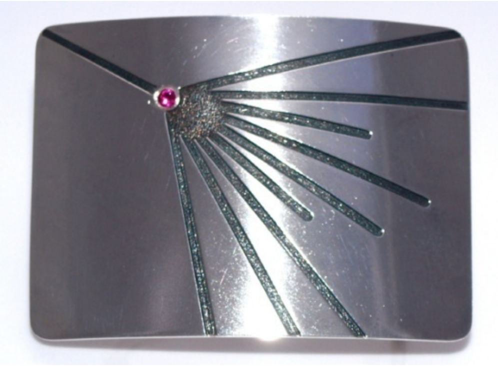
59th Krakow School of Theoretical Physics
Zakopane June 2019

Probing the Violent Universe with multi-messenger eyes: gravitational waves, high-energy neutrinos, gamma rays, and cosmic rays

Ultra High-Energy Cosmic Rays
Lecture 2

Alan Watson



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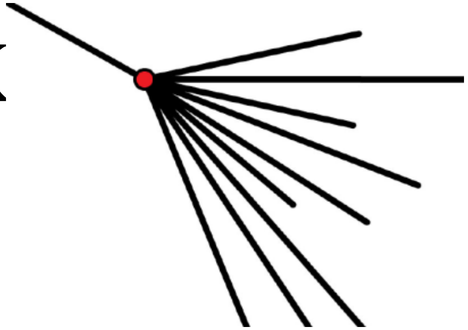
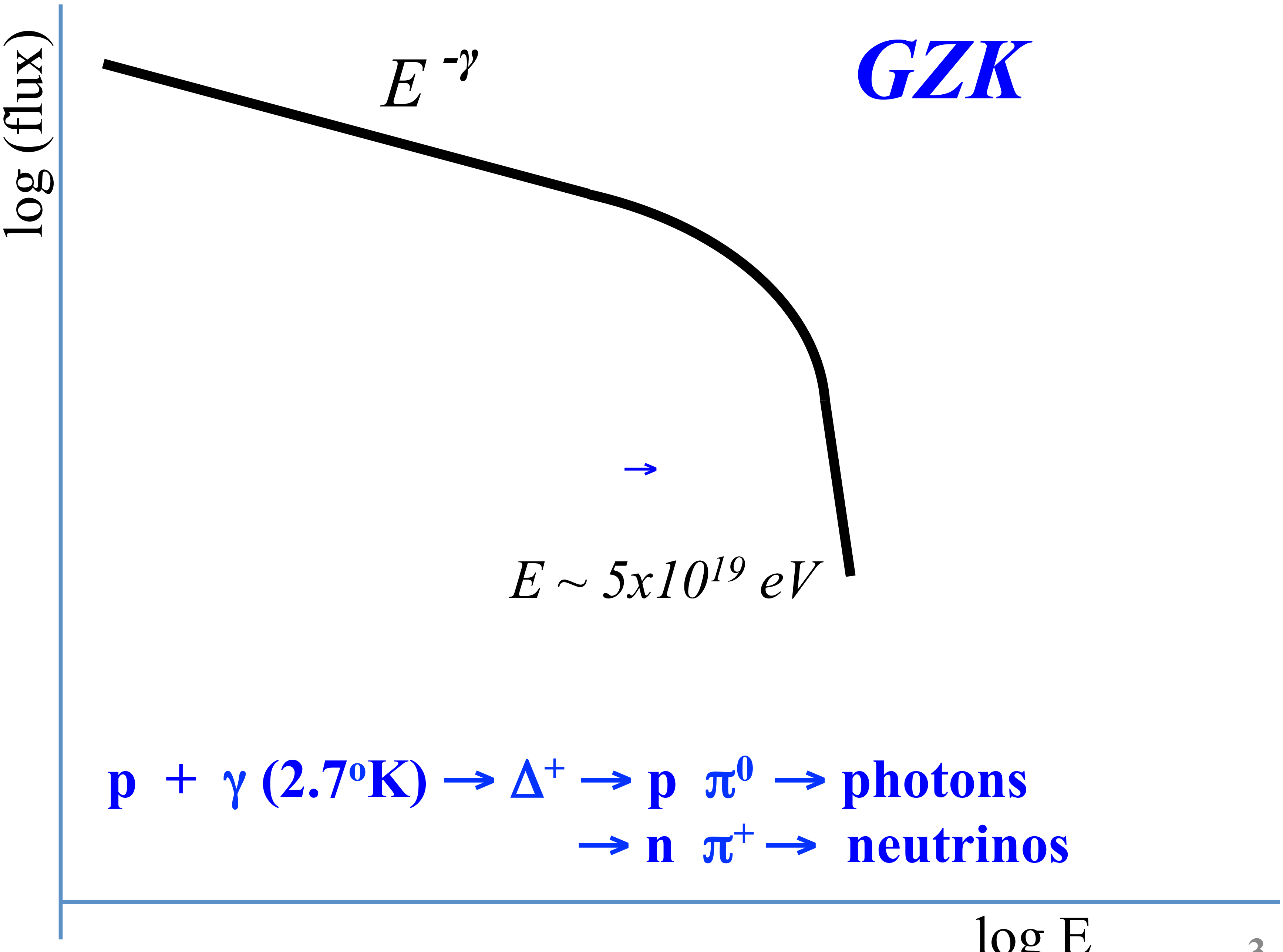


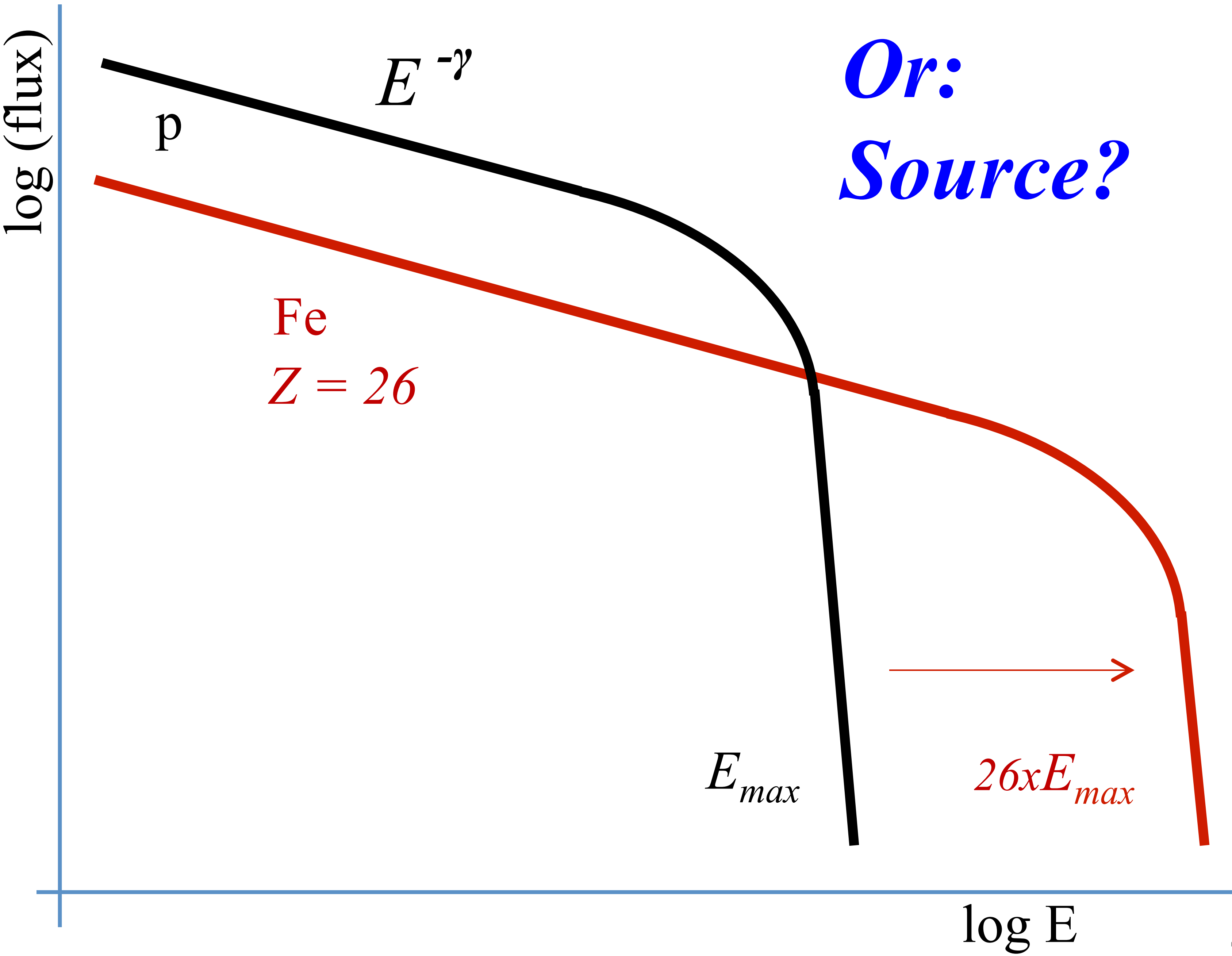
Lecture 2:

Properties of High Energy Cosmic Rays

- Energy Spectrum
- Arrival Direction Distributions
- Mass Composition

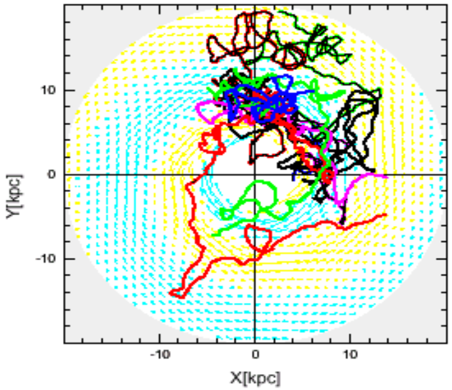
Possible interpretations


GZK
$E^{-\gamma}$
$E \sim 5x10^{19}\ eV$
log (flux)
log E
$p + \gamma\ (2.7^oK) \rightarrow \Delta^+ \rightarrow p\ \pi^0 \rightarrow$ photons
$\rightarrow n\ \pi^+ \rightarrow$ neutrinos

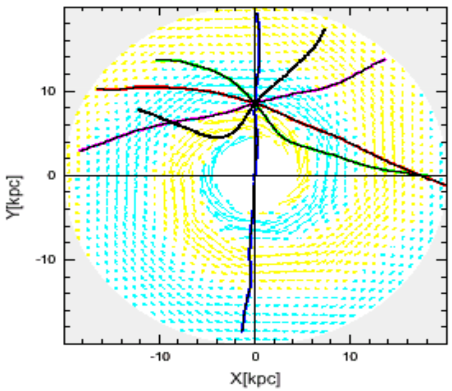

Or:
Source?
log (flux)
$E^{-\gamma}$
p
Fe
Z = 26
E_{max}
$26xE_{max}$
log E

Trajectories of Cosmic Ray Protons in the Galaxy

- **protons are trapped in our Galaxy up to ~10^{18}eV**
- **protons can travel straight lines above ~10^{20}eV**



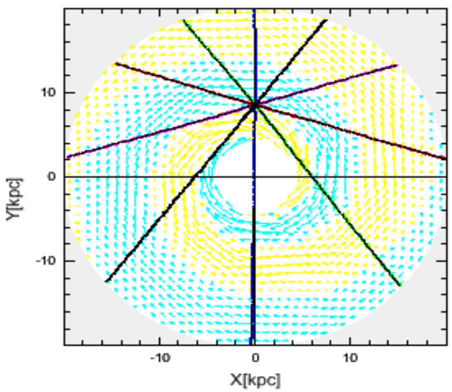
E=10^{18}eV



E=10^{19}eV

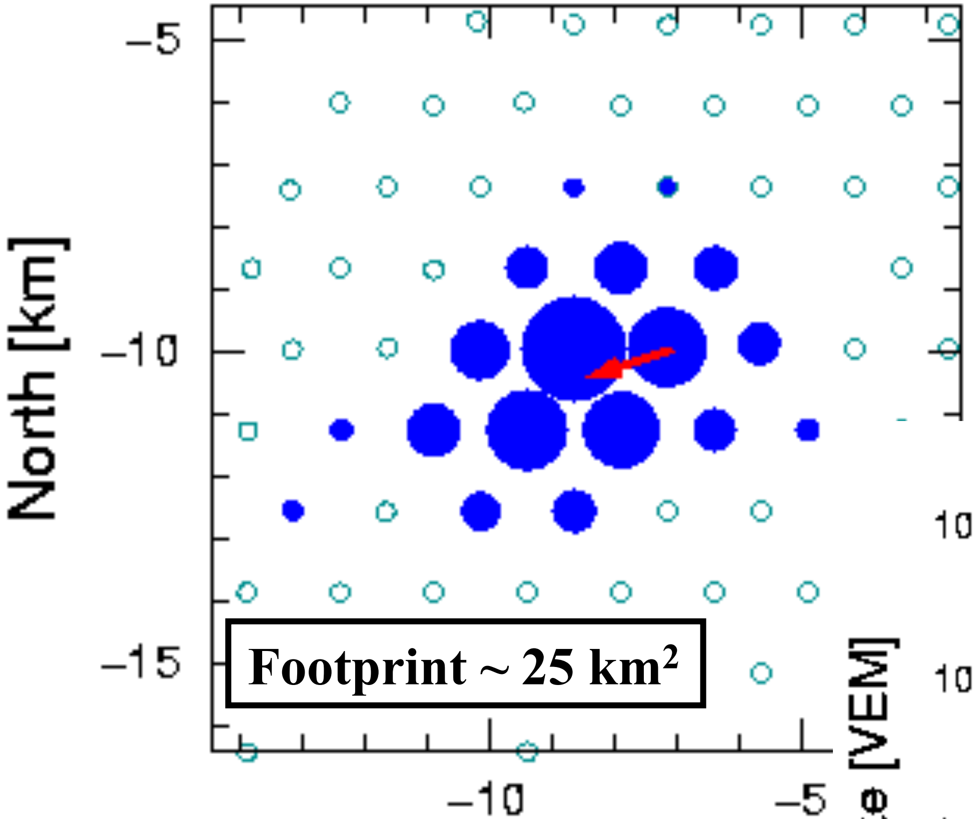
↓

- **charged-particle astronomy?**

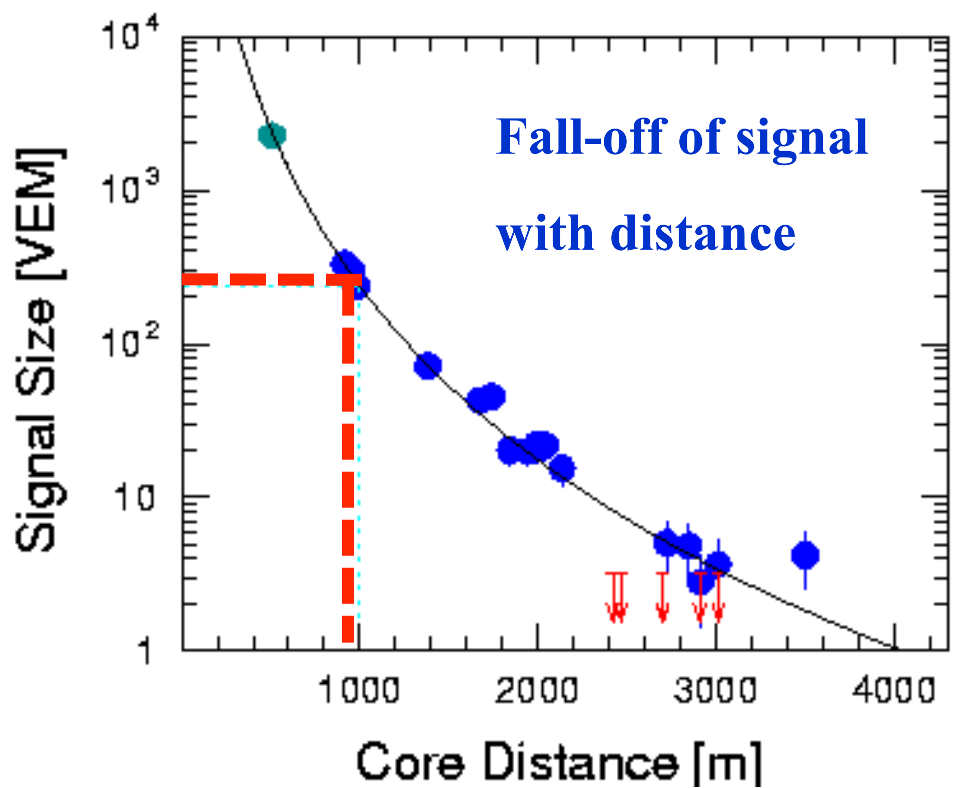


E=10^{20}eV

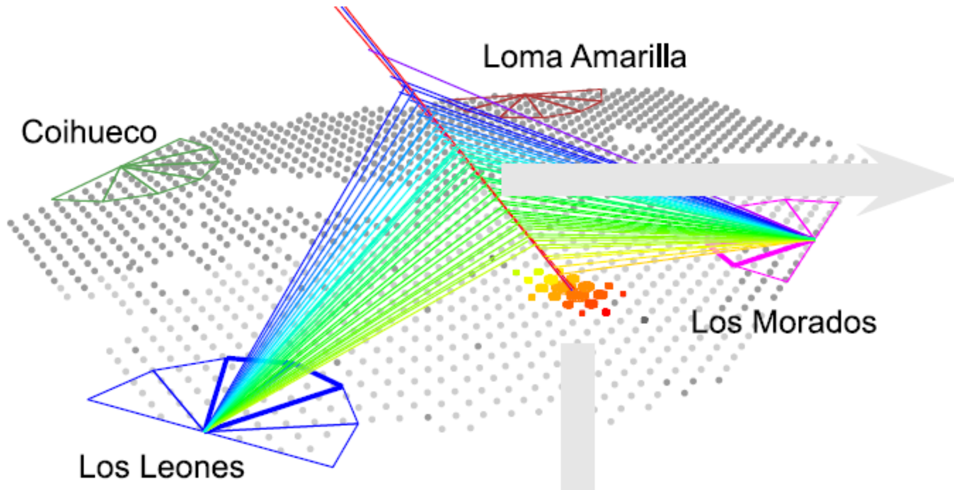
A large event: 7 x 10^{19} eV

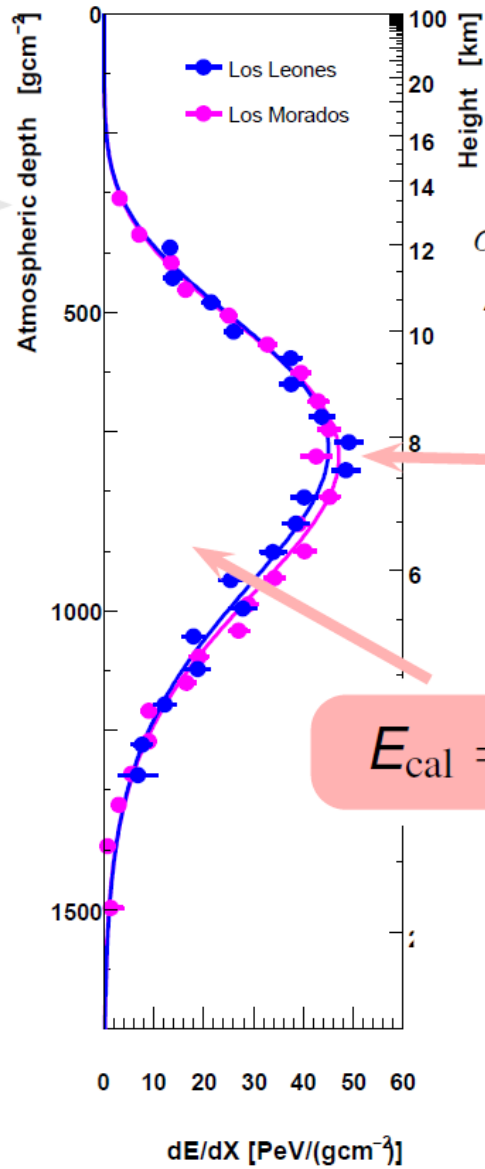


Signal at 1000 m from densest part of shower is chosen to define the 'size' of the shower



Hybrid Detection of Air Showers



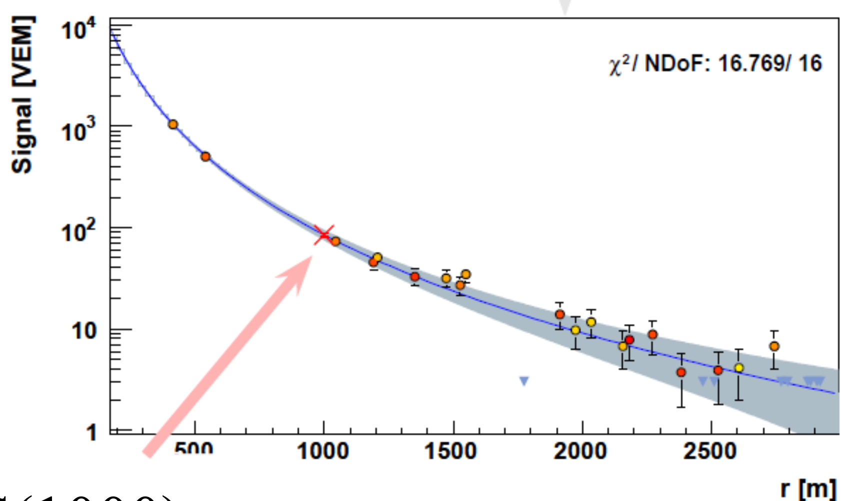


$\sigma_{X_{\max}} \leq 20\,\mathrm{g/cm^2}$
$\Delta_{\rm sys} \leq 10\,\mathrm{g/cm^2}$

$X_{\max}$

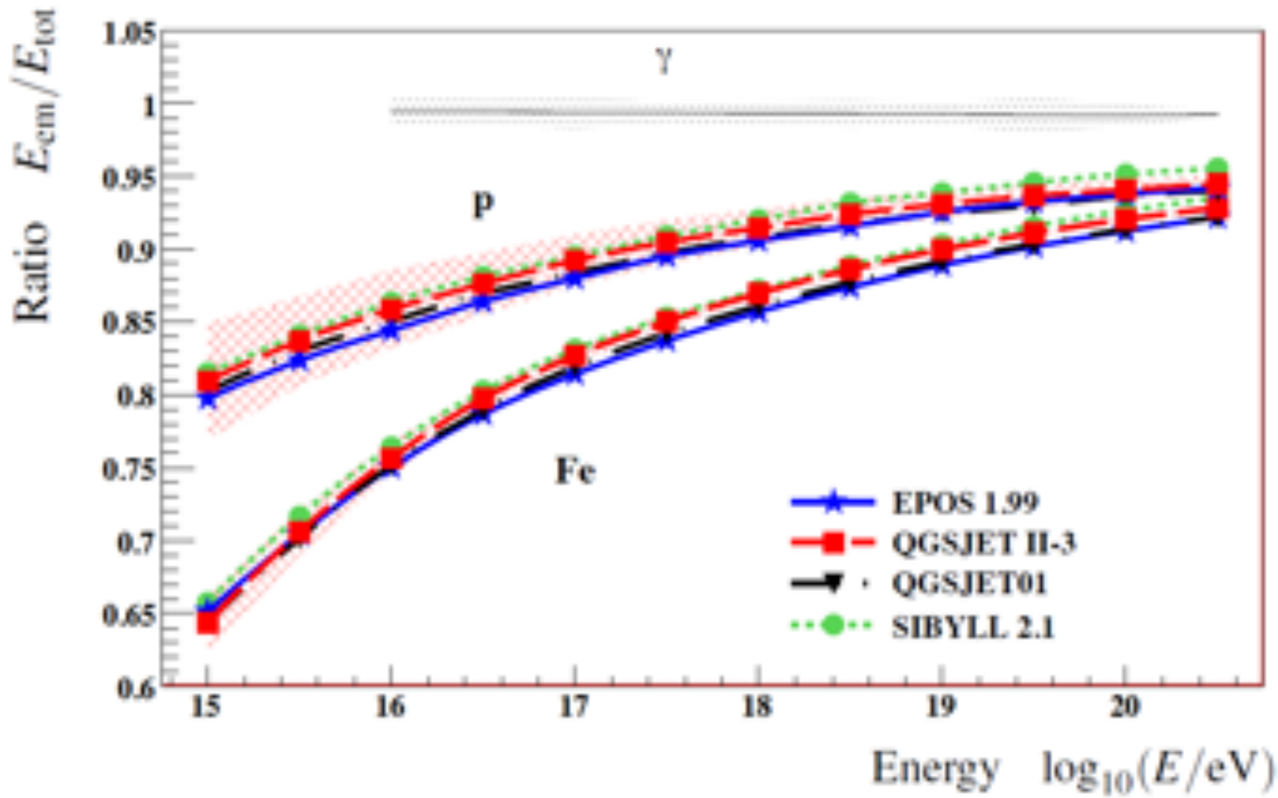
$E_{\rm cal} = \int \frac{\mathrm{d}E}{\mathrm{d}X}\,\mathrm{d}X$

$\sigma_E/E \sim 8\,\%$
$\Delta_{\rm sys} \approx 15\,\%$



S(1000)

$E_{\rm surface} = f(S_{1000},\ \theta)$

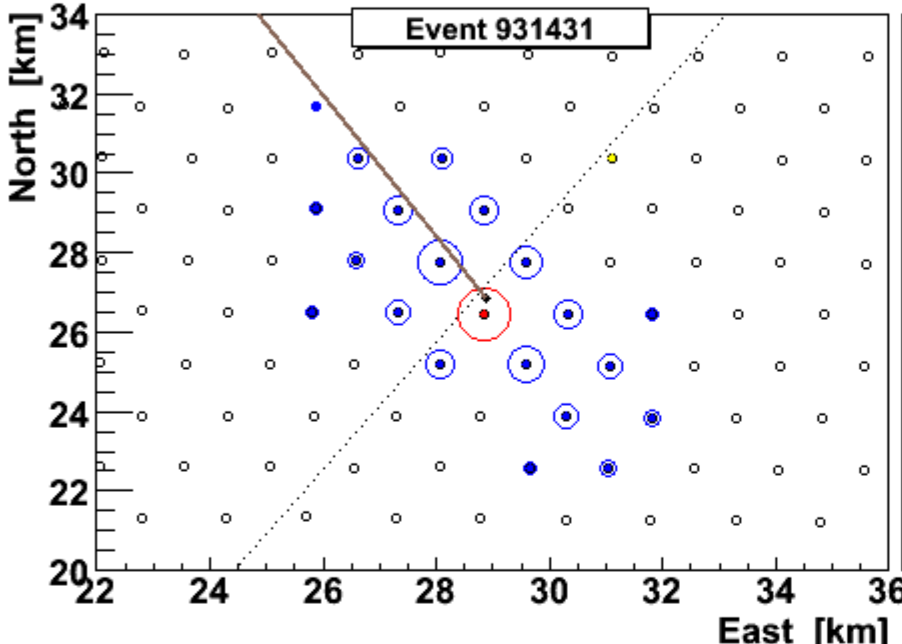


Invisible Energy

This is the energy carried into the ground by muons and neutrinos. Not measured by the fluorescence detectors

Reason that this is relatively more of a correction at low energies is because at the higher energies pions tend to interact, not producing muons or neutrinos. Also explains difference between p and Fe (think energy per nucleon)

A Hybrid Event



Core location

Easting 468693 ± 59

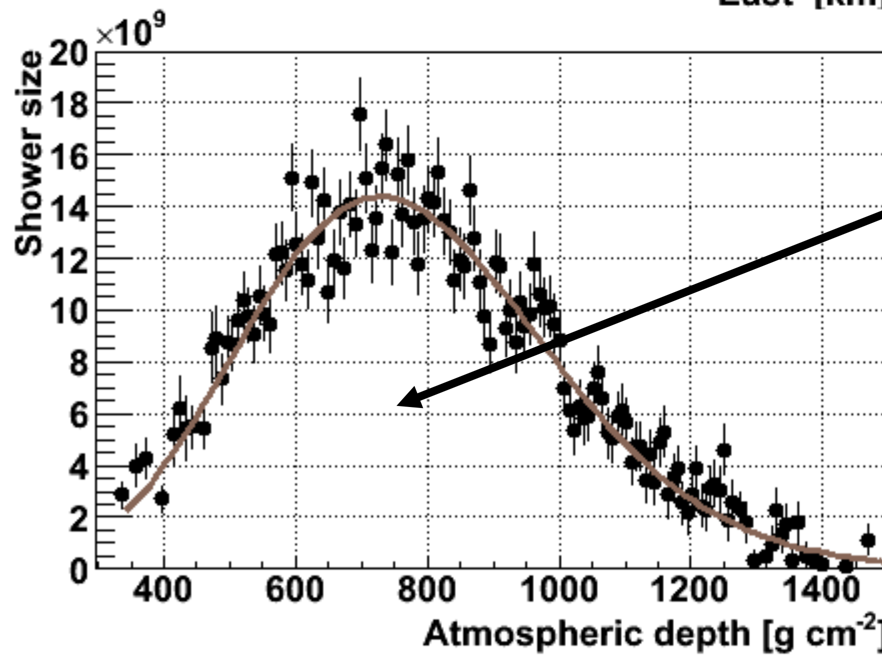
Northing 6087022 ± 80

Altitude = 1390 m a.s.l.

Shower Axis

$\theta = (62.3 \pm 0.2)^\circ$

$\phi = (119.7 \pm 0.1)^\circ$

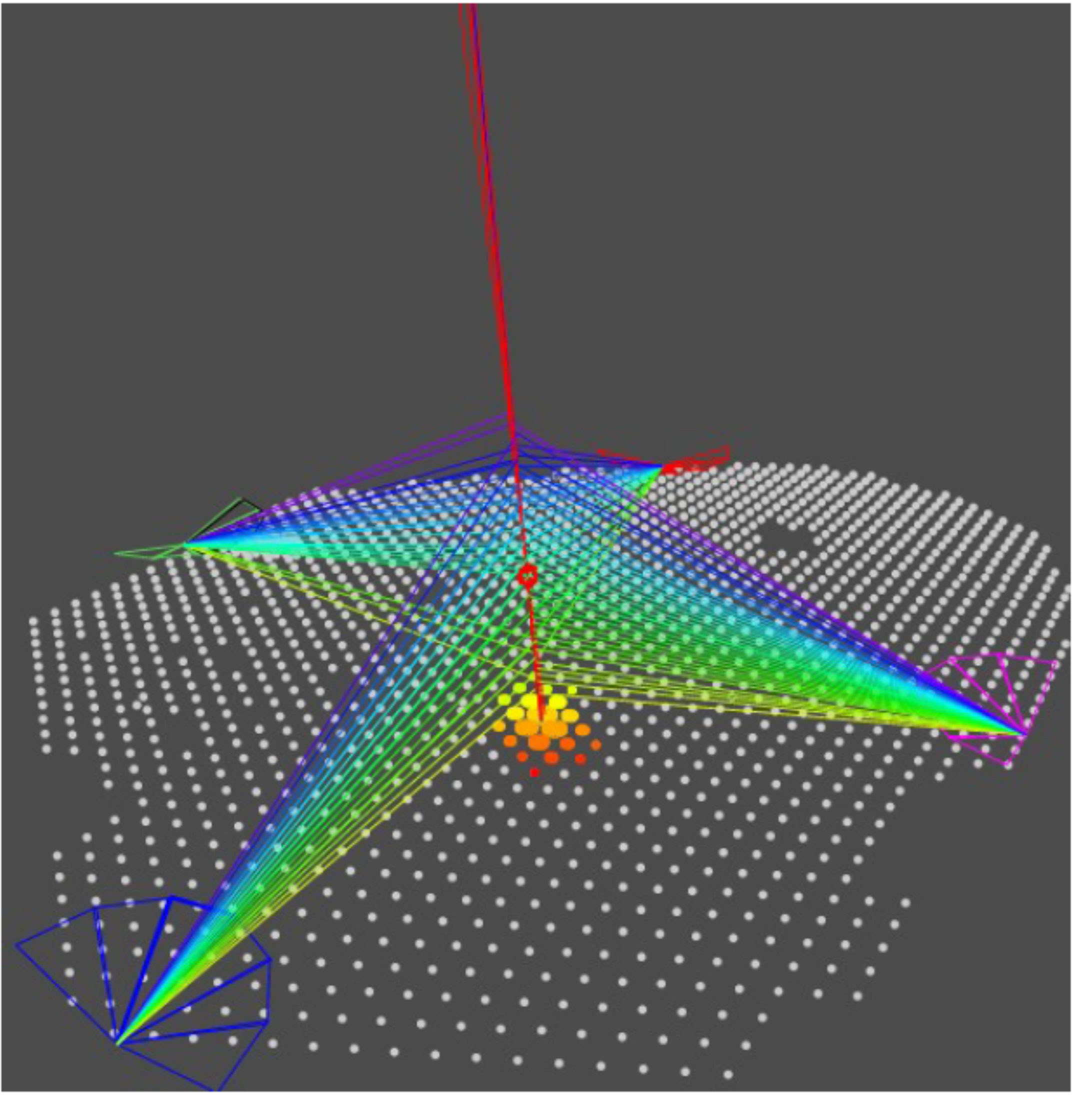


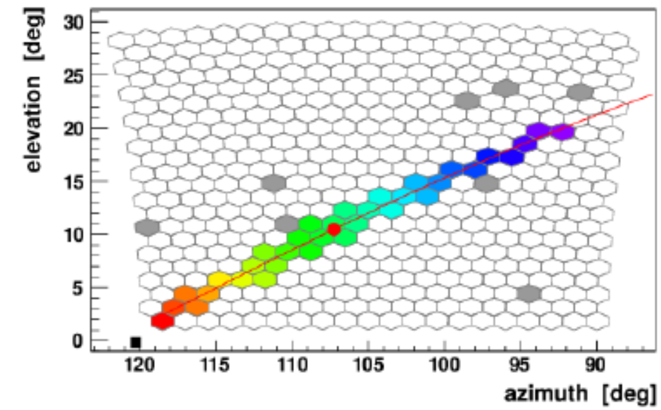
Energy Estimate
- from area under curve

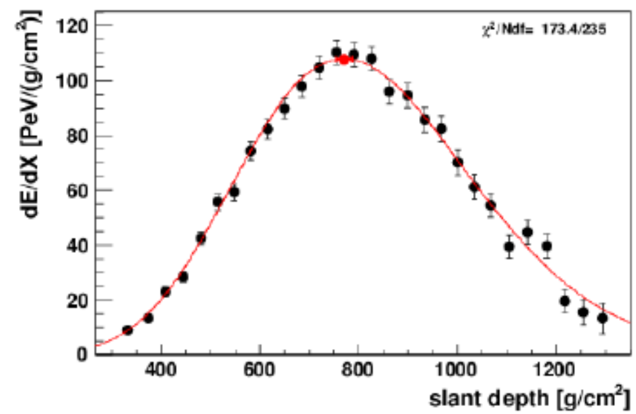
$(2.1 \pm 0.5) \times 10^{19}$ eV

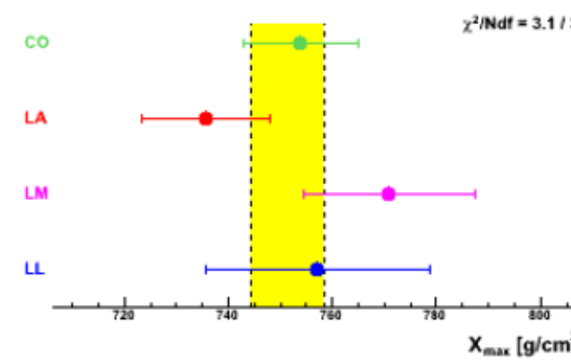
must account for 'invisible energy'

Getting the Energy and X_{max}

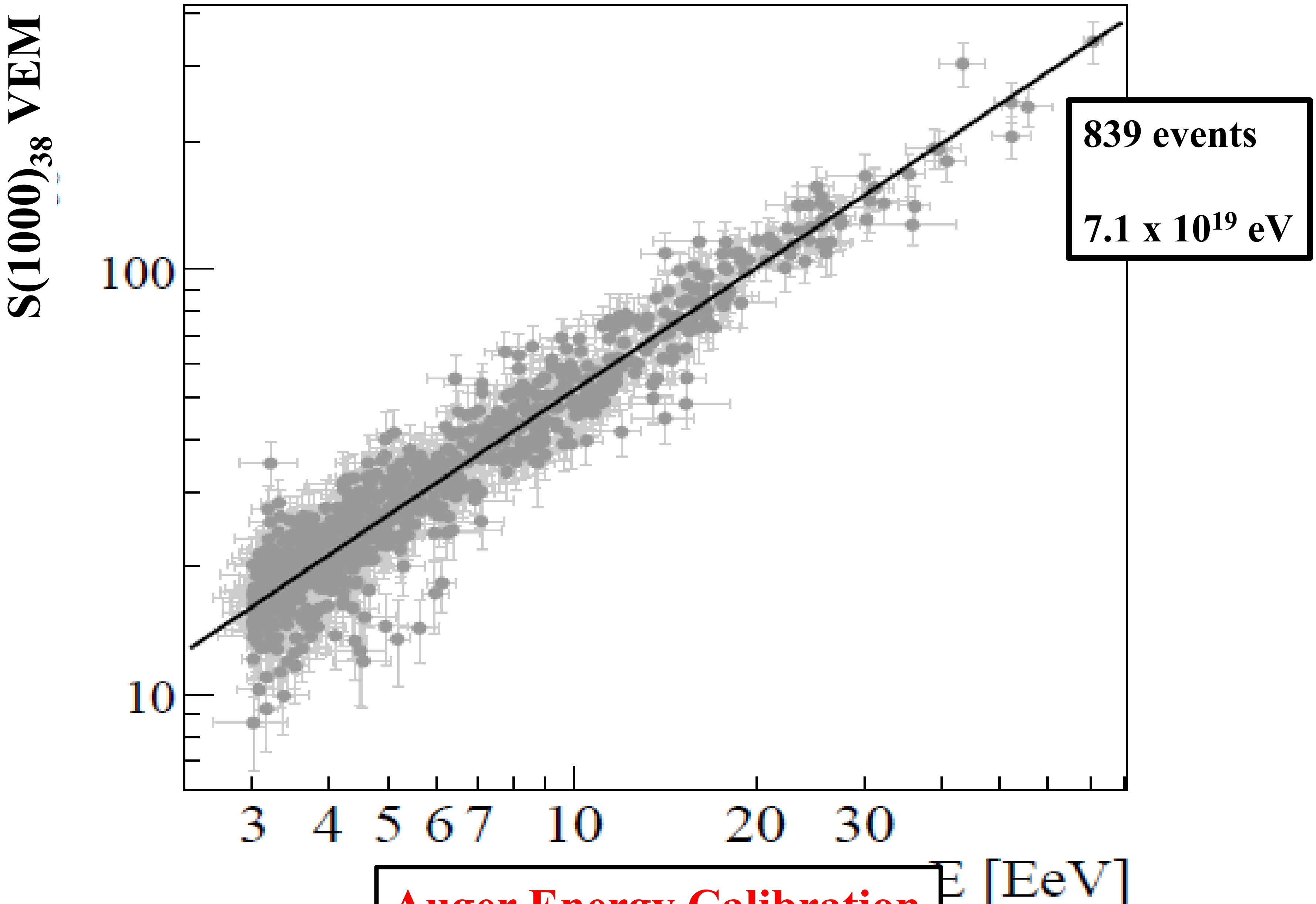




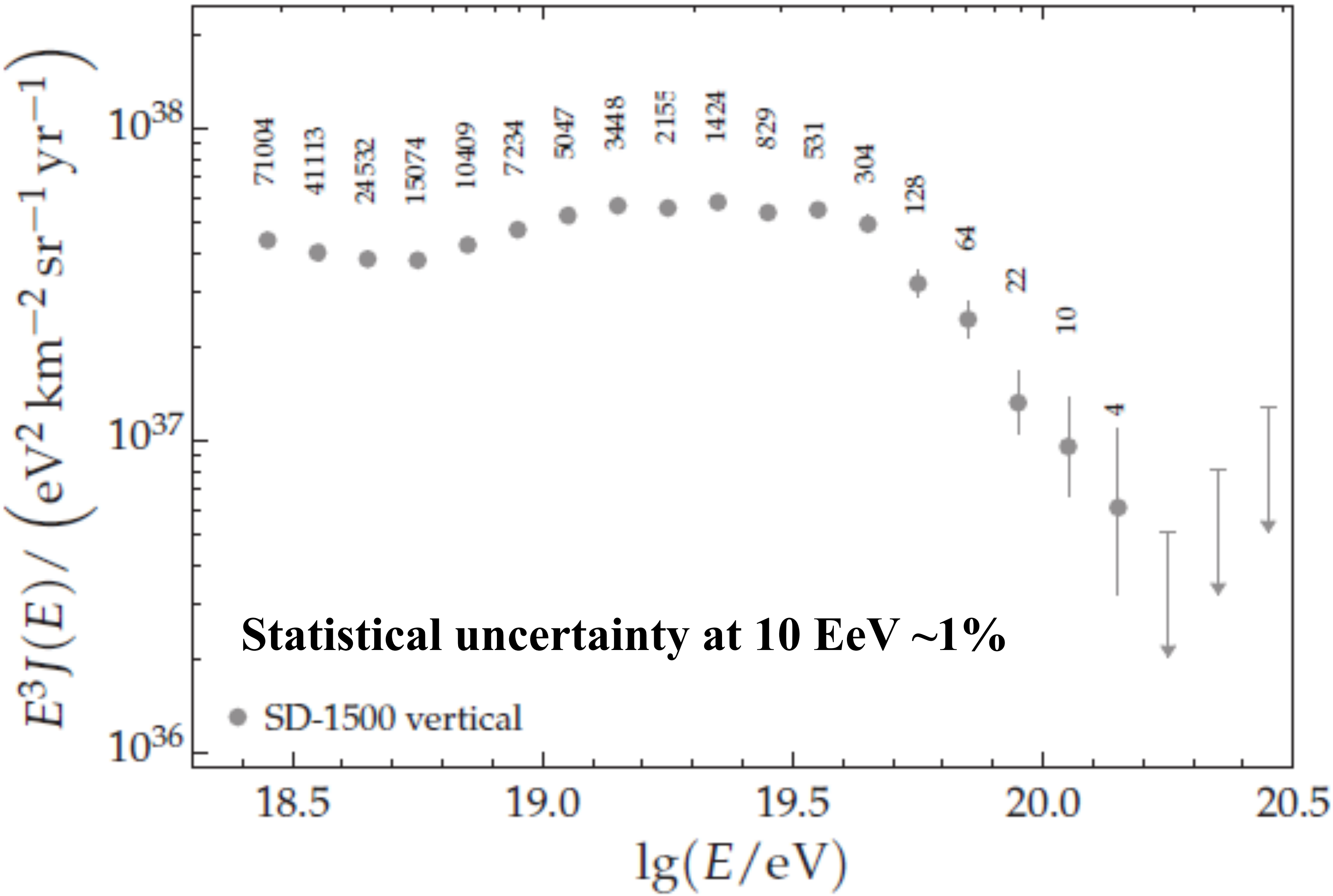




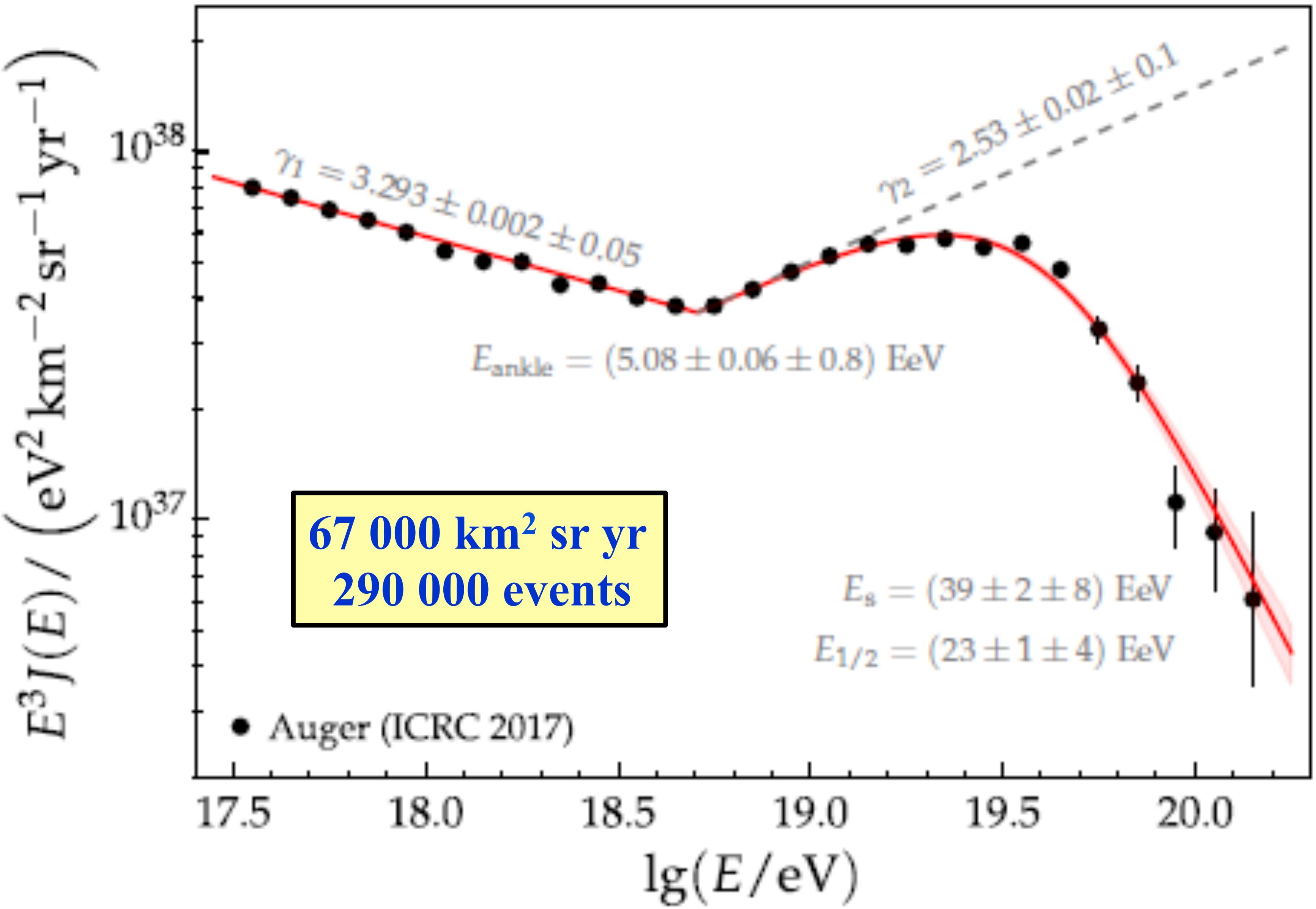
$E = 7.1 \pm 0.2\ 10^{19}$ eV - $X_{max} = 752 \pm 7$ g/cm^2



Auger Energy Calibration



Statistical uncertainty at 10 EeV ~1%



$E^3 J(E) / (\mathrm{eV}^2 \mathrm{km}^{-2} \mathrm{sr}^{-1} \mathrm{yr}^{-1})$
10^{38}
10^{37}
$\gamma_1 = 3.293 \pm 0.002 \pm 0.05$
$\gamma_2 = 2.53 \pm 0.02 \pm 0.1$
$E_{\mathrm{ankle}} = (5.08 \pm 0.06 \pm 0.8)$ EeV
$E_s = (39 \pm 2 \pm 8)$ EeV
$E_{1/2} = (23 \pm 1 \pm 4)$ EeV
67 000 km^2 sr yr
290 000 events
Auger (ICRC 2017)
17.5
18.0
18.5
19.0
19.5
20.0
$\lg(E/\mathrm{eV})$

Comparisons between Telescope Array and Pierre Auger Observatory

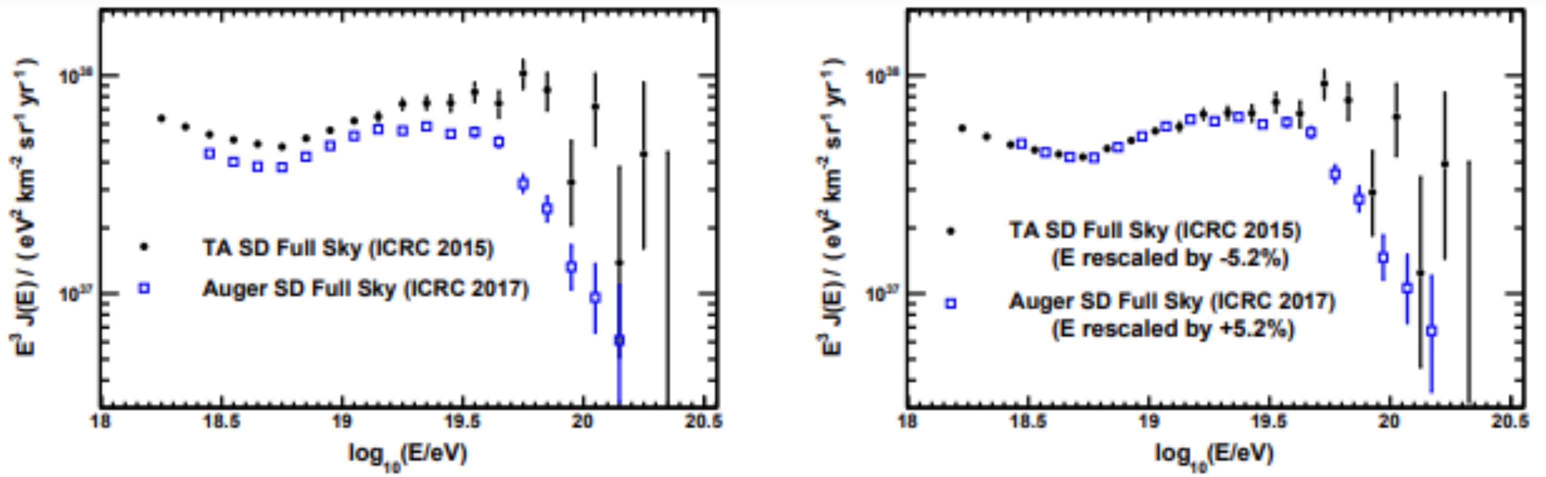
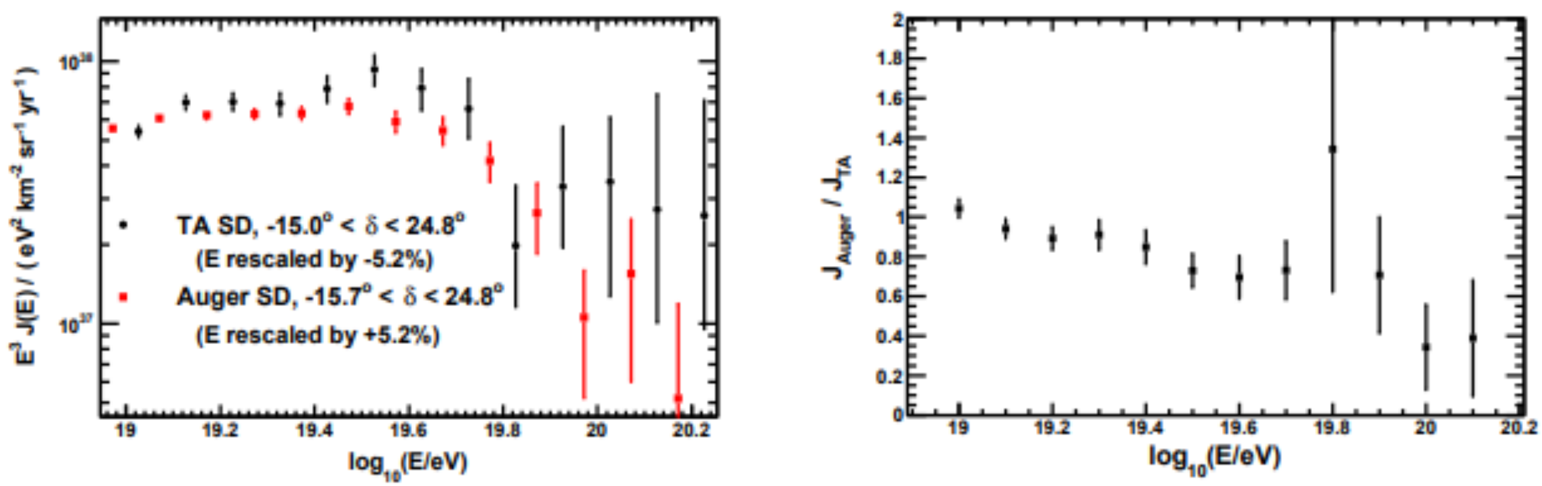


Figure 1. Energy spectra over the entire fields of view for TA [10] and Auger [5]: (left) calculated using the nominal energy scales of T. and Auger, (right) calculated after applying the overall +5.2% (Auger) and -5.2% (TA) energy scale corrections. Significant differenc between the Auger and TA energy spectra remains after rescaling the TA and Auger energies by constant (energy-independent) factor:



What might the steepening mean?

Rigidity-limited | **Photo-disintegration effects**

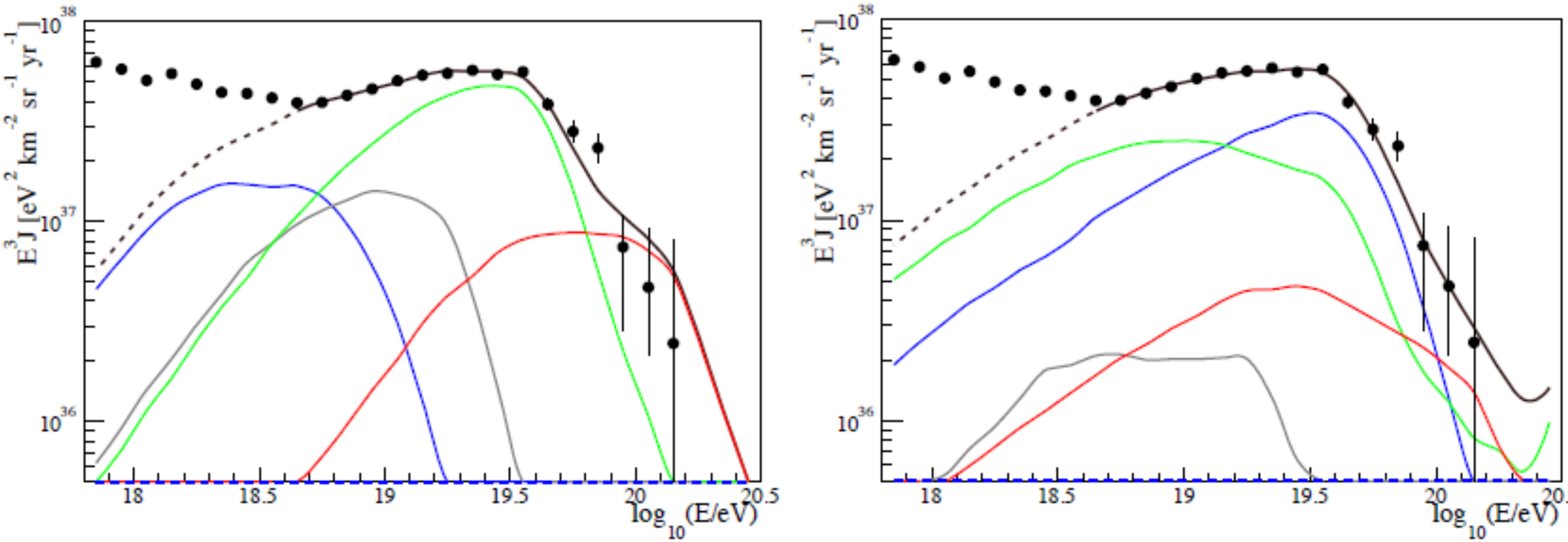


Figure 2.10: Examples of fluxes of different mass groups for describing the Auger spectrum and composition data. Shown are the fluxes of different mass groups that are approximations of one maximum-rigidity scenario (left panel) and one photo-disintegration scenario (right panel). The col-

p He N Fe

The steepening itself is INSUFFICIENT for us to claim that we have seen the Greisen-Zatsepin-Kuz'min effect

It might simply be that the sources cannot raise particles to energies as high as 10^{20}eV – Nature could be teasing us!

probably is!

Energy densities of CMB, galactic magnetic field, cosmic rays and starlight are very similar – this may be another coincidence

- **Are there anisotropies in the arrival direction distributions?**

- **Knowing the mass composition would be useful**
  – but for this we need to extrapolate key features of hadronic interactions to high energies
  - cross-section, multiplicity, inelasticity, pion collisions…

Arrival Direction studies

- The cosmic-ray sky is remarkably isotropic, even at the very highest energies
- This may reflect the high charge of the particles and magnetic fields that lie between us and the sources – or there could be a huge number of sources

We now have:

- Very strong evidence for a dipole anisotropy 8 EeV (5 sigma)
- The amplitude of this dipole increases with energy
- There may be hot-spots in the sky at the highest energies

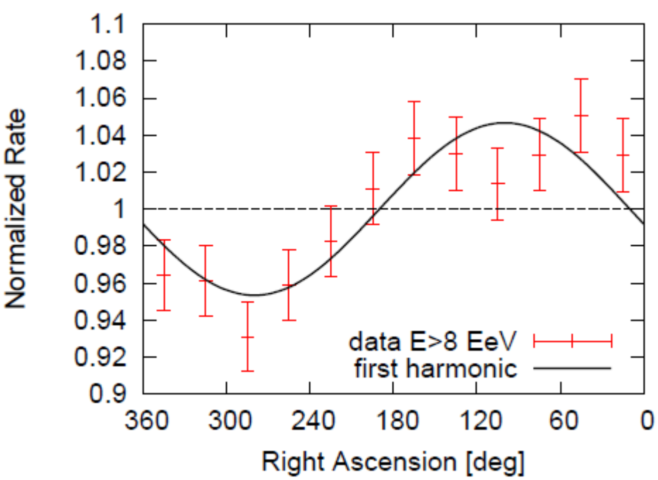
Observation of Dipolar anisotropy above 8 EeV

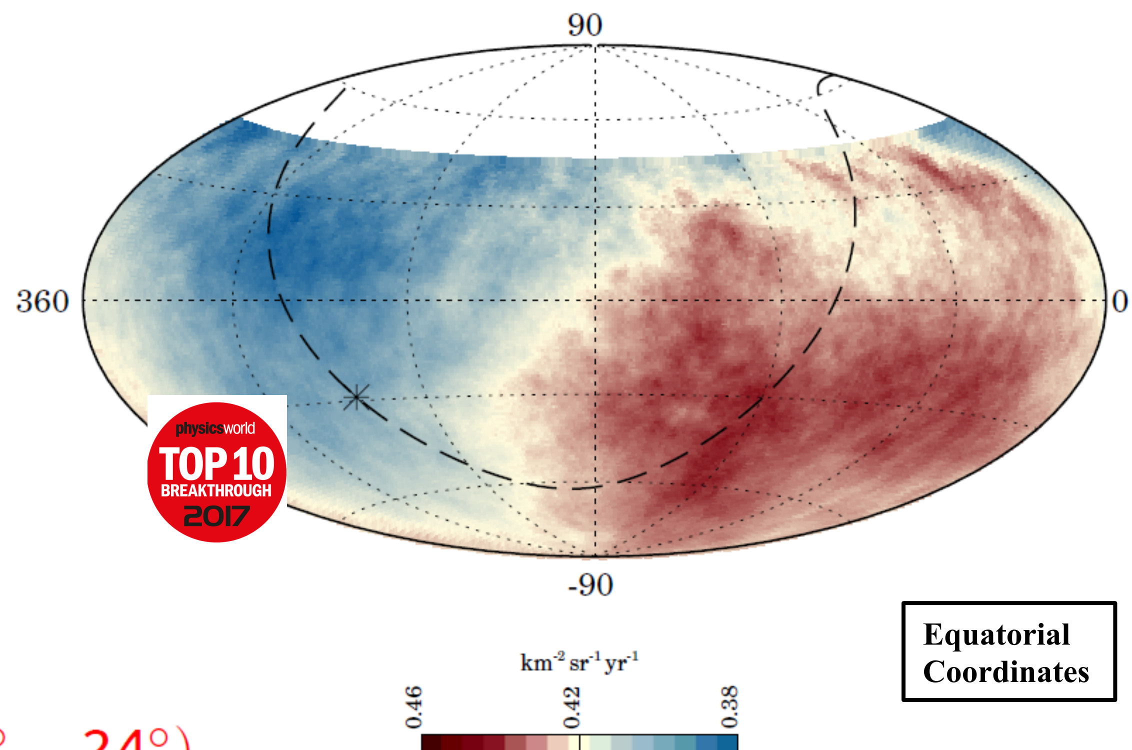
Harmonic analysis in right ascension α

E [EeV]	events	amplitude r	phase [deg.]	$P(\geq r)$
4-8	81701	$0.005^{+0.006}_{-0.002}$	80 ± 60	0.60
> 8	32187	$0.047^{+0.008}_{-0.007}$	100 ± 10	2.6×10^{-8}

significant modulation at 5.2 σ (5.6σ before penalization for energy bins explored)

Science Sept 2017



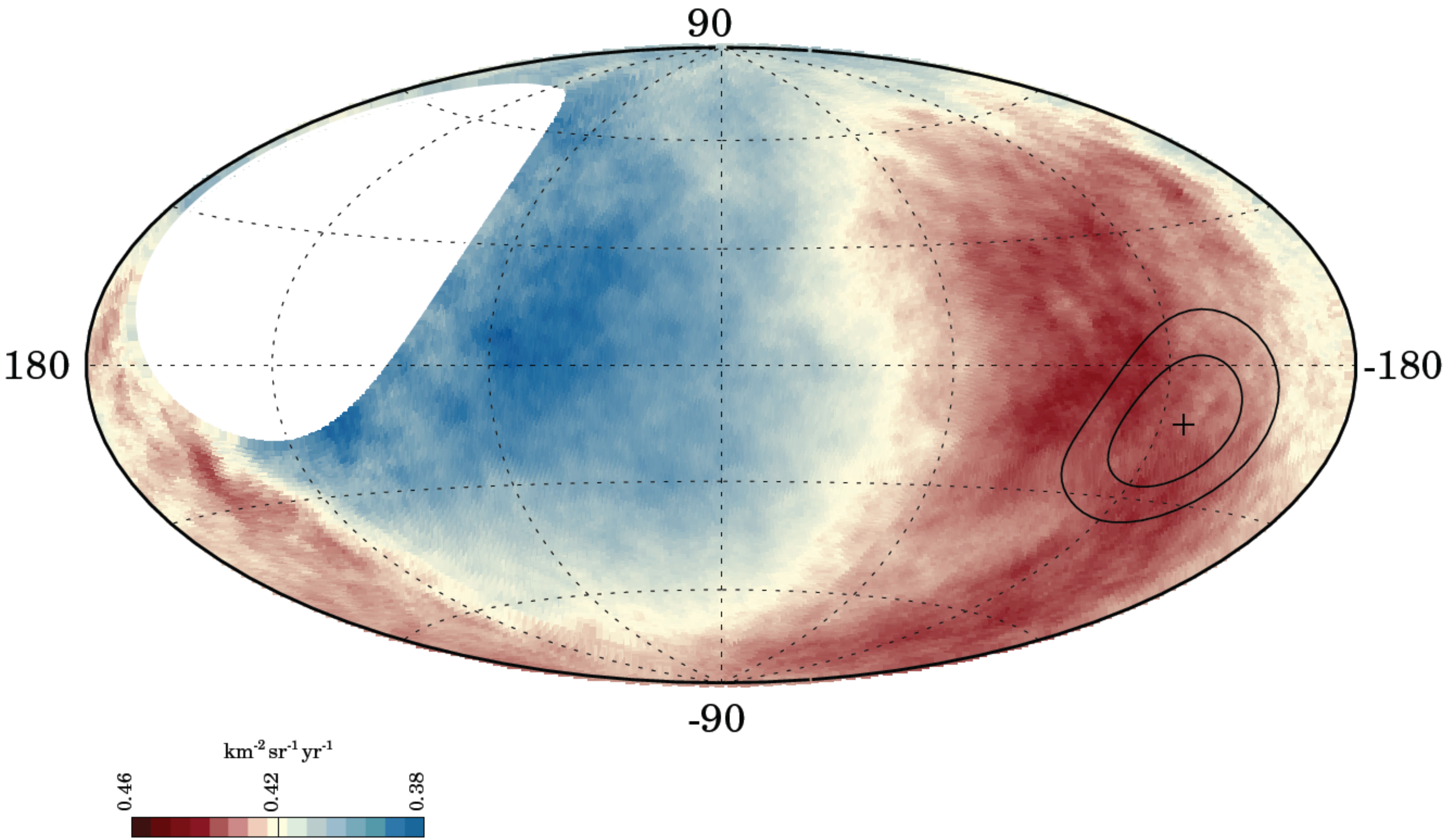


Equatorial Coordinates

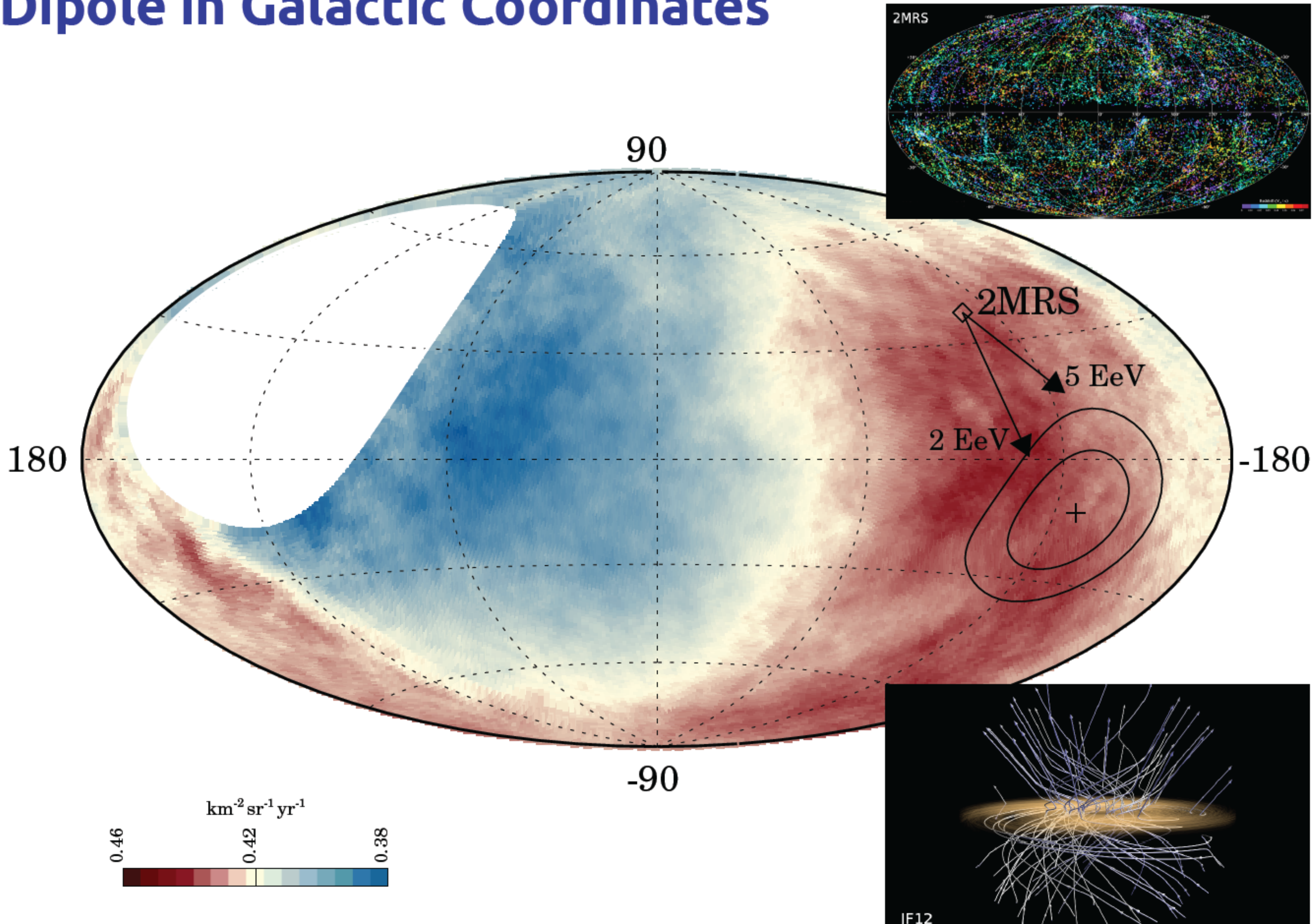
3-d dipole above 8 EeV:

$(6.5^{+1.3}_{-0.9})$% at $(\alpha, \delta) = (100°, -24°)$

Dipole in Galactic Coordinates

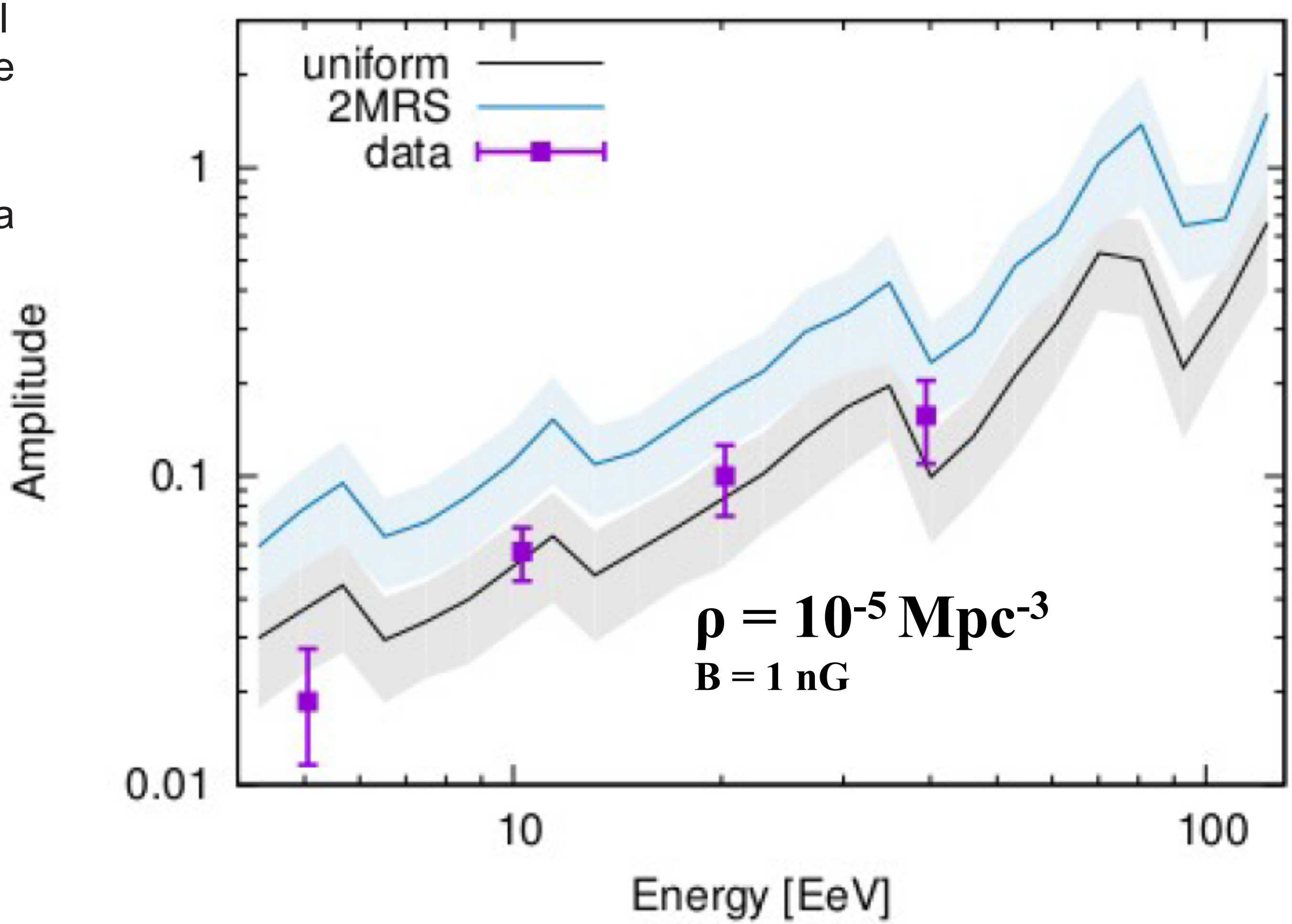


Dipole in Galactic Coordinates



Mean amplitude of the total expected dipole when local sources within 100 Mpc are distributed like galaxies in the 2MRS catalog (blue dashed lines) considering a density $\rho = 10^{-5}$ Mpc^{-3} and a turbulent field with B = 1 nG.

The red line shows the expected amplitude for uniformly distributed sources for the same parameters



What are the accelerators?

Might help to guide the search for anisotropies at higher energies

- **Synchrotron Acceleration**

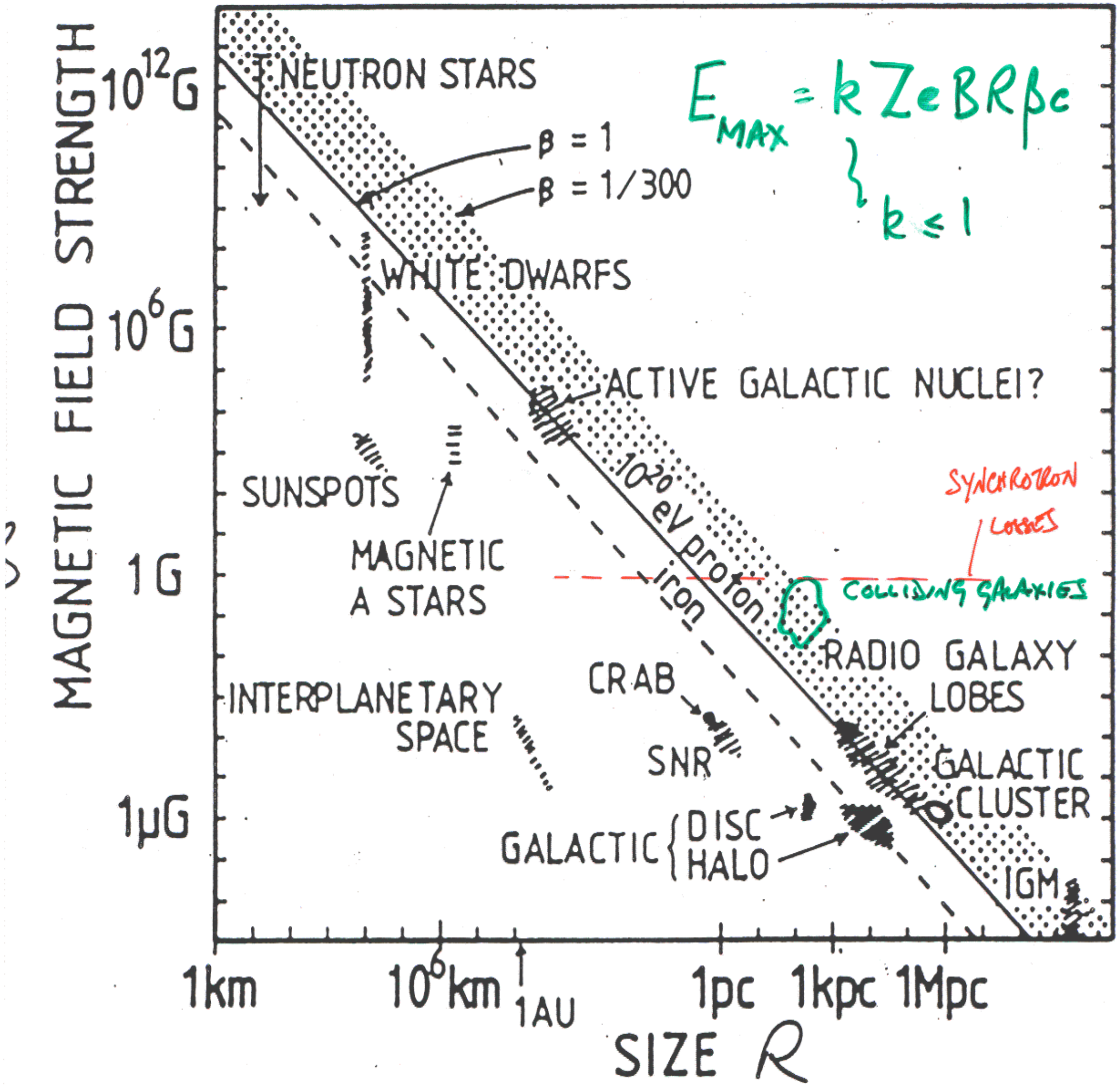
  $E_{max} = ZeBR\beta c$

- **Single Shot Acceleration**

  $E_{max} = ZeBR\beta c$

- **Diffusive Shock Acceleration**

  $E_{max} = kZeBR\beta c$, with $k<1$



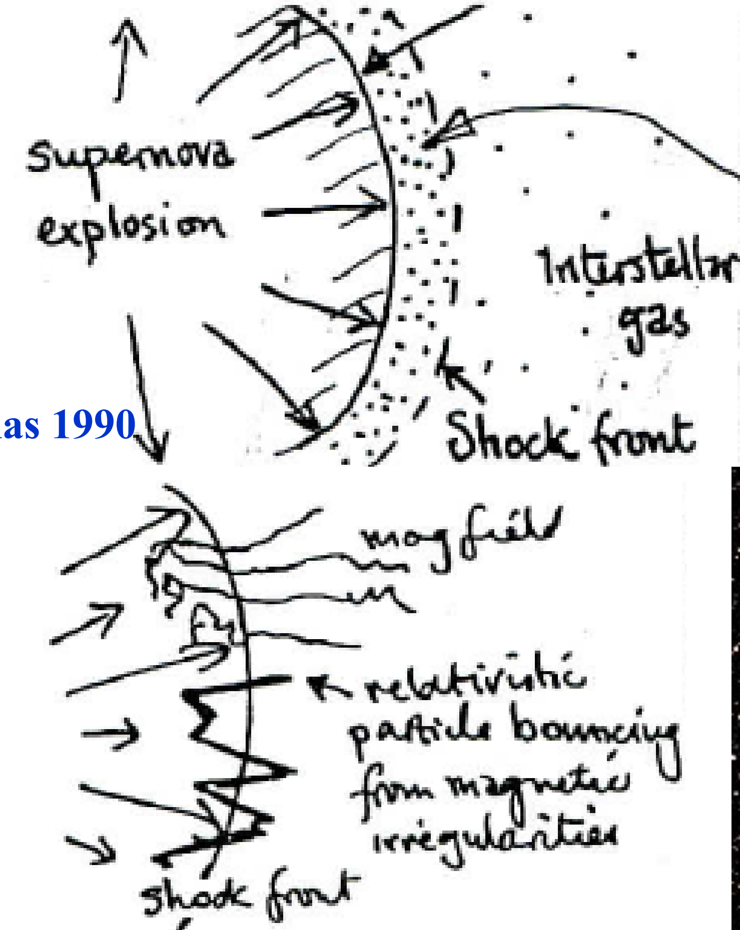
Hillas 1984
ARA&A
B vs R

High-Z nuclei easier to accelerate

Diffusive Shock Acceleration (Krimsky, Blandford, Ostriker, Axford, Bell 1987/1988)

$$E_{max} = kZeBR\beta c, \text{ with } k<1$$

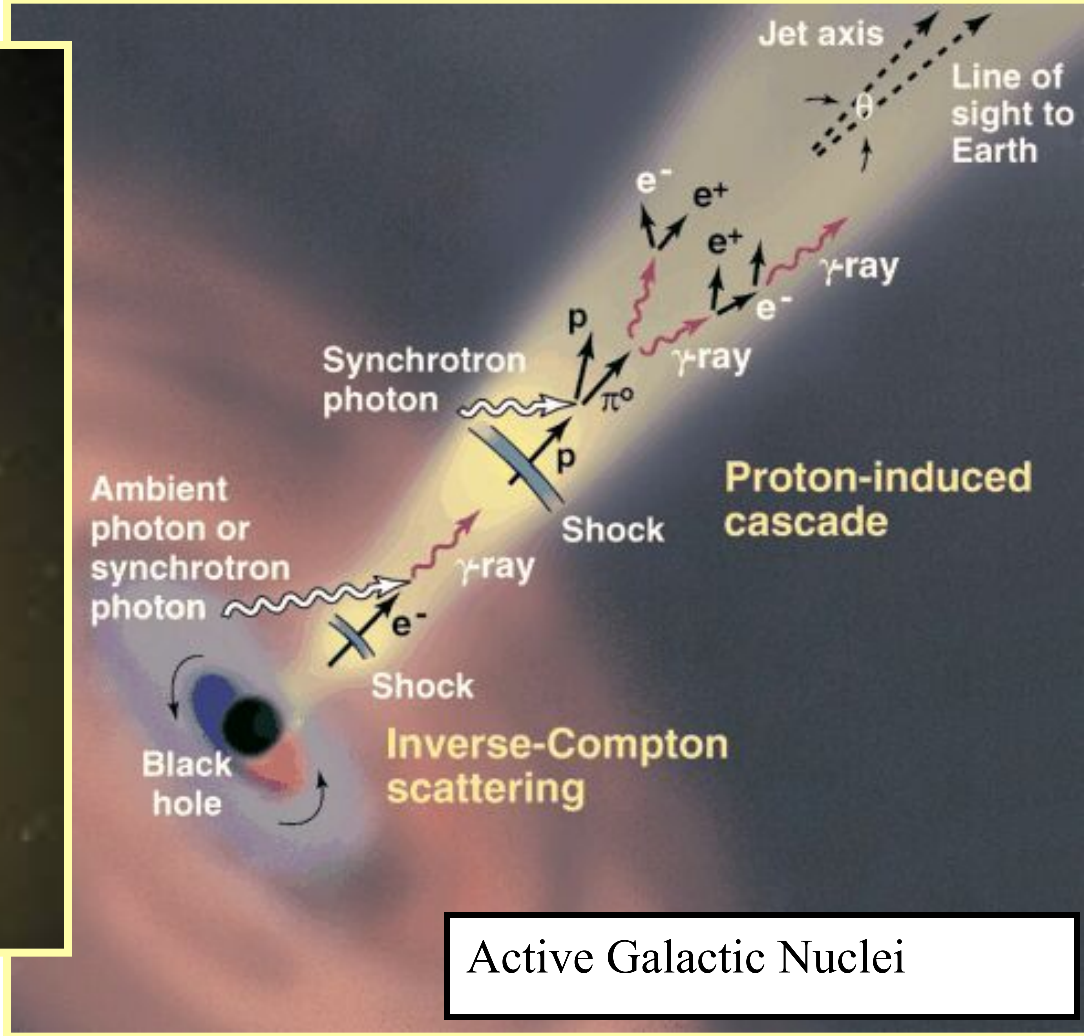
(e.g. Shocks near AGNs, near Black Holes, Supernova……?)



Hillas 1990

Testing for correlations with candidate source-types at highest energies

image of M87 with Hubble Space Telescope



Active Galactic Nuclei

Ilana Feain, Tim Cornwell & Ron Ekers (CSIRO/ATNF);

Bell et al. arXiv 1906.02508

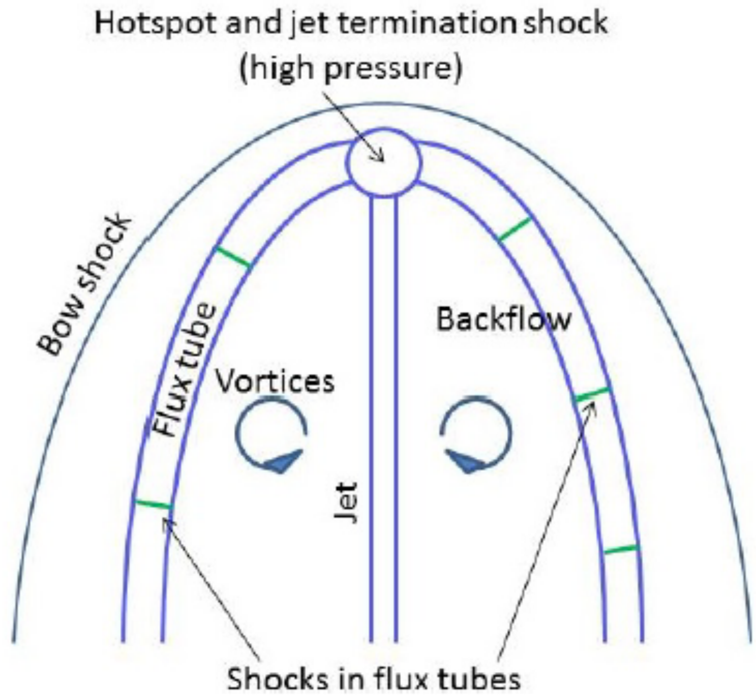


Figure 1. Idealised model of shocks and flux tubes in the lobes of radio galaxies.

Both first and second order shock acceleration can take place in the flux tubes

Production in Starburst Galaxies ApJ Letters (Jan 2018)

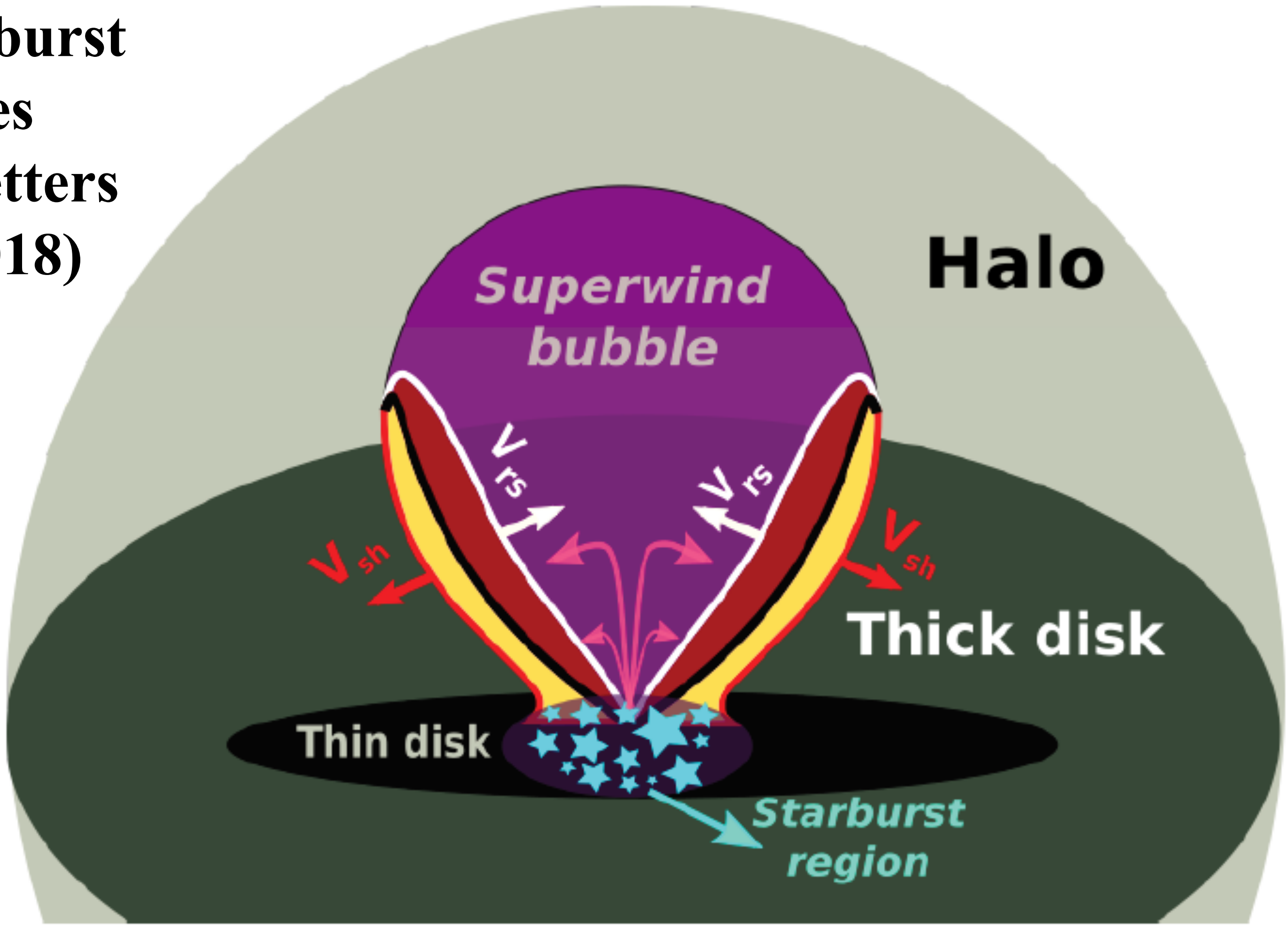


Fig. 1. Scheme of the physical scenario considered in this work. Not to scale. Adapted from Strickland et al. (2002).

Search for Intermediate-scale Anisotropies

Analysis Strategy:

- arrival directions of data, D
- sky model from source candidates, M_i

$M_i =$ (flux model) $\times$ (attenuation model) $\times$ (angular smearing) $\times$ (exposure)

- null hypothesis: isotropy M_0
- single population signal model:

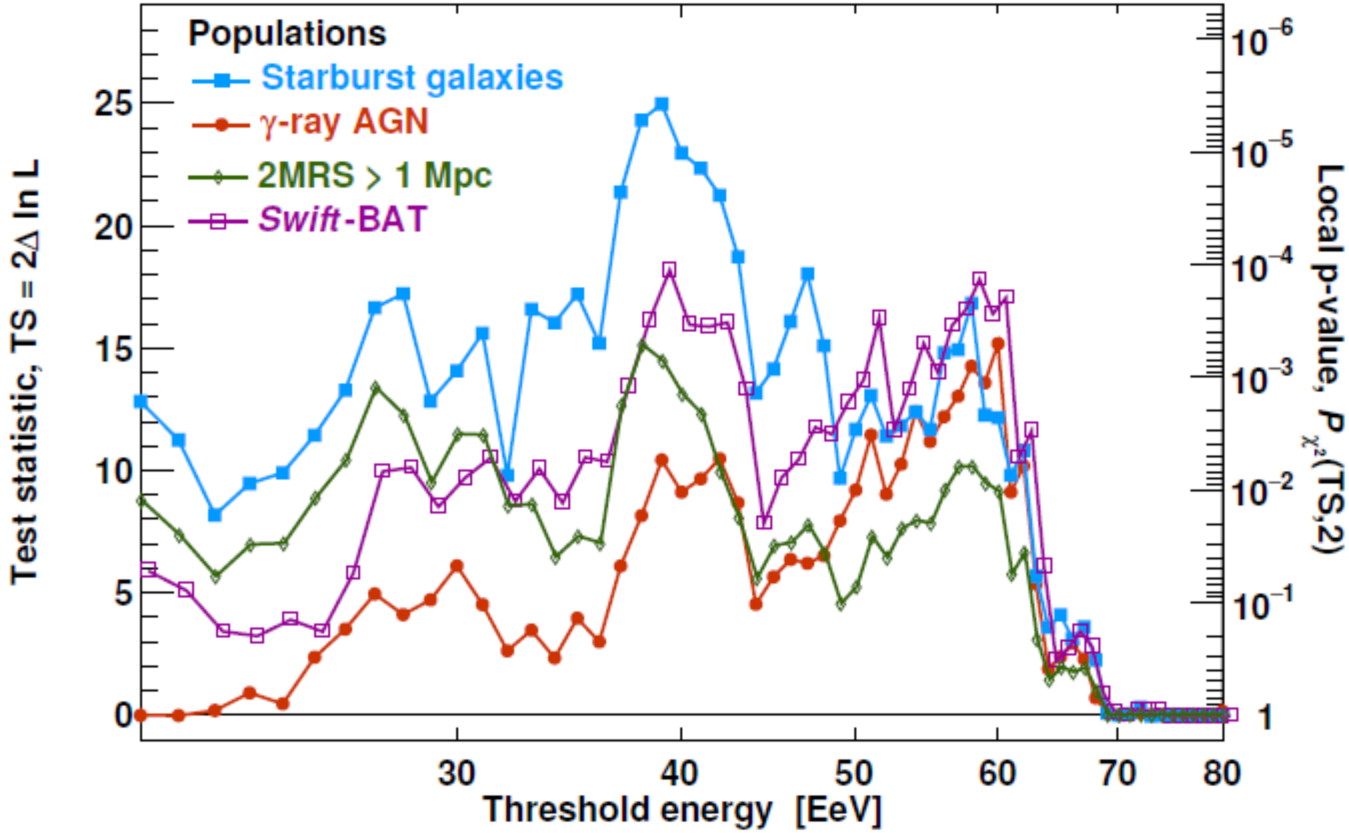
$$M = (1 - \alpha)\, M_0 + \alpha\, M_i$$

- test statistics:
  - ratio of likelihoods of model-data comparison

    $$\mathrm{TS} = 2\log(P(D|M)/P(D|M_0))$$

    think $\Delta\chi^2$ of (isotropy + signal) vs. isotropy
  - p-value from Wilk's theorem: $p(\mathrm{TS}) = p_{\chi^2}(\mathrm{TS}, \Delta\mathrm{ndf})$
  - of large TS
    - M describes D much better than M_0
    - M_0 excluded at p (**not**: M "proven" at p)

Test Statistics vs. Energy



starburst model fits data better than isotropy, significance of 4 σ^*.

* P_{χ^2}(TS, 2) penalized for energy scan

Auger/TA all sky survey at high energies

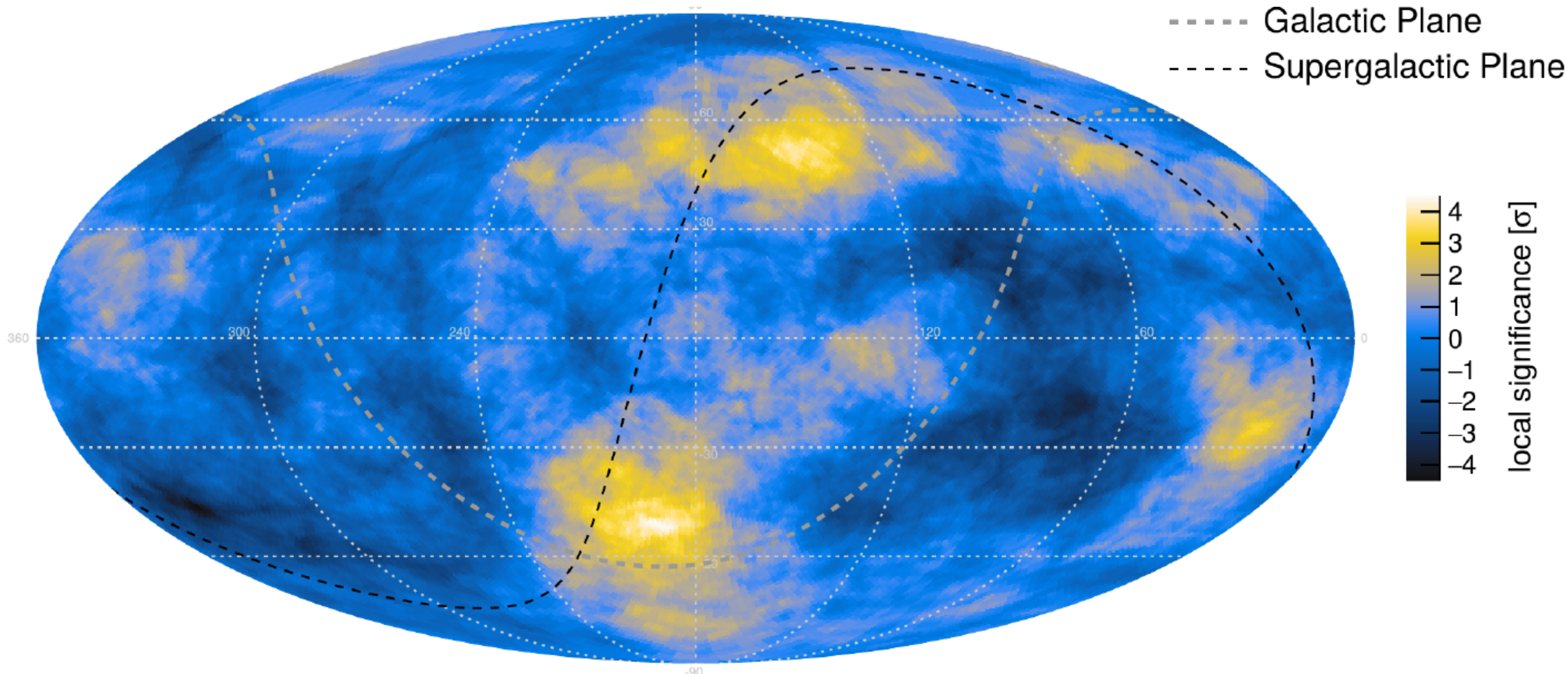
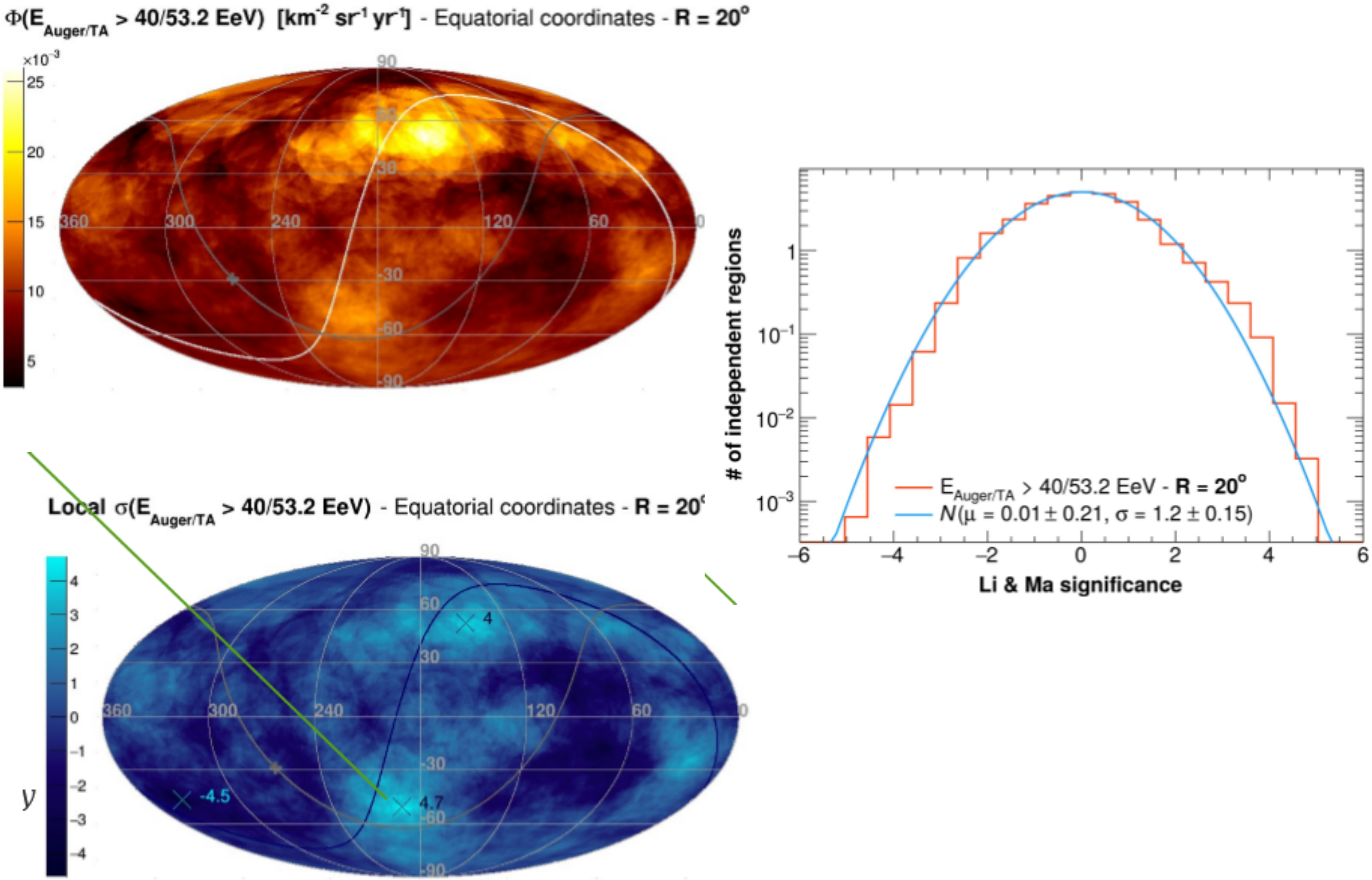


Figure 2: Sky map, in equatorial coordinates, of local over- and under-densities in units of standard deviations of UHECRs above 47 ± 7 EeV.


Φ(E_Auger/TA > 40/53.2 EeV) [km^-2 sr^-1 yr^-1] - Equatorial coordinates - R = 20°
×10^-3
25
20
15
10
5
90
60
30
360
300
240
120
60
-30
-60
-90
Local σ(E_Auger/TA > 40/53.2 EeV) - Equatorial coordinates - R = 20°
y
4
3
2
1
0
-1
-2
-3
-4
-4.5
4.7
# of independent regions
Li & Ma significance
E_Auger/TA > 40/53.2 EeV - R = 20°
N(μ = 0.01 ± 0.21, σ = 1.2 ± 0.15)
1
10^-1
10^-2
10^-3
−6
−4
−2
0
2
4
6

It would be enormously useful to know the mass composition

Uncovering the mass composition is extremely difficult

In absence of a strong point-like anisotropy (protons?), one must rely on extrapolations of hadronic physics from accelerators to help interpret the data

Eventually, we will find a hadronic model that fits all of the data

It will give a unique mass composition – but we are not there yet!

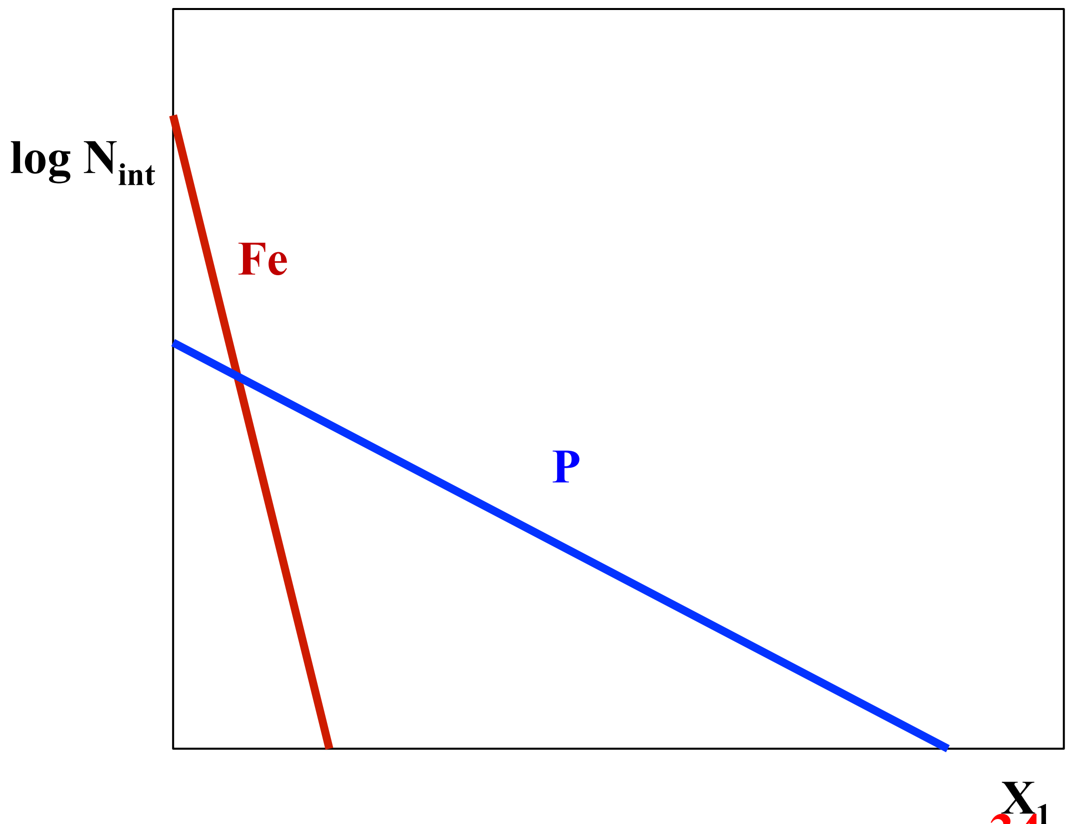
Will also benefit from using galactic magnetic field as
a magnetic spectrometer

Inferring the Primary Mass with X_{max}

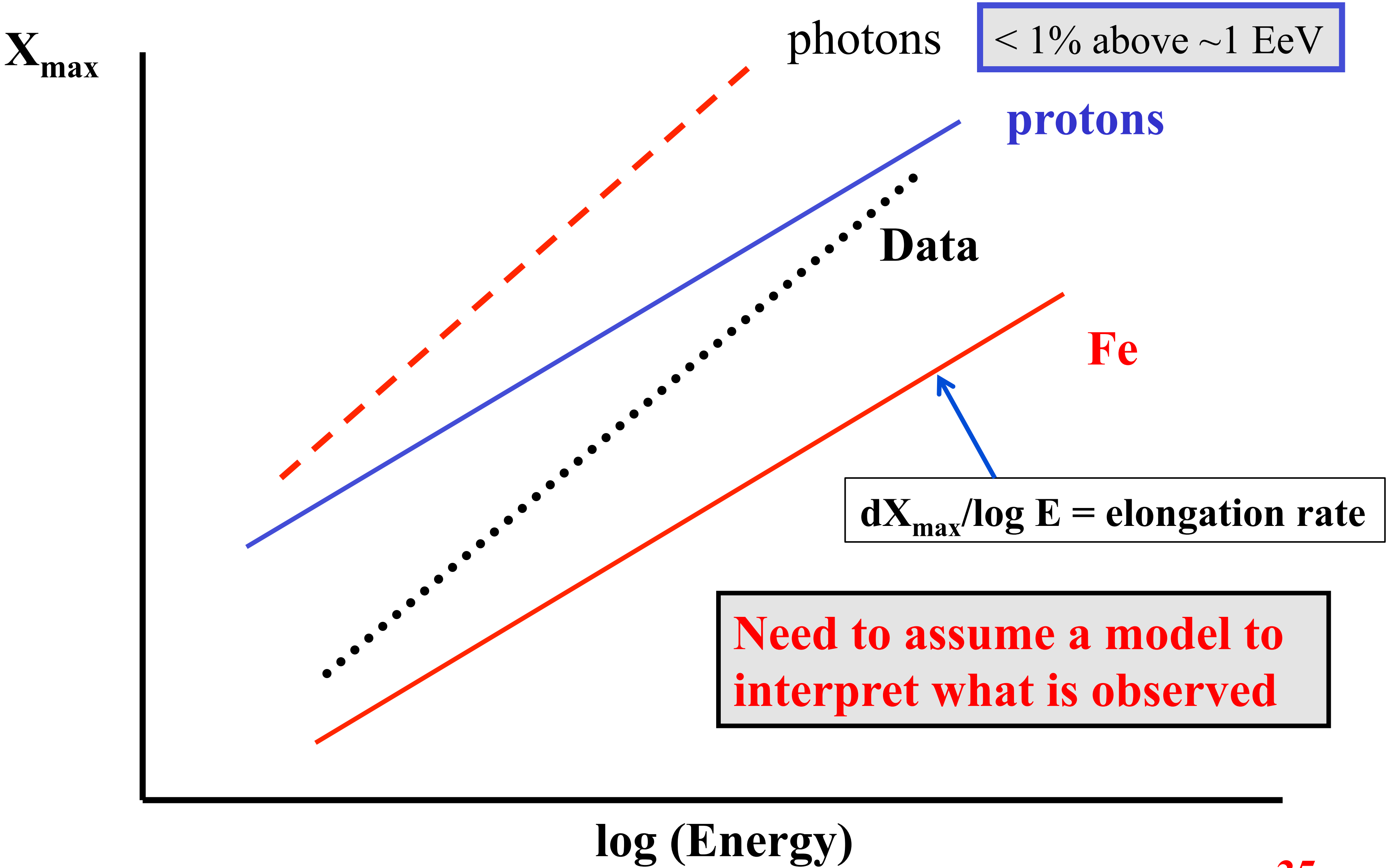
Geometric cross section: $\lambda_p = 4\ \lambda_{Fe}$

$\lambda_p \approx 40\ g/cm^2$

$\lambda_{Fe} \approx 10\ g/cm^2$



One method to try to infer the variation of mass with energy



Need to assume a model to interpret what is observed

Given the necessity of using models, an important question is

"Are the cosmic-ray models adopted sensible?"

Here, the LHC results have proved an excellent test-bed

- **to evaluate three different models -All within Gribov's Reggeon Field Theory framework**

- **EPOS: parton-based Gribov-Regge Theory**

- **QGS: quark-gluon string model – multi-pomeron amplitudes calculated to all orders**

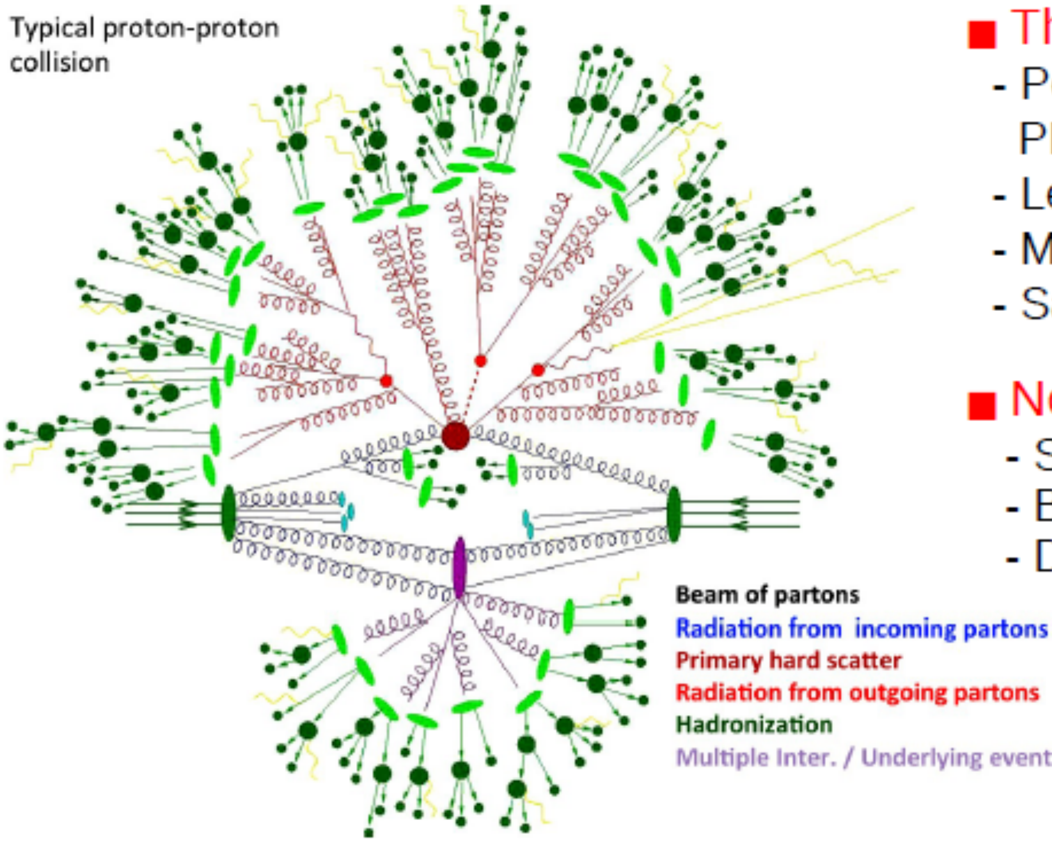
- **Sibyll: based on Dual-parton model – mini-jet model**

- **Each model has a different but self-consistent assumptions to describe hadronic interactions.**

This is ALL I really can tell you about the details of the models!

Hadronic Monte Carlos for LHC collisions

- Proton-proton collisions in PYTHIA, HERWIG,...



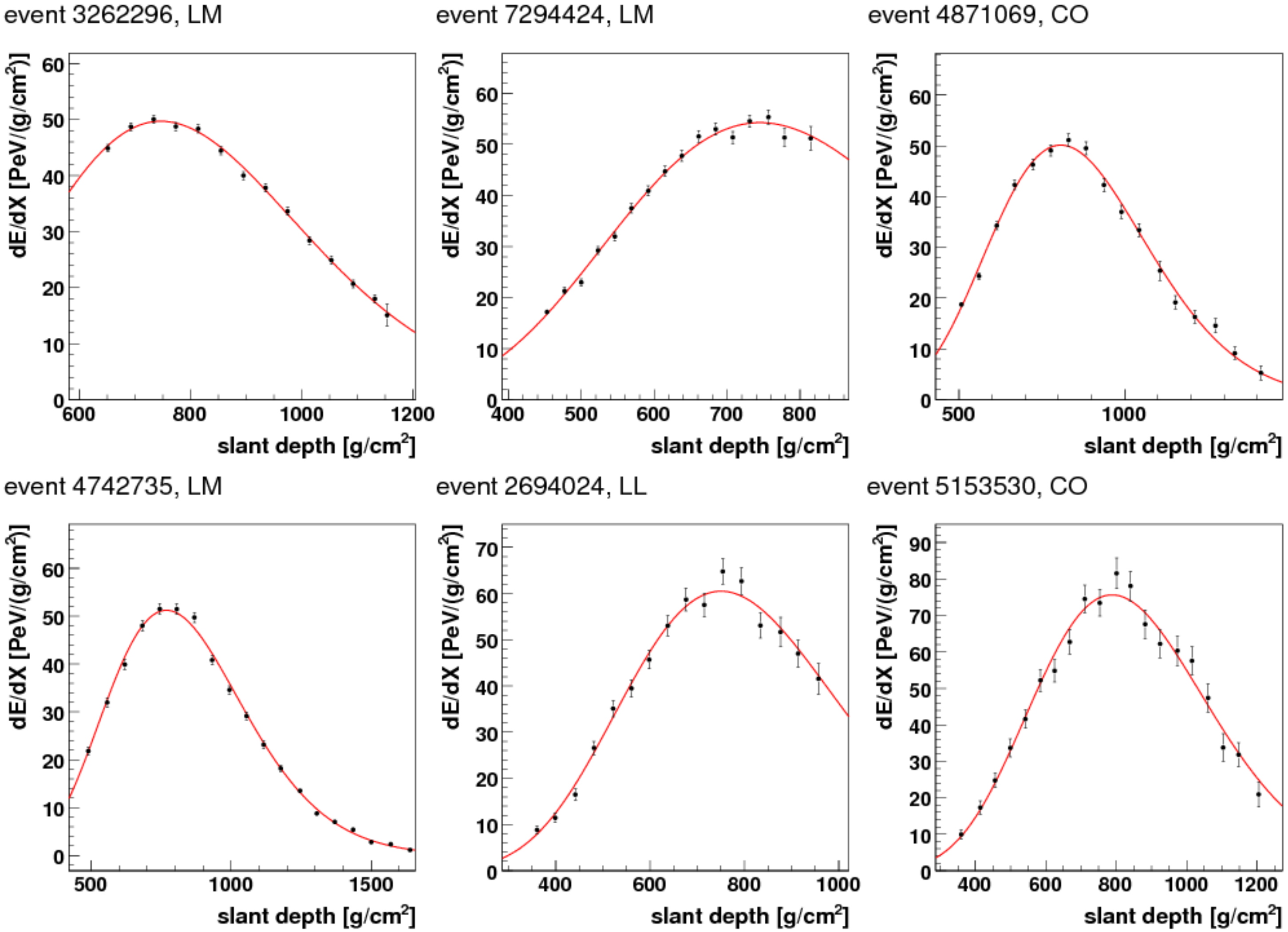
- Theoretical basis:
  - Perturbative QCD (LO + K-factor): PDFs, matrix-elements.
  - Leading-log parton shower.
  - Multiparton interactions.
  - Saturation-based infrared p_T cut-off

- Non-pQCD modeling:
  - String fragmentation (Lund model).
  - Beam-remnants.
  - Diffraction.

- Model parameters:
  - *O*(100) parameters
  - Multiples tunes to many collider measurements.

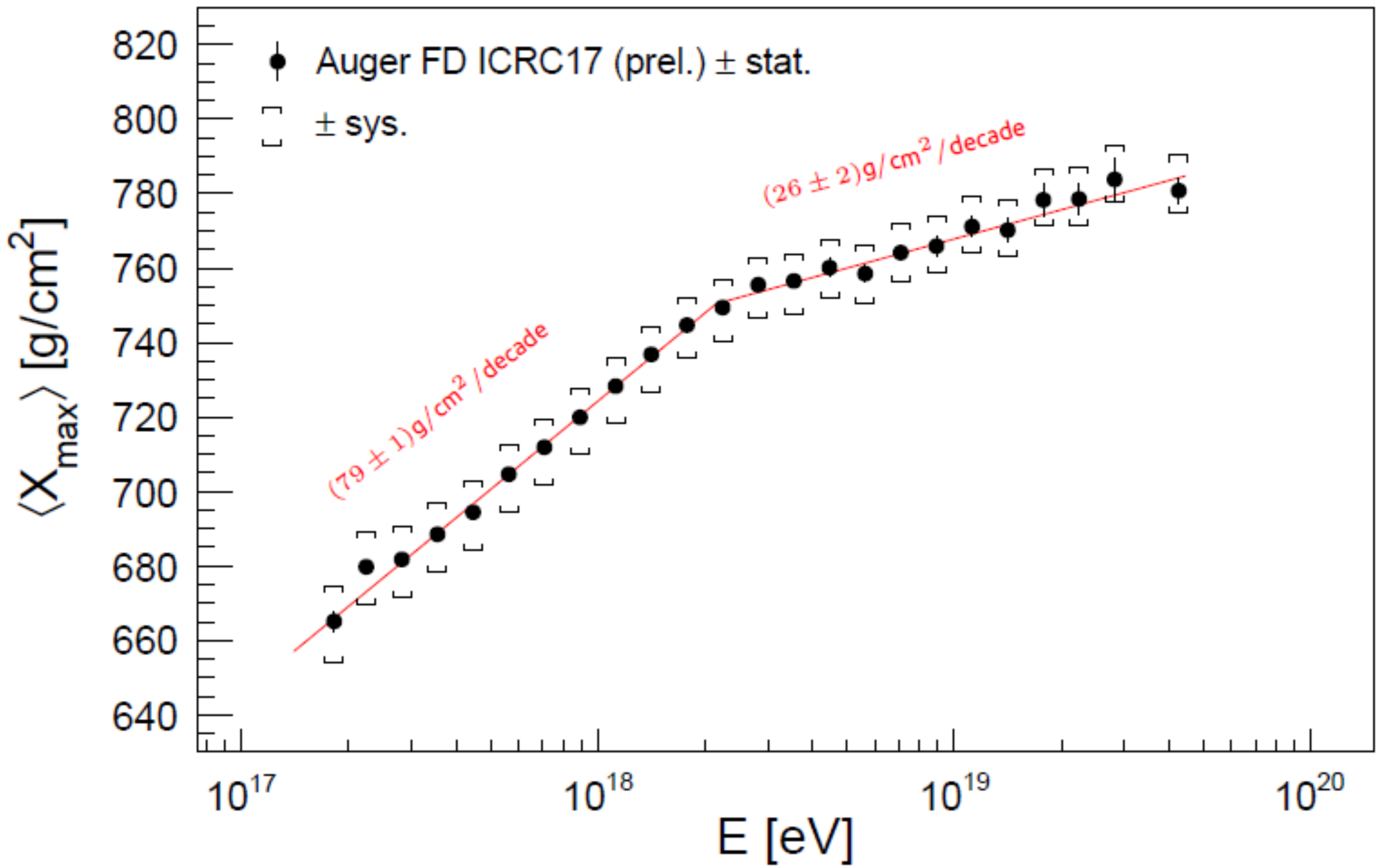
- No p-A, A-A available (yet). But PYTHIA comparable to EPOS/QGSJET via:
  - Constructing a CONEX hydrogen atmosphere with same density as air.
  - Running PYTHIA-6 proton-hydrogen with varying MC tunes to LHC data.

Reconstructed longitudinal profiles

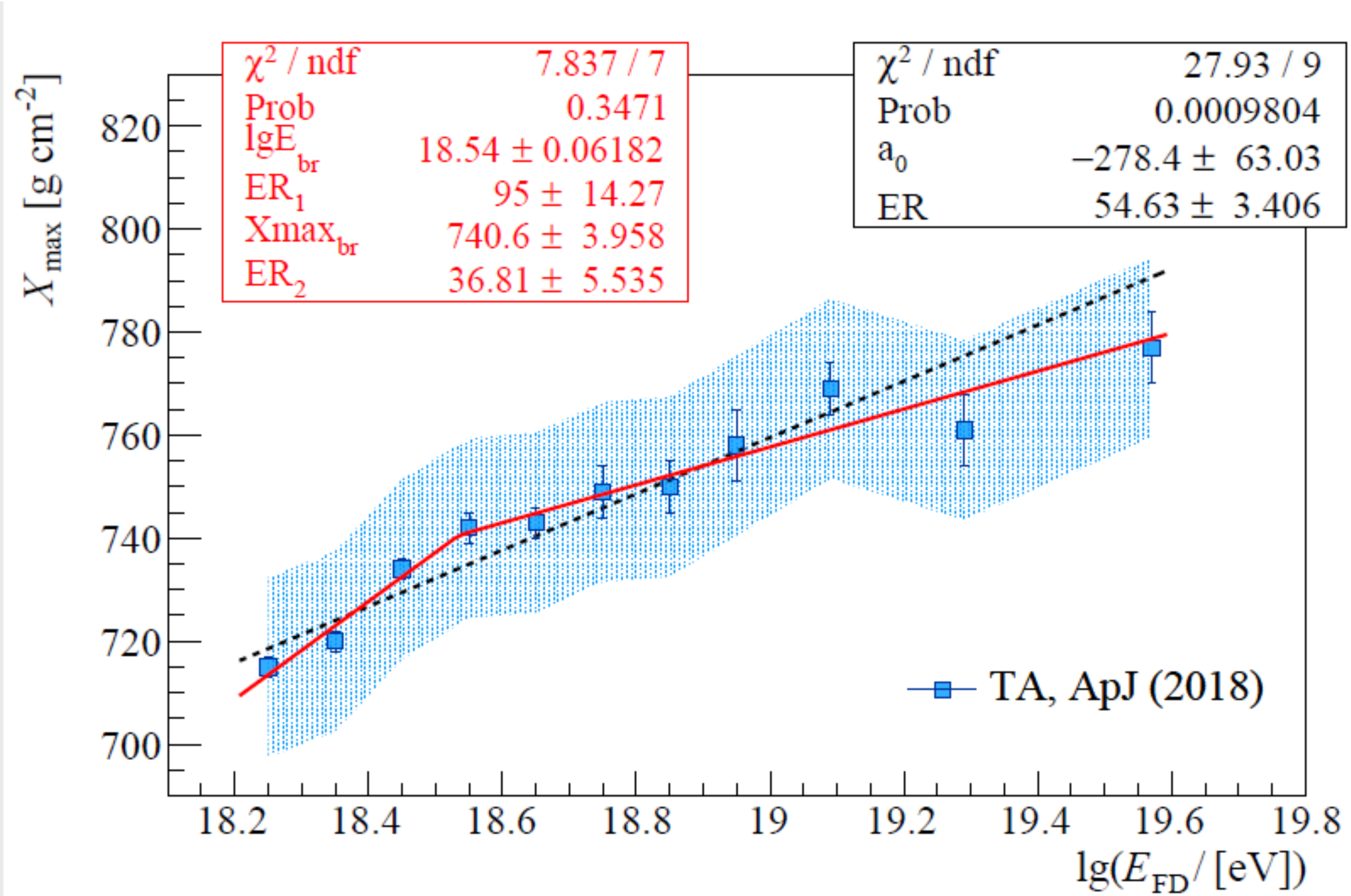


rms uncertainty in X_{max} < 20 g cm^{-2} from stereo measurements

Average X_{max} Fluorescence Detector



Results from Telescope Array also show a break



For technical reasons it is not helpful to plot both data sets on same graph

Results on mass from depth of maximum with fluorescence detectors

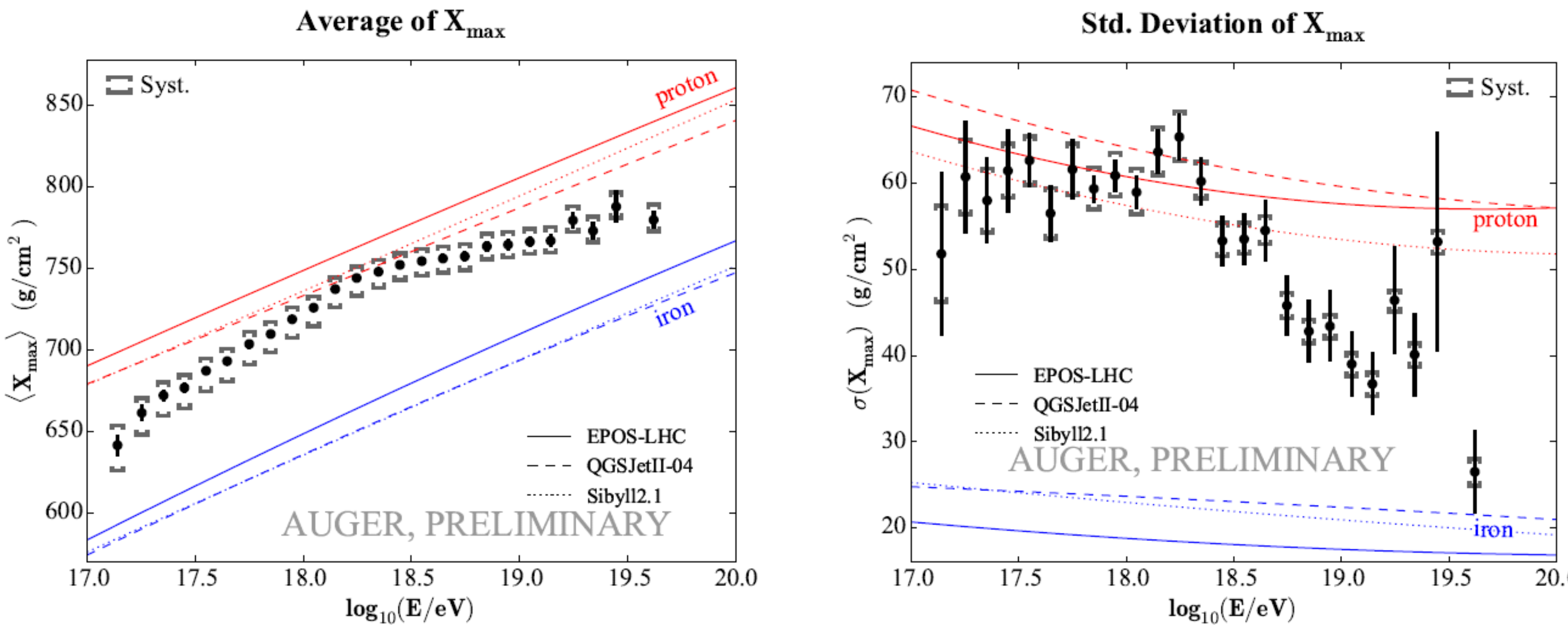


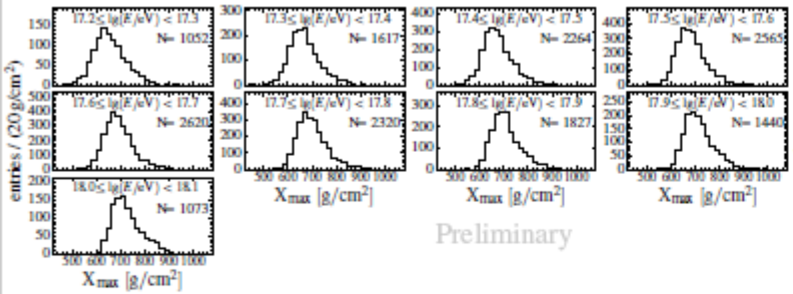
Figure 3: The mean (left) and the standard deviation (right) of the measured X_{max} distributions as a function of energy compared to air-shower simulations for proton and iron primaries.

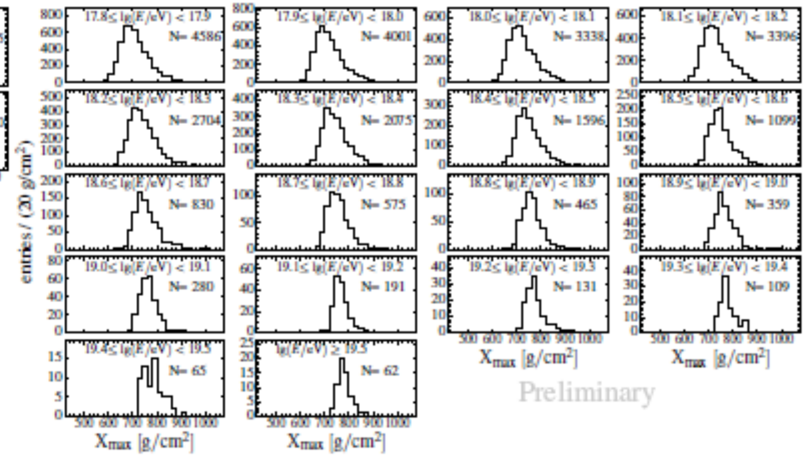
Predictions from Sibyl model lie between those with QGSjet and EPOS-LHC

(p-He-N-Fe)-fit of X_{max} Distributions

FD data:

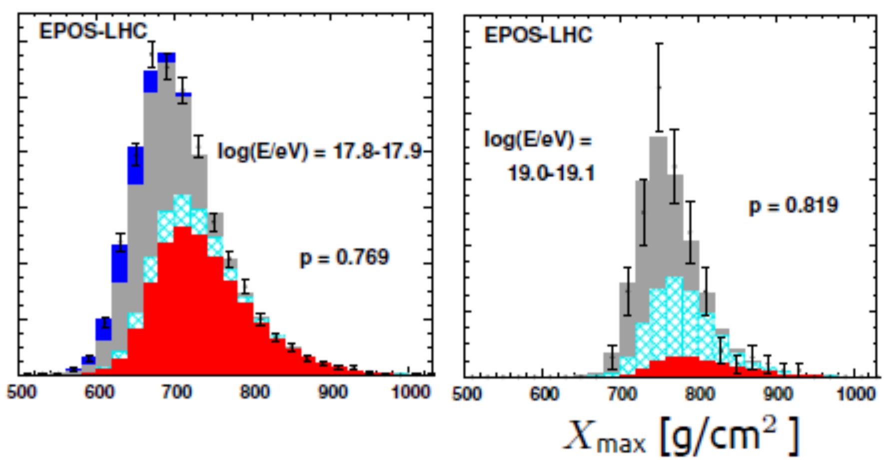
$\lg(E/\text{eV}) = 17.2 \ldots 18.1$ $\lg(E/\text{eV}) = 17.8 \ldots > 19.5$



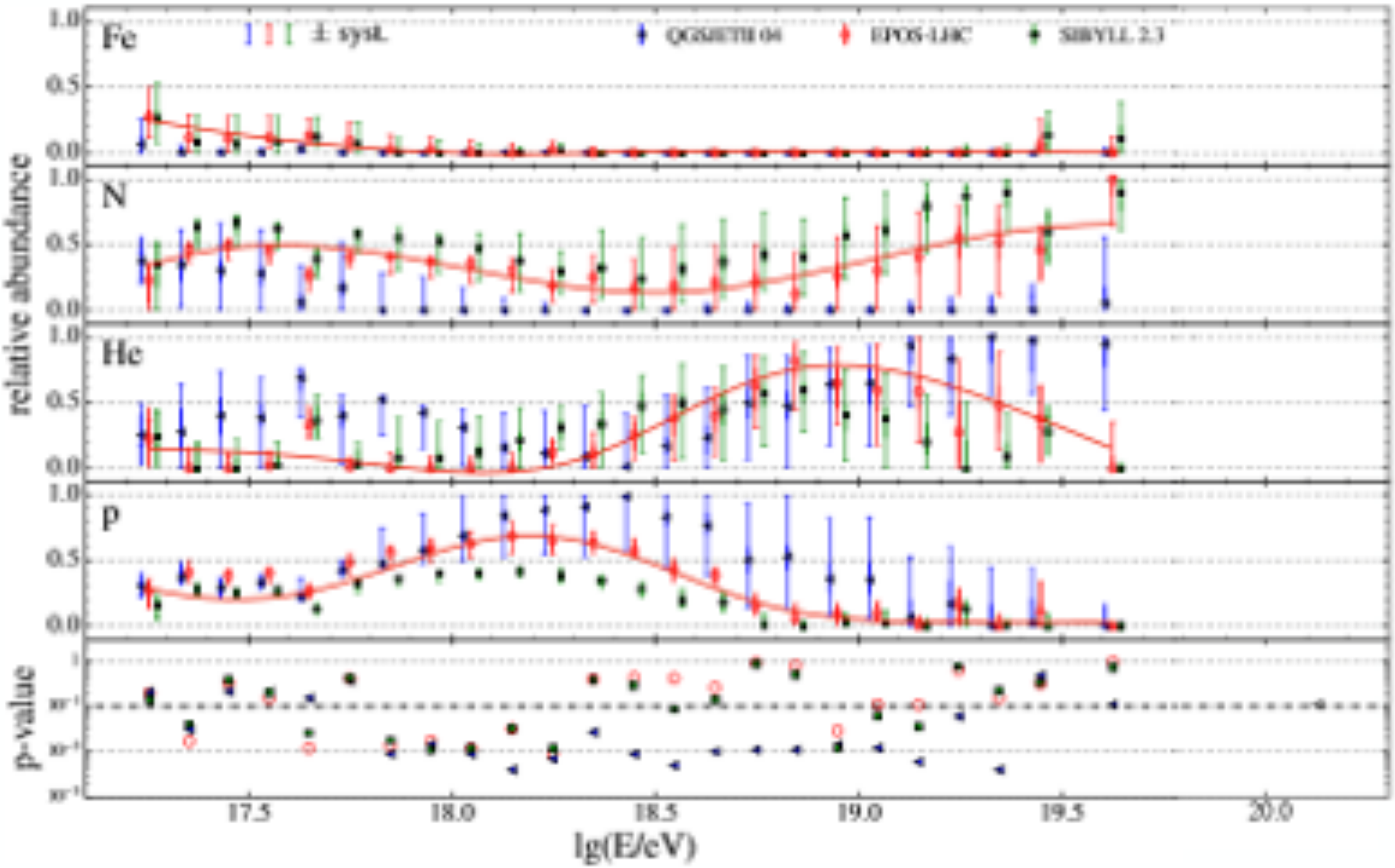


Examples of 4-component fit:

p He N Fe



Fraction of p, He, N and Fe as function of energy



(Bellido ICRC 2017)

Summary of experimental results

- Ankle at ~ 5 EeV and steepening at ~ 40 EeV clearly established
- Strong evidence for dipole anisotropy in Auger data above 8 EeV which increases with energy
- At highest energies some evidence that Starburst Galaxies and AGNs are sources
- Mass composition getting heavier above the ankle
- (No neutrinos seen, at level similar to IceCube, - tomorrow)