LASR Seminar March 99.

Some Problems are Just Hard: Capabilities and Limitations of Air Shower Experiments

Talk outline:

- Cosmic Rays — what are they and why do we care? What do we know and what would we like to find out?
- Anatomy of an Extensive Air Shower.
- Detection Techniques:
  - Particle and Čerenkov arrays
  - Fluorescence remote sensing
- Air shower simulations — what can they tell us?
- Prospects and conclusions

Clem Pryke - University of Chicago

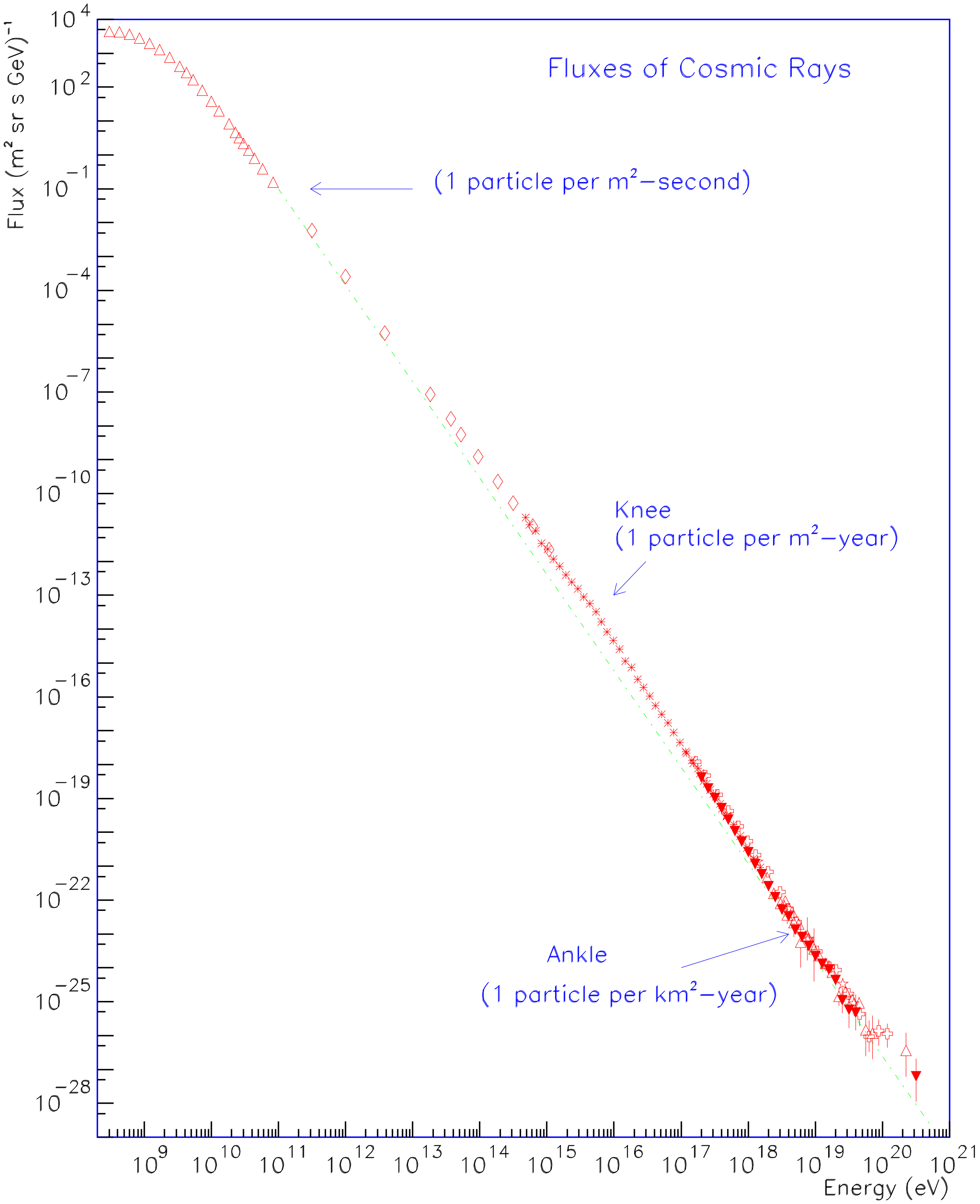
What are they and why do we care?

- A flux of relativistic charged particles apparently filling galactic space.
- Most important observational feature is a power law energy spectrum: $\frac{dN}{dE} \propto E^{-2.5}$
- An important/intriguing fact: Many energy densities are similar (~ 1 MeV m^{-3})

CR $\sim$ B-Field $\sim$ Starlight $\sim$ CMB ($\sim$ Gas-motion)

- However, most of the energy is at the bottom end of the spectrum... Though not as overwhelming as you might think: $\frac{dE}{dlog(E)} \propto E^{-0.5}$.

The Cosmic Ray Energy Spectrum

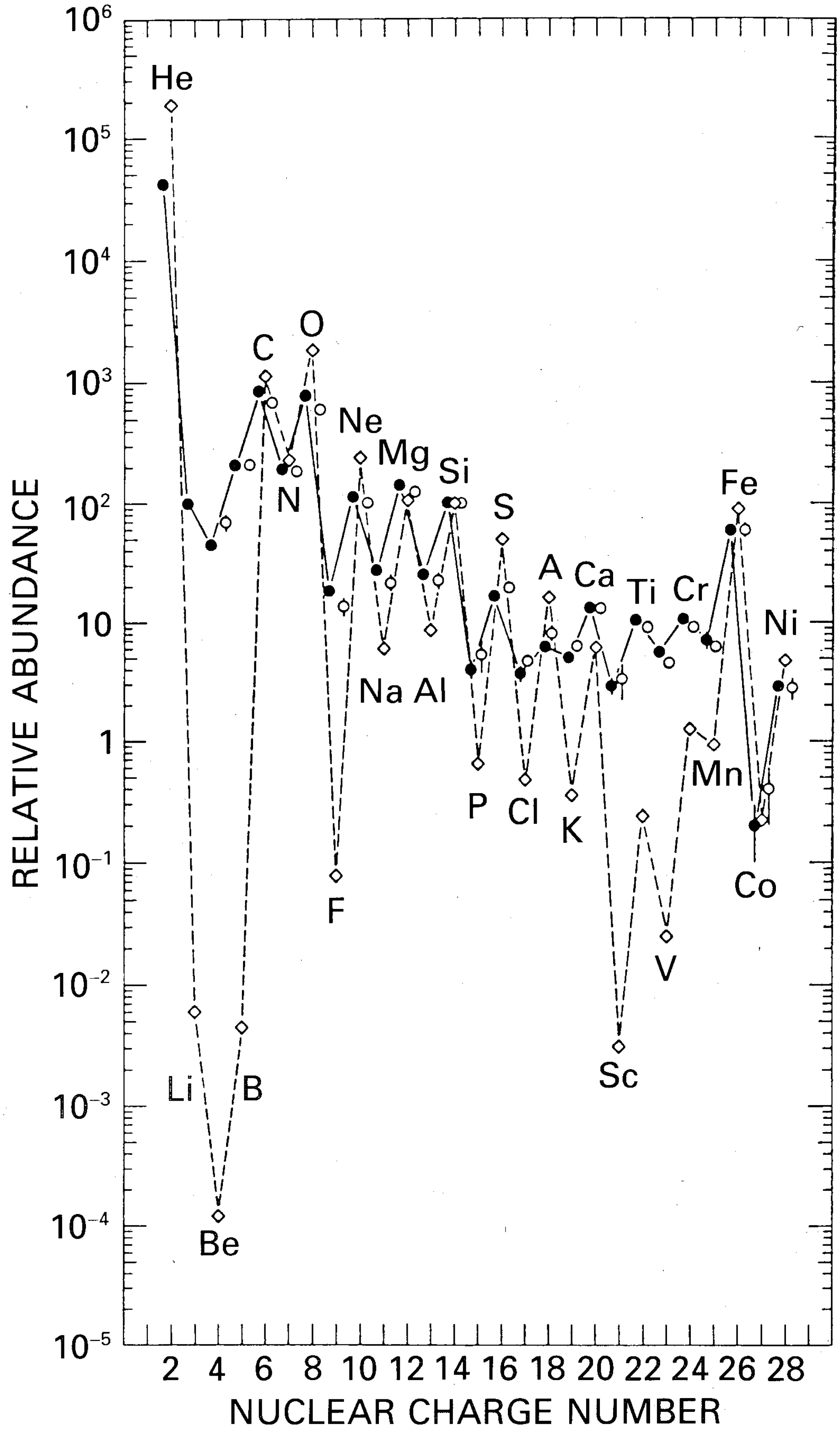


from Swordy, Scientific American

What we know at
Lower Energies

- Can directly measure particle type and energy with satellite and balloon experiments.
- Also arrival direction — but tells us nothing due to interstellar magnetic fields...
- Elemental composition tells us many things... Spallation etc...
- High resolution isotopic ratios tell us even more... Radio isotope "clocks" etc...
- Plausible source theory: Supernova shock acceleration.
- All of this is possible because we get to measure the uninteracted primary...

Low Energy Cosmic Ray Composition

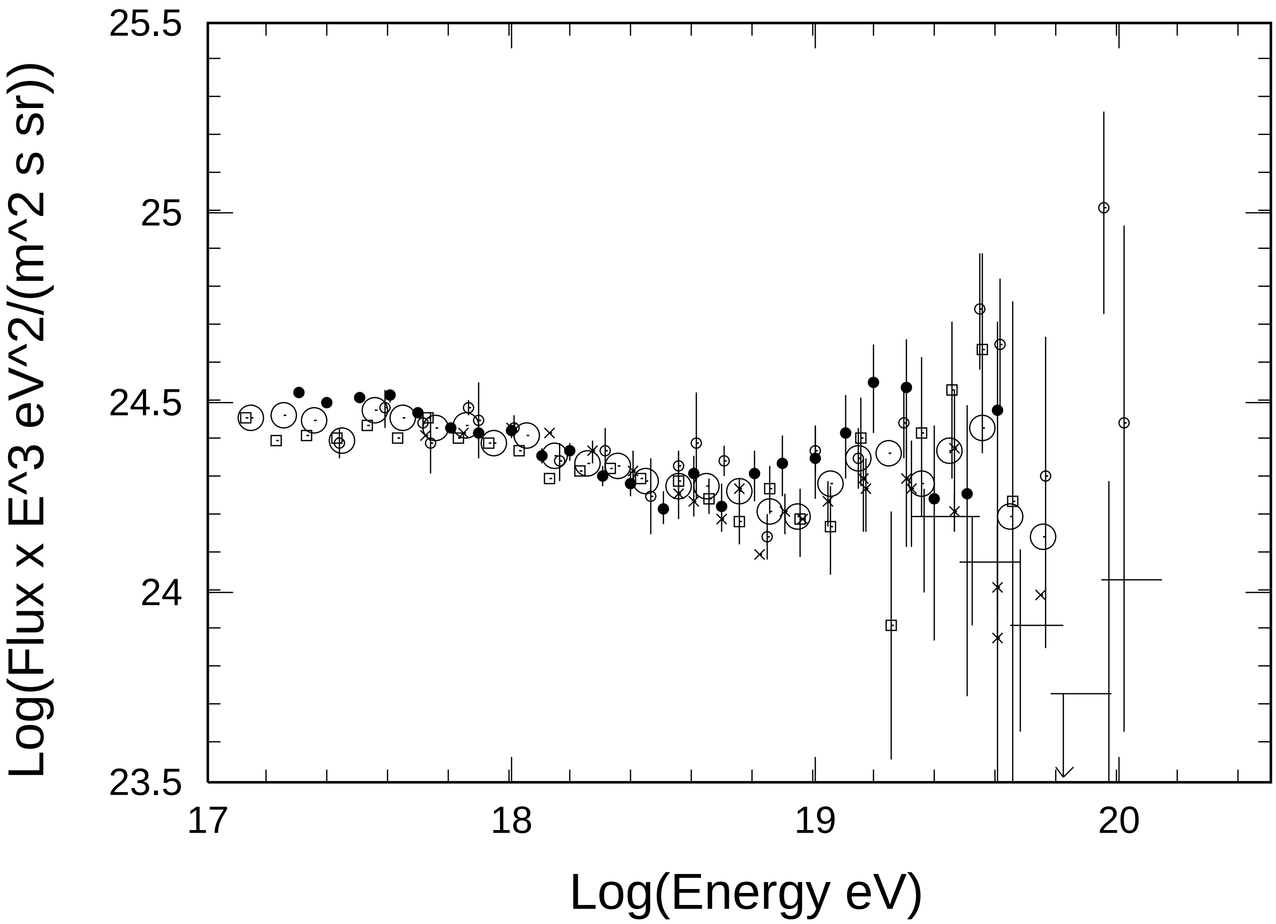


from Simpson Ann. Rev. Nucl. Part. Sci. **33** (1983) 326

What we know at Higher Energies

- Must measure cosmic ray primaries through the extensive air showers they produce.
- Can measure total particle energy.
- Can measure arrival direction — and at 10^{20} eV might tell us something!
- Very hard to measure particle type (main theme of this talk).
- Extremely hard to make plausible source theories: galactic or extra-galactic.

Top end of the Energy Spectrum

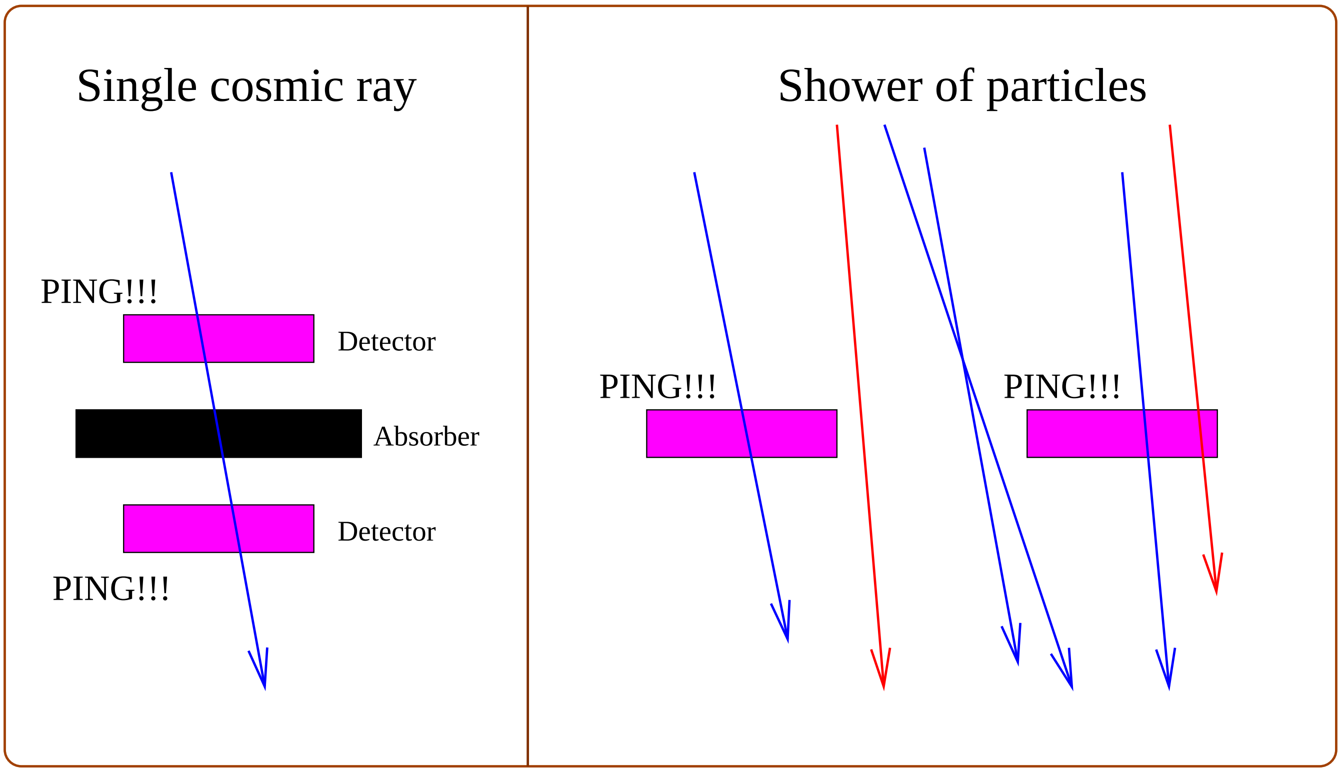


4 experiments: $\sim$ 15% energy scale shifts.

from Yoshida *et al*, Astro. Part. Phys. **3** (1995) 105

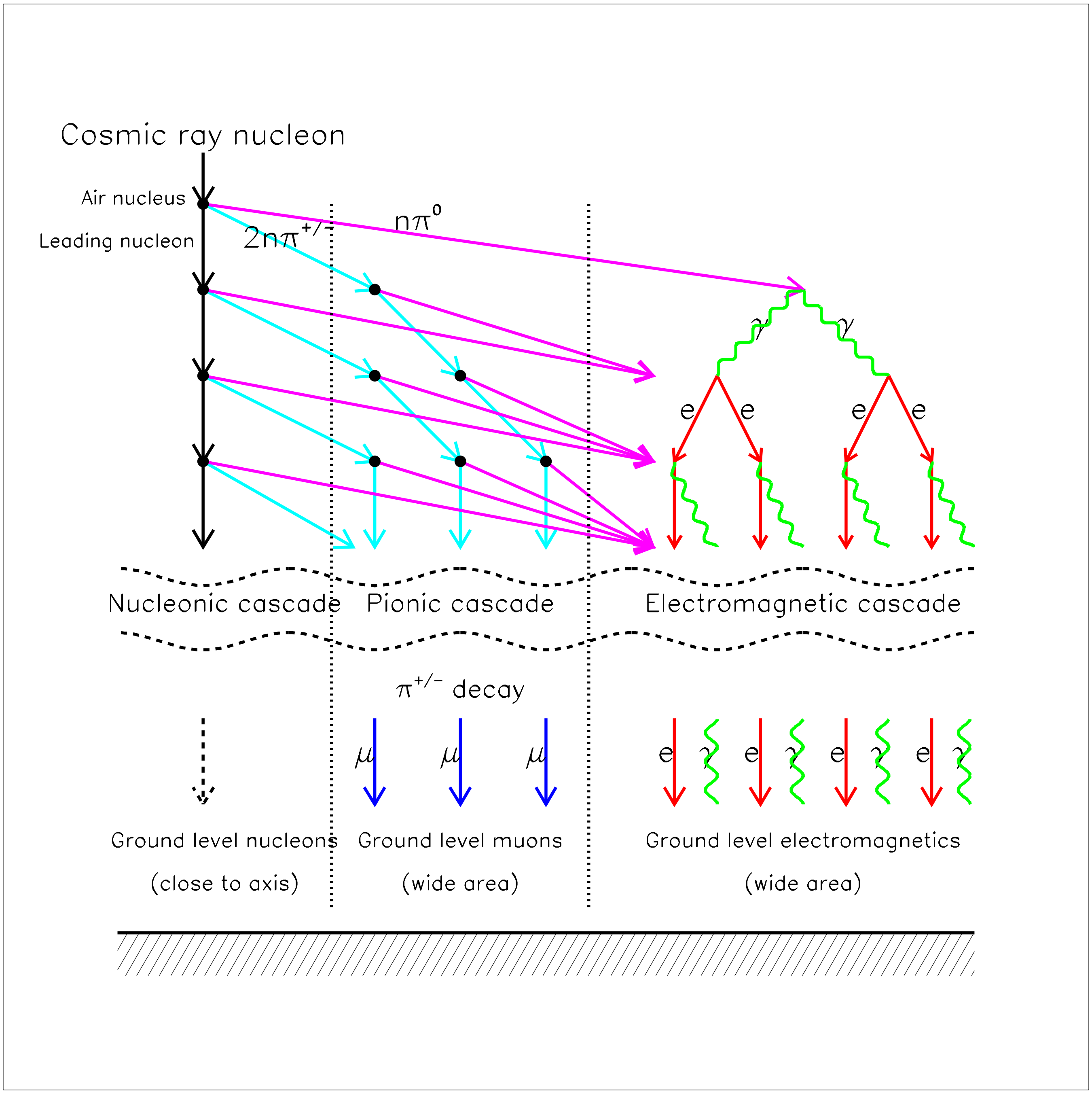
Discovery of Air Showers

- In late 1930's by Frenchman Pierre Auger.
- Using newly invented coincidence circuit (μ sec).
- Detectors on top of each other fire together
  $\Rightarrow$ due to single particles.
- Separated detectors fire together
  $\Rightarrow$ showers of particles.



- Inference: Showers of secondary particles.
  Over 300 meter baseline $\Rightarrow 10^{15}$ eV primary!

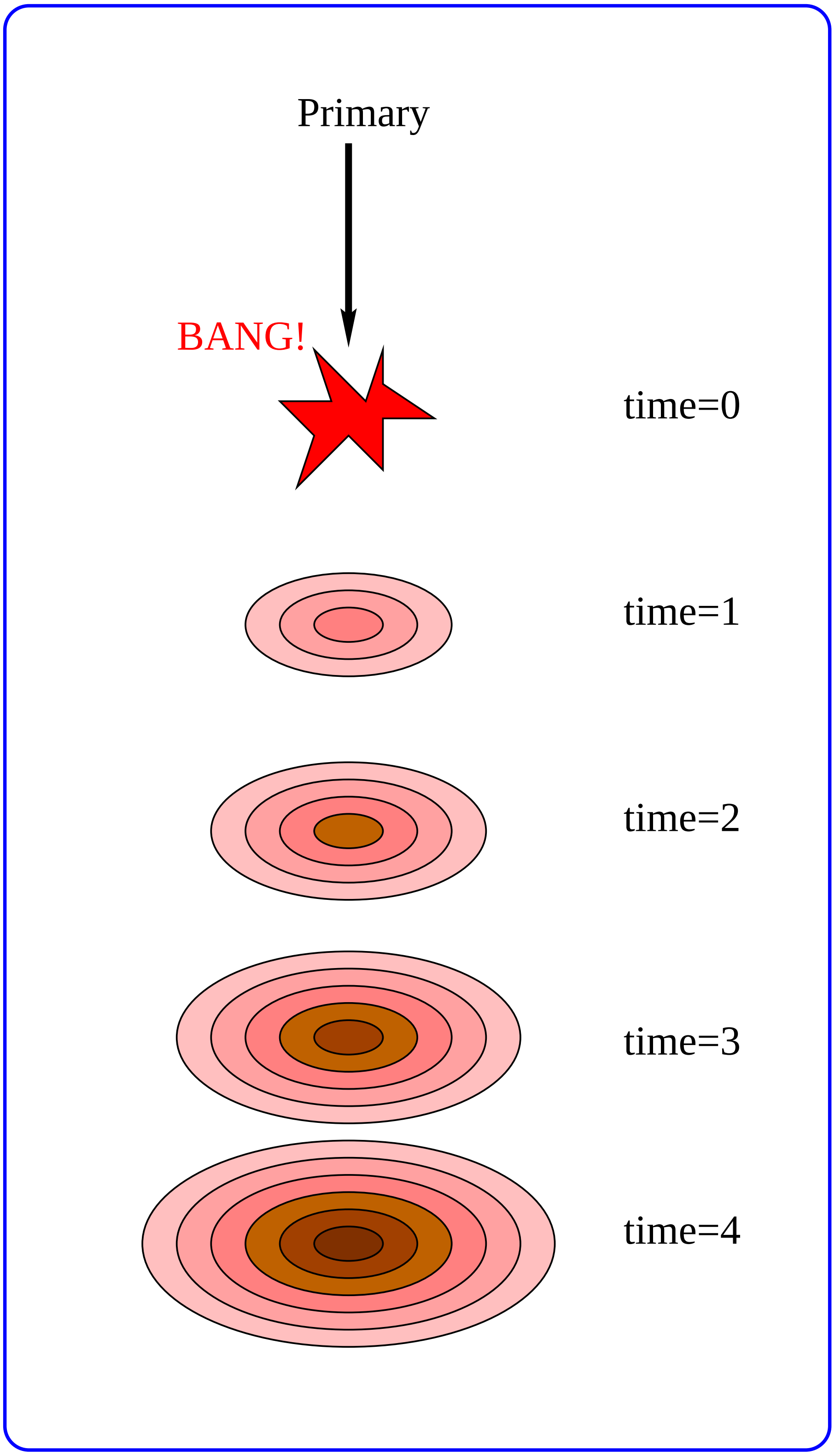
Anatomy of an air shower



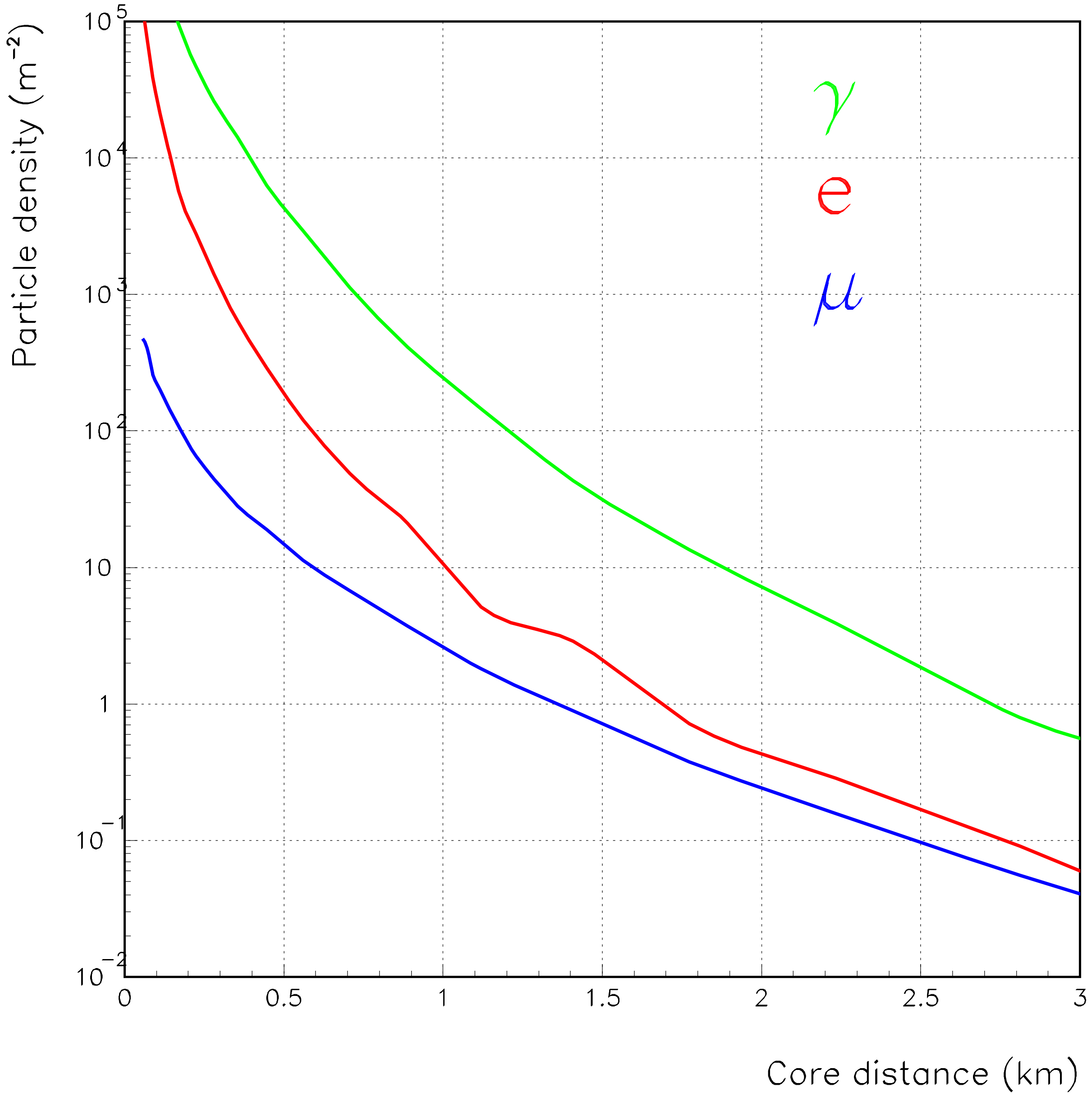
Cascade processes

- At each "generation" $\approx \frac{1}{3}$ of the available pionic energy is transferred to the electromagnetic cascade $(\pi^0 \Rightarrow \gamma + \gamma)$.
- After some number of generations the $\pi^{+/-}$ start to decay before interacting ($\approx$ 20 GeV).
- At this point the remaining energy is dumped into muons which propagate to ground level with little further interaction.
- Electromagnetic cascade diffuses out from the axis through multiple scattering.
- At ground level, and large core distances, muon energies are typically GeV, while electromagnetics have 10's of MeV.

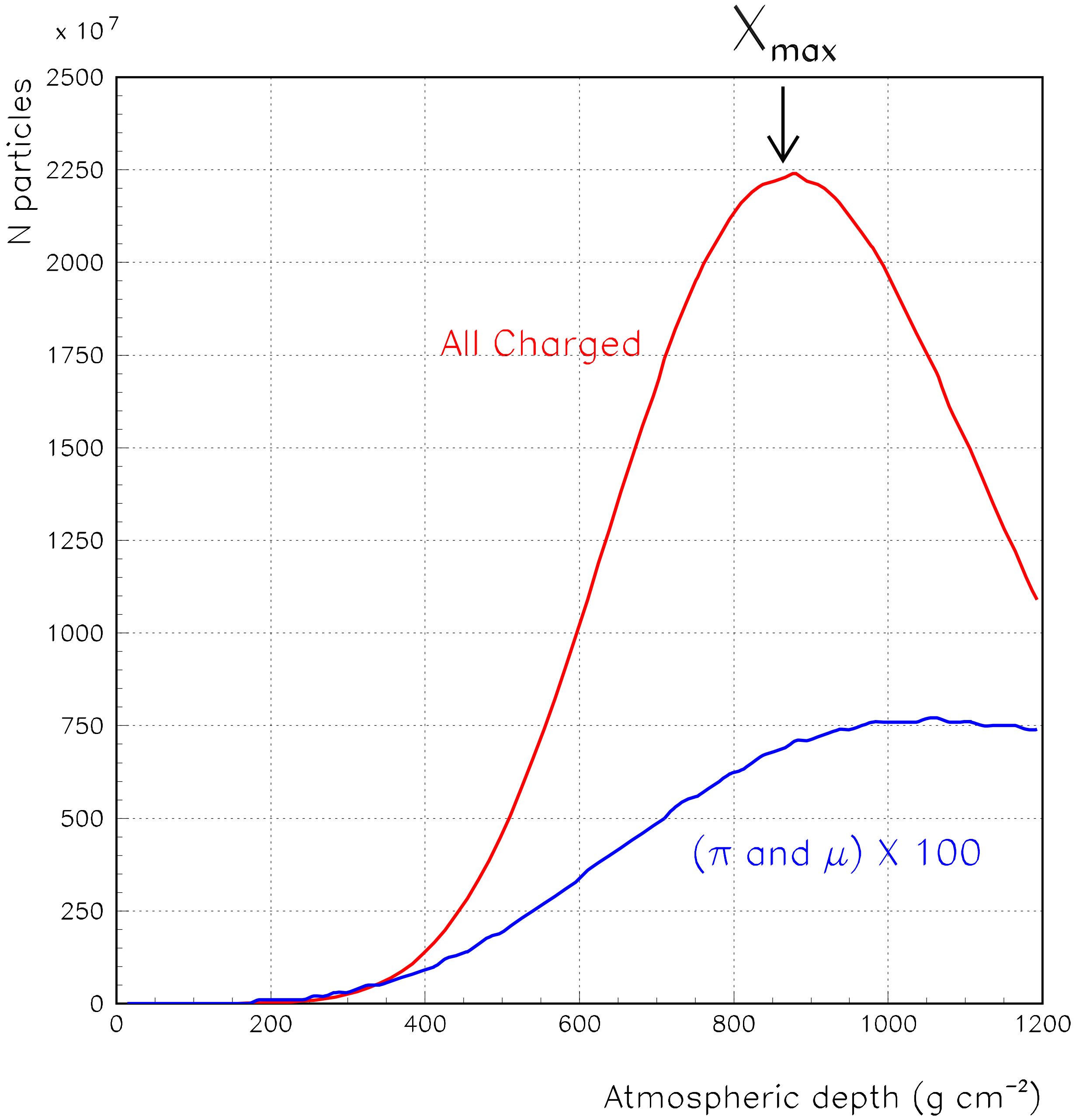
Air Shower Development



Lateral Distribution



Longitudinal Distribution



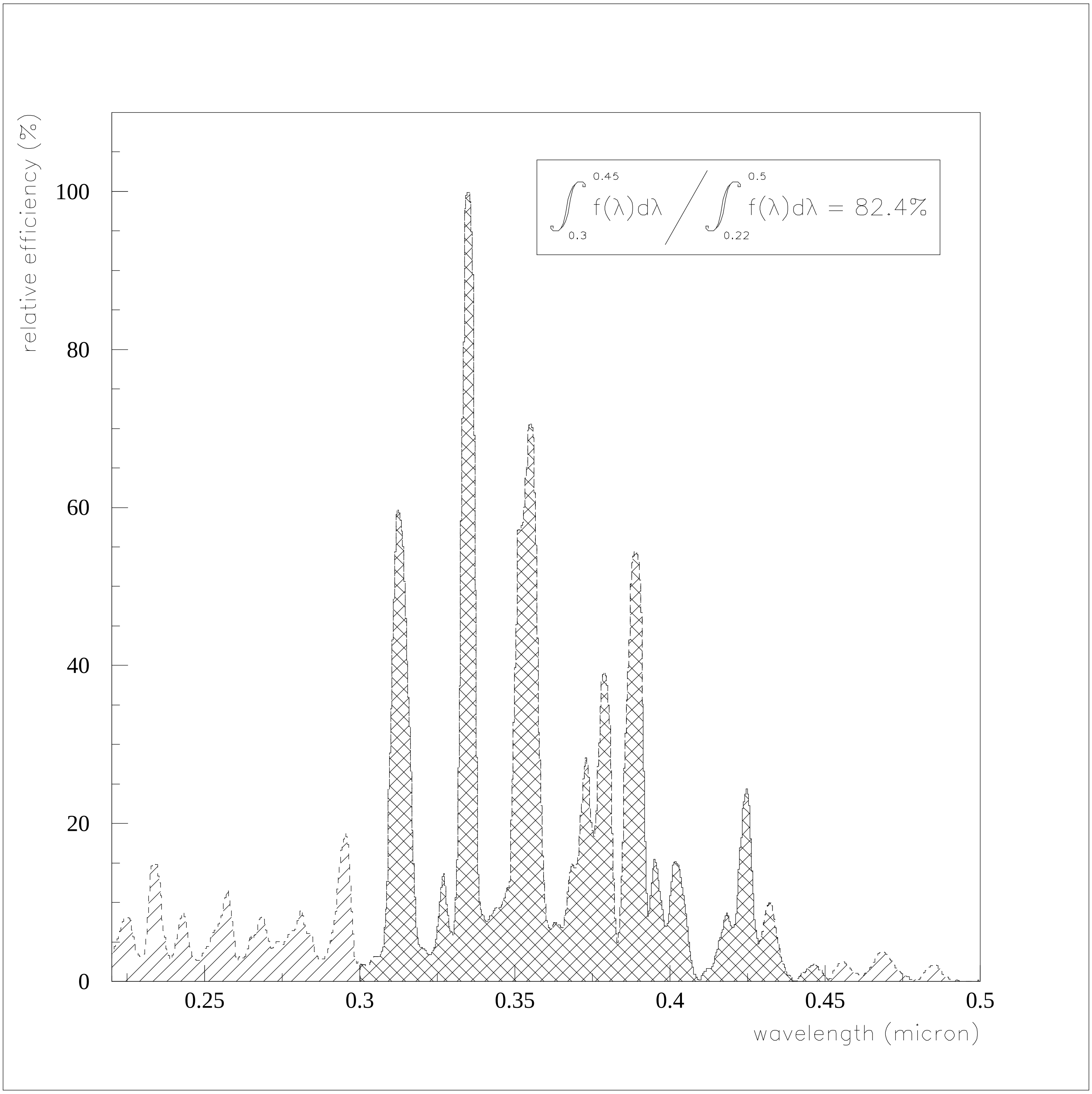
Light Generation

The shower also makes two types of light in the atmosphere:

- Intense Čerenkov light emitted in the forward direction. (Parallel to the shower axis.) Continuum emission falling as λ^{-2}.

- Weaker fluorescence (scintillation) light emitted isotropically. Line emission: 7 lines between 290 and 430 nm.

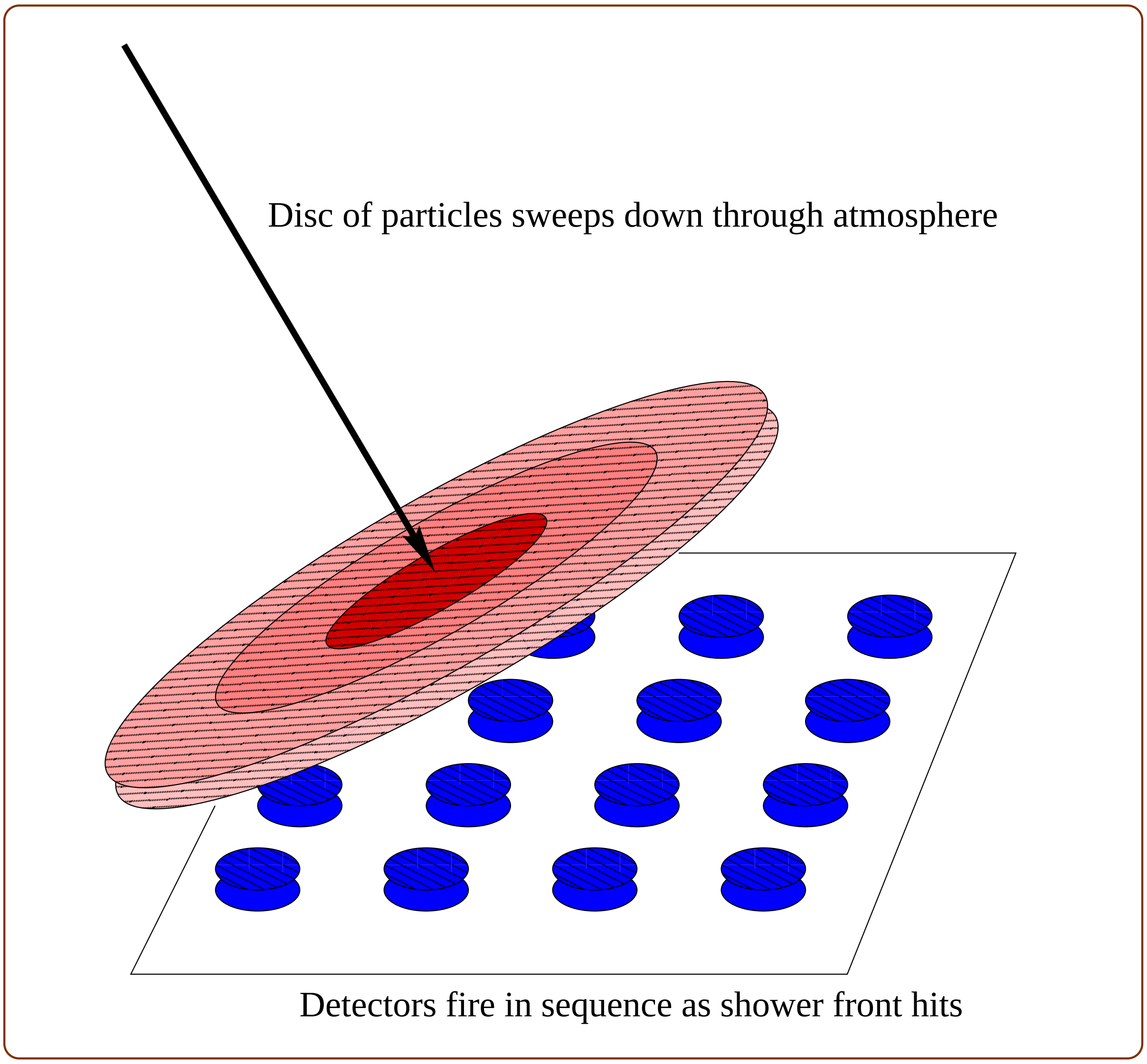
Fluorescence Spectrum



Detection Techniques

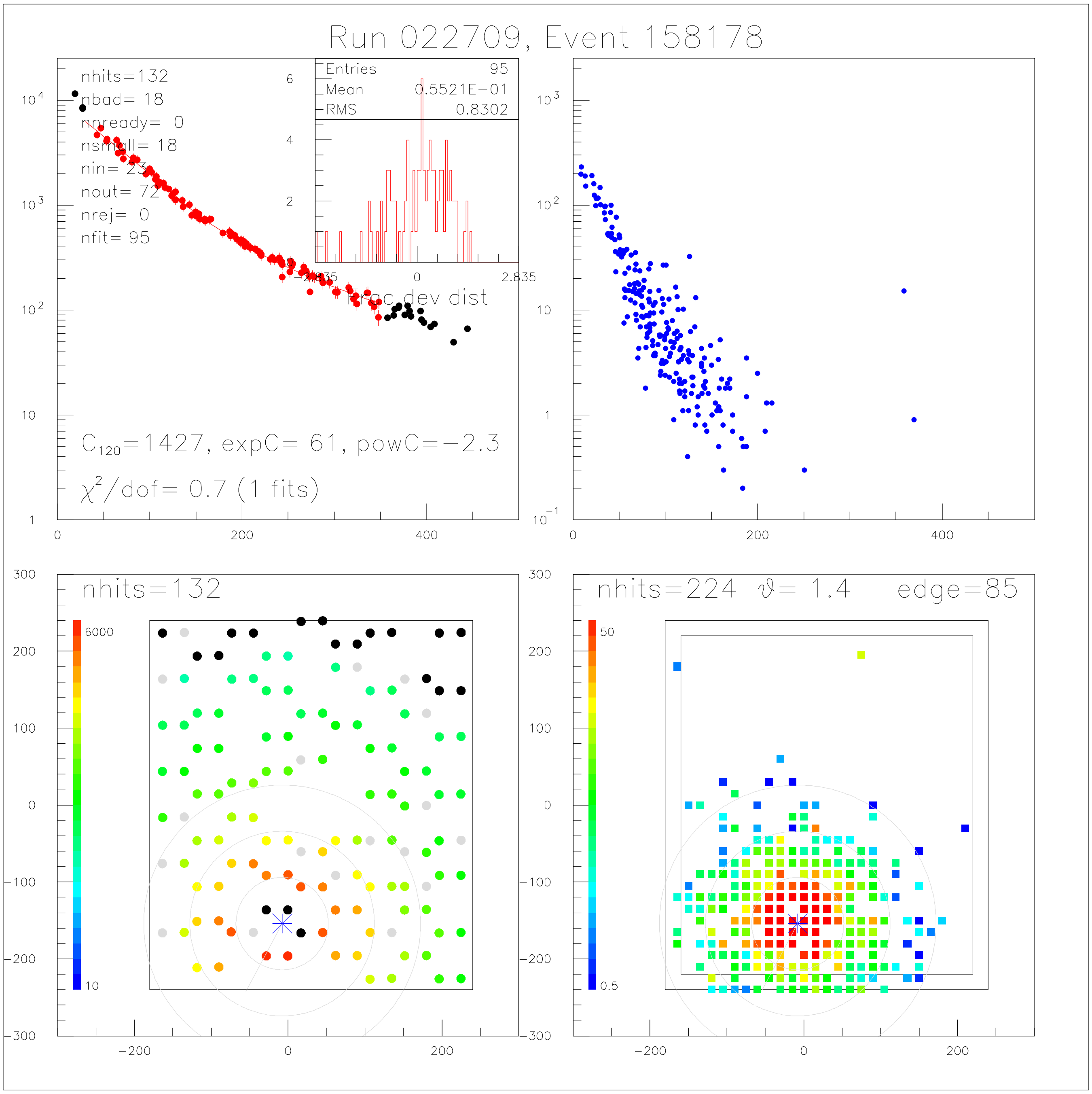
- Ground Arrays
  - Original technique. (Developed in the 50's).
  - Measure the Lateral Distribution at Ground Level.
  - Works detecting both particles and Čerenkov light.
- Fluorescence Detectors
  - Atmosphere as remote sensing calorimeter.
  - Measure the Longitudinal Distribution.

Ground Array Technique



- Incidence angle found from timing.
- Parameterization simple.
  $\Rightarrow$ Model simple (and atmosphere unvarying).
- Finding Energy and Composition requires shower development calculations.

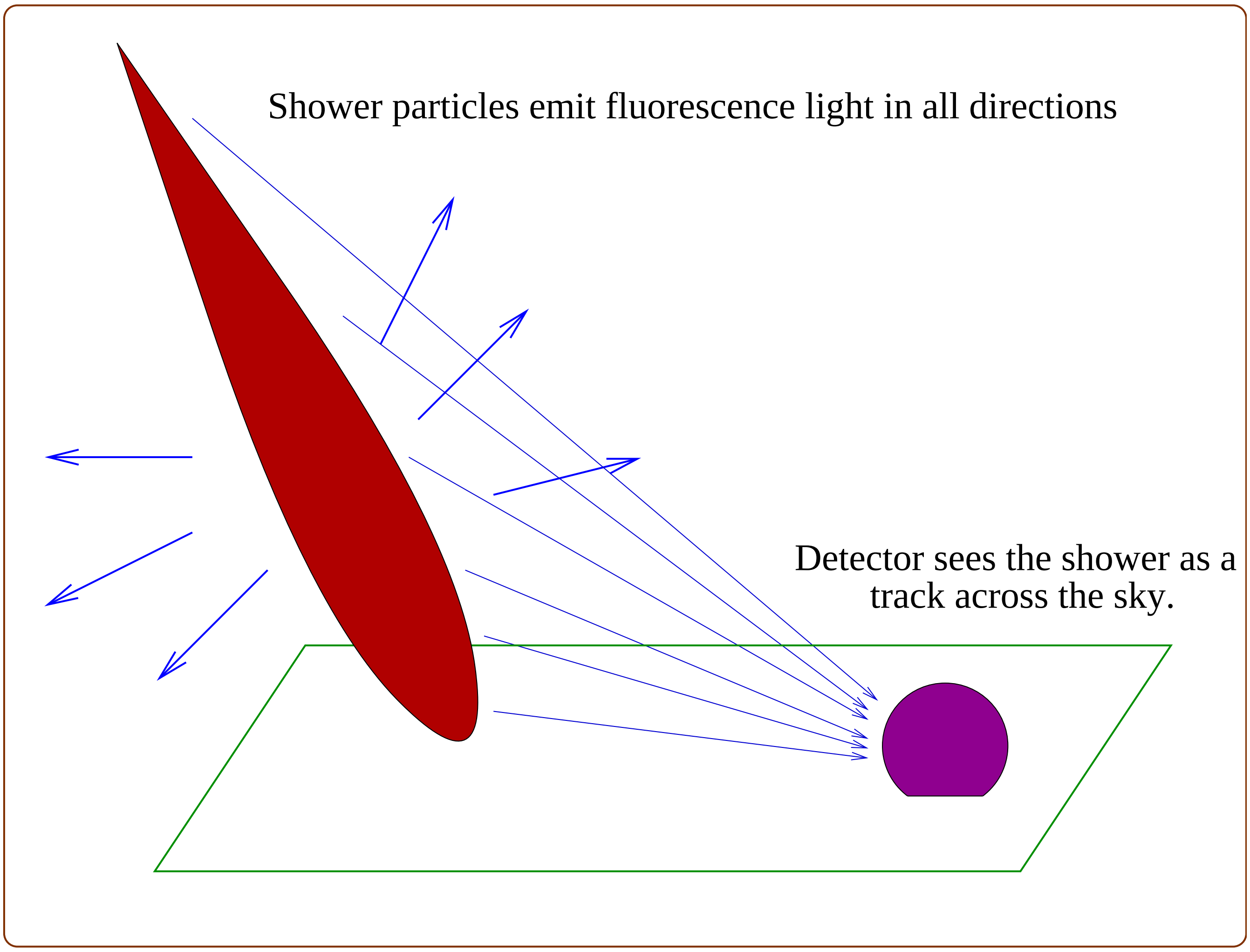
An Example Ground Array Event



CASA/BLANCA

⇒ Measures both Particles and Čerenkov light.

Fluorescence Detectors



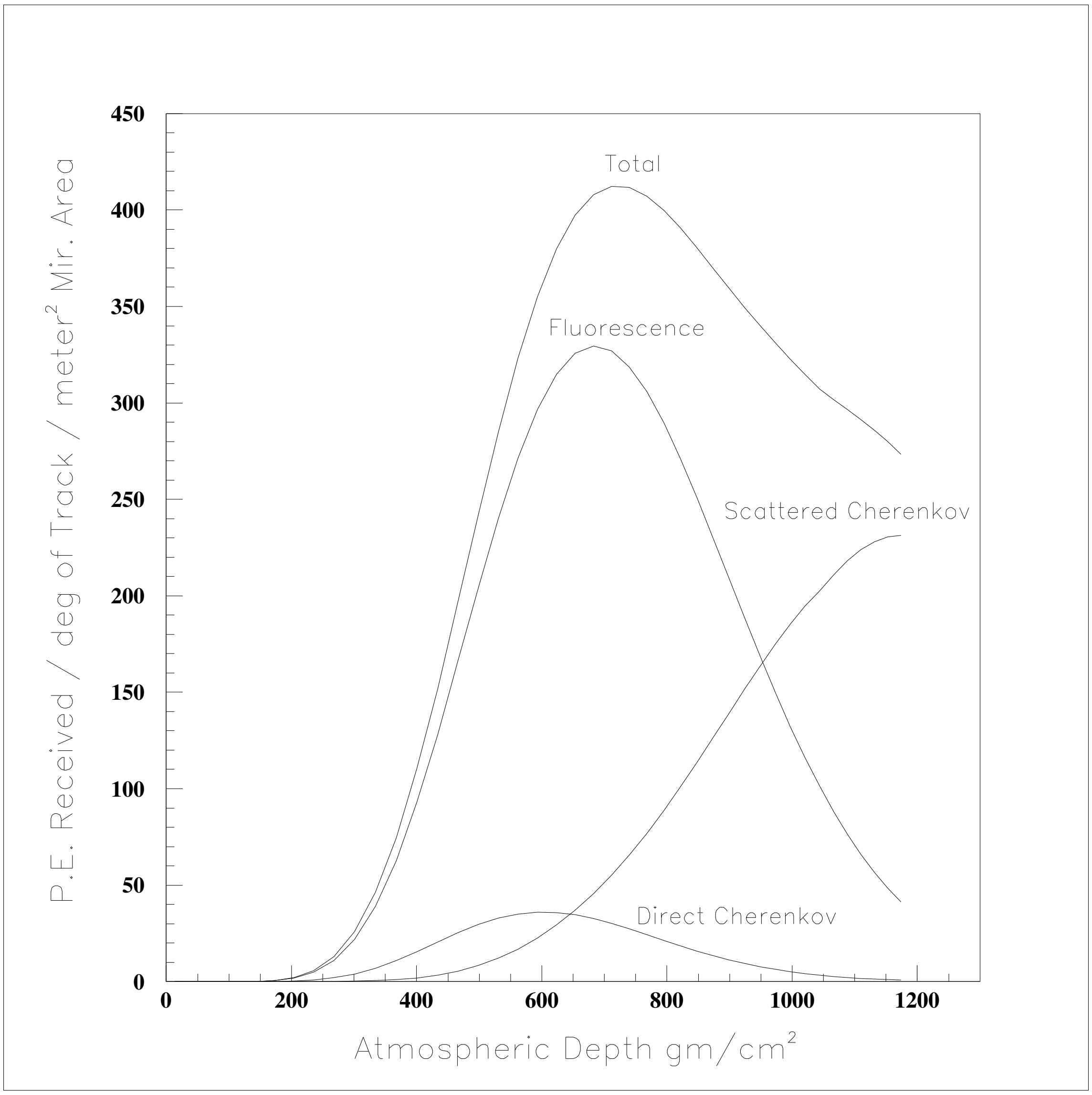
- Normally make "stereo" observations
  $\Rightarrow$ incidence angle follows from geometry alone.

- Parameterization hard $\Rightarrow$ Čerenkov contamination complicates analysis and atmosphere varies.

- Find energy from integral of longitudinal profile
  $\Rightarrow$ Solid calorimetric lower limit on primary energy.

- Finding Composition requires shower development calculations.

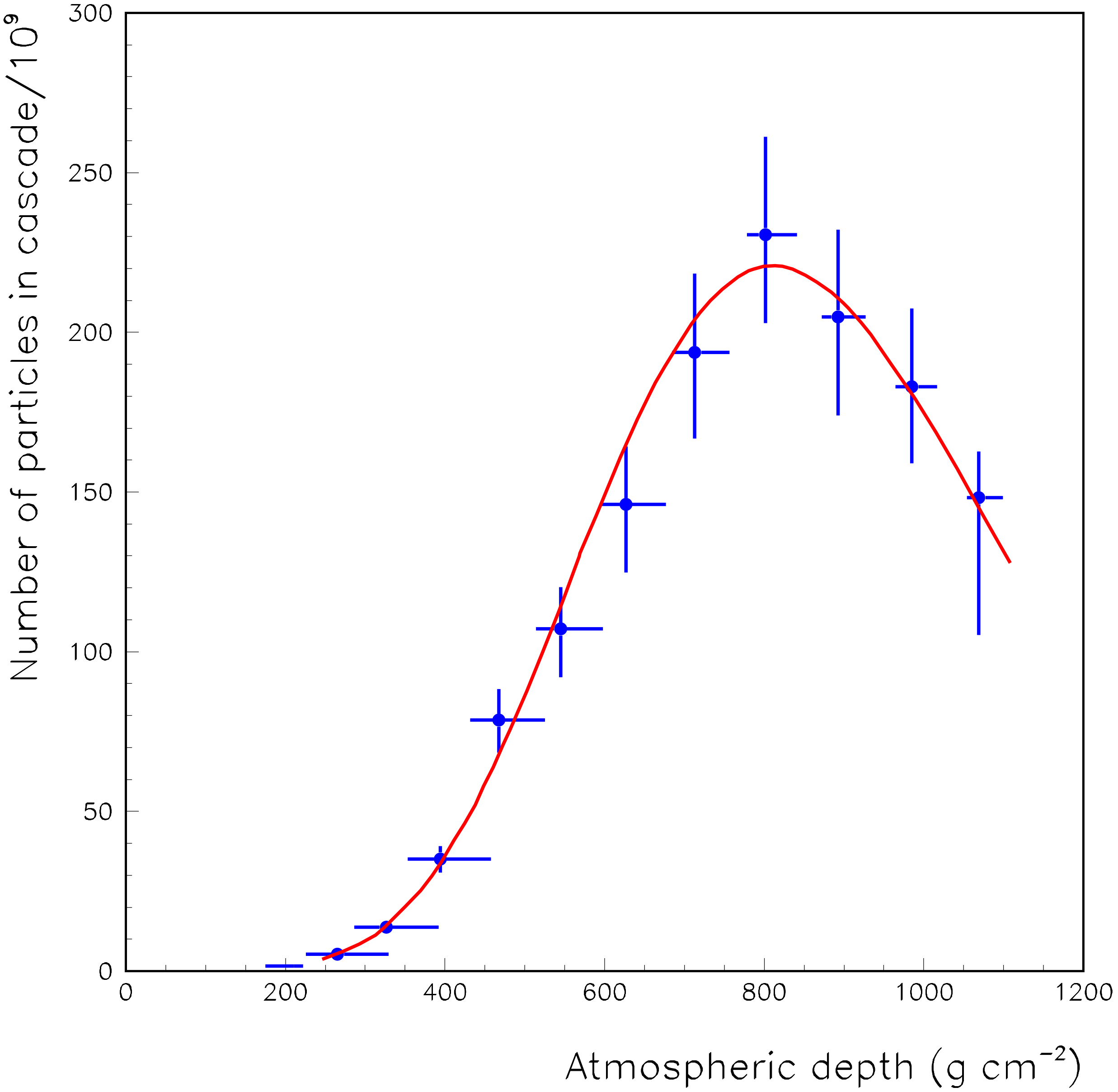
Fluorescence Reconstruction Model



How the shower appears to the detector depends on geometry and atmosphere as well as well as the shower itself.

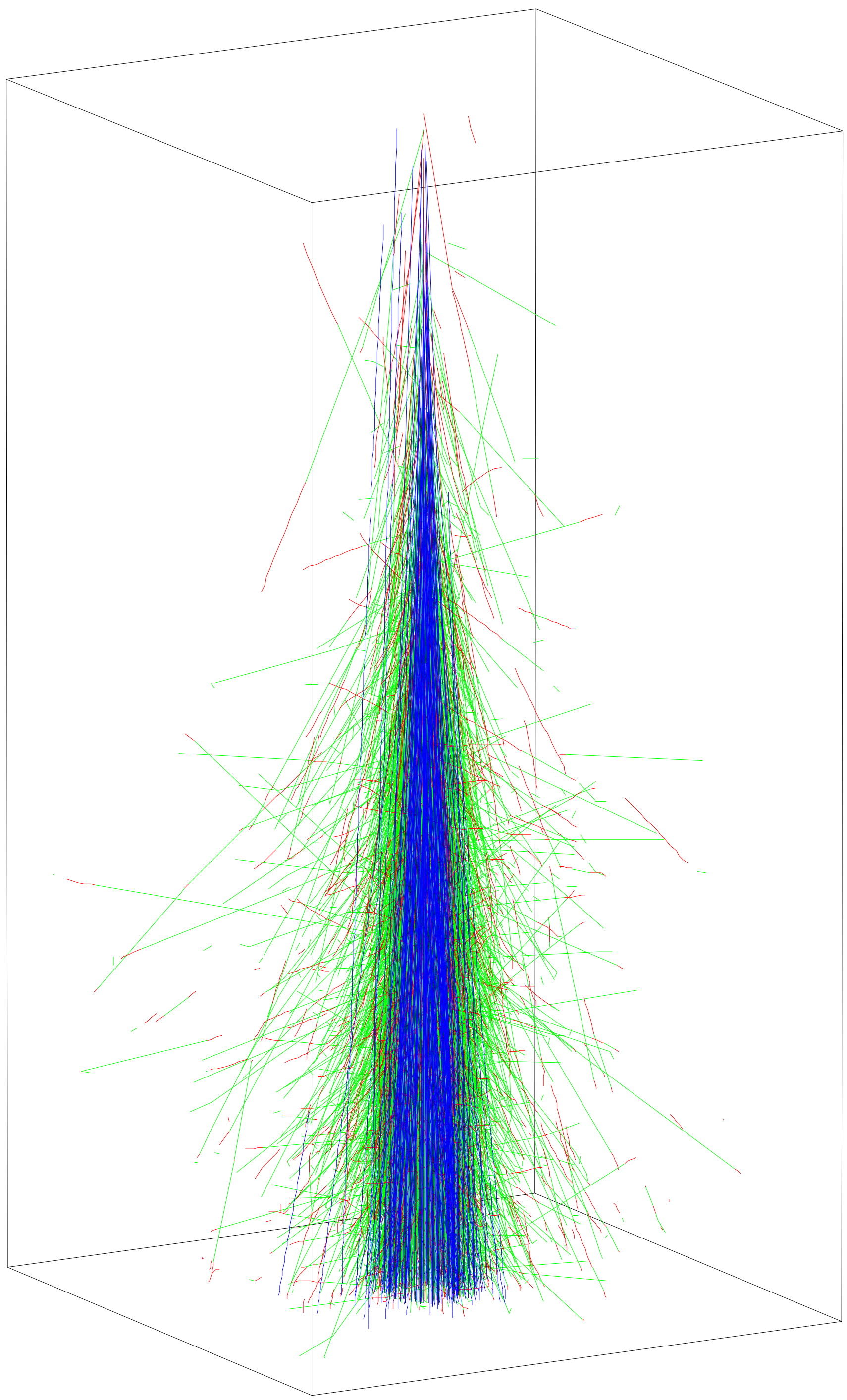
Fly's Eye 3×10^{20} eV Event

$\approx$ 200 billion particles at cascade maximum!



from Bird *et al*, Ap. J. **441** (1995) 144

Air Shower Simulation



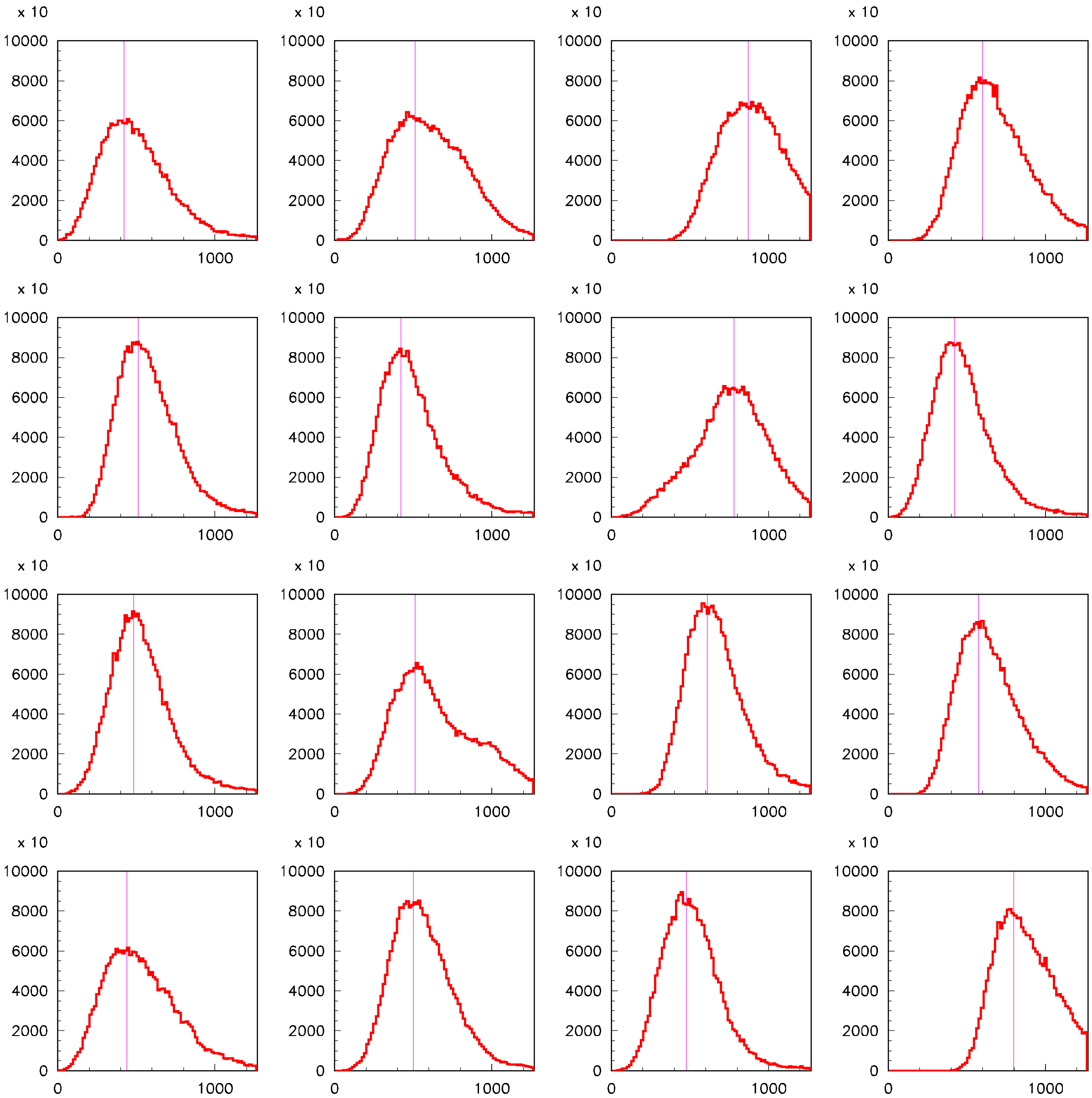
Frame box: 6 x 6 x 12 km high.

Color code: γ, e, μ.

Air Shower Simulation

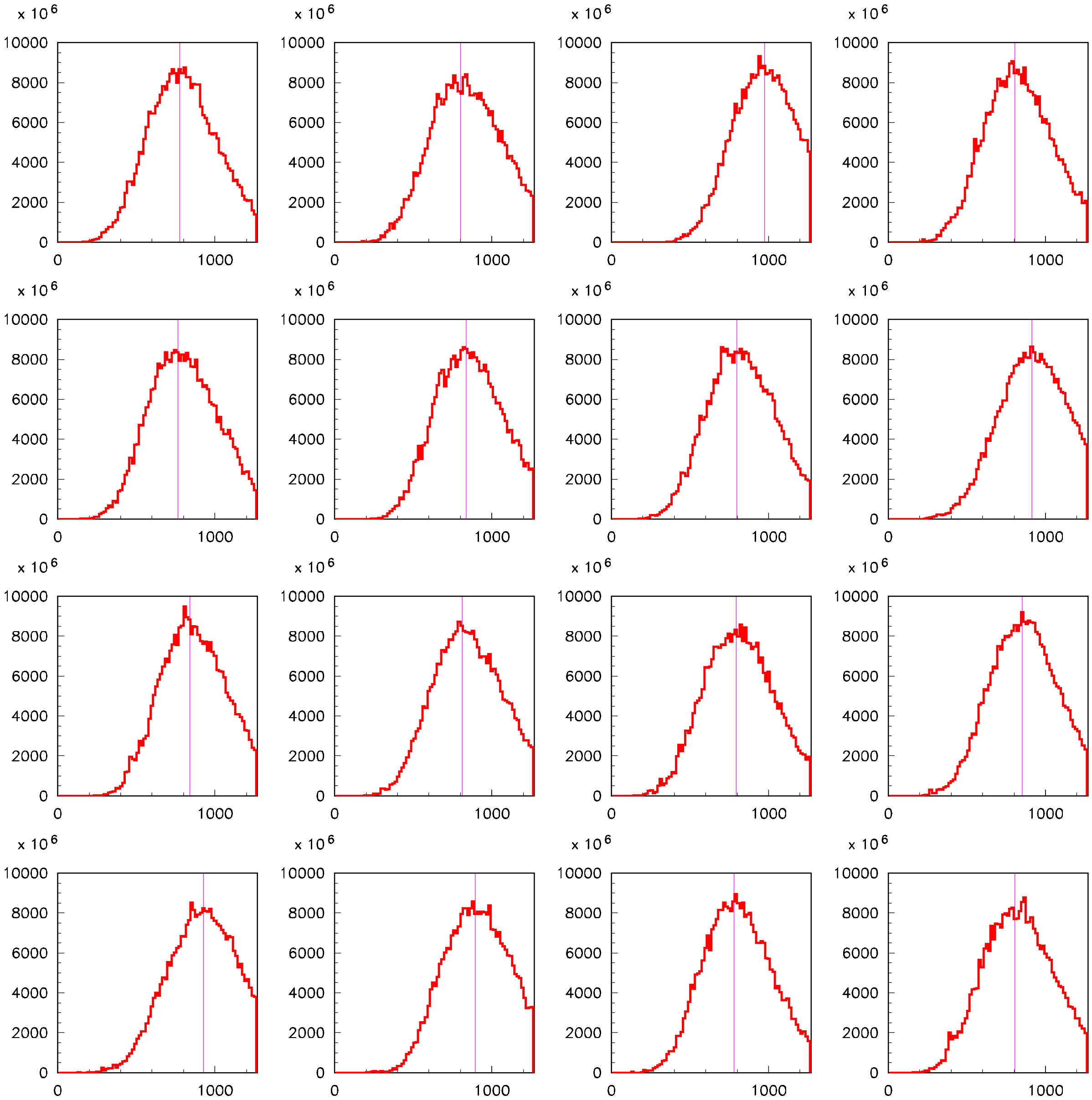
- The first interaction fluctuates...
- ...so the resulting shower also fluctuates.
- Full Monte Carlo simulation is the only way.
- Problem is to find observable parameters which correlate as closely as possible with the energy and type of the primary cosmic ray.

Low energy showers are “badly behaved”



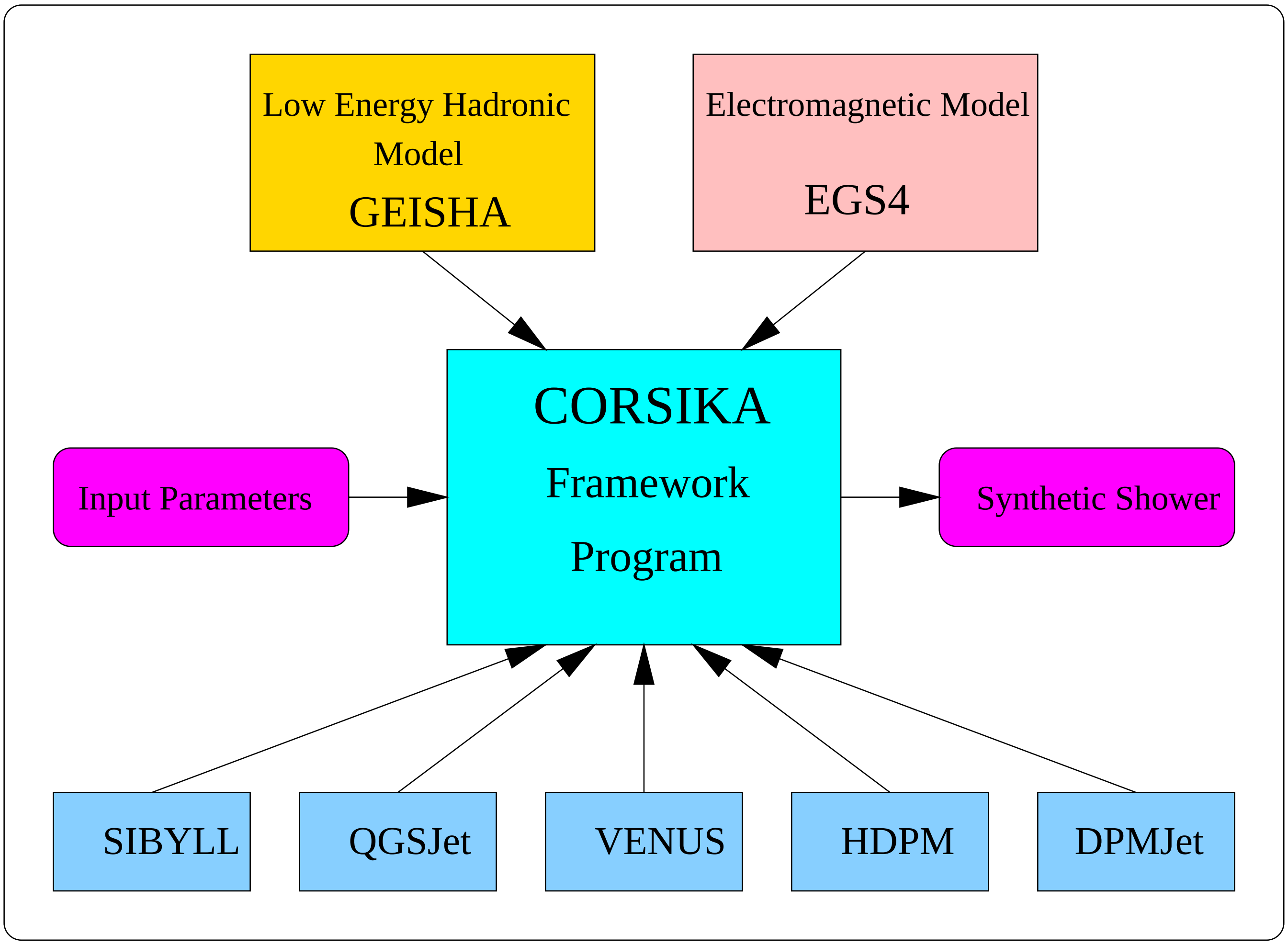
10^{14} eV proton

High energy showers are much nicer....



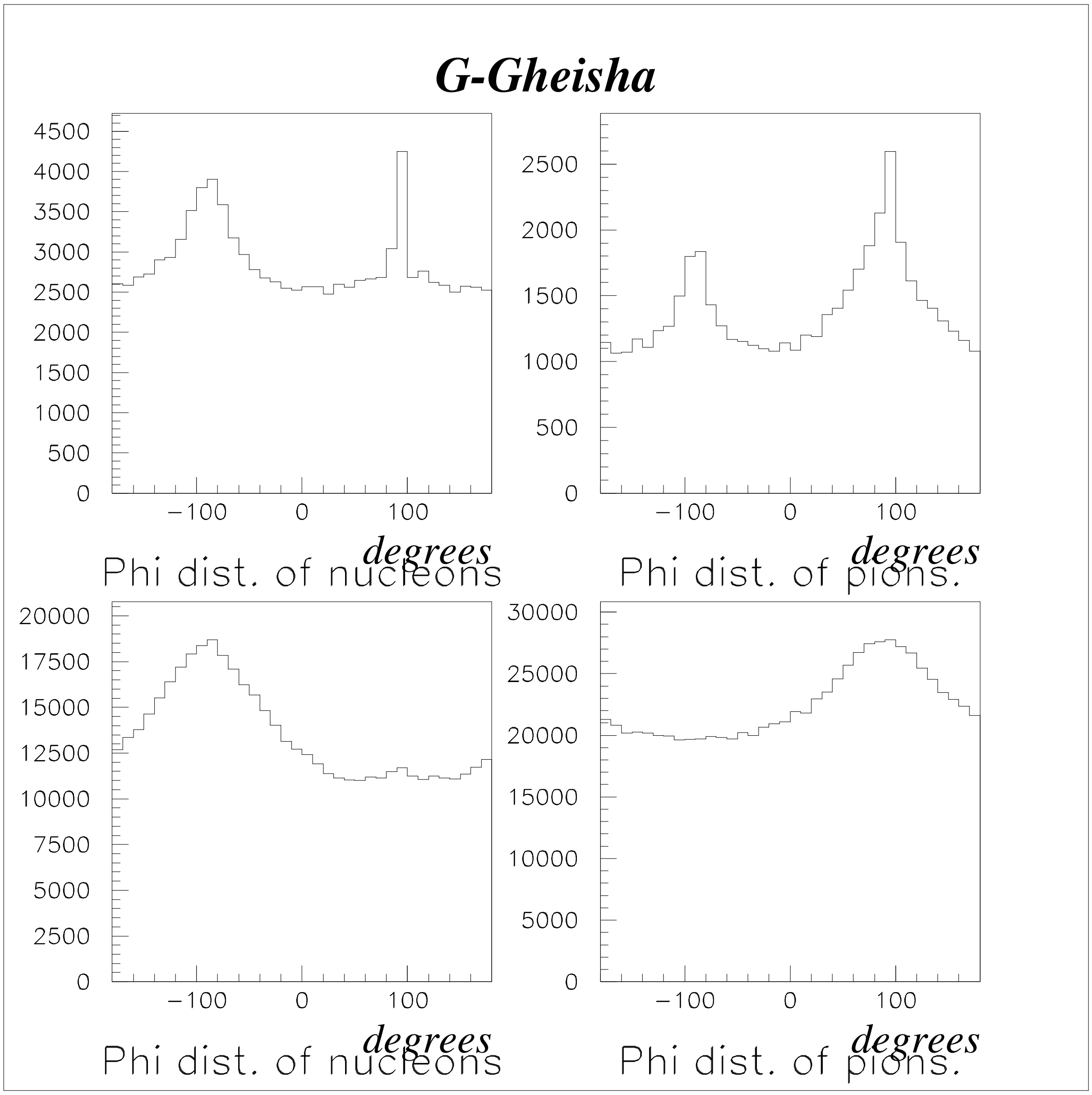
10^{19} eV proton

CORSIKA Simulation Program



- Uses highly respected HEP simulation codes for the low energy modeling — GEISHA and EGS4
- Pluggable high energy hadronic models (uncertain).
- Prepared in support of the KASCADE experiment but freely available.
- Philosophy - don't try and reinvent the wheel...

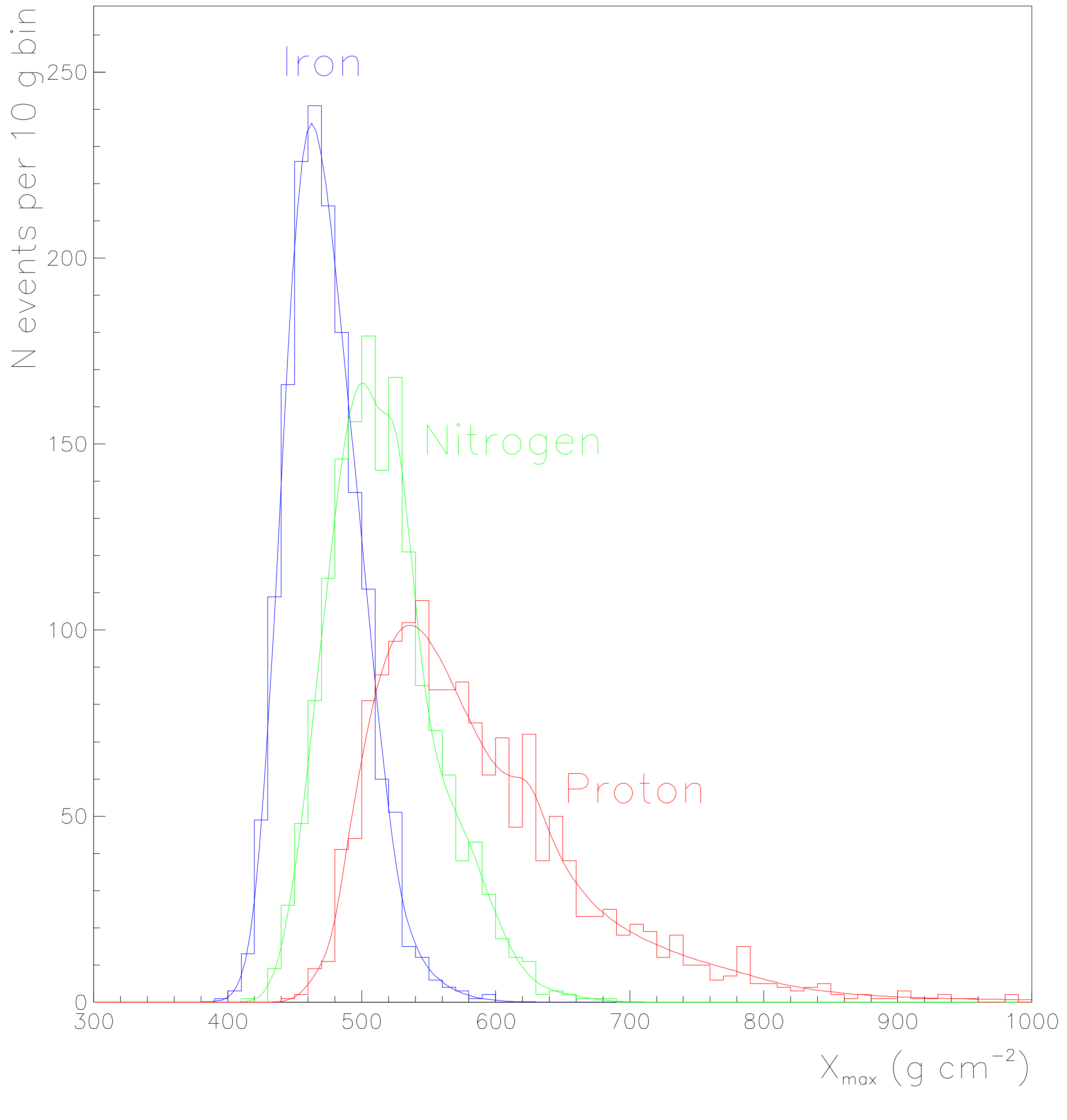
The Mighty GEISHA?!



Basic physics demands that these plots be flat!

`From ATLAS Internal Note PHYS-No-086`

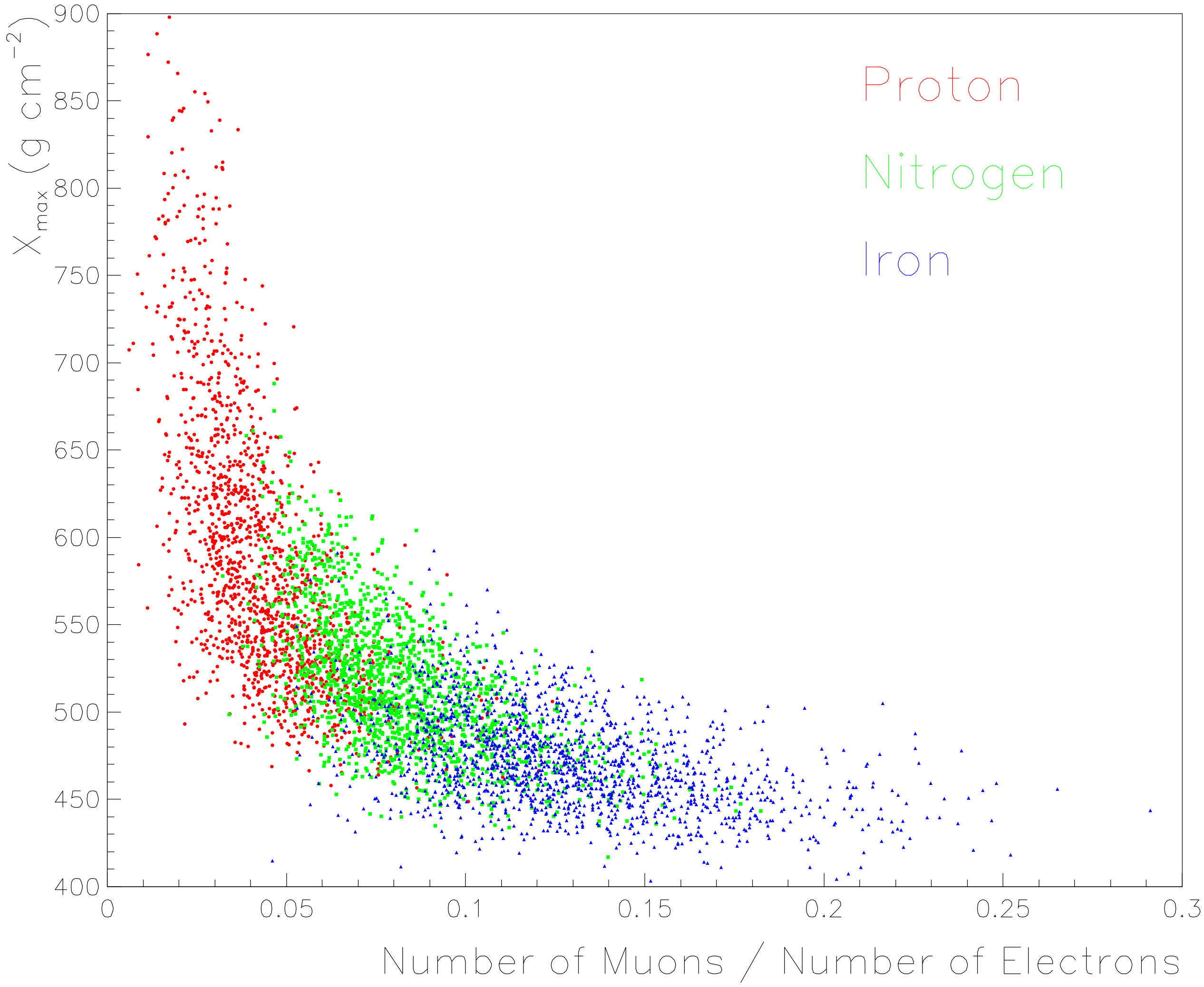
Composition Parameter X_{max}



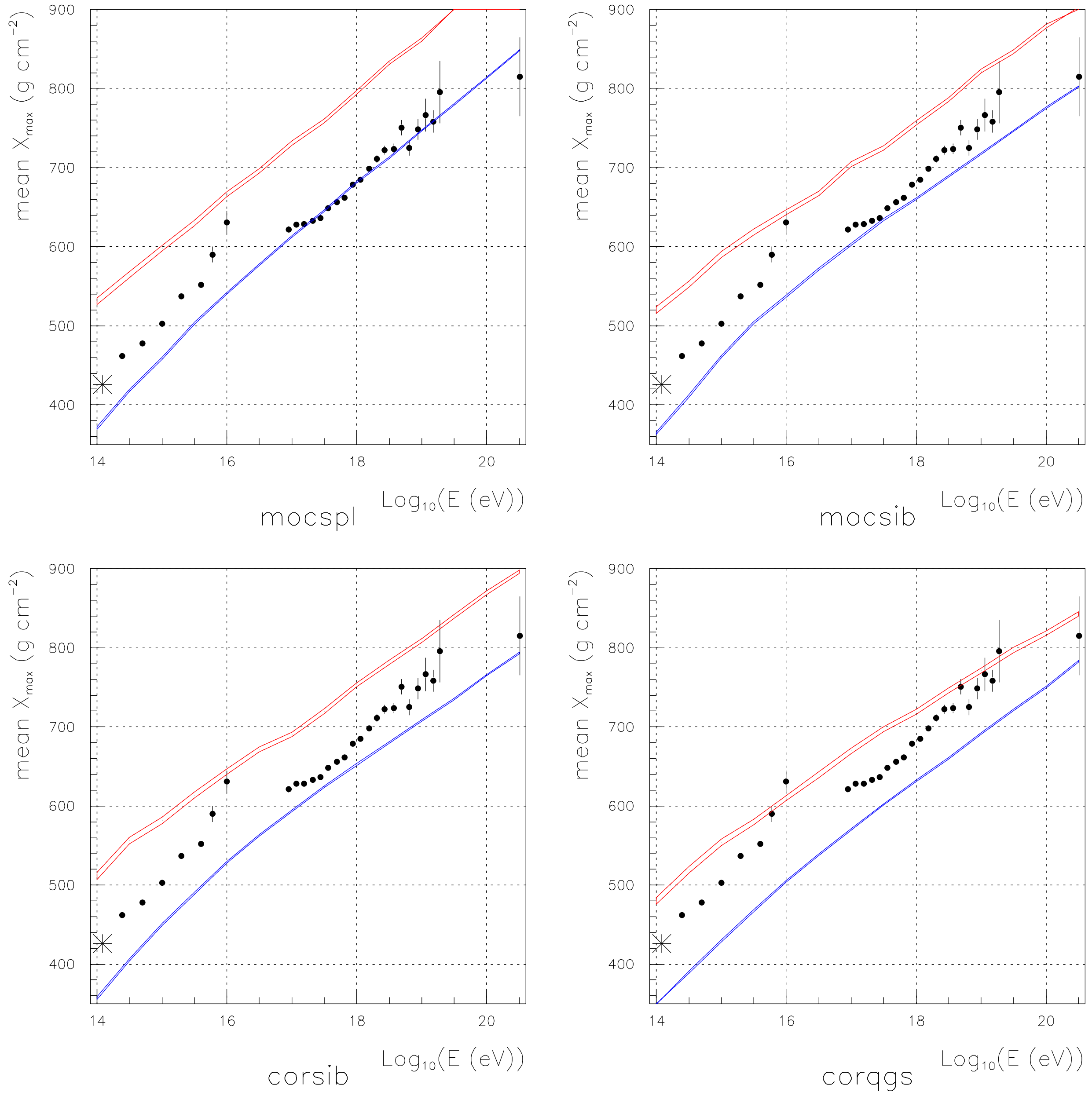
Distribution of the depth of shower maximum for primaries of the same energy.

Multi-Parameter Measurements

- Only really help with measurement errors.
- Most every parameter seems to be correlated with the rest...
- ...not surprising since the whole shower comes from the first interaction.



Existing Data and Simulation



The average value of X_{max} is usually presented.

Summary

At the moment two things limit our ability to measure cosmic ray composition using air showers:

- Uncertainty in the hadronic interaction models.
  - In principle this could be removed up to $\sim 10^{15}$ eV with the right accelerator experiments...
  - Above that energy it's never going to go away.
- Shower Fluctuations
  - No amount of human ingenuity will eliminate them.

Conclusions

Extensive air showers experiments will probably always remain the only way to obtain information on cosmic rays with $E > 10^{16}$ eV.

They can tell us:

- The energy of the primary particles.
- Their arrival direction.

In my opinion they will never yield more than the most sketchy information on their composition.

$\Rightarrow$ Nevertheless these particles are fascinating and deserve to be studied.