The Latest Results from the Pierre Auger Observatory

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LEPP JOURNAL CLUB SEMINAR

April 23, 2010 - Cornell University

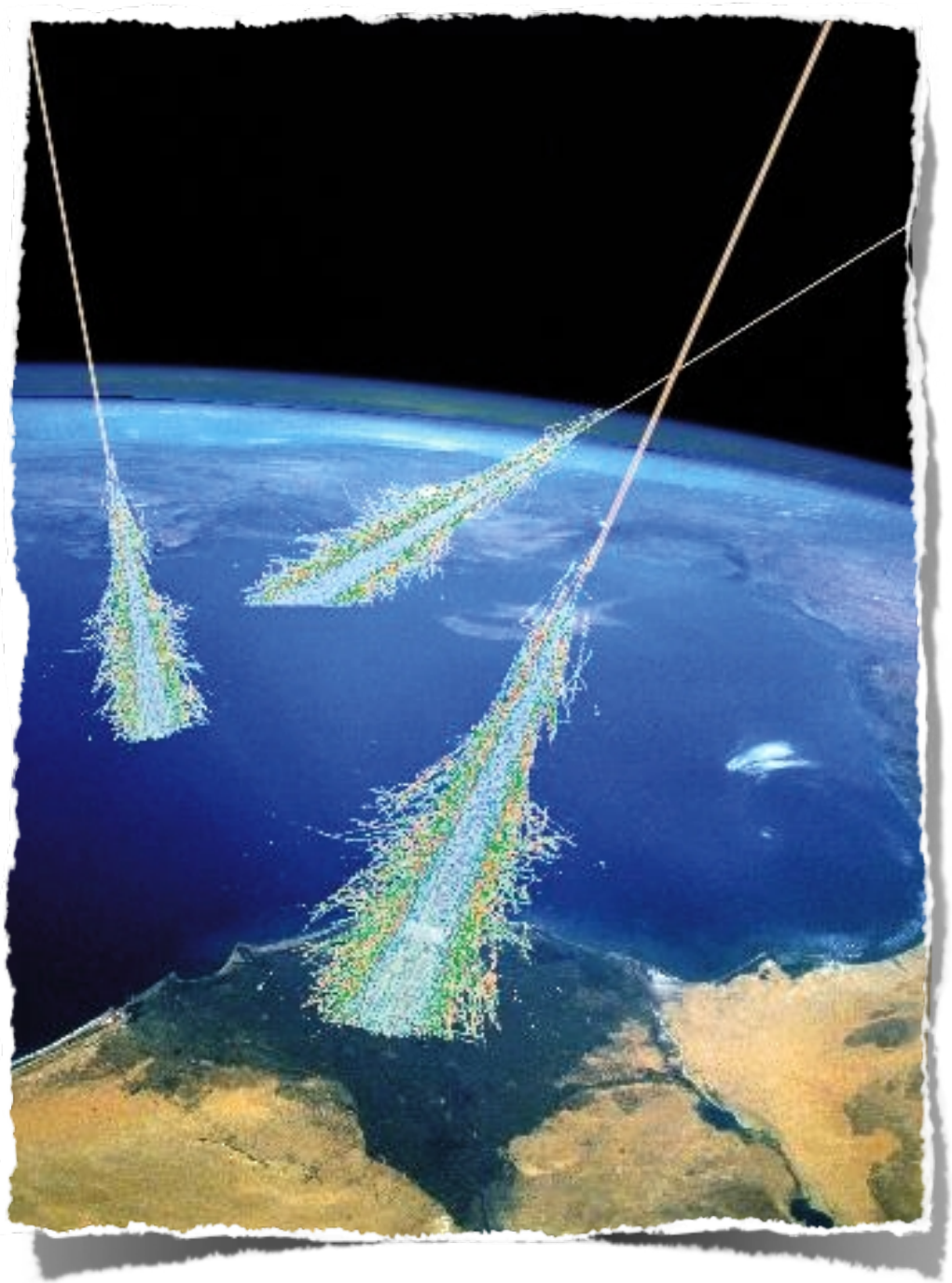
Cosmic Rays - Outline

- Motivation
- A detector of UHE particles
- Science Results
- Summary & Conclusions
- Outlook

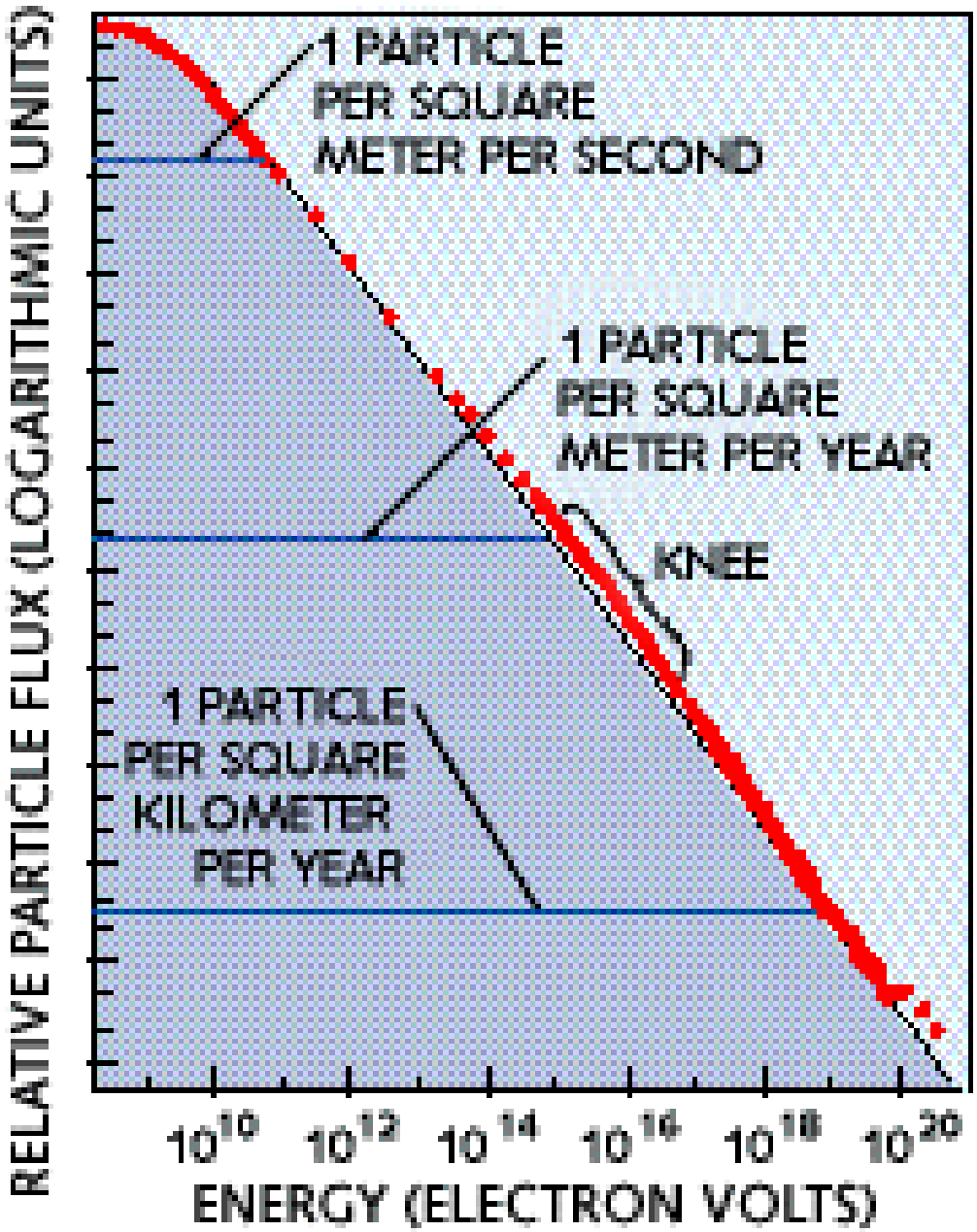
Introduction
&
Motivation

Cosmic Rays

All the time you are being hit by a beam of high energy particles from above!



Ultra-High Energies



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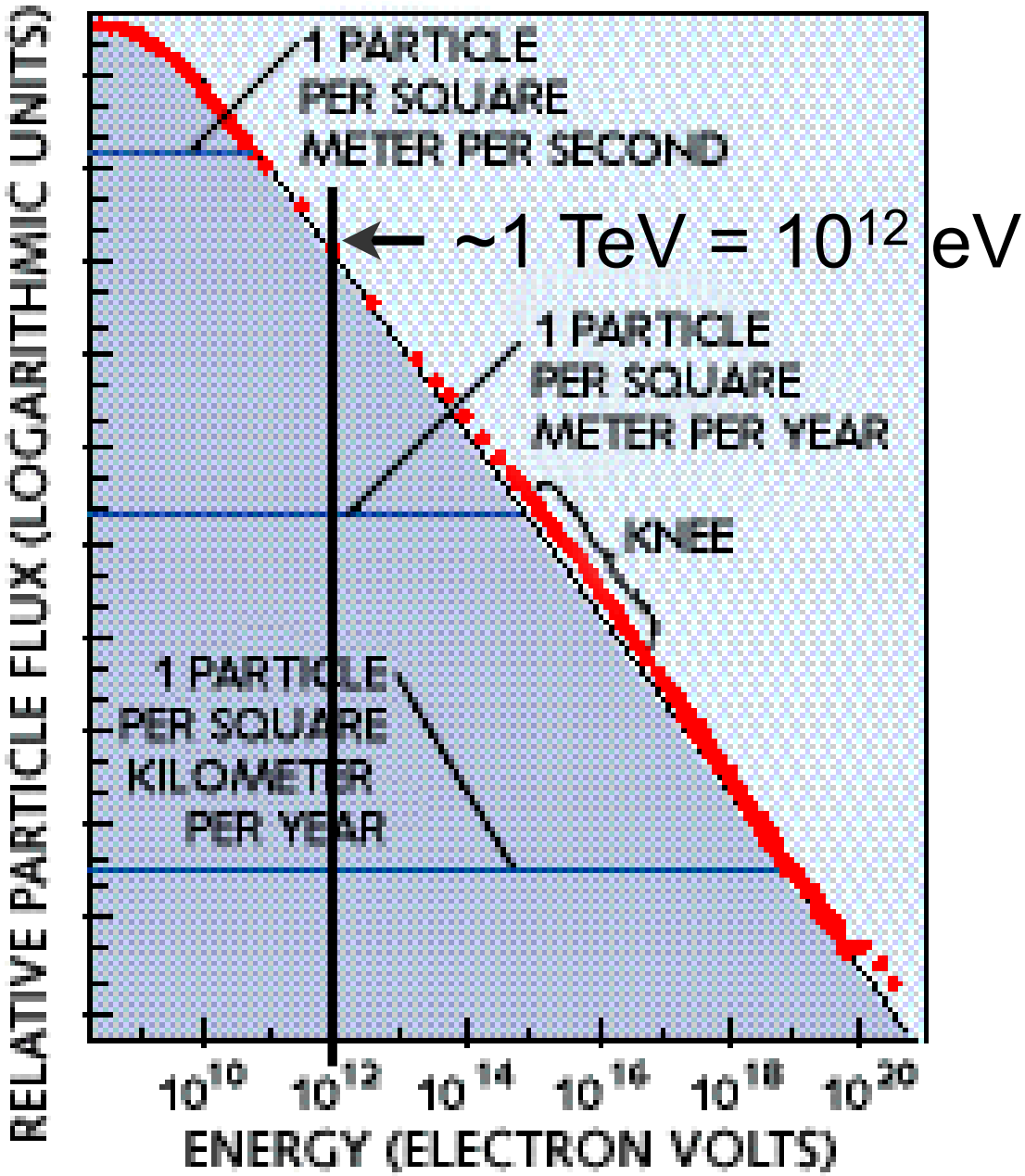

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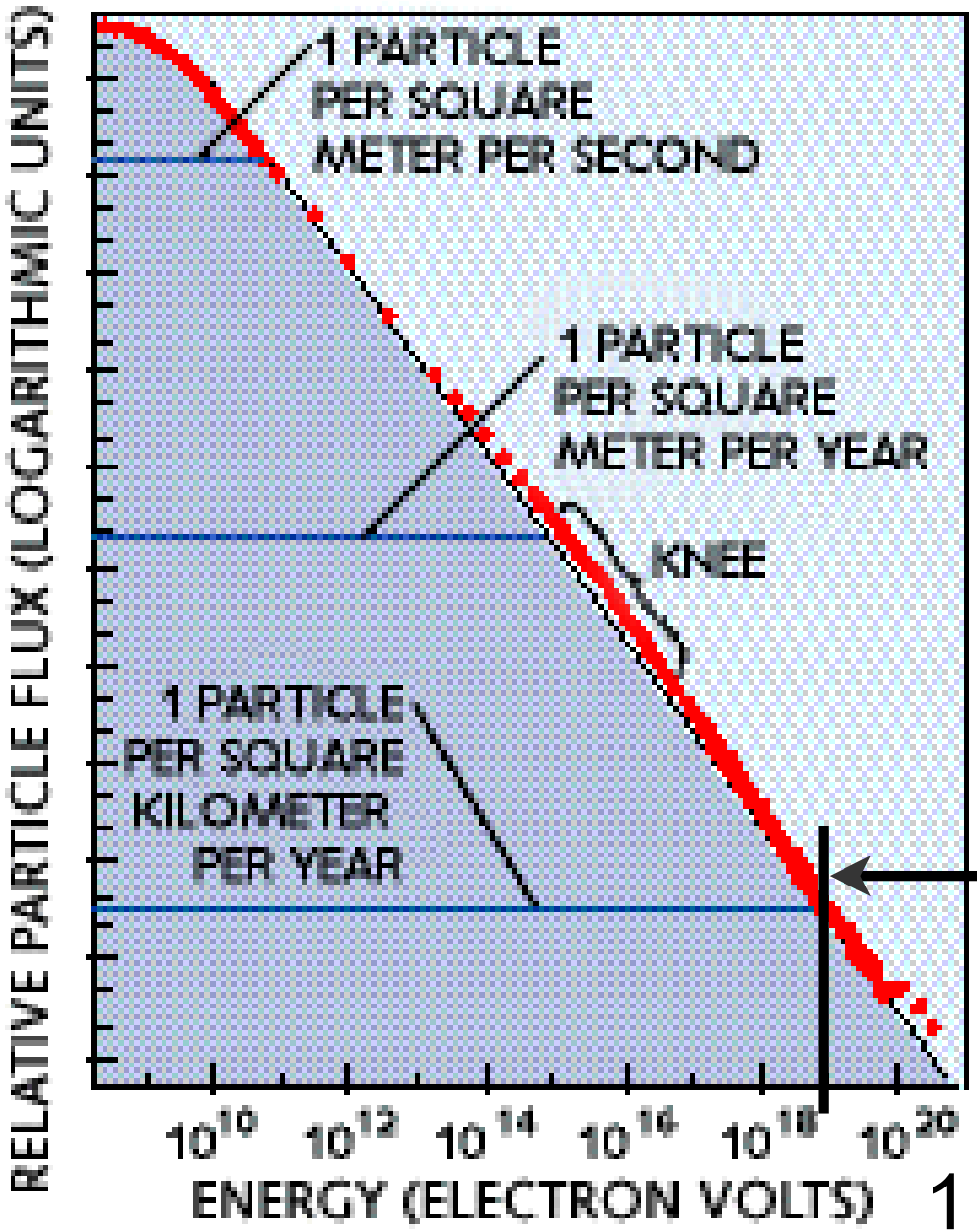


UHECRs

10^{19} eV

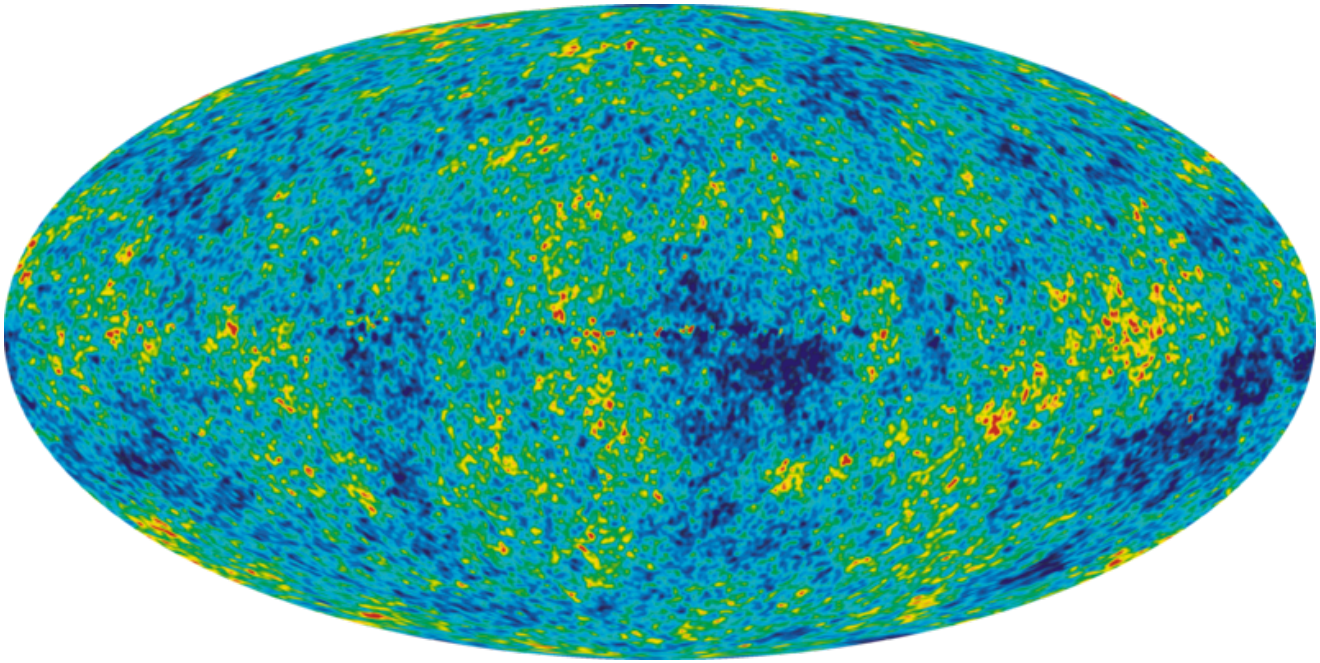
1 EeV $\stackrel{\text{def}}{=}$ 10^{18} eV

Scientific Motivation

They should not be there!

$$\gamma + p \rightarrow \Delta^+ \rightarrow p + \pi^0$$

$$\gamma + p \rightarrow \Delta^+ \rightarrow n + \pi^+$$



Cosmic Microwave Background

Scientific Motivation

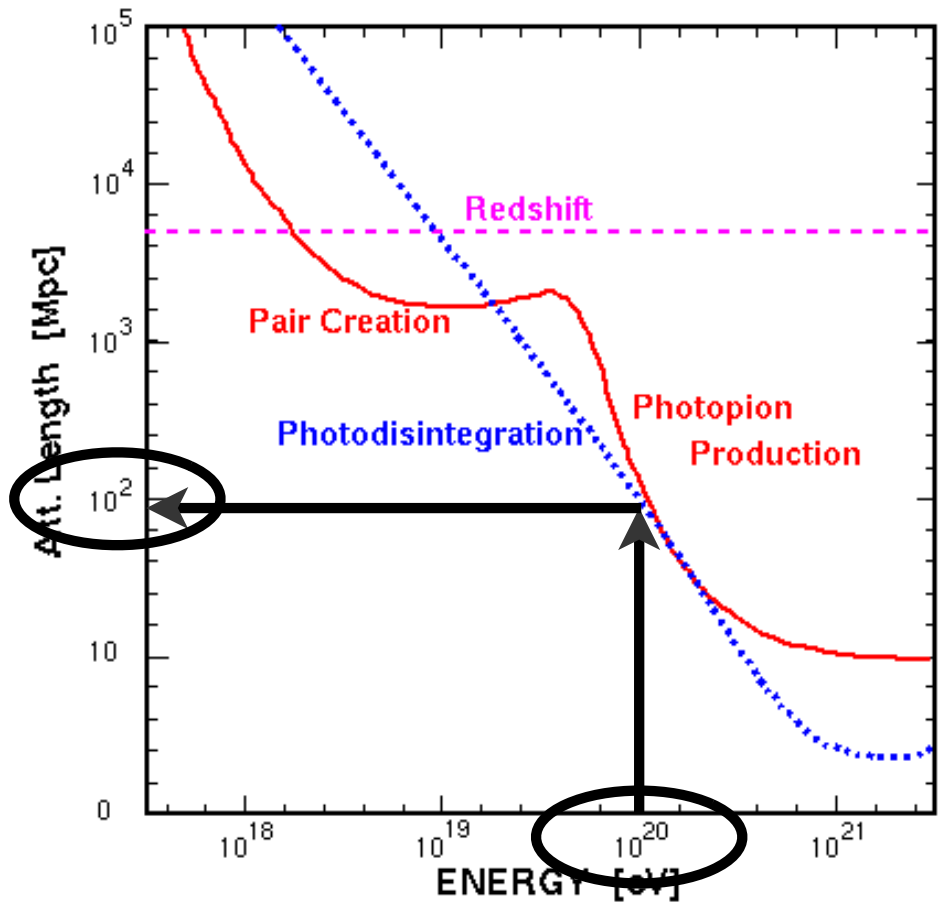
They should not be there!

$$\gamma + p \rightarrow \Delta^+ \rightarrow p + \pi^0$$

$$\gamma + p \rightarrow \Delta^+ \rightarrow n + \pi^+$$

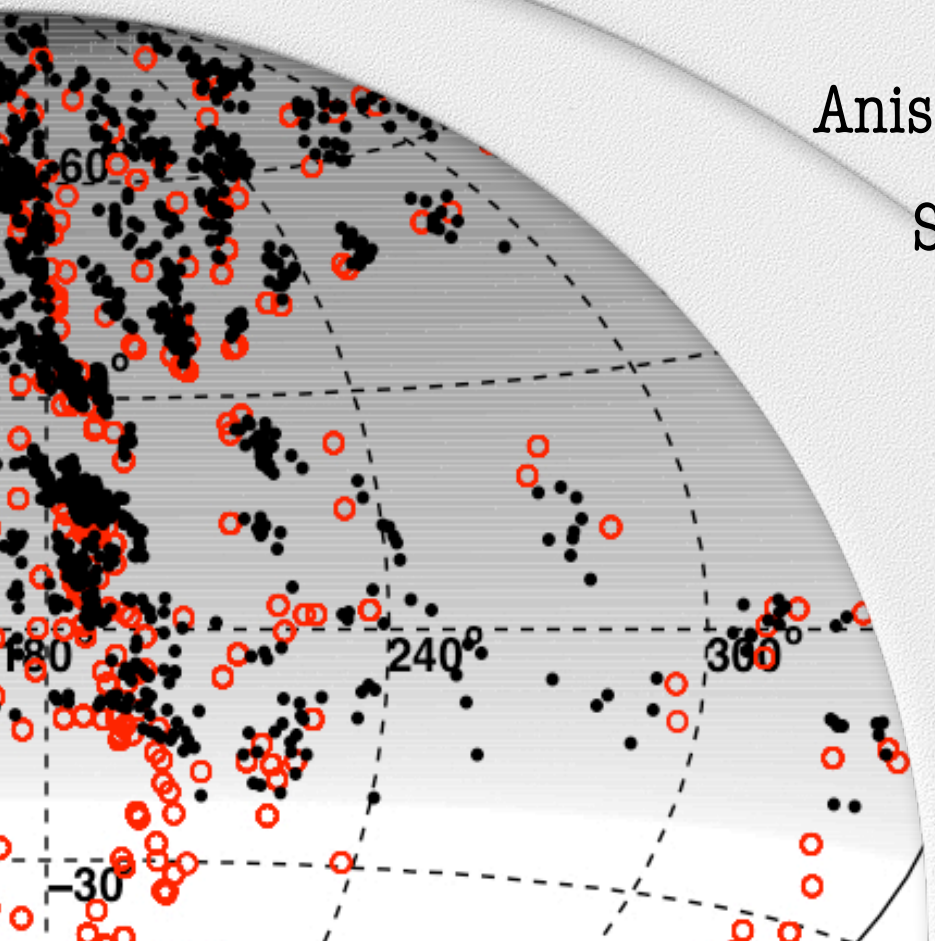
1 pc = 3.26 ly

326 Mly ≡



To GZK or not to GZK...

Motivation



Sources of UHECR

Anisotropy ⇒ Correlations ⇒ Source classes

Study individual sources with spectra and composition over the whole sky

Motivation

Acceleration Mechanism

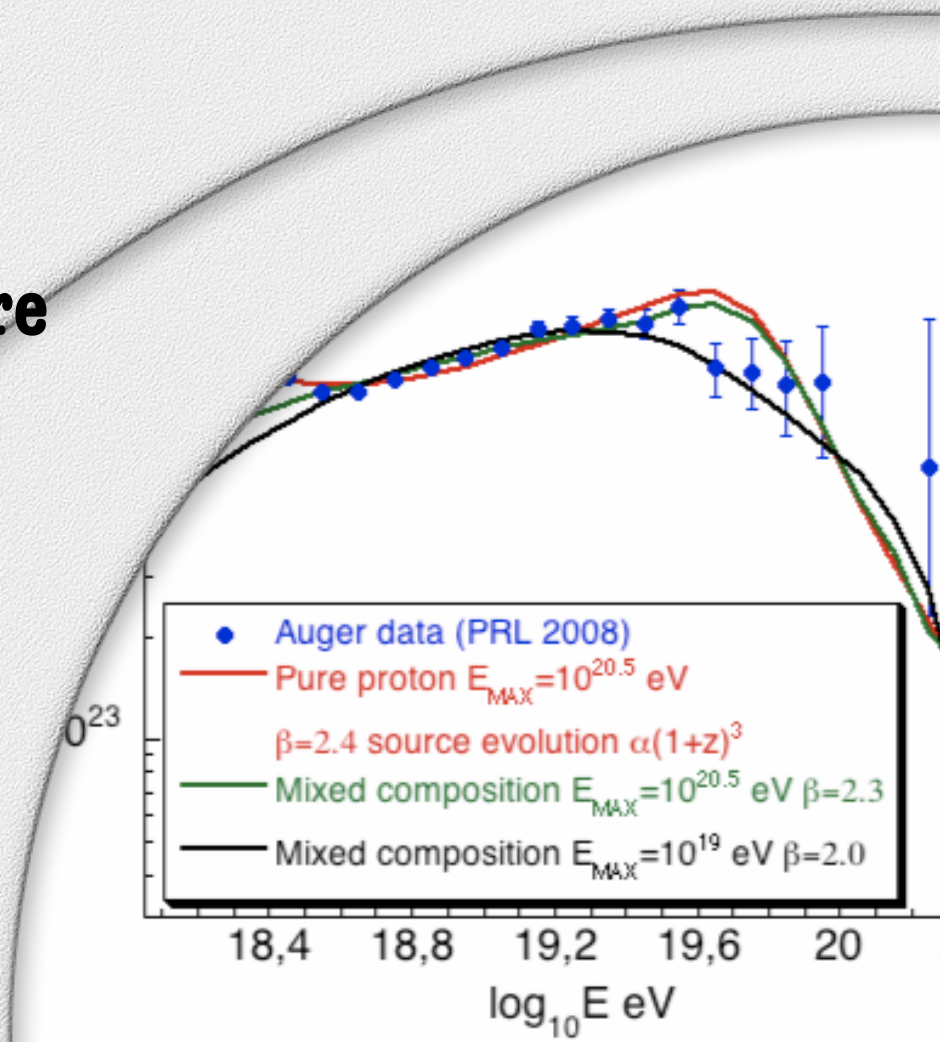
Composition evolution

Proton beam? E_{max}?

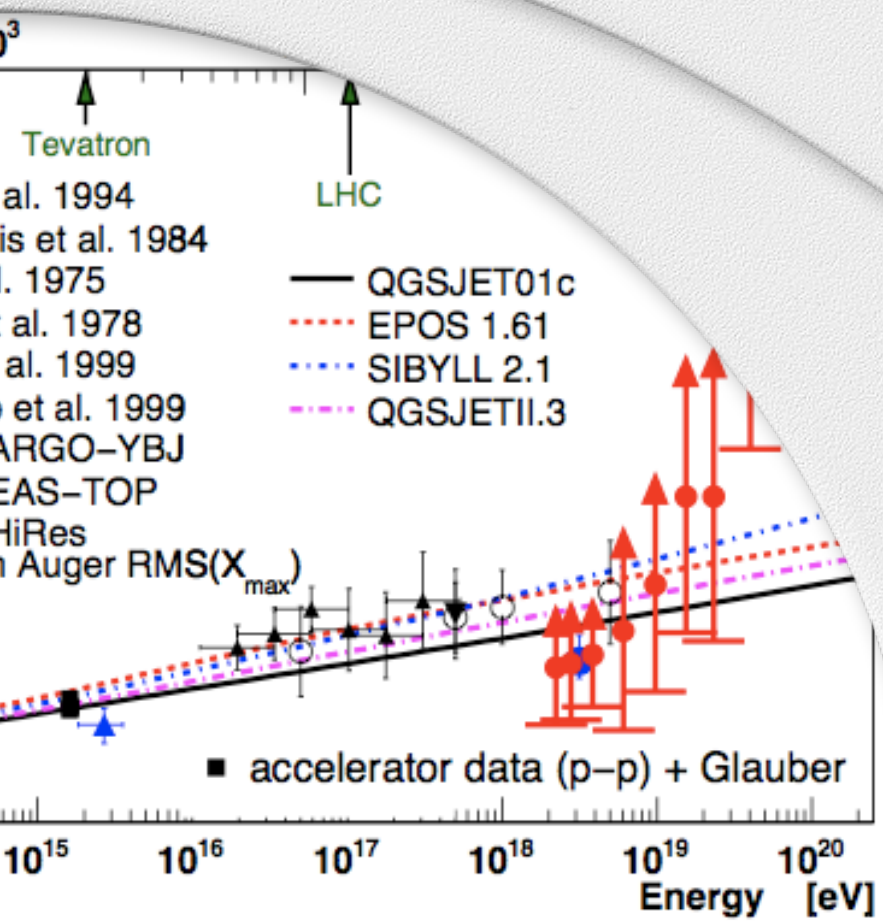
Propagation and Cosmic Structure

Map Galactic magnetic fields

Matter within 100 Mpc



Motivation



Particle Physics @ 350 TeV

Mass and X_{max}

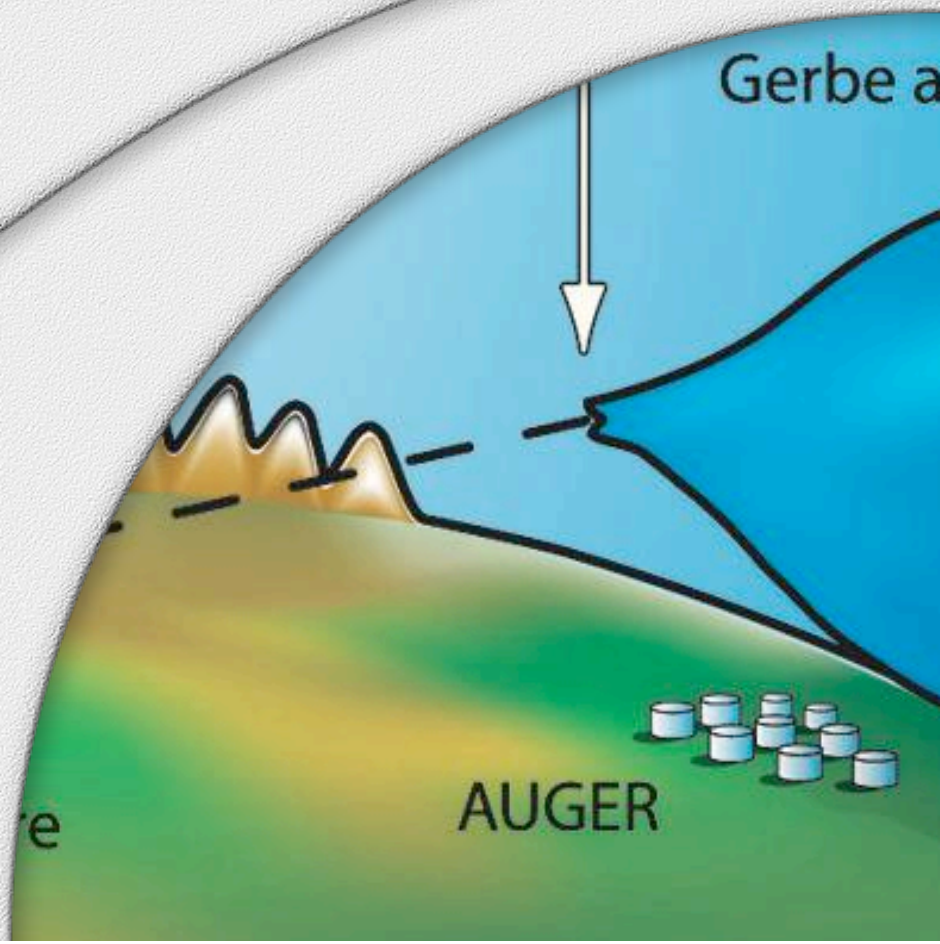
Hadronic interactions, cross sections

New Particle Physics?

Motivation

Multi-Messenger Astrophysics

Combine data from photons, neutrinos, and charged particles



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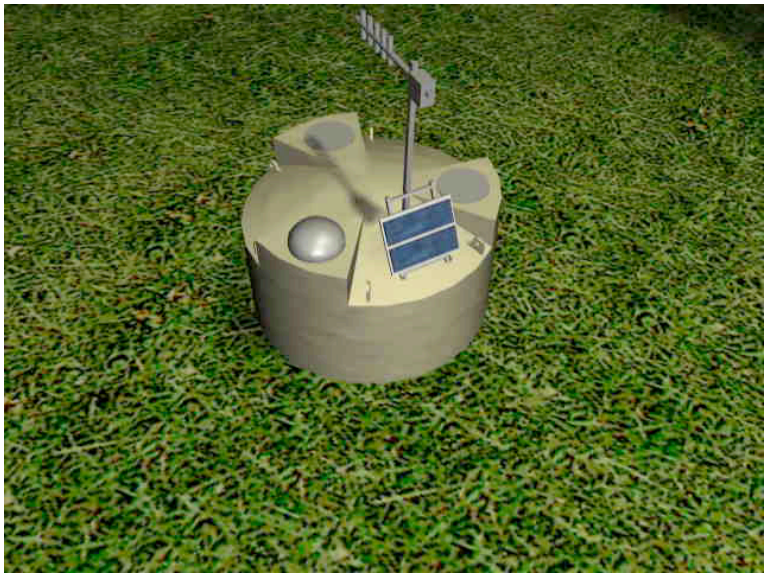
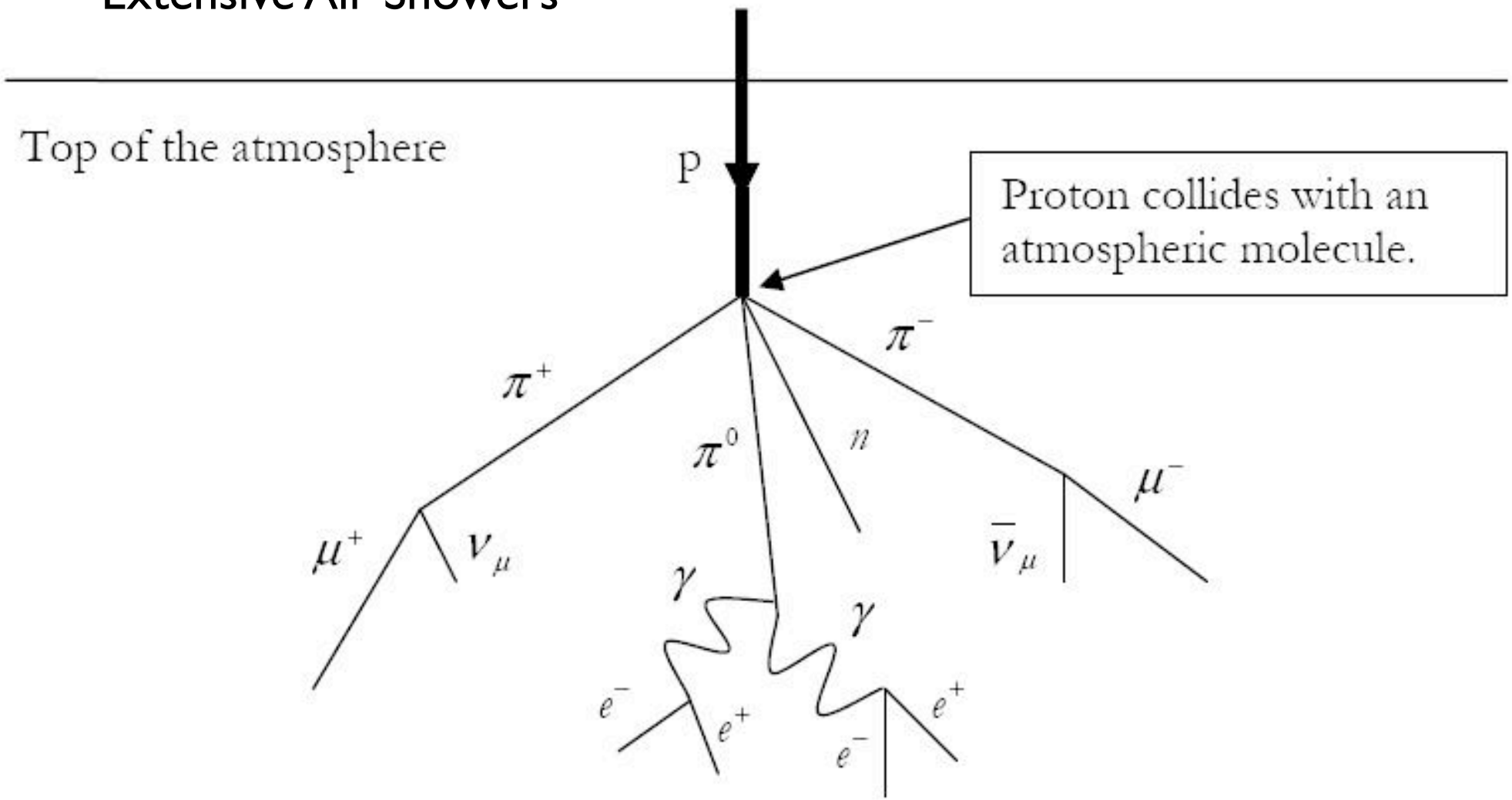


The Pierre Auger Observatory

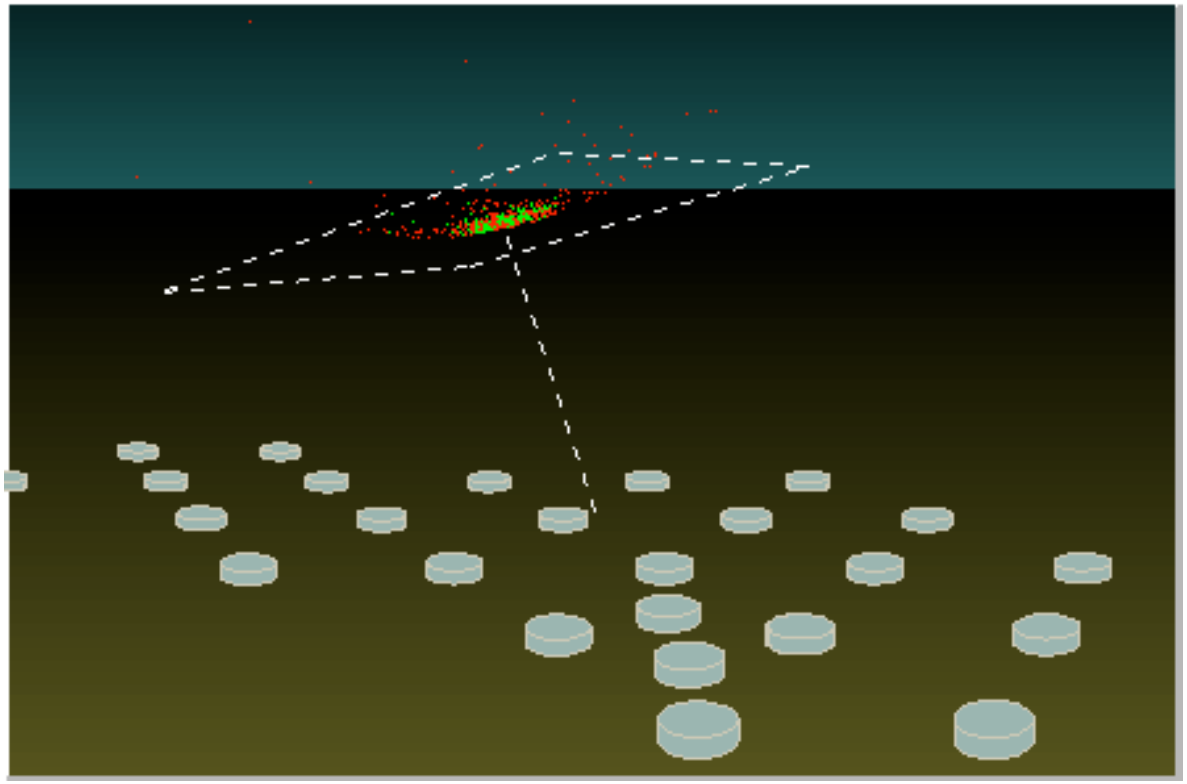
Detection Techniques

Extensive Air Showers



Detection Techniques

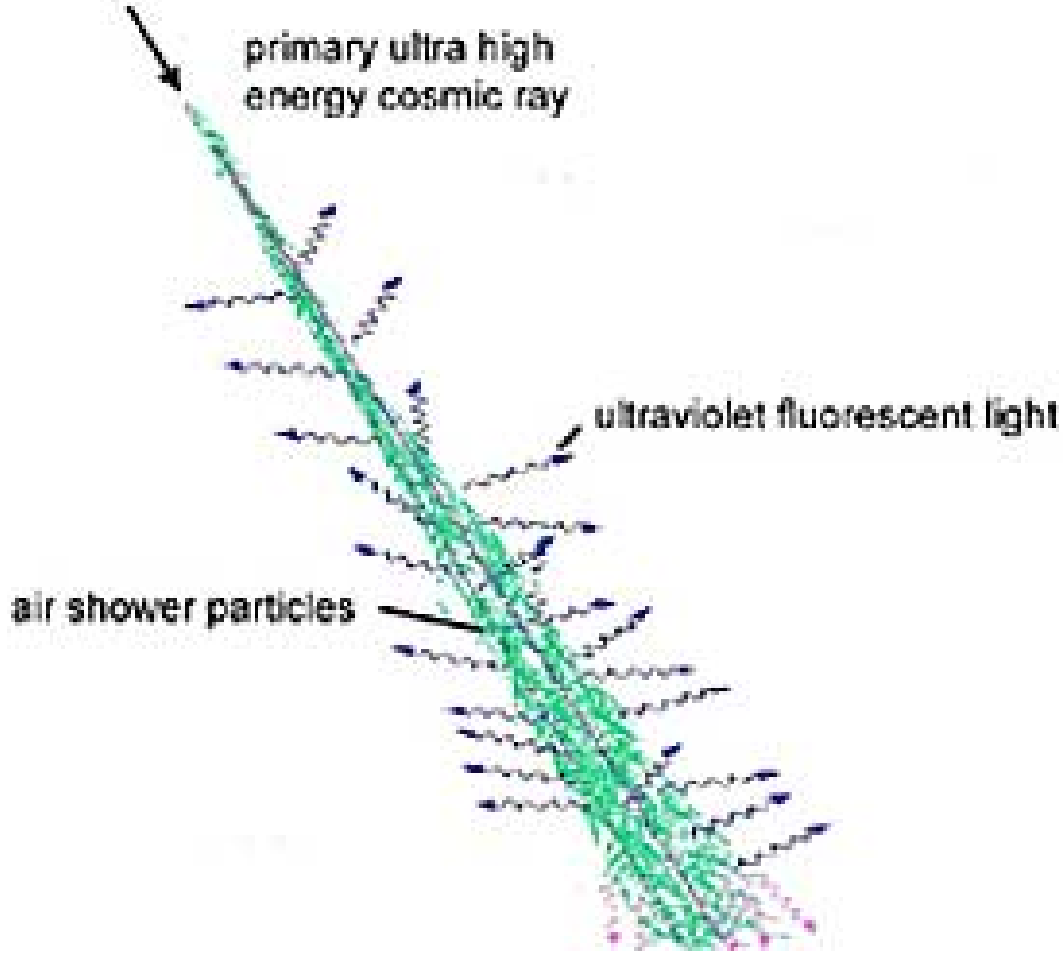
Using Extensive Air Showers

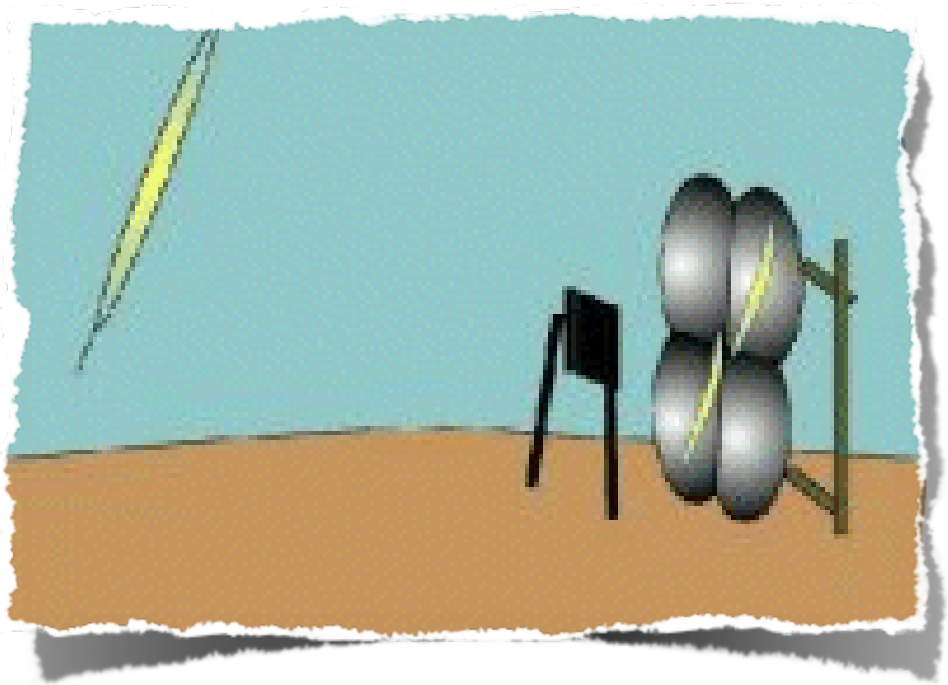


Array of Particle Detectors
on the ground

Detection Techniques

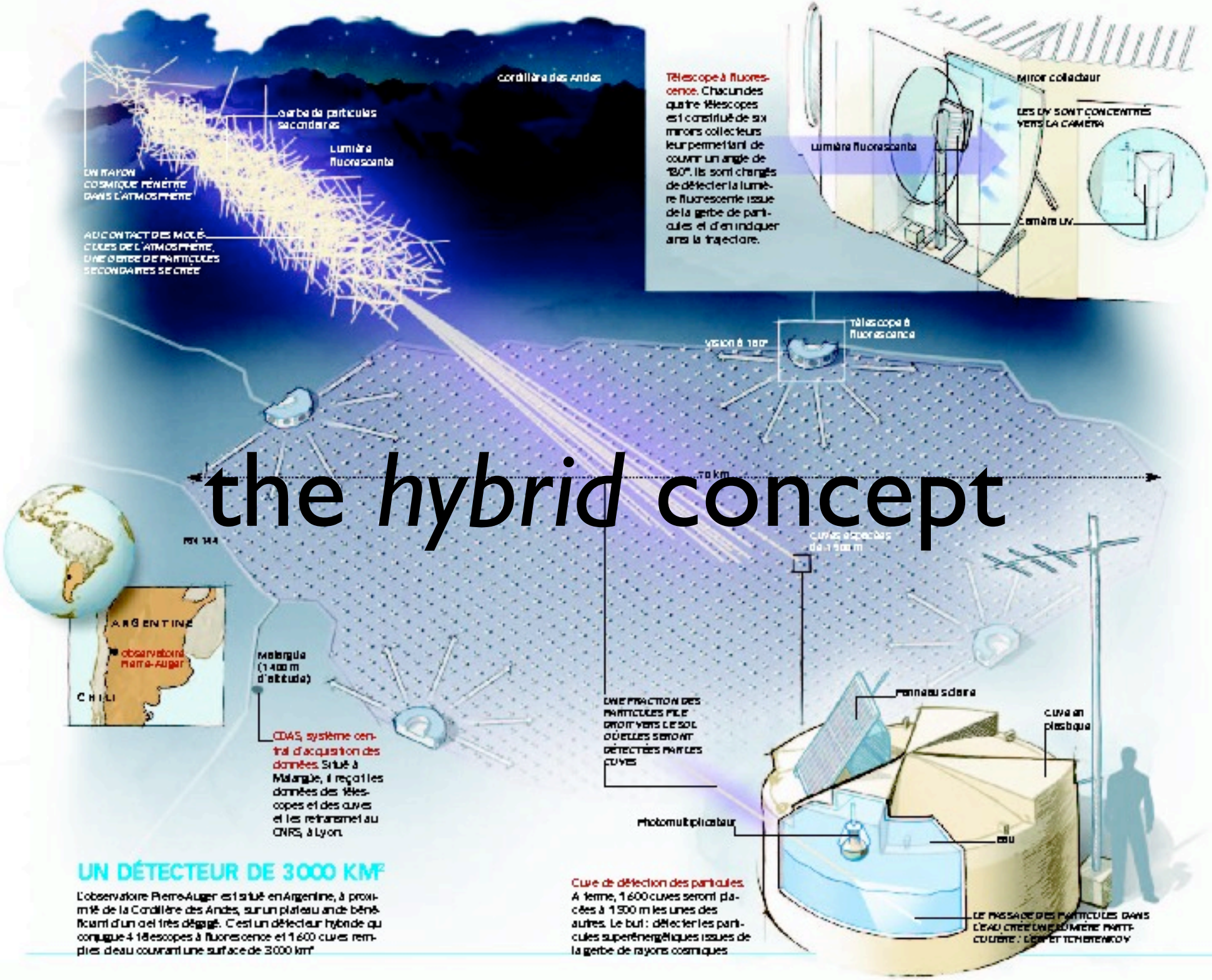
Using Extensive Air Showers





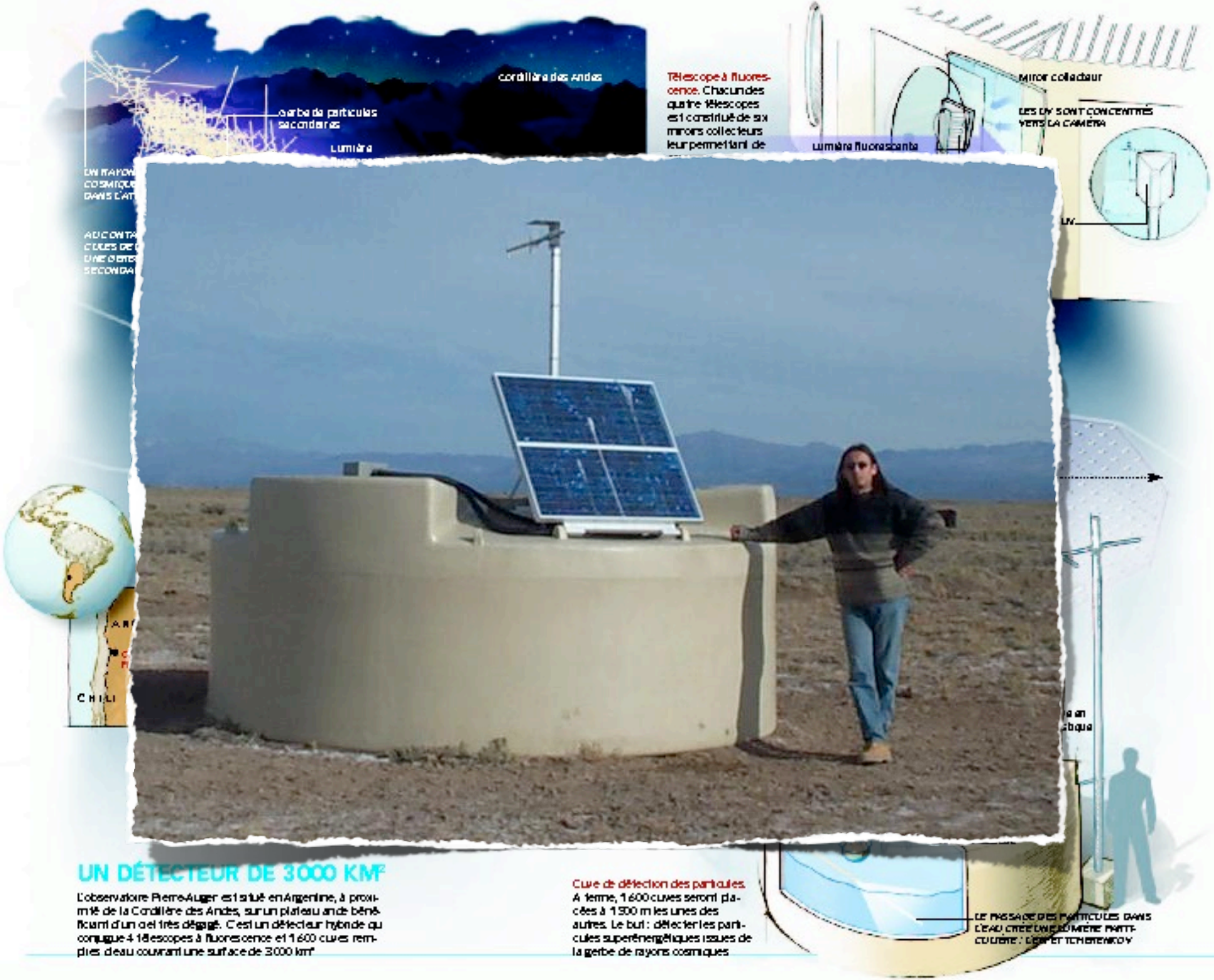
Fluorescence Telescopes

the *hybrid* concept



UN DÉTECTEUR DE 3000 KM²

L'observatoire Pierre-Auger est situé en Argentine, à proximité de la Cordillère des Andes, sur un plateau ainsi bénéficiant d'un ciel très dégagé. C'est un détecteur hybride qui conjugue 4 télescopes à fluorescence et 1 600 cuves remplies d'eau couvrant une surface de 3 000 km².



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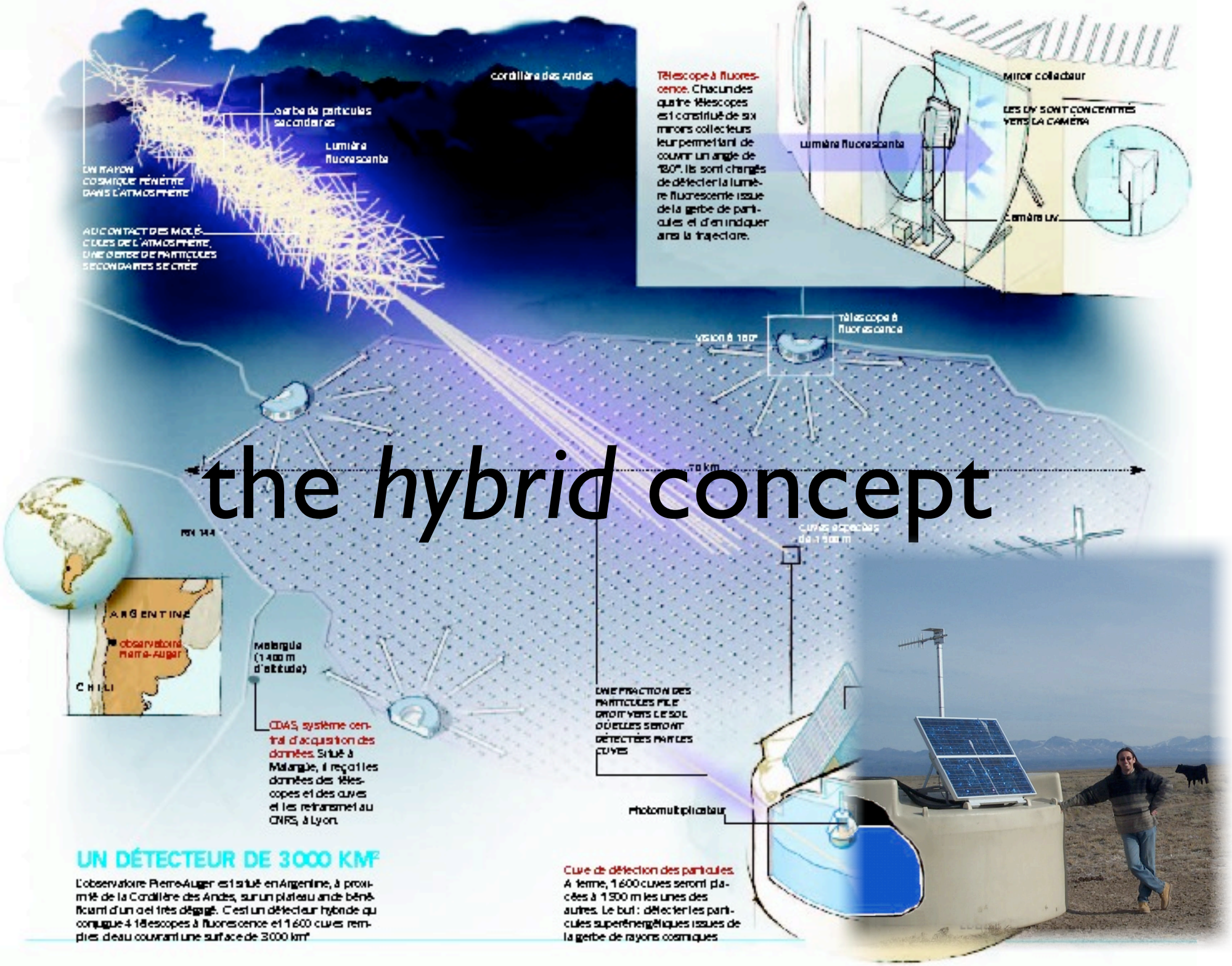
Cuve de détection des particules. A terme, 1 600 cuves seront placées à 1 500 m les unes des autres. Le but : détecter les particules superénergétiques issues de la gerbe de rayons cosmiques.

LE PASSAGE DES PARTICULES DANS L'EAU CRÉE UNE LUMIÈRE PARTICULIÈRE : L'EFFET TCHERENKOV

the *hybrid* concept



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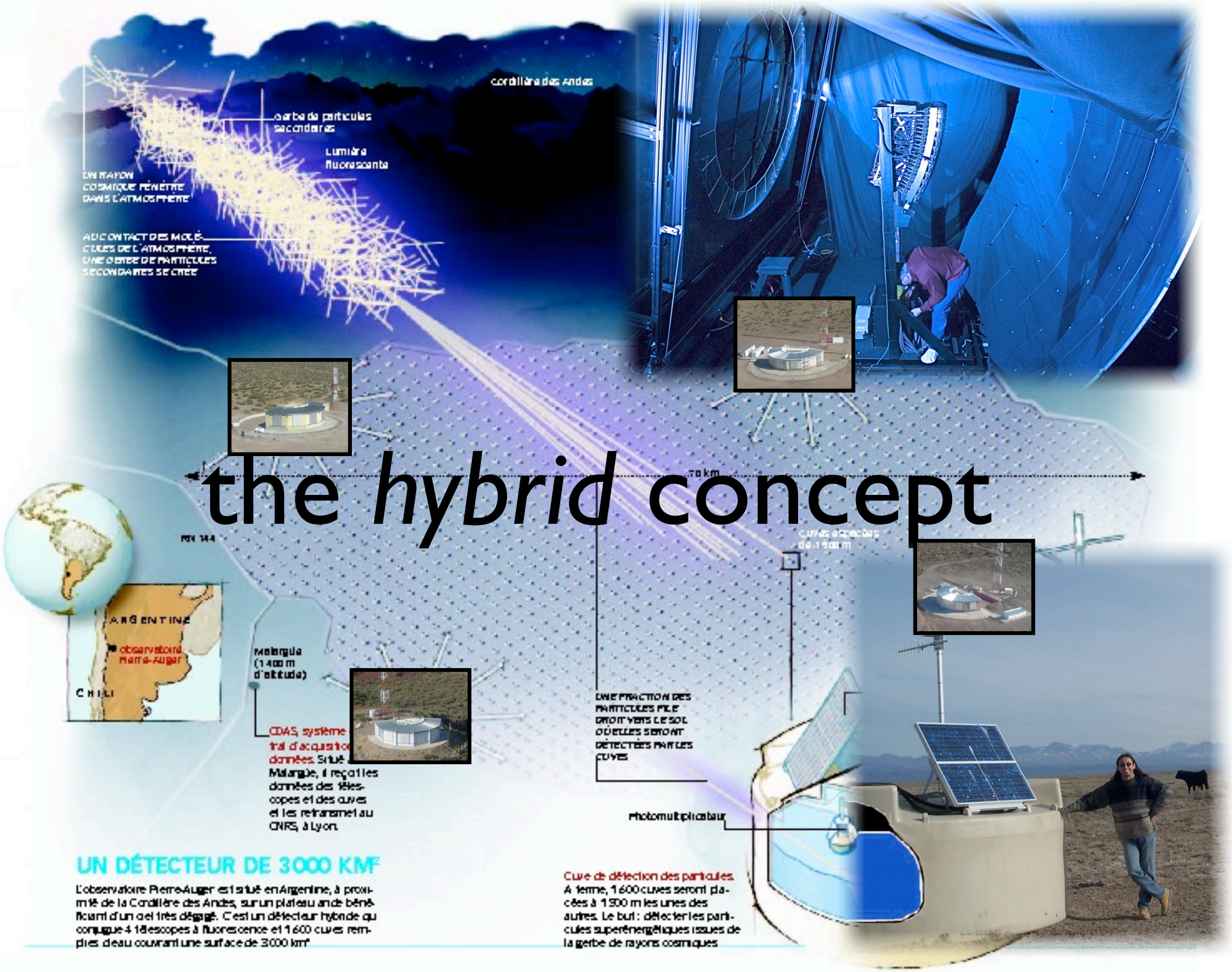

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the

aperture box

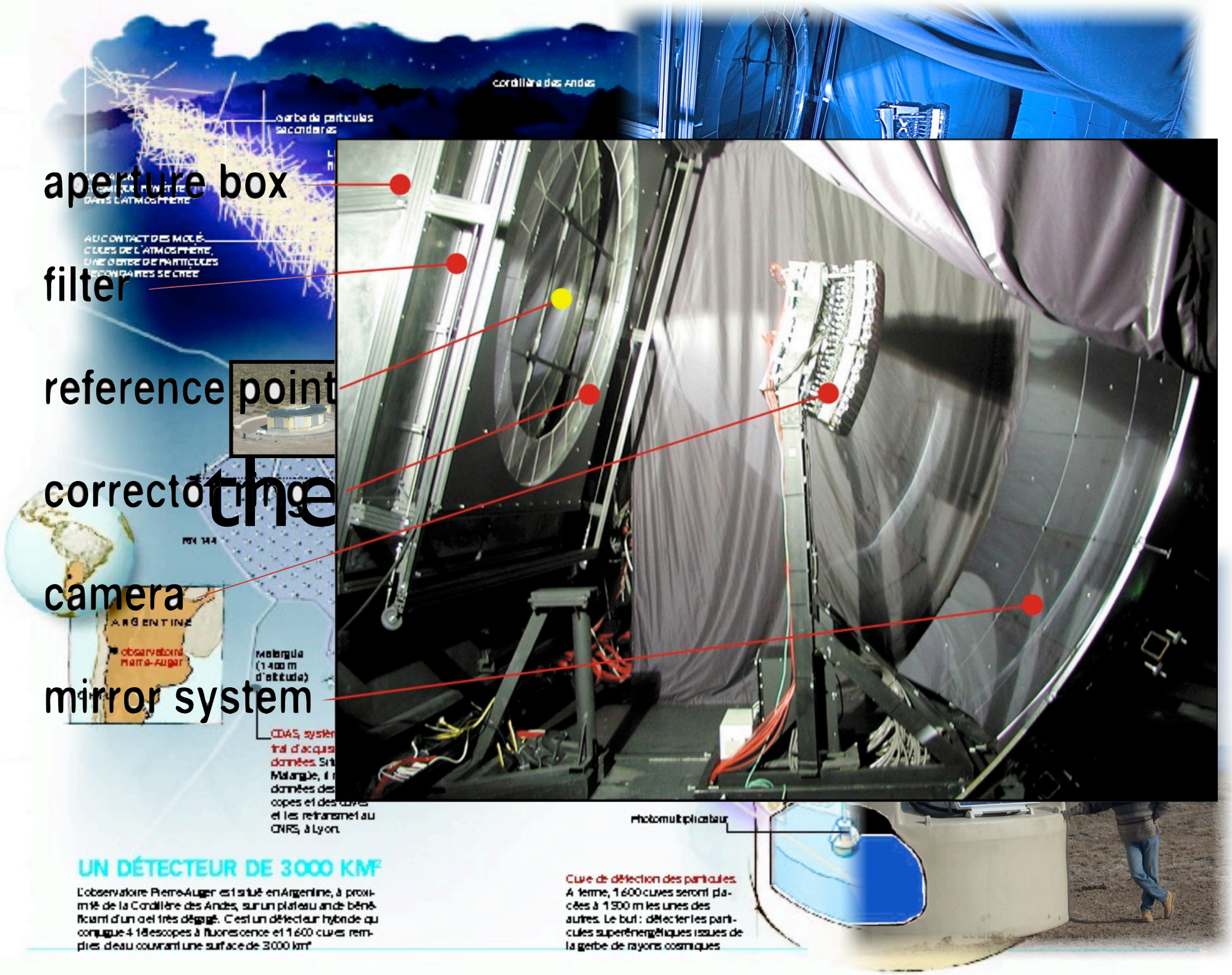
filter

reference point

corrector ring

camera

mirror system



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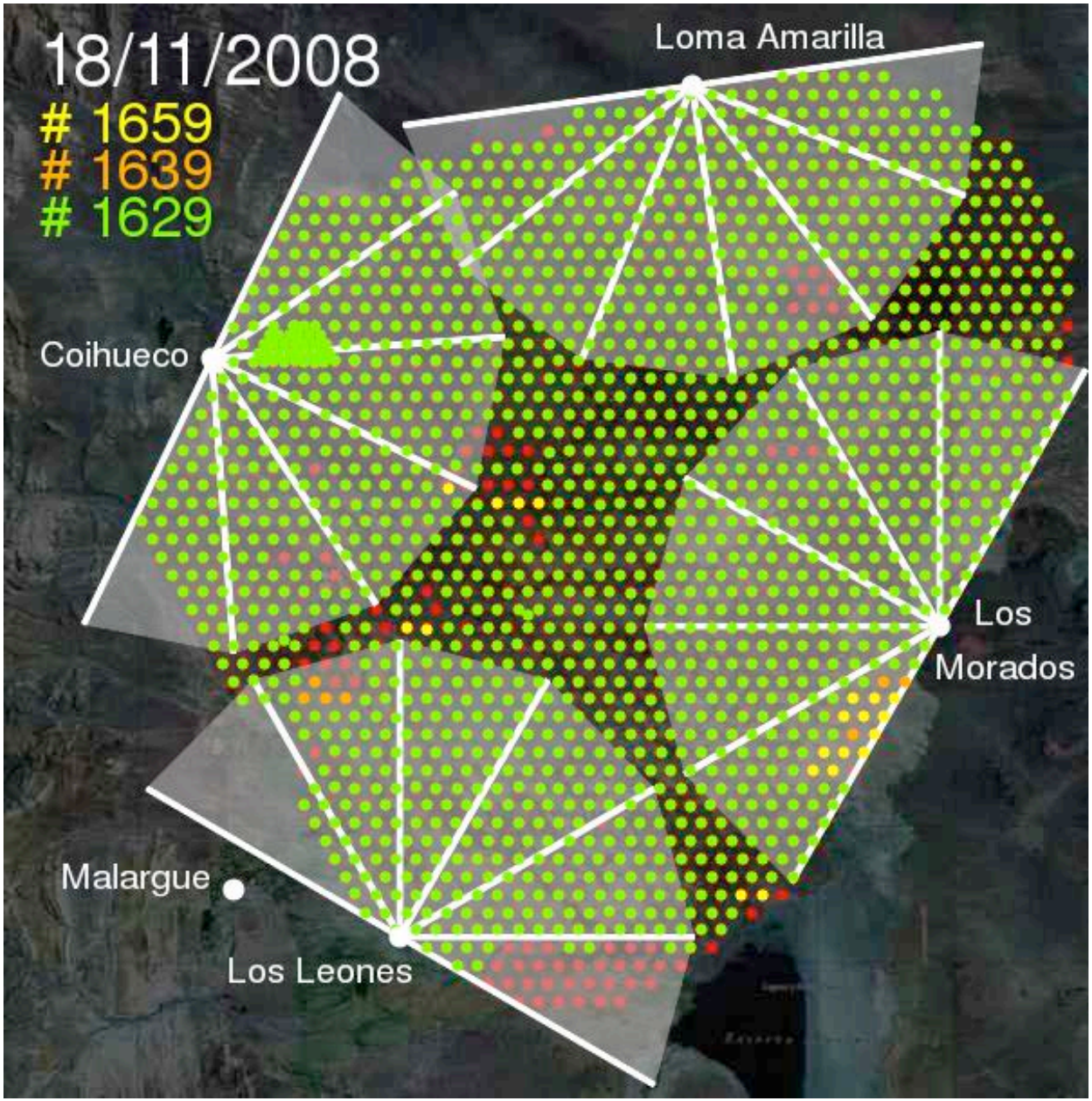
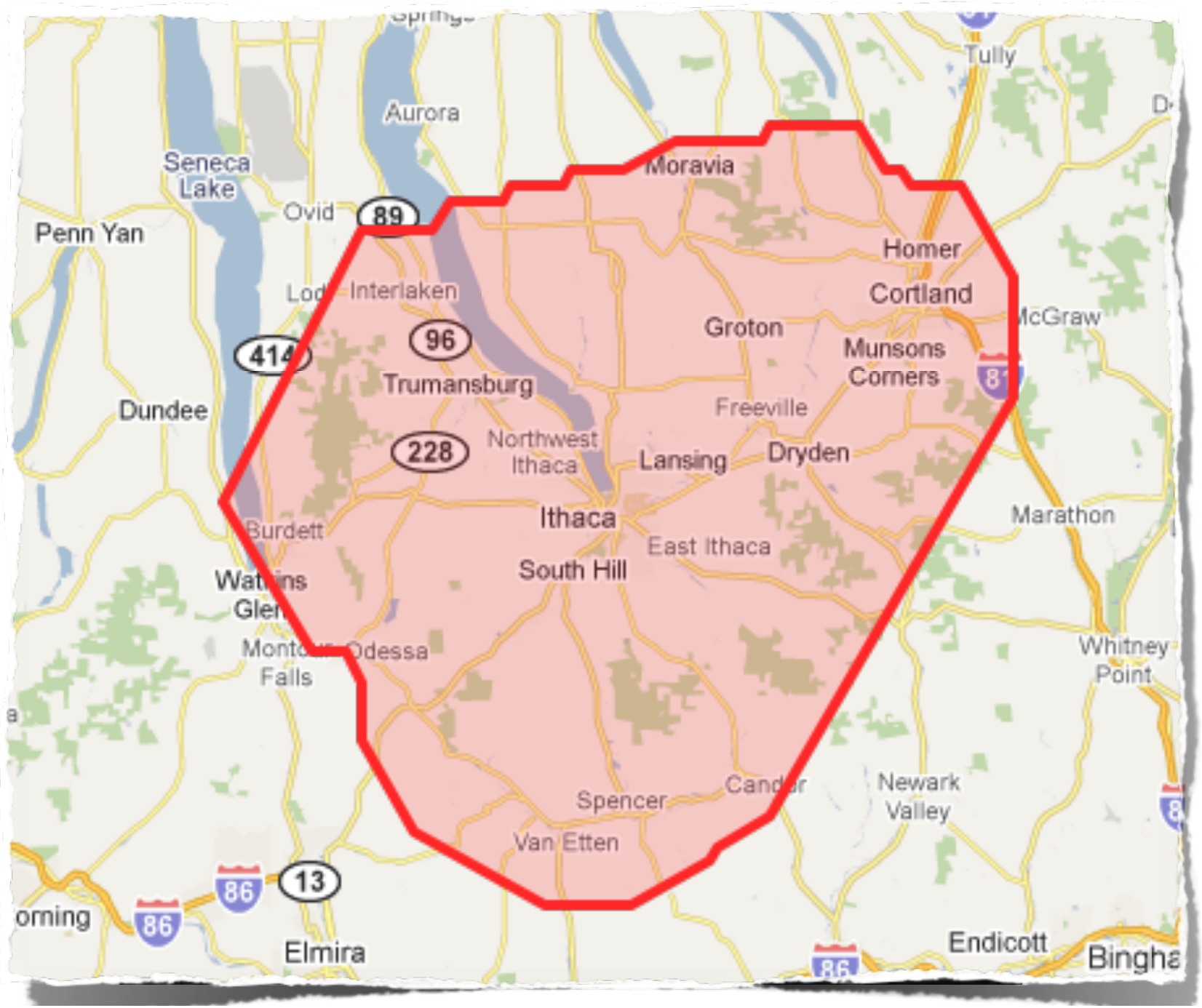
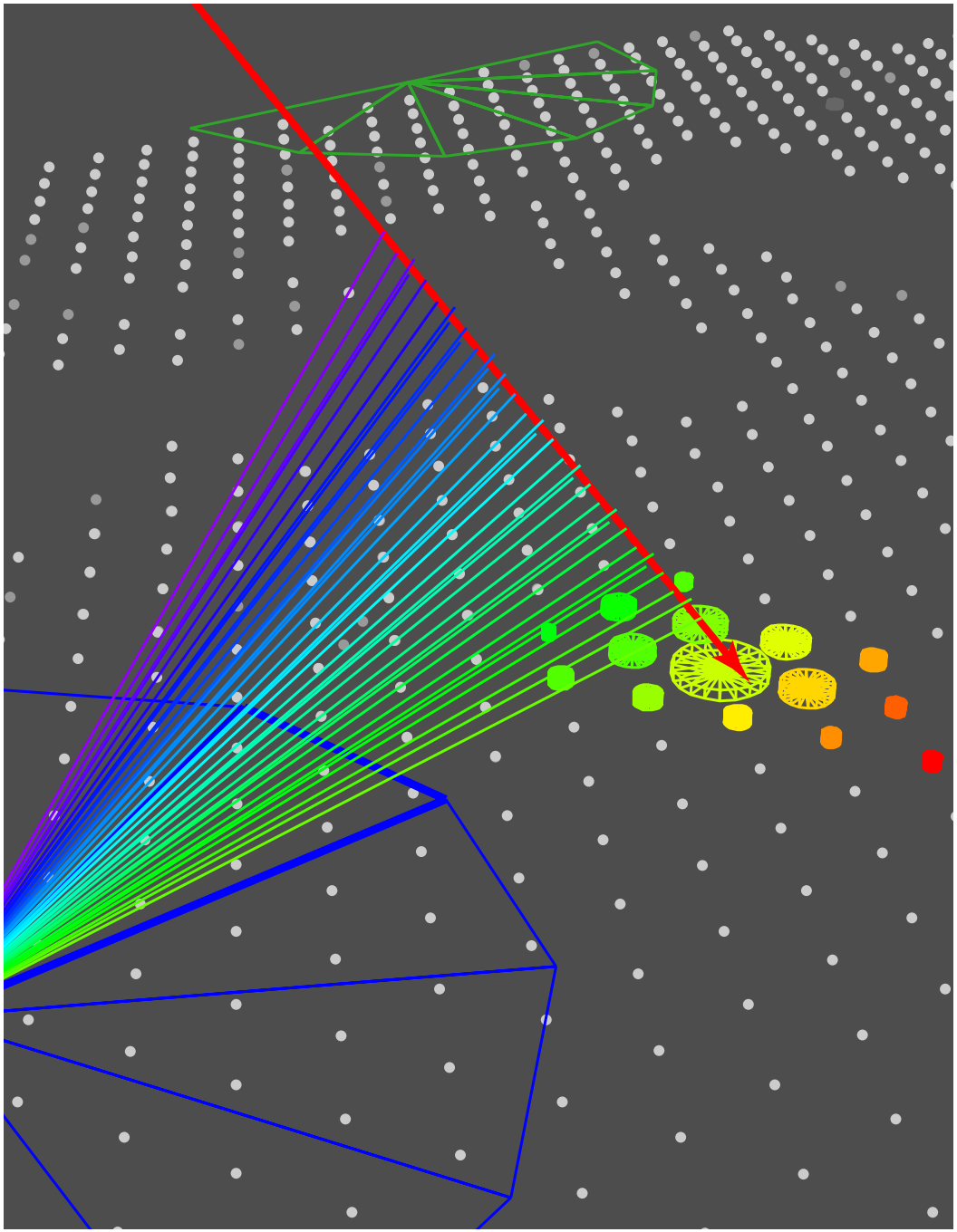
Auger South size & status

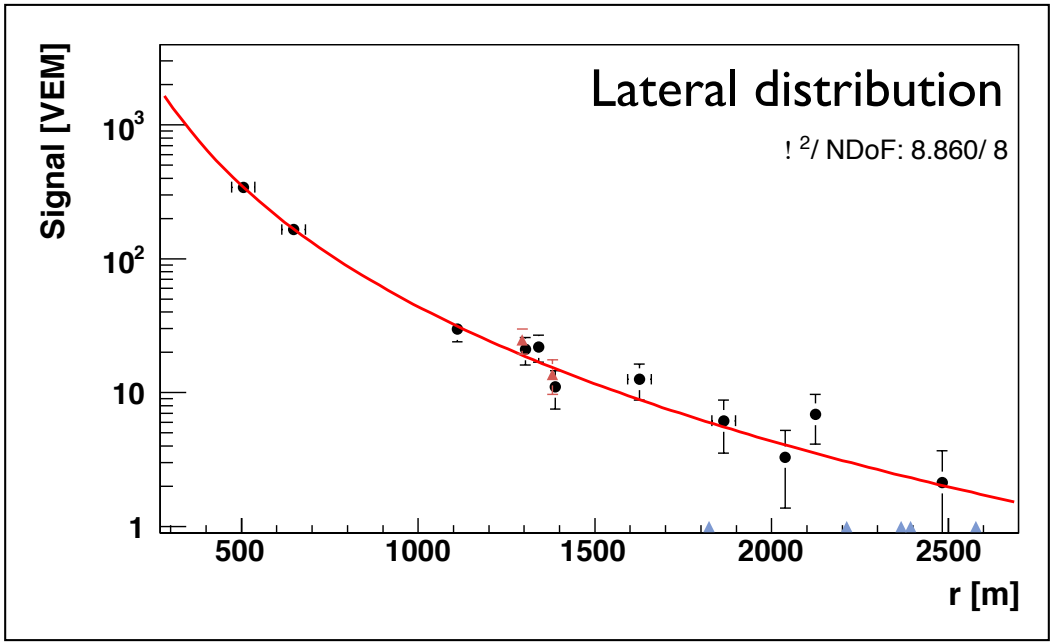


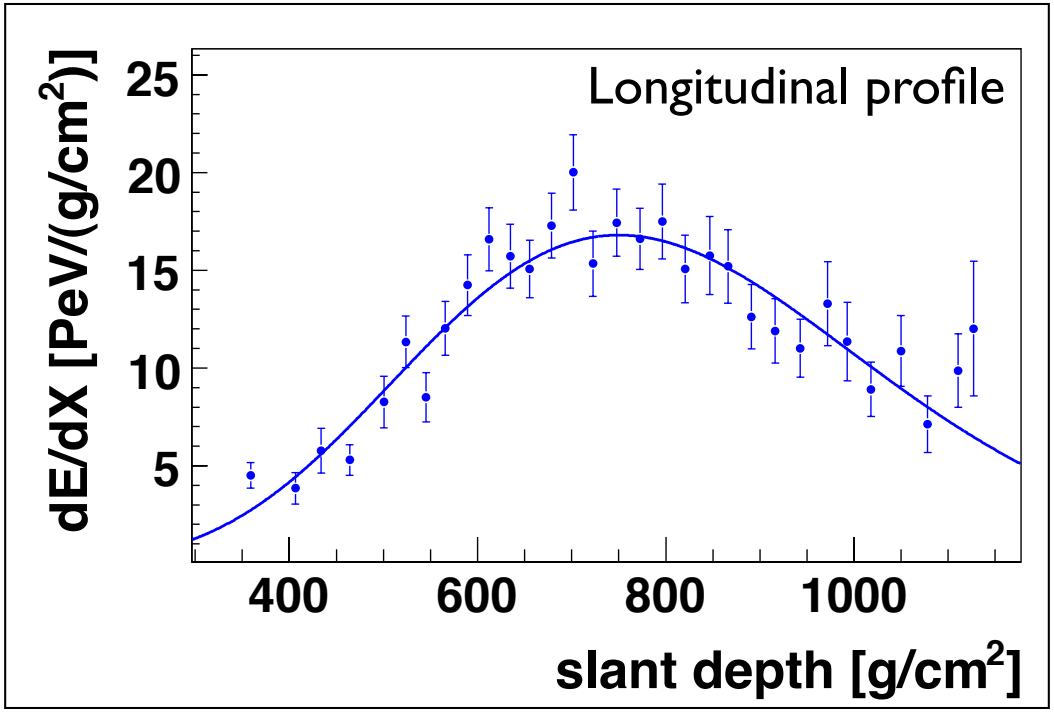
Auger South size & status



Hybrid Events







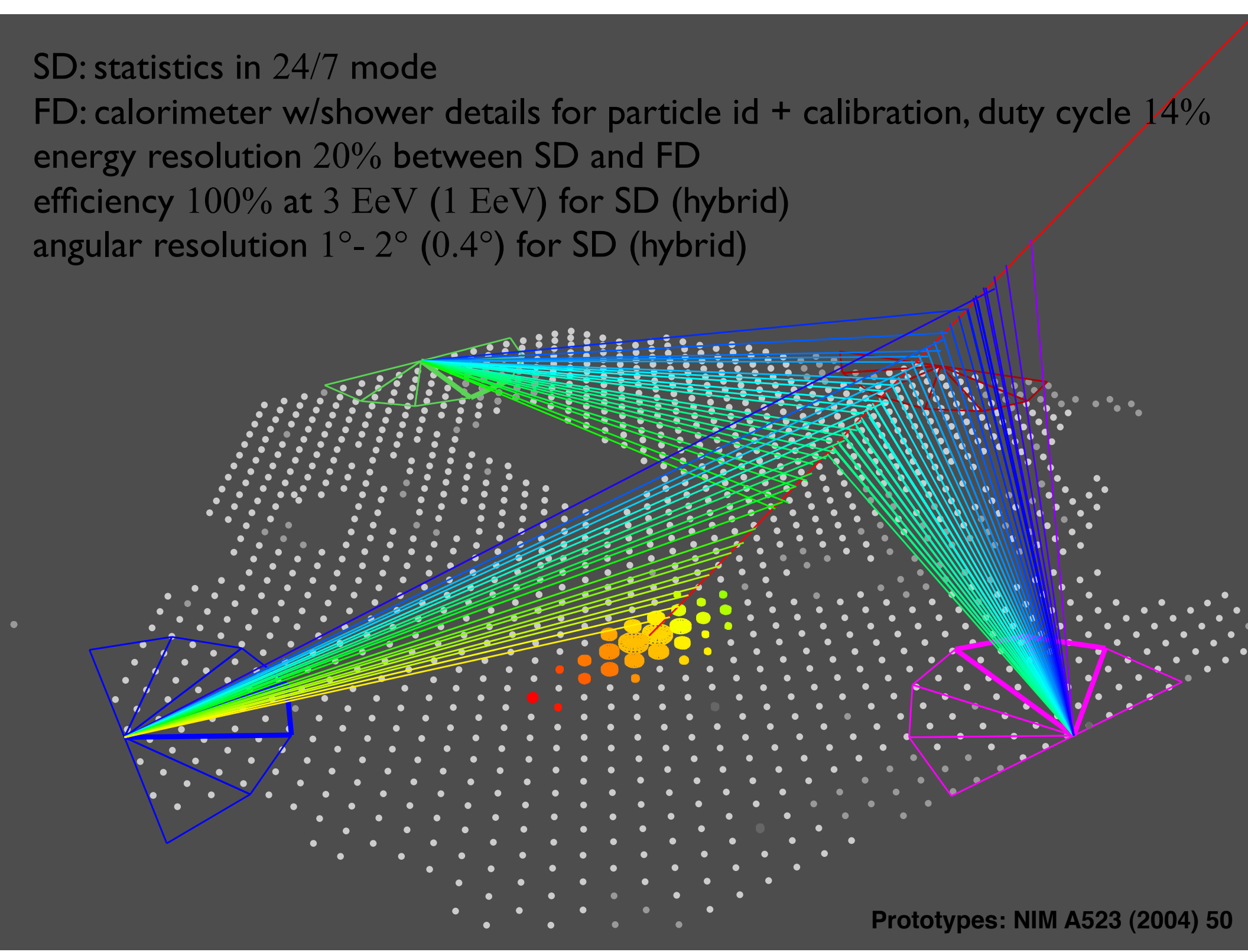
SD: statistics in 24/7 mode

FD: calorimeter w/shower details for particle id + calibration, duty cycle 14%

energy resolution 20% between SD and FD

efficiency 100% at 3 EeV (1 EeV) for SD (hybrid)

angular resolution 1°- 2° (0.4°) for SD (hybrid)



Prototypes: NIM A523 (2004) 50

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Auger South Science Results

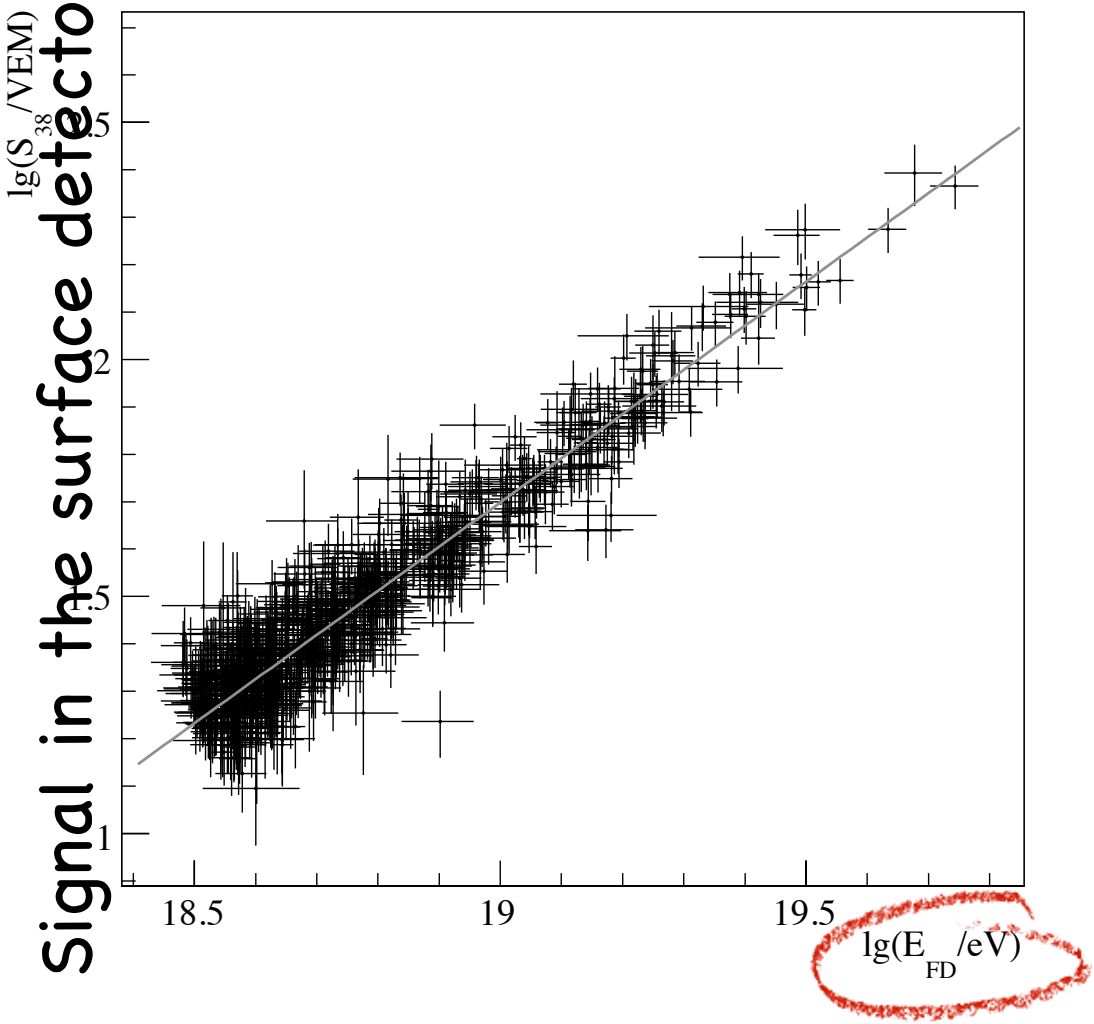
Summary of AS Results

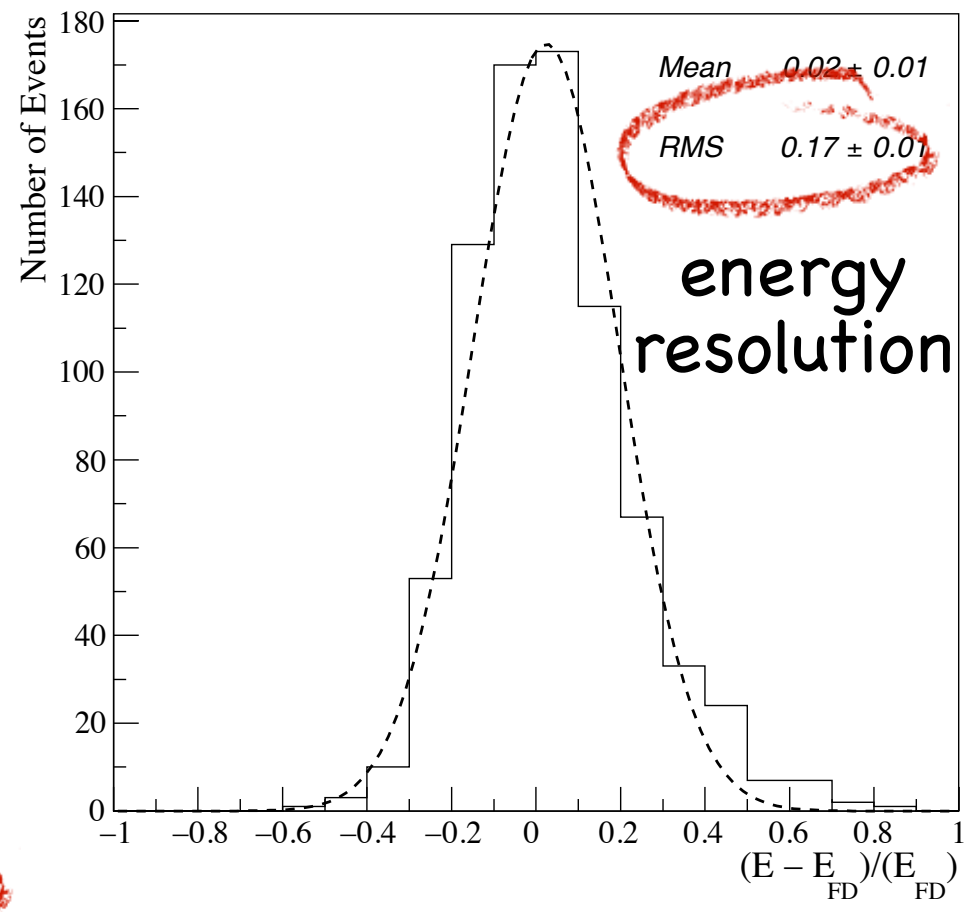
- The energy spectrum exhibits the ankle and the existence of a GZK-like flux suppression.
- At energies above 60 EeV the arrival directions of cosmic rays become anisotropic. In addition, a correlation between the arrival directions and Active Galactic Nuclei (AGN) listed in the Veron-Cetty and Veron catalogue has been found.
- There is no evidence for significant excess of cosmic ray arrival directions from the galactic center, for clustering on different angular scales at the highest energies and for correlations with BL Lac objects.
- We can infer the primary particle composition from the dependence of X_{max} on energy (the elongation rate), yielding a significant change from 'heavy' at 10^{18} eV to 'light' at $\geq 10^{19}$ eV.
- The photon fraction is less than 2 percent above 10^{19} eV with 95% confidence level; this limit restricts the so-called top-down, non-acceleration models for the origin of the most energetic particles.
- The Auger Observatory is sensitive to neutrinos in the EeV range and has set the currently best limit on the diffuse tau neutrino flux in this range as $E_\nu^2 dN_{\nu_\tau}/dE_\nu < 1.3 \times 10^{-7}$ GeV cm^{-2} s^{-1} sr^{-1}.

Energy measurement

The absolute energy scale is determined from data.

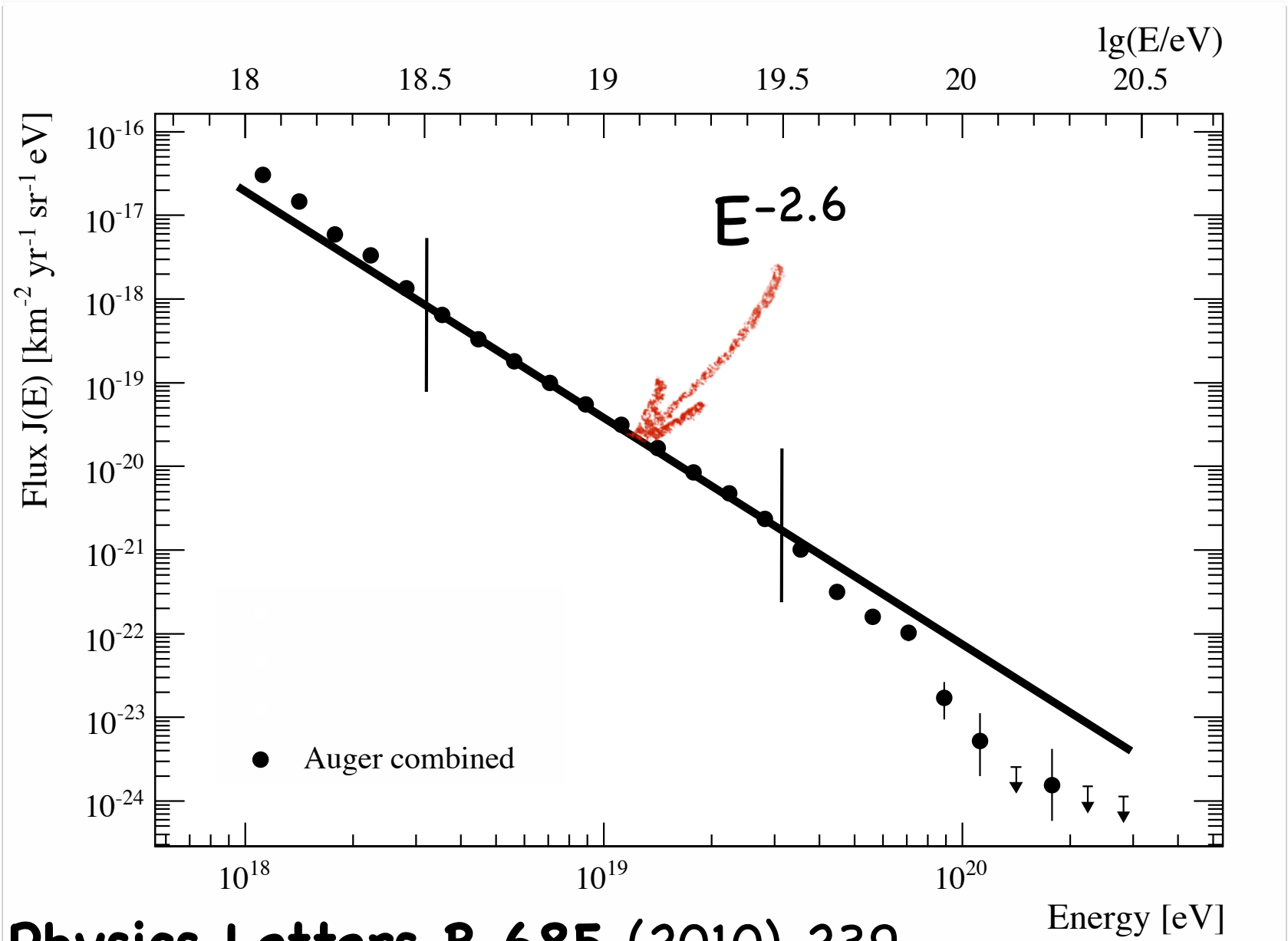
Signal in the surface detectors





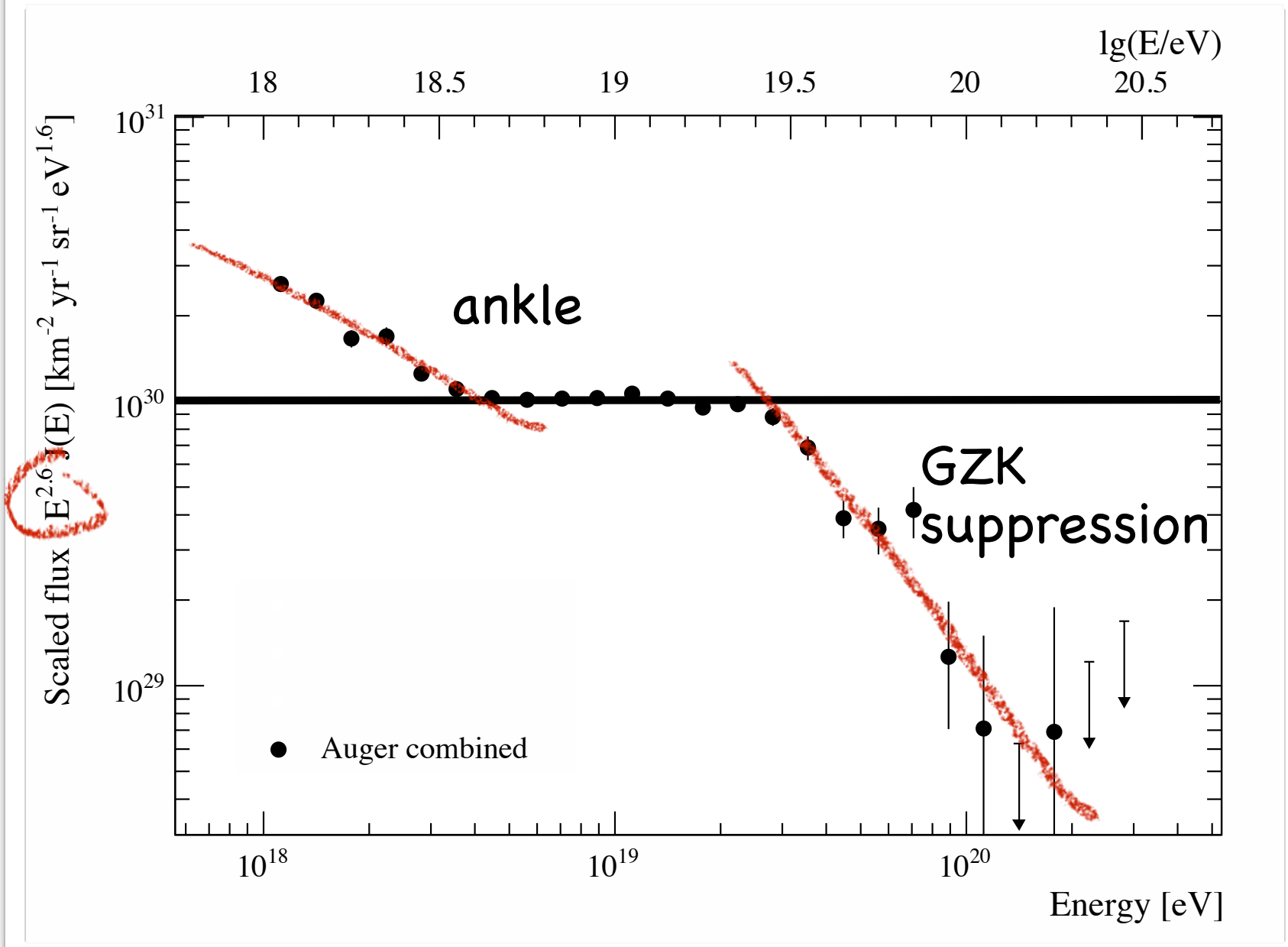
Calorimetric measurement

CR energy spectrum

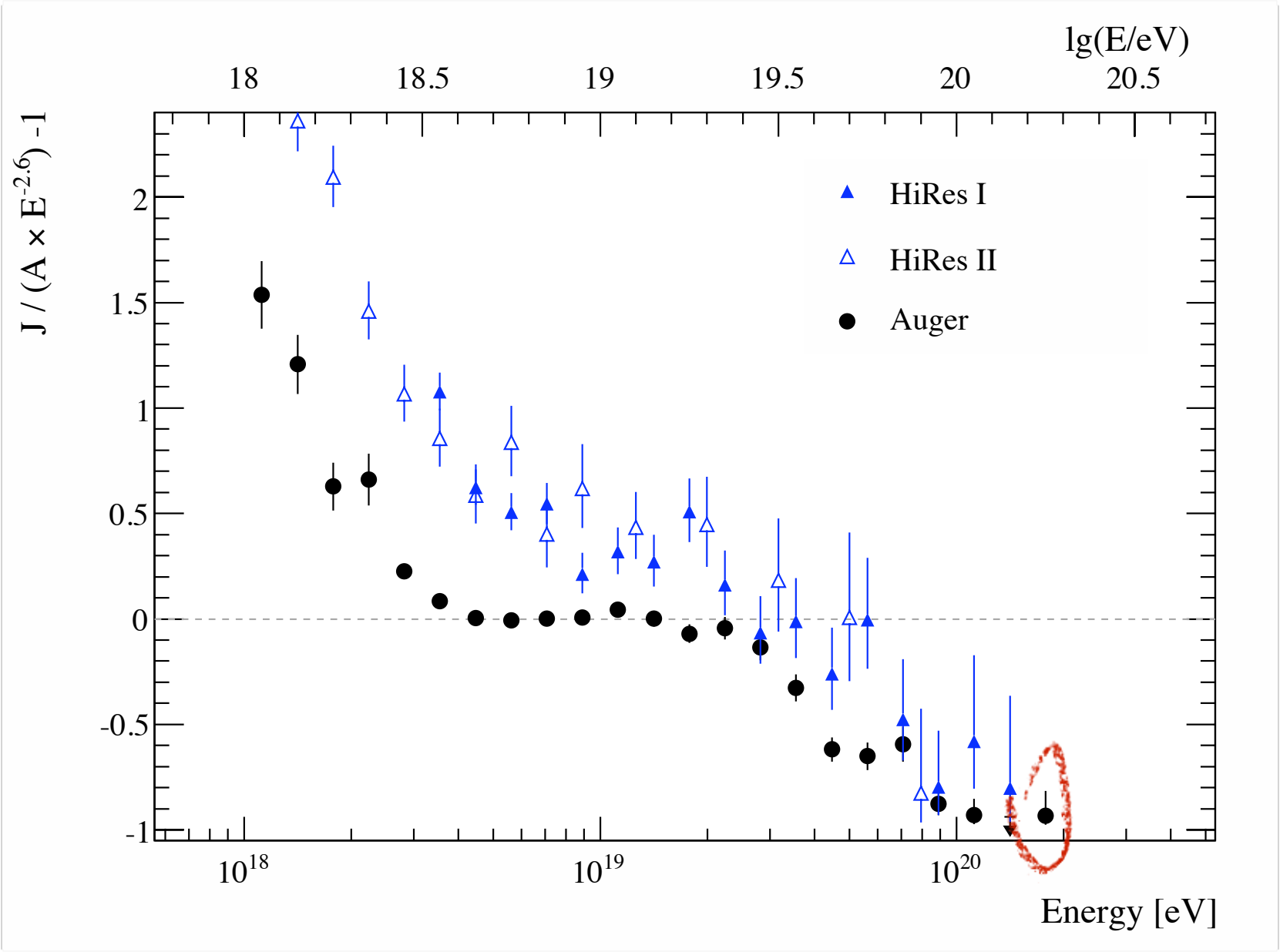


Physics Letters B 685 (2010) 239

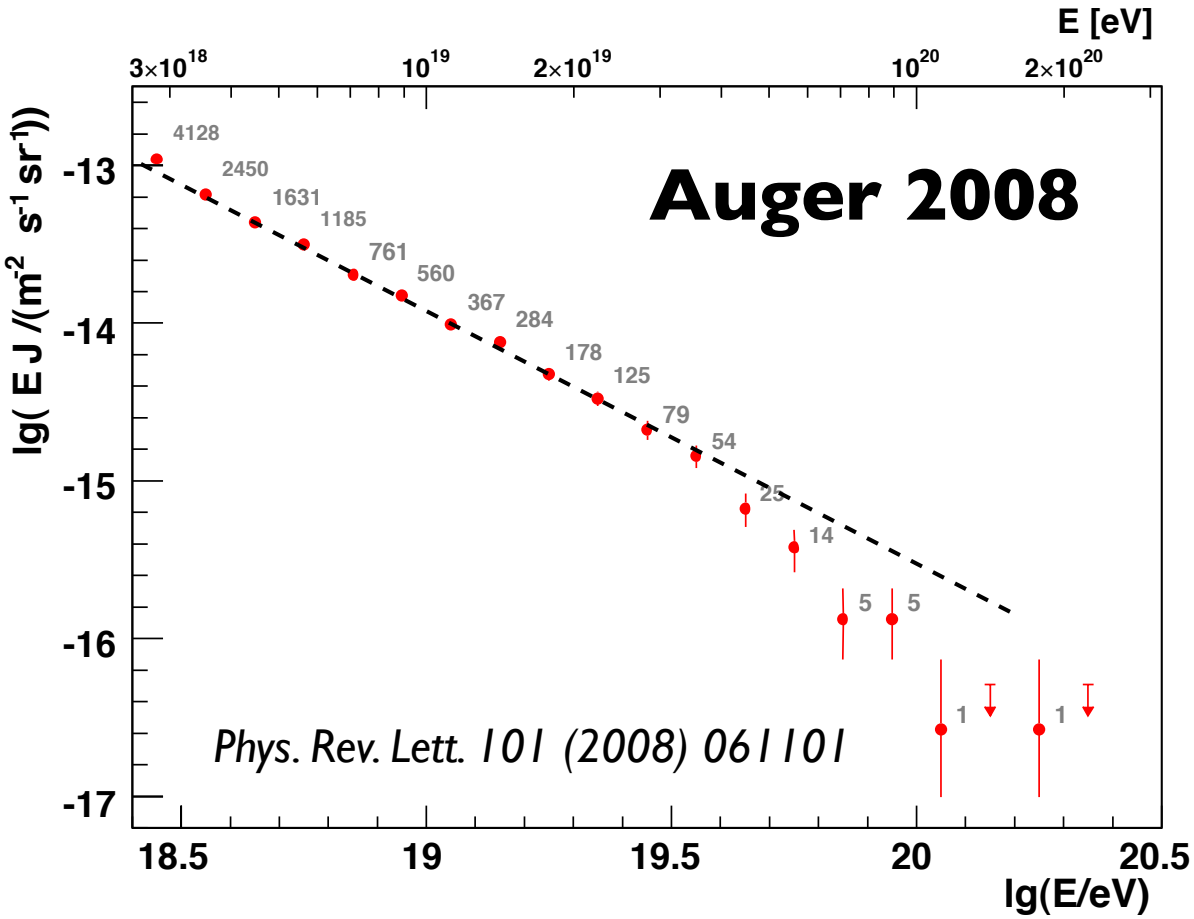
CR energy spectrum

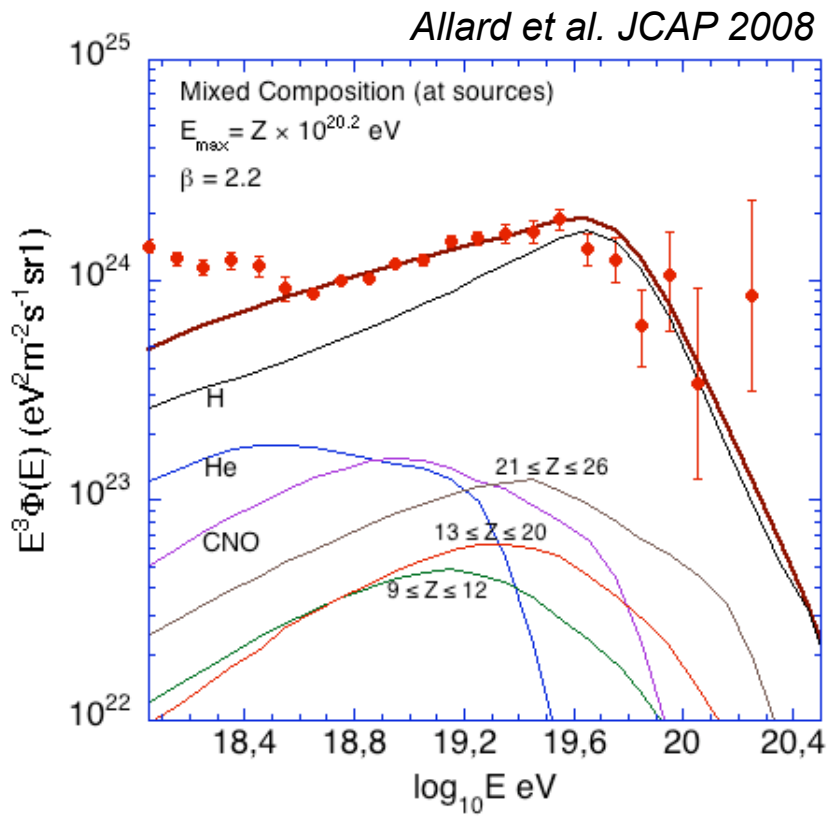


stats @ the highest E



AS Results - Flux suppression





Model-independent measurement

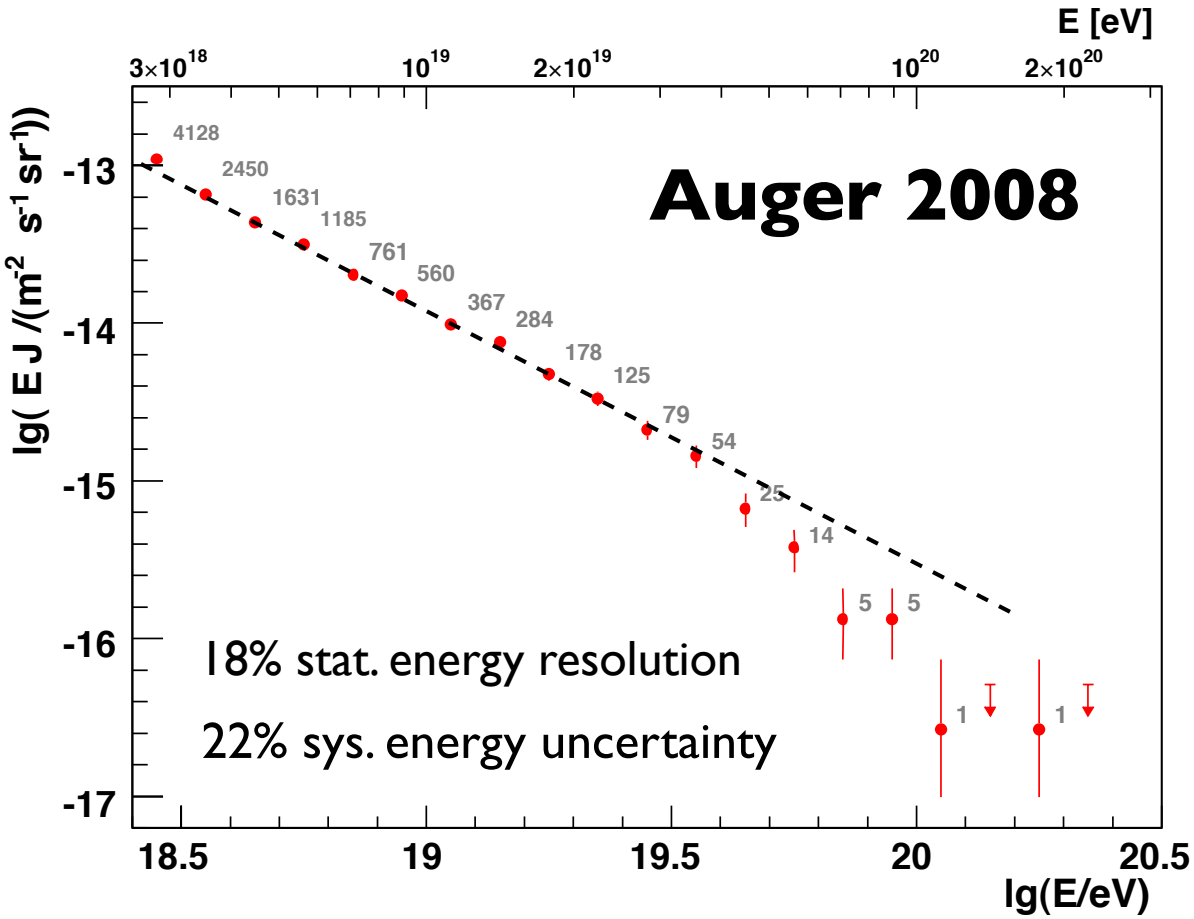
18% stat. energy resolution

22% sys. energy uncertainty

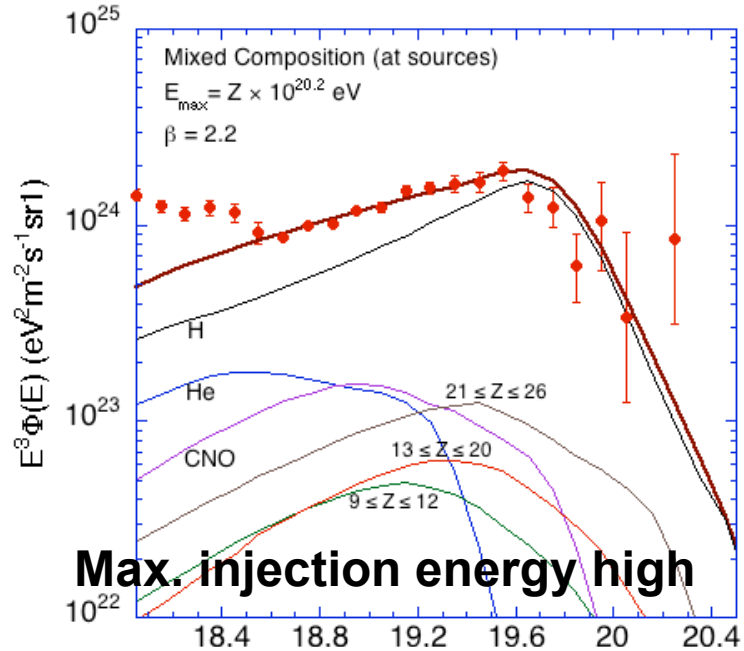
Possible interpretations

- **GZK effect**
- **Maximum injection energy**
- **Superposition of both**

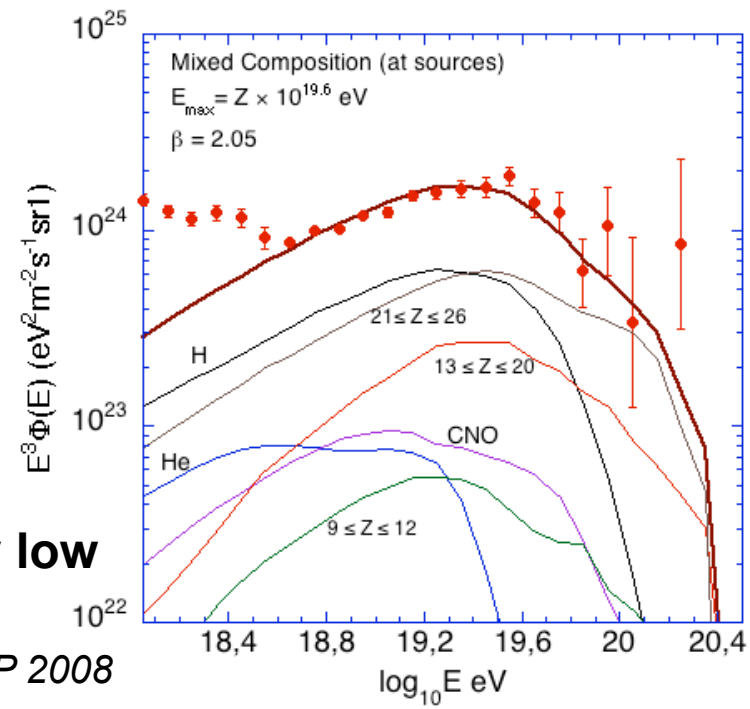
AS Results - Flux suppression



Phys. Rev. Lett. 101 (2008) 061101



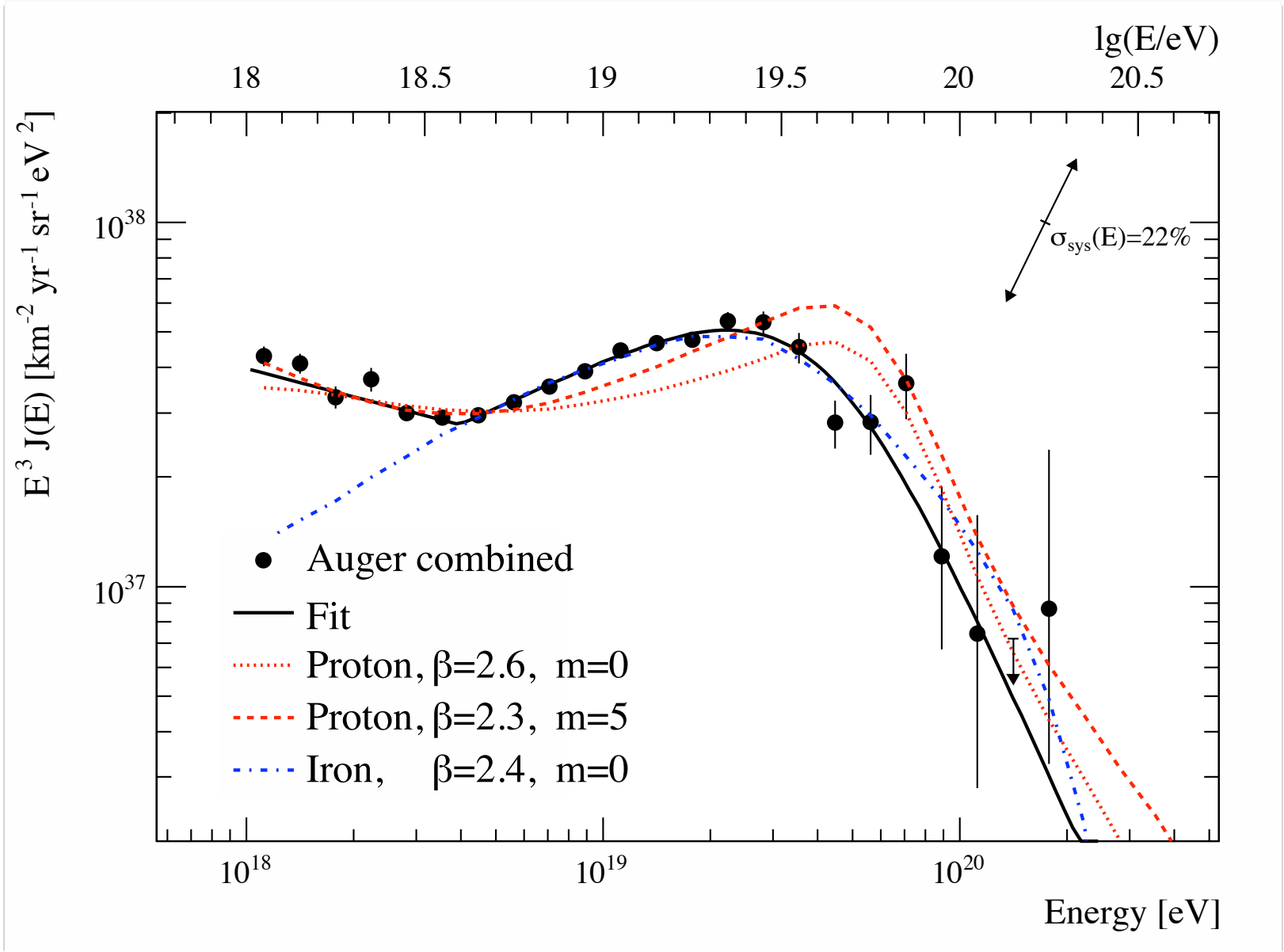
Max. injection energy high



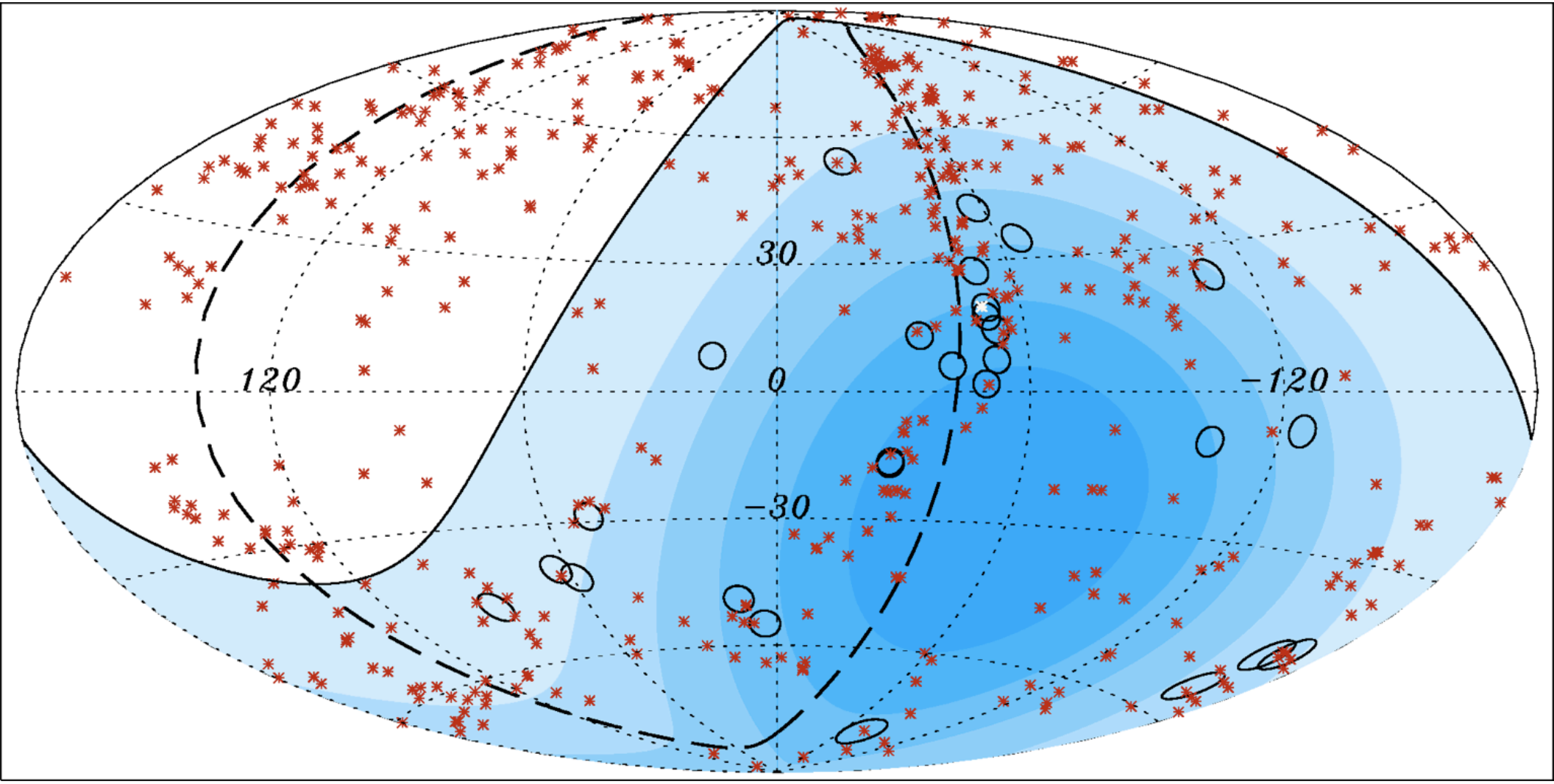
Max. injection energy low

Allard et al. JCAP 2008

take home message



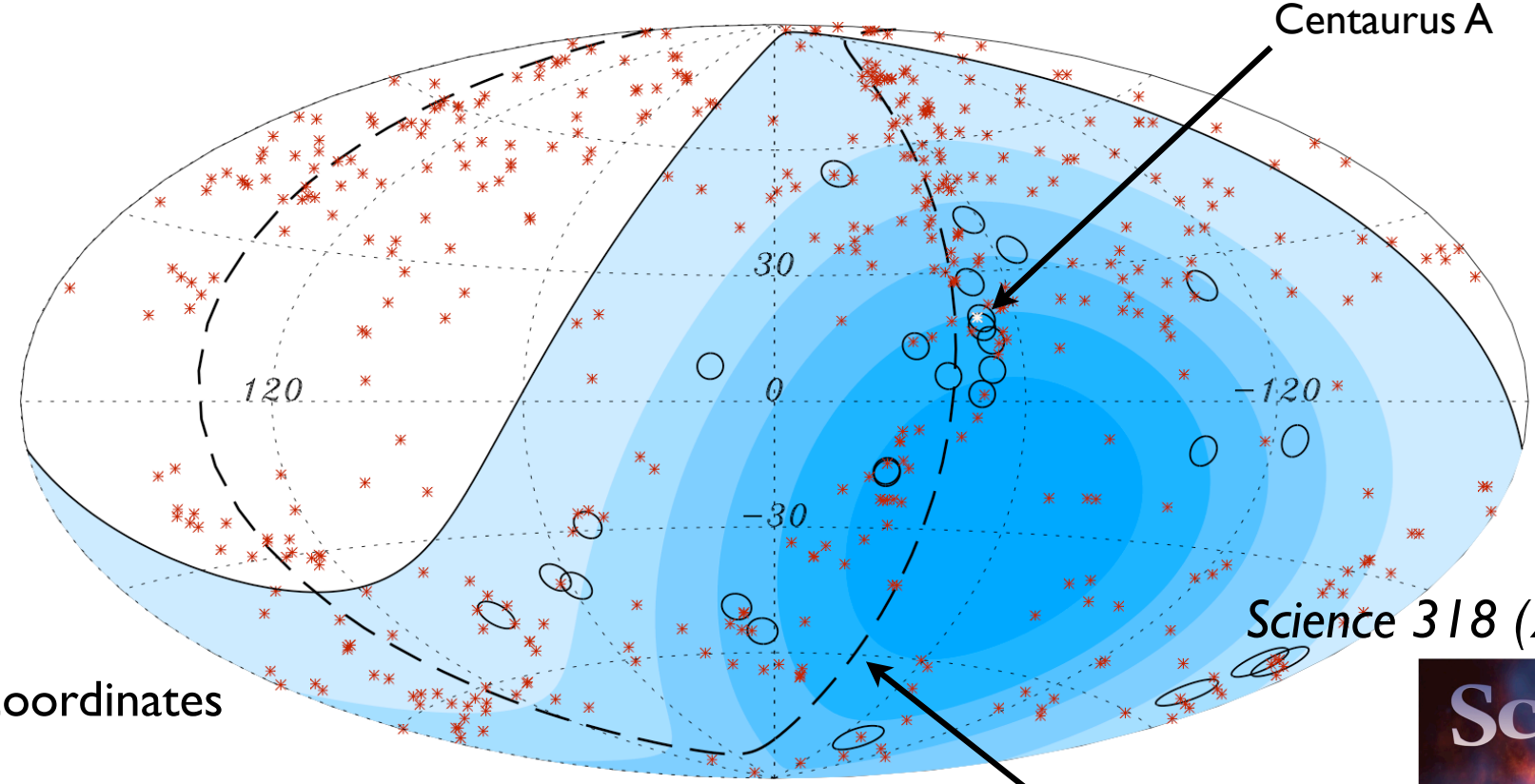
Science result



Pierre Auger Collaboration, Science **318** (2007) 939

AS Results - Anisotropy

AGN Correlation (Status Aug 2007)



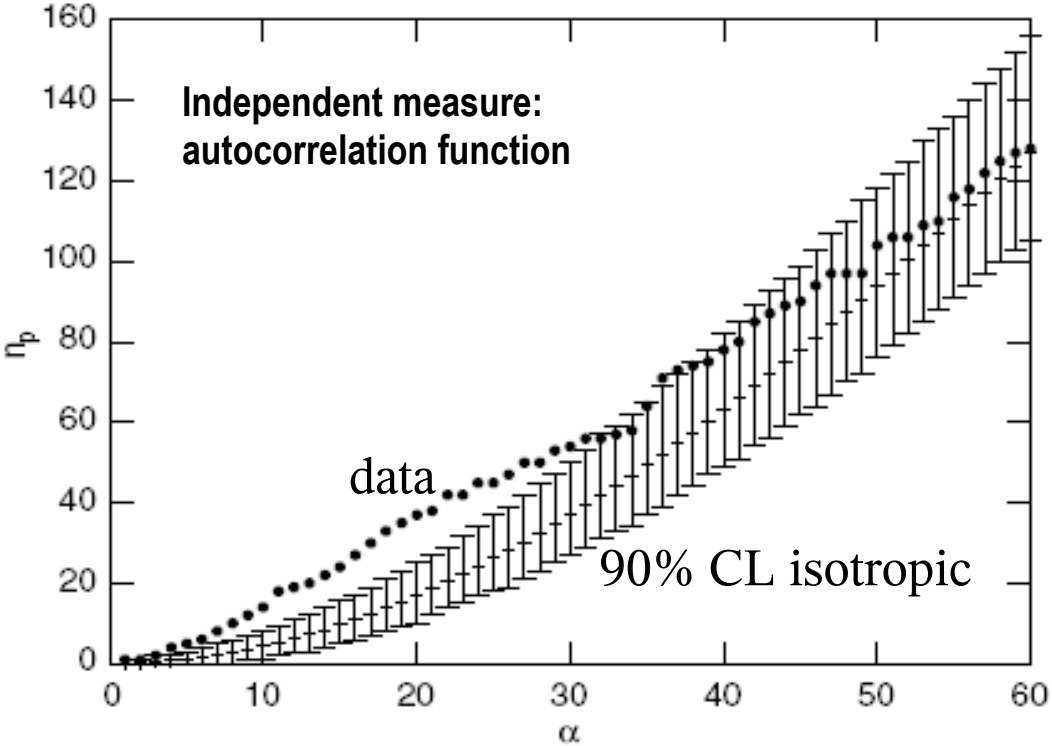
Galactic coordinates

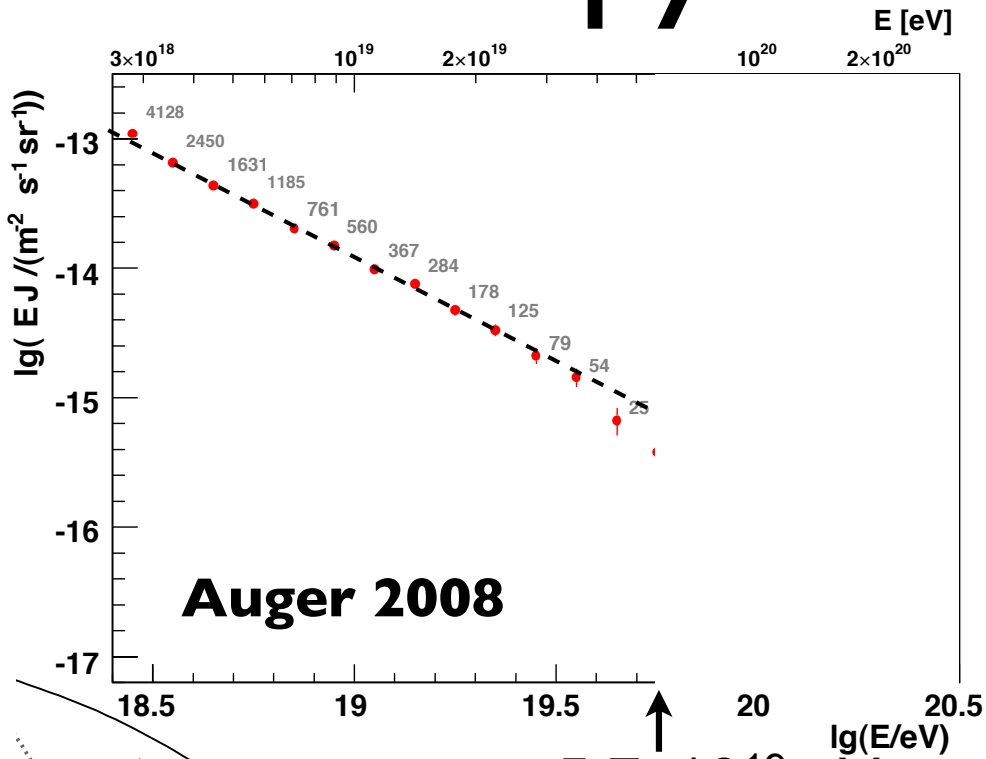
Science 318 (2007) 939

Veron-Cetty: 472 AGN (z< 0.018, ~75 Mpc)
318 in field of view of Auger

Auger: 27 events above 5.7 10^{19} eV,
20 correlated within 3.1°

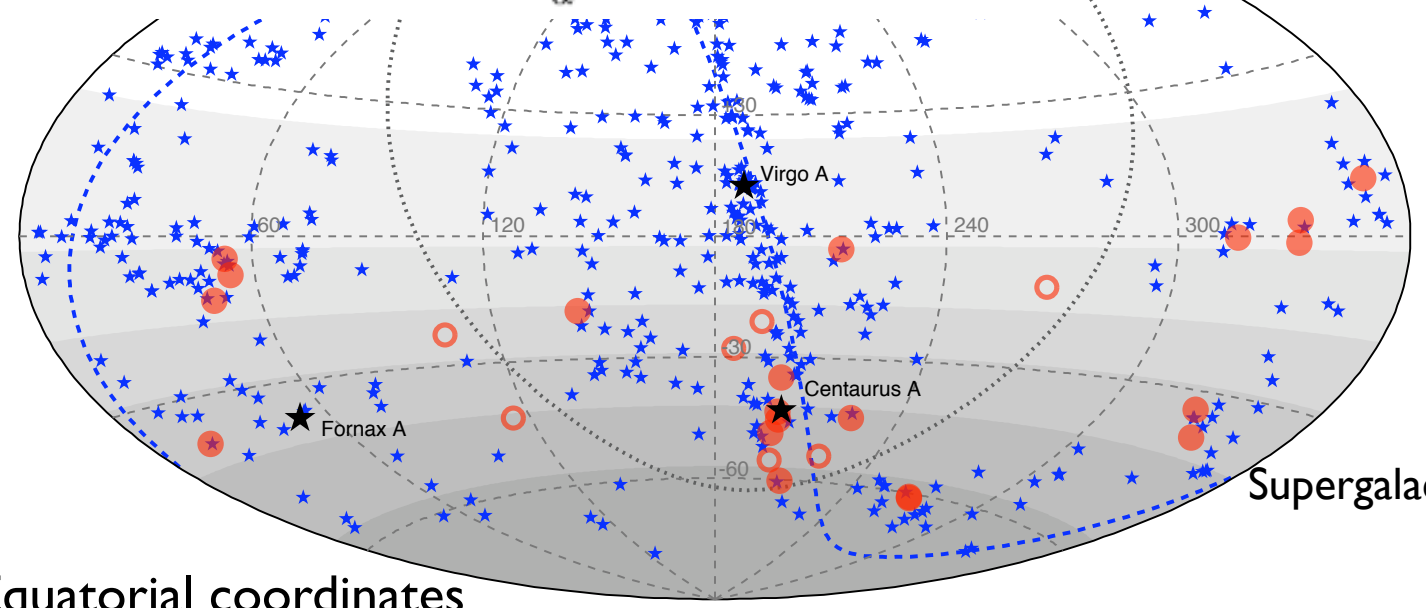
AS Results - Anisotropy





5.7×10^{19} eV

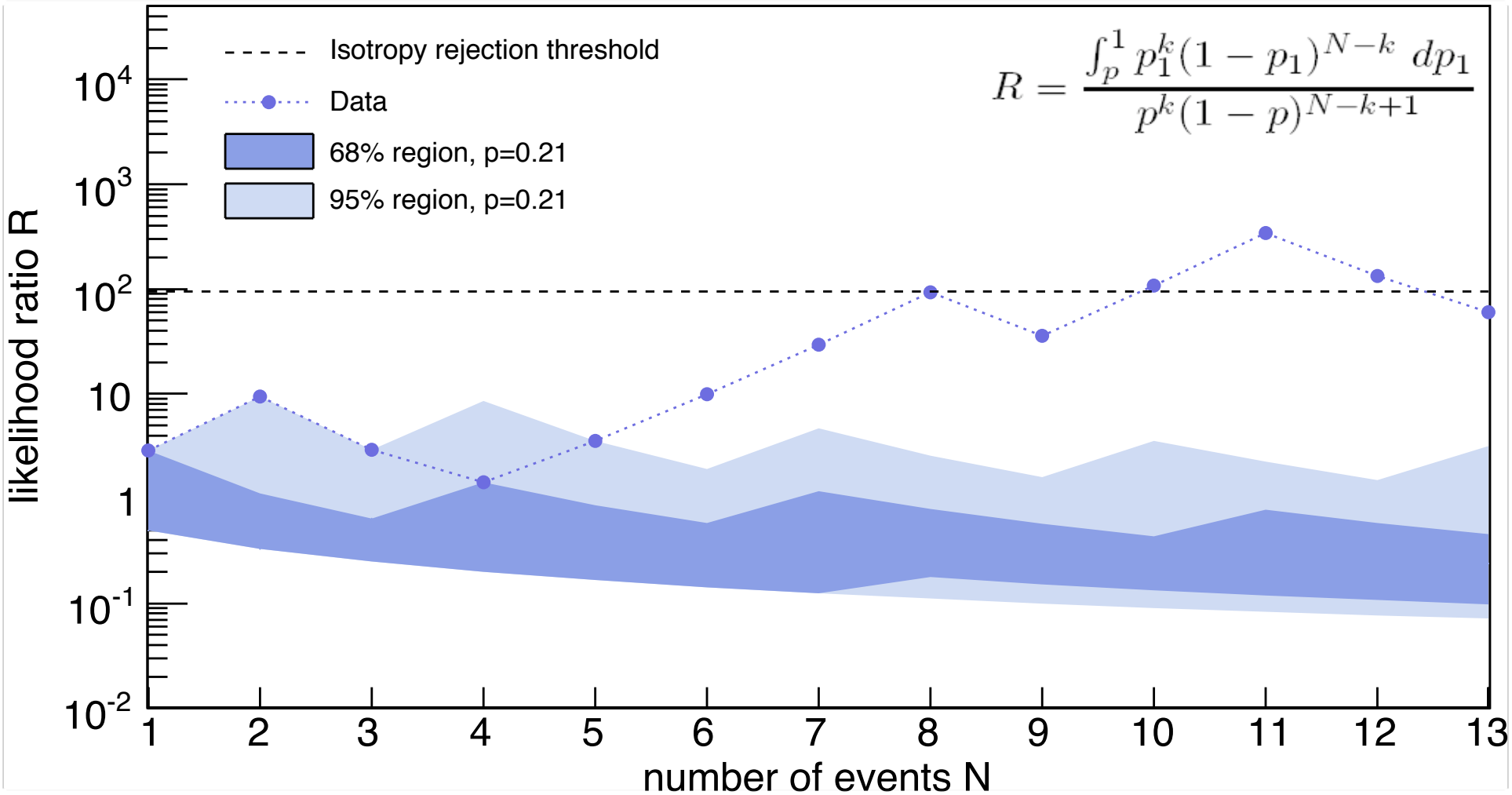
Science 318 (2007) 939



Supergalactic plane

Equatorial coordinates

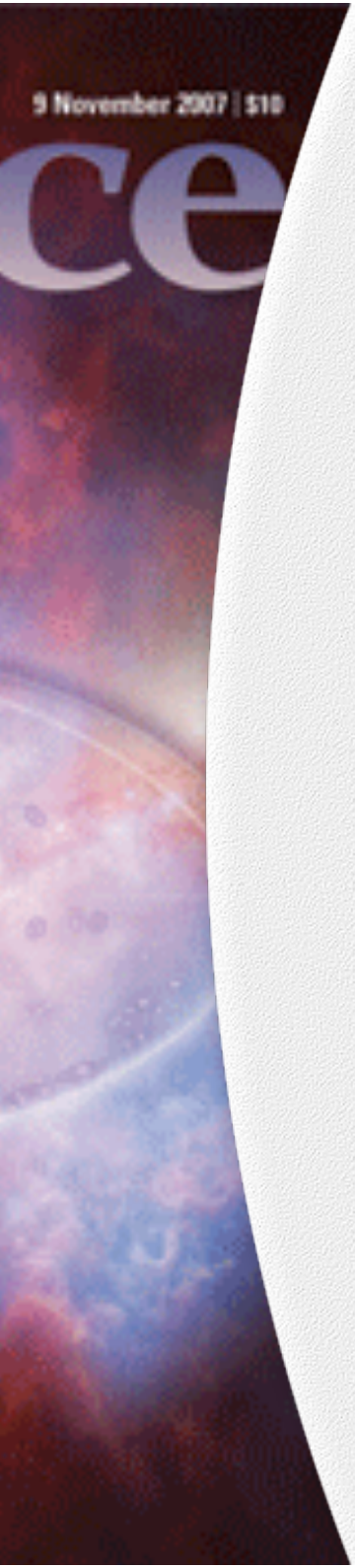
a priori analysis



8/14 9/13

correlation conclusions

- ✓ UHECR are not Galactic
- ✓ Likely astrophysical sources
- ✓ AGN are plausible acceleration sites
- ✓ Over 200 citations!
- ✓ More data needed to identify & characterize the sources

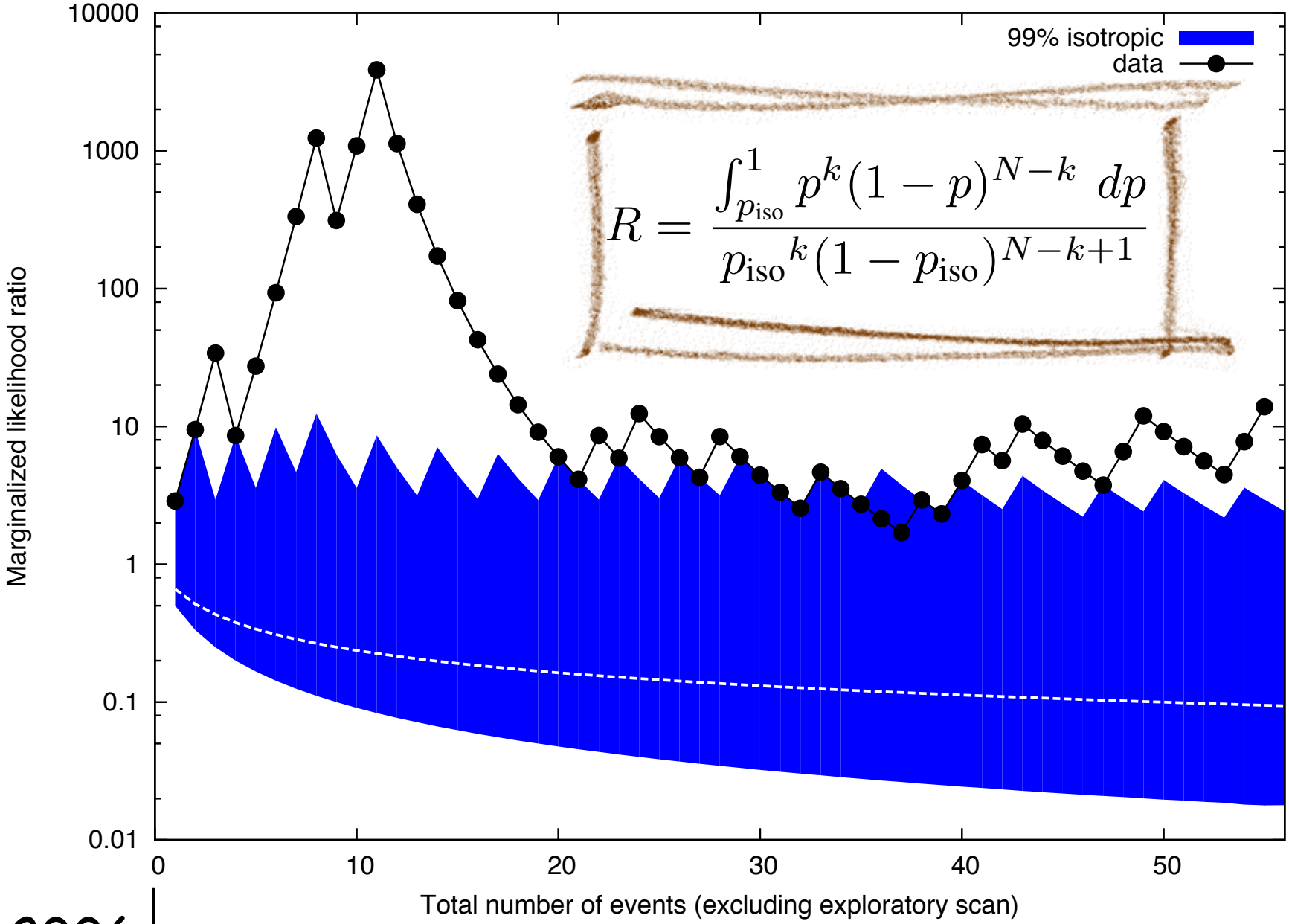


Correlation Update

- Data up to **February 1, 2010**
- More than double the data;

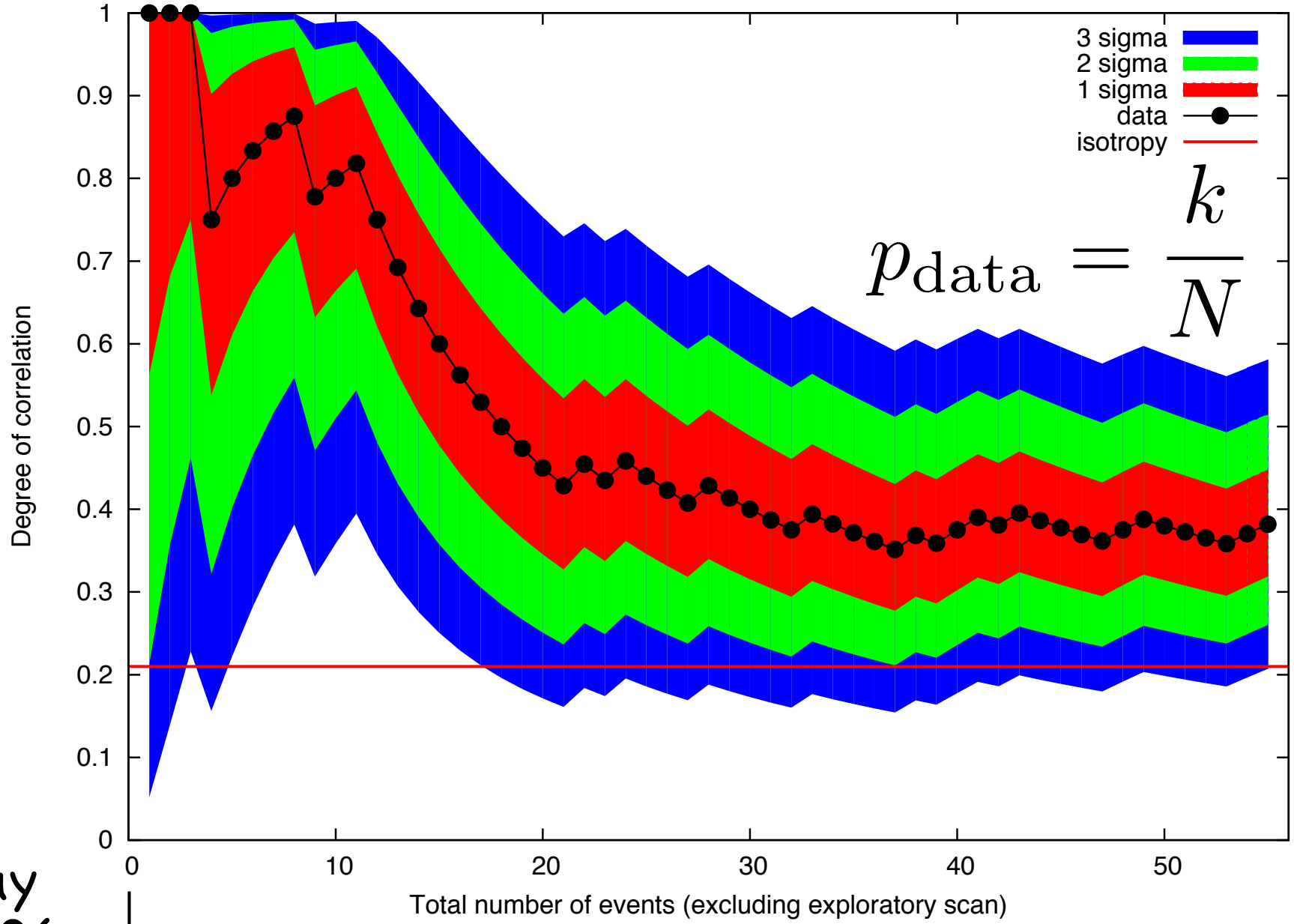
  i.e. 69 events above **55 EeV**

monitoring the signal



May 2006

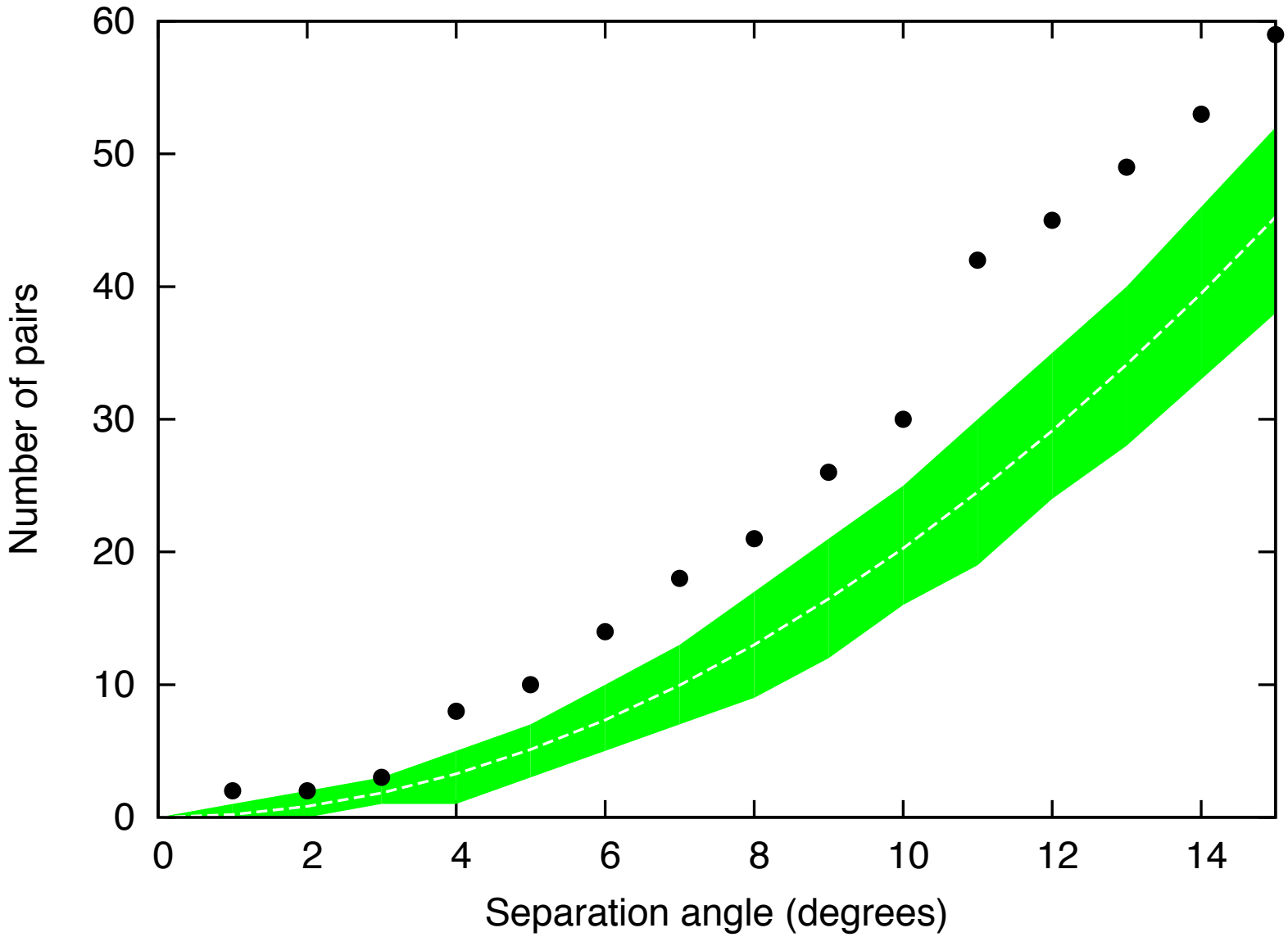
monitoring the signal



21/55

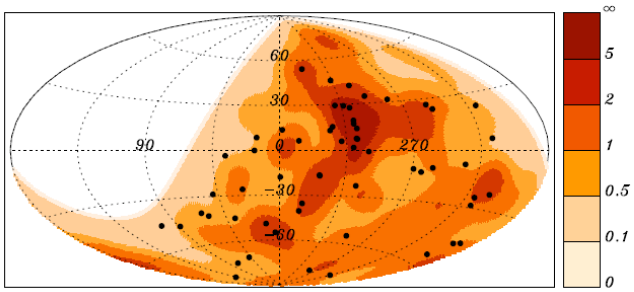
May 2006

Auto-Correlation

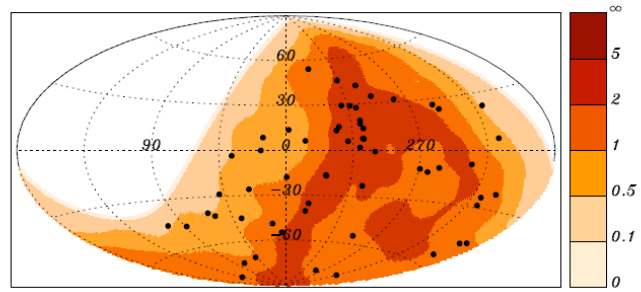


AS Results - Anisotropy

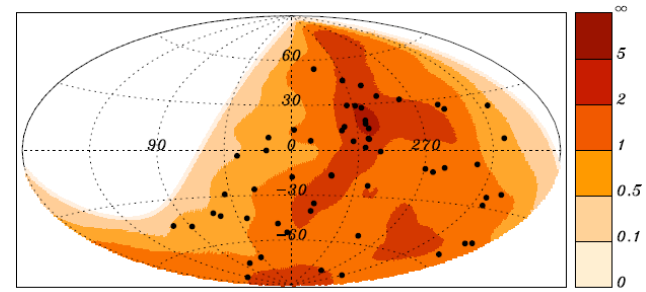
AGN Correlation Update



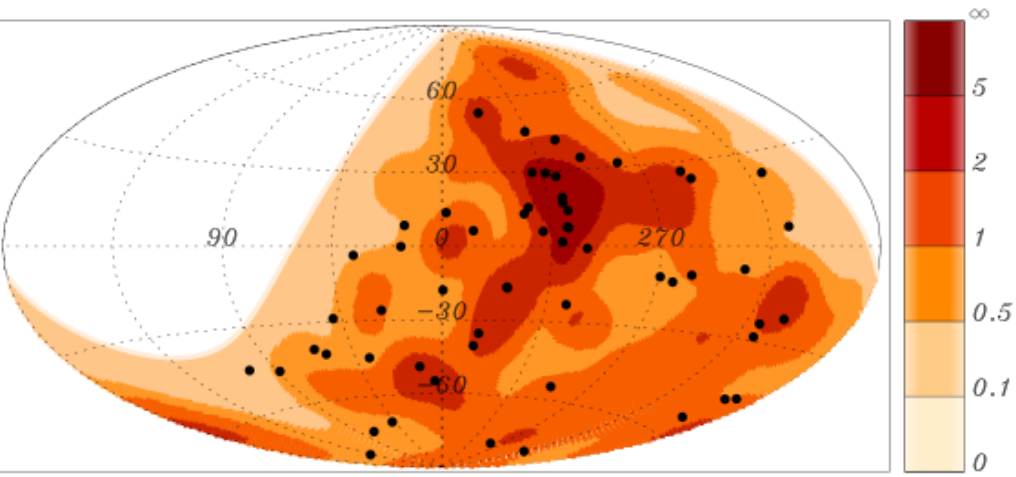
SWIFT- BAT AGN

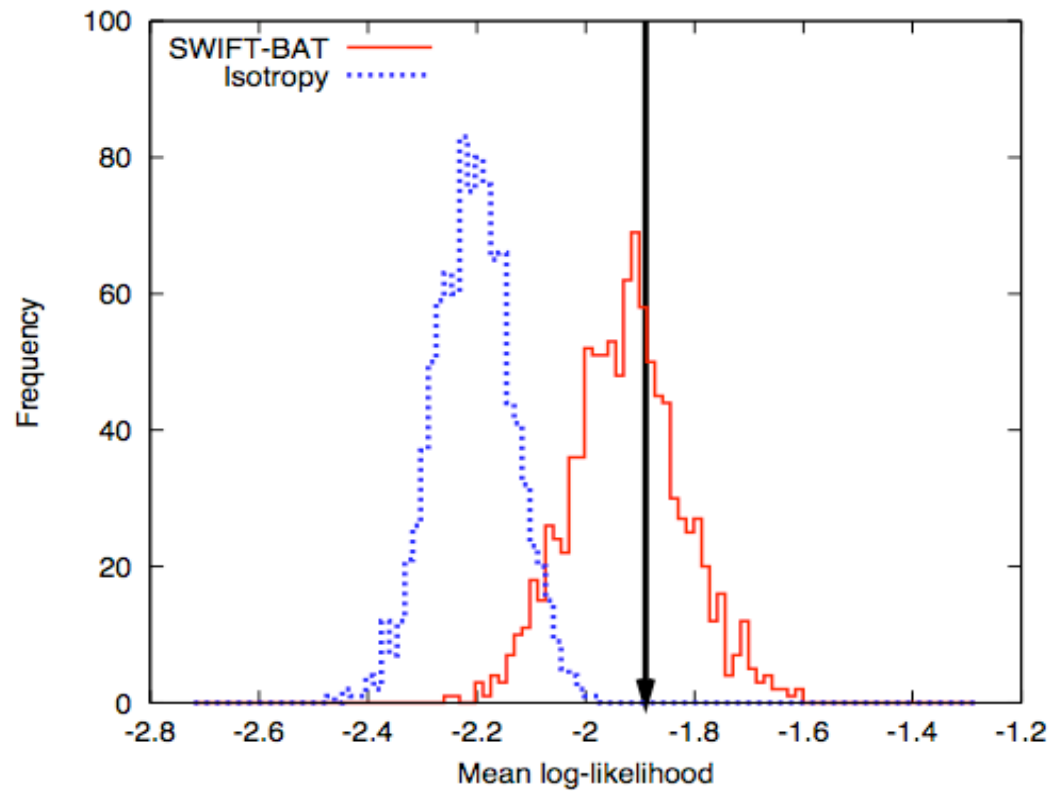


HIPASS GALAXIES

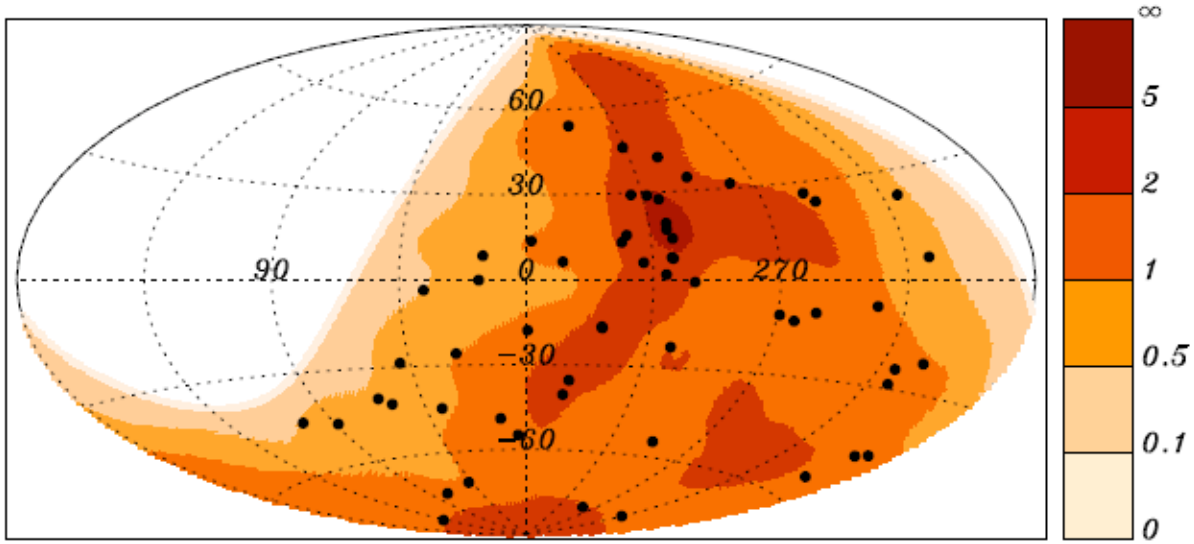


2MASS GALAXIES

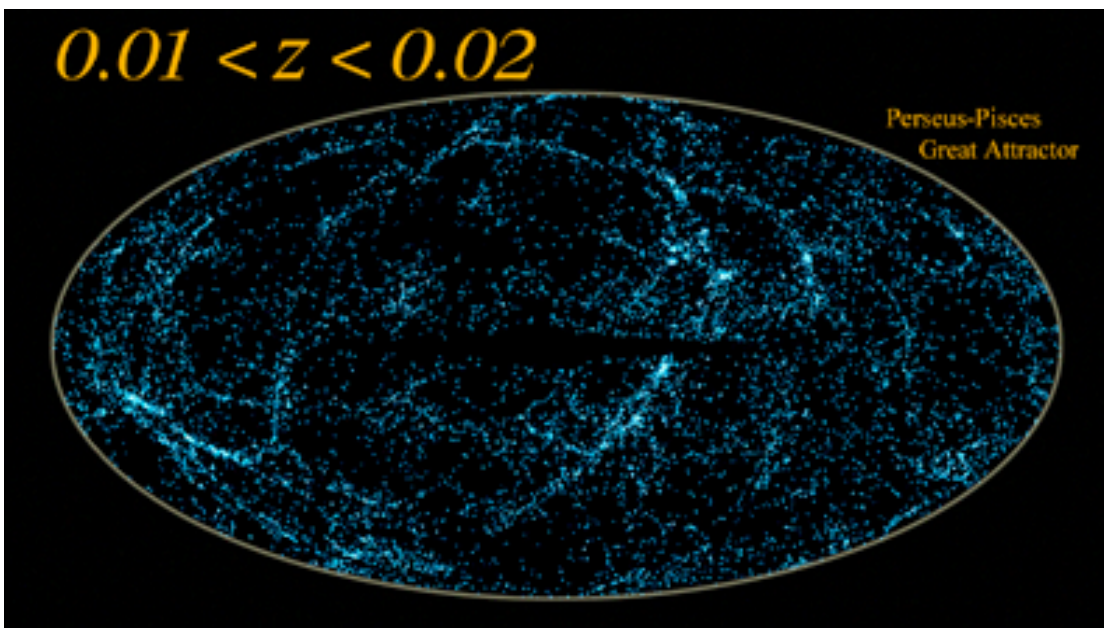




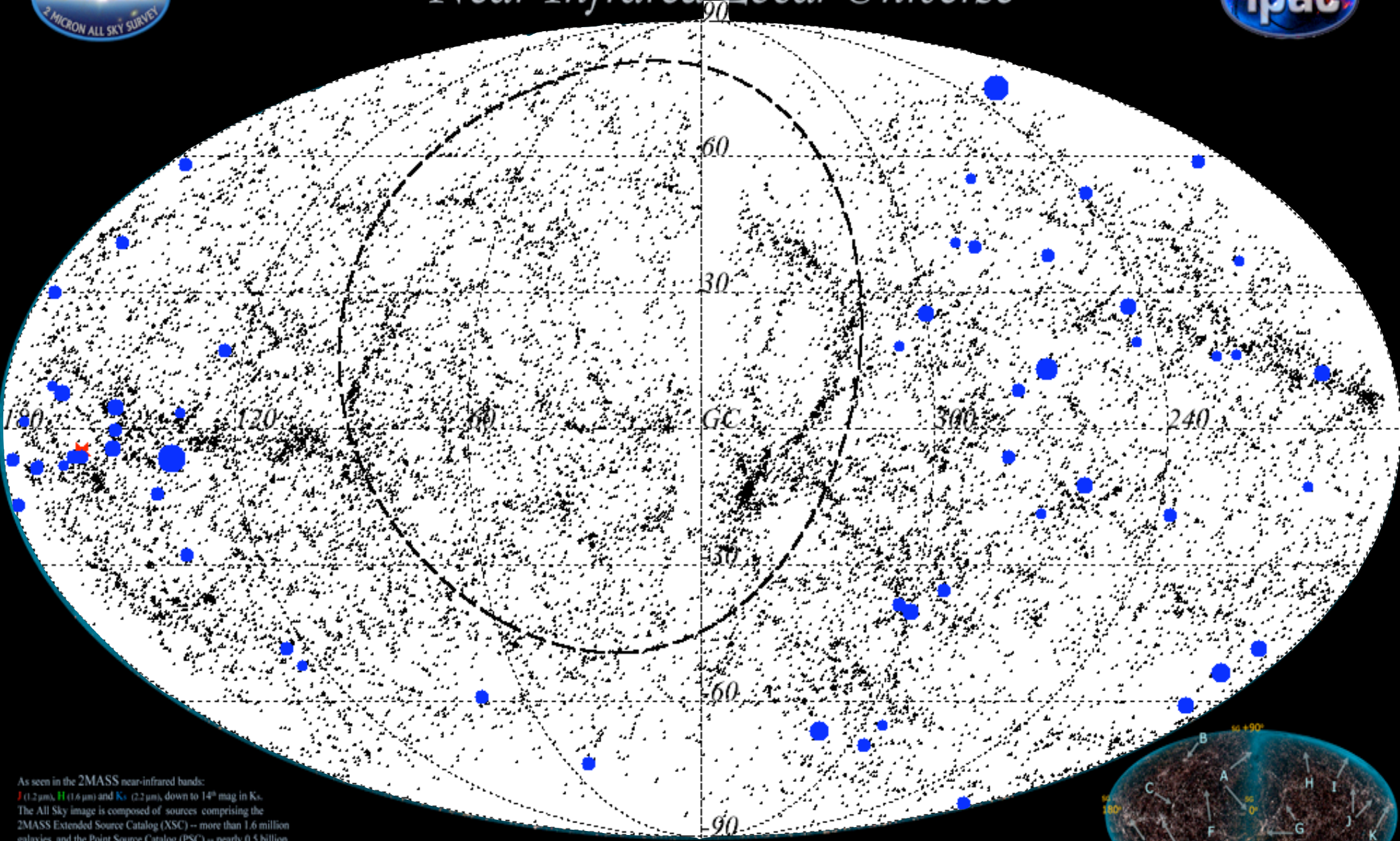
AN - Anisotropy



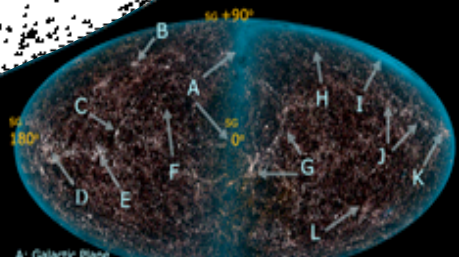
2MASS GALAXIES



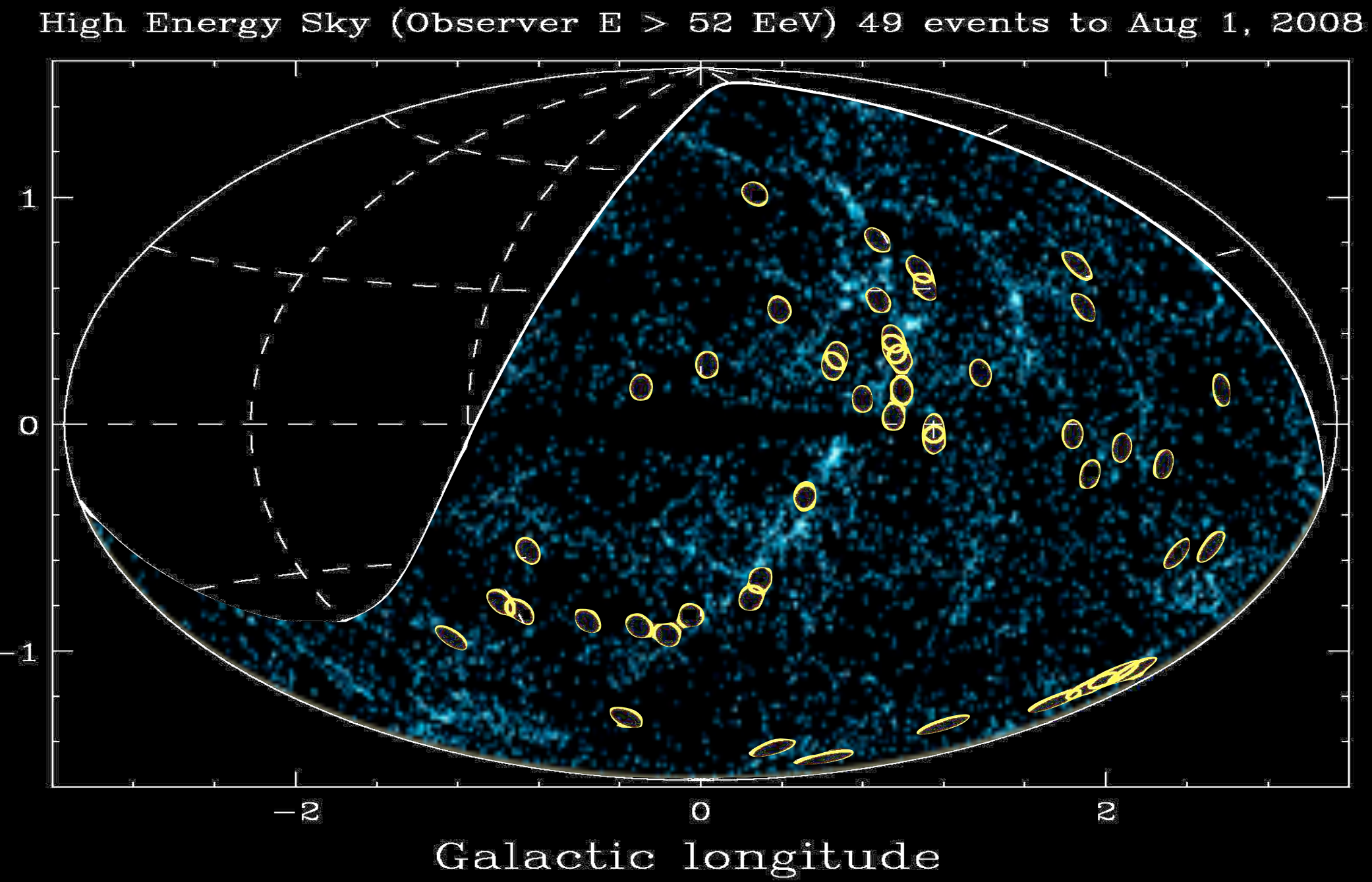
SuperGalactic View of the Near-Infrared Local Universe



As seen in the 2MASS near-infrared bands: J (1.2 μm), H (1.6 μm) and K_s (2.2 μm), down to 14th mag in K_s. The All Sky image is composed of sources comprising the 2MASS Extended Source Catalog (XSC) -- more than 1.6 million galaxies, and the Point Source Catalog (PSC) -- nearly 0.5 billion Milky Way stars (here shown with a blue tint to contrast with the background galaxies.) The map is projected with an equal area aitoff in the SuperGalactic system (representing the plane of the Local Supercluster, including the Virgo-Coma supercluster of galaxies.) The plane of the Milky Way runs vertically across the image, with the Galactic Center to the upper right. The image was created by Drs. T.H. Jarrett, J. Carpenter & R. Hurt (IPAC/Caltech).



A: Galactic Plane
B: Hercules Supercluster
C: Coma Cluster
D: Shapley Concentration/ Hydra-Centaurus Supercluster
E: Virgo Cluster/Local Supercluster
G: Perseus-Pisces Supercluster
H: "Local Void"
I: Galactic Center
J: Pavo-Indus Supercluster
K: "Great Attractor"/Abell 3627


High Energy Sky (Observer E > 52 EeV) 49 events to Aug 1, 2008
1
0
−1
−2
0
2
Galactic longitude

Updated conclusions

- ✓ UHECR are extragalactic
- ✓ We still reject isotropy at the **99%** level
- ✓ VCV & parameters are not unbiased
- ✓ GZK suppression

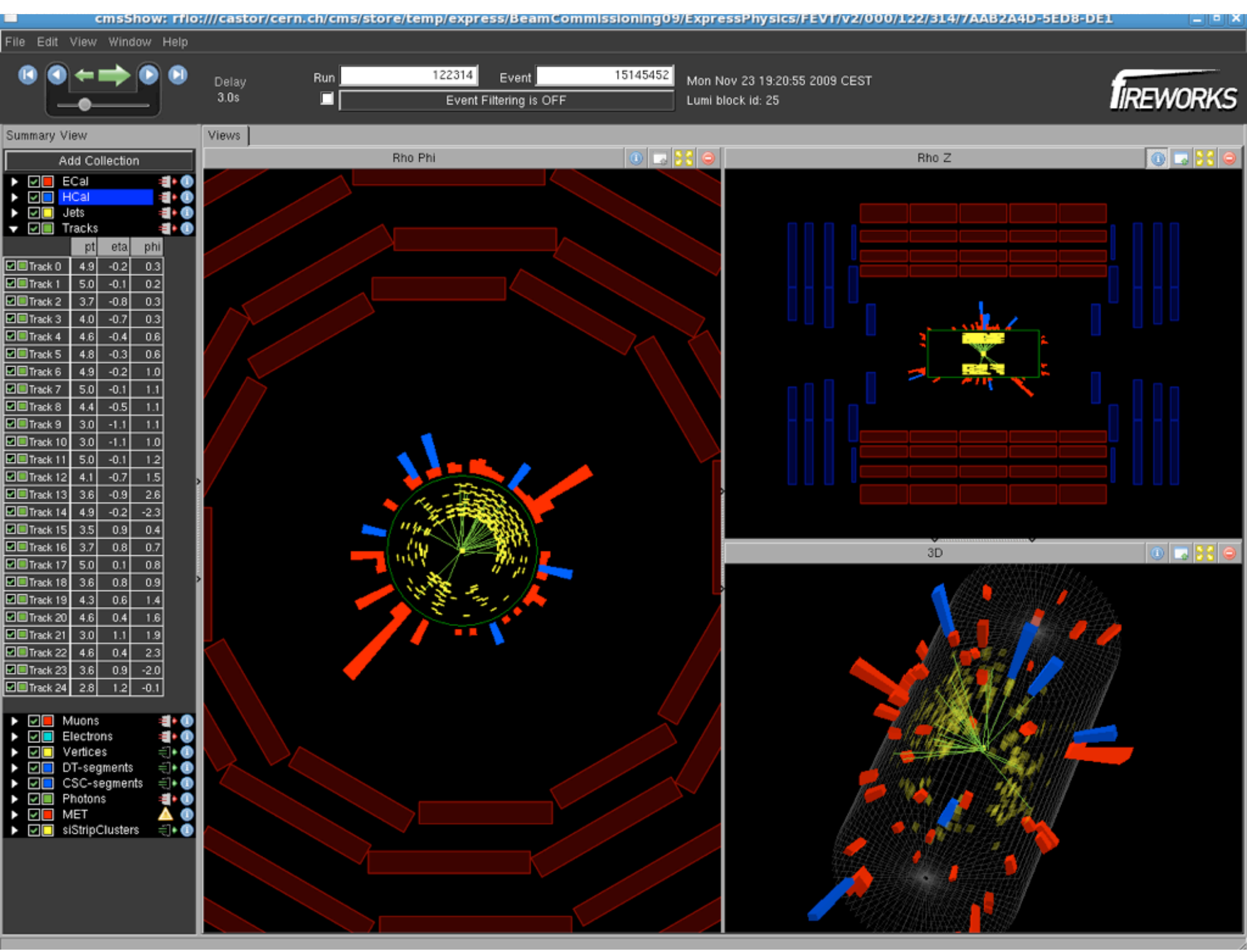
  ⇒ we can see local sources ☺

  ⇒ we see only 2 events/month above 55 EeV ☹

- ✓ **Additional data** needed to identify potential sources of UHECR

Latest Results

Composition - Inferring the identity of the primary CR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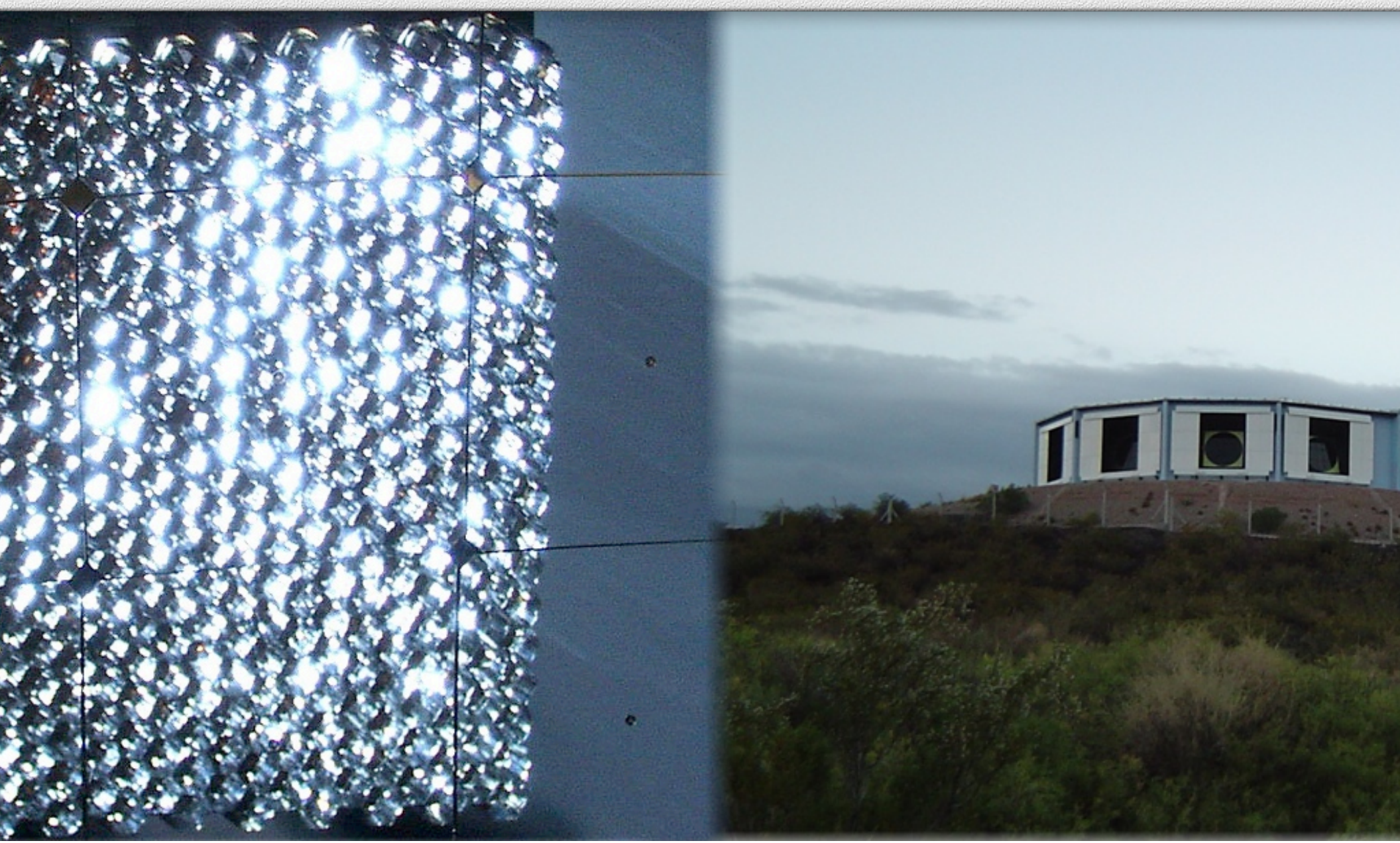
File Edit View Window Help
Delay
3.0s
Run 122314
Event 15145452
Event Filtering is OFF
Mon Nov 23 19:20:55 2009 CEST
Lumi block id: 25
FIREWORKS
Summary View
Add Collection
ECal
HCal
Jets
Tracks
pt eta phi
Track 0 4.9 -0.2 0.3
Track 1 5.0 -0.1 0.2
Track 2 3.7 -0.8 0.3
Track 3 4.0 -0.7 0.3
Track 4 4.6 -0.4 0.6
Track 5 4.8 -0.3 0.6
Track 6 4.9 -0.2 1.0
Track 7 5.0 -0.1 1.1
Track 8 4.4 -0.5 1.1
Track 9 3.0 -1.1 1.1
Track 10 3.0 -1.1 1.0
Track 11 5.0 -0.1 1.2
Track 12 4.1 -0.7 1.5
Track 13 3.6 -0.9 2.6
Track 14 4.9 -0.2 -2.3
Track 15 3.5 0.9 0.4
Track 16 3.7 0.8 0.7
Track 17 5.0 0.1 0.8
Track 18 3.6 0.8 0.9
Track 19 4.3 0.6 1.4
Track 20 4.6 0.4 1.6
Track 21 3.0 1.1 1.9
Track 22 4.6 0.4 2.3
Track 23 3.6 0.9 -2.0
Track 24 2.8 1.2 -0.1
Muons
Electrons
Vertices
DT-segments
CSC-segments
Photons
MET
siStripClusters
Views
Rho Phi
Rho Z
3D

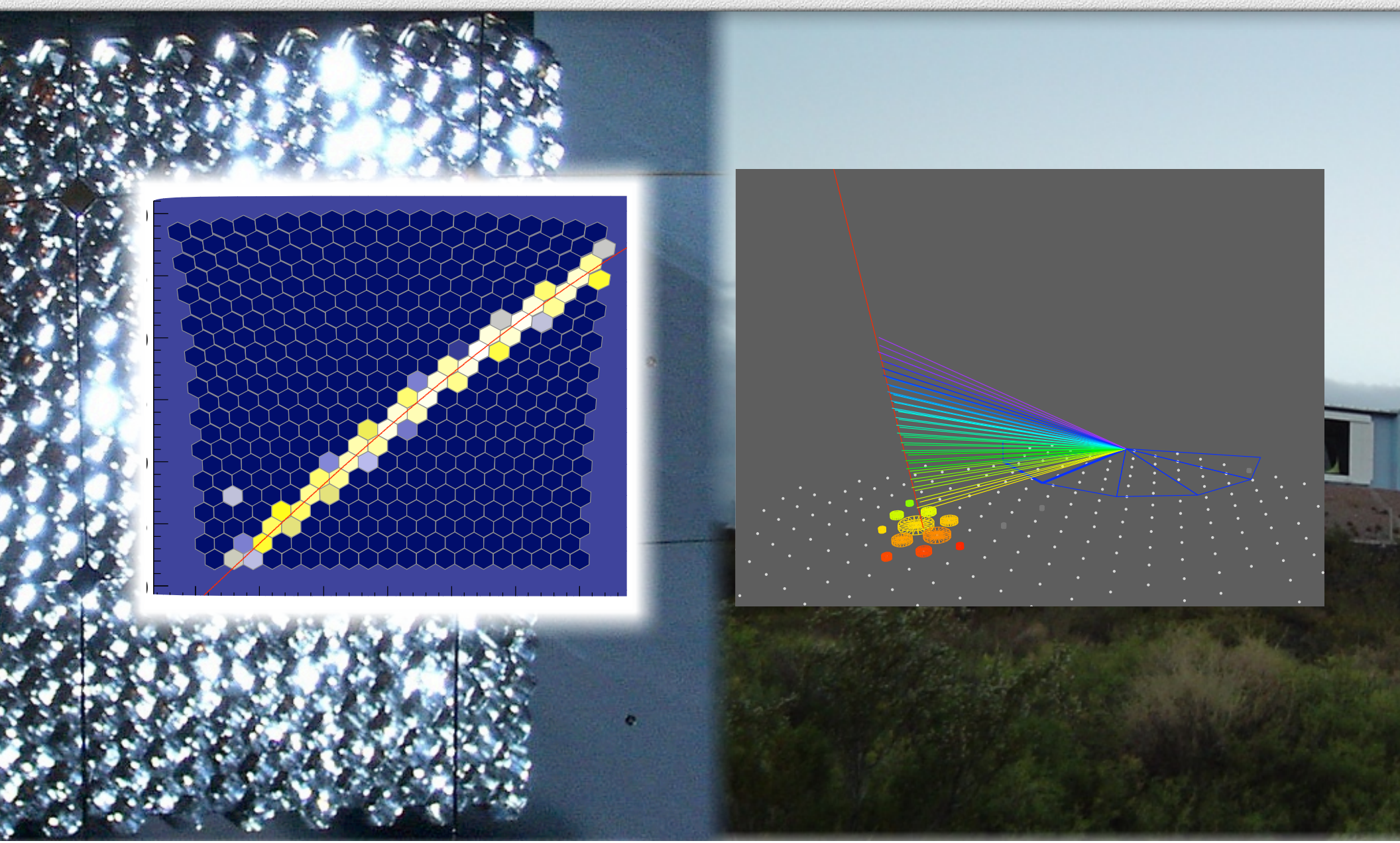
Latest Results

Composition - Inferring the identity of the primary CR

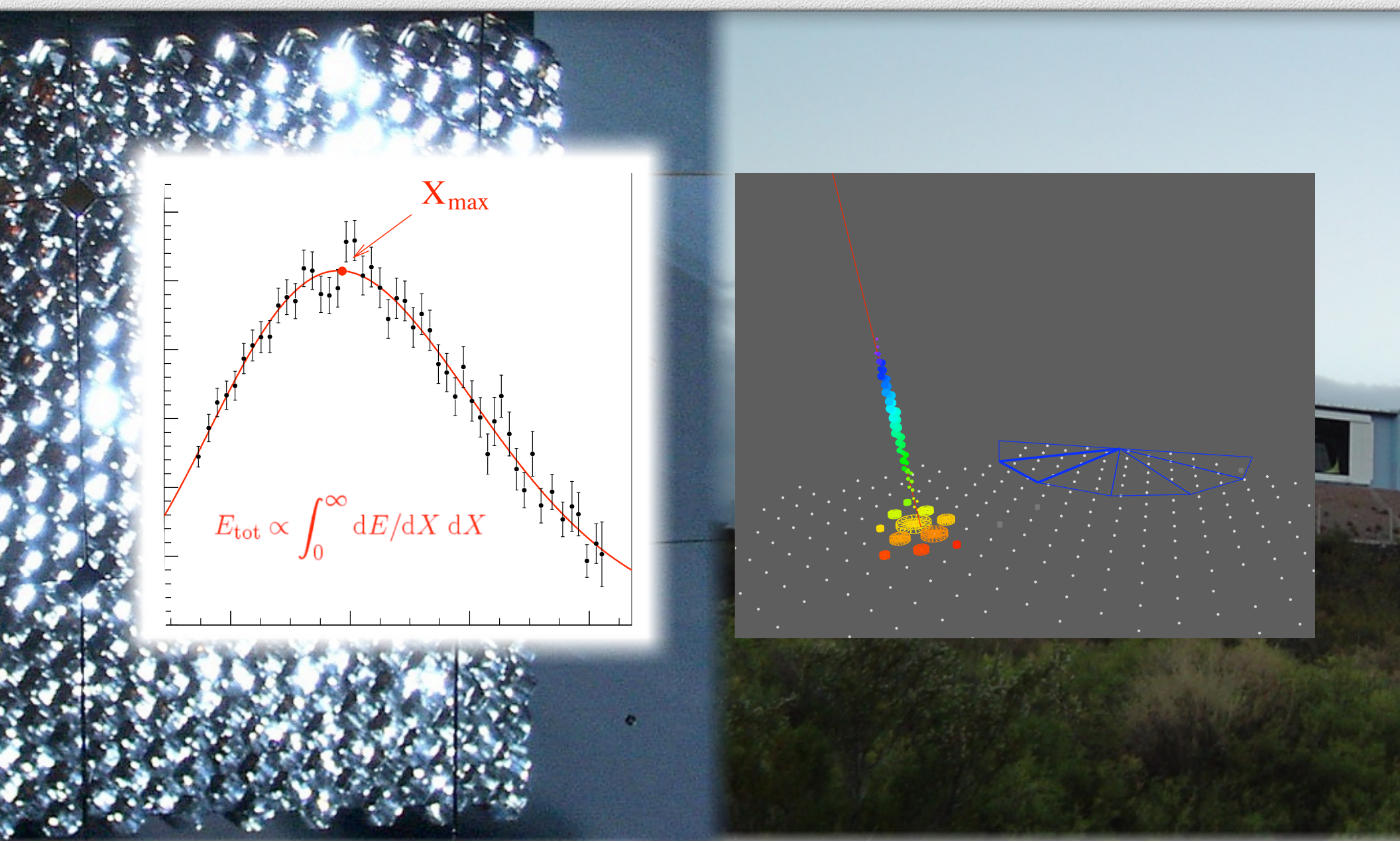
Air shower properties



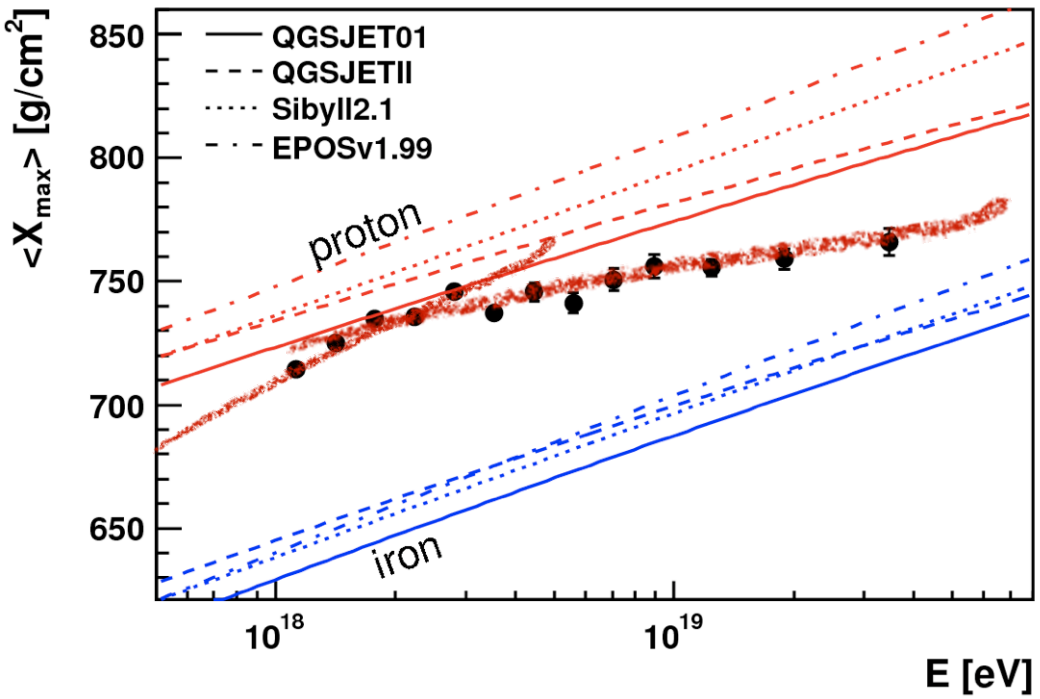
Air shower properties

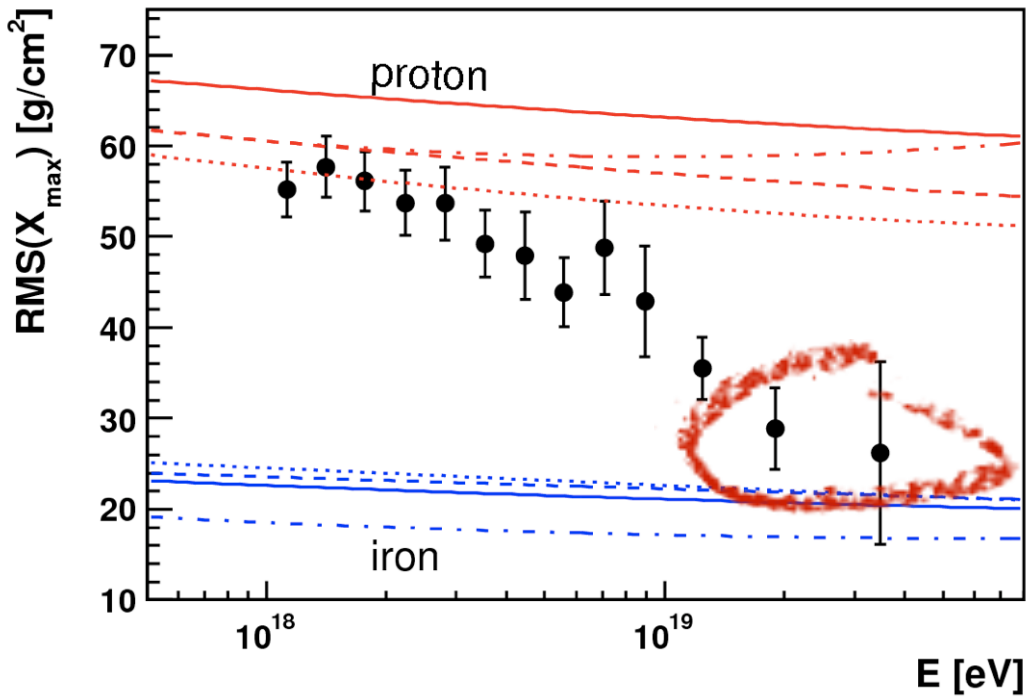


Air shower properties



AS Results - Composition

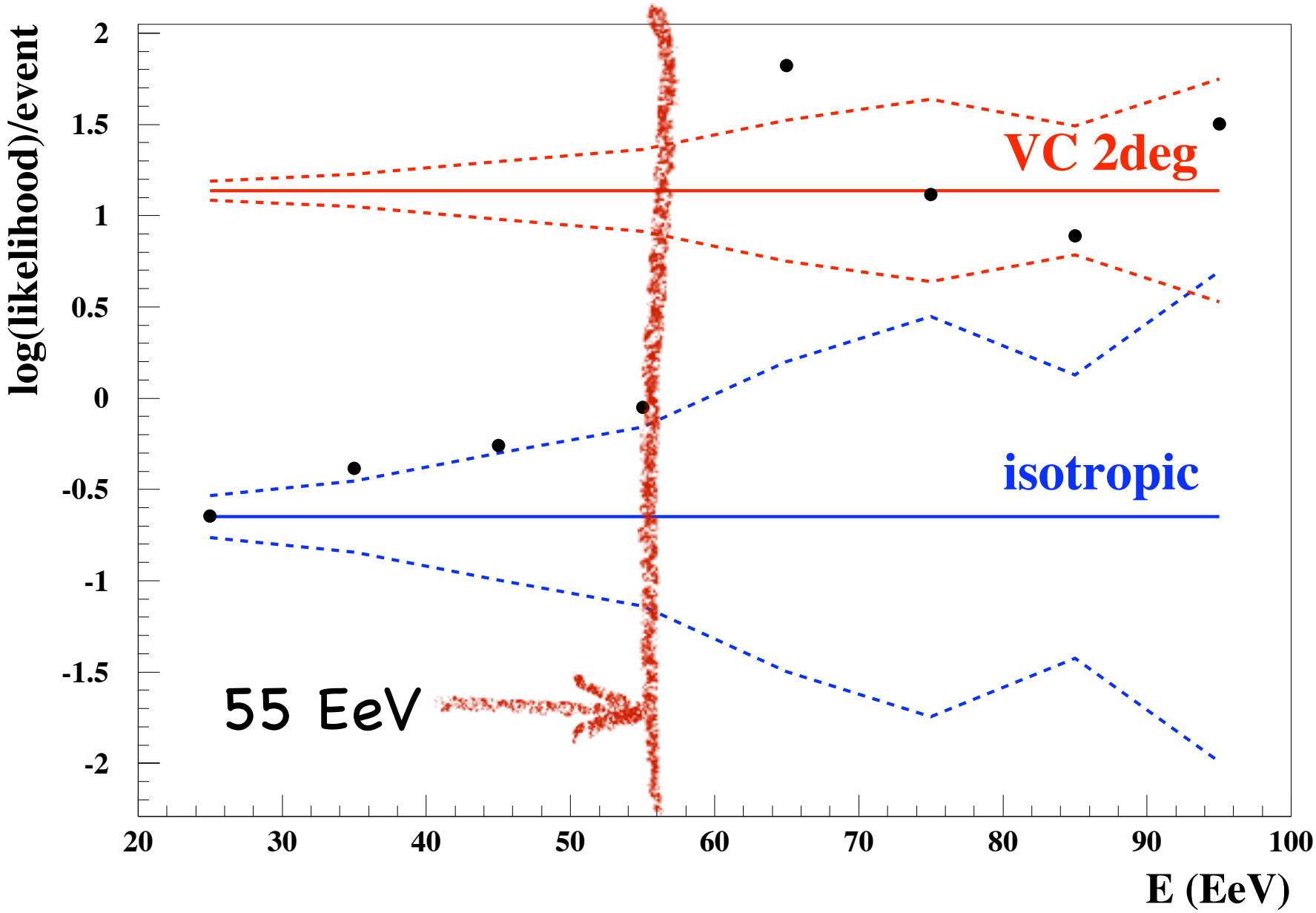




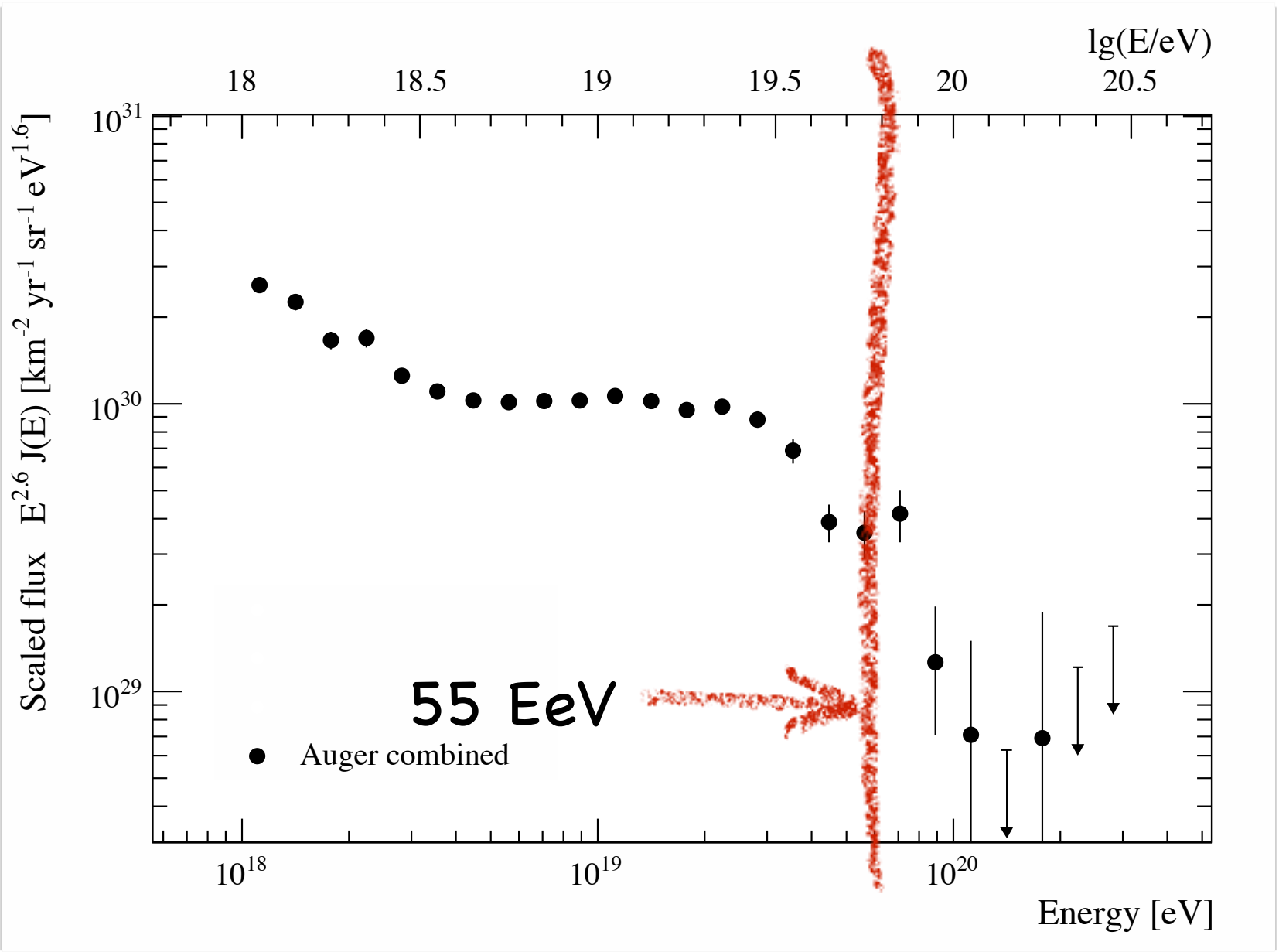
Depth of shower maximum ⇒ UHE hadronic interactions

Physical Review Letters **104** (2010) 091101

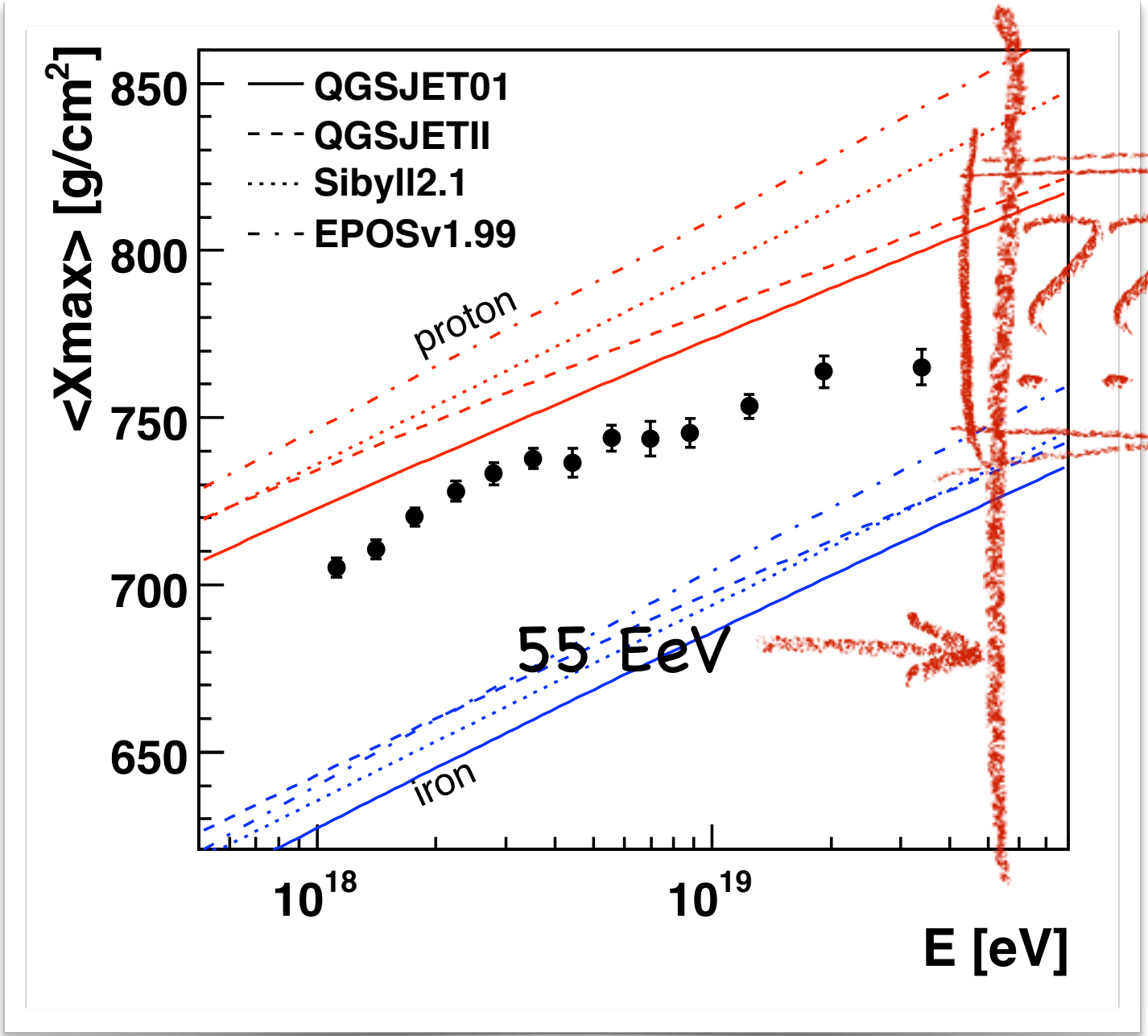
Energy threshold



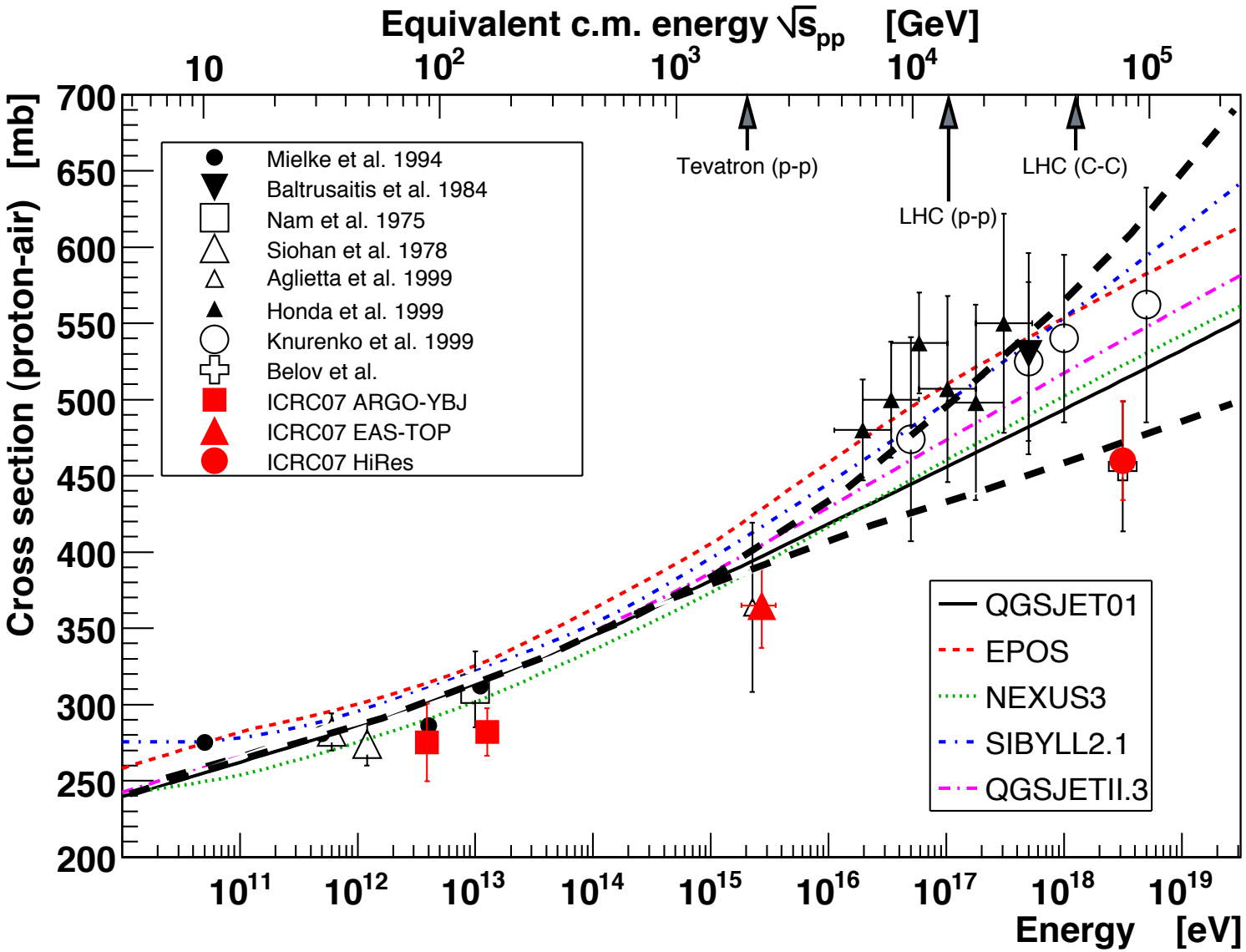
Energy threshold



Energy threshold



AN - Composition



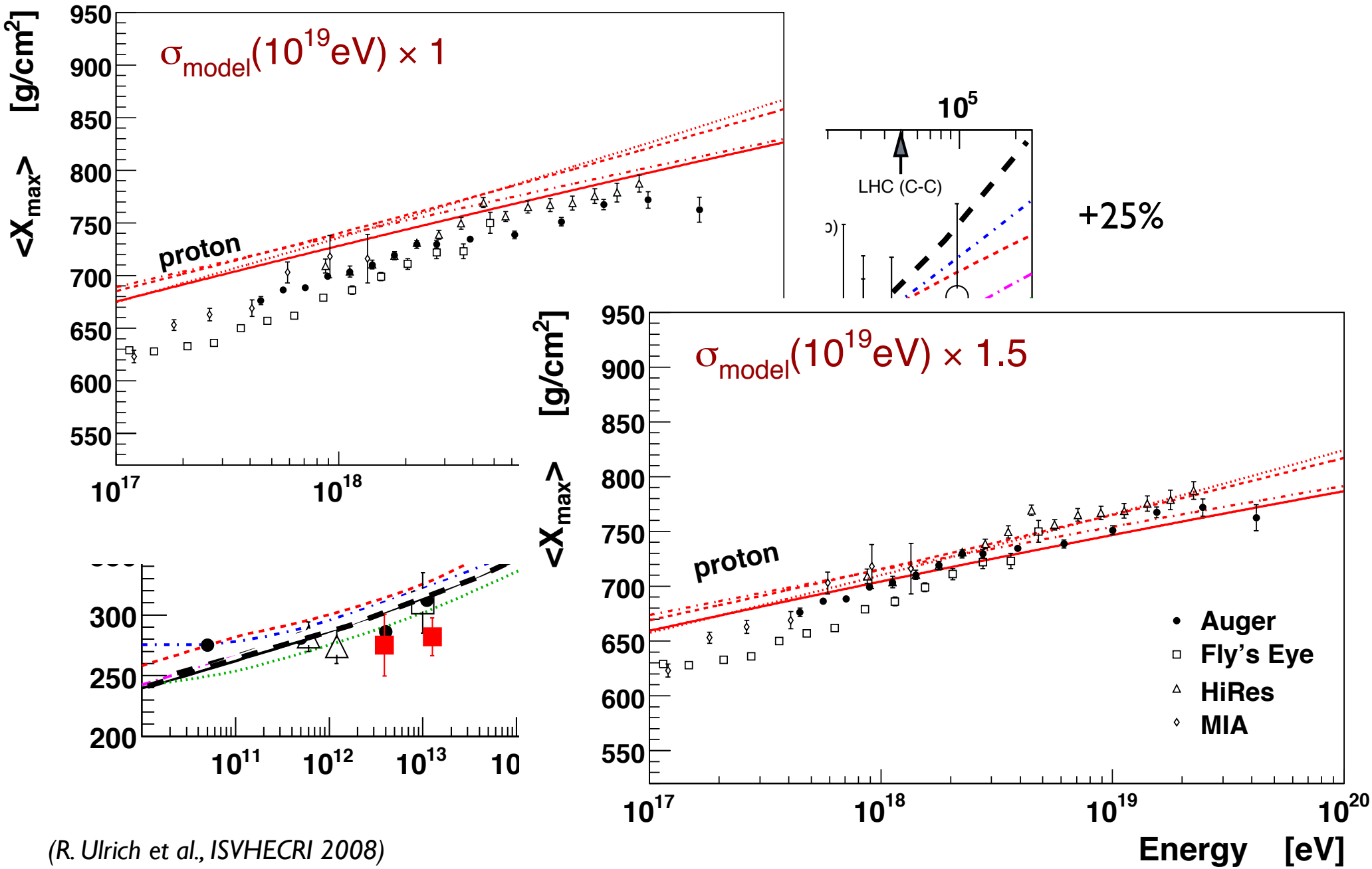
+25%

-10%

Interaction model changed phenomenologically

(R. Ulrich et al., ISVHECRI 2008)

AN - Composition

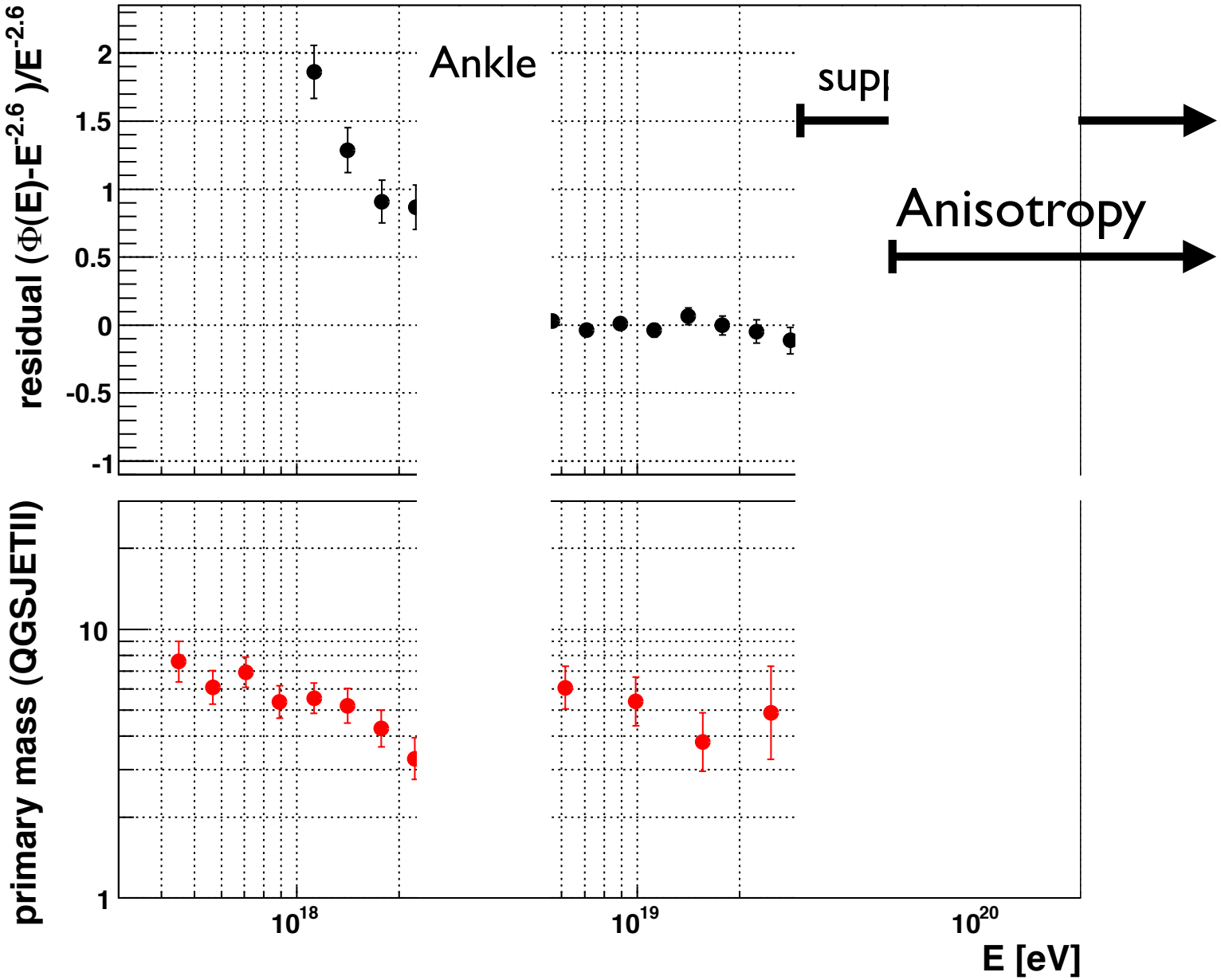


(R. Ulrich et al., ISVHECRI 2008)

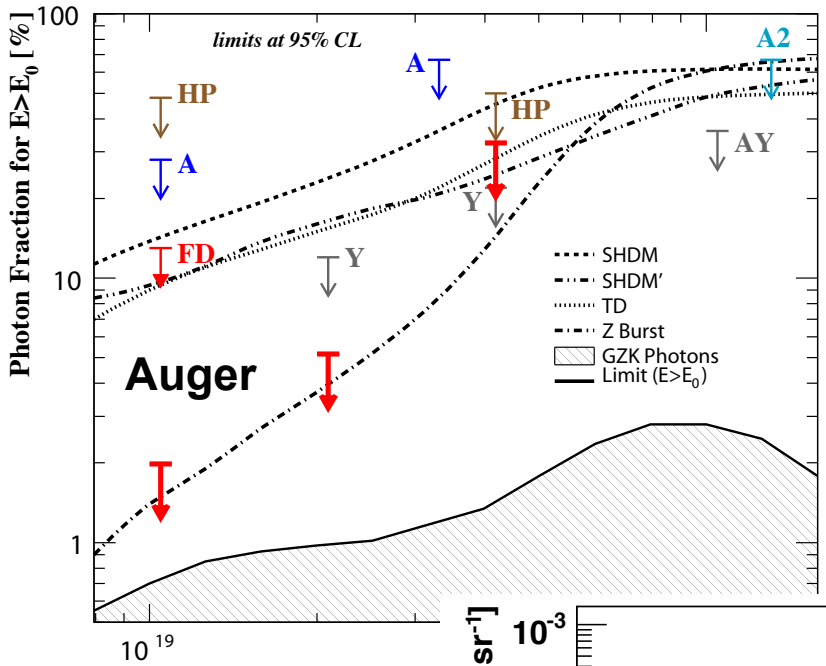
take home message

Deviation from $E^{-2.6}$ flux

Mean mass number



AS Results - Composition

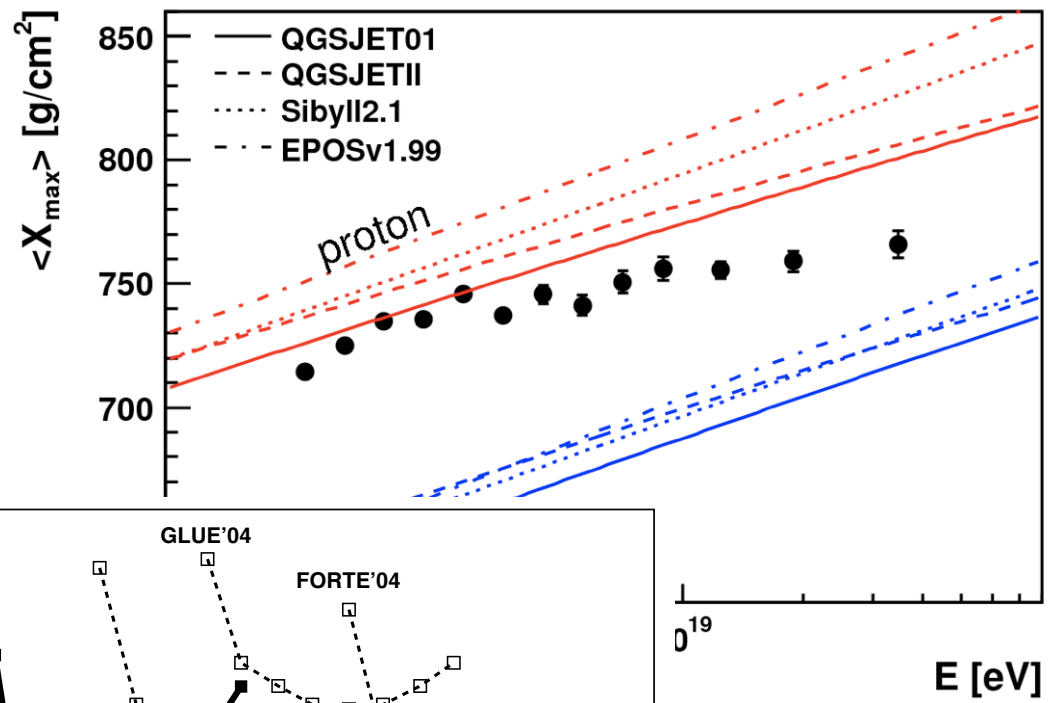


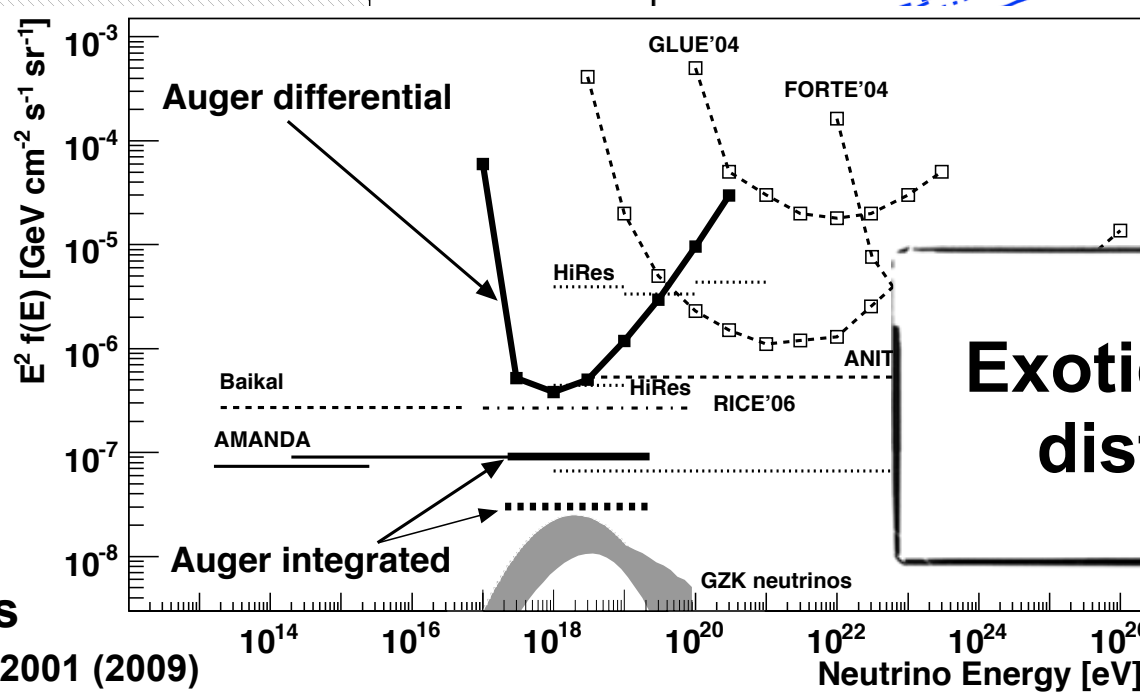
Photon limits

Astrop. Phys. 31 (2009) 399

Hadronic composition

Phys. Rev. Lett. 104 (2010) 091101





Exotic sources disfavored

Neutrino limits

Phys. Rev. D 79, 102001 (2009)

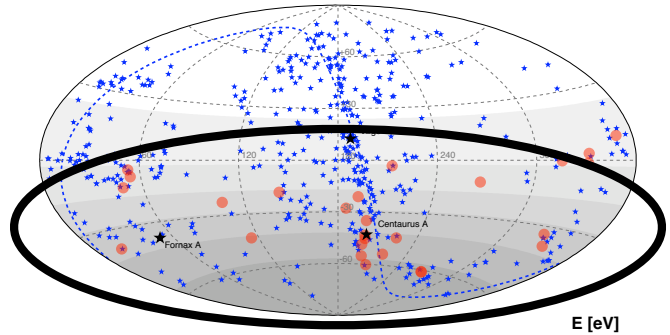
Cosmic Rays - Outline

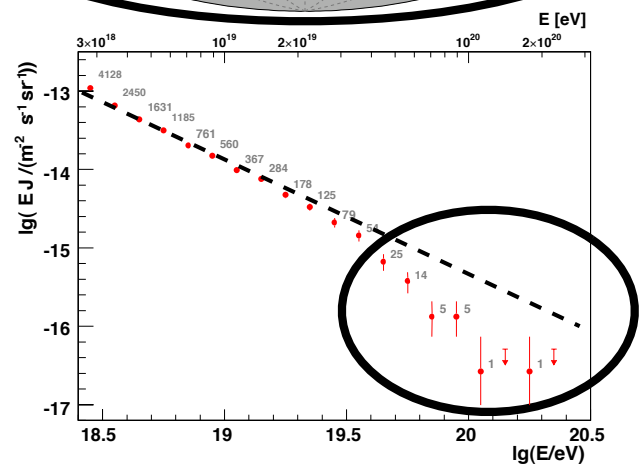
- Motivation
- A detector of UHE particles
- Science Results
- Summary & Conclusions
- Outlook

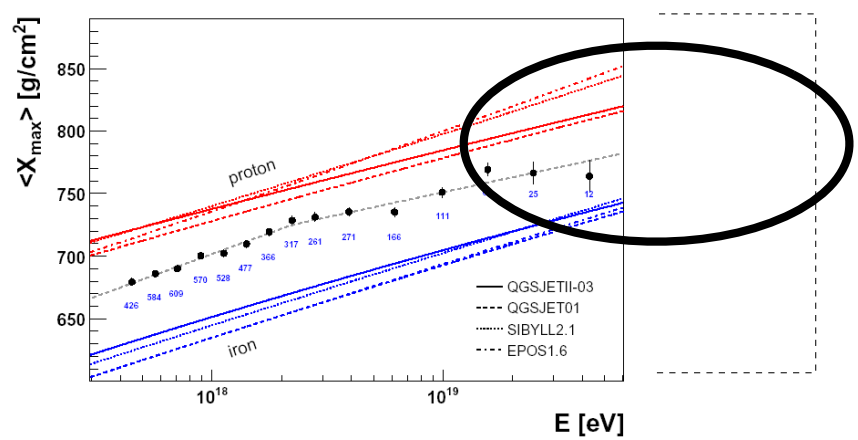
Summary & Conclusions

Auger South has shown

- There is a flux suppression
- The sky is anisotropic above 60 EeV
- There are nearby UHE sources, and they follow the matter distribution
- Exotic models are disfavored







Pierre Auger Observatory

studying the universe's highest energy particles

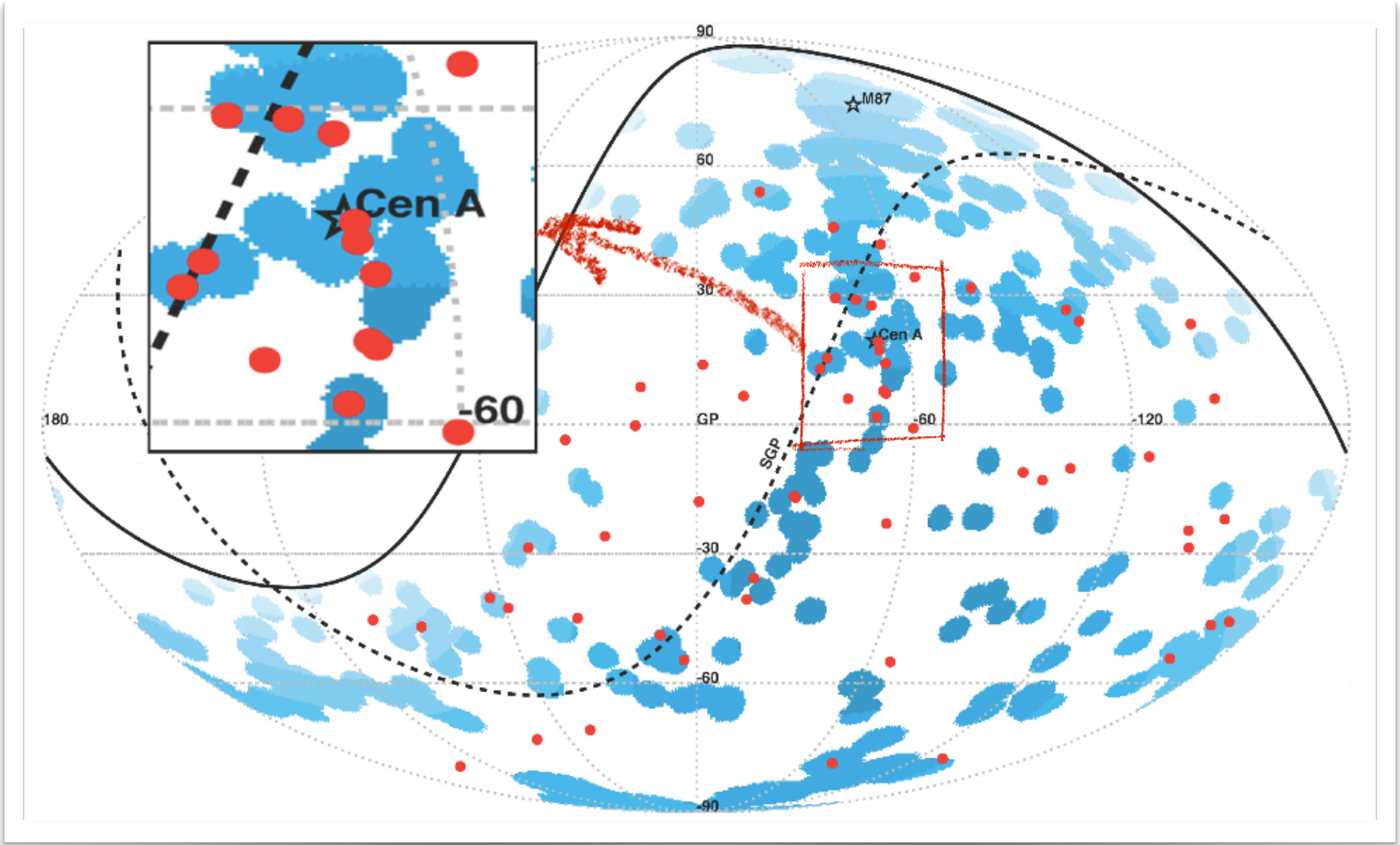
- discover the sources of UHECRs
- study UHE interactions
- detect UHE neutrinos & photons

Cosmic Rays - Outline

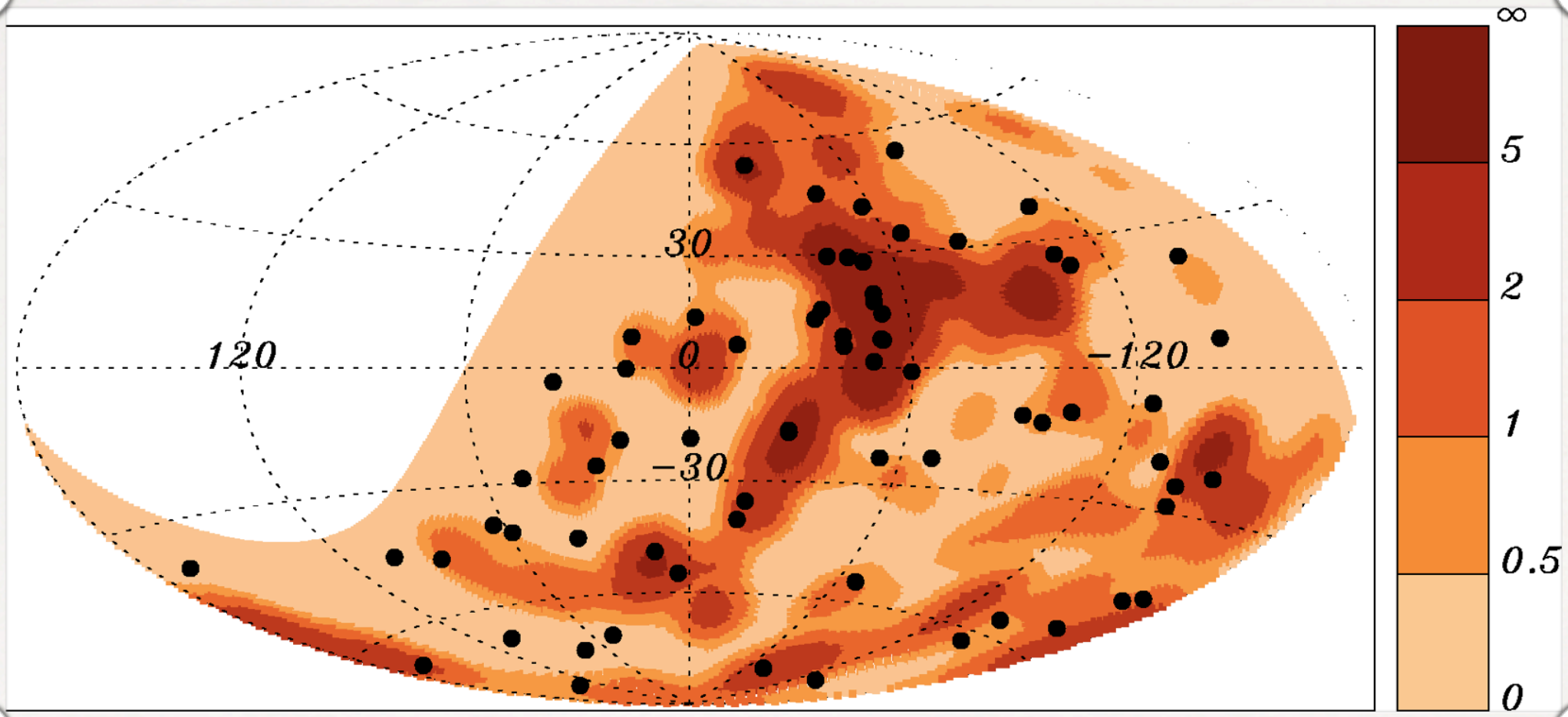
- Motivation
- A detector of UHE particles
- Science Results
- Summary & Conclusions
- Outlook


THE FOLLOWING PREVIEW HAS BEEN APPROVED FOR
ALL AUDIENCES
BY THE MOTION PICTURE ASSOCIATION OF AMERICA, INC.
www.filmratings.com
www.mpaa.org

Find those sources!

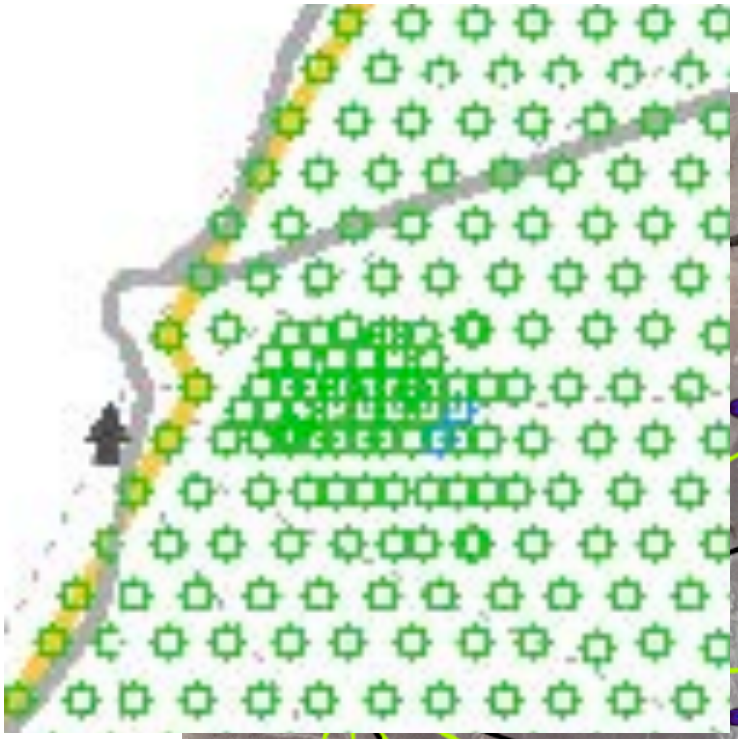


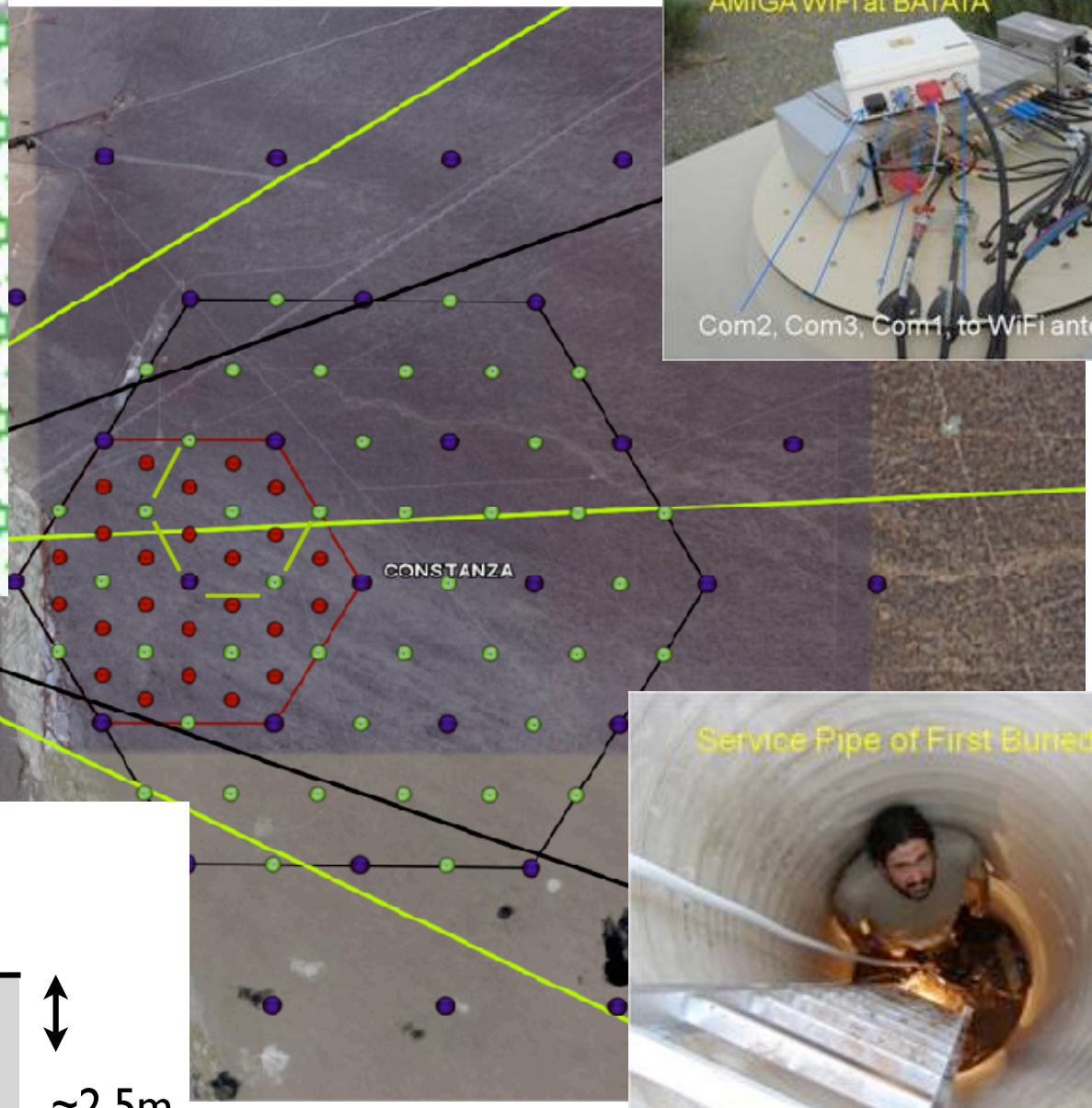
Local matter

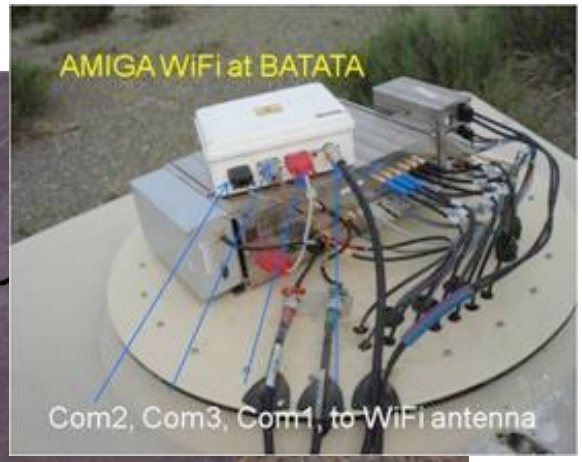


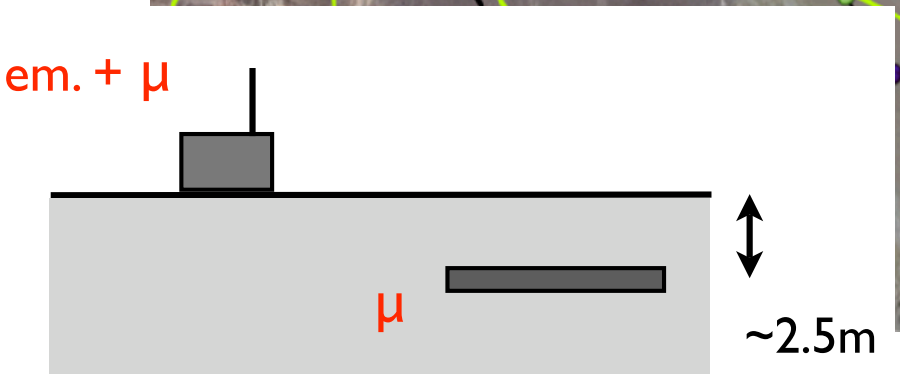
Our 69 events compared to X-ray AGN detected by SWIFT-BAT, using a smoothing angle 4 degrees.

Enhancing the South

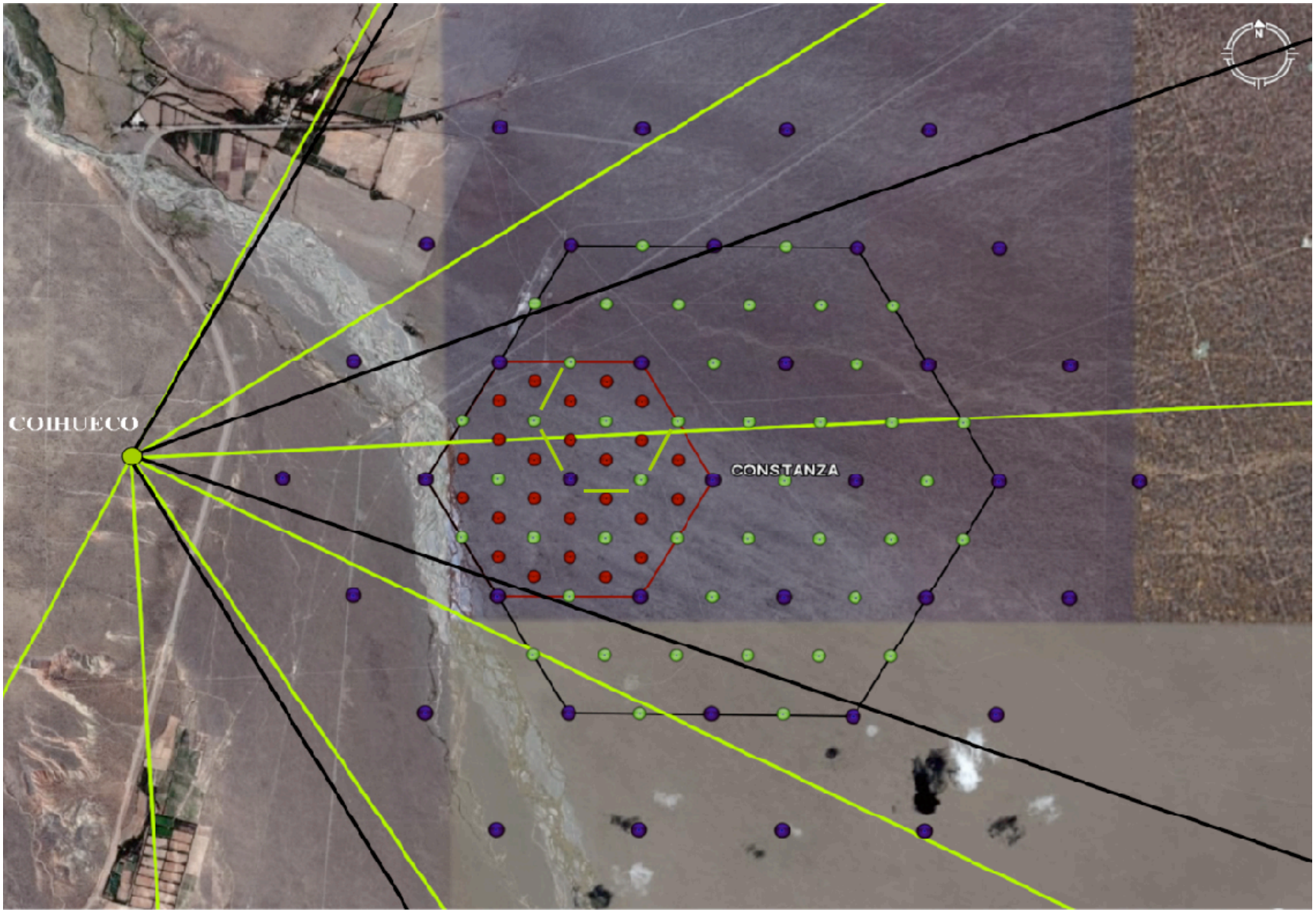




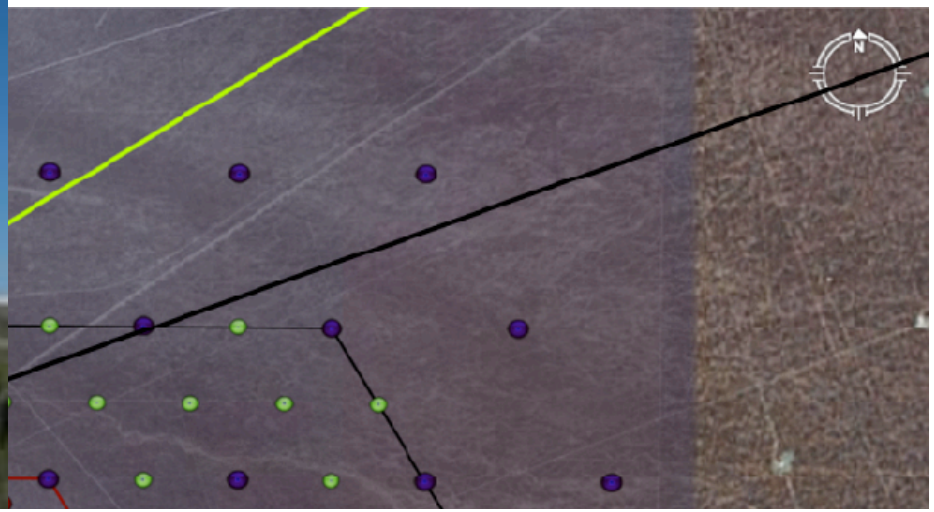


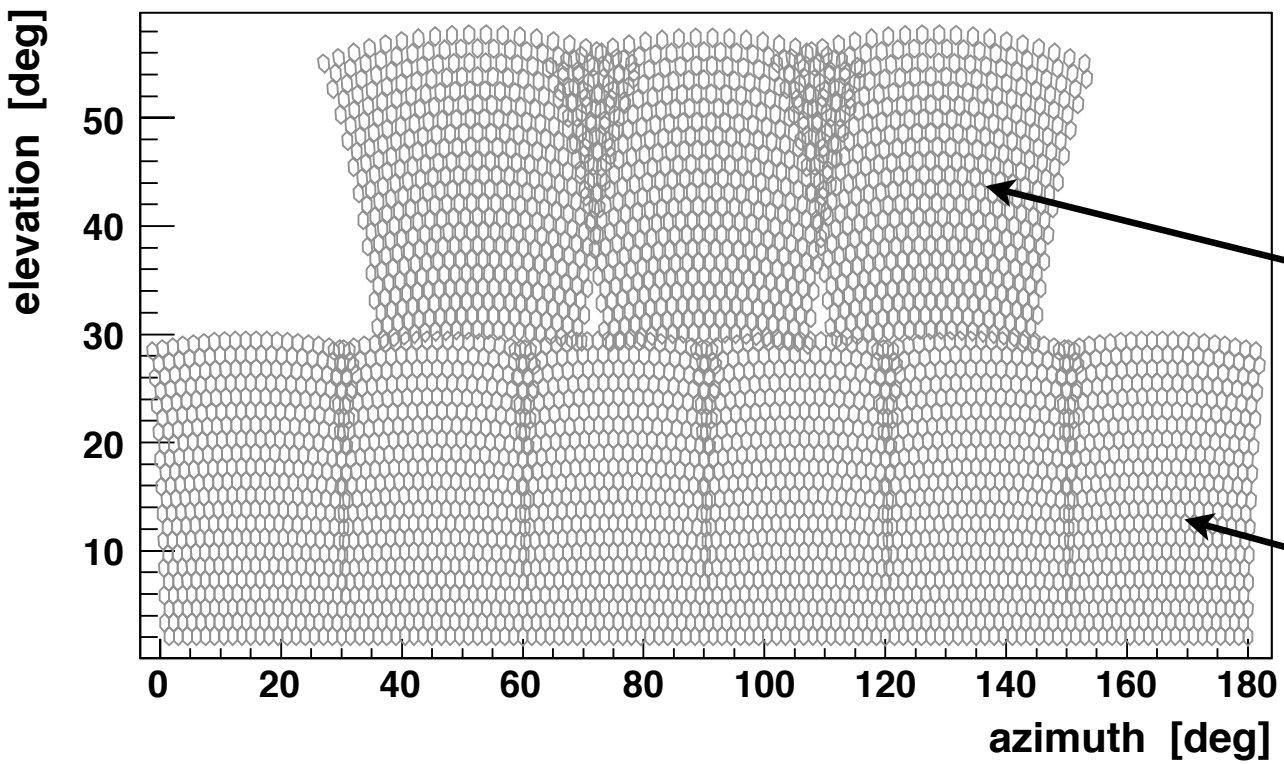


Enhancing the South



Enhancing the South

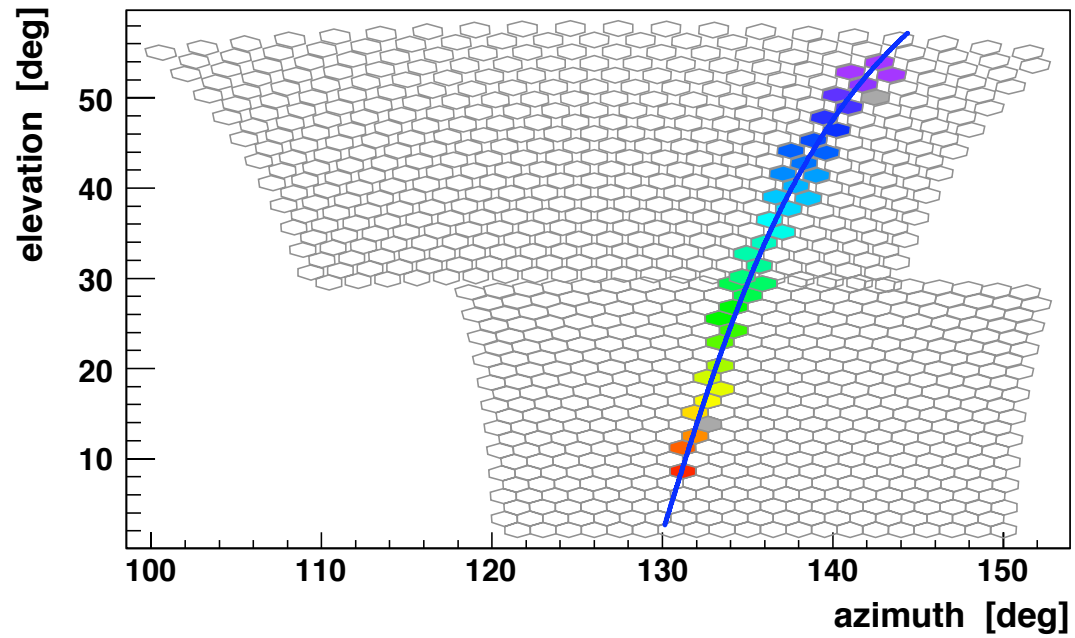


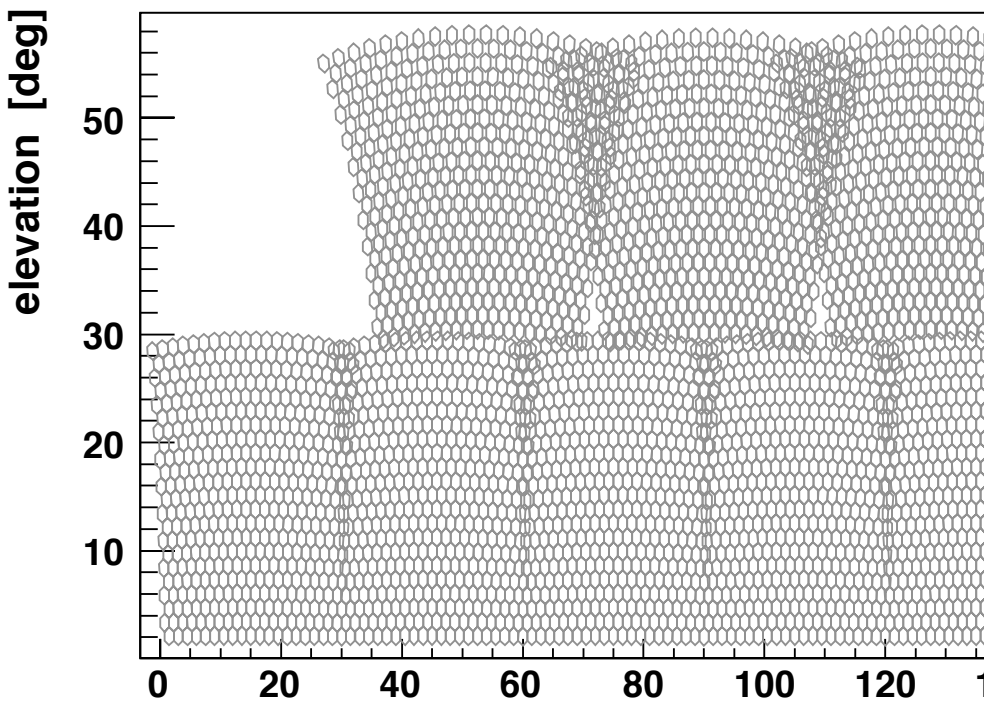


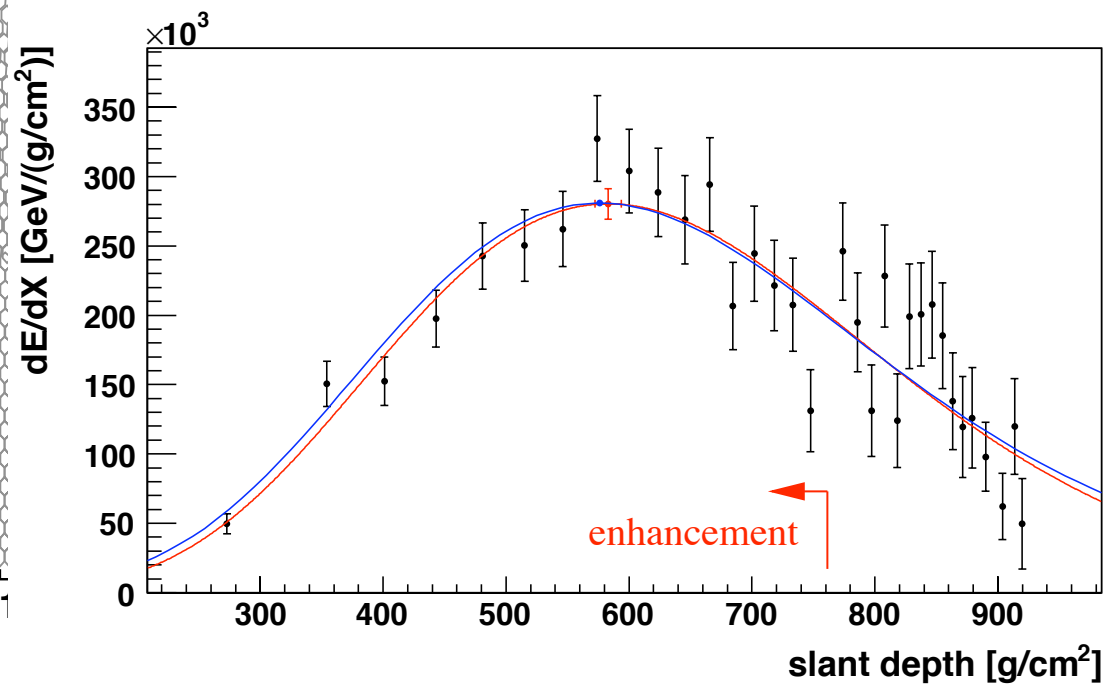
HEAT telescopes (40° separation)

Standard Auger telescopes

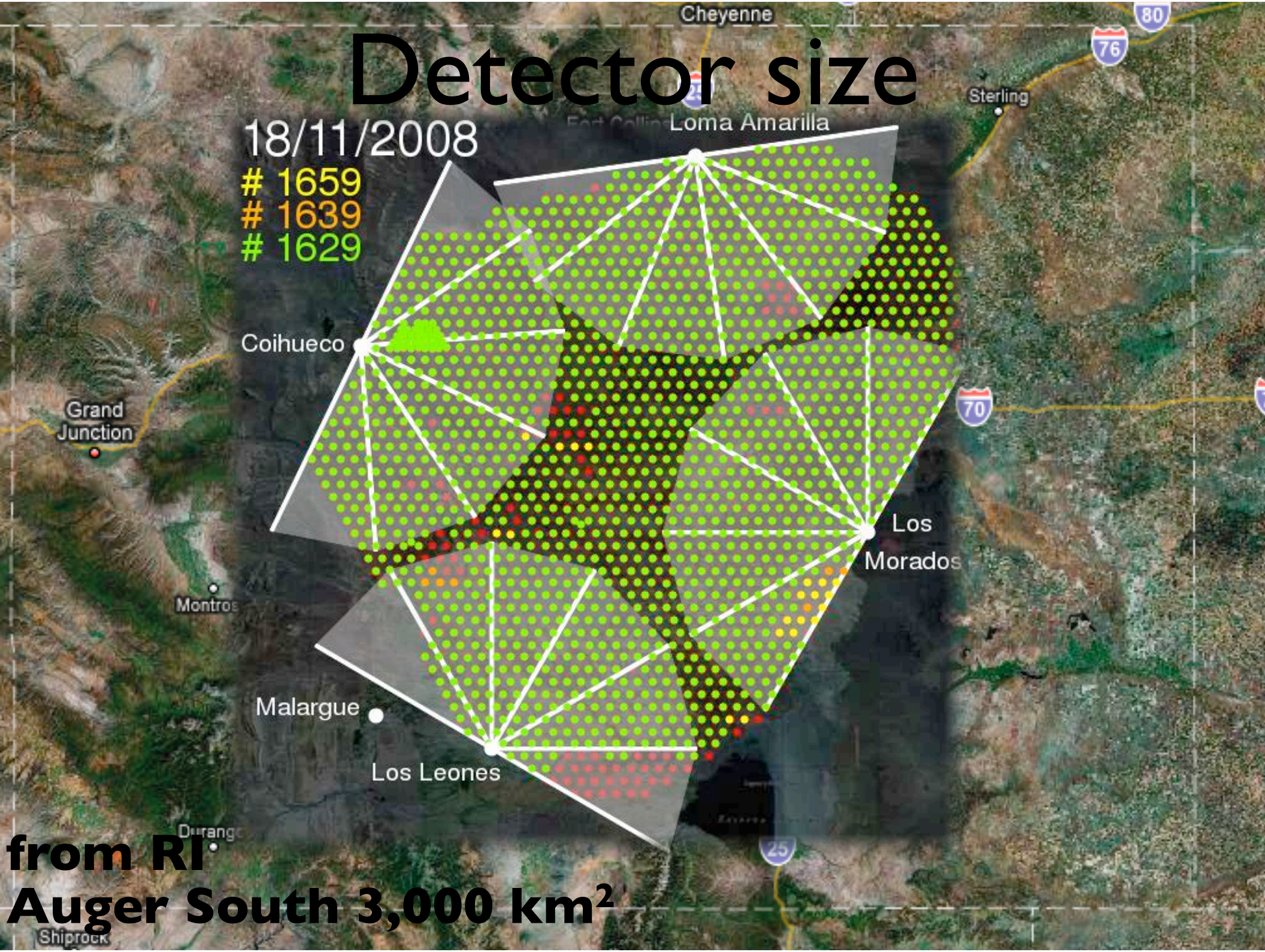
Enhancing the South







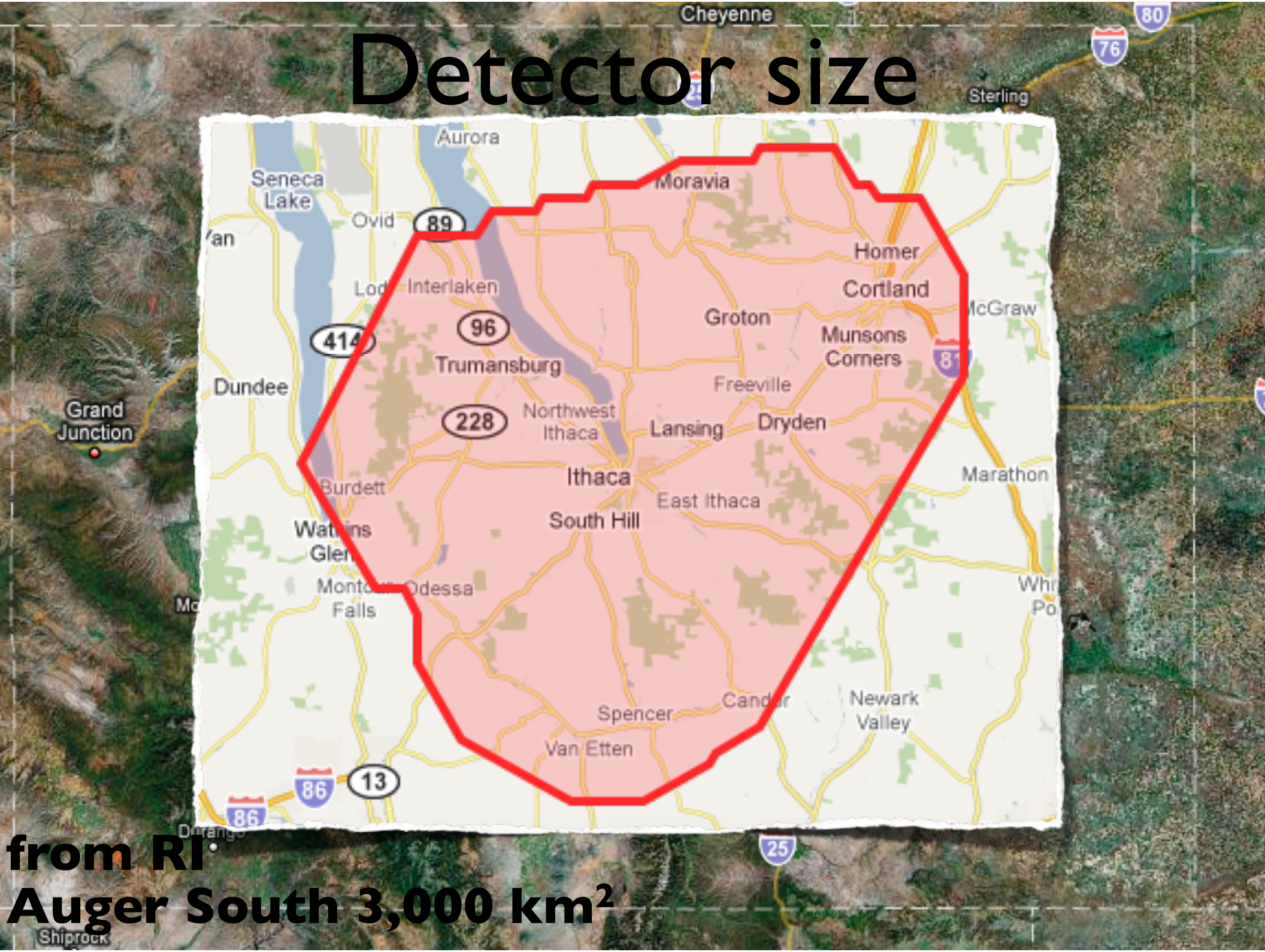
Detector size



from RI

Auger South 3,000 km^2

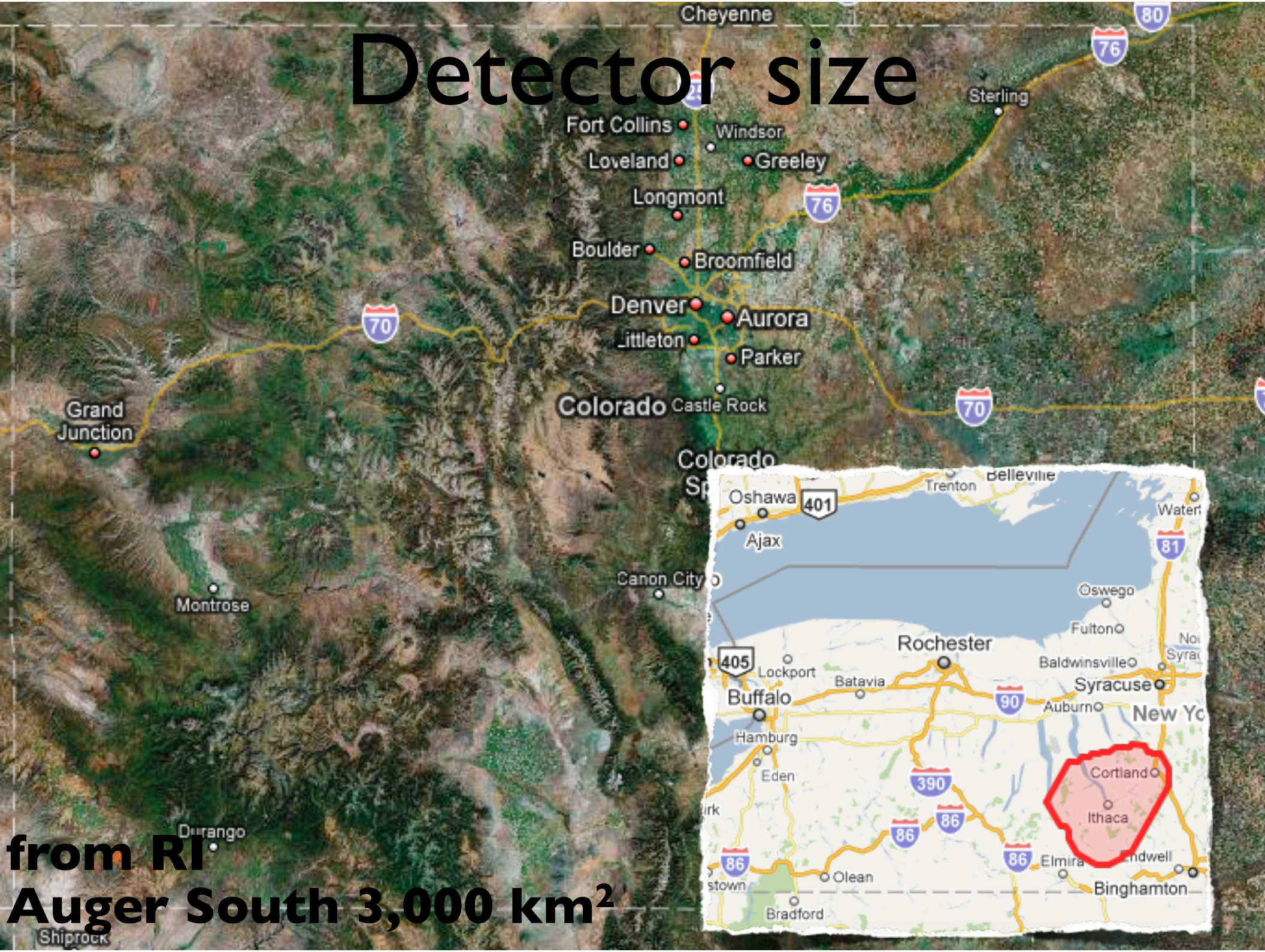
Detector size



from RI

Auger South 3,000 km^2

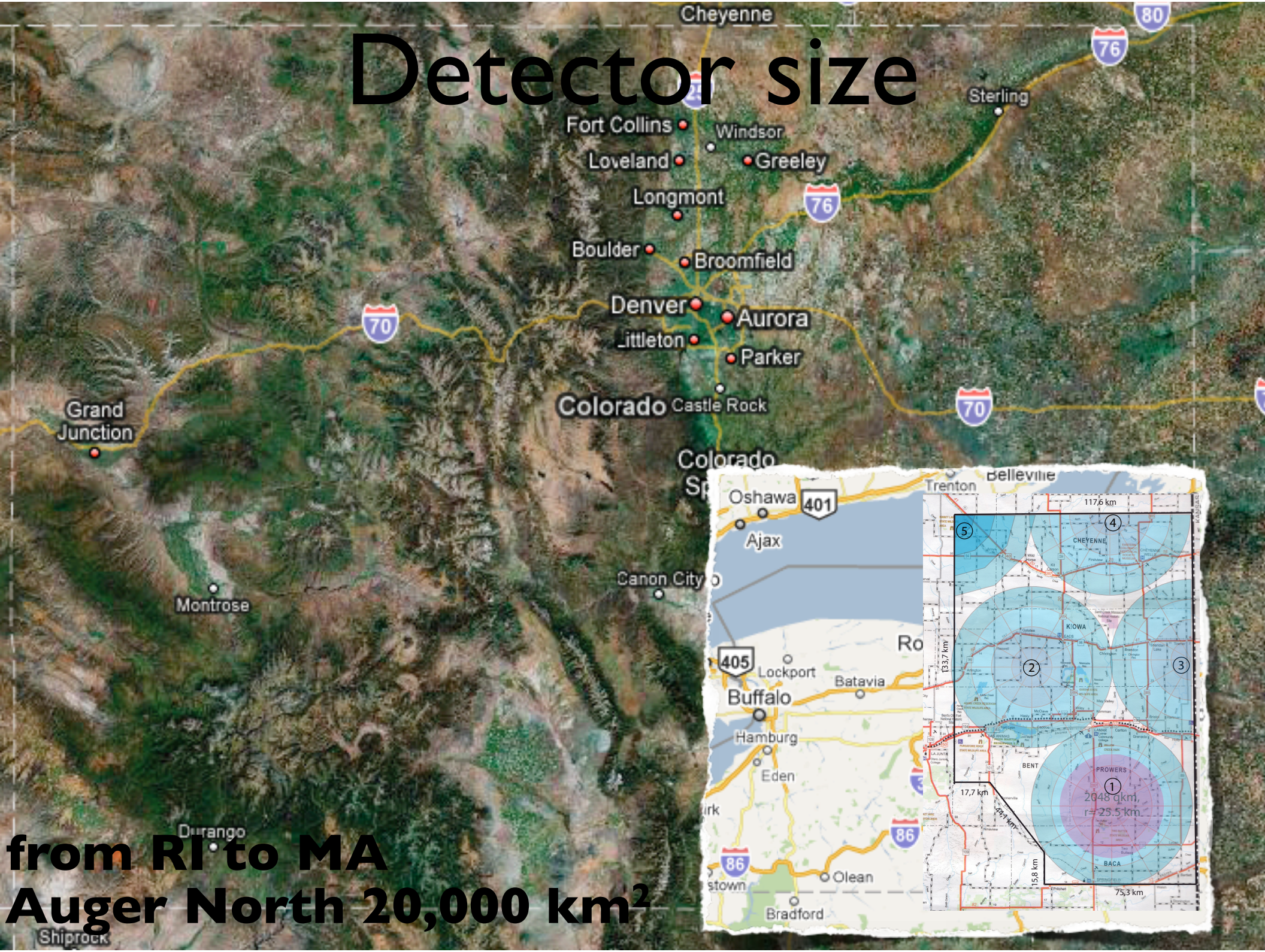
Detector size



from RI

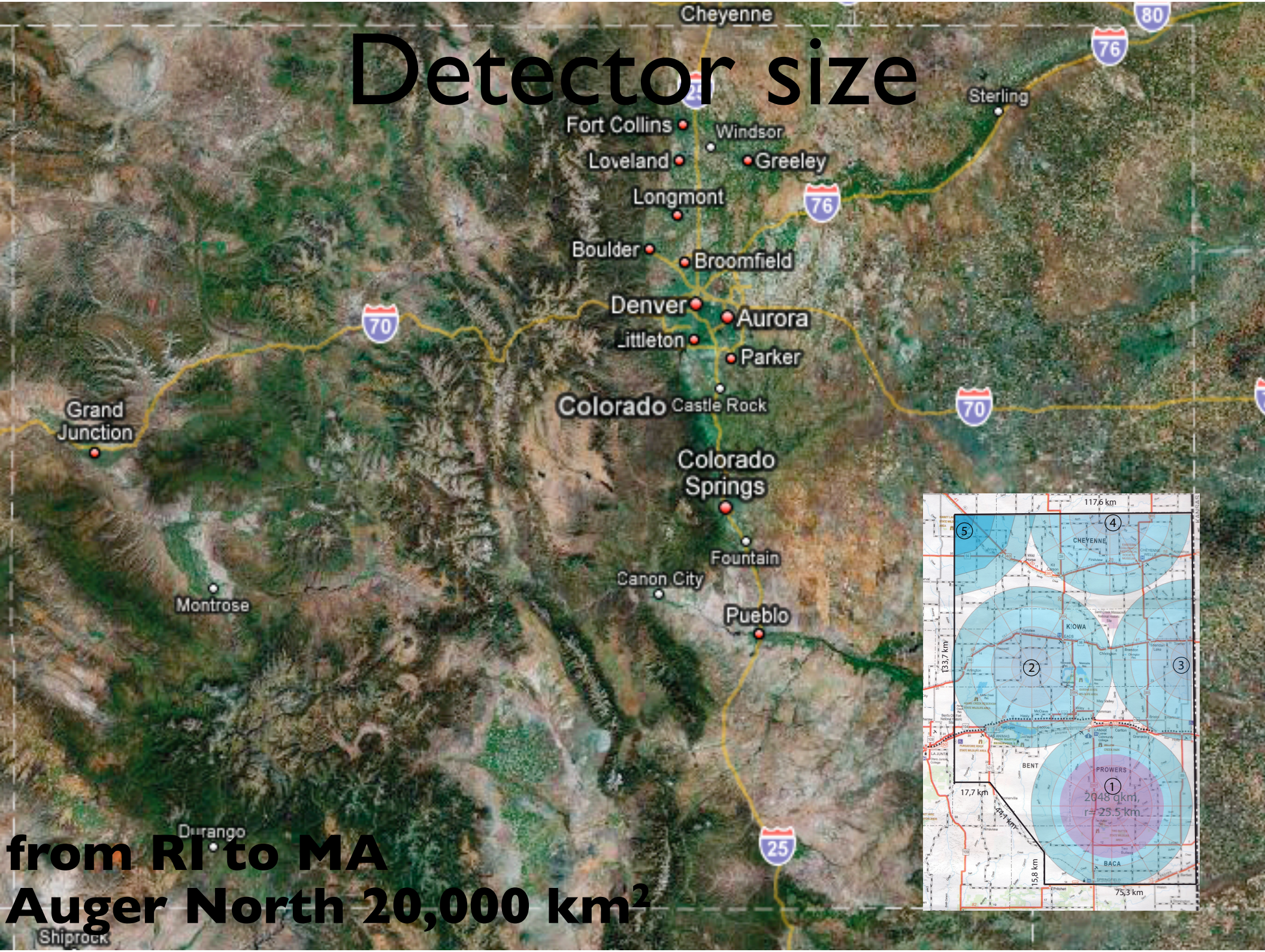
Auger South 3,000 km²

Detector size



from RI to MA
Auger North 20,000 km²

Detector size

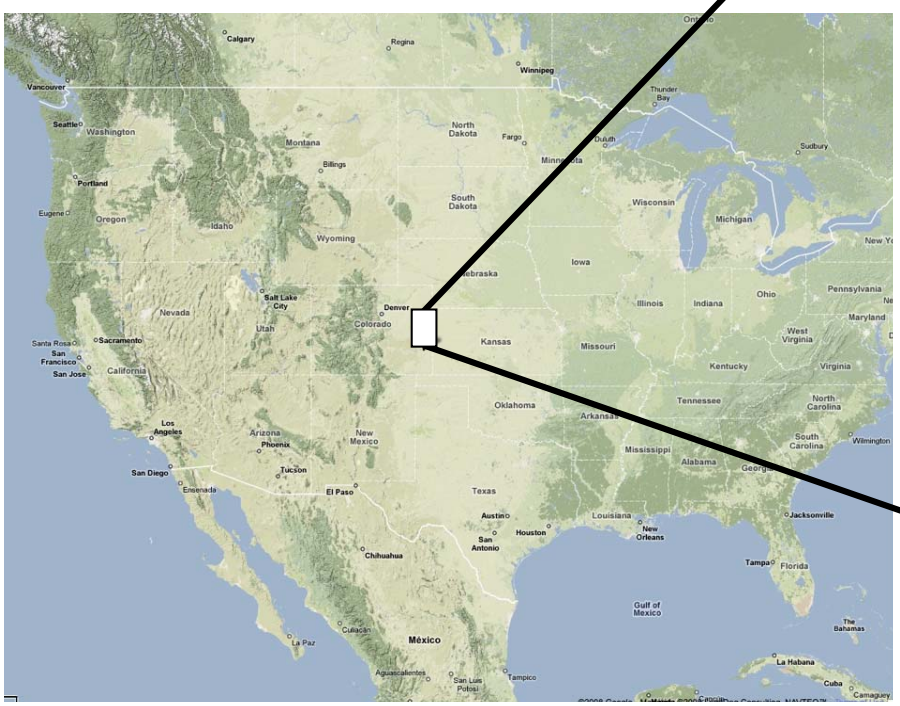


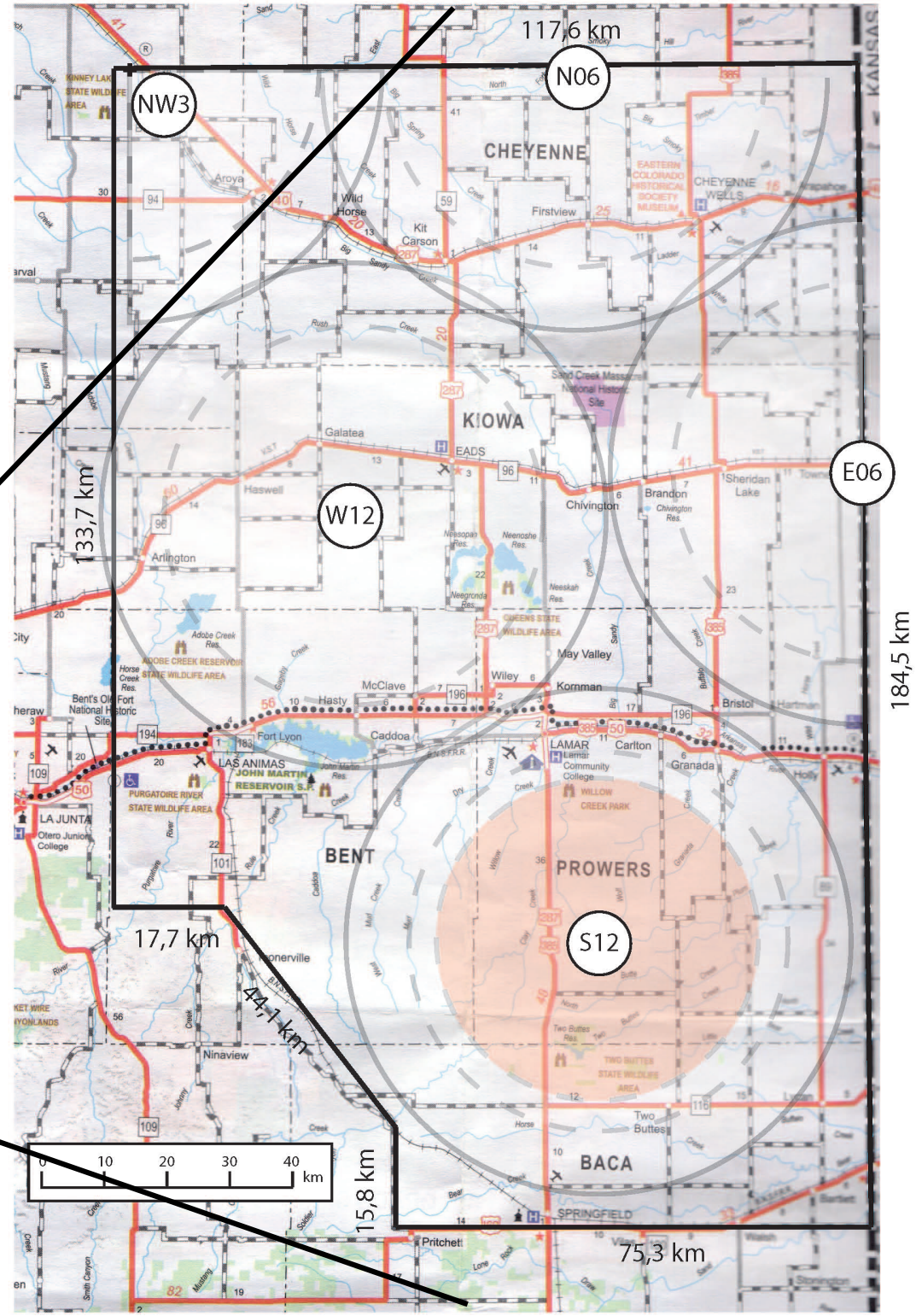
from RI to MA

Auger North 20,000 km²

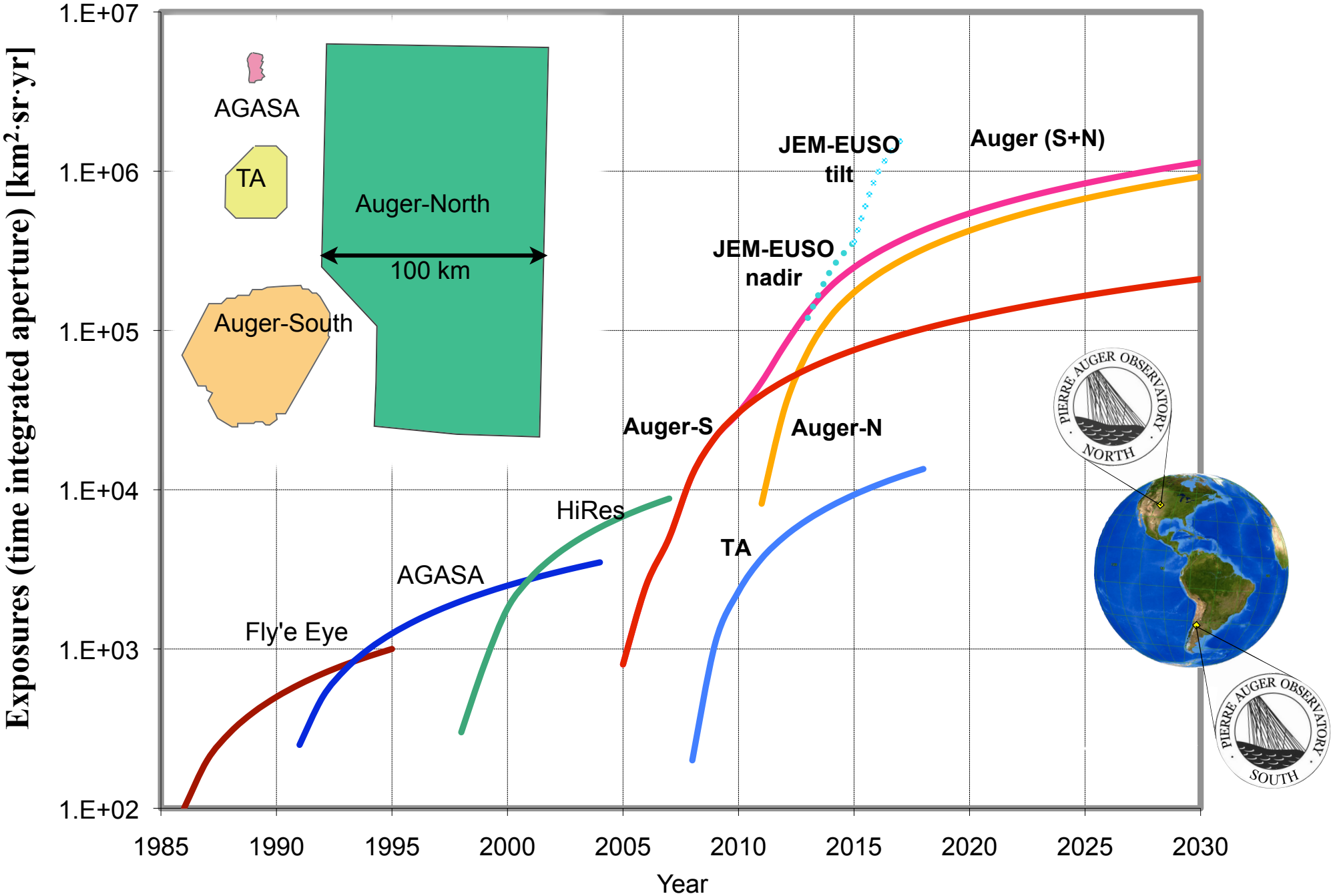
AN design

- 20,000 km^2 with 4,400 surface stations
- 39 fluorescence telescopes (~85% coverage)

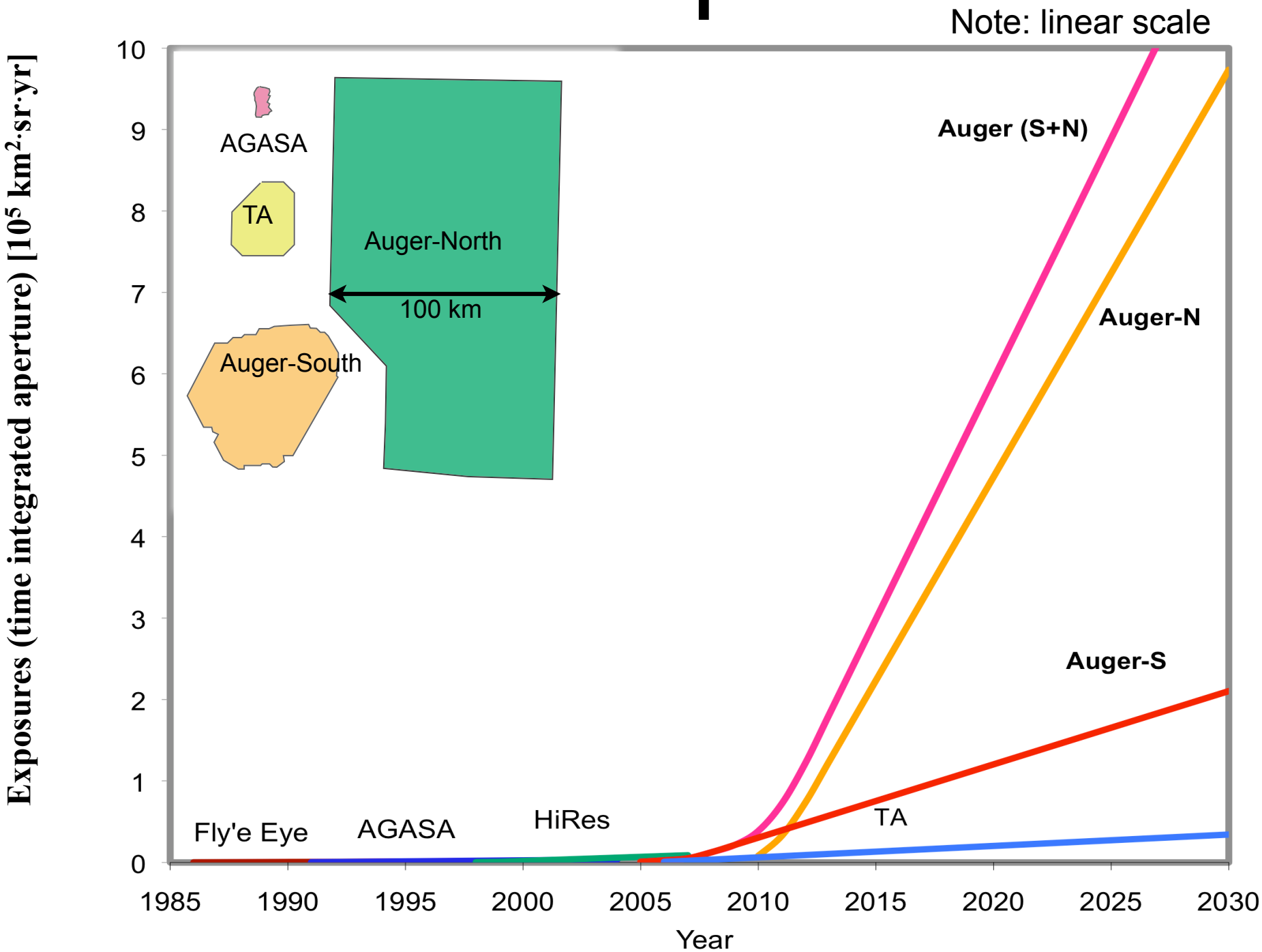




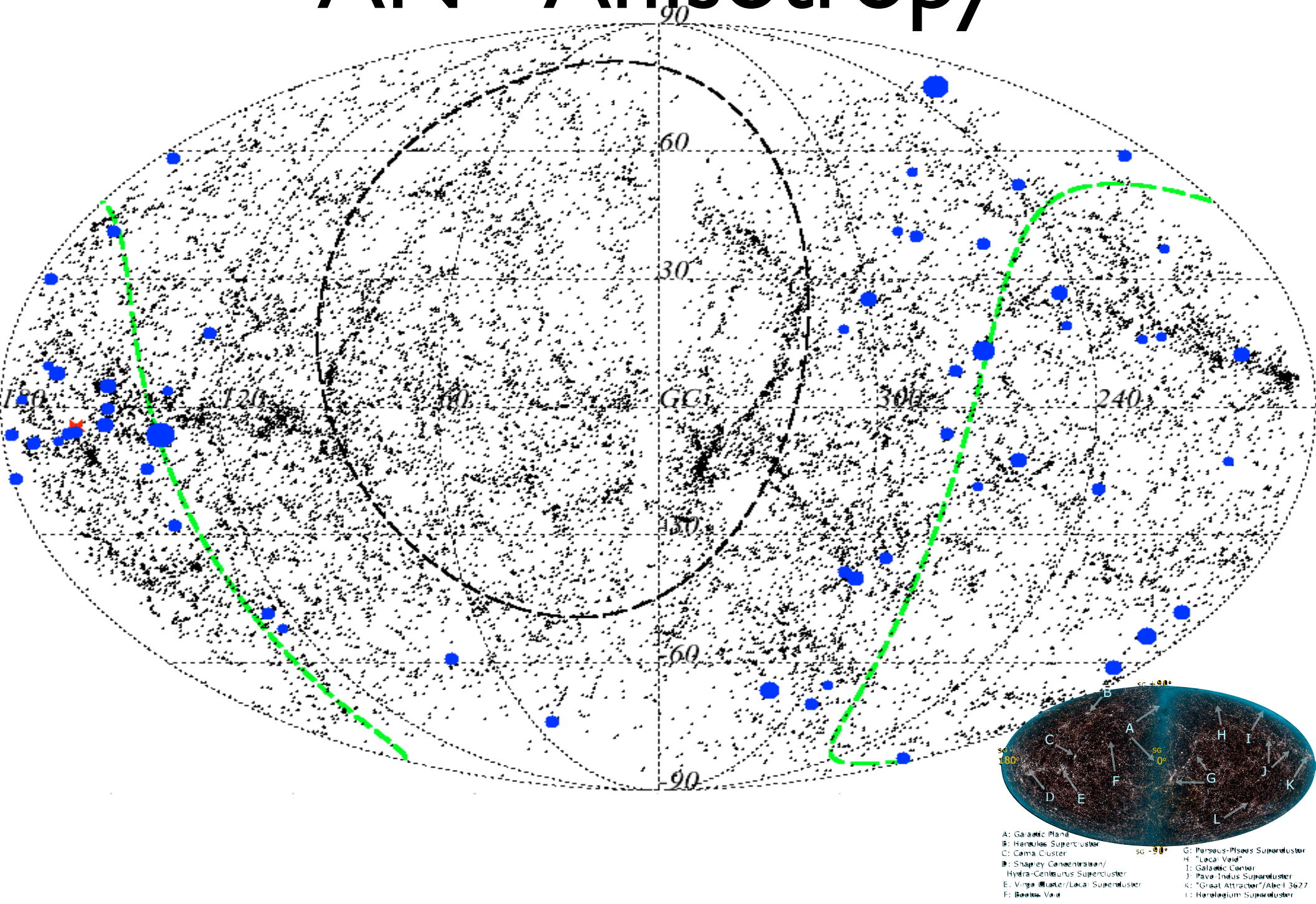
AN - Exposure


Exposures (time integrated aperture) [km²·sr·yr]
1.E+07
1.E+06
1.E+05
1.E+04
1.E+03
1.E+02
1985
1990
1995
2000
2005
2010
2015
2020
2025
2030
Year
AGASA
TA
Auger-North
100 km
Auger-South
JEM-EUSO tilt
JEM-EUSO nadir
Auger (S+N)
Auger-S
Auger-N
HiRes
TA
AGASA
Fly'e Eye
PIERRE AUGER OBSERVATORY NORTH
PIERRE AUGER OBSERVATORY SOUTH

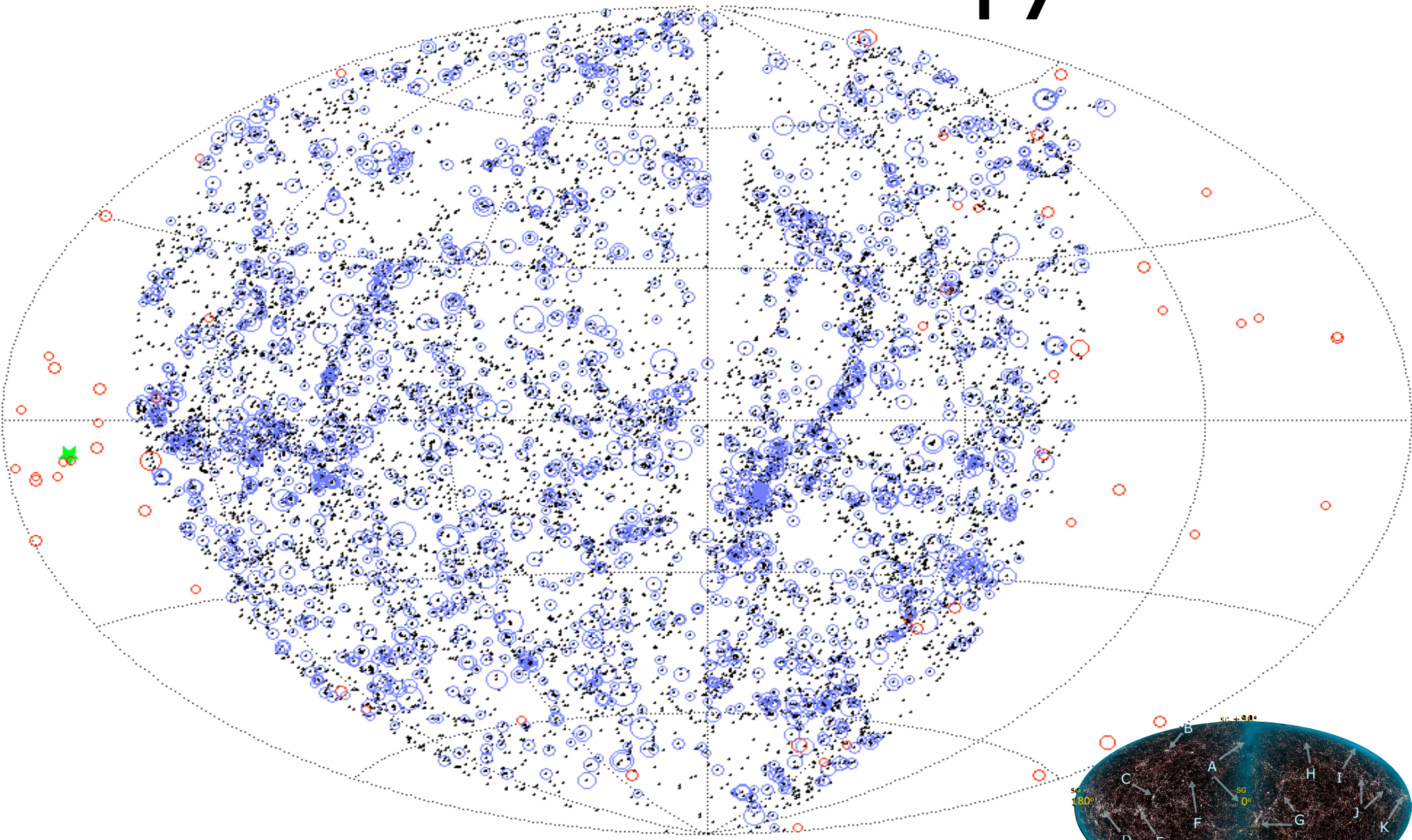
AN - Exposure

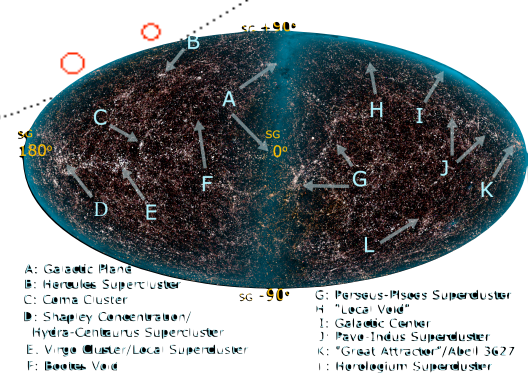

Note: linear scale
Exposures (time integrated aperture) [10^5 km^2·sr·yr]
10
9
8
7
6
5
4
3
2
1
0
AGASA
TA
Auger-North
100 km
Auger-South
Auger (S+N)
Auger-N
Auger-S
Fly'e Eye
AGASA
HiRes
TA
1985
1990
1995
2000
2005
2010
2015
2020
2025
2030
Year

AN - Anisotropy



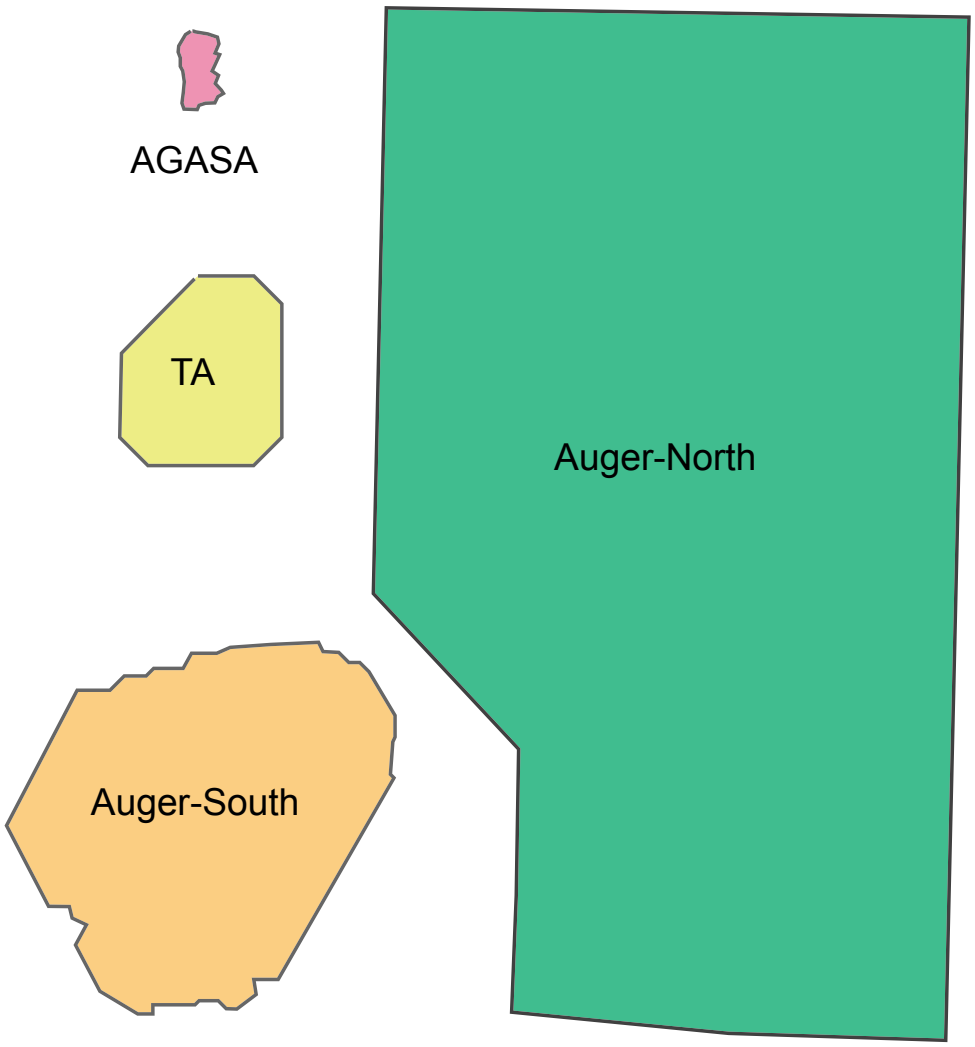
AN - Anisotropy

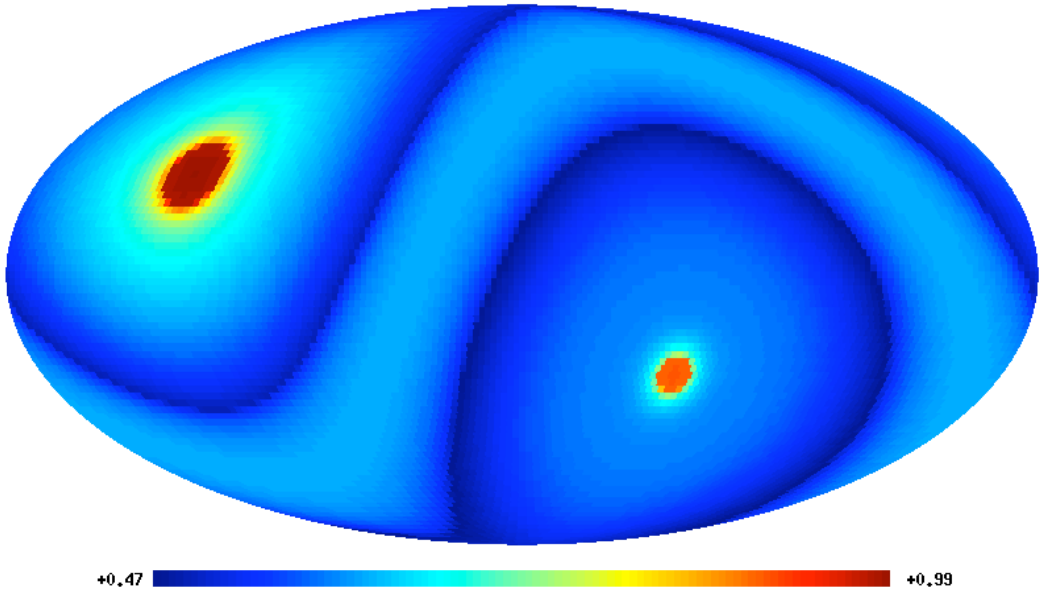




Sky map with 10 years of AN

AN -Take home message

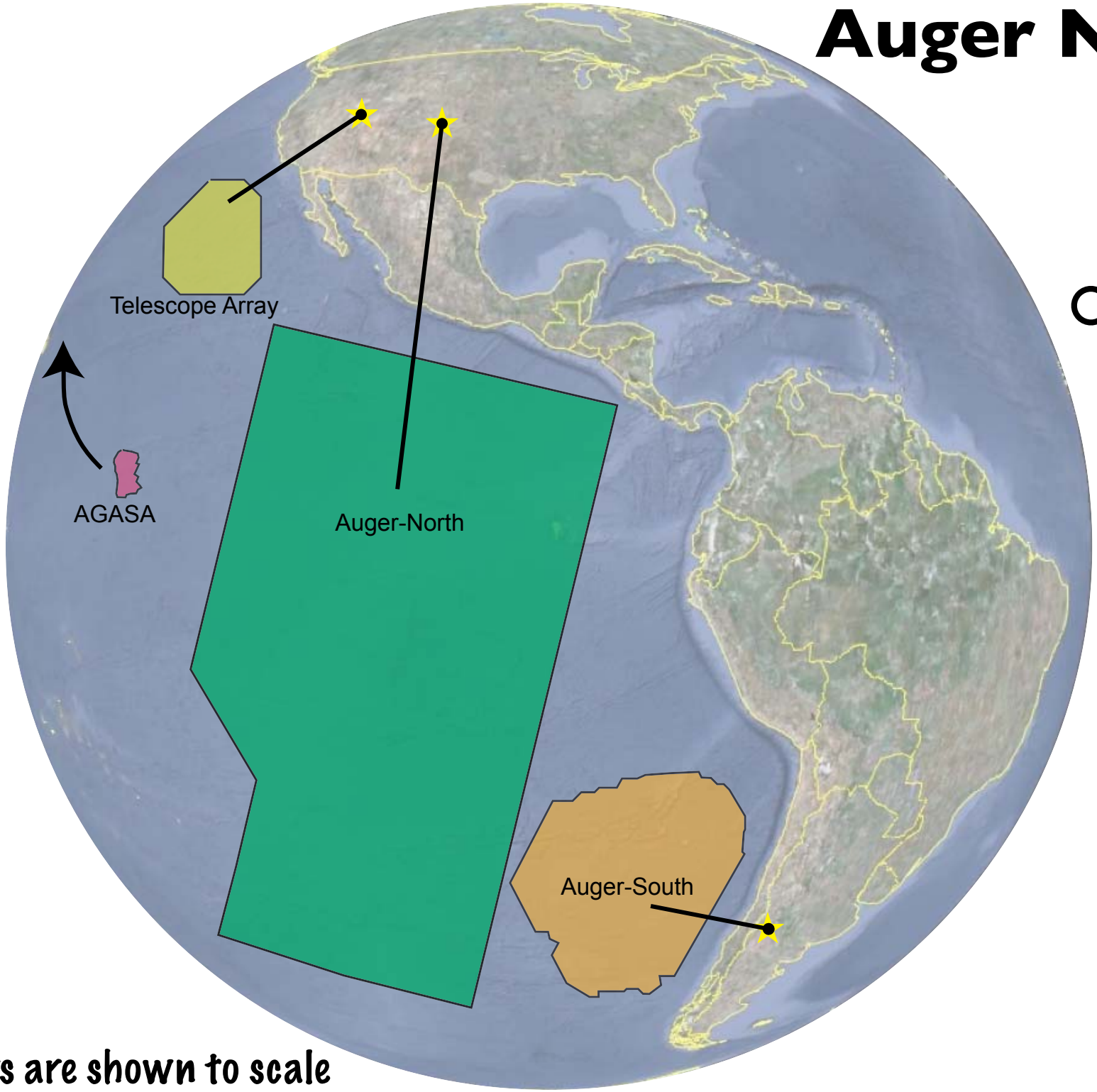




- **7** times bigger for twice the money
- full sky coverage

thank you

Auger North



LHC

all detectors are shown to scale