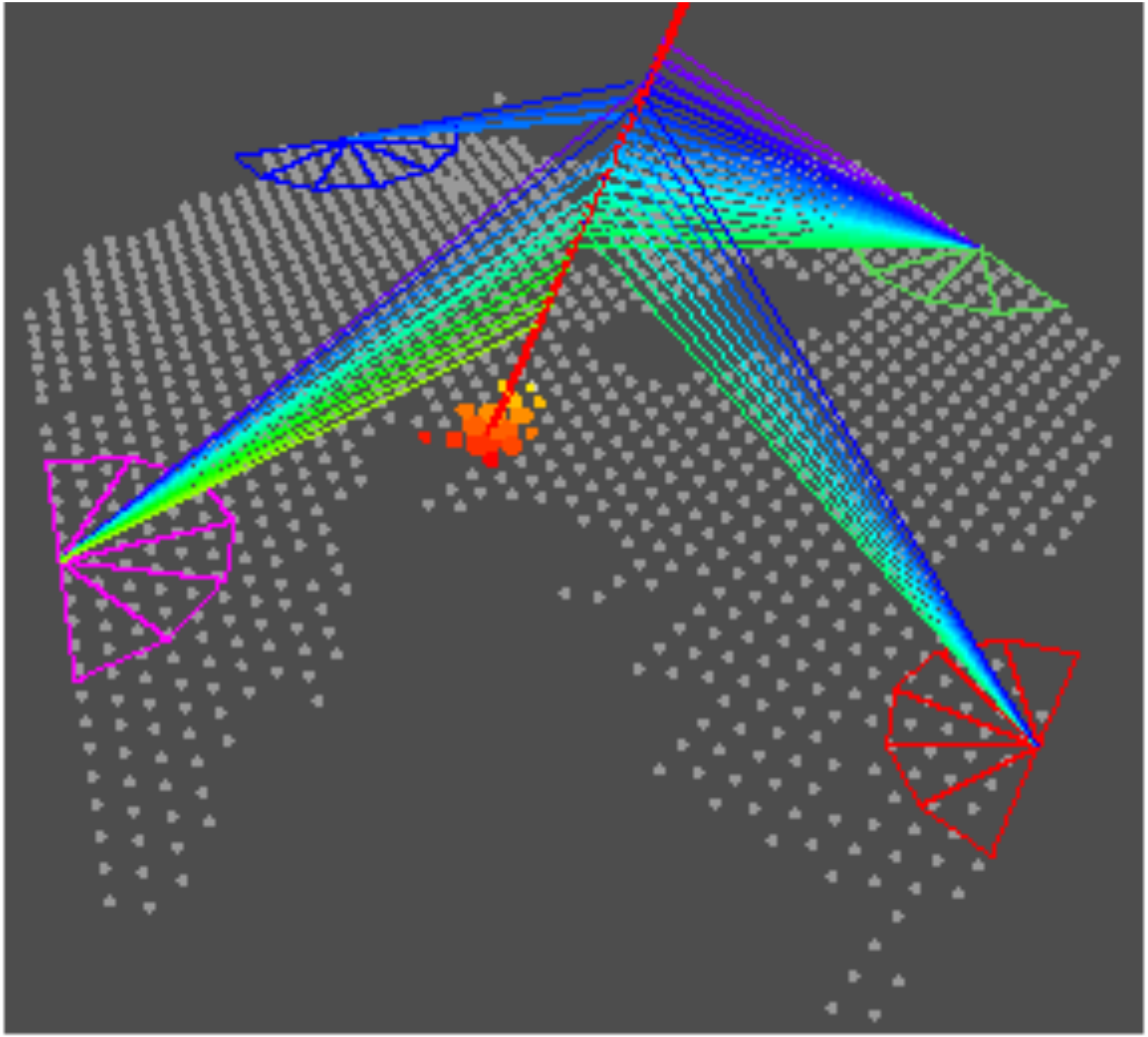
A Hybrid Event - Pierre Auger Observatory



20 May 2007 E ~ 10^{19} eV

Energy spectrum

ankle E=4 10^{18} eV

pair production at 3-K photons

$$CR + \gamma_{3K} \rightarrow e^+ e^-$$

depression E>4 10^{19} eV

- **photo pion production at 3-K photons GZK effect**

$p + \gamma_{3K} \rightarrow \Delta^+ \rightarrow p + \pi^0$; $n + \pi^+$

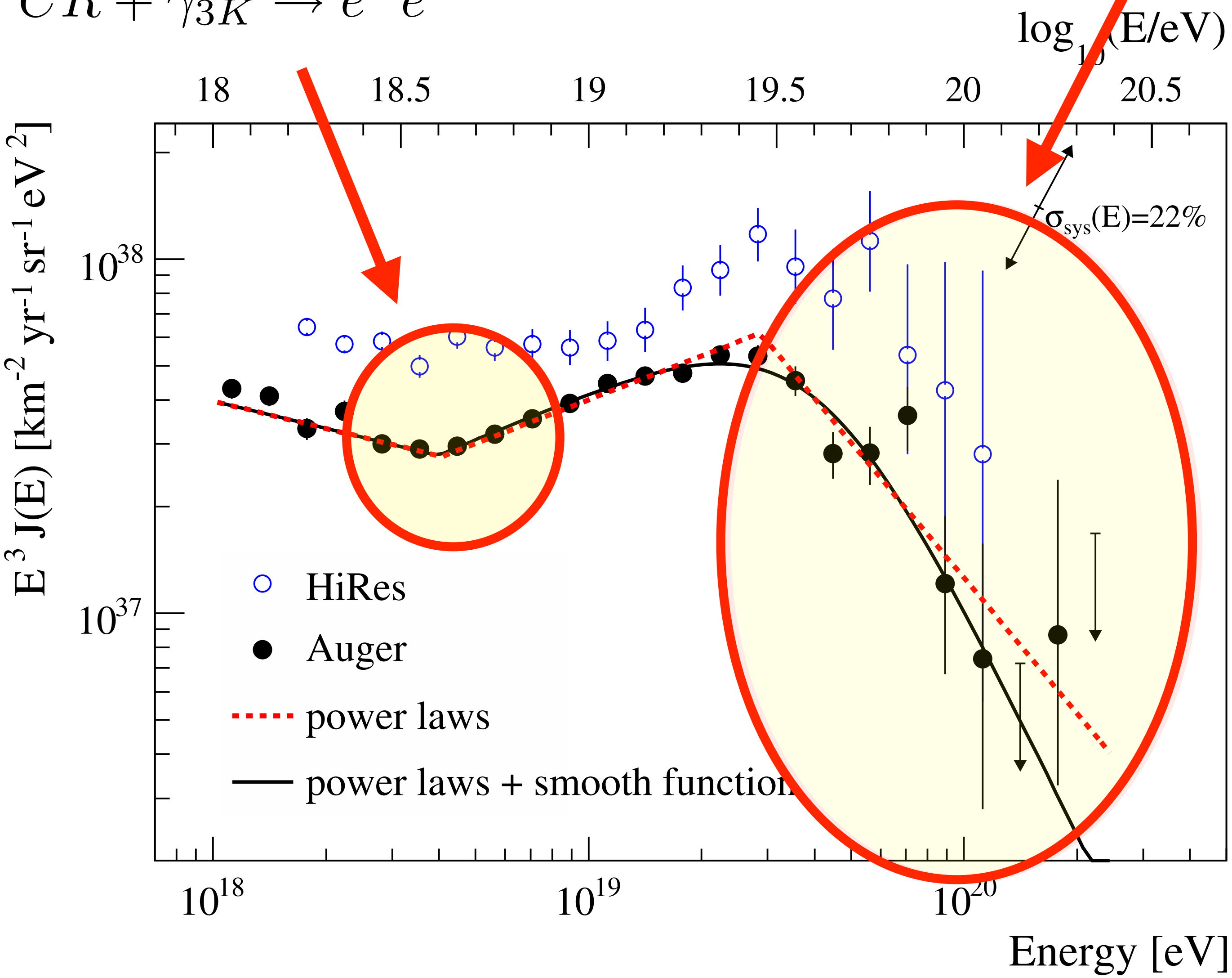
➡ **light composition**

- **maximum energy of accelerators**

$$E_{max} \propto Z \cdot B \cdot L$$

(Hillas condition)

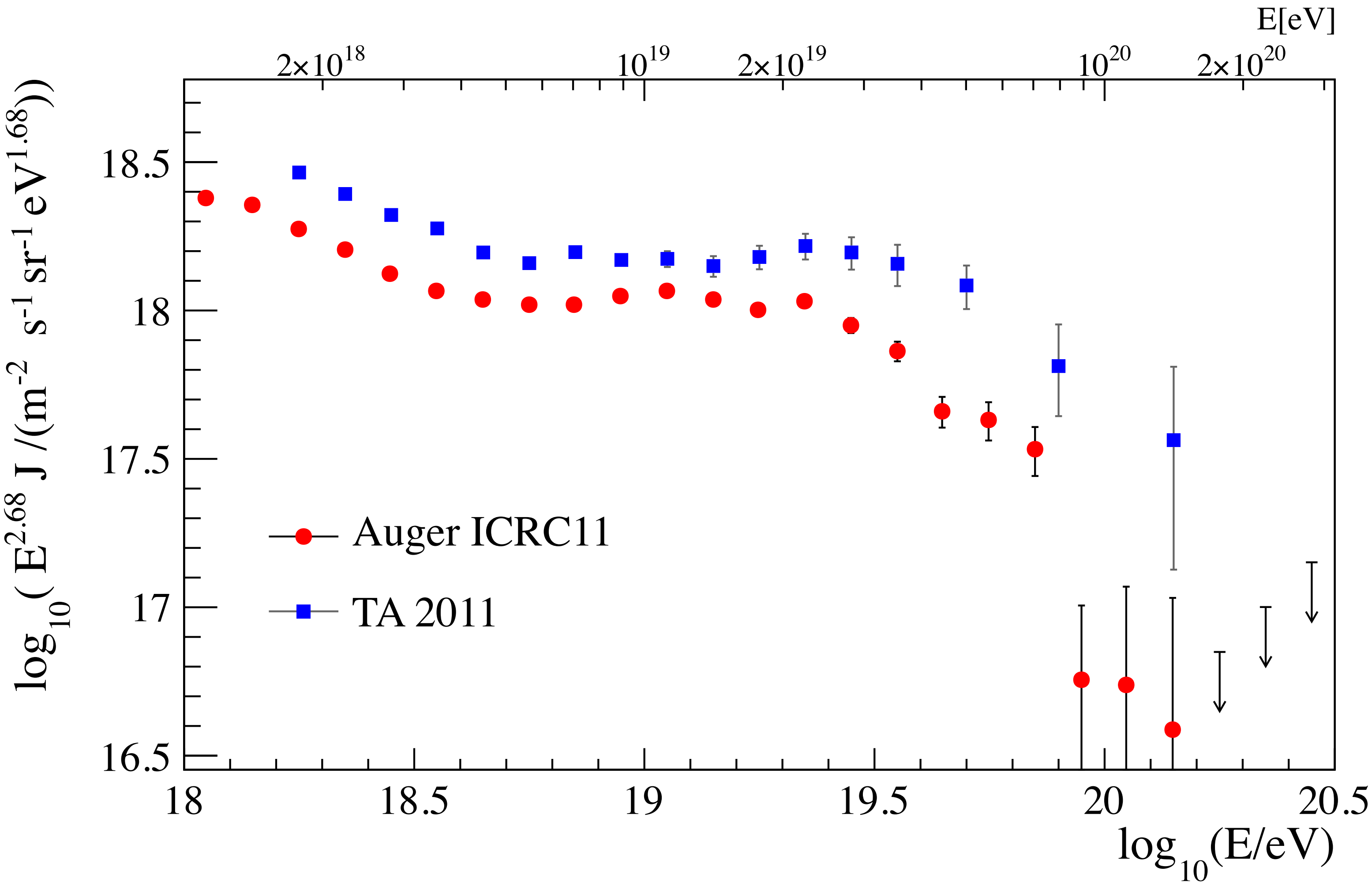
➡ **heavy composition**



J. Abraham et al., Physics Letters B 685 (2010) 239

Cosmic-ray spectrum at highest energies

Comparison of Spectra

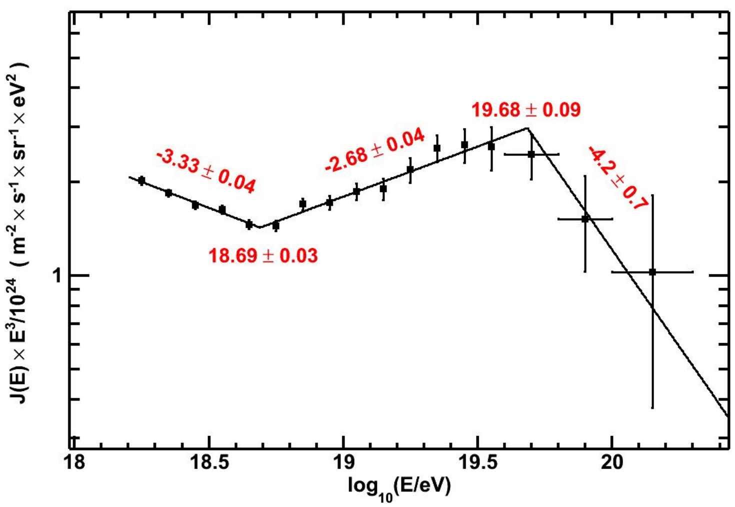


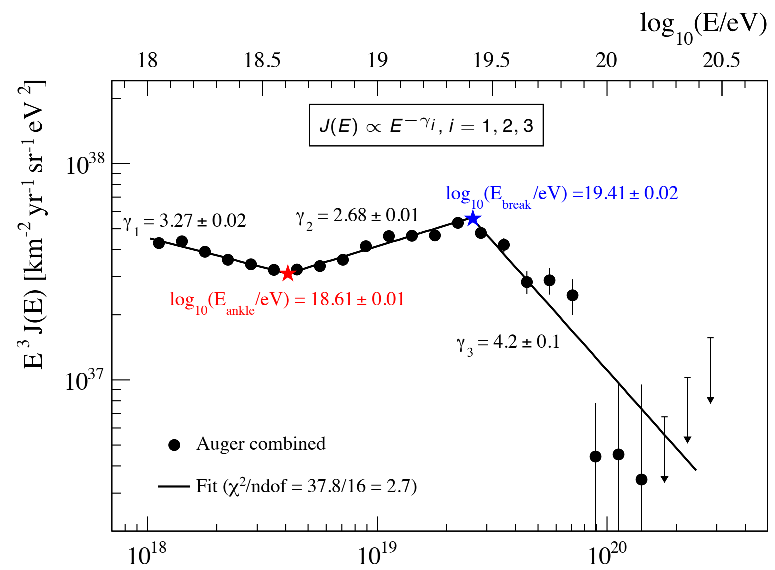
energy scale difference of $\sim$ 20%?

M. Unger, ICRC 2011

Cosmic-ray spectrum at highest energies

Comparison of spectral features





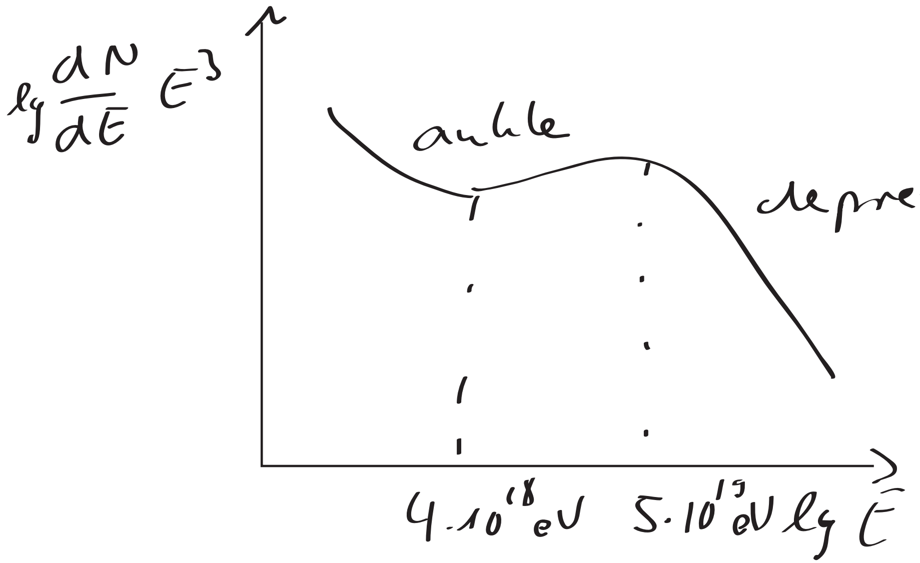
	TA	Auger
γ_1	3.33 ± 0.04	3.27 ± 0.02
γ_2	2.68 ± 0.04	2.68 ± 0.01
γ_3	4.2 ± 0.7	4.2 ± 0.1
$\lg(E_1/\mathrm{eV})$	18.69 ± 0.03	18.61 ± 0.01
$\lg(E_2/\mathrm{eV})$	19.68 ± 0.09	19.41 ± 0.02

B. Stokes [TA Coll.], icrc1297

F. Salamida [Auger Coll.], icrc893

M. Unger, ICRC 2011

- energy spectrum at highest energies



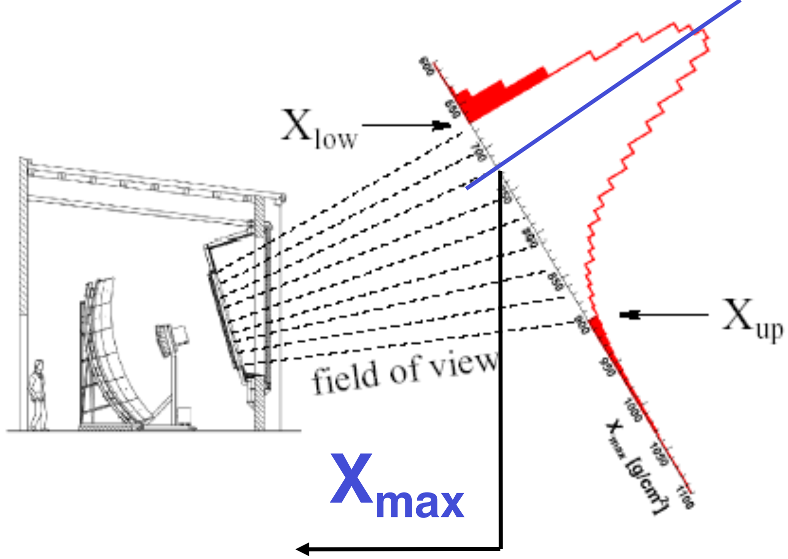
- ankle:
  e^+e^- pair production of CRs with 3K photons

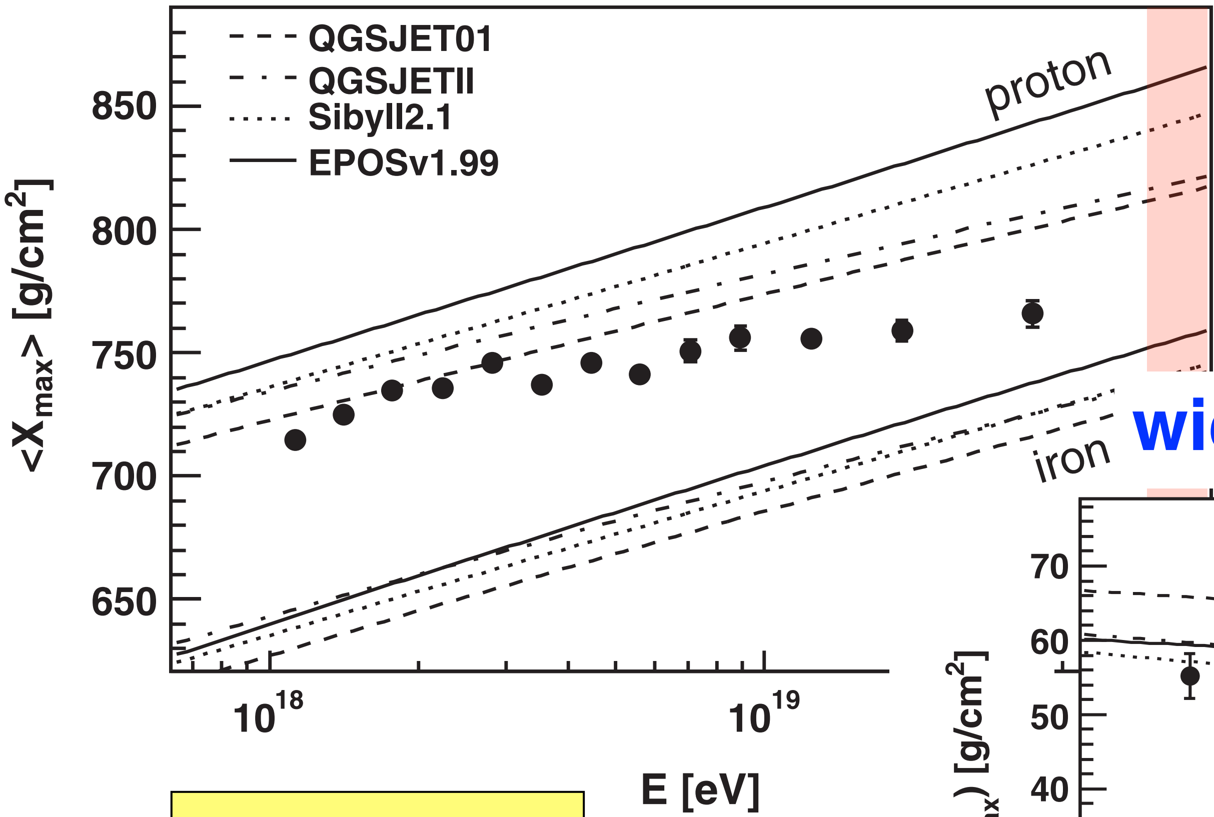
- depression:
  - GZK cutoff
  - maximum energy of accelerators

- mass composition
  Auger sees trend to heavy composition at the highest energies

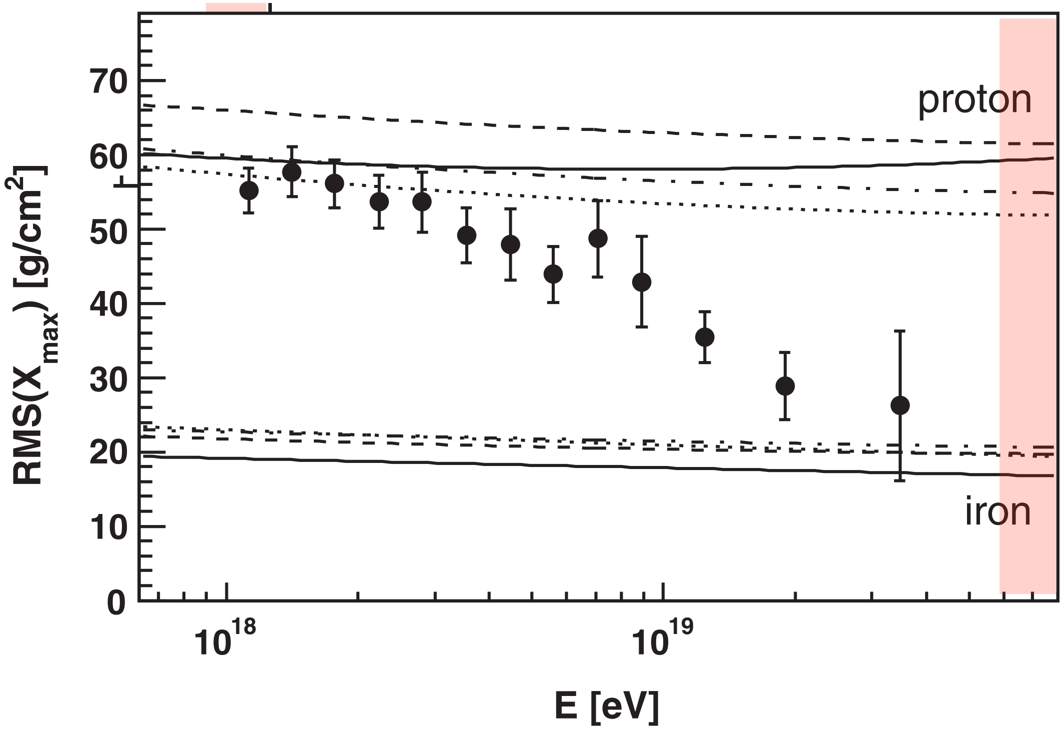
Mass Composition

Depth of the shower maximum X_{max}





width of X_{max} distribution

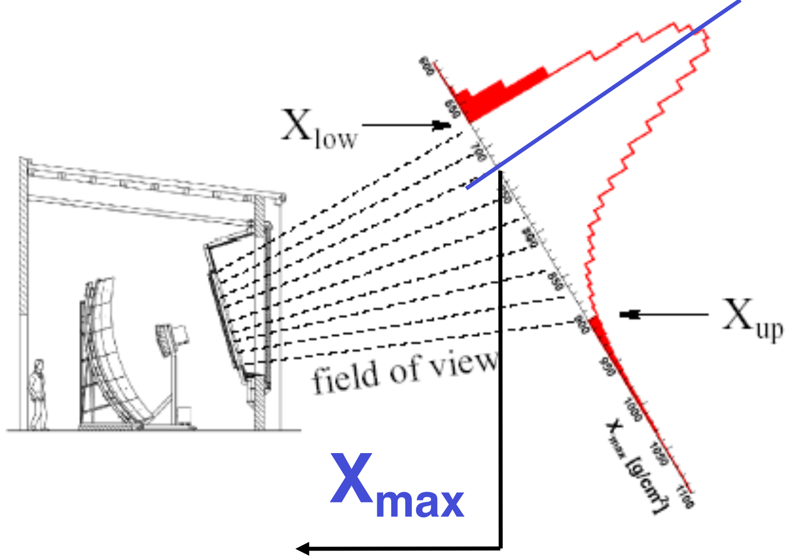


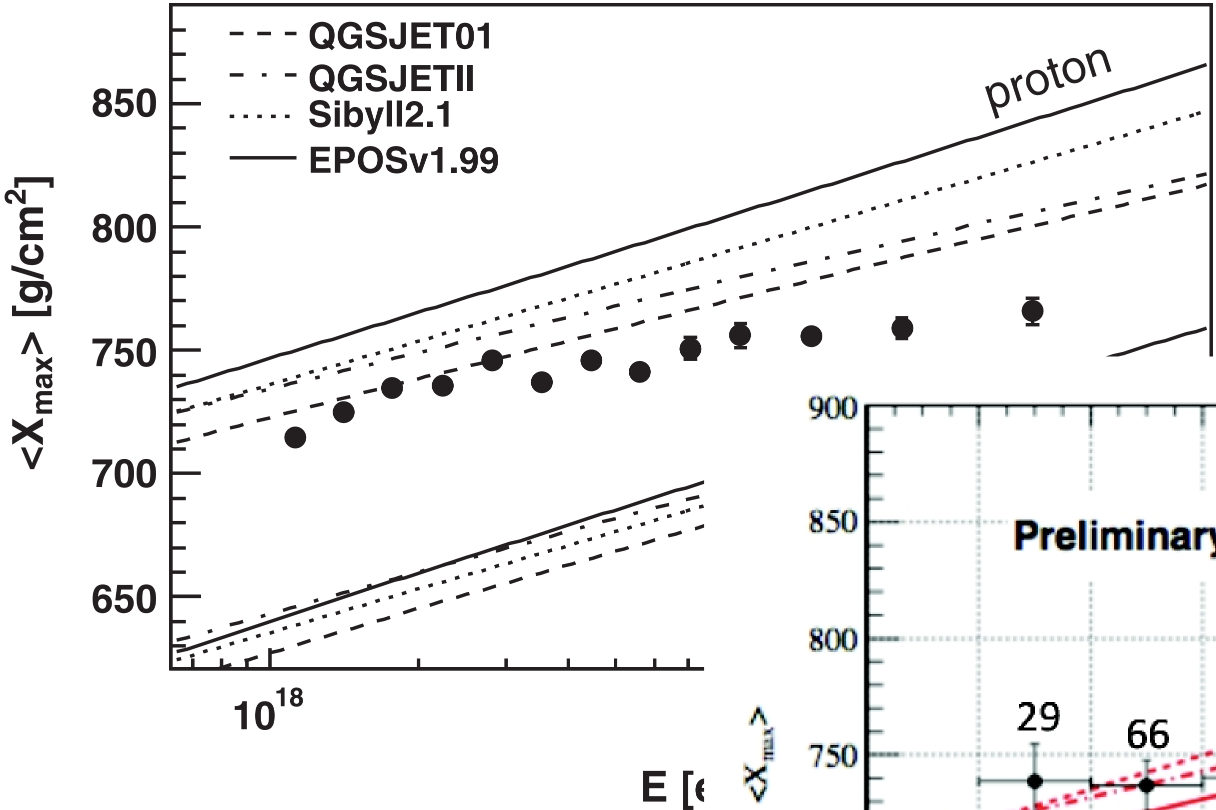
remember:
GZK effect requires light particles!

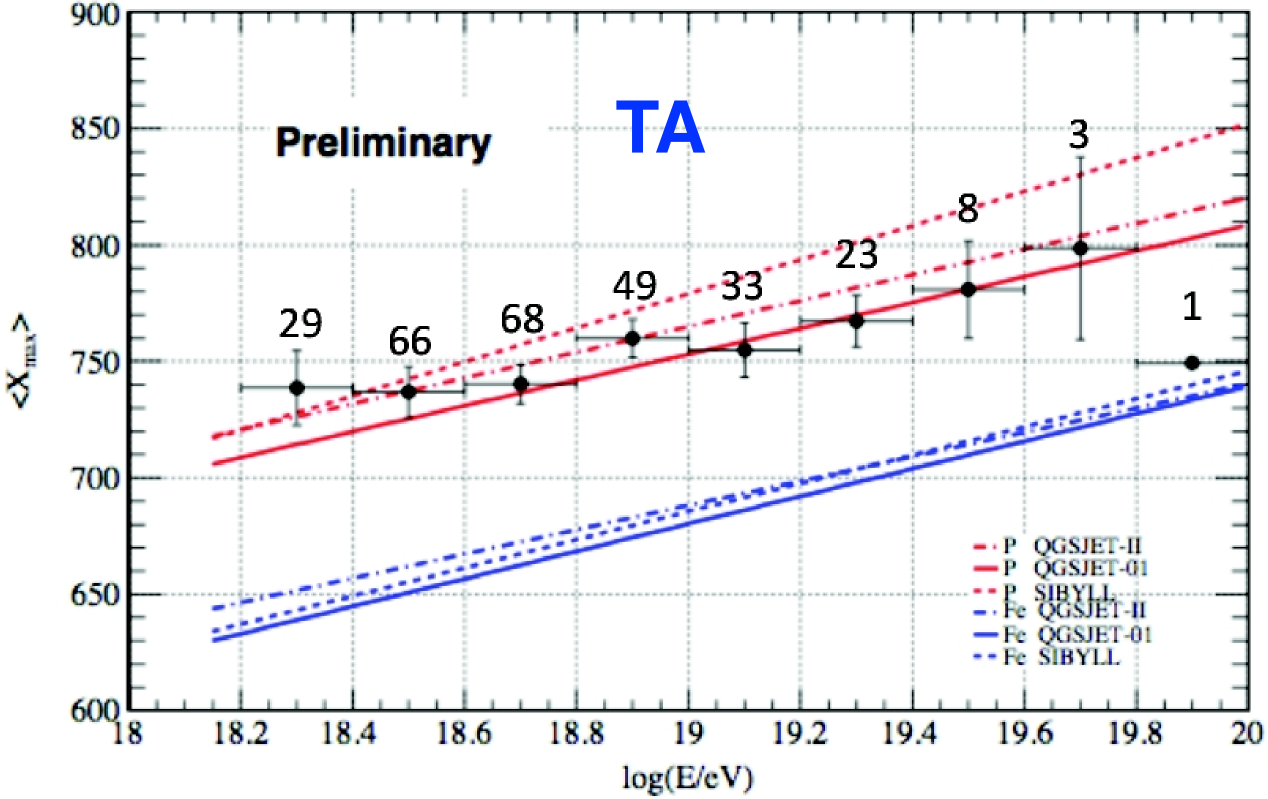
J. Abraham et al., Physical Review Letters 104 (2010) 091101

Mass Composition

Depth of the shower maximum X_{max}







J. Abraham et al., Physical Review Letters 104

A. Tameda et al., ICRC 2011

TA sees light composition

-> further investigations

- arrival direction

a cosmic ray with charge Z that travels a distance D in a regular magnetic field B is deflected by an angle

$$\delta = 2{,}7^{\circ} \frac{60\,\mathrm{EeV}}{E/Z} \left| \int_0^D \left(\frac{dx}{\mathrm{kpc}} \times \frac{B}{3\,\mu\mathrm{G}} \right) \right|$$

coherence scale $\approx 1\,\mathrm{kpc}$

=> protons are deflected only by a few degrees ($\sim 3^{\circ}$ at $60\,\mathrm{EeV}$)

Arrival directions of highest energy cosmic rays

Best correlation between arrival directions and positions of AGNs for
$E>5.7\ 10^{19}$ eV - $d<75$ Mpc - $\Theta<3.1°$

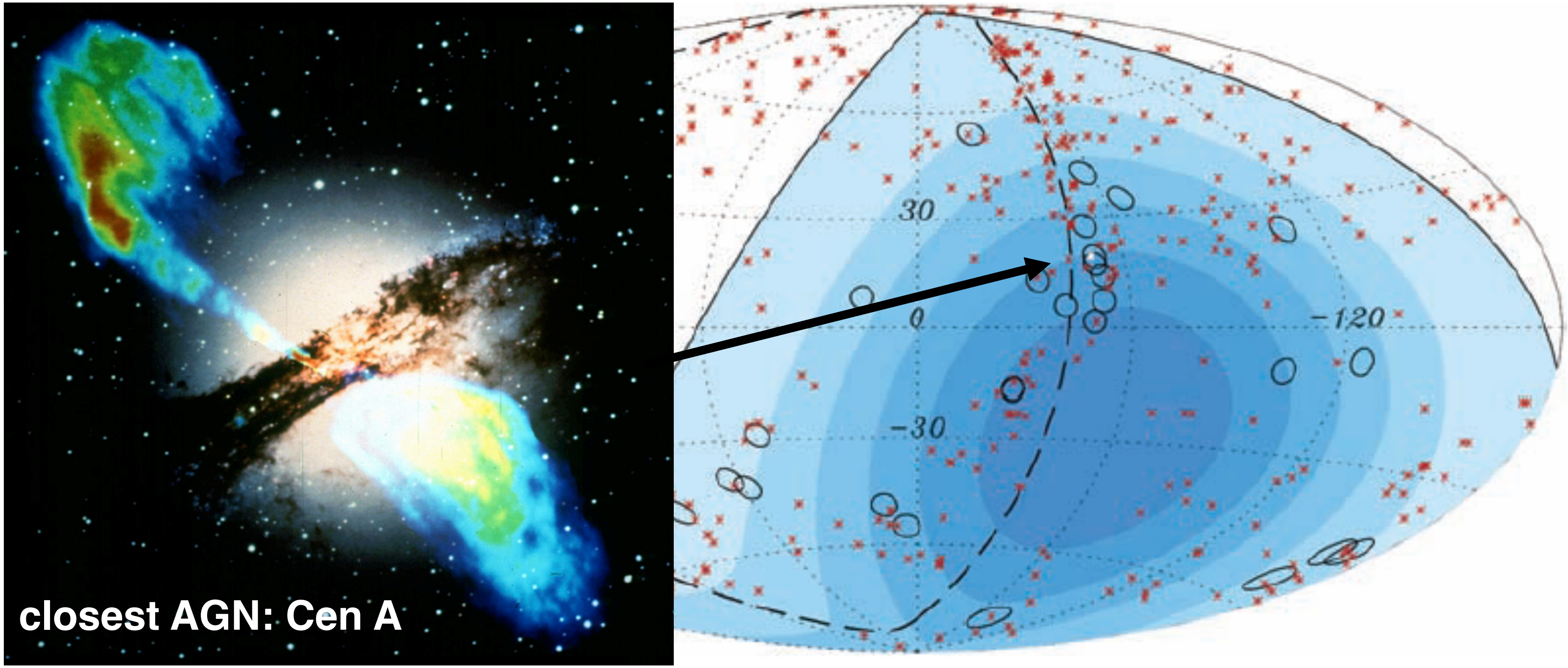


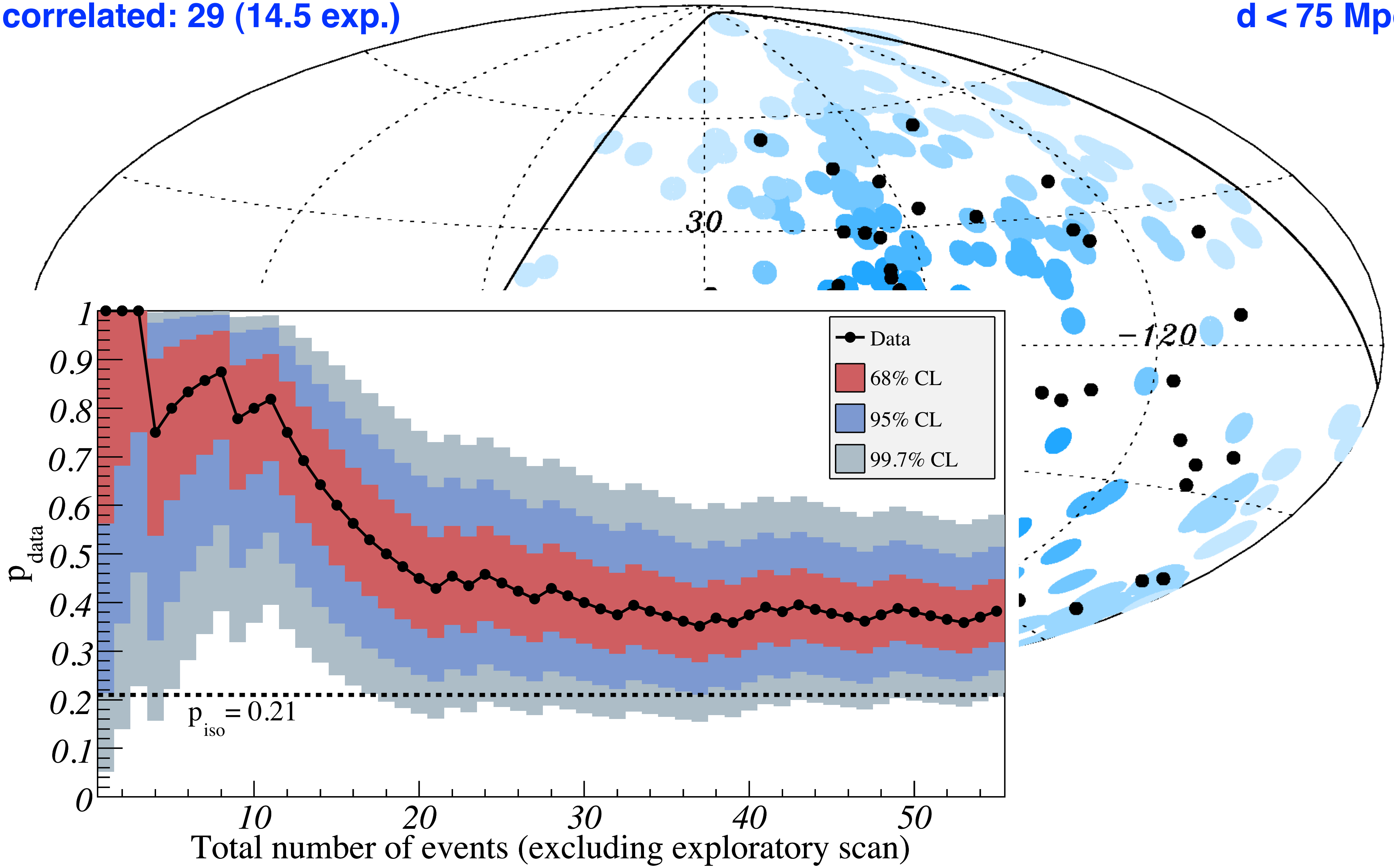
Fig. 2. Aitoff projection of the celestial sphere in galactic coordinates with circles of radius 3.1° centered at the arrival directions of the 27 cosmic rays with highest energy detected by the Pierre Auger Observatory. The positions of the 472 AGN (318 in the field of view of the Observatory) with redshift $z \leq 0.018$ ($D < 75$ Mpc) from the 12th edition of the catalog of quasars and active nuclei (*12*) are indicated by red asterisks. The solid line represents the border of the field of view (zenith angles smaller than 60°). Darker color indicates larger relative exposure. Each colored band has equal integrated exposure. The dashed line is the supergalactic plane. Centaurus A, one of our closest AGN, is marked in white.

J. Abraham et al., Science 318 (2007) 938

Arrival directions of highest-energy cosmic rays

data up to 31.12.2009
69 events E > 55 EeV
correlated: 29 (14.5 exp.)

position of AGNs from
VCV catalog (3.1°)
d < 75 Mpc



P. Abreu et al., Astropart. Phys. (2010)

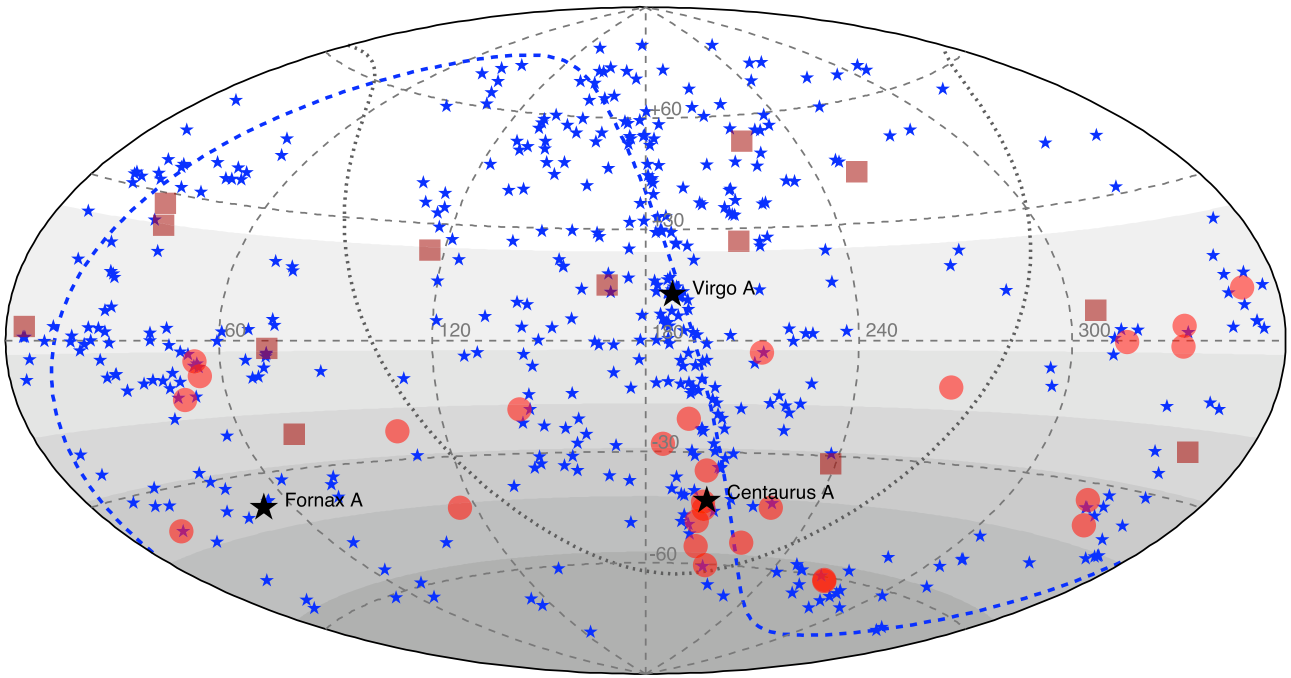


Fig. 21. Arrival directions (equatorial coordinates) of the highest energy cosmic rays observed with the Pierre Auger Observatory [410] (circles) and the HiRes telescopes [278] (squares). The asterisks indicate the position of active galactic nuclei (AGN) from the Veron-Cetty Veron catalogue [407] up to a distance of 75 Mpc. The shaded area indicates the relative exposure of the Auger data set. The dotted line marks the galactic disk and the dashed curve is the super galactic plane.

$\Rightarrow$ astronomy with charged particles?

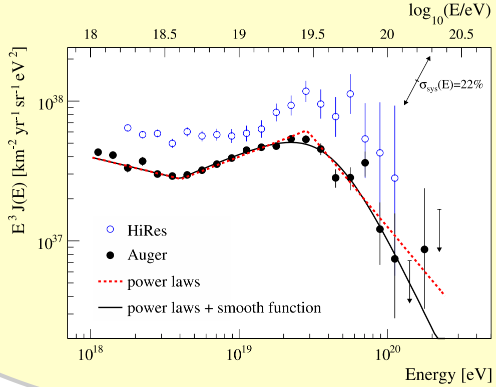
Auger finds correlation of arrival direction of cosmic rays with supergalactic plane $E > 6 \cdot 10^{19}$ eV

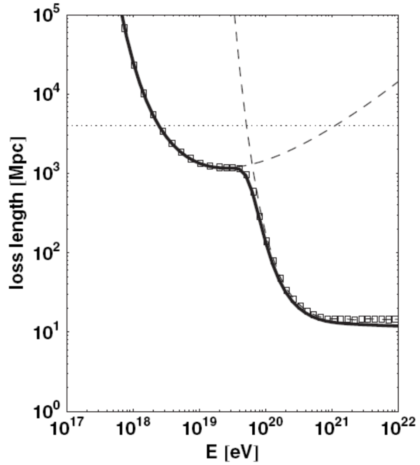
arrival direction of CRs is anisotropic for highest energies $E > 6 \cdot 10^{19}$ eV

(weak) correlation between arrival direction and position of AGNs

$\rightarrow$ further investigations

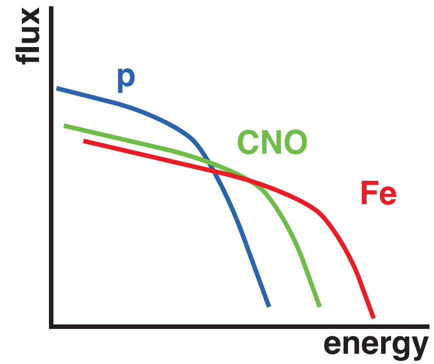
energy spectrum





GZK effect

light composition

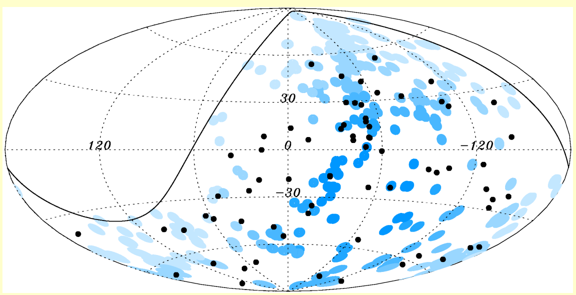


max energy of accelerators

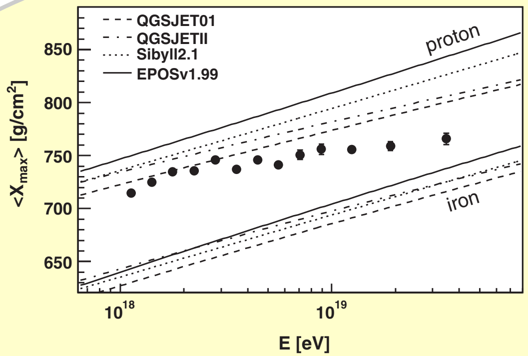
heavy composition

PIERRE
AUGER
OBSERVATORY

?



arrival direction

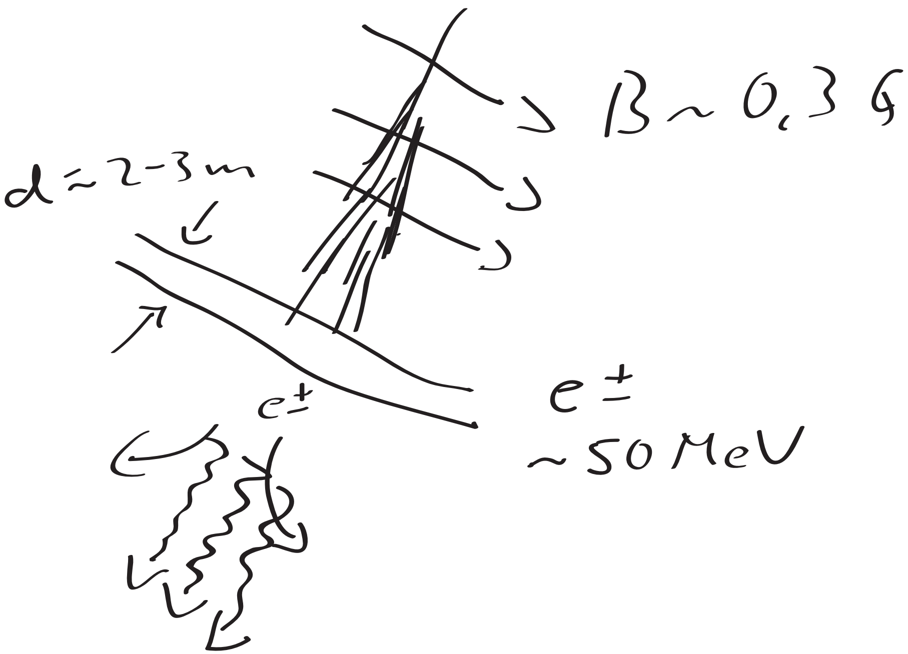


mass composition

Radio detection of air showers

a new technique to measure the properties of air showers/cosmic rays at energies $> 10^{16}$ eV

Coherent geosynchrotron radio emission



- CRs produce showers in atmosphere
- shower front is 2-3 m thick $\sim$ wavelength at 100 MHz
- $e^\pm$ emit synchrotron radiation in B field

- emissions from all $e^\pm$ add up coherently
- radio power grows quadratically with N_e

=> total energy $E_0 = N_e \cdot \bar{E}_e$

=> power $\propto \bar{E}_e^2 \propto N_e^2$

=> γ flares on 20ns time scales

more detail:

synchrotron radiation of electrons in B field of Earth

general formula (e.g. Jackson):

$$E = \frac{e}{4\pi\varepsilon_0}\left[\frac{n-v}{\gamma^2(1-v\cdot n)^3 R^2}\right]_{ret} + \frac{e}{4\pi\varepsilon_0 c}\left[\frac{n\times(n-v)\times\dot{v}}{(1-v\cdot n)^3 R}\right]_{ret}$$

general formula for accelerated relativistic particle

n direction of observer

v velocity of particle

second term represents synchrotron emission

when $\dot{v} = \frac{e}{\gamma m} v \times B$ Lorentz acceleration in B field

assume observation point is on shower axis:

$v // n$

$$\Rightarrow E_2 \propto u \times \{ (u - v) \times (v \times B) \}$$

$$\propto \underbrace{\{ u (v \times B) \}}_{=0 \text{ on axis}} (u - v) - \{ u (u - v) \} (v \times B)$$

$$\propto -(1 - v)(v \times B)$$

$$\propto -(v \times B)$$

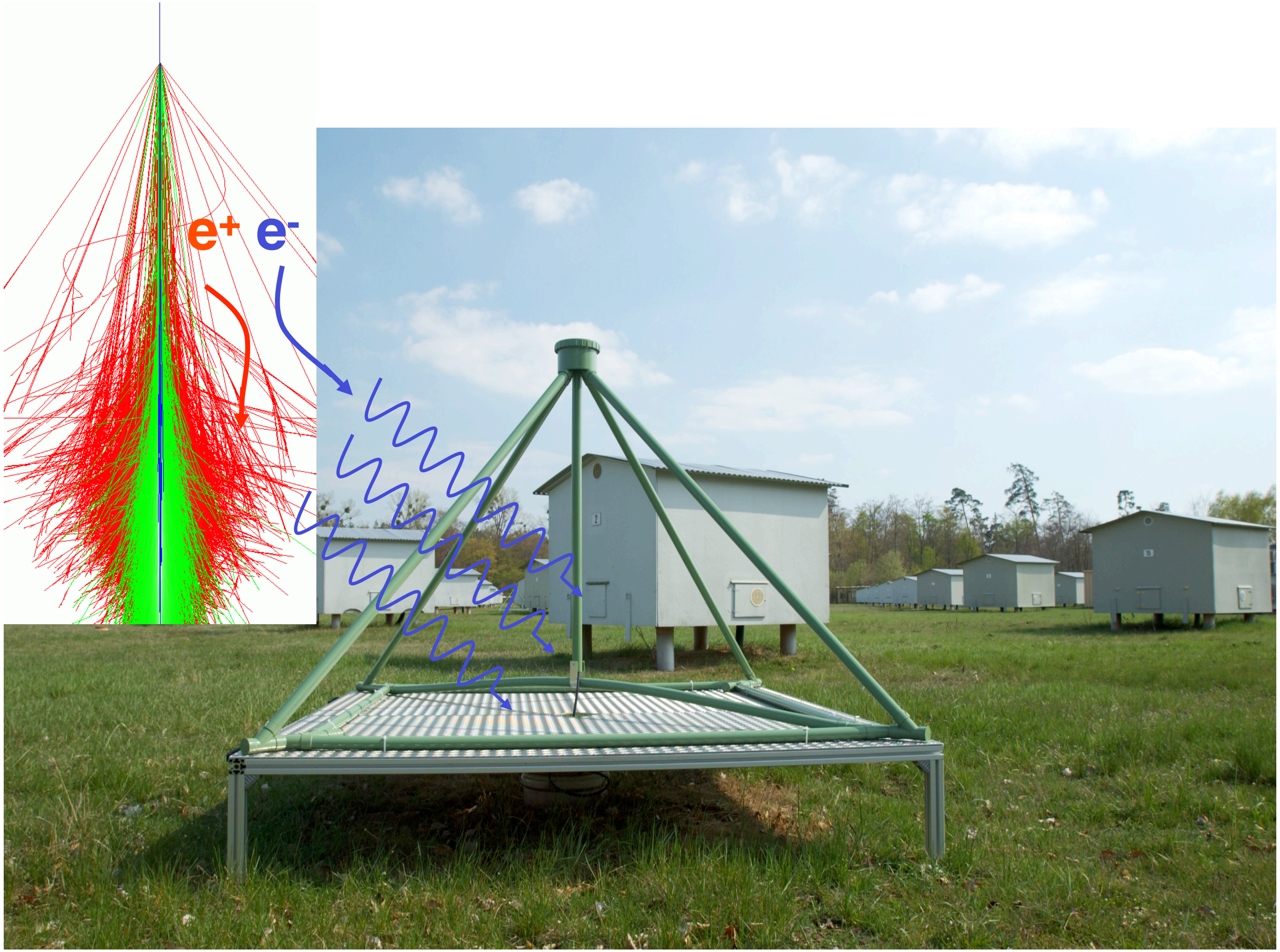
$\rightarrow$ field strength of observed radiation is expected as $E \propto -v \times B$

in addition to this geosynchrotron emission there is a contribution ($< 20\%$)

- from Askaryan effect (charge separation)

- Čerenkov radiation

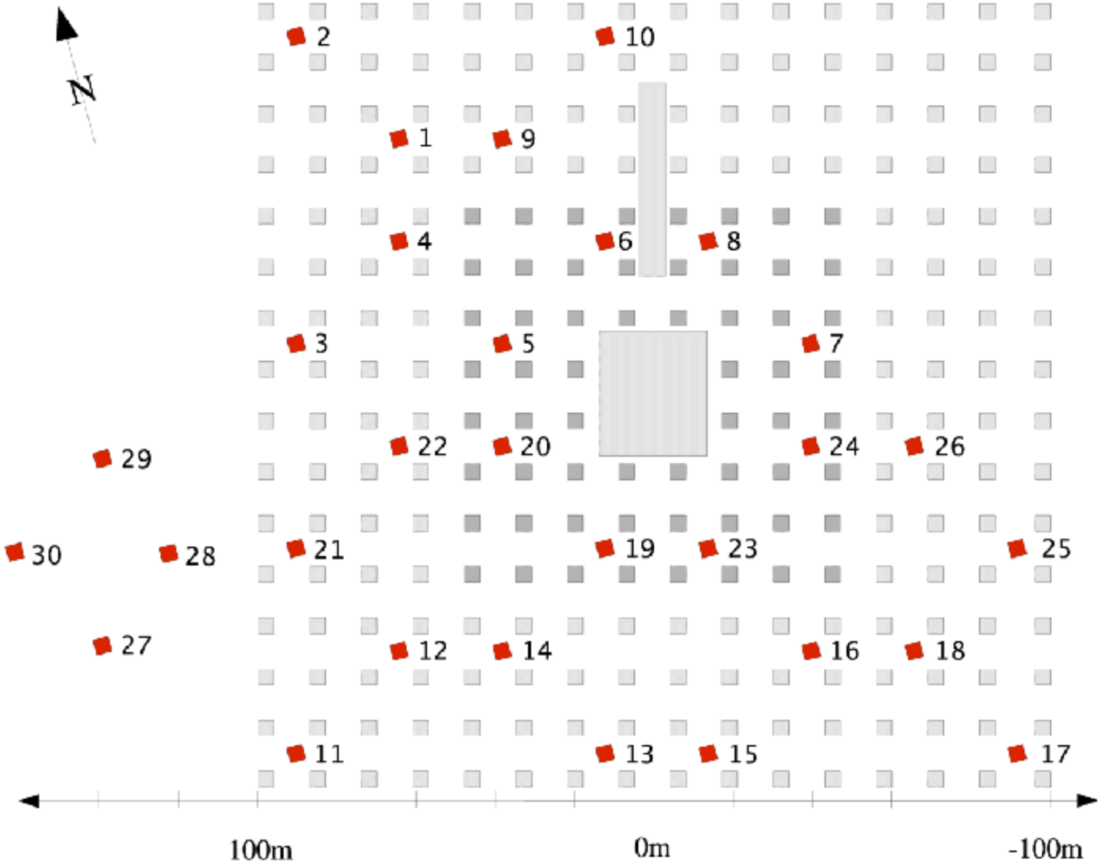
Measurement of Radio Emission in Extensive Air Showers

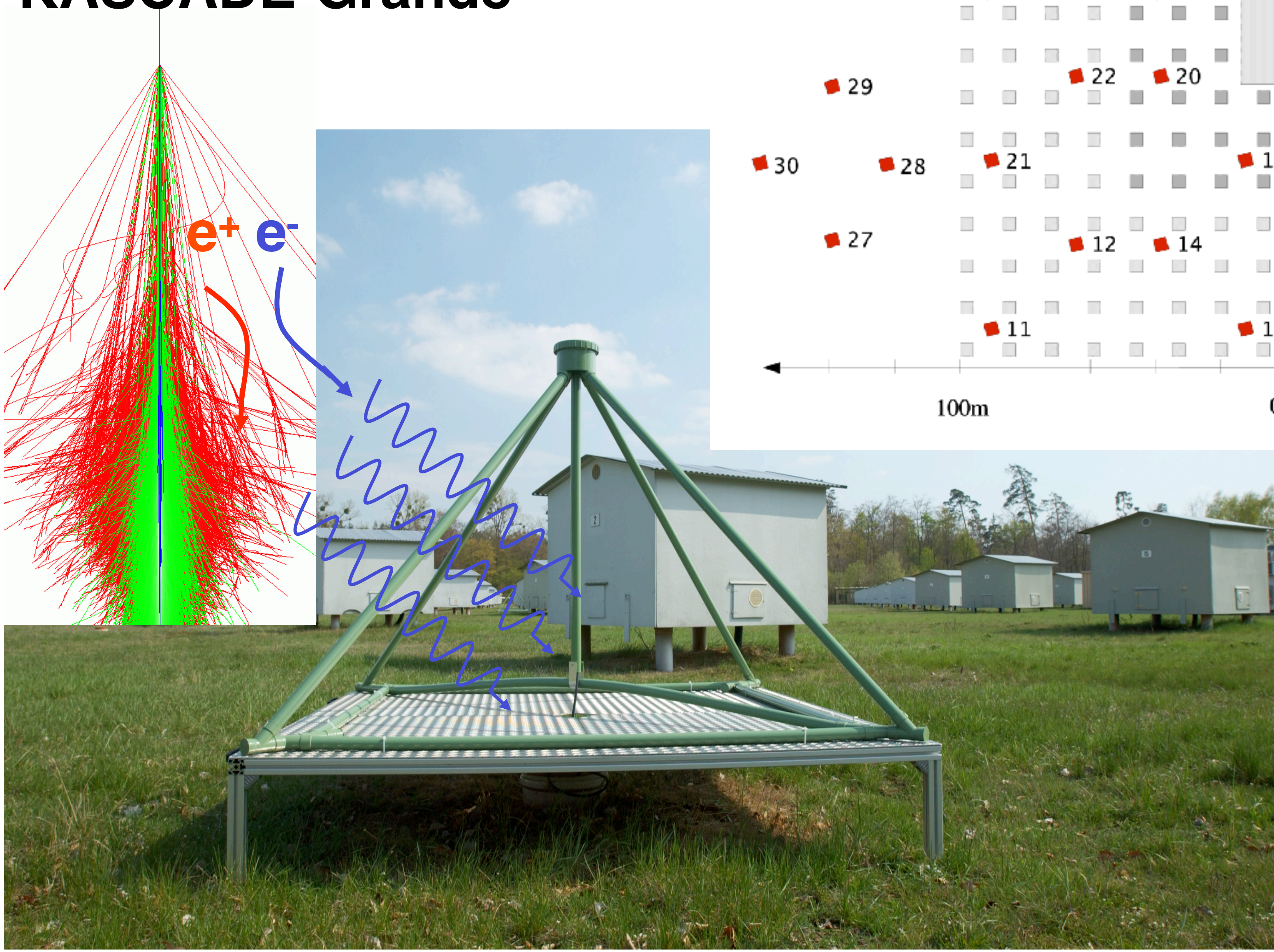


LOPES

Lofar Prototype Station

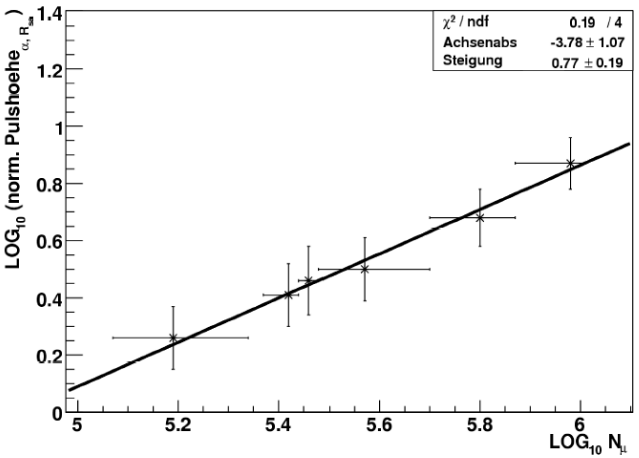
30 antennas operating at KASCADE-Grande



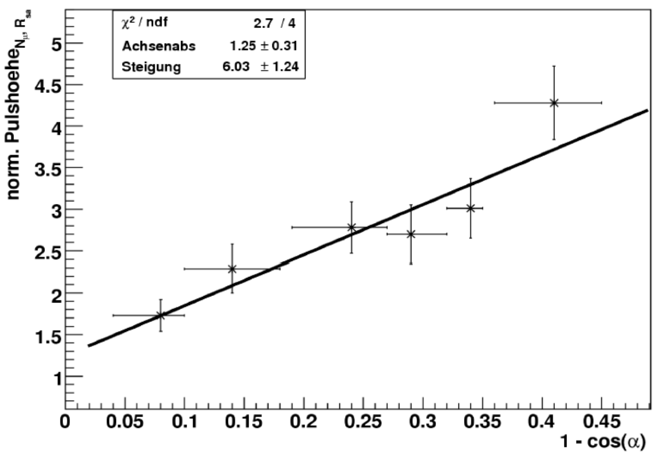


Correlation between radio signal and air shower parameters

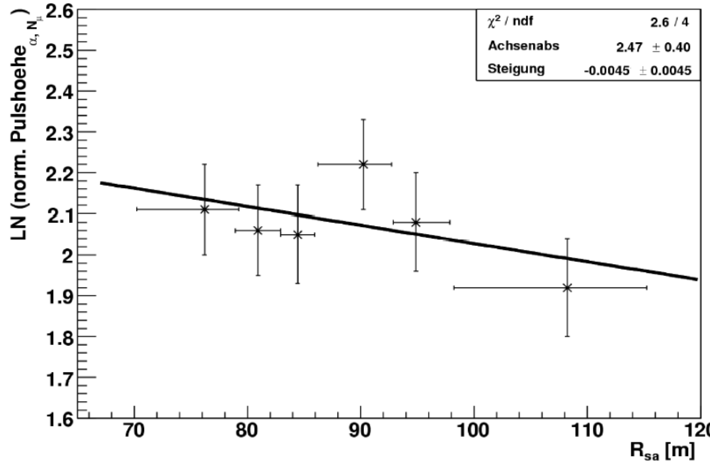
.. number of muons, i.e. primary energy



.. angle with respect to geomagnetic field



.. distance to shower axis



E. Bettini, diploma thesis, U Karlsruhe, 2006

$$\varepsilon_{est} = (11 \pm 1)((1.16 \pm 0.025) - \cos\alpha)\cos\theta \exp\left(\frac{-R}{236 \pm 81\ \mathrm{m}}\right)\left(\frac{E_p}{10^{17}\ \mathrm{eV}}\right)^{0.95\pm0.04} \left[\frac{\mu\mathrm{V}}{\mathrm{m\,MHz}}\right]$$

- α geomagnetic angle
- θ zenith angle
- r distance to shower axis
- E_0 energy of primary particle

A. Horneffer et al., 30th ICRC 4 (2008) 83

CODALEMA: Geomagnetic Origin v x B

A model to understand the asymmetry

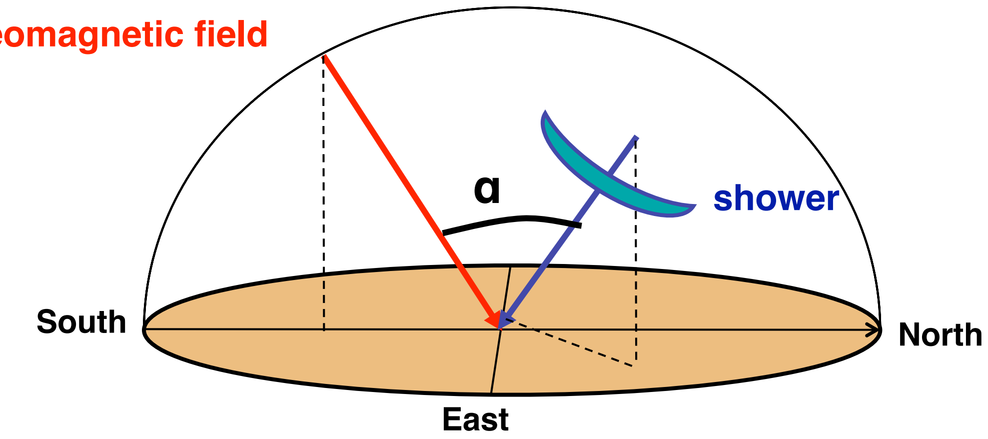
Hypothesis:

- The electric field is proportional to the Lorentz force E ~ Iv x BI
  - Charged particles in the shower are deflected by the geomagnetic field
  - Electric field polarization in the direction of the Lorentz force :

    a linear polarization is assumed E // to v x B

-The number of count (i.e. the efficiency) depends on the electric field magnitude:

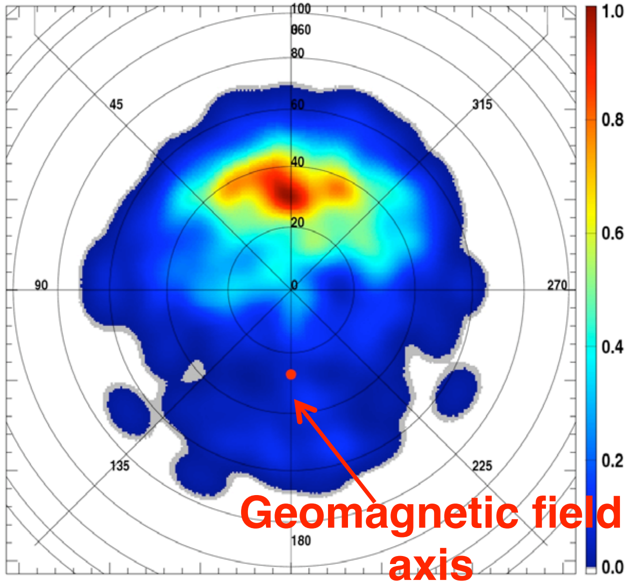
a simple linear dependence is assumed

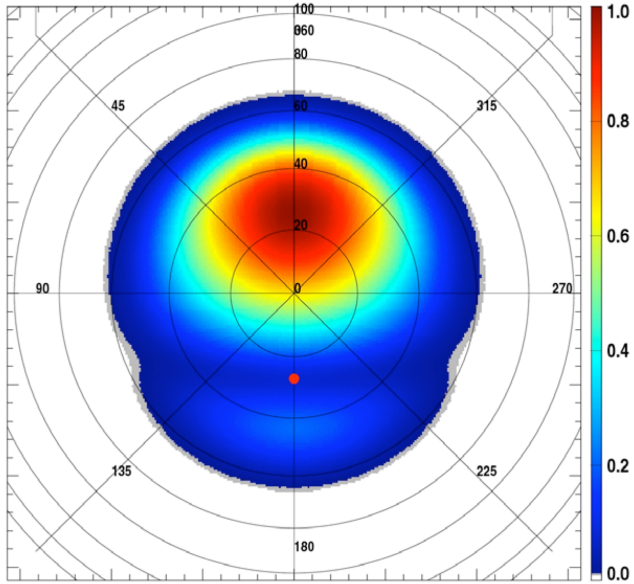


D. Arduin et al., Astropart. Phys. 31 (2009) 192

CODALEMA: Geomagnetic Origin v x B

sky map of radio events (E-W component)



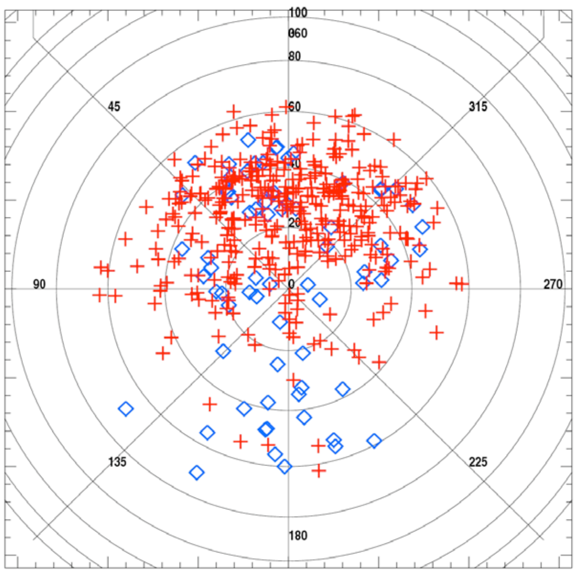


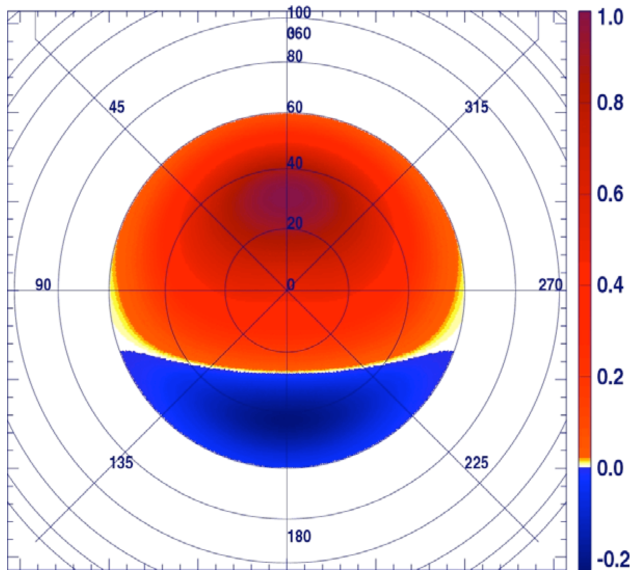
measured **simulated**

asymmetry of observed events

Lorentz force $\vec{v} \times \vec{B}$

v direction of shower axis
B direction of Earth magnetic field



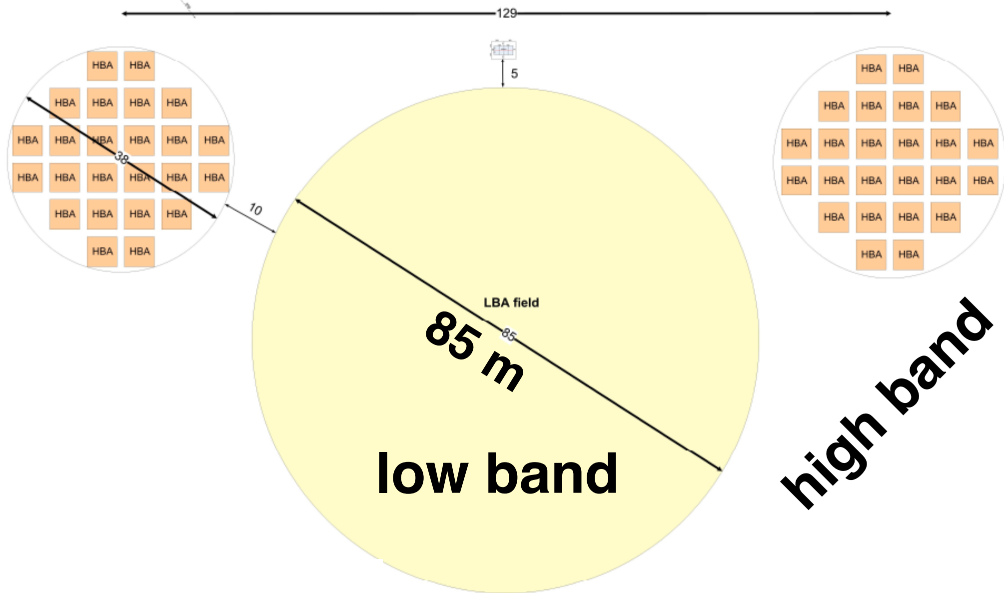


polarity of electric field

geomagnetic origin

D. Arduin et al., Astropart. Phys. 31 (2009) 192

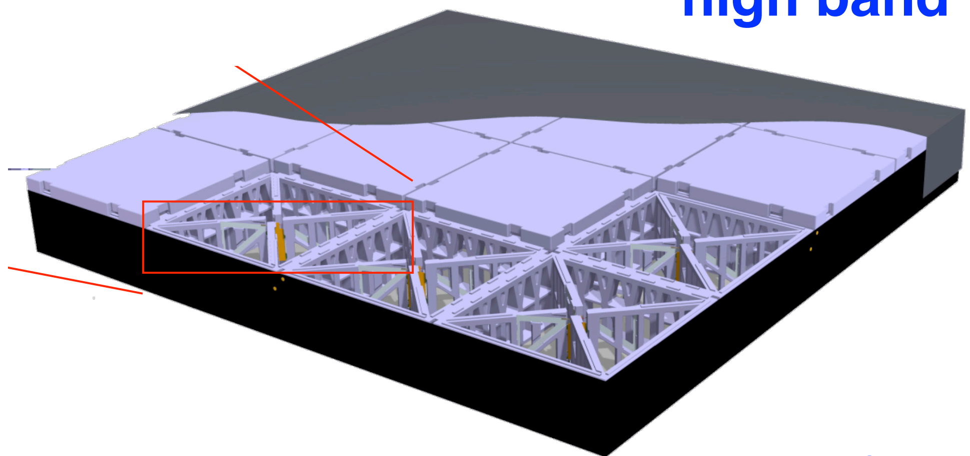
Station Layout



each (dutch) station:

96 low-band antennae 30- 80 MHz

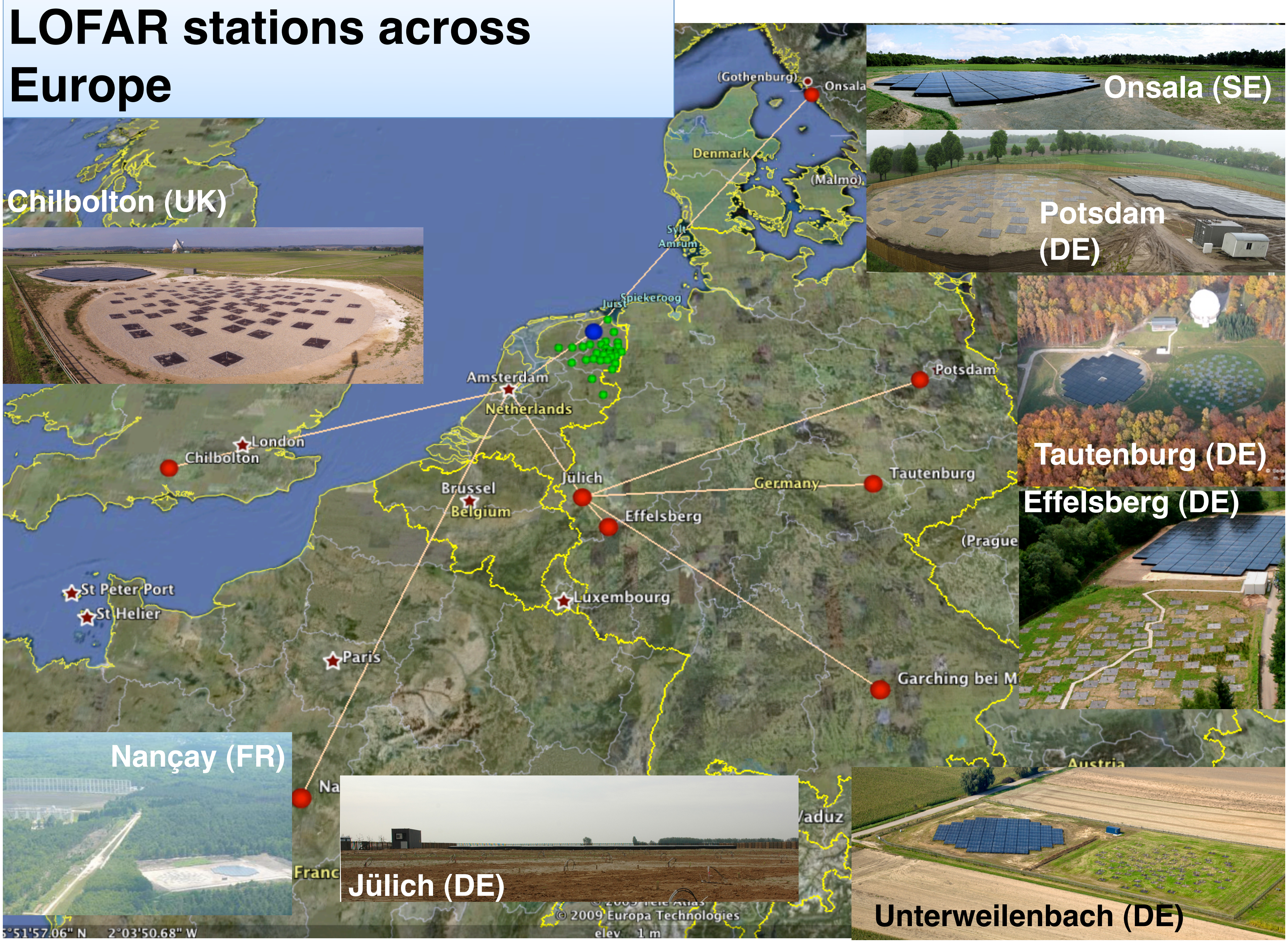
high-band antennae (2x24 tiles) 120-240 MHz

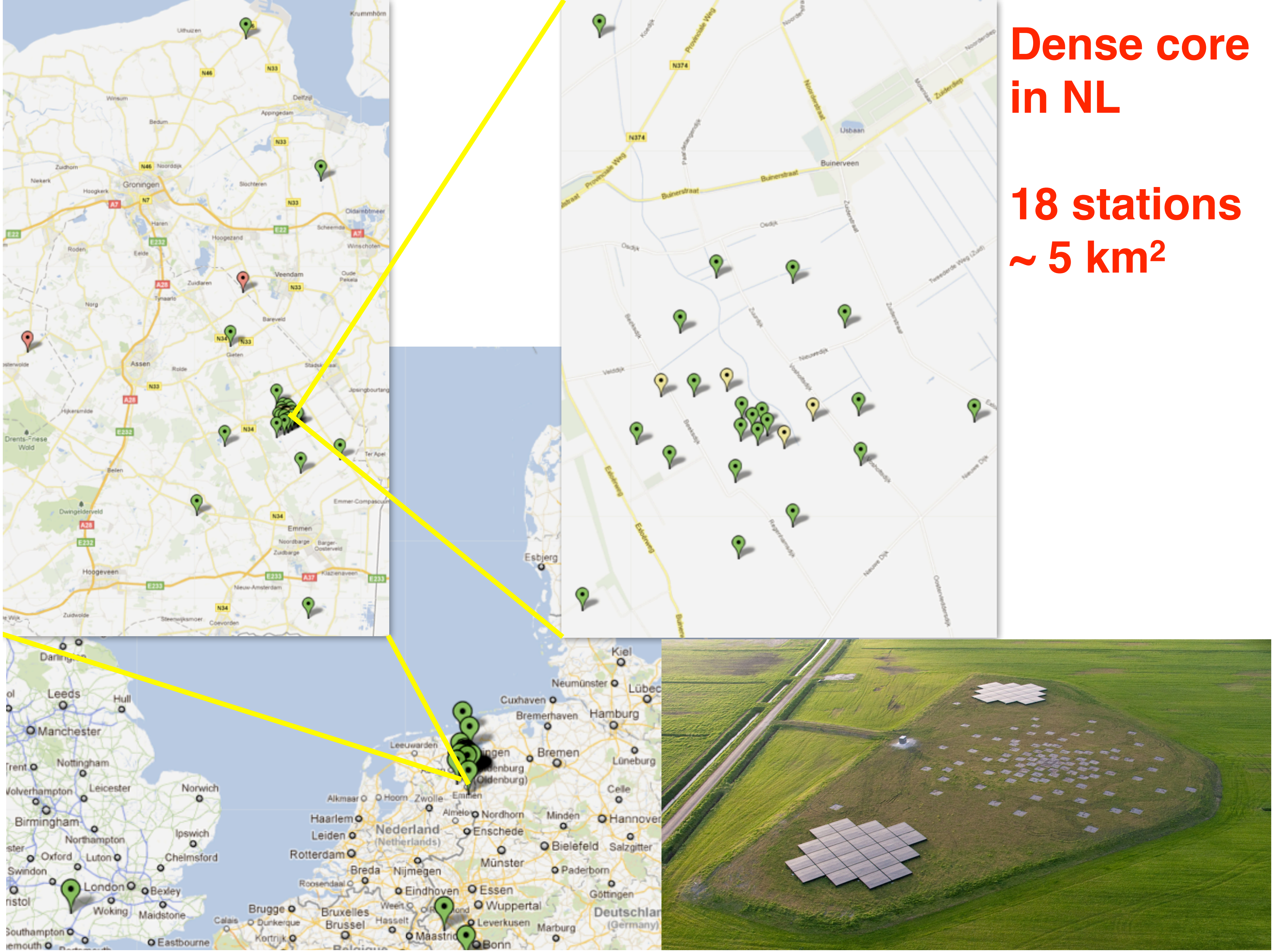


www.lofar.org

Construction of stations

LOFAR stations across Europe





Dense core in NL

18 stations

~ 5 km^2


early July 2008


late July 2008


September 2008


October 2008


14 August 2009

24 August 2009

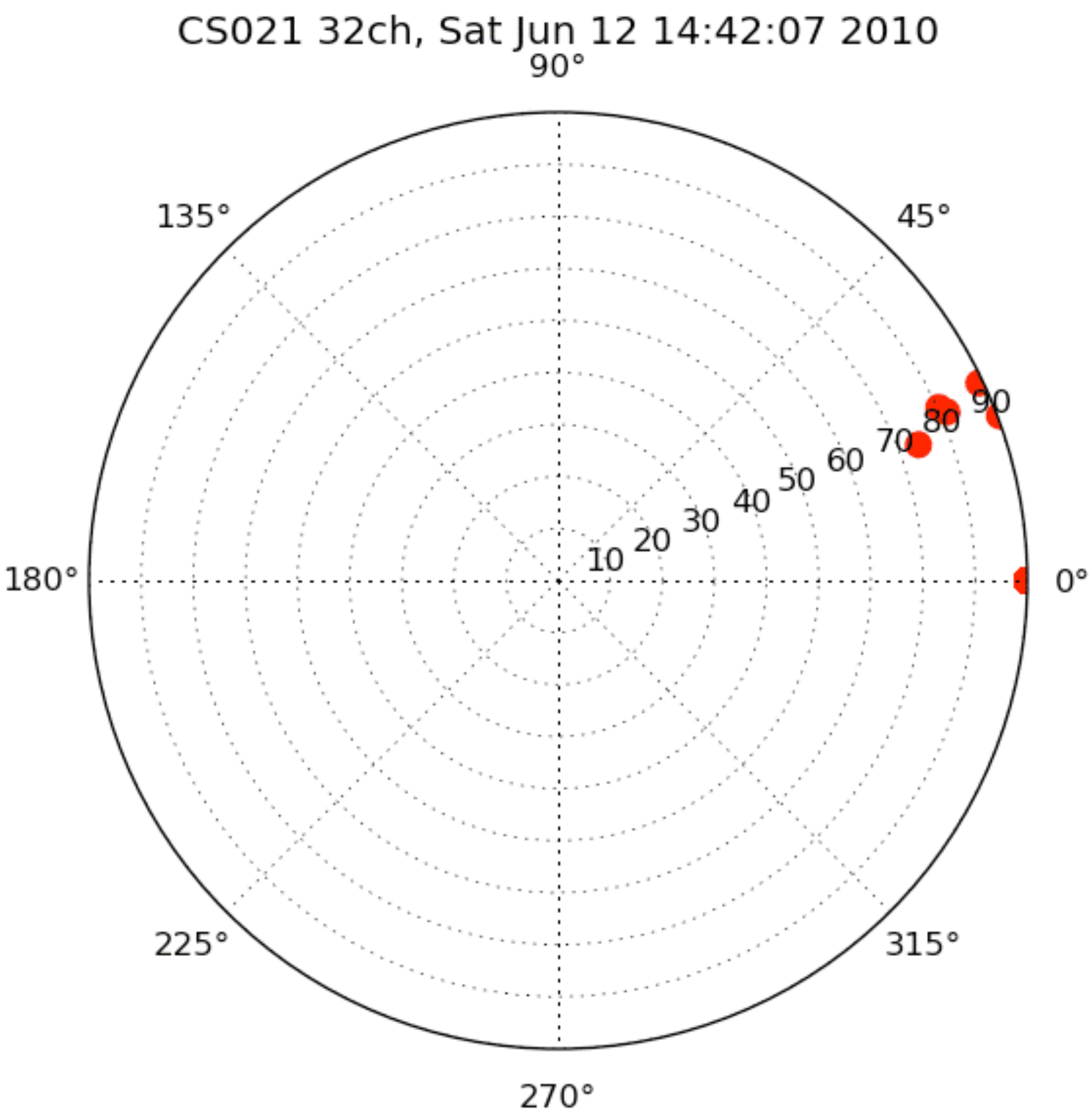

9 March 2010


23 May 2010

LOFAR Opening 12th June 2010

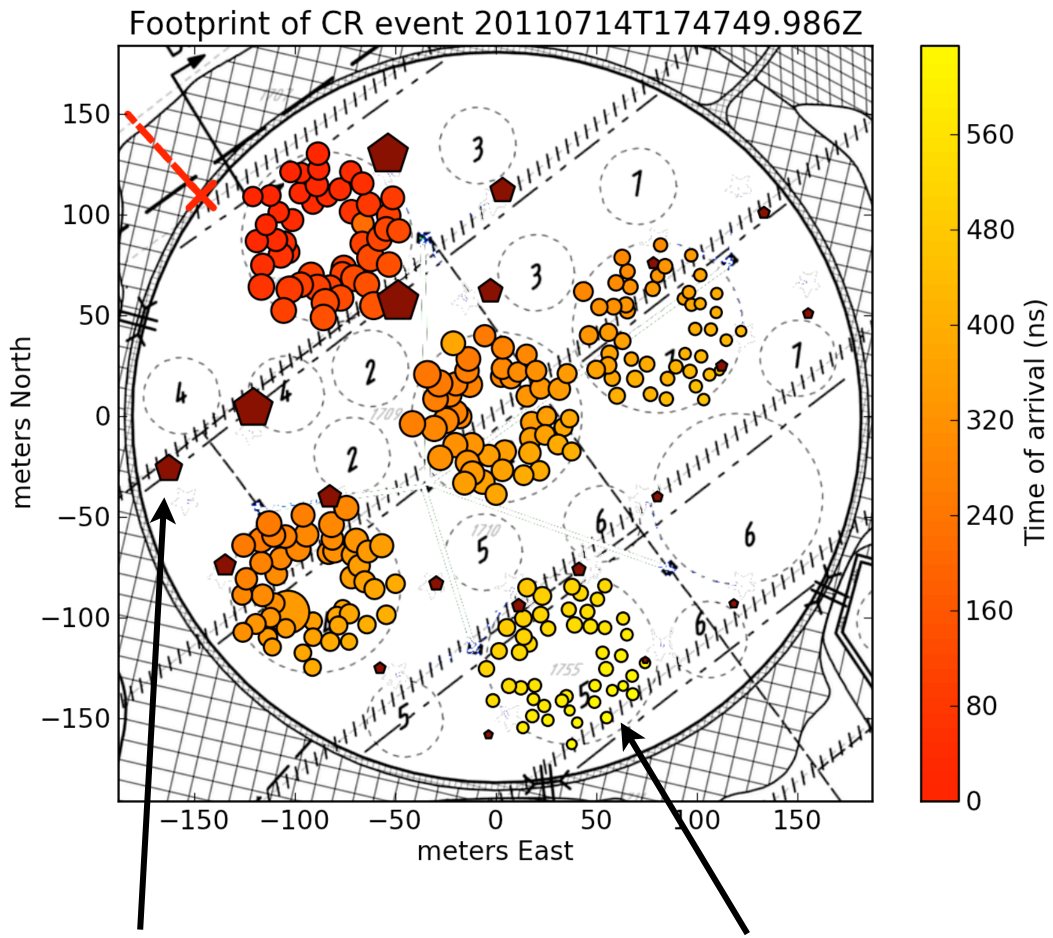
LOFAR

Royal Festive Intermezzo (RFI)



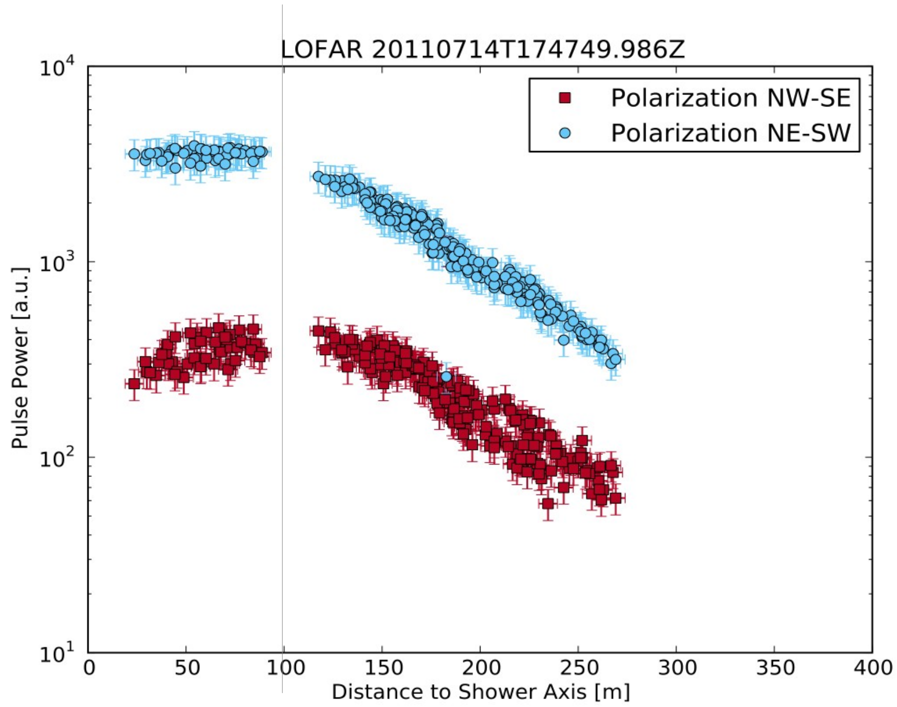
A measured air shower

lateral distribution



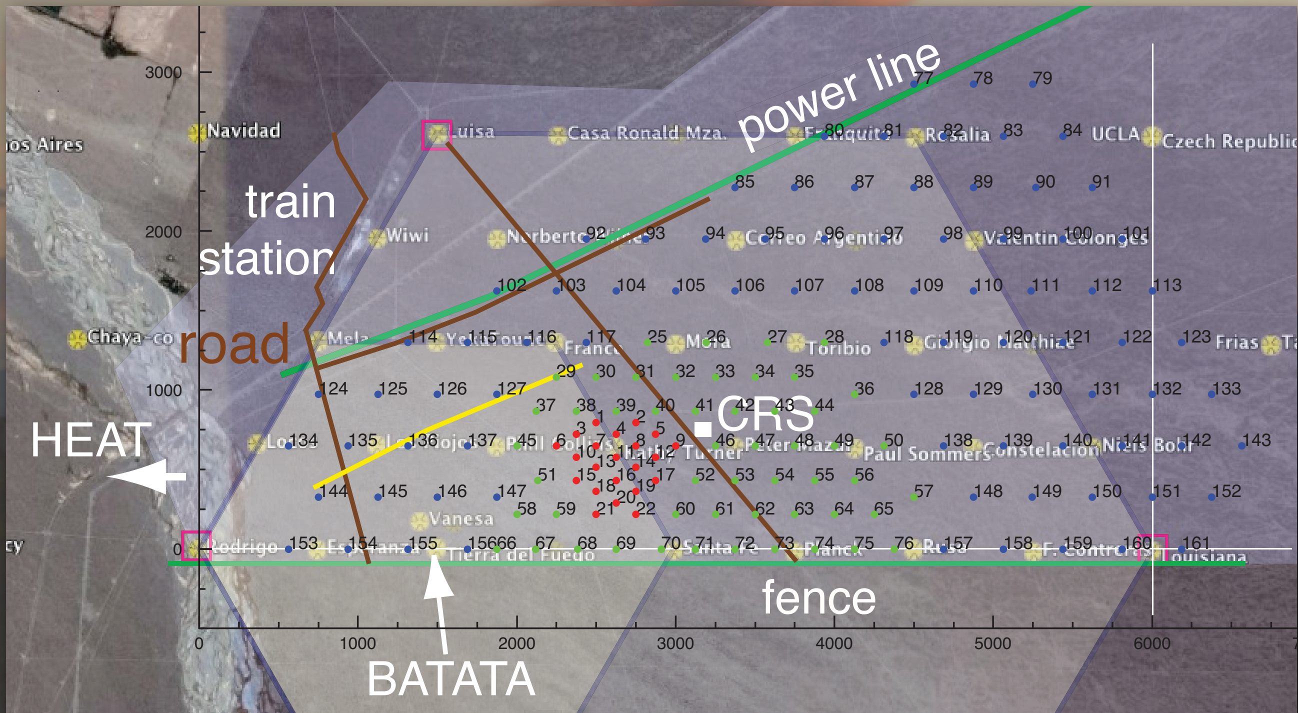
scintillation detector

radio antennas

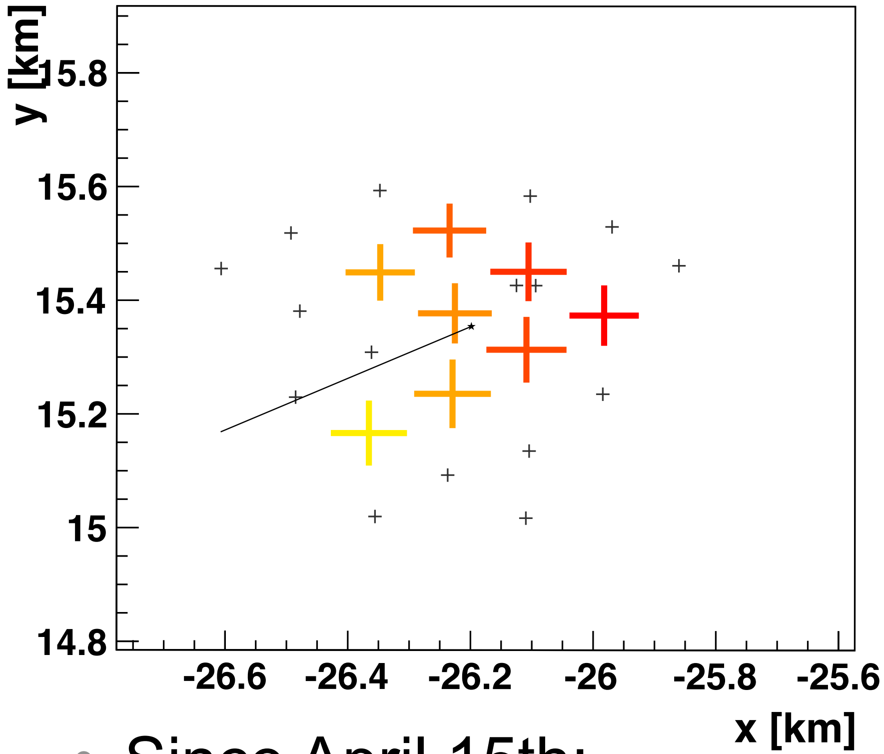


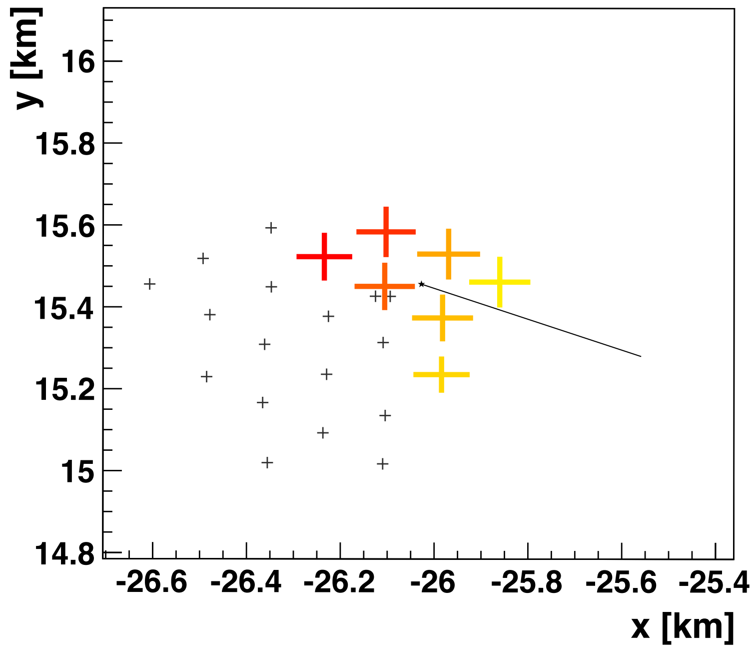
AERA
Auger Engineering Radio Array

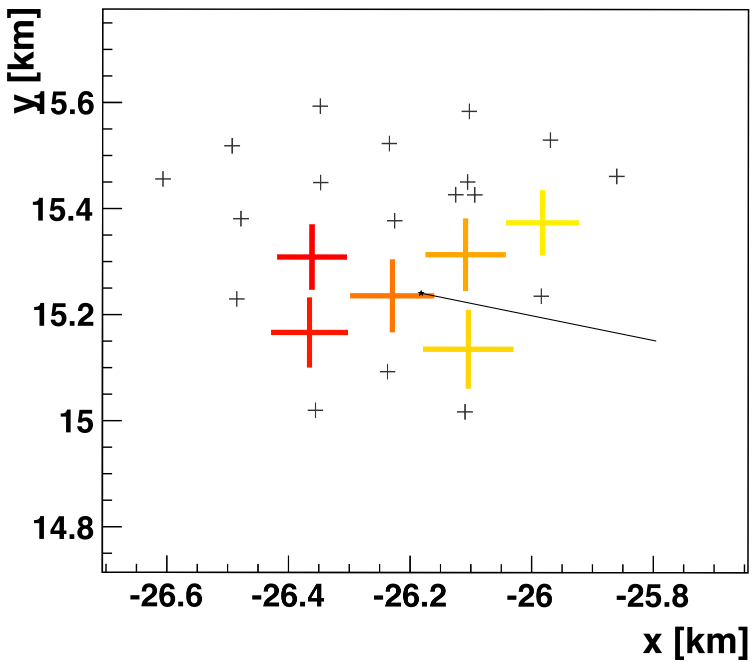
Objective:
- measure radio emission from EAS in frequency range 30 MHz - 80 MHz
- ~20 km² array with ~160 antennas
- operation together with infill/HEAT/AMIGA
- three antenna spacings to cover efficiently 17.2 < lg E/eV < 19.0
- measure composition of cosmic rays in energy region of transition from galactic to extragalactic cosmic rays



Events

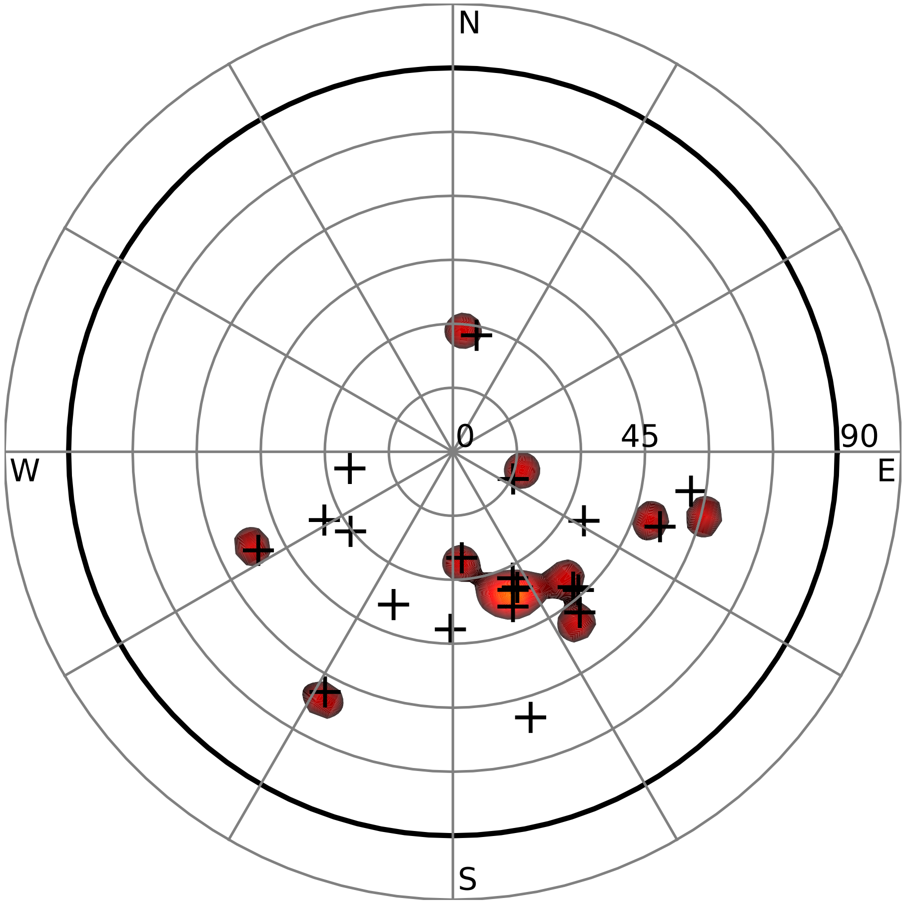




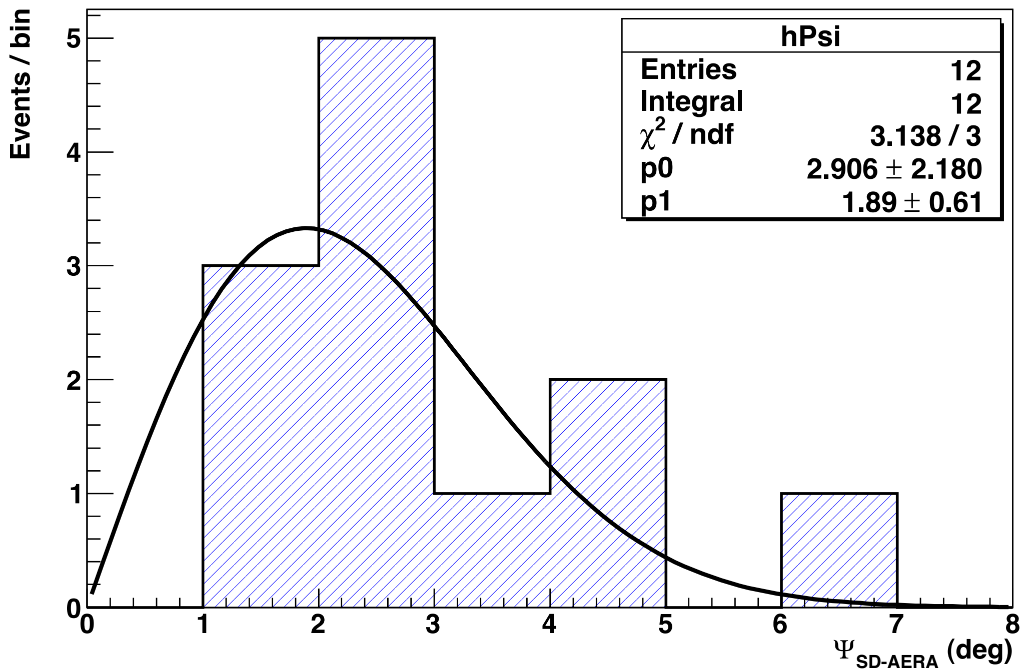


- Since April 15th:
  - self-triggered cosmic ray events in coincidence with SD
  - now: 24 events and counting
  - about 0.5 events per day

Arrival Directions



- Red: AERA
- Black: SD
- also AERA events with only 2 stations: no direction



High energy γ rays

In addition to charged particles we obtain information on the high-energy Universe from γ-rays

$$E \sim 100\,\text{MeV} \rightarrow 50\,\text{TeV}$$

Production & interactions

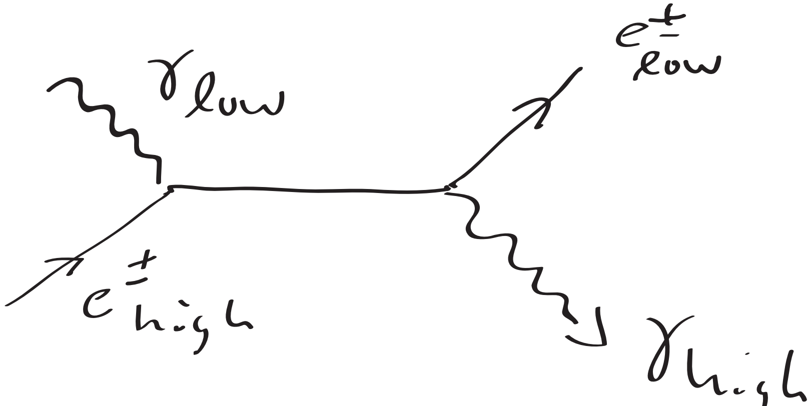
1) synchrotron radiation of electrons in B fields

depending on energy of electrons and strength of B field, the energy of photons ranges from radio (meV) to ~10 MeV

$$E_\gamma \propto B^2 \cdot \gamma_e^2$$

radiation is polarized

2) Inverse Compton scattering



energy of electrons is transfered to photons "heating of photons through electrons"

$$E_\gamma \propto U_{rad} \cdot \gamma_e^2$$

temperature (kinetic energy) of photons

photon energies up to about E_e can be reached

3) Hadronic interactions

$$p + \text{'ISM'} \rightarrow \pi^0 + X$$
$$\hookrightarrow \gamma + \gamma$$

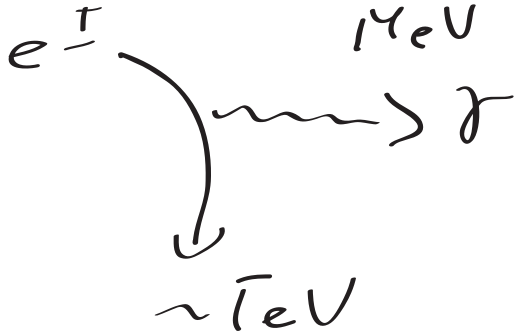
requires the presence of hadronic particles

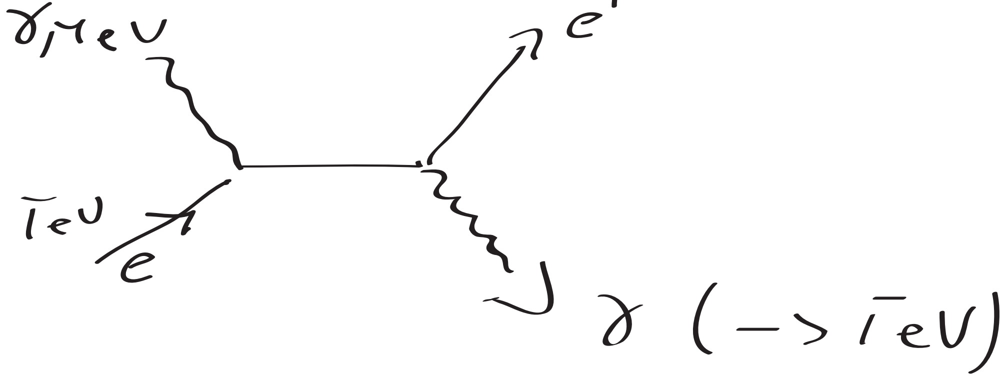
4) Bremsstrahlung

$$e + \text{target} \rightarrow \text{Bremsstrahlung}$$
$$E_\gamma \sim \frac{E_e}{2} \quad \text{(power law)}$$

important combination of 1) & 2)

synchrotron-self-Compton (SSC)





the photons for inverse Compton scattering are produced in situ

typical form of spectrum