Cosmic Ray Physics: An Overview

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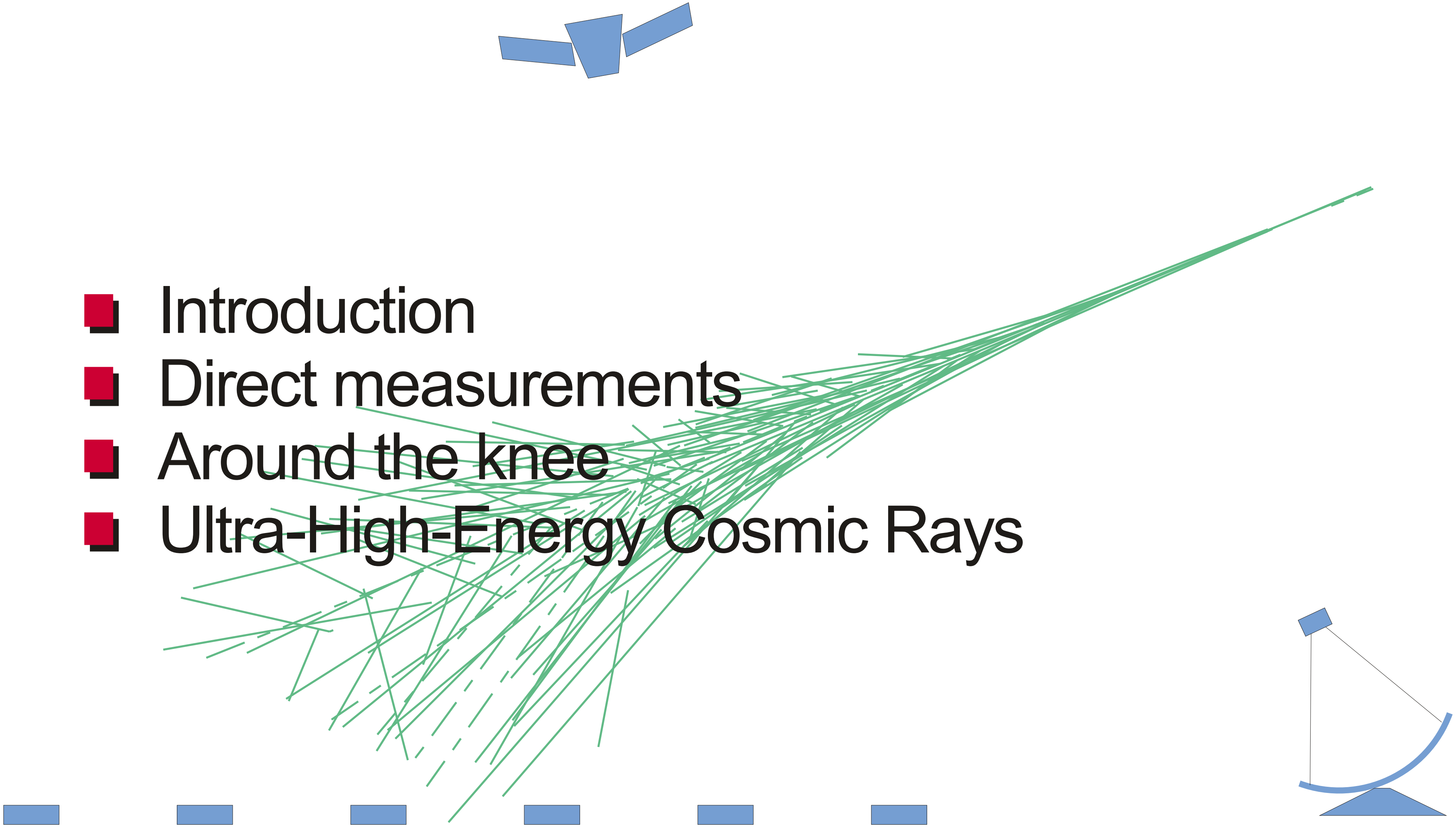


- Introduction
- Direct measurements
- Around the knee
- Ultra-High-Energy Cosmic Rays

Cosmic Rays:

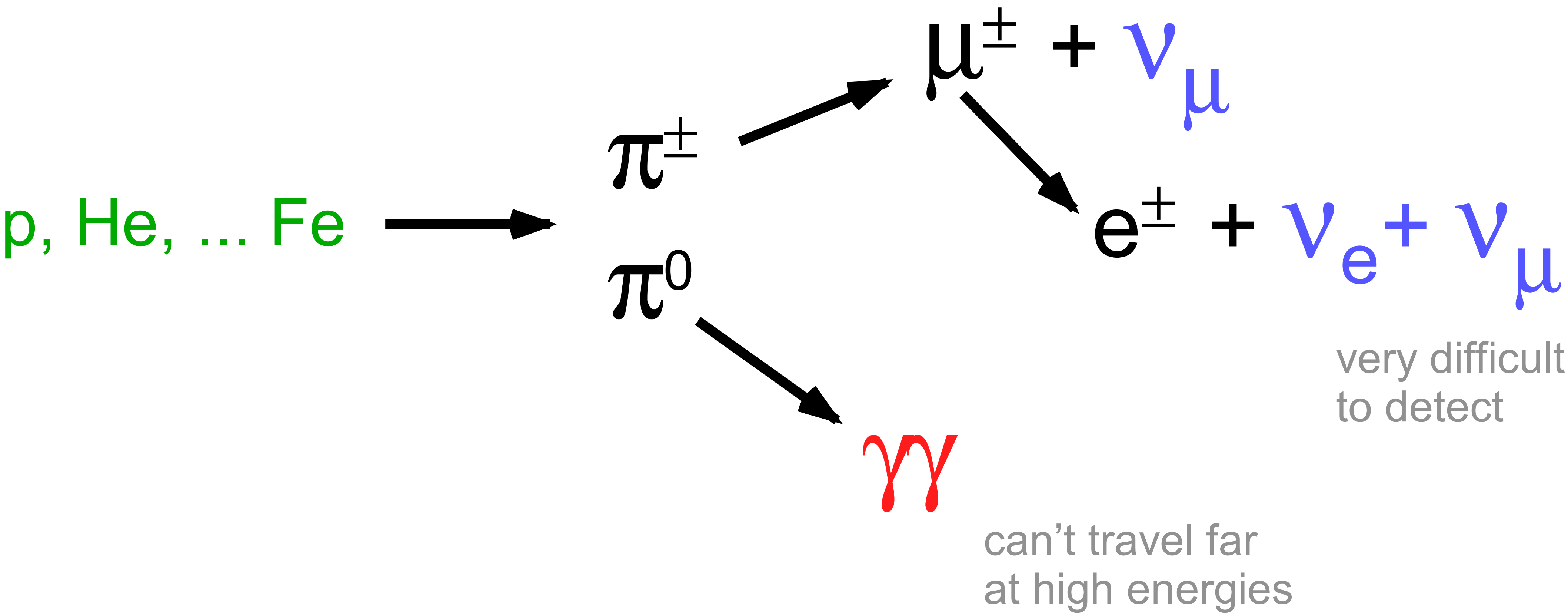
relativistic, charged particles

$E_{CR} \sim E_{starlight} \sim E_{CMB} \sim E_{mag} \sim E_{gas} \sim 1\ eV/cm^3$

total: $\sim 10^{49}$ J in Galaxy

CRs are a **major** component of our Galaxy

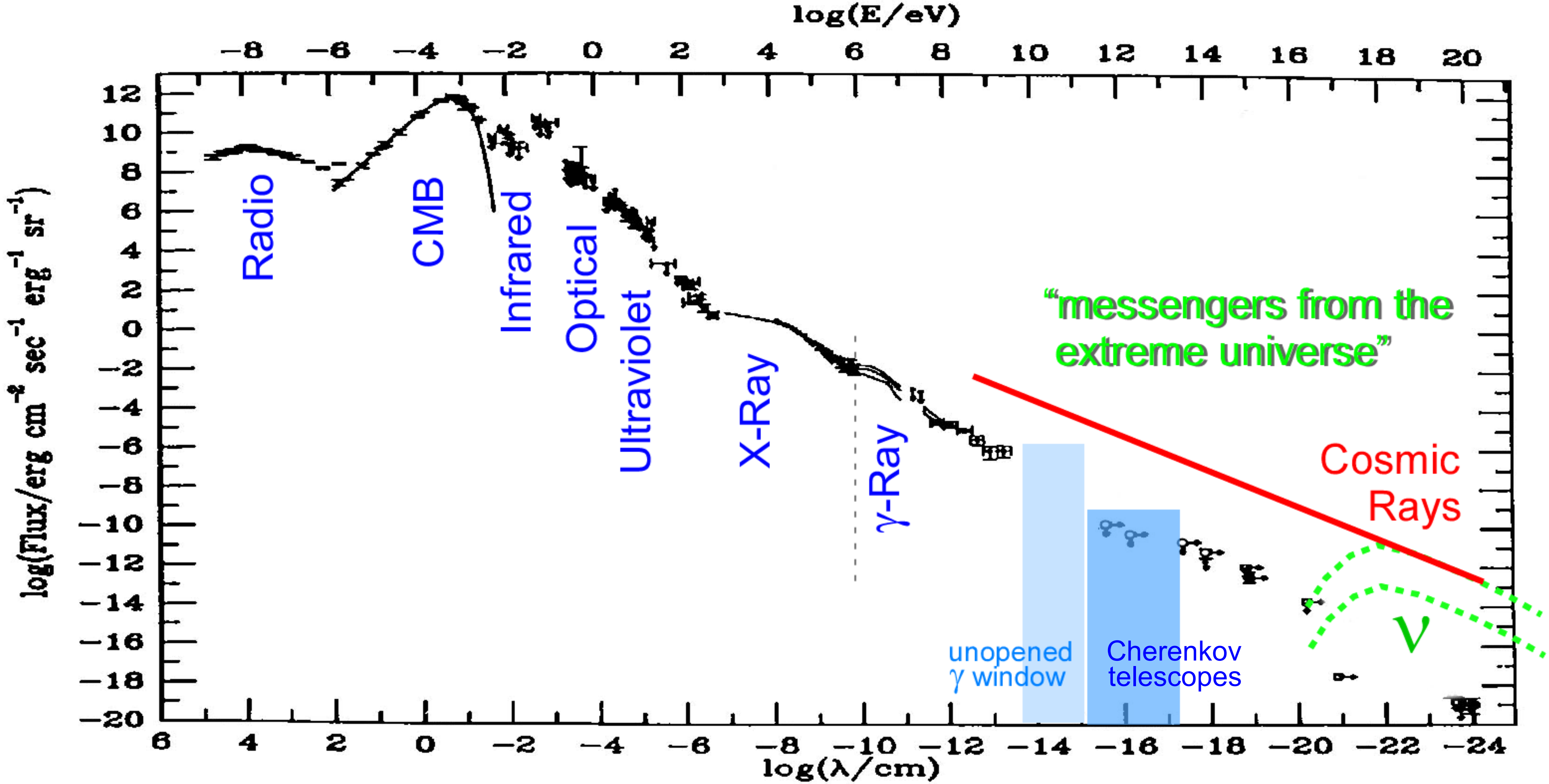
Spectrum ? Composition ?
Identity ? Origin ? Acceleration ?



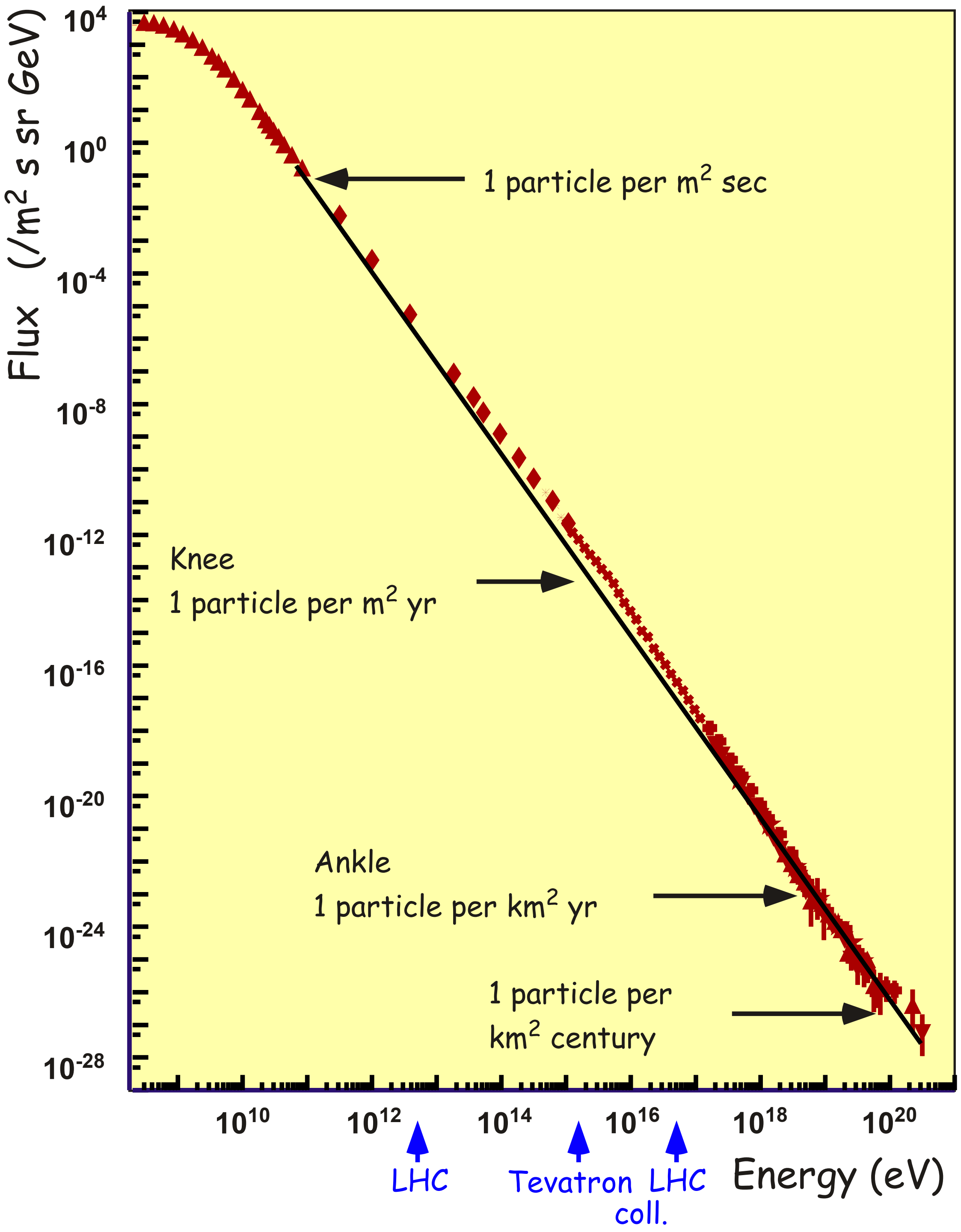
Cosmic rays, gammas and neutrinos are linked.

So far only CRs are detected at $E > 10^{14}$ eV.

Universal Photon Spectrum



Flux of cosmic rays



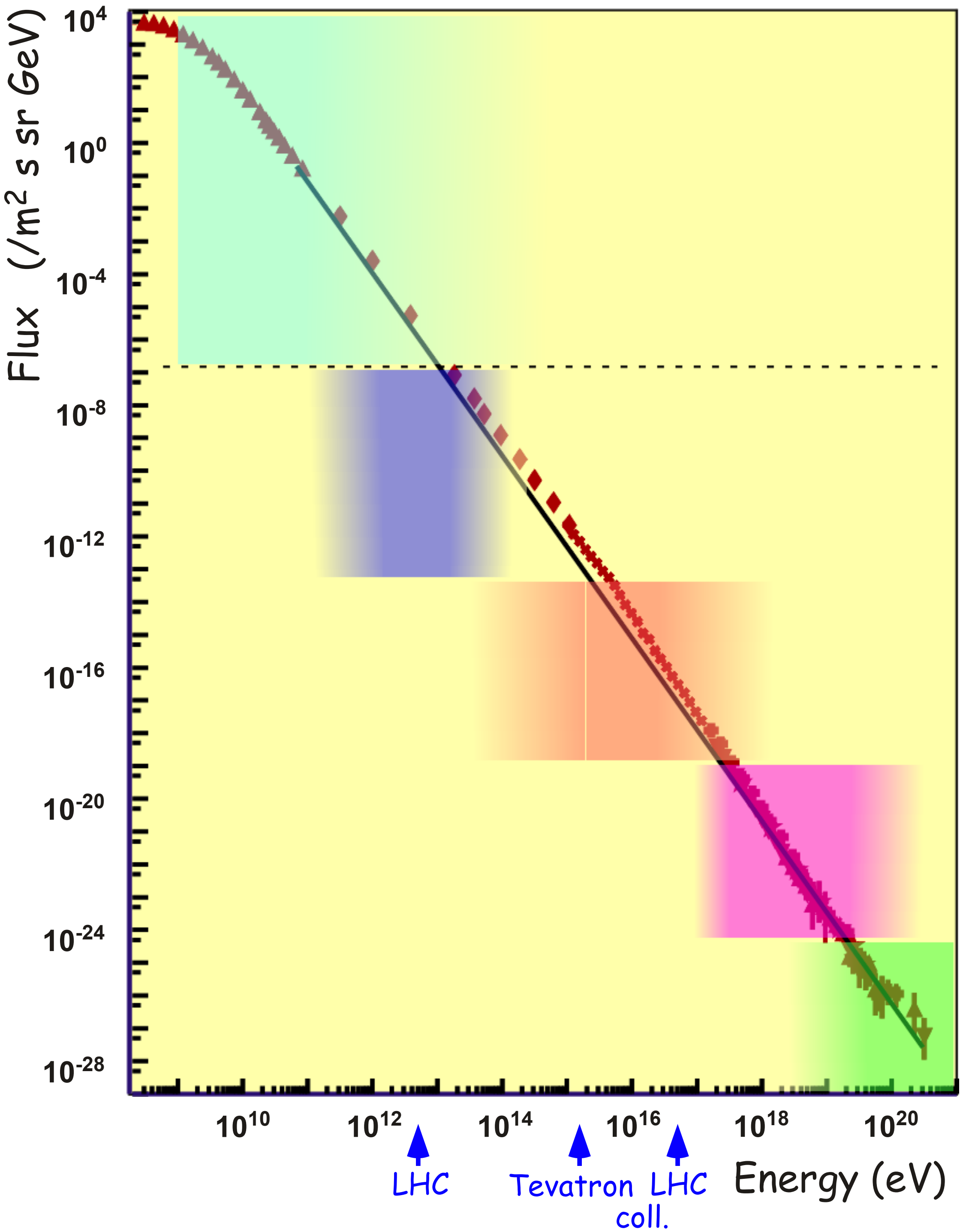
11 orders of magnitude in energy,
32 in flux !!!!

Power law with almost no structure.
(makes it difficult to interpret)

Highest energy events:

AGASA ~3.3 x 10^{20} eV
Fly's Eye ~3 x 10^{20} eV

One detector setup can hardly span more than ~2 decades in energy, i.e. it is difficult to see the "greater picture".



Direct Measurements:

balloon & satellite experiments
particle identification,
elements, isotopes

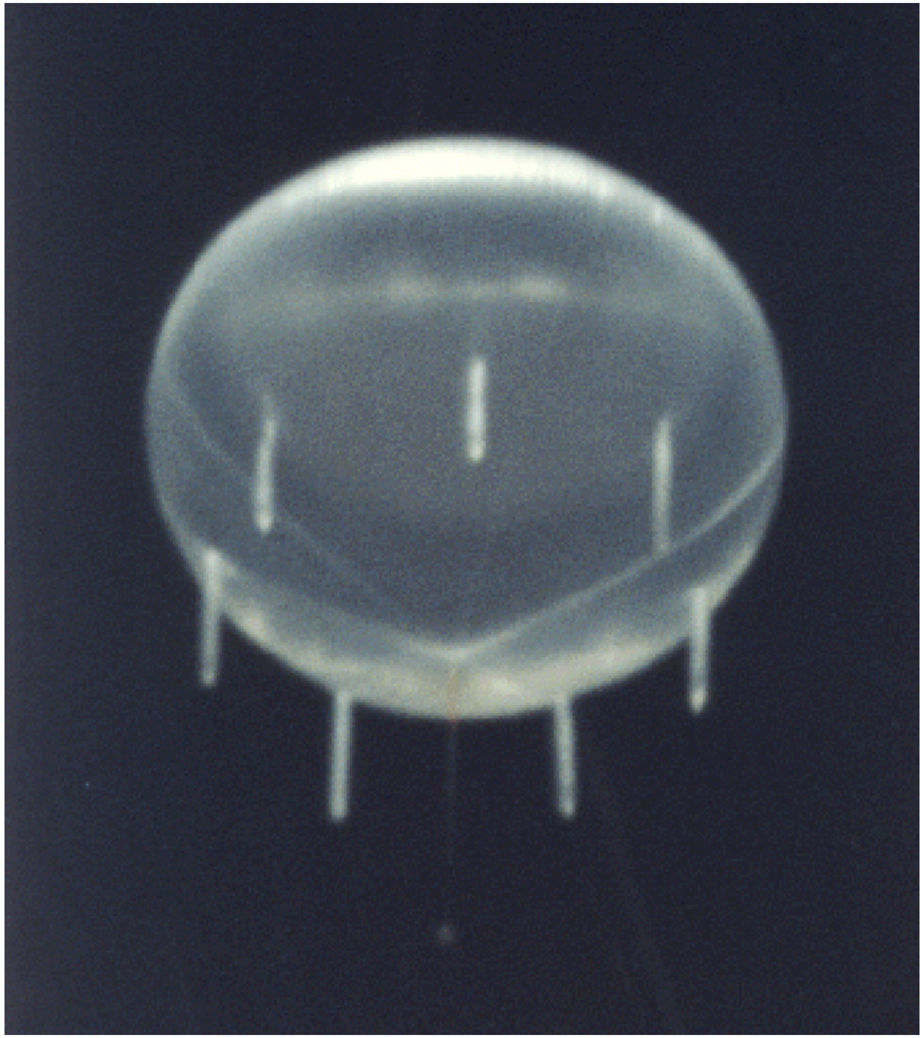
Air Shower Experiments:

MAGIC, HESS, VERITAS, ...

KASCADE, KASCADE-GRANDE

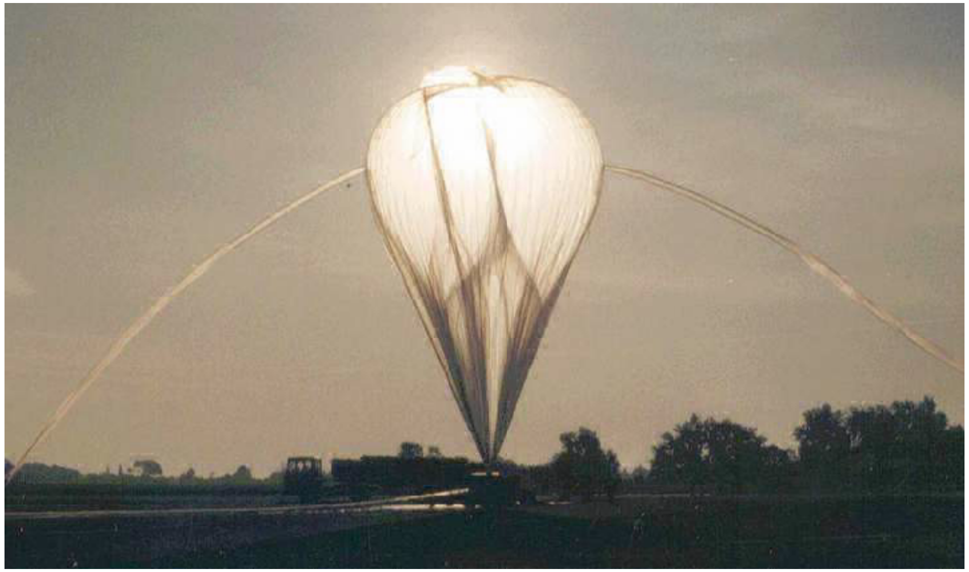
Telescope Array

HIRES
AGASA
Auger
EUSO / OWL



Scientific Ballooning:

balloon:	10^6 m^3 filled with He
payload:	up to 3500 kg,
height:	35 km
flight time:	few days, soon 100 days ?



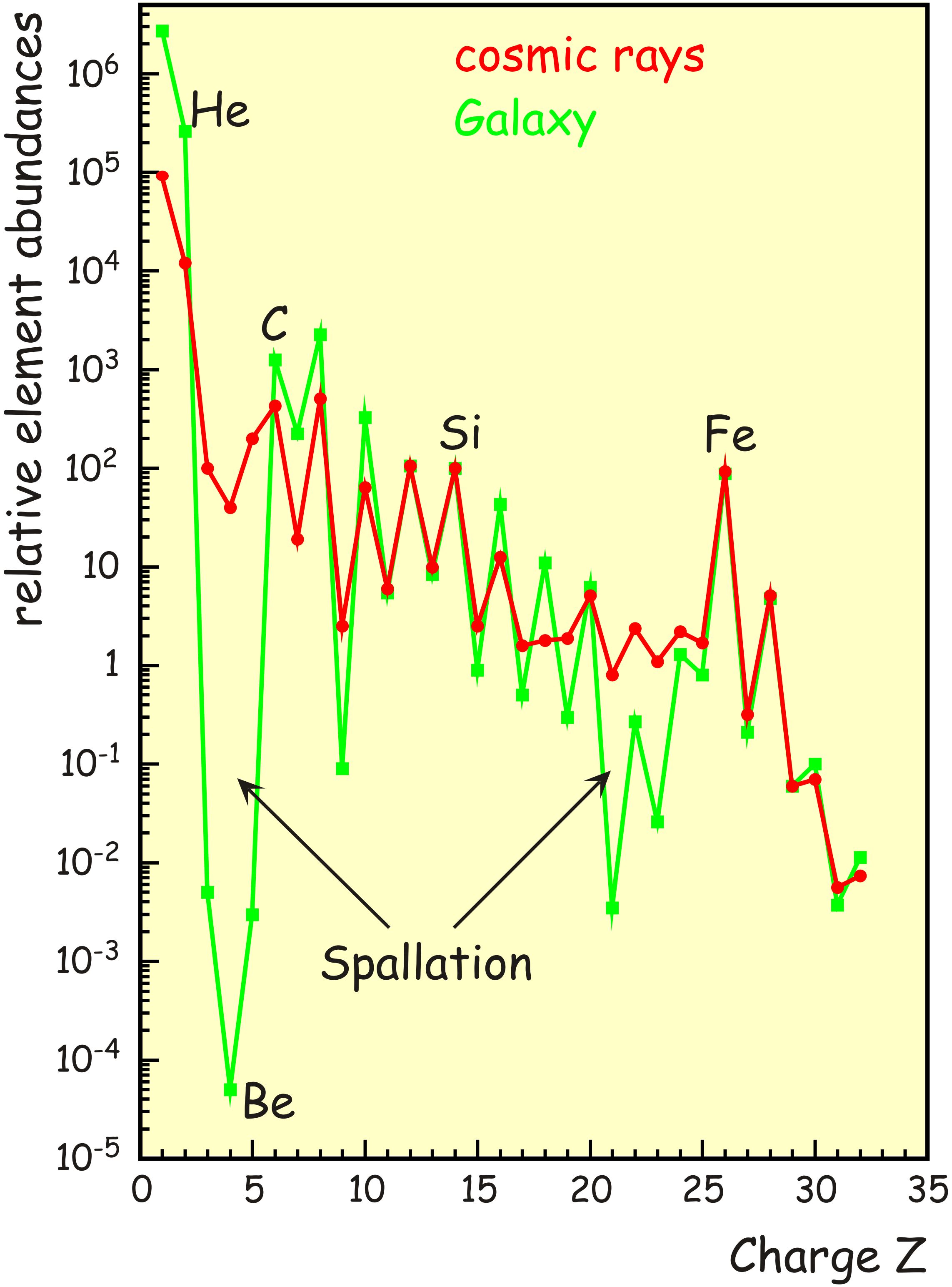
Mass composition
(GeV range)

element and isotope composition well known (< GeV)

89% p, 9% He, 2% other nuclei
<1% electrons
"CRs are star matter"

secondary/primary nuclei:
~ 10 g/cm^2

unstable/stable secondaries:
~10^7 years
(decreases with ~$E^{-0.6}$)



Result: (... the current paradigm)

Fermi Acceleration (1st order) in shock fronts

$$dN/dE \sim E^{-2.1} \cdot E^{-0.6} \sim E^{-2.7}$$

in sources ($E^{-2.1}$)

residence time in Galaxy ($E^{-0.6}$)

measured ($E^{-2.7}$)

prime candidates: SNR (up to ~10^{14} eV)

frequent & powerful enough to account for observed CR density

low-energy CRs are galactic,

diffusing in gal. magnetic field

direct evidence?

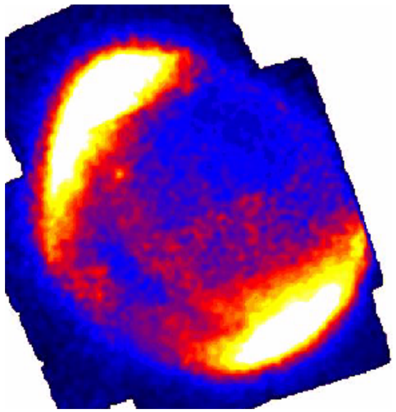
synchrotron & IC radiation from relativistic electrons

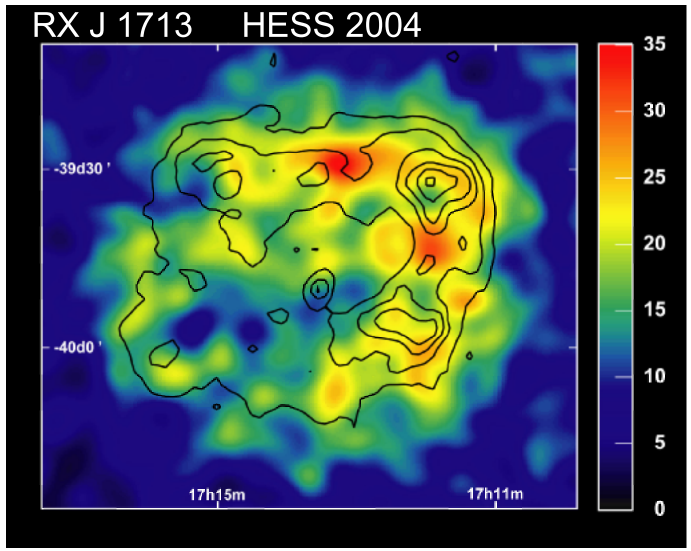
Not much evidence for CR acceleration yet.

(hope for γ-ray experiments)

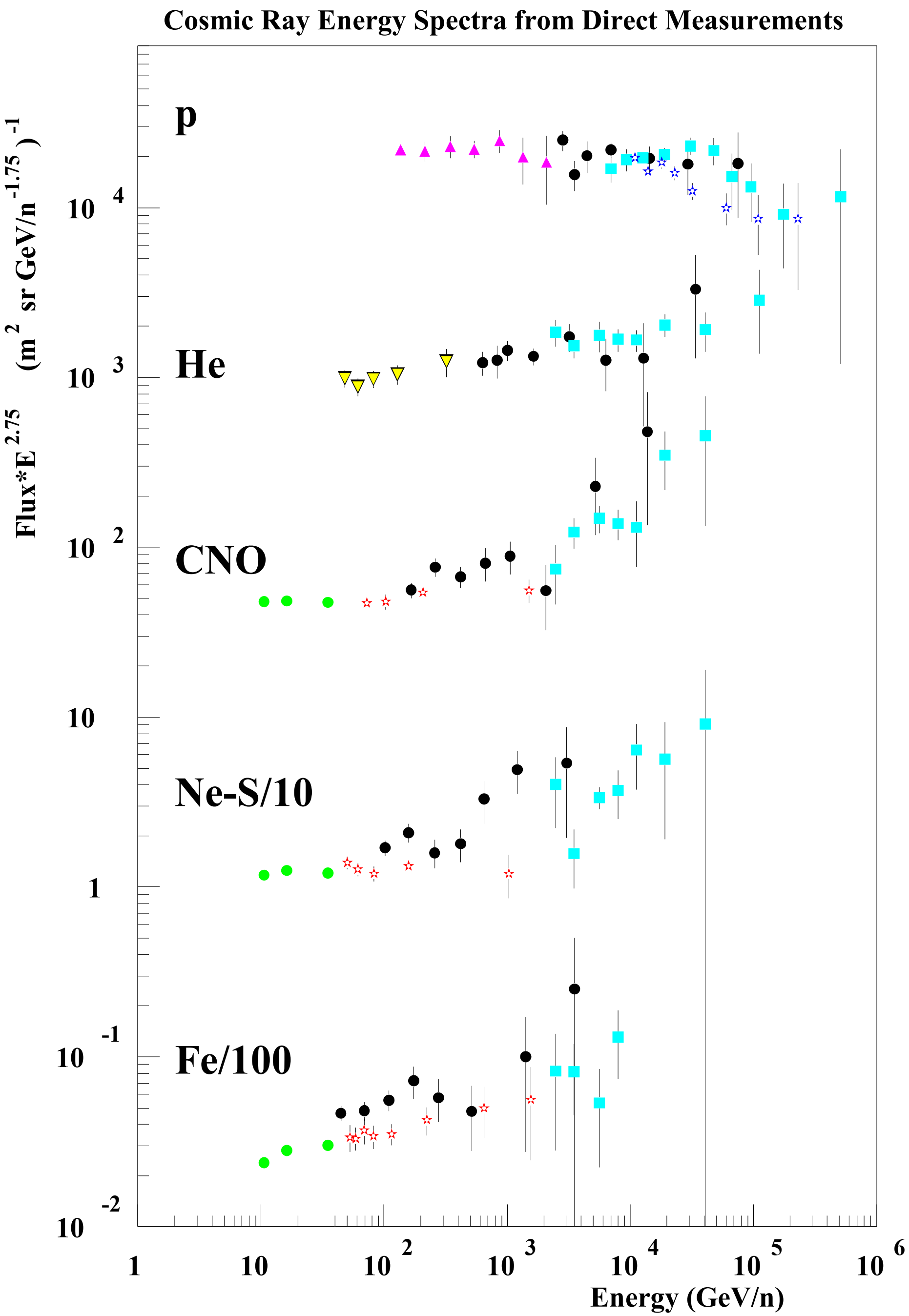

SN1006
CHANDRA (2003)

SN1006
ASCA (1995)



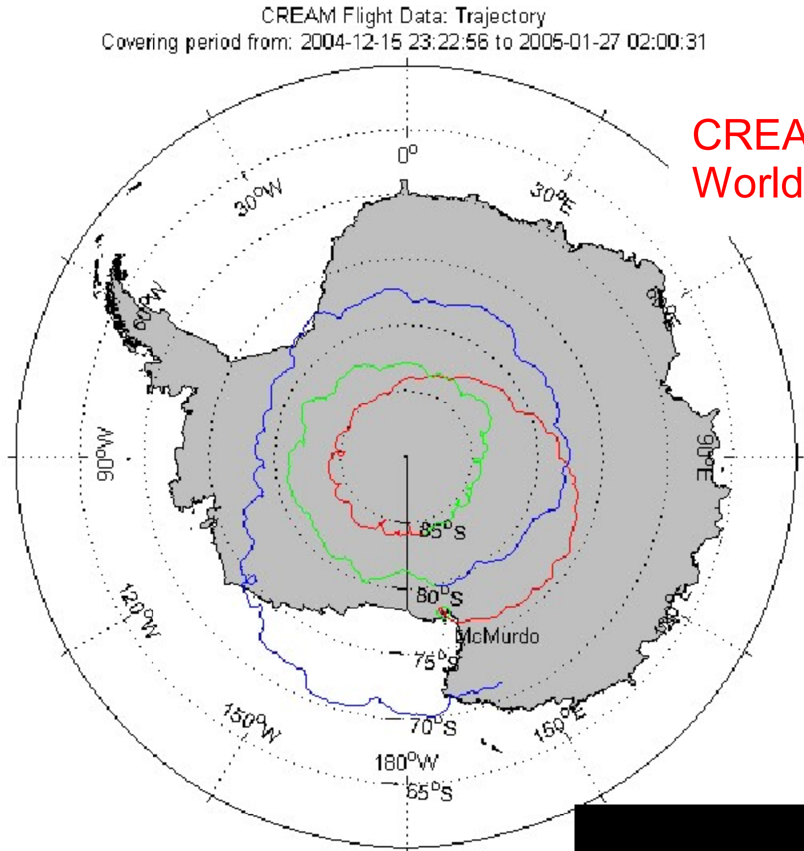


various satellite and balloon experiments...



Extension to higher energies?

- larger light-weight detectors
- longer flight times

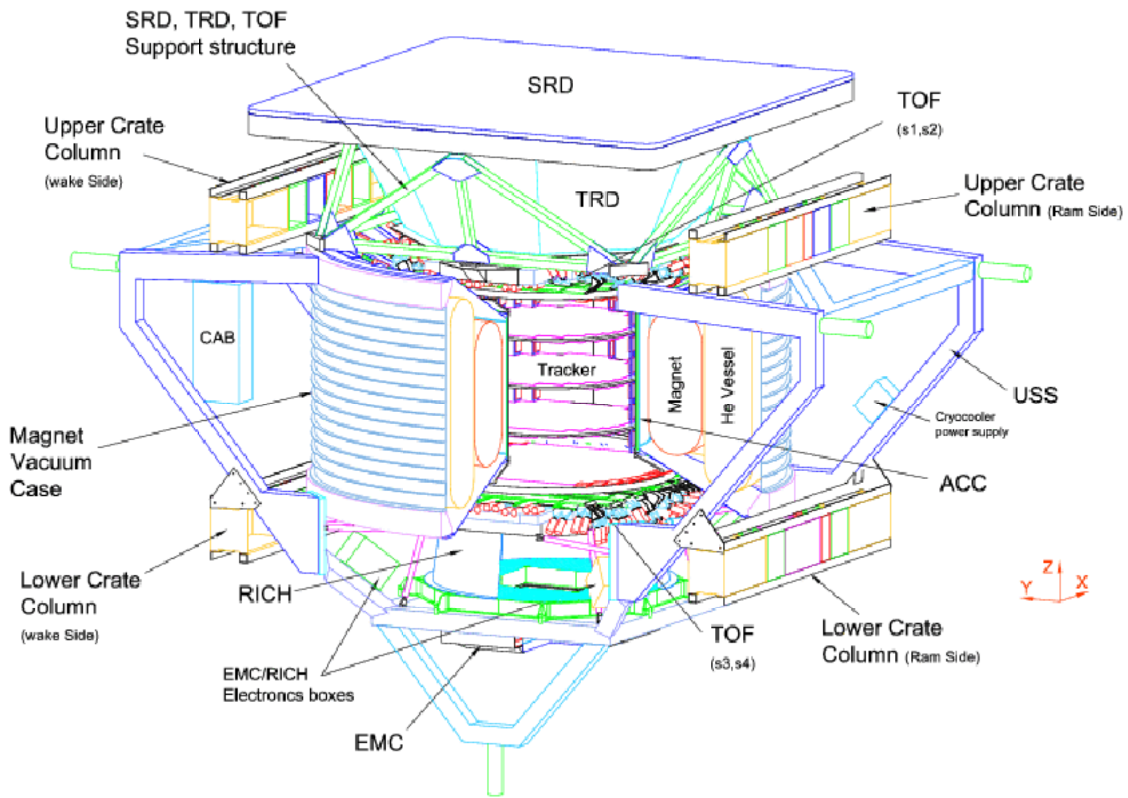


CREAM Experiment:
World record: 42 days
Jan 2005

(near) future:
Ultra-long duration flights
(pressurized balloons)
> 100 days.

Satellites & Space Station ?

e.g. AMS



measurement times ~ 1-3 years
detector size ~ as for balloon experiment

but ~100x more expensive...

Indirect Measurements: Air Showers

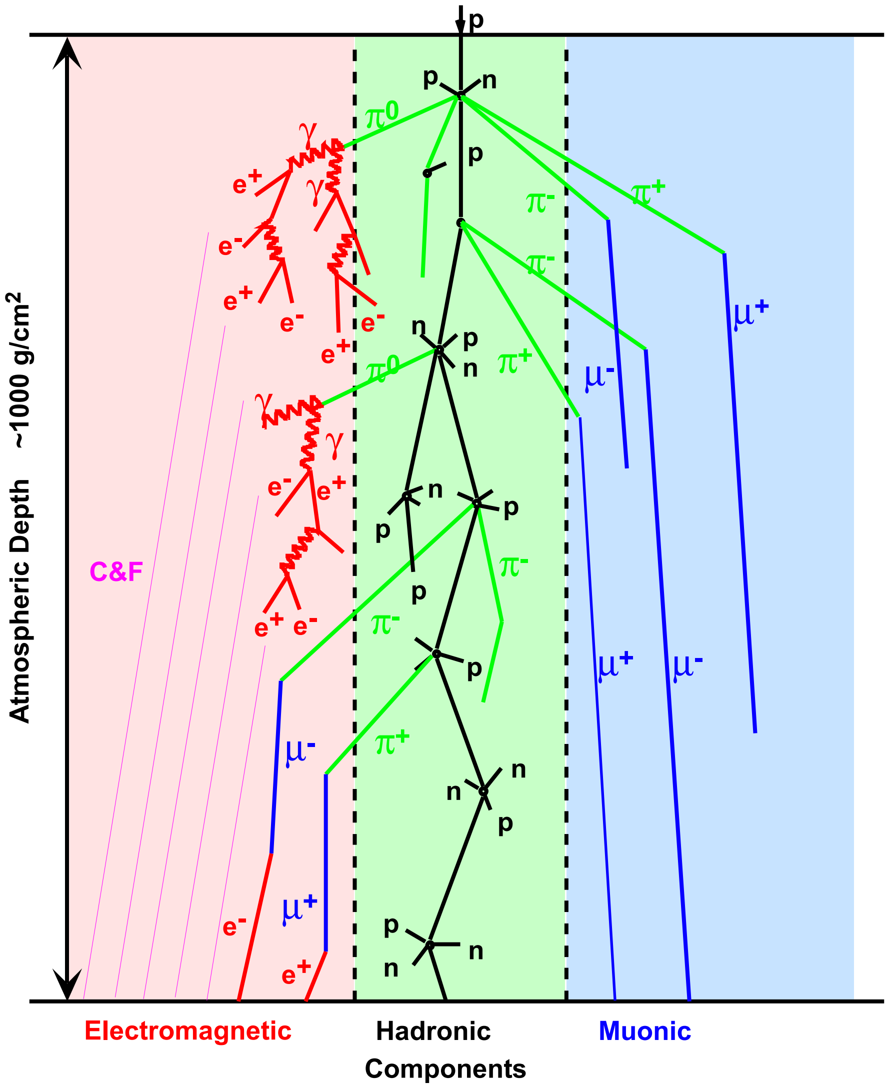
steepy falling spectrum: 10 x in energy   / 500 in flux

Higher energies require very large detectors:

Instrument large natural absorbers
(e.g. atmosphere, water, ice)

Deduce properties of primary CRs
from the shape and particle content of
the shower of secondaries produced.

Schematic Shower Development



Fluorescence & (isotropic)
Cherenkov-Light (forward peaked)

p, n, π : near shower axis

μ**, e,** γ : widely spread

e, γ **:** from π^0, μ decays ~ 10 MeV

μ : from $\pi^{\pm}$, K, ... decays ~ 1 GeV

$N_{e,\gamma}$ **:** N_{μ} ~ 10 ... 100 varying with core distance, energy, mass, Θ, ...

Details depend on:
- interaction cross-sections,
- hadronic and el.mag. particle production,
- decays, transport, ...

at energies well above man-made accelerators.

Complex interplay with many correlations
requires MC simulations

Detection Techniques

- Particles at ground level

large detector arrays (scintillators, wire chambers, calorimeters...)

small sample of secondary particles (e, μ, γ, h, $\rho(r)$, t, θ, ϕ, ...)

e.g.

	area	coverage
Kascade	0.04 km^2	1.5×10^{-2}
Haverah Park	12 km^2	
Yakutsk	25 km^2	
AGASA	100 km^2	2.5×10^{-6}
Auger SD	3000 km^2	5.3×10^{-6}

100% duty cycle, relatively easy to operate

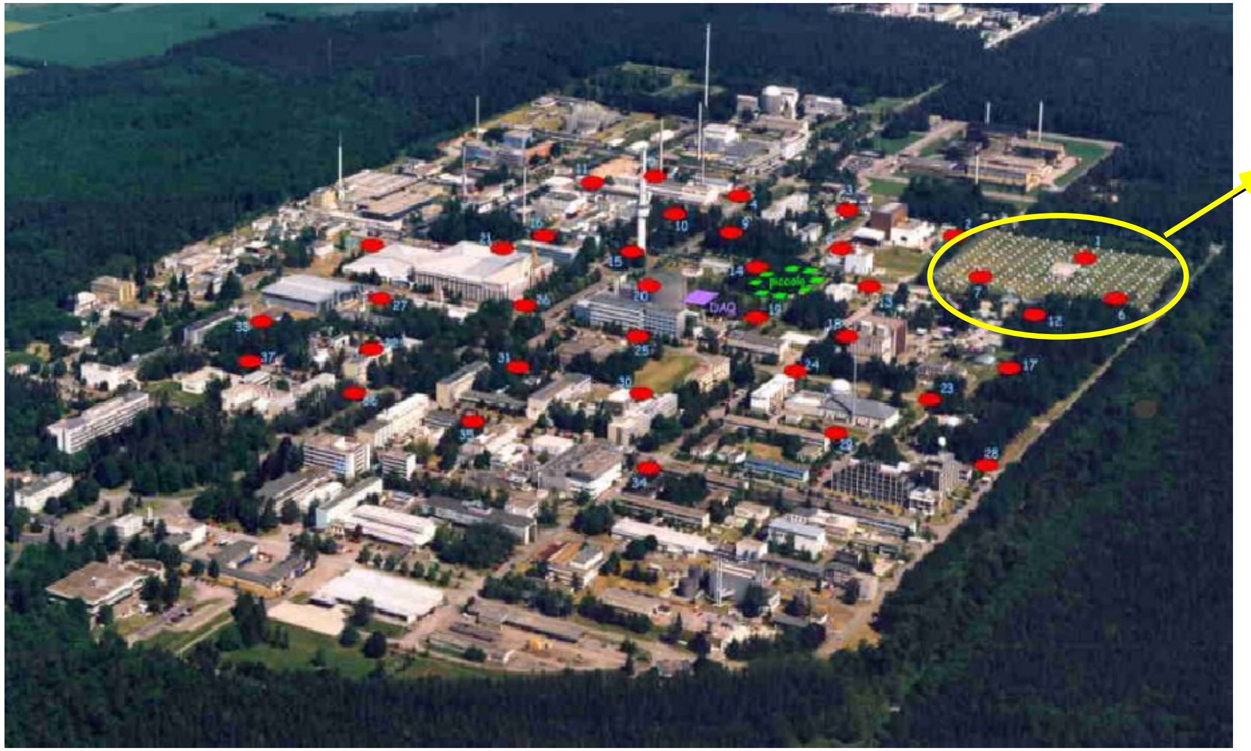
aperture = area of array (independent of energy)

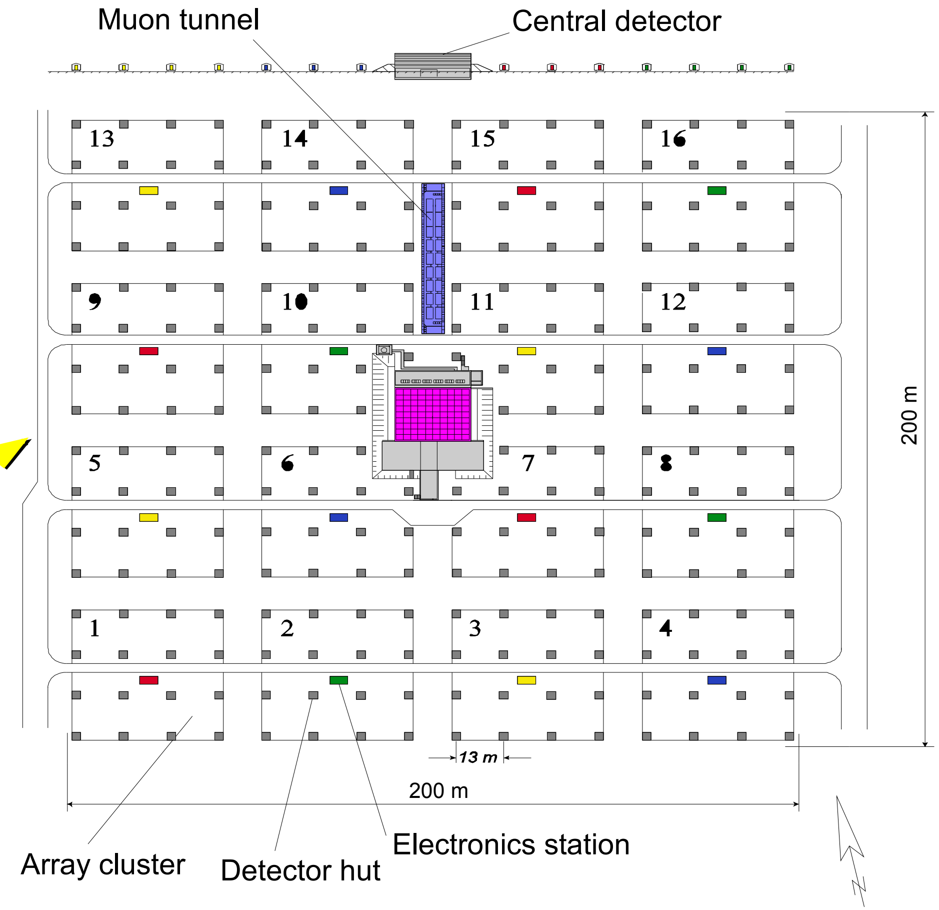
$\sigma(E)/E \sim 30\%$ but: primary energy / mass composition is model dependent

KASCADE & KASCADE GRANDE

$\sim 10^{14} - 10^{16}$ eV

$\sim 10^{15} - 10^{17}$ eV

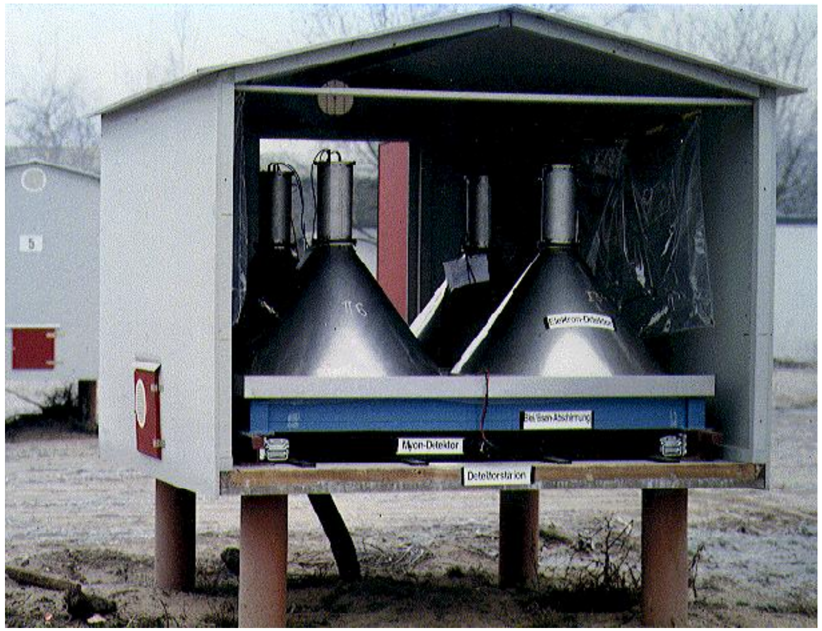




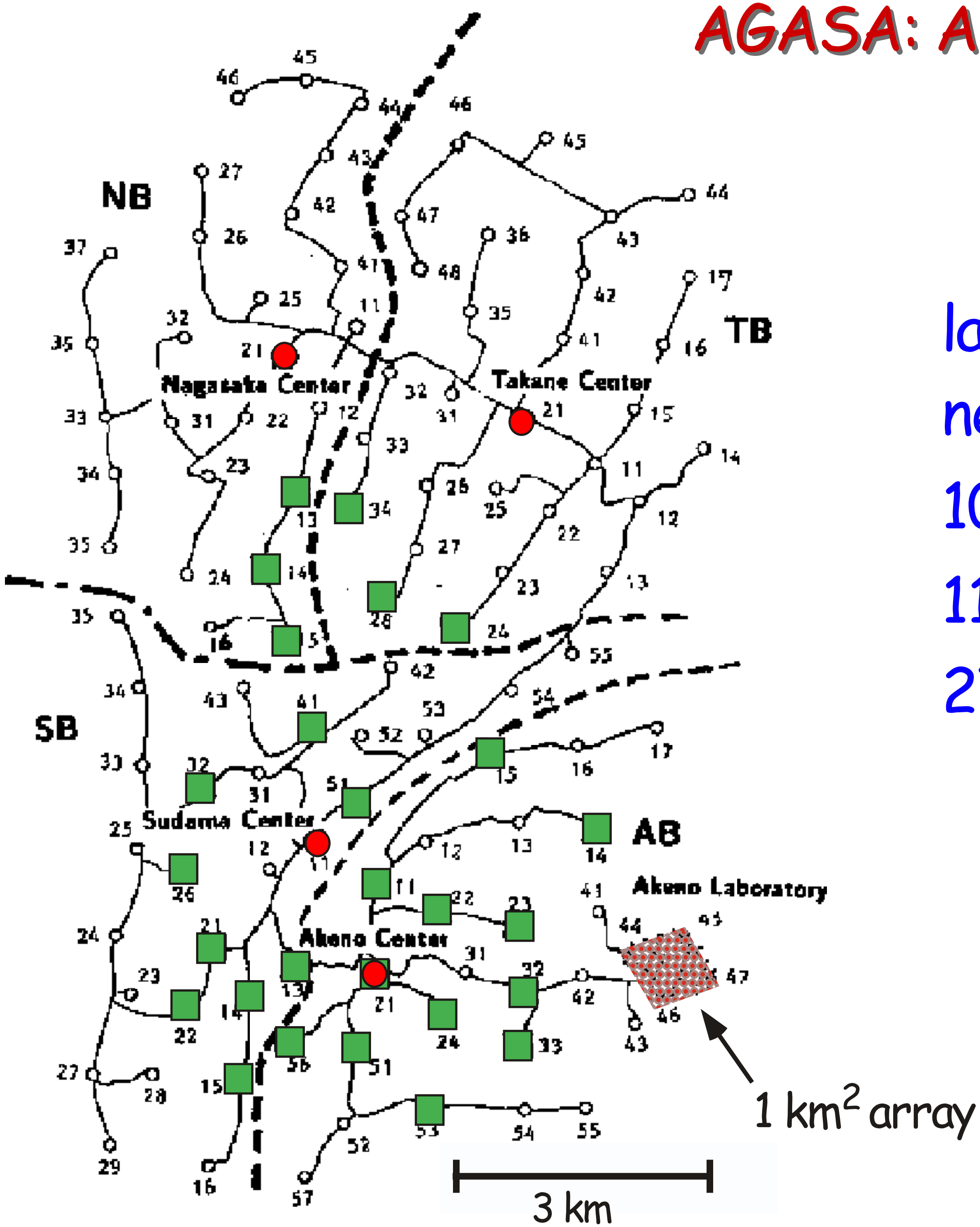
Total area of array determines
- the maximum energy (statistics)

Detector spacing determines
- low-energy threshold
- quality of the sampling

Limiting factor:
- the cost



AGASA: Akeno Giant Air Shower Array



largest array from 1993-2003

near Tokyo, Japan

100 km^2 area

111 x 2.2 m^2 scintillators (○)

27 μ detectors (■, E_μ > 0.5 GeV)

Detection Techniques II

- Fluorescence of N_2 in atmosphere

  calorimetric energy measurement as fct. of atmospheric depth

  $\sigma(E)/E \sim 20\ \%$

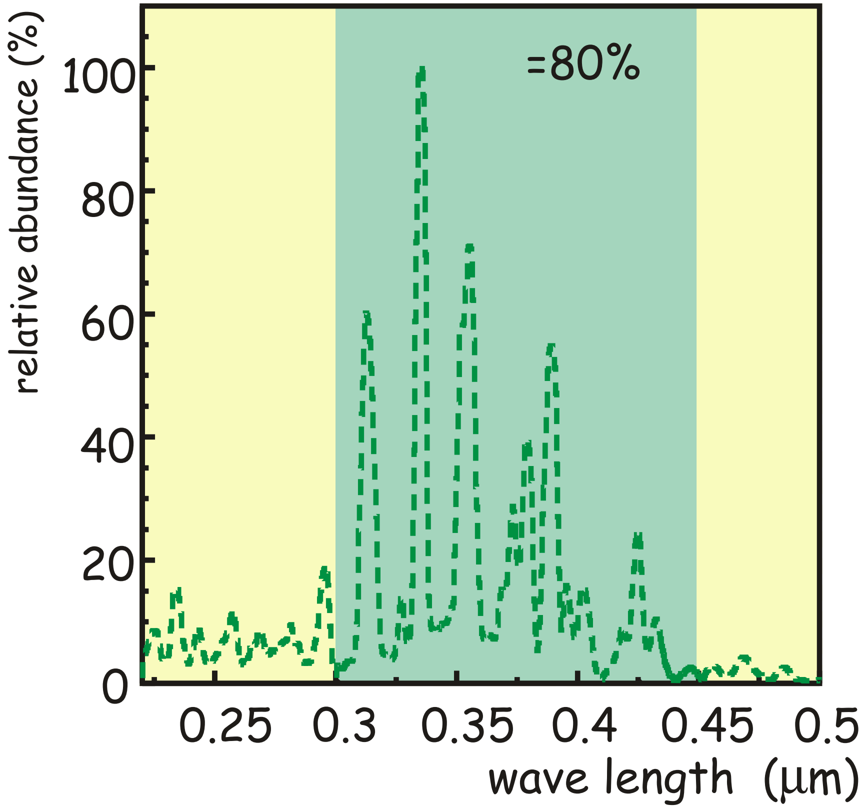
  works only for $E > 10^{17}$ eV, only in dark nights (10%)

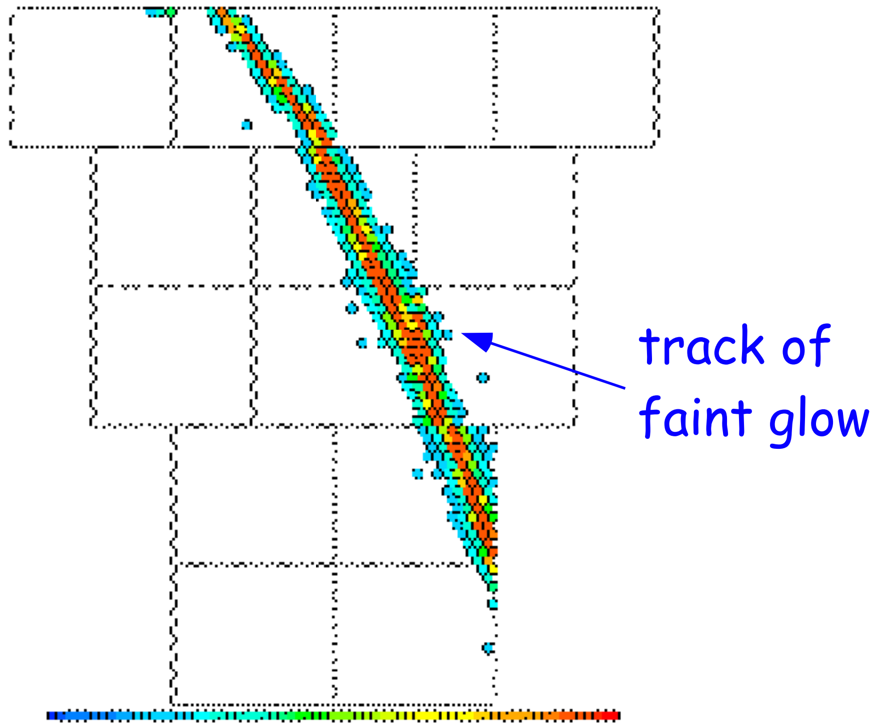
  requires good knowledge of atmospheric conditions

  aperture grows with energy, varies with atmosphere

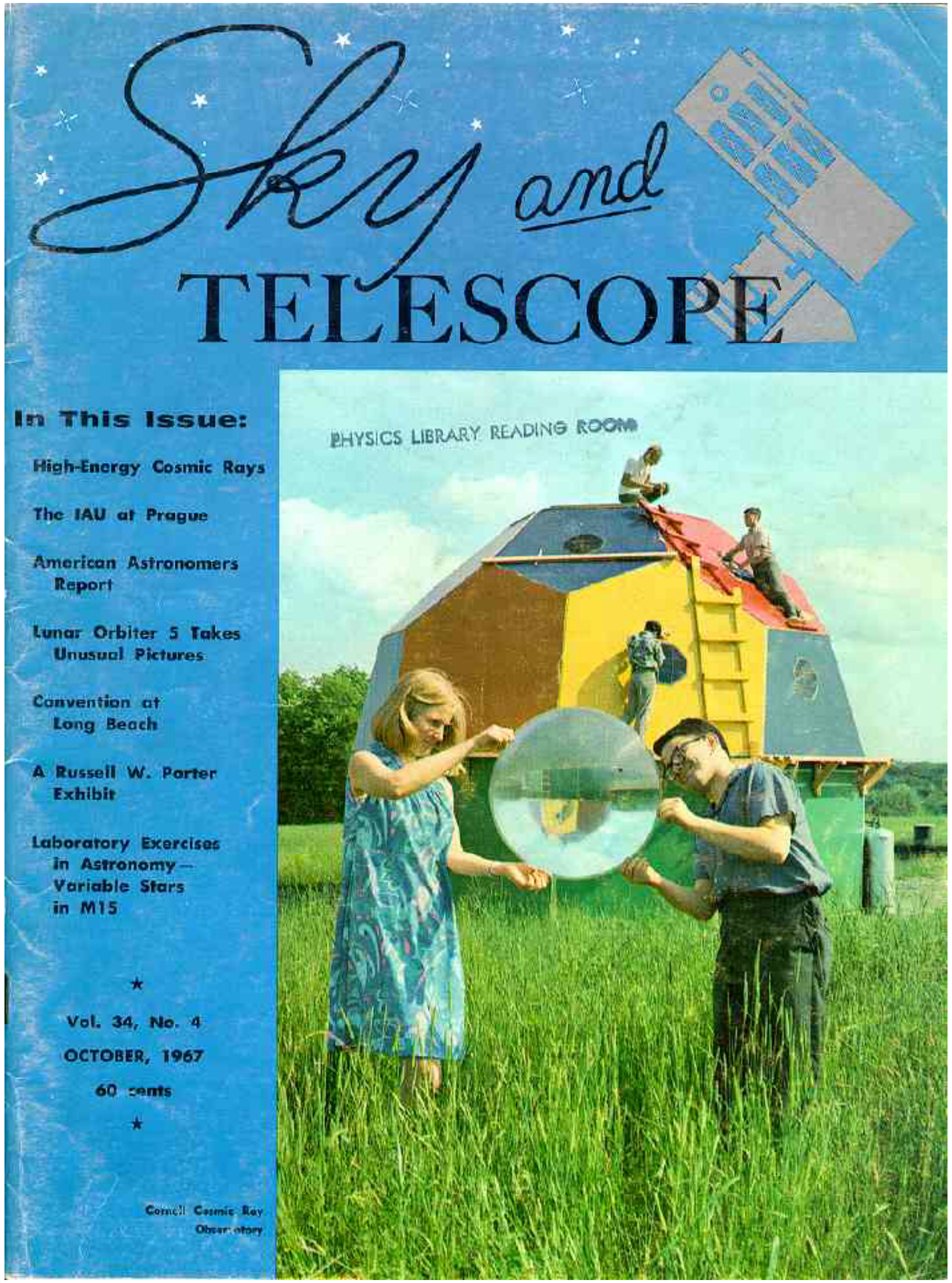
  e.g. Fly's Eye,
  High Resolution Fly's Eye (Utah)
  Telescope Array
  Auger FD

Fluorescence of N_2 und N_2^+





C.f. 100 Watt bulb (UV), moving with speed of light, in 20-40 km distance, through the atmosphere.



The First Fluorescence Detector:

Cornell University

K. Greisen, 1967

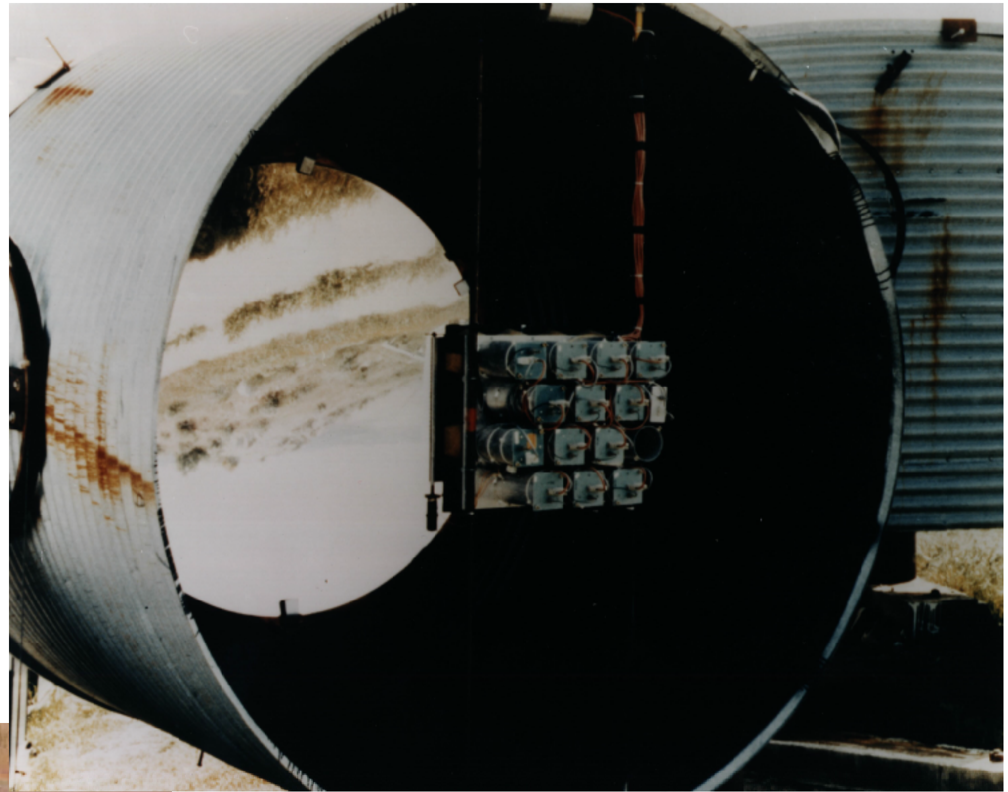
10 x 50 PMTs

$6^o \times 6^o$ pixels

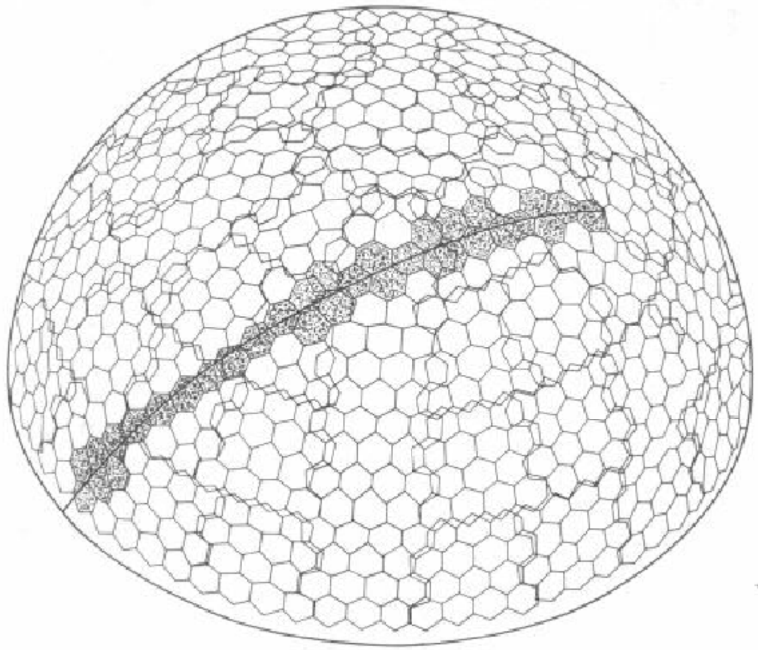
0.1 m^2 Fresnel lenses

(not successful)

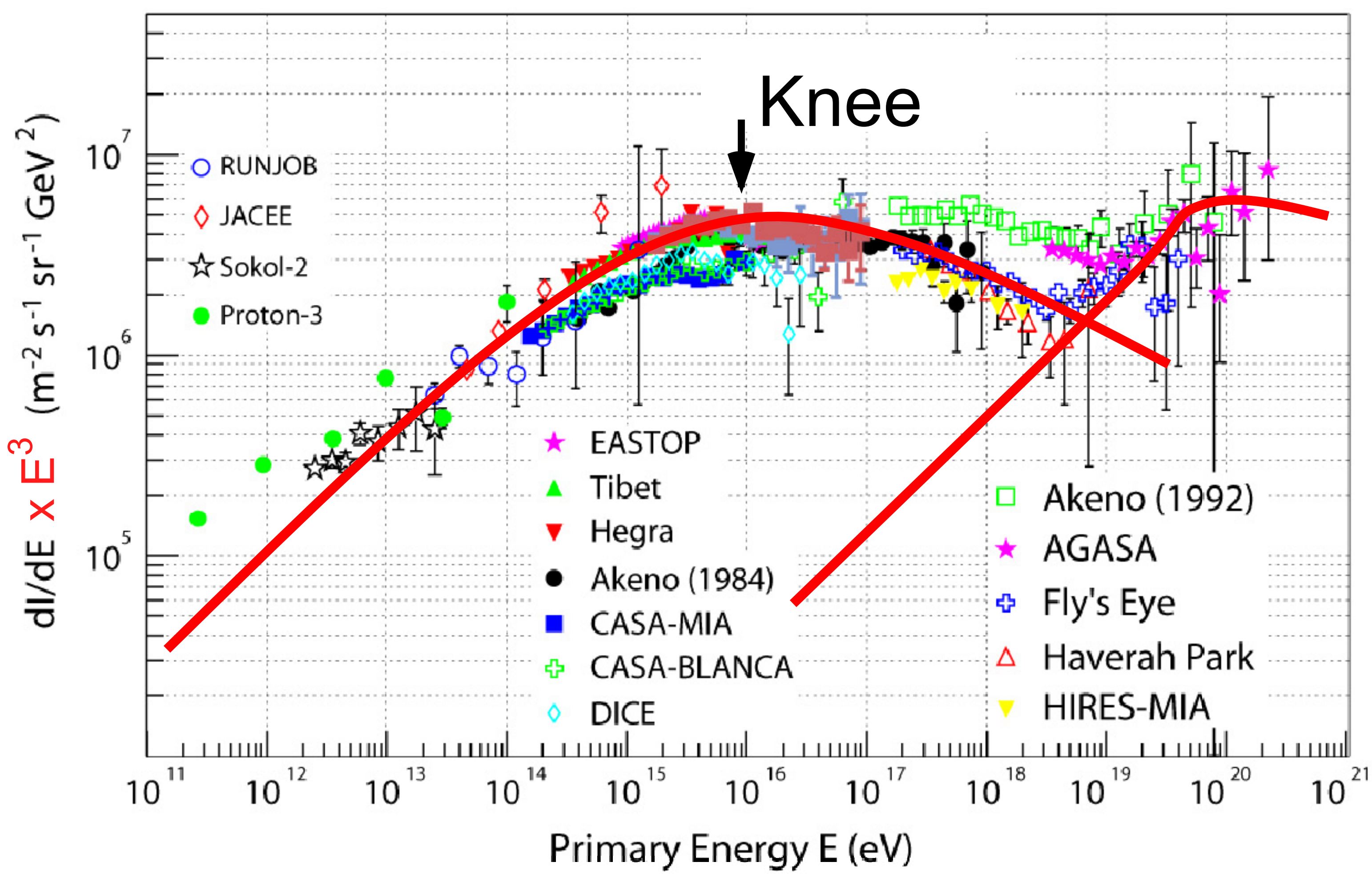
Fly's Eye (Utah)



2 stations, 3.4 km apart
101 mirrors, 1.5 m Ø
12-14 pixels each (PMTs)
5^o field of view per pixel
operational: 1980-1993



Around the "Knee" in the spectrum



discovered in 1959
by Khristiansen et al.

Is it property of the source? e.g. maximum energy of accelerator? $E_{max} \sim Z$

Is it the propagation? e.g. leakage from galaxy? $E_{max} \sim Z$

Is it the particle physics? e.g. had. interaction in atmosphere? $E_{max} \sim A$

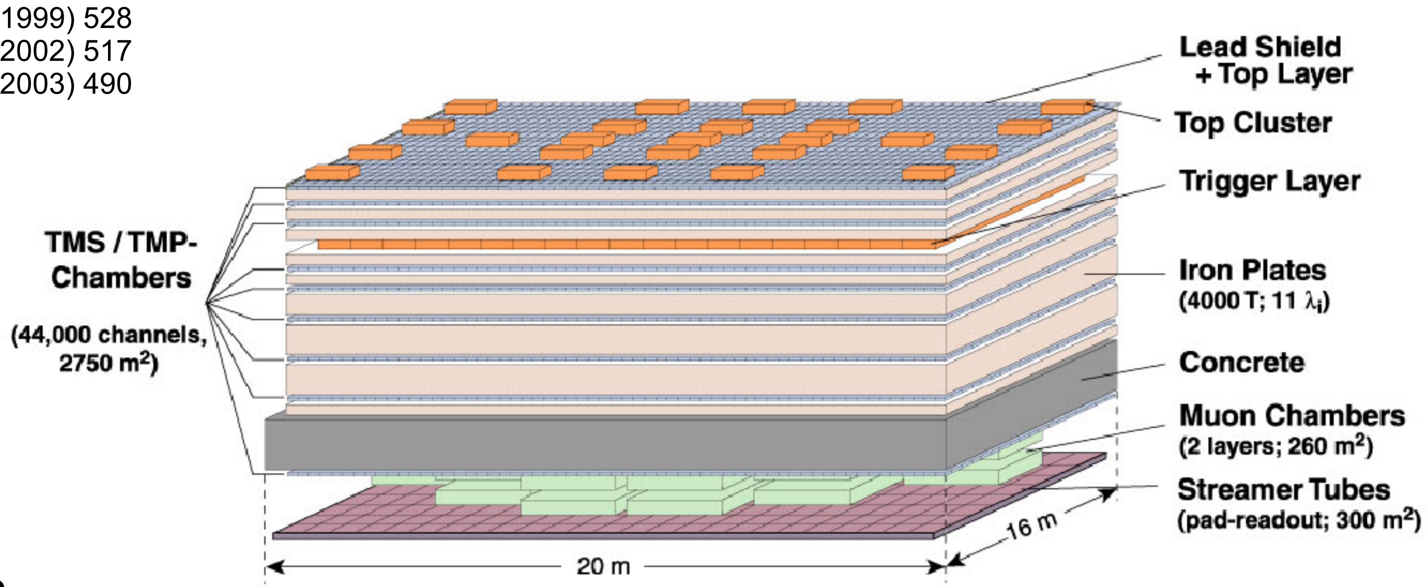
Change of mass composition?

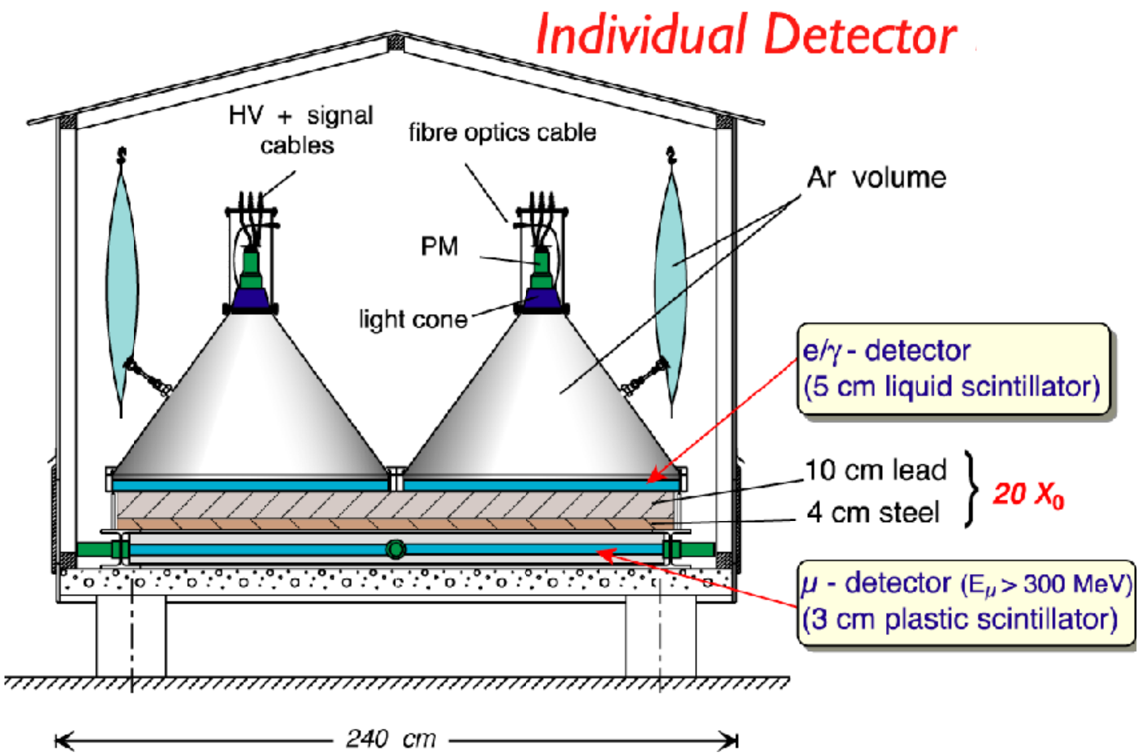
KASCADE:

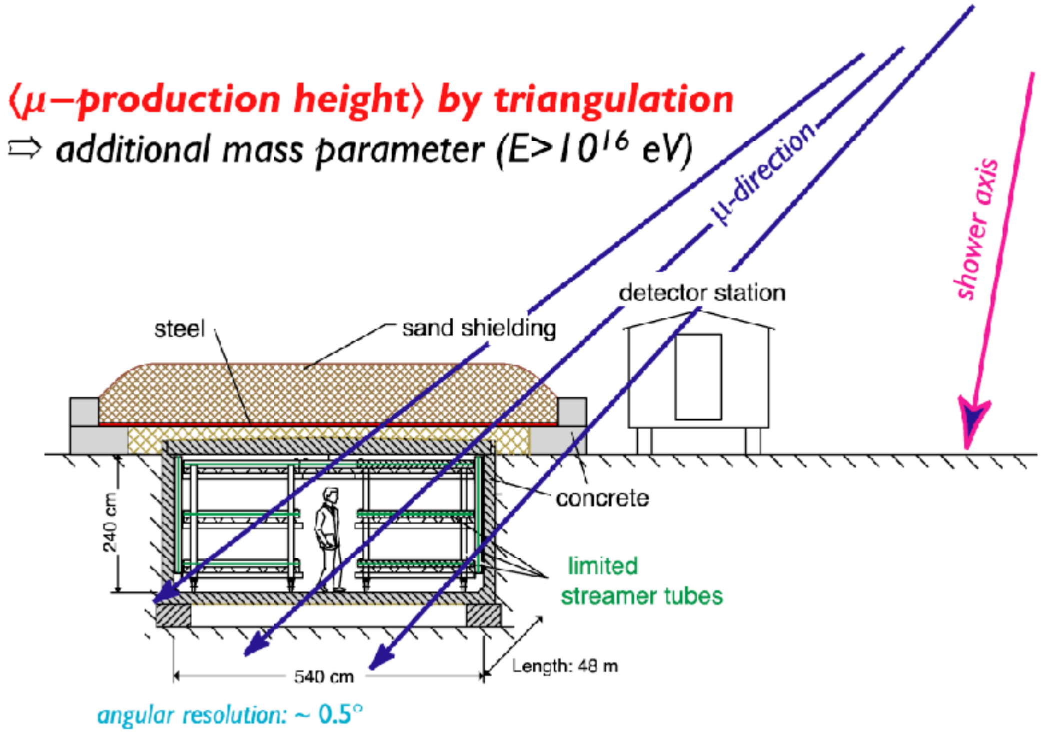
NIM A427 (1999) 528
NIM A448 (2002) 517
NIM A513 (2003) 490

high-quality
multi-parameter
measurement

good sensitivity,
control of systematics.



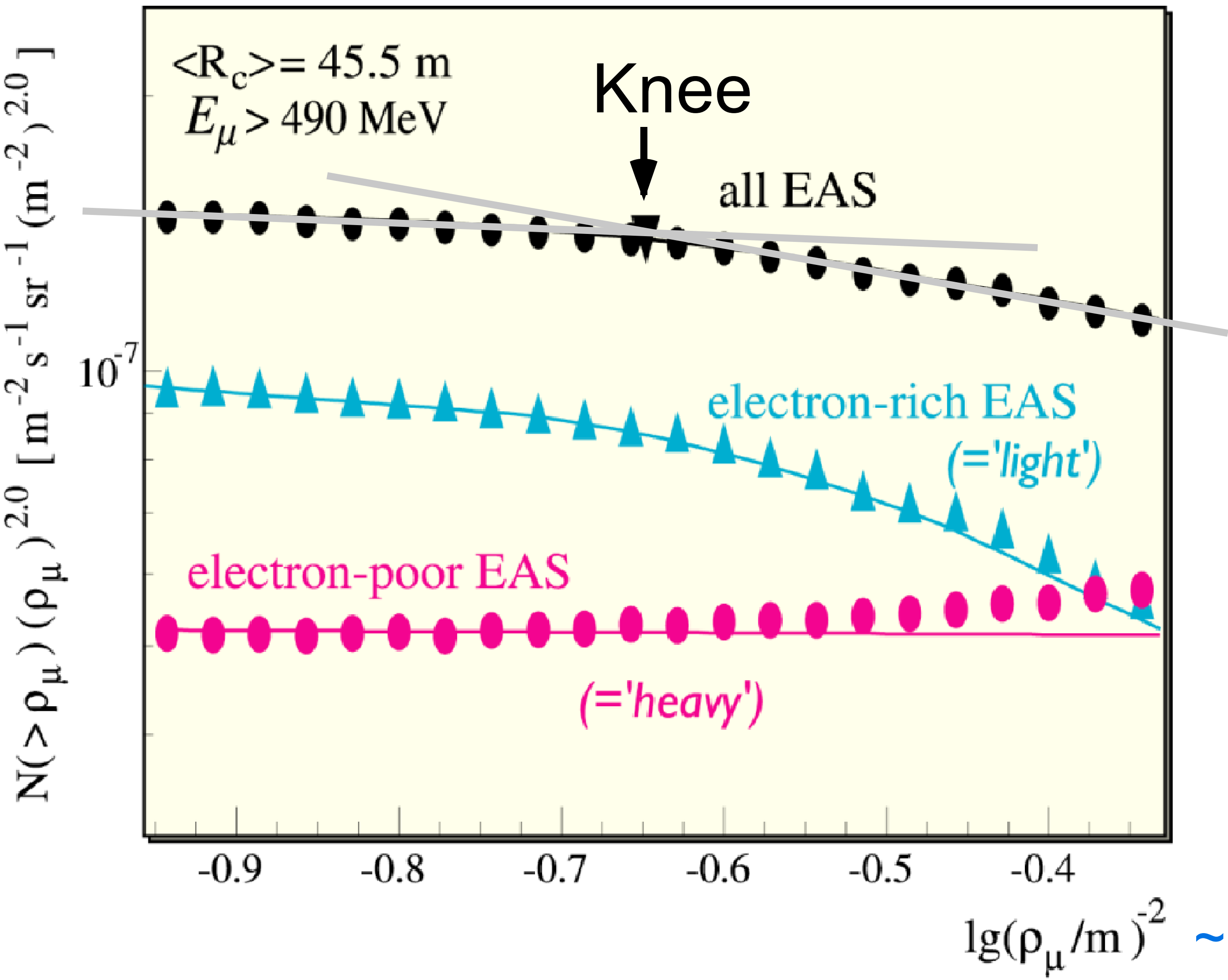




Muon density spectra

model-independent

divide data in electron poor (i.e. heavy) and
electron rich (i.e. light)



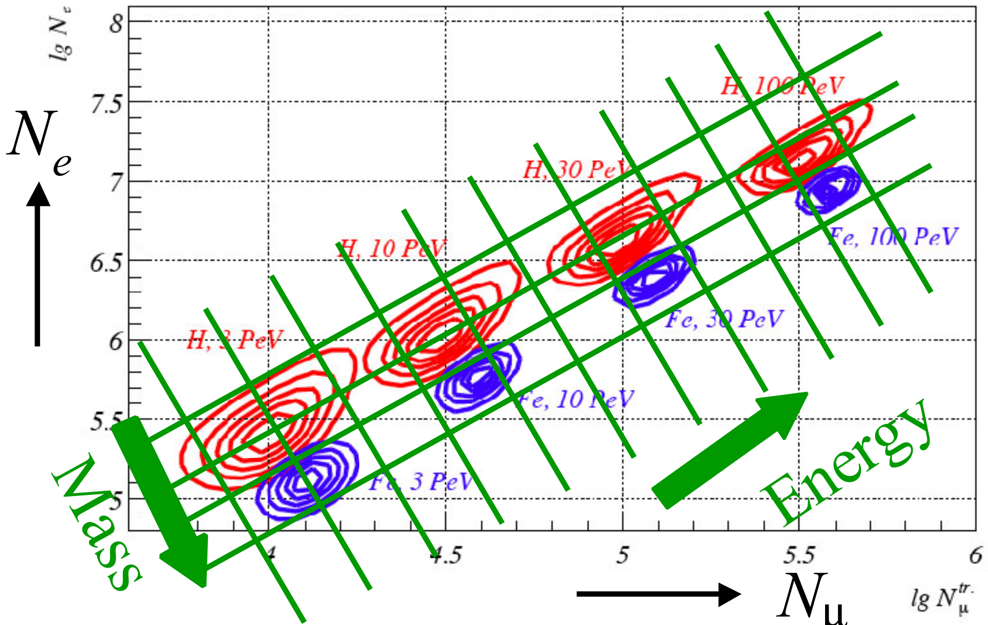
~ Energy

Knee is only visible in light component !

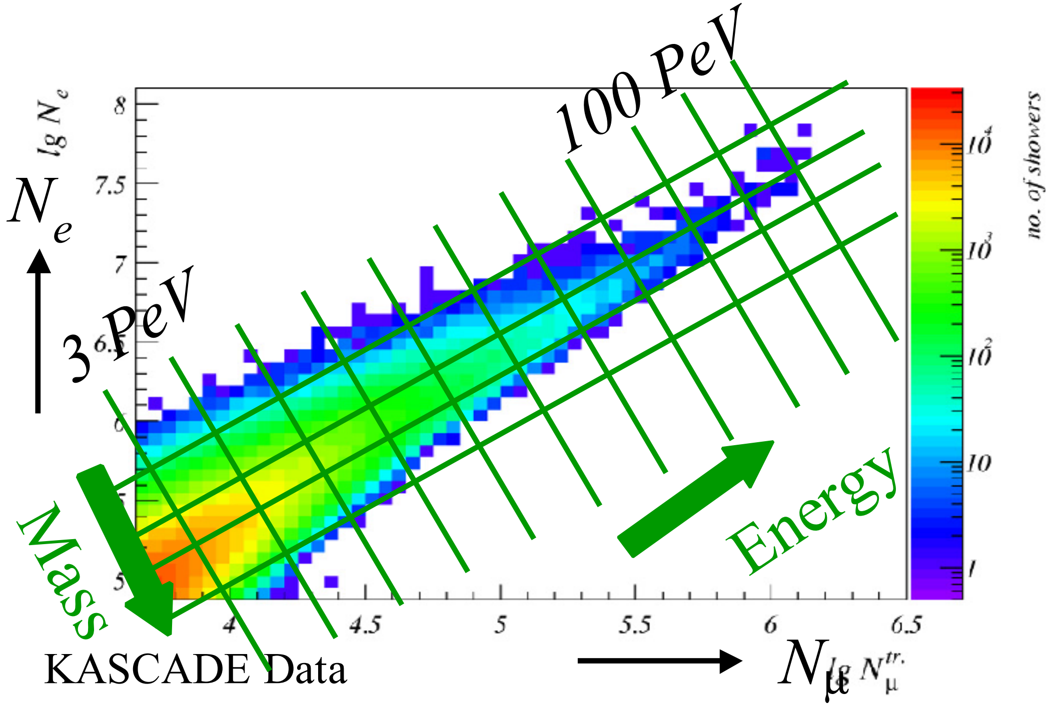
(in this energy range)

Astrop. Ph. 16 (2002) 373

N_μ vs N_e ⟷ Energy , Mass



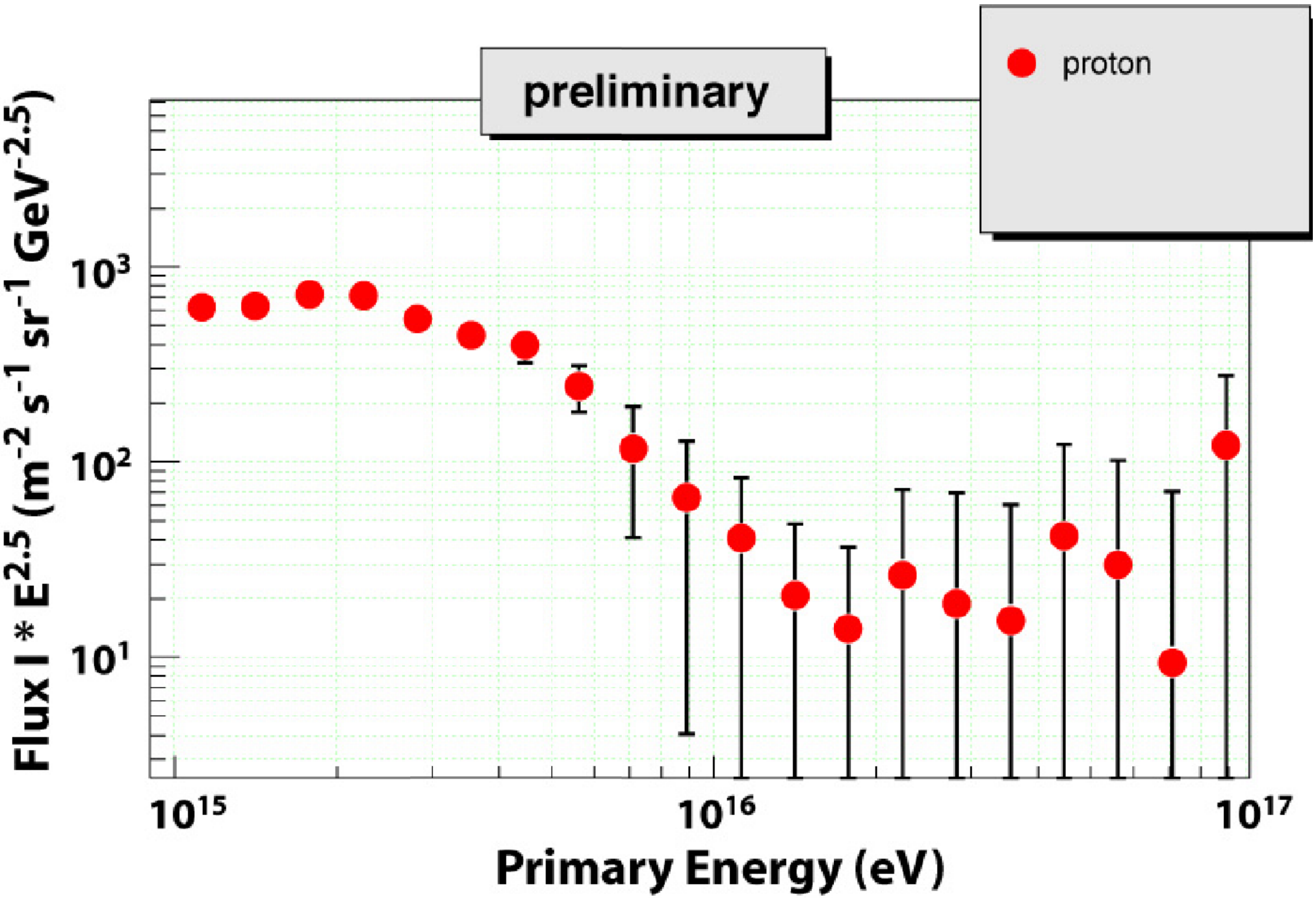
CORSIKA Simulations



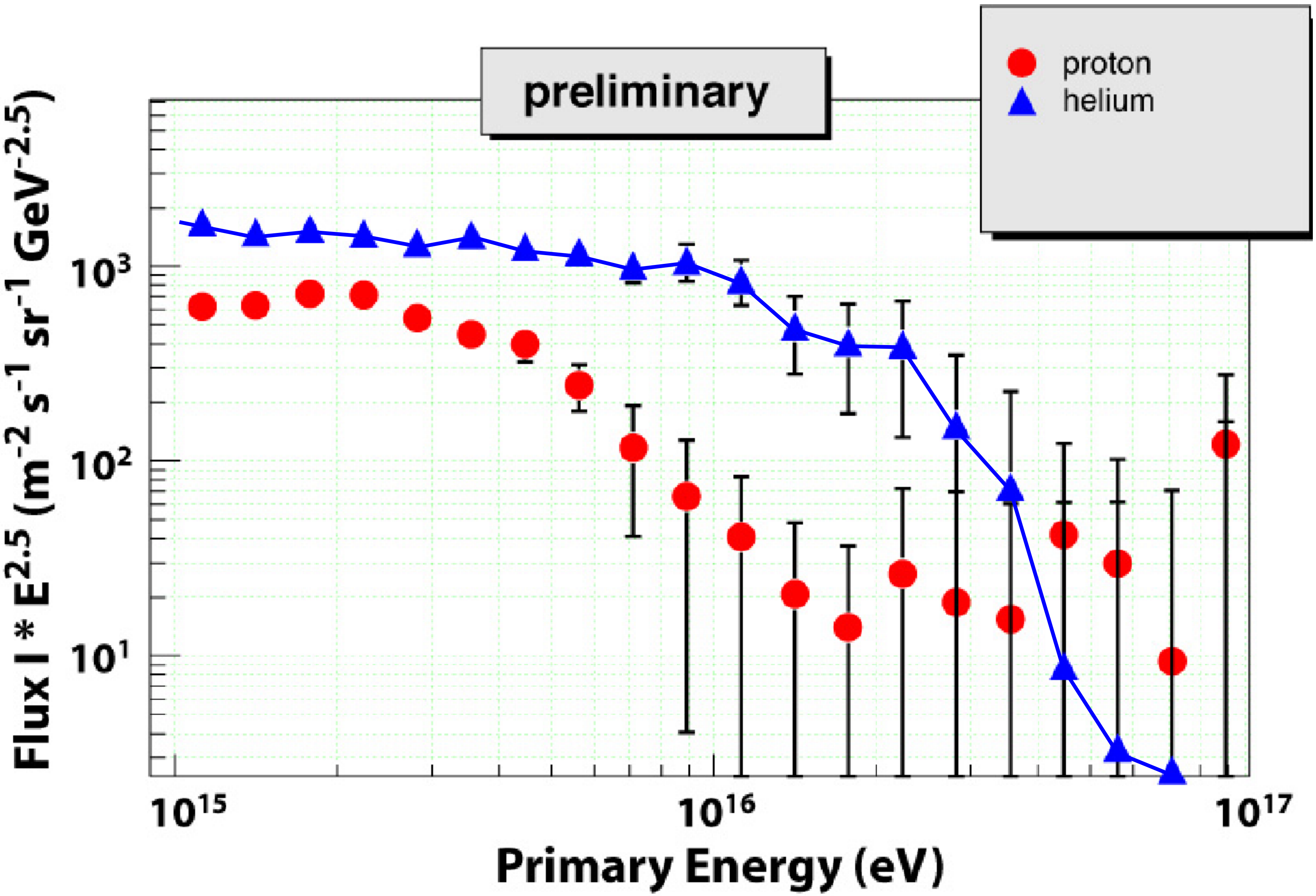
Data

$$\frac{dJ}{d\lg N_e\, d\lg N_\mu^{tr}} = \sum_A \int_{-\infty}^{+\infty} \frac{dJ_A}{d\lg E} p_A(\lg N_e, \lg N_\mu^{tr} \mid \lg E)\, d\lg E$$

set of coupled integral equations
to be unfolded (various methods tried)



Holger Ulrich PhD Thesis (2003)



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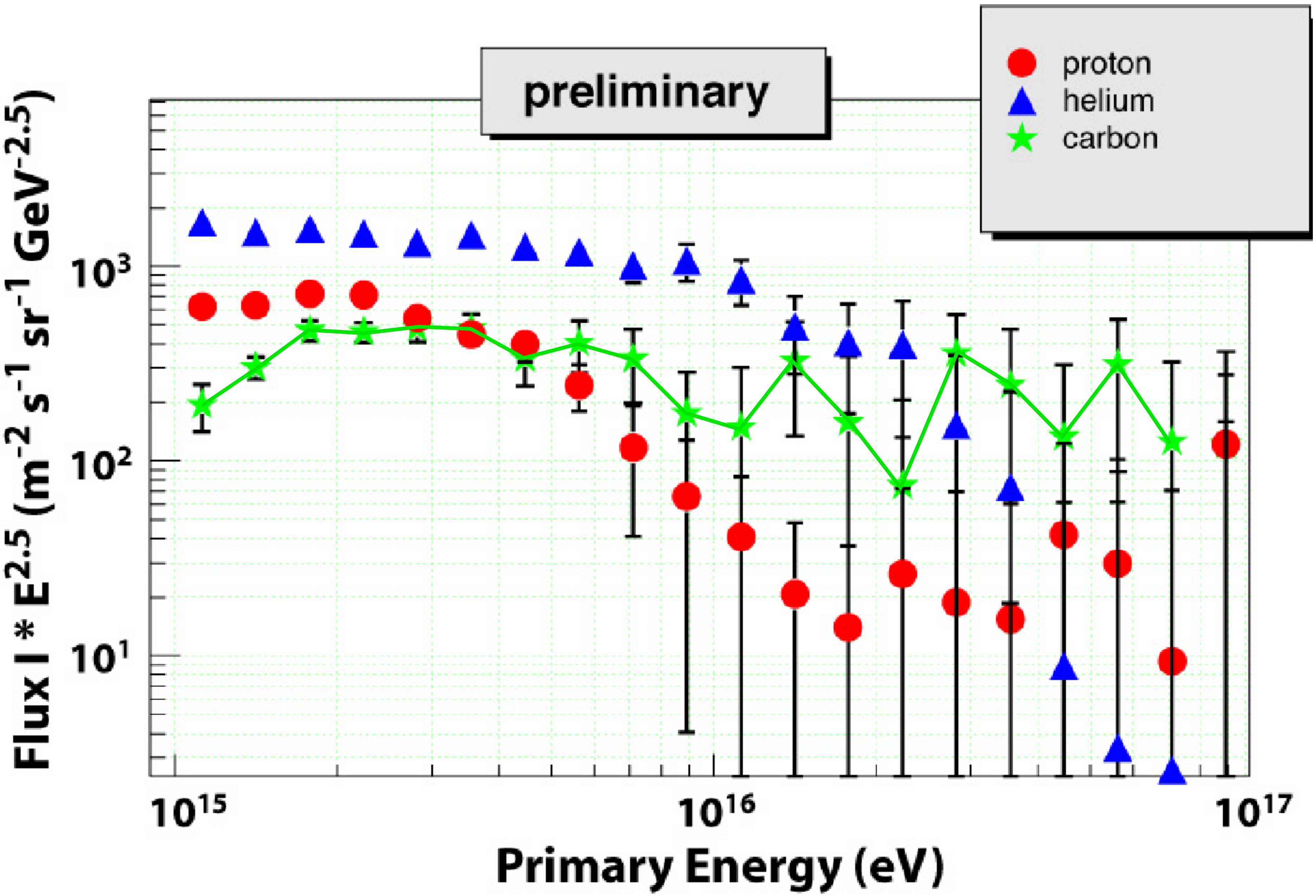

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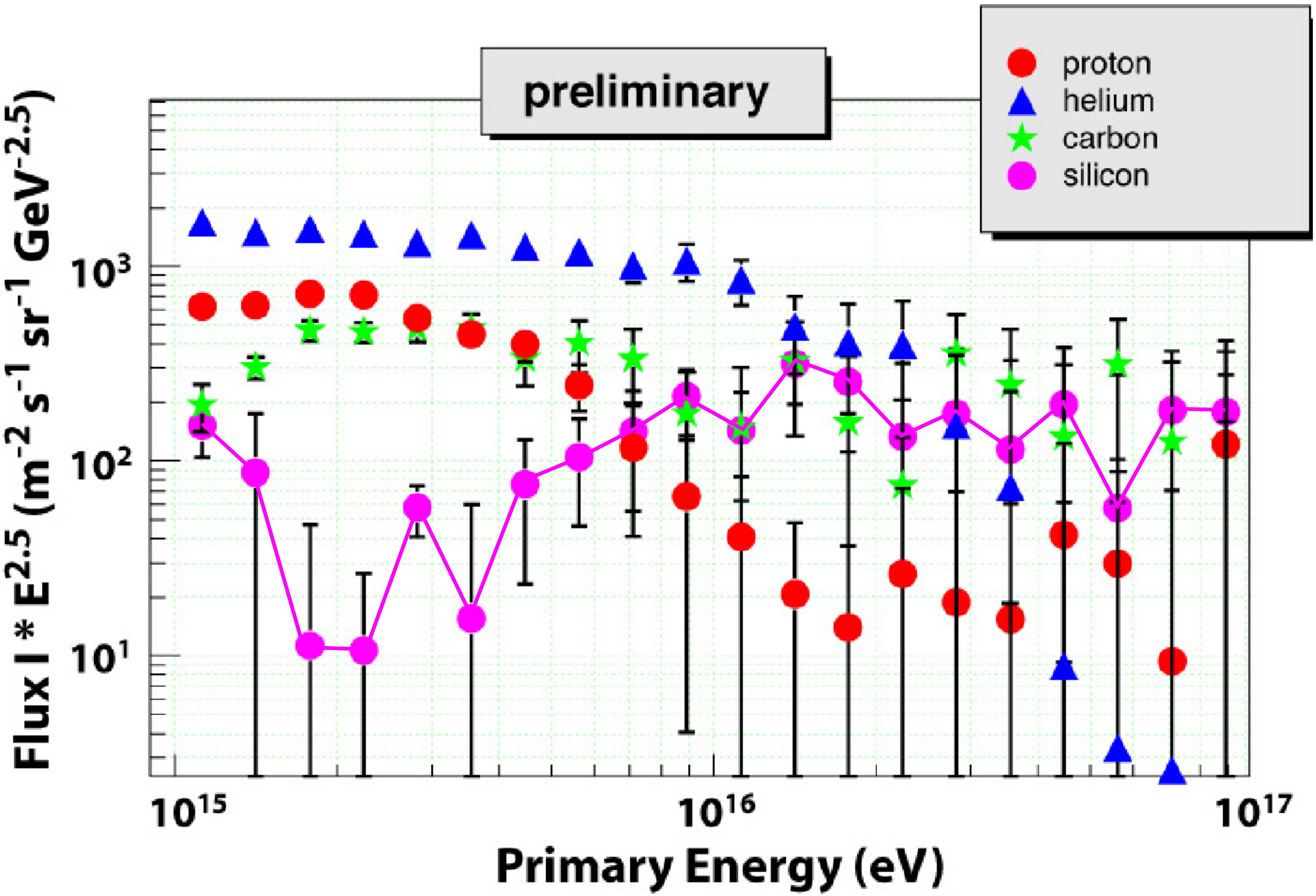

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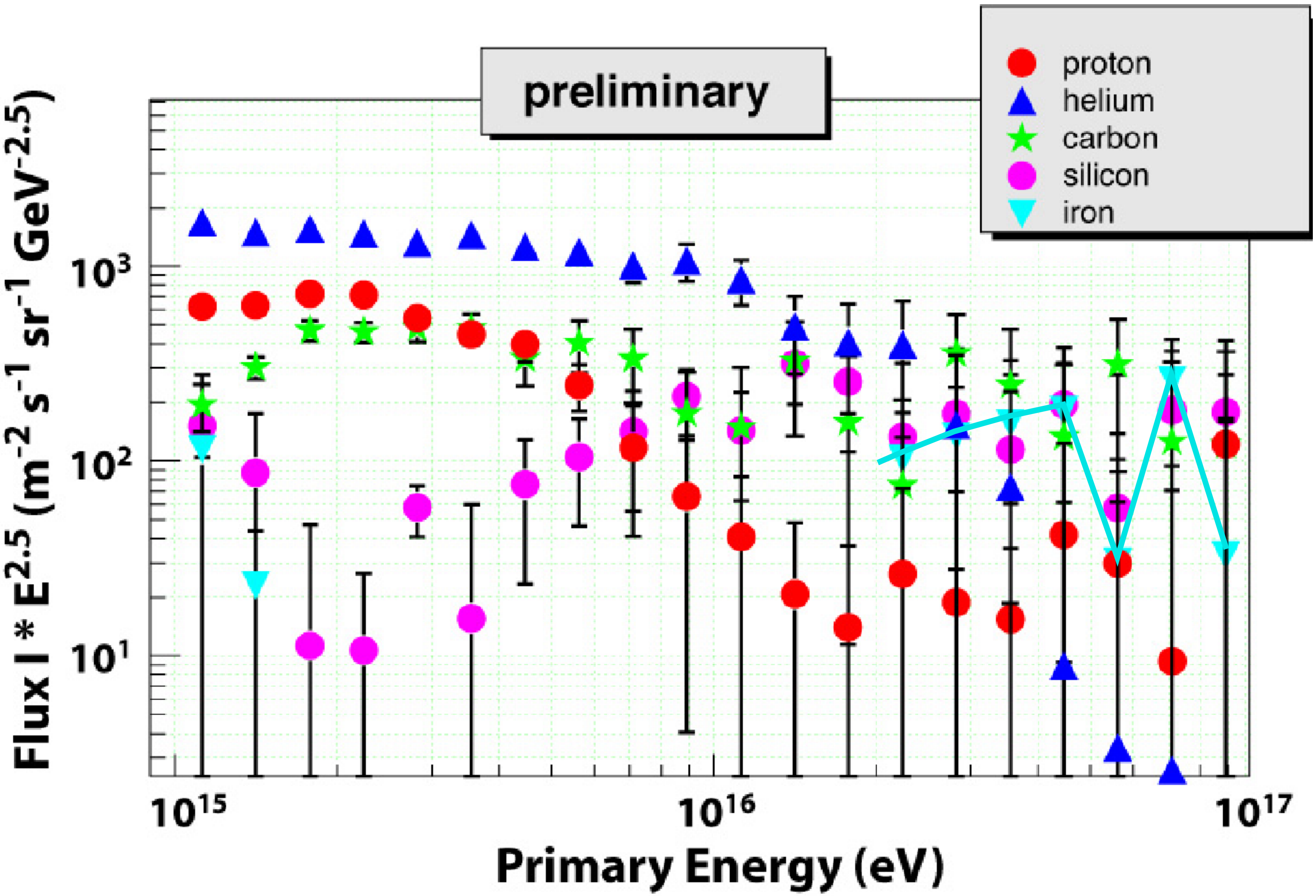

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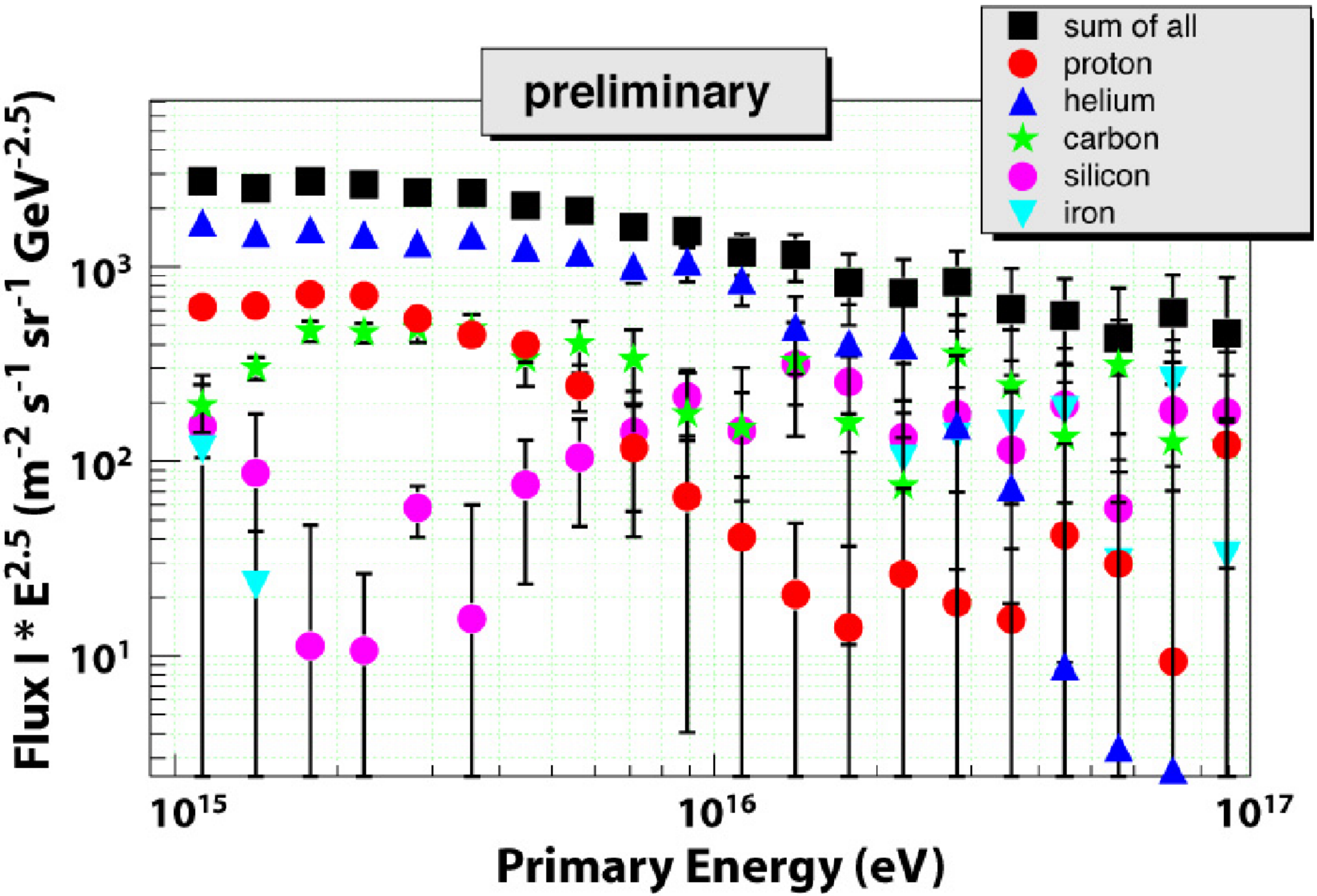
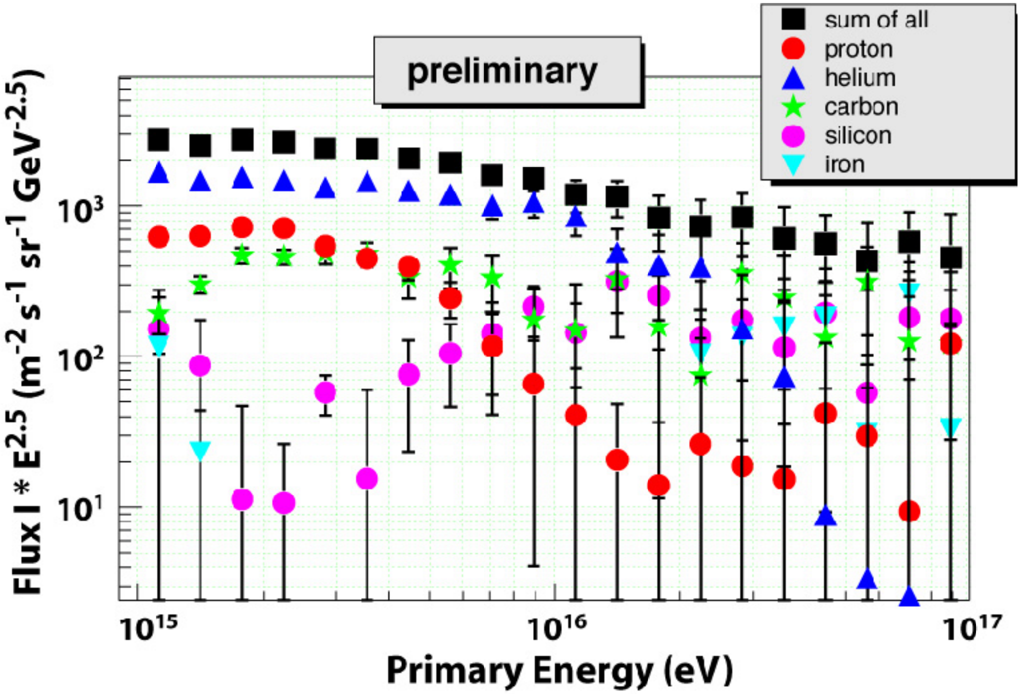
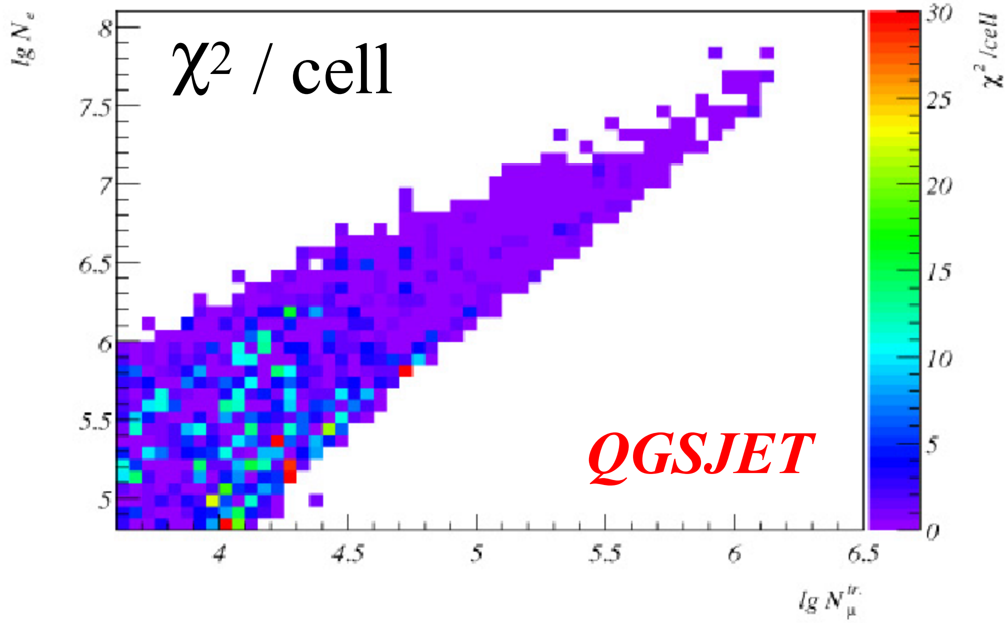


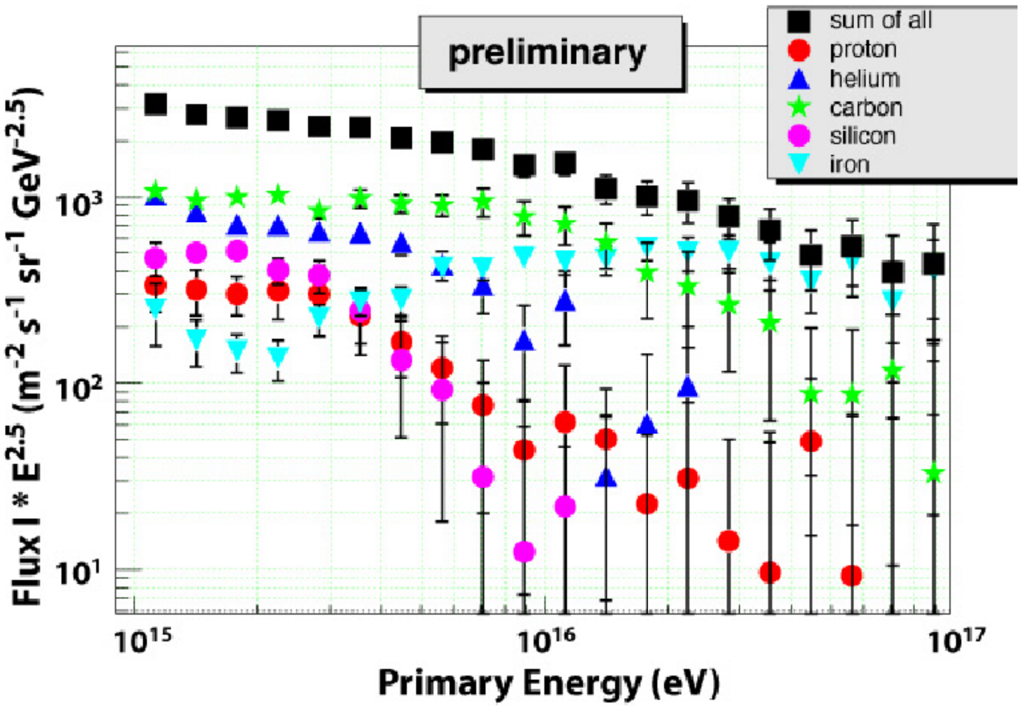
preliminary
sum of all
proton
helium
carbon
silicon
iron
Flux I * $E^{2.5}$ (m^{-2} s^{-1} sr^{-1} $GeV^{-2.5}$)
10^3
10^2
10^1
10^{15}
10^{16}
10^{17}
Primary Energy (eV)

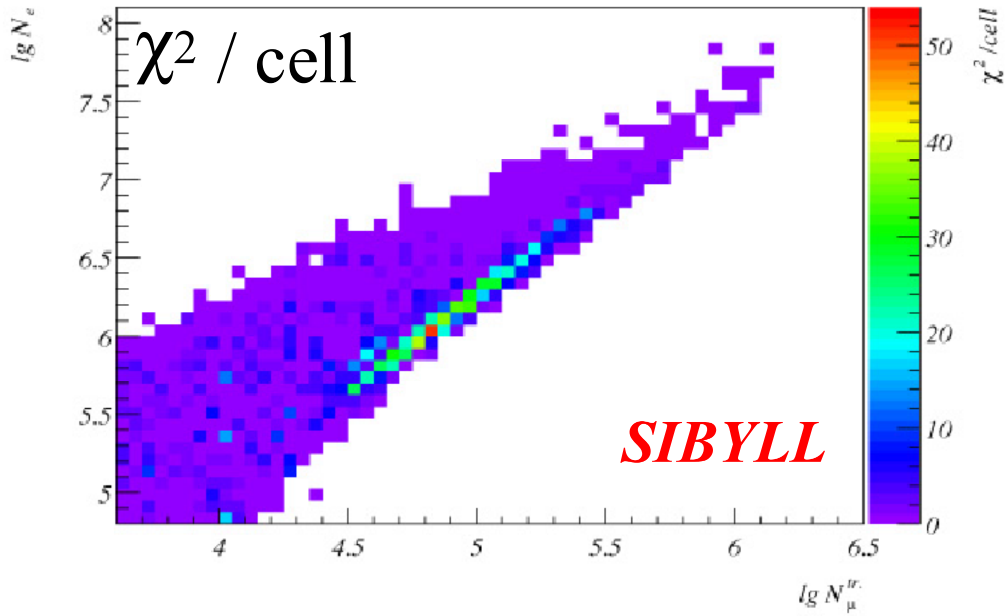
QGSJET vs SIBYLL

None of the models is perfect.
Results are model dependent.





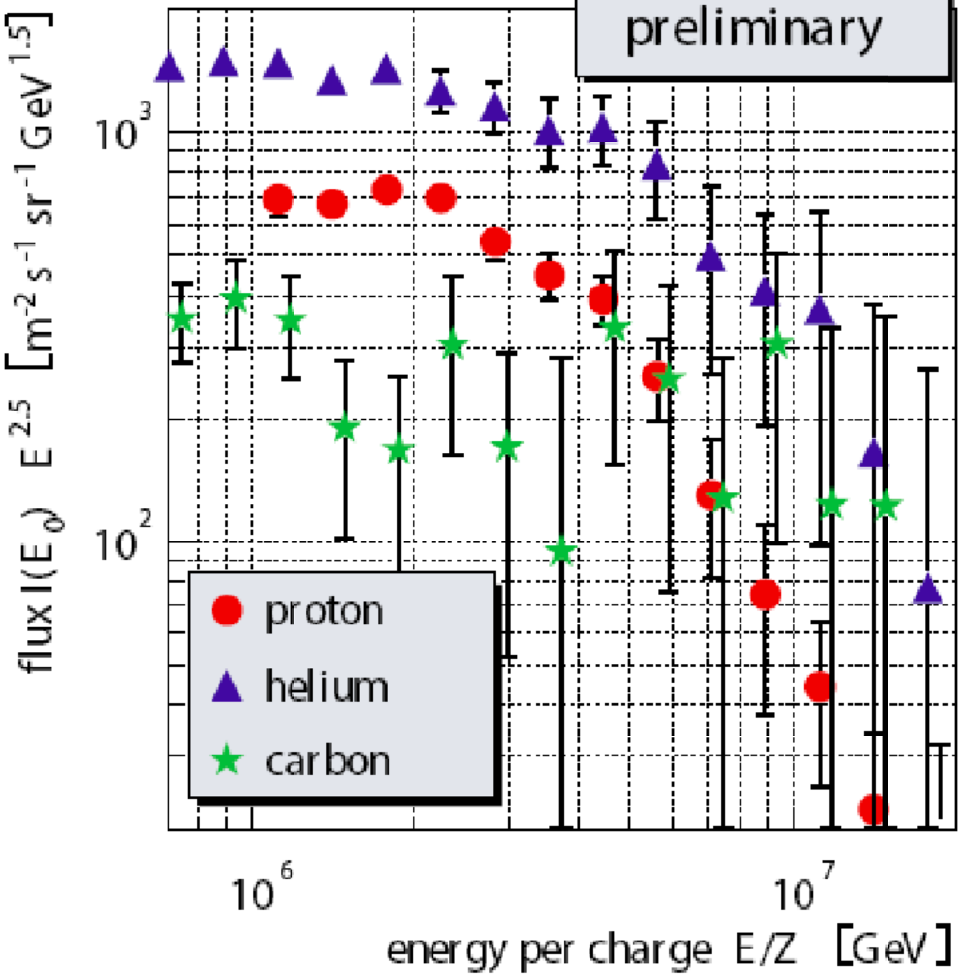




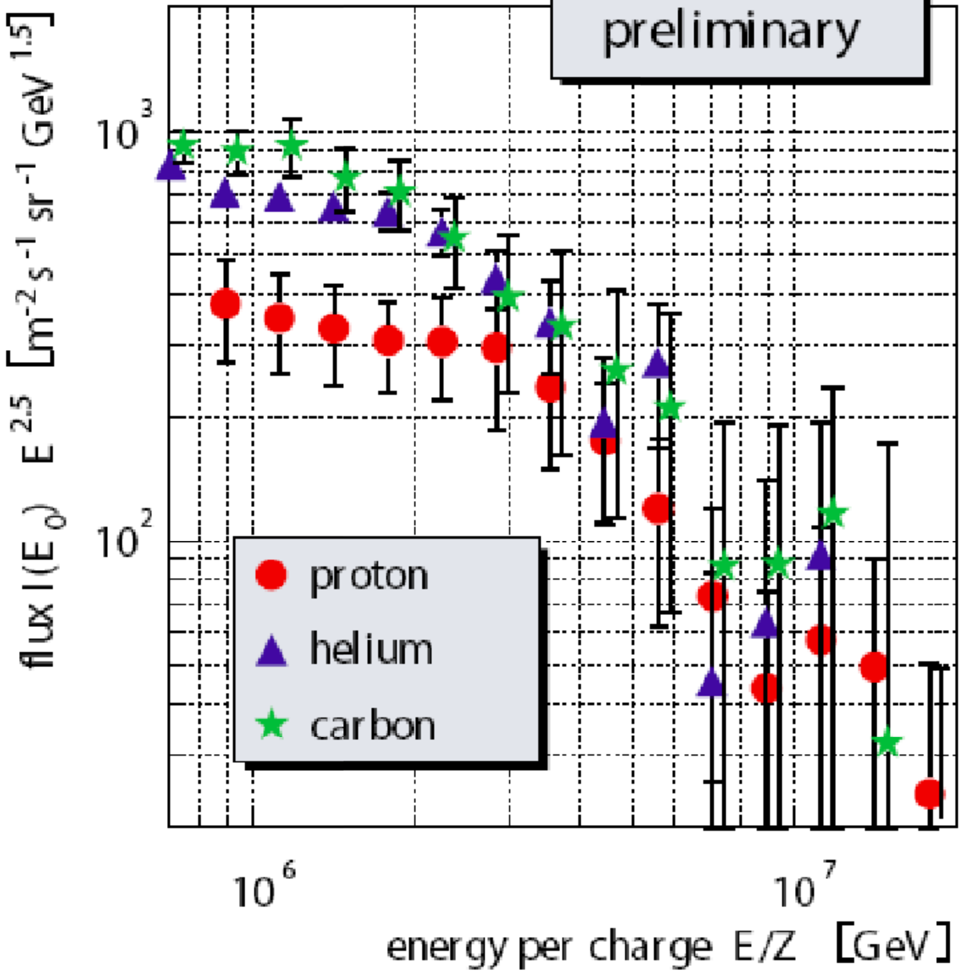
Energy / Z

Z-dependent cut-off favored over A-dependent

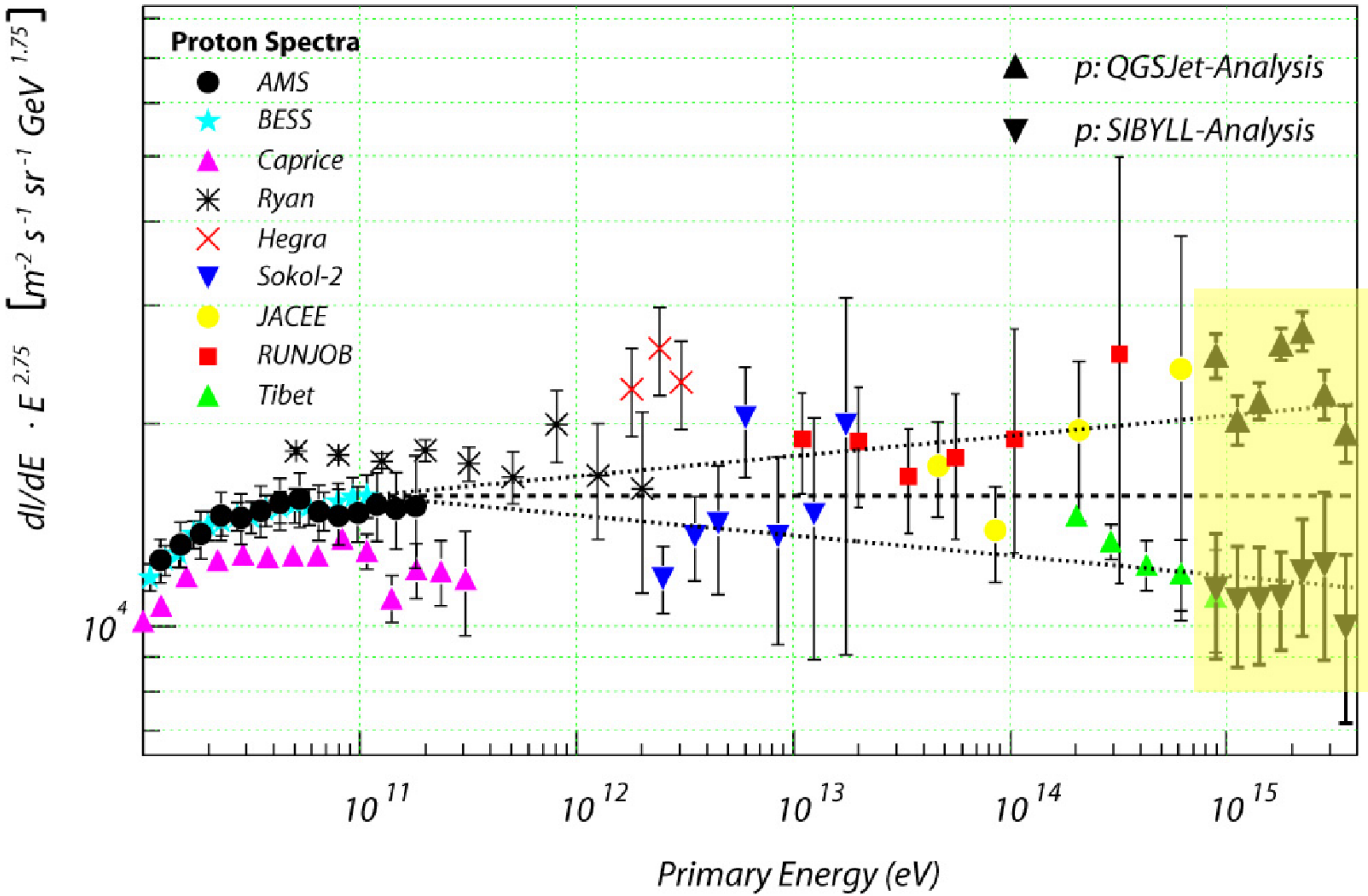
QGSJET



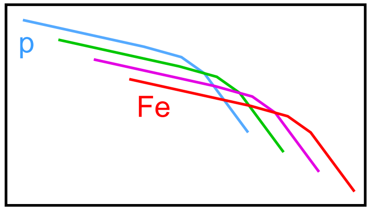
SIBYLL

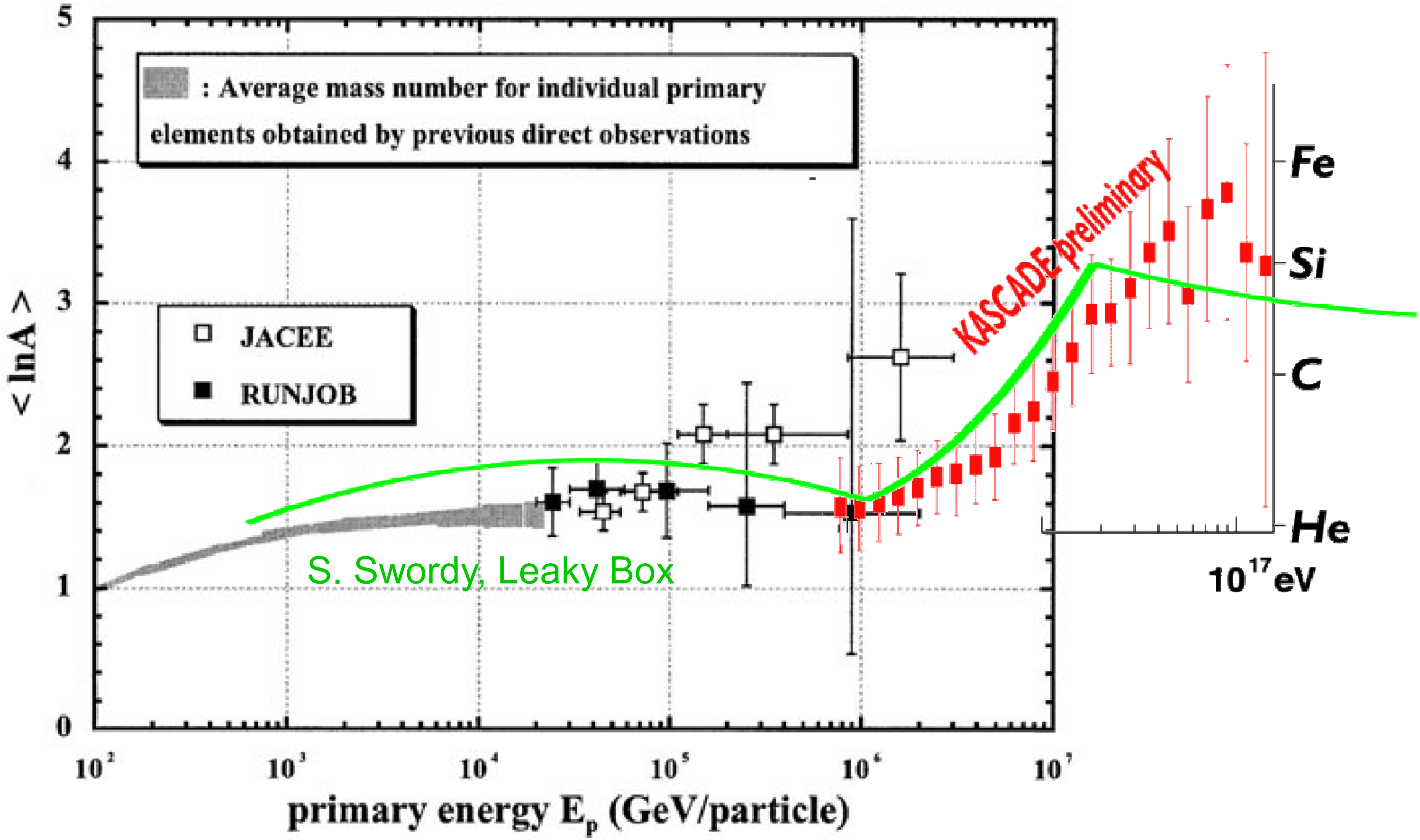


Direct measurements vs KASCADE



Average Mass





KASCADE-GRANDE

extend spectrum to $>10^{17}$ eV
detect Fe-knee