

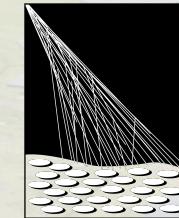
Technologie van de nieuwe sterrenkunde

25 January 2016

**LOFAR/Pierre Auger Observatory
(radio-golfelengte)**



LOFAR



**PIERRE
AUGER
OBSERVATORY**

Measurement of cosmic rays

Jörg R. Hörandel

Radboud University Nijmegen & Nikhef

<http://particle.astro.ru.nl>

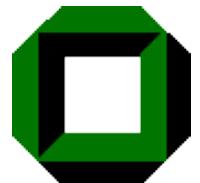


HOVO
CURSUSAANBOD VOORJAAR 2016

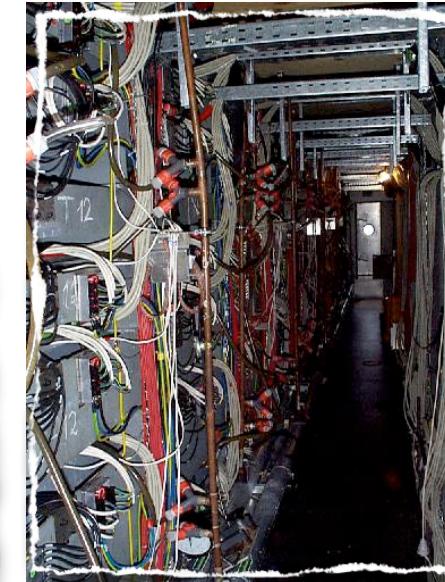
HOVO is onderdeel van
de Radboud Universiteit



**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**



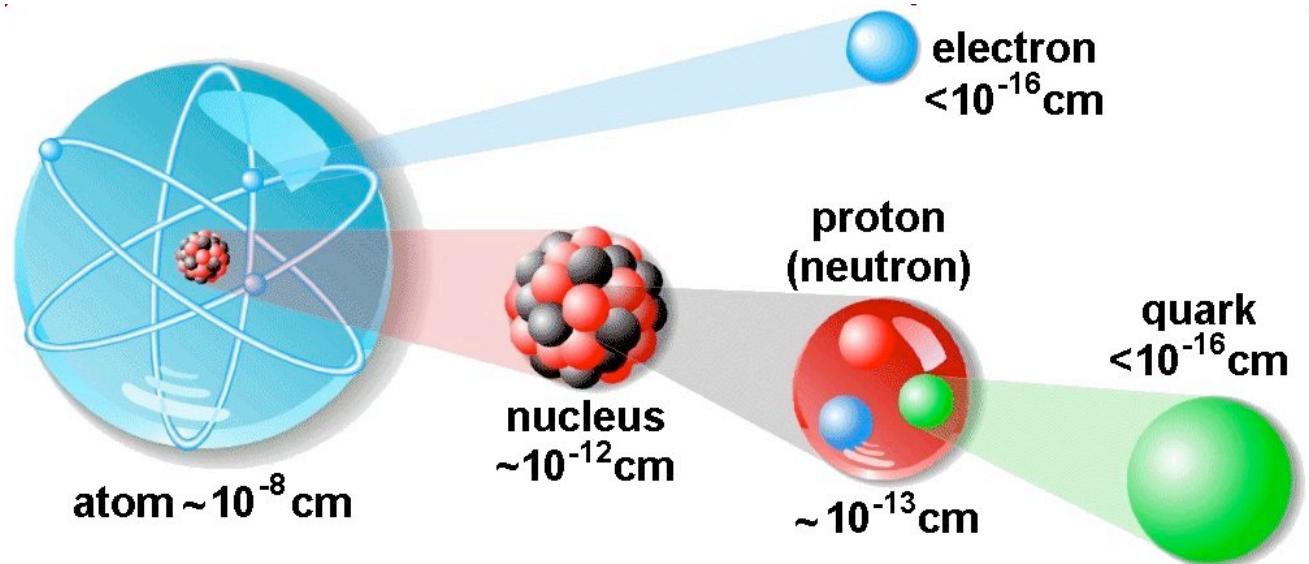
*What are
Cosmic rays?*

THE HUMAN BODY

ELEMENTAL COMPOSITION BY MASS



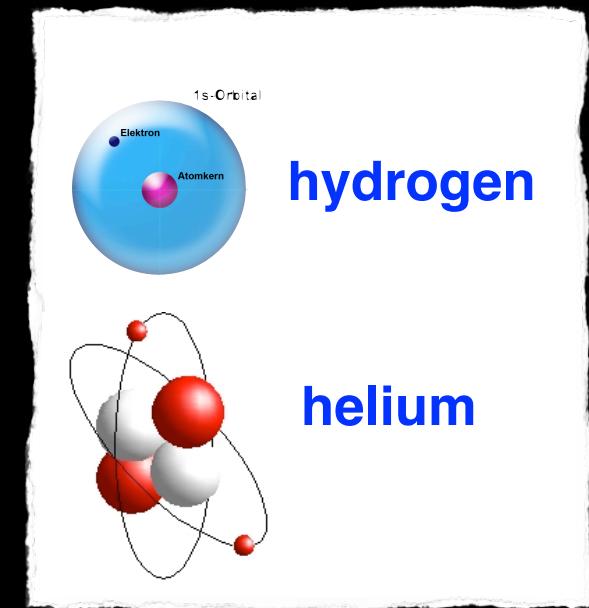
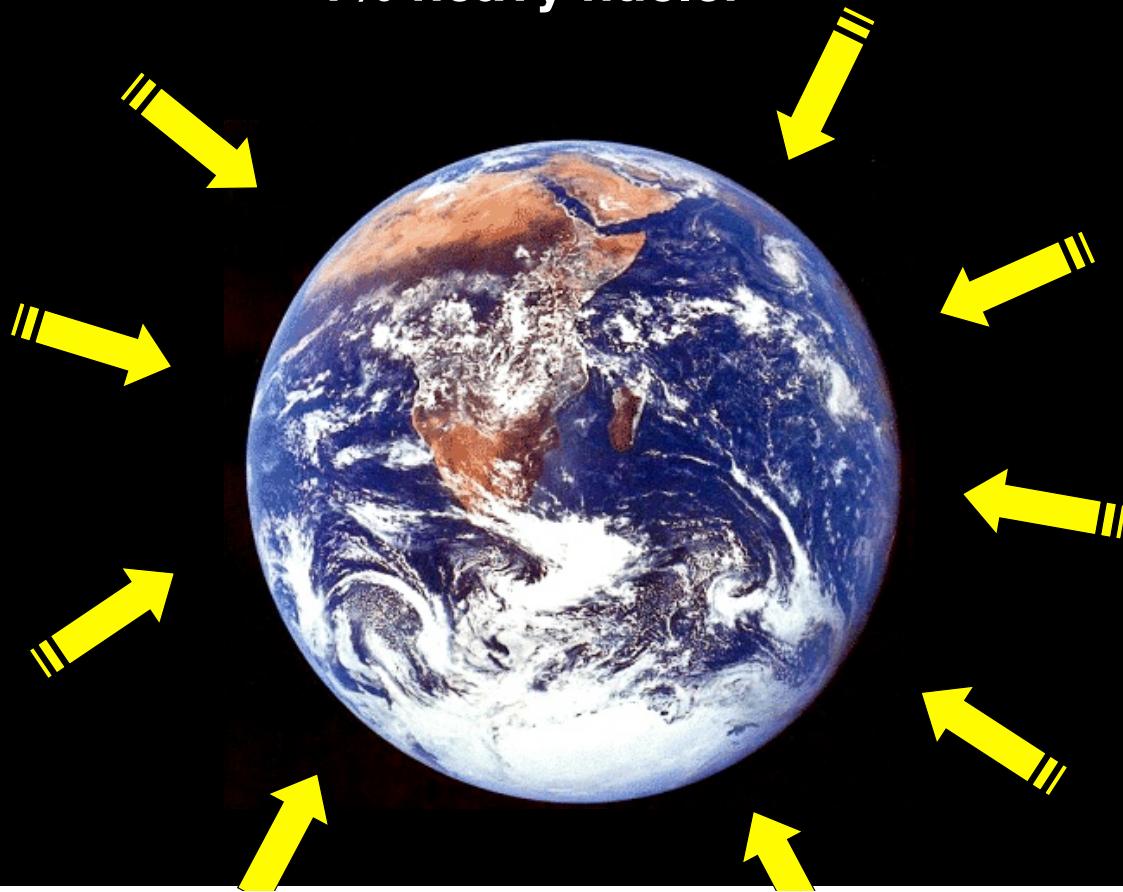
Structure of matter



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

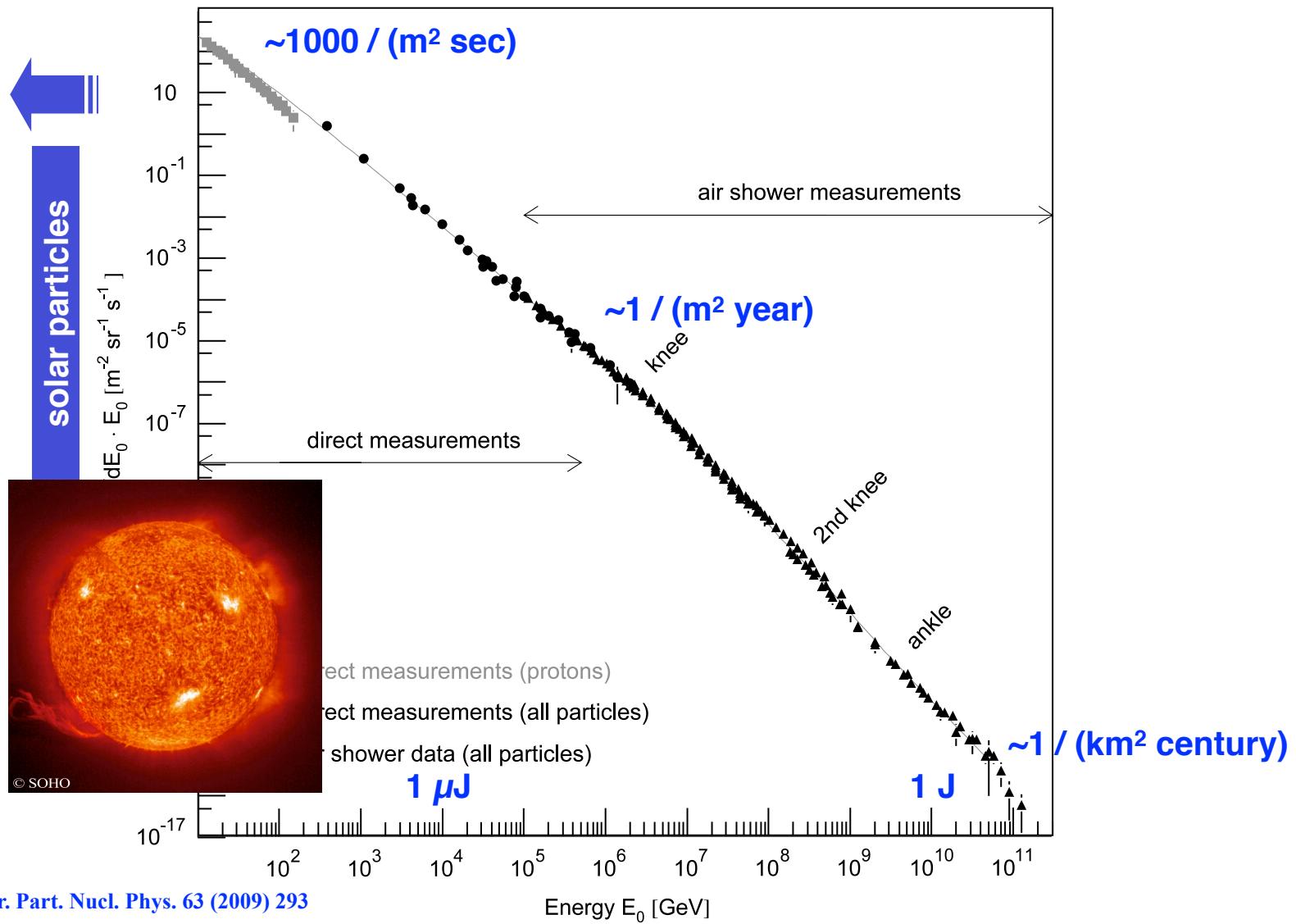
Cosmic rays are comprised of

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

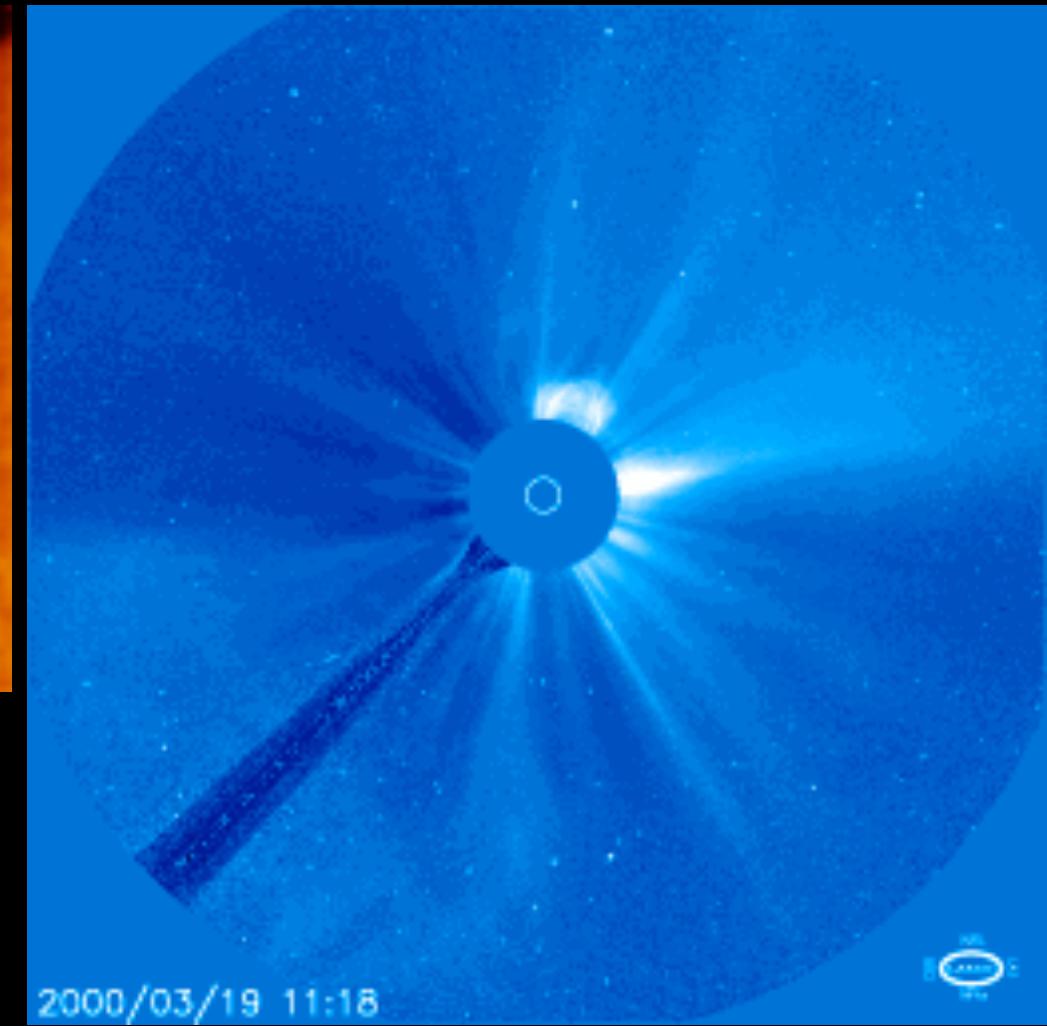
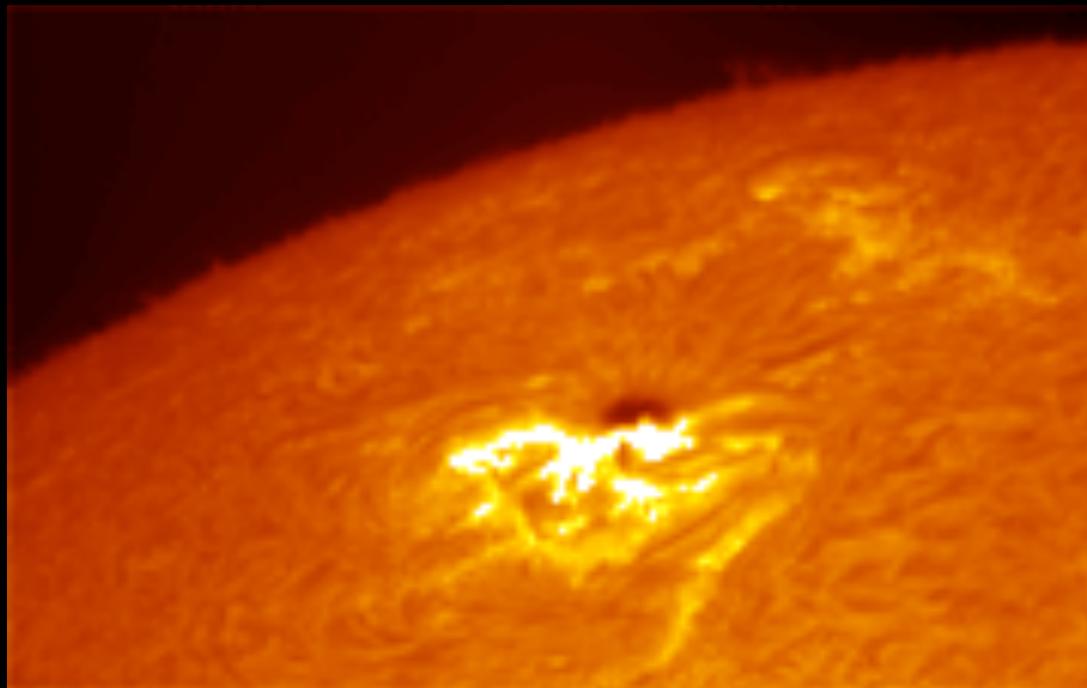


flux: ~ 1000 particles per square meter and second

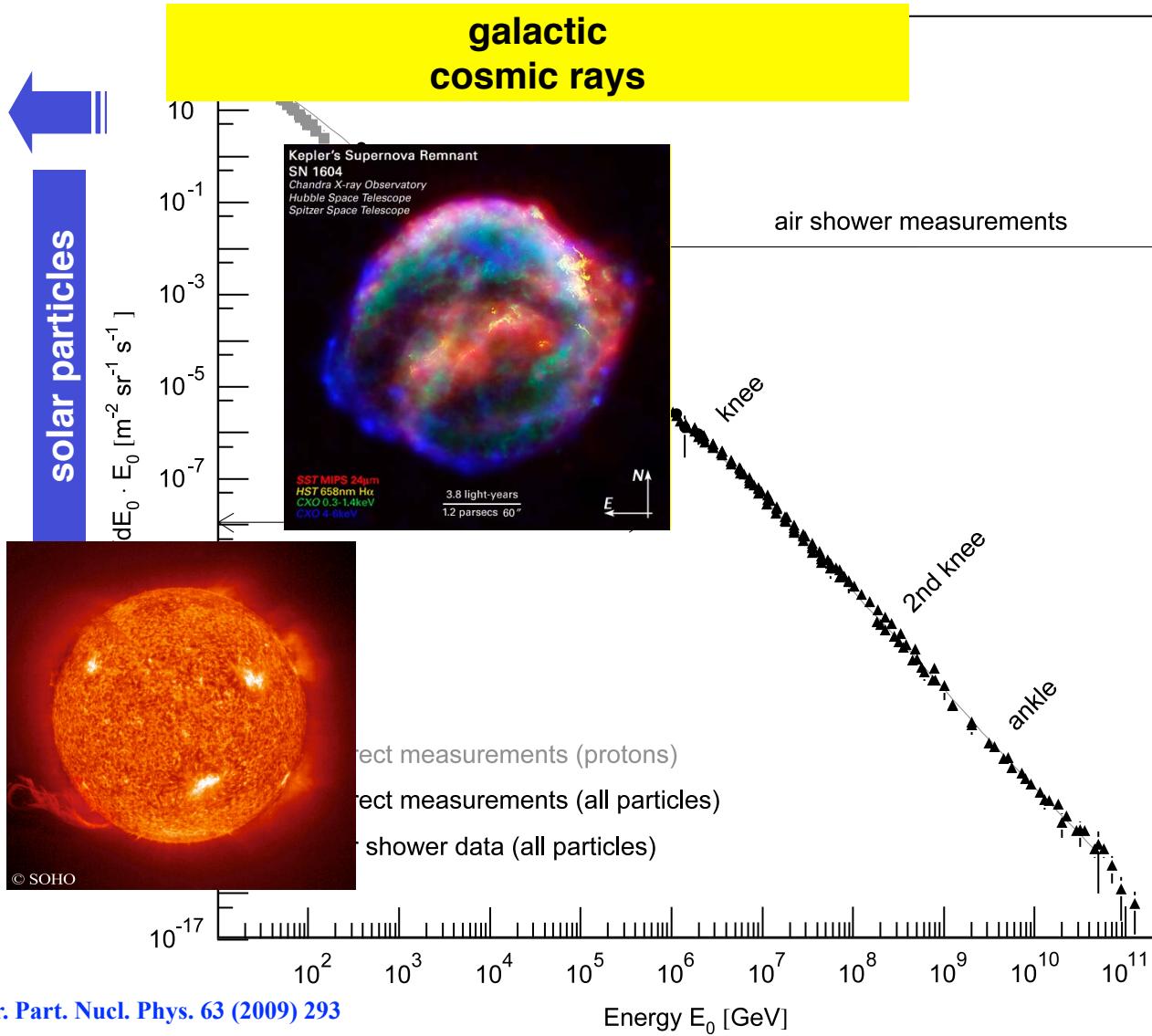
Energy Spectrum of Cosmic Rays



Solar flares



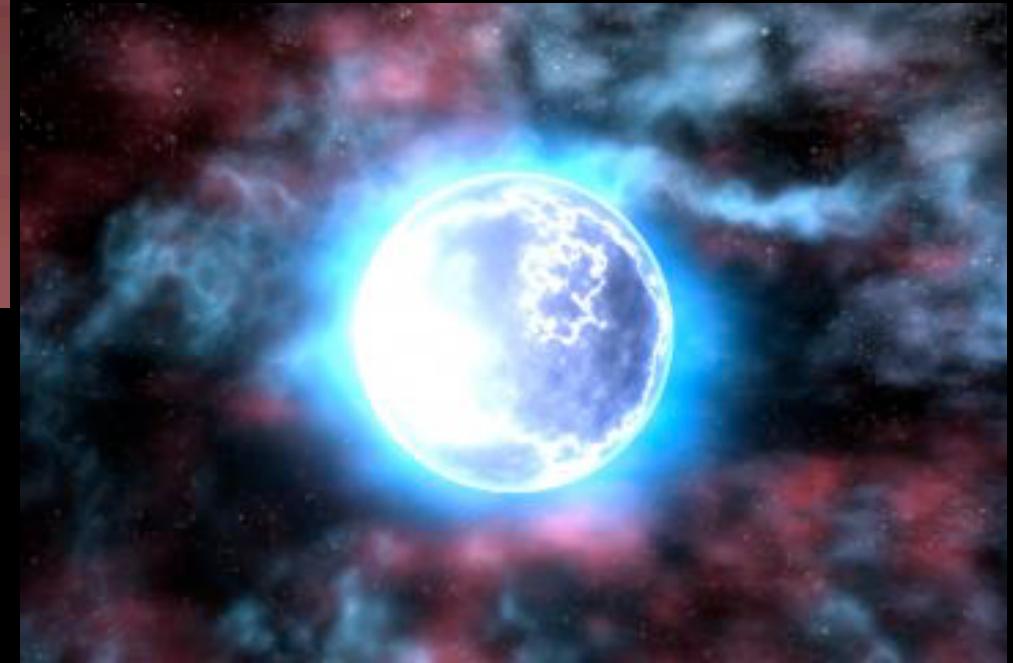
Energy Spectrum of Cosmic Rays



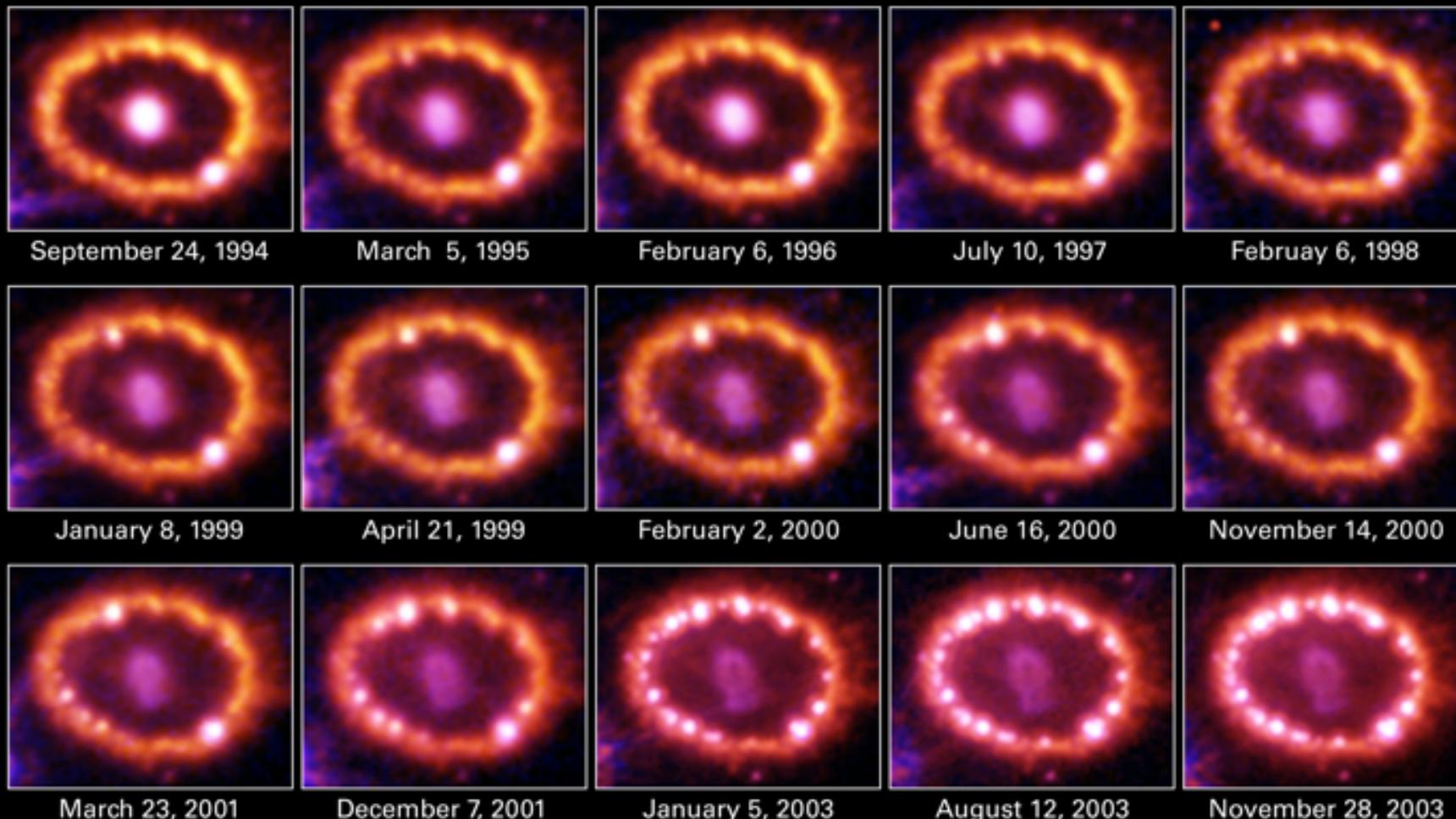
Acceleration of cosmic rays in supernova remnants



Cassiopeia A



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

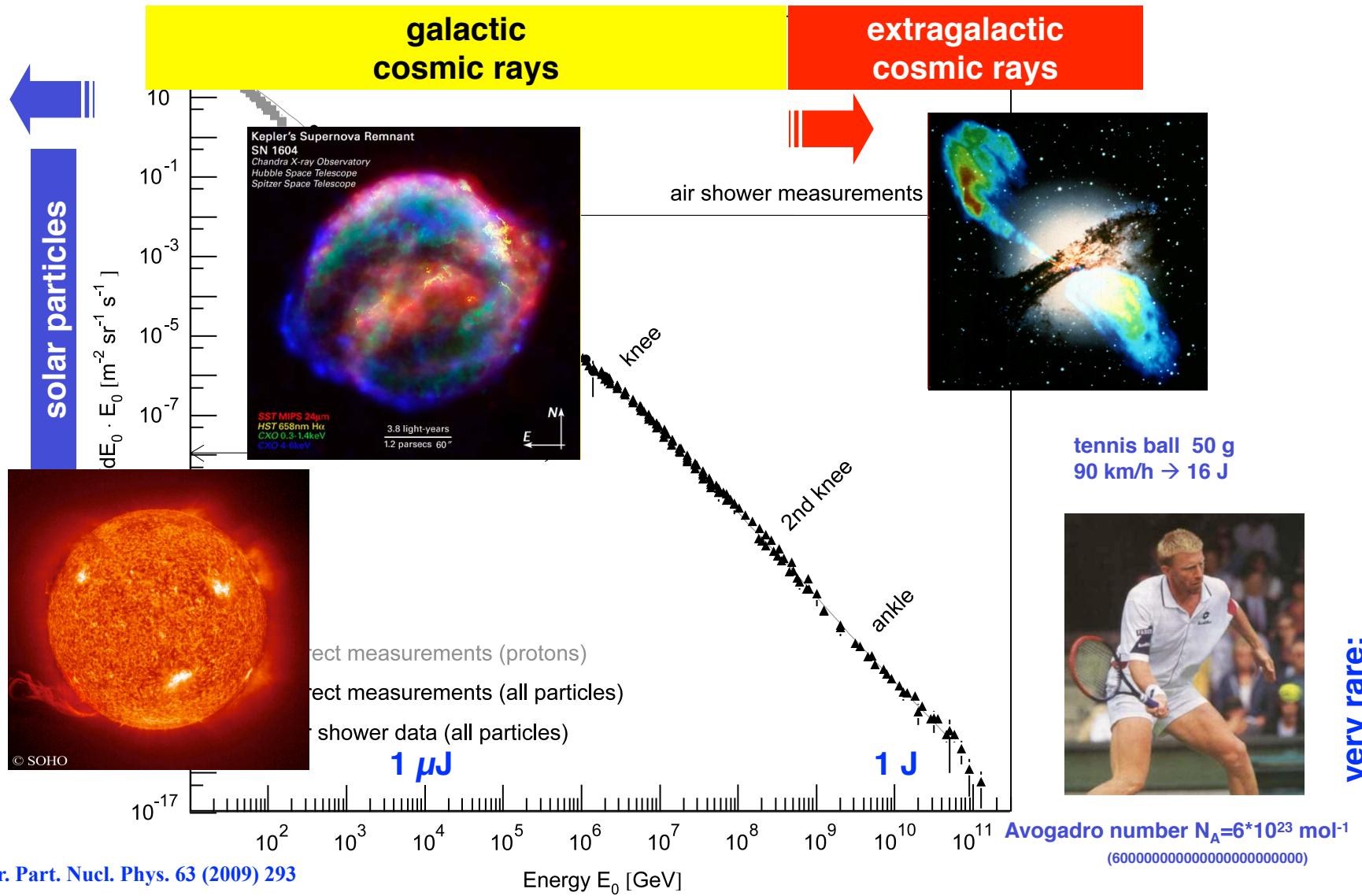


Supernova 1987A • 1994-2003 Hubble Space Telescope • WFPC2 • ACS

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

STScI-PRC04-09b

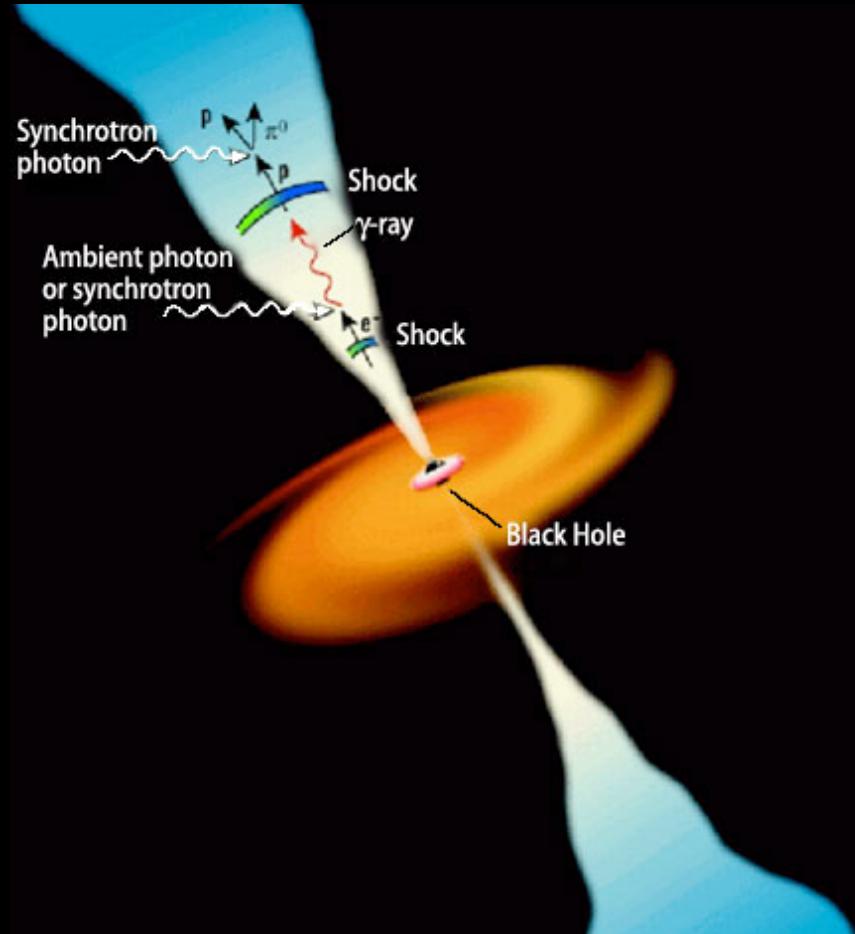
Energy Spectrum of Cosmic Rays



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)

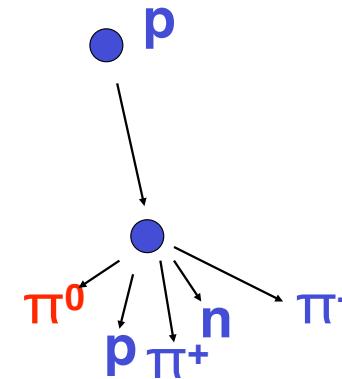


Propagation of cosmic rays through the Galaxy



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

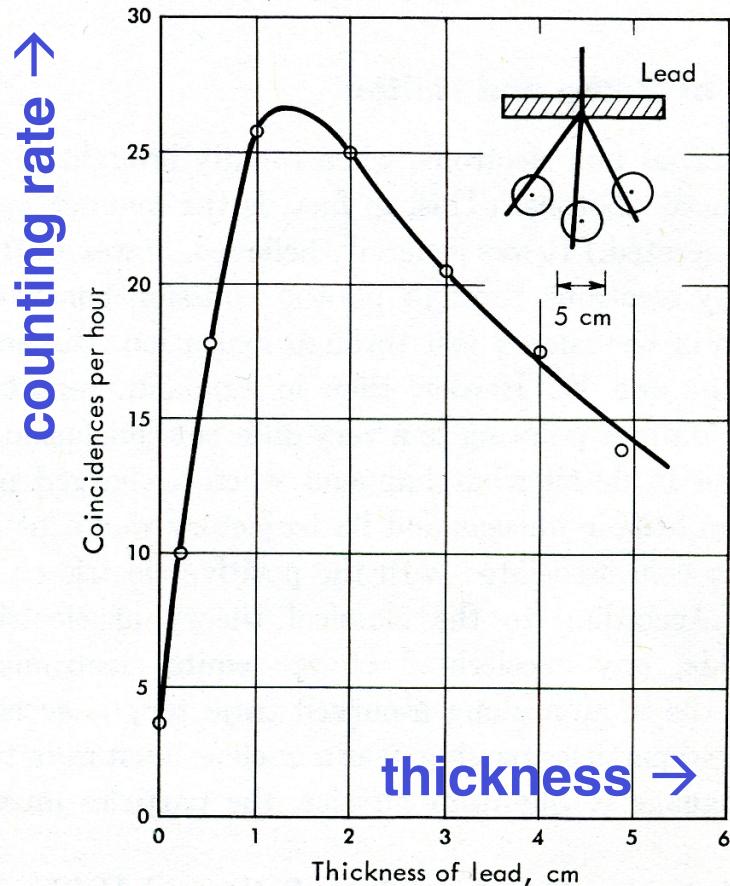


Fig. 7-1 Shower curve. The number of coincidences per hour is plotted as a function of the thickness of lead above the counters. The experimental arrangement is shown schematically in the inset. The circles are experimental points. (This figure is based on one appearing in a paper by the author in *Zeitschrift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

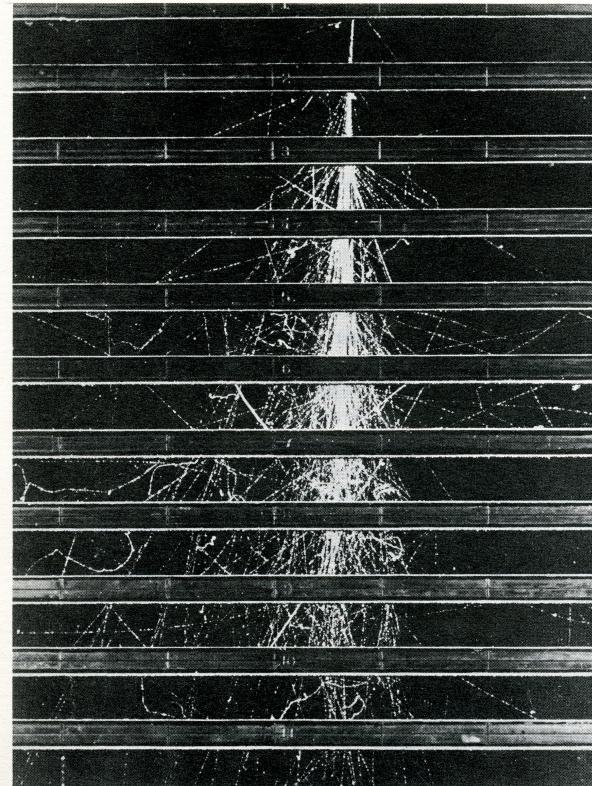
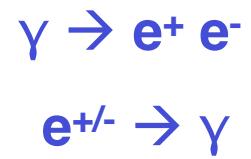
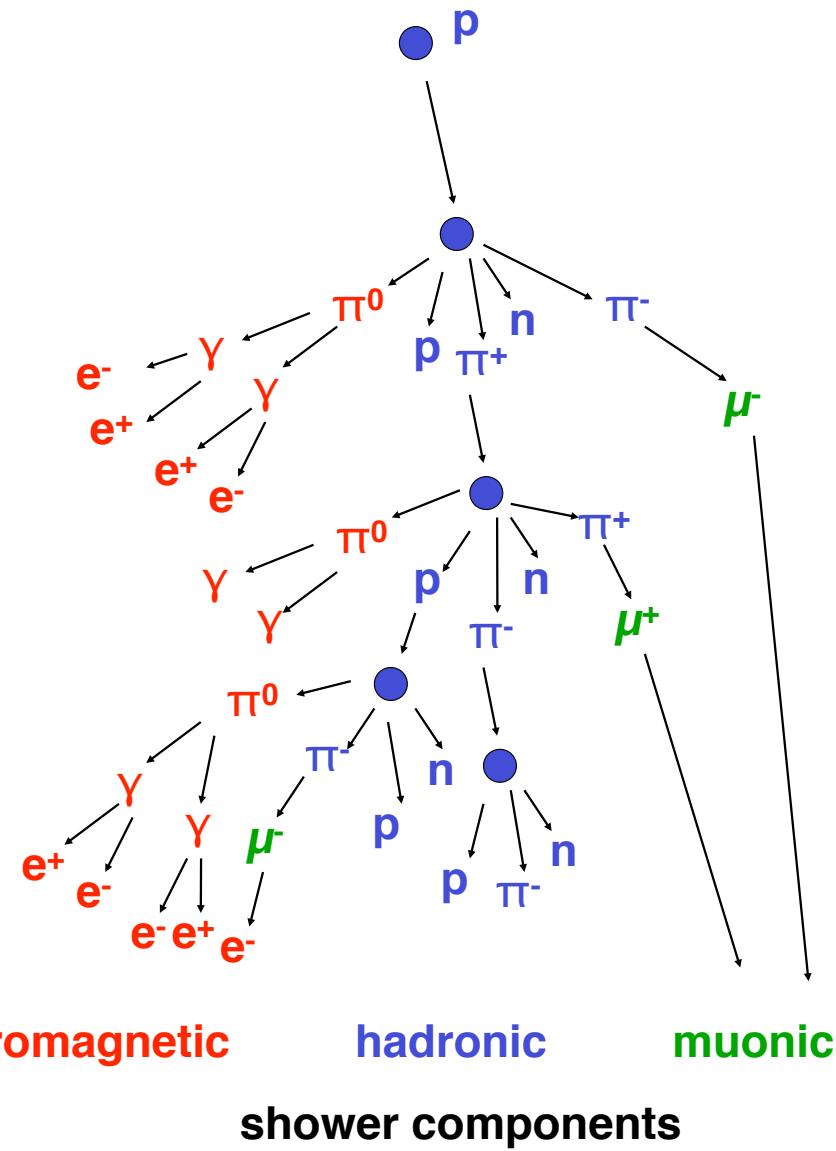
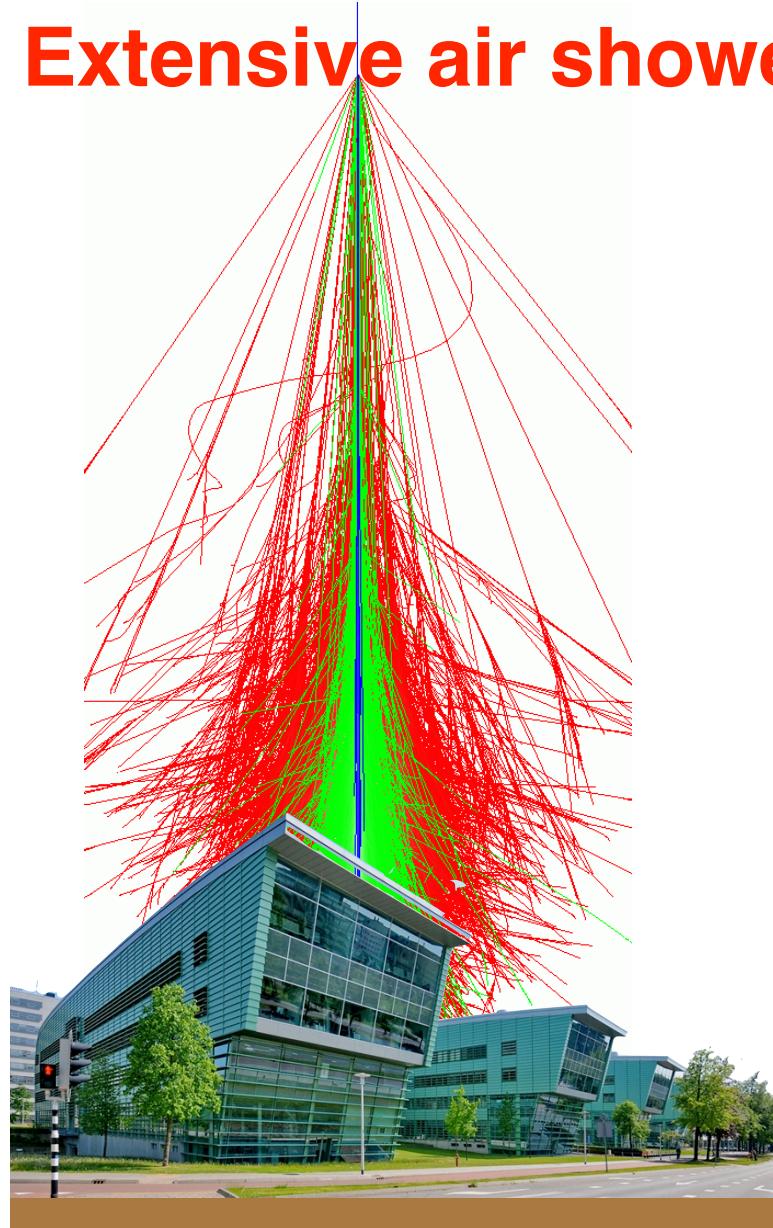


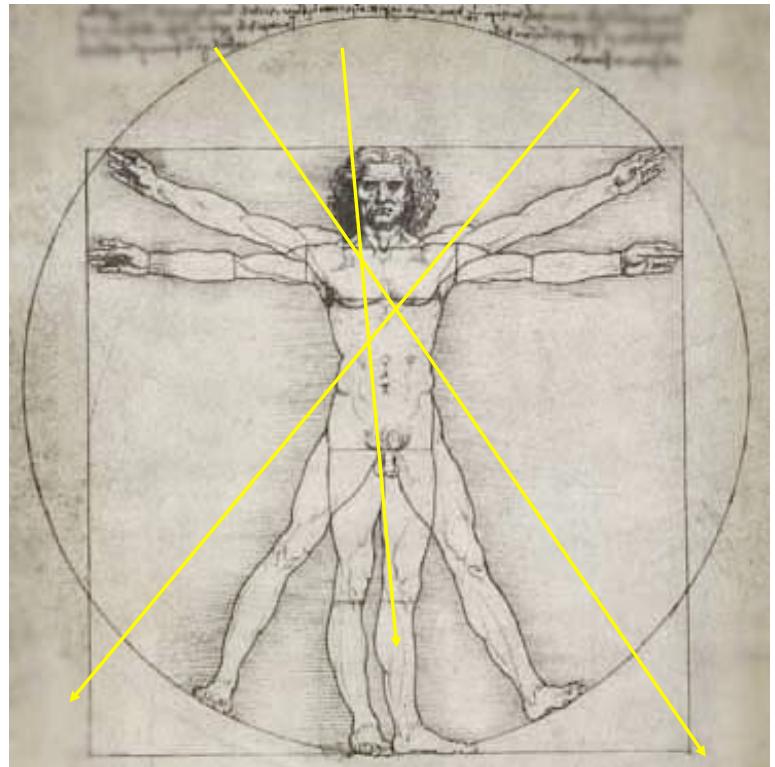
Fig. 7-5 A shower developing through a number of brass plates 1.25 cm thick placed across a cloud chamber. The shower was initiated in the top plate by an incident high-energy electron or photon. The photograph was taken by the MIT cosmic-ray group.



Extensive air showers



Particles at ground level

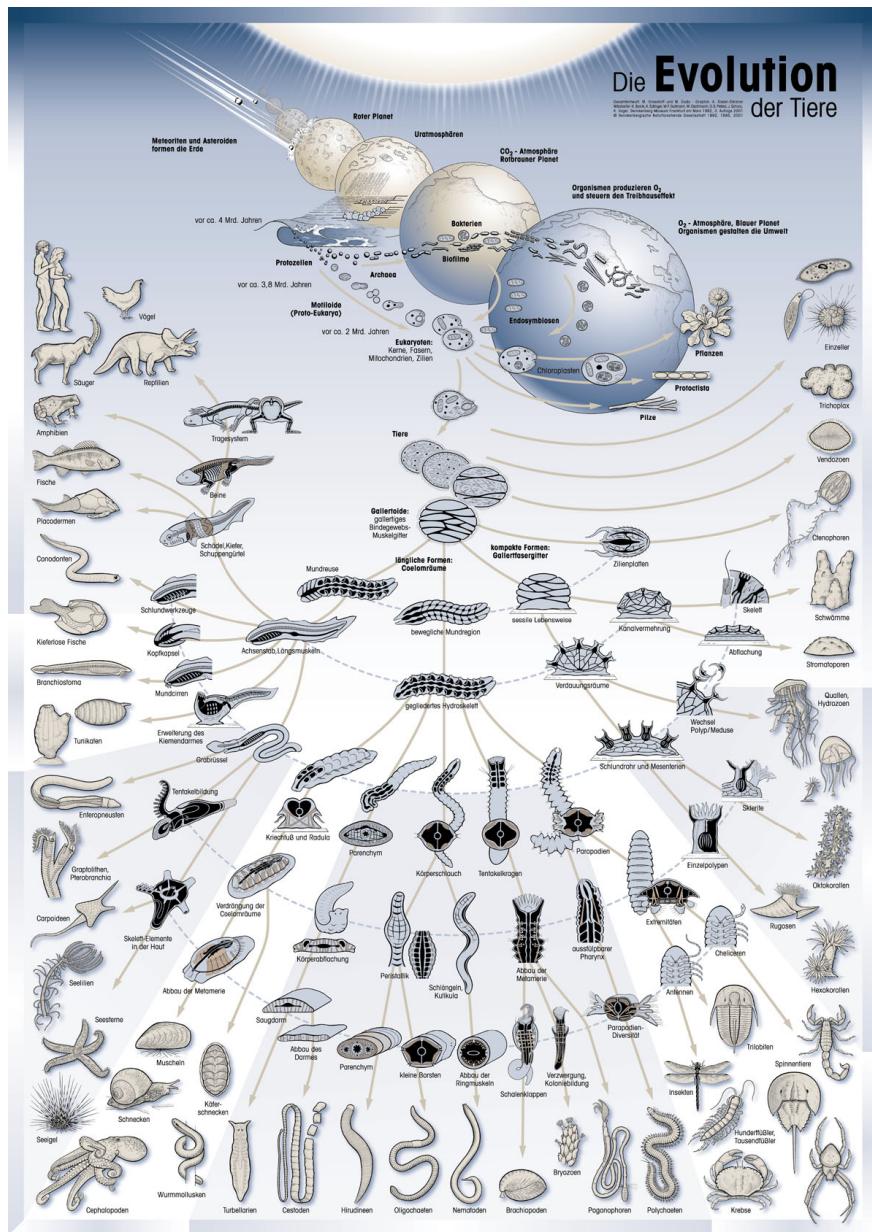
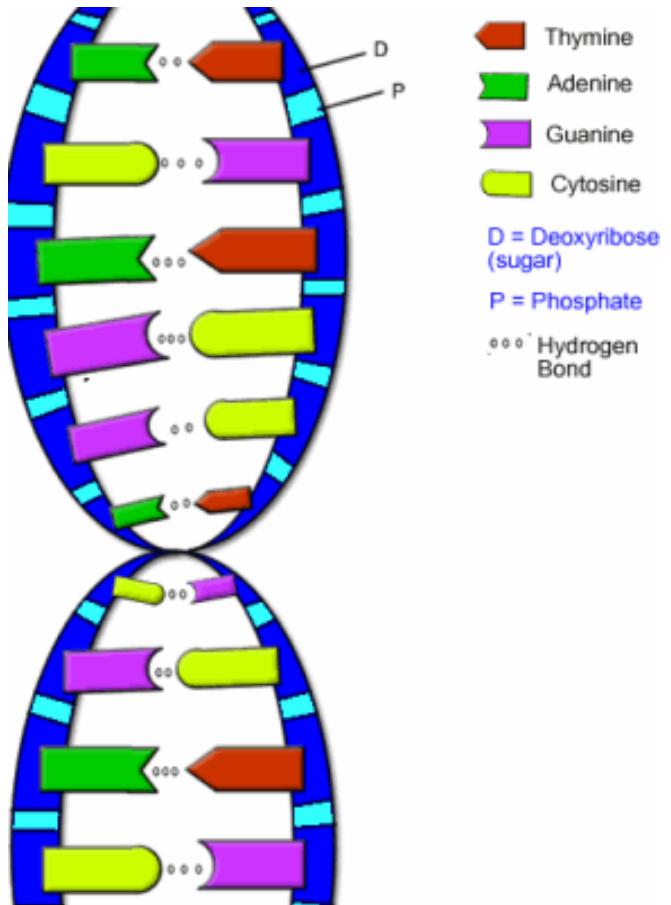


cross section of a human ~ 1 qm

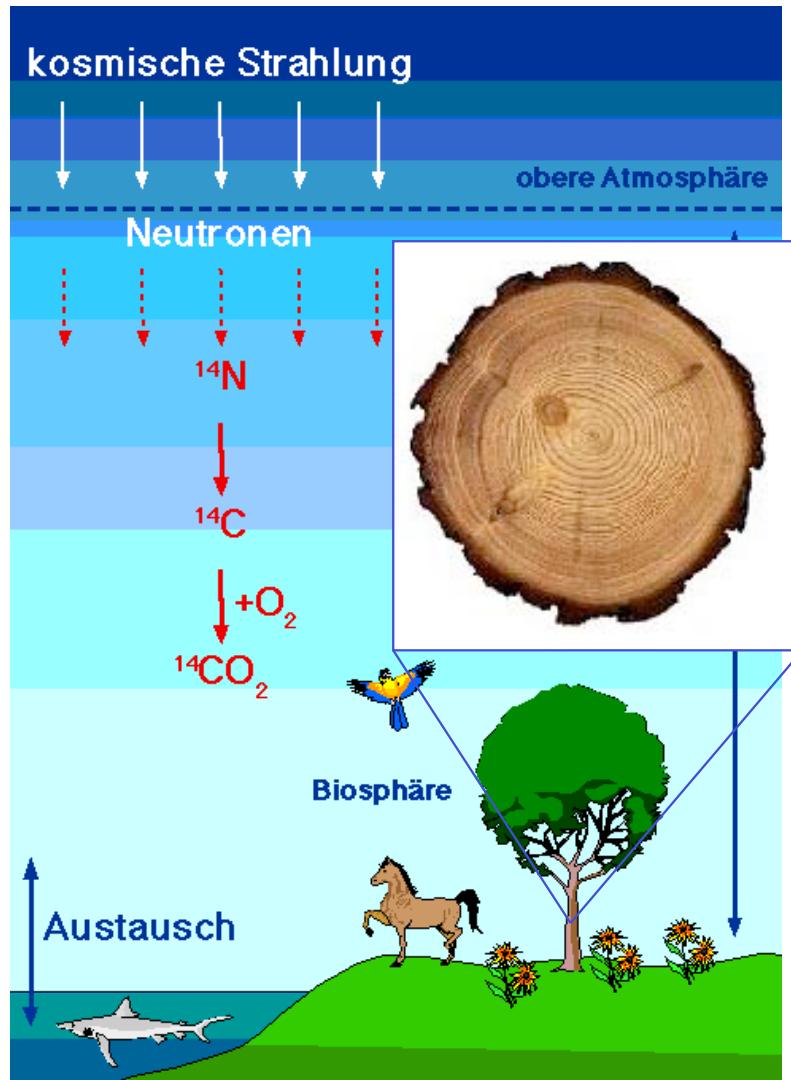
**Flux at ground level:
~ 130 muons per square
meter and second**

Cosmic rays and evolution

DNA



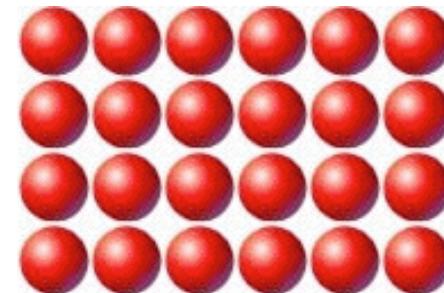
Carbon 14 method



Production of ^{14}C



Decay of ^{14}C half life time 5730 years

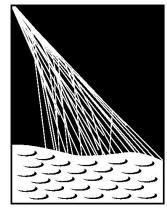


Gehalt an C-14 nach
0 Jahren: 100%

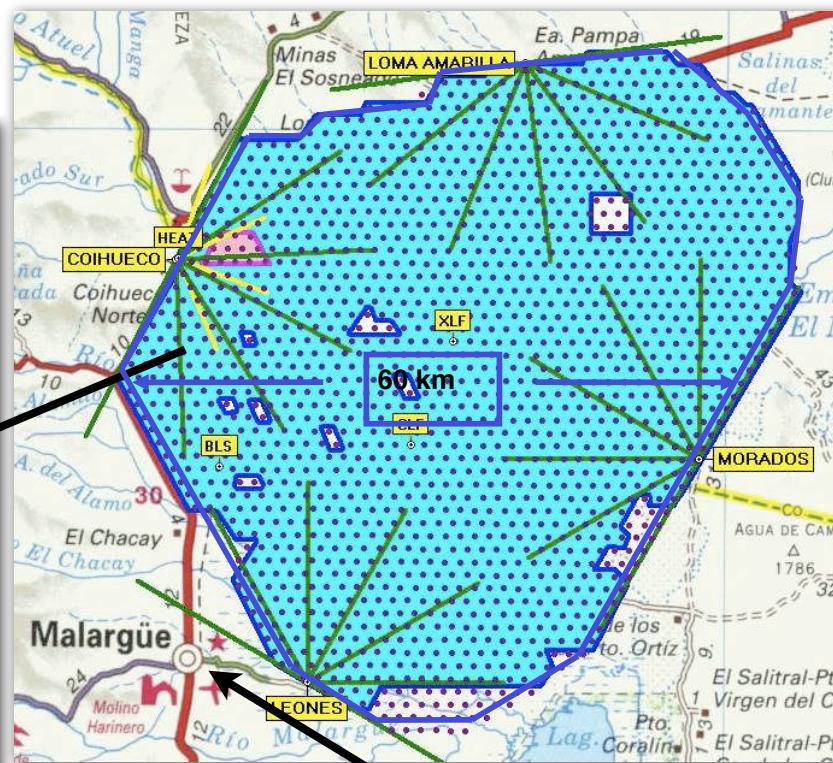
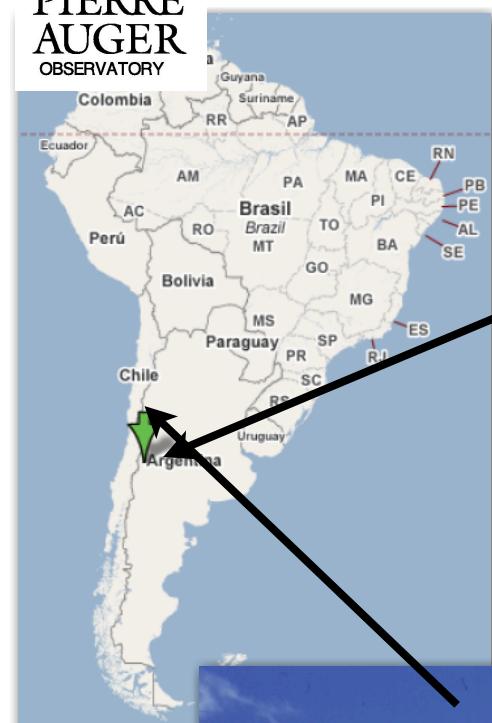


*The new
observatories:
LOFAR
and
the Pierre Auger
Observatory*





PIERRE
AUGER
OBSERVATORY



Aconcagua (6962 m)



The Pierre Auger Observatory

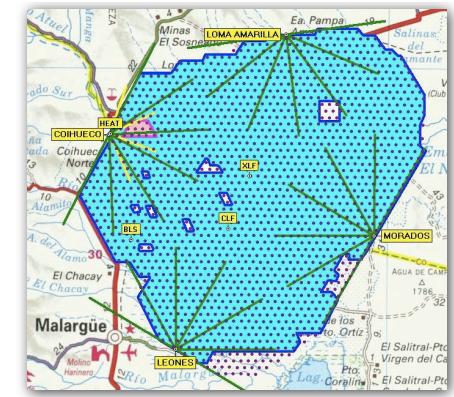


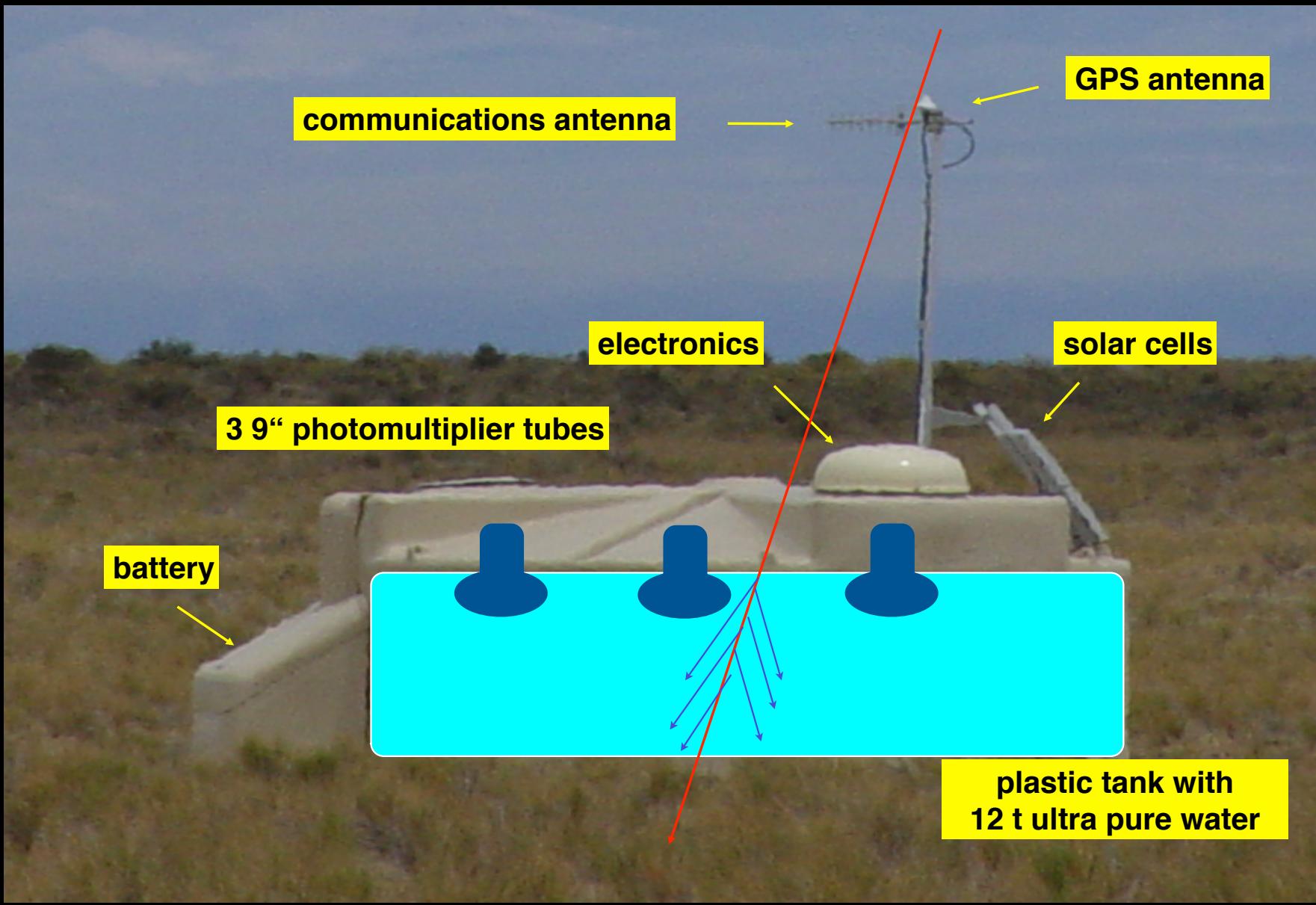
27 fluorescence
light telescopes



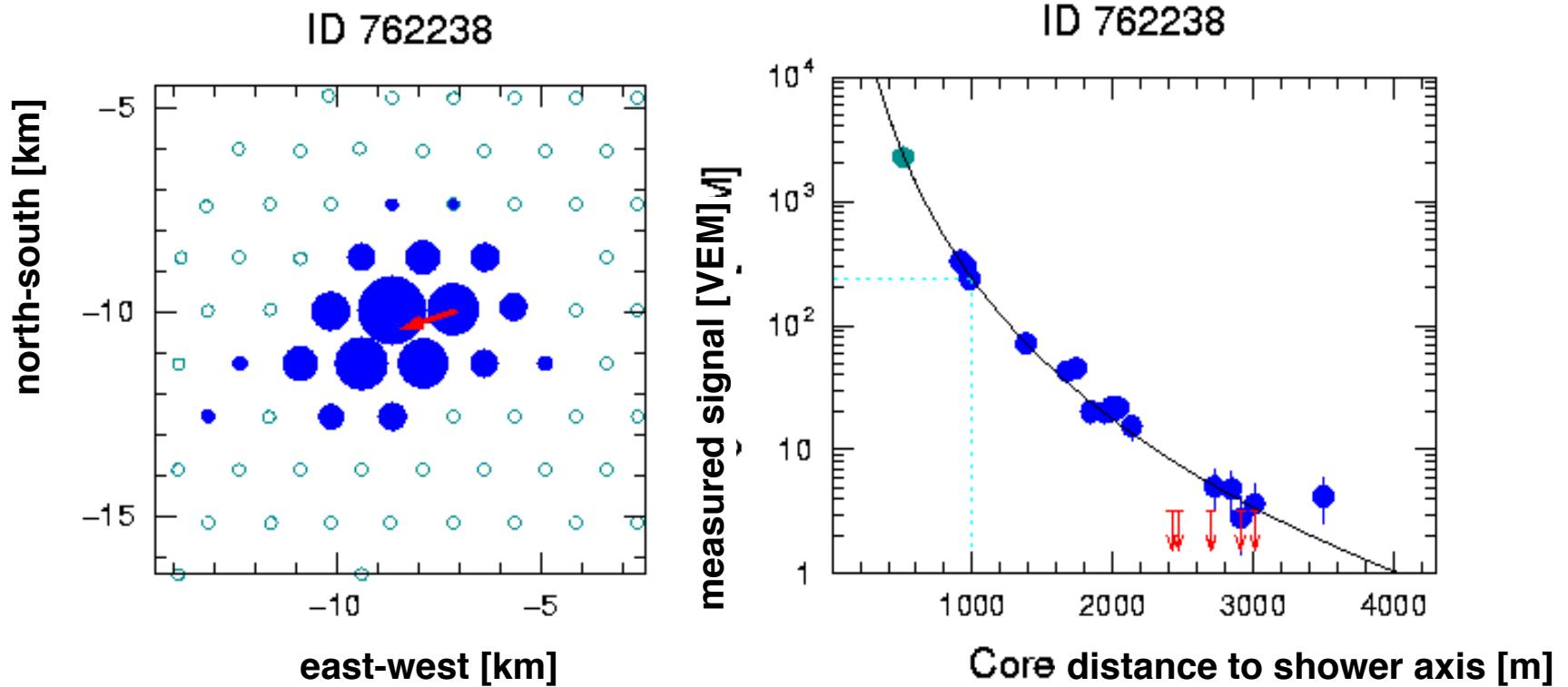
1600 water
Cerenkov detectors

3000 km²





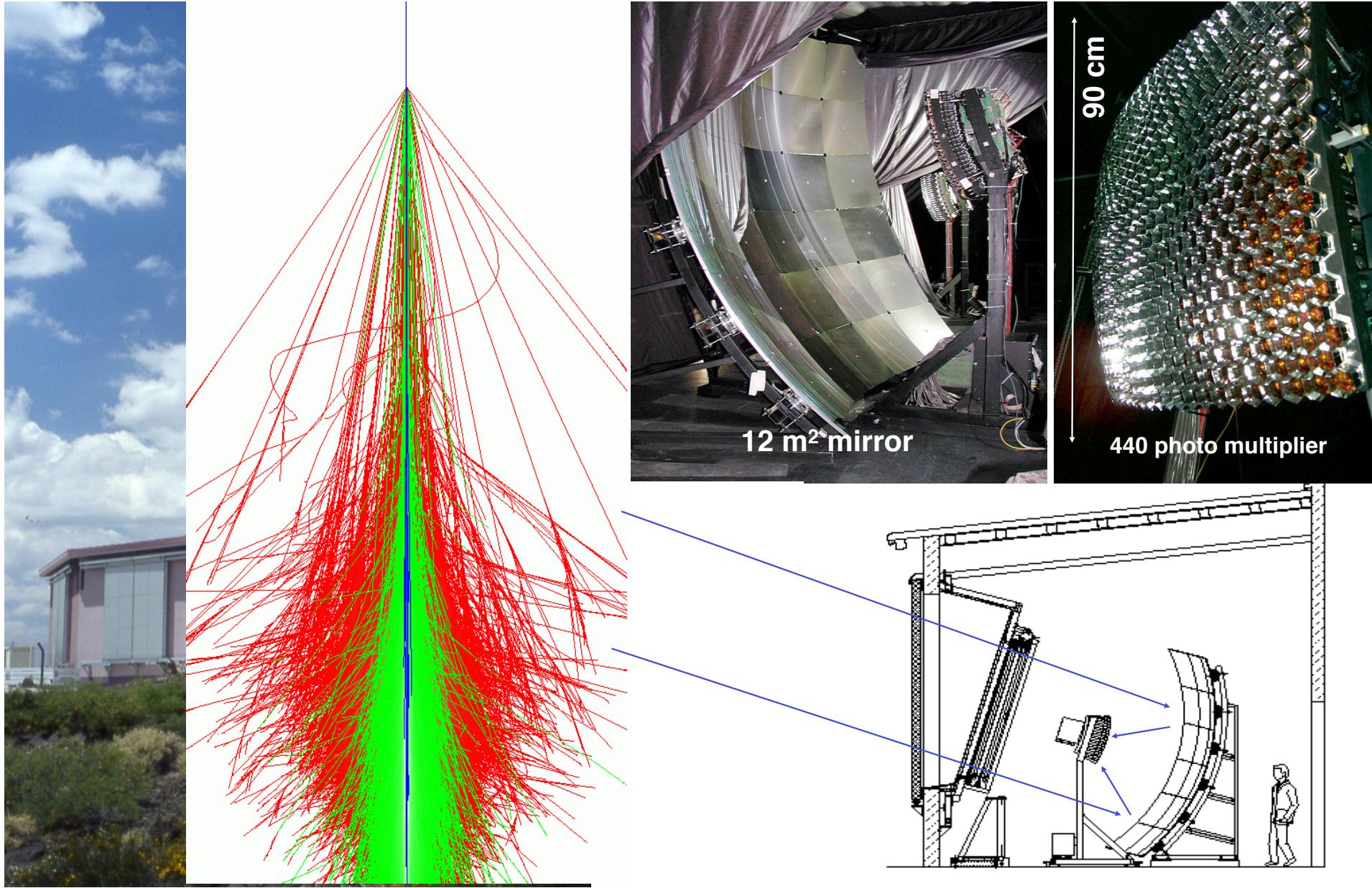
Air shower registered with water Cherenkov detectors

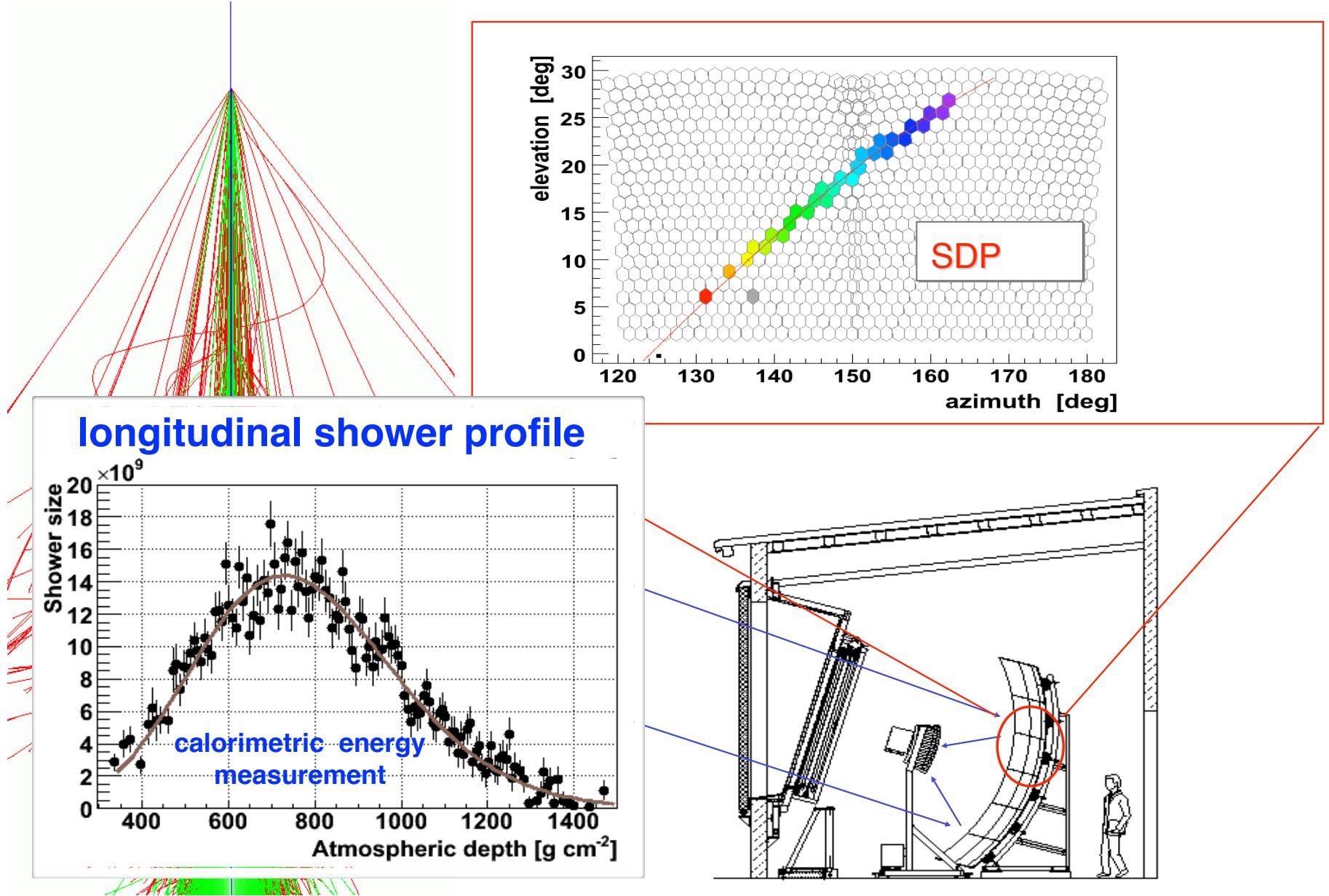


FD eye view

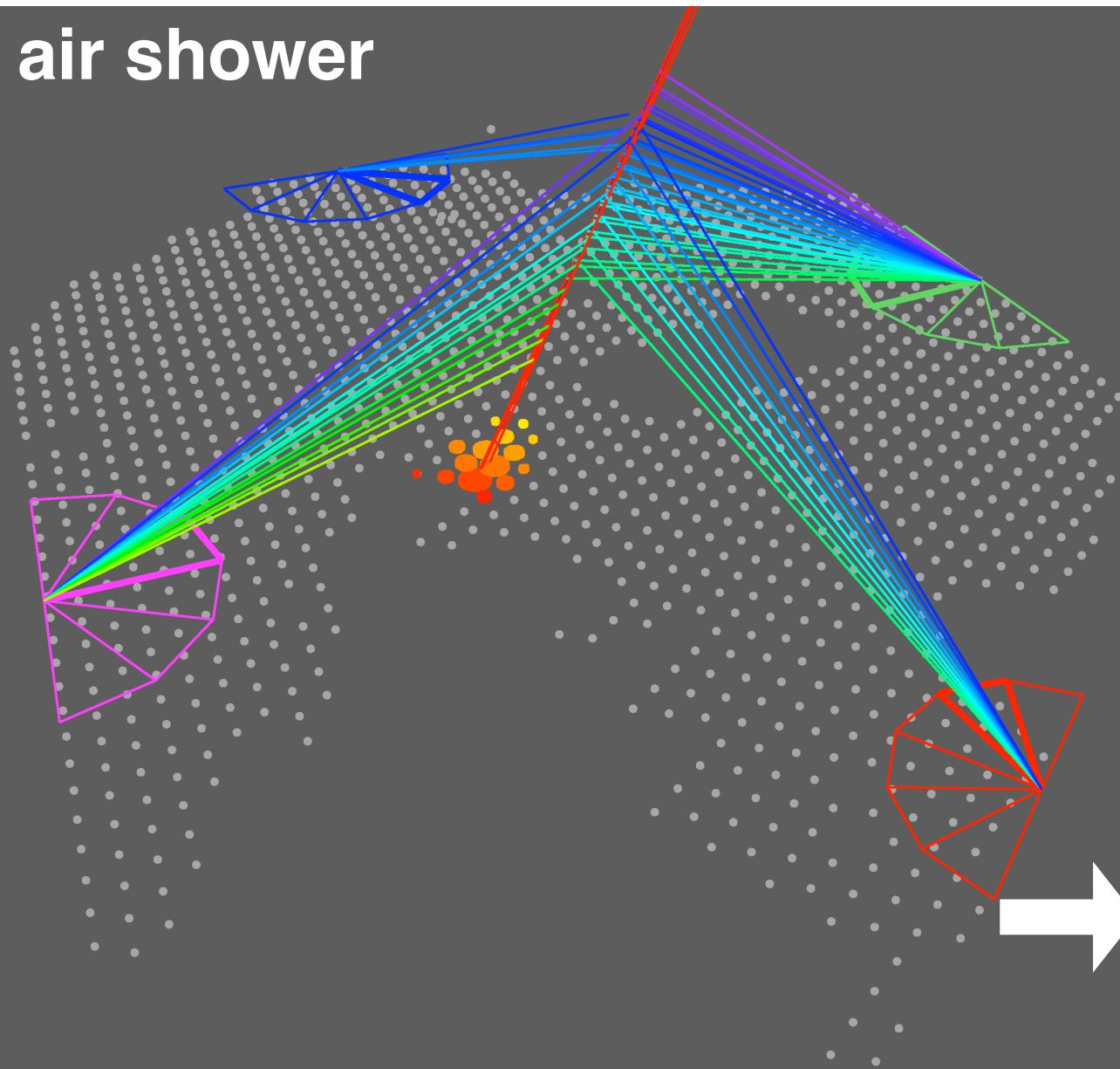


Four sites
Six telescopes
viewing $30^\circ \times 30^\circ$ each





A measured air shower

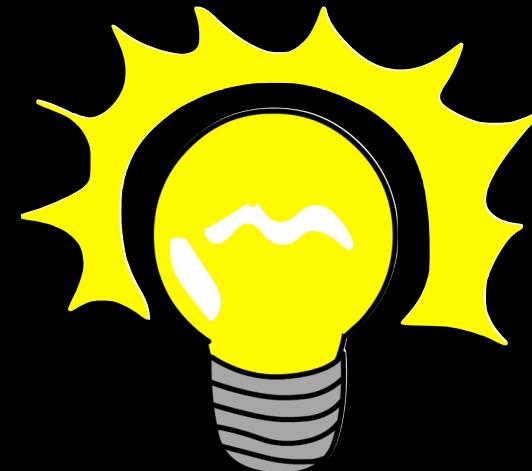


20. May 2007
 $E \sim 10^{19}$ eV

energy,
type (mass),
direction

We are interested in three properties:

- *direction*
- *energy*
- *type of particle (mass)*



Periodic Table of Elements



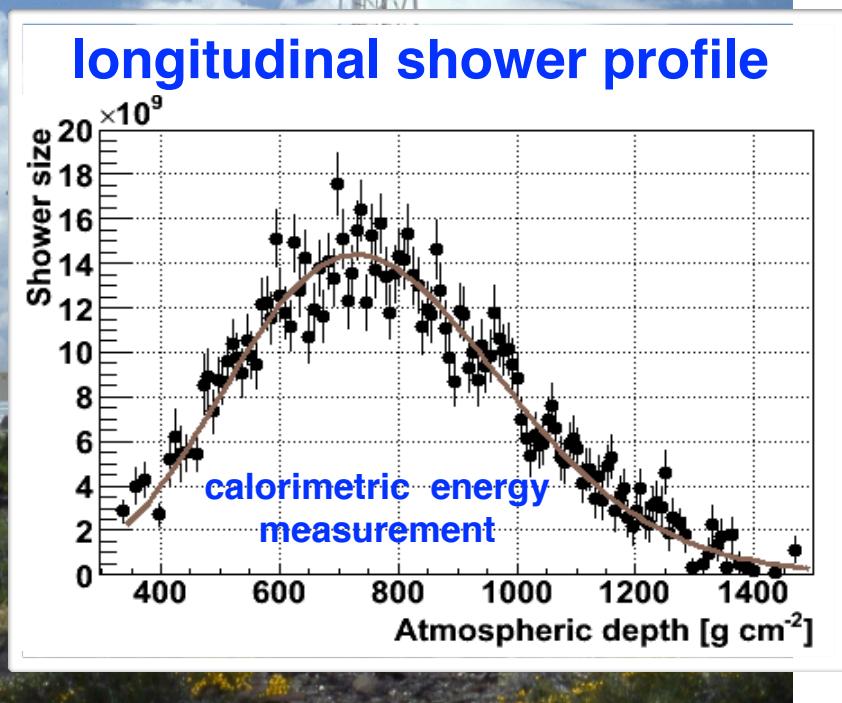
1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18																													
1 H Hydrogen 1.00794	2 He Helium 4.002602	3 Li Lithium 6.941	4 Be Beryllium 9.012182	5 B Boron 10.811	6 C Carbon 12.0107	7 N Nitrogen 14.0067	8 O Oxygen 15.9994	9 F Fluorine 18.9984032	10 Ne Neon 20.1797	11 Na Sodium 22.98976928	12 Mg Magnesium 24.3050	13 Al Aluminum 26.9815388	14 P Phosphorus 30.973762	15 S Sulfur 32.065	16 Cl Chlorine 35.453	17 Ar Argon 39.949	18 K Potassium 39.0983																													
1 Hg Liquid	2 H Gas	3 Rf Unknown	4 Sc Scandium 44.955912	5 Ti Titanium 47.867	6 V Vanadium 50.9415	7 Cr Chromium 51.9901	8 Mn Manganese 54.938045	9 Fe Iron 55.845	10 Co Cobalt 58.933195	11 Ni Nickel 58.6934	12 Cu Copper 63.548	13 Zn Zinc 65.38	14 Ga Gallium 69.723	15 Ge Germanium 72.64	16 As Arsenic 74.92160	17 Se Selenium 78.95	18 Br Bromine 79.904	19 K Rubidium 85.4678																												
20 Ca Calcium 40.078	21 Sc Scandium 44.955912	22 Ti Titanium 47.867	23 V Vanadium 50.9415	24 Cr Chromium 51.9901	25 Mn Manganese 54.938045	26 Fe Iron 55.845	27 Co Cobalt 58.933195	28 Ni Nickel 58.6934	29 Cu Copper 63.548	30 Zn Zinc 65.38	31 Ga Gallium 69.723	32 Ge Germanium 72.64	33 As Arsenic 74.92160	34 Se Selenium 78.95	35 Br Bromine 79.904	36 Kr Krypton 83.798	37 Rb Rubidium 85.4678																													
38 Sr Strontium 87.62	39 Y Yttrium 88.90585	40 Zr Zirconium 91.224	41 Nb Niobium 92.90638	42 Mo Molybdenum 95.96	43 Tc Technetium (97.9072)	44 Ru Ruthenium 101.07	45 Rh Rhodium 102.90550	46 Pd Palladium 106.42	47 Ag Silver 107.8882	48 Cd Cadmium 112.411	49 In Indium 114.818	50 Sn Tin 118.710	51 Sb Antimony 121.760	52 Te Tellurium 127.60	53 I Iodine 126.90447	54 Xe Xenon 131.293	55 Cs Cesium 132.9054519	56 Ba Barium 137.327																												
57 Fr Francium (223)	58 Ce Cerium 140.116	59 Pr Praseodymium 140.90765	60 Nd Neodymium 144.242	61 Pm Promethium (145)	62 Sm Samarium 150.36	63 Eu Europium 151.964	64 Gd Gadolinium 157.25	65 Tb Terbium 158.92535	66 Dy Dysprosium 162.500	67 Ho Holmium 164.93032	68 Er Erbium 167.259	69 Tm Thulium 168.93421	70 Yb Ytterbium 173.054	71 Lu Lutetium 174.9668	72 Hf Hafnium 178.49	73 Ta Tantalum 180.94788	74 W Tungsten 183.84	75 Re Rhenium 185.207	76 Os Osmium 190.23	77 Ir Iridium 192.217	78 Pt Platinum 195.084	79 Au Gold 196.986569	80 Hg Mercury 200.59	81 Tl Thallium 204.3833	82 Pb Lead 207.2	83 Bi Bismuth 208.90404	84 Po Polonium (208.9824)	85 At Astatine (209.9871)	86 Rn Radon (222.0176)	87 Rf Rutherfordium (281)	88 Db Dubnium (282)	89 Sg Seaborgium (286)	90 Bh Bohrium (284)	91 Hs Hassium (277)	92 Mt Meitnerium (288)	93 Ds Darmstadtium (271)	94 Rg Roentgenium (272)	95 Uub Ununbium (285)	96 Uut Ununtrium (284)	97 Uuo Ununquadium (289)	98 Cf Ununpentium (288)	99 Es Ununhexium (289)	100 Fm Ununseptupium (292)	101 Md Mendelevium (258)	102 No Nobelium (259)	103 Lr Lawrencium (262)
57-71	89-103																																													

For elements with no stable isotopes, the mass number of the isotope with the longest half-life is in parentheses.

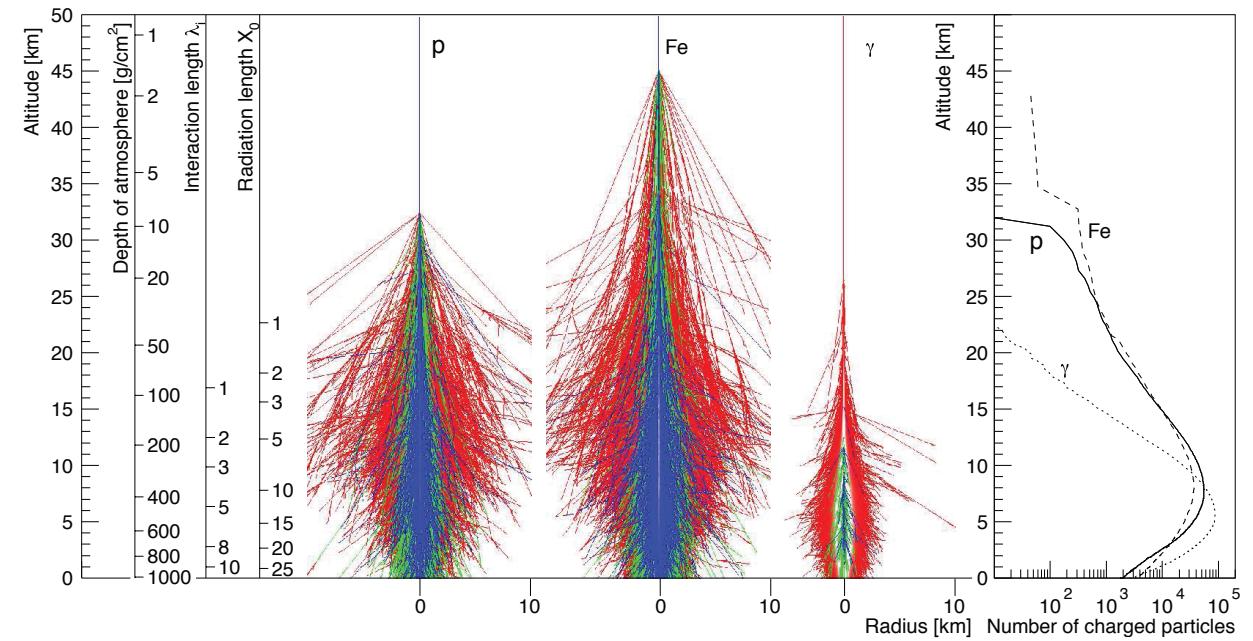
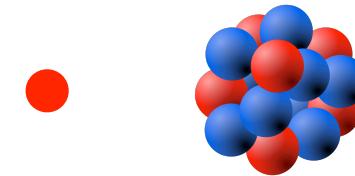
Design and Interface Copyright © 1997 Michael Dayah (michael@dayah.com). <http://www.ptable.com/>

57 La Lanthanum 138.90547	58 Ce Cerium 140.116	59 Pr Praseodymium 140.90765	60 Nd Neodymium 144.242	61 Pm Promethium (145)	62 Sm Samarium 150.36	63 Eu Europium 151.964	64 Gd Gadolinium 157.25	65 Tb Terbium 158.92535	66 Dy Dysprosium 162.500	67 Ho Holmium 164.93032	68 Er Erbium 167.259	69 Tm Thulium 168.93421	70 Yb Ytterbium 173.054	71 Lu Lutetium 174.9668	72 Hf Hafnium 178.49	73 Ta Tantalum 180.94788	74 W Tungsten 183.84	75 Re Rhenium 185.207	76 Os Osmium 190.23	77 Ir Iridium 192.217	78 Pt Platinum 195.084	79 Au Gold 196.986569	80 Hg Mercury 200.59	81 Tl Thallium 204.3833	82 Pb Lead 207.2	83 Bi Bismuth 208.90404	84 Po Polonium (208.9824)	85 At Astatine (209.9871)	86 Rn Radon (222.0176)	87 Rf Rutherfordium (281)	88 Db Dubnium (282)	89 Sg Seaborgium (286)	90 Bh Bohrium (284)	91 Hs Hassium (277)	92 Mt Meitnerium (288)	93 Ds Darmstadtium (271)	94 Rg Roentgenium (272)	95 Uub Ununbium (285)	96 Uut Ununtrium (284)	97 Uuo Ununquadium (289)	98 Cf Ununpentium (288)	99 Es Ununhexium (289)	100 Fm Ununseptupium (292)	101 Md Mendelevium (258)	102 No Nobelium (259)	103 Lr Lawrencium (262)
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How do we identify the type of particle?

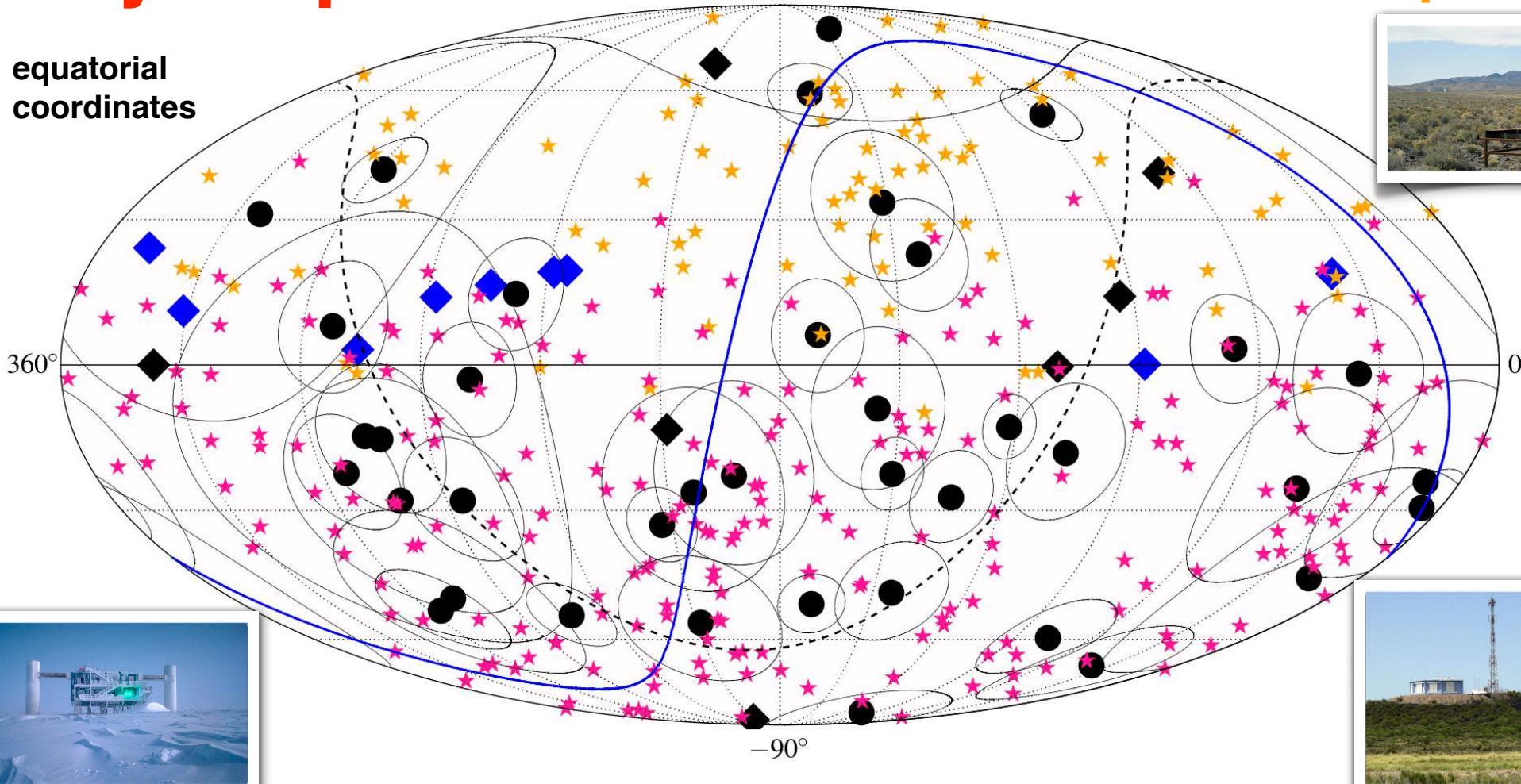


proton Fe nucleus



Sky map

equatorial
coordinates



Ice-Cube neutrino telescope

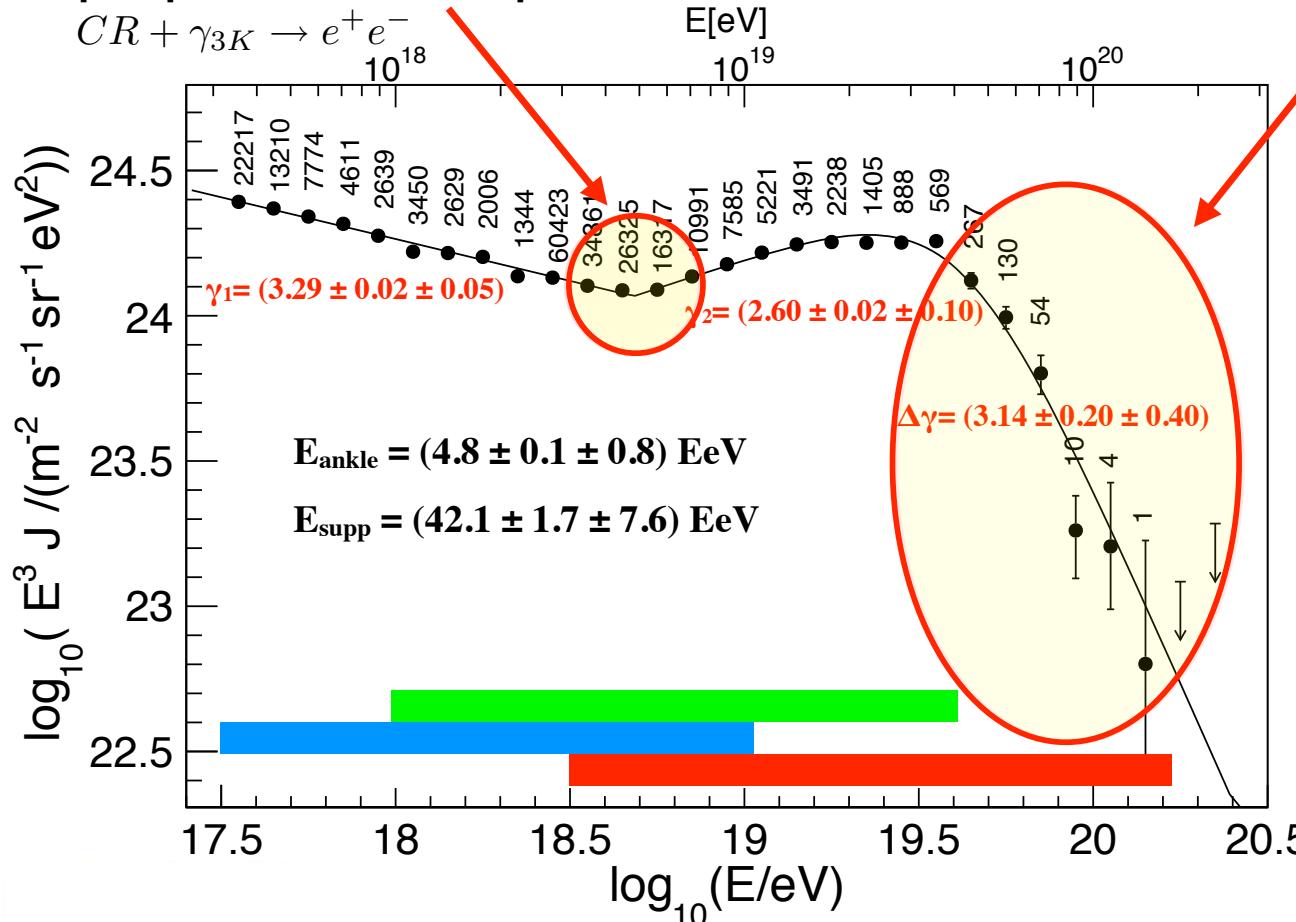
Telescope Array

Pierre Auger Observatory

Precise measurement of the all-particle energy spectrum over 3 decades in energy

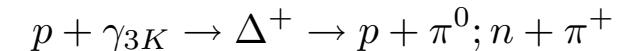
ankle $E=4 \cdot 10^{18}$ eV

pair production at 3-K photons



depression $E > 4 \cdot 10^{19}$ eV

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



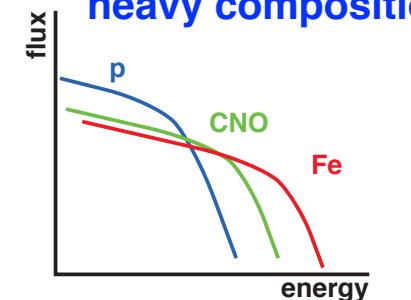
light composition

- maximum energy of accelerators

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

(Hillas condition)

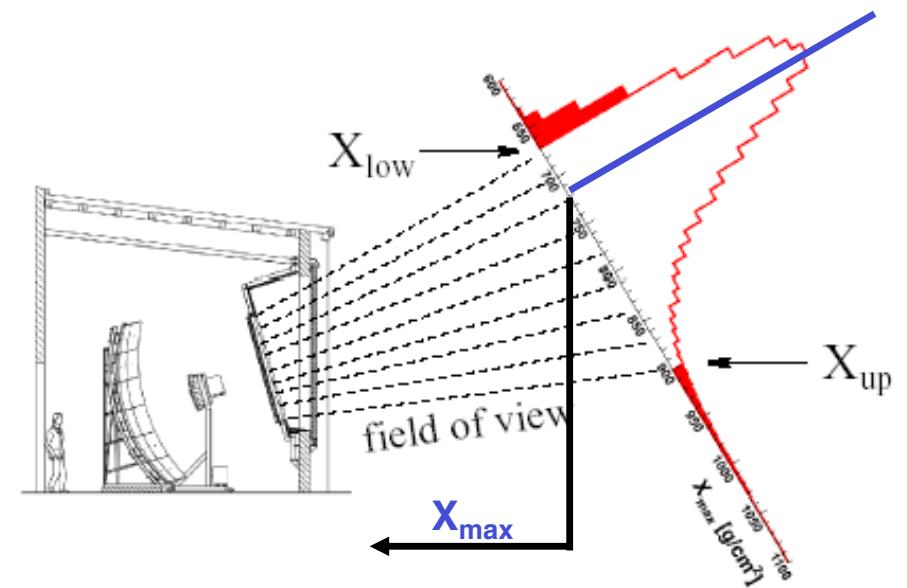
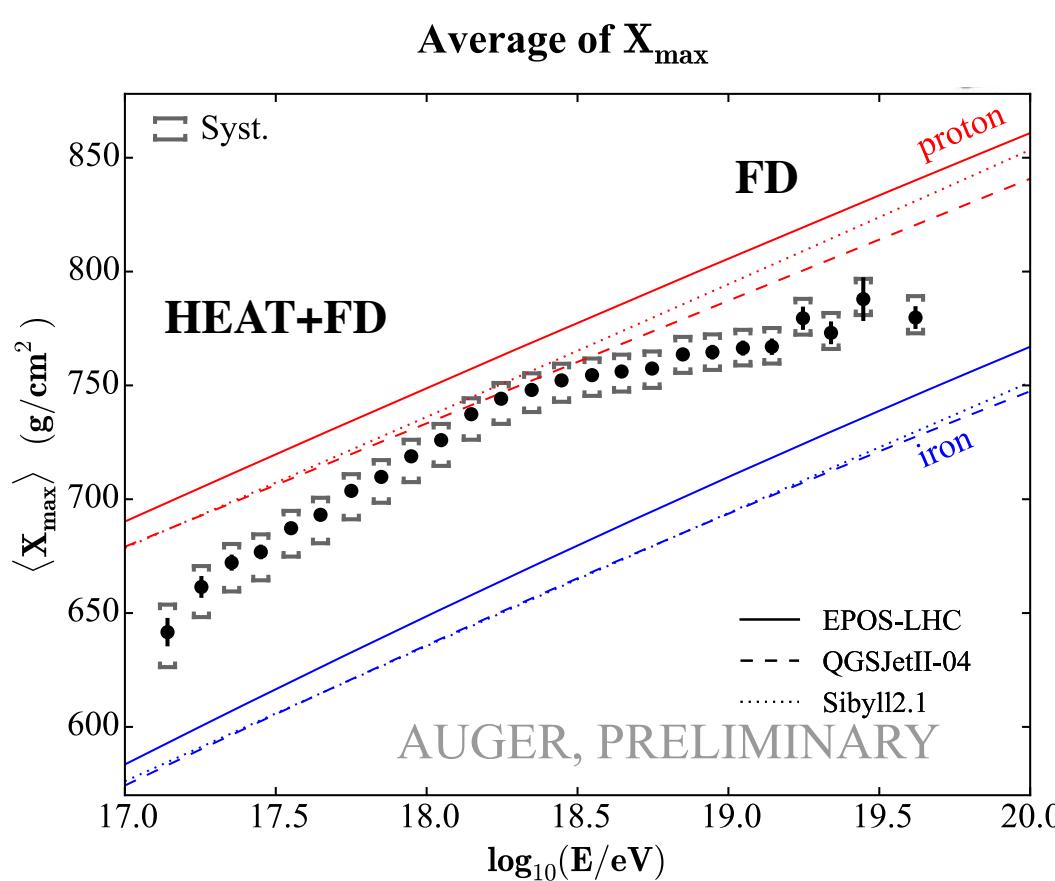
heavy composition



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, Sibyll2.1

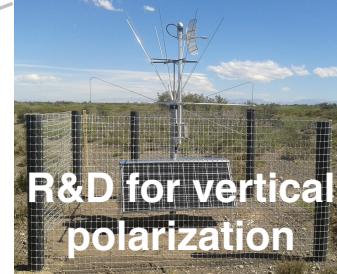
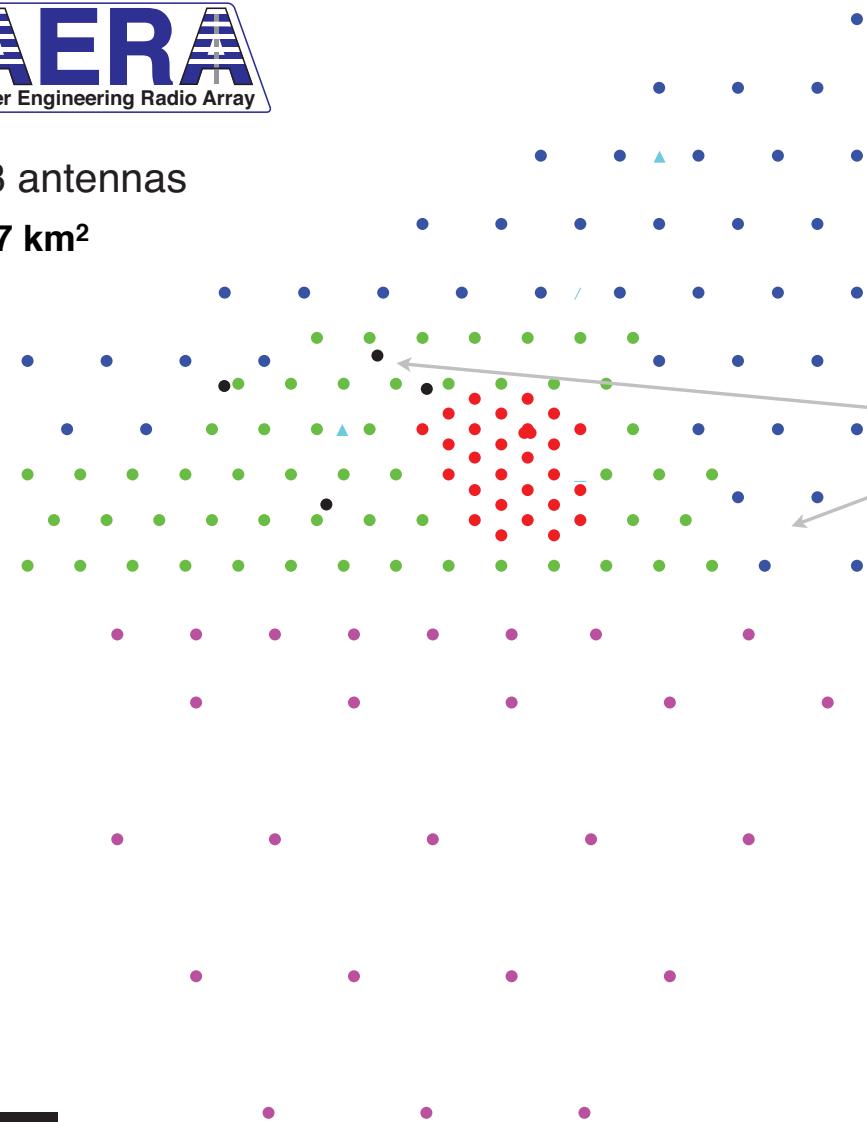


*Measuring
cosmic rays
with the radio
technique*



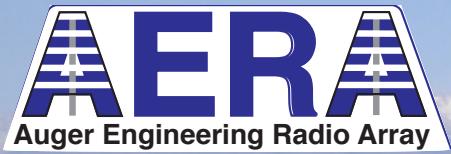
153 antennas

~17 km²



100 stations
since May 2013 +25 stations
since March 2015

since August 2010
24 stations



GPS antenna

comms antenna

physics antenna
30 - 80 MHz

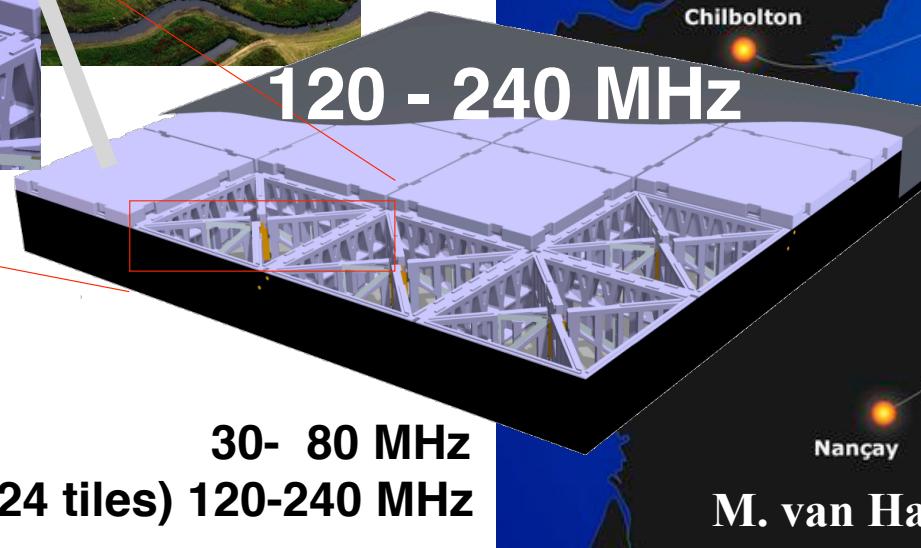
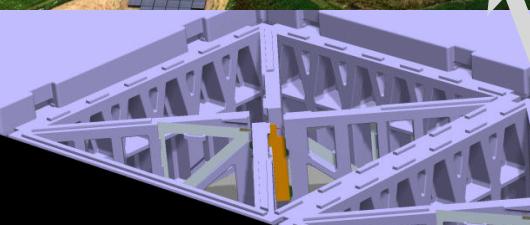
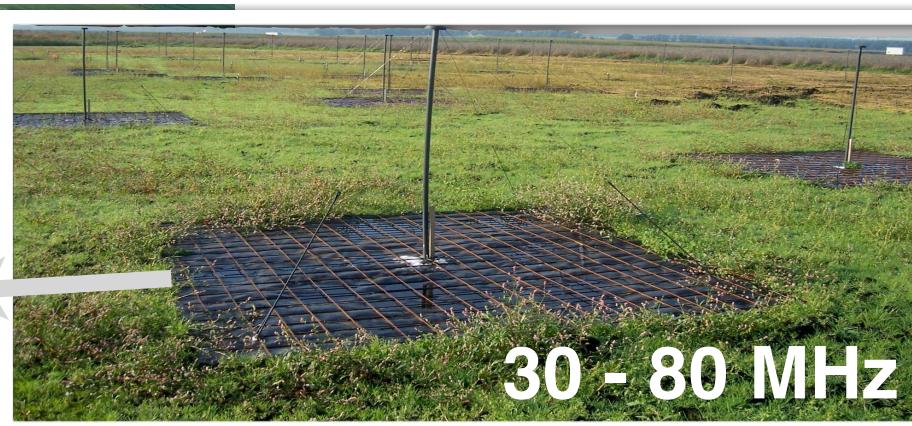
electronics
& battery

solar panel



**installation April/May
2013**





each (dutch) station:

96 low-band antennas

high-band antennas (2x24 tiles)

30- 80 MHz

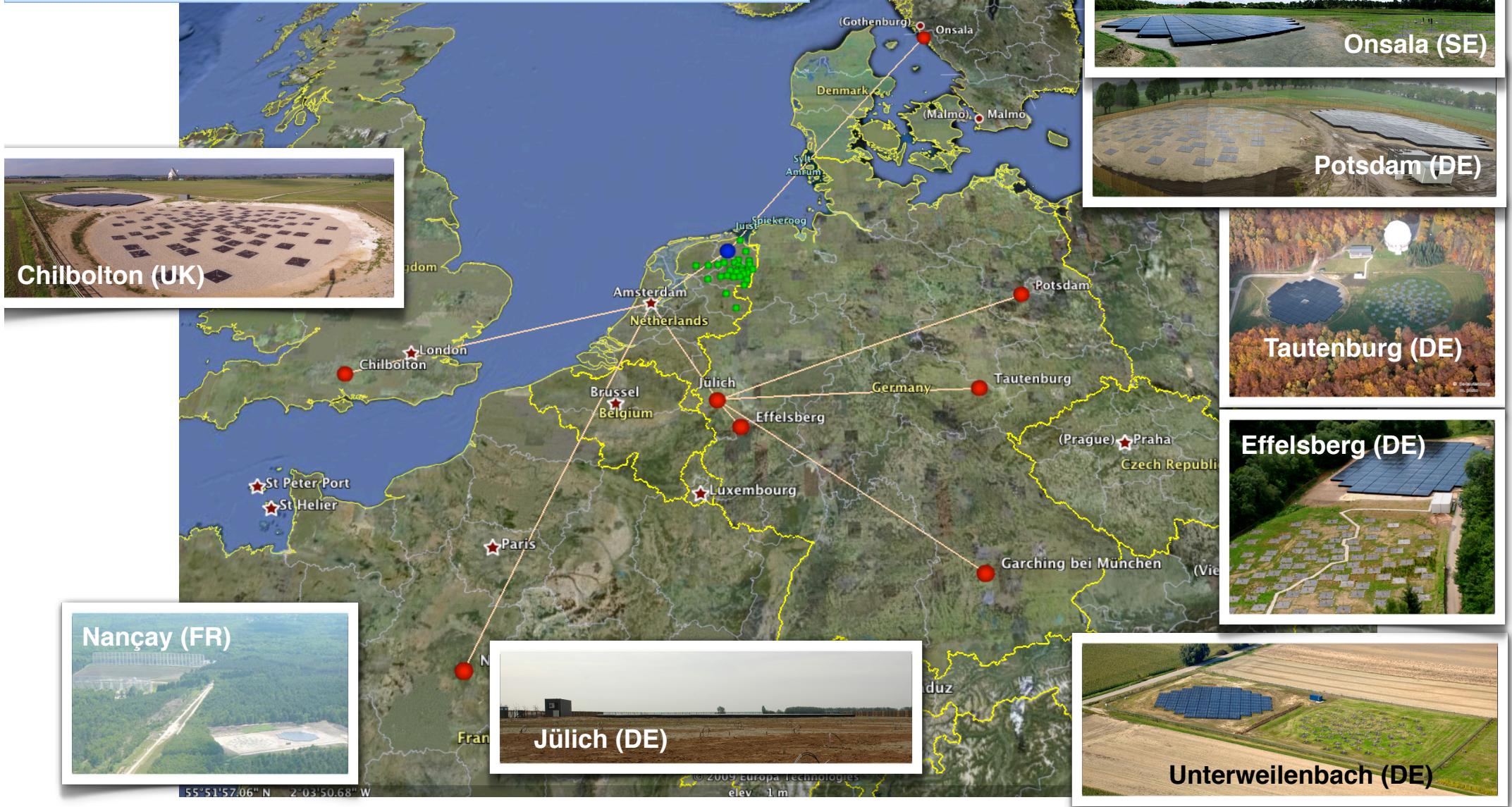
120-240 MHz

M. van Haarlem et al., A&A 556 (2013) A2

Construction of stations

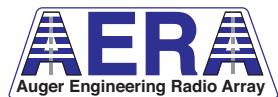


LOFAR stations across Europe



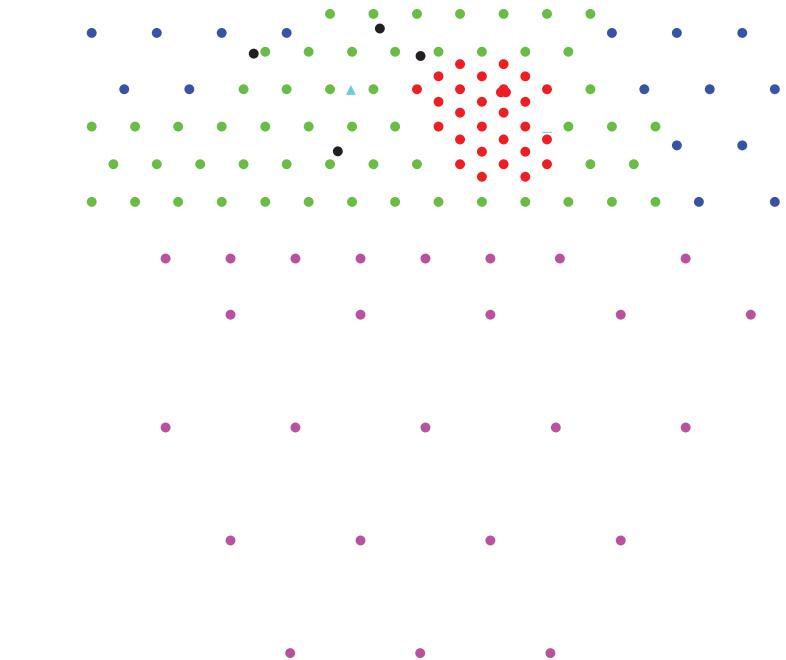
LOFAR Opening 12th June 2010



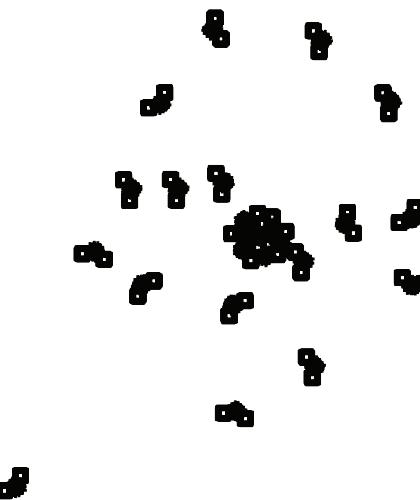


153 antennas

~17 km²



LOFAR core
23 stations ~5 km²



>2000 antennas

1 km
—

Radio Emission in Air Showers

>Mainly: Charge separation in geomagnetic field

$$\vec{E} \propto \vec{v} \times \vec{B}$$

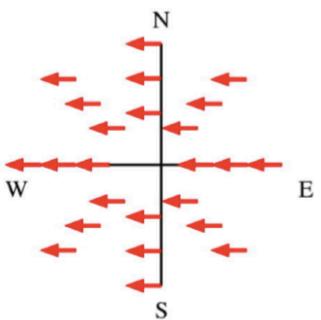
Theory predicts additional mechanisms:

excess of electrons in shower:
charge excess

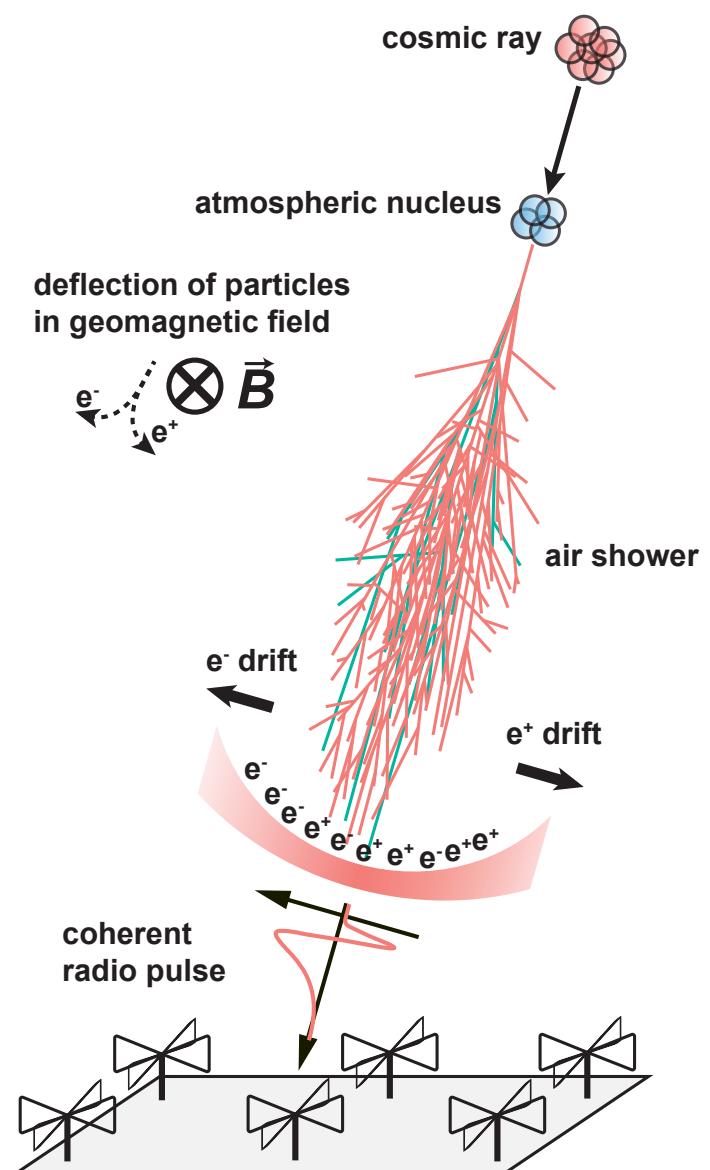
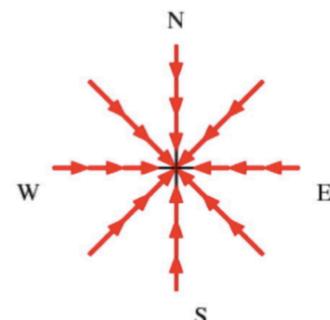
superposition of emission due to
Cherenkov effects in atmosphere

polarization of radio signal

geomagnetic

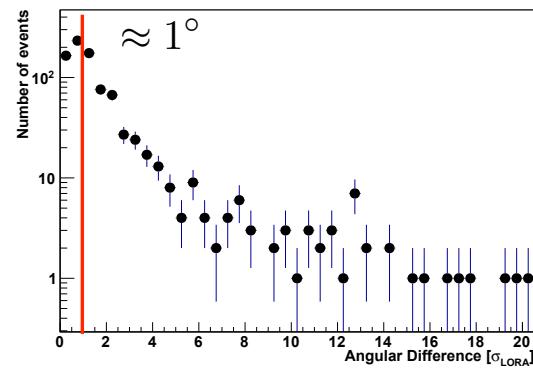


Askaryan

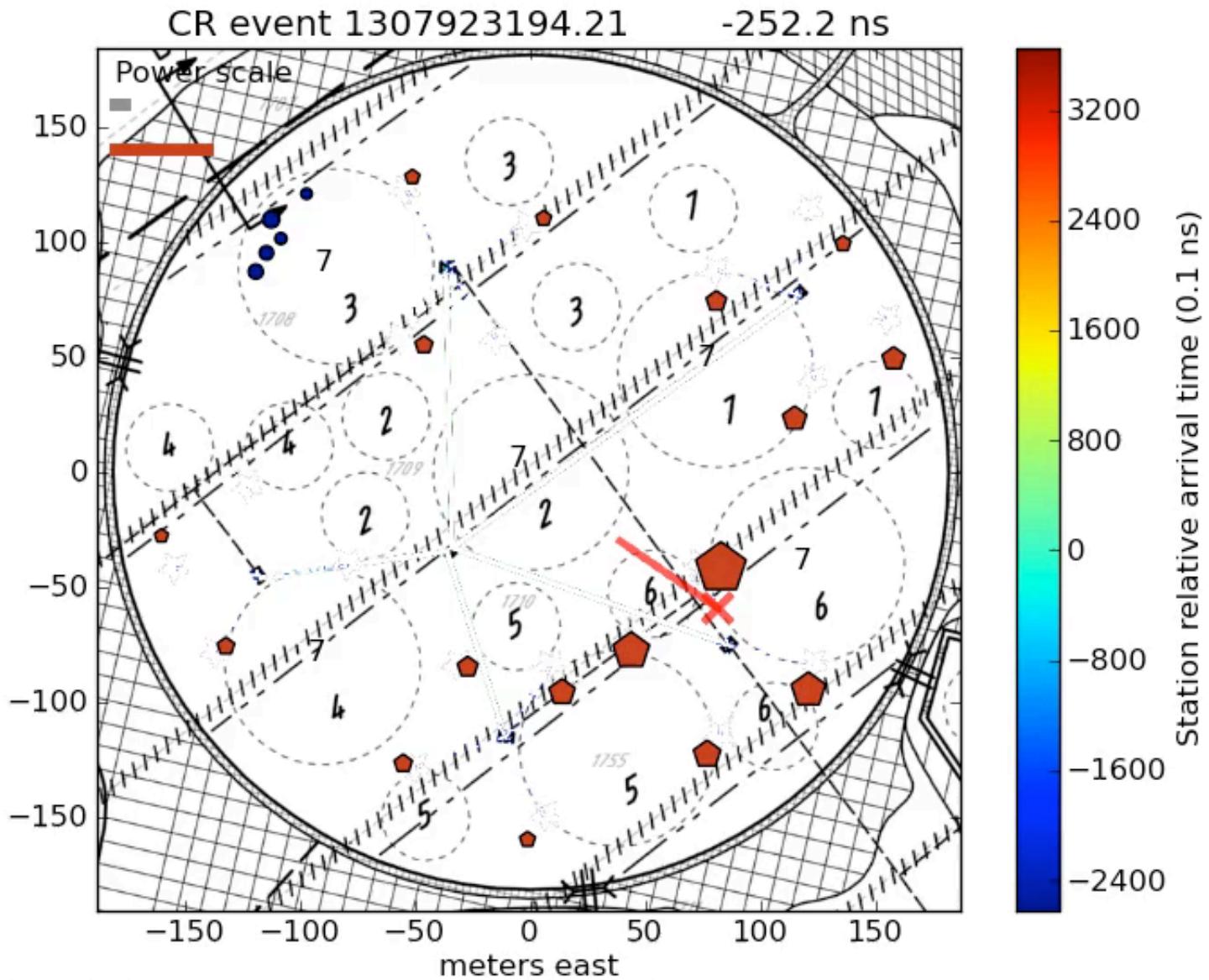


A measured air shower

angular difference
particles - radio



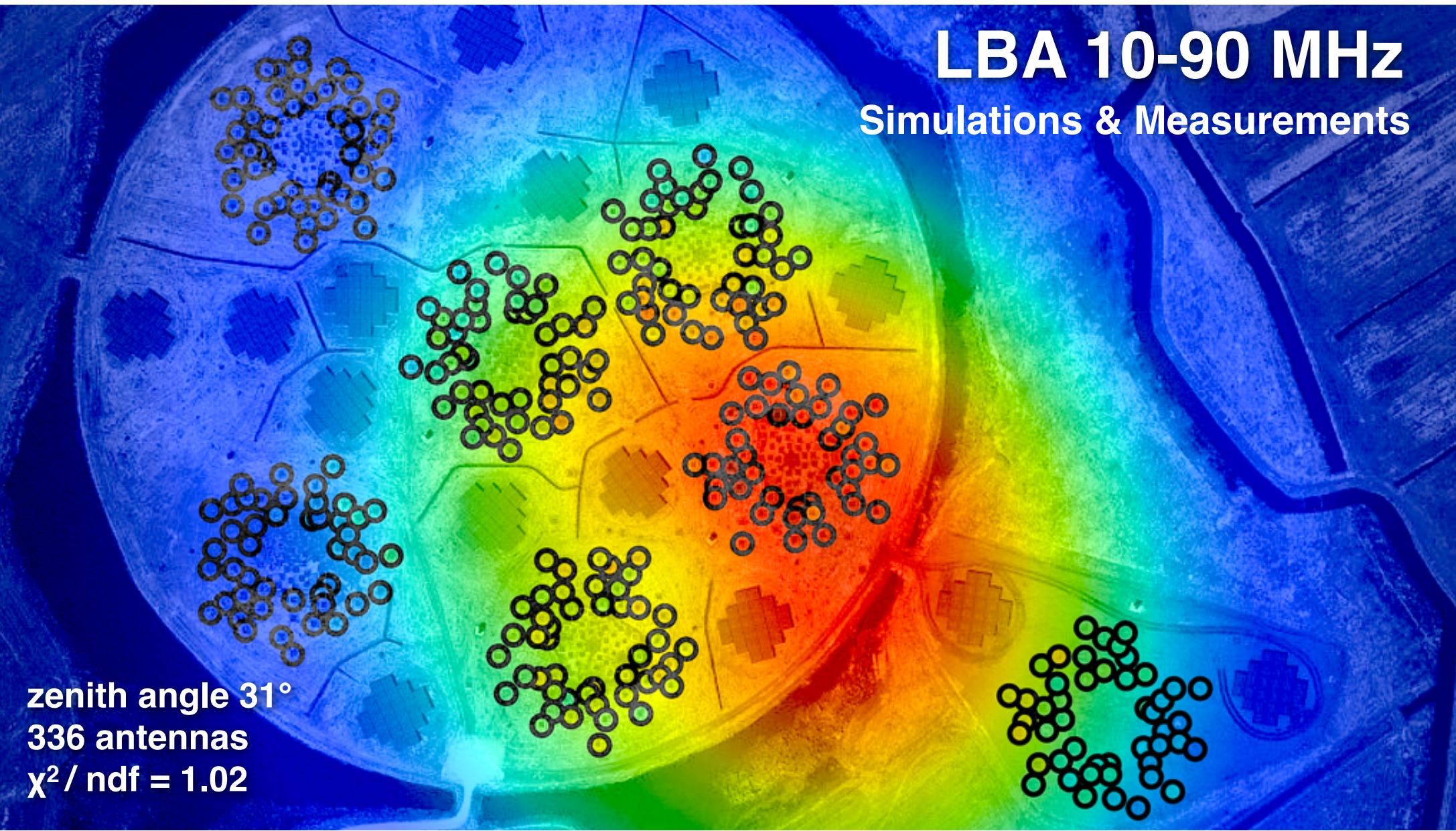
Circles: LOFAR antennas, Pentagons: LORA particle detectors, size denotes signal strength



LBA 10-90 MHz

Simulations & Measurements

zenith angle 31°
336 antennas
 $\chi^2 / \text{ndf} = 1.02$

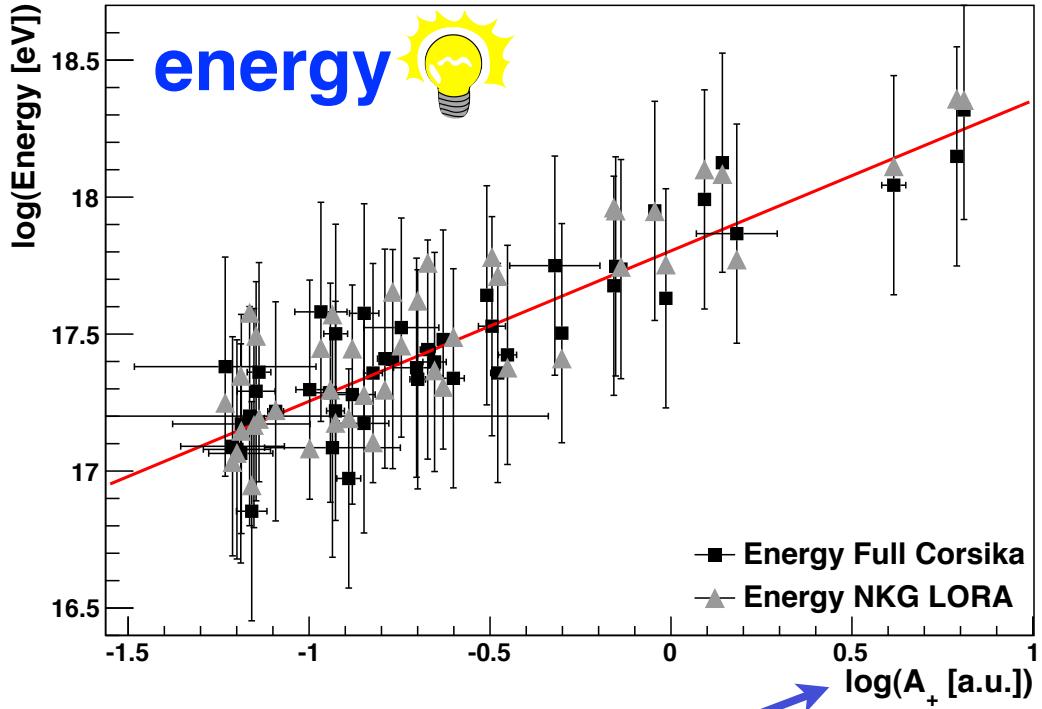


HBA 110-240 MHz

Simulations & Measurements

Relativistic time compression gives a Cherenkov ring

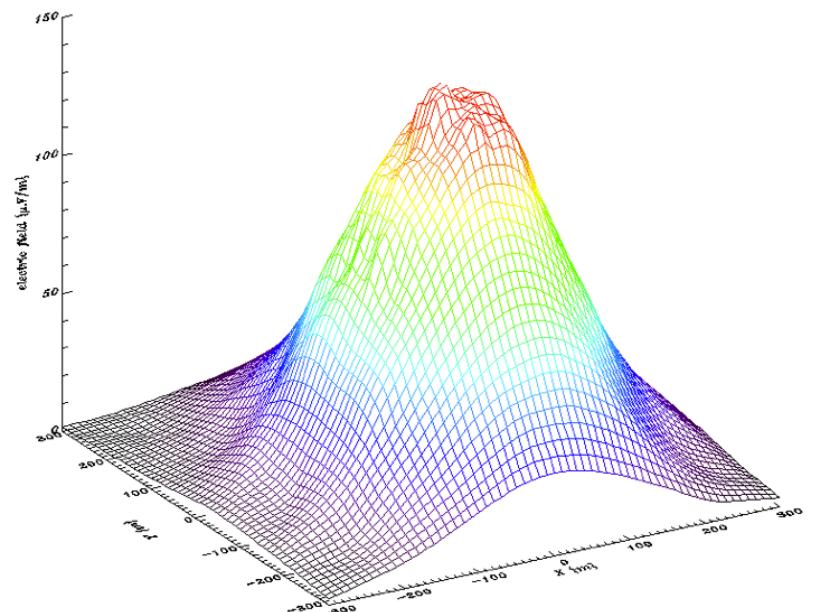
Properties of primary particle



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



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Energy content of the radio component of an EAS

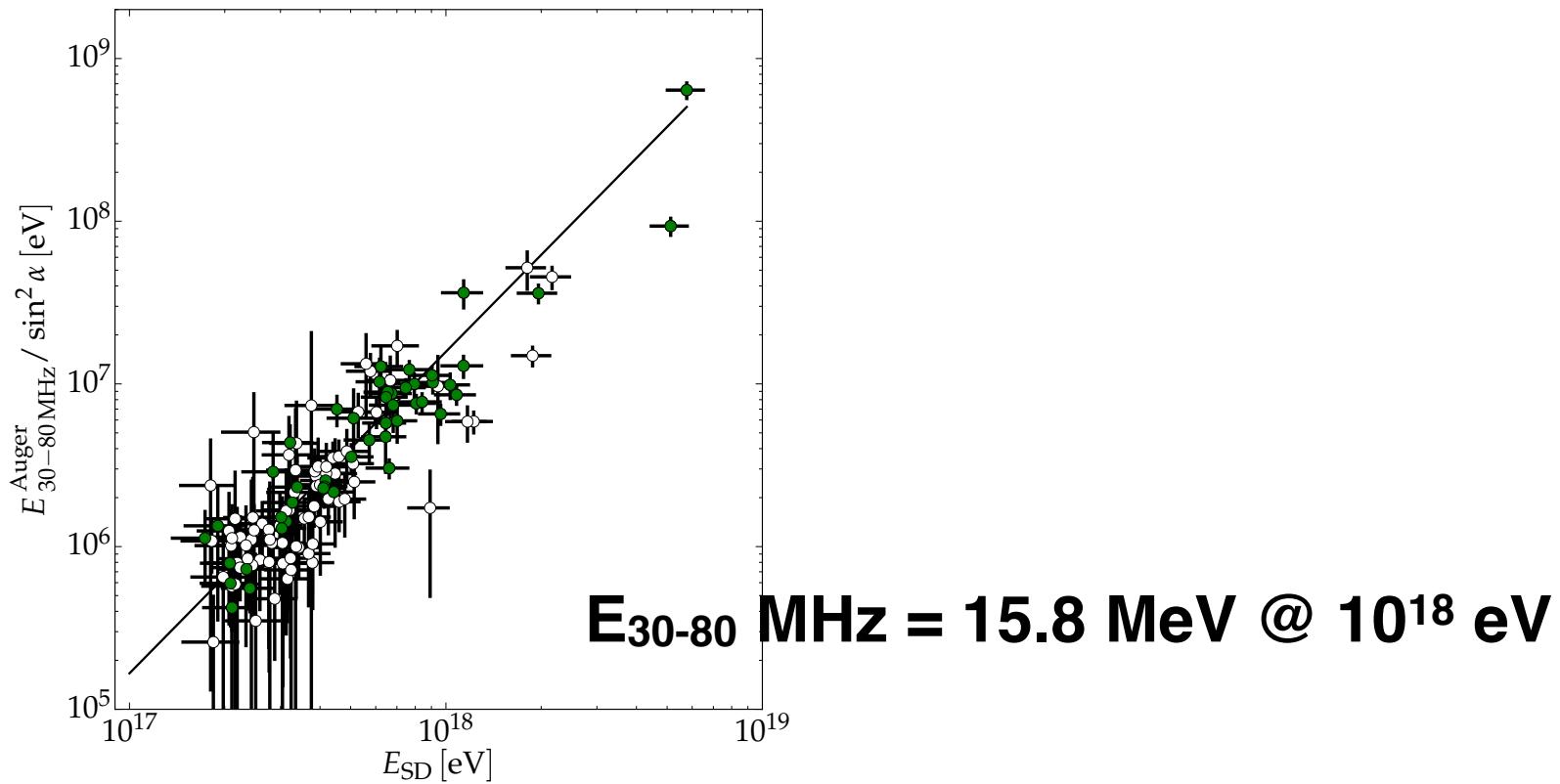
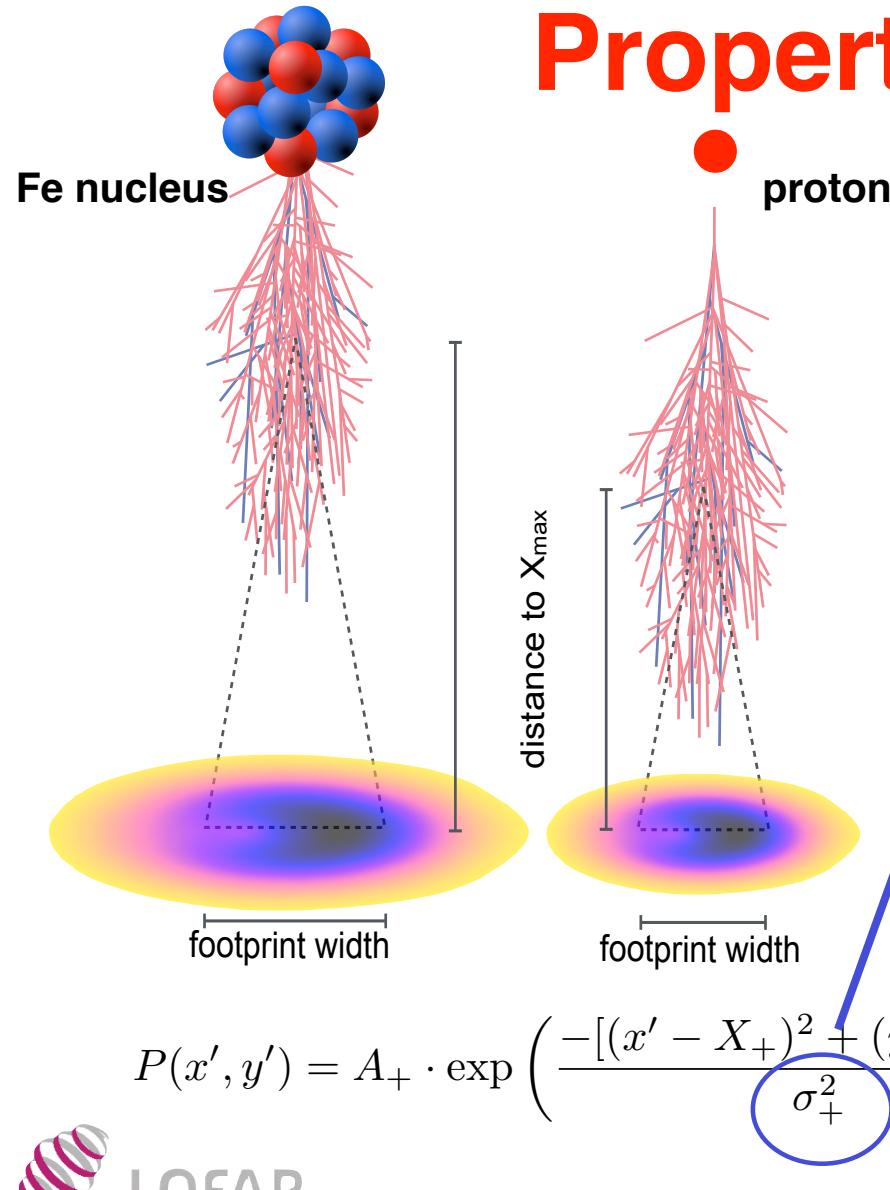


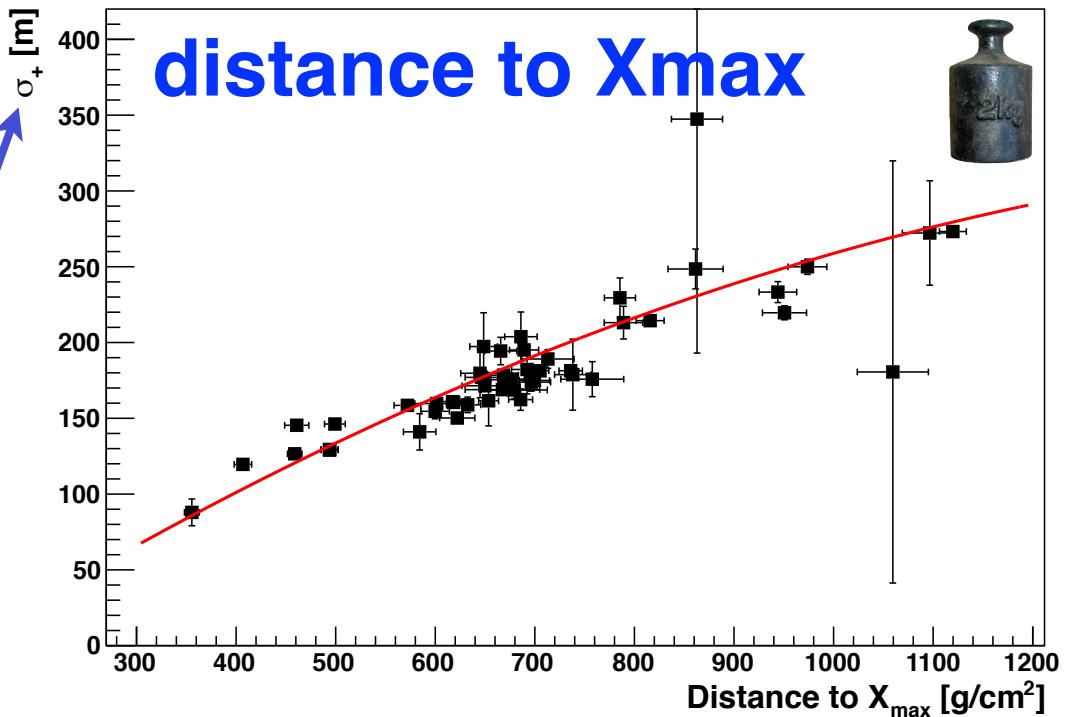
FIG. 2. Correlation between the normalized radiation energy and the cosmic-ray energy E_{SD} as determined by the Auger surface detector. Open circles represent air showers with radio signals detected in three or four radio detectors. Filled circles denote showers with five or more detected radio signals.



Properties of primary particle

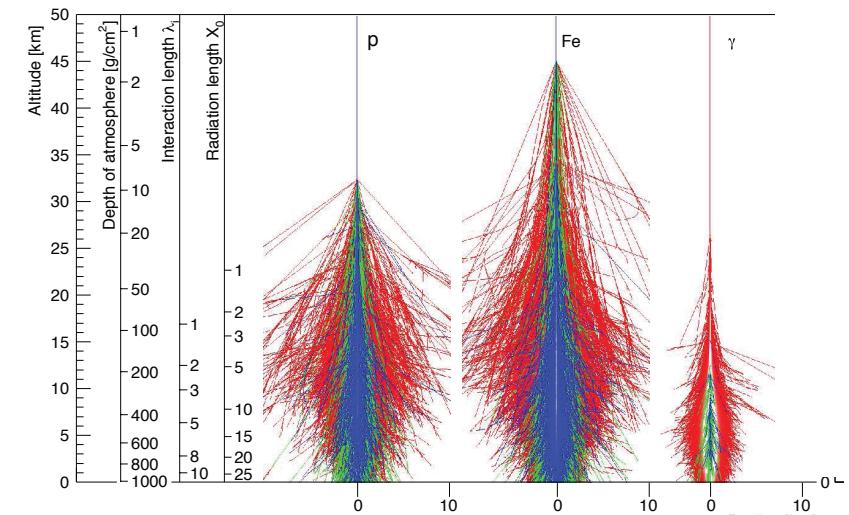
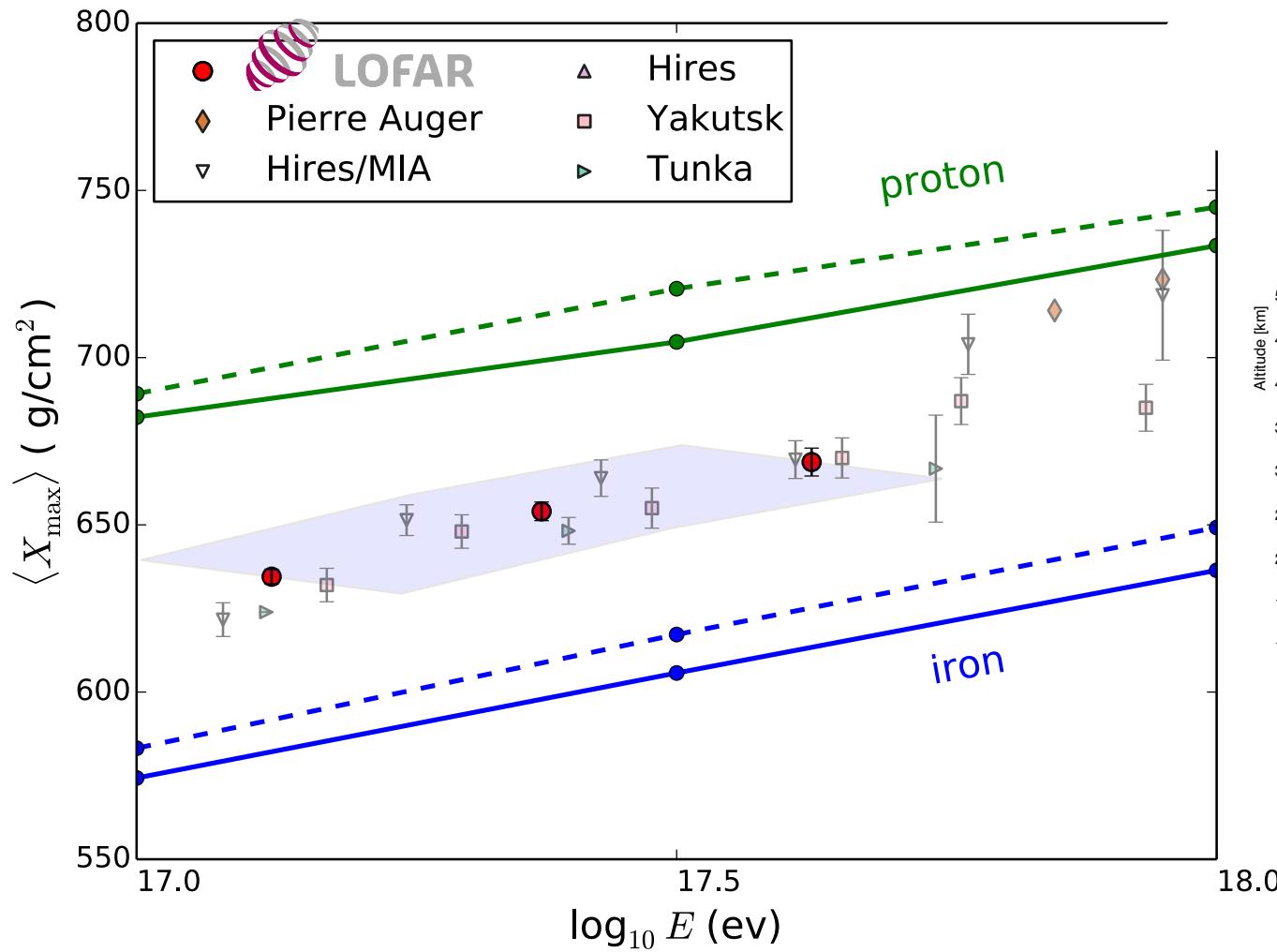


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Depth of the shower maximum



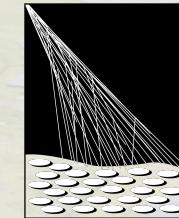
Technologie van de nieuwe sterrenkunde

25 January 2016

**LOFAR/Pierre Auger Observatory
(radio-golfelengte)**



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**PIERRE
AUGER
OBSERVATORY**

Measurement of cosmic rays

Jörg R. Hörandel

Radboud University Nijmegen & Nikhef

<http://particle.astro.ru.nl>



HOVO

CURSUSAANBOD VOORJAAR 2016

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