Karlsruher Institut für Technologie

Kern- und Teilchenphysik

SS2012

Vorlesung-Website

Johannes Blümer

KIT-Centrum Elementarteilchen- und Astroteilchenphysik KCETA

Die höchsten Energien im Universum

- Kosmische Strahlung: 100 Jahre in 10 Minuten

V. Hess	C. Anderson	P. Auger	J. Linsley	J. Cronin
1912	1936	1938	1963	1992
Elektrometer	Nebelkammer	Luftschauer	Volcano Ranch	Auger-Obs.

- Teilchen mit mehr als 100 EeV
  - Heitler-Modelle
  - Modellierungen
  - 1964: John Linsley, Penzias& Wilson, Greisen-Zatzepin-Kuzmin
  - WW von p mit CMB: Pionproduktion; GZK-Photonen, GZK-Neutrinos
  - AGASA, Exotica
  - Pierre Auger-Observatorium
- Teilchenphysik bei 300 TeV im c.m.s.?
  - Messung des pp-Wirkungsquerschnitts mit Auger

- Multi-messenger Astroteilchenphysik
- Neue Projekte

John Linsley's Entdeckung

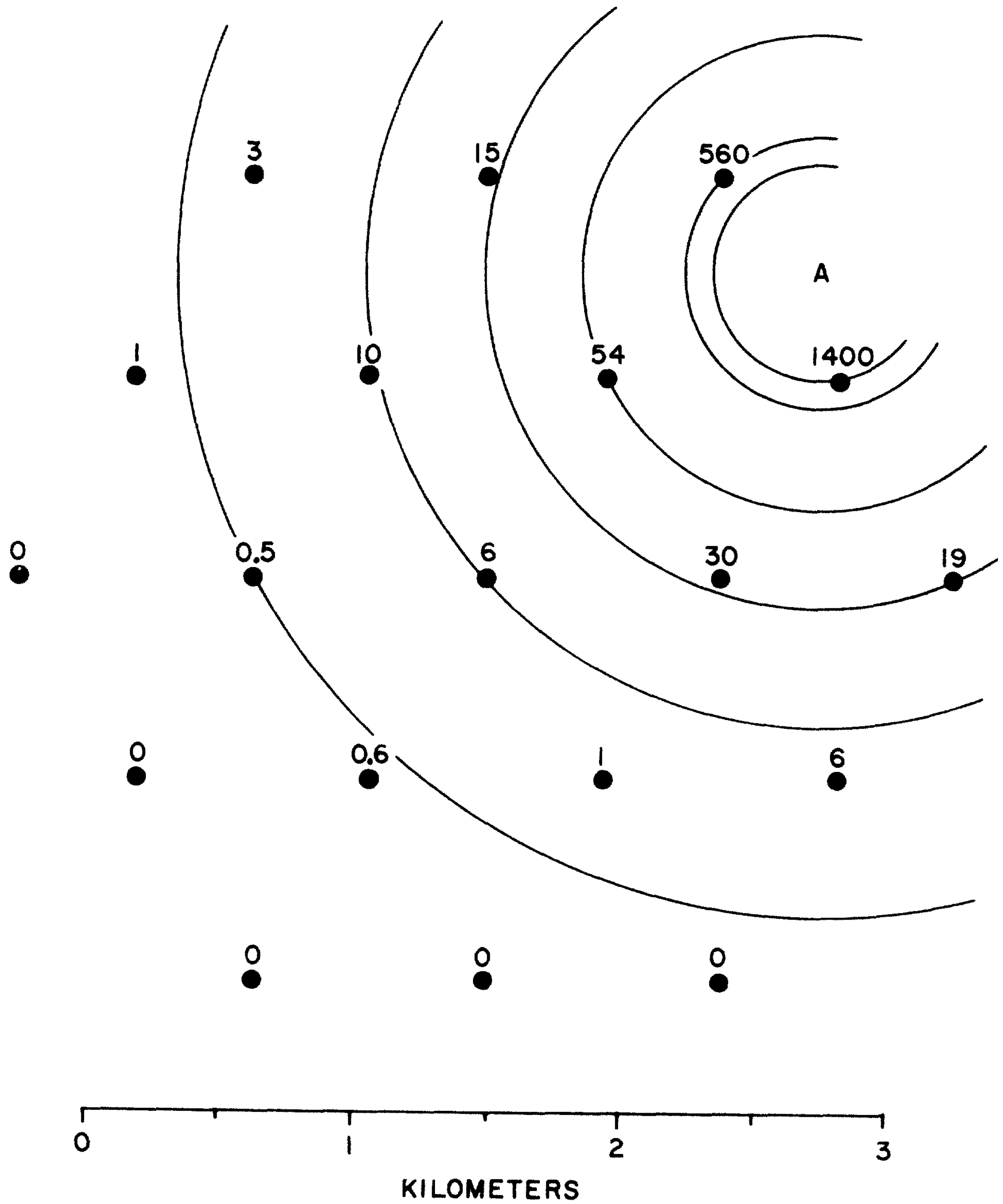


FIG. 1. Plan of the Volcano Ranch array in February 1962. The circles represent 3.3-m^2 scintillation detectors. The numbers near the circles are the shower densities (particles/m^2) registered in this event, No. 2-4834. Point "*A*" is the estimated location of the shower core. The circular contours about that point aid in verifying the core location by inspection.

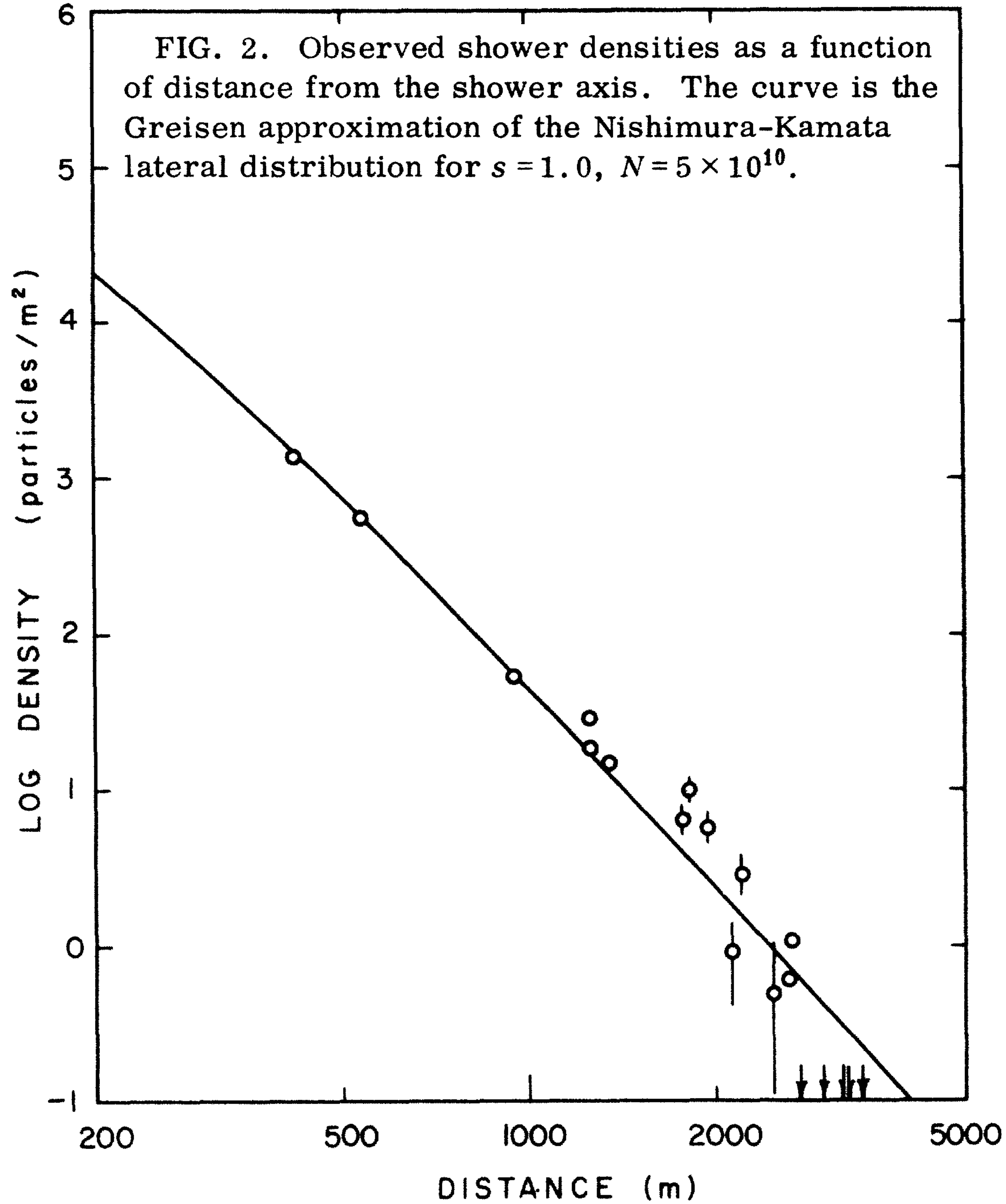
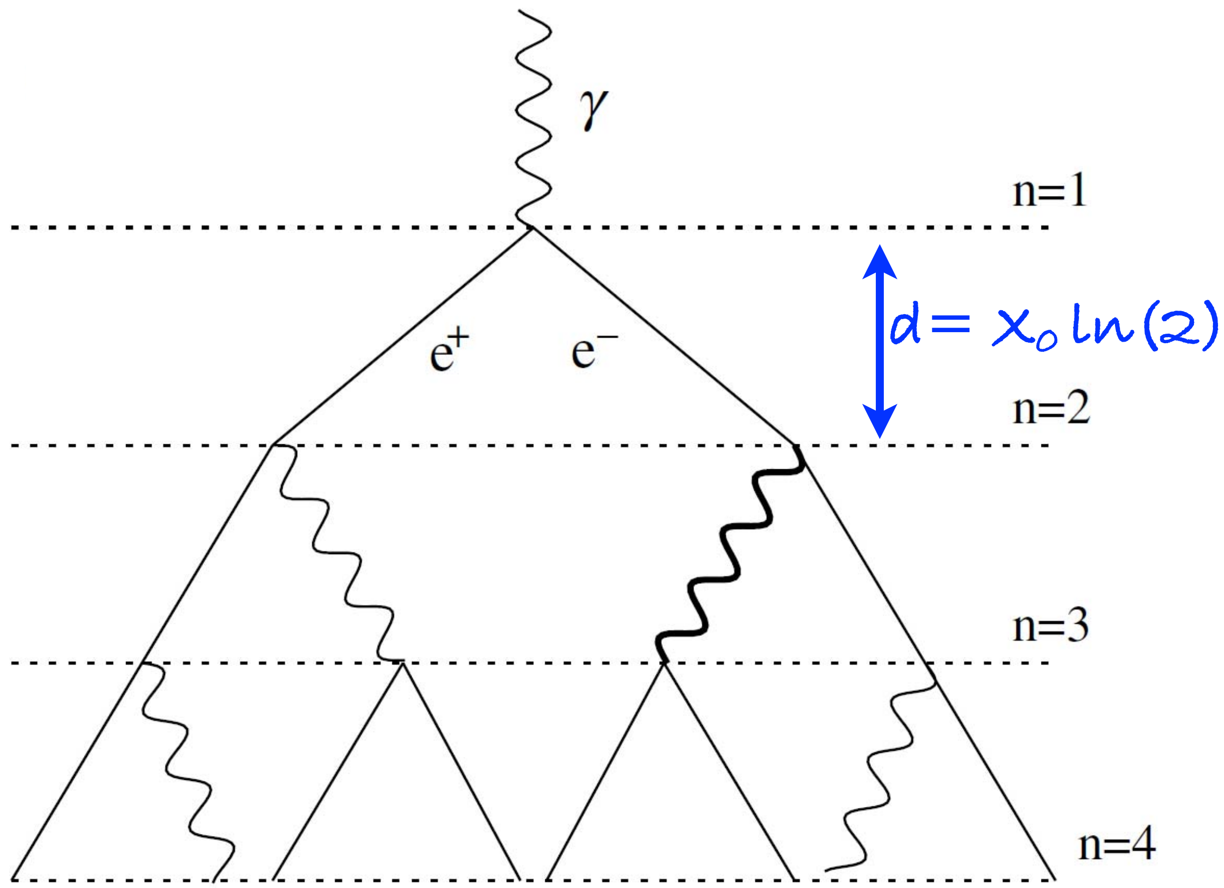


FIG. 2. Observed shower densities as a function of distance from the shower axis. The curve is the Greisen approximation of the Nishimura-Kamata lateral distribution for $s = 1.0$, $N = 5 \times 10^{10}$.

One can evaluate how much energy a primary particle has to have in order to produce a given shower by considering the total amount of ionization that is produced. This is Greisen's method of the "track length integral." Finding the size of the shower is equivalent to determining the lateral distribution of ionization. Longitudinal-

e.m. Luftschauer

Jim Matthews, Astroparticle Physics 22 (2005) 387–397



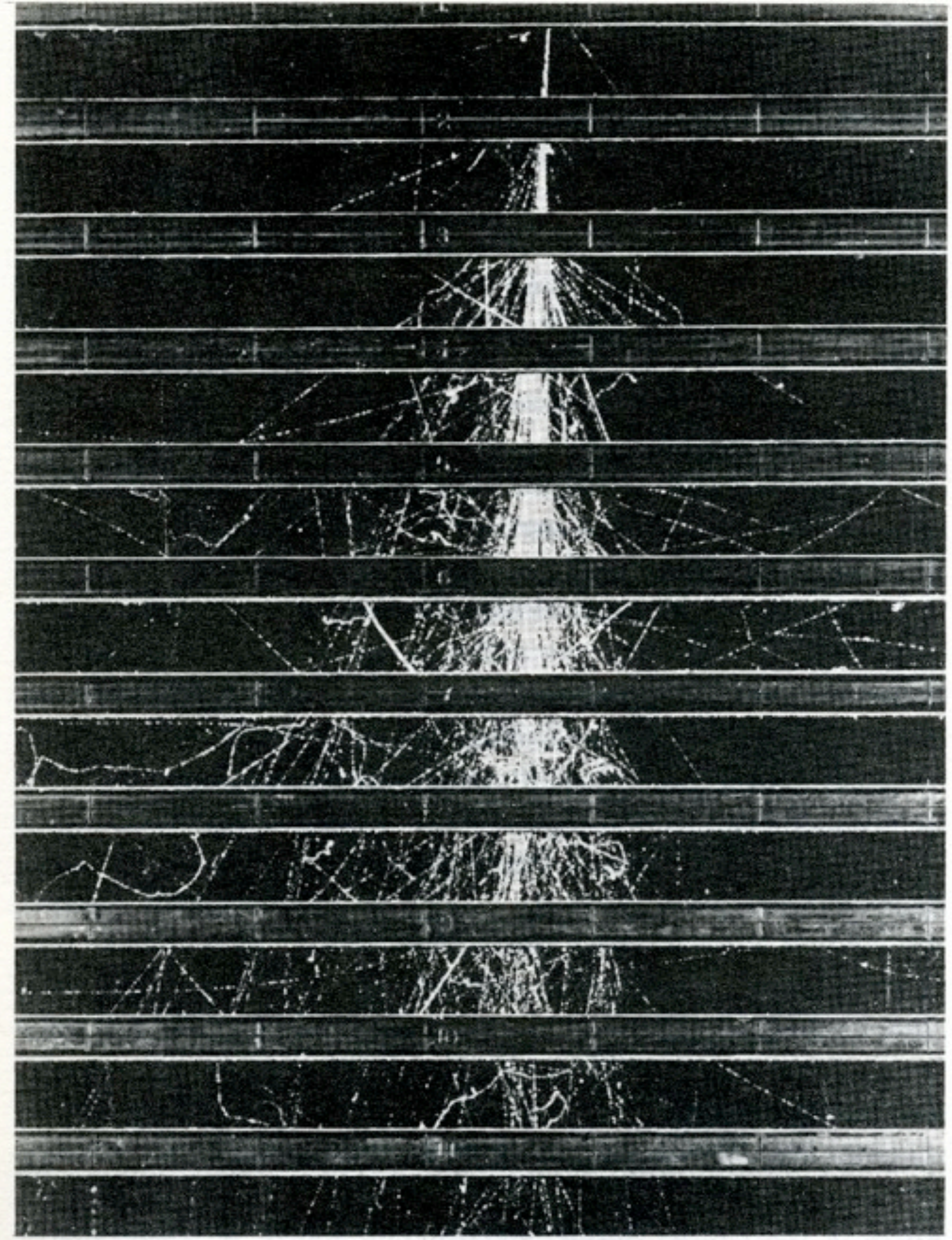


Fig. 7-5 A shower developing through a number of brass plates 1.25 cm thick placed across a cloud chamber. The shower was initiated in the top plate by an incident high-energy electron or photon. The photograph was taken by the MIT cosmic-ray group.

e.m. Luftschauer

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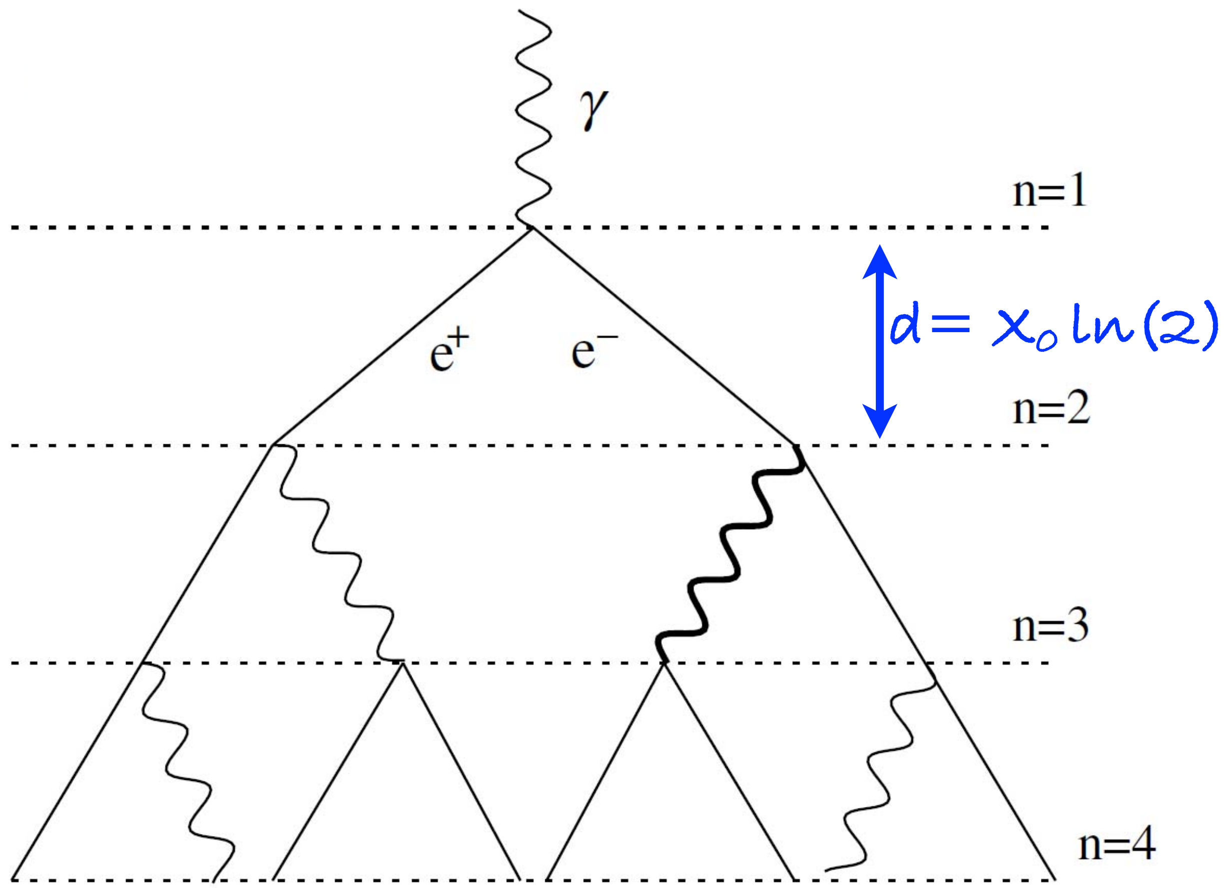


$N_{max} \propto E_0$ Linearität des Signals

$X_{max} \propto \ln(E_0)$ log. Größenskala

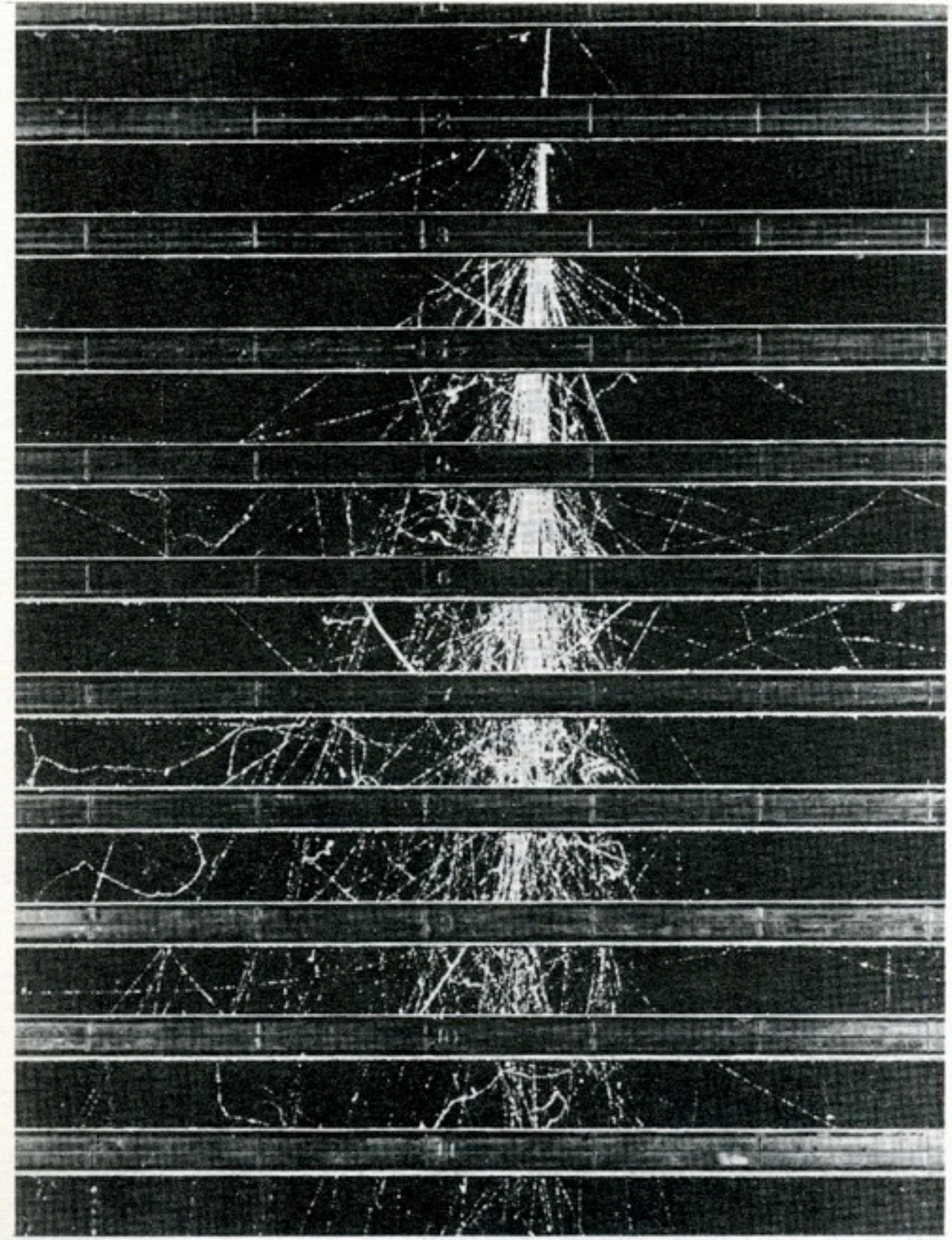
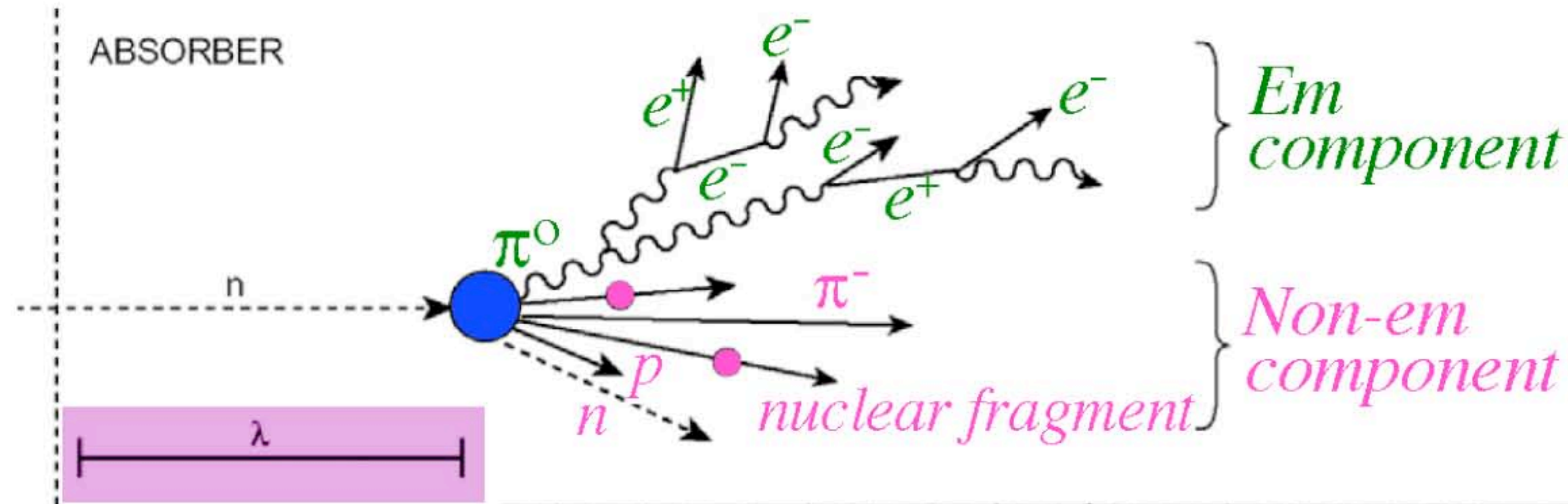


Fig. 7-5 A shower developing through a number of brass plates 1.25 cm thick placed across a cloud chamber. The shower was initiated in the top plate by an incident high-energy electron or photon. The photograph was taken by the MIT cosmic-ray group.

Hadronschauer

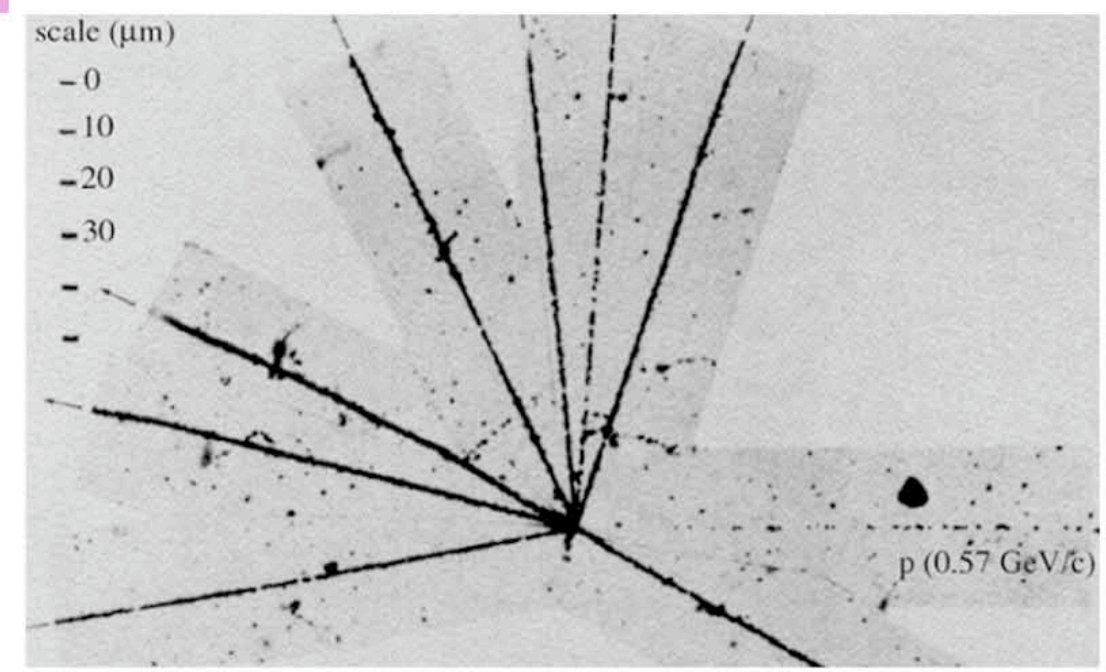


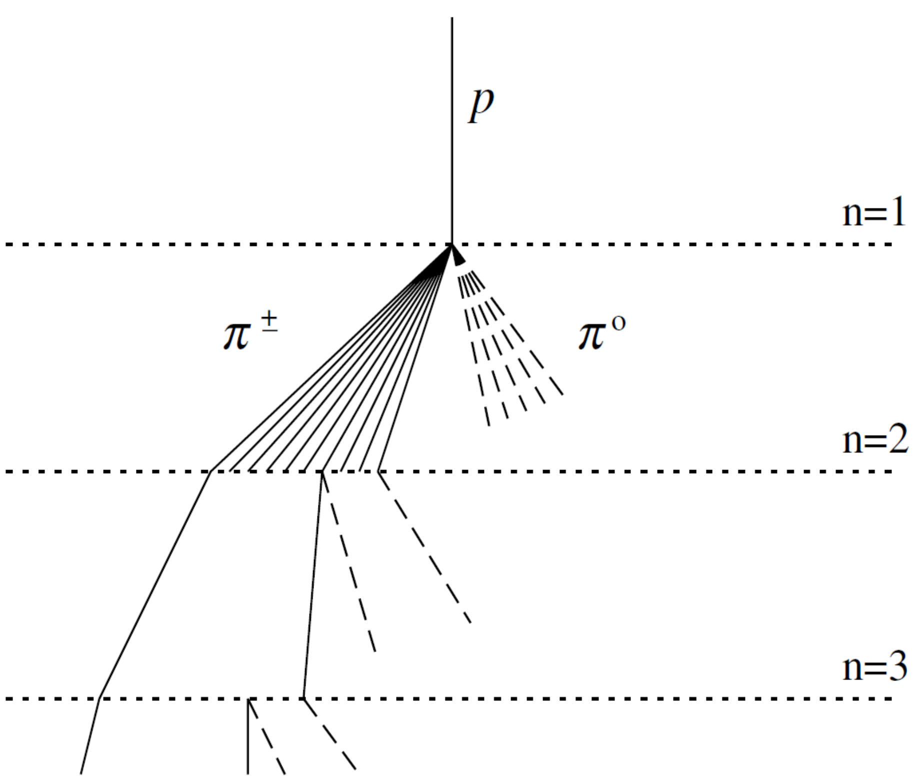
Electromagnetic component

- electrons, photons
- neutral pions → 2 γ

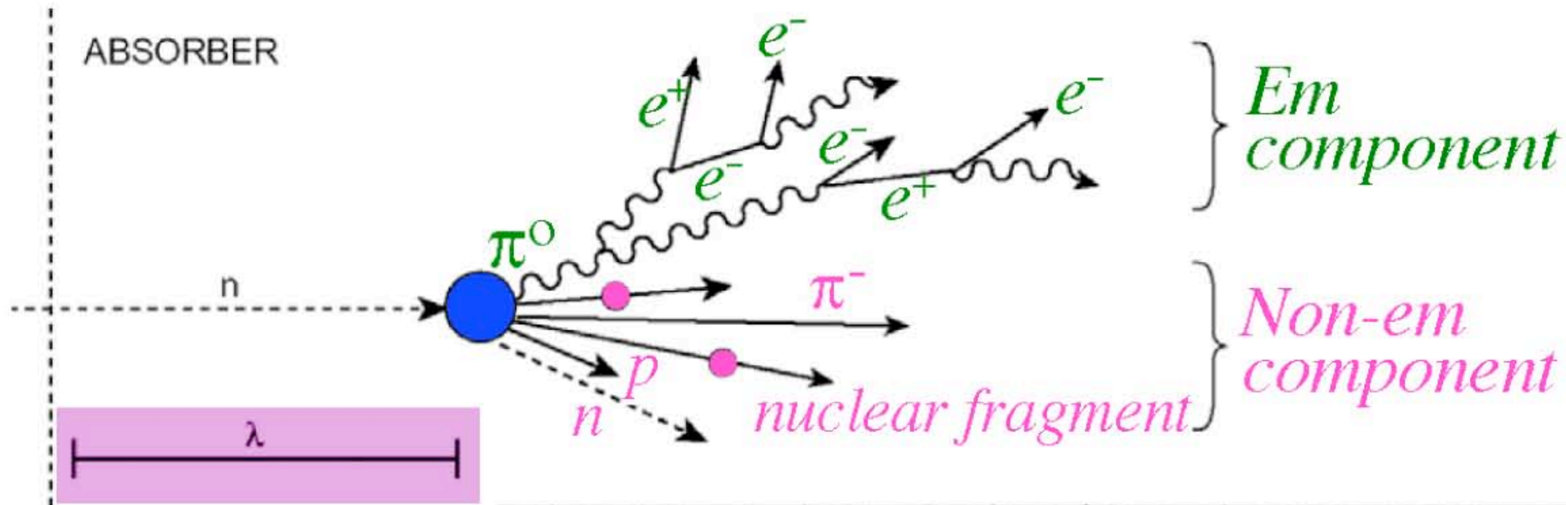
Hadronic (non-em) component

- charged hadrons $\pi^\pm$,$K^\pm$ (20%)
- nuclear fragments, p (25%)
- neutrons, soft γ's (15%)
- break-up of nuclei (*"invisible"*) (40%)





Hadronschauer



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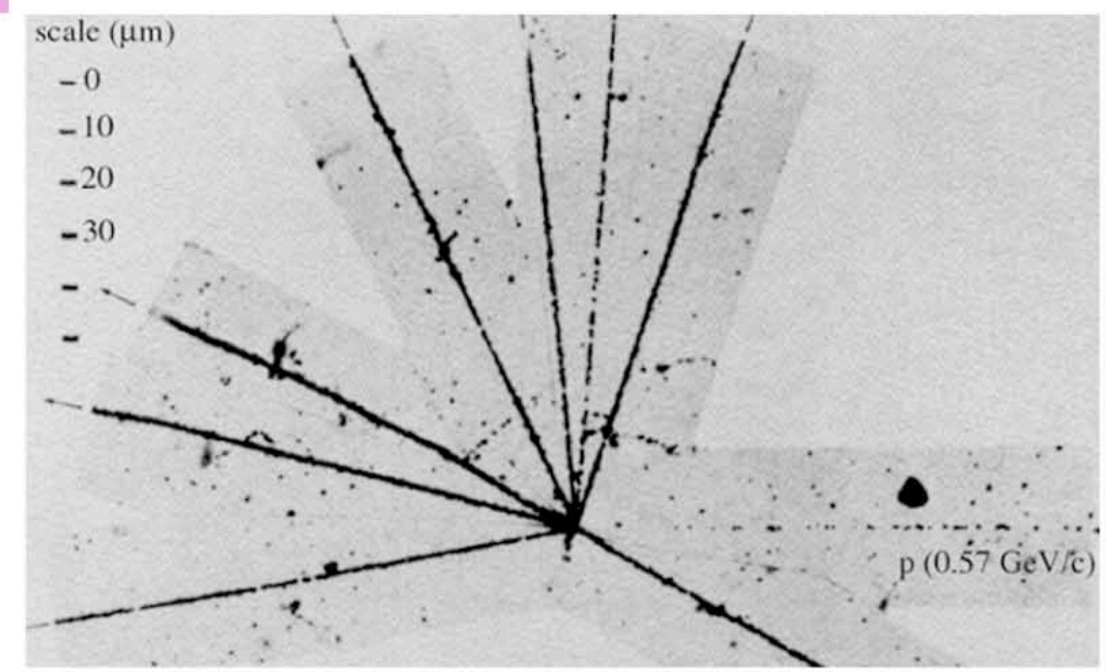
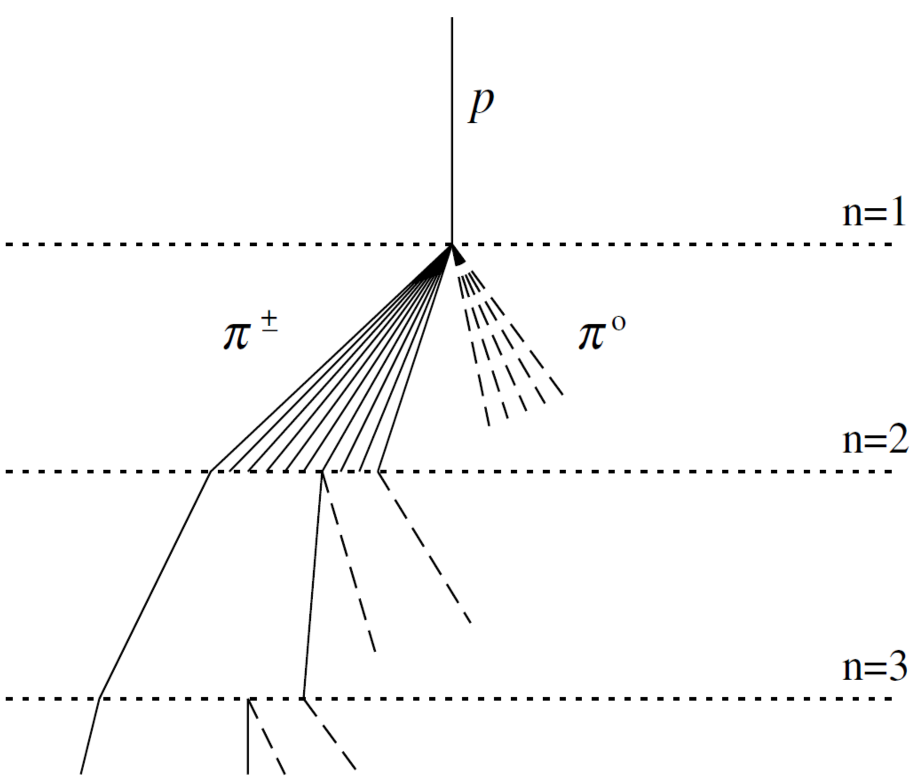




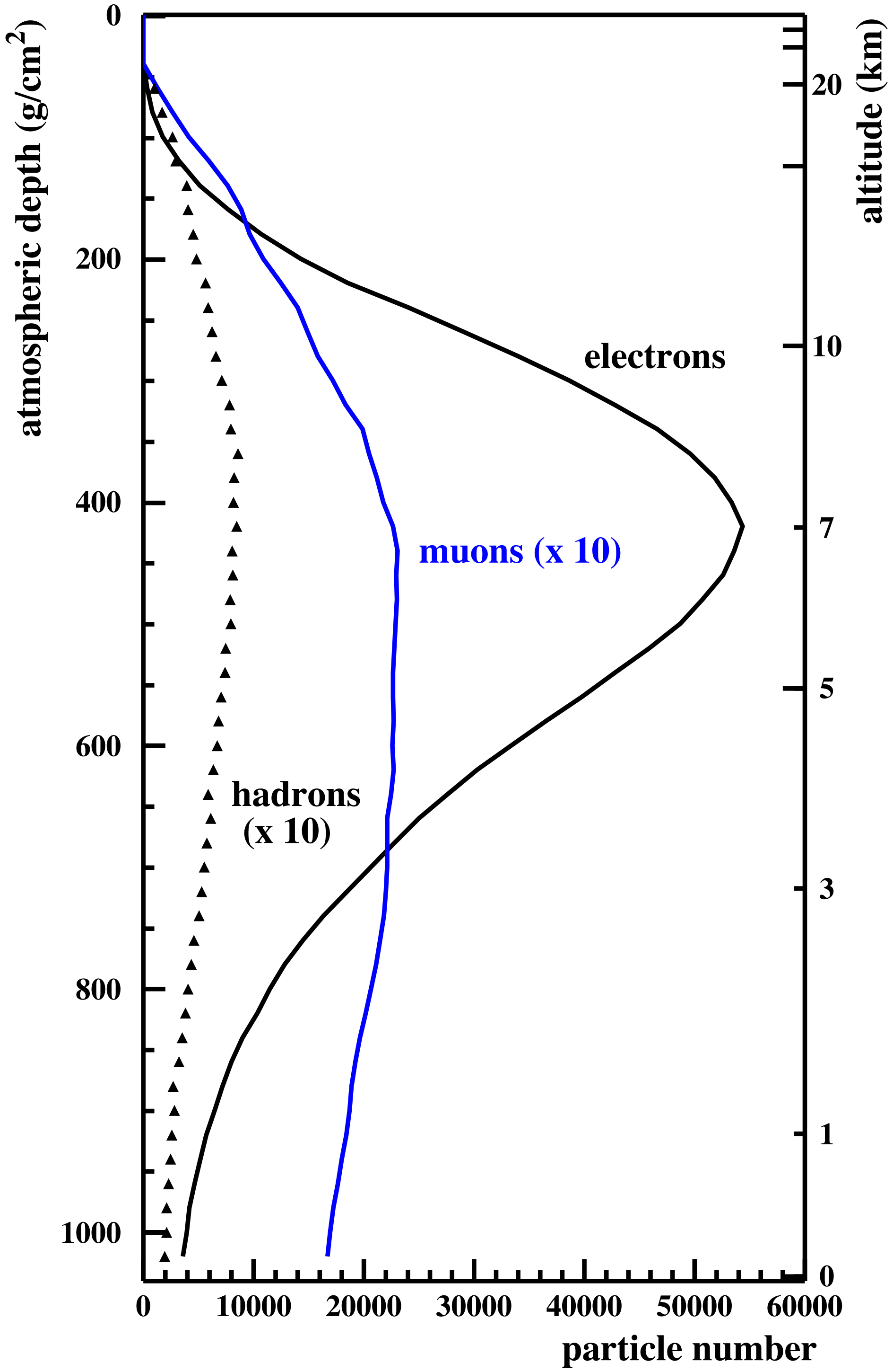
auch für Hadronschauer näherungsweise:

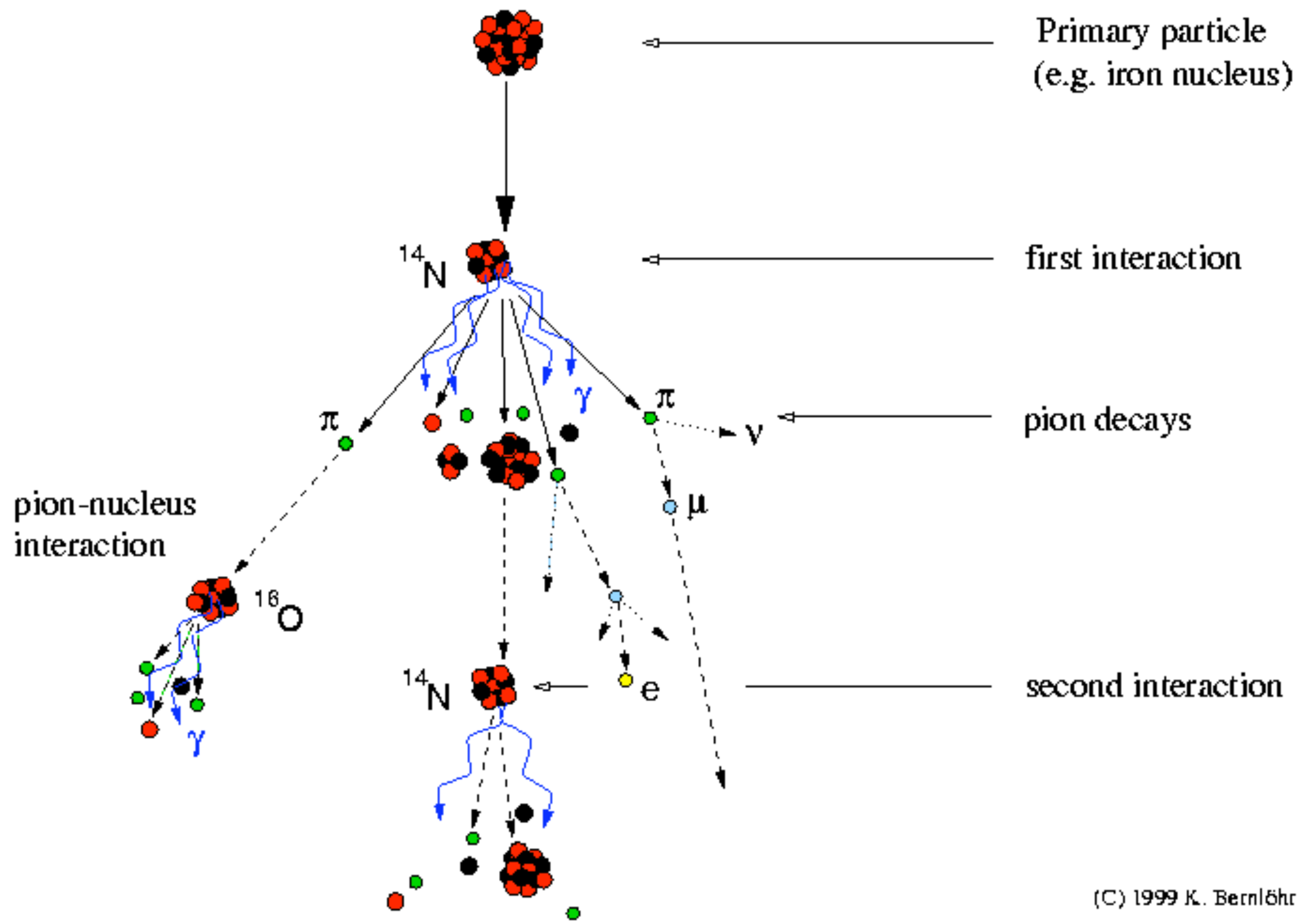
$N_{max} \propto E_0$ Linearität des Signals

$X_{max} \propto \ln(E_0)$ log. Größenskala

aber mit anderen Skalierungen

Extensive air showers



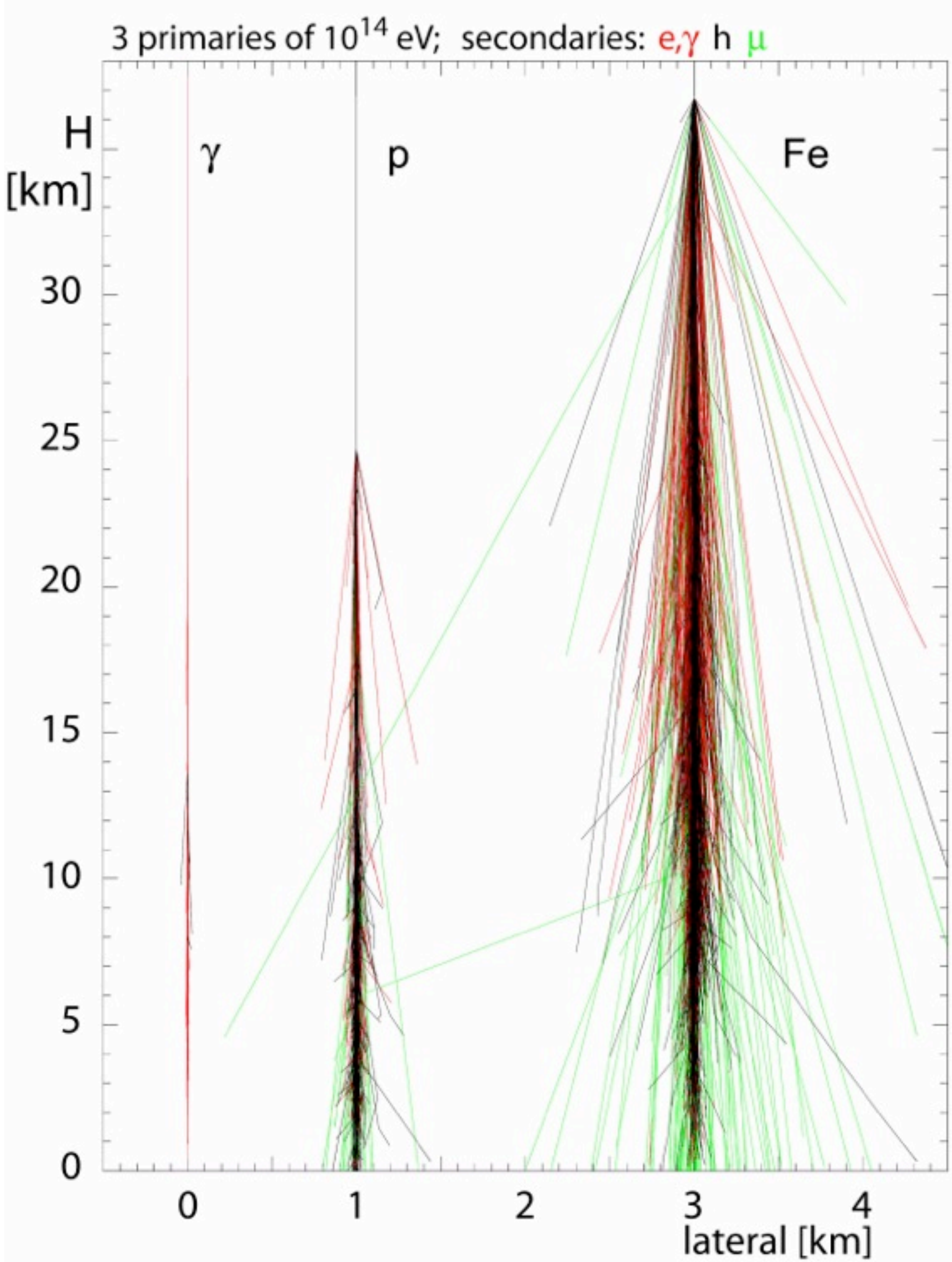


Decay of neutral pions feeds em. shower component

Decay of charged pions (~30 GeV) feeds muonic component

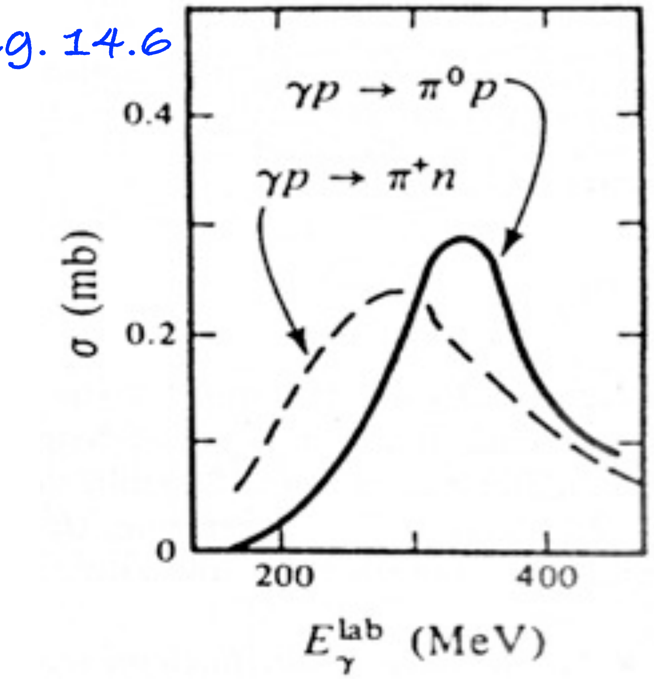
CORSIKA

Schauer-Video!



Photon-Proton-Reaktion: GZK

Henley Fig. 14.6



END TO THE COSMIC-RAY SPECTRUM?

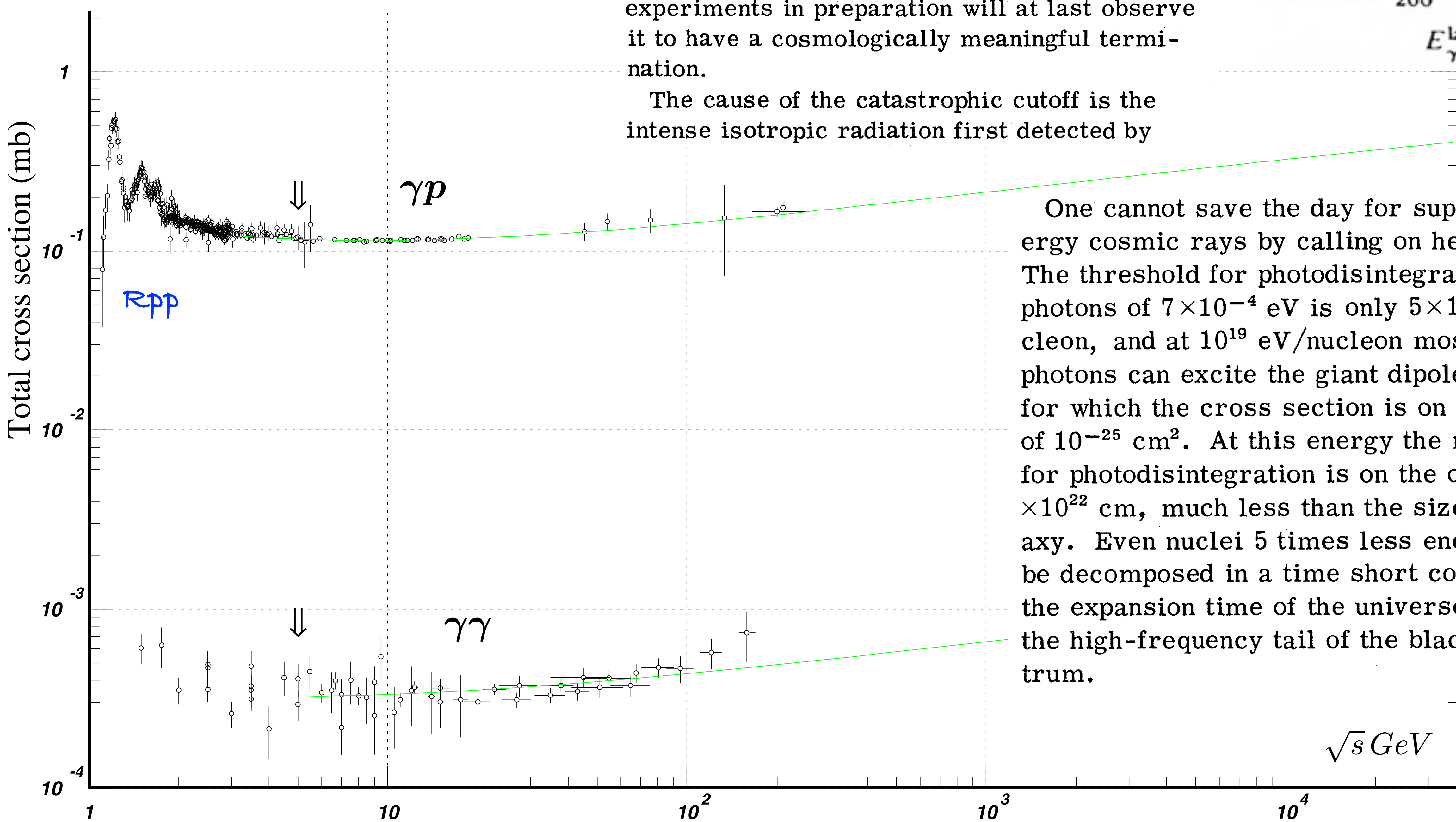
PRL 1966 Kenneth Greisen

Cornell University, Ithaca, New York

(Received 1 April 1966)

The primary cosmic-ray spectrum has been measured up to an energy of 10^{20} eV,[1] and several groups have described projects under development or in mind[2] to investigate the spectrum further, into the energy range 10^{21}-10^{22} eV. This note predicts that above 10^{20} eV the primary spectrum will steepen abruptly, and the experiments in preparation will at last observe it to have a cosmologically meaningful termination.

The cause of the catastrophic cutoff is the intense isotropic radiation first detected by



One cannot save the day for superhigh-energy cosmic rays by calling on heavy nuclei. The threshold for photodisintegration against photons of 7×10^{-4} eV is only 5×10^{18} eV/nucleon, and at 10^{19} eV/nucleon most of the photons can excite the giant dipole resonance, for which the cross section is on the order of 10^{-25} cm^2. At this energy the mean path for photodisintegration is on the order of 2×10^{22} cm, much less than the size of the galaxy. Even nuclei 5 times less energetic would be decomposed in a time short compared with the expansion time of the universe, owing to the high-frequency tail of the black-body spectrum.

GZK: Frühe analytische Berechnungen...

$$\tau(E_p) = 2\gamma^2\hbar^3\pi^2c^2\left[\int_{(\epsilon_{th}'/2\gamma)}^{\infty}\frac{d\epsilon}{\exp(\epsilon/kT)-1}\int_{\epsilon_{th}'}^{2\gamma\epsilon}d\epsilon'\epsilon'\sigma(\epsilon')K_p(\epsilon')\right]^{-1}$$

Stecker PRL 21 (1968) 1016

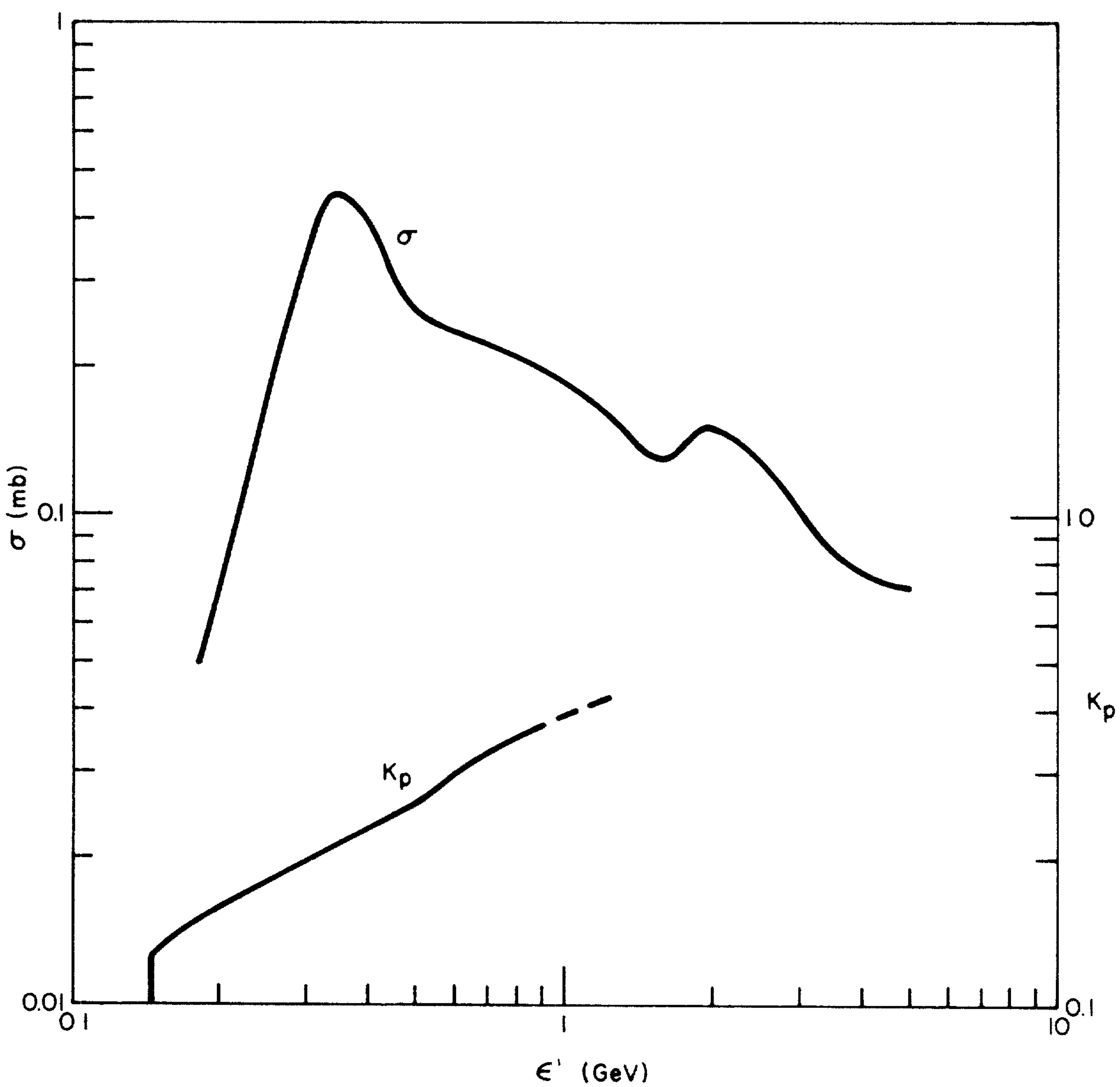


FIG. 1. Total photomeson production cross section and inelasticity as a function of gamma-ray energy in the proton rest system.

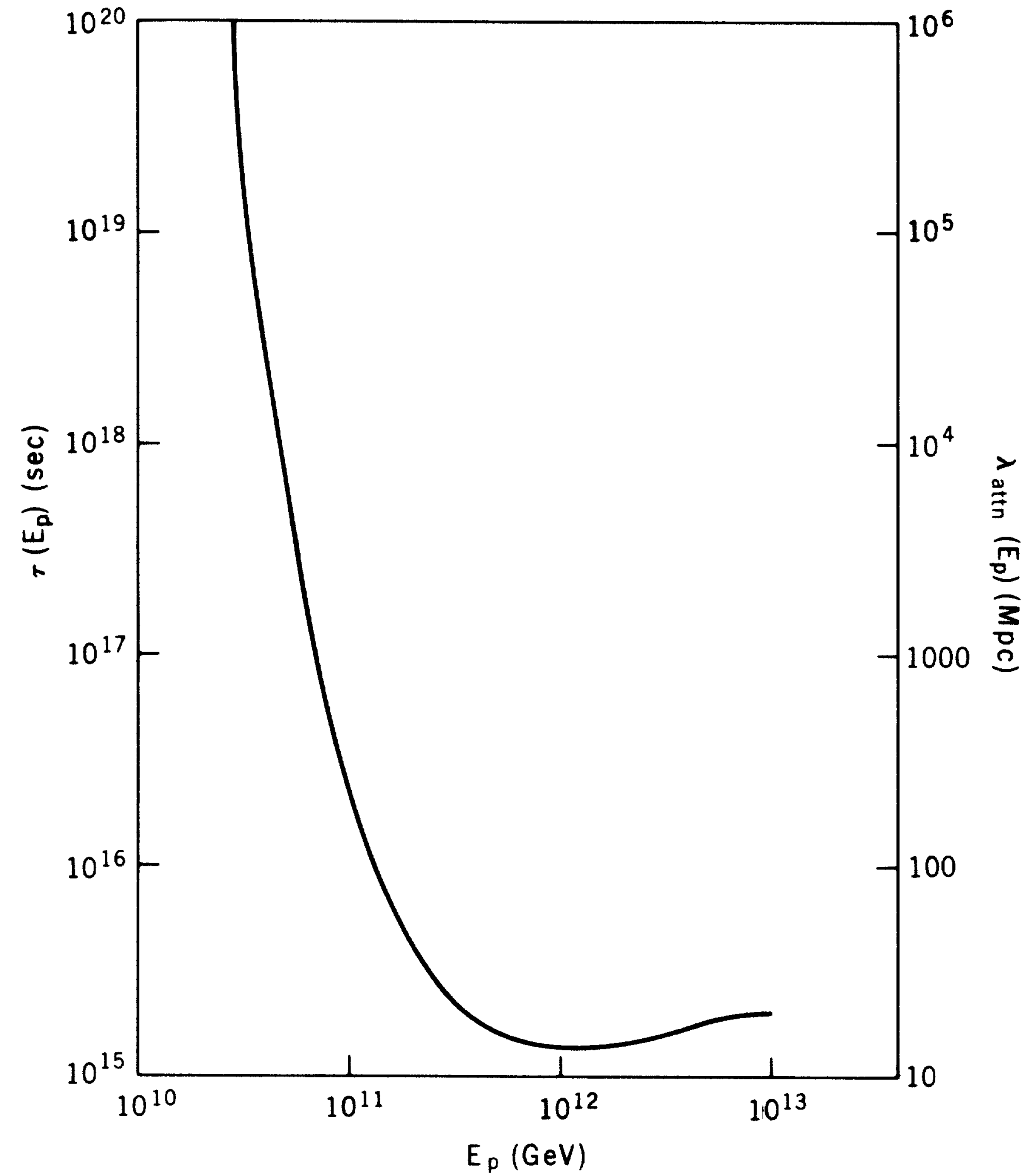


FIG. 2. Characteristic lifetime and attenuation mean free path for high-energy protons as a function of energy.

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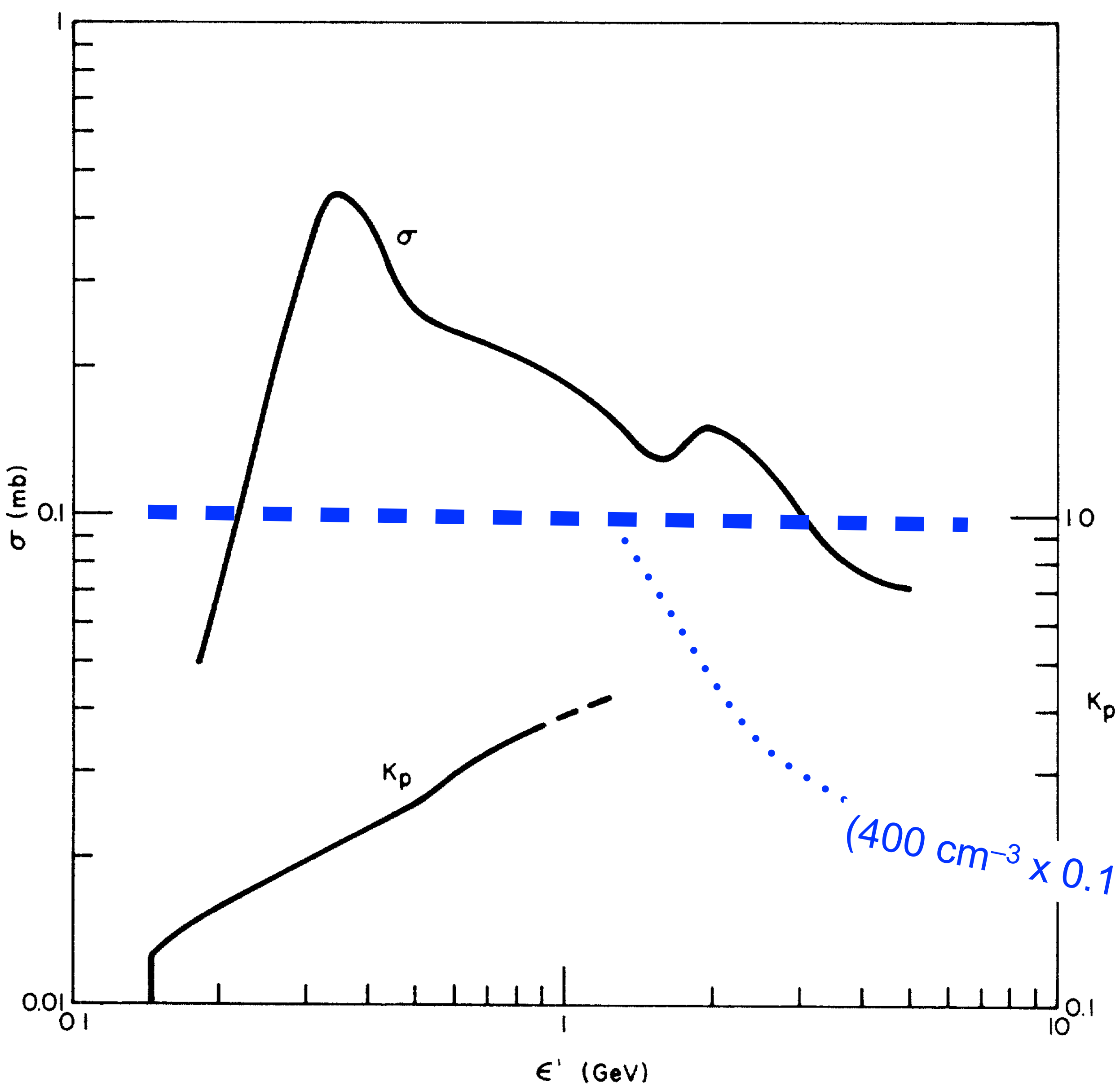
Stecker PRL 21 (1968) 1016



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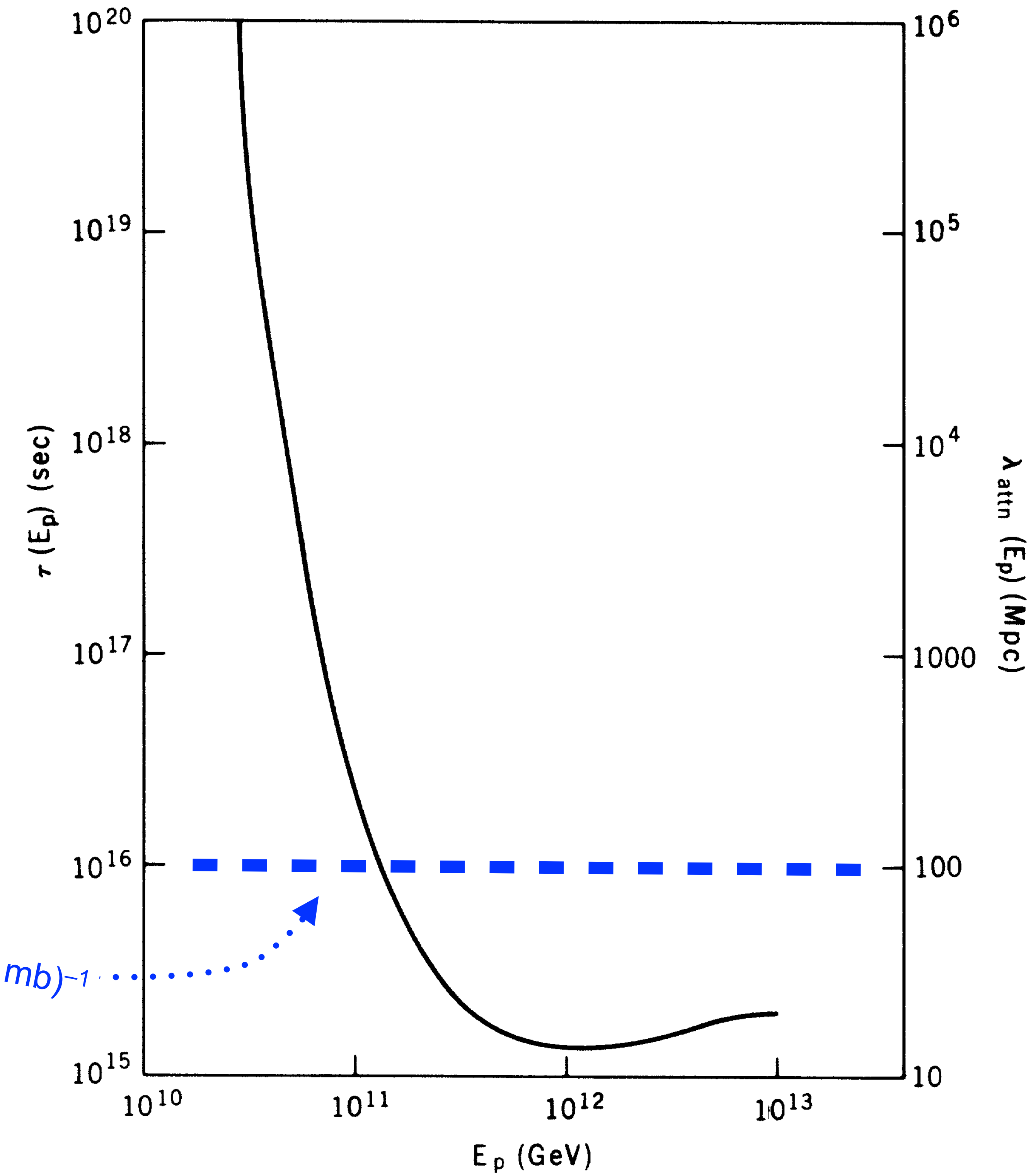
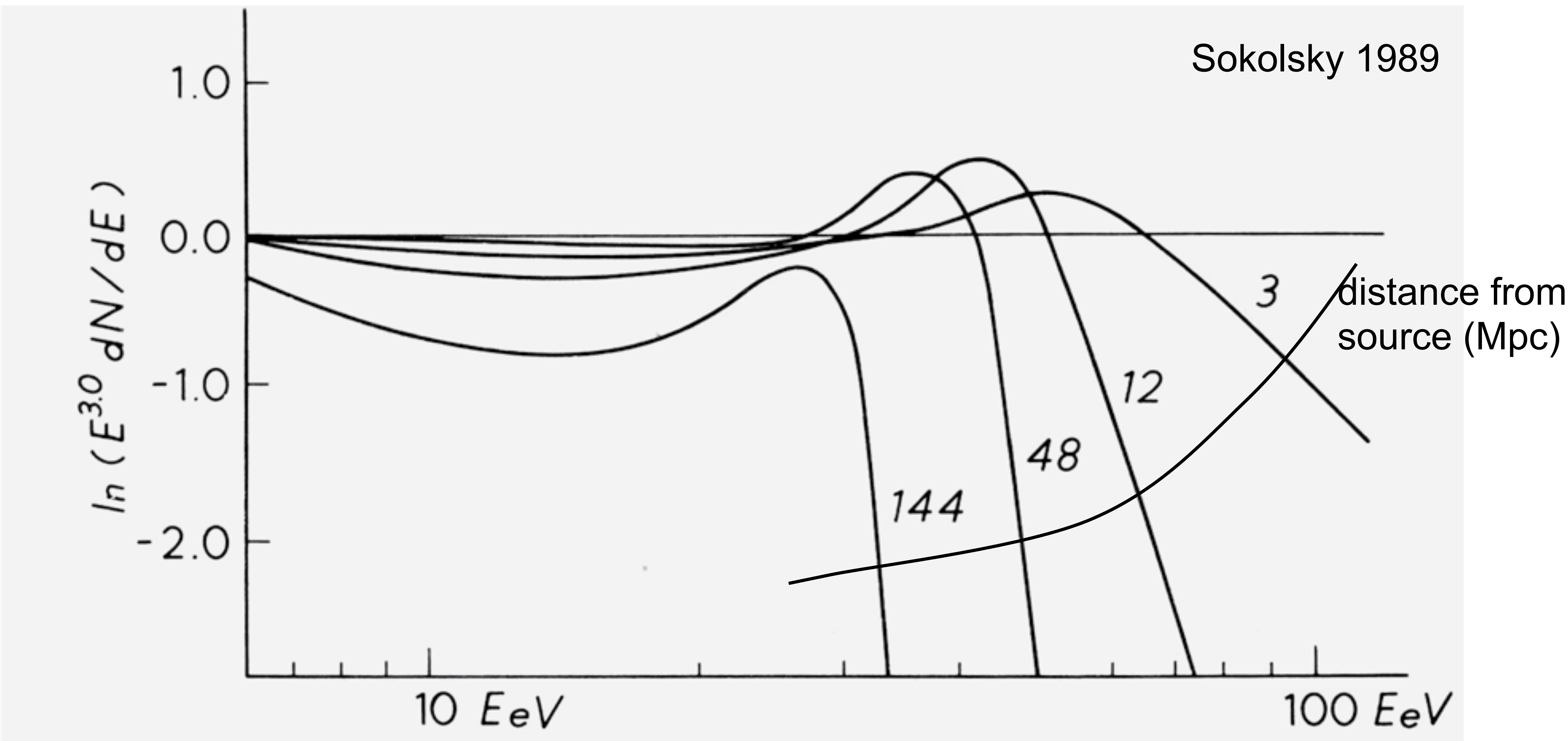


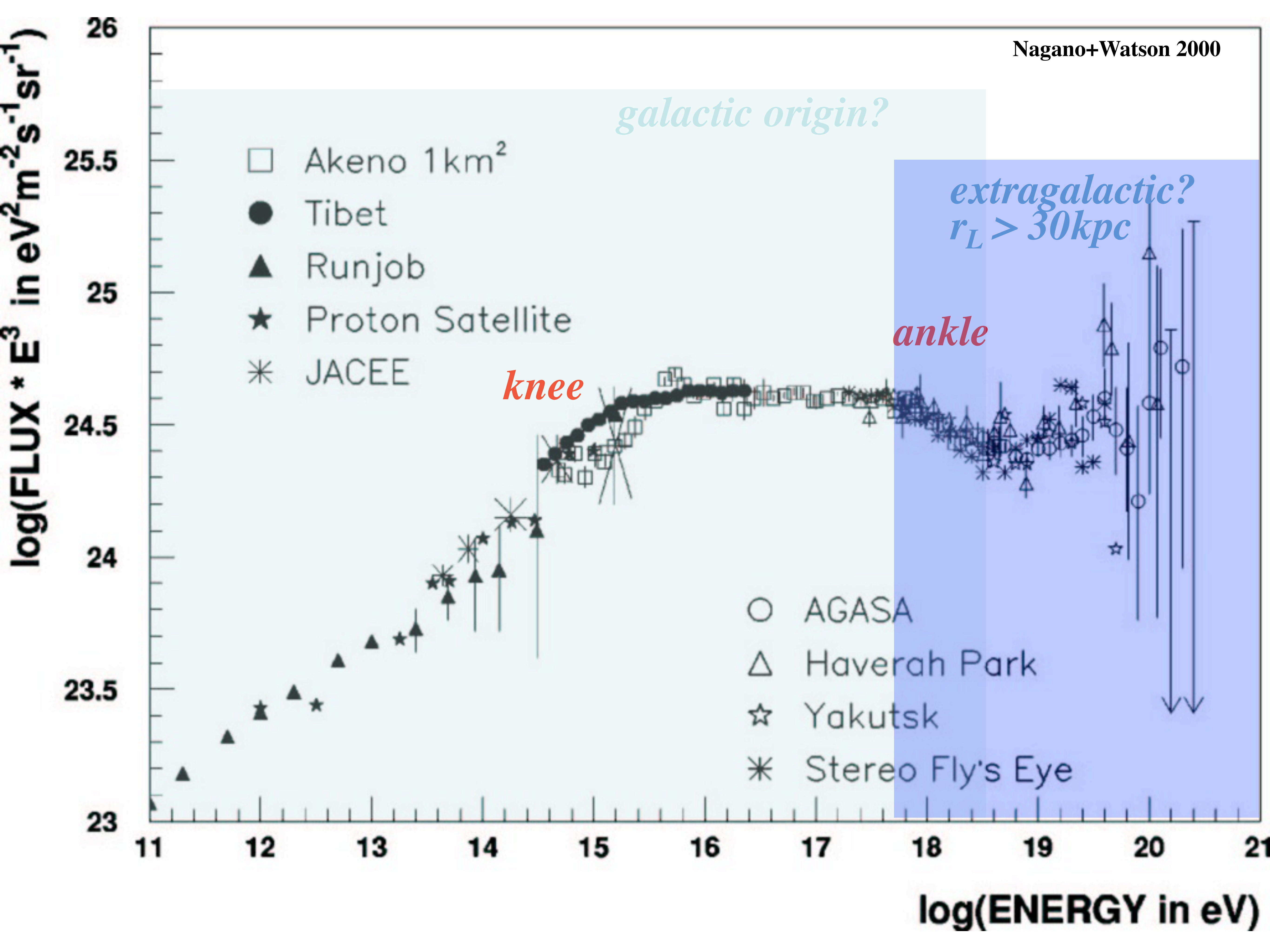
FIG. 2. Characteristic lifetime and attenuation mean free path for high-energy protons as a function of energy.

Greisen-Zatsepin-Kuzmin-Effekt

protons scatter with the CMB: threshold effect above 5×10^{19} eV:
$p+\gamma_{3K} \rightarrow \Delta(1232) \rightarrow p\pi^0 \rightarrow p\,\gamma\gamma$ or $n\pi^+ \rightarrow pe^+\nu$

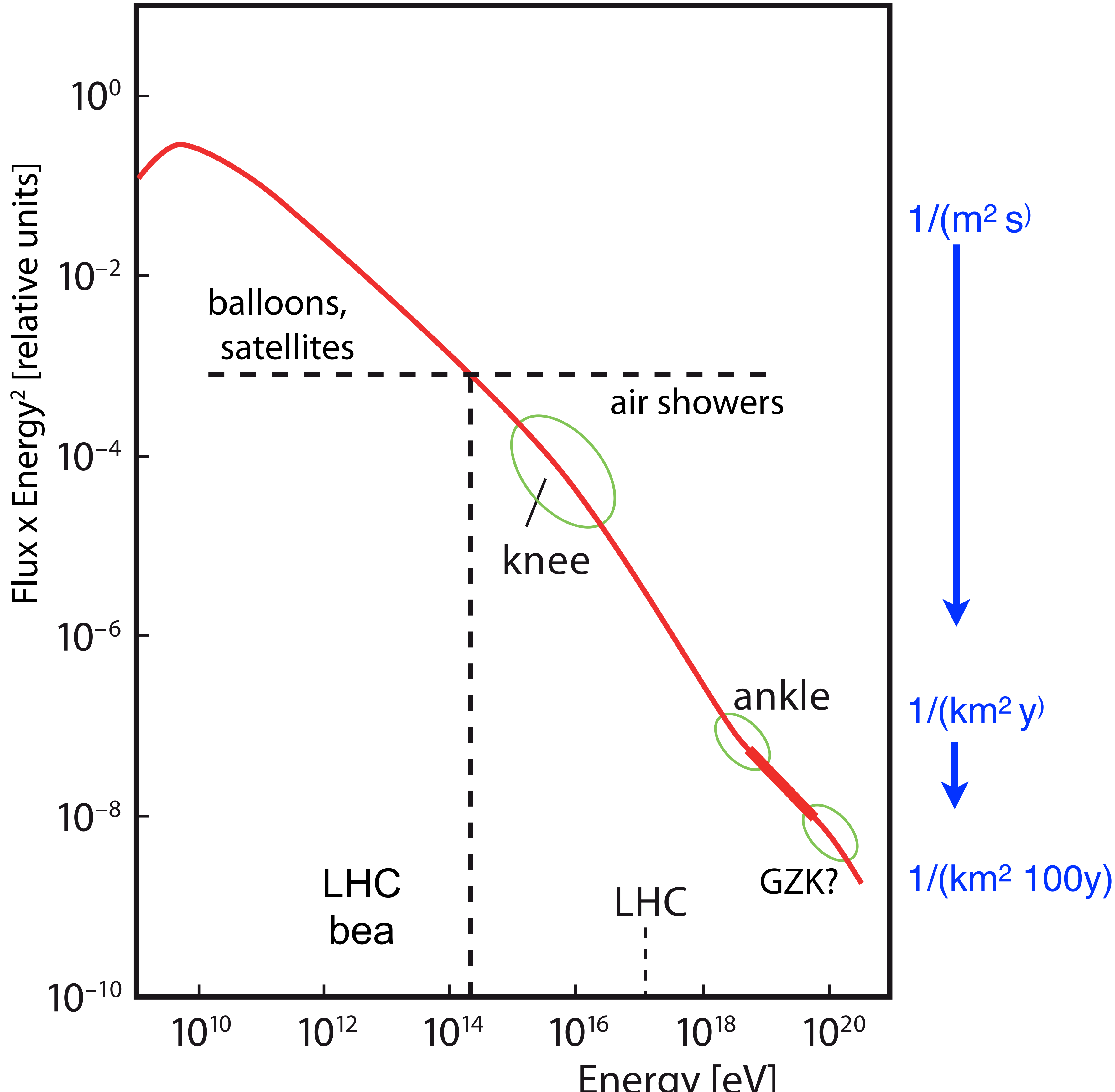
$$2E_p\epsilon > (m_\Delta^2 - m_p^2)$$



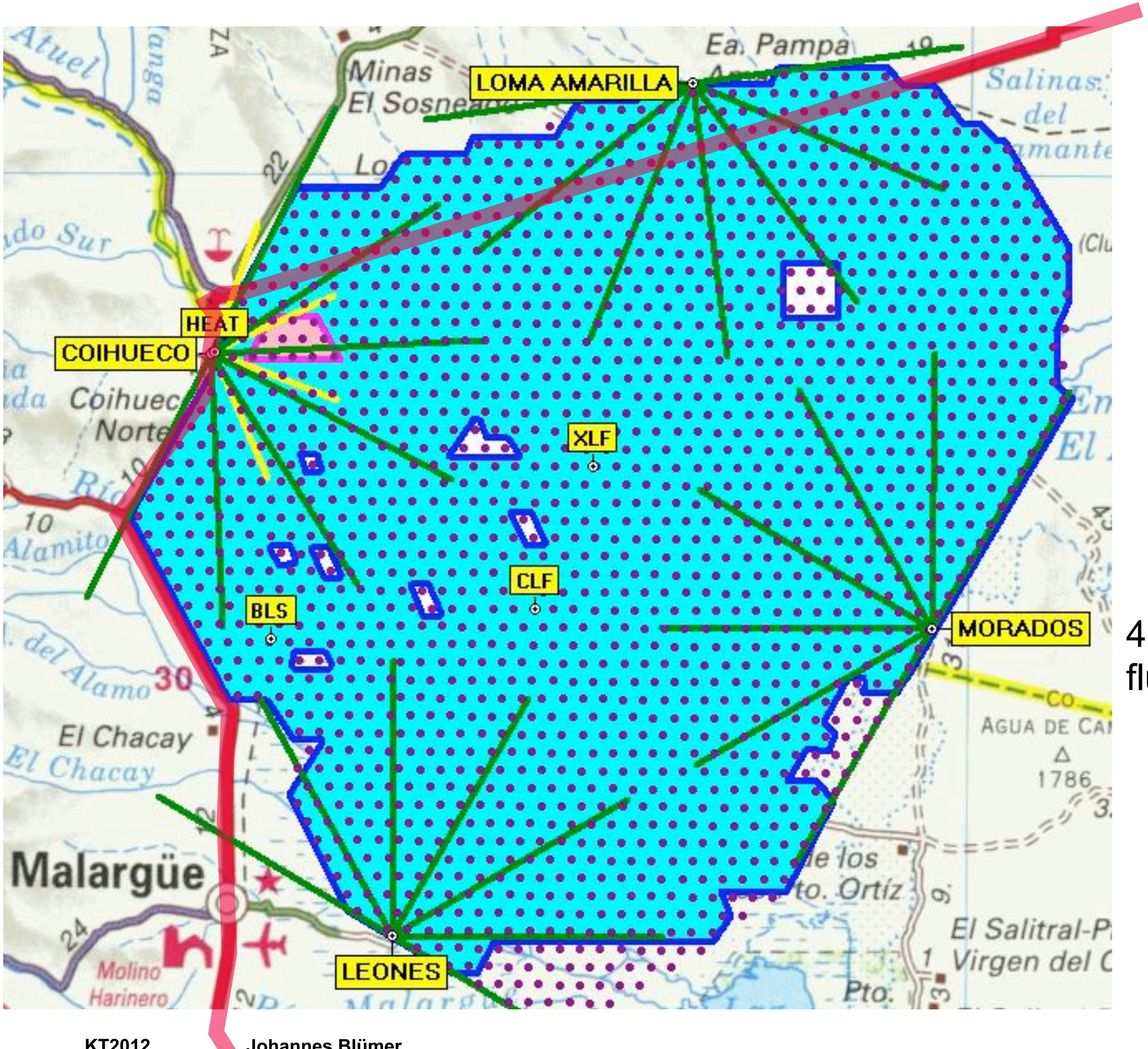


Nagano+Watson 2000
galactic origin?
extragalactic?
$r_L > 30kpc$
ankle
knee
Akeno 1km^2
Tibet
Runjob
Proton Satellite
JACEE
AGASA
Haverah Park
Yakutsk
Stereo Fly's Eye
log(FLUX * E^3 in eV^{2}m^{-2}s^{-1}sr^{-1})
log(ENERGY in eV)
26
25.5
25
24.5
24
23.5
23
11
12
13
14
15
16
17
18
19
20
21

Energiespektrum der kosmischen Strahlung

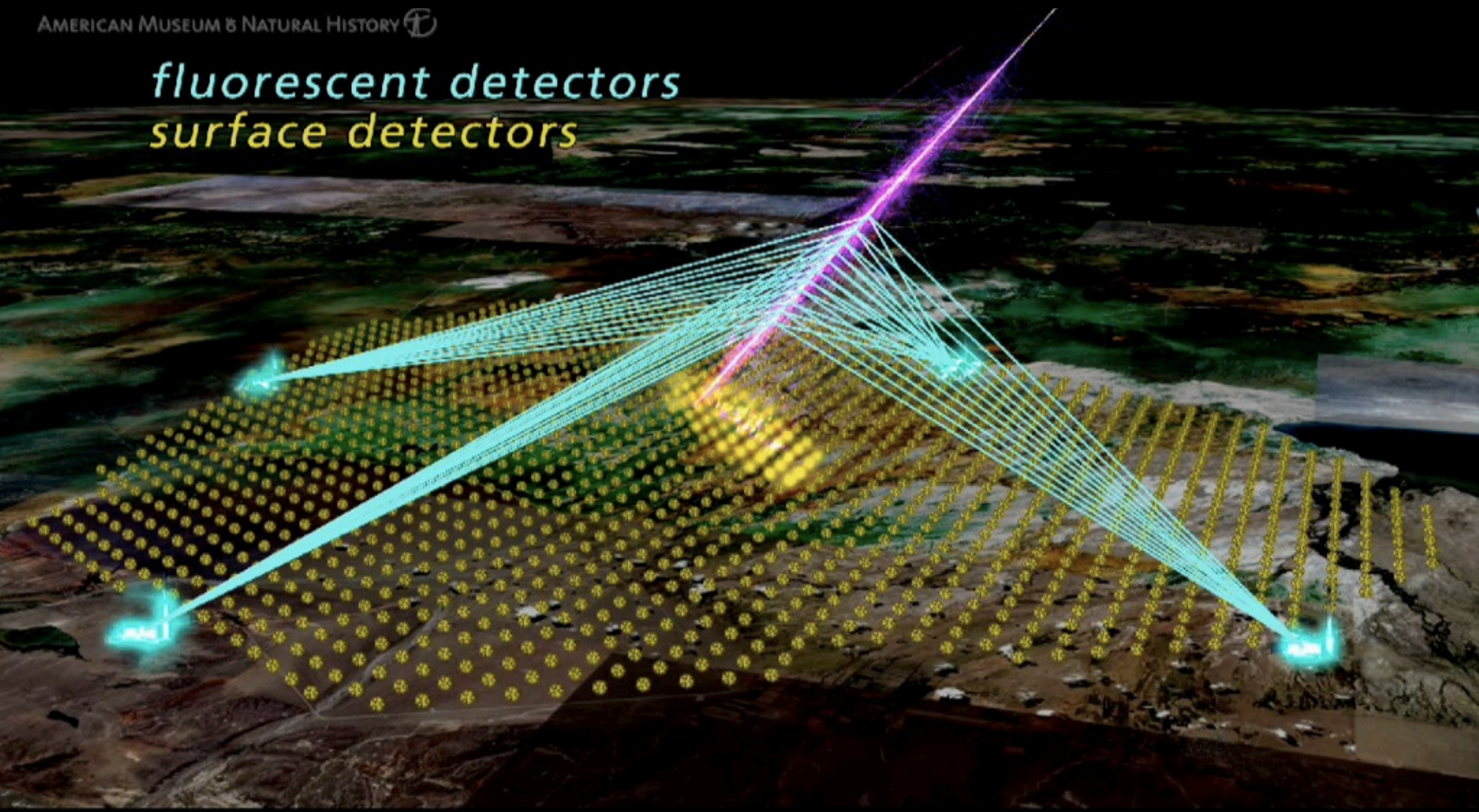


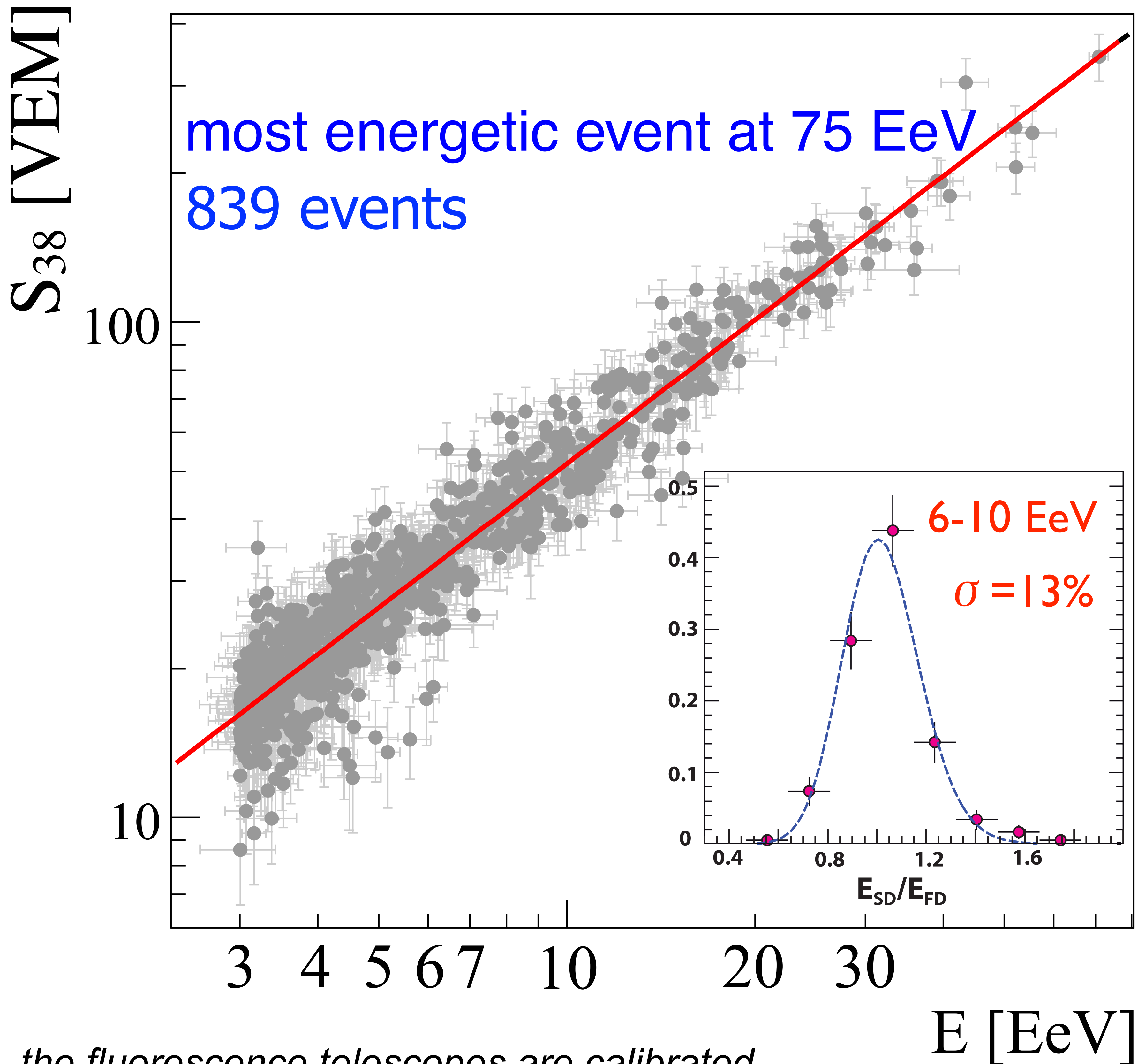
Pierre Auger-Observatorium



1660 water Cherenkov detectors covering 3000 km^2

4 x 6 + 3 fluorescence telescopes


AMERICAN MUSEUM & NATURAL HISTORY
fluorescent detectors
surface detectors

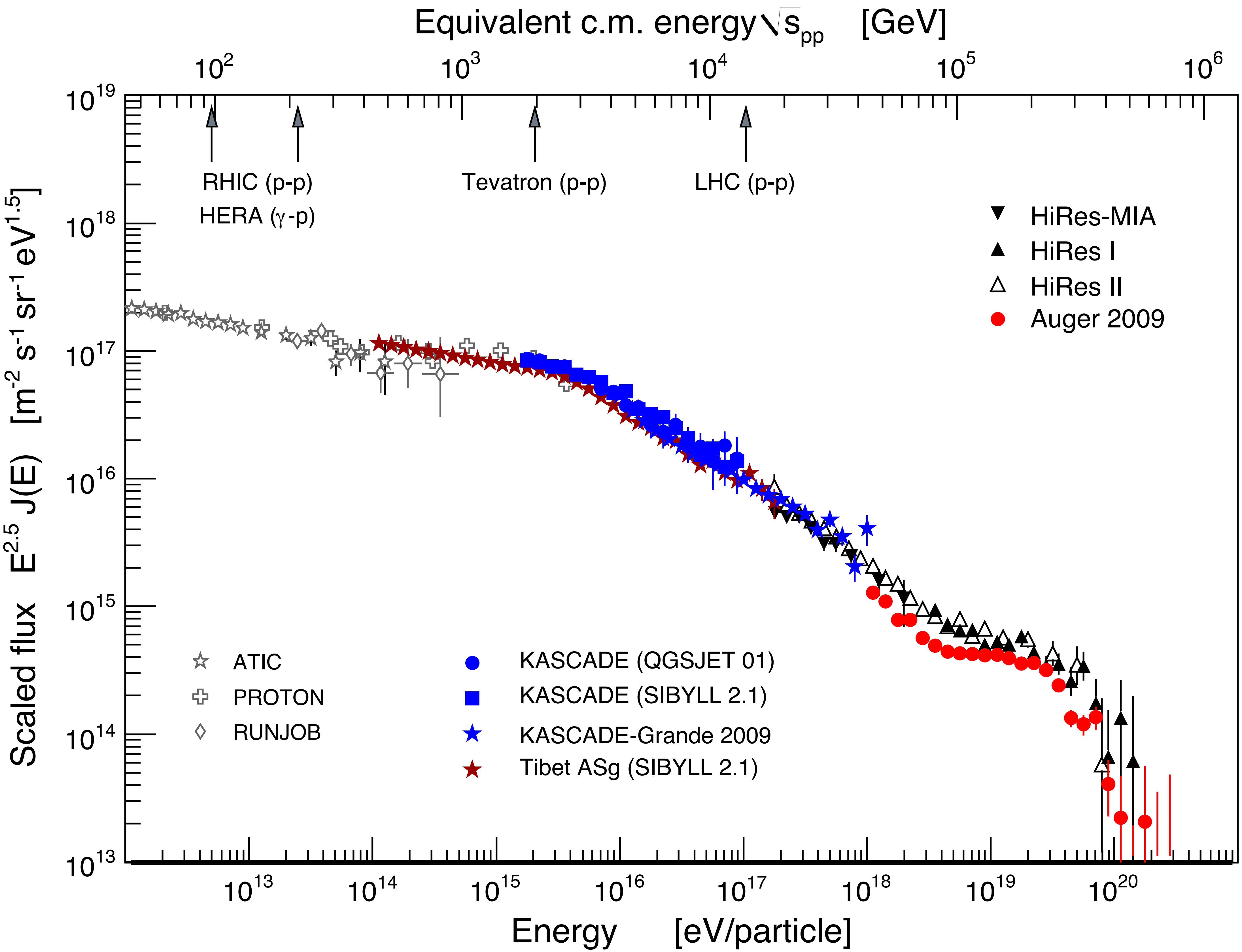


The surface detectors are self-calibrating by single muons VEM = Vertical Equivalent Muon

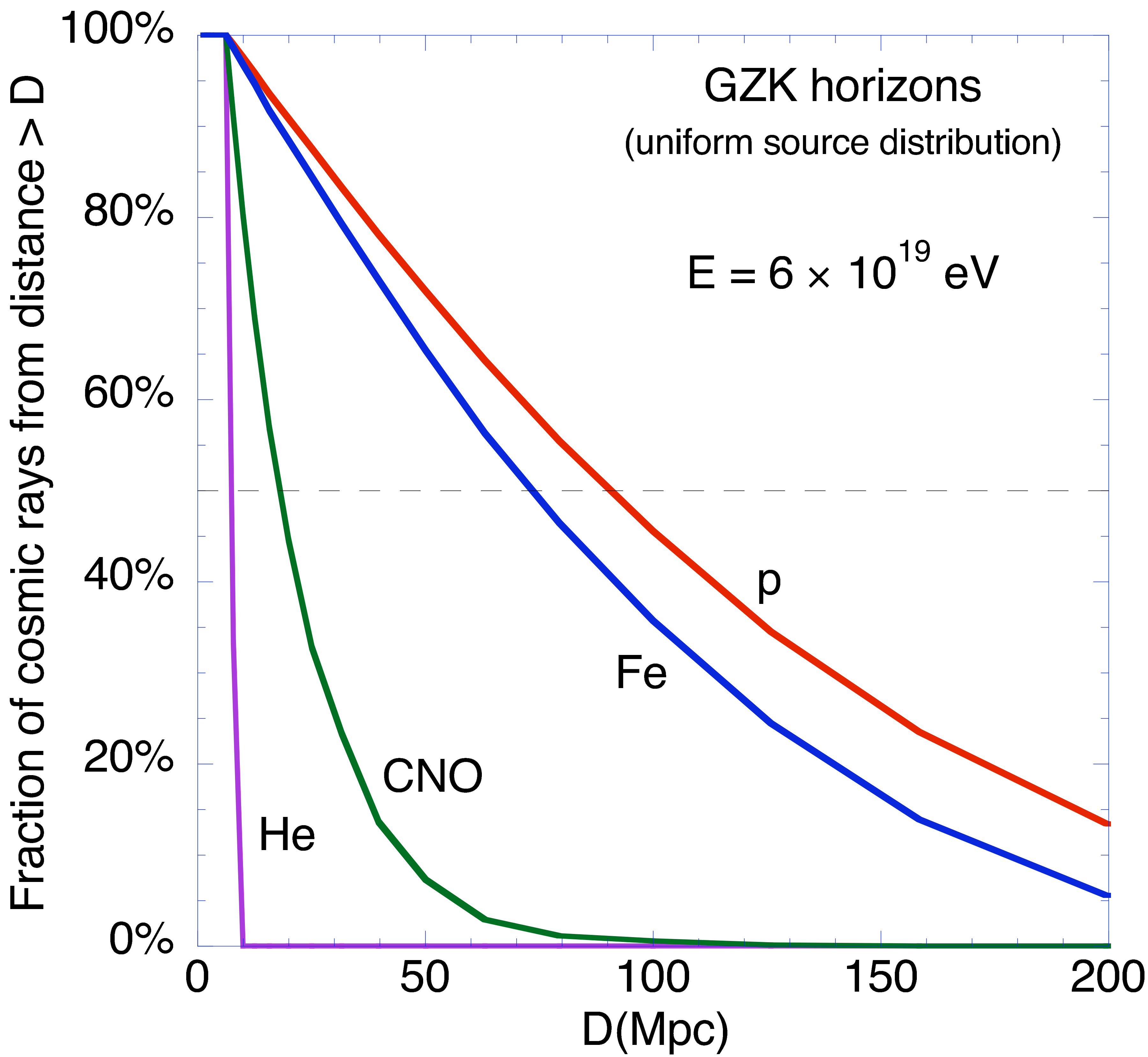
correct for attenuation of the shower as function of zenith angle!

the fluorescence telescopes are calibrated piece by piece on an absolute scale
it is an optical calorimeter!

Energiespektrum und Schwerpunktsenergie



neue MC-Simulation zur Ausbreitung von Kernen



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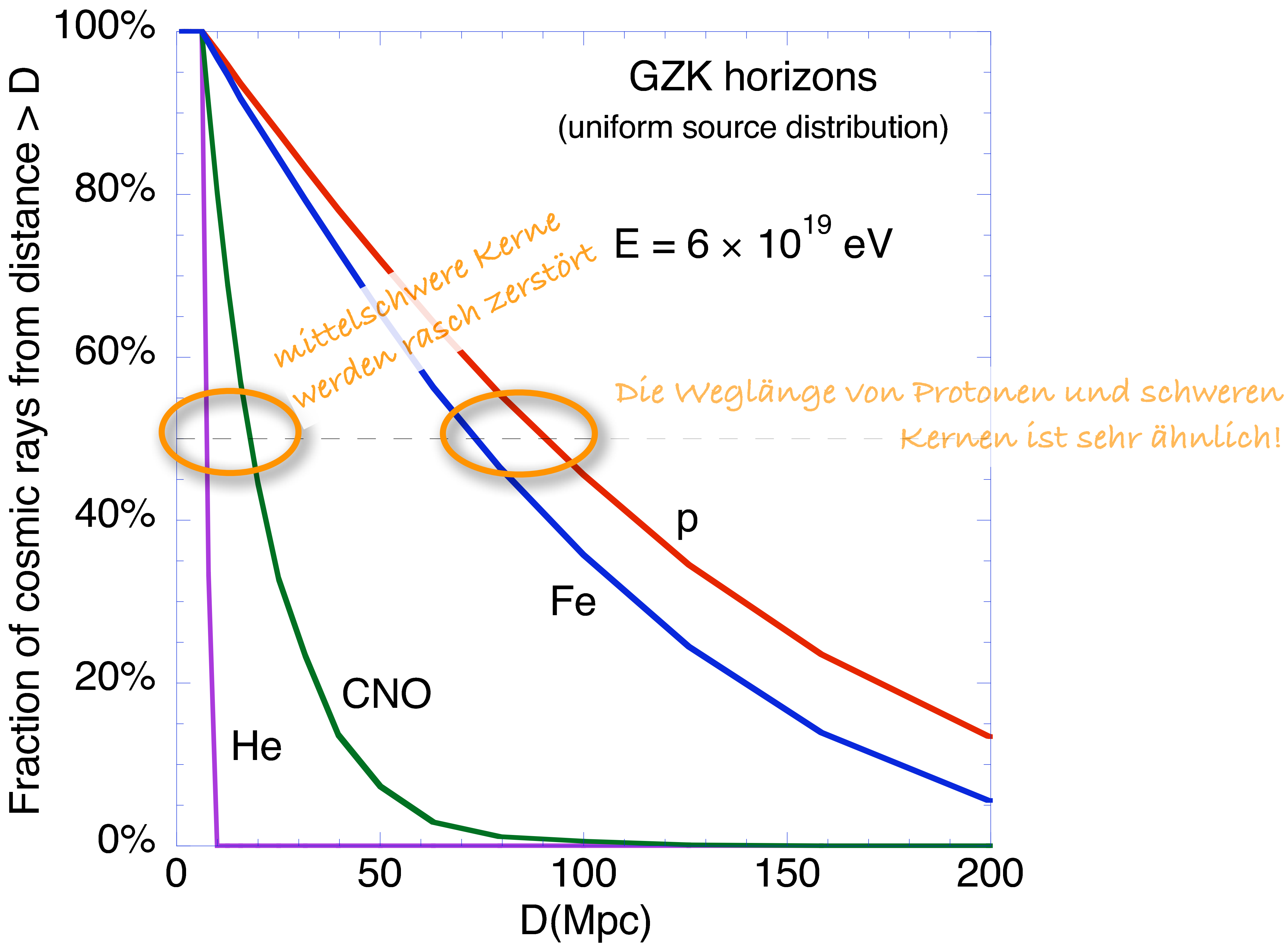
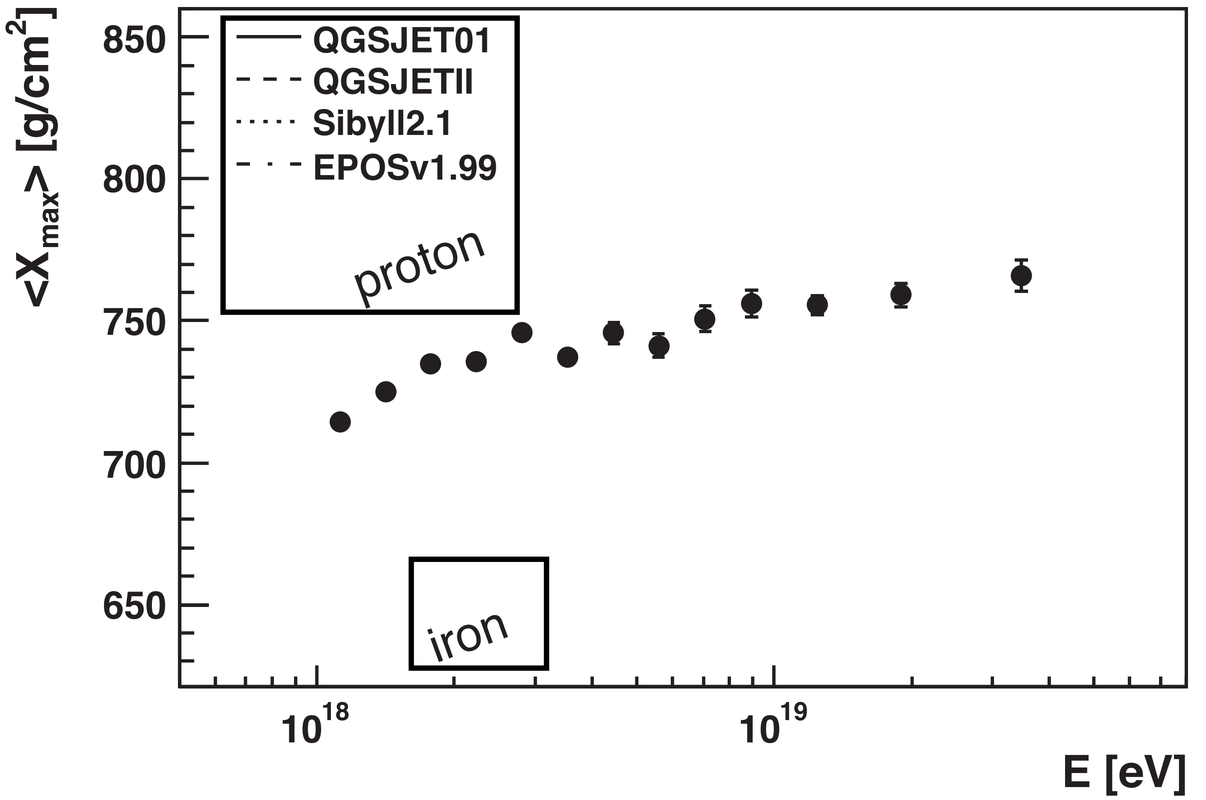
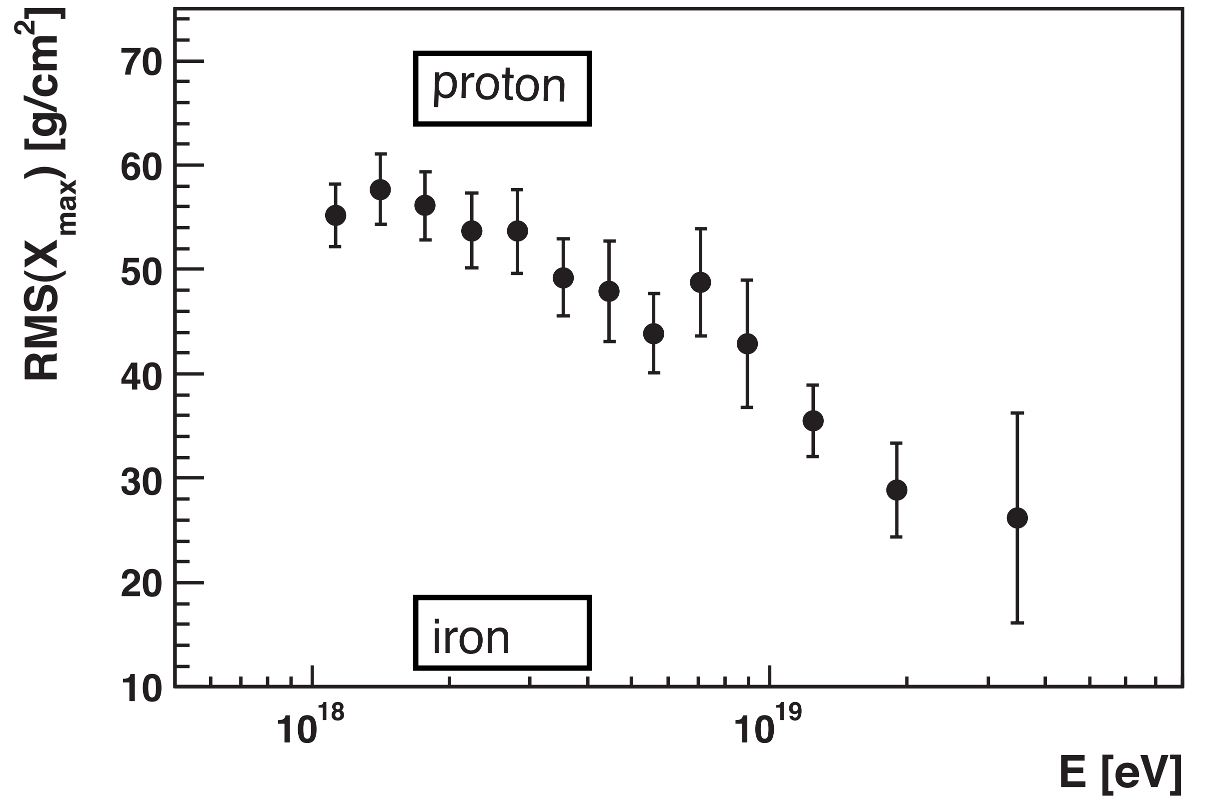
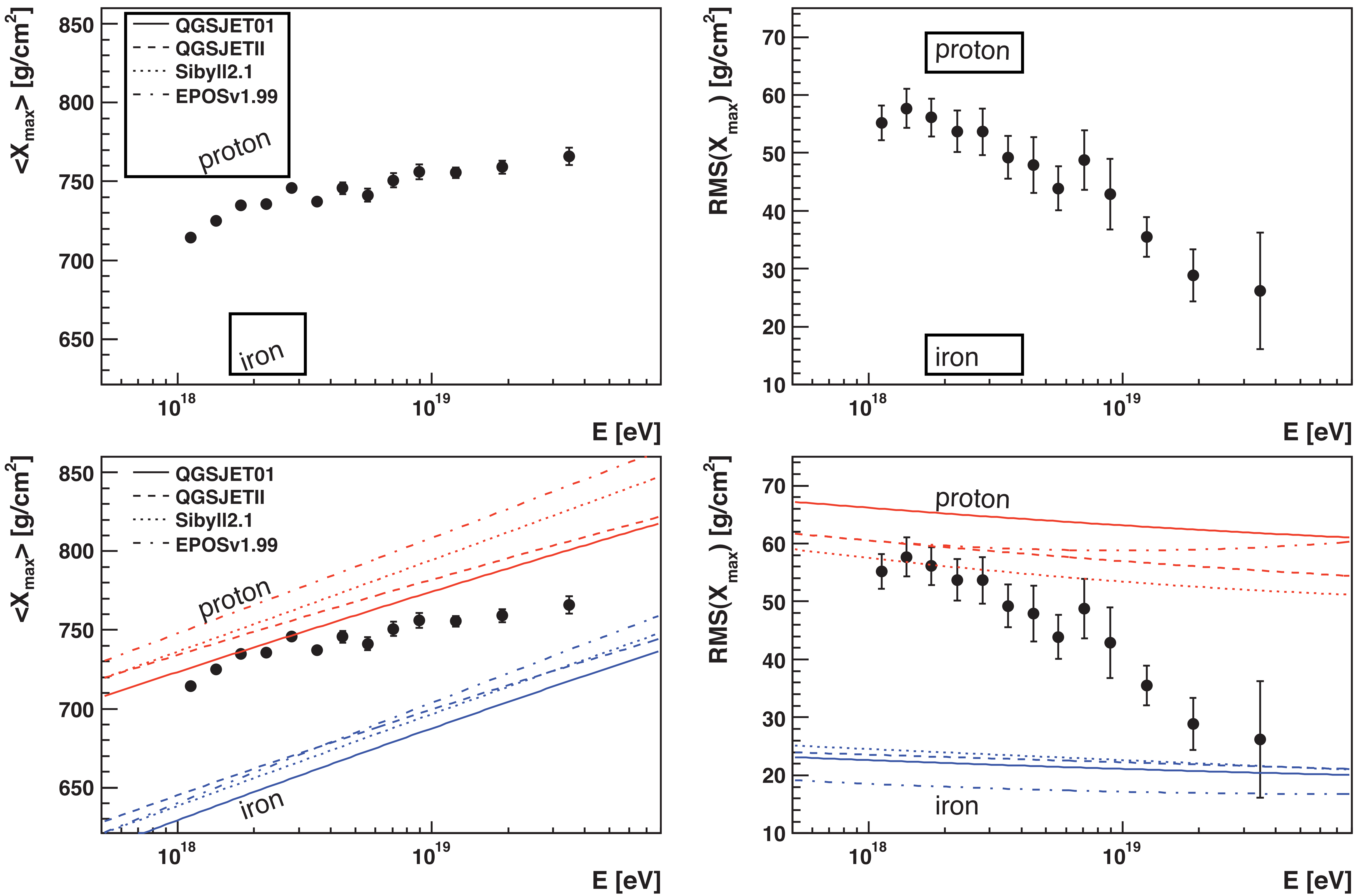


Zusammensetzung bis 40 EeV





Zusammensetzung bis 40 EeV



WQ-Messung aus Luftschauern

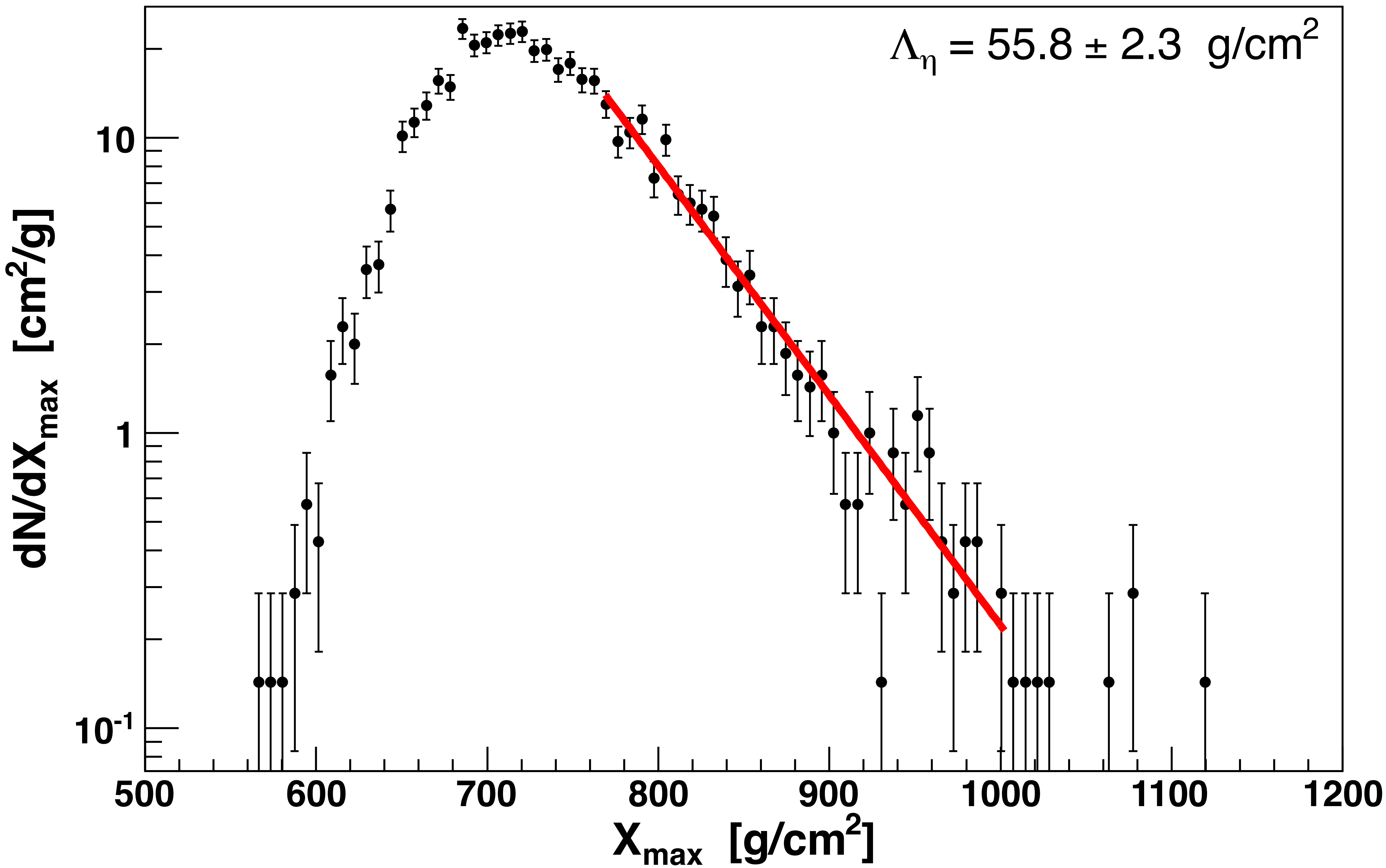
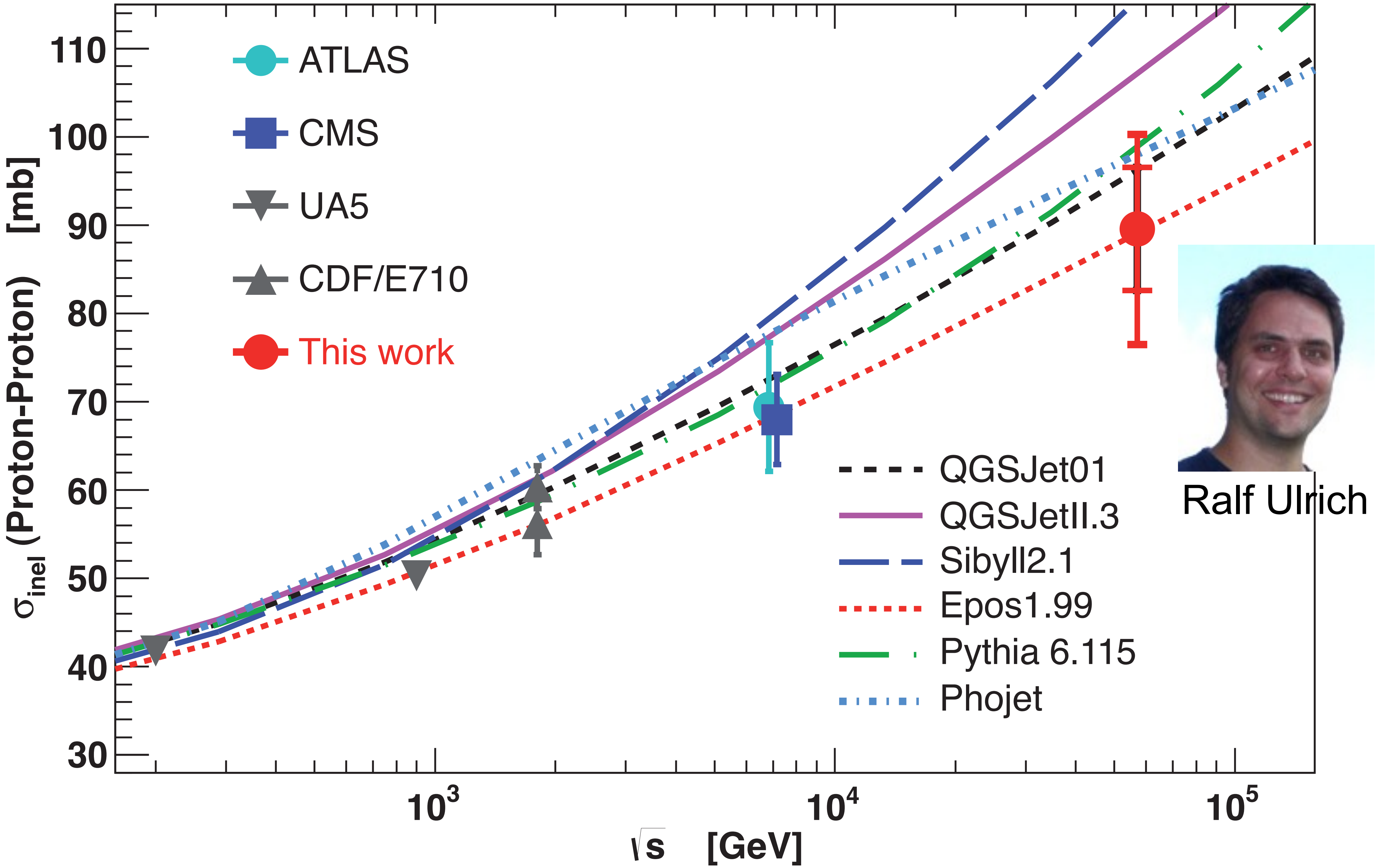


FIG. 1: Unbinned likelihood fit to obtain Λ_η (thick line). The $X_{\max}$-distribution is unbiased by the fiducial geometry selection applied in the range of the fit.

pp cross-section at $\sqrt{s}$ = 57 TeV



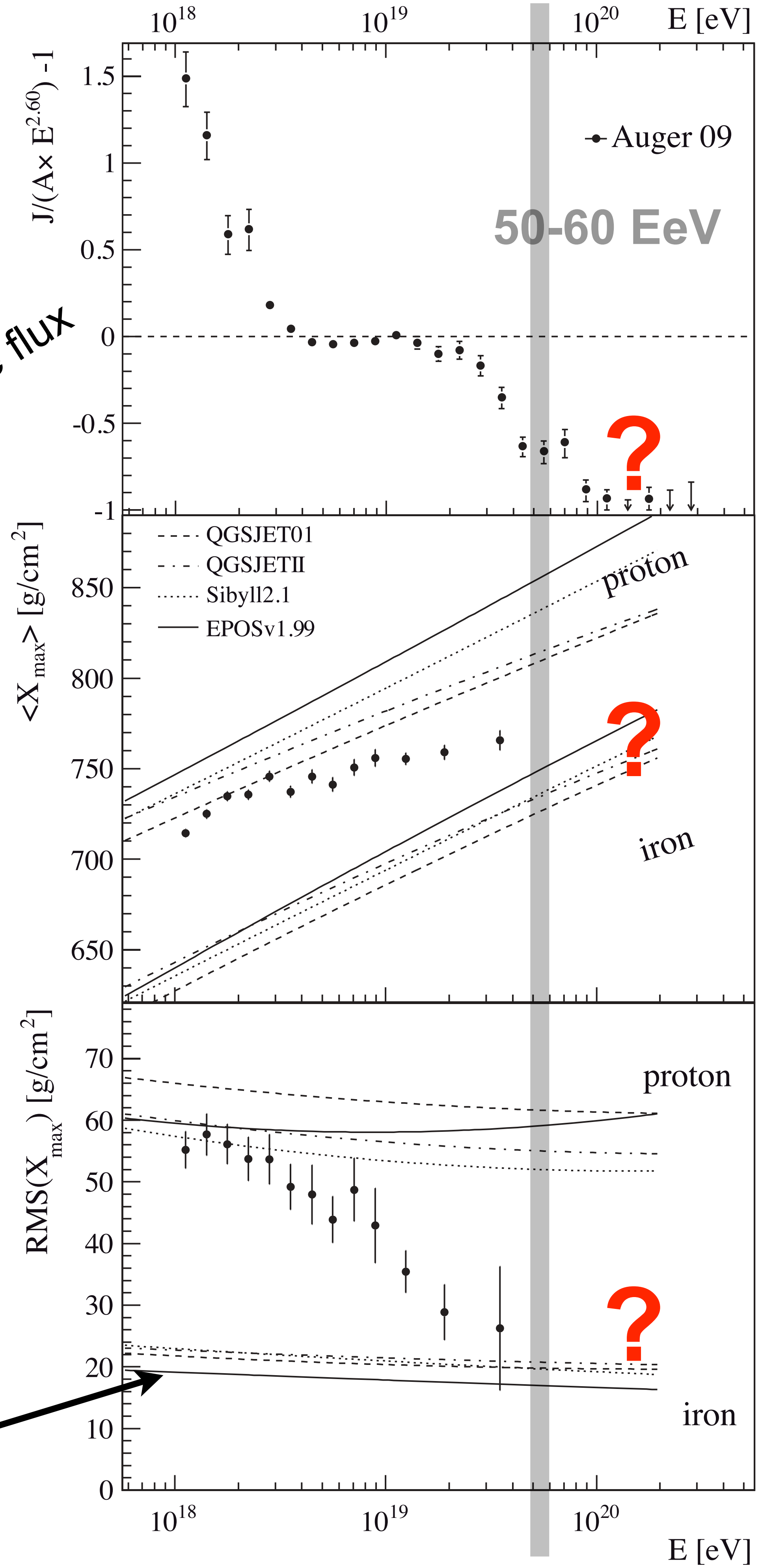
Ralf Ulrich

$$\sigma_{pp}^{inel} = \left[90 \pm 7_{stat} \left({}^{+9}_{-11}\right)_{sys} \pm 1.5_{Glauber}\right] \text{ mb}$$

$$\sqrt{s_{pp}} = [57 \pm 6] \text{ TeV}$$

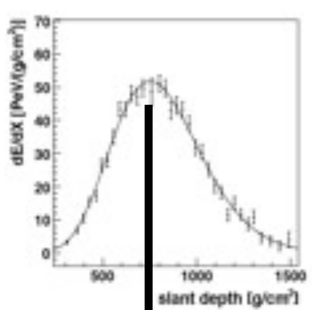
spectrum: convoluted information about sources, particles and propagation

relative flux



shower profile: independent, best estimator of primary particle mass

de/dX

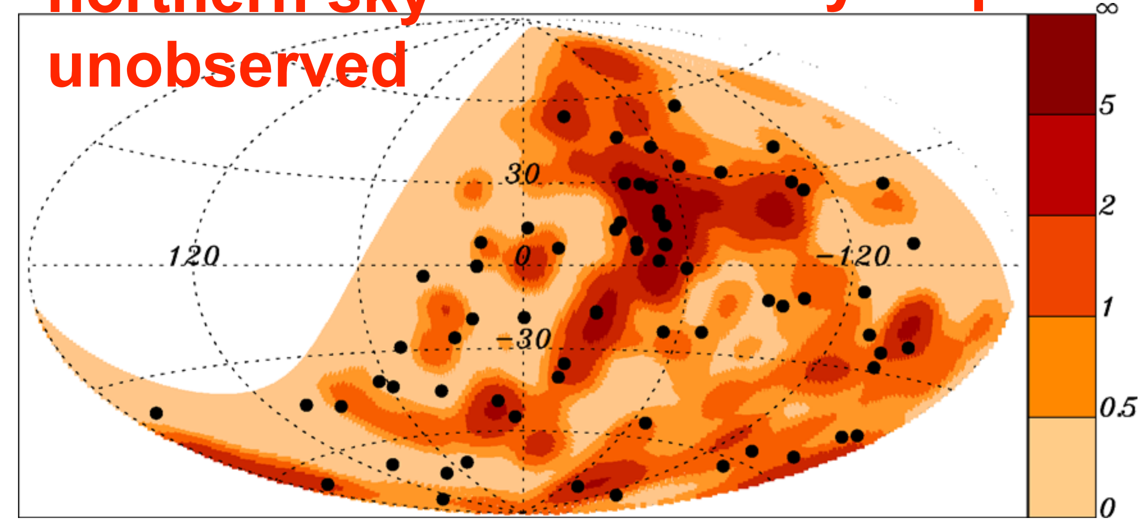


X_{max} X

models assume no change in basic physics

few events in sky map

northern sky unobserved



[Astroparticle Physics 34 (2010) 314–326]

spectrum:
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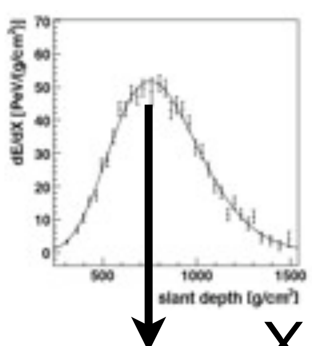

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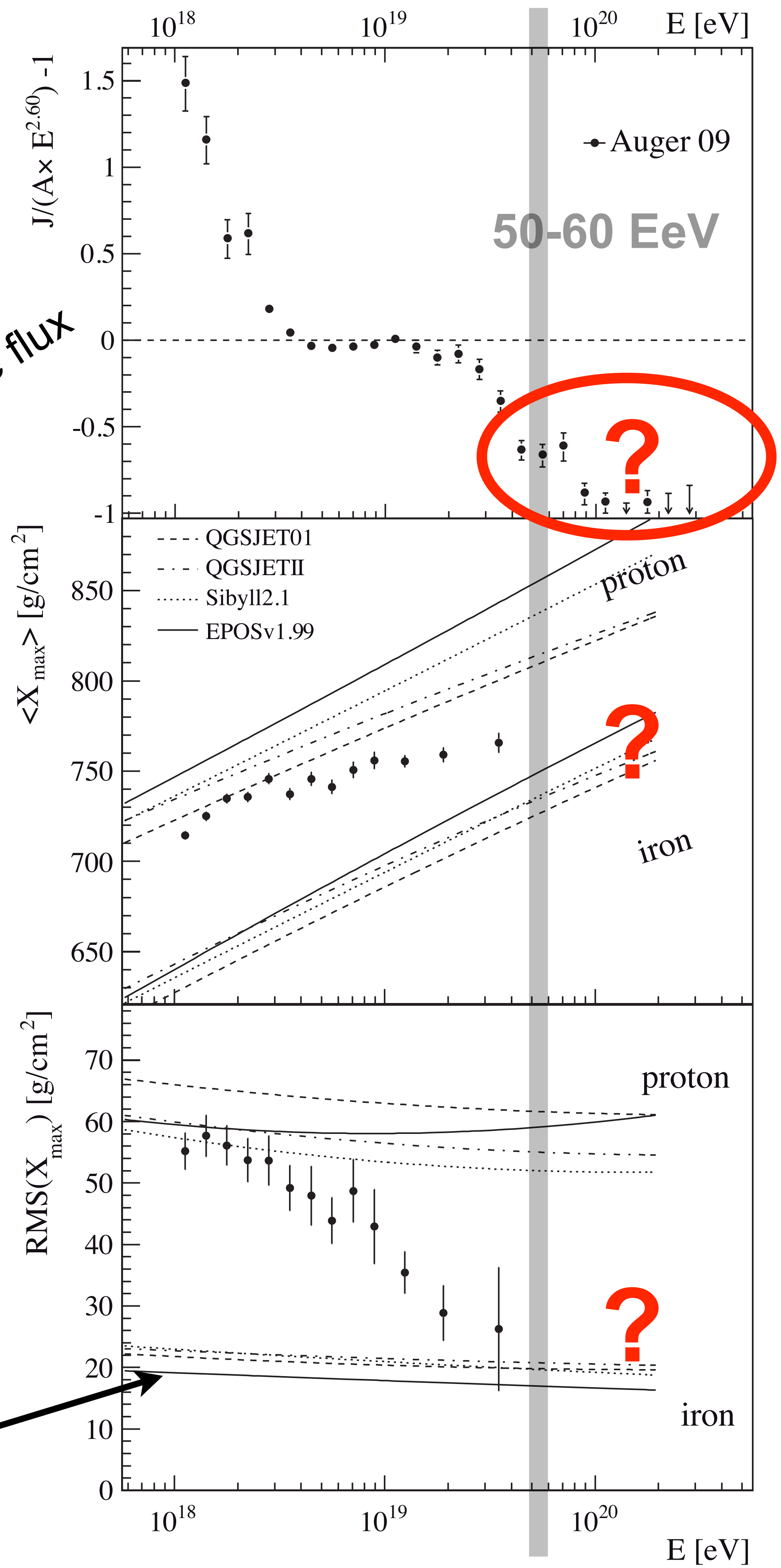

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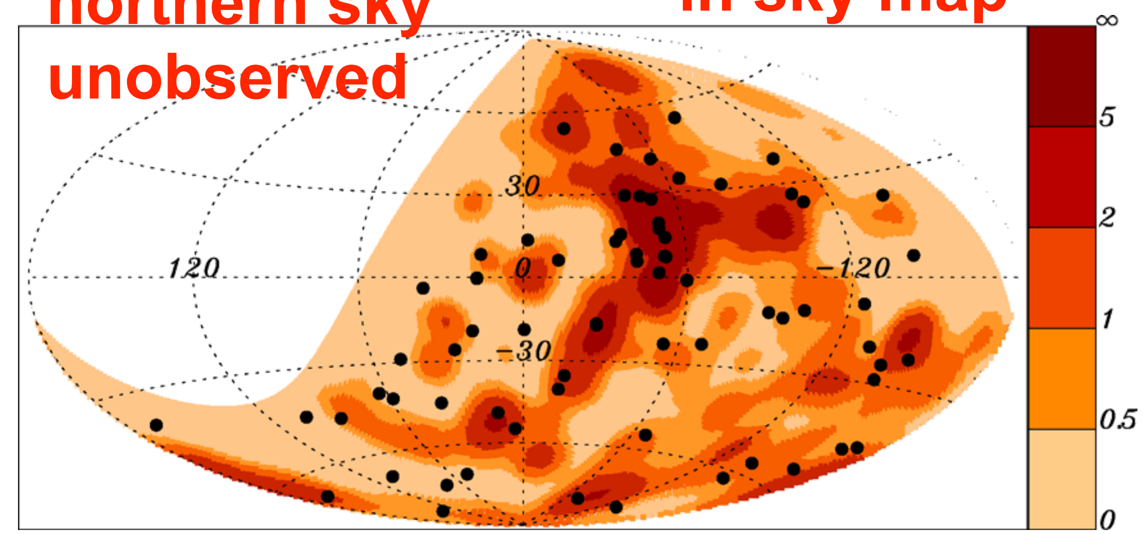
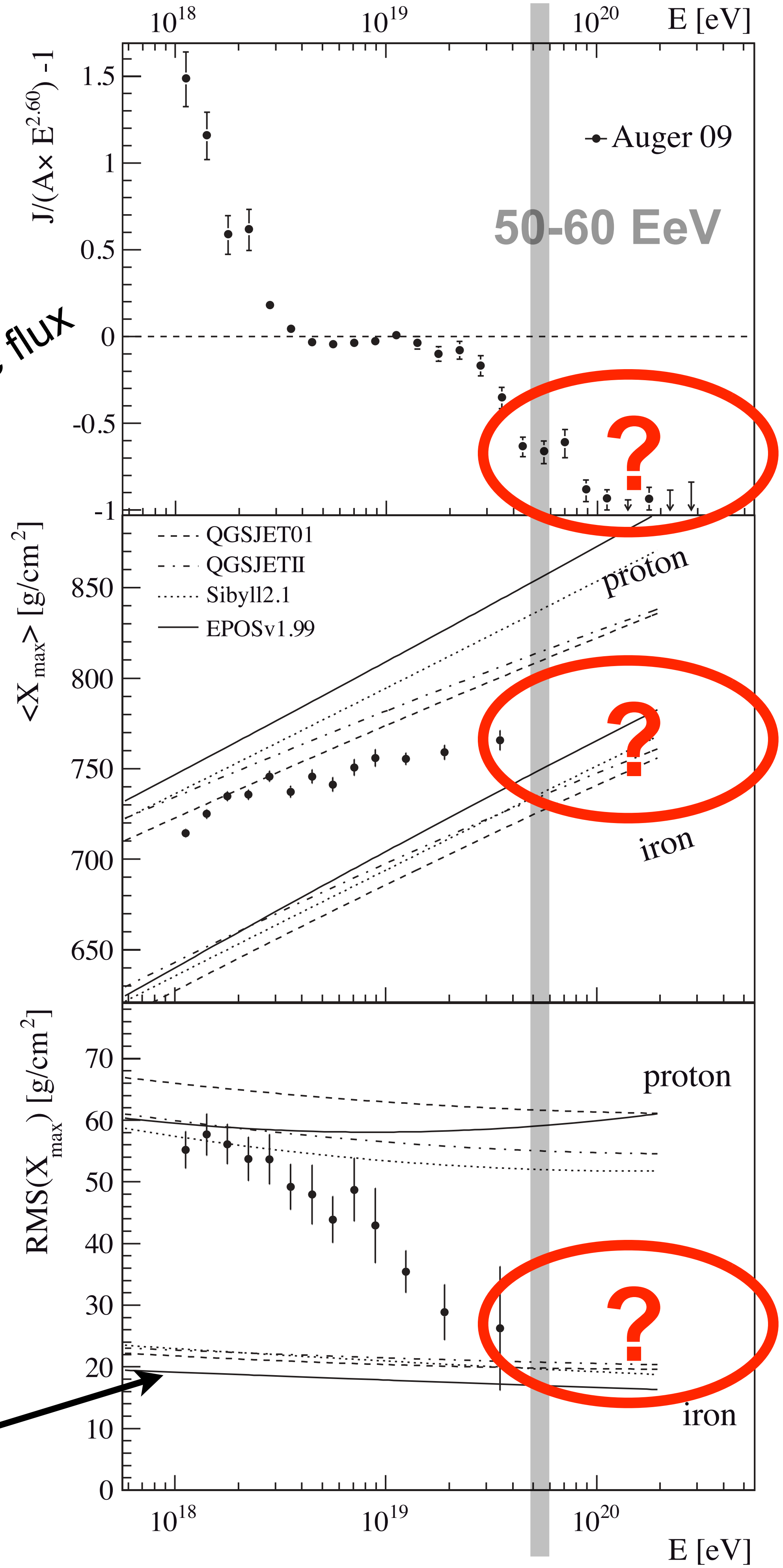


[Astroparticle Physics 34 (2010) 314–326] spectrum: convoluted information about sources, particles and propagation

relative flux



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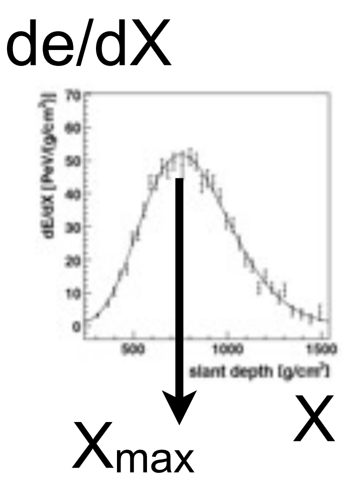
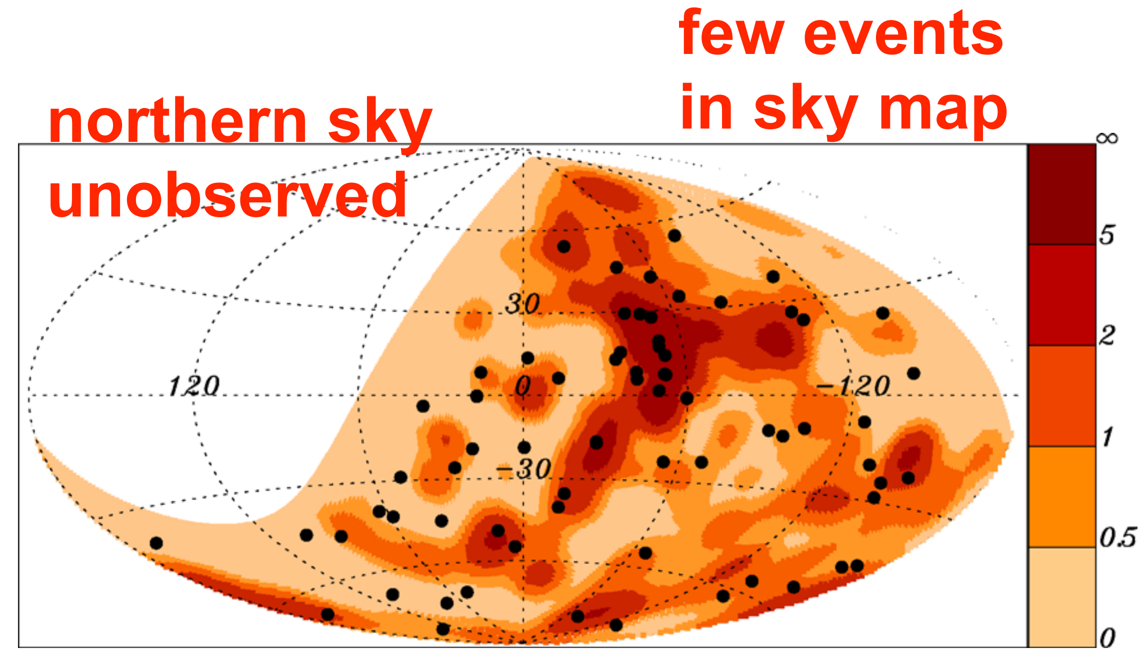


models assume no change in basic physics



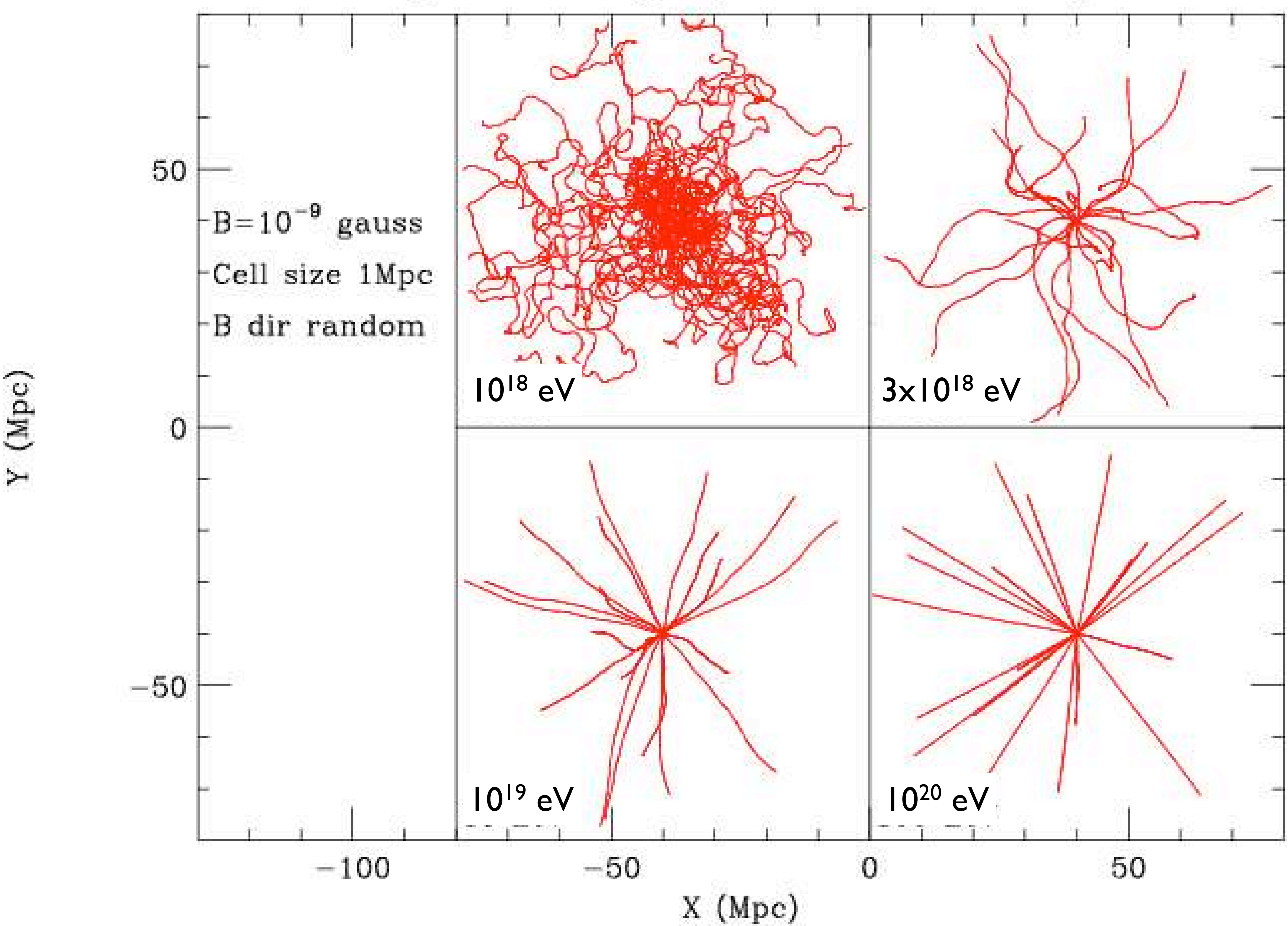
[Astroparticle Physics 34 (2010) 314–326]

composition at and above the GZK threshold?

alternative explanations like increasing cross section?

particle physics at $\sqrt{s}$ > 350 TeV

Magnetfelder und extragalaktische Kosm. Strahlung



	Klassif.	Energie	B-Feld	Rad-Feld	Beob.-Reichw	Status	Quellen	Det	Proj	Fragen
e+e–		MeV..GeV	!!!	!!!	lokal	√	Paarb	div		
Photonen	CMB	meV	–	"GZK"	Kosm	√	Urknall	Sat	COBE, WMAP, PLANCK	Kosmologie
	Radio	10-100 meV	–	–	Kosm	√	Obj	Ant	LOFAR SKA	Frühes Universum
	vis	eV	–	"IR, Vis"	Kosm	√	Obj	Tel	div	viele
	X	keV..GeV	–	–	e-gal	√	Obj	Sat	Fermi	viele; Obj
	γ	GeV..100 TeV	–	!	e-Gal	√	Obj	Sat, ChTel	HESS MAGIC CTA	viele; Obj
	GZK	1..>100 EeV	! paar	–	e-Gal <100 Mpc	–	GZK	Cher	Auger	∃ GZK?
Teilchen	Sol	<10 GeV	!!!	–	Sol	√	Sol	Sat	div	viele; Obj; Anw
	Gal.	<1 EeV	!!	–	Gal	√	SN?	Sat, Array	Kascade Grande, AMS	(Quellen); Spektren A, E
	eGal.	1..>100 EeV	!	IR, GZK	e-Gal <100 Mpc	√	AGN?	Array (ISS Tel)	Auger	Quellen; Spektren A, E
Neutrinos	relic	1.9 K	–	–	Kosm	–	Urknall	?	?	∃ ?
	SN	10 MeV	–	–	Gal	20	SN	UG-kt	SNO, SuperK uvam	SN-Modellierung
	Sol	<10 MeV	–	–	Sol	√	Sol	UG-kt	Borexino	Sonnenmodell; ν-Oszill.
	HE-Obj	TeV..EeV	–	–	e-Gal	–	Obj	UG-Gt	IceCube	Existenz? Quellen, DM-Suche
	GZK	1..>100 EeV	–	–	e-Gal	–	GZK	UG-Gt	Auger	Existenz? GZK
DM		?	–	–	?	–	Clust	UG-kg..t		Existenz? Quellen? DM-Teilchen?
GW		n.a.	–	–	Gal	–	Kollapse	Intf.		Existenz? Quellen

Neue Projekte

- LHC, LHC, LHC
- ILC
- SuperB
- Neutrinostrahlen, Neutrino-Factory
- Megatonnen-Detektoren
- CR-Observatorium mit 30 000 km^2
- Weltraum-basierte Teleskope: JEM-EUSO o.ä.
- Gamma-Astronomie: H.E.S.S. (2), MAGIC, CTA
- HE-Neutrino-Astronomie: IceCube++, KM3NeT
- Suche nach Dunkler Materie mit ≥ 1 t Targetmaterial
- Doppelter Betazerfall
- +++

The predictable future: LHC Time-line

2009 — Start of LHC

Run 1: 7 TeV centre of mass energy, luminosity ramping up to few 10^{33} cm^{-2} s^{-1}, few fb^{-1} delivered

2013/14 — LHC shut-down to prepare machine for design energy and nominal luminosity

Run 2: Ramp up luminosity to nominal (10^{34} cm^{-2} s^{-1}), ~50 to 100 fb^{-1}

2017 or 18 — Injector and LHC Phase-I upgrades to go to ultimate luminosity

Run 3: Ramp up luminosity to 2.2 x nominal, reaching ~100 fb^{-1} / year accumulate few hundred fb^{-1}

~2021/22 — Phase-II: High-luminosity LHC. New focussing magnets and CRAB cavities for very high luminosity with levelling

Run 4: Collect data until > 3000 fb^{-1}

2030 — ILC, High energy LHC, ... ?

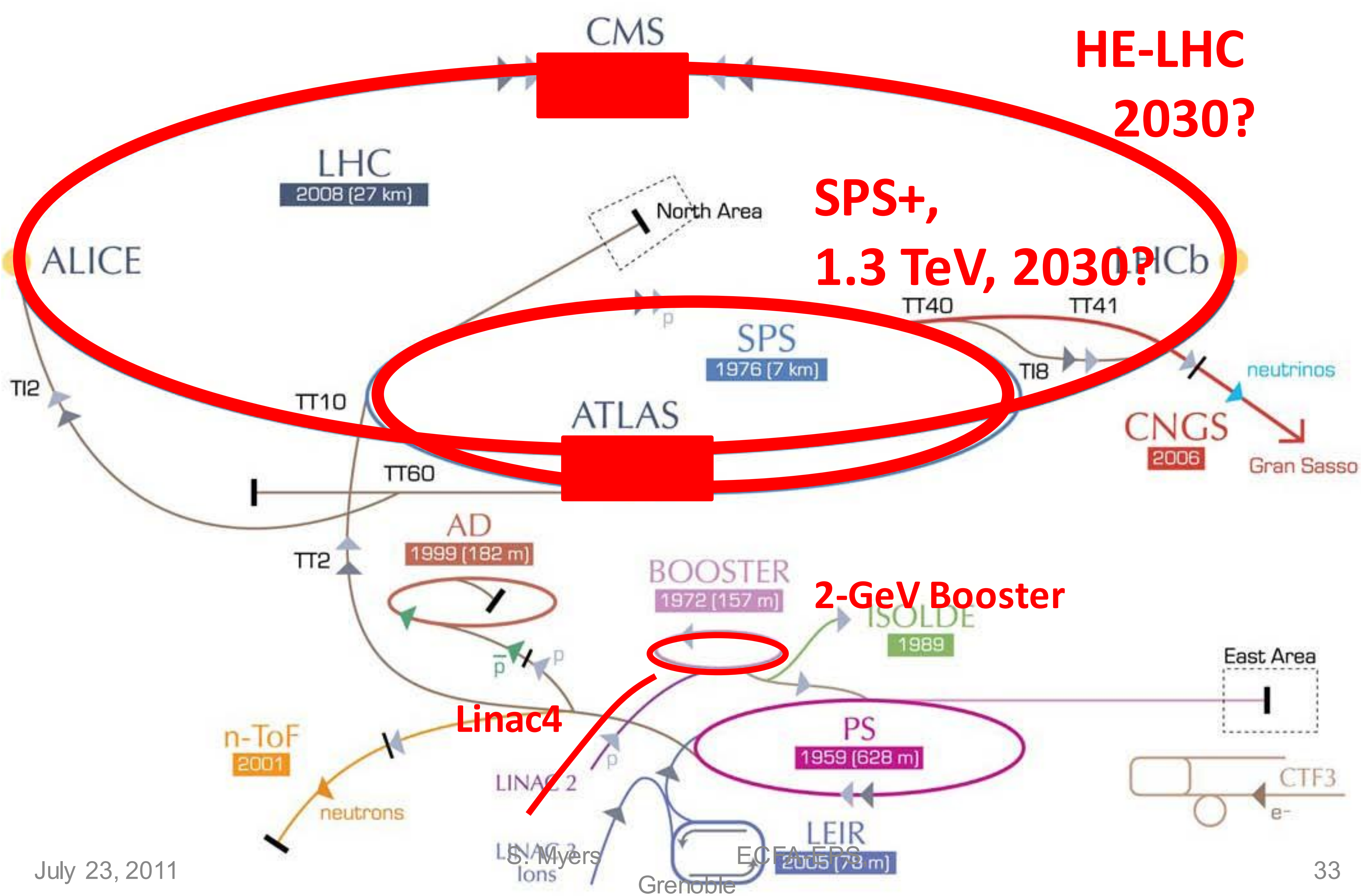
H Bachacou

Oversimplified summary

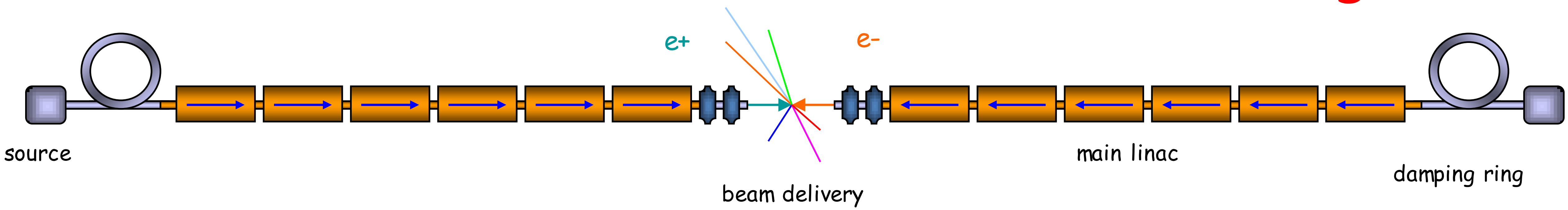
Unfortunately, no hint of New Physics in the LHC data (yet)

	Lower Limit (95% C.L.)
SUSY ($m_{\tilde{q}} = m_{\tilde{g}}$)	1 TeV
Gauge bosons (SSM)	2 TeV
Excited quark	3 TeV

HE-LHC – LHC modifications



Multi-TeV Linear Colliders challenges



Energy reach $E_{cm} = 2F_{fill} L_{linac} G_{RF}$

- Accelerating structures: large accelerating fields with low breakdown rate
- RF power source: high peak power with high efficiency

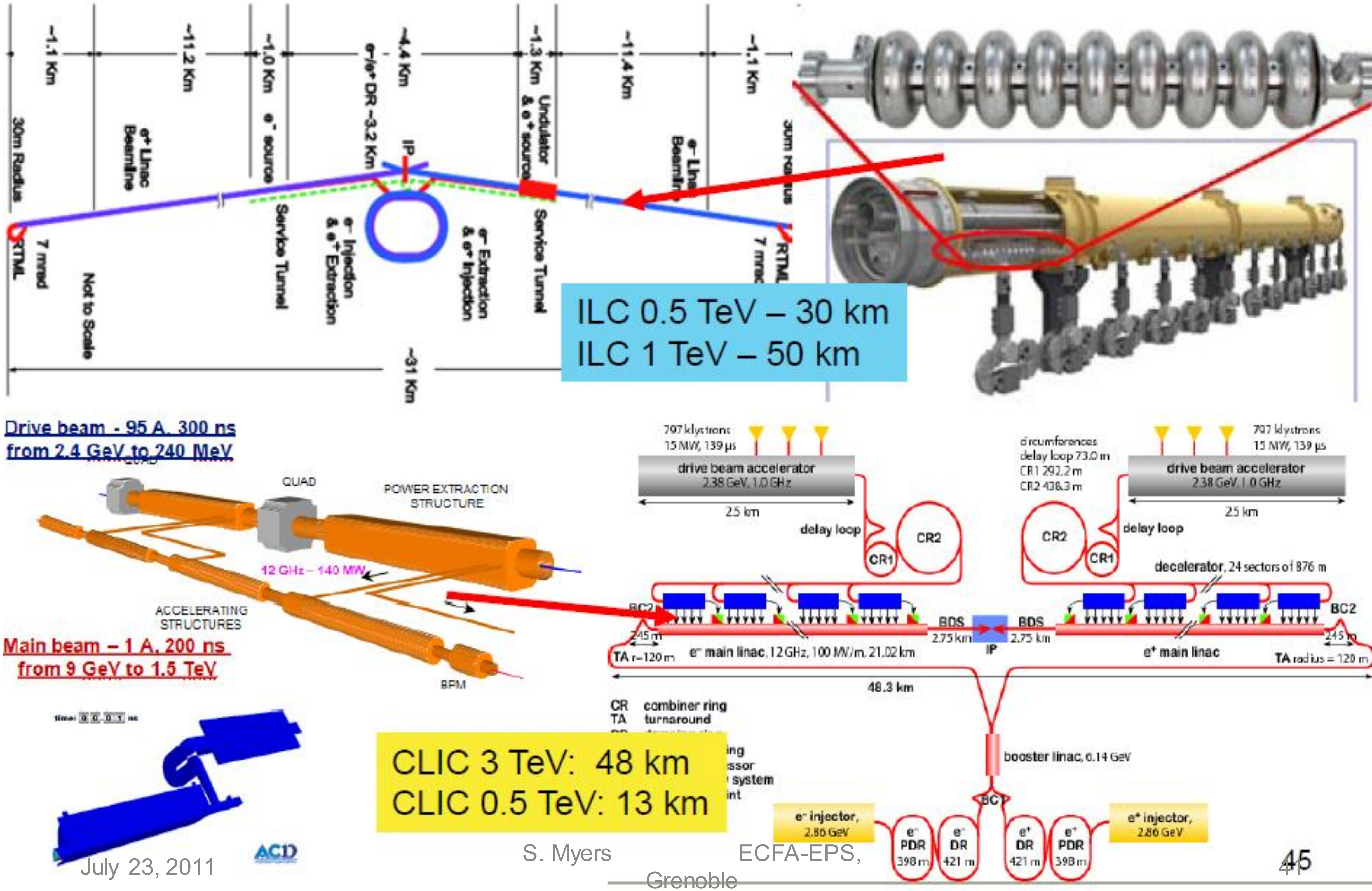
Luminosity

$$L = \frac{n_b N^2 f_{rep}}{4\pi\sigma_x^*\sigma_y^*} \times H_D \propto \frac{\eta_{beam}^{AC} P_{AC}}{\varepsilon_y^{1/2}} \frac{\delta_{BS}^{1/2}}{E_{cm}}$$

- Beam acceleration: MW of beam power with high gradient and high efficiency
- Generation of ultra-low emittances: micron rad-m in H, nano rad-m in V
- Preservation of low emittances in strong wake field environment
  Alignment (micron range)
  Stability (nano-meter range)
- Small beam sizes at Interaction Point: Focusing to nm beam sizes
  Stability to sub nano-meter

Linear Collider layouts

http://www.linearcollider.org/cms http://clic-study.web.cern.ch/CLIC-Study/



The ILC – a step-by-step guide

How does the ILC work? Like any complex machine, the 31 kilometre-long accelerator is made up of several systems – each one an essential component for launching particles at close to the speed of light. This step-by-step guide explains how the ILC works.

Electrons

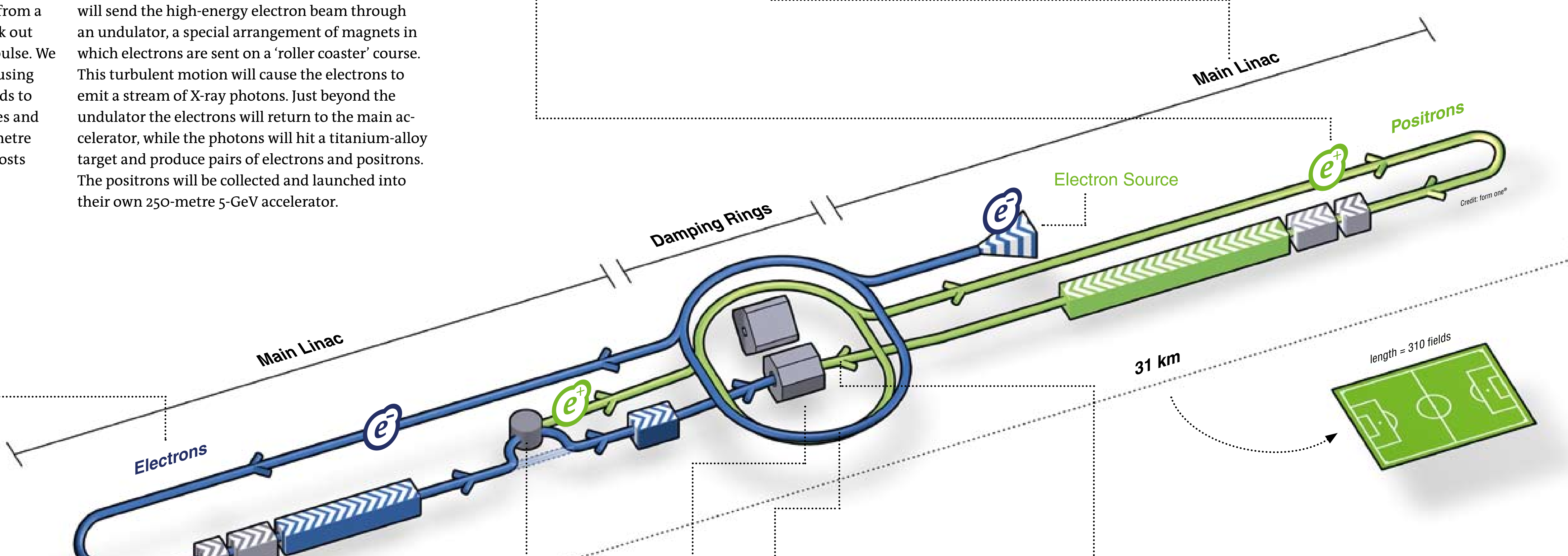
To produce electrons we will direct high-intensity, two-nanosecond light pulses from a laser at a target and knock out billions of electrons per pulse. We will gather the electrons using electric and magnetic fields to create bunches of particles and launch them into a 250-metre linear accelerator that boosts their energy to 5 GeV.

Positrons

Positrons, the antimatter partners of electrons, do not exist naturally on Earth. To produce them, we will send the high-energy electron beam through an undulator, a special arrangement of magnets in which electrons are sent on a ‘roller coaster’ course. This turbulent motion will cause the electrons to emit a stream of X-ray photons. Just beyond the undulator the electrons will return to the main accelerator, while the photons will hit a titanium-alloy target and produce pairs of electrons and positrons. The positrons will be collected and launched into their own 250-metre 5-GeV accelerator.

The linacs

Two main linear accelerators (called linacs), one for electrons and one for positrons, each 12 kilometres long, will accelerate the bunches of particles toward the collision point. Each accelerator consists of hollow structures called superconducting cavities, nestled within a series of cooled vessels known as cryomodules. The modules use liquid helium to cool the cavities to –271 °C, only slightly above absolute zero, to make them superconducting. Electromagnetic waves fill the cavities to ‘push’ the particles, accelerating them to energies up to 250 GeV. Each electron and positron bunch will then contain an energy of about a kilojoule, which corresponds to an average beam power of roughly 10 megawatts. The whole process of production of electrons and positrons, damping, and acceleration will repeat five times every second.



The damping rings

When created, neither the electron nor the positron bunches are compact enough to yield the high density needed to produce copious collisions inside the detectors. Two 6.7 kilometre-circumference damping rings, one for electrons and one for positrons, will solve this problem. In each ring, the bunches will repeatedly traverse a series of wigglers, devices that causes the beam trajectories to ‘wiggle’ in a way that makes the bunches more compact. Each bunch will spend approximately two tenths of a second in its damping ring, circling roughly 10,000 times before being kicked out. Magnets will keep the particles on track and focused in their circular orbits around the ring. Upon exiting the damping rings, the bunches will be a few millimetres long and thinner than a human hair.

The beam delivery systems

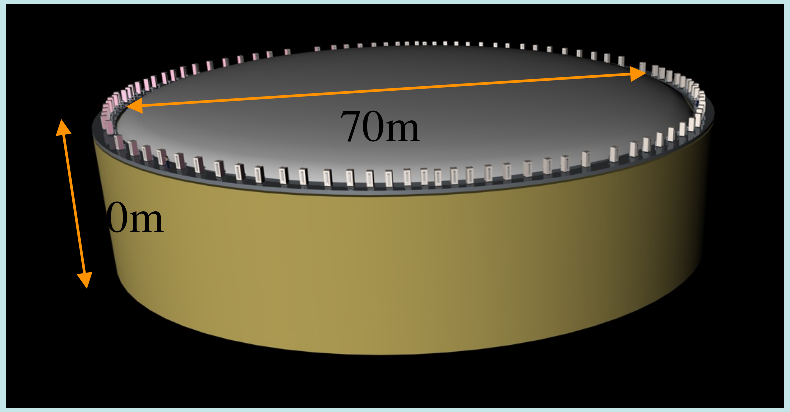
In order to maximise the luminosity, the bunches of particles must be extremely small. A series of magnets, arranged along two 2-kilometre beam delivery systems on each side of the collision point, will focus the beams to a few nanometres in height and a few hundred nanometres in width. The beam delivery systems will scrape off stray particles in the beams and protect the sensitive magnets and detectors. Magnets will steer the electrons and positrons into head-on collisions.

The detectors

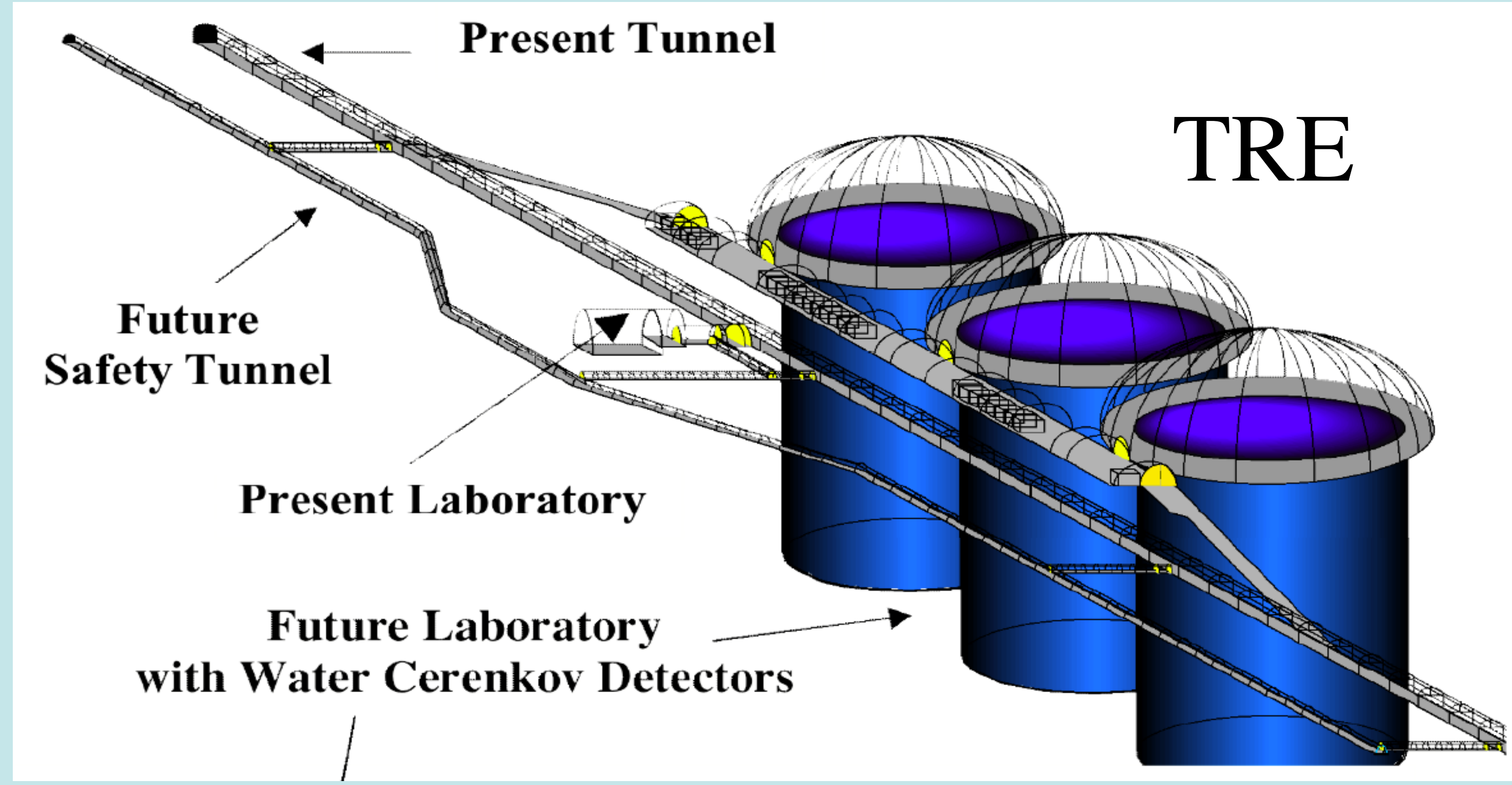
Travelling towards each other at nearly the speed of light, the electron and positron bunches will collide with a total energy of up to around 500 GeV. We will record the spectacular collisions in two interchangeable giant particle detectors. These work like gigantic cameras, taking snapshots of the fleeting particles produced by the electron-positron collisions. The two detectors will incorporate different but complementary state-of-the-art technologies to capture this precious information about every particle produced in each interaction. Having these two detectors will allow vital cross-checking of the potentially subtle physics discovery signatures.

LAGUNA-Projekt

GLACIER Liquid Argon (≈10→100 kton)



MEMPHYS



JEM-EUSO

Signals: Detectable shower energies with the EUSO camera are above 3×10^{19} eV.

Energy Resolution:
$\Delta E/E=30\%$

Track Angular Resolution:
$\Delta\theta\leq 2.5°$

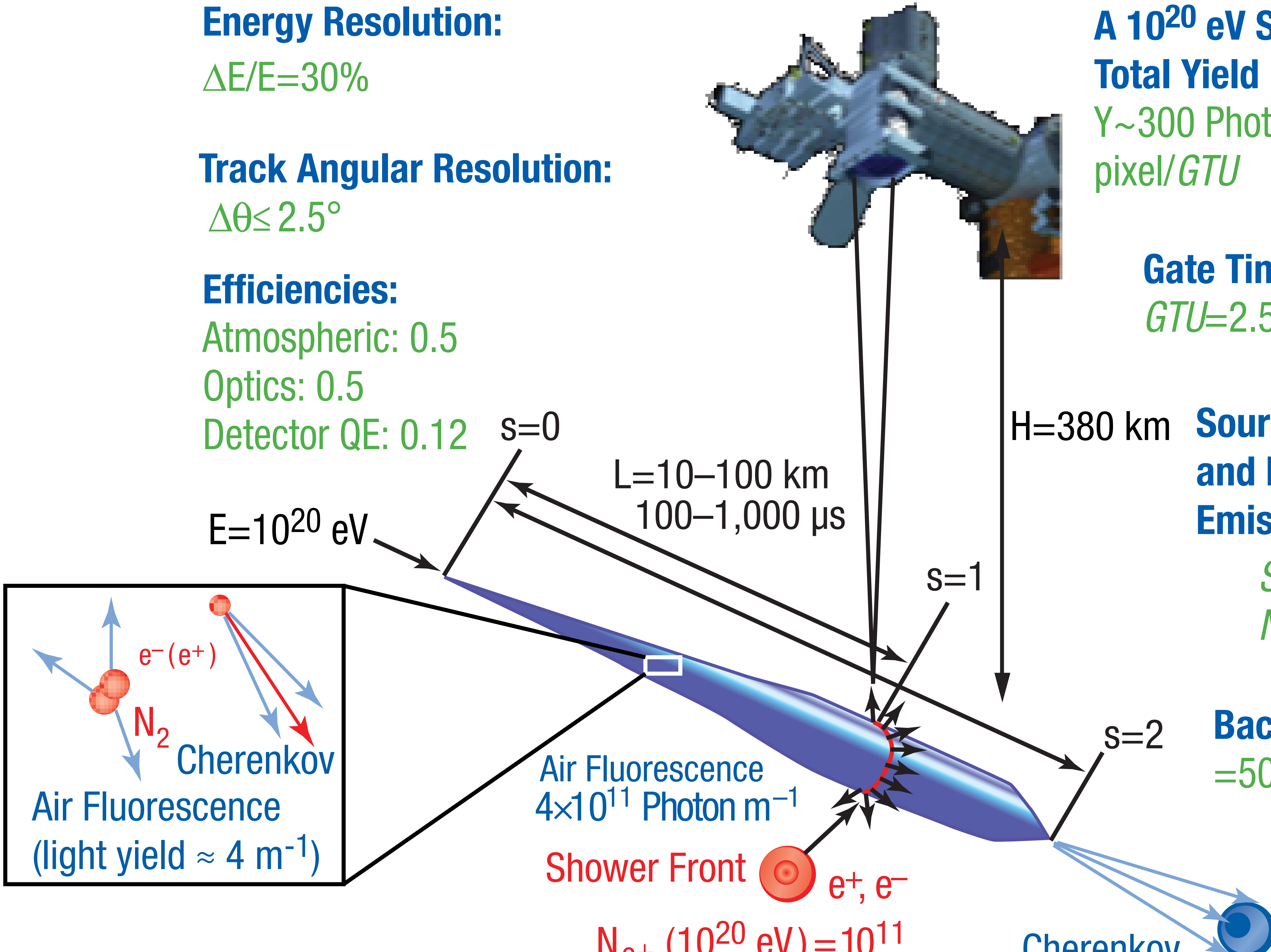
Efficiencies:
Atmospheric: 0.5
Optics: 0.5
Detector QE: 0.12

A 10^{20} eV Shower Total Yield (Y):
Y~300 Photoelectrons/pixel/*GTU*

Gate Time Unit:
GTU=2.5 µs

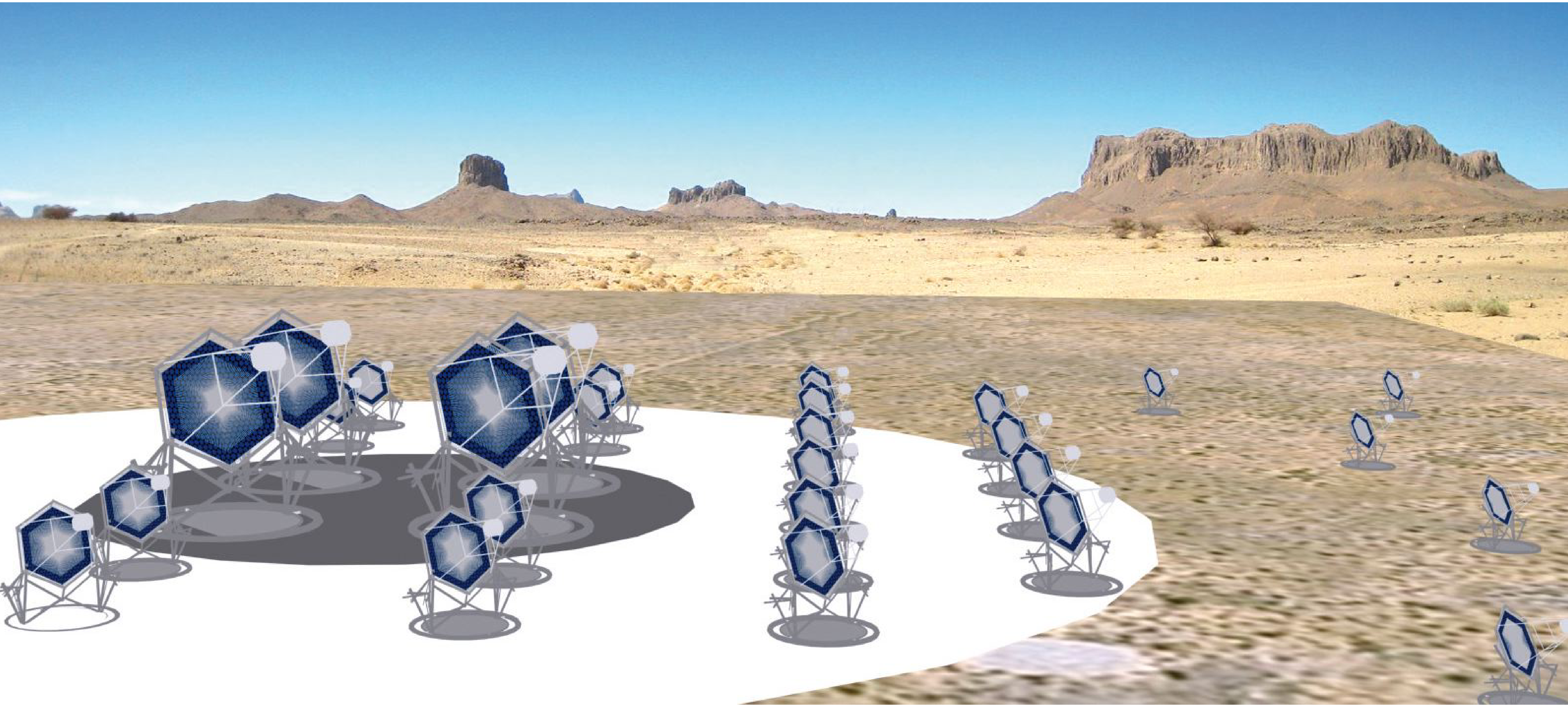
Source Signal (S*) and Background (N) Emissions per *GTU*:**
$S^*=3\times10^{14}$
$N_{bg}^{**}=4\times10^{11}$

Background Flux:
=500/m²–sr–ns

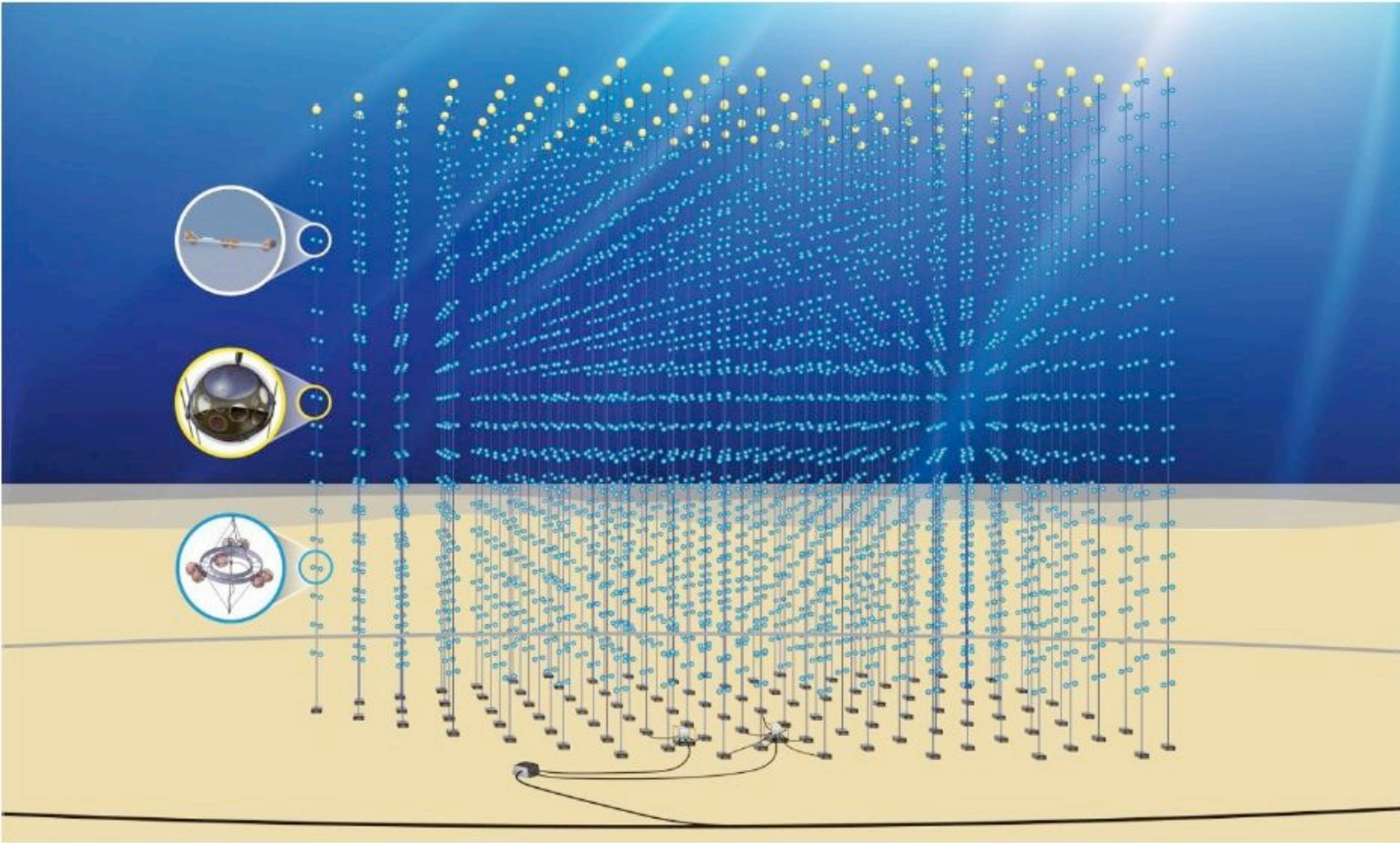


HESS-2

Cherenkov Telescope Array CTA



KM3NeT




endlich Semesterferien!
UND WEIL SICH DAS UNIVERSUM IMMER WEITER AUSDEHNT, BRAUCHEN WIR EBEN EIN GRÖSSERES TELESKOP!
OH