Title: The highest-energy particles of the Universe as viewed by the Pierre Auger Observatory

Date: Oct 23, 2012 09:00 AM

URL: http://pirsa.org/12100089

Abstract: One century after the seminal balloon flights of Victor Hess, the Pierre Auger Observatory aims at unveiling some of the mysteries of the highest-energy cosmic rays: what are their sources? Is there an end to the spectrum? What kind of particles are they? Are there signatures of new physics or of a violation of fundamental laws of physics? The Auger Observatory measures cosmic rays with energies of 10^20 eV or more by observing the giant air showers created when the particles hit the atmosphere. Located in Argentina, two complementary detector systems are used: an array of 1600 water-Cherenkov detectors distributed over 3000 sqkm, and fluorescence telescopes which monitor the atmosphere above the array in clear nights. Since 2005, data of unprecedented quantity and quality could be taken. In the talk, the observation principles, successes and limitations are described. Current, partly surprising results are presented. Data interpretations related to the search for violation of Lorentz invariance are mentioned.

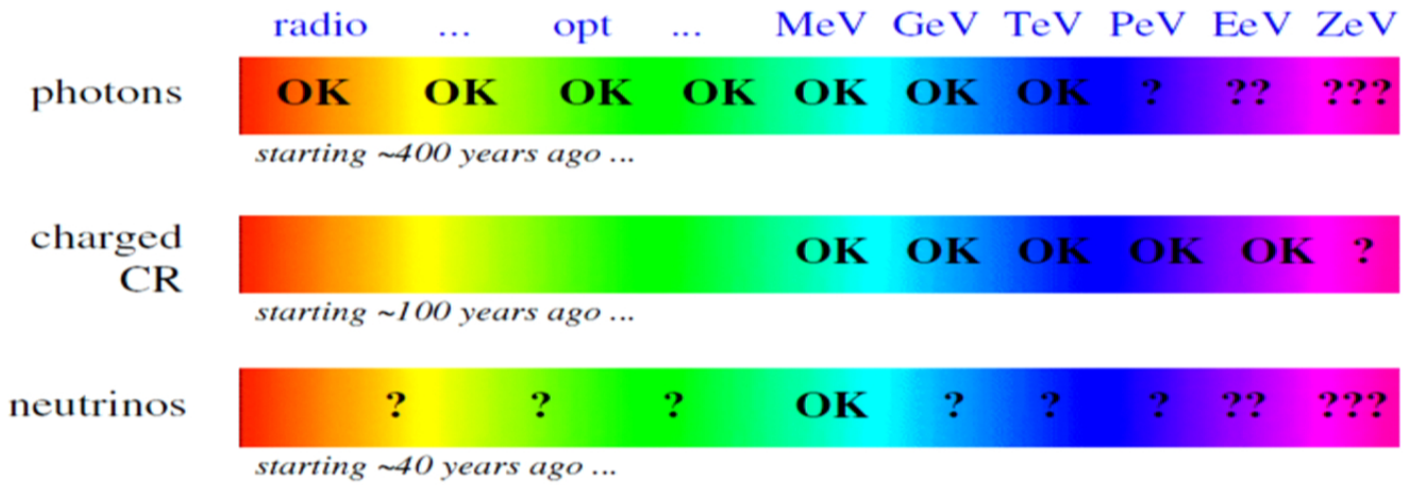
The highest-energy particles of the Universe as viewed by the Pierre Auger Observatory

Markus Risse (University of Siegen)
for the Pierre Auger Collaboration

Experimental Search for Quantum Gravity - The hard facts
Perimeter Institute, Waterloo, Canada
October 22-25, 2012

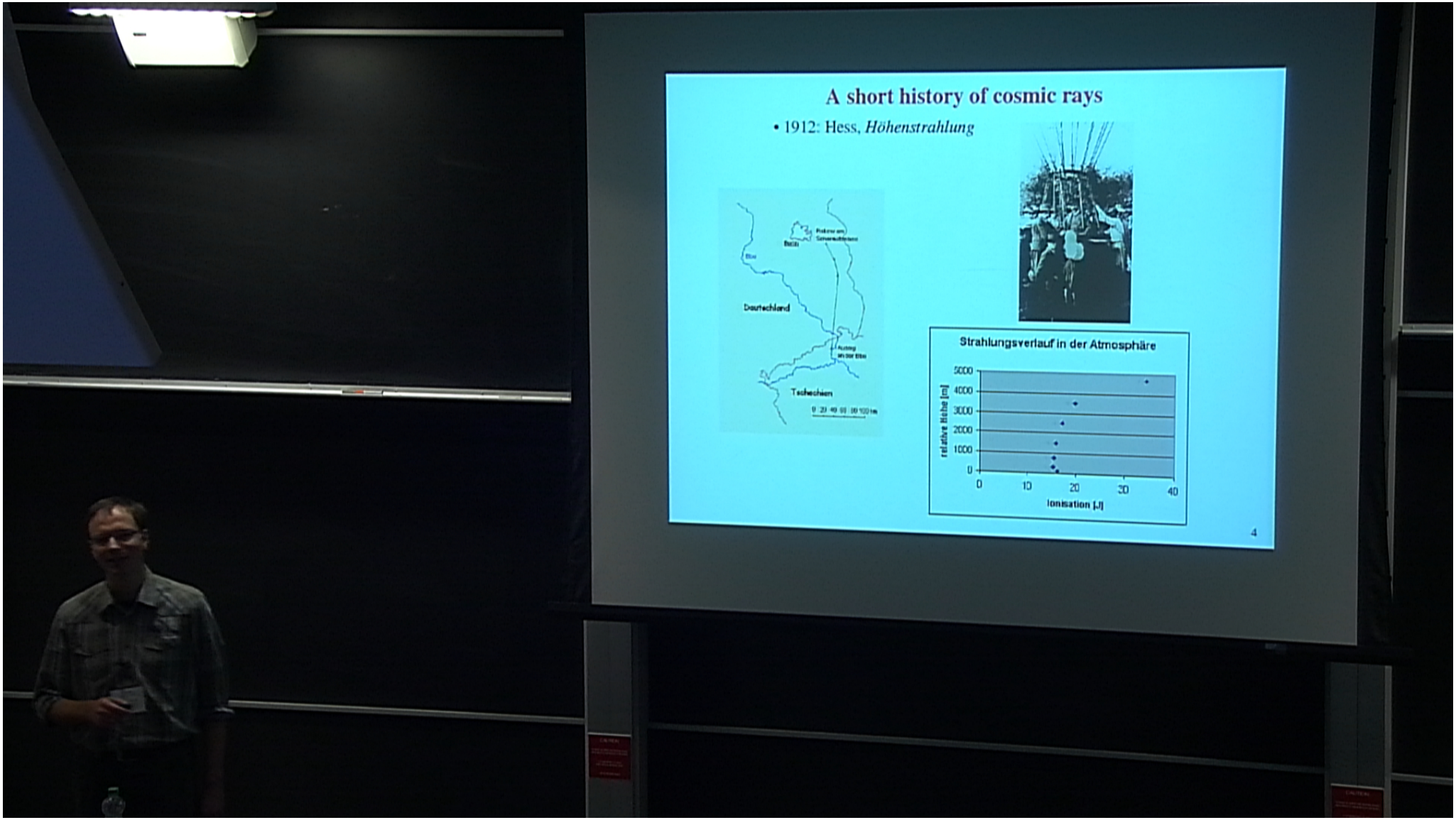
- A historical introduction
- Pierre Auger Observatory
- Some results and outlook

Windows to the Universe



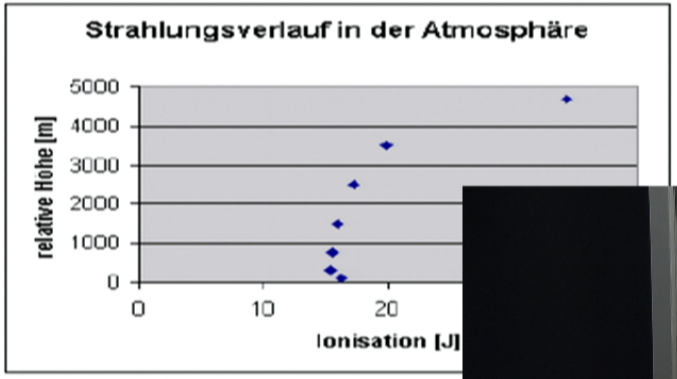
new window or deeper look - new discoveries

- e.g. CMB, γ-ray bursts, muon, neutrino oscillation
- sometimes completely unexpected
- impact on different fields of physics *(astro /particle /cosmo / fundamental ...)*


A short history of cosmic rays
• 1912: Hess, *Höhenstrahlung*
Deutschland
Tschechien
Strahlungsverlauf in der Atmosphäre
relative Höhe [m]
5000
4000
3000
2000
1000
0
0
10
20
30
40
Ionisation [J]
4

A short history of cosmic rays

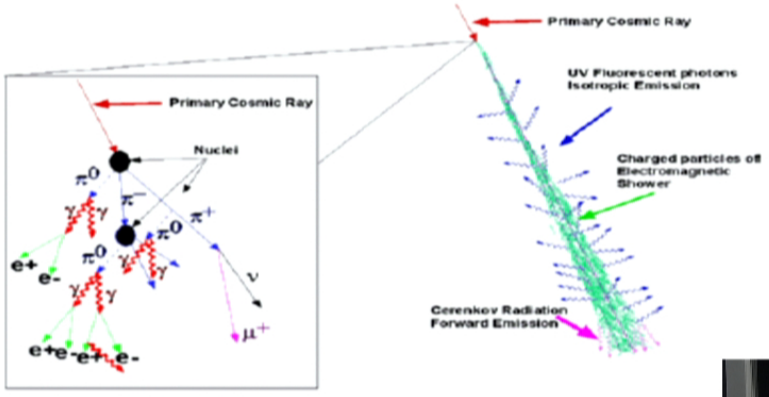
- 1912: Hess, *Höhenstrahlung*



A short history of cosmic rays

- 1912: Hess, *Höhenstrahlung*
- 1938: Auger / Kohlhörster ..., *air shower [~PeV]*

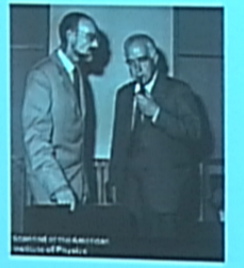
P. Auger, N. Bohr



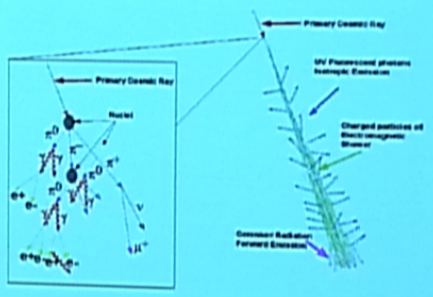
(still) the tool to observe UHECR !

A short history of cosmic rays

- 1912: Hess, *Höhenstrahlung*
- 1938: Auger / Kohlhörster ..., *air shower [~PeV]*



P. Auger, N. Bohr



(still) the tool to observe UHECR !

5

A short history of cosmic rays

- 1912: Hess, *Höhenstrahlung*
- 1938: Auger / Kohlhörster ..., *air shower [~PeV]*
- 1961: Linsley, *>10 EeV showers*

Linsley (checking for rattlesnakes)

2 km^2 array of scintillators

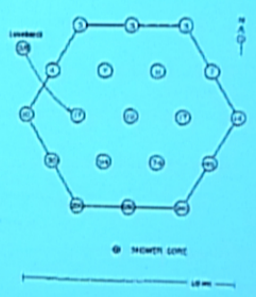


FIG. 1. Diagram of the Volcano Ranch 2-km^2 array, showing the location of the shower axis and measured densities in particles/m^2 for this event, No. 30565. The shielded detector was located very near the individual route detector.

6

A short history of cosmic rays

- 1912: Hess, *Höhenstrahlung*
- 1938: Auger / Kohlhörster ..., *air shower [~PeV]*
- 1961: Linsley, *>10 EeV showers*

Linsley (checking for rattlesnakes)

2 km^2 array of scintillators

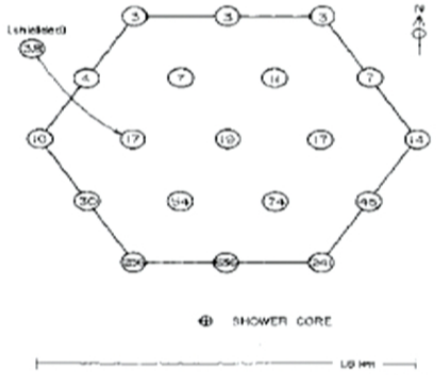


FIG. 1. Diagram of the Volcano Ranch 2
showing the location of the shower axis and
densities in particles/m^2 for this event. No
The shielded detector was located very nea
cated main detector.

A short history of cosmic rays

- 1912: Hess, *Höhenstrahlung*
- 1938: Auger / Kohlhörster ..., *air shower [~PeV]*
- 1961: Linsley, *>10 EeV showers*
- 1965: Penzias and Wilson, *CMB*
- 1966: Greisen, Zatsepin, Kuzmin, *prediction flux suppression*

>50 EeV proton and CMB (energy loss length ~20 Mpc)

$$p + \gamma_{2.7K} \rightarrow \Delta(1232) \rightarrow \begin{cases} n + \pi^+ \rightarrow \begin{cases} \mu^+ + \nu_\mu \\ e^+ + \bar{\nu}_\mu + \nu_e \end{cases} \\ p + \pi^0 \rightarrow \gamma + \gamma \end{cases}$$

3ν, each ~5% E_p

2γ, each ~10% E_p

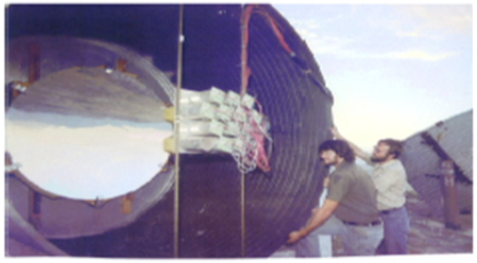
expect flux suppression !
unless source very close
nuclei: photodisintegration

correlation to close sources ?

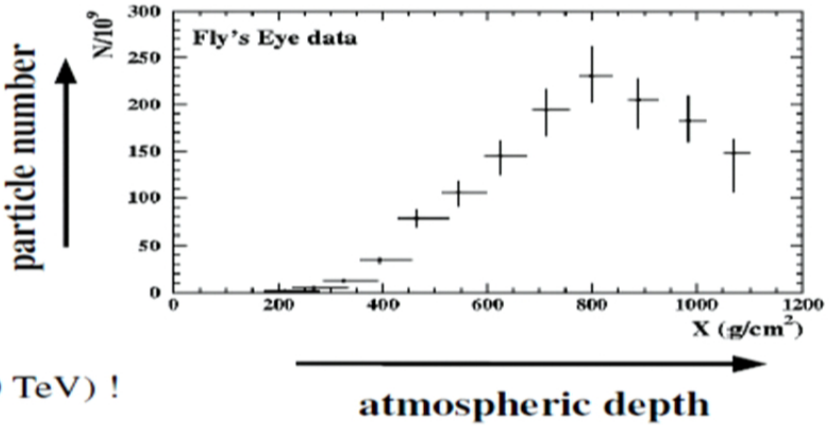
search for GZK photons and neutrinos !

A short history of cosmic rays

- 1912: Hess, *Höhenstrahlung*
- 1938: Auger / Kohlhörster ..., *air shower [~PeV]*
- 1961: Linsley, *>10 EeV showers*
- 1965: Penzias and Wilson, *CMB*
- 1966: Greisen, Zatsepin, Kuzmin, *prediction flux suppression*
- 1991: Fly's Eye Collaboration, *~300 EeV shower*



Fly's Eye fluorescence telescope



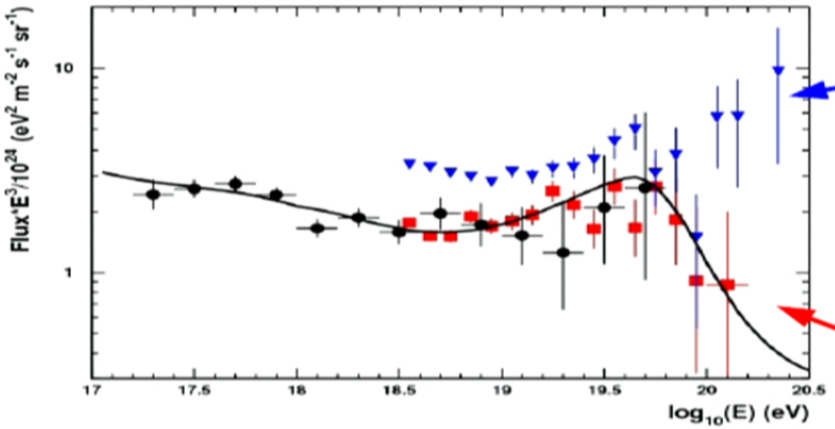
enormous energy (cf. LHC ~10 TeV) !
no obvious source correlation !?

8

A short history of cosmic rays

- 1912: Hess, *Höhenstrahlung*
- 1938: Auger / Kohlhörster ..., *air shower [~PeV]*
- 1961: Linsley, *>10 EeV showers*
- 1965: Penzias and Wilson, *CMB*
- 1966: Greisen, Zatsepin, Kuzmin, *prediction flux suppression*
- 1991: Fly's Eye Collaboration, *~300 EeV shower*
- 2004: AGASA array vs HiRes telescope: *suppression or not?*

flux scaled by E^3 !



No ! (AGASA, 100 km^2)

Yes ! (HiRes)

Problem: **statistics** & **systematics**. Needed: **BIG** & **BOTH**

Theory status 2004

- **bottom-up models (astrophysics):**
  - active galactic nuclei, gamma-ray bursts, jets in radio galaxies, pulsars, ...
  - → *but not easy to accelerate particles to* $>10^{20}$ *eV*

    and arrival directions ~isotropic, no obvious correlations.

    Mostly ***protons*** *discussed as primaries.*

photon fractions < ~1%

smoking gun !

- **top-down models (particle physics):**
  - super-heavy dark matter, topological defects; monopoles, strings, necklaces, WIMPZILLAS, cryptons ...
  - → *hypothetical massive objects produce normal particles*

photon fractions > ~10%

10

To Do:

→ *big & both: Pierre Auger Observatory*

flux suppression at highest energies ?

large photon fluxes ? general: **particle type - proton ?**

directional correlation (anisotropy) ?

particle / fundamental physics ?

....

Pierre Auger Collaboration

J. Cronin
A. Watson

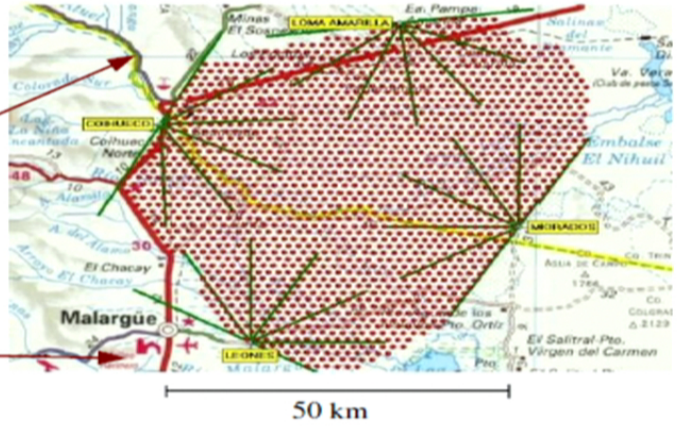
~500 scientists from 19 countries

Pierre Auger Collaboration

J. Cronin
A. Watson

~500 scientists from 19 countries

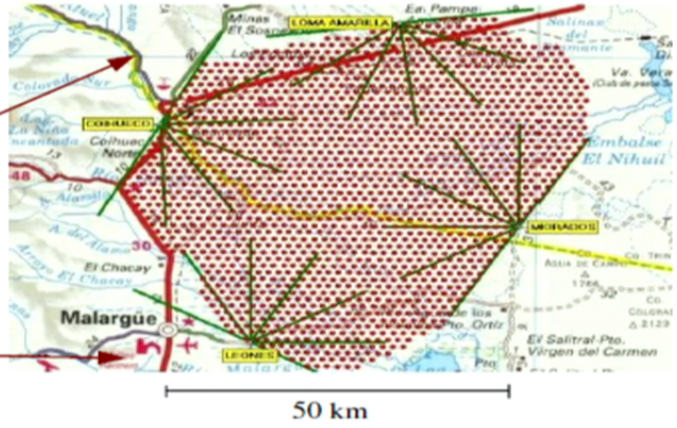
Pierre Auger Observatory



Pampa Amarilla (*Malargüe, province of Mendoza*)

- 1600 **water Cherenkov tanks** (1.5 km distance) **=> 3000 km²**
- 4 stations, each of 6 (fluorescence) **telescopes**
- **physics data since 2004**, inauguration November 2008

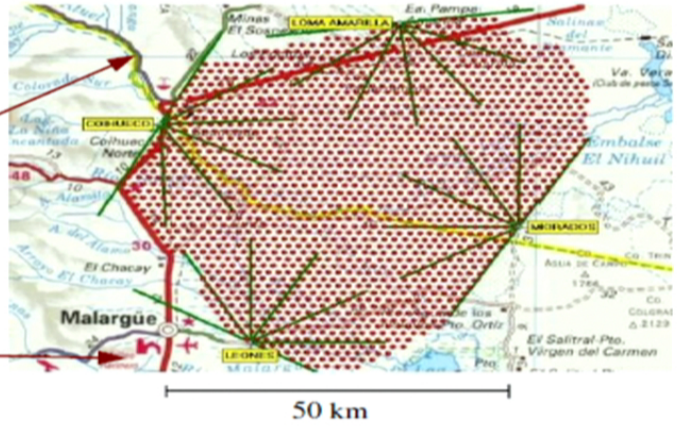
Pierre Auger Observatory



Pampa Amarilla (*Malargüe, province of Mendoza*)

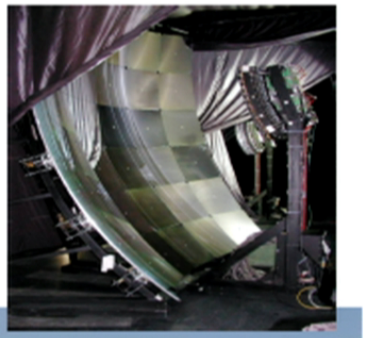
- 1600 **water Cherenkov tanks** (1.5 km distance) **=> 3000 km²**
- 4 stations, each of 6 (fluorescence) **telescopes**
- **physics data since 2004**, inauguration November 2008

Pierre Auger Observatory

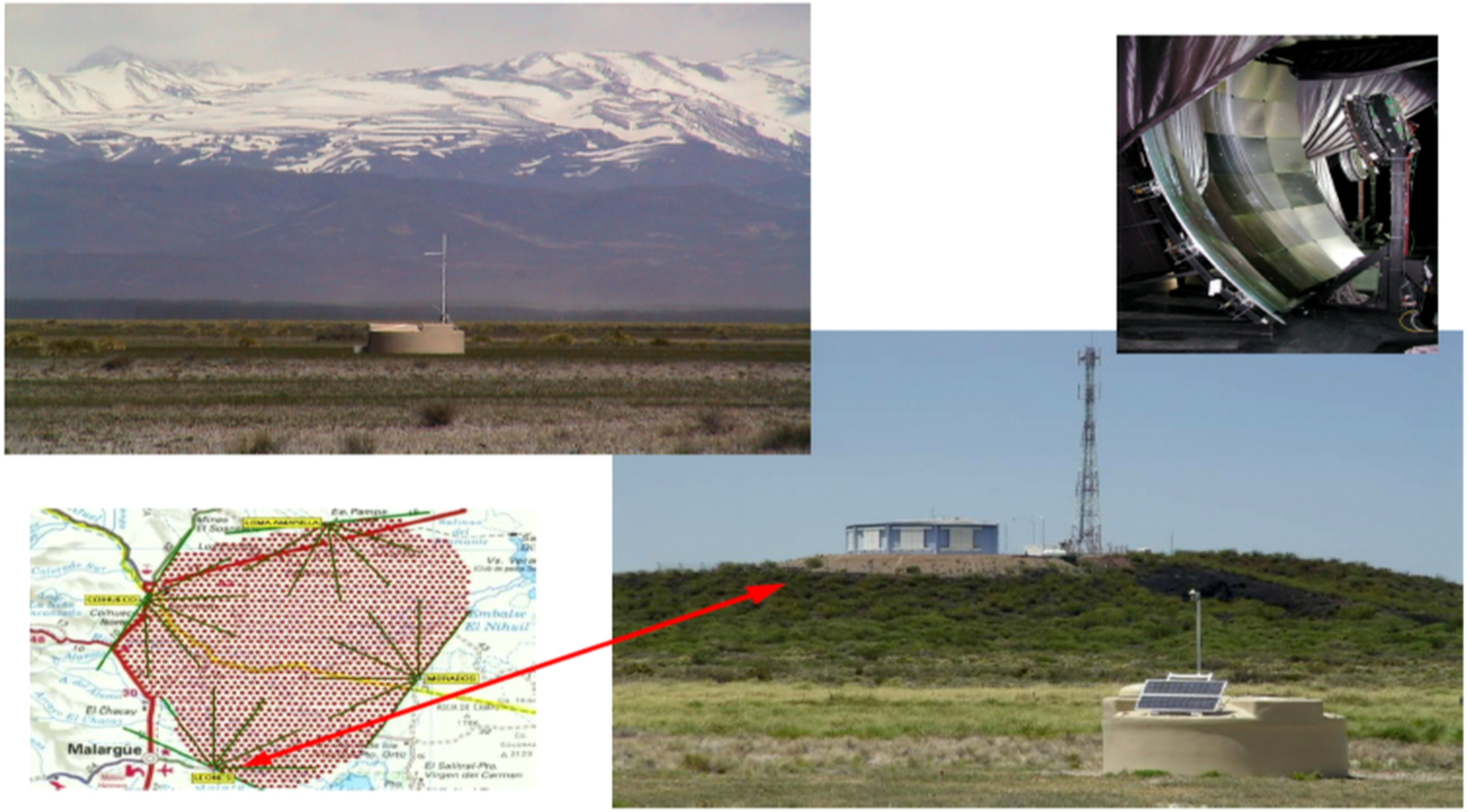


Pampa Amarilla (*Malargüe, province of Mendoza*)

- 1600 **water Cherenkov tanks** (1.5 km distance) **=> 3000 km²**
- 4 stations, each of 6 (fluorescence) **telescopes**
- **physics data since 2004**, inauguration November 2008



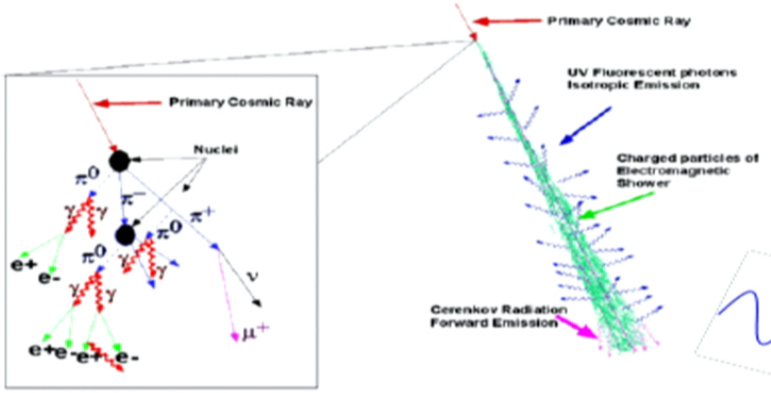

Malargüe
El Chacay
Embalse
El Nihuil


Malargüe
Embalse El Nihuil
El Chacay

... out to the Pampa ...

Test your eyes !

One air shower, two techniques

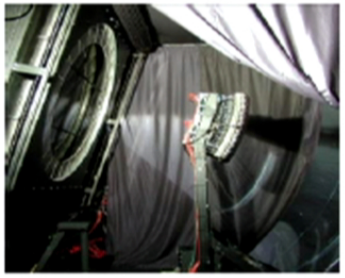


- collisions in atmosphere
- → secondary particle cascades
- → direction ~1°, energy ~20%, type

fluorescence light

particles on ground

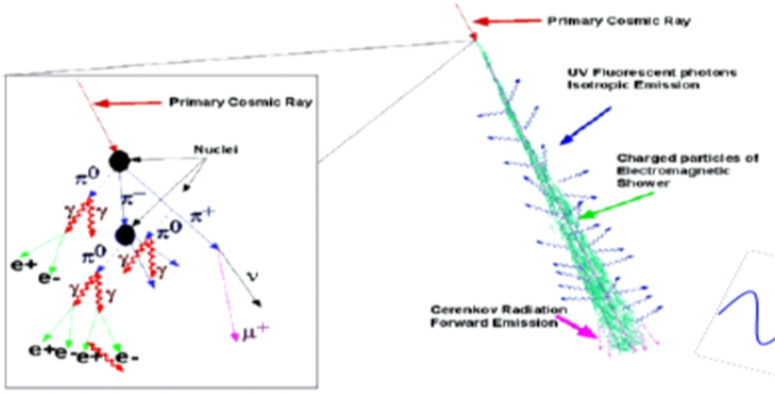
water tanks =>
Cherenkov light



only in clear nights (~10%)

22

One air shower, two techniques

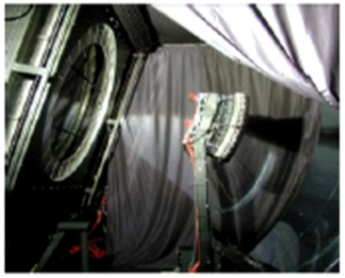


- collisions in atmosphere
- → secondary particle cascades
- → direction ~1°, energy ~20%, type

fluorescence light

particles on ground

water tanks =>
Cherenkov light

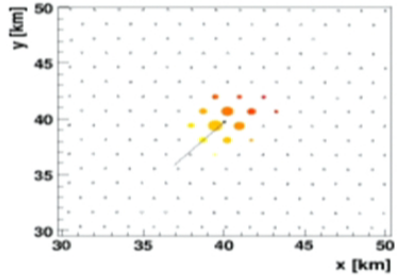


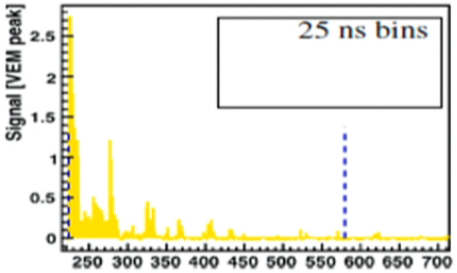
only in clear nights (~10%)

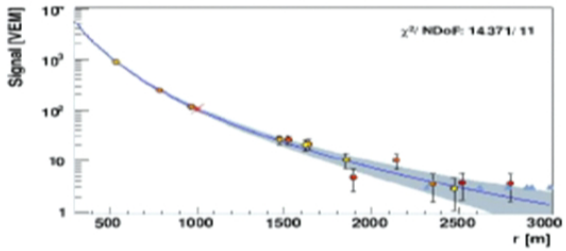
22

Ground array

tank signal
= s(r,t)

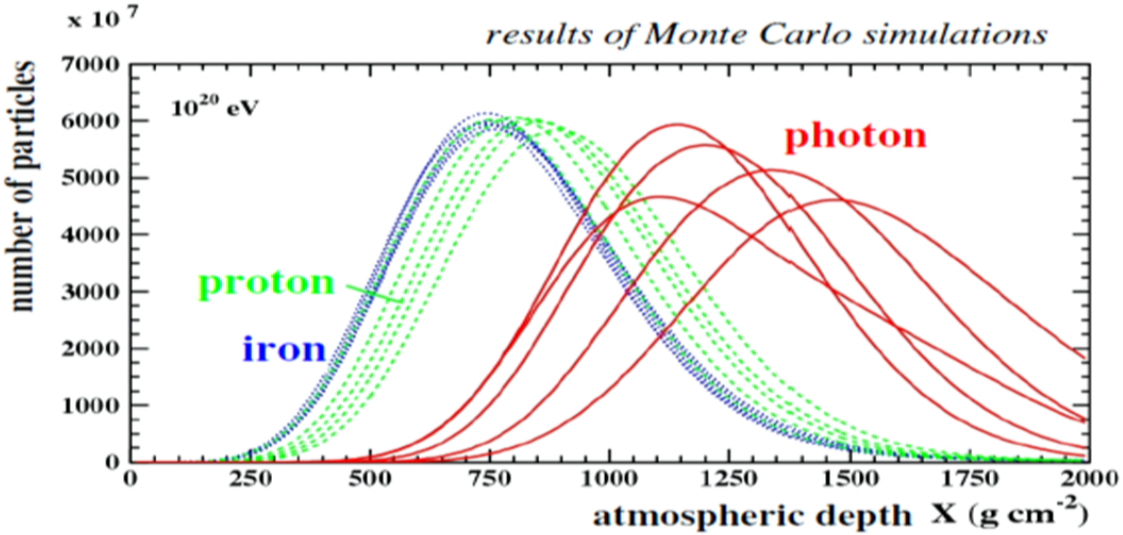






- **geometry** (timing of triggered tanks)
- **lateral distribution**
- → **S(1000)** (→ energy) and signal **risetime ...** (→ primary type)

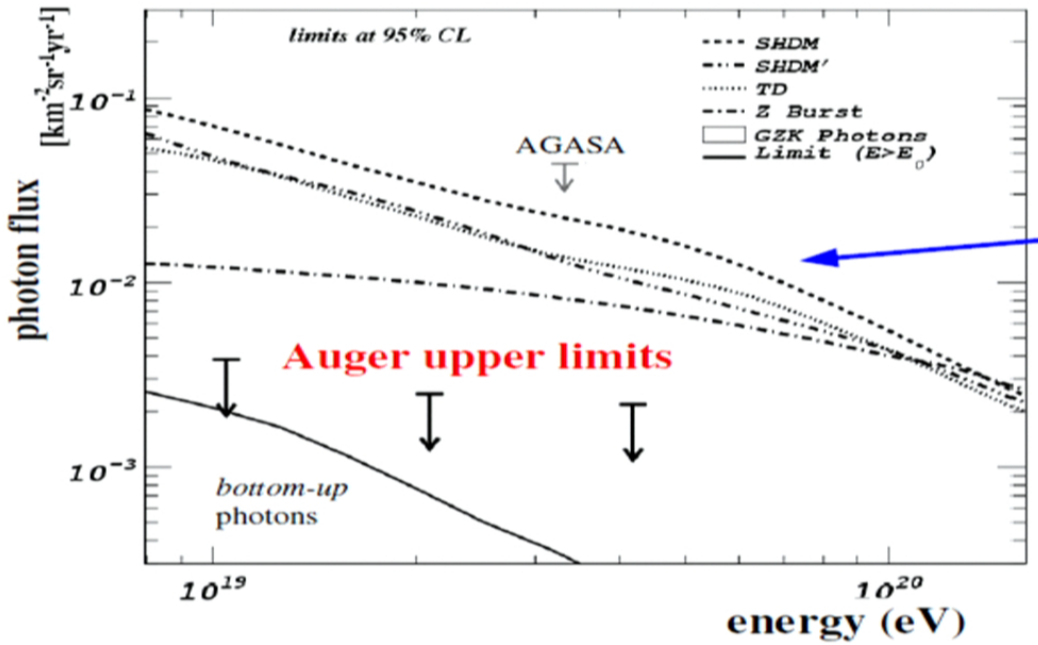
Large photon fluxes ? Separate photon & hadron



photon showers: larger X_{max} (and fewer muons) !

compare data to photon simulations → upper limits

Large photon fluxes ?



Auger 2008

top-down predictions

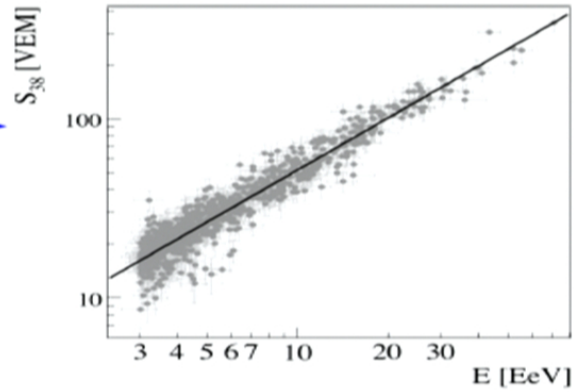
No ! → *top-down* models strongly constrained

... confi
neutri

continue search for GZK photons and neutrinos

Flux suppression at high energy ?

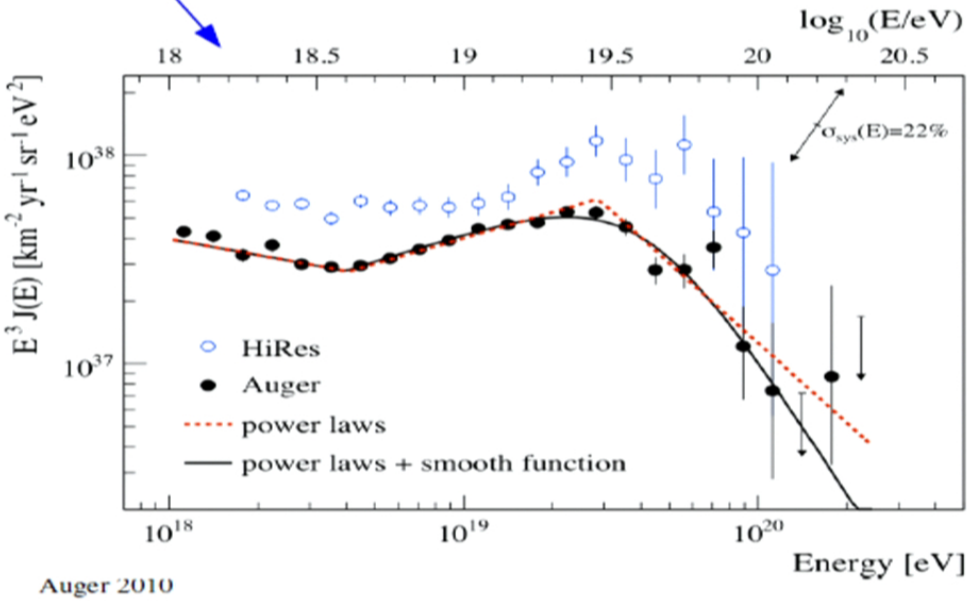
(A) calibration of array with telescopes
(B) flux = # events / exposure



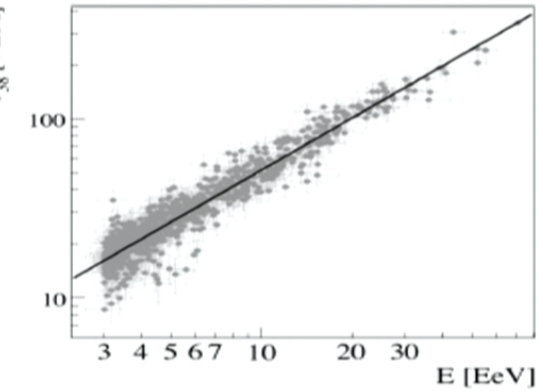
Flux suppression at high energy ?

(A) calibration of array with telescopes

(B) flux = # events / exposure



Auger 2010



Yes !

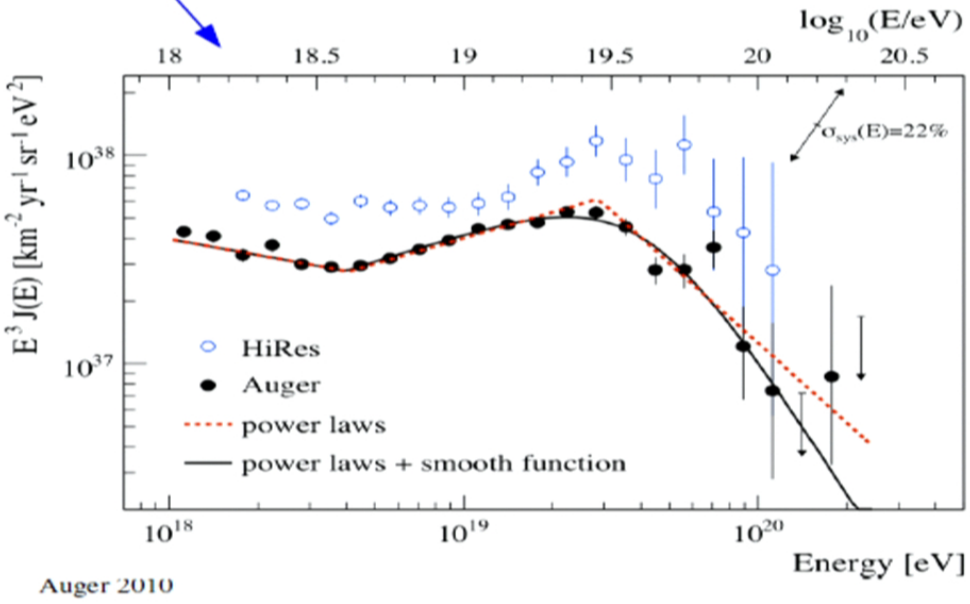
agrees to expectations
but no GZK-proof yet

ankle at 3 EeV

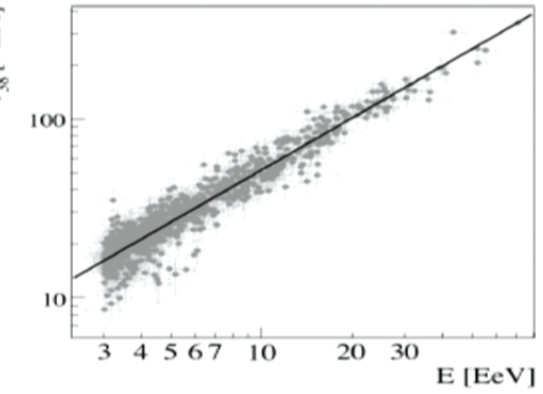
28

Flux suppression at high energy ?

(A) calibration of array with telescopes
(B) flux = # events / exposure



Auger 2010



Yes !

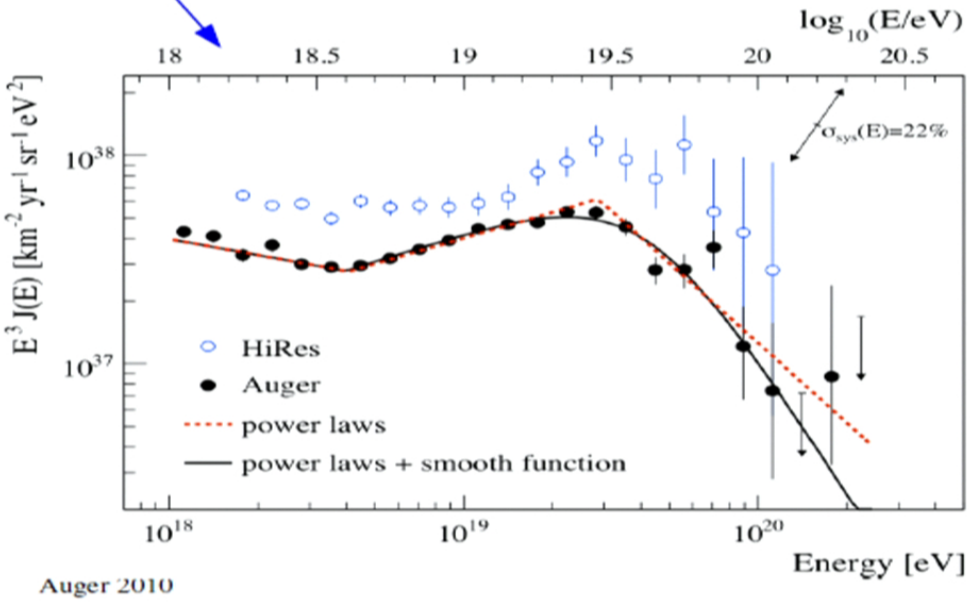
agrees to expectations
but no GZK-proof yet

ankle at 3 EeV

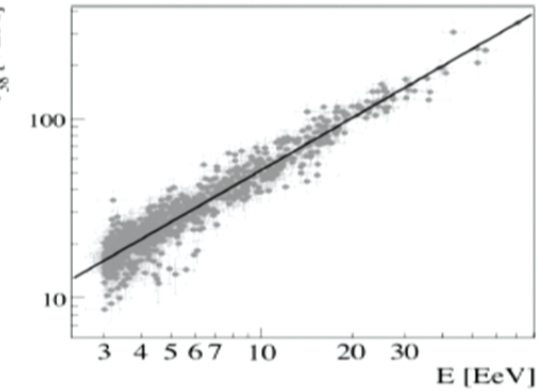
28

Flux suppression at high energy ?

(A) calibration of array with telescopes
(B) flux = # events / exposure



Auger 2010



Yes !

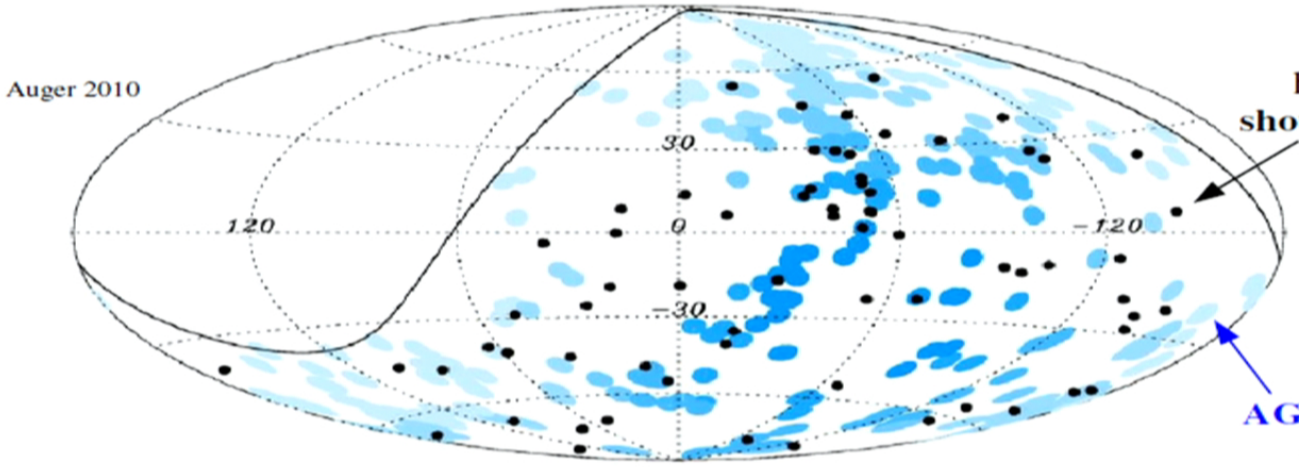
agrees to expectations
but no GZK-proof yet

ankle at 3 EeV

28

Directional correlations with nearby extragalactic matter ?

(1) fix energy threshold, AGN distance, angular radius by *exploratory scan*
(2) then test correlation with new data



2011 update:

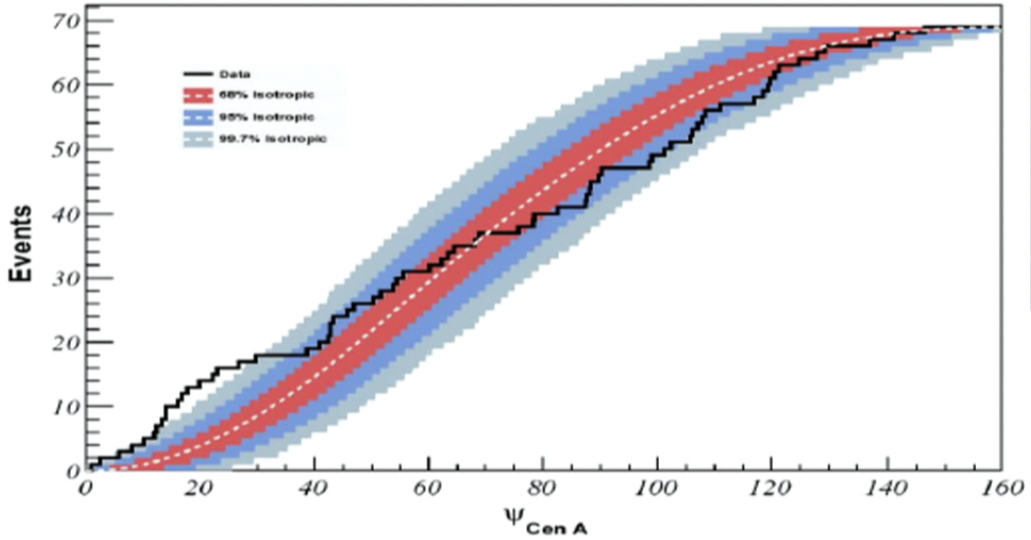
observed: 28 out of 84 matches (excluding exploratory scan)

expected: 17.6 random matches (if isotropy)

reject isotropy at ~99% CL

29

Directional correlation with Centaurus A ?



closest AGN
~4 Mpc

cumulative distribution around Cen A:

at 18°: 13 observed, 3.2 expected from isotropy

caveat: *a posteriori*

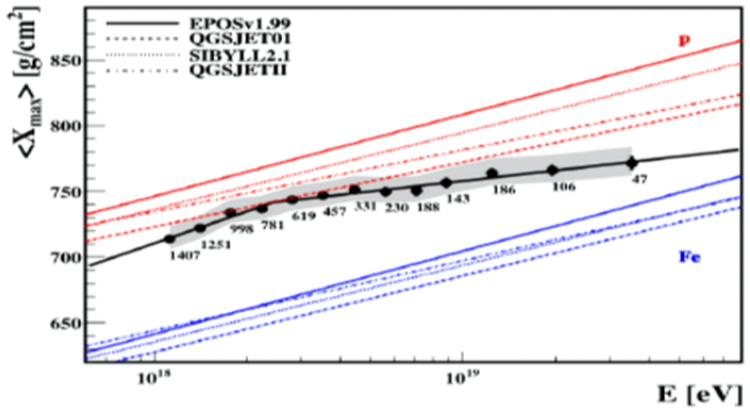
Primary type ?

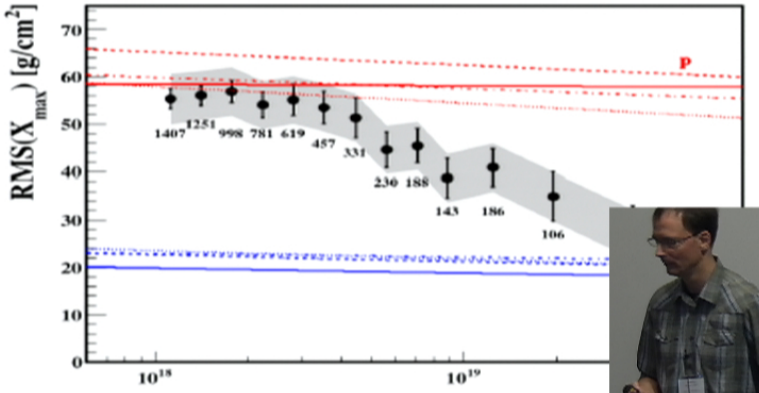
slopes change at the ankle

comparing to simulations:
from (rather) light to (more) heavy ?

particularly for RMS:
"proton-only" disfavoured

... unless drastic changes in interaction





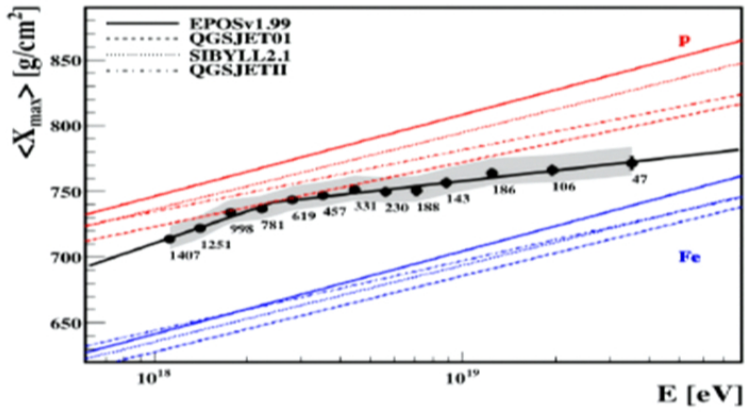
Primary type ?

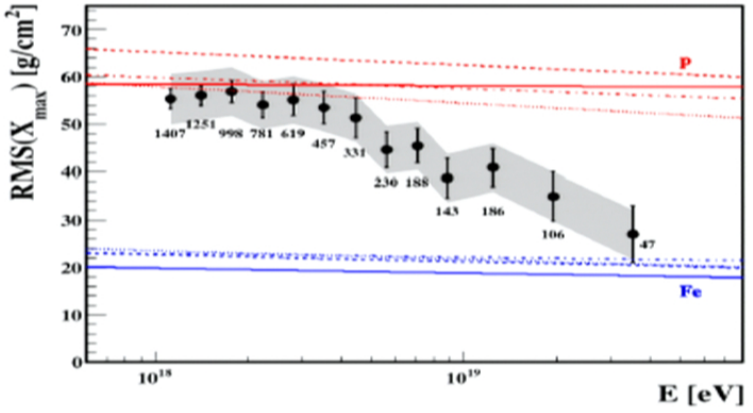
slopes change at the ankle

comparing to simulations:
from (rather) light to (more) heavy ?

particularly for RMS:
"proton-only" disfavoured

... unless drastic changes in interaction





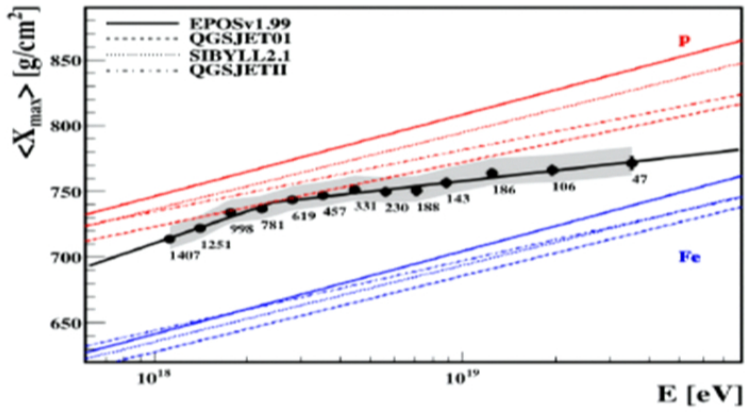
Primary type ?

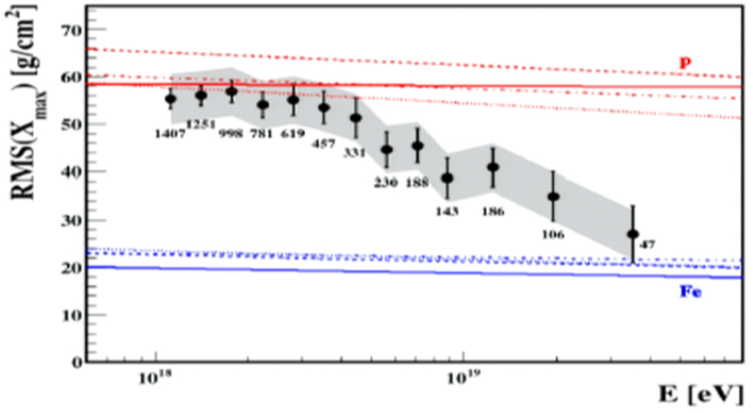
slopes change at the ankle

comparing to simulations:
from (rather) light to (more) heavy ?

particularly for RMS:
"proton-only" disfavoured

... unless drastic changes in interaction





Status & (some) open questions

- **photon limits:** top-down models disfavoured
  - bottom-up not necessarily right, but favoured
- **flux suppression** at highest energy
  - from propagation (GZK) or maximum source energy ?
- **directional correlation** only at highest energy (at 99% CL)
  - sources extragalactic; which ones exactly? Cen A?
  - indication of small charge and/or small magnetic fields ?
- **particle type:** small RMS(X_{max}) at highest energy
  - heavy nuclei or drastic change in interaction ?
- **ankle** at ~3 EeV (and composition change?)
  - transition gal./extragal. CR or "dip" from extragal. pure protons ?

important data input - no UHECR standard model yet

32

Status & (some) open questions

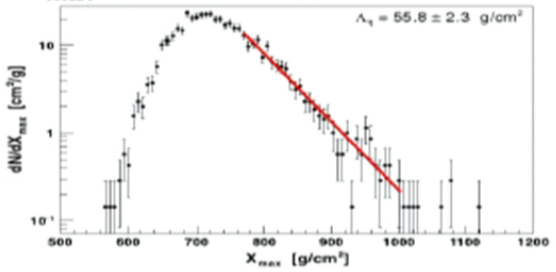
- **photon limits:** top-down models disfavoured
  - bottom-up not necessarily right, but favoured
- **flux suppression** at highest energy
  - from propagation (GZK) or maximum source energy ?
- **directional correlation** only at highest energy (at 99% CL)
  - sources extragalactic; which ones exactly? Cen A?
  - indication of small charge and/or small magnetic fields ?
- **particle type:** small RMS(X_{max}) at highest energy
  - heavy nuclei or drastic change in interaction ?
- **ankle** at ~3 EeV (and composition change?)
  - transition gal./extragal. CR or "dip" from extragal. pure protons ?

important data input - no UHECR standard model yet

32

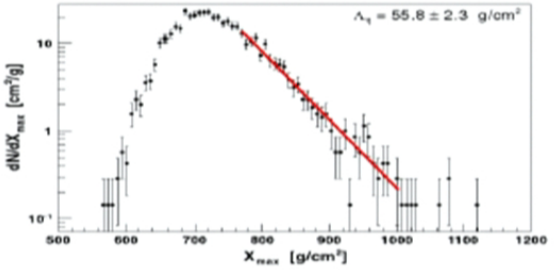
Cross-section at 2 EeV (or 57 TeV c.m.)

X_{max} connected to 1st interaction (and thus to cross-section)

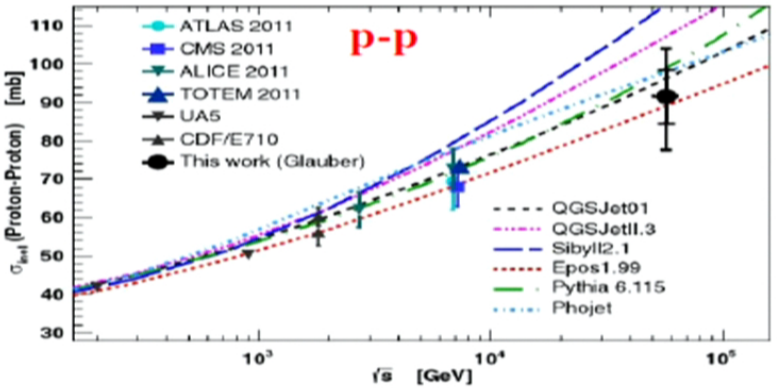


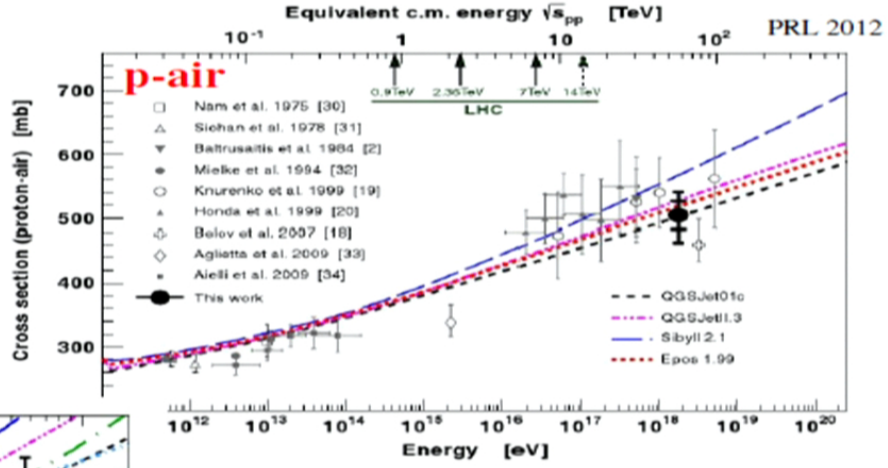
Cross-section at 2 EeV (or 57 TeV c.m.)

X_{max} connected to 1st interaction



transformation based on Glauber:





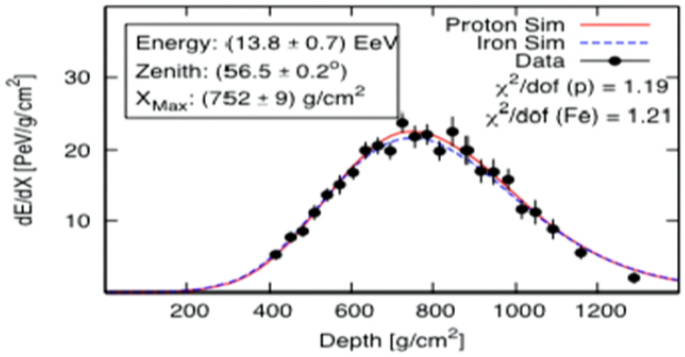
$$\sigma^{inel}_{p-air} = [505 \pm 22(stat)^{+28}_{-36}(syst)] \text{ mb}$$

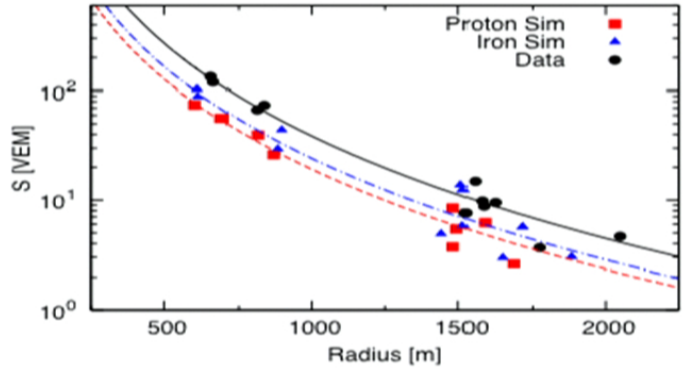
$$\sigma^{inel}_{pp} = [92 \pm 7(stat)^{+9}_{-11}(syst) \pm 7(Glauber)] \text{ mb}$$

$$\sigma^{tot}_{pp} = [133 \pm 13(stat)^{+17}_{-20}(syst) \pm 16(Glauber)] \text{ mb}$$

no indication for extrem

Too few muons in simulations ?





if longitudinal shower profile fits ...

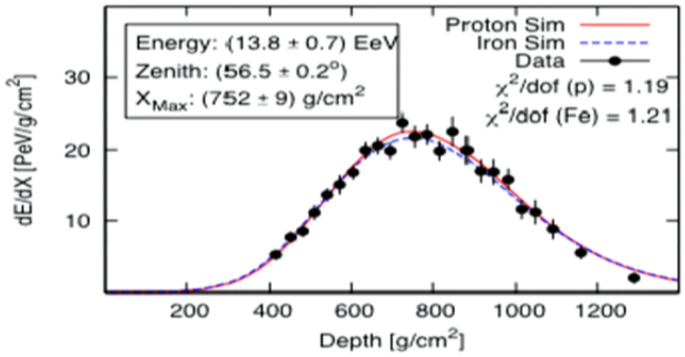
... simulated ground signal too small

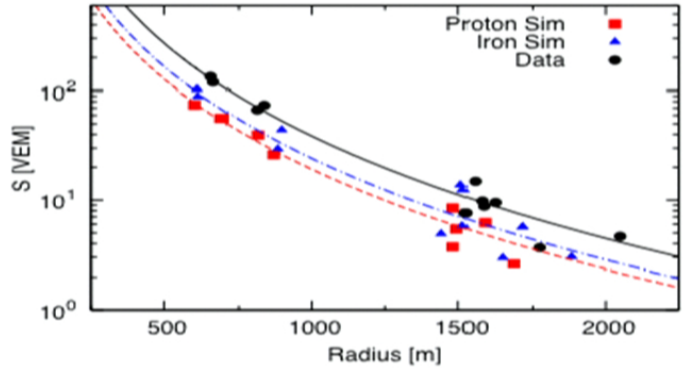
data even above expectation for Fe

... and Fe-only disfavoured by X_{max} at 10 EeV

34

Too few muons in simulations ?





if longitudinal shower profile fits ...

... simulated ground signal too small

data even above expectation for Fe

... and Fe-only disfavoured by X_{max} at 10 EeV

34

Lorentz transformation OK ? (1)

idea: check for accumulation of GZK photons! *(absence of standard interactions?)*

standard physics: GZK photons ~0.1% (due to energy loss by collisions)

$$p + \gamma_{CMB} \rightarrow \Delta \rightarrow p + \pi^0 \quad \hookrightarrow \gamma\gamma \not\rightarrow e^+e^-$$

but:

if Lorentz transformation not OK => larger fraction possible

Lorentz transformation OK ? (1)

idea: check for accumulation of GZK photons! *(absence of standard interactions?)*

standard physics: GZK photons ~0.1% (due to energy loss by collisions)

$$p + \gamma_{CMB} \rightarrow \Delta \rightarrow p + \pi^0 \quad \hookrightarrow \gamma\gamma \not\rightarrow e^+e^-$$

but:

if Lorentz transformation not OK => larger fraction possible

Lorentz transformation OK ? (1)

idea: check for accumulation of GZK photons! *(absence of standard interactions?)*

standard physics: GZK photons ~0.1% (due to energy loss by collisions)

$$p + \gamma_{CMB} \rightarrow \Delta \rightarrow p + \pi^0$$
$$\hookrightarrow \gamma\gamma \not\rightarrow e^+e^-$$

but:

if Lorentz transformation not OK => larger fraction possible

Lorentz transformation OK ? (1)

idea: check for accumulation of GZK photons! *(absence of standard interactions?)*

standard physics: GZK photons ~0.1% (due to energy loss by collisions)

$$p + \gamma_{CMB} \rightarrow \Delta \rightarrow p + \pi^0 \quad \hookrightarrow \gamma\gamma \not\rightarrow e^+e^-$$

but:

if Lorentz transformation not OK => larger fraction possible

Lorentz transformation OK ? (2)

idea: mere existence of UHECR ! *(presence of non-standard interactions?)*

LV theory

rapid energy loss $>E_{th}$

observing $E \Rightarrow E_{th}>E \Rightarrow$ constrain κ

Lorentz transformation OK ? (2)

idea: mere existence of UHECR ! *(presence of non-standard interactions?)*

LV theory [e.g. nonbirefringent modified Maxwell theory, 9 LV parameters κ]

rapid energy loss $>E_{th}$ [e.g. vacuum-Cherenkov $p \rightarrow p\gamma$, with $E_{th}(\kappa)\rightarrow\infty$ for $\kappa\rightarrow 0$]

observing $E \Rightarrow E_{th}>E \Rightarrow$ **constrain** κ [e.g. 1 isotropic $\kappa_{tr}< 2\cdot 10^{-19}$]

[Klinkhamer 2010, Klinkhamer & MR 2008]

roughly: $E_{\text{thresh}} \sim M_{\text{prim}} c^2/\sqrt{\kappa}$

$\Rightarrow \kappa < (M/E)^2 \simeq (50\ \text{GeV} / 100\ \text{EeV})^2 \simeq 2\cdot 10^{-19}$ (!)

UHECR do reach us
=> no indication for LV

interesting constraints also once UHE photons are found *(absence of* γ –

Lorentz transformation OK ? (2)

idea: mere existence of UHECR ! *(presence of non-standard interactions?)*

LV theory [e.g. nonbirefringent modified Maxwell theory, 9 LV parameters κ]

rapid energy loss $>E_{th}$ [e.g. vacuum-Cherenkov $p \rightarrow p\gamma$, with $E_{th}(\kappa)\rightarrow\infty$ for $\kappa\rightarrow 0$]

observing $E \Rightarrow E_{th}>E \Rightarrow$ **constrain** κ [e.g. 1 isotropic $\kappa_{tr}< 2\cdot 10^{-19}$]

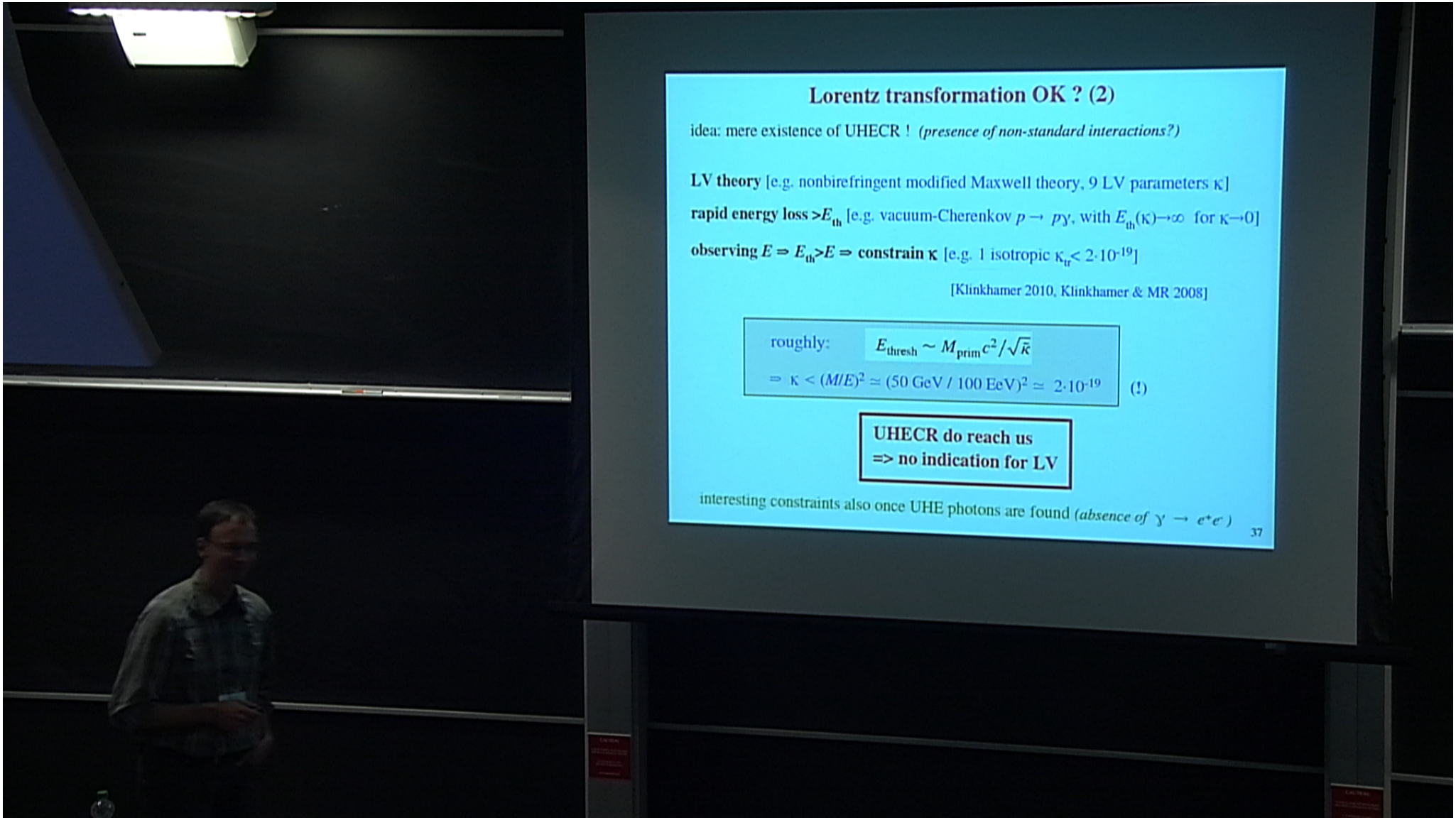
[Klinkhamer 2010, Klinkhamer & MR 2008]

roughly: $E_{\text{thresh}} \sim M_{\text{prim}} c^2/\sqrt{\kappa}$

$\Rightarrow \kappa < (M/E)^2 \simeq (50\ \text{GeV} / 100\ \text{EeV})^2 \simeq 2\cdot 10^{-19}$ (!)

UHECR do reach us
=> no indication for LV

interesting constraints also once UHE photons are found *(absence of* γ –


Lorentz transformation OK ? (2)
idea: mere existence of UHECR ! (presence of non-standard interactions?)
LV theory [e.g. nonbirefringent modified Maxwell theory, 9 LV parameters κ]
rapid energy loss >E_{th} [e.g. vacuum-Cherenkov $p \rightarrow p\gamma$, with $E_{th}(\kappa)\rightarrow\infty$ for $\kappa\rightarrow 0$]
observing $E \Rightarrow E_{th} > E \Rightarrow$ constrain κ [e.g. 1 isotropic $\kappa_{tr} < 2\cdot10^{-19}$]
[Klinkhamer 2010, Klinkhamer & MR 2008]
roughly: $E_{thresh} \sim M_{prim}c^2/\sqrt{\kappa}$
$\Rightarrow \kappa < (M/E)^2 \simeq (50\ \text{GeV} / 100\ \text{EeV})^2 \simeq 2\cdot10^{-19}$ (!)
UHECR do reach us
=> no indication for LV
interesting constraints also once UHE photons are found (absence of $\gamma \rightarrow e^+e^-$)
37

Upgrades and R&D at the Auger Observatory

AMIGA - infill array:
750 m on ~20 km^2

HEAT: low-energy shower profiles

AMIGA - dedicated muon detectors

AERA (radio), EASIER ... (microwave):
observe profiles with 100% duty cycle?

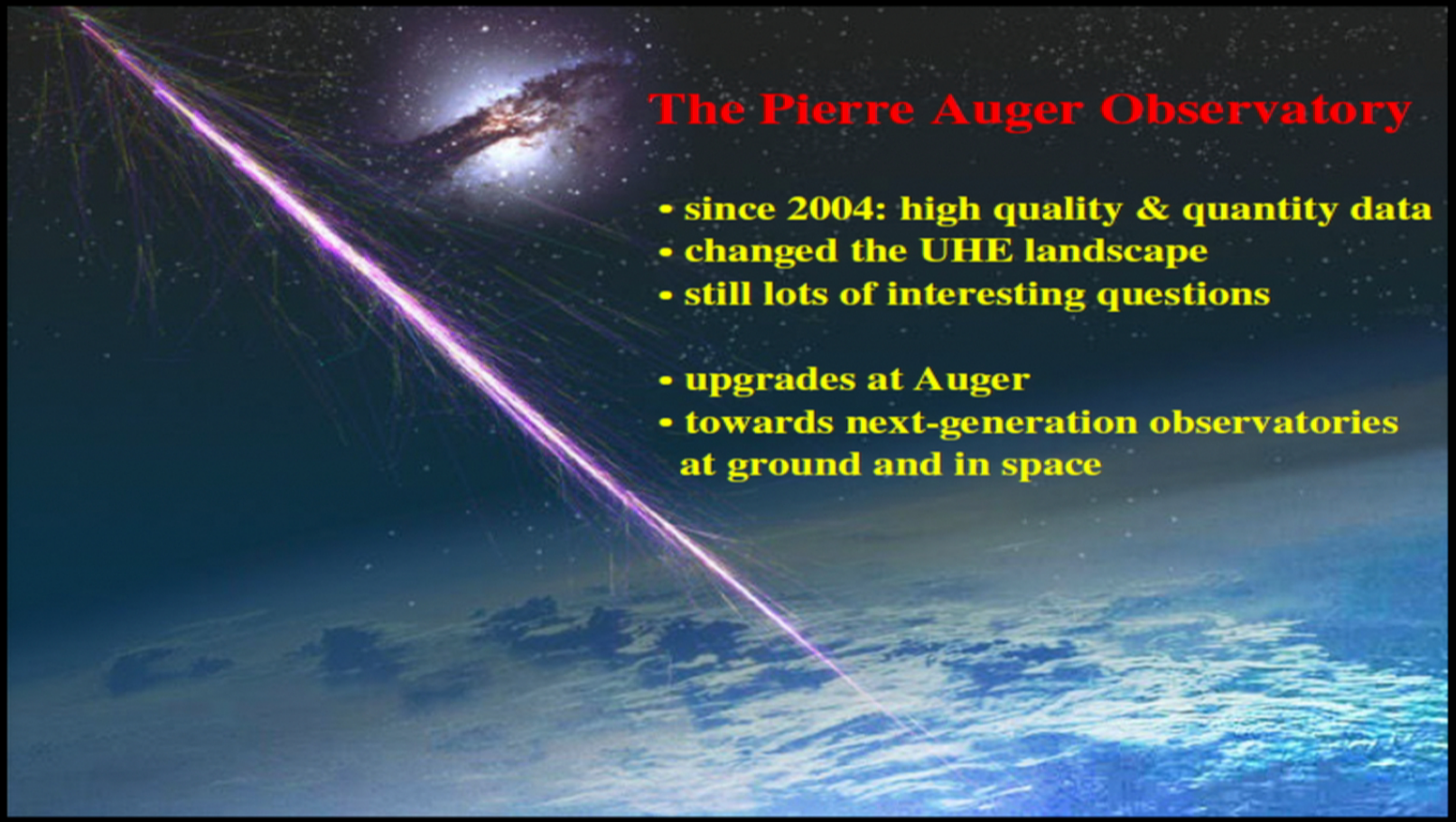
38

Beyond the Auger Observatory

joint symposium of UHE community:

"prepare for next generation ground based giant detector"

- working groups established
- follow-up meetings


The Pierre Auger Observatory
• since 2004: high quality & quantity data
• changed the UHE landscape
• still lots of interesting questions
• upgrades at Auger
• towards next-generation observatories
at ground and in space