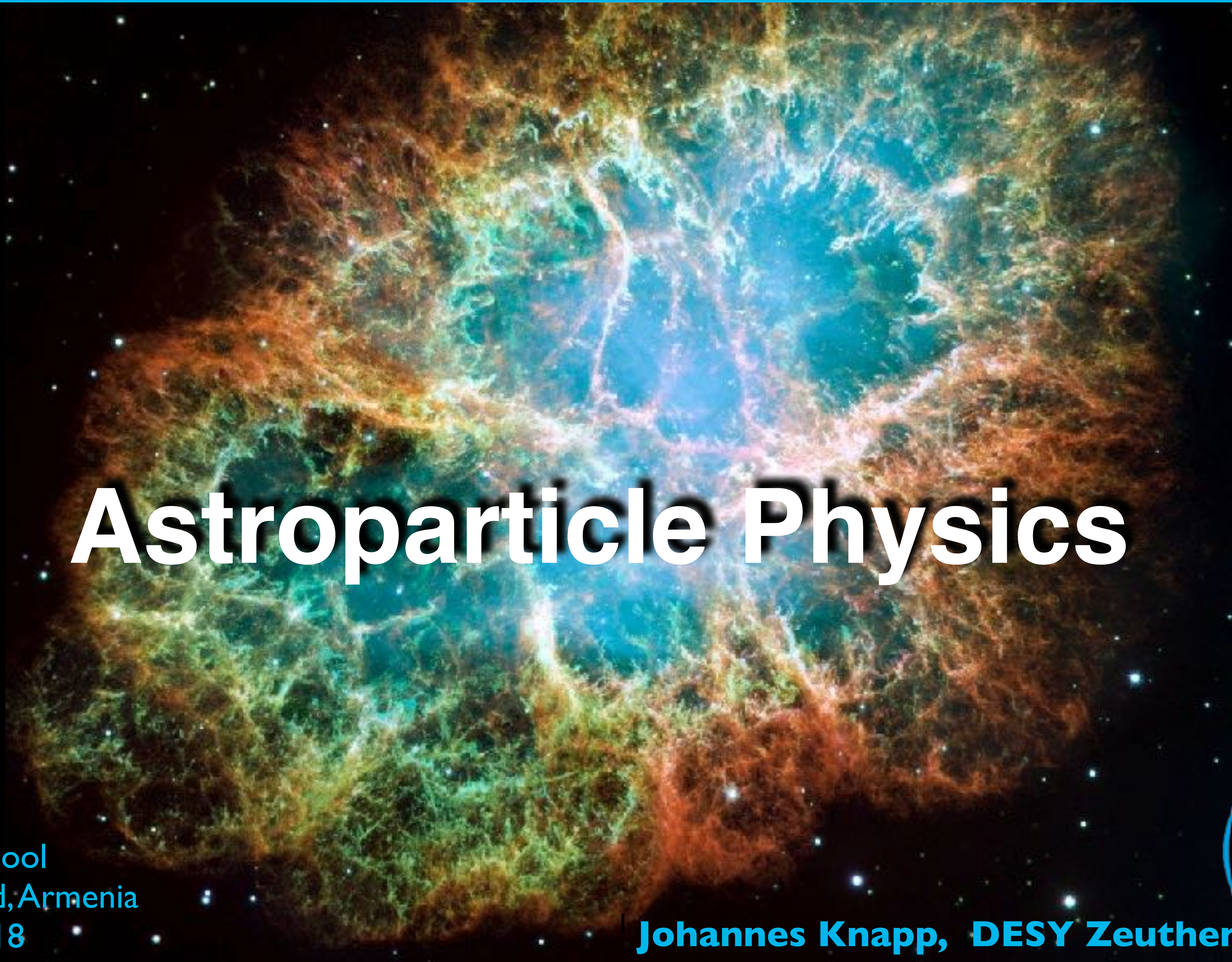
From Measurement to Discovery – The Scientific Method in Physics



Astroparticle Physics

Summer School
Nor Amberd, Armenia
5-8 June, 2018

Johannes Knapp, DESY Zeuthen

From Measurement to Discovery

My Plan for APP:

Discovery

Discovery

Lecture 1: Cosmic Rays: discovery, techniques, spectra & spectral features

Lecture 2: Neutrinos ν: neutrino hypothesis & detection, the solar model, solar neutrino problem, neutrino oscillations

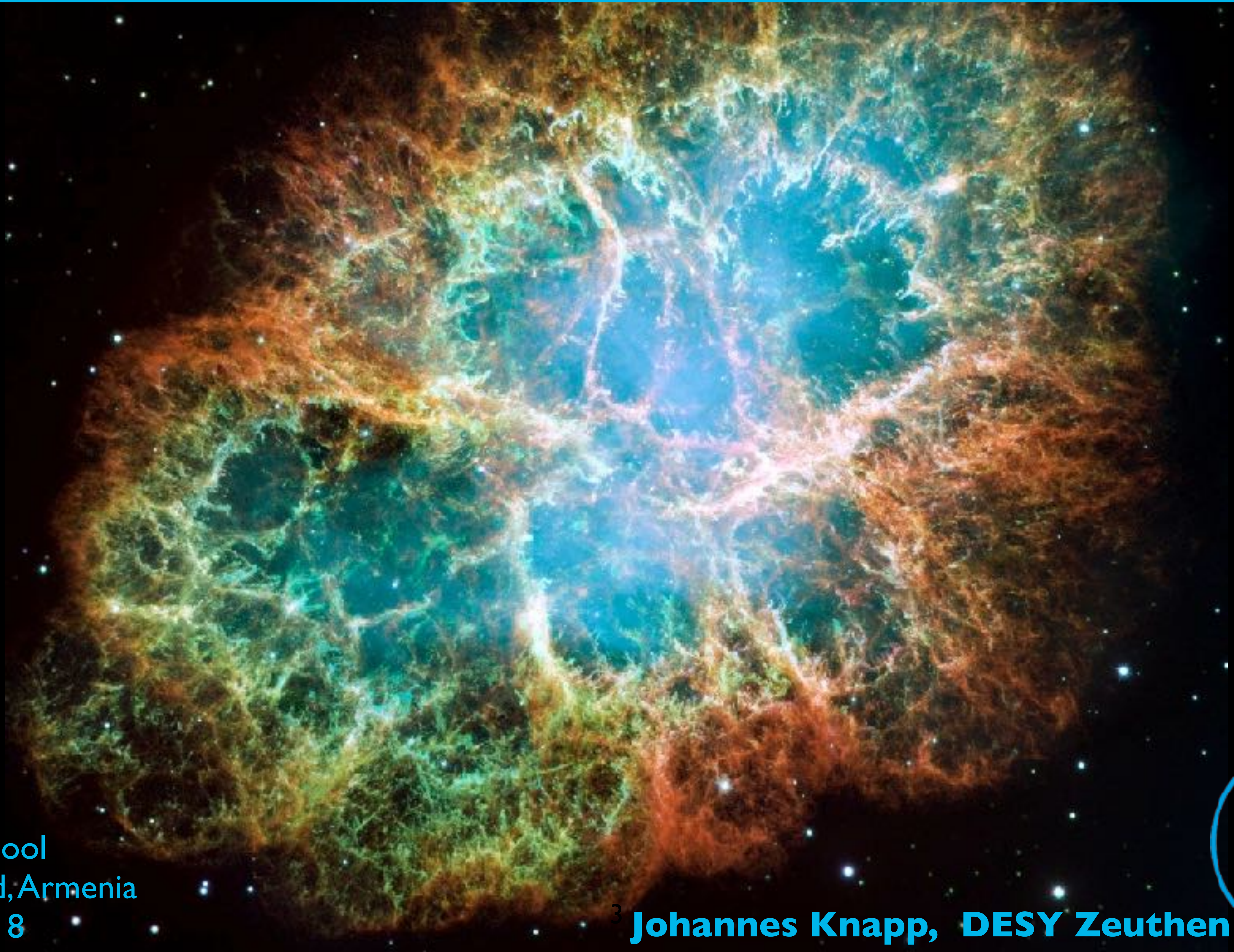
Lecture 3: Neutrino astronomy: the idea, techniques atmospheric neutrinos, sources **Discovery**

Lecture 4: Gamma Rays γ: early ideas, techniques, path to maturity, sources & successes

very many discoveries

Much of this is what we call today "Astroparticle Physics"

I. Cosmic Rays



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1896: Discovery of radioactivity by H Bequerel

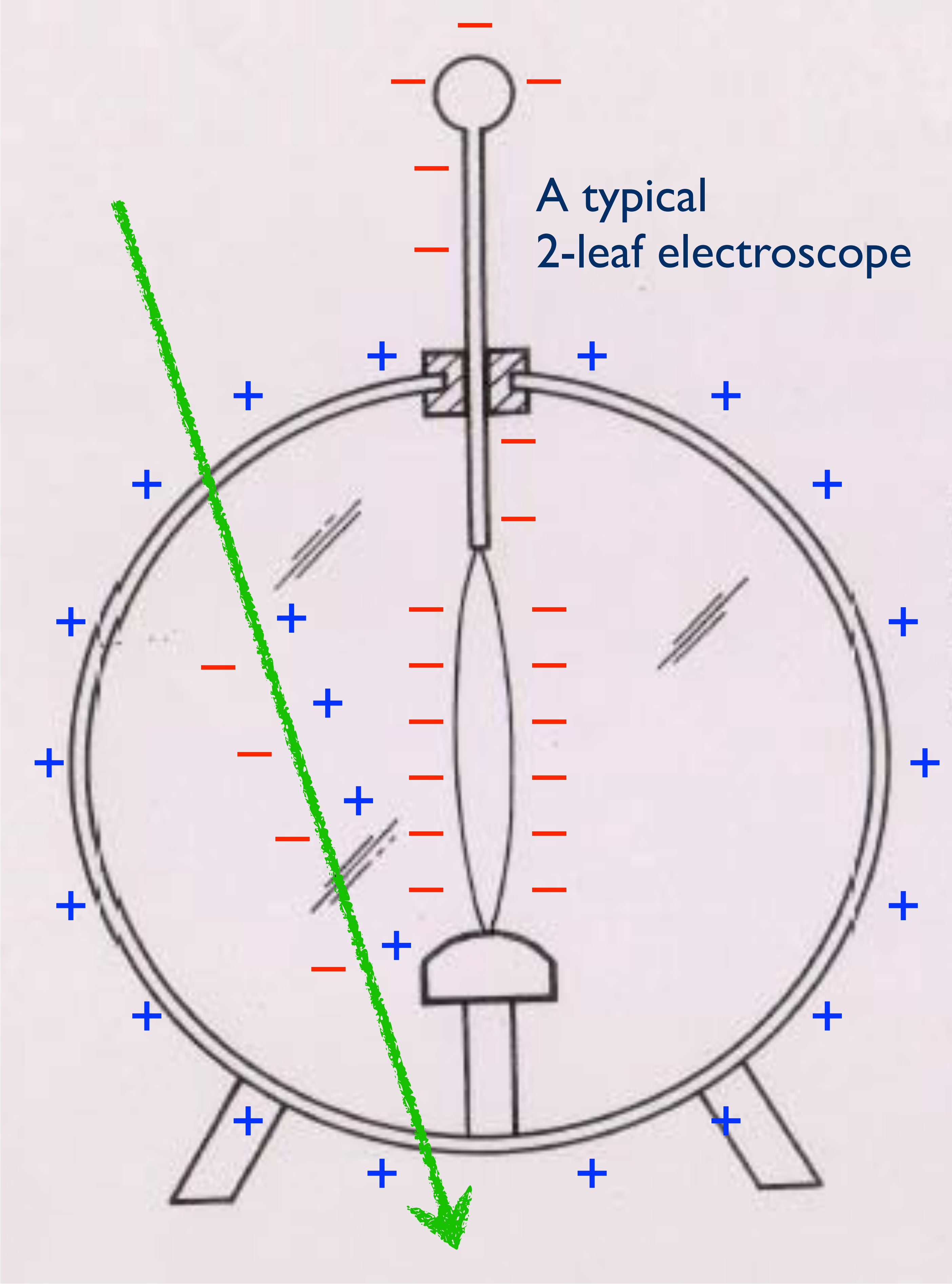
Ionising radiation leads to discharge of electroscopes

α , β, γ radiation

γ radiation very penetrating (compared to α , β)

believed to be electromagnetic ("rays")

Mysterious discharge,
even without radioactivity nearby,
and with massive shielding.



1896 – H Bequerel discovered radioactivity;
1897 – J. J. Thomson discovered the electron (experiments with cathode rays)
1899 – Ernest Rutherford discovered the alpha and beta particles emitted by uranium;
1900 – Paul Villard discovered the gamma ray in uranium decay.
1905 – Albert Einstein hypothesized the photon to explain the photoelectric effect.
1911 – Ernest Rutherford discovered the nucleus of an atom;

Investigation of this “background” radiation

A type of radioactivity?   But much more penetrating
Coming out of the Earth?

Elster and Geitel
Pacini
Wulf
Hess
C. T. R. Wilson   (inventor or cloud chamber)
Rutherford
Schrödinger
....   tried to answer the questions.

Phys. Zeit. 11, 811 (1910)

Datum	Ort	Ionen / ccm sec
28. März	Valkenburg	22,5
29. „	Paris, Boden	17,5
30. „	„ Eiffelturm	16,2
31. „	„ „	14,4
1. April	„ „	15,0
2. „	„ „	17,2
3. „	„ Boden	18,3
4. „	Valkenburg	22,0

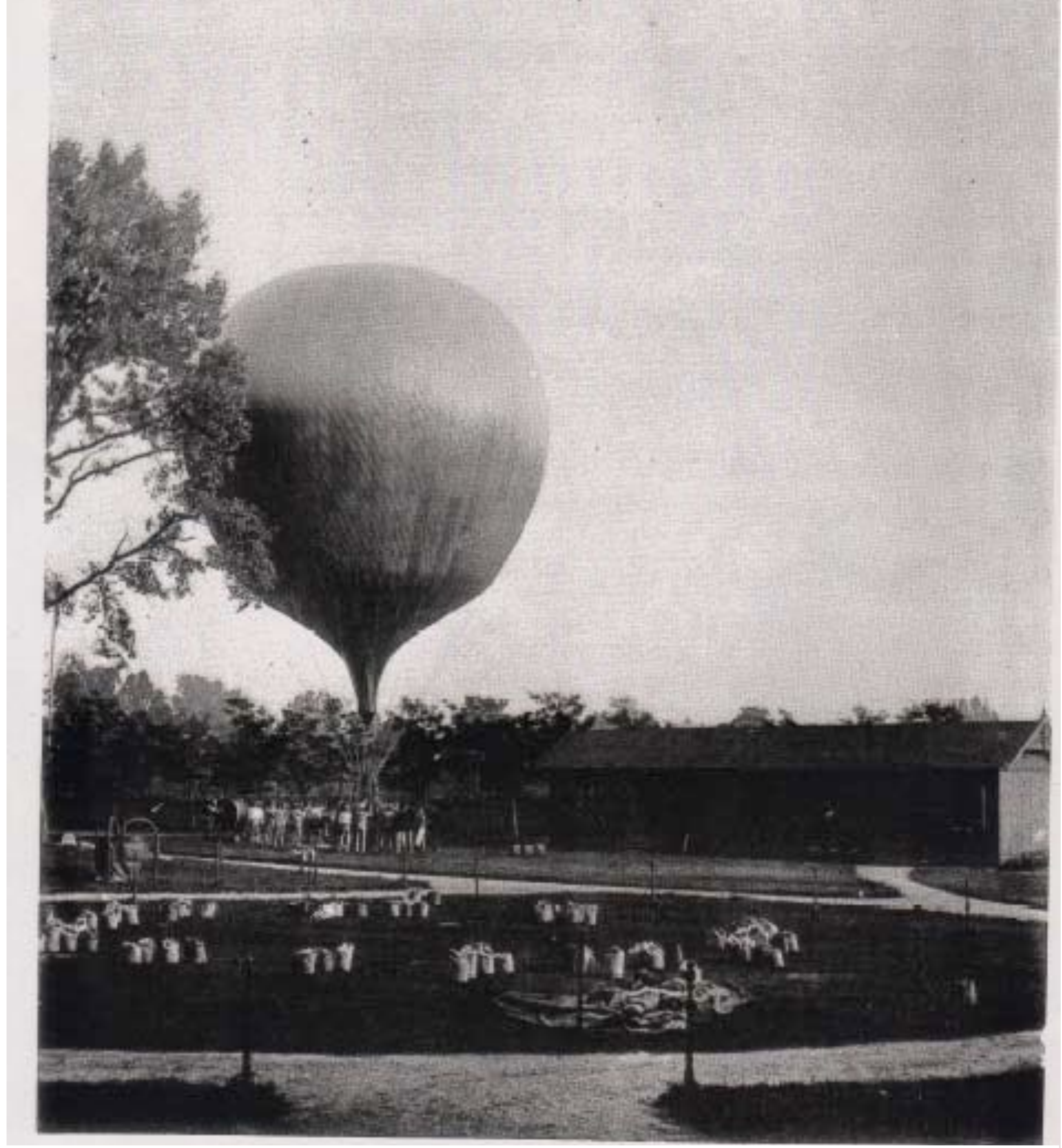
Daraus ergeben sich als Mittelwerte für die drei Orte

Valkenburg	22,25	Ionen / ccm · sec
Paris Boden	18,0	„
Paris Eiffelturm . .	15,7	„

a small decrease ??
no errors given

T Wulf

Viktor Hess,
Vienna



… several balloon flights in 1910-11

Table 2. Results for the six balloon flights of Hess which started in Vienna [Hess 1912]. ('Ions(γ-1)' means the ionisation measured by the γ-detector 1., etc.)

Flight	Date	Time	Height, m	Ions (γ-1), cm^{-3} s^{-1}	Ions (γ-2), cm^{-3} s^{-1}	Ions (β-Det.), cm^{-3} s^{-1}
1	17.4.1912	08:30-09:30	0	14.4	10.7	
		11:00-12:15	1700	13.7	11.1	
		12:15-12:50	1700–2100	27.3	14.4	
		12:50-13:30	1100		15.1	
2	26.-27.4.1912	16:00-22:30	0	17.0	11.6	20.2
		23:00-09:35	140–190	14.9	9.8	18.2
		06:35-09:35	800–1600	17.6	10.5	20.8
3	20.-21.5.1912	17:00-21:30	0	16.9	11.4	19.8
		22:30-02:30	150–340	16.9	11.1	19.2
		02:30-04:30	~500	14.7	9.6	17.6
4	03.-04.5.1912	17:10-20:40	0	15.8	11.7	21.3
		22:30-00:30	800–1100	15.5	11.2	21.8
5	19.6.1912	15:00-17:00	0	13.4		
		17:30-18:40	850–950	10.3		
6	28.-29.6.1912	20:10-23:10	0	15.5	12.2	
		00:40-05:40	90–360	14.9	11.4	

all balloon flights with Coalgas or Methan, not enough lift.

The 7th flight of V Hess: 7 Aug 2012 (using hydrogen gas, had a good lift)

7. Fahrt (7. August 1912).

Ballon: „Böhmen“ (1680 cbm Wasserstoff). Führer: Hauptmann W. Hoffory.
Meteorolog. Beobachter: E. Wolf. Luftelektr. Beobachter: V. F. Hess.

Nr.	Zeit	Mittlere Höhe absolut m	Mittlere Höhe relativ m	Beobachtete Strahlung Apparat 1 q_1	Apparat 2 q_2	Apparat 3 q_3	Apparat 3 reduz. q_3	Temp.	Relat. Feucht. Proz.
1	15h 15—16h 15	156	0	17,3	12,9	—	—	—	—
2	16h 15—17h 15	156	0	15,9	11,0	18.4	18,4	1½ Tag vor dem Aufstiege (in Wien)	
3	17h 15—18h 15	156	0	15,8	11,2	17.5	17,5		
4	6h 45— 7h 45	1700	1400	15,8	[illegible]	21.1	25.3	+6.4°	60
5	7h 45— 8h 45	2750	2500	17 3	12,3	22.5	31,2	+1.4°	41
6	8h 45— 9h 45	3850	3600	19,8	16,5	21.8	35,2	—6.8°	64
7	9h 45—10h 45	4800 (4400—5350)	4700	40,7	31,8	—	—	—9,8°	40
8	10h 45 – 11h 15	4400	4200	28,1	22,7	—	—	—	—
9	11h 15—11h 45	1300	1200	(9,7)	11,5	—	—	—	—
10	11h 45—12h 10	250	150	11,9	10,7	—	—	+16,0°	68
11	12h 25—13h 12	140	0	15,0	11,6	—	—	(nach der Landung in Pieskow, Brandenburg)	

“ ... the most likely explanation is a highly penetrating radiation from the top ...”

The 7th flight of V Hess: 7 Aug 2012

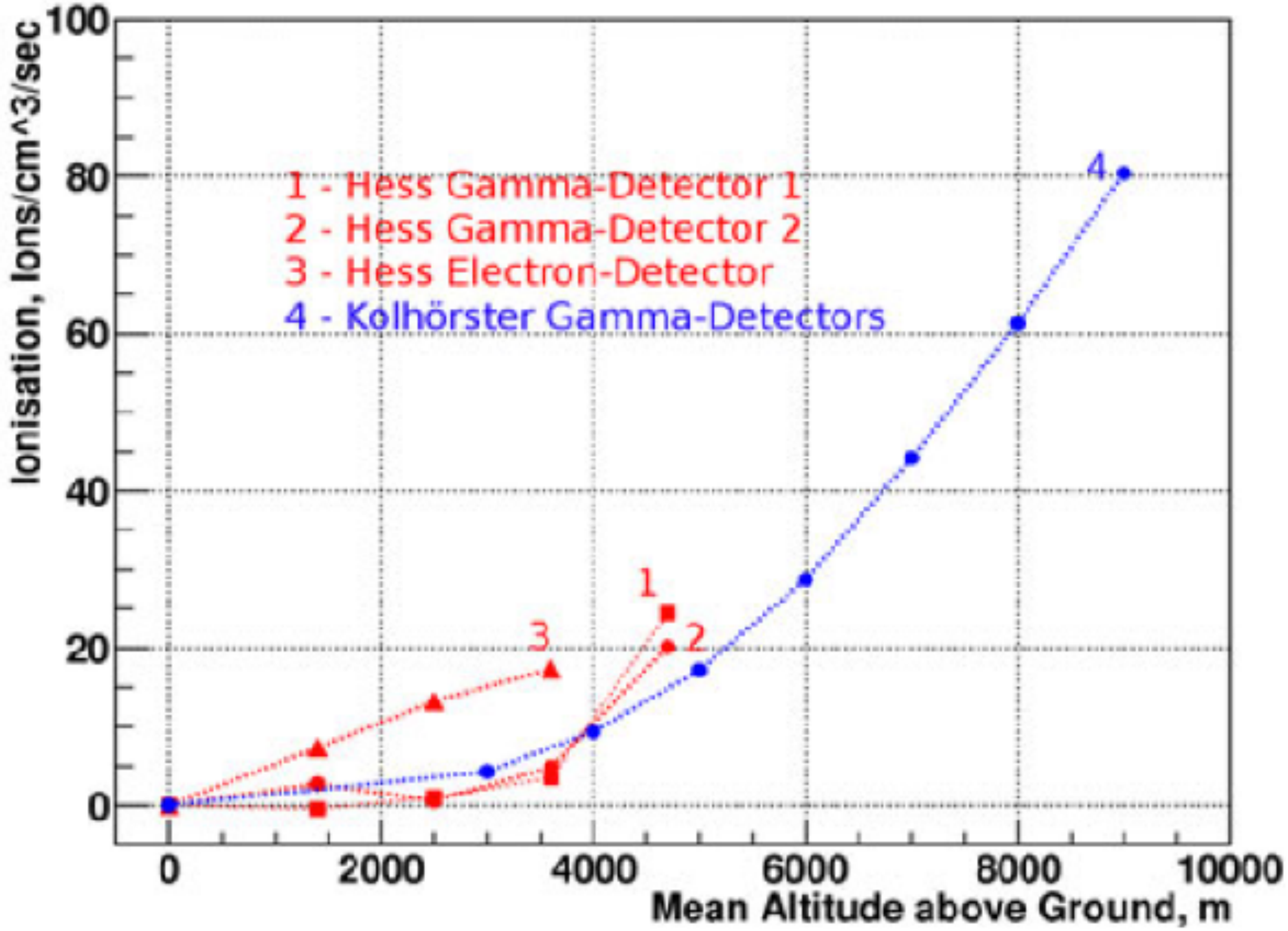
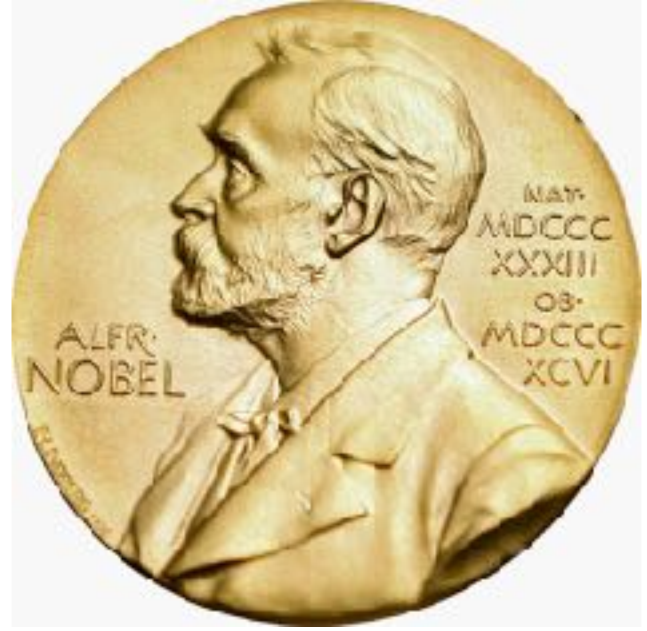


Fig. 2. Number of ions $cm^{-3}s^{-1}$ measured by Hess at the seventh flight in August 1912 (1-3) [Hess 1912] and by Kolhörster (4) in 1914 [Kolhörster 1914].

Nobel Prize 1936



Victor Franz Hess

Cosmic Rays

Carl David Anderson

Positron

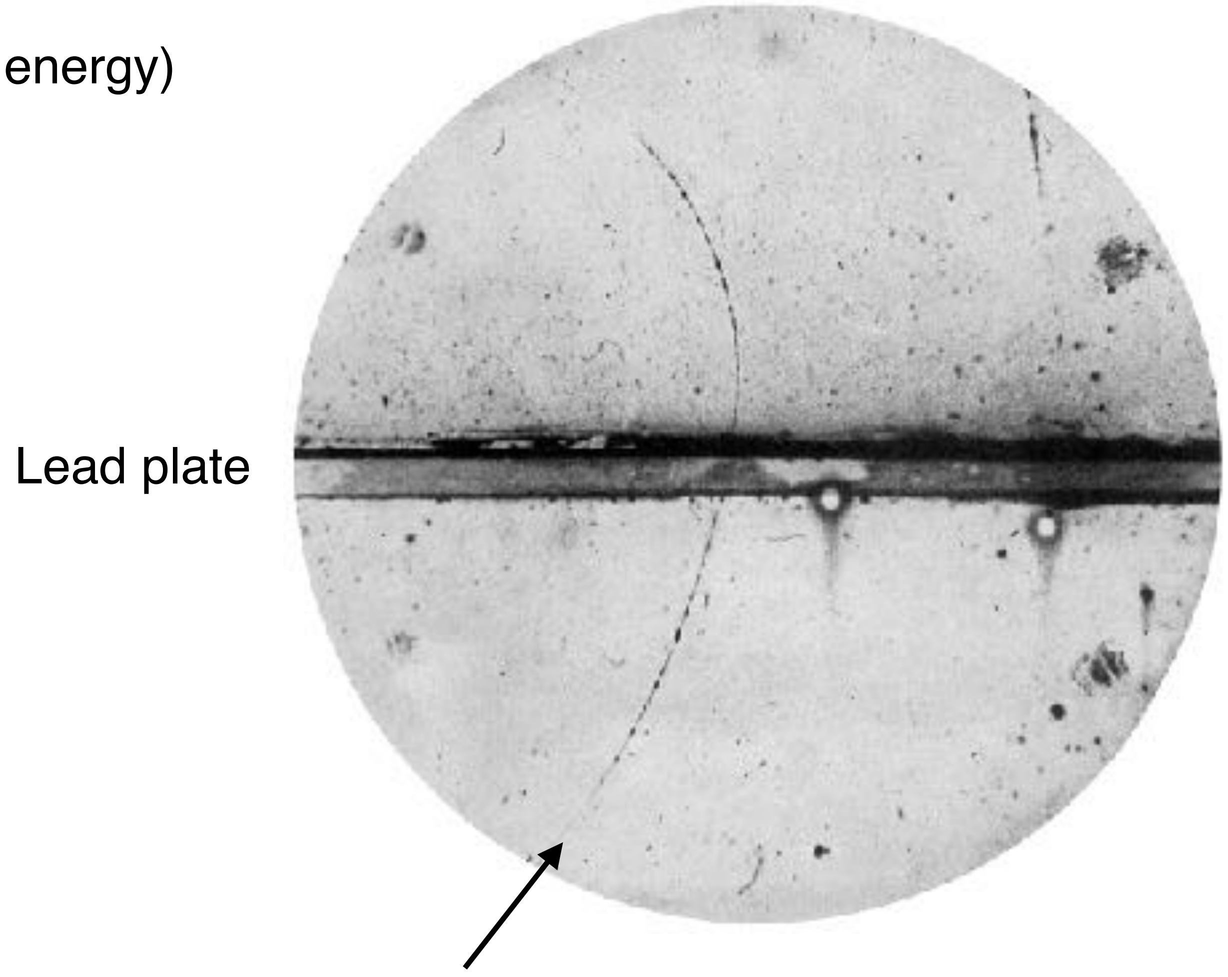
Start of particle physics:

High-energy (GeV) particles seen in cosmic rays.
Secondaries produced in atmosphere or in detectors.

A cloud chamber picture:

A charged particle is bent in a magnetic field.
It ionises the gas and causes droplets to condense along the track.
(droplet density: it is an electron)
The particle goes through a lead plate (where it loses energy)
(it comes from below)

Thus, it was a positively charged electron:
The discovery of the "positron"



discovered in cosmic rays

1912 – V Hess discovered cosmic radiation;
1912 – CTA Wilson invents the cloud chamber (a prime tool to observe radiation)

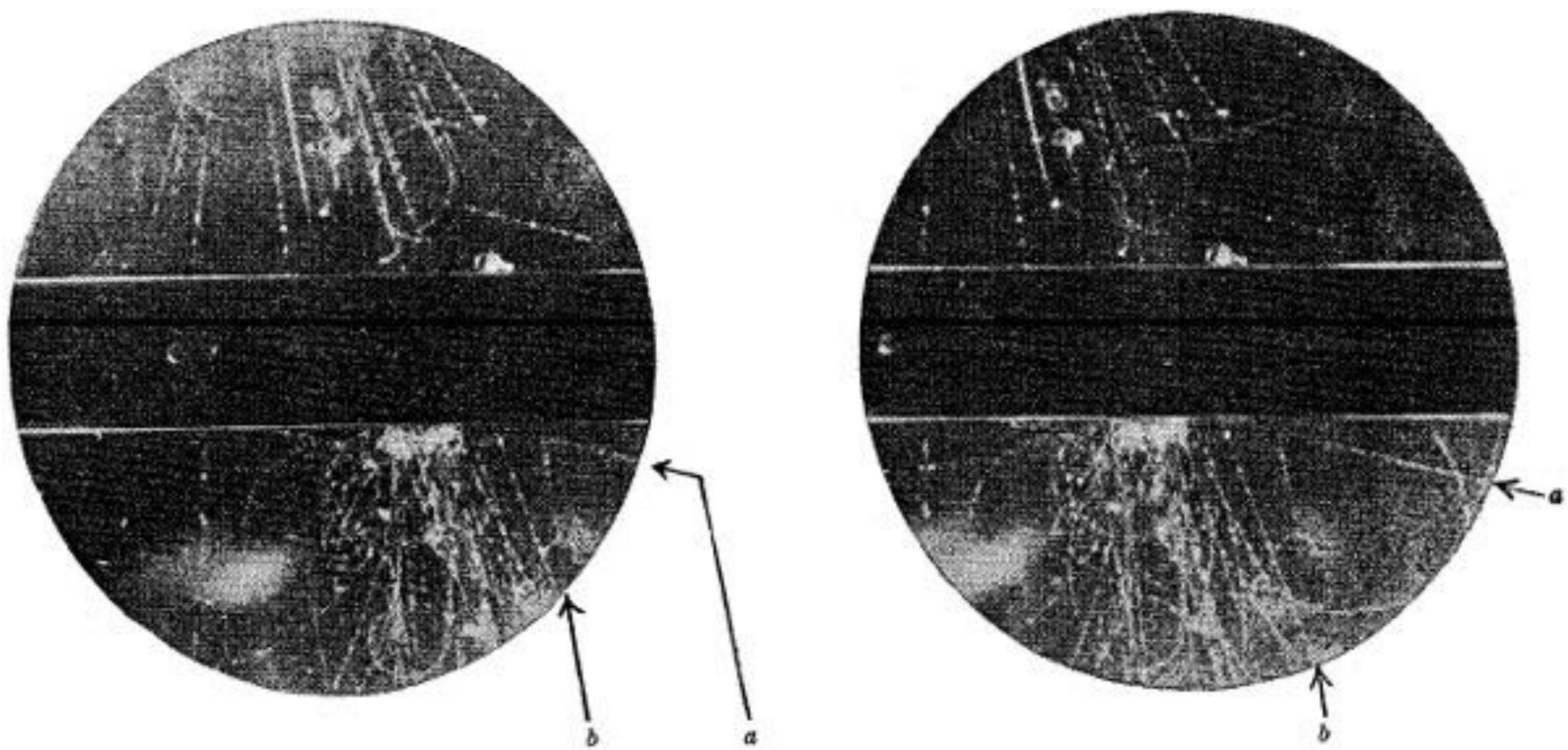
1919 – Ernest Rutherford discovered the proton;
1928 – Paul Dirac postulated the existence of positrons as a consequence of the Dirac equation;
1930 – Wolfgang Pauli postulated the neutrino to explain the energy spectrum of beta decays;
1932 – James Chadwick discovered the neutron;
1932 – Carl D. Anderson discovered the positron;
1933 – Pierre Auger detects air showers
1935 – Hideki Yukawa predicted the existence of mesons as the carriers of the strong nuclear force;
1936 – Carl D. Anderson discovered the muon while he studied cosmic radiation;
1936 – Pierre Auger discovers air showers, (formed by single high-energy cosmic rays; E up to **10^{15} eV**)
1947 – George Rochester and Clifford Butler discovered the kaon, the first strange particle;
1947 – Cecil Powell, César Lattes and Giuseppe Occhialini discovered the pion;

1955 – Owen Chamberlain et al. discovered the antiproton;
1956 – Clyde Cowan and Frederick Reines discovered the (electron) neutrino;
1957 – Bruno Pontecorvo postulated the flavour oscillation;
1962 – Leon M. Lederman, Melvin Schwartz and Jack Steinberger discovered the muon neutrino;
1967 – Bruno Pontecorvo postulated neutrino oscillation;
1974 – Burton Richter and Samuel Ting discovered the J/ψ particle composed of charm quarks;
1977 – Upsilon particle discovered at Fermilab, demonstrating the existence of the bottom quark;
1977 – Martin Lewis Perl discovered the tau lepton after a series of experiments;
1979 – Gluon observed indirectly in three-jet events at DESY;
1983 – Carlo Rubbia and Simon van der Meer discovered the W and Z bosons;
1995 – Top quark discovered at Fermilab;
2000 – Tau neutrino proved distinct from other neutrinos at Fermilab.
2012 – Higgs boson-like particle discovered at CERN's Large Hadron Collider (LHC).

discovered at accelerators/reactors

Kaon discovery (first "strange" particle):

"Evidence for the existence of new unstable elementary particles"

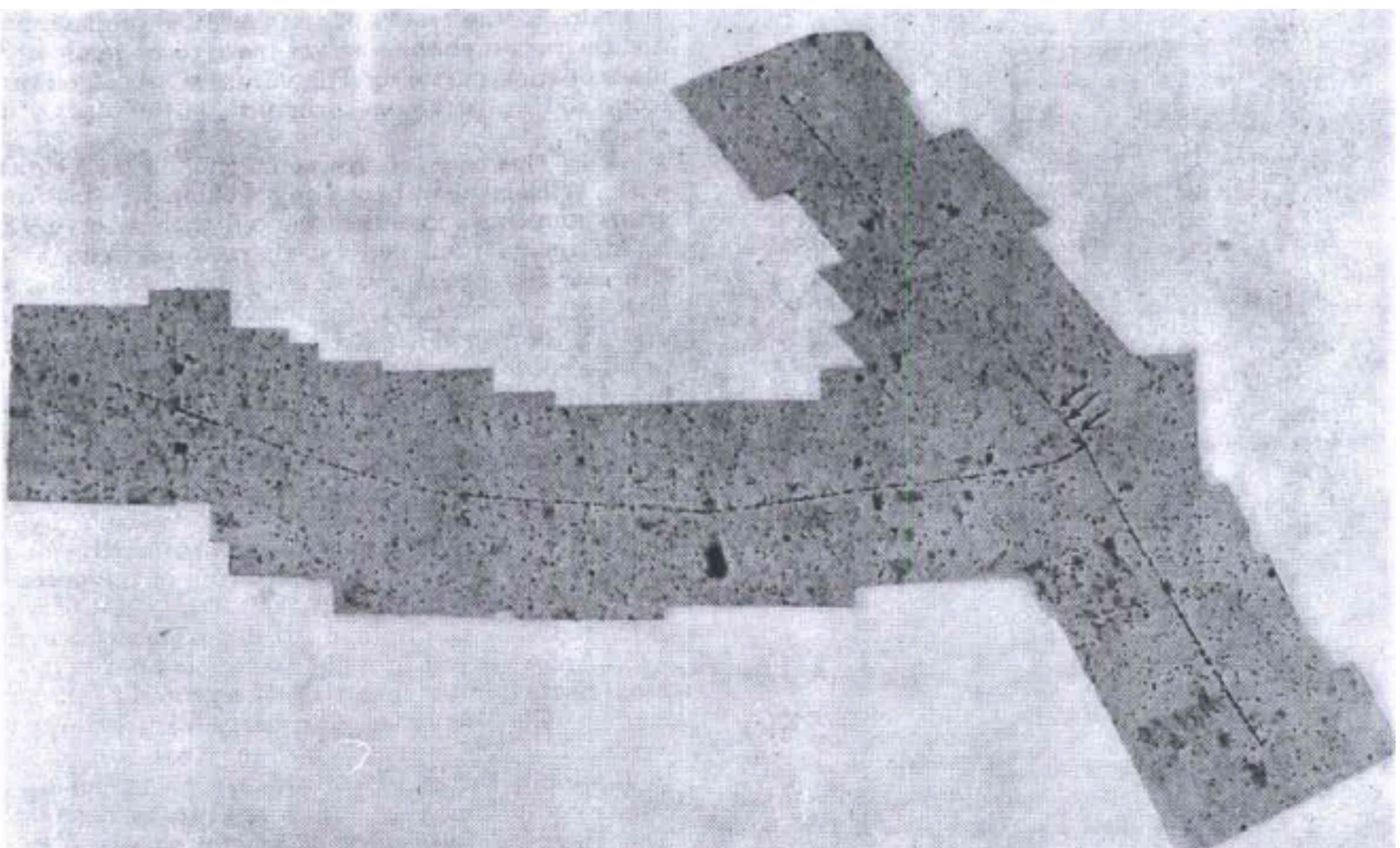


Stereo view of a fork of two newly created particles (a,b) in a decay of a yet unknown particle.

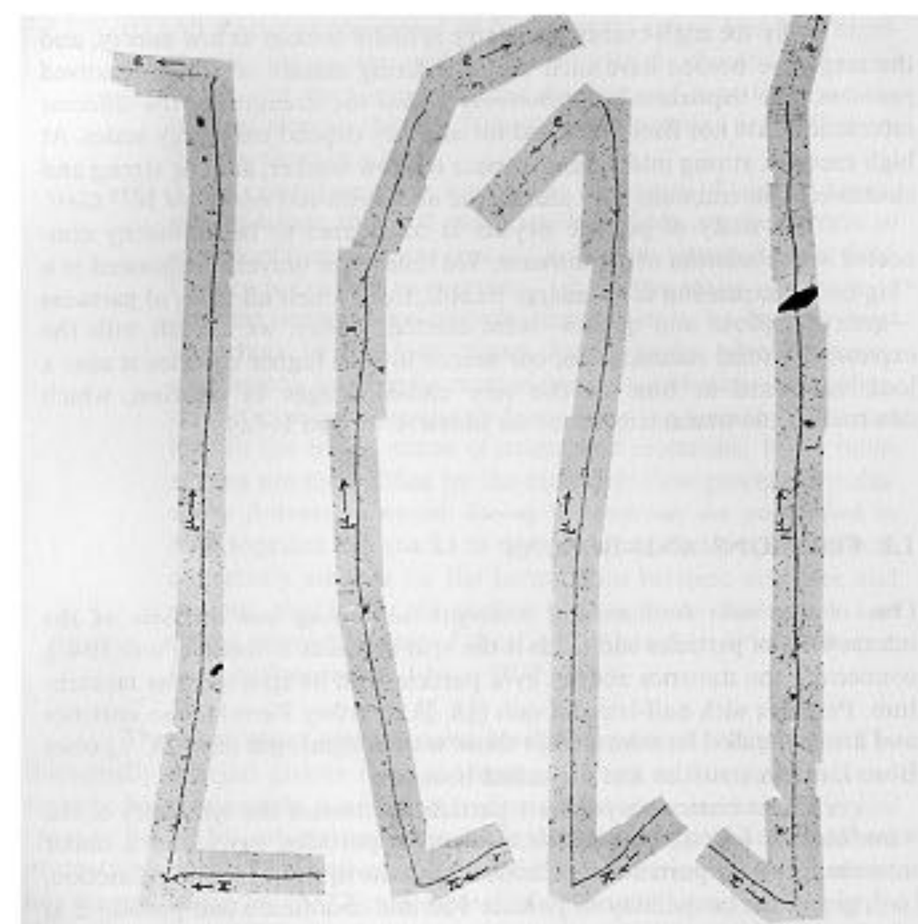
Pion discovery:

"Nuclear Disintegrations Produced by Slow Charged Particles of Small Mass"

the particle postulated in 1935 by Yukawa
as mediator of the strong force (?)



images of particle tracks in
photographic emulsions



"Cosmic Rays" a misnomer, that stuck.

It turned out that cosmic rays are
charged, energetic **particles**

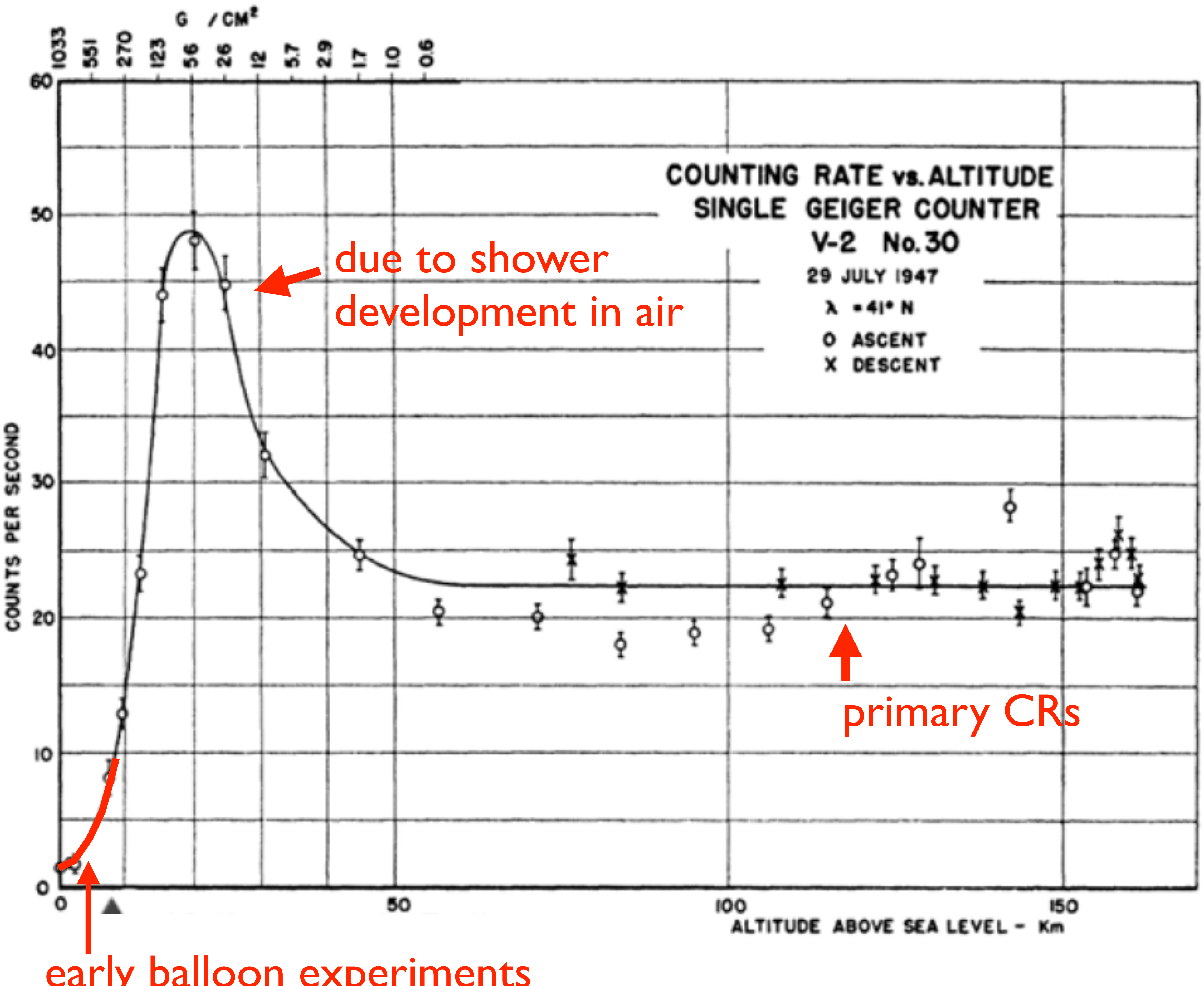
nuclei (fully ionised), electrons, some anti particles
p, He, … C, N, O, …. Ni, Co, Fe, …
e^-, e^+, $\bar{p}$ …

Primary cosmic rays (on top of atmosphere).

research with stratospheric balloons and satellites

Secondaries, produced through interactions in the atmosphere.

Easier to study at accelerators from 1950s on.



G / CM²
1033
551
270
123
56
26
12
5.7
2.9
1.7
1.0
0.6
COUNTING RATE vs. ALTITUDE
SINGLE GEIGER COUNTER
V-2 No. 30
29 JULY 1947
λ = 41° N
O ASCENT
X DESCENT
COUNTS PER SECOND
ALTITUDE ABOVE SEA LEVEL - Km
due to shower development in air
primary CRs
early balloon experiments

Astro-Particles

energetic (elementary) **particles**
from space (Sun, Milky Way, distant galaxies)
bombard Earth continuously.

Energies from MeV .... >10^{20} eV

1 eV = 1.6 x10^{-19} J
10^{20} eV = 16 J

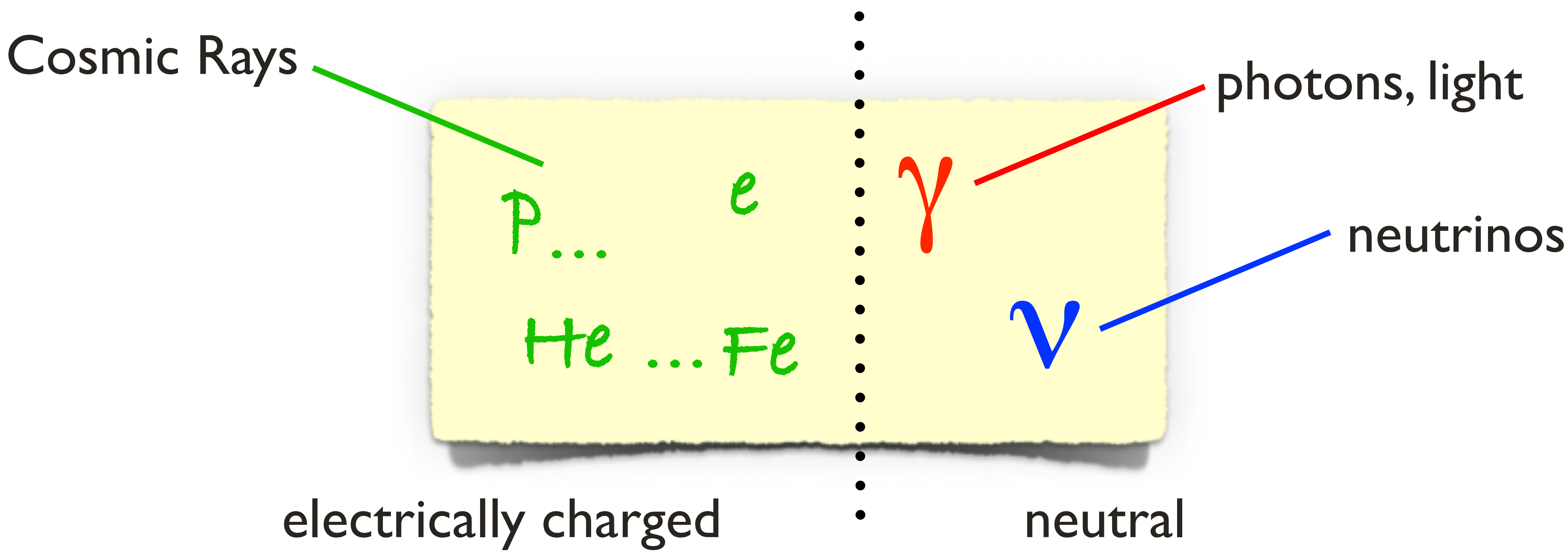
most relativistic particles in the Universe

Astrophysics with high energy photons and particles.

Particle physics with probes of astrophysical origin.

What are these cosmic particles?

must be stable (to survive the travel to us)



+ can be accelerated in electric fields
– are deflected in magnetic fields

+ move in straight lines (good for astronomy)
– secondary particles

other astro particles: **dark matter**
... not in this talk.

Energy scale:

radio

IR

visible light

UV

X rays

γ rays

the range of astroparticle physics

meV ... eV ... keV ... MeV ... GeV ... TeV ... PeV ... EeV ... ZeV

10^{-3} ... 1 ... 10^{3} ... 10^{6} ... 10^{9} ... 10^{12} ... 10^{15} ... 10^{18} ... 10^{21} eV

non-thermal processes

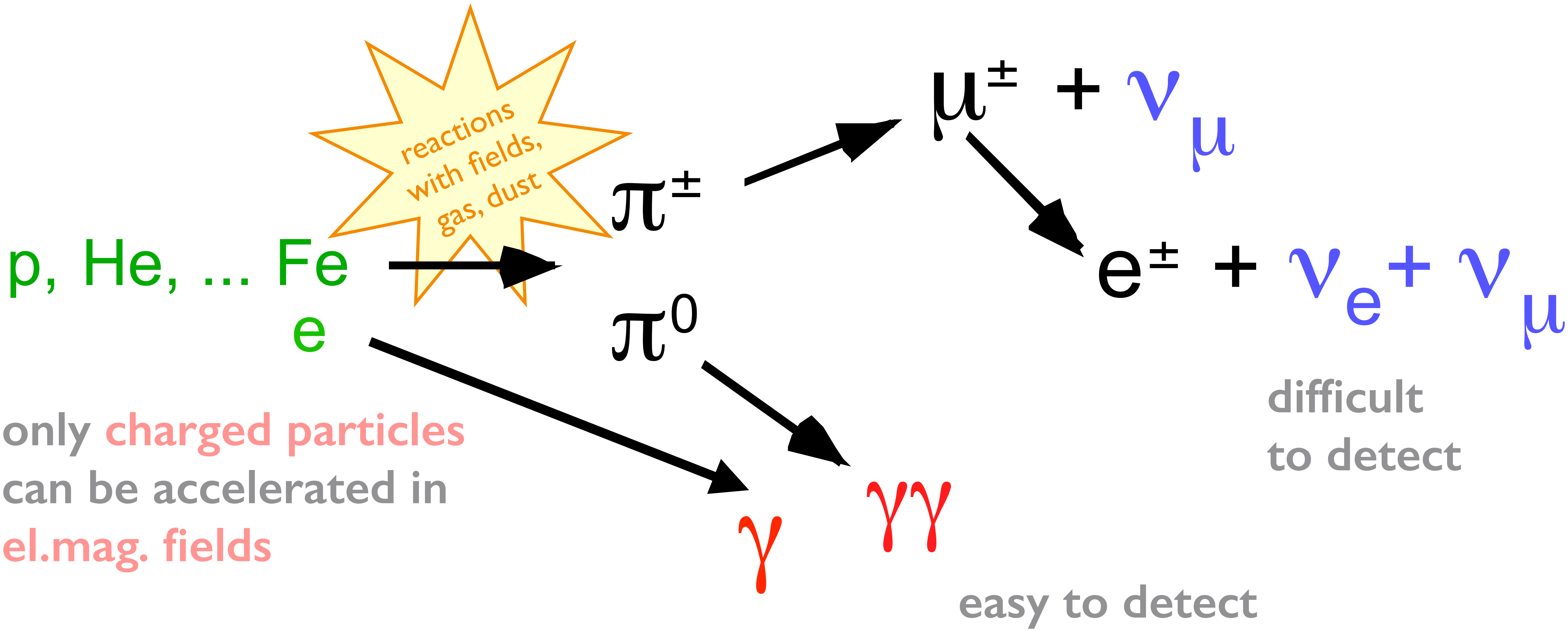
Photons: astronomy

charged: p, He, ... Fe, ... completely ionised nuclei

electrons

Neutrinos: Reactor, solar, SN neutrinos

Cosmic rays, gamma rays and neutrinos come likely from the same sources



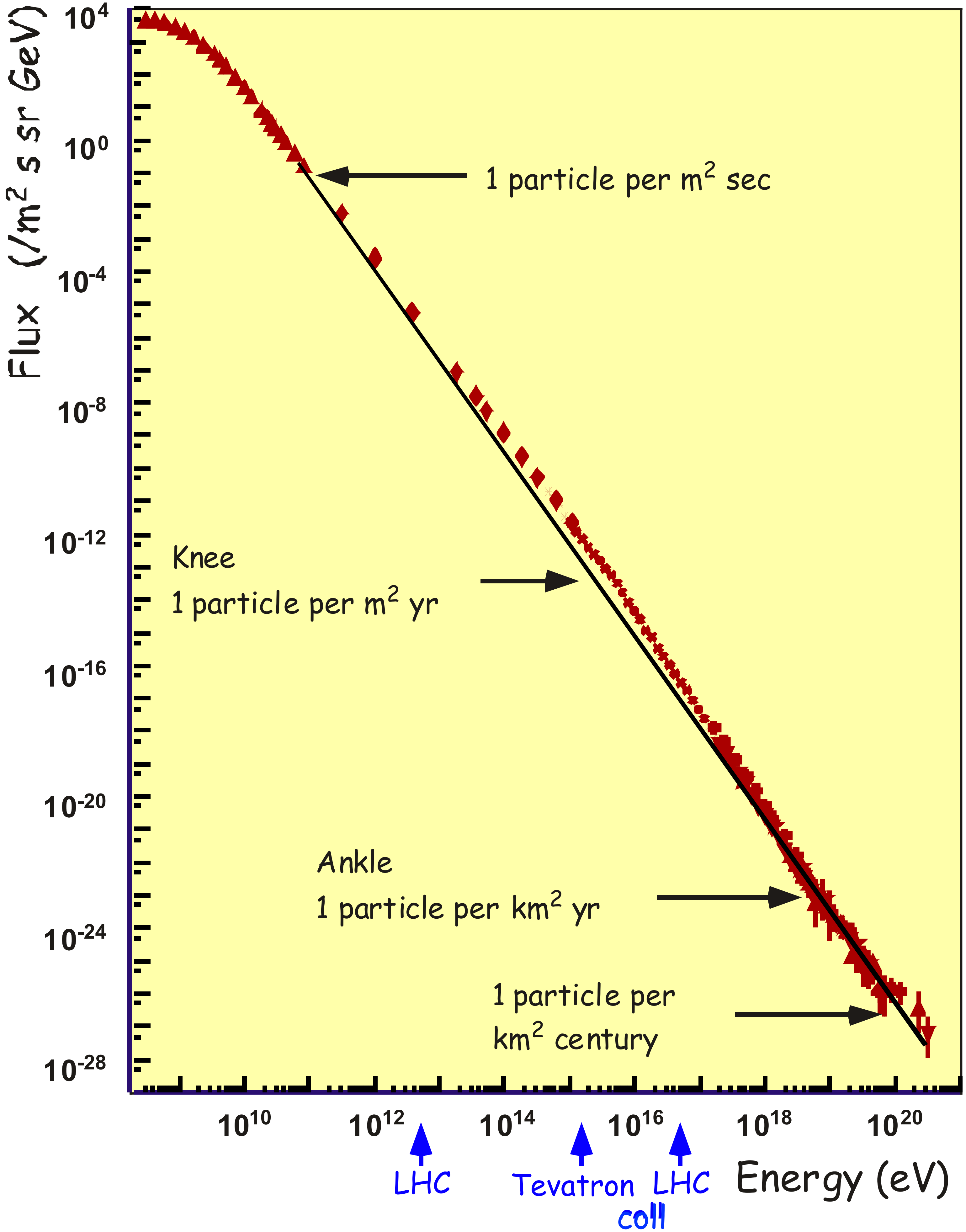
"multi-messenger astrophysics"

but gamma rays are currently the most "productive" messengers.

γ, ν

point back to sources (good for astronomy)
but serious backgrounds

Cosmic Ray spectrum



steeply falling spectra,
low fluxes at high energies

require huge detectors

in general: for all particle types

the higher the energy,
the lower the flux

the lower the flux,
the larger the required detectors

$$N_{evts} = \text{flux} \times \text{area} \times \text{time}$$

N_{evts}: > 100

flux: small, given by nature

area: $\approx 1\ m^2$ for satellite expts.

time: ≈ 3 yrs

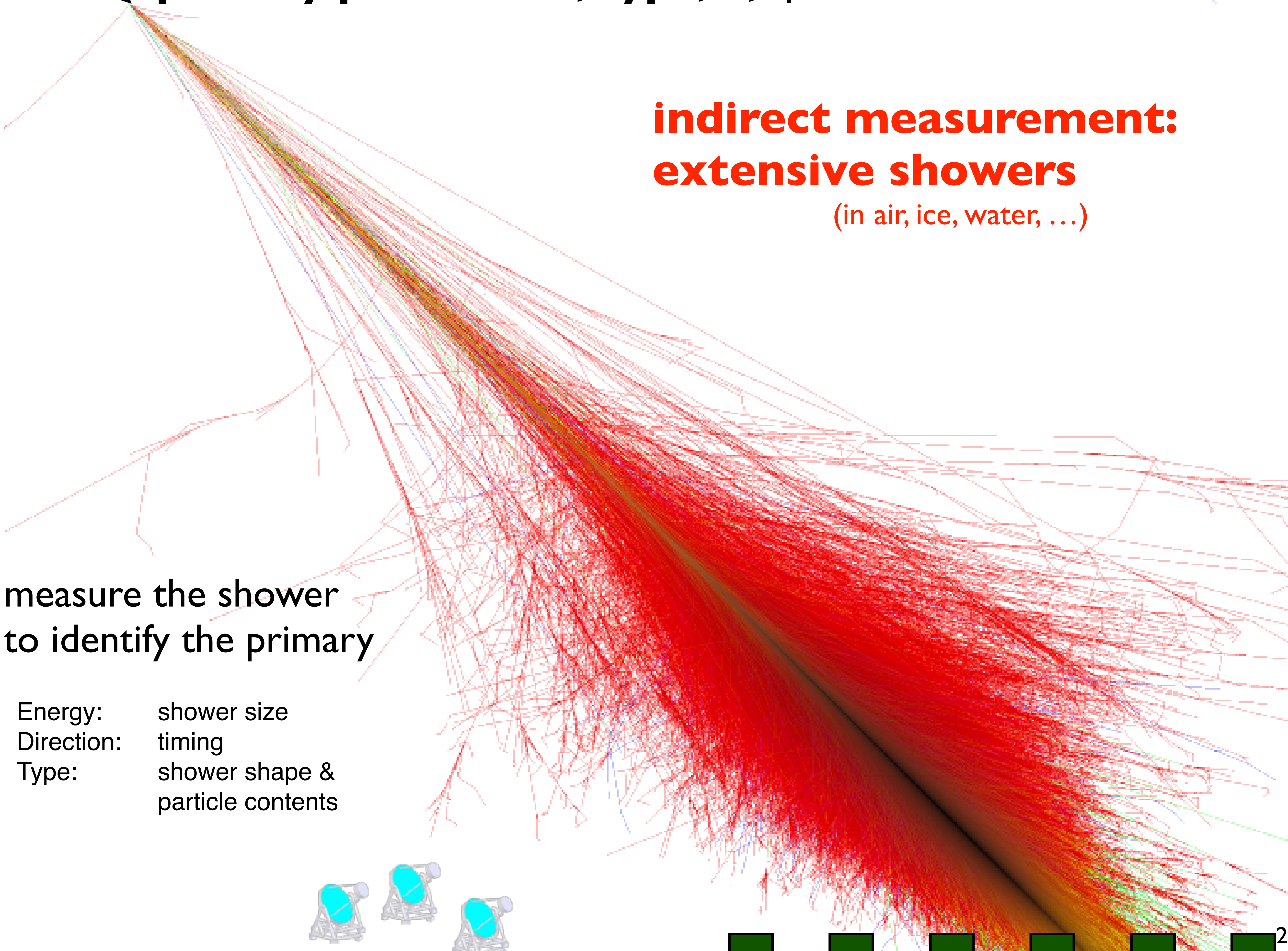
Detector size limits the smallest measurable fluxes.

Large, natural, transparent volume
e.g. the atmosphere
becomes part of the detector:

instrument it (sparsely)
to record secondaries
produced by particle interactions

understand / monitor
the atmosphere

primary particle: E, type, θ, φ



indirect measurement: extensive showers

(in air, ice, water, …)

measure the shower to identify the primary

Energy:	shower size
Direction:	timing
Type:	shower shape & particle contents

Cosmic Rays (are the primary particles)

relativistic, charged particles, up to $>10^{20}$ eV

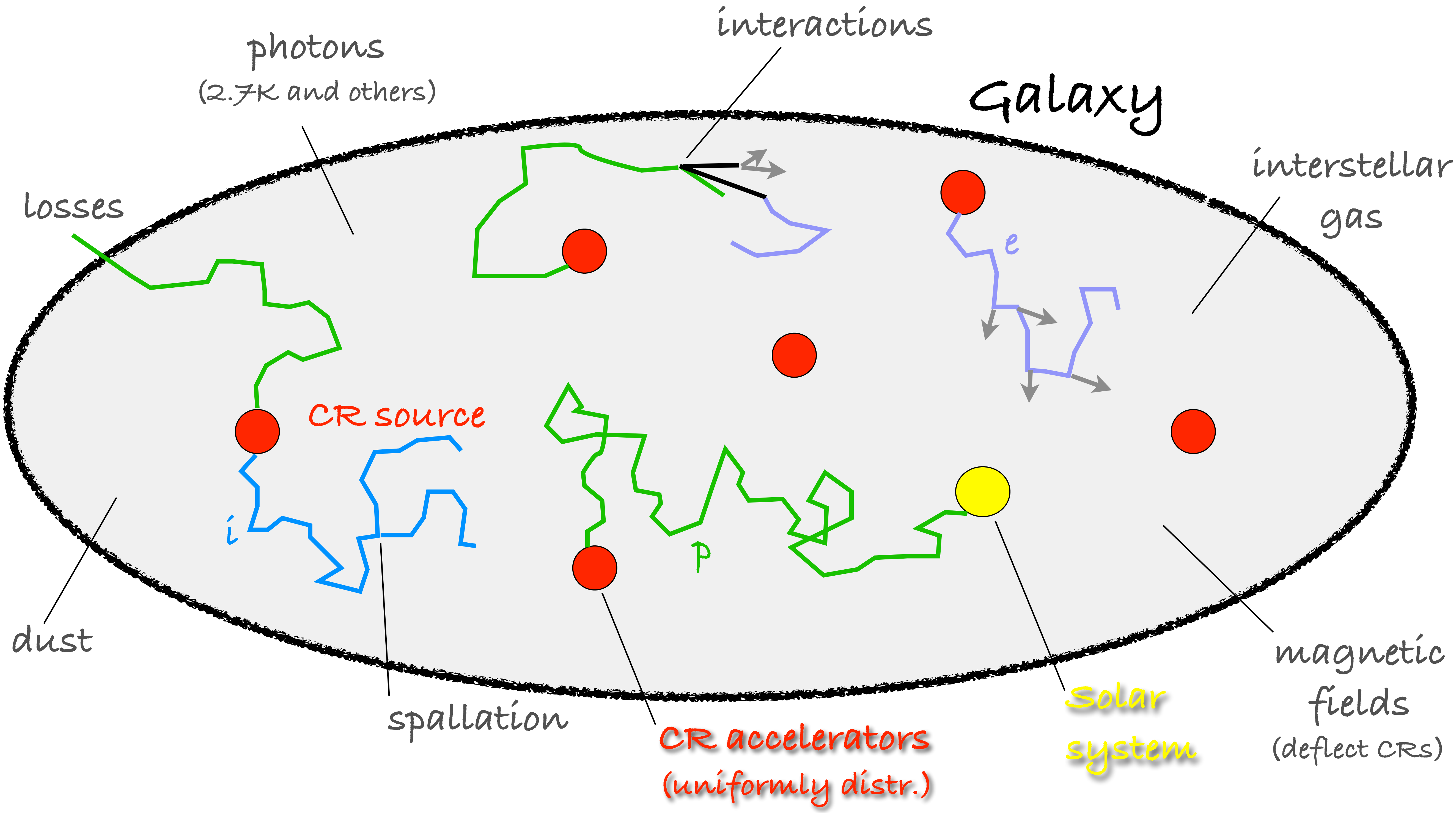
$E_{CR} \approx E_{starlight} \approx E_{CMB} \approx E_{mag} \approx E_{Gas} \approx 1\ \mathrm{eV/cm^3}$

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

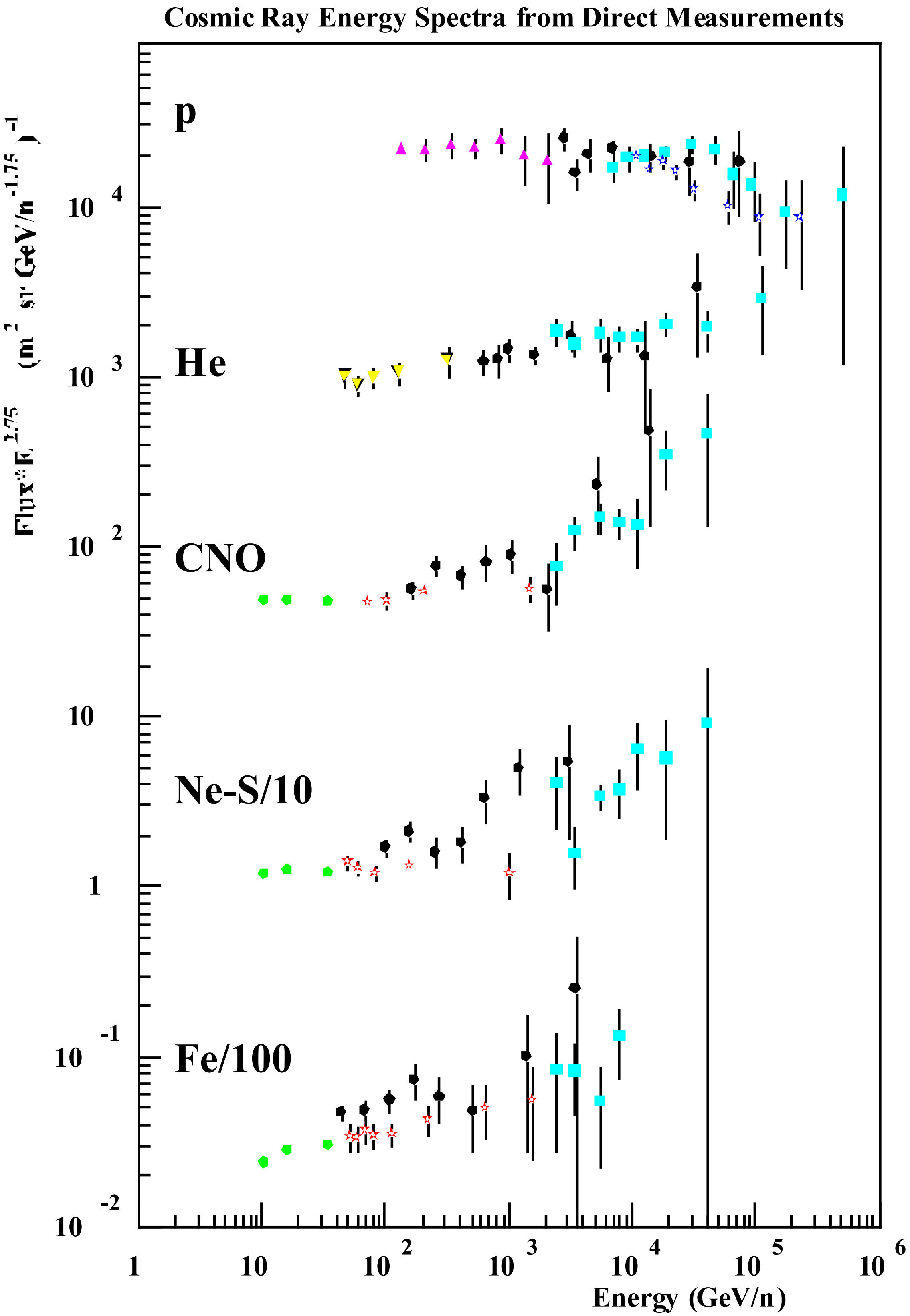
CRs are a major component of our Galaxy
must come from most violent objects in the universe

easy to detect :-)
don't point back :-(

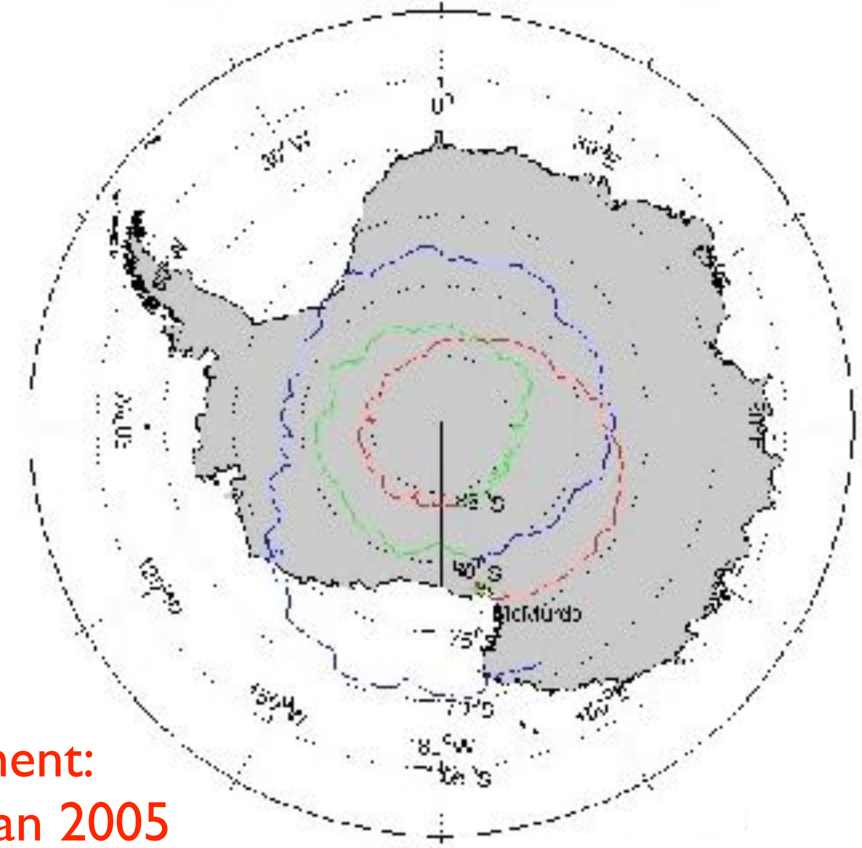
The (simple) world of low energy cosmic rays



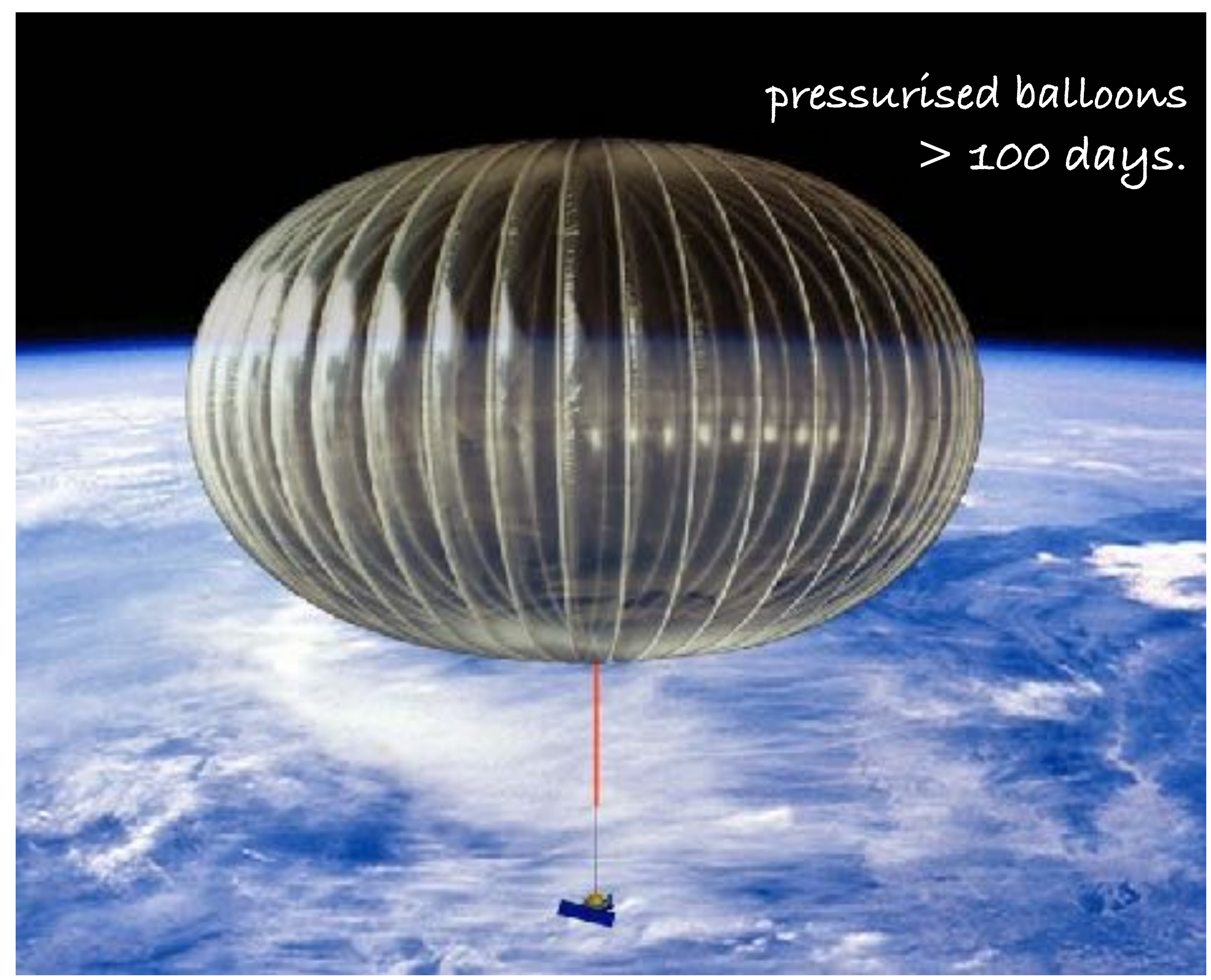
various balloon and satellite experiments ...

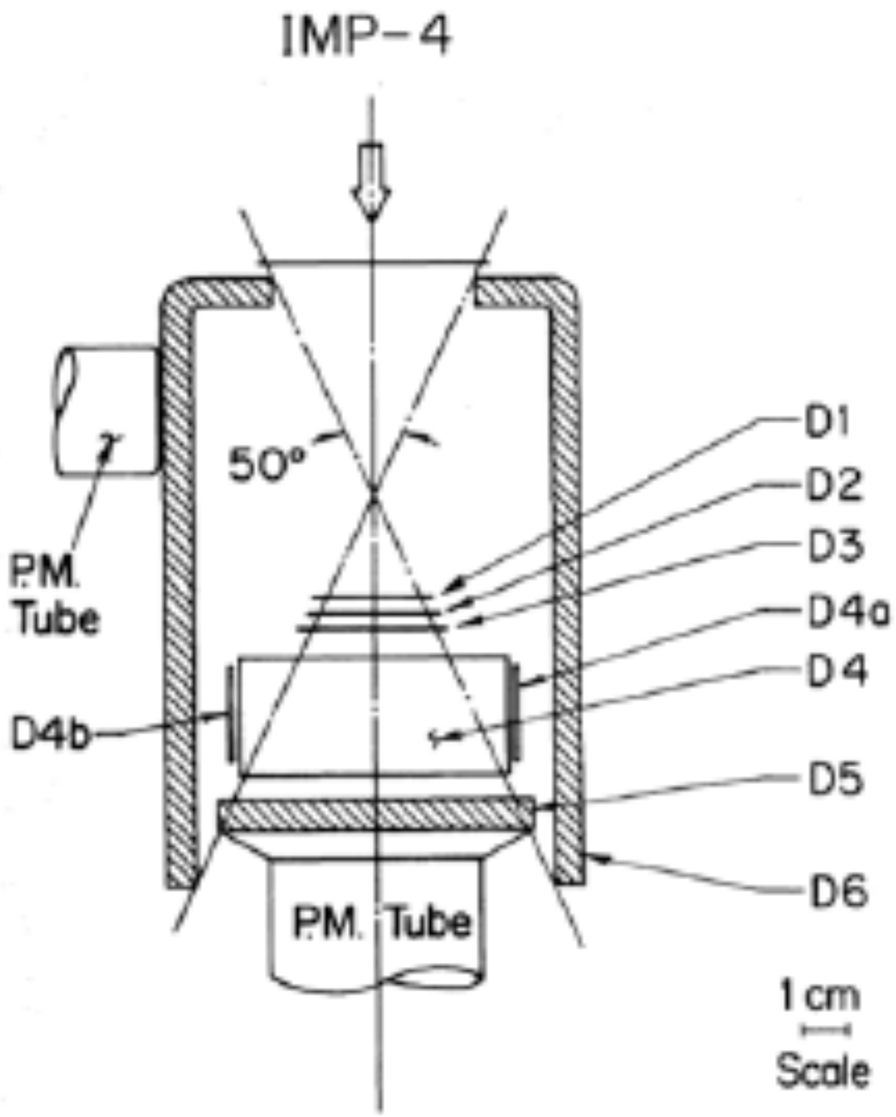


larger detectors?
longer times?



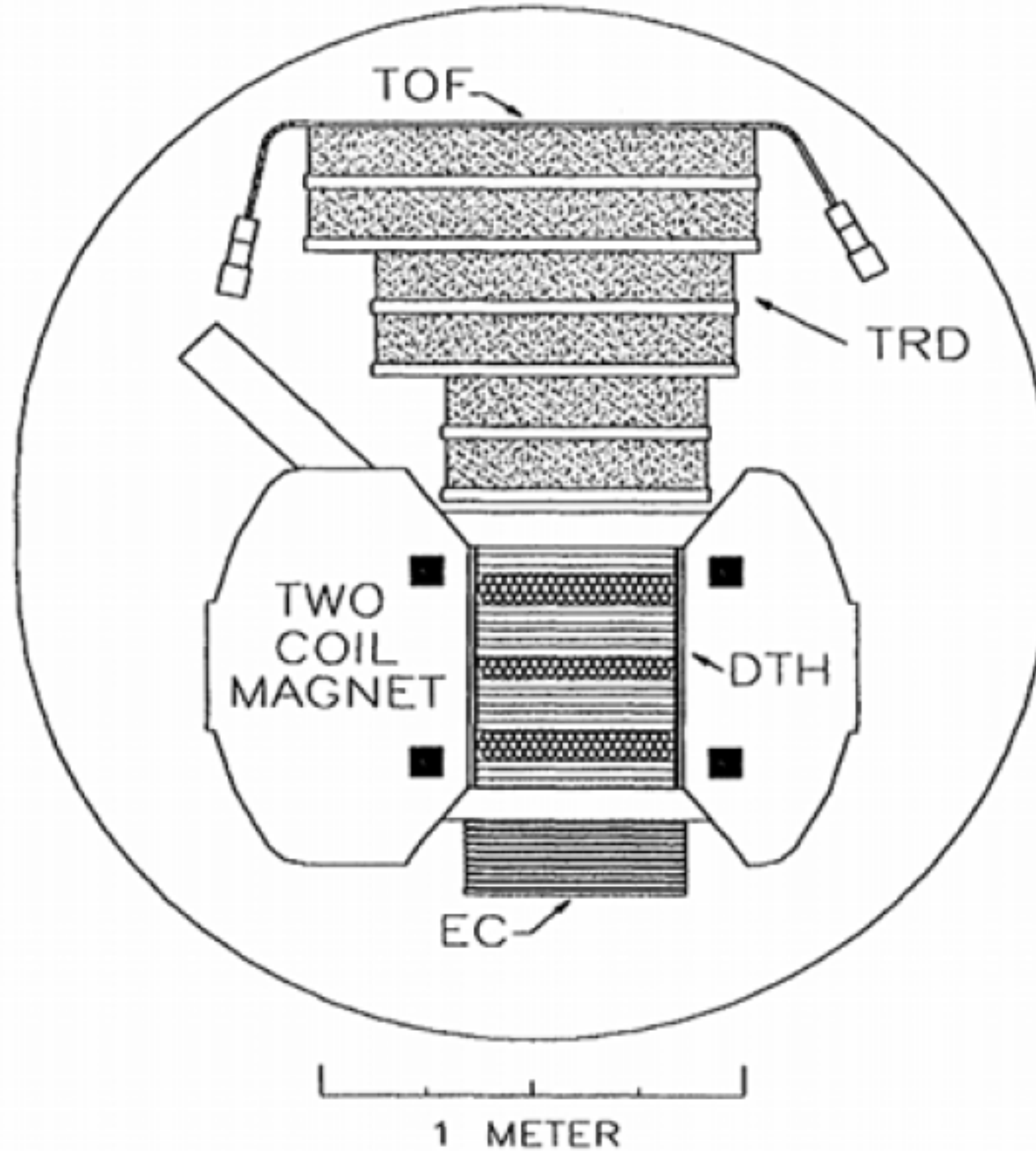
CREAM Experiment:
e.g. 42 days, Jan 2005





IMP-4 ~1970

HEAT 1995



CR Mass Composition
(in GeV range)

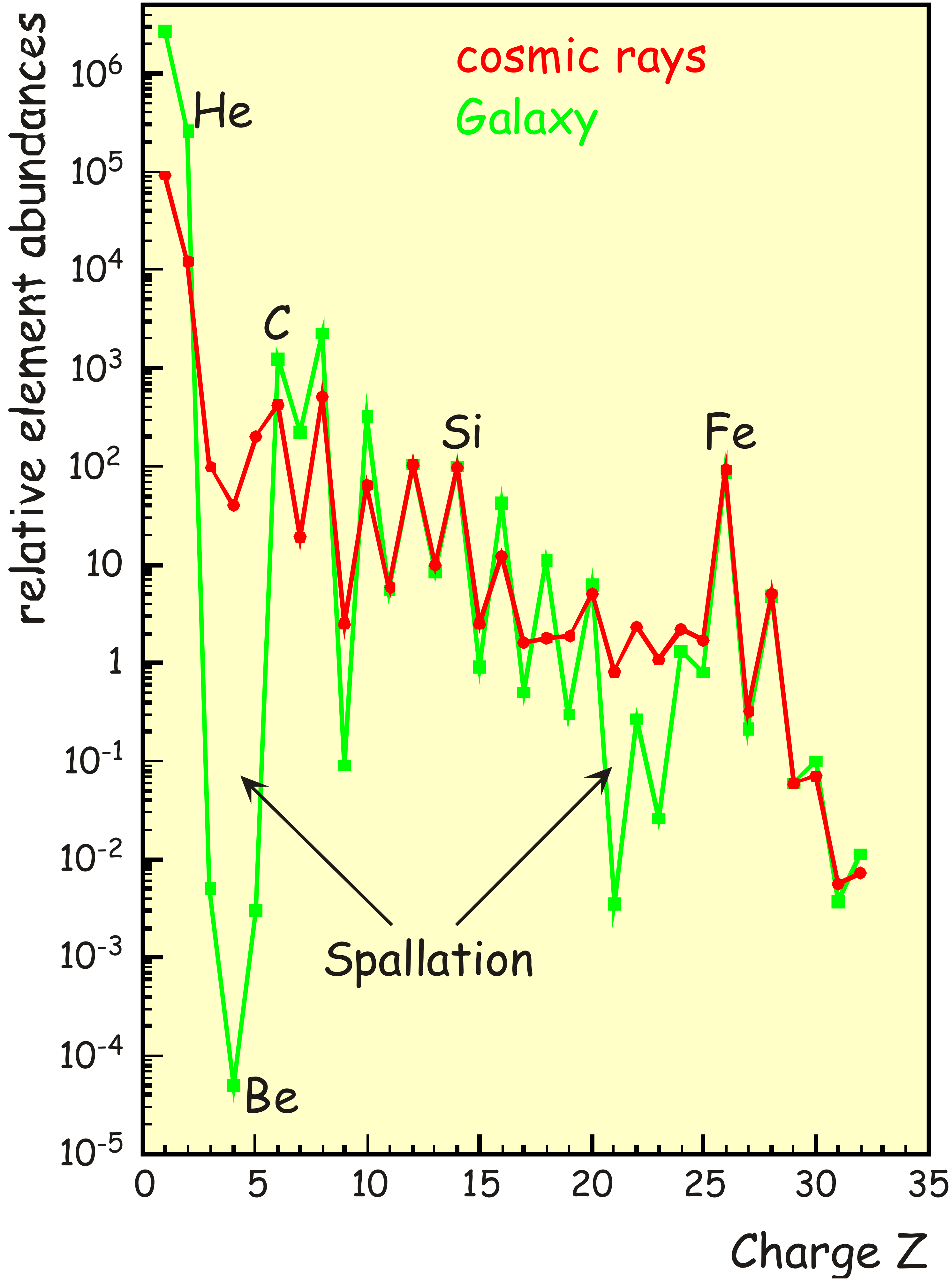
element and isotope composition well known (for E < GeV)

89% p, 9% He, 2% other nuclei
<1% electrons

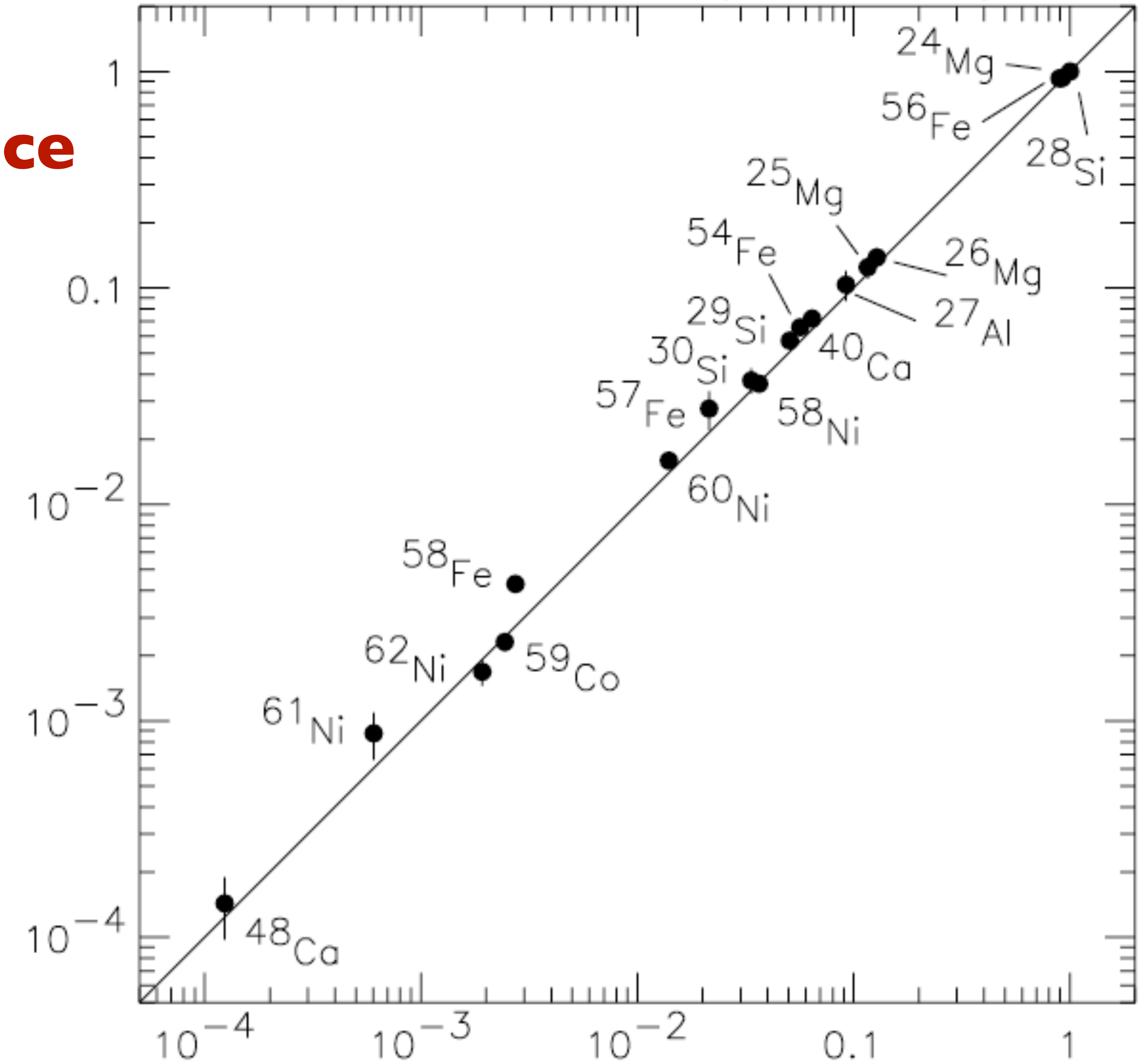
"CRs are star matter"
≈ ejecta from SN (?)

secondary/primary nuclei:
~ 10 g/cm²

unstable/stable secondaries:
~ 10^7 years



Galactic CR source abundance



Solar system abundance

good agreement !
CRs are made from well-mixed "star matter".

The currently favoured model:

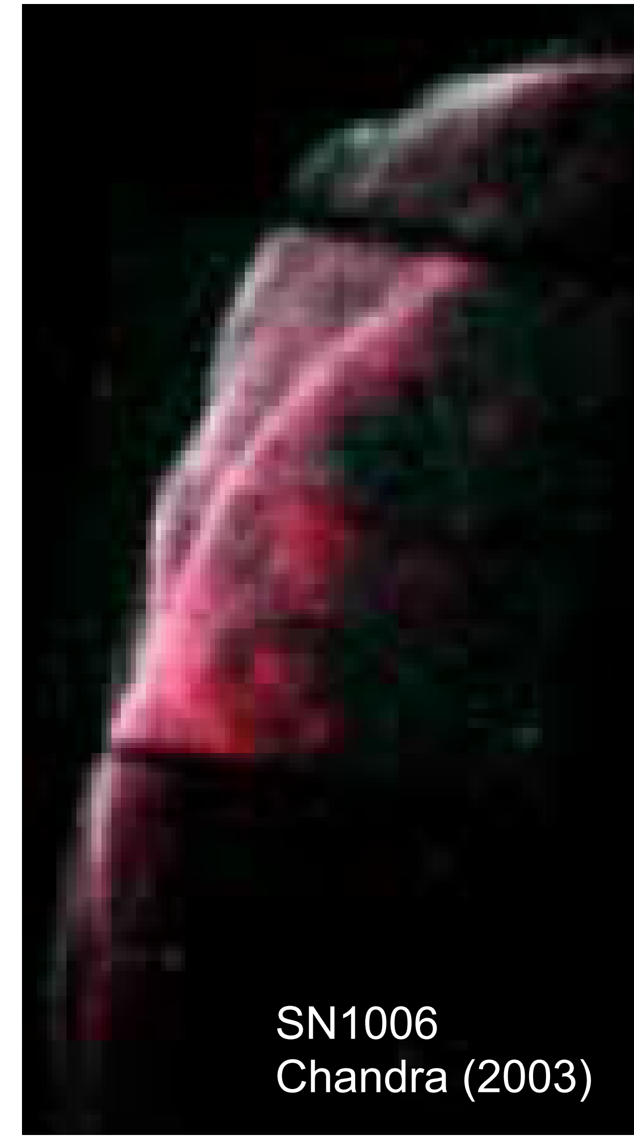
Fermi Acceleration (1^{st} order) in shock fronts

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

in sources

"residence" time in galaxy

measured at Earth



prime source candidates: Supernova Remnants SNR

- frequent & powerful enough to account for observed CR density
- magnetic field amplification (up to $E_{max} \approx Z\ 10^{15}$ eV)

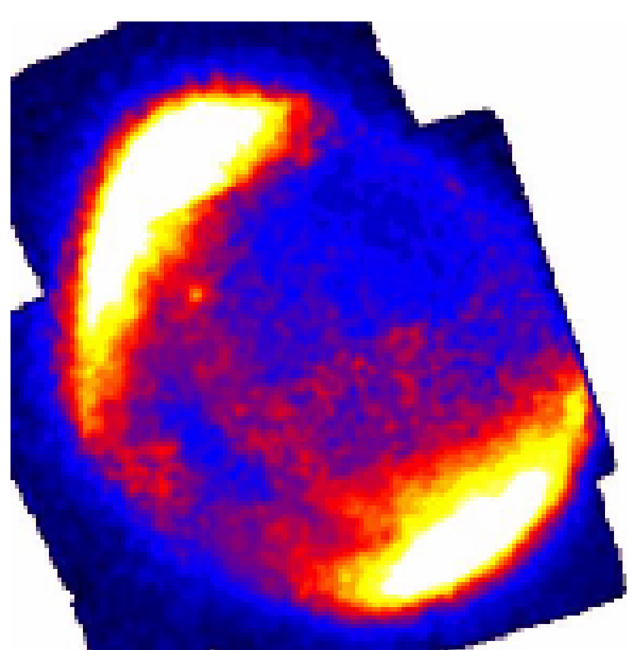
low-energy CRs are galactic,

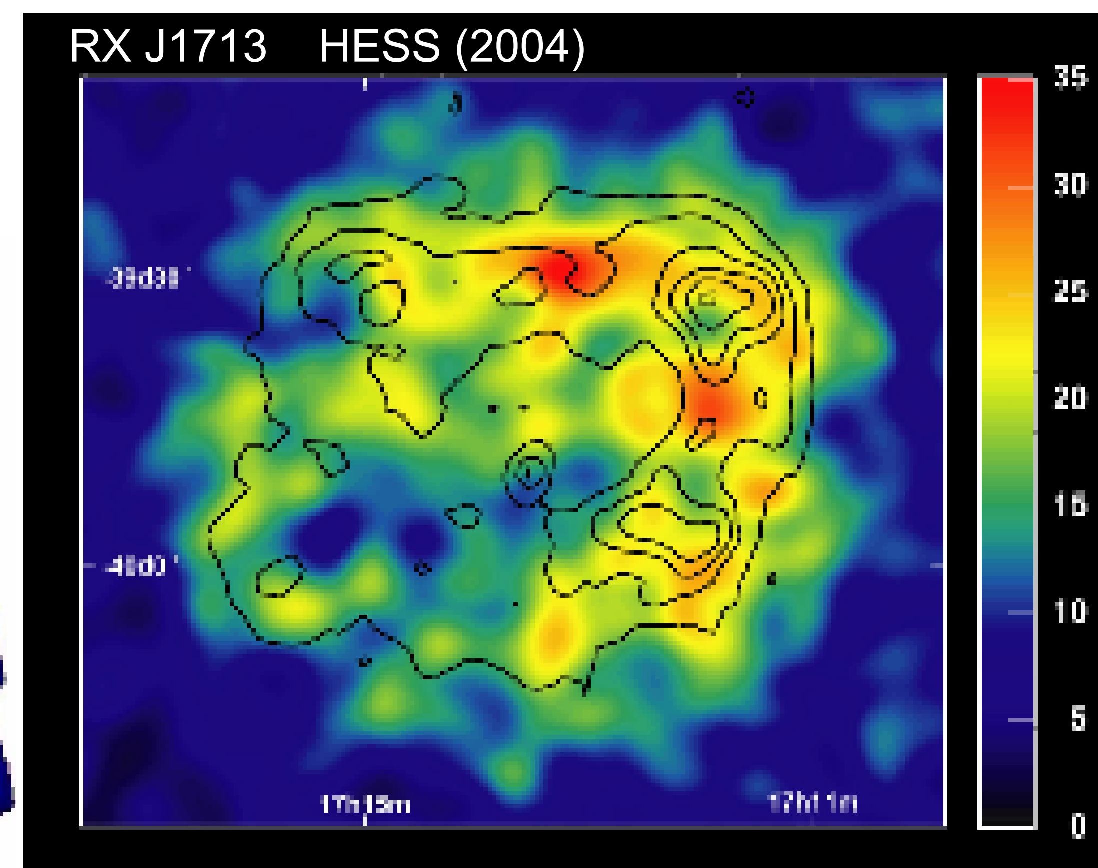
- diffusing in gal. magnetic field

direct evidence ?

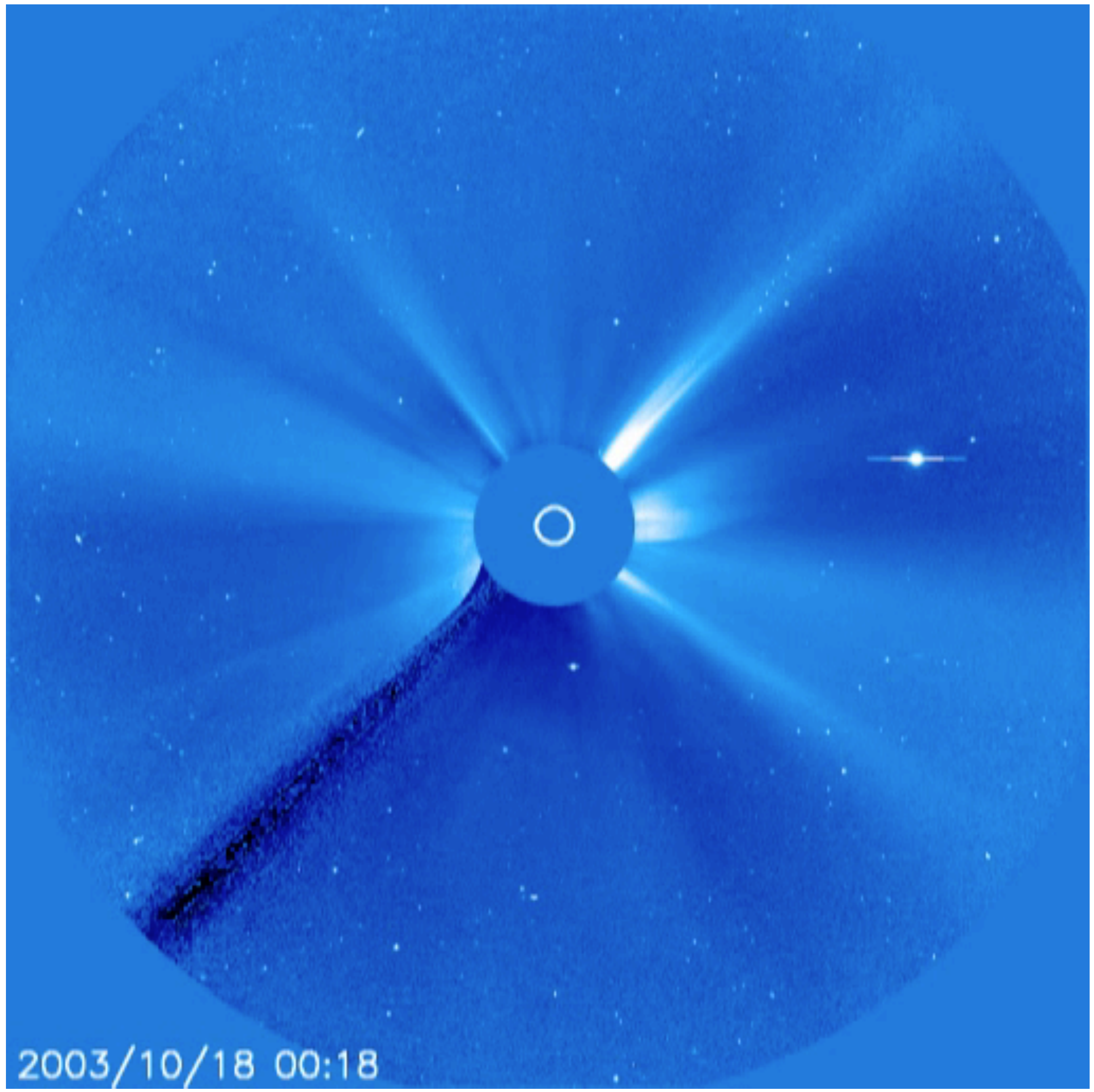
- synchrotron & IC radiation from relativistic electrons
- pion production from CRs

SN1006 ASCA (1995)





Particle Acceleration in magnetic fields does really work ... e.g. in our Sun.



SOHO - Lasco

The power argument for SNR:

Cosmic ray energy density: $\rho \approx 1$ eV / cm^3
Cosmic ray "lifetime": $t \approx 6 \times 10^6$ years
Galaxy volume: $V \approx \pi r^2 d \approx 4.2 \times 10^{66}$ cm^3

$dE/dt = \rho V / t \approx 4 \times 10^{33}$ J/s a galactic phenomenon

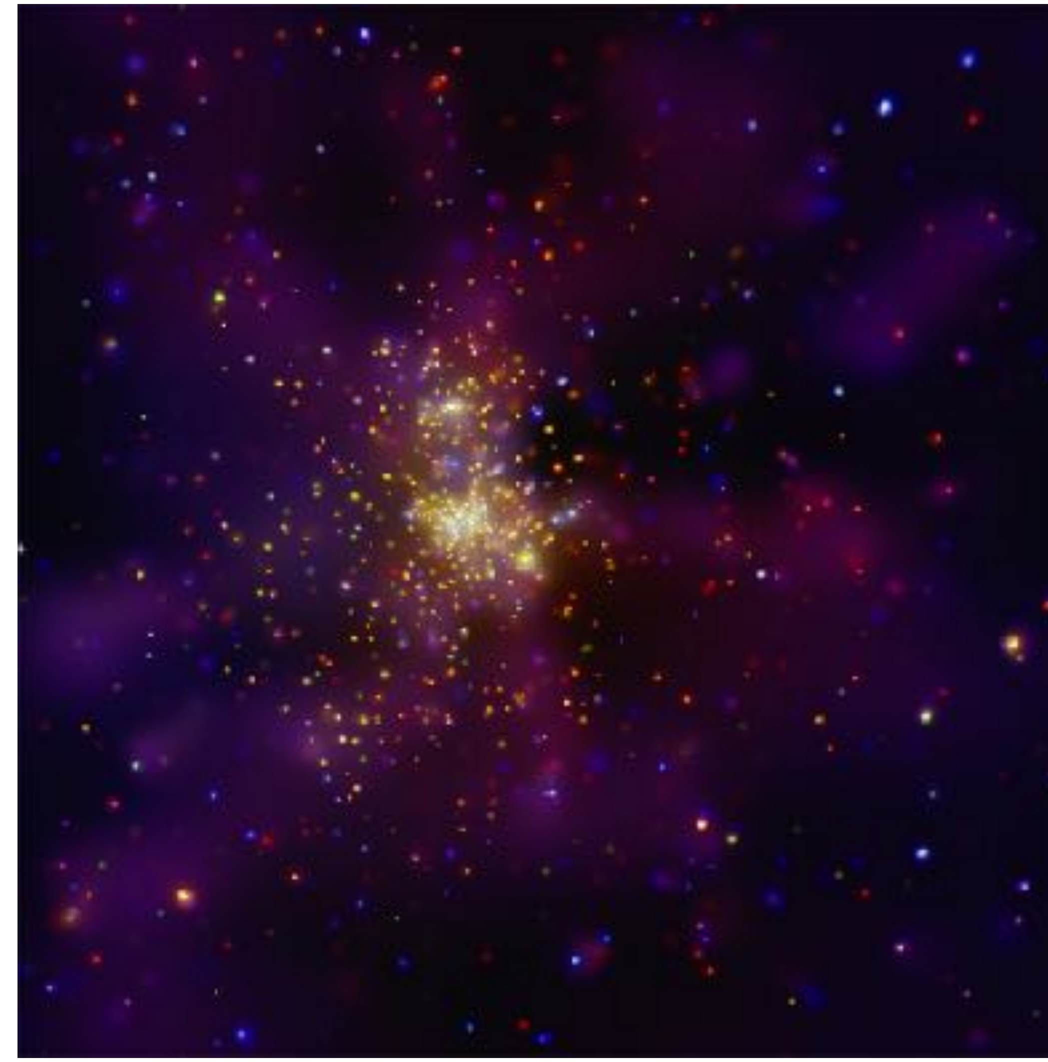
Supernova rate: $f \approx 1 / 30$ years
kinetic energy of emission: $E \approx 10^{44}$ J
fraction in CRs: $\varepsilon \approx 10$ %

$dE/dt = f \varepsilon E \approx 10^{34}$ J/s

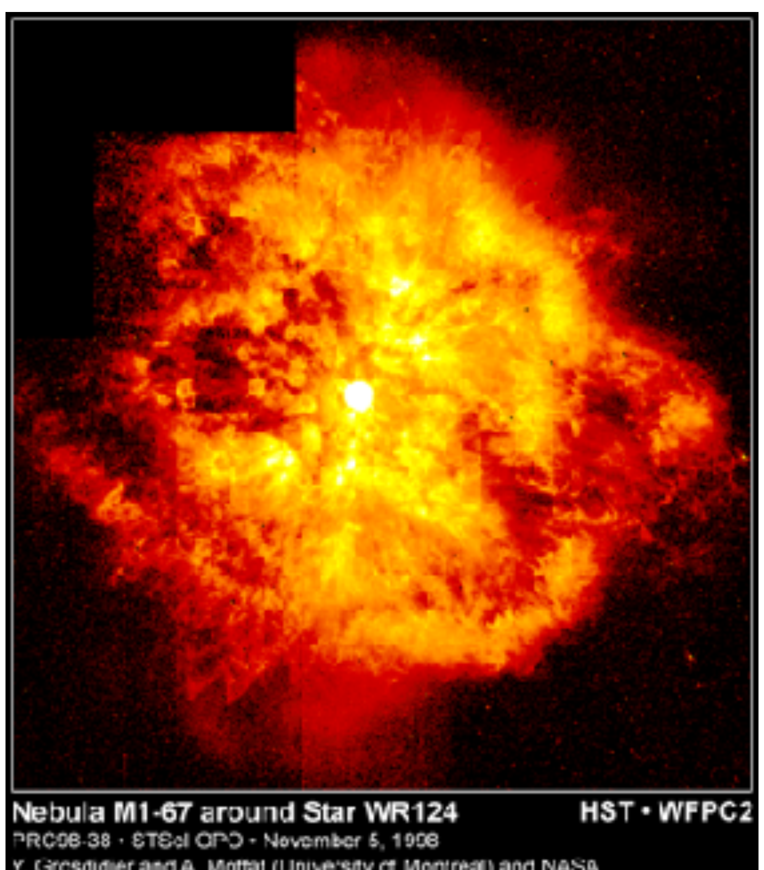
No obvious alternative can provide this energy.
... thus, Supernovae are prime candidates
for the sources of cosmic rays.

... but other sources could contribute too.

Superbubbles



Star forming regions



Wolf-Rayet Stars

... all producing outflows and shock fronts where particles can be accelerated (seen in X-rays and gamma rays)

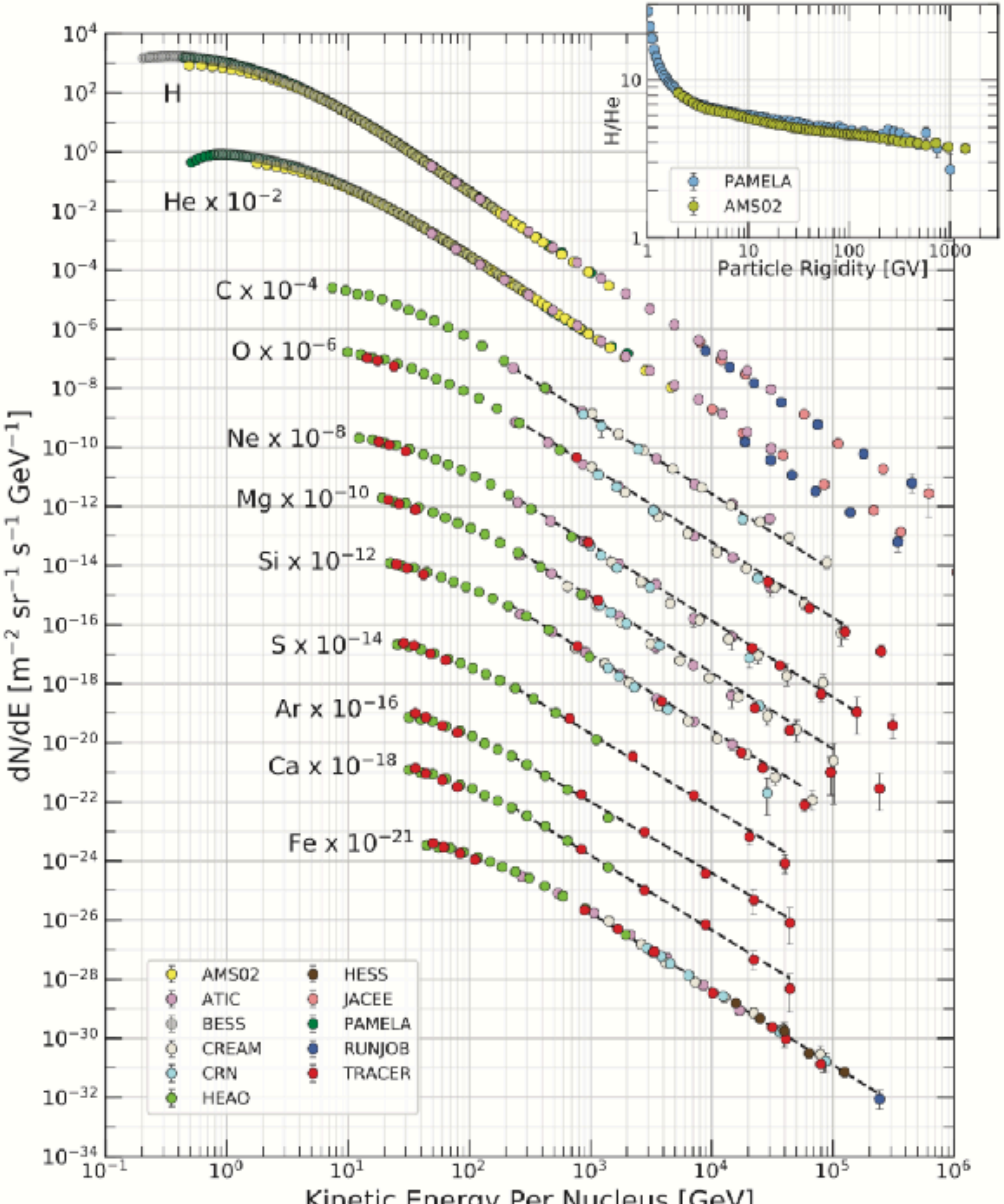
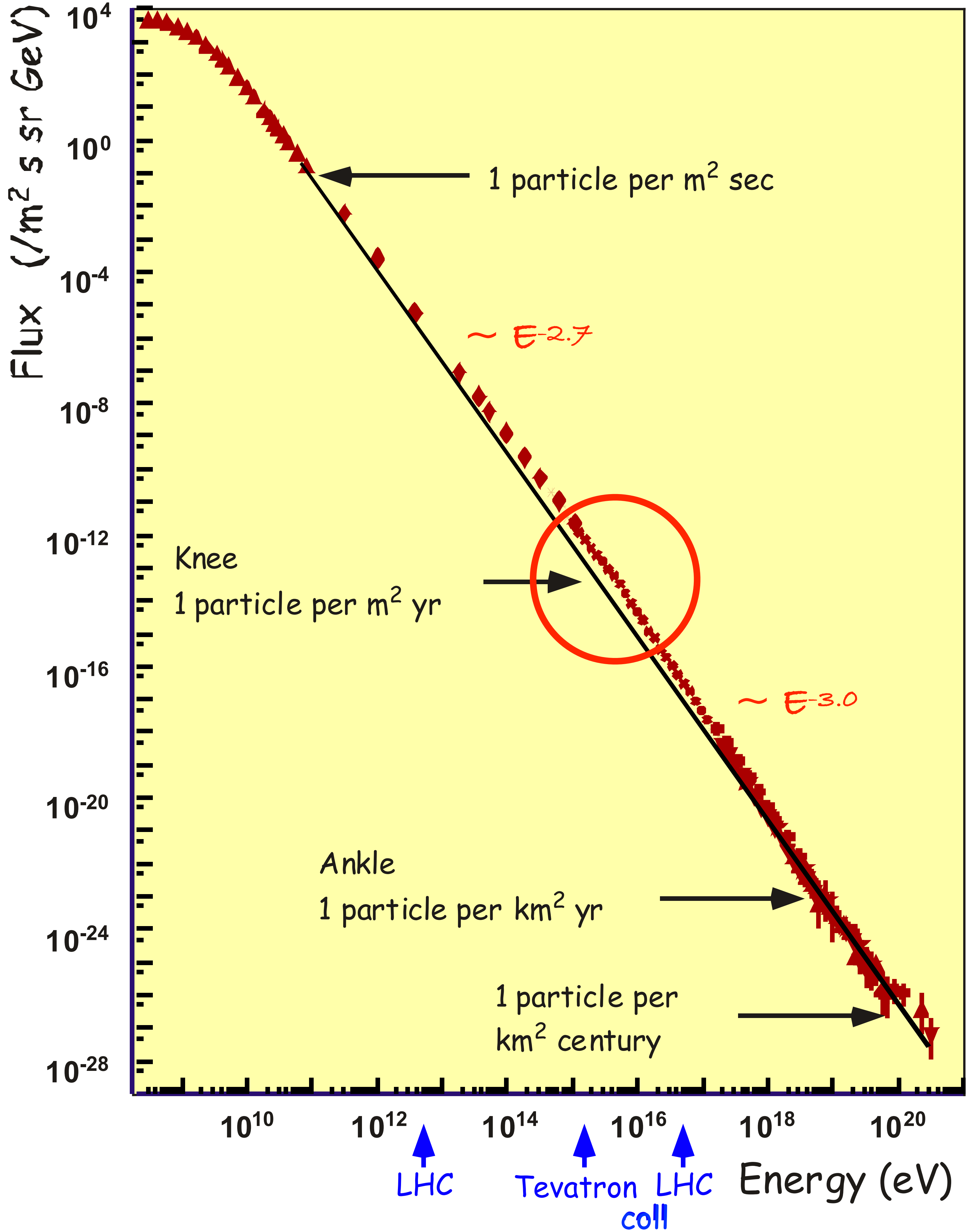


Figure 30.1: Fluxes of nuclei of the primary cosmic radiation in particles per energy-per-nucleus are plotted vs energy-per-nucleus using data from Refs. [2–13]. The inset shows the H/He ratio at constant rigidity [2,4].

Flux of Cosmic Rays



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

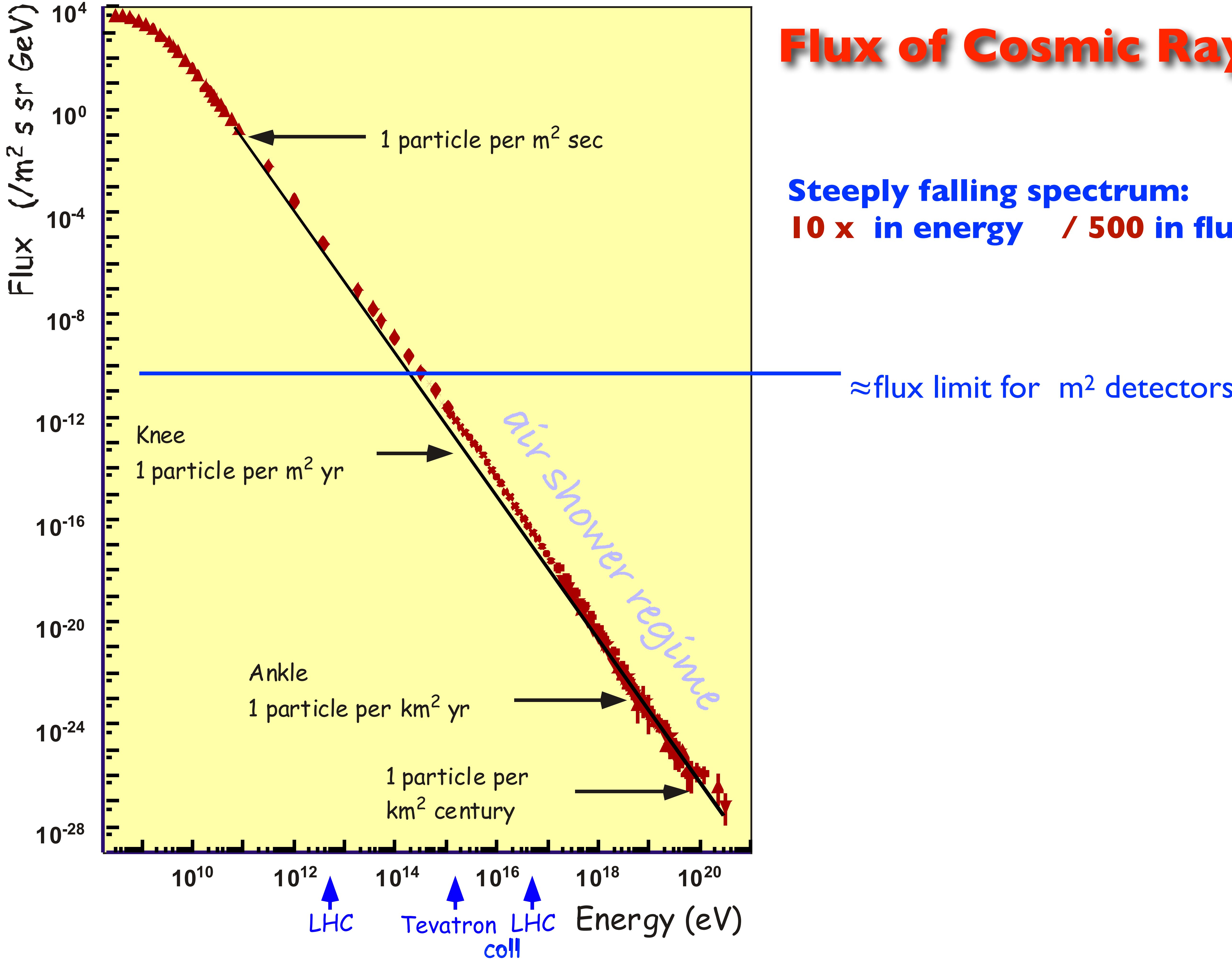
CR are detected up to
highest energies: > 10^{20} eV

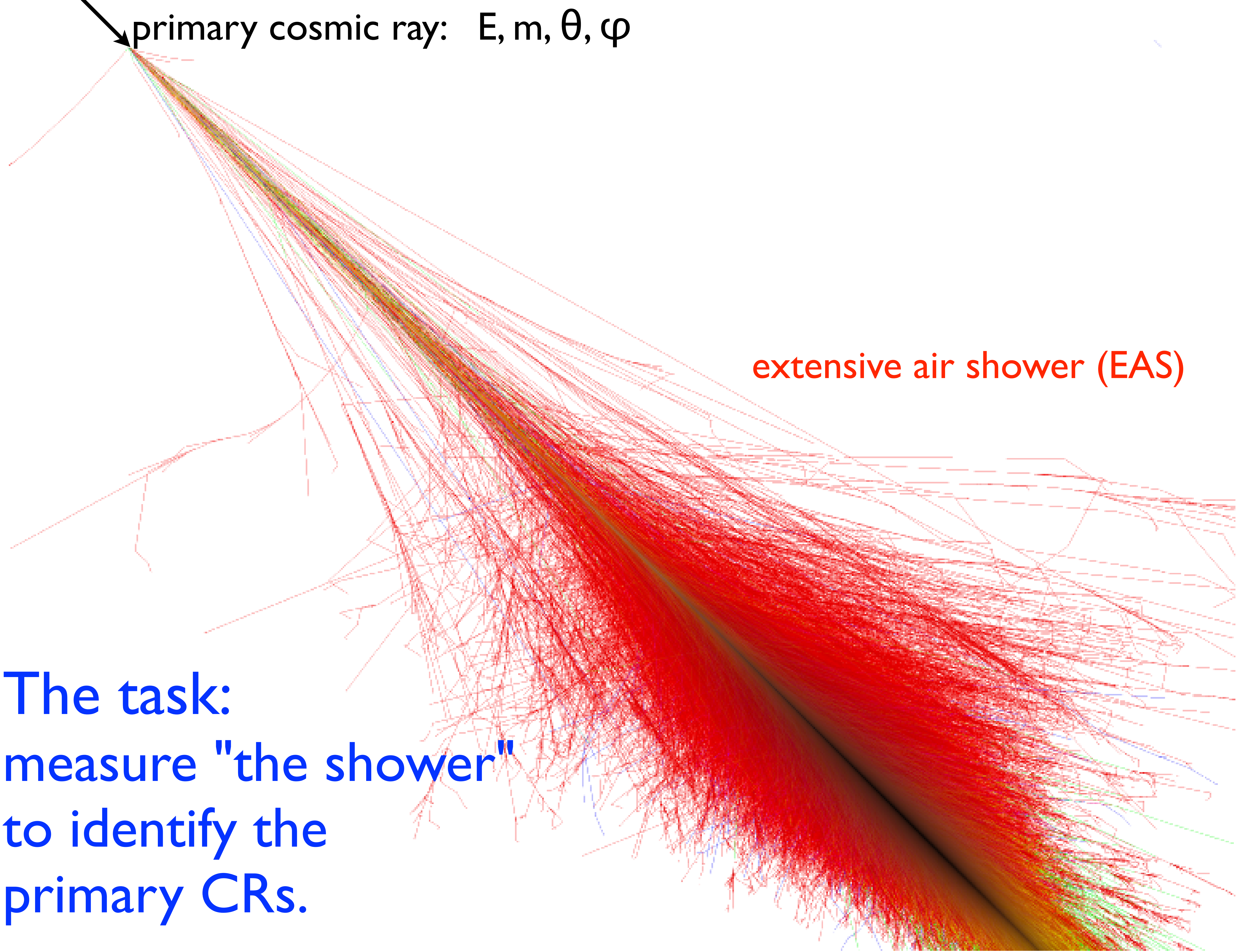
Power law with not much structure.
(makes it difficult to interpret)

One process at work over the whole energy range ???

Flux of Cosmic Rays

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

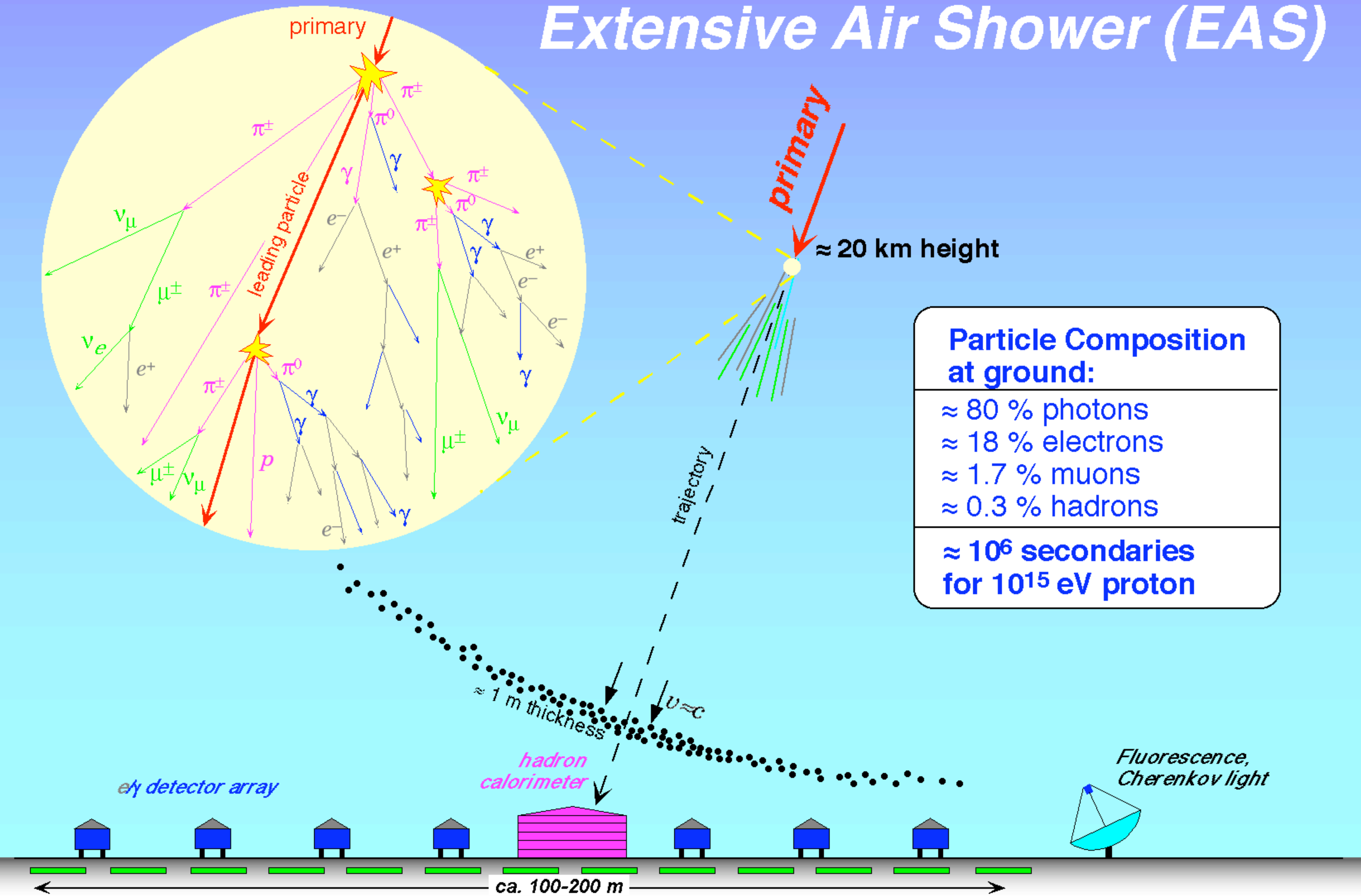




The task:

measure "the shower" to identify the primary CRs.

Extensive Air Shower (EAS)



Particle Composition at ground:

≈ 80 % photons
≈ 18 % electrons
≈ 1.7 % muons
≈ 0.3 % hadrons

≈ 10^6 secondaries for 10^{15} eV proton

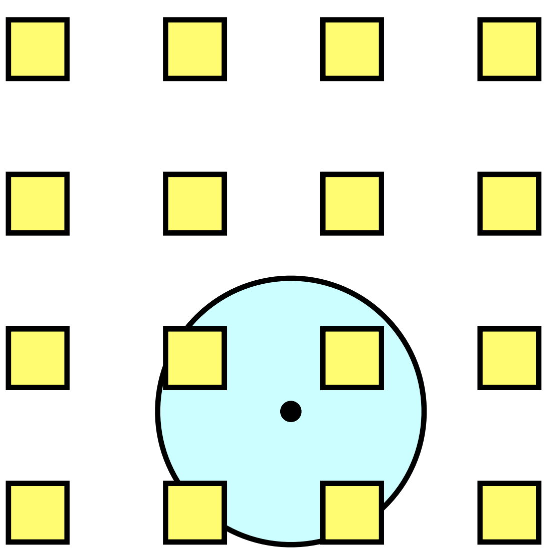
Detection Techniques I

Particle detectors at ground level

large detector arrays (scintillators, wire chambers, calorimeters, Cherenkov det.)
only a small sub-set of secondary particles are recorded
(numbers of particles, densities, energies, angles, arrival times, ...)

e.g.	area	d	coverage	energy range
Kascade	0.04 km^2	15 m	1.5×10^{-2}	10^{-14} - 10^{-16} eV
Haverah Park	12 km^2			10^{-16} - 10^{-18} eV
Yakutsk	25 km^2			10^{-17} - 10^{-19} eV
AGASA	100 km^2	1 km	2.5×10^{-6}	10^{-17} - 10^{-20} eV
Auger SD	3000 km^2	1.5 km	5.3×10^{-6}	10^{-18} - 10^{-20} eV

100% duty cycle, relatively easy to operate
aperture = area of array (independent of energy)
energy resolution $\sigma(E)/E \approx 30\%$
but: primary energy / mass composition is model dependent



Sample lateral distribution with an array of detectors

A: area of the array

determines the rate of high energy events recorded

(i.e. the maximum energy via limited statistics)

d: grid distance

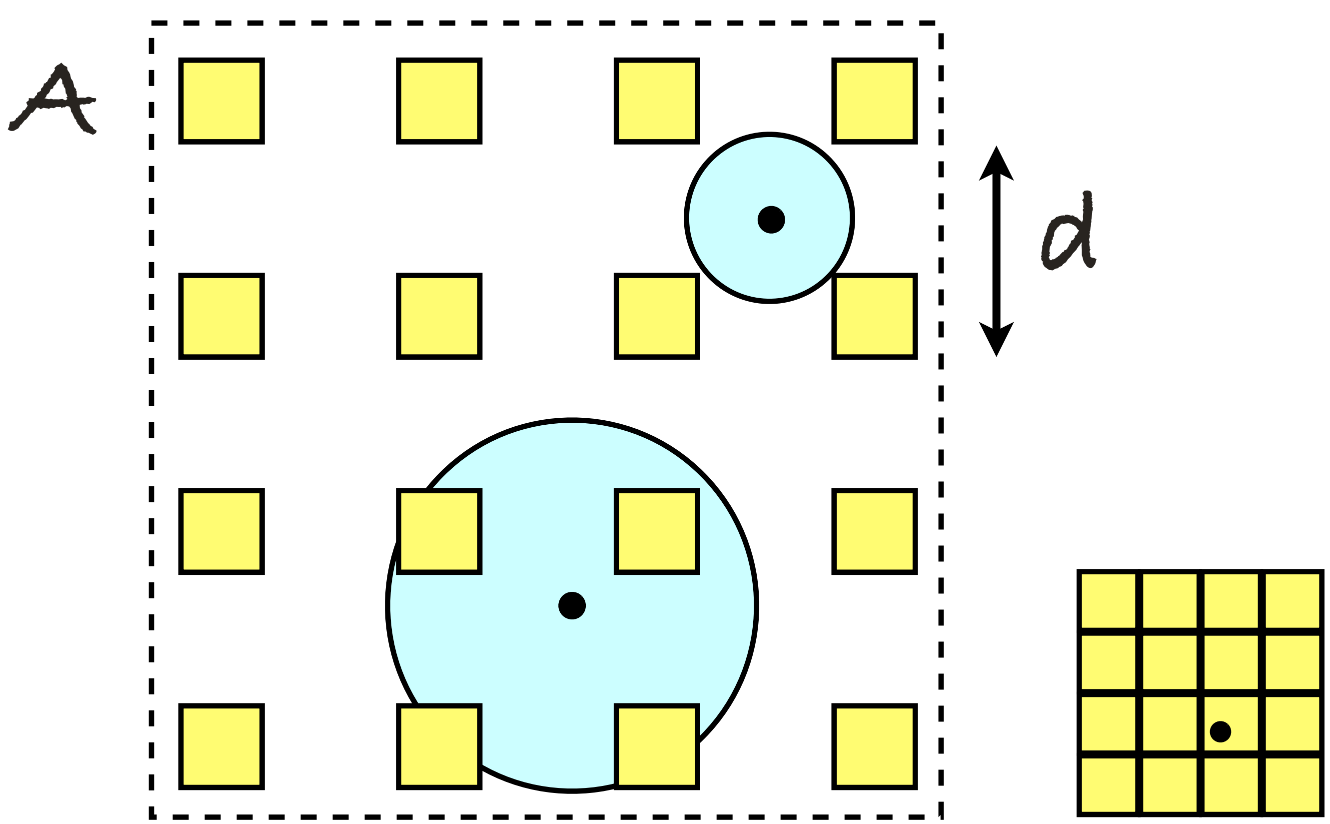
determines the low energy threshold

(small showers are lost in gaps between detectors.)

and the quality of sampling of the shower

C_d: Cost per detector

determines quality, size, efficiency, resolution, ... i.e. detail of measurement



For best physics:

A: large, d: small, C_d: high

but cost rises with $C_d \, A/d^2$

Always compromise needed.

How good is "good enough"?

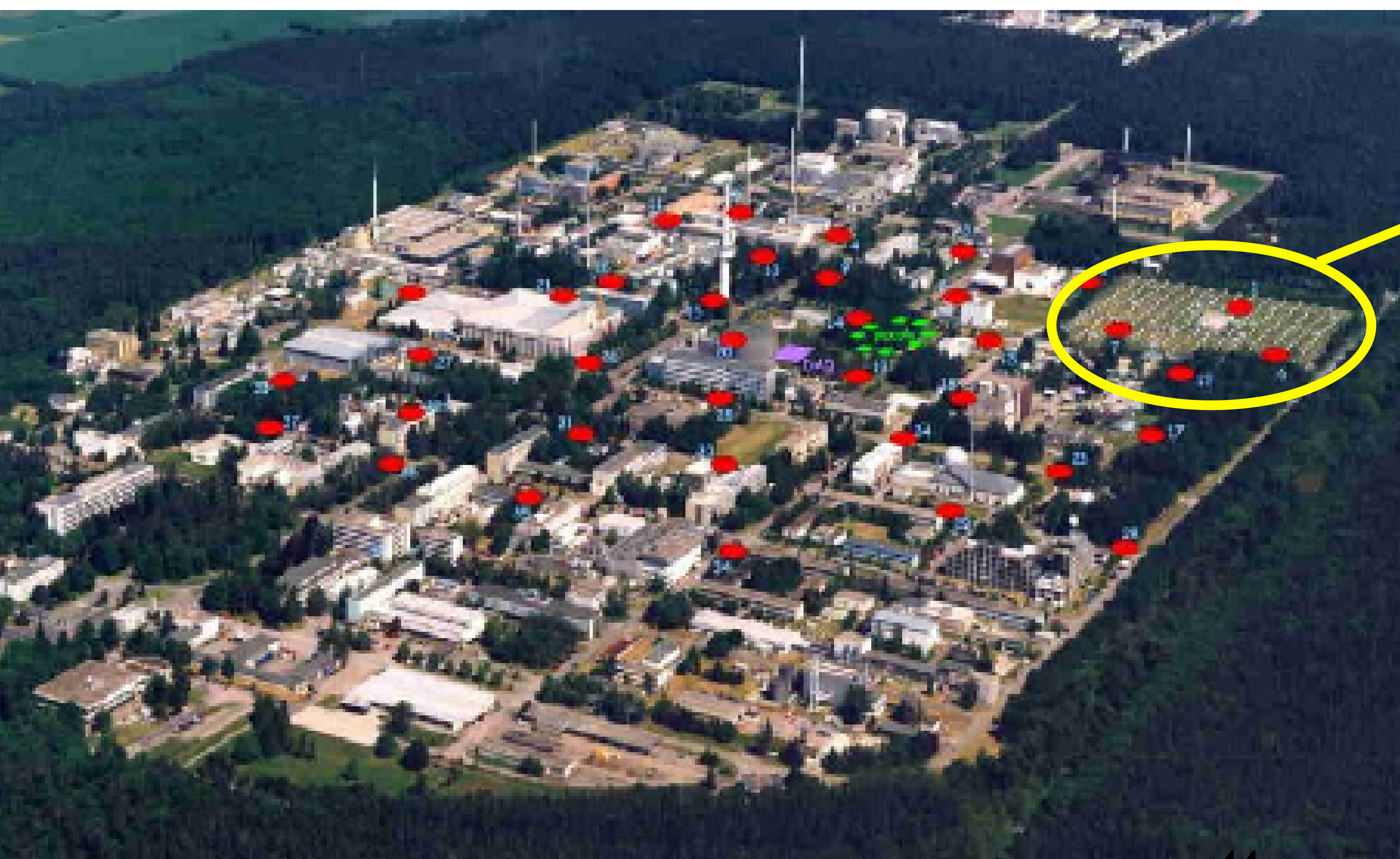
KASCADE
KASCADE Grande

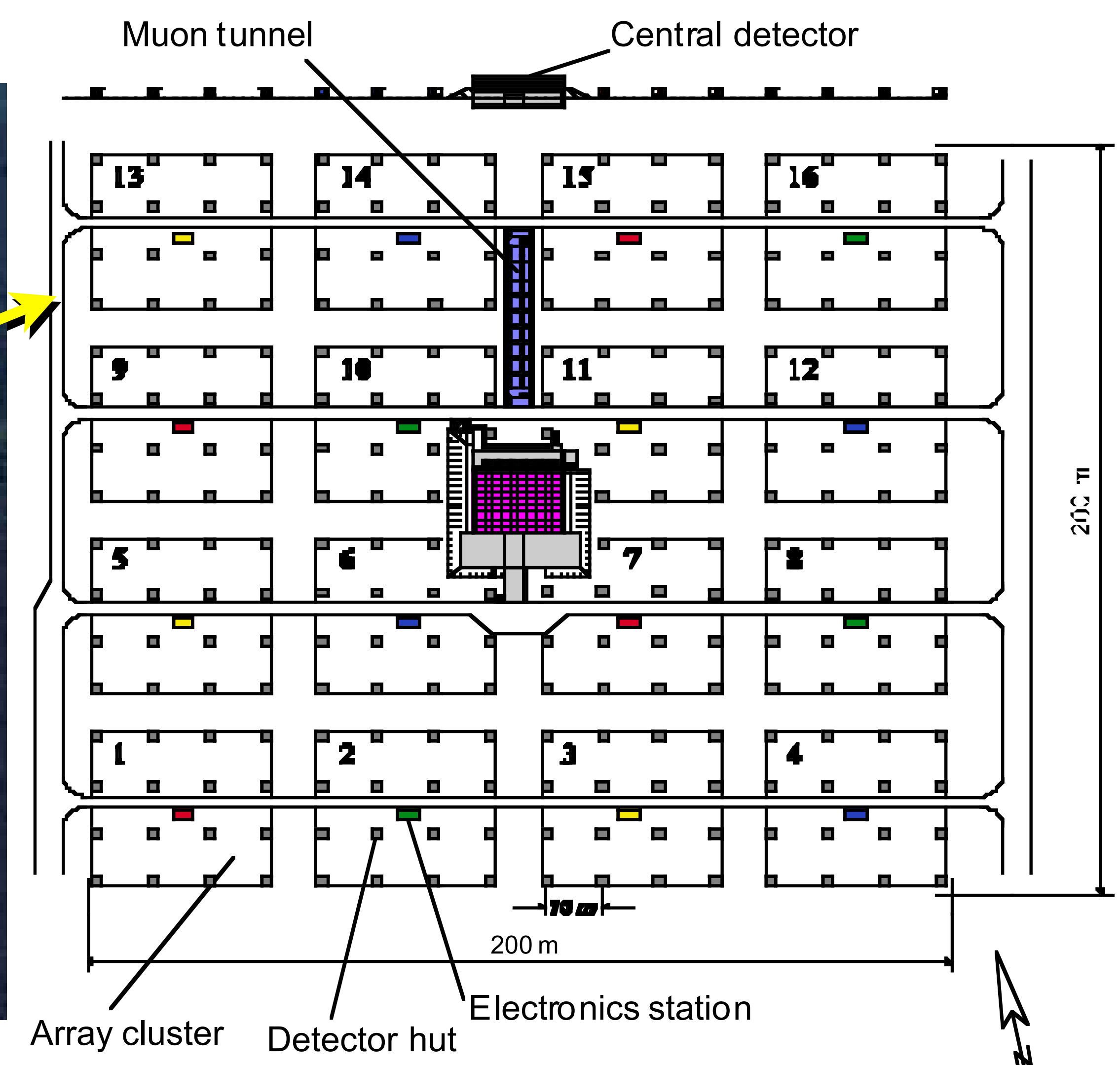
Karlsruhe

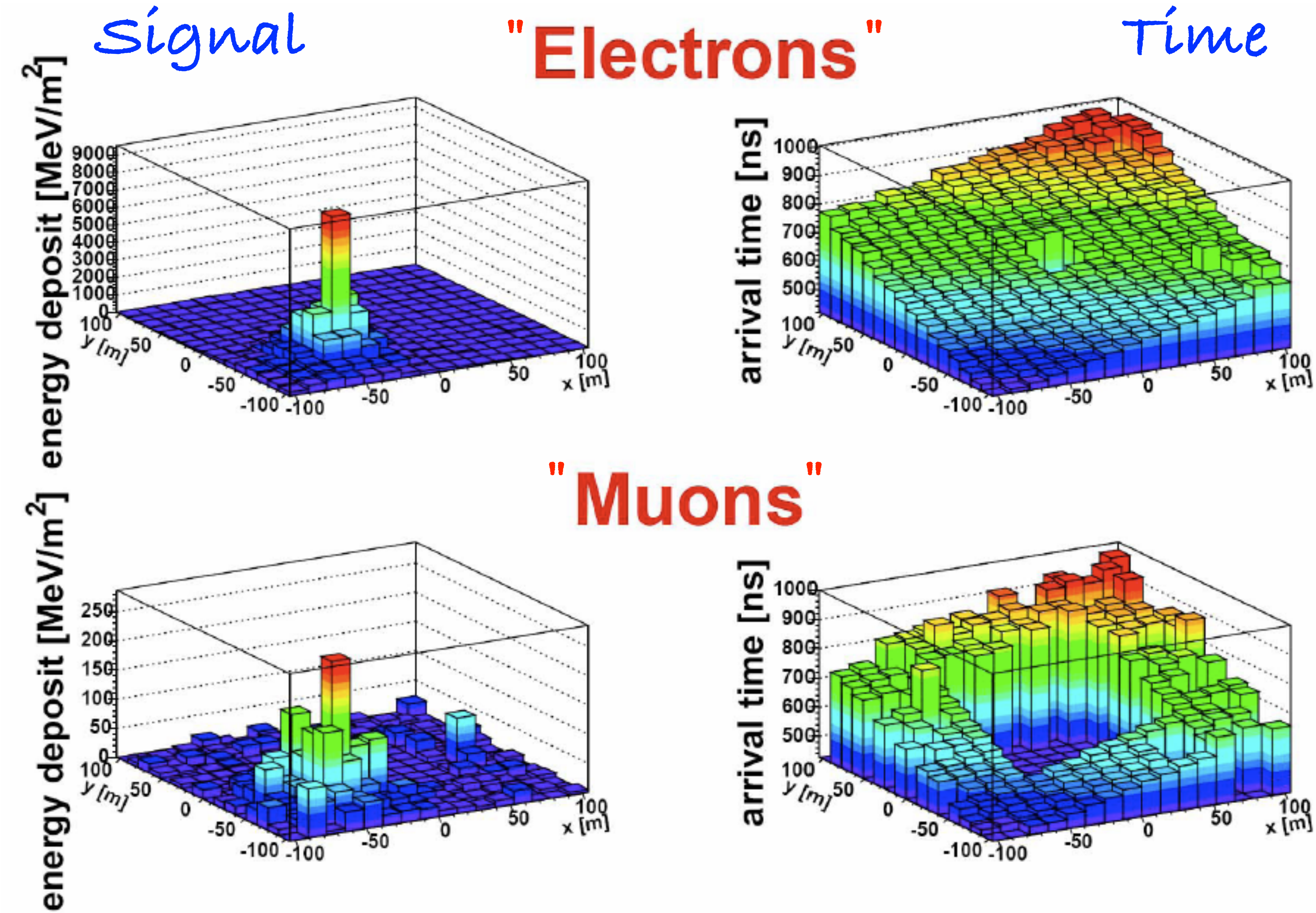
array of electron/gamma/muon detectors

200 x 200 m^2 E $\approx 10^{14} - 10^{16}$ eV

1 x 1 km^2 E $\approx 10^{14} - 10^{18}$ eV






Signal
"Electrons"
Time
energy deposit [MeV/m²]
arrival time [ns]
"Muons"
energy deposit [MeV/m²]
arrival time [ns]
y [m]
x [m]

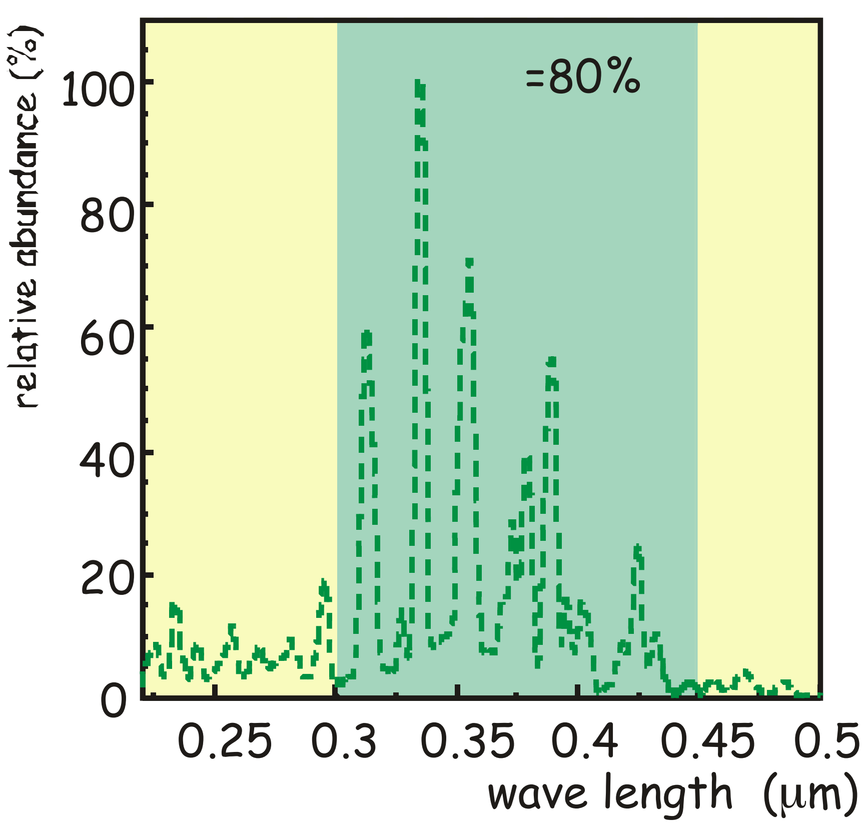
Detection Techniques 2

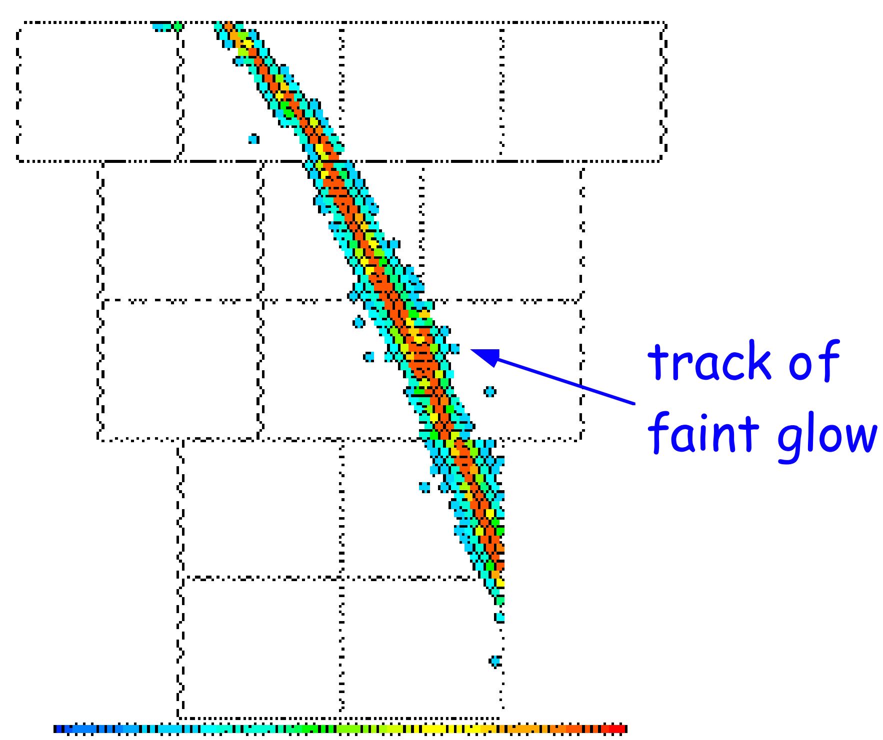
Fluorescence of N_2 molecules in atmosphere, isotropic emission
little absorption in atmosphere, view also upper part of shower
calorimetric energy measurement as functio. of atmospheric depth

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

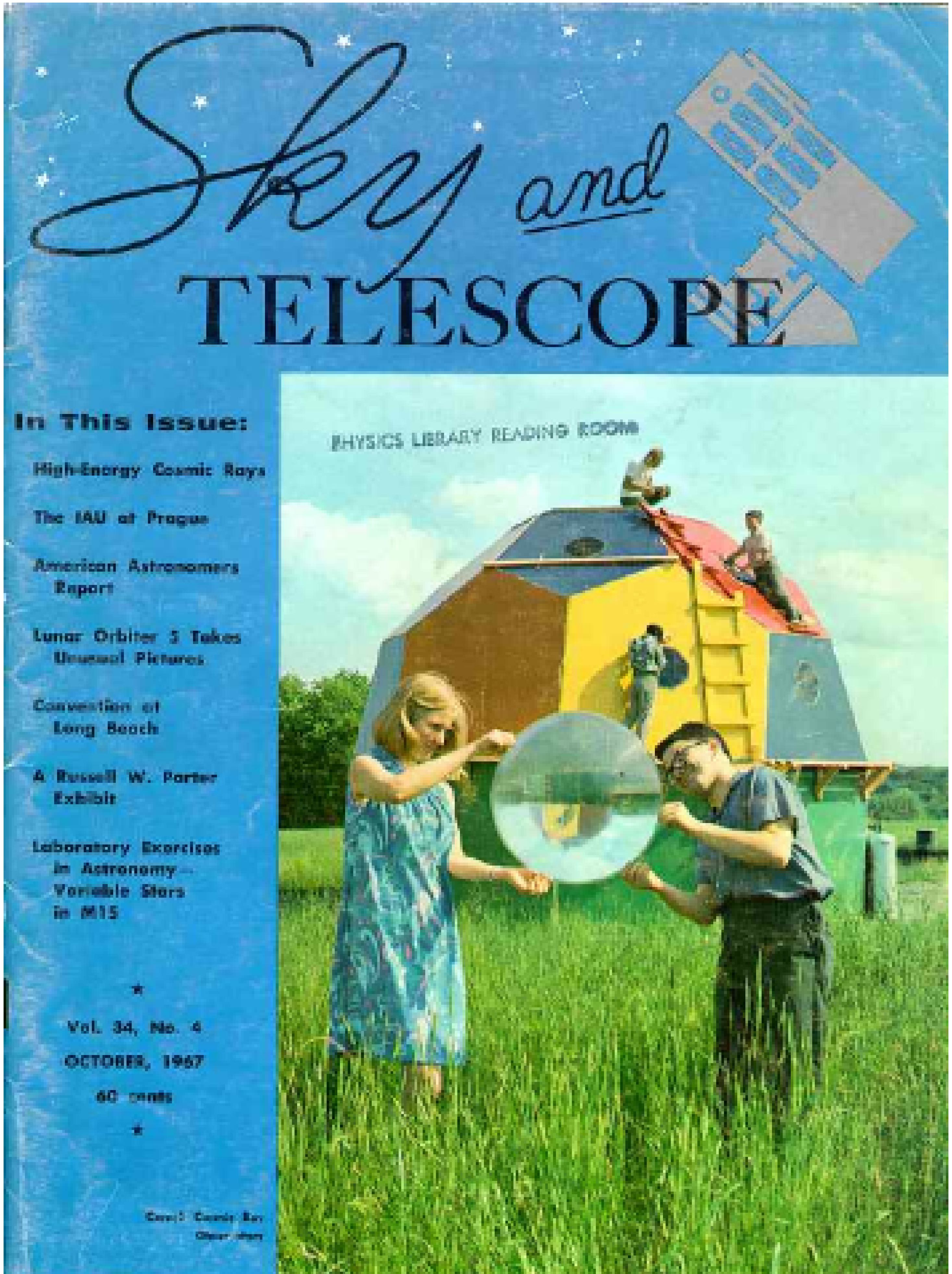
works only for $E > 10^{17}$ eV, only in dark nights (10%)
requires good knowledge of atmospheric conditions
aperture grows with energy, varies with atmosphere

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





c.f. 40 W light bulb
moving with c
at 30 km distance
through atmosphere



The First Fluorescence Detector:

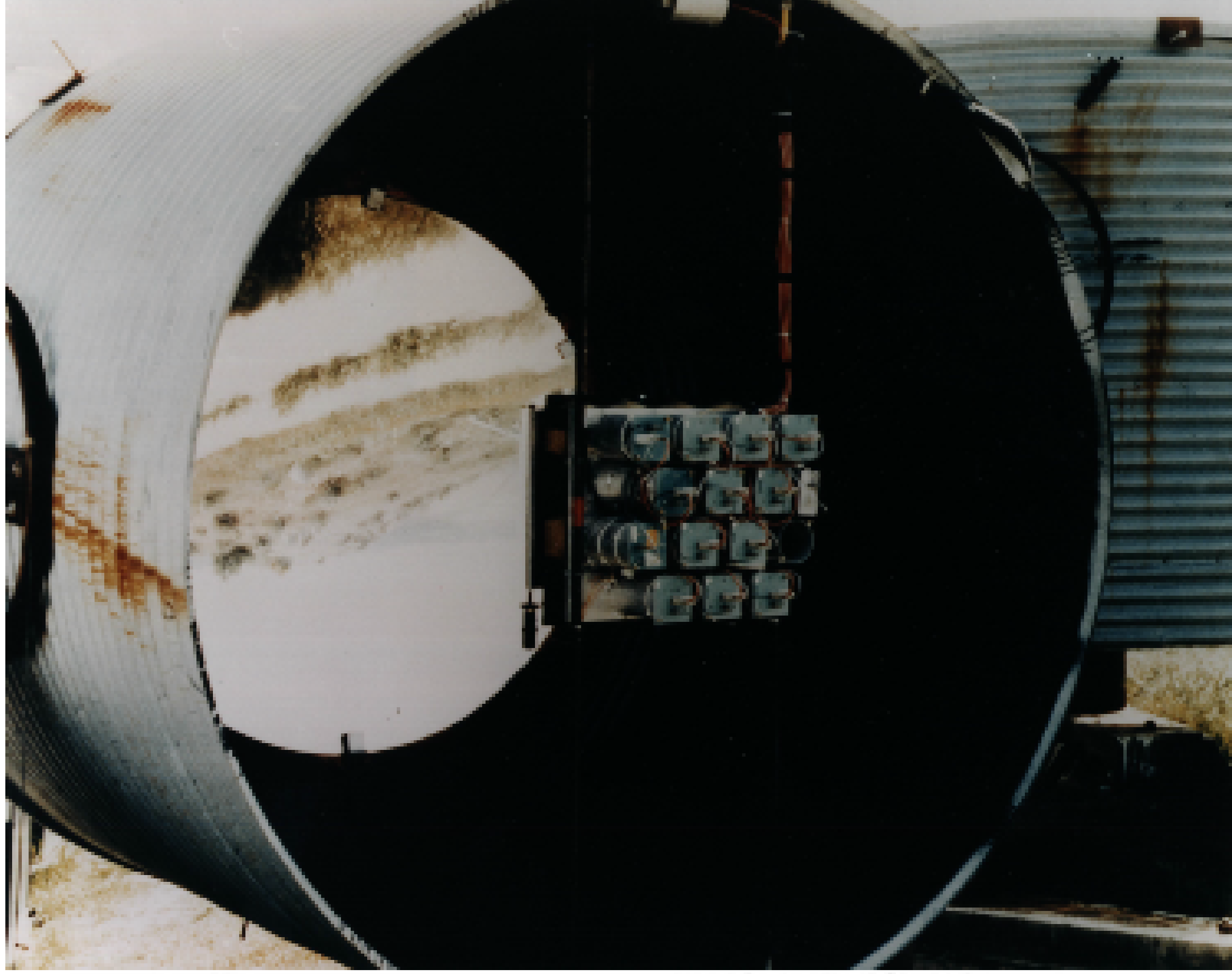
Cornell University
K. Greisen, 1967

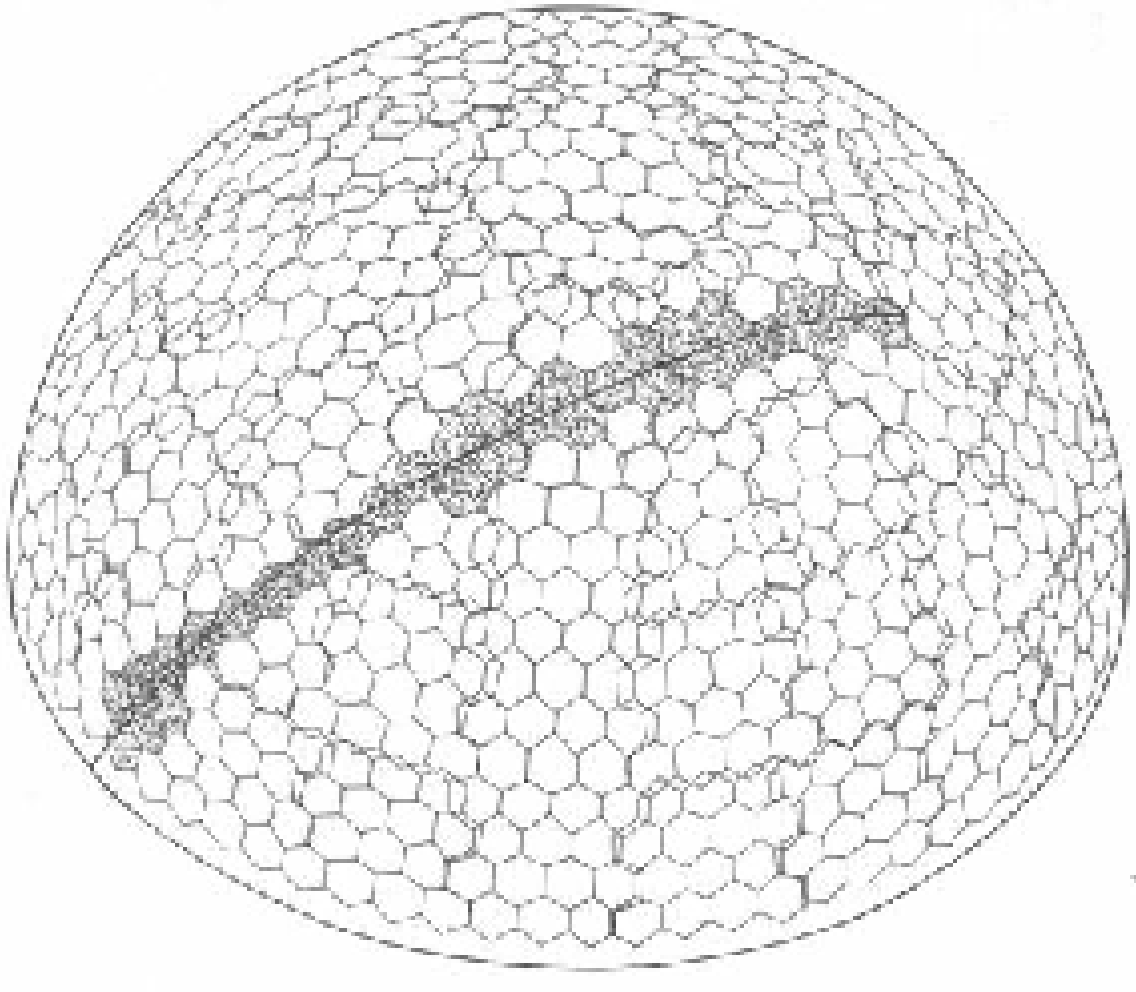
10 x 50 PMTs
6°x6° pixels
0.1 m² Fresnel lenses

(not successful)

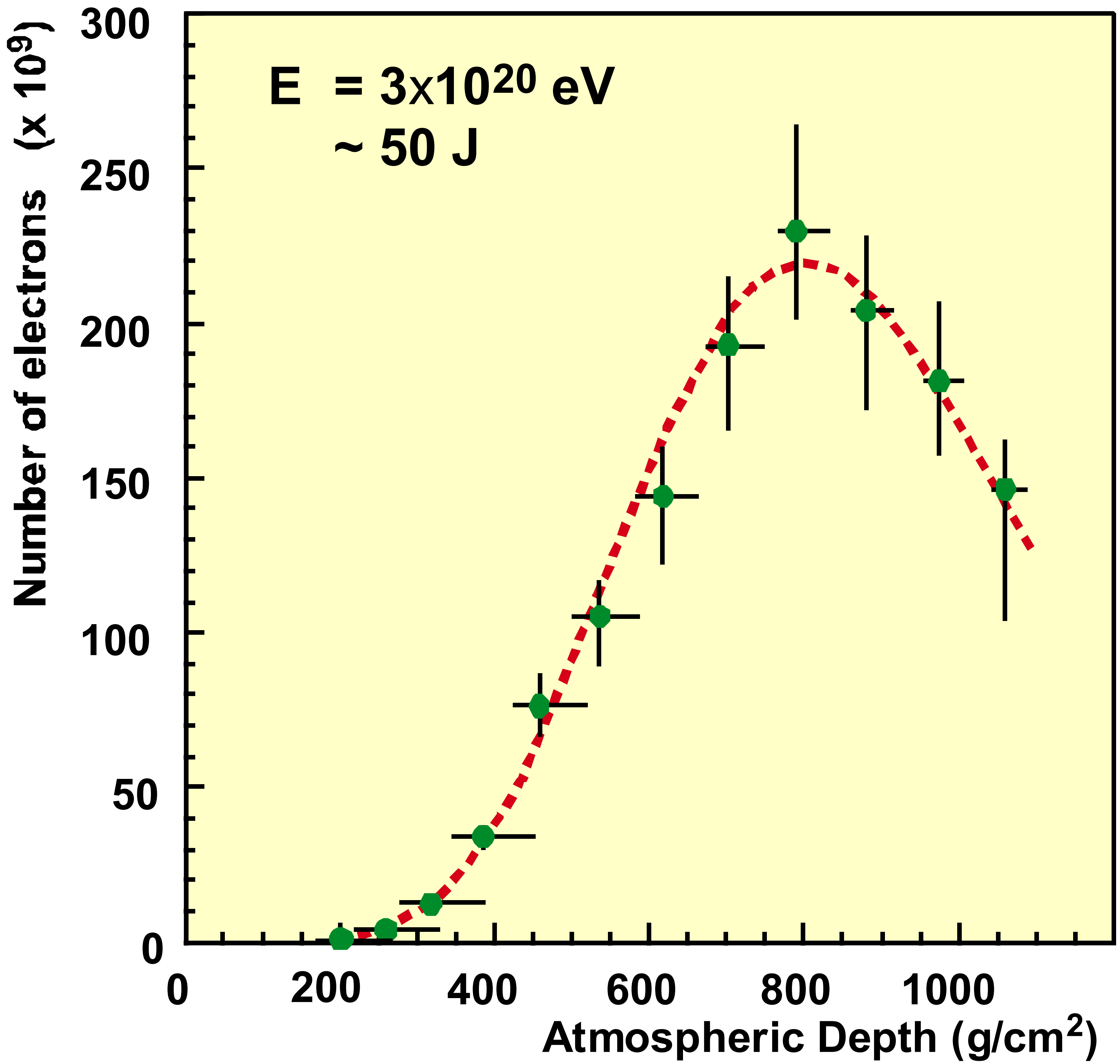
Fly's Eye (Utah)

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





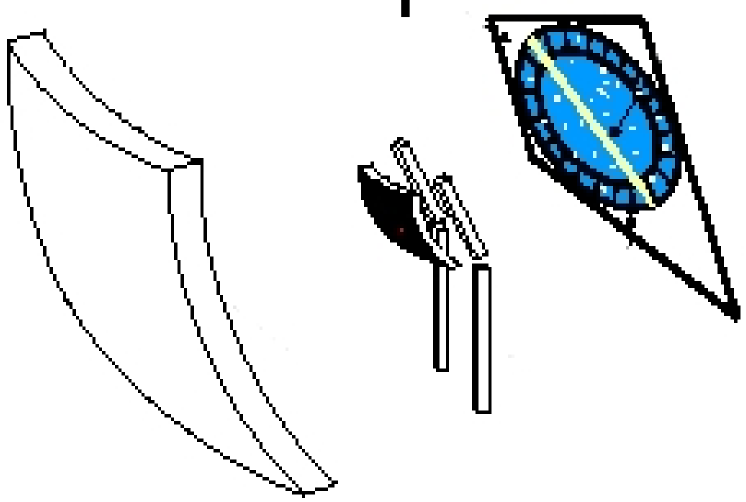
The Big Fly's Eye Event

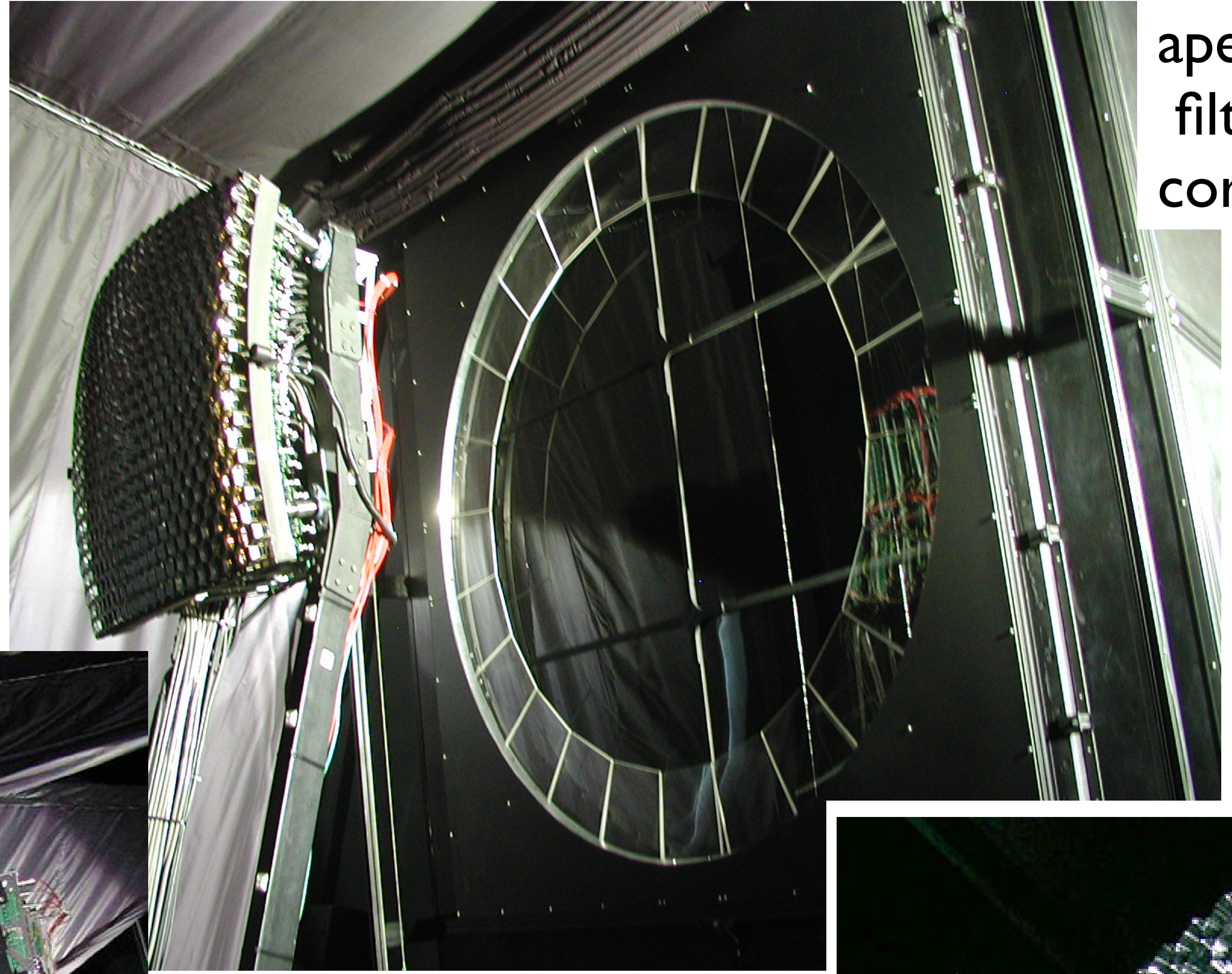


50 J !!!!

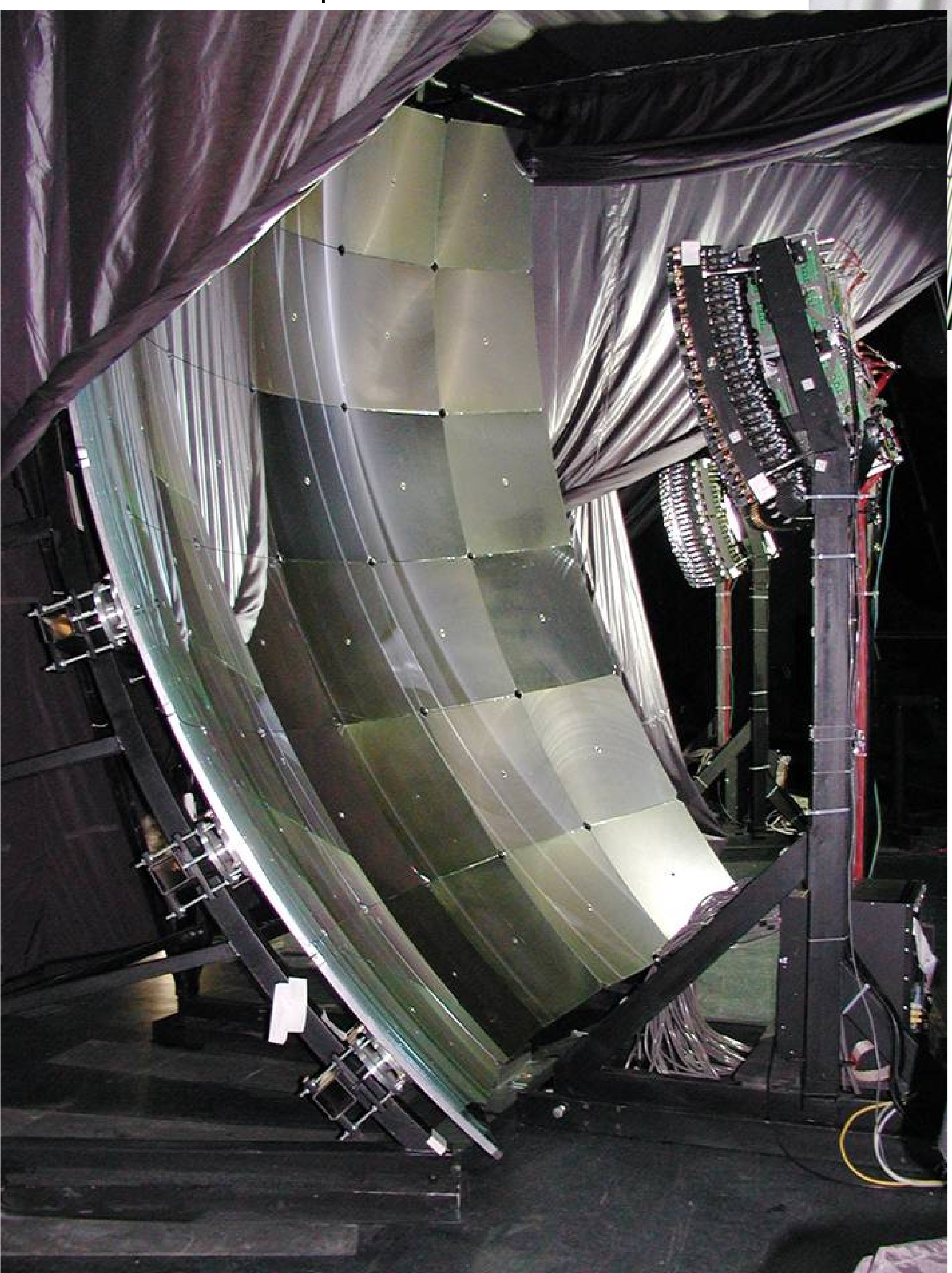
> 200 billion secondaries at maximum

Pierre Auger Obs. FD telescope:



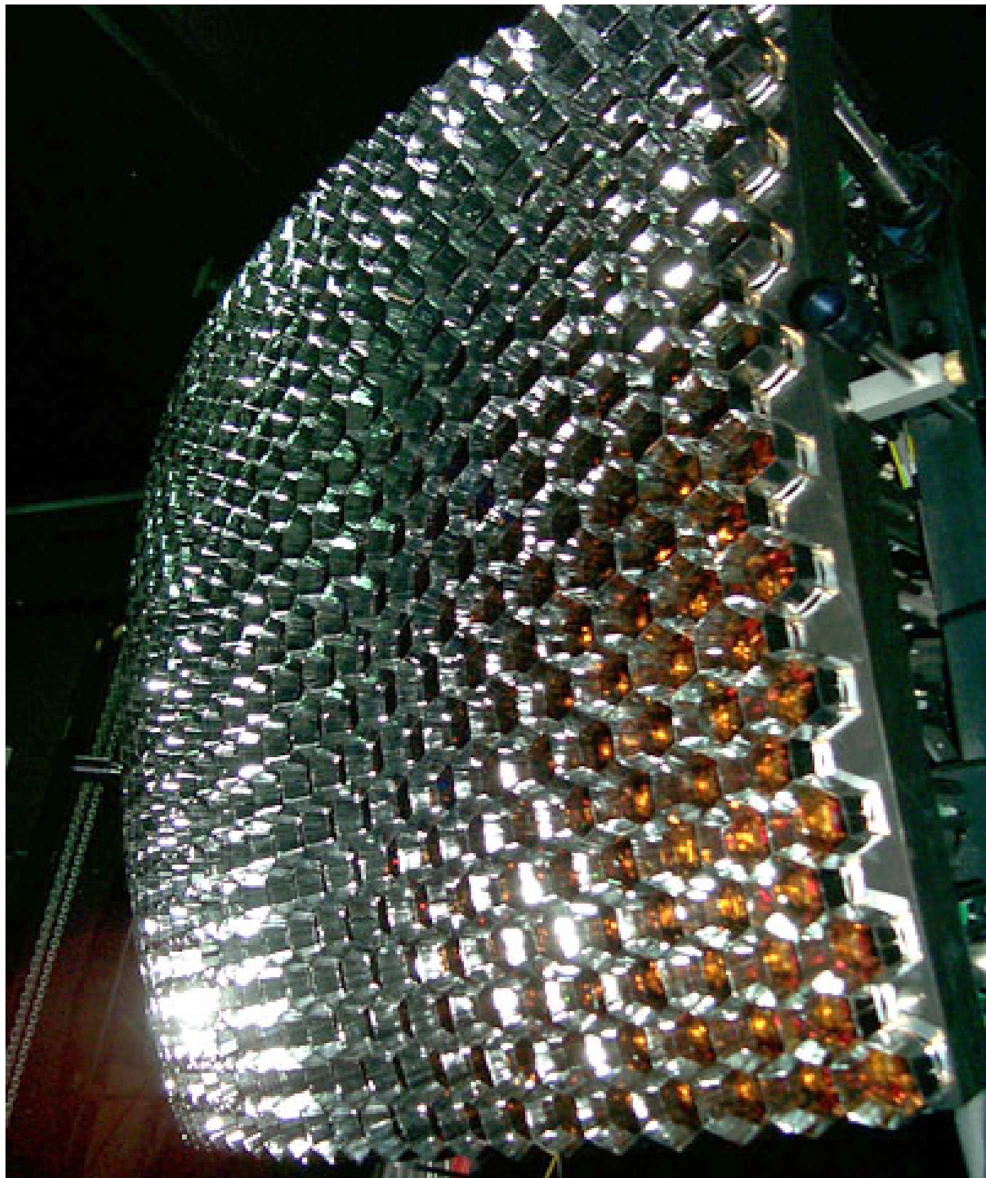


aperture with shutter, filter and Schmidt corrector lenses

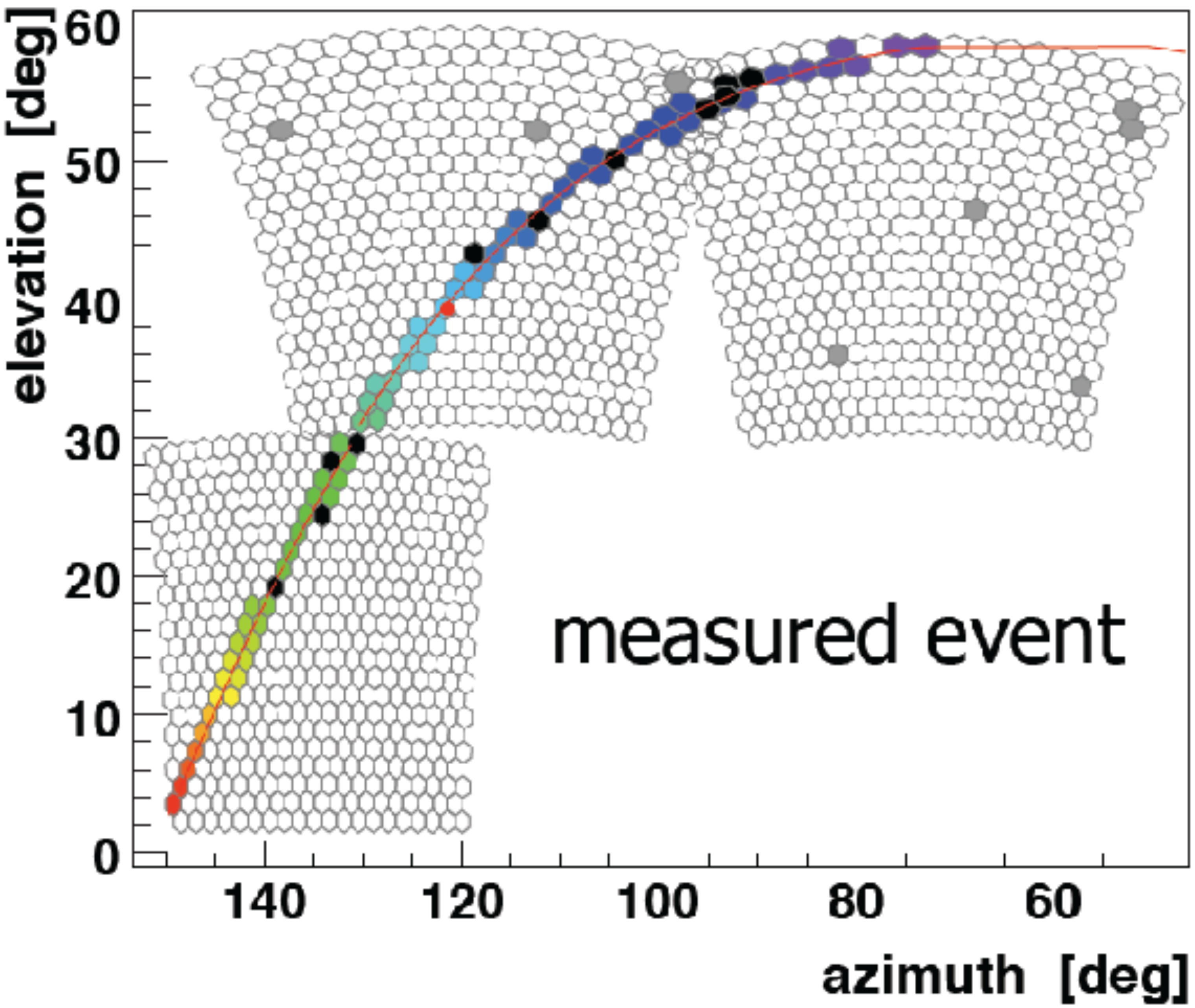


11 m² mirror (Aluminium)

440 PMT camera



24 telescopes at 4 sites
30°x30° FOV, each


elevation [deg]
60
50
40
30
20
10
0
140
120
100
80
60
azimuth [deg]
measured event

Auger: unprecedented statistics and precision

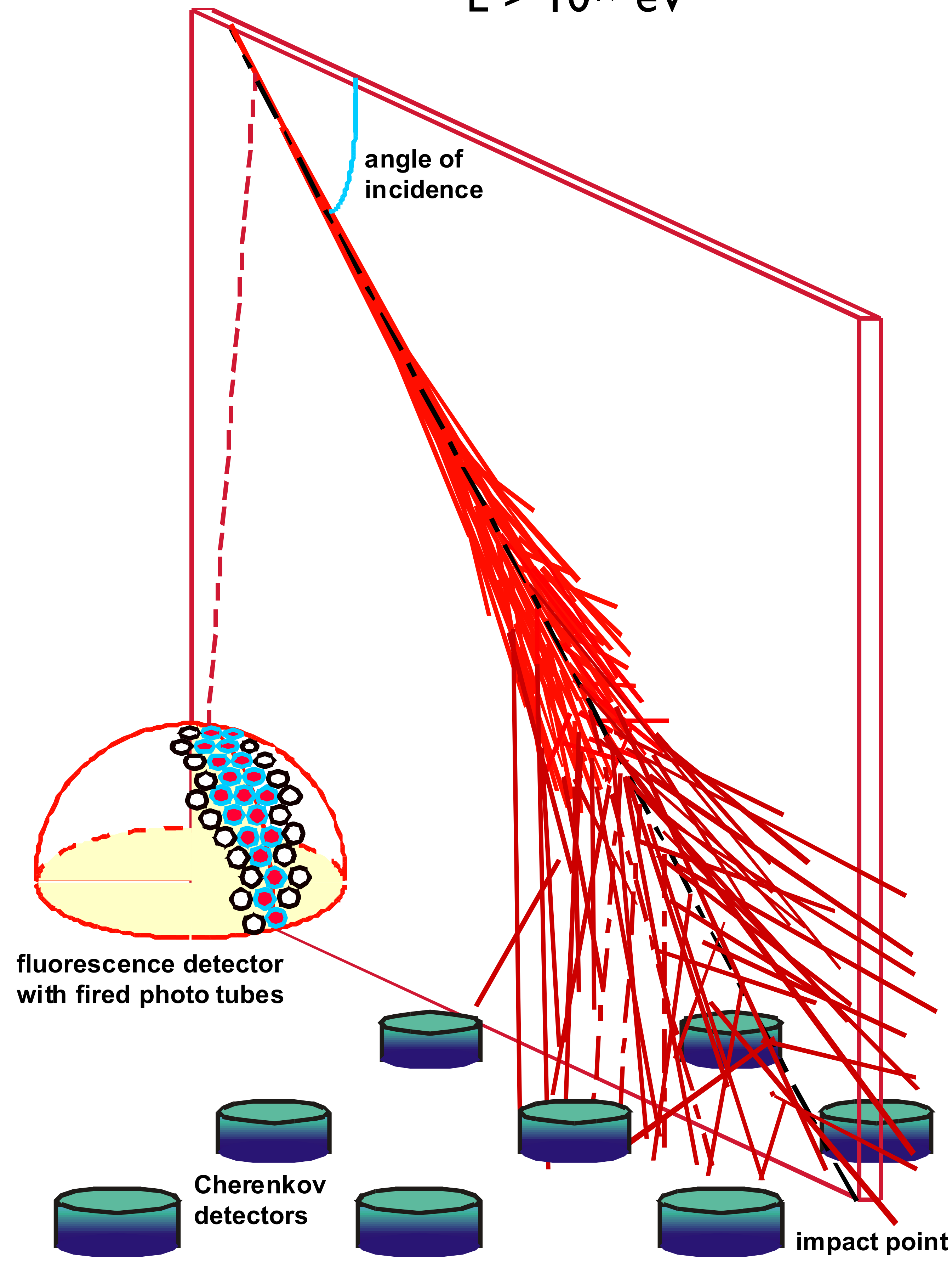
≈ 3000 evts/yr with $E > 10^{19}$ eV

Hybrid Detector:

Array of 1600 water Cherenkov detectors
covering 3000 km²
duty cycle: 100%

Fluorescence telescopes
24 FDs (30°x30° each)
duty cycle: 10%

Better geometric reconstruction, cross-calibration, control of systematics.



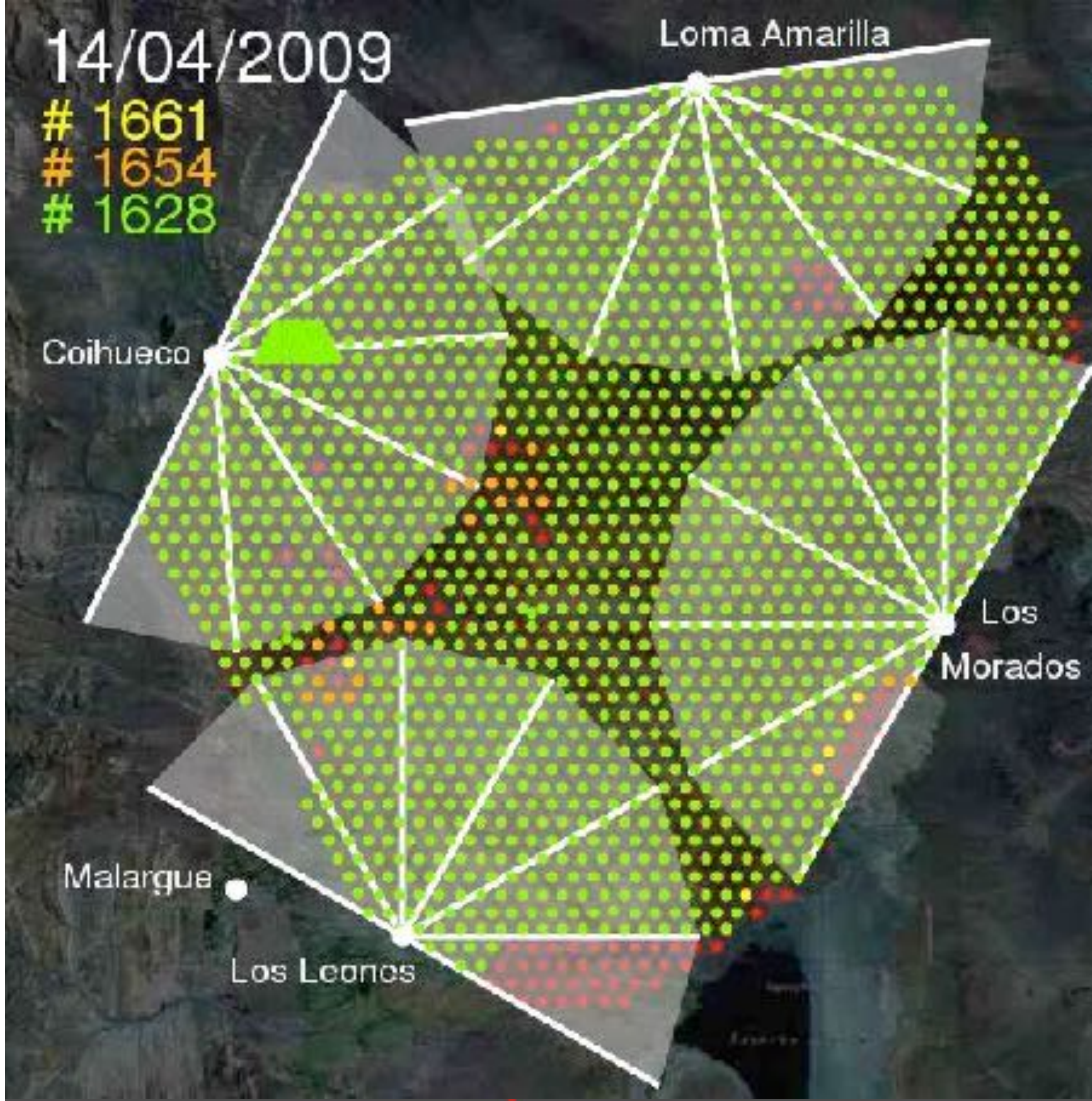
Pierre Auger Observatory
Argentina: 3000 km^2

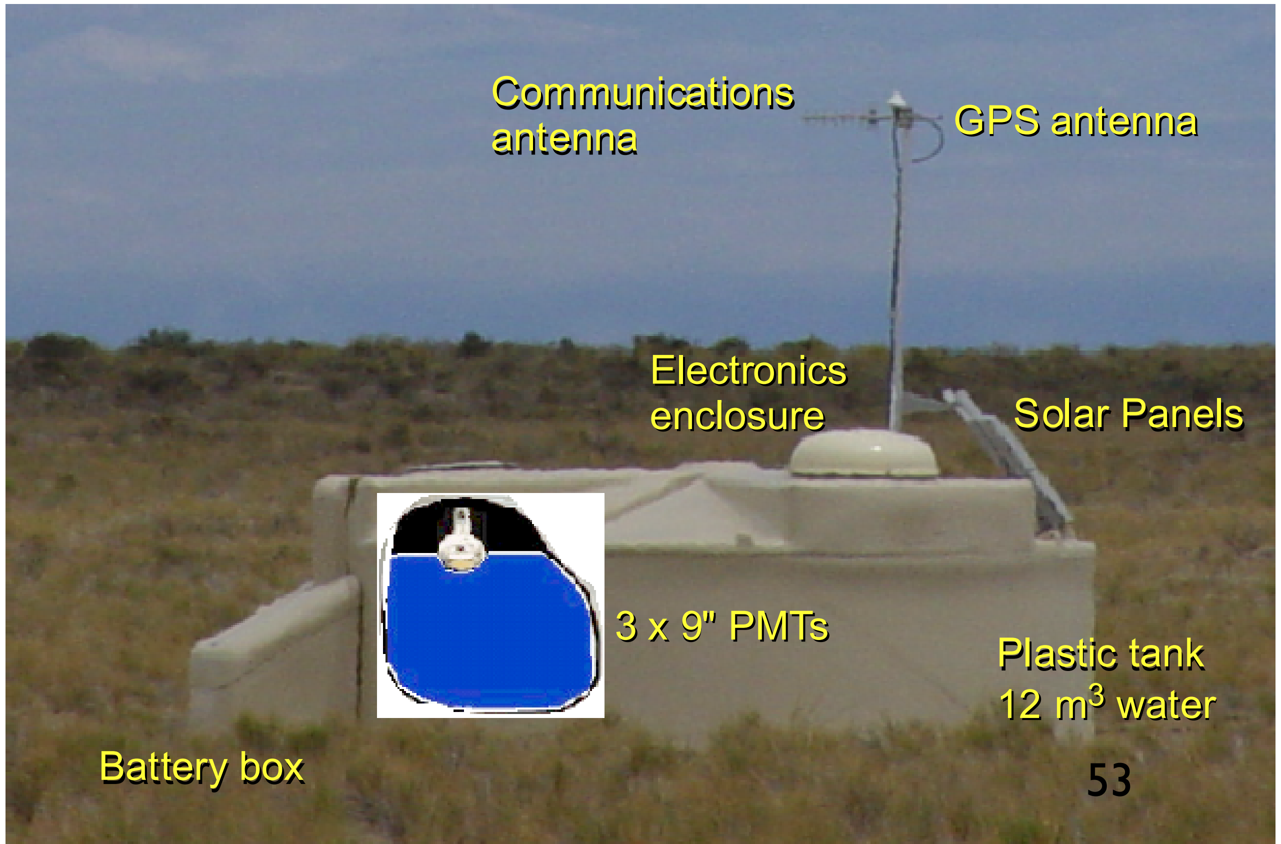
1600 particle detectors +

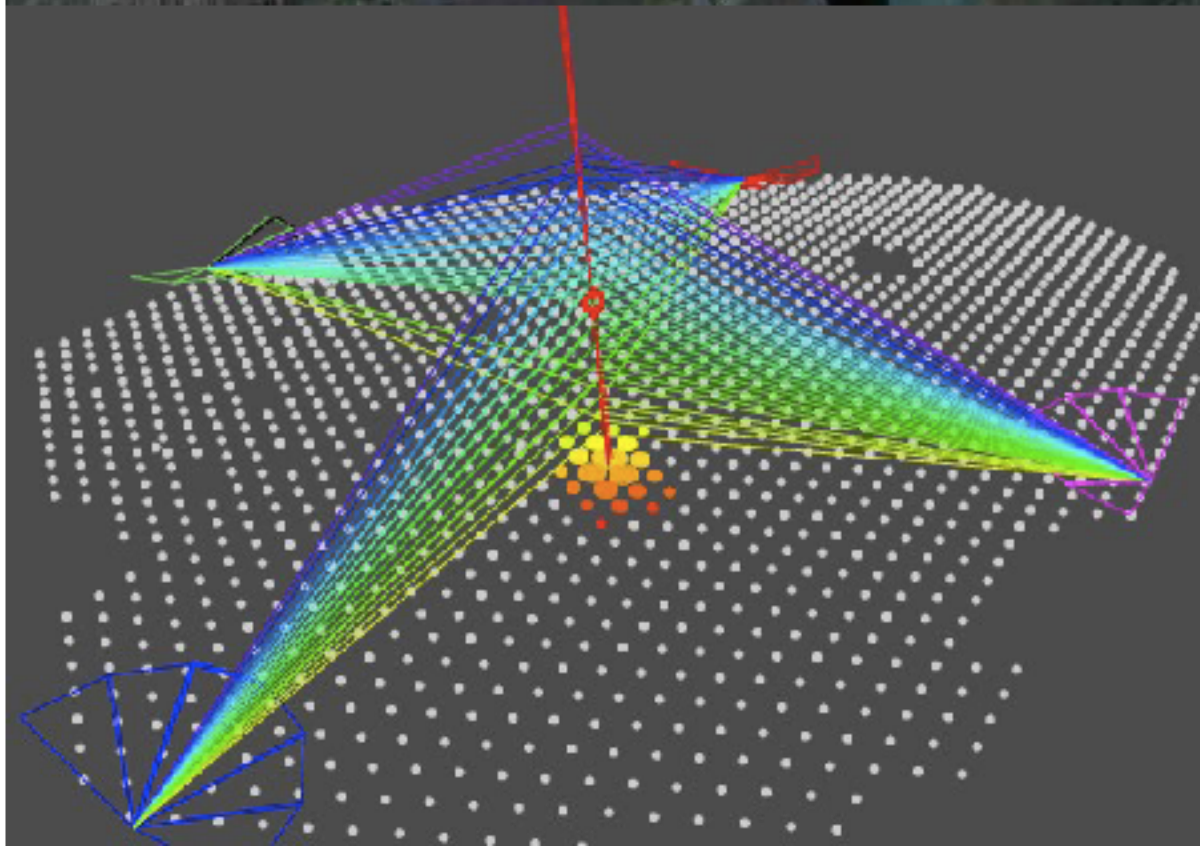
27 fluorescence telescopes

UHE cosmic particles
(E > 10^{18} eV)

low-energy extensions: HEAT & infill
(E ≥ 10^{17} eV)







The State of the Art

We **know** that CRs at $<10^{15}$ eV are galactic.

SNR explain the CR power reasonably well for the volume of the Galaxy.
The "knee" in the spectrum
seems to be a cut-off of gal. CRs. (see KASCADE)

We **know** that CRs at $>10^{18}$ eV are extra-galactic.

Galactic magnetic field cannot confine CRs of $>10^{18}$ eV,
so one would expect to see the galactic disk in CRs,
which is not the case.

Where does the transition happen?
Is there a GZK cut-off?

The spectrum: clear structures (Discovery)

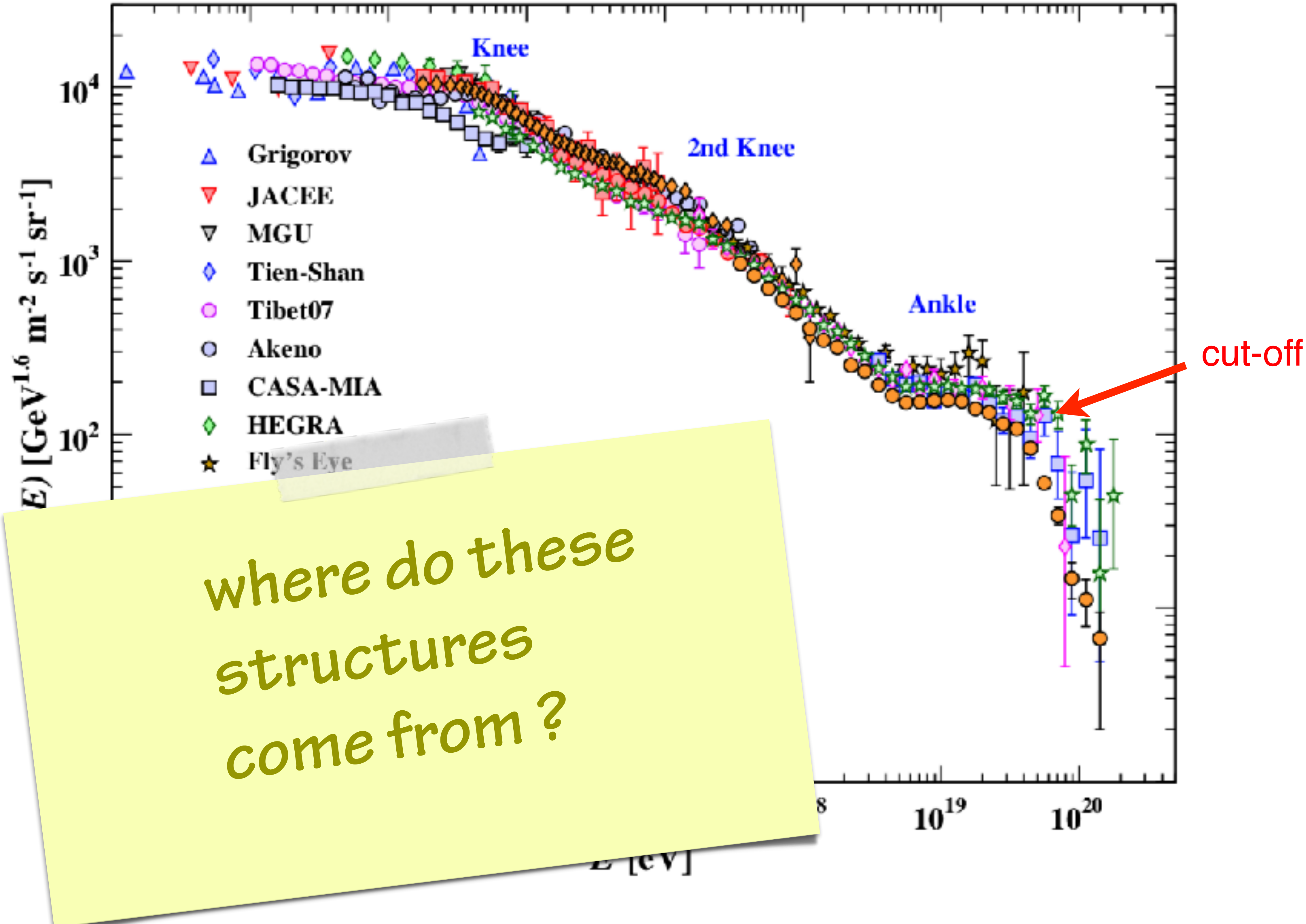


Figure 30.8: The all-particle spectrum as a function of E (energy-per-nucleus) from air shower measurements [91–106].

The spectrum: structures: need composition

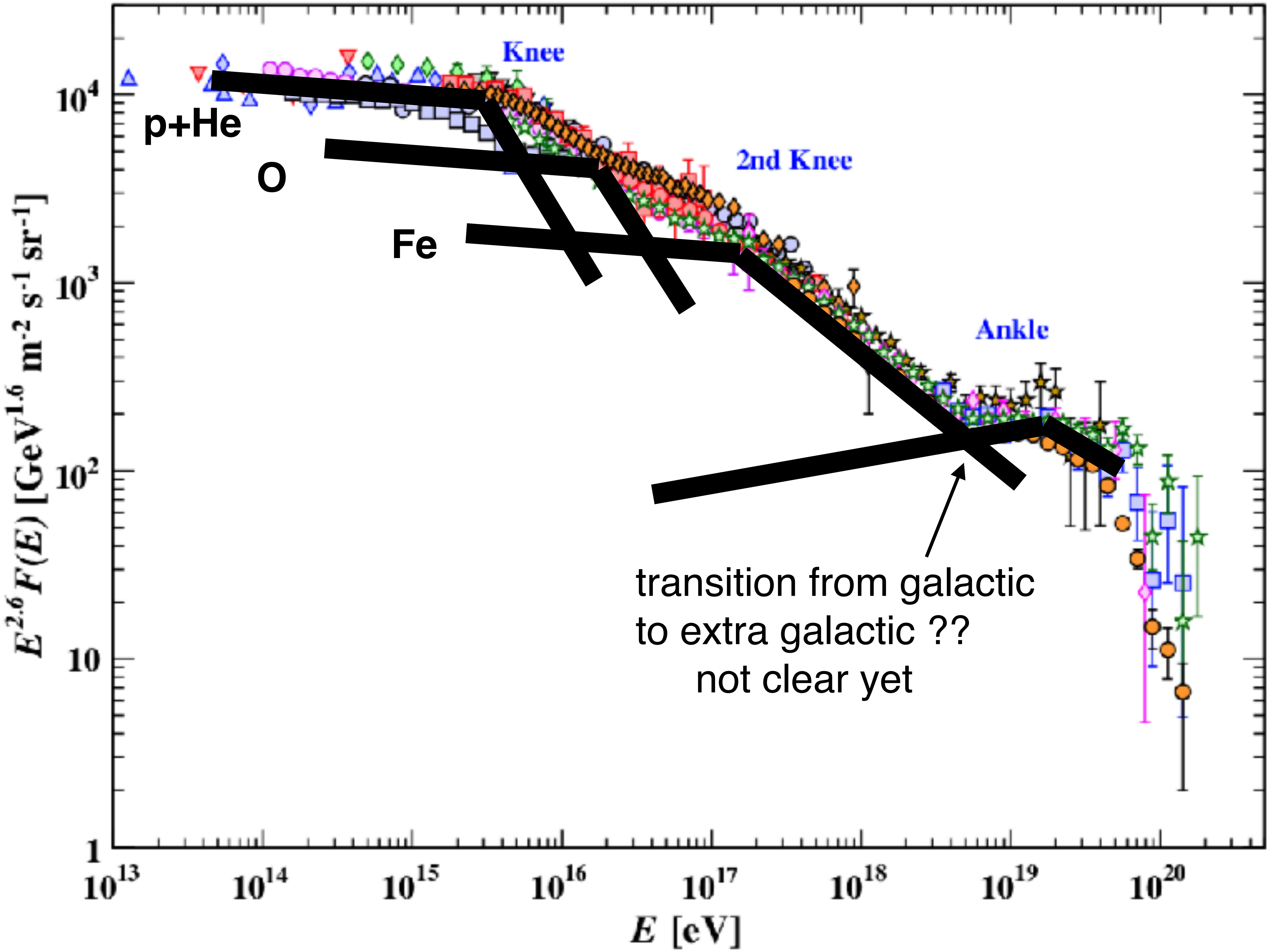


Figure 30.8: The all-particle spectrum as a function of E (energy-per-nucleus) from air shower measurements [91–106].

Indeed cutoff of p first, then He, …. then Fe

knee   2nd knee

the accelerator runs out first for p, then He, … then Fe.

KASCADE, MAKET-Ani

The spectrum cuts off ...

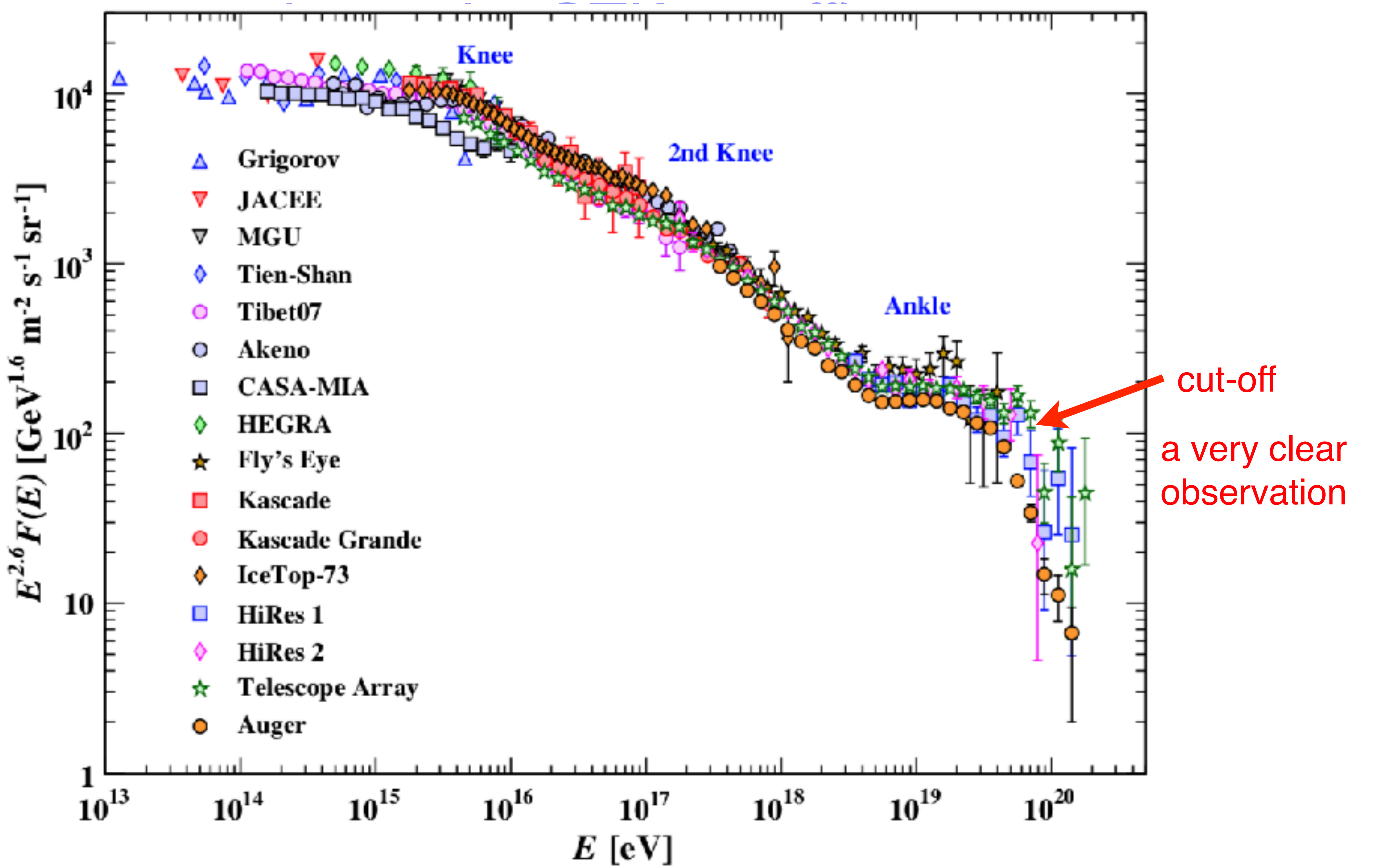
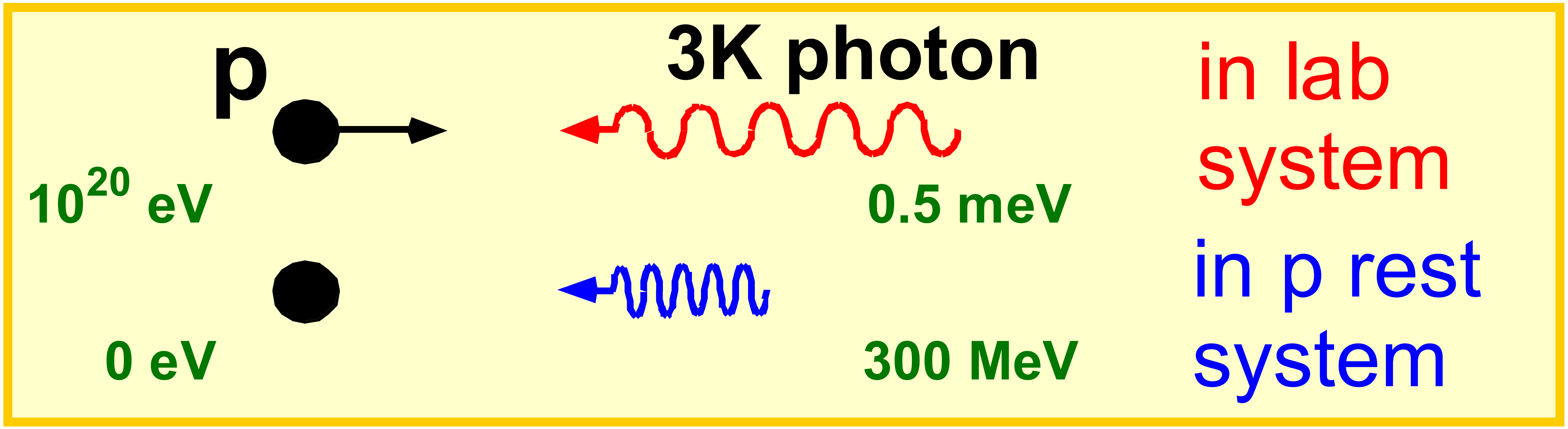


Figure 30.8: The all-particle spectrum as a function of E (energy-per-nucleus) from air shower measurements [91–106].

GZK Cut-Off

Greisen Zatsepin Kuzmin 1966



$p + \gamma_{3K} \rightarrow \Delta^+ \rightarrow p + \pi^0$ ($\rightarrow \gamma$)

$\rightarrow n + \pi^+$ ($\rightarrow \nu$)

Photo-pion production

$^{56}Fe + \gamma_{3K} \rightarrow {}^{55}Fe + n$

Photo dissociation

Universe is opaque for $E > 5 \times 10^{19}$ eV.

Spectrum cuts off (absorption of CRs from distant sources)

If CRs are protons, then …

reactions of protons with CMBR should effectively absorb CRs from distances larger than about 100 Mpc. (Greisen-Zatsepin-Kuzmin cut-off)

⟶ a sharp cutoff in the spectrum.

If CRs are higher-Z nuclei, then …

reactions of nuclei with CMBR would destroy nuclei (photo disintegration)

⟶ may also produce cutoff in the spectrum (depends on mix with Z)

Also the CR accelerator could have an intrinsic maximum energy and what we see is just the end of the most powerful accelerator we are seeing.

i.e. we do not know yet what the origin of the observed cut-off is.
We need more info on the CR particle type.

Summary CRs

CRs are charged particles (nuclei),
import part of Galaxy and universe
relativistic, most energetic particle in universe
must come from violent objects, extreme physics, (e.g. supernovae)

CRs are difficult, because:

- we see only the sum of many sources, distances, times
  largely isotropic arrival directions
- extend over 10 orders of magnitude in energy
  i.e. need different experiments for diff. ranges
  for <100 TeV only space access (expensive, short term)
  for >100 TeV only air showers (poor/no particle identification, variable atmosphere)

Spectrum shows structure: knee, second knee, ankle, cut-off

knee, second knee,	ankle,	cut-off
likely z-dependent cut-off. end of gal. accelerator	still unclear	likely GZK cut-off don't see CRs from distant sources.