Title: Cosmic Ray experiments and Lorentz Invariance Violations.

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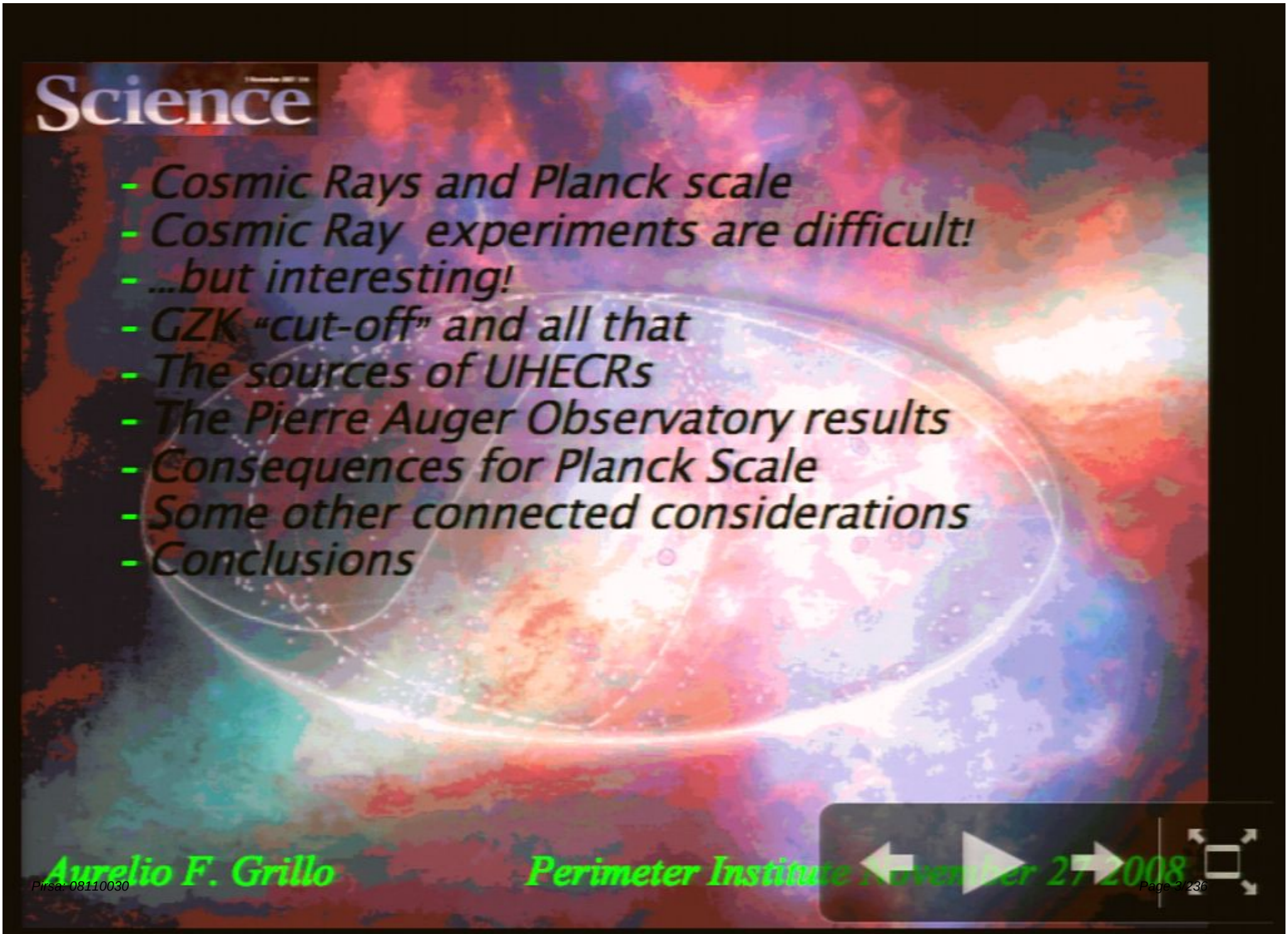
Abstract: As well known, cosmic ray experiments can put strong constraints on possible Lorentz Invariance Violations. In particular, the presence of the so called GZK \'cut-off\' may indicate that protons do propagate in the Universe as expected from relativistic invariance. The presence of this feature in the spectrum has been convincingly indicated by the HiRes and Auger experiments, while the Auger Observatory has given indication on the correlation of Ultra High Energy Cosmic particles with nearby sources, as predicted by the GZK feature. I review the experimental results and discuss in particular both the theoretical and experimental intricacies and the limits on LIV parameters that can be deduced.


Science
Cosmic Ray experiments and
Lorentz Invariance Violations
Aurelio F. Grillo
Perimeter Institute November 27 2008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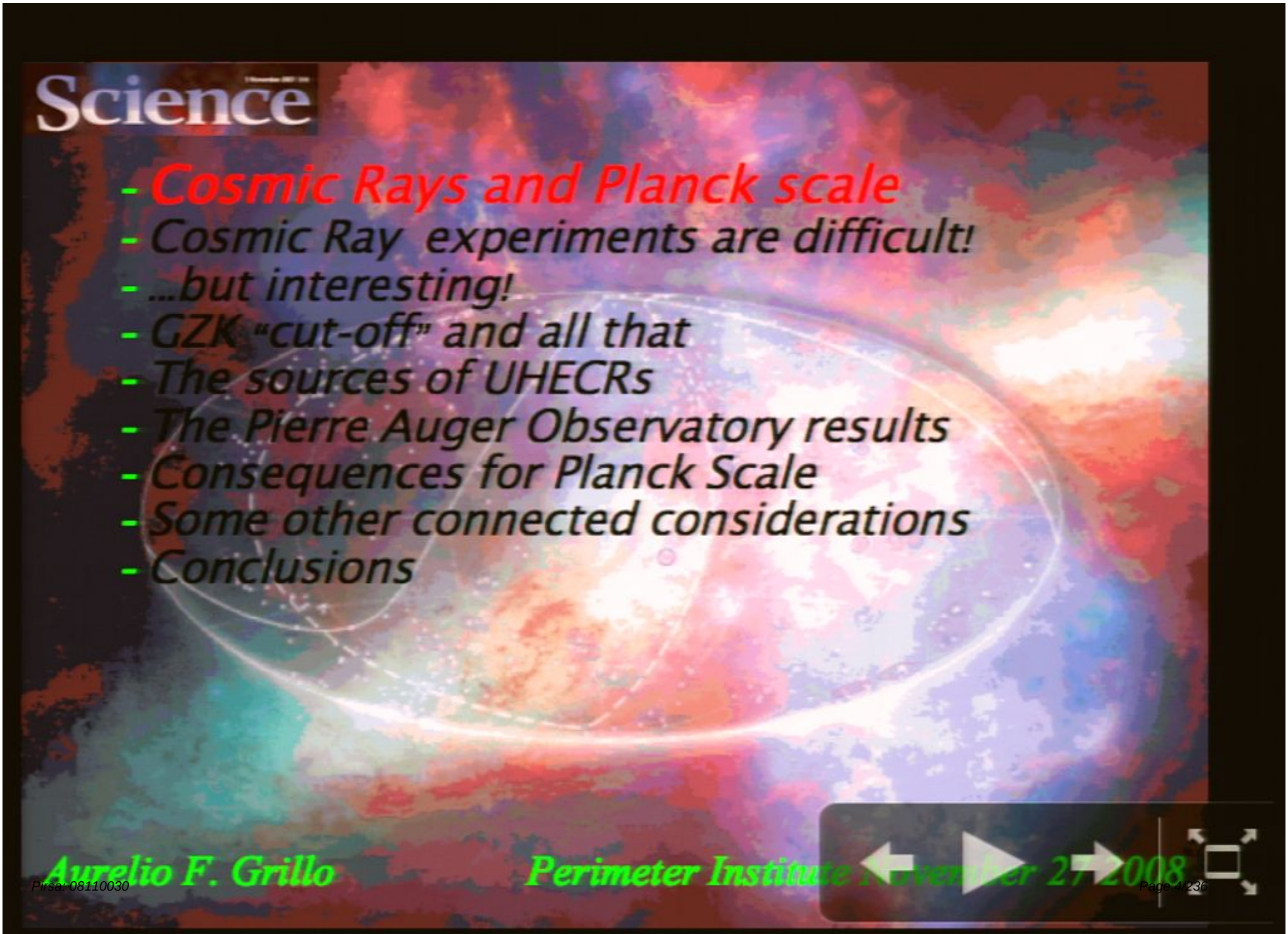
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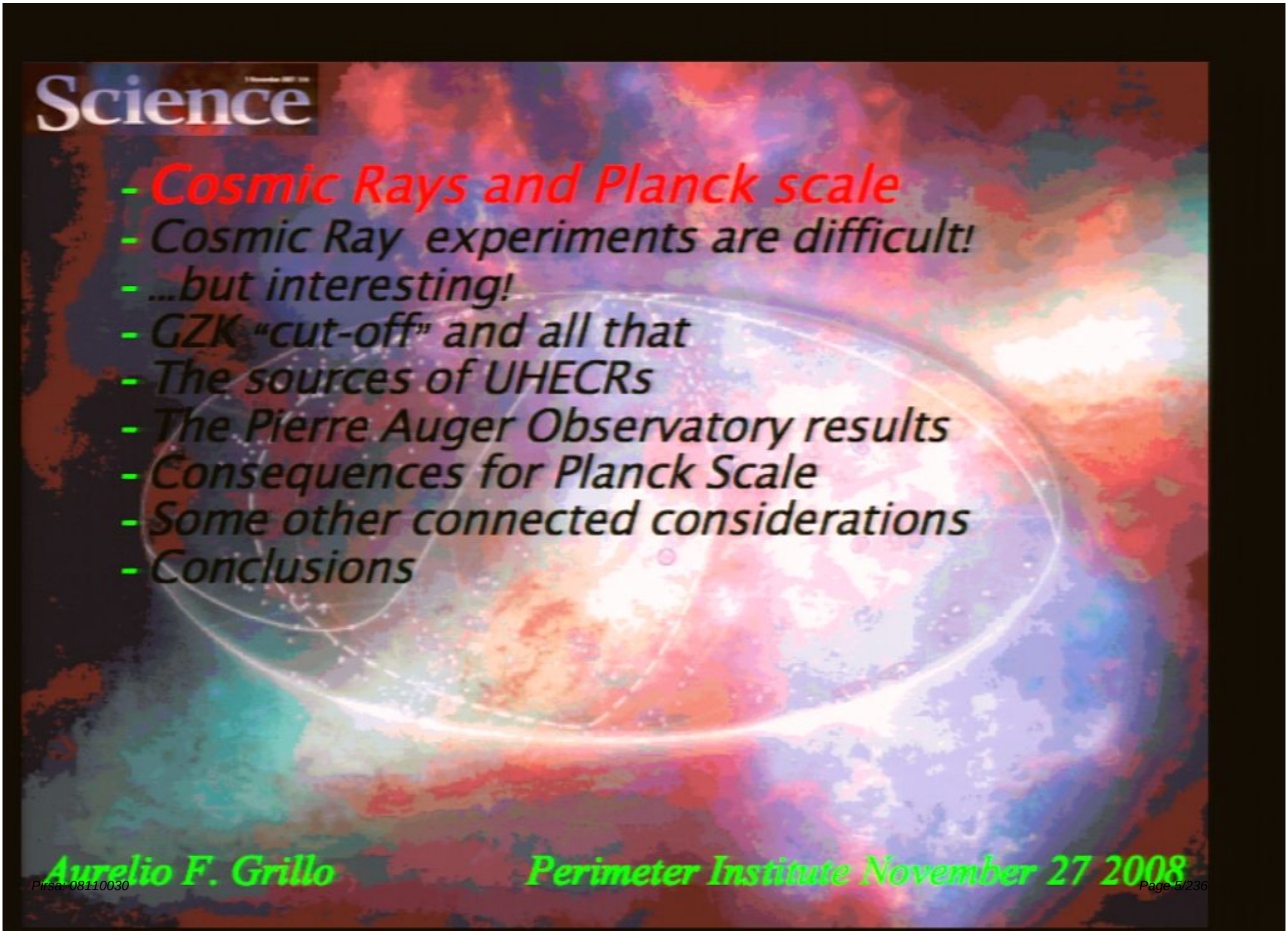
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Why UHECRs can probe Planck scale ?

High Energy Cosmic Ray Physics from Underground at LNGS

- LVD
- MACRO
- Coincidences with EAS-TOP
  (see G.Navarra)
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as laboratory for testing Special Relativity?

(P. Blasi, AFG, in preparation, submitted to XXV ICRC)

Very simple idea: What are the hypotesis leading to the ZKG cutoff?

→ photoproduction $\gamma p \to \pi p$ very well known in Lab. ($\vec{p}_p = 0$) frame.
→ translates into a threshold for EHE protons in the γ_{ZK} reference frame.

→ IF PA experiment will find a sign of ZKG cutoff
↦ *direct* experimental verification of equivalence of reference frames moving with relative $\gamma \simeq 10^{11}$

Other thresholds possible with even larger γ (e.g. pair production by 10^{21} eV γs on IG radio bkg), but more model dependent or less easily (?) detectable

cfr also S. Coleman, S. Glashow (HUTP-97/A008, hep-ph/9703240 5 Mar 1997) who reach similar numerical conclusions, in a slightly more model dependent, more indirect way.

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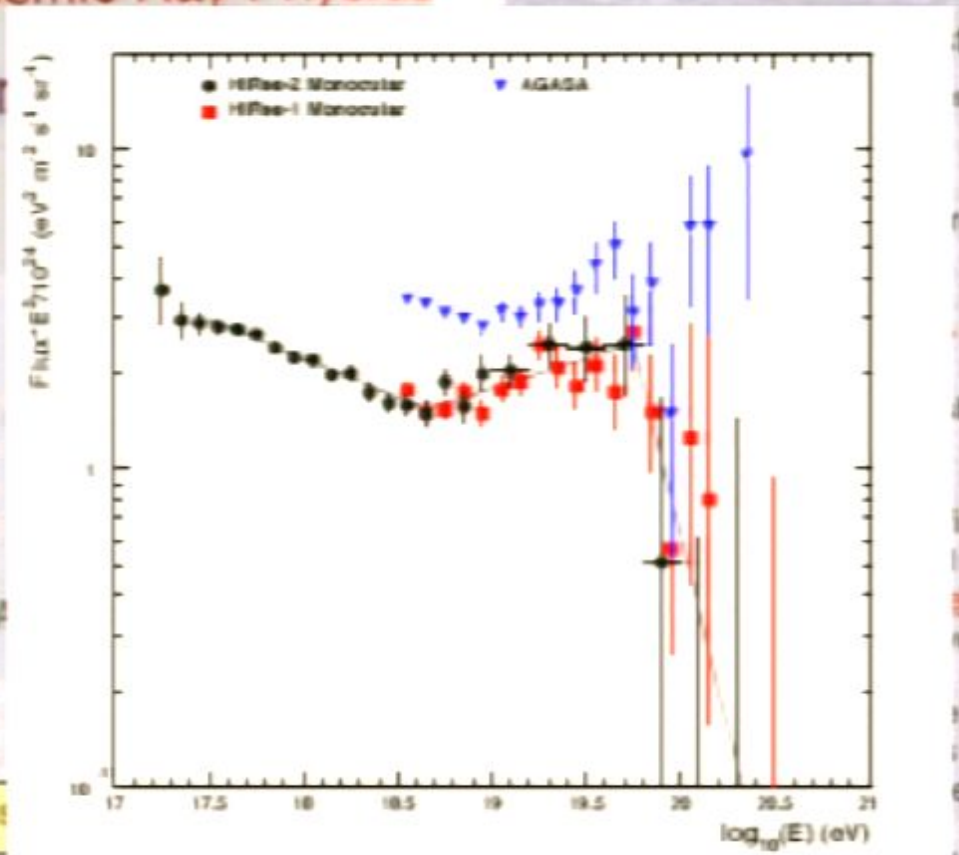

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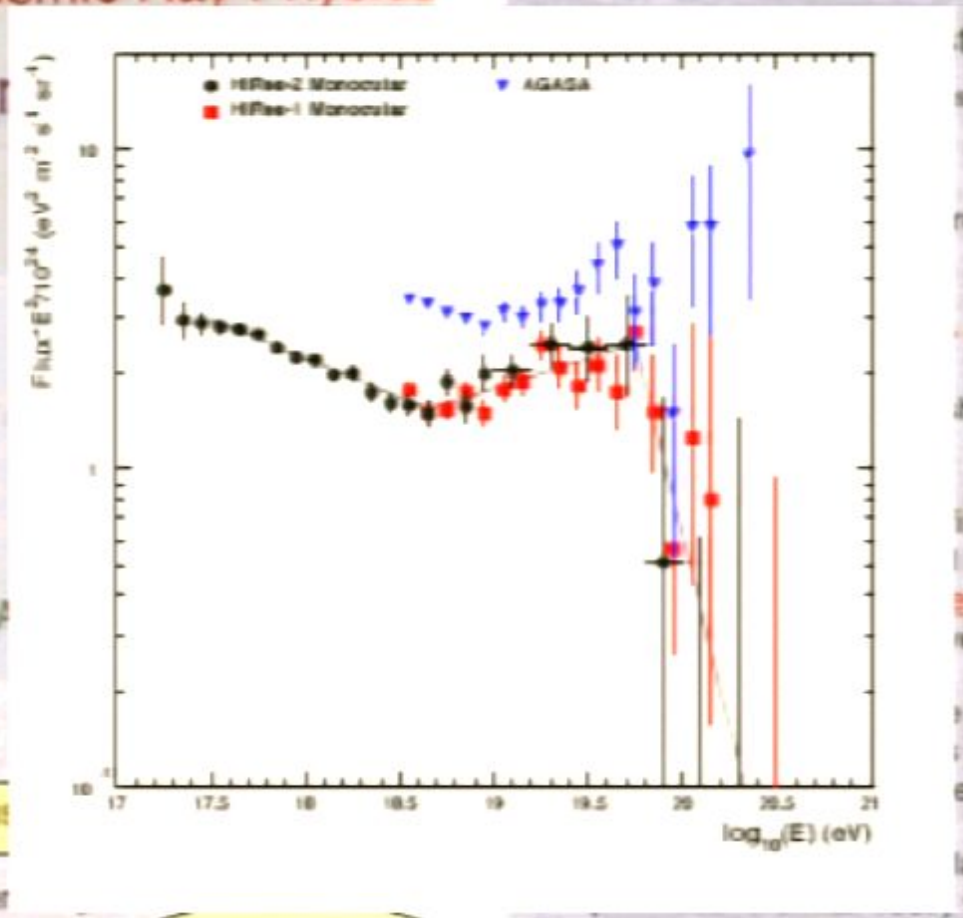

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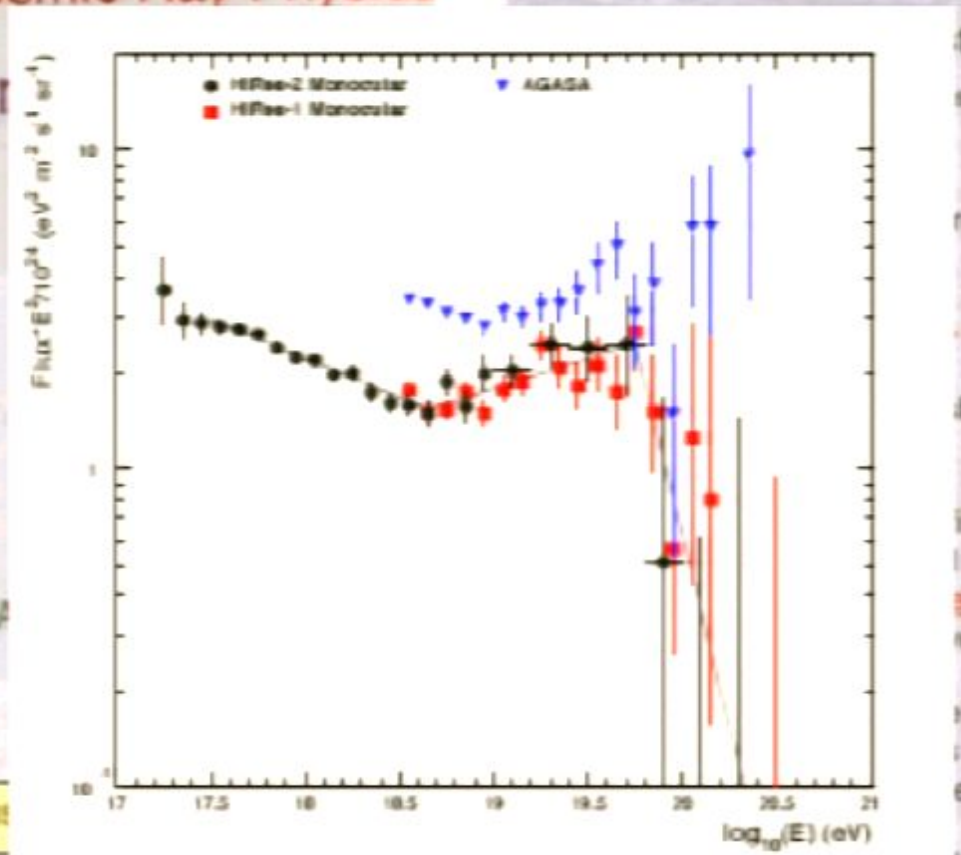

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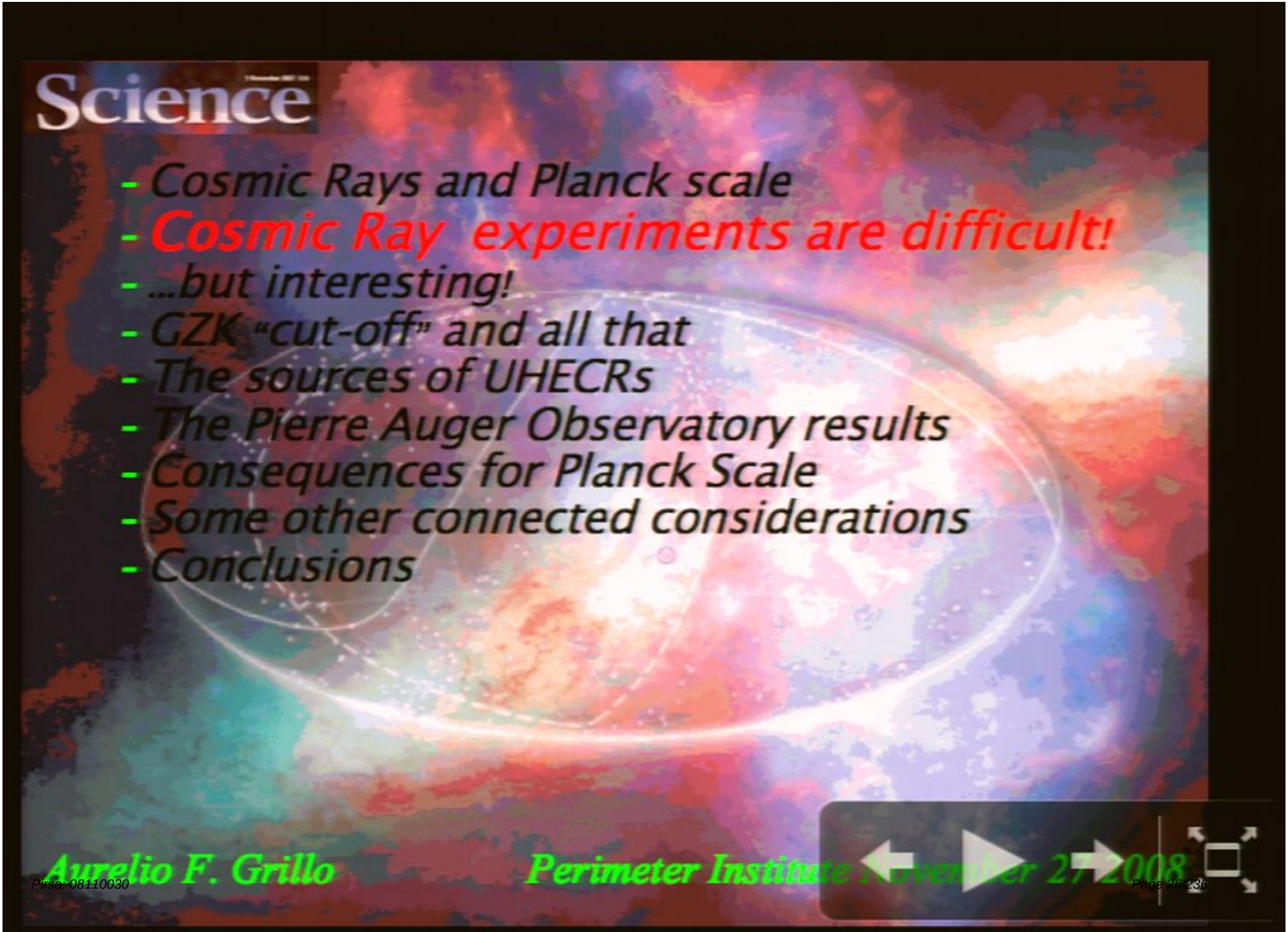
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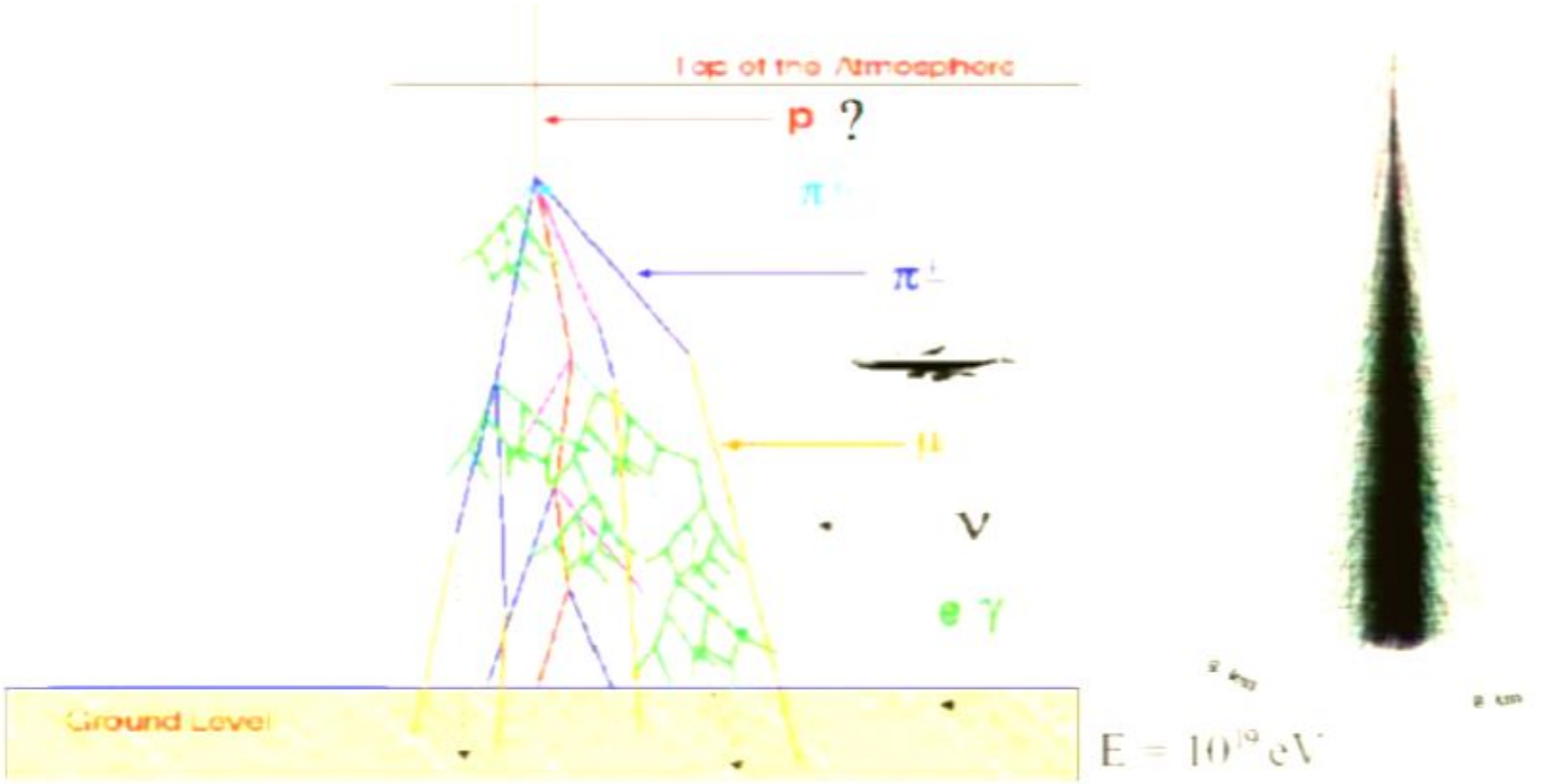

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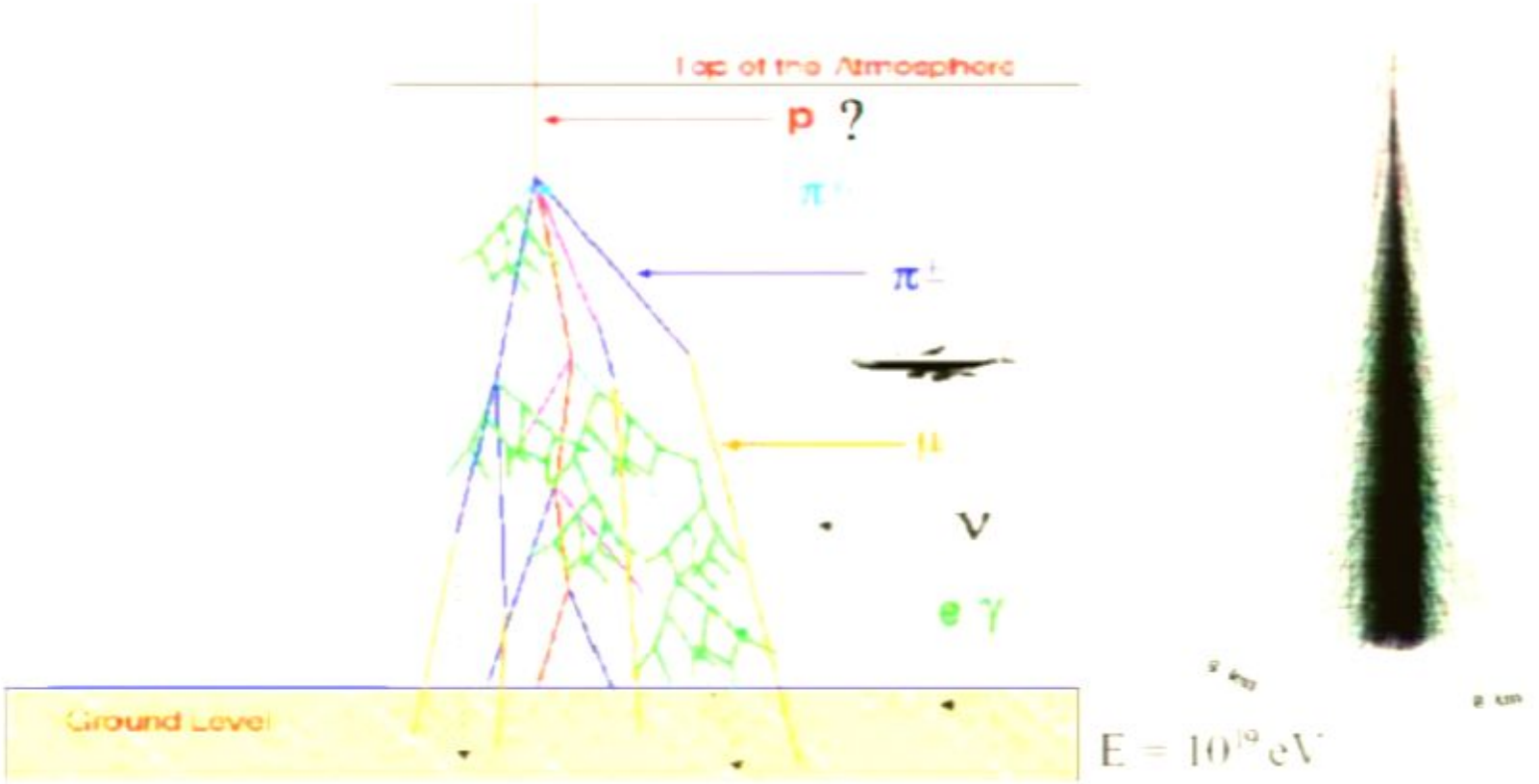

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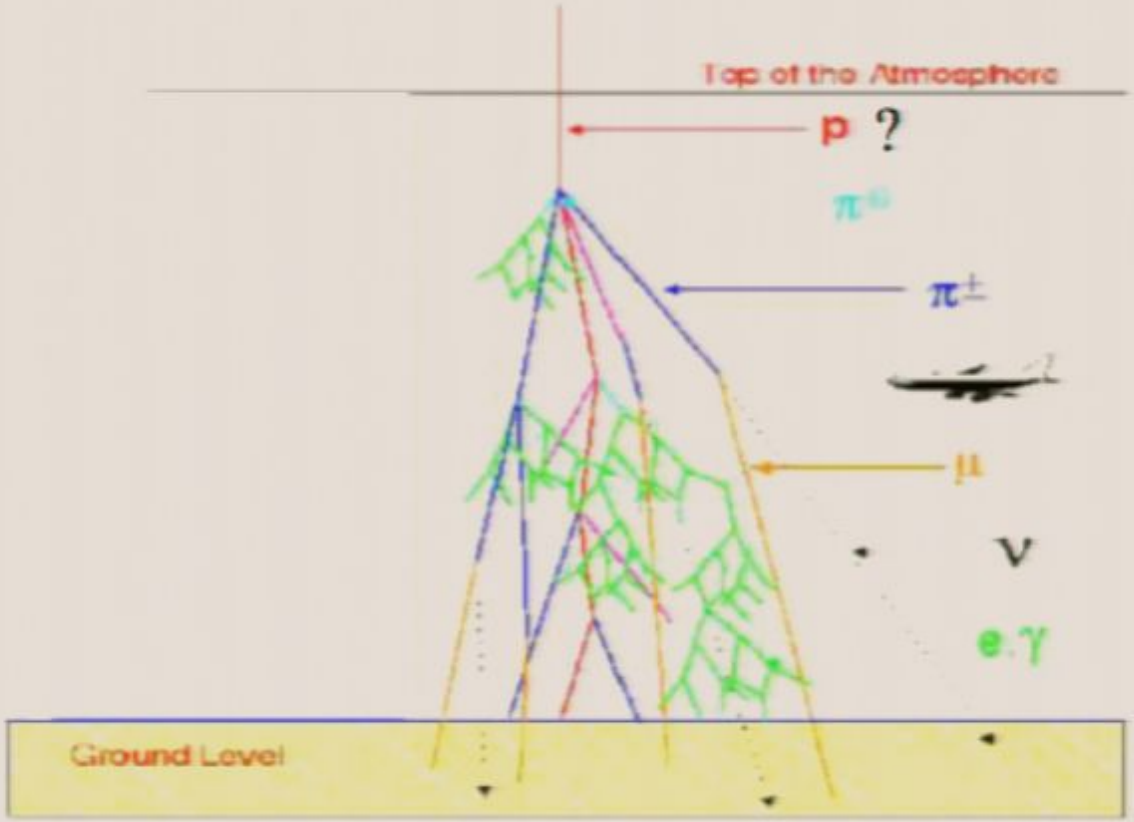

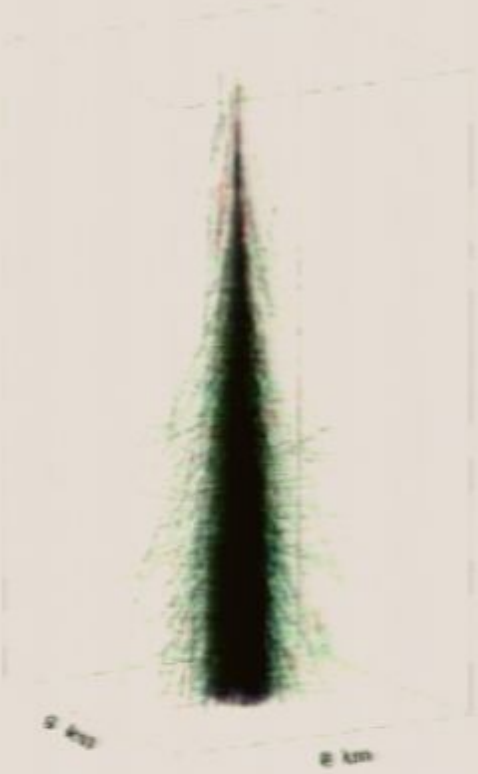

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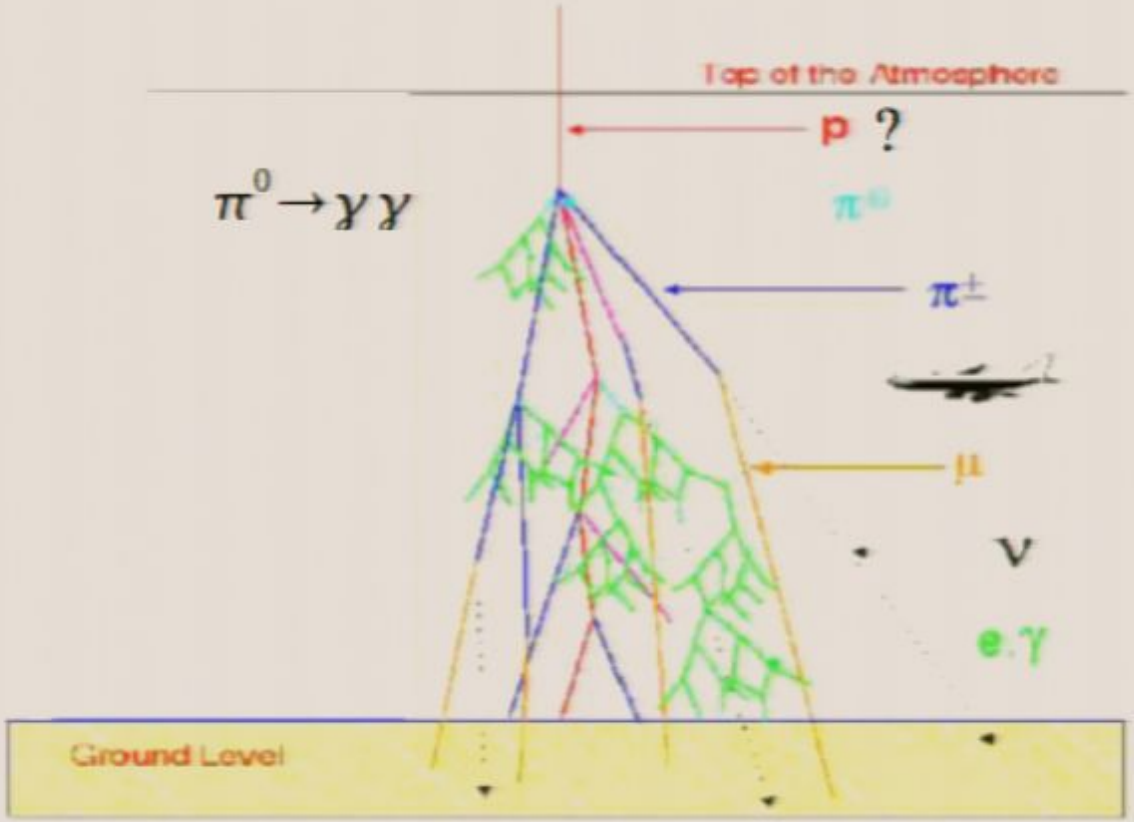

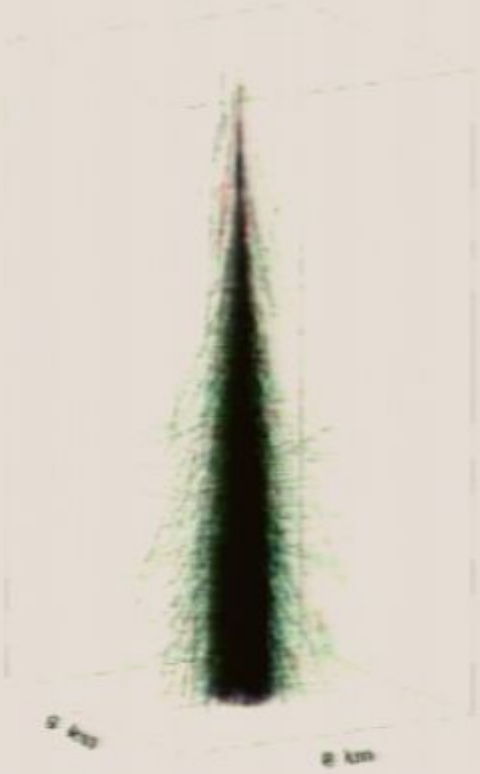

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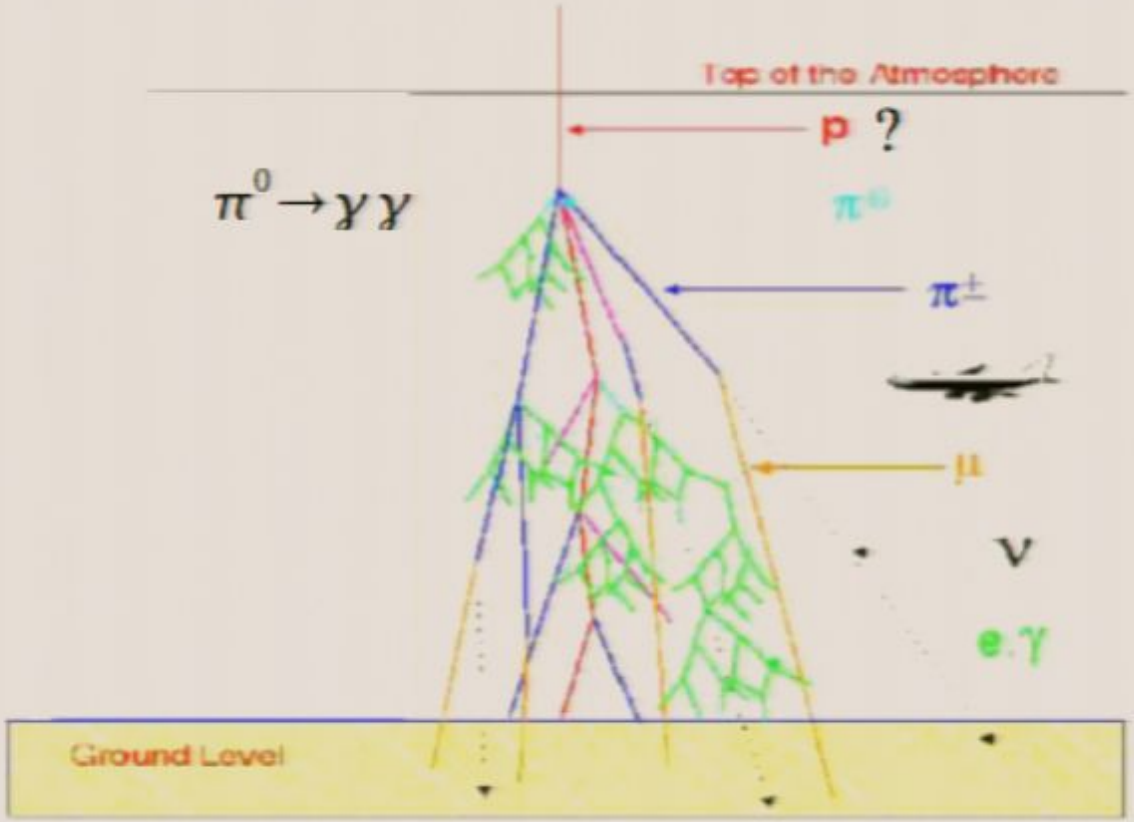

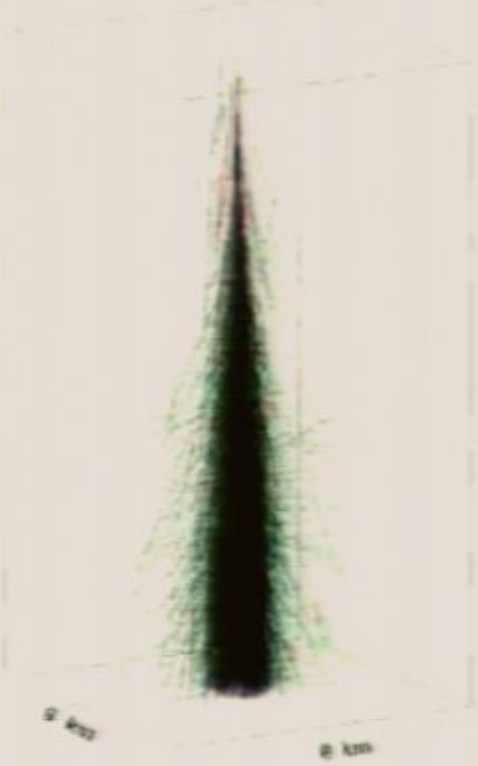

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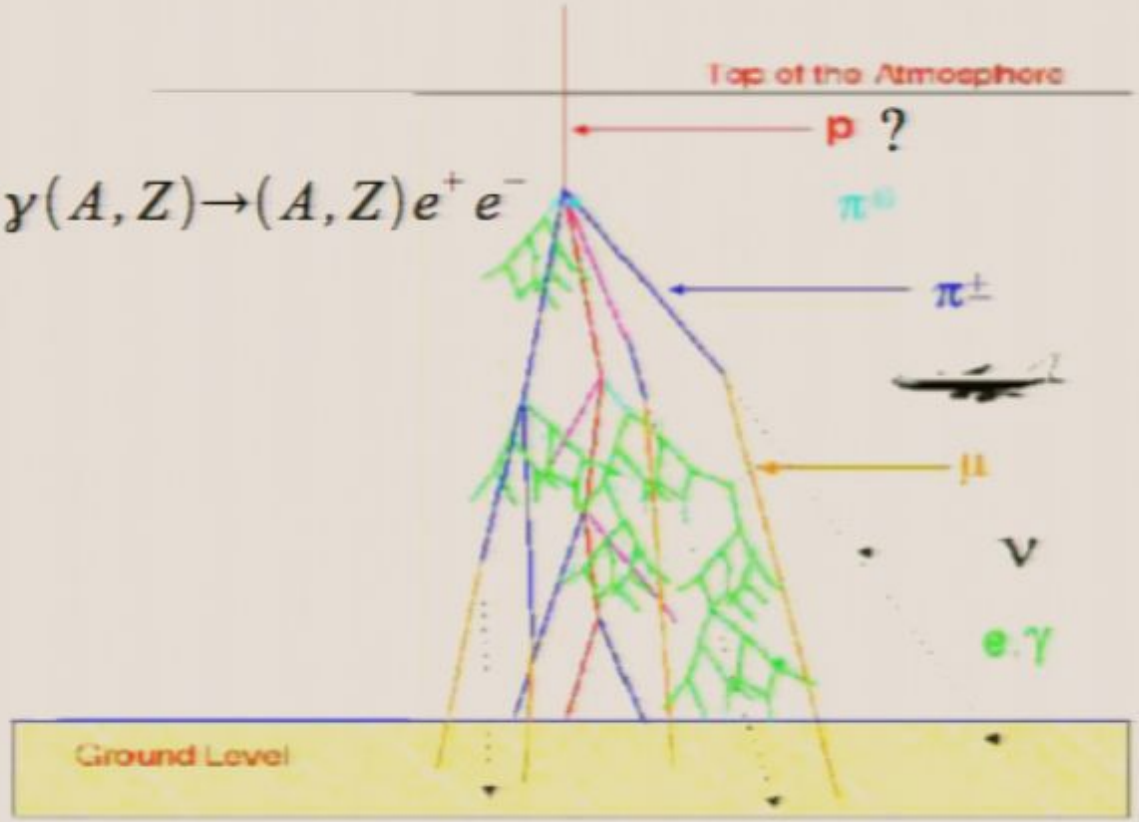

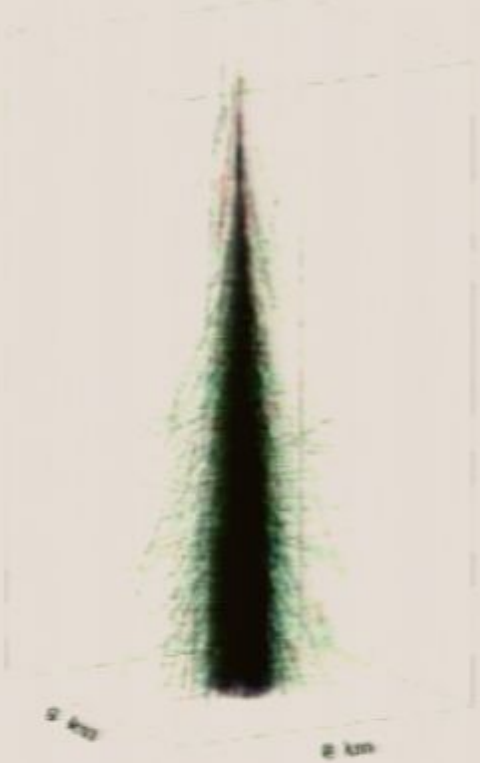

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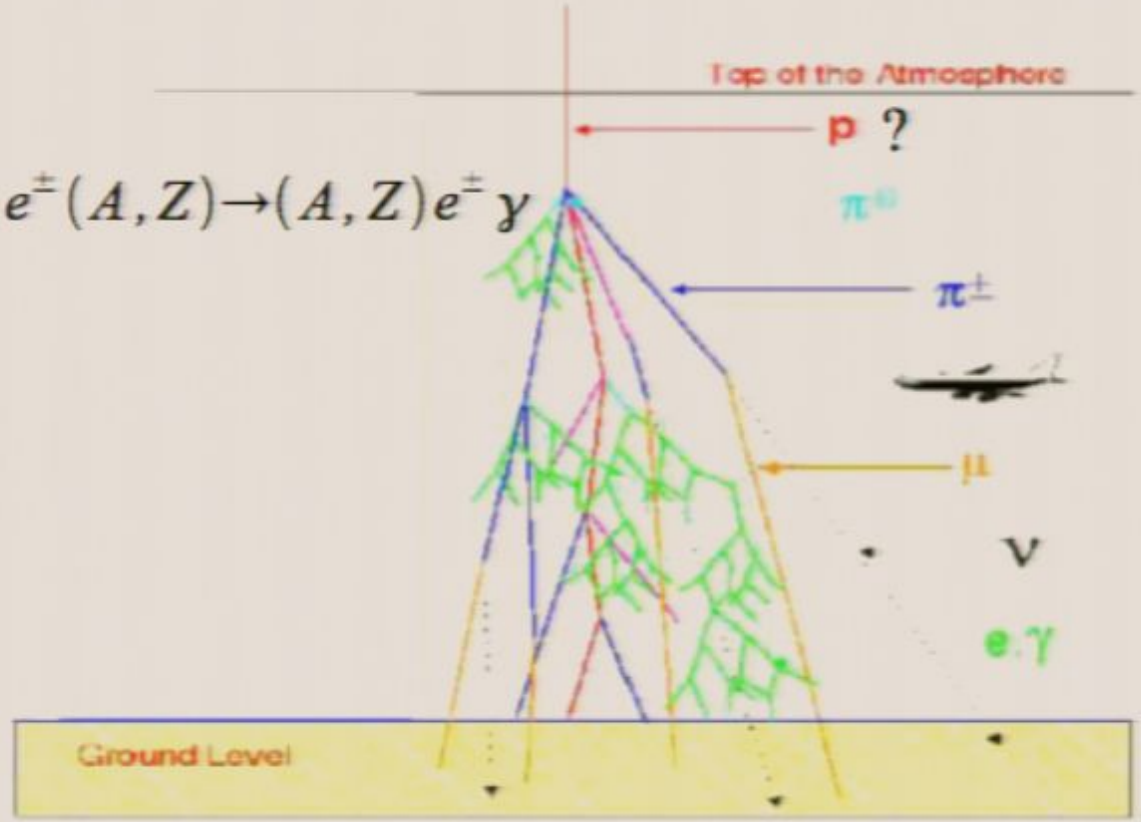

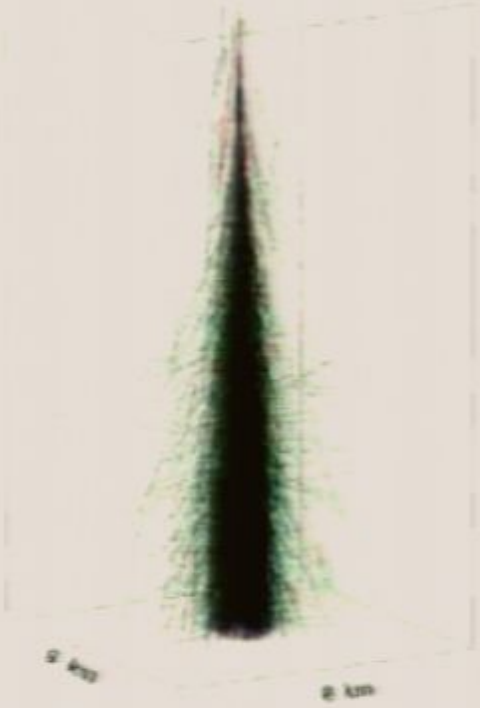

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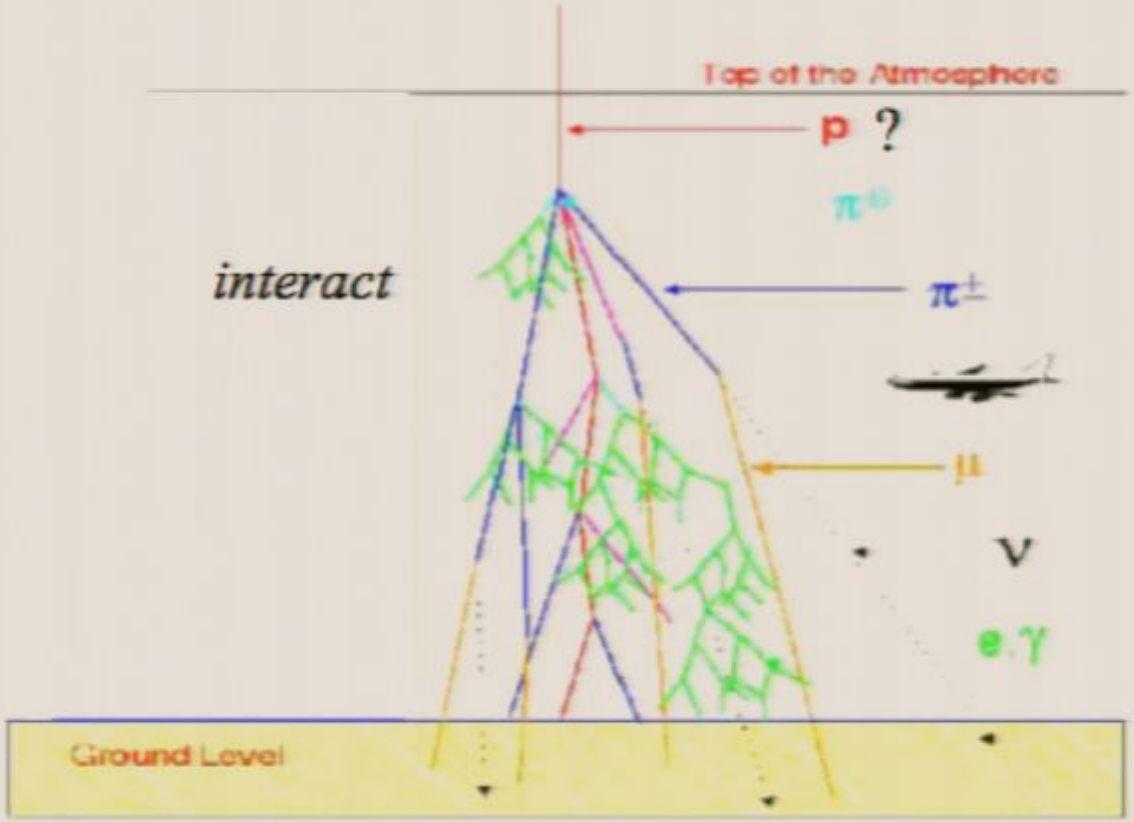

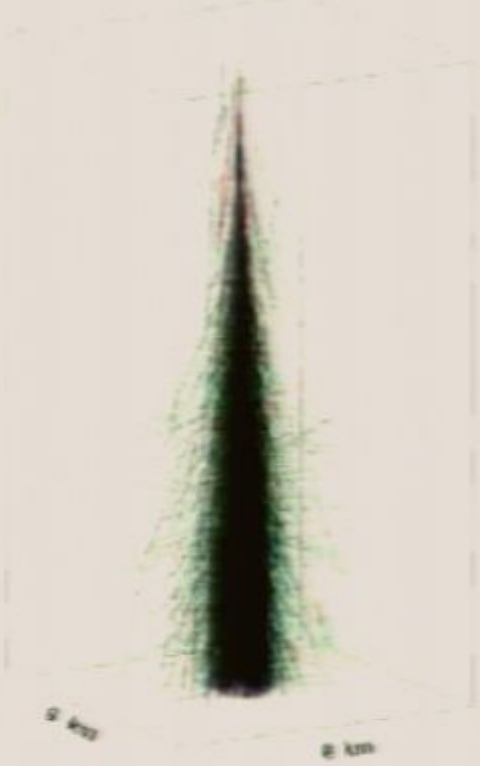

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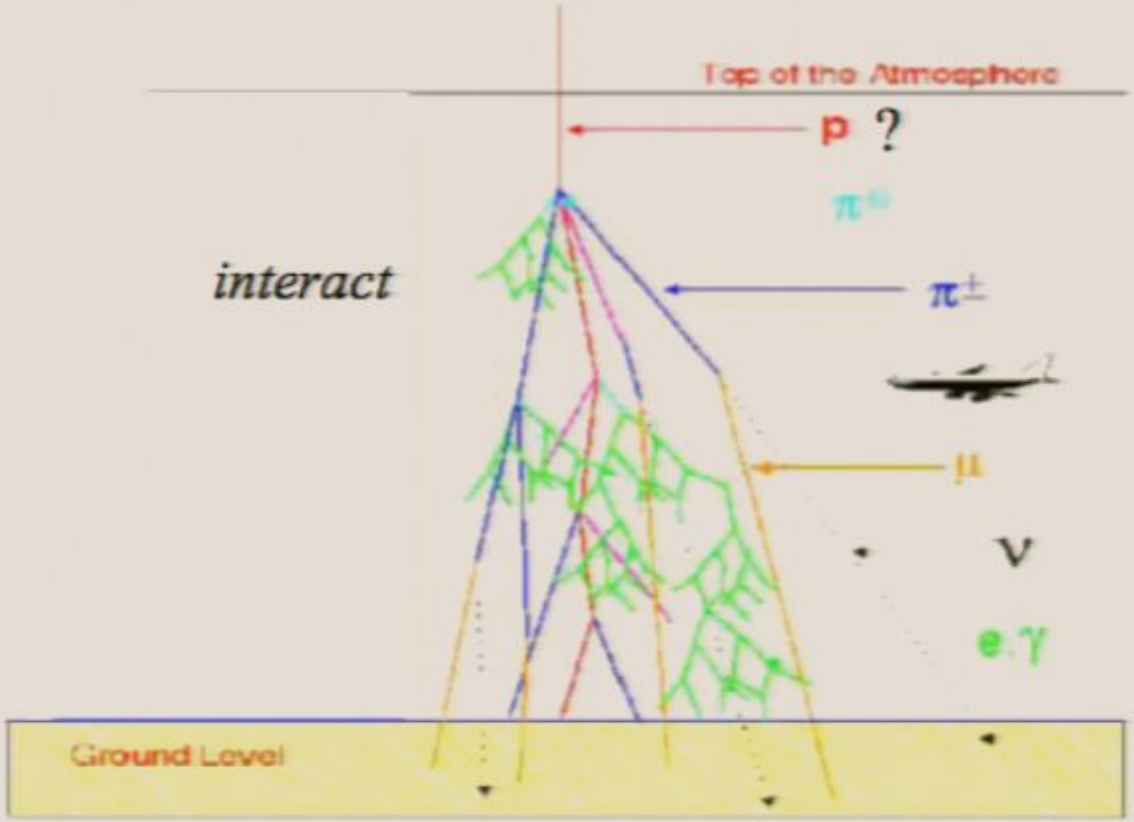

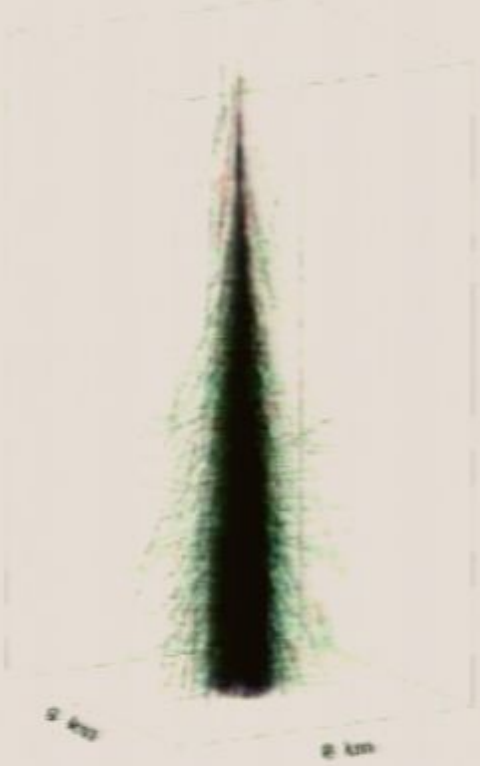

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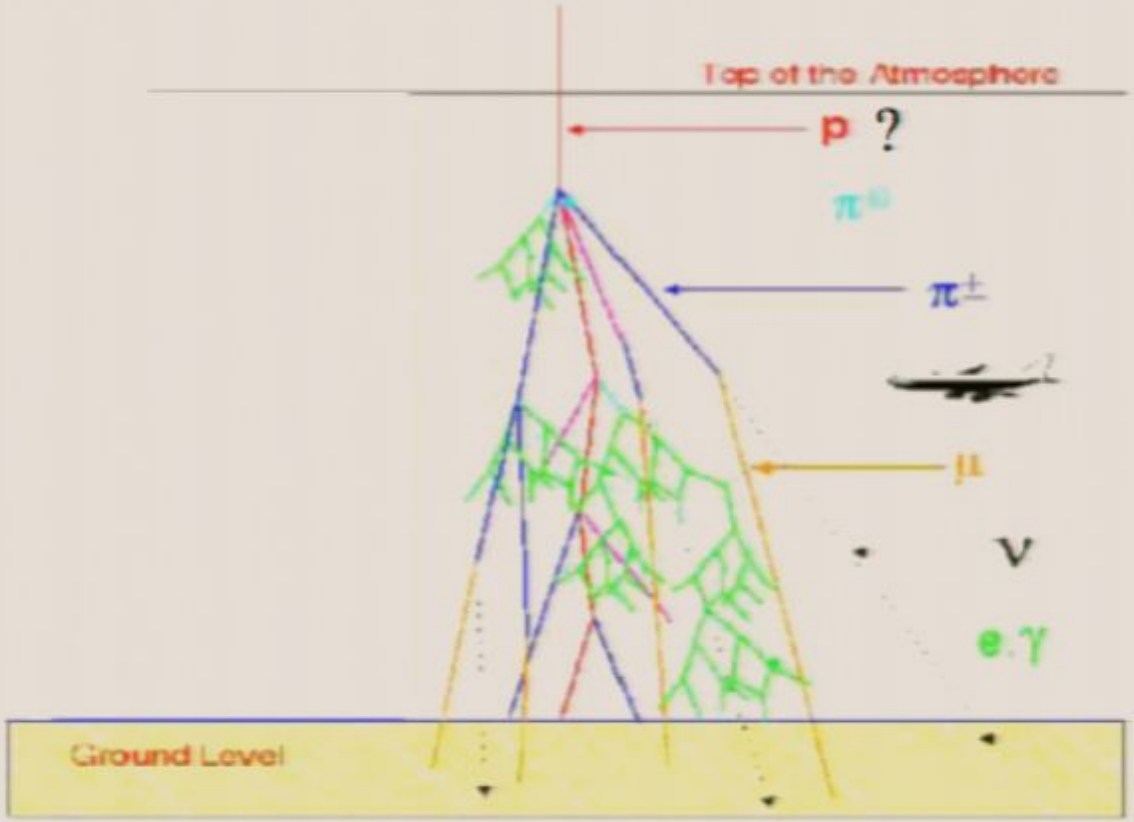

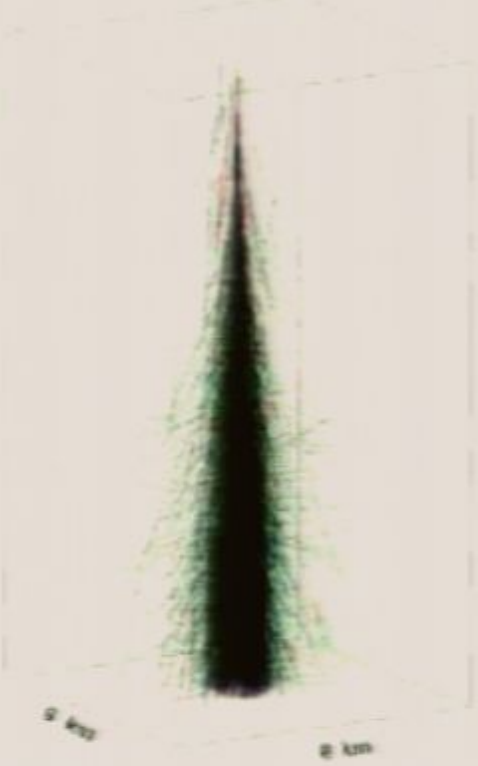

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at ground level : $\gamma\, e^{\pm}\, \mu$ fluorescence light

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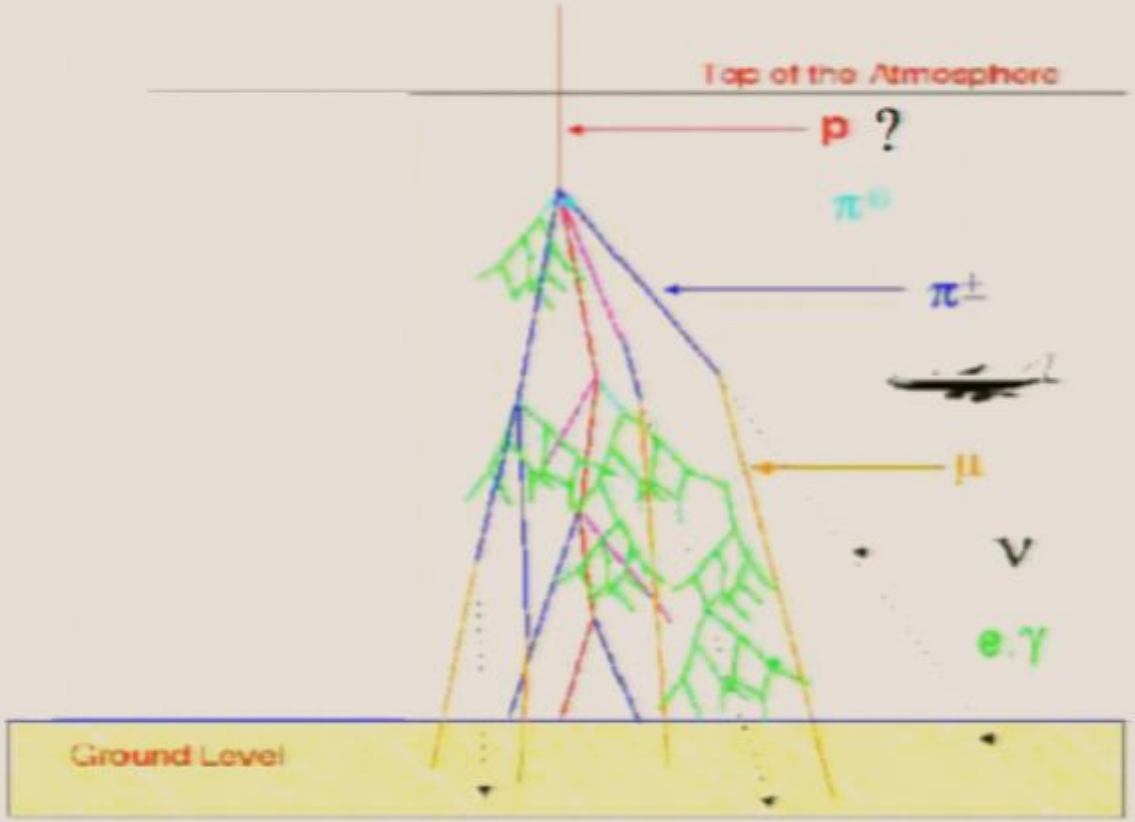

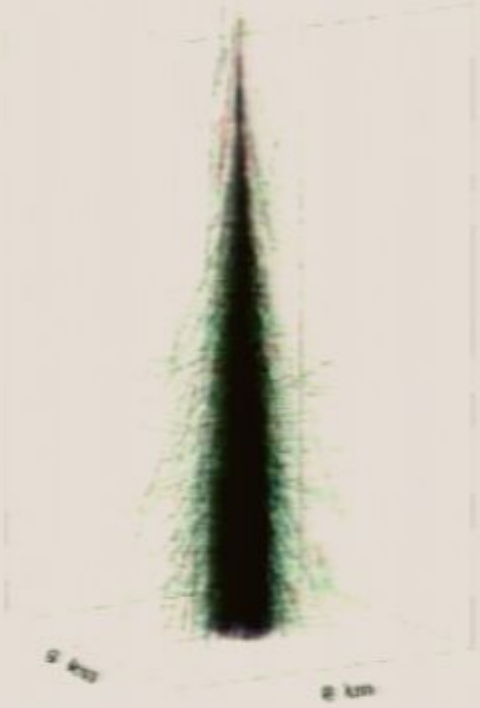

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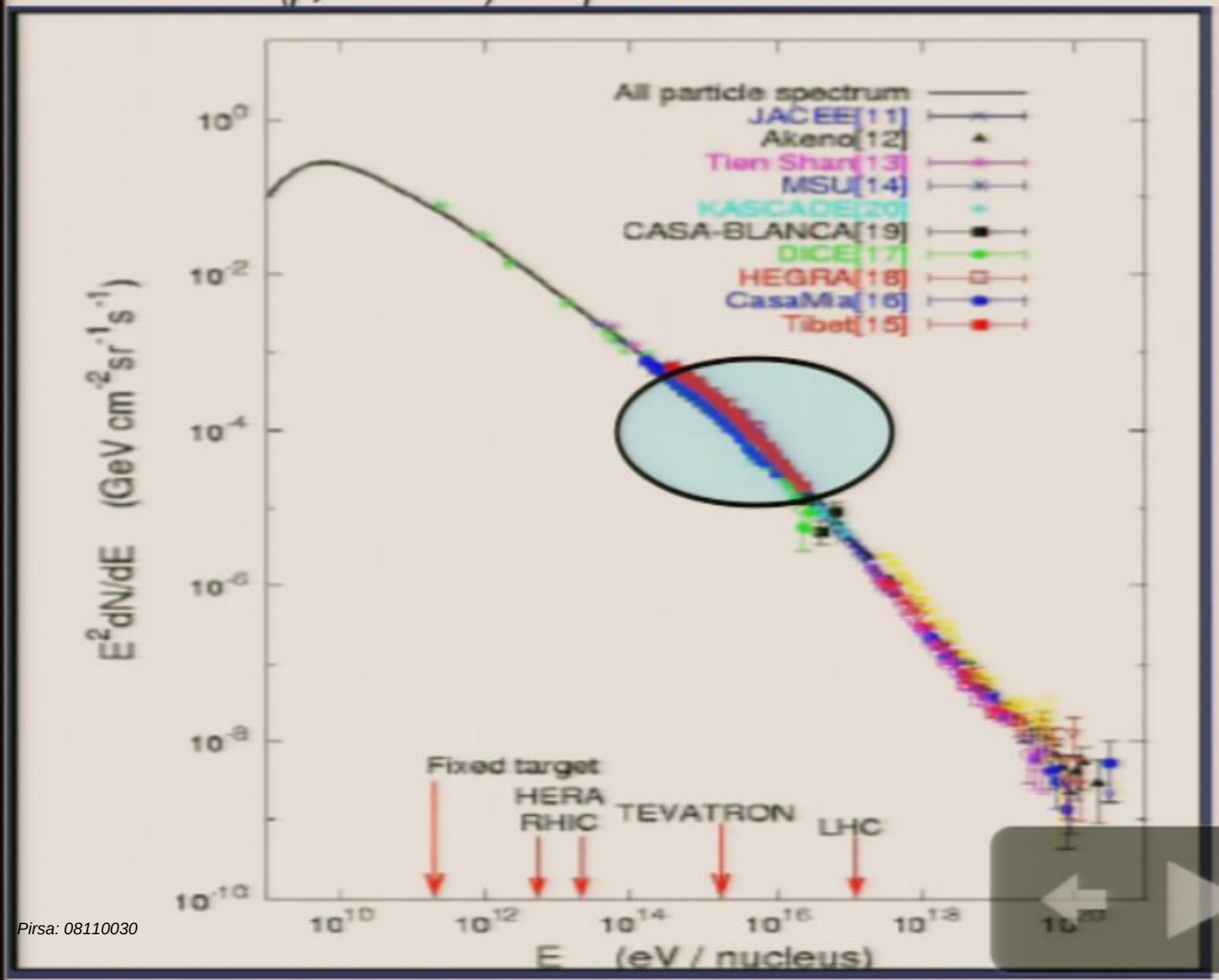

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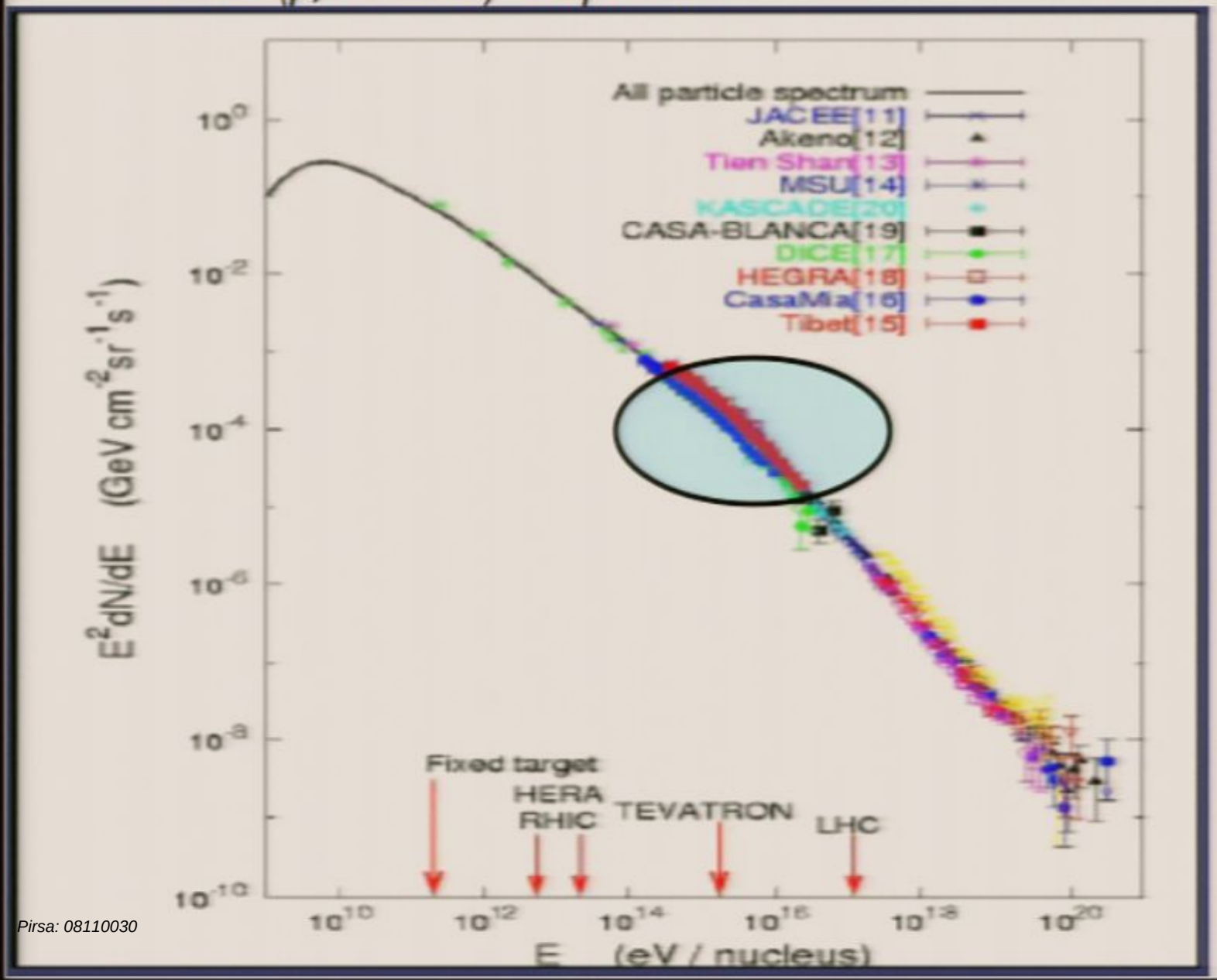

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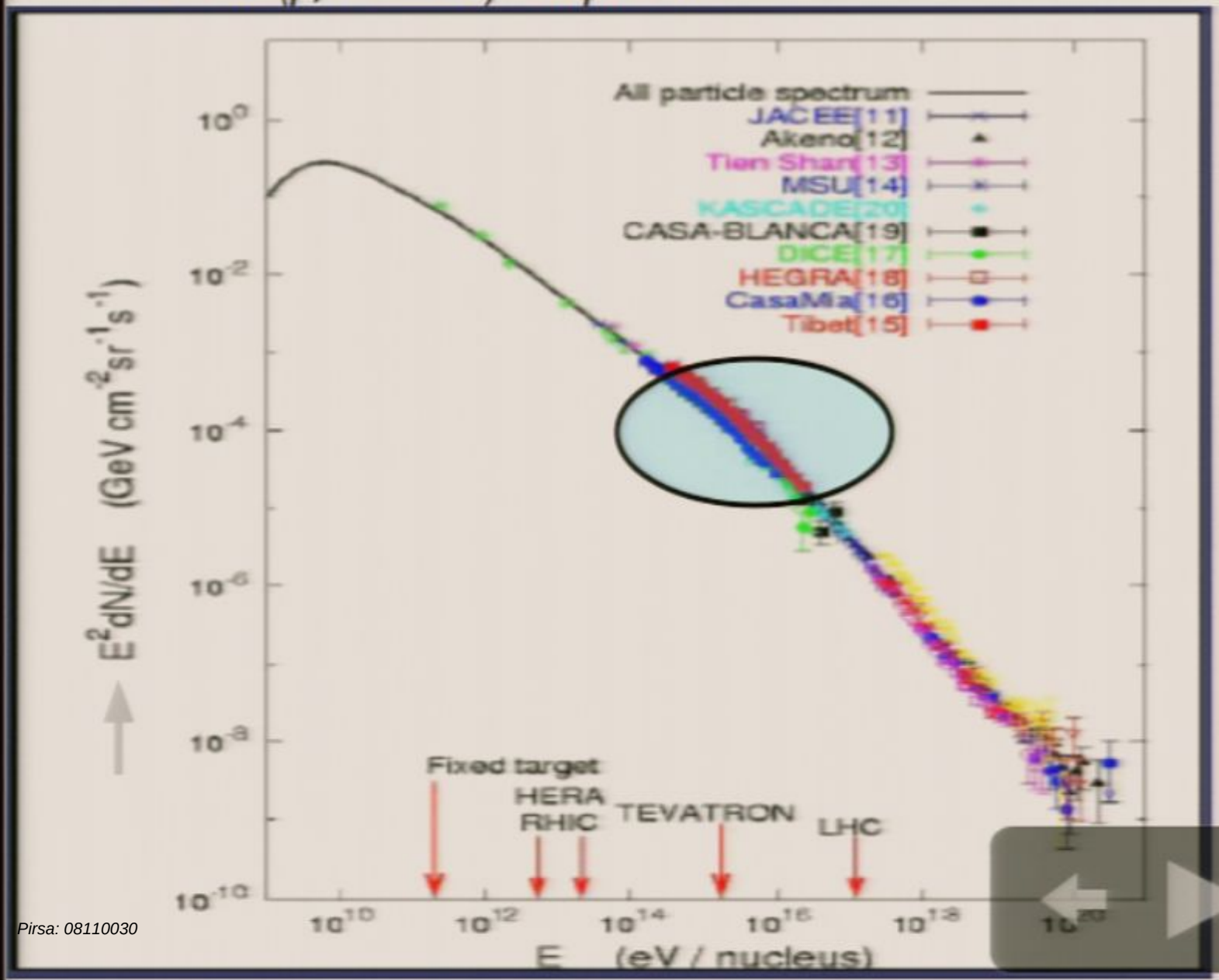

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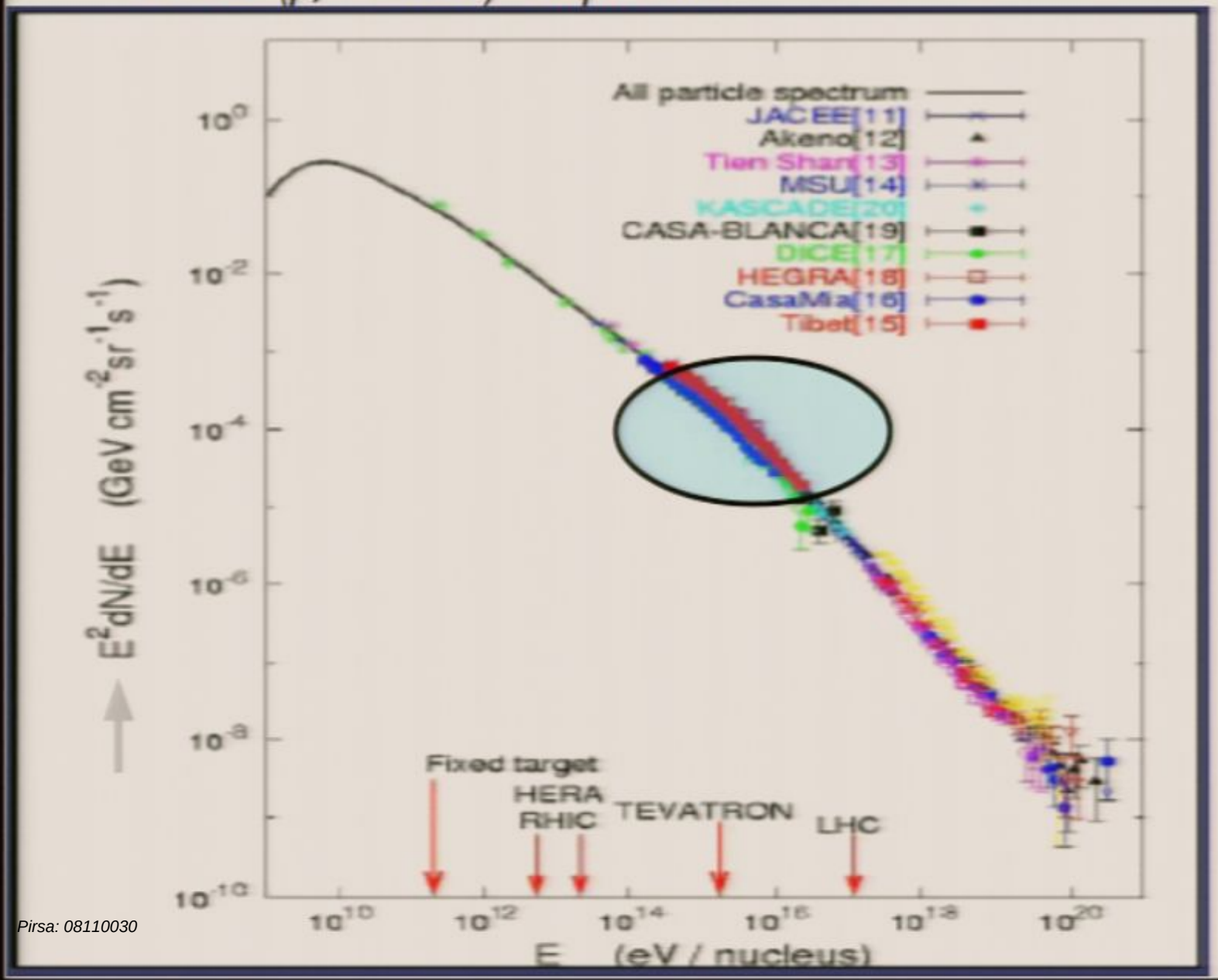

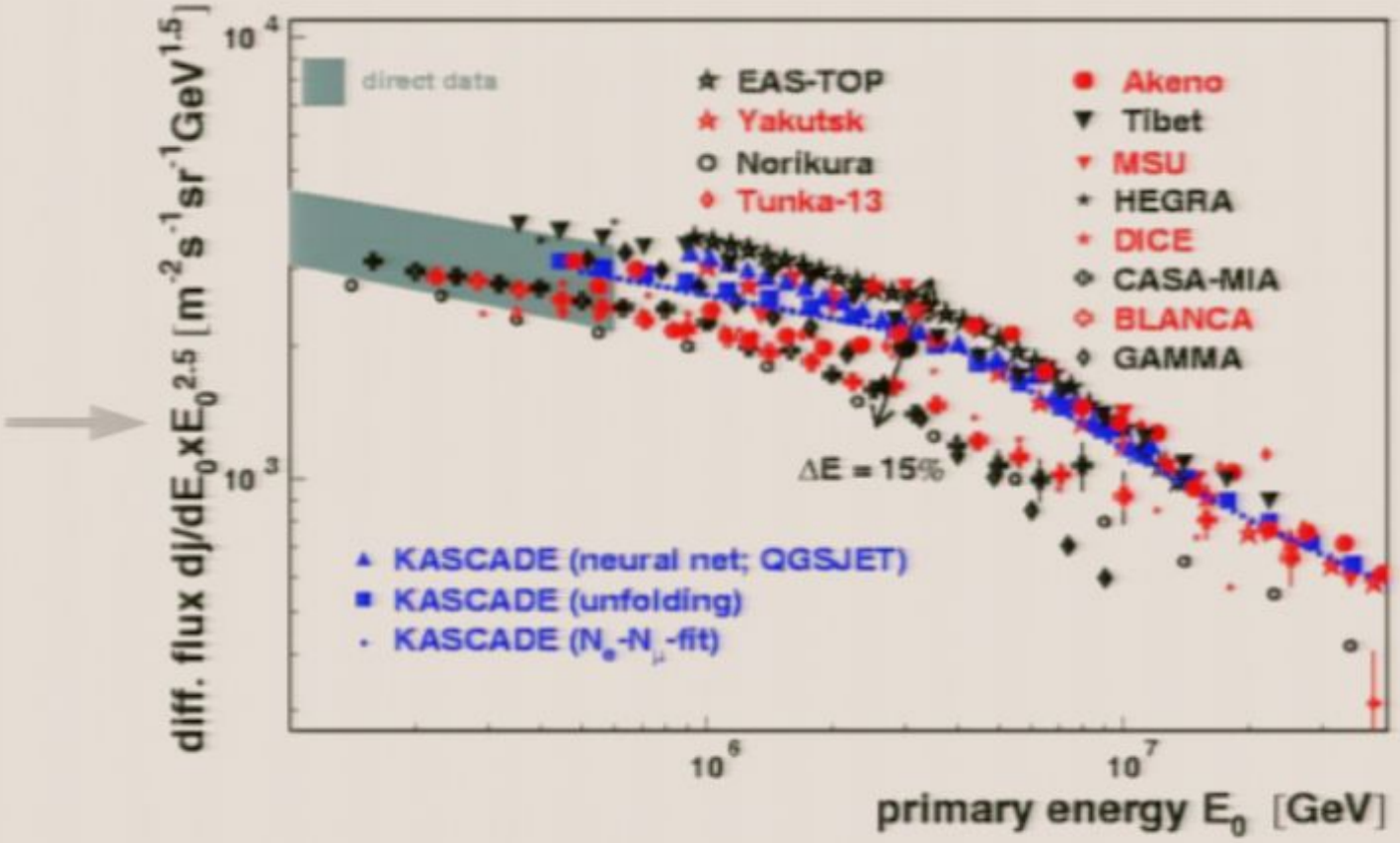
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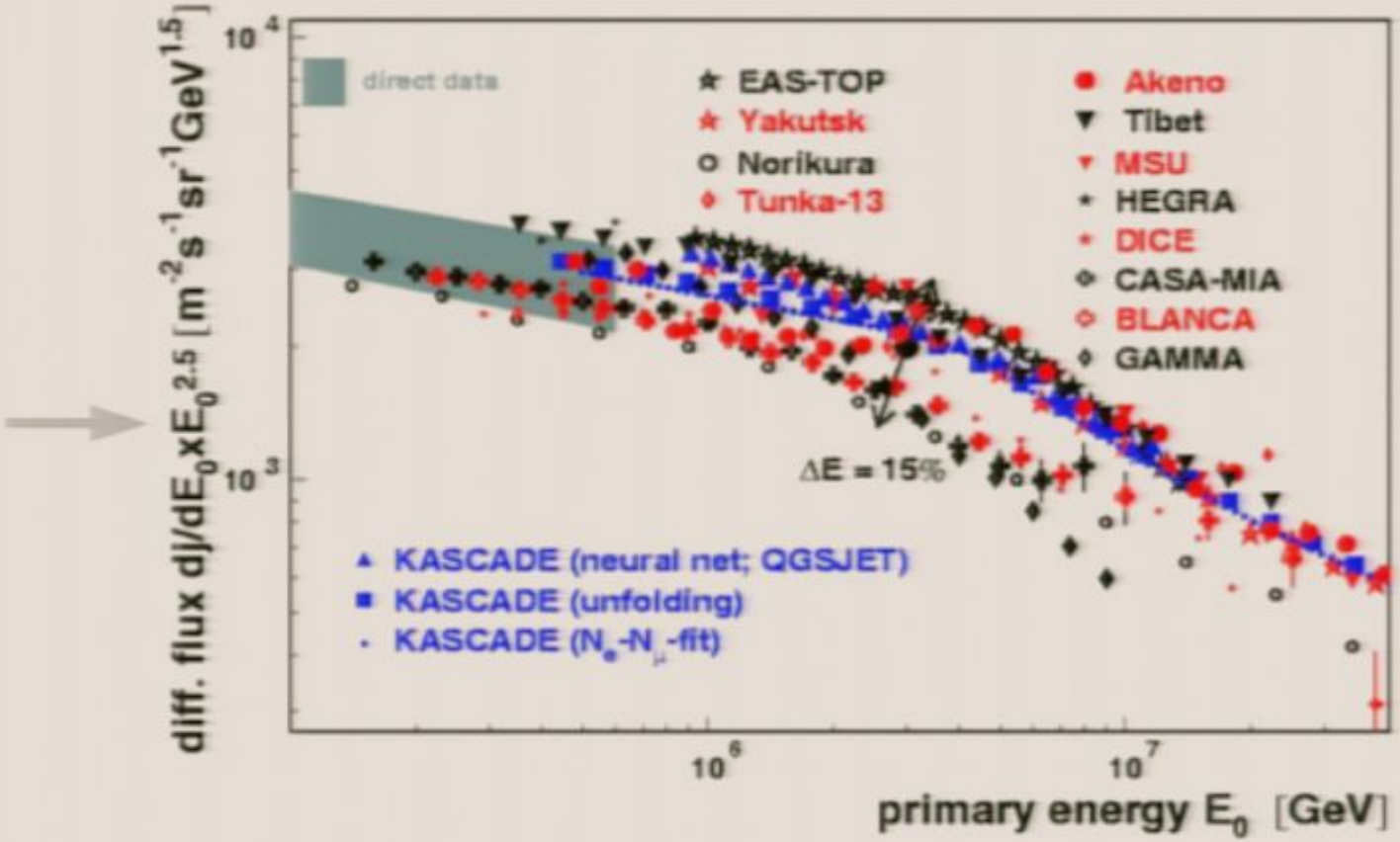
HEGRA
DICE
CASA-MIA
BLANCA
GAMMA
ΔE = 15%
KASCADE (neural net; QGSJET)
KASCADE (unfolding)
KASCADE (N_e-N_μ-fit)
diff. flux dJ/dE_0 x E_0^2.5 [m^-2 s^-1 sr^-1 GeV^1.5]
primary energy E_0 [GeV]
10^4
10^3
10^6
10^7


direct data
EAS-TOP
Yakutsk
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Akeno
Tibet
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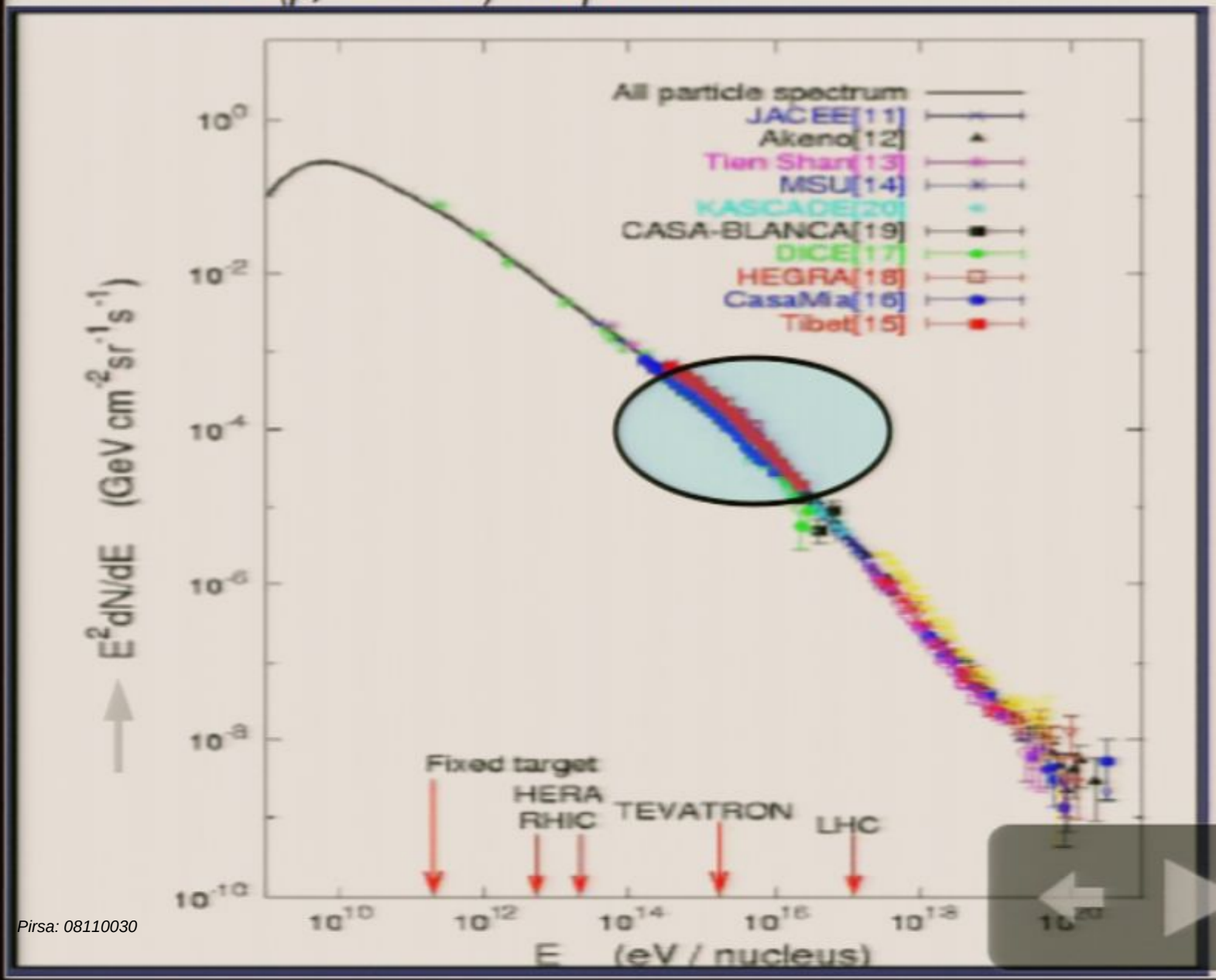

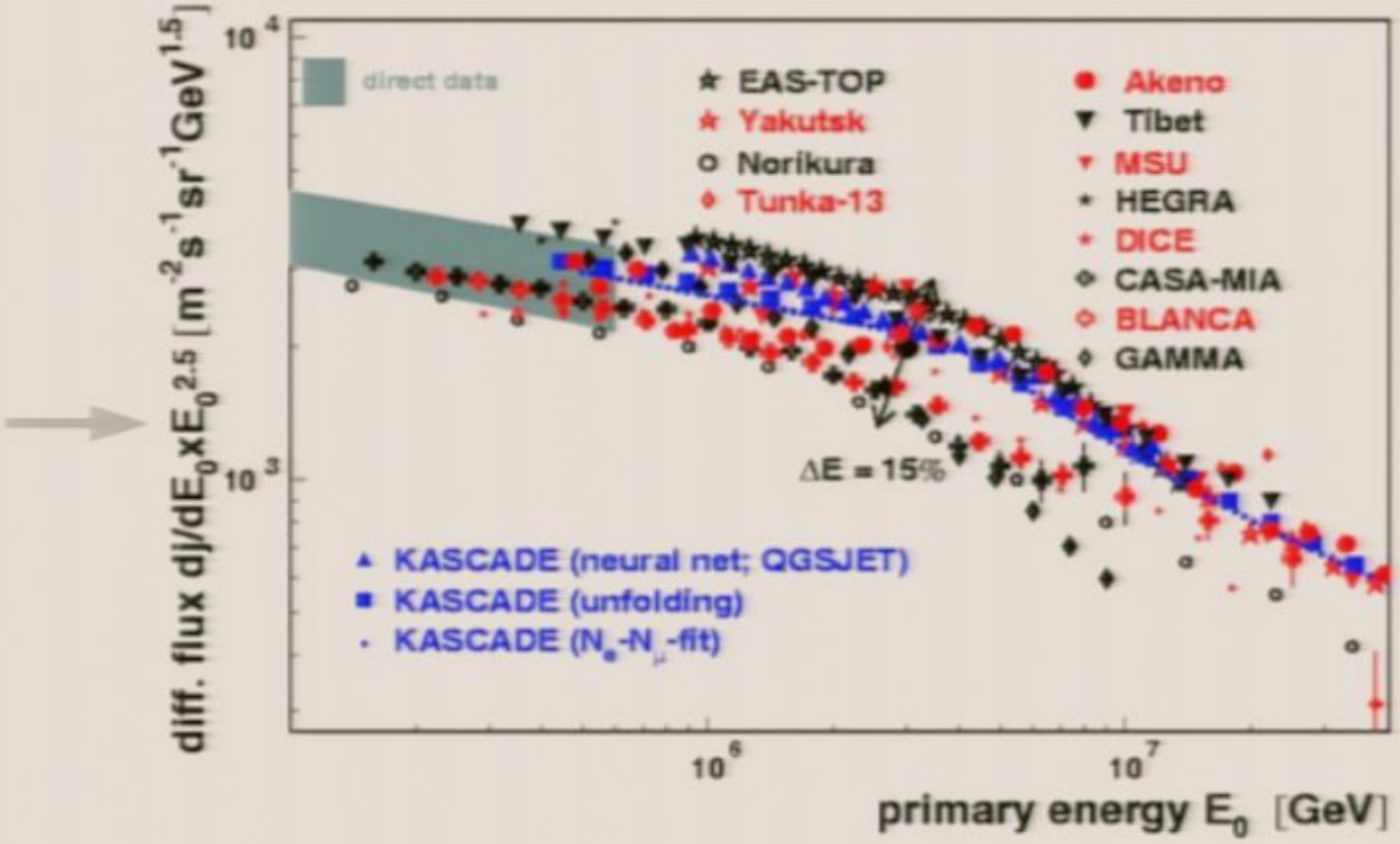
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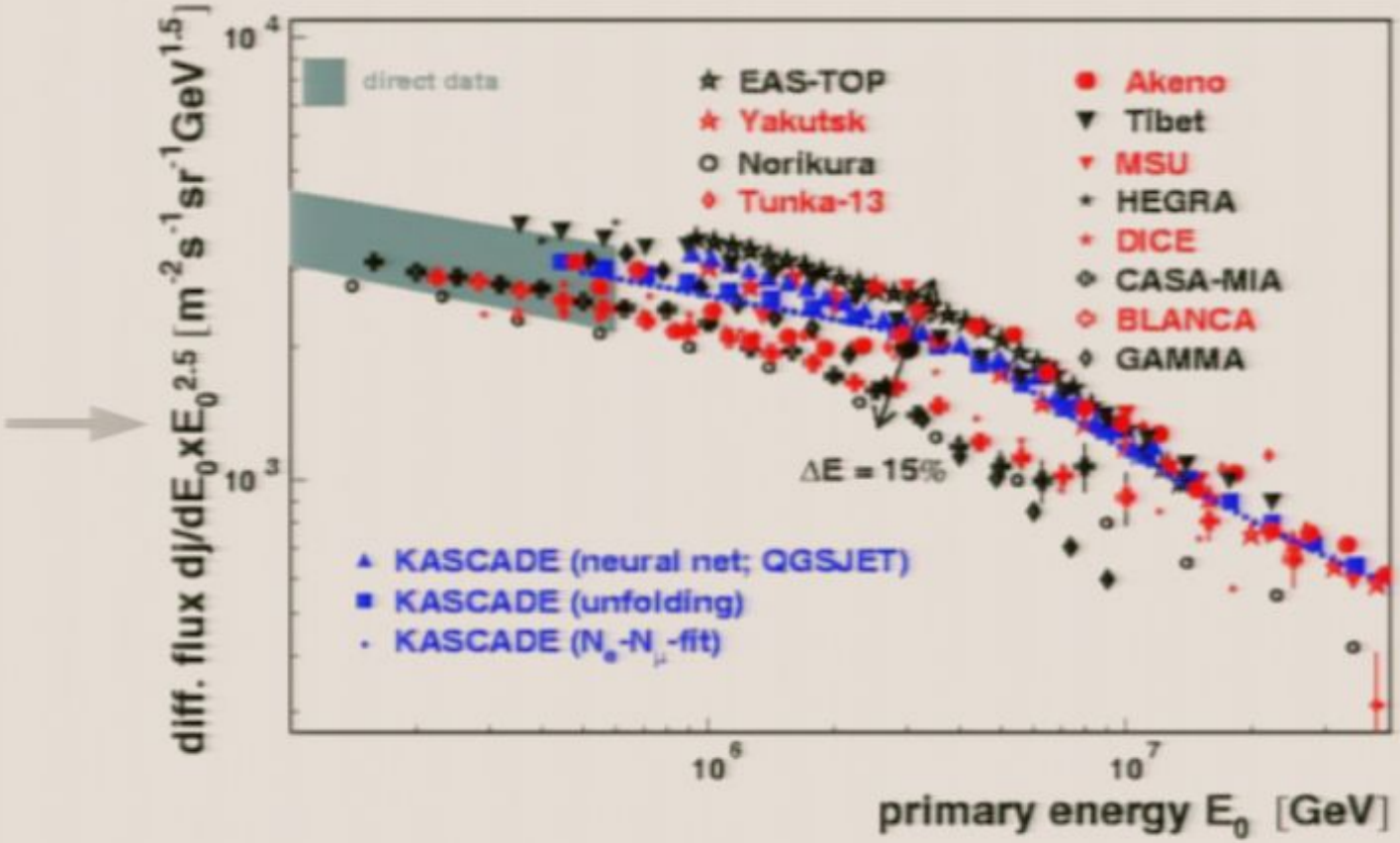
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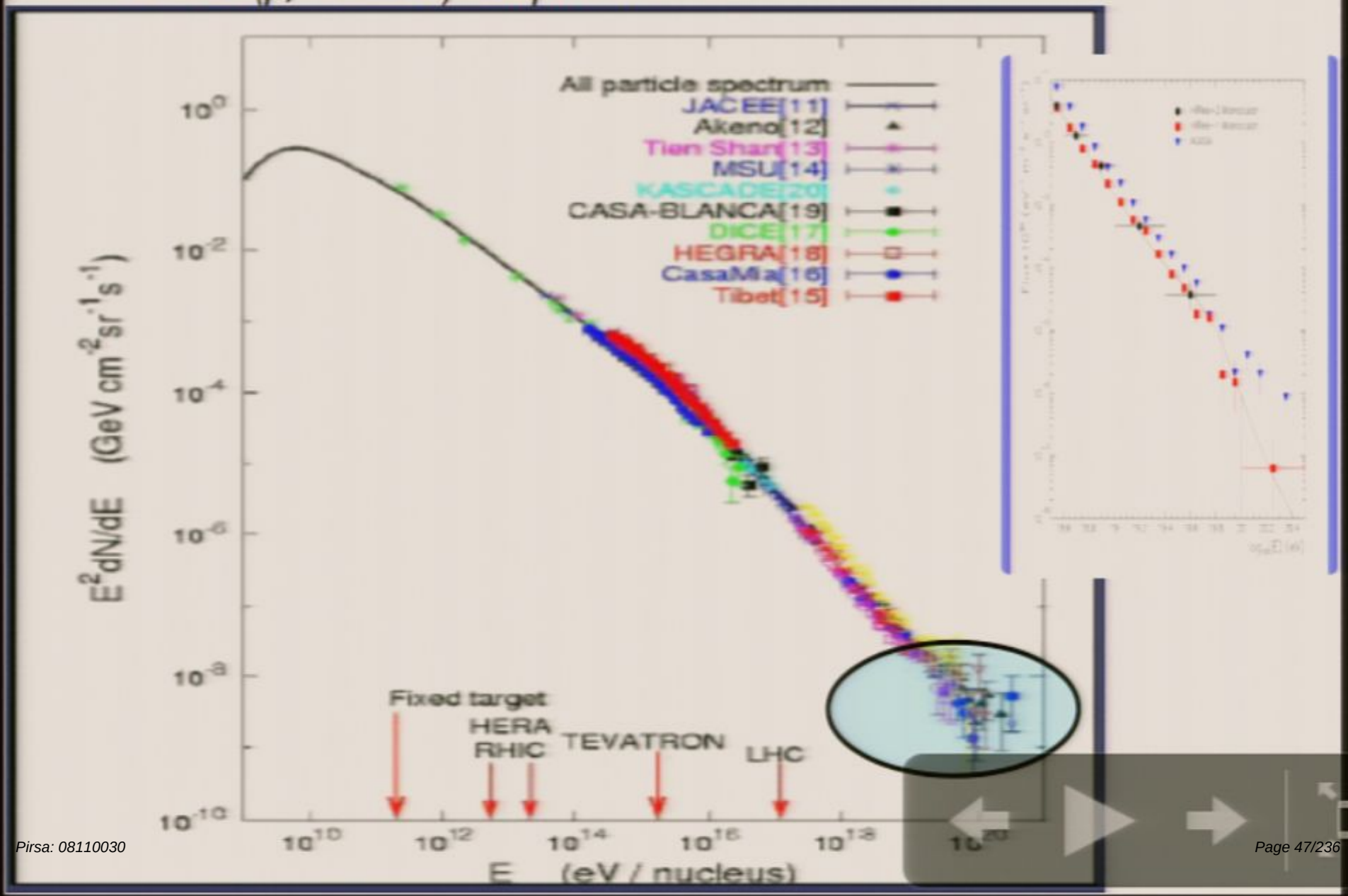

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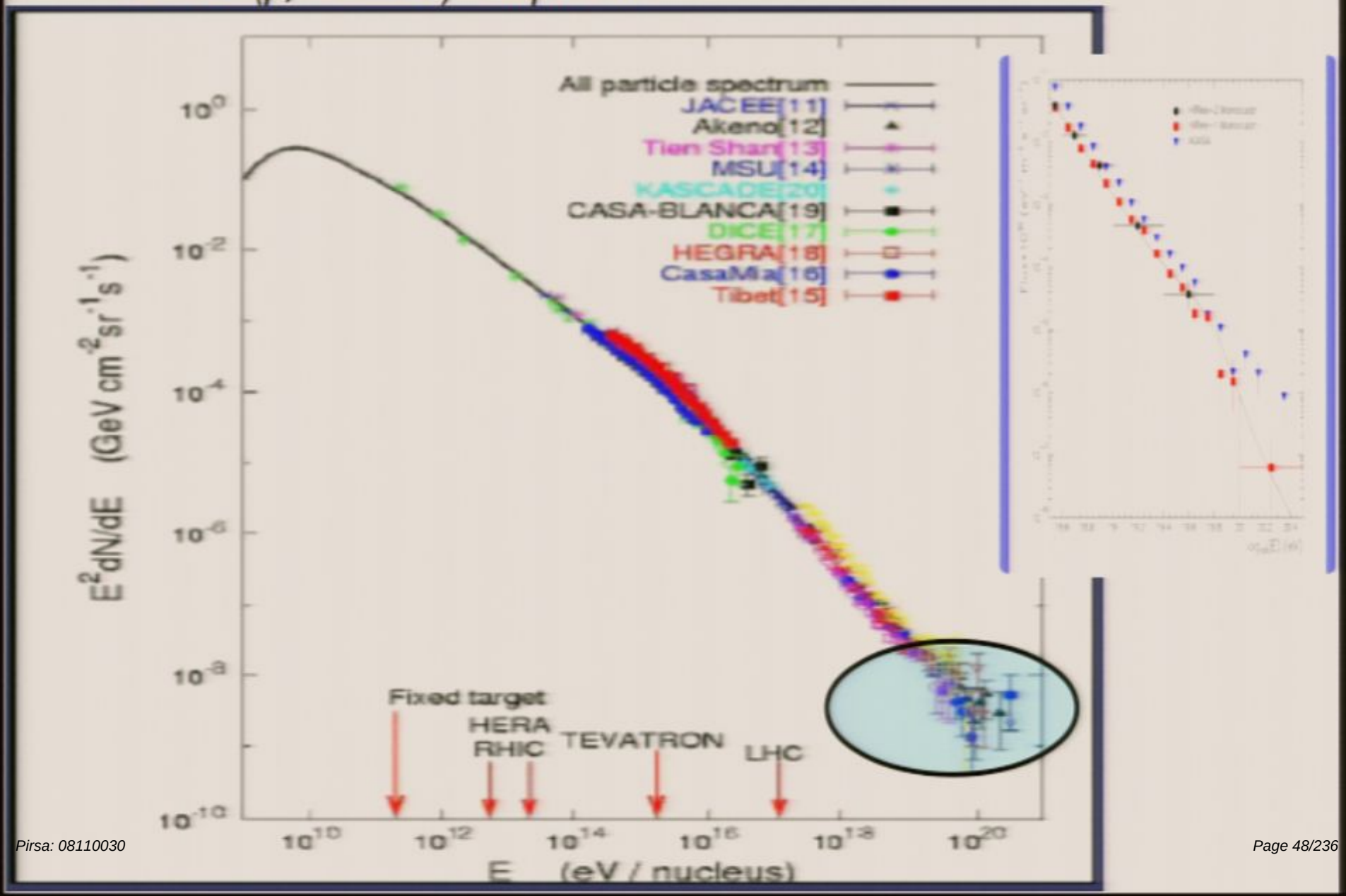

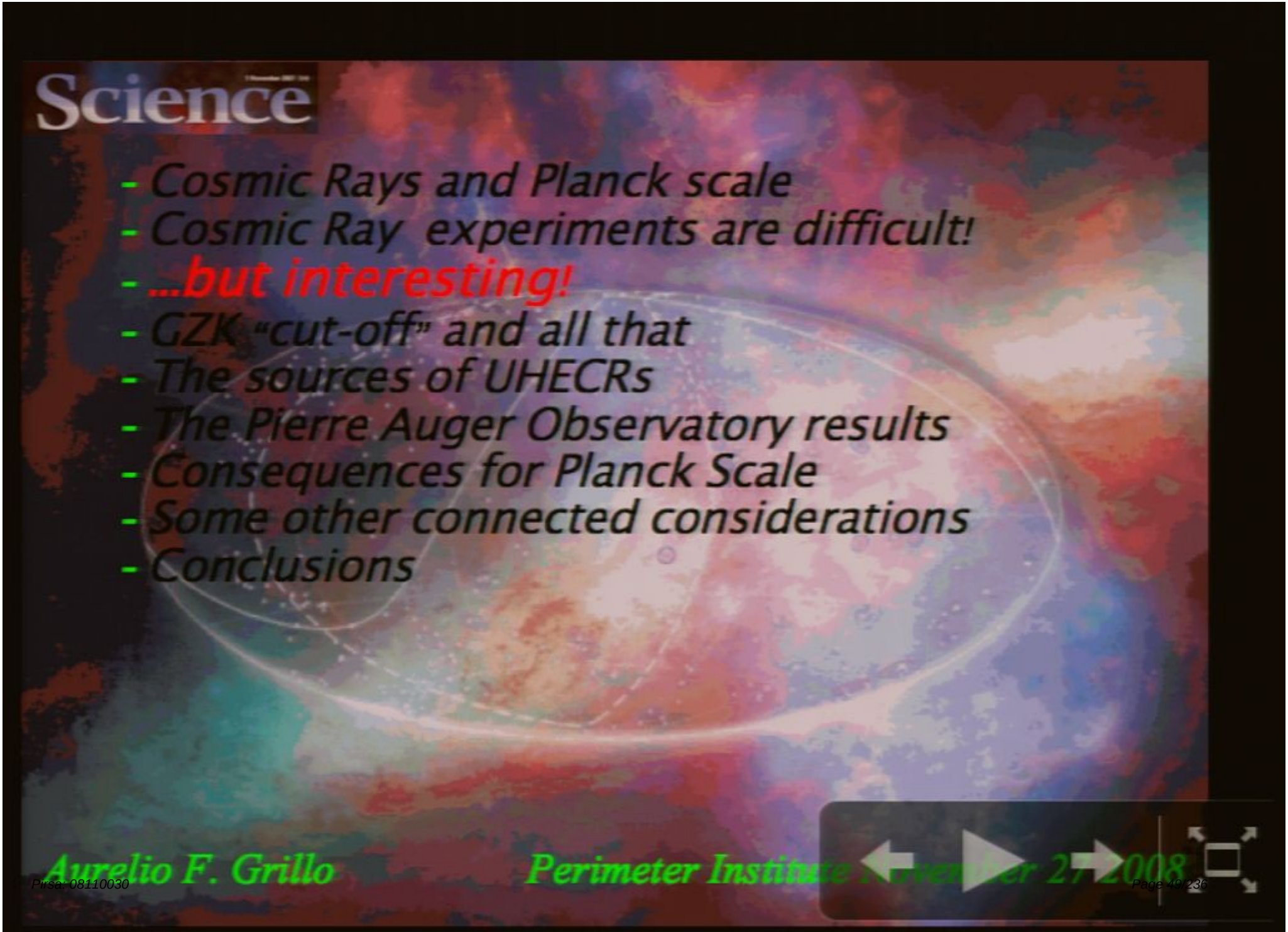
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Aurelio F. Grillo
Perimeter Institute November 27 2008

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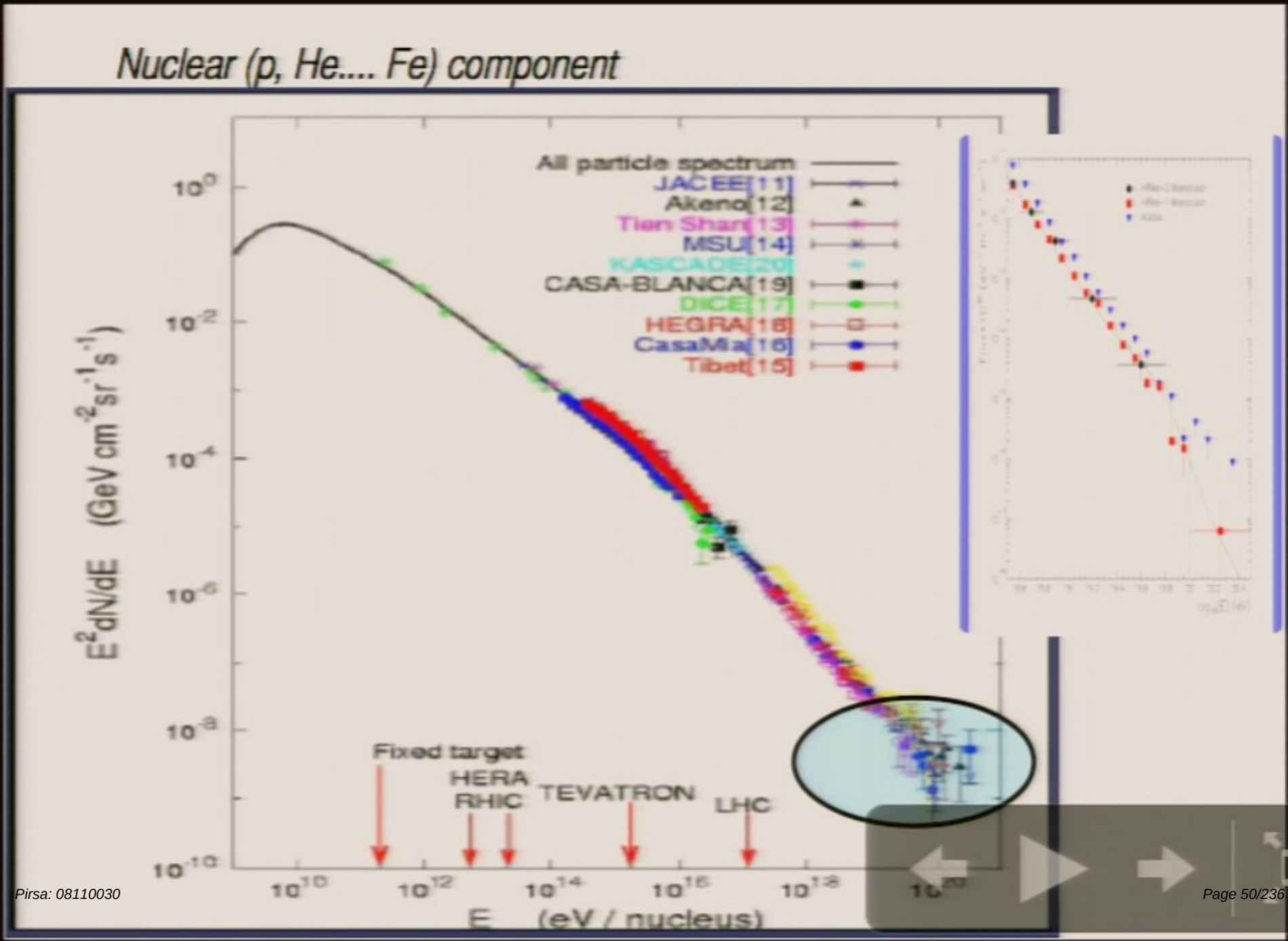

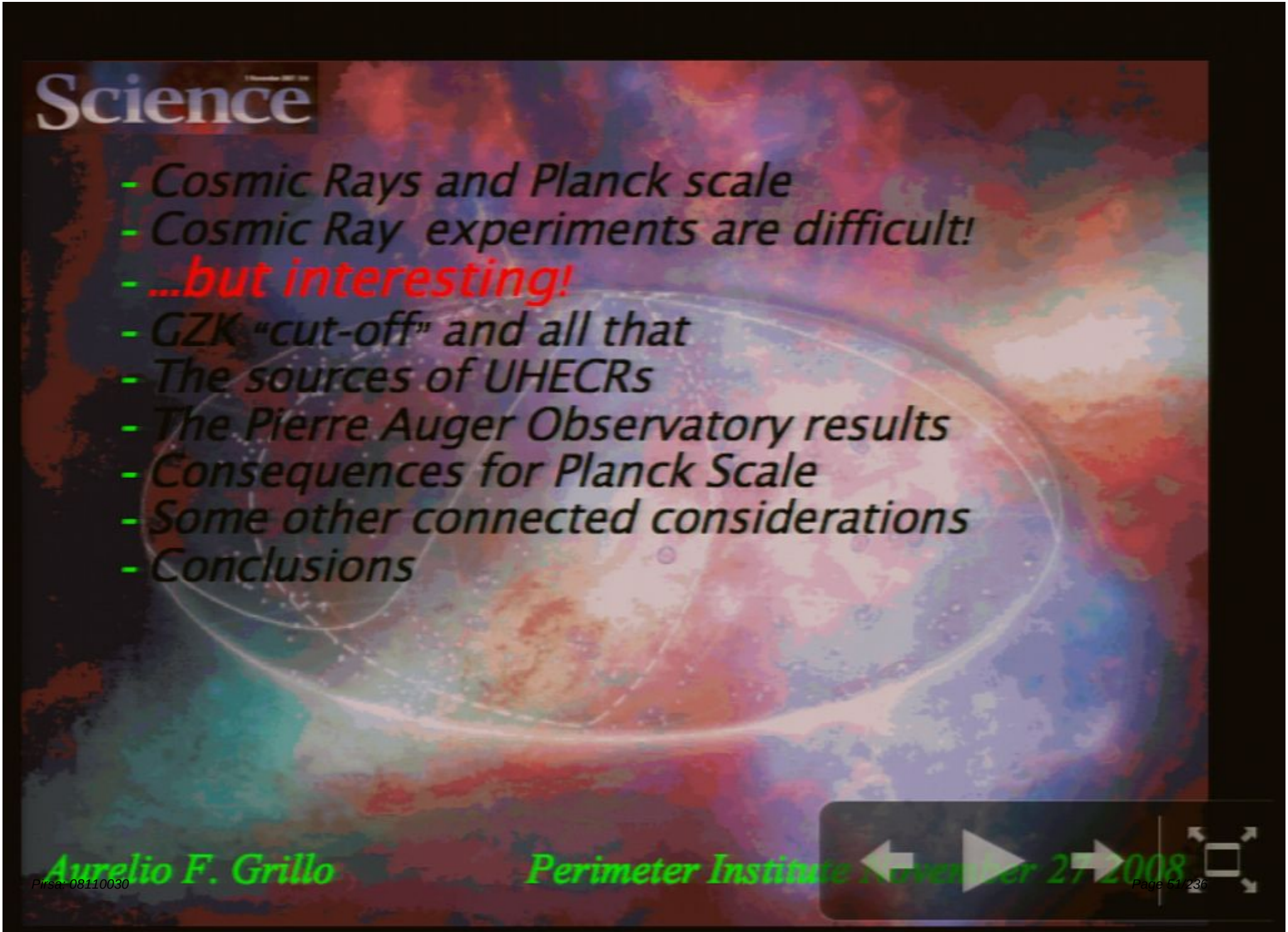
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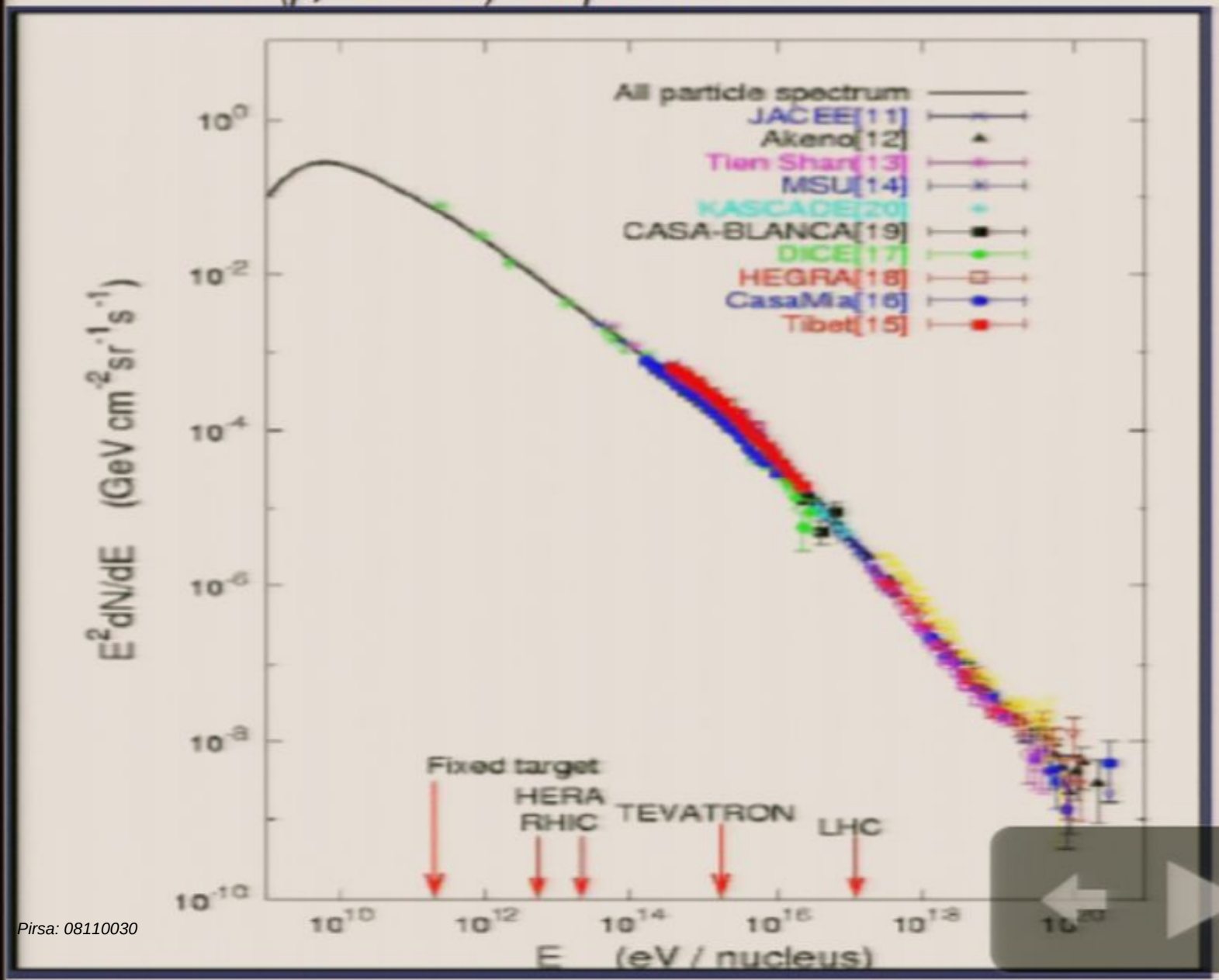

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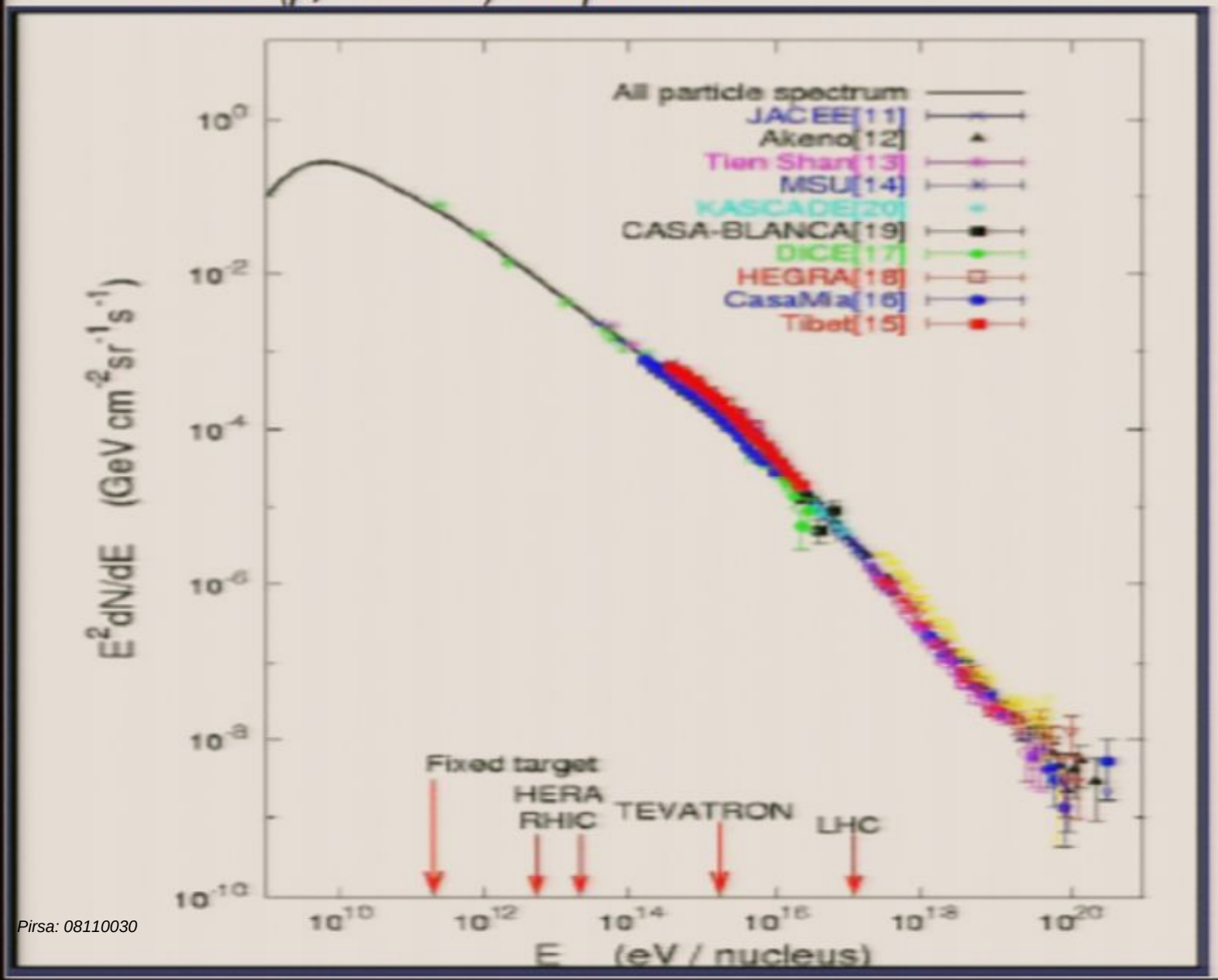

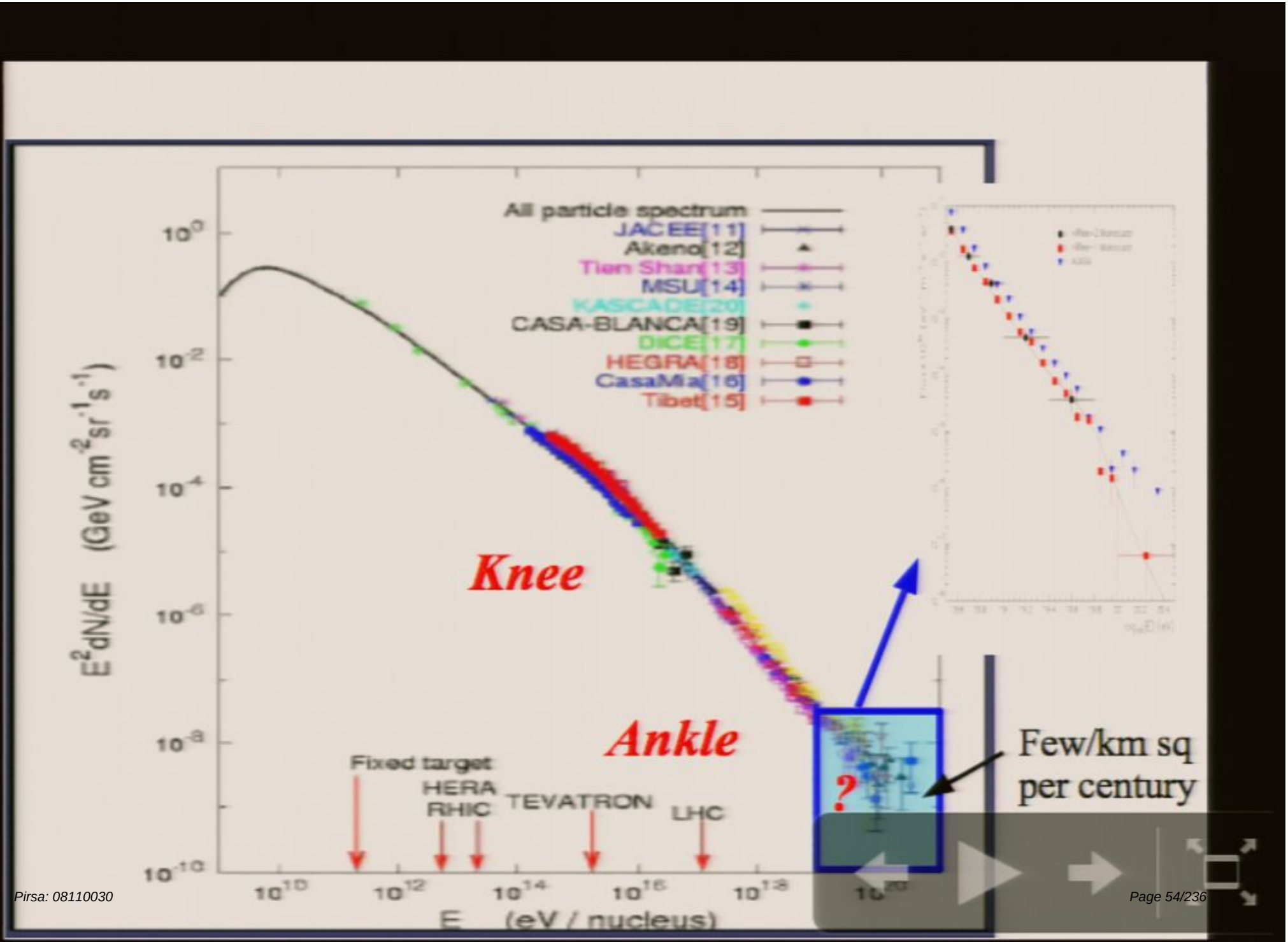
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Akeno[12]
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Knee
Ankle
Fixed target
HERA
RHIC
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?
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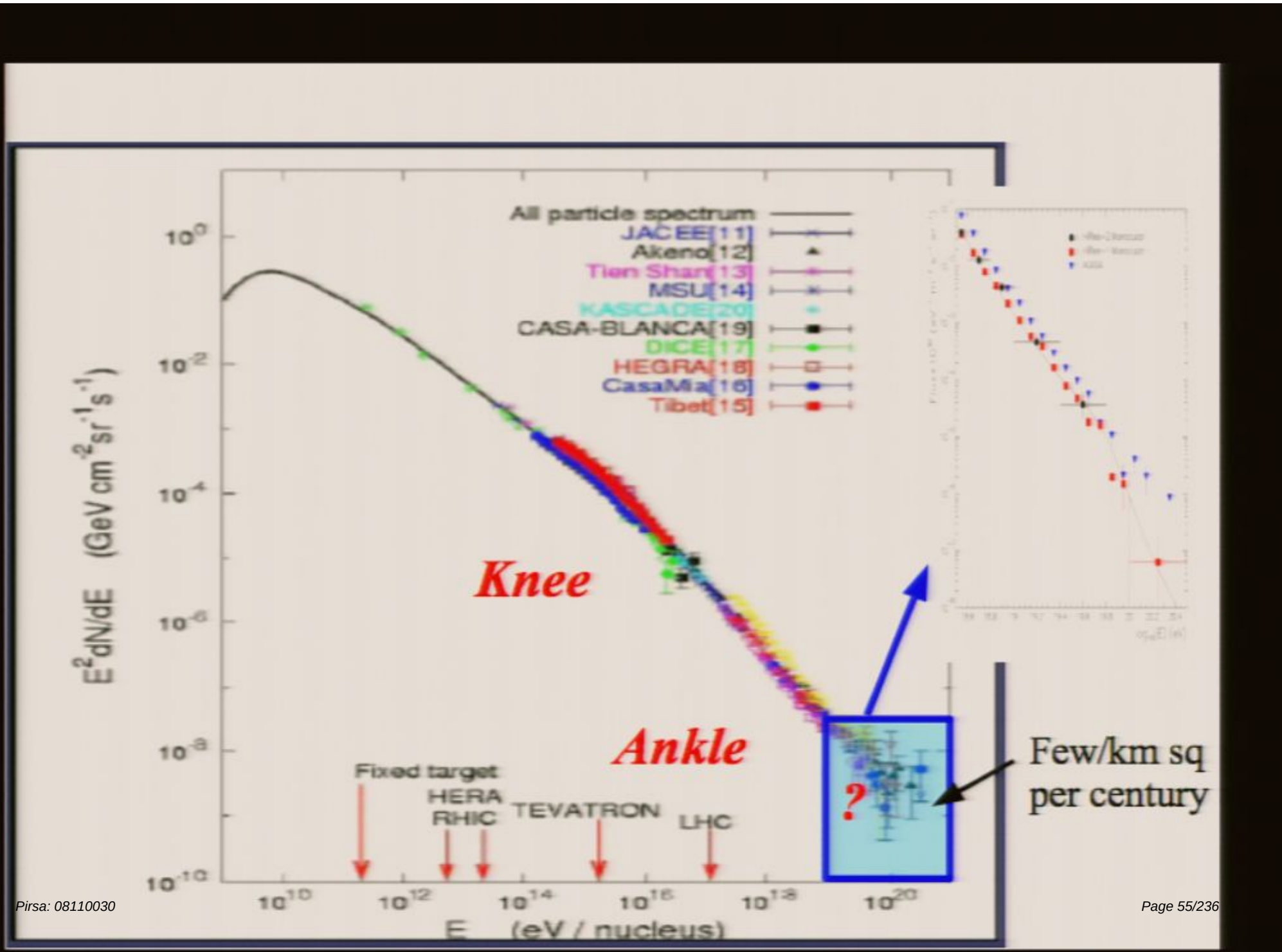
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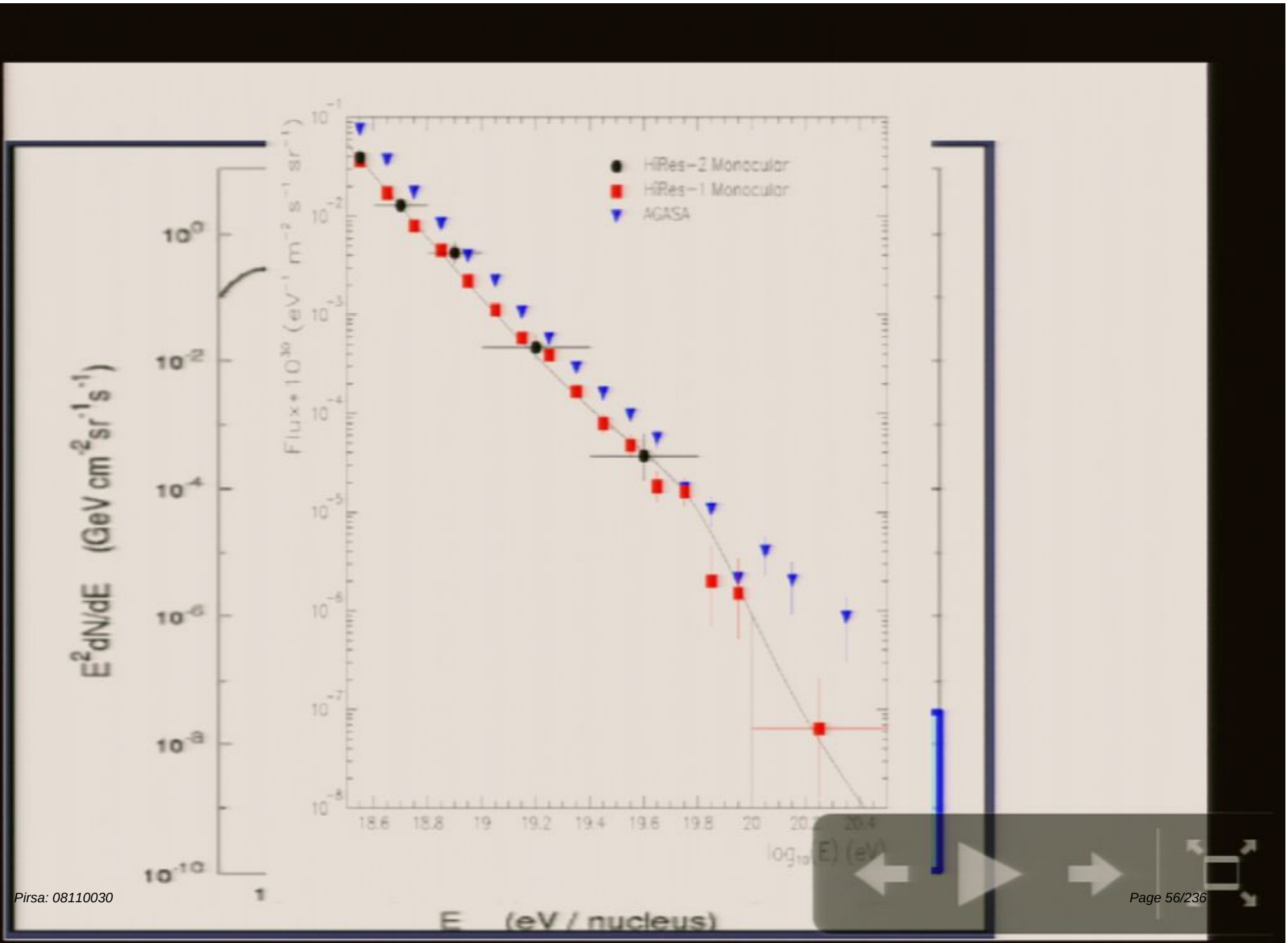
HiRes–2 Monocular
HiRes–1 Monocular
AGASA
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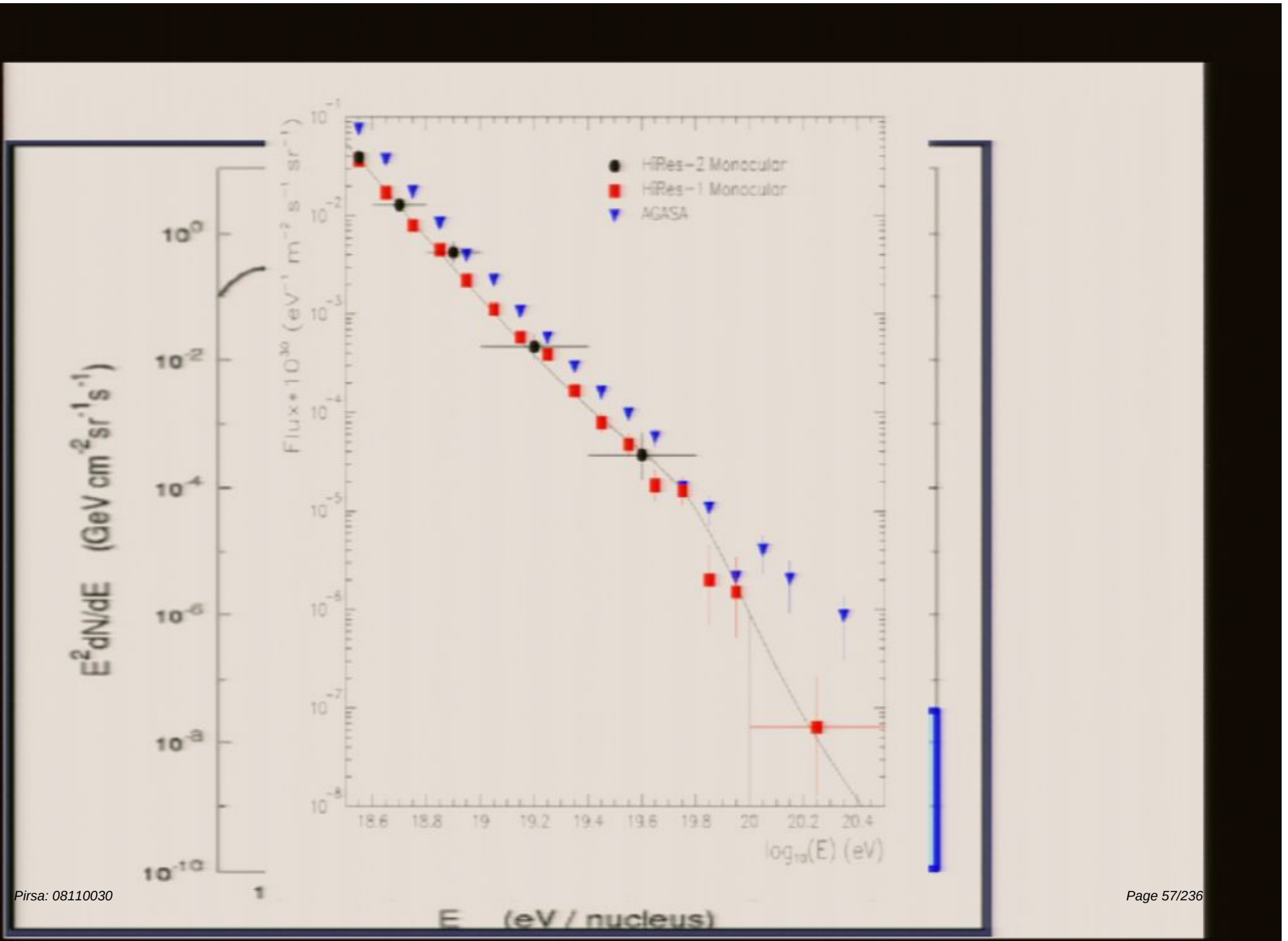
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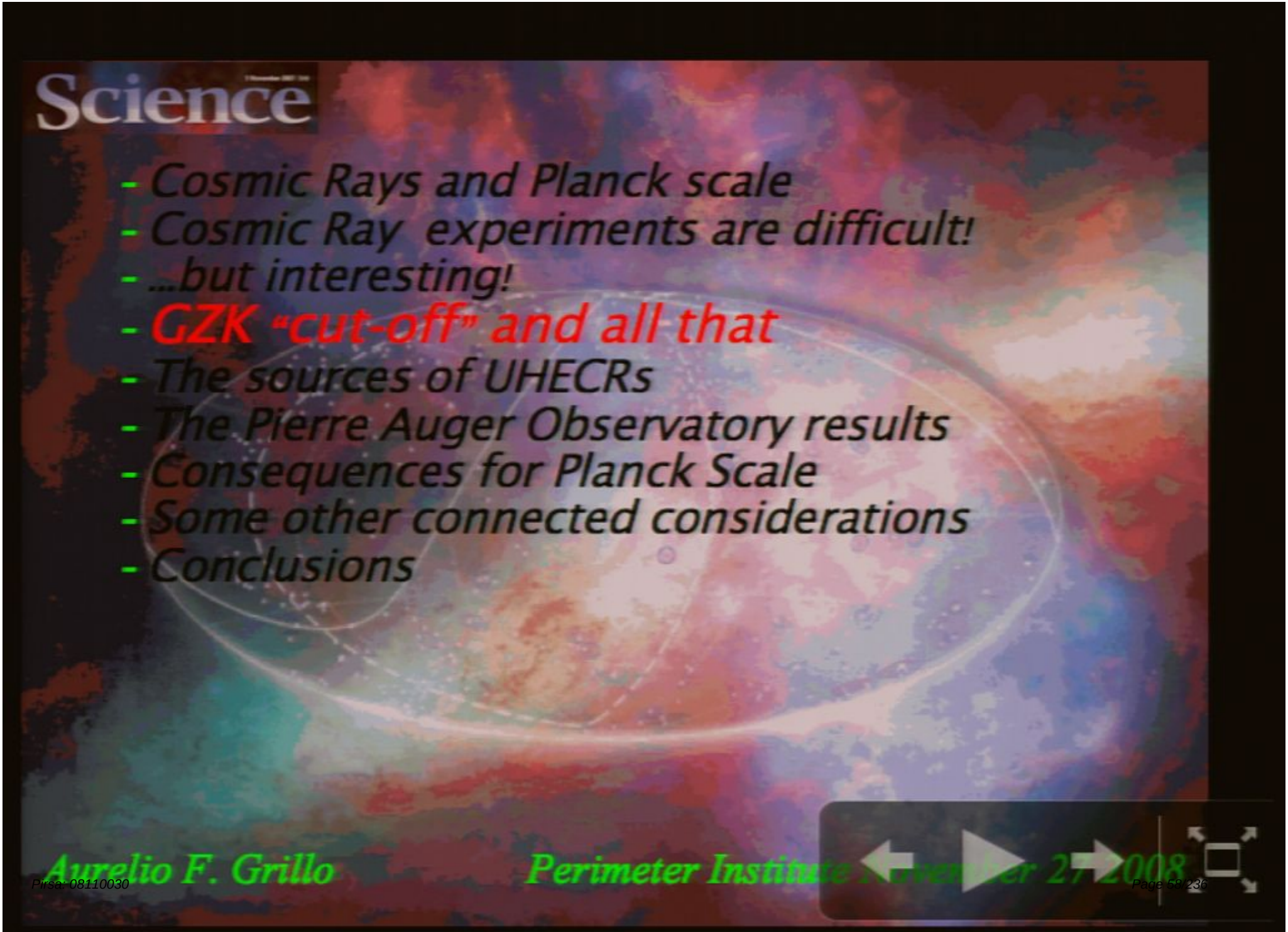
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Energy Loss Mechanisms for extragalactic protons

- Redshift
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The Greisen -Zatsepin-Kuzmin "cutoff"

$$p + \gamma \rightarrow p + \pi^\circ$$

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Photoproduction Threshold

$$s = m_p^2 + 2\,E_p\,\epsilon\,(1 - \beta\cos\theta_{\gamma p}) > (m_p + m_\pi)^2$$

$$E \geq \frac{(m_p + m_\pi)^2 - m_p^2}{2\,\varepsilon\,(1 - \cos\theta_{\gamma e})} \geq \frac{(m_p + m_\pi)^2 - m_p^2}{4\,\varepsilon}$$

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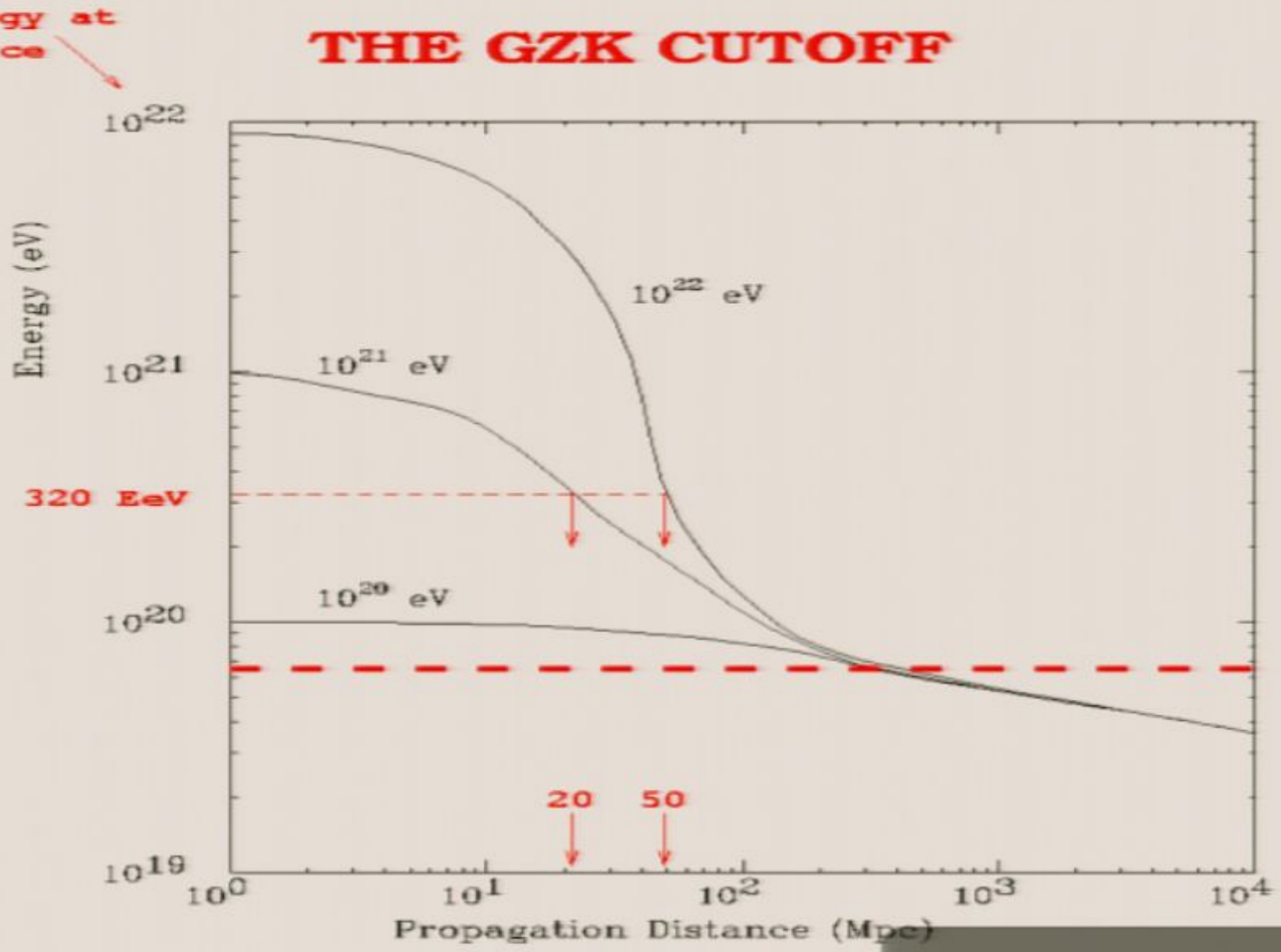

Energy attenuation of protons

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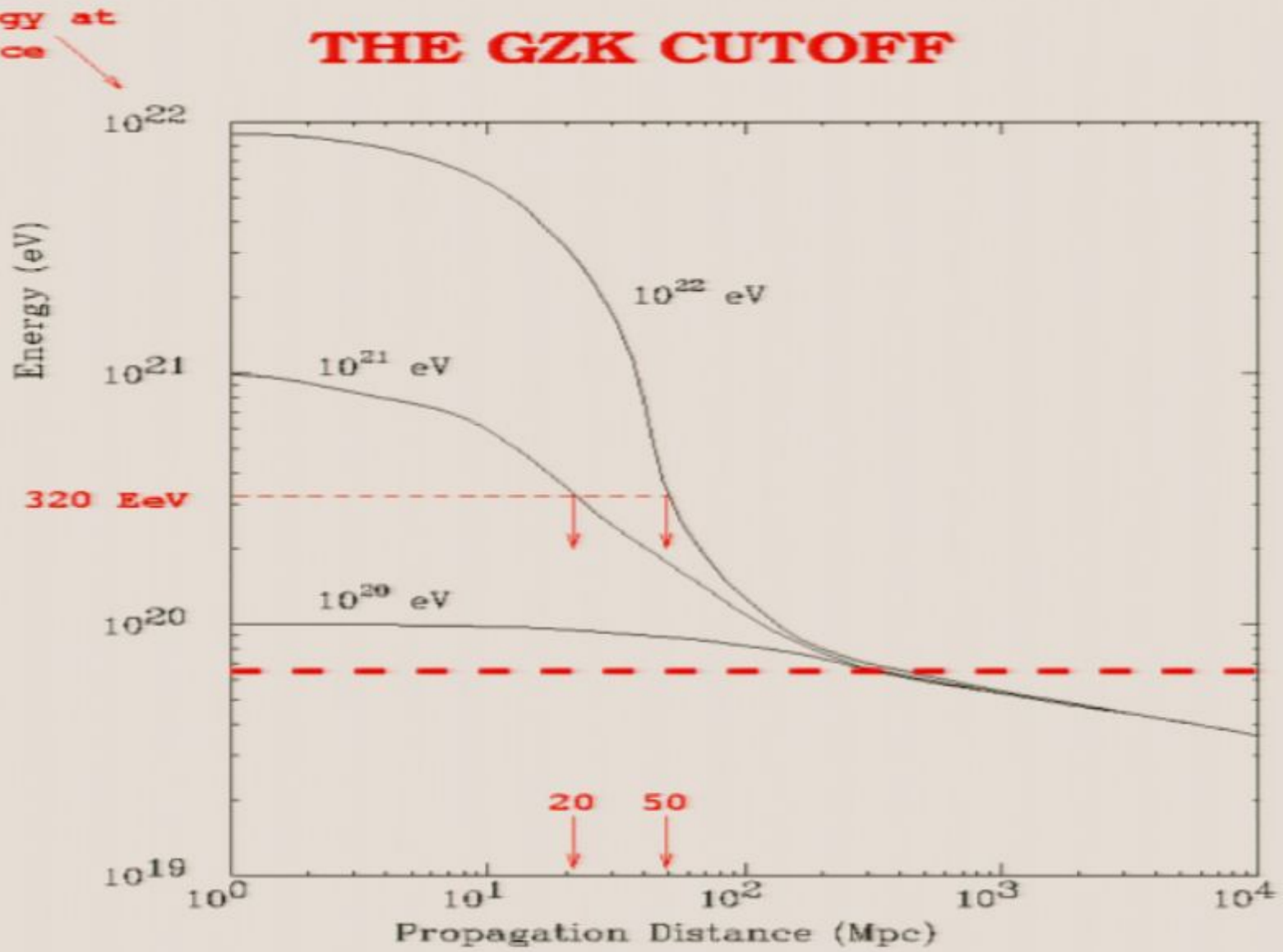

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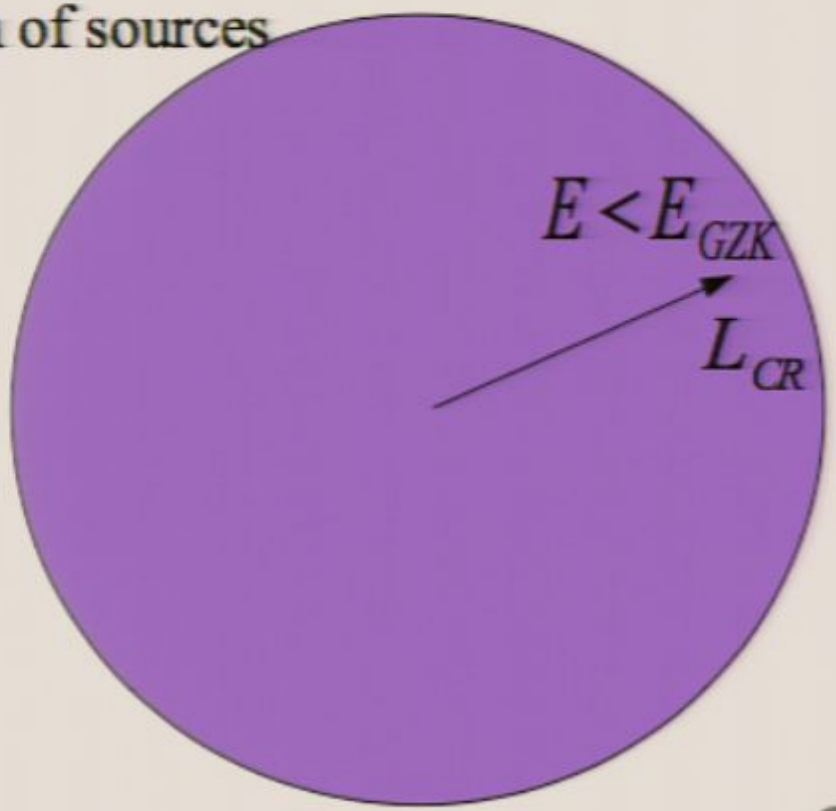

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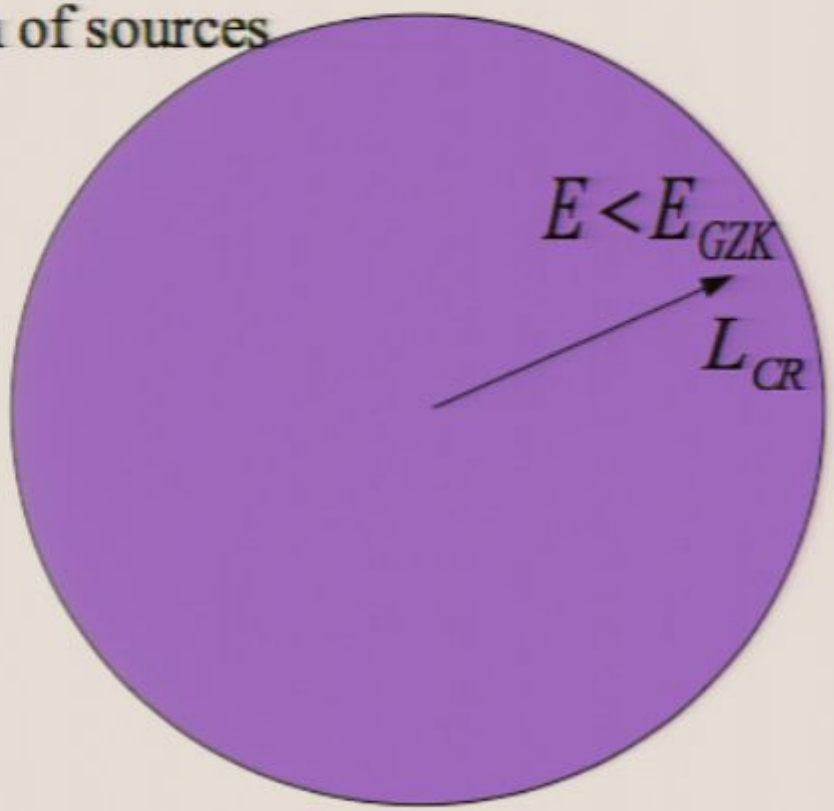

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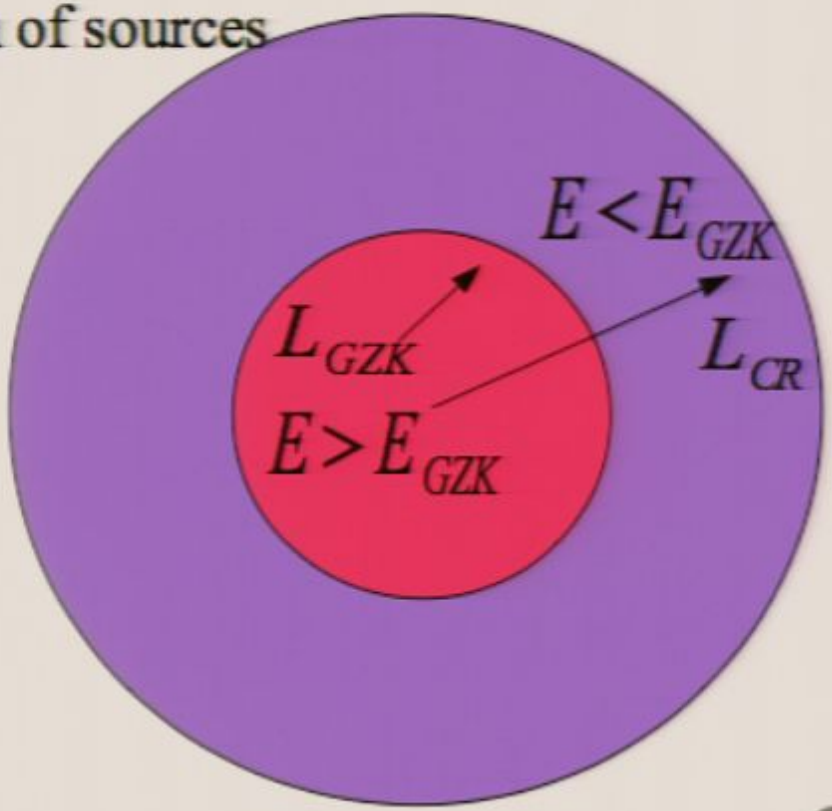

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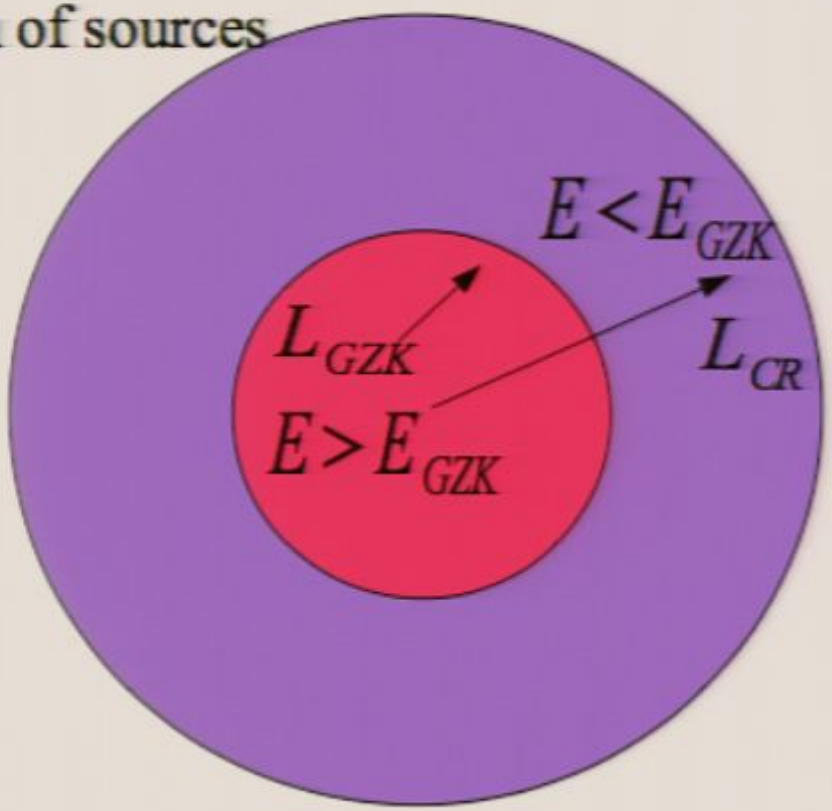

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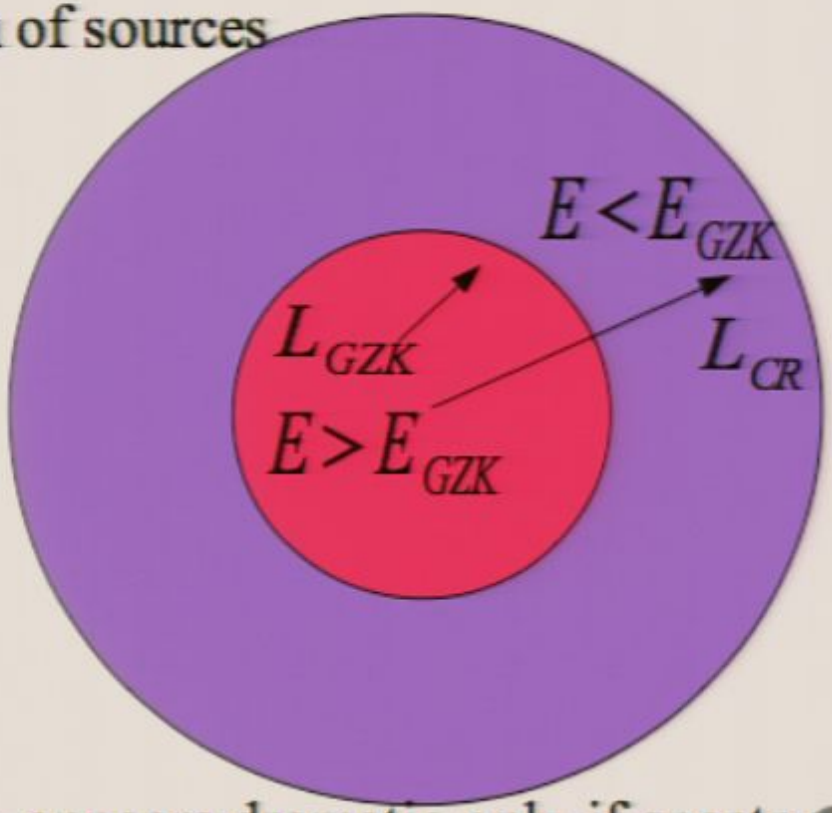

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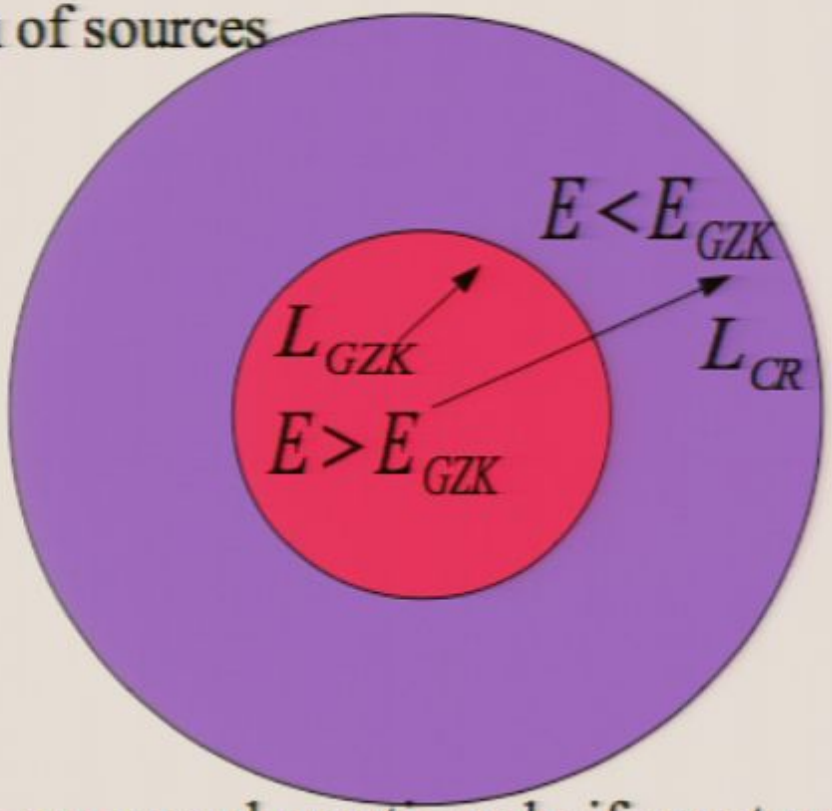

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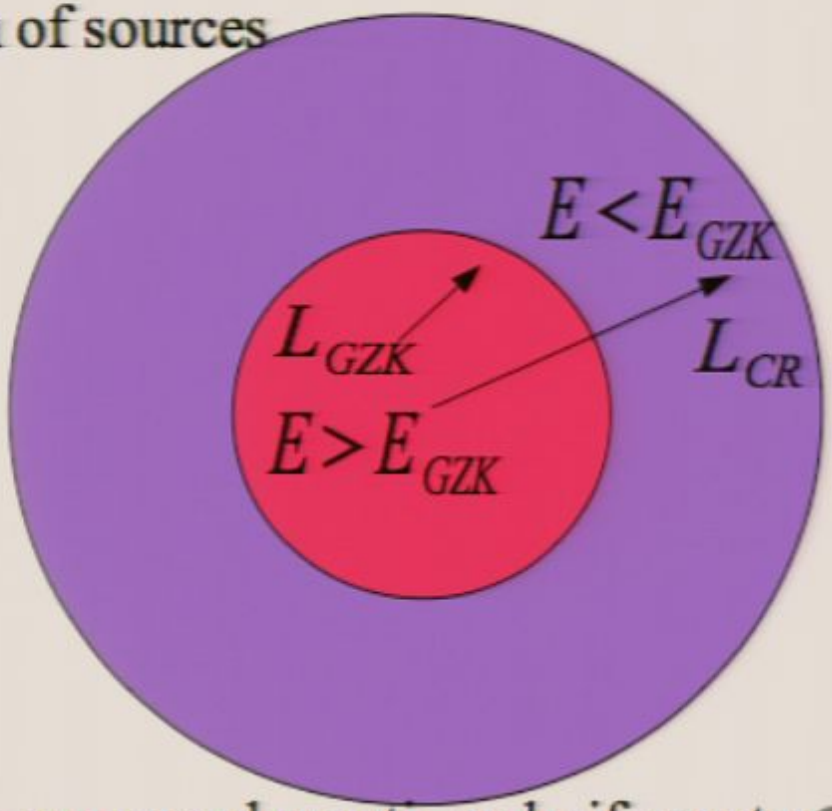

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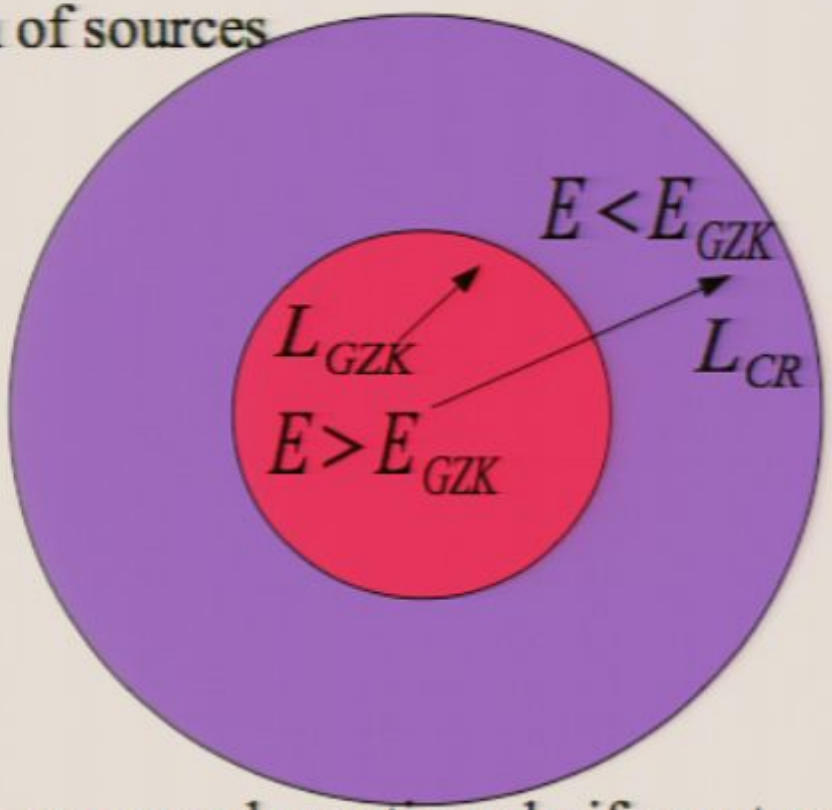

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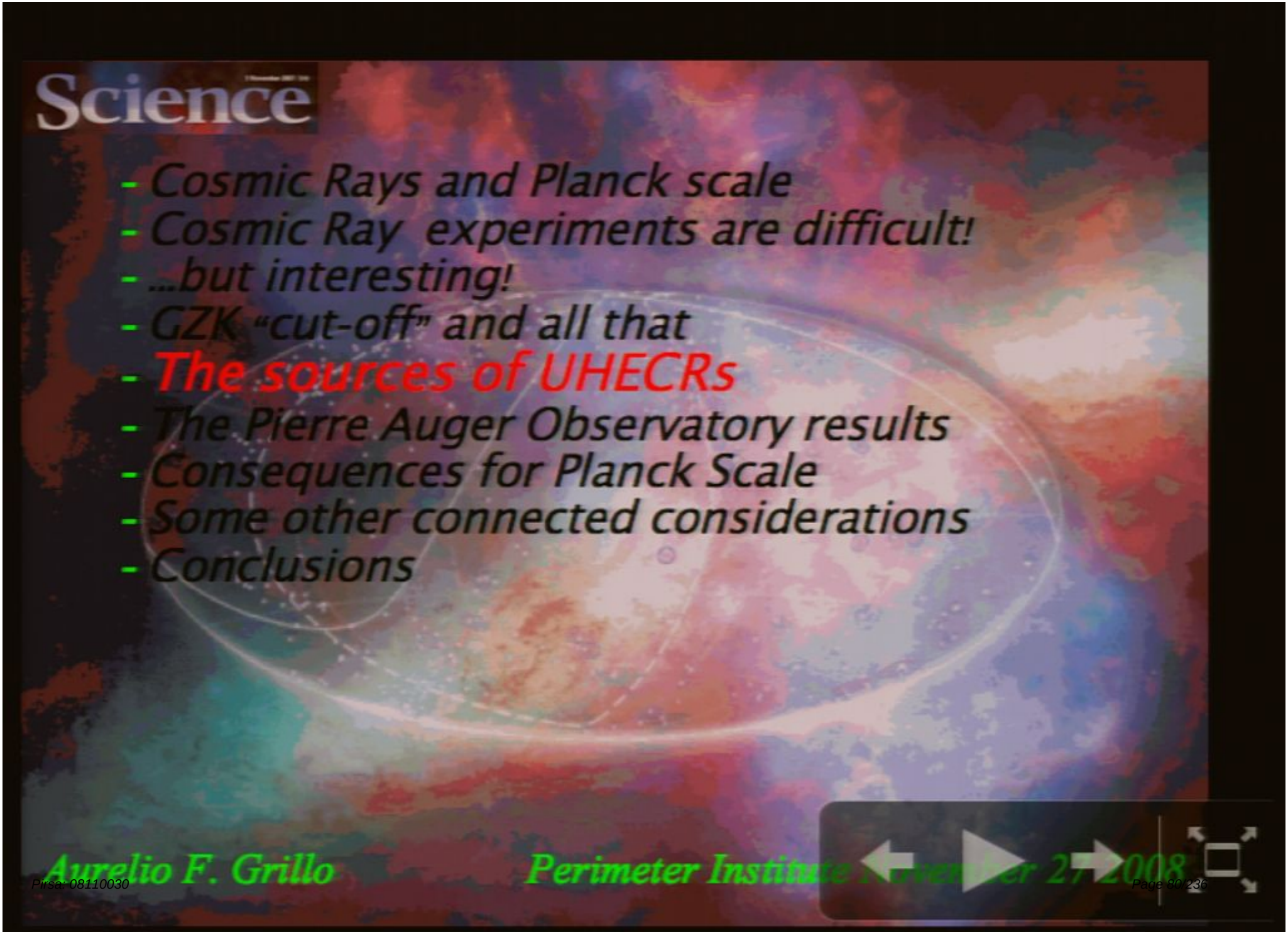
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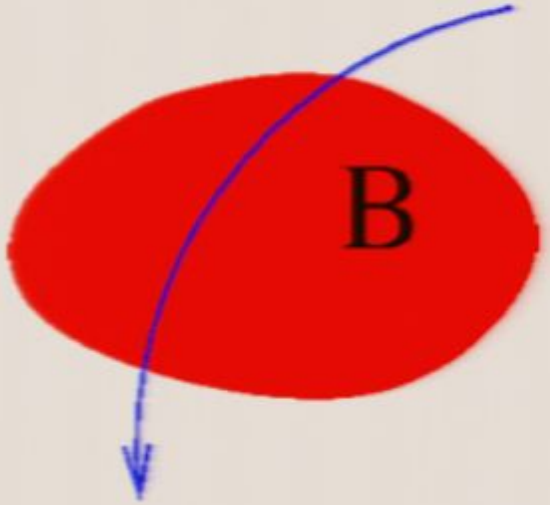

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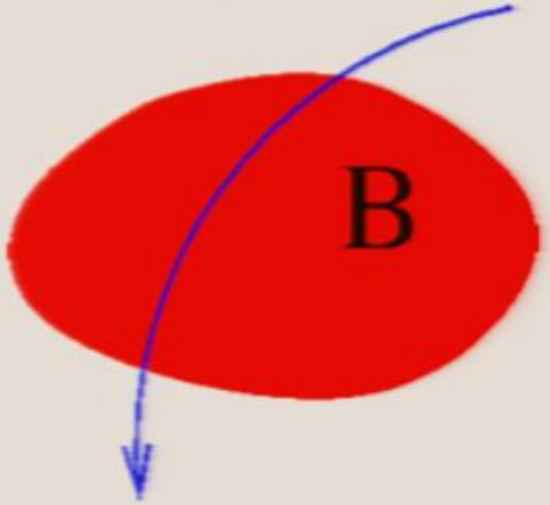

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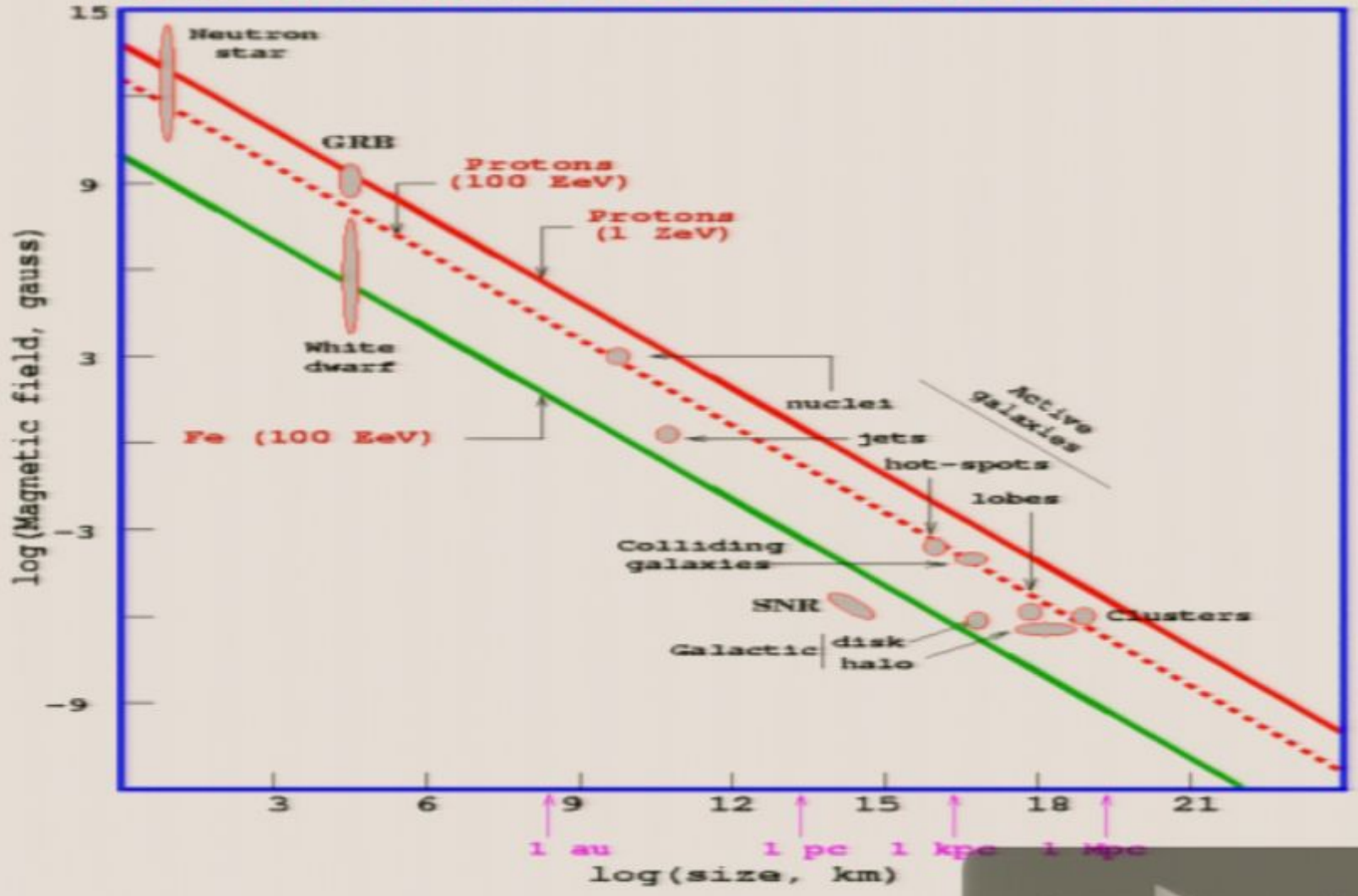
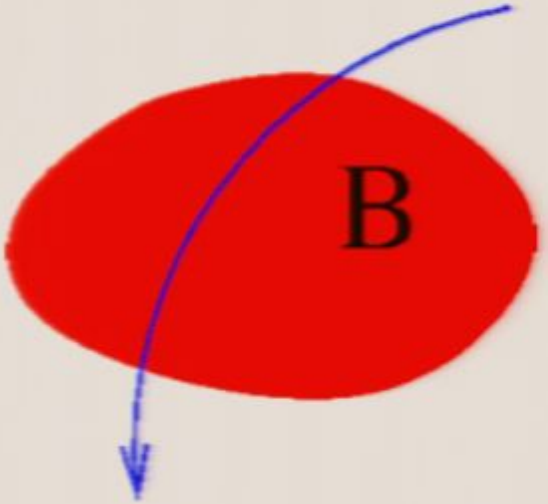
Hillas-plot
(candidate sites for E=100 EeV and E=1 ZeV)



$E_{max} \sim ZBL$ (Fermi)

$E_{max} \sim ZB\Gamma$ (Ultra-relativistic shocks)

Astrophysical sources



$$R_L \propto E/(Z\,B) < D_{acc}$$

$$E < ZB\,D_{acc}$$

In general max energy depends on lifetime of source, typical duration of acceleration cycles, efficiency of acceleration mechanism and energy losses

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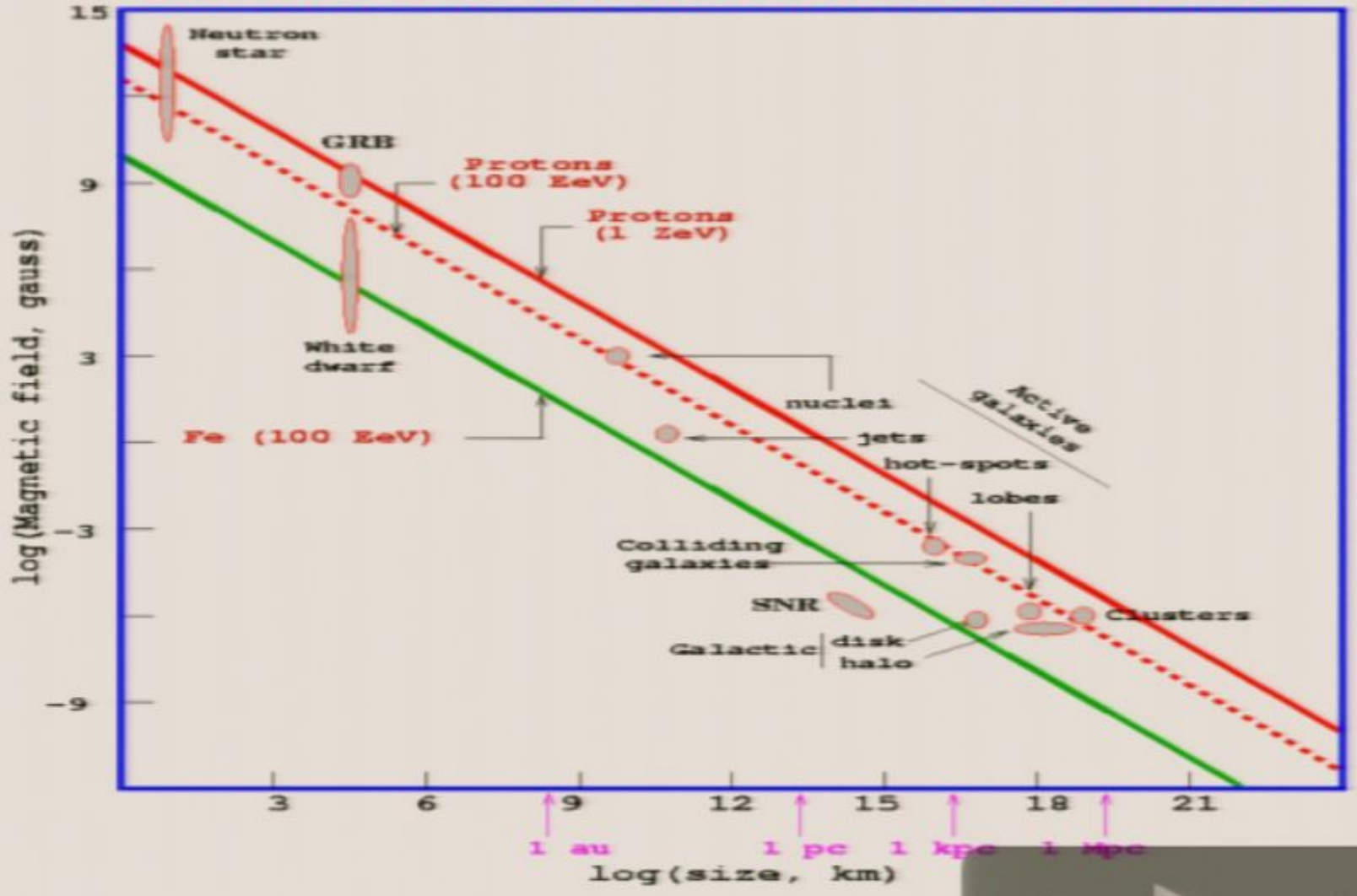

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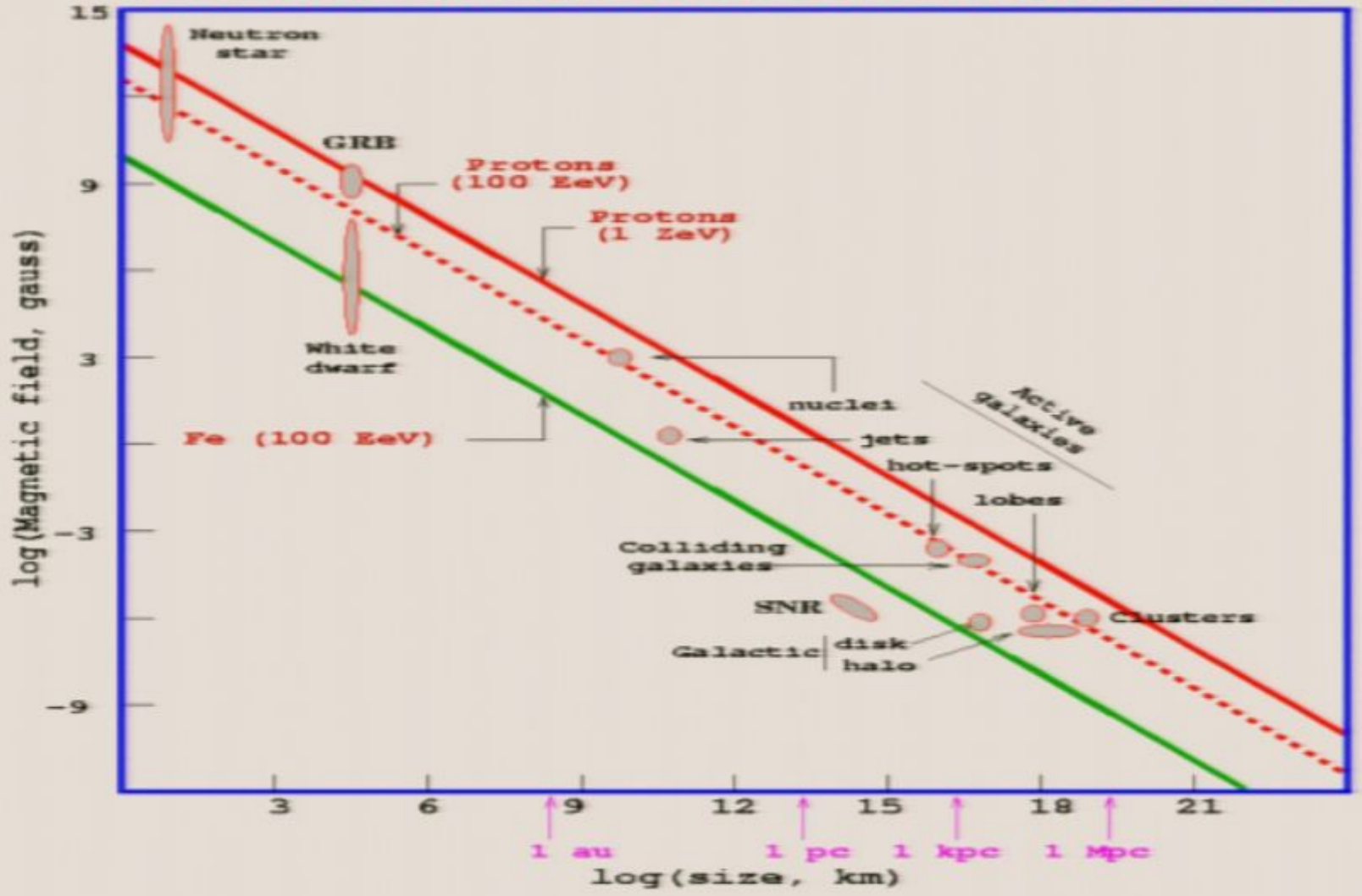

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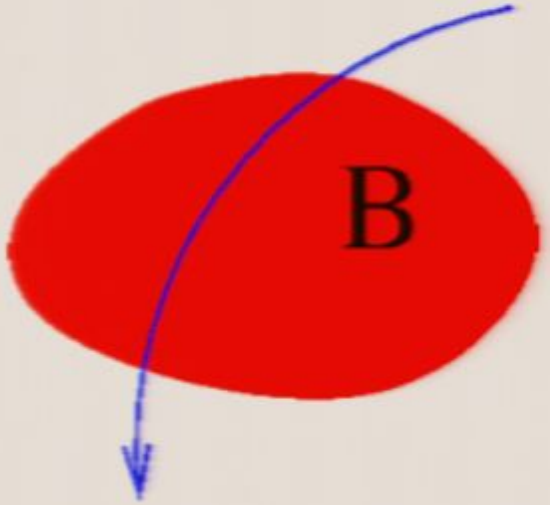

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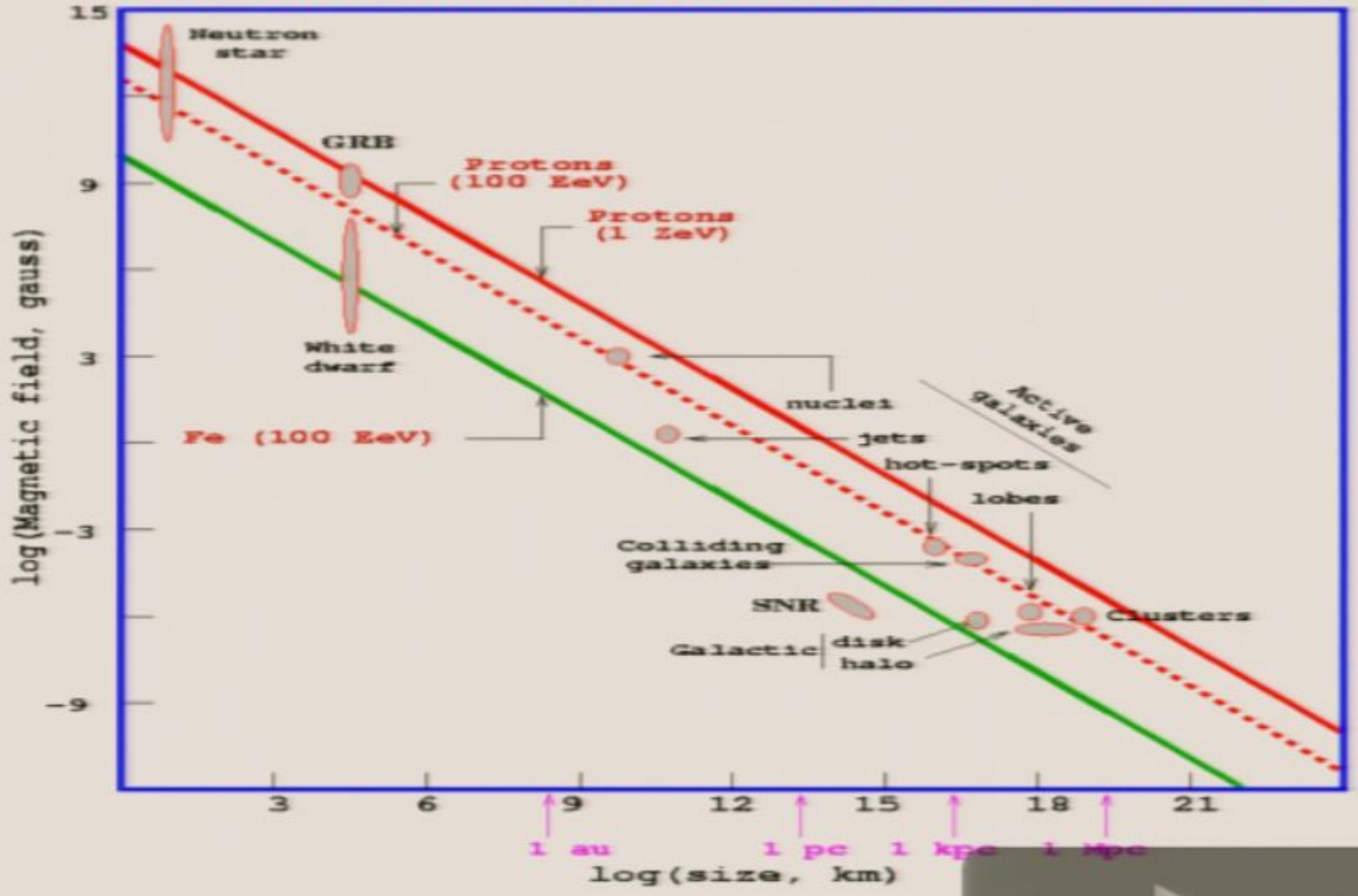

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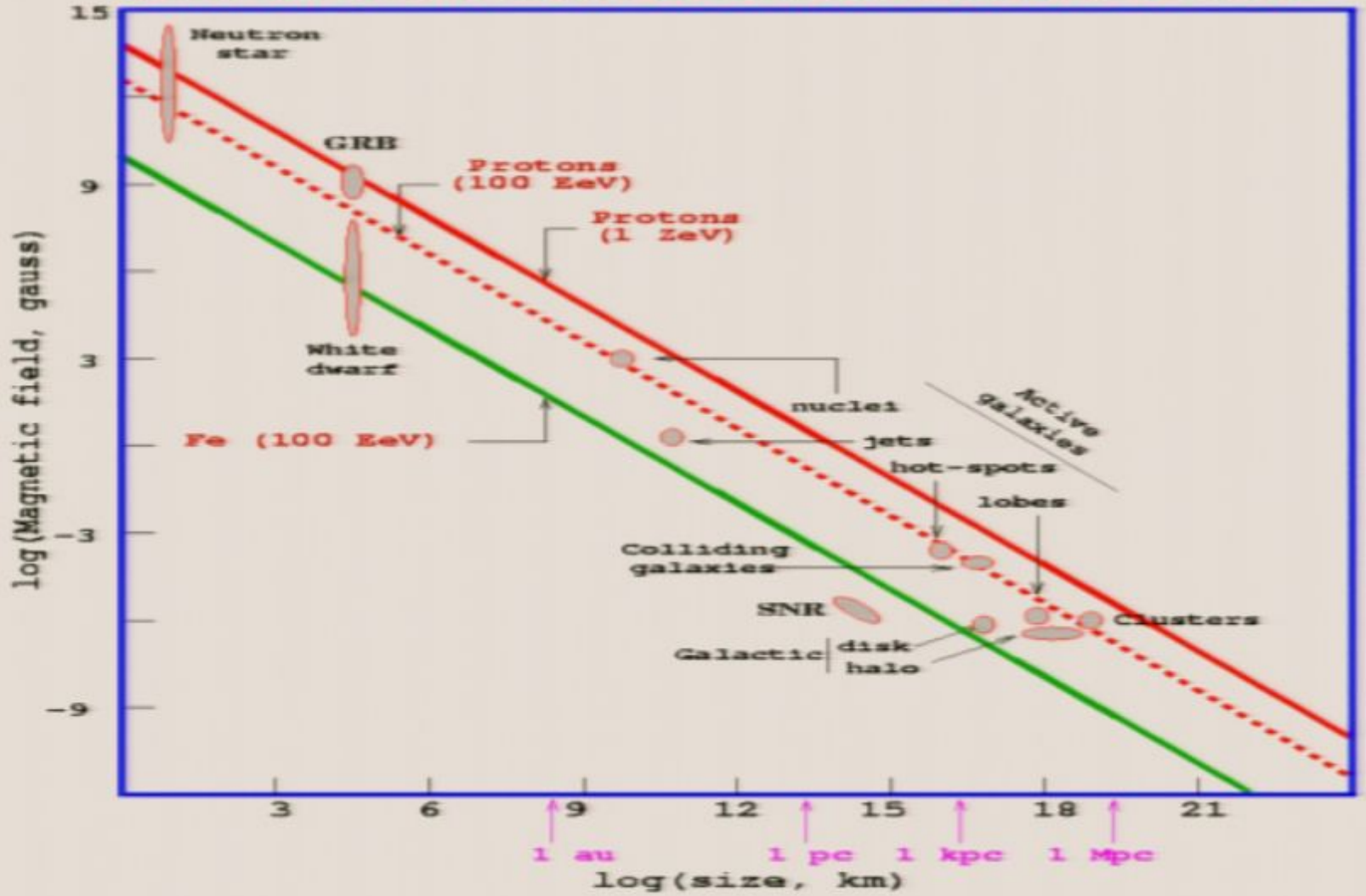

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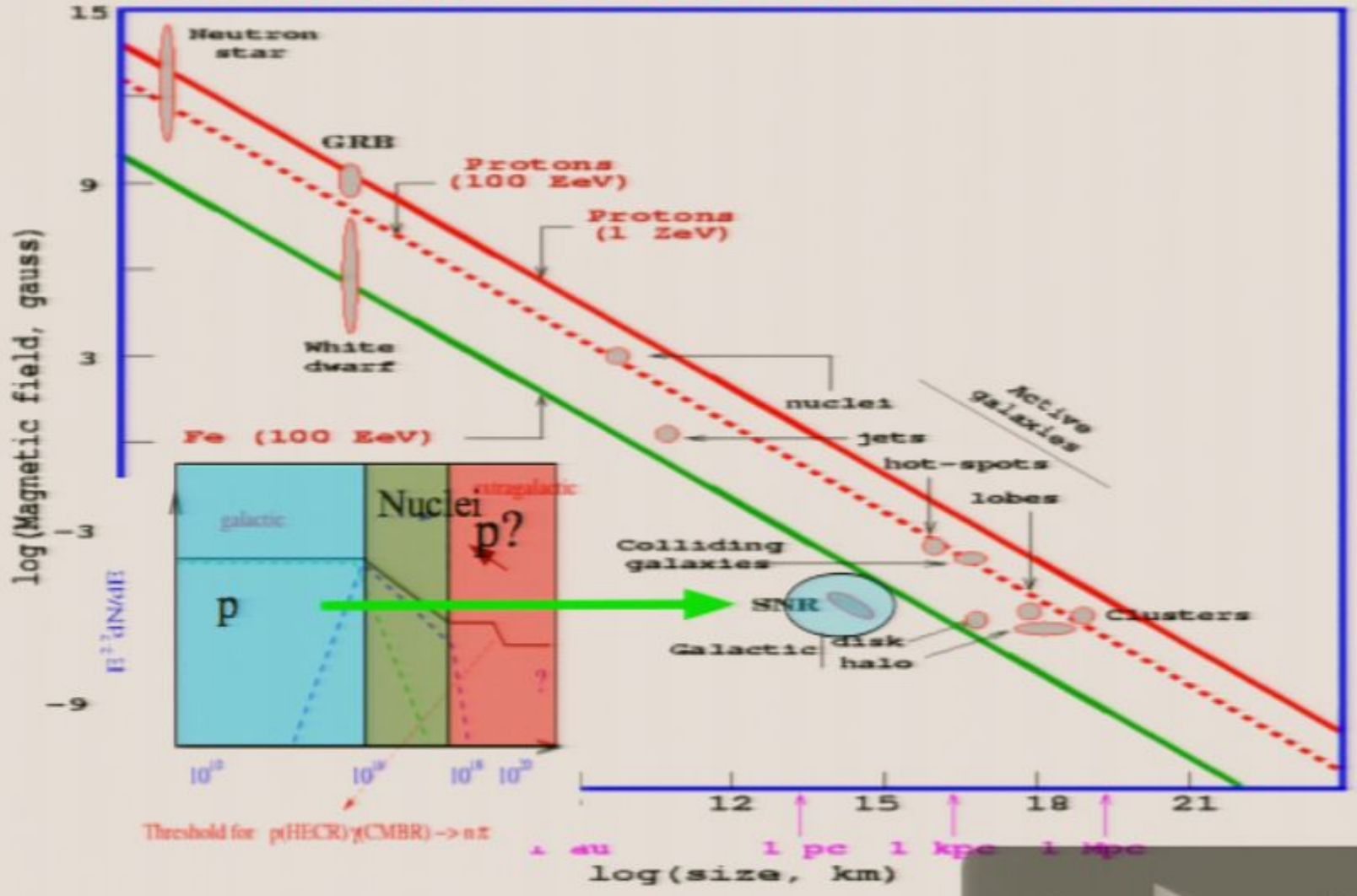

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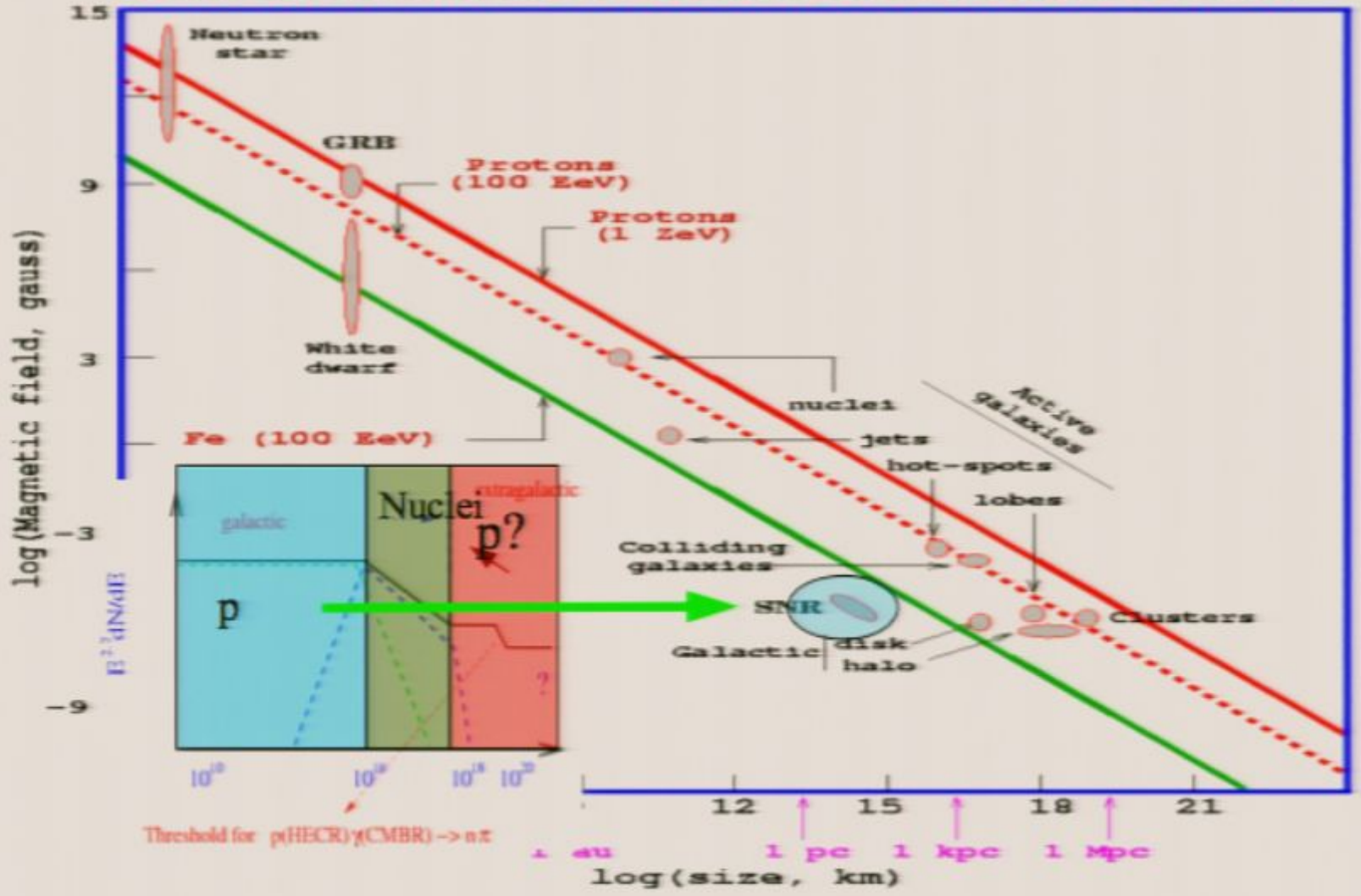

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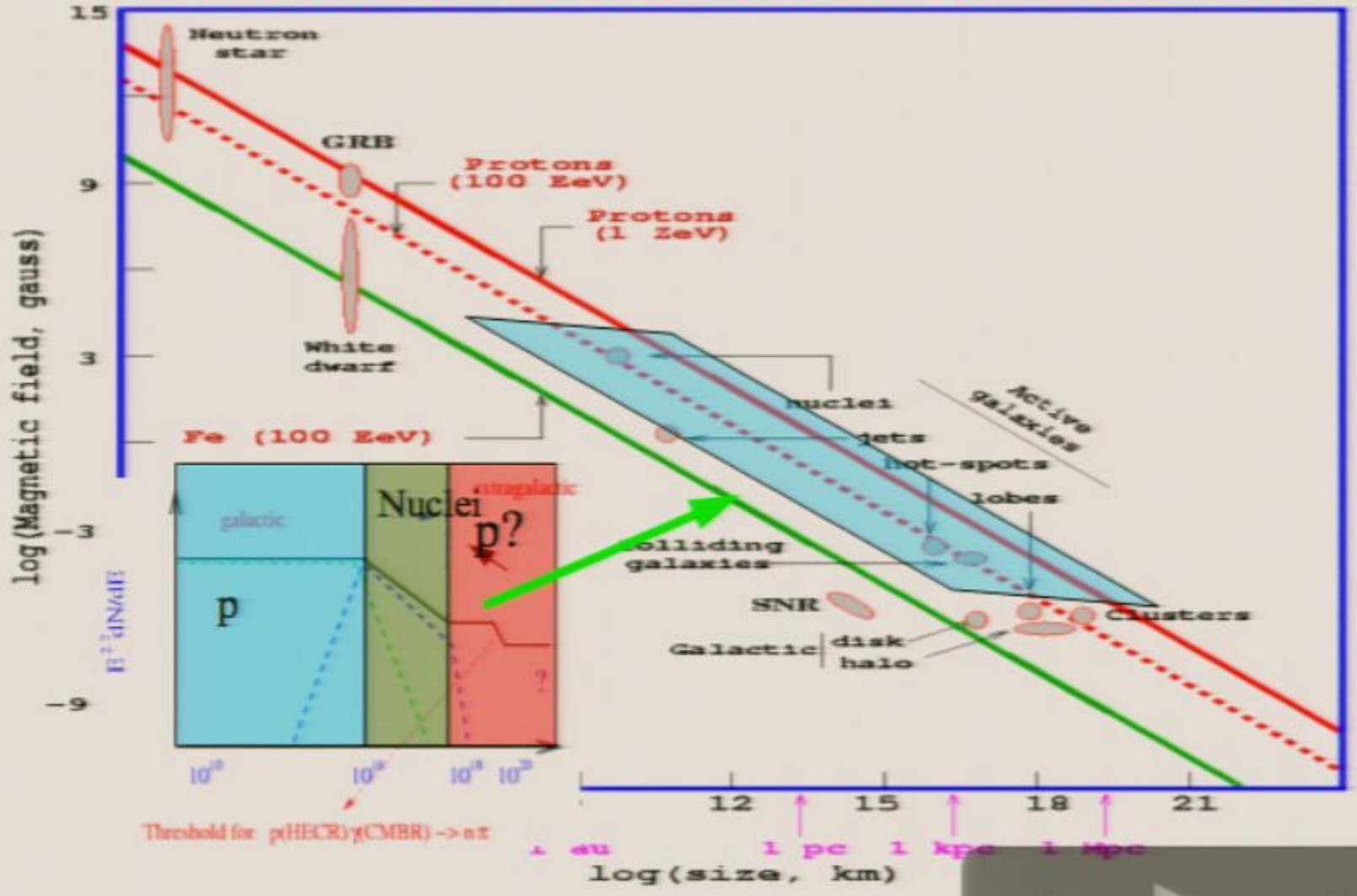

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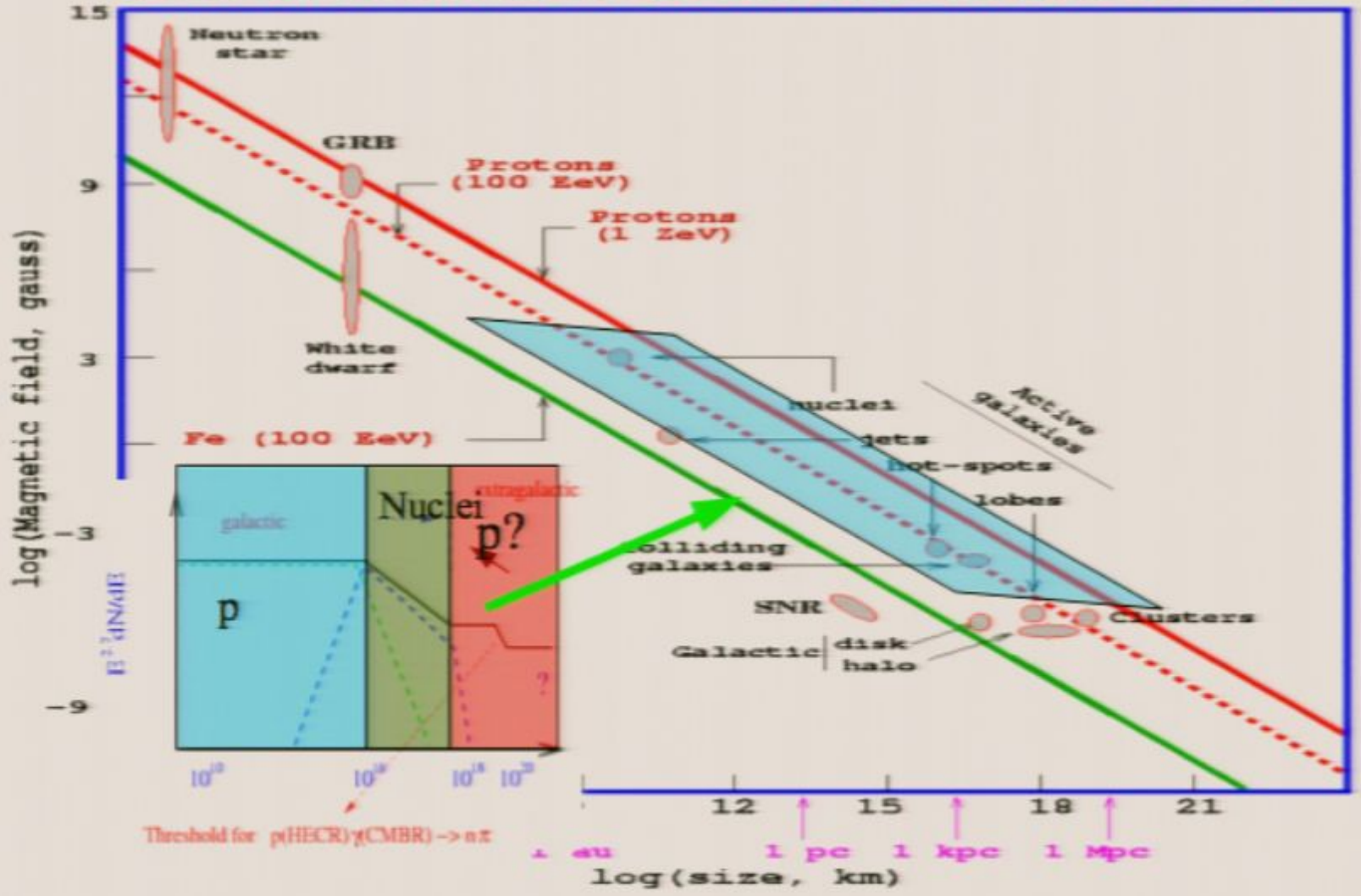

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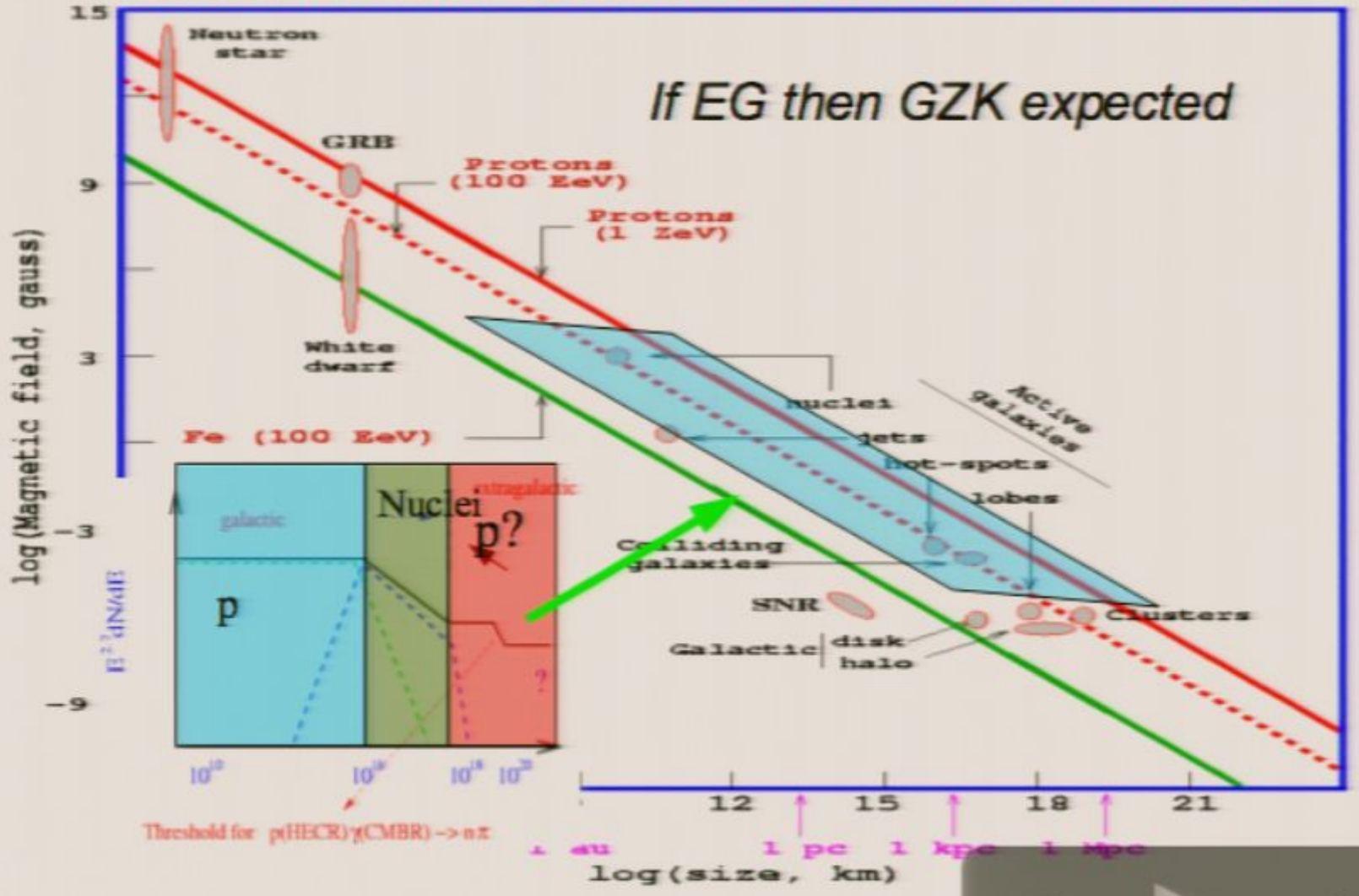

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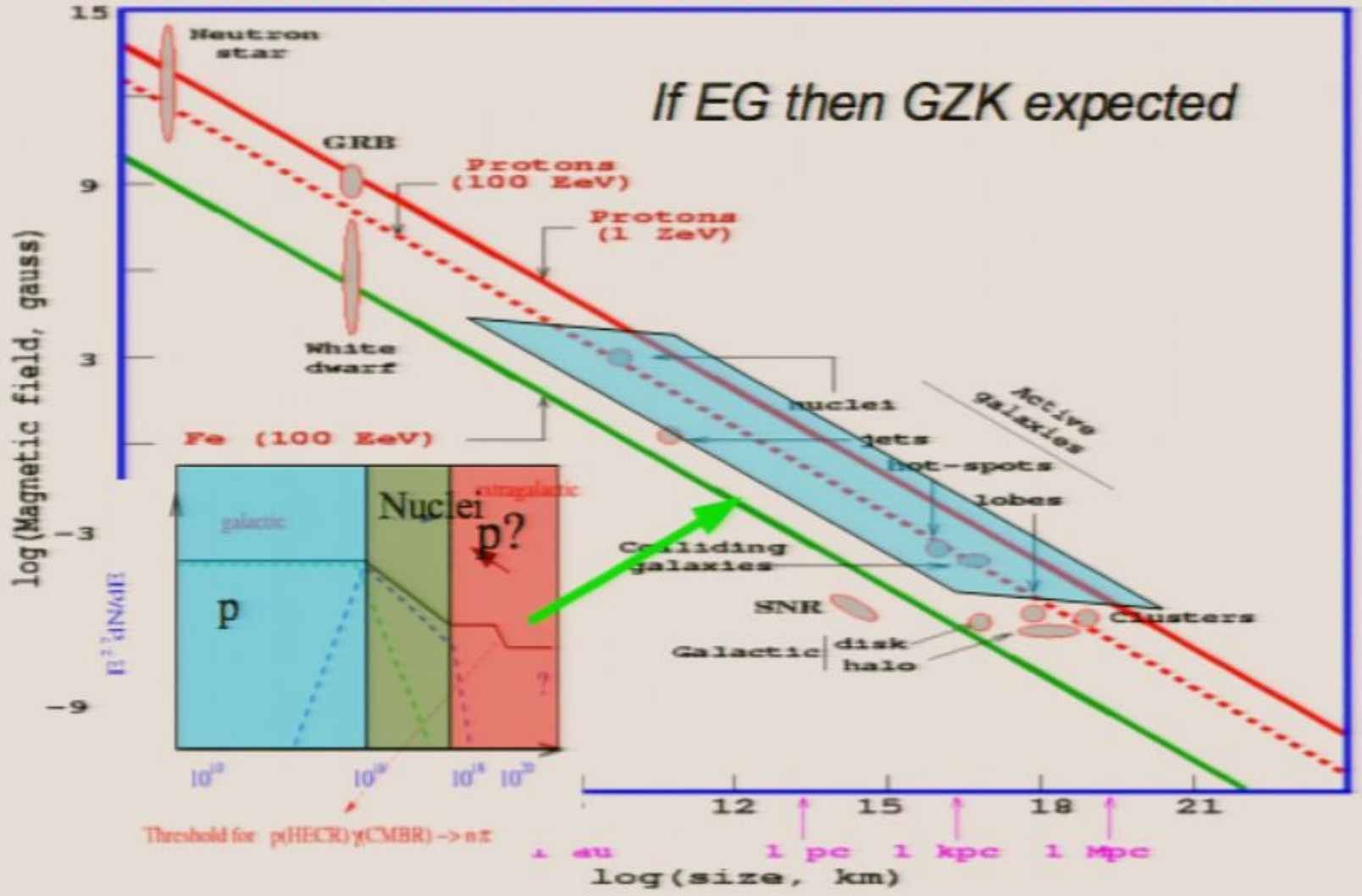

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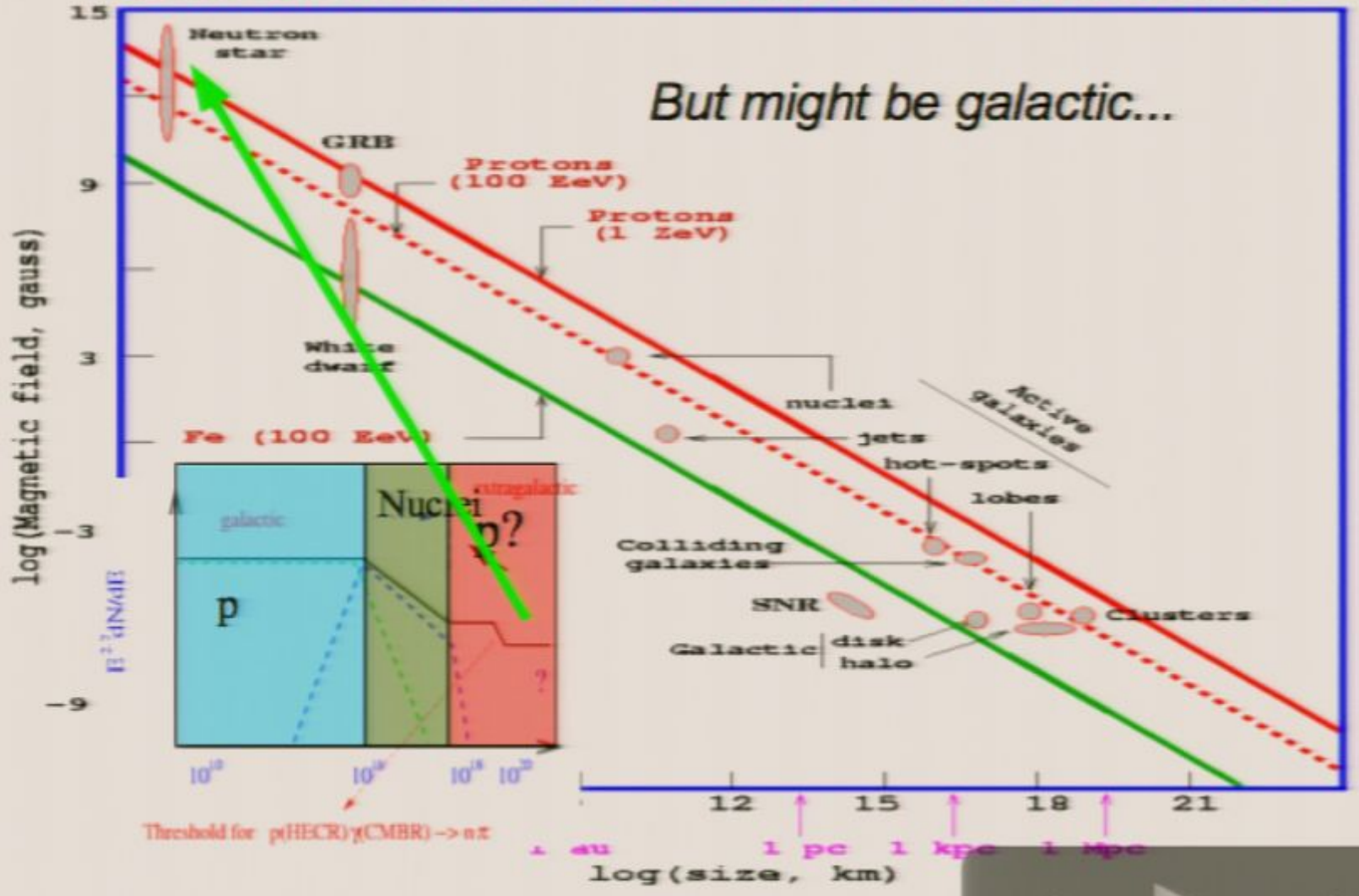

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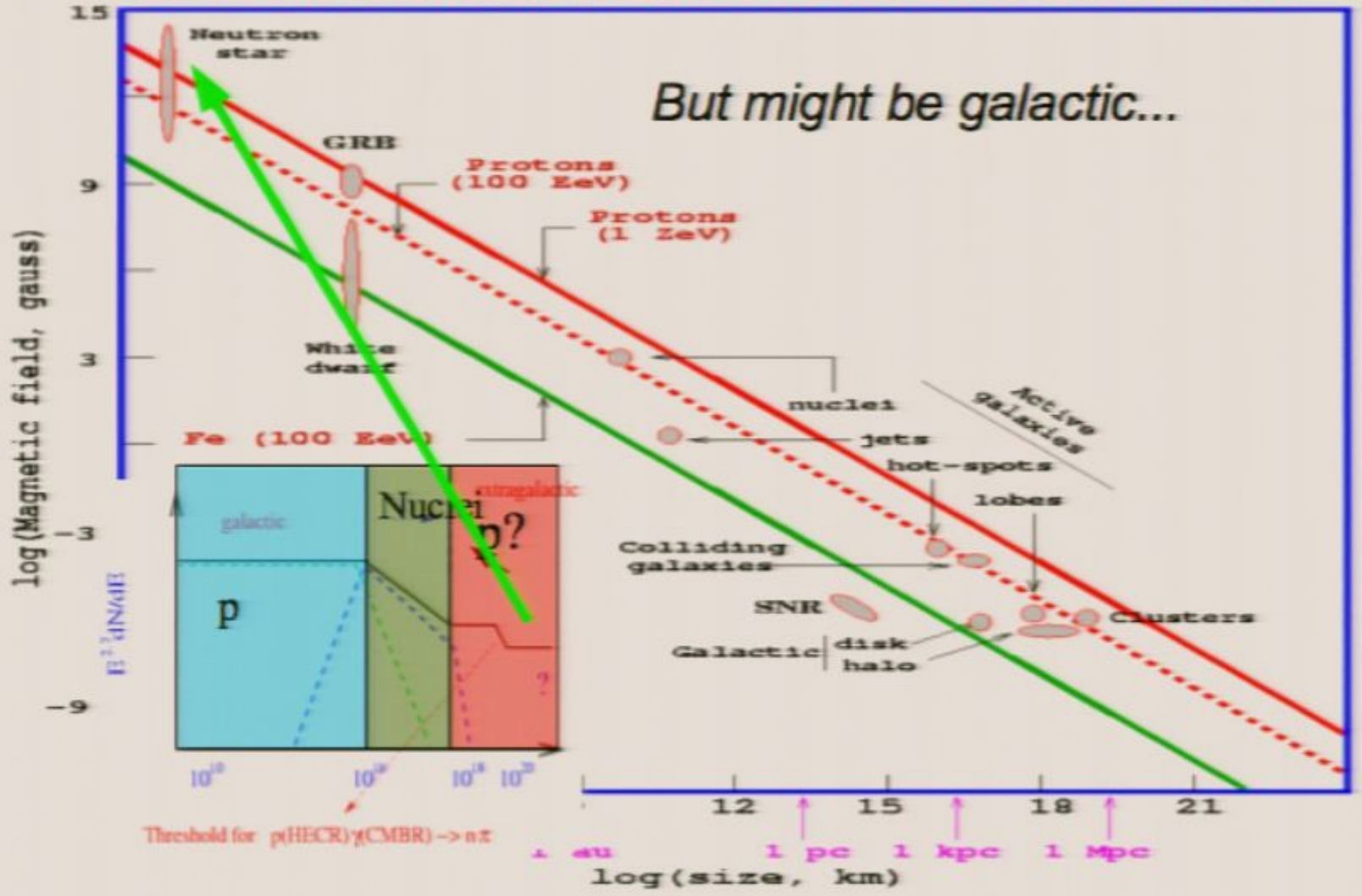

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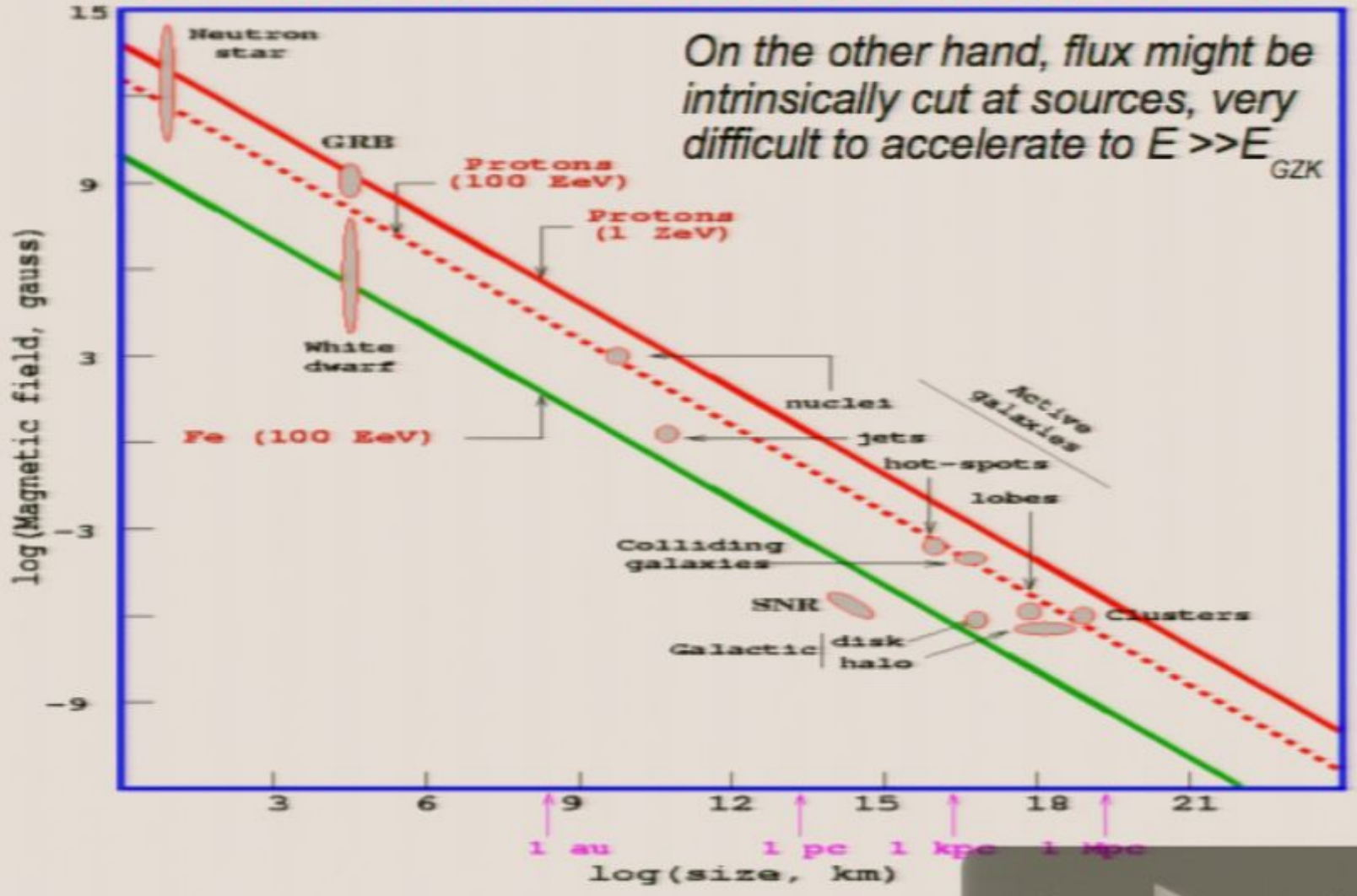

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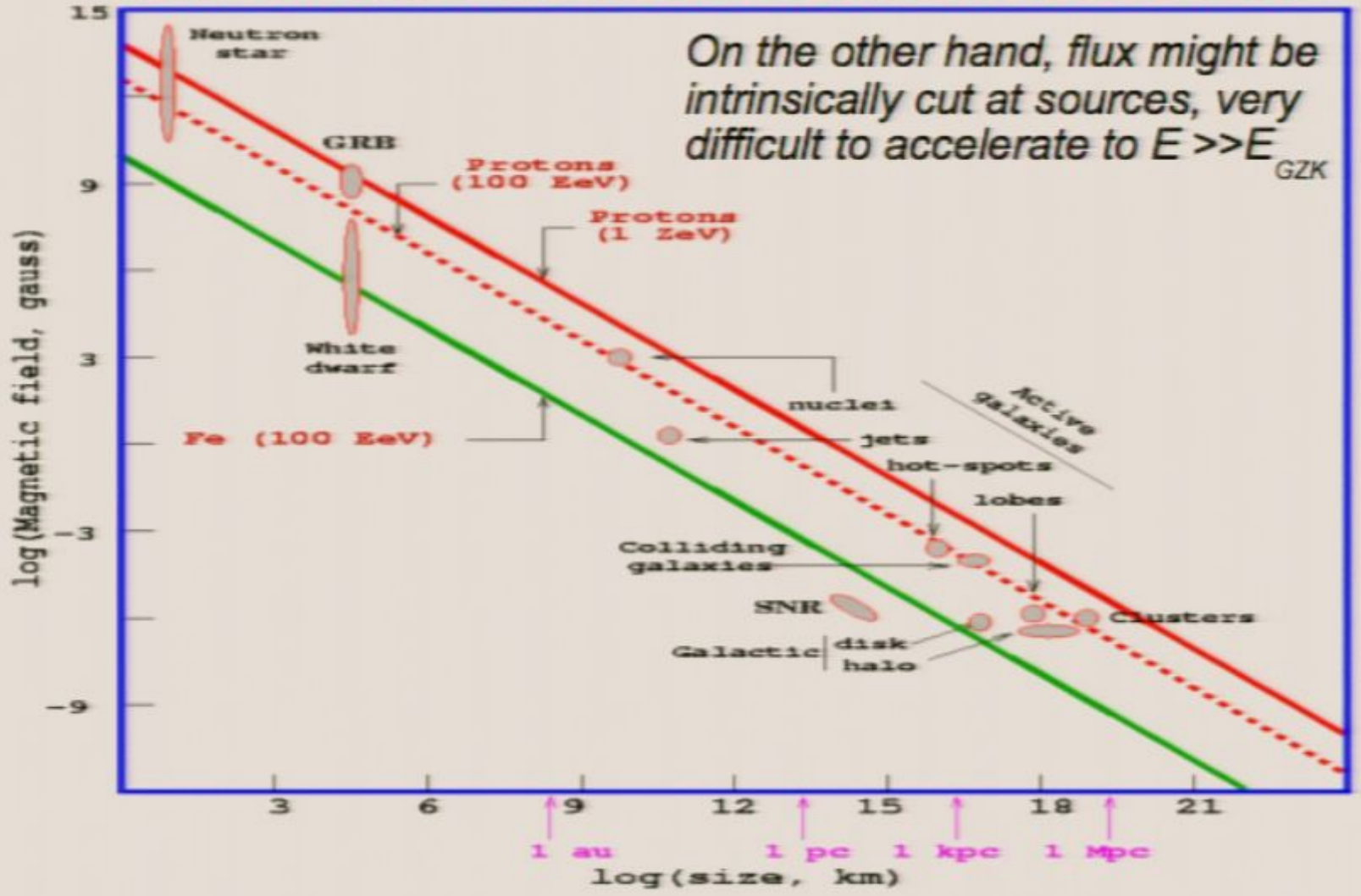

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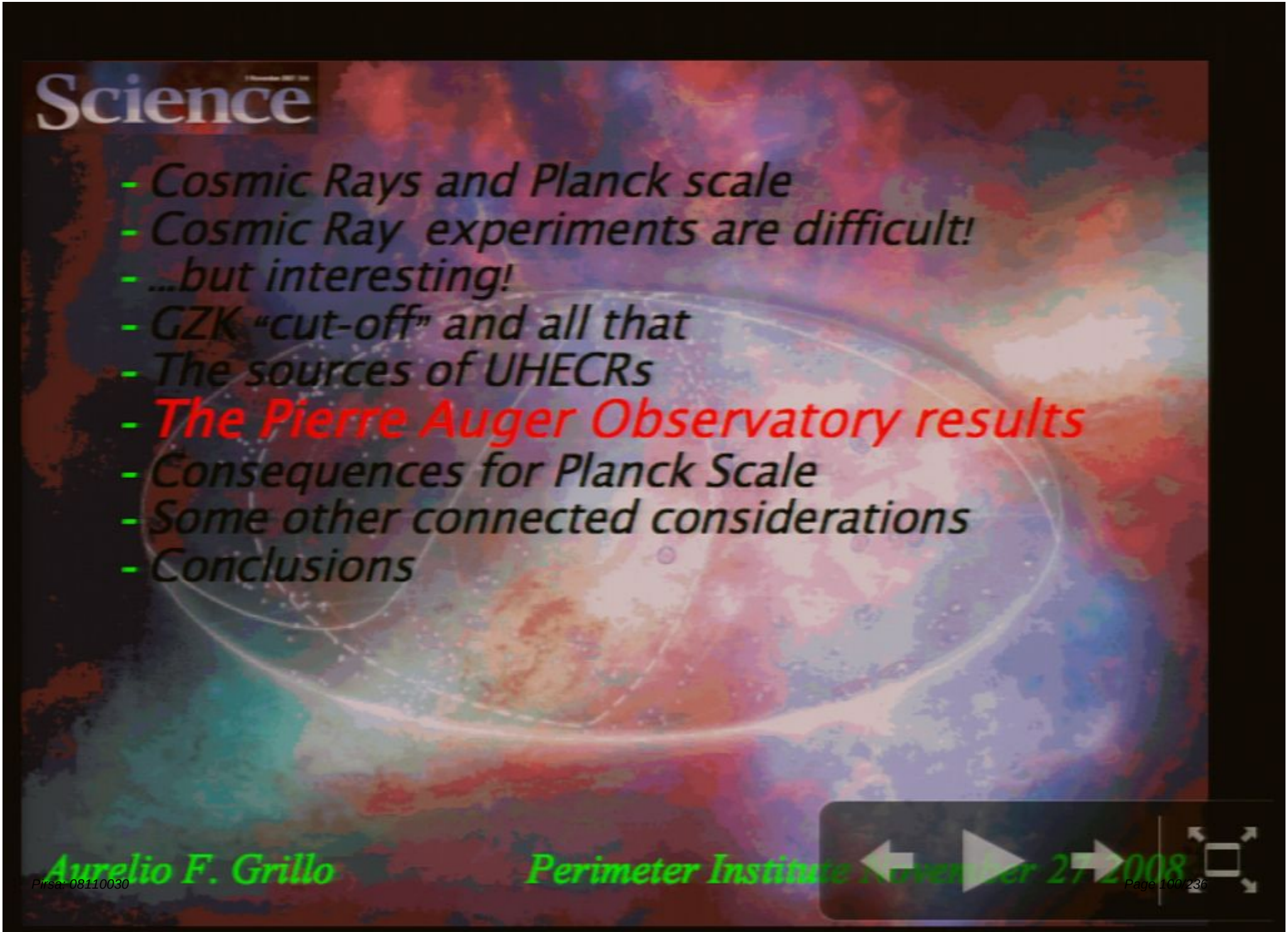
Science
- Cosmic Rays and Planck scale
- Cosmic Ray experiments are difficult!
- ...but interesting!
- GZK "cut-off" and all that
- The sources of UHECRs
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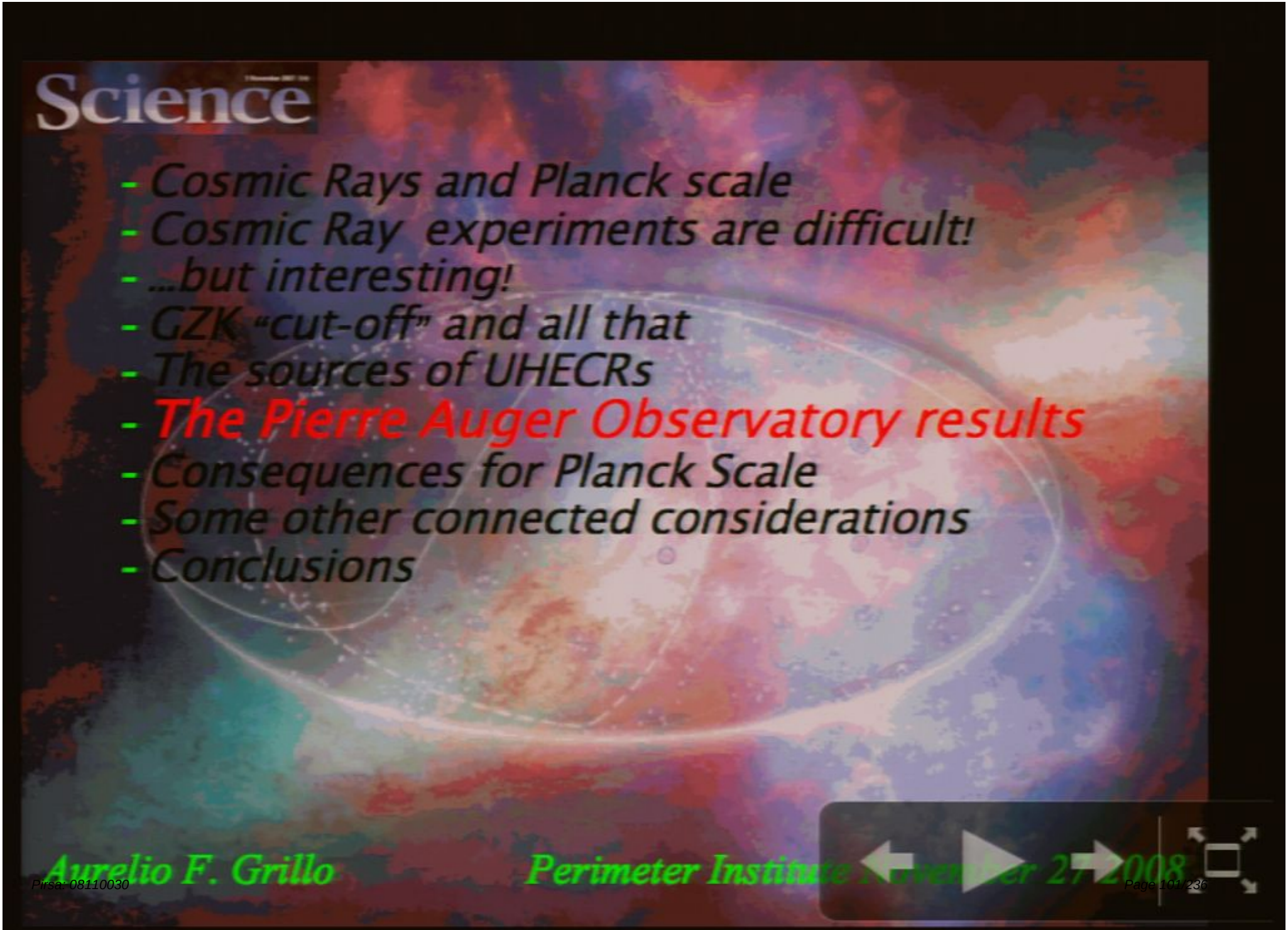
- Consequences for Planck Scale
- Some other connected considerations
- Conclusions
Aurelio F. Grillo
Perimeter Institute, December 27, 2008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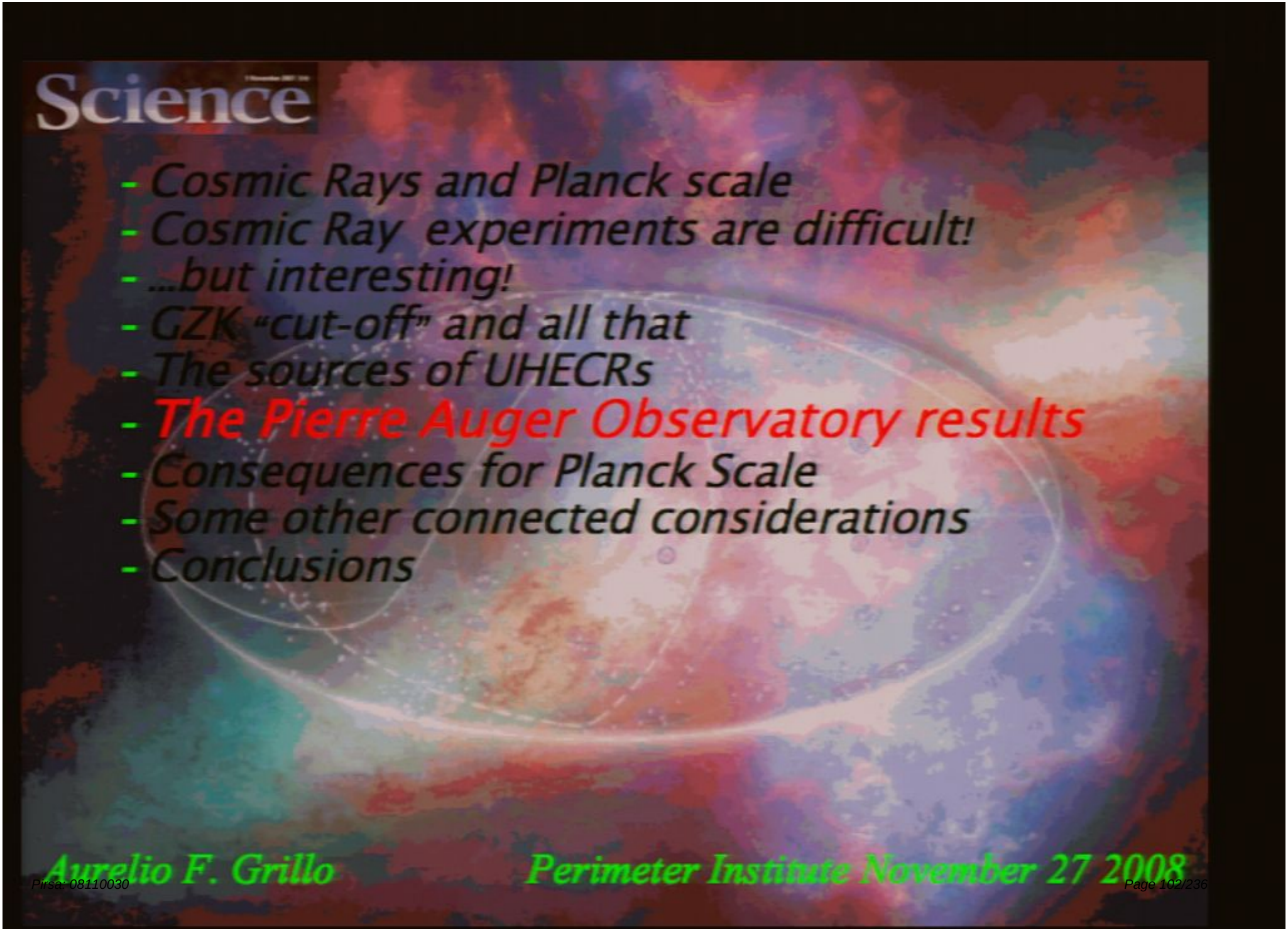
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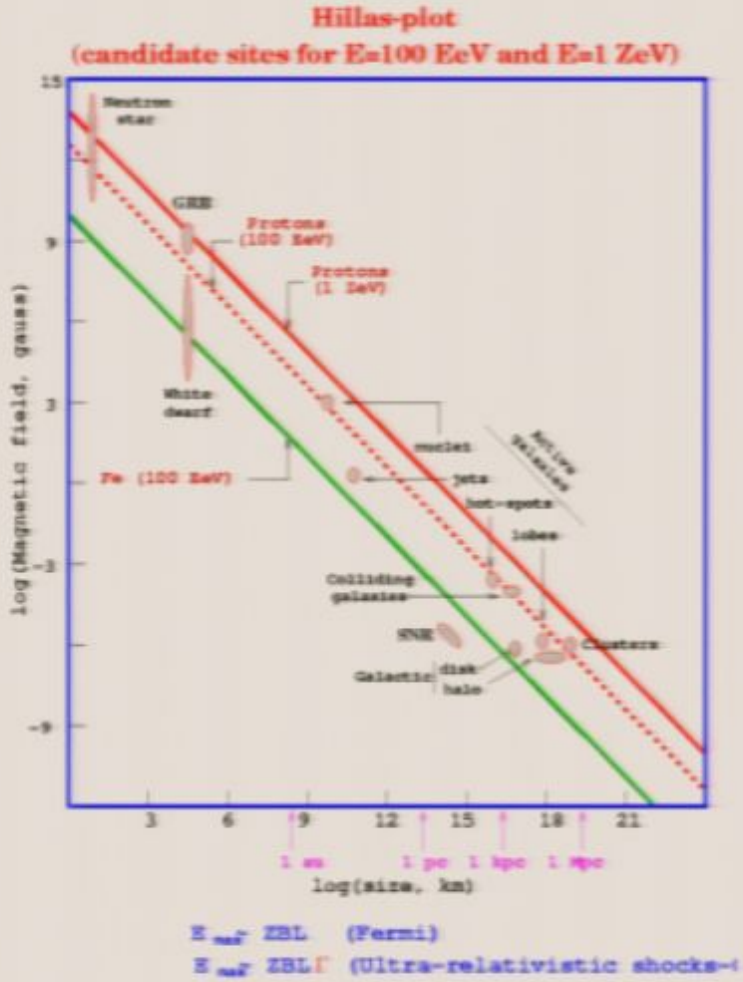
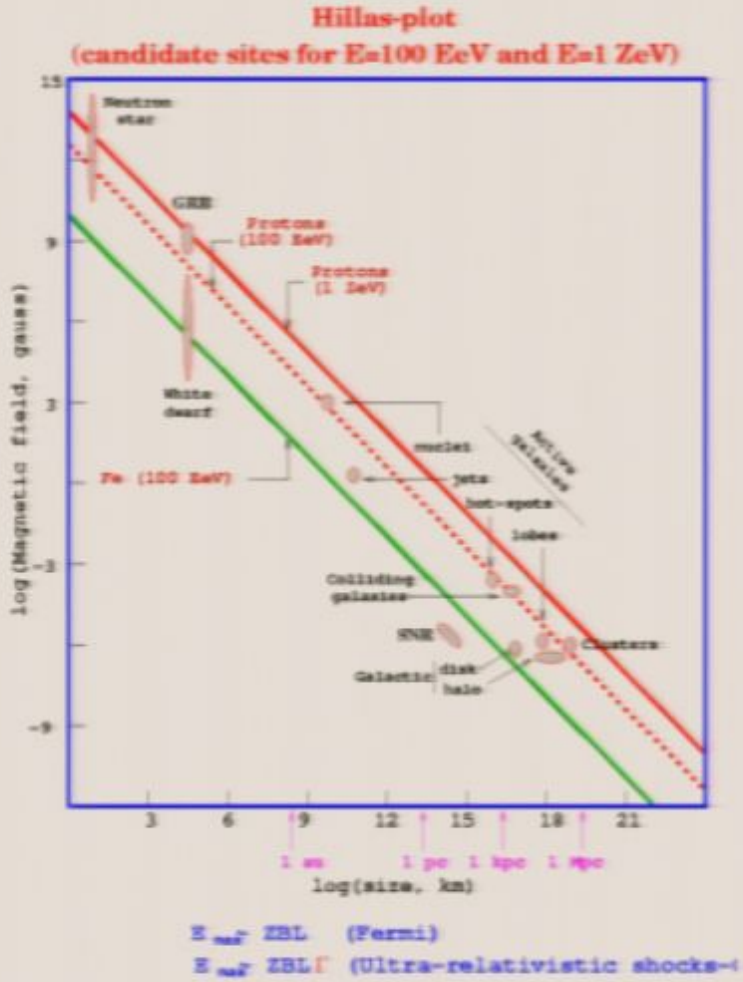


Summarizing:

drop not present: EG sources → LIV
G sources

drop present: If associated with nearby sources → GZK

If no association: flux cut at sources, no conclusion about LI



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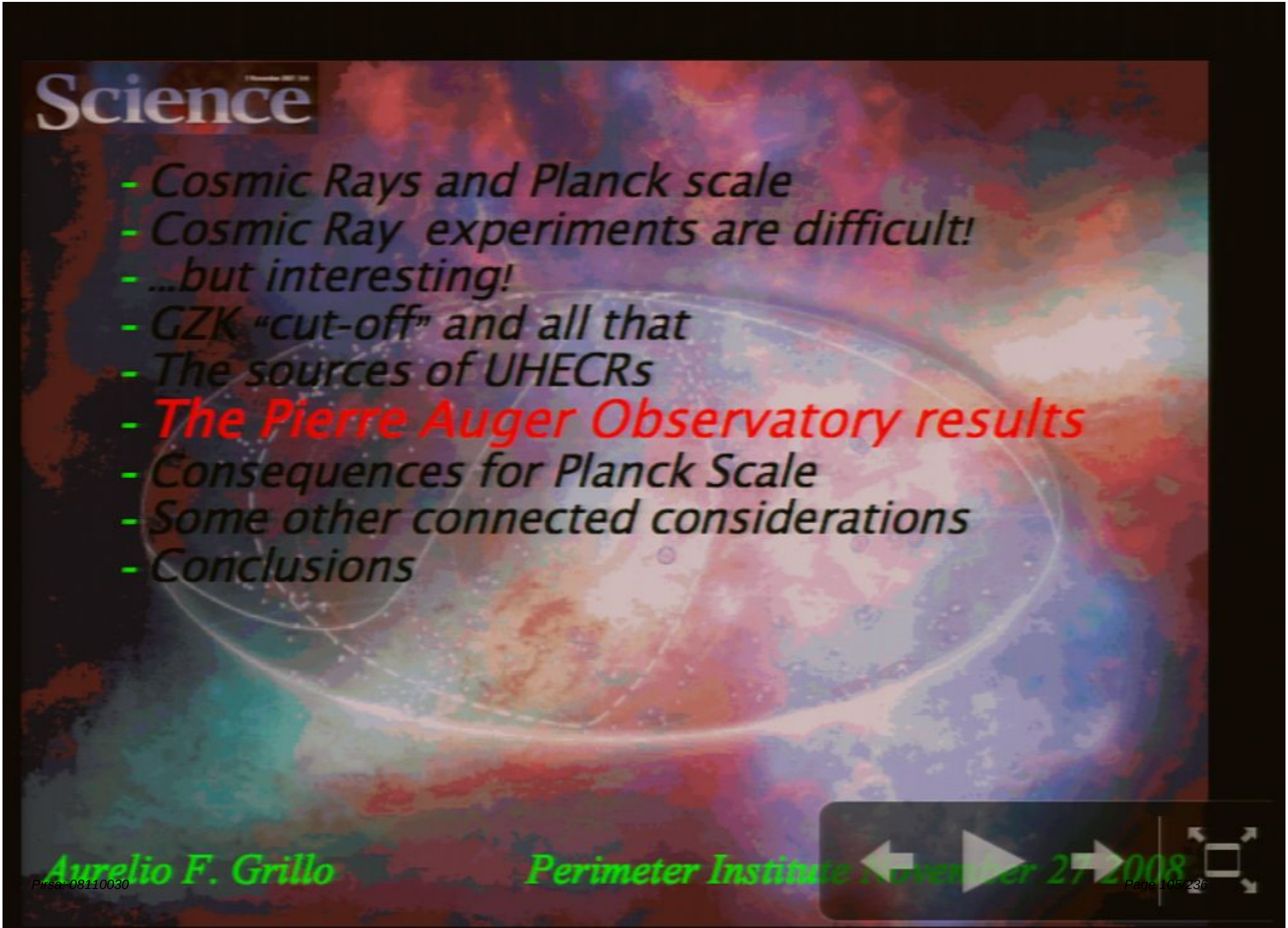
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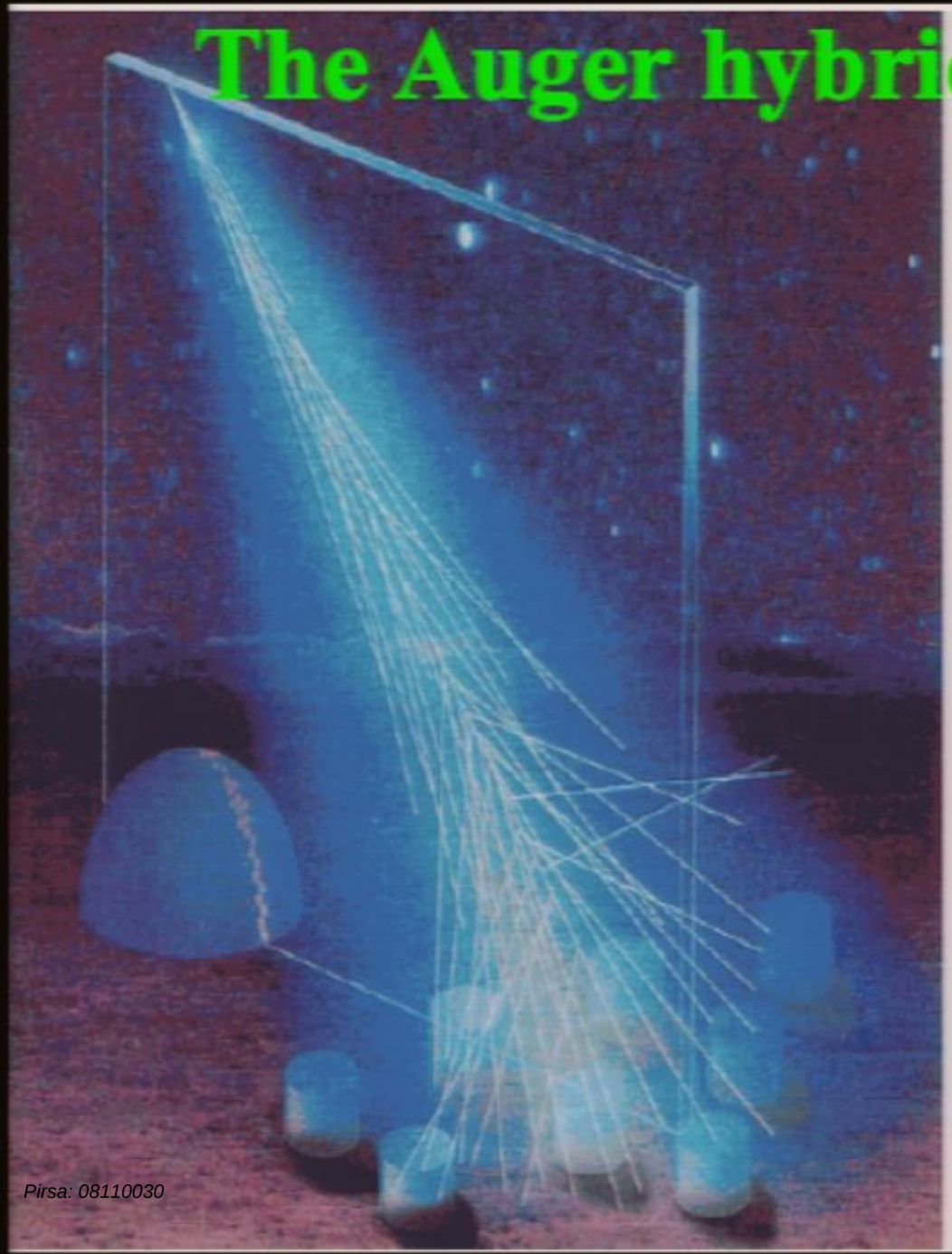
The Auger hybrid concept



EAS at 10^{20} eV

- 50 W light bulb at speed of light
- 10^{12} particles spread over >20 km^2

Detector

- Fluorescence Telescope
- Ground Array

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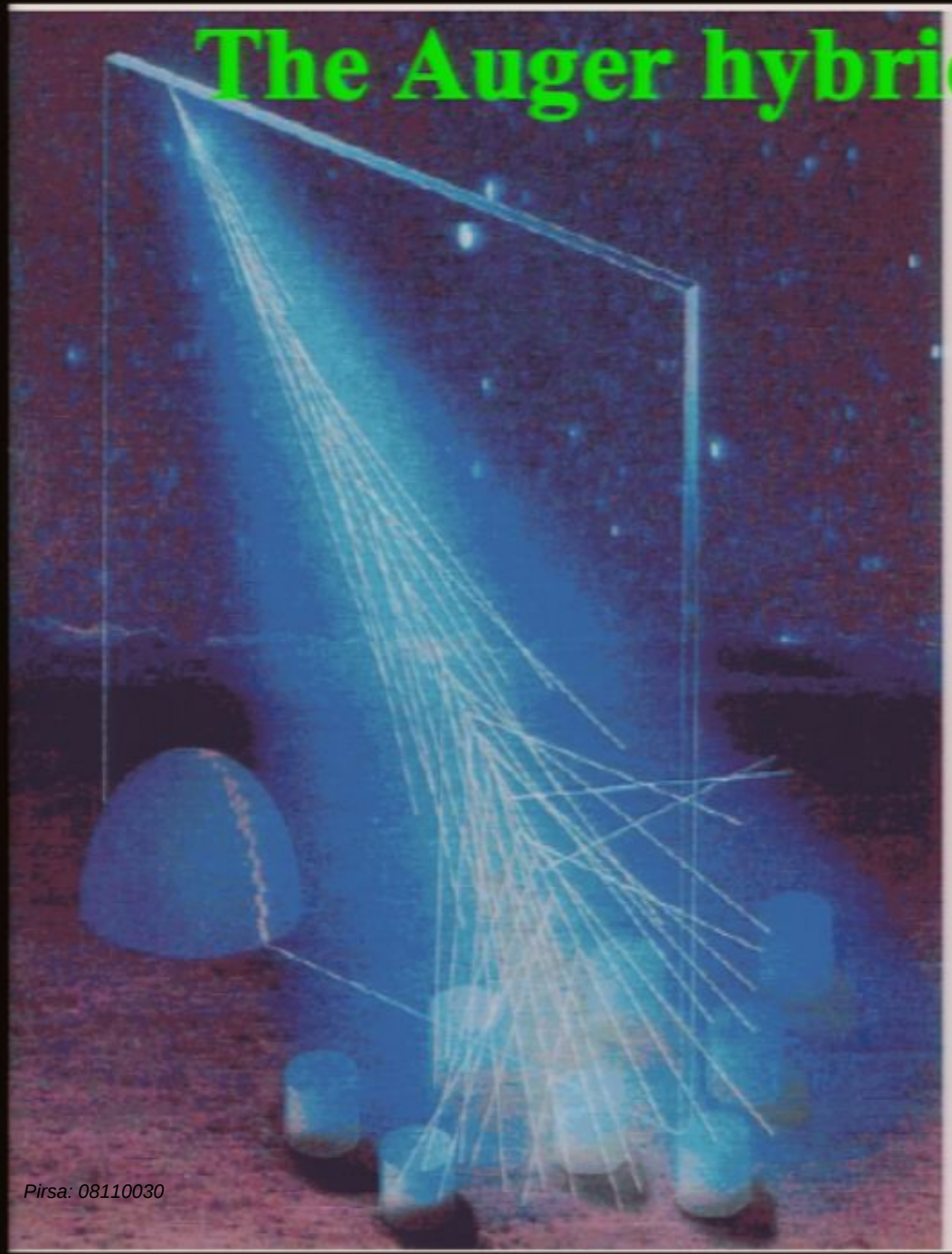

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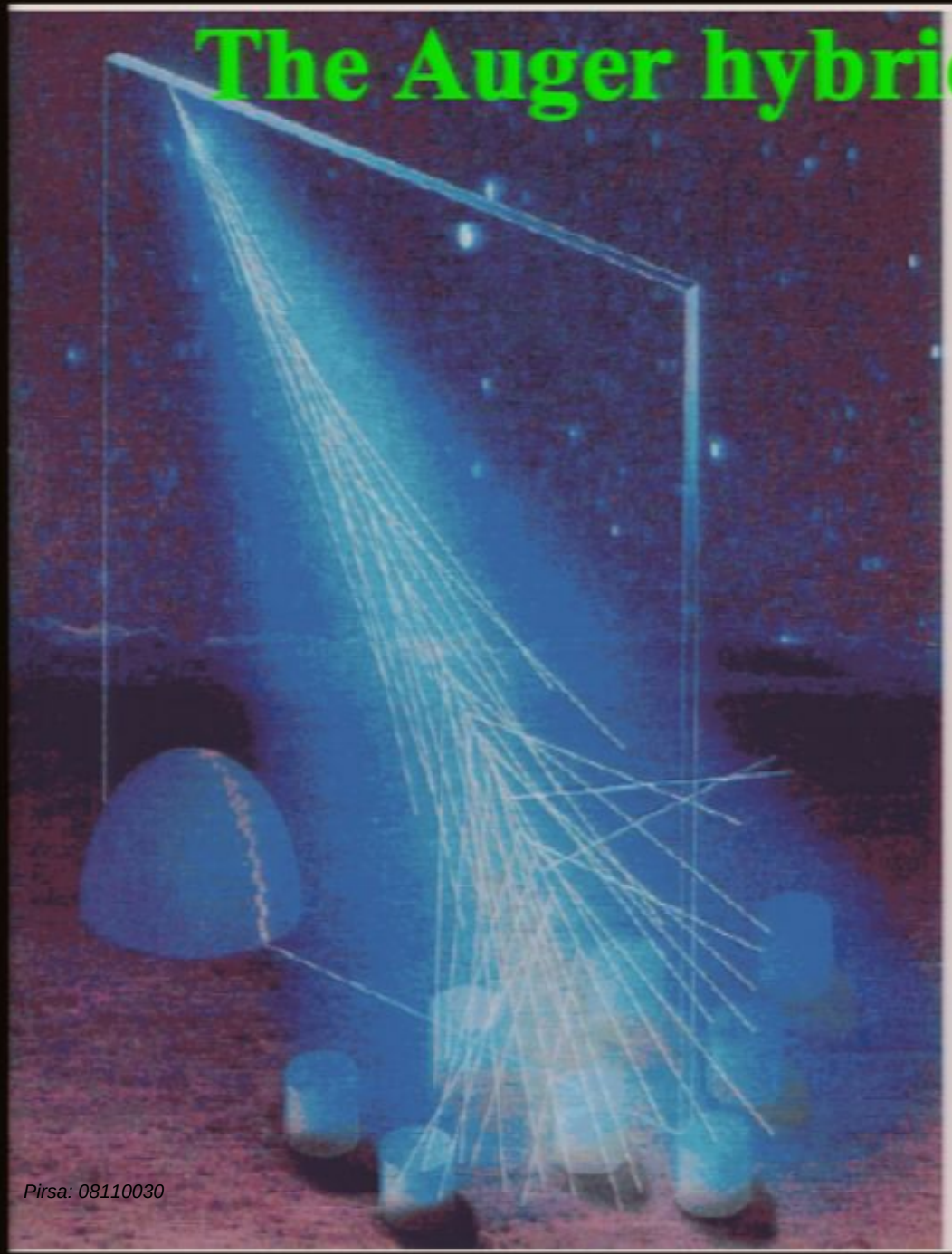

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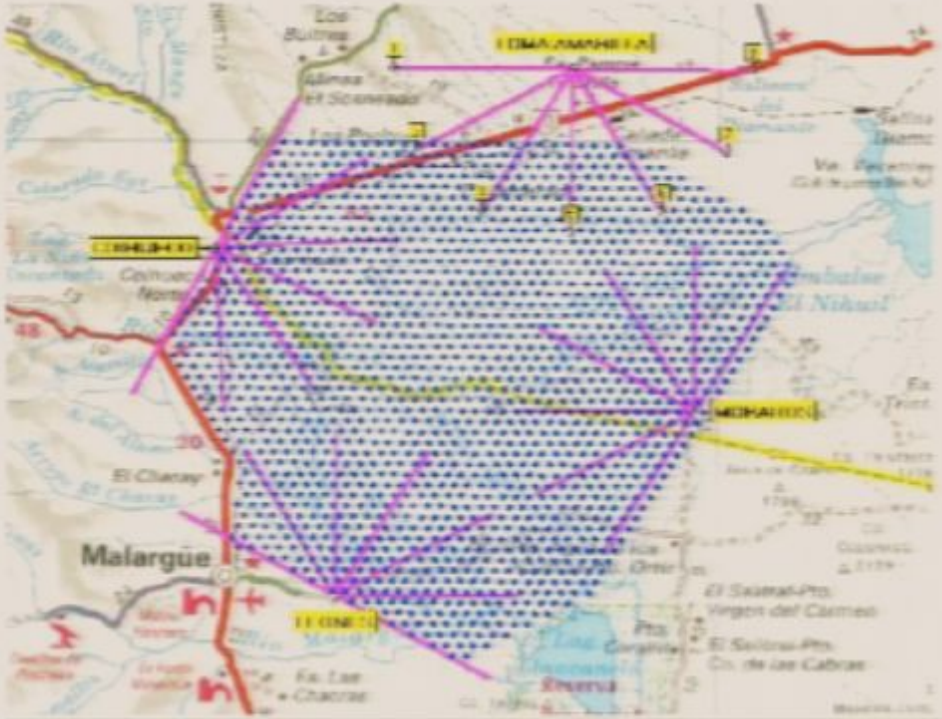
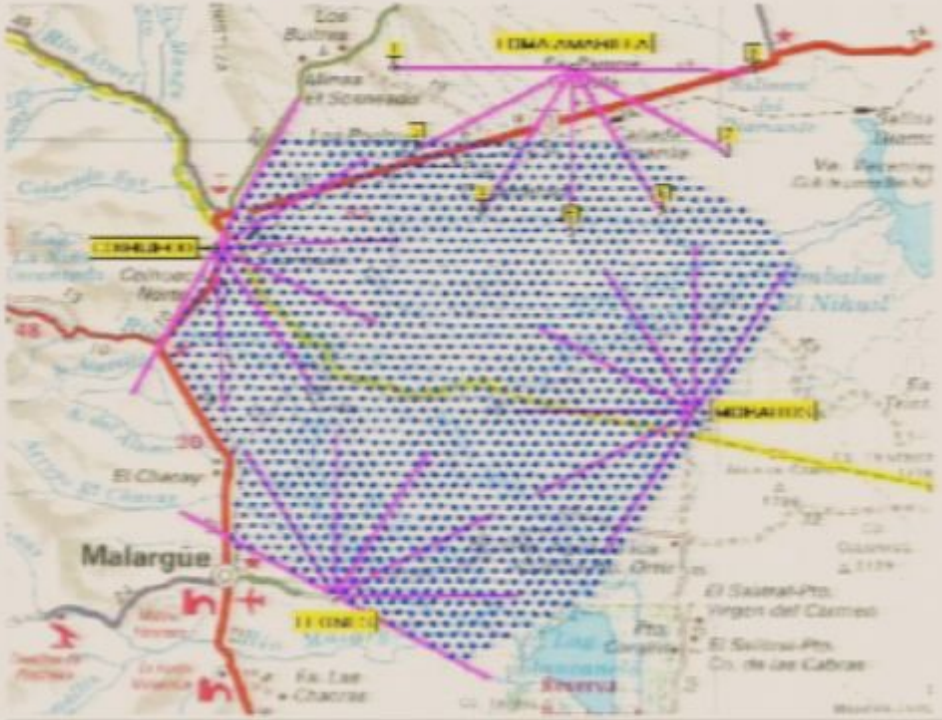
The Observatory Plan



Surface Array
1600 detector stations
1.5 km spacing
3000 km²

Fluorescence Detectors
4 Telescope enclosures
6 Telescopes per enclosure
24 Telescopes total

The Observatory Plan



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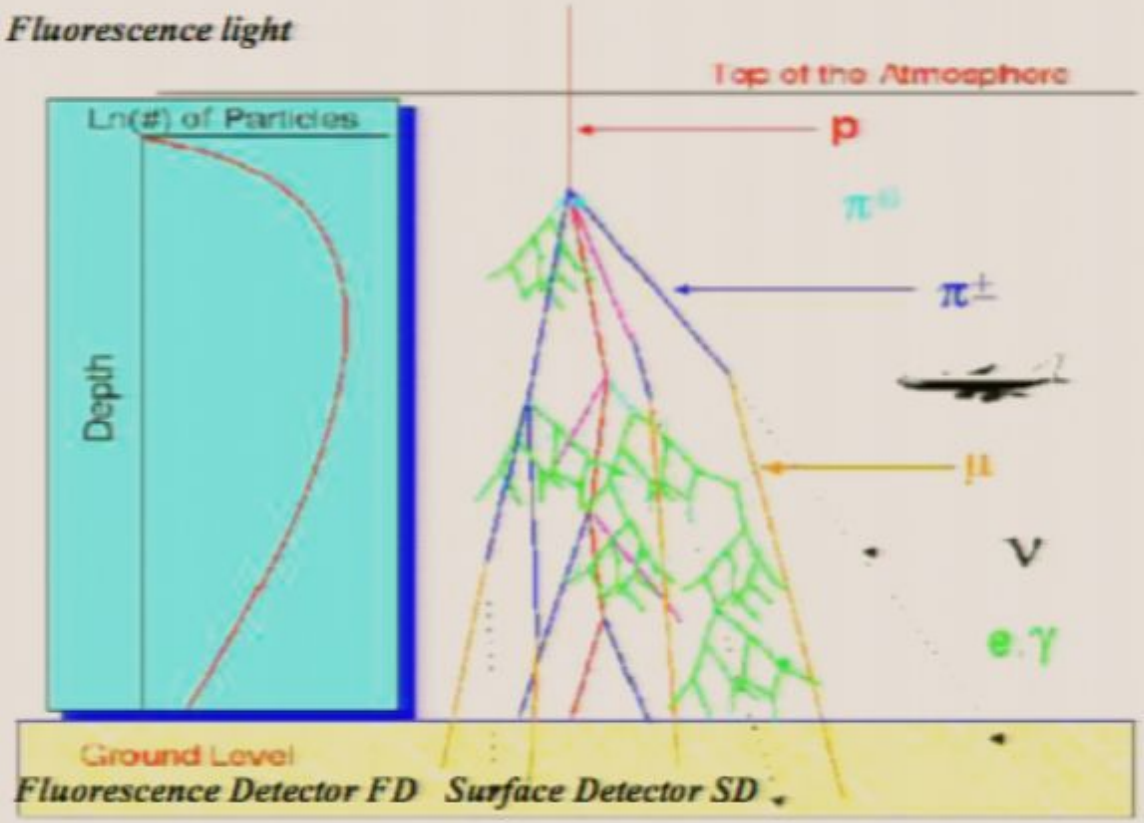
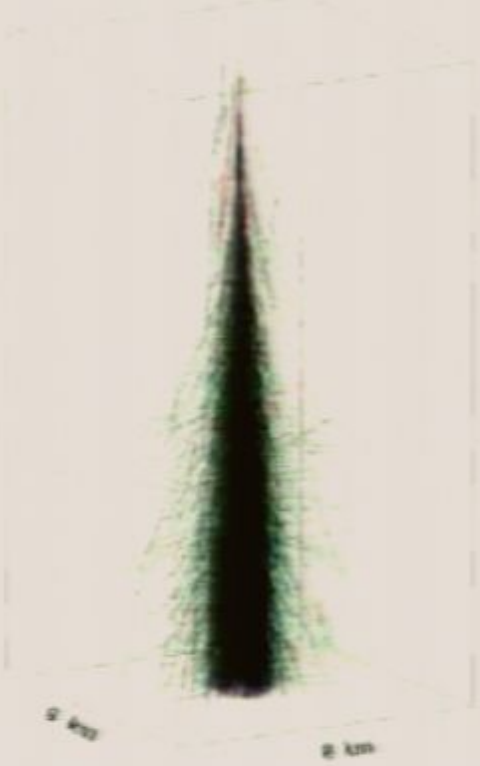
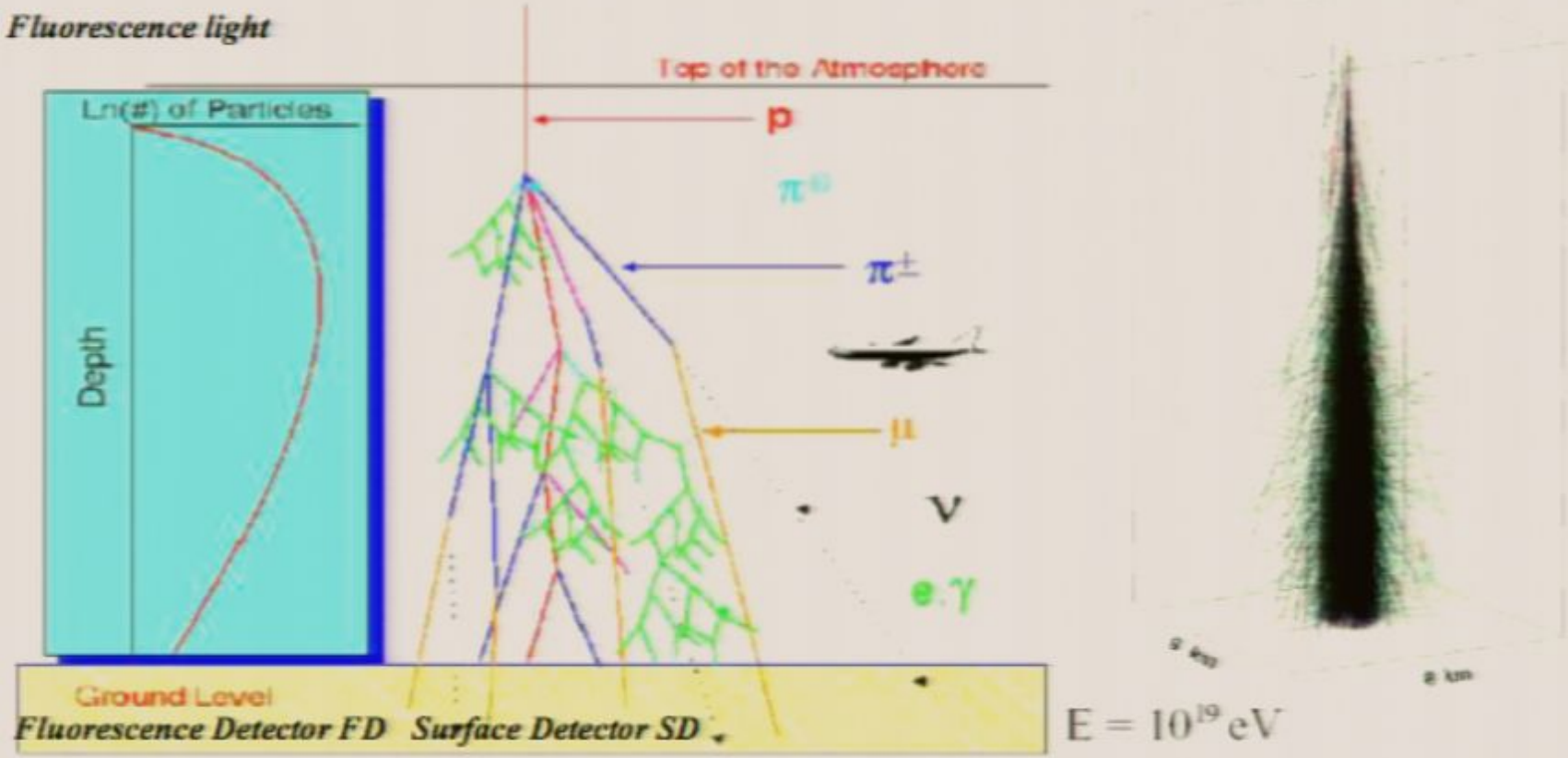




$E = 10^{19}$ eV

SHOWER DEVELOPMENT



Physics results

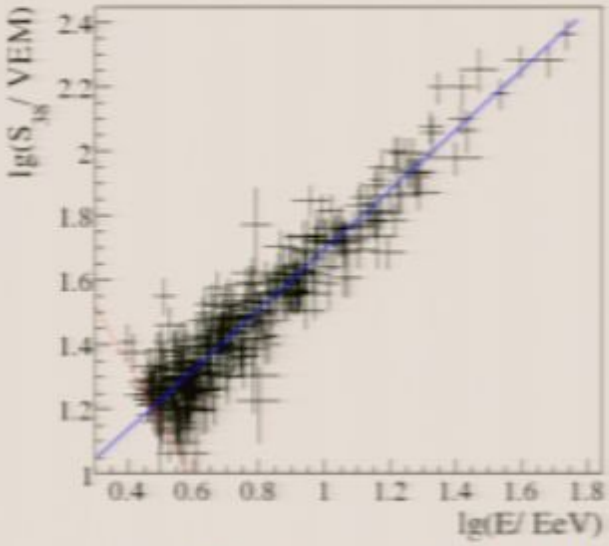
cover important aspects:

- *spectrum*
- *search for sources*
- *composition and comparison with top-down models*

The spectrum: most statistically significant from SD calibrated in energy by "hybrid" events

- *energy systematic error ~22 %, mostly from systematic of the FD detector (fluorescence yield, atmospheric transparency....)*

Surface Detector SD



Fluorescence Detector FD

- $E(EeV) = (0.149 \pm 0.009)\, S_{38}^{\,1.078 \pm 0.017}$

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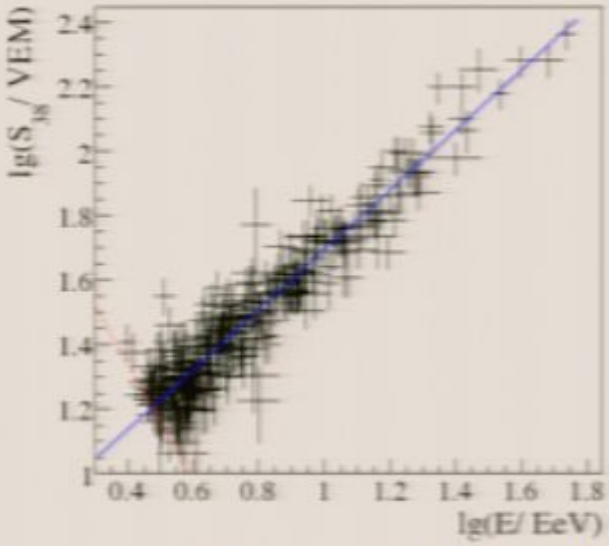

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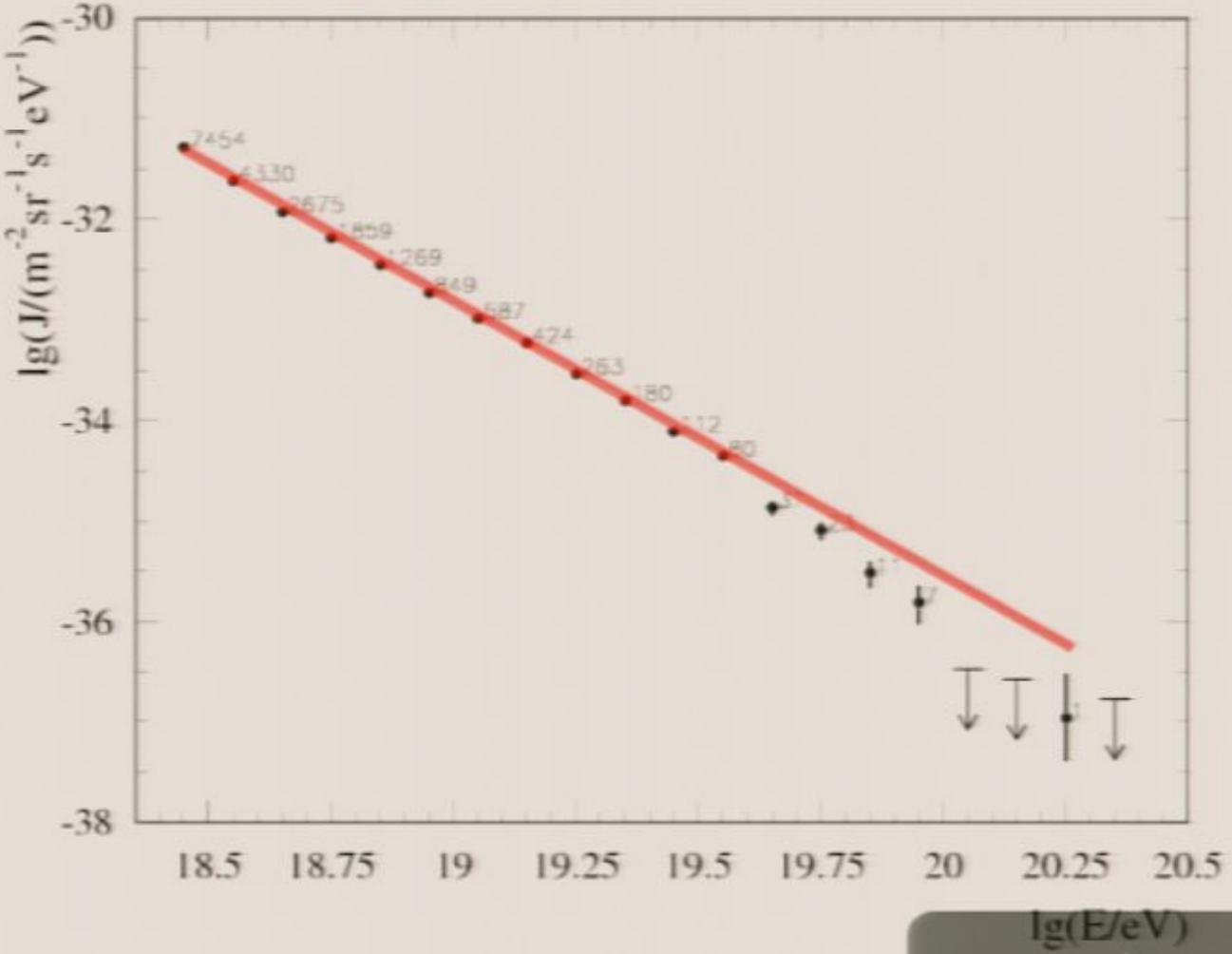
latest analysis, PRL 101, 061101 (2008)

N >10^{19} eV = 2500 evts



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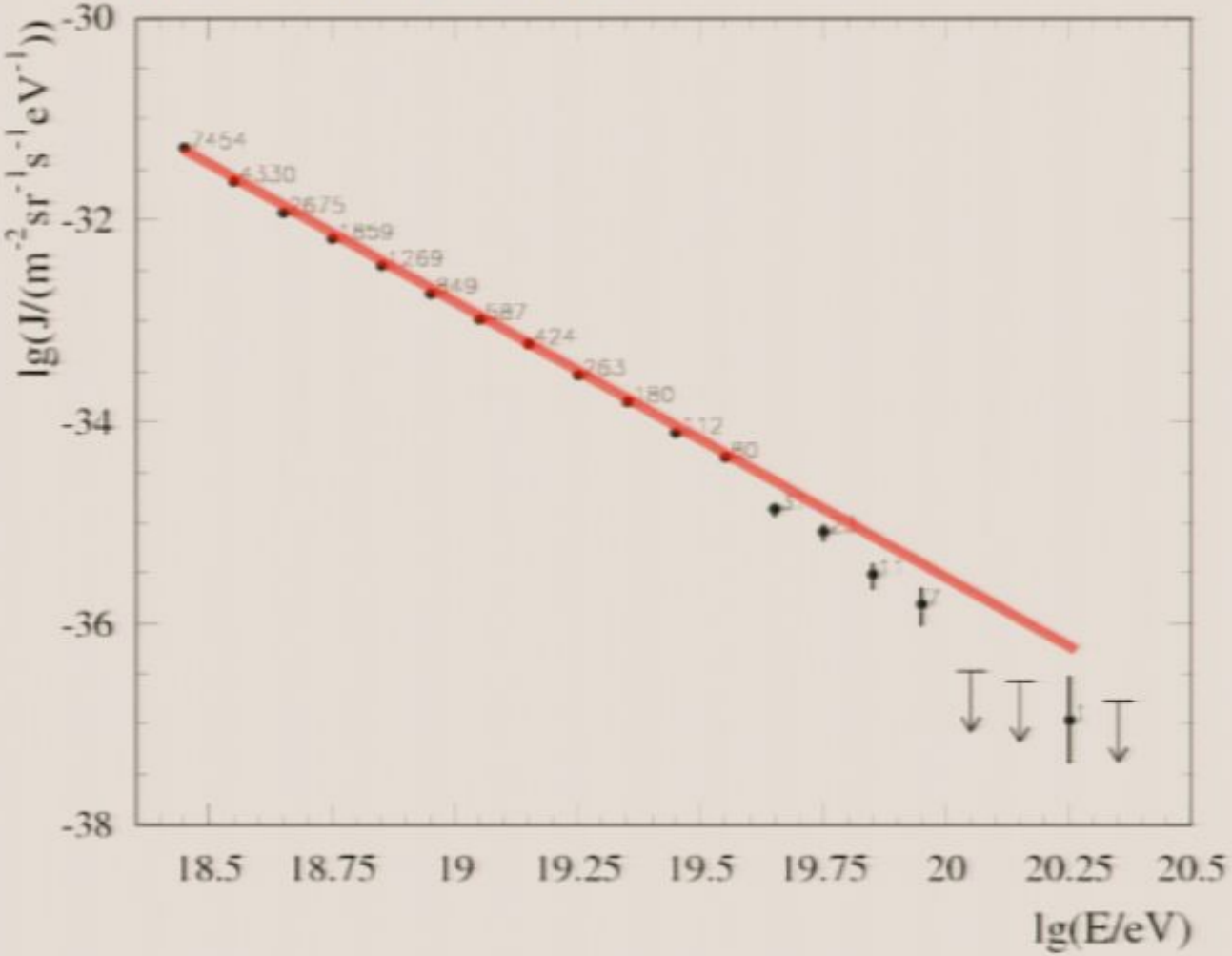

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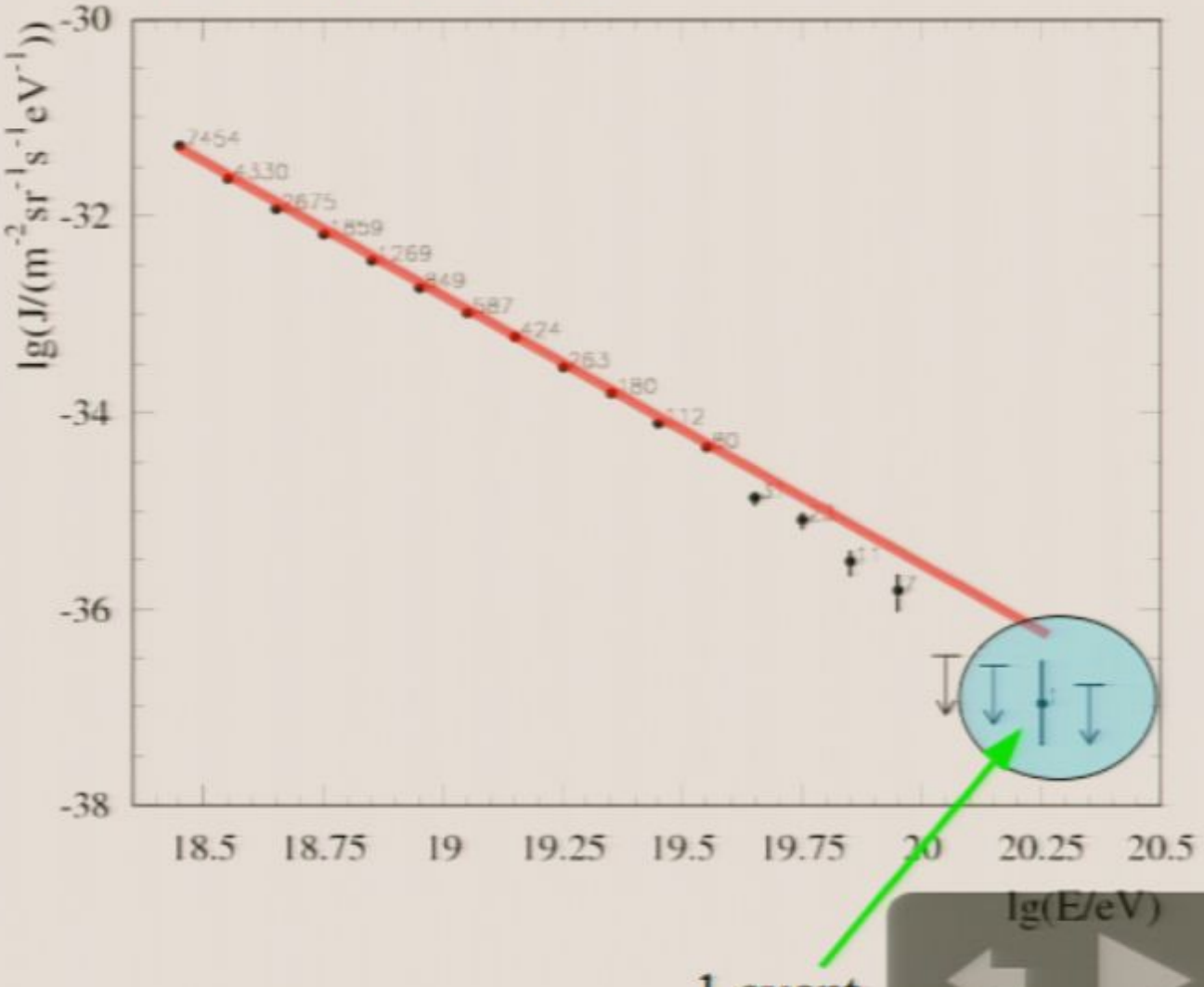

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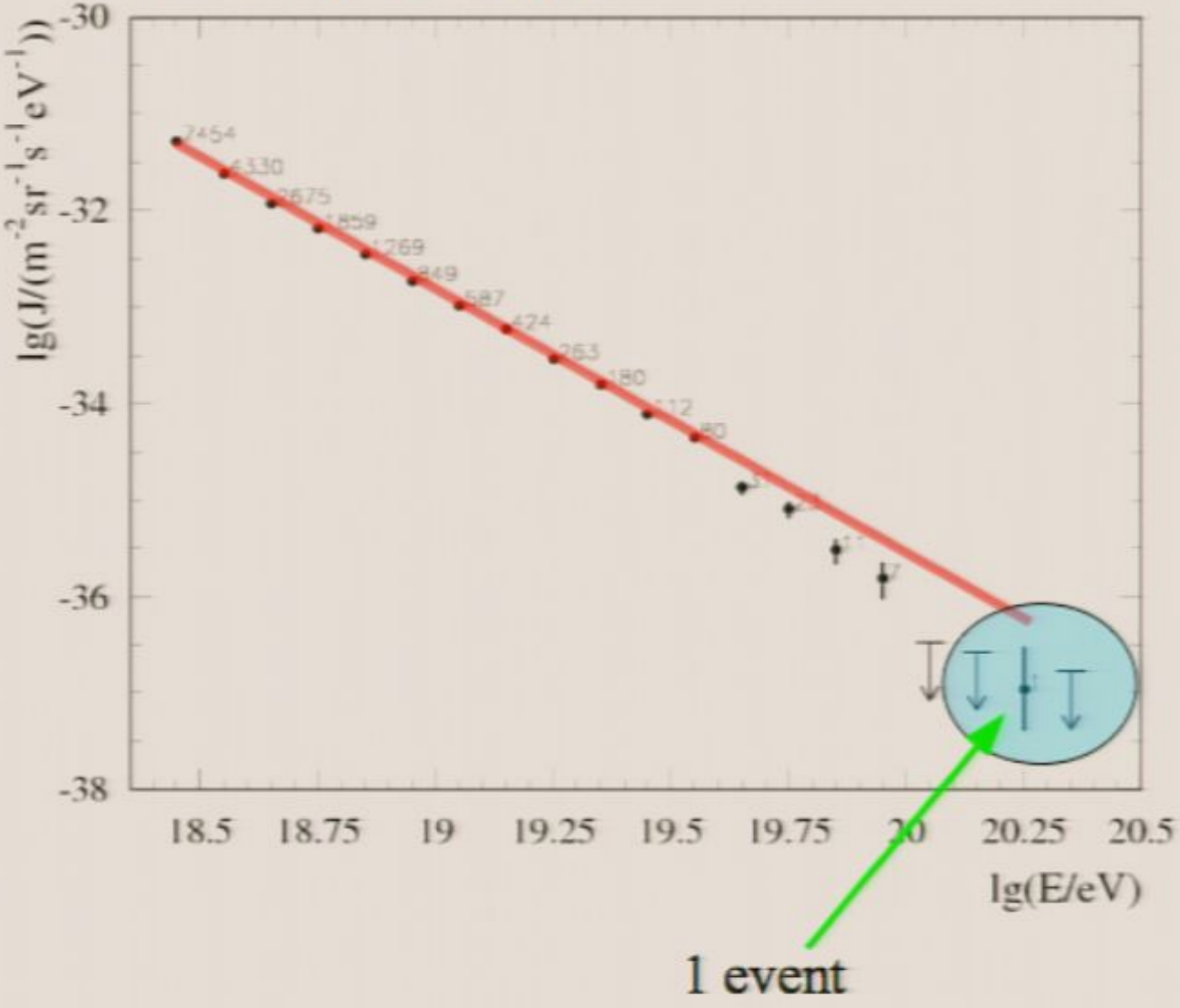
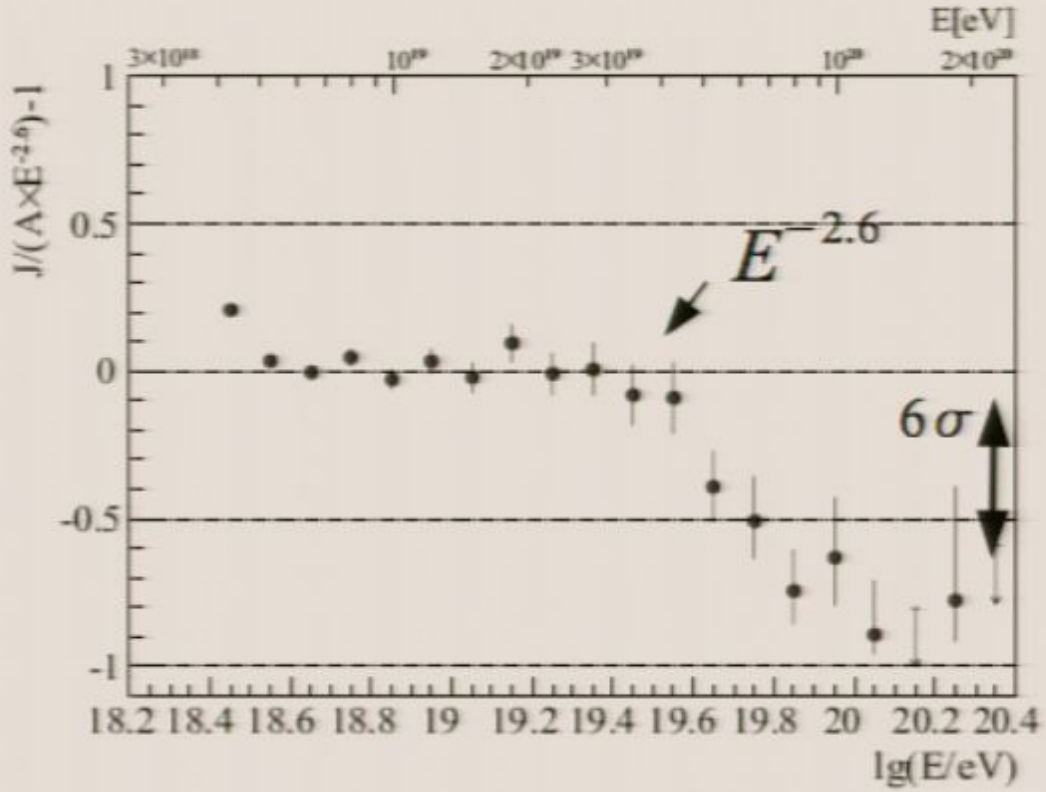
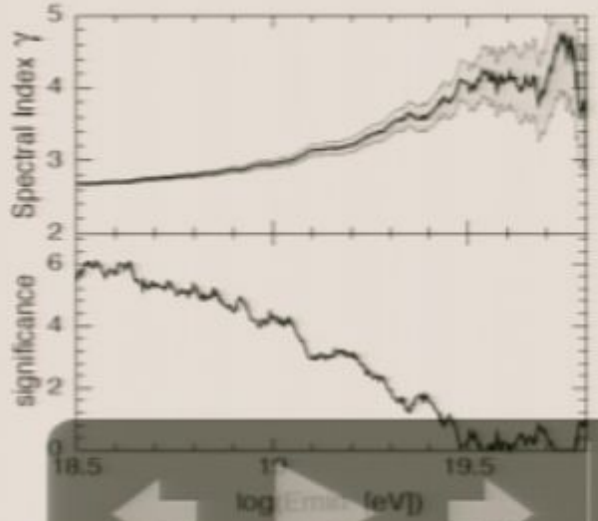
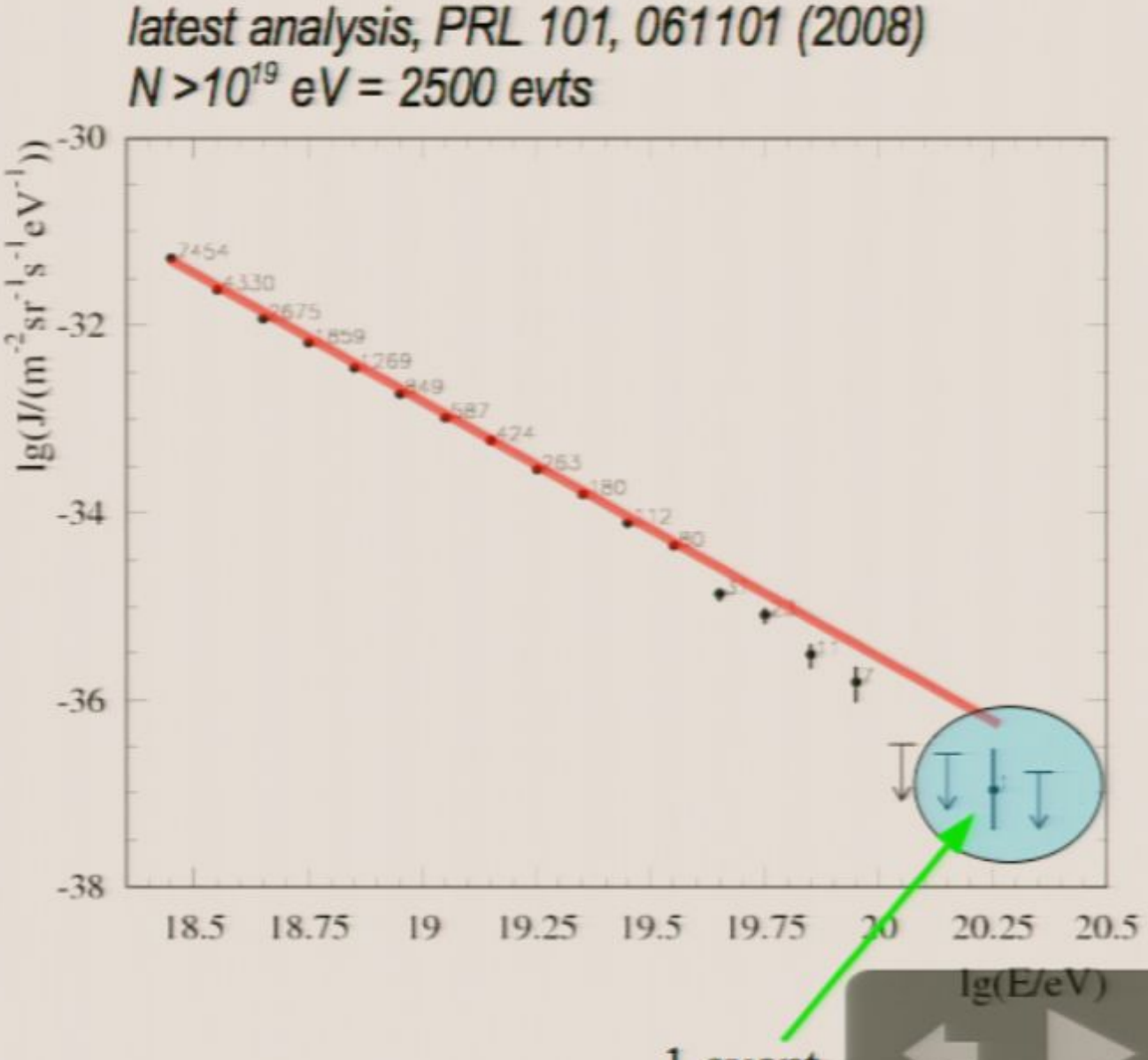



E[eV]
3×10¹⁸
10¹⁹
2×10¹⁹
3×10¹⁹
10²⁰
2×10²⁰
J/(A×E^-2.6)-1
1
0.5
0
-0.5
-1
E^-2.6
6σ
18.2 18.4 18.6 18.8 19 19.2 19.4 19.6 19.8 20 20.2 20.4
lg(E/eV)


Spectral Index γ
5
4
3
2
significance
6
4
2
0
18.5
19.5
log(E/eV)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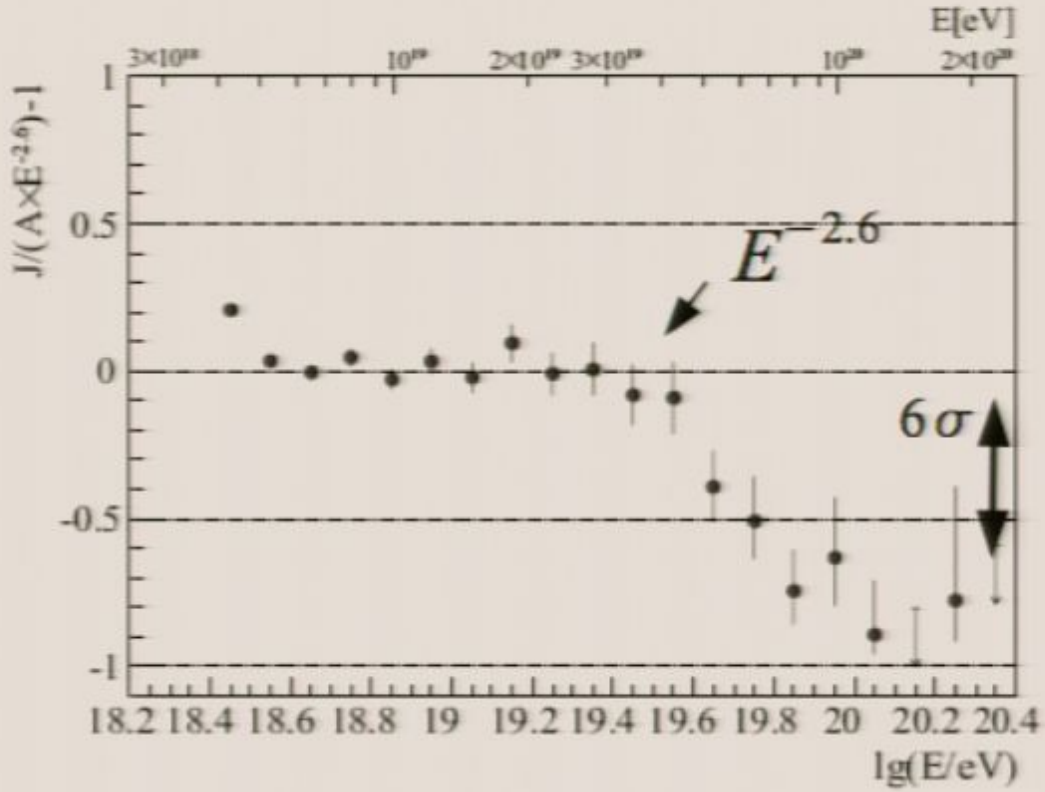
N >10^19 eV = 2500 evts
lg(J/(m^-2 sr^-1 s^-1 eV^-1))
-30
-32
-34
-36
-38
18.5
18.75
19
19.25
19.5
19.75
20
20.25
20.5
lg(E/eV)
1 event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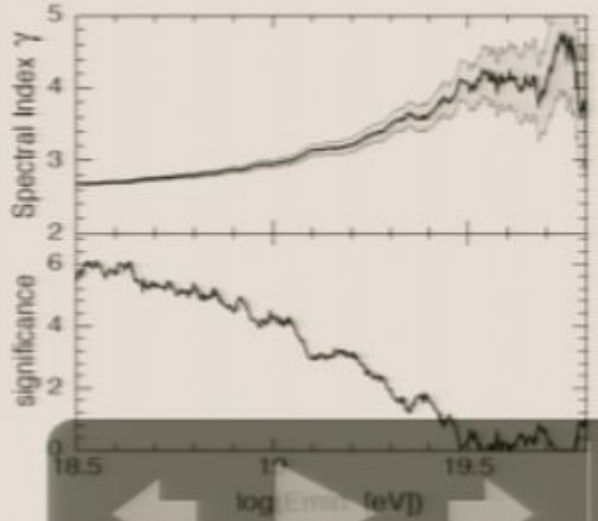
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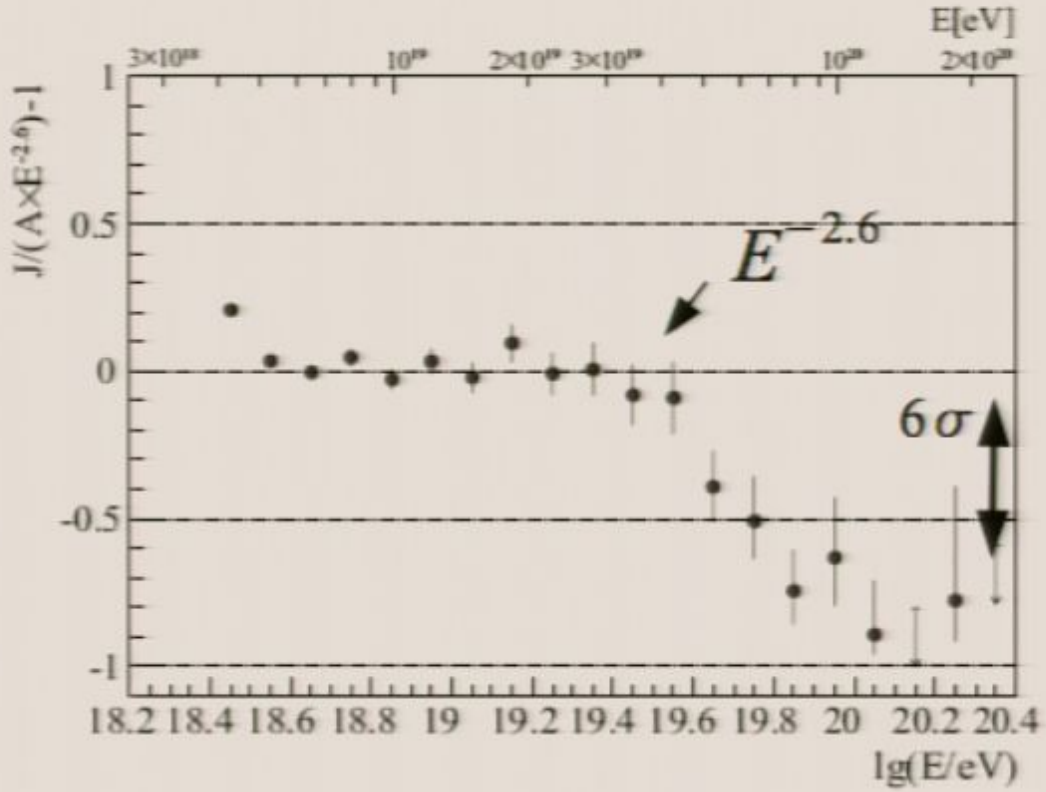
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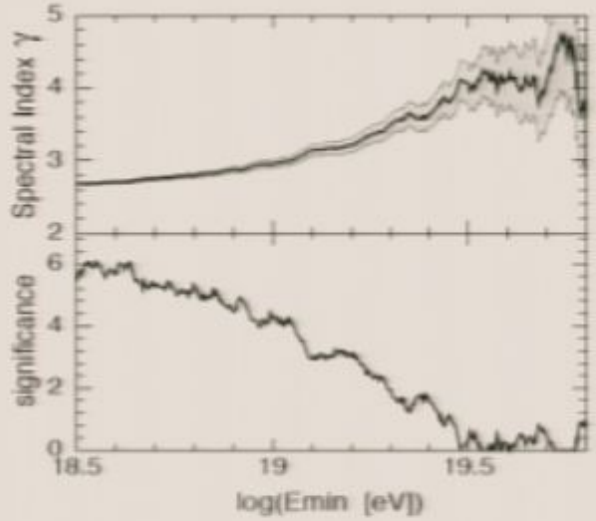
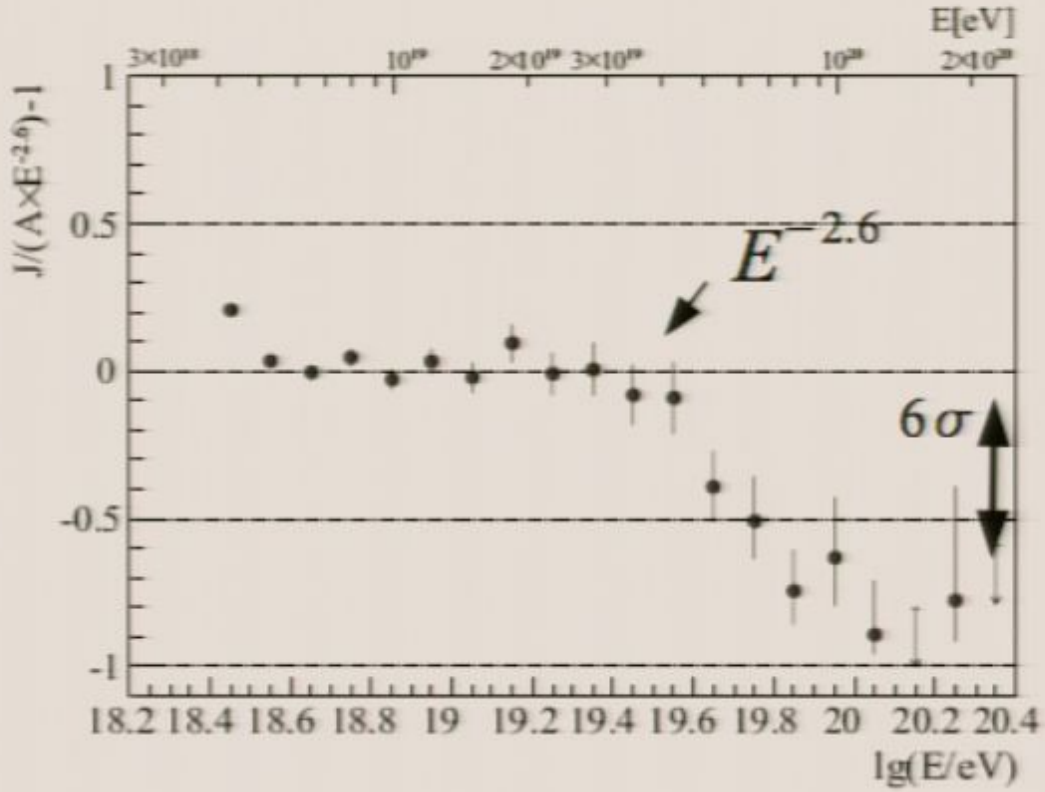
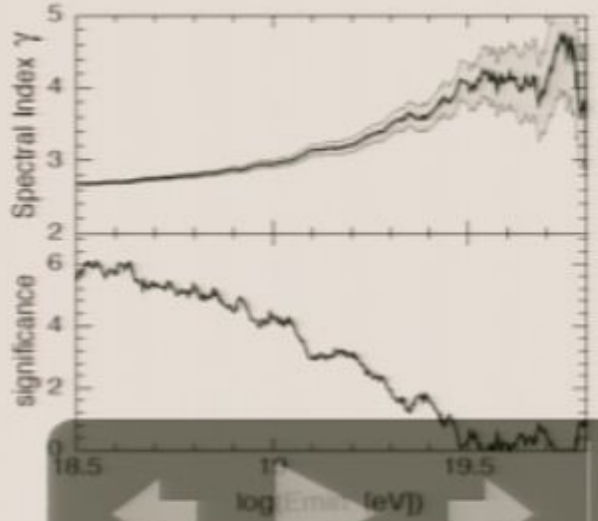
18.2 18.4 18.6 18.8 19 19.2 19.4 19.6 19.8 20 20.2 20.4
lg(E/eV)


Spectral Index γ
5
4
3
2
significance
6
4
2
0
18.5
19
19.5
log(Emin [eV])

- *Is a sudden UHECR spectrum drop a sure indication of the GZK effect?*

- *Does the existence of super-GZK particles contraddict the GZK feature?*


E[eV]
3×10¹⁸
10¹⁹
2×10¹⁹
3×10¹⁹
10²⁰
2×10²⁰
J/(A×E^-2.6)-1
1
0.5
0
-0.5
-1
E^-2.6
6σ
18.2 18.4 18.6 18.8 19 19.2 19.4 19.6 19.8 20 20.2 20.4
lg(E/eV)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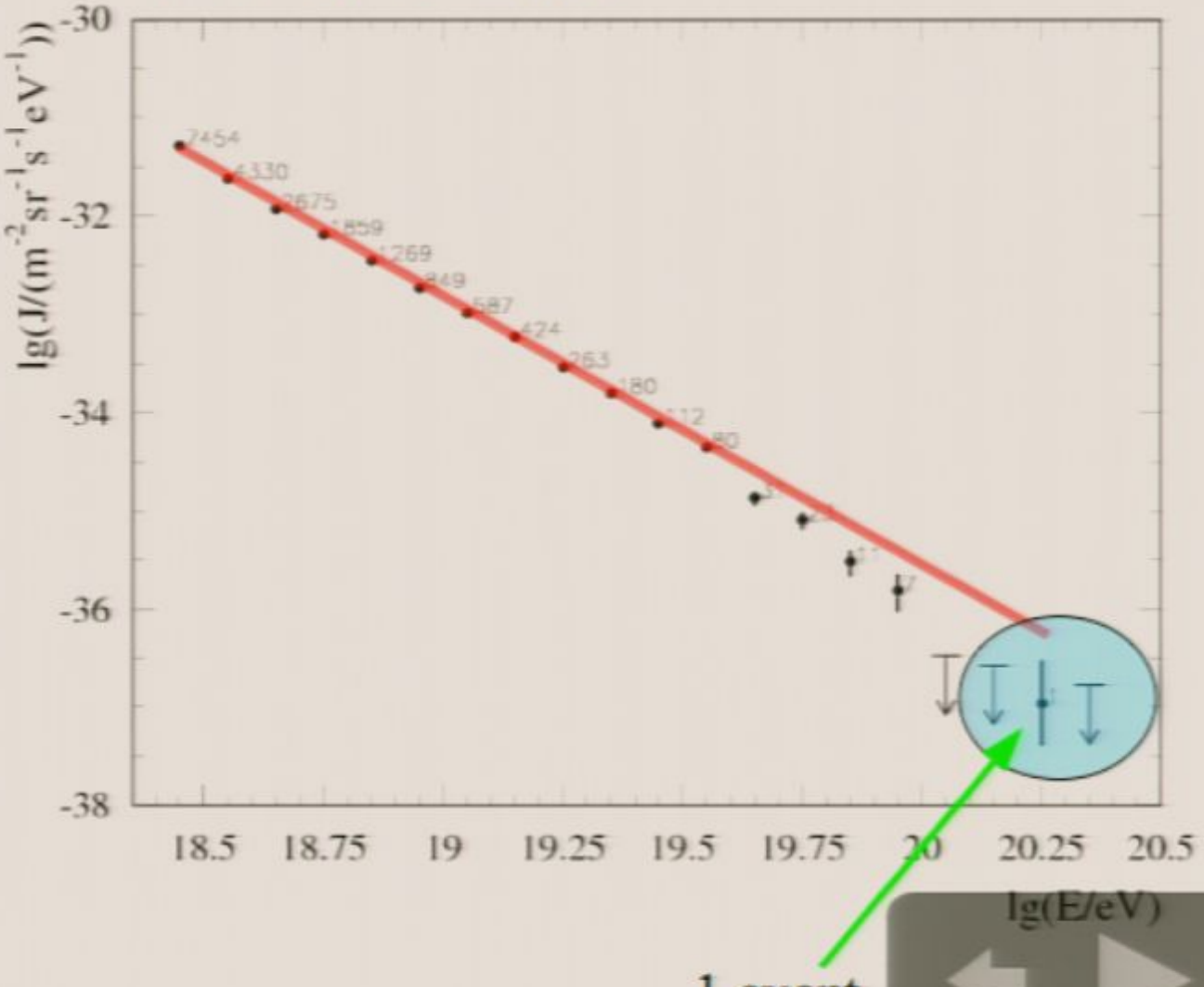
latest analysis, PRL 101, 061101 (2008)

$N > 10^{19}$ eV = 2500 evts



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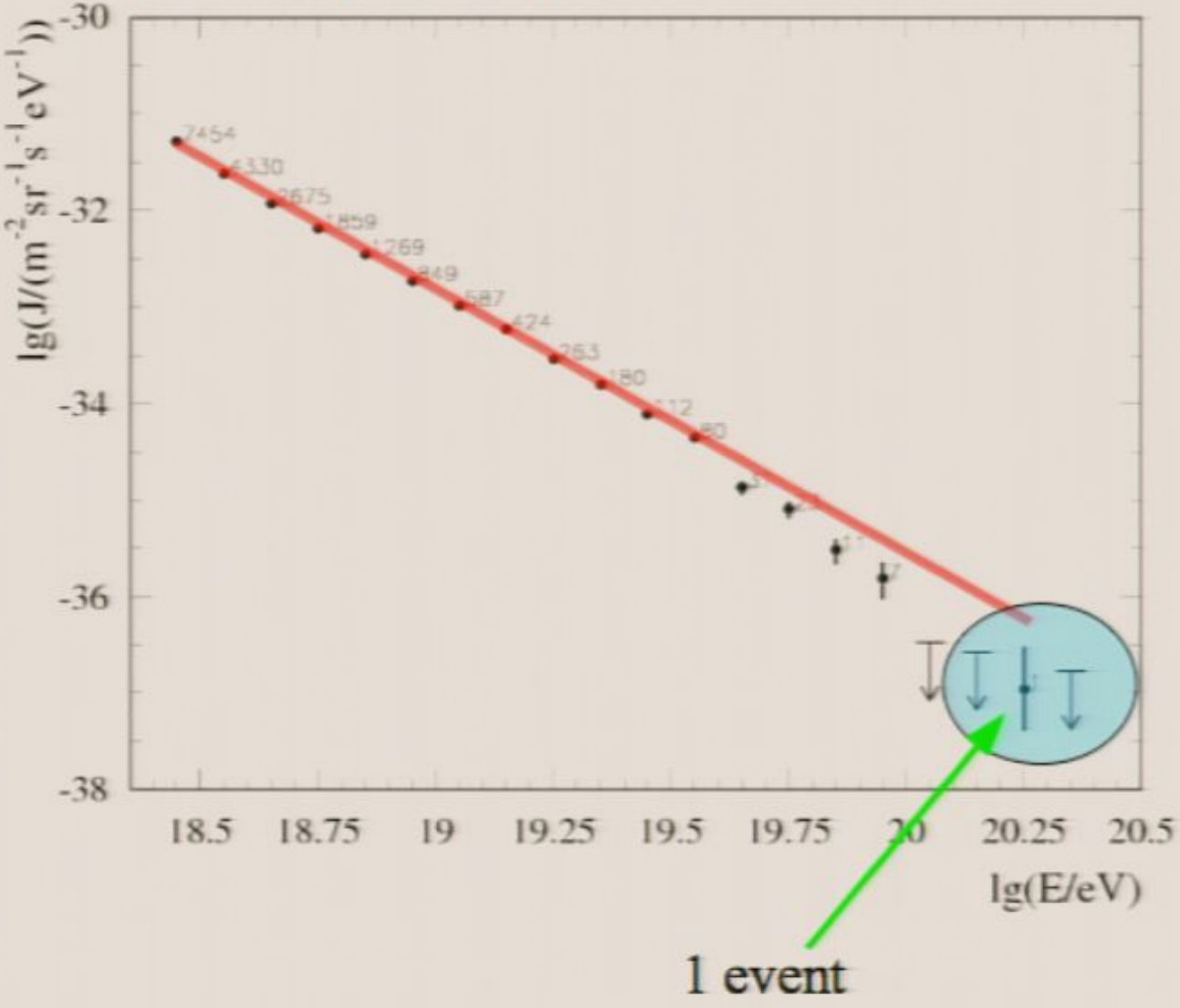

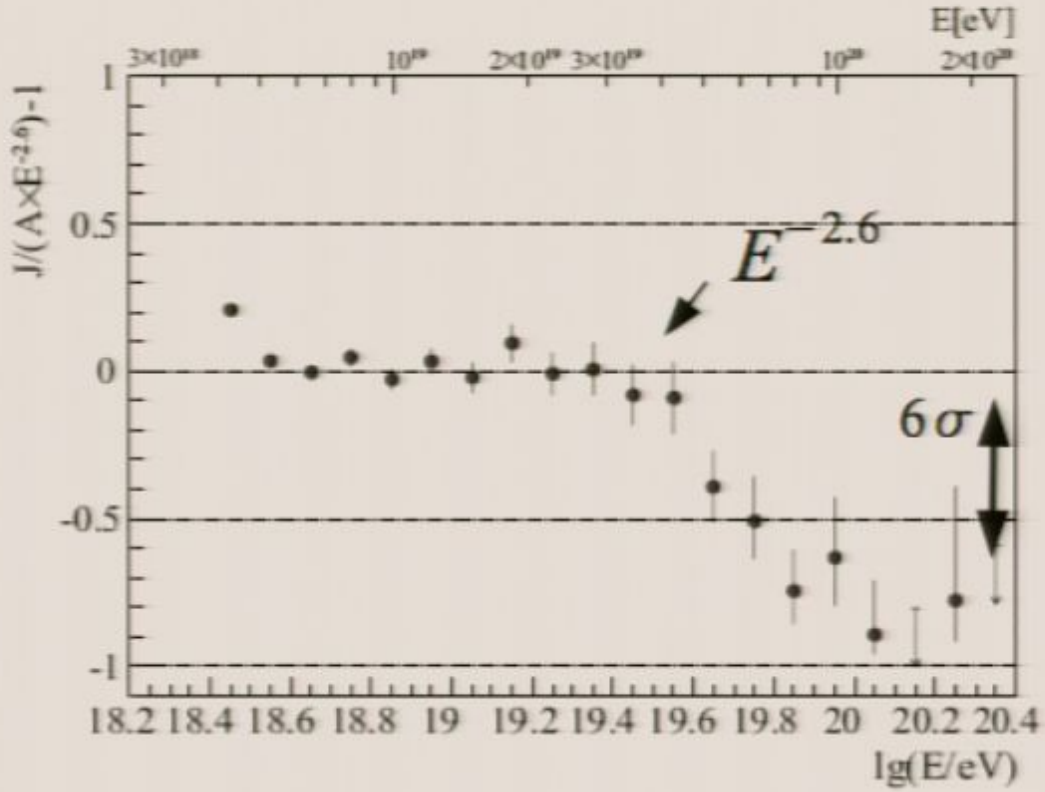
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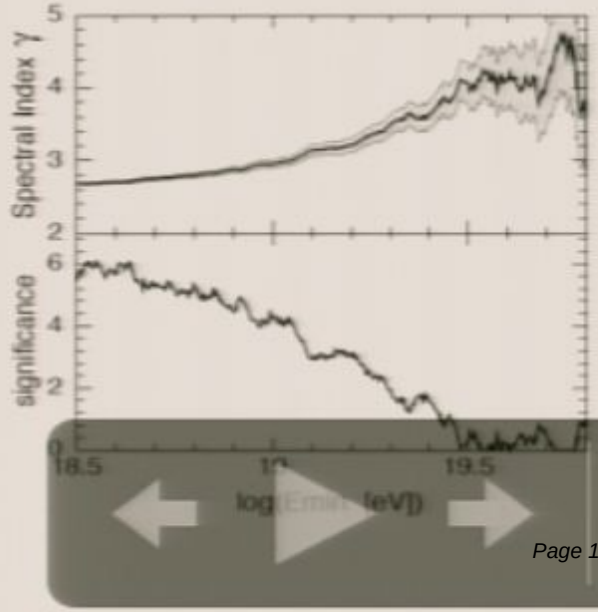
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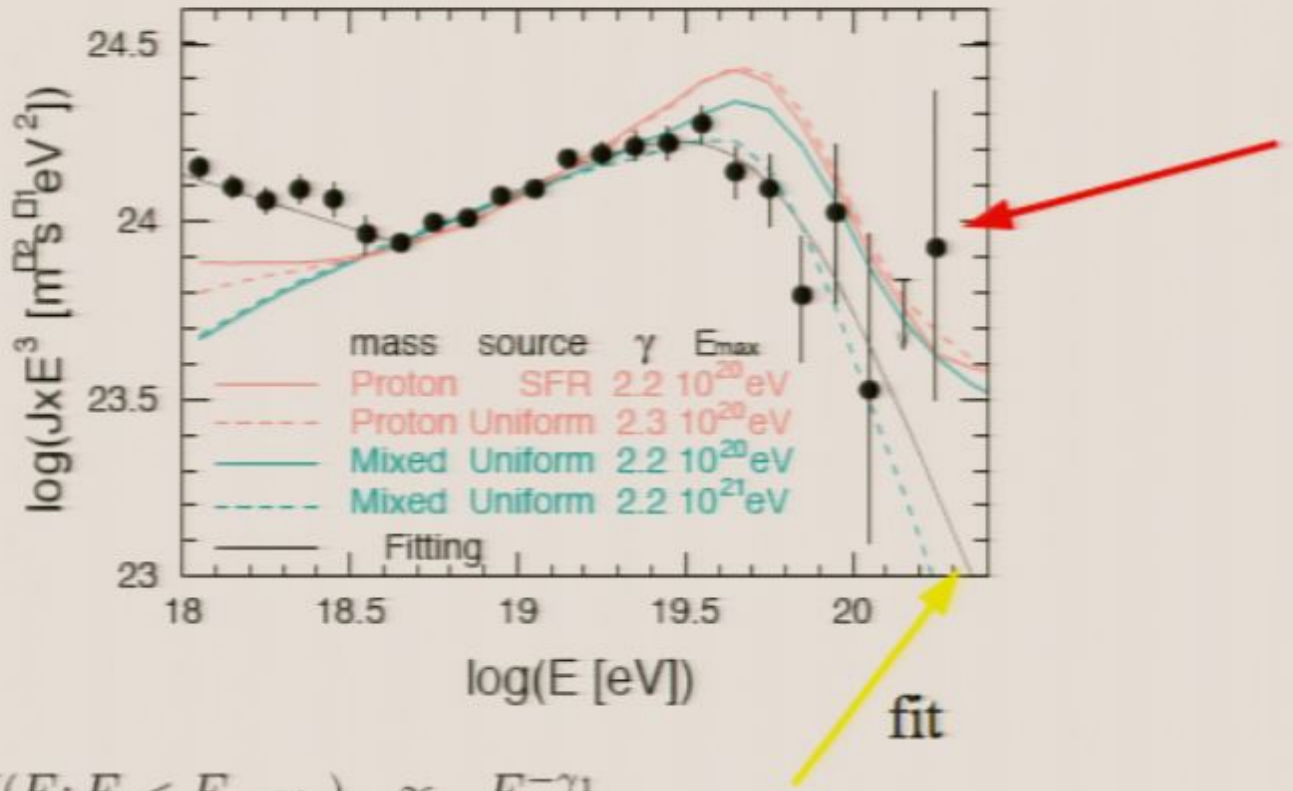
Evidence for GZK cutoff? Likely



$$J(E; E < E_{ankle}) \propto E^{-\gamma_1}$$

$$J(E; E > E_{ankle}) \propto E^{-\gamma_2} \frac{1}{1 + \exp\left(\frac{\lg E - \lg E_s}{W_s}\right)}$$

The promised land....
CR astronomy

If UHECRs origin is astrophysical, astronomy may be possible above some x 10^{19} eV if particles are protons (and IG magnetic fields small)

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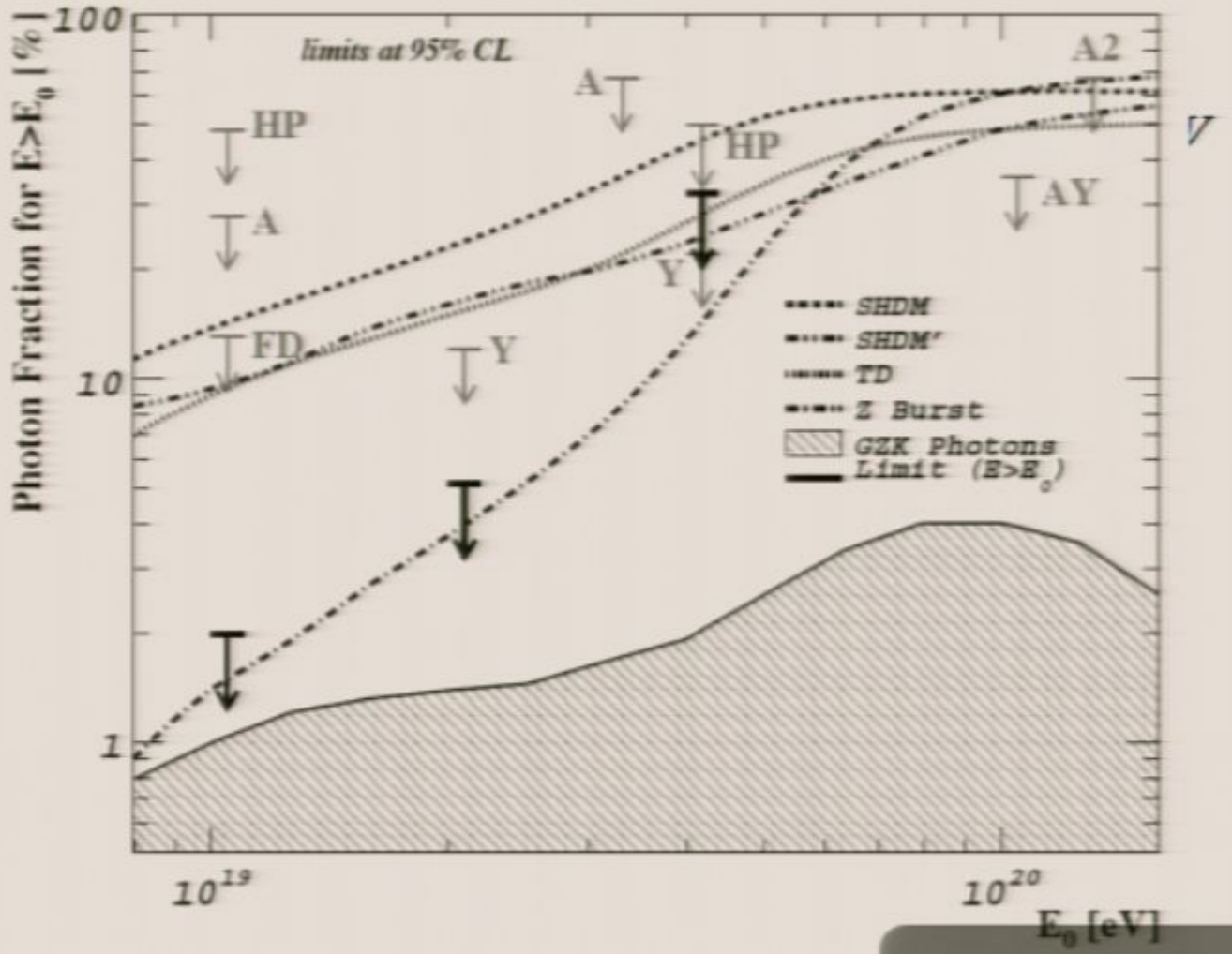
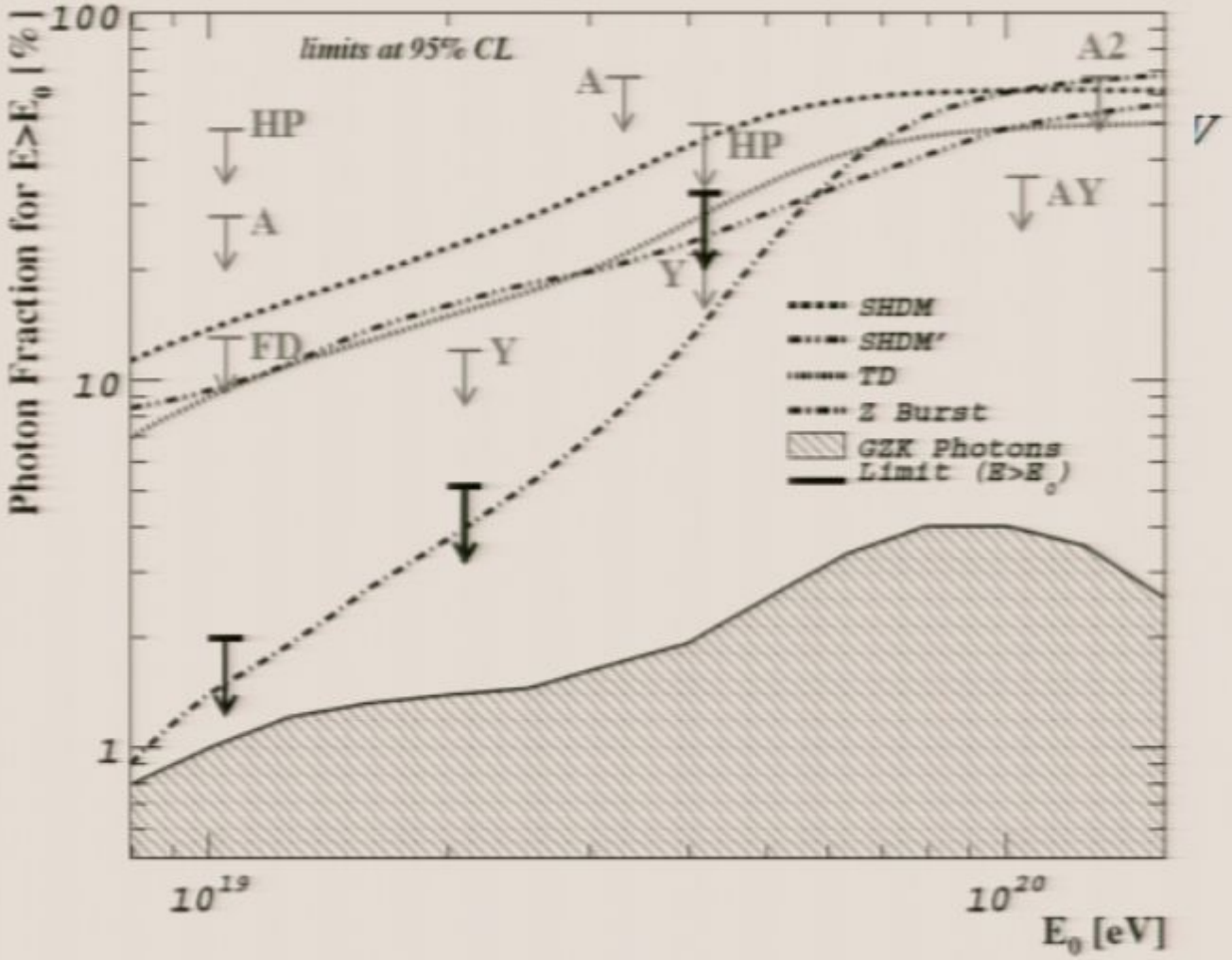


Search for point sources:



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- Angular resolution ~ 1 degree

- Pointing Accuracy ~ 1 degree

- Charged Messengers => deviation in mag. fields

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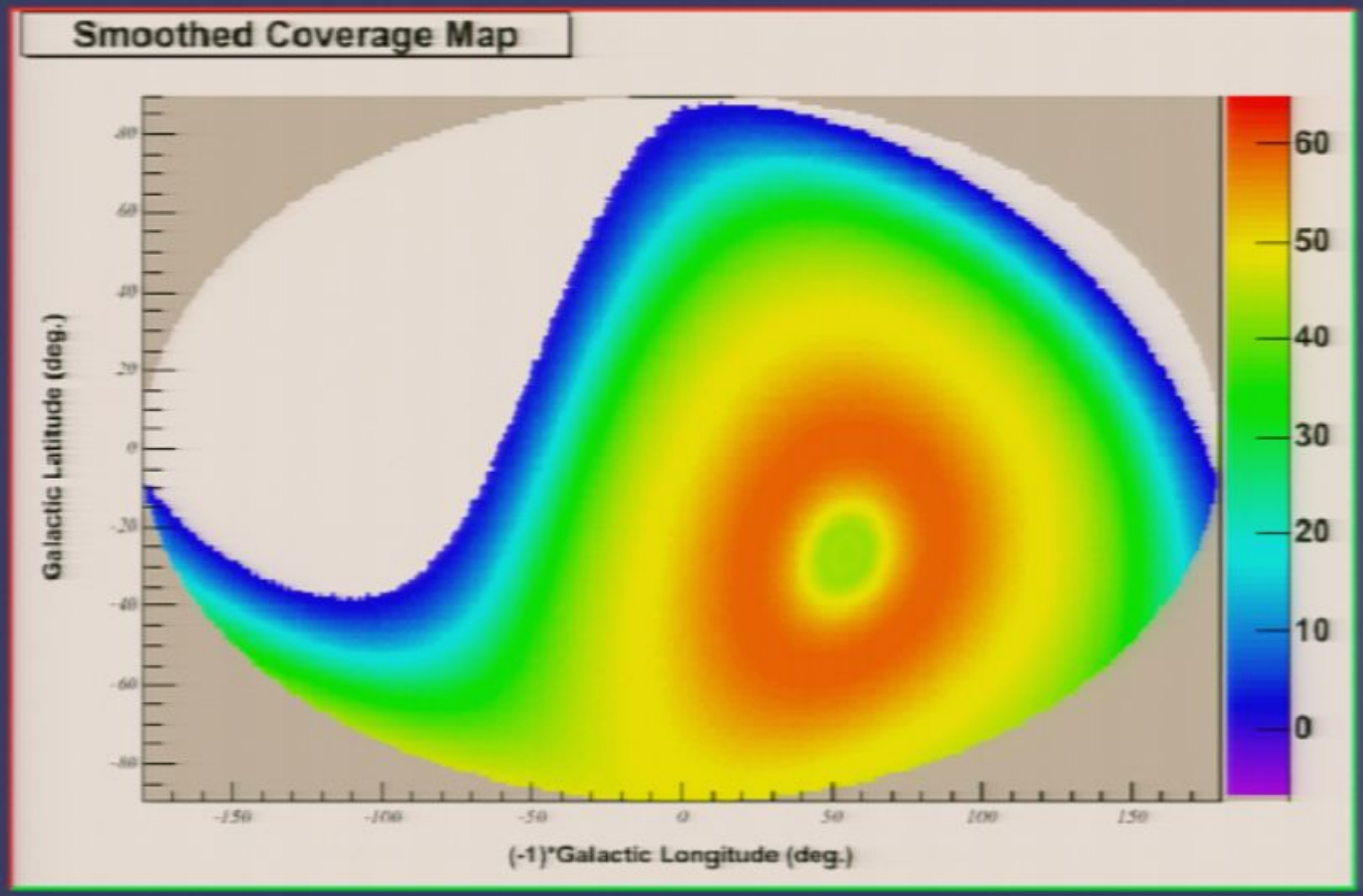
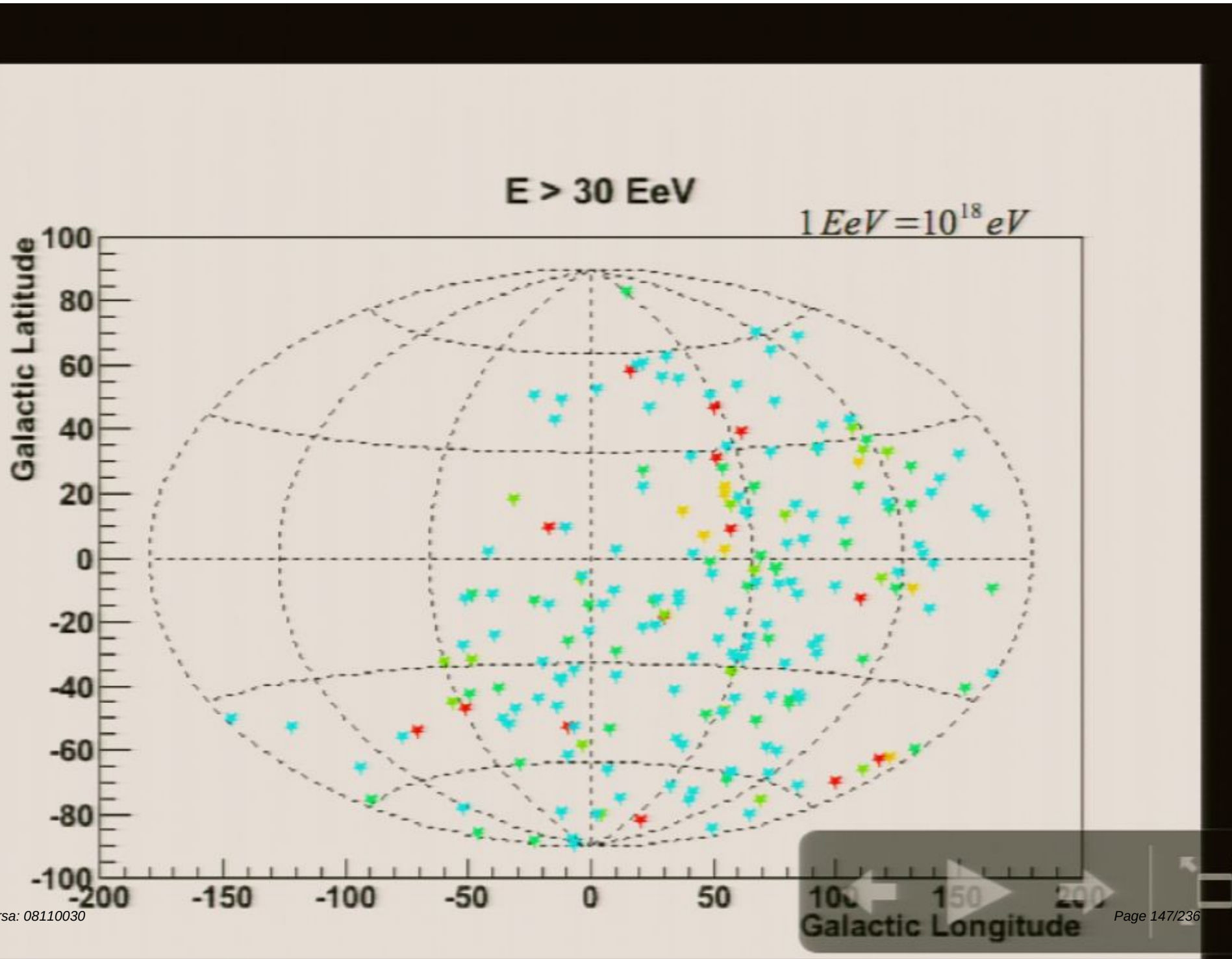
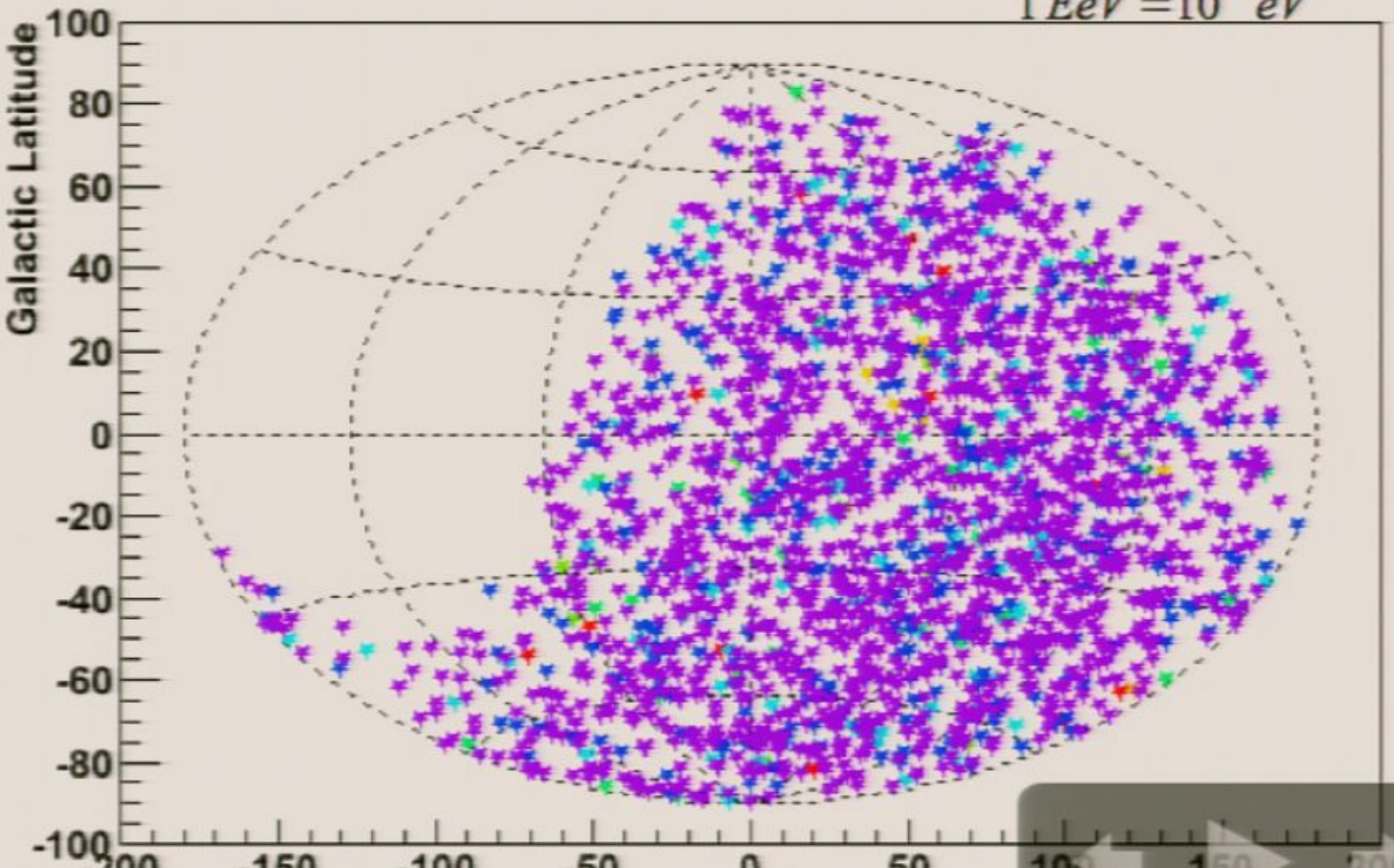
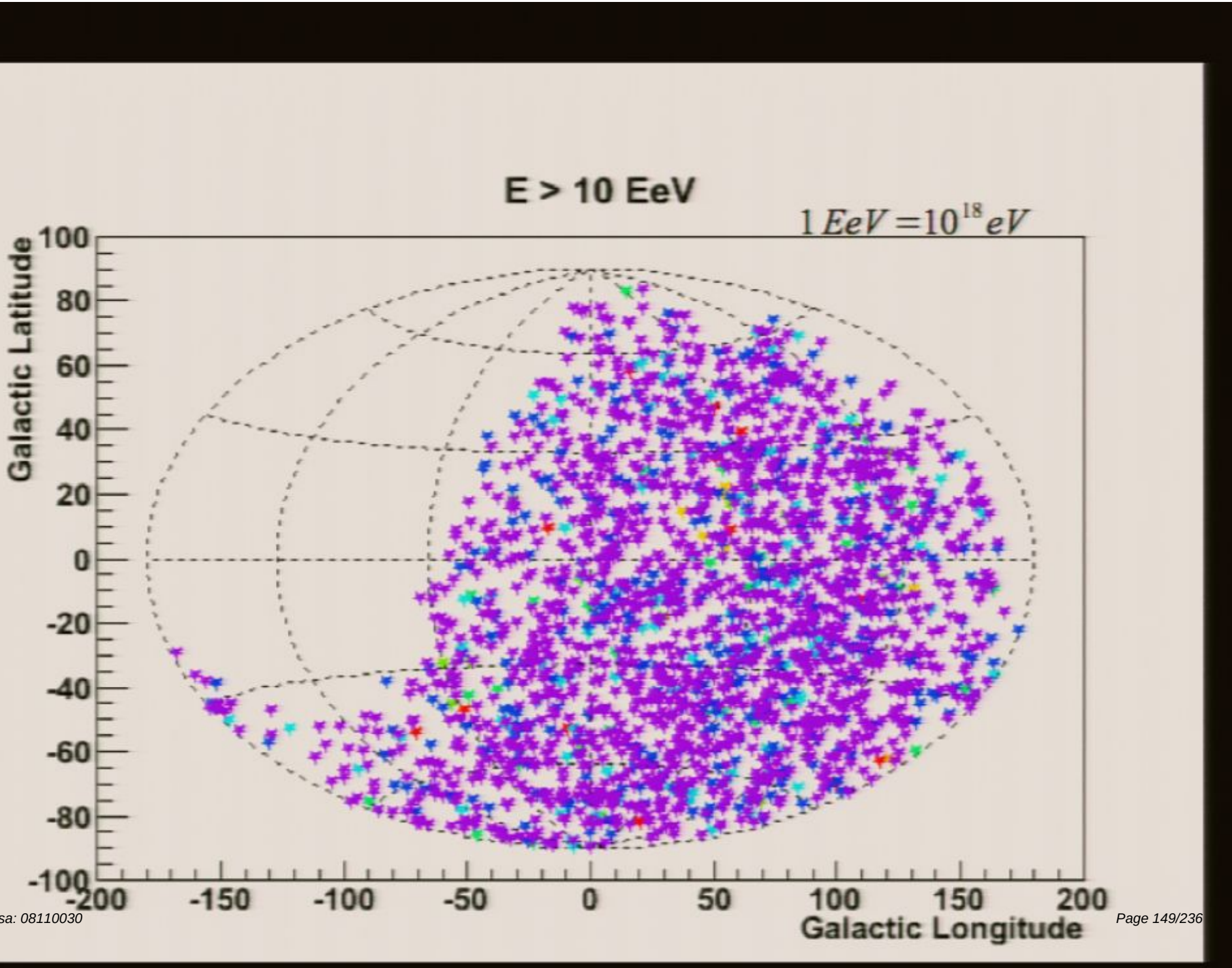
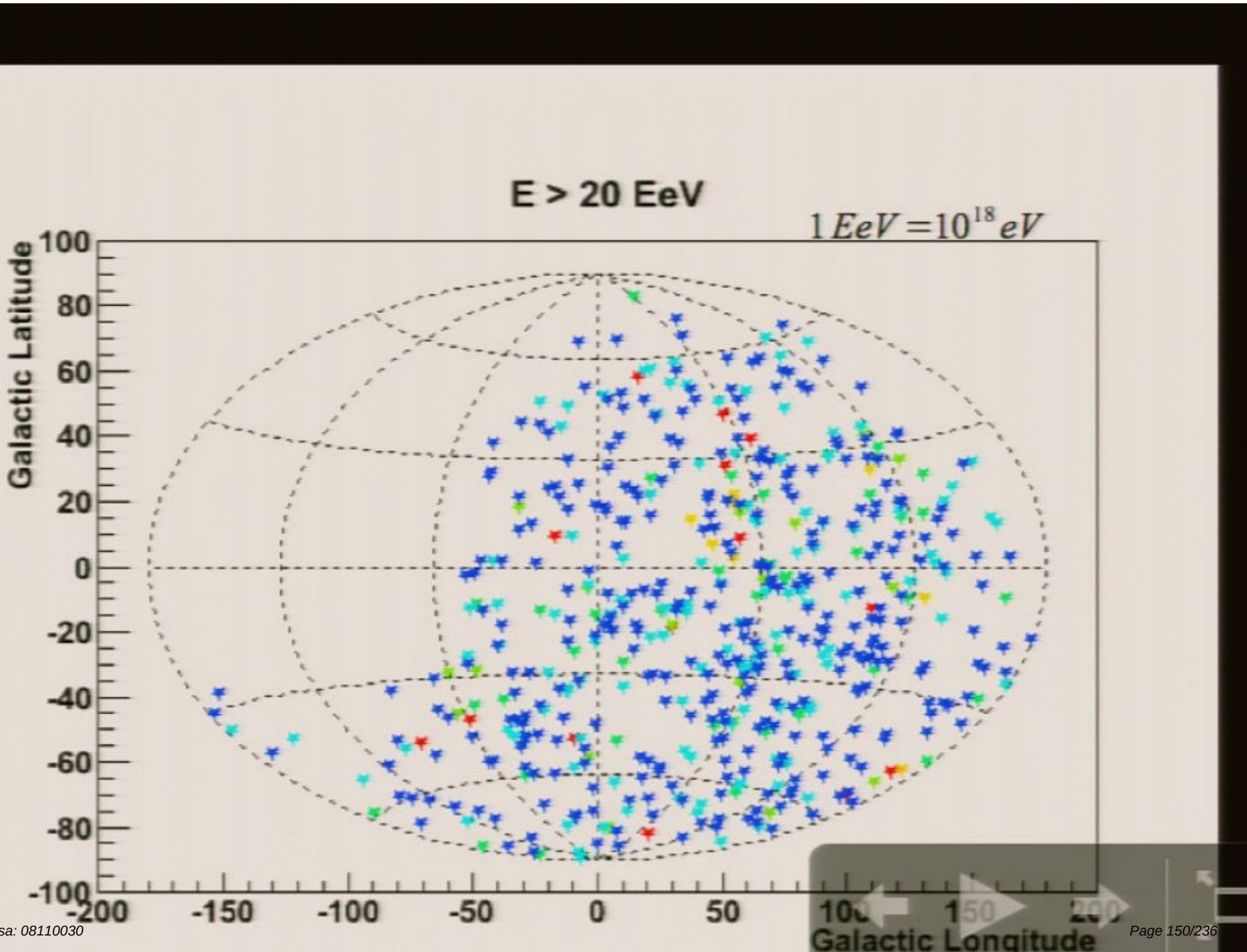


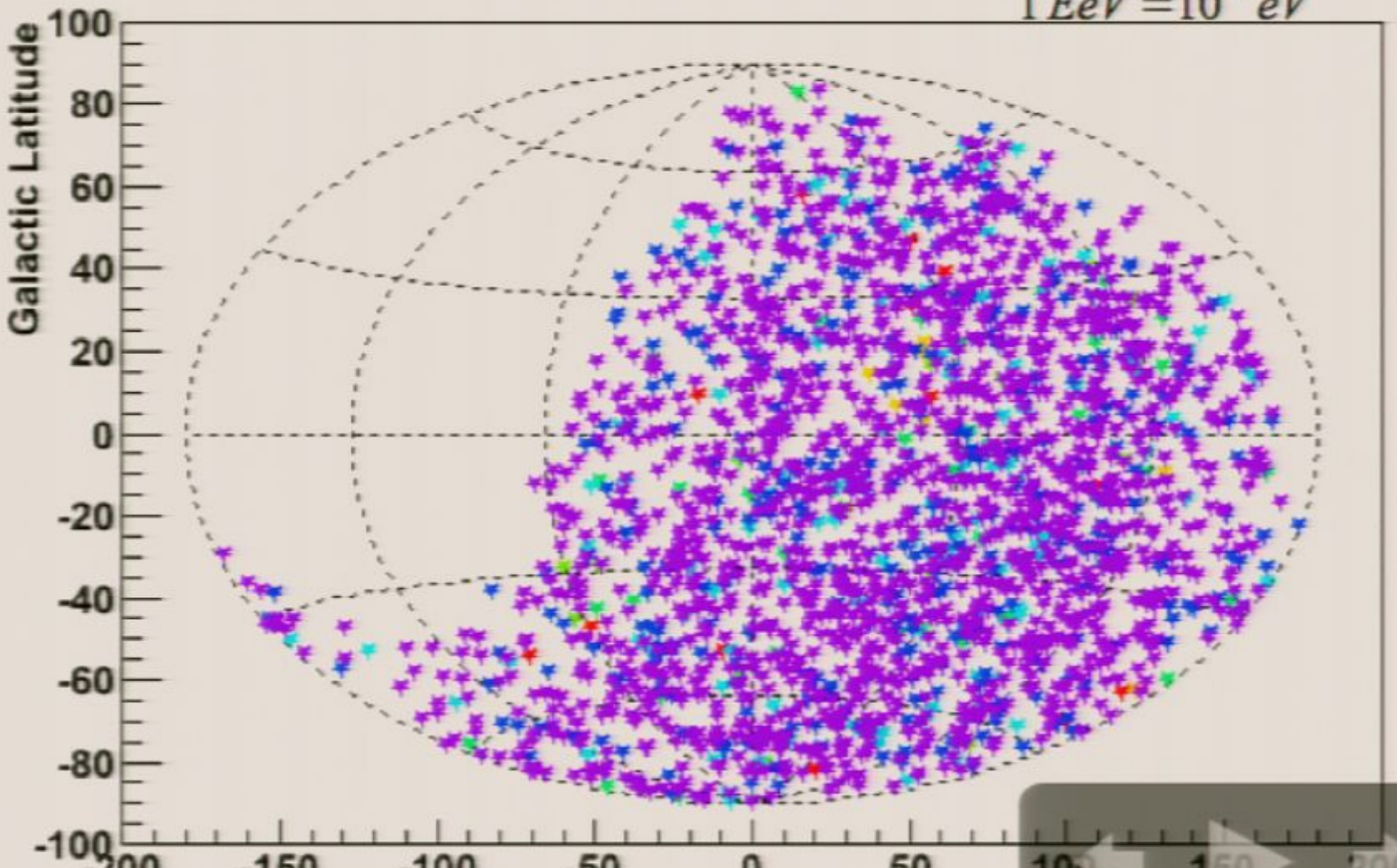
Exposure of the experiment in Galactic coordinates

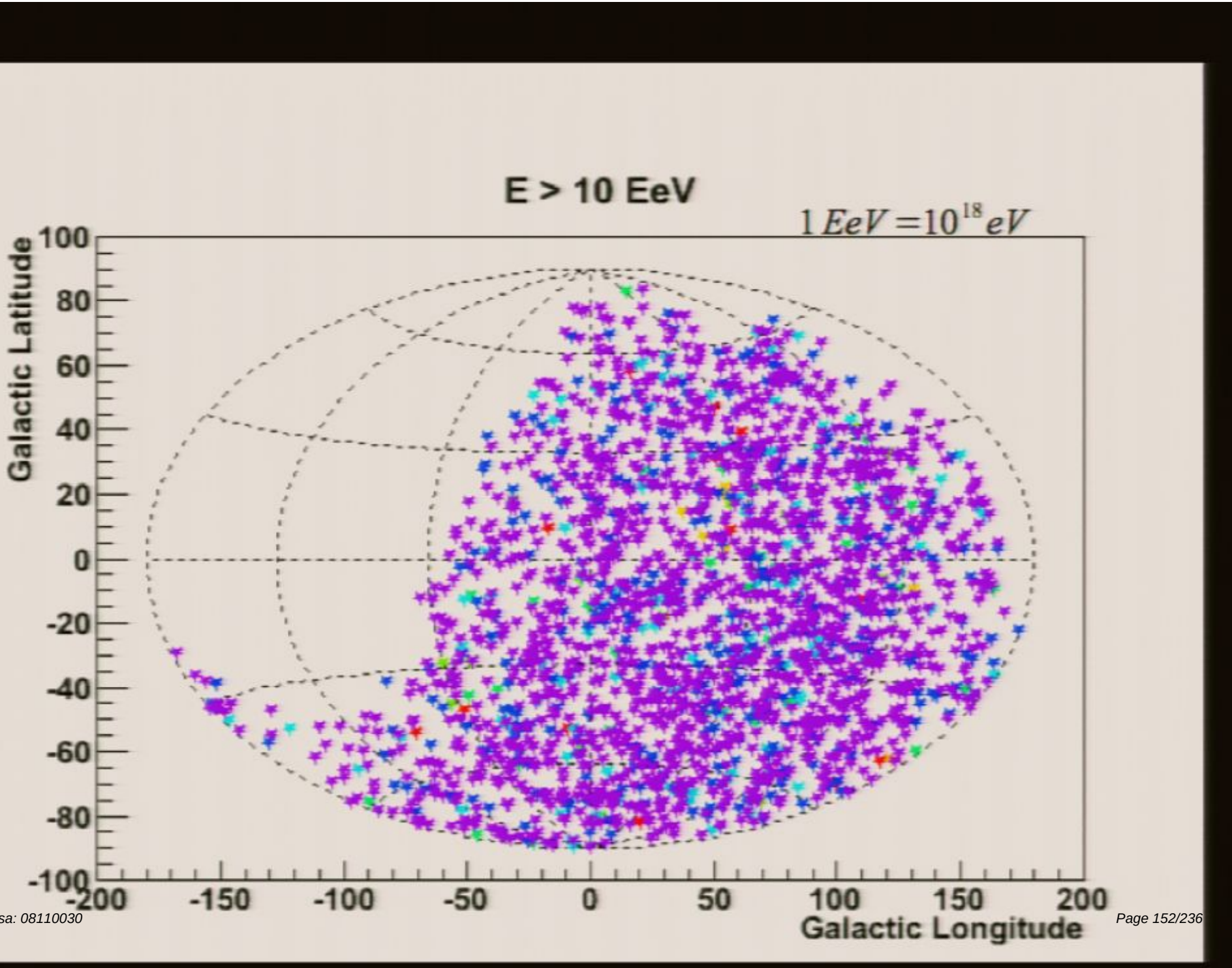

E > 30 EeV
$1\,EeV = 10^{18}\,eV$
Galactic Latitude
100
80
60
40
20
0
-20
-40
-60
-80
-100
-200
-150
-100
-50
0
50
Galactic Longitude

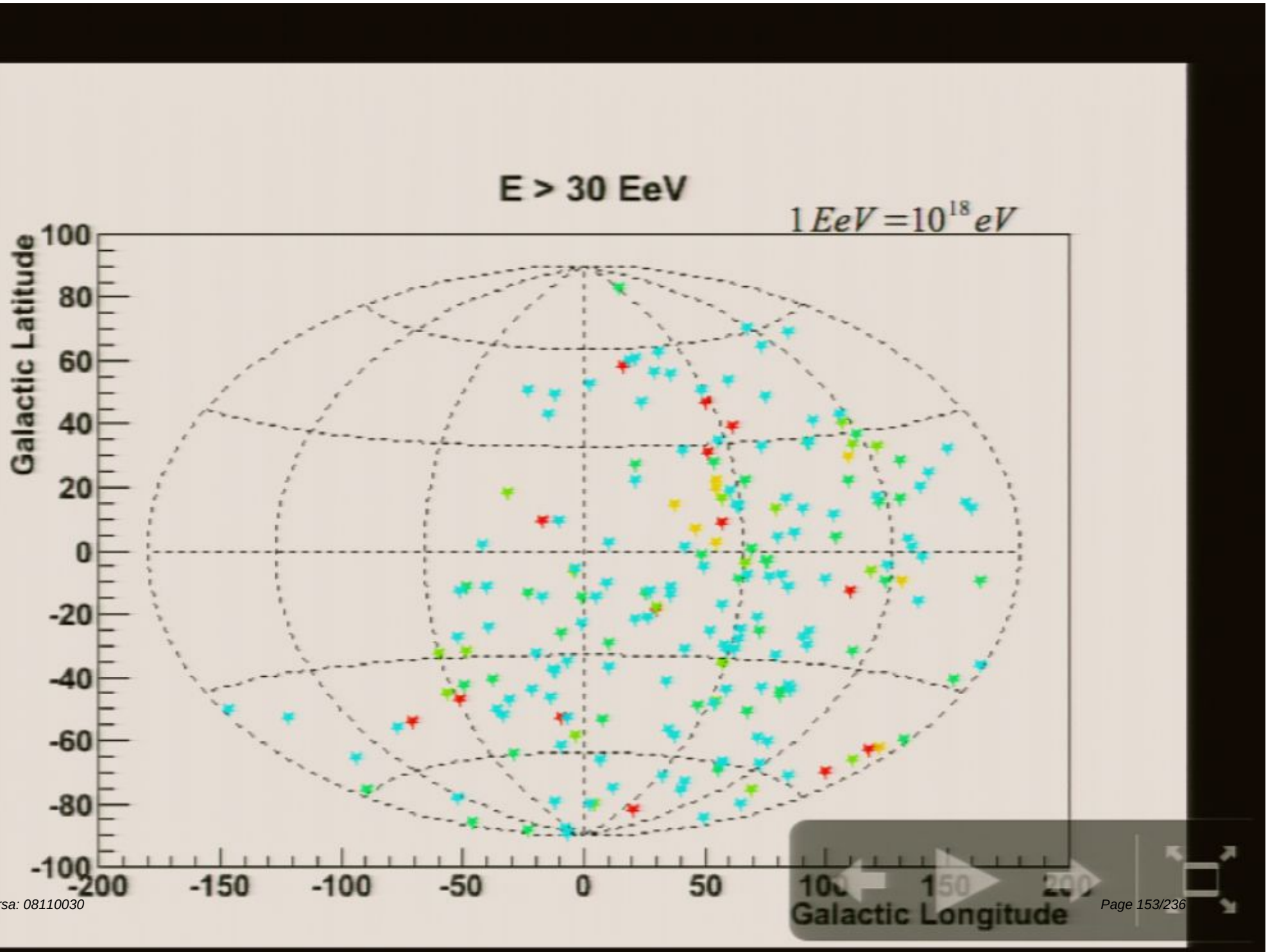

E > 10 EeV
$1\,EeV = 10^{18}\,eV$
Galactic Latitude
100
80
60
40
20
0
-20
-40
-60
-80
-100
-200
-150
-100
-50
0
50
Galactic Longitude


E > 10 EeV
$1\,EeV = 10^{18}\,eV$
Galactic Latitude
100
80
60
40
20
0
-20
-40
-60
-80
-100
-200
-150
-100
-50
0
50
100
150
200
Galactic Longitude


E > 20 EeV
$1\,EeV = 10^{18}\,eV$
Galactic Latitude
100
80
60
40
20
0
-20
-40
-60
-80
-100
-200
-150
-100
-50
0
50
Galactic Longitude


E > 10 EeV
$1\,EeV = 10^{18}\,eV$
Galactic Latitude
100
80
60
40
20
0
-20
-40
-60
-80
-100
-200
-150
-100
-50
0
50
Galactic Longitude


E > 10 EeV
$1\,EeV = 10^{18}\,eV$
Galactic Latitude
100
80
60
40
20
0
-20
-40
-60
-80
-100
-200
-150
-100
-50
0
50
100
150
200
Galactic Longitude


E > 30 EeV
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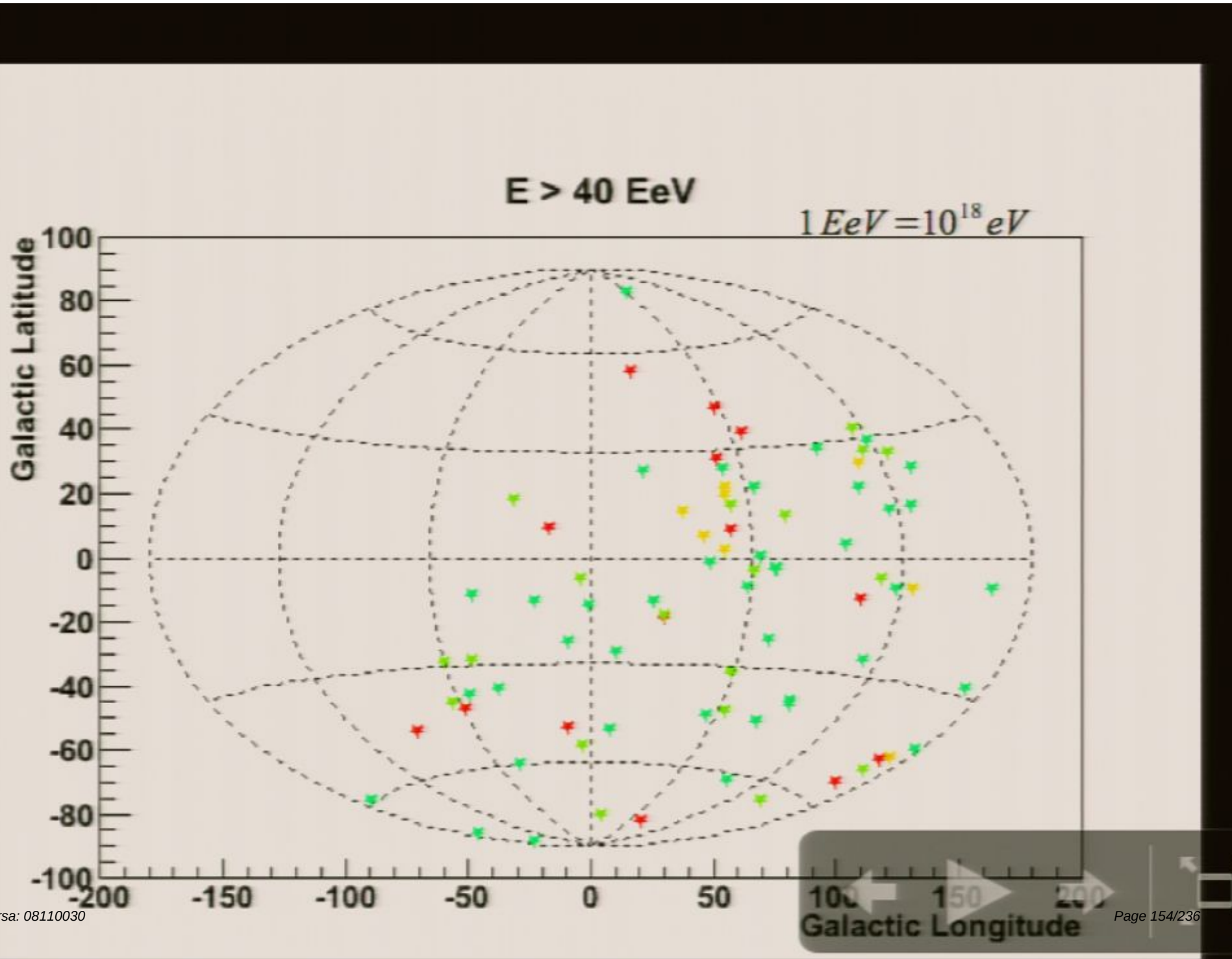
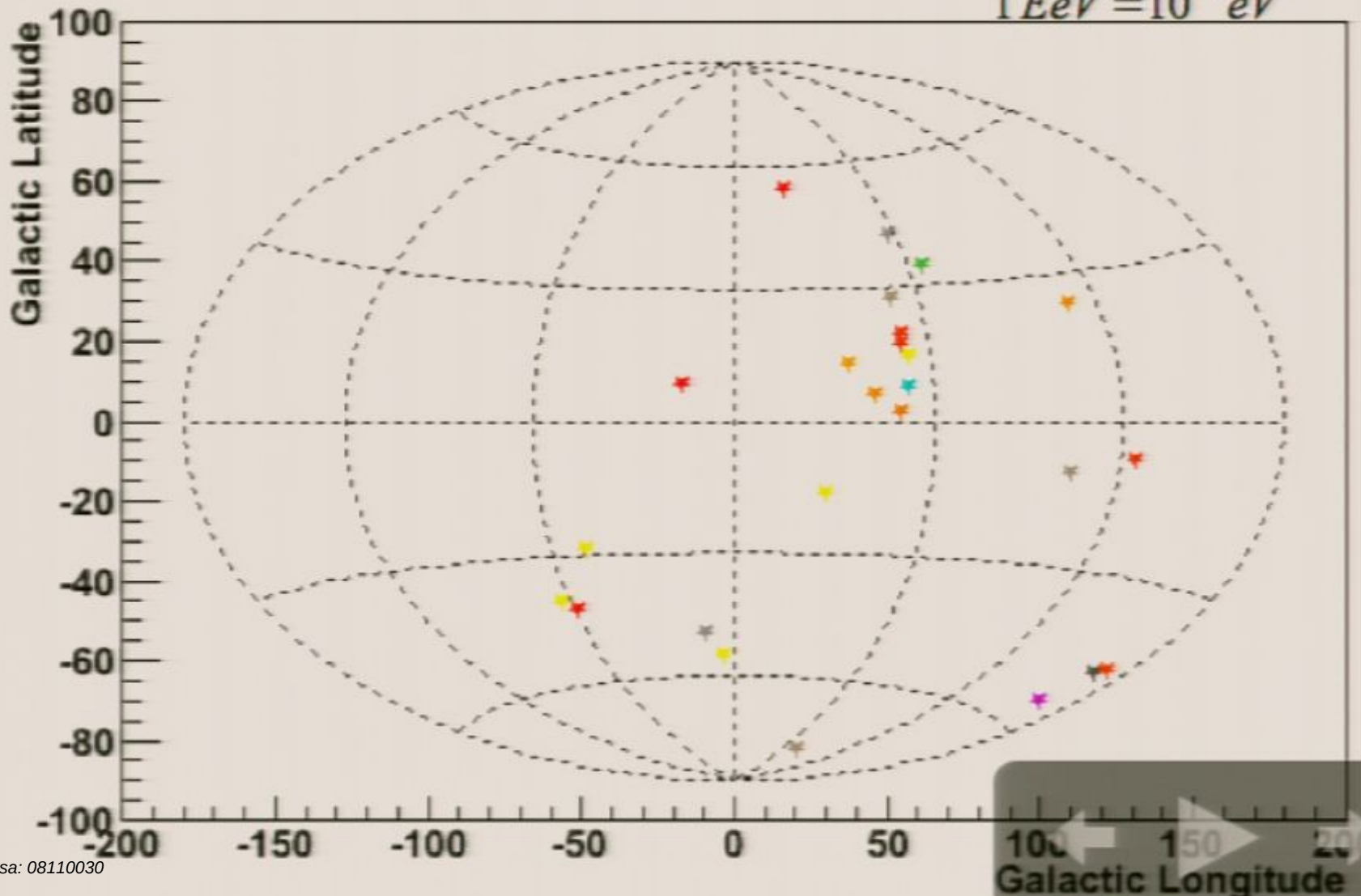
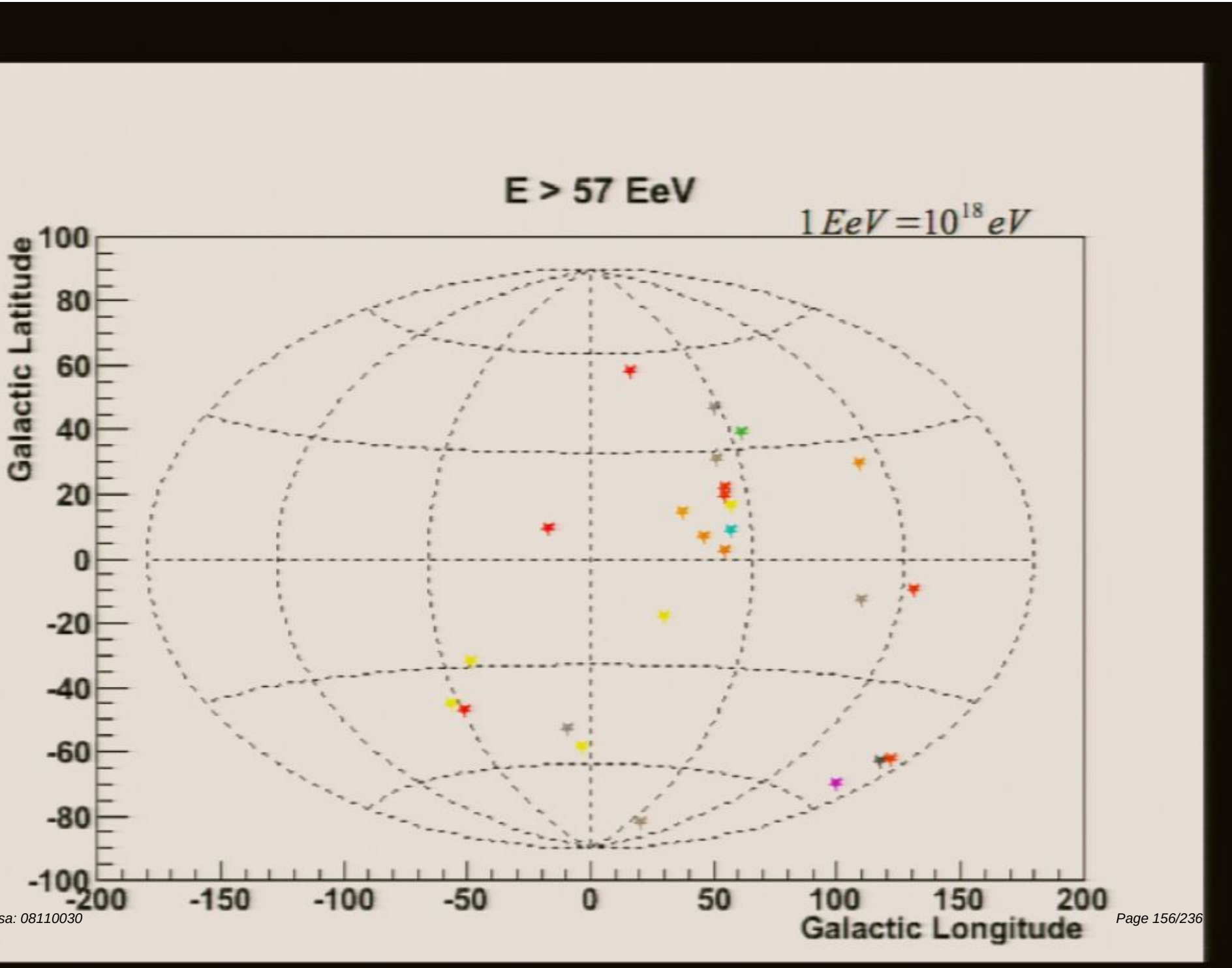
Galactic Latitude
100
80
60
40
20
0
-20
-40
-60
-80
-100
-200
-150
-100
-50
0
50
Galactic Longitude


E > 40 EeV
$1\,EeV = 10^{18}\,eV$
Galactic Latitude
100
80
60
40
20
0
-20
-40
-60
-80
-100
-200
-150
-100
-50
0
50
Galactic Longitude


E > 57 EeV
$1\,EeV = 10^{18}\,eV$
Galactic Latitude
100
80
60
40
20
0
-20
-40
-60
-80
-100
-200
-150
-100
-50
0
50
Galactic Longitude


E > 57 EeV
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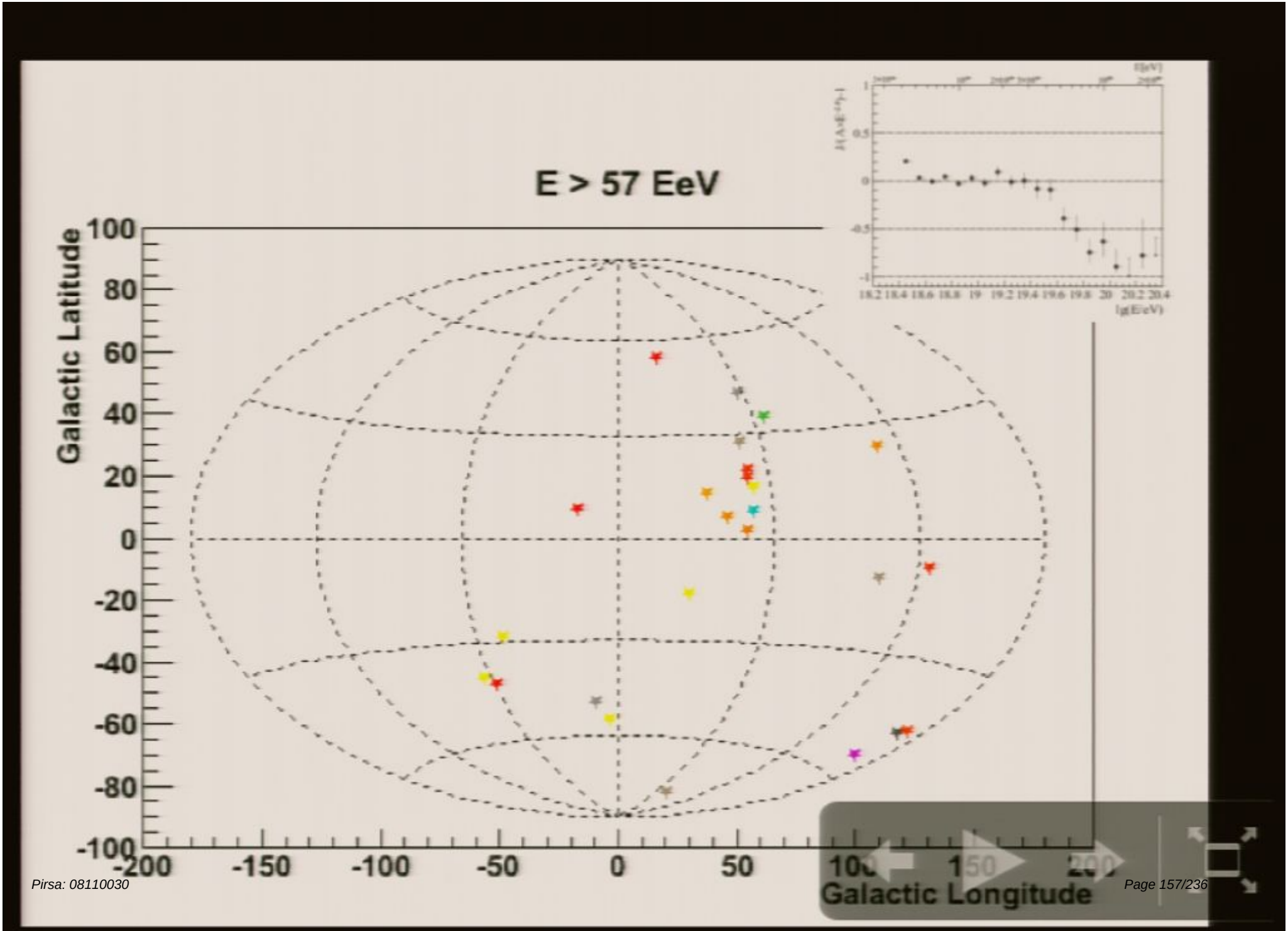
Galactic Latitude
100
80
60
40
20
0
-20
-40
-60
-80
-100
-200
-150
-100
-50
0
50
100
150
200
Galactic Longitude


E > 57 EeV
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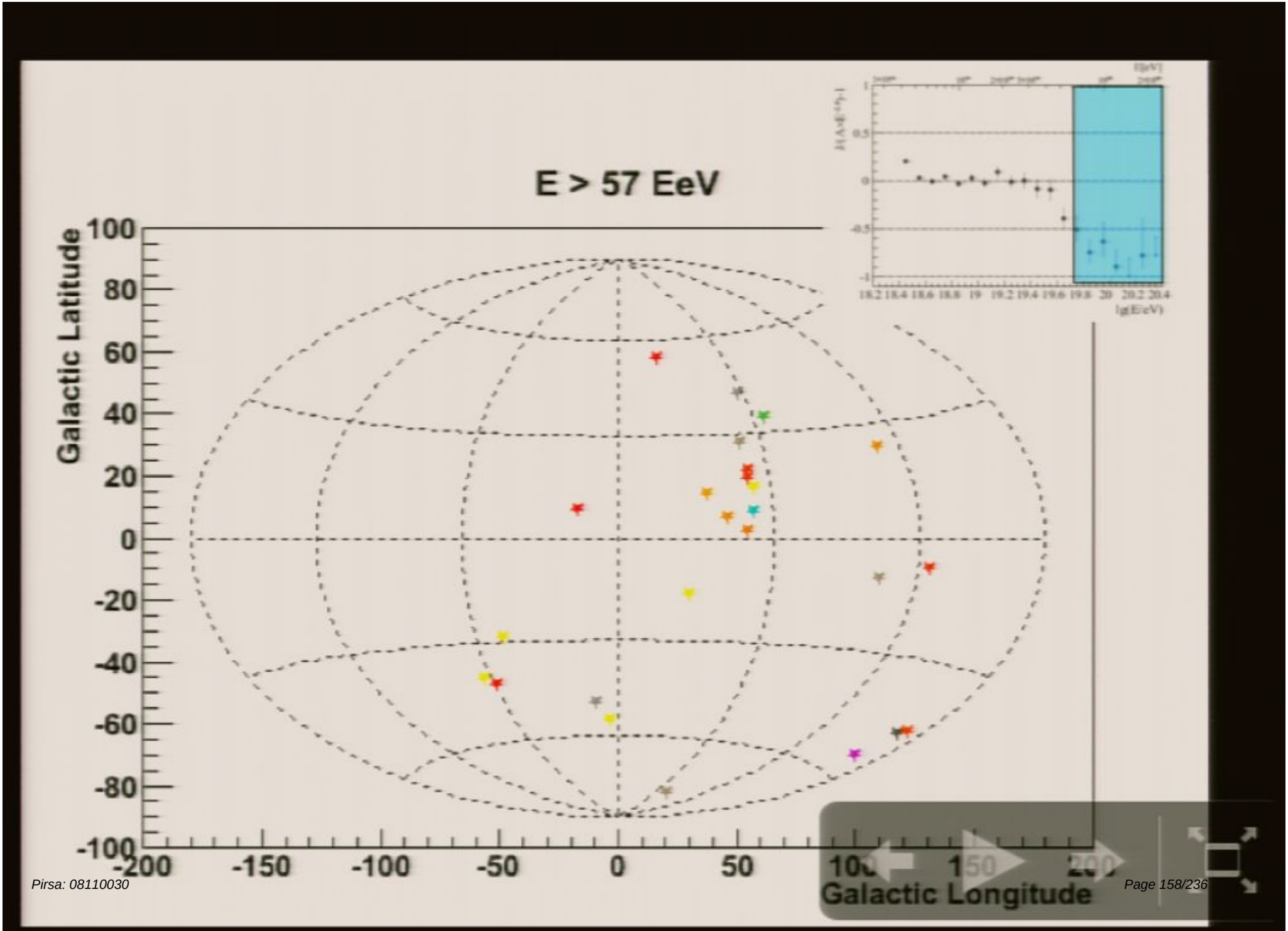
100
80
60
40
20
0
-20
-40
-60
-80
-100
-200
-150
-100
-50
0
50
Galactic Longitude
lg(E/eV)


E > 57 EeV
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100
80
60
40
20
0
-20
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-60
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-100
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-150
-100
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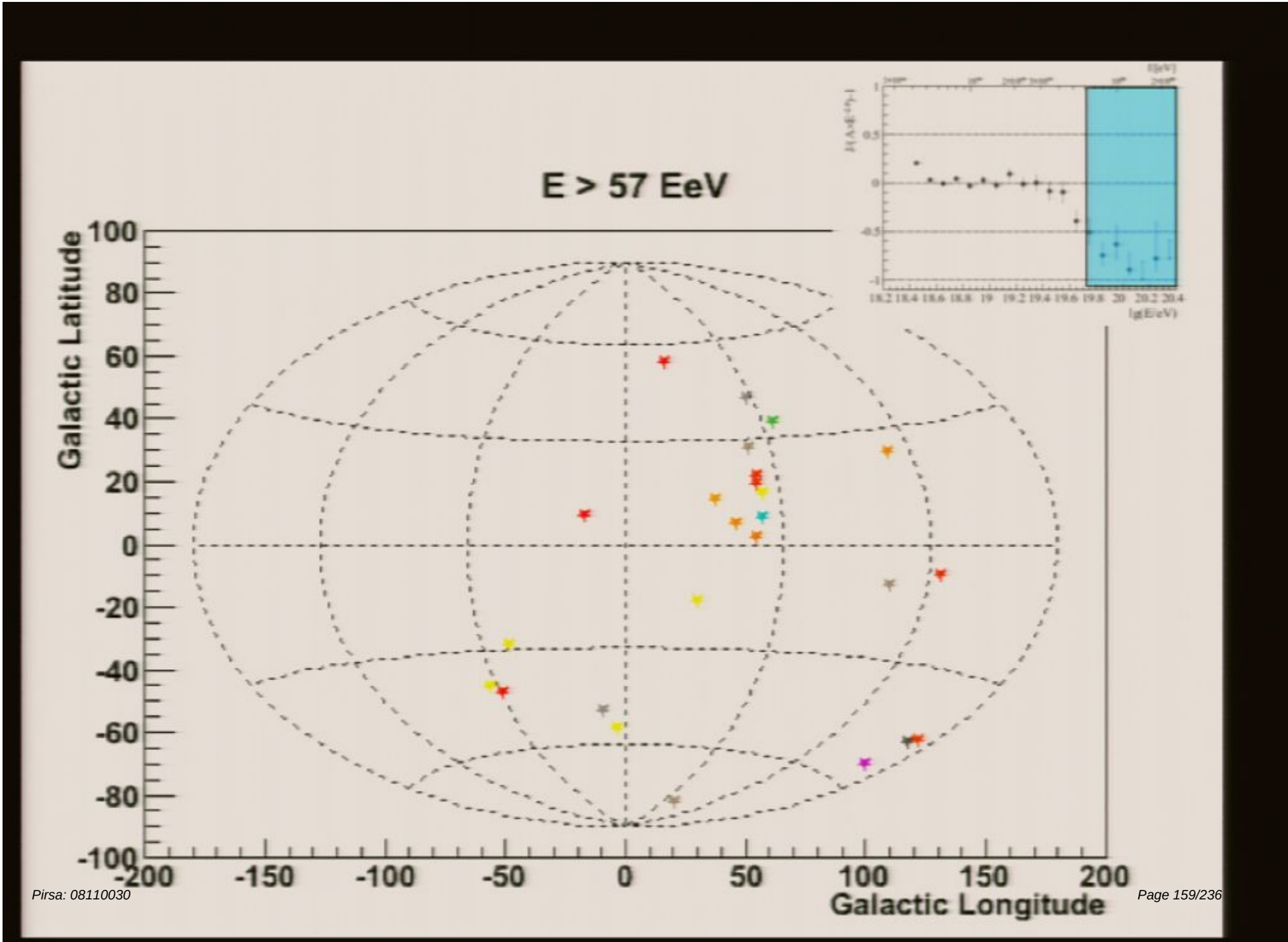
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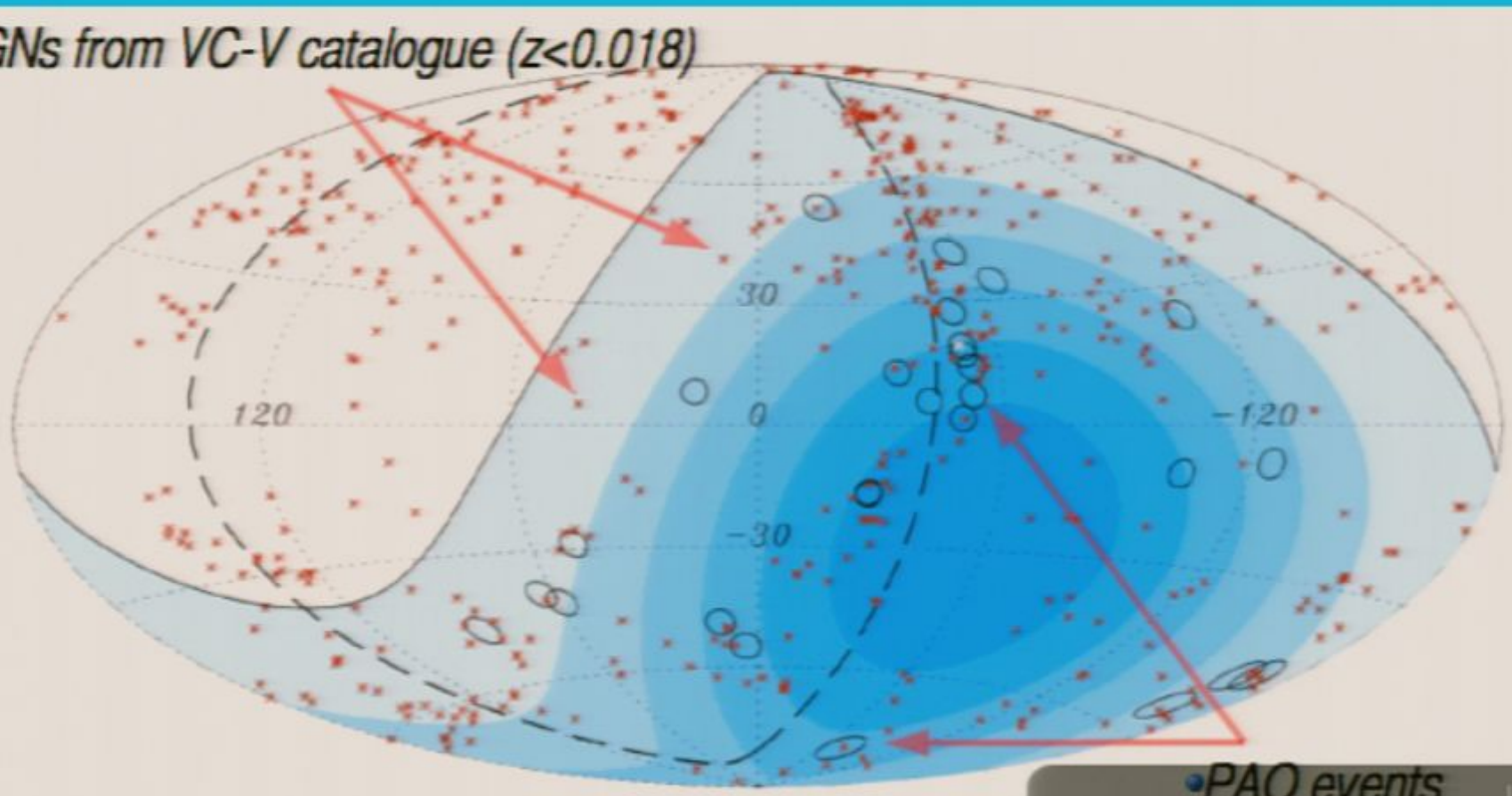
Search for point sources: the PAO Sky Map



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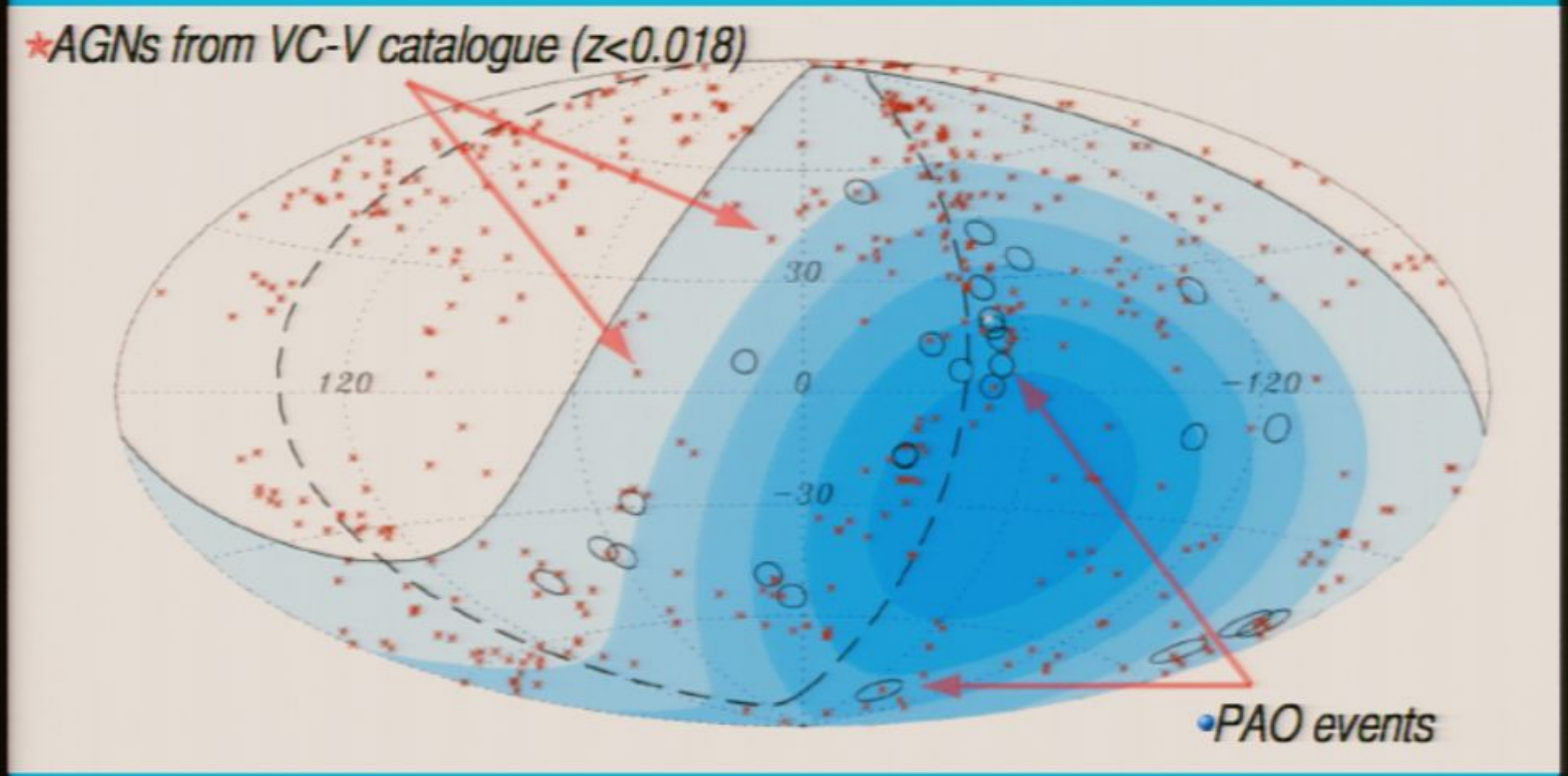

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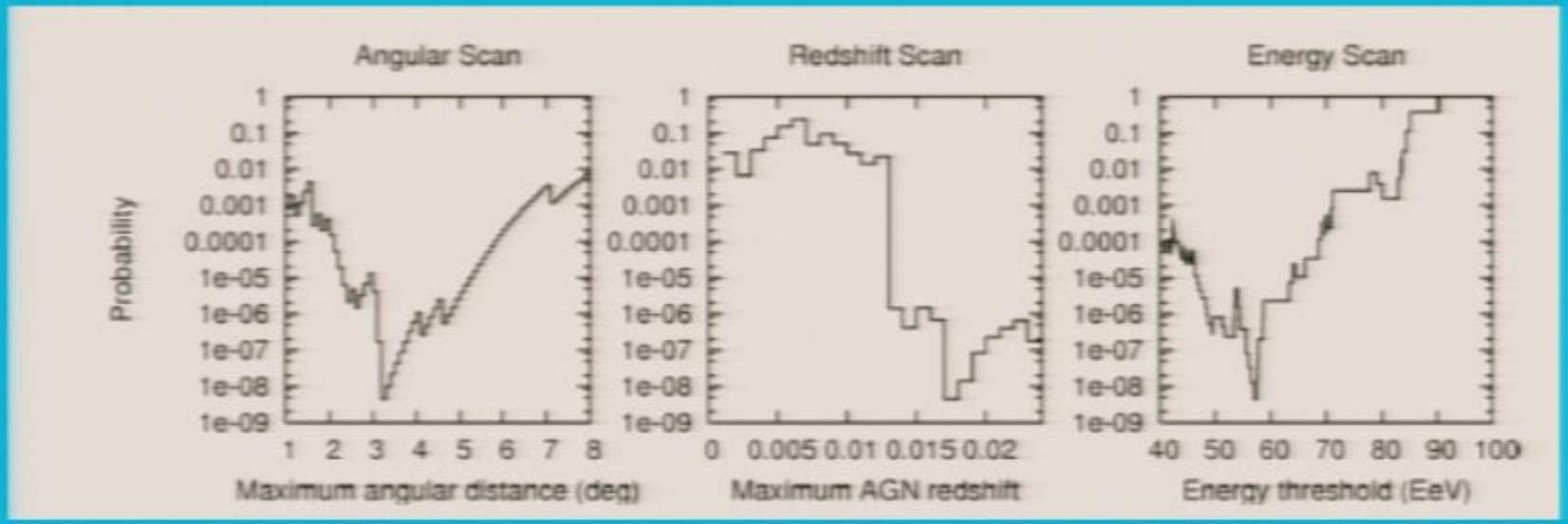

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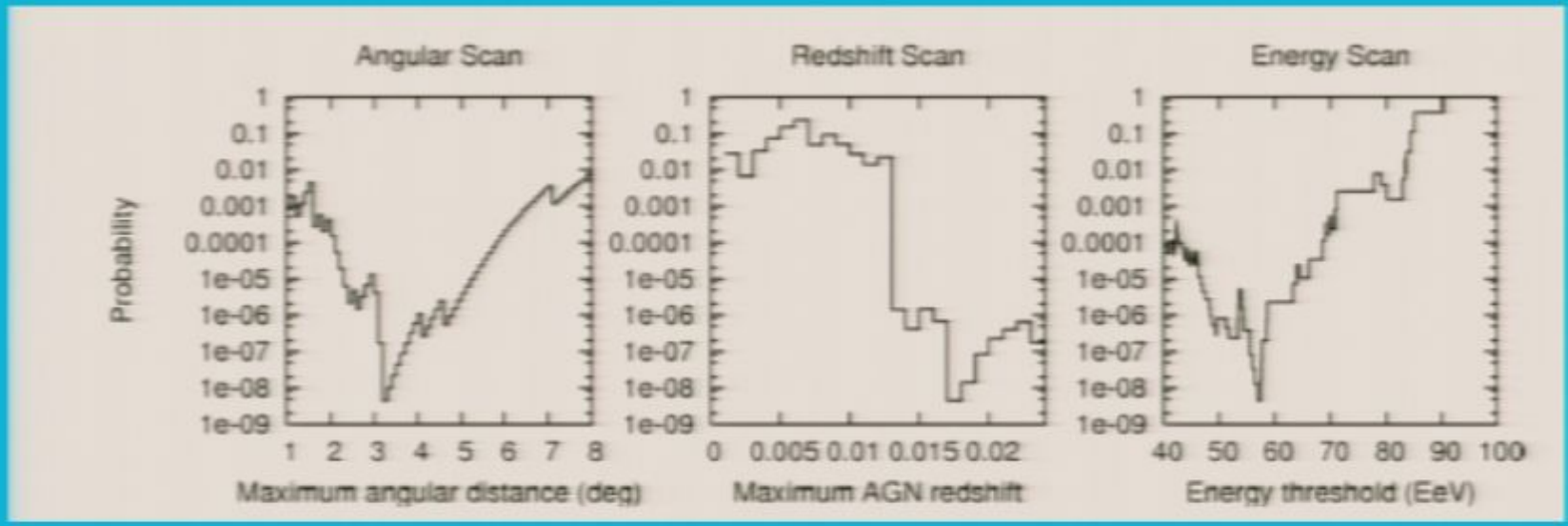

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★*AGNs from VC-V catalogue (z<0.018)*

Anisotropy has been established with more than 99% confidence level in the arrival directions of events with energy above ~ 60 EeV detected by the Pierre Auger Observatory. These correlate over angular scales of less than 6° with the directions towards nearby ($D < 100$ Mpc) AGN.

The observed correlation demonstrates the extragalactic origin of the highest energy cosmic rays. It is consistent with the hypothesis that cosmic rays with energies above approximately 60 EeV are predominantly protons that come from AGN within our "GZK horizon". This provides evidence that the observed steepening of the cosmic ray spectrum at the highest energies is due to the "GZK effect", and not acceleration limits at the sources.

•*PAO events*

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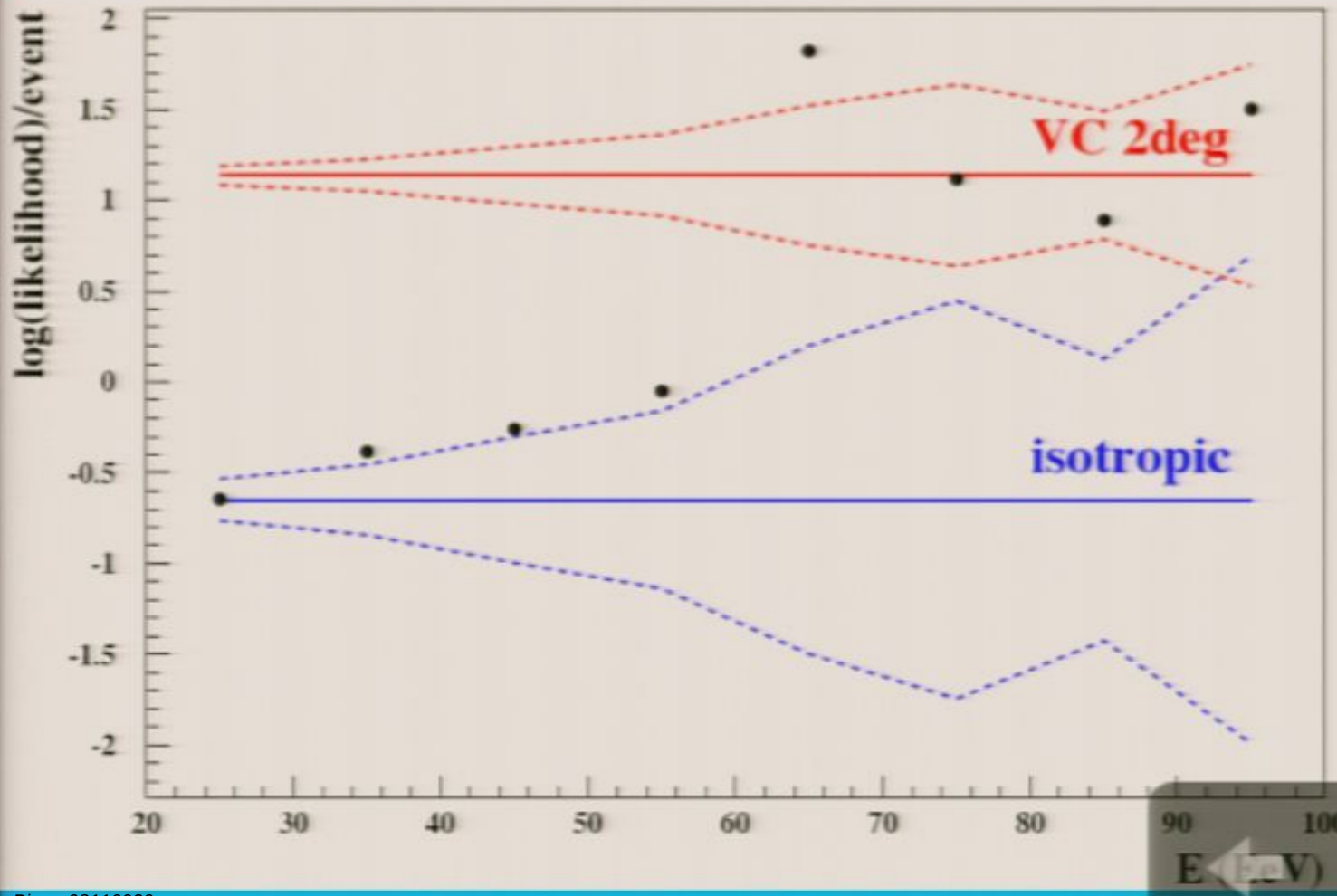
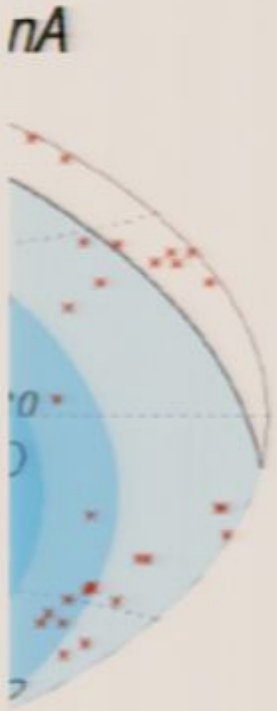
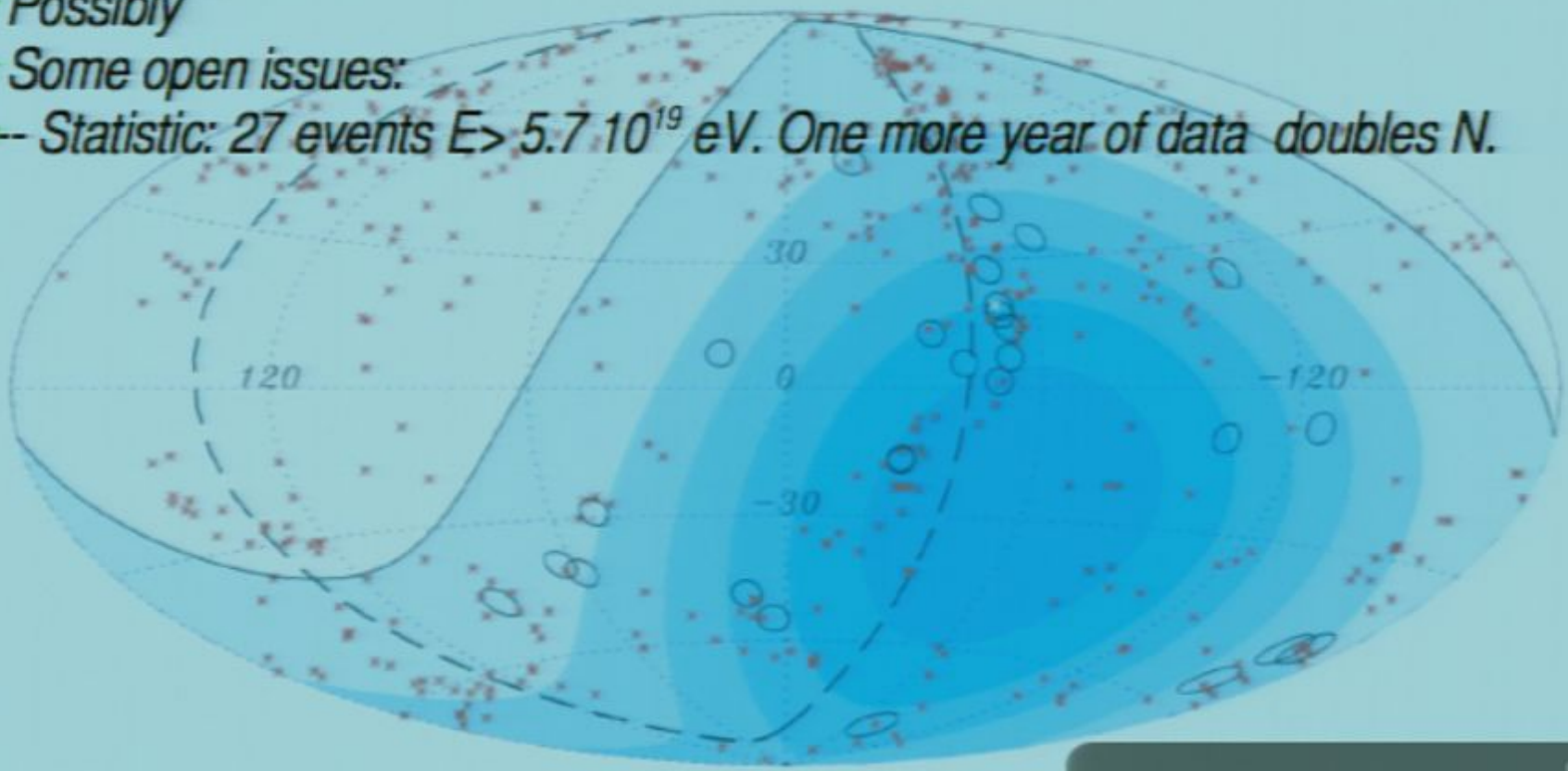




Birth of (nuclear) Cosmic Ray Astronomy?

- Possibly
- Some open issues:
- -- Statistic: 27 events $E > 5.7\ 10^{19}$ eV. One more year of data doubles N.



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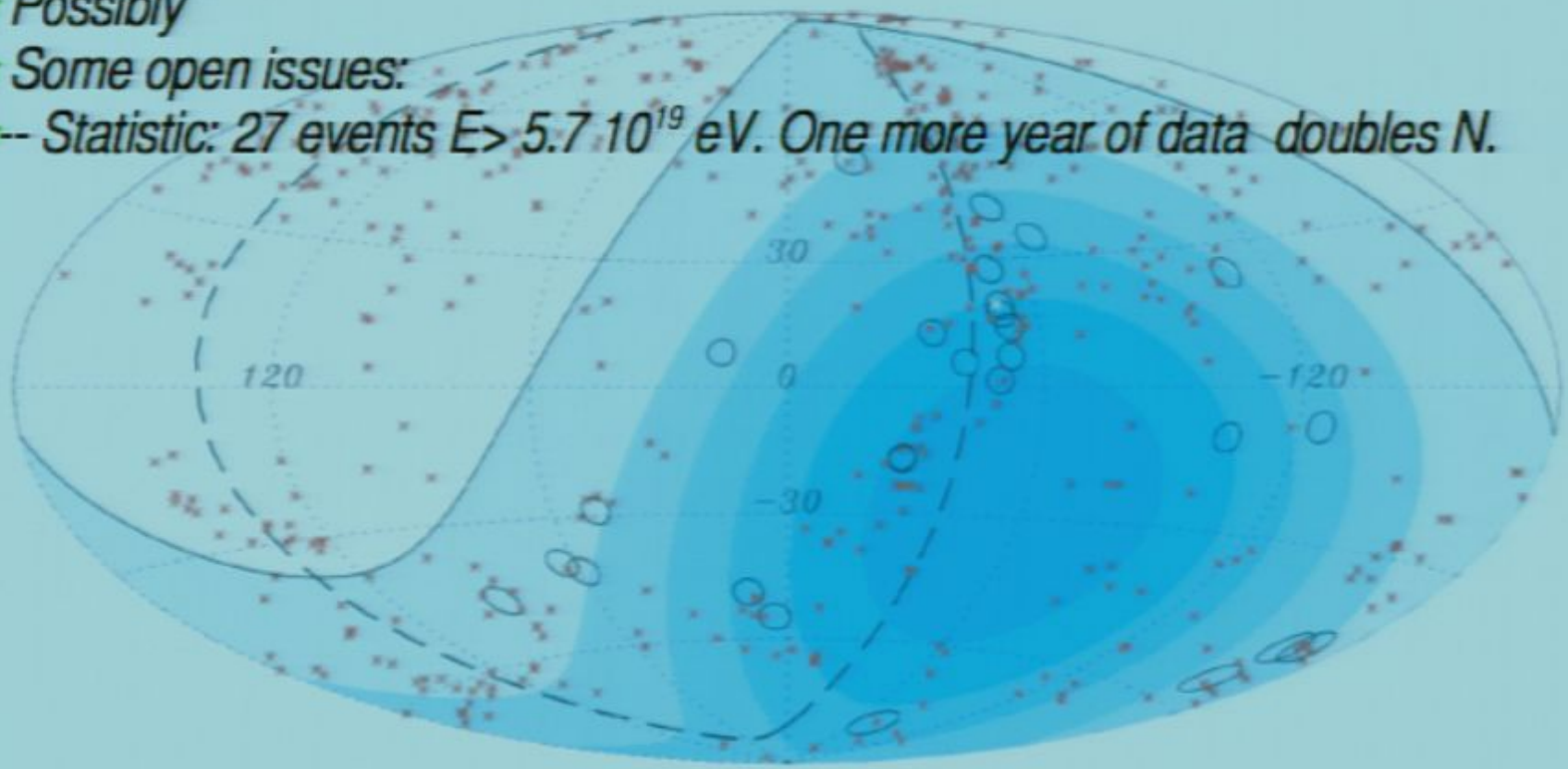

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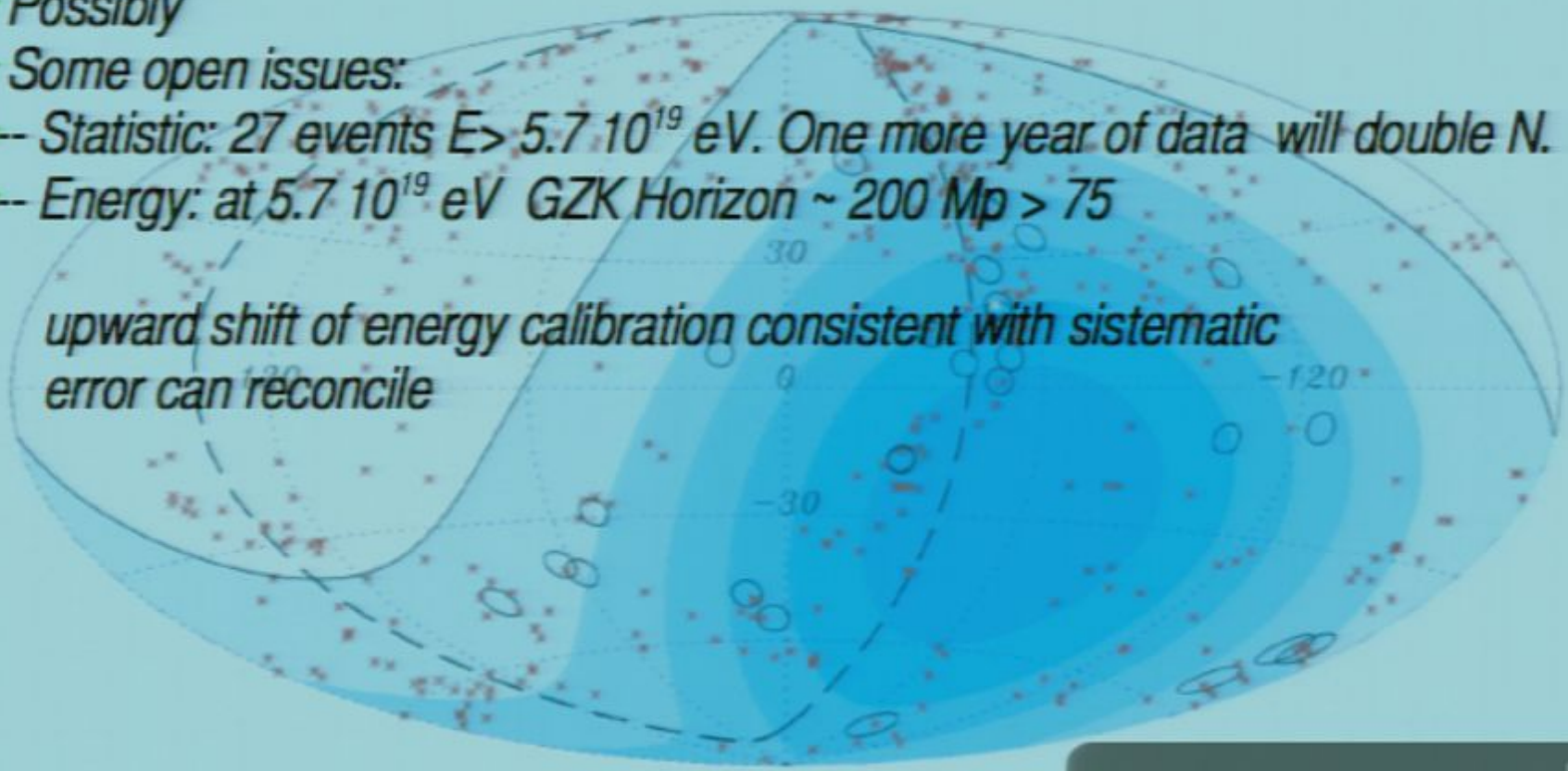
upward shift of energy calibration consistent with sistematic error can reconcile



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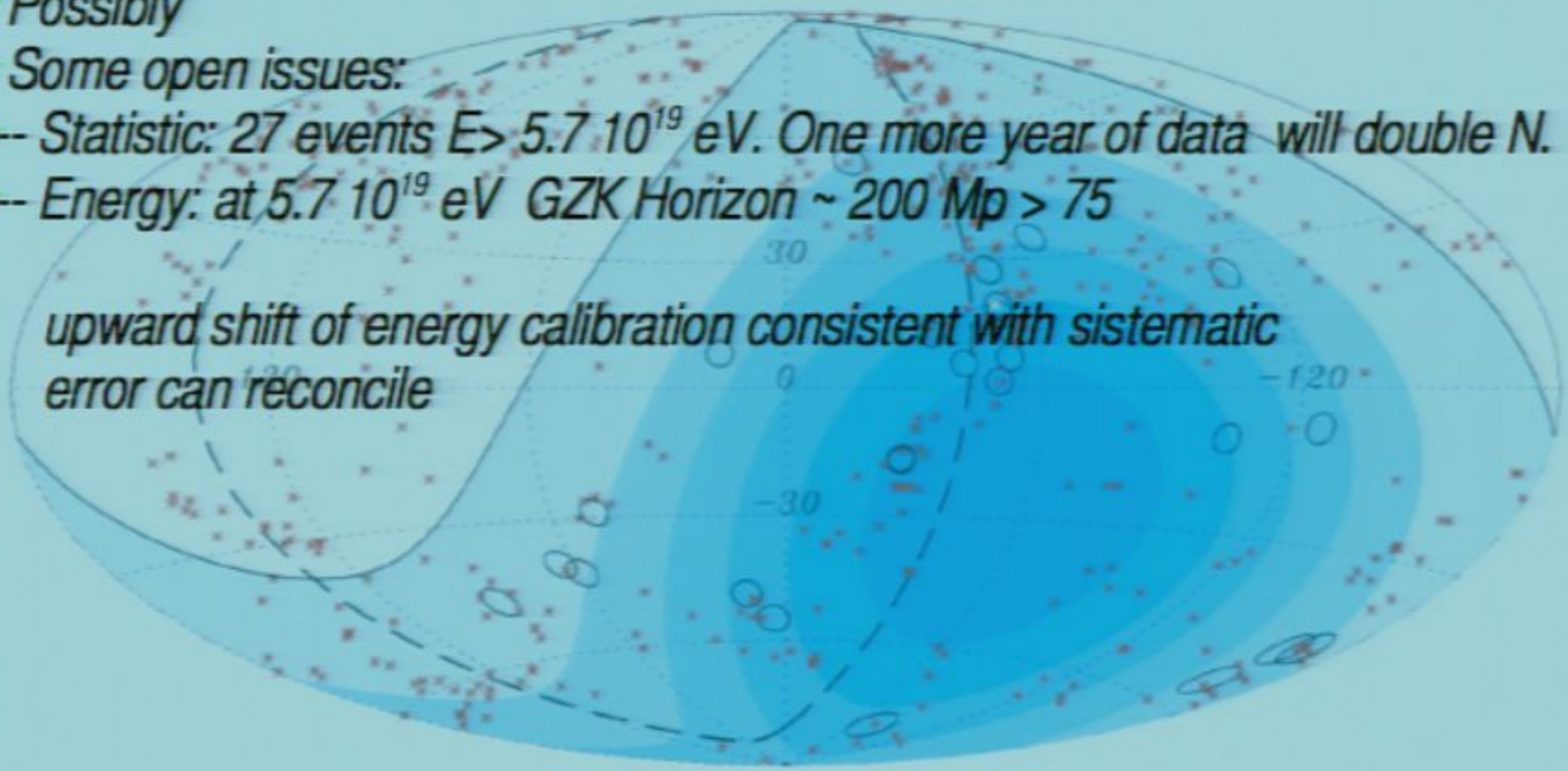

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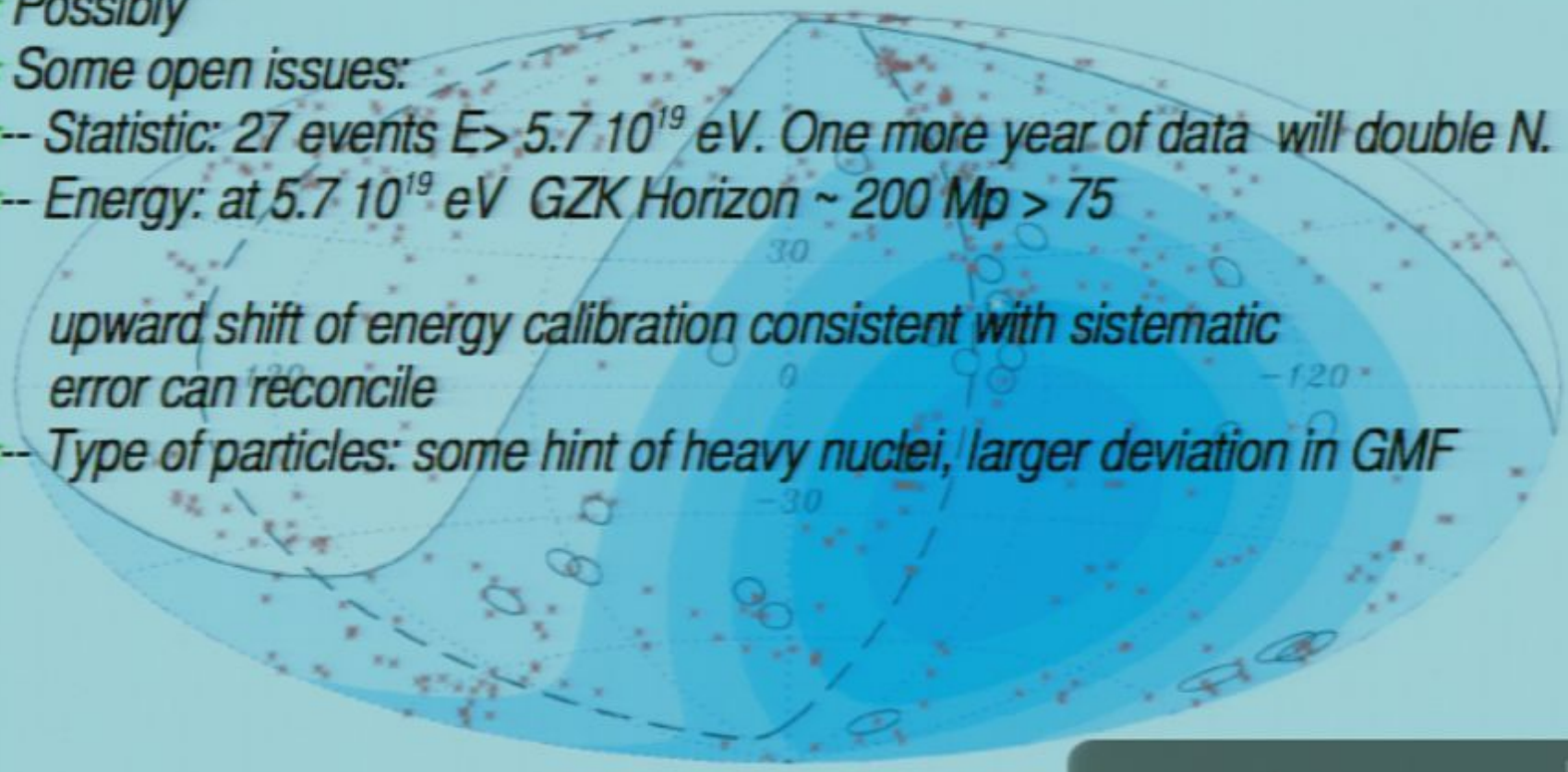
  upward shift of energy calibration consistent with sistematic error can reconcile
- -- Type of particles: some hint of heavy nuclei, larger deviation in GMF



Birth of (nuclear) Cosmic Ray Astronomy?

Magnetic fields

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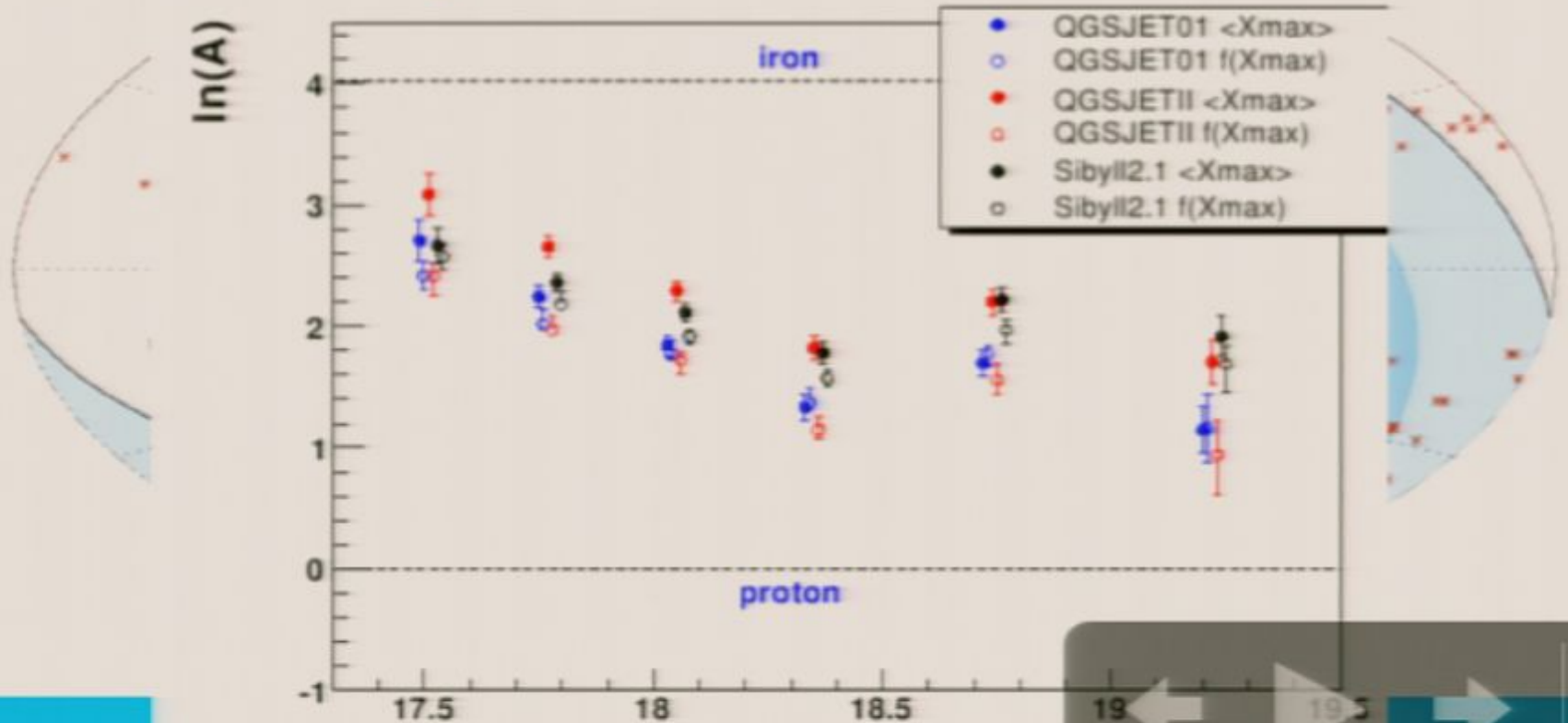

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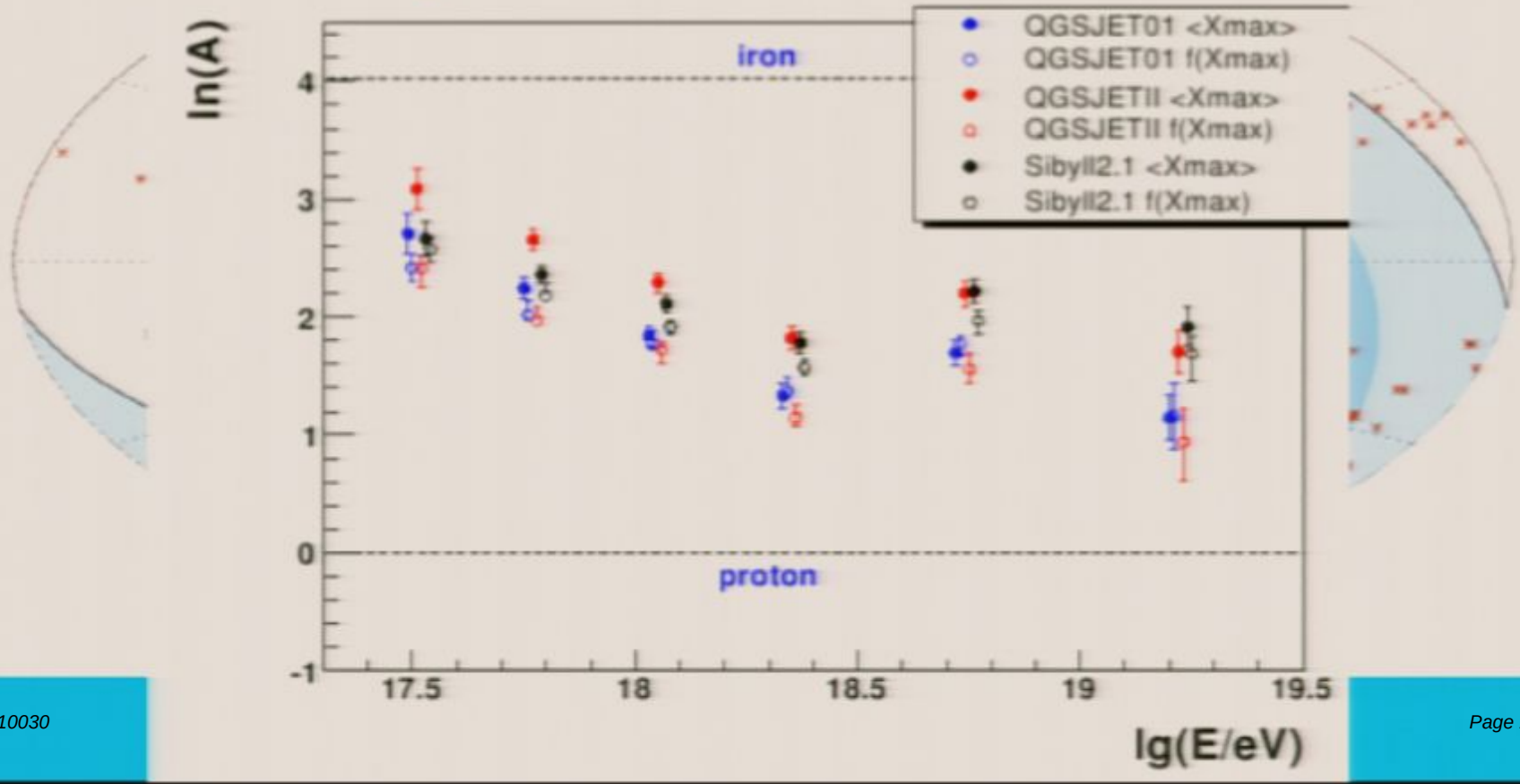

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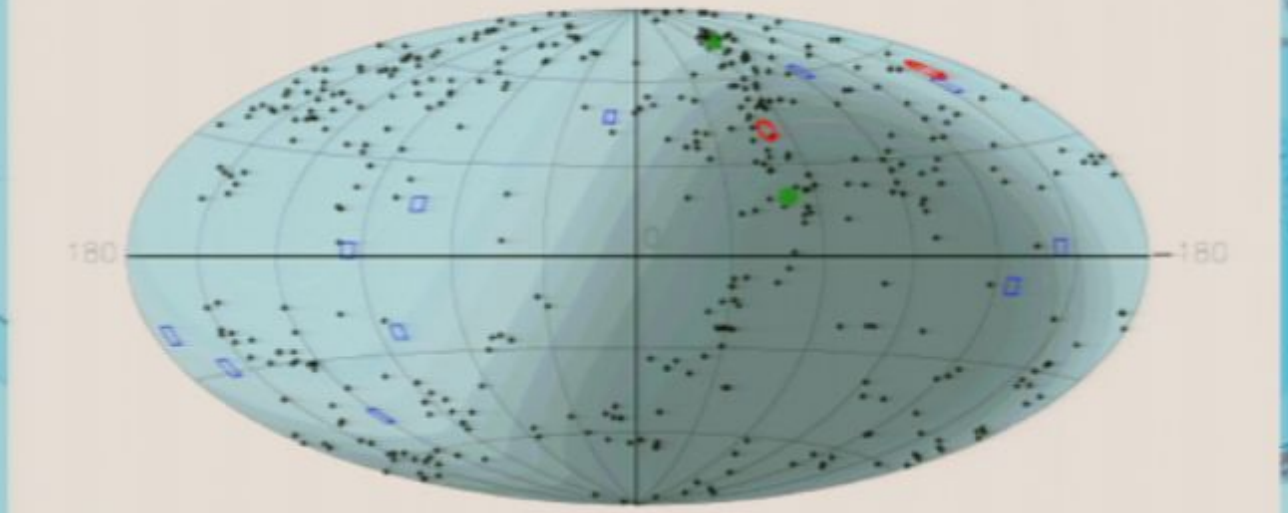

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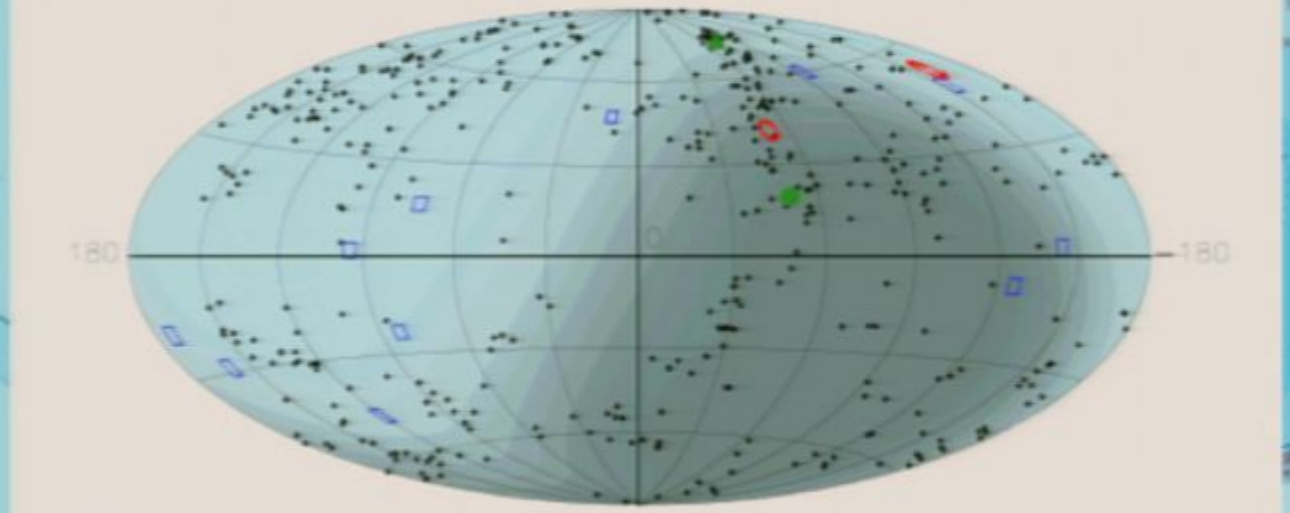

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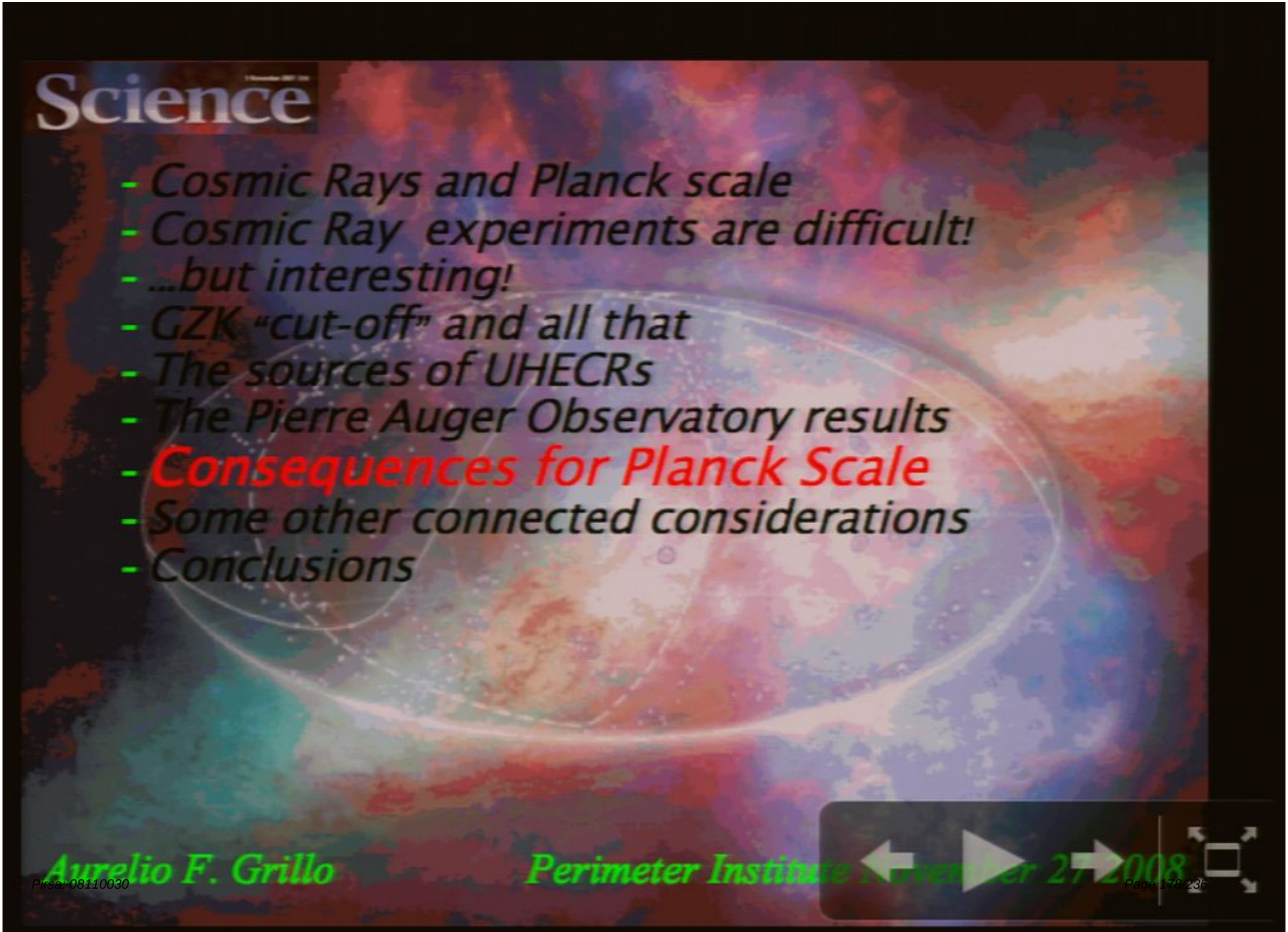
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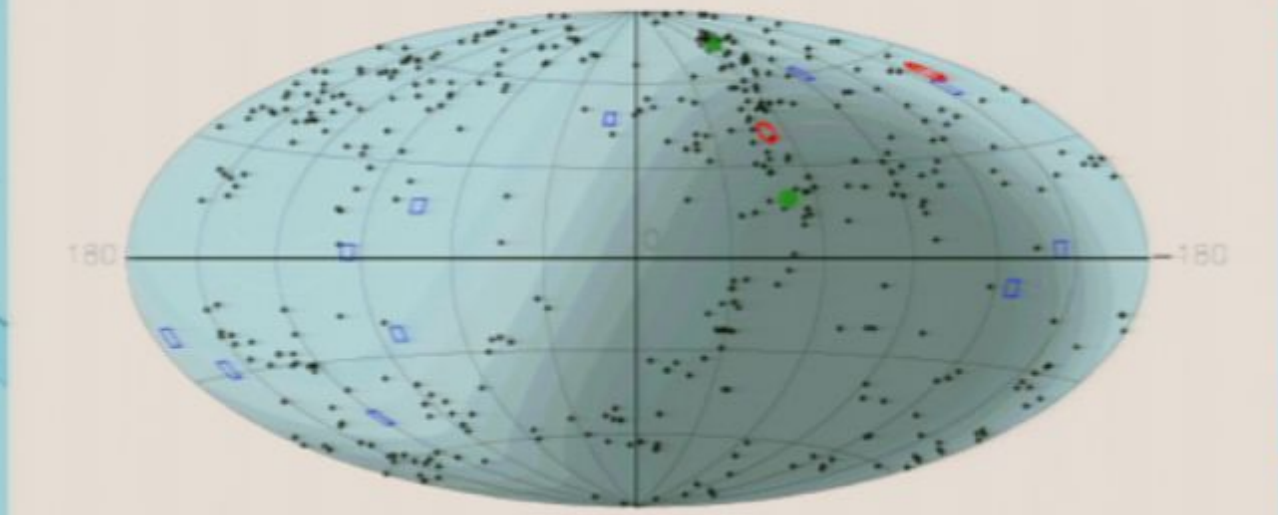

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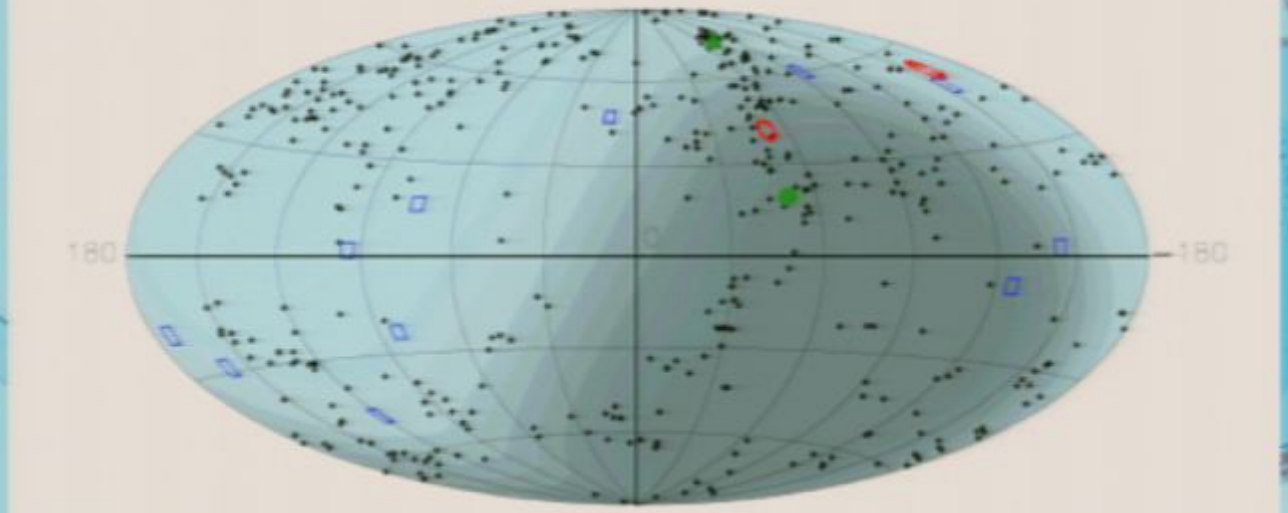

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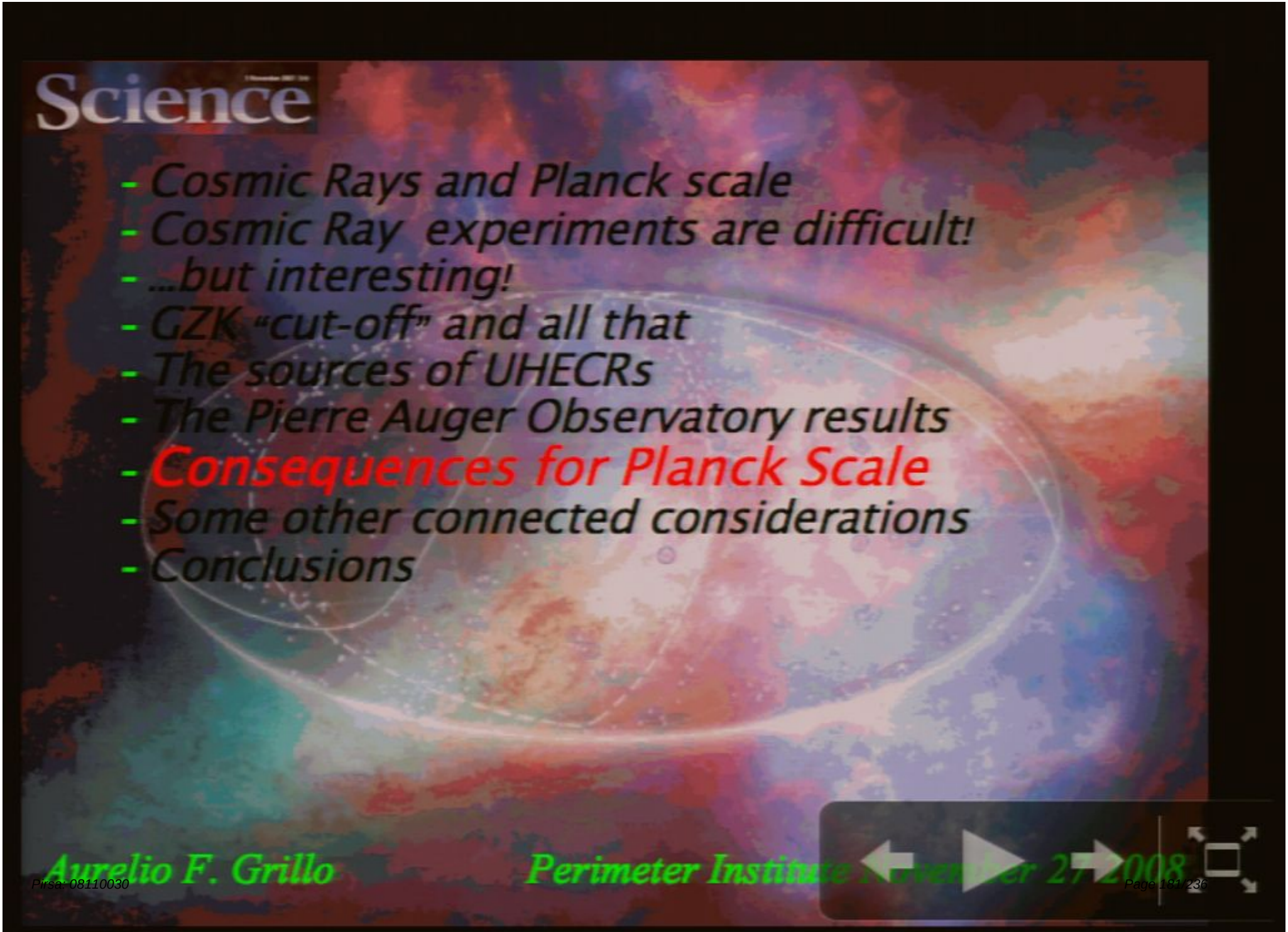
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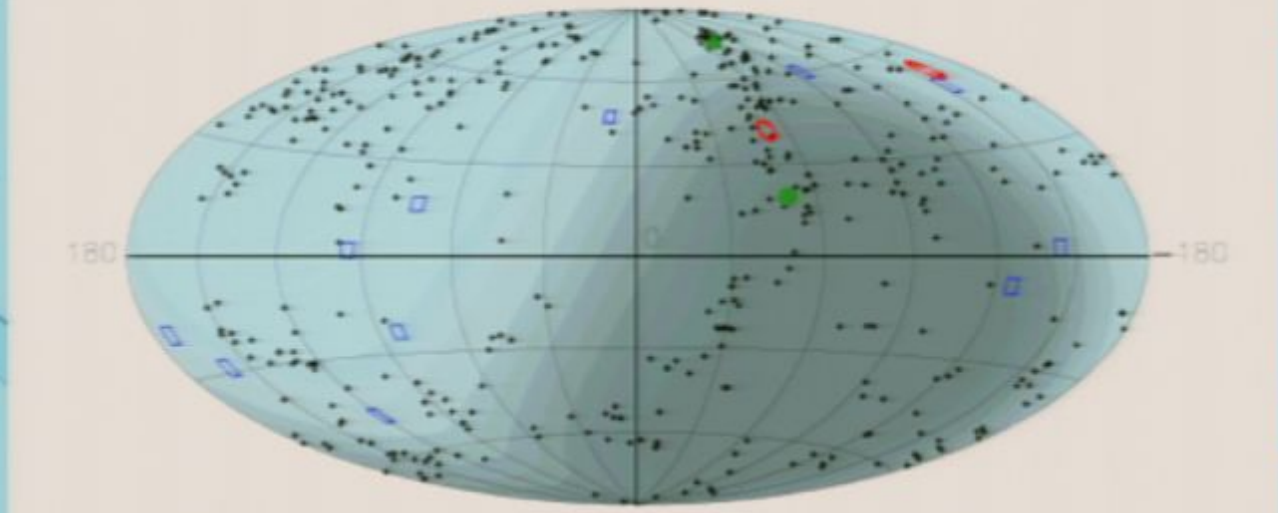

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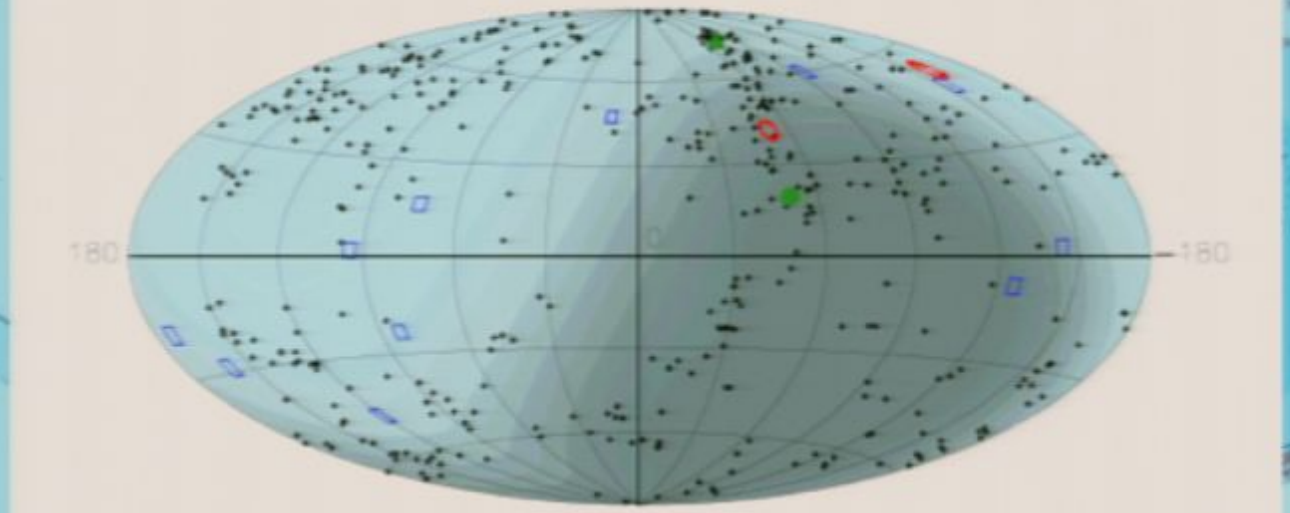

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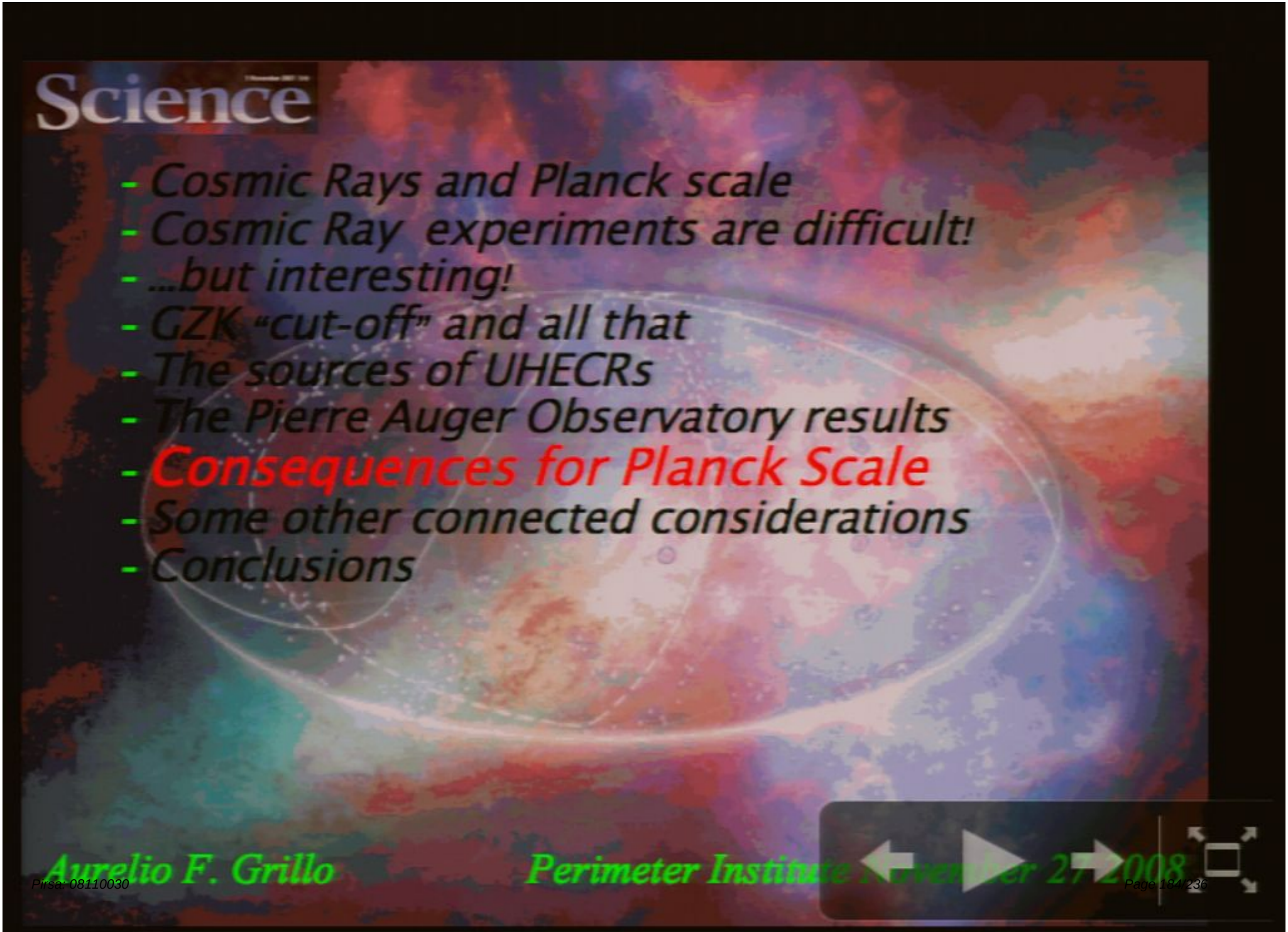
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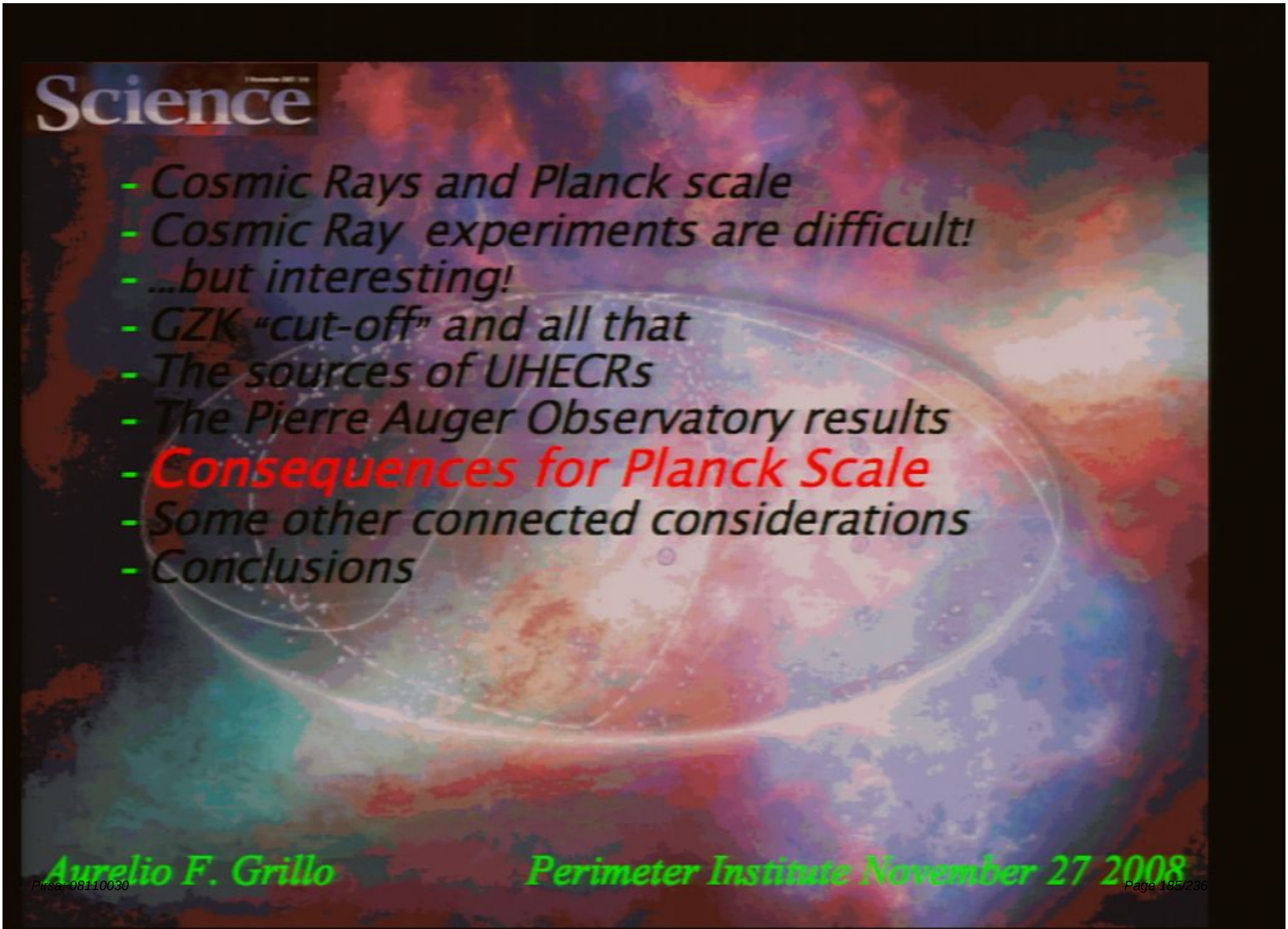
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astro-ph/0001258

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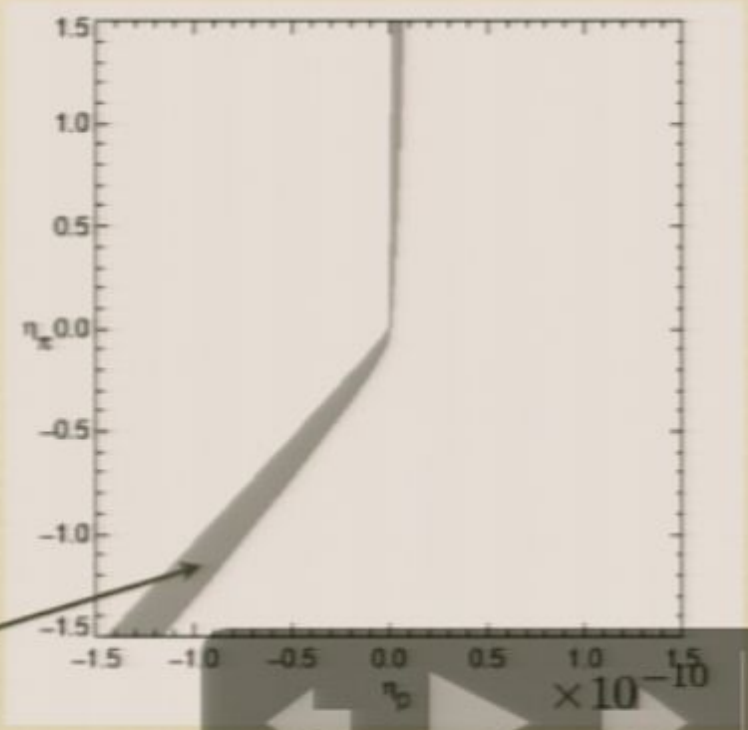

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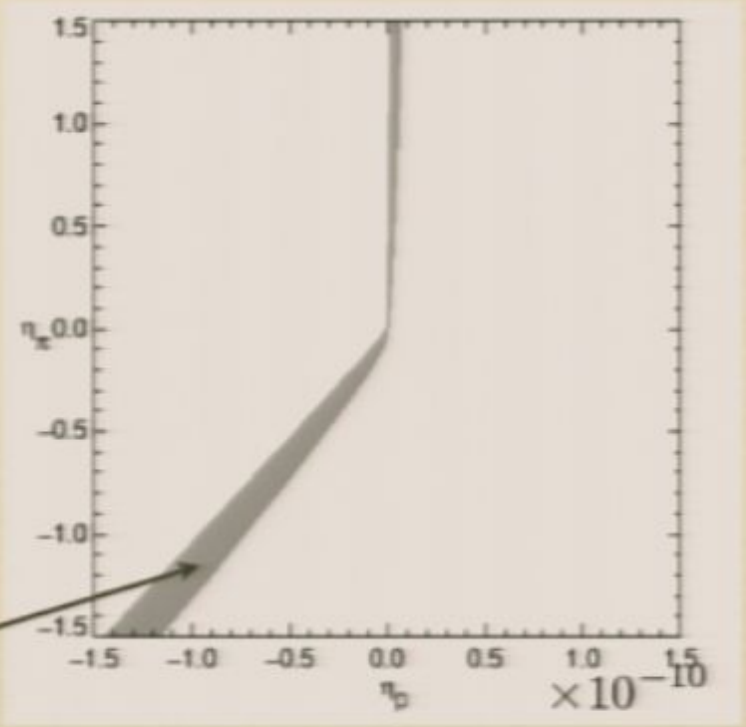

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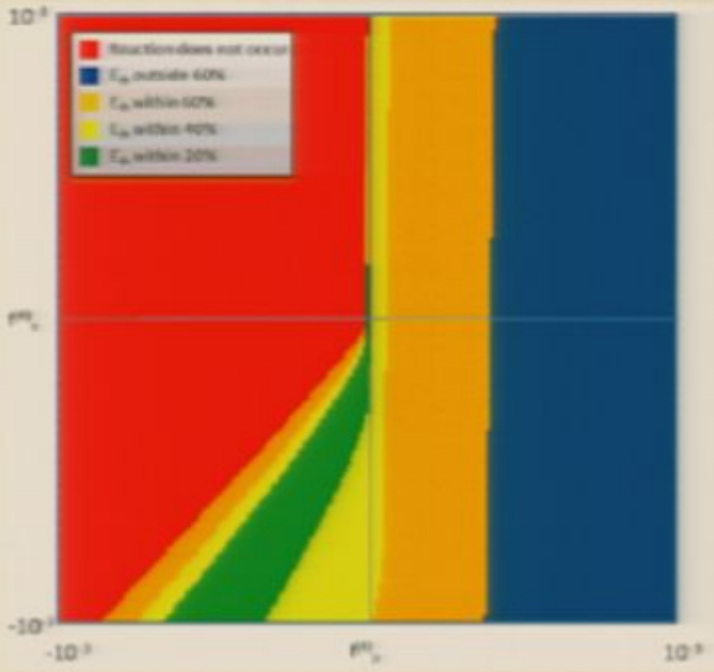

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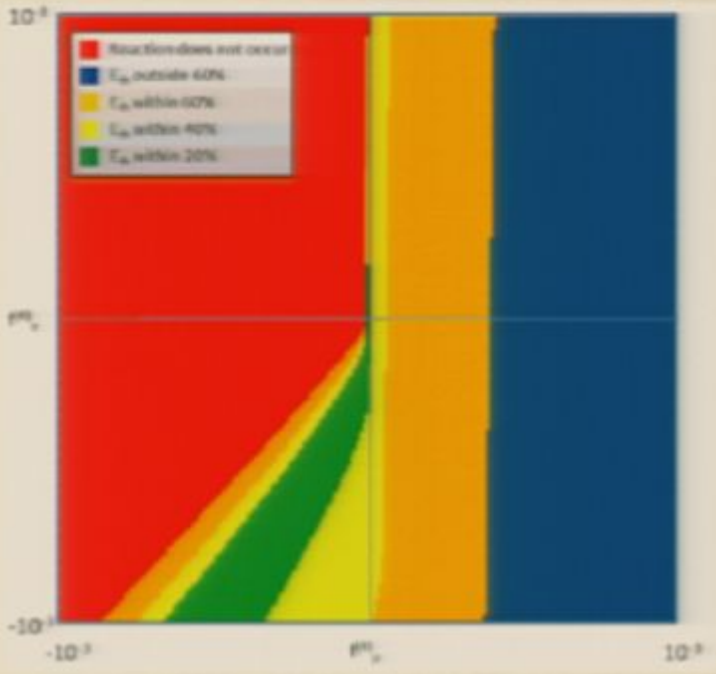

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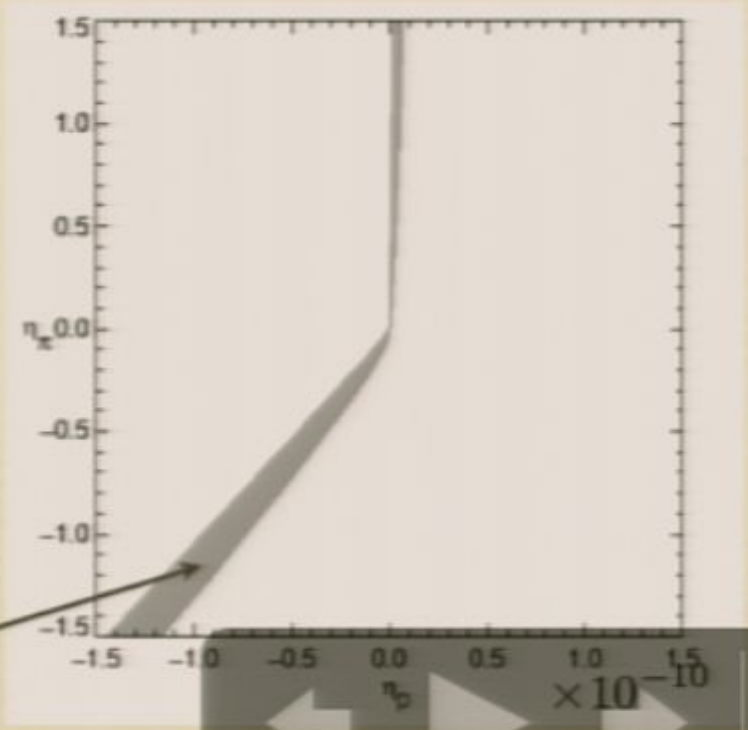

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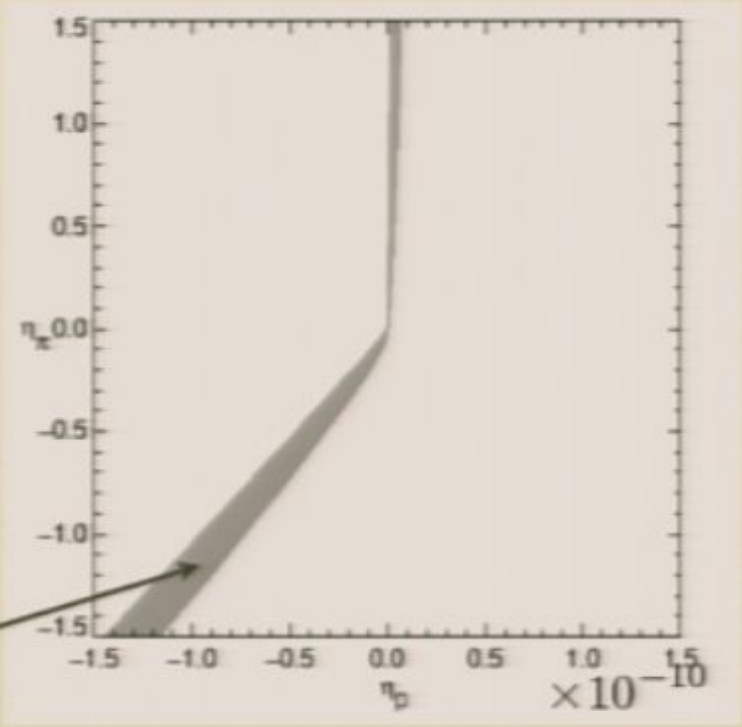

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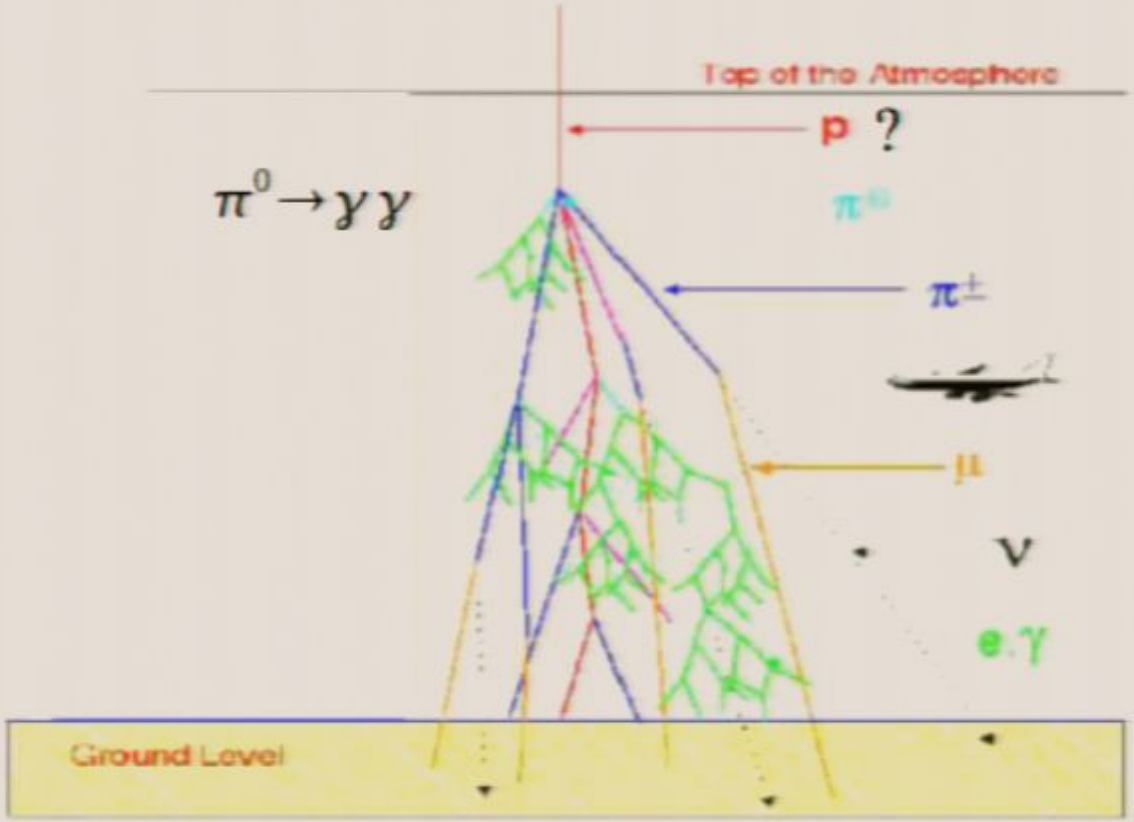

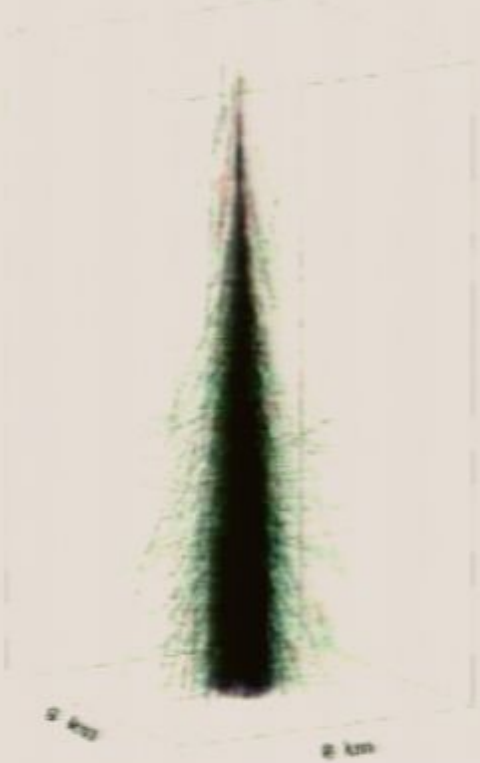

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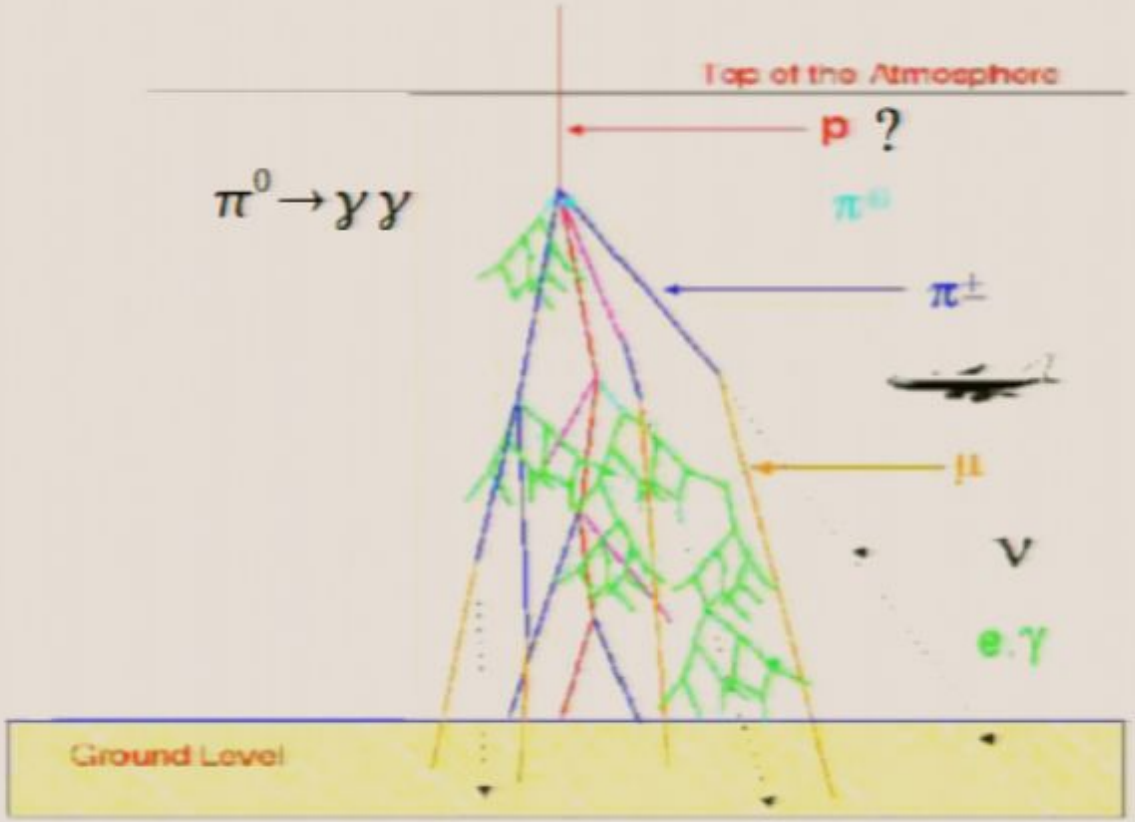

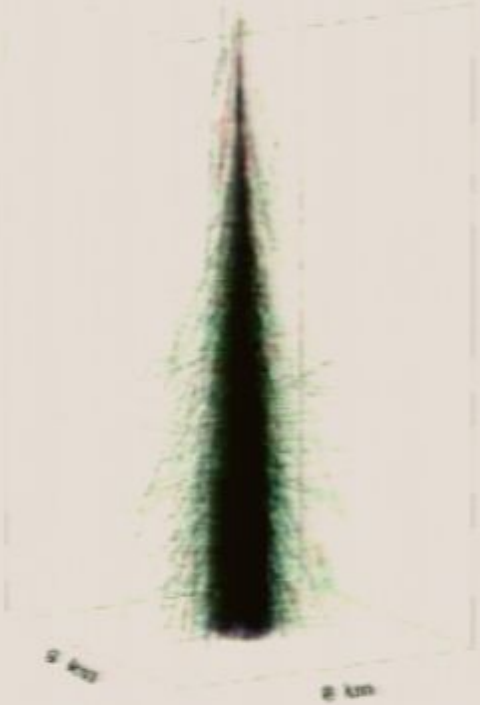

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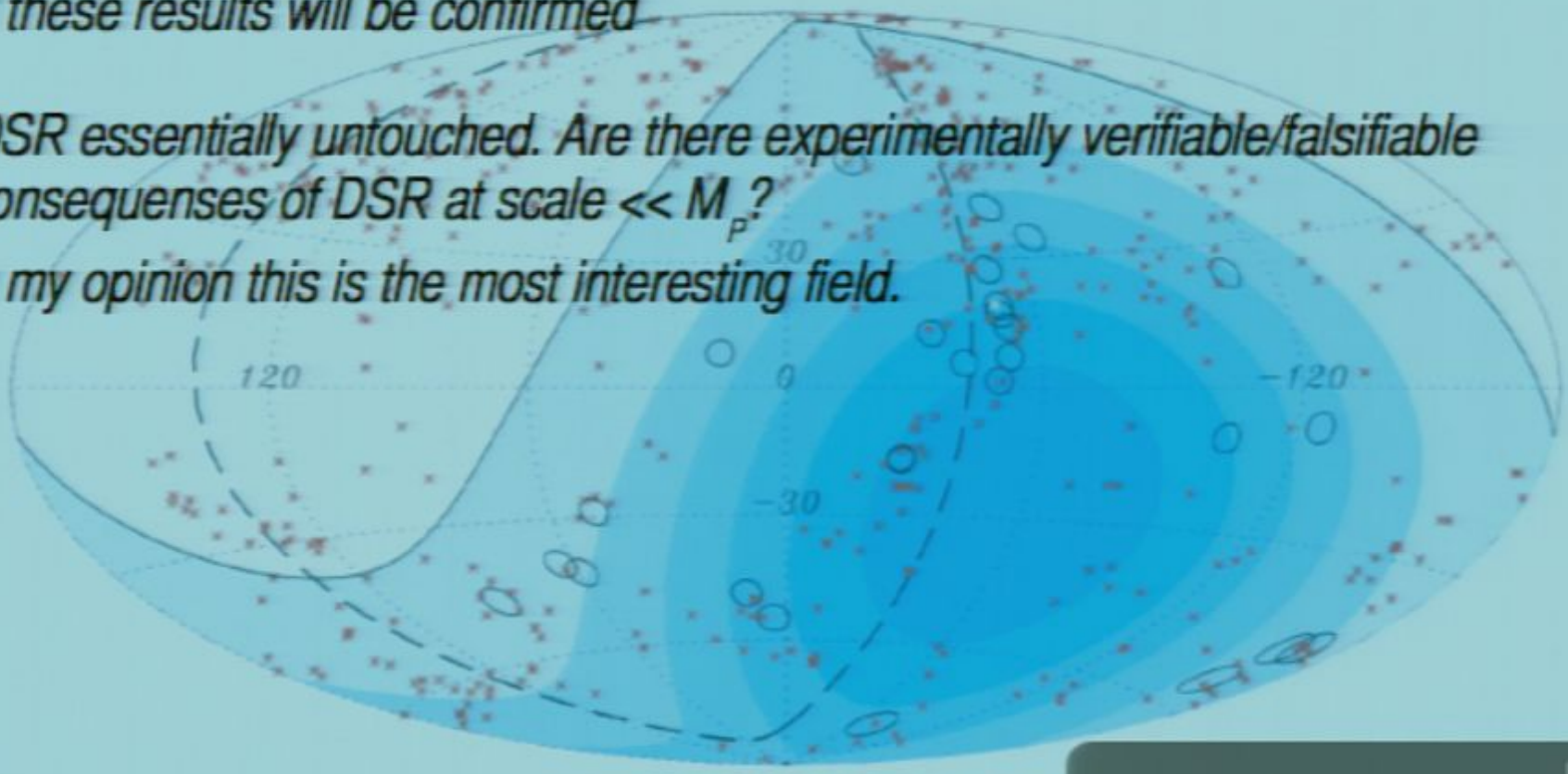

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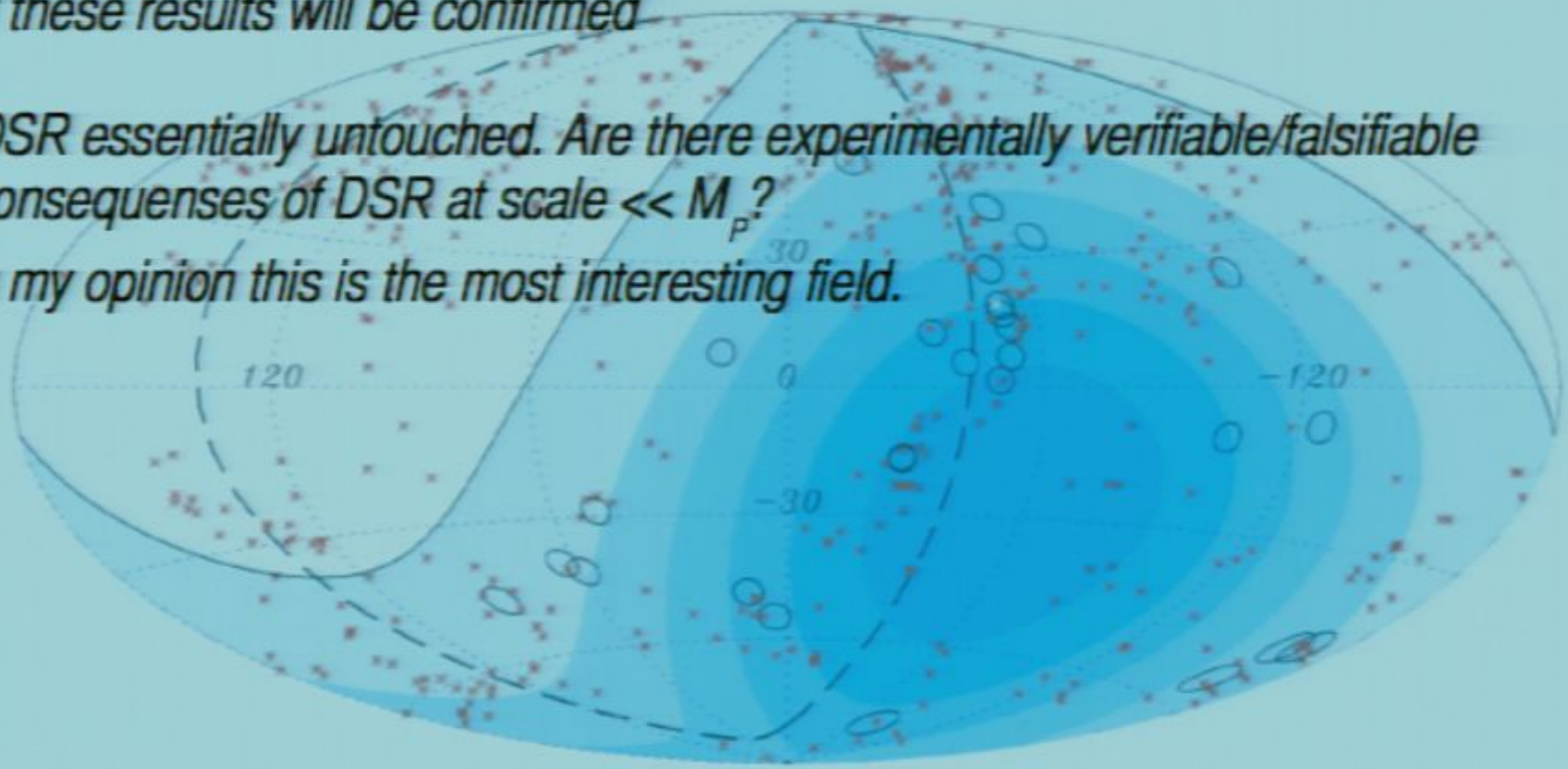

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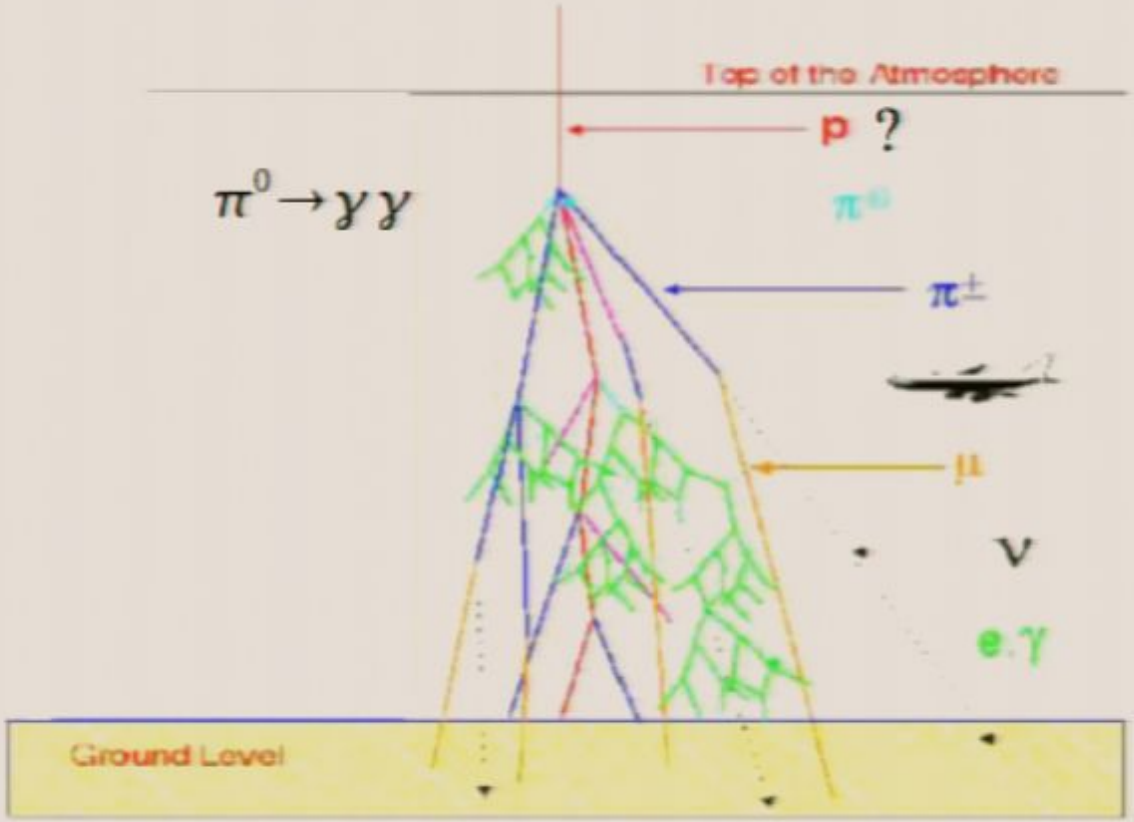

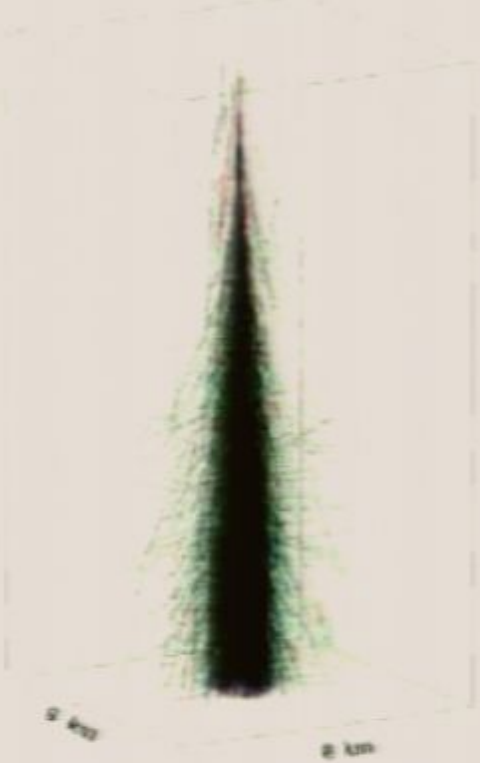

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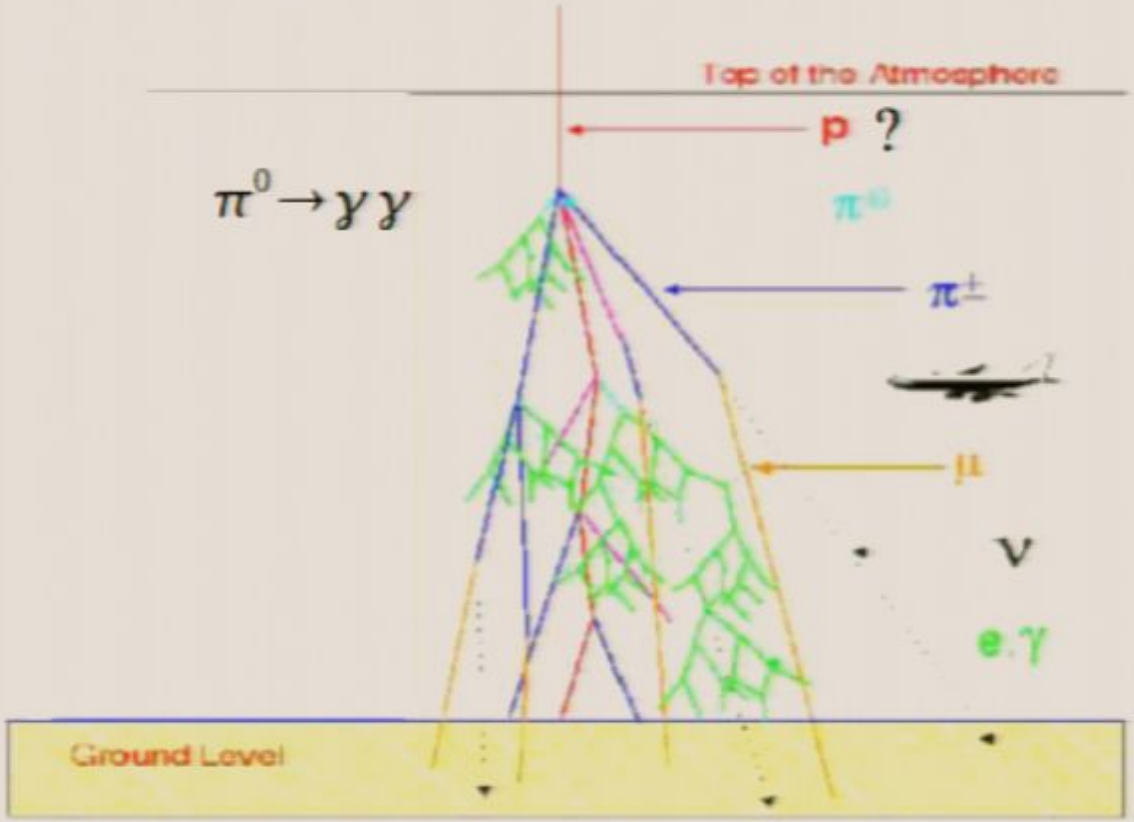

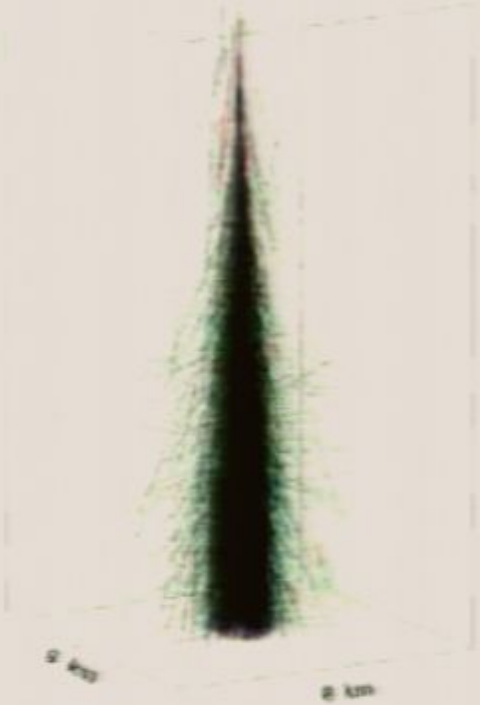

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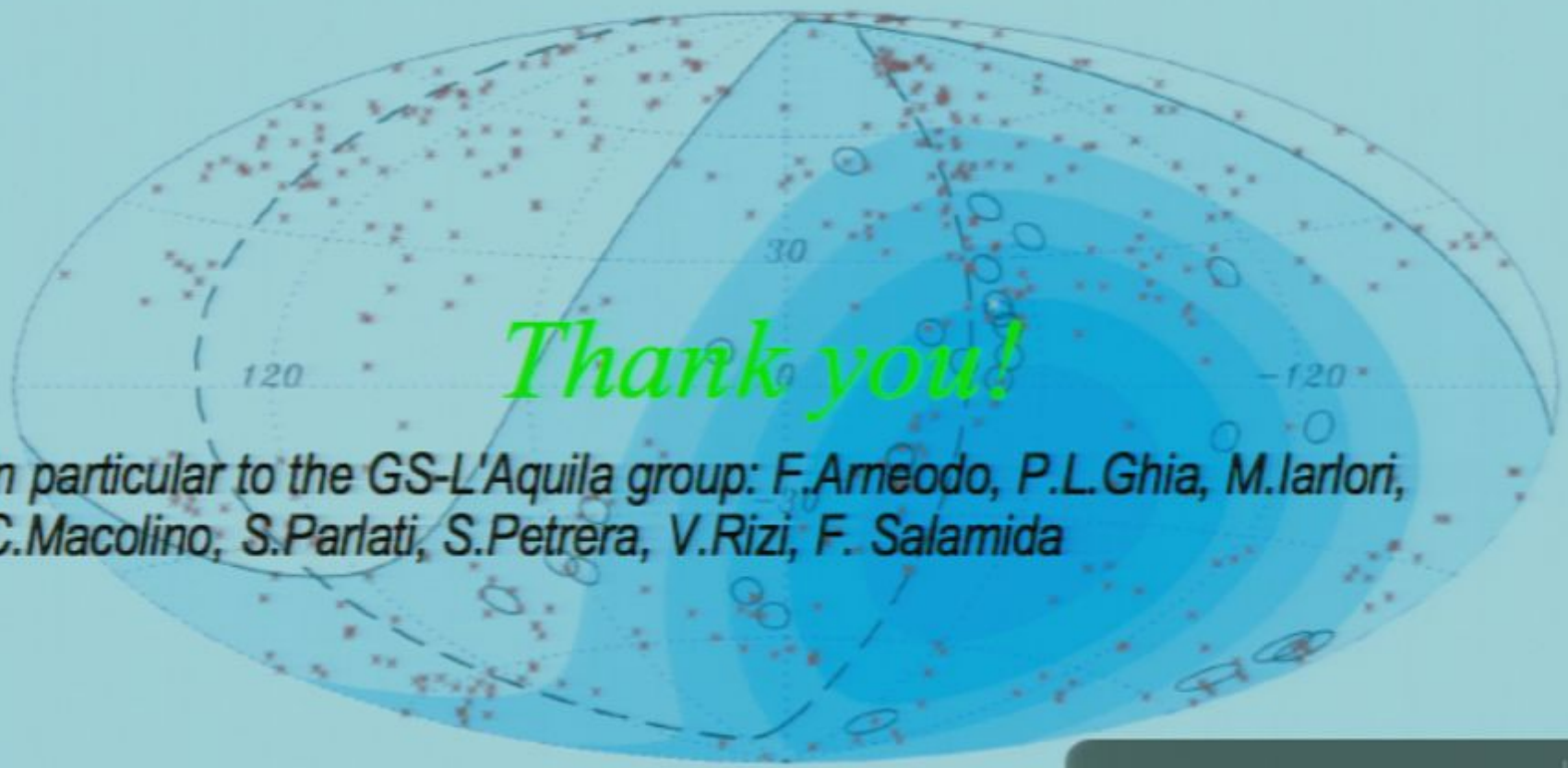
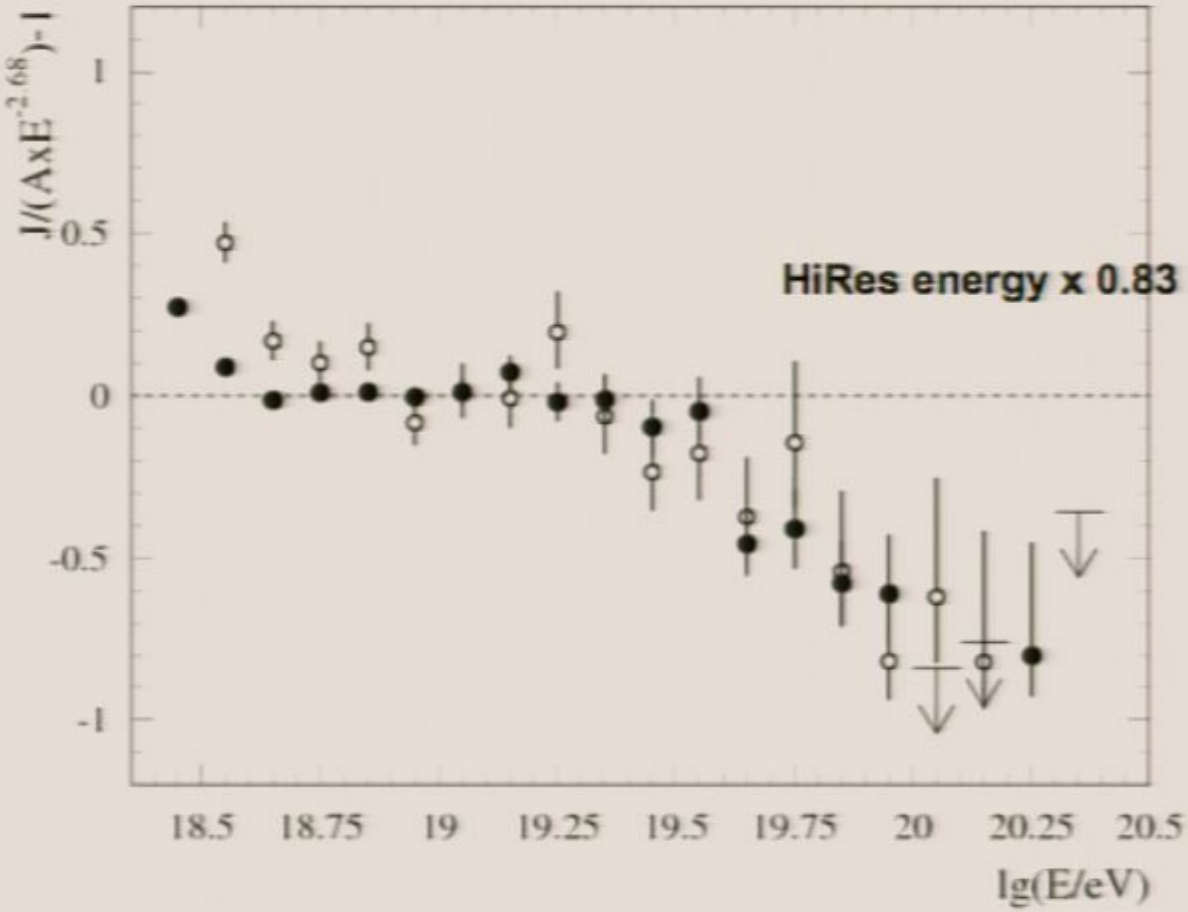
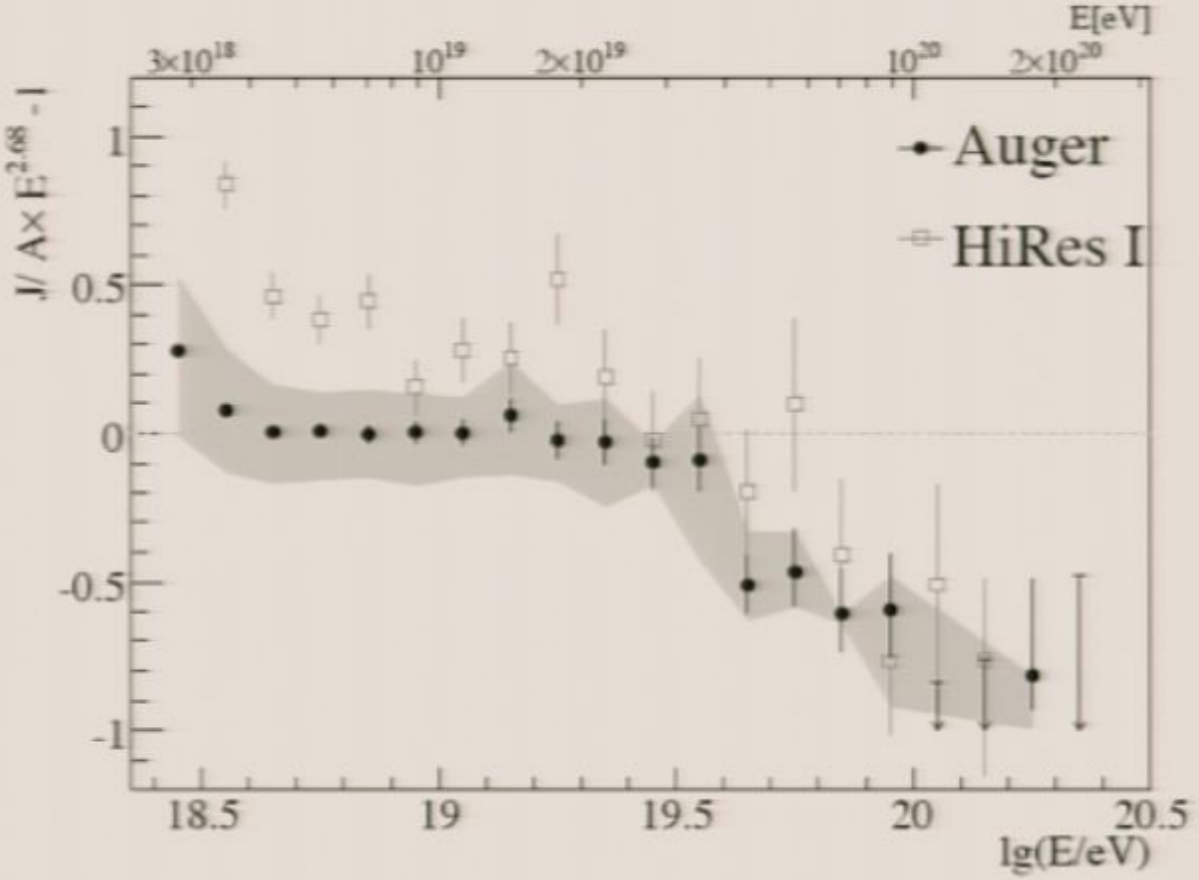


Thank you!

In particular to the GS-L'Aquila group: F.Arneodo, P.L.Ghia, M.Iarlori, C.Macolino, S.Parlati, S.Petrera, V.Rizi, F. Salamida


J/(AxE^-2.68)-1
1
0.5
0
-0.5
-1
HiRes energy x 0.83
18.5
18.75
19
19.25
19.5
19.75
20
20.25
20.5
lg(E/eV)


E[eV]
3×10^18
10^19
2×10^19
10^20
2×10^20
J/ A× E^2.68 - I
1
0.5
0
-0.5
-1
Auger
HiRes I
18.5
19
19.5
20
20.5
lg(E/eV)

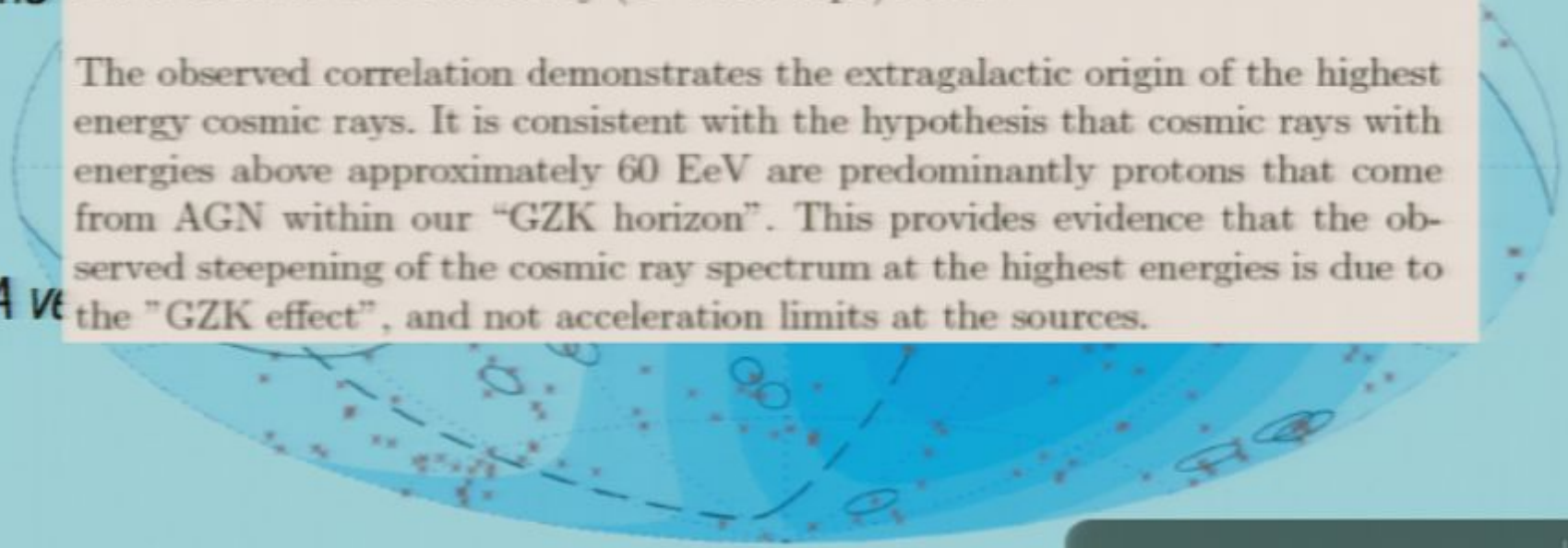
Conclusions?

- We are probably at a turning date for Cosmic Ray Astrophysics
- Sou… …entity still
- The

Anisotropy has been established with more than 99% confidence level in the arrival directions of events with energy above ~ 60 EeV detected by the Pierre Auger Observatory. These correlate over angular scales of less than 6° with the directions towards nearby ($D < 100$ Mpc) AGN.

The observed correlation demonstrates the extragalactic origin of the highest energy cosmic rays. It is consistent with the hypothesis that cosmic rays with energies above approximately 60 EeV are predominantly protons that come from AGN within our "GZK horizon". This provides evidence that the observed steepening of the cosmic ray spectrum at the highest energies is due to the "GZK effect", and not acceleration limits at the sources.

- A ve…



Conclusions?

- We are probably at a turning date for Cosmic Ray Astrophysics
- Sources of Cosmic Rays may have been detected, although their real identity still unclear
- The Greisen-Zatsepin-Kuzmin feature has been probably detected
- However UHECR physics is complex – time is needed
- The parameter space for LIV begins to be severely constrained, but the full consequences of LIV for the experimental detection of CRs are to be taken into account – short cuts are not allowed
- DSR unconstrained, but can be made unambiguously predictive?

- *The GZK drop and the similar drop in gamma sources provide a confirmation of the cosmological origin of the distance red-shift relation on a totally different physical ground. It is in fact an essentially direct measurement of distance (red-shift effects on proton energies should be small..)*

ABSTRACT

The Hubble parameter H_0 is still not very well measured. Although the Hubble Key Project, Chandra and WMAP gave good estimates, the uncertainties remain quite large. In this brief report, we suggest an original and independent method to derive a lower limit on H_0 using the absorption of very high energy gamma-rays by the cosmic infrared background. With conservative a hypothesis, we obtain $H_0 > 74$ km.s^{-1}.Mpc^{-1} at the 68% confidence level, which favors the upper end of the intervals allowed by dedicated experiments.

astro-ph/0804.3699v3

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It has to be taken into account before deriving limits on LIVs

Consequences for Planck scale physics

- If these results will be confirmed
-
- The presence of GZK cut combined with evidence for nearby sources severely constrains LIV: most naïve modified dispersion relations

$$E^2 = m^2 + p^2 \pm \eta_i \frac{E^{2+n}}{M_P^n}$$

- essentially ruled out up to n=2, if same for all particles

- There are subtelties also in this case!! (AFG, G.A-C, S.L et al, in preparation)

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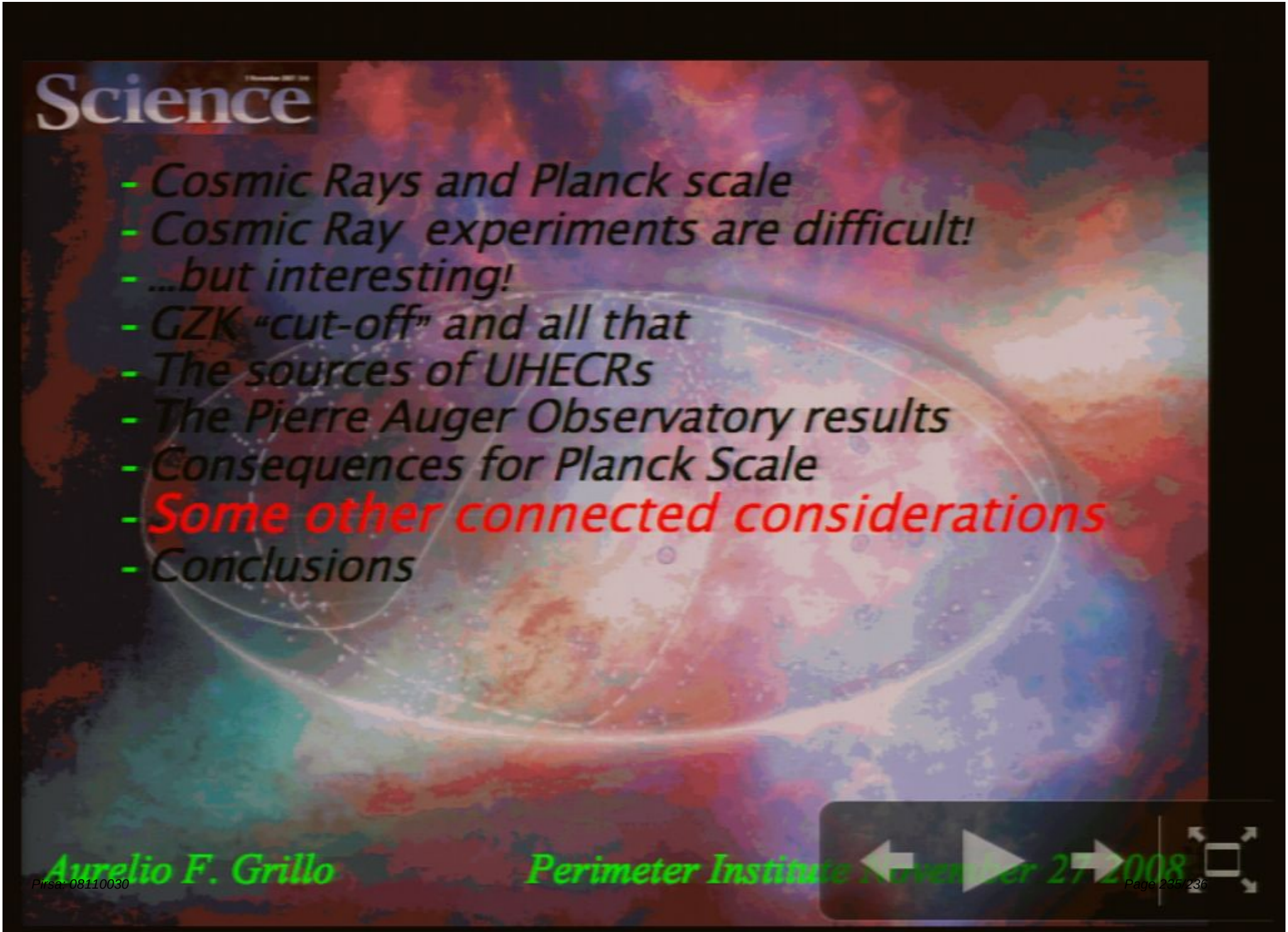
Science
- Cosmic Rays and Planck scale
- Cosmic Ray experiments are difficult!
- ...but interesting!
- GZK "cut-off" and all that
- The sources of UHECRs
- The Pierre Auger Observatory results
- Consequences for Planck Scale
- Some other connected considerations
- Conclusions
Aurelio F. Grillo
Perimeter Institute

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