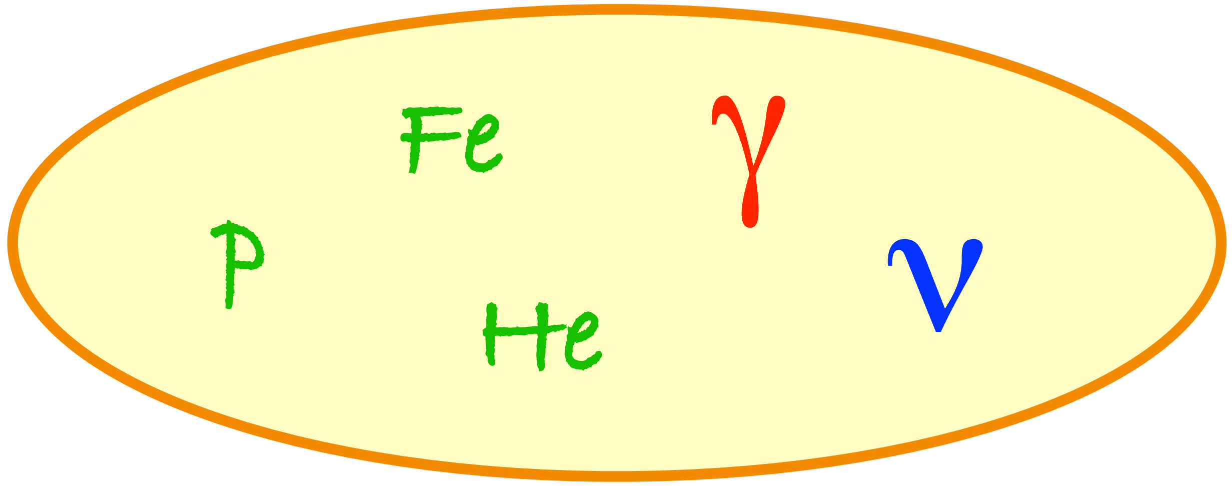
Introduction to Astroparticle Physics

Johannes Knapp, U of Leeds, UK

Winterschool on Astroparticle Physics

Darjeeling, India, December, 2011



Astroparticles: particles from astrophysical sources

… The highest energy particles in the universe !!!!!

Energies keV … MeV … GeV … TeV … PeV … EeV … ZeV

10^3 … 10^6 … 10^9 … 10^{12} … 10^{15} … 10^{18} … 10^{21} eV

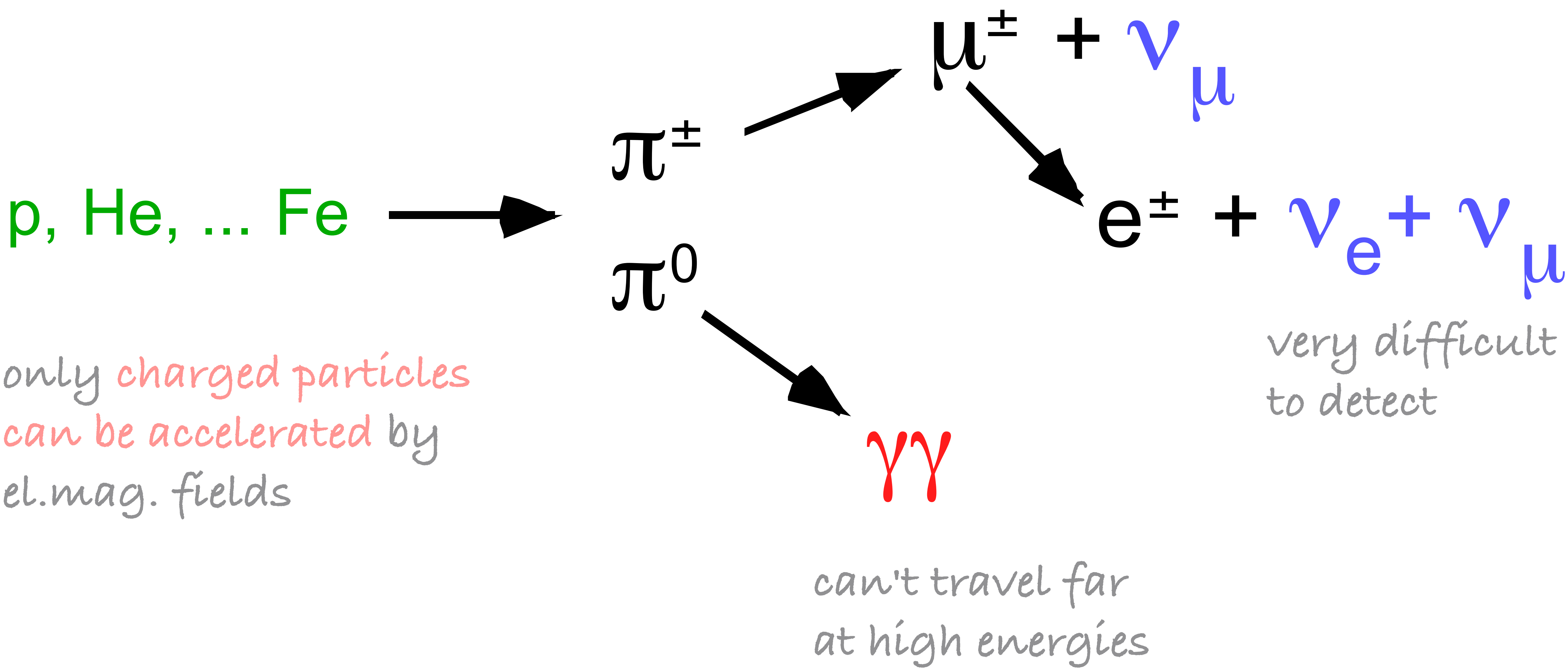
Cosmic Rays: p, He, …. Fe, … fully ionised nuclei,

electrons

Photons: classical astronomy + high-energy gamma rays

Neutrinos: astrophysical ν (solar, SN, AGN, …)

Cosmic Rays, Gamma Rays and Neutrinos are linked



γ and ν travel in straight lines, i.e. point back at source.
CRs are deflected in galactic and intergalactic magnetic fields.

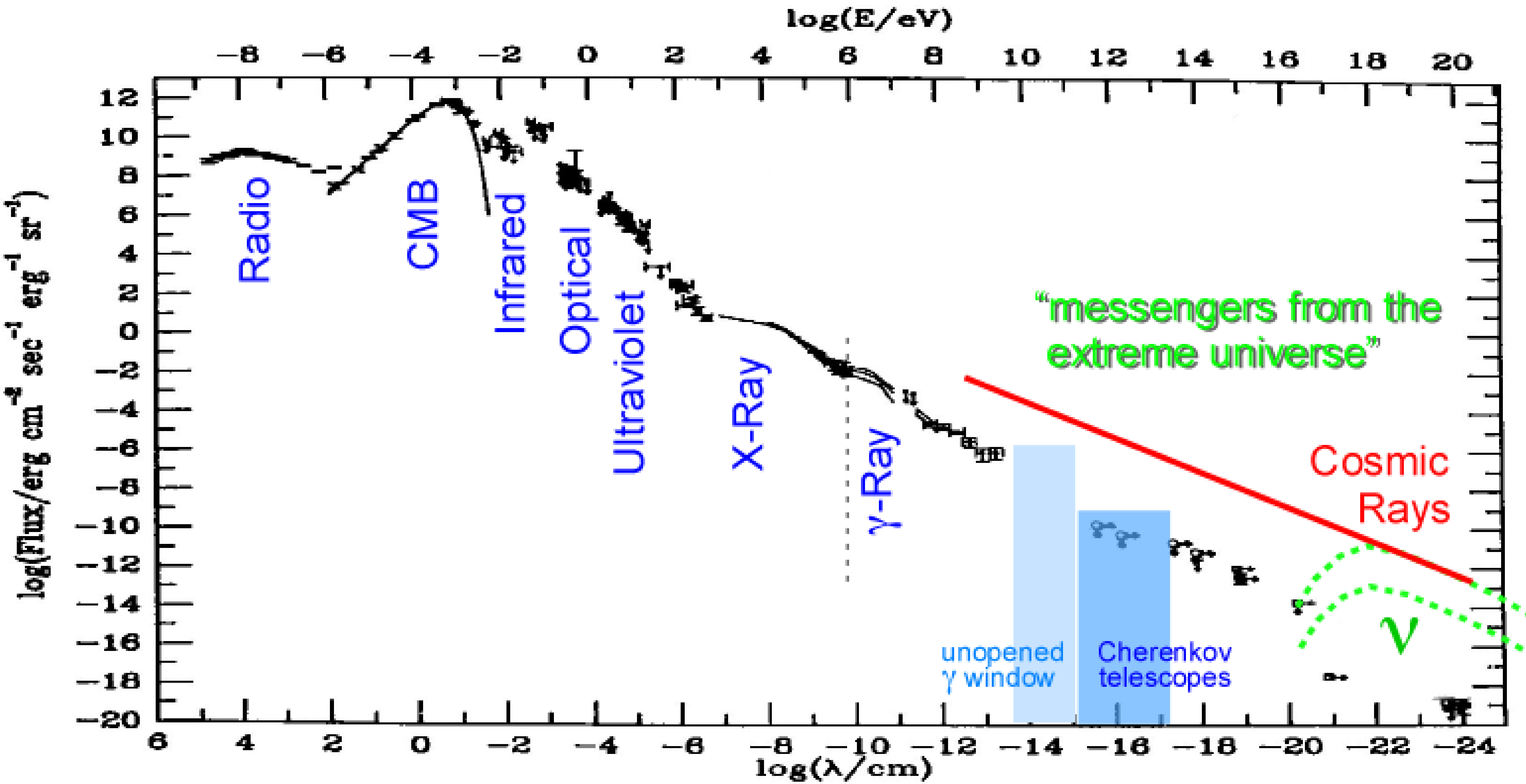
If	Cosmic Rays exist,
then	also ν and γ must exist at similar energies.

But: can they be detected above backgrounds ???

γ : 100-1000 x more cosmic rays

ν : low interaction cross section
atmospheric neutrinos from atmosphere

universal photon / particle spectrum



CRs are detected up to $>10^{20}$ eV !

Extreme Energies ....
.... Extreme Environments:

Power sources ?

Accretion of matter onto compact objects

e.g. Neutron stars, black holes, supermassive black holes

Explosions: Supernova (SN), compact binary mergers

Rotation: rotating neutron star with strong magnetic field generate relativistic electron-positron wind

How ?

(all on charged particles)

Diffusive shock (Fermi) acceleration e.g. SN blast wave hits ISM

Magnetic reconnection ? Plasma waves ?

Creation of gamma rays ?

π^0 decay — hadronic primaries

synchrotron emission in magnetic fields
Inverse Compton effect

} relativistic e^+, e^-

Astrophysical Questions:

Origin :	Where are they from?
	How do their sources work?
Identity :	What are they?
Acceleration :	How do they get their energy?
Propagation :	What happens on their way?

by measuring their:

- Energy spectrum
- Composition
- Arrival directions

other astroparticles: dark matter

... also very interesting,

but not topic of this talk.

Cosmic Rays

Cosmic Rays (are the primary particles)

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

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

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

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

gamma rays and neutrinos are secondaries

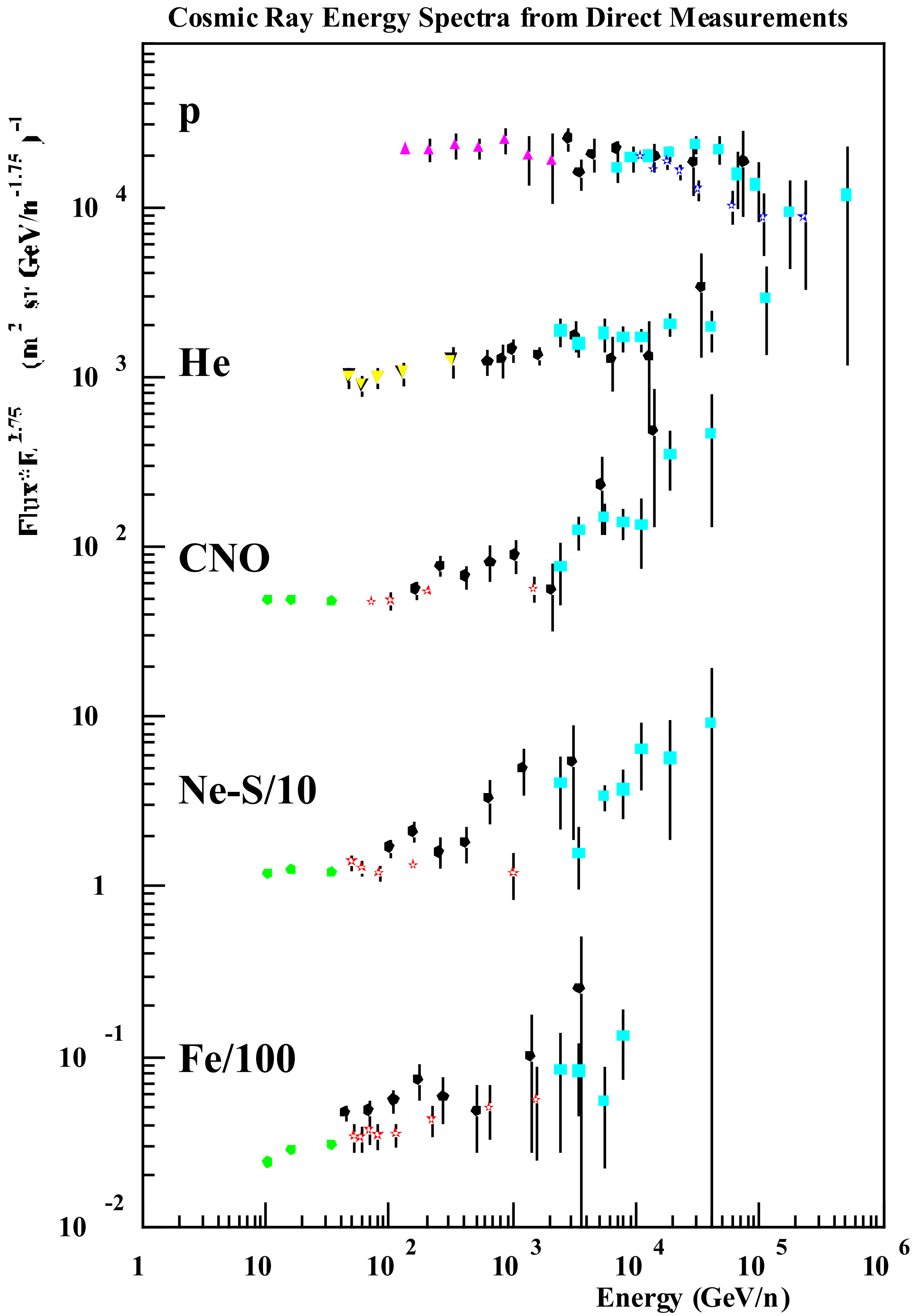
Cosmic Rays:

Main difficulties:

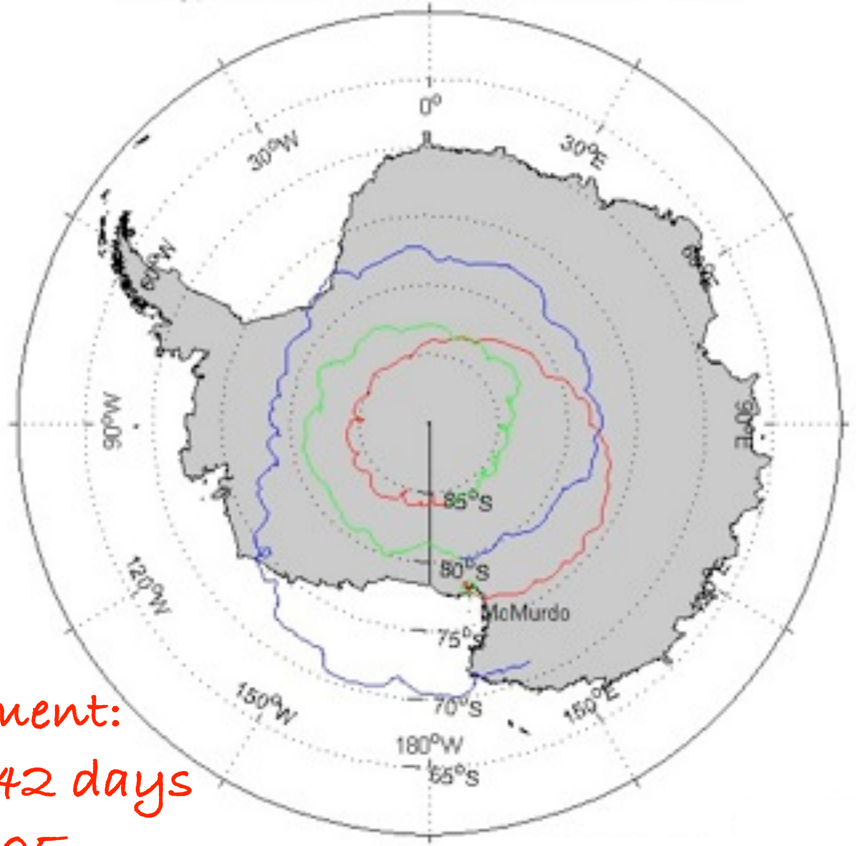
their charge: deflection in magnetic fields, directional information largely lost

steep spectrum: very low fluxes

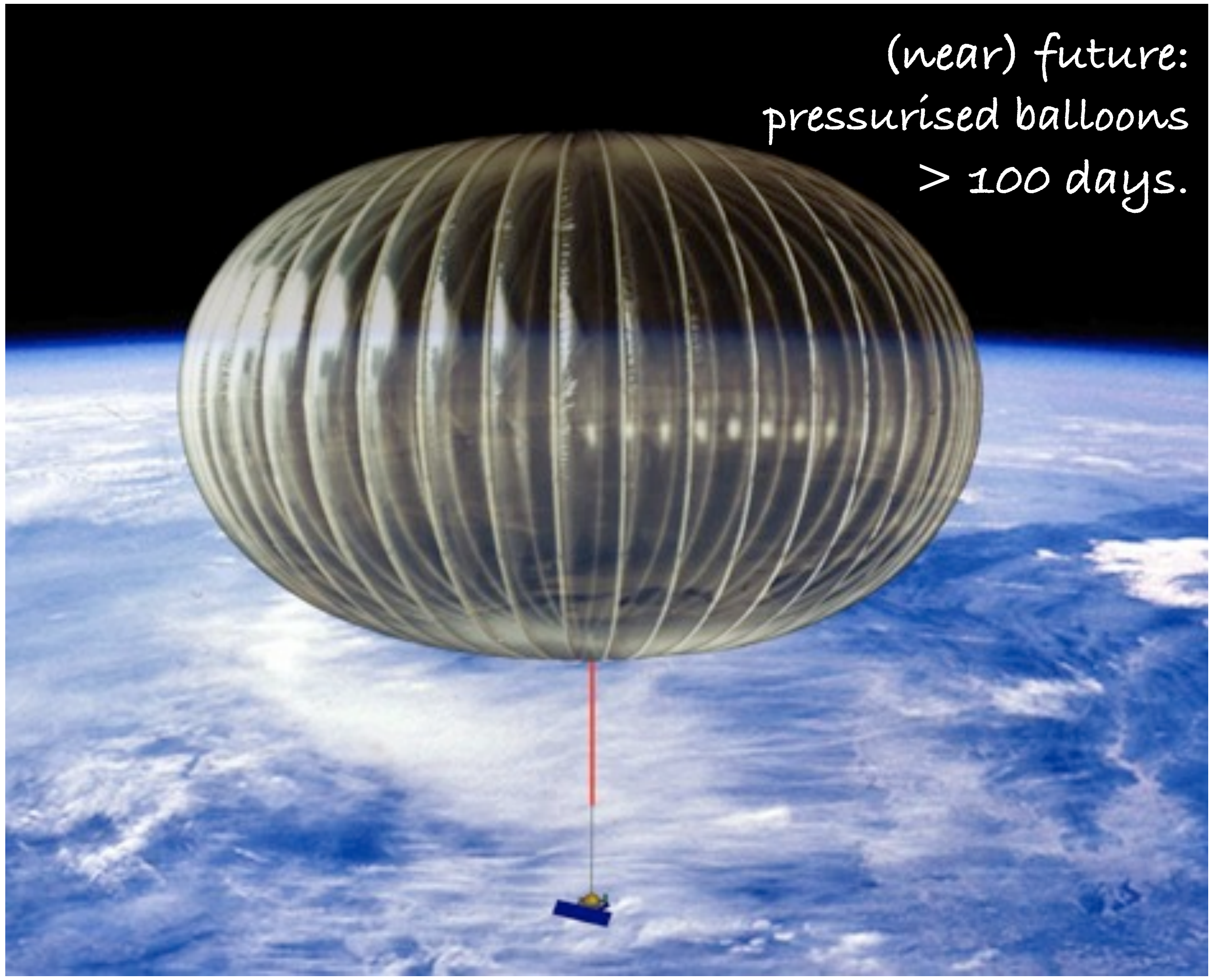
various balloon and satellite experiments ...



larger detectors?
longer times?



CREAM Experiment:
World record: 42 days
Jan 2005



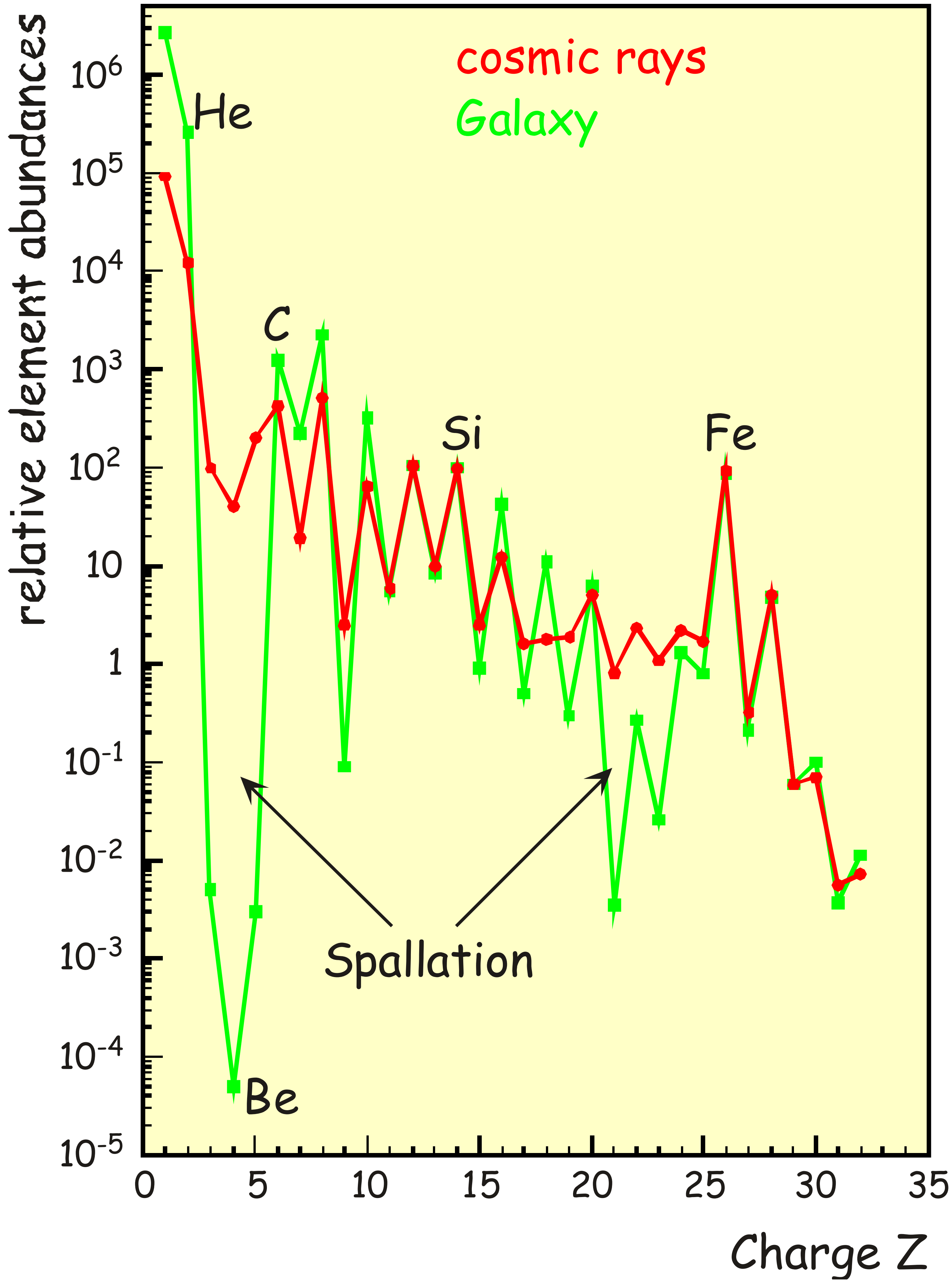
CR Mass Composition
(in GeV range)

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

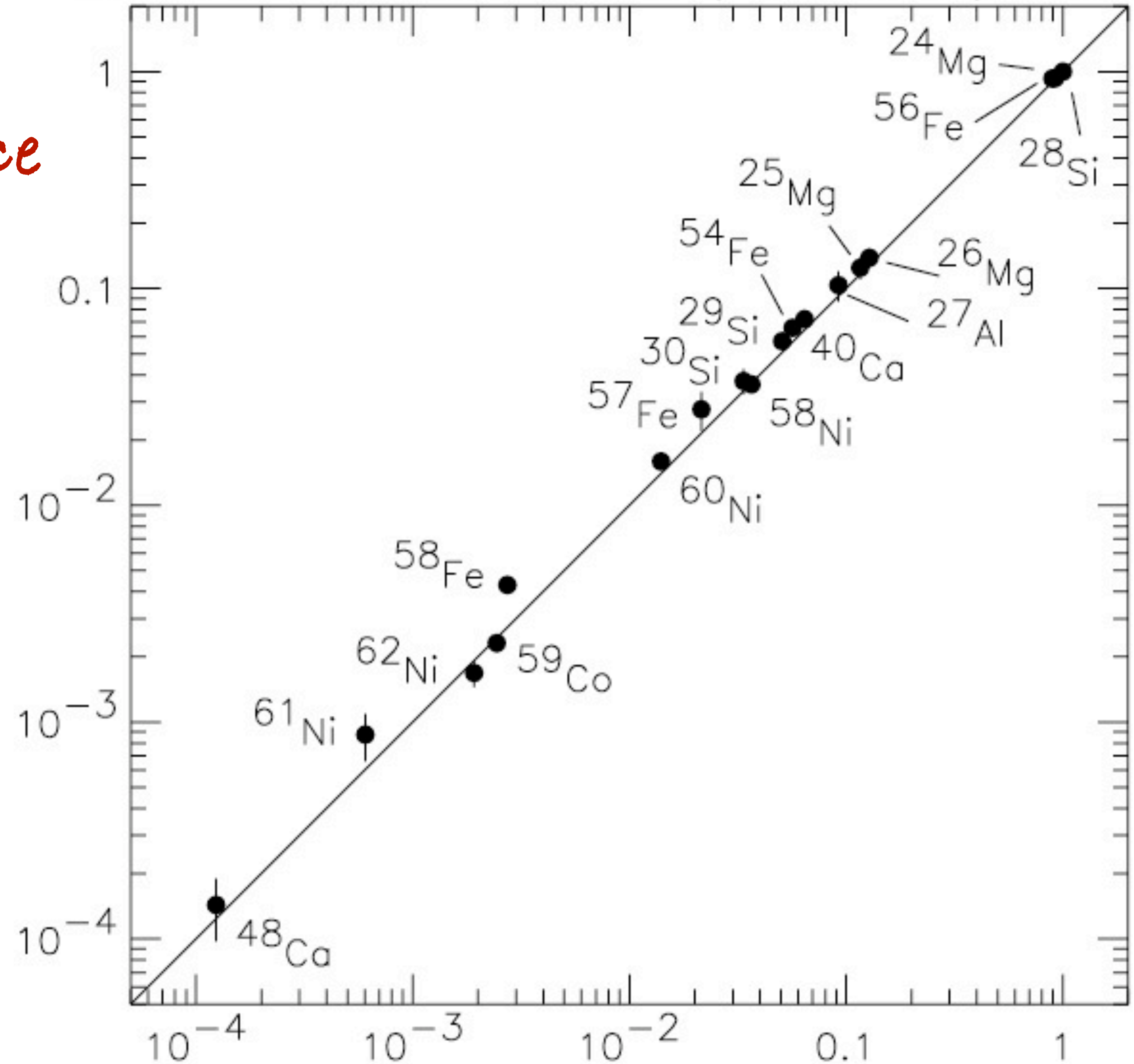
89% p, 9% He, 2% other nuclei
<1% electrons
"CRs are star matter"
≈ ejecta from SN

secondary/primary nuclei:
$\sim 10\ g/cm^2$

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



Galactic CR source abundance



Solar system abundance

good agreement !

CRs are made from well-mixed normal matter.

The currently favoured model:

Fermi Acceleration (1st order) in shock fronts

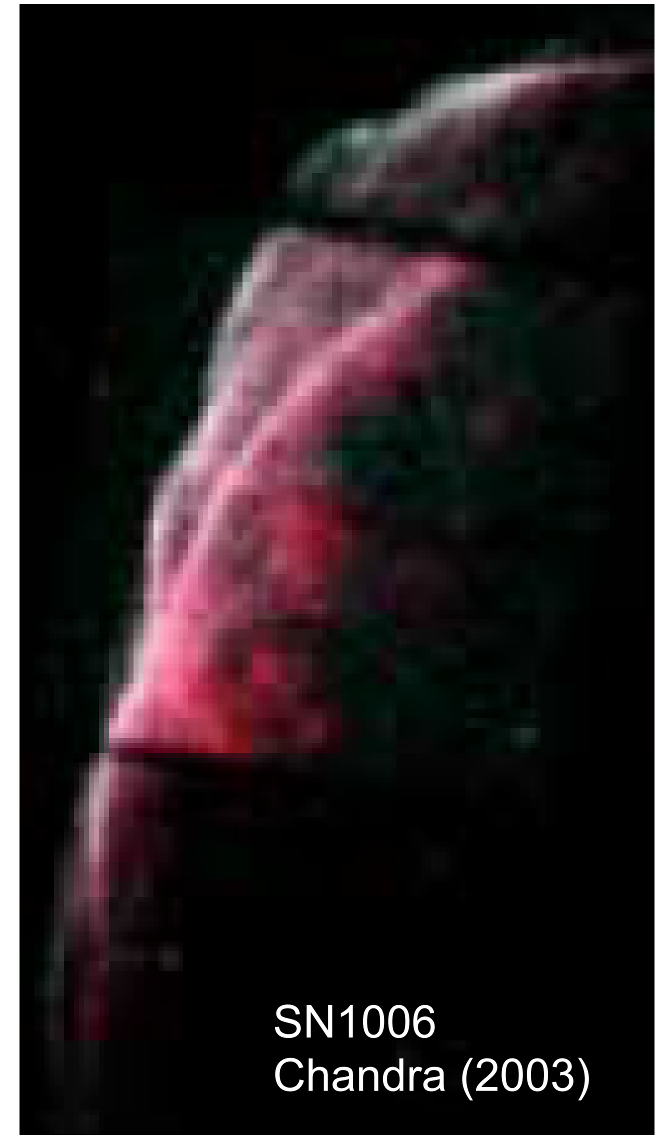
$$dN/dE \sim E^{-2.1} \cdot E^{-0.6} \approx E^{-2.7}$$

in sources — "residence" time in galaxy — measured at Earth

prime source candidates: SNR

frequent & powerful enough to account for observed CR density

magnetic field amplification (up to $E_{max} \approx Z\ 10^{15}$ eV)



SN1006
Chandra (2003)

low-energy CRs are galactic,

diffusing in gal. magnetic field

direct evidence ?

synchrotron & IC radiation

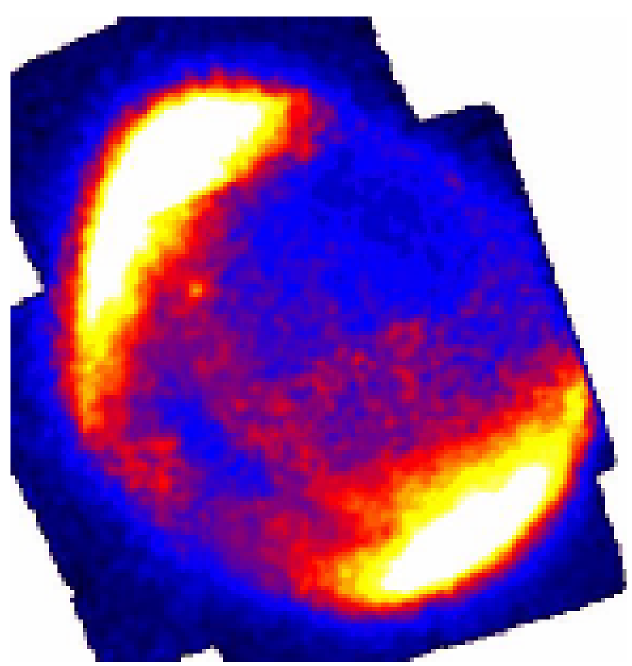
from relativistic electrons

No conclusive evidence for

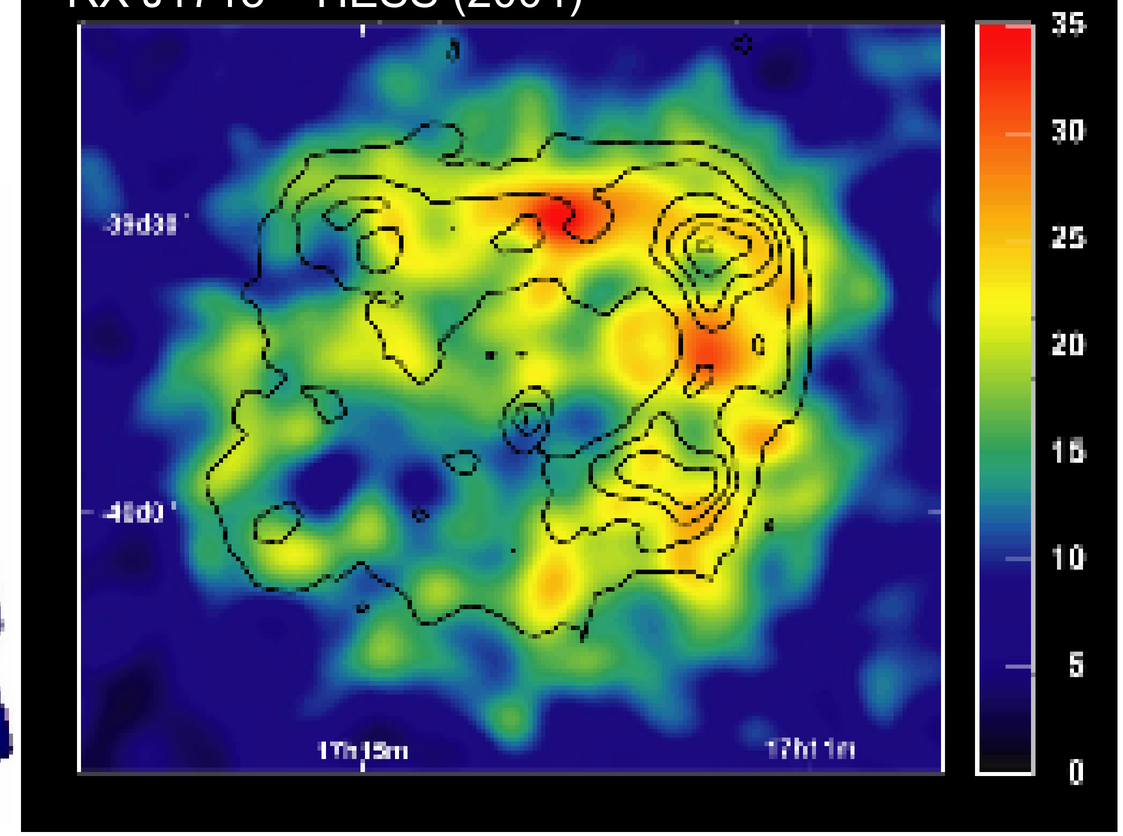
CR acceleration yet.

(hope for gamma-ray experiments)

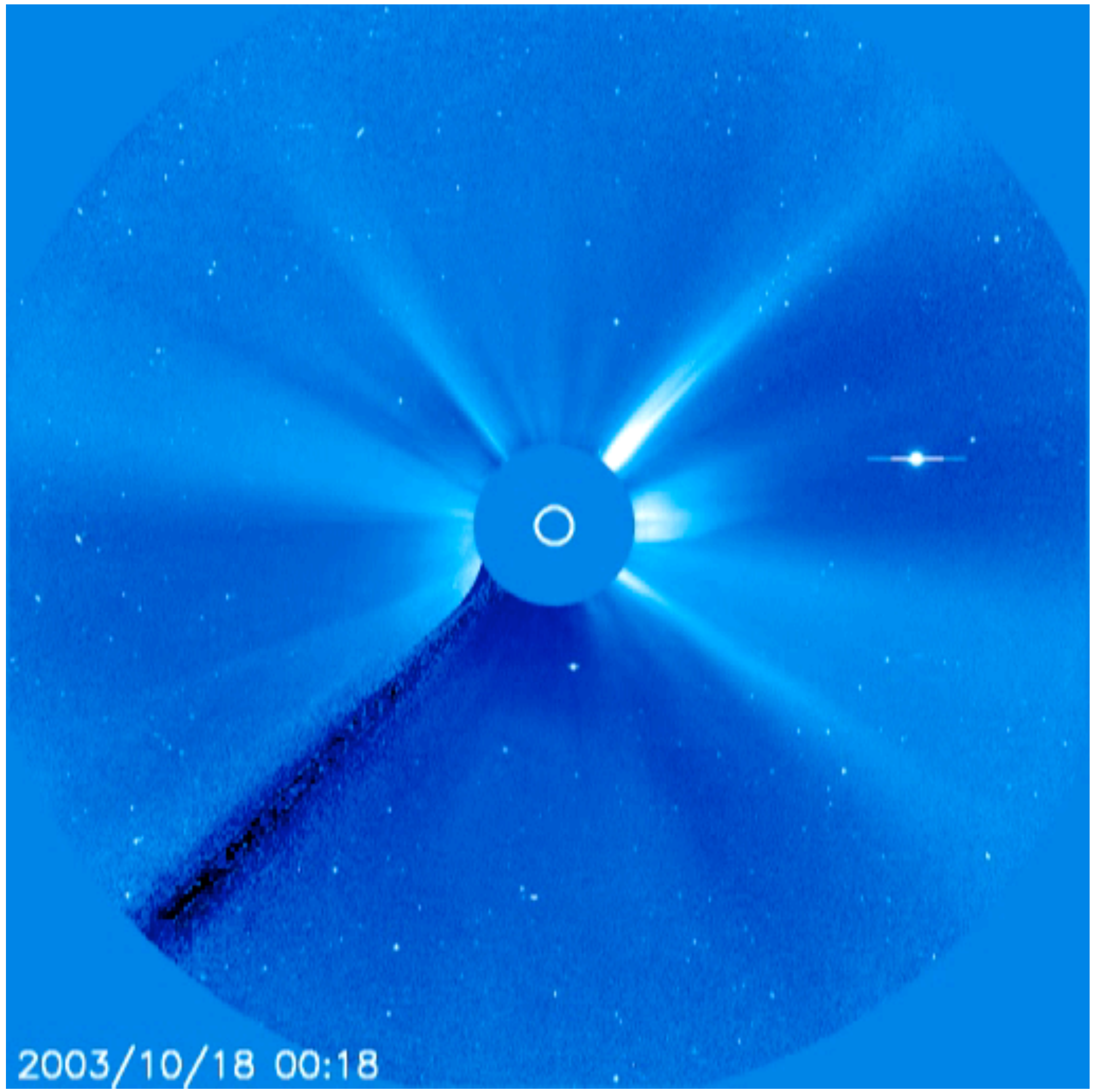
SN1006 ASCA (1995)



RX J1713 HESS (2004)



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

galactic phenomenon

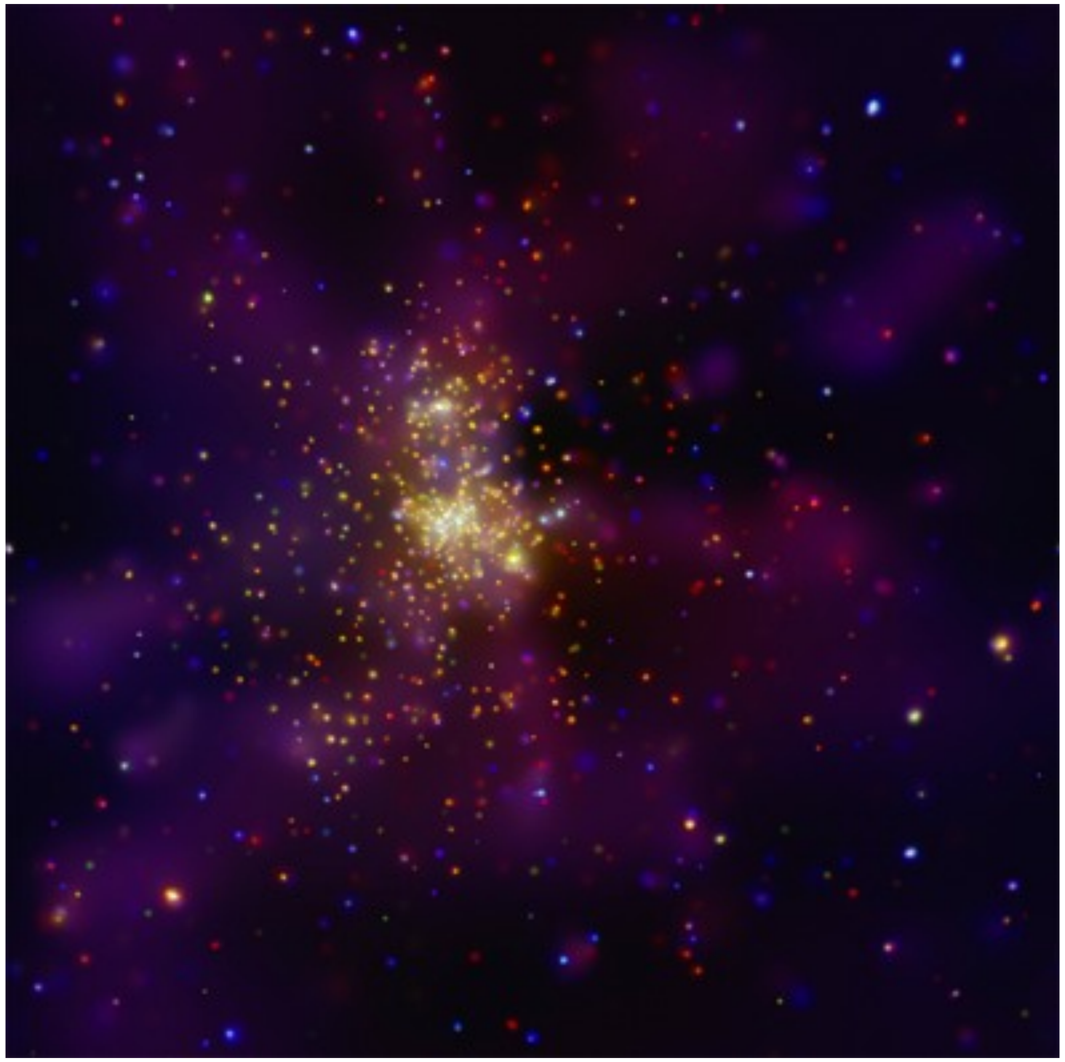
Supernova rate: $f \approx 1 / 30$ years
kinetic energy of emission: $E \approx 10^{44}$ J
fraction in CRs: $\varepsilon \approx 10\,\%$

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

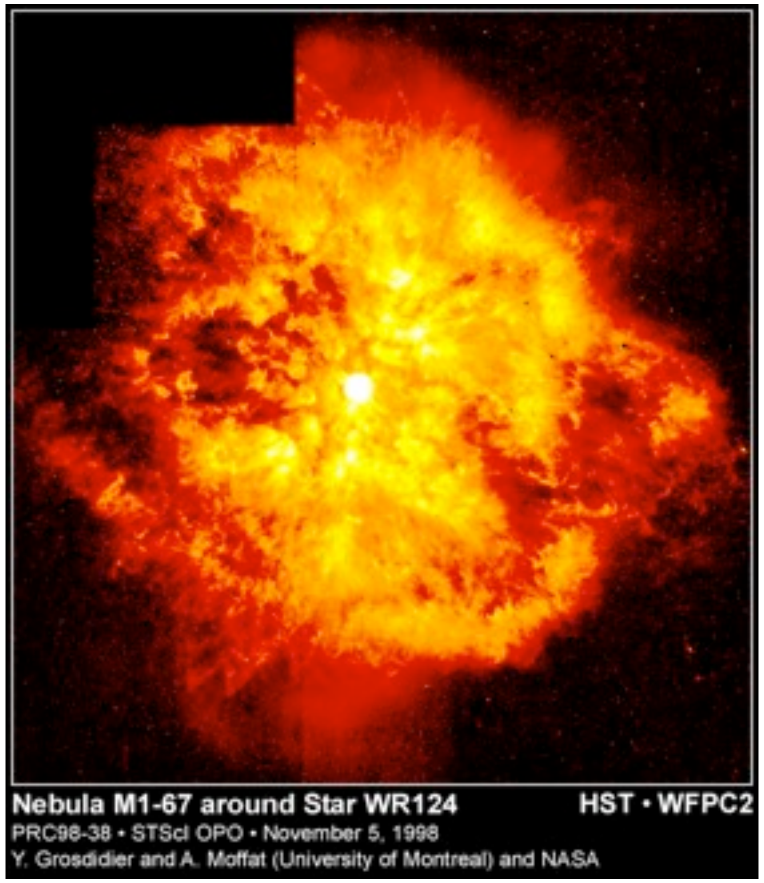
No obvious alternative can provide this energy.
... thus, Supernovae are good candidates
for the sources of cosmic rays.

… but other sources could contribute too.

Superbubbles



Star forming regions

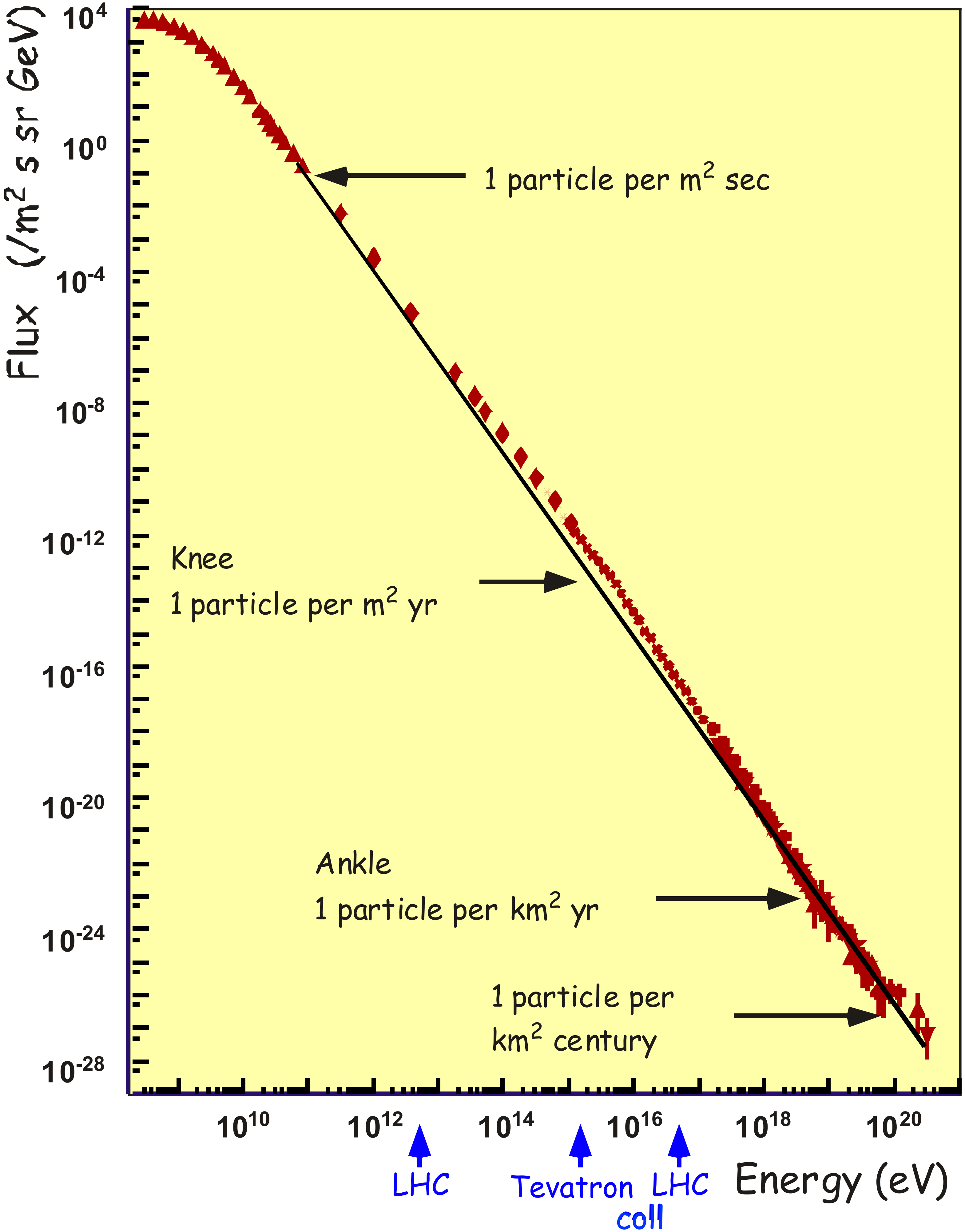


Wolf-Rayet Stars

… all producing outflows and shock fronts where particles can be accelerated

(seen in gamma rays)

Flux of Cosmic Rays



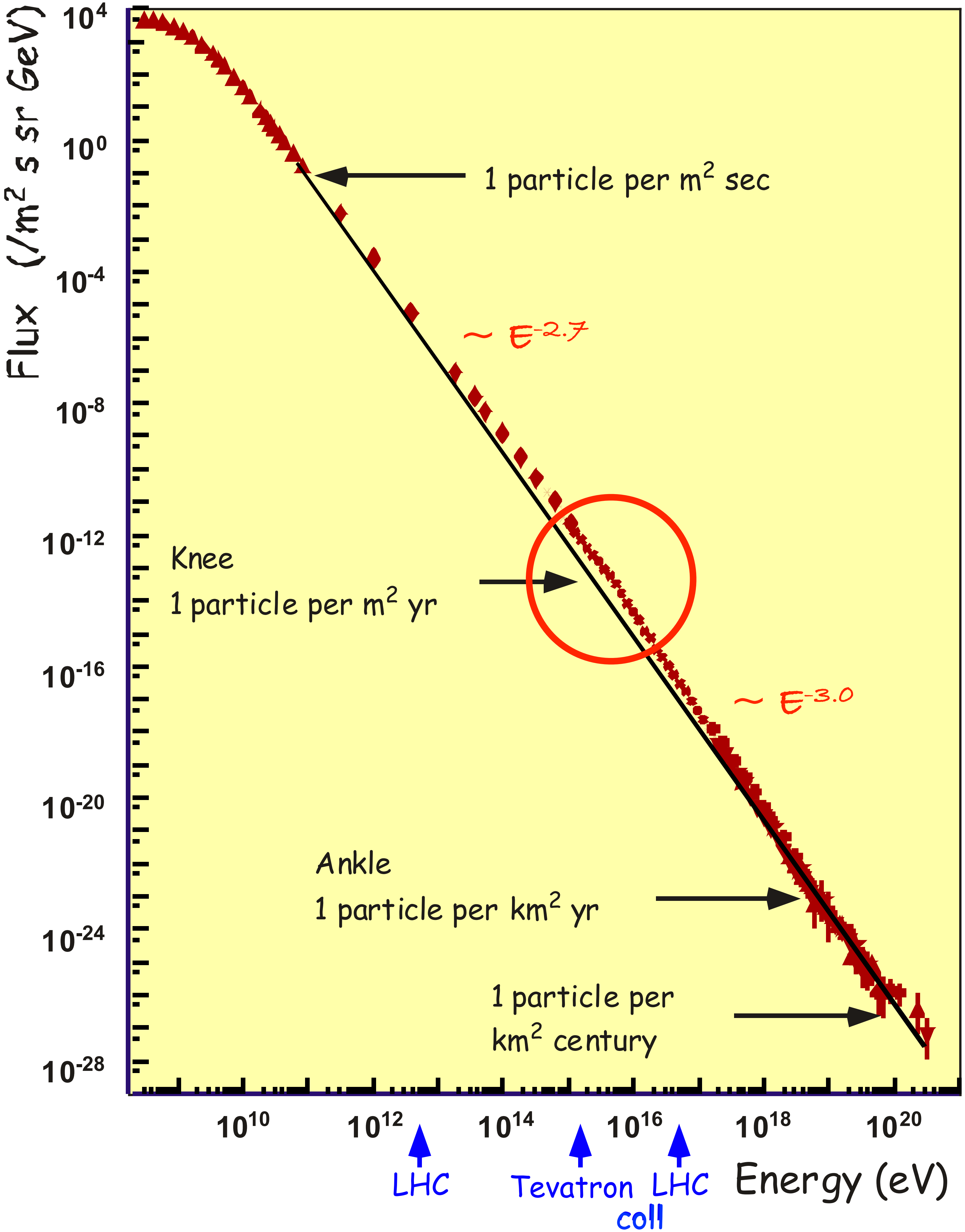
11 orders of magnitude in energy,
32 in flux !!!!

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



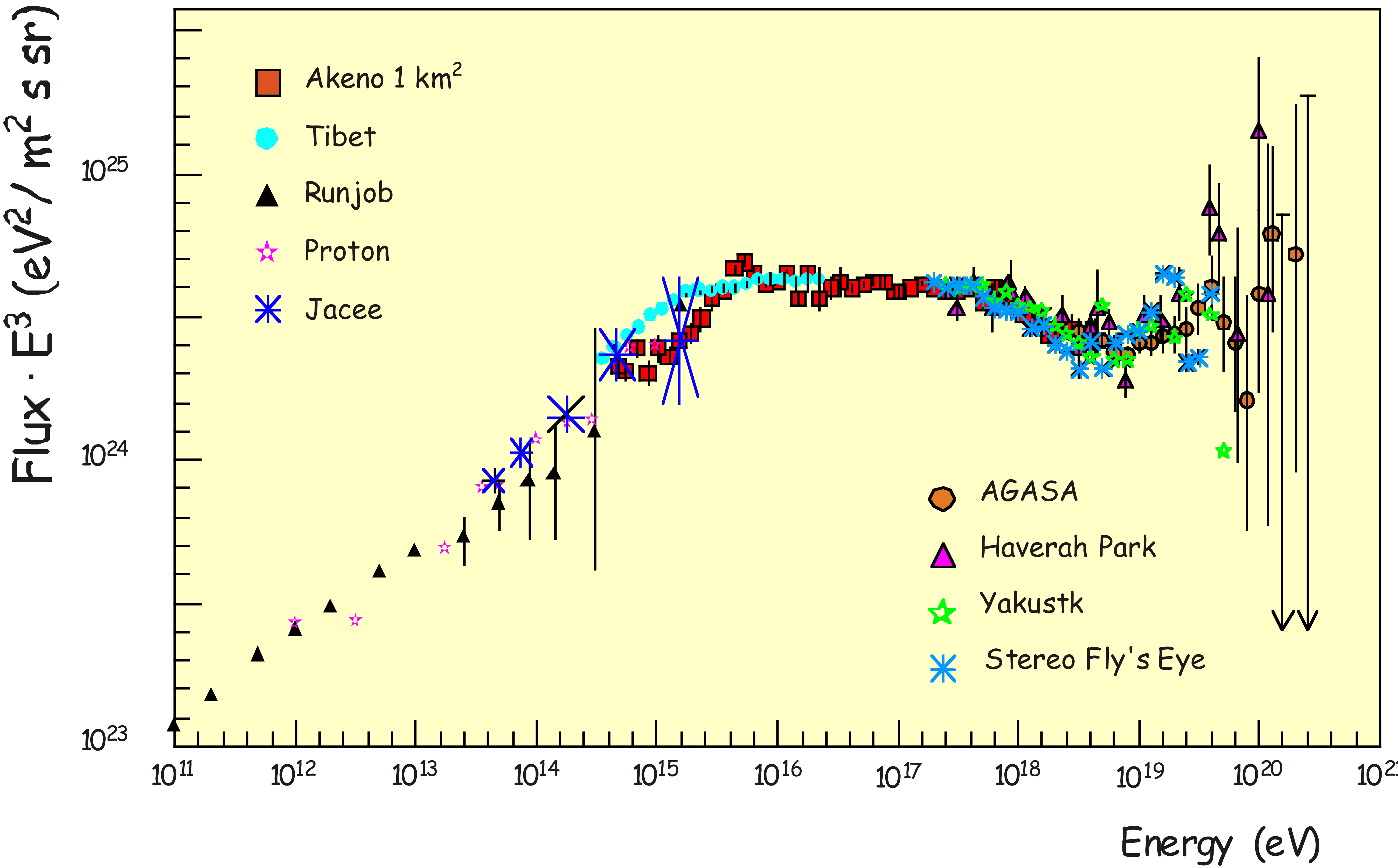
11 orders of magnitude in energy,
32 in flux !!!!

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 ???

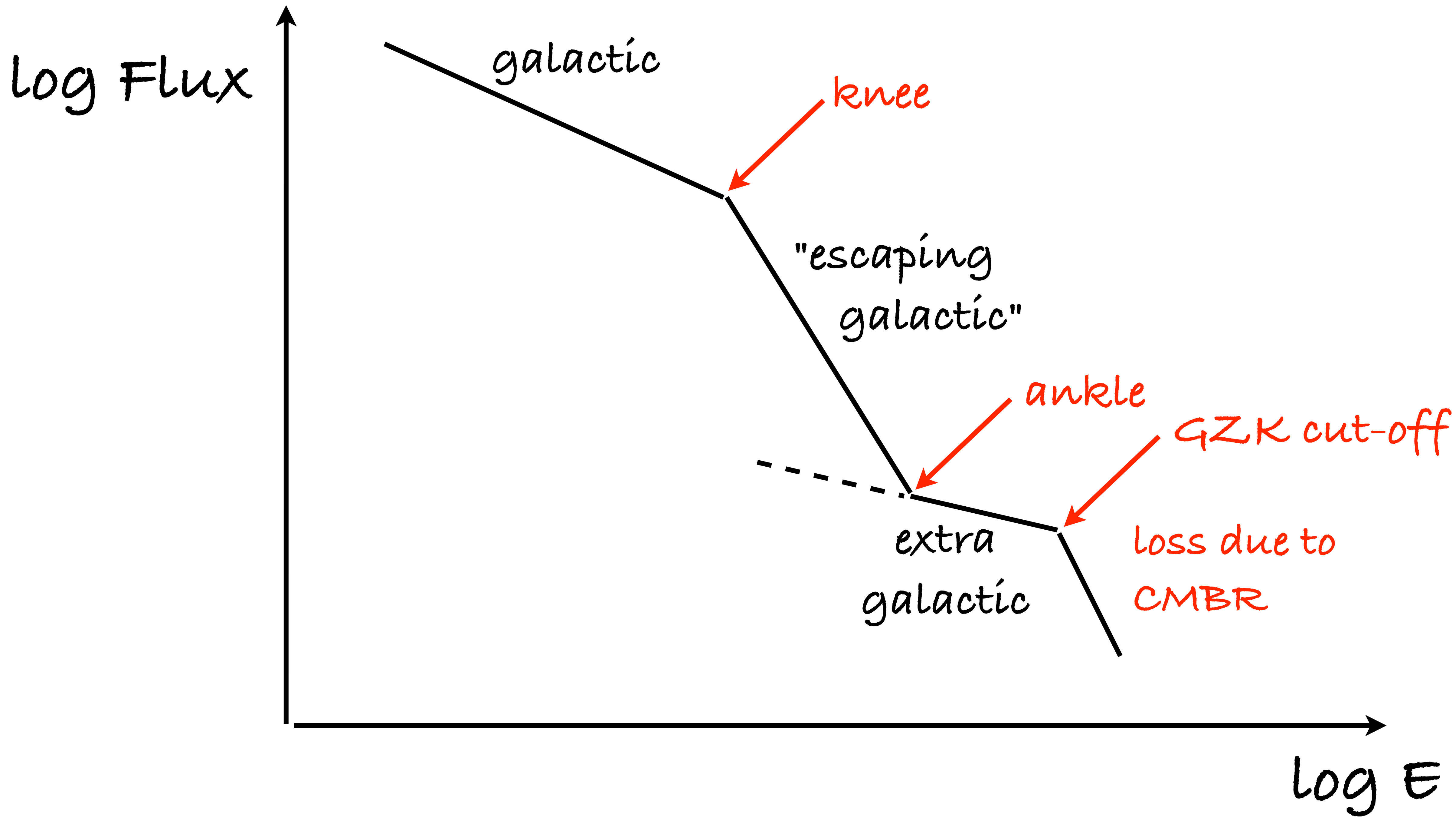
Differential Energy Spectrum: Flux x E^3



Agreement: < ± 45 % in flux at 10^{19} eV
< ± 15 % in energy

adjusted by ± 15% in energy
(within respective energy resolution)

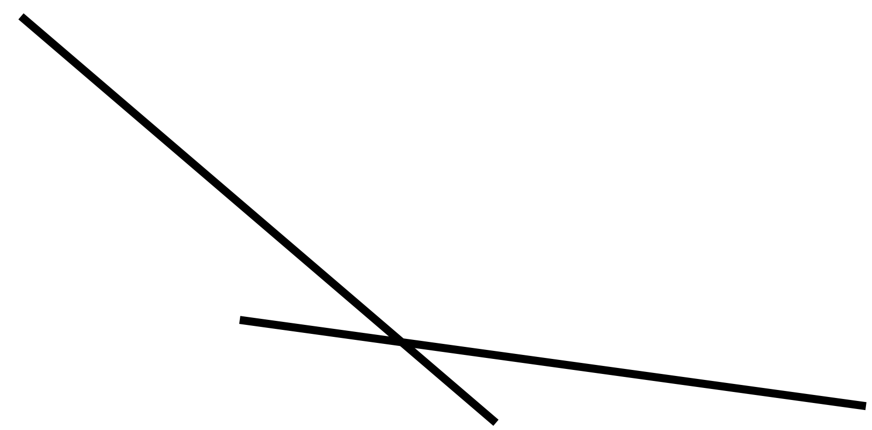
Early Interpretation (~1970)



knee-like

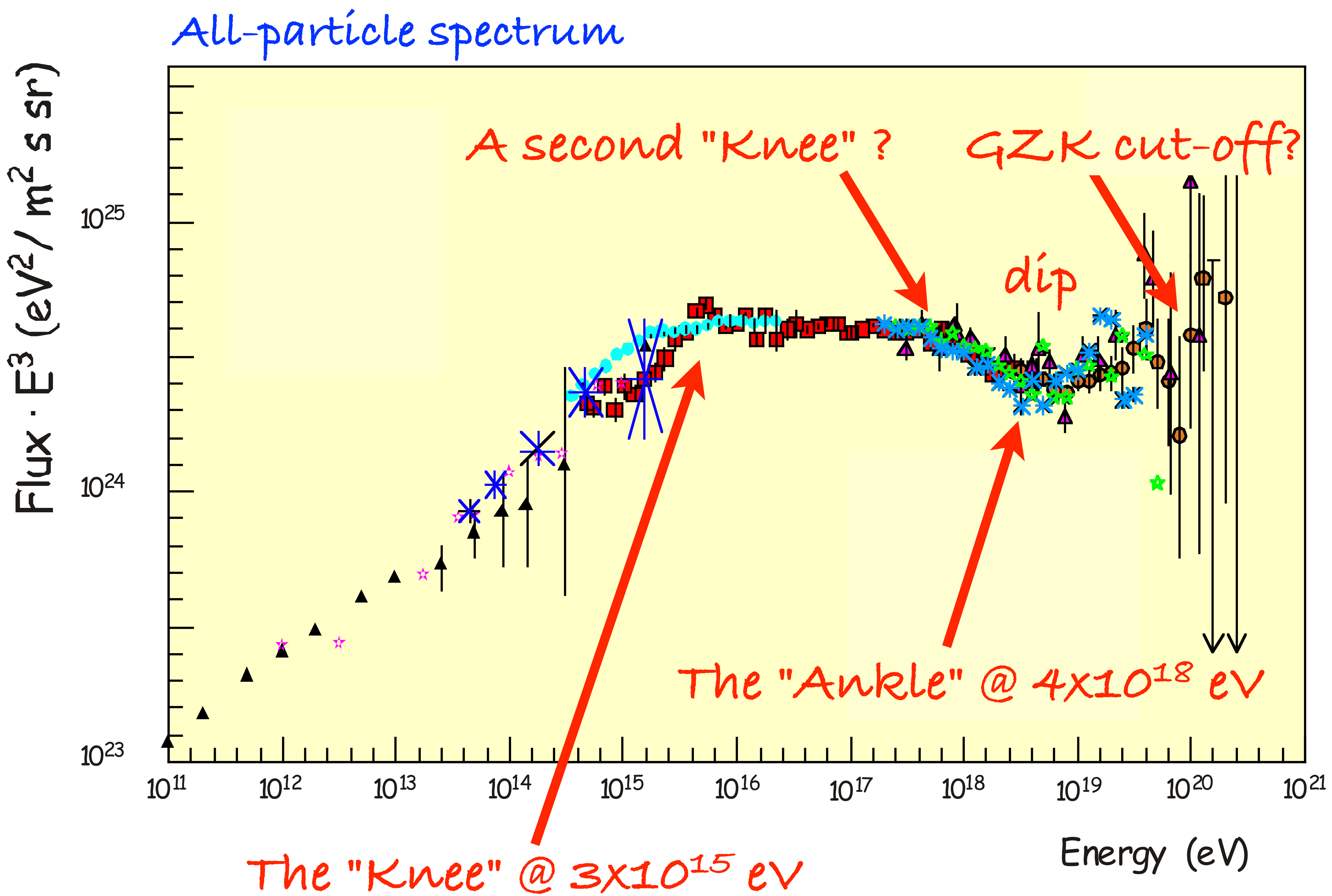
cut-off

ankle-like



sum of 2 components

"The anatomy of the CR energy spectrum" Flux x E^3



The Knee … many possibilities:

seen first in 1958

1. Acceleration in SNRs:

cut-off in acceleration due to limited B

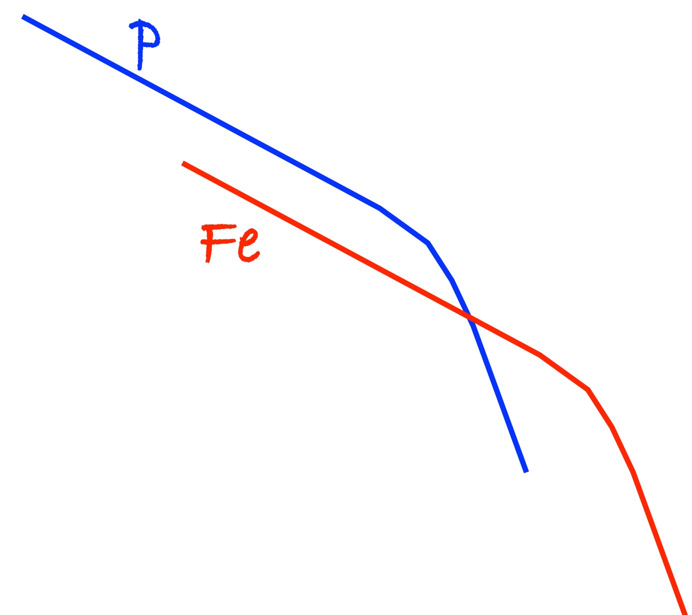
$E_{max} \approx Z e B_{acc} L_{acc} \propto Z \; 10^{15}$ eV

Bell, Lucek

cut-off in acceleration due to finite lifetime T of shock

$E_{max} \approx Z e B (T v) \beta_s \propto Z \; 10^{15}$ eV

expansion time (T) — shock speed v/c (β_s)

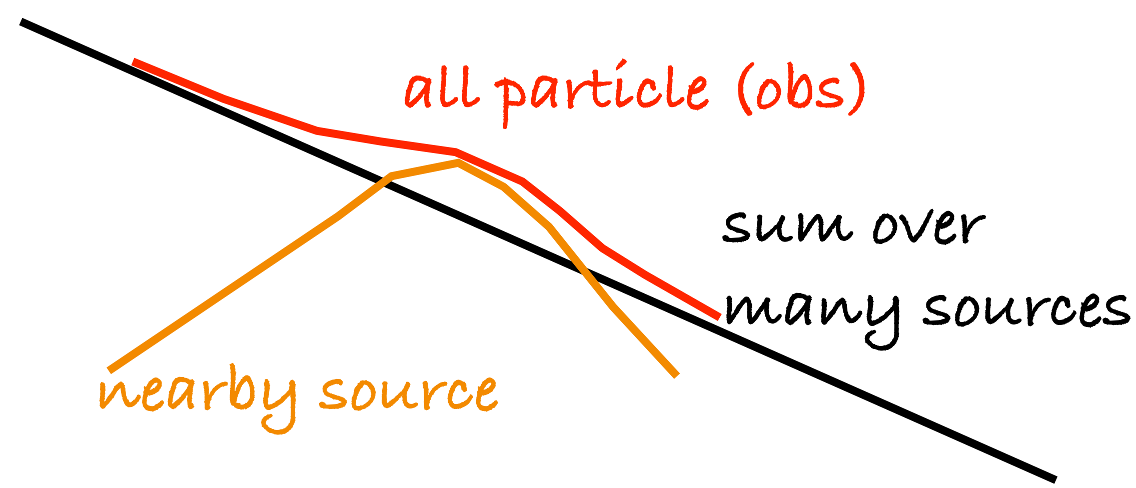


- $E_{cut\text{-}off} \propto Z$, protons cut of at lower energies than Fe
- Composition turns heavier at the knee
- No change in anisotropy

Variations of the diffusive shock acceleration possible:

… in SNR type and environments
… in oblique shocks
… field amplification …

Single source model ? a single nearby source dominates around the knee



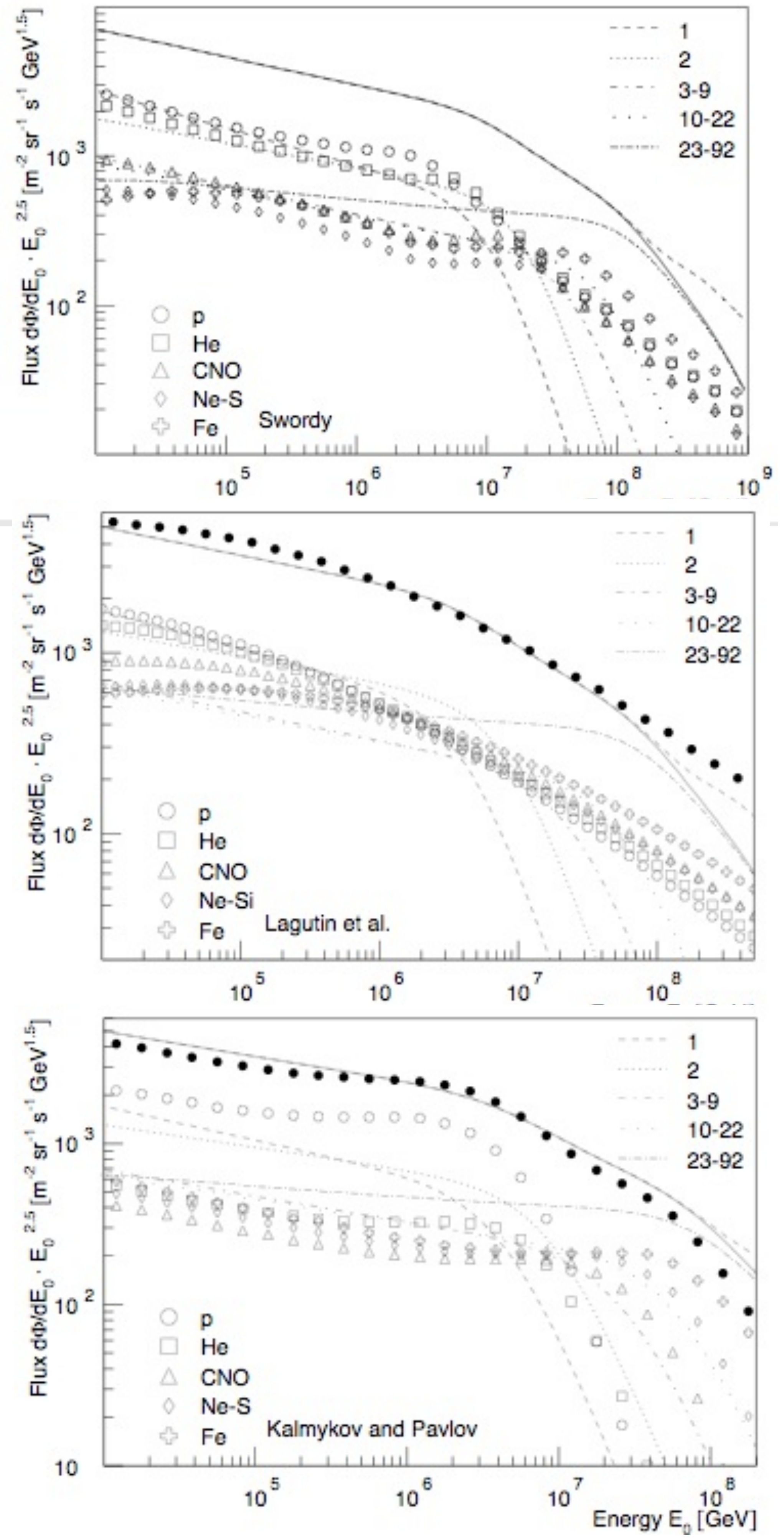
2. Diffusion processes during propagation:

escape from Galaxy (probability ~ Z)
.... many open details ...

- $E_{leak} \propto Z$
- Composition turns heavier at knee
- emerging anisotropy $\propto E$

"minimum path length",
"anomalous" diffusion,
diffusion + drift,
....

N.B. if CRs leak out of our Galaxy
we expect to see at high energies
CRs coming in from other galaxies.



3. Interactions of high-energy cosmic rays

- with ISM near source and during propagation:
  Photo-disintegration (for nuclei),
  interaction with νs in galactic halo?
  ....

- in atmosphere
  Change in hadronic particle interaction ?
  rapidly changing cross sections?
  QGP?, new physics? new particles?

i.e. $\frac{d\sigma}{dE}$

- $E_{threshold} \propto A$
- Composition turns heavier at knee
- No change in anisotropy

....

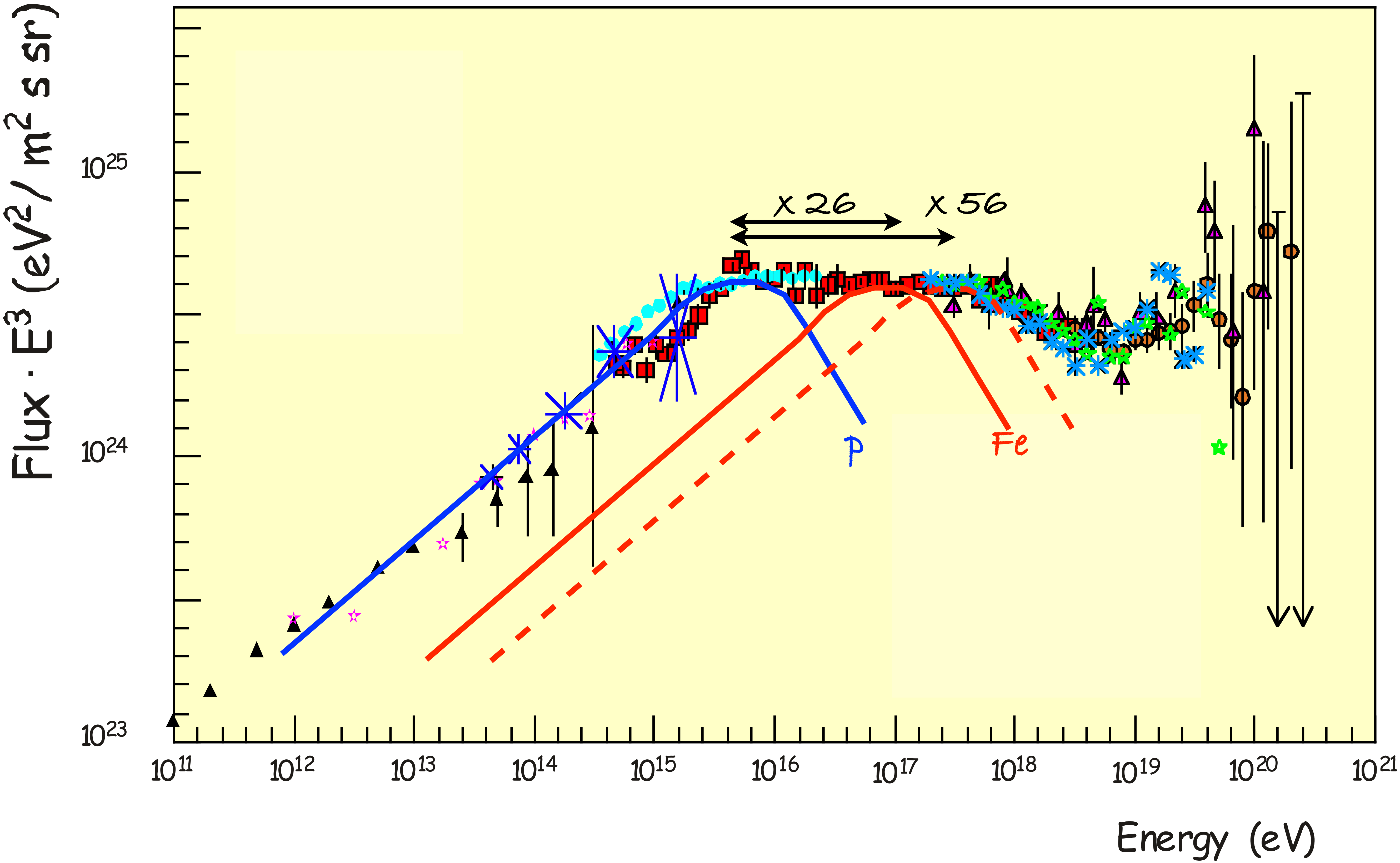
Differential Energy Spectrum ?

the energy is not measured directly,
but deduced from an observable quantity:
e.g. the signal produced by shower particles
in the detectors at ground level ($S = f(E)$).

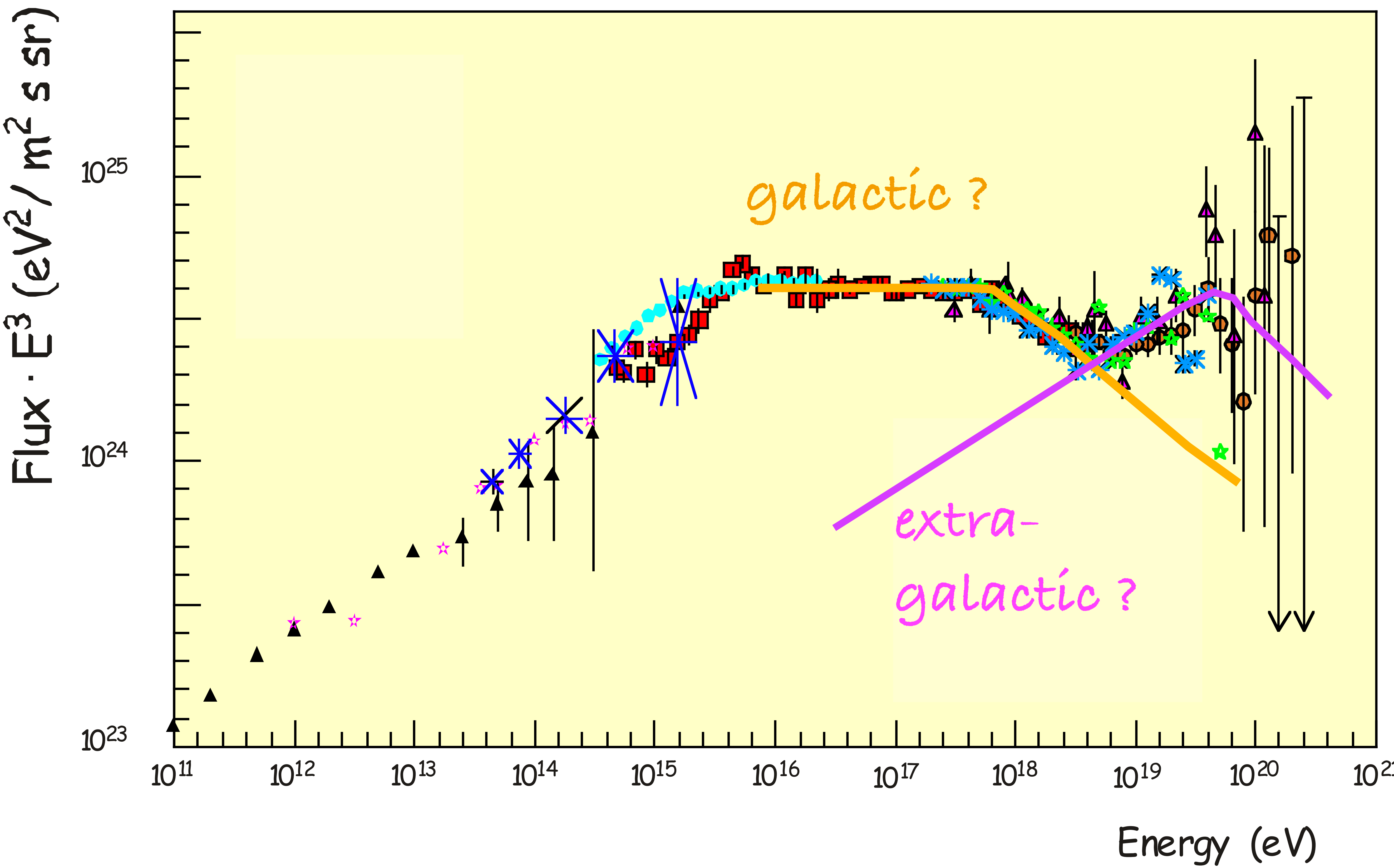
$$\frac{dN}{dE} = \frac{dN}{dS}\,\frac{dS}{dE}$$

desired — measured — S-E relation (can be quite complicated)

N: number of showers in a certain area



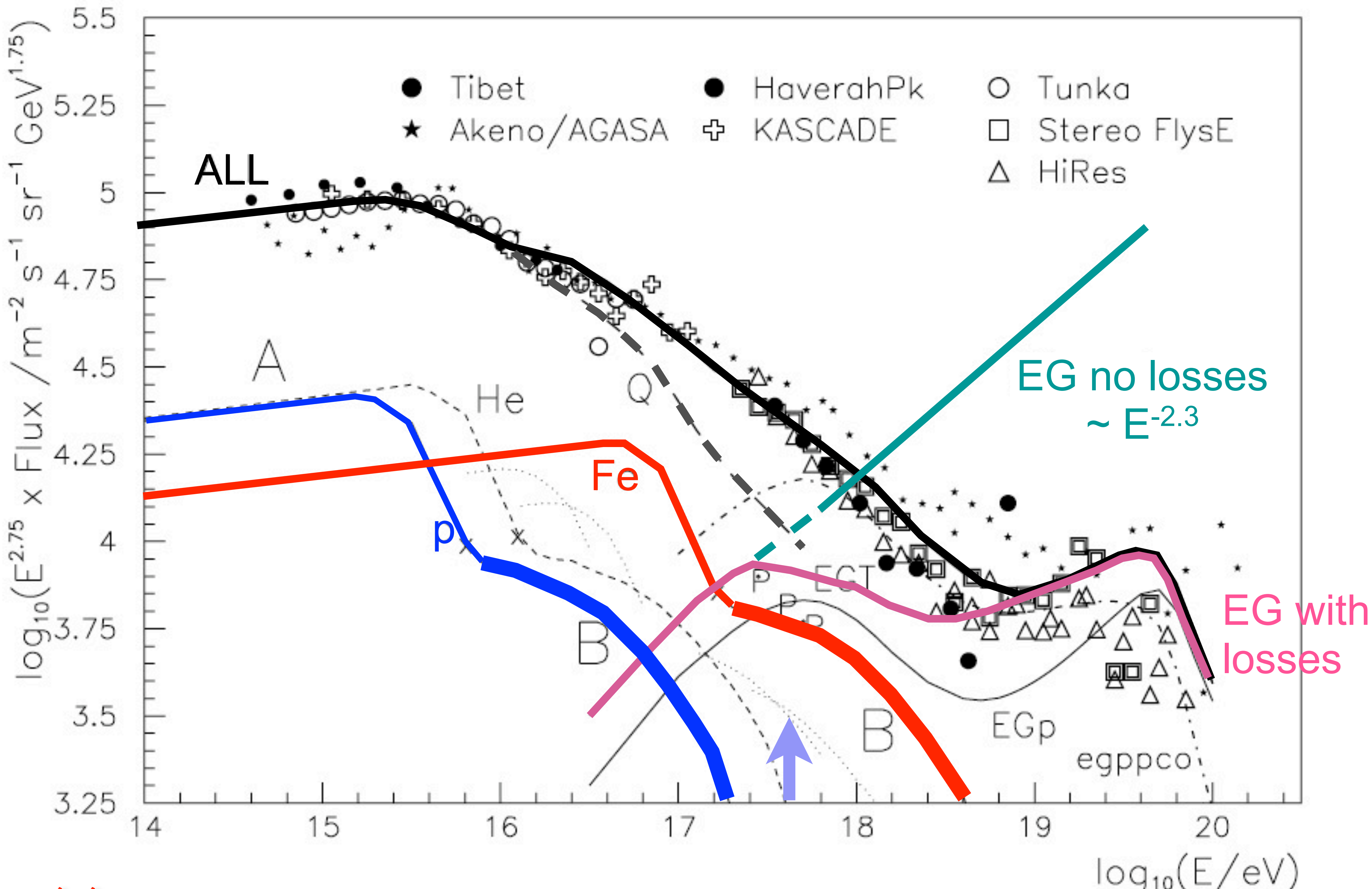
if p cut off at E then Fe should cut off at 26 x E (if Z-dependent)
56 x E (if A-dependent)



Flux · E³ (eV²/ m² s sr)
10^25
10^24
10^23
galactic ?
extra-
galactic ?
10^11
10^12
10^13
10^14
10^15
10^16
10^17
10^18
10^19
10^20
10^21
Energy (eV)

Ankle model:

A.M. Hillas

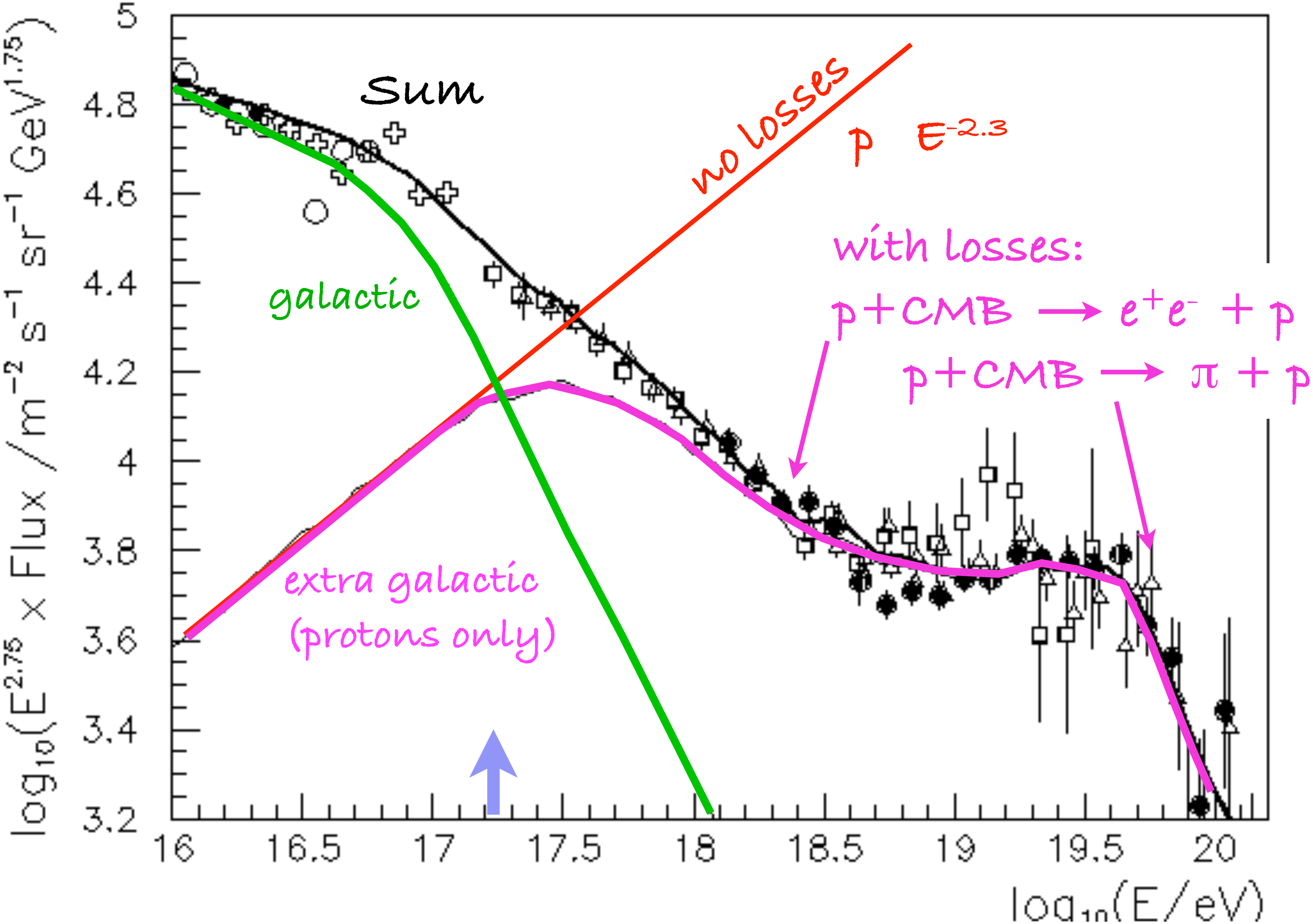


Transition gal - extra gal : at the ankle

Extra component (B) needed (e.g. SN in strong precursor wind, 100x higher E_{max})

Dip model:

V. Berezinsky

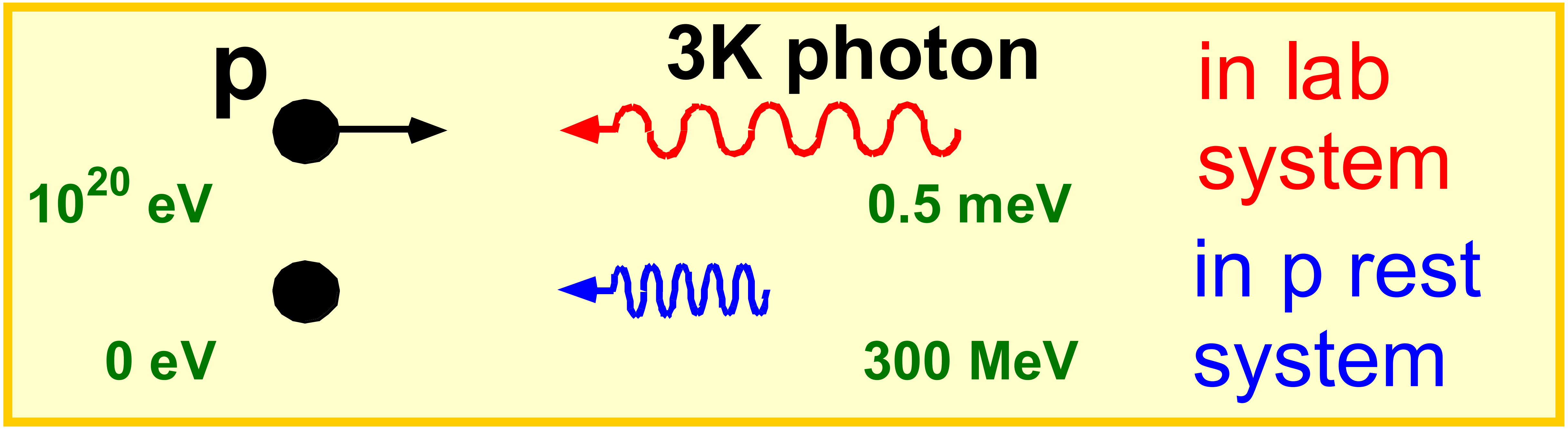


Transition gal - extra gal well below the ankle : 1.7×10^{17} eV

dip occurs naturally from pair production with CMB.

GZK Cut-Off

Greisen Zatsepin Kuzmin



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

$$\longrightarrow n + \pi^{+} \; (\rightarrow \nu)$$

Photo-pion production

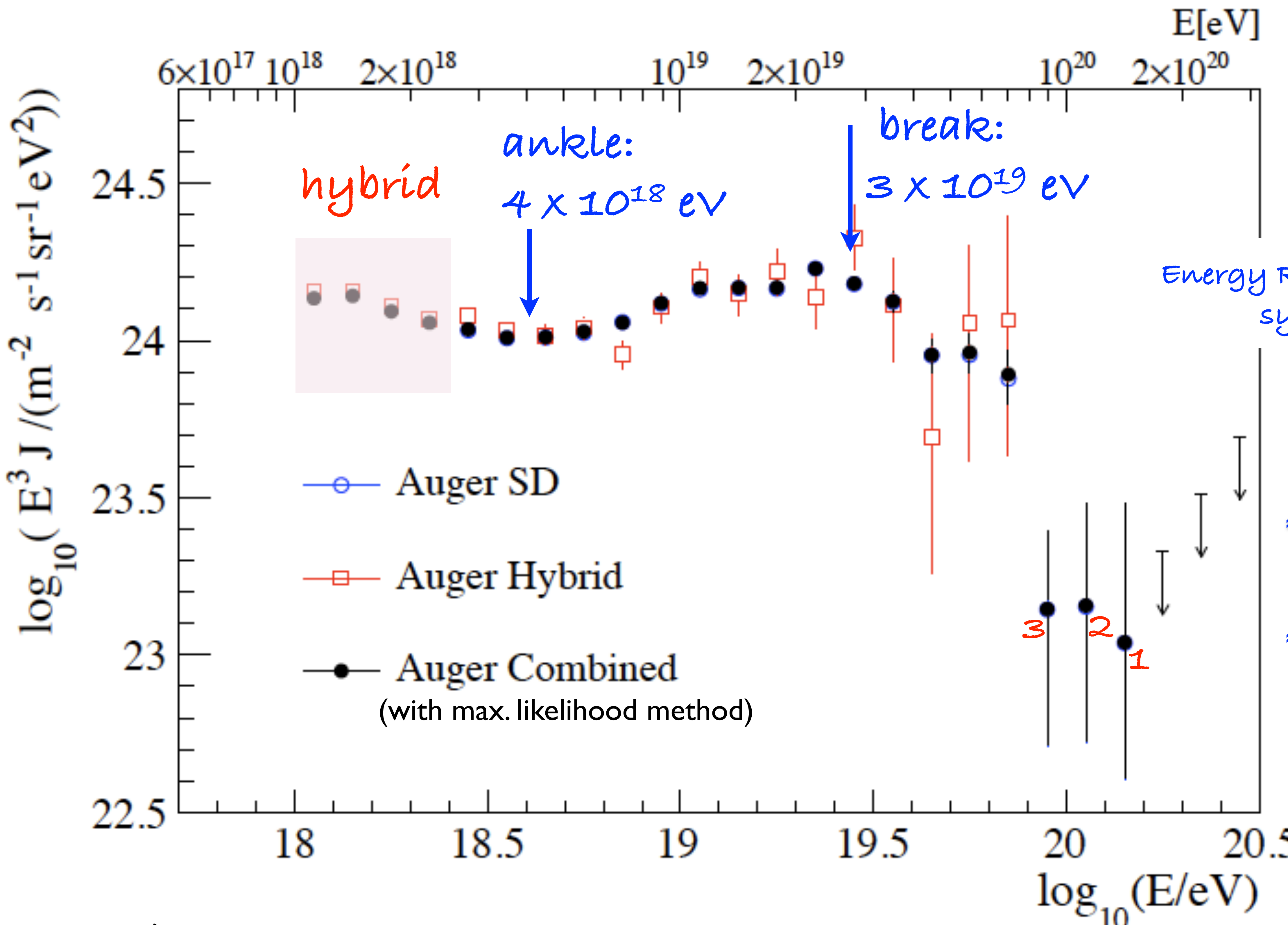
$$^{56}Fe + \gamma_{3K} \longrightarrow {}^{55}Fe + n$$

Photo dissociation

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

Spectrum cuts off (absorption of CRs from distant sources)

Energy spectrum Pierre Auger Observatory



Energy Resolution : 17%
systematics: 22%

$>10^{20}$ eV:

≈ 1 evt/yr on 3000 km²

≈ 1 evt/min on surface of Earth !

Auger finds "ankle" and a clear (>20 σ) spectral steepening at E ≈ 3 x 10^{19} eV.

θ = 0 - 60°

Anisotropy :

- Diffusion of particles in Galaxy, away from centre creates a gradient (radial and in height) anisotropy expected $\approx 10^{-4}$

- Movement of Earth through a "CR gas" (Compton-Getting effect)
  Earth around Sun through gal. CRs (30 km/s) $\approx 5 \times 10^{-4}$
  Solar system through extra gal. CRs (CMB system) $\approx 6 \times 10^{-3}$
  (650 km/s)

To measure small anisotropies requires:

huge statistics,

control of effects that could fake an anisotropy at 10^{-3} - 10^{-4}

(weather, stability of detector, exposure, ...)

At high energies larger anisotropies expected, but statistics is poor.

Are there any real (i.e. astrophysical) anisotropies?

e.g. from very nearby sources? local galaxy arms ?

strong magnetic fields? neutral CRs? ...

Knee & Ankle are clearly seen: What are they ?

Many scenarios ....

Are the data correct ?

Energy, Flux, Mass composition ?

How (and how well) can these be measured ?

A single variable (e.g. N_e) is not enough.

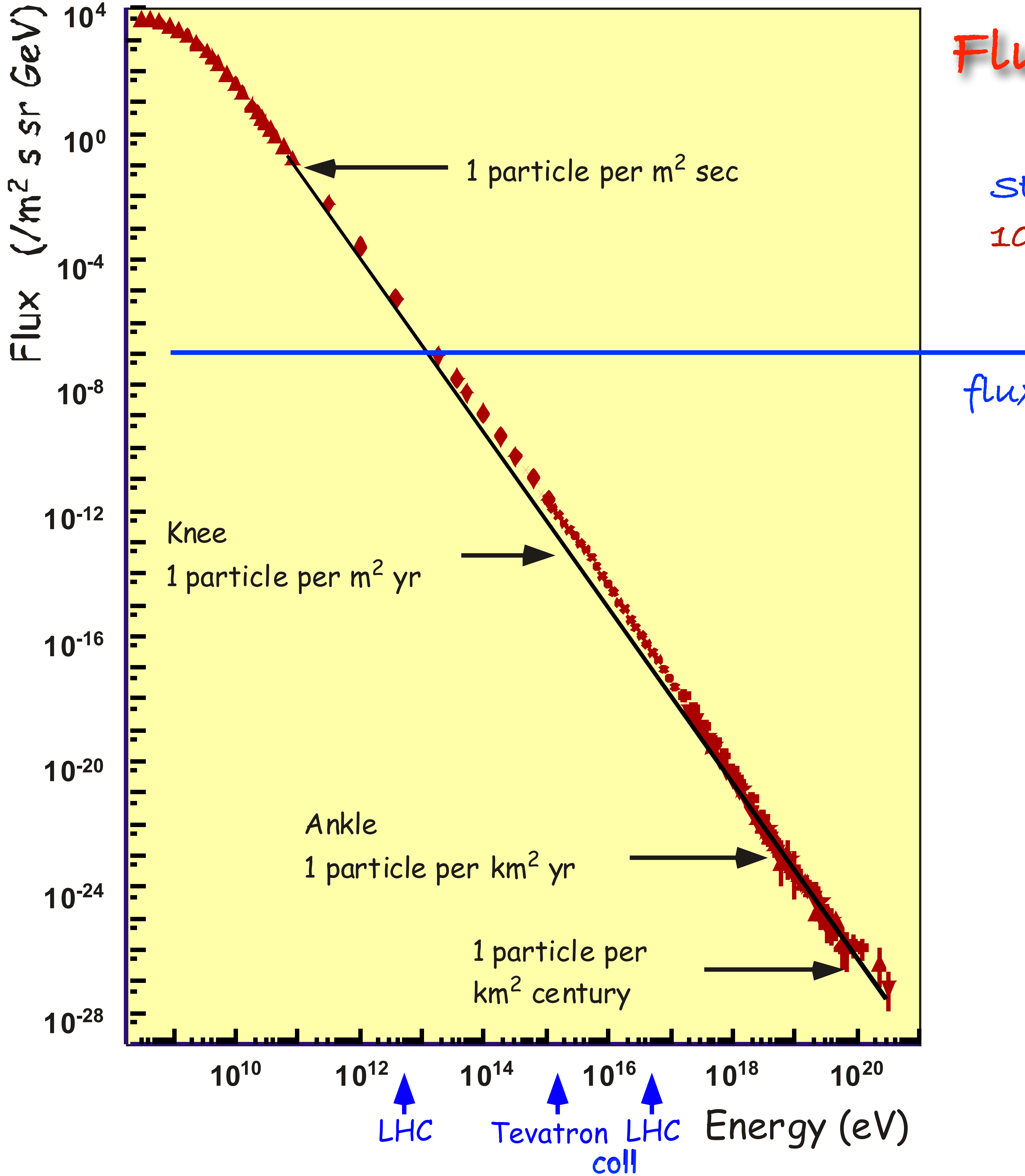
Multivariate analysis: use many observables
(and their correlations)

Air Showers and Experimental Techniques

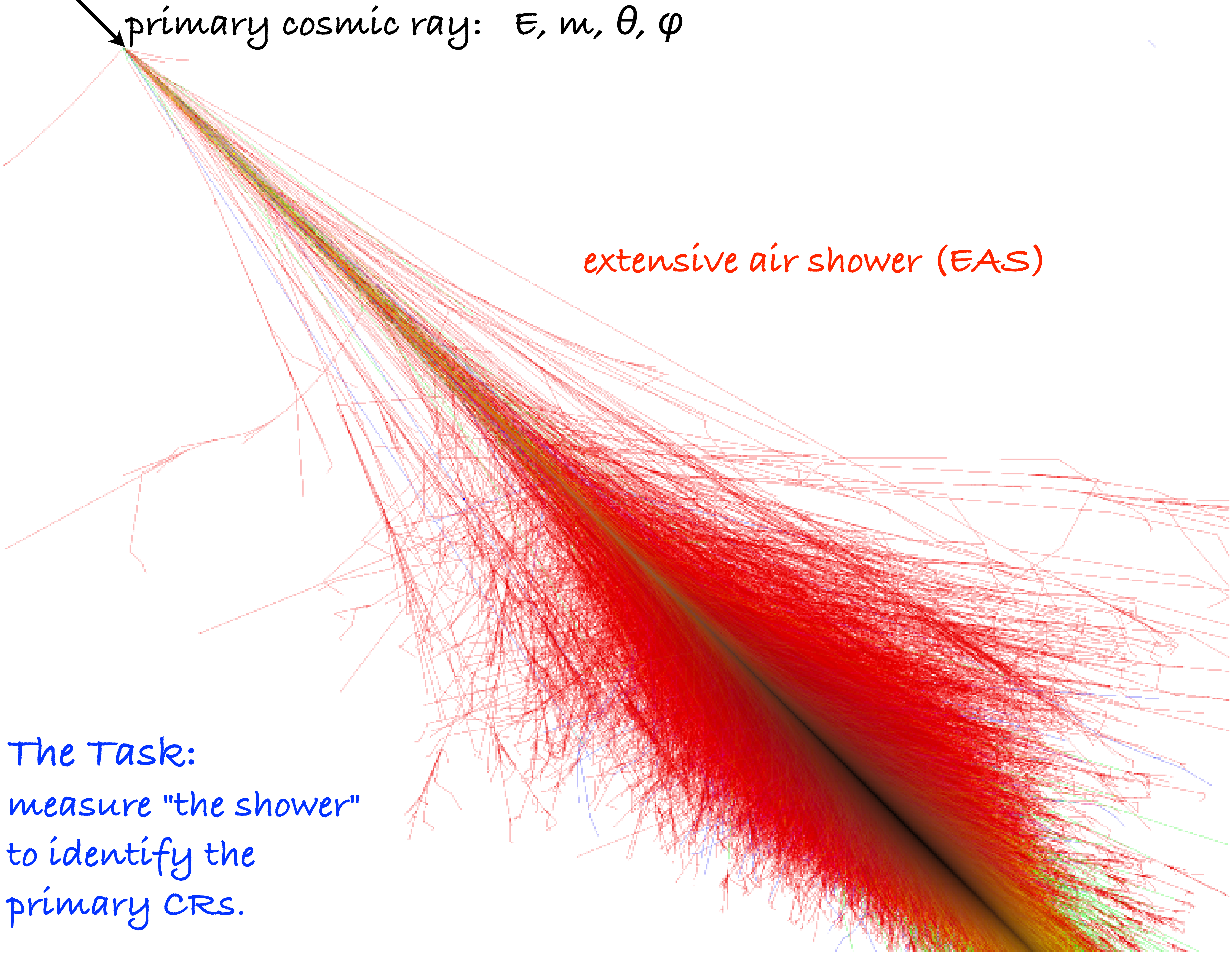
Flux of Cosmic Rays

Steeply falling spectrum:

10 x in energy / 500 in flux



flux limit for ≈m² detectors



The Task:
measure "the shower"
to identify the
primary CRs.

+ Particle Multiplication:

Instead of 1 particle (the primary) one has to detect
a shower with many particles scattered over a wide area.
much easier to detect !

- Indirect Measurements:

Deduce properties of primary Cosmic Rays from
the shape and particle content of the shower of secondaries.

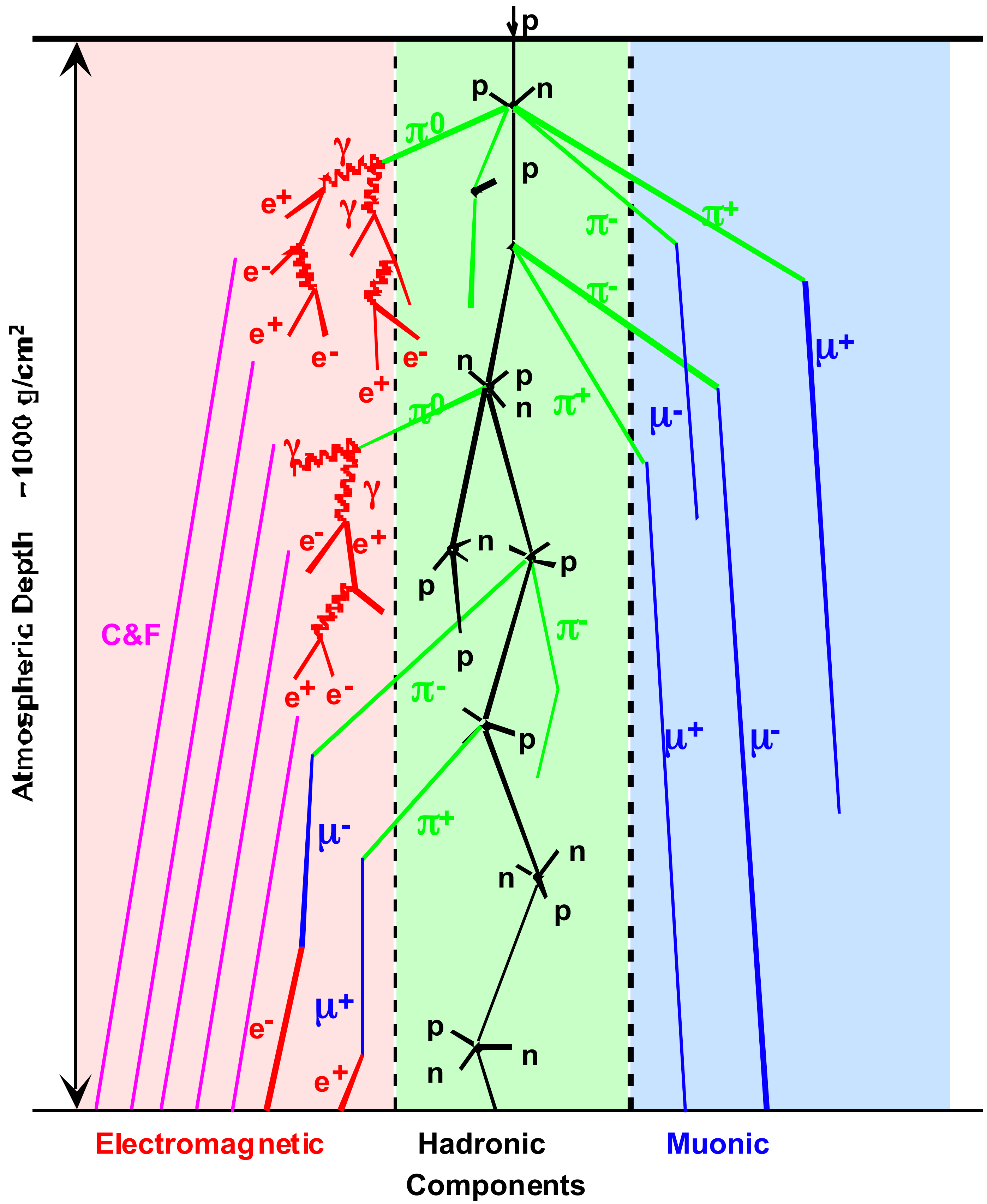
- particles (e, γ , μ , ...) at ground level
- Cherenkov light from charged secondaries (forward)
- Fluorescence light from ionised air (isotropic)
- Radio emission from charges in Earth magnetic field (forward)

for all: density, lateral-, energy-, time distributions

This is tricky:
it requires knowledge on how a shower develops
depending on its primary, energy, angle,
hadronic interaction, ...

simulations!

Air Shower Experiments



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 ~ 2 GeV

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

Cherenkov and Fluorescence photons are much more abundant

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

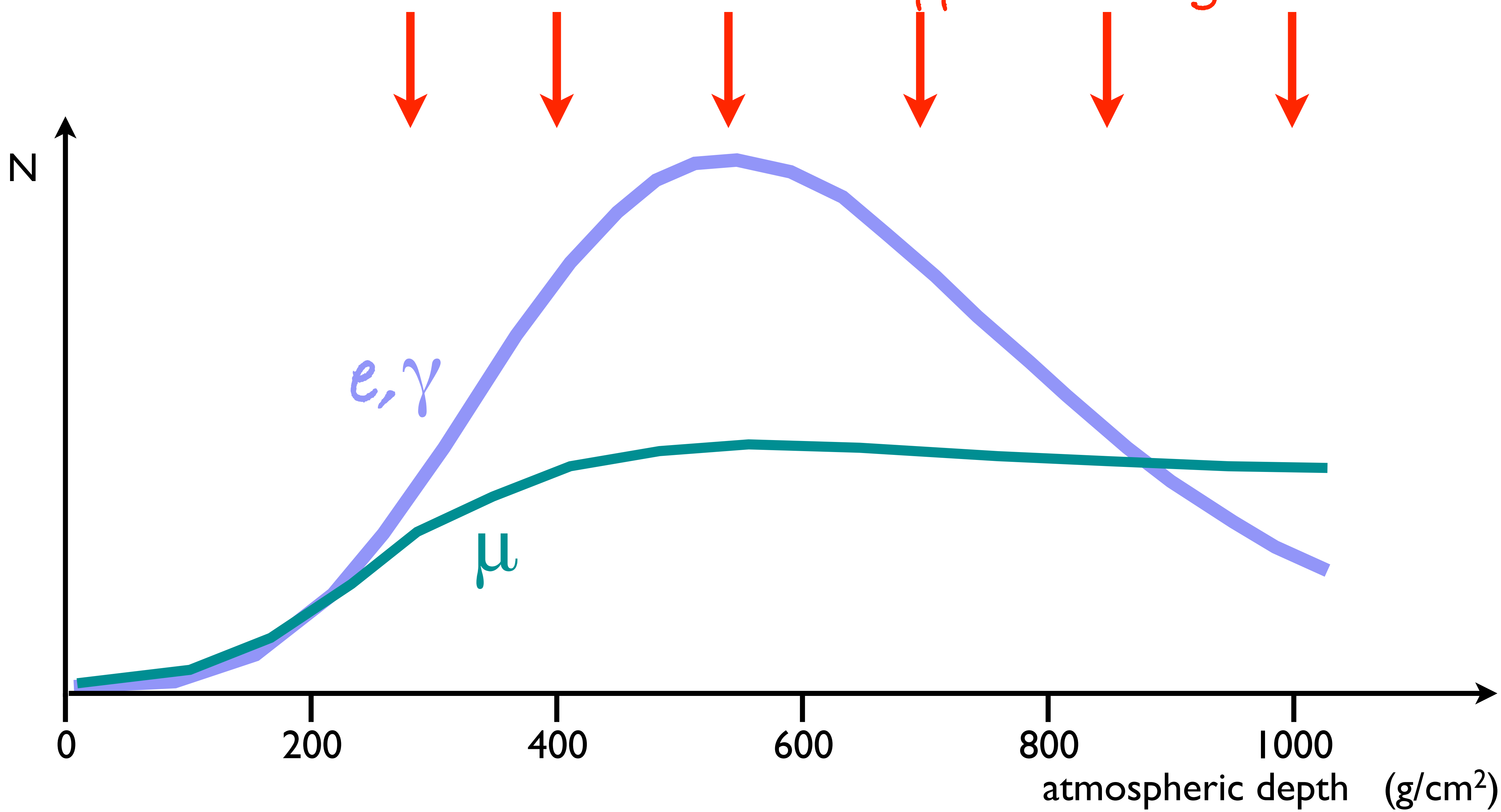
at energies of MeV to 10^{20} eV well above man-made accelerators.

Complex interplay with many correlations
requires MC simulations

Longitudinal Development:

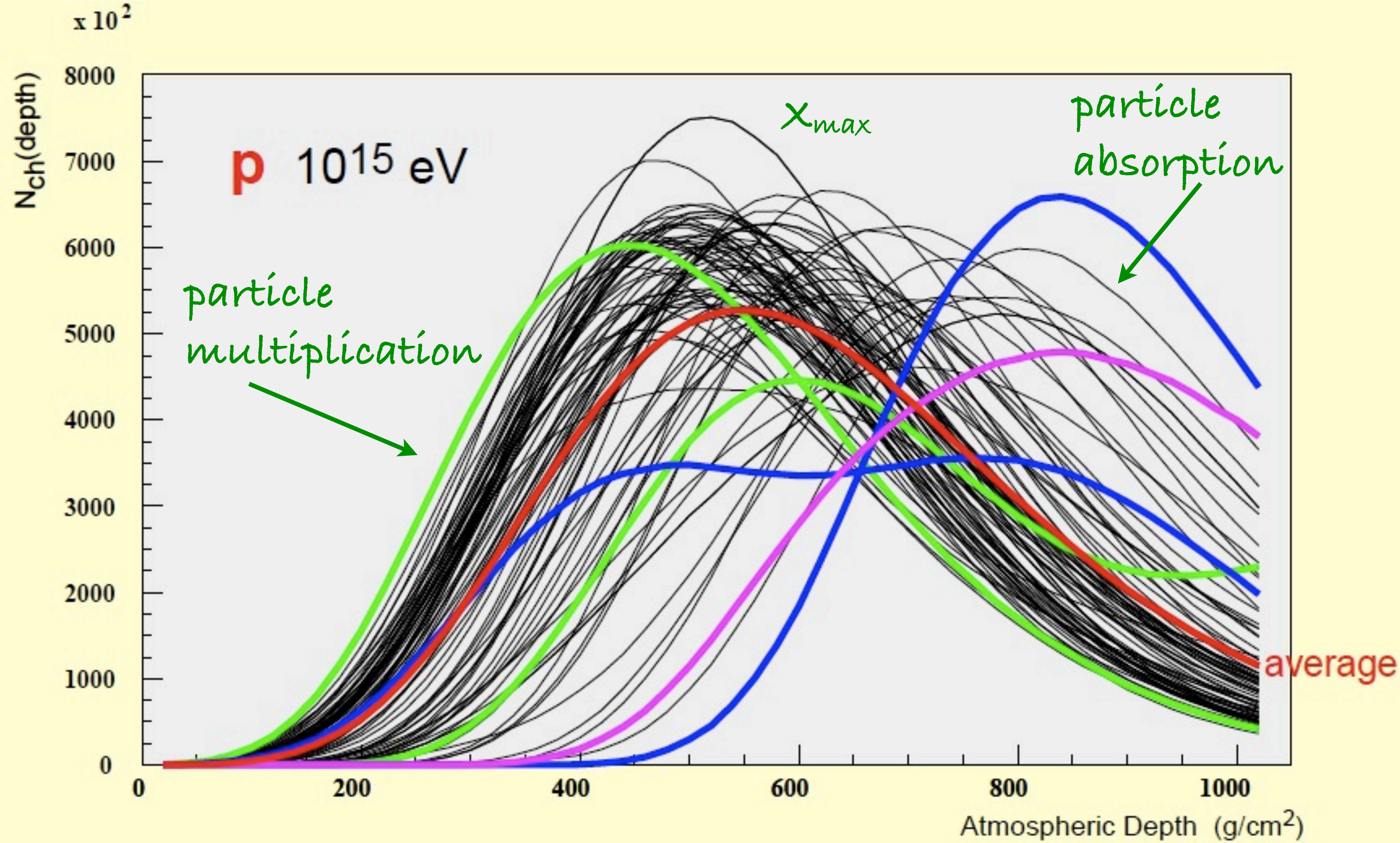
... for e, γ and μ

Distributions at different heights....



the muon component is nearly "calorimetric"

Longitudinal Development:



considerable fluctuations !

(get smaller at higher energies)

On average Fe showers have

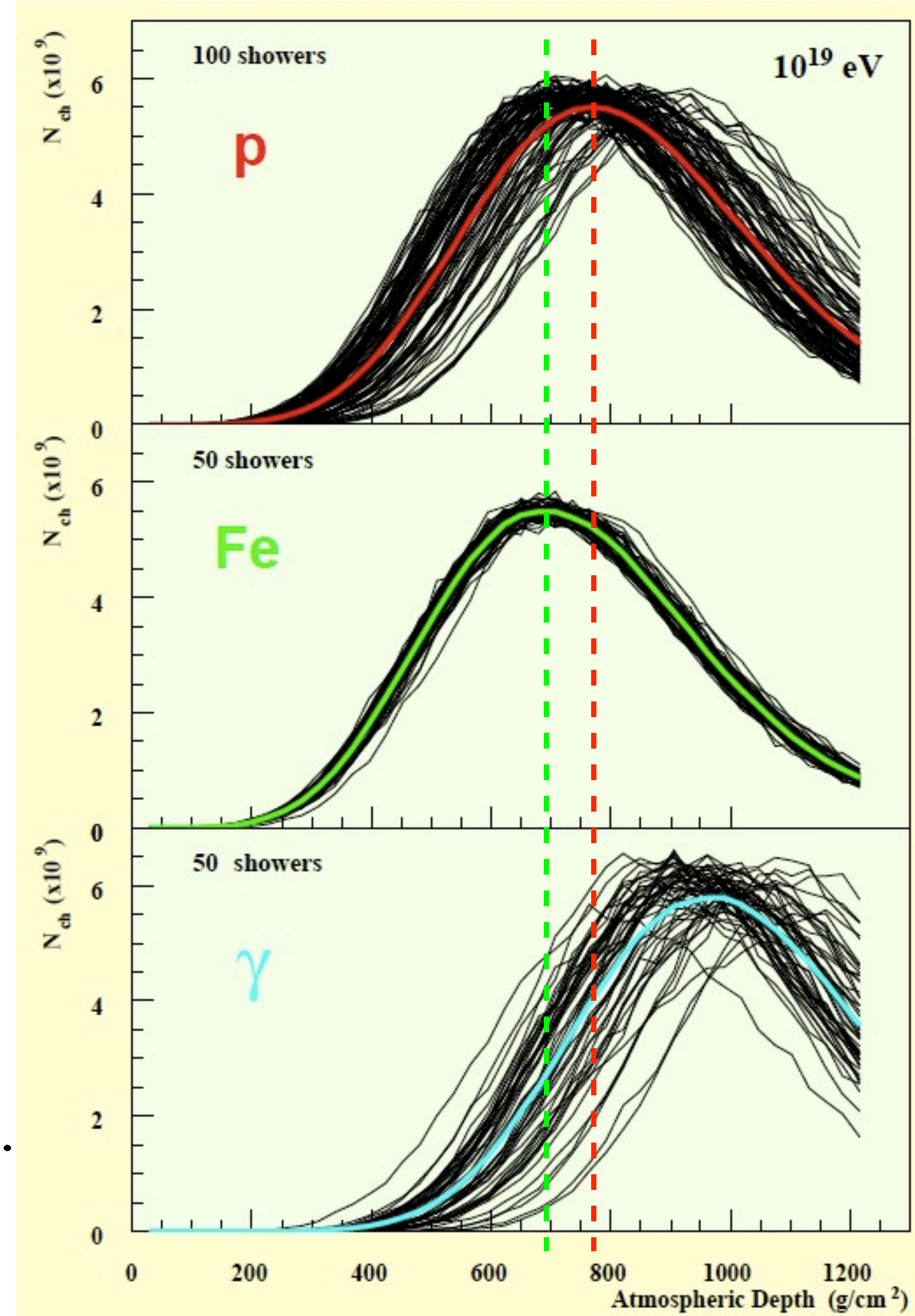
- higher 1^{st} interact. and maximum
  (since σ_{int} larger)
- more secondaries
  (since $N_{sec} \sim \ln(E)$)
- more μ, less e,γ at ground
- smaller fluctuations
  (since superposition of 56 subshowers)

than p showers

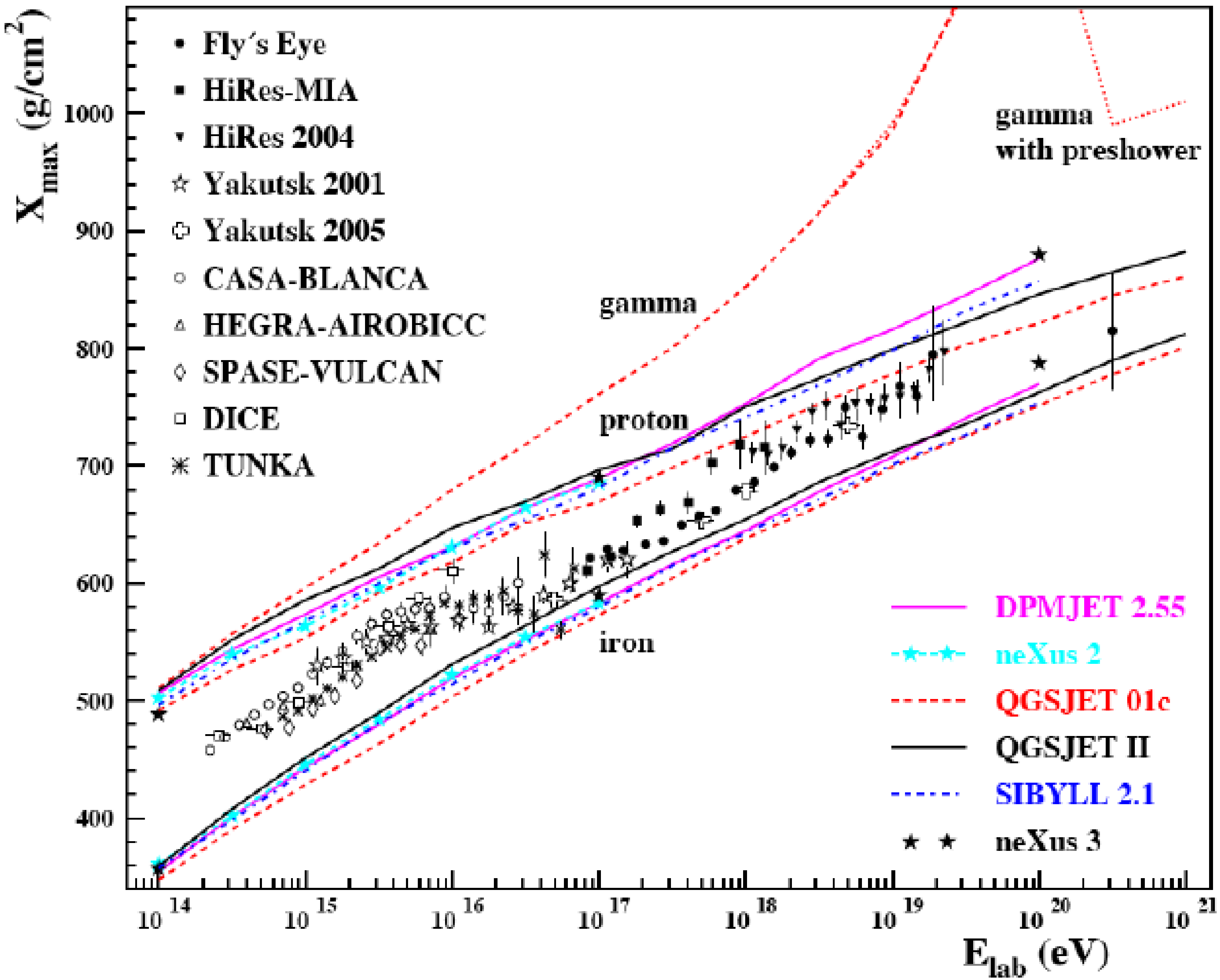
difference p - Fe $\approx$
fluctuations in p

γ showers are more different.

- have (almost) no muons
- different longitudinal dist.



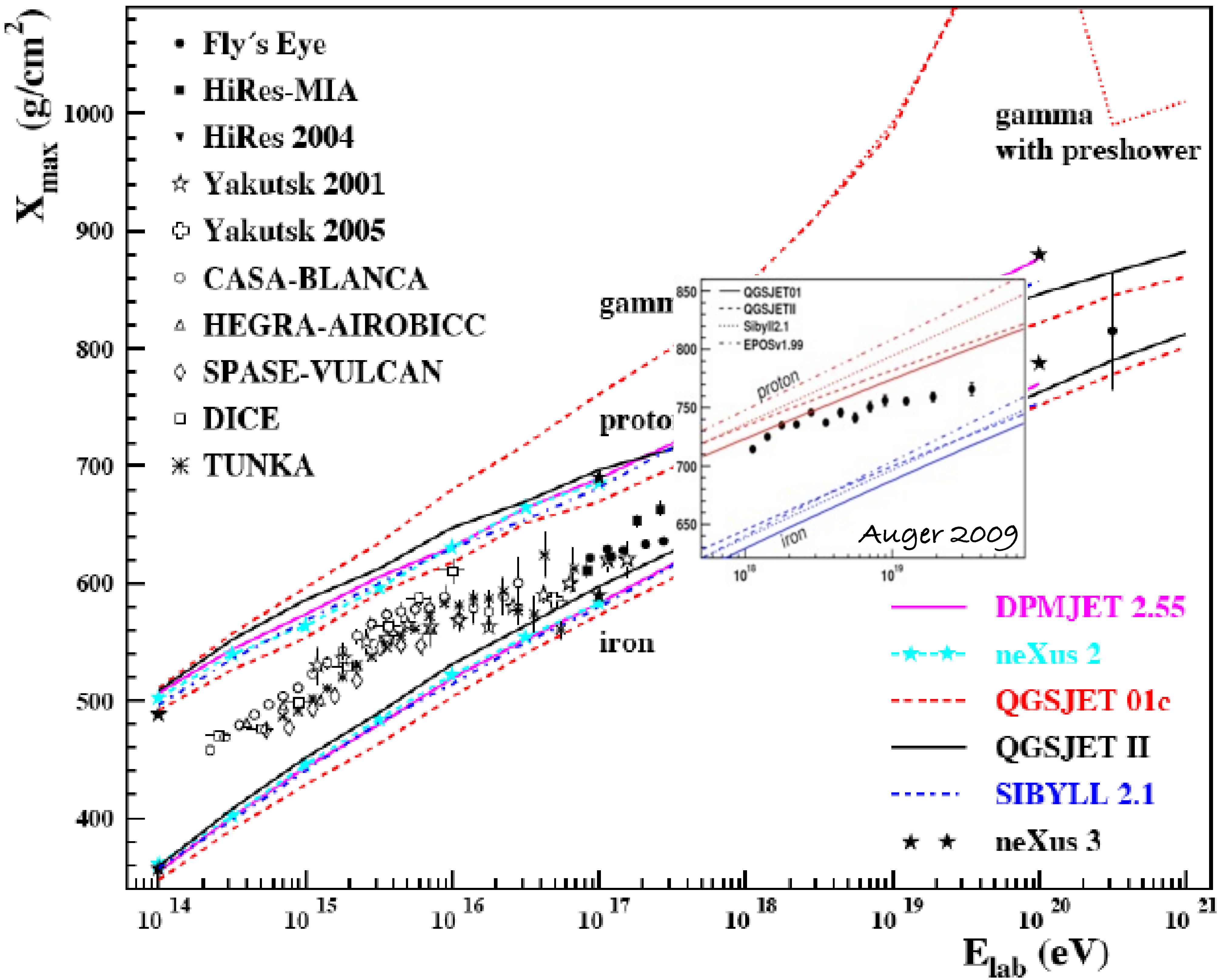
X_{max} as fct. of energy



MCs for mixed hadronic comp. are consistent with data.

γ, ν showers look very different.

X_{max} as fct. of energy



MCs for mixed hadronic comp. are consistent with data.

γ, ν showers look very different.

Measure longitudinal development via fluorescence (or Cherenkov) light:

+ X_{max} is very direct indicator for primary mass
+ profile gives good energy estimate (model free)
- 10% duty cycle

- requires good resolution (« difference p - Fe)
  i.e. it is an "expensive" technique.
  (stereo and hybrid desirable, atmospheric monitoring)

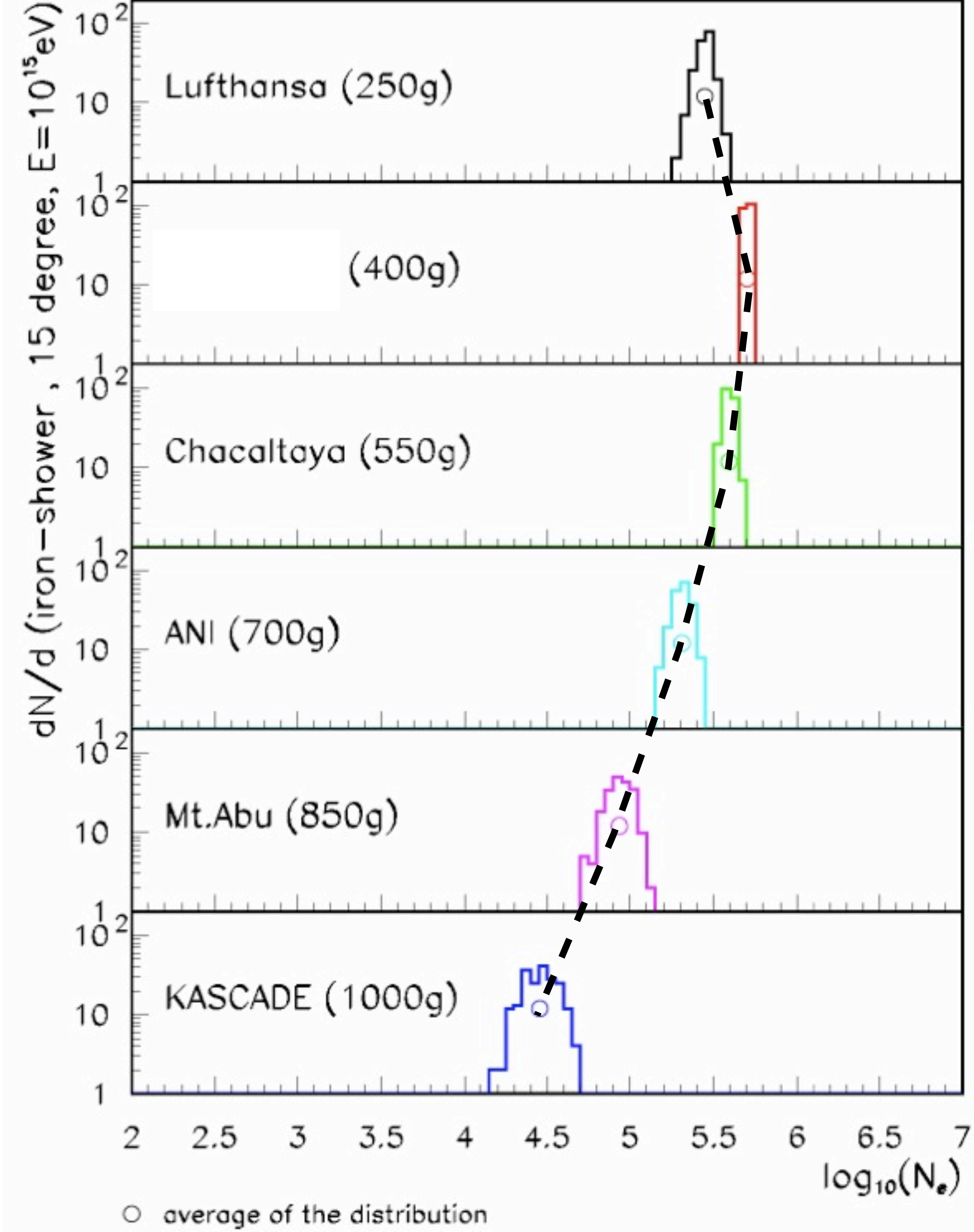
p-Fe impossible on event basis, due to large p fluctuations

Ch.light is more difficult, due to very forward emission

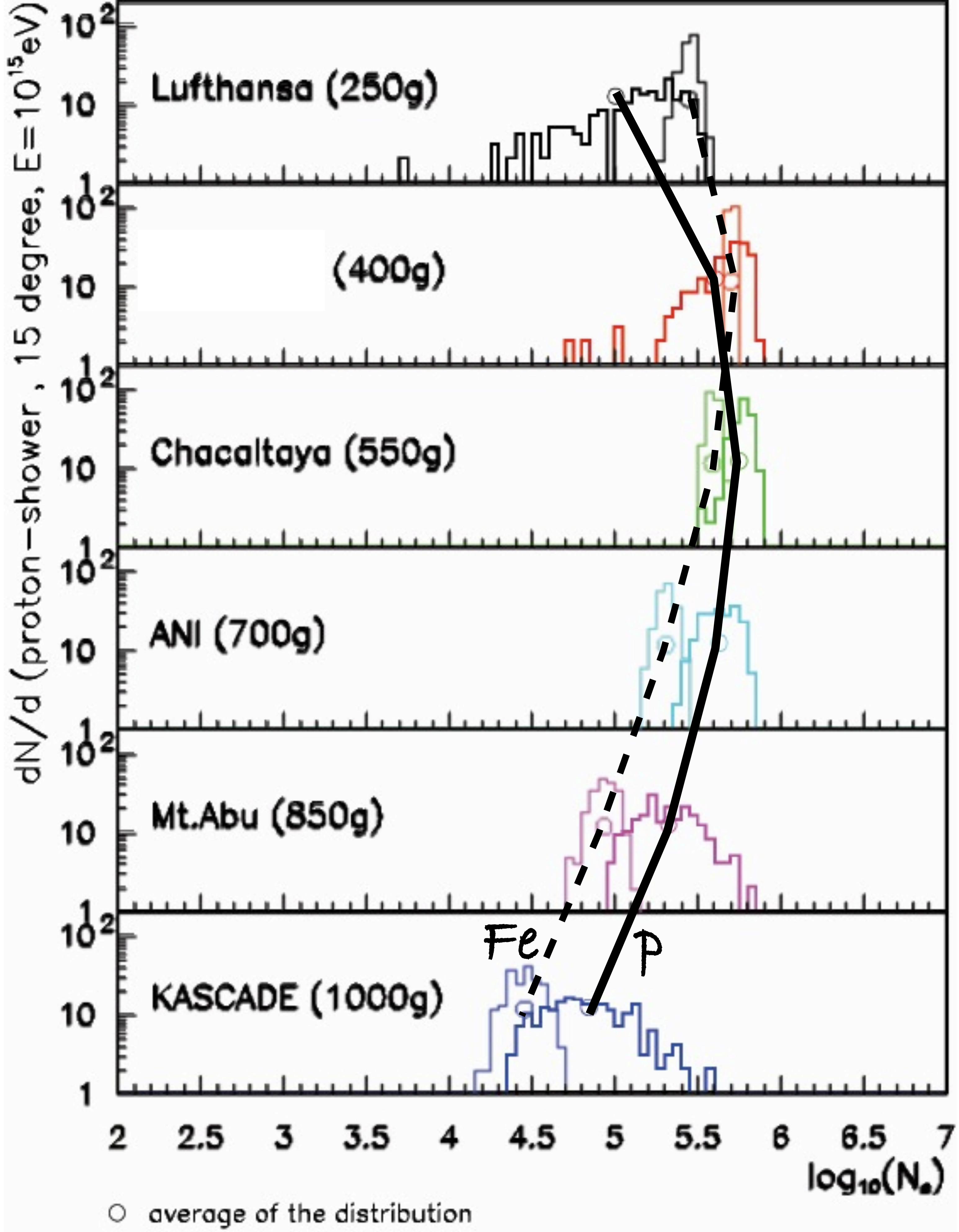
Fe

10^{15} eV

electrons



Fe, p
10^{15} eV
electrons

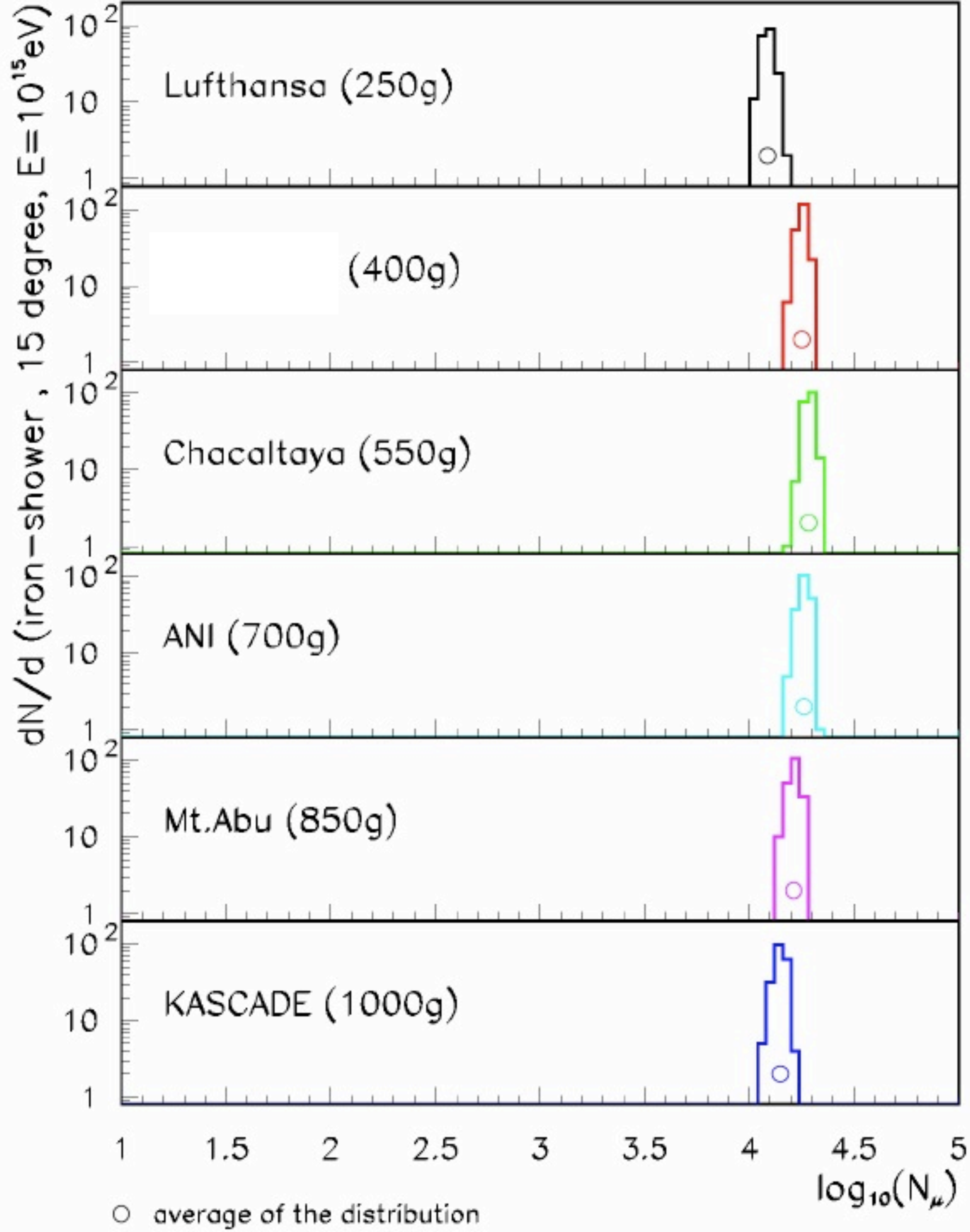


not good for
p-Fe separation
with Ne

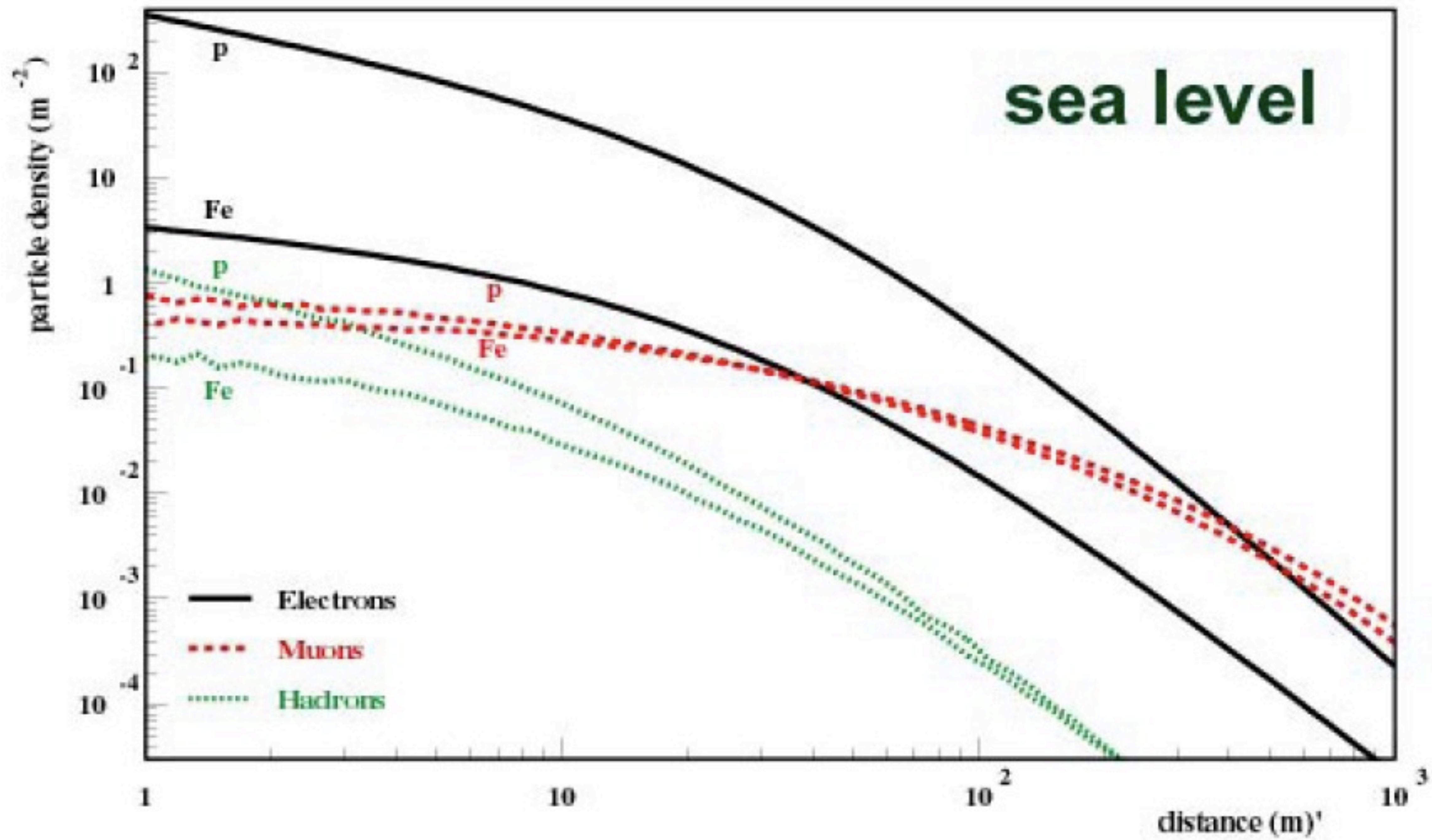
Fe

10^{15} eV

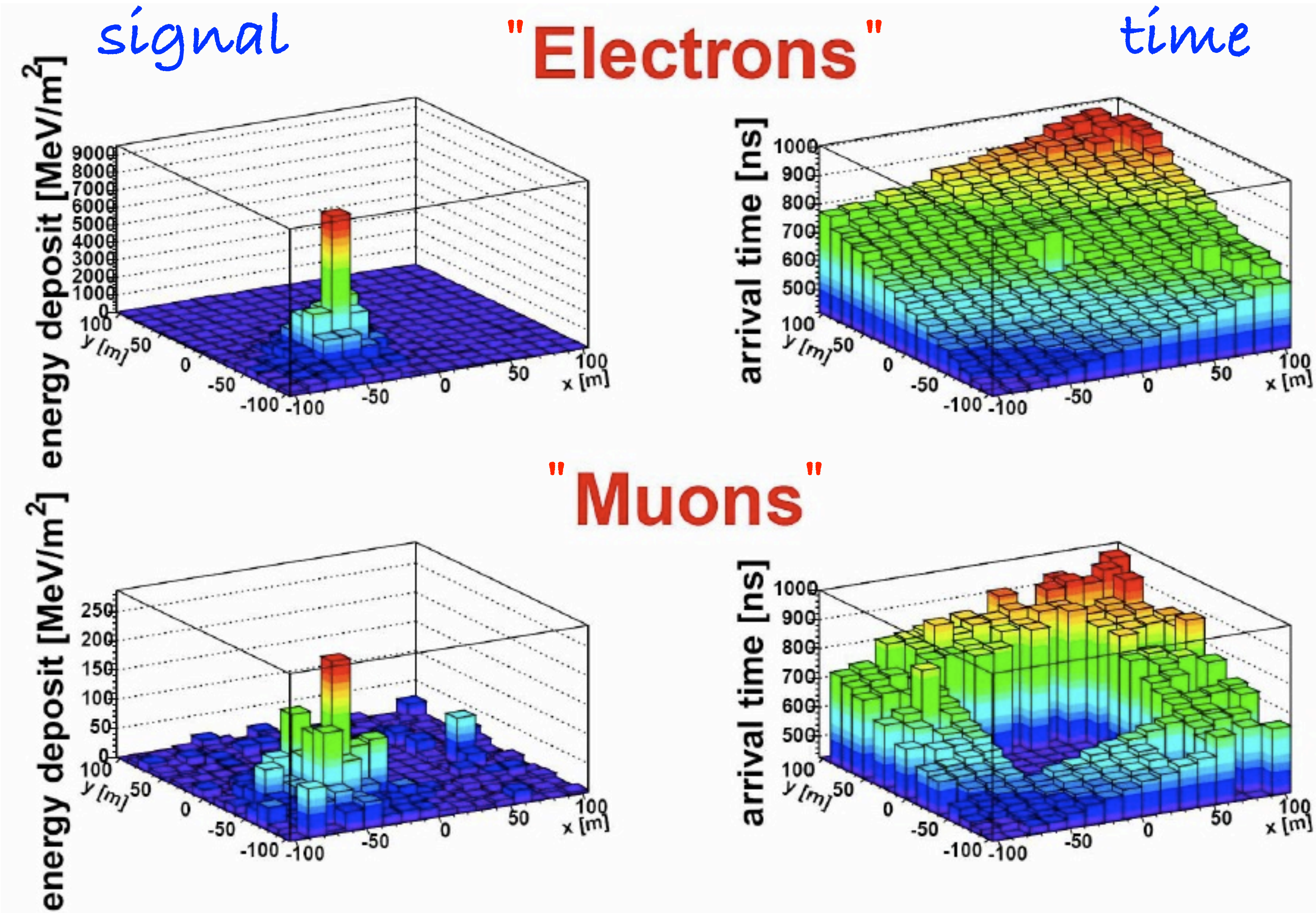
Muons



Lateral Particle Distribution   (~10^{15} eV):



Typical mass dependence



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

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

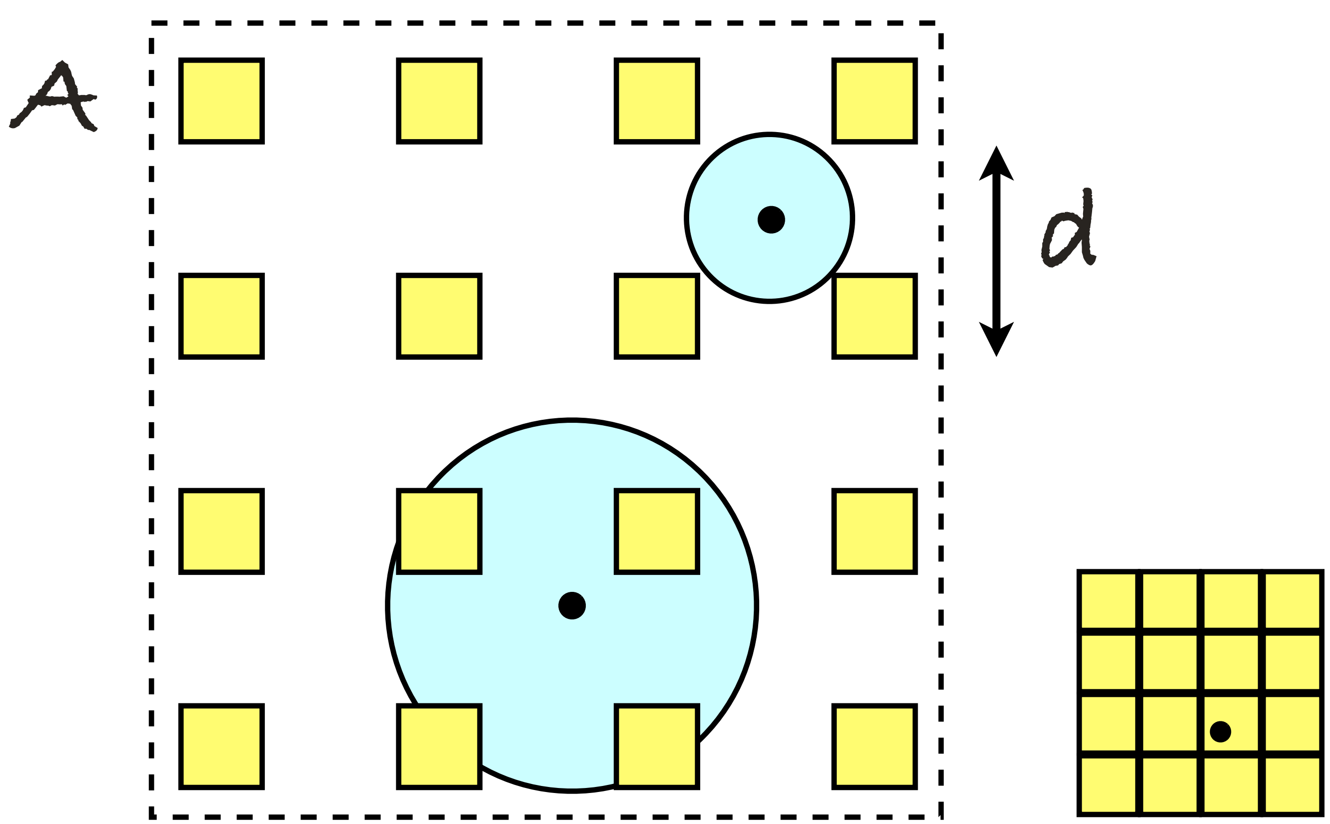
determines the low energy threshold

(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:

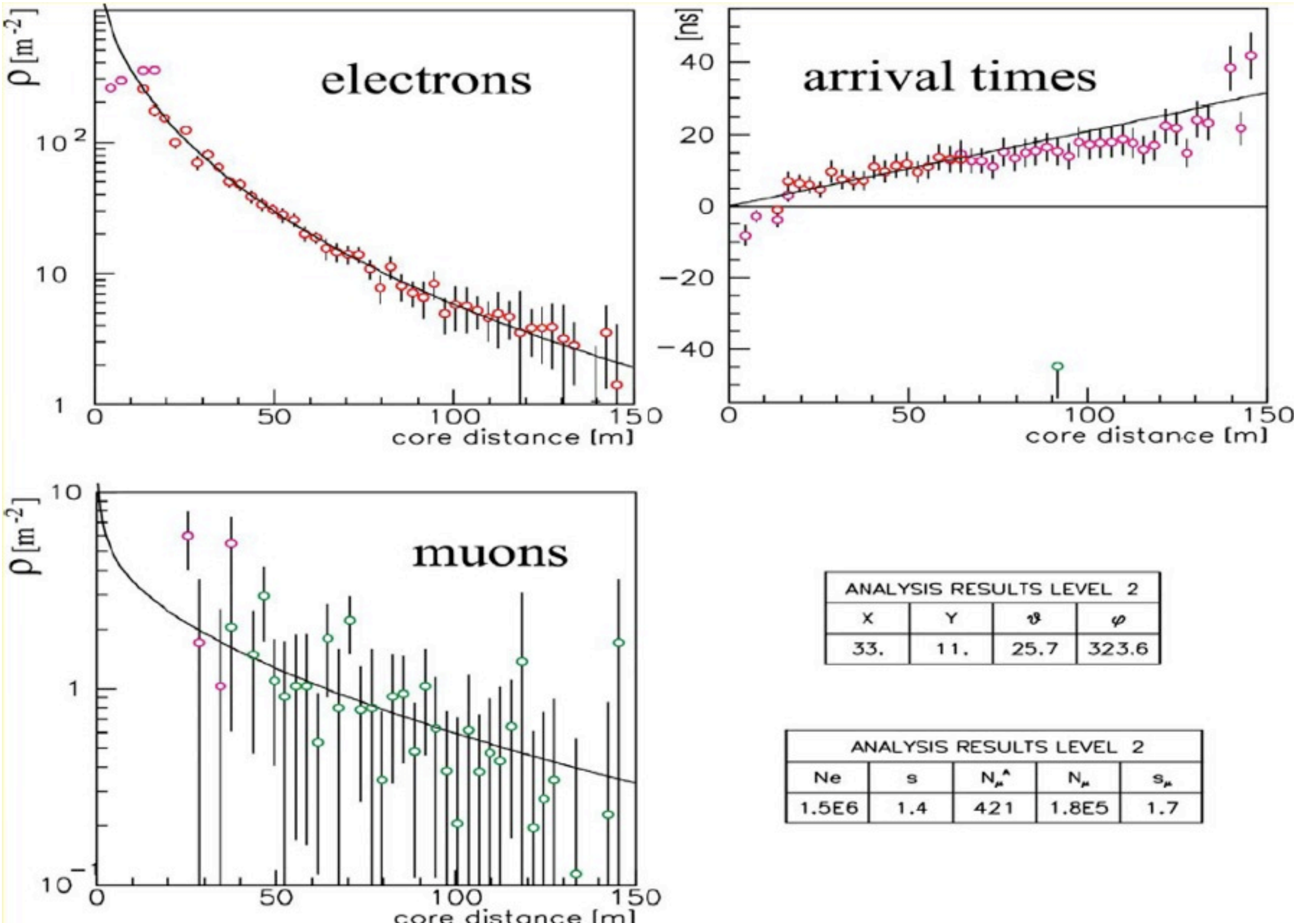
A: large, d: small, C_d: high

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

Always compromise needed.

How good is "good enough"?

Lateral Particle Distribution ($\approx 10^{15}$ eV):
...an event.

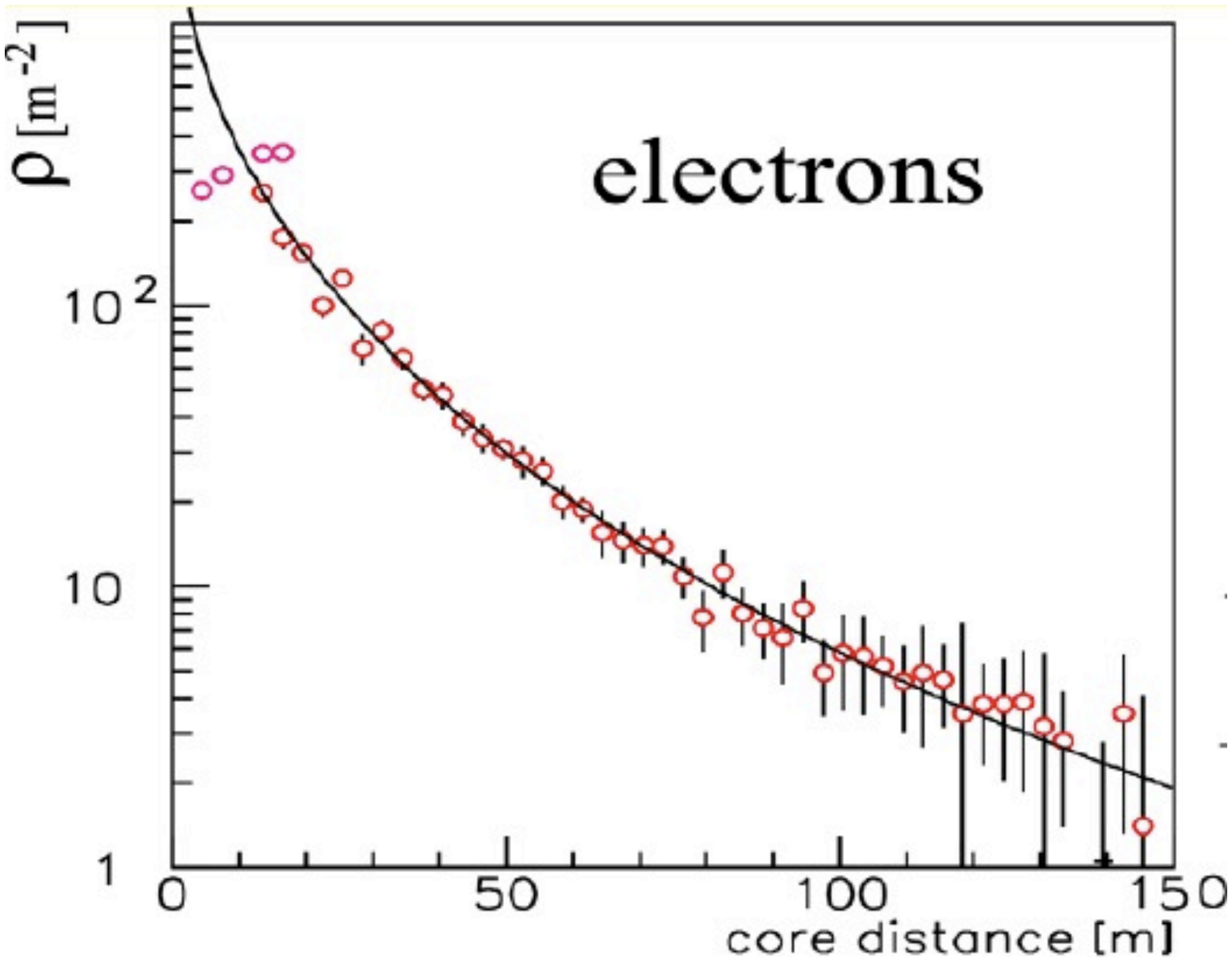


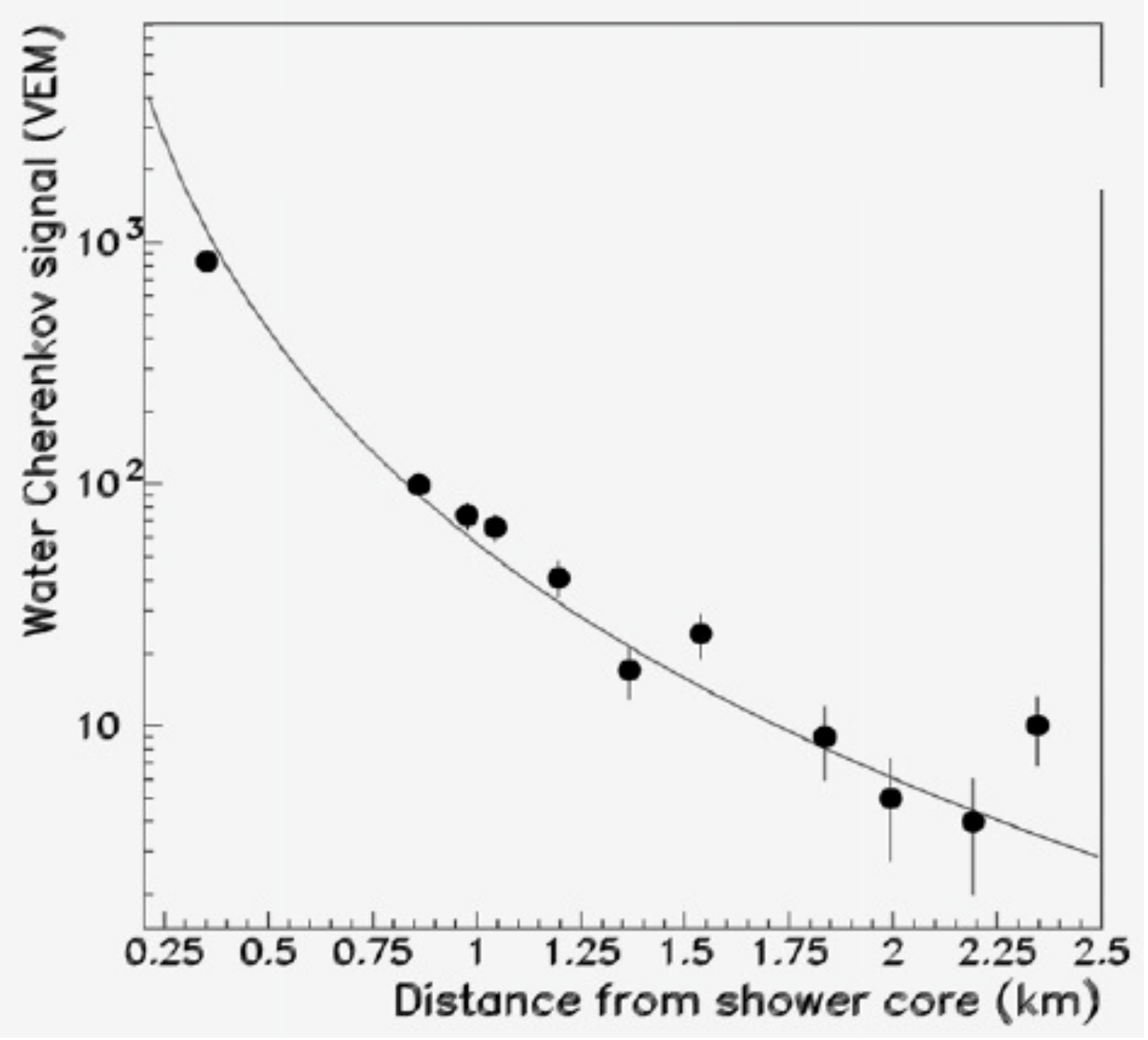
ANALYSIS RESULTS LEVEL 2			
X	Y	ϑ	φ
33.	11.	25.7	323.6

ANALYSIS RESULTS LEVEL 2				
Ne	s	N_μ^*	N_μ	s_μ
1.5E6	1.4	421	1.8E5	1.7

≈ 10^{15} eV

≈ 10^{19} eV

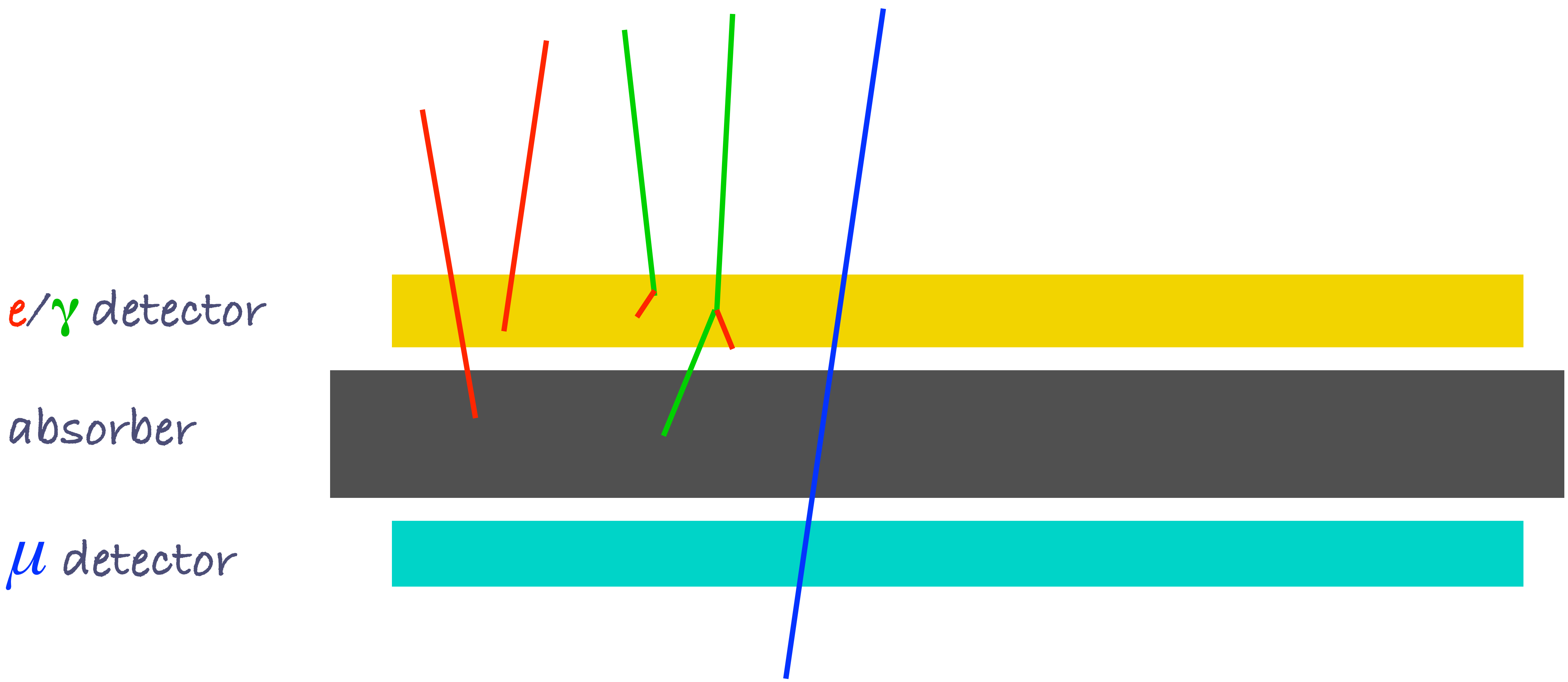




detector distance: 13 m
252 samples

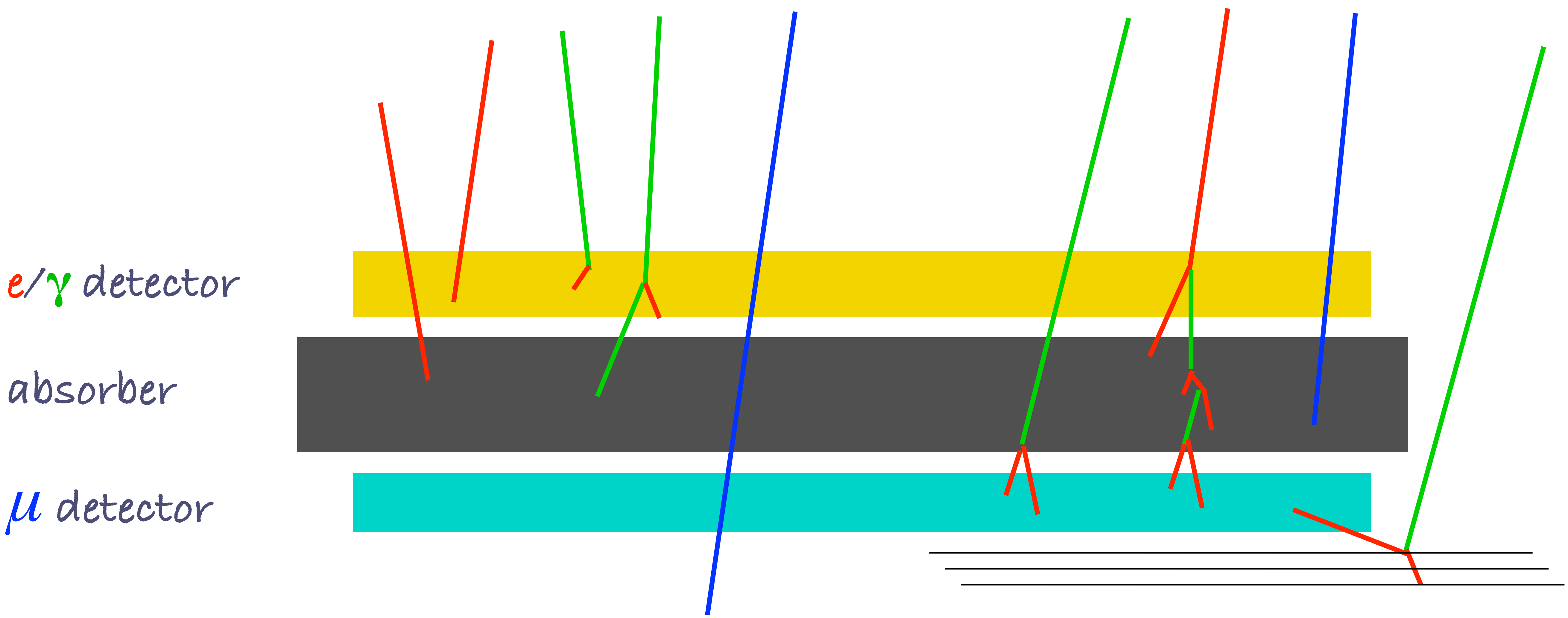
detector distance: 1500 m
11 samples

Identifying secondaries is not so easy ....

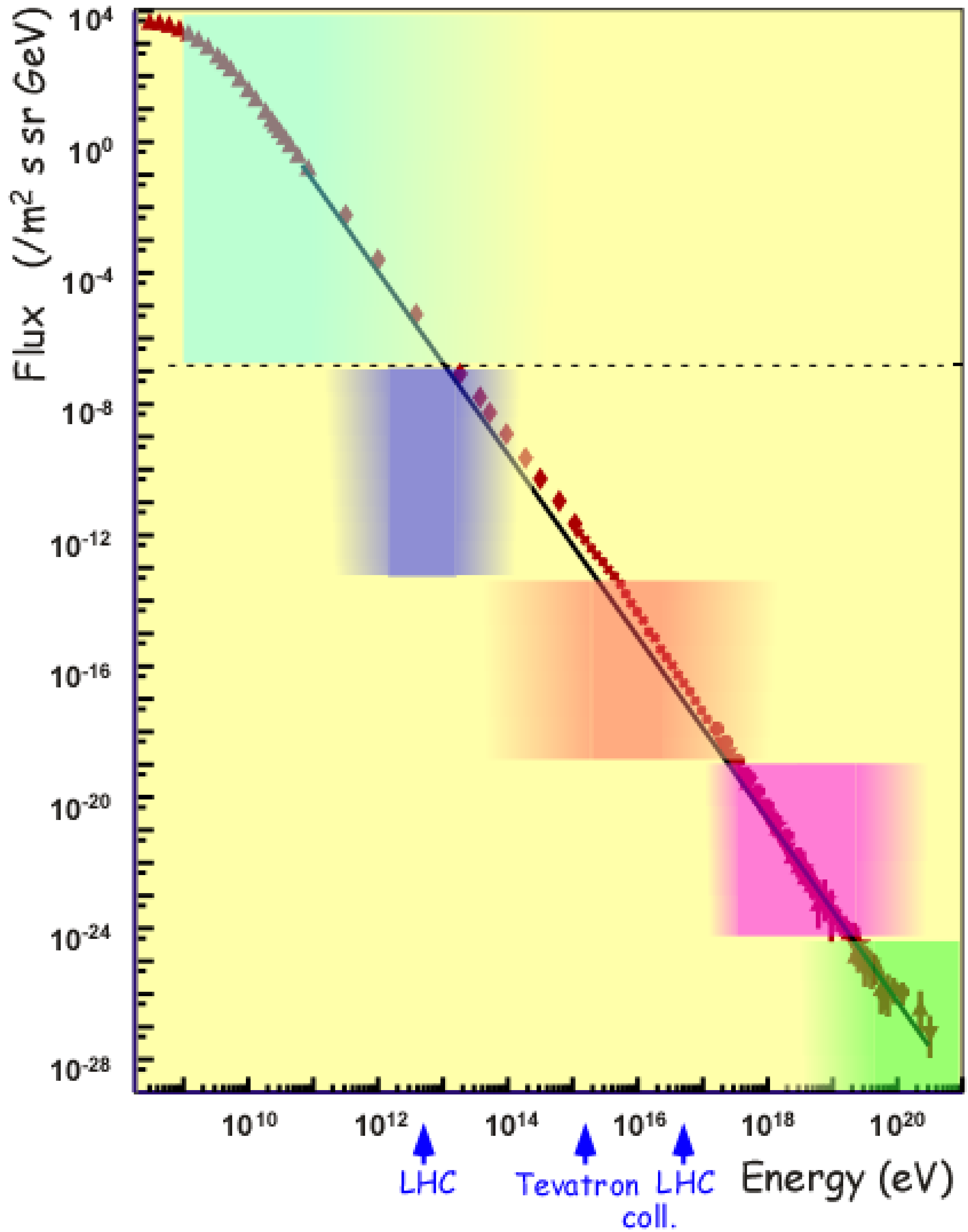


detector response is crucial

Identifying secondaries is not so easy ....



detector response is crucial



Direct Measurements:

balloon & satellite experiments
particle identification,
elements, isotopes

Air Shower Experiments:

MAGIC, HESS, VERITAS, ...
Tibet, Milagro

KASCADE, KASCADE-GRANDE

Haverah Park, Akeno,
Telescope Array

HIRES
AGASA
Auger
EUSO / OWL

x100 in energy
per experiment.

Detection Techniques 1

Particle detectors at ground level

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

only a small sub-set of secondary particles are recorded

(numbers of particles, densities, energies, angles, arrival times, ...)

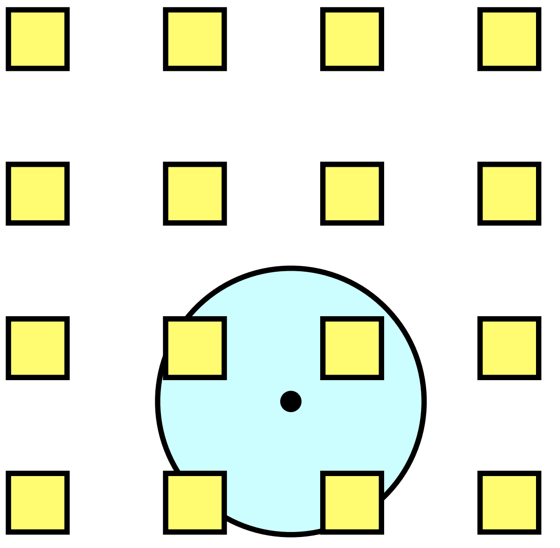
e.g.	area	d	coverage
Kascade	0.04 km²	15 m	1.5×10^{-2}
Haverah Park	12 km²		
Yakutsk	25 km²		
AGASA	100 km²	1 km	2.5×10^{-6}
Auger SD	3000 km²	1.5 km	5.3×10^{-6}

100% duty cycle, relatively easy to operate

aperture = area of array (independent of energy)

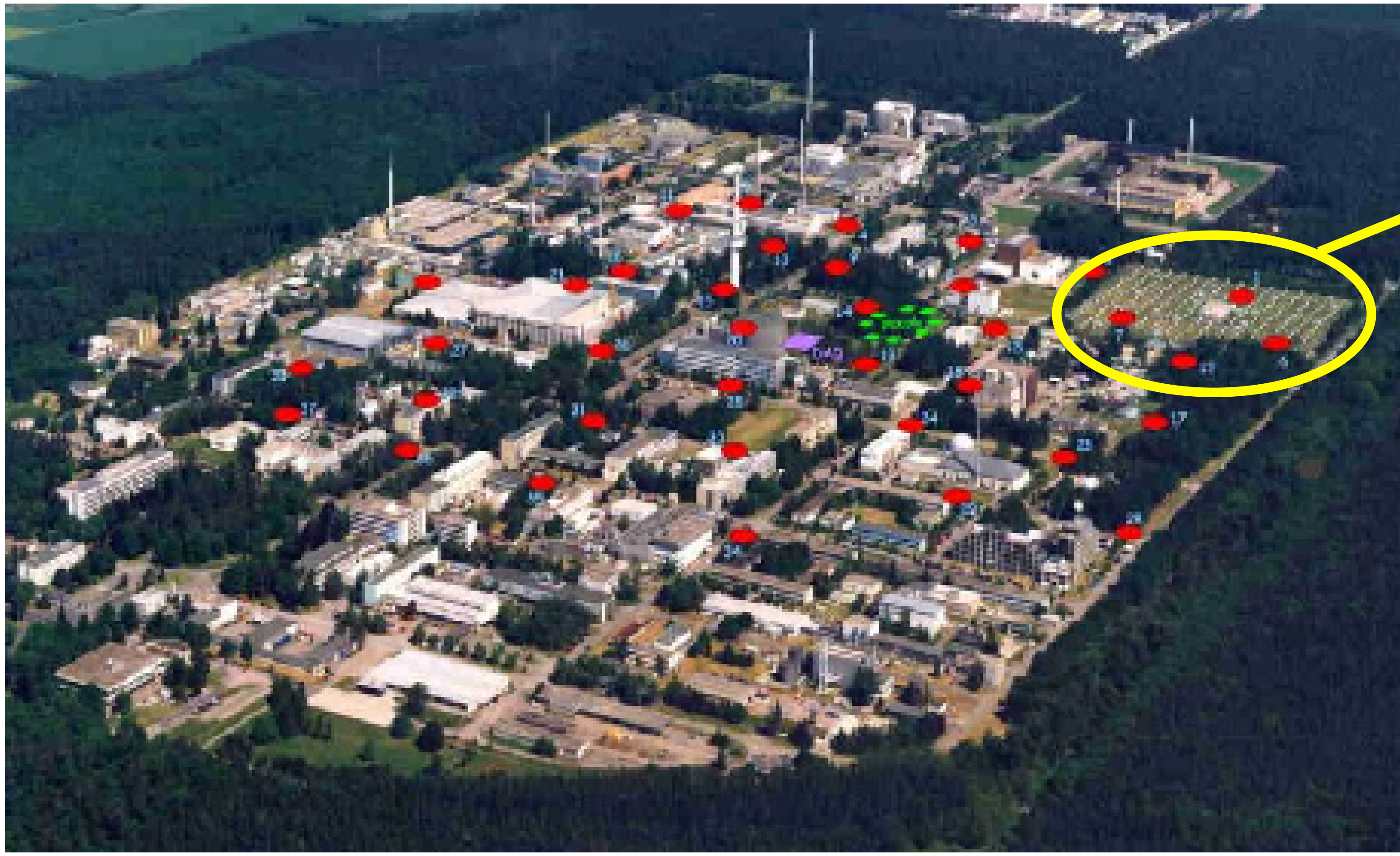
energy resolution $\sigma(E)/E \approx 30\%$

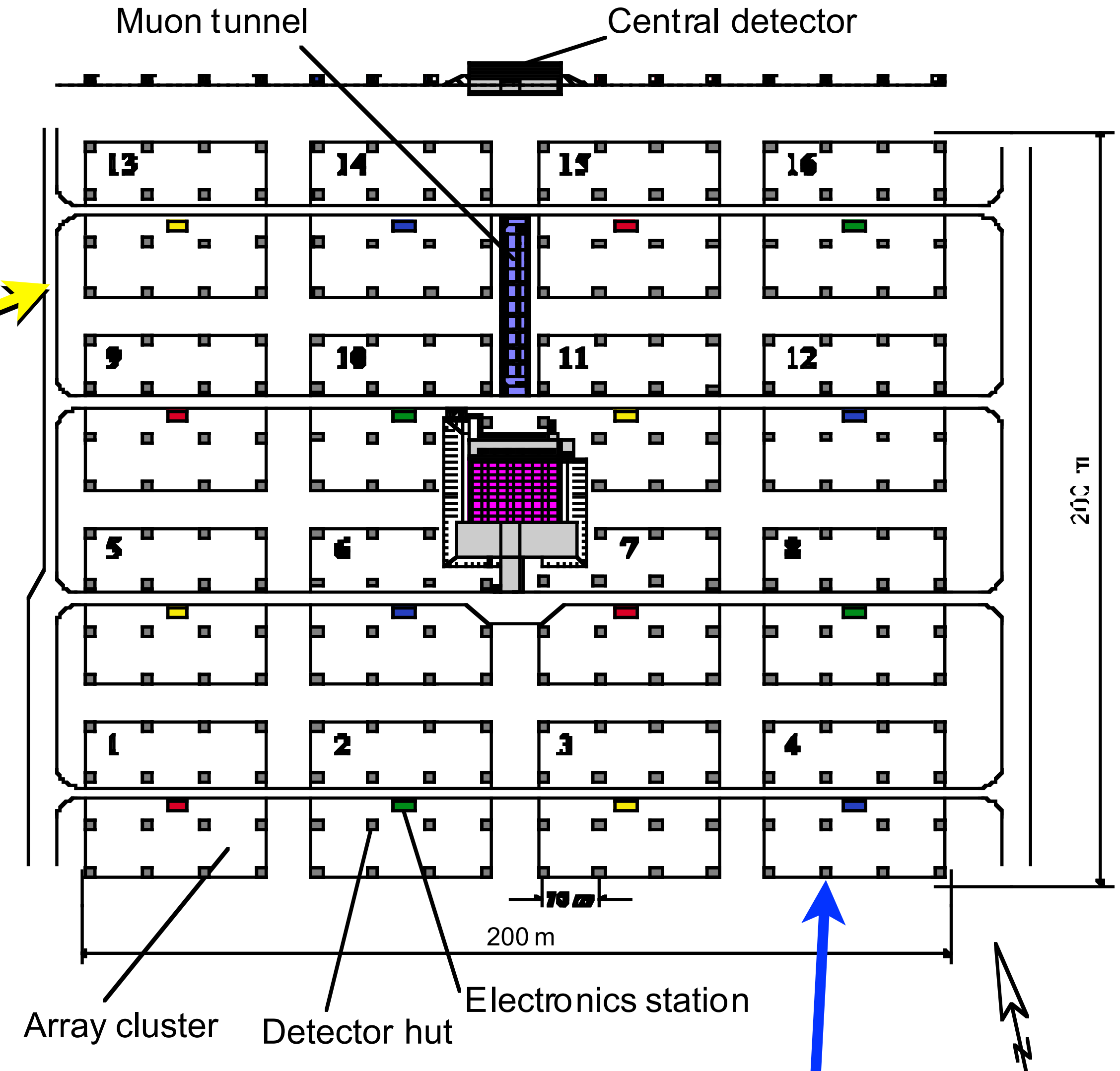
but: primary energy / mass composition is model dependent



KASCADE & KASCADE GRANDE

≈ 10^{14} - 10^{16} eV   ≈ 10^{15} - 10^{17} eV

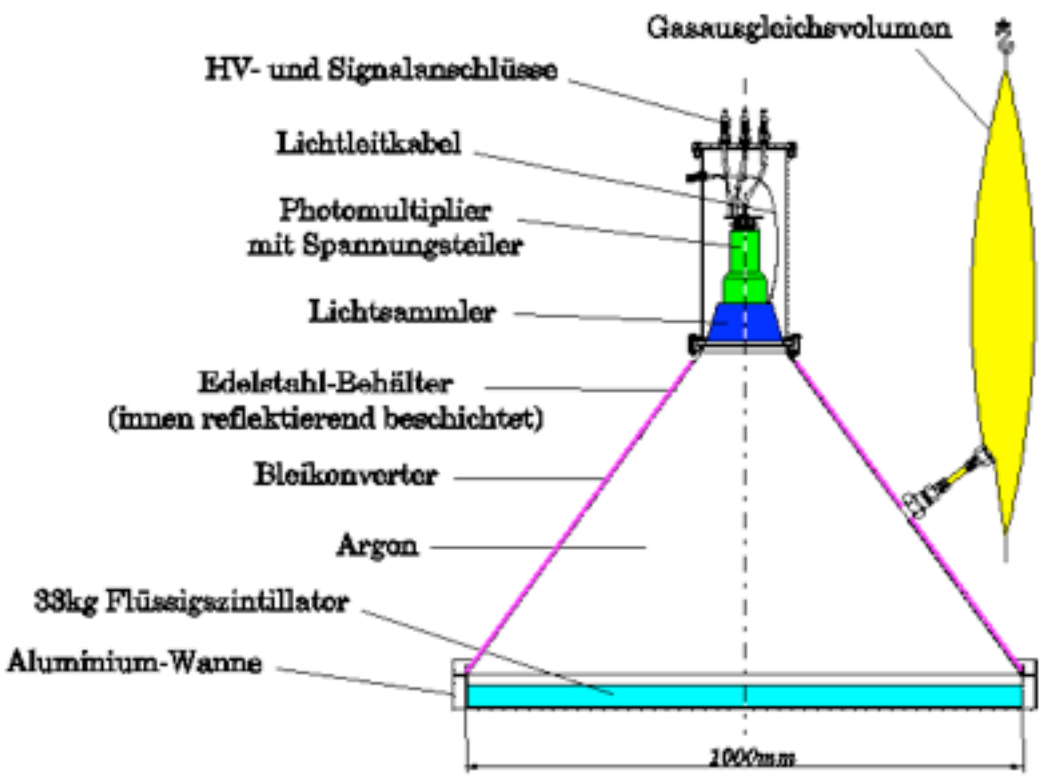


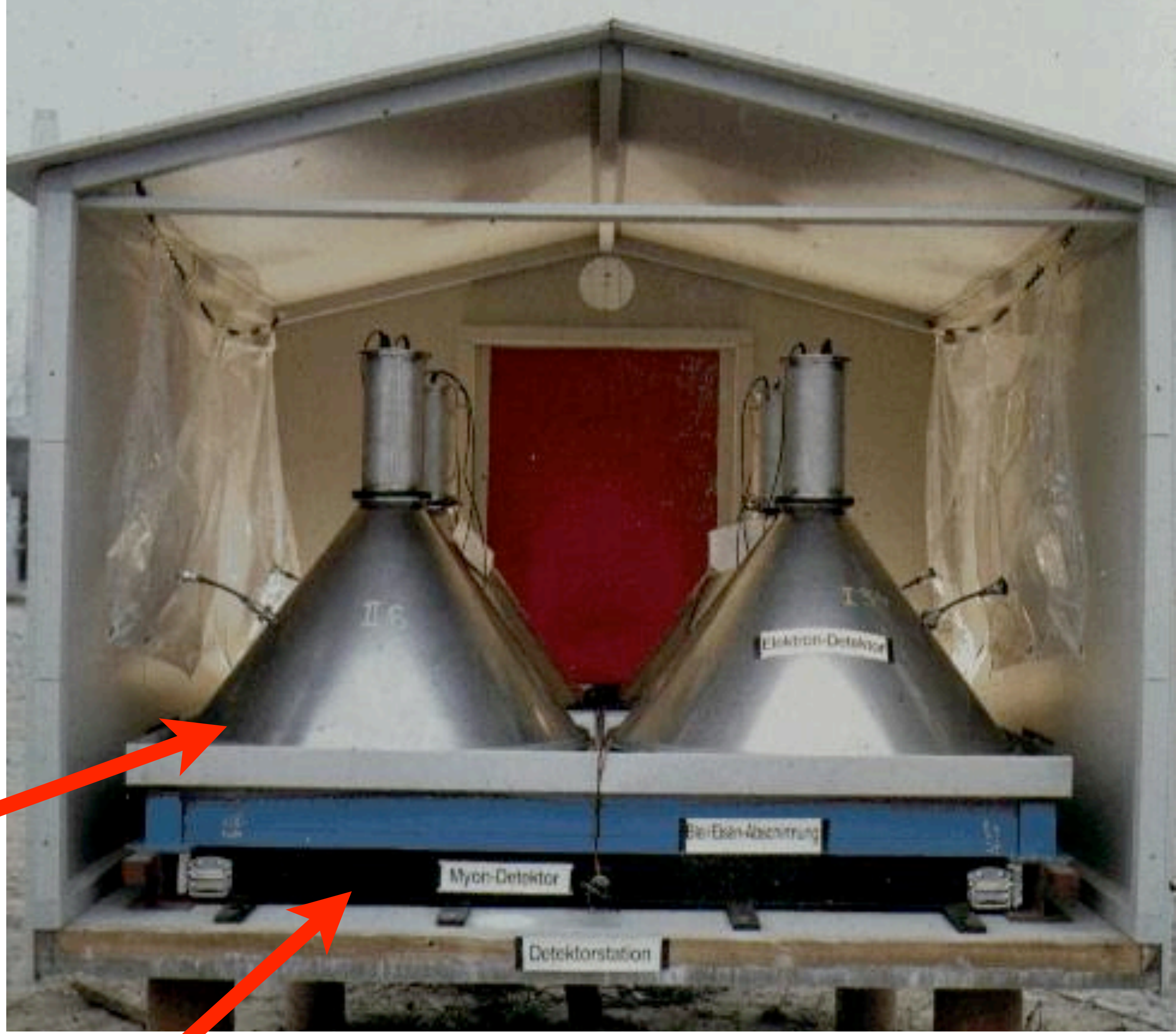


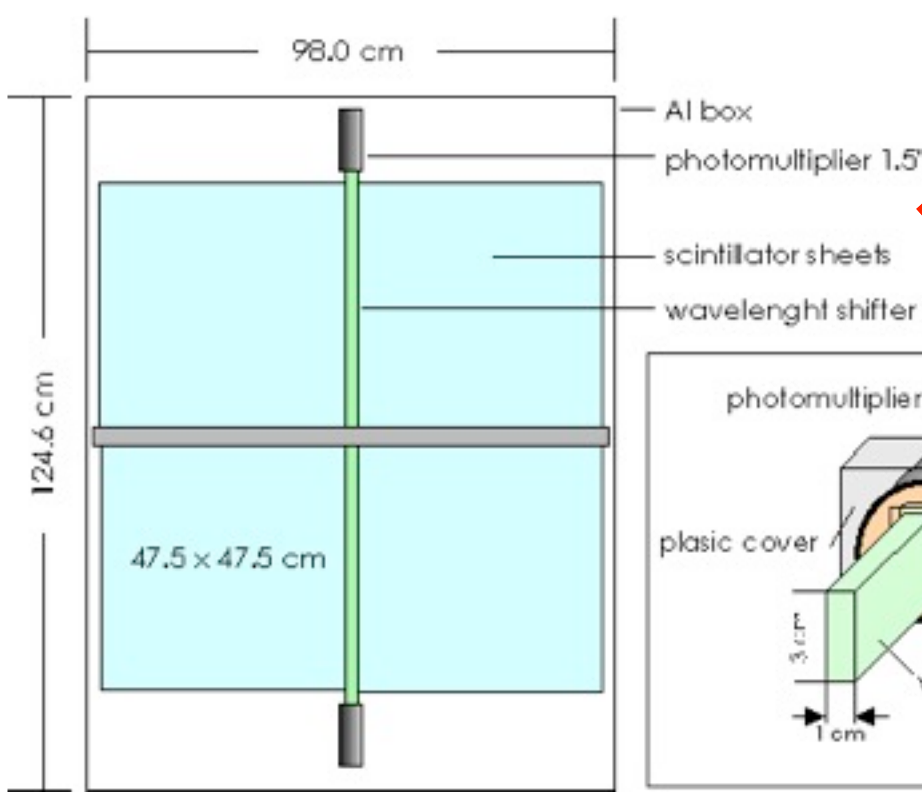
Array of electron/gamma detectors
+muon detectors under absorbers

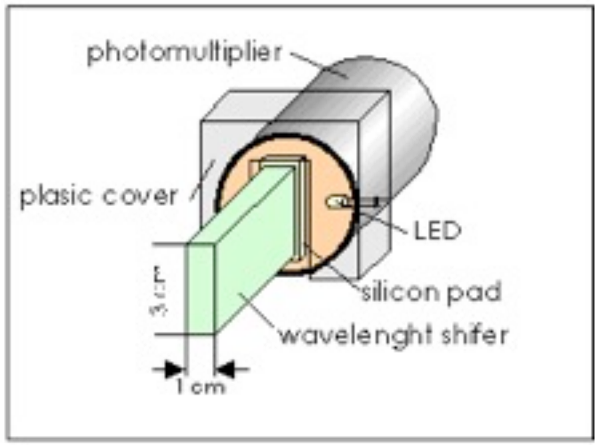
320 m² Hadron calorimeter (11 λ_0)
+streamer tube detectors below (for muons)

+muon tunnel (for muons)







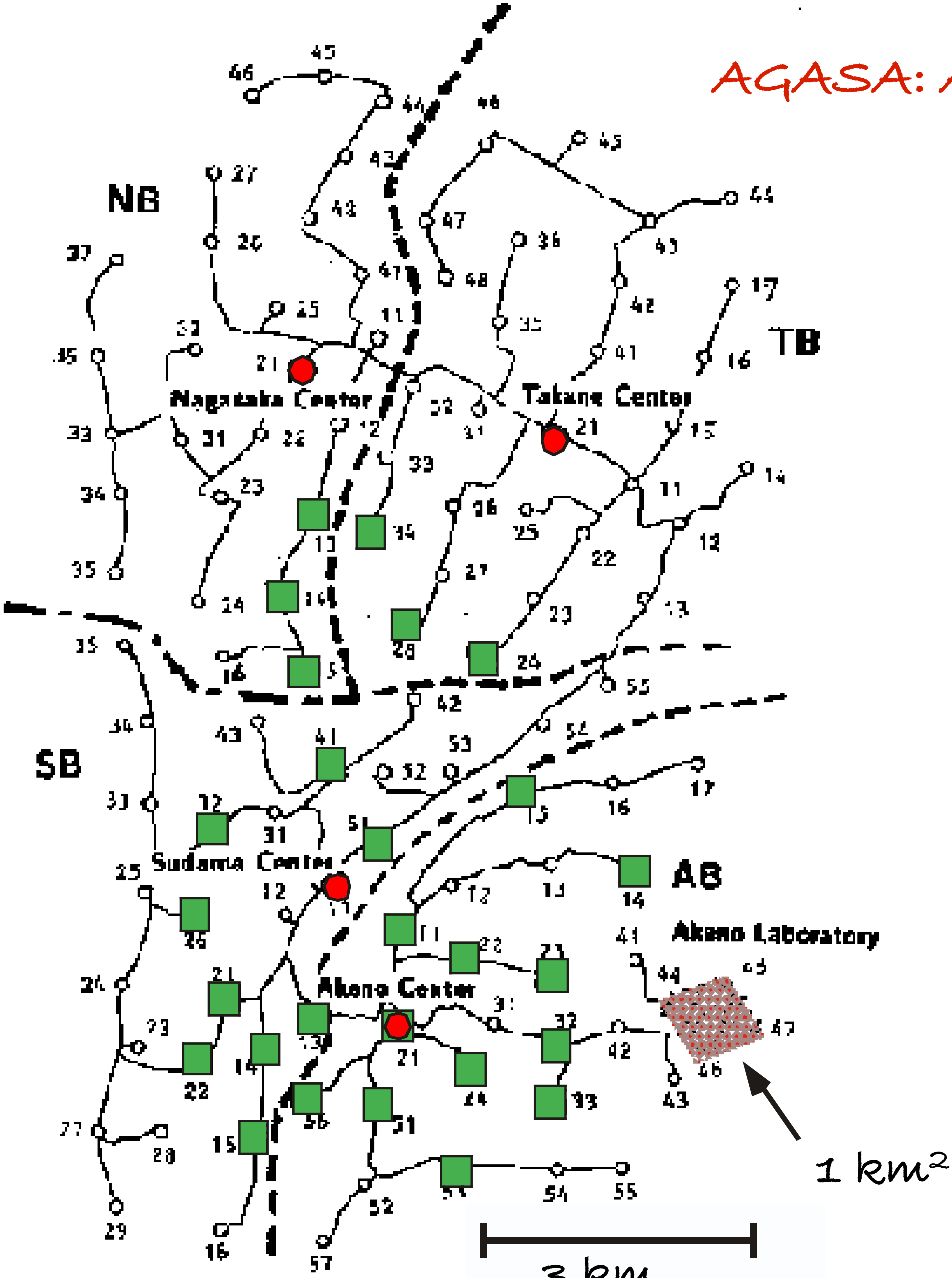


electron/gamma detector

Pb/Fe absorber

muon detector

AGASA: Akeno Giant Air Shower Array



largest array from 1993-2003

near Tokyo, Japan

100 km² area

111 x 2.2 m scintillators (o)

27 μ detectors (■, E_μ > 0.5 GeV)

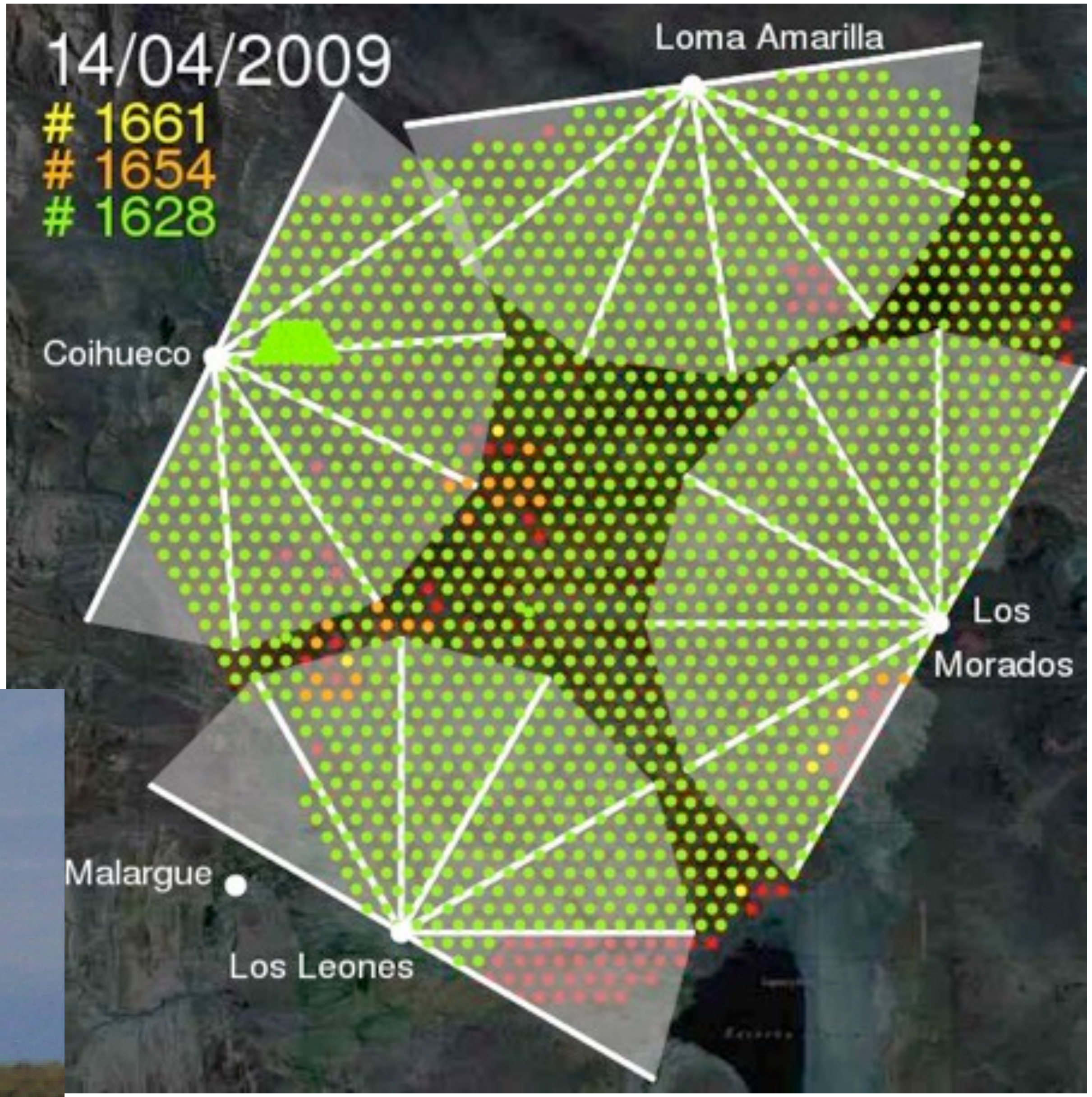
Auger detector:

surface detector array:

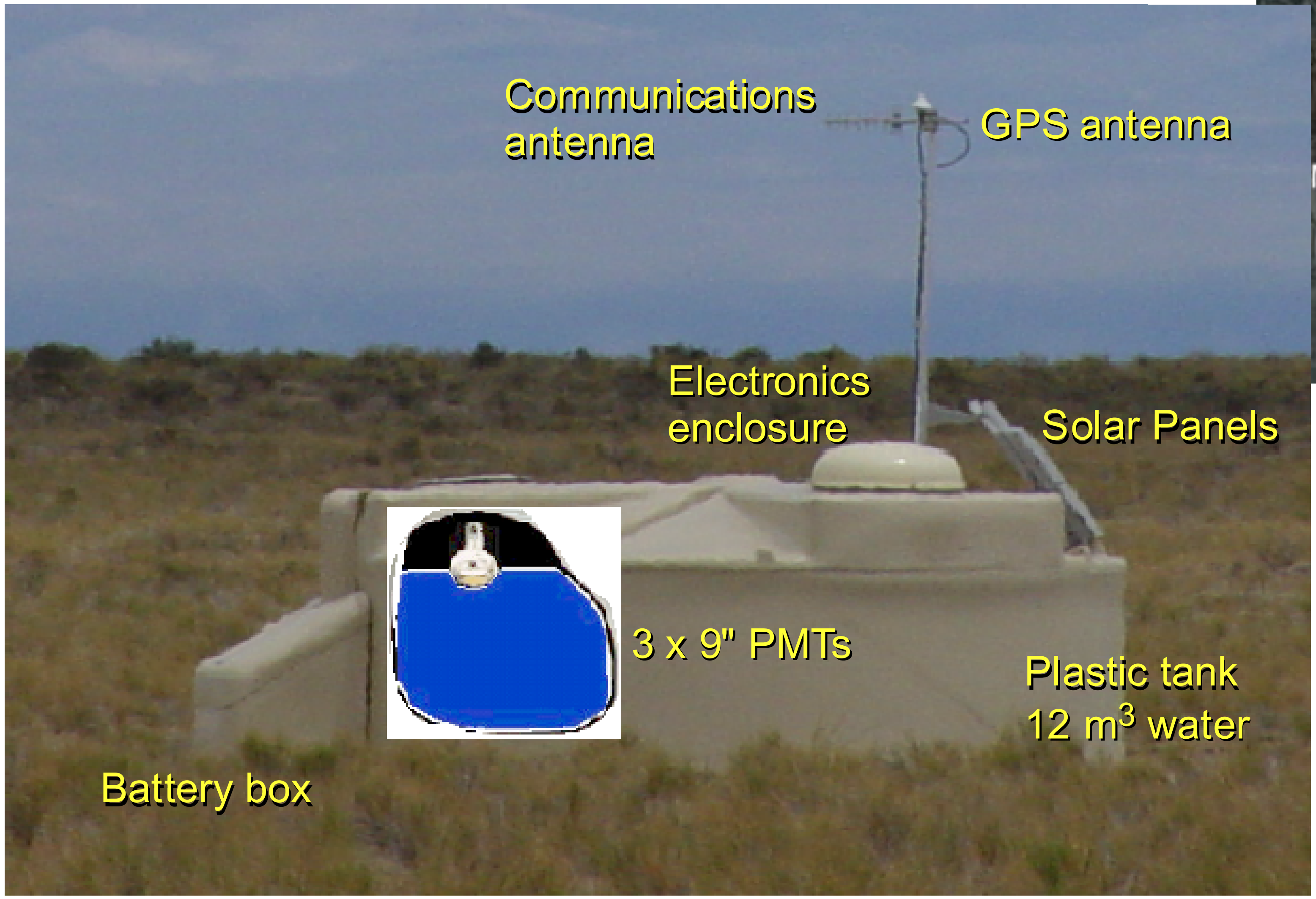
3000 km²

>1600 water Cherenkov det.

10 m² each, 1.5 km apart



planned
tank deployed
with water
send data



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 fct. of atmospheric depth

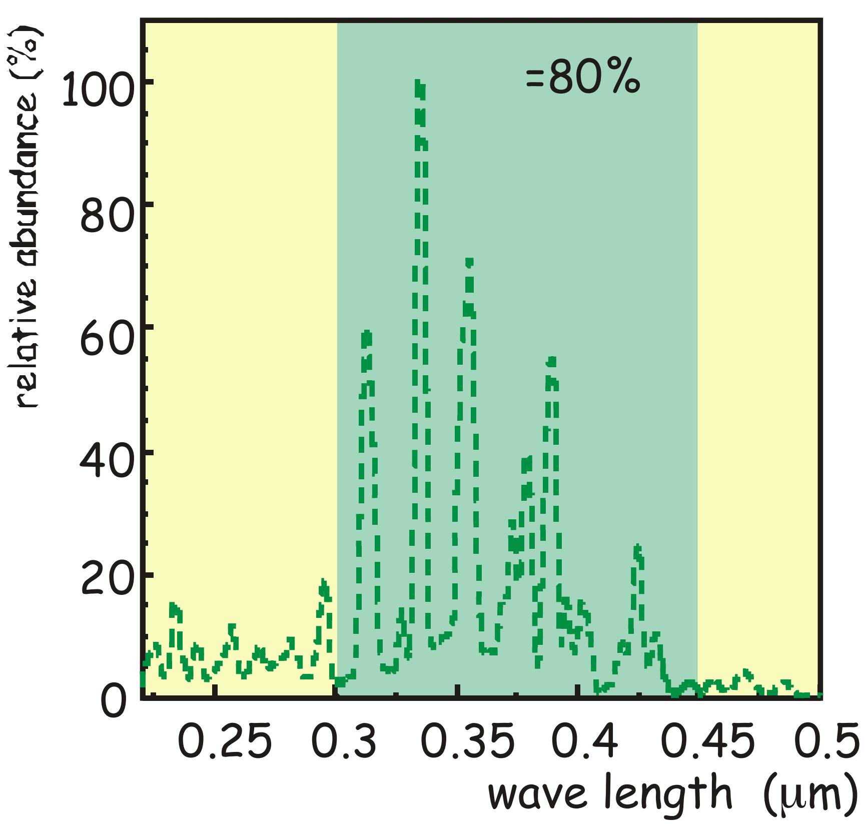
$\sigma(E)/E \approx 20\ \%$

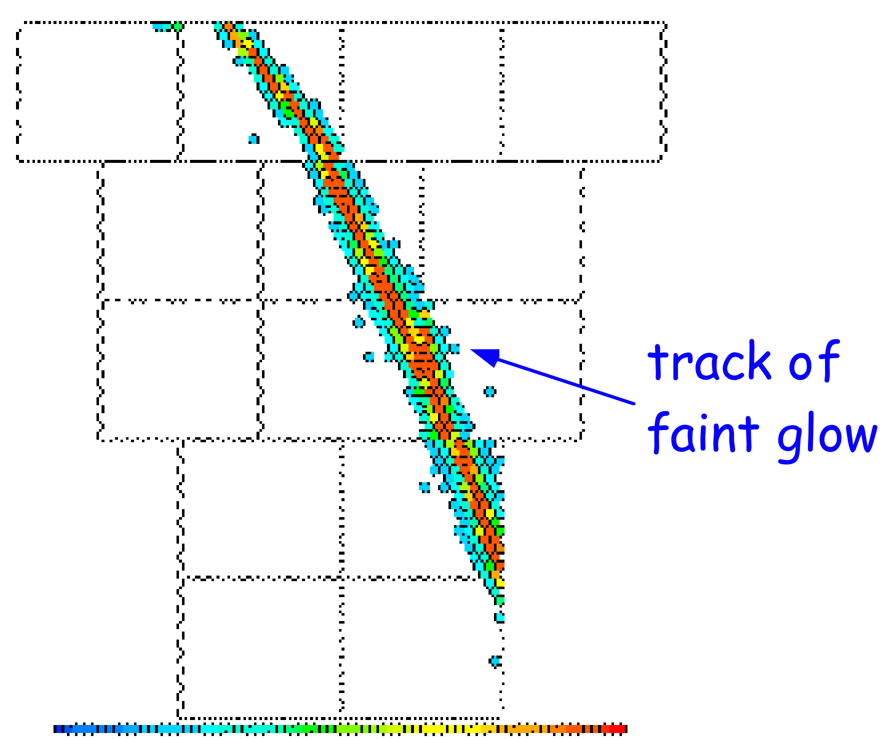
works only for $E > 10^{17}$ eV, only in dark nights (10%)

requires good knowledge of atmospheric conditions

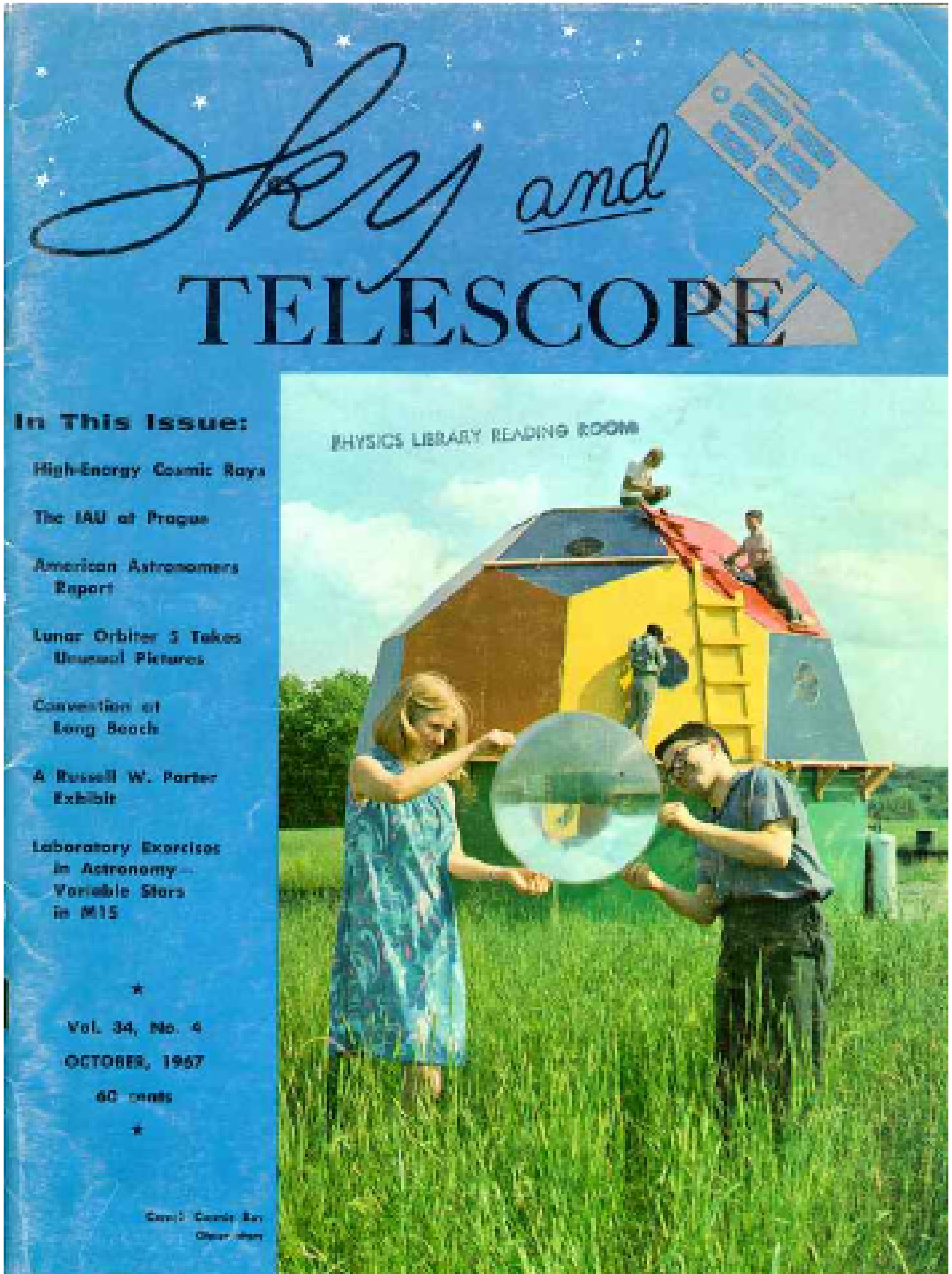
aperture grows with energy, varies with atmosphere

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





c.f. 100 W light bulb
moving with c
at 30 km distance
through atmosphere



The First Fluorescence Detector:

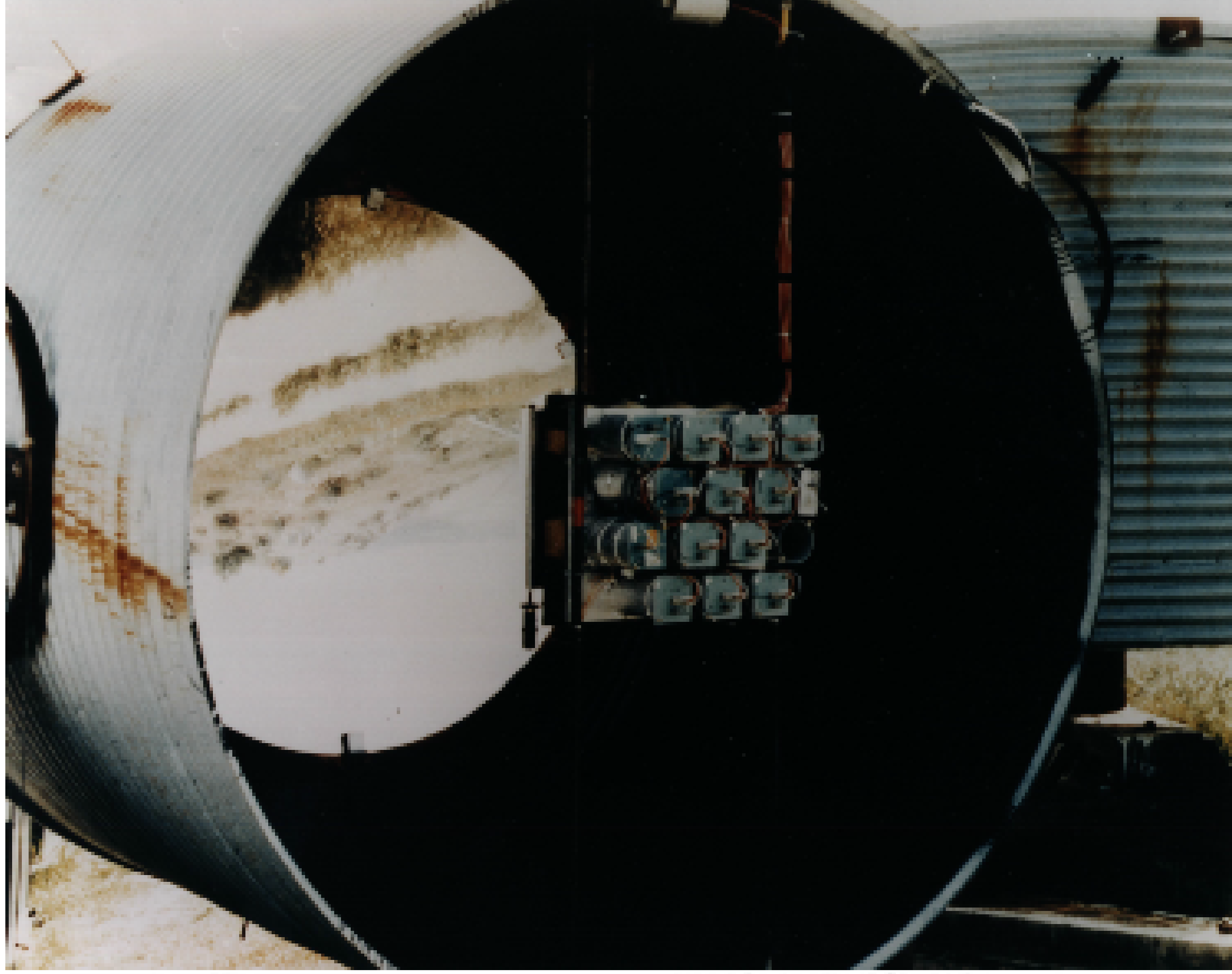
Cornell University
K. Greisen, 1967

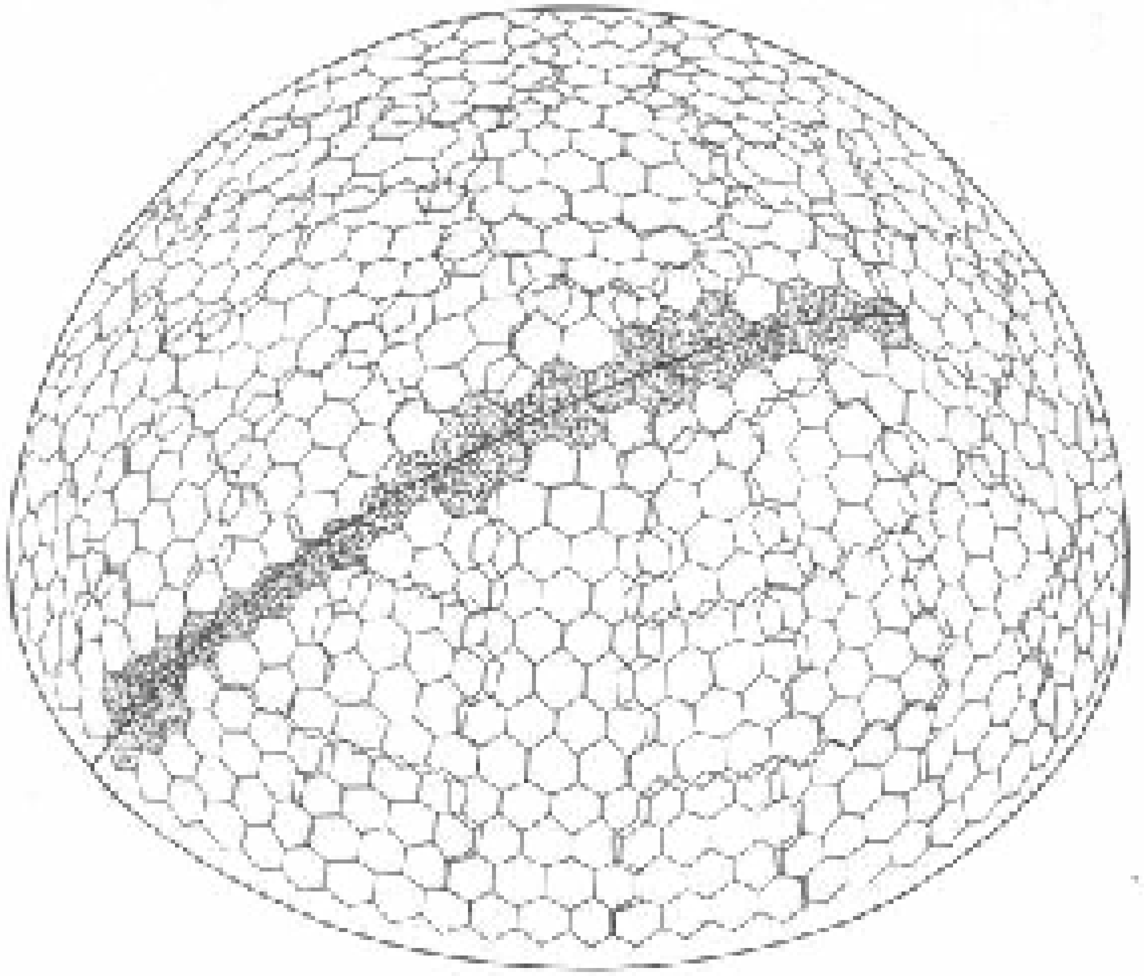
10 x 50 PMTs
$6^0 \times 6^0$ pixels
0.1 m^2 Fresnel lenses

(not successful)

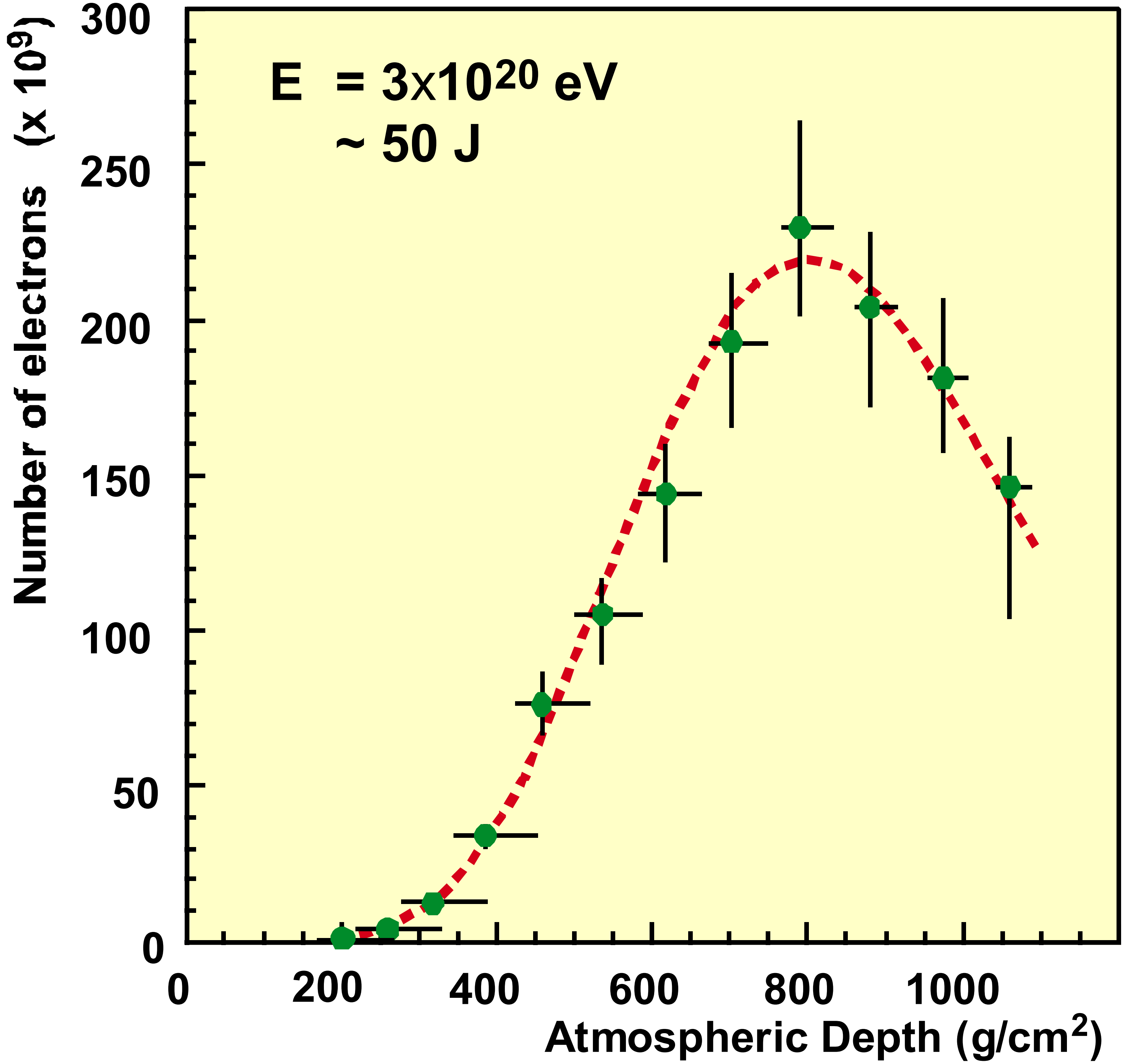
Fly's Eye (Utah)

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





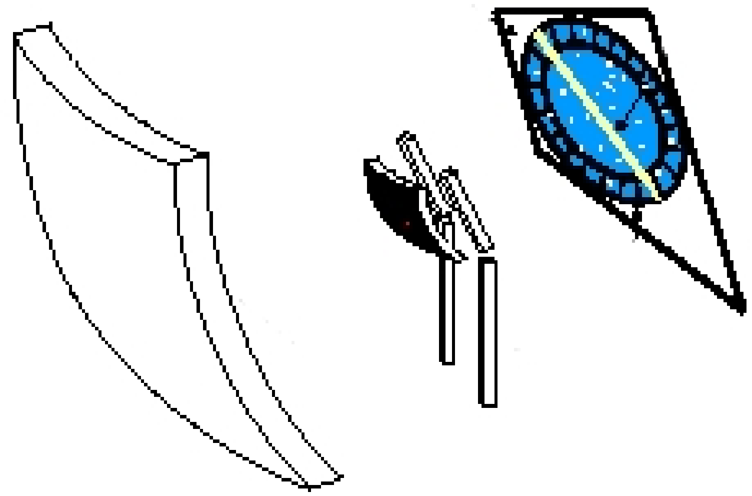
The Big Fly's Eye Event

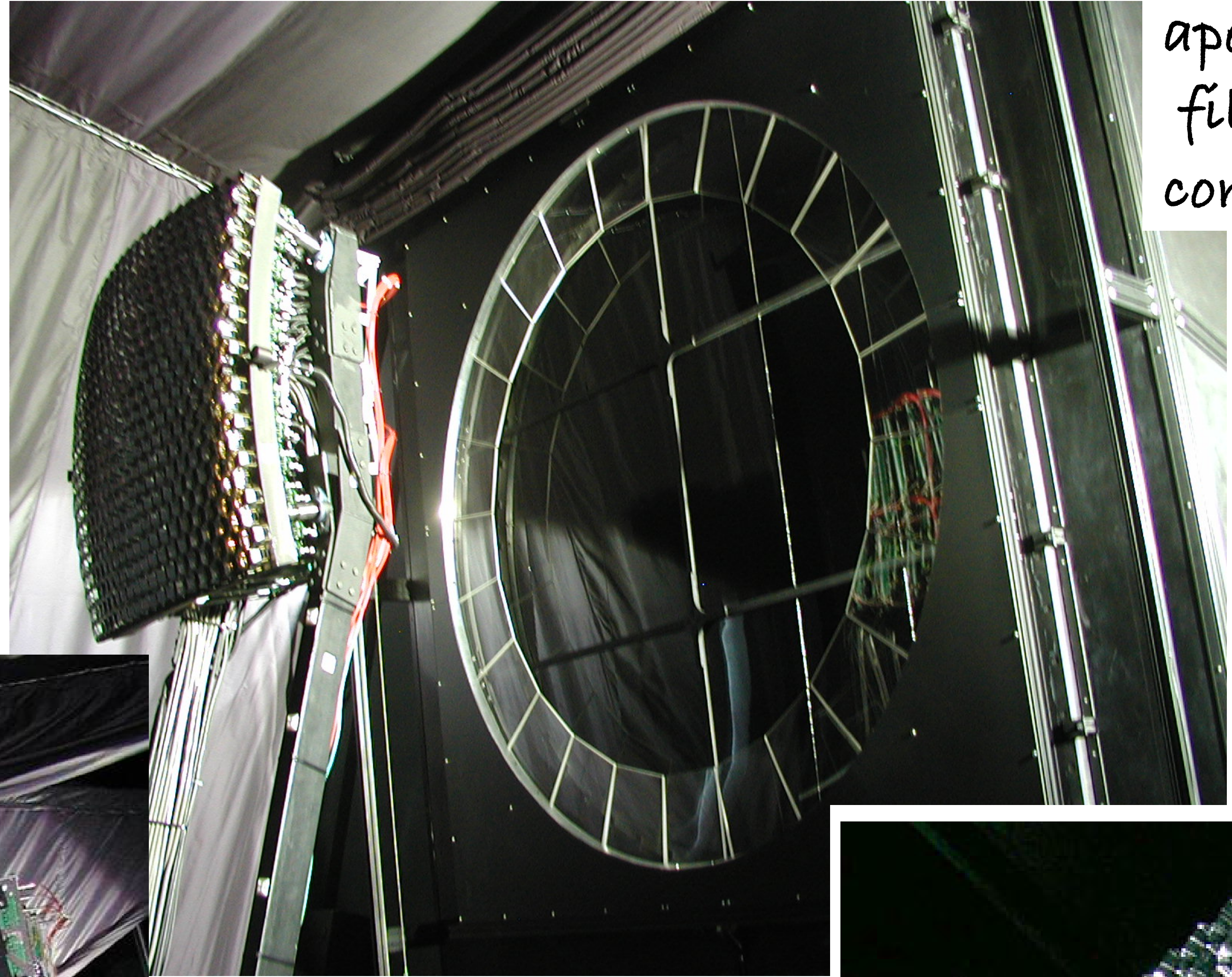


50 J !!!!

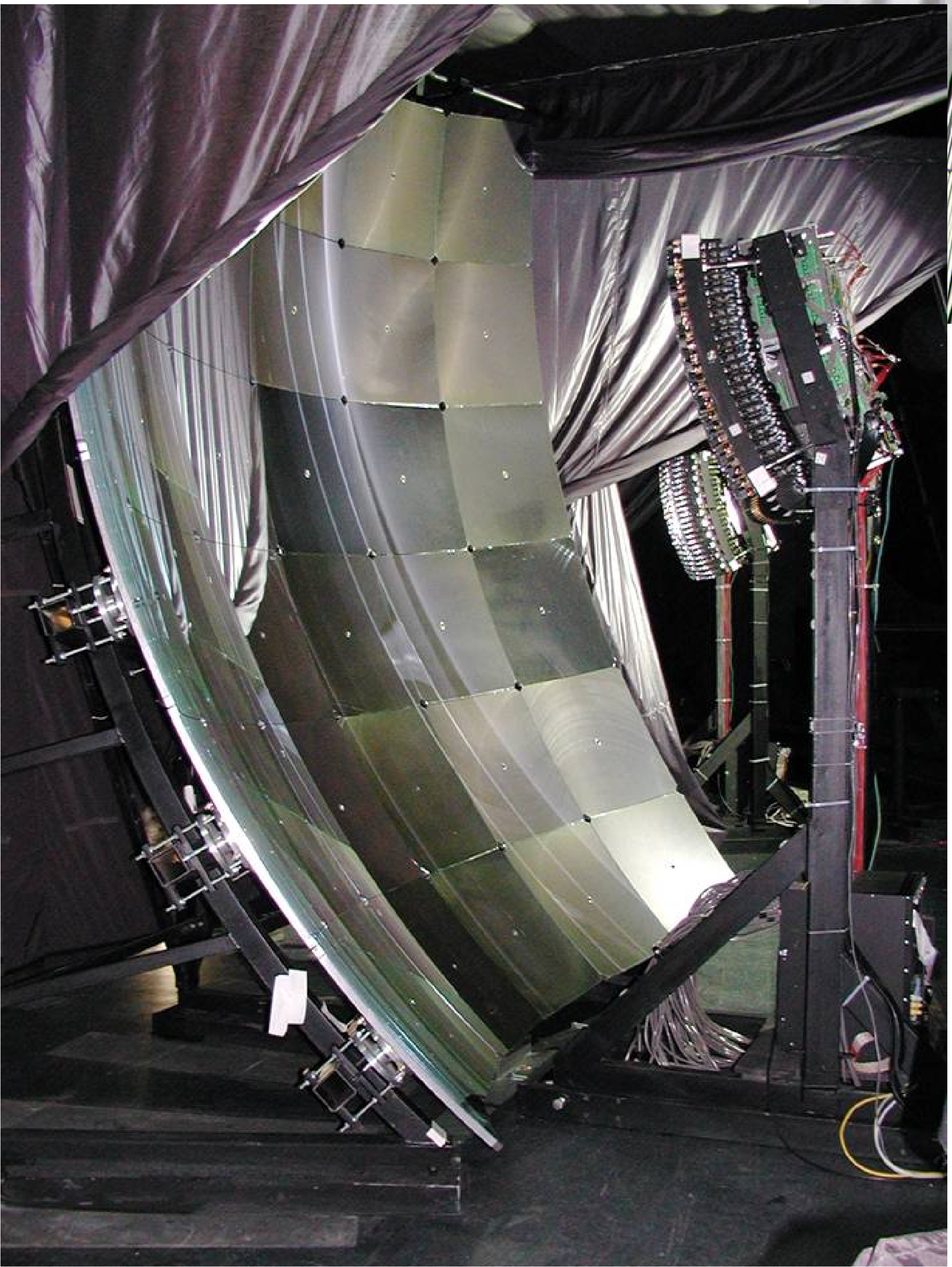
> 200 billion secondaries at maximum

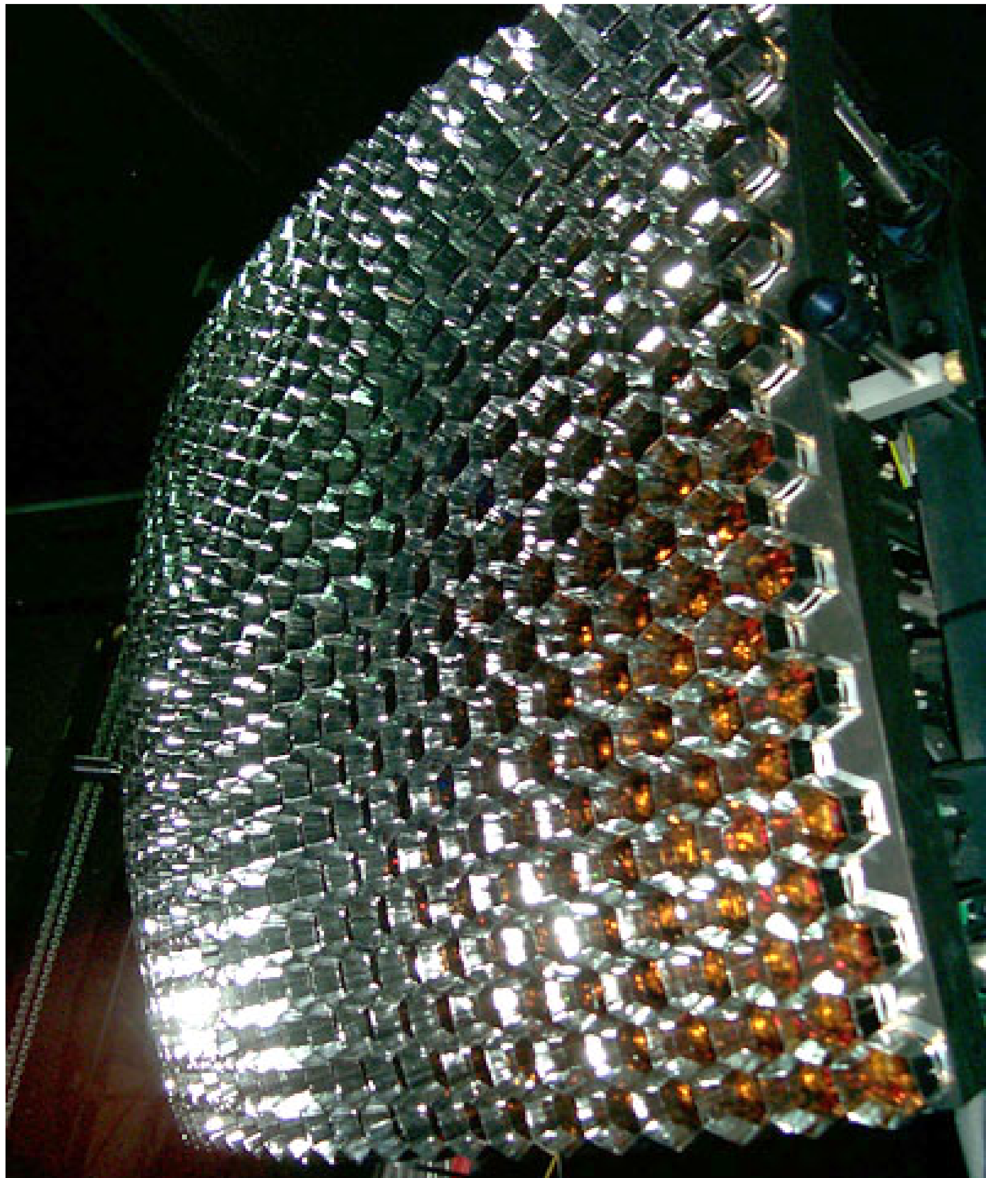
FD telescope:





aperture with shutter, filter and Schmidt corrector lenses





11 m² mirror (Aluminium)

440 PMT camera

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

Auger: unprecedented statistics and precision

≈ 3000 evts/yr with $E > 10^{19}$ eV

Hybrid Detector:

Array of 1600 water Cherenkov detectors

covering 3000 km²

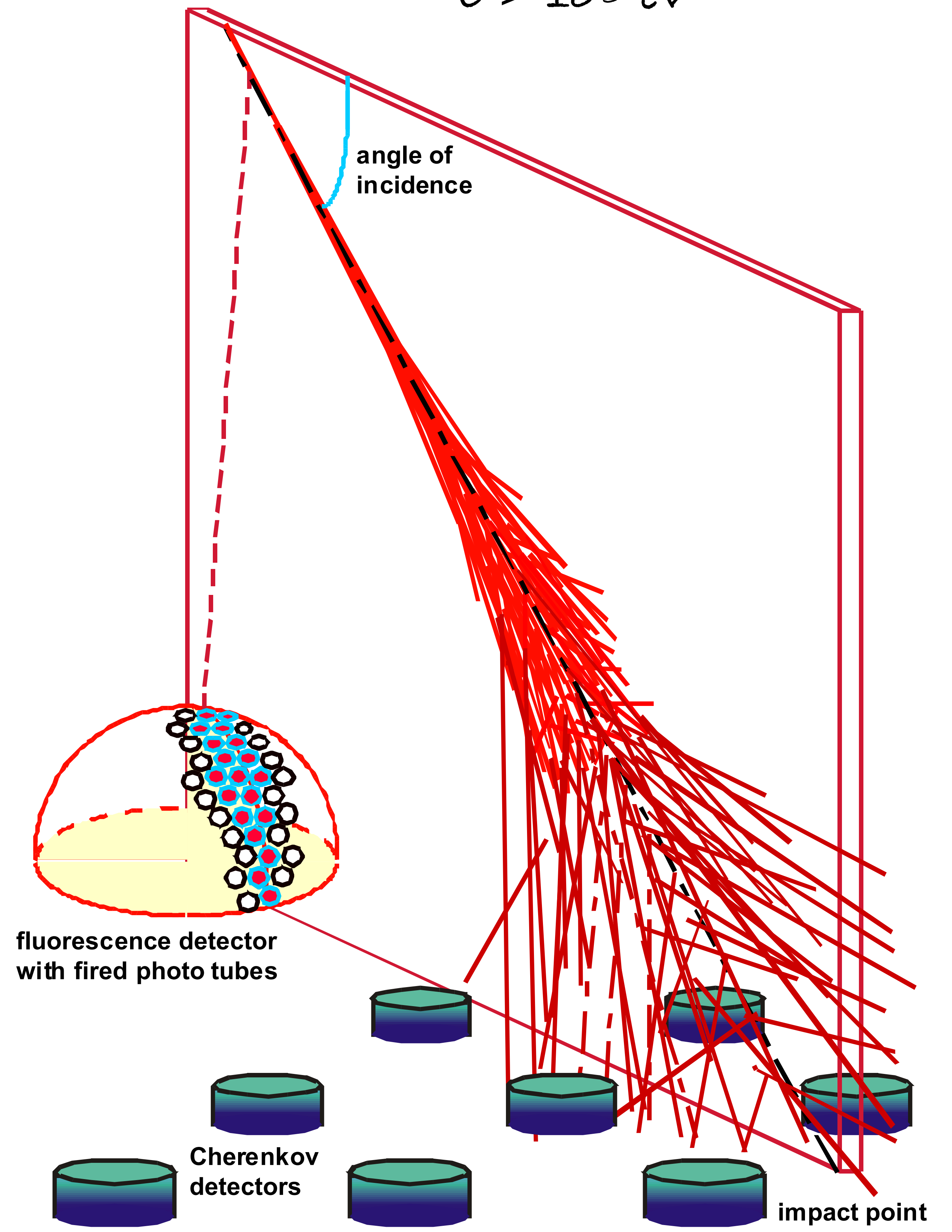
duty cycle: 100%

Fluorescence telescopes

24 FDs (30°x30° each)

duty cycle: 10%

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

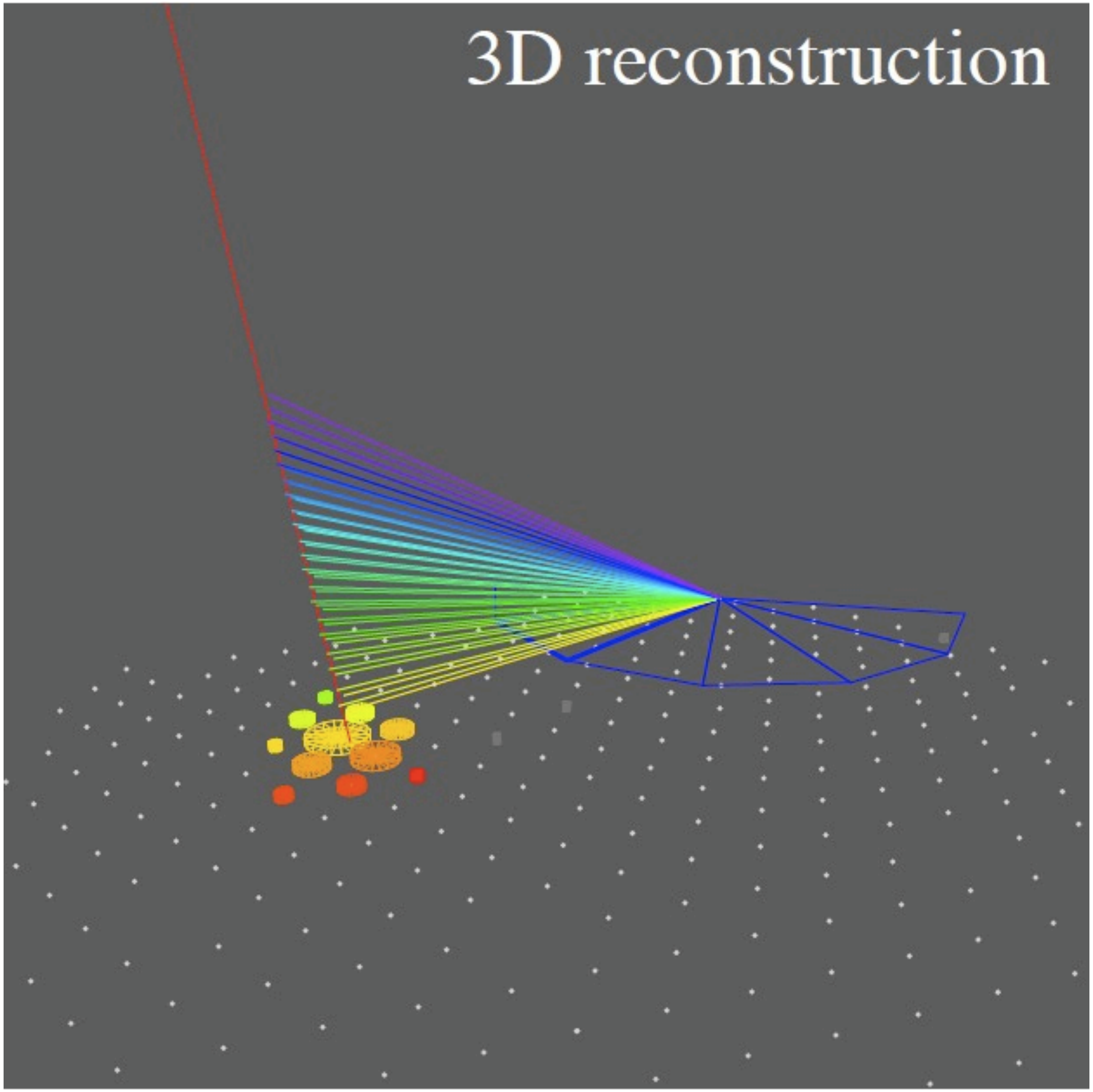


low-energy extensions:

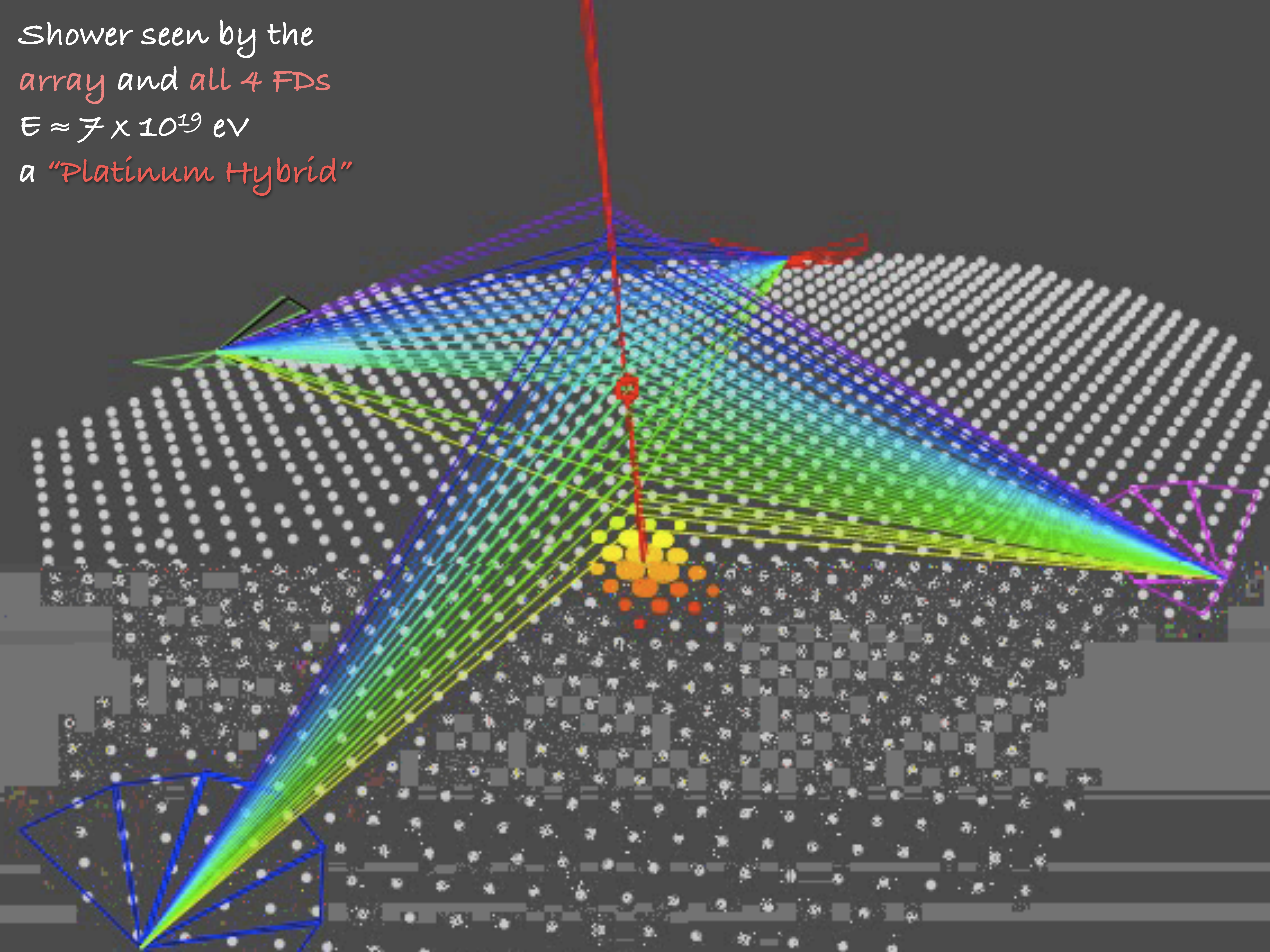
HEAT & infill

$E \geq 10^{17}$ eV

golden hybrid event



Shower seen by the
array and all 4 FDs
$E \approx 7 \times 10^{19}$ eV
a "Platinum Hybrid"



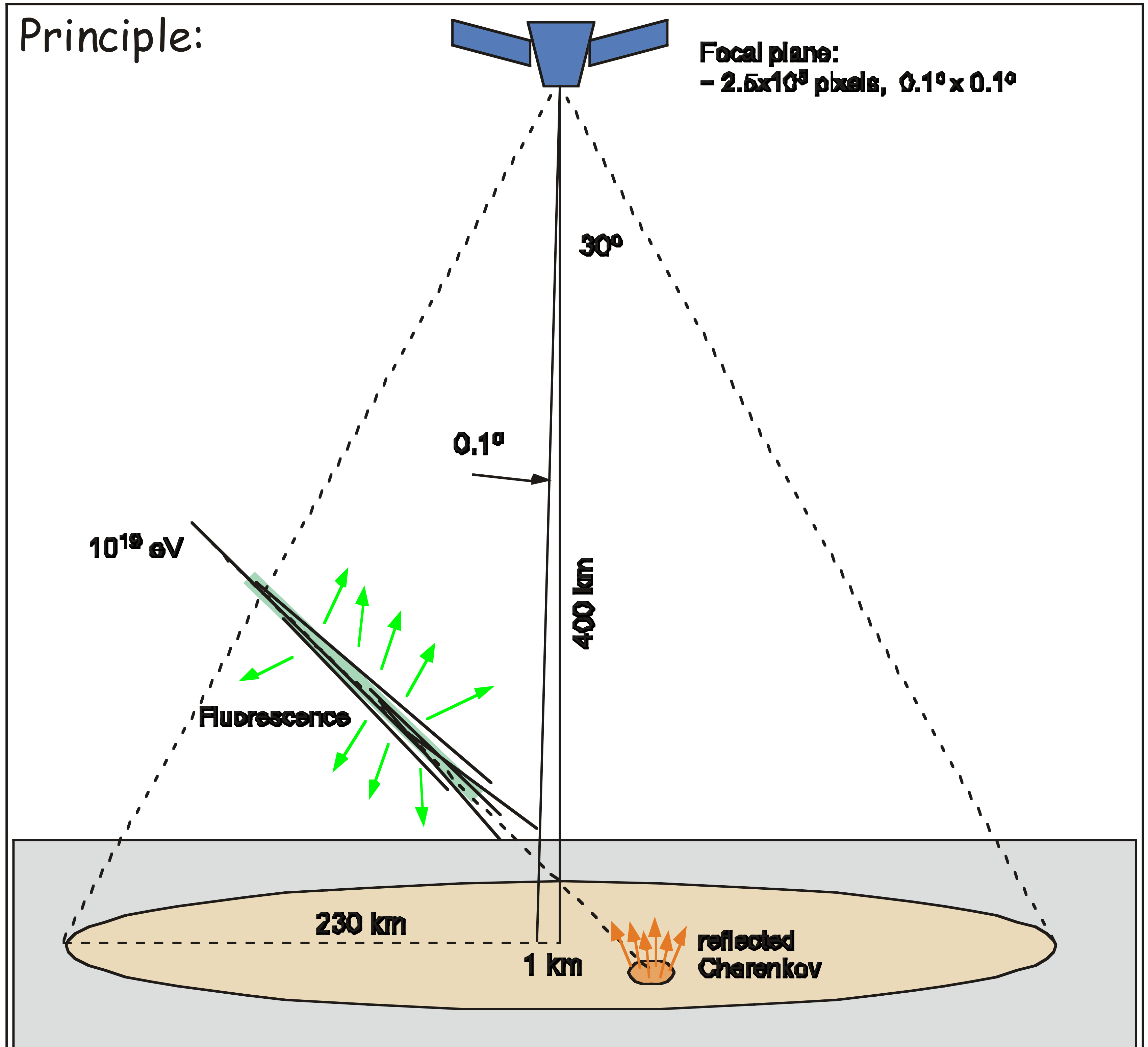
even larger: Space-based UHECR Experiments e.g. Jem-EUSO

Fluorescence obs. from space:

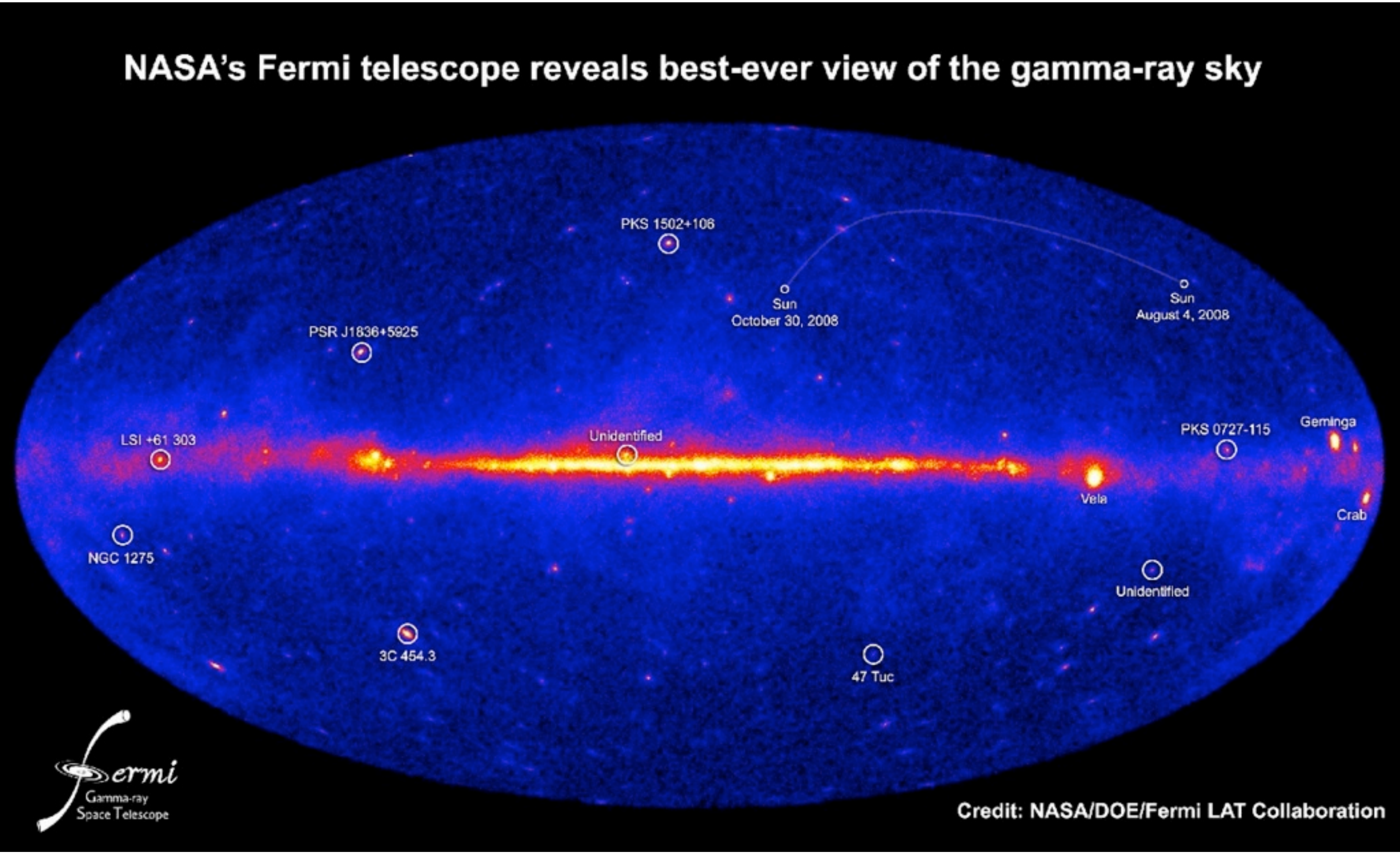
$A\Omega \approx 10^6$ km² sr

$> 10^2$ Events/year with $E > 10^{20}$ eV

(50-100 x Auger)



γ Rays



Satellite experiment: 100 MeV - 100 GeV

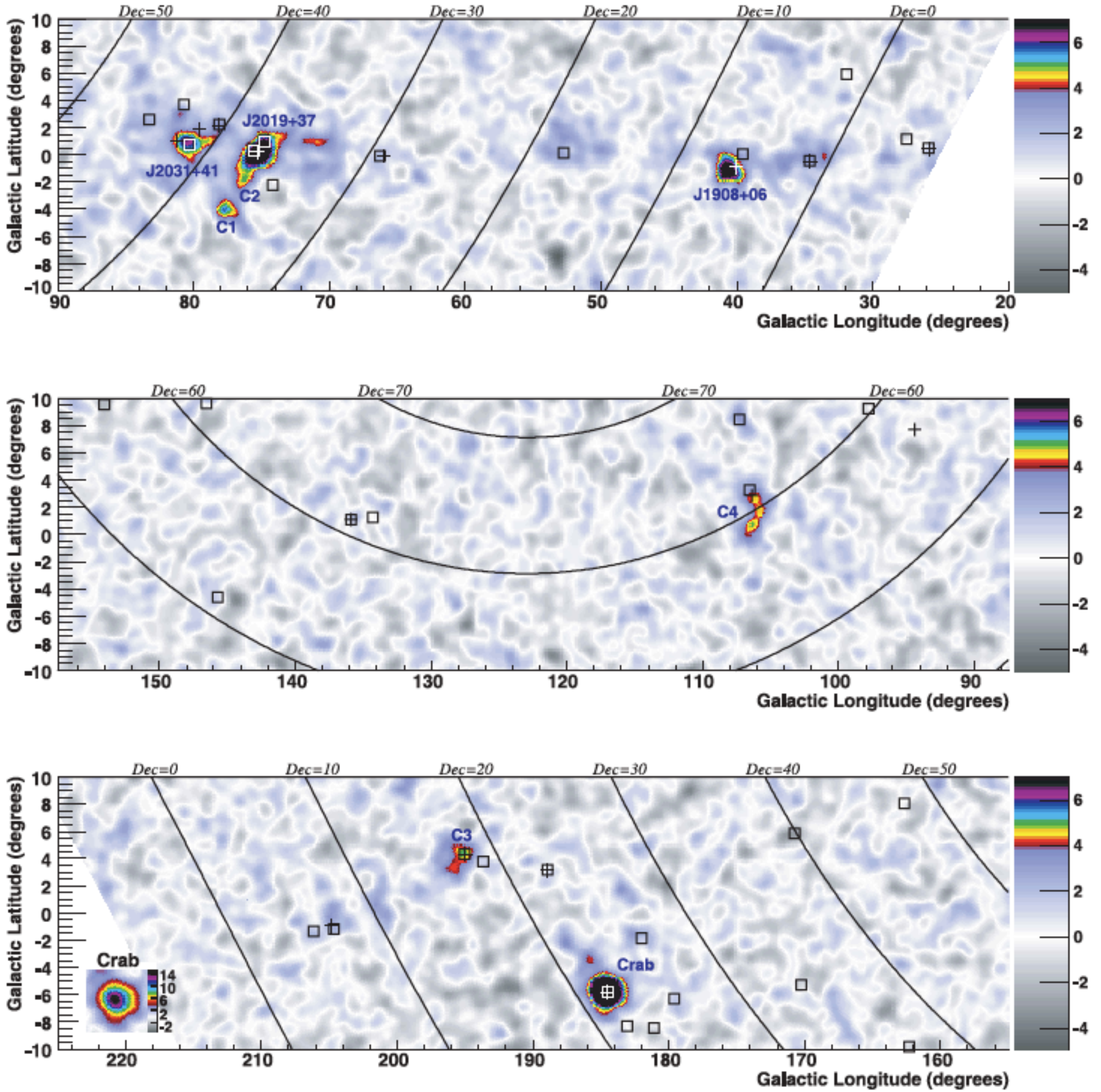
point sources, extended sources and diffuse emission, ...

MILAGRO gal. plane

□ EGRET sources

detecting particles at ground:

few strong sources



Imaging Atmospheric Cherenkov Tels.

Cherenkov light in atmosphere

very forward emission

little absorption, view all parts of shower

only in dark nights (10%)

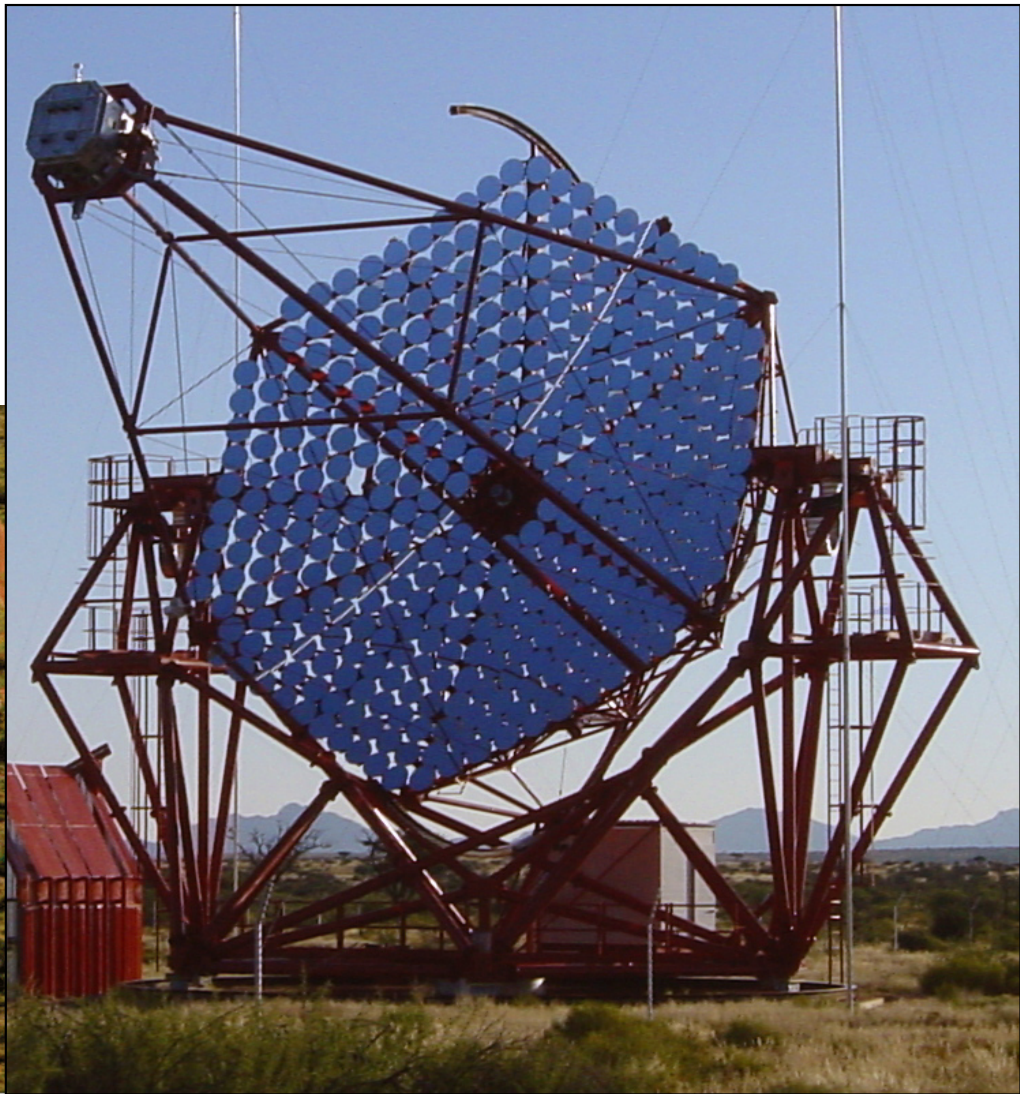
- basis of TeV gamma ray astronomy (<100 GeV - >300 TeV)
- requires good knowledge of atmospheric conditions

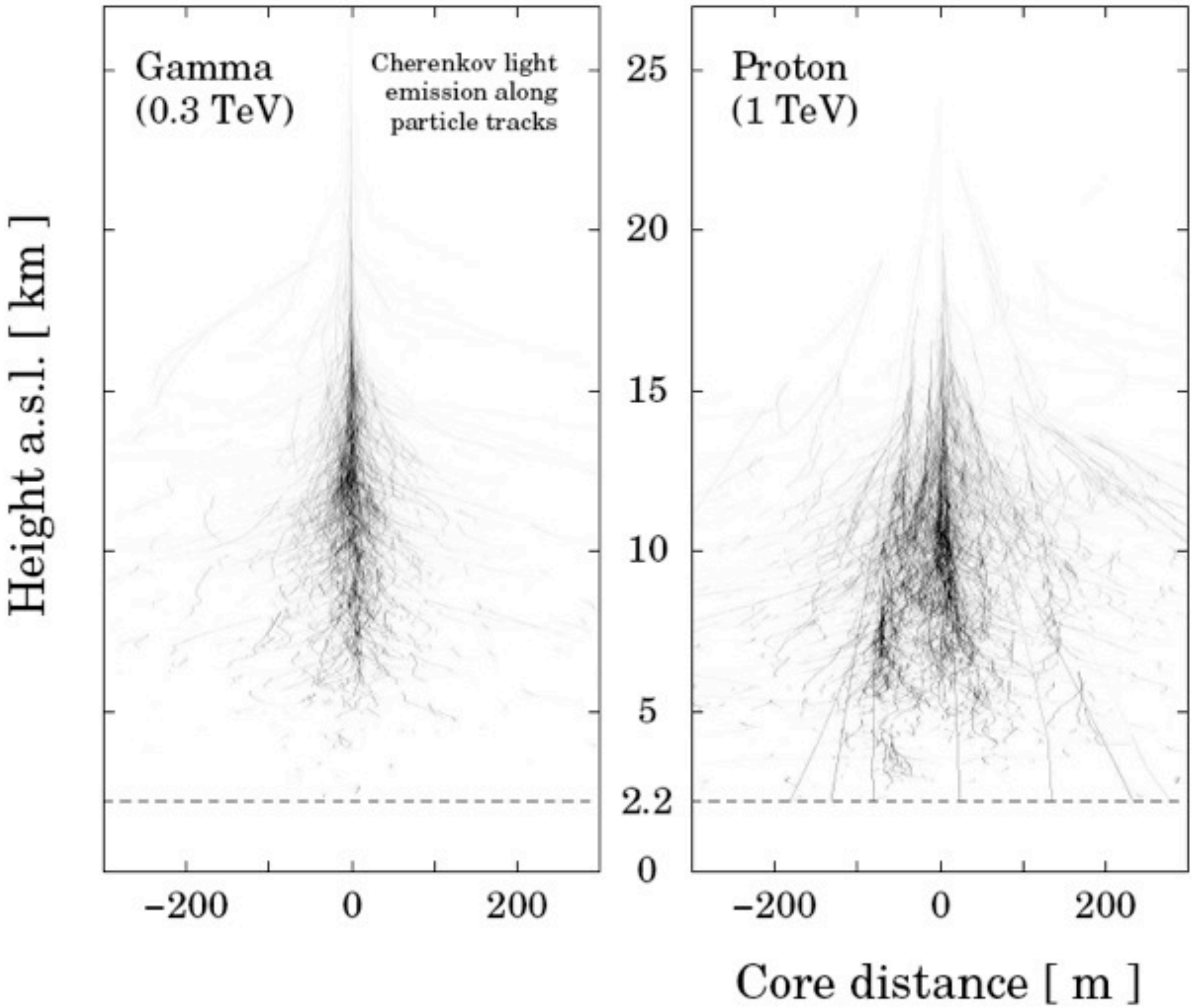
Imaging Atmospheric Cherenkov Telescopes:

- e.g. HESS, MAGIC, VERITAS, CTA

Light samplers:

- e.g. Stacee, Airobicc, Blanca





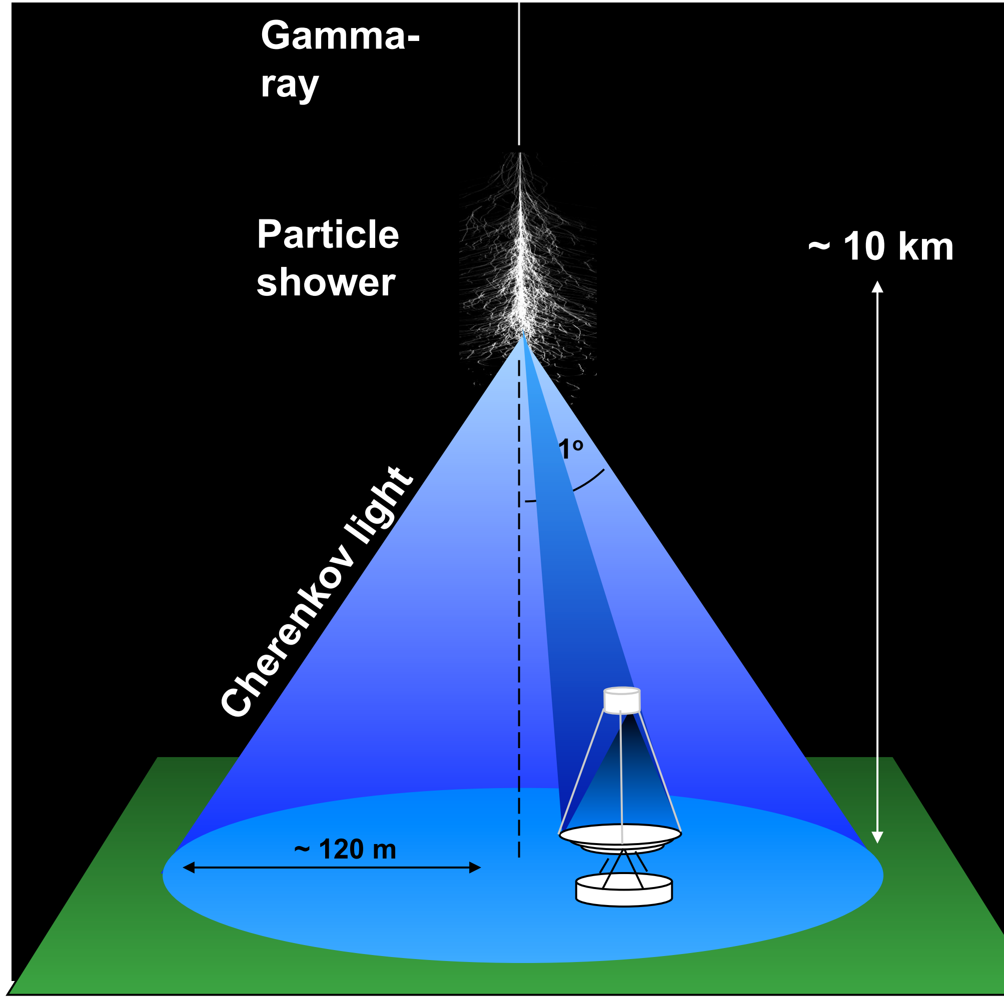


Image the shower,

distinguish protons and photons from the shape of the images.

.... very successful technique

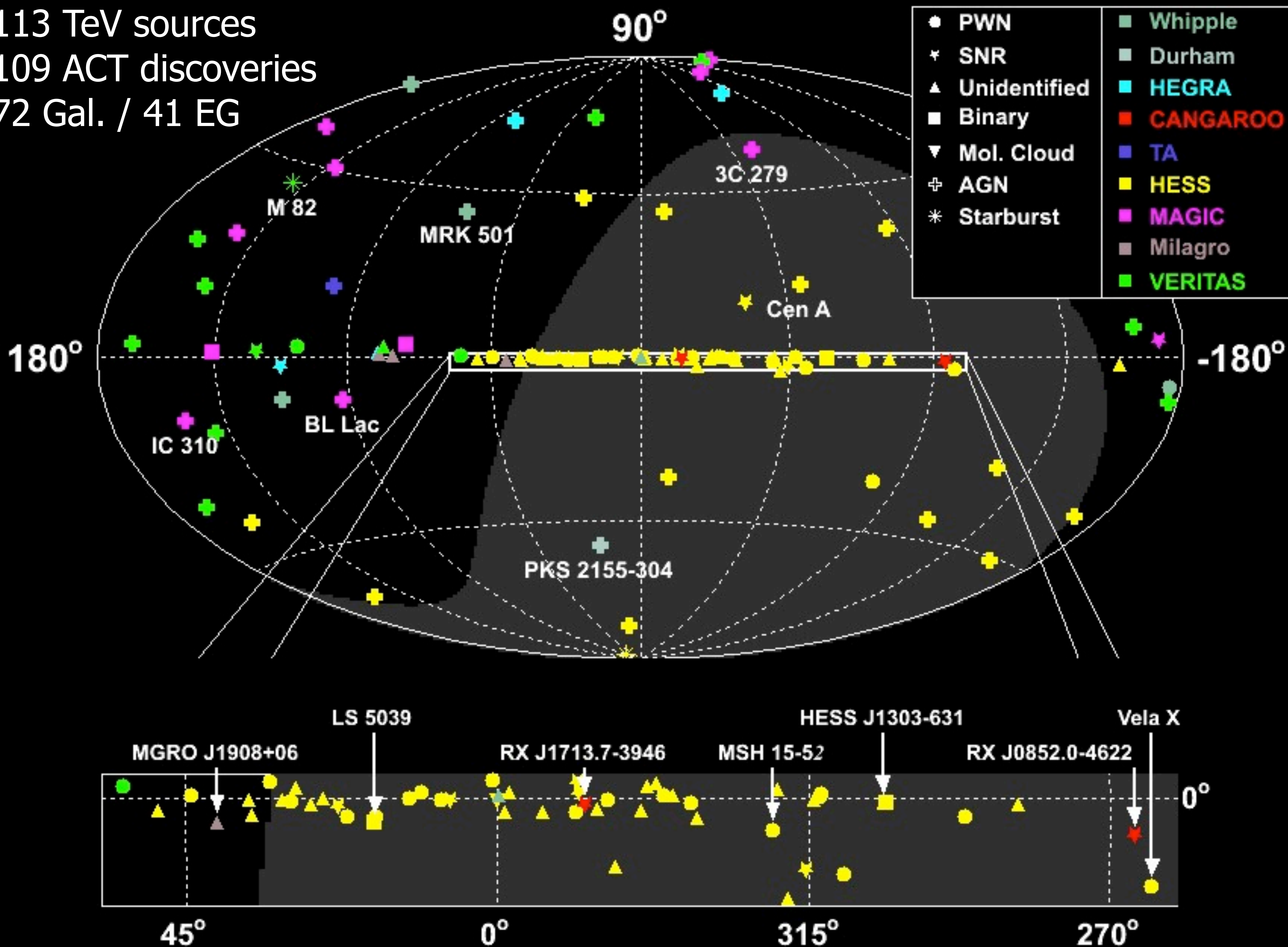
also possible to identify e^- and Fe

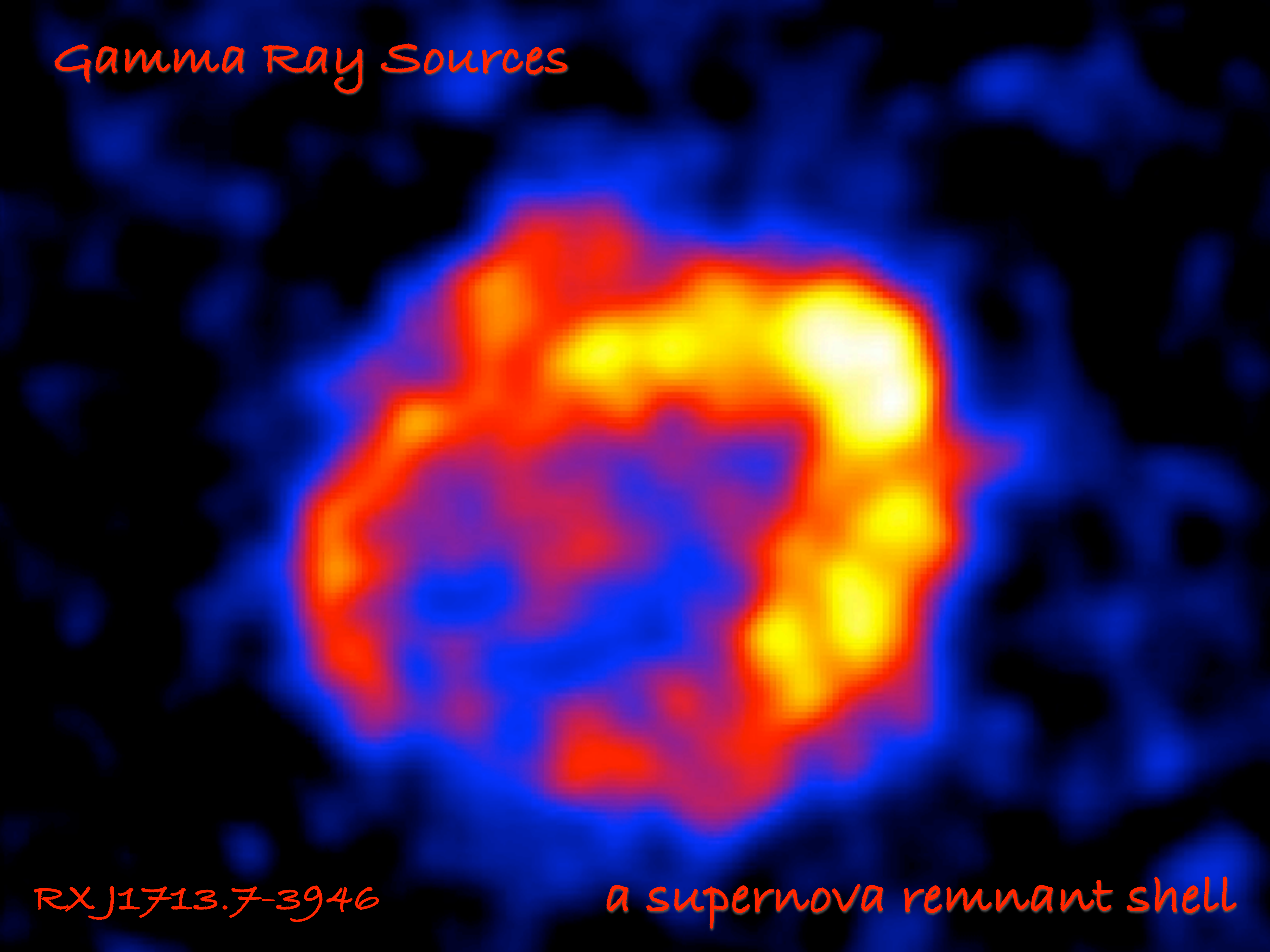
2010:

113 TeV sources

109 ACT discoveries

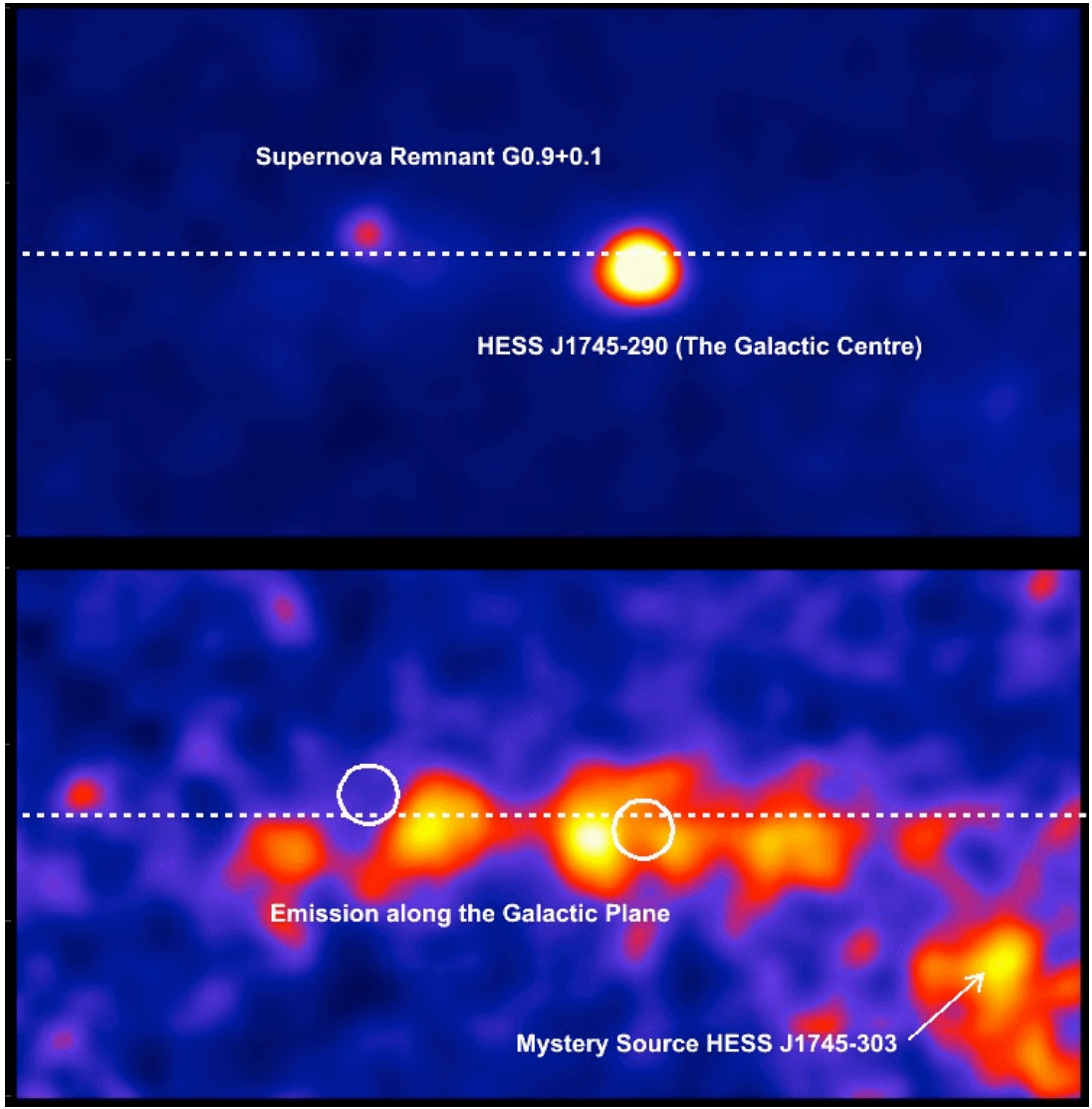
72 Gal. / 41 EG

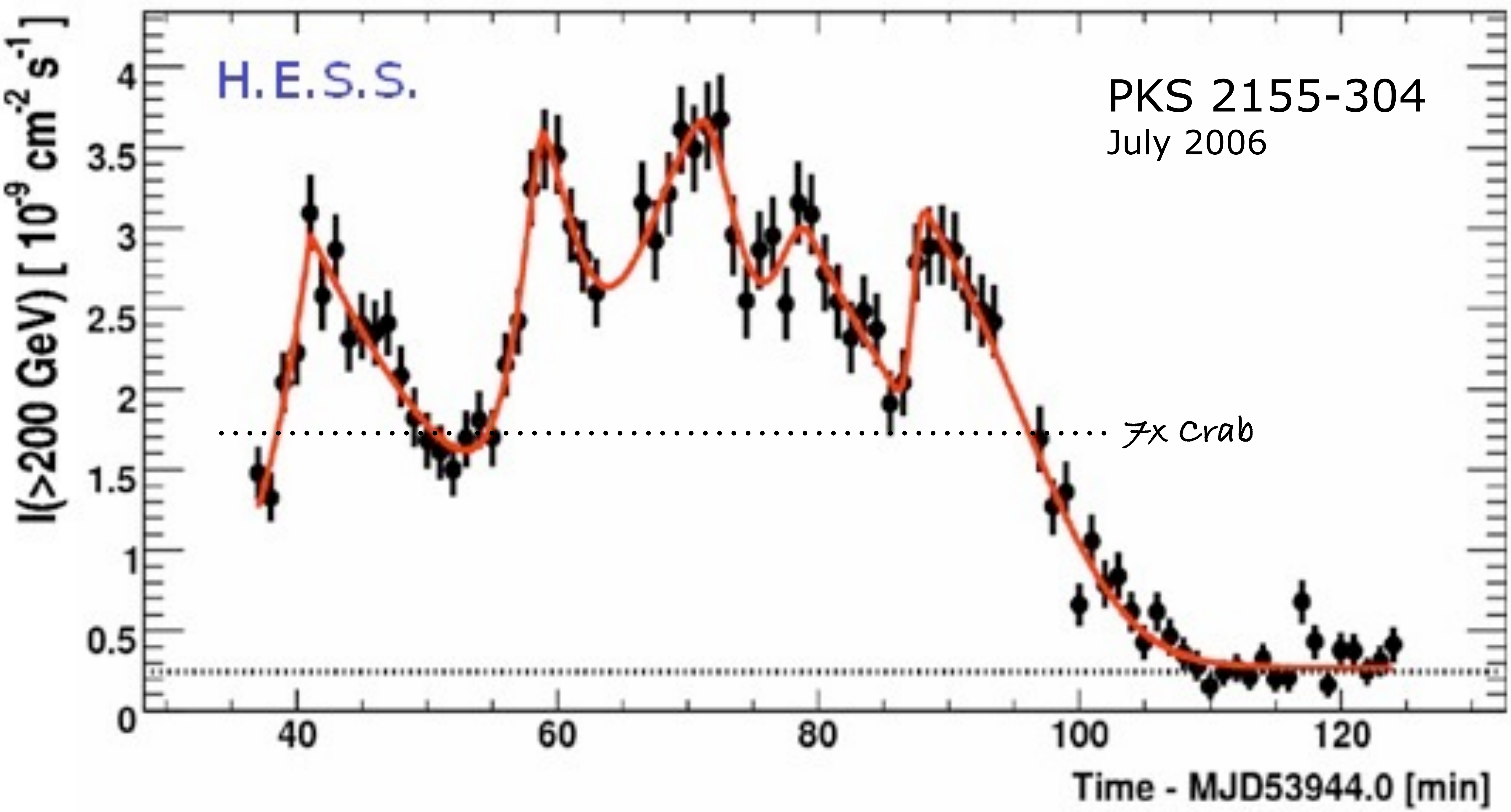



Gamma Ray Sources
RX J1713.7-3946
a supernova remnant shell

HESS:
gal. centre

CRs with
mol. clouds

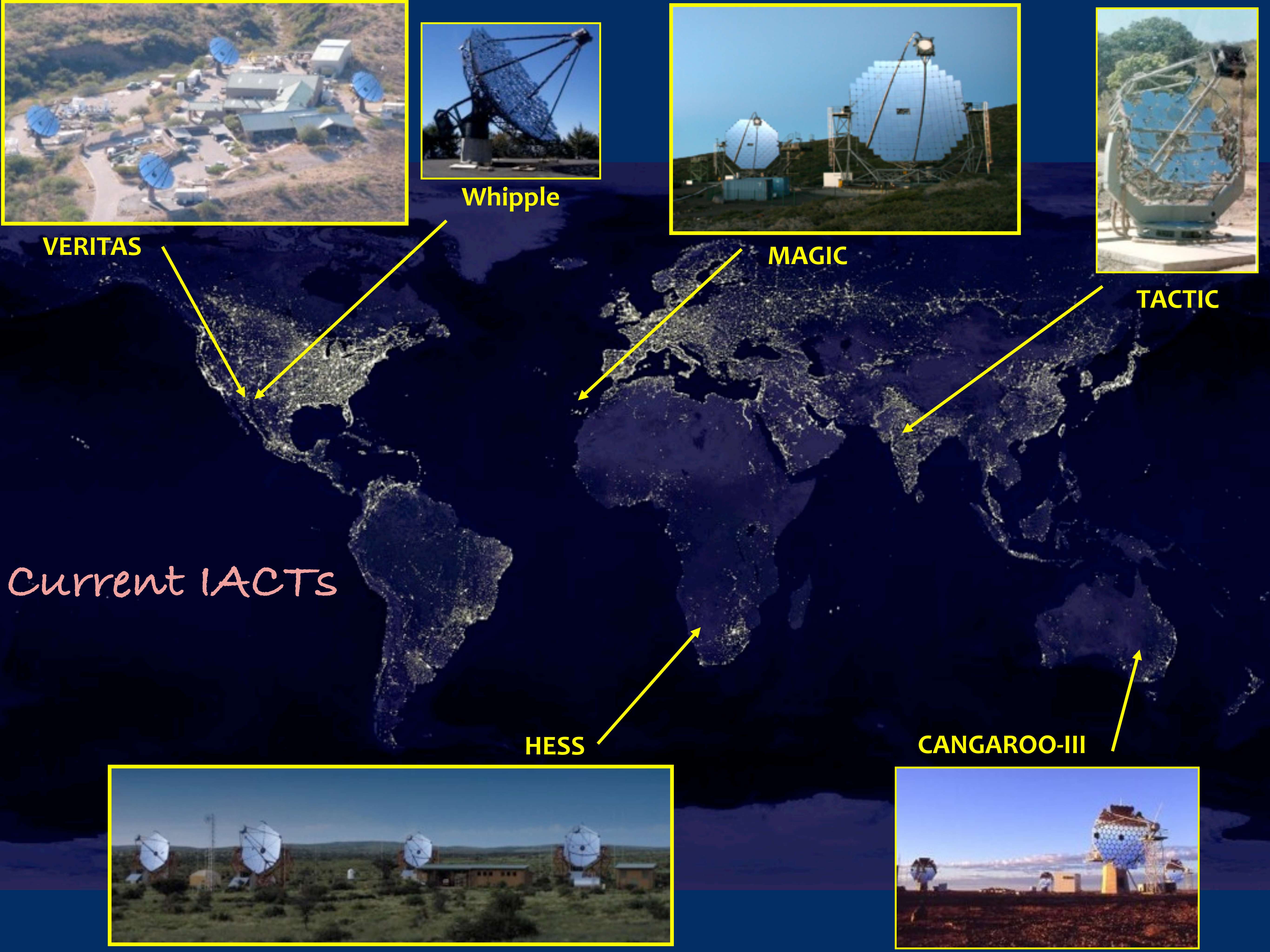




BL Lac object z = 0.116

bursts on 200 s scales

$\Gamma \geq 100$ are required


Current IACTs
VERITAS
Whipple
MAGIC
TACTIC
HESS
CANGAROO-III

Scientific Objectives:

Cosmic energetic particles

Origin of the galactic cosmic rays

Also UHECR signatures

Role of ultra-relativistic particles in

in clusters of galaxies, AGN, Starbursts...

The physics of (relativistic) jets and shocks

Fundamental Physics

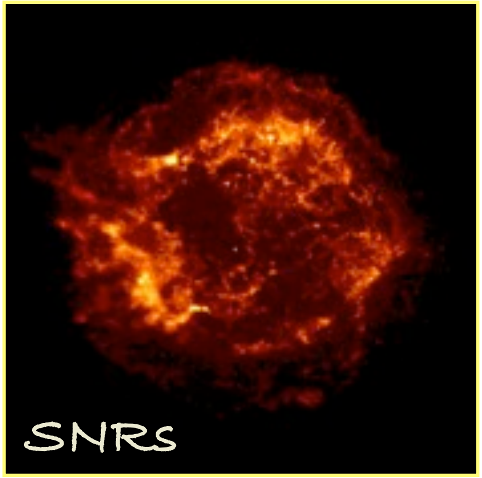
Dark Matter annihilation / decay

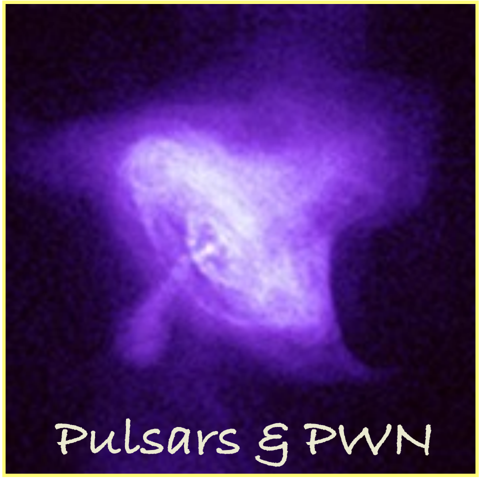
Lorentz Invariance violation

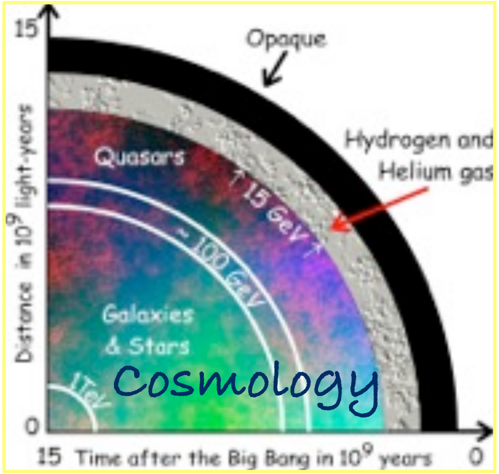
Cosmology

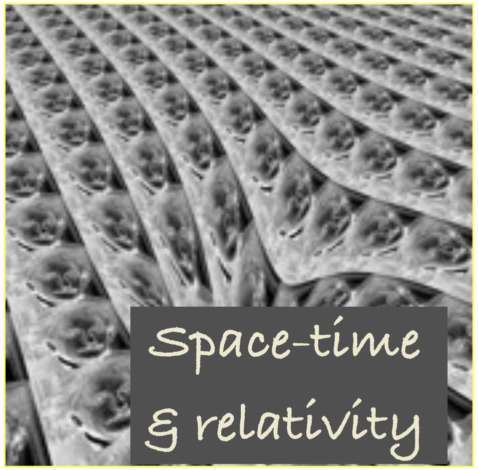
cosmic FIR-UV radiation,

cosmic magnetism









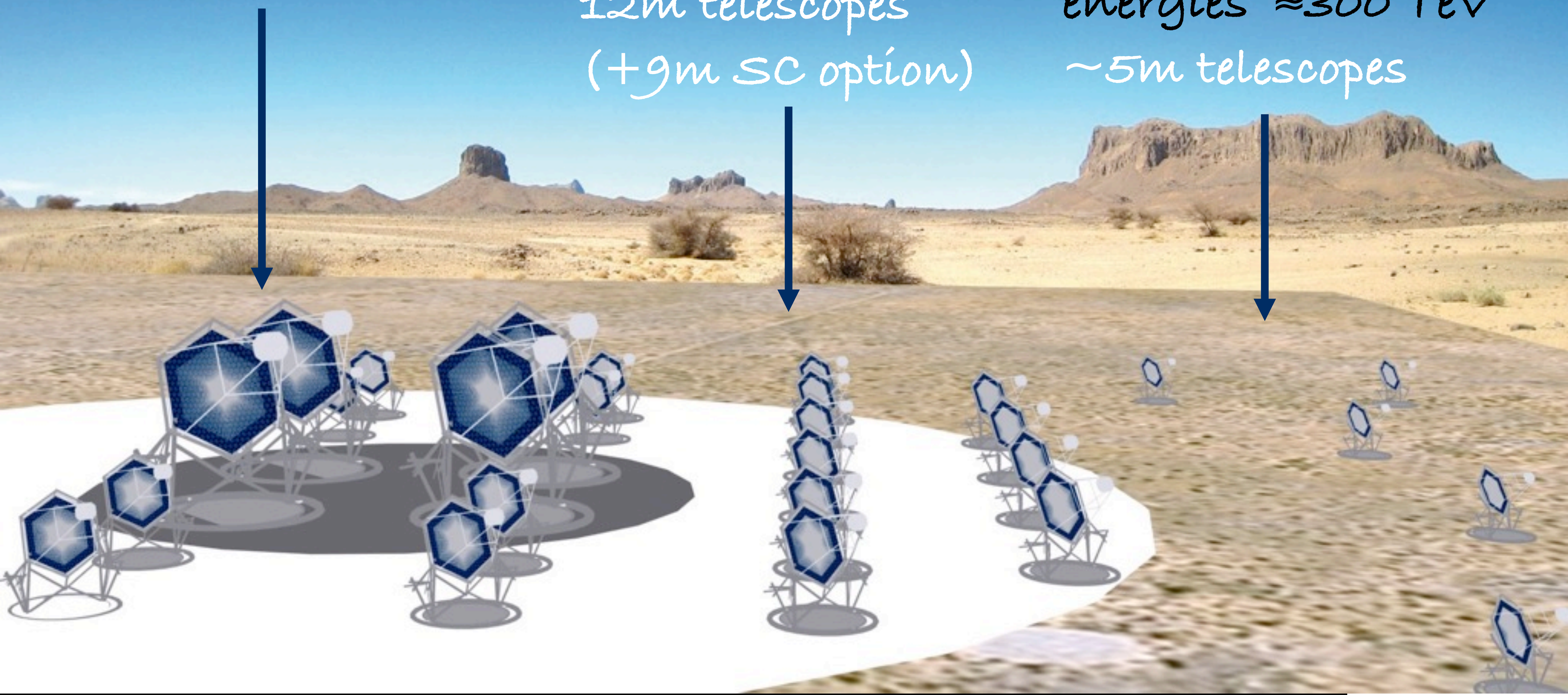
An observatory with ≈ 100 telescopes.

(South Only)

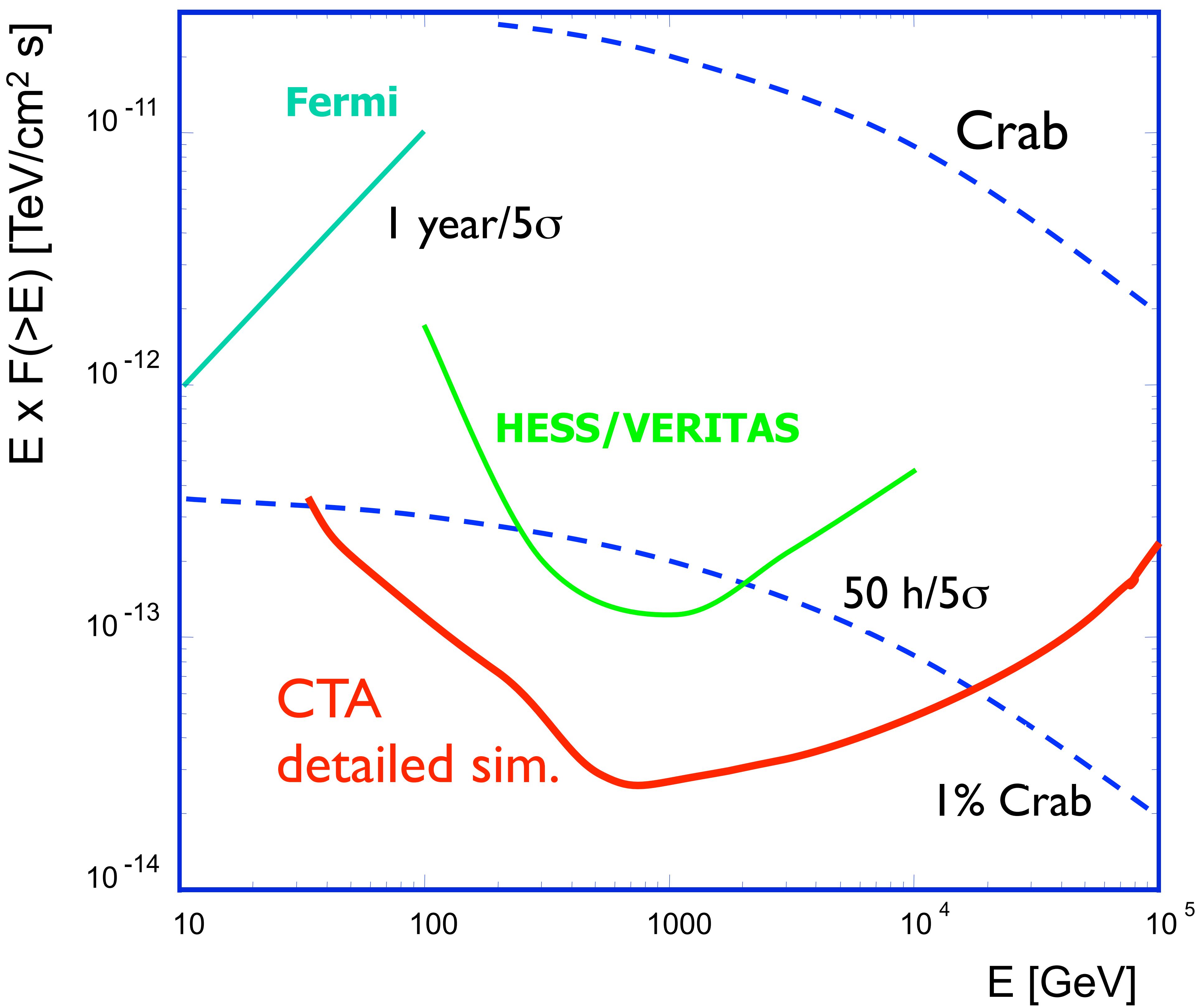
Low-energy section
energy threshold
of 20-30 GeV
~24m telescopes

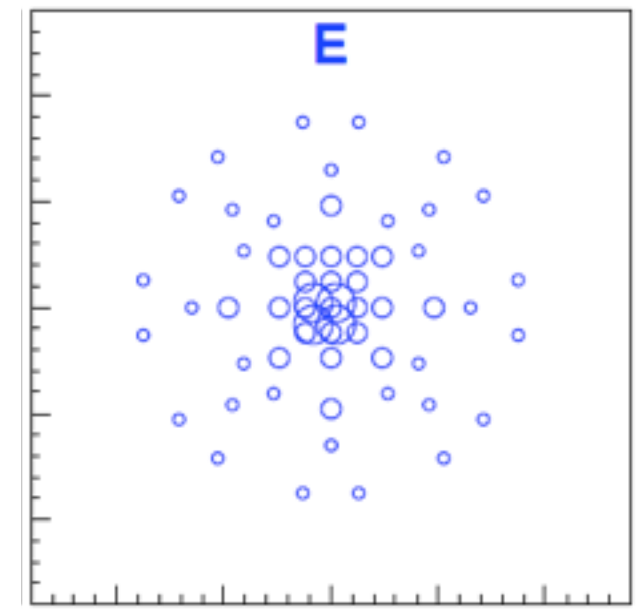
Medium Energies:
mCrab sensitivity
0.1–10 TeV
12m telescopes
(+9m SC option)

High-energy section
10 km^2 area for up to
energies ≈300 TeV
~5m telescopes



Point Source Sensitivity

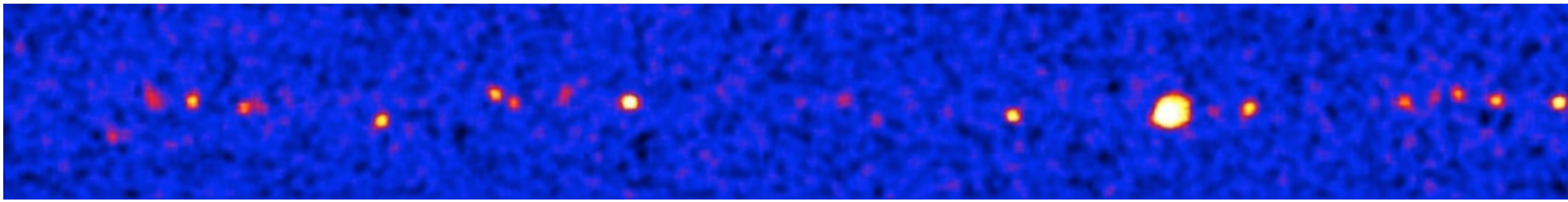




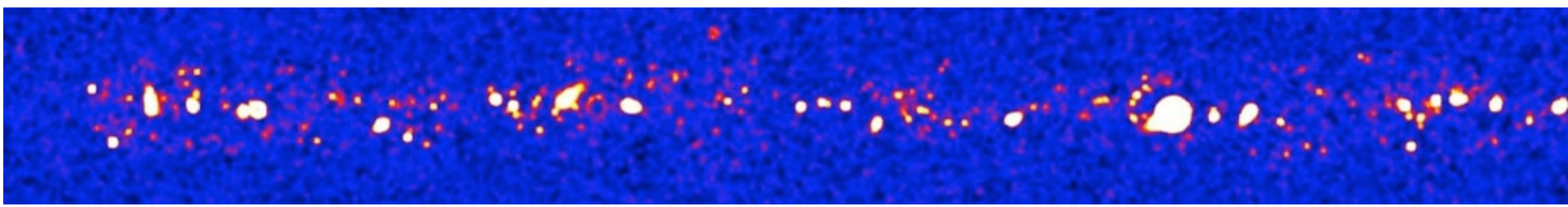
array "E" :
59 telescope config.
(analysis & layout
not optimised yet)

€80M nominal cost

CTA expectation:



HESS ~500 h



CTA expectation: >1000 sources

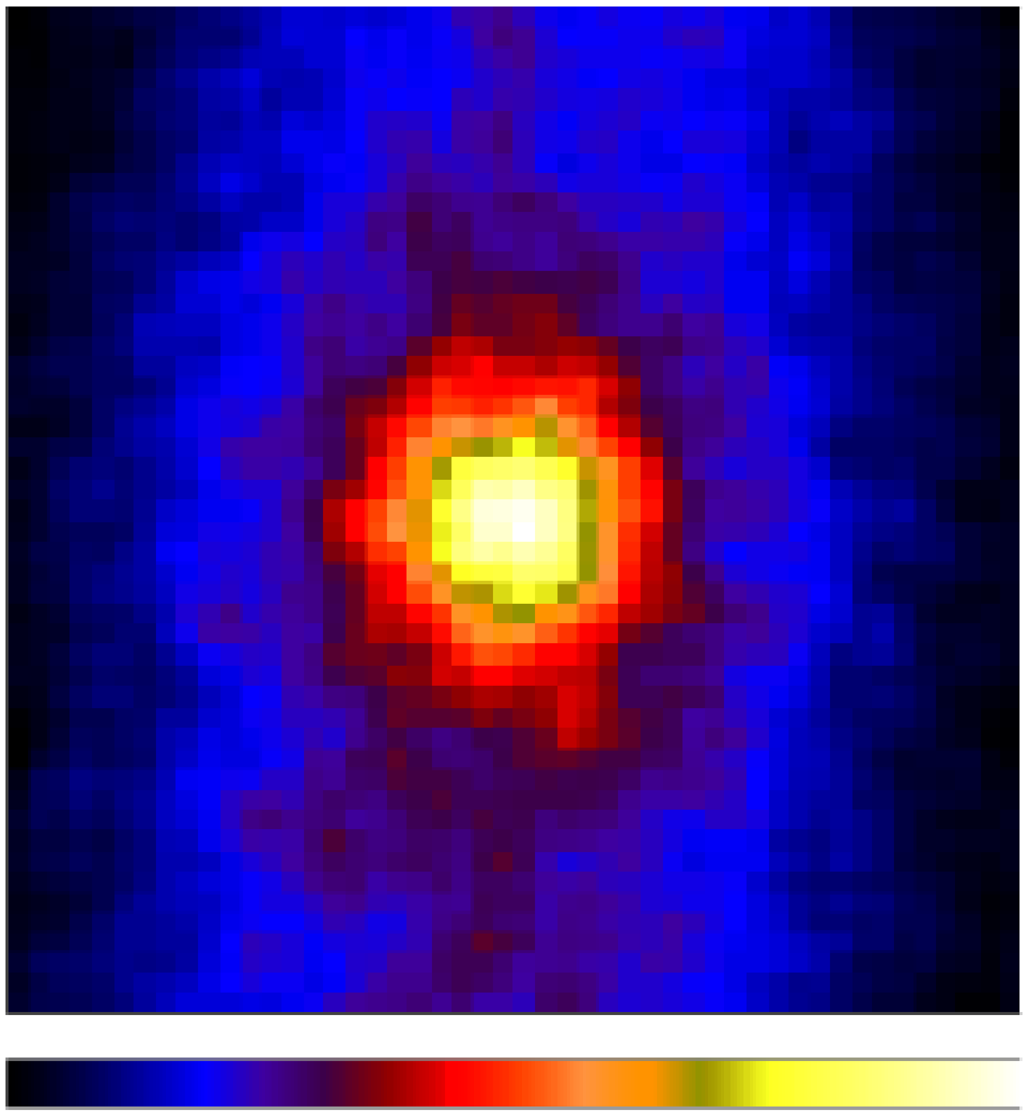
Different detectors for different purposes ...

EAS Observables:		Suitable Detectors:
Number, distribution, fluctuation of electrons arrival times	....	arrays of scintillators, water Cherenkov detectors or gas chambers
Number, distribution, angle, energy, fluctuation of μ	....	buried detectors, tracking chambers
Number, distribution and energy of hadrons	....	deep hadronic calorimeters
Number and distribution, angular distribution of Cherenkov photons	....	wide angle and imaging Cherenkov detectors
angular distribution of fluorescence photons	....	fluorescence telescopes
Depth of shower maximum	....	Cherenkov or fluorescence detectors

Neutrinos

The Neutrino Sky so far: (energies: MeV)

The Sun



Super- K (Japan) image
of the sun using neutrinos

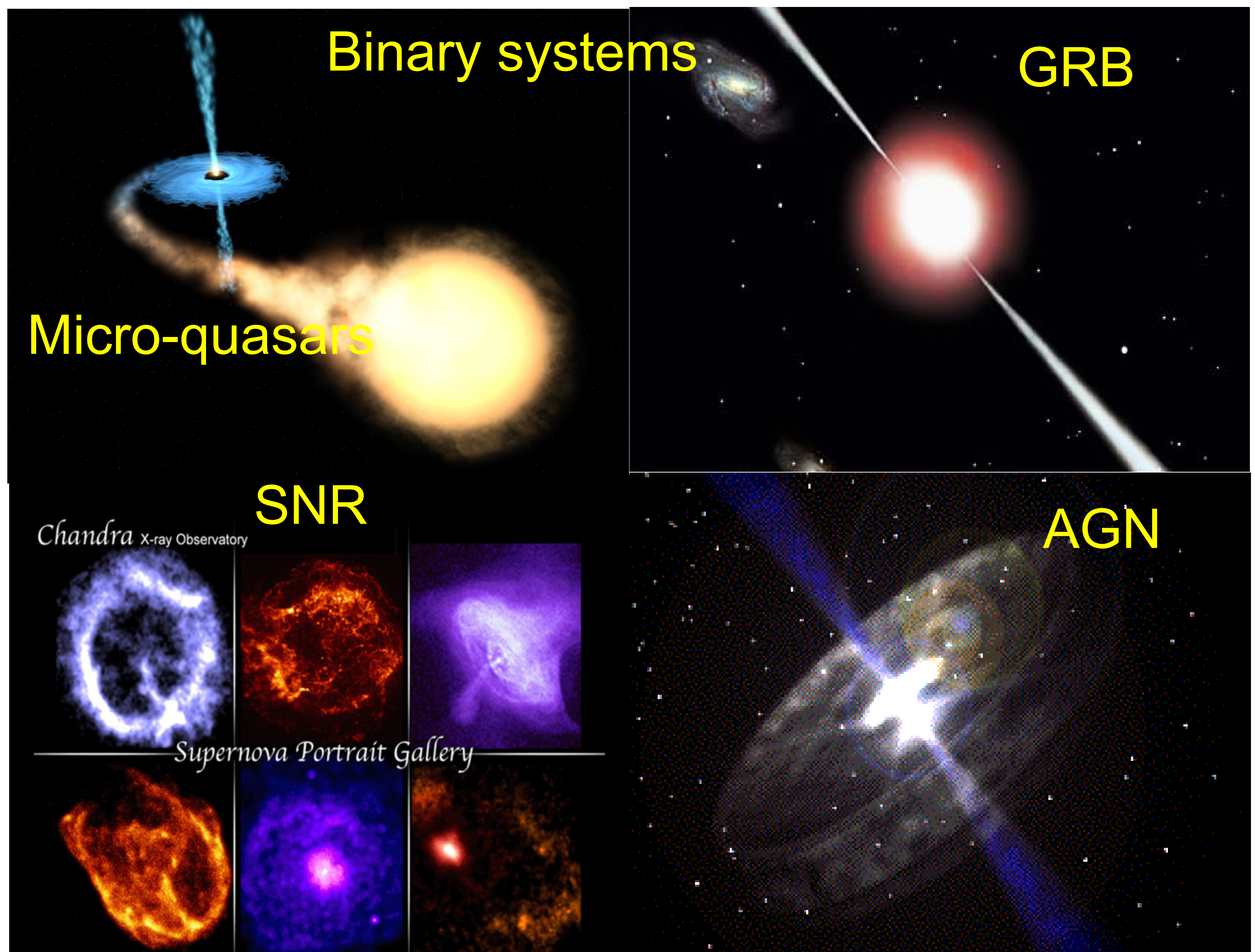
SN 1987 A

few (<20) neutrinos seen
by 3 experiments
during 10 seconds

Potential neutrino sources
(galactic and extra galactic)

… wherever energetic particles interact

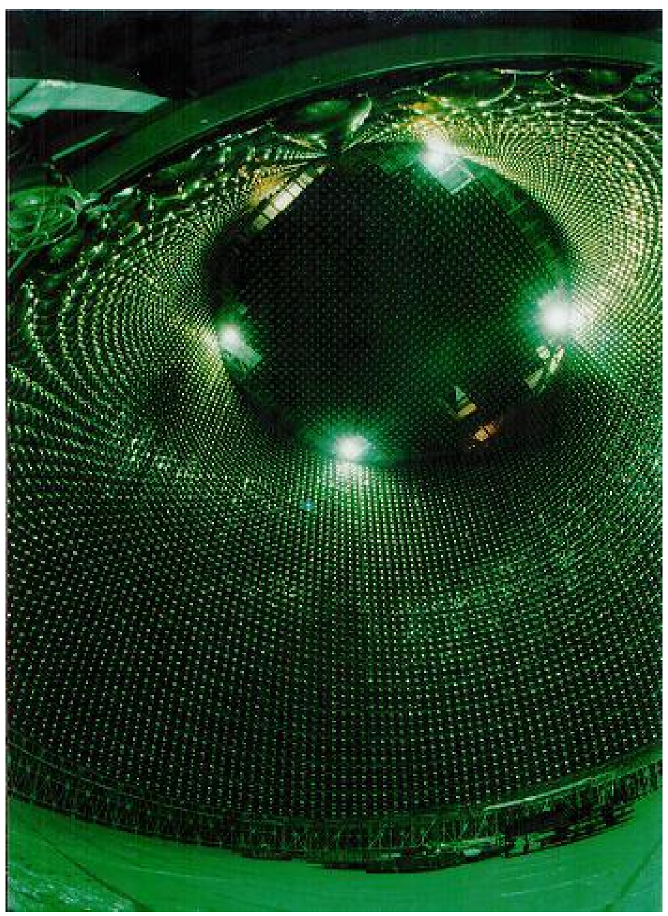
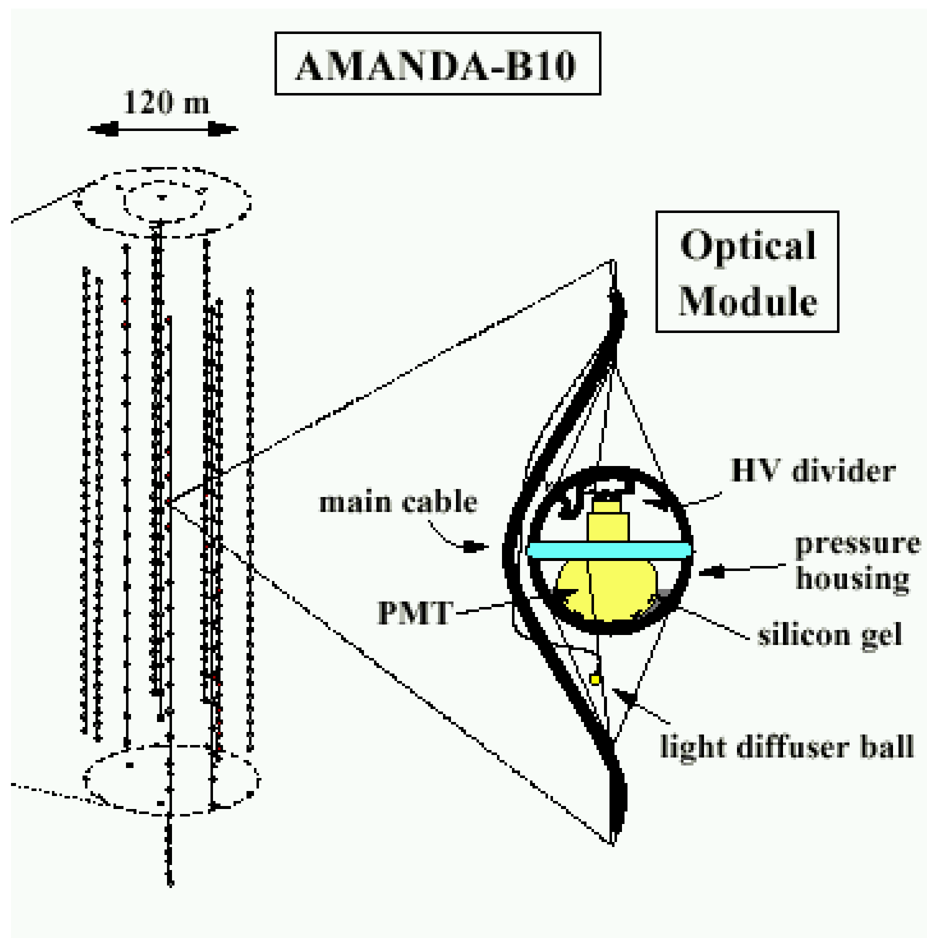
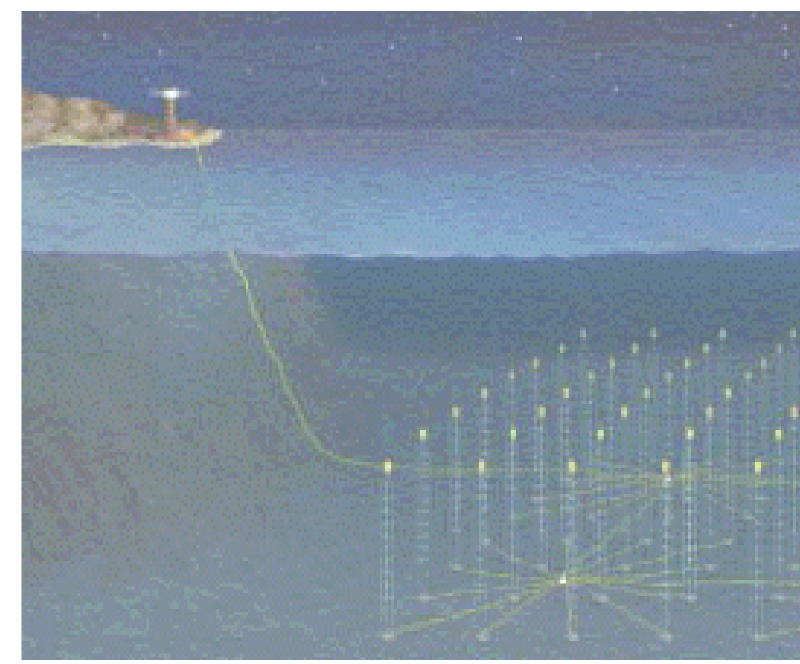
e.g.:



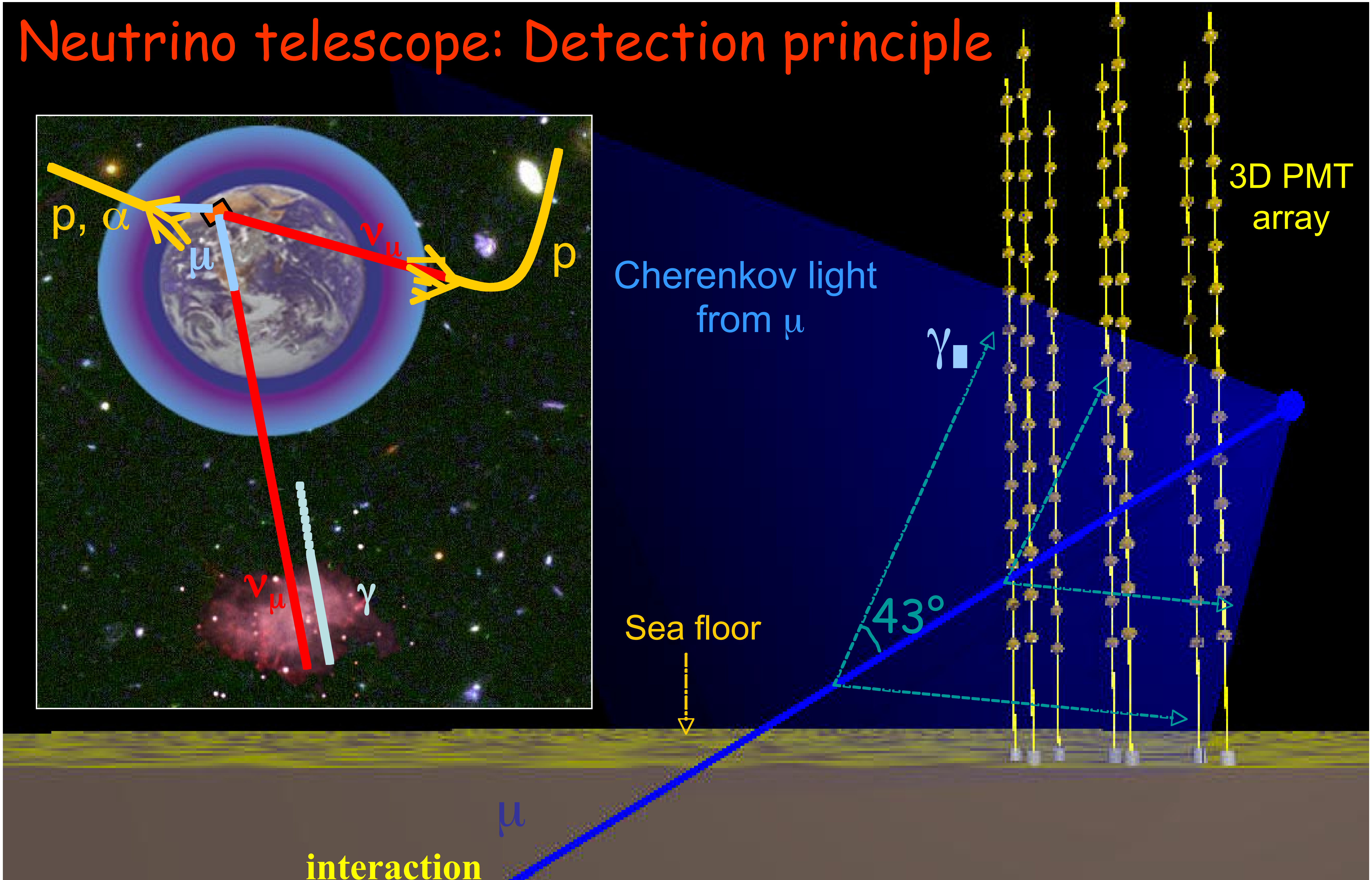
Same sources as for gamma rays …

but predicted neutrino fluxes are very uncertain.

large detection volumes: e.g. air, water or ice;
Cherenkov effect to detect fast, charged particles;
deep underground to shield cosmic rays

Super Kamiokande	AMANDA (south Pole)	KM3-Net (Mediterranean)
		
dist. of modules: 0.5 m	20 m	100 m
threshold: 5 MeV	50 GeV	200 GeV

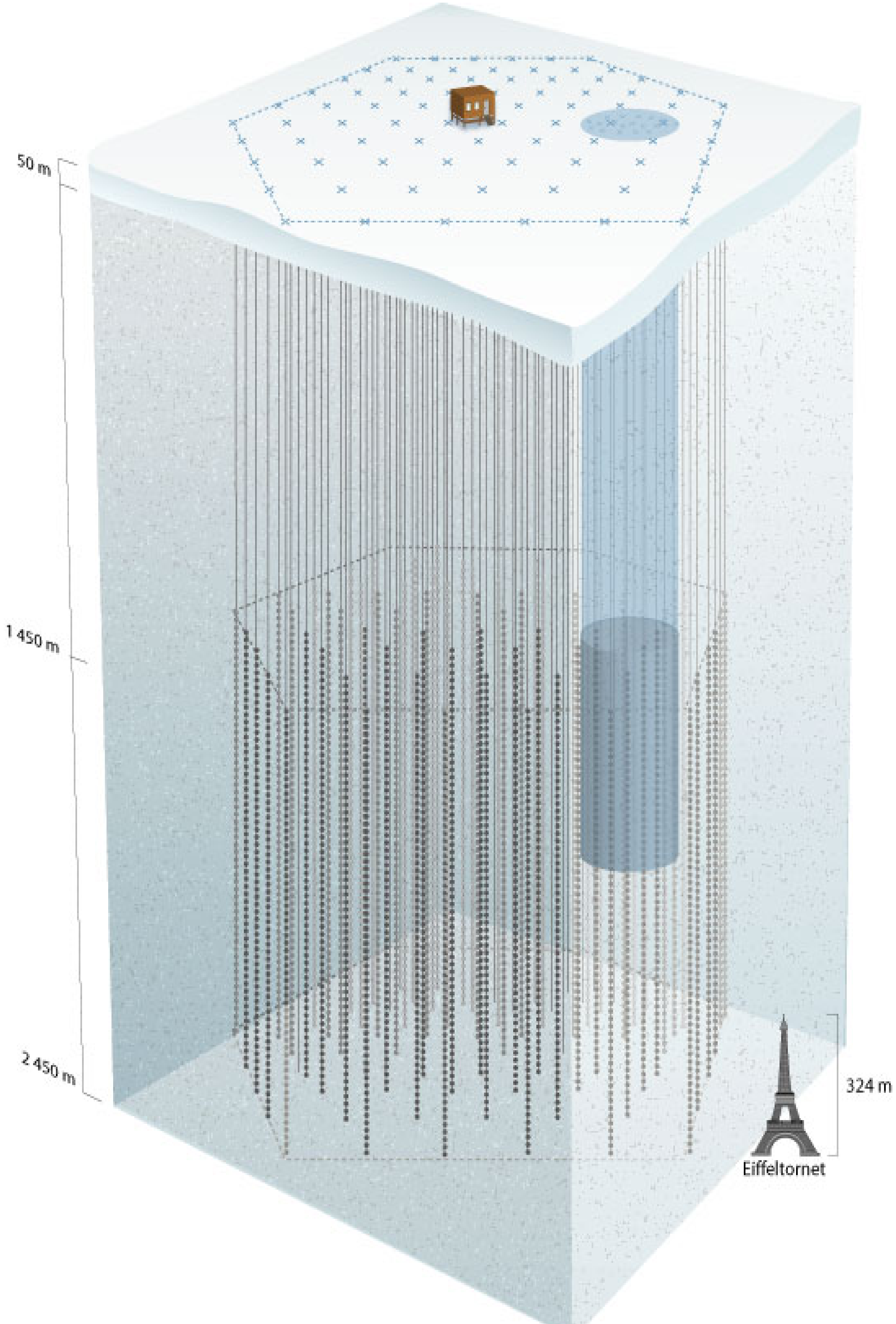
Neutrino telescope: Detection principle



Reconstruction of μ trajectory (~ ν)
from timing and position of PMT hits


IceCube / Amanda in Antarctic Ice Shield

IceCube



instrument 1 km³ ice

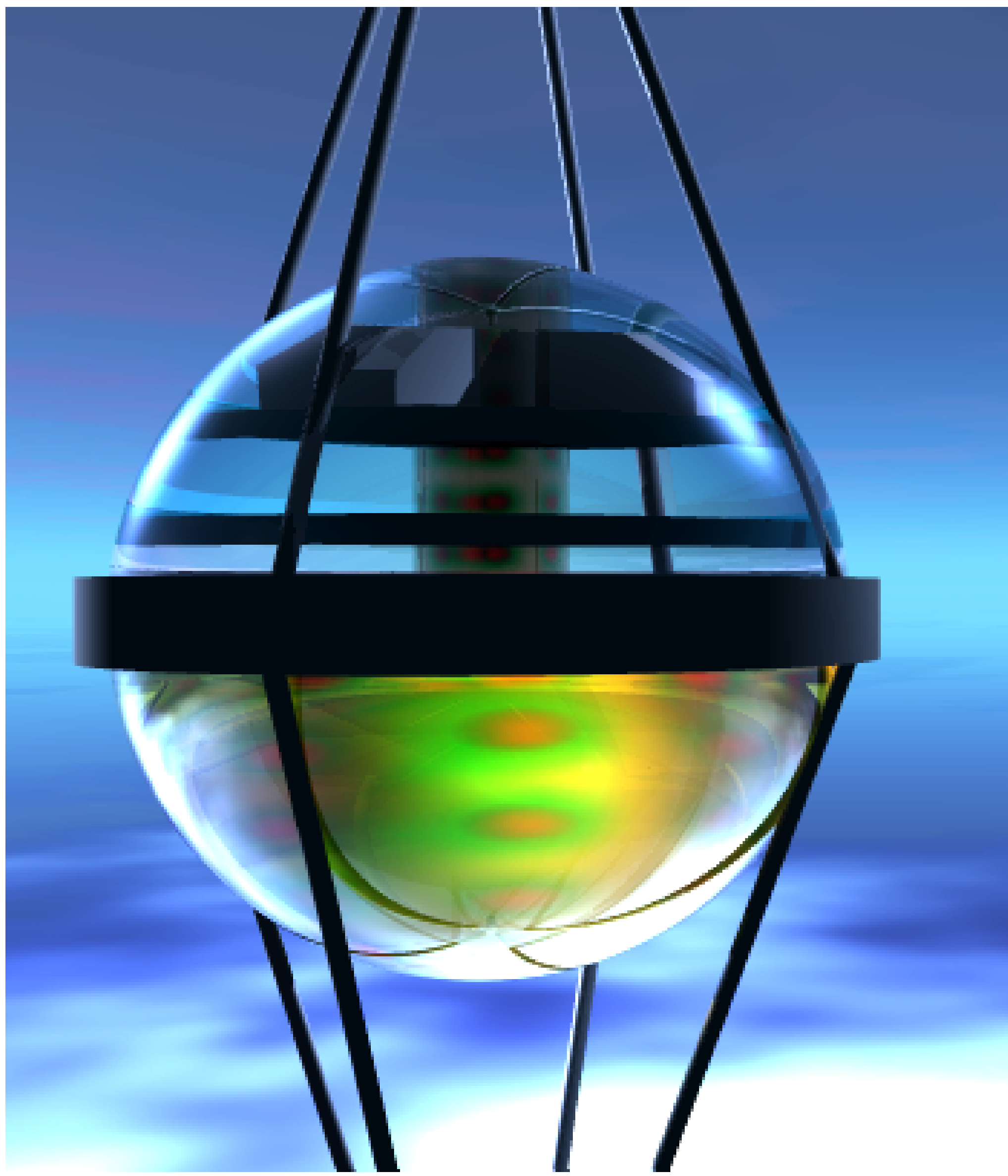
IceTop: 80 pairs of ice Cherenkov tanks

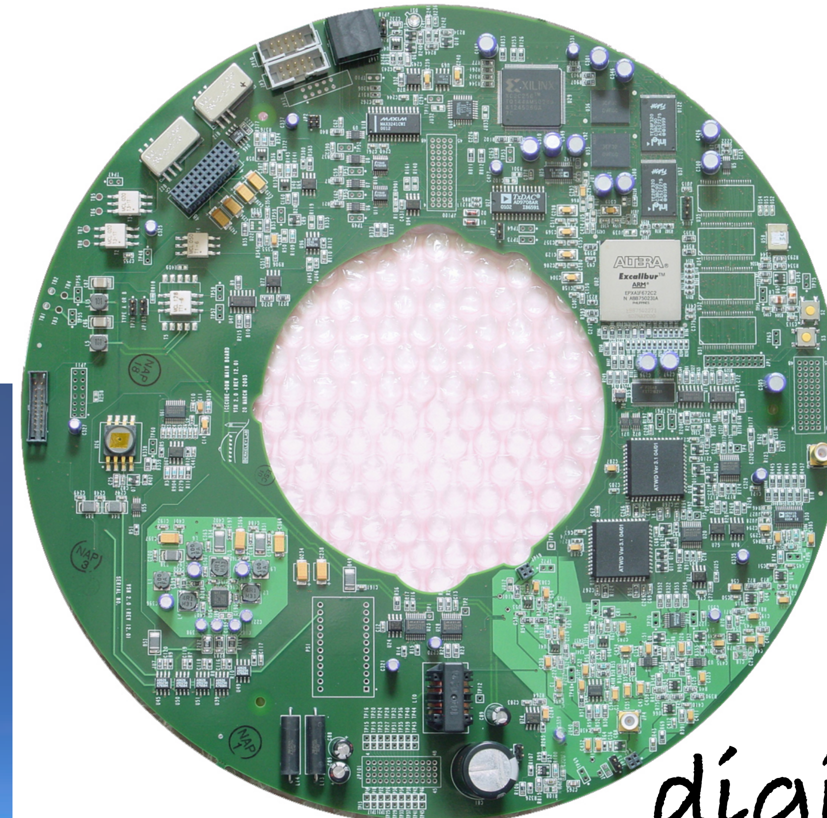
22/80 strings deployed
60 modules each

Amanda: 19 strings/ 677 modules

Completion: 2011

optical module

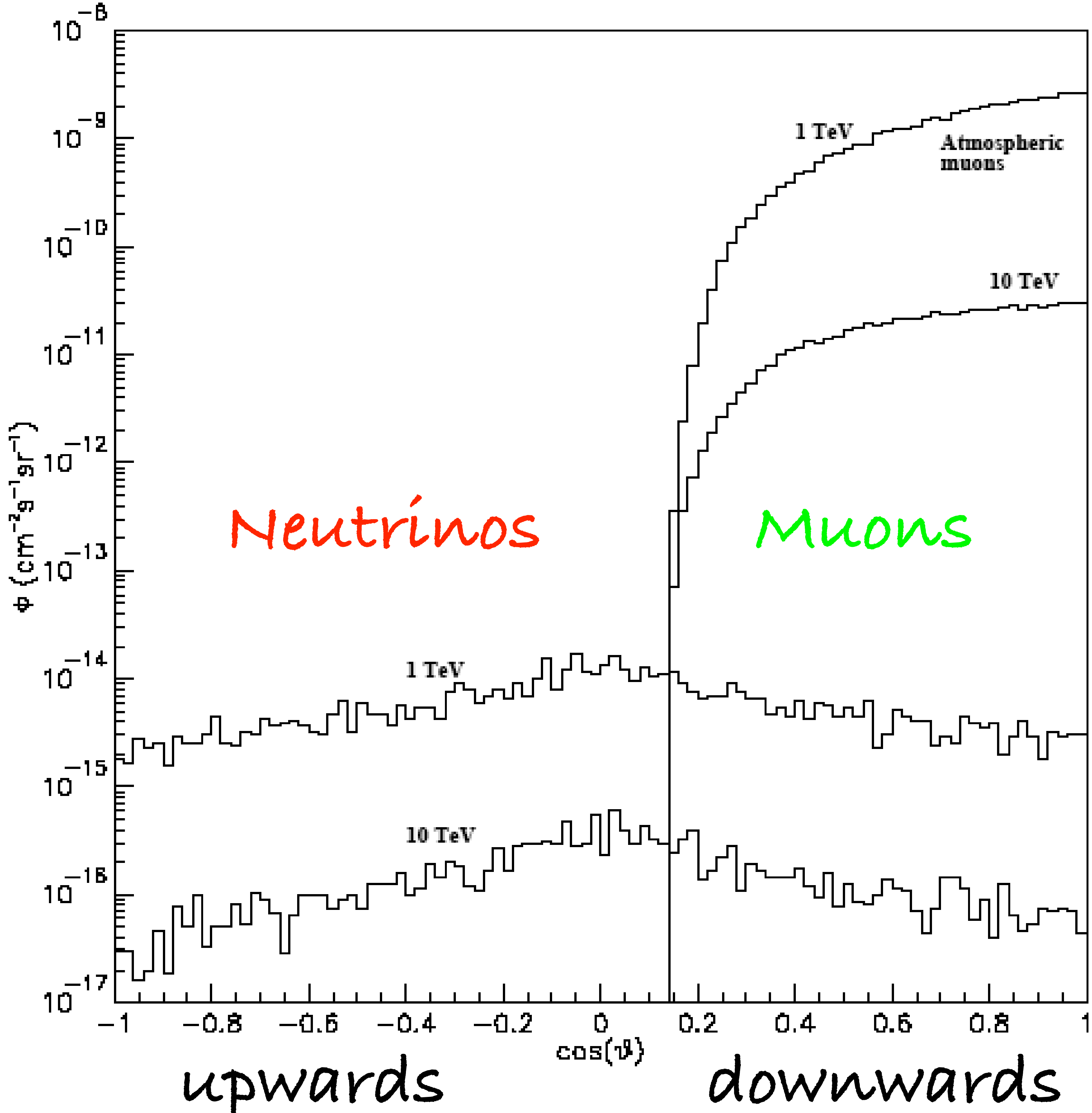




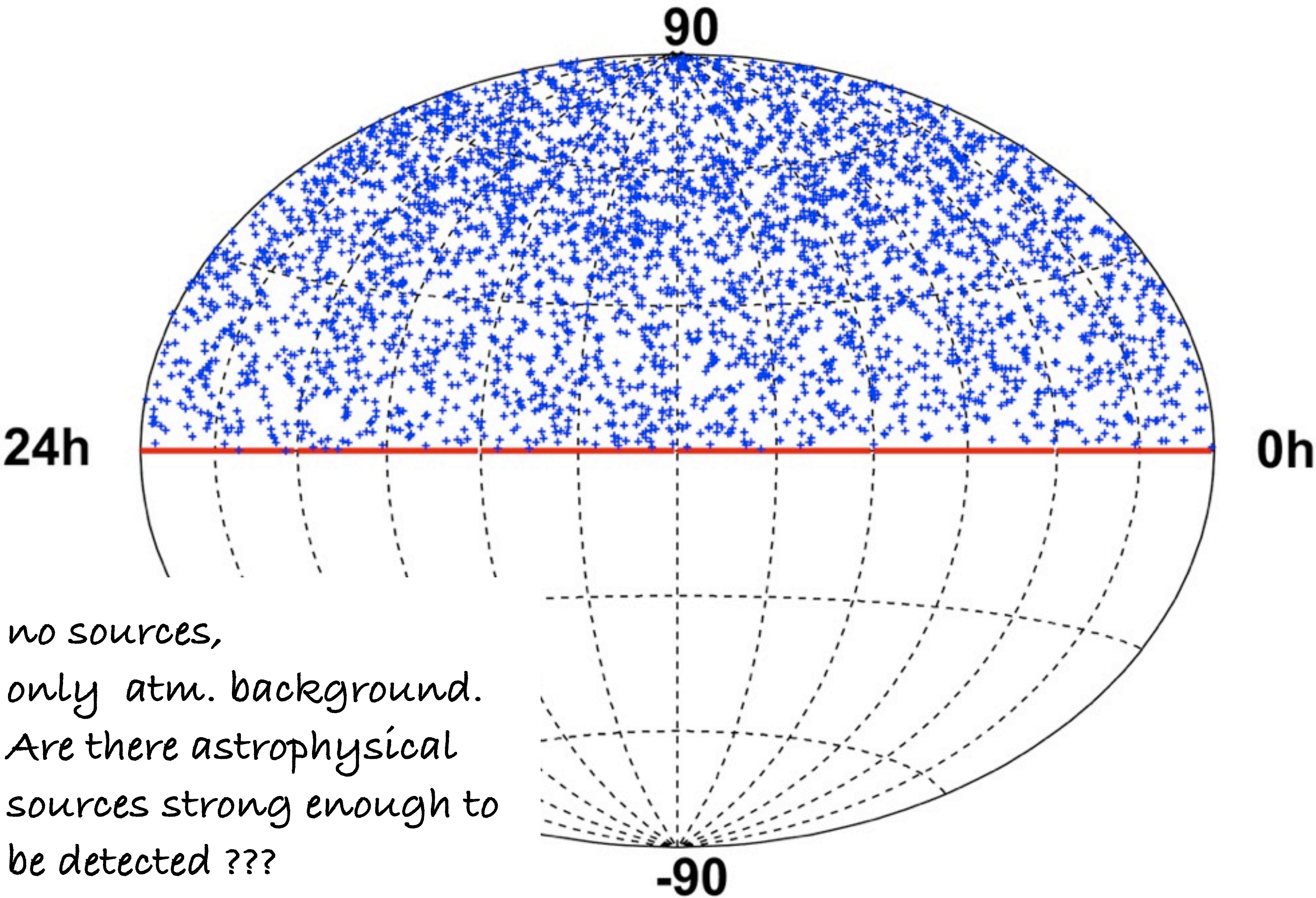
digital electronics

PMT

Rates of Muons / atmospheric Neutrinos



Amanda Skymap



no sources,
only atm. background.
Are there astrophysical sources strong enough to be detected ???

Are there sources strong enough ...

... to be unambiguously detected?

... to do neutrino spectroscopy?

... to do astrophysics with the sources?

Current (optimistic?) estimates for AGN:

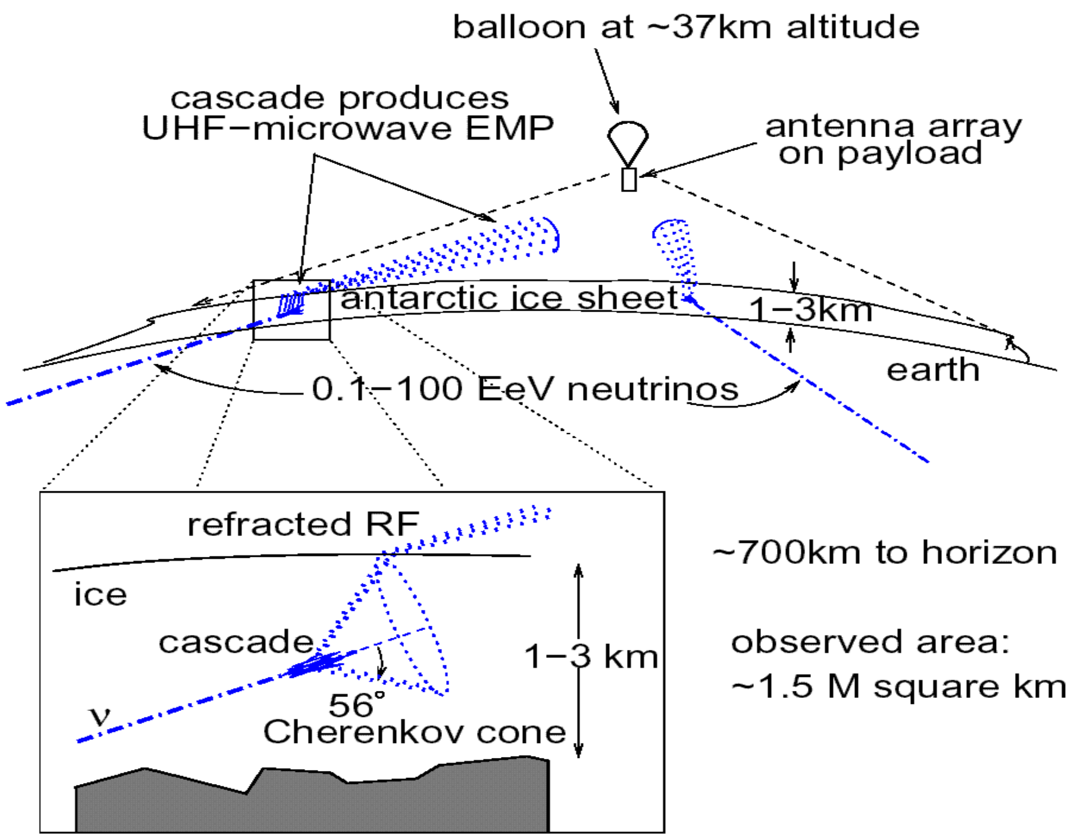
2-4 neutrinos per source in IceCube

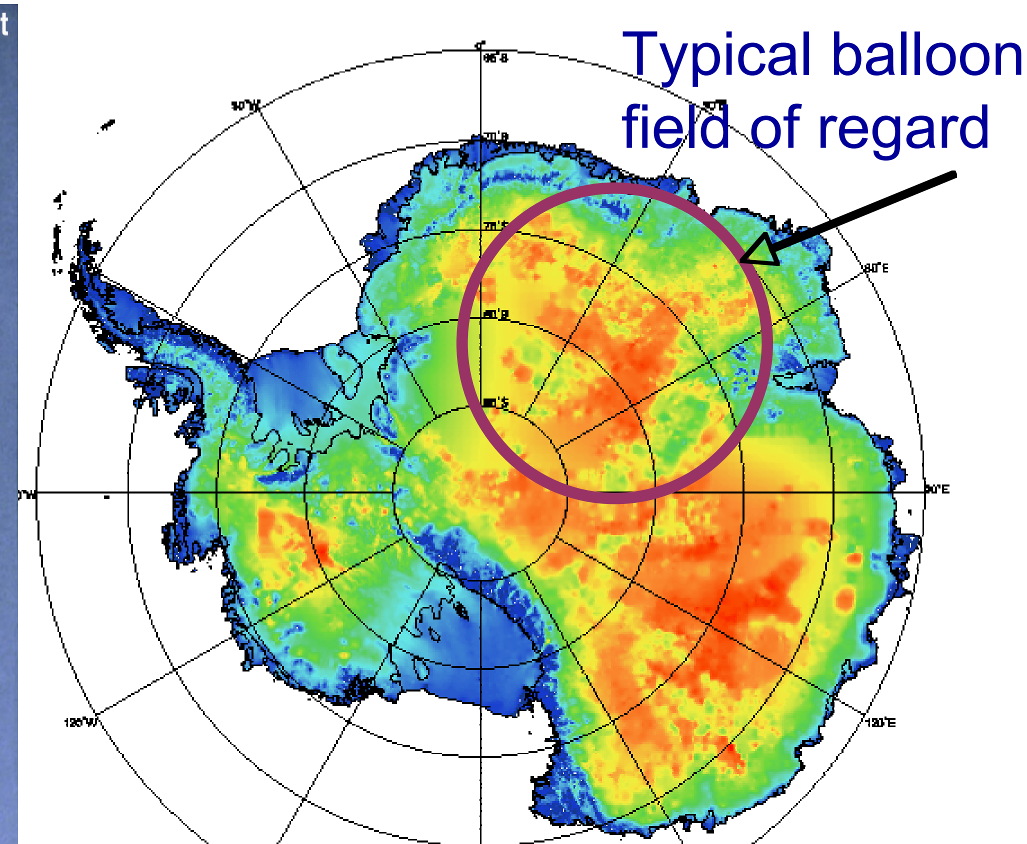
Unexpected super-strong sources ?

Is 1 km^3 big enough ?

Is current technique usable for 100-1000 km^3 ?

Radio emission of showers in Ice:
Antarctic Impulsive Transient Antenna ANITA





1st flight (2007)
successful,
2 more to come,
analysis ongoing

Summary:

- Astroparticle Physics is an exciting field.
- Highest energy particles are rare & difficult to detect

  ... but new experiments (with increased sensitivity)

  aim to detect these particle and identify their sources.
- The most-energetic CRs, gamma rays & neutrinos come likely from the same, most violent environments in the universe.

  (Multi-messenger approach for improved understanding)
- Three new windows in Astronomy:

  TeV gamma rays, UHECRs, Neutrinos
- Bright future with many challenges for bright young theorists and experimentalists.

Astroparticle Physics poses many puzzles.

The experimental findings and theoretical ideas do not (yet) form a coherent and clear image. The situation may seem messy.

Astroparticle Physics poses many puzzles.

The experimental findings and theoretical ideas
do not (yet) form a coherent and clear image.
The situation may seem messy.

Steven Weinberg,
Four golden lessons (for young physicists)
Nature 426 (2003) 389

"My advice is to go for the messes
- that's where the action is."

Astroparticle Physics poses many puzzles.

The experimental findings and theoretical ideas
do not (yet) form a coherent and clear image.
The situation may seem messy.

Steven Weinberg,
Four golden lessons (for young physicists)
Nature 426 (2003) 389

"My advice is to go for the messes
- that's where the action is."

Experiments & analyses are challenging and
require **bright young students** (i.e. you ?)
to answer some of the most exciting questions in physics.