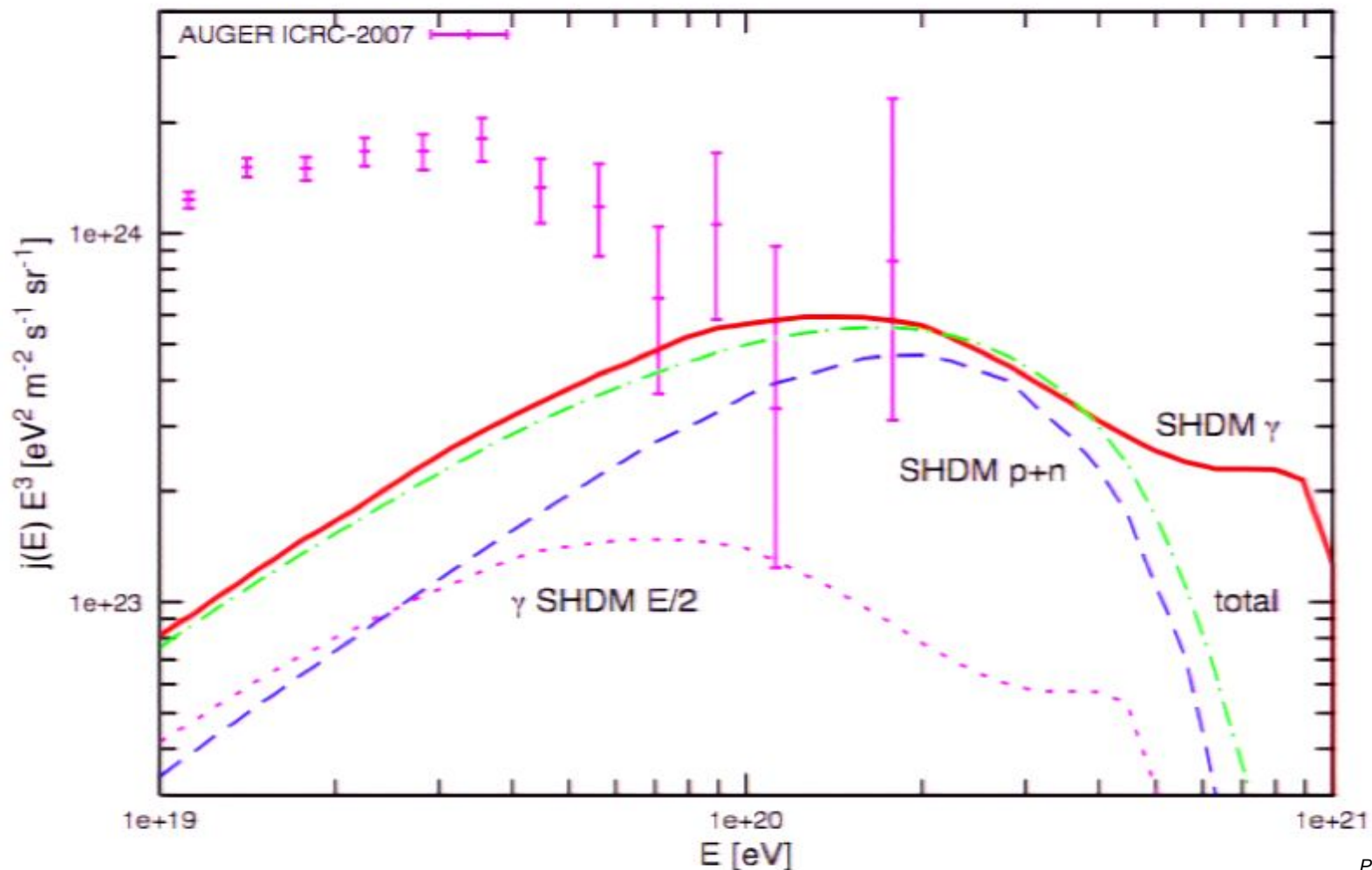
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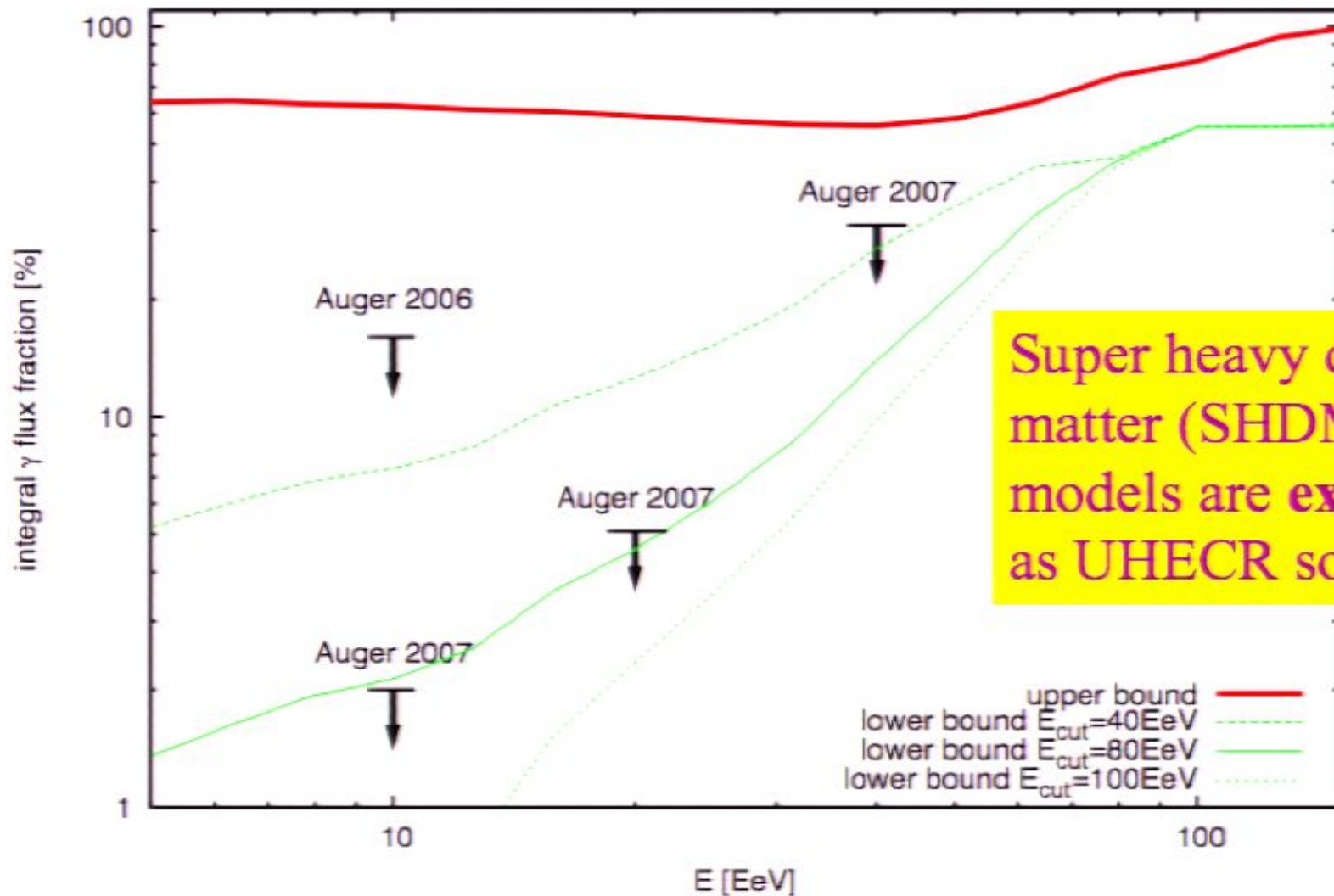


Implications & Future

Constraints on Super-Heavy Dark Matter as sources of UHECRs

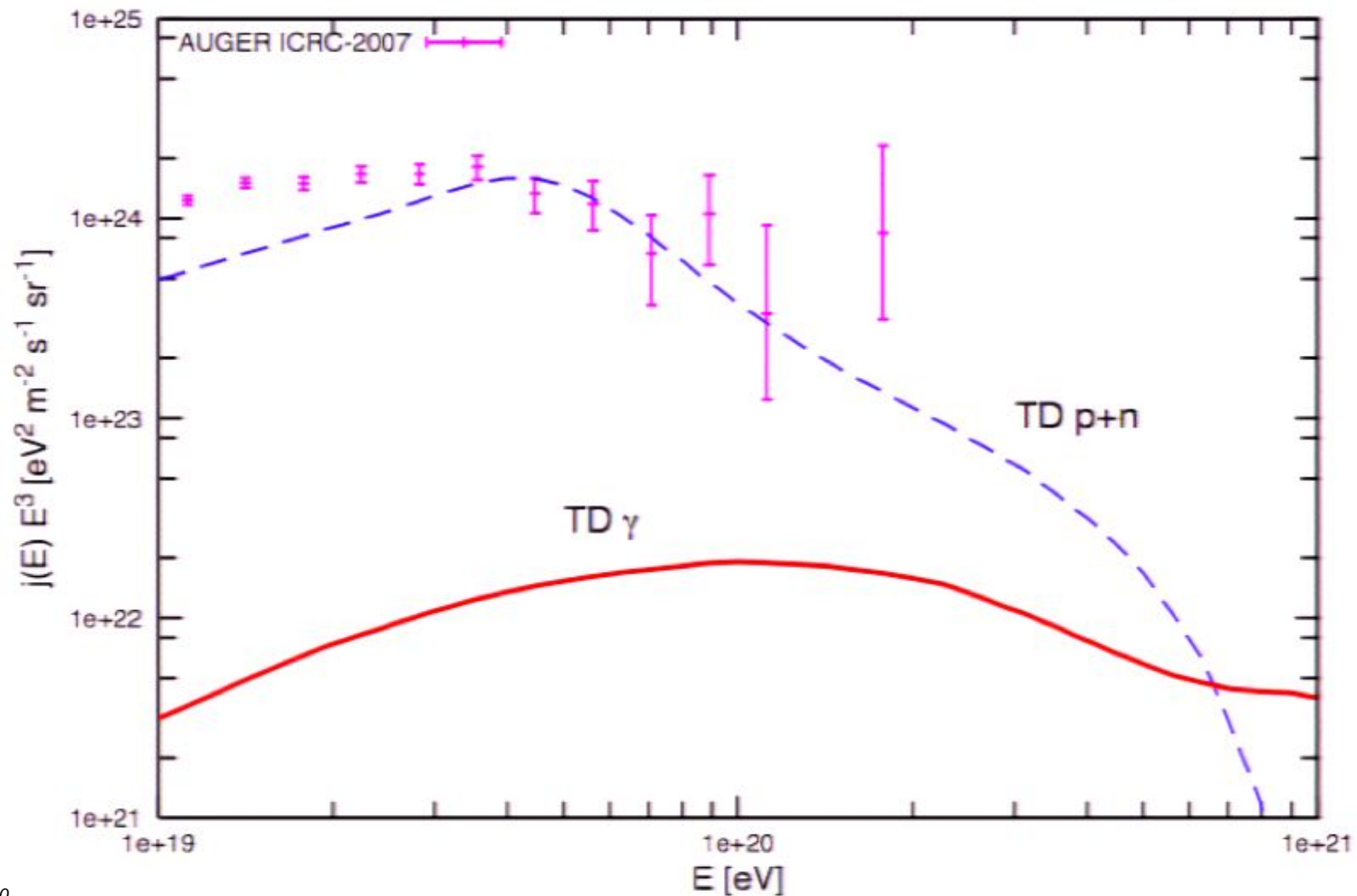


Auger results (photon limit)

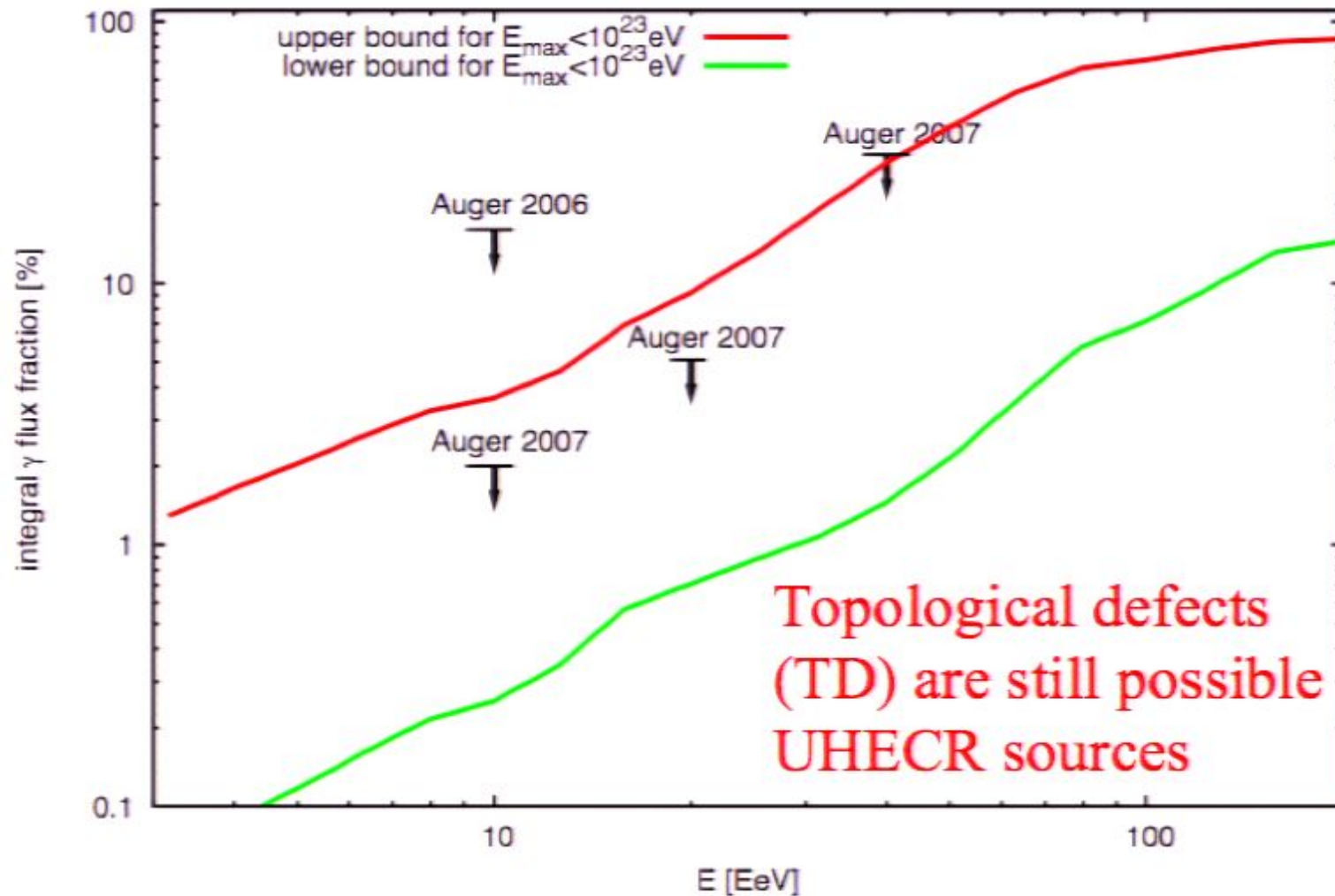


Super heavy dark matter (SHDM) models are **excluded** as UHECR sources!

Constraints on topological defects as sources of UHECRs as sources of UHECRs

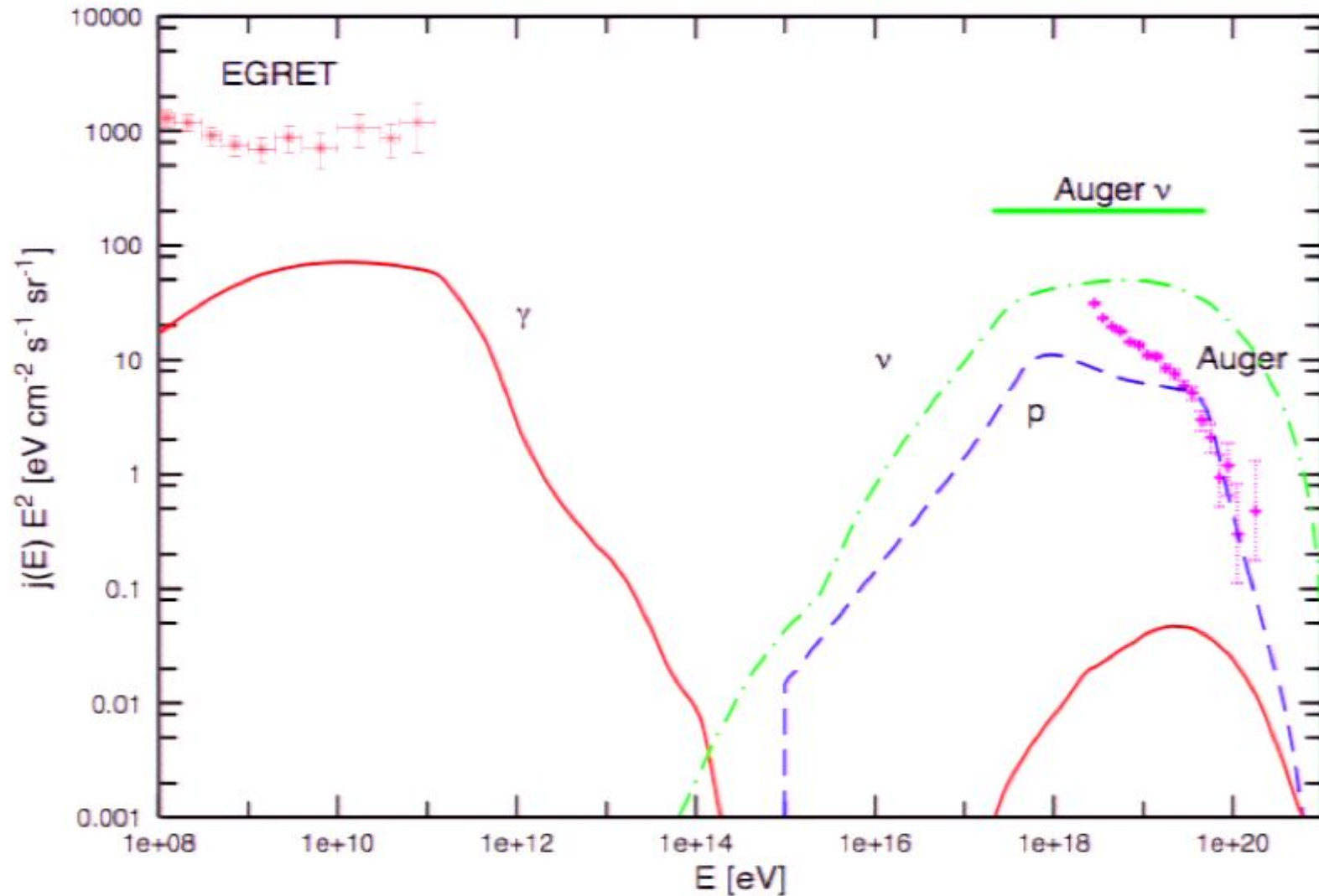


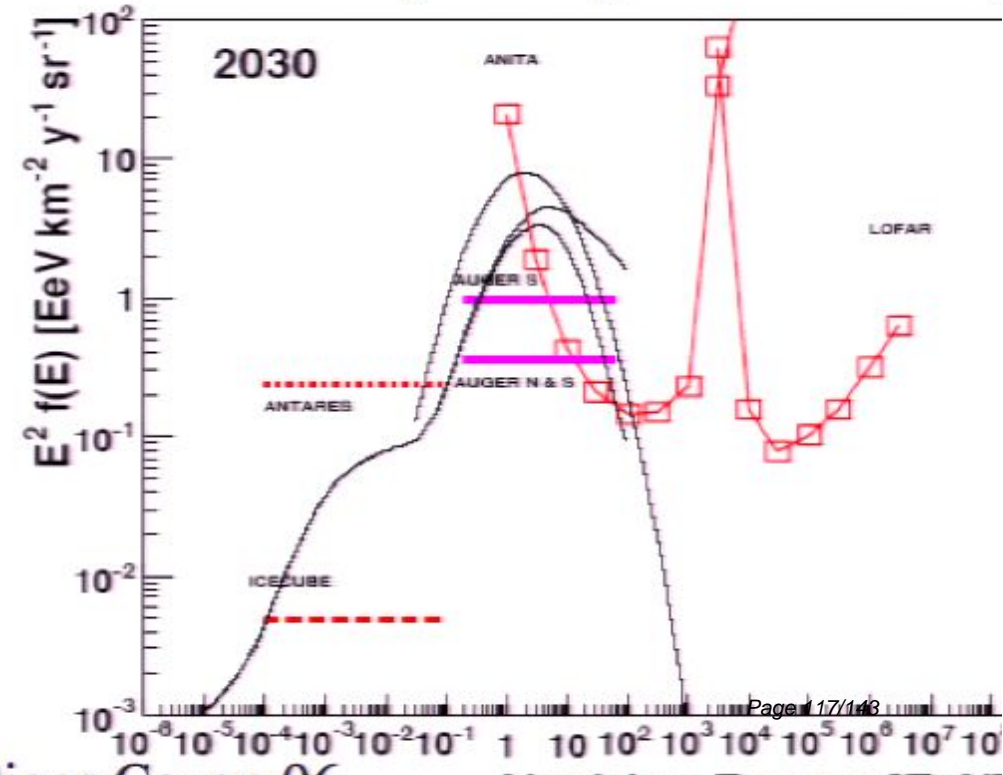
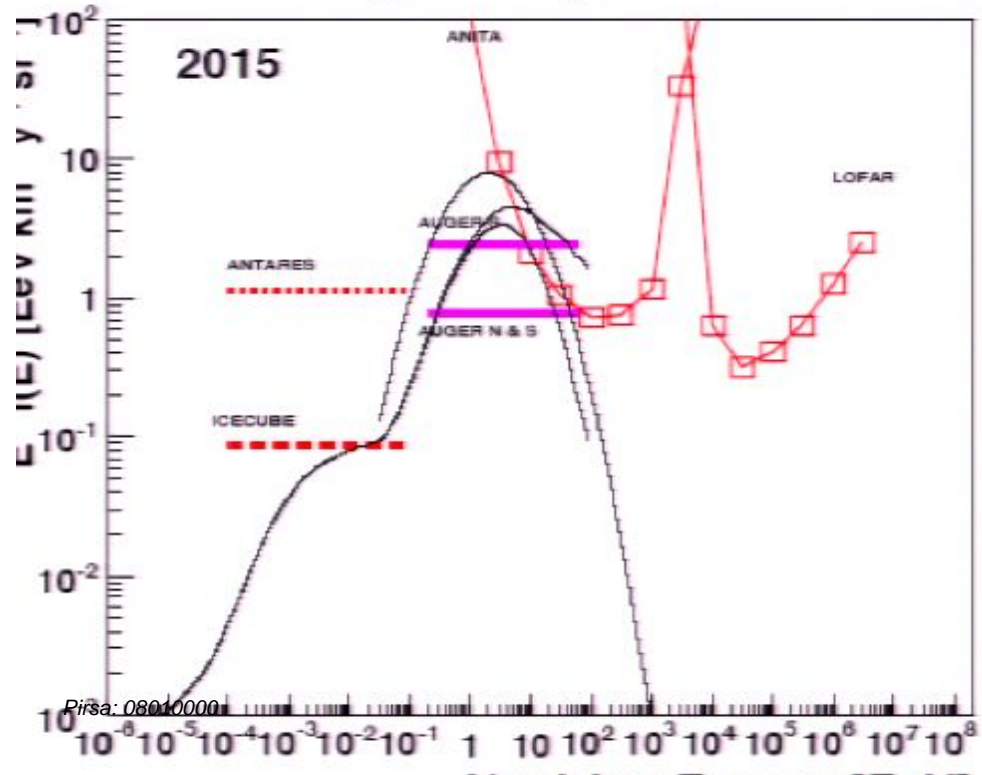
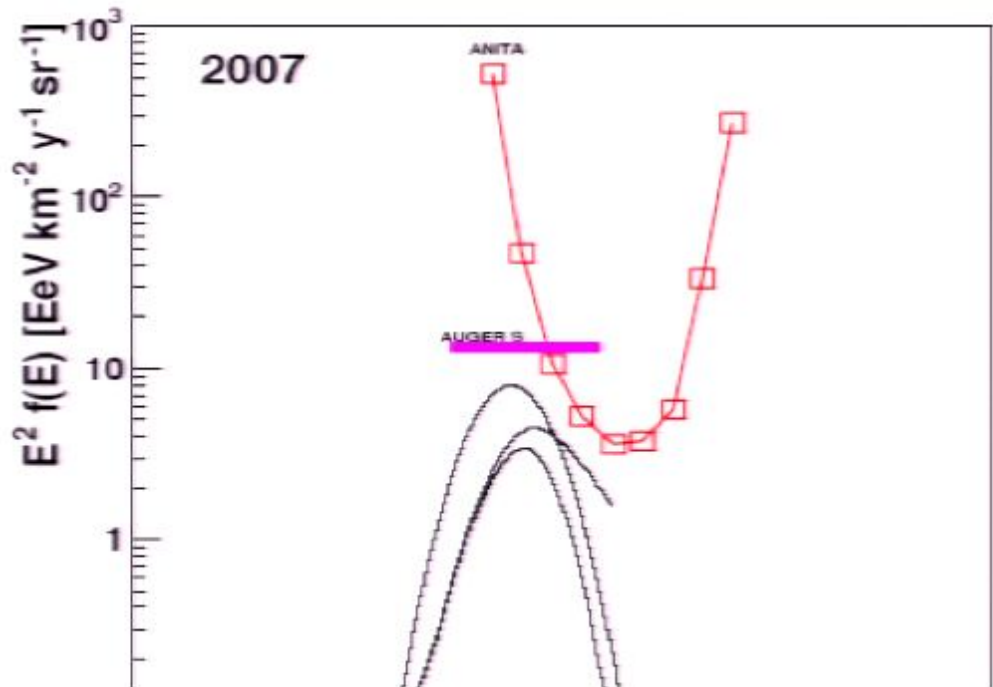
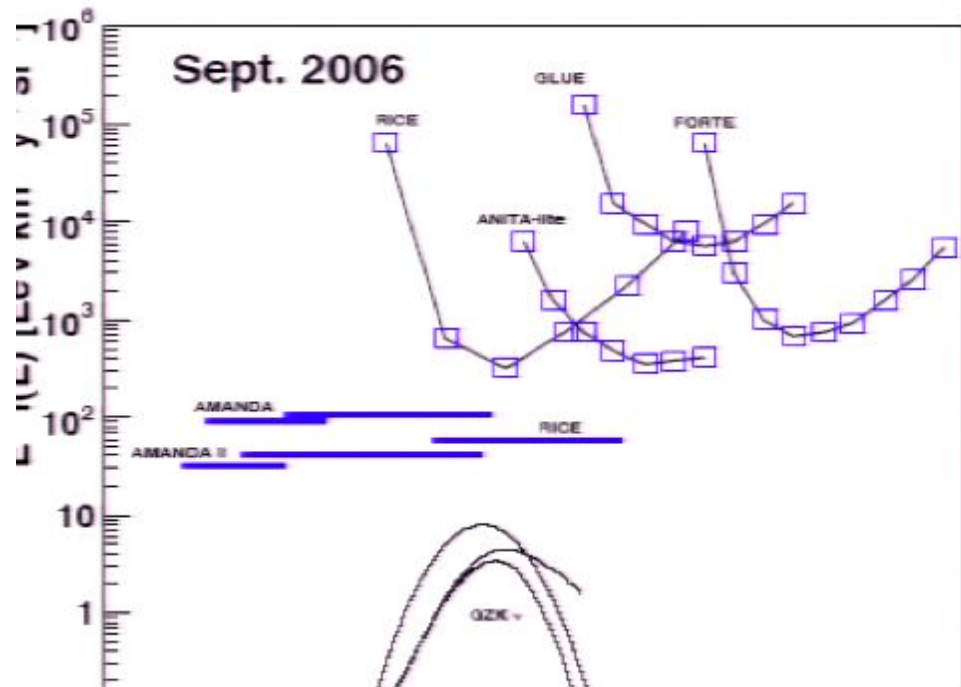
Auger results (photon limit)



Auger results

TD models closer to be constrained by Auger neutrino limits





Anisotropies!!!

Auger anisotropy results

Angular resolution of $\sim 1^\circ$: good enough!

No large-scale signal (dipole) at any energy above 1 EeV

e.g. $\alpha < 0.7\%$ for $1 \text{ EeV} \leq E \leq 3 \text{ EeV}$

No significant excess emission from Galactic center

No signal from BL-Lacs as possibly seen by HiRes

→ none of the previous reports have been confirmed...

Main Auger result

Highest energy cosmic rays have
an anisotropic distribution!

First evidence that proton
astronomy is possible!

Correlation with the most nearby
AGNs in the 12th Véron-
Cetty/Véron catalogue

Opening of a new era:

Study of particle acceleration in high-
energy astrophysical sources

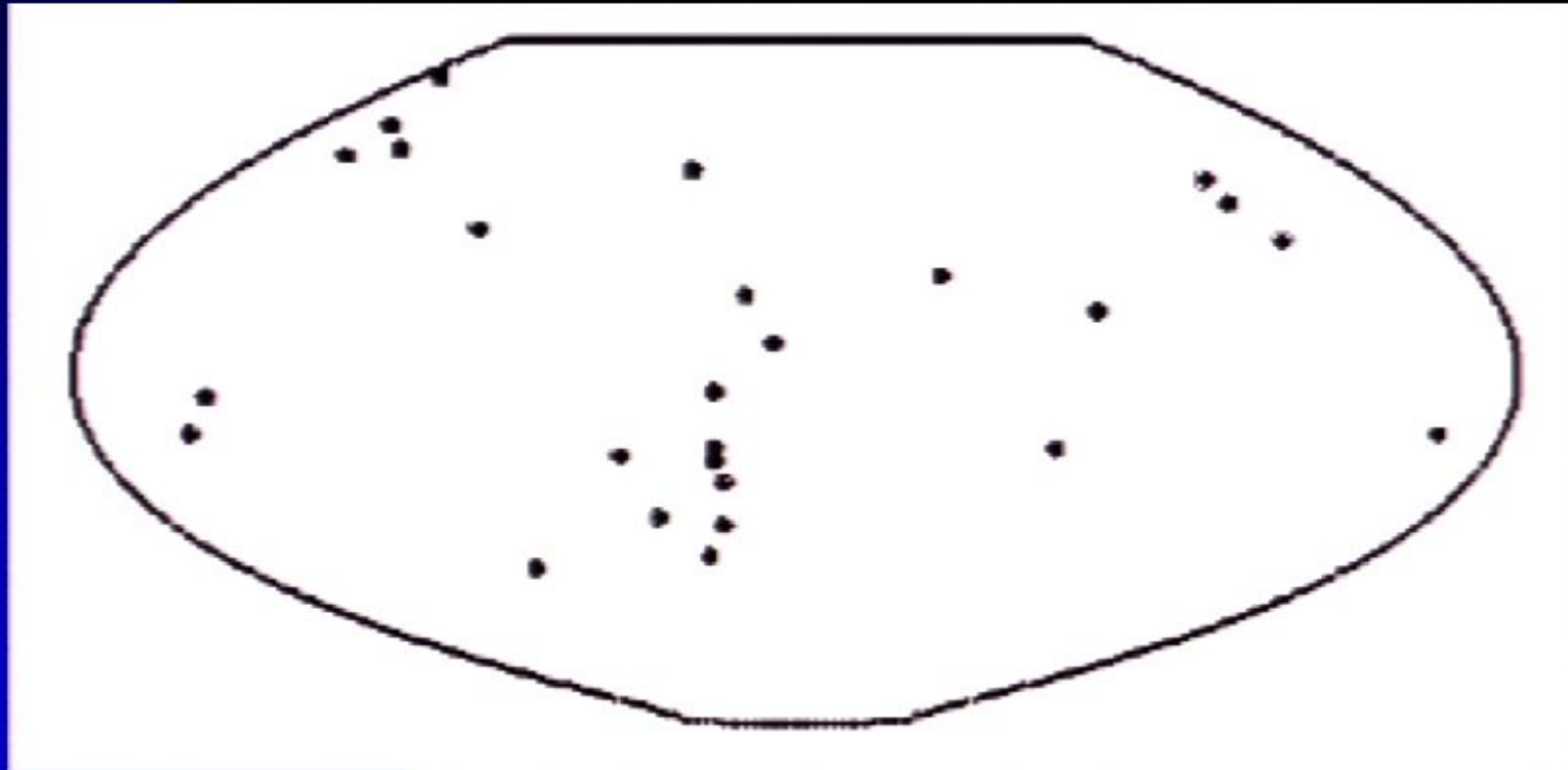
Multi-messenger study of sources

High-energy physics!

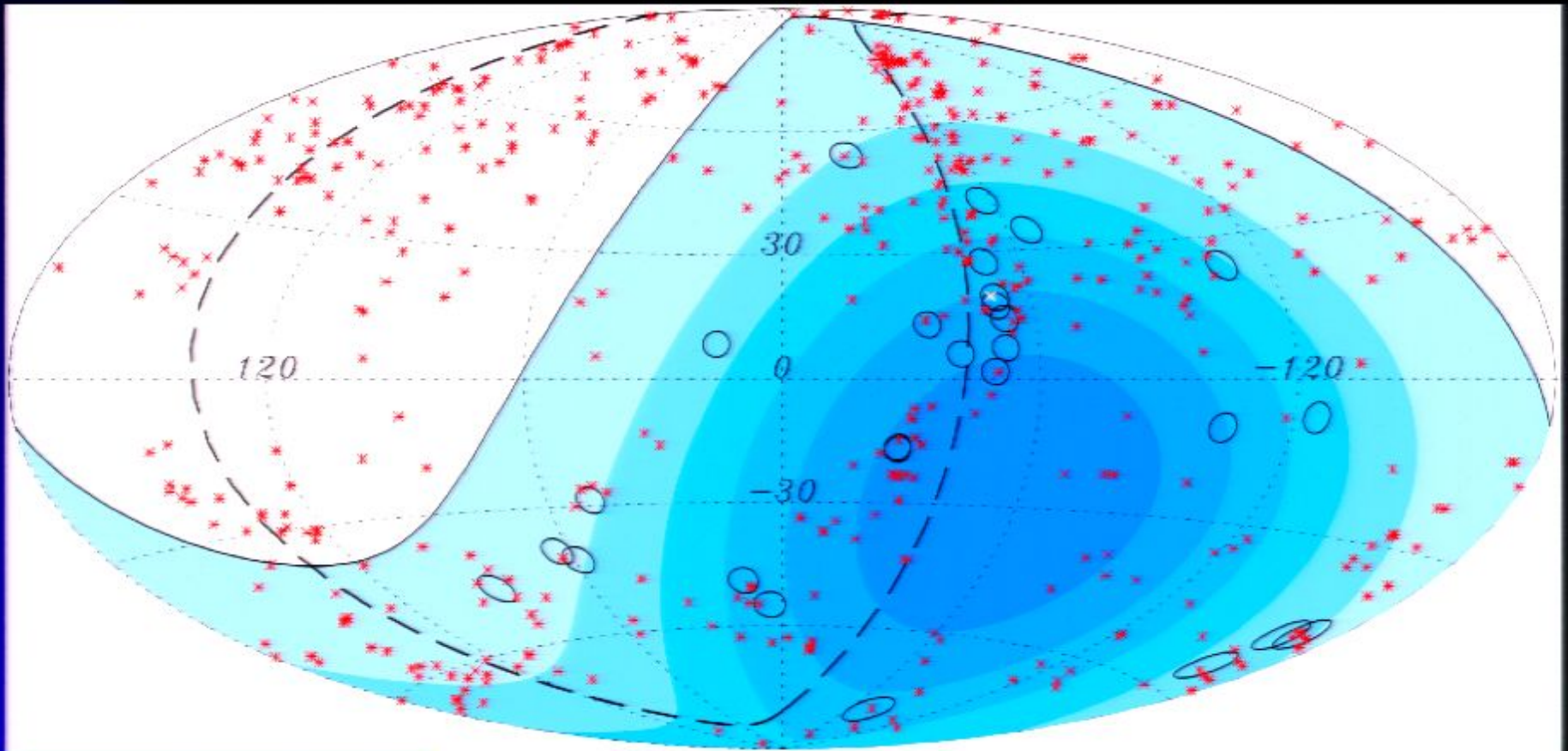


Auger main anisotropy result

Position of the 27 highest energy events on an equal exposure map

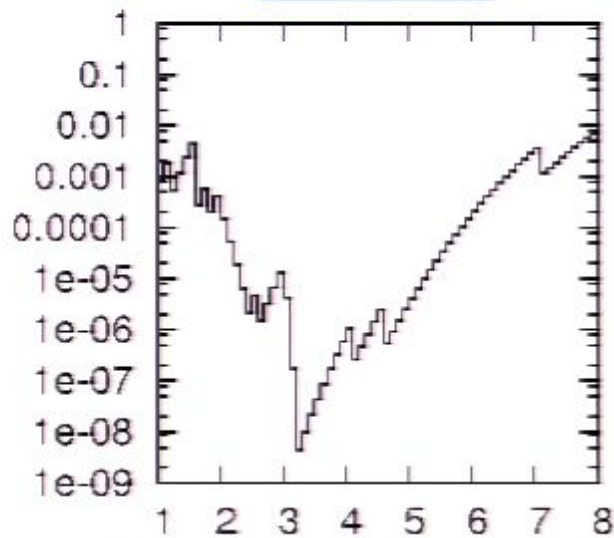


Auger main anisotropy result

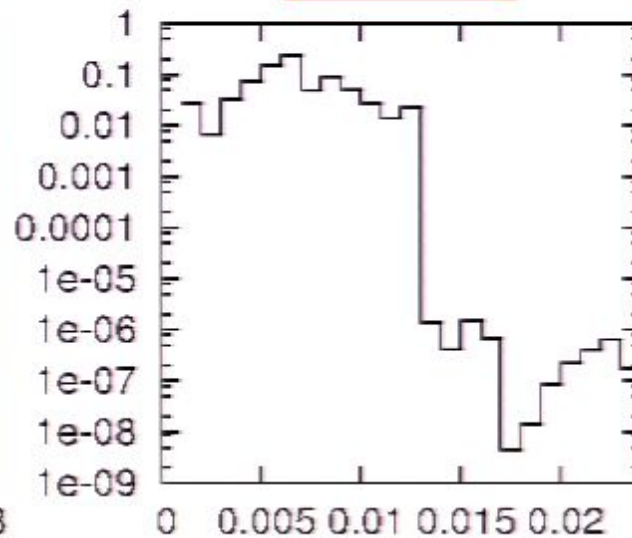


Auger main anisotropy result

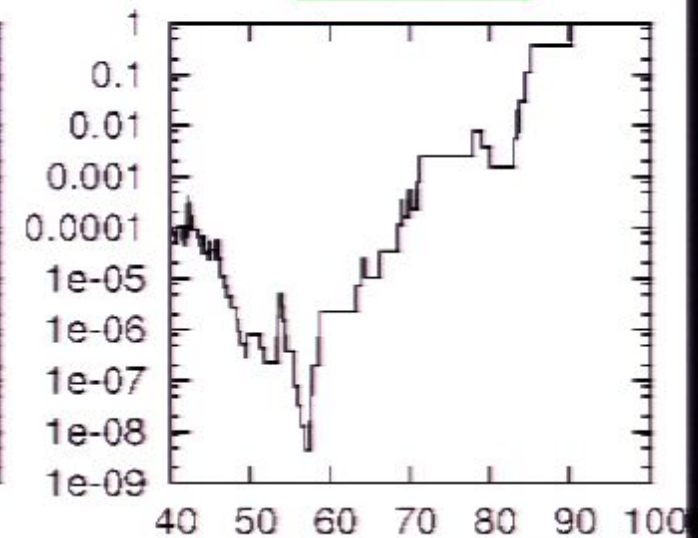
Angular Scan



Redshift Scan



Energy Scan



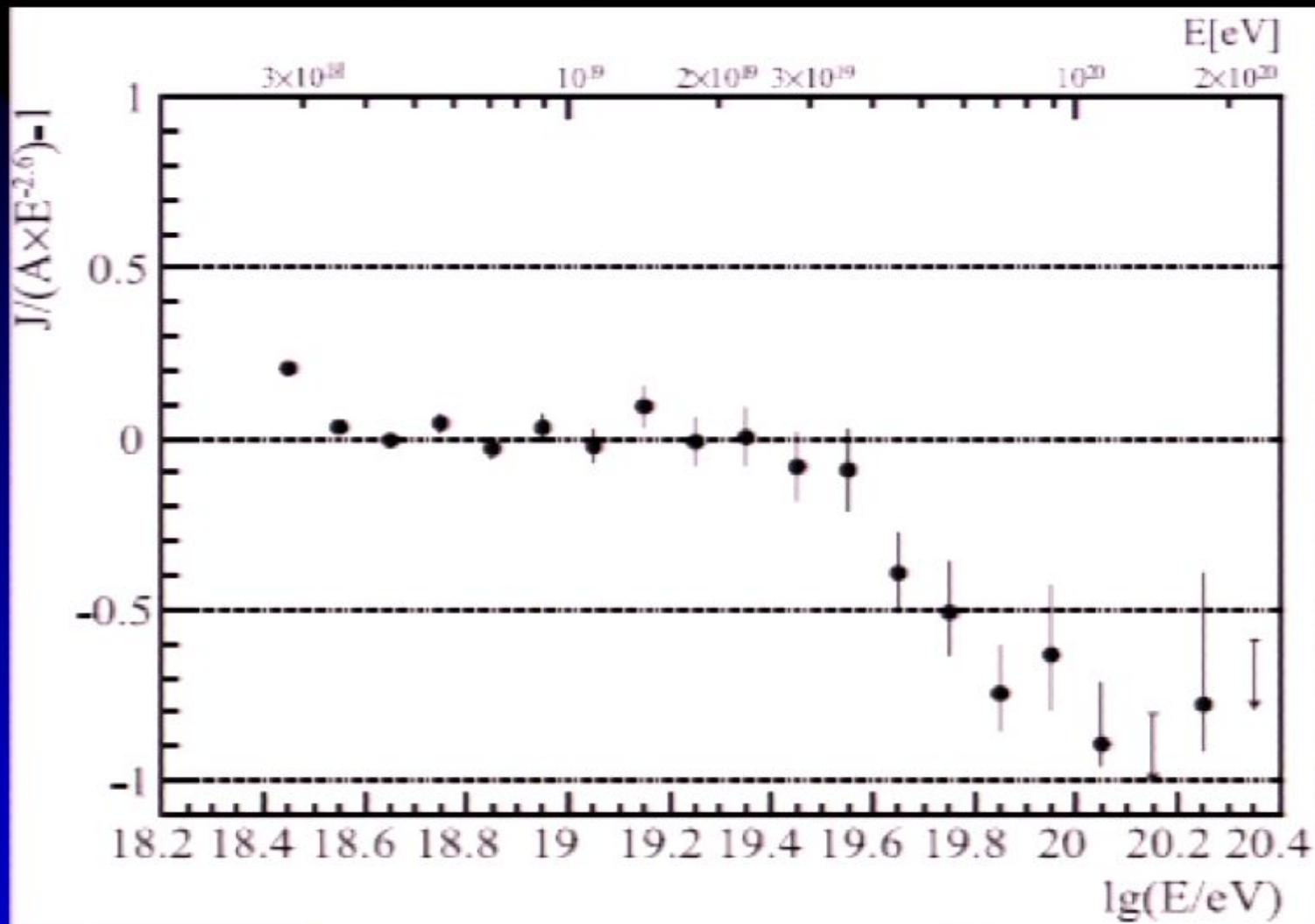
$$\Delta\theta \leq 3.1^\circ$$

$$z \leq 0.018$$

$$(D \leq 75 \text{ Mpc})$$

$$E \geq 56 \text{ EeV}$$

Auger main anisotropy result



The energy above which the correlation is most significant corresponds to an energy where the CR flux drops... (supporting the GZK interpretation)

Significance of the anisotropy result

Véron-Cetty / Véron, 12th Edition, 2006

“This catalogue should not be used for any statistical analysis as it is not complete in any sense, except that it is, we hope, a complete survey of the literature.”

Significance of the anisotropy result

1st step: search between HECR arrival directions and various source catalogues (hard to estimate how many, how intensively, etc.)

(data from 2004/01/01 to 2006/05/26)

A very large “raw significance” was found with the 12th VCV catalogue of AGNs

Even after taking into account generous penalty factors for a posteriori searches and scanning of parameter space

⇒ Did not seem to be fluctuation

⇒ Auger collaboration set up a prescription for future data

Most significant *a posteriori* “correlation signal”:

12 out of 15 events above “56 EeV” are closer than 3.1° from an AGN in 12th VCV with $z \leq 0.018$ ($D \leq 75$ Mpc)

3.2 expected
from isotropic
distribution

Significance of the anisotropy result

2nd step: predefine a region in the sky where there seems to be an excess of CR flux, and see if the next highest energy cosmic rays come from this region



Independent data set
prescribed parameters
unambiguous significance (Confidence Level)

21% chance
from isotropic
distribution

Result: 99% CL that the excess we had seen in the original data set was not a random fluctuation from an otherwise isotropic cosmic ray distribution

8 “correlating
events” out of 13
(2.7 expected)



“CR distribution is anisotropic at the highest energies!”

**Largely corroborated by other analyses, independent
of any source catalogue**

Astrophysical implications?

Not clear yet! (very low statistics to check against any model, whether naive or sophisticated)

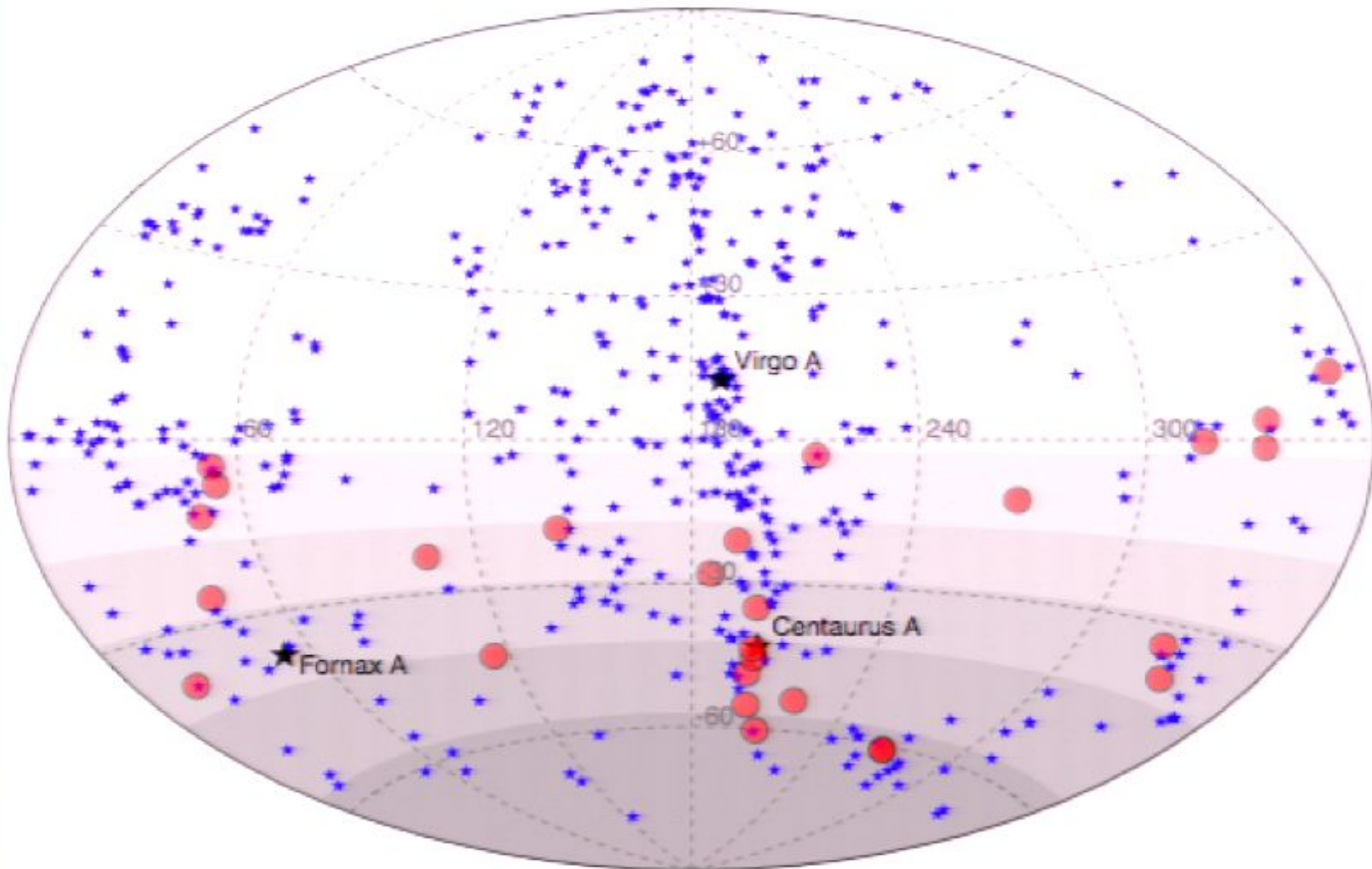
Can UHECRs come from AGNs? → YES

Do UHECRs have to come from AGNs? → NO!

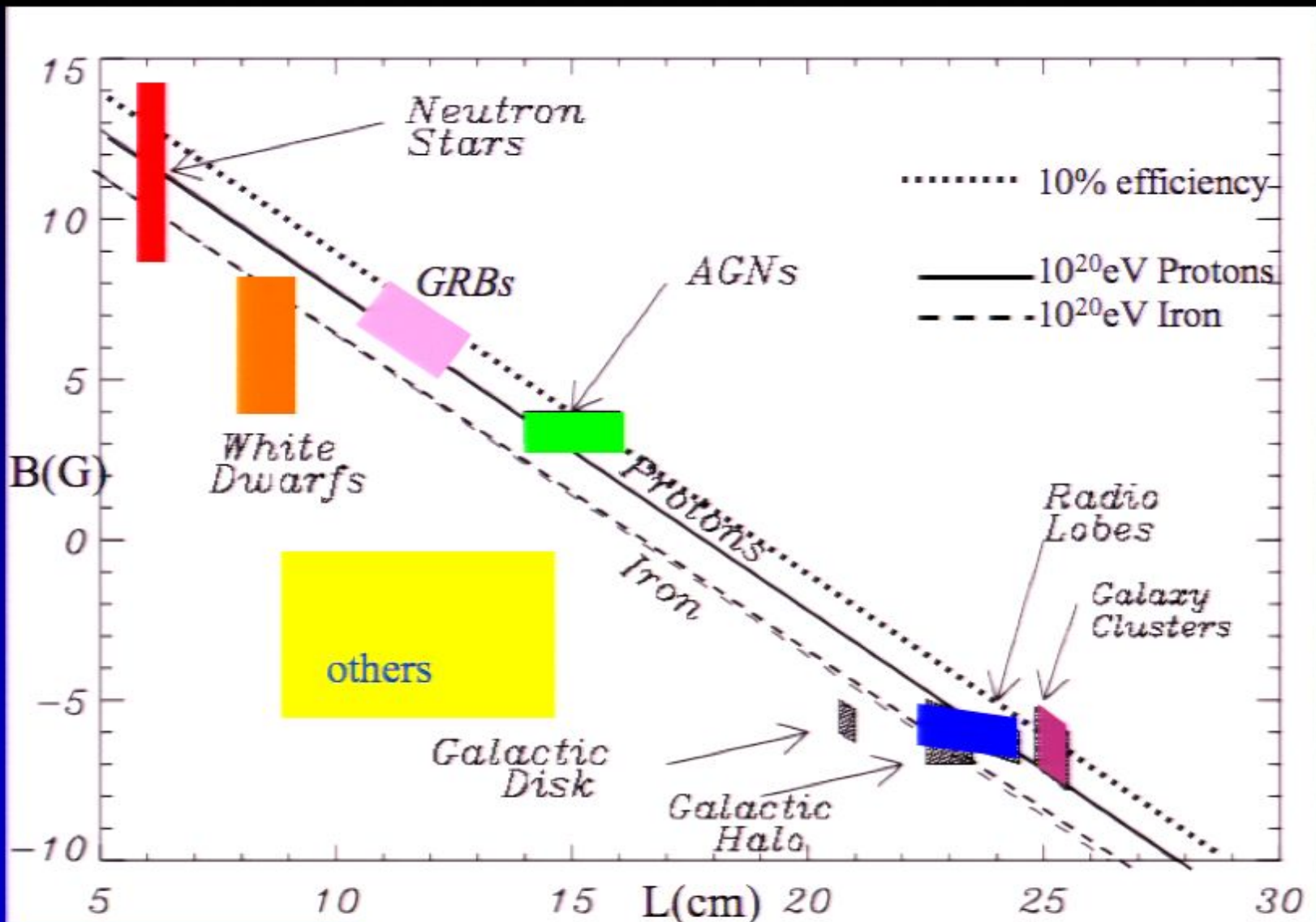
NB: no claim from Auger!

See further analysis of the observed “correlation” and analyses with other catalogues

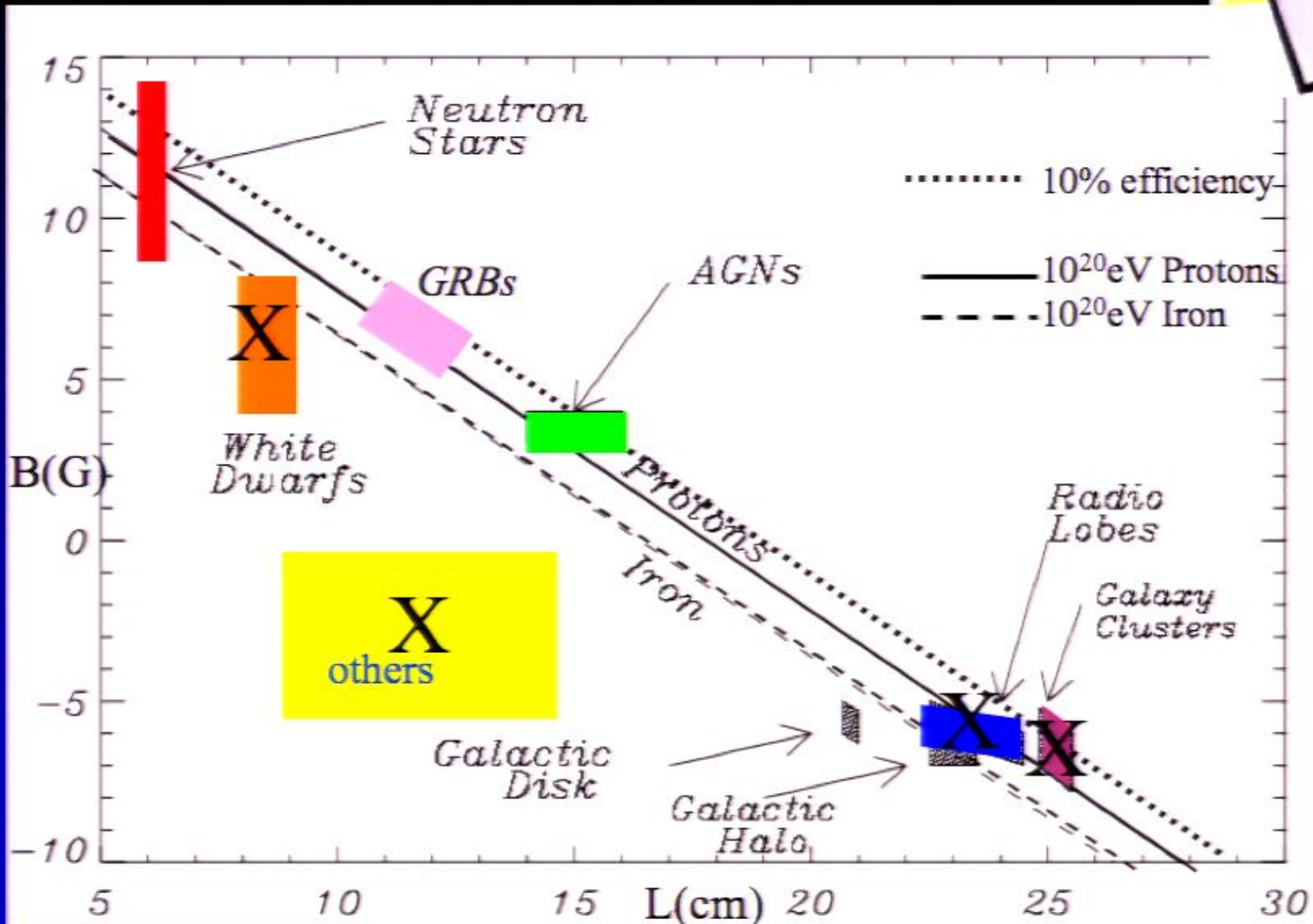
Centaurus A, Virgo, Fornax, etc.



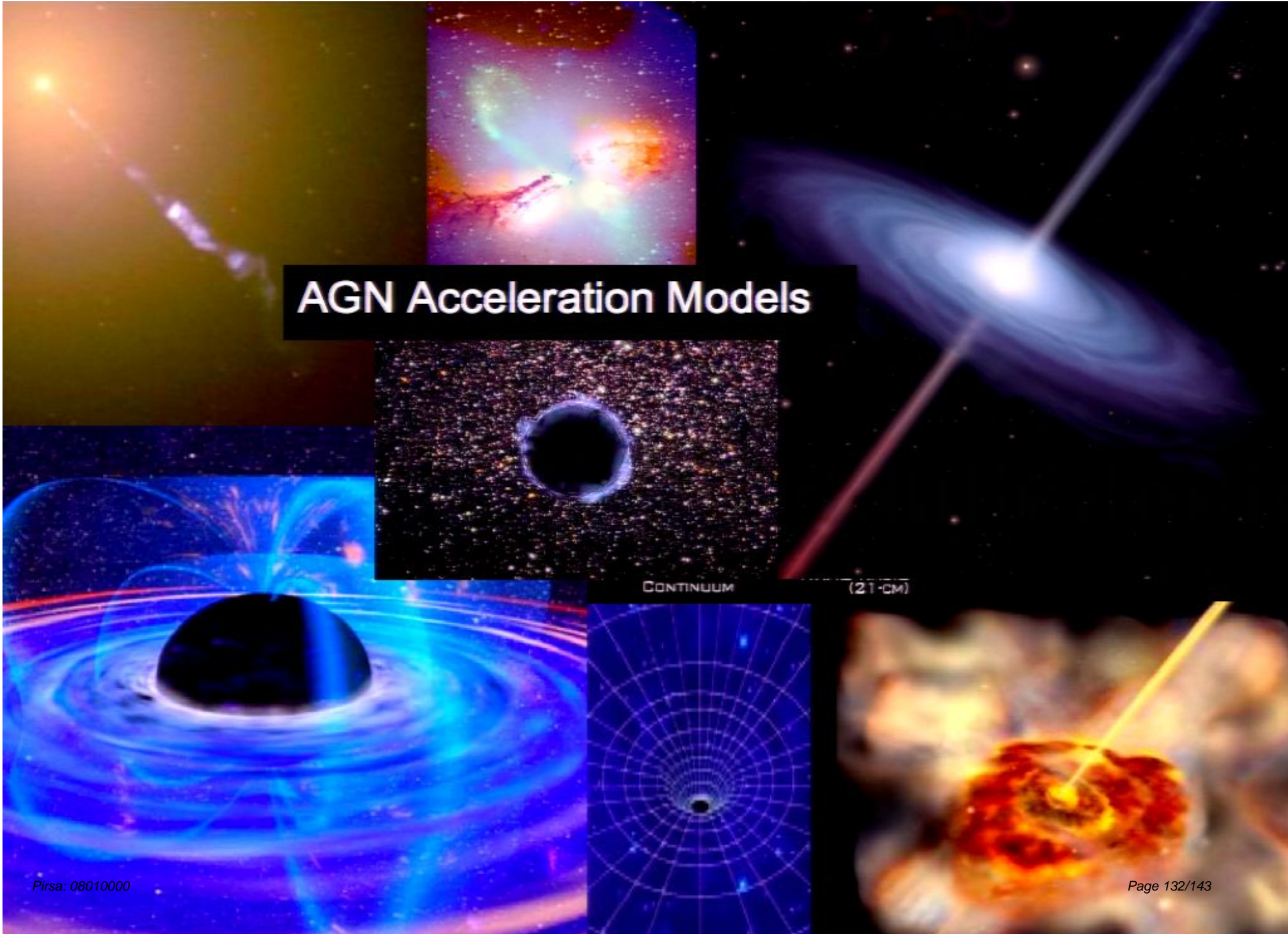
$$E = ZeBL$$



$$E = ZeBL$$



AGN Acceleration Models



Implications for Models

Implications for “proposed” Models

Implications for Models

Implications for “proposed” Models

Implications for Models

TOP DOWN MODELS:

Super Heavy Dark Matter

“beating a dead horse” - photon limit
not correlated with Galactic Halo

Topological Defects

not totally dead yet - neutrino limit
clustering a la AGN - unnatural
but watch astro-ph for
the next (baroque) model!

Astrophysical Accelerators

Death to Galactic Accelerators

Neutron Stars

Magnetars

Microquasars

shocks in the Galaxy

...

Astrophysical Accelerators

Death to very Distant Accelerators

Clusters of Galaxies

(cluster shocks)

Quasars

BL Lacs

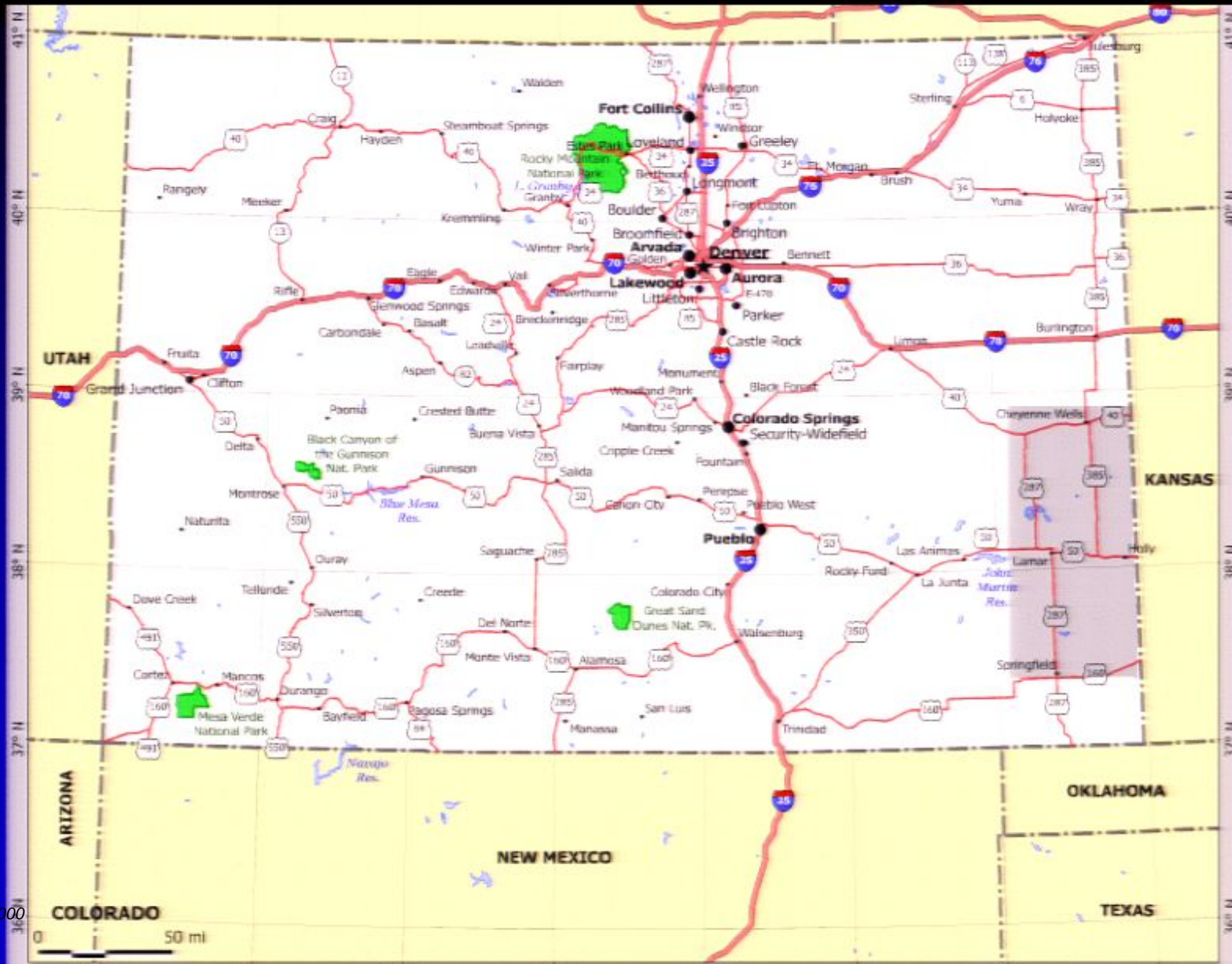
What Next?

Auger SOUTH 2007

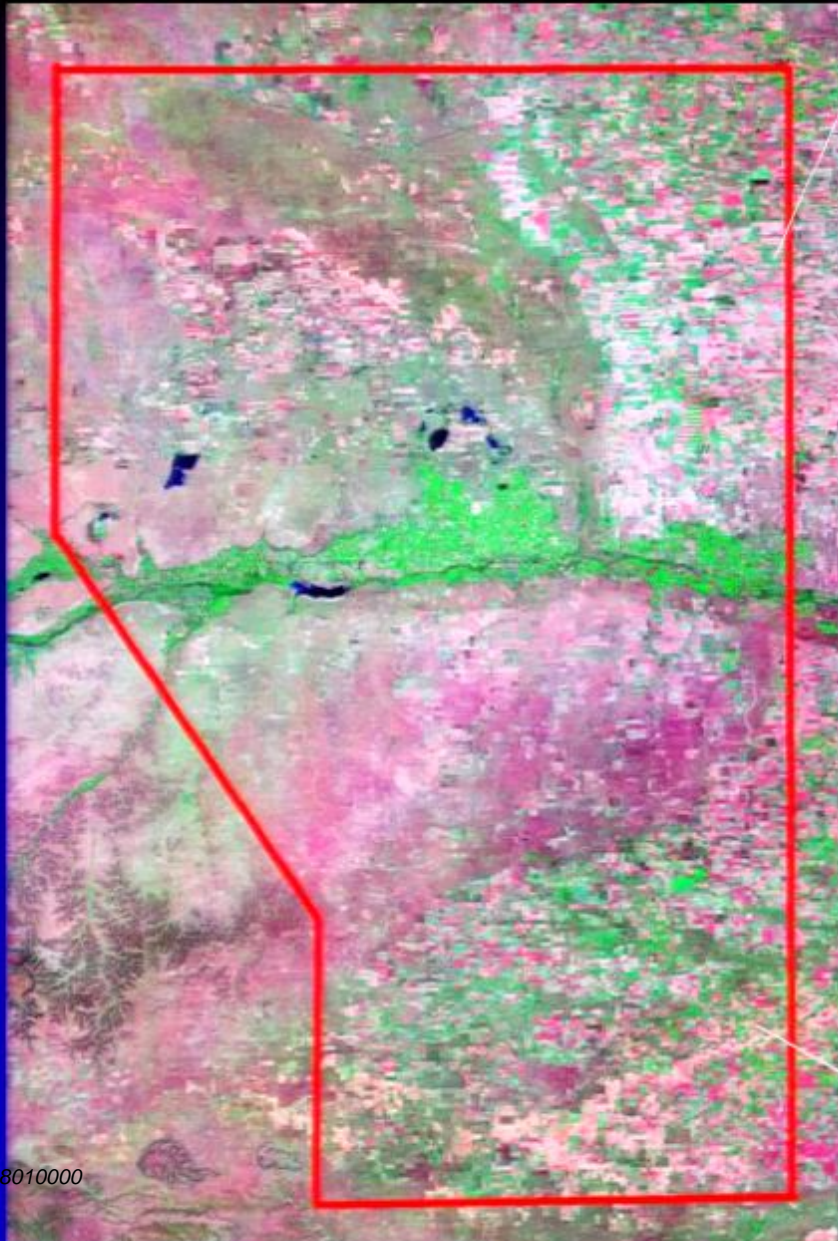
The diagram consists of a large dark blue area on the left side, which tapers towards the right. On the right side, there is a series of colorful triangles pointing upwards, representing different Auger observatory sites. The triangles are colored in red, cyan, orange, yellow, green, and purple. Two horizontal white lines are drawn across the diagram, one above the other, representing different energy levels or detection thresholds.

Auger NORTH, JEM-EUSO,

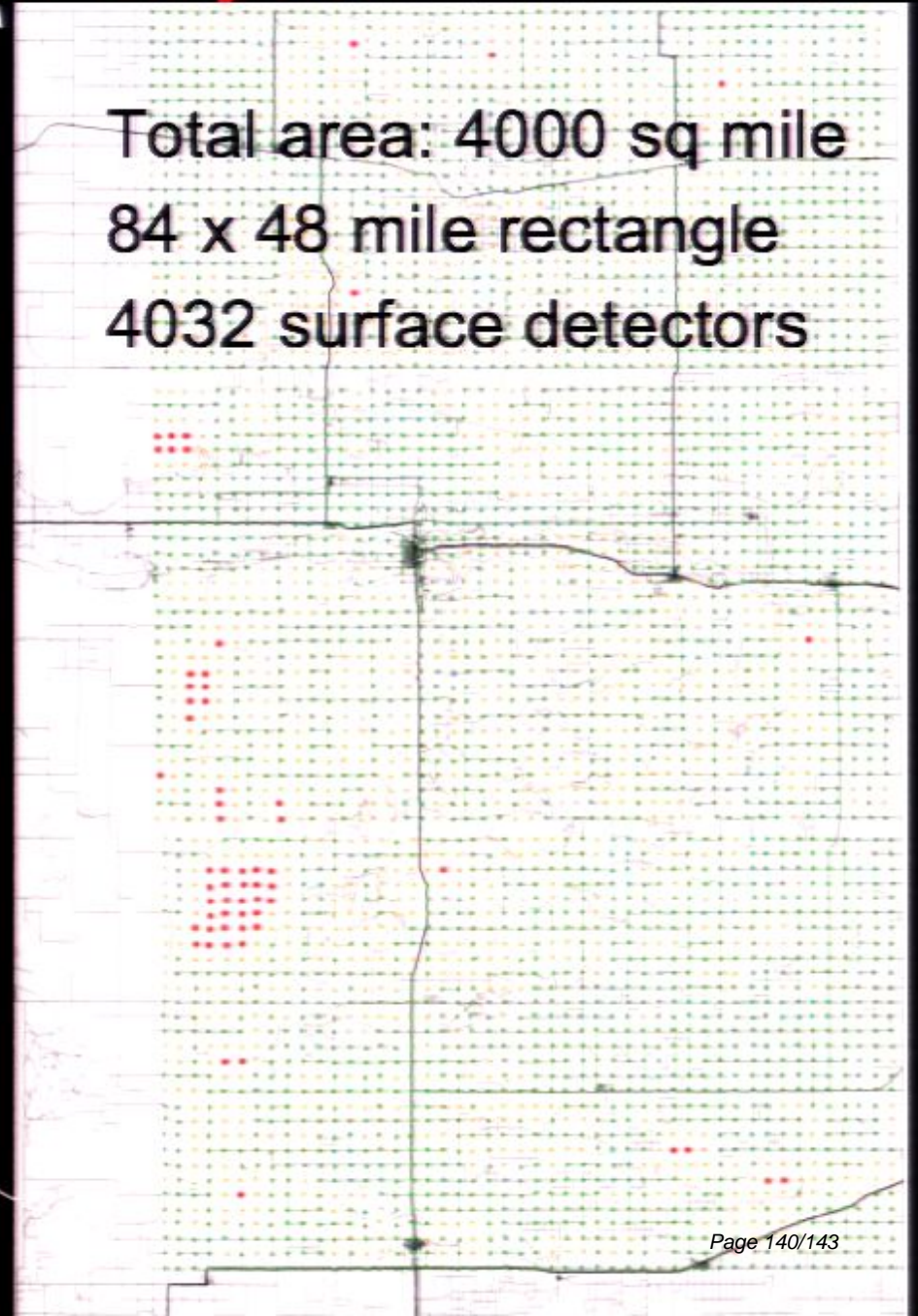
Auger North in SE Colorado



Auger North Layout

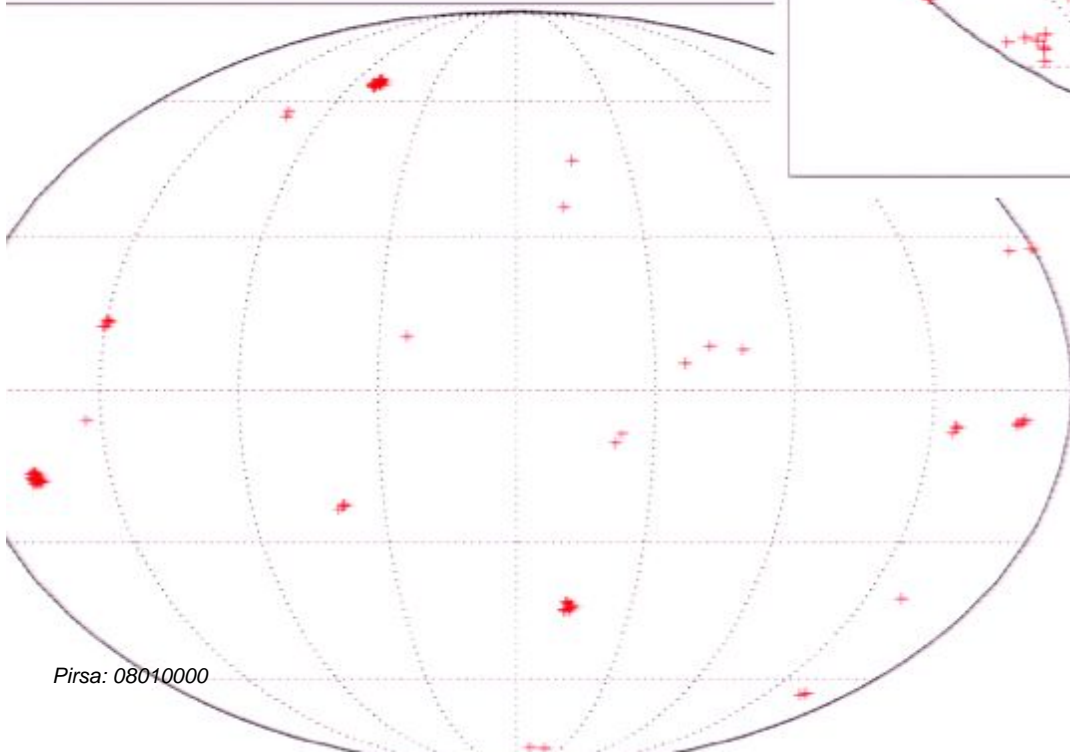
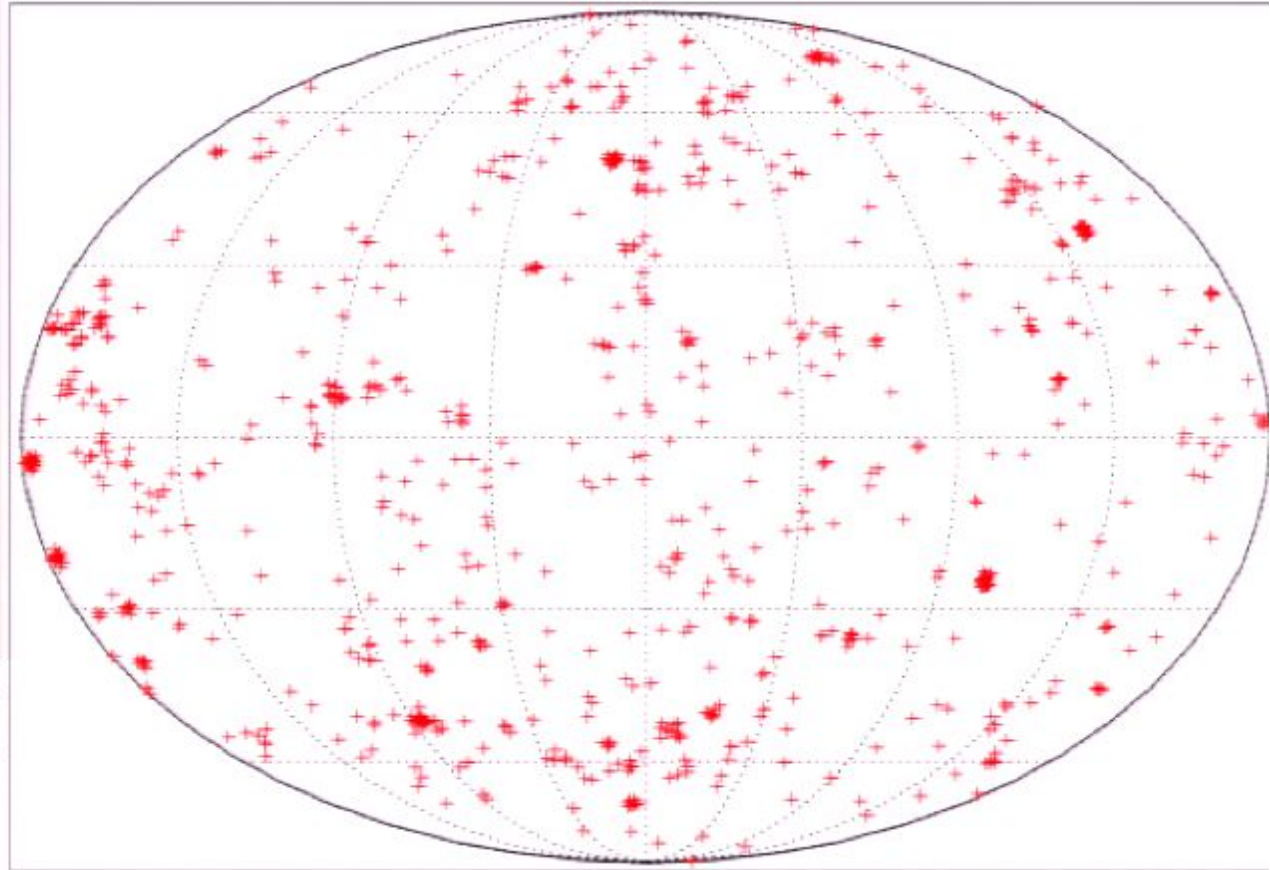


Total area: 4000 sq mile
84 x 48 mile rectangle
4032 surface detectors



Source Spectra

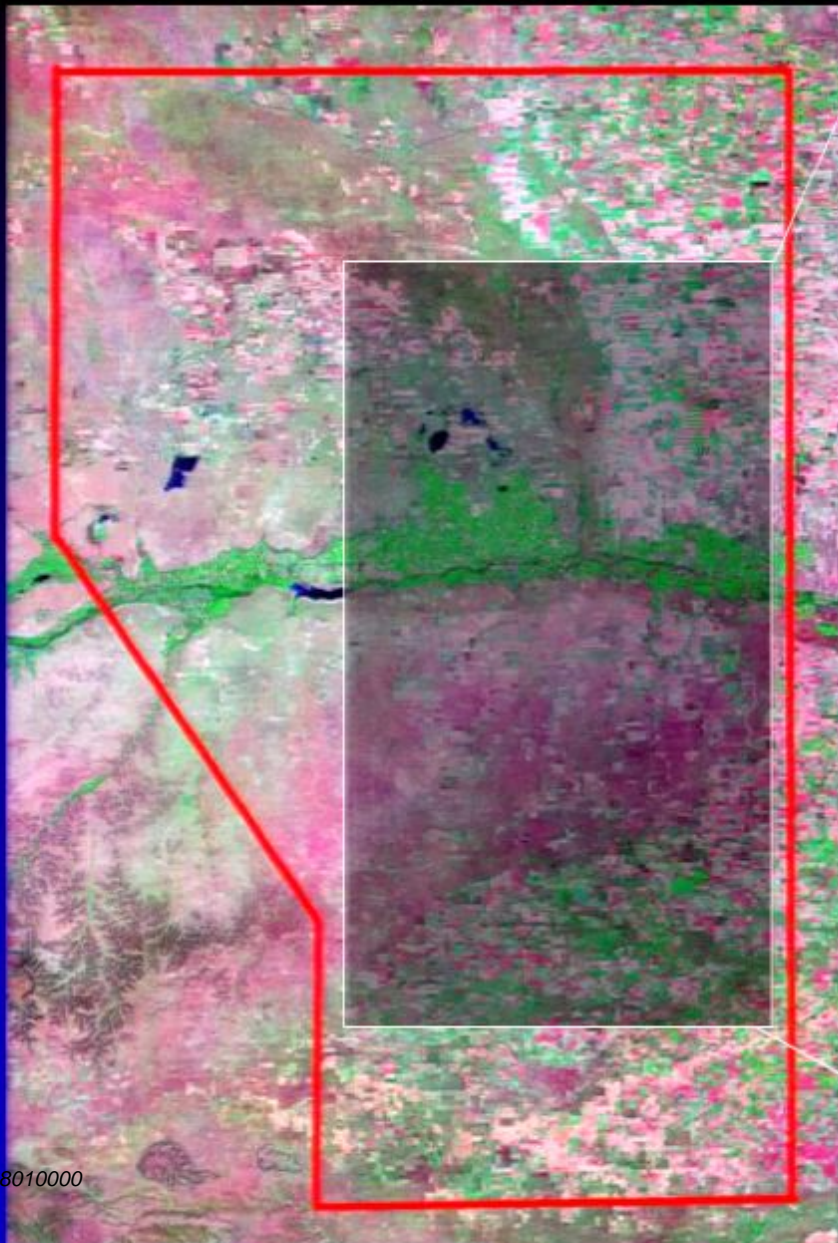
$10^{-5}/\text{Mpc}^3 \text{ AN+S } 10^5 \text{ L}$



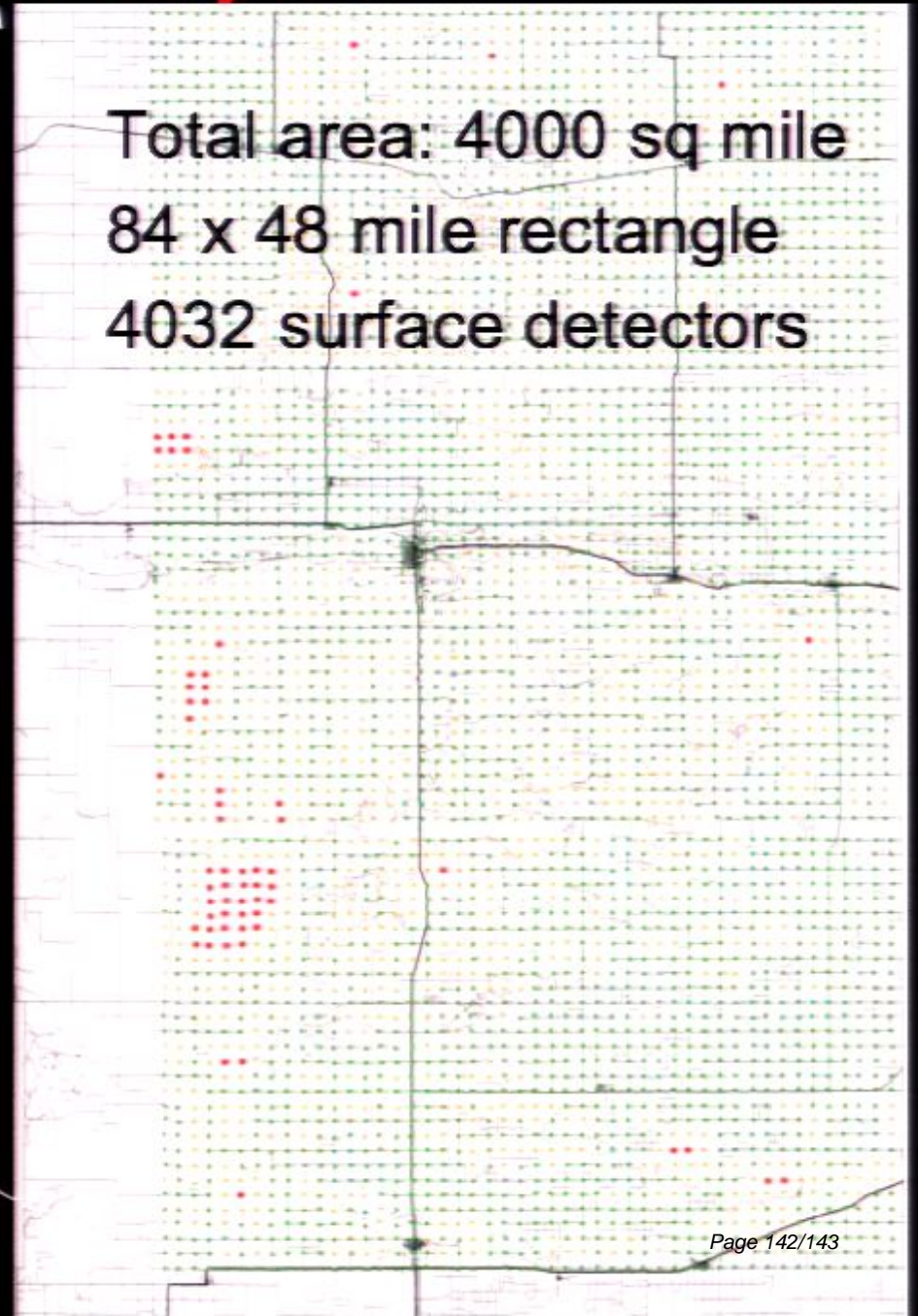
$10^{-3}/\text{Mpc}^3 \text{ AN+S } 7 \cdot 10^5 \text{ L}$

Sources!

Auger North Layout

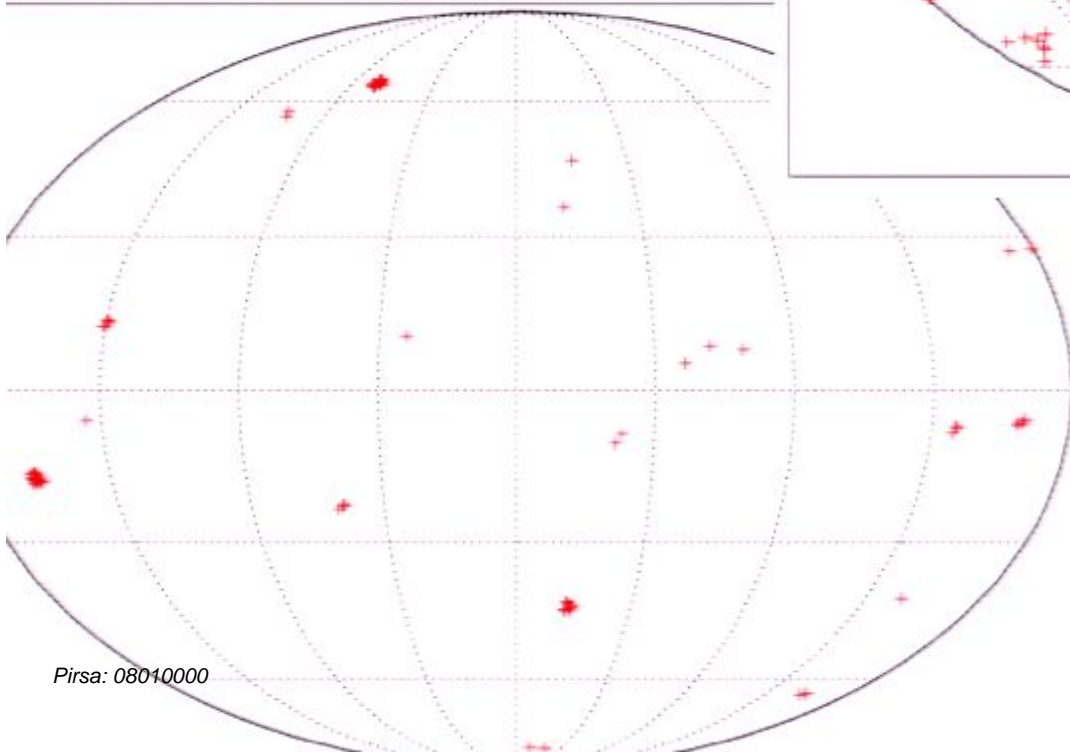
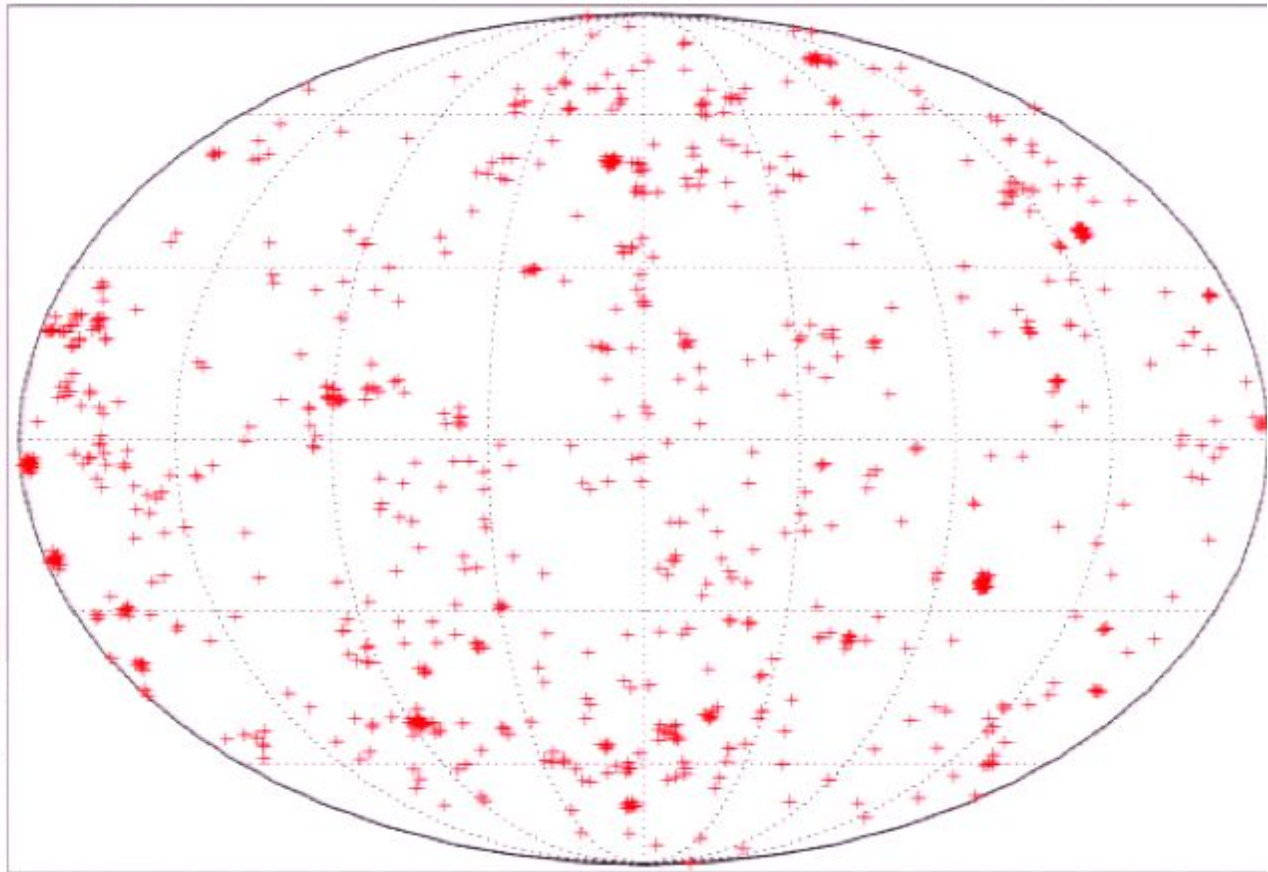


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Sources!