An introduction to
Ultra-High Energy Cosmic Rays

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Codes in Astroparticle Research

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HELMHOLTZ | GEMEINSCHAFT

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Astroteilchenphysik

Großgeräte der physikalischen Grundlagenforschung

Ultra-high energy cosmic rays

Definition wikipedia:

In astroparticle physics, an **ultra-high-energy cosmic ray** (**UHECR**) is a cosmic ray particle with a kinetic energy greater than 10^{18} eV, far beyond both its rest mass and energies typical of other cosmic ray particles.

Let's have a closer look…

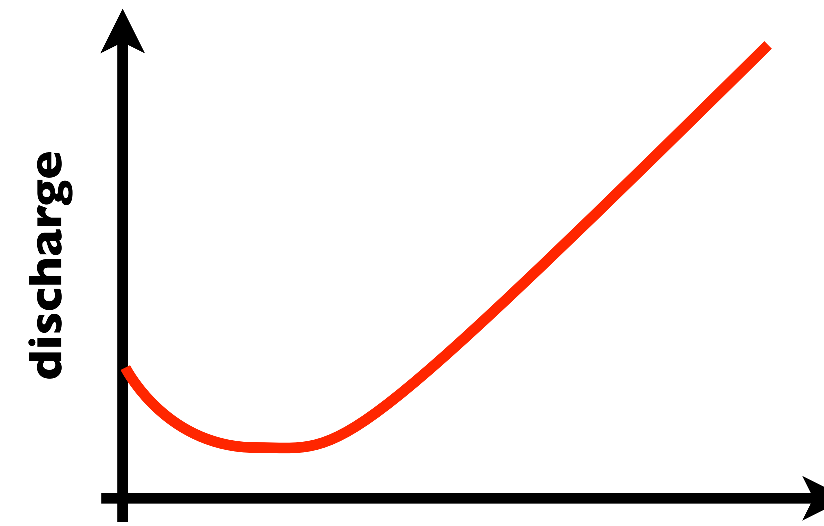
It was August 7 1912 - 6am ...

Victor Franz Hess

Victor Franz Hess:
How fast does an electroscope discharge when we leave the surface of the Earth?

Expectation:
Discharge should decrease for increasing altitude

Observation:
After a specific height discharge increases!!



Ballon of Franz Victor Hess

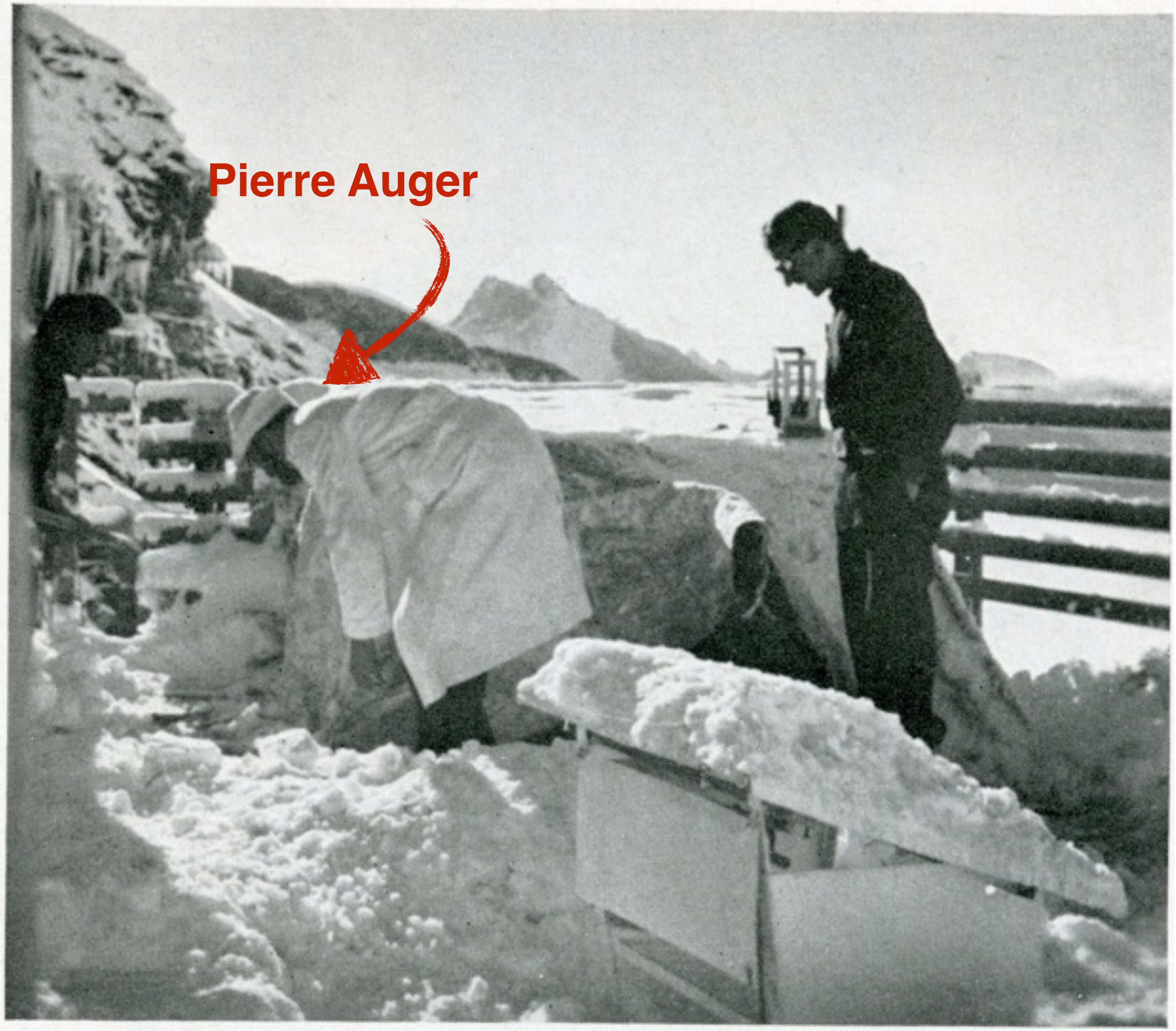
Hess after landing

Conclusion:
This radiation is not from Earth, it's from space!

24 years later he receives the Nobel price for the discovery of cosmic rays

… the story continues…

Year 1938:



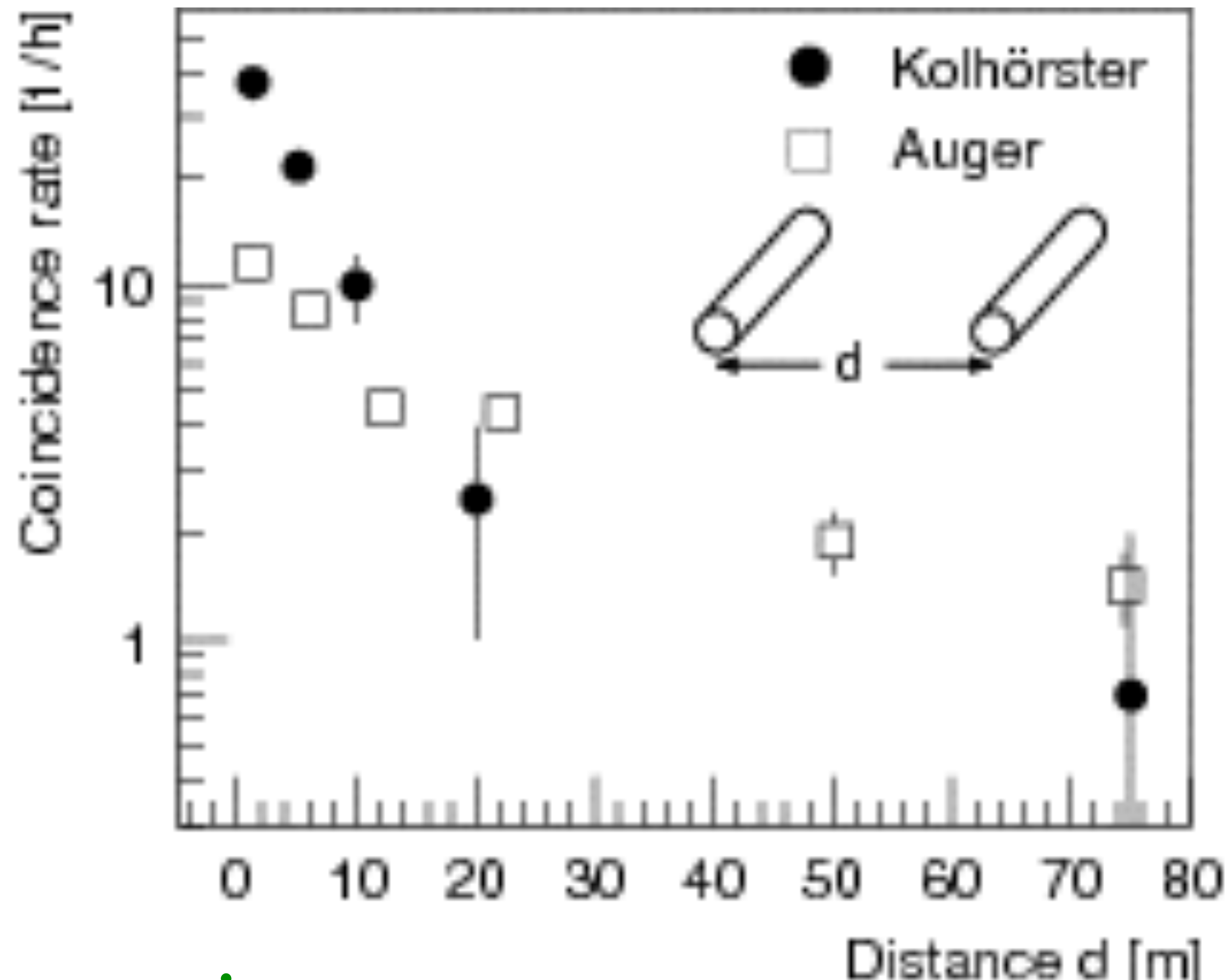
MEASURING COSMIC RAYS IN THE SWISS ALPS

The author (*left*) and his collaborator, P. Ehrenfest, set up their apparatus in the Jungfraujoch.

Extensive air showers (EAS)

Pierre Auger

Werner Kolhörster



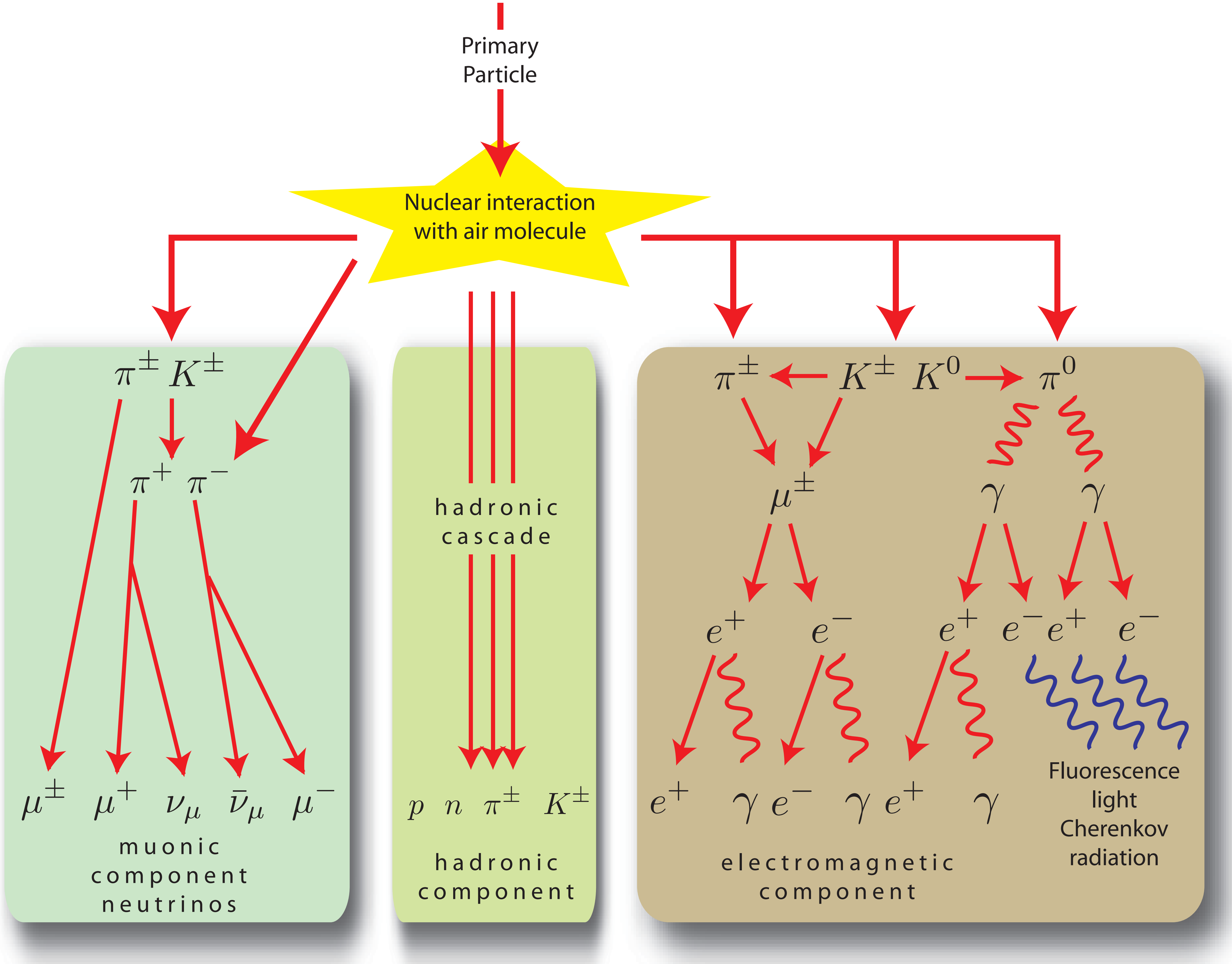
Observation:

Even at spacings of ~80 m they detect coincidences of particles

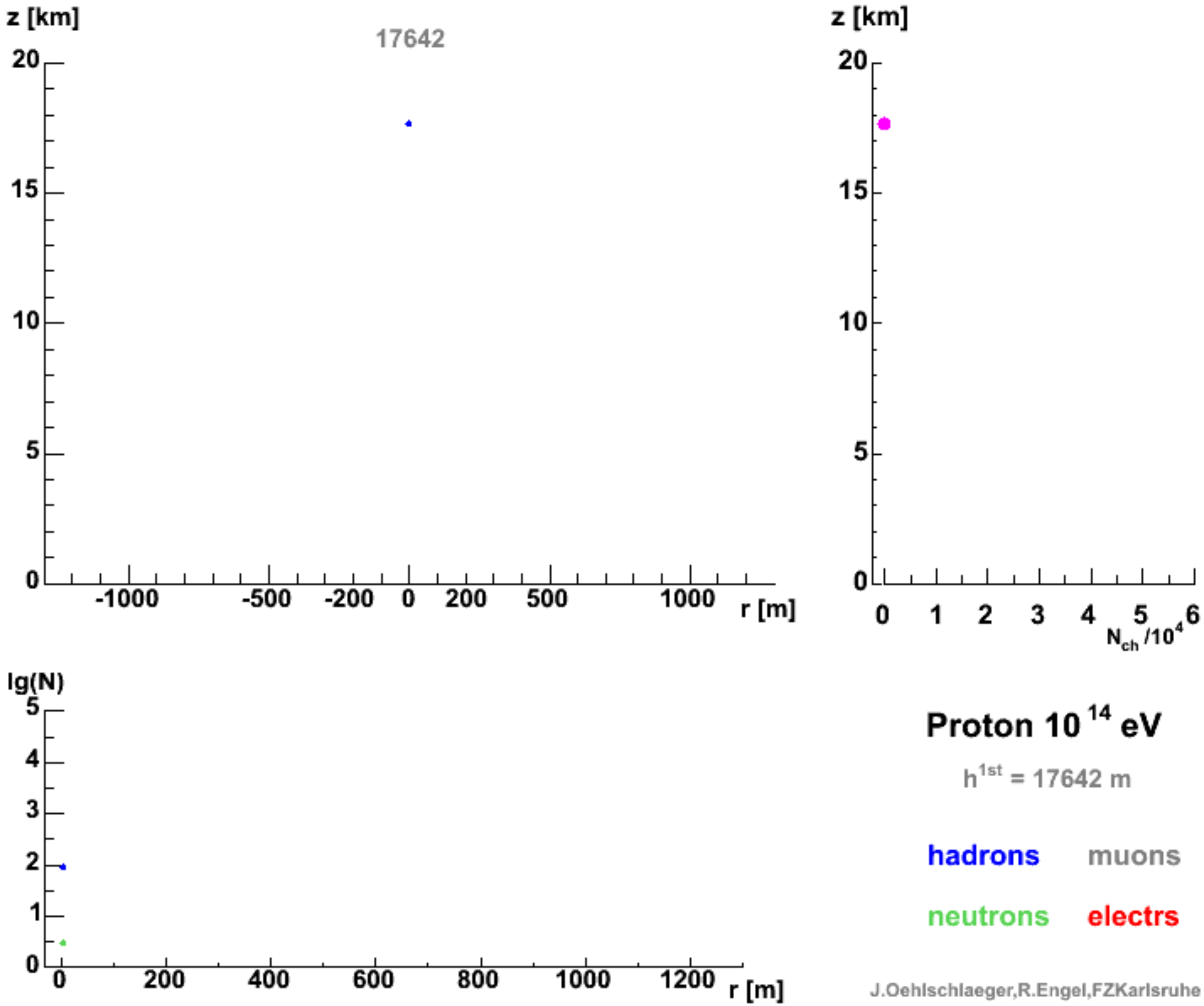
Explanation:

These particles are secondary particles from **extensive air showers**!

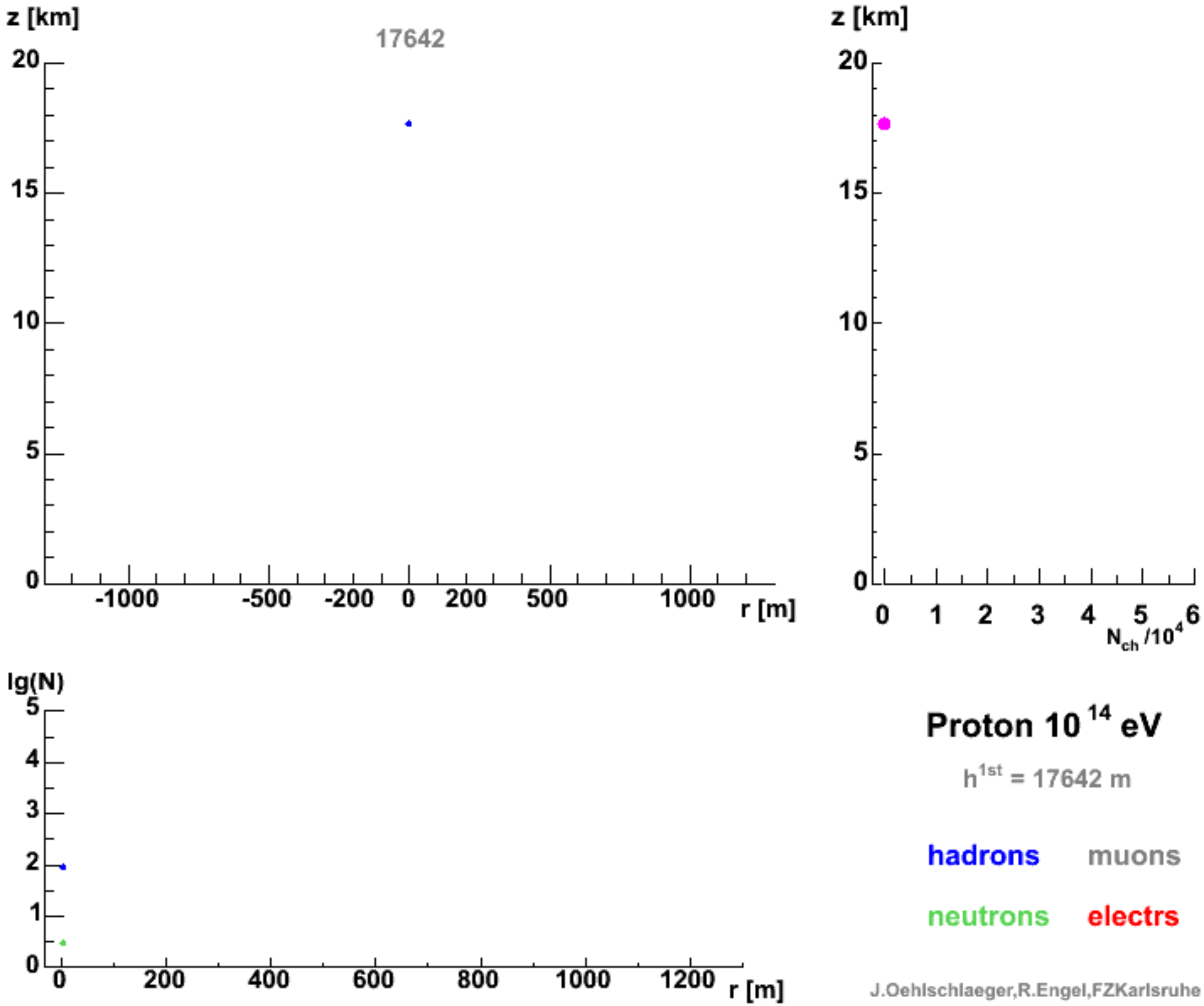
Extensive air showers



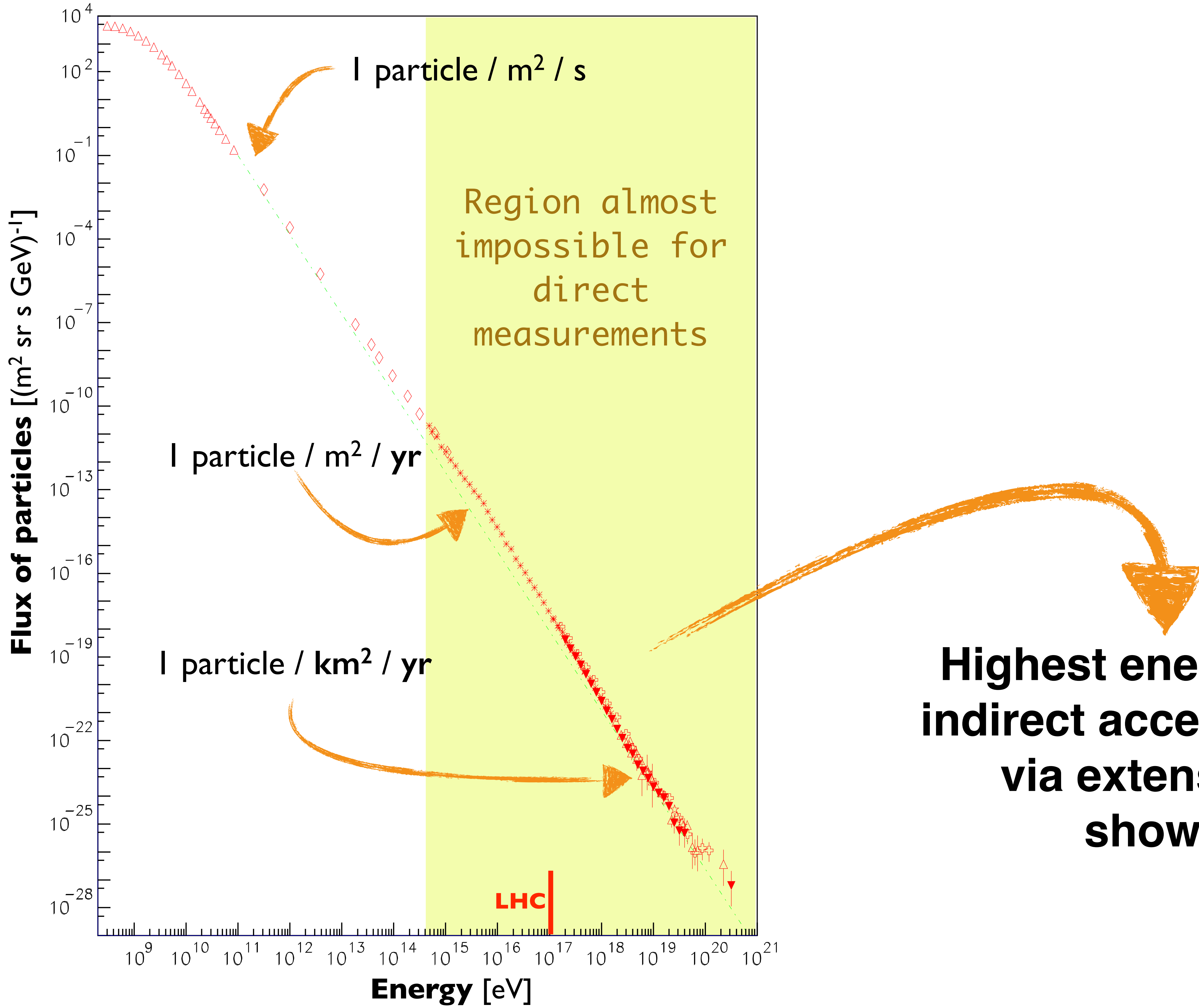
Extensive air showers (EAS)



Extensive air showers (EAS)



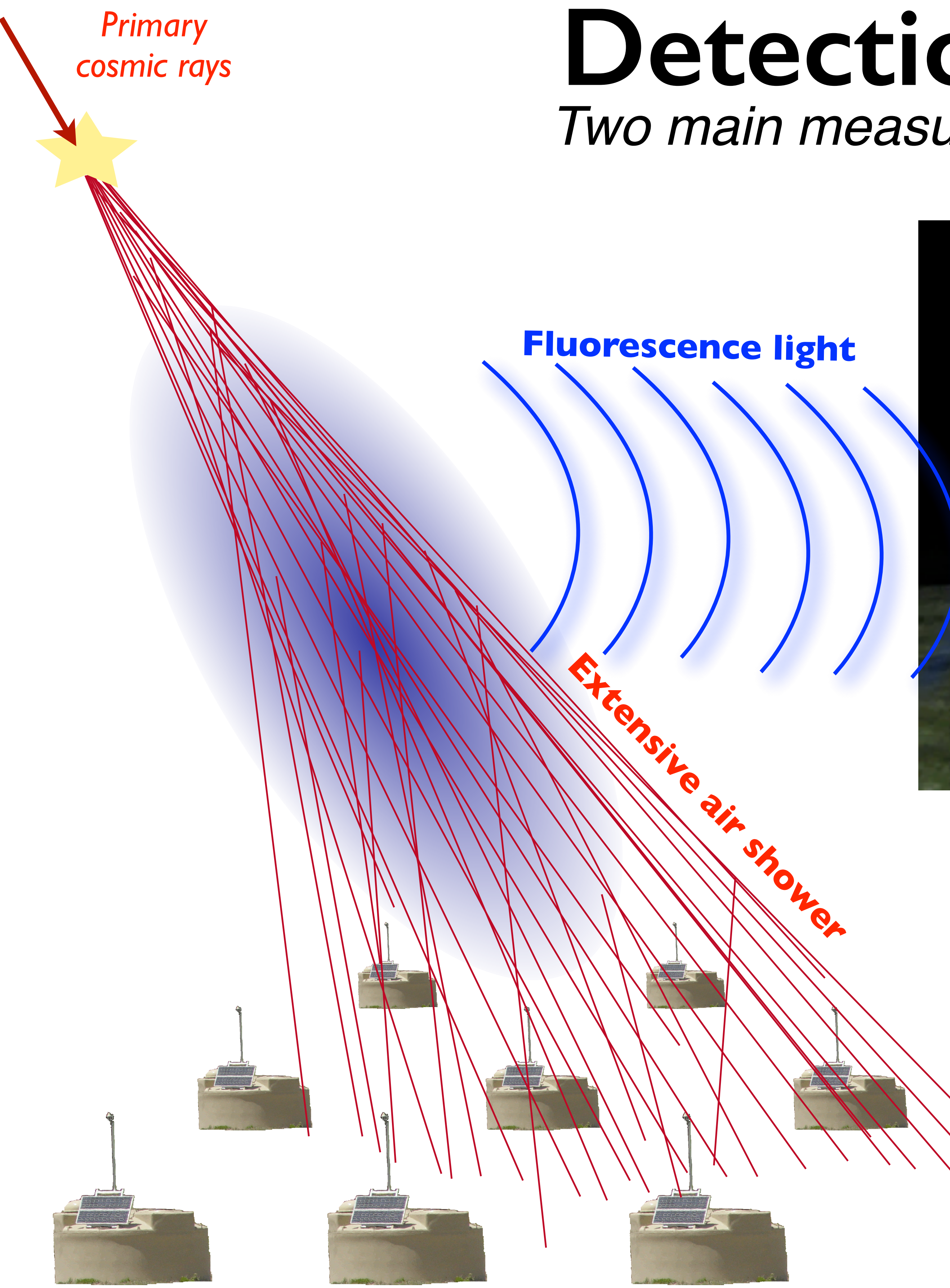
Why do we care about EAS?



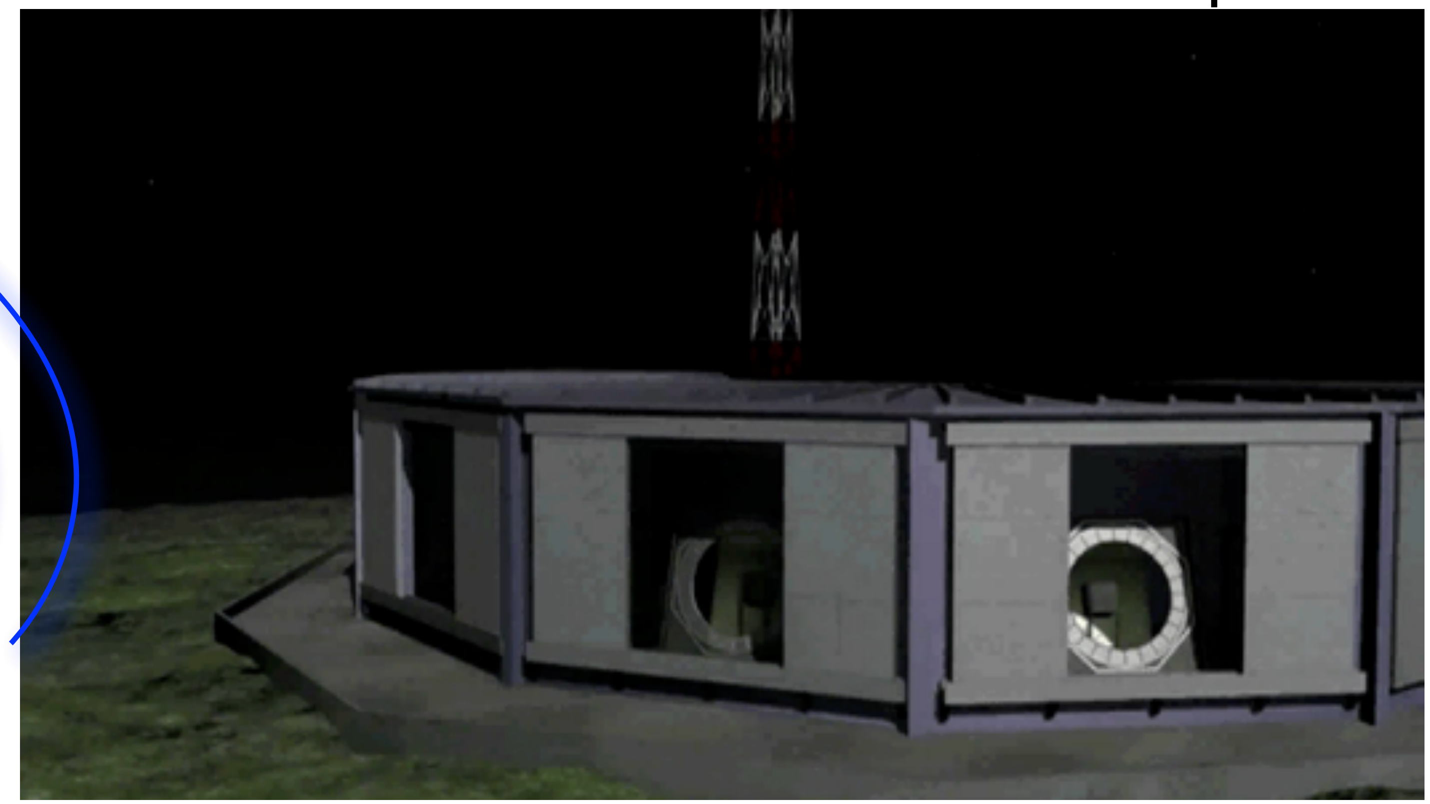
Highest energies only indirect accessible, e.g. via extensive air showers

Detection of EAS

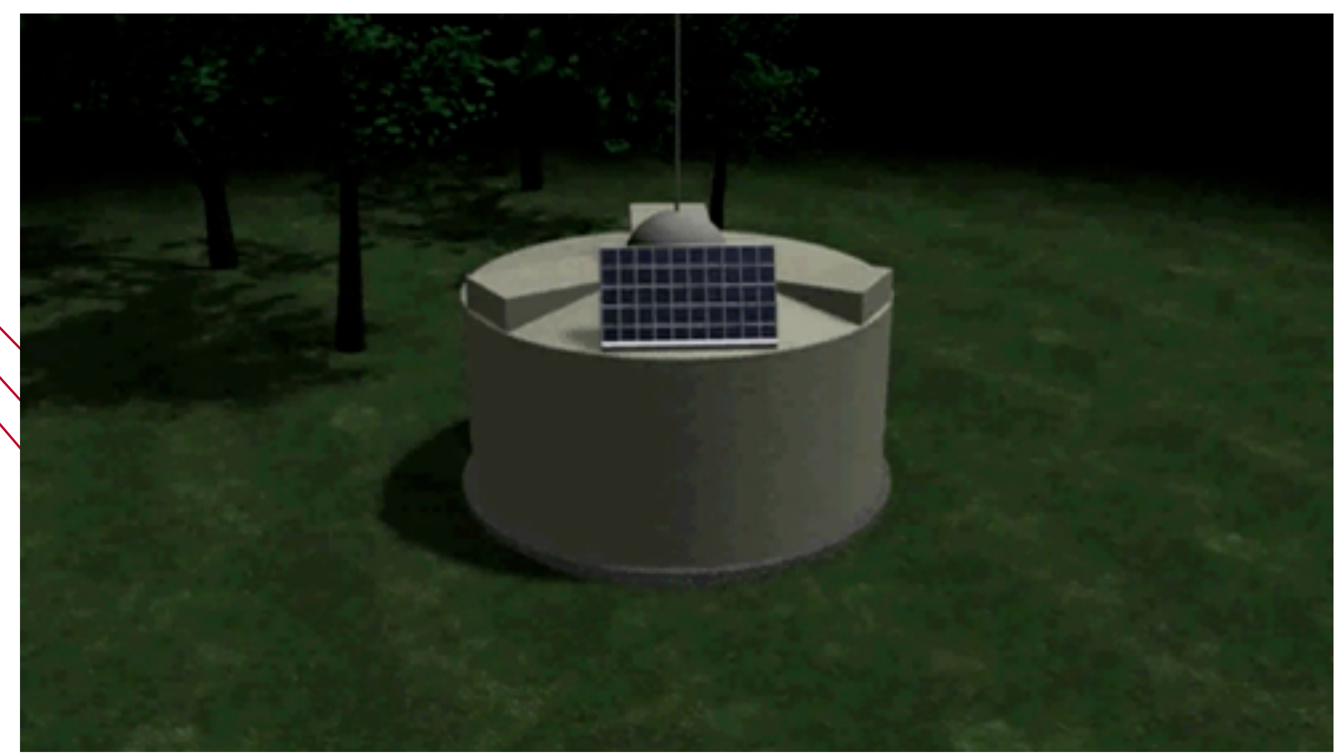
Two main measurement techniques:



Fluorescence telescope

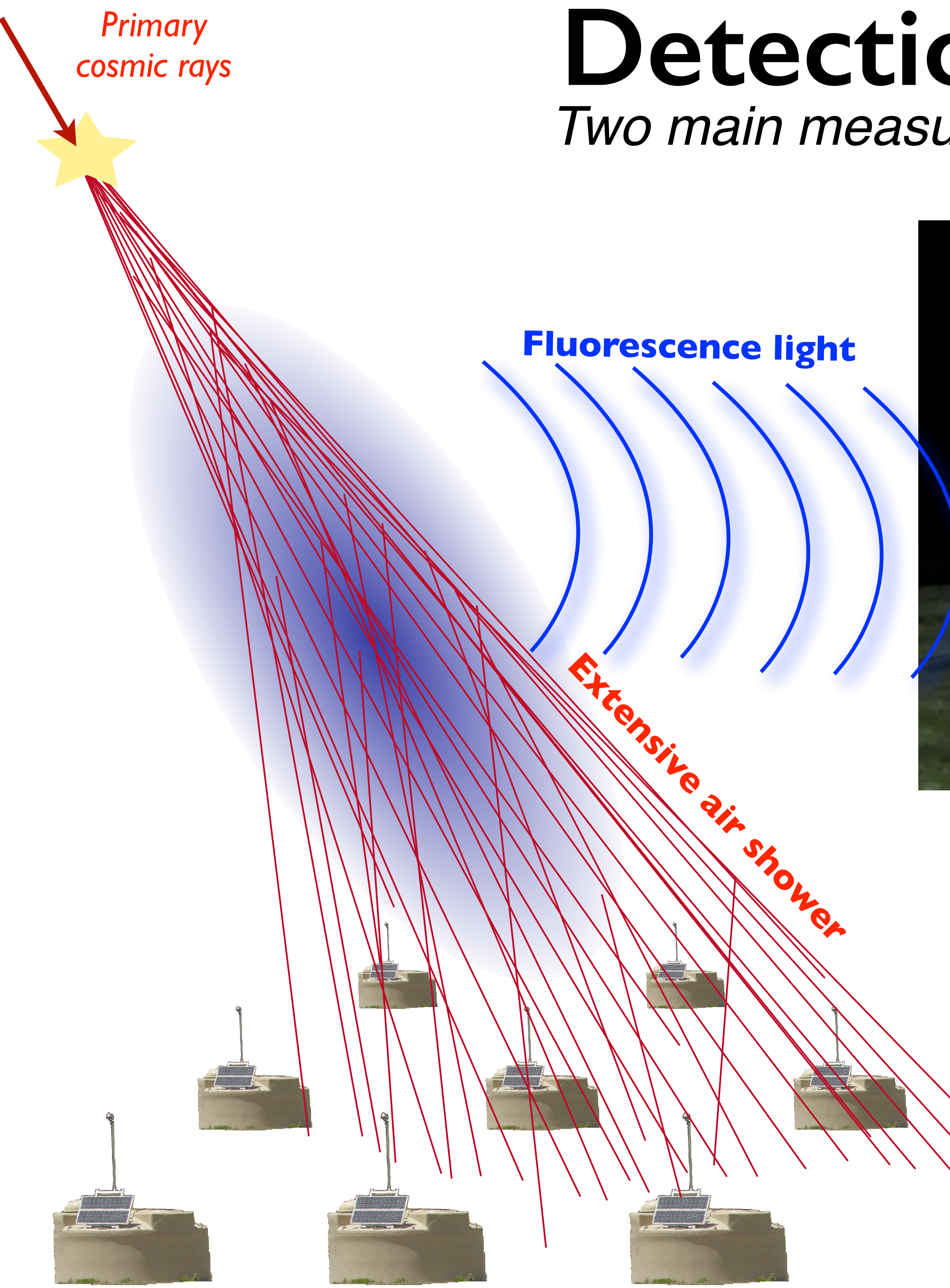


Water-Cherenkov detector



Detection of EAS

Two main measurement techniques:



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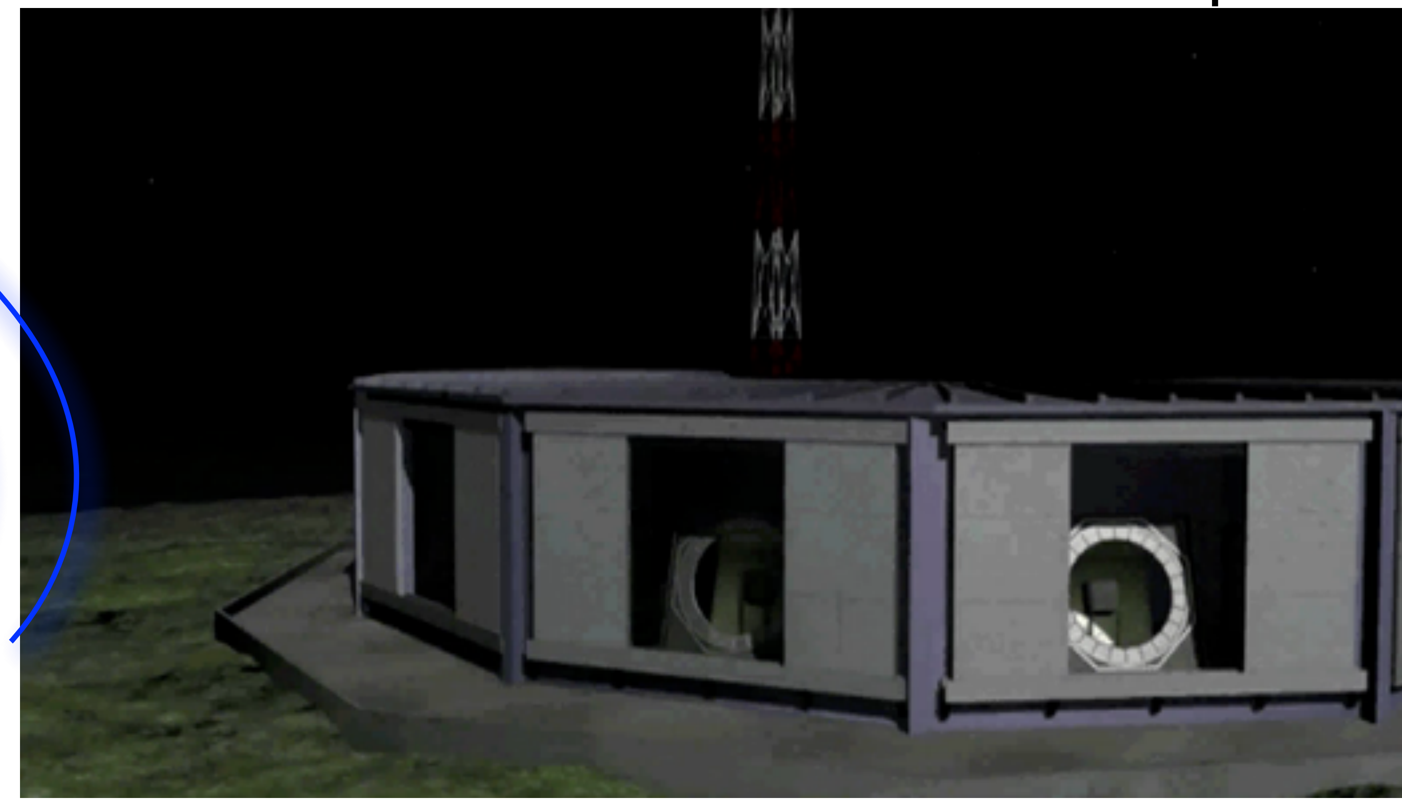
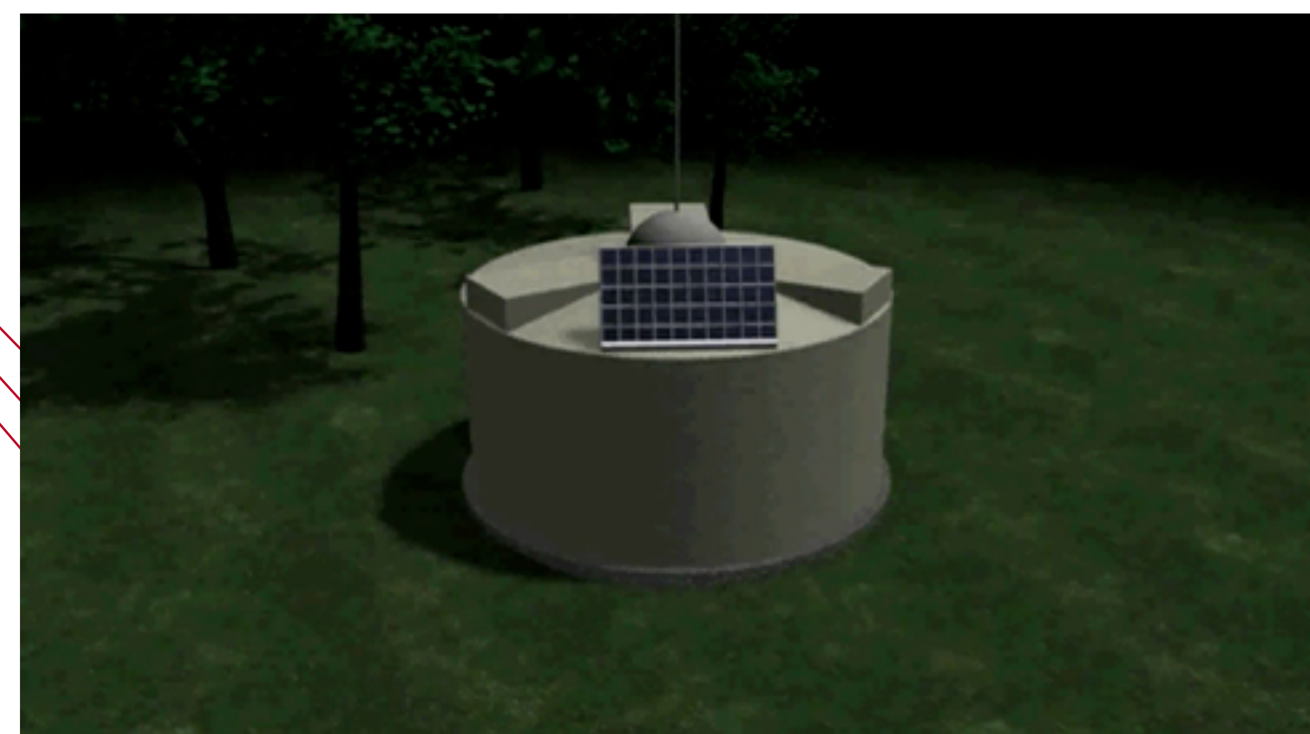
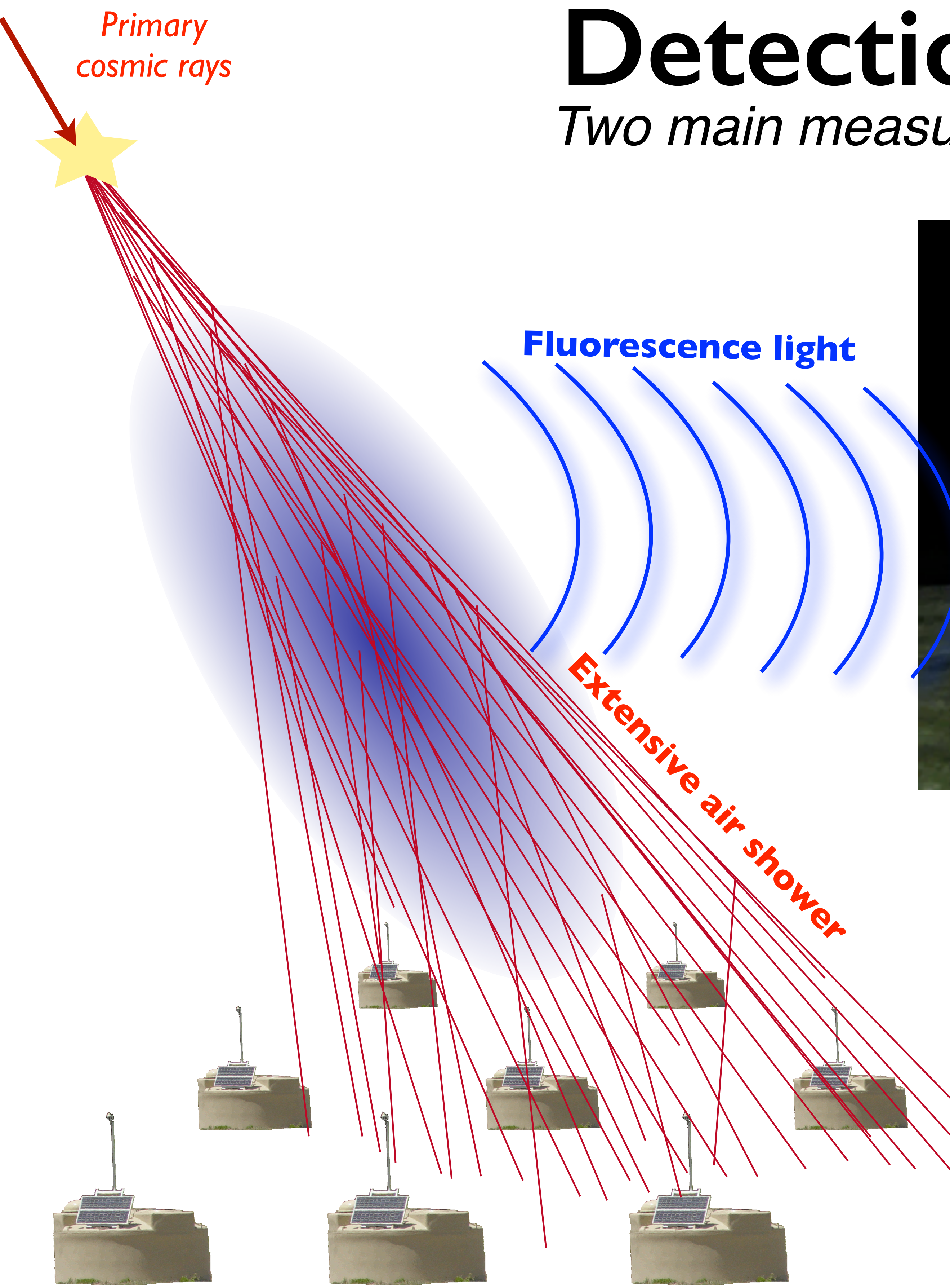


Water-Cherenkov detector



Detection of EAS

Two main measurement techniques:



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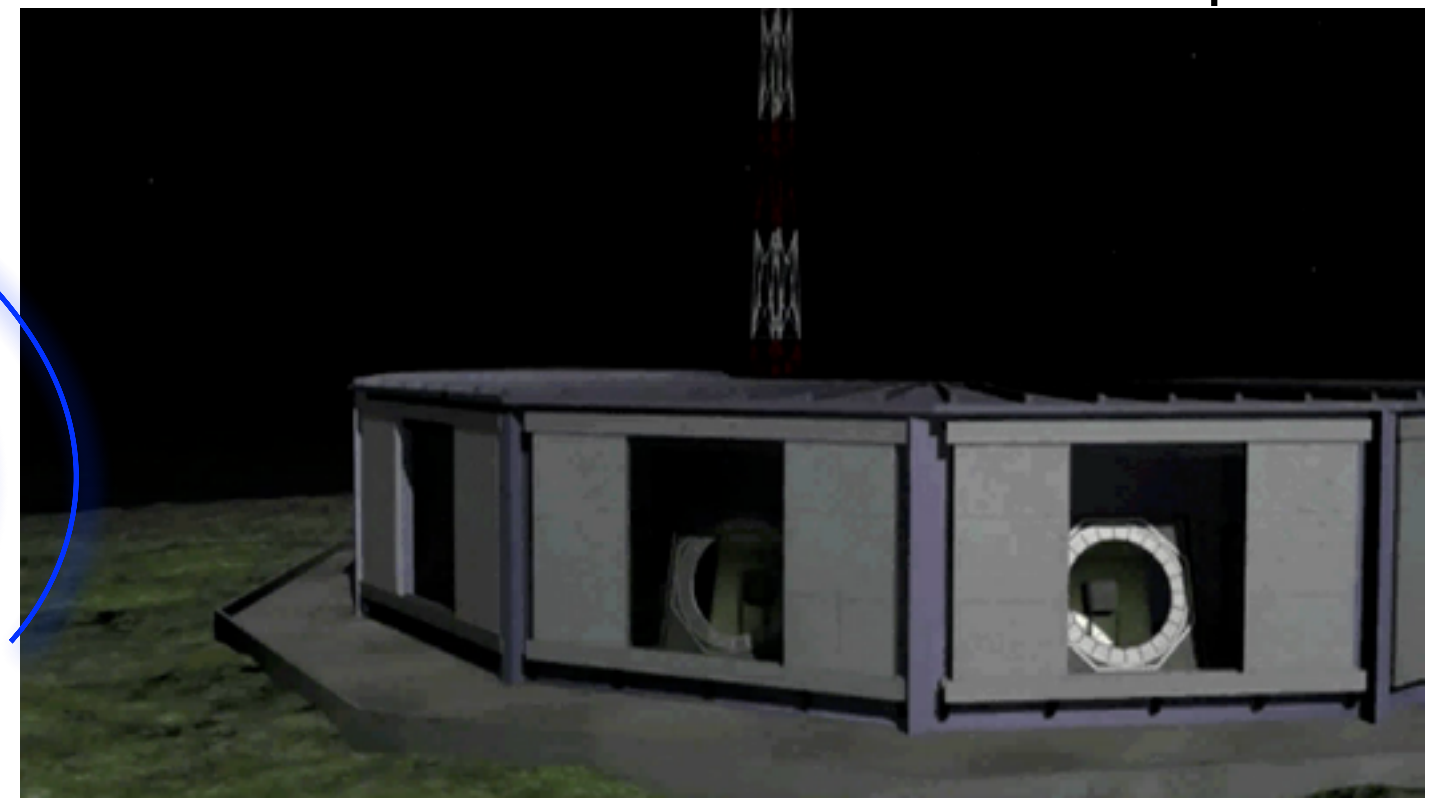
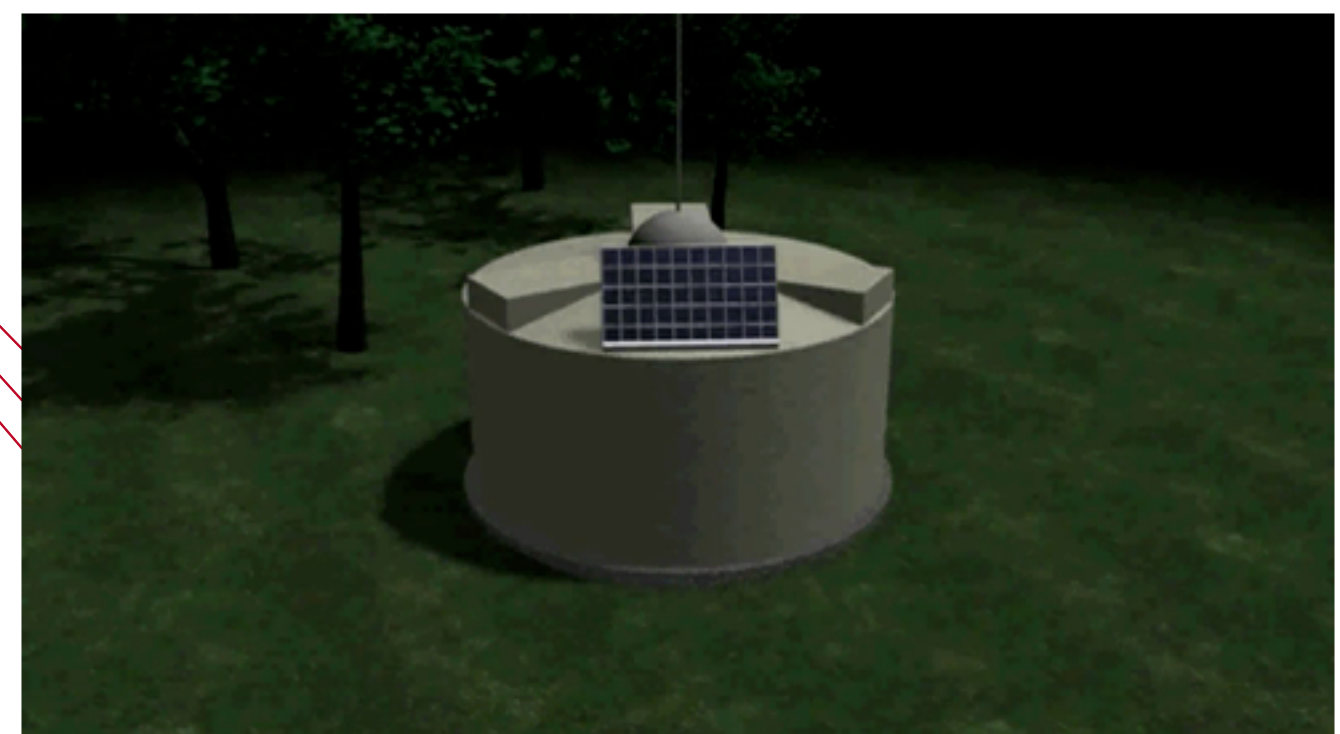


Water-Cherenkov detector



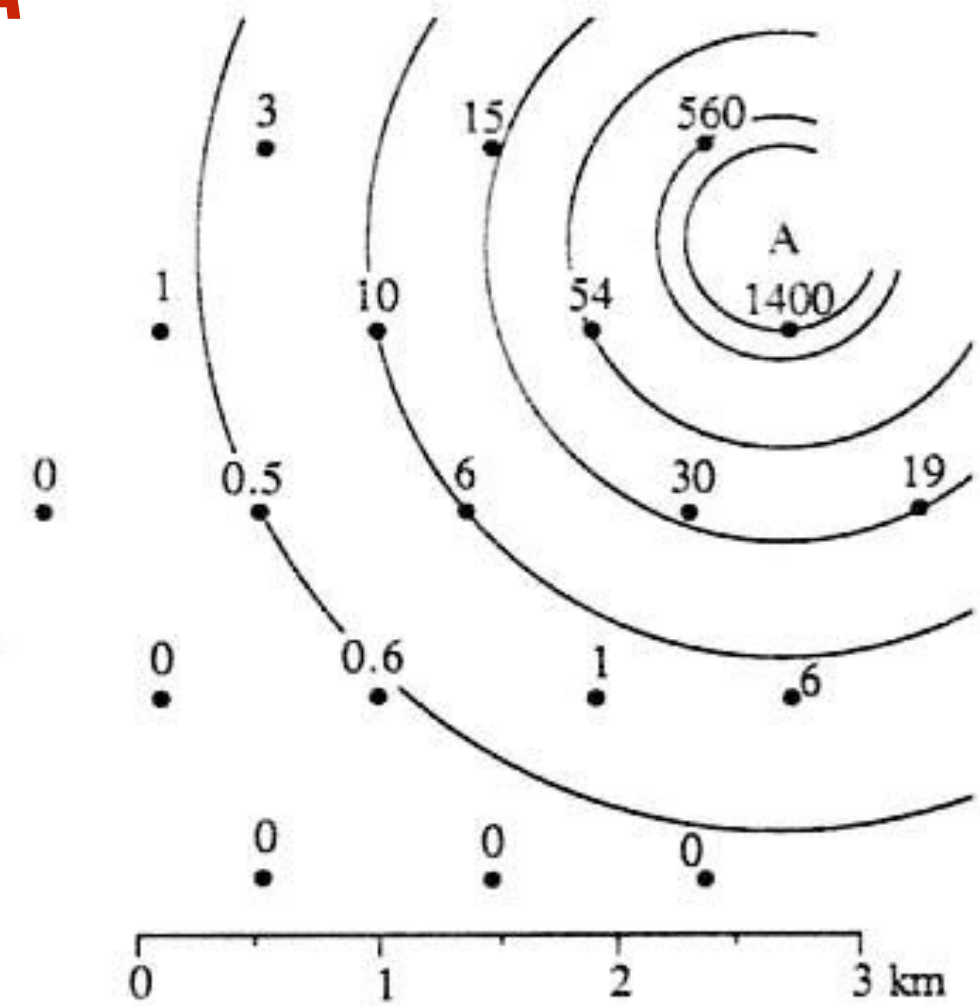
Pioneering experiment in 1961

John Linsley

First giant air shower array at Vulcano ranch / USA

- 19 plastic scintillation counters
- total 8.1 km^2 area

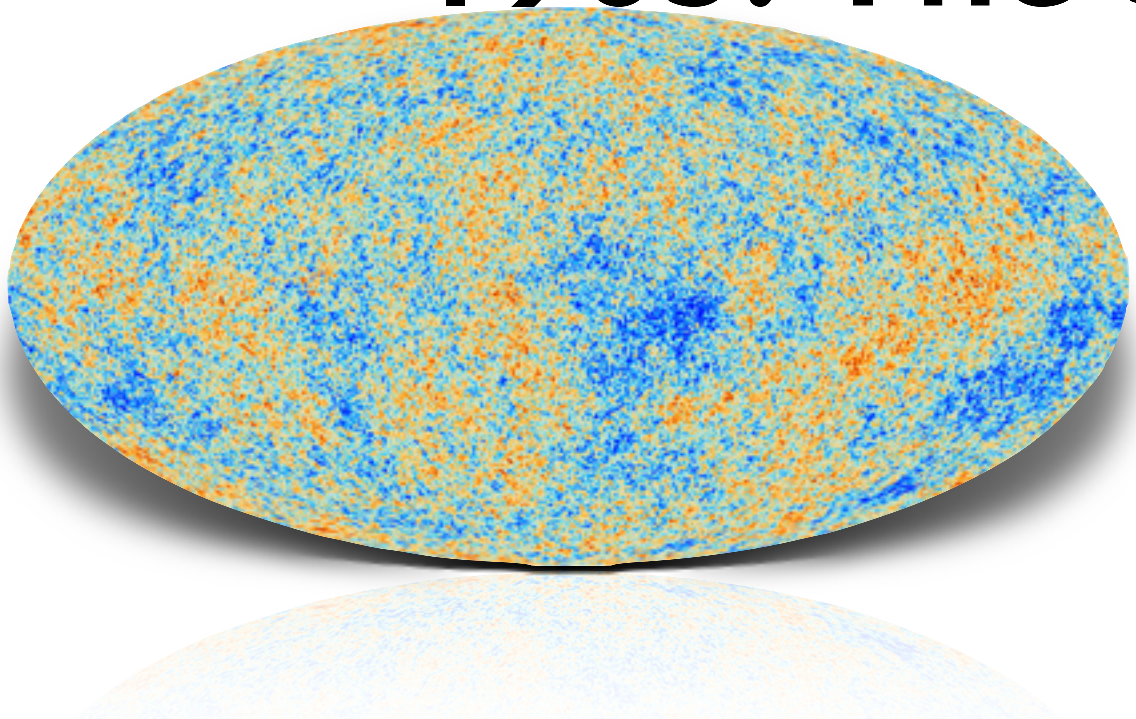
Linsley's event **> 10^{20} eV**



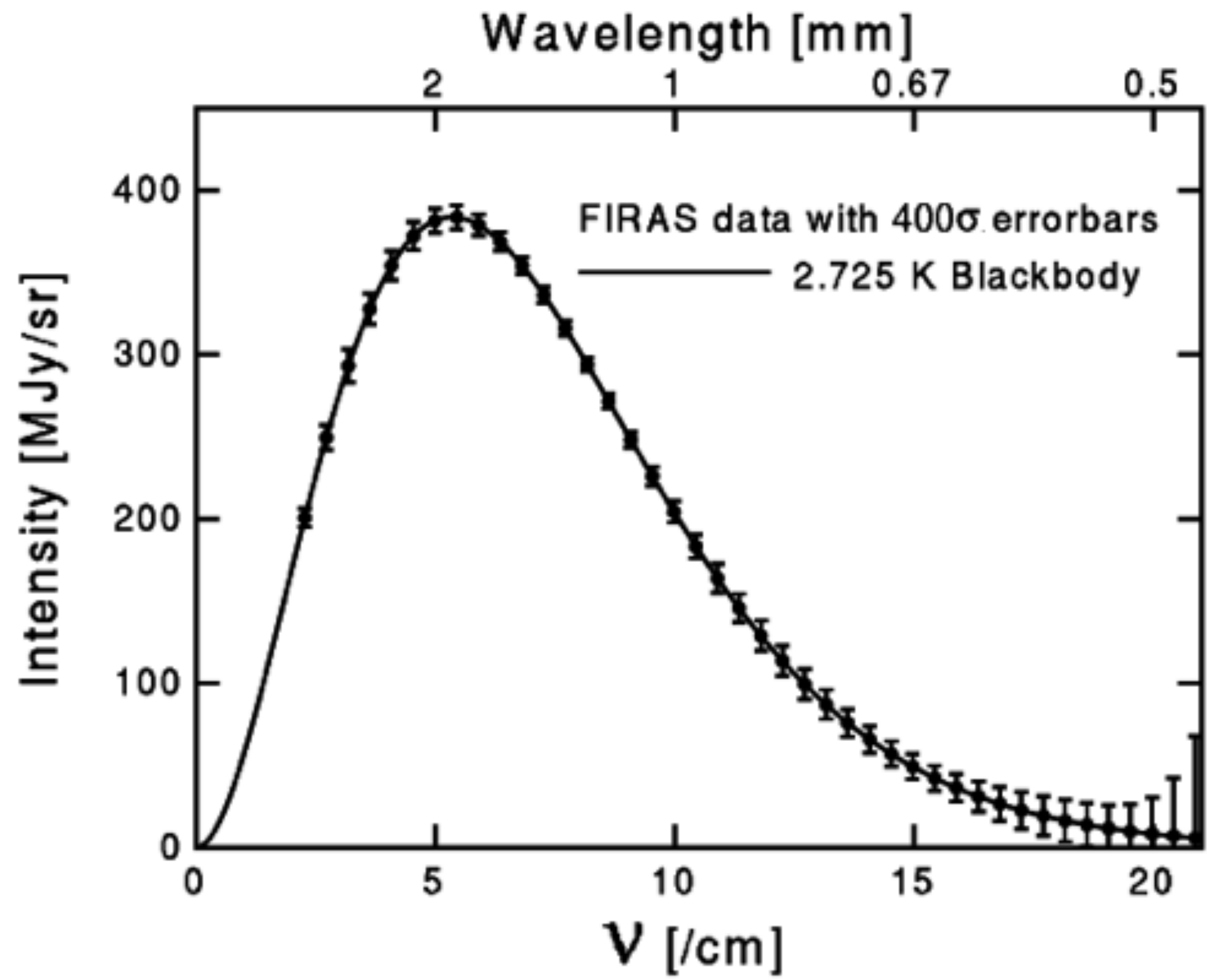
Linsley (checking for rattlesnakes)

- First measurement of energy spectrum above 10^{18} eV
- First observation of 10^{20} eV air shower
- Extragalactic origin likely!

1965: The big discovery



Wilson **Penzias**



„Universe is filled with photons“

Impact on propagation of ultra-high energy cosmic rays.

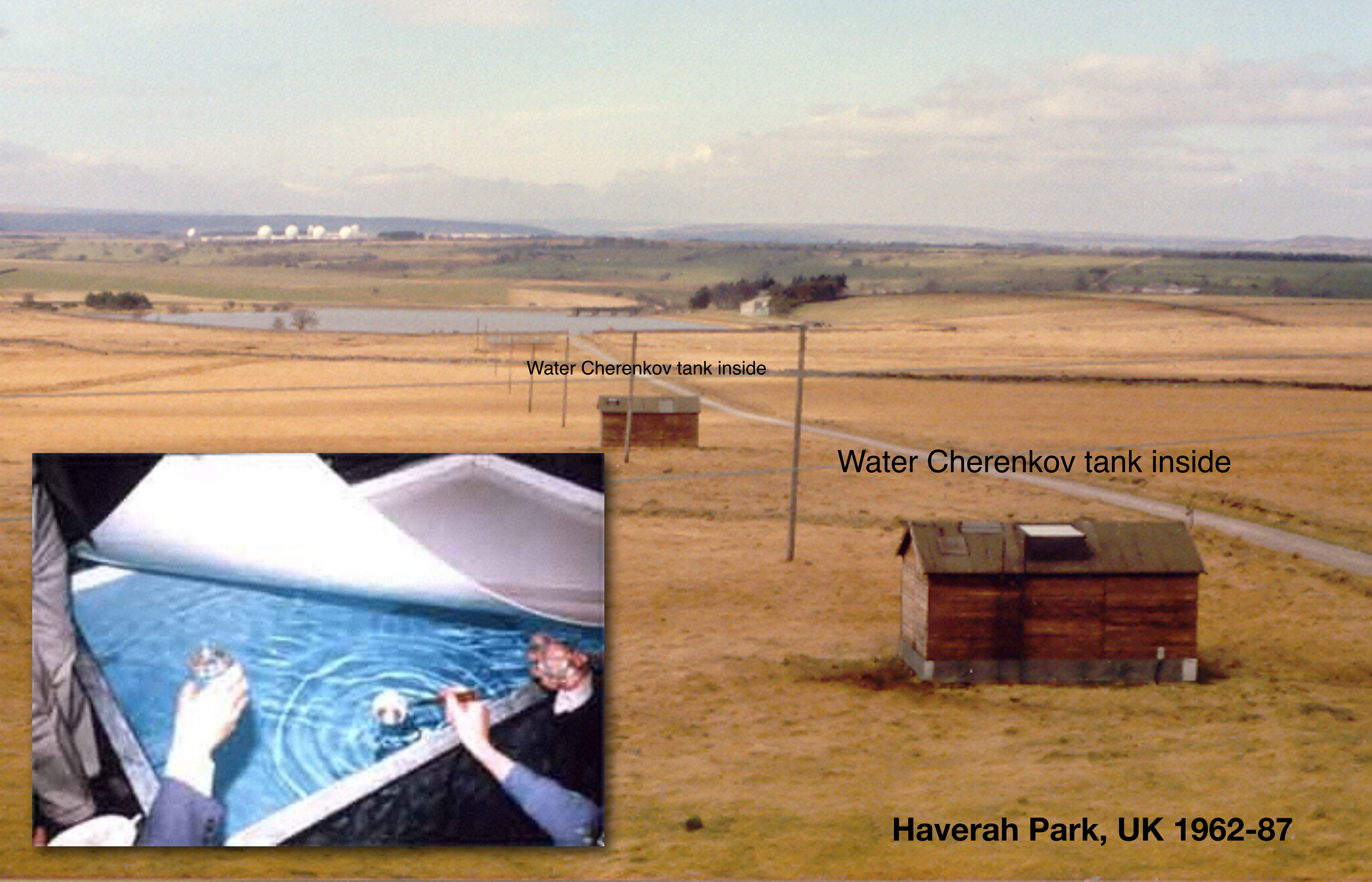
More to come…

Haverah Park, UK 1962 - 1987

Using water-Cherenkov tanks

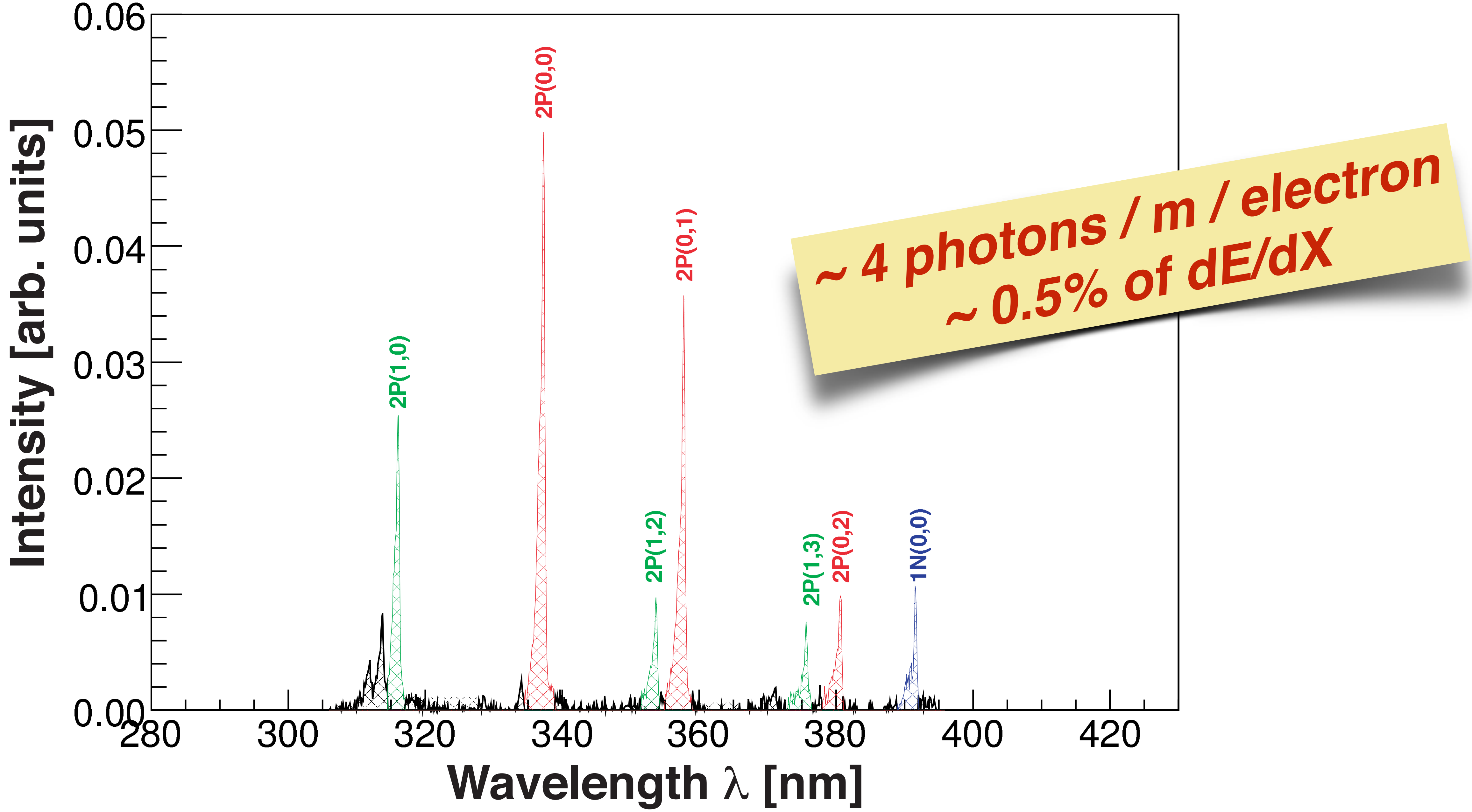
Haverah Park, UK 1962 - 1987

Using water-Cherenkov tanks



Fluorescence light

Light emitted isotropically at near-UV wavelength



Light originates from transitions from the second positive system (2P) of molecular nitrogen N_2 and the first negative system (1N) of ionized nitrogen molecules.

Fly's Eye experiment, Utah, USA

Utilizing fluorescence light *1981 - 1993*

First detection of particle with 3.2×10^{20} eV (Bird et al. Astrophys.J. 441 (1995) 144-150)
Primary type: *Unknown*

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Primary type: *Unknown*

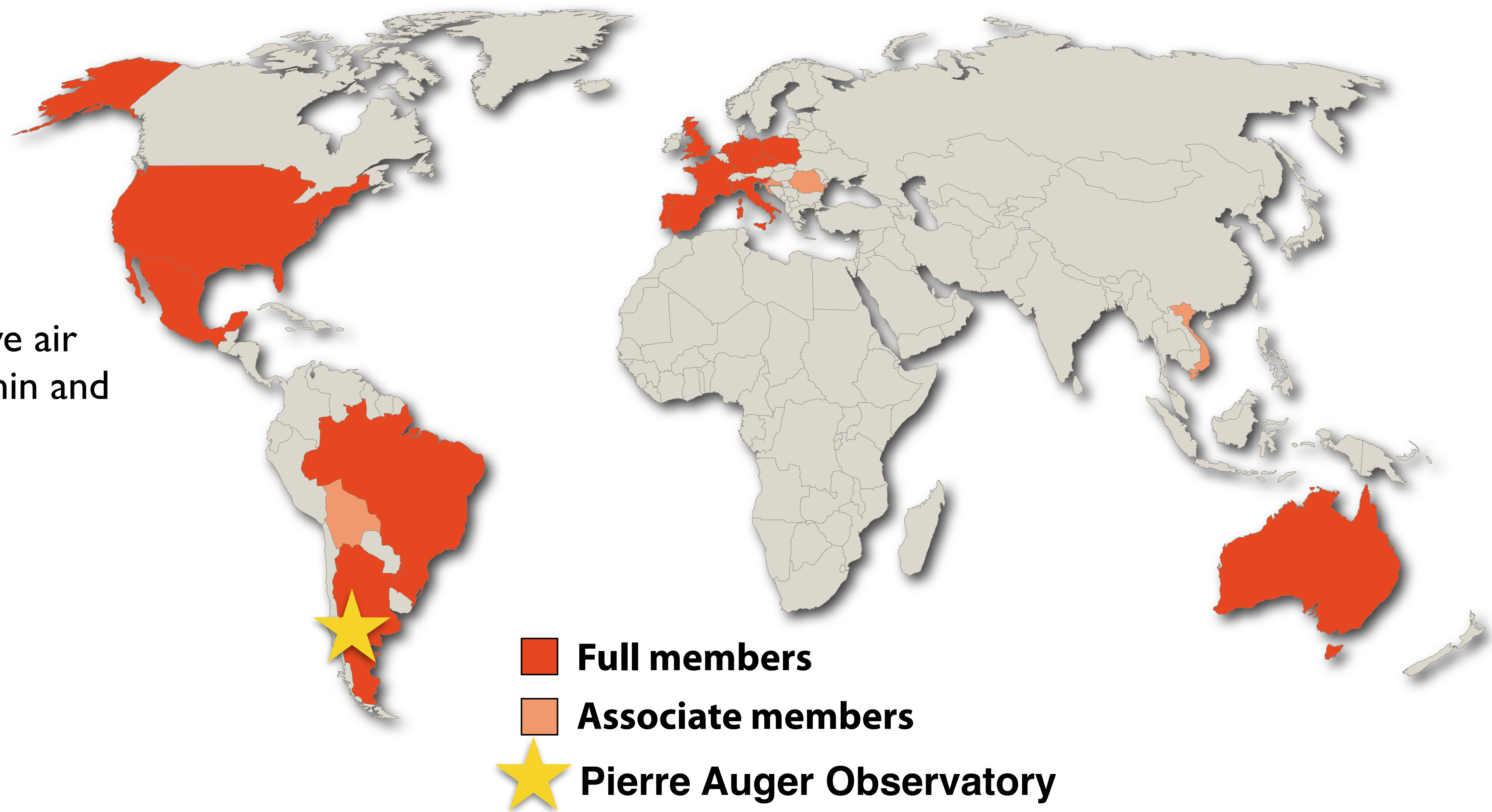
… today: The Pierre Auger Observatory

PIERRE AUGER OBSERVATORY

***Aim:* Study ultra-high energy cosmic rays above 10^{17} eV**

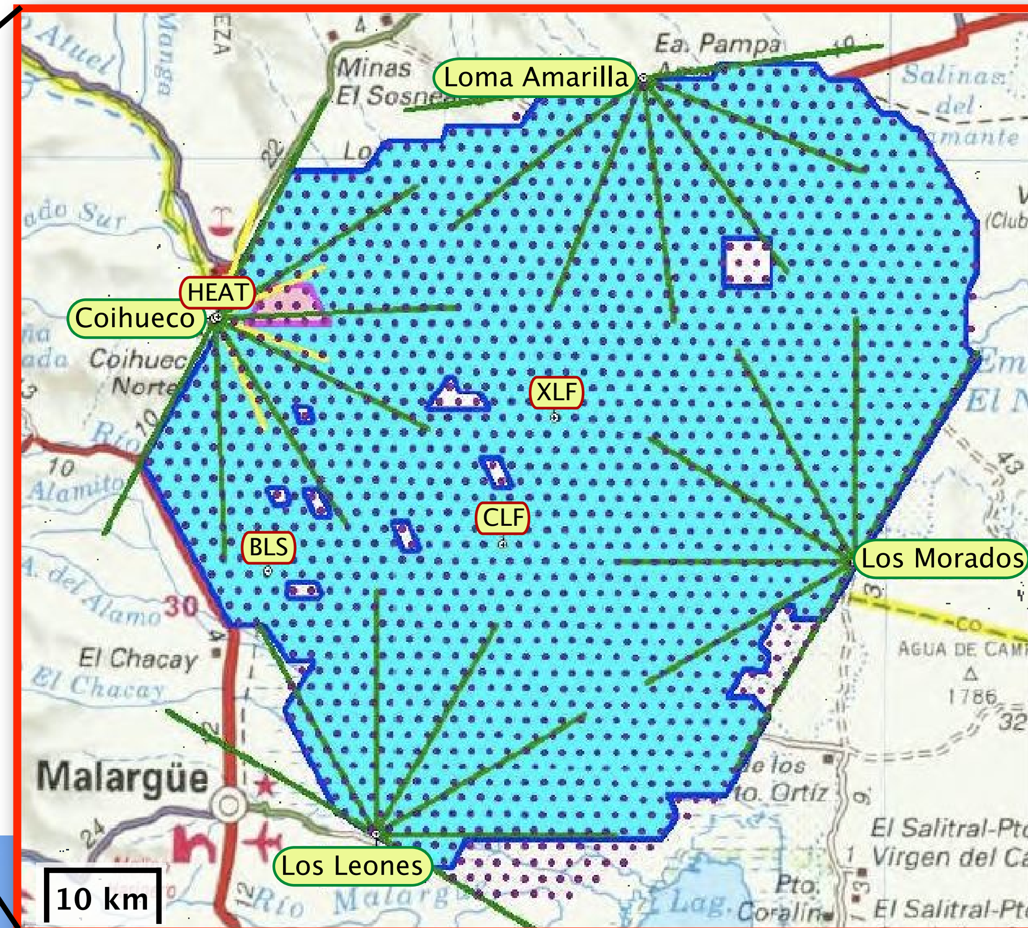
Dates:

- **1992**: First ideas for a giant extensive air shower experiment by J. Cronin and A. Watson
- **2000**: Start of construction
- **Since 2004**: Data taking
- **2008**: Construction complete



About 500 collaborators from 18 countries

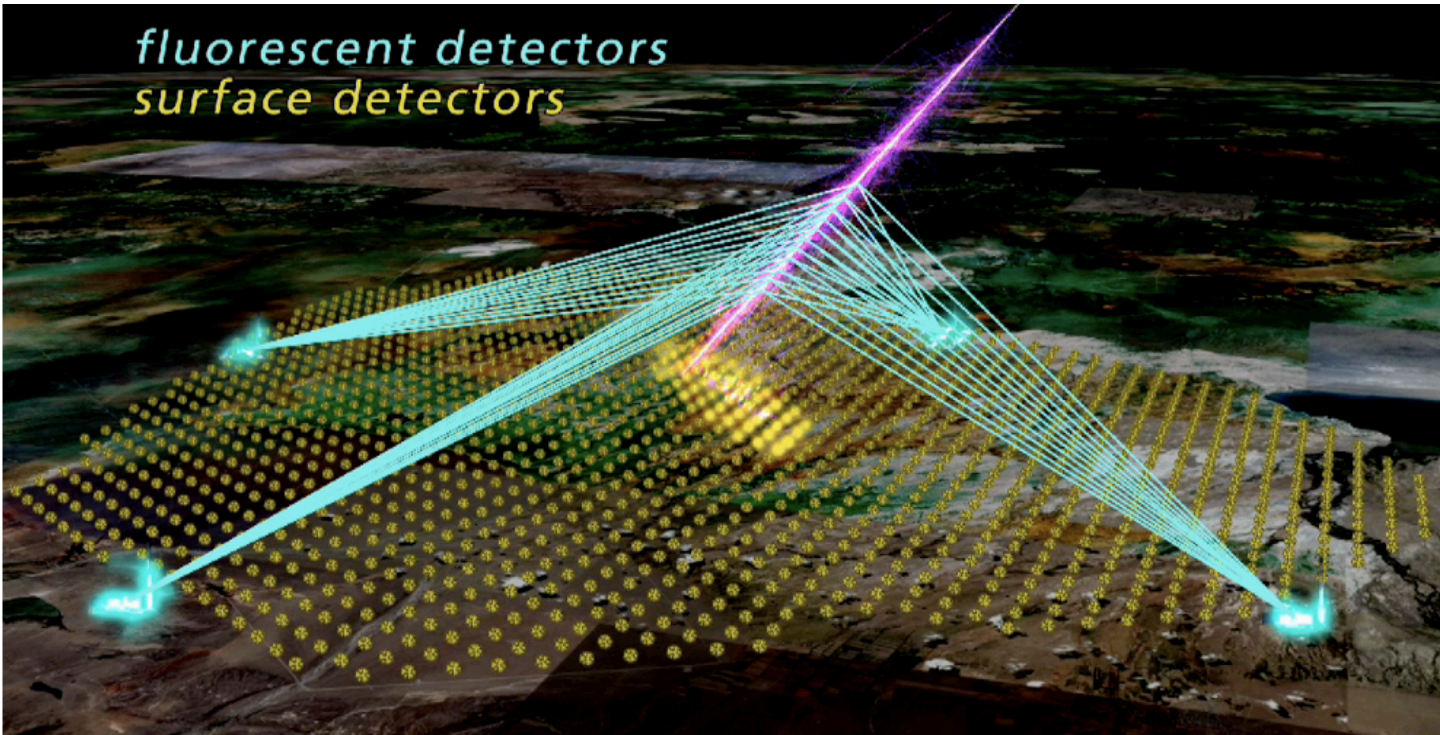
Pierre Auger Observatory



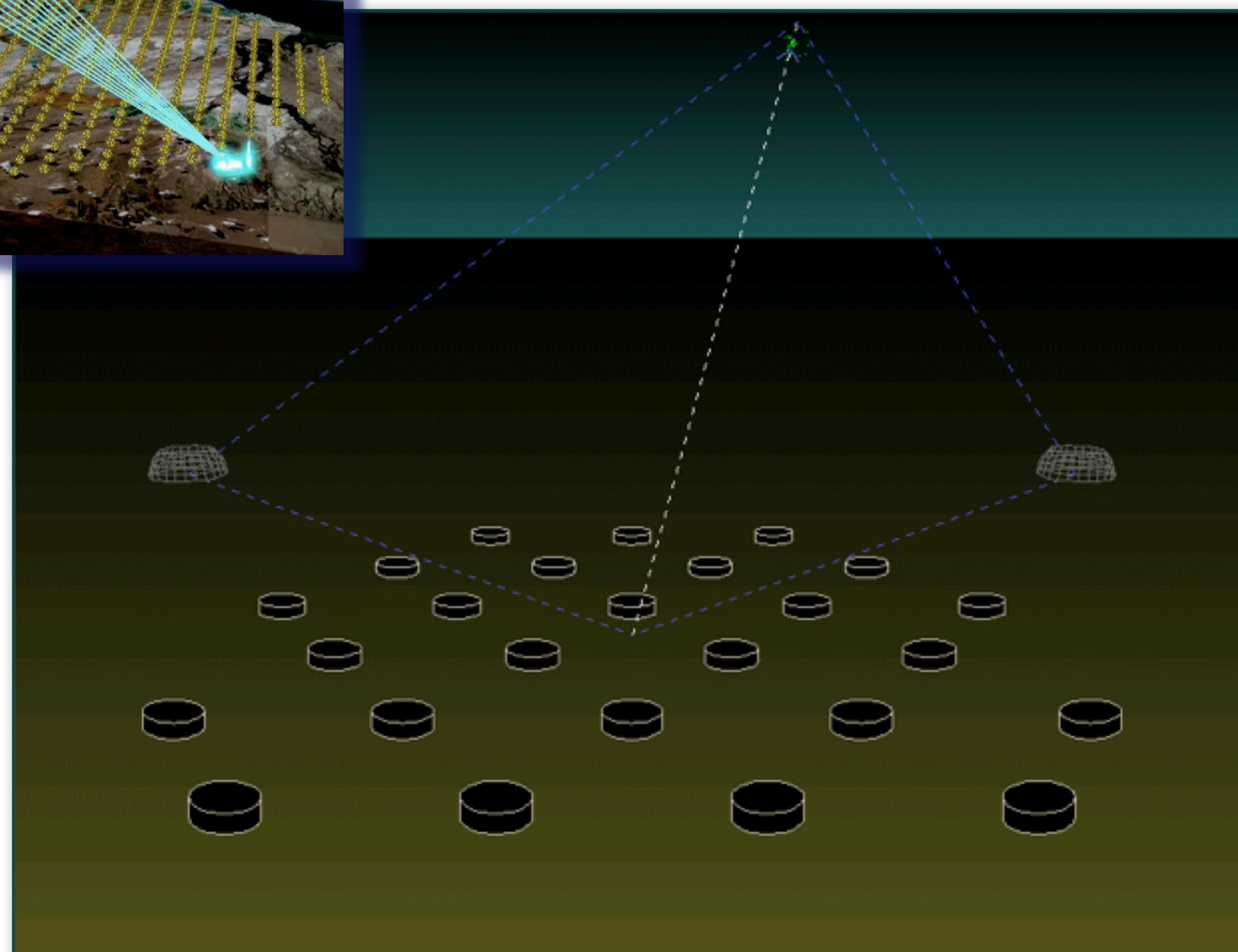
- About **3000 km²** area
- **1660** water-Cherenkov tanks
- **27** fluorescence telescopes

Additional R&D antennas

Pierre Auger Observatory



Hybrid technique



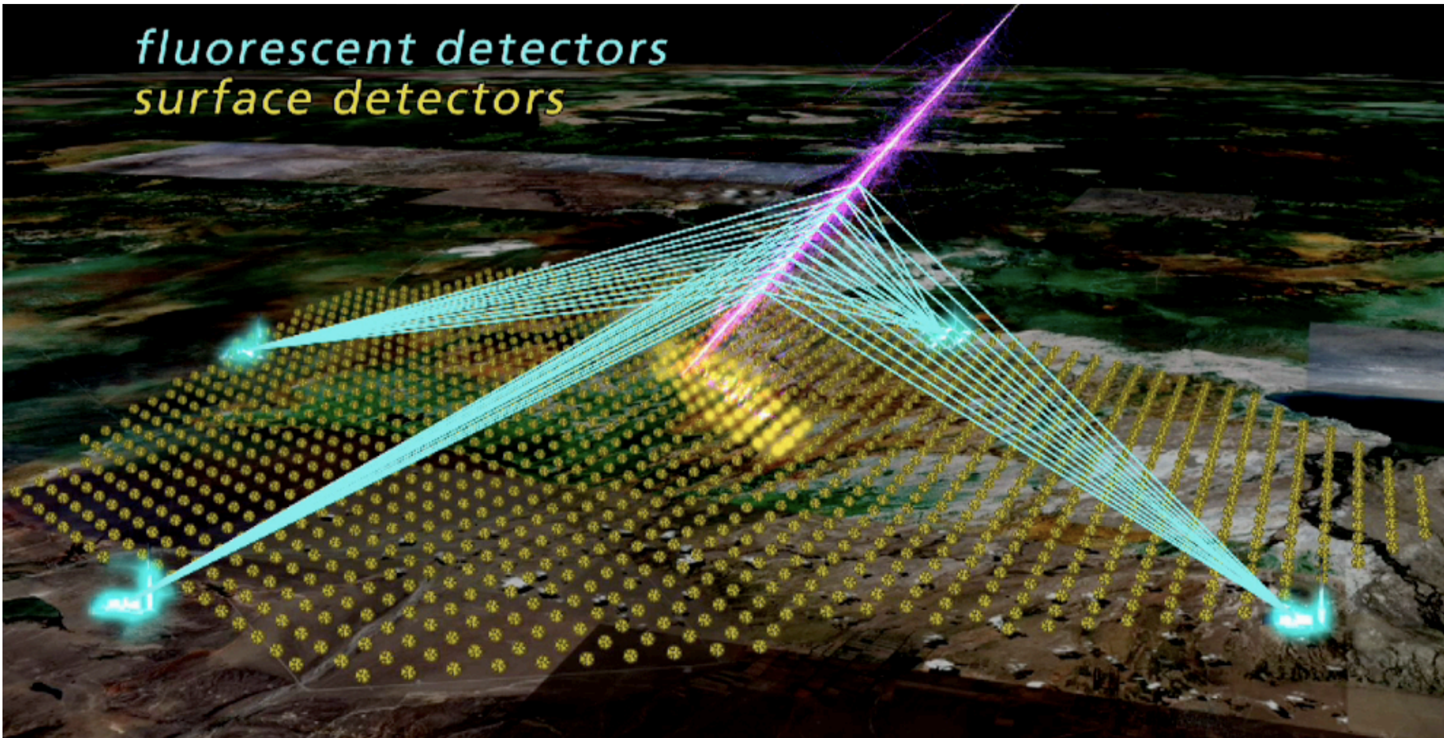
Advantage:

- More accurate energy and directional information
- Lower energy threshold
- Small dependence on interaction models

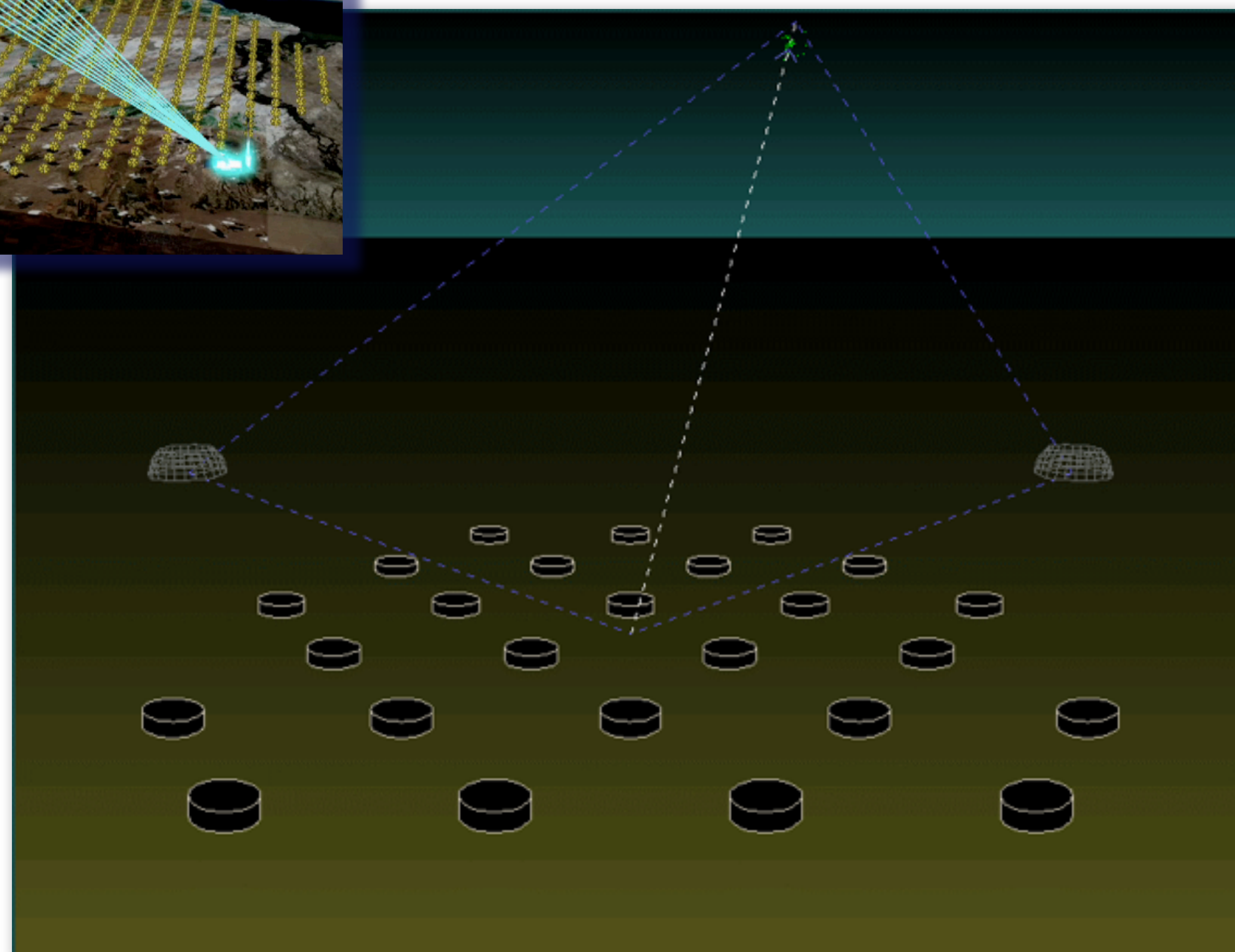
Disadvantage:

- Only 10-15% duty cycle

Pierre Auger Observatory



Hybrid technique



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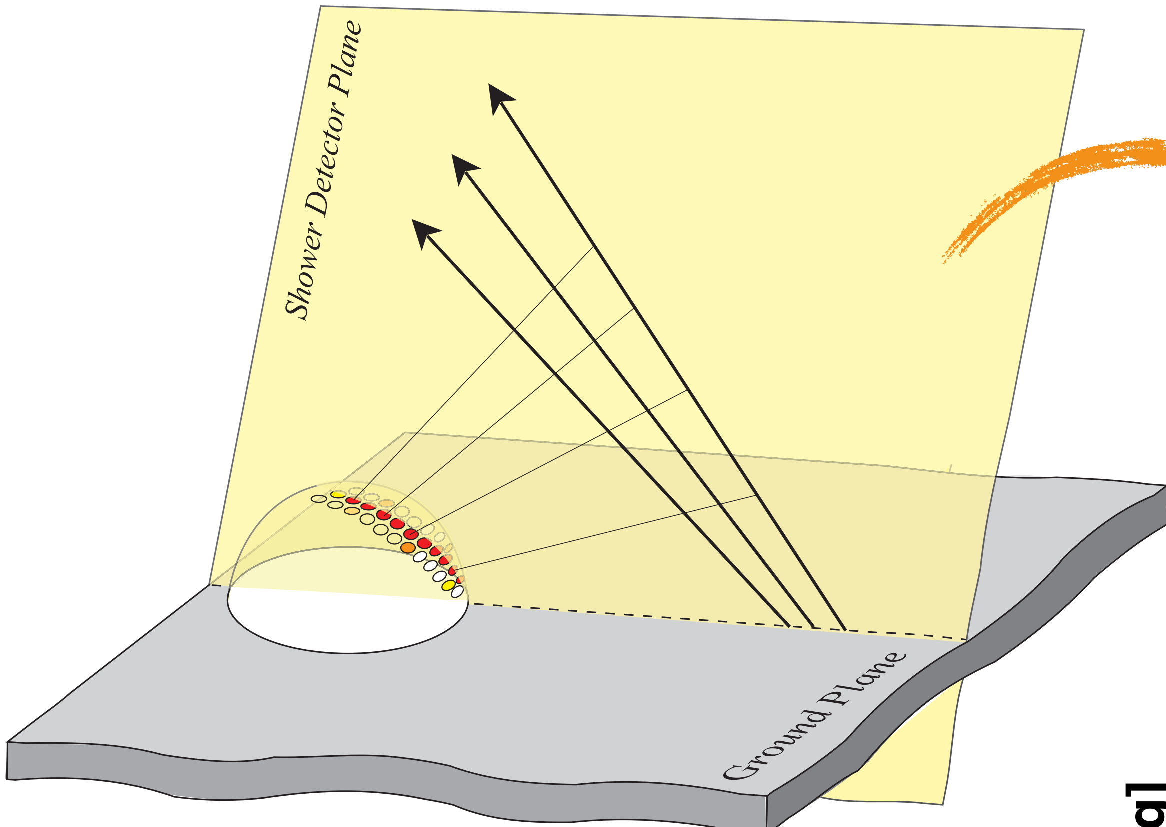
Disadvantage:

- Only 10-15% duty cycle

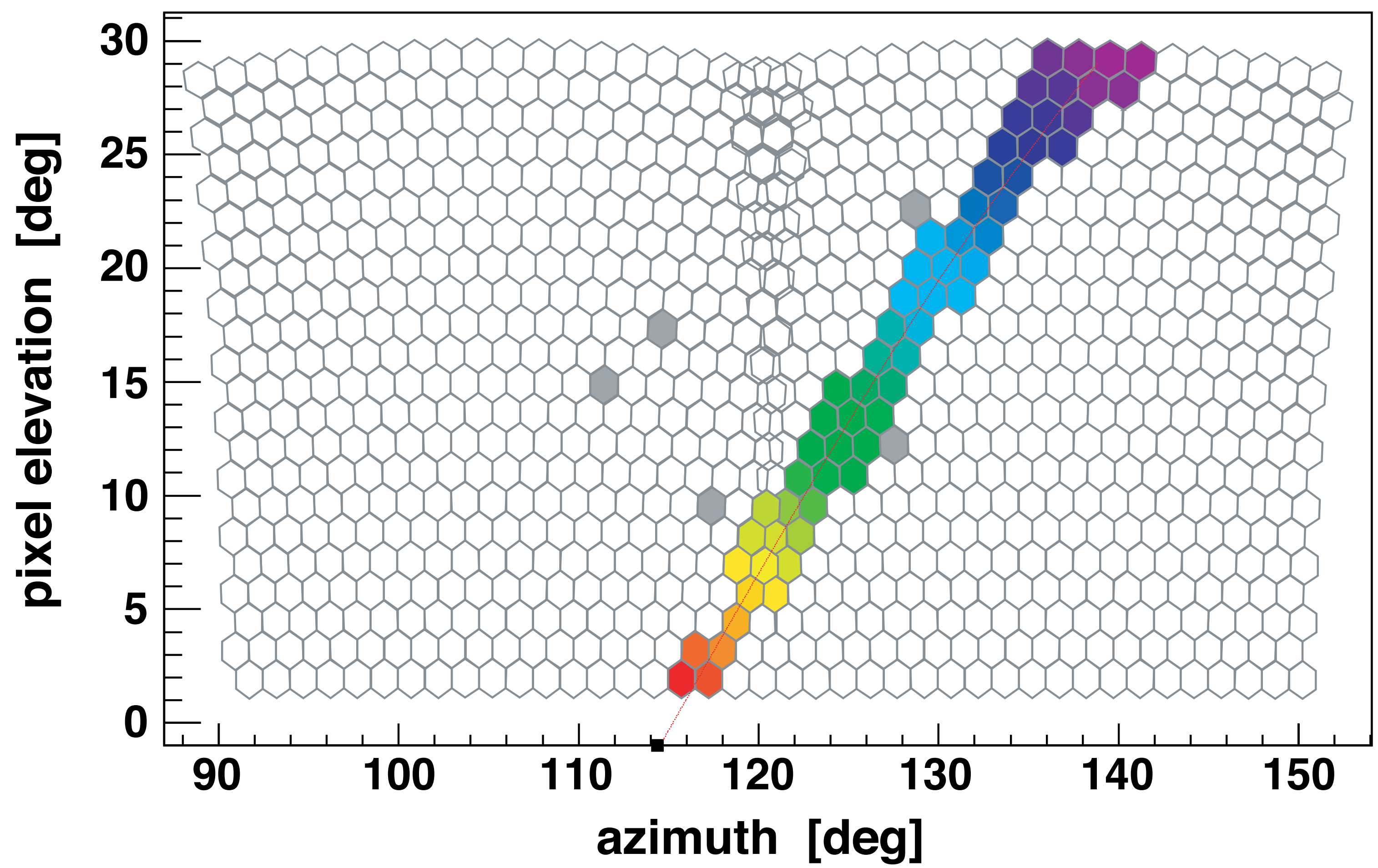
Geometry reconstruction

Two step process:



1. Determination of the shower detector plane (SDP)

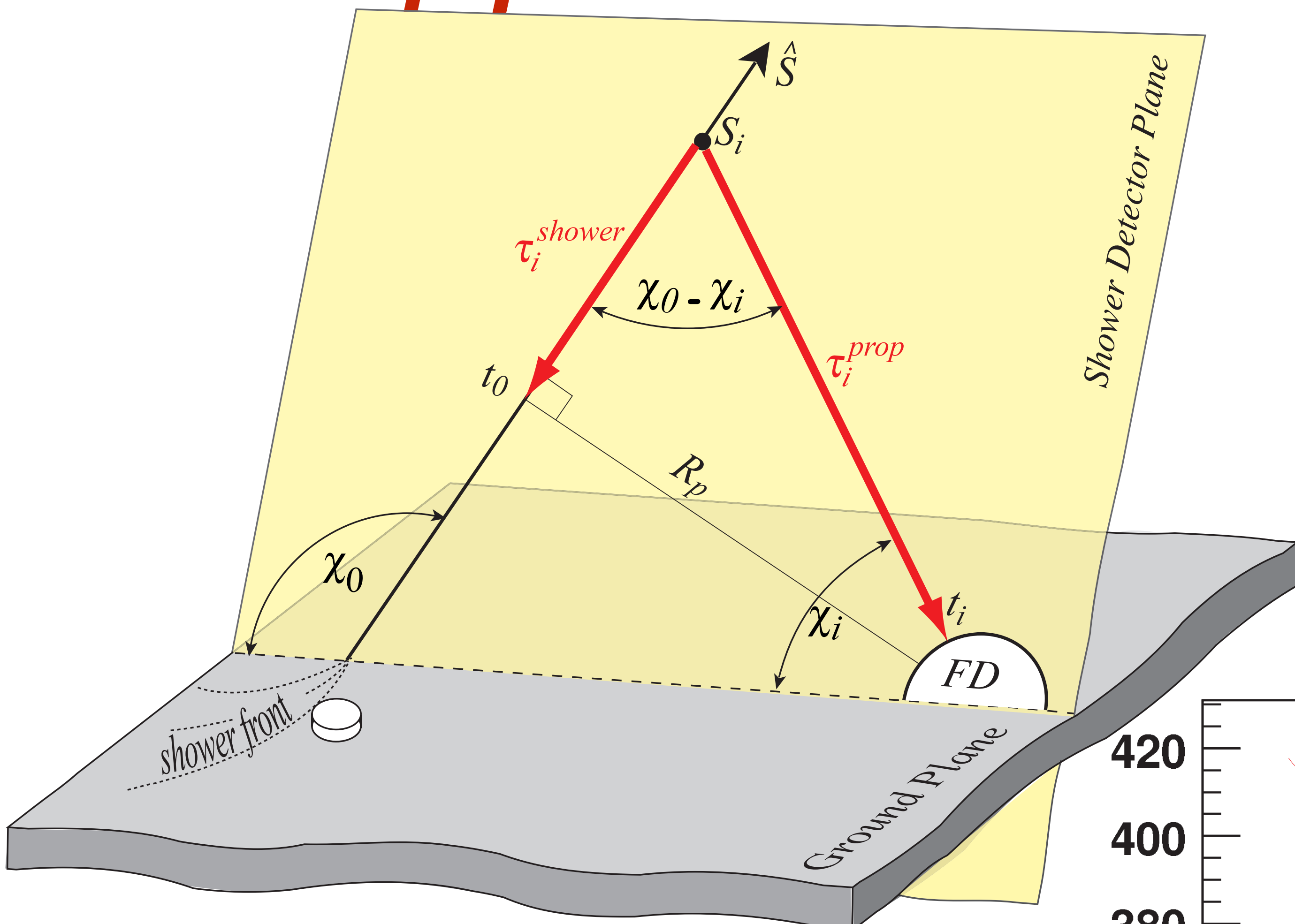
Plane spanned by the (signal-weighted) viewing directions of the triggered camera



Direction within this plane still unclear…

Geometry reconstruction

Two step process:



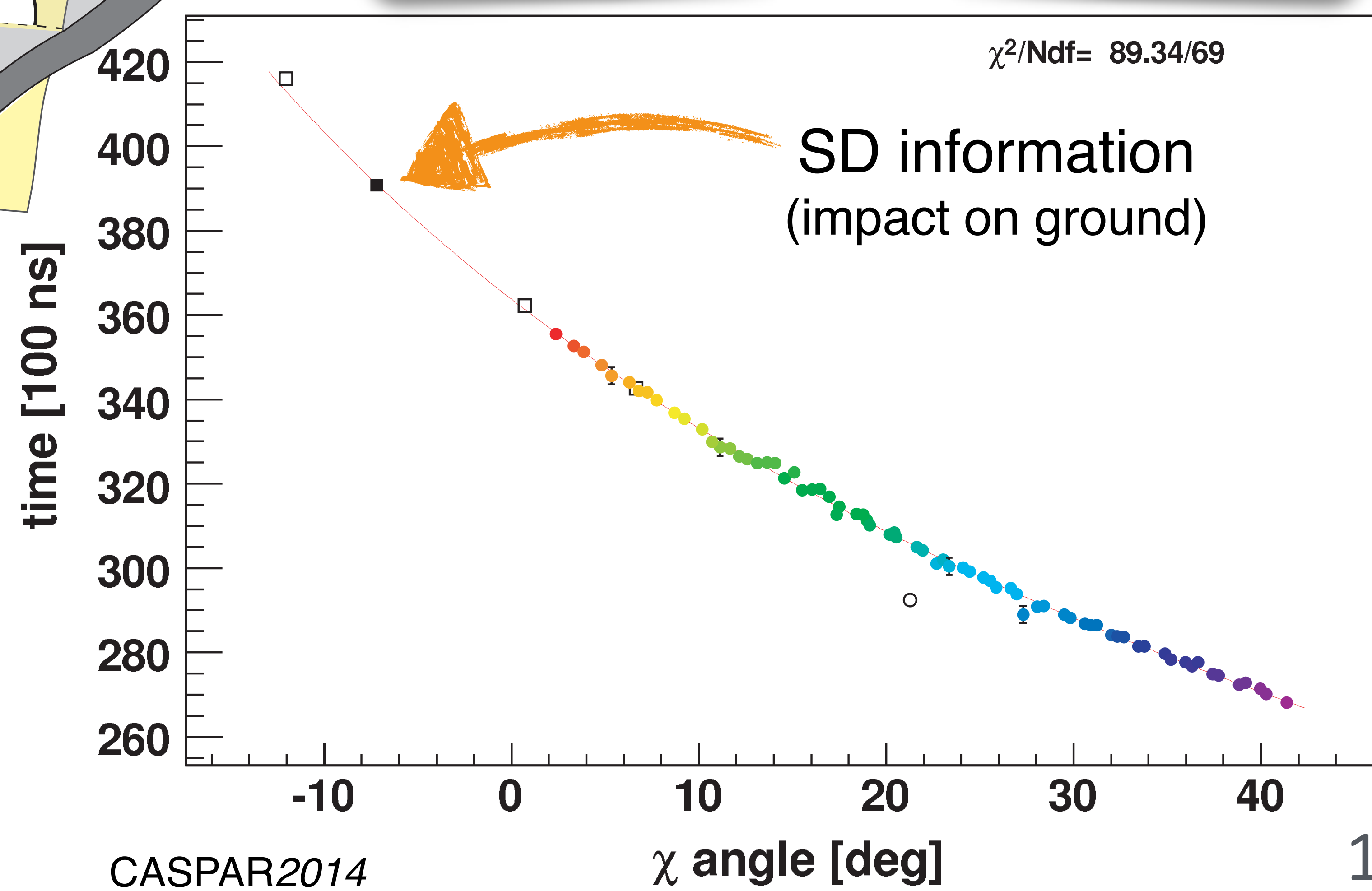
2.Determine geometry within SDP

Use timing information of pixel!

Express expected arrival time t_i at telescope as function of R_p, t_0 and chi_0 :

$$t_i = t_0 - \tau_i^{\text{shower}} + \tau_i^{\text{prop}}$$

$$t_i = t_0 + \frac{R_p}{c} \tan\left(\frac{\chi_0 - \chi_i}{2}\right)$$



Fit R_p, t_0 and chi_0 *to determine geometry*

Angular resolution typically less than 1°

Geometry reconstruction

Two step process:

2.Determine geometry within SDP

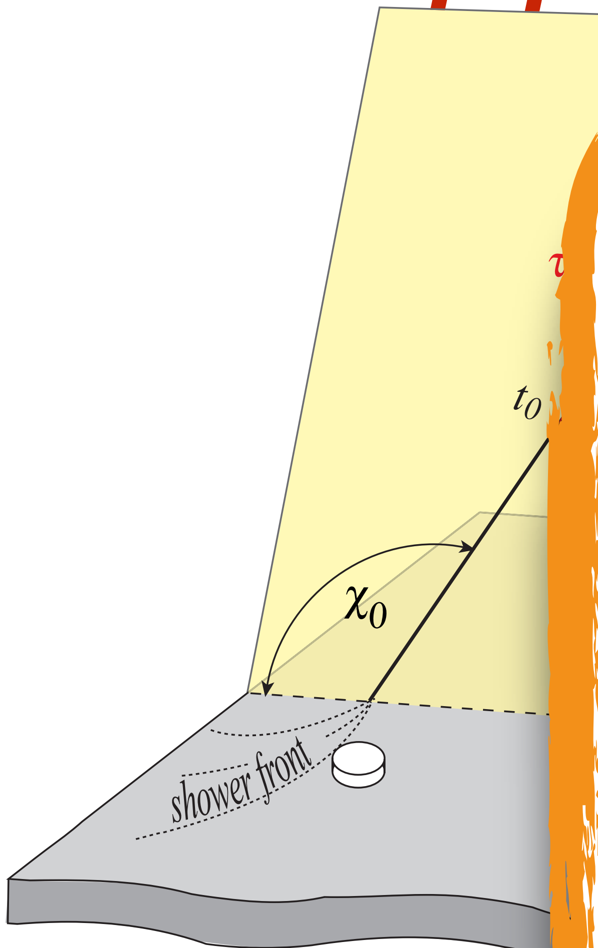
...ation of pixel!

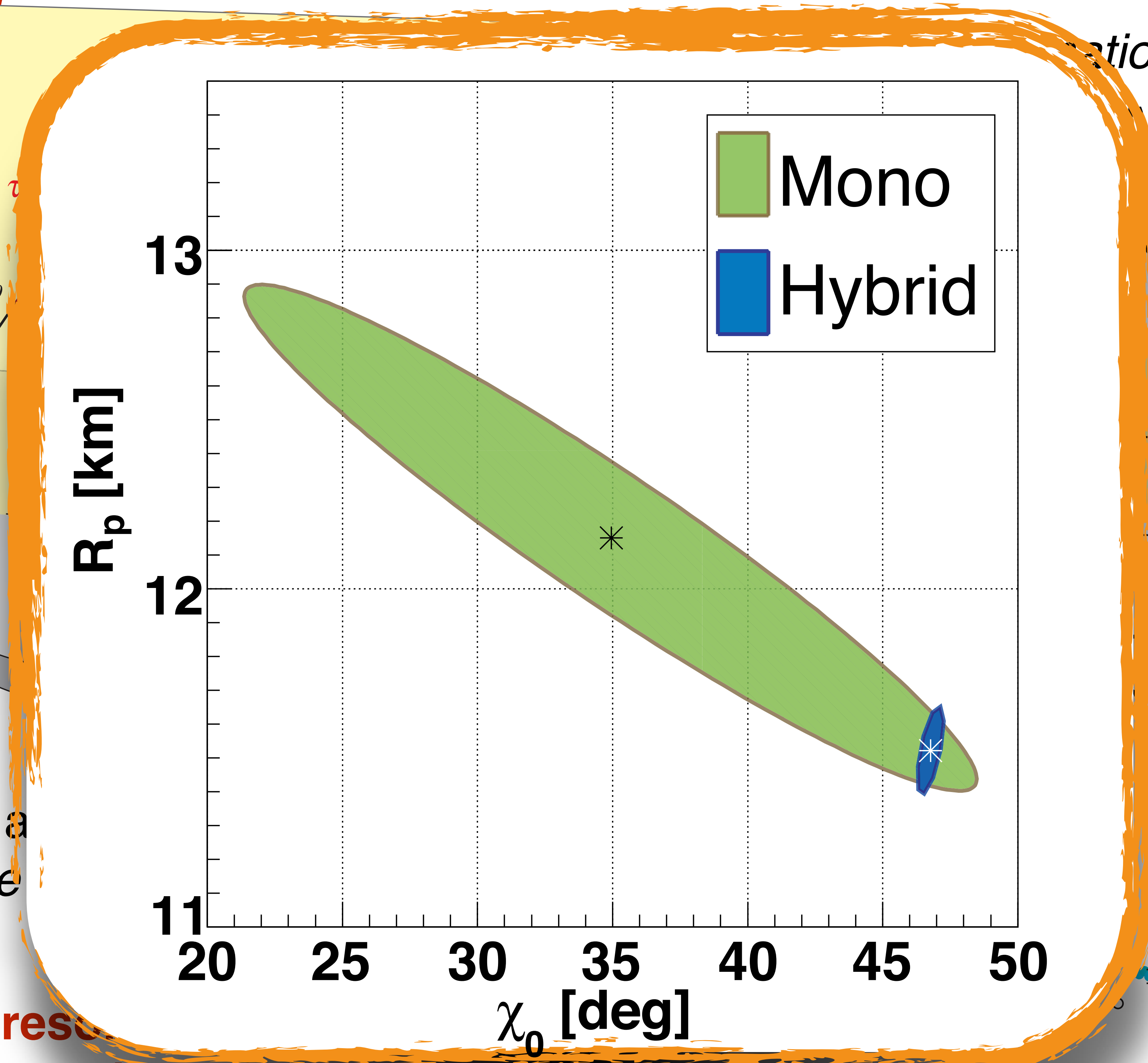
...val time t_i at

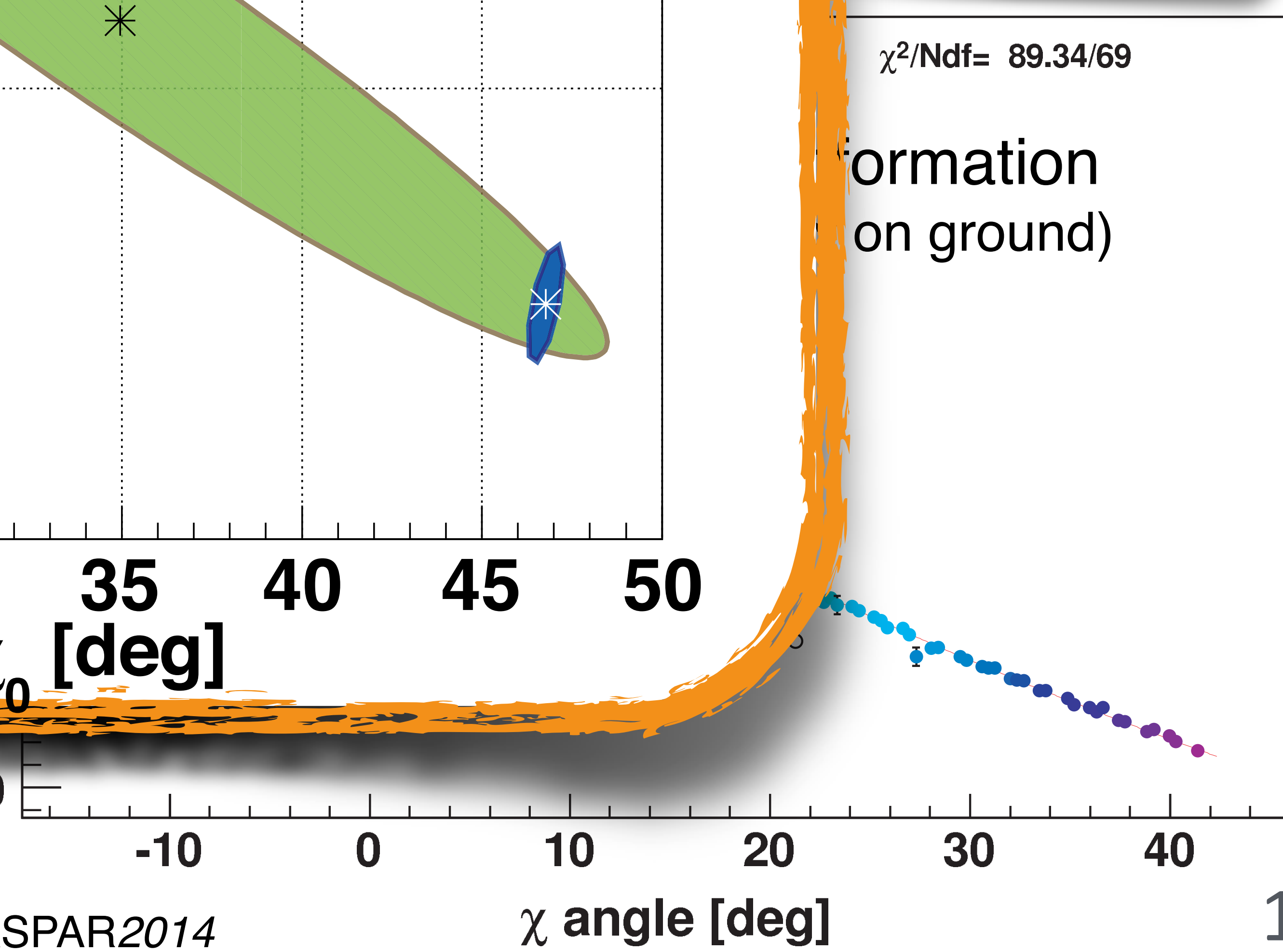
R_p, t_0 and chi_0 :

$$\ldots + \tau_i^{\mathrm{prop}}$$

$$\ldots \left(\frac{\chi_0 - \chi_i}{2}\right)$$







...formation

... on ground)

Fit R_p, t_0 a...

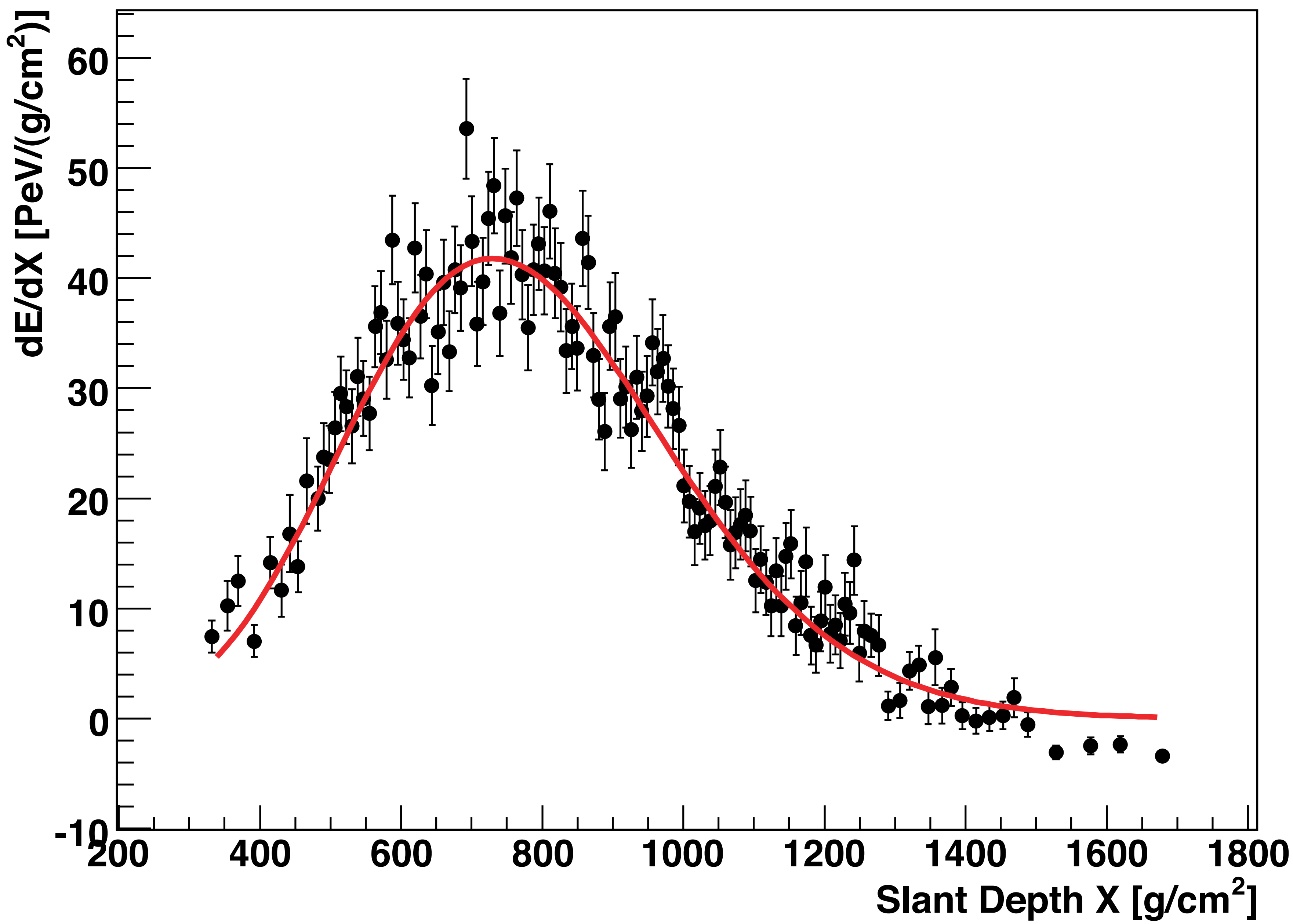
determine...

Angular res...

typically less than 1°

Energy reconstruction

Energy determination from profile fit



$$\int \frac{dE}{dX}\, dX \sim E$$

Largest uncertainty from fluorescence yield

Systematic uncertainty ~14%

Auger in operation…

Video by S. Saffi

Auger in operation…

Video by S. Saffi

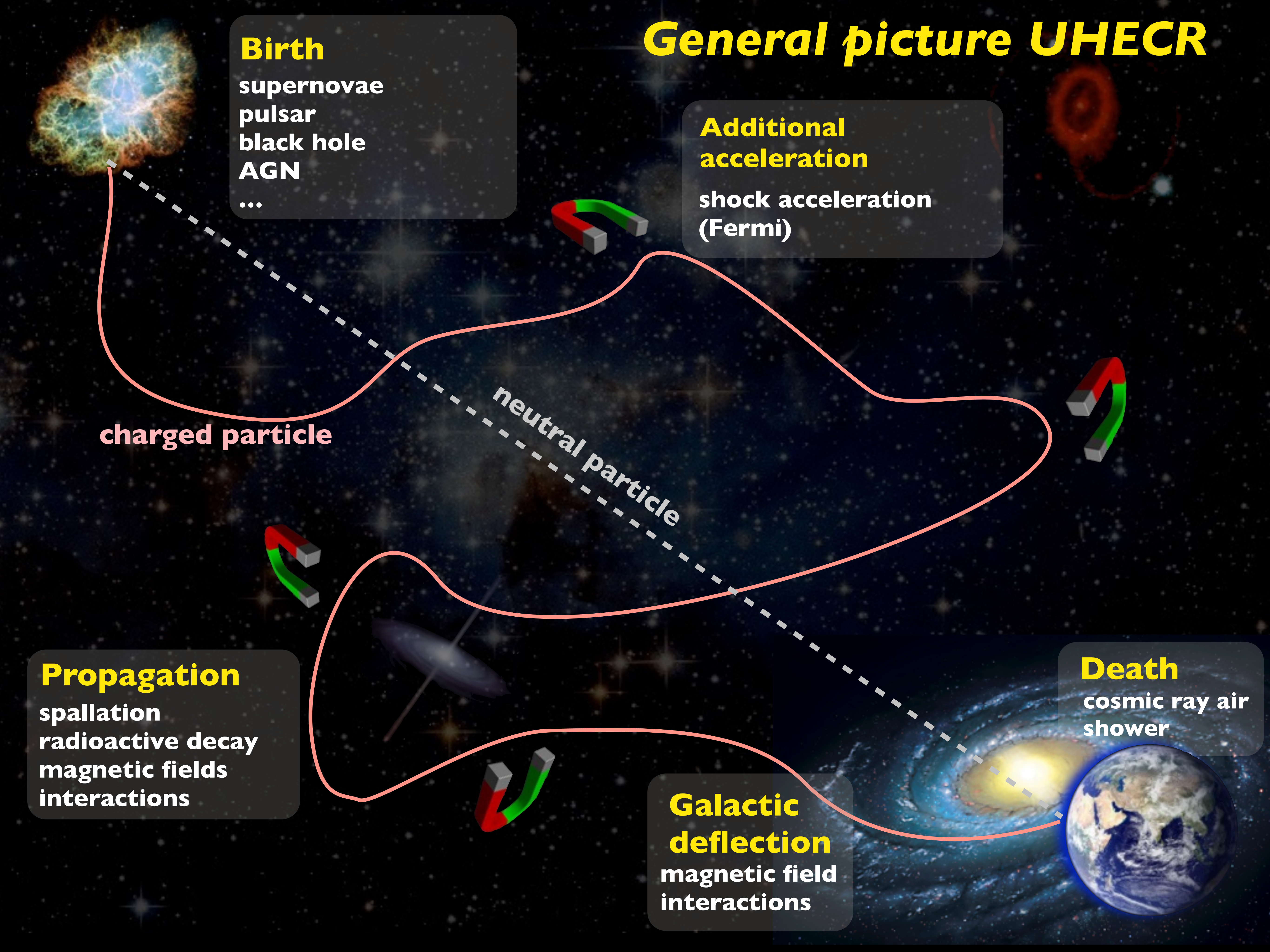
… and today,
more than 100 years after the discovery of cosmic rays?

… *still many open questions:*

1. Where do they come from?
2. What are they made of?
3. How are they accelerated?
4. What can they tell us about fundamental and particle physics?
5. Is there a maximal energy?

Ultra-high energy cosmic rays (UHECR)

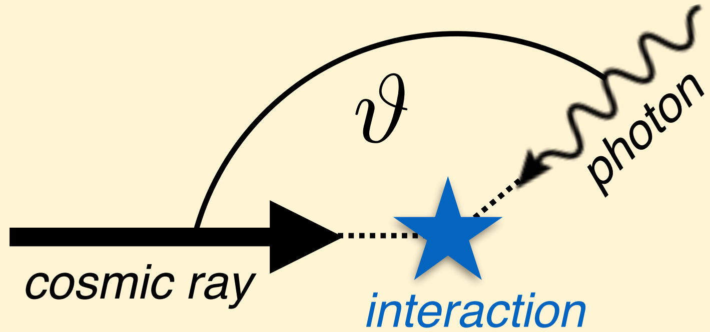
E > 10


General picture UHECR
Birth
supernovae
pulsar
black hole
AGN
...
Additional acceleration
shock acceleration (Fermi)
charged particle
neutral particle
Propagation
spallation
radioactive decay
magnetic fields
interactions
Galactic deflection
magnetic field
interactions
Death
cosmic ray air shower

Extra-galactic energy density

- Cosmic rays can interact with background photons:

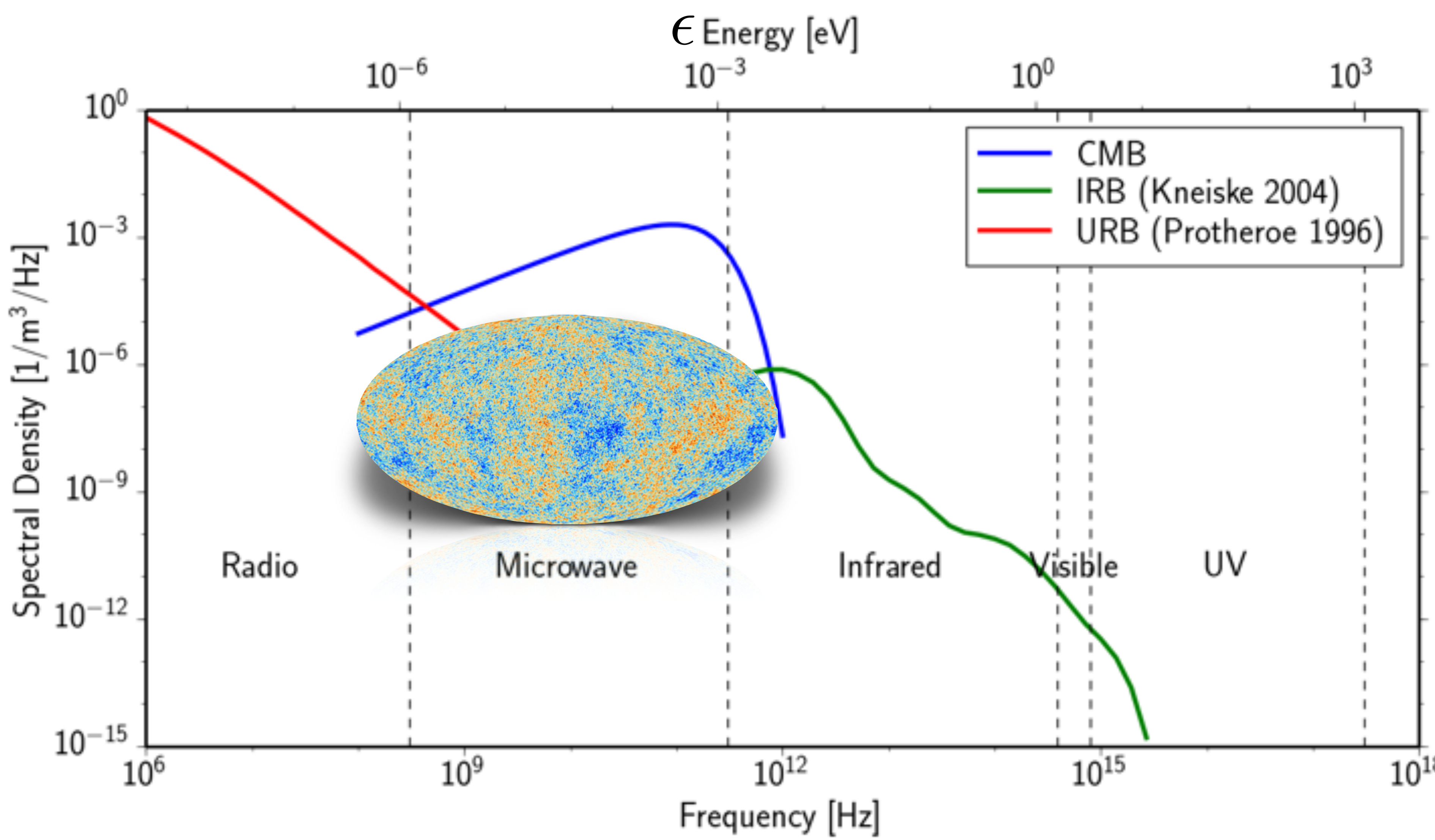
$$\Gamma = \frac{E}{m}$$



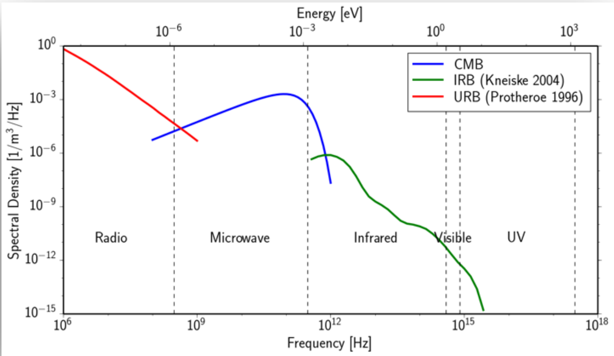
$$\epsilon' = \epsilon\Gamma(1 - \cos(\vartheta))$$

photon energy in nucleus rest frame

ϵ' is the relevant energy scale for interaction



Interactions



- **Pion production**

Pion production for a head-on collision of a nucleon *N*:

$$N + \gamma \rightarrow N + \pi$$

with the threshold energy

$$E_{\text{thres}} = \frac{m_\pi (m_N + m_\pi/2)}{2\epsilon} \approx 6.8 \cdot 10^{19} \left(\frac{\epsilon}{10^{-3}\ \text{eV}}\right)^{-1} \text{eV}$$

where $\epsilon \sim 10^{-3}$ eV represents a typical target photon such as a CMB photon.
Both the electromagnetic and the strong interaction play a role.
Example: Pion production by protons via delta resonance:

EM interaction

strong interaction

$$p + \gamma \xrightarrow{\text{EM interaction}} \Delta^+ \xrightarrow{\text{strong interaction}} \begin{cases} n + \pi^+ & \text{with branching ratio } 1/3 \\ p + \pi_0 & \text{with branching ratio } 2/3 \end{cases}$$

$\pi^+ \rightarrow \mu^+ + \nu_\mu$ main production channel of neutrinos by hadronic cosmic rays

$\pi_0 \rightarrow \gamma + \gamma$ main channel of high energy photons by hadronic cosmic rays

After the discovery of the CMB (1965) people realized:

Universe gets opaque for cosmic rays at ultra-high energies: GZK-effect

first realized by Greisen, Zatsepin and Kuzmin in 1966

K. Greisen, PRL 16 748 (1966), G.T. Zatsepin and V.A. Kuzmin Sov. Phys. JETP Lett. 4 78 (1966)

Interactions

- **Pair production**

Pair production by a nucleus with mass number *A* and charge *Z* on a photon:

$$^{A}_{Z} + \gamma \rightarrow ^{A}_{Z} + e^{+} + e^{-}$$

induces electromagnetic cascades via inverse Compton scattering

with the threshold energy

$$E_{\mathrm{thres}} = \frac{m_e(m + m_e)}{\epsilon} \approx 4.8 \cdot 10^{17}\ A\ \left(\frac{\epsilon}{10^{-3}\ \mathrm{eV}}\right)^{-1} \mathrm{eV}$$

where $\epsilon \sim 10^{-3}\ \mathrm{eV}$ represents a typical target photon such as a CMB photon.

Interactions

- **Pair production**

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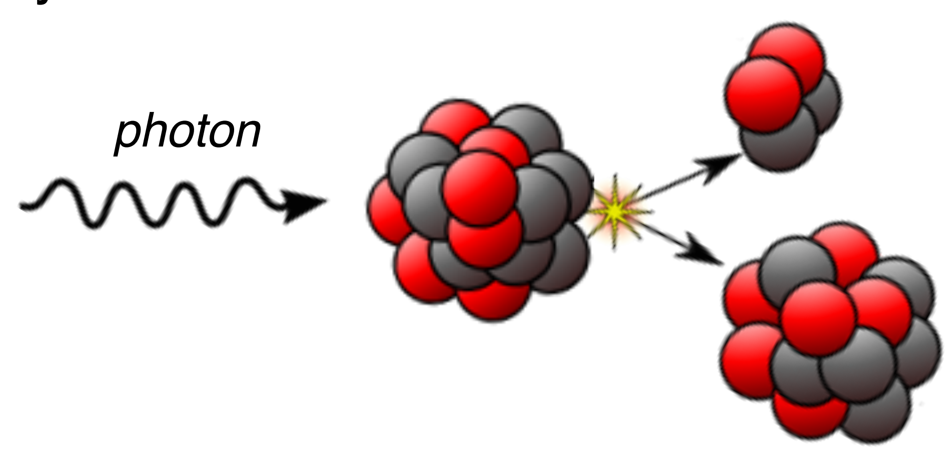
with the threshold energy

$$ E_{\mathrm{thres}} = \frac{m_e(m + m_e)}{\epsilon} \approx 4.8 \cdot 10^{17} \ A \ \left(\frac{\epsilon}{10^{-3} \ \mathrm{eV}} \right)^{-1} \mathrm{eV} $$

where $\epsilon \sim 10^{-3} \ \mathrm{eV}$ represents a typical target photon such as a CMB photon.

- **Photodisintegration of nuclei**

Gamma ray is absorbed by nuclei and causes it to enter excited state before splitting in two parts.



Changes in energy ΔE, and atomic number ΔA, are related by $\Delta E/E = \Delta A/A$
Thus, effective energy loss rate is given by:

$$ \frac{1}{E} \frac{\mathrm{d}E}{\mathrm{d}t}\bigg|_{\mathrm{eff}} = \frac{1}{A} \frac{\mathrm{d}A}{\mathrm{d}t} = \sum_i \frac{i}{A} l_{A,i}(E) $$

rate for emission of *i* nucleons of mass *A*

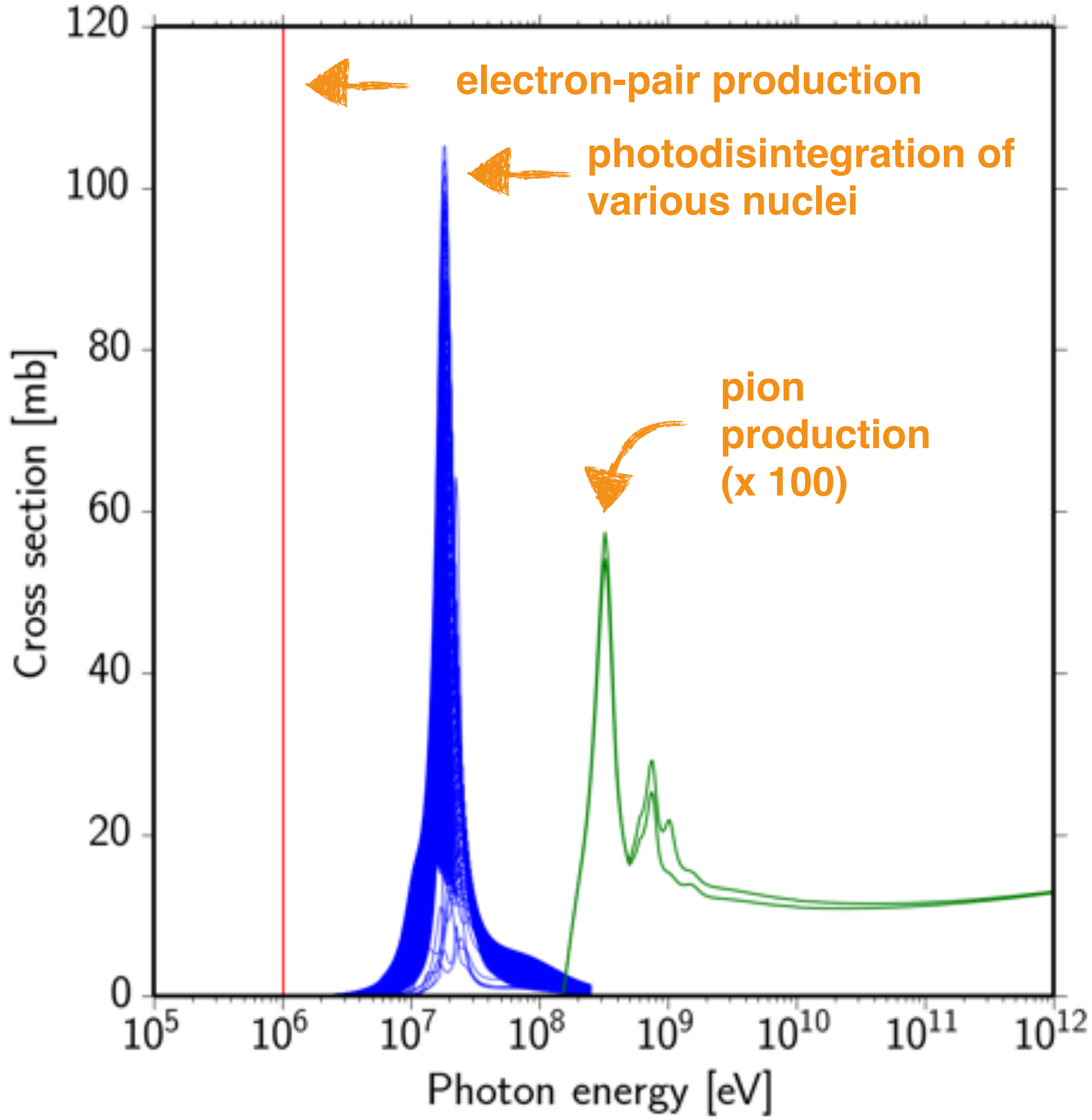
Interaction rate

Interaction rate can be calculated as

$$\lambda^{-1} = \int_0^\infty n(\epsilon)\sigma_{\mathrm{avg}}(\epsilon)\ \mathrm{d}\epsilon$$

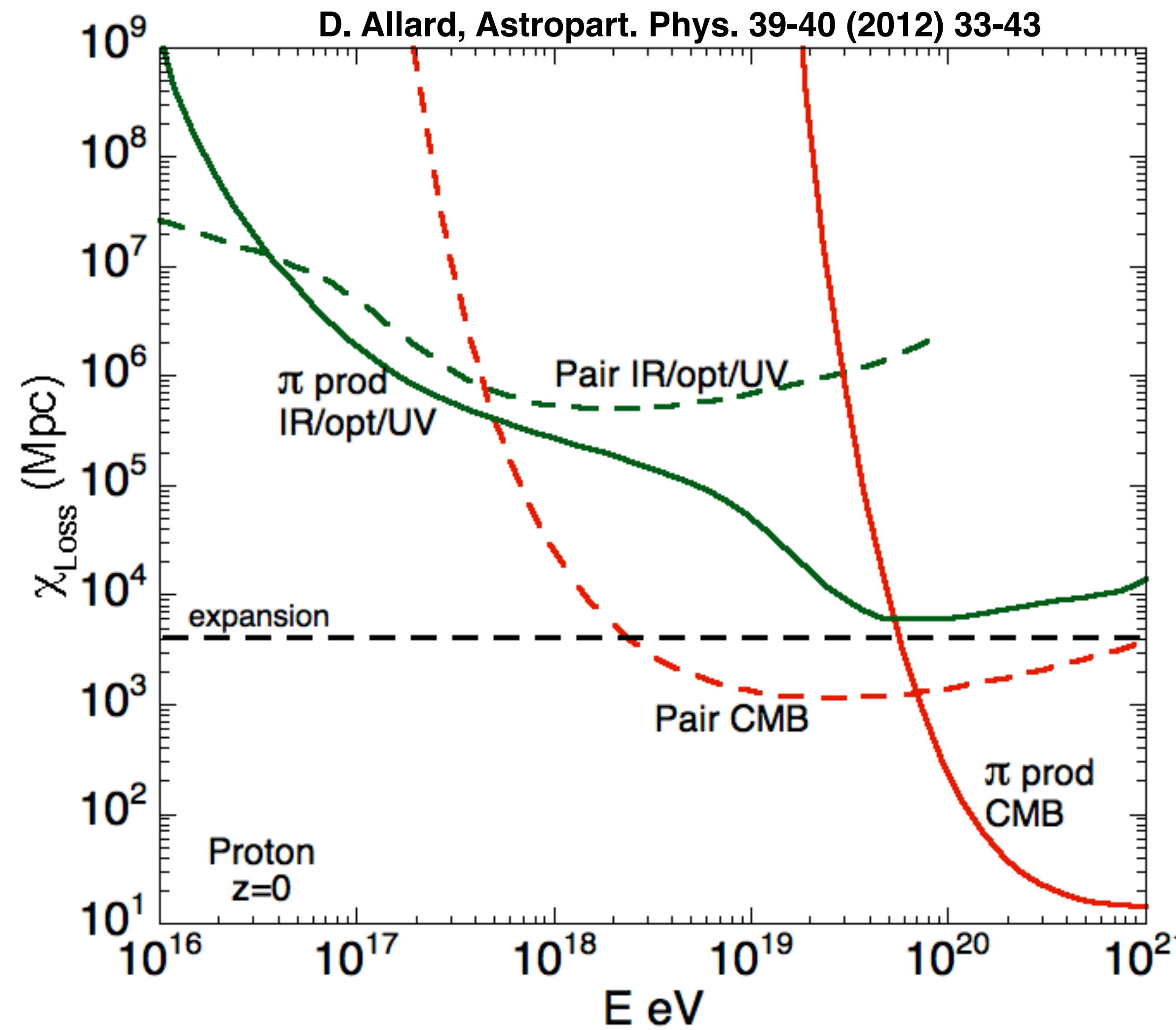
photon number density

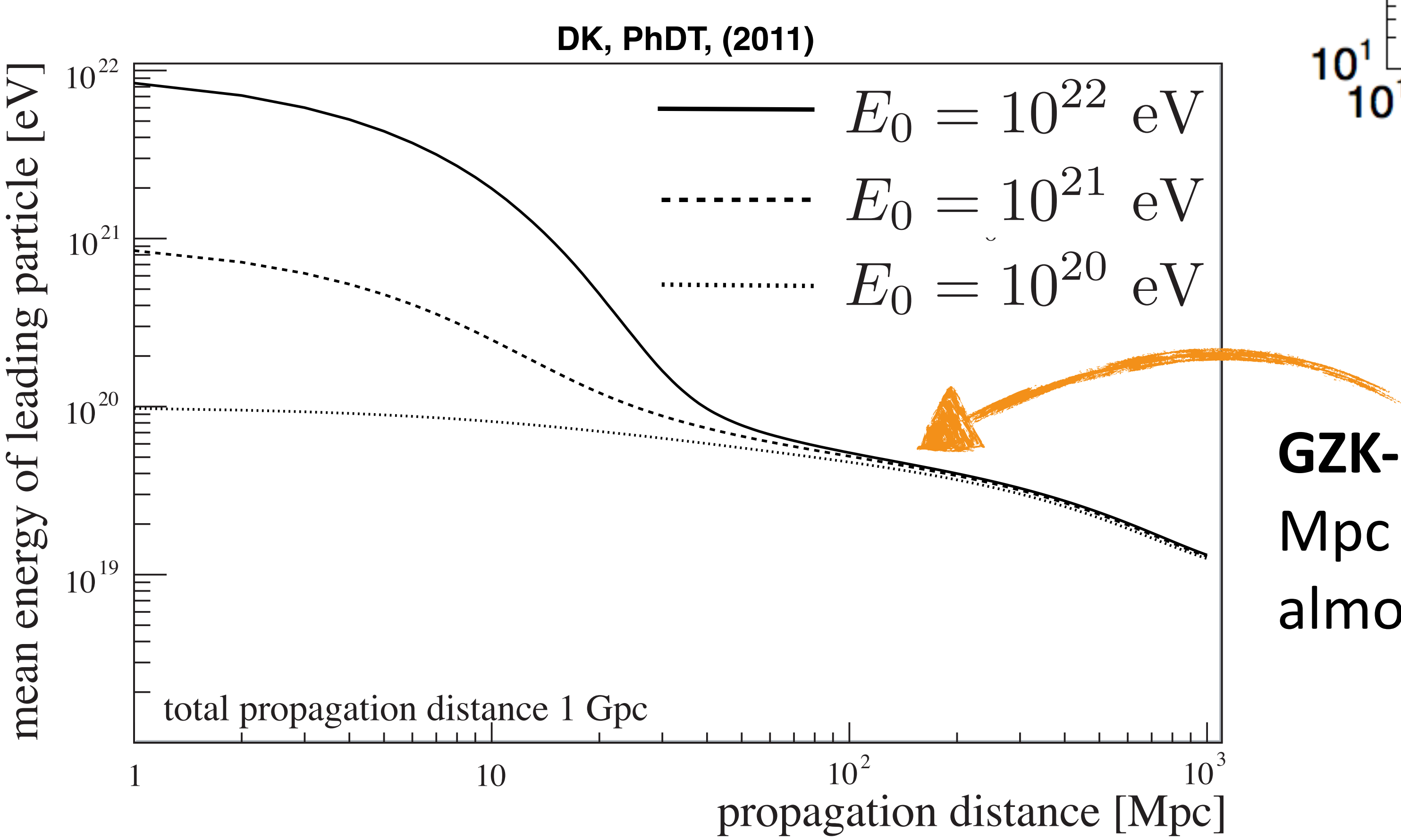
collision angle averaged
cross section



Attenuation length for protons

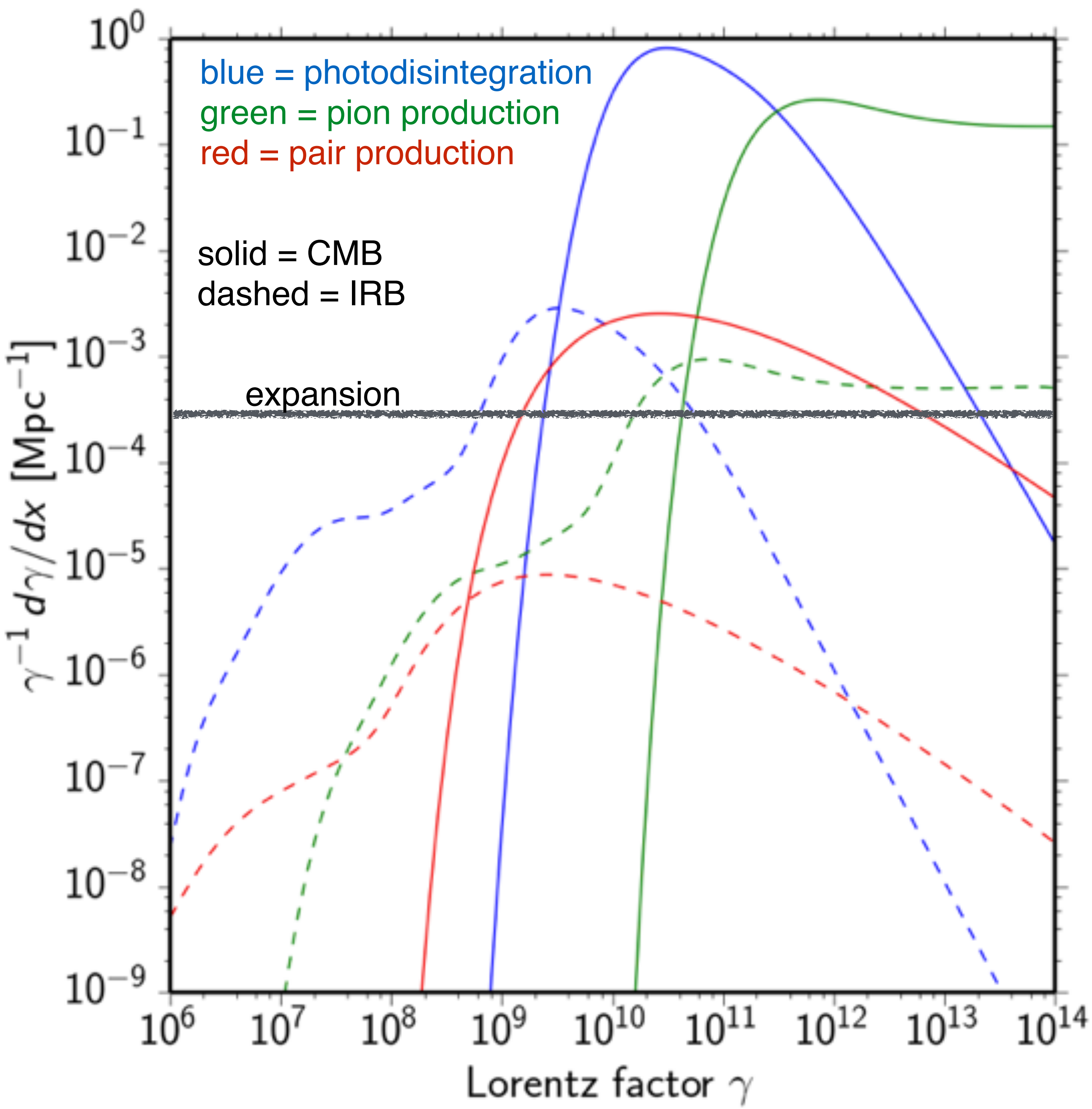
- **Low energies:**
  energy loss dominated by expansion of the universe
- **Intermediate energies:**
  Most important loss length is pair production on CMB
- **High energies:**
  Most important loss length is pion production on CMB





GZK-effect: For propagation distances > 100 Mpc the primary energy is attenuated to almost the same value

Energy loss rate for Carbon-12

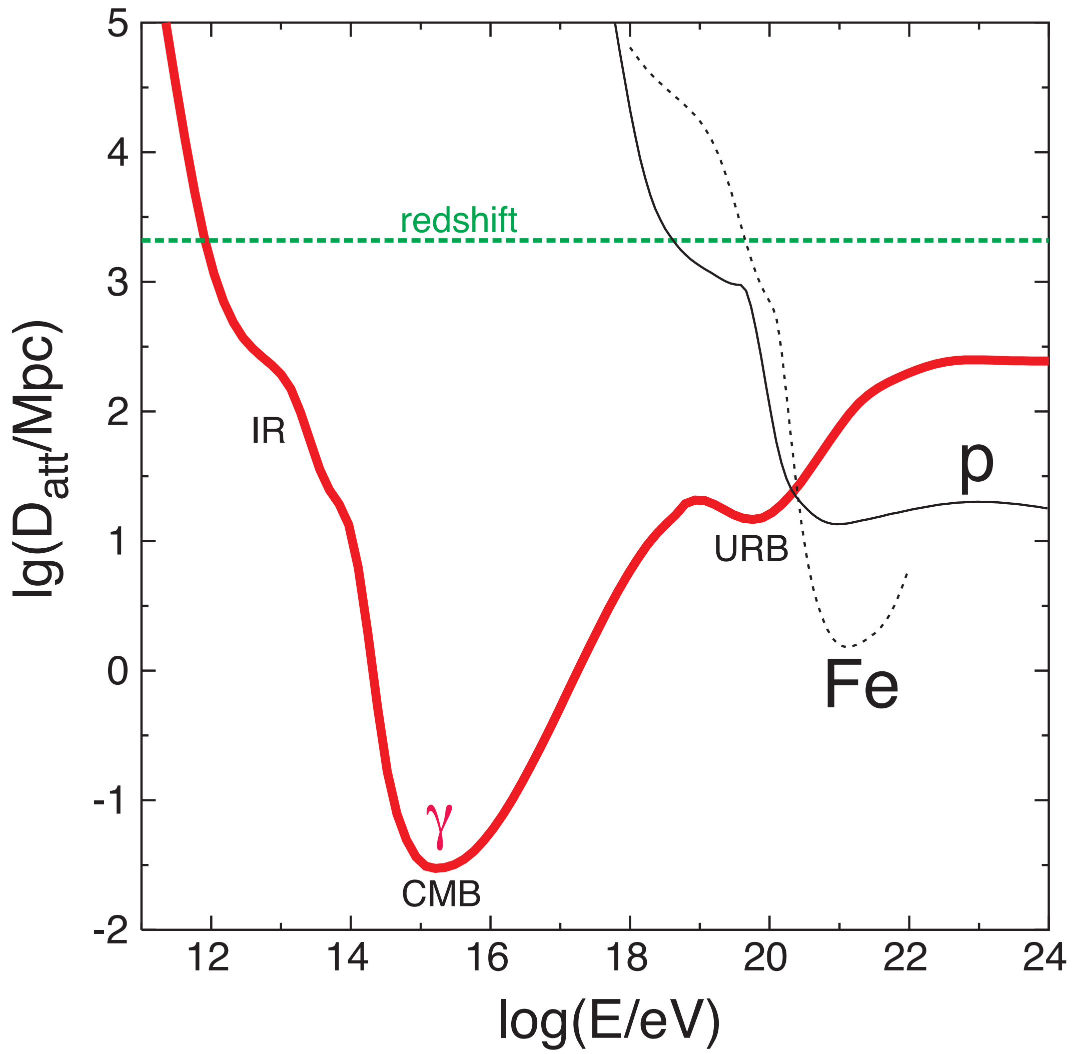


$$E \sim \Gamma\ A\ 10^9\ \mathrm{eV}$$

- **Low energies:**
  energy loss dominated by expansion of the universe
- **Intermediate energies:**
  Most important energy loss is photodisintegration
- **High energies:**
  Pion production on CMB

Secondary photons

DK, PhDT, (2011)

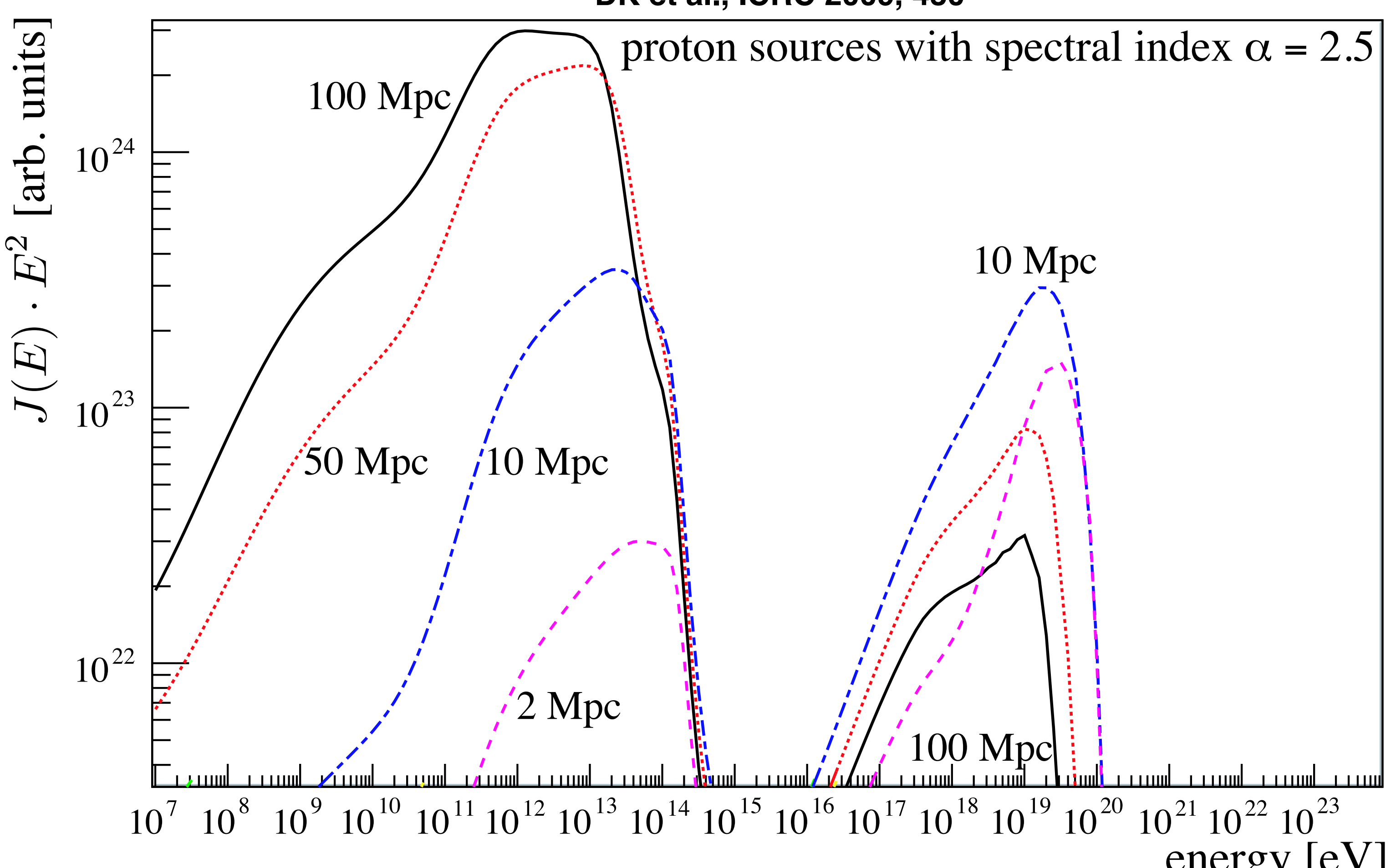


- Dominant interaction process is pair production:

$$\gamma_{\mathrm{UHE}} + \gamma_b \rightarrow e^+ + e^-$$

- Strong attenuation in PeV regime by CMB photons

DK et al., ICRC 2009, 430

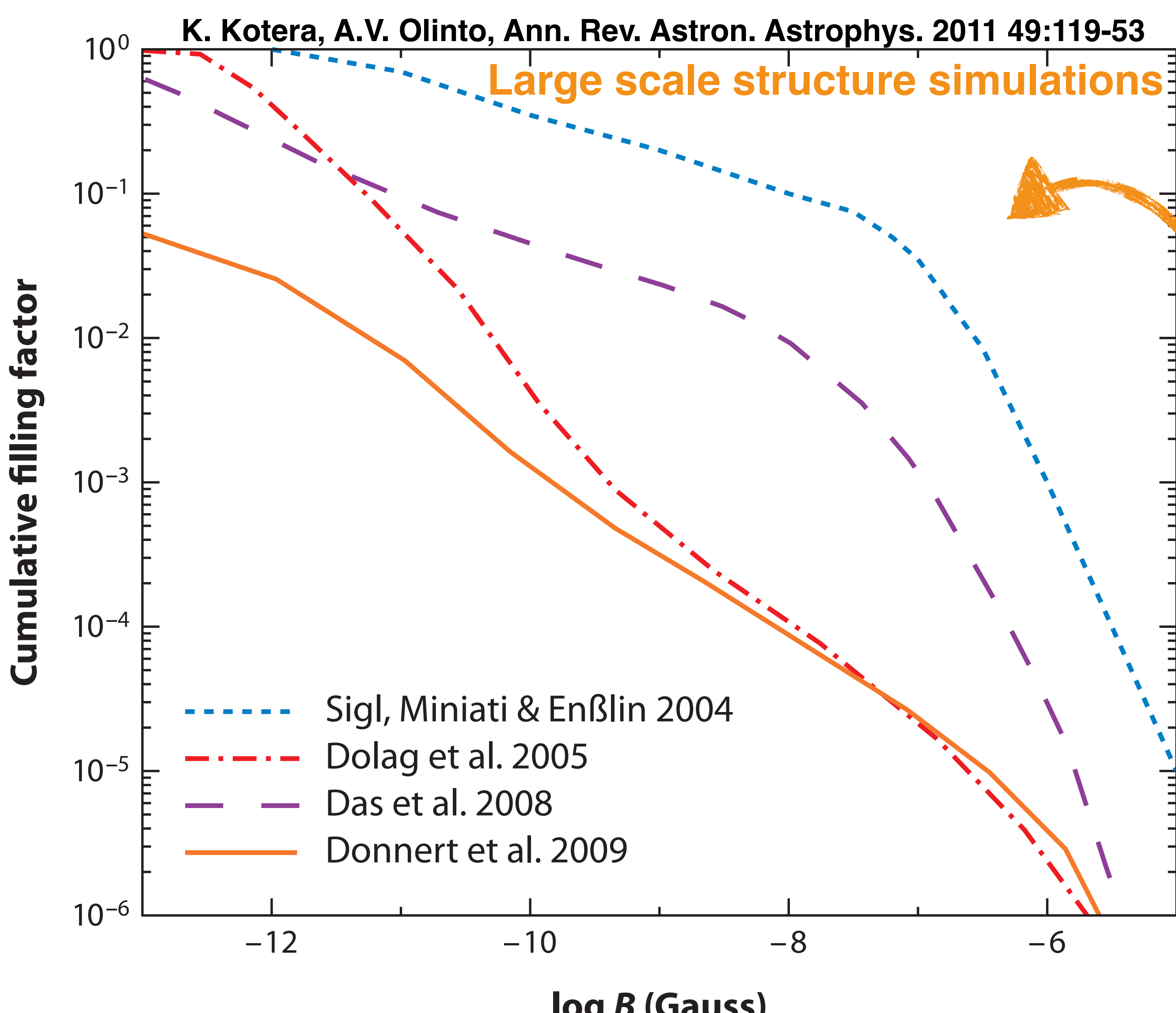


- Typical energy loss length:
  - 7-15 Mpc at 10^{19} eV
  - 5-30 Mpc at 10^{20} eV

observation of galactic and nearby extragalactic sources may be possible

Extragalactic magnetic fields

- **Some words of caution**: **Extragalactic** magnetic fields are currently poorly constrained.
- Their origin is not well understood (primordial Universe, magnetic pollution from astrophysical sources, e.g. jets from radio galaxies, …)
- Typical strength of the field varies:
  - **1-40 μG** with coherence length of about 10 kpc *(clusters of galaxies)*
  - **10^{-16} - 10^{-6} G** with coherence length between 1-10 Mpc *(in filaments)*
- Field strength probably related to matter density in this environment

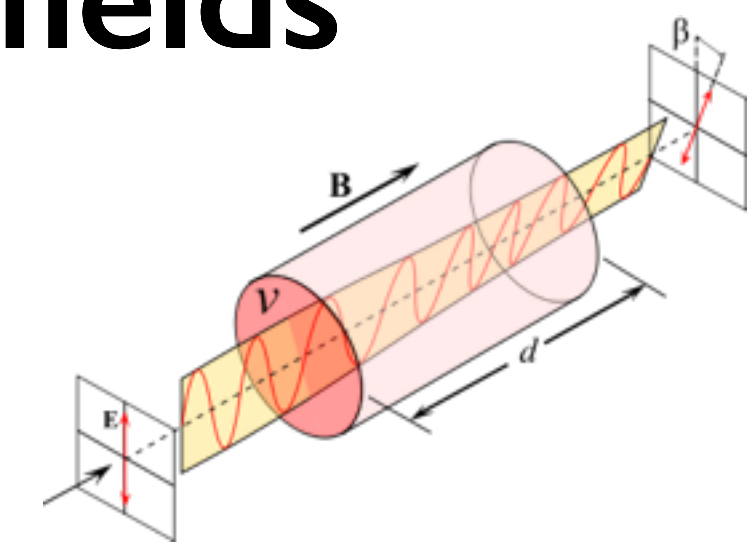


- Absence of powerful counterparts in the arrival direction of UHECRs is probably related to magnetic fields

- Simulations lead to **very discrepant results**
- Illustrates **variety of assumptions** made
- E.g. Sigl, Miniati & Enßlin estimate proton deflection with energy > 100 EeV by **10-20°**, whereas Dolag et al. **< 1°** of the same energy

Galactic magnetic fields

- Much progress in recent years
- Models based on Faraday rotation measurements and polarized and unpolarized synchrotron emission
- Concentrate on field from Jannson & Farrar: **JF12**
  R. Jansson and G. R. Farrar, ApJ 757 (2012) 14
  R. Jansson and G. R. Farrar, ApJL 761 (2012) L11
- Field strength of order micro-Gauss

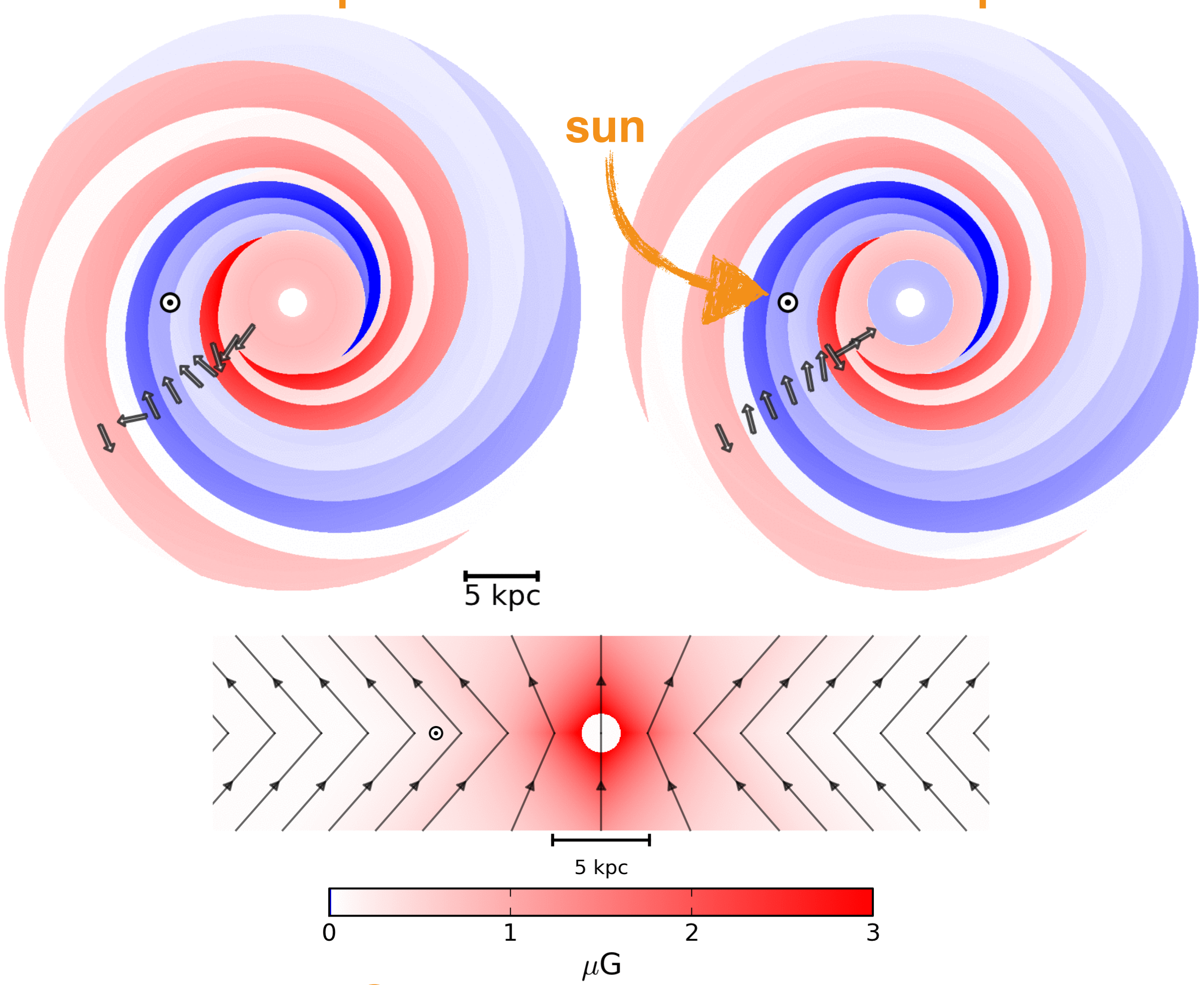


Slices in *x-y* plane

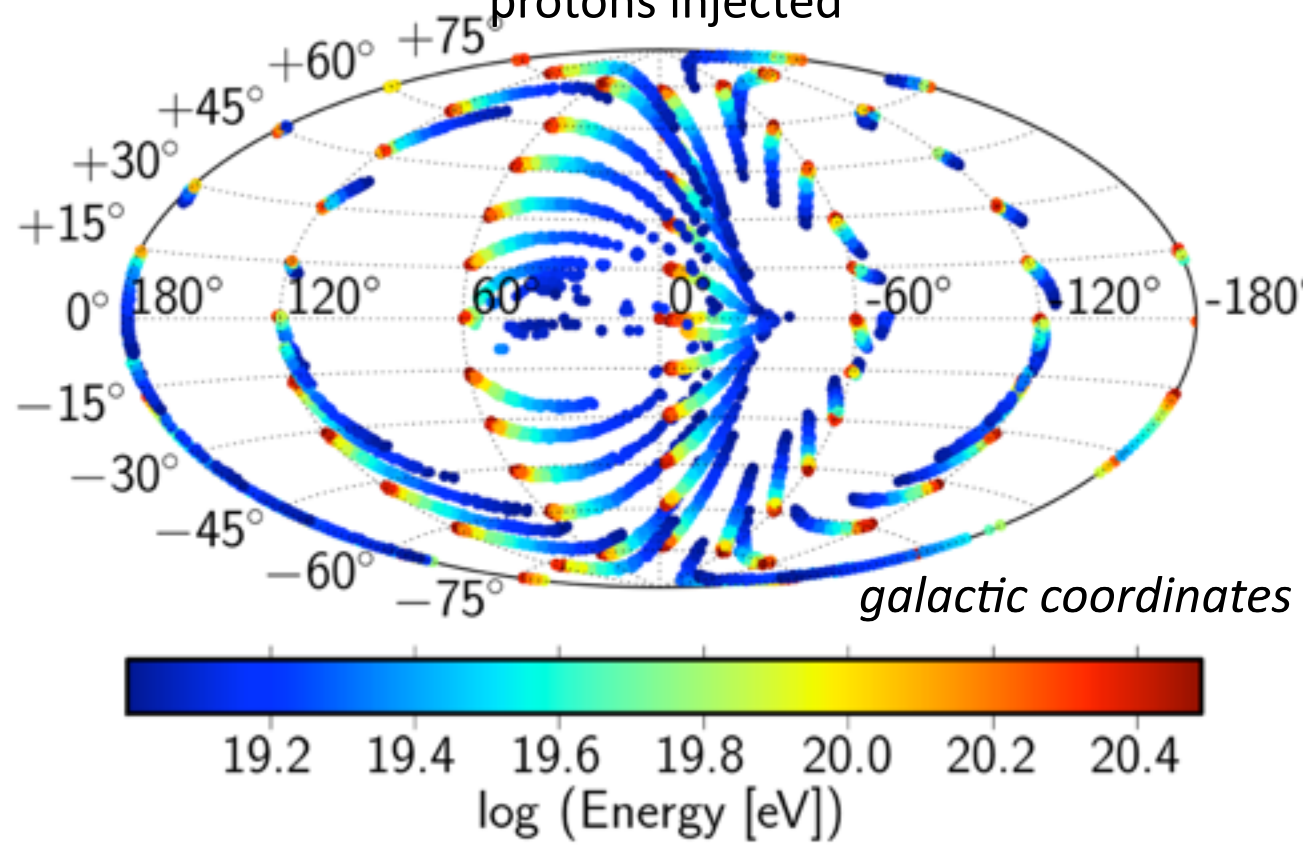
z = 10 pc

z = -10 pc

sun



Slices in *x-z* plane
out of the plane component

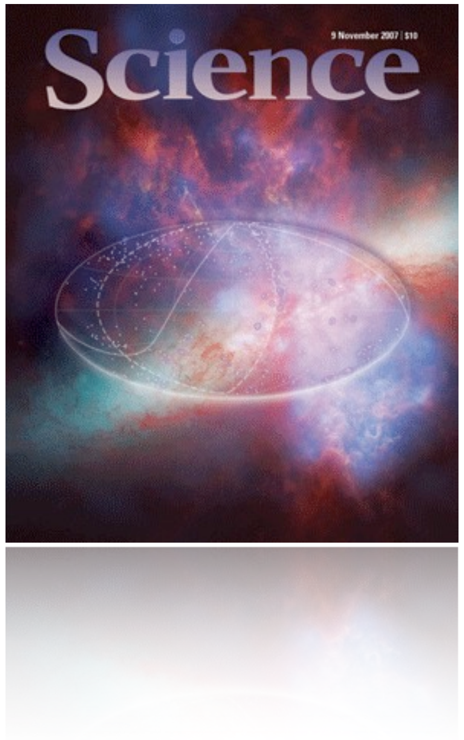


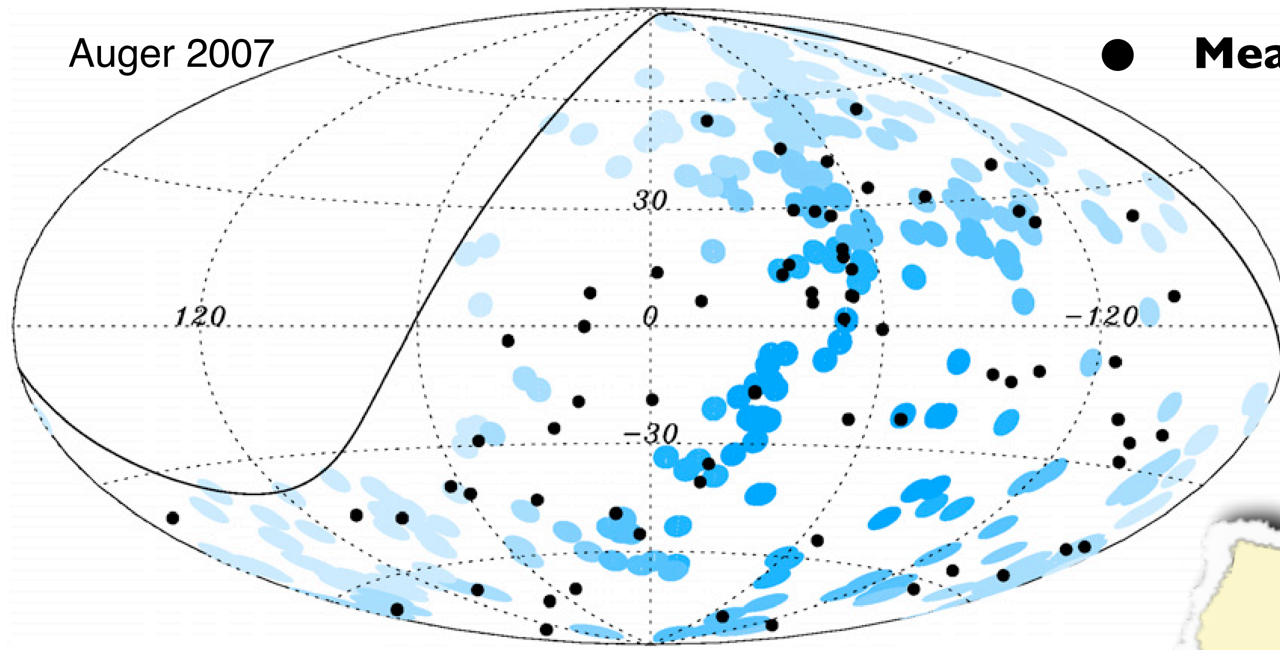
Deflections important in anisotropy studies

Key results

anisotropy

AGN correlation

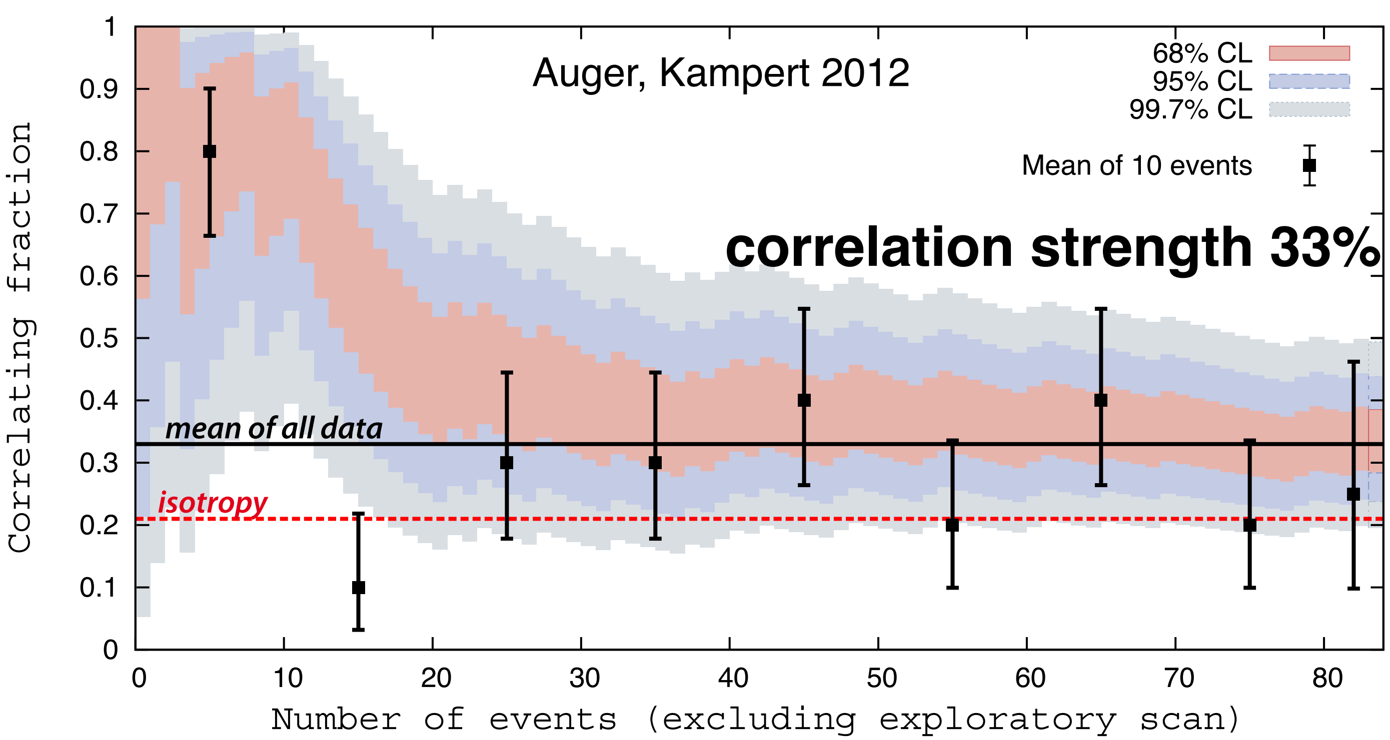


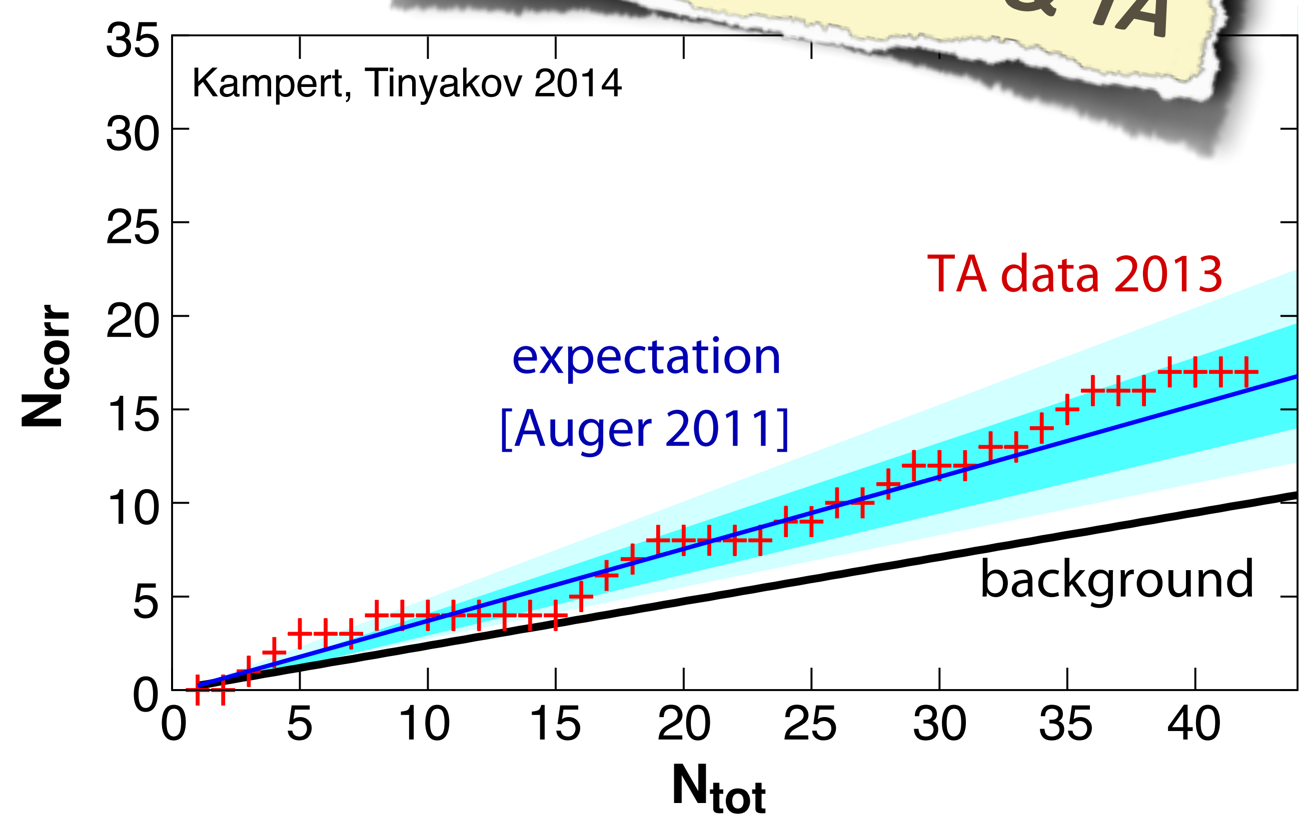


AGN position < 75 Mpc with 3.1° opening angle

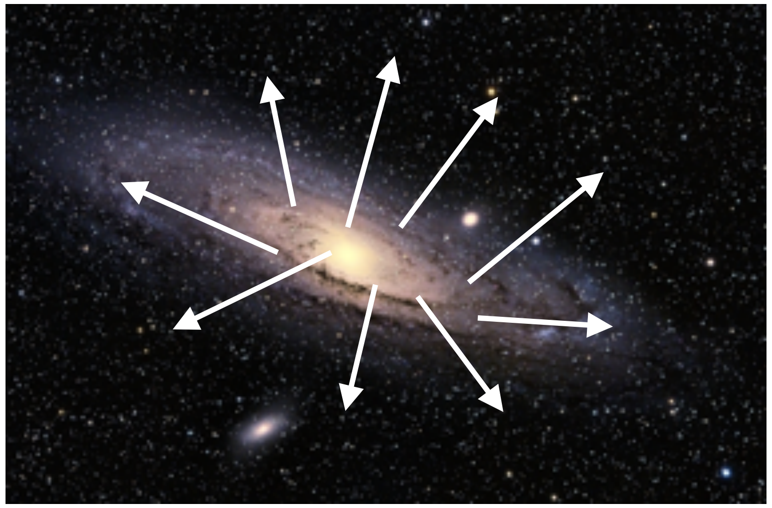
Measured arrival direction

perfect agreement between Auger & TA

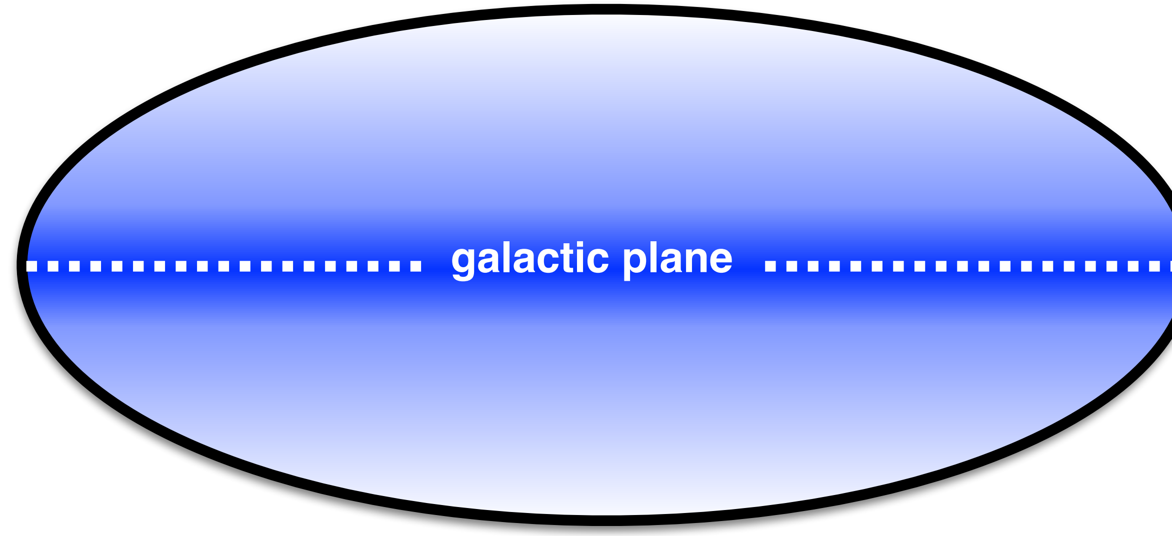


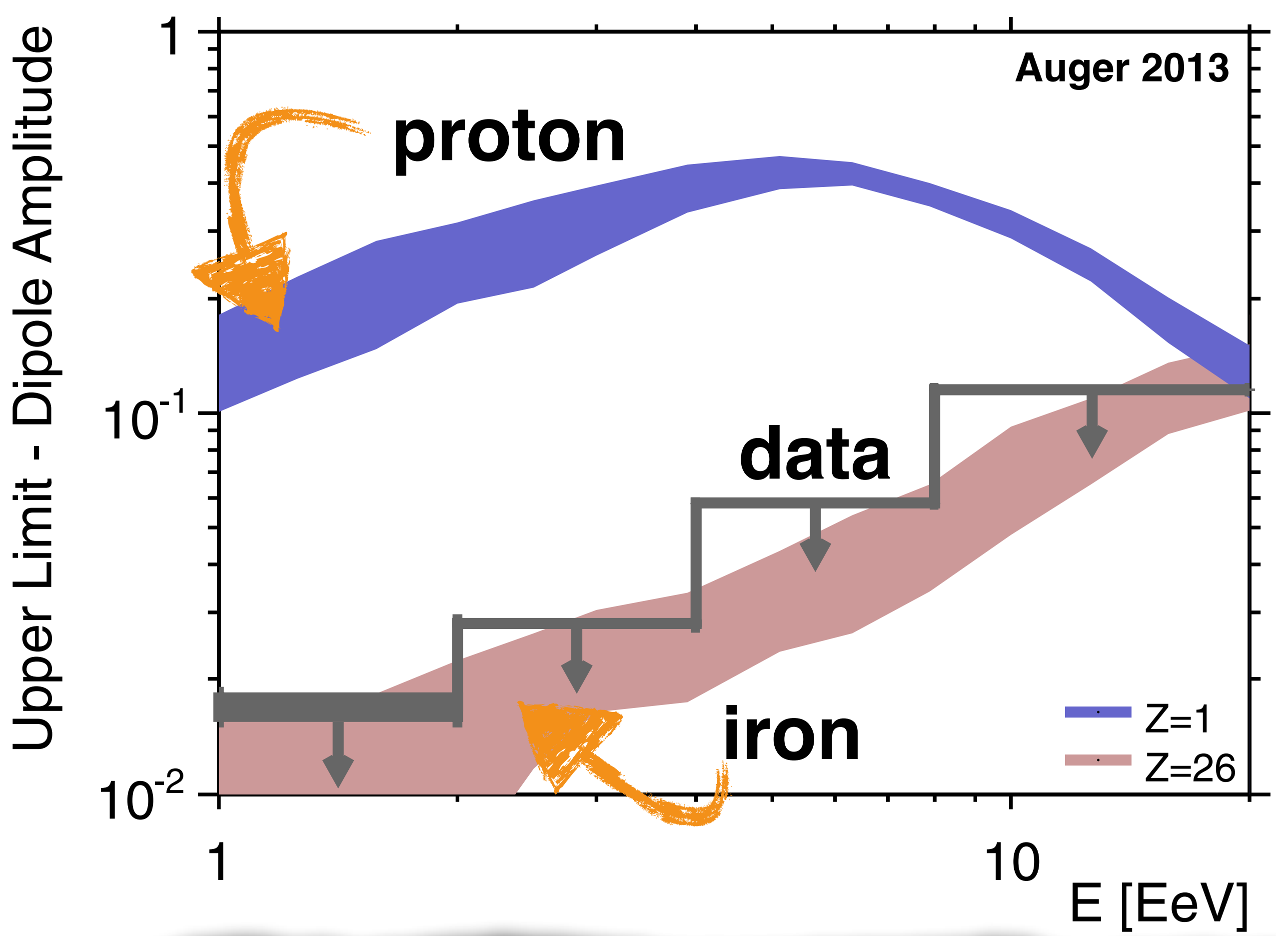


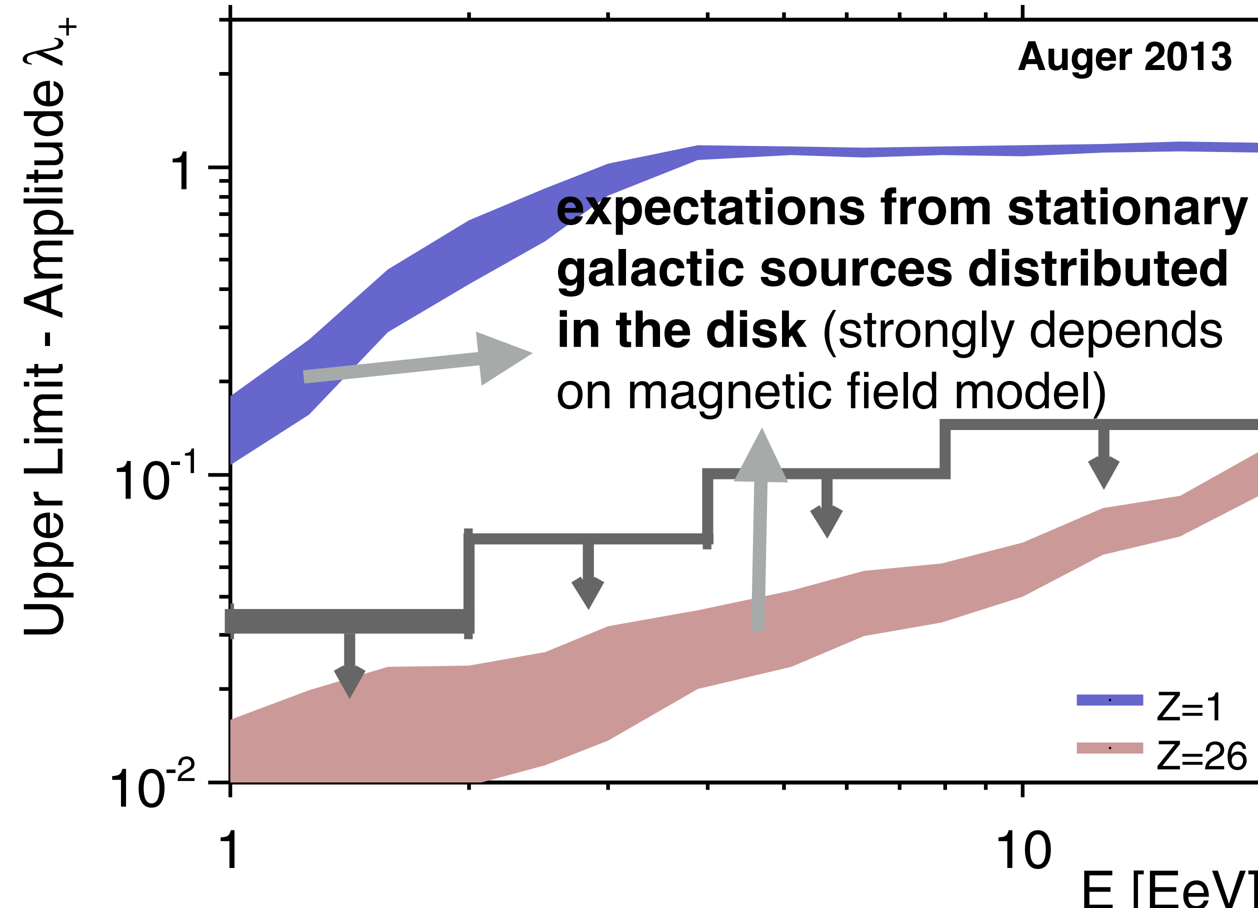
Large scale anisotropy



Expect dipolar anisotropies as a result of the escape of UHECR from the galaxy





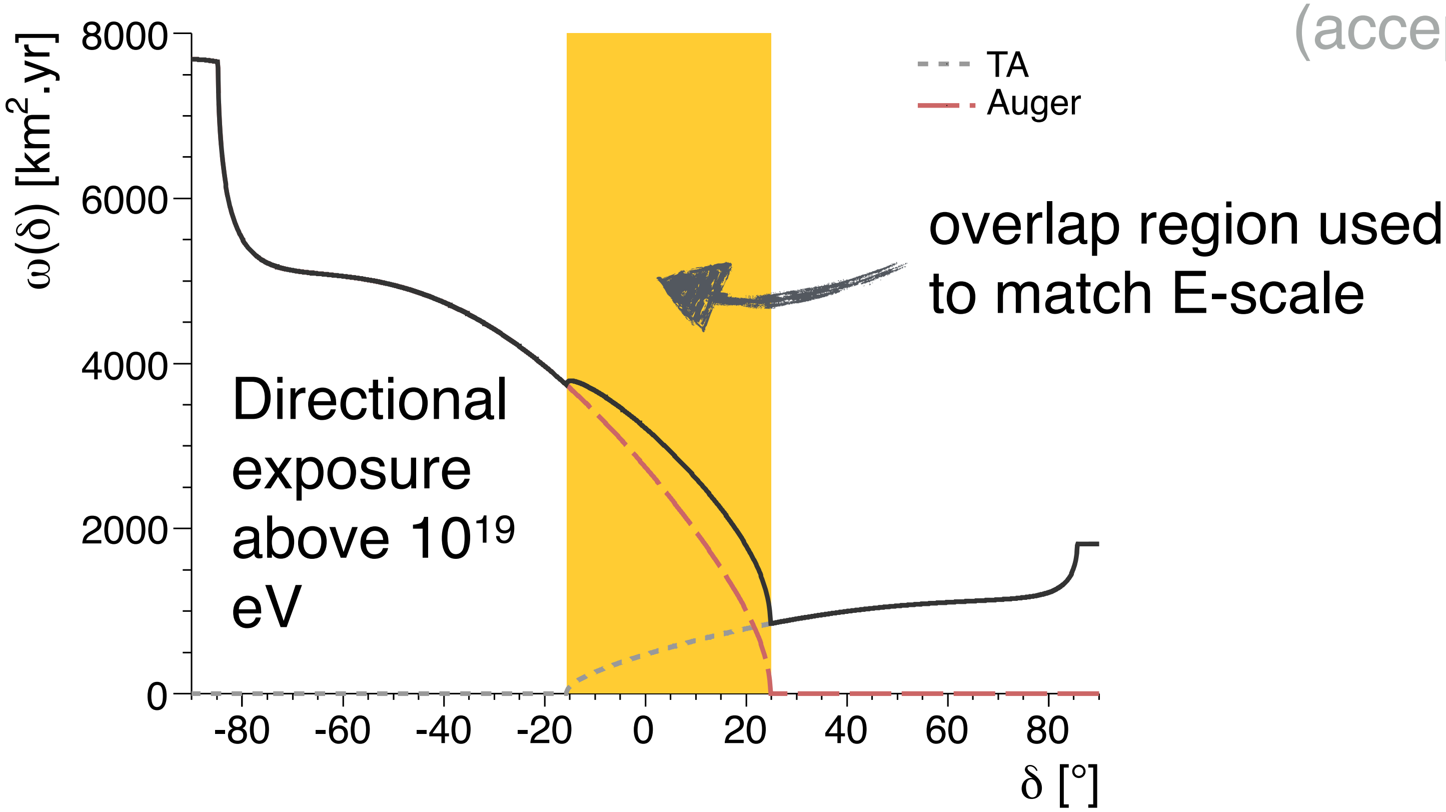


light CR component seen at 1 EeV cannot originate from stationary sources in the galactic disk

Large scale anisotropy

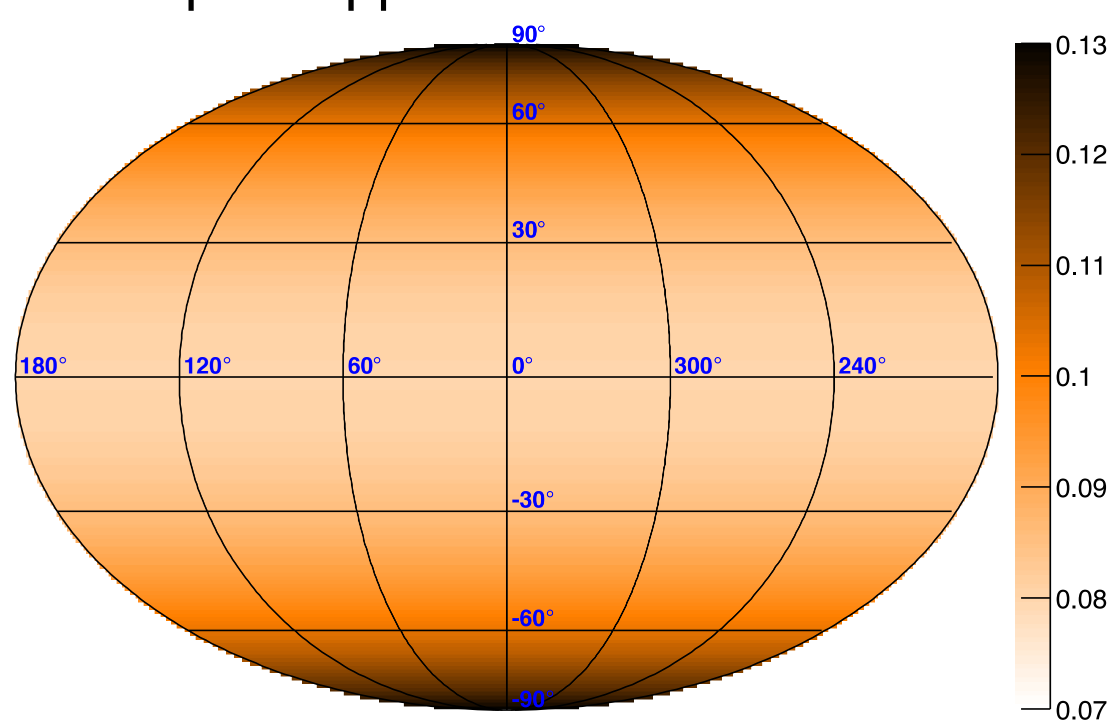
Combined Auger and TA analysis (E>10 EeV)

(accepted for publication in ApJ)

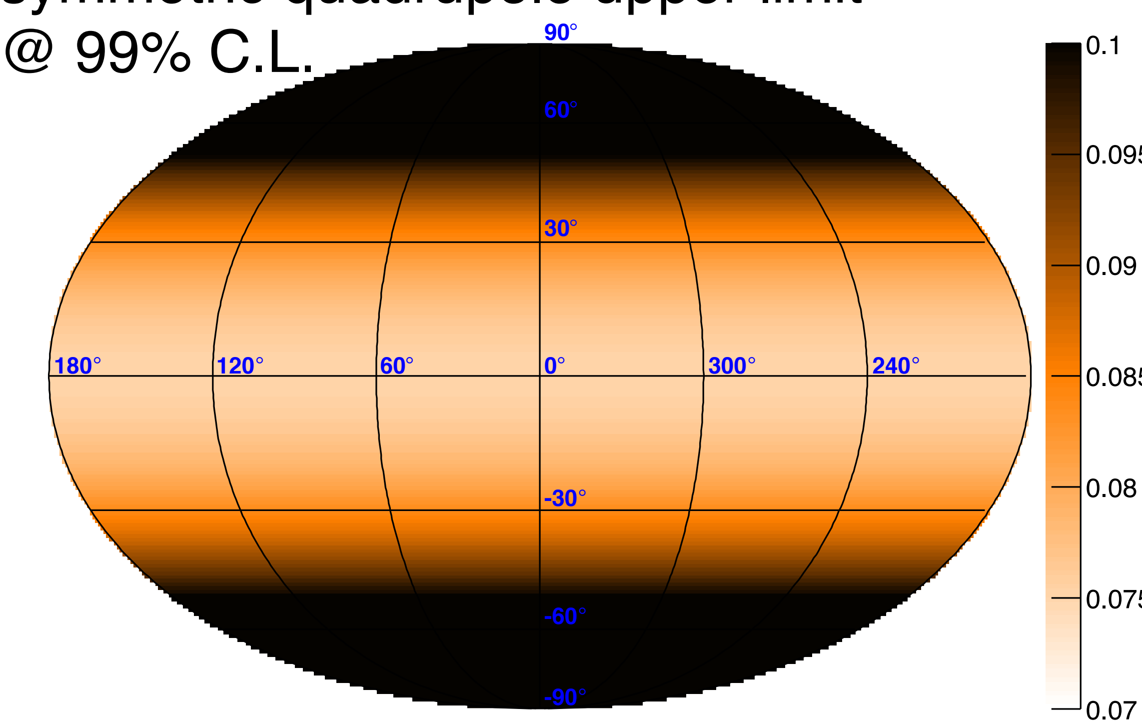


No significant deviation from isotropic expectation

dipole upper limits @ 99% C.L.



symmetric quadrupole upper limit @ 99% C.L.



TA hotspot

Science AAAS *July 8 2014*


Physicists spot potential source of 'Oh-My-God' particles

Tweet 151 Share 2.4k 8+1 54

By Adrian Cho | 8 July 2014 1:00 am | 40 Comments

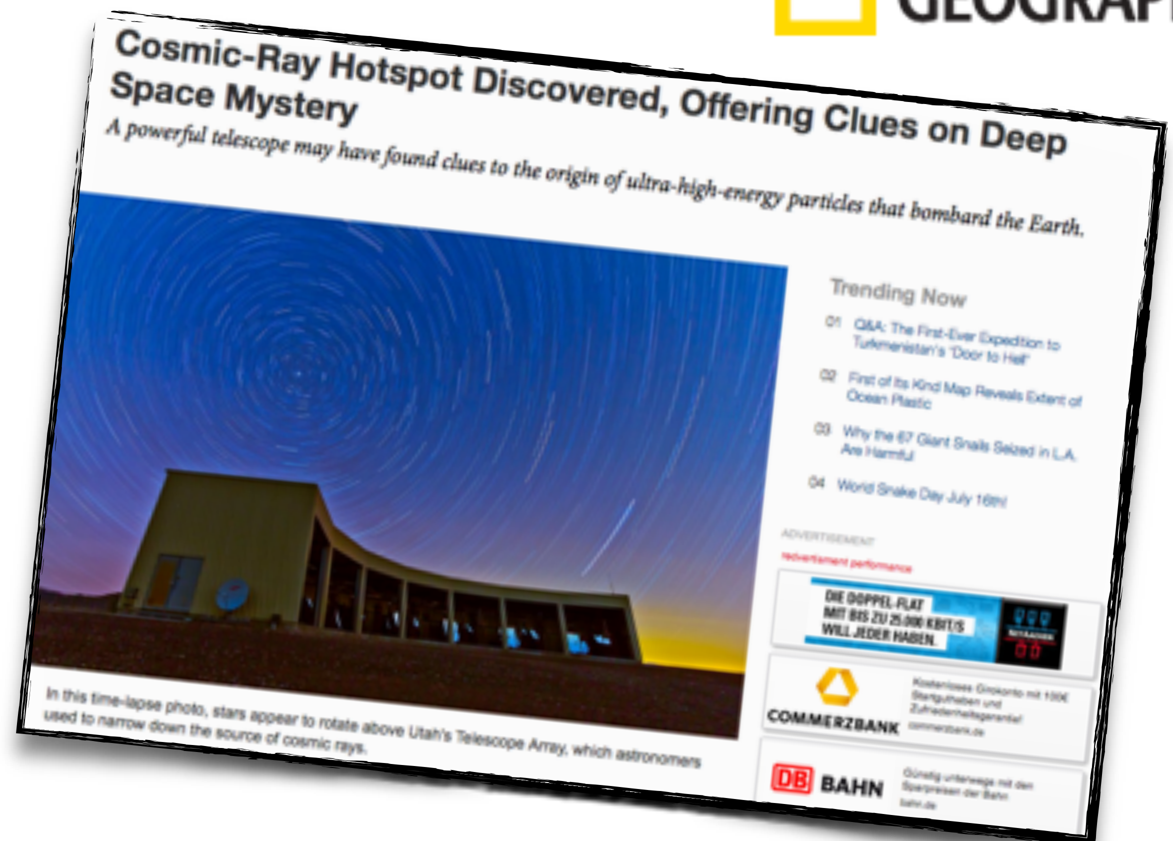
40 Comments

Staff Writer

Email Adrian

For decades, physicists have sought the sources of the most energetic subatomic particles in the universe—cosmic rays that strike the atmosphere with as much energy as well-thrown baseballs. Now, a team working with the Telescope Array, a collection of 507 particle detectors covering 700 square kilometers of desert in Utah, has observed a broad "hotspot" in the sky in which such cosmic rays seem to originate. Although not definitive, the observation suggests the cosmic rays emanate from a distinct source near our galaxy and not from sources spread all over the universe.

July 9 2014 NATIONAL GEOGRAPHIC


Cosmic-Ray Hotspot Discovered, Offering Clues on Deep Space Mystery

A powerful telescope may have found clues to the origin of ultra-high-energy particles that bombard the Earth.

In this time-lapse photo, stars appear to rotate above Utah's Telescope Array, which astronomers used to narrow down the source of cosmic rays.

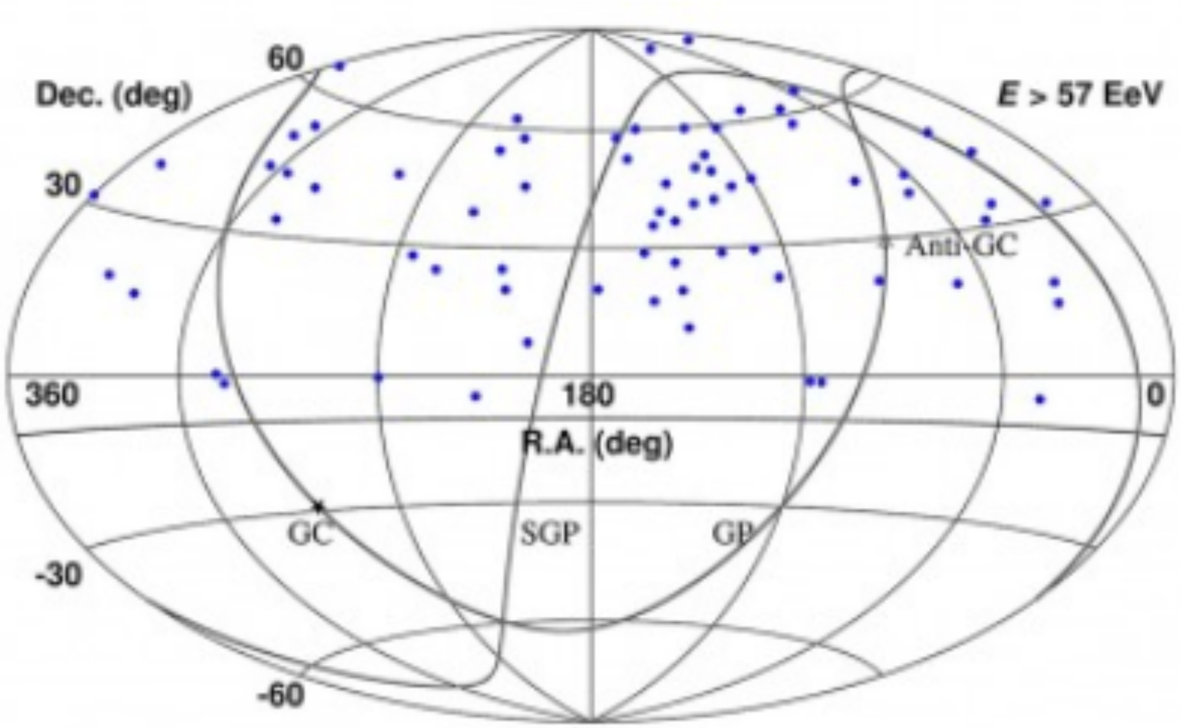
Trending Now

01 Q&A: The First-Ever Expedition to Turkmenistan's 'Door to Hell'

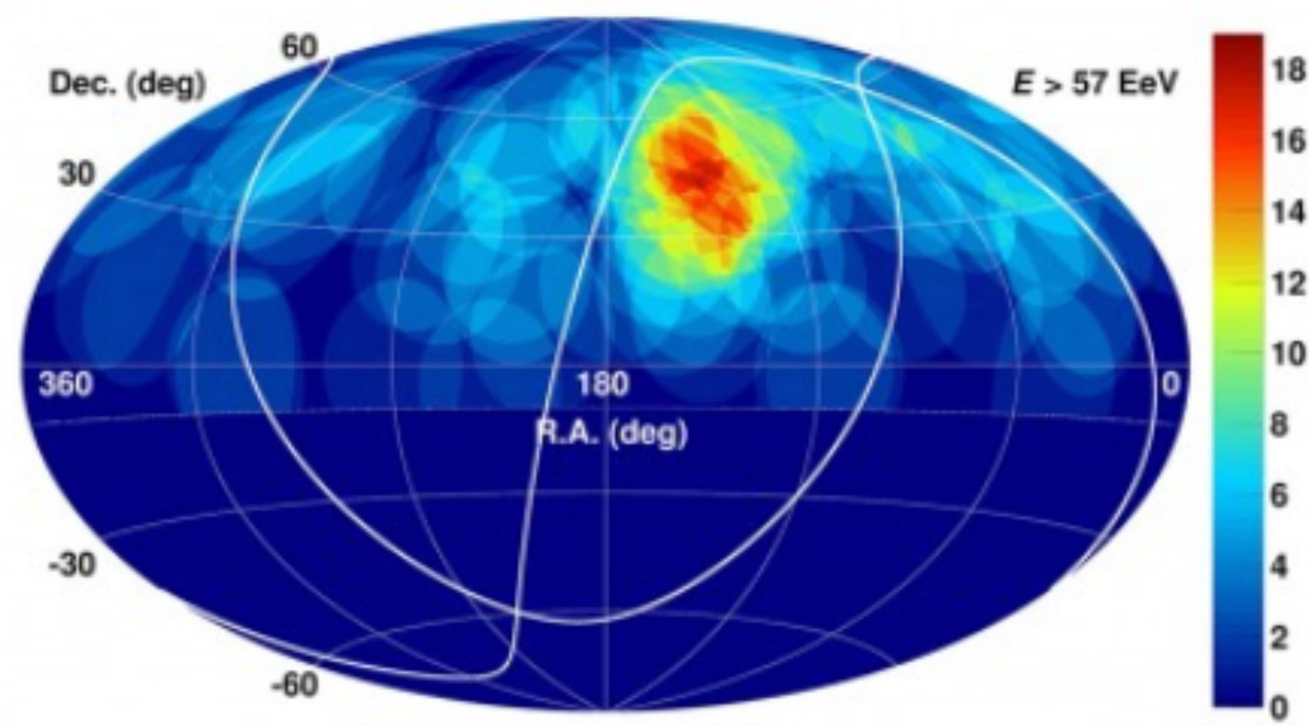
02 First of its Kind Map Reveals Extent of Ocean Plastic

03 Why the 67 Giant Snails Seized in L.A. Are Harmful

04 World Snake Day July 16th!



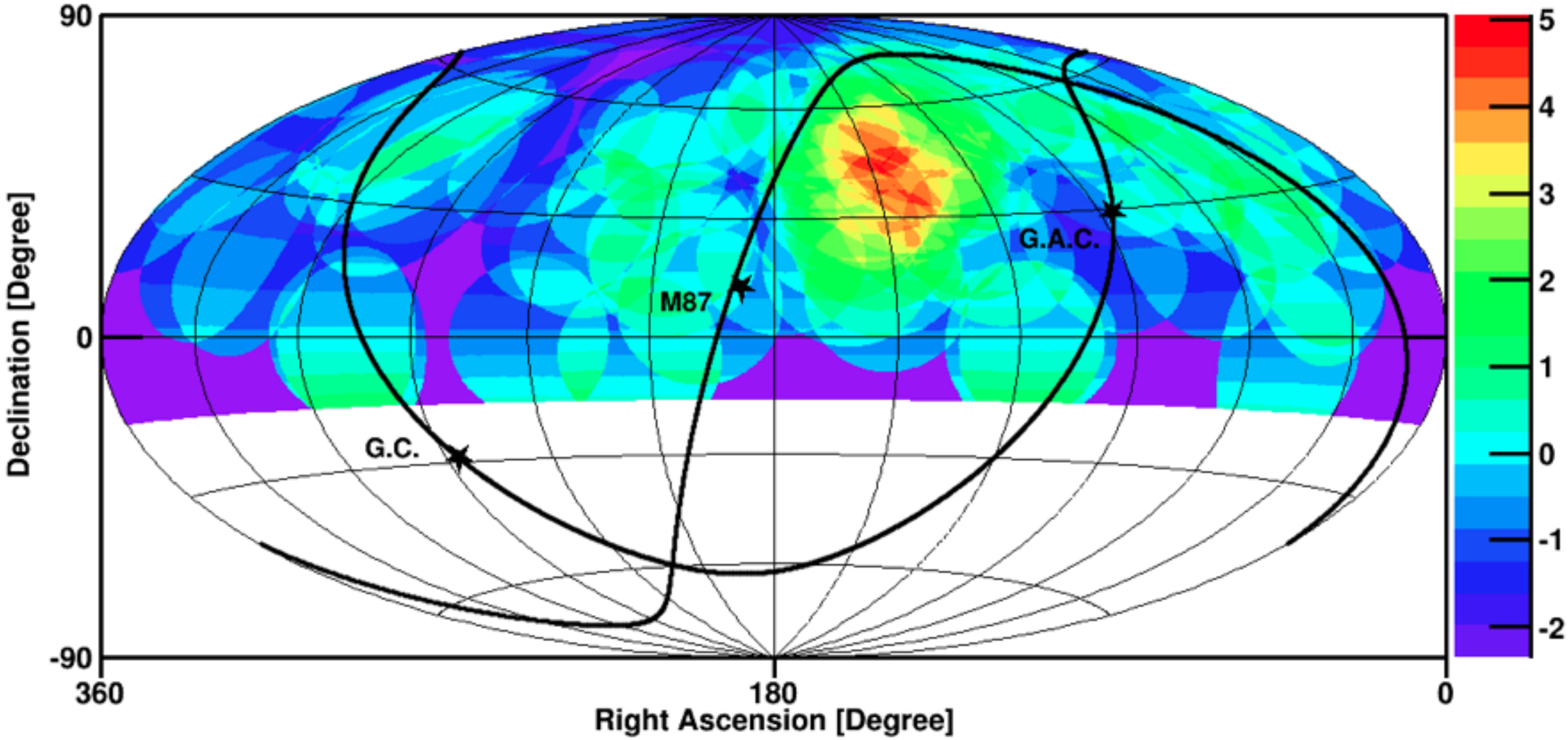
equatorial coordinates



equatorial coordinates

TA hotspot

Let's have a closer look…

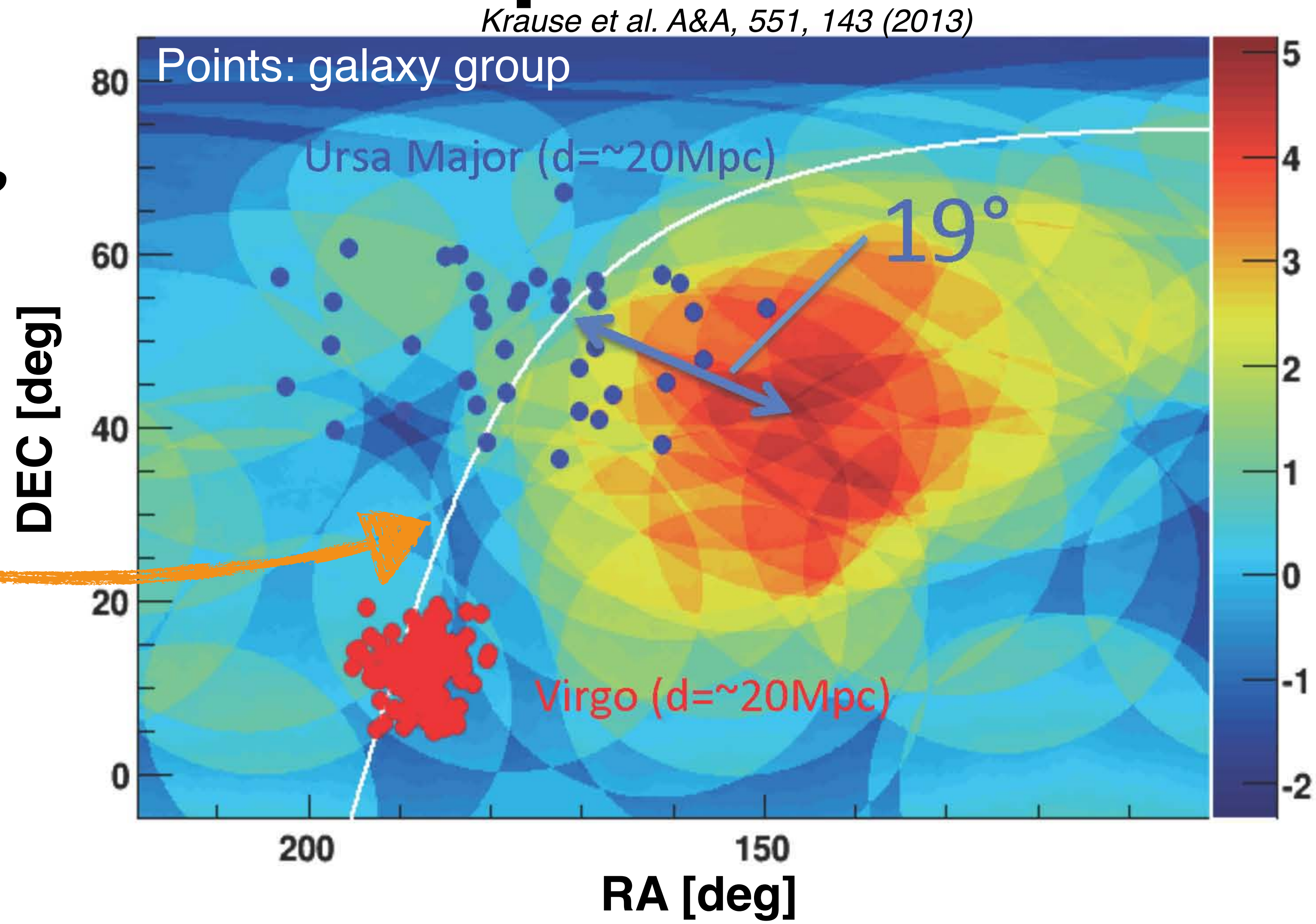


- E > 5.7 x 10^{19} eV (72 events)
- 19/72 events fall in hotspot (RA=146.7, DEC = 43.2°)
- 4.5 events expected
- LiMa significance = 5.2 sigma
- Estimate 3.4 sigma chance probability ***(4.6 sigma for 6 years TA data)***

TA hotspot

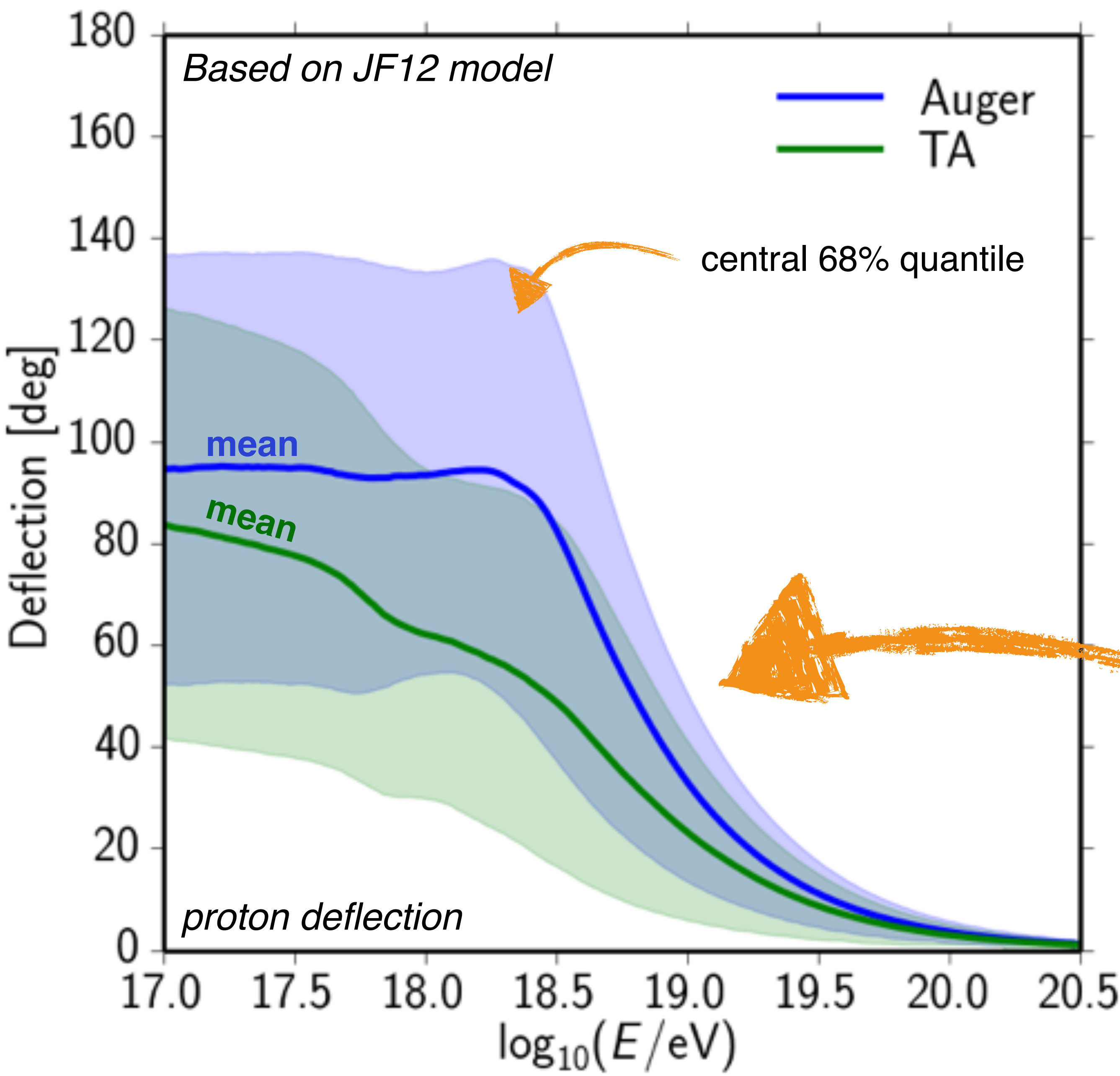
Connection to Ursa Mayor Supercluster?

supergalactic plane



- Angular distance between hotspot and super galactic plane 19°
- Ursa supercluster is extended by more than 10° from super galactic plane
- TA can not rule out some relationship between hotspot and this supercluster

Mean deflection for Auger and TA site

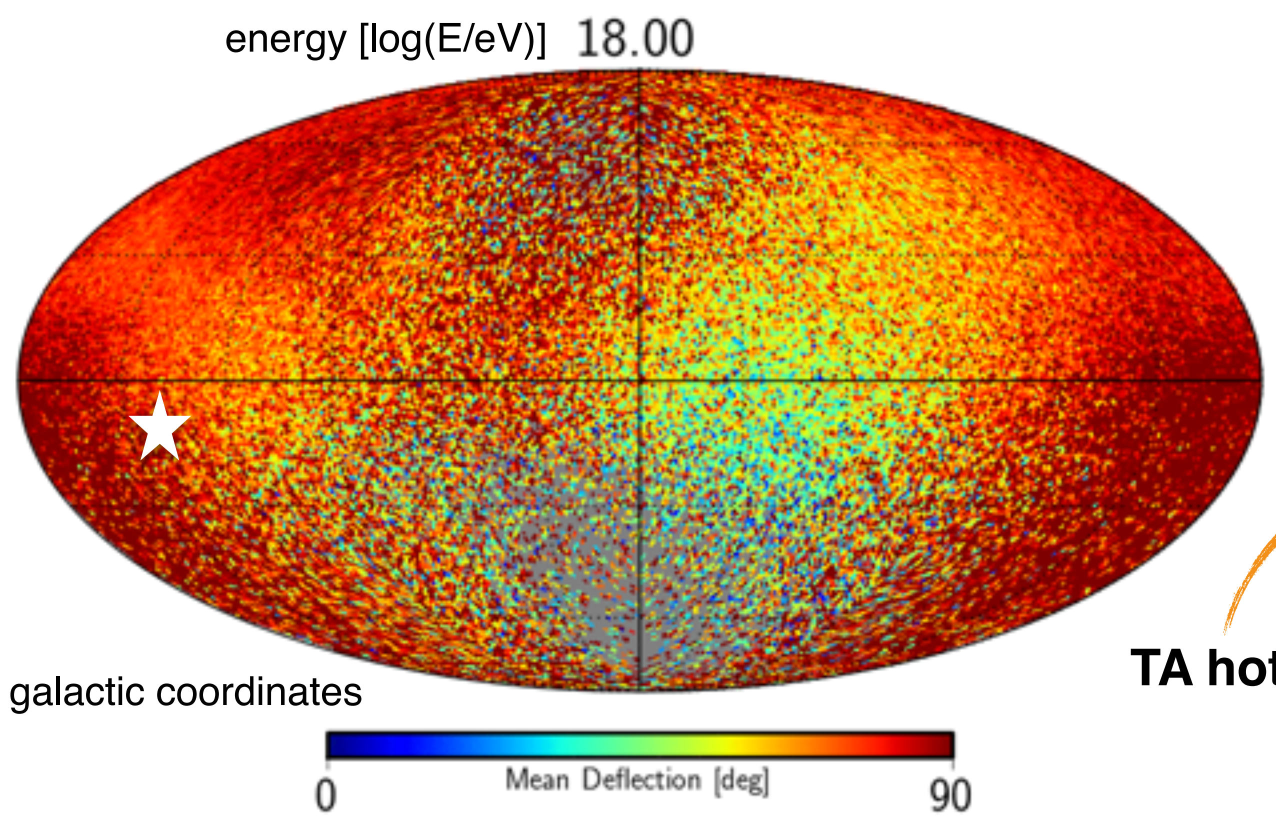


- Mean deflection assuming that particles arrive isotropically at the edge of the galaxy
- Events recorded at each site up to 60° in zenith angle

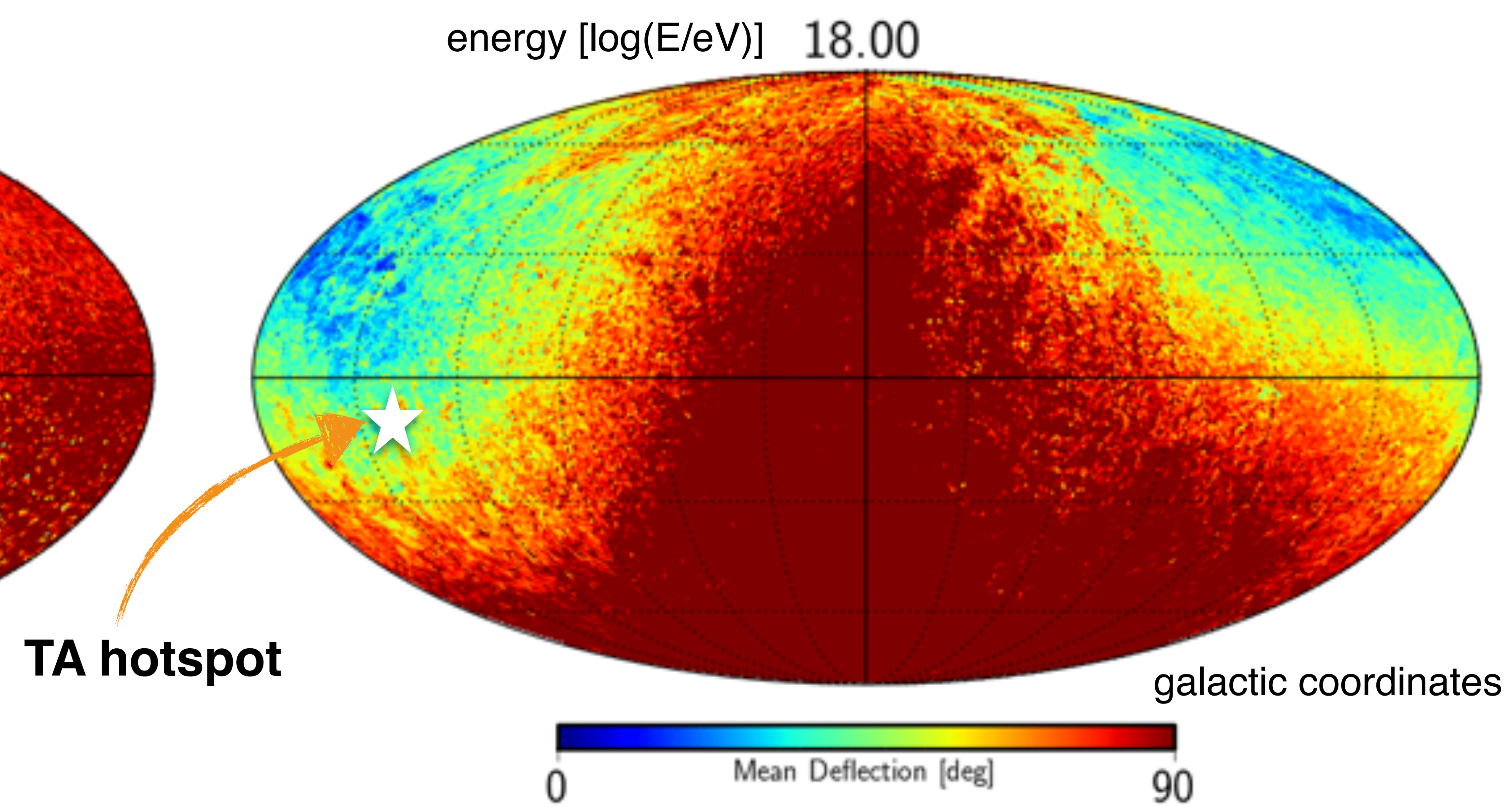
TA and Auger observe different deflections. Important when comparing Auger and TA measurements

Mean galactic deflection

Mean deflection of protons arriving at the edge of the galaxy



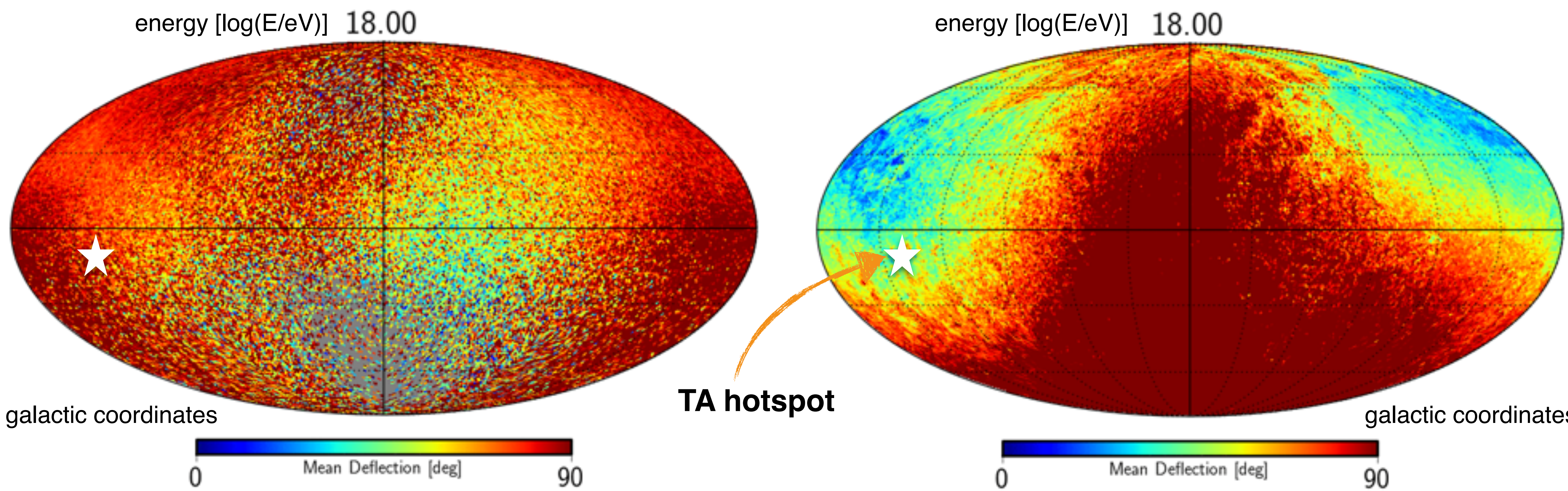
Mean deflection of protons as seem from Earth



Mean galactic deflection

Mean deflection of protons arriving at the edge of the galaxy

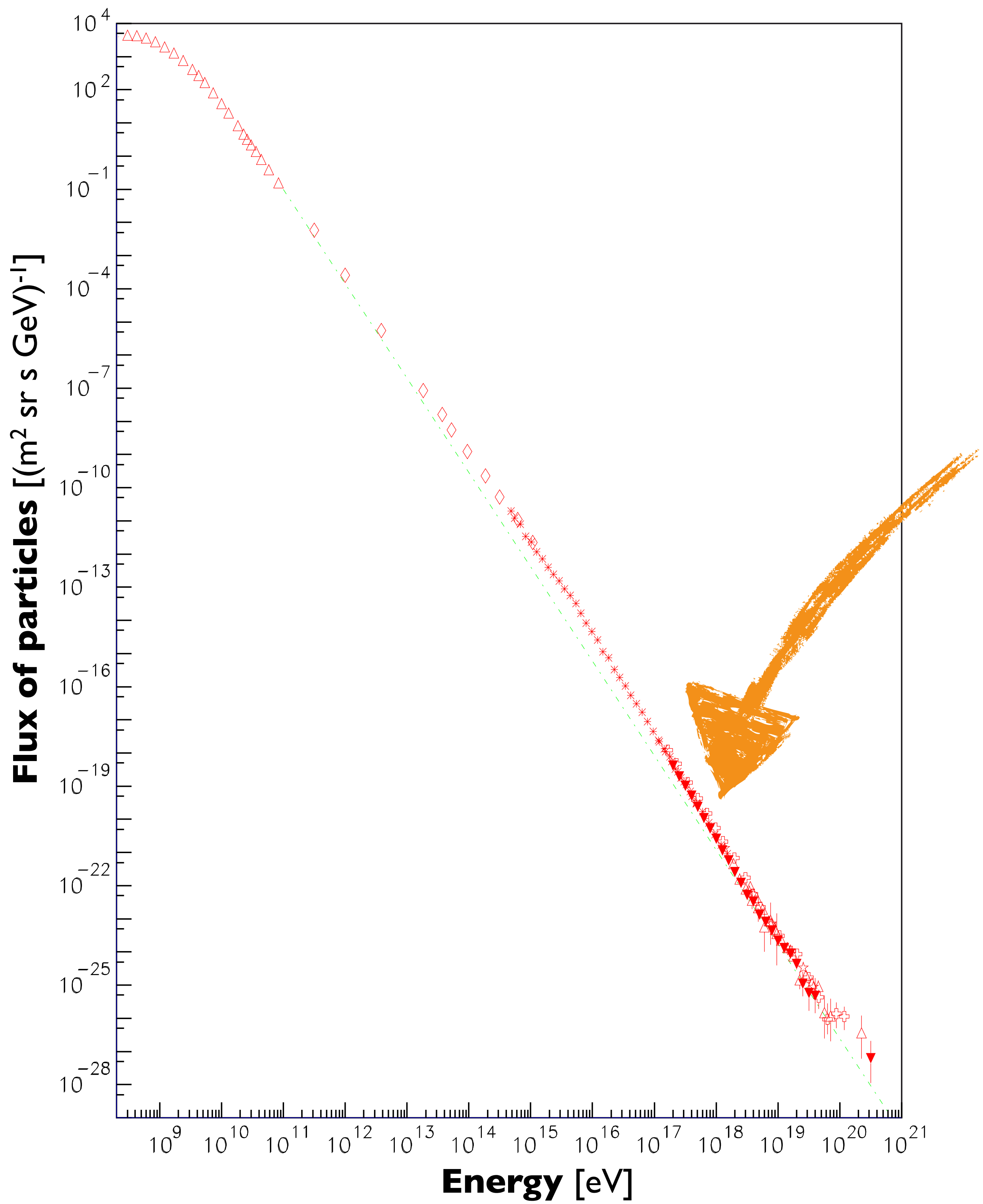
Mean deflection of protons as seem from Earth



Key results

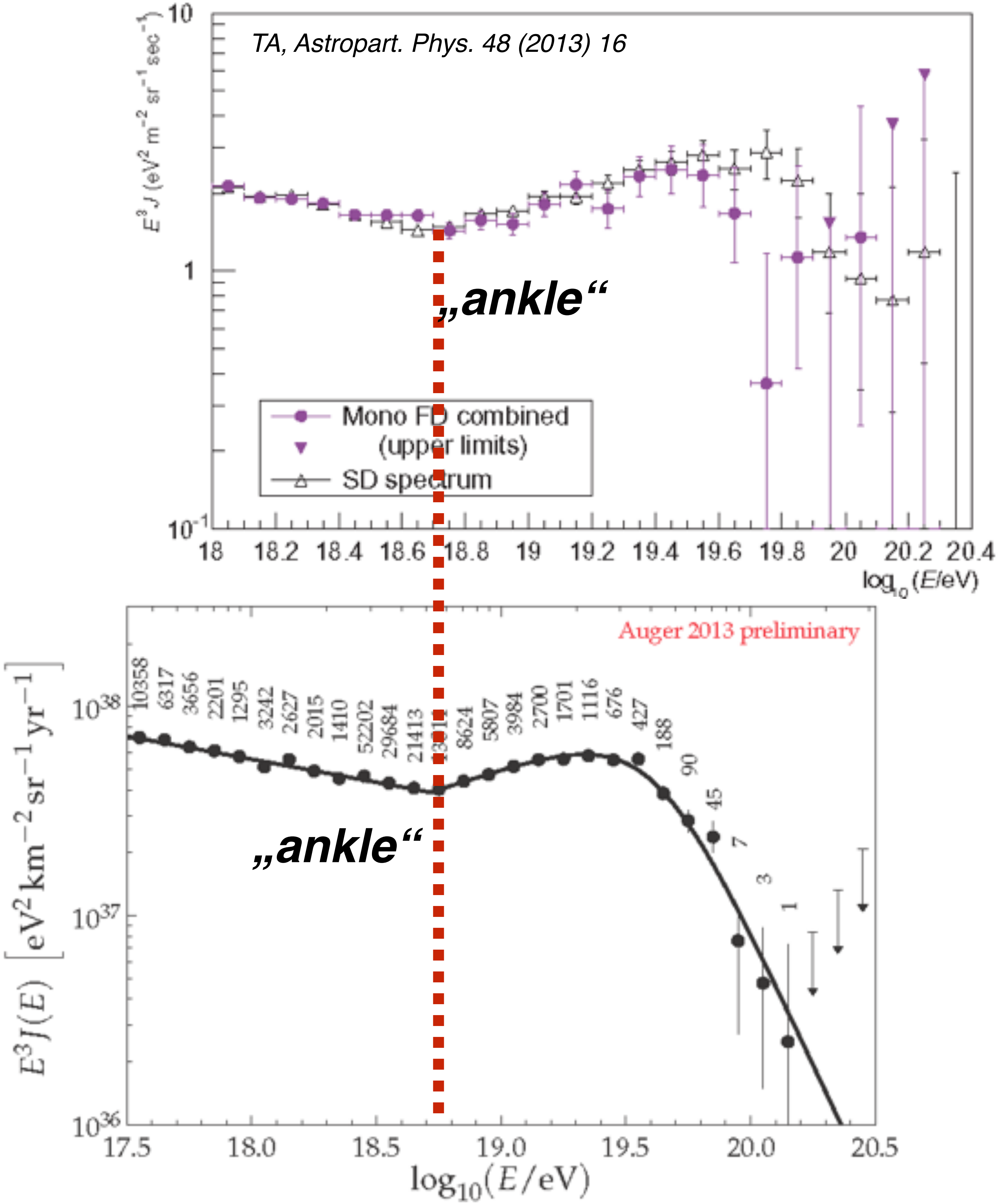
energy spectrum

Key results - Energy spectrum



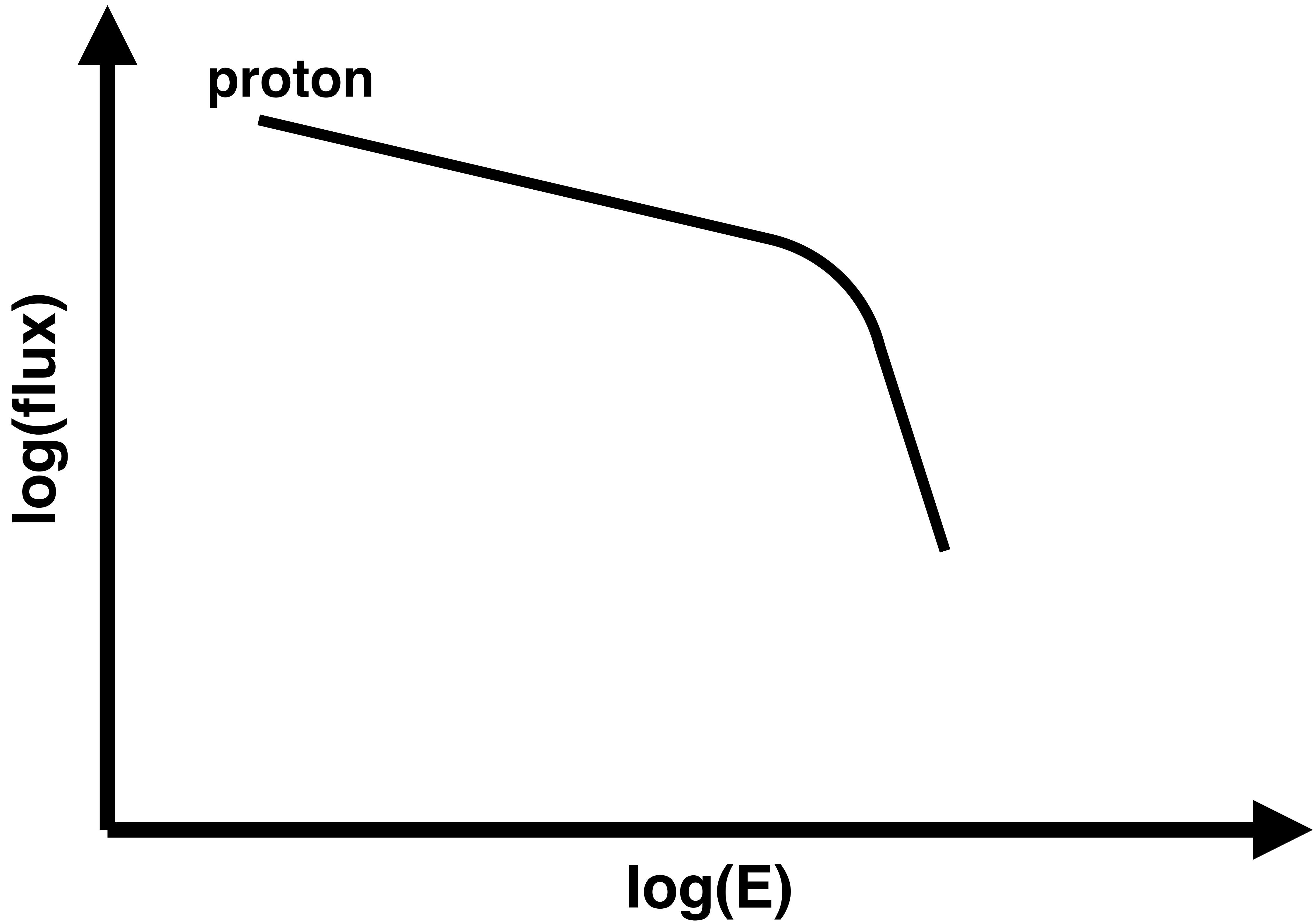
- Spectral index seems to be rather constant.
- Need better resolution: Multiply flux by E^3

Key results - Energy spectrum

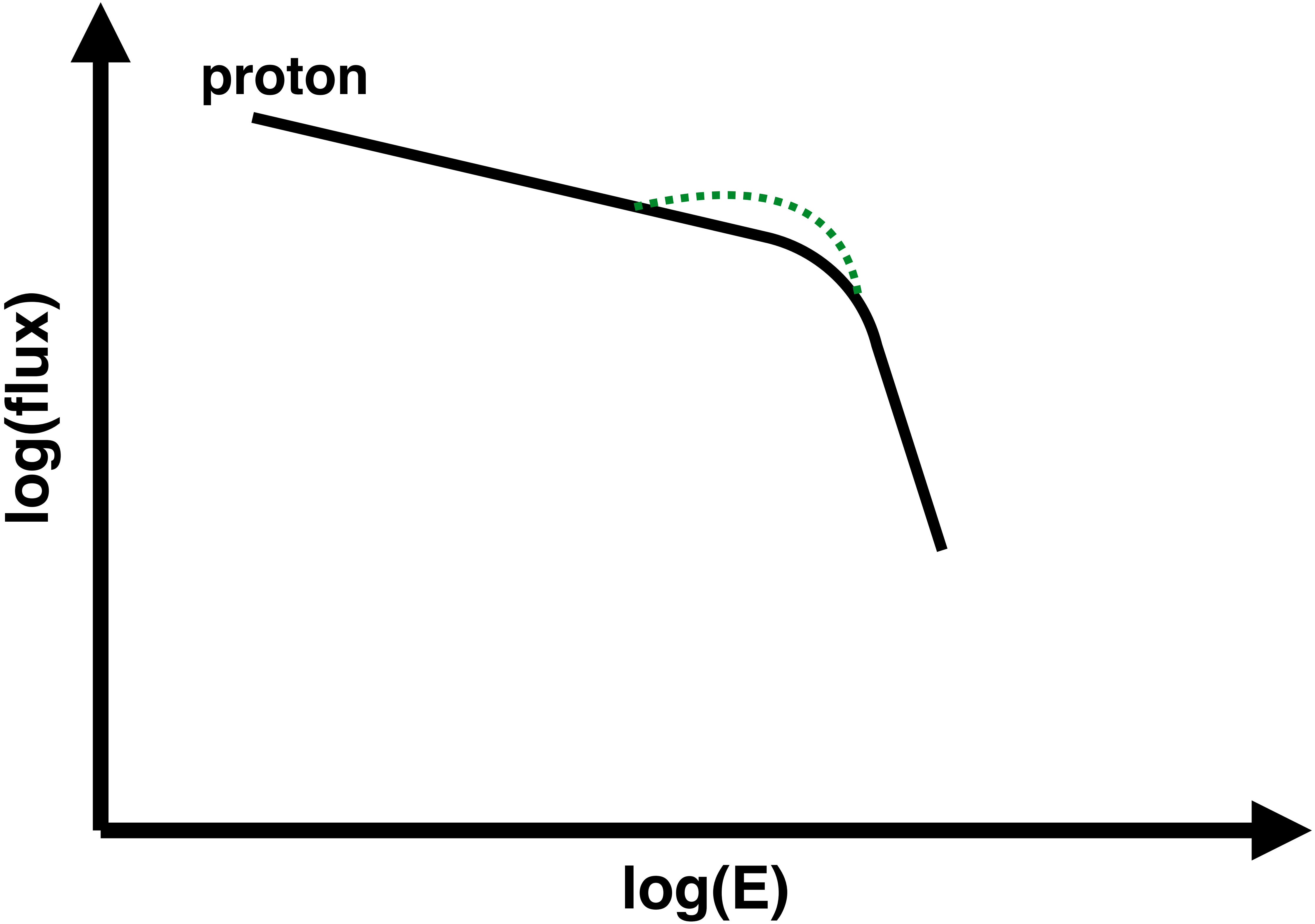


- Both experiments see **spectral structure**:
  - The „**ankle**“ at about 5 x 10^{18} eV
  - **Flux suppression** at highest energies
  - Origin still unclear

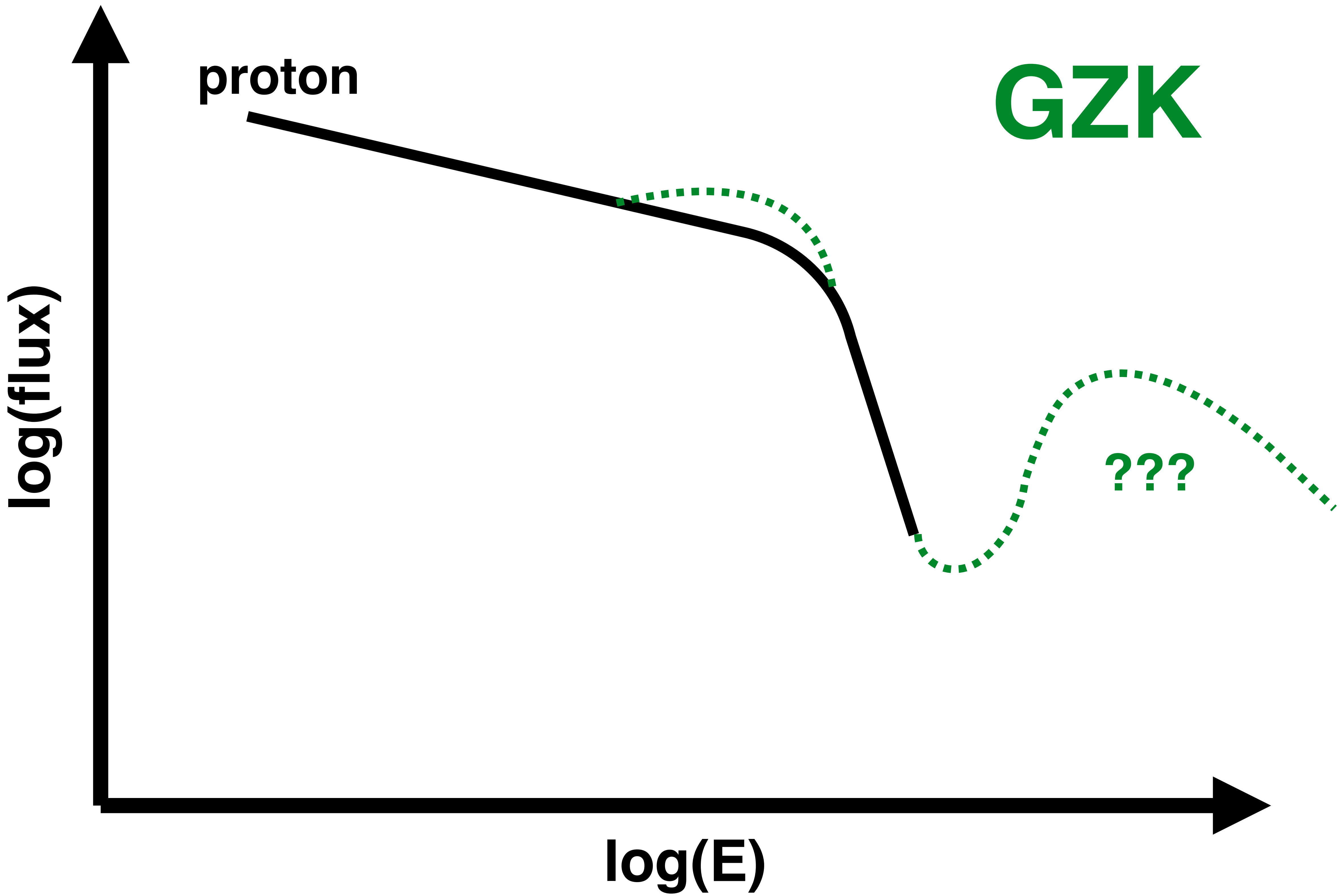
GZK or Source?



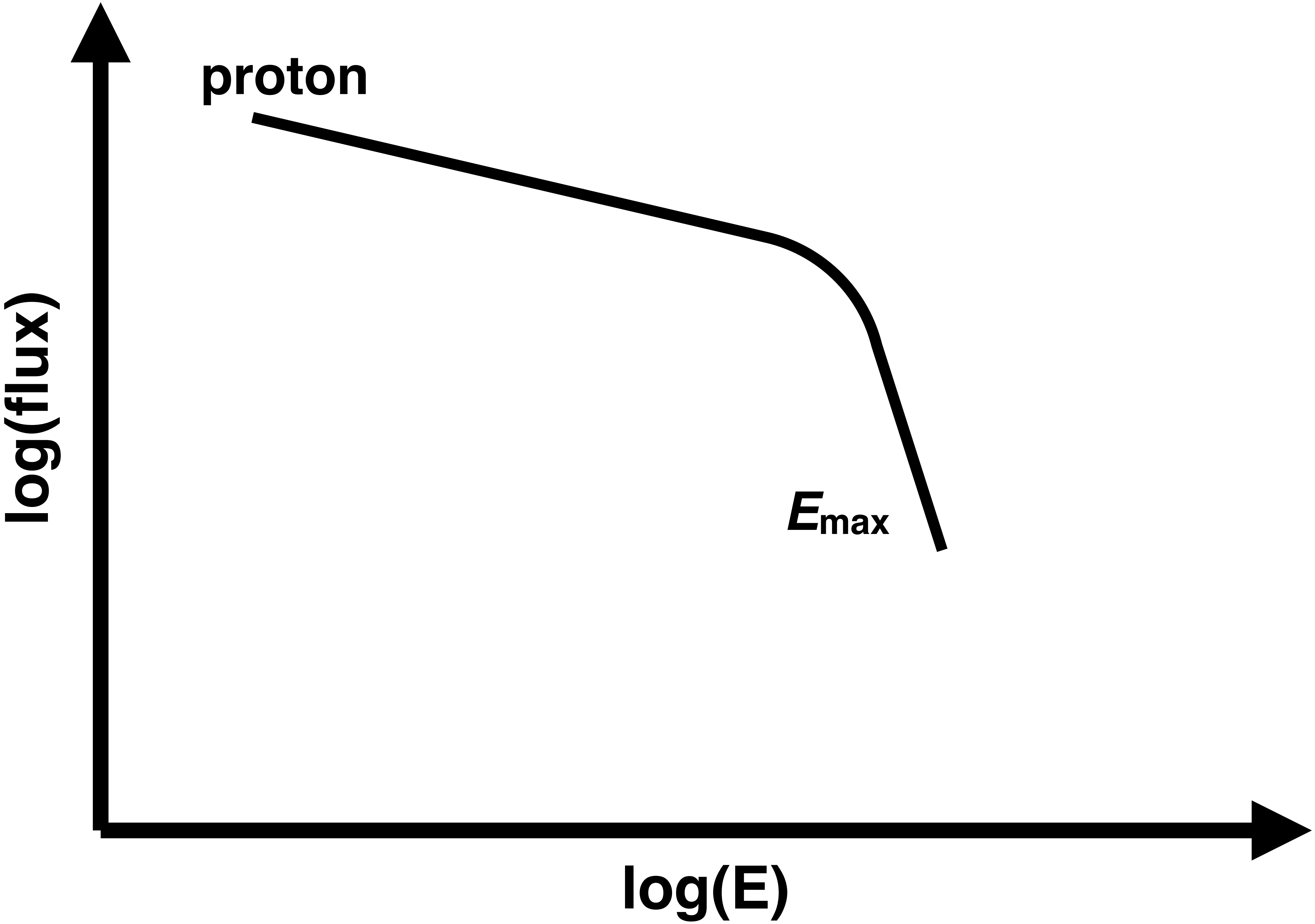
GZK or Source?



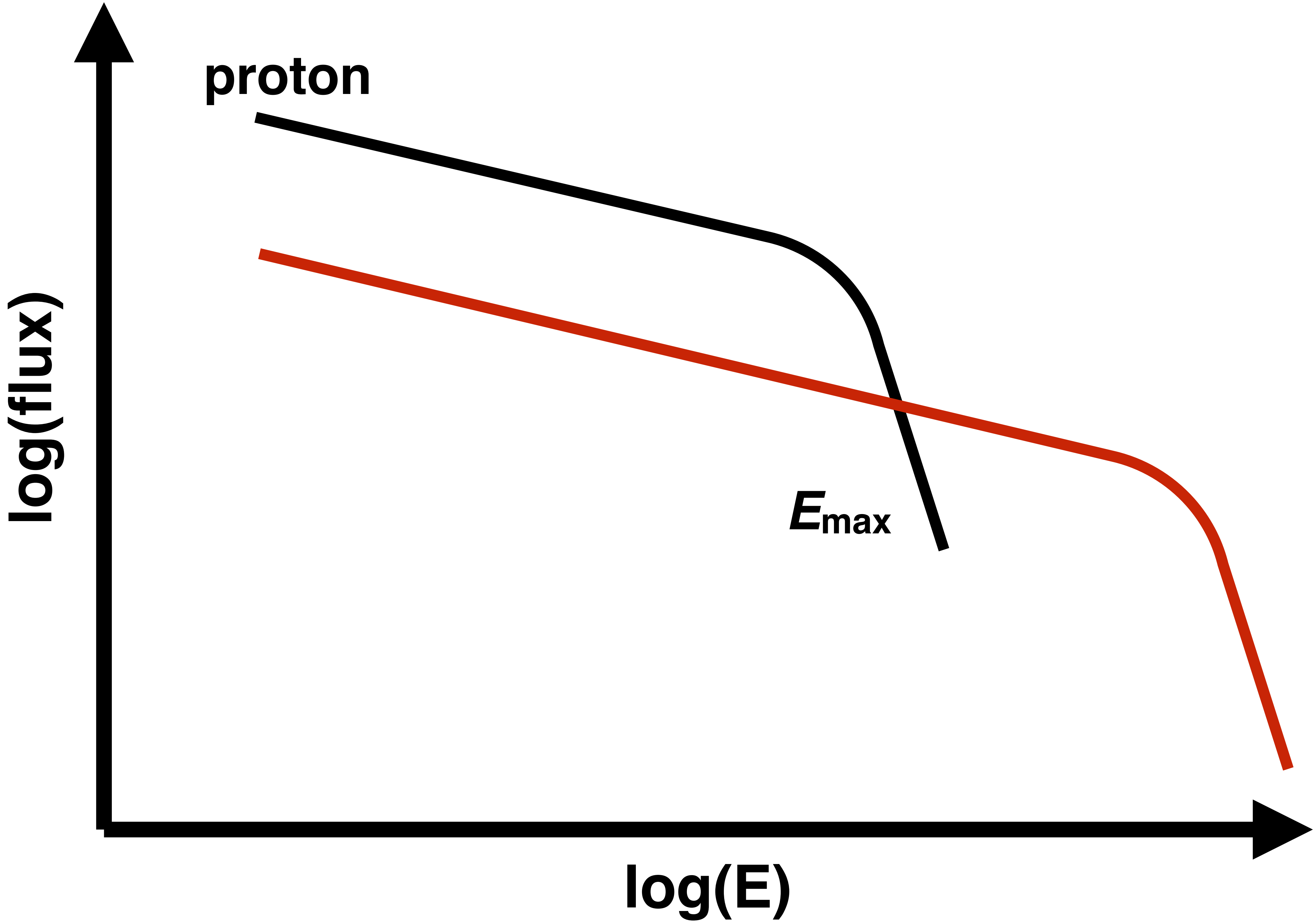
GZK or Source?



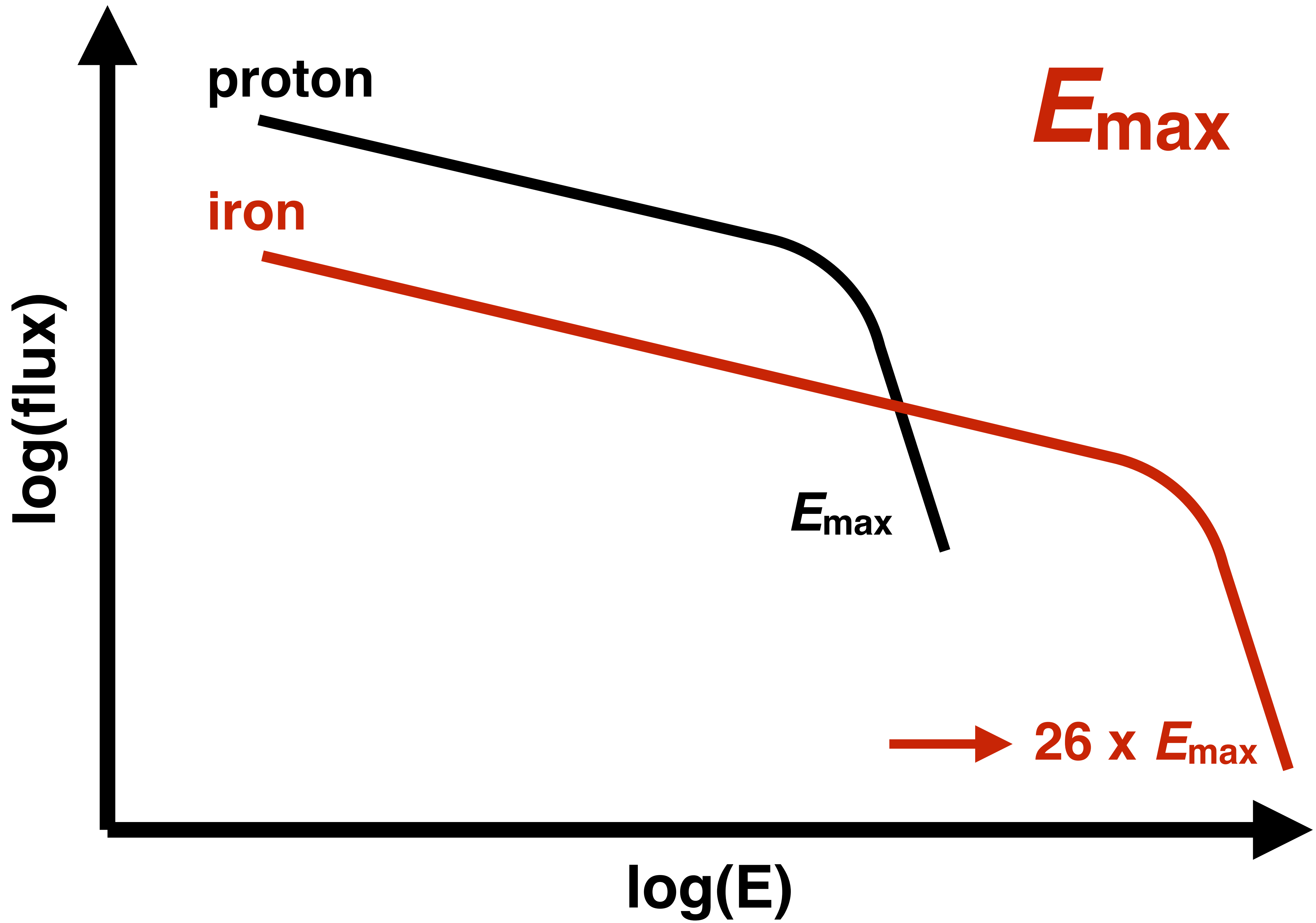
GZK or Source?



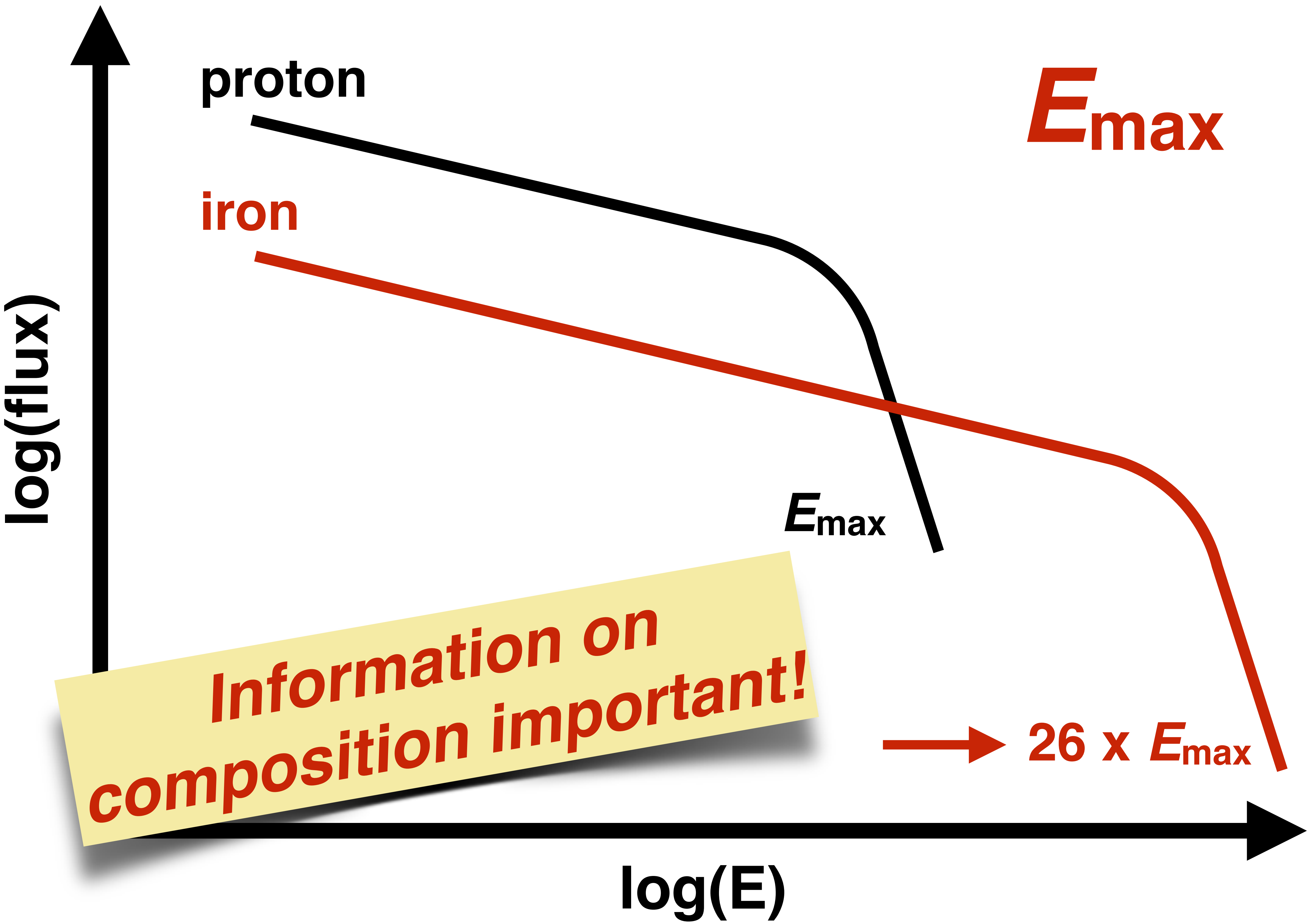
GZK or Source?



GZK or Source?



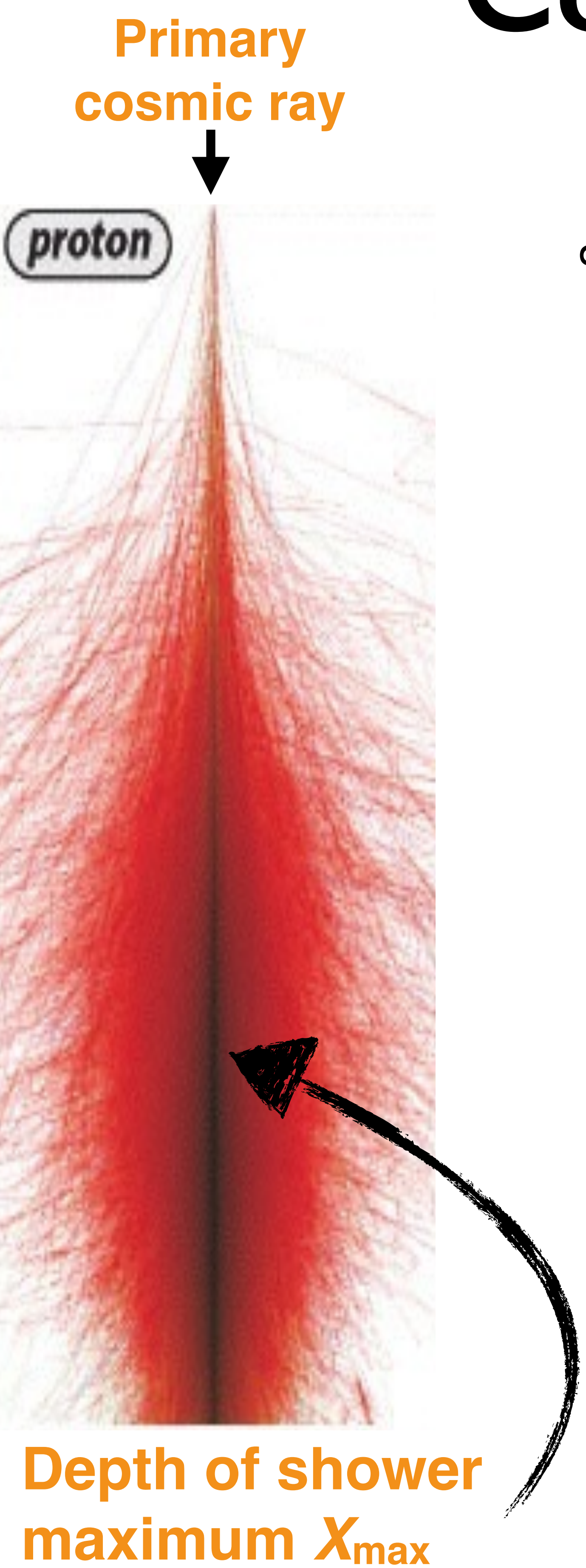
GZK or Source?

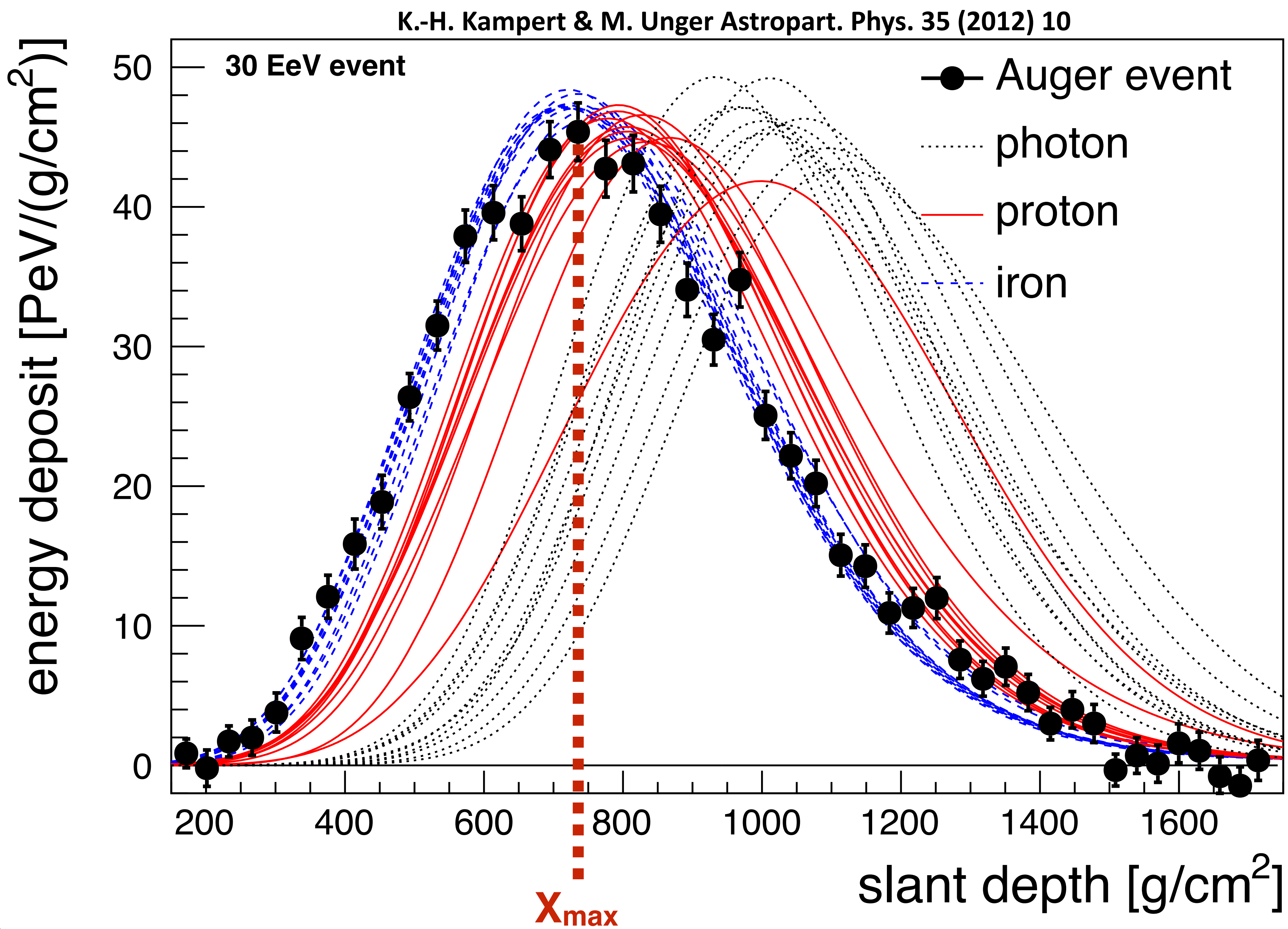


Key results

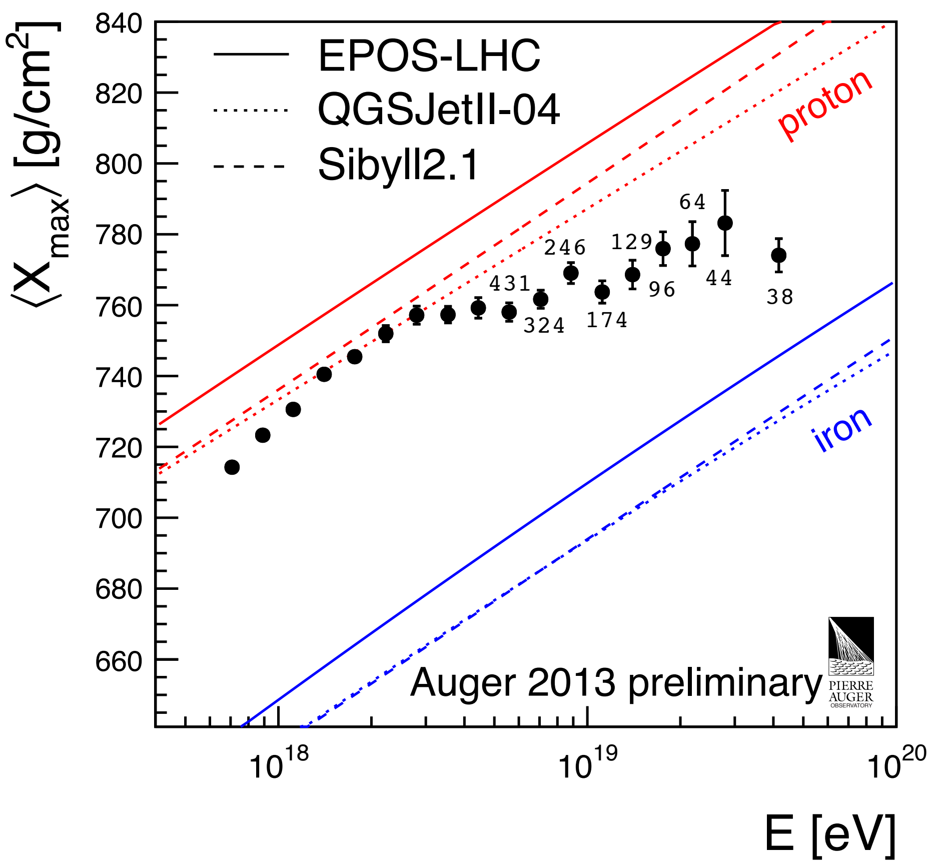
composition

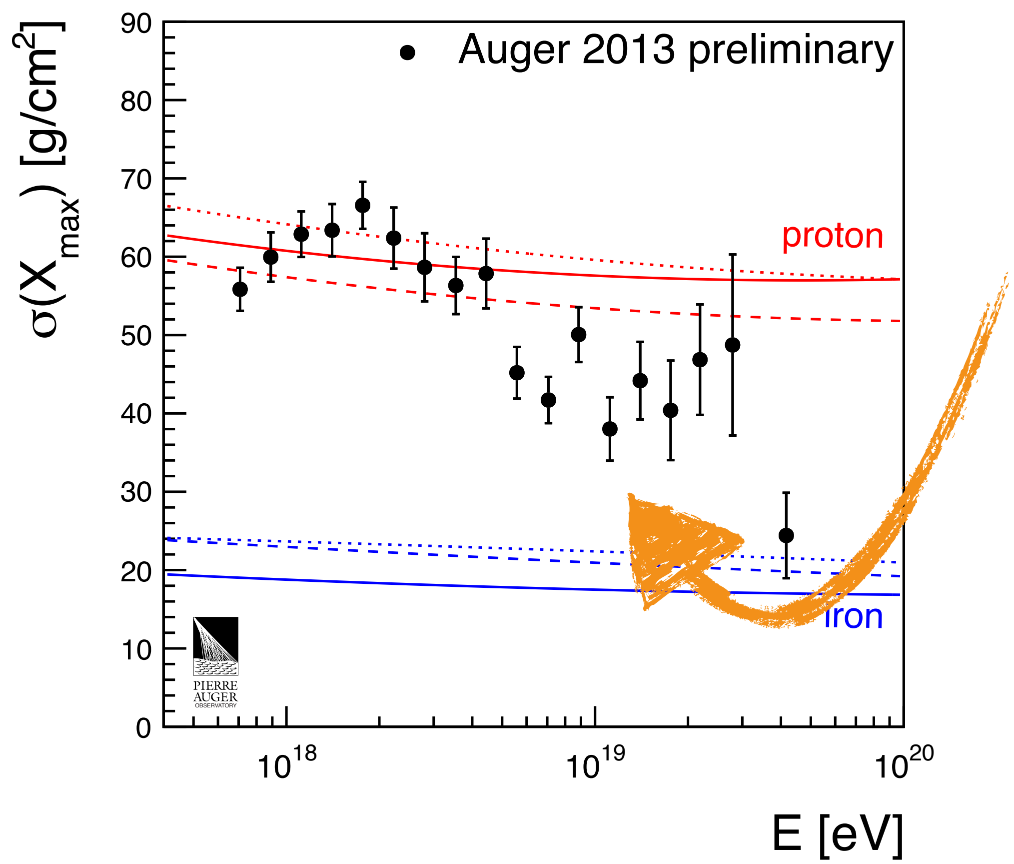
Composition observable



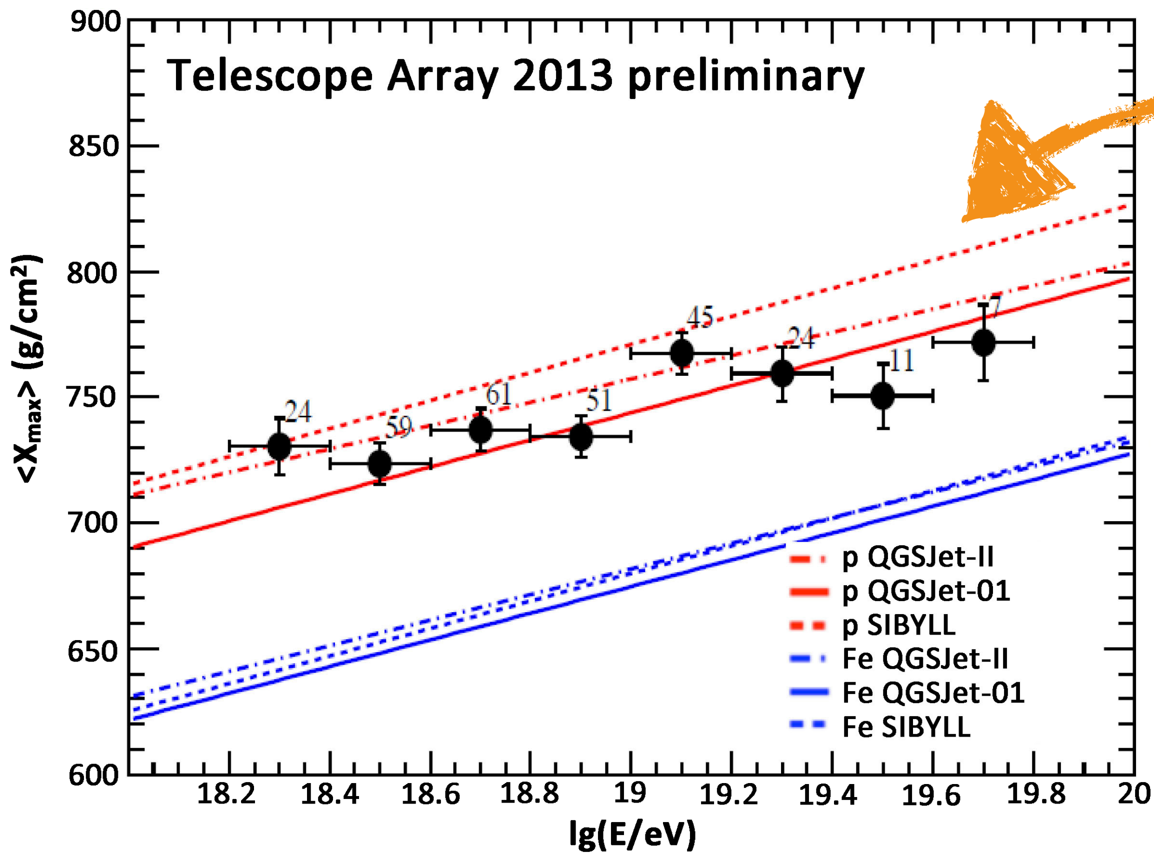


Key results - Composition





Auger data shows a smooth change to a heavier composition

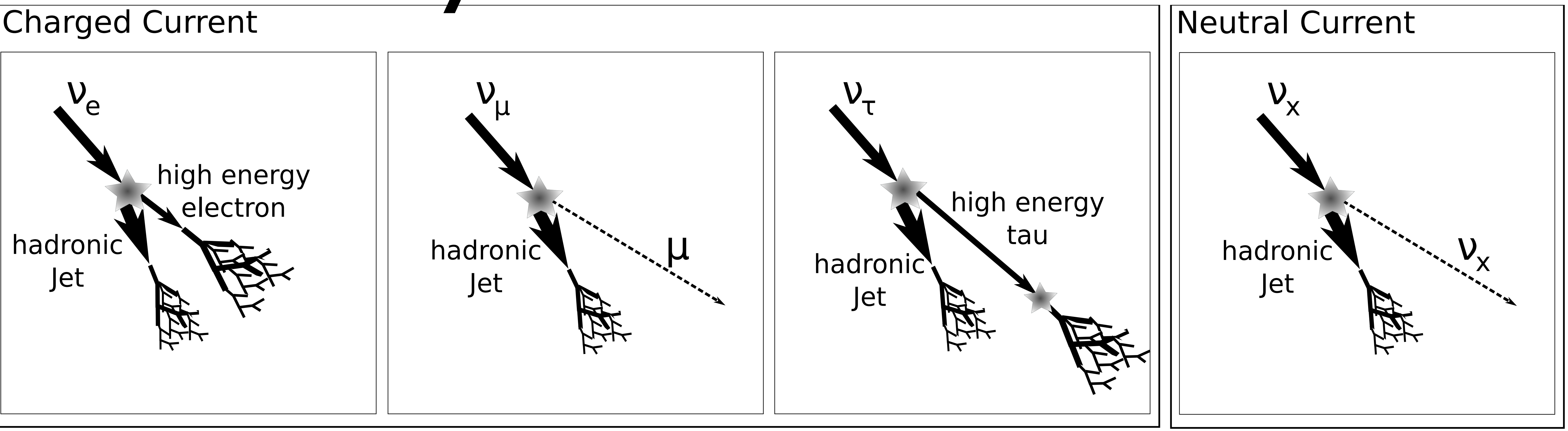


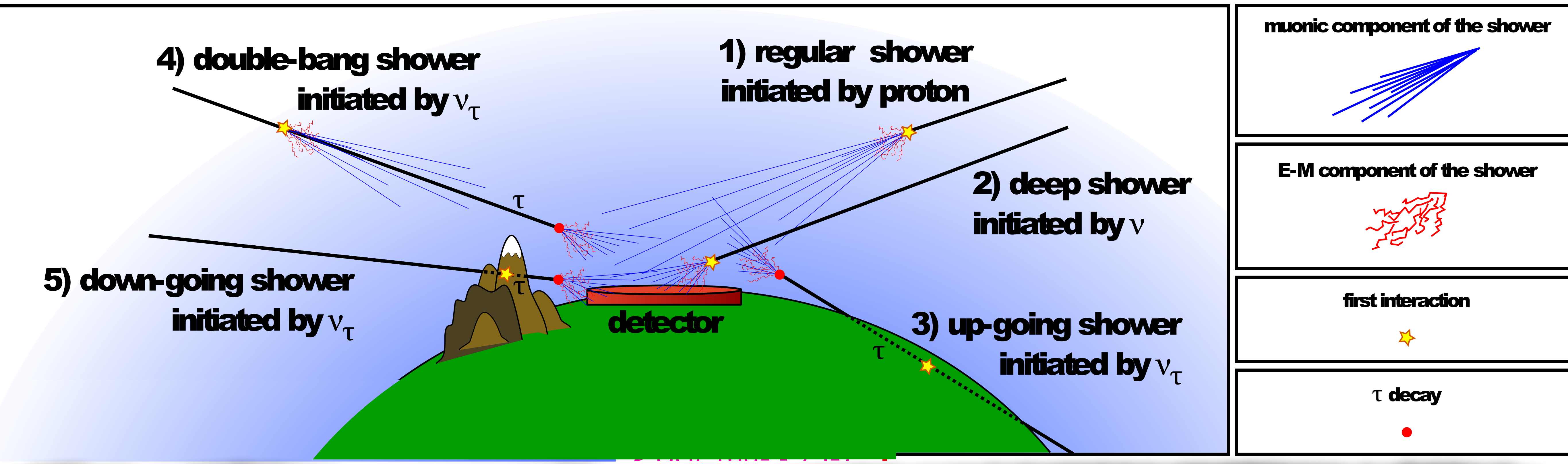
TA results are consistent with pure proton composition at all energies and inconsistent with iron

Key results

secondaries

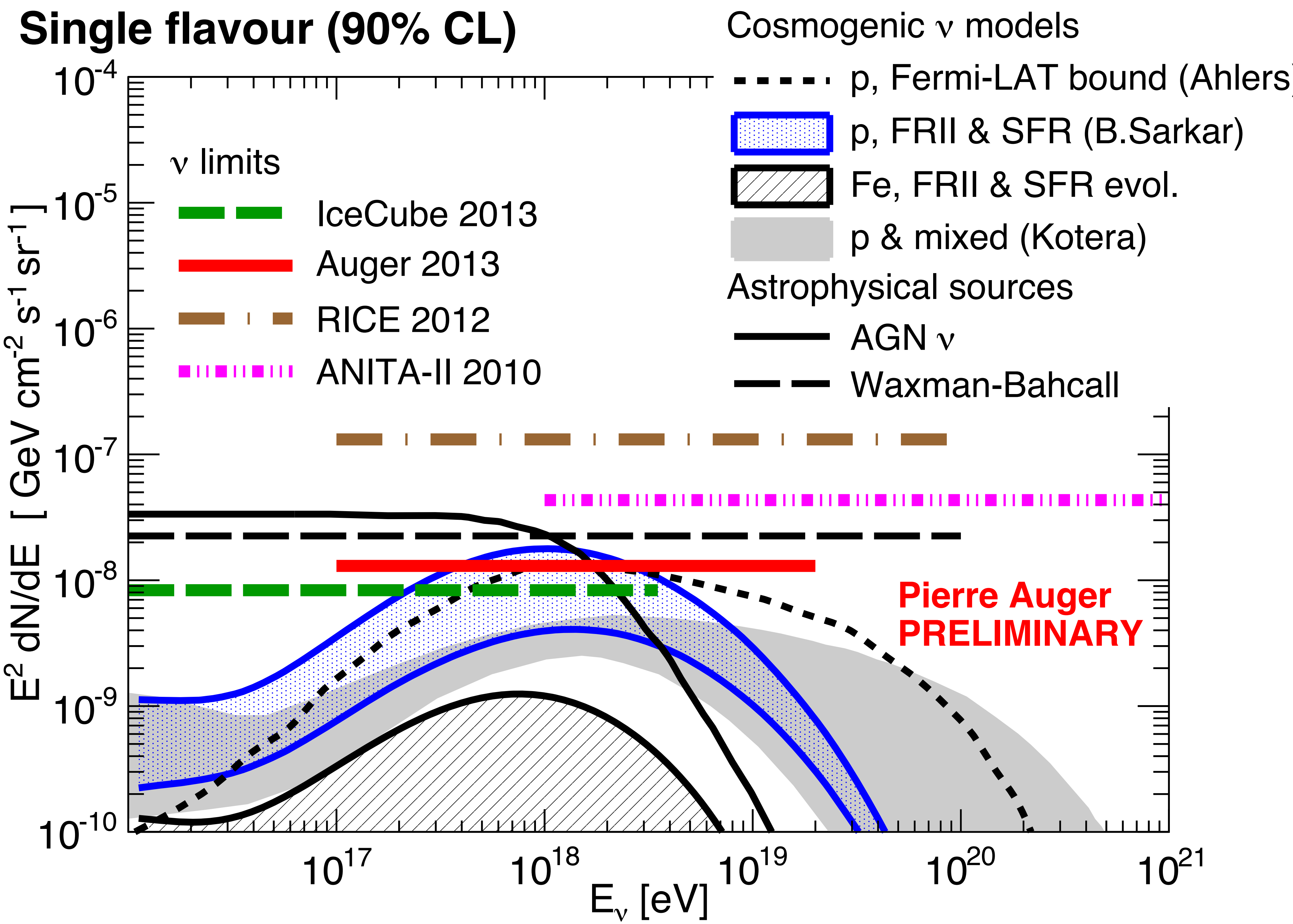
Key results - Neutrinos





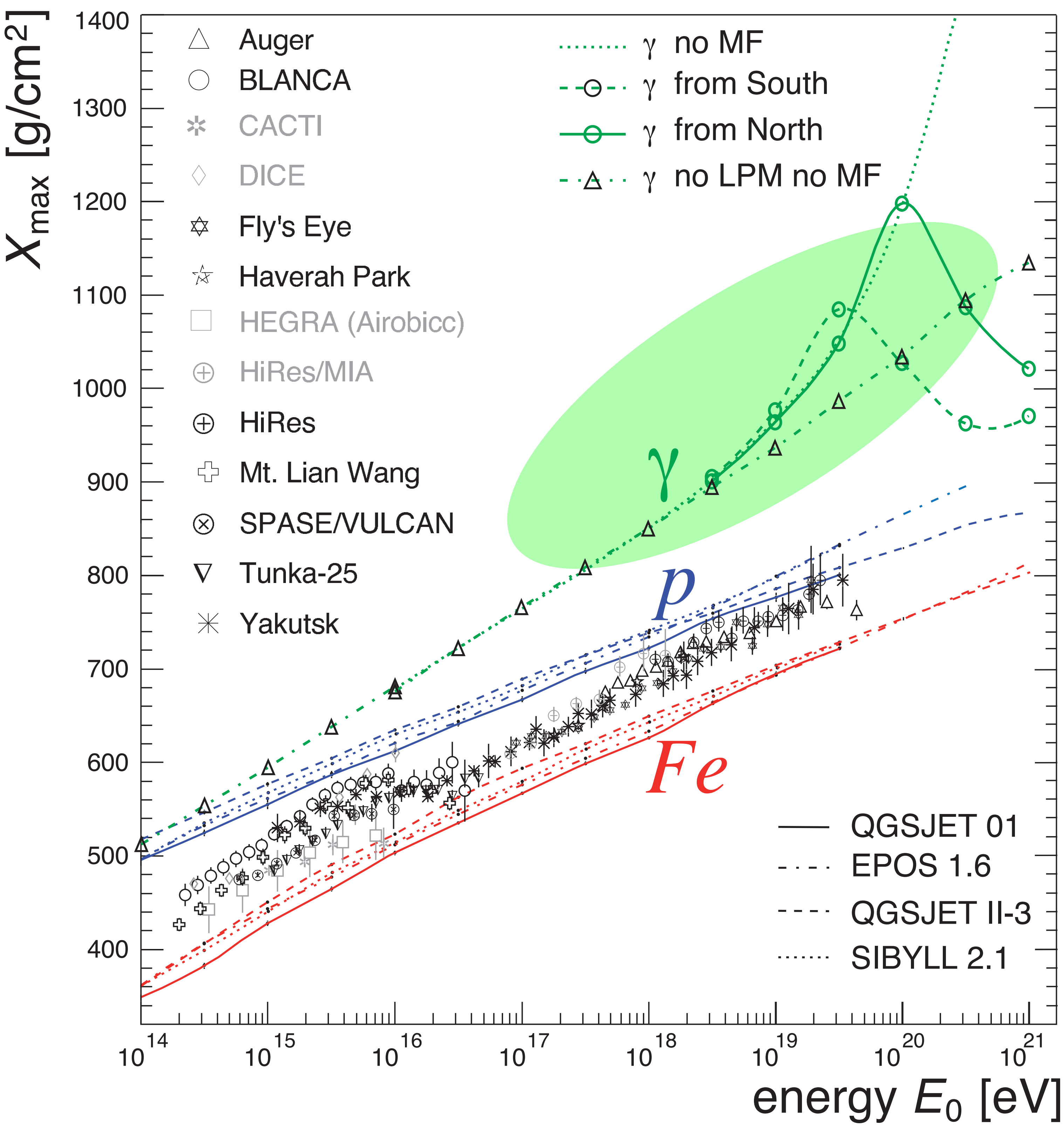
Only a neutrino can induce a young horizontal shower!

Key results - Neutrinos



Limits constrain models with proton primaries & strong source evolution

Key results - Photons



Identification:

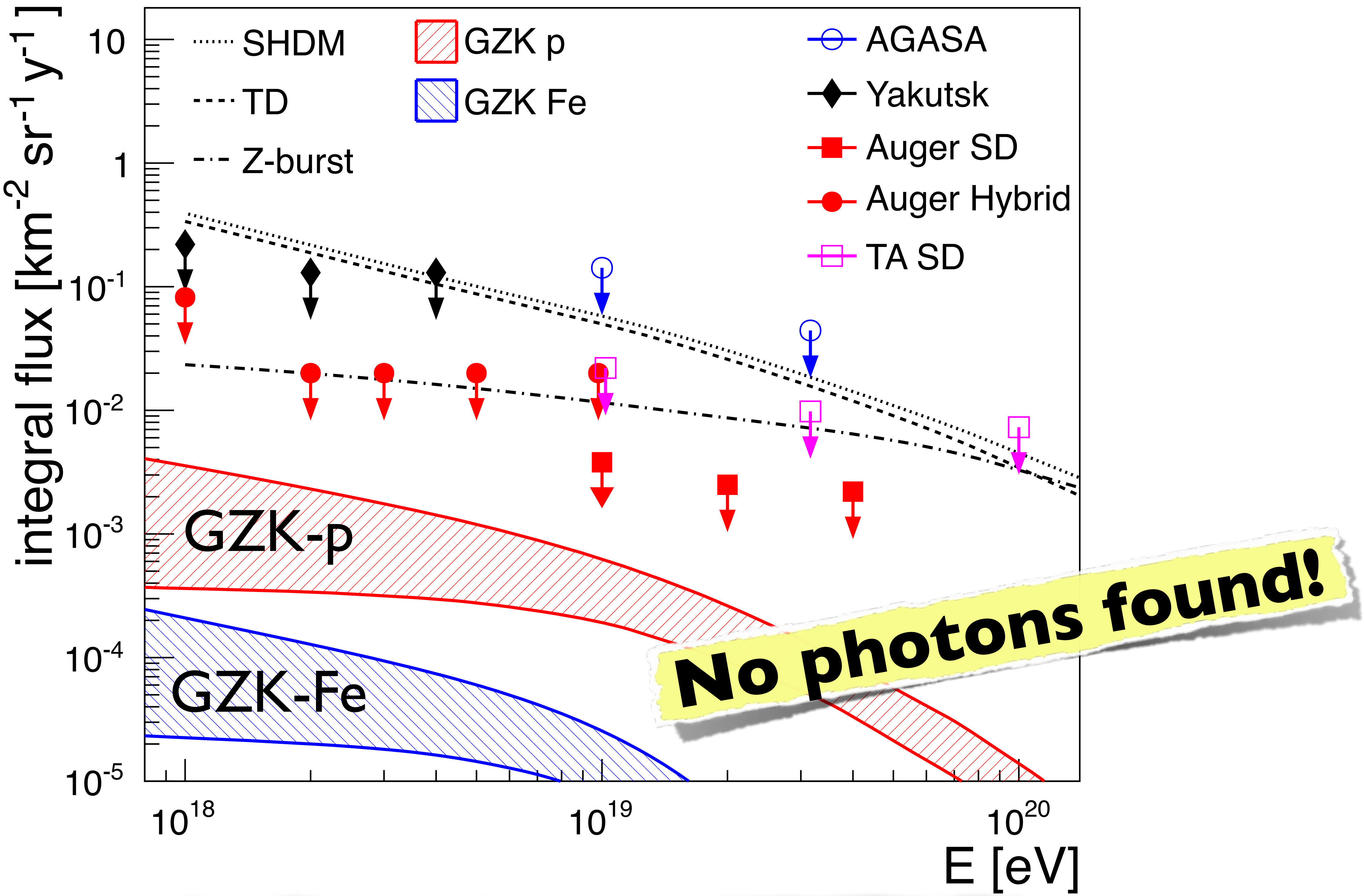
Photon induced air showers:

Two main characteristics:

1. Delayed shower development (larger X_{max})
2. Lack of muons due to smaller photo-nuclear cross-section

Combine in multivariate analysis

Key results - Photons



Top-down models severely constrained

Idea: Directional search for photon point sources

Measure extensive air showers

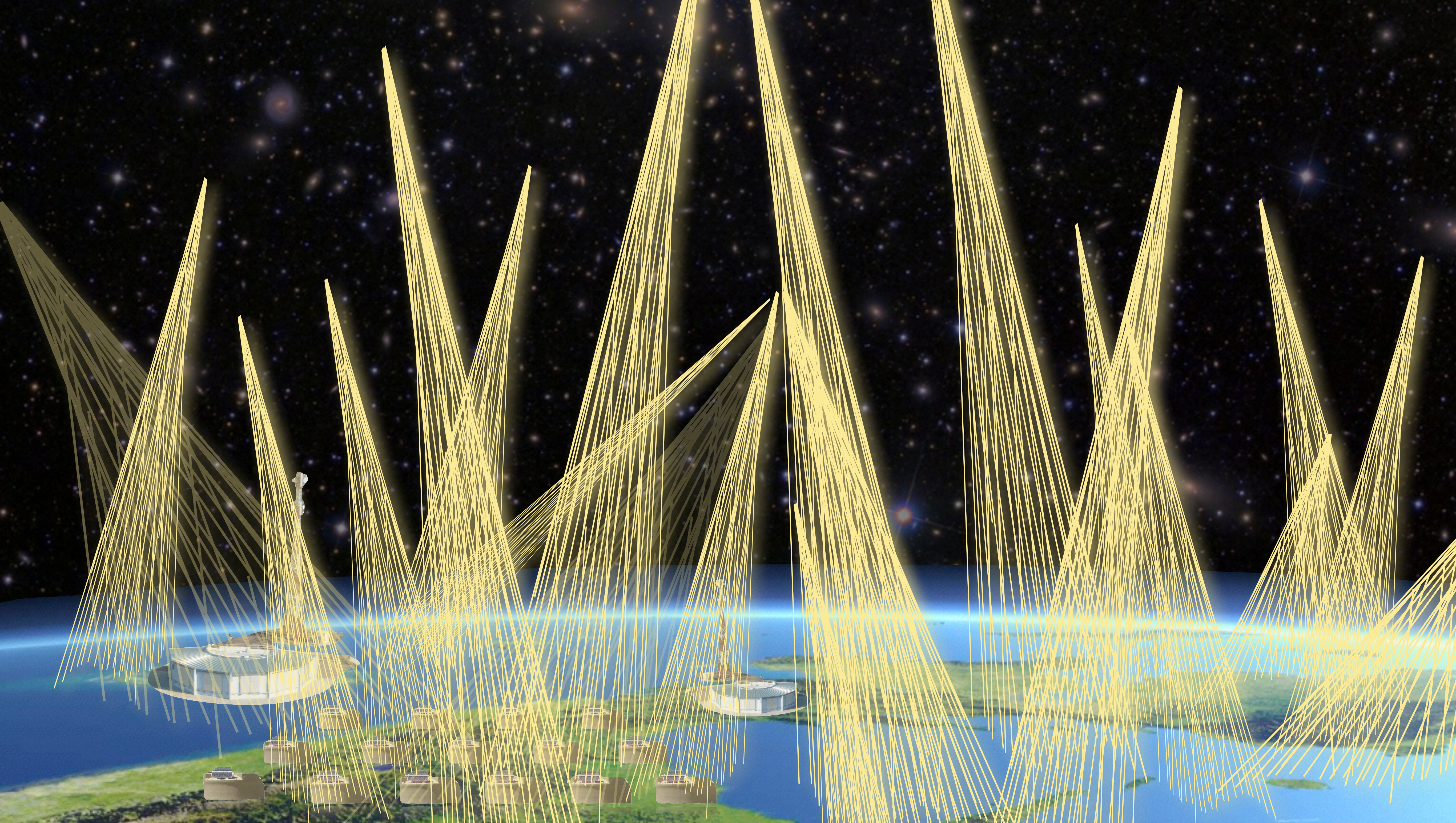
- Arrival direction
- Shower characteristics

Idea: Directional search for photon point sources

Any point sources visible?

Measure extensive air showers

- Arrival direction
- Shower characteristics



Idea: Directional search for photon point sources

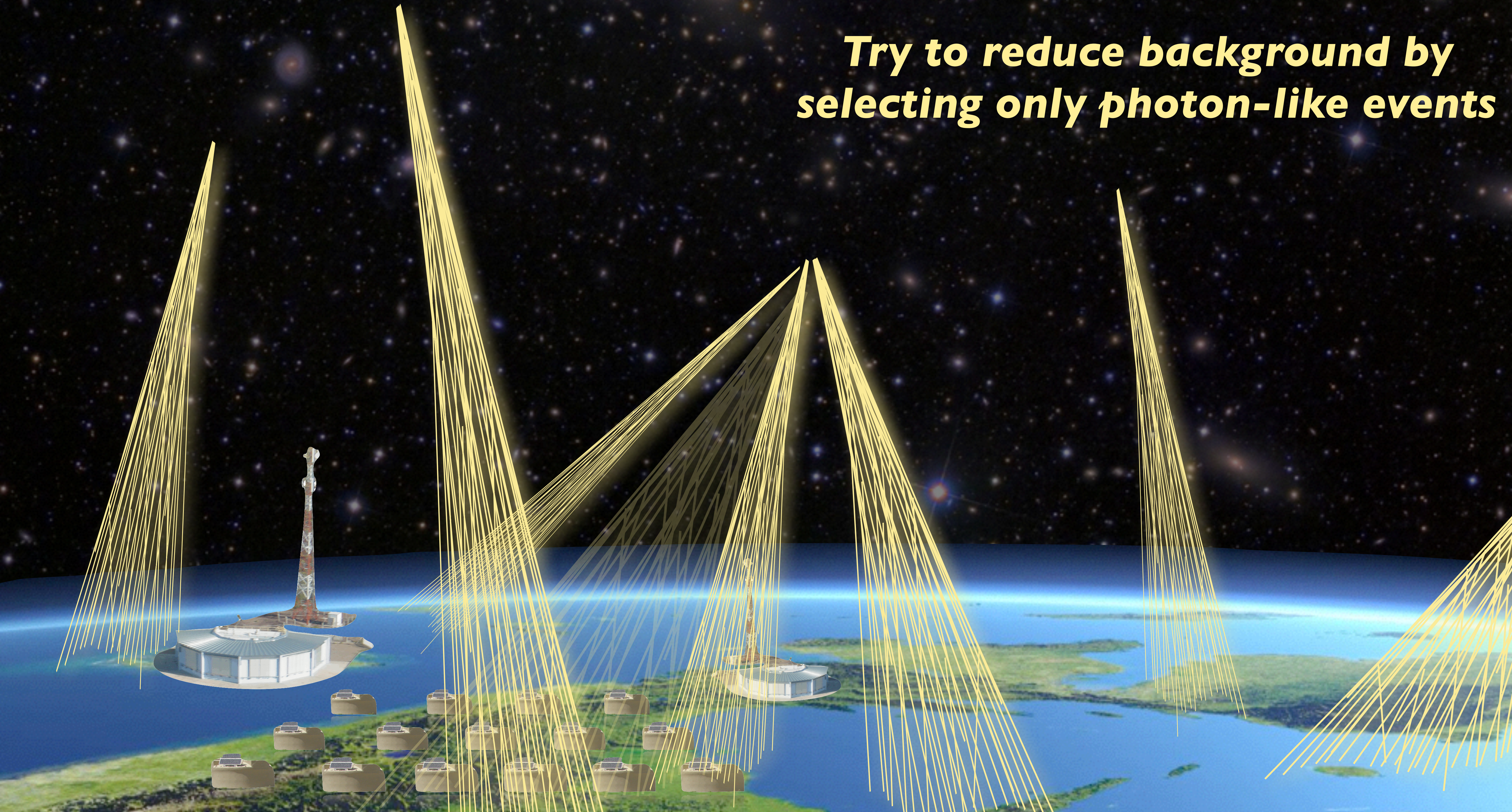
Measure extensive air showers

- Arrival direction
- Shower characteristics

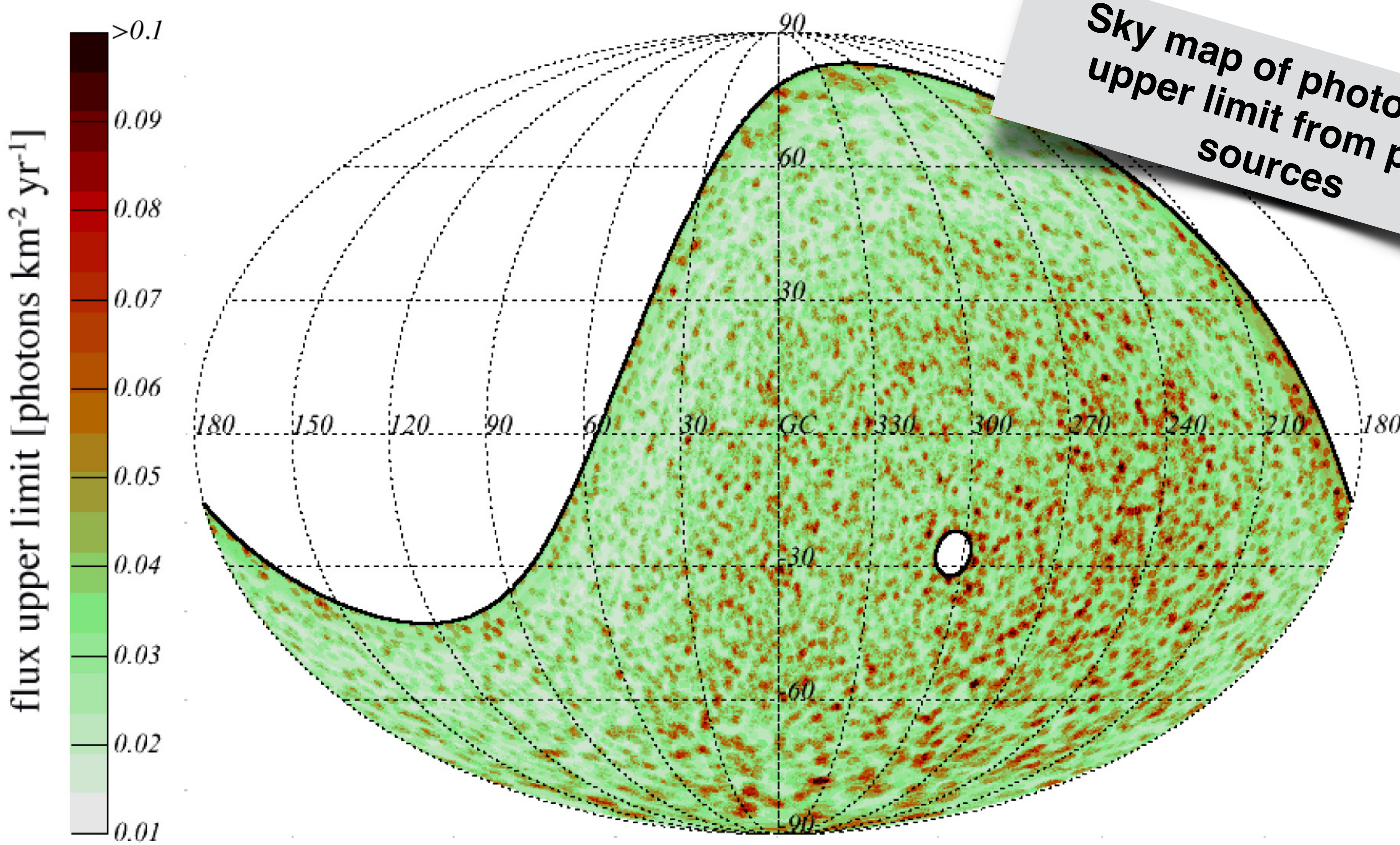
Any point sources visible?

No!?

Try to reduce background by selecting only photon-like events



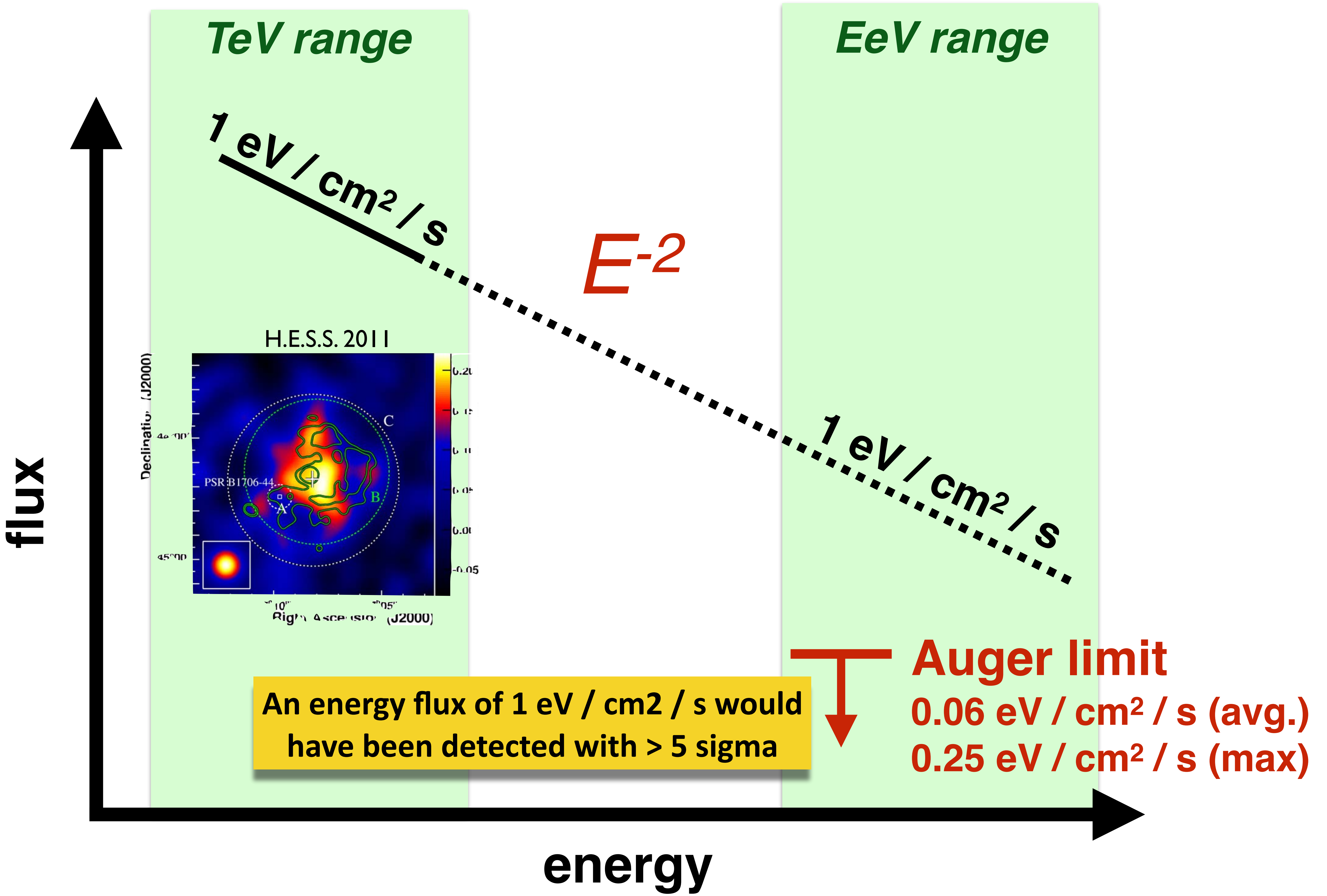
Key results - Photons



Sky map of photon flux upper limit from point sources

Average particle flux upper limit: 0.035 photons / km^2 / yr
Average energy flux upper limit: 0.06 eV / cm^2 / s **(energy spectral index -2)**

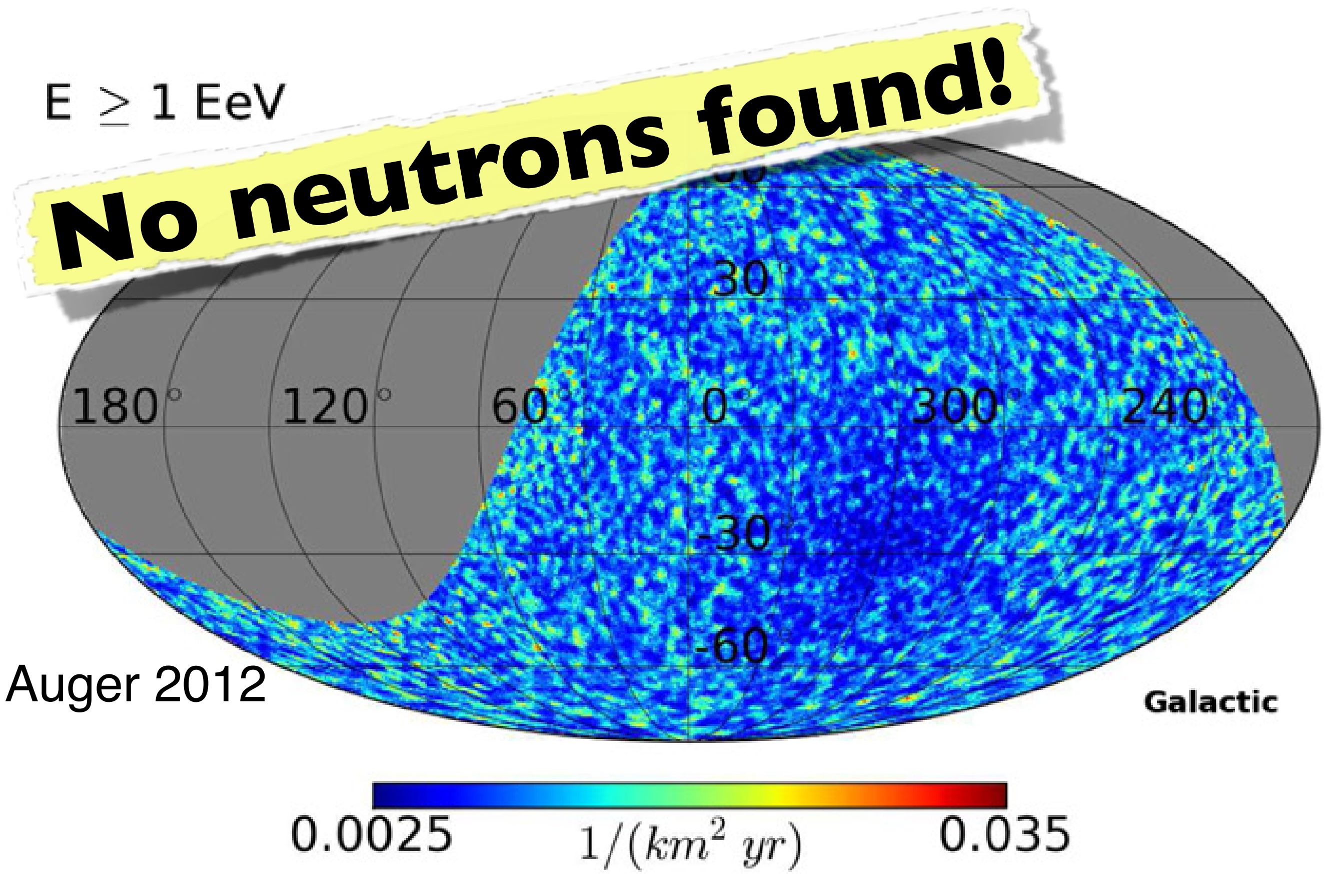
Key results - Photons



Key results - Neutral particles

(from point sources)

Similar to directional photon search but using no photon cut and surface detector information



Auger 2012

Auger 2014

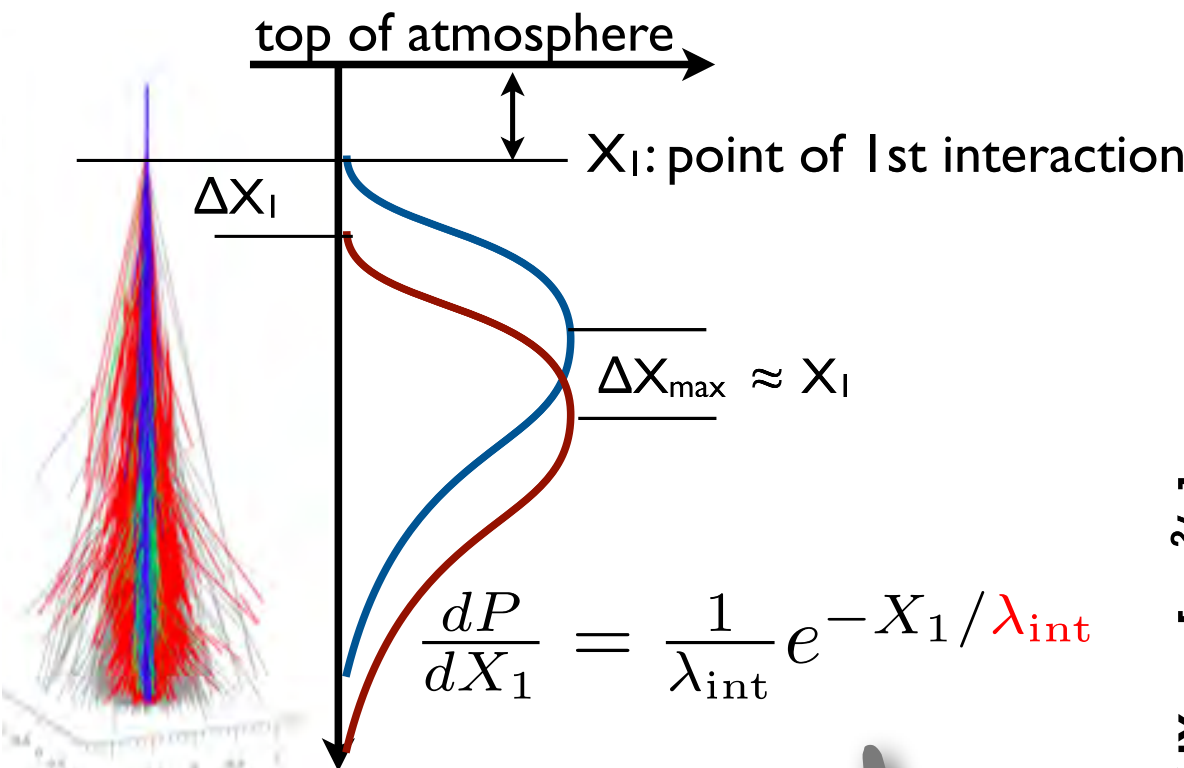
Class	No.	weighted P-value $\geqslant$1 EeV	Unweighted P-value $\geqslant$1 EeV
msec PSRs	68	0.48	0.86
γ-ray PSRs	77	0.23	0.82
LMXB	87	0.37	0.041
HMXB	48	0.014	0.095
H.E.S.S. PWN	17	0.083	0.88
H.E.S.S. other	16	0.91	0.42
H.E.S.S. UNID	15	0.82	0.48
Microquasars	13	0.28	0.031
Magnetars	16	0.69	0.73
Gal. center	1	...	0.24
Gal. plane	1	...	0.96

Absence of neutrons suggests that sources are extragalactic
(or transient, or emitting in jets, or optically thin to escaping protons)

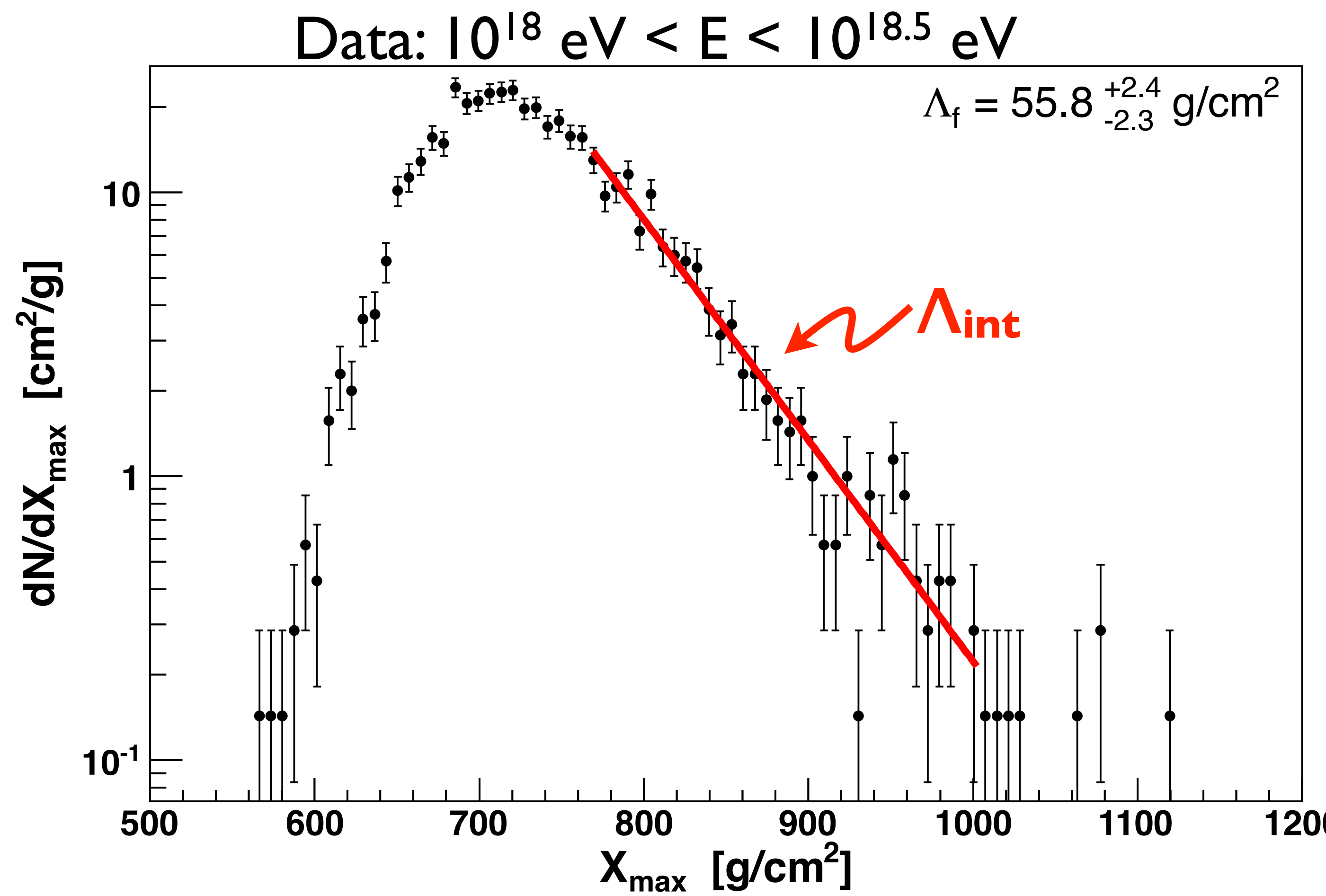
Constrain models in which EeV protons are produced by a low density of strong sources in the galaxy

UHECR - HEP connection

p-Air cross section



$$\frac{dP}{dX_1} = \frac{1}{\lambda_{\rm int}} e^{-X_1/\lambda_{\rm int}}$$



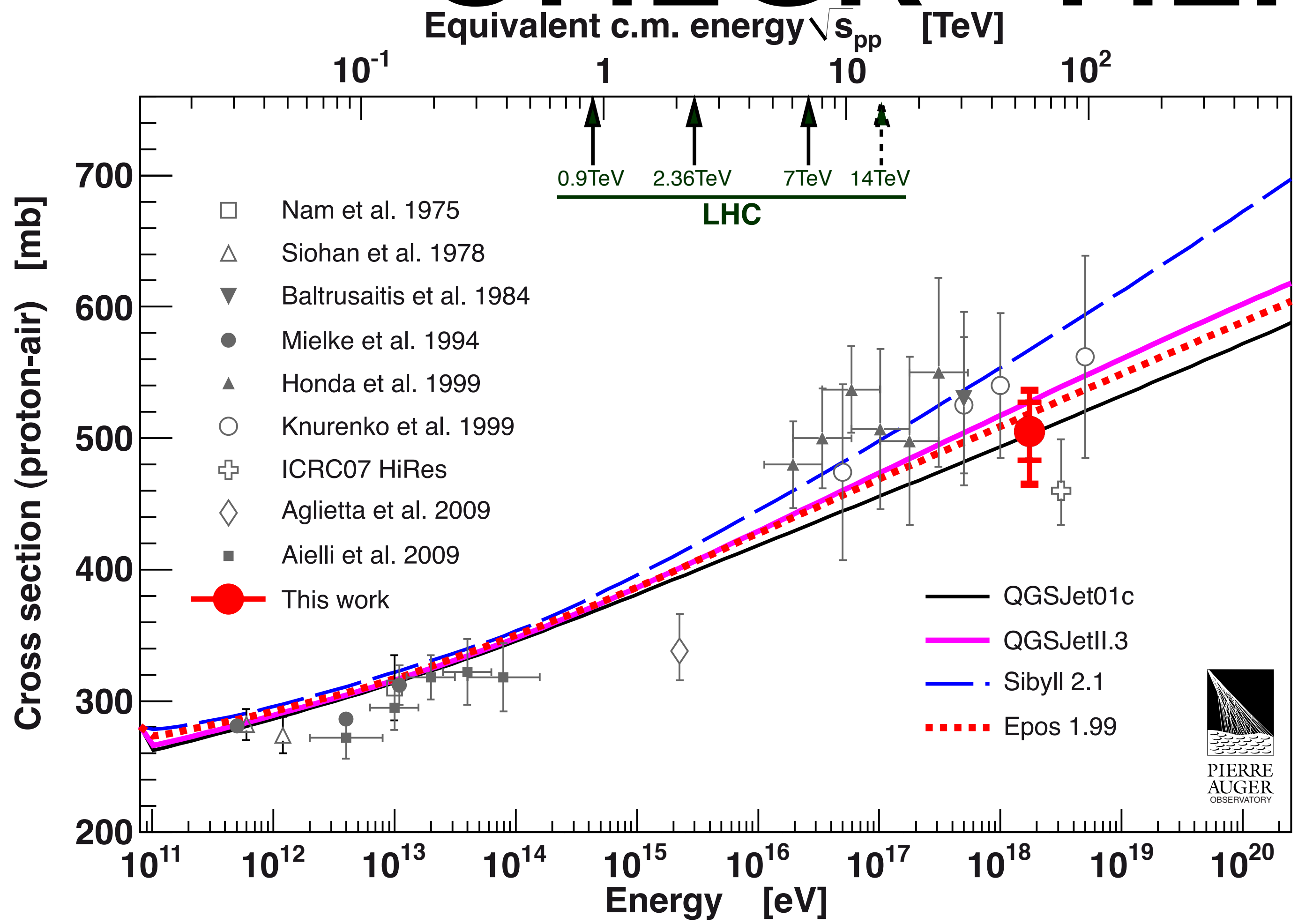
Difficulties:

- mass composition can alter Λ
- fluctuations in X_{max}
- experimental resolution ~ 20 g/cm^2

$$\sigma_{p-Air} = \frac{\langle m_{Air} \rangle}{\lambda_{int}}$$

In practice: $\sigma_{p\text{-}Air}$ by tuning models to describe Λ seen in data

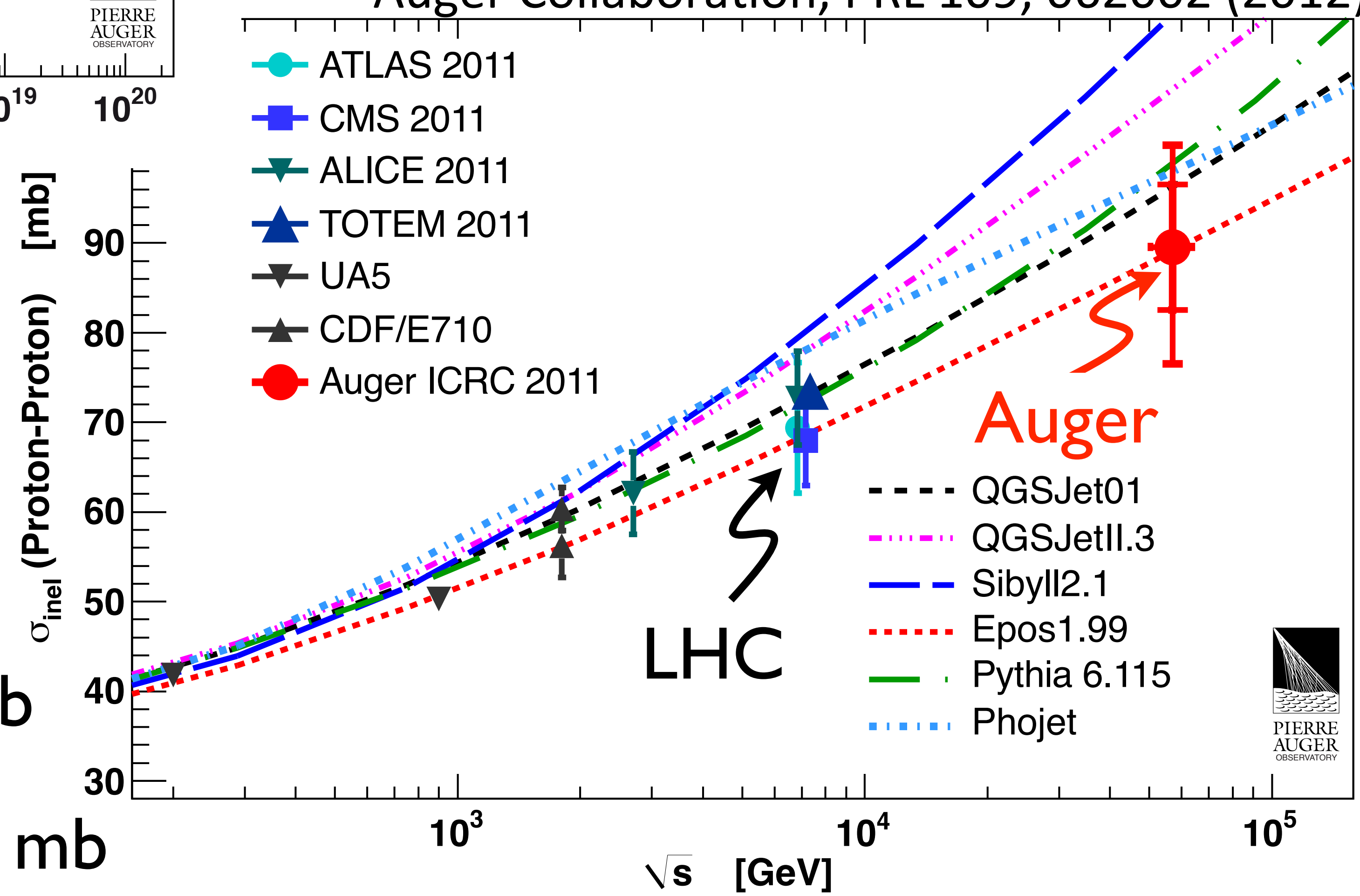
UHECR - HEP connection



Conversion from p-air
to p-p cross section
by Glauber-approach

$$\sigma^{prod}_{p\text{-}Air} = (505 \pm 22_{stat}\ (^{+26}_{-34})_{sys}\ )\ \text{mb}$$

Auger Collaboration, PRL 109, 062002 (2012)



$$\sigma^{inel}_{pp} = [92 \pm 7_{stat}\ (^{+9}_{-11})_{sys} \pm 7.0_{Glauber}]\ \text{mb}$$

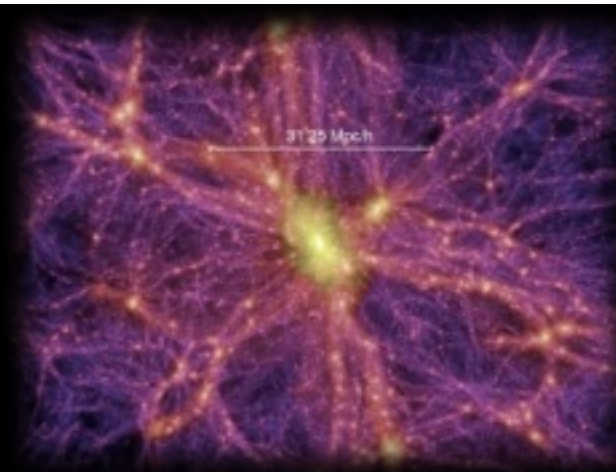
$$\sigma^{tot}_{pp} = [133 \pm 13_{stat}\ (^{+17}_{-20})_{sys} \pm 16_{Glauber}]\ \text{mb}$$

UHECR today:
multiparameter challenge

Multiparameter challenge

Aim: Constrain / determine astrophysical parameters
Challenge: Many unknown/uncertain parameters

Sources



Propagation

Observation

Number
Position
Size
Luminosity
Spectrum
Composition
Evolution
Transient sources
Emission patterns

→

Energy loss, cross sections
Change in composition
Background radiation model
Redshift effects

Extragalactic Mag. Field
Strength, coherence length,
structure (filaments, voids, cluster)

Galactic Mag. Field
Model and strength
scale heights, turbulence

→

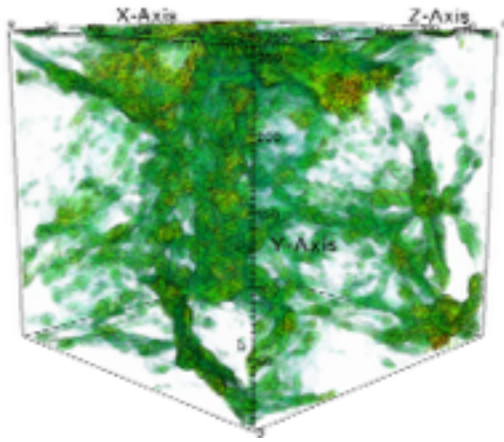
Direction *(direct)*
Energy *(direct)*
Composition
(indirect e.g. X_{max}*)*

Now you come into play

Simulations

- Much progress in recent years

Propagation codes



CRPropa
R.A. Batista et al. ICRC 2013
https://crpropa.desy.de
SimProp
R. Aloisio et al. JCAP 10 007 (2012)

Experimental data

PIERRE AUGER OBSERVATORY

TELESCOPE ARRAY PROJECT

Computing power

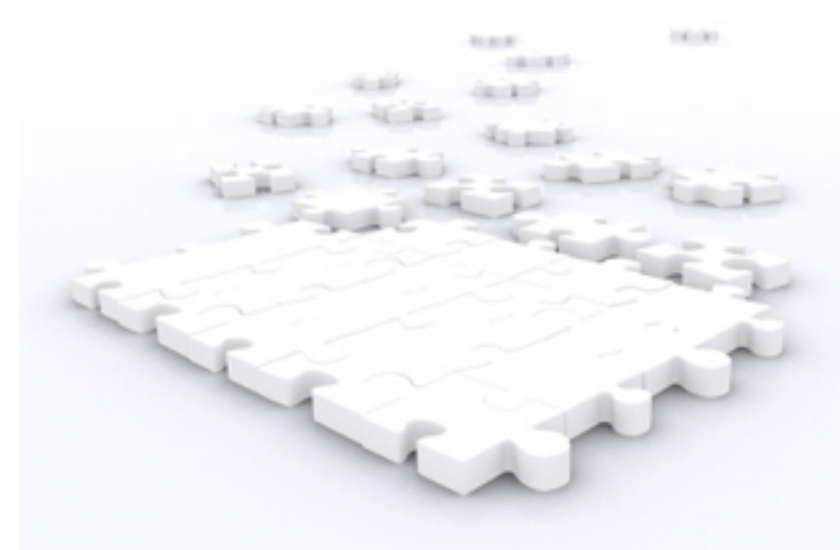
Using high statistic experimental data in combination with sophisticated propagation tools and powerful computing clusters we are entering a **new phase of data / MC comparison**

Motivation 3D benchmark scenario

Motivation can be divided into two parts:

1. **Physics Motivation**:
   Simulate a realistic astrophysical scenario and calibrate it to recent observations including:
   ➡ *3D simulation*
   ➡ *Nuclei implementation*
   ➡ *Galactic and extragalactic propagation*
   ➡ *Sources according to large-scale structure*
   ➡ *Extragalactic and galactic magnetic fields*

2. **Also community Motivation**:
   Provide a common scenario for collaborators
   ➡ *Test observables (e.g. anisotropy sensitive parameters)*
   ➡ *Benchmark observables for an easy (and standardized) comparison*



Simulation details

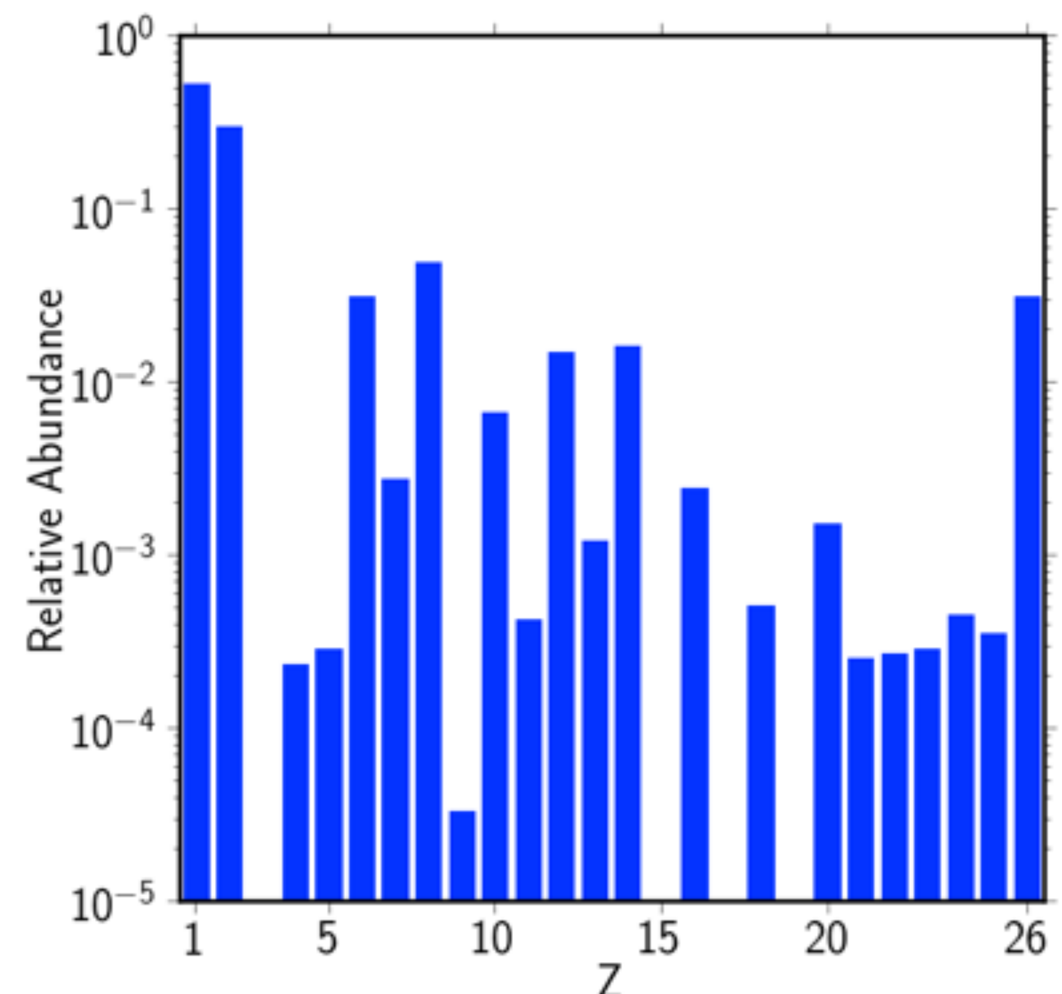
Sources:

- ➡ Randomly distributed according to large scale structure
- ➡ Minimum distance of 3 Mpc
- ➡ Isotropic emission
- ➡ Composition according to (galactic composition, DuVernois et al. 1996)

$$\frac{\mathrm{d}N_i}{\mathrm{d}E} \propto x_i A_i^{\alpha-1} E^{-\alpha}$$

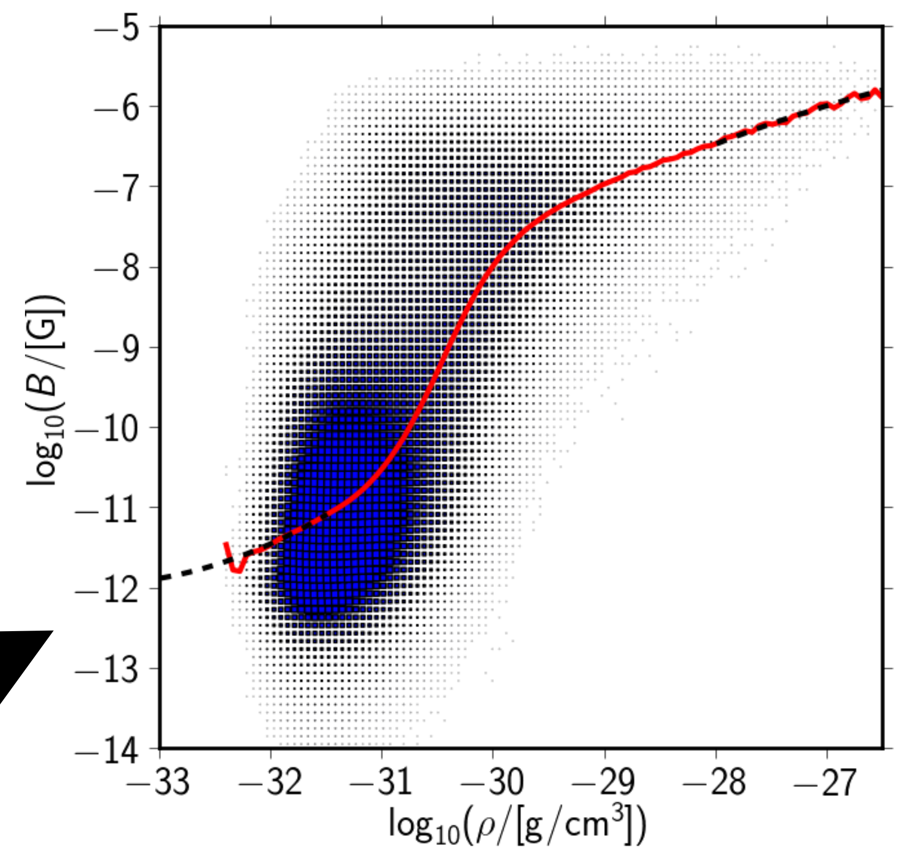
x_i : relative abundance
A_i : mass number
α : spectral index = 2.0

- ➡ Abundances for $Z > 2$ scaled by factor k_c=10
- ➡ Maximum energy of each element is rigidity dependent:
  $E_{max} = Z_i R_{max}$, with R_{max} = 150 EeV
- ➡ Source density: 10^{-4} Mpc^{-3}



Simulation details

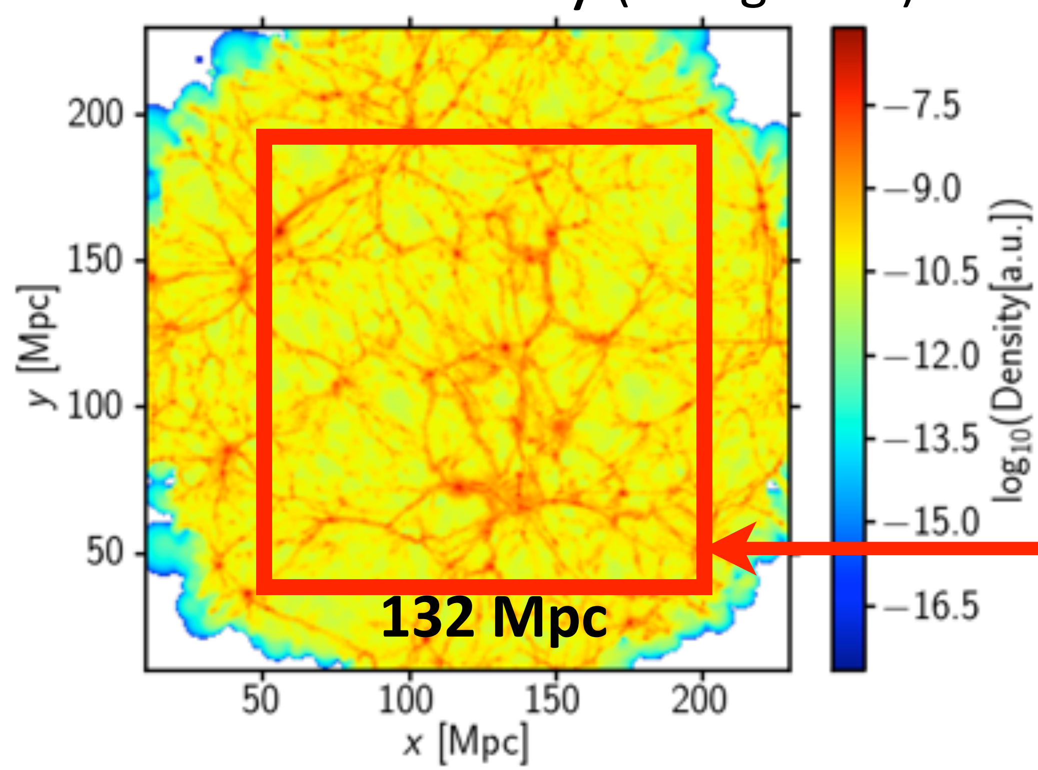
Extragalactic magnetic field:



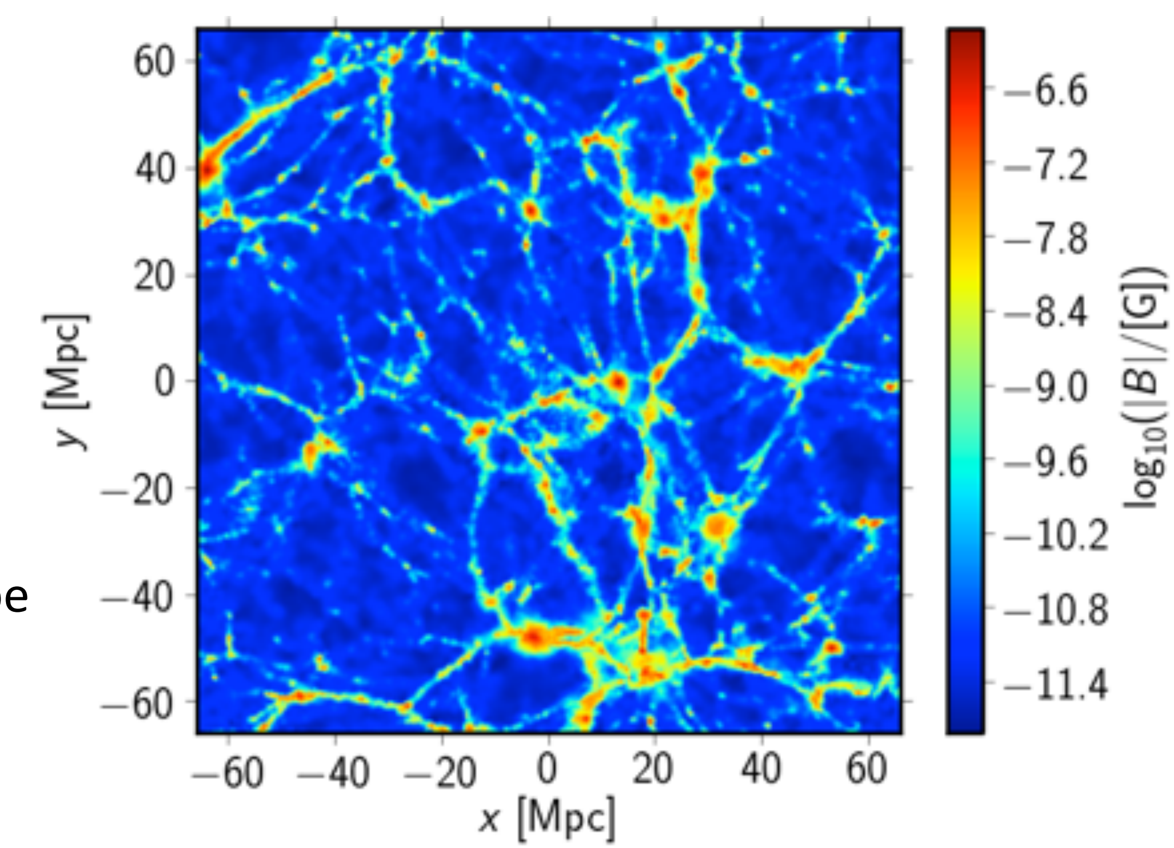
Obtain field strength from mass density using *B-rho* profile (Miniati *et al.*)

Resulting *B*-strength

LSS mass density (Dolag *et al.*)



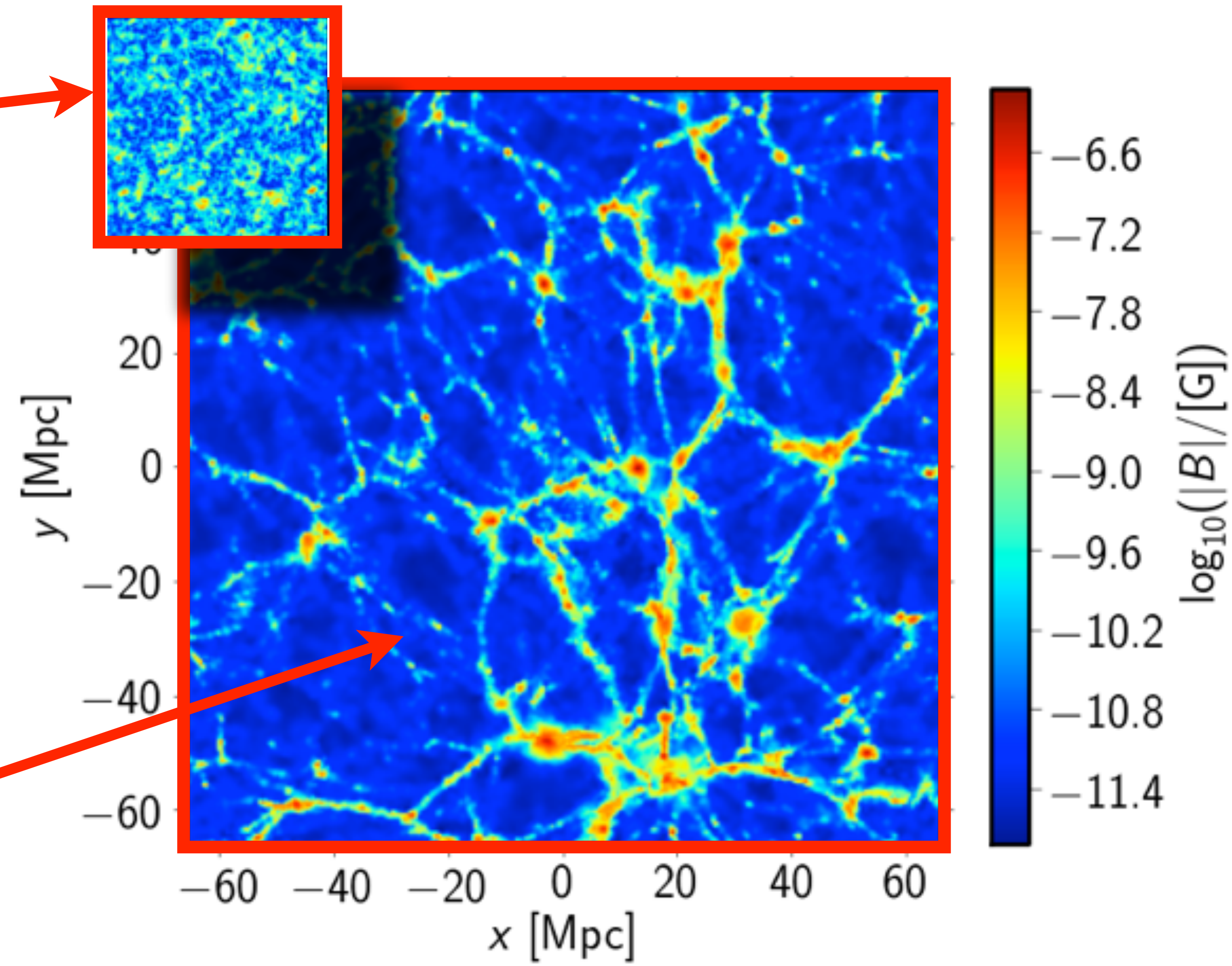
Select largest cube that fits inside



Simulation details

Extragalactic magnetic field:

- Periodically repeated turbulent field grid
- Small grid size
- High resolution (50 kpc)

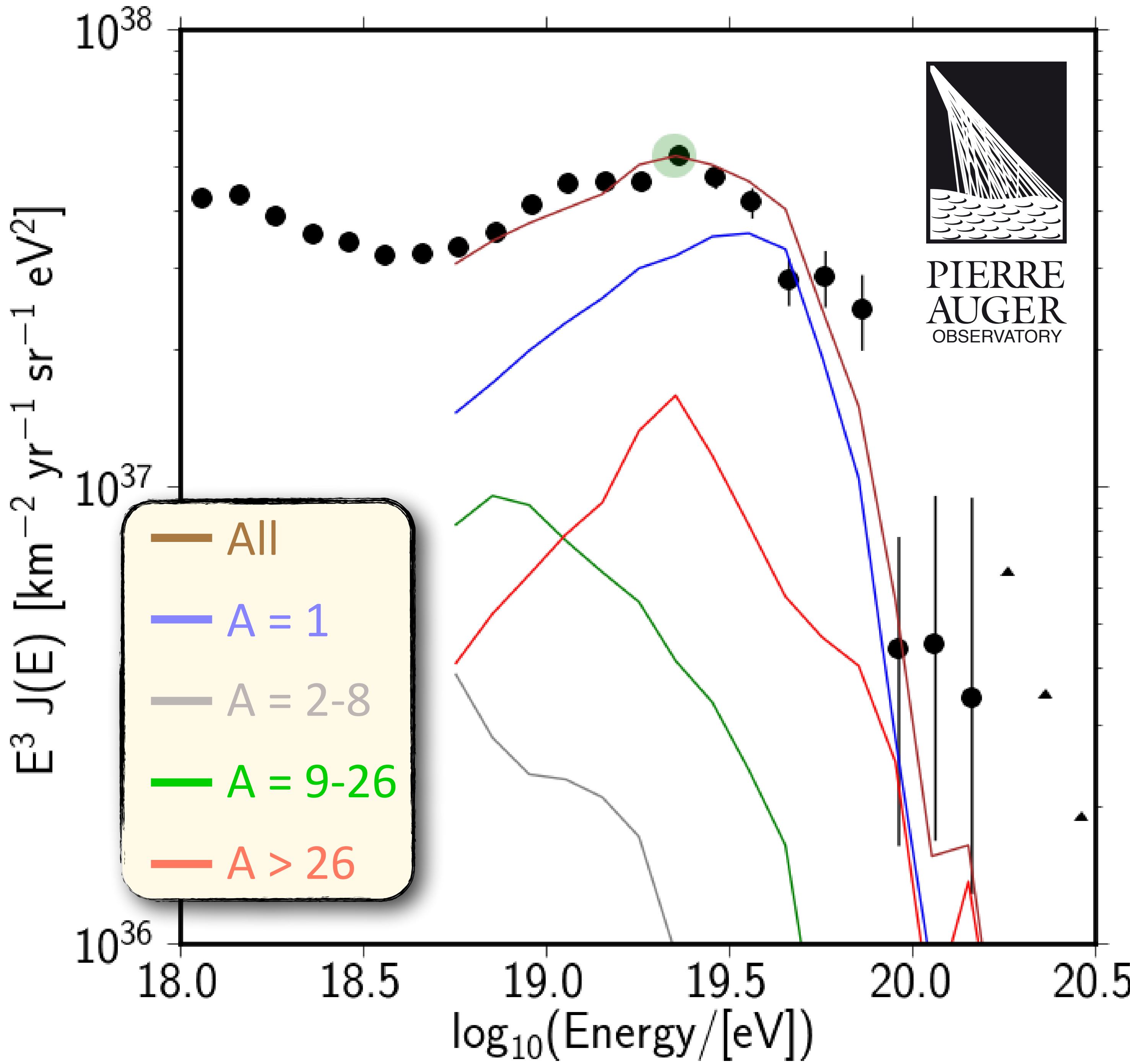


- Large scale structure
- Large grid size
- Low resolution (500 kpc)

Magnetic field direction given by multiplying turbulent field grid and large scale structure

Results

Comparison with Auger spectrum



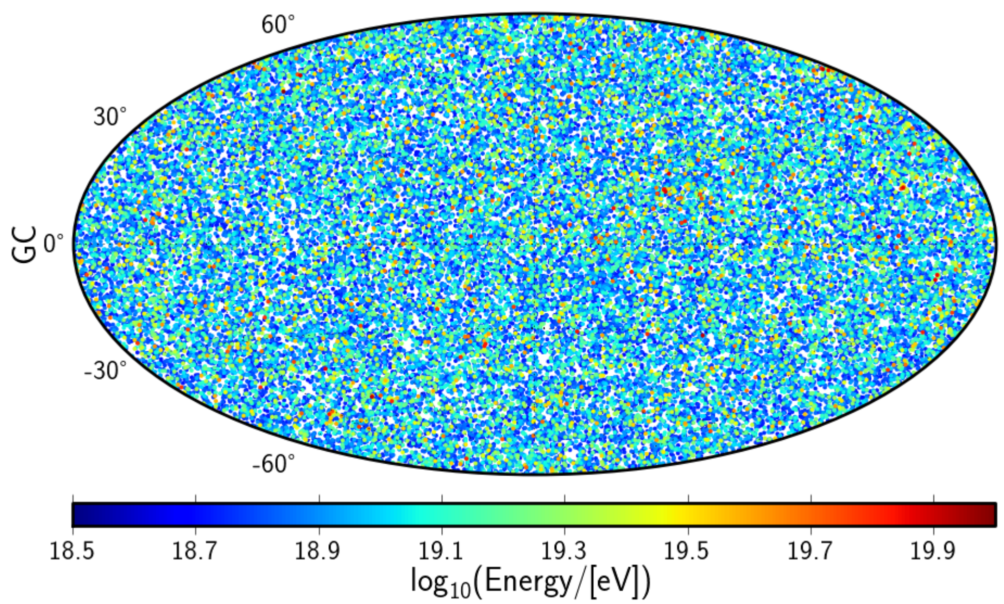
➡ *Protons dominate at lower energies*

➡ *Heavy elements become important at highest energies*

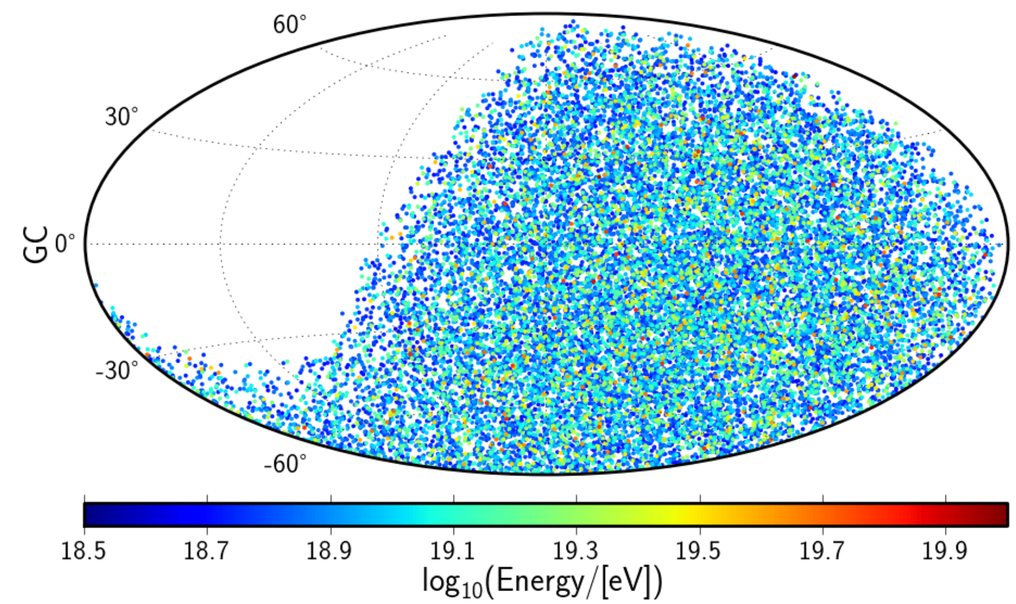
Results

Arrival directions:

All events

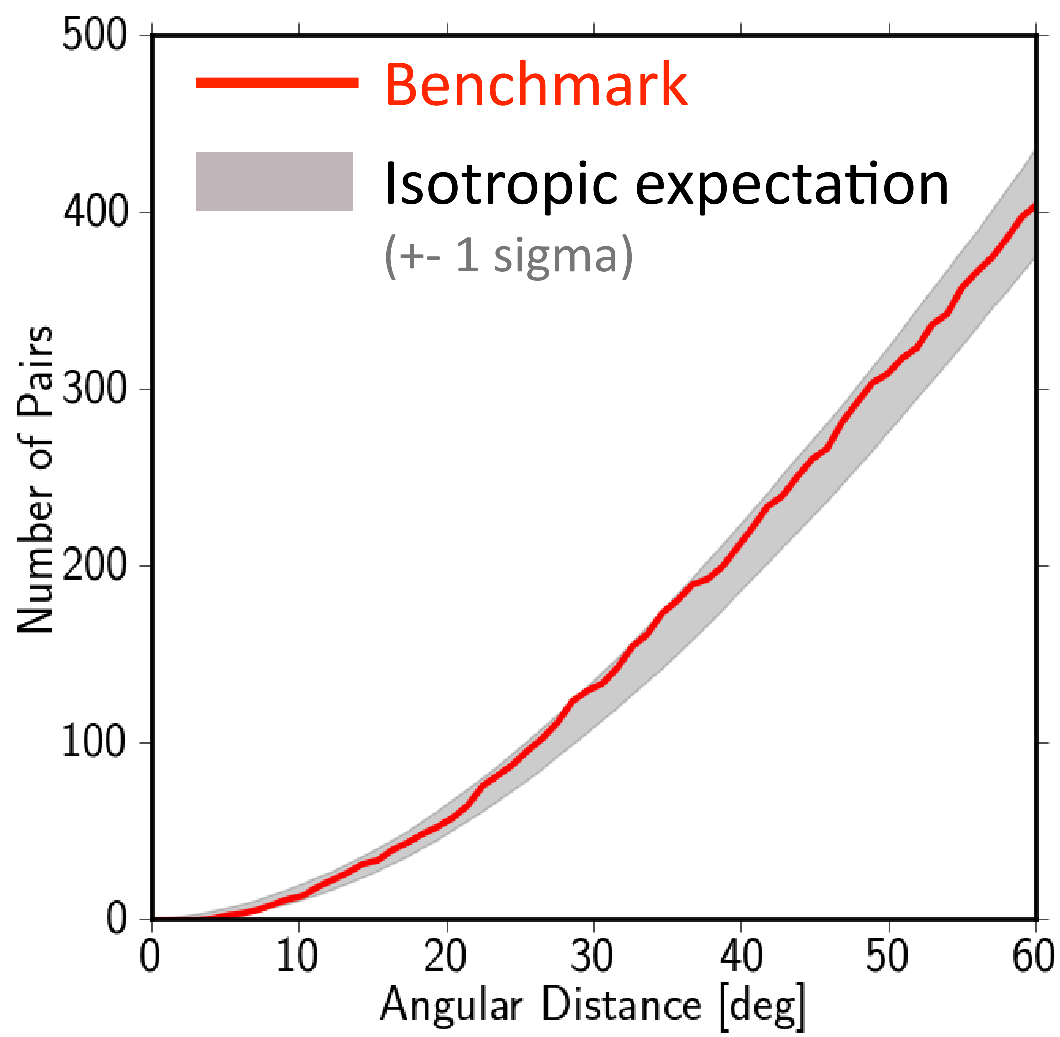


Events after detector acceptance



PIERRE AUGER OBSERVATORY

Results



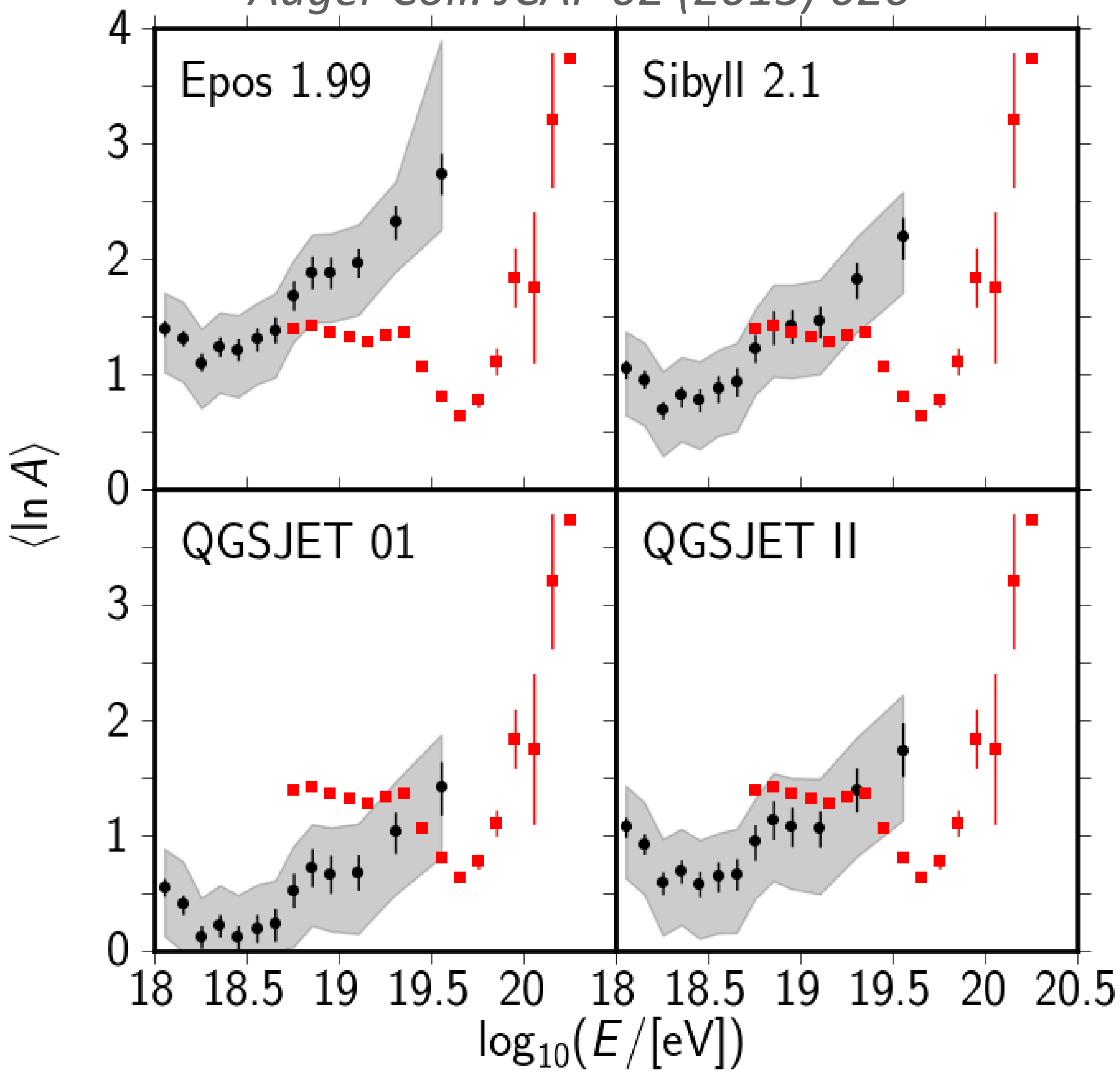
➡ ***Autocorrelation:***

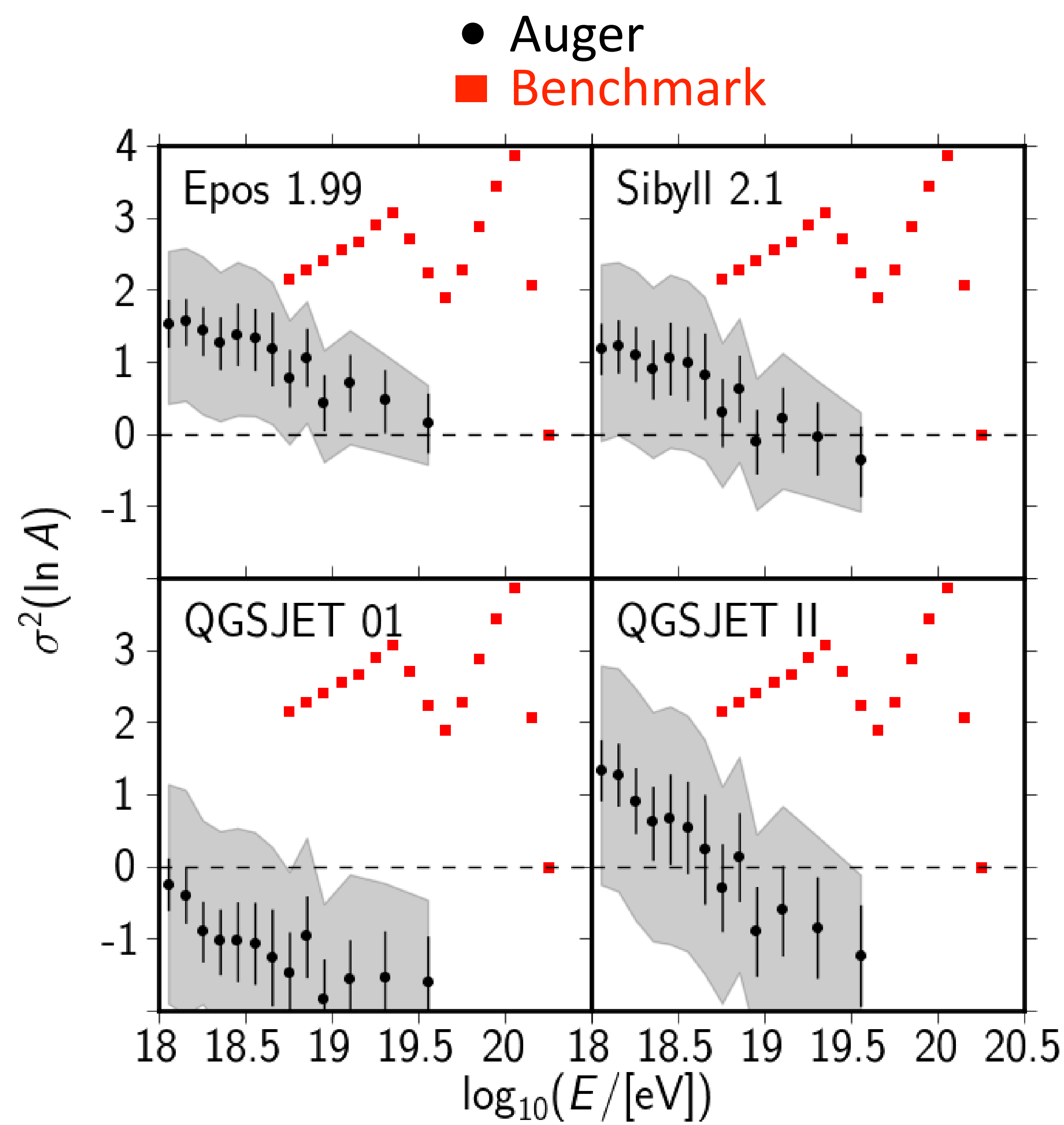
No clear deviation from isotropic expectation

Results

Composition measurements

Auger Coll. JCAP 02 (2013) 026





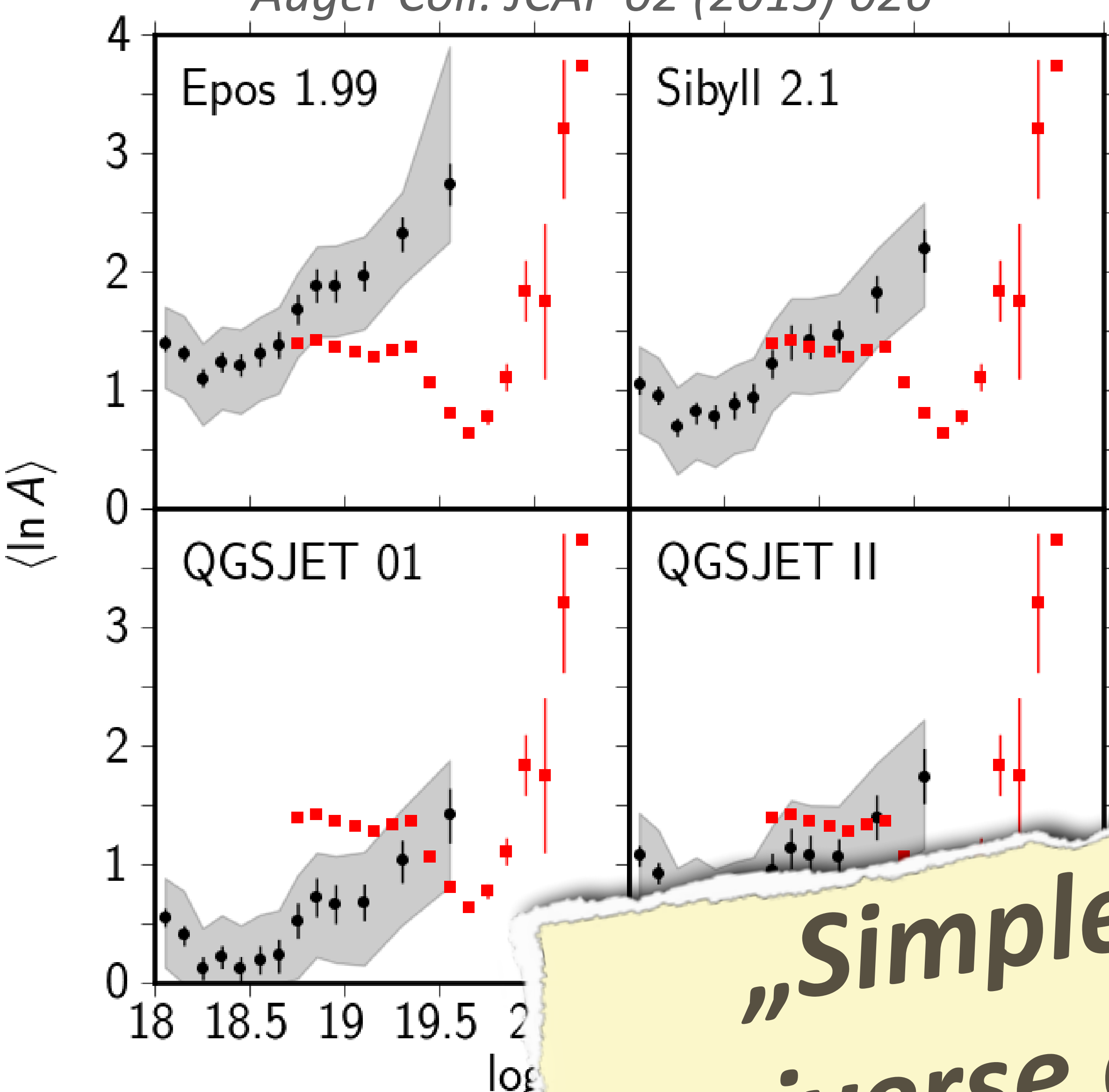
➡ *Deviation from measurements*

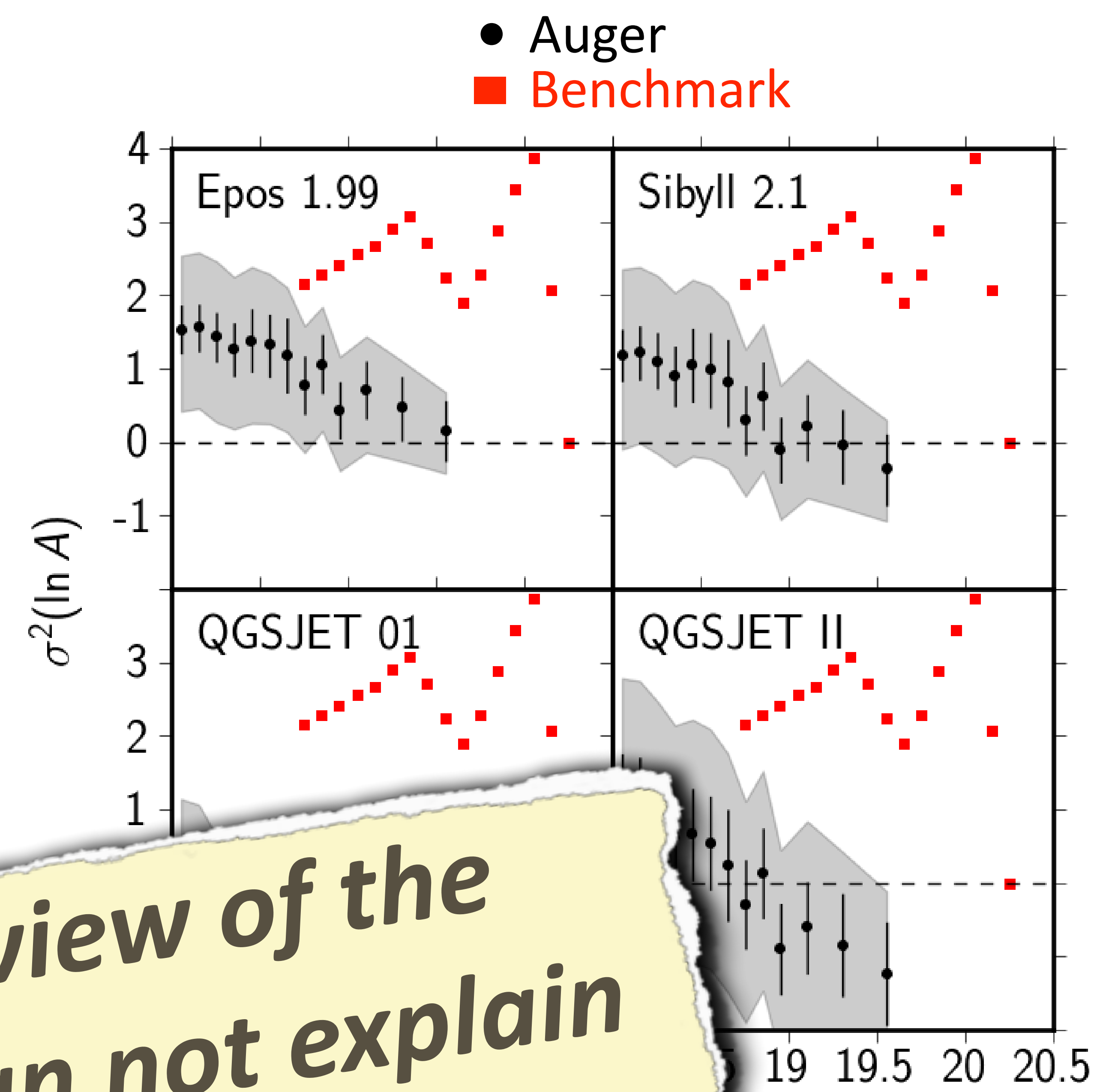
➡ *Better model needed*

Results

Composition measurements

Auger Coll. JCAP 02 (2013) 026





„Simple view of the universe can not explain measurements“

urements

ter model needed

Many other papers on this subject

Astroparticle Physics 39–40 (2012) 33–43
Astroparticle Physics
journal homepage: www.elsevier.com/locate/astropart
ELSEVIER

Extragalactic propagation of ultrahigh energy cosmic-rays

Denis Allard
Laboratoire Astroparticule et Cosmologie (APC), Université Paris 7/CNRS, 10 rue A. Domon et L. Duquet, 75205 Paris Cedex 13, France

Astroparticle Physics 54, 48 (2014)
Astroparticle Physics
journal homepage: www.elsevier.com/locate/astropart
ELSEVIER

UHECR composition models

Andrew M. Taylor
Dublin Institute for Advanced Studies, 31 Fitzwilliam Place, Dublin 2, Ireland

Astroparticle Physics 33 (2010) 151–159
Astroparticle Physics
journal homepage: www.elsevier.com/locate/astropart
ELSEVIER

On the heavy chemical composition of the ultra-high energy cosmic rays

Dan Hooper [a,b], Andrew M. Taylor [c,d,*]

PHYSICAL REVIEW D 84, 105007 (2011)

Need for a local source of ultrahigh-energy cosmic-ray nuclei

Andrew M. Taylor,[1] Markus Ahlers,[2] and Felix A. Aharonian[3,4]

Frontiers of Physics
December 2013, Volume 8, Issue 6, pp 748-758

Cosmic ray energy spectrum from measurements of air show...

T. K. Gaisse...

Ultra high energy cosmic rays: implications of Auger data for source spectra and chemical composition

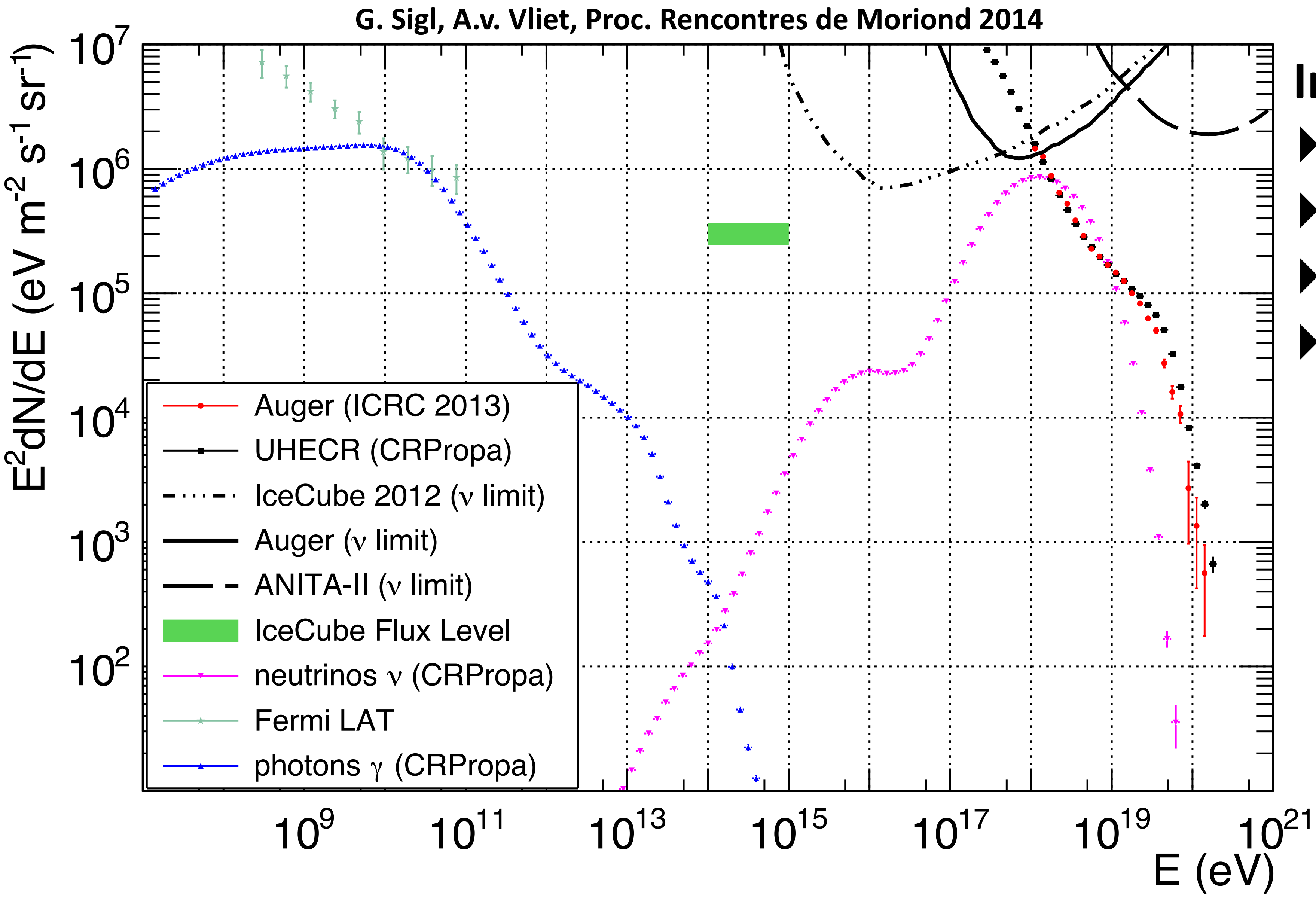
Subm. to JCAP 2013

Bottom line:

- Typically these papers only use **spectrum** and **composition** observables
- **Hard source spectral index** needed, unless **nearby source** (additional component) is assumed
- **Too early to draw decisive conclusions** (large parameter space and big uncertainties)

Multi-messenger approach

- IceCube PeV neutrino events from extragalactic UHECRs?



In this example:

- pure proton injection
- source spectral index 2.2
- E_{max} = 200 EeV
- Relatively strong source evolution model

- Difficult to interpret IceCube events in terms of cosmogenic neutrino flux
- Gamma ray flux of the order of Fermi diffuse level

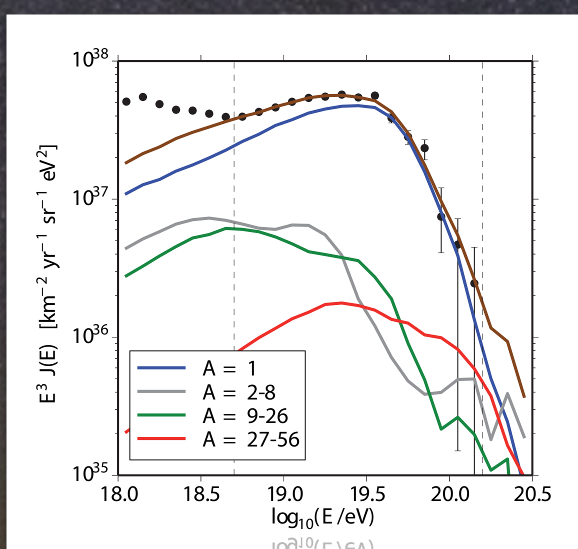
Conclusion I

- **Even more than 100 years after the discovery of cosmic rays many questions at ultra-high energies are still unanswered.**
- **Current large-scale observatories offer a unique opportunity to tackle these questions**
- **Major achievements in recent years:**
  - Clear observation of flux suppression
  - Strongest bounds on EeV neutrinos and photons
  - Strongest bounds on large-scale anisotropies
  - First hints on correlations with nearby matter
  - Increasing heavier composition (Auger) or continuously light (TA)?
  - Proton-proton cross section at very high energy

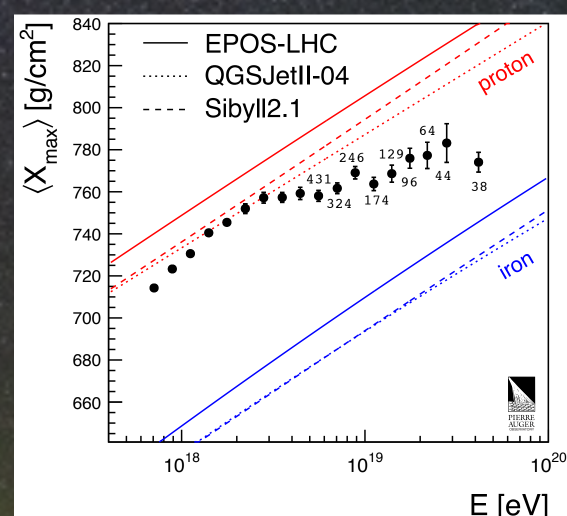
Conclusion II

- Propagation of UHECRs plays an important role constraining astrophysical parameters
- Modern simulation tools enable 1D and 3D simulations in structured (extra)galactic environments including secondaries
- Too early to draw decisive conclusions on astrophysical parameters
  ➡ Use more observables and experimental data

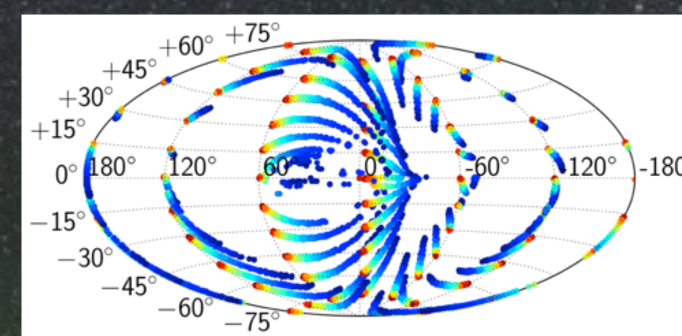
spectrum



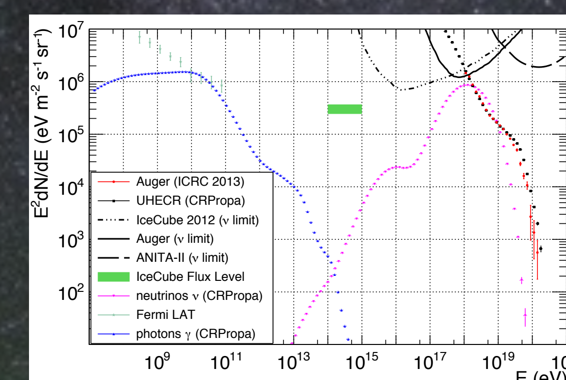
composition



arrival direction



photons, neutrinos



- Secondaries as messengers may further constrain astrophysical parameters, e.g. by comparing with TeV observations

<u>Now it's up to you!</u>

… the future is bright