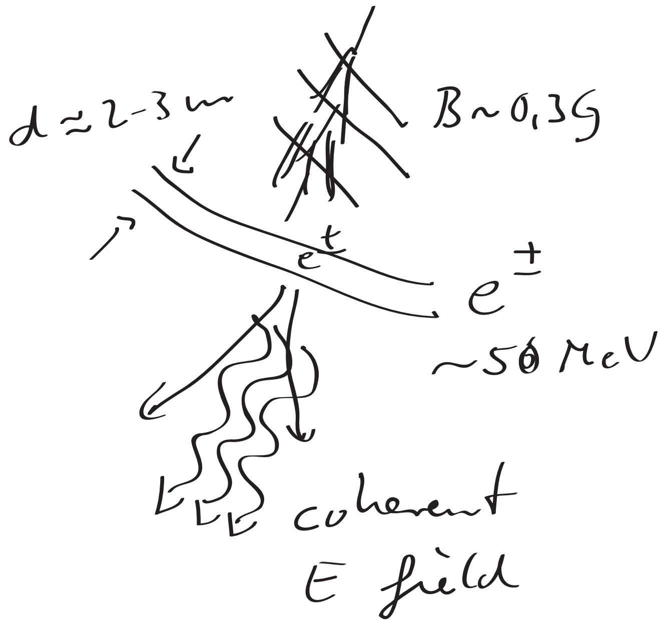
Radio detection of air showers

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

Coherent geosynchrotron radio emission



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

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

$\Rightarrow$ total energy $E_0 = N_e \cdot E_e$

$\Rightarrow$ power $\propto E_e^2 \propto N_e^2$

$\Rightarrow$ GJy flares on 20ns scales

<u>more detail:</u>

synchrotron radiation of electrons in magnetic field of Earth $\rightarrow$ geosynchrotron radiation 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

v velocity of particle

n direction of observer

second term represents synchrotron emission when

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

assume observation point on shower axis: $v \parallel n$

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

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

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

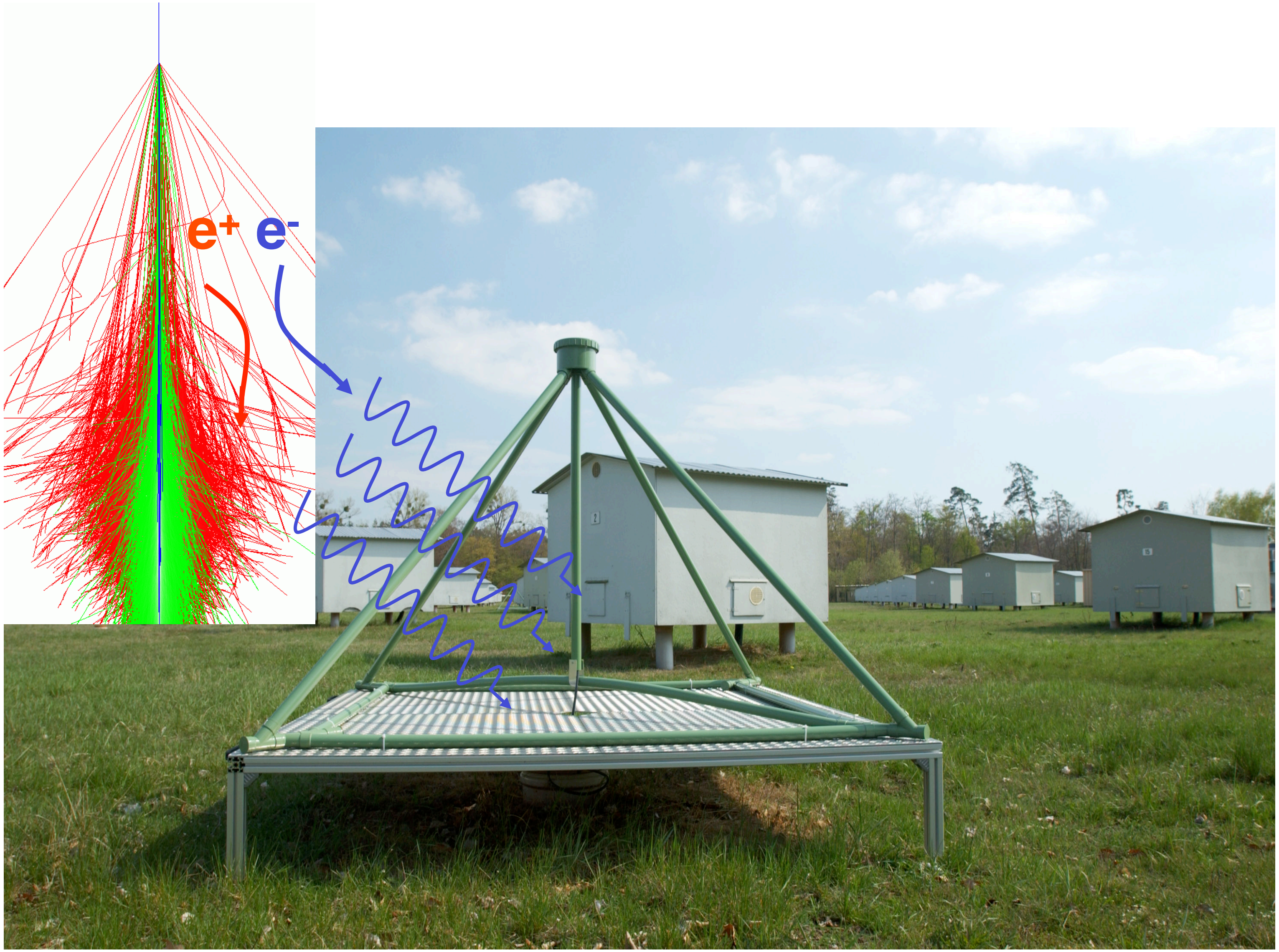
$$\propto -(v \times B)$$

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

total field amplitude

in experiments, projection on E-W or N-S direction is measured

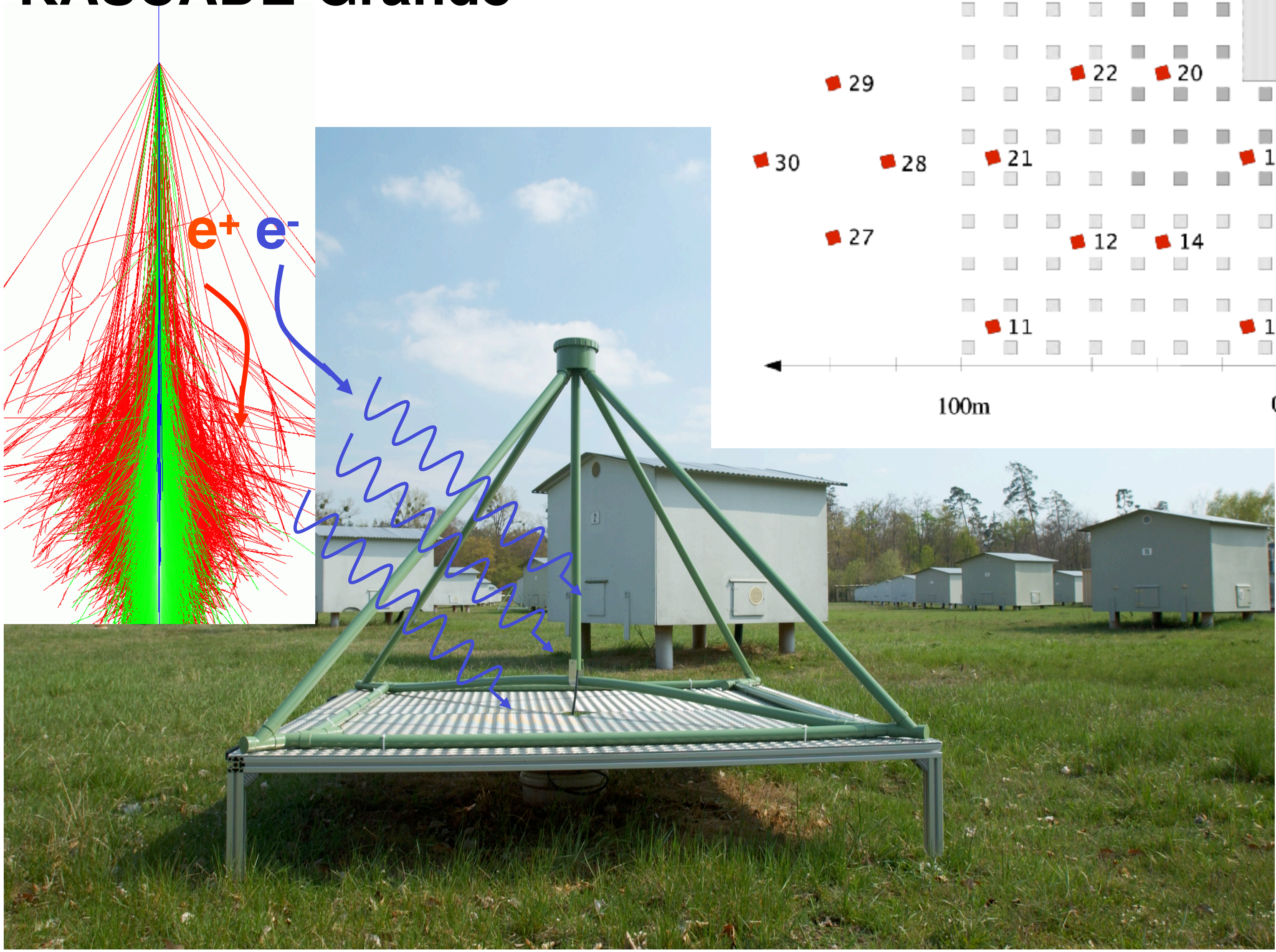
Measurement of Radio Emission in Extensive Air Showers

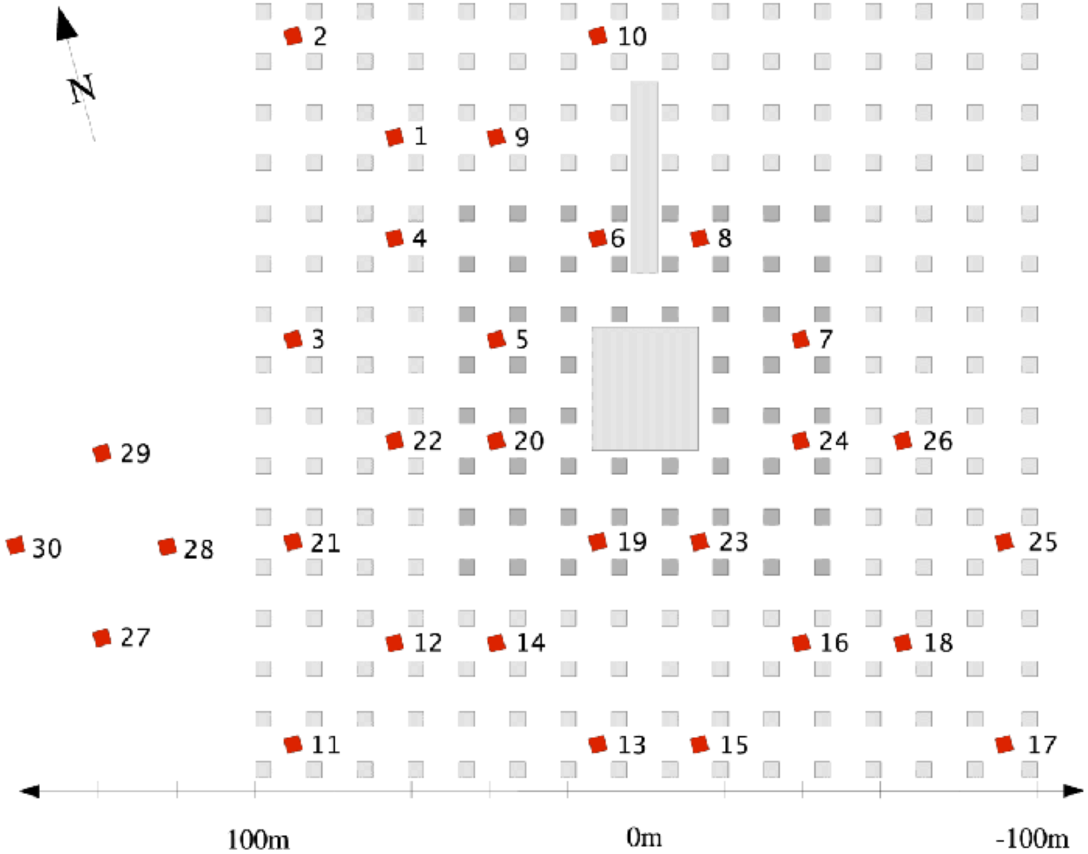


LOPES

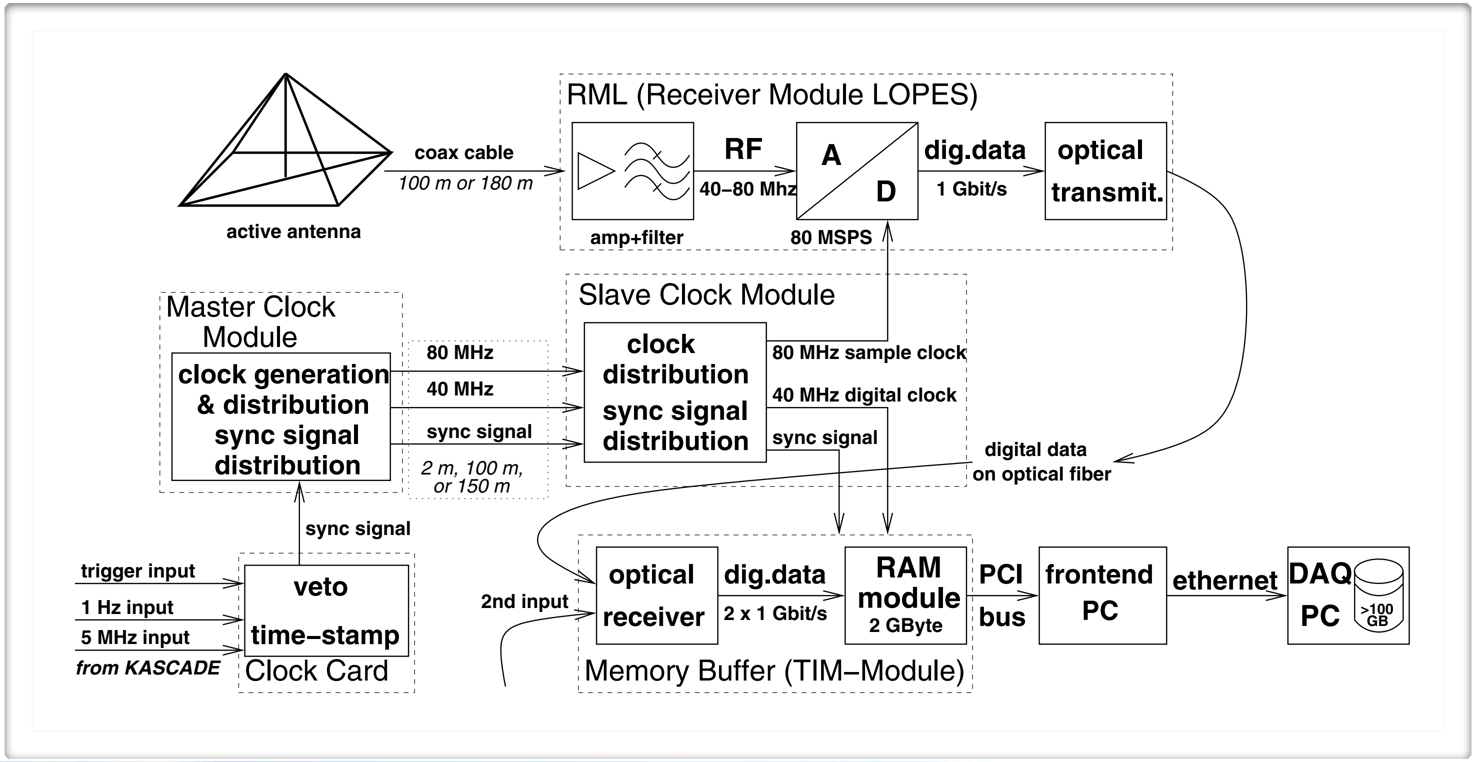
Lofar Prototype Station

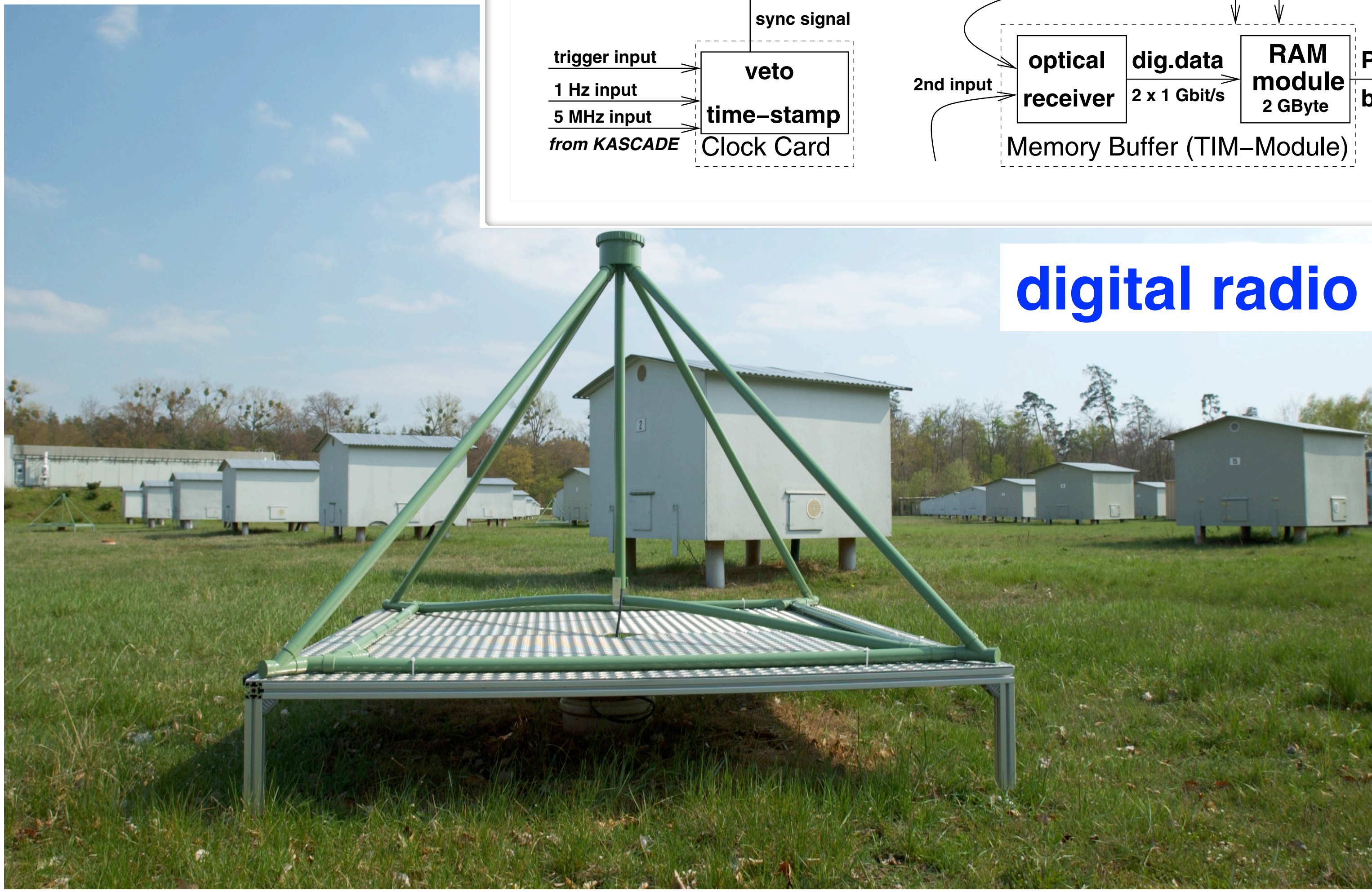
30 antennas operating at KASCADE-Grande





LOPES





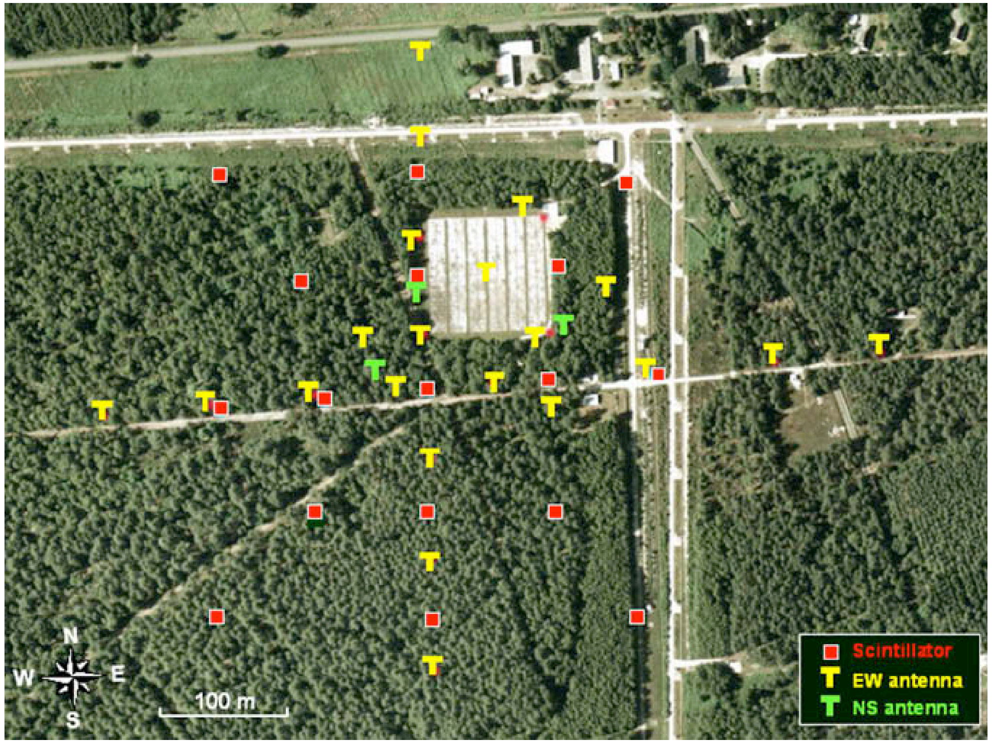
digital radio interferometer

LOPES
RADIO EMISSION FROM COSMIC RAY AIR SHOWERS

CODALEMA

1st stage: decametric array, Nancay

COsmic ray
Detection
Array with
Logarithmic
Electro
Magnetic
Antennas

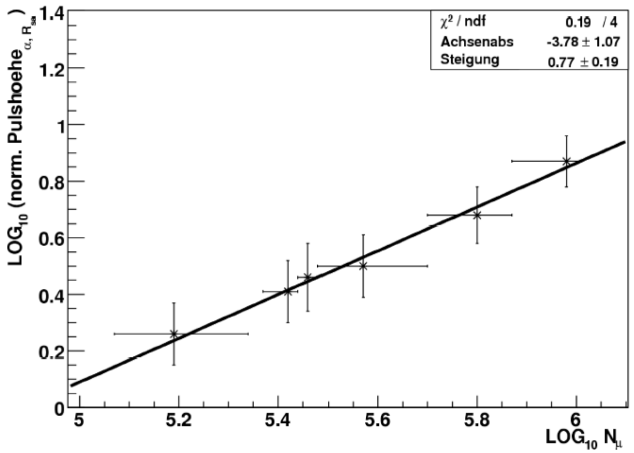


now: low noise, active dipole antenna,
21 dipoles EW pol., 3 dipoles NS pol.
1-220 MHz
17 scintillators for EAS identification

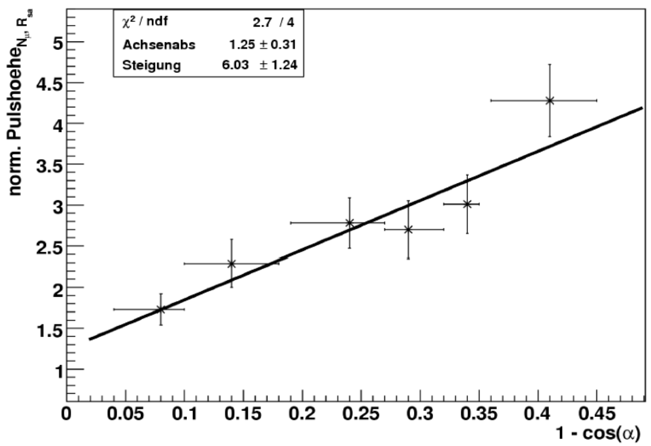
D. Arduin et al., Astropart. Phys. 31 (2009) 192
Nucl. Instr. & Meth. A 572 (2007) 481

Correlation between radio signal and air shower parameters

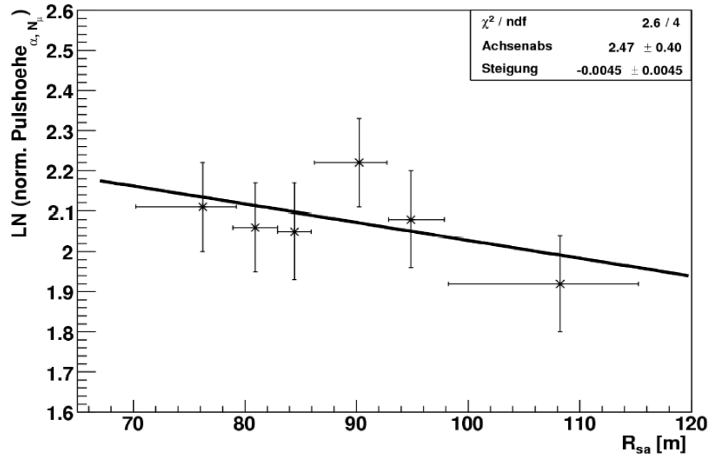
.. number of muons, i.e. primary energy



.. angle with respect to geomagnetic field



.. distance to shower axis



E. Bettini, diploma thesis, U Karlsruhe, 2006

$$\varepsilon_{est} = (11 \pm 1)((1.16 \pm 0.025) - \cos\alpha)\cos\theta \exp\left(\frac{-R}{236 \pm 81\ \mathrm{m}}\right)\left(\frac{E_p}{10^{17}\ \mathrm{eV}}\right)^{0.95 \pm 0.04}\left[\frac{\mu\mathrm{V}}{\mathrm{m\,MHz}}\right]$$

- 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

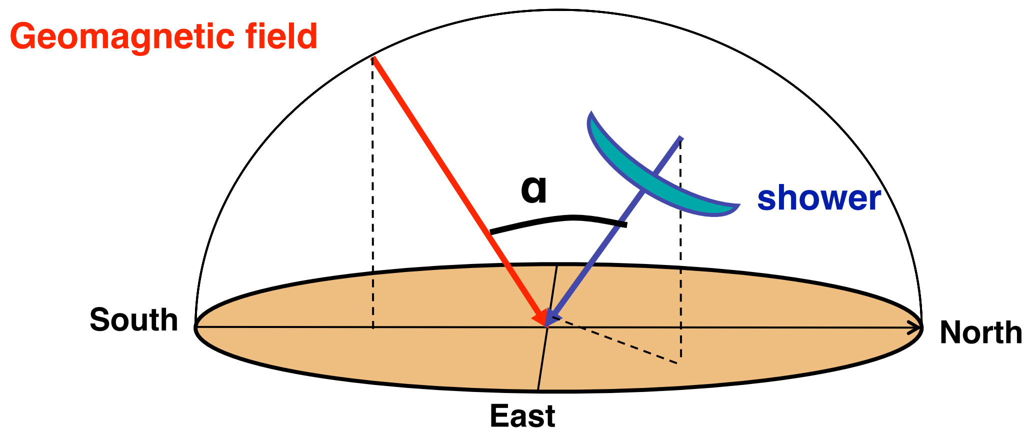
A model to understand the asymmetry

Hypothesis:

- The electric field is proportional to the Lorentz force E ~ lv x Bl
    - 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:

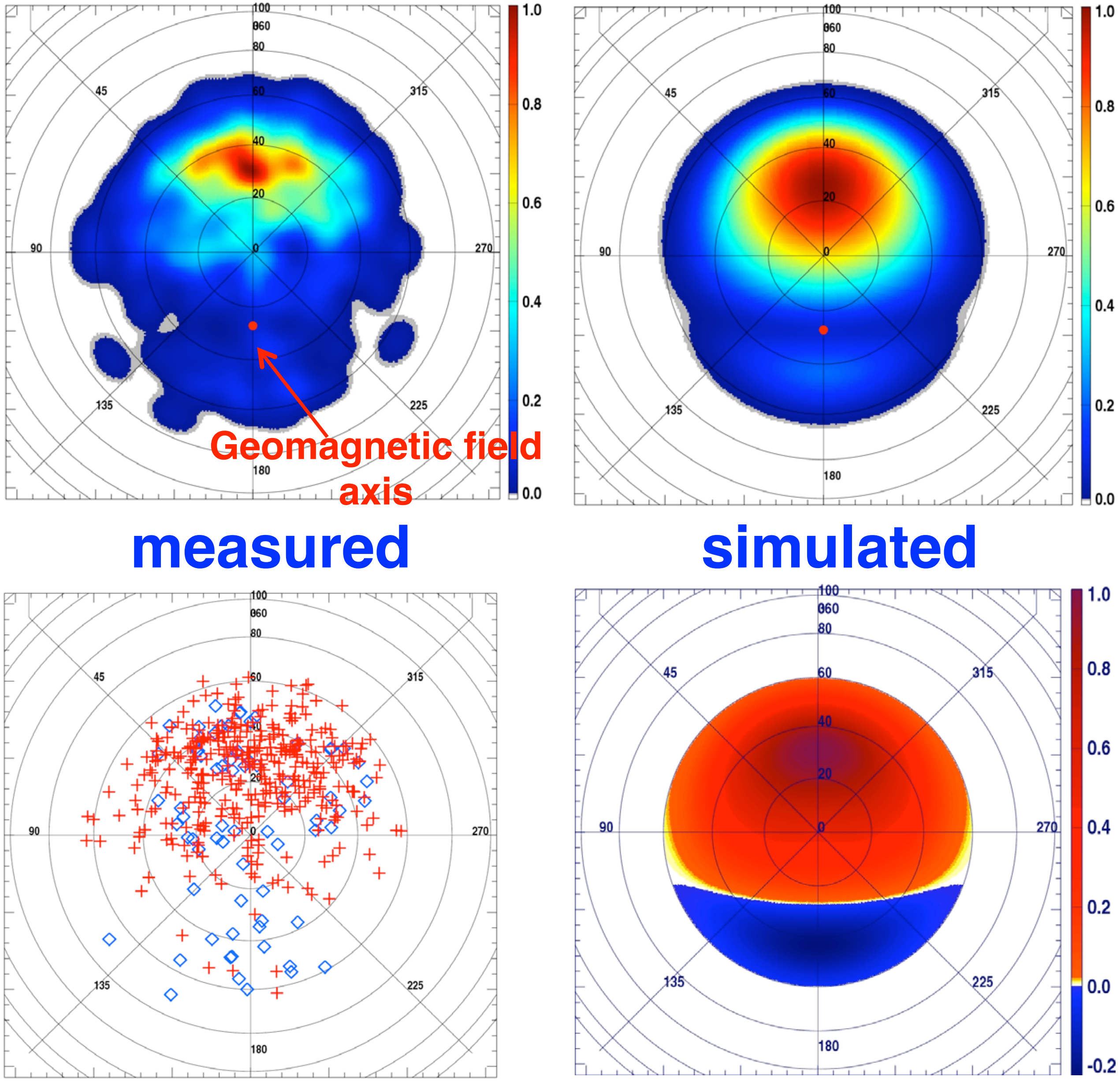
  a simple linear dependence is assumed



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

CODALEMA: Geomagnetic Origin v x B

sky map of radio events (E-W component)



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

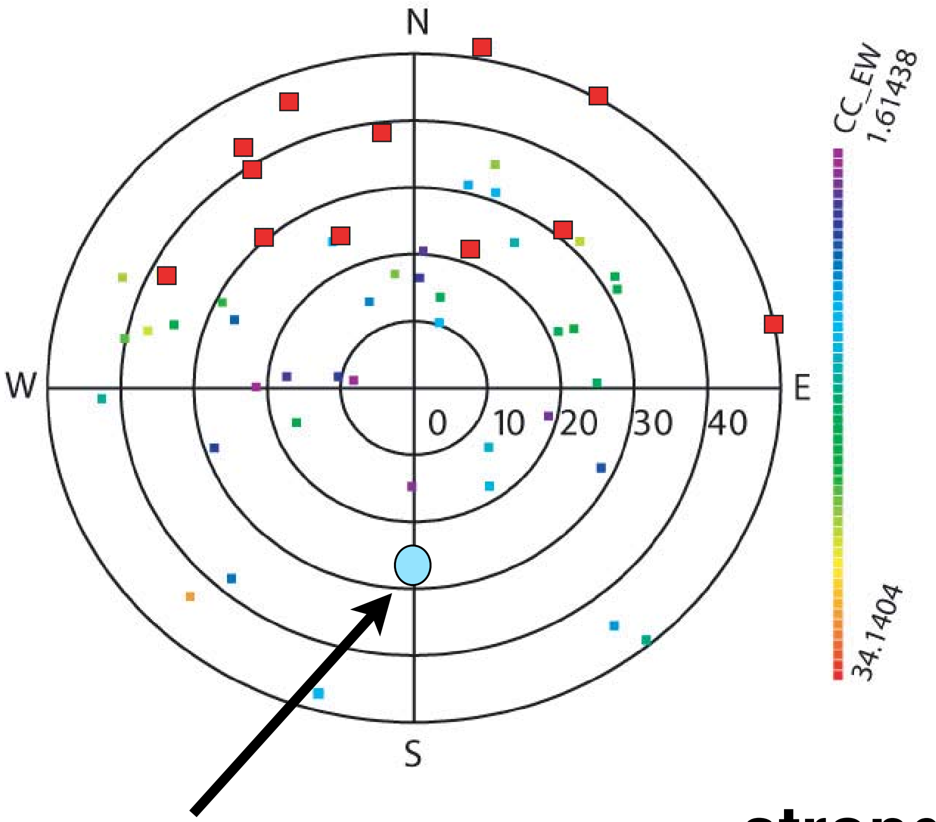
D. Arduin et al., Astropart. Phys. 31 (2009) 192

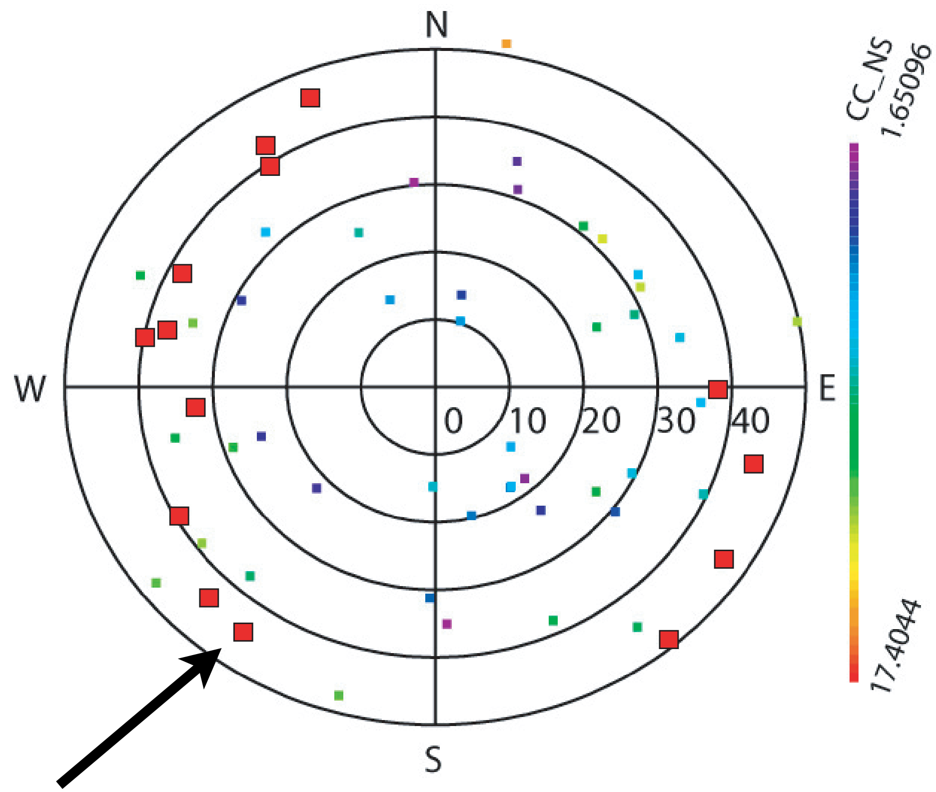
LOPES: Polarization Measurements

arrival direction of cosmic rays (sky map)

E-W polarization

N-S polarization

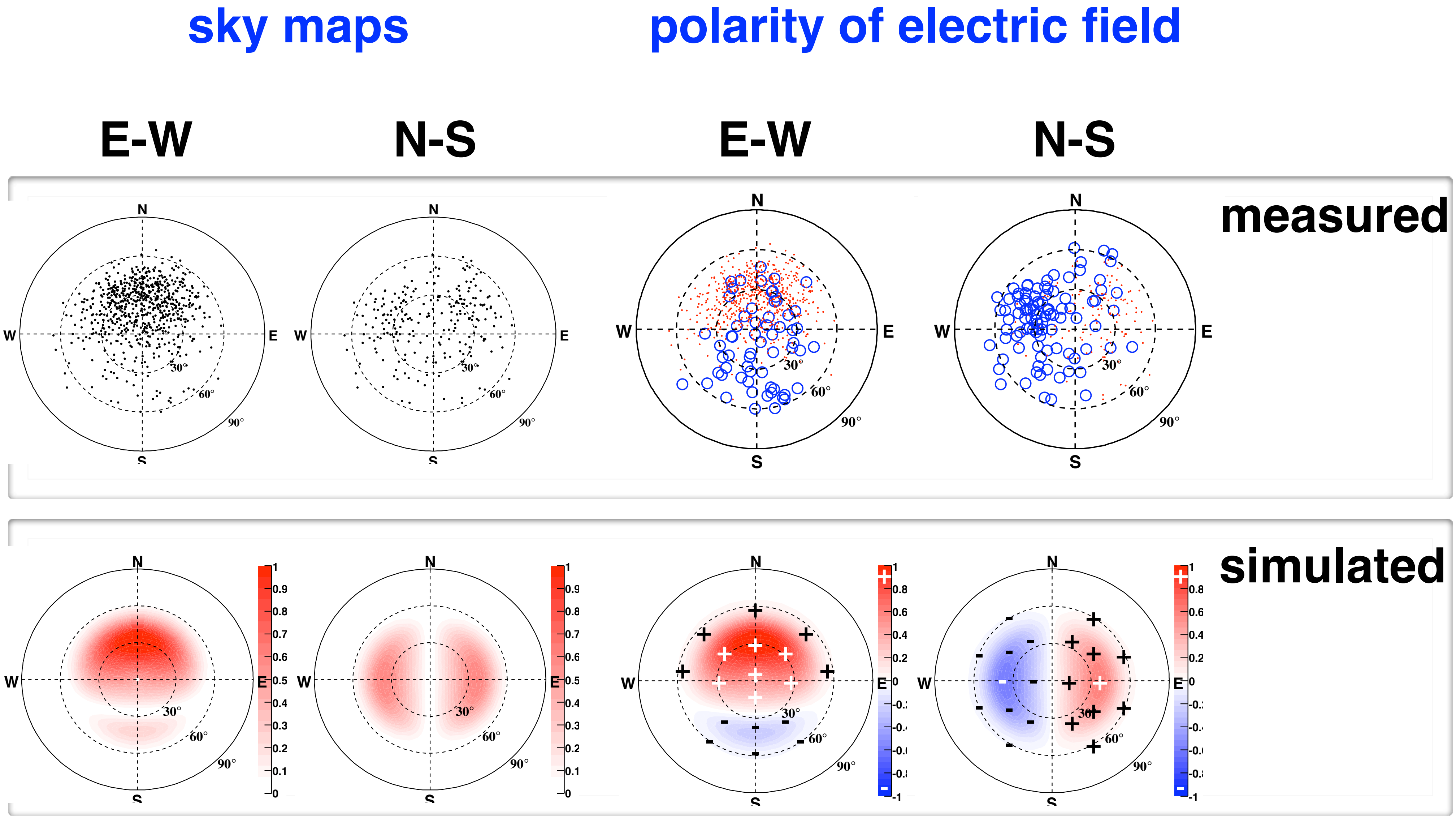




magnetic field
inclination: 64° 36'
declination: 1° 22'

P.G. Isar et al., Nucl. Instr. & Meth. A 604(2009) S81

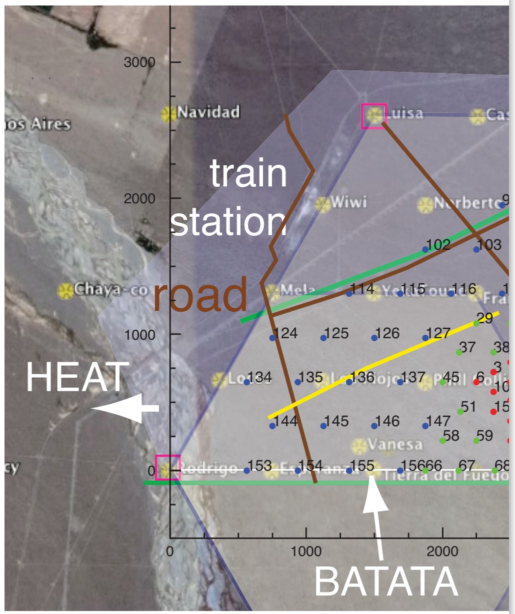
CODALEMA: Polarization of radio signal

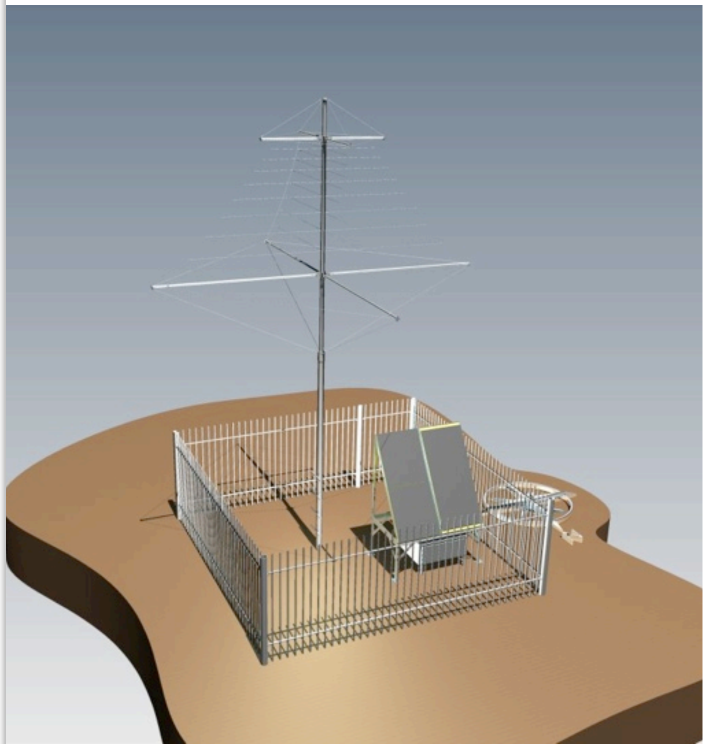


polarization proportional to $E \propto \vec{v} \times \vec{B}$

C. Rivière et al., ICRC 2009

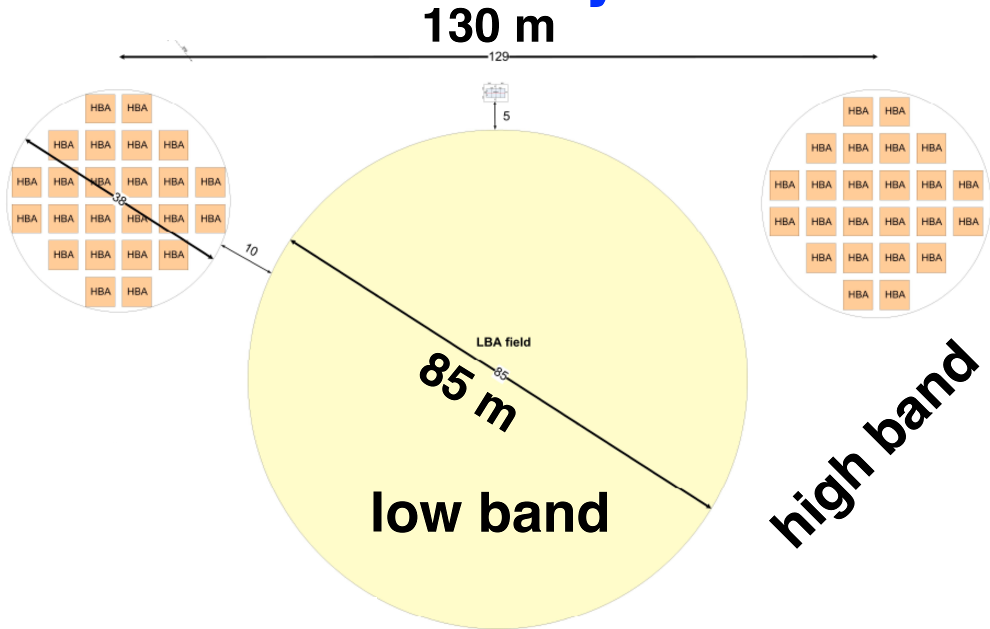
Auger Engineering Radio Array





- **~20 km²**
- **~150 antennas**
- **operation together with infill/HEAT/AMIGA**
- **three antenna spacings to cover efficiently 17.2 < lg E < 19.0**
- **measure composition of cosmic rays in energy region of transition from galactic to extragalactic cosmic rays**

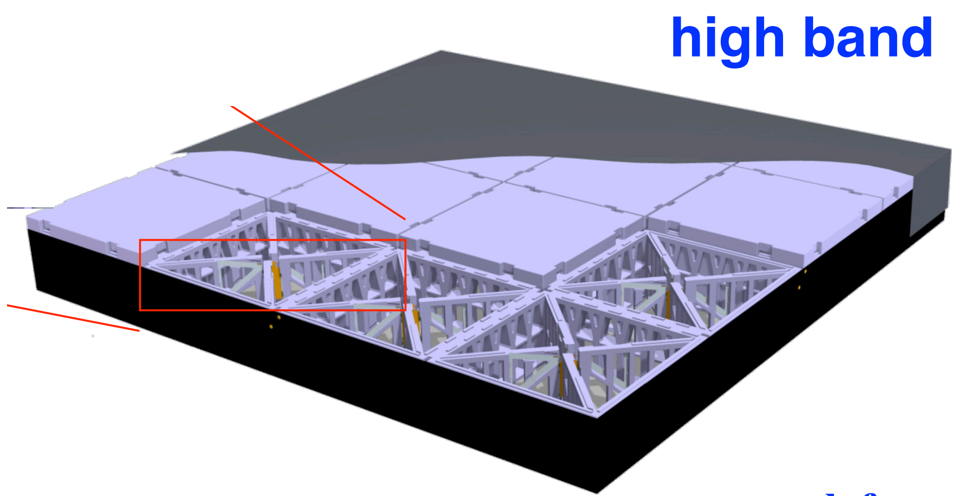
Station Layout



each (dutch) station:

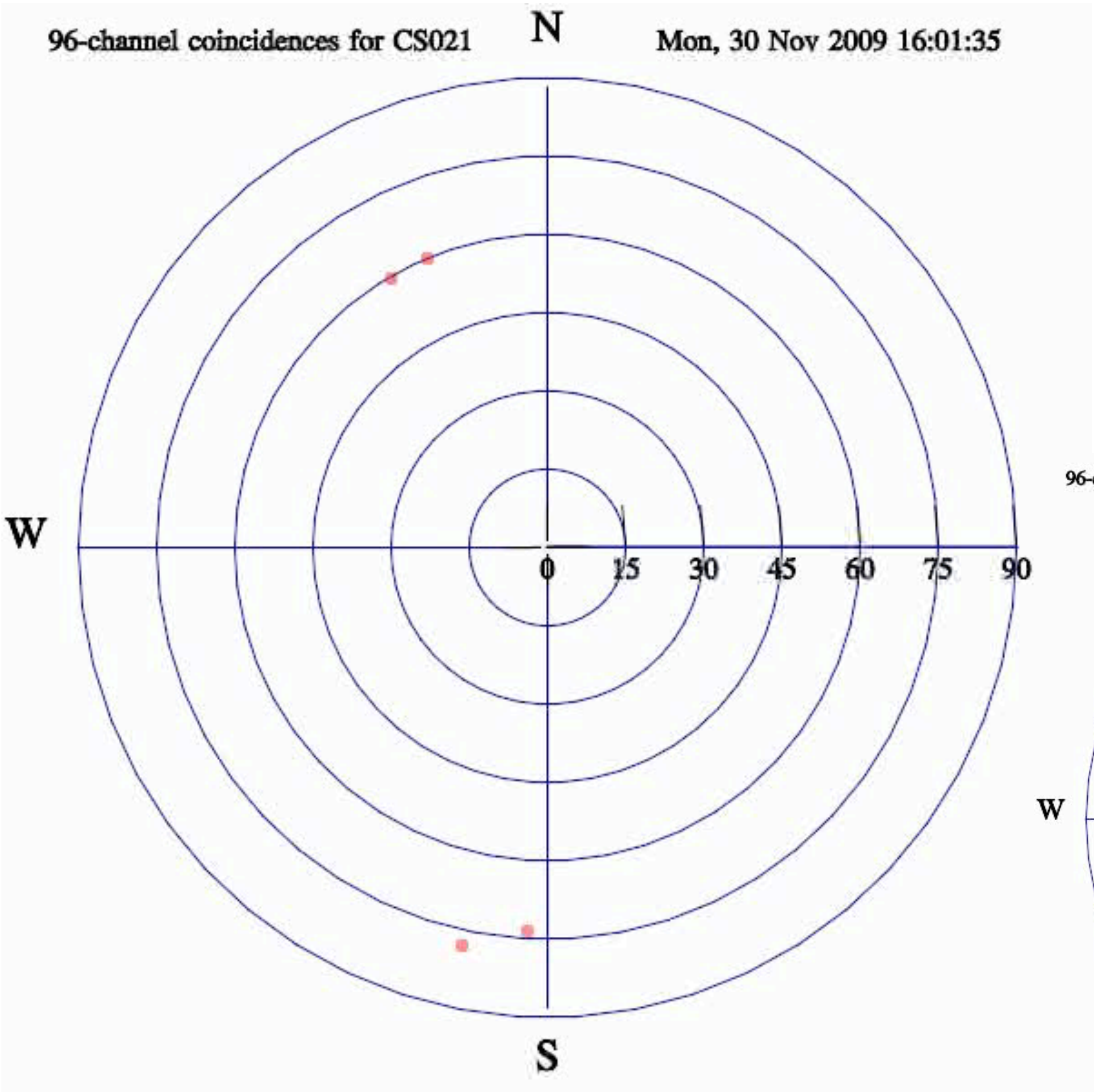
96 low-band antennae 30- 80 MHz

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

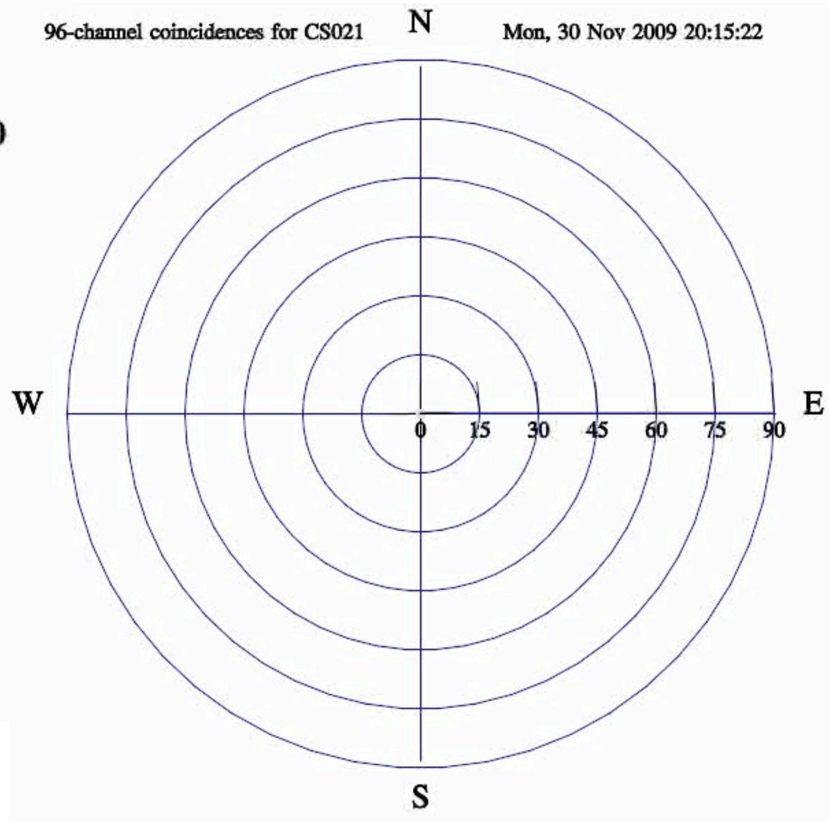


www.lofar.org

Sky map of TBB triggers



airplane



High energy γ rays

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

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

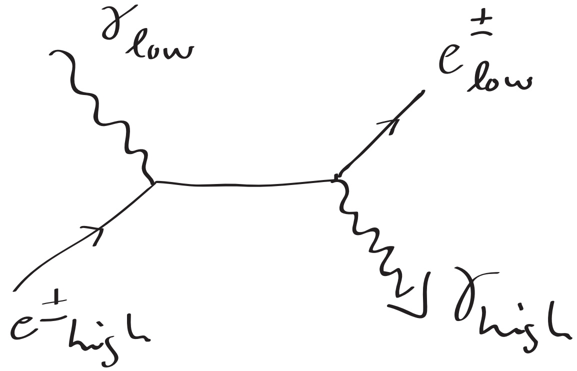
Production & interactions

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

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

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

requires presence of hadronic particles

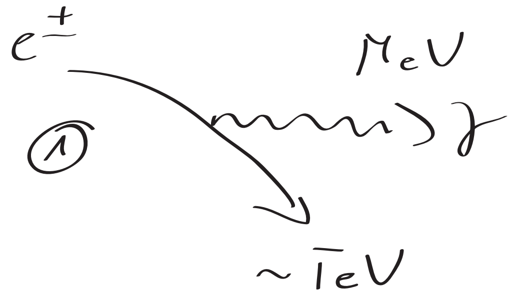
4) Bremsstrahlung

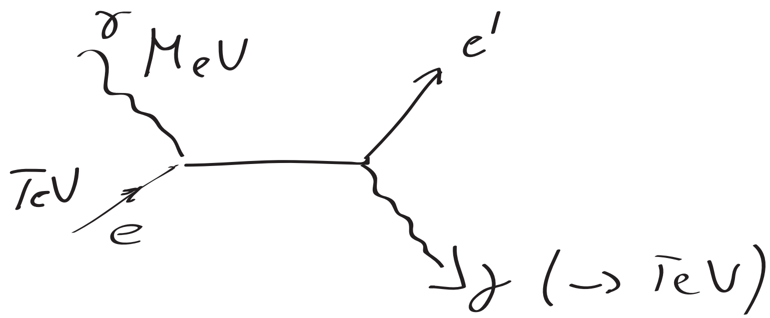
$$e + \text{target} \longrightarrow \text{Bremsstrahlung}$$

$$E_\gamma \sim \frac{E_e}{2} \quad \text{(power law)}$$

important combination of 1) & 2)

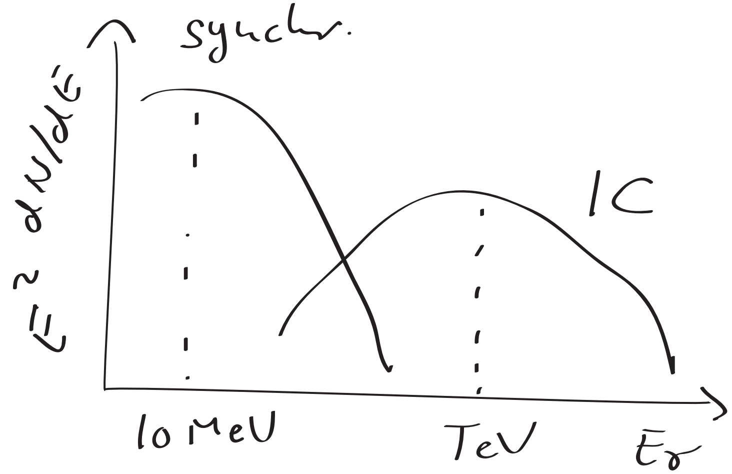
synchrotron-self-Compton : SSC





the photons for inverse Compton scattering are produced in situ

typical form of spectrum



Measurement of high-energy gamma rays

a) in space (satellites)

keV $\longrightarrow$ ~ 10 GeV

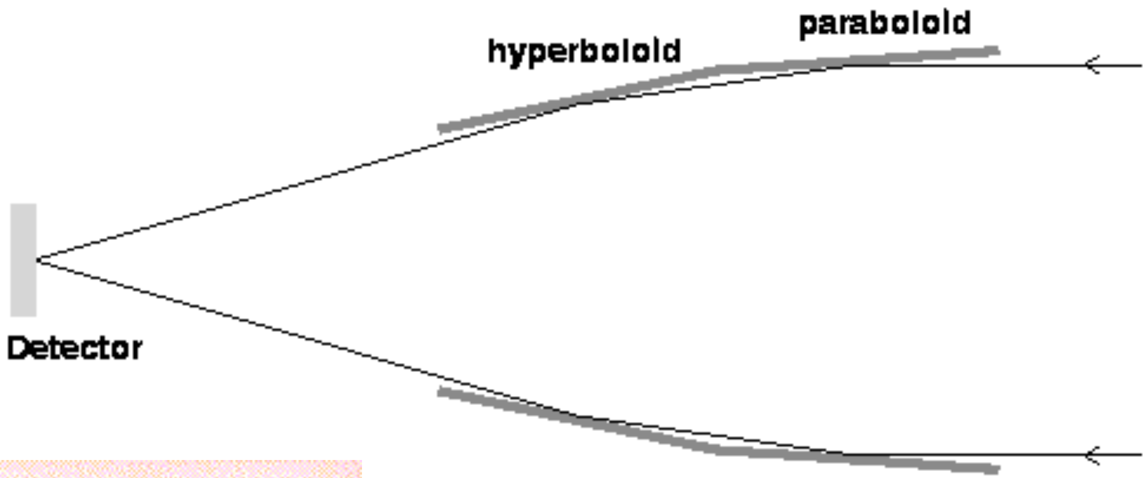
keV $\downarrow$ X rays

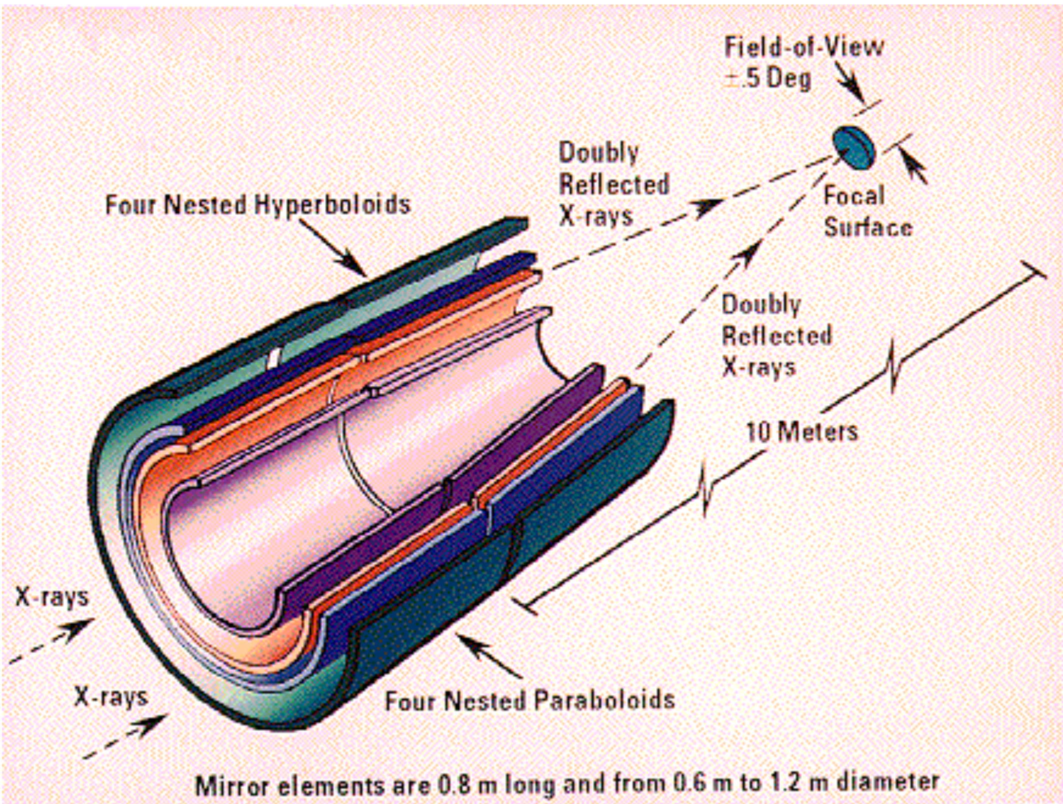
~ 10 GeV $\downarrow$ γ rays

X rays Wolter telescope

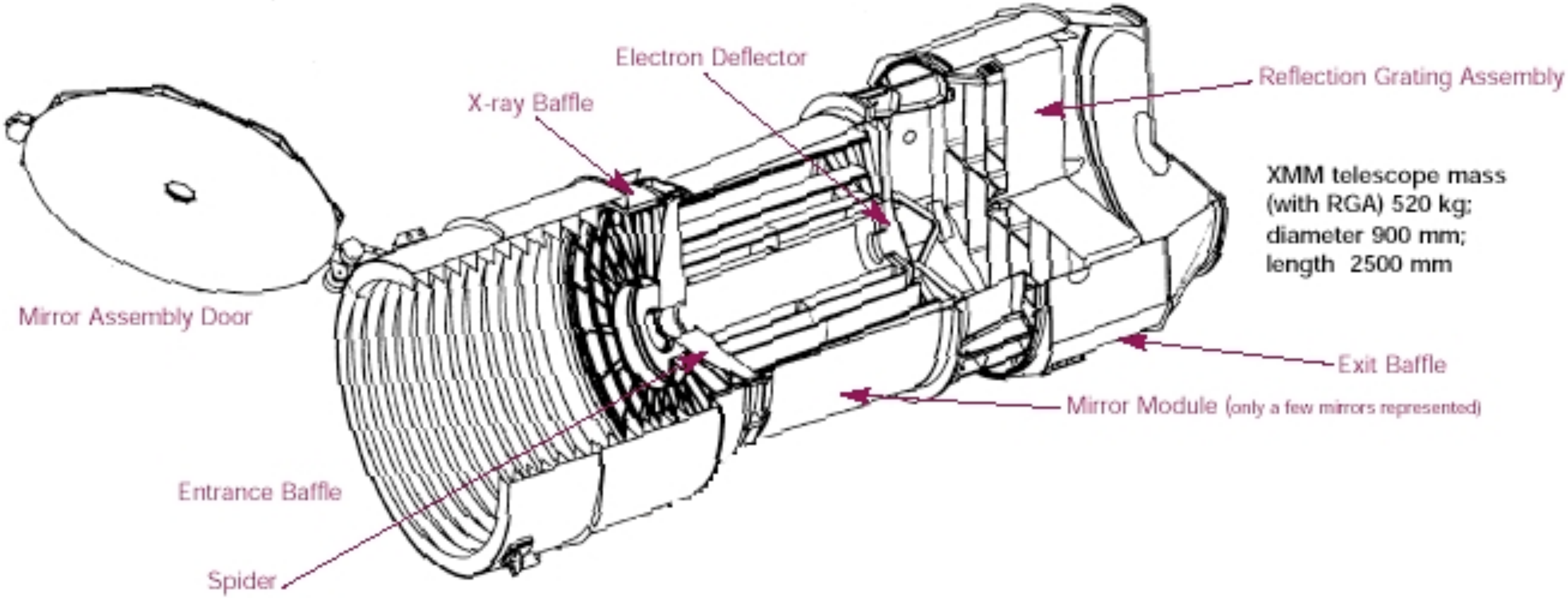
reflection on polished metal plates

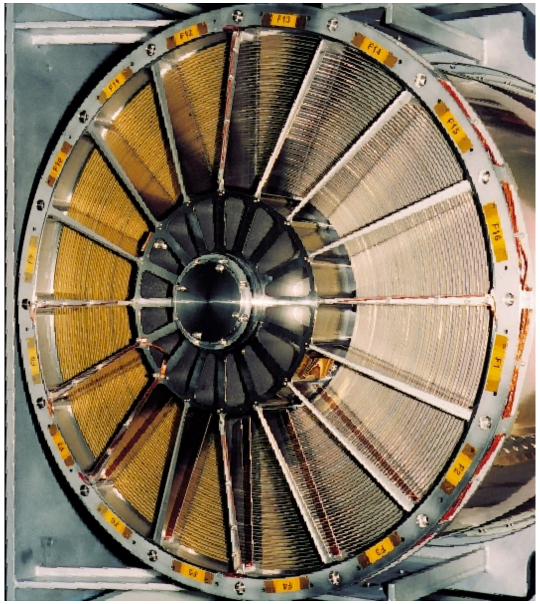
Wolter telescope

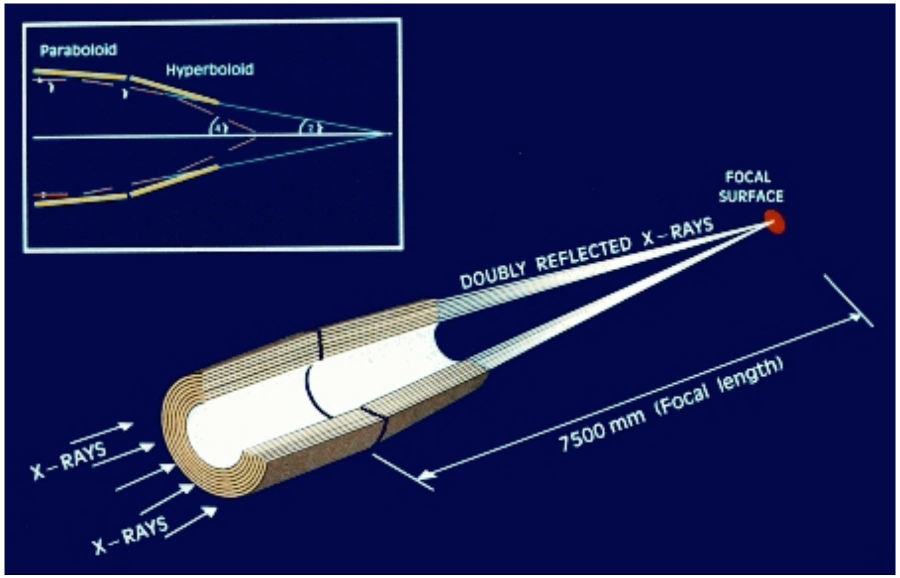




XMM-Newton x-ray telescope







GLAST / Fermi   gamma detection in space

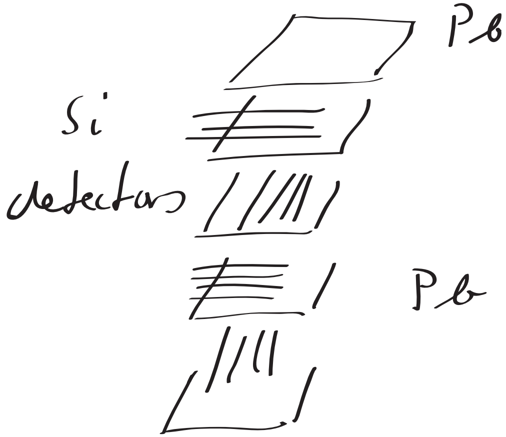
electromagnetic calorimeter

10 layers Pb converter

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

interspaced with 12 layers

of Si strip detectors

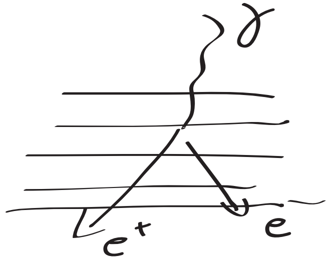


electromagnetic cascade

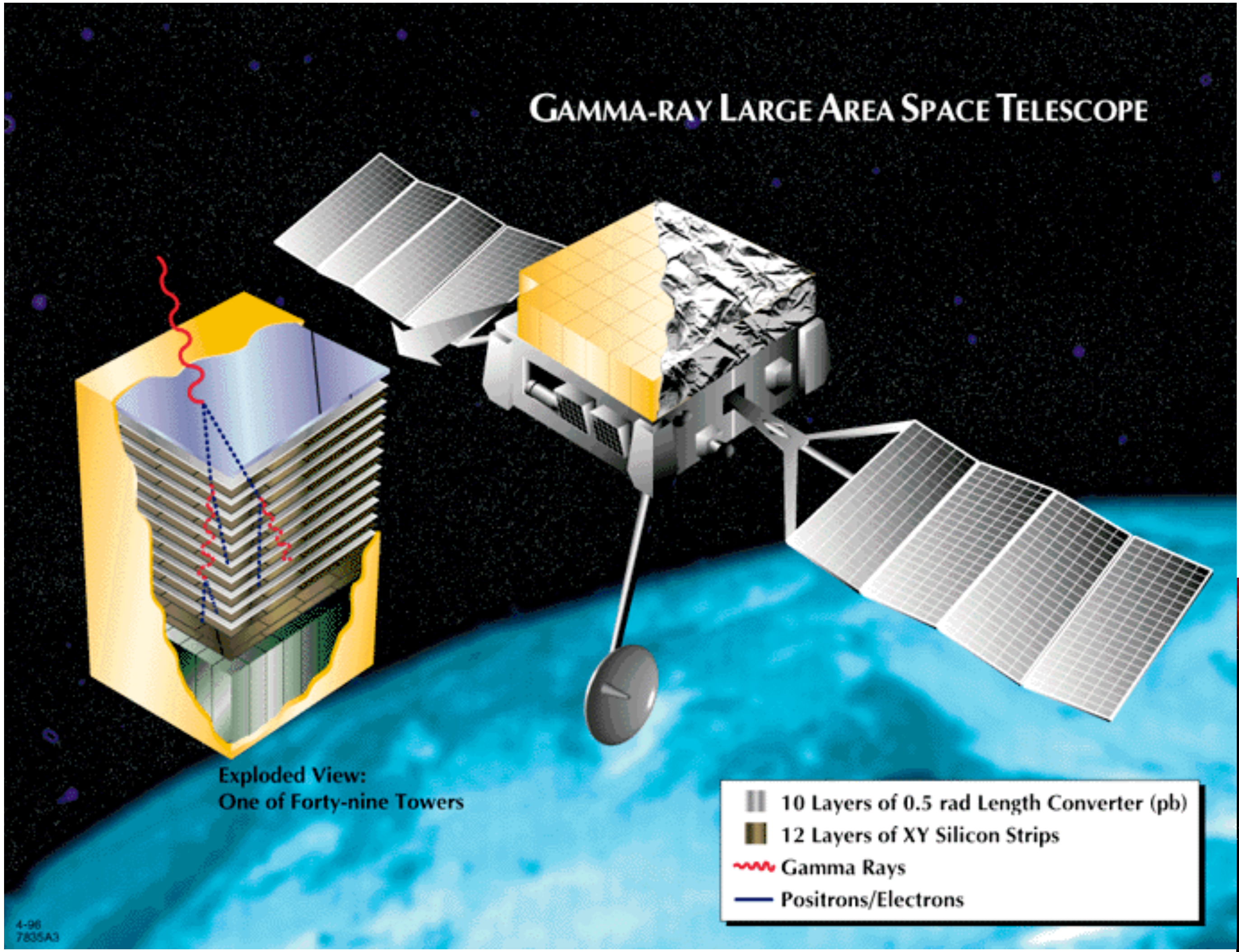
$\longrightarrow$ trajectory

$\longrightarrow \ \sum E \Rightarrow E_\gamma$

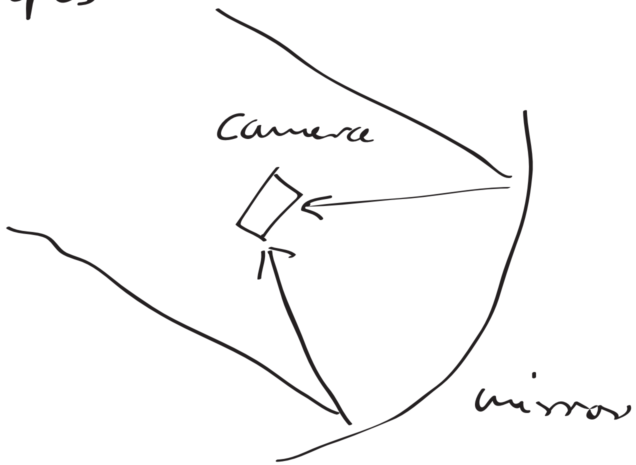
up to $E_\gamma \sim 10-20$ GeV



GLAST/Fermi


GAMMA-RAY LARGE AREA SPACE TELESCOPE
Exploded View:
One of Forty-nine Towers
10 Layers of 0.5 rad Length Converter (pb)
12 Layers of XY Silicon Strips
Gamma Rays
Positrons/Electrons
4-96
7835A3

b) atmospheric Čerenkov telescopes



picture of shower recorded with fast camera (PMTs)

total number of Č photons → E_0

field of view ~ 4°

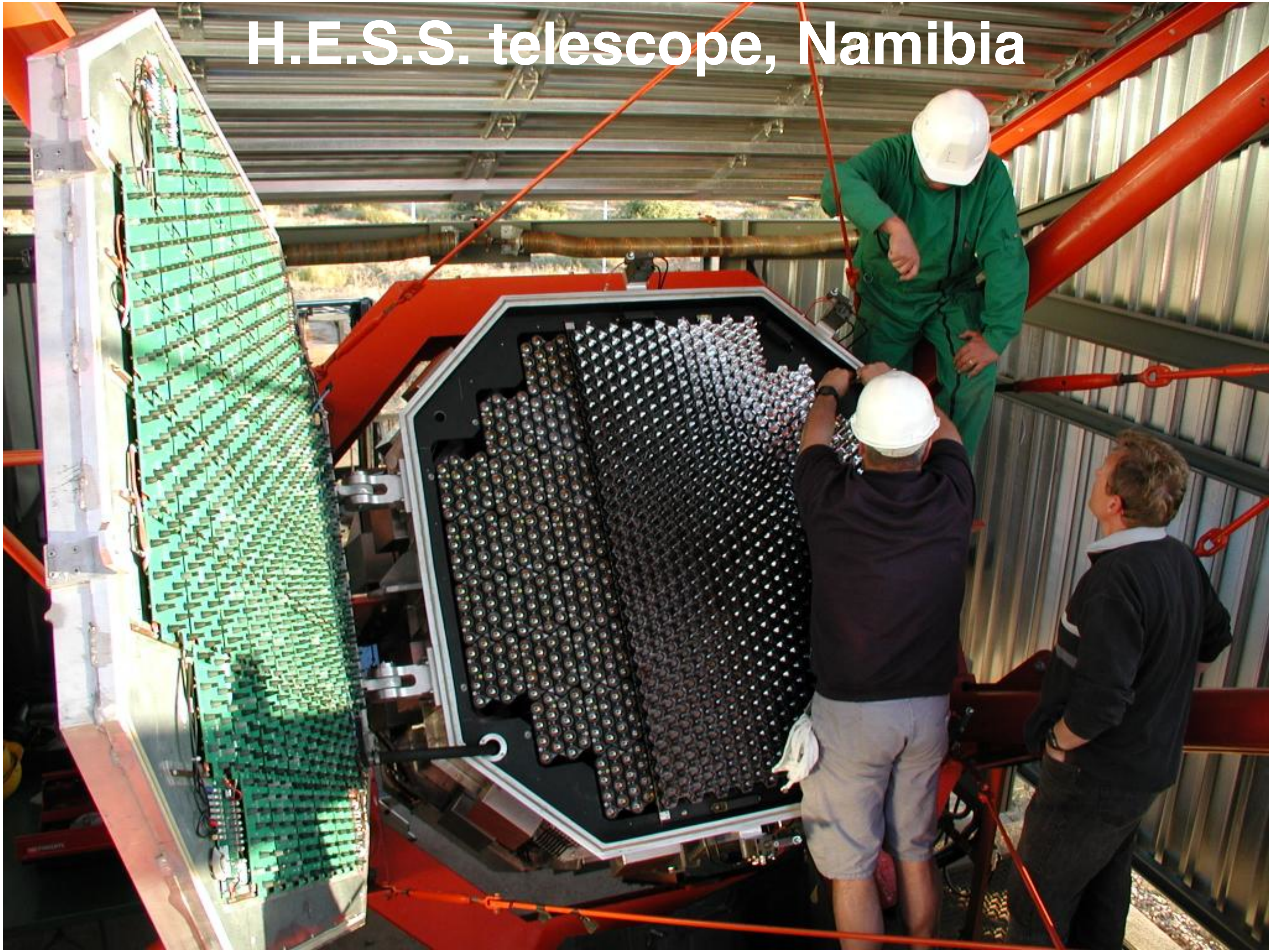
stereo observation

→ 3 dim trajectory of shower in atmosphere

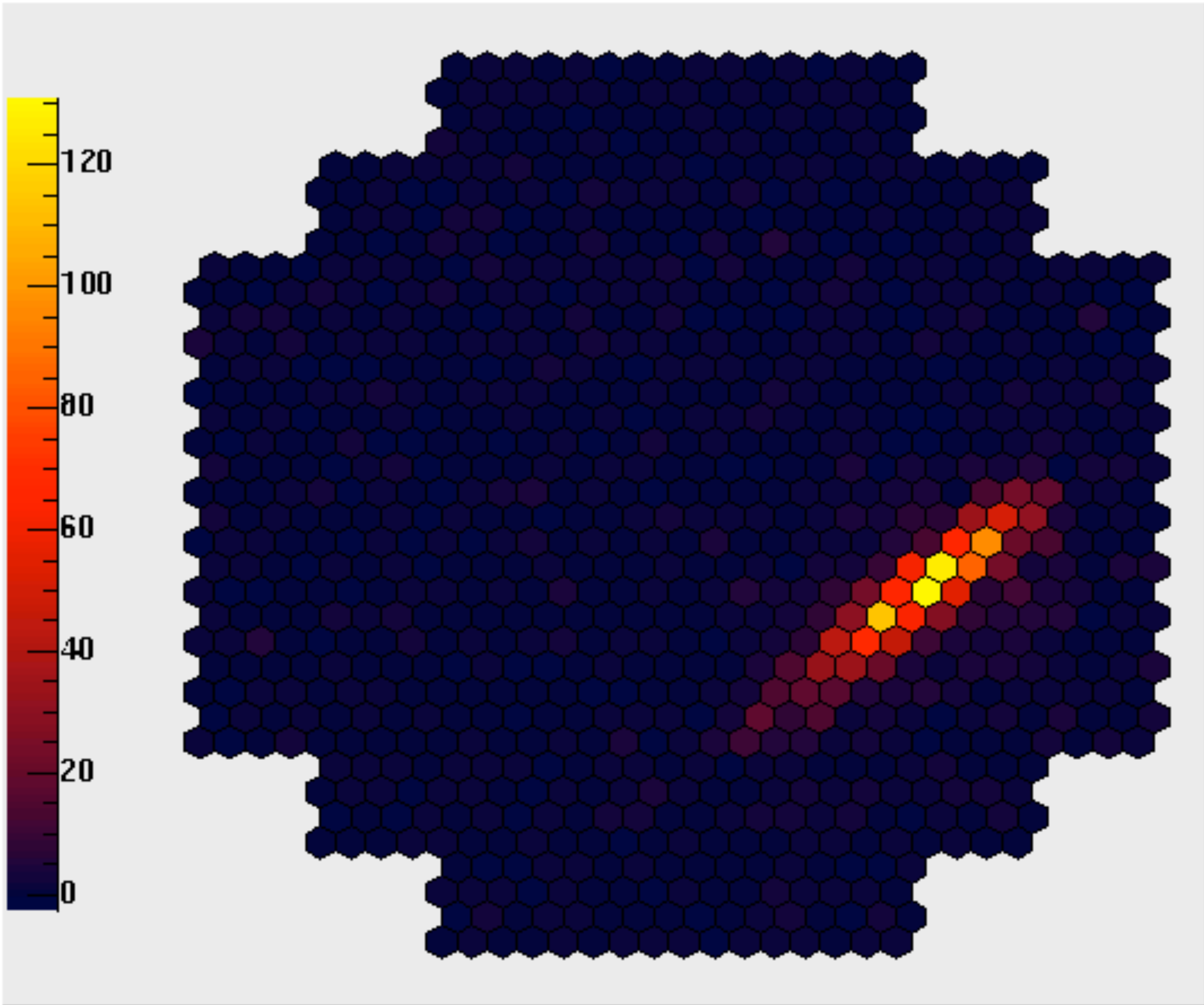
→ direction of incoming photon

H.E.S.S. telescope, Namibia

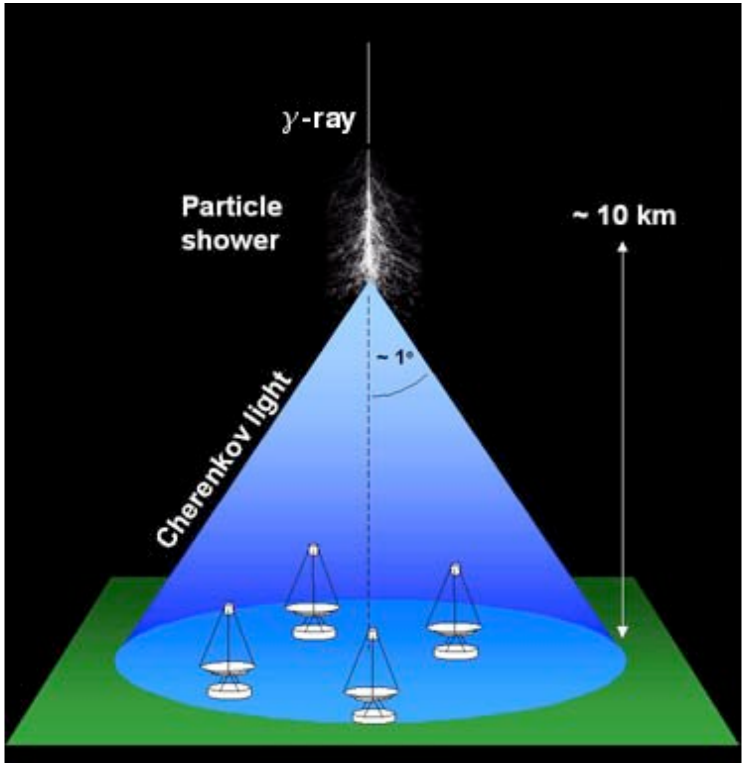
H.E.S.S. telescope, Namibia

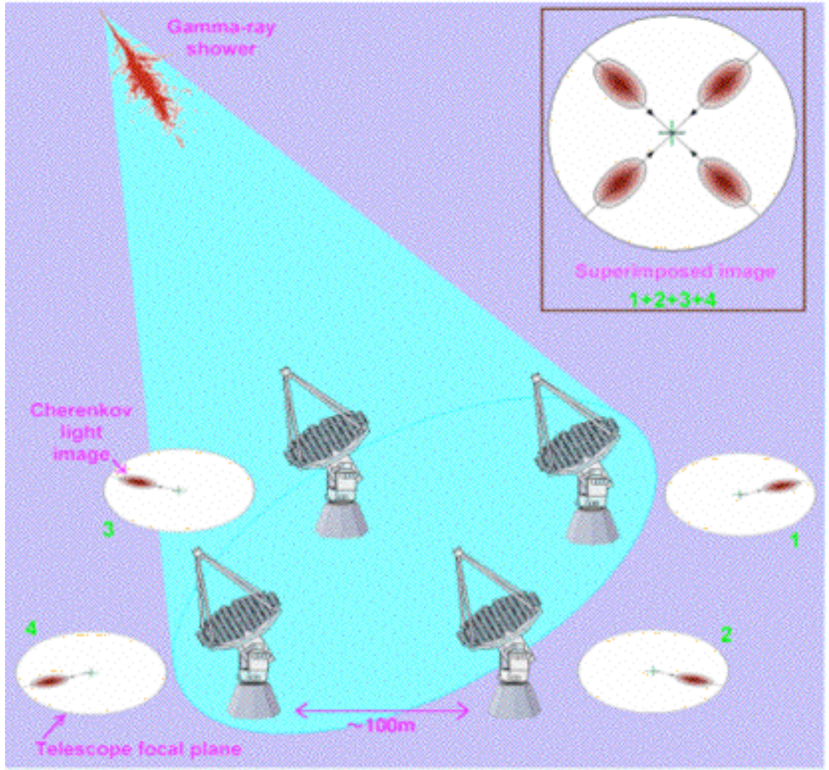


H.E.S.S. telescope, Namibia



stereo observation

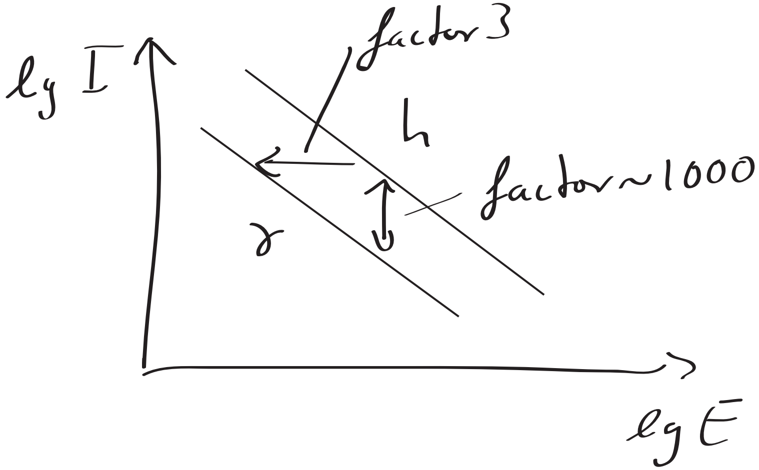




problem: high background of hadronic particles

reduction: two effects:

1) hadronic particles produce only $\frac{1}{3}$ of Č light as photons at same energy



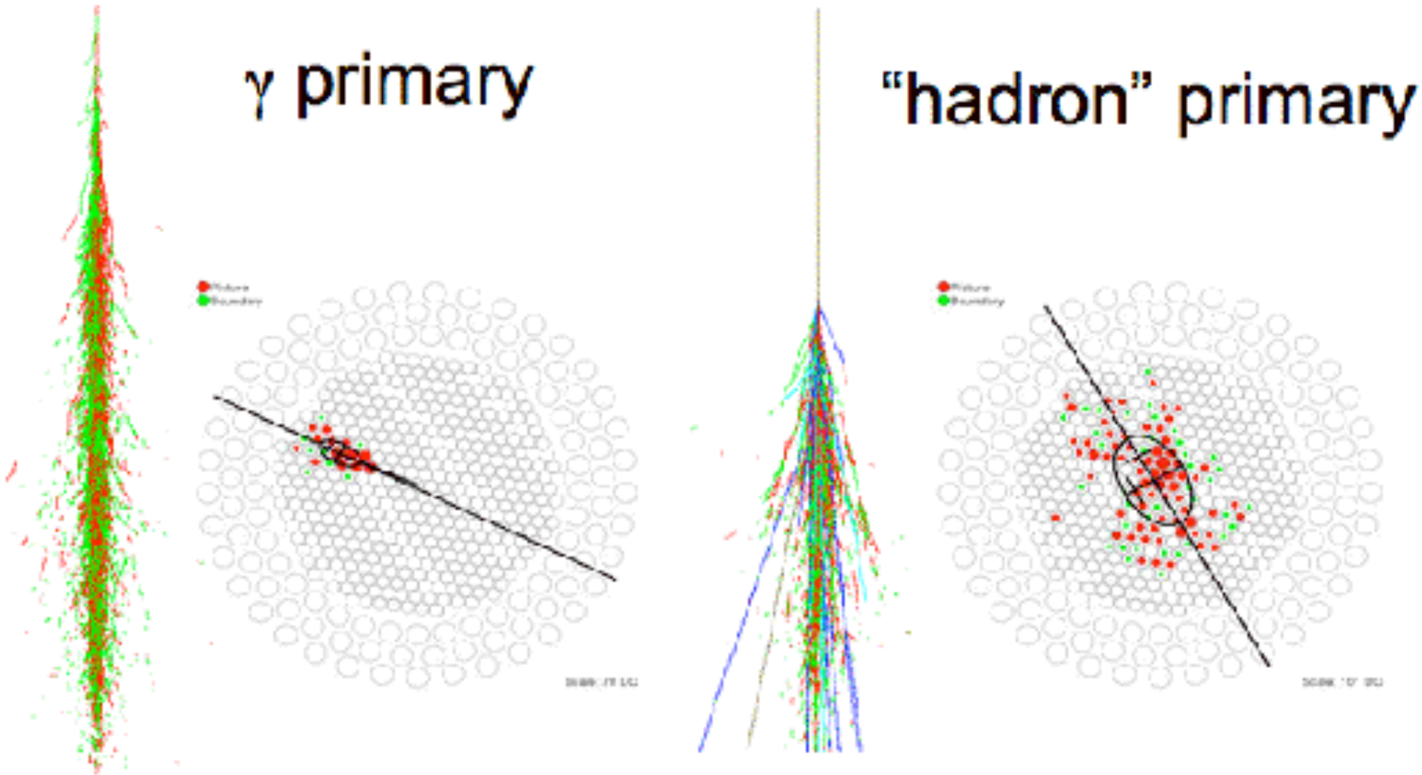
$$\frac{dN}{dE} \propto E^{-3}$$

$3^3 = 27$ hadronic particles at same number of Č photons are only $\frac{1000}{27} \sim 37$ times more abundant

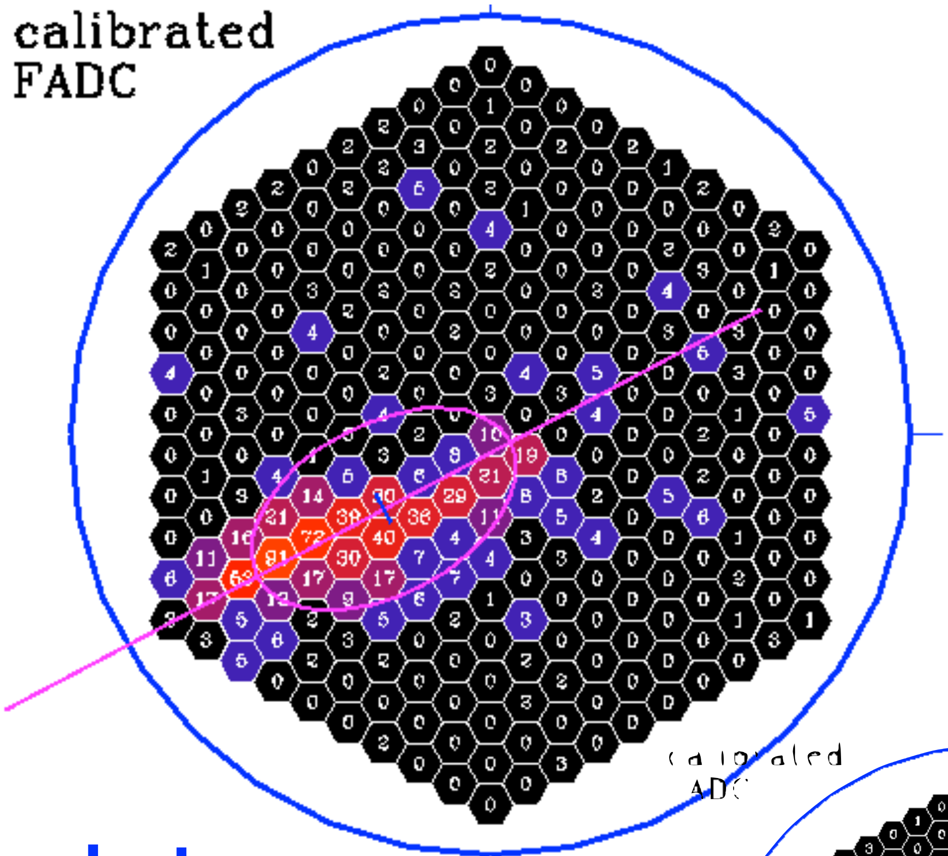
2) pattern recognition in Č image

e/γ cascades produce "smoother" images

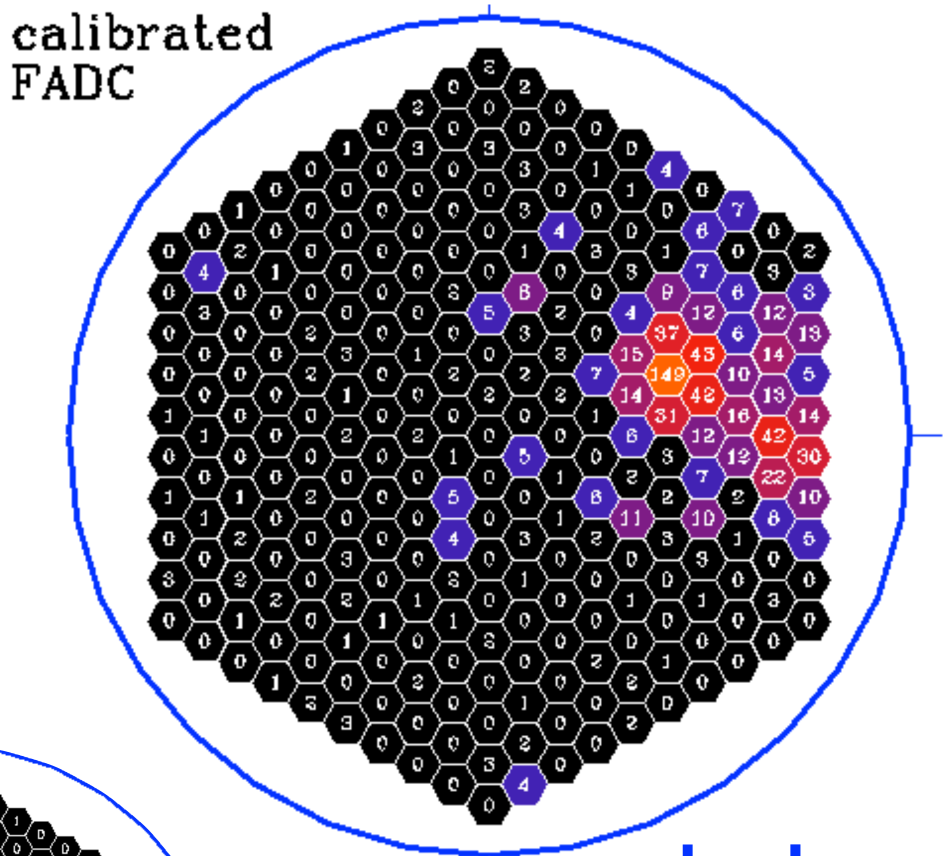
gamma-hadron separation



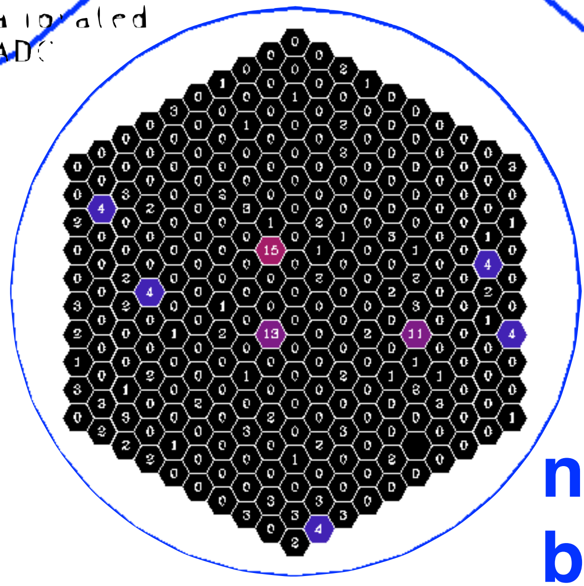
gamma-hadron separation



photon



hadron



night sky
background

modern Cherenkov telescopes
energy threshold for gamma rays ~50 GeV
limited by collecting area --> large mirrors

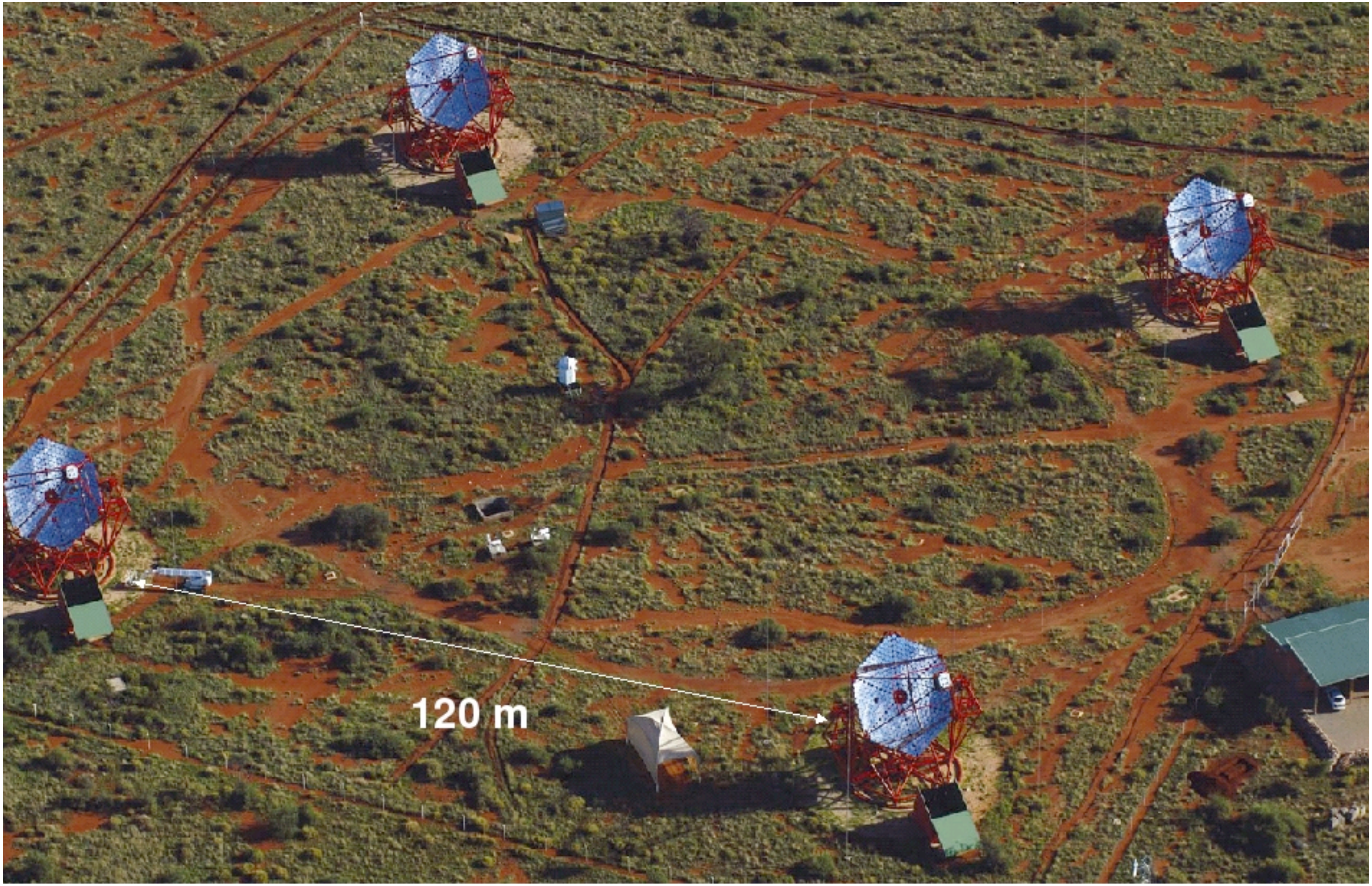
H.E.S.S. (Namibia)
4 telescopes on 120 m square
segmented mirror, 108 m^2 per telescope
point spread function 0.03°
5th central telescope under construction

Magic (La Palma)
two telescopes 236 m^2 mirror

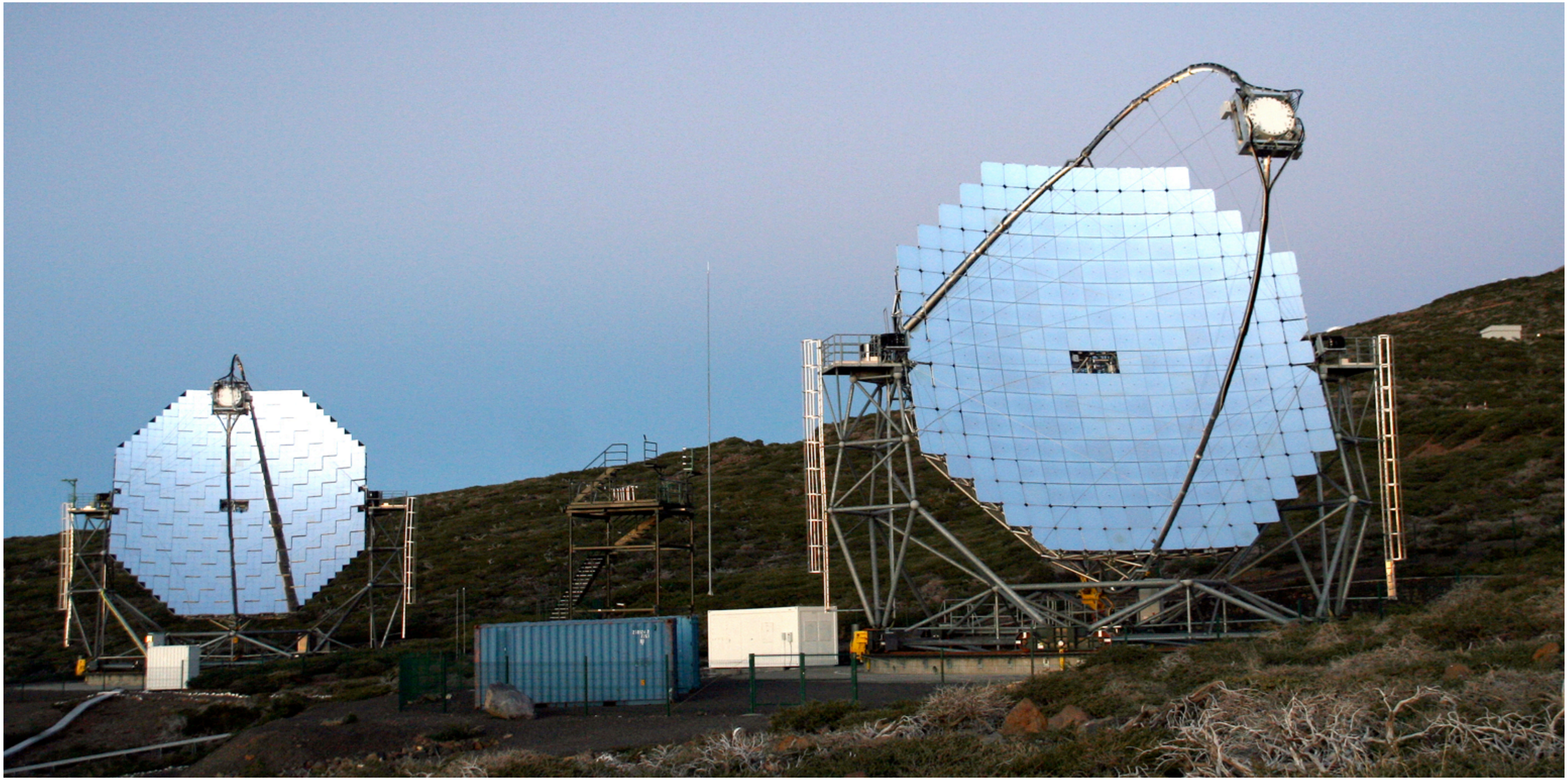
Veritas (USA, Arizona)
4 telescopes, 12 m mirror

future: CTA
large array of telescopes
- low energy threshold
- excellent angular resolution
- good sensitivity

H.E.S.S. telescope, Namibia



MAGIC telescope, La Palma



VERITAS, Arizona

CTA