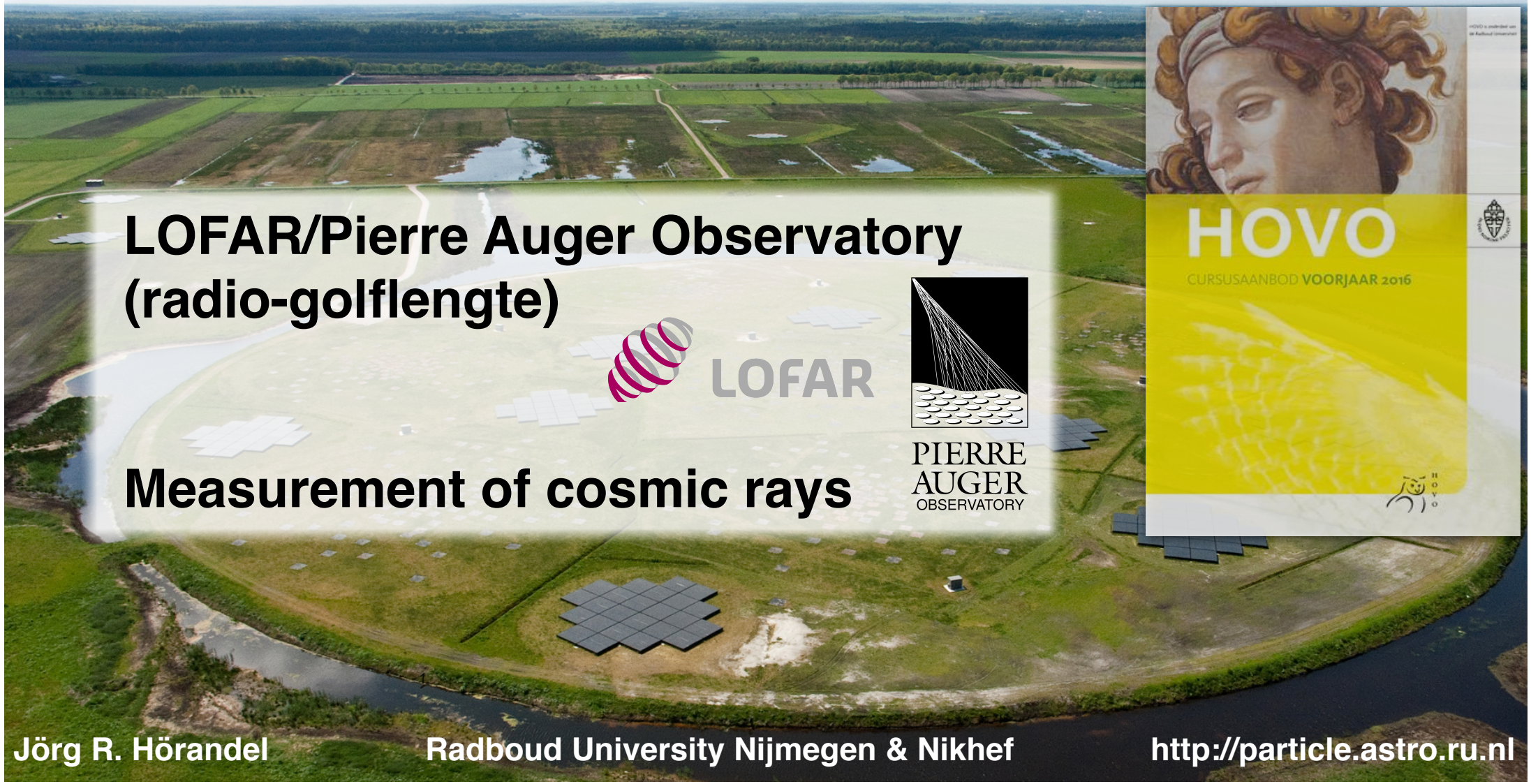
Technologie van de nieuwe sterrenkunde

25 January 2016



LOFAR/Pierre Auger Observatory (radio-golflengte)

LOFAR

PIERRE AUGER OBSERVATORY

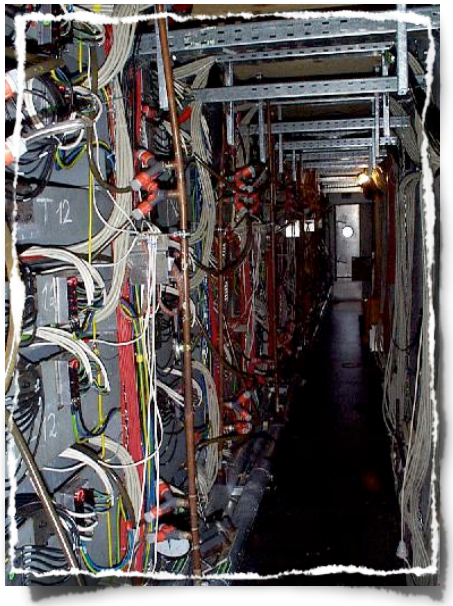
Measurement of cosmic rays

Jörg R. Hörandel

Radboud University Nijmegen & Nikhef

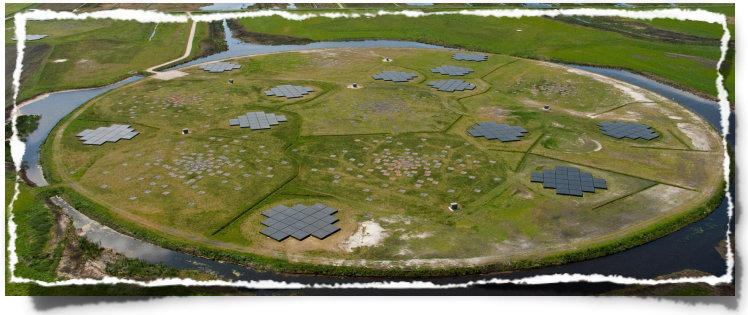
http://particle.astro.ru.nl

PhD Physics (University of Karlsruhe)
measurement of air showers with KASCADE

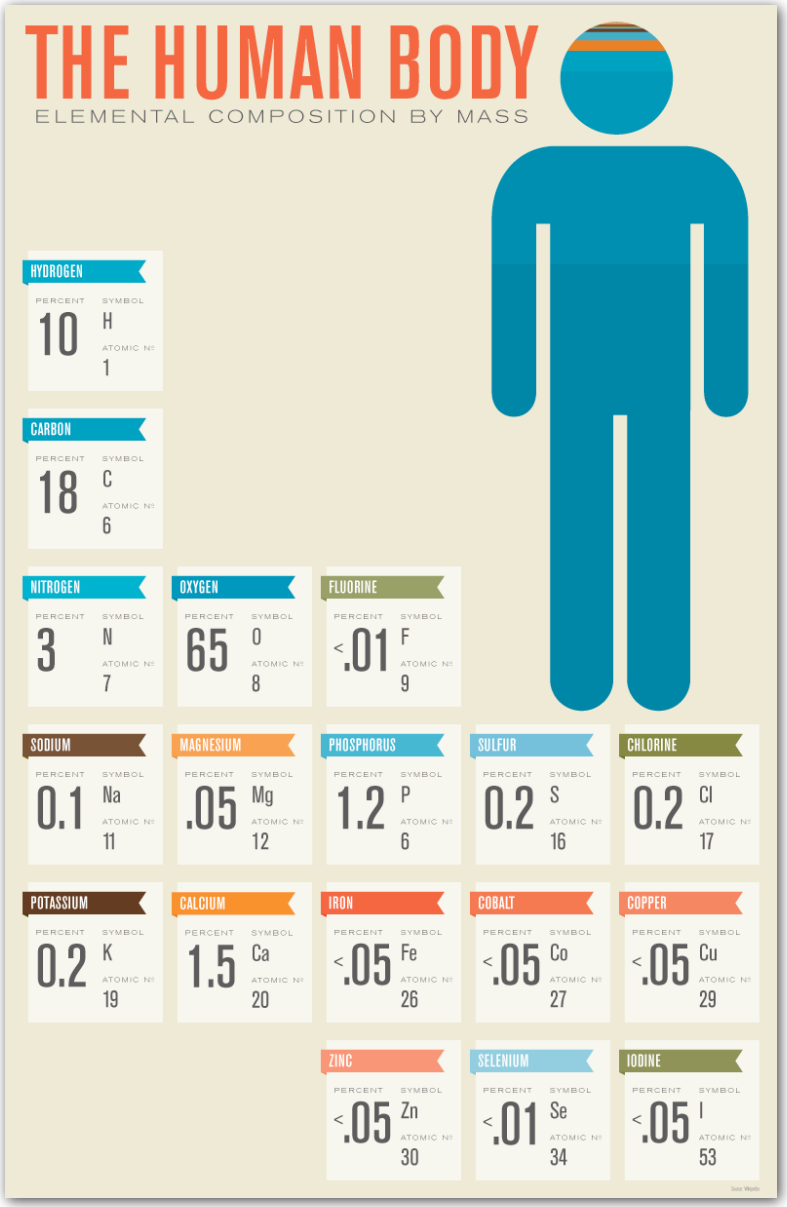


University of Chicago
direct measurement of cosmic rays with the TRACER balloon experiment

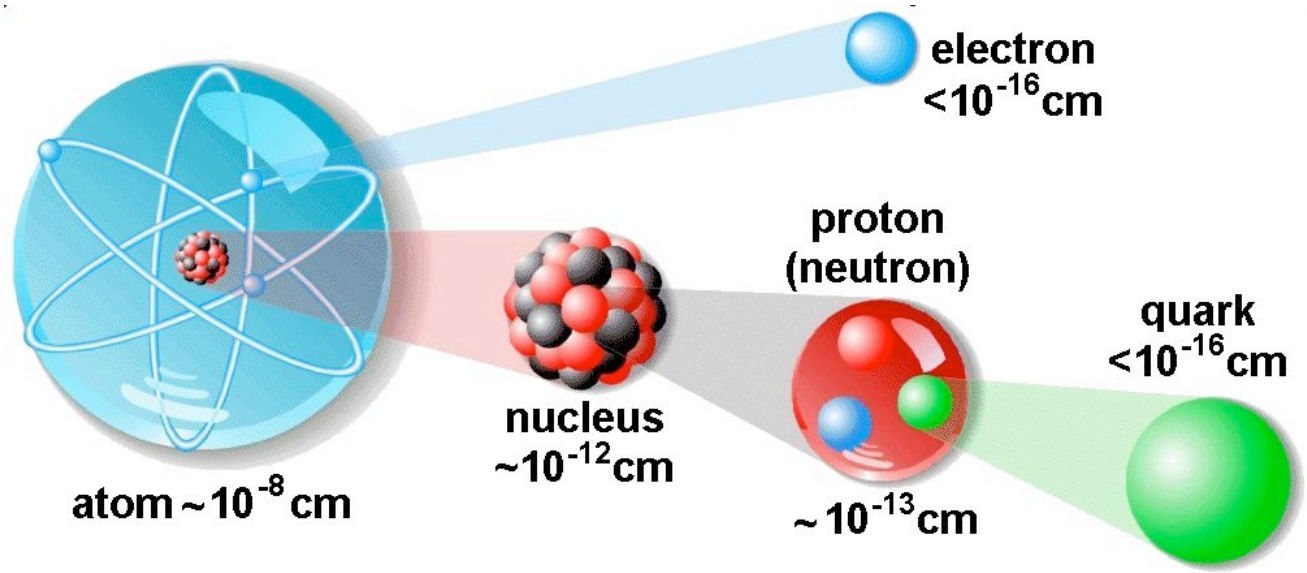
Radboud University Nijmegen
PI LOFAR key science project Cosmic Rays
taskleader Auger Engineering Radio Array



What are Cosmic rays?



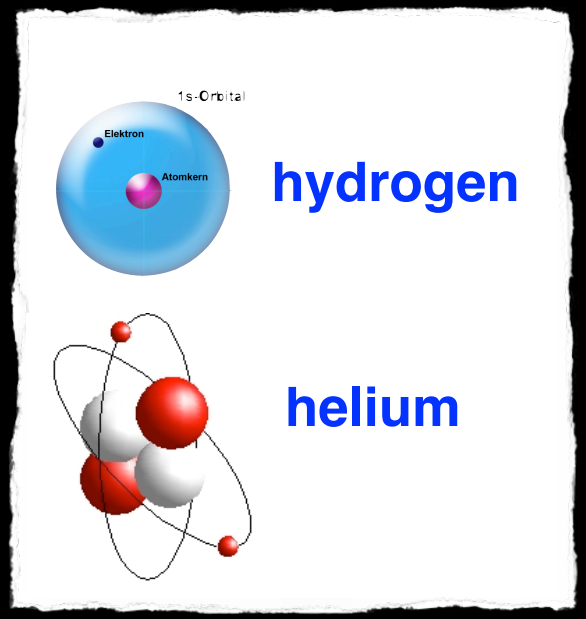
Structure of matter



Cosmic rays are ionized atomic nuclei, i.e. atoms without electrons

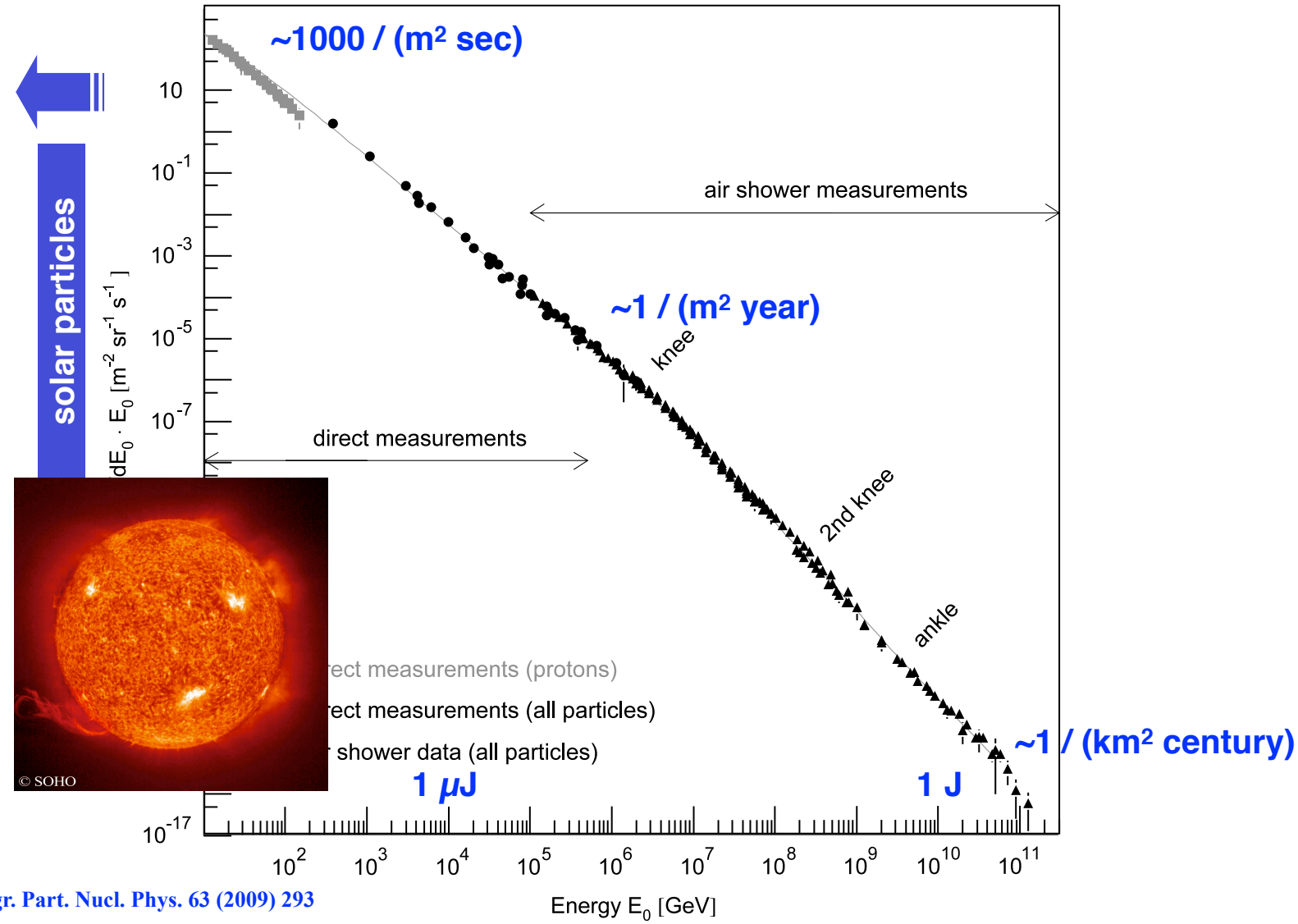
Cosmic rays are comprised of

~ 90% hydrogen nuclei (protons)
~ 9% helium nuclei (alpha particles)
~ 1% heavy nuclei



flux: ~ 1000 particles per square meter and second

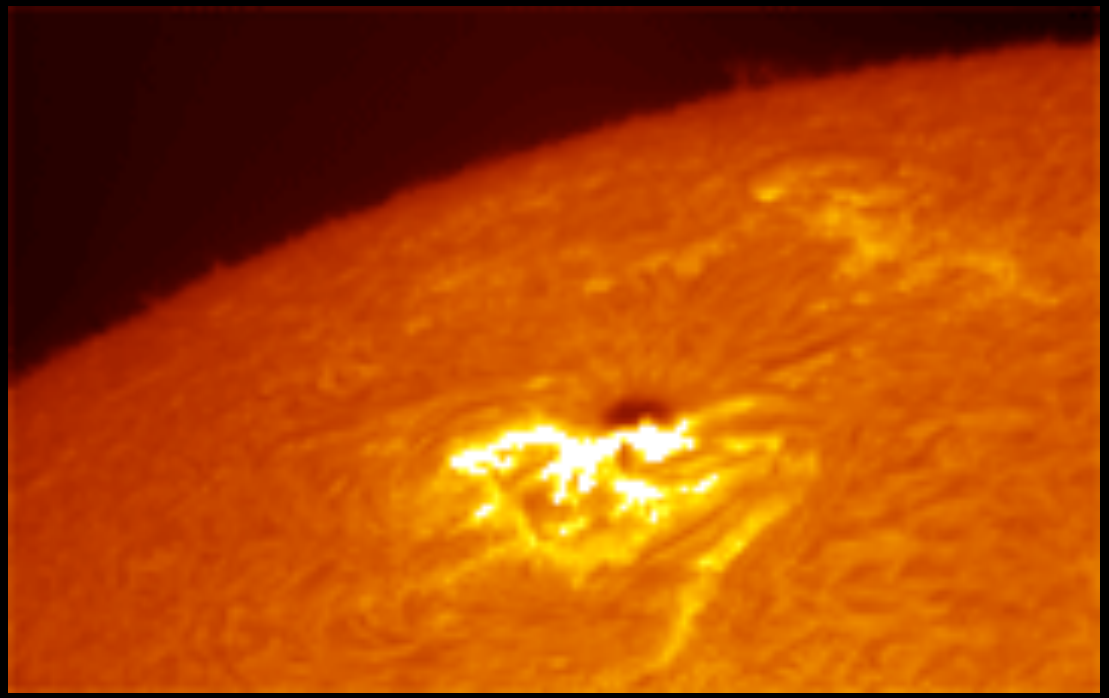
Energy Spectrum of Cosmic Rays

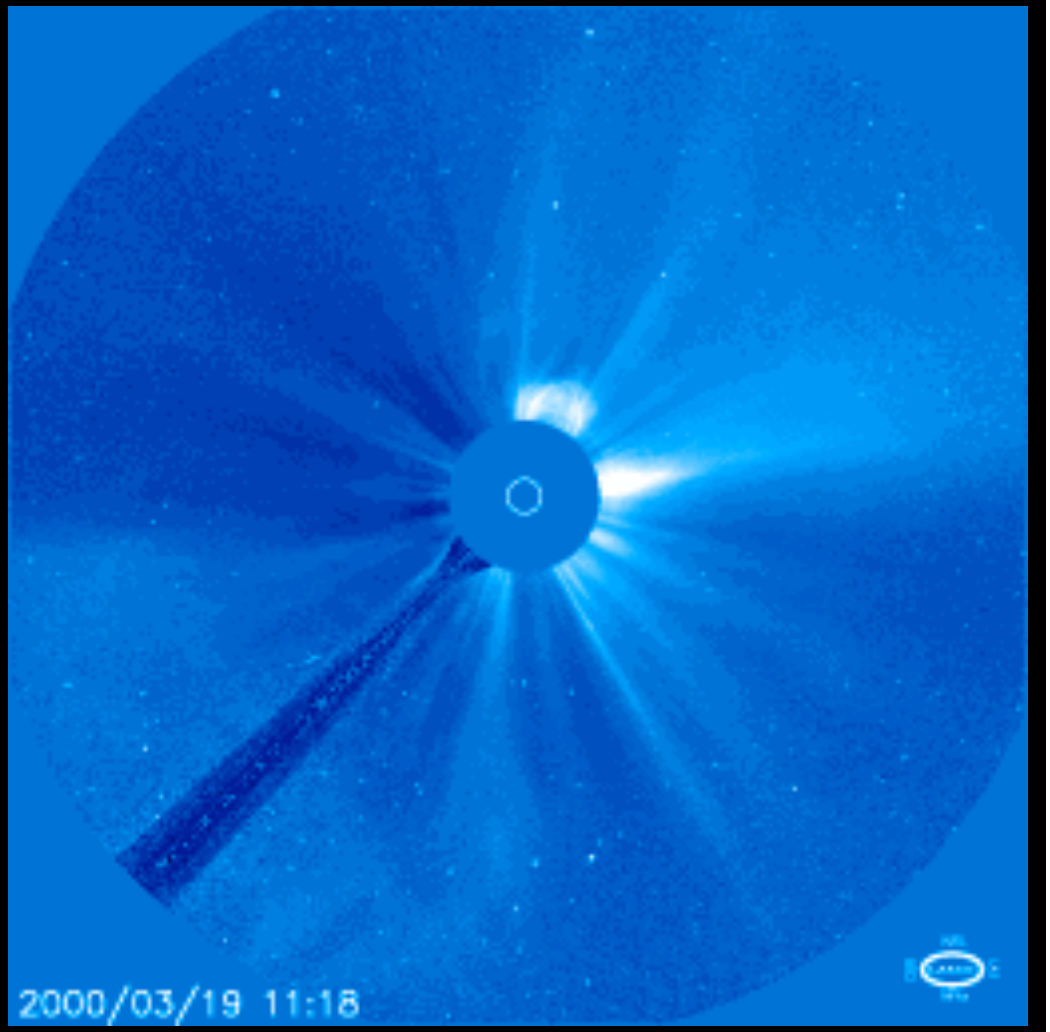


1 eV = 1.6 * 10^{-19} J

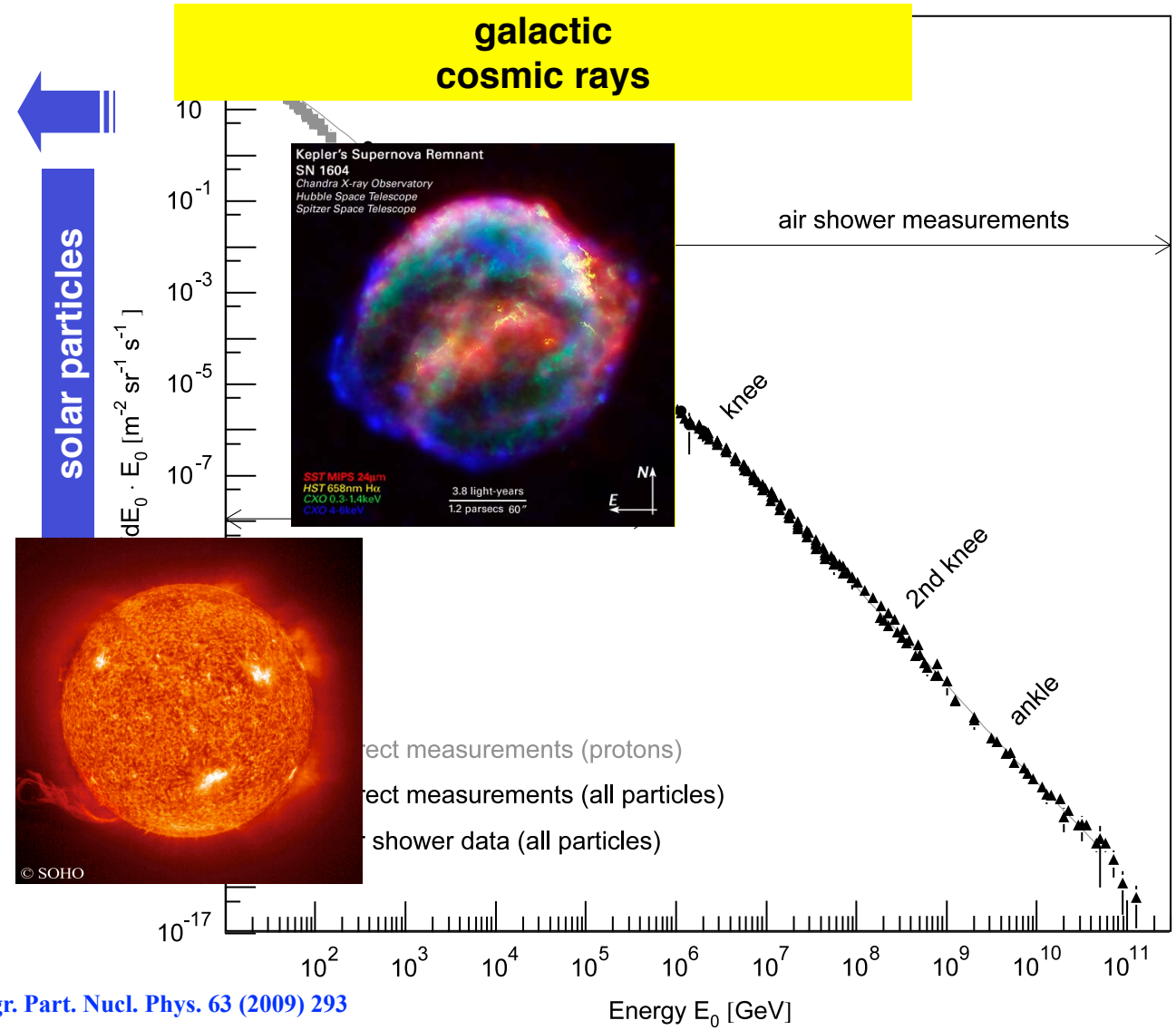
J. Blümer, R. Engel, JRH, Progr. Part. Nucl. Phys. 63 (2009) 293

Solar flares





Energy Spectrum of Cosmic Rays



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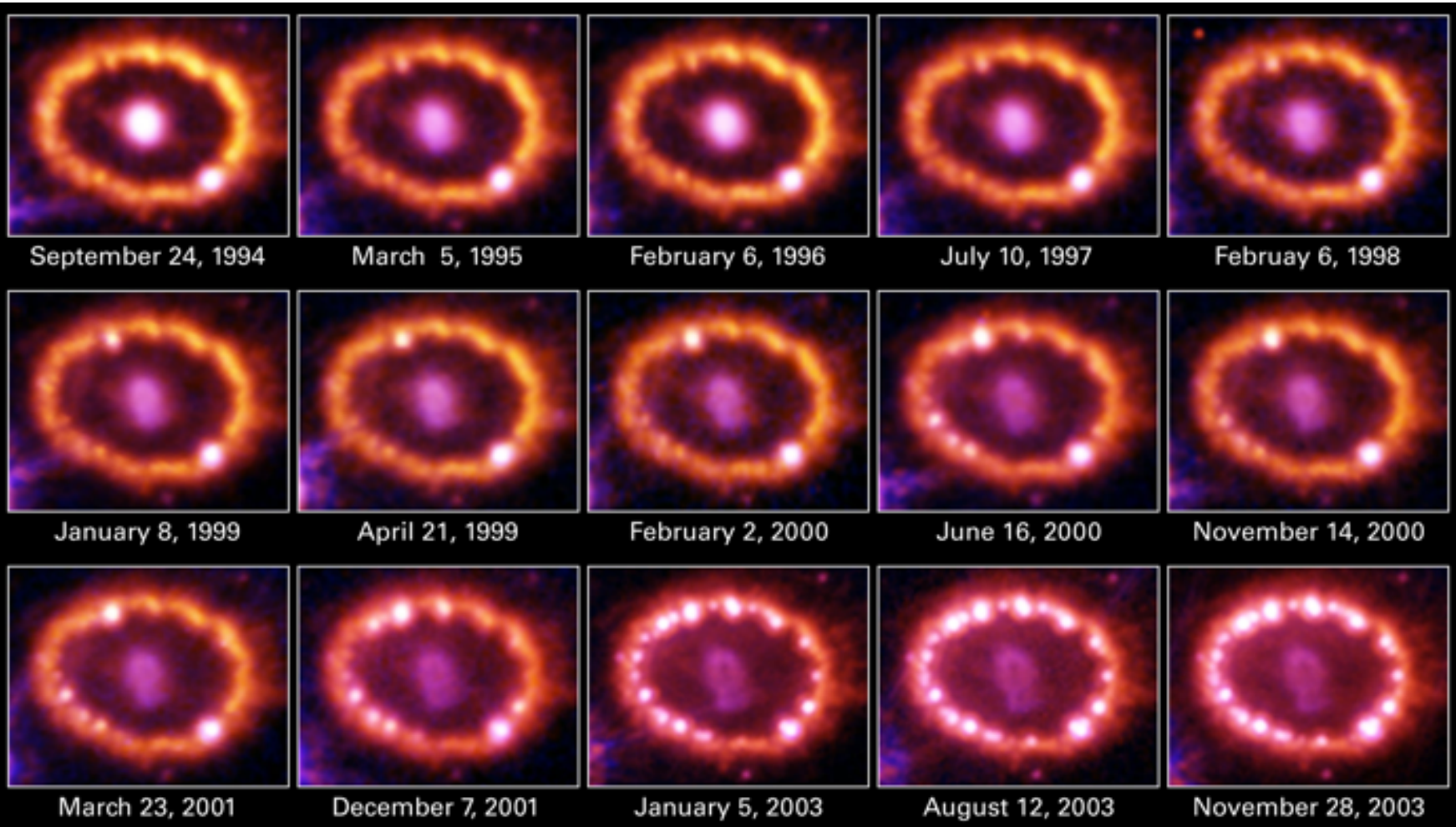
Acceleration of cosmic rays in supernova remnants

Cassiopeia A

animations based on measured data
(Chandra x-ray satellite)

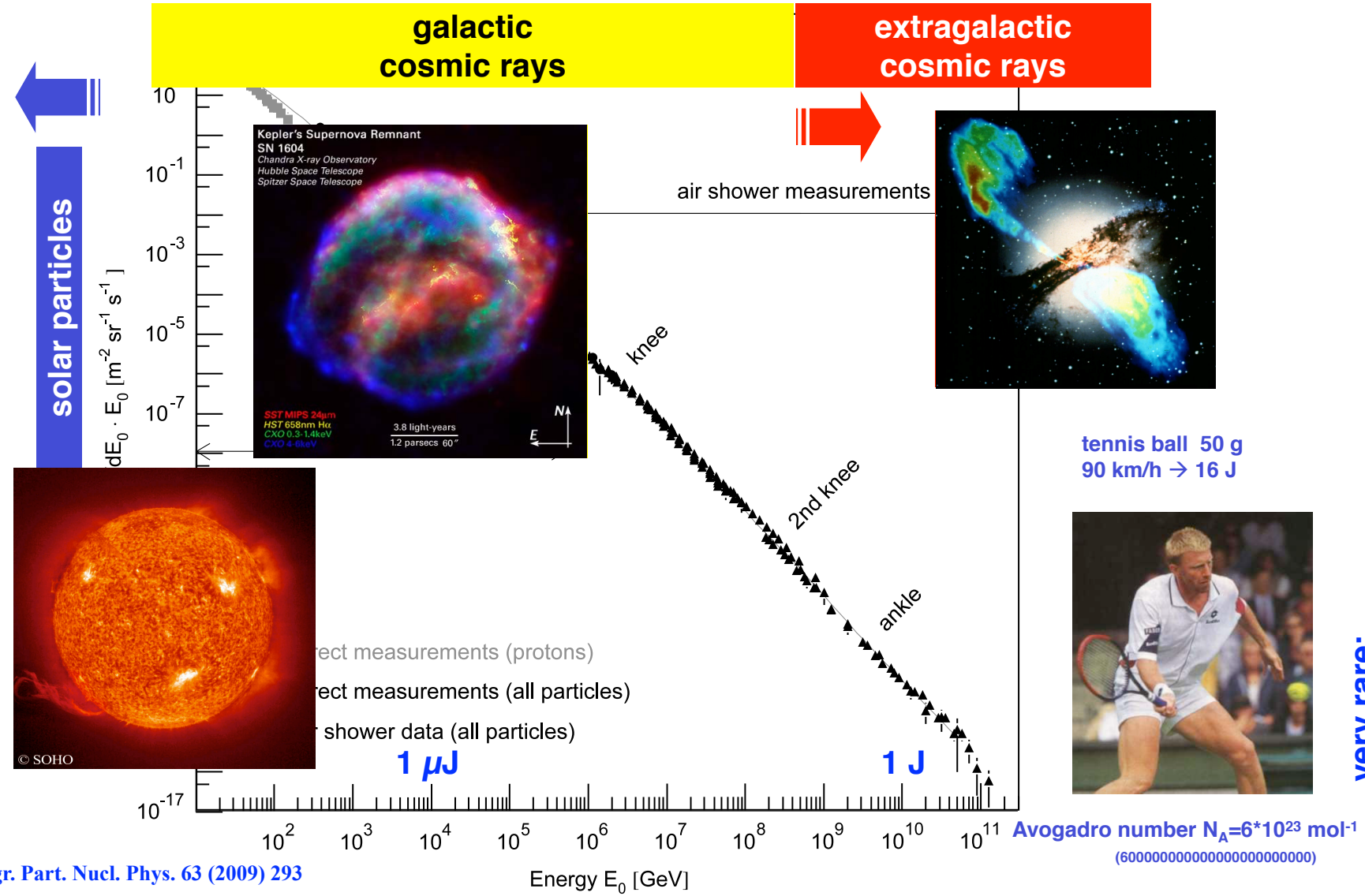


Supernova 1987A • 1994-2003
Hubble Space Telescope • WFPC2 • ACS

NASA and R. Kirshner (Harvard-Smithsonian Center for Astrophysics)

STScI-PRC04-09b

Energy Spectrum of Cosmic Rays



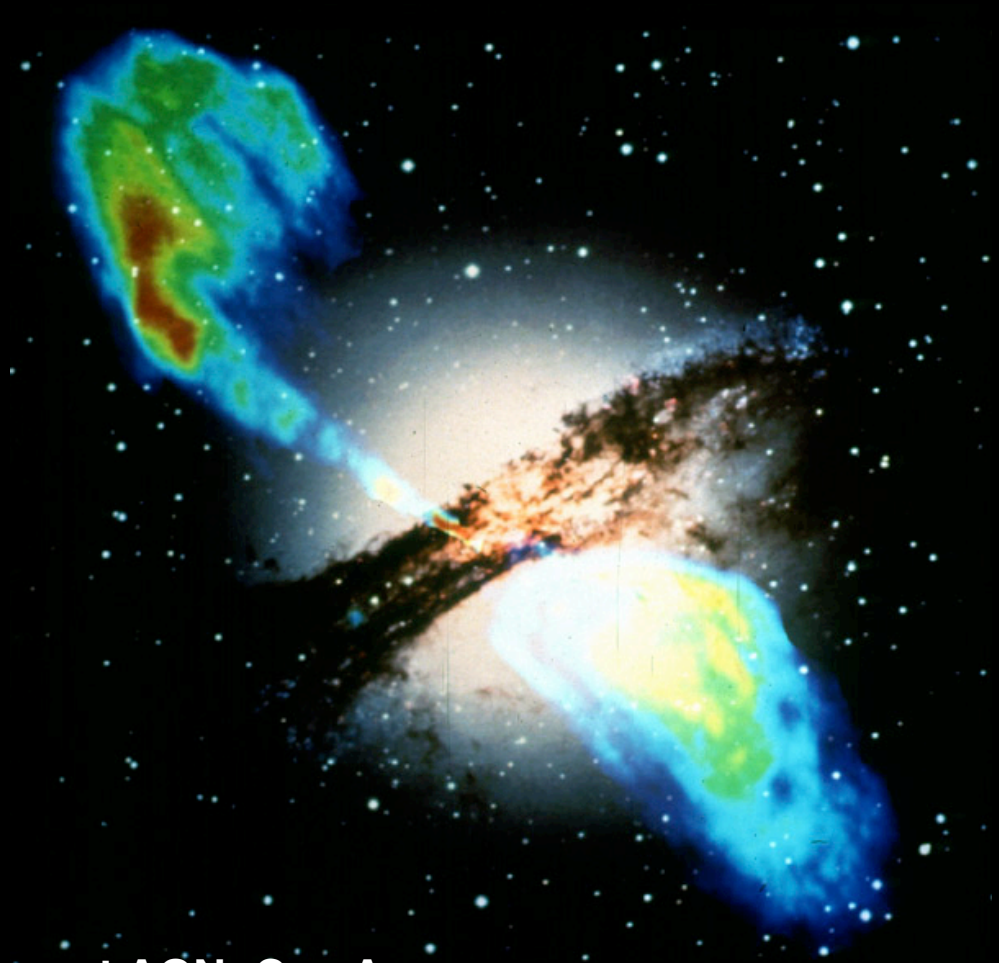
tennis ball 50 g
90 km/h → 16 J

very rare:
~1 particle per square km and 100 years

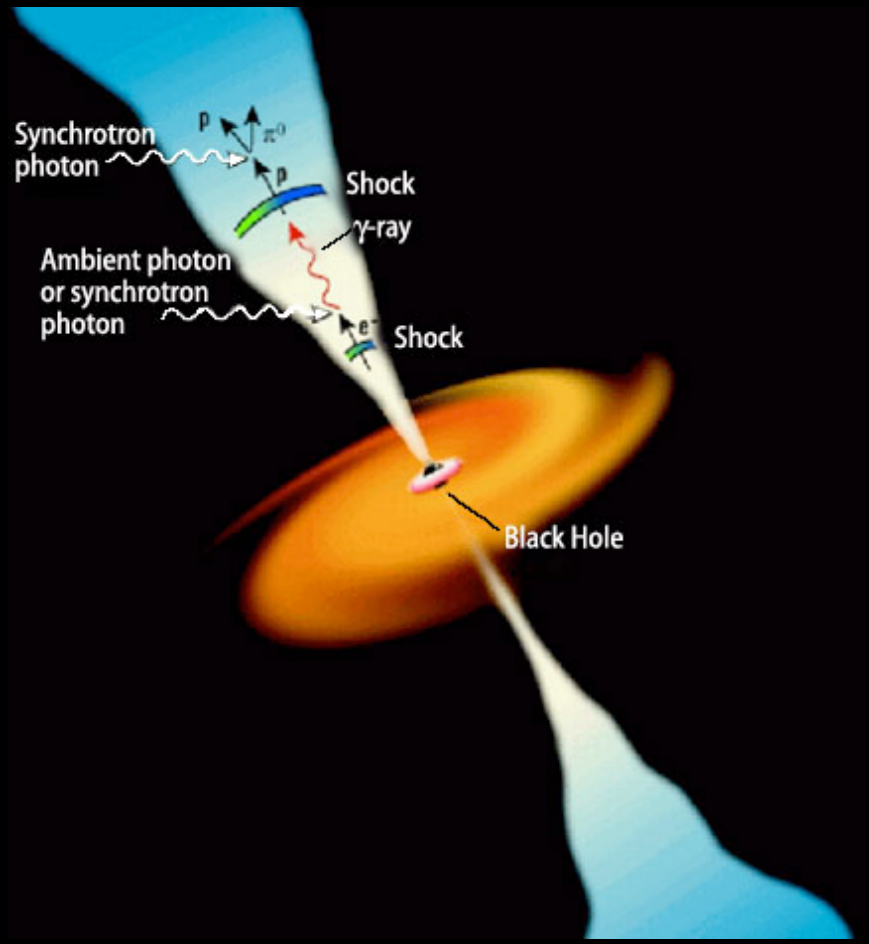
Avogadro number $N_A=6*10^{23}$ mol^{-1}
(600000000000000000000000)

J. Blümer, R. Engel, JRH, Progr. Part. Nucl. Phys. 63 (2009) 293

Active galactic nuclei (AGN)

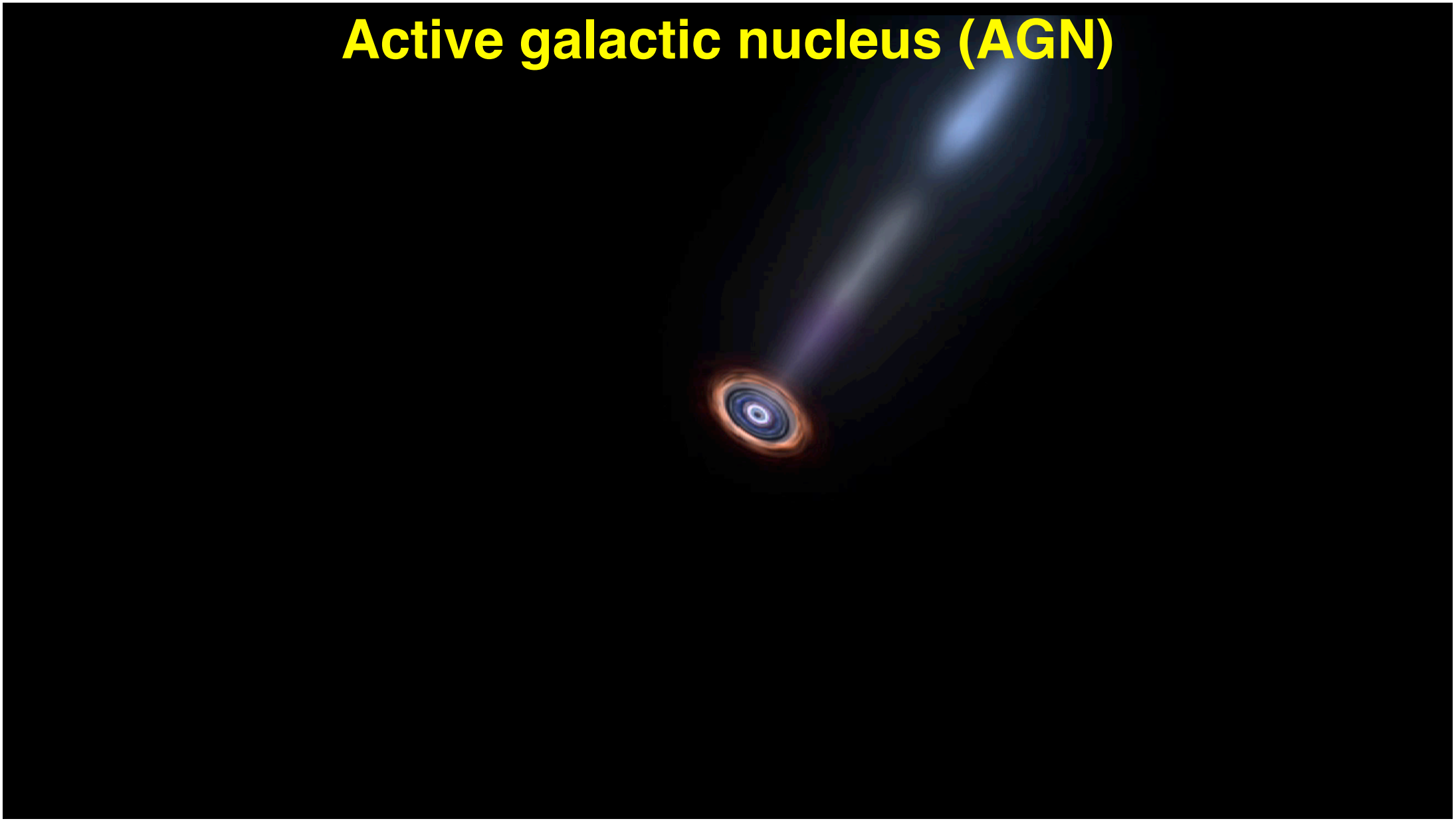


closest AGN: Cen A,
d~12 million light years

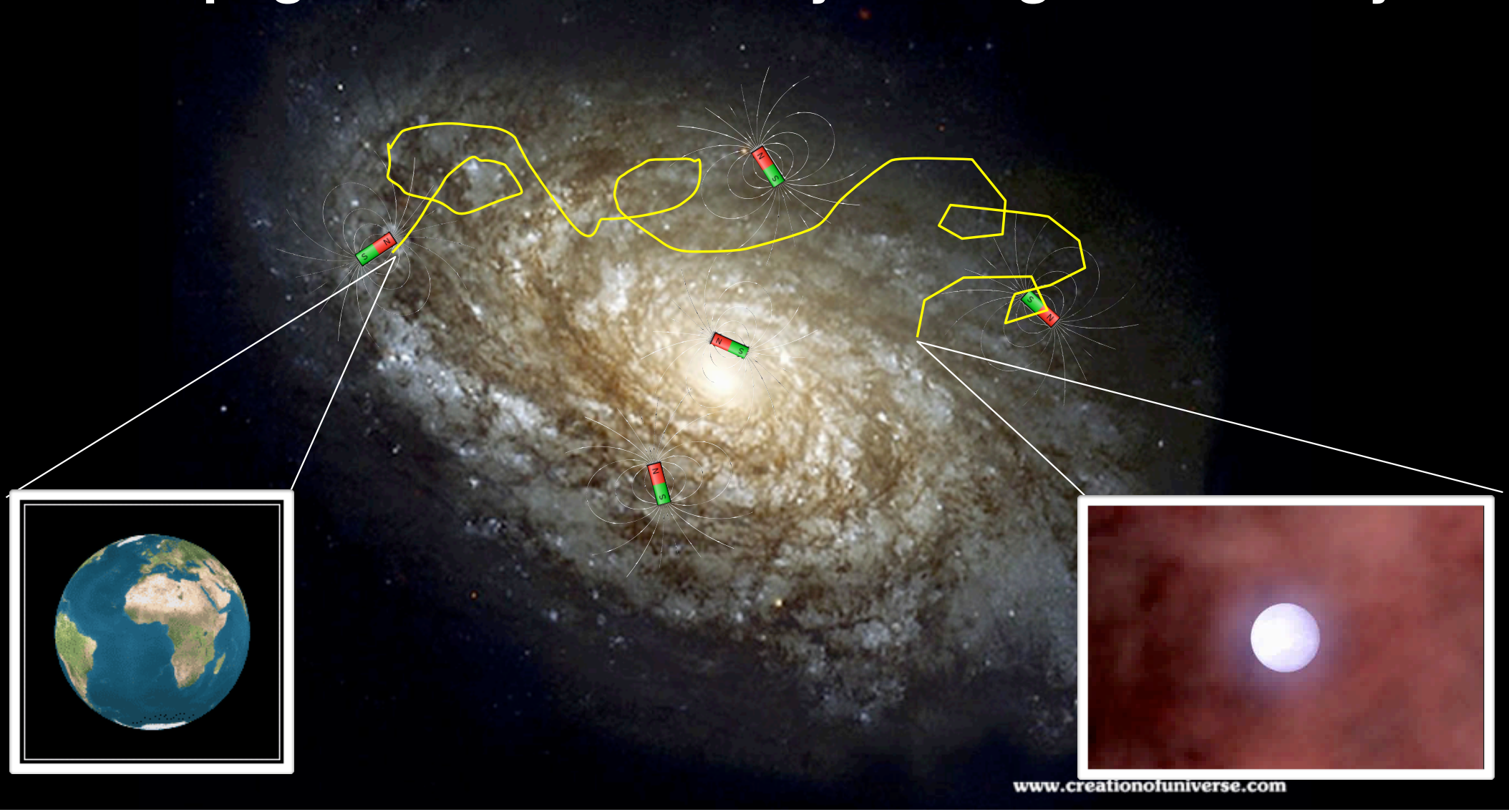


Acceleration of highest-energy cosmic rays in AGN

Active galactic nucleus (AGN)

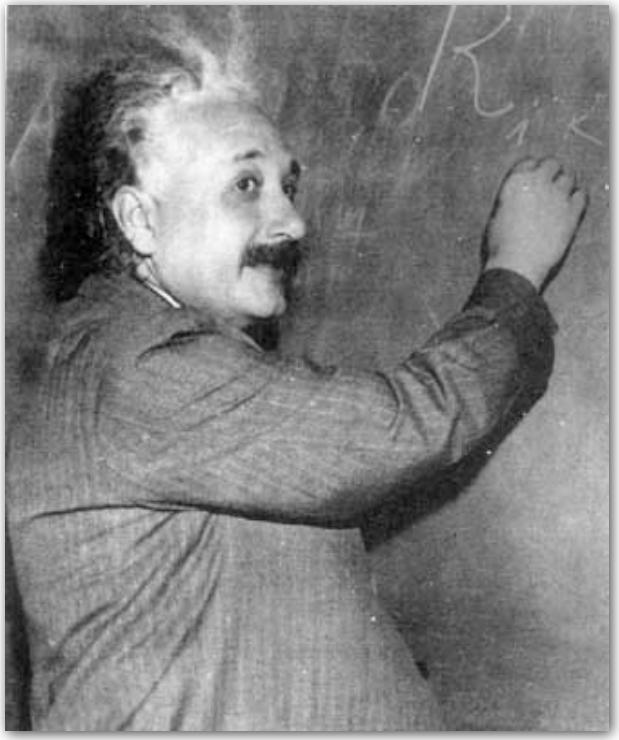


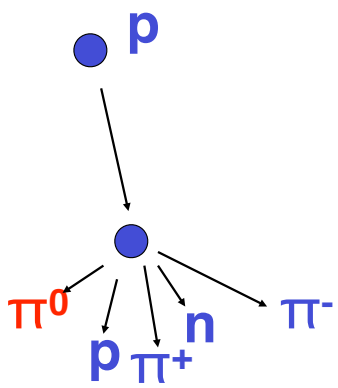
Propagation of cosmic rays though the Galaxy



Interactions of high-energy particles

Energy is converted into matter
New elementary particles are generated





$$E = m \cdot c^2$$

*energy = mass * speed of light²*

Electromagnetic cascades B. Rossi 1933

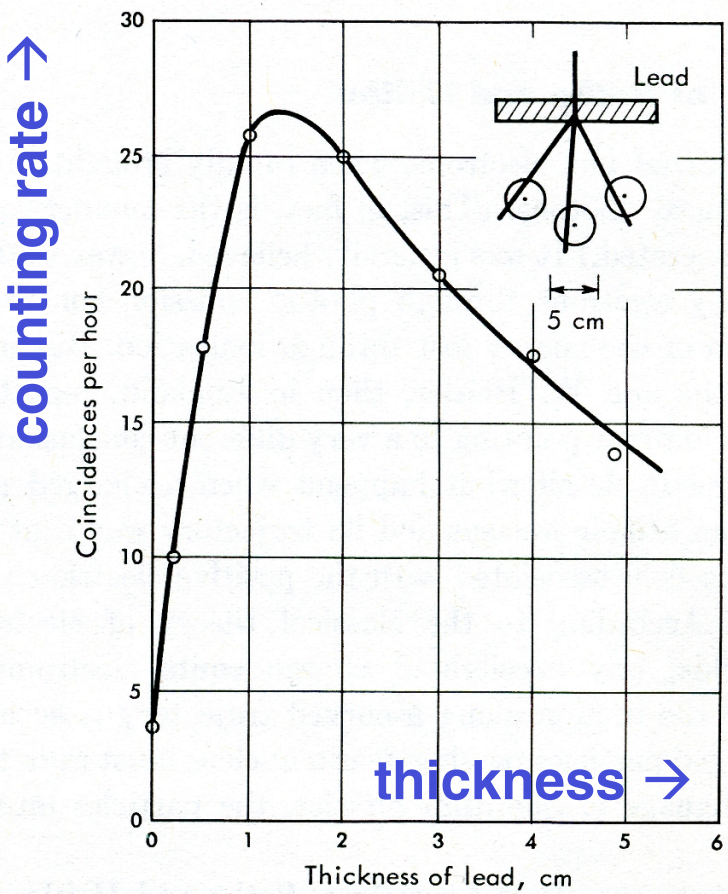


Fig. 7-1 Shower curve. The number of coincidences per hour is plotted as a function of the thickness of lead above the counters. The experimental arrangement is shown schematically in the inset. The circles are experimental points. (This figure is based on one appearing in a paper by the author in *Zeitschrift für Physik*, vol. 82, p. 151, 1933.)

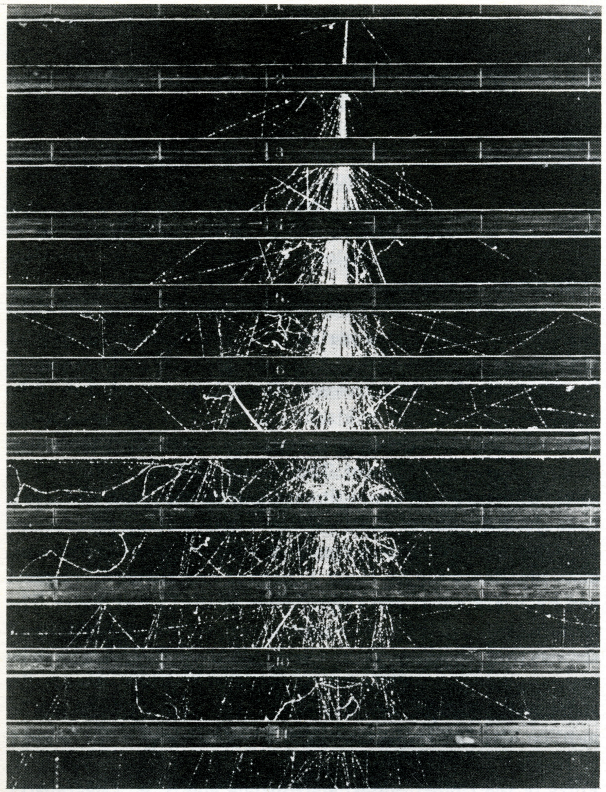
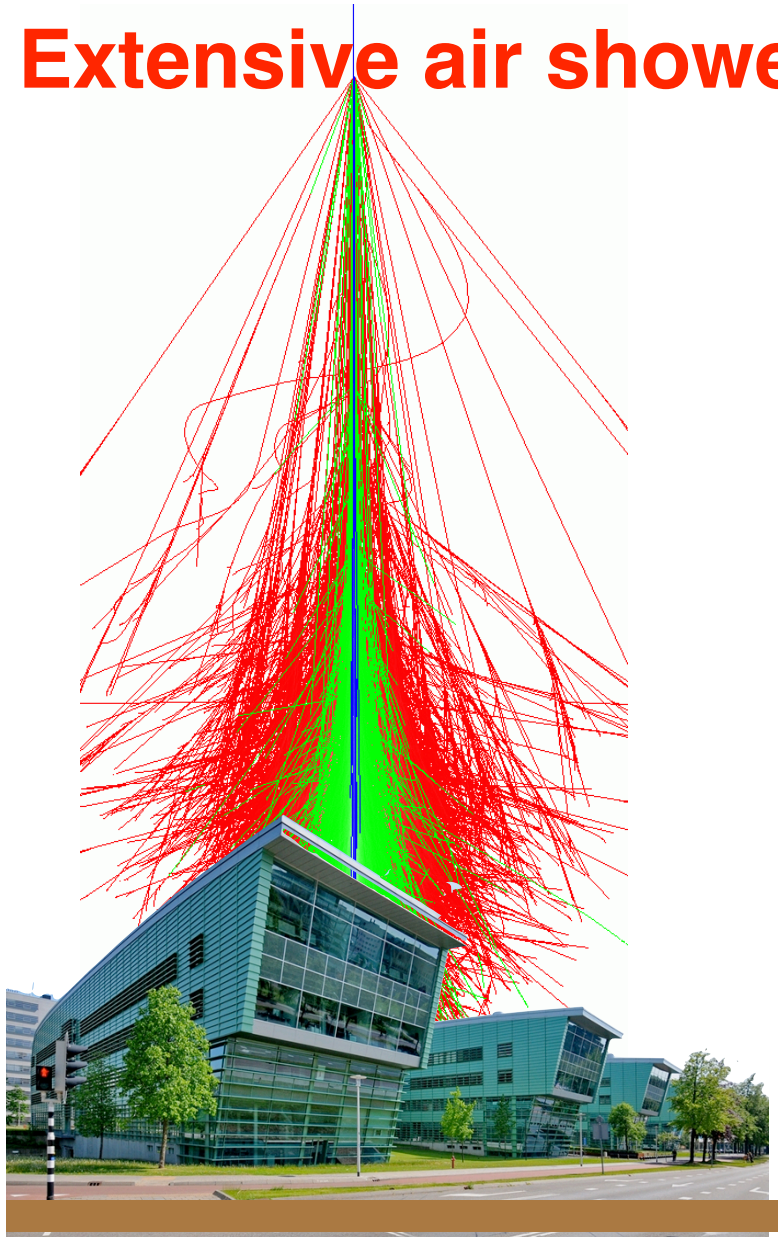


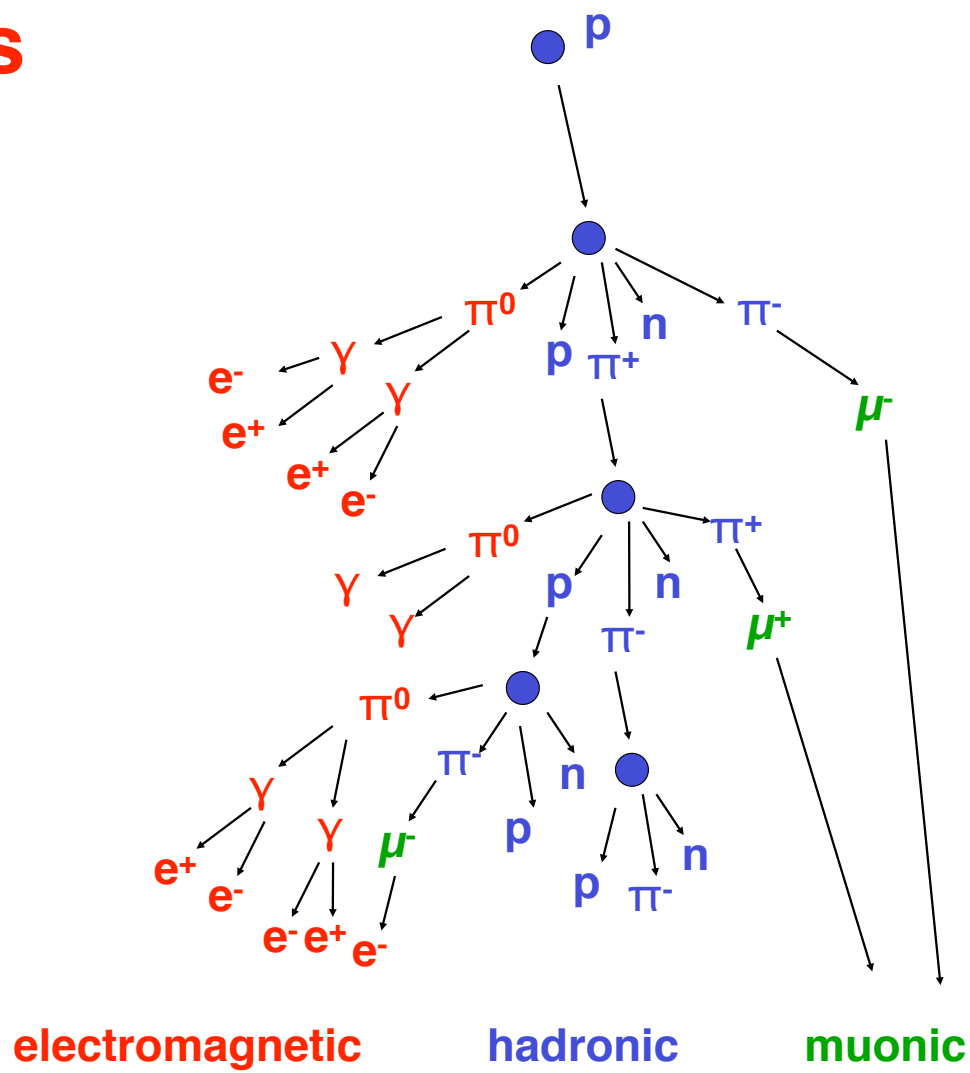
Fig. 7-5 A shower developing through a number of brass plates 1.25 cm thick placed across a cloud chamber. The shower was initiated in the top plate by an incident high-energy electron or photon. The photograph was taken by the MIT cosmic-ray group.

$\gamma \rightarrow e^+ e^-$

$e^{+/-} \rightarrow \gamma$

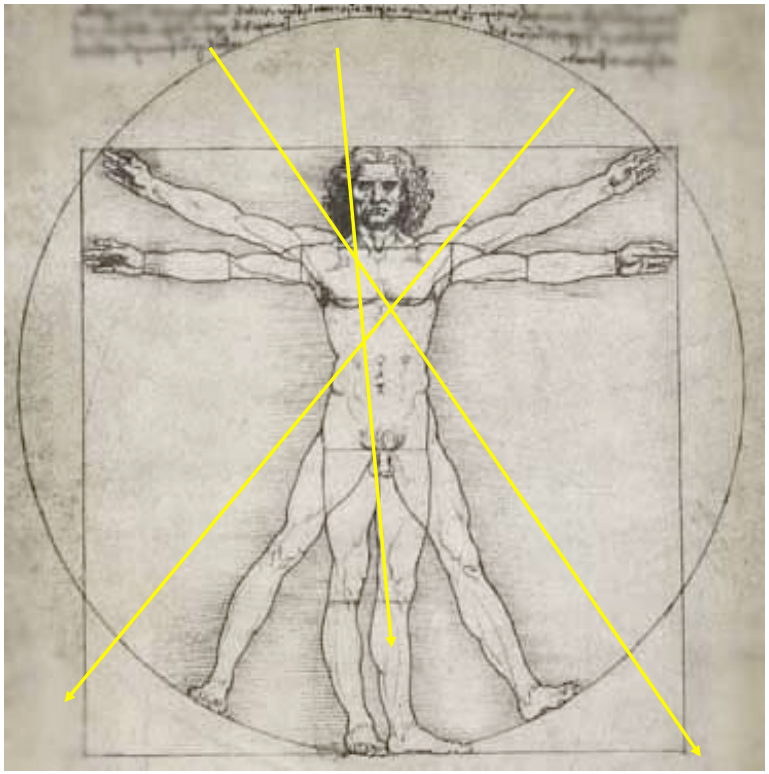
Extensive air showers





shower components

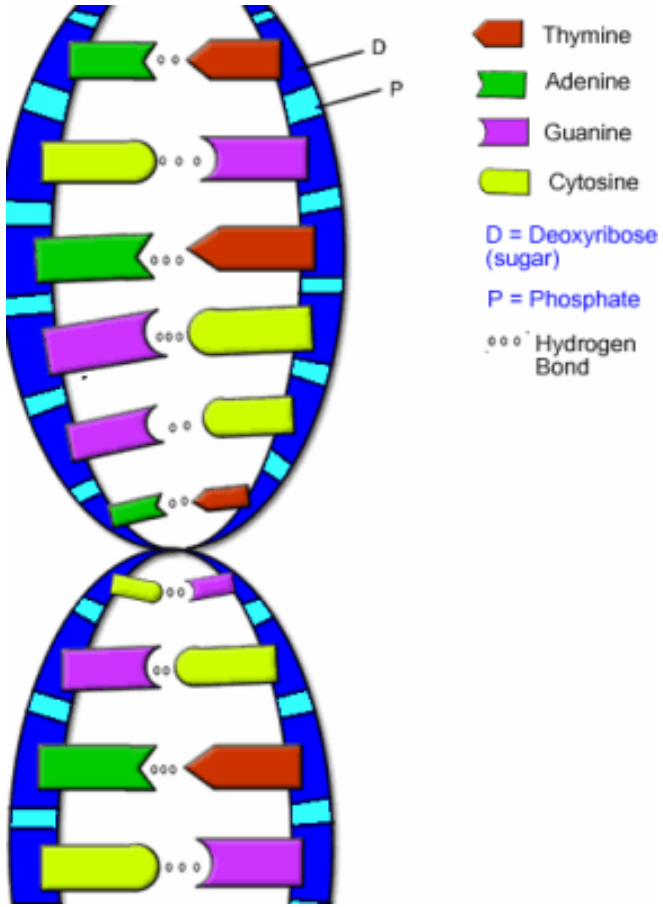
Particles at ground level



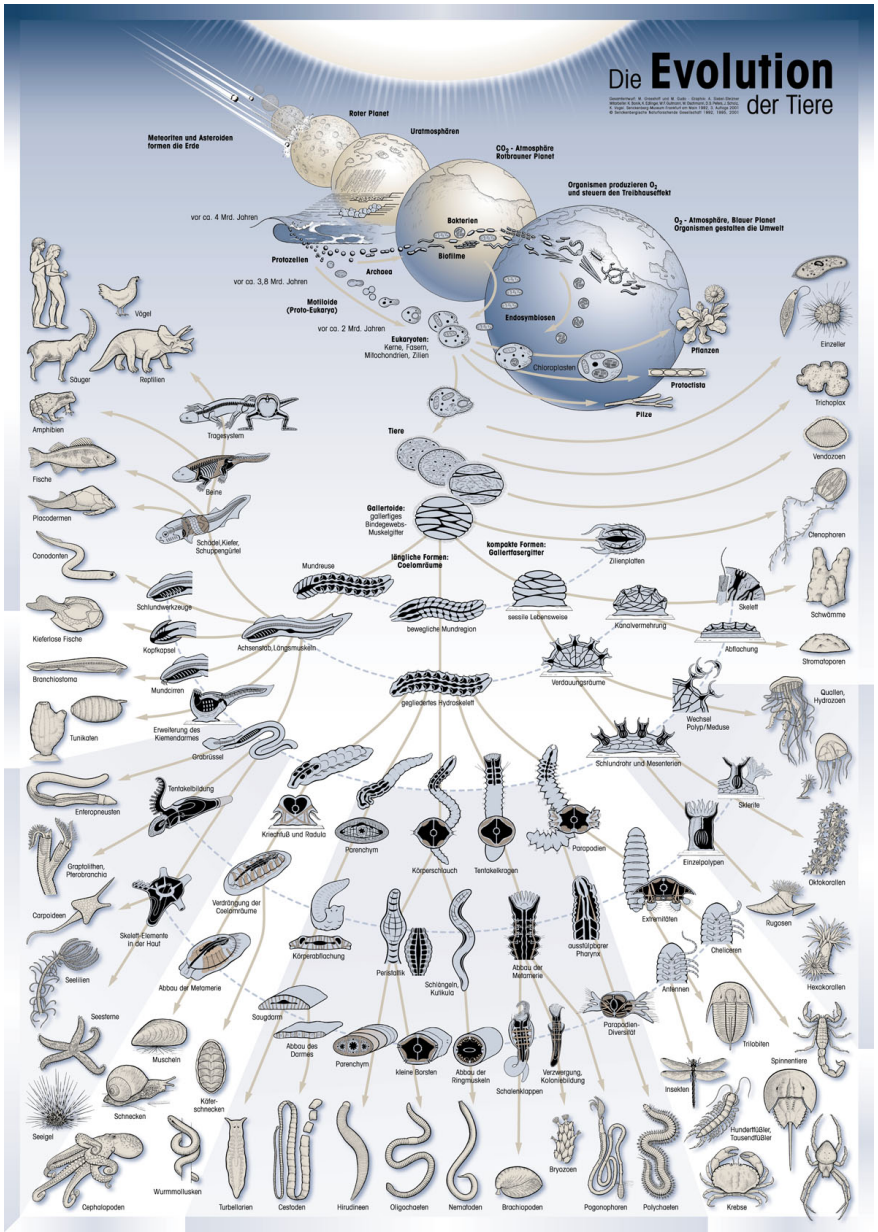
cross section of a human ~ 1 qm

Flux at ground level:
~ 130 muons per square meter and second

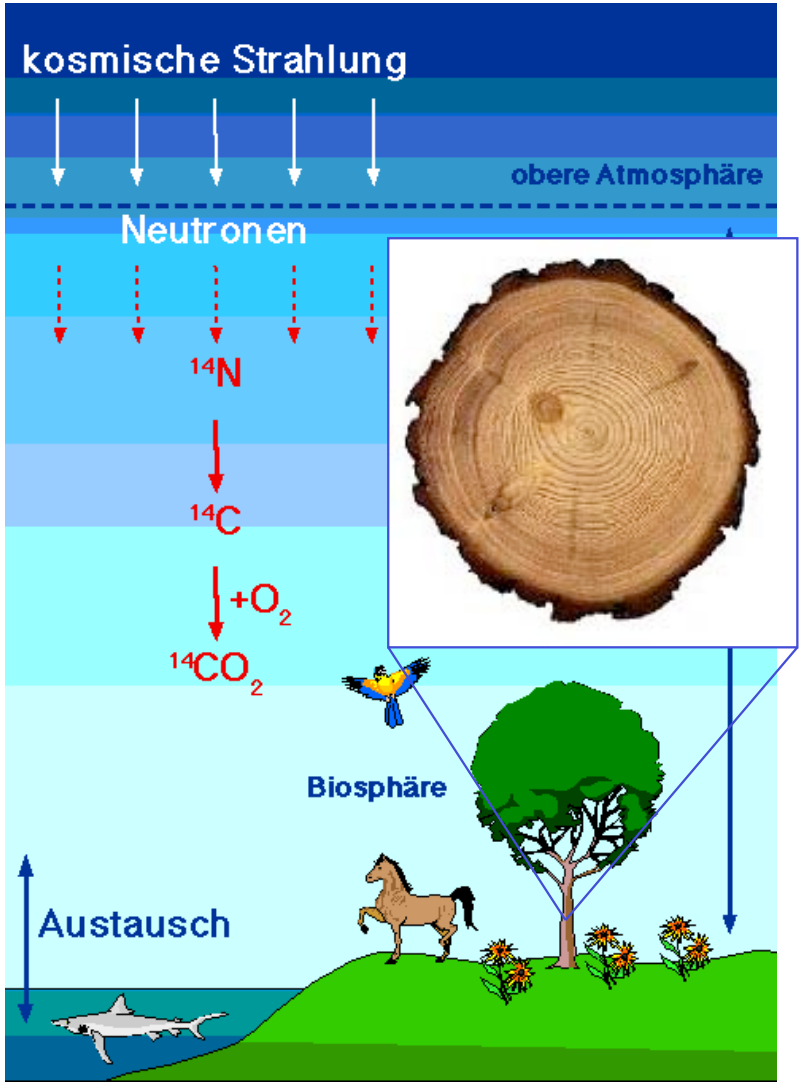
Cosmic rays and evolution



DNA



Carbon 14 method

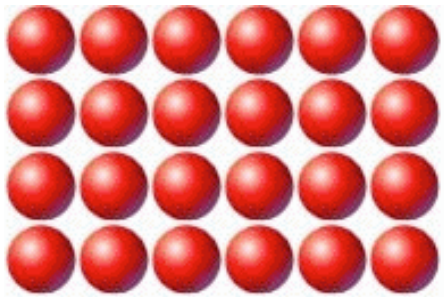


Production of ^{14}C

$^{14}N + {}^{1}n \rightarrow {}^{14}C + {}^{1}p$

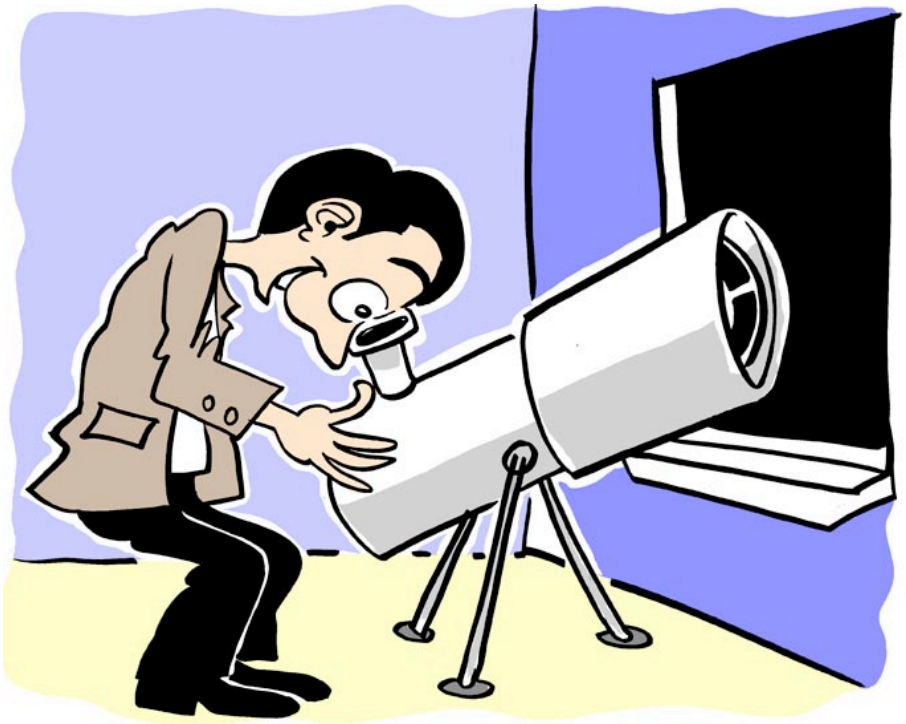
Decay of ^{14}C

half life time 5730 years



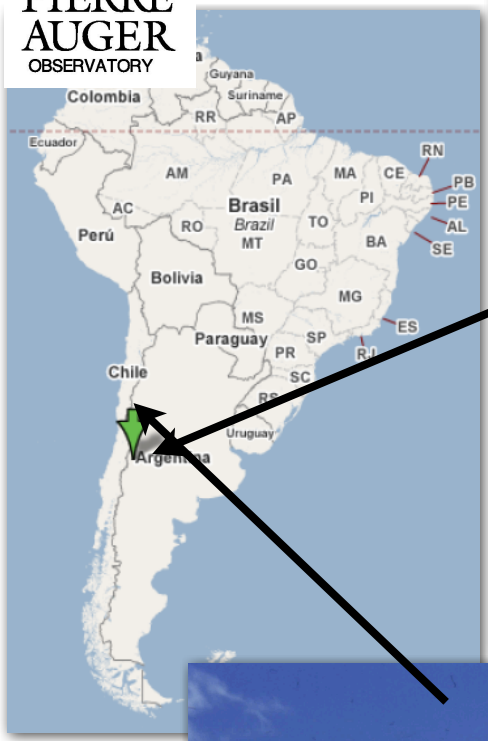
Gehalt an C-14 nach
0 Jahren: 100%

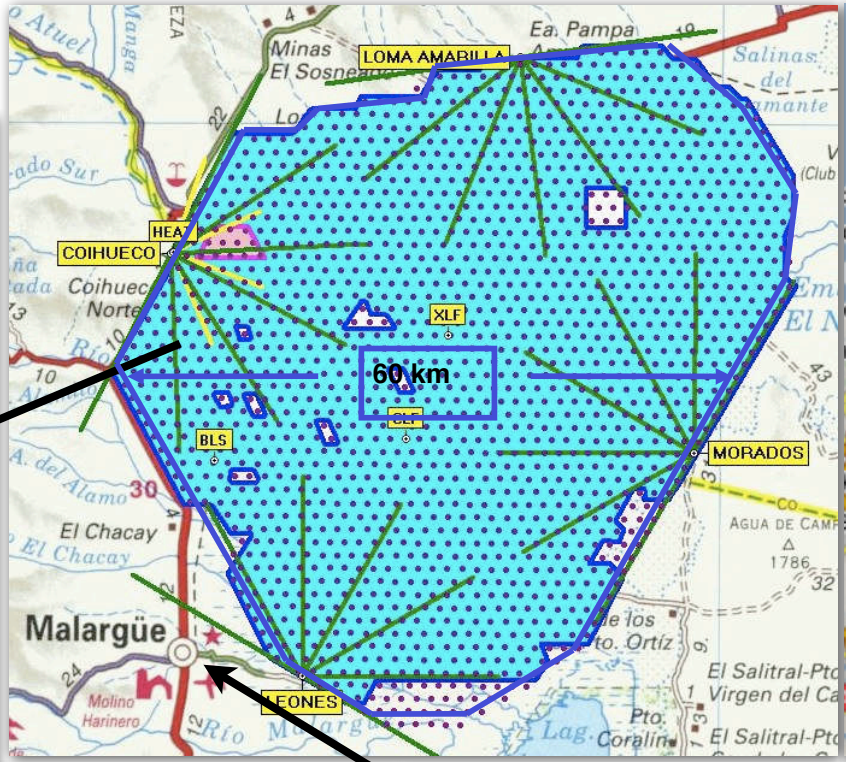
$^{14}C \rightarrow {}^{14}N + e^{-}$

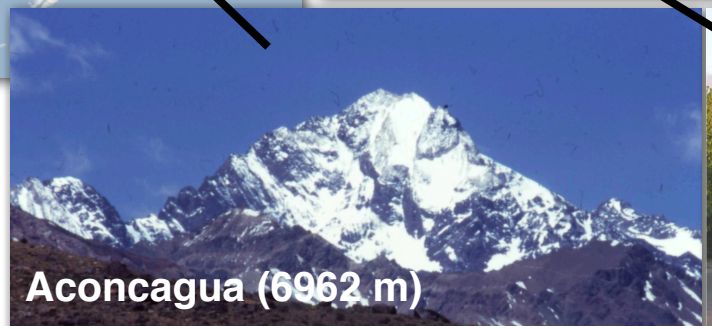


The new observatories: LOFAR and the Pierre Auger Observatory

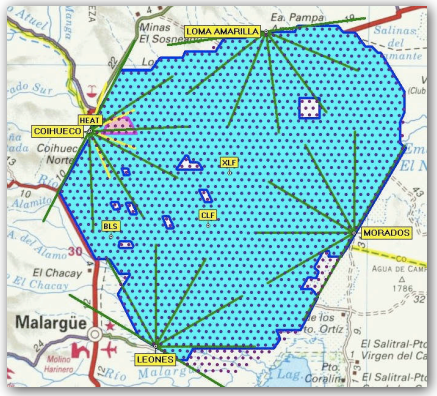
The Pierre Auger Observatory



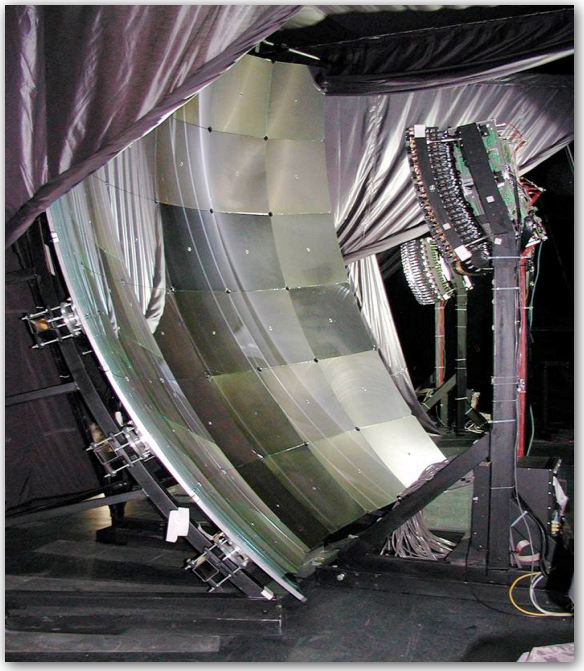




The Pierre Auger Observatory

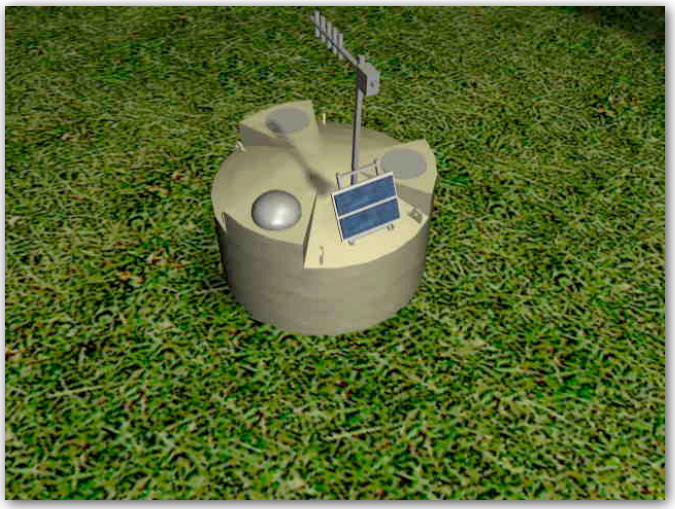


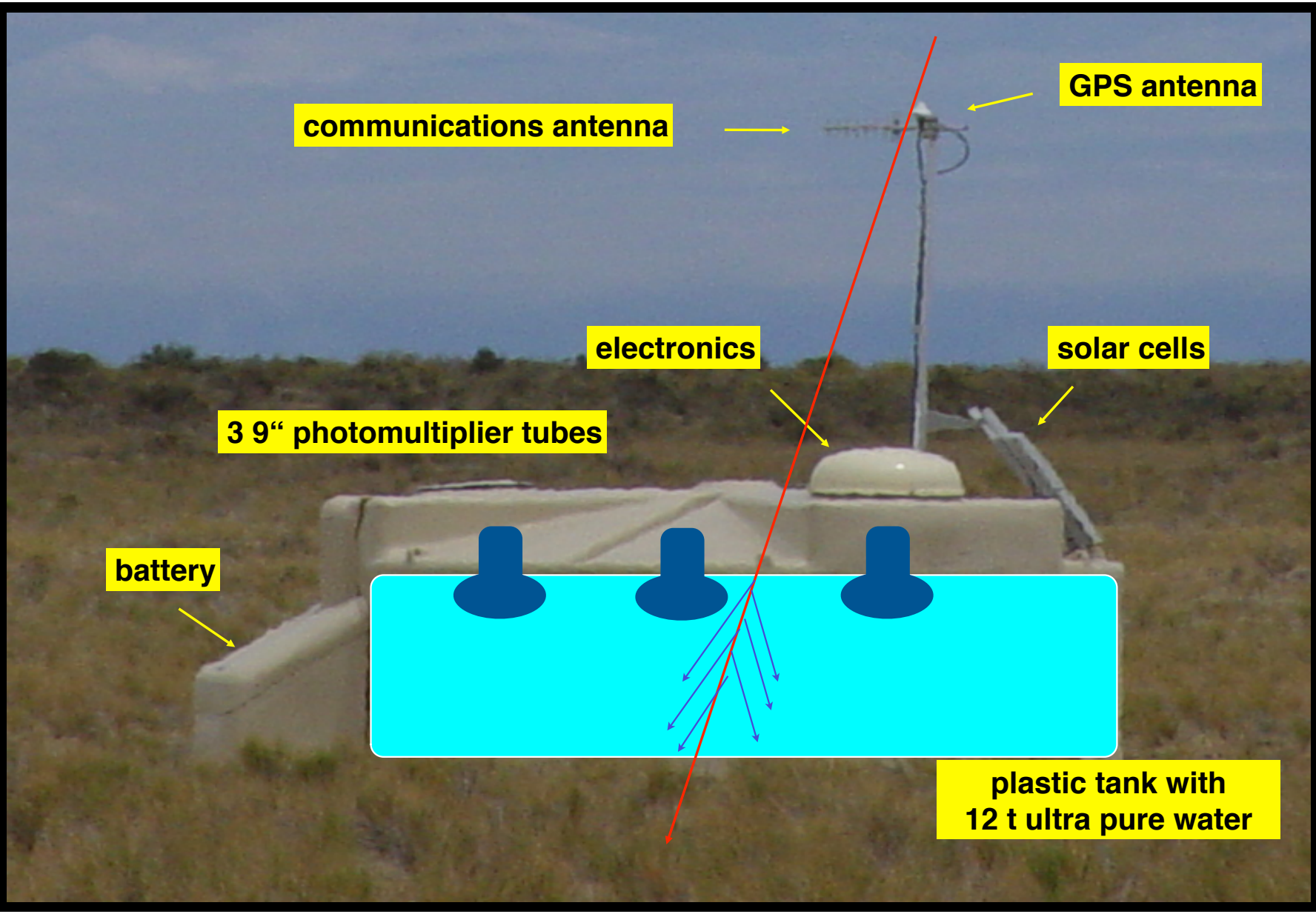
27 fluorescence light telescopes



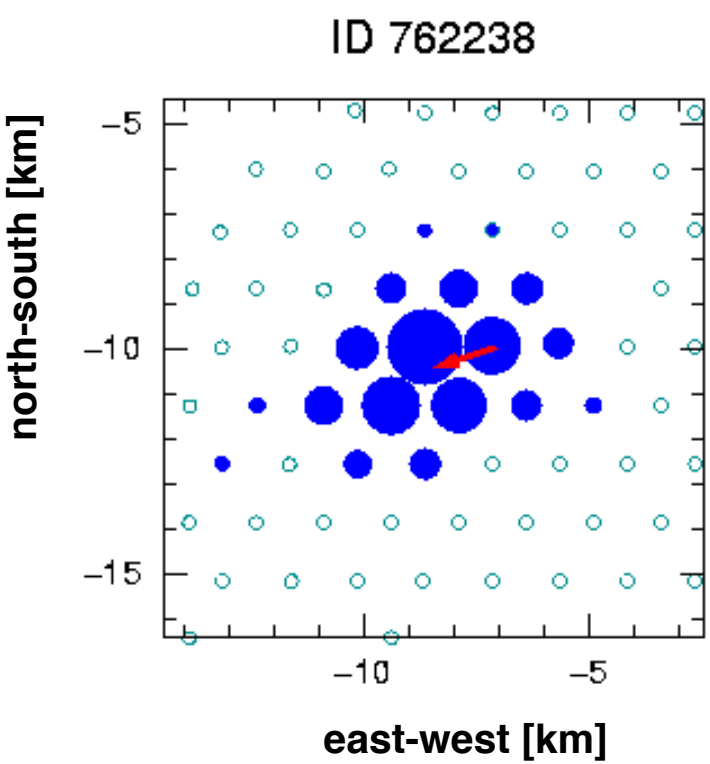
1600 water Cerenkov detectors

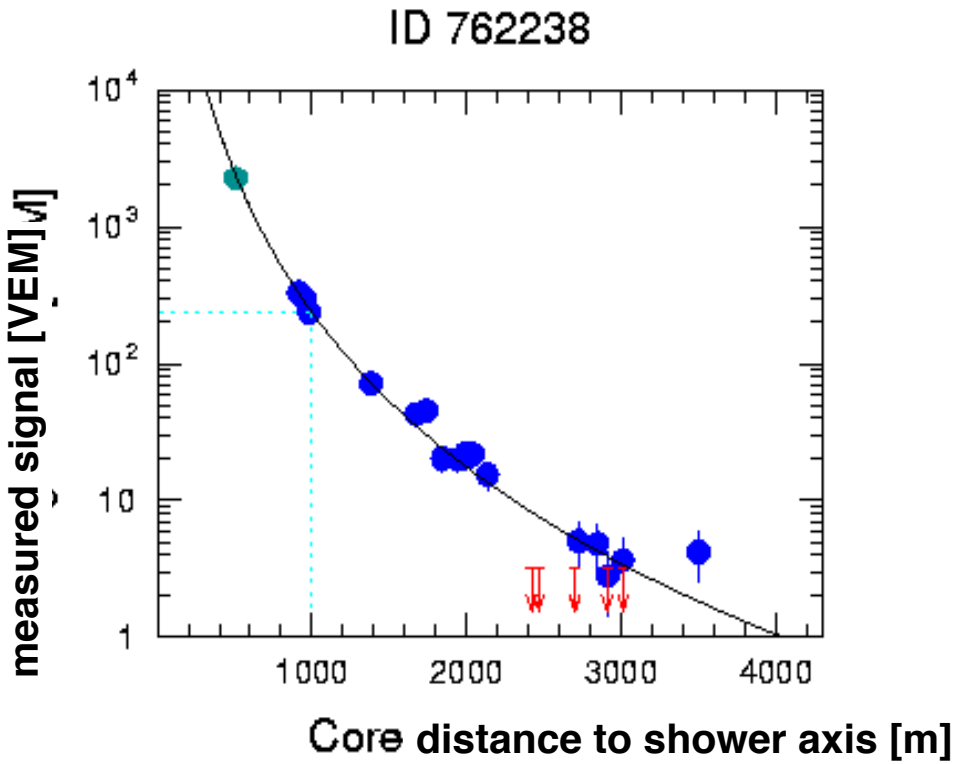
3000 km^2



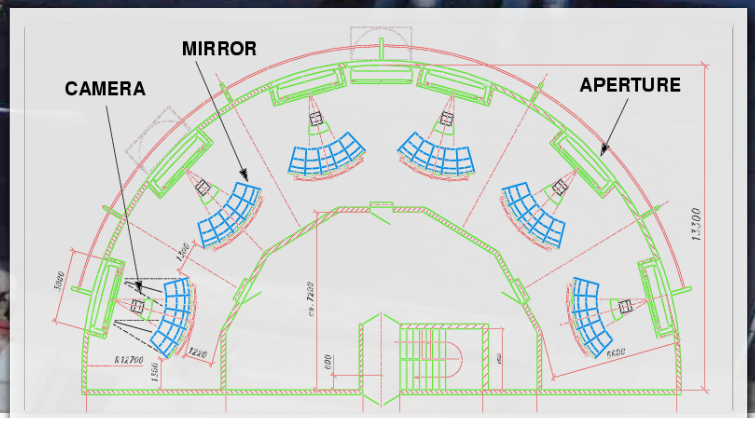

GPS antenna
communications antenna
electronics
solar cells
3 9“ photomultiplier tubes
battery
plastic tank with
12 t ultra pure water

Air shower registered with water Cherenkov detectors

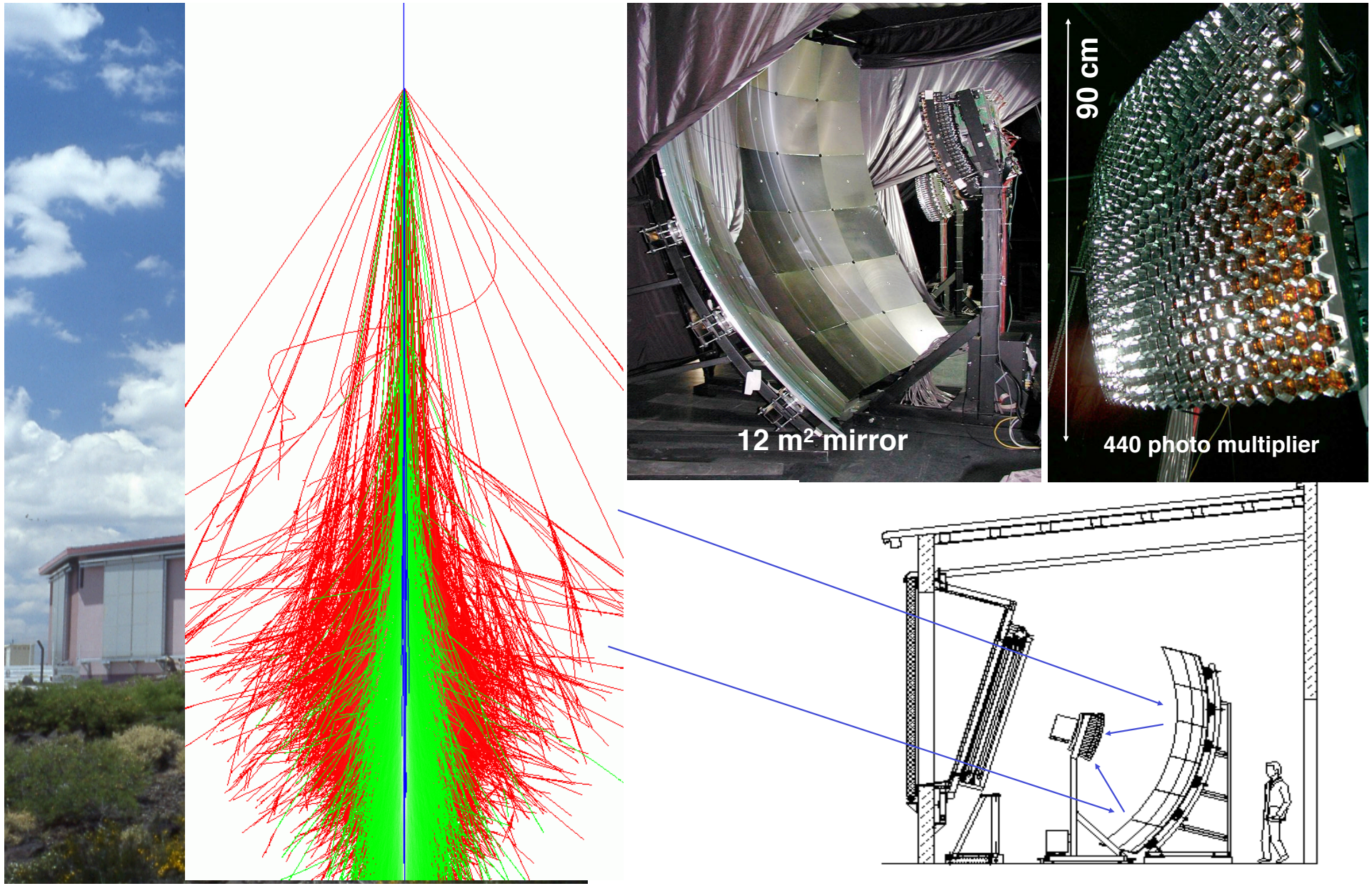


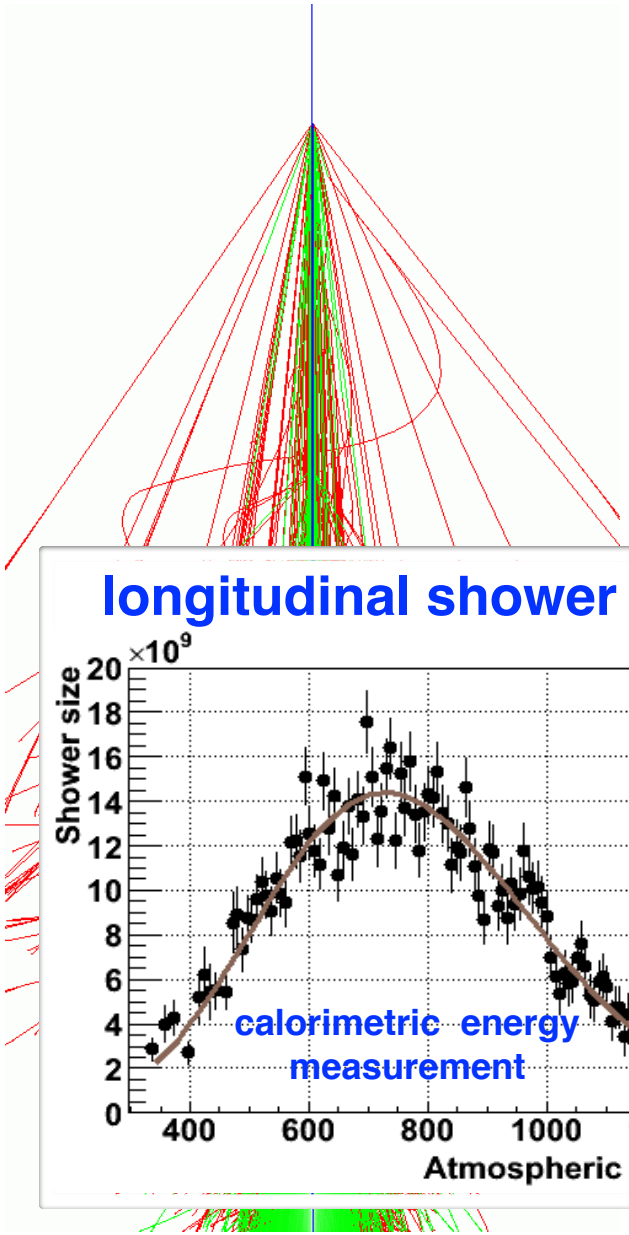


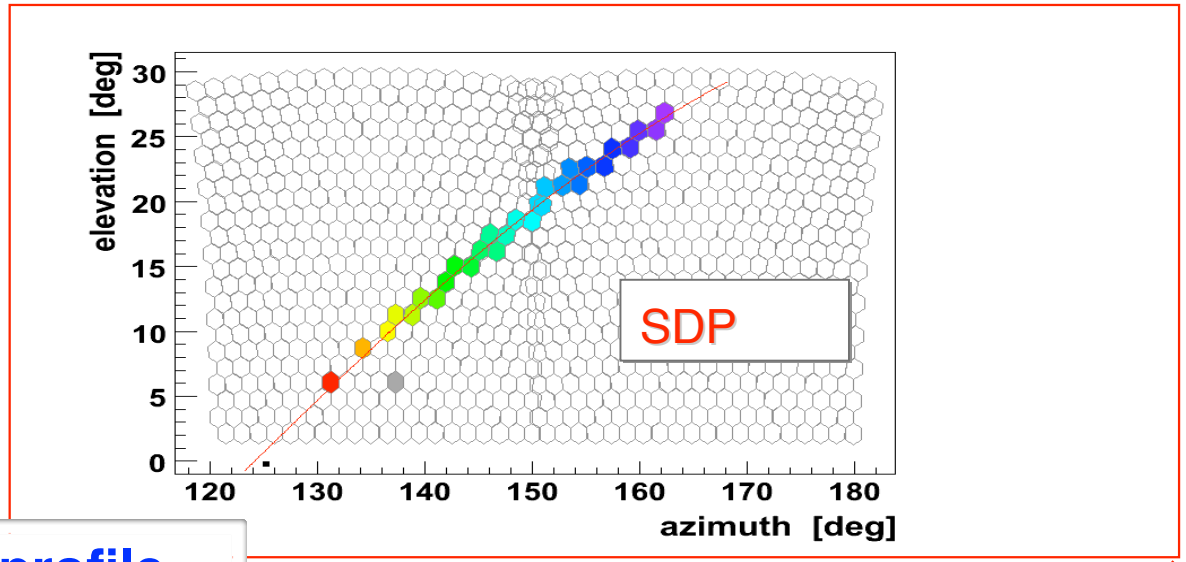
FD eye view



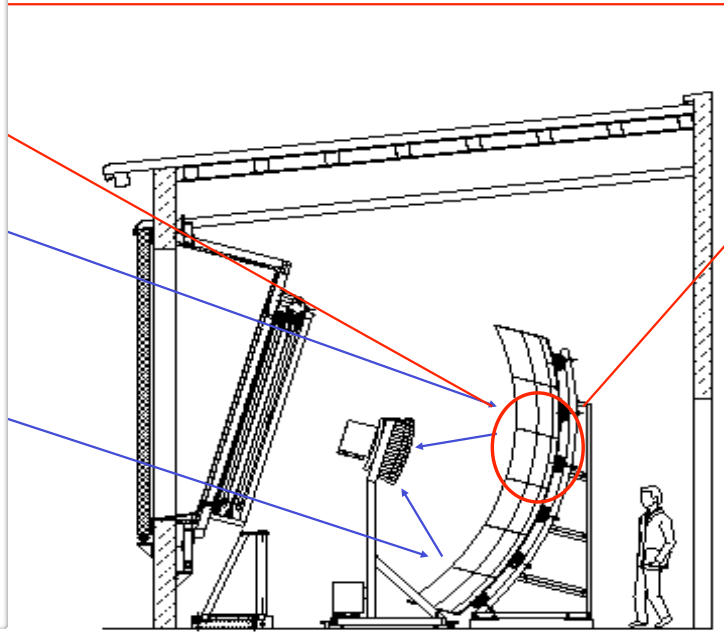
Four sites
Six telescopes
viewing 30°x30° each


12 m² mirror
90 cm
440 photo multiplier

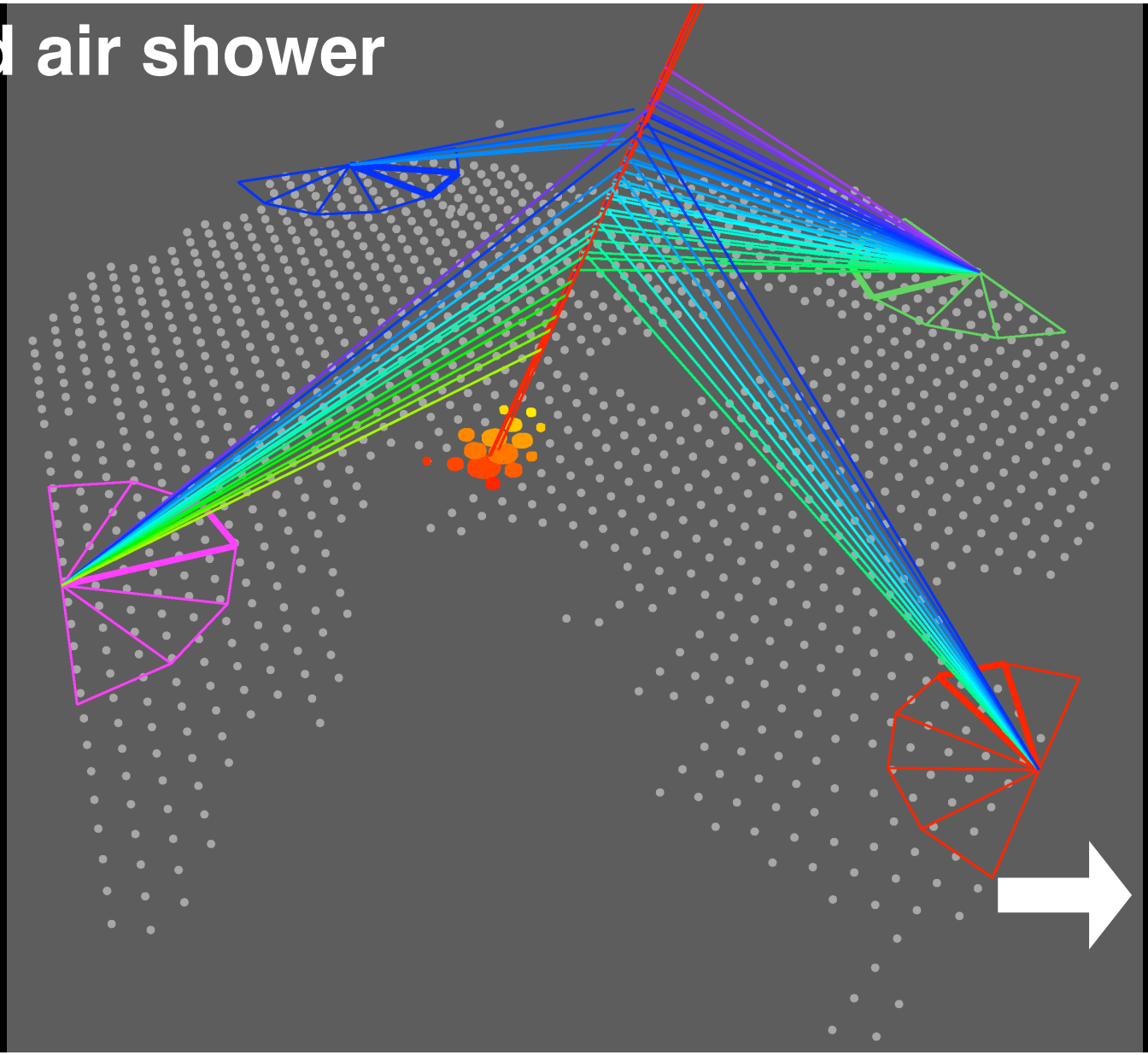



elevation [deg]
30
25
20
15
10
5
0
120
130
140
150
160
170
180
azimuth [deg]
SDP

longitudinal shower profile
Shower size
×10^9
20
18
16
14
12
10
8
6
4
2
0
400
600
800
1000
1200
1400
Atmospheric depth [g cm^-2]
calorimetric energy
measurement



A measured air shower

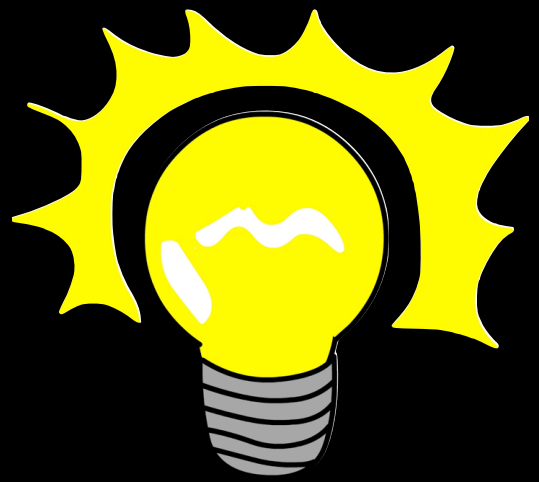


20. May 2007
E ~ 10^{19} eV

energy,
type (mass),
direction

We are interested in three properties:

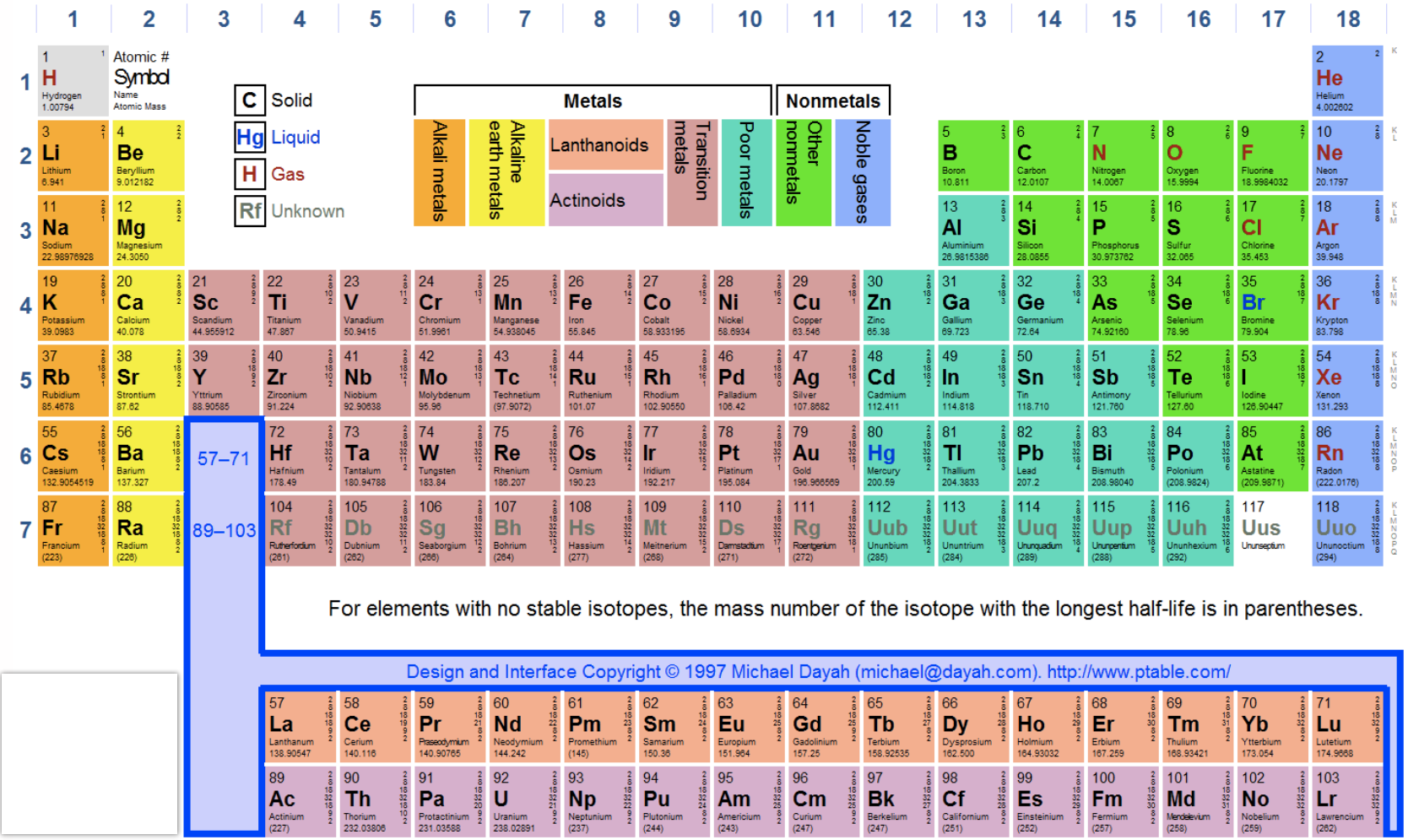
- direction



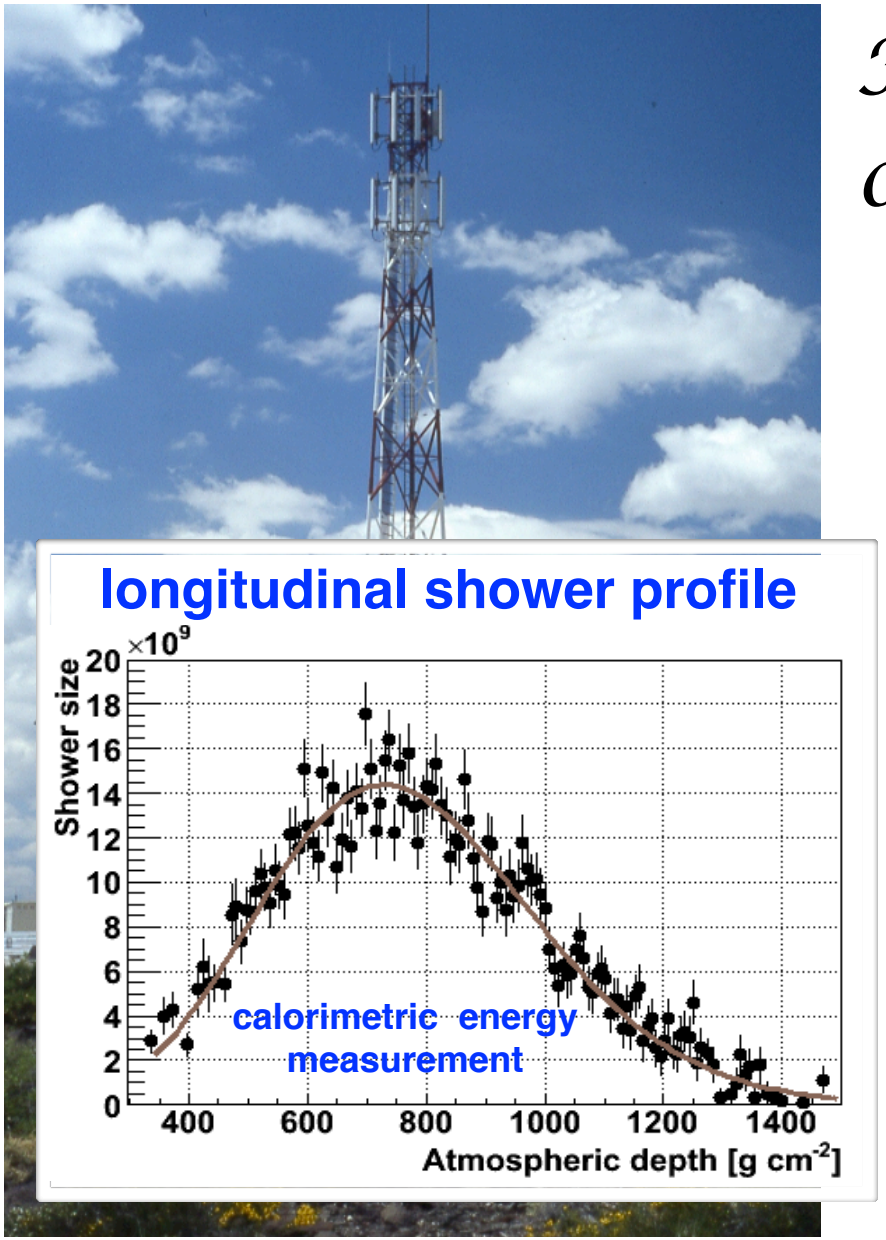
- energy

- type of particle (mass)

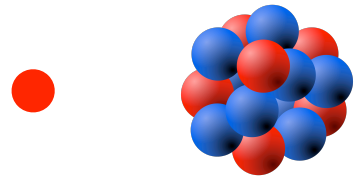
Periodic Table of Elements

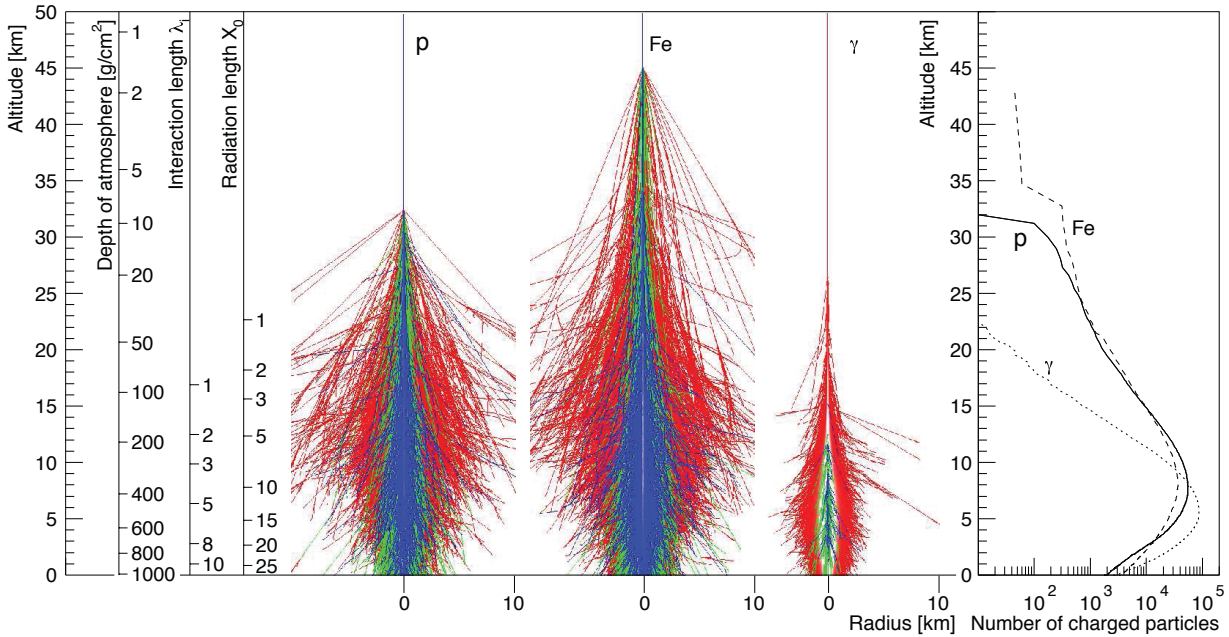


How do we identify the type of particle?



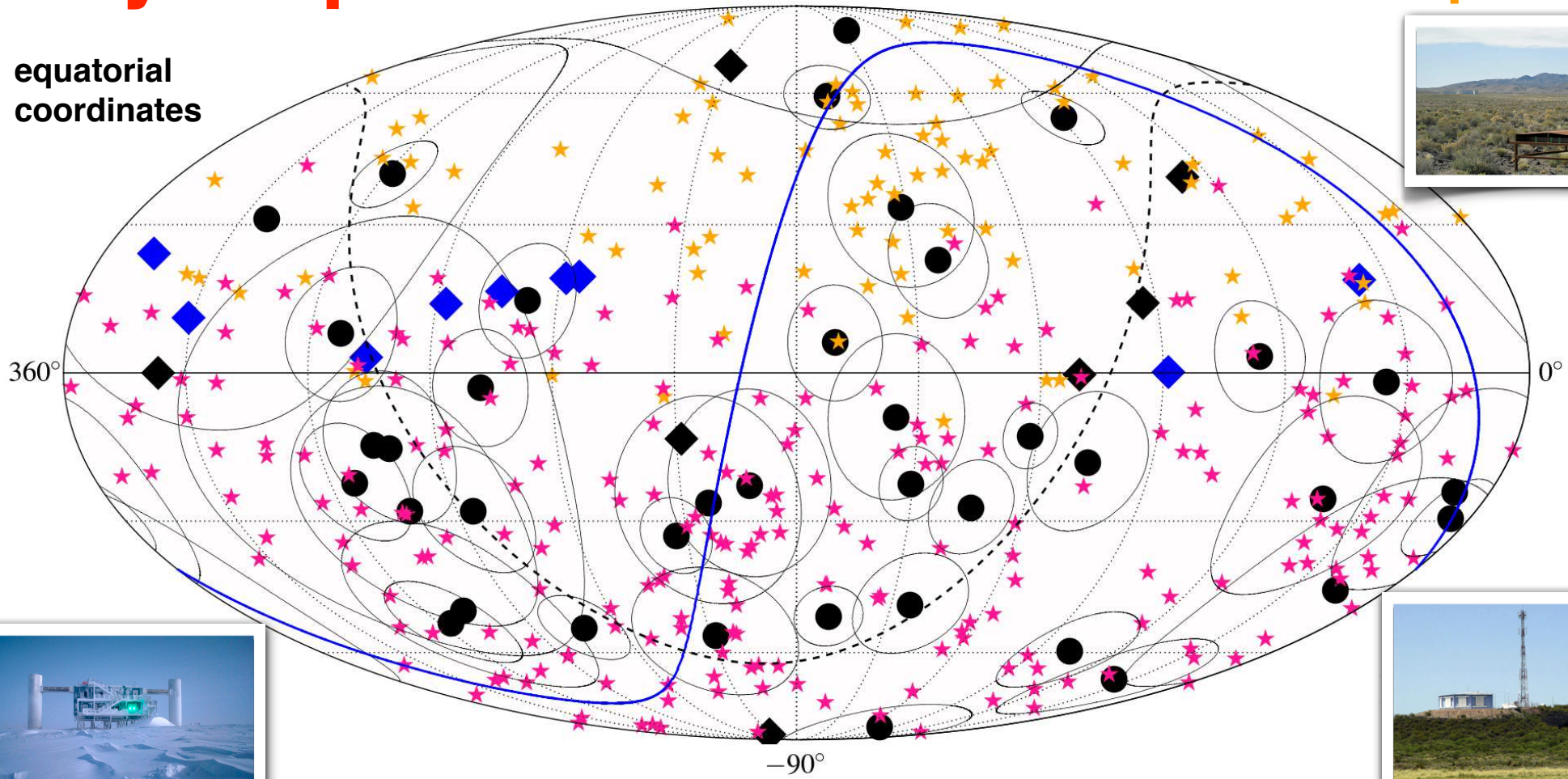
proton **Fe nucleus**



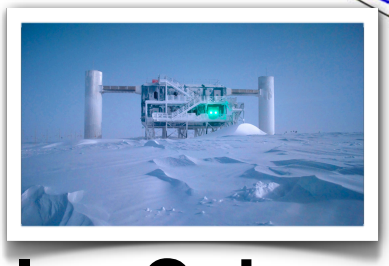


Sky map

equatorial coordinates



Telescope Array



Ice-Cube neutrino telescope

Pierre Auger Observatory

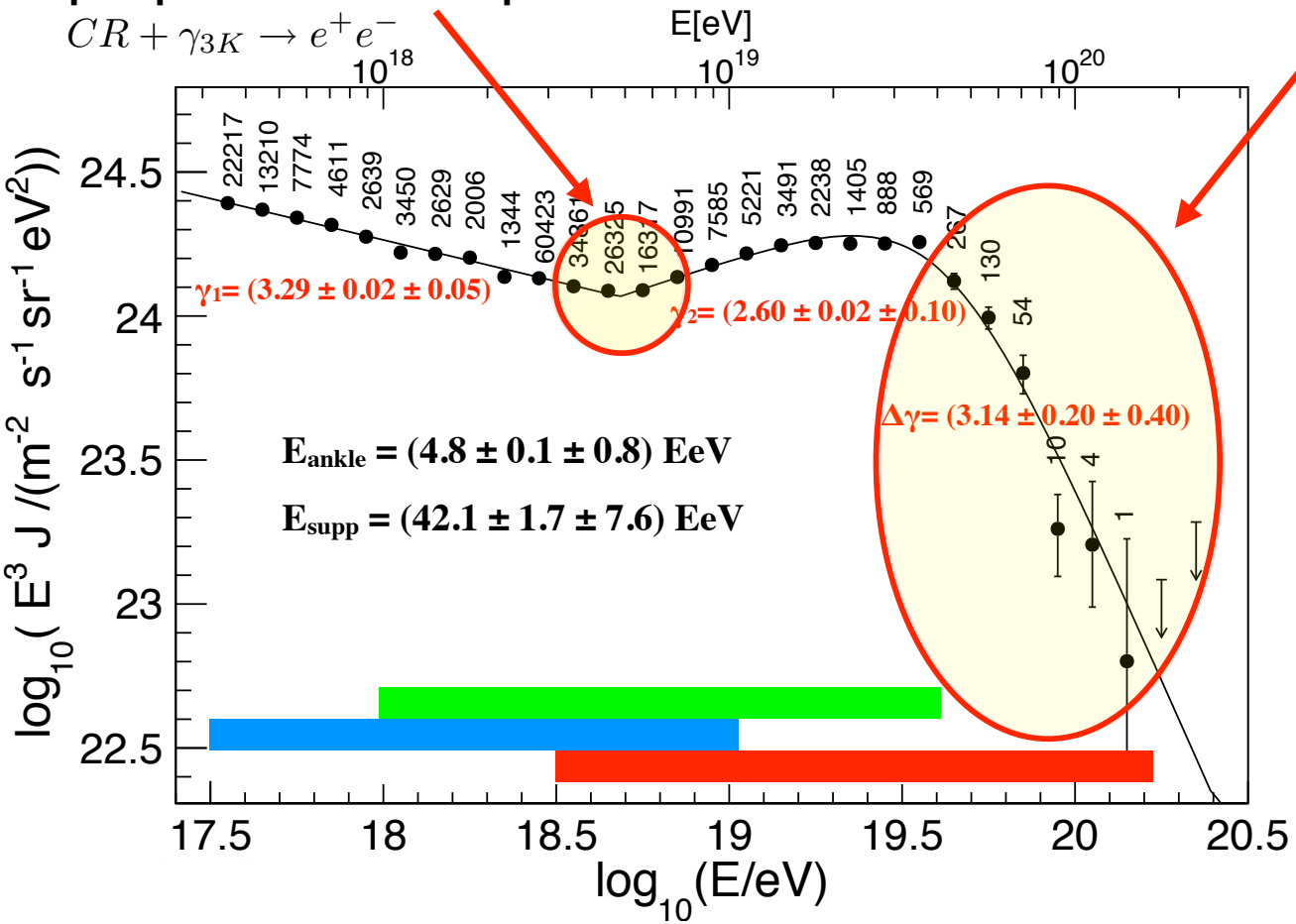
Precise measurementof the all-particle energy spectrum over 3 decades in energy

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**

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

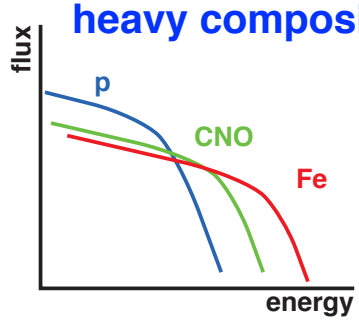
light composition

- **maximum energy of accelerators**

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

(Hillas condition)

heavy composition

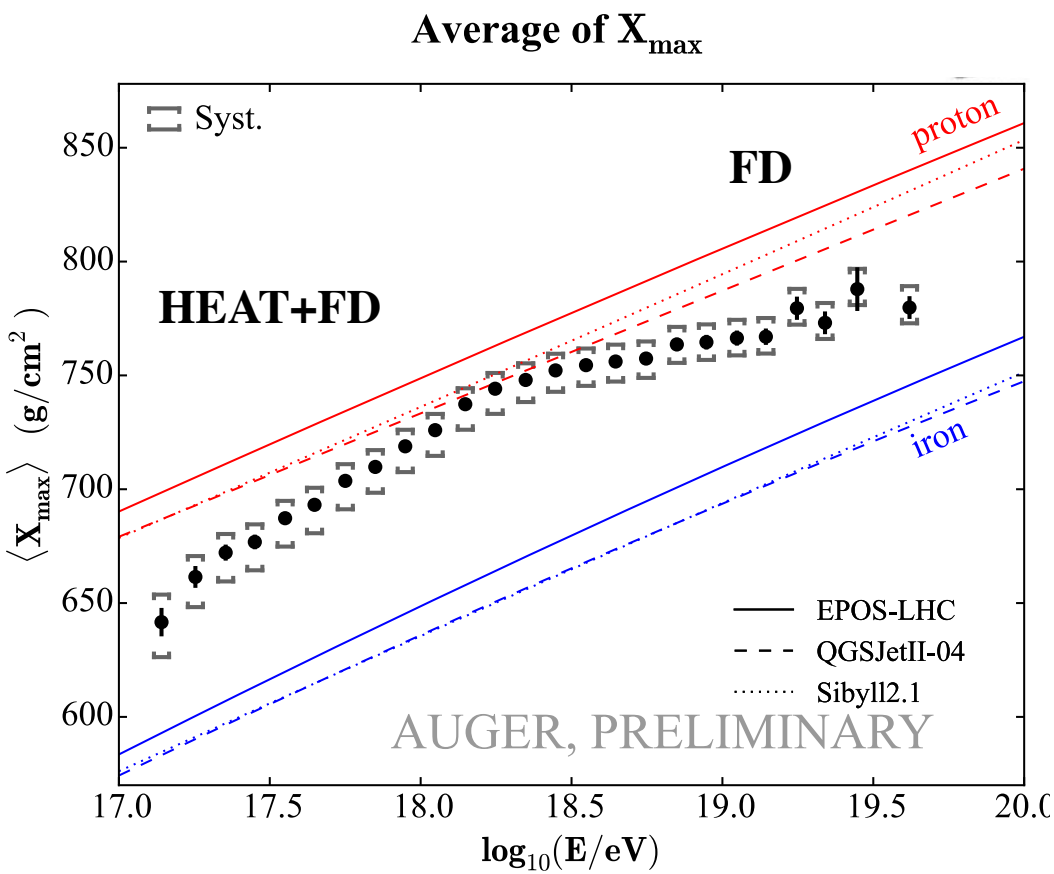


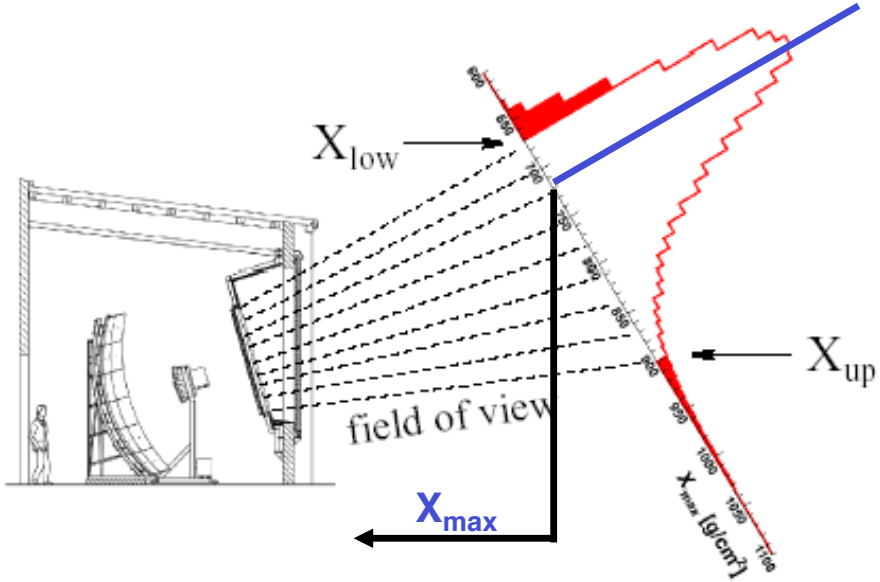
4 data sets combined: SD 750 m, FD (hybrid), SD 1500 m (0°-60°), SD 1500 m (60°-80°)

~200000 showers, ~50000 km2 sr yr exposure, FOV -90° < d < 25°

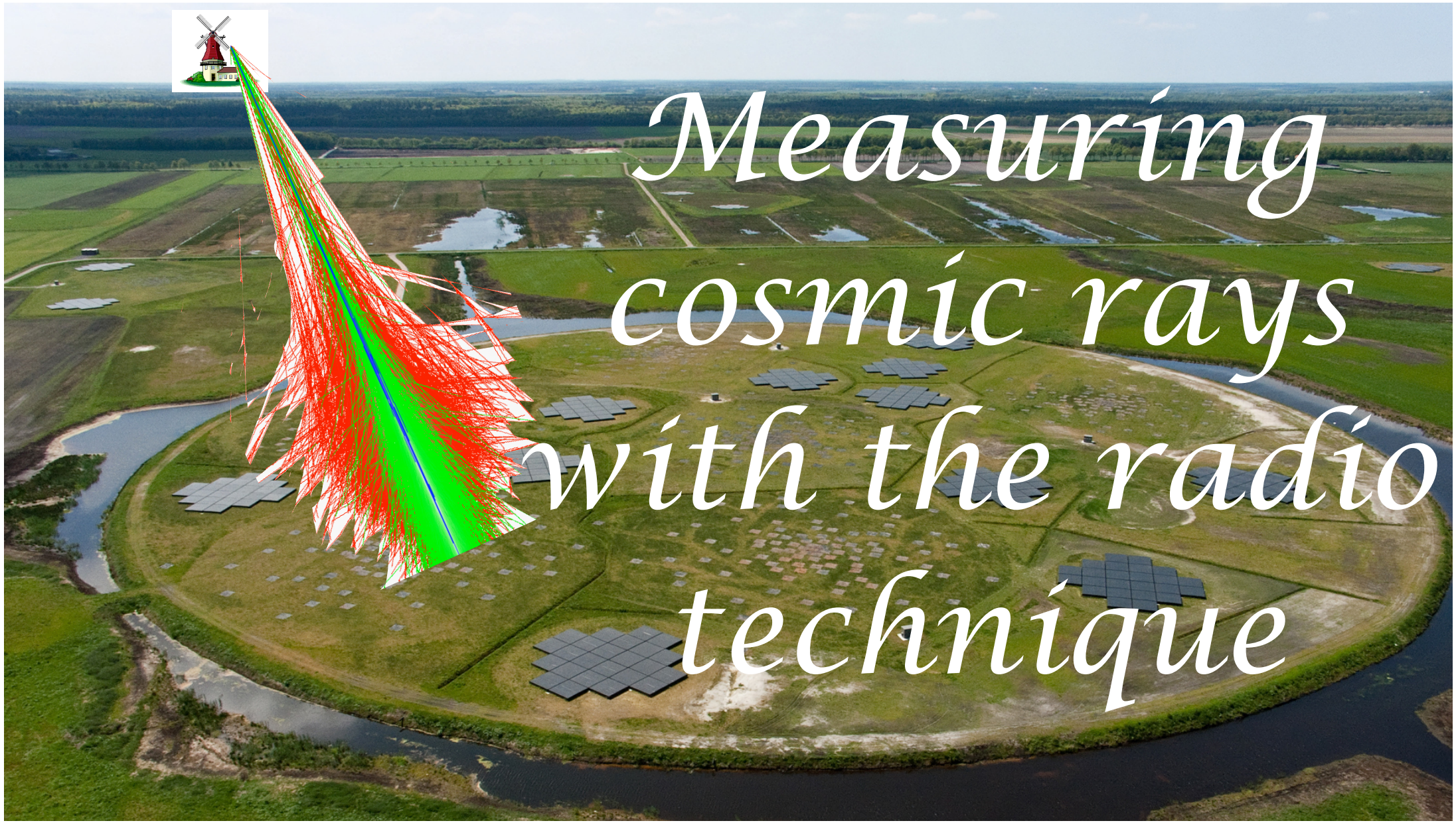
First measurement of the depth of shower maximum over 3 decades in energy

Depth of shower maximum is premiere observable for mass composition studies .
HEAT data extend the FOV of the fluorescence detector up to 60°.
Extension of the depth of shower maximum measurements down to 10^{17} eV.





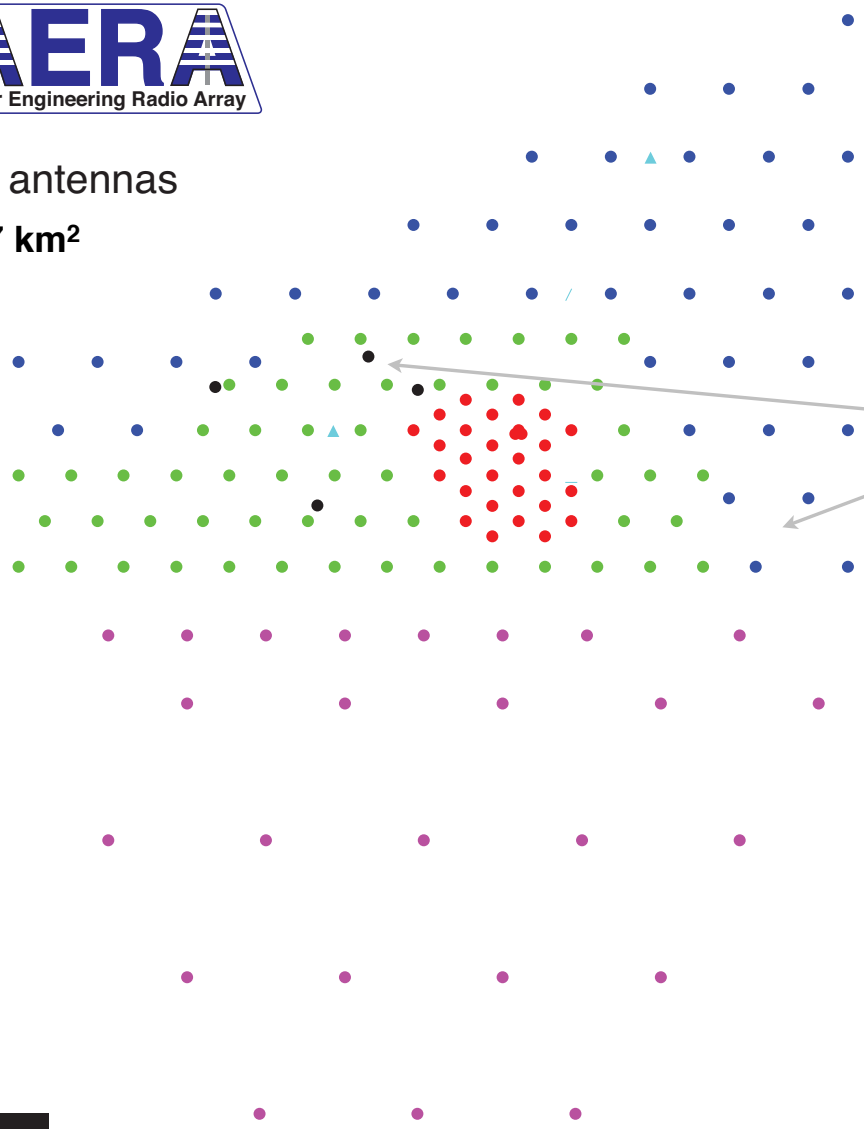
Compared to prediction for protons and iron nuclei according to the hadronic interaction models EPOS-LHC, QGSJETII-04, Sybill2.1


Measuring
cosmic rays
with the radio
technique

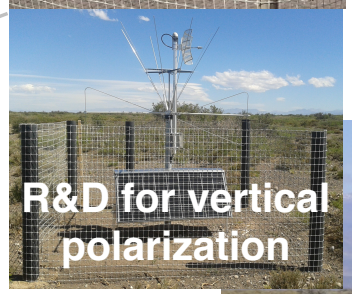
AERA
Auger Engineering Radio Array

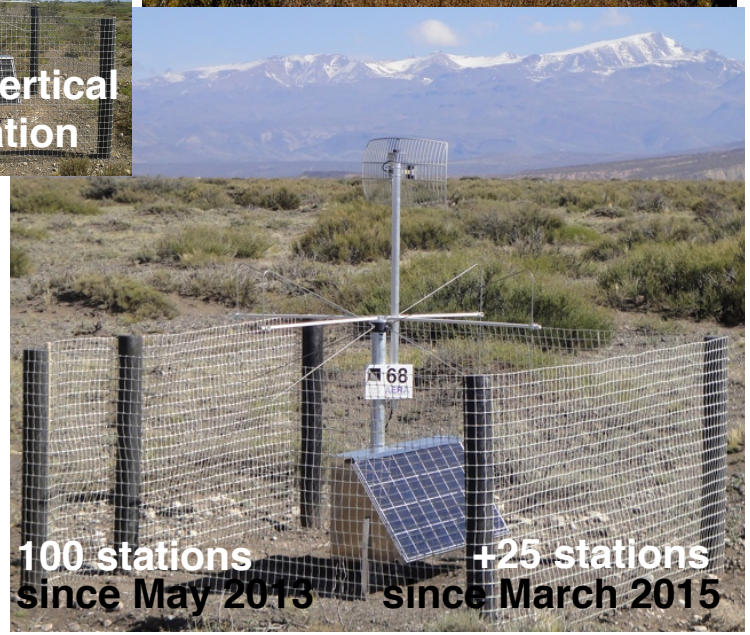
153 antennas

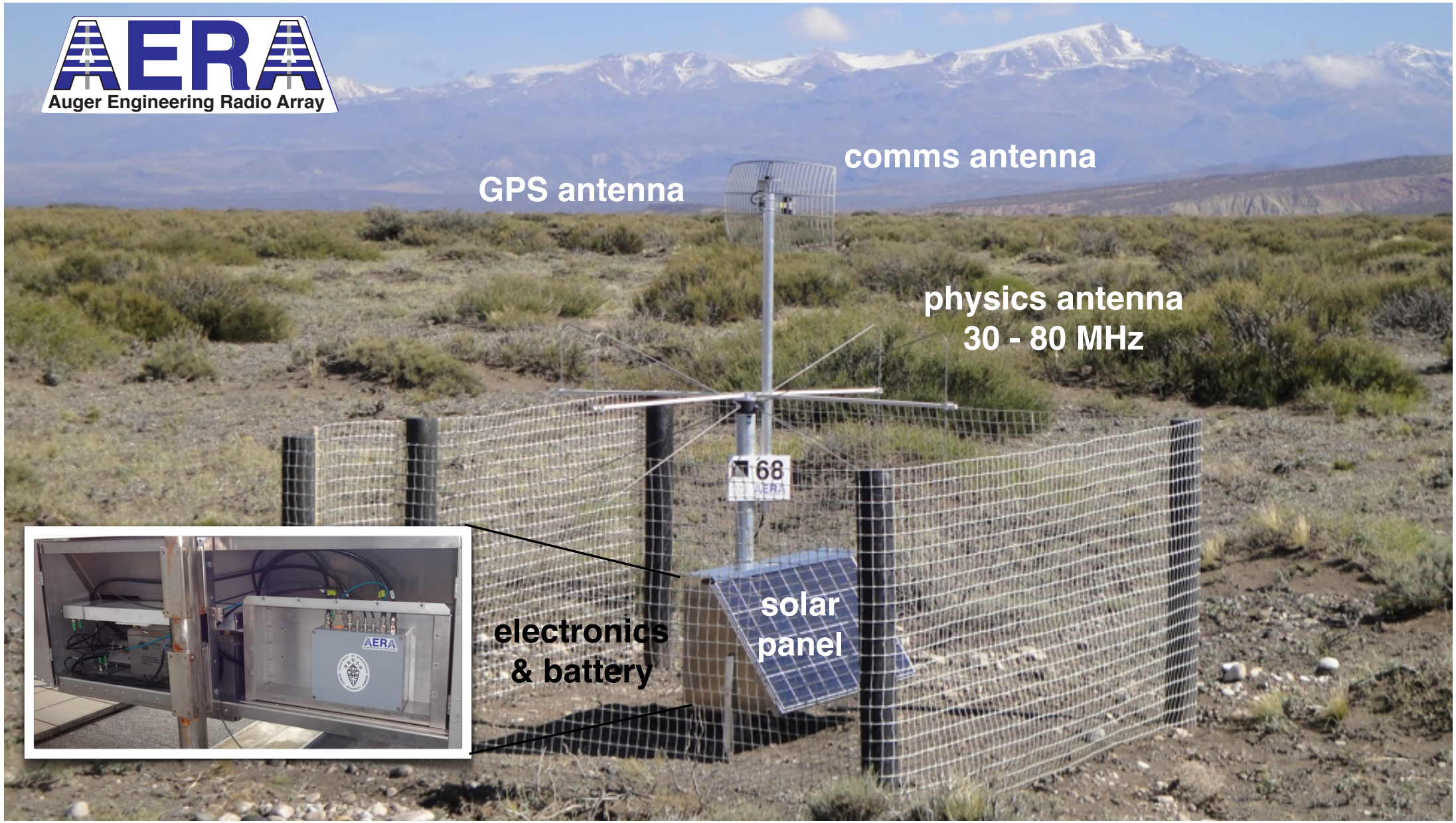
~17 km²



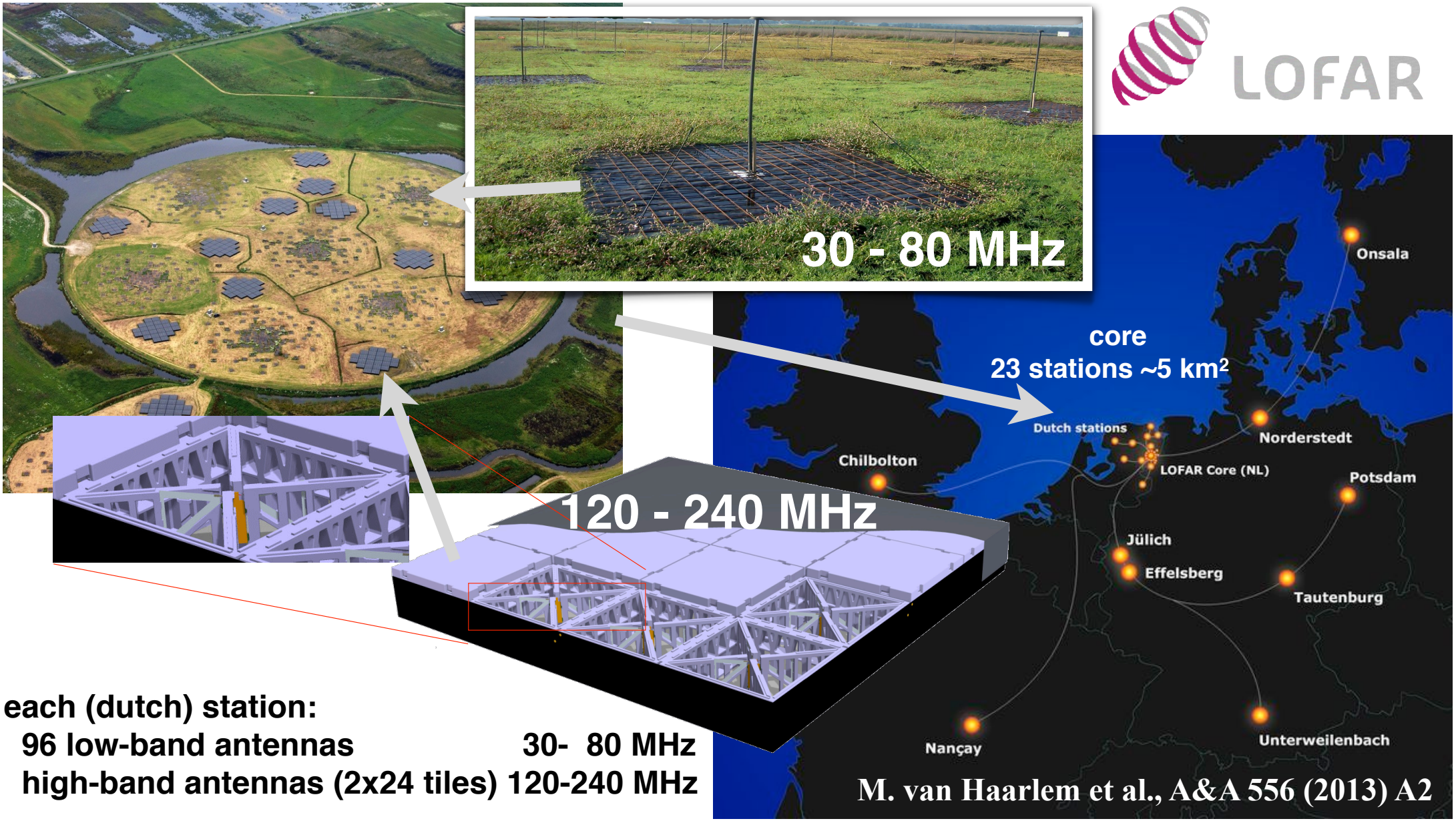
1 km






AERA
Auger Engineering Radio Array
comms antenna
GPS antenna
physics antenna
30 - 80 MHz
68
AERA
solar
panel
electronics
& battery
AERA

installation April/May 2013



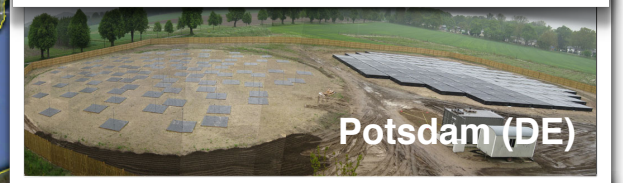
each (dutch) station:

96 low-band antennas 30- 80 MHz

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

Construction of stations

LOFAR stations across Europe

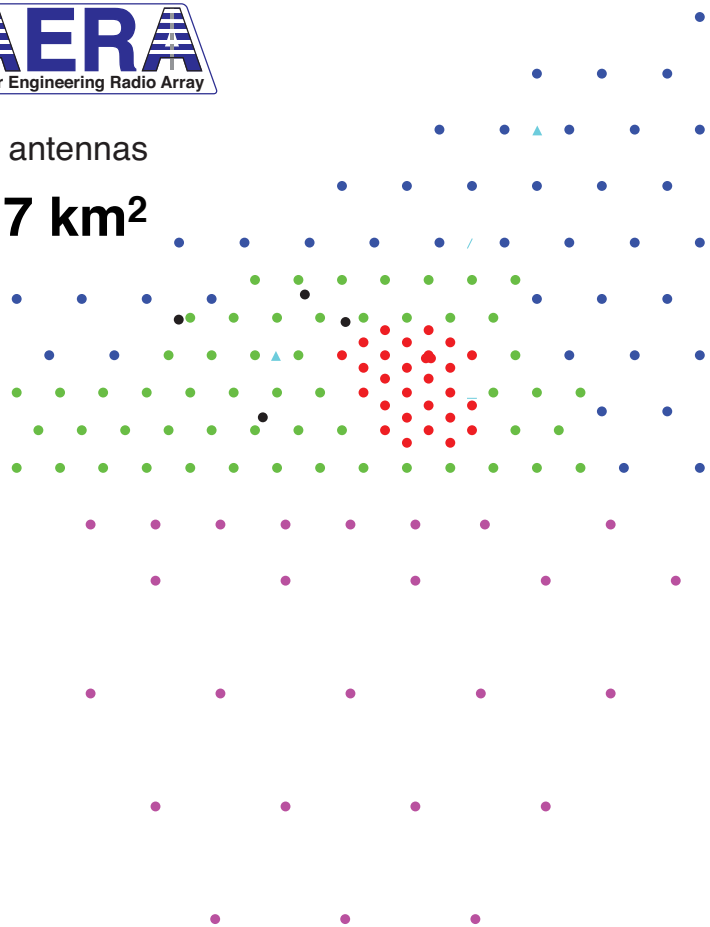


LOFAR Opening
12th June 2010

AERA
Auger Engineering Radio Array

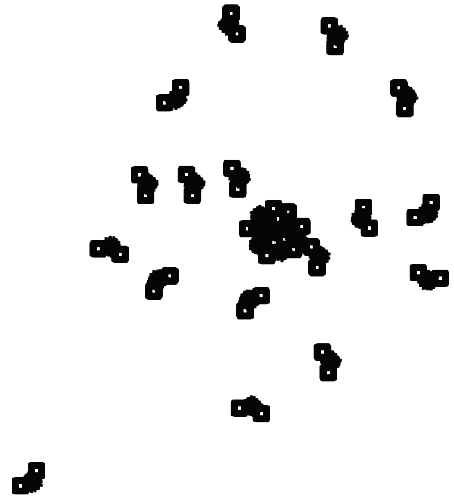
153 antennas

~17 km²



LOFAR **core**

23 stations ~5 km²



>2000 antennas

1 km

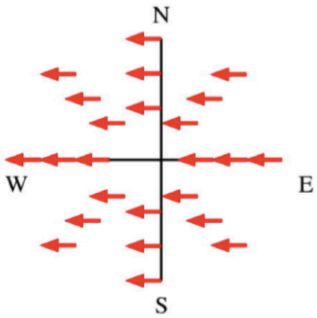
Radio Emission in Air Showers

- Mainly: Charge separation in geomagnetic field $\vec{E} \propto \vec{v} \times \vec{B}$

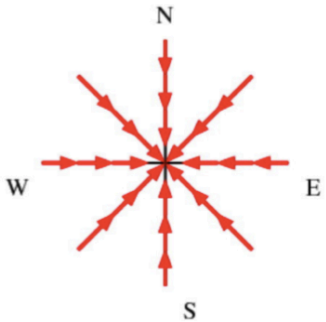
  Theory predicts additional mechanisms:
- excess of electrons in shower: charge excess
- superposition of emission due to Cherenkov effects in atmosphere

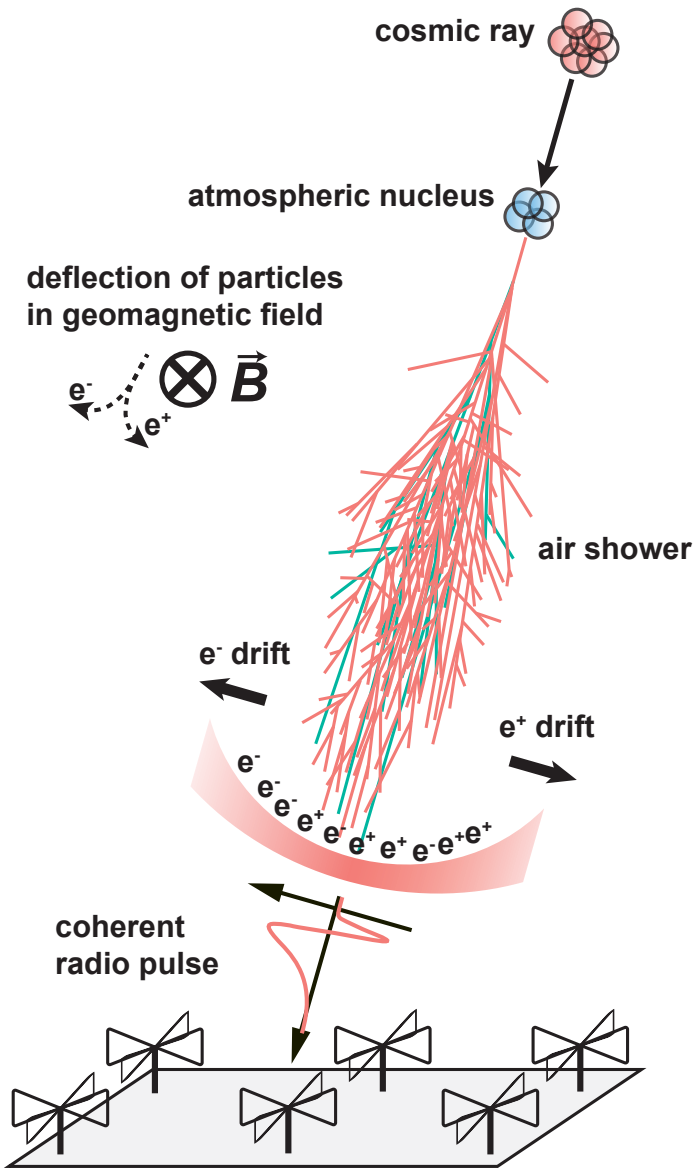
polarization of radio signal

geomagnetic

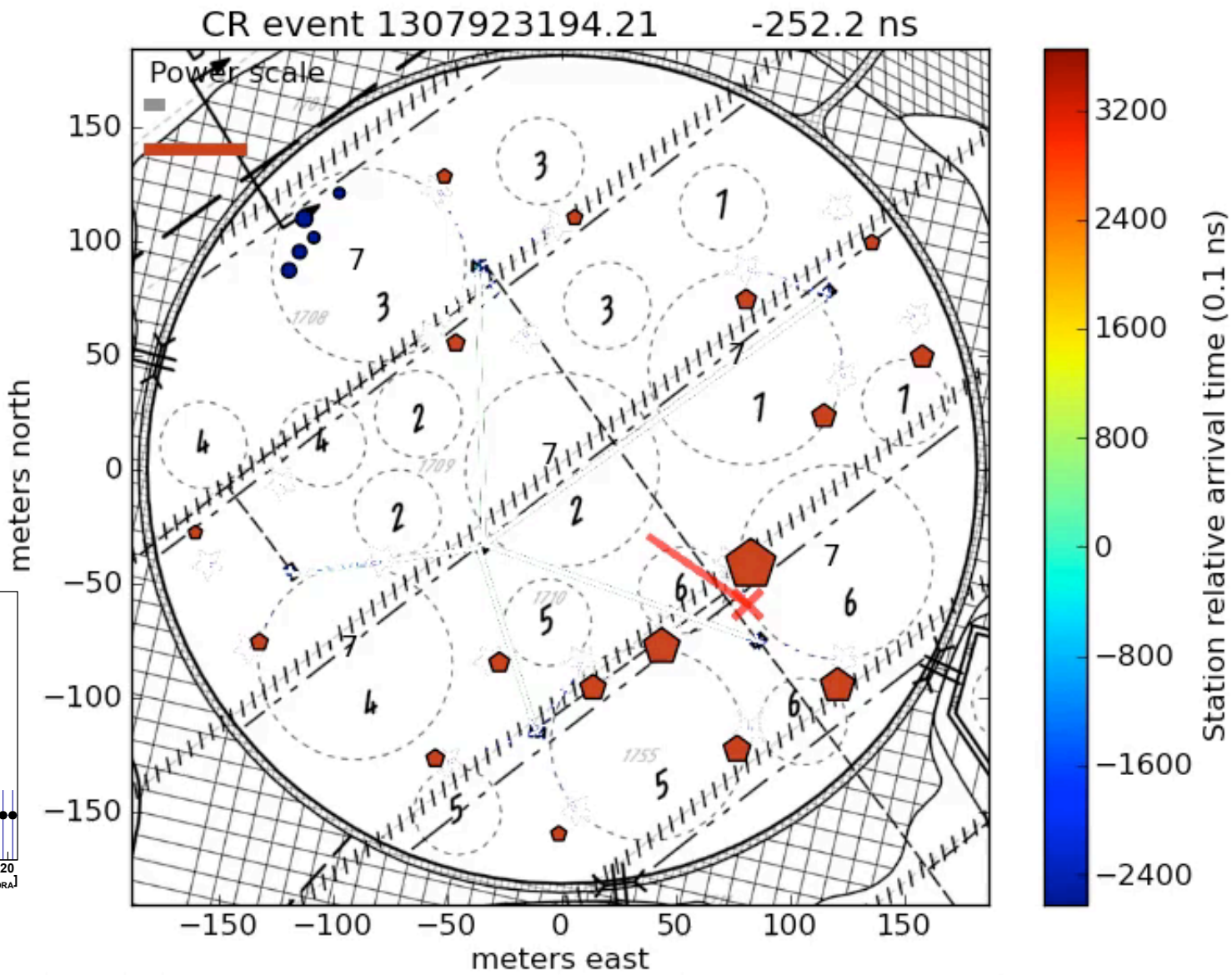


Askaryan



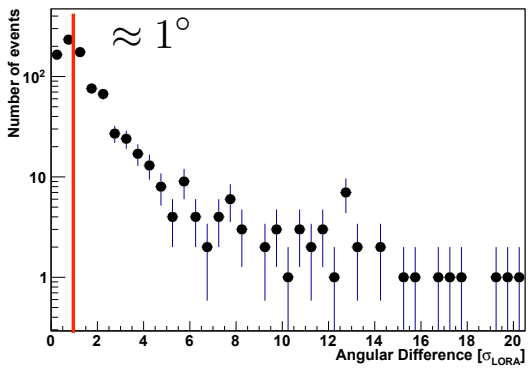


A measured air shower

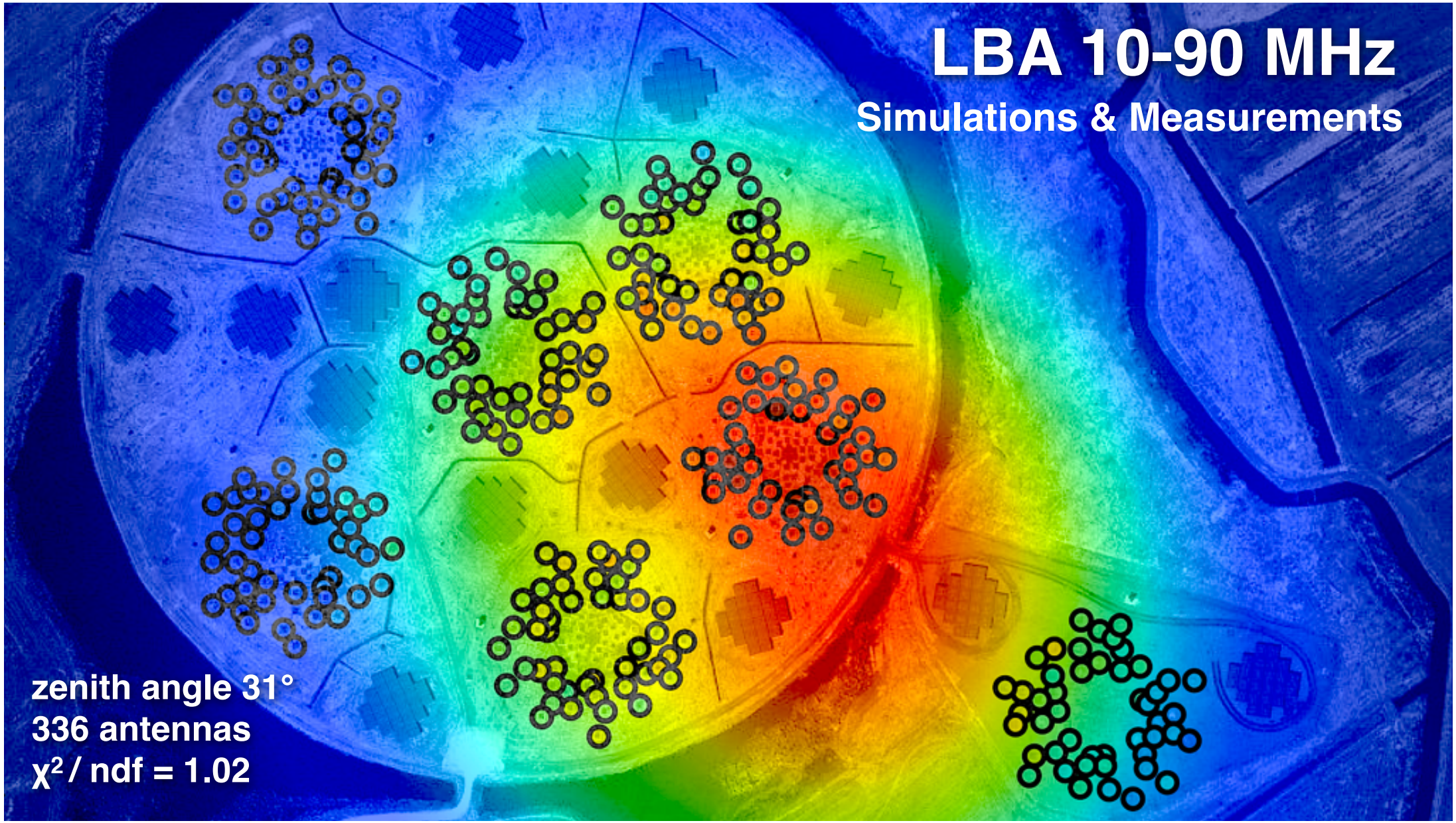


Circles: LOFAR antennas, Pentagons: LORA particle detectors, size denotes signal strength

angular difference particles - radio

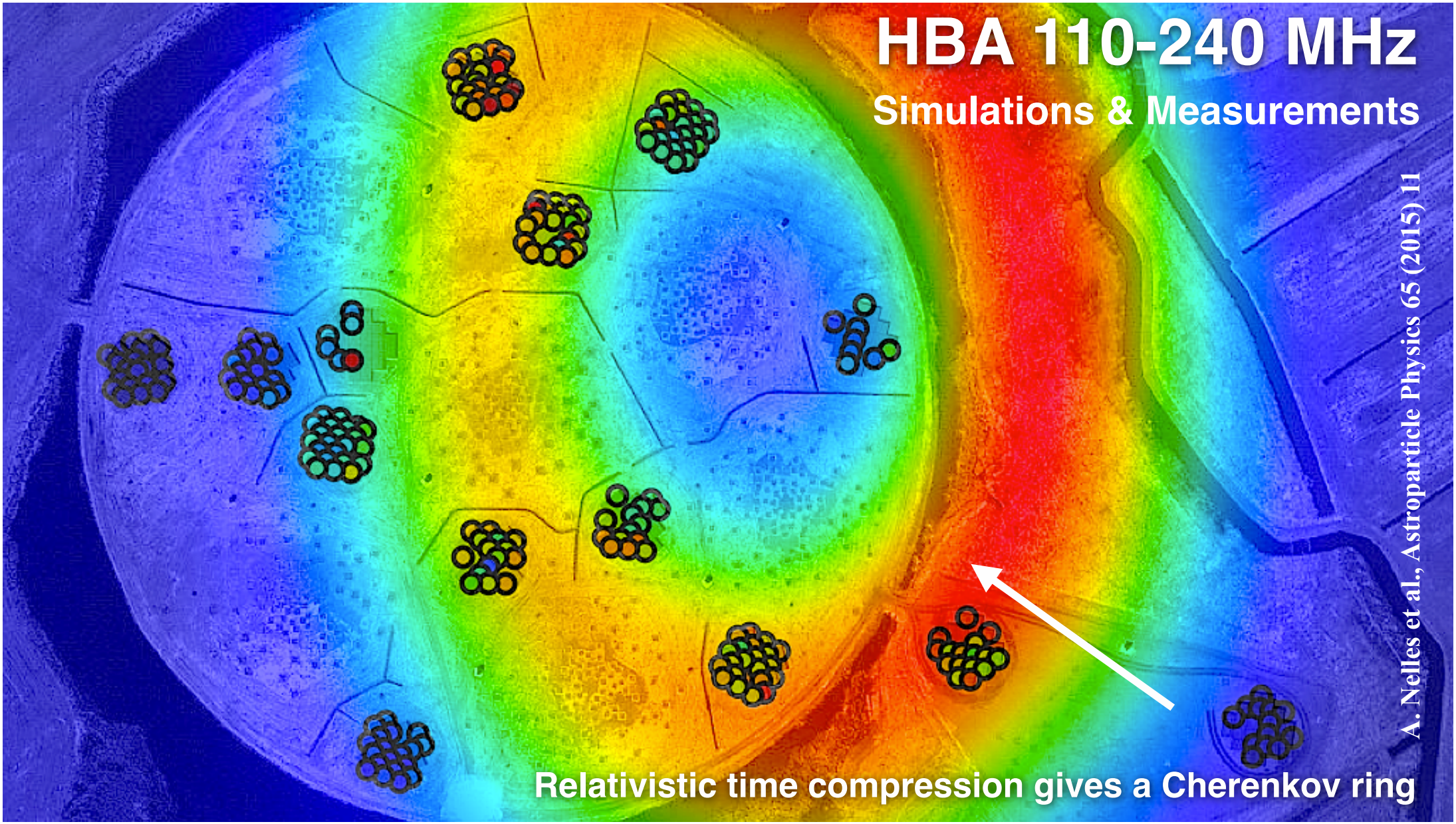


LOFAR


LBA 10-90 MHz
Simulations & Measurements
zenith angle 31°
336 antennas
χ² / ndf = 1.02

HBA 110-240 MHz

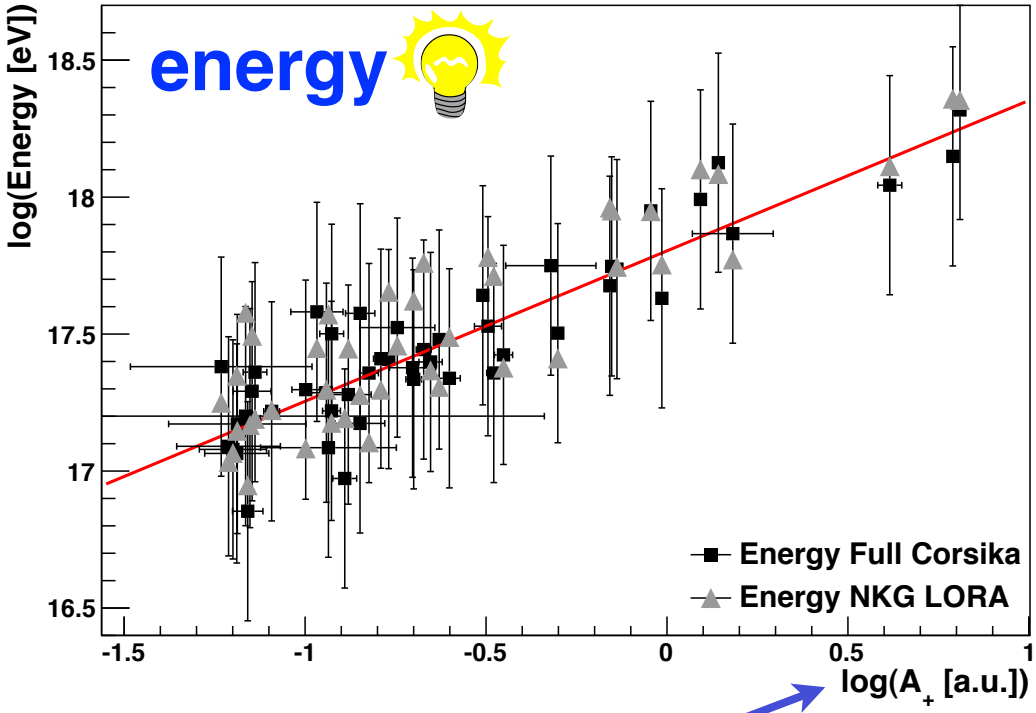
Simulations & Measurements

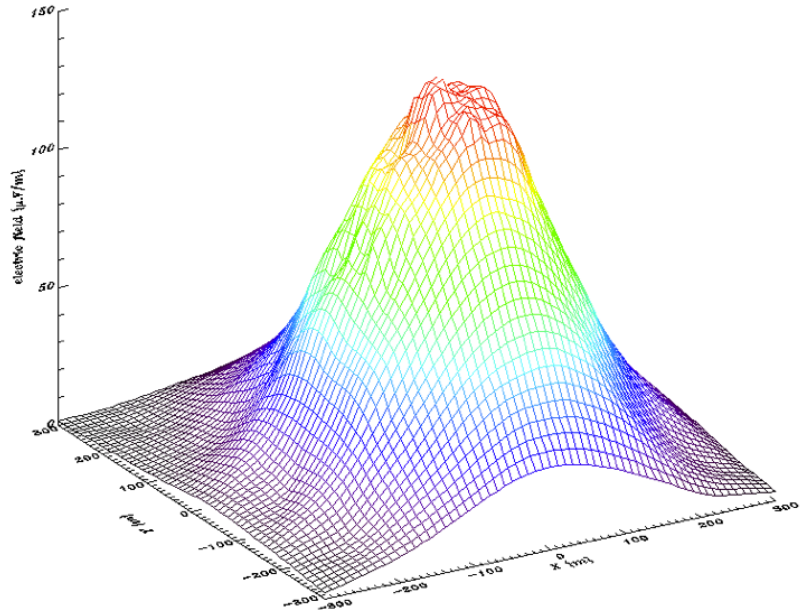


Relativistic time compression gives a Cherenkov ring

A. Nelles et al., Astroparticle Physics 65 (2015) 11

Properties of primary particle



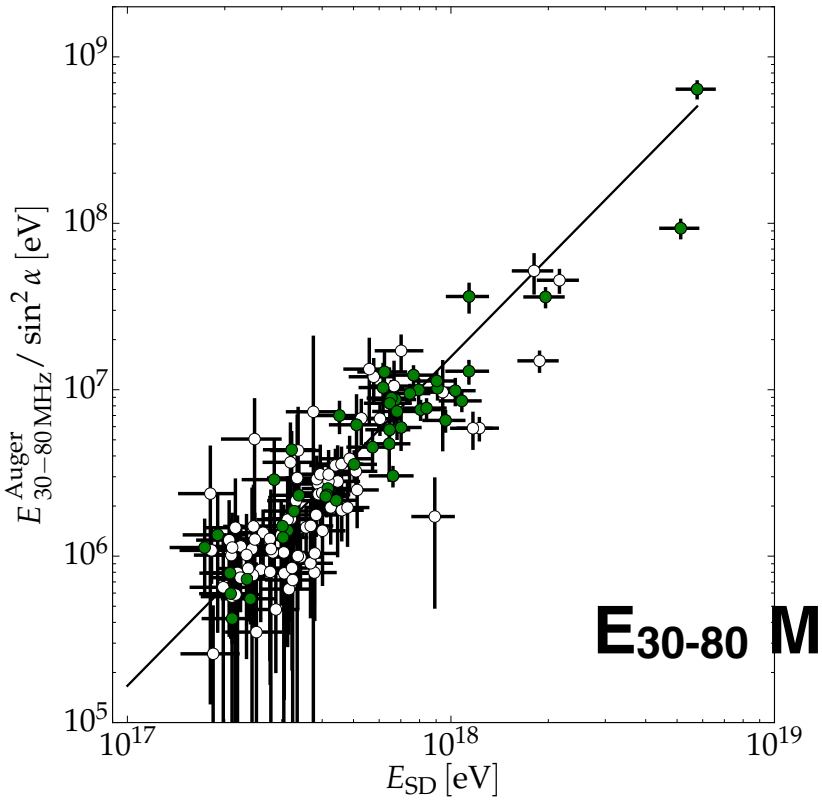


$$P(x', y') = A_+ \cdot \exp\left(\frac{-[(x' - X_+)^2 + (y' - Y_+)^2]}{\sigma_+^2}\right) - A_- \cdot \exp\left(\frac{-[(x' - X_-)^2 + (y' - Y_-)^2]}{\sigma_-^2}\right) + O$$

LOFAR

A. Nelles et al., JCAP 05 (2015) 018

Energy content of the radio component of an EAS

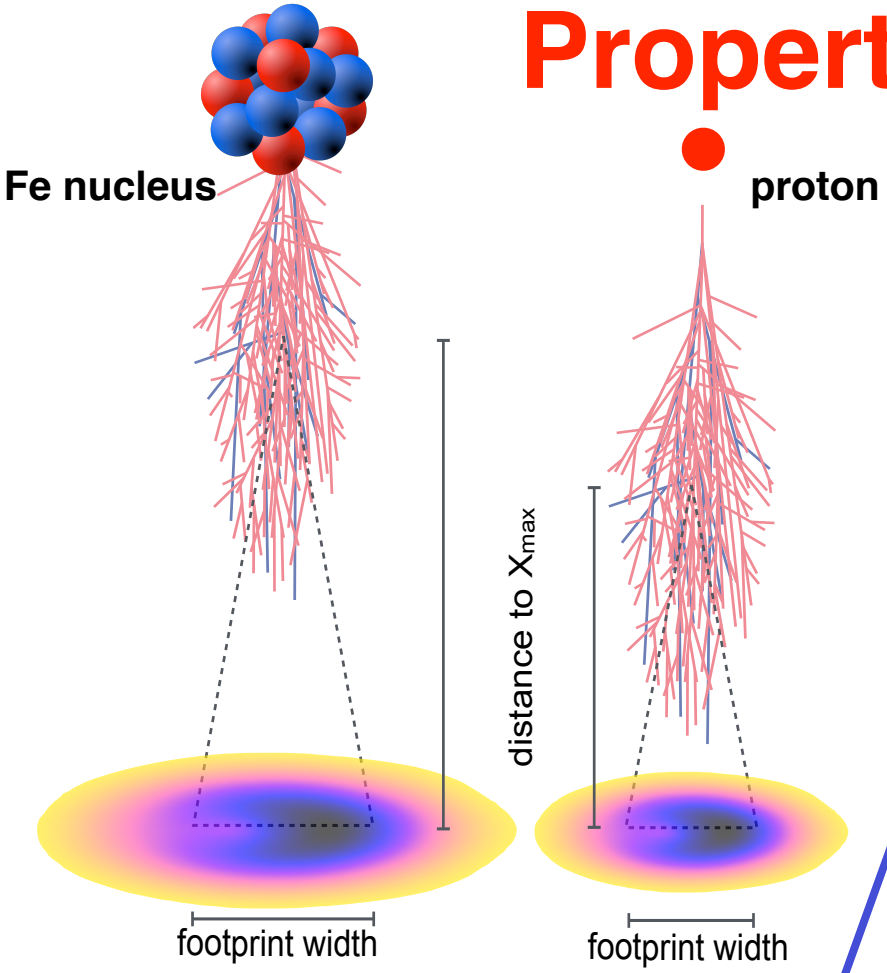


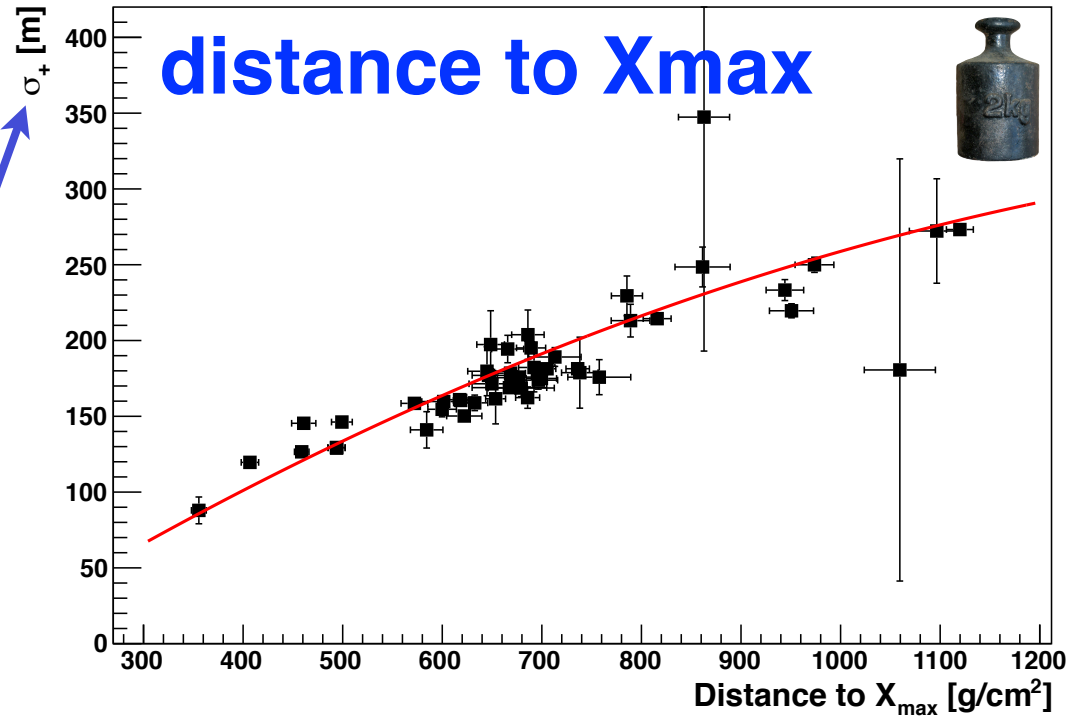
$E_{30\text{-}80}$ MHz = 15.8 MeV @ 10^{18} eV

FIG. 2. Correlation between the normalized radiation energy and the cosmic-ray energy E_{SD} as determined by the Auger surface detector. Open circles represent air showers with radio signals detected in three or four radio detectors. Filled circles denote showers with five or more detected radio signals.

Auger Engineering Radio Array

Properties of primary particle



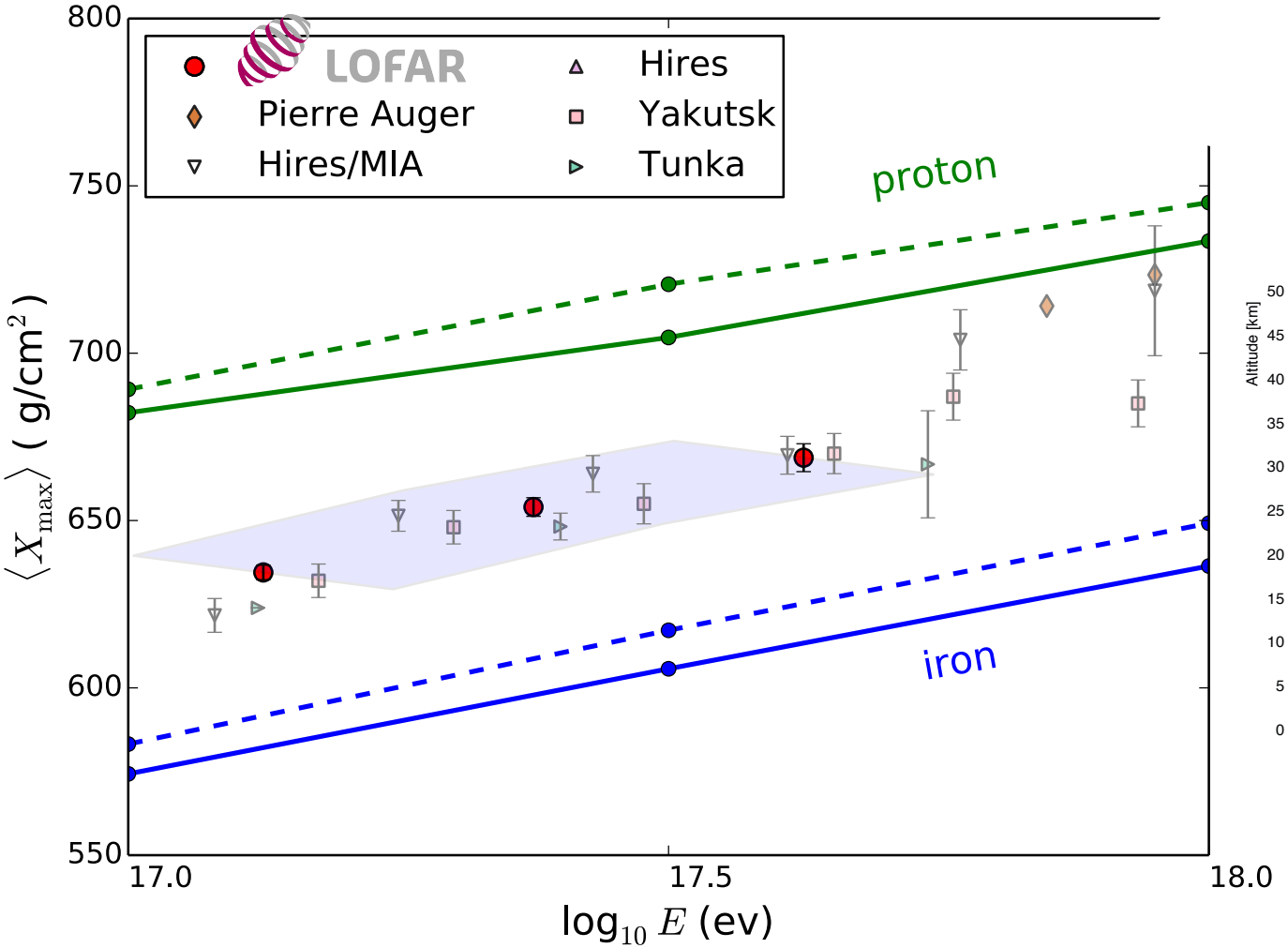


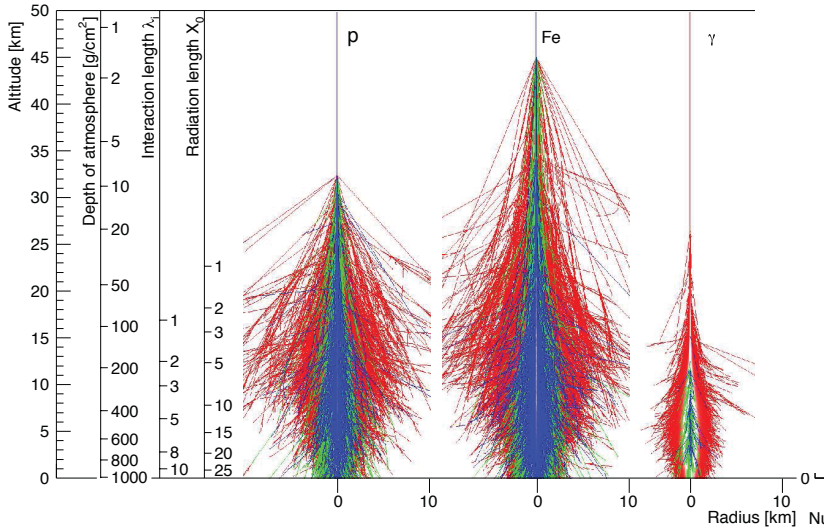
$$P(x', y') = A_+ \cdot \exp\left(\frac{-[(x' - X_+)^2 + (y' - Y_+)^2]}{\sigma_+^2}\right) - A_- \cdot \exp\left(\frac{-[(x' - X_-)^2 + (y' - Y_-)^2]}{\sigma_-^2}\right) + O$$

LOFAR

A. Nelles et al., JCAP 05 (2015) 018

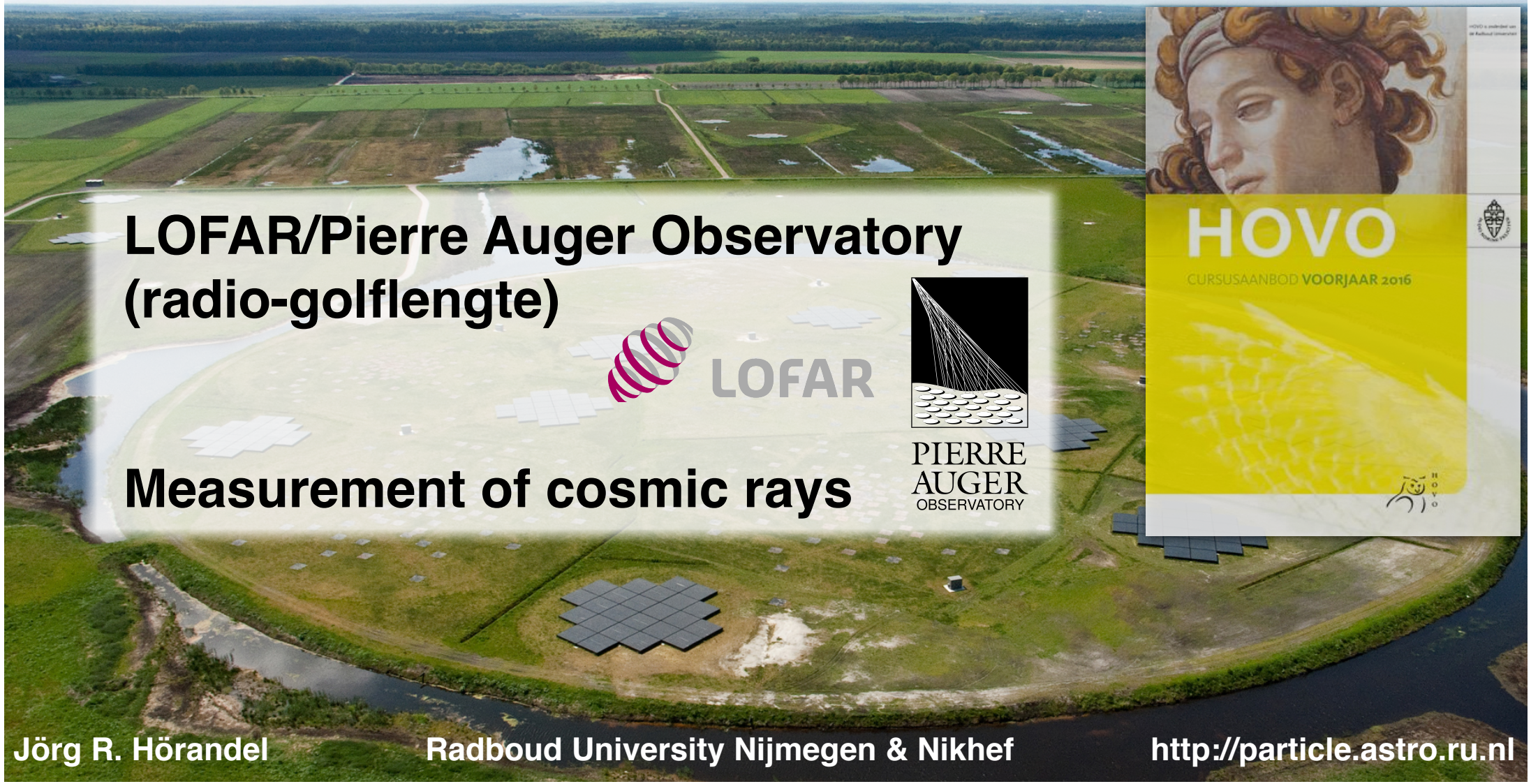
Depth of the shower maximum





Technologie van de nieuwe sterrenkunde

25 January 2016



LOFAR/Pierre Auger Observatory (radio-golflengte)

LOFAR

PIERRE AUGER OBSERVATORY

Measurement of cosmic rays

Jörg R. Hörandel Radboud University Nijmegen & Nikhef http://particle.astro.ru.nl