New Results on the Highest Energy Particles

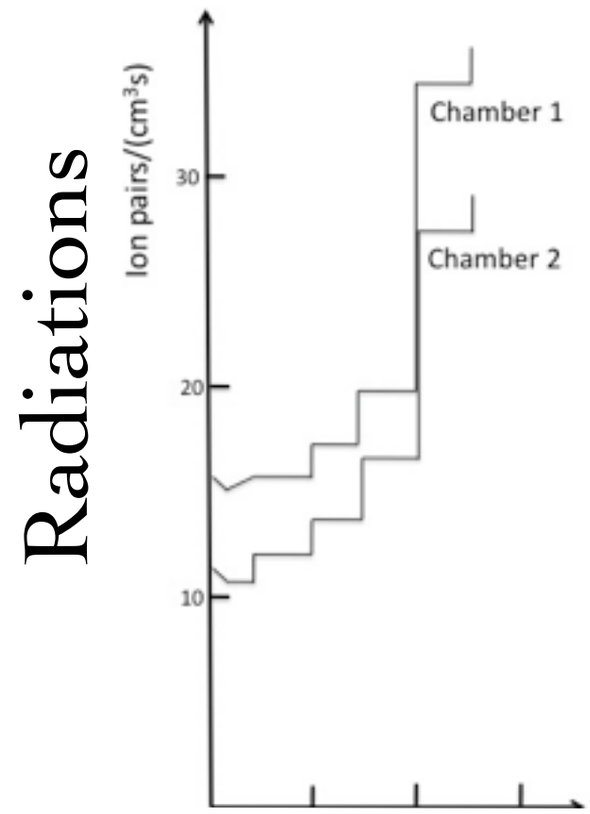
Photography : Steven Saffi, Production assistant : Max Malacari http://vimeo.com/88029390

Toshihiro Fujii
KICP, University of Chicago

APS April Meeting Apr/07/2014

Cosmic rays

- Energetic particles injected from the universe.
- Discovered by V. F. Hess (1912)
  - **Proton, Helium or heavier nuclei (~99%)**
  - Electron ~ 1%
  - Gamma-ray ~ 0.1%

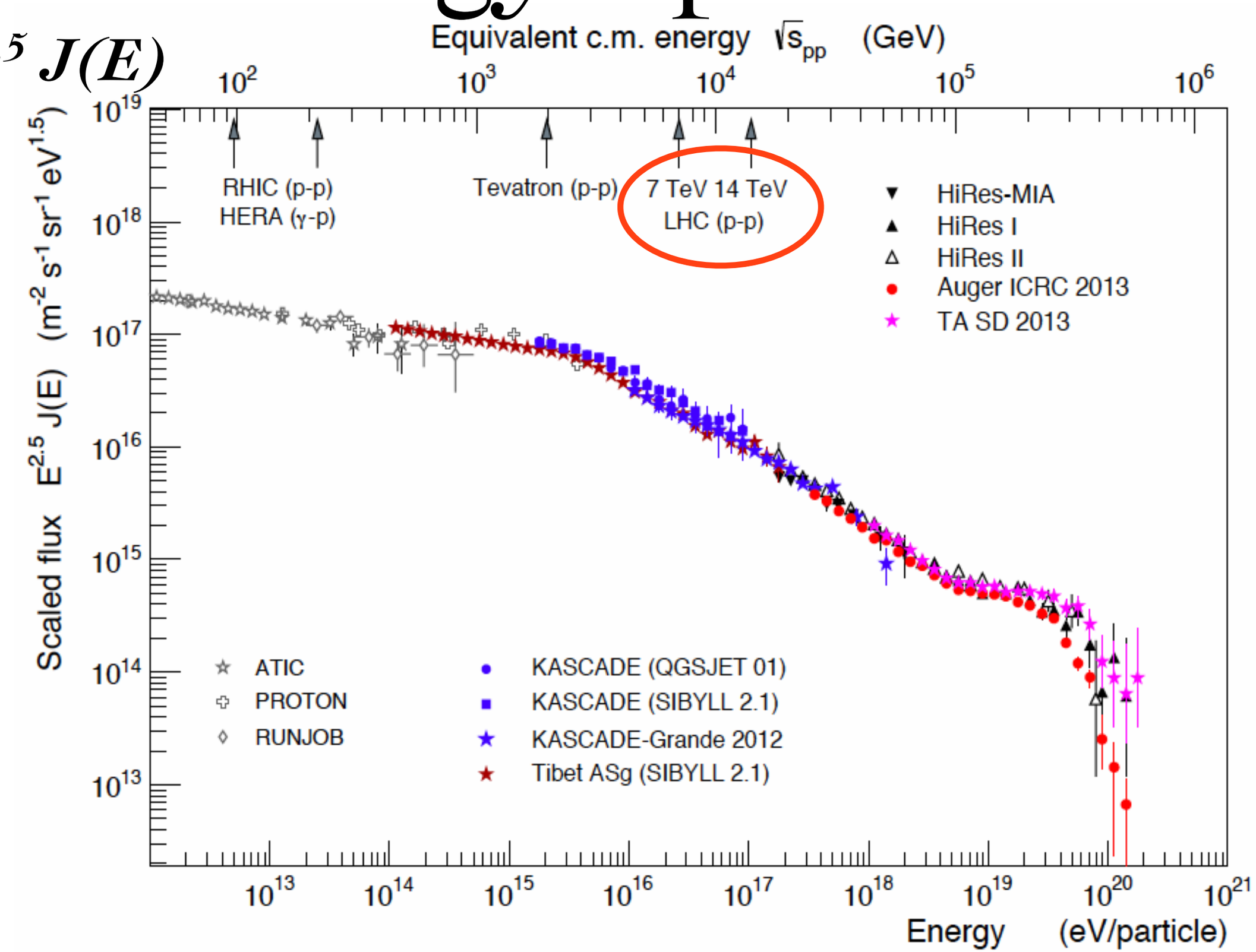


2 Grandson of Hess

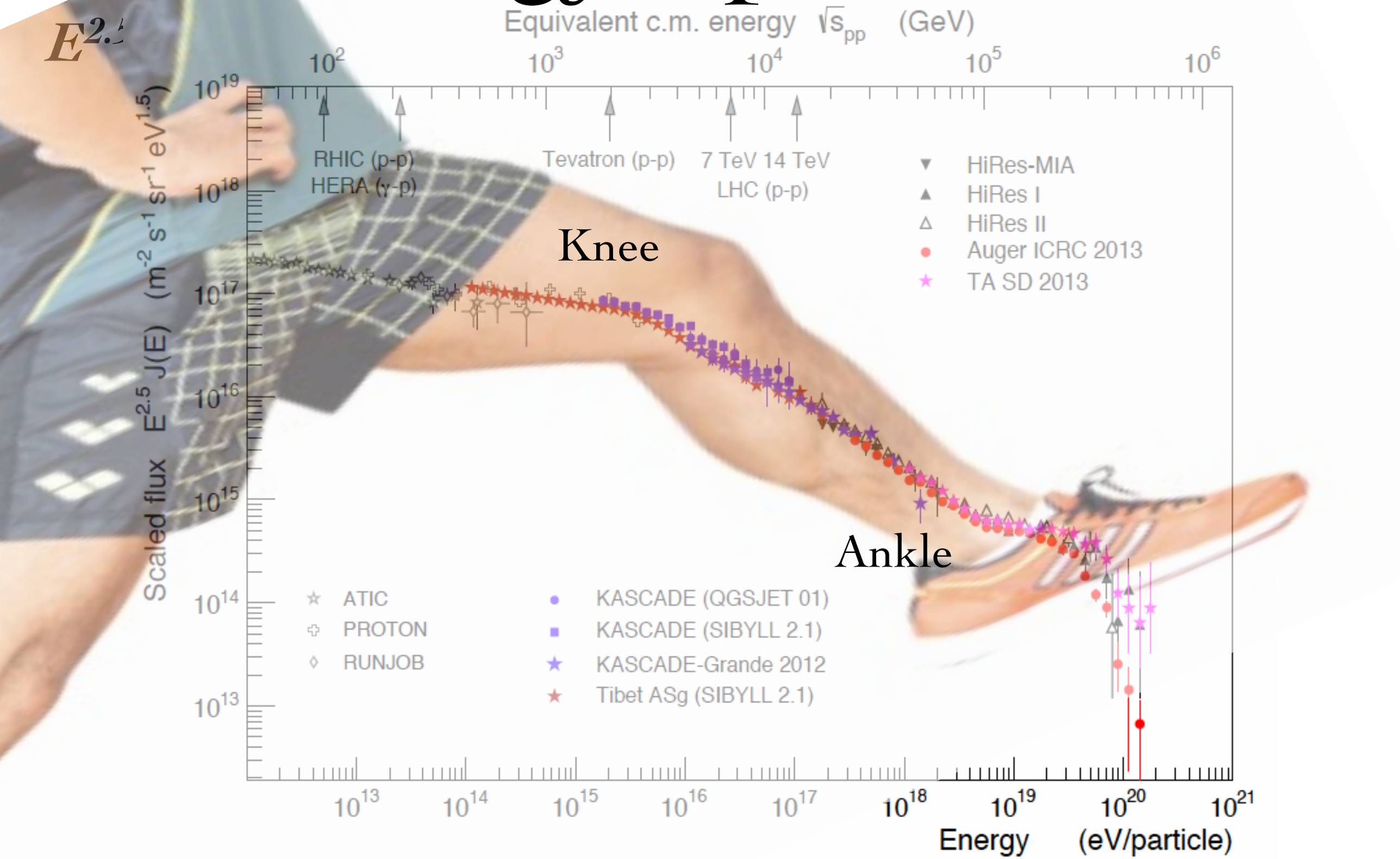
Memorial Stone

Energy Spectrum

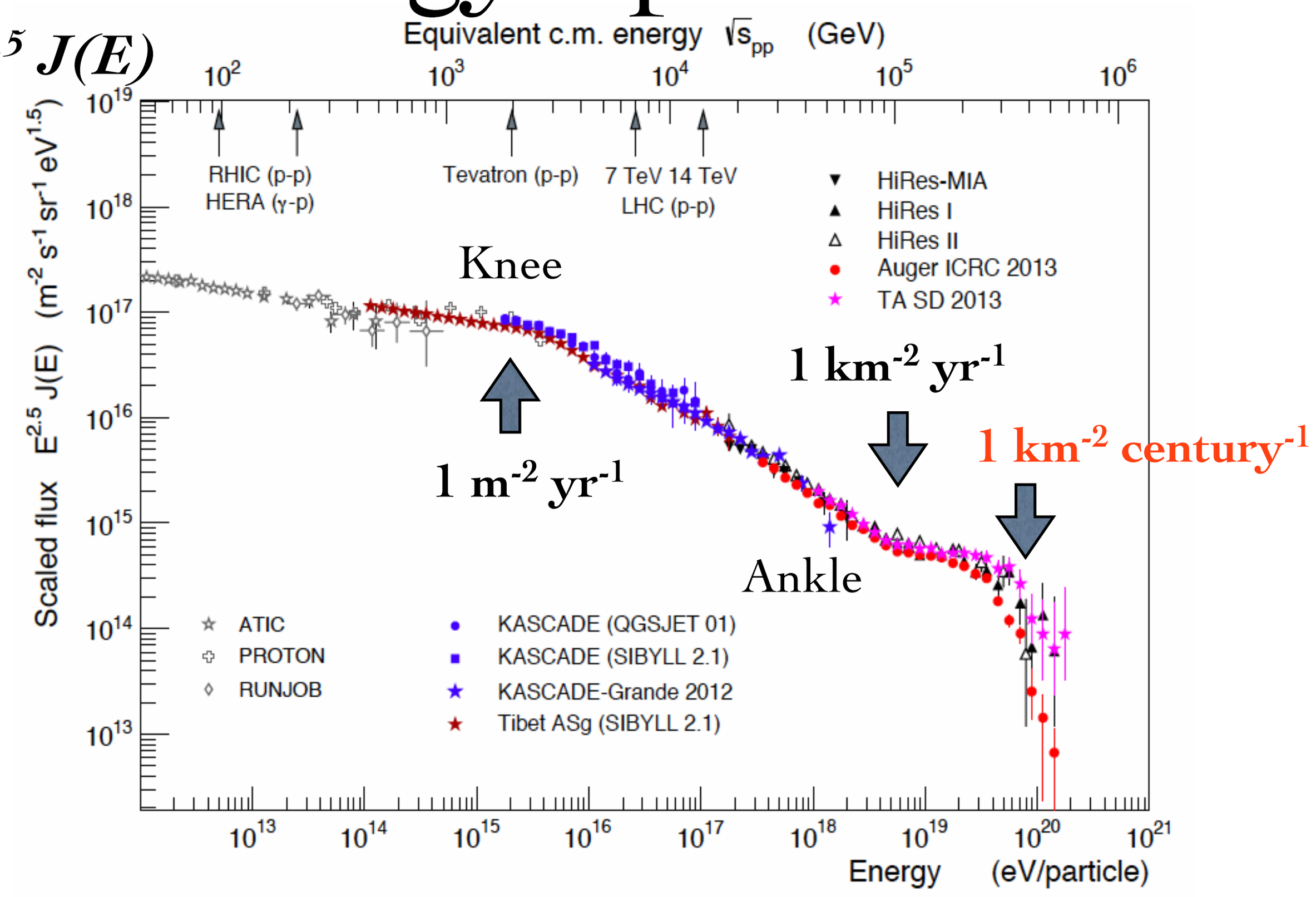
$E^{2.5}\,J(E)$



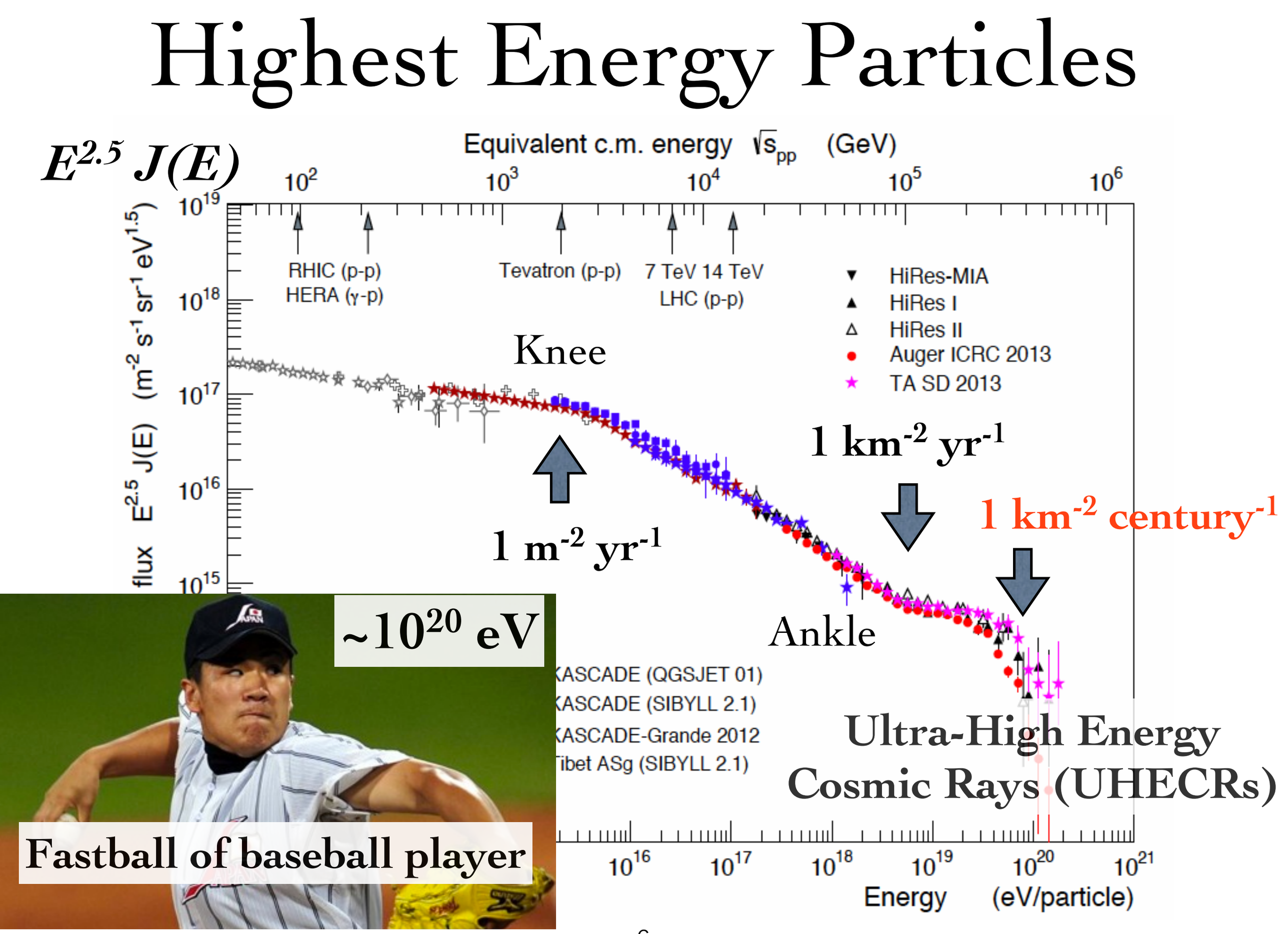
Energy Spectrum



Energy Spectrum



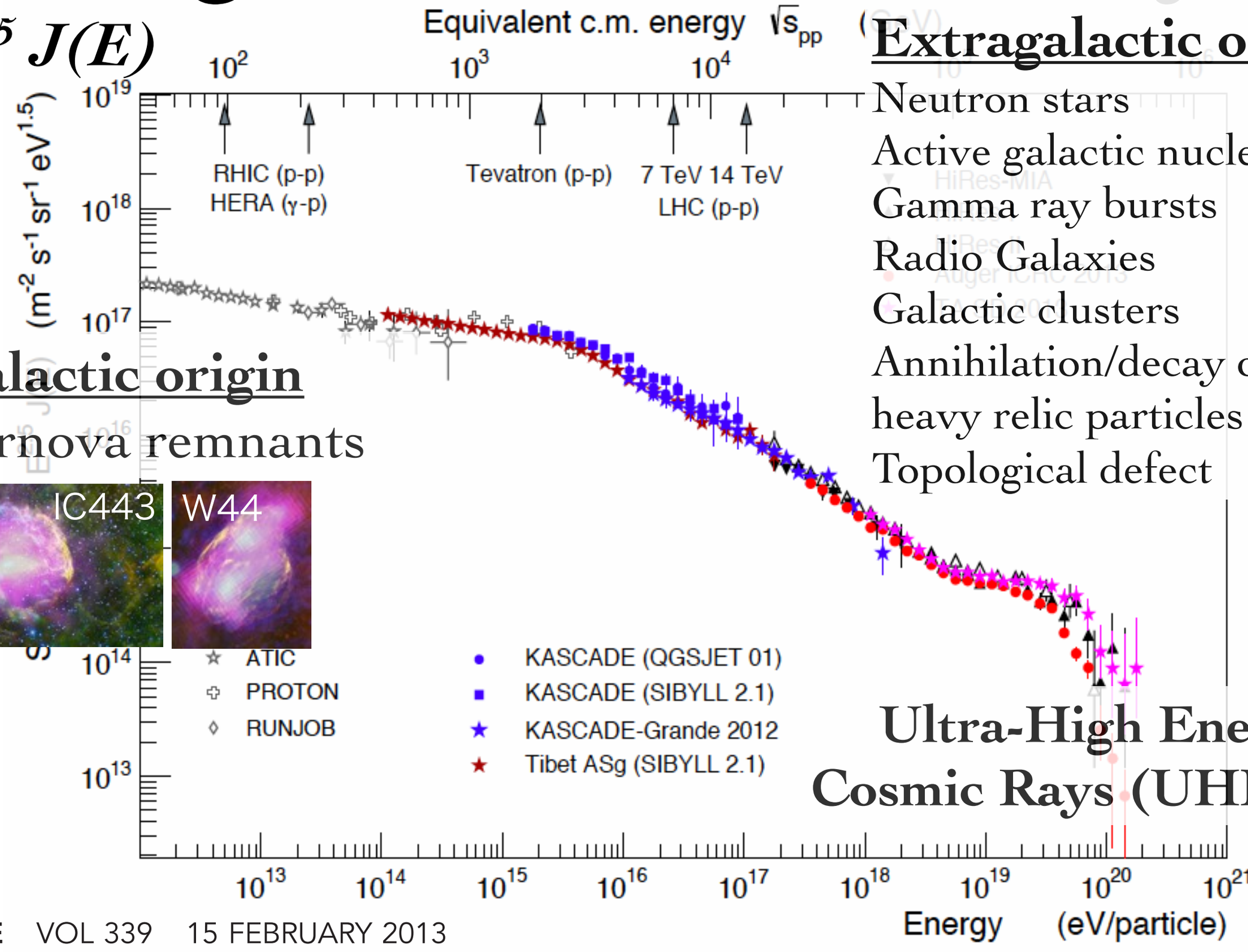
Highest Energy Particles



http://www.nydailynews.com/sports/baseball/

Origins of Cosmic Rays

$E^{2.5}\,J(E)$



Galactic origin

Supernova remnants

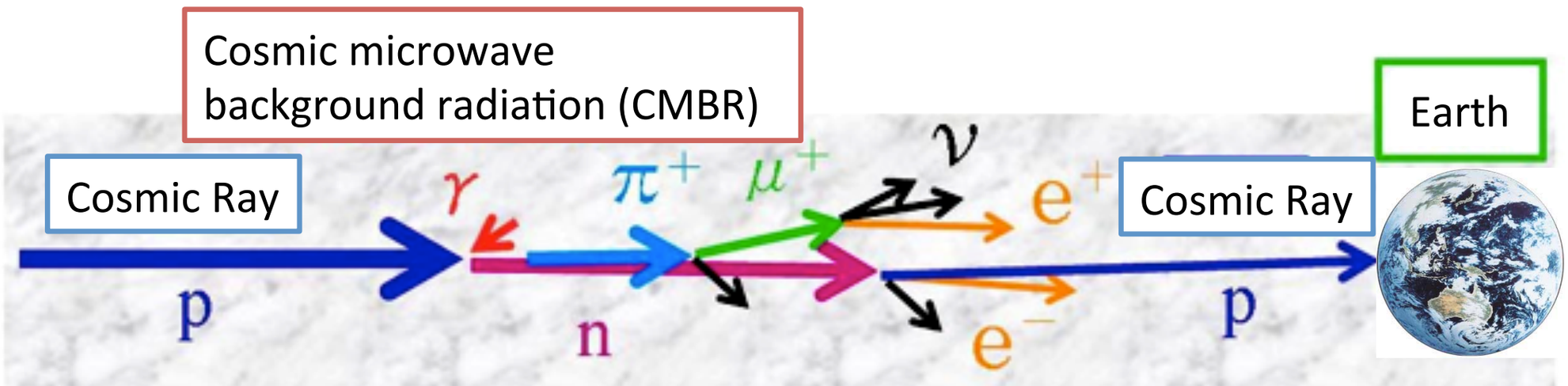
Extragalactic origin?

Neutron stars
Active galactic nuclei
Gamma ray bursts
Radio Galaxies
Galactic clusters
Annihilation/decay of super heavy relic particles
Topological defect

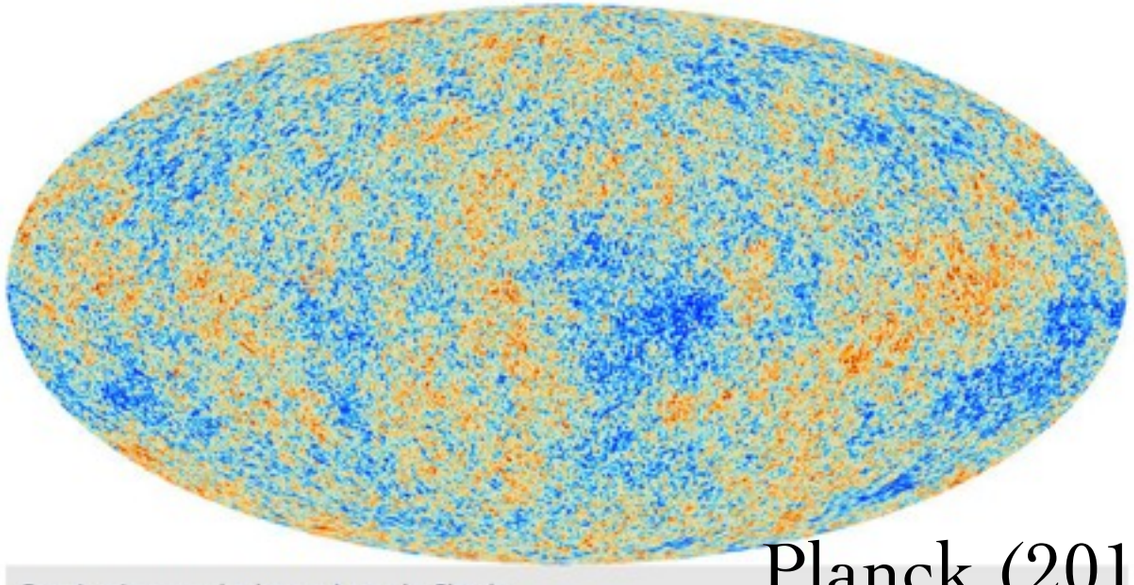
Ultra-High Energy Cosmic Rays (UHECRs)

SCIENCE VOL 339 15 FEBRUARY 2013

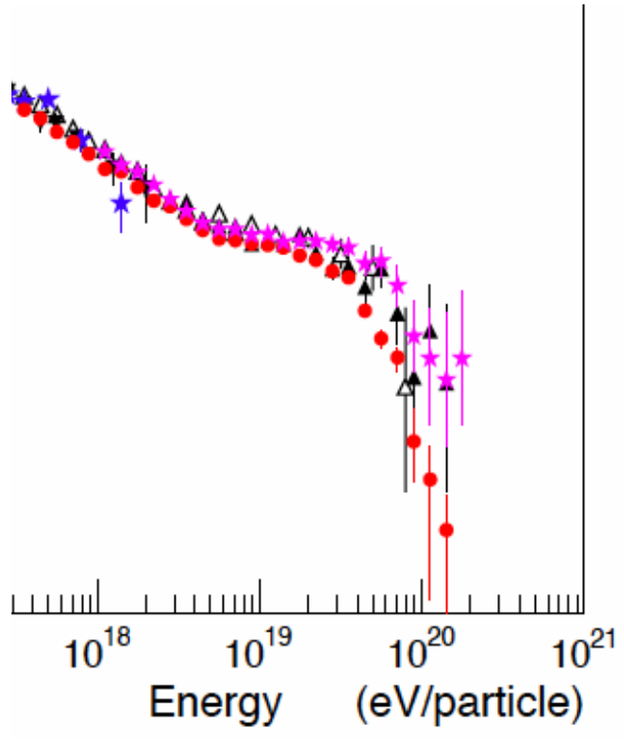
Greisen Zatsepin Kuzmin (GZK) Cutoff



- Interaction between UHE "protons" with energies above 6×10^{19} eV and CMBR via a pion production.
- Mean free path : 50-100 Mpc (compare to the Universe size ~ 5000 Mpc)
- Expect suppression of flux above 6×10^{19} eV.



Planck (2013)



1 pc = 3.26 l.y. ~ 3×10^{16} m

Propagation in the Universe

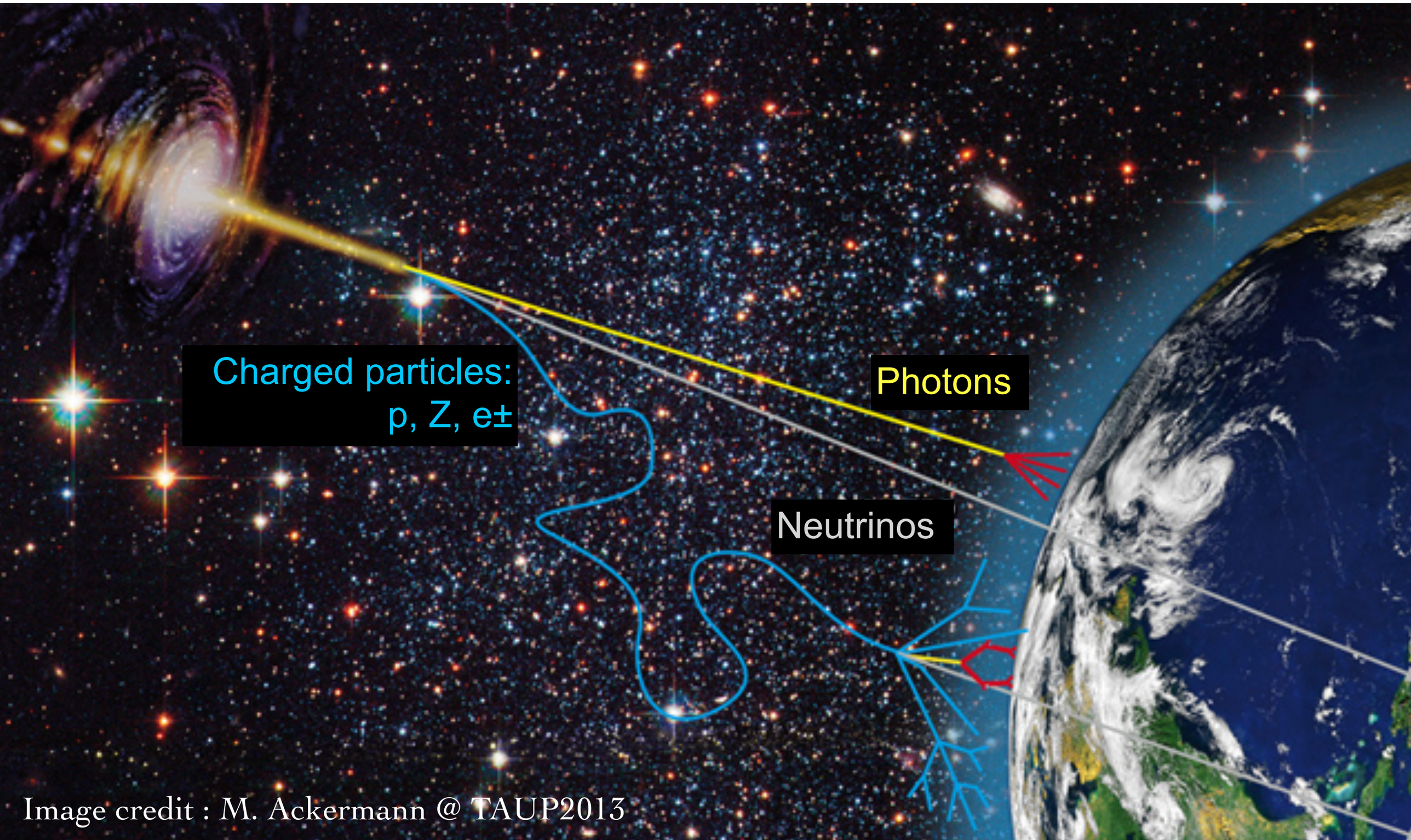


Image credit : M. Ackermann @ TAUP2013

Ultra-High Energy Cosmic Rays

(Almost) Go straight!

Charged particles: p, Z, e±

10^{20}

Photons

Neutrinos

http://en.wikipedia.org/wiki/Usain_Bolt

$$\delta \simeq 3^{o} \frac{B}{3\,\mu G} \frac{L}{kpc} \frac{6\times 10^{19} eV}{E/Z}$$

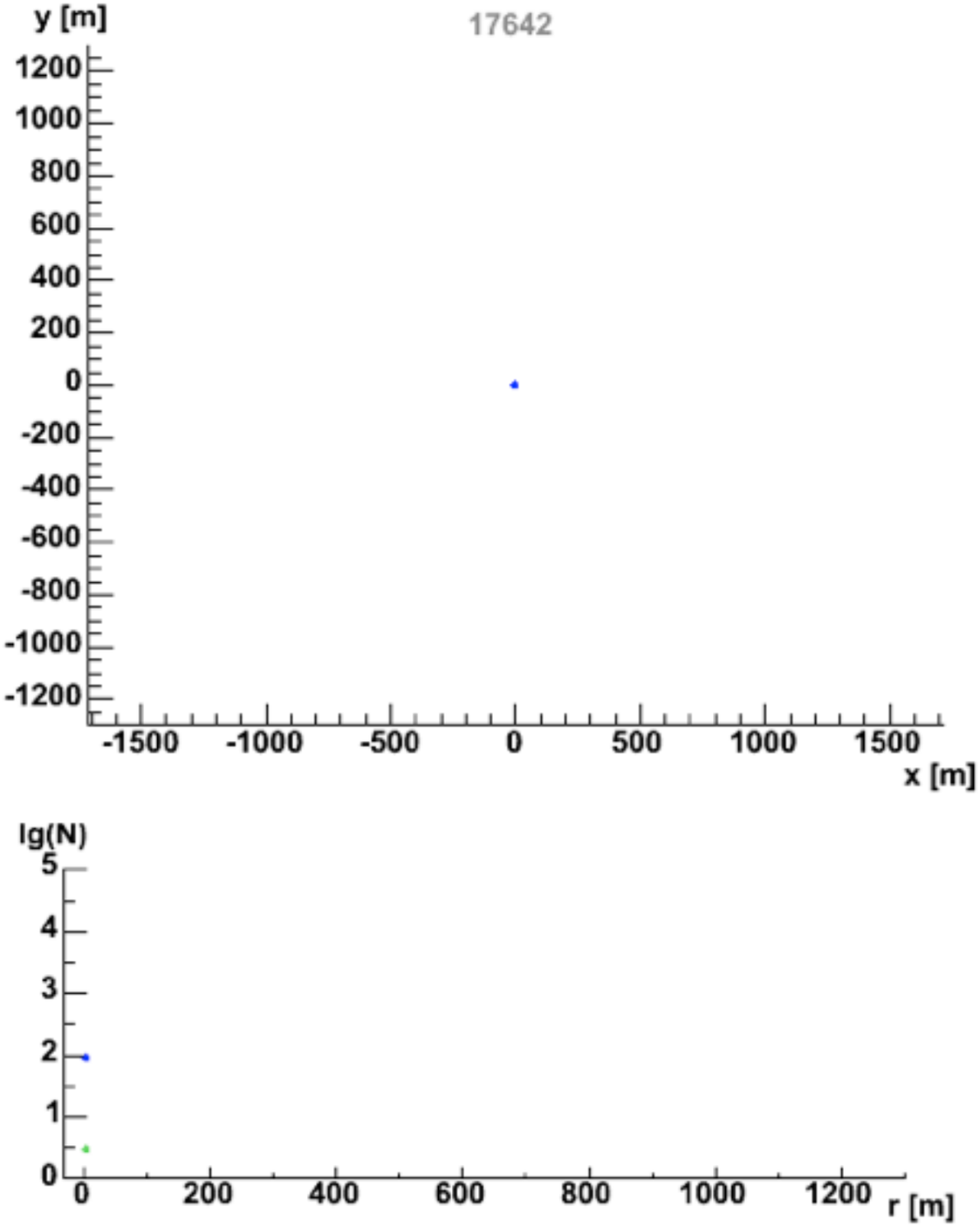
Charged Particle Astronomy

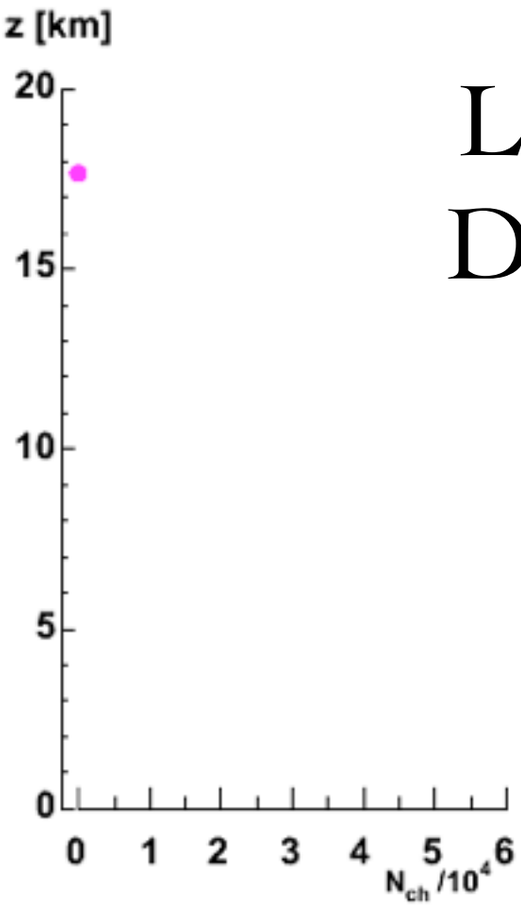
Image credit : M. Ackermann @ TAUP2013

Extensive Air Shower (EAS)

Image credit: ASPERA/Novapix/L.Bret

Extensive Air Shower





Longitudinal Development

Xmax

Lateral Density Distribution

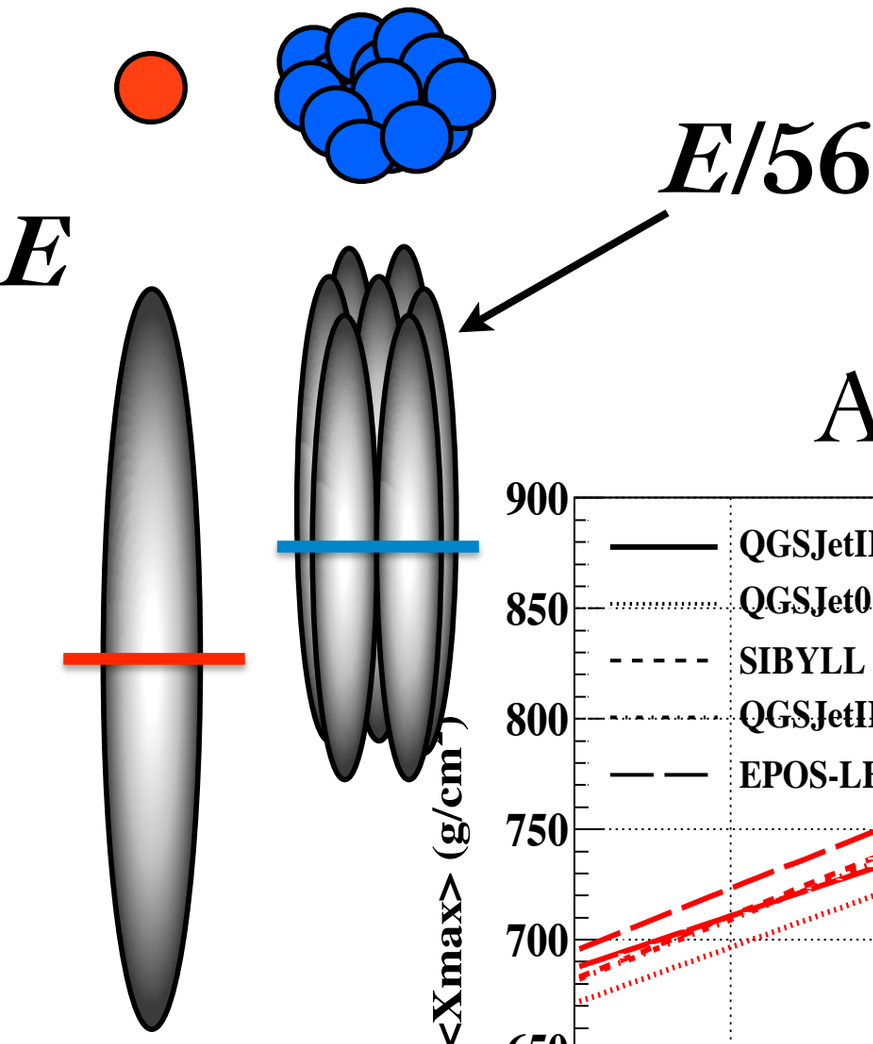
CORSIKA simulation

https://web.ikp.kit.edu/corsika/movies

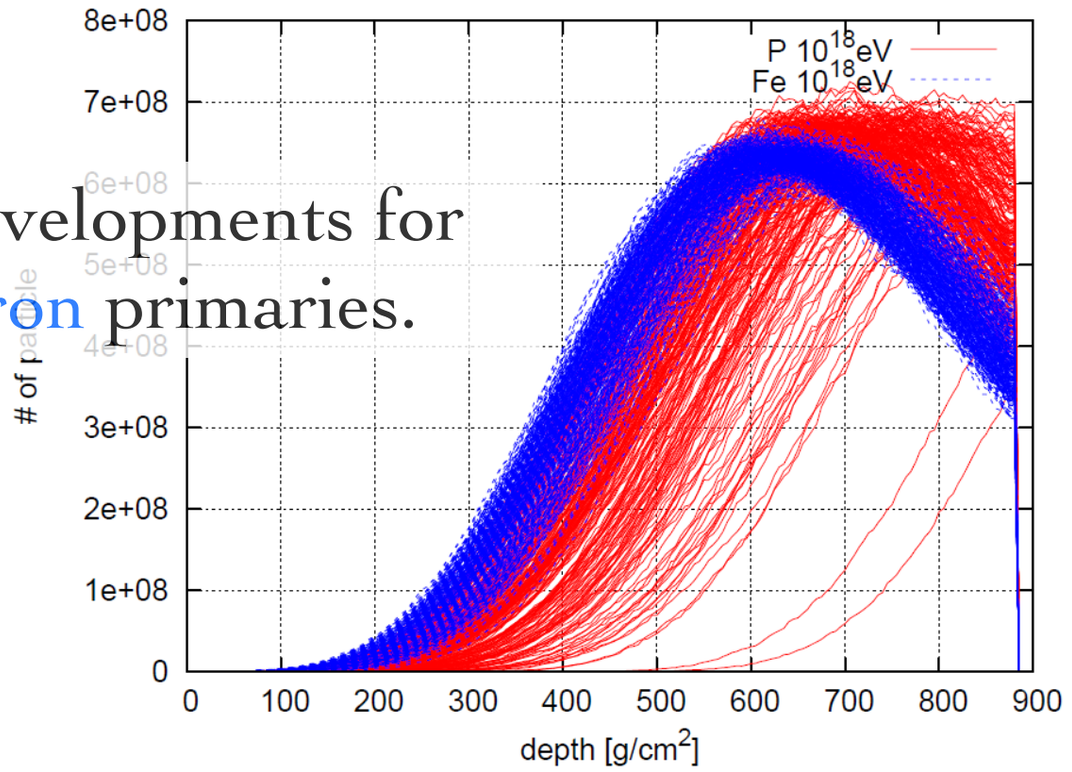
Mass Composition Measurement

With the same energy, ***E***

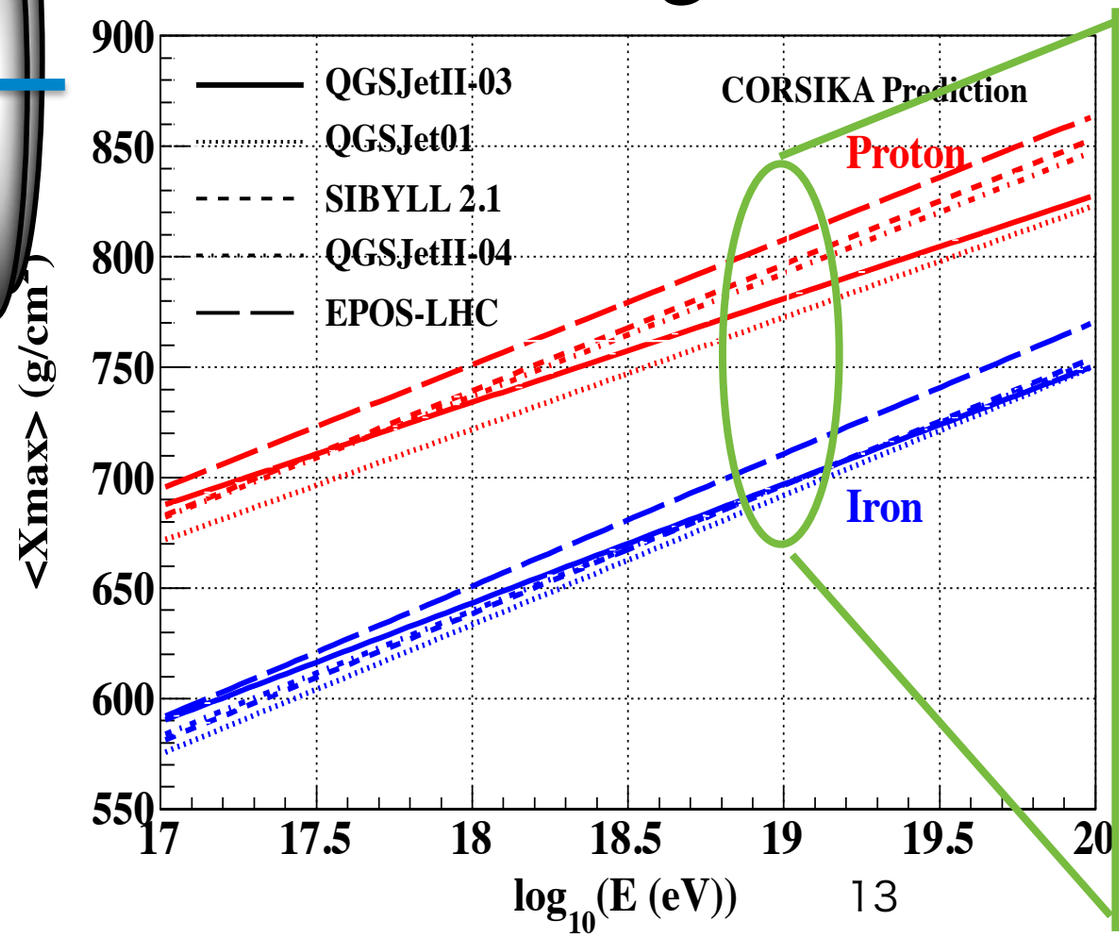
Proton(1) Iron(56)

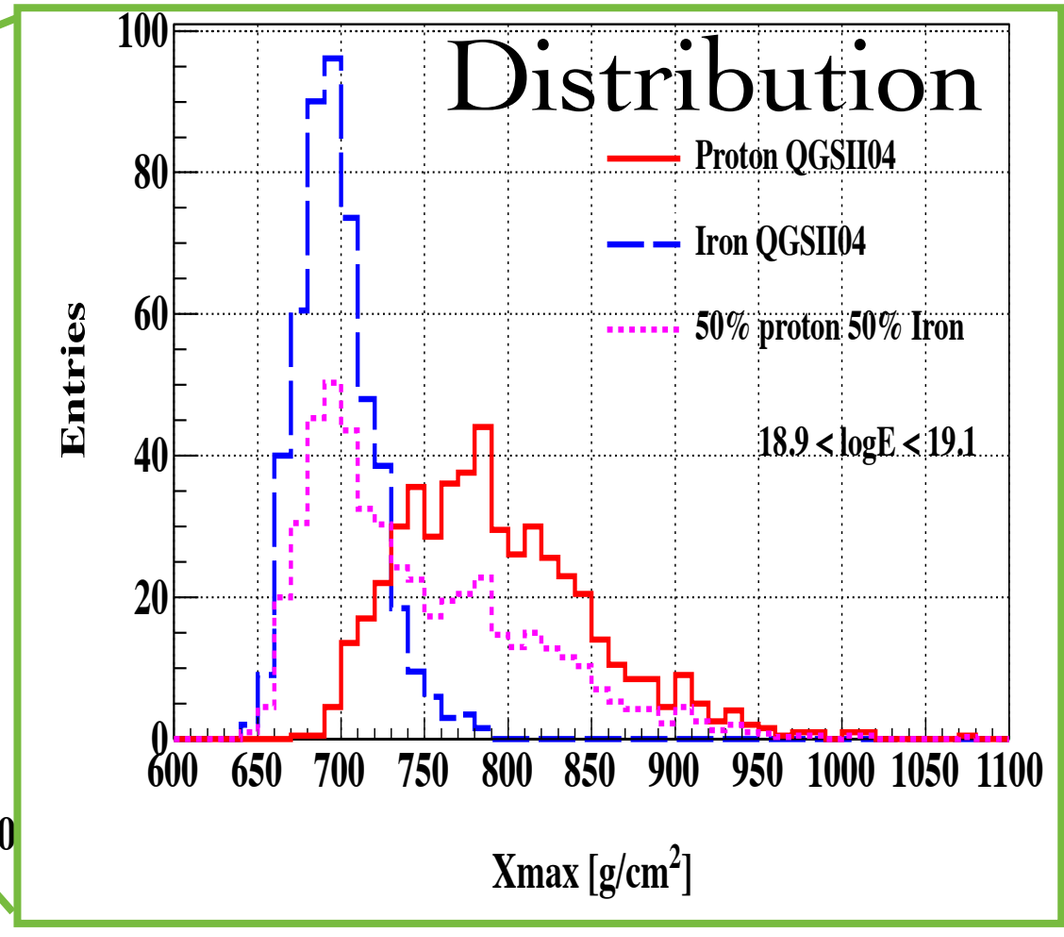


longitudinal developments for Proton and Iron primaries.



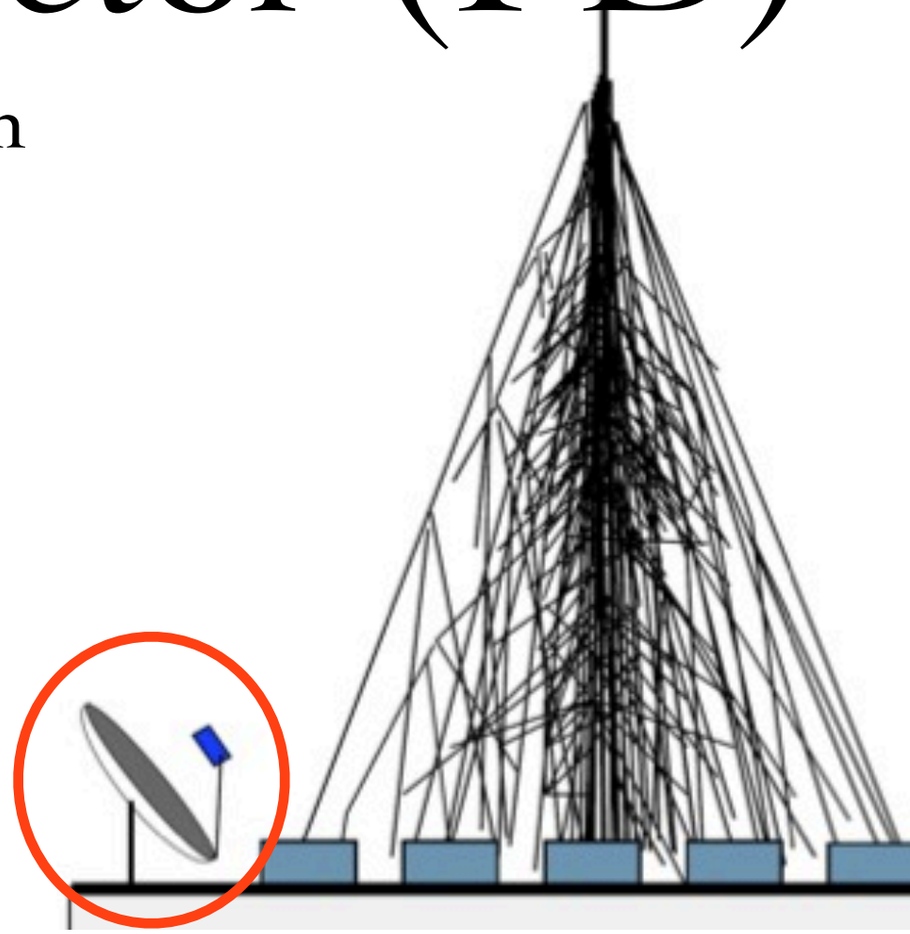
Average

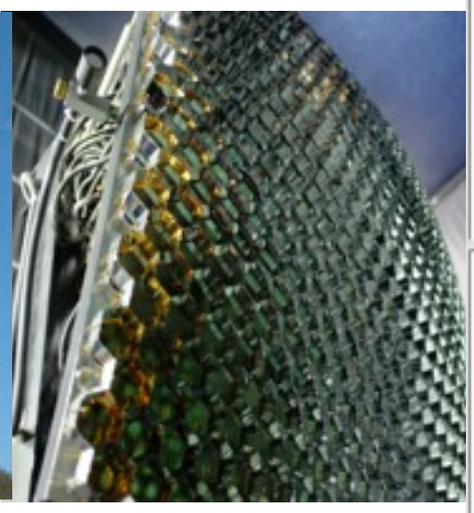


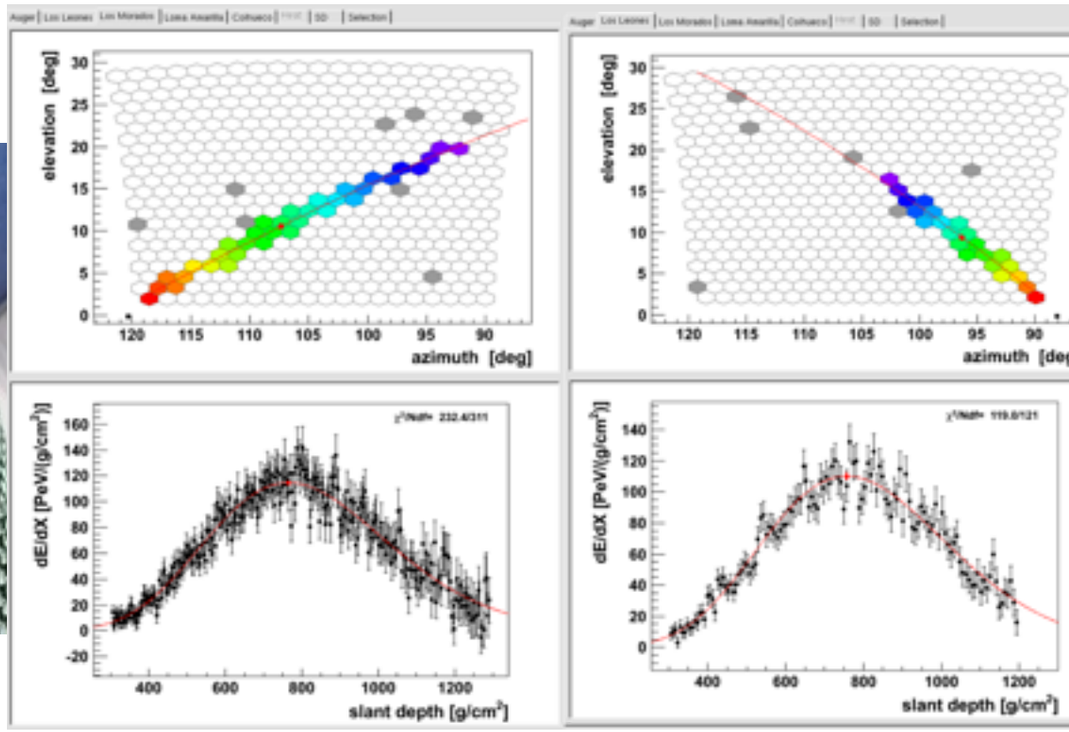


Fluorescence Detector (FD)

- Detect fluorescence photons emitted from atmospheric molecule excited by EAS.
- Measure longitudinal development of EAS = sensitive mass composition
- Only moonless clear night, duty cycle ~ 10%
- Many calibration factors: atmosphere, mirror reflectance, PMT gain and so on.

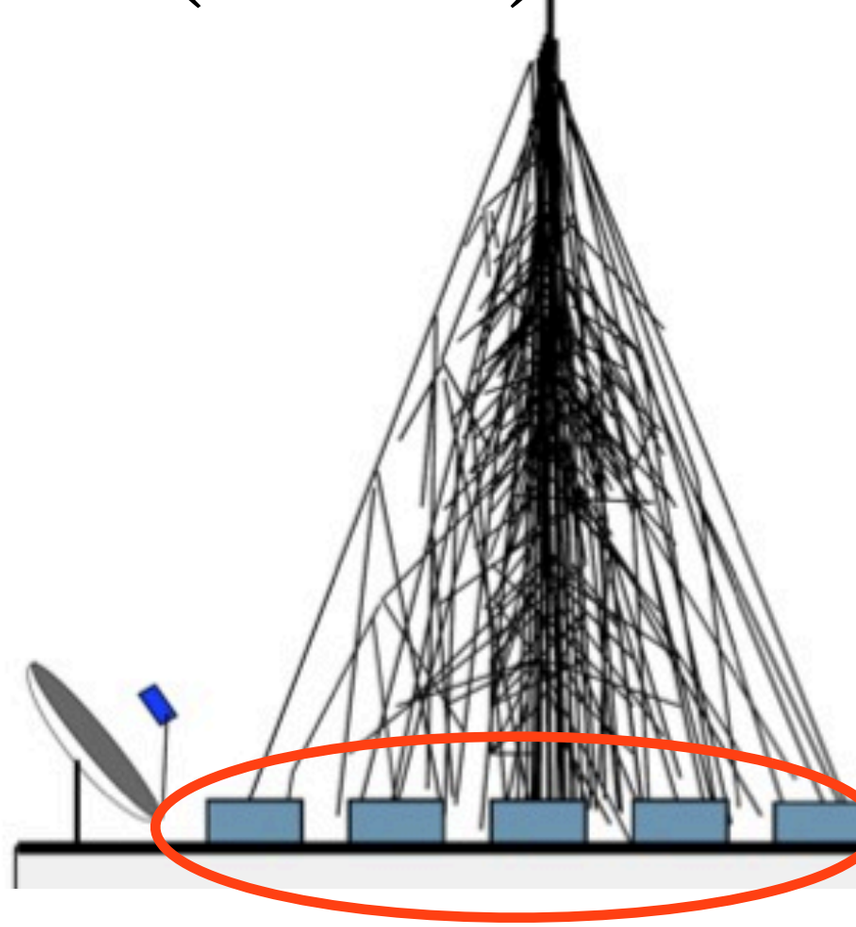


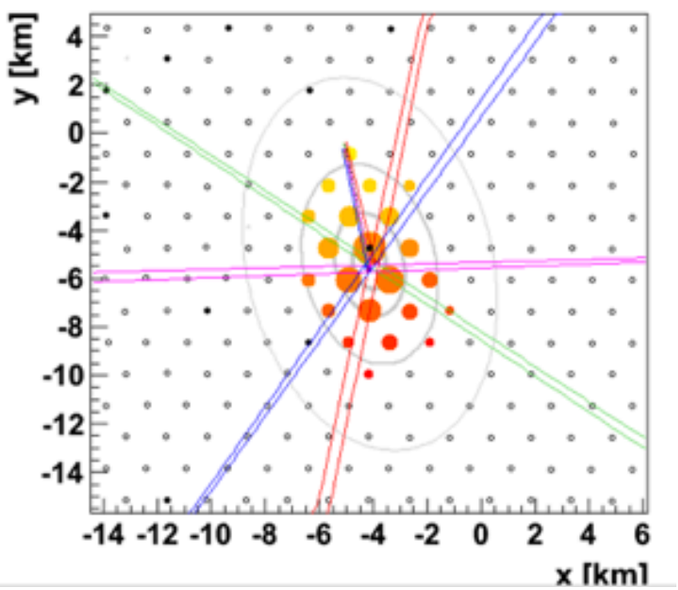


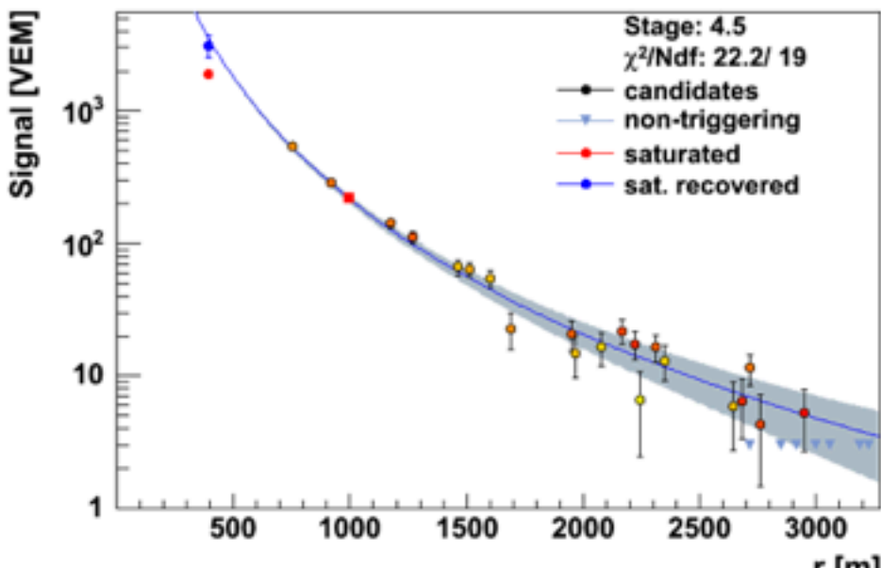


Surface Detector (SD)

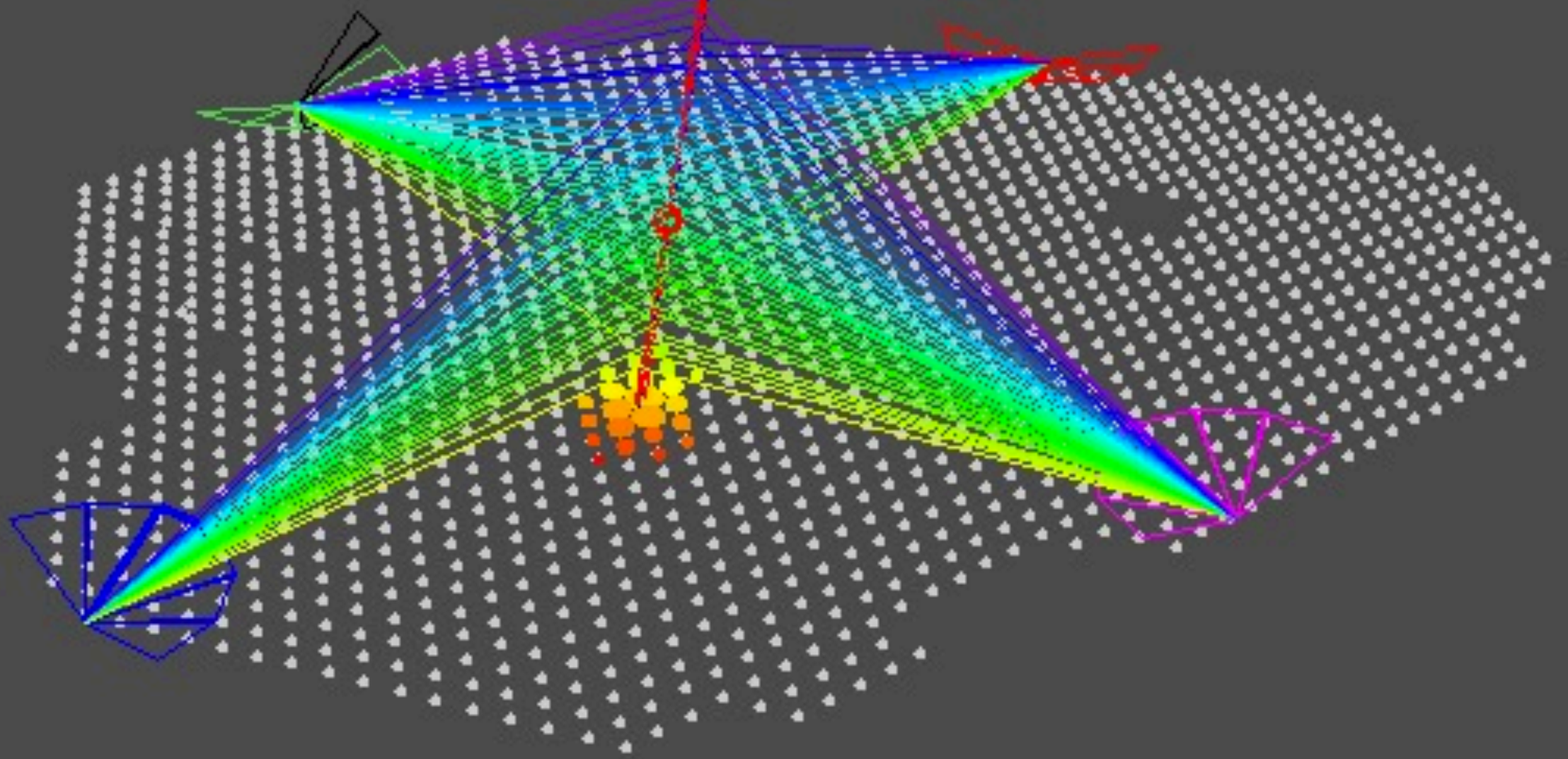
- Observe EAS particles on the ground by SD Array
- Measure lateral density distributions
- 24 hour, 365 days. Duty cycle ~100%
- Large systematic uncertainty of hadron interaction models.
- Dependent on shower developments.







Hybrid Detector
FD + SD



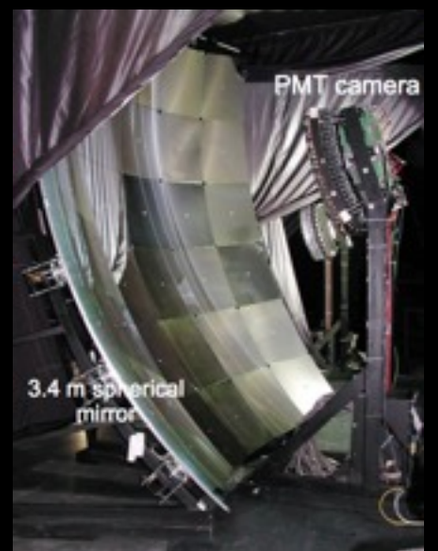
Observatory of UHECRs

Telescope Array
Experiment (TA)

Utah, USA

Pierre Auger
Observatory (Auger)

Malargue, Argentina



Pierre Auger Observatory

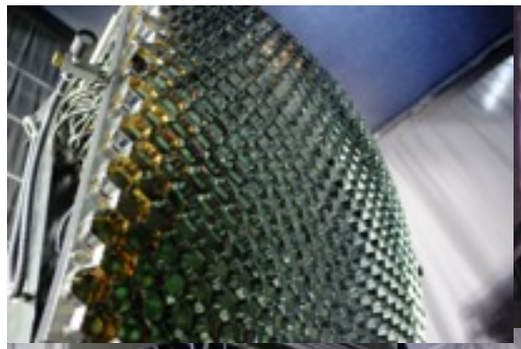
The world's largest hybrid detector 3000 km^2
In operation from 2004.
1660 (SDs), 24+3 (FDs)

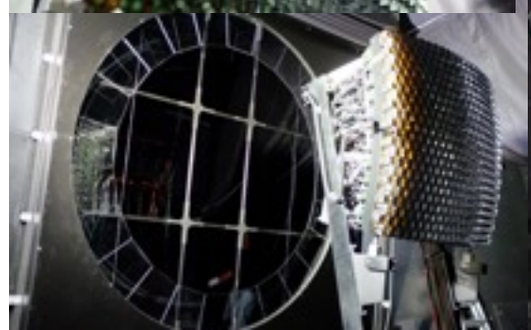
Auger SD

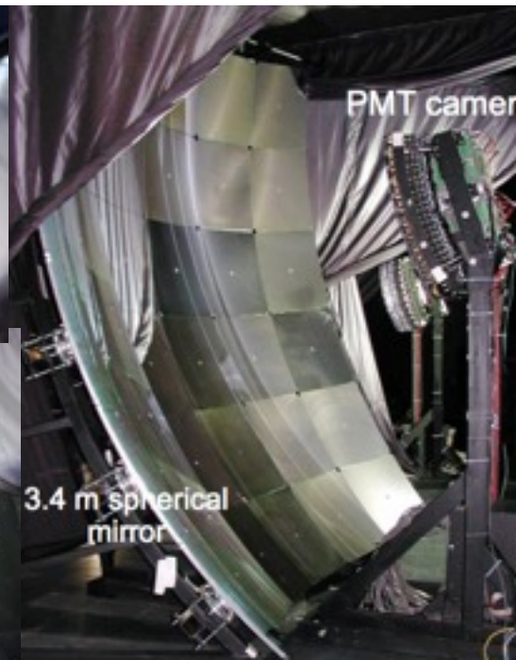
Water Cerenkov Tank with
1.5 km spacing
Sensitive to muons

Auger FD

3.4 m spherical mirror
440 PMT
light guide + collector ring







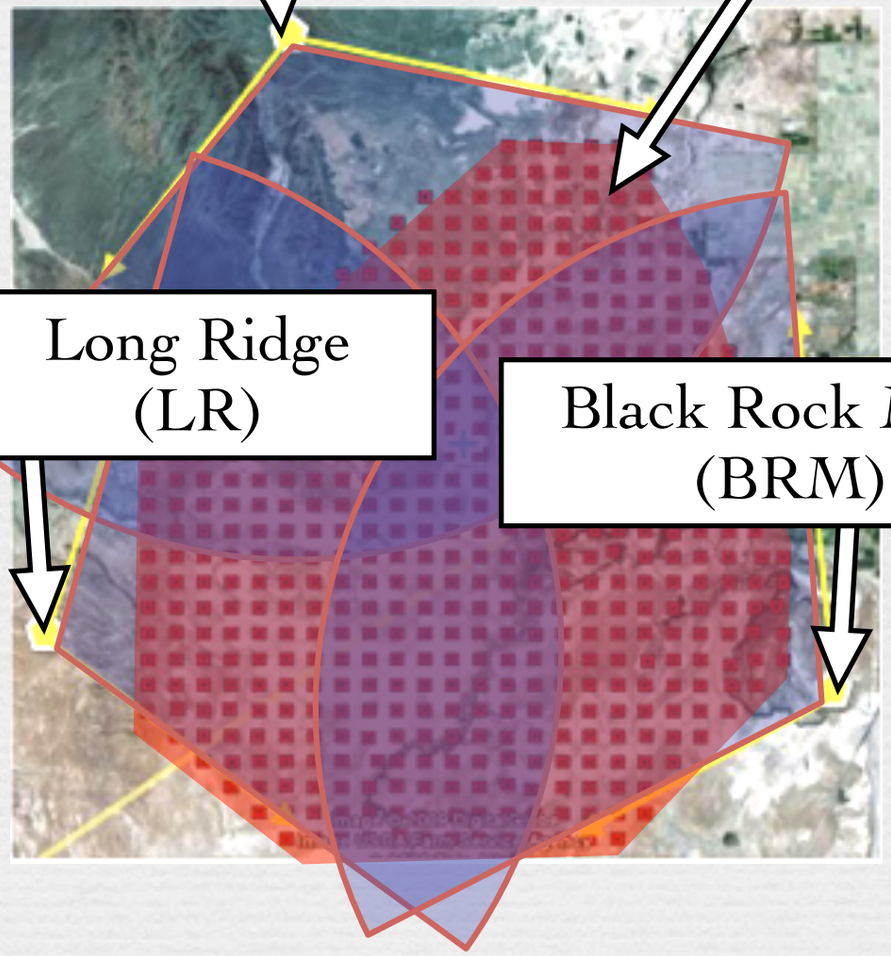
Telescope Array Experiment

- The largest detector in northern hemisphere : 700 km^2
- Utah desert, US
- Hybrid detector using SDs and FDs
- Full operation from 2008
- Plastic Scintillator, sensitive to EM

Middle Drum (MD)

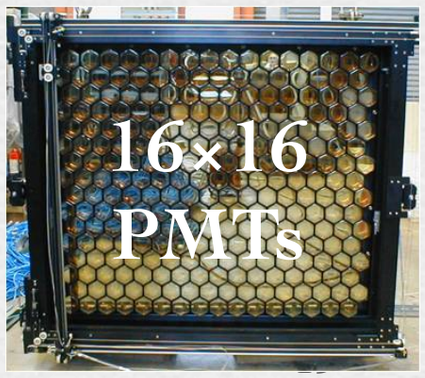
507 Surface Detectors(SD)

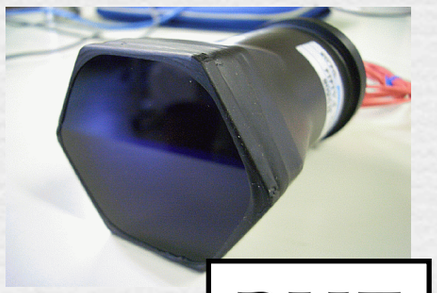
38 Fluorescence Detectors



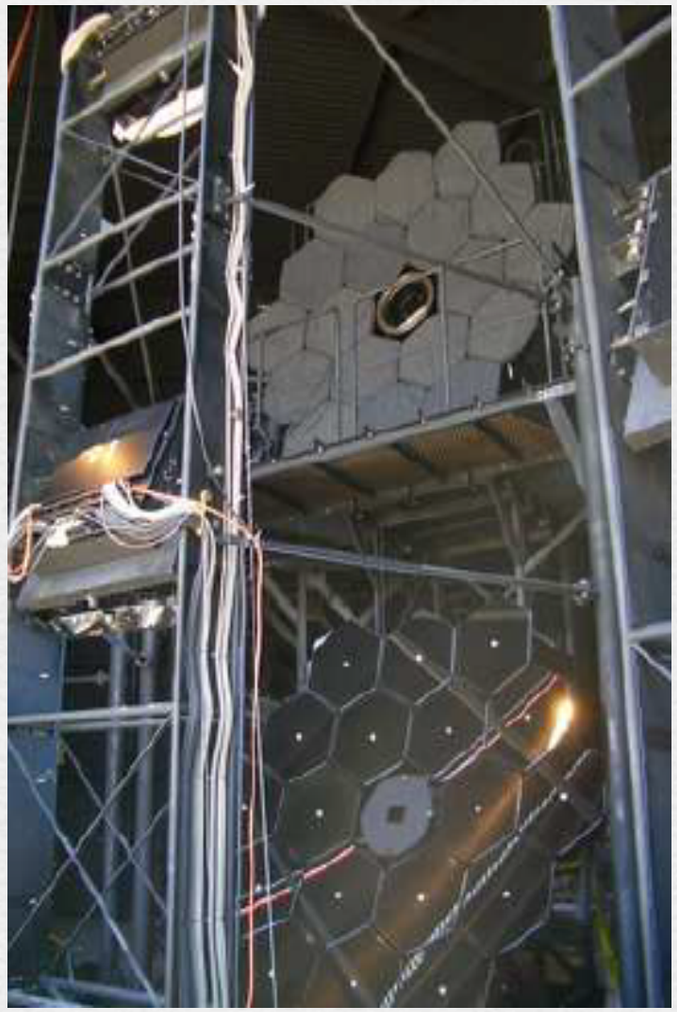
Long Ridge (LR)

Black Rock Mesa (BRM)





PMT

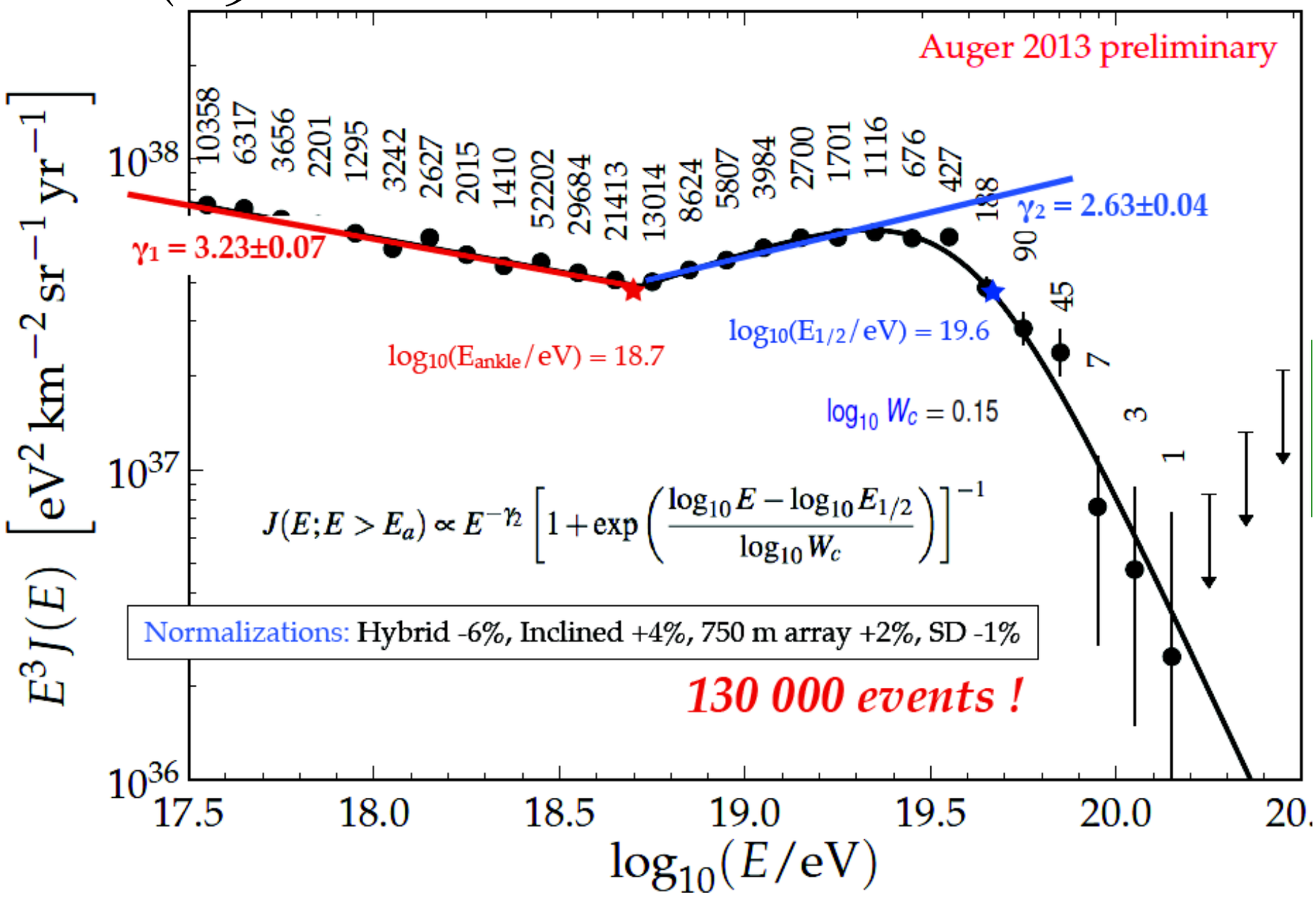


Energy Spectrum

Auger Energy Spectrum

PIERRE AUGER OBSERVATORY

$E^3 J(E)$



Updated new energy scale in ICRC 2013

Energy increased by

+16% at 10^{18} eV

+10% at 10^{19} eV

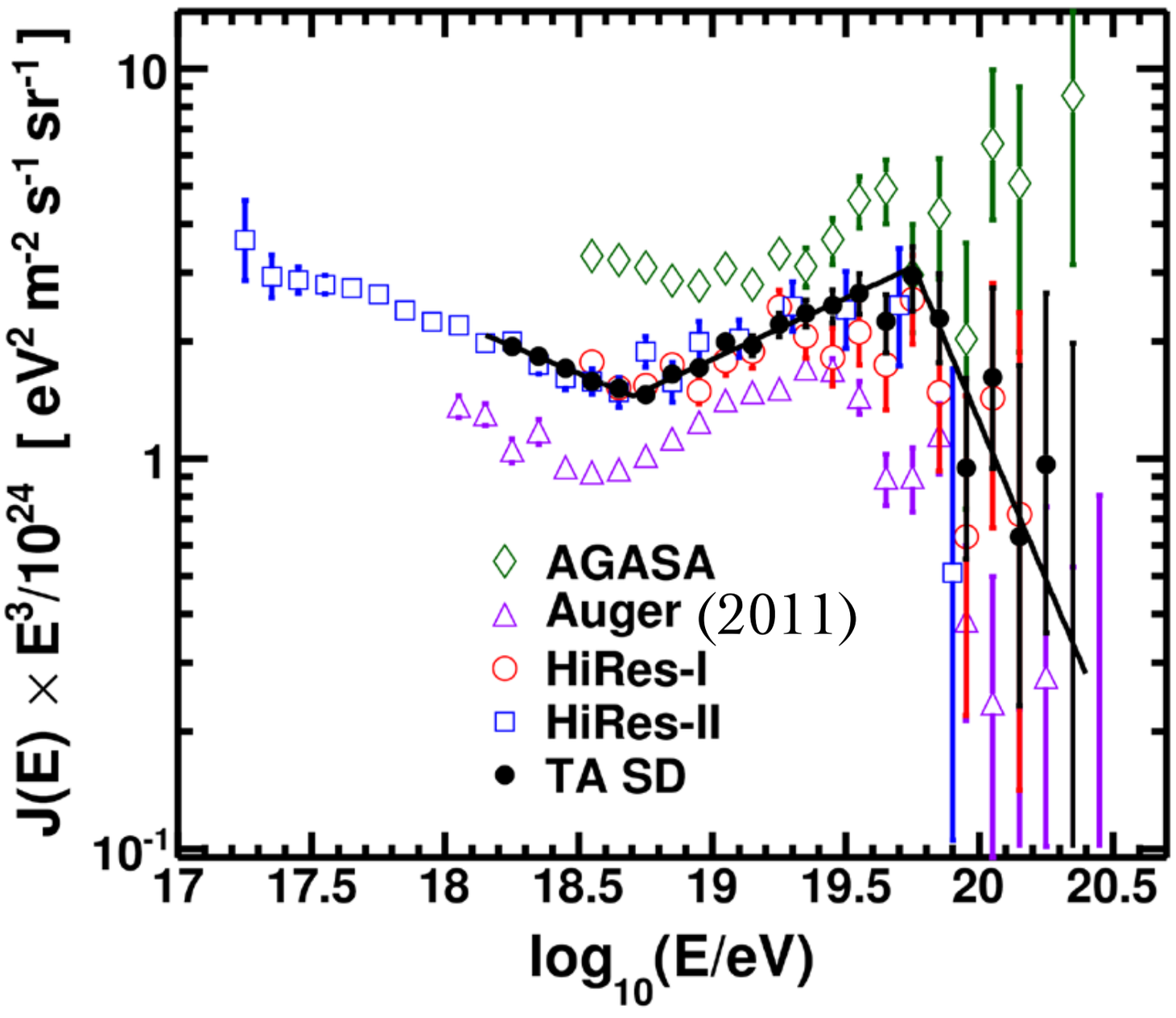
Systematic uncertainty 14%

V. Verzi ICRC 2013

A. Lettessier-Selvon, ICRC 2013

TA Energy Spectrum

$E^3 J(E)$



5 years SD data
2008 May ~ 2013 May
Zenith < 45 degree

Broken power law fit

$\gamma_1 = -3.283 \pm 0.032$

$E_{ankle} = (5.04 \pm 0.27) \times 10^{18}$ eV

$\gamma_2 = -2.685 \pm 0.030$

$E_{GZK} = (5.68 \pm 1.05) \times 10^{19}$ eV

$\gamma_3 = -4.62 \pm 0.74$

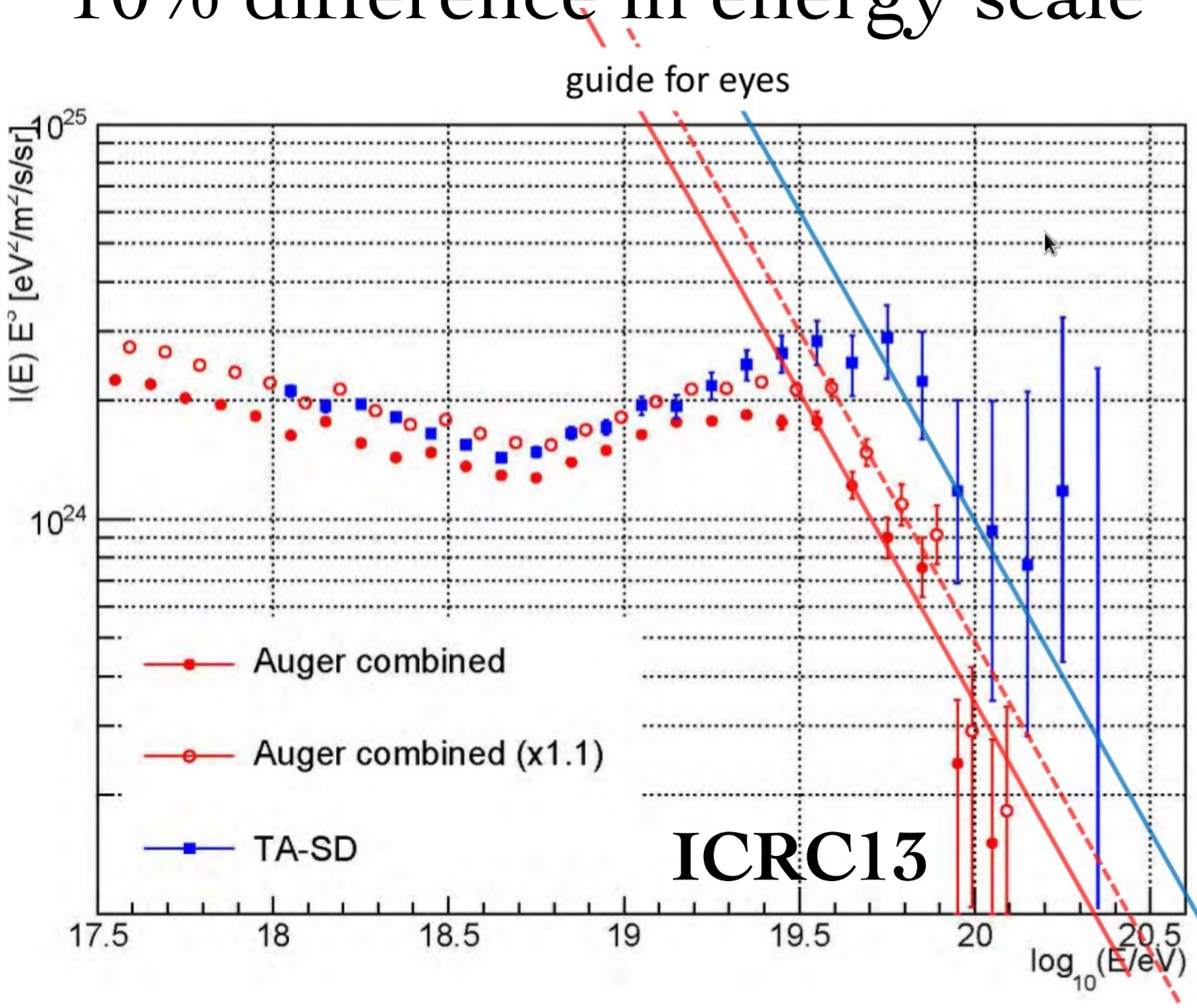
Systematic uncertainty 21%

H. Sagawa, D. Bergman
ICRC 2013

ApJ 768:L1 (2013)

Energy Spectrum Comparison

10% difference in energy scale



Results of Broken Power Law Fit

	Auger	TA
γ-1	3.23 ± 0.01	3.28 ± 0.03
E_{ANKLE}	$10^{18.72}$ eV	$10^{18.70}$ eV
γ-2	2.63 ± 0.02	2.69 ± 0.03
$E_{1/2}$	$10^{19.63}$ eV	$10^{19.74}$ eV

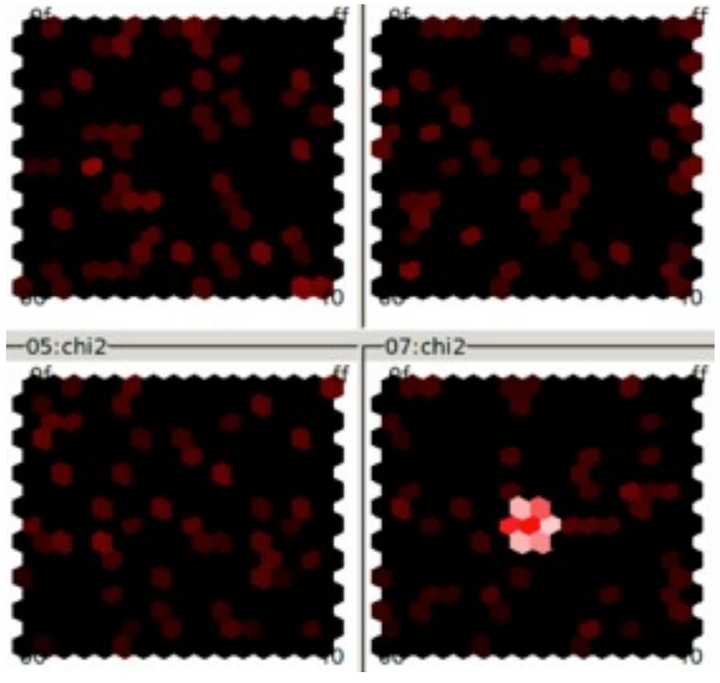
- Spectral shape: Auger and TA agree well for $E < \sim 10^{19.3}$ eV if overall E-scale shifted by 10%.
- $E_{1/2}$: $E_{AUGER} = 0.78 \times E_{TA}$ (w/o 10% rescale)

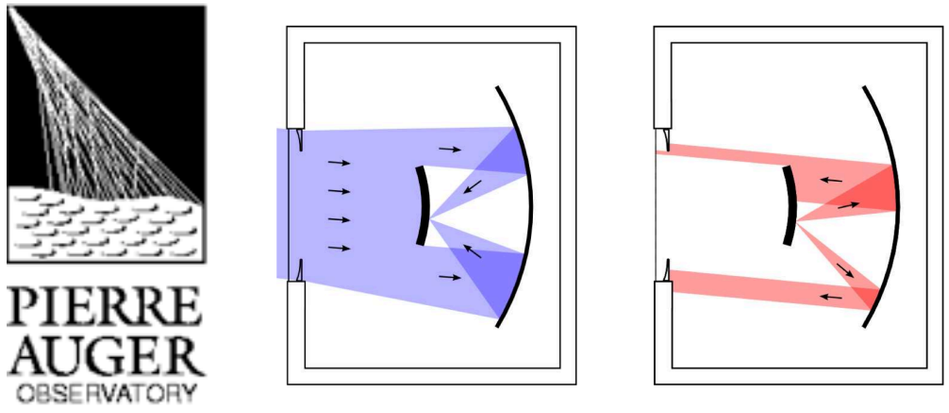
D. Bergman ICRC 2013

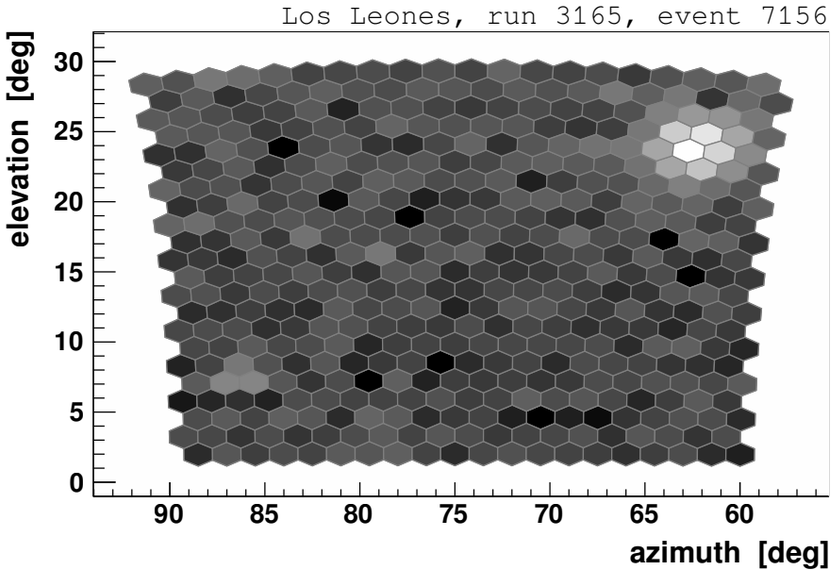
From Y. Tsunesada ICRC 2013 Rapporteur Talk

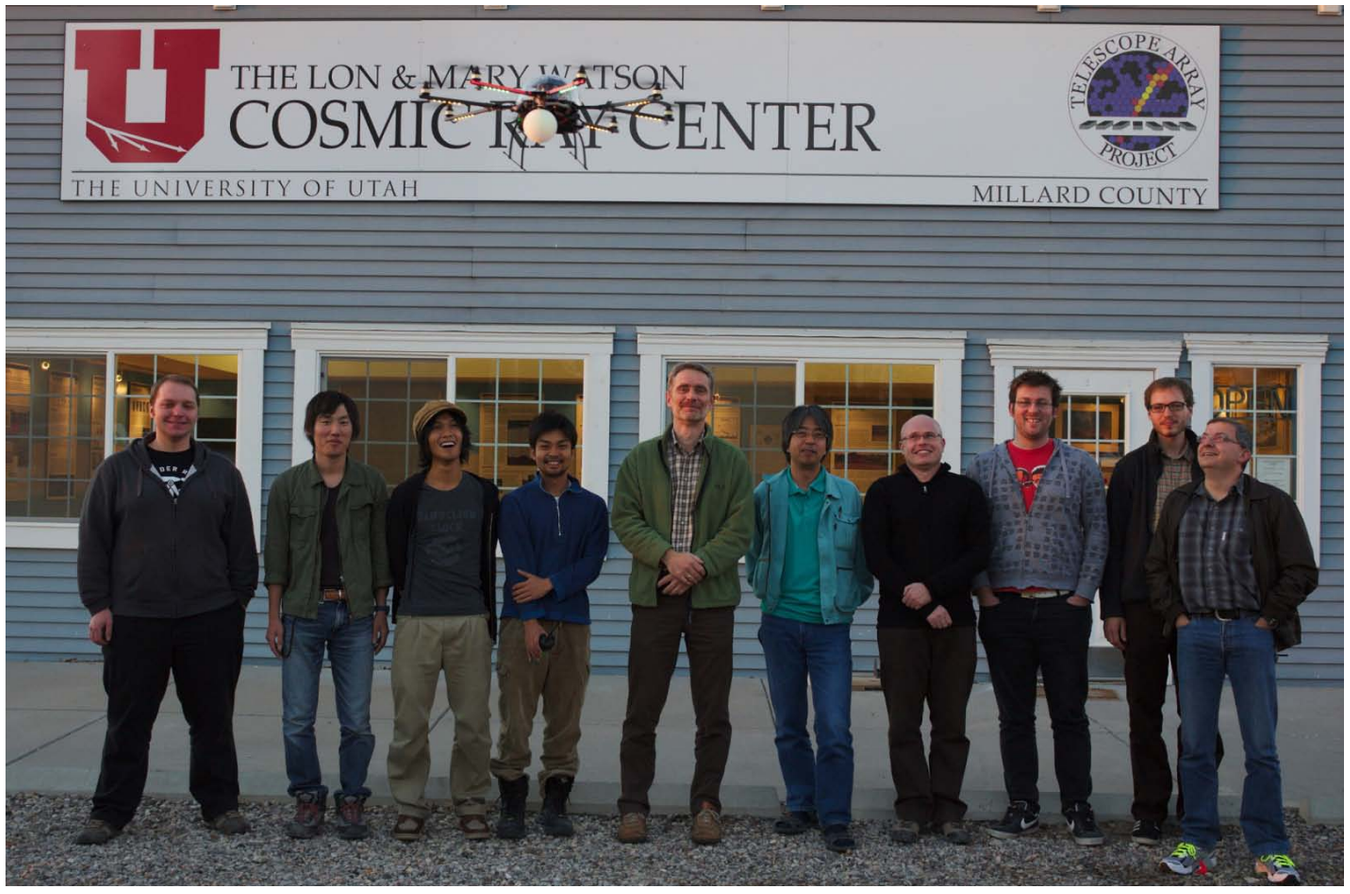
The energy spectrum around ankle are in good agreement, but an energy of suppression is different.

Cross Calibration





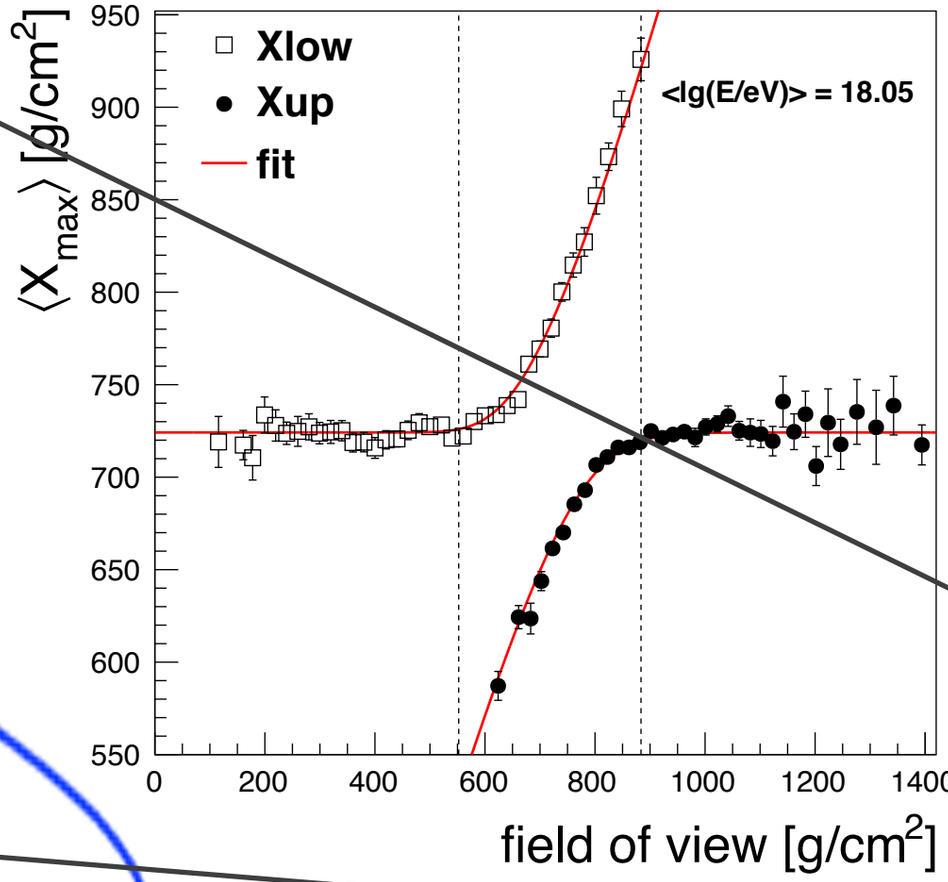




Mass Composition

Reconstructed Bias on Xmax

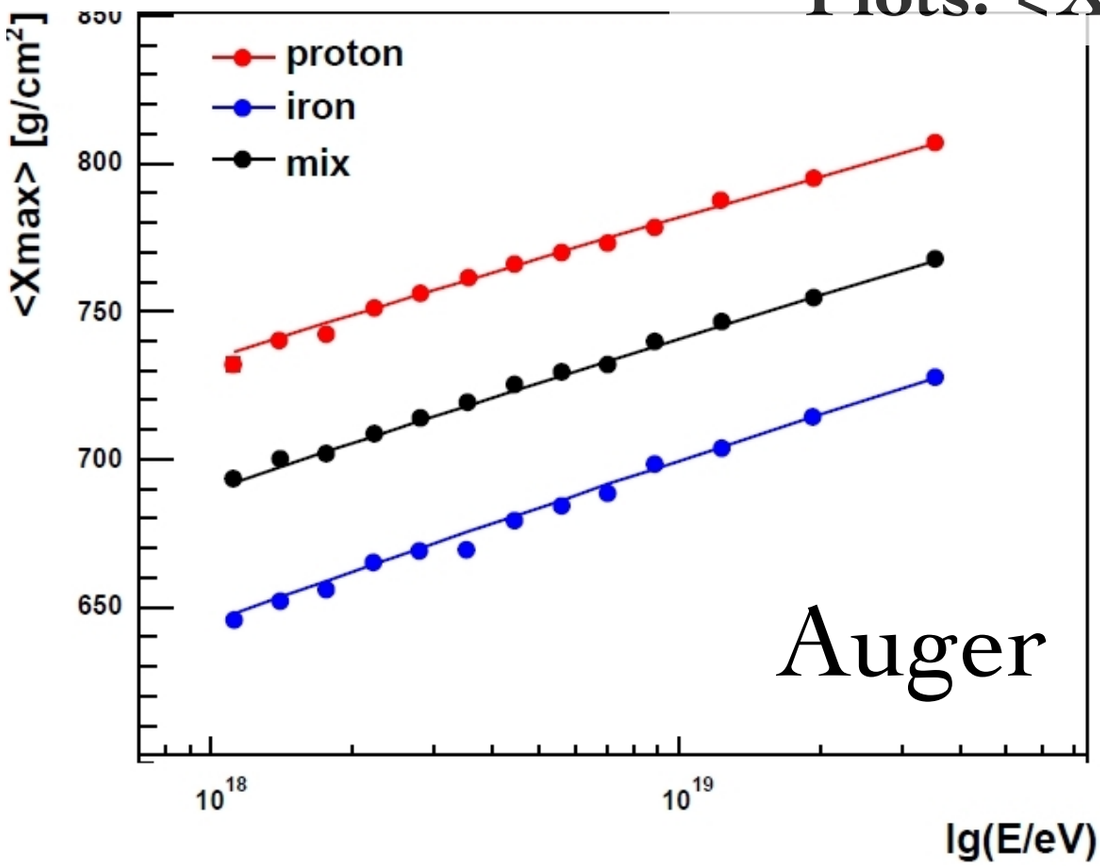
- Xmax should be observed within field of view (FOV) of FD.
- Because of Limited field of view of FD, observed Xmax is biased.

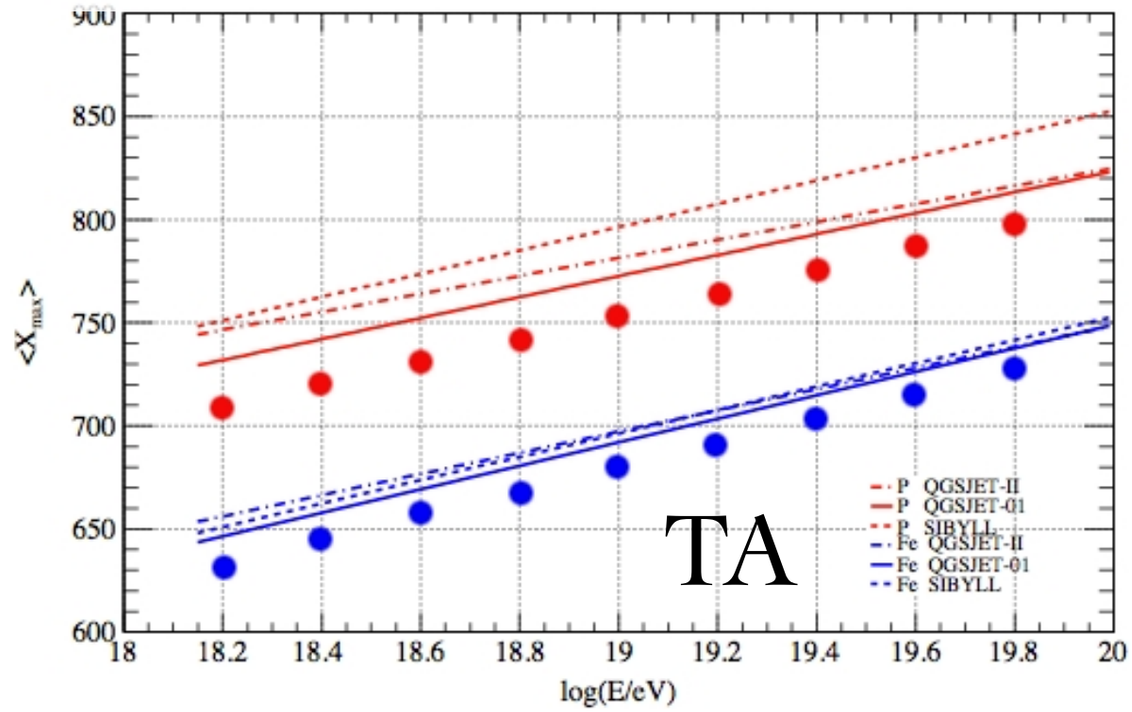


Xmax measurement strategies

Lines: <Xmax> in the atmosphere

Plots: <Xmax> in detector





- Fiducial volume cut to avoid reconstruction bias.
  - ~30% showers are survived.
- Compare unbiased data to simulation at generator level

- Apply identical cuts in data/ MC.
  - All reconstructed showers are survived.
- Compare biased data to biased simulation

Mass Composition by Auger

PIERRE AUGER OBSERVATORY

Updated in ICRC 2013

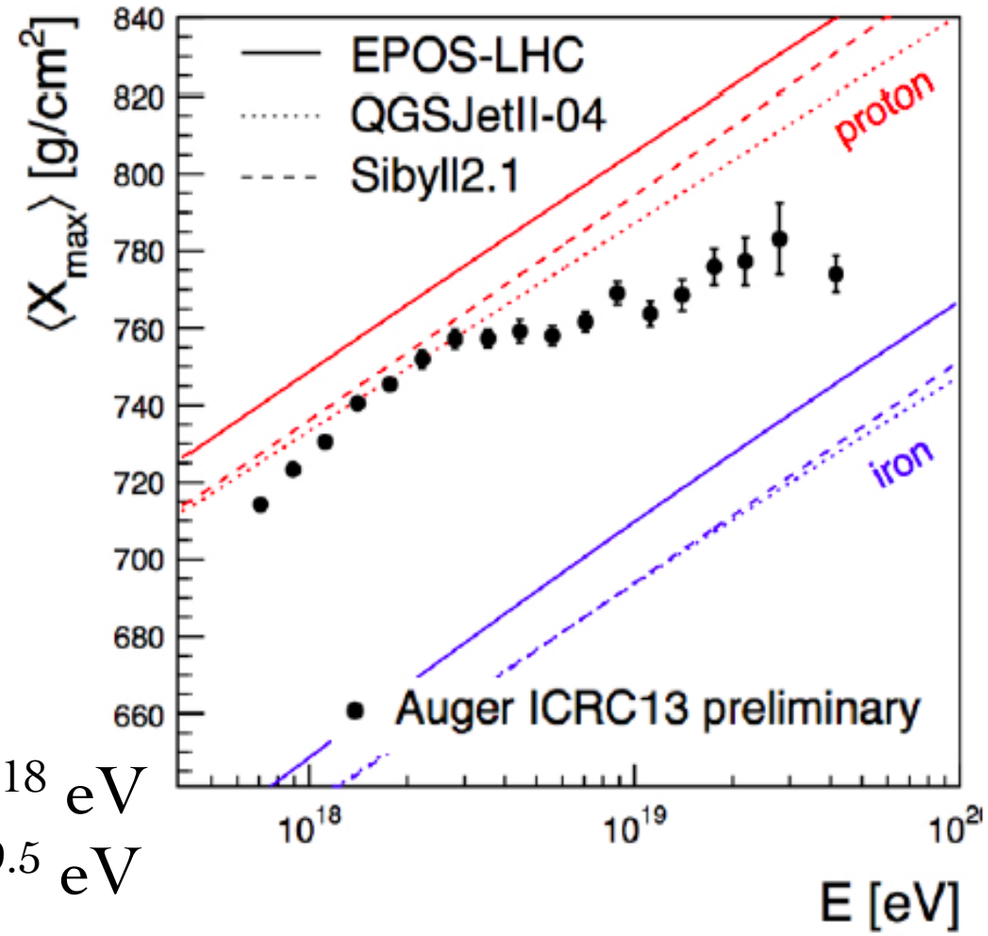
<Xmax>

+13 g/cm^2 at 10^{18} eV

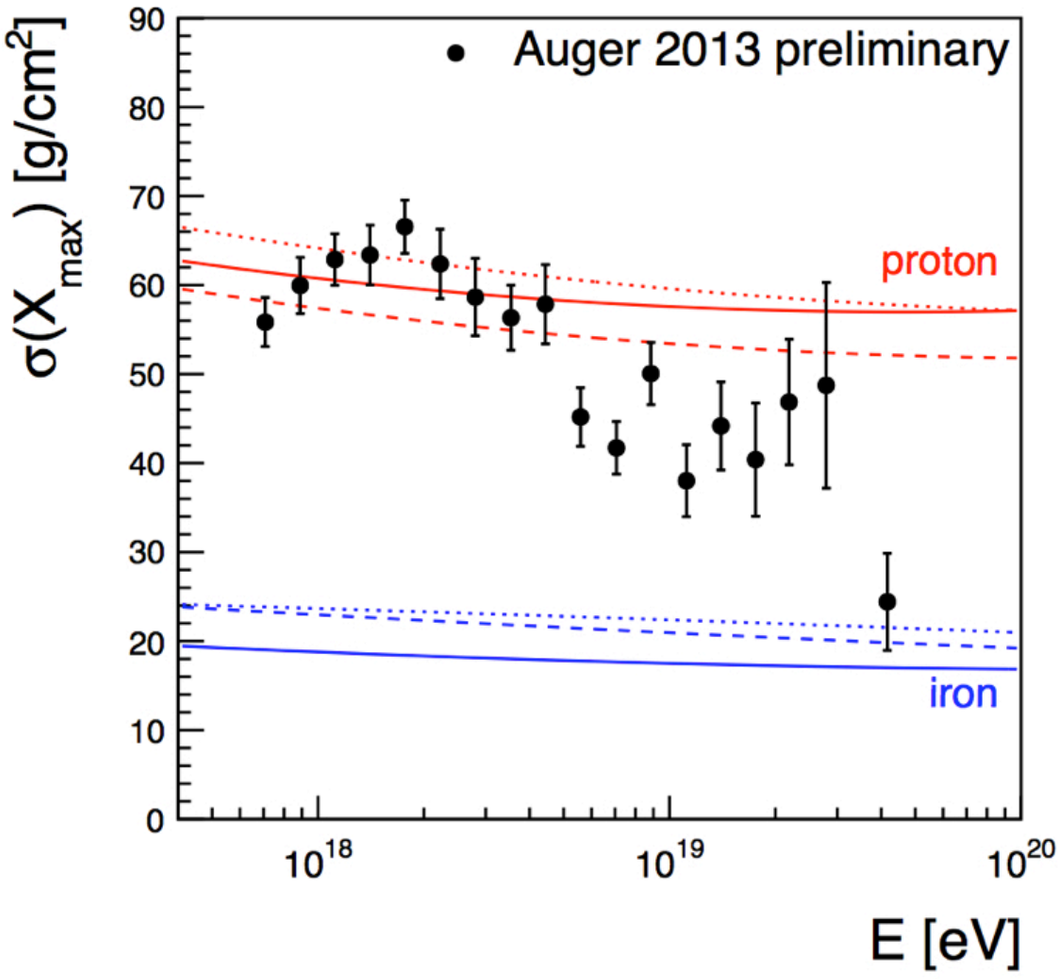
+6 g/cm^2 at $10^{19.5}$ eV

σ(Xmax)

< +10 g/cm^2 for $10^{18\text{-}19}$ eV



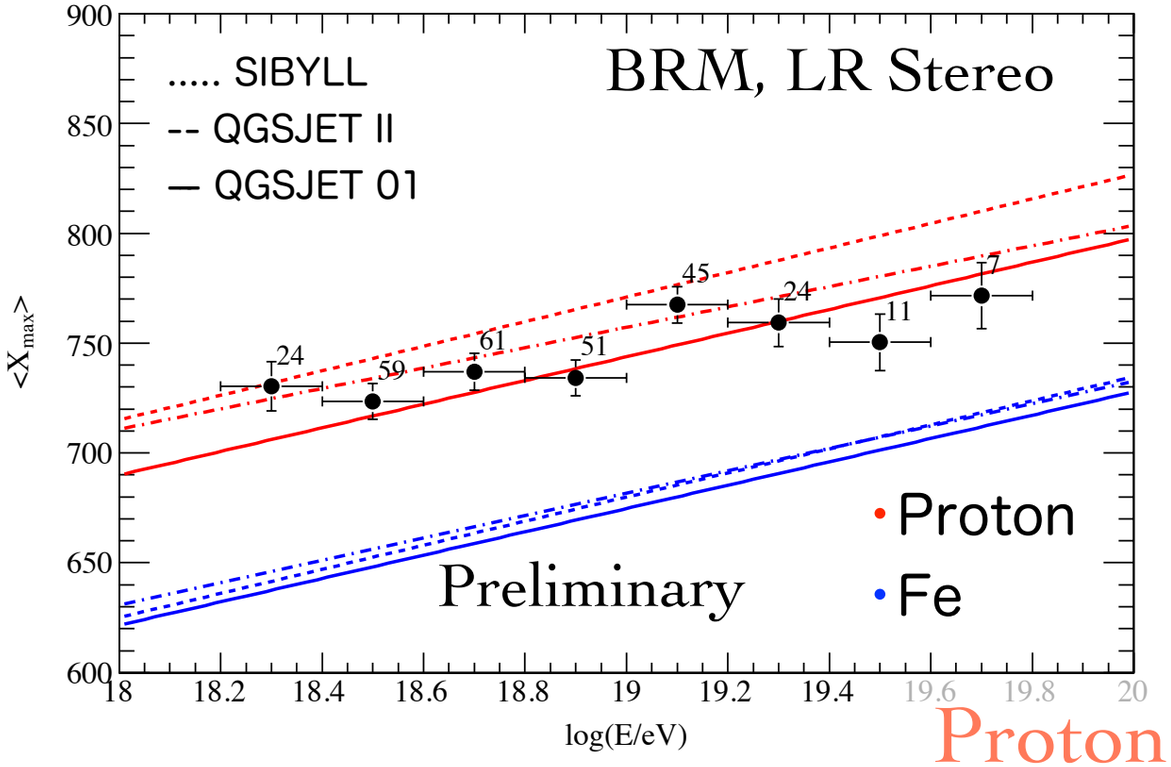
<Xmax> and σ(Xmax) data

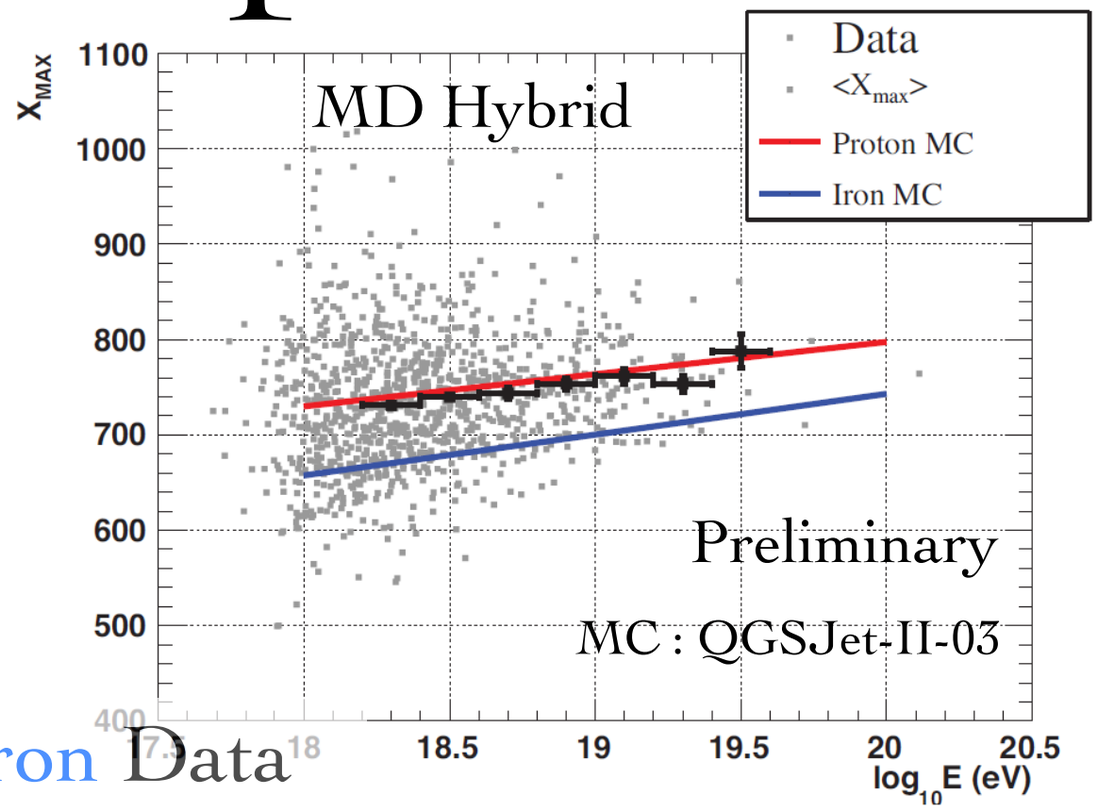


- σ(Xmax) is smaller than proton simulation above 10^{19} eV
  - Suggest a change of composition above ~$10^{18.5}$ eV with increasing mass number and small mixing

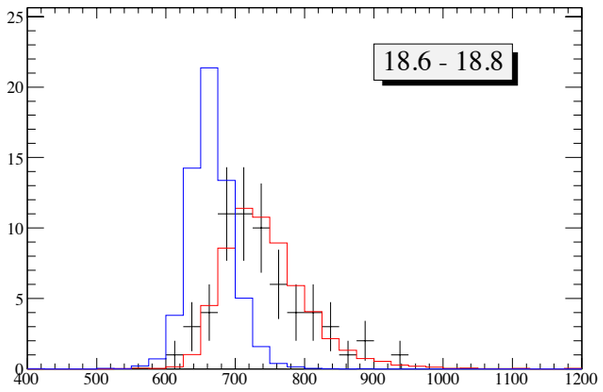
 E.J. Ahn, M. Unger, ICRC2013 J. Bellido, TAUP2013

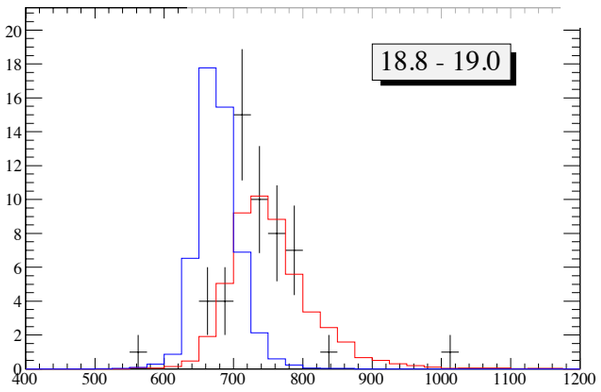
TA Mass composition

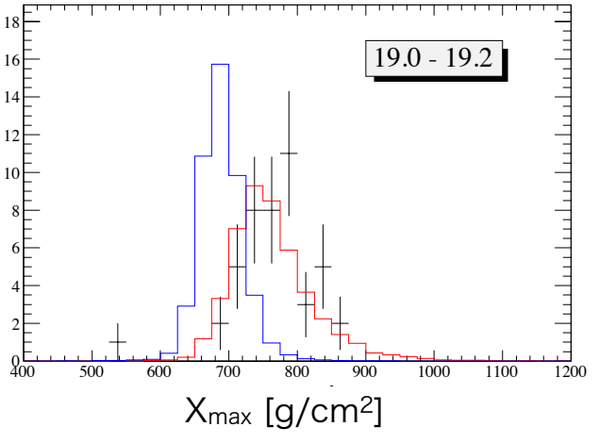


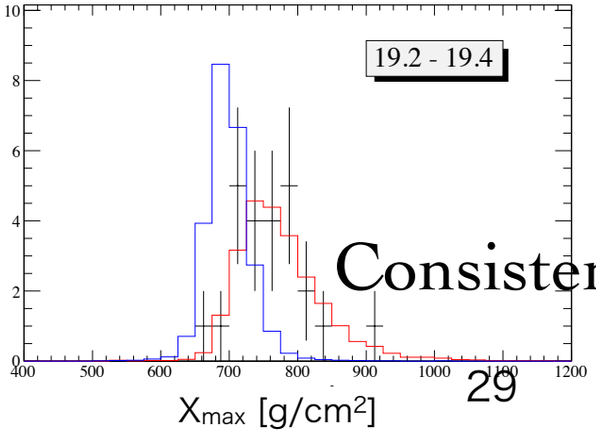


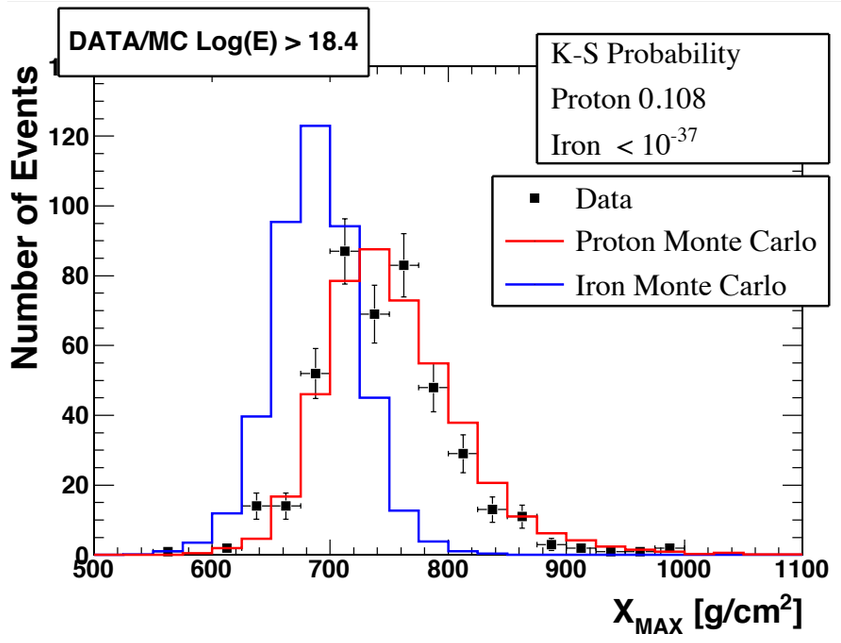
Proton Iron Data









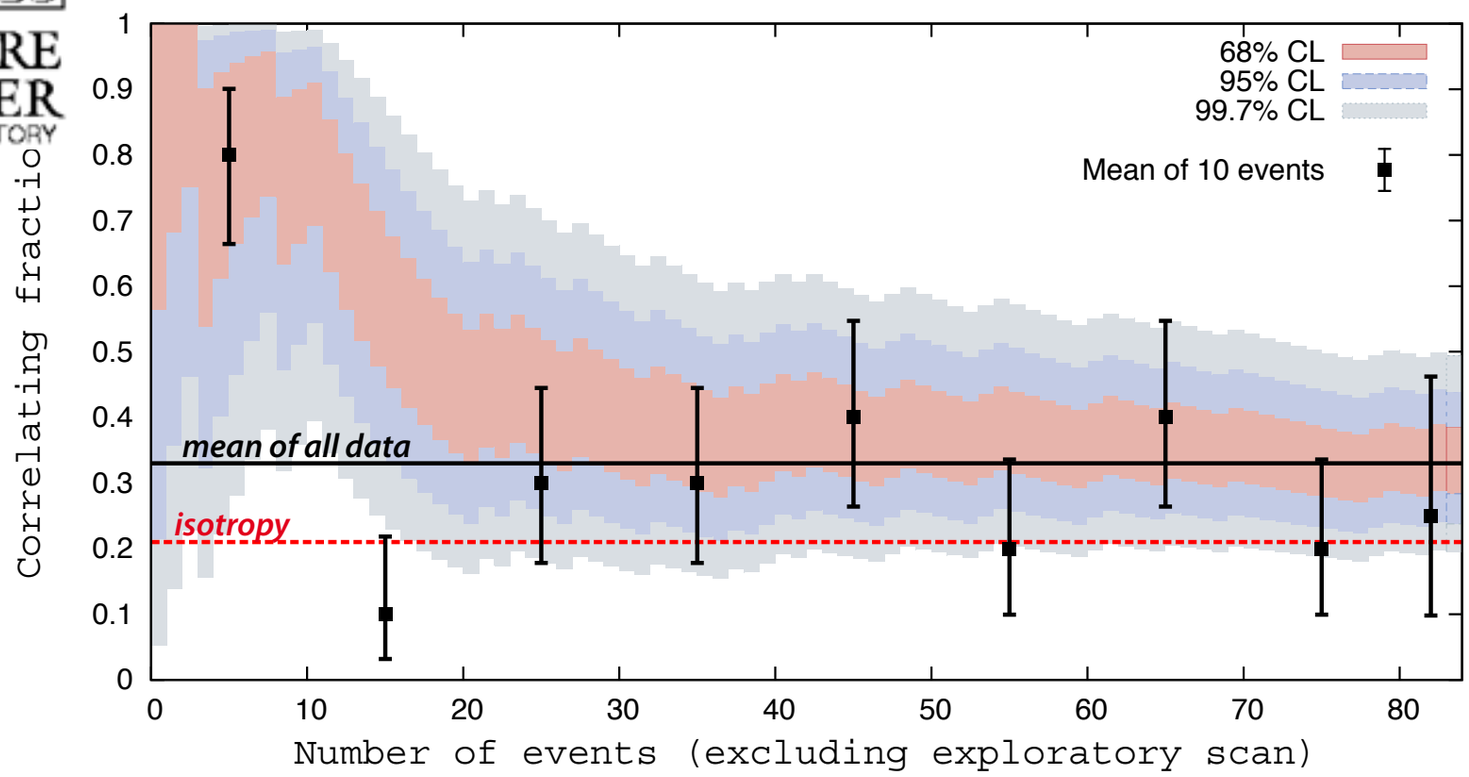


Consistent with proton QGSJet-II-03 prediction.

Y. Tameda, A. Monica ICRC 2013

Arrival direction

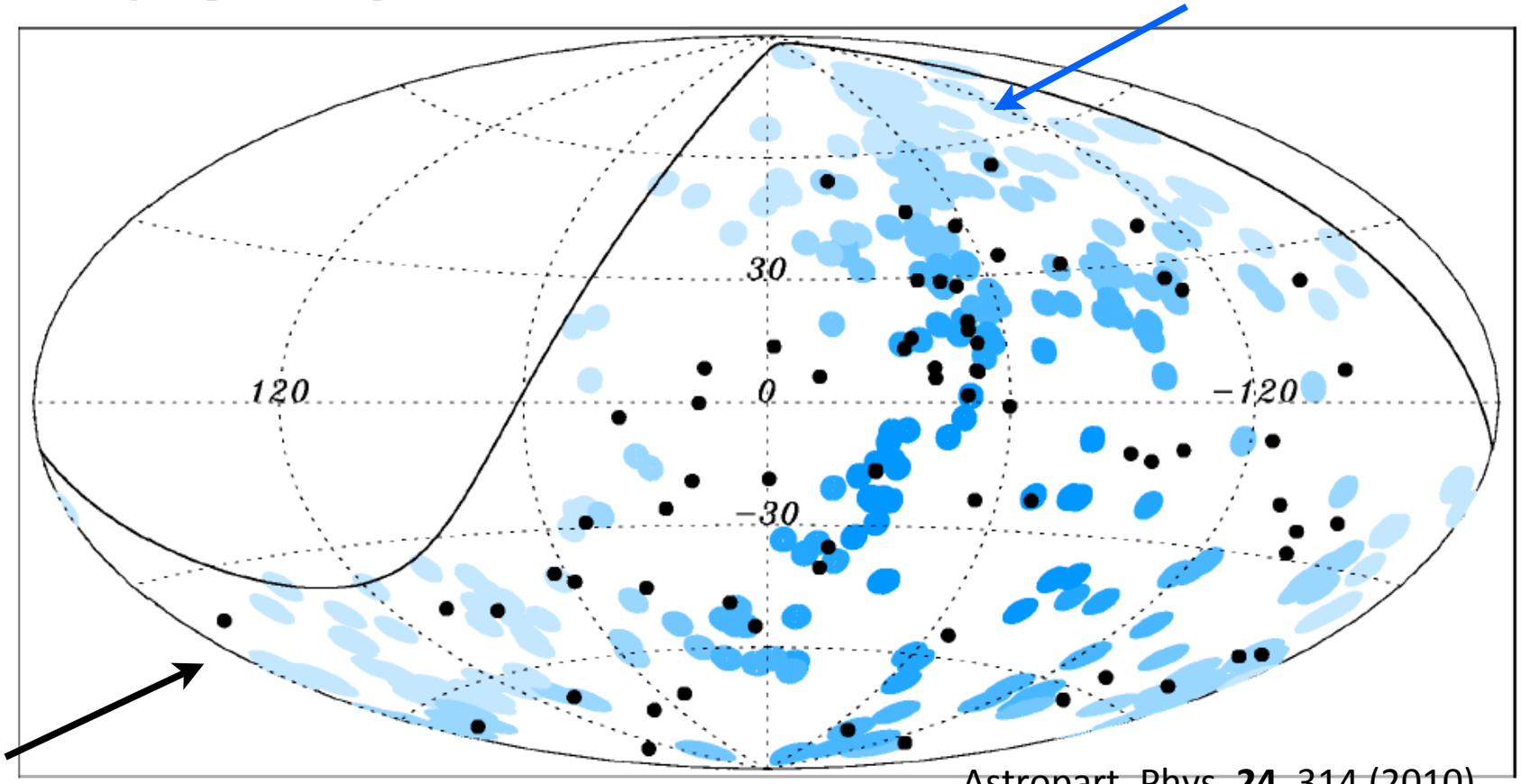
Correlation with Nearby AGN (Auger)



3.1 degree circle
VCV catalog $z < 0.018$
$E > 5.7 \times 10^{19}$ eV
in 2011 E-scale,
28 out of 84 events
(33%, P=0.006)

Data until 2011 July.

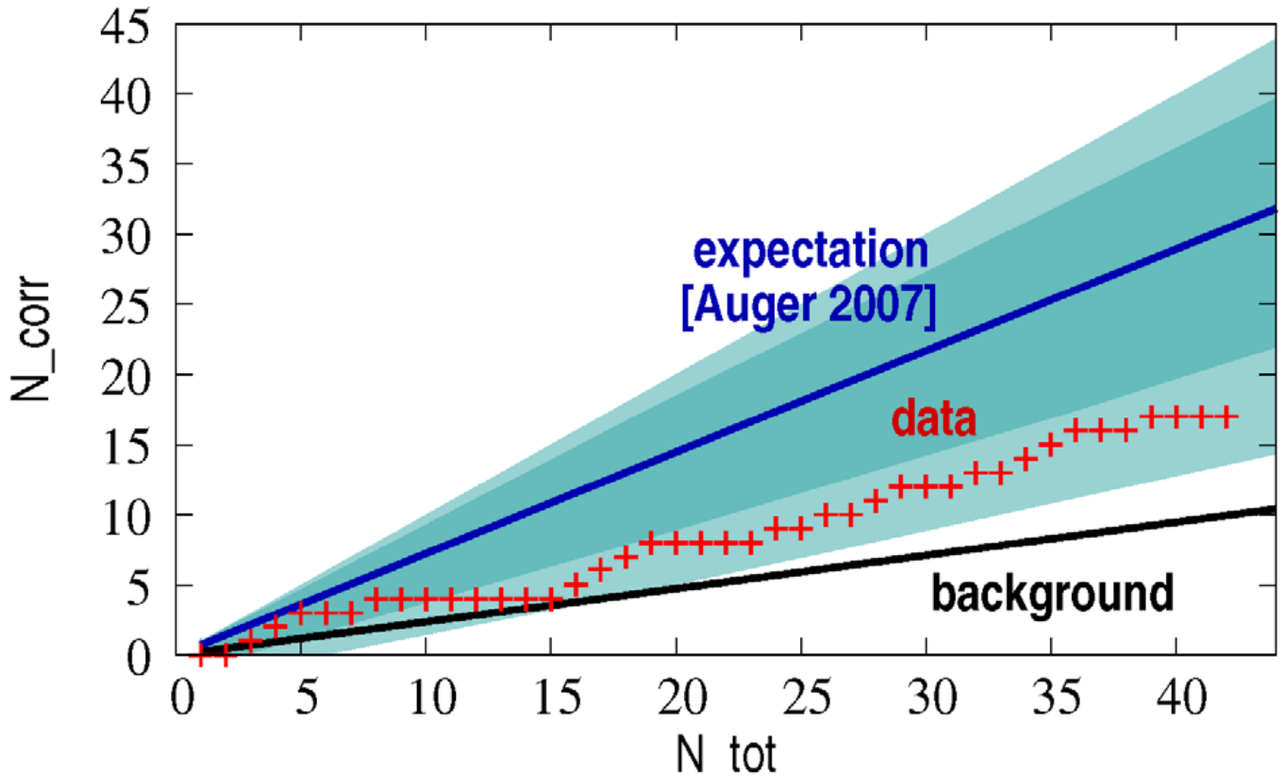
AGN 3.1° circle



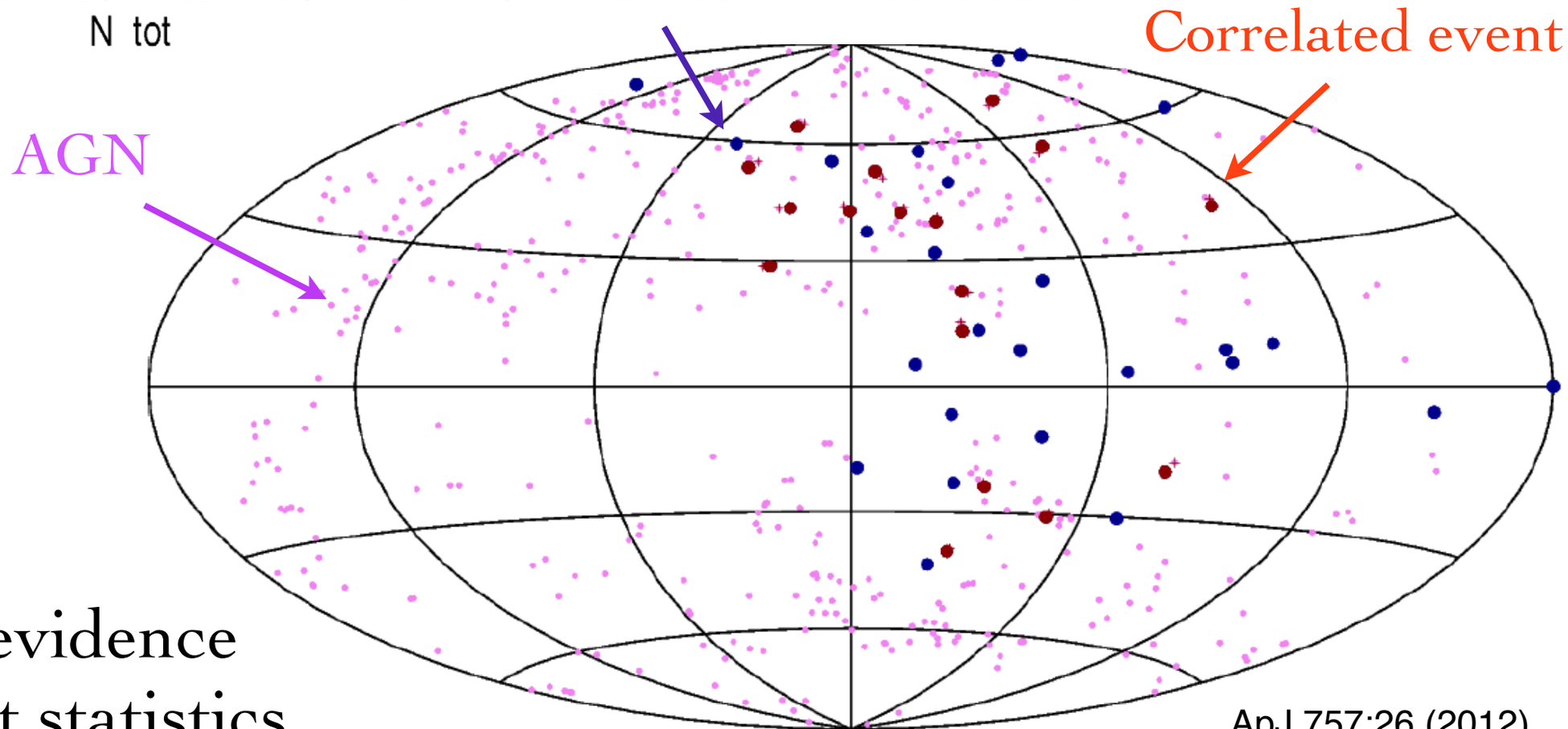
UHECR events

Astropart. Phys. **24**, 314 (2010)

Correlation with Nearby AGN (TA)



3.1 degree circle
VCV catalog z < 0.018
(same condition with Auger)
$E > 5.7\times10^{19}$ eV in TA E-scale,
17 out of 42 events
(40%, P=0.014)



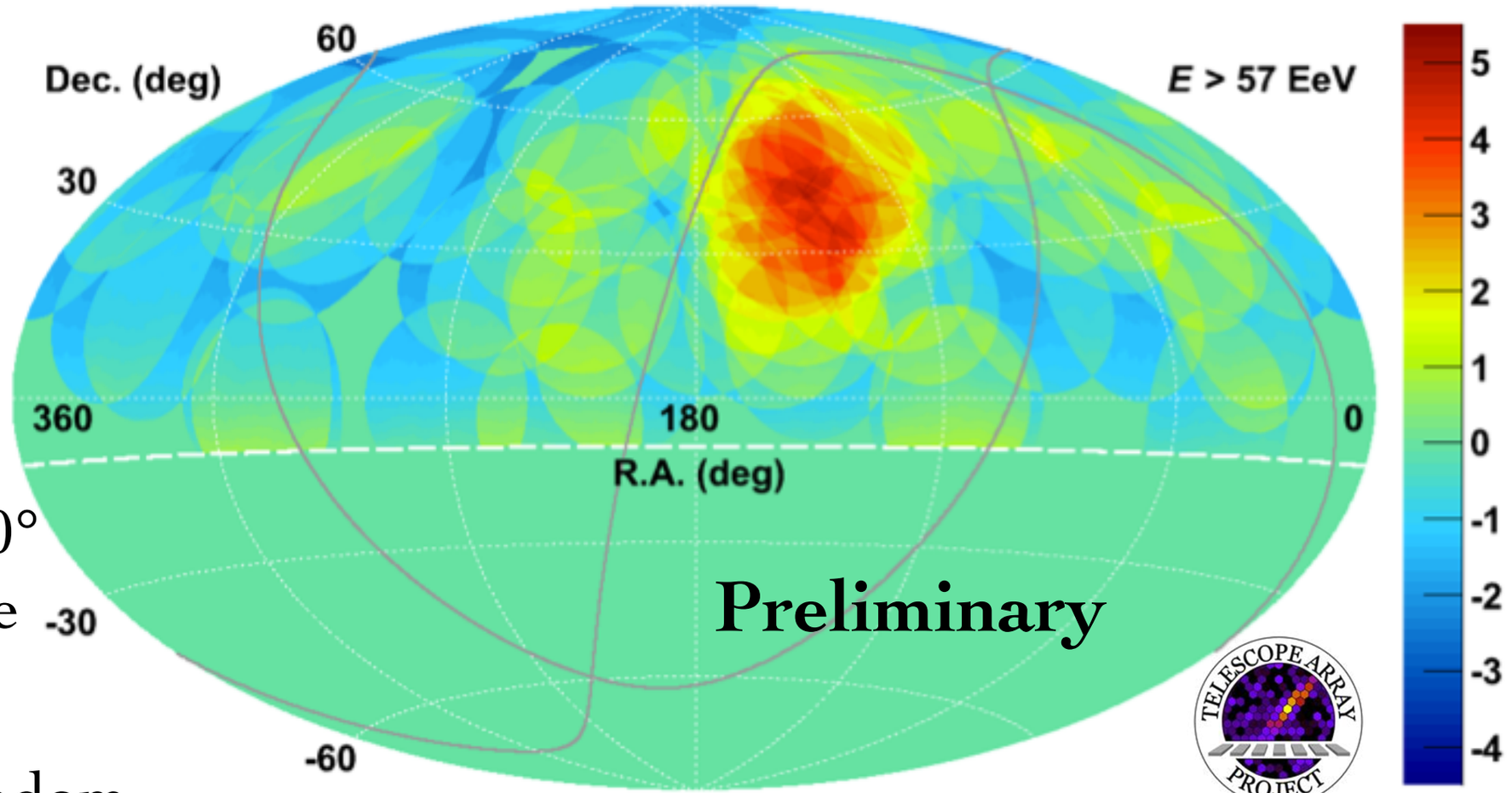
Inconclusive evidence
with the current statistics

ApJ 757:26 (2012)

A cluster event in hotspot (TA)

Looser cut
no 1.2 km border cuts
Zenith < 55 degree (45)
$E > 5.7\times10^{19}$ eV

2008 May - 2013 May
52 -> 72 events selected



Oversampling with r=20°
same with AGASA large scale anisotropy.

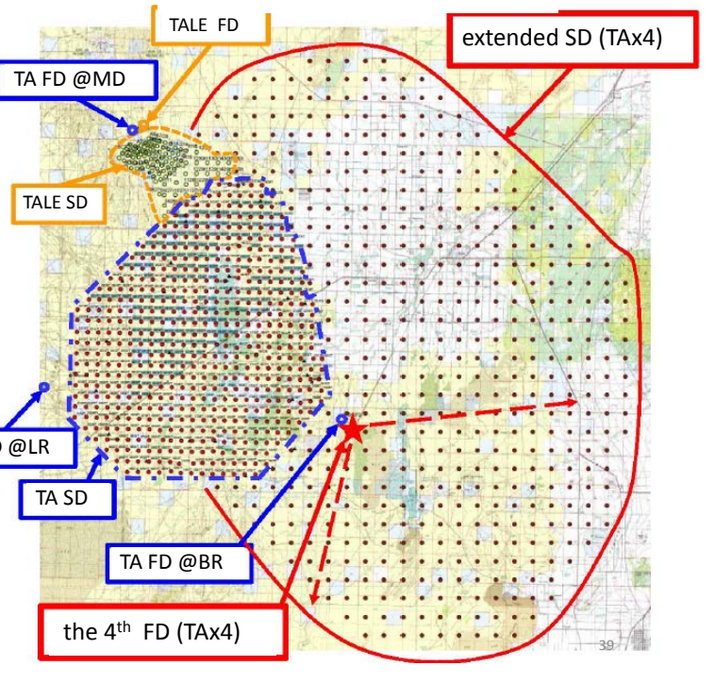
Background from 72 random isotropic events estimated by MC

Maximum significant in hotspot is 5.1 σ as pre-trial.
Post-trial chance probability is being estimated.

Future prospects

- Steadily precise measurement by TA×4 + Auger upgrade from ground
- Pioneering all sky survey from space by JEM-EUSO
- High performance of Super-Ground-Array by FD/SD/Radio Detector

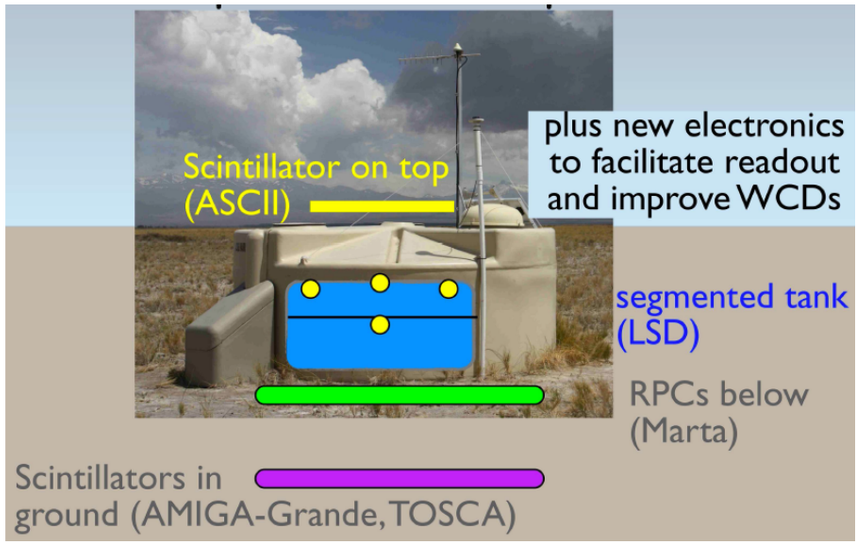
TA×4



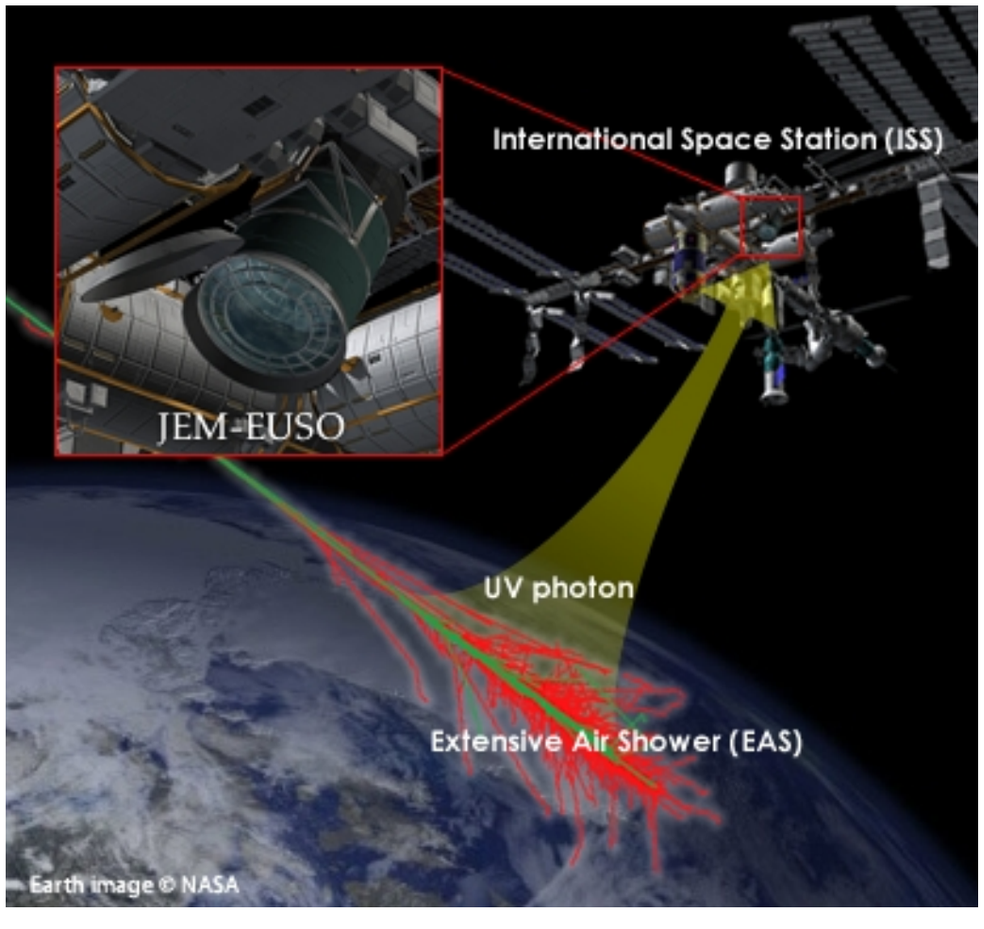
5σ confirmation of hotspot by 2019

Auger

upgrade of muon detection capability



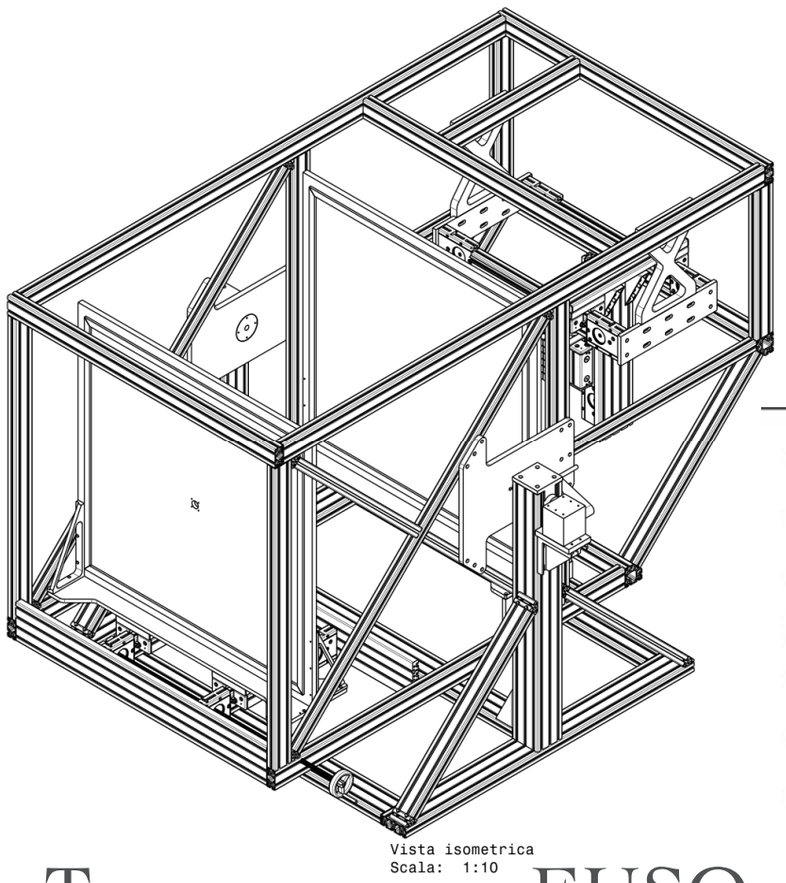
JEM-EUSO



A. Olinto K08.01 APS April 2014

As a candidate of Super-Ground-Array, Fluorescence detector Array of Single-pixel Telescope (FAST)

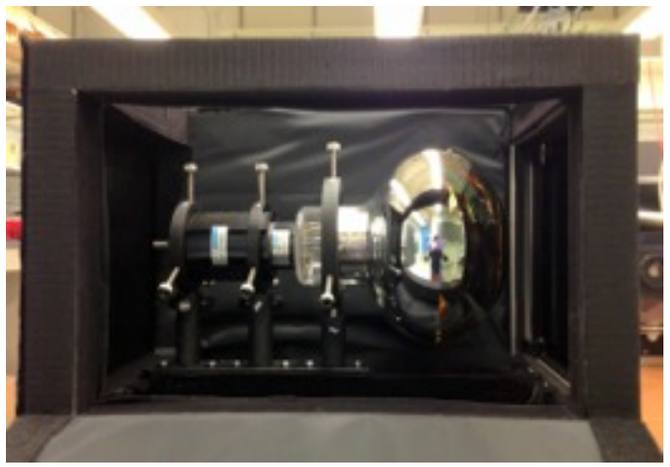
Economical FD to achieve 10 times larger area than Auger.



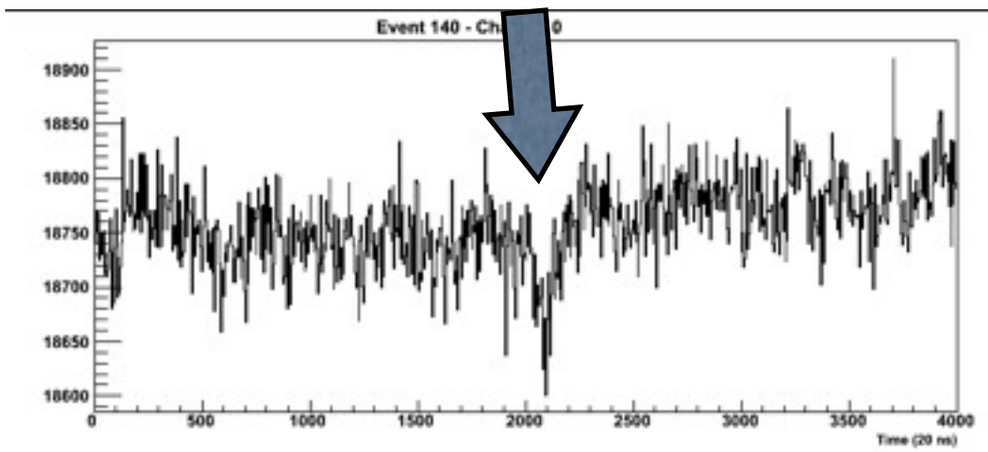
Temporary use EUSO Prototype in TA

14°×14° FOV

M. Marengo, F. Borotto, B. Giraudo, M. Bertaina (INFN-TO)

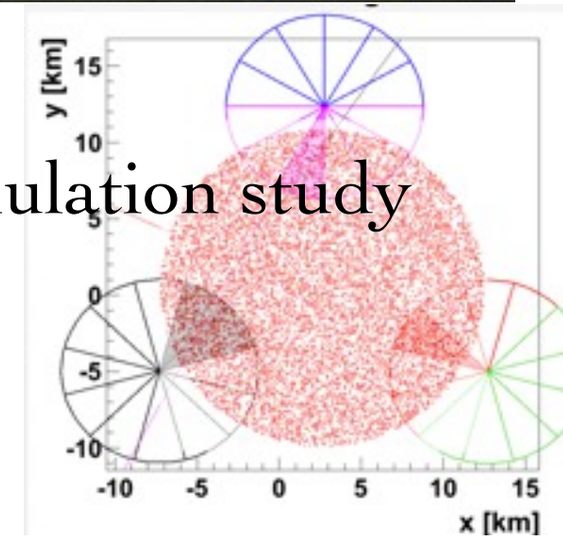


Laser at a distance of 20.1 km

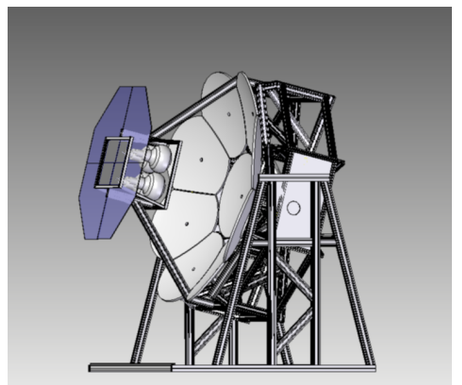


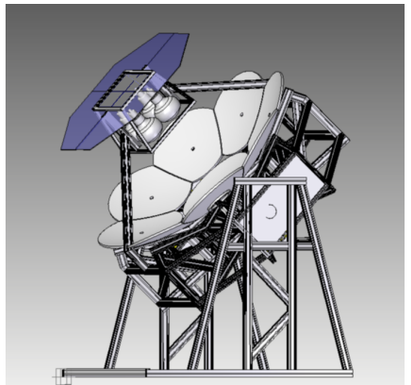
Start operation in Feb. 2014

Simulation study

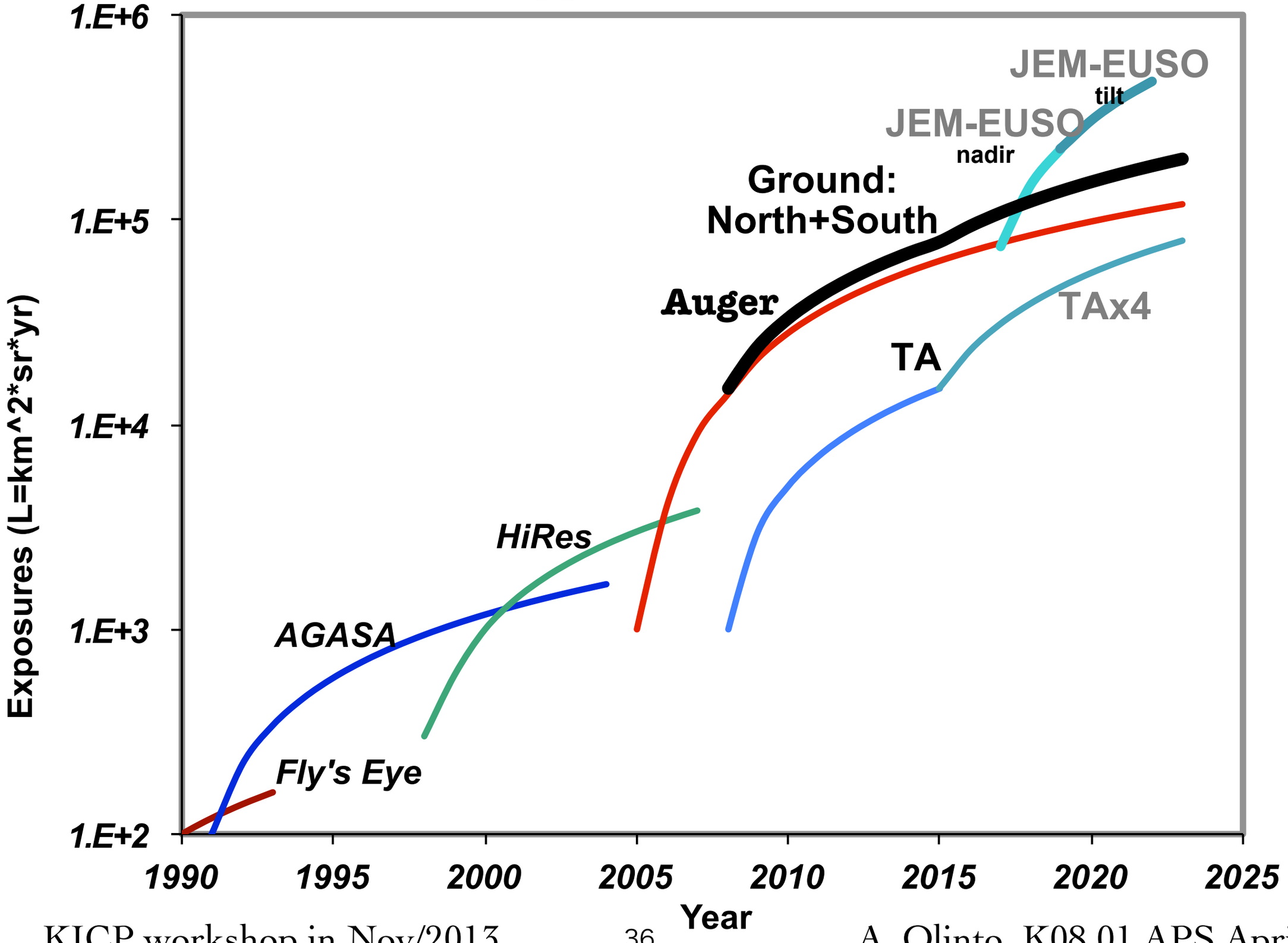


Detector design

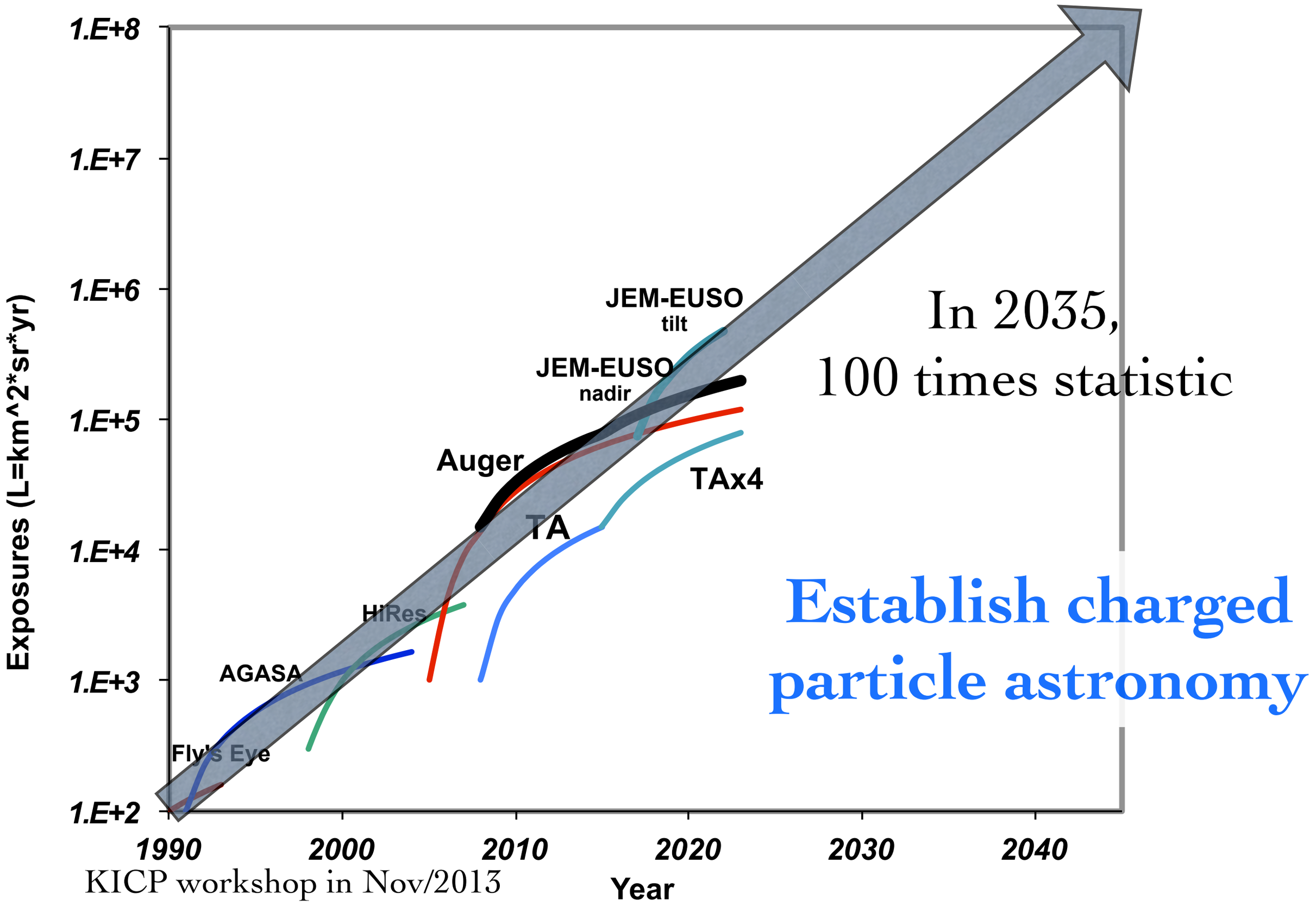




Exposure


1.E+6
1.E+5
1.E+4
1.E+3
1.E+2
Exposures (L=km^2*sr*yr)
1990
1995
2000
2005
2010
2015
2020
2025
Year
JEM-EUSO
tilt
JEM-EUSO
nadir
Ground:
North+South
Auger
TAx4
TA
HiRes
AGASA
Fly's Eye

Exposure (Extrapolation)



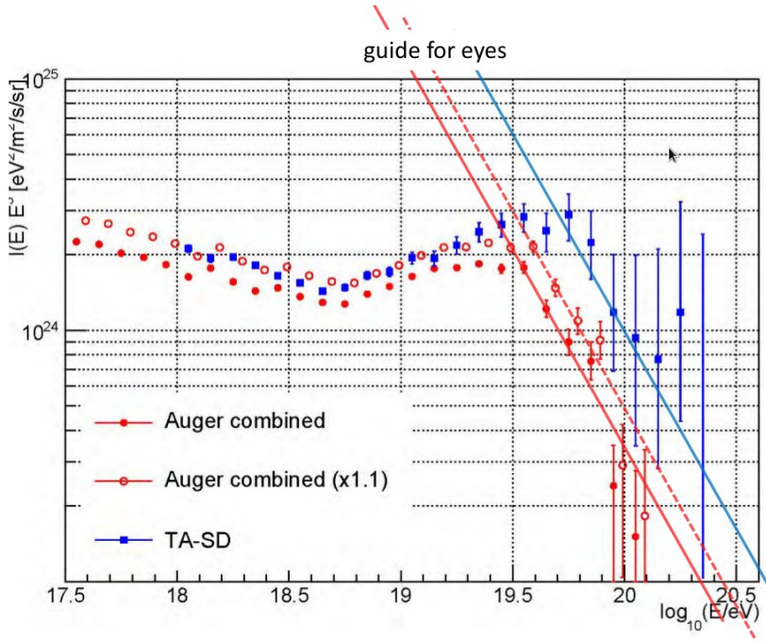
In 2035,
100 times statistic

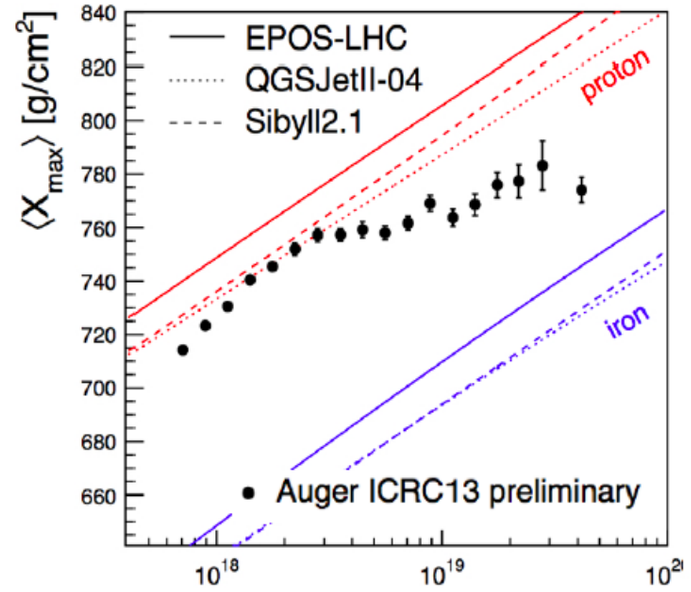
Establish charged particle astronomy

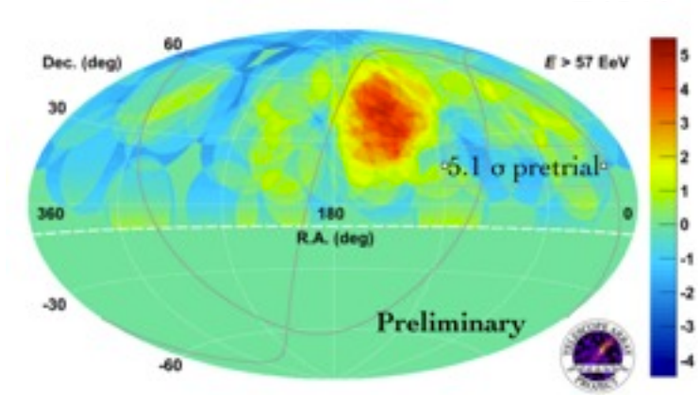
KICP workshop in Nov/2013

Summary

- **Energy Spectrum**
  - Precise measurement of ankle and suppression.
  - Good agreement in Auger/TA with energies less than $10^{19.3}$ eV, but suppression energy is different.
- **Mass composition**
  - Proton dominate around $10^{18.3}$ eV
  - Increasing mass number above $10^{18.5}$ eV and small mixing by Auger.
- **Arrival direction**
  - Hint of UHECR origins?







Need more statistic!