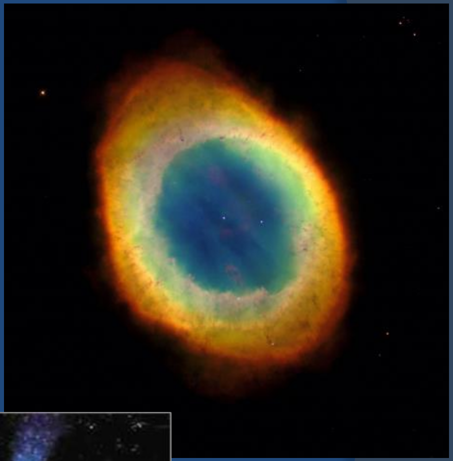
Macroscopic modeling of radio emission from particle cascades

Krijn de Vries
IIHE
Vrije Universiteit Brussel

Why do we study high energy cosmic rays and neutrinos?

- **Origin** of cosmic rays at the highest energies and their **acceleration mechanism still unknown**:

  AGN, GRB, Exotic decay?



- Do we see the ***GZK*** effect?

- Cascade **physics**:

  E>E(LHC), new physics…?

What do we need to find an answer to these questions?

- Origin, acceleration mechanisms of cosmic rays at the highest energies and the GZK effect:

The cosmic-ray / neutrino spectrum

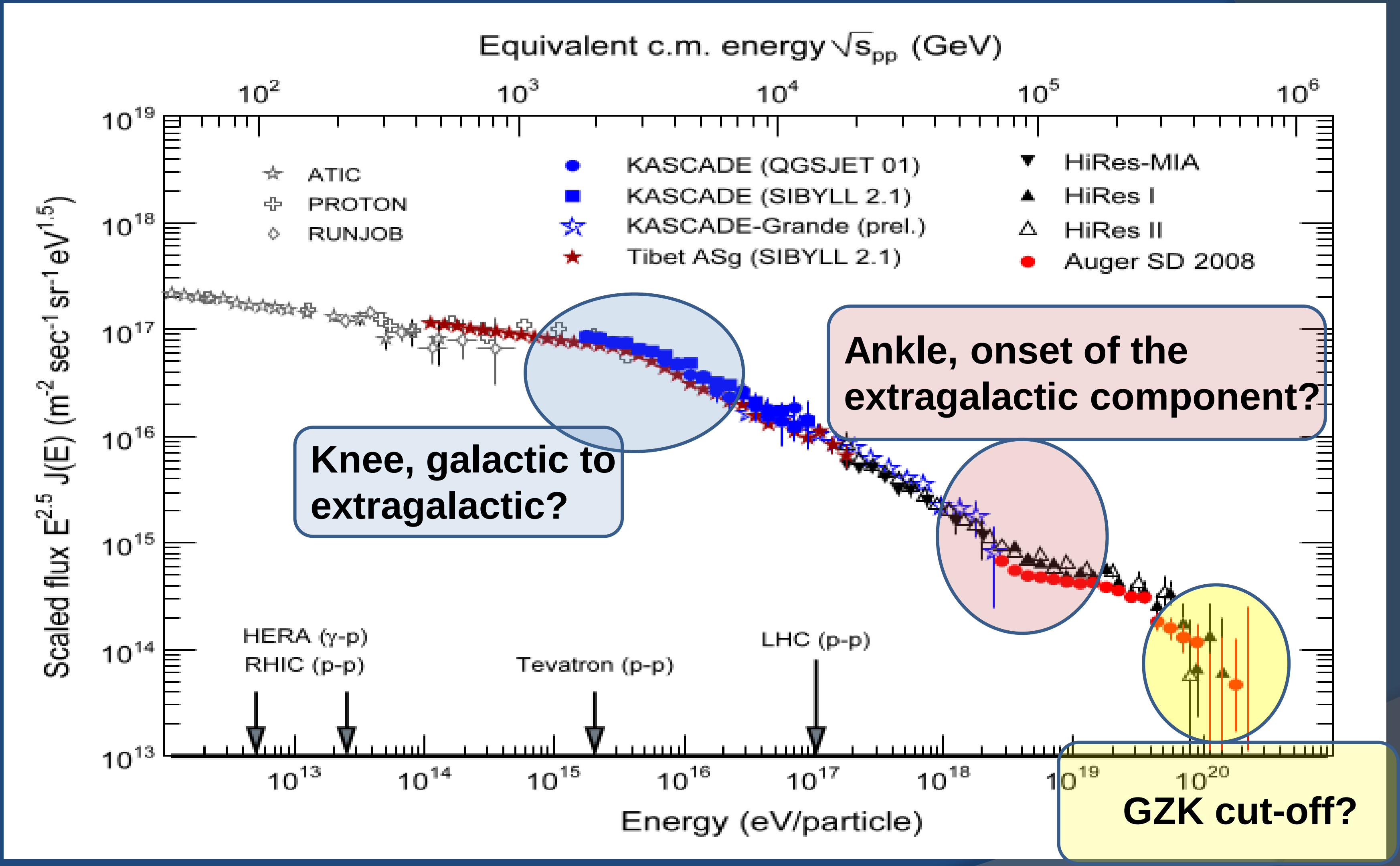
Composition of the initial cosmic ray

↕

- Shower physics:

Accurate shower measurements

The cosmic-ray spectrum



Knee, galactic to extragalactic?

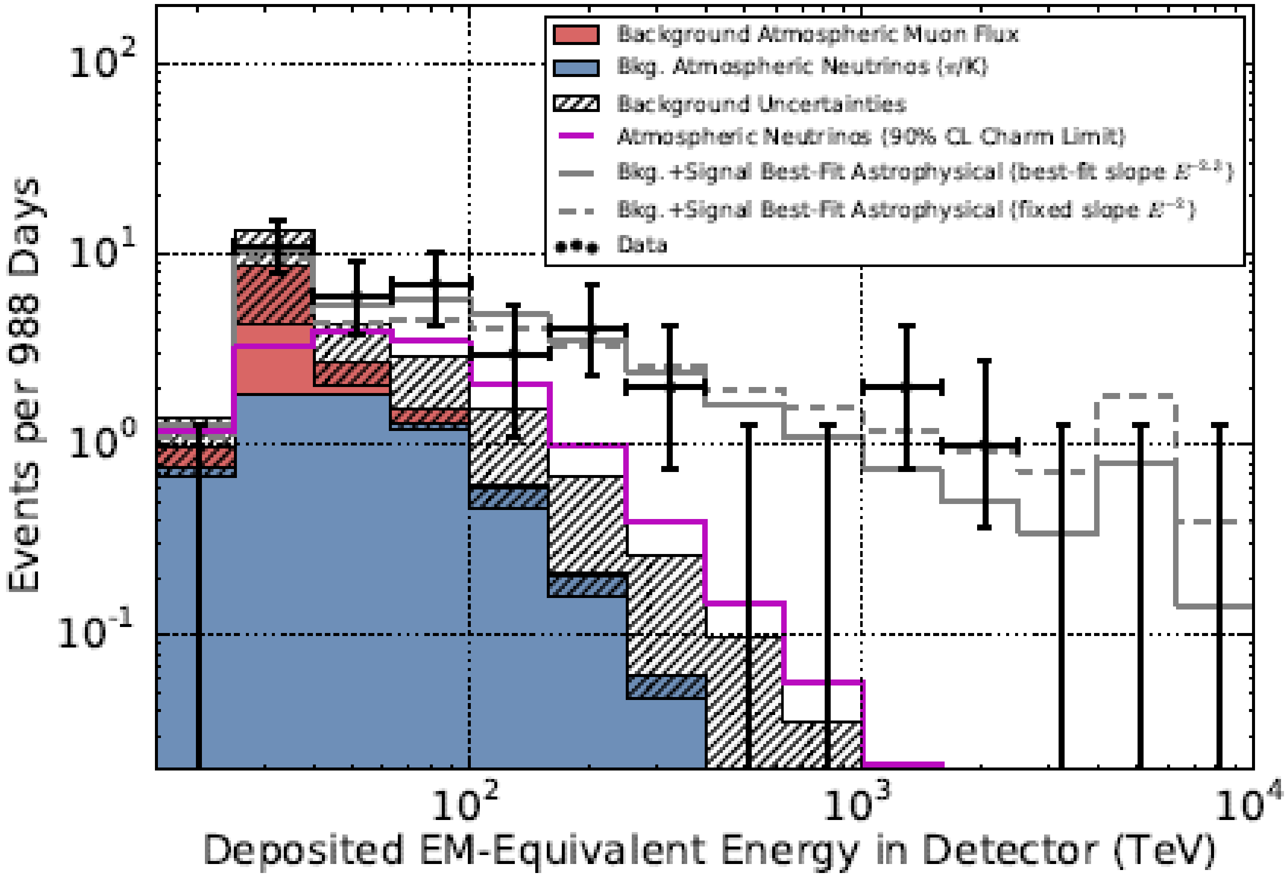
Ankle, onset of the extragalactic component?

GZK cut-off?

Very low flux at the highest energies

The cosmic-neutrino spectrum

Phys. Rev. Lett. 113, 101101 (2014)



Very low flux at the highest energies

Very low flux at the highest energies

To detect this flux we need a very large detection volume

- **Signal with long attenuation length**
- **Cost efficient detector**

Can we use the Radio detection technique to measure air showers? YES!!

PIERRE AUGER
OBSERVATORY

AERA
Auger Engineering Radio Array

Tunka-Rex

GRAND

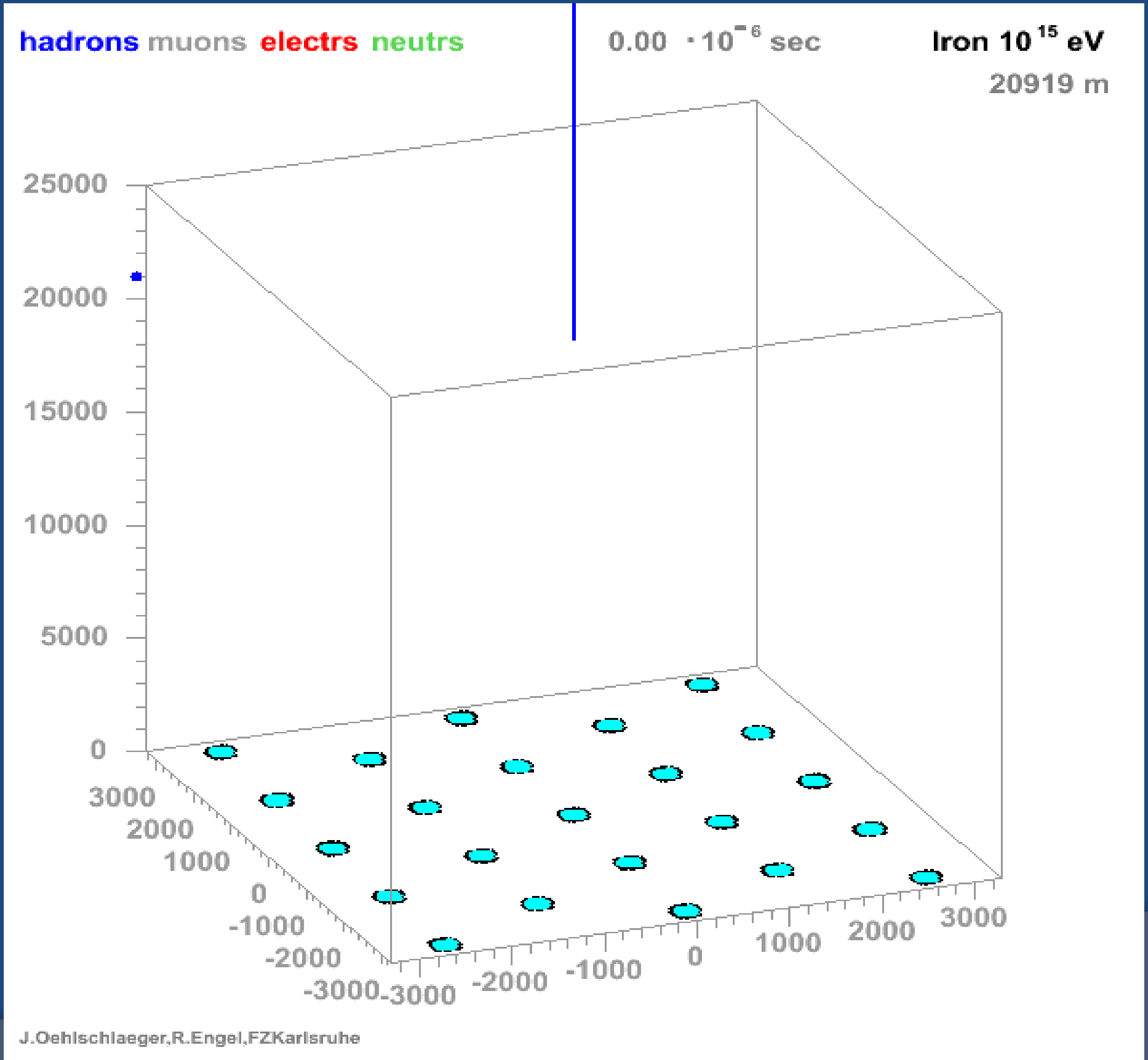
TREND

CODALEMA

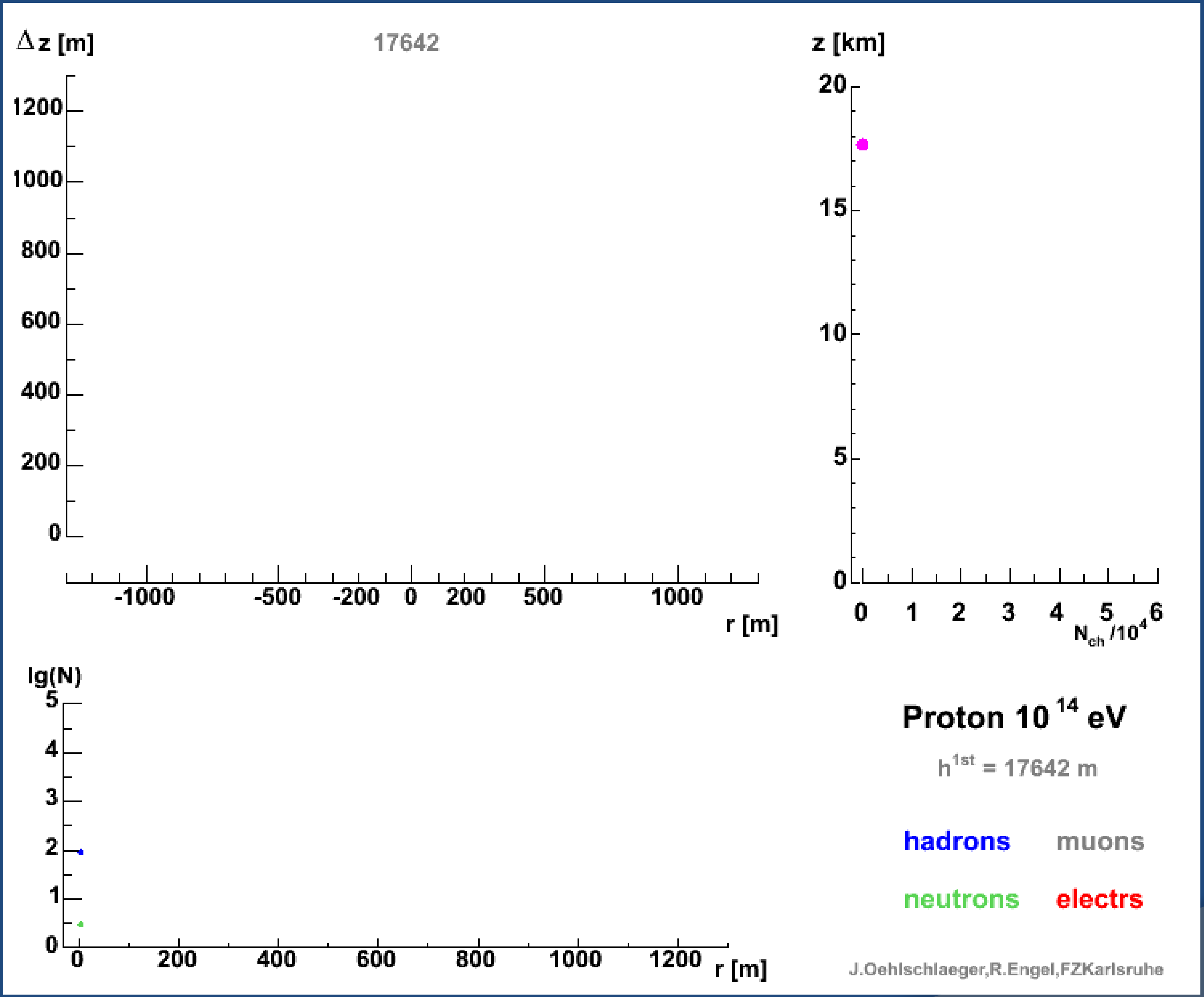
LOFAR

LOPES

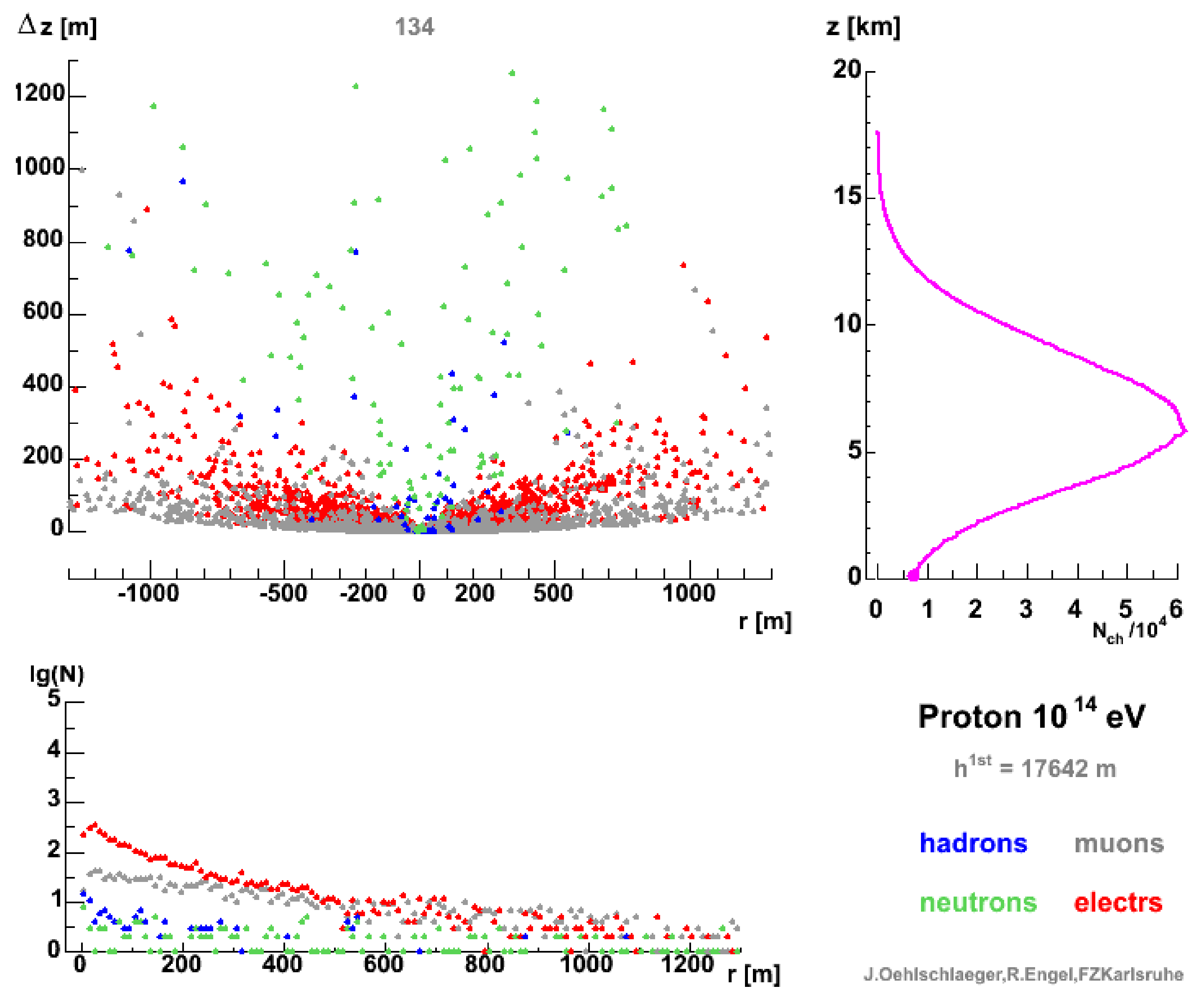
Ultra-high-energy cosmic ray detection: Extensive Air Showers



J. Oehlschläger and R. Engel: http://www-ik.fzk.de/corsika/movies/Movies.htm



J. Oehlschläger and
R. Engel: http://www-ik.fzk.de/corsika/movies/Movies.htm

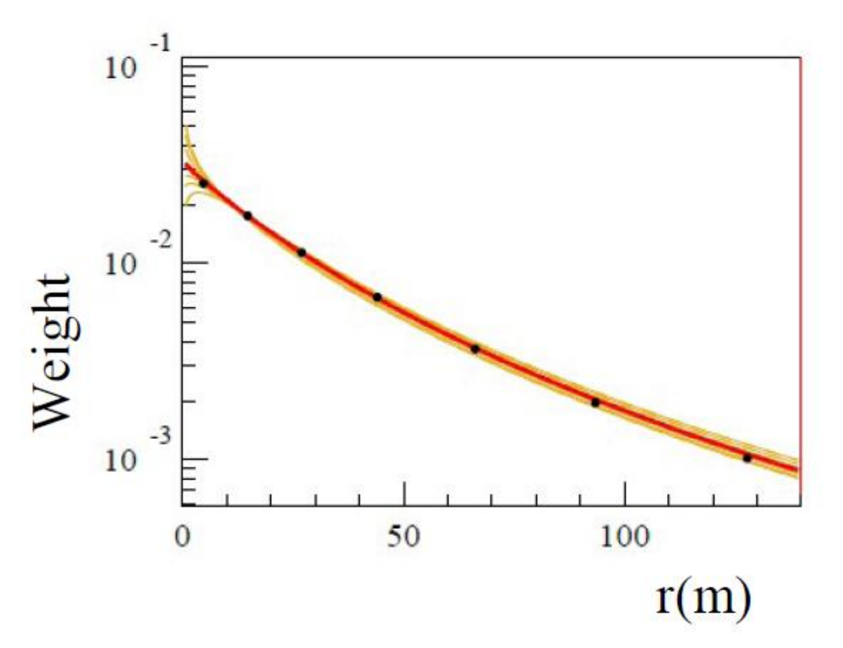


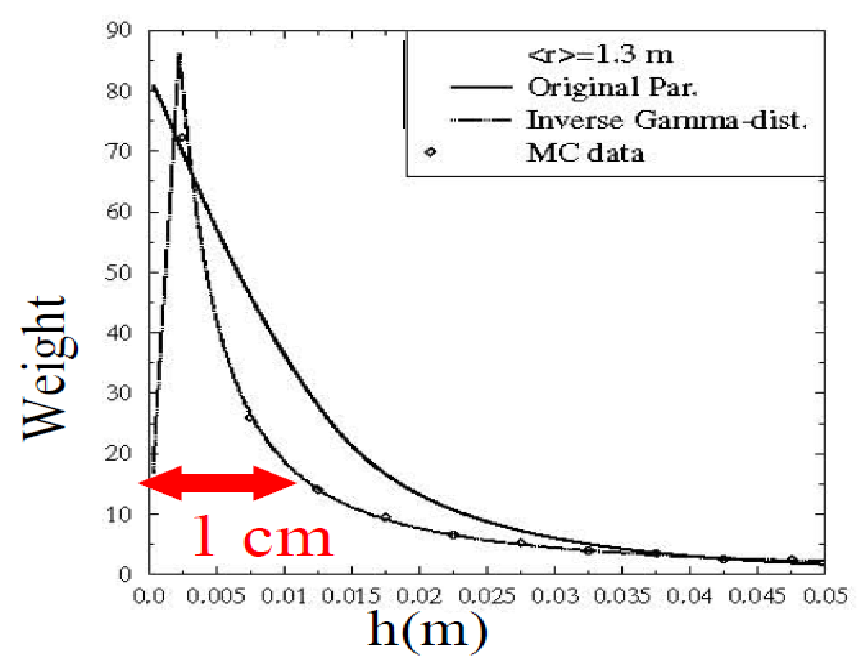
J. Oehlschläger and R. Engel: http://www-ik.fzk.de/corsika/movies/Movies.htm

Particle distributions in the shower front

The lateral particle distribution in the pancake

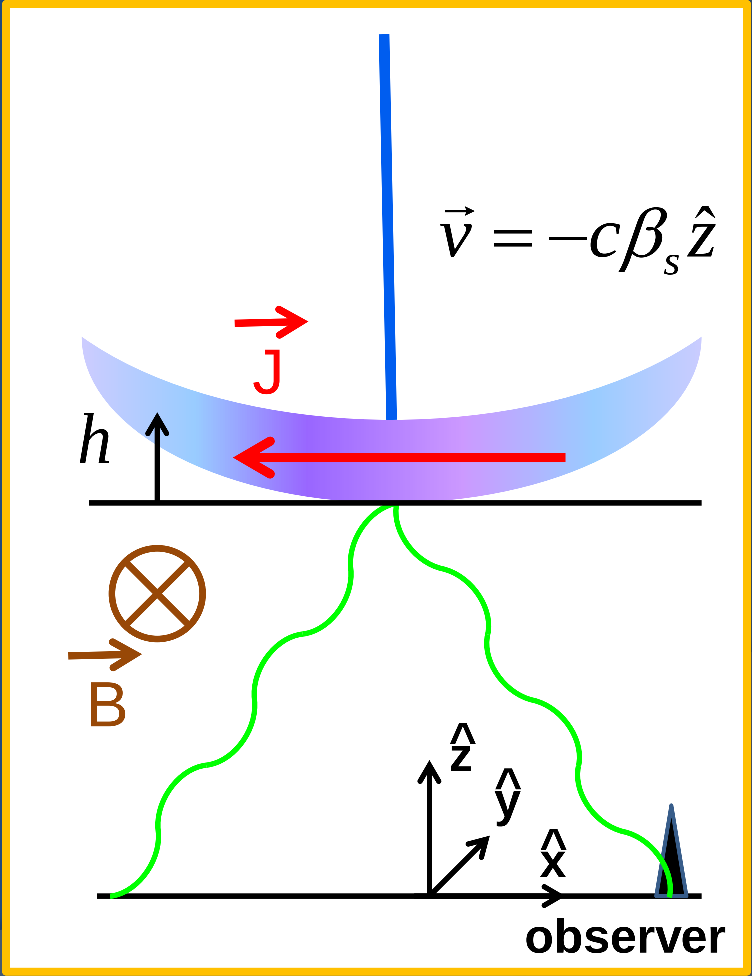
Coherence determined by particle distribution close to the shower axis





Radio emission mechanisms: Geomagnetic radiation

- e^+e^- pairs are deflected in Earth’s magnetic field due to the Lorentz force.
- Net macroscopic current in the direction of the Lorentz force.



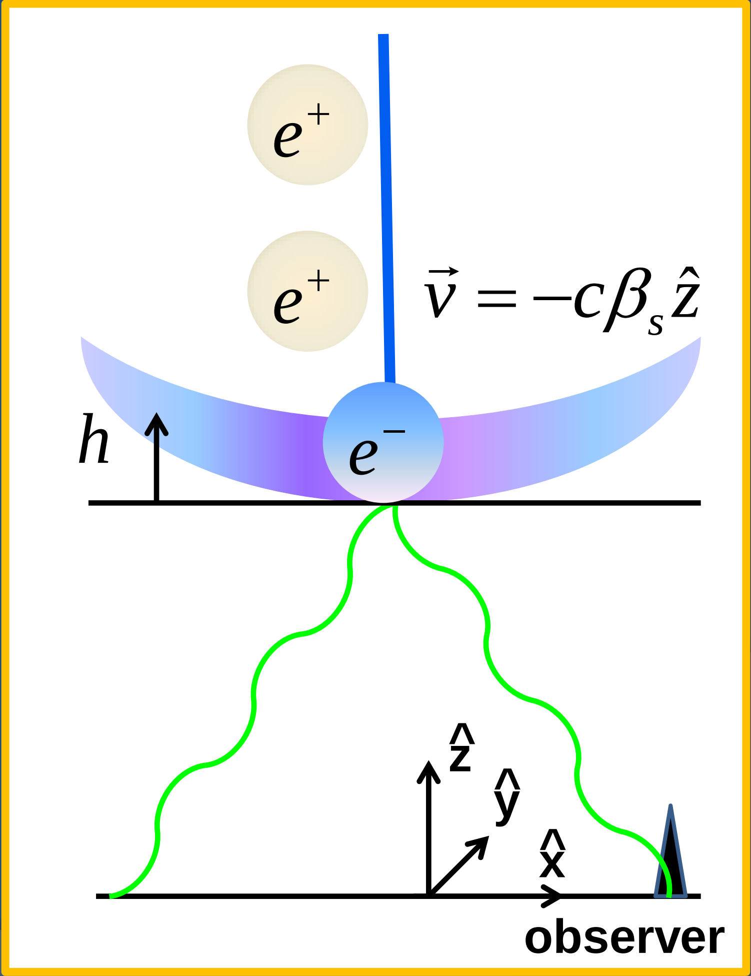
Radio emission mechanisms: Charge-excess emission

- **Several processes give rise to a net negative charge of the shower front (Askaryan):**

1. Compton scattering

2. Knock out by shower particles

- **This leads to a net negative current in the direction of movement of the shower.**



Modelling: The Liénard-Wiechert potentials

$$A^{\mu}{}_{PL}(\vec{x},t) = \frac{J^{\mu}{}_{PL}(t')}{|D(\vec{x},t)|}$$

$$D = R(1 - n\beta\cos(\theta))$$

$$= R\frac{dt}{dt'}$$

$$\vec{E}(\vec{x},t) =$$

$$-\frac{d}{dt}\vec{A}(\vec{x},t) - \frac{d}{d\vec{x}}A^{0}(\vec{x},t)$$

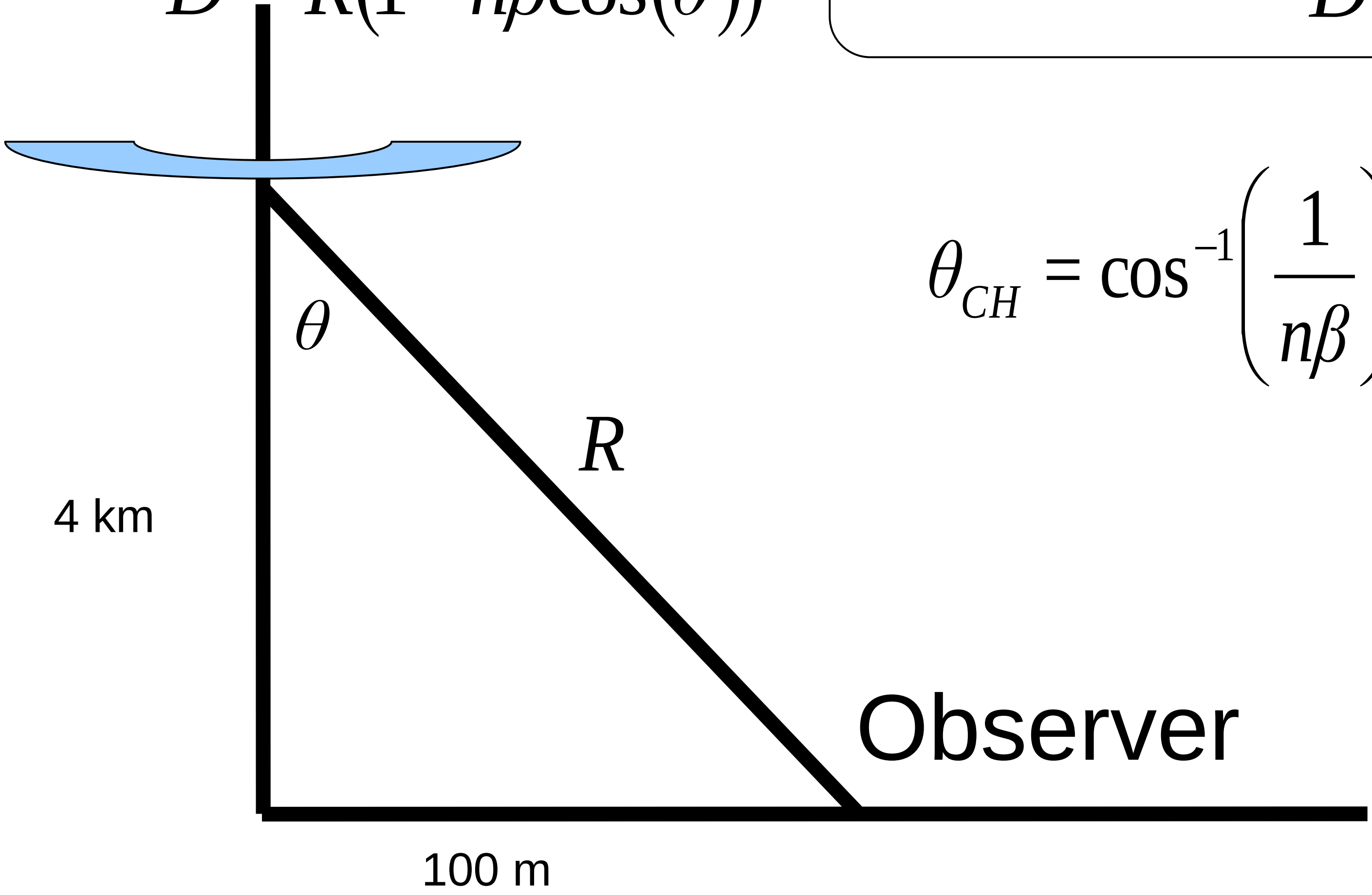
$$\vec{E}(\vec{x},t) \propto \frac{1}{D^{2}}$$

D can become zero for index of refraction deviating from unity!

Retarded distance D(1)

$$\vec{E}(\vec{x},t) \propto \frac{1}{D^2}$$

$$D = R\left(1 - n\beta\cos(\theta)\right)$$



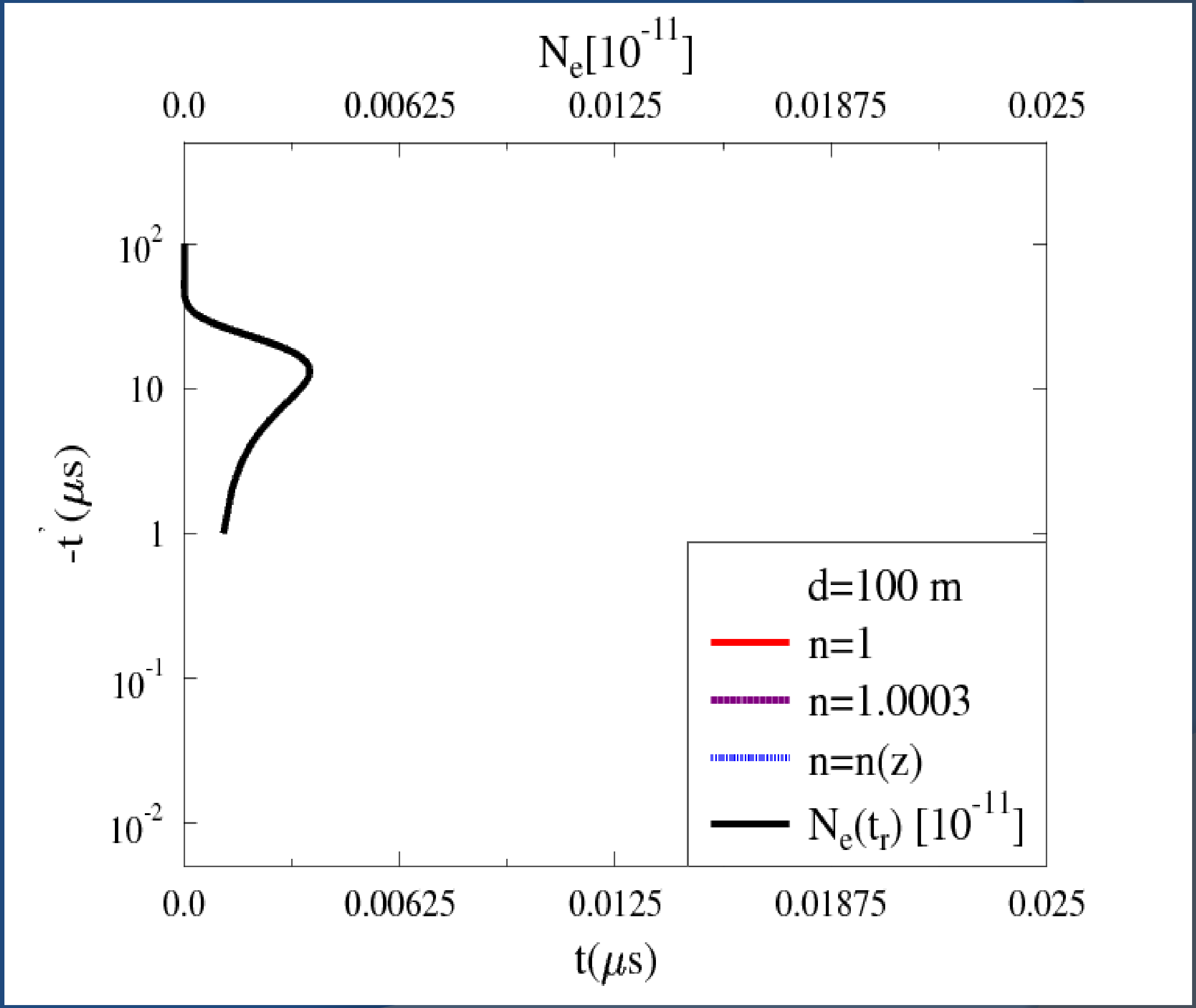
$$\theta_{CH} = \cos^{-1}\left(\frac{1}{n\beta}\right)$$

Retarded distance D(2)

$$\frac{1}{D} = \frac{1}{R}\frac{dt'}{dt}$$

t': emission time

t: observer time

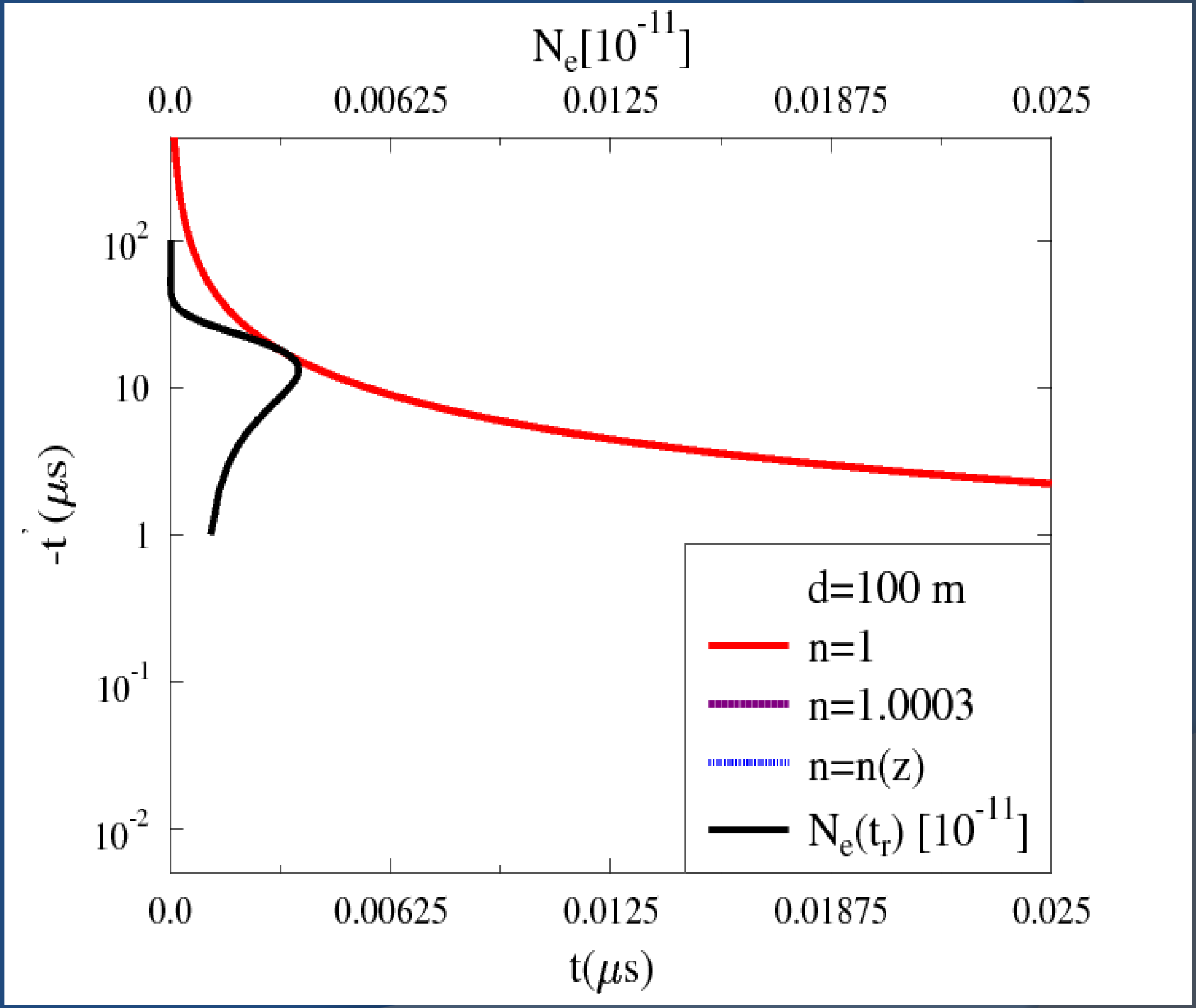


Retarded distance D(2)

$$\frac{1}{D} = \frac{1}{R}\frac{dt'}{dt}$$

t': emission time

t: observer time

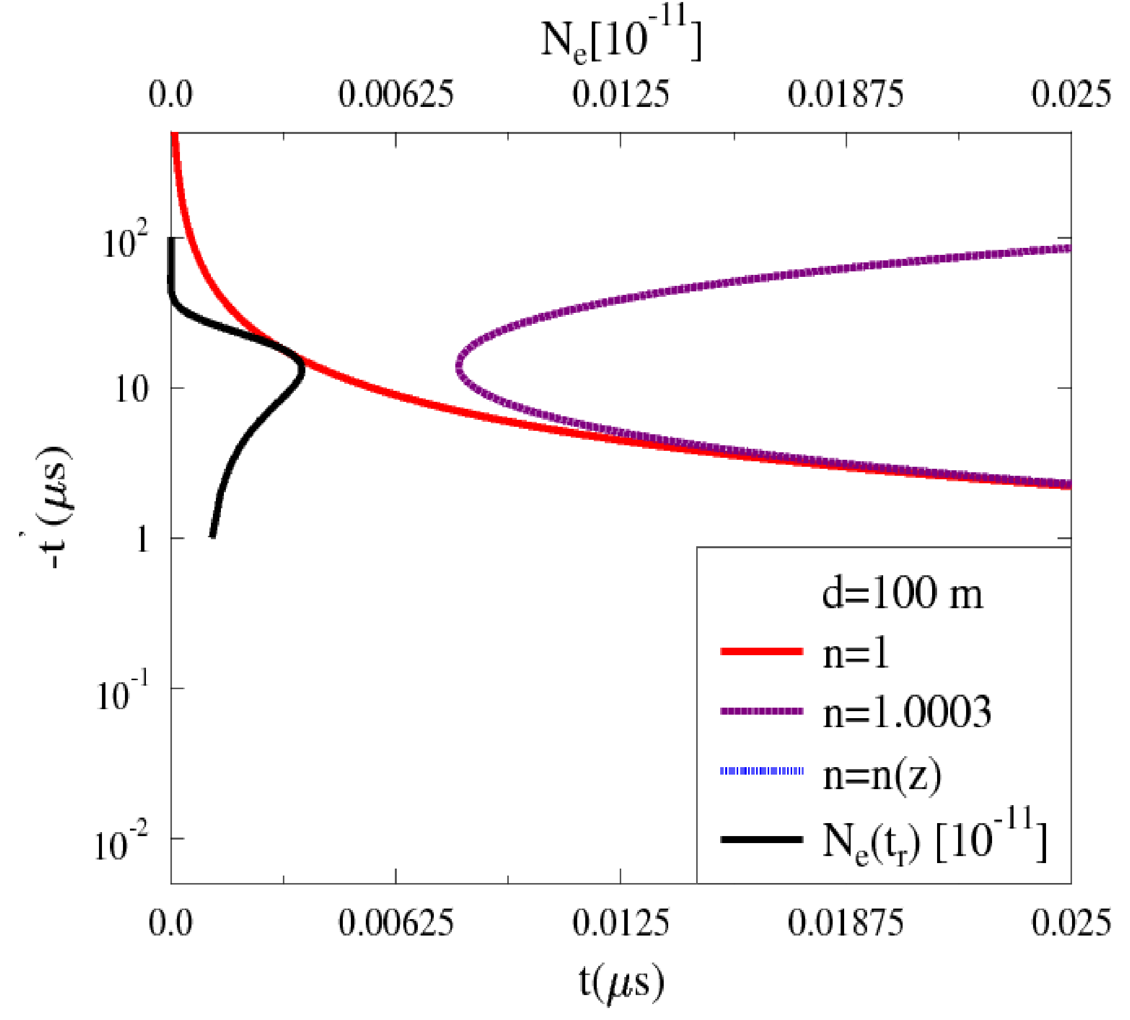


Retarded distance D(2)

$$\frac{1}{D} = \frac{1}{R}\frac{dt'}{dt}$$

t': emission time

t: observer time

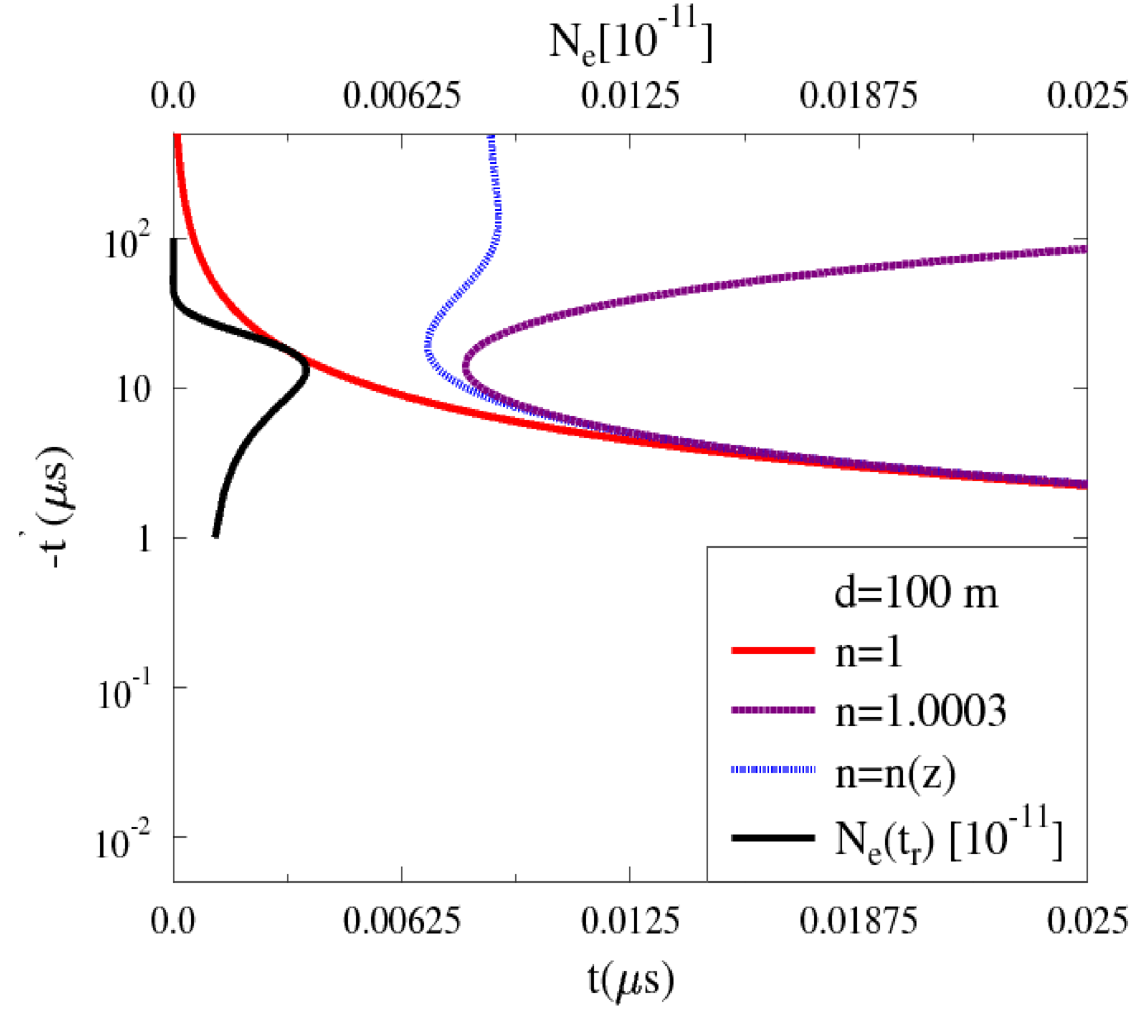


Retarded distance D(2)

$$\frac{1}{D} = \frac{1}{R}\frac{dt'}{dt}$$

t': emission time

t: observer time

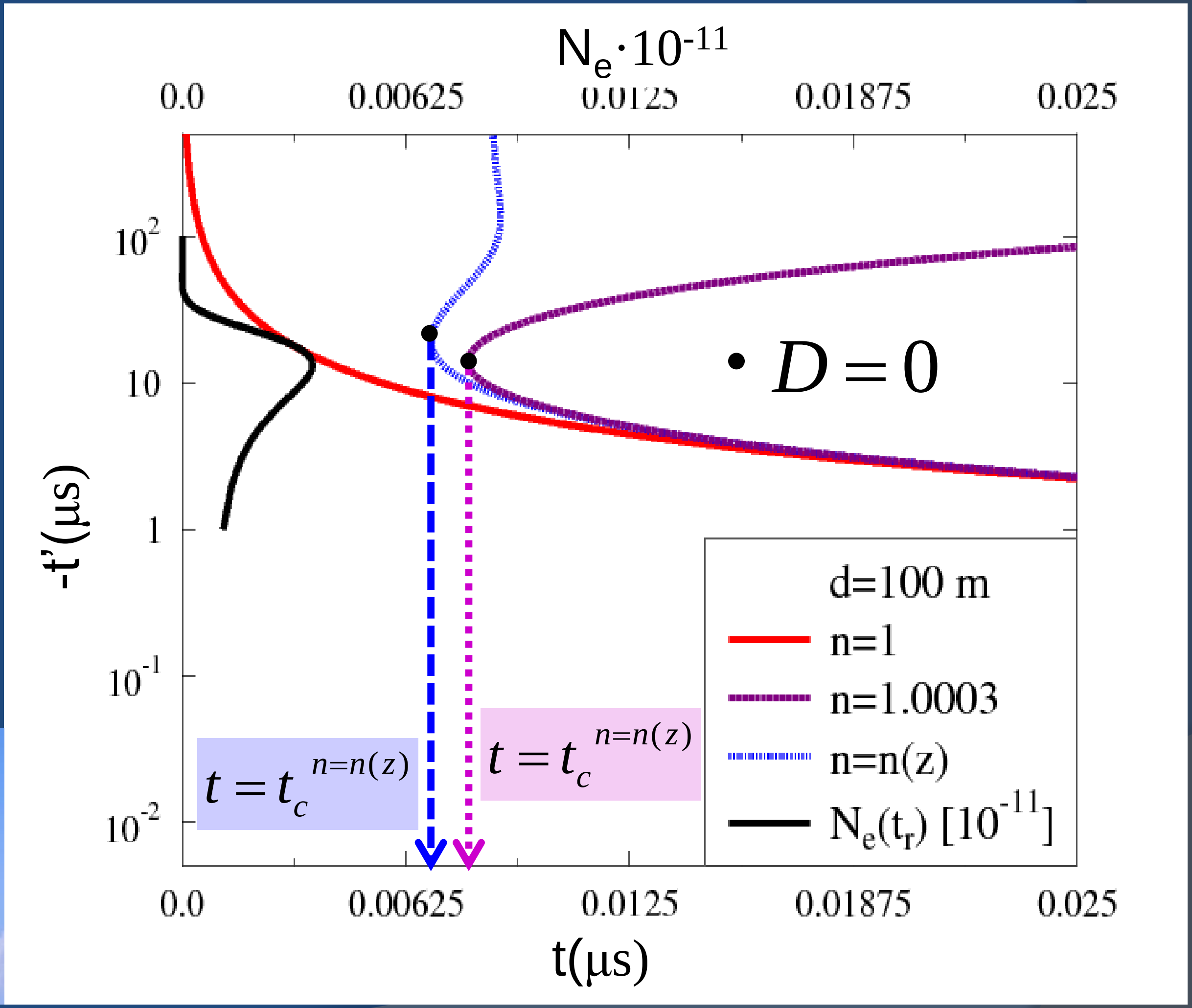


Retarded distance D(2)

$$\frac{1}{D}=\frac{1}{R}\frac{dt'}{dt}$$

t': emission time

t: observer time



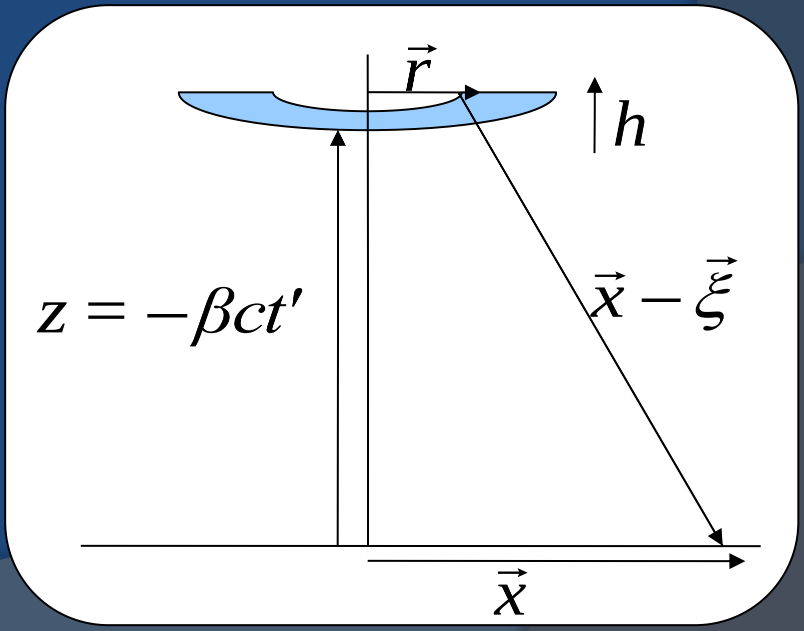
Resolve the divergences: Finite dimensions of the shower front

- Link emission time t' to observer time t:

$$t(t', \vec{x}, h, \vec{r})$$

- Integrate over the particle distributions to obtain the full vector potential at the observer time t:

$$A^{\mu}_{w}(t, \vec{x}) = \int d^2 r \int dh \; w(h, \vec{r}) A^{\mu}_{PL}(t, \vec{x} - \vec{\xi})$$

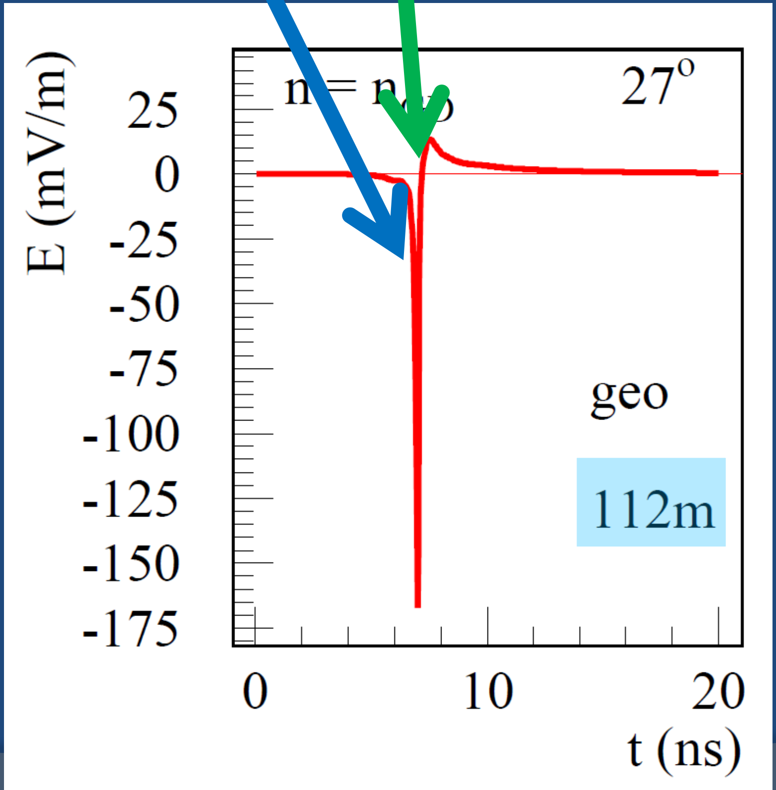


General pulse shape

Cherenkov distance:

Sharp edge of shower front

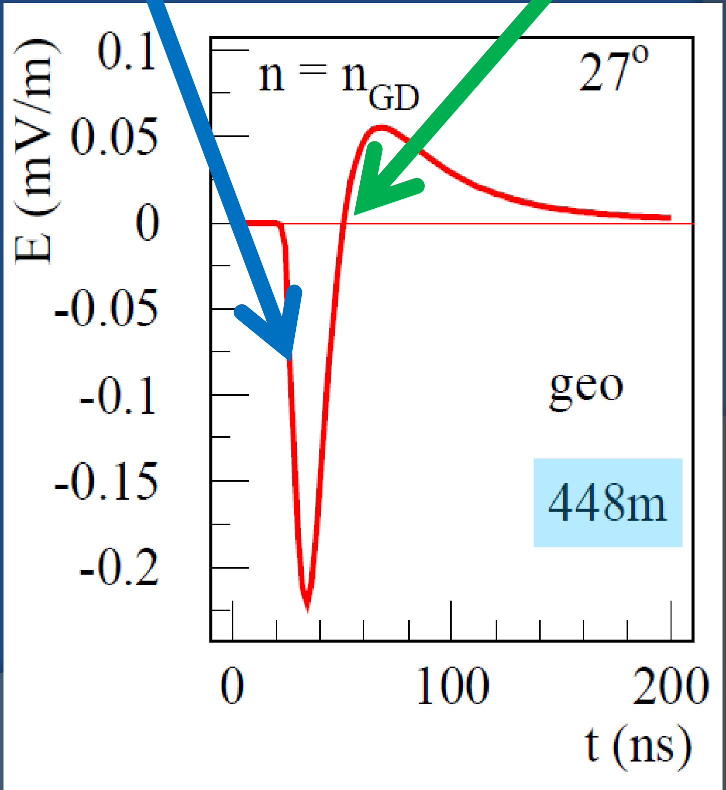
Particle max



Far from the Cherenkov distance:

Shower profile pre shower max

Shower max



EVA simulations

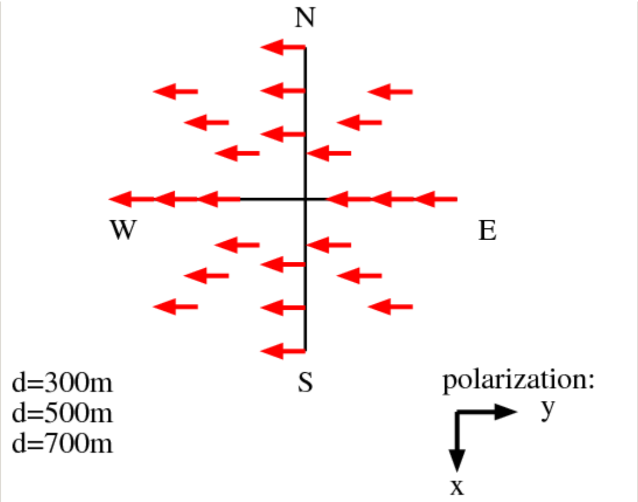
- Can we observe Cherenkov effects in radio emission from air showers?

- Can we observe and distinguish the different emission mechanisms:

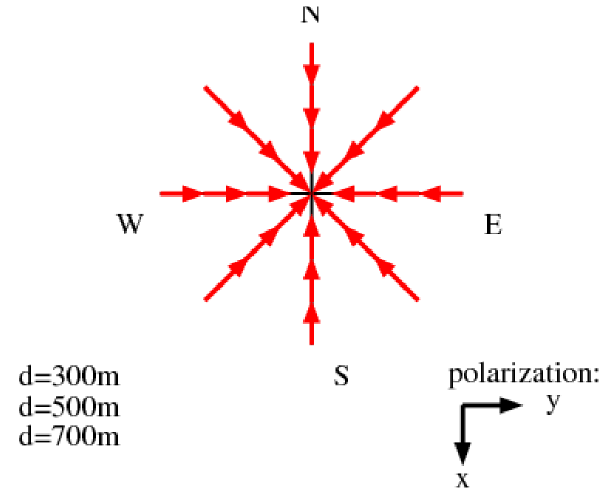
- ***Geomagnetic emission***
- ***Charge-excess emission***

Results: The emission mechanisms
The polarization of the radio emission

Leading: Geomagnetic



Sub Leading: Charge Excess



Geomagnetic:

$$\vec{A} \propto \vec{J}_{Lorentz} \qquad \vec{E} = \frac{d\vec{A}}{dt} \propto \vec{v} \times \vec{B}$$

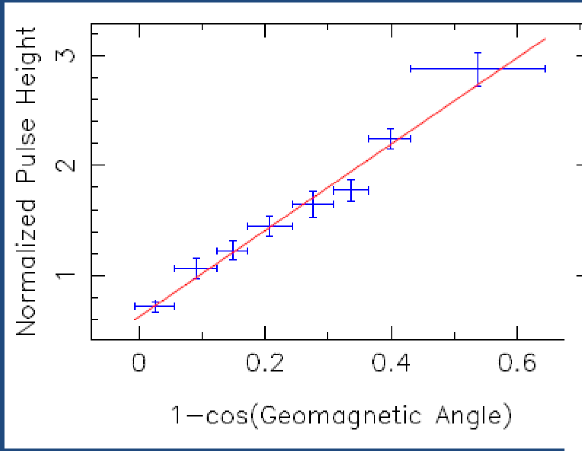
Charge excess (Askaryan):

$$A \propto J^0 \qquad \vec{E} = \frac{dA^0}{d\vec{x}} \propto \vec{x}$$

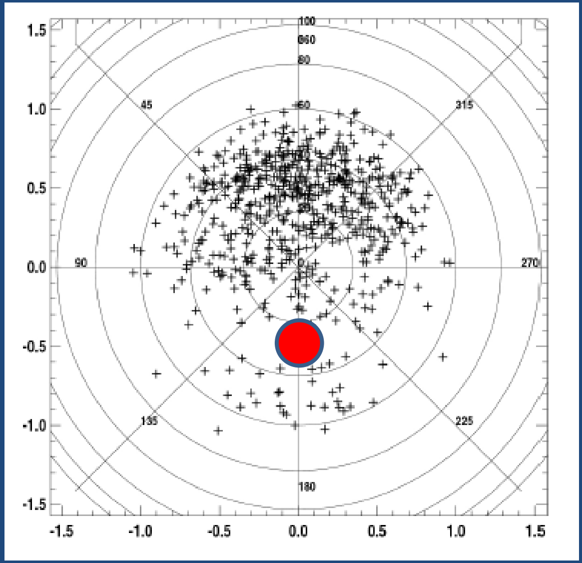
K.D. de Vries, O. Scholten, K. Werner: Proceedings of the 31th ICRC (2009), Lodz, Poland.

Results: The emission mechanisms
Geomagnetic emission

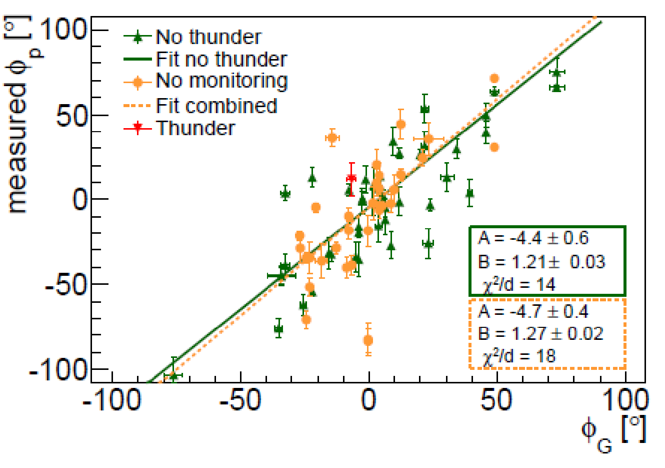
Well established!!



Tim Huege, **LOPES**, http://arxiv.org/pdf/1009.0345



B. Revenu **CODALEMA**, http://arxiv.org/abs/0906.2832



H. Schoorlemmer, **Pierre Auger Collaboration,** Nucl.Instrum.Meth. A662 (2012) S134-S137

Results: The emission mechanisms
Charge-excess emission

$$R = 2 \cdot \frac{x \cdot y}{\sqrt{x^2 + y^2}}$$

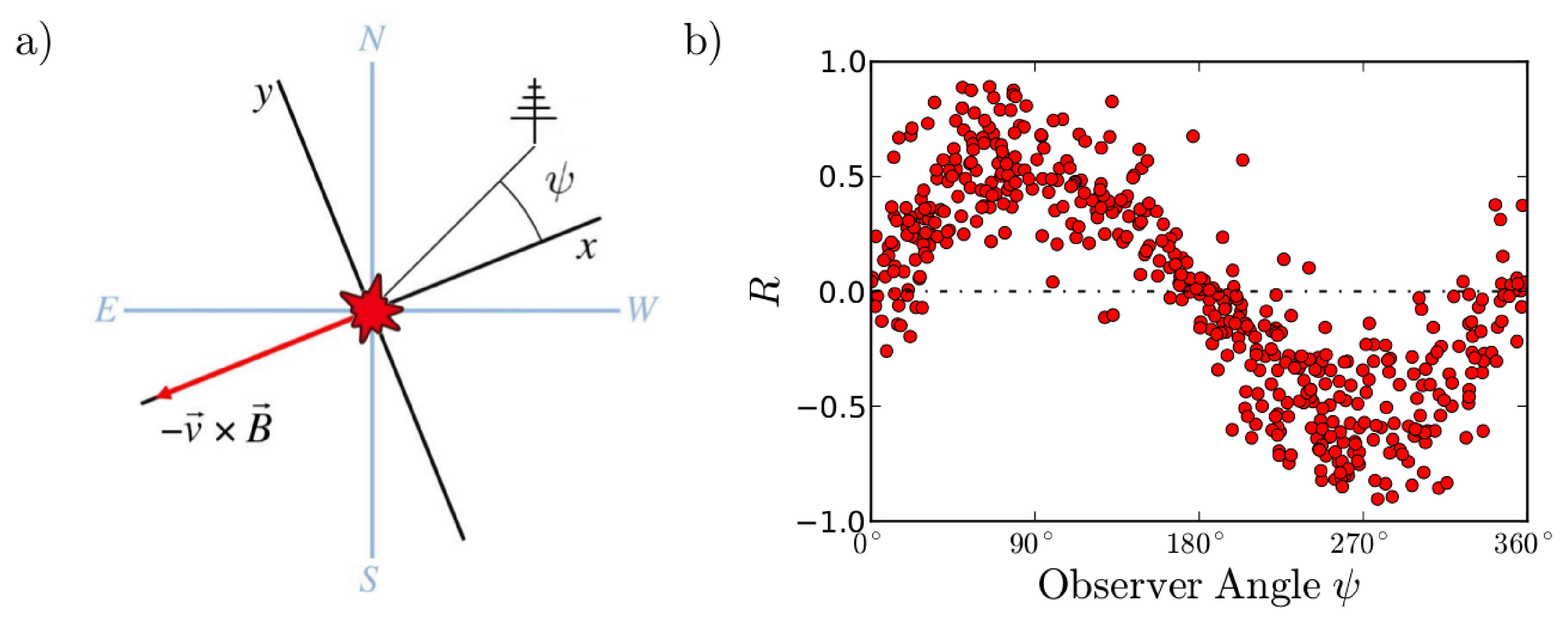
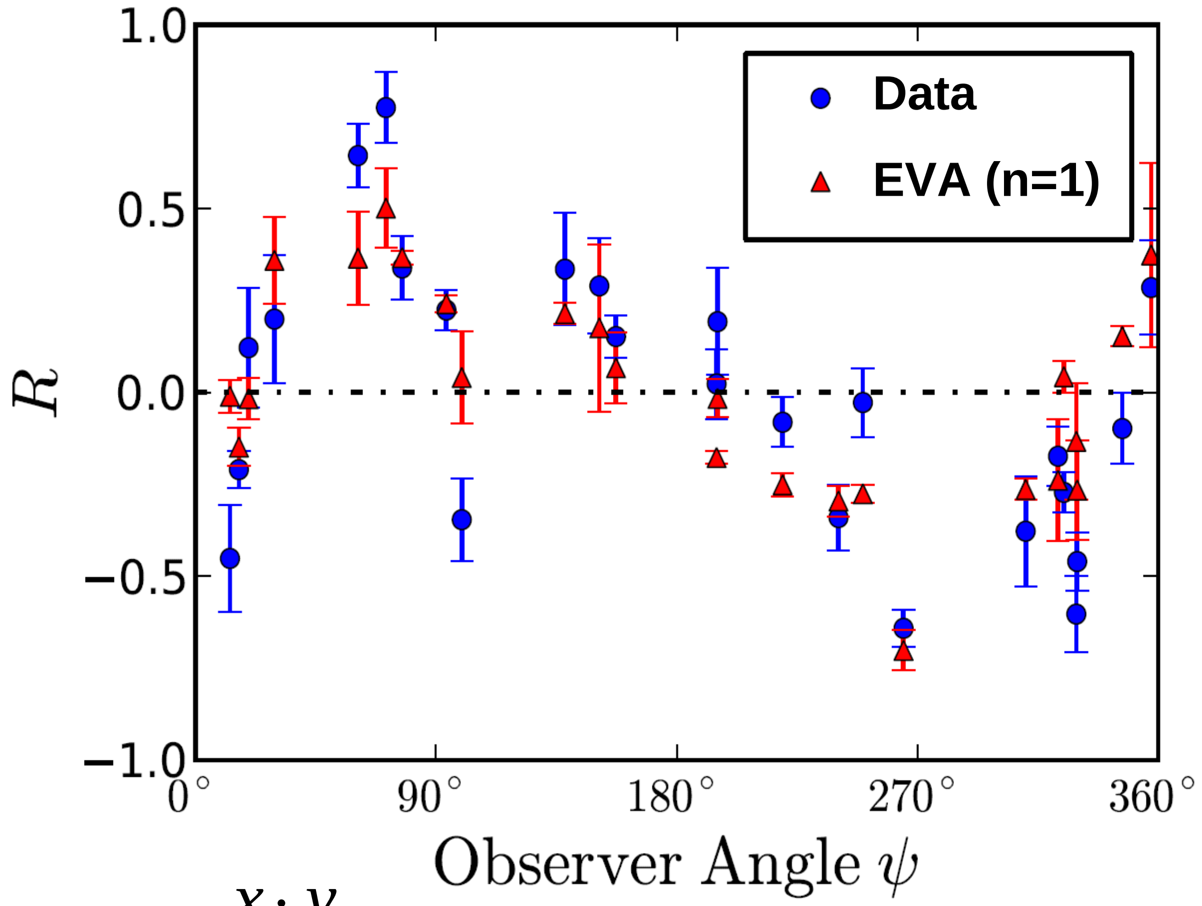
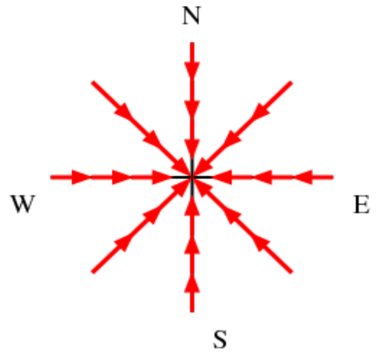
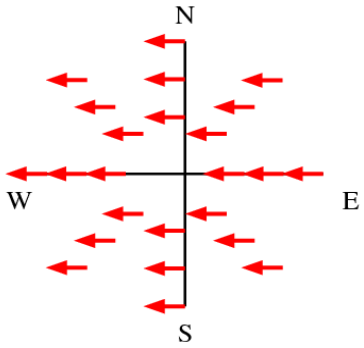


Figure from E.D. Fraenkel

Results
Charge-excess emission



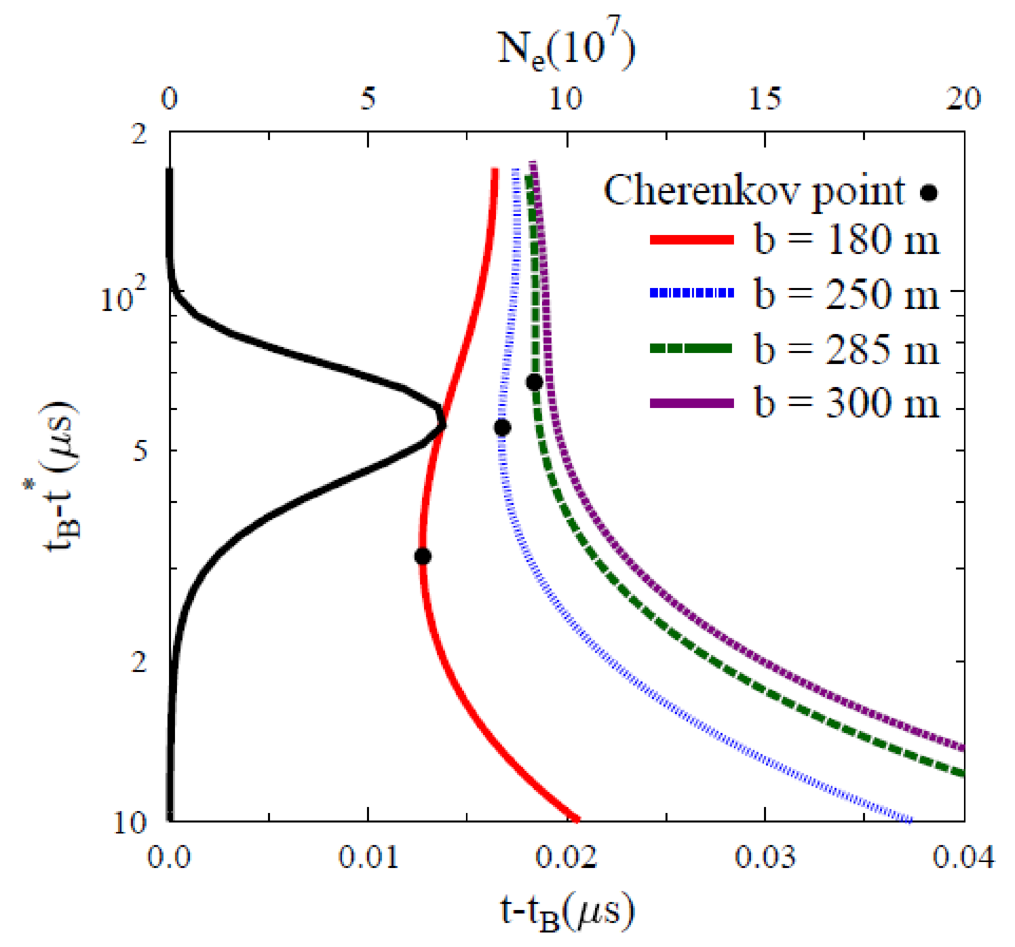


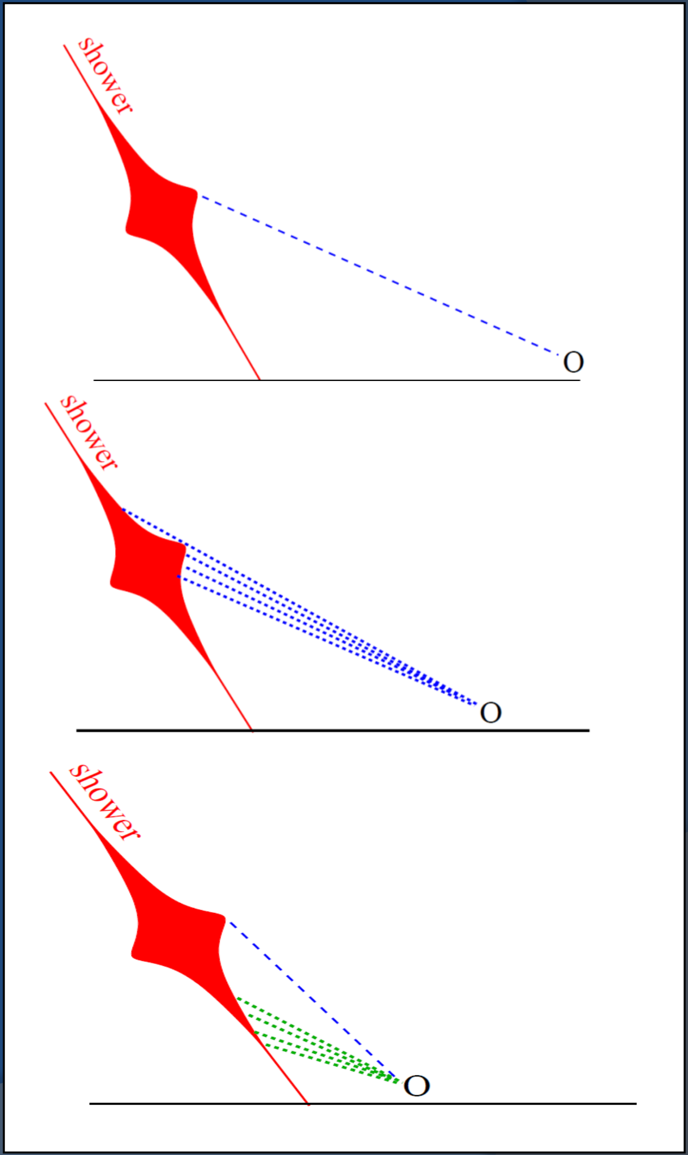


$$R = 2 \cdot \frac{x \cdot y}{x^2 + y^2}$$

E.D. Fraenkel. Data from MAXIMA Setup @ Pierre Auger.

Cherenkov effects: Probing the shower profile





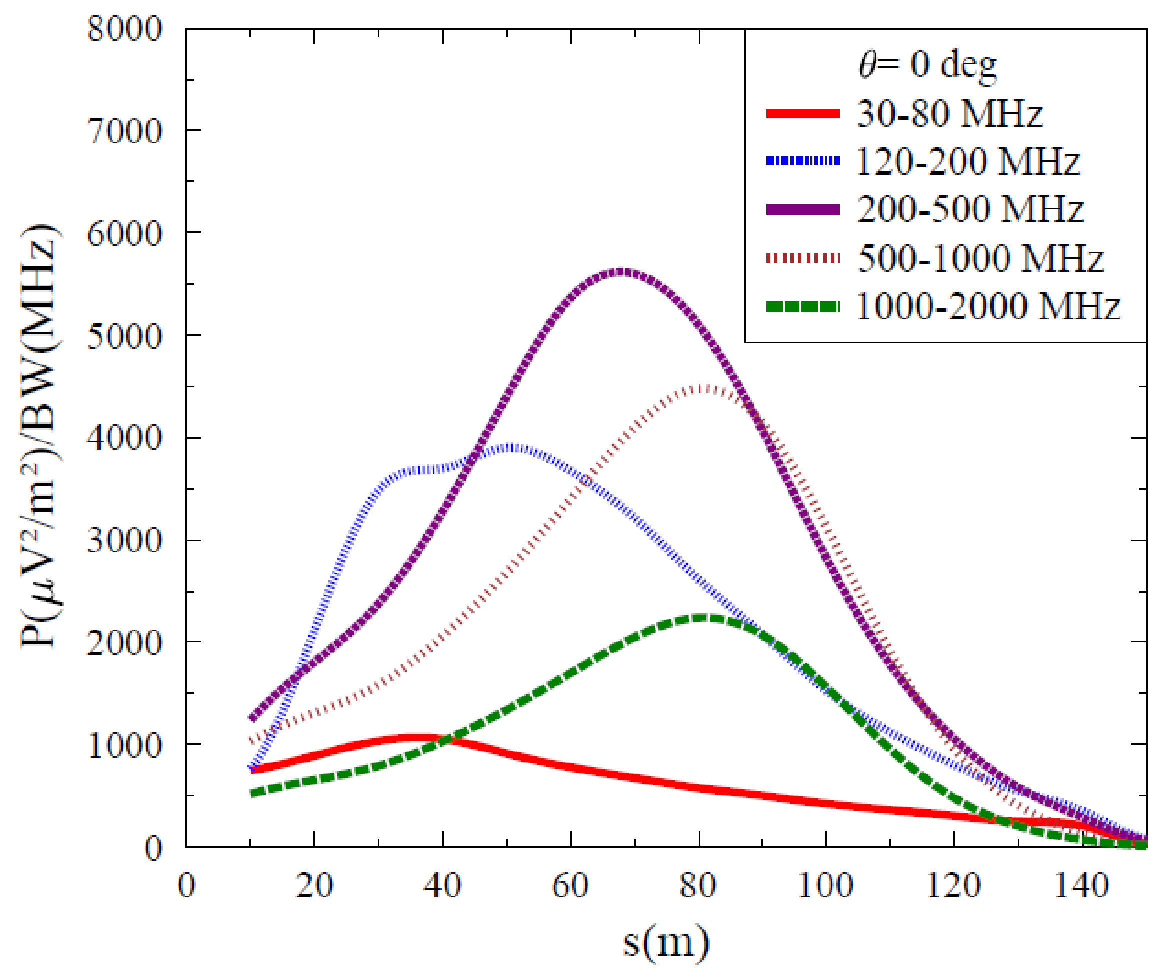
K.D. de Vries et al., PhysRevLett. 107, 061101 (2011) ; K. Werner et al., Astroparticle Physics 37 (2012) 5-16

Results: Cherenkov effects the LDF

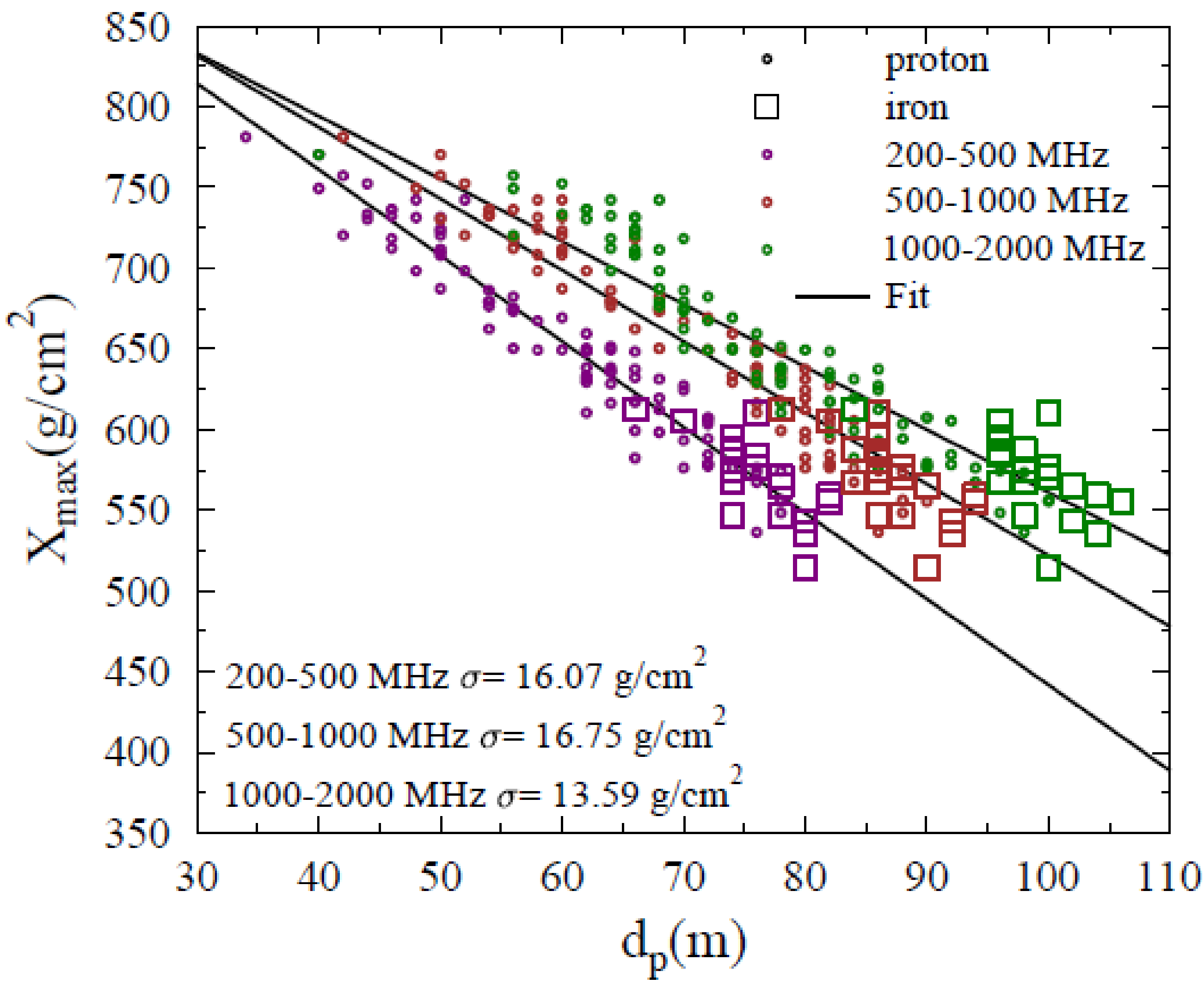
Chernkov ring clearly visible, becomes sharper at high frequencies!

Link position d_max to emission height by:

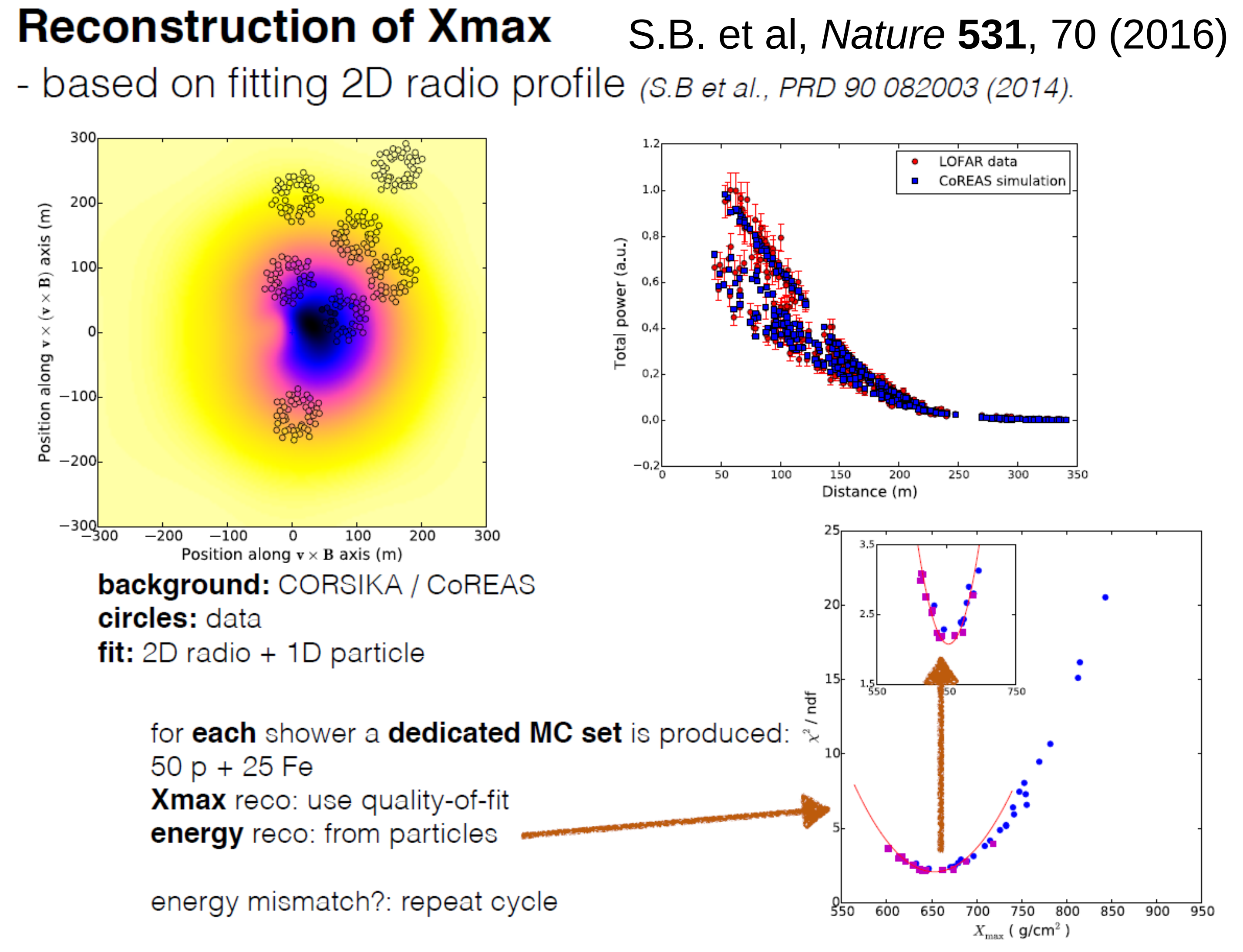
$$z_c = \frac{d_{\max}}{\sqrt{n^2 \beta^2 - 1}}$$



Results: Cherenkov effects determining X_max



Results
Cherenkov effects + Emission mechanisms
Slide from Stijn Buitink @ ARENA 2016



Reconstruction of Xmax

S.B. et al, *Nature* **531**, 70 (2016)

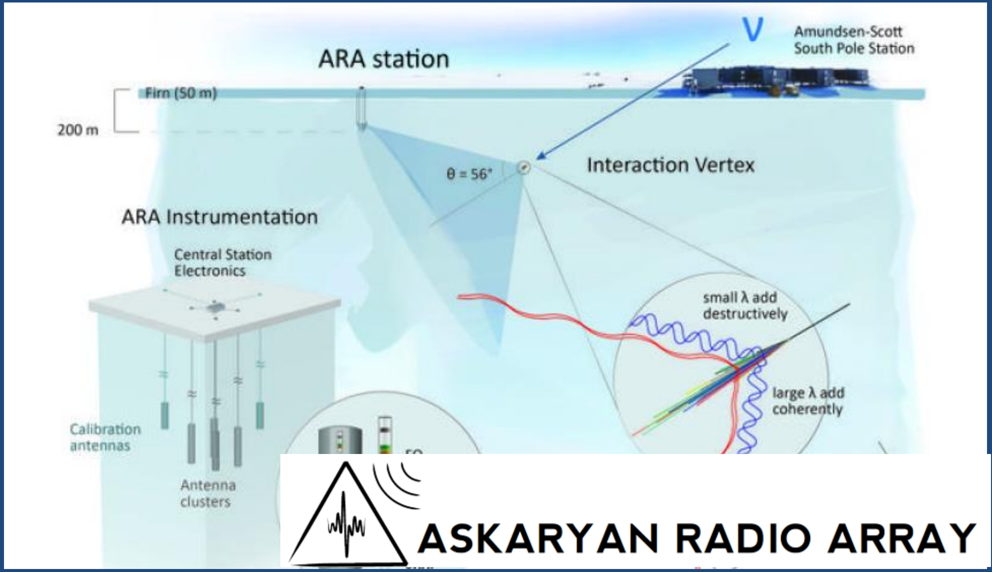
- based on fitting 2D radio profile *(S.B et al., PRD 90 082003 (2014).*

background: CORSIKA / CoREAS
circles: data
fit: 2D radio + 1D particle

for **each** shower a **dedicated MC set** is produced:
50 p + 25 Fe
Xmax reco: use quality-of-fit
energy reco: from particles

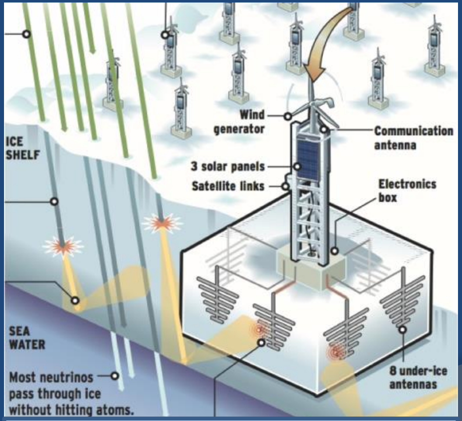
energy mismatch?: repeat cycle

From air to ice/rock
High-energy neutrino detection
(GZK neutrino flux)



GRAND

ANITA

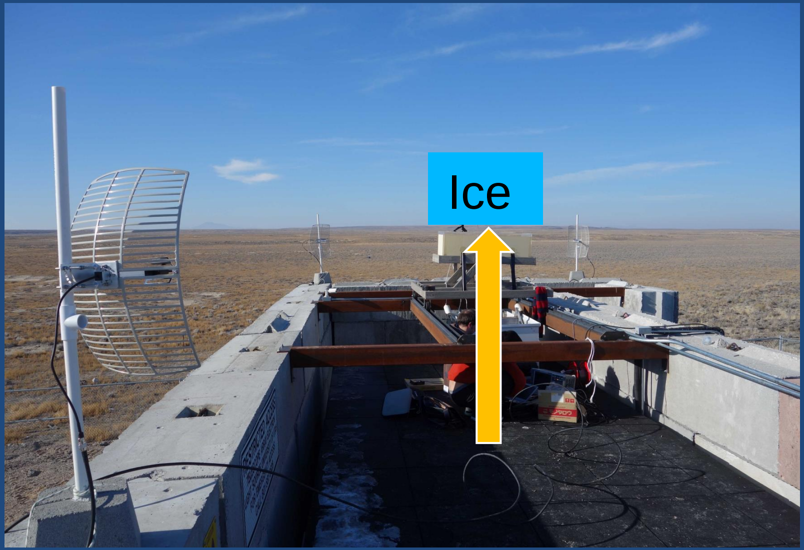


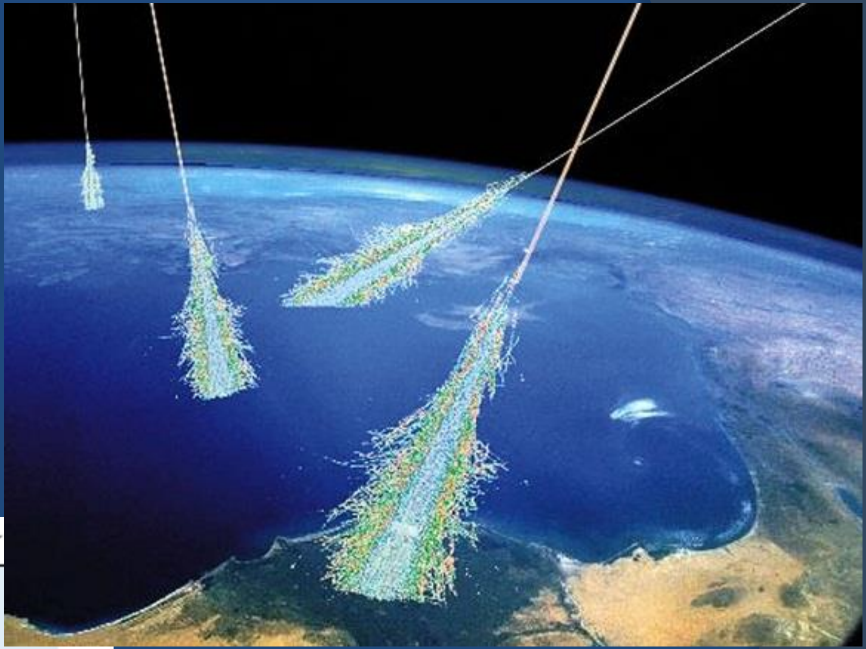
ARIANNA

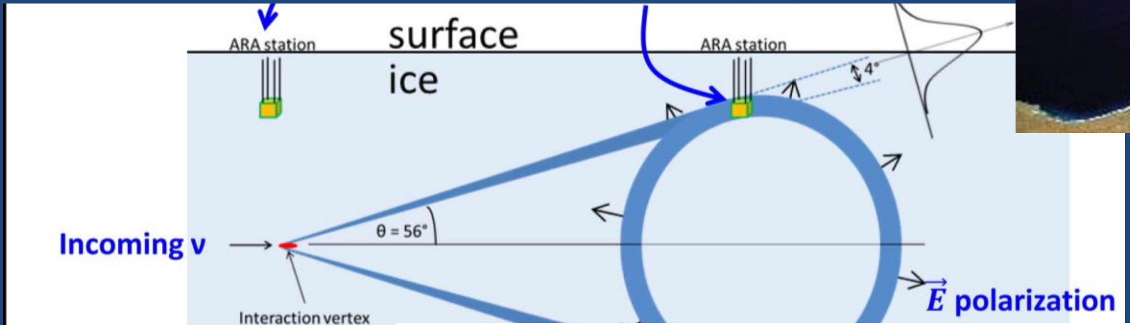
PIERRE AUGER OBSERVATORY

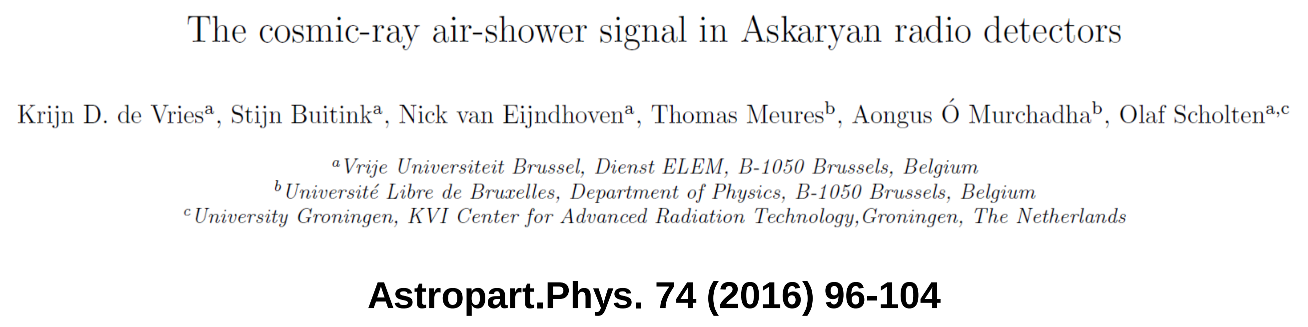
Pierre Auger

From air to ice:
Transition radiation and sudden appearance









The cosmic-ray air-shower signal in Askaryan radio detectors

Krijn D. de Vries[a], Stijn Buitink[a], Nick van Eijndhoven[a], Thomas Meures[b], Aongus Ó Murchadha[b], Olaf Scholten[a,c]

[a] *Vrije Universiteit Brussel, Dienst ELEM, B-1050 Brussels, Belgium*
[b] *Université Libre de Bruxelles, Department of Physics, B-1050 Brussels, Belgium*
[c] *University Groningen, KVI Center for Advanced Radiation Technology, Groningen, The Netherlands*

Astropart.Phys. 74 (2016) 96-104

The cosmic ray air shower signal in Askaryan radio detectors

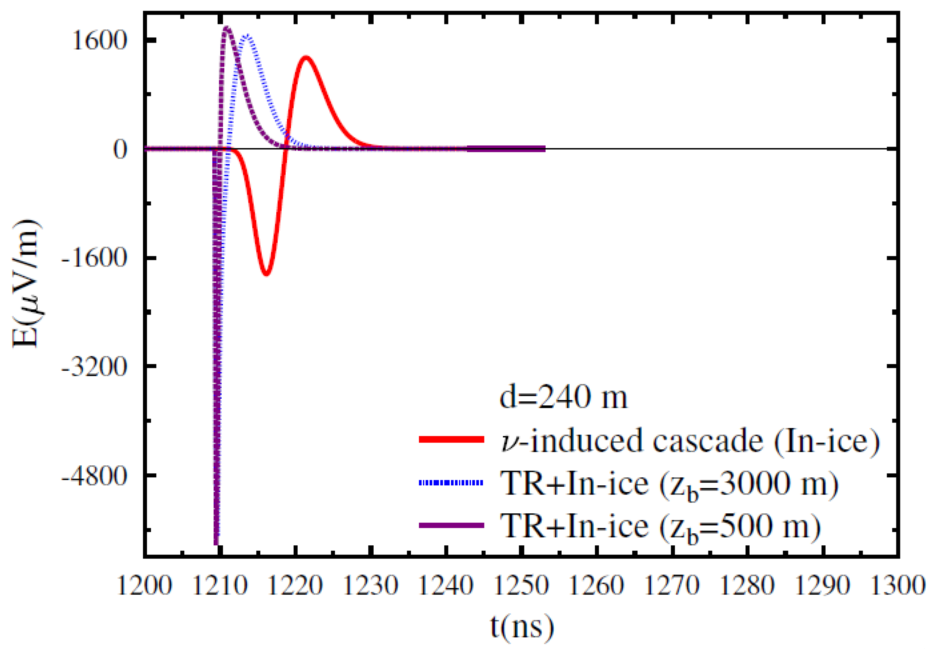
$$E^i_{tr}(t,\vec{x}) = \frac{\partial t_r}{\partial x^i}\frac{\partial}{\partial t_r}A^0$$

$$= \frac{e\delta(c(t_r - t_b))}{4\pi\epsilon_0 c}\lim_{\epsilon\to 0}\left(\frac{x^i}{|\mathcal{D}|^2_{t_r+\epsilon}} - \frac{x^i}{|\mathcal{D}|^2_{t_r-\epsilon}}\right)$$

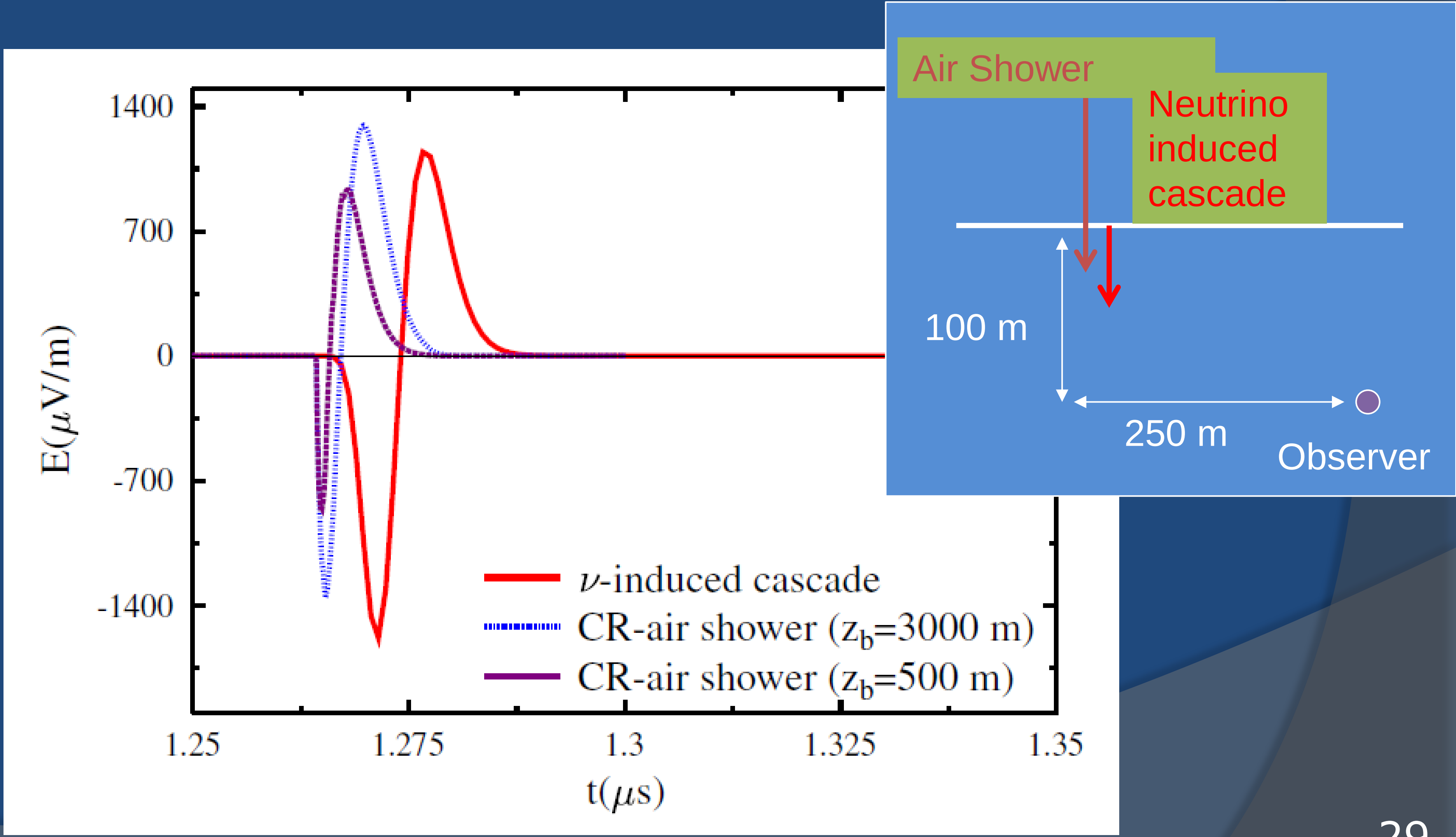
Sudden appearance signal very similar to transition radiation!!

Cosmic-ray air shower signal very similar to neutrino induced signal.

1) **Possible background for Askaryan radio detectors**
2) **In combination with surface detectors, the signal becomes a very interesting calibration signal.**
3) **Observed signal would show on-site feasibility of the detection method!!**

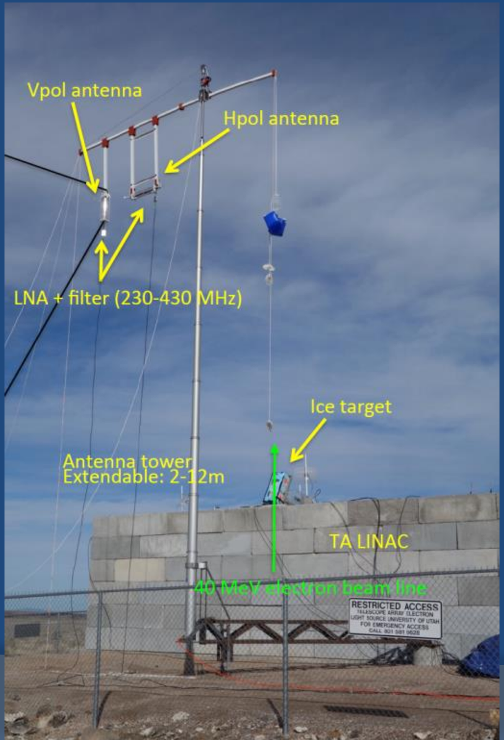


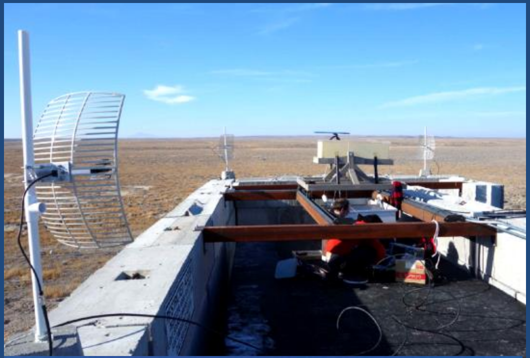
The air shower signal vs the neutrino induced cascade

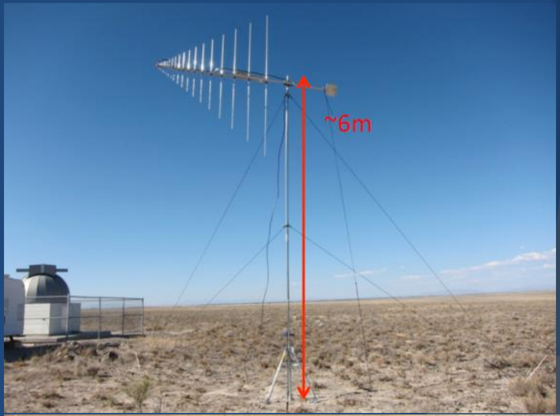


Beam “sudden appearance” signal in radio beam test experiments

Tokonatsu Yamamoto, Izumi S. Ohota (Konan U)
Krijn de Vries (Vrije Universiteit Brussel)
Kael Hanson, Thomas Meures (UW-Madison), Aongus O' Murchadha (ULB)
Daisuke Ikeda, Masaki Fukushima, Hiroyuki Sagawa, (ICRR)
Romain Gaior, Keiichi Mase, Shigeru Yoshida, Aya Ishihara, Matthew Relich, Takao Kuwabara, Shunsuke Ueyama (U of Chiba)
Gordon Thomson, John N. Matthews (U of Utah)
Shouich Ogio (OCU), **Shin Bakkyun** (Hanyang U), **Tatsunobu Shibata** (KEK)

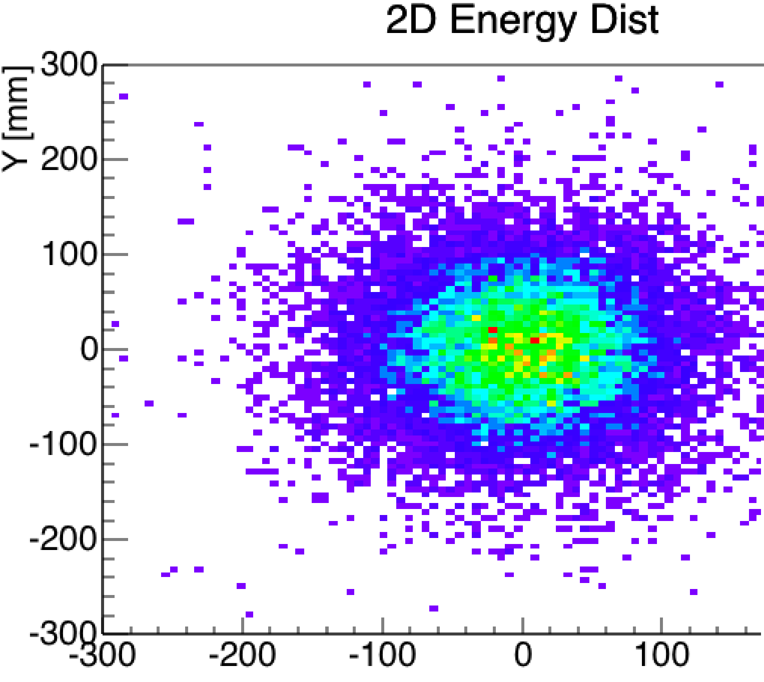




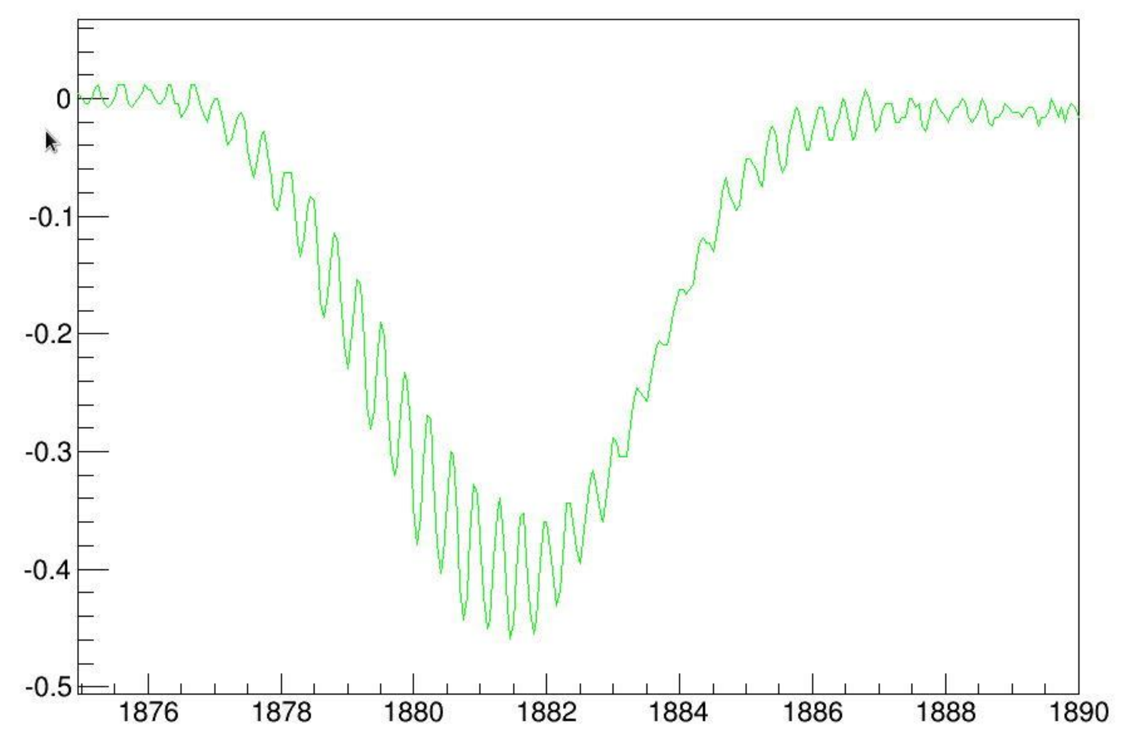


Experimental setup

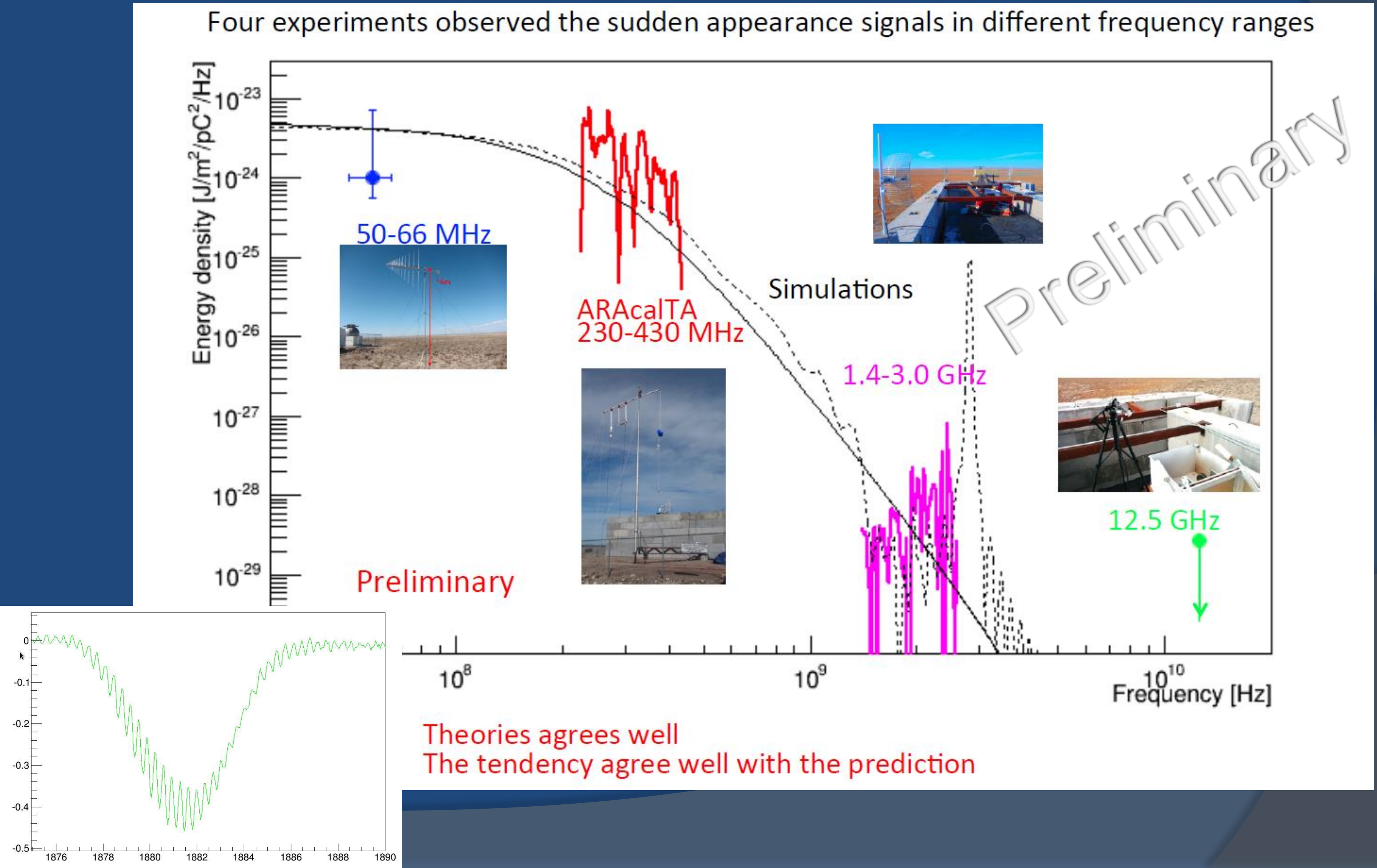
Beam characteristics



- ~10^9 (40 MeV) electrons
- ~ 40 PeV



Sudden appearance energy density spectrum



Four experiments observed the sudden appearance signals in different frequency ranges

Theories agrees well
The tendency agree well with the prediction

The Cosmic-Ray air shower signal in Askaryan radio detectors

- The in-ice emission is due to the same mechanism (Askaryan emission) as for a neutrino induced cascade. The expected signal is similar for CR and neutrino induced cascades.

- In combination with surface detector the detected signal might provide an excellent (cross-) calibration.

- Emission mechanisms under investigation with experimental results. Preliminary results show good understanding.

Conclusions

- Radio emission mechanisms very well understood!
- Geomagnetic emission
- Charge excess (Askaryan) emission

- Geometry effects well understood!!
- Cherenkov effects (crucial in air!!)
- Transition radiation / sudden appearance radiation

- Detailed air shower physics possible:
- Xmax determination -> Chemical composition
- Thunderstorm detection (not treated)

The hunt for GZK neutrinos has started!!!

Questions?

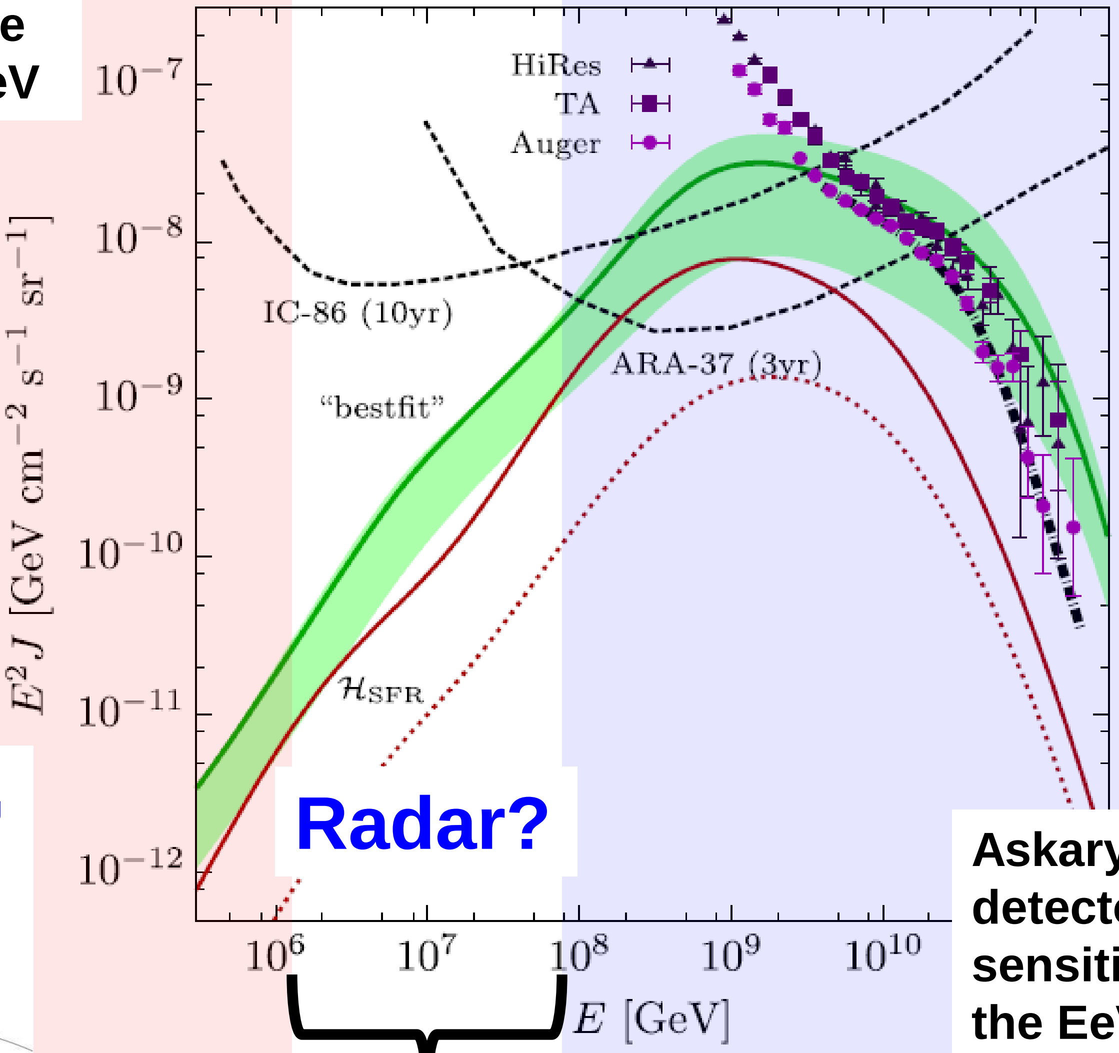
iihe
BRUXELLES BRUSSEL

Vrije
Universiteit
Brussel

fwo

Radar detection

IceCube sensitive below several PeV

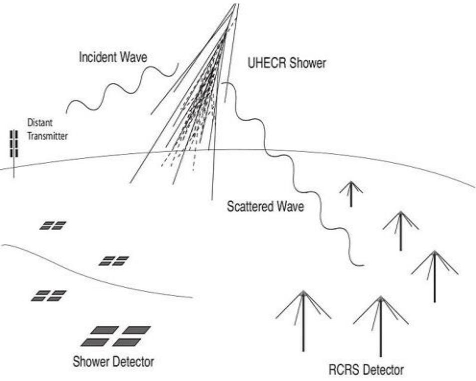


Radar?

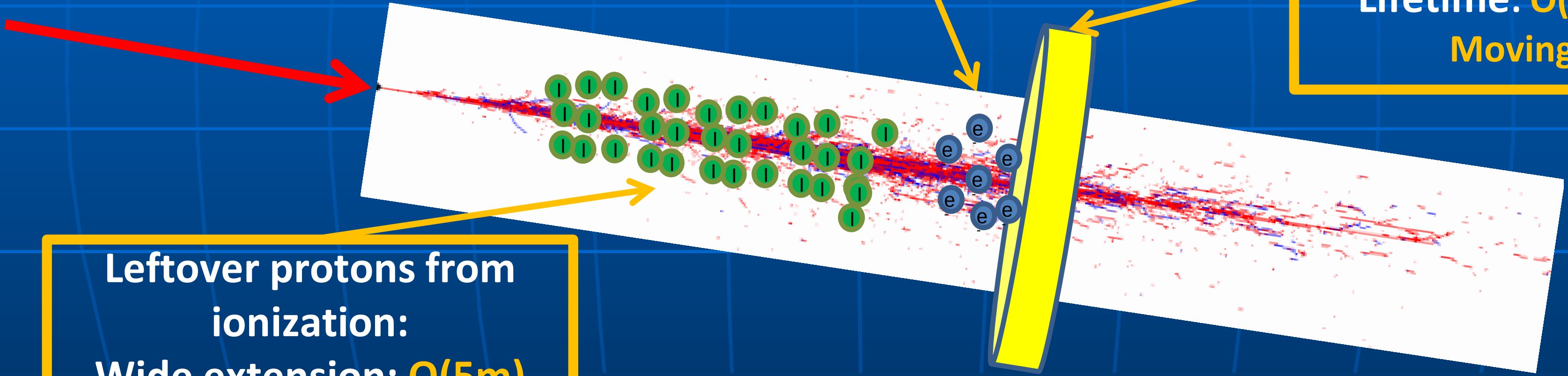
Askaryan Radio detectors become sensitive close to the EeV region

Sensitivity Gap in PeV – EeV region

M. Abou Bakr Othman et al, Proceedings 32nd ICRC, Beijing 2011



Radar scattering of a neutrino induced plasma

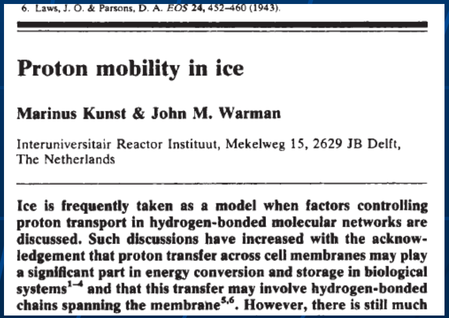


Leftover electrons from ionization:
Extension: O(30 cm)
Lifetime: O(1-20 ns)

Shower front electrons:
Extension: R_L = O(10 cm)
Lifetime: O(100ns)
Moving!

Leftover protons from ionization:
Wide extension: O(5m)
Lifetime: O(10-1000 ns)

Ionization numbers come from Physical Chemistry research!



6. Laws, J. O. & Parsons, D. A. *EOS* **24**, 452–460 (1943).

Proton mobility in ice

Marinus Kunst & John M. Warman

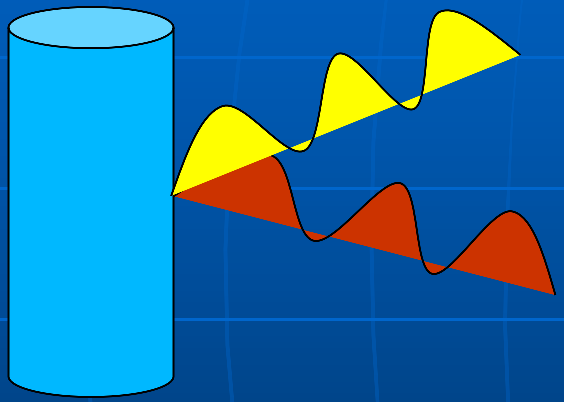
Interuniversitair Reactor Instituut, Mekelweg 15, 2629 JB Delft,
The Netherlands

Ice is frequently taken as a model when factors controlling proton transport in hydrogen-bonded molecular networks are discussed. Such discussions have increased with the acknowledgement that proton transfer across cell membranes may play a significant part in energy conversion and storage in biological systems[1–4] and that this transfer may involve hydrogen-bonded chains spanning the membrane[5,6]. However, there is still much

Figure from arXiv:1210.5140v2

RADAR scattering

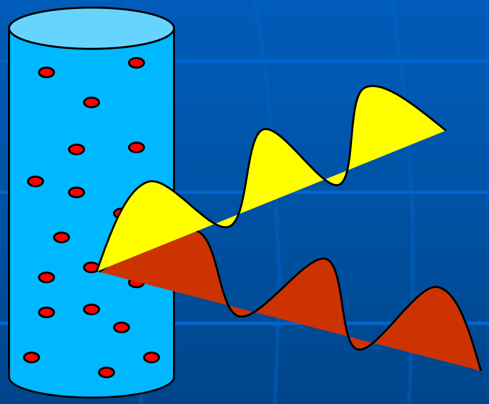
- Over-dense scattering:



Radar frequency < Plasma Frequency

Reflection from the surface of the plasma tube

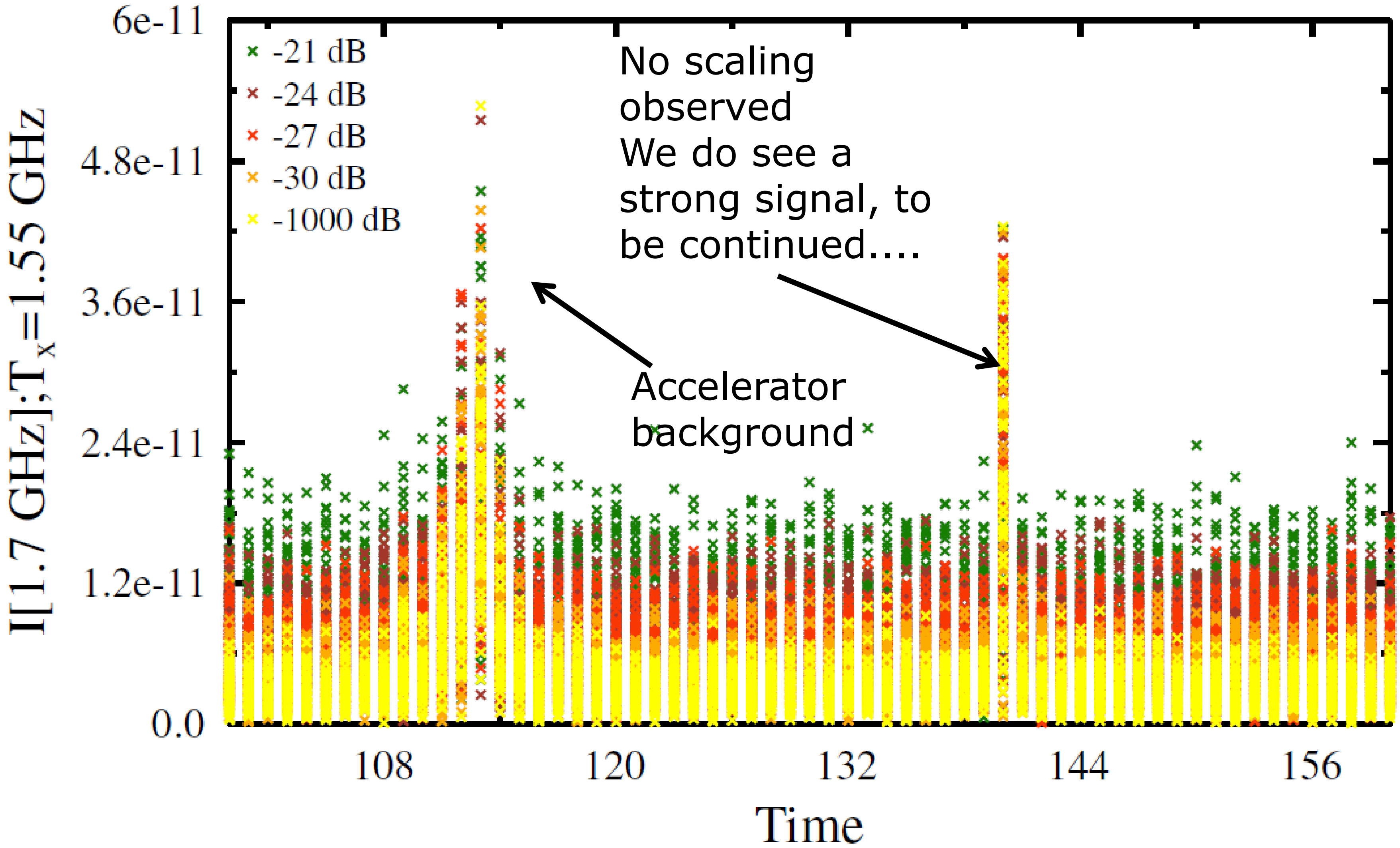
- Under-dense scattering:



Radar frequency > Plasma Frequency

Scattering off of the individual charges in the plasma

Radar scattering
Air

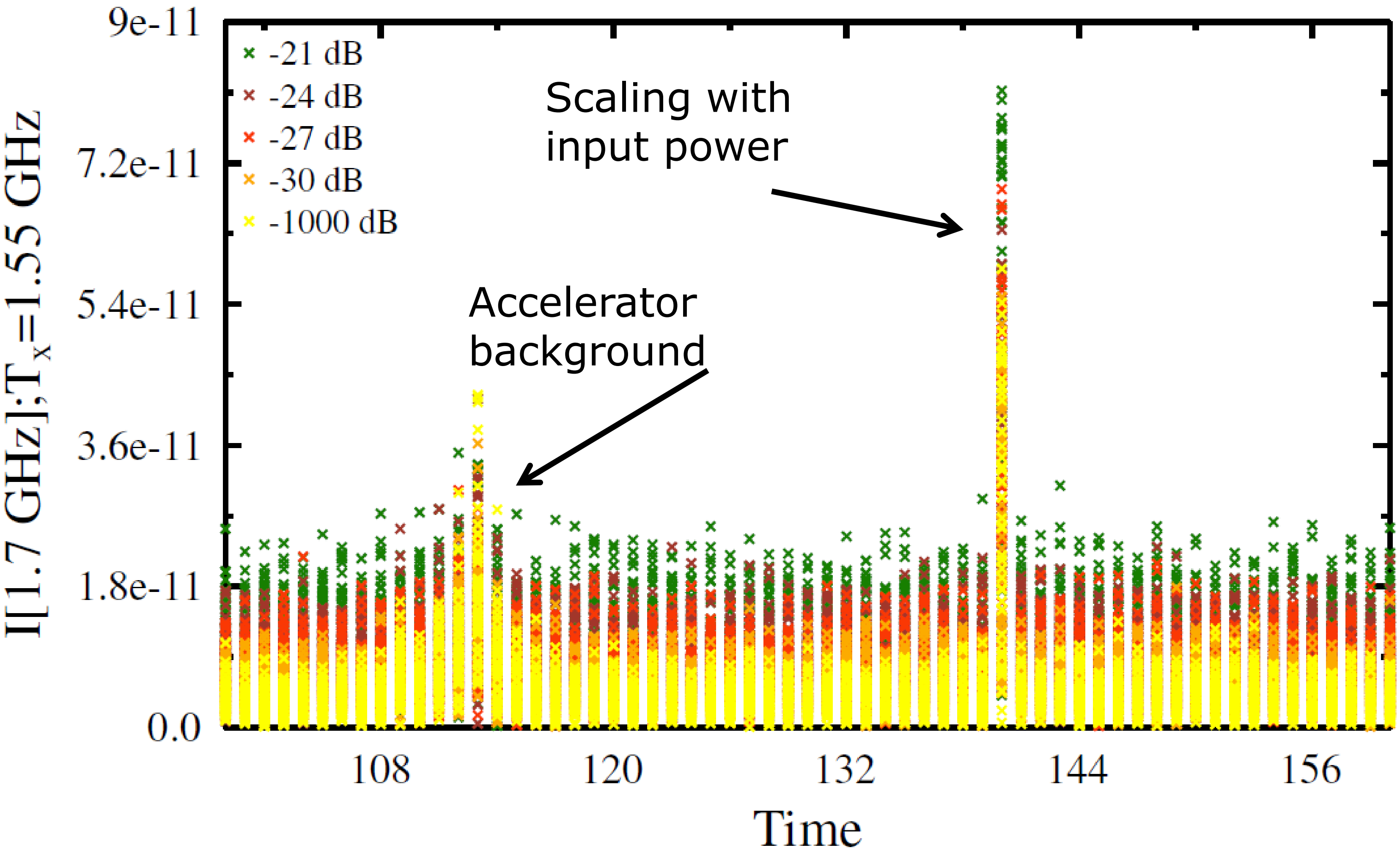


No scaling observed

We do see a strong signal, to be continued....

Accelerator background

Radar scattering Ice



Scaling with input power

Accelerator background

Conclusions

- Modeling the RADAR scattering of high-energy neutrino induced cascades gives an energy threshold of several PeV.

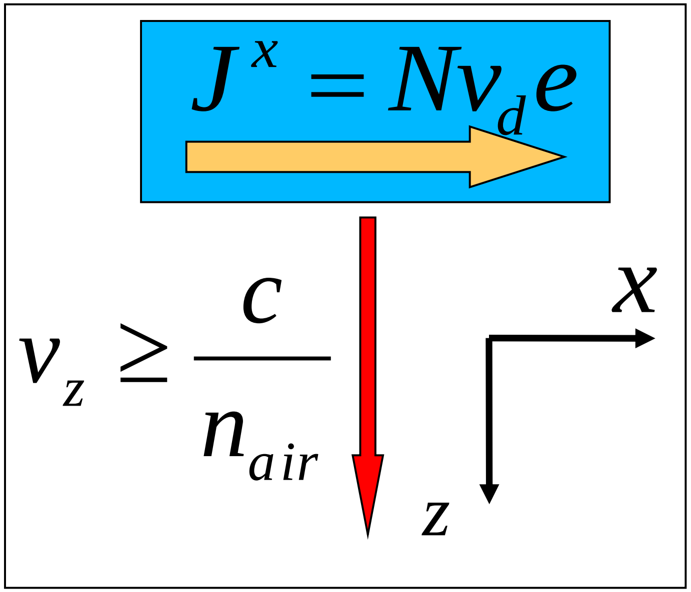
- We performed a measurement to determine the feasibility of this method.

- Obtained data hints toward a scattered signal, analysis is ongoing.

Electric field: Geomagnetic radiation

$$A^x(\vec{x},t) = -\frac{\mu_0 c}{4\pi}\int d^2\vec{r}\int dh\,\frac{1}{|D|}\,w(\vec{r},h)\,J^x{}_{PL}(t')$$

Make a partial integration such that the derivatives acting on 1/|D| act on the particle distributions.



$$J^x = N v_d e$$

$$v_z \geq \frac{c}{n_{air}}$$

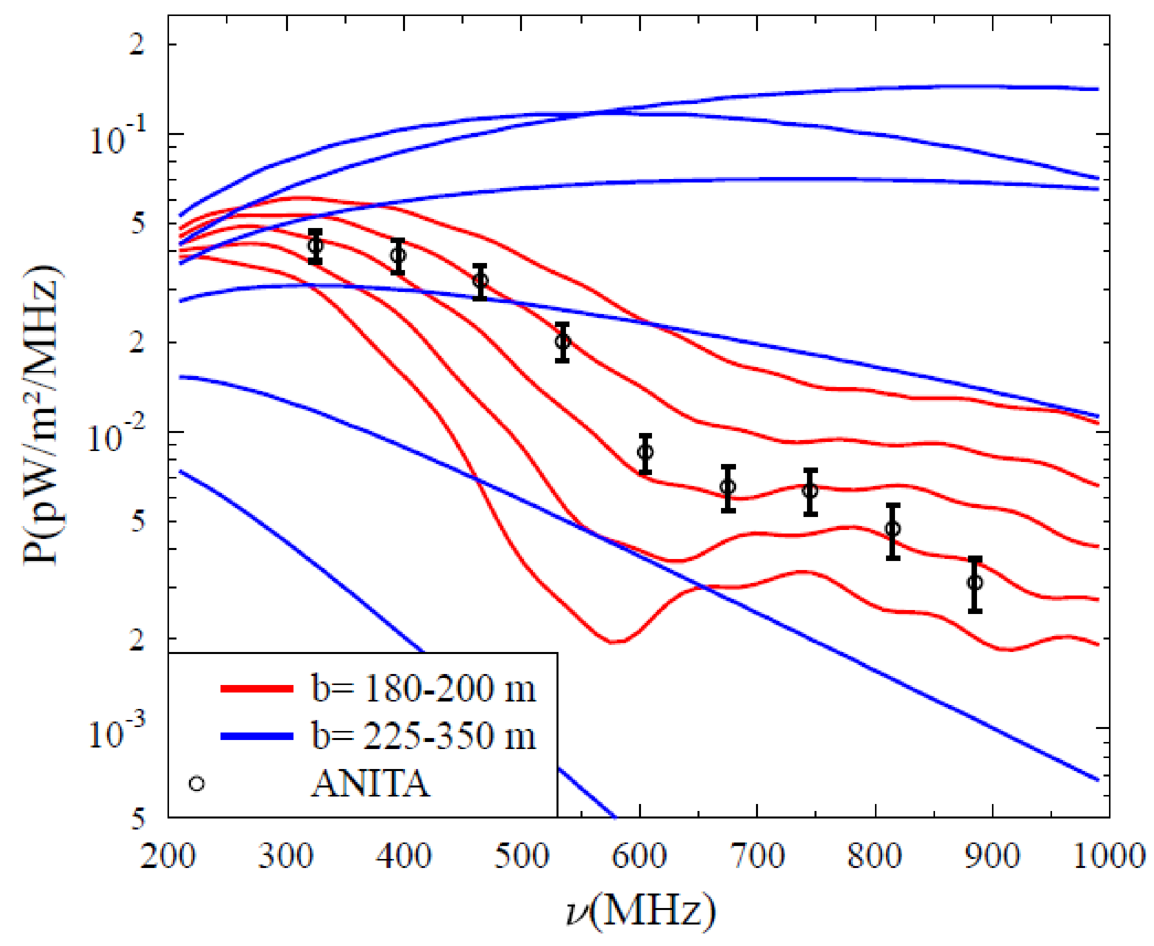
$$E^x(\vec{x},t) = -\frac{dA^x}{dt}$$

$$= -\frac{\mu_0 c}{4\pi}\int d^2\vec{r}\int dh\,\frac{1}{|D|}\left(\frac{dw(\vec{r},h)}{dh}\,J^x{}_{PL}(t') + w(\vec{r},h)\,\frac{dJ^x{}_{PL}(t')}{dt'}\right)$$

Results: Cherenkov effects

EVA Simulation for 60 degrees shower at the Auger site.

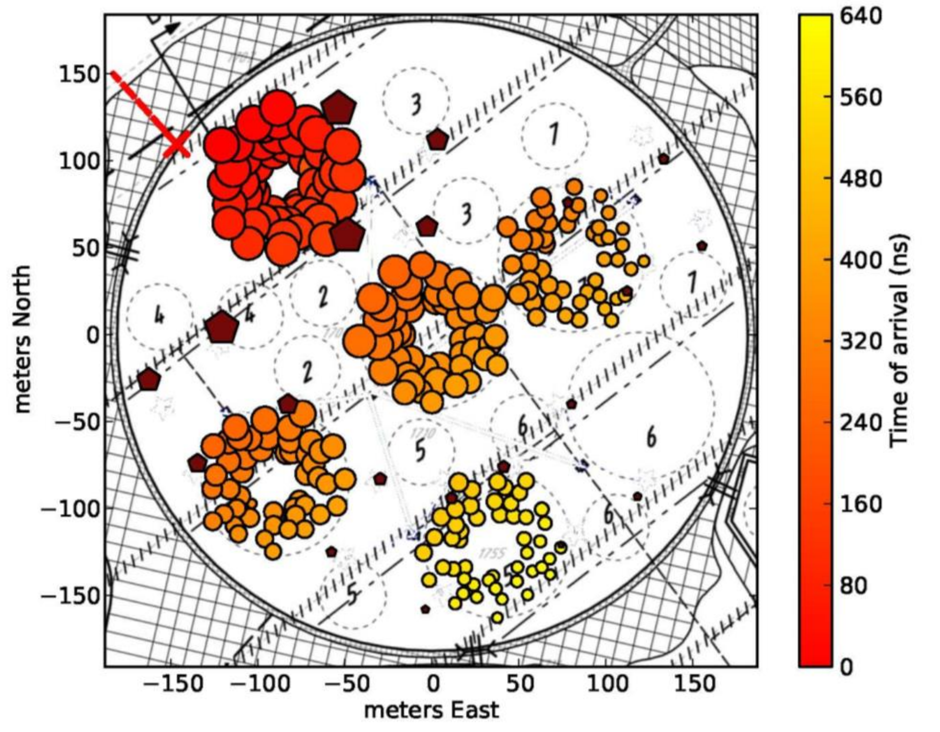
Geometry of **ANITA** event not known, so not 1 to 1 comparable!

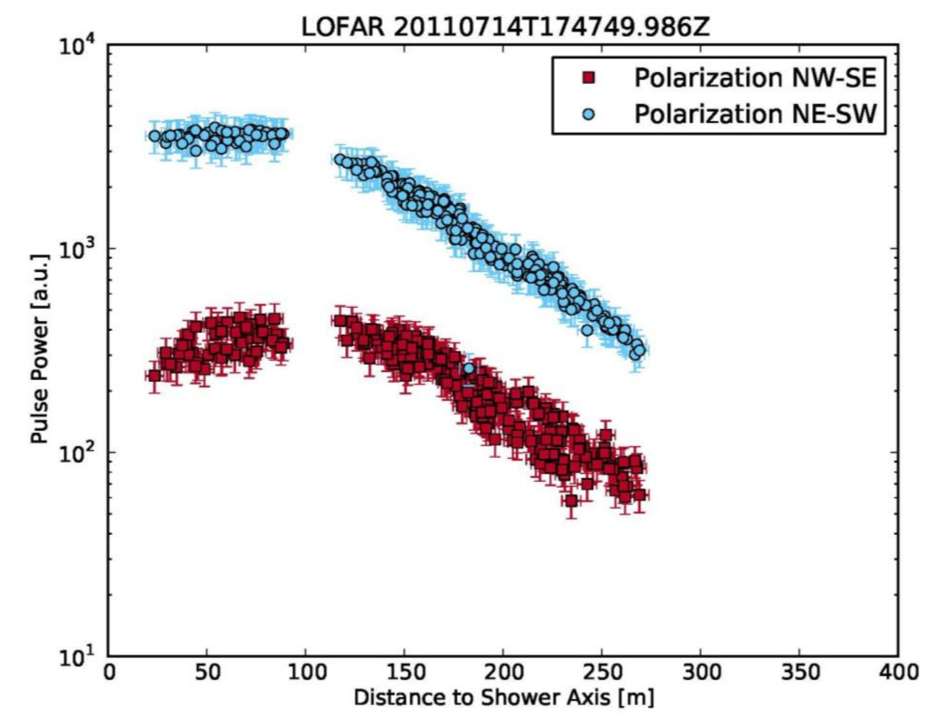


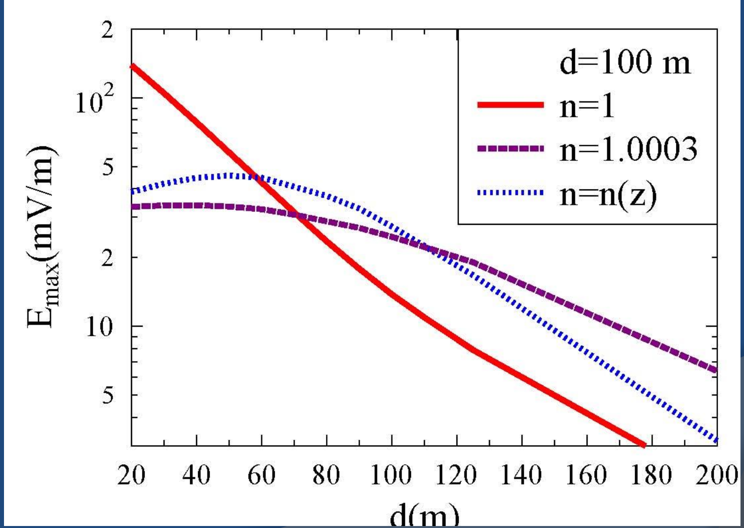
LOFAR

6 x 48 antennas 40-70 MHz

A. Corstanje et al, arXiv:1109.5805v1
[astro-ph.HE] (ICRC)

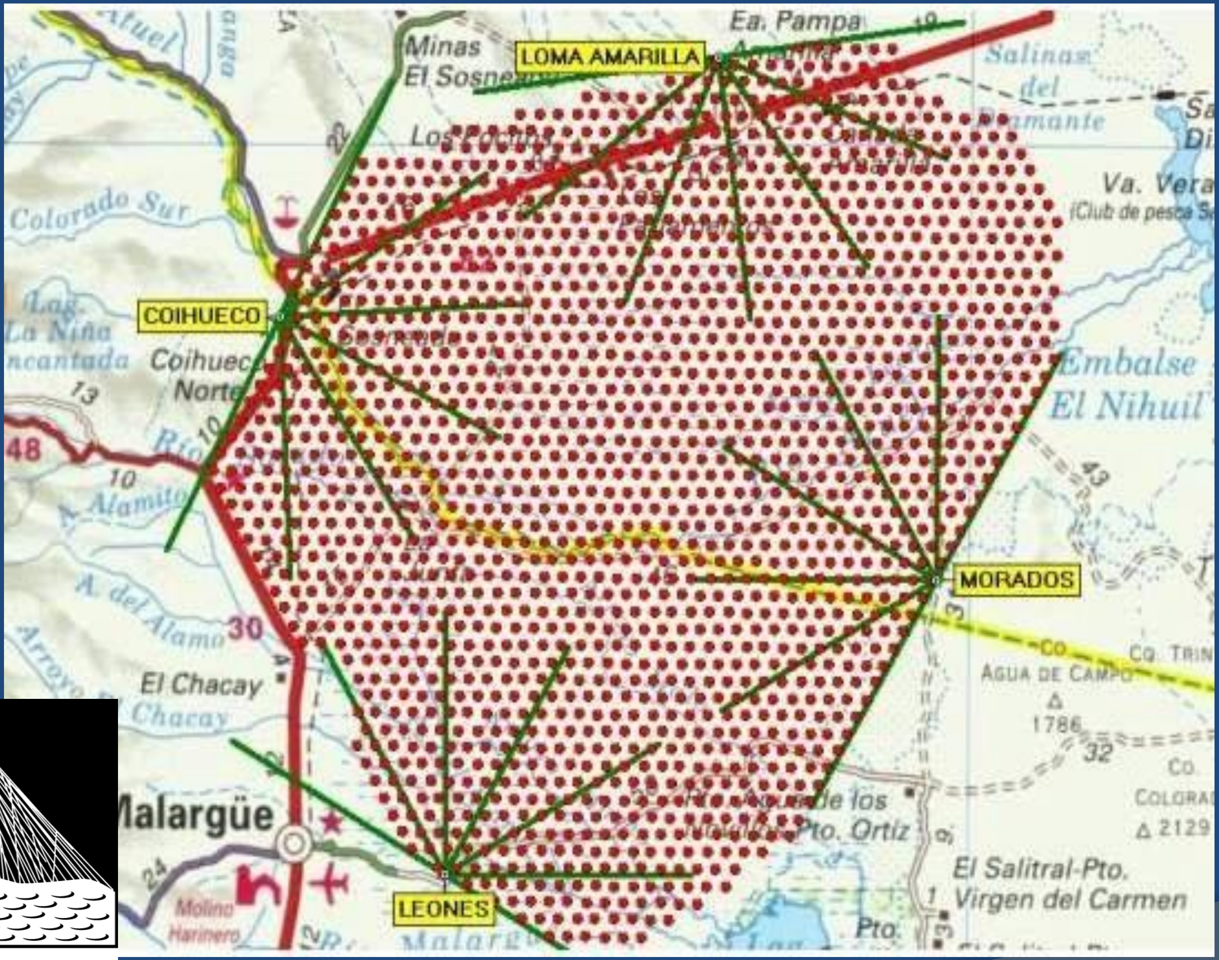






K.D. de Vries et al., PhysRevLett. 107, 061101 (2011)

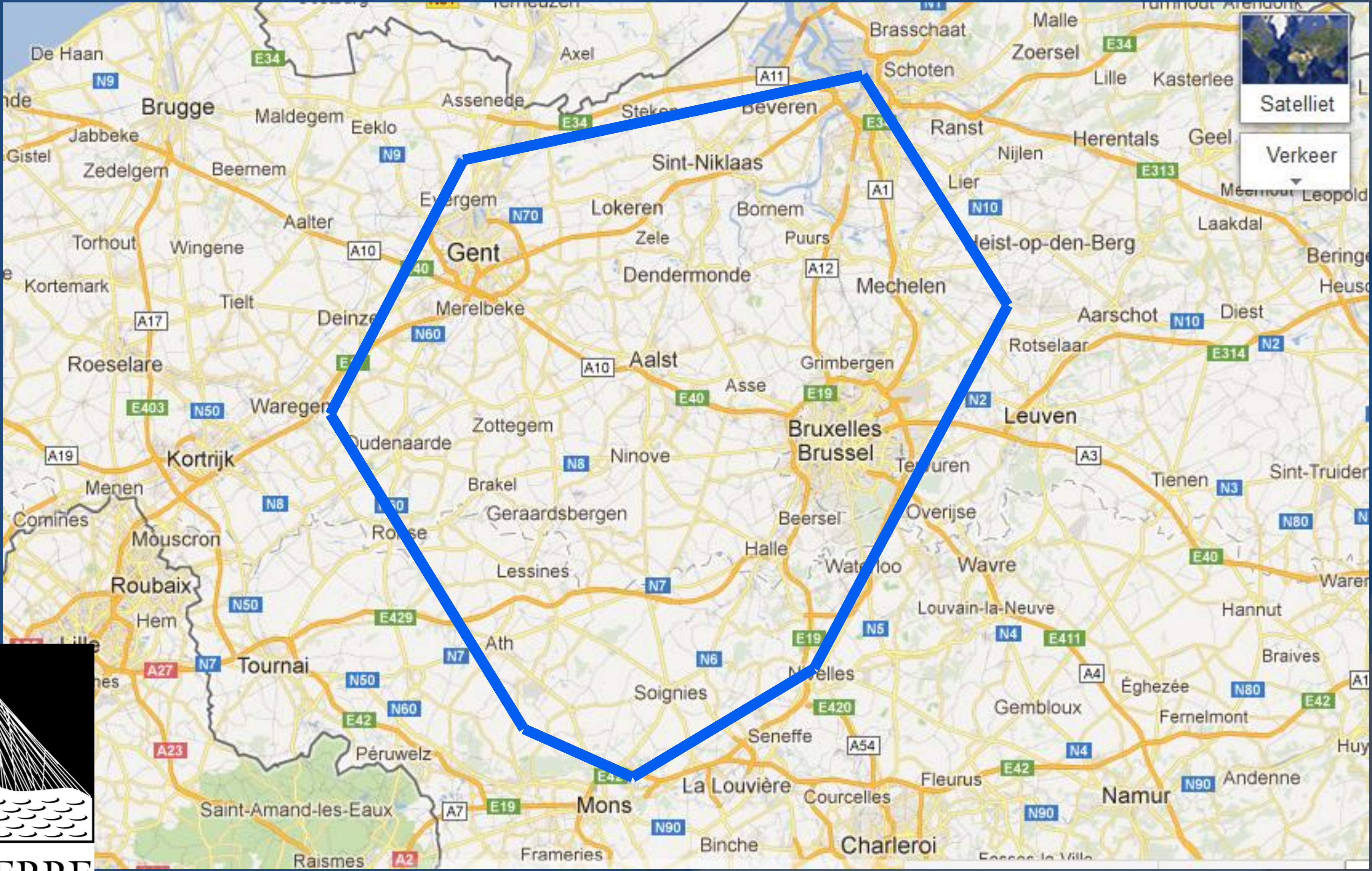
The Pierre Auger Observatory



- 3000 km^2
- 1660 water Cherenkov tanks
- 4 Fluorescence detectors
- Muon detectors
- Radio detection stations

PIERRE
AUGER
OBSERVATORY

The Pierre Auger Observatory



The Pierre Auger Observatory: Air shower detection

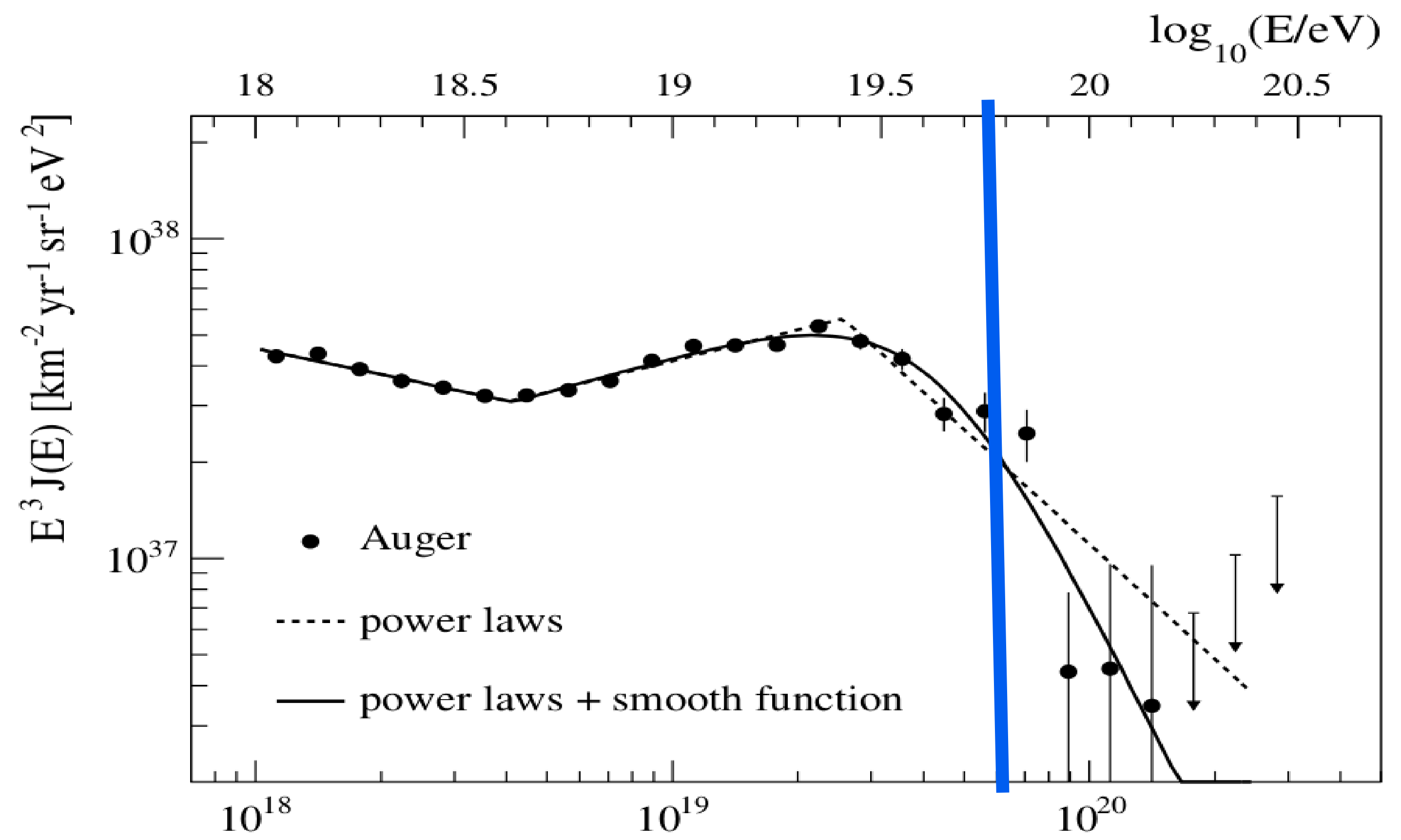
Fluorescence detection (FD): Measure electronic component due to excited nitrogen atoms

Surface detector (SD): Measure muonic component through Cherenkov light of high energetic muons hitting the water tanks.

PIERRE
AUGER
OBSERVATORY

The Pierre Auger Observatory: Latest results

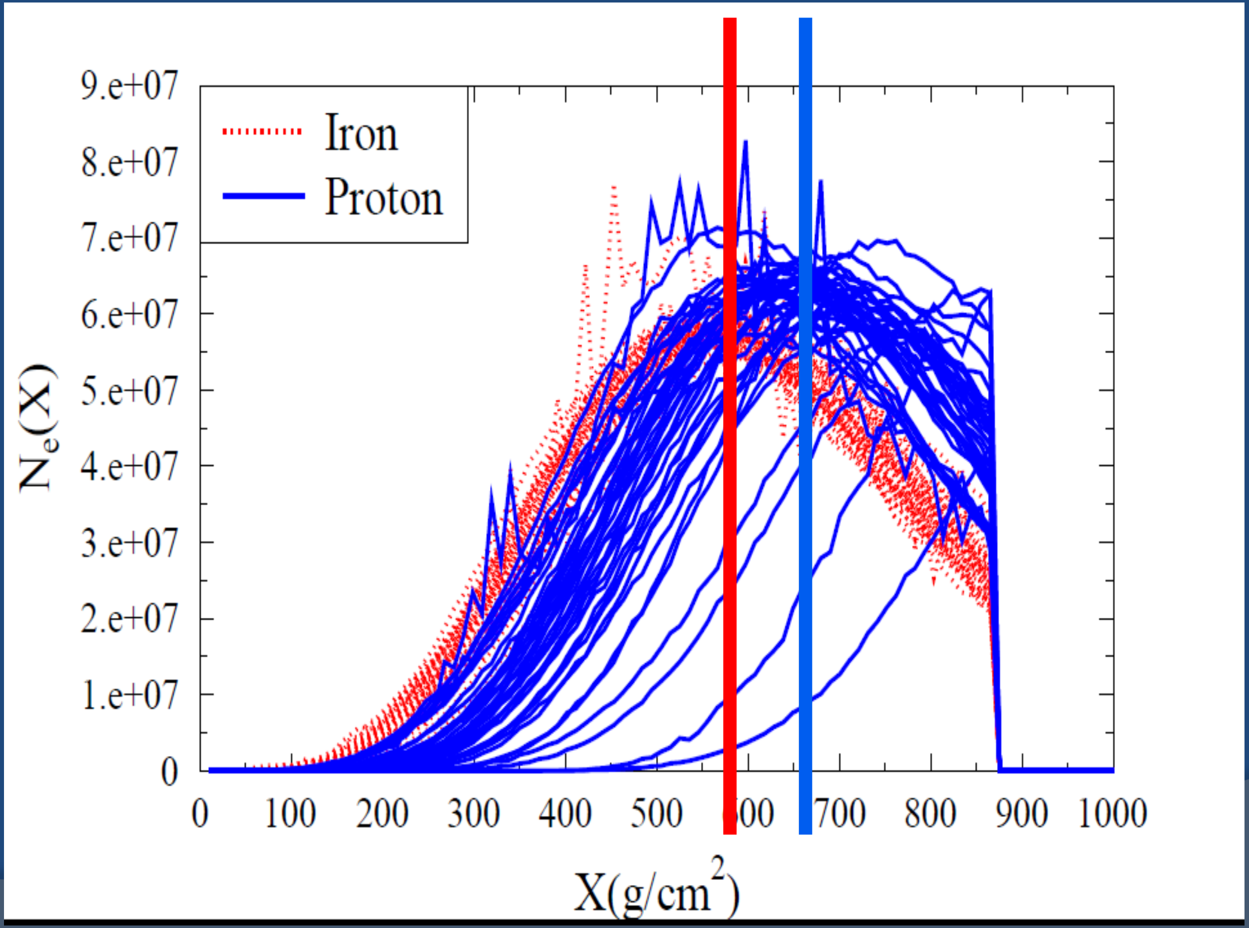
The cosmic-ray spectrum, GZK effect??:



F. Salmida for the Pierre Auger Collaboration, Proc. of the 32nd ICRC, Beijing, China, 2011

The Pierre Auger Observatory: Latest results

The Chemical composition:

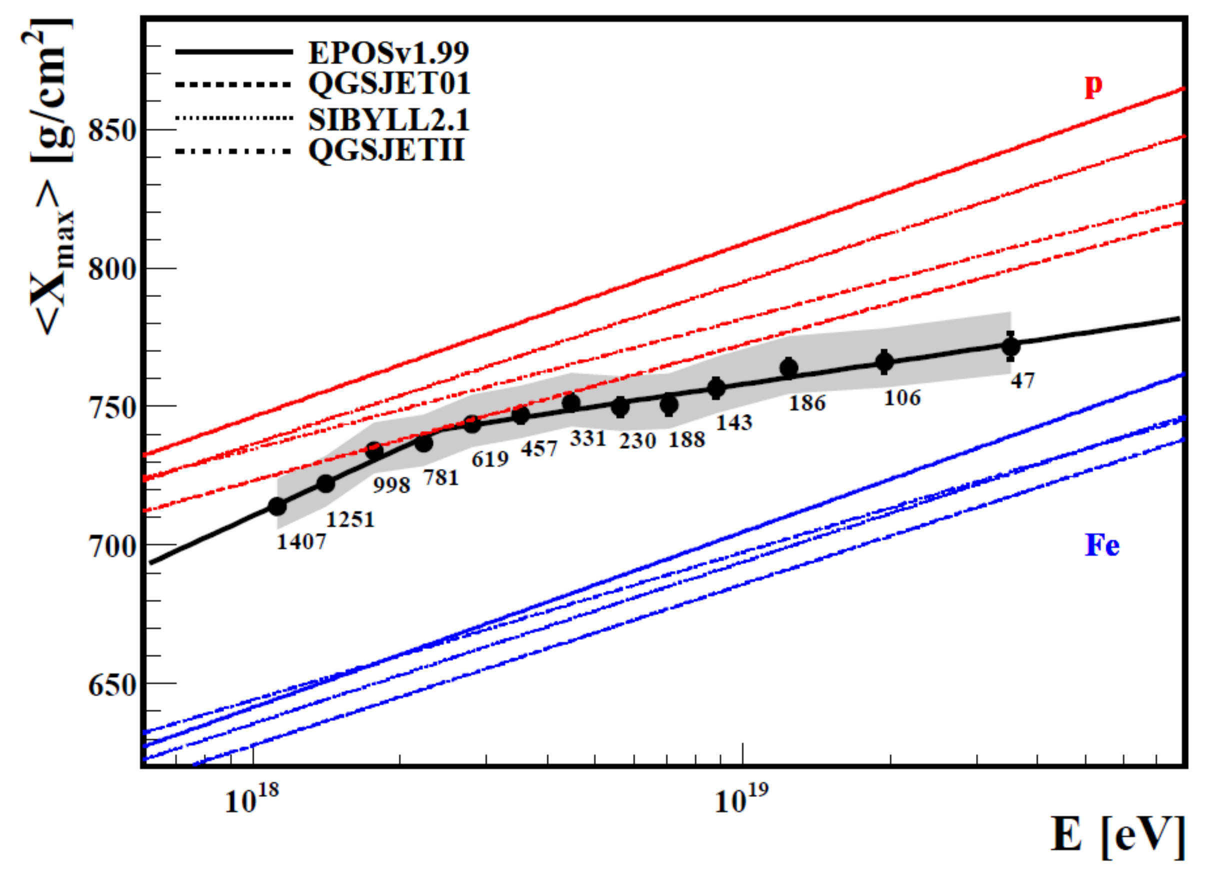


Xmax: Proton penetrates deeper compared to iron.

<Xmax>: More statistical fluctuations for protons compared to iron.

The Pierre Auger Observatory: Latest results

The Chemical composition:

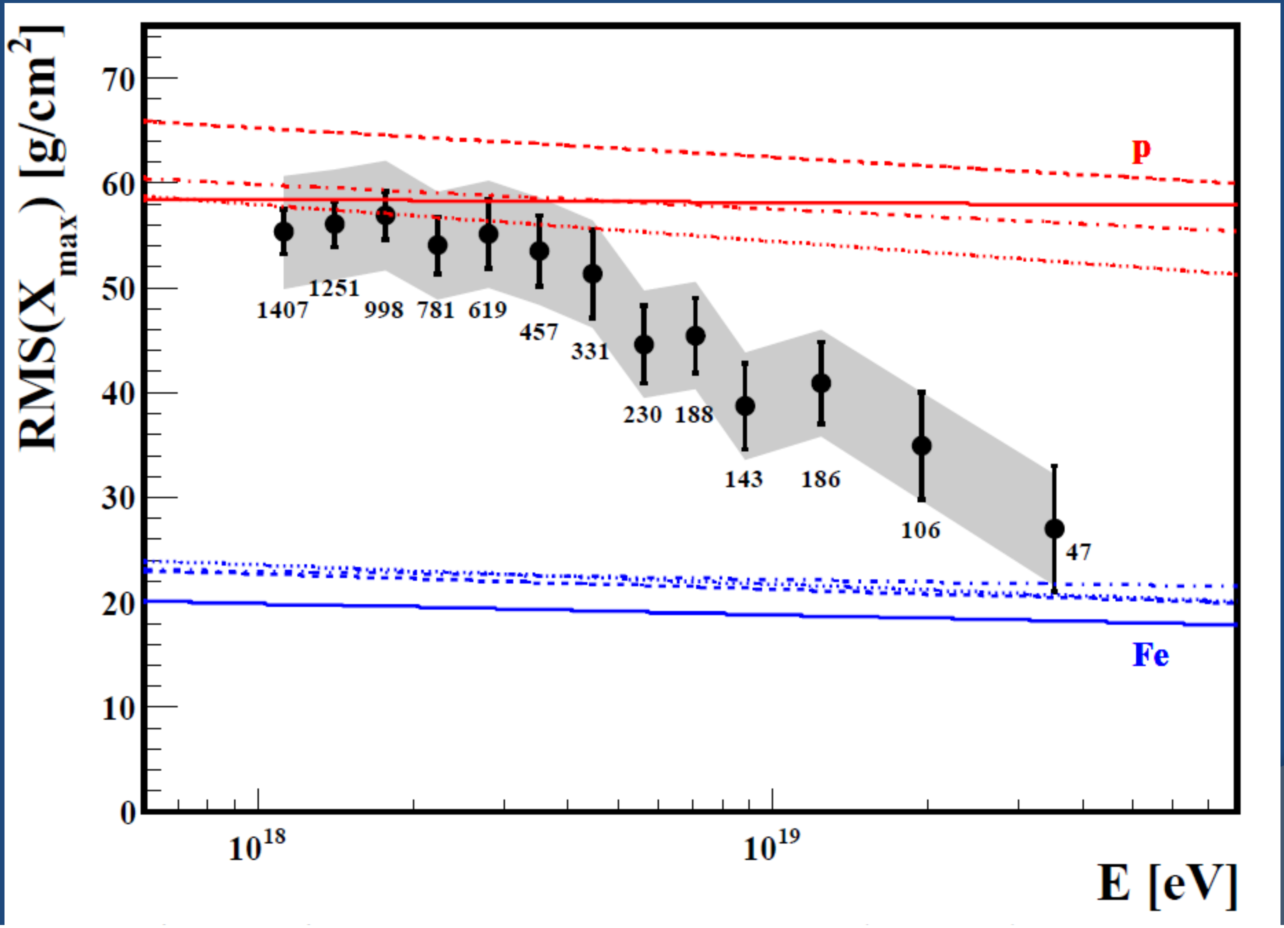


PIERRE
AUGER
OBSERVATORY

P. Facal San Luis *et al.* The distribution of shower maxima of UHECR air showers

The Pierre Auger Observatory: Latest results

The Chemical composition:

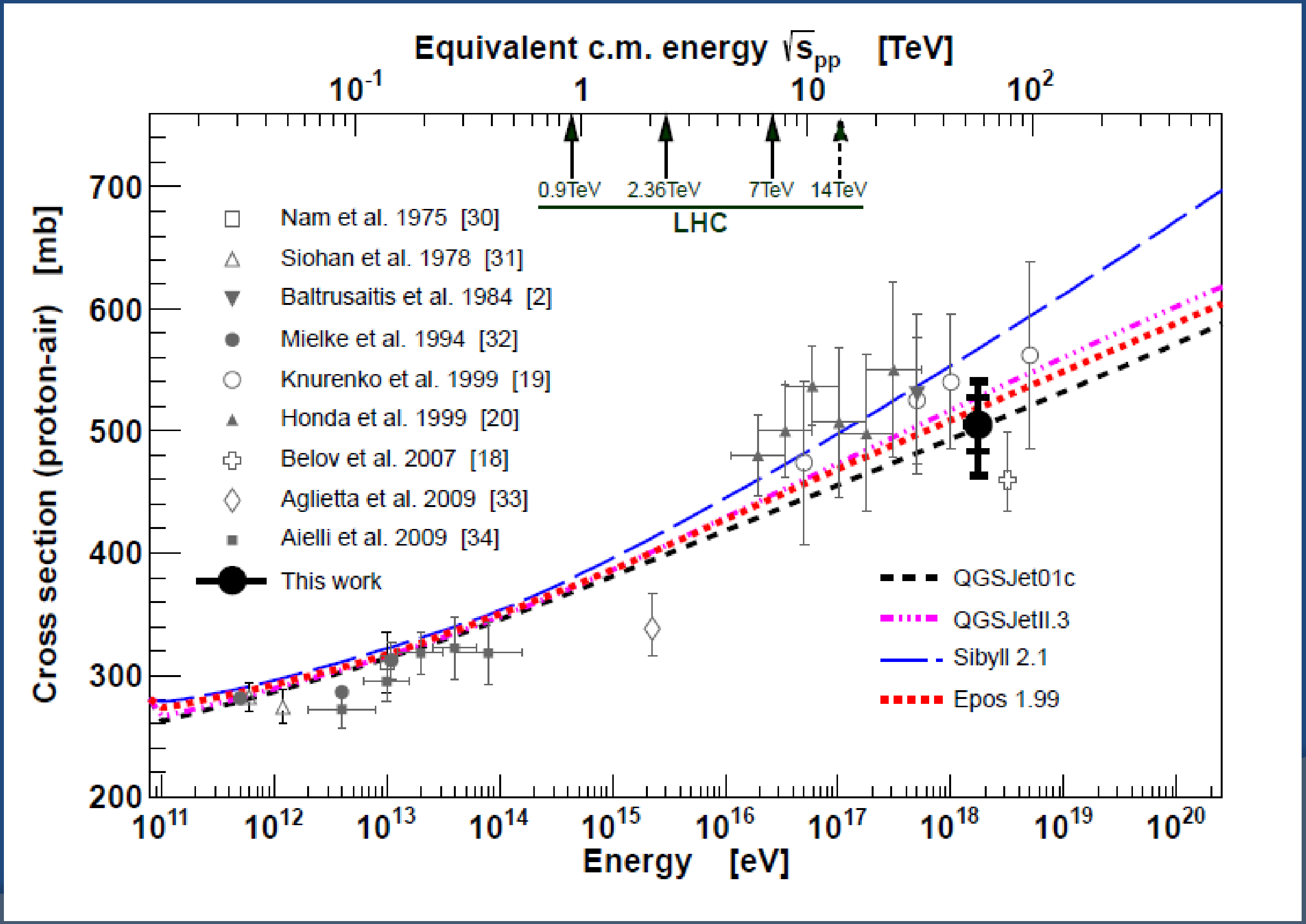


PIERRE
AUGER
OBSERVATORY

P. Facal San Luis *et al.* The distribution of shower maxima of UHECR air showers

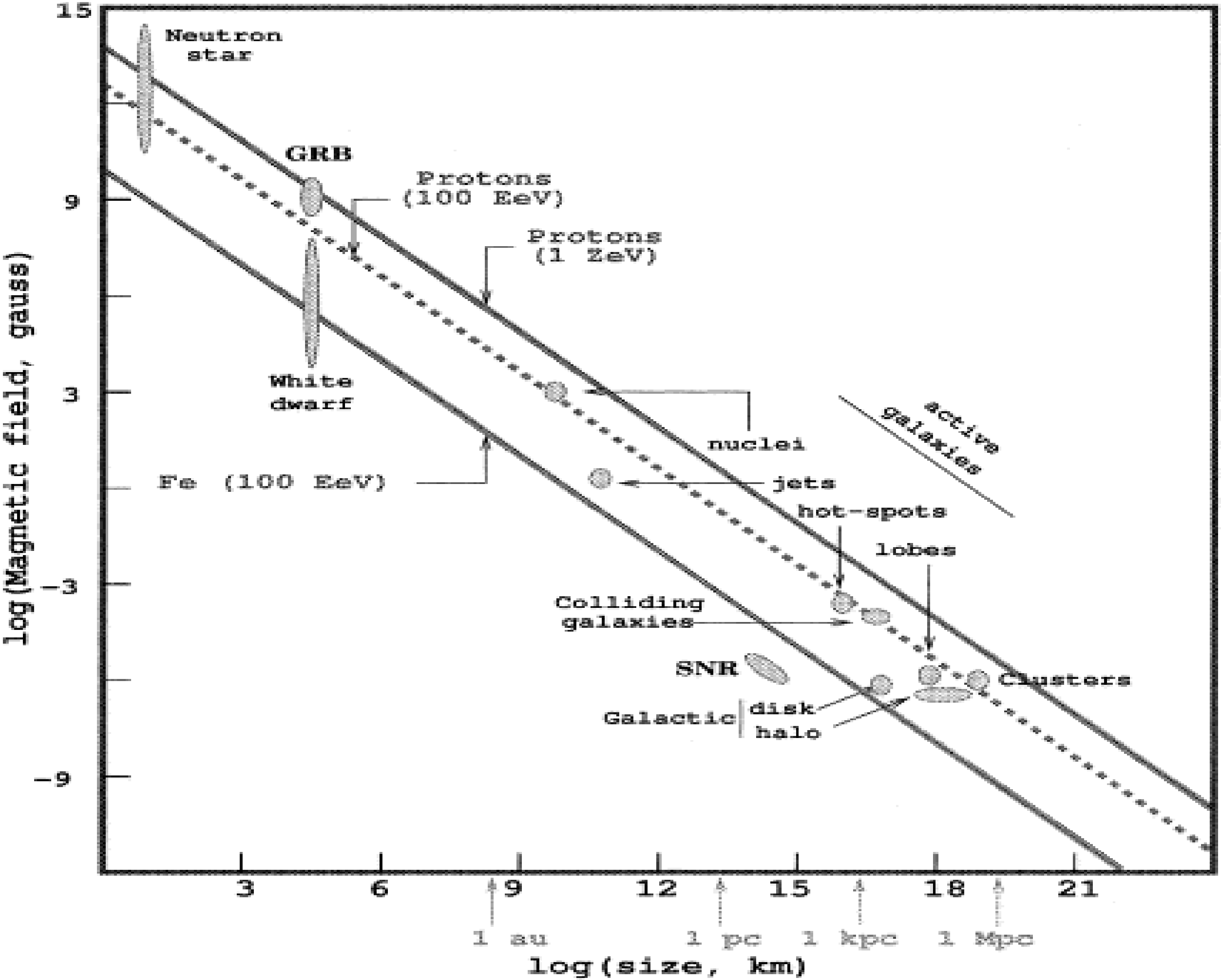
The Pierre Auger Observatory: Latest results

New Physics at the highest energies?



P. Abrue *et al* (Pierre Auger Collaboration) Phys. Rev. Lett. 109, 062002 (2012)

Acceleration mechanisms



Cosmic Ray propagation

- Deflection in galactic and intergalactic magnetic fields

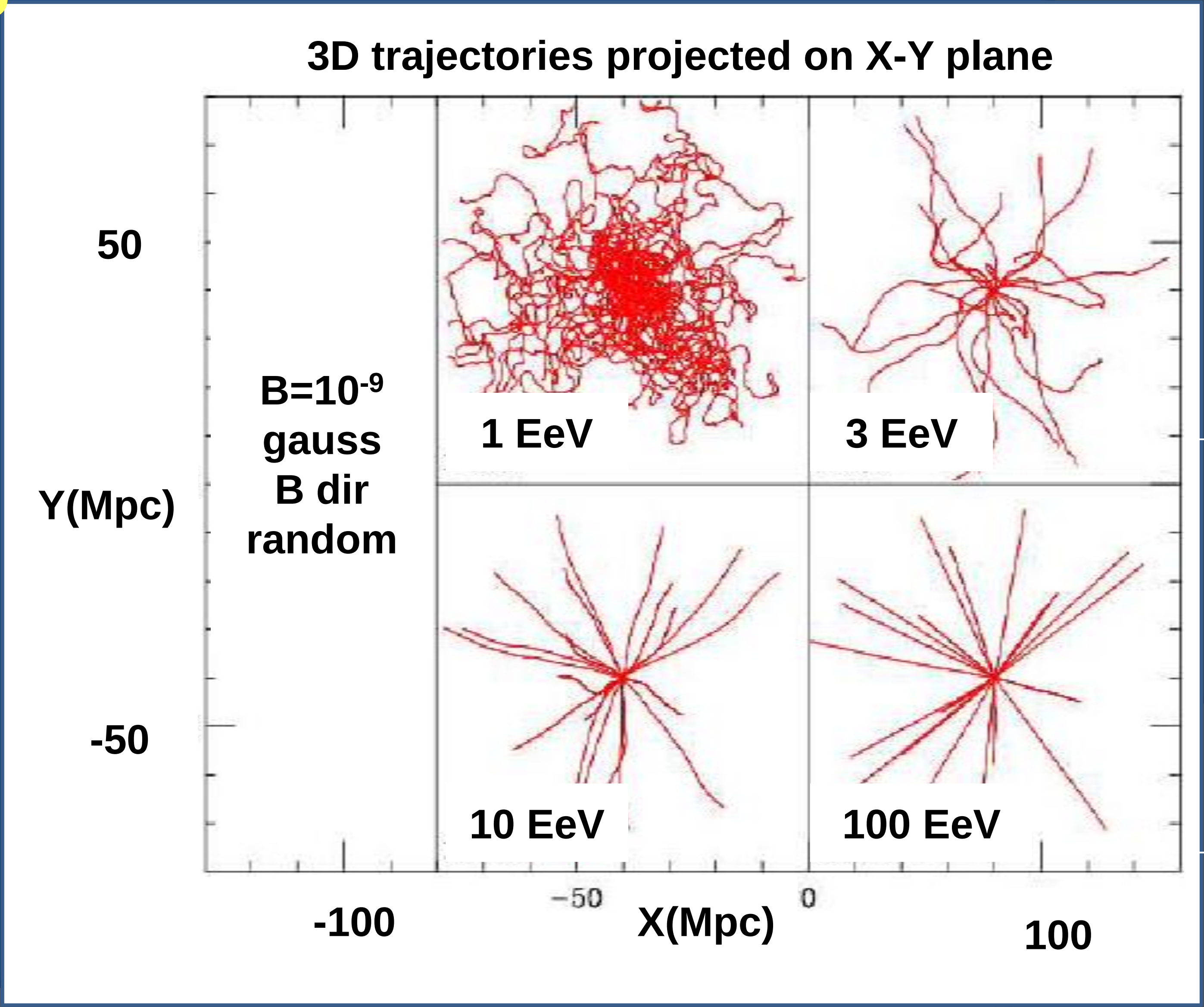
- Particle production:

- GZK effect
- Photodesintegration

Transport: Magnetic Field containment

Inter-Galactic

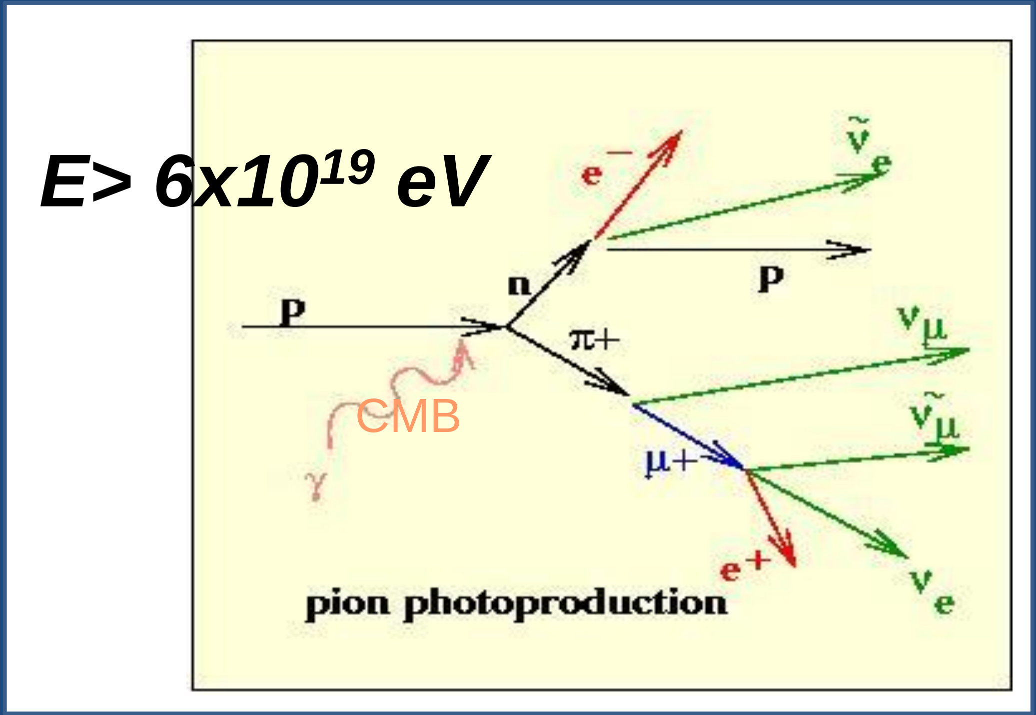
B≤ 1-10 nG



From: J. Cronin, 2004

The GZK cut-off

Energetic protons loose energy through Interactions with the cosmic microwave background



E> 6x10^{19} eV

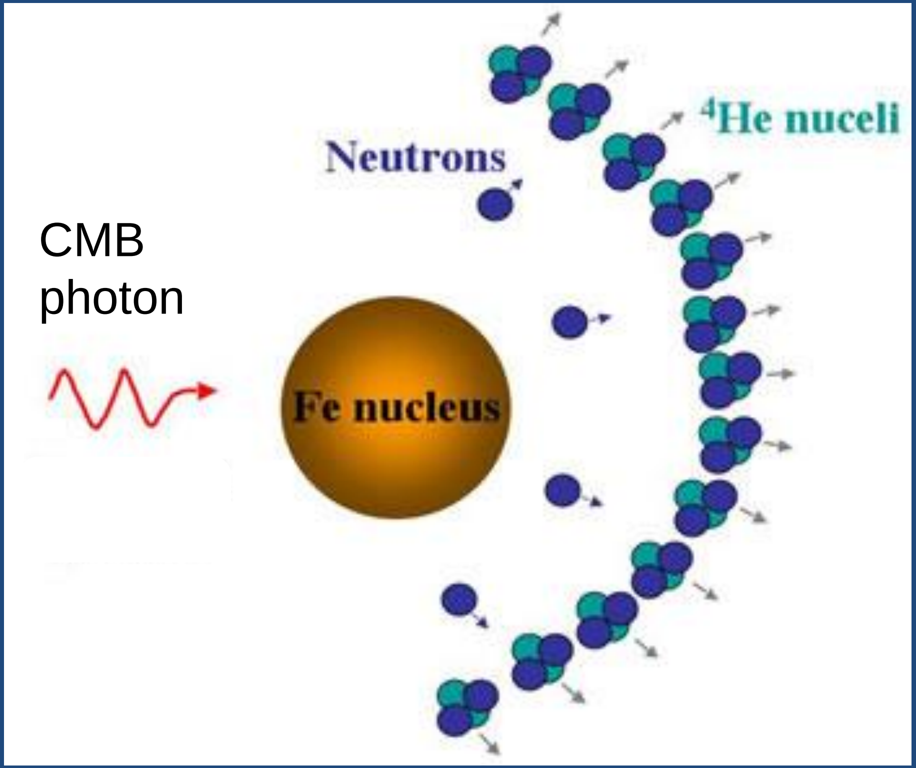
UHE protons loose energy

Production of energetic neutrino's

Based on Lorentz Invariance, What if …?

Greisen – Zatsepin - K'uzmin (GZK)

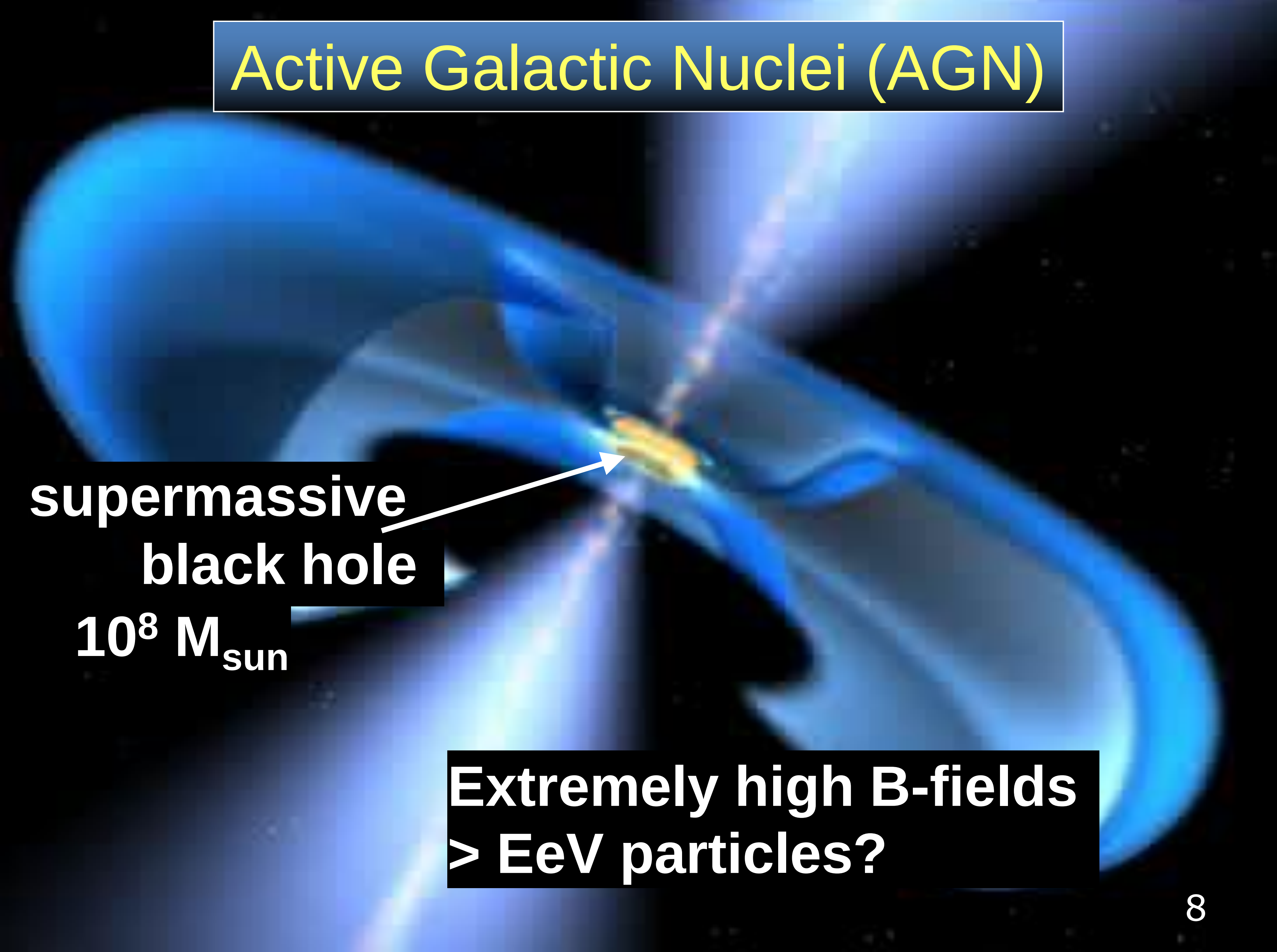
The GZK cut-off, but also…..



$$^{56}\mathrm{Fe} + \gamma \rightarrow 13\,^{4}\mathrm{He} + 4n$$
$$^{4}\mathrm{He} + \gamma \rightarrow 2p^{+} + 2n$$

Photodisintegration at similar energies, so we need to know the composition

Active Galactic Nuclei (AGN)

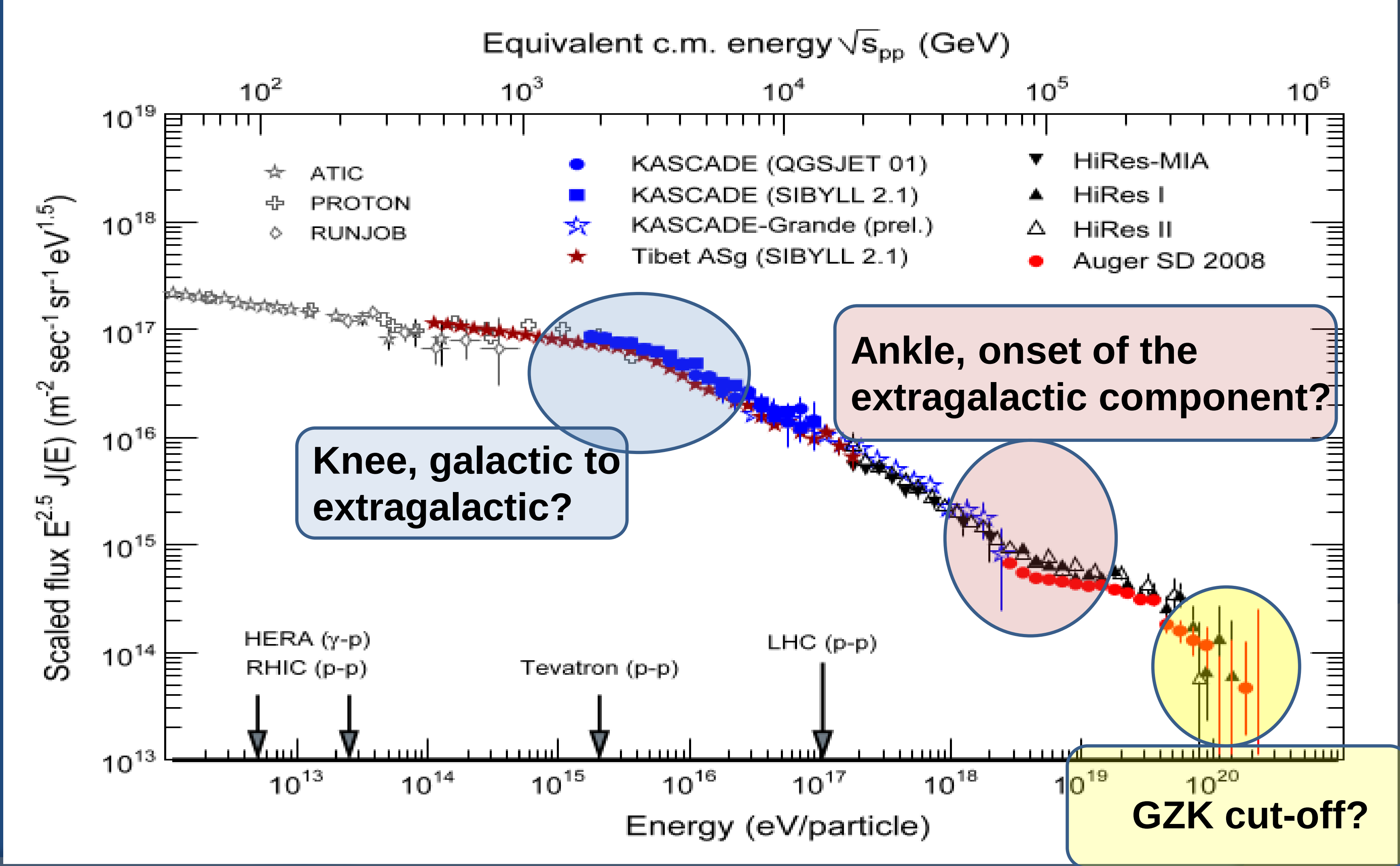


supermassive black hole

10^8 M_{sun}

Extremely high B-fields
> EeV particles?

The cosmic-ray spectrum:



Knee, galactic to extragalactic?

Ankle, onset of the extragalactic component?

GZK cut-off?