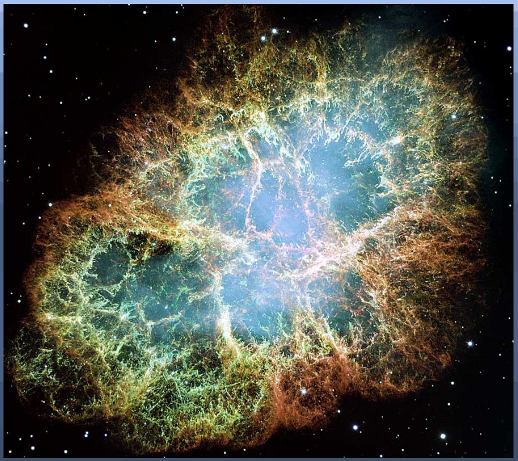
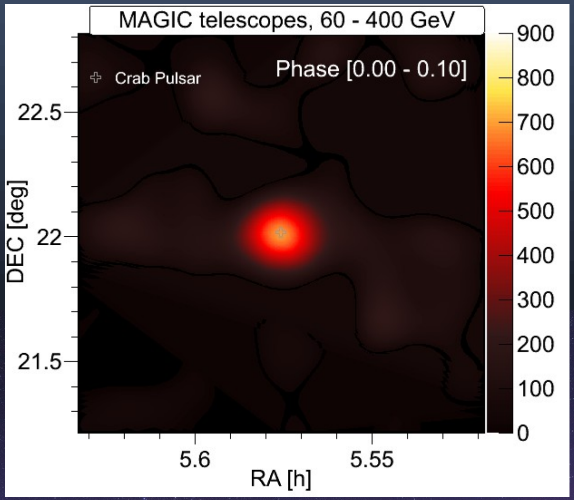
There is MAGIC in the air





Christian Fruck

IMPRS/GK Young Scientist Workshop at Ringberg Castle 2013

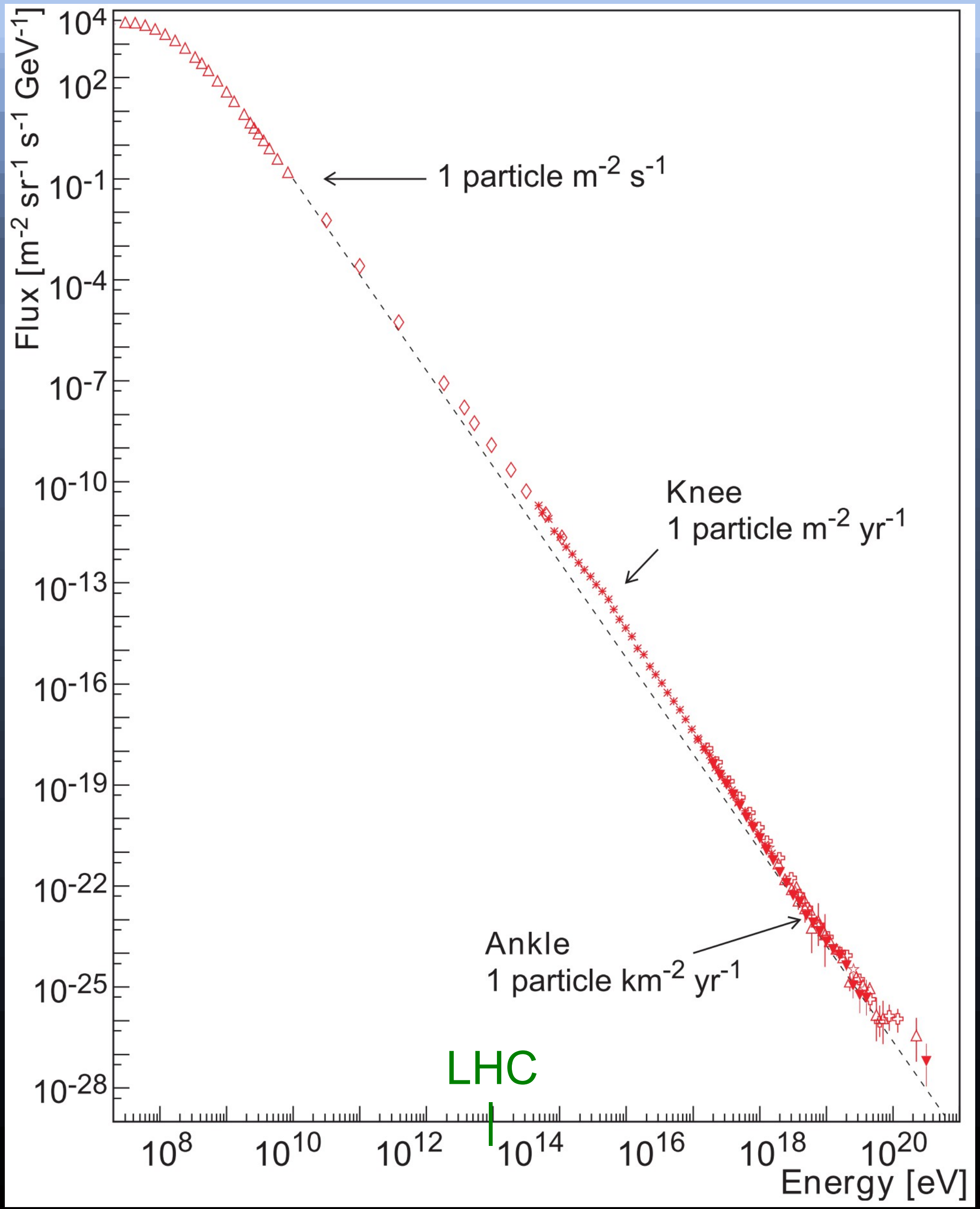
The Universe as a particle physics lab

There is astrophysical objects that manage to accelerate charged particles to energies far beyond those reachable by human-made instruments.

What kind of objects?

What mechanisms?
(non thermal processes)

How can they reach such high energies?



Acceleration mechanisms

The probably most common mechanism is "First order Fermi acceleration" in shock waves (Fermi ~1949).

Energy gain per cycle is proportional to Energy

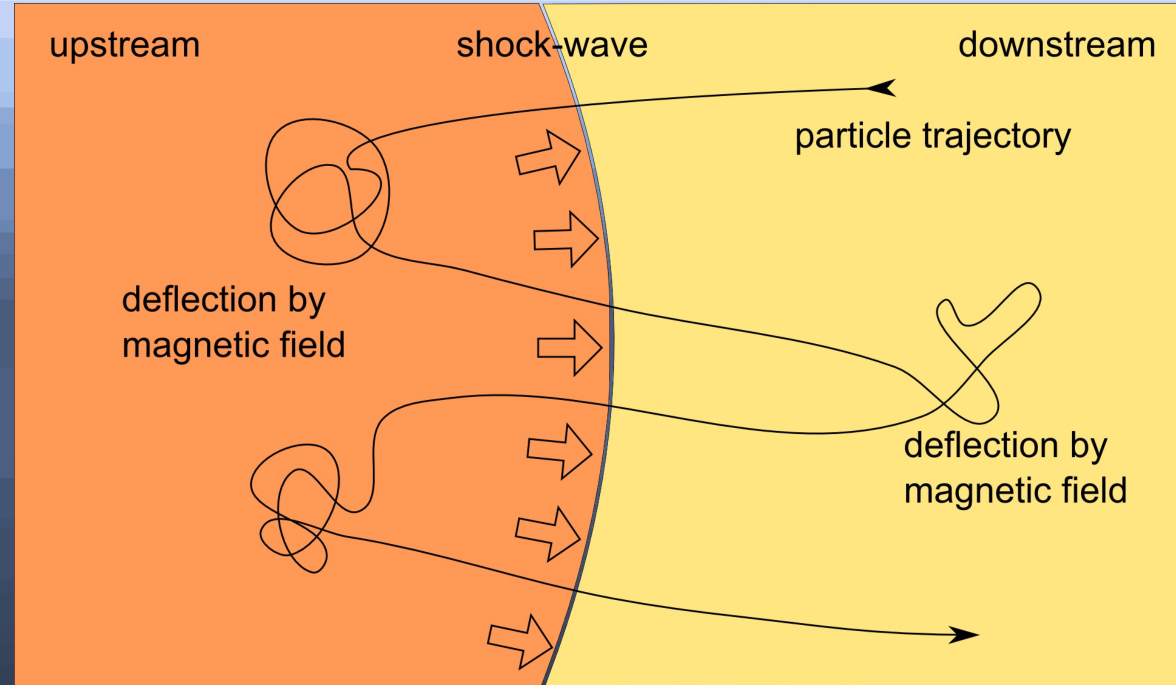
$$\Delta E = \epsilon E$$

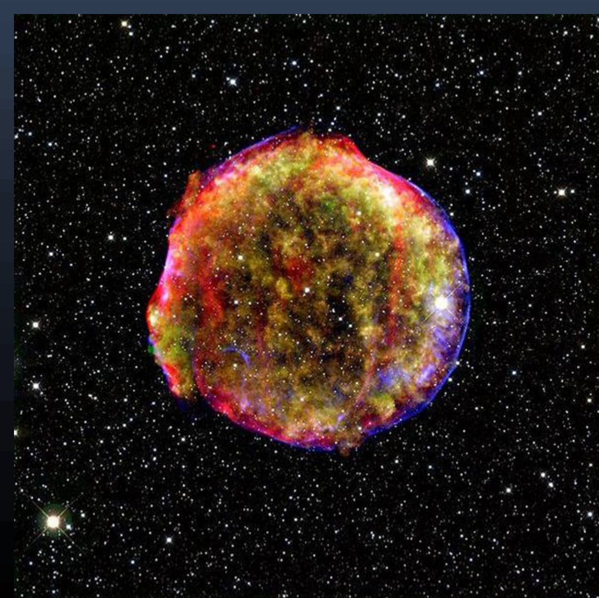
Particle escapes with certain probability

$$N_{n+1} = (1 - P_e) N_n$$

Proper calculation results in a power-law

$$N(E) = N_0 e^{\gamma}, \quad \gamma \approx -2$$





Acceleration mechanisms

Spatial extension and magnetic field strength constrain the maximal accessible energy

The so-called “Hillas Plot” shows potential sources of cosmic rays.

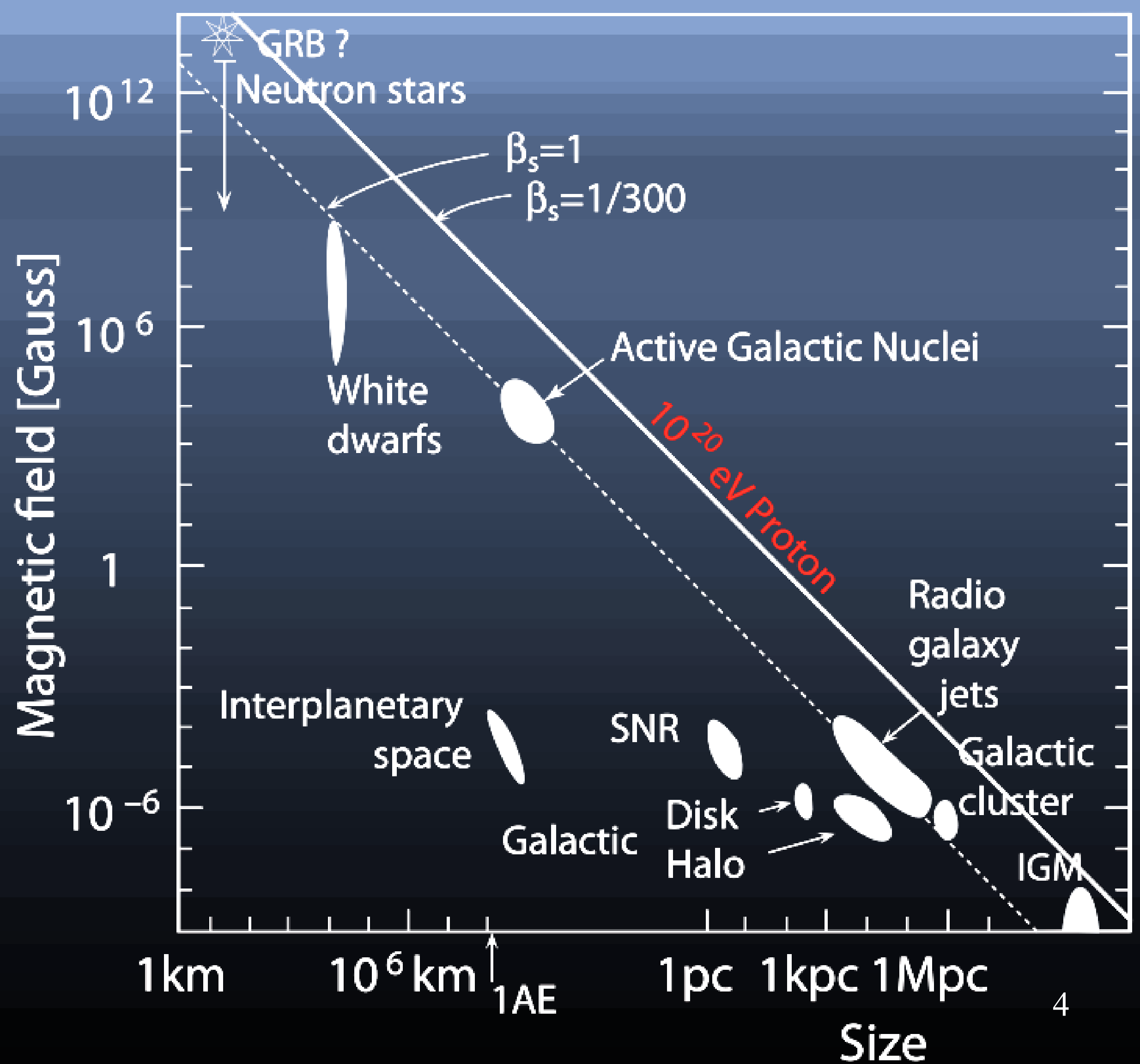
$$E_{max} \propto \beta_s \cdot z \cdot B \cdot L$$

$\beta_s = \frac{v_S}{c}$, velocity of the shock-wave

z, charge of the particle

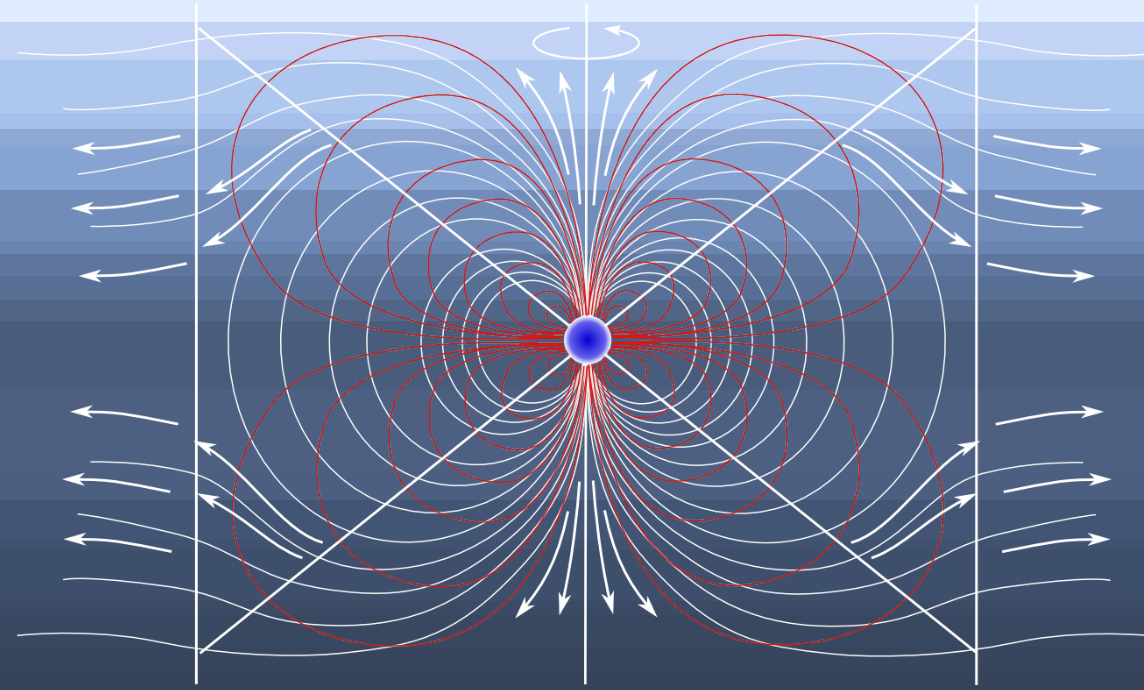
B, magnetic flux density

L, size of the accelerator



Acceleration mechanisms

There is also objects like Pulsars (rotating/radiating Neutron Stars), where other acceleration mechanisms are at work



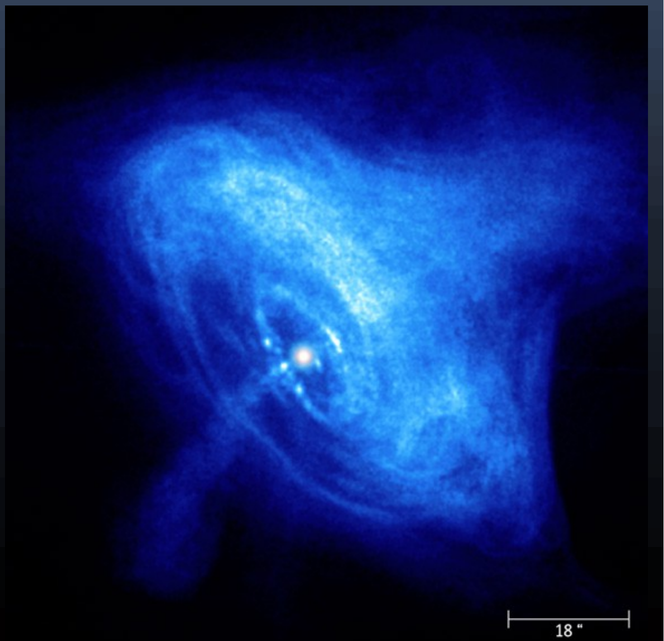
Conductive sphere in strong magnetic field

e+/e- are accelerated along magnetic field lines by induced electric field

Cannot move perpendicular due to strong magnetic field

Need vacuum gap for long enough free path

e+/e- emit curvature radiation



Electromagnetic radiation as probe

Charge is needed for acceleration

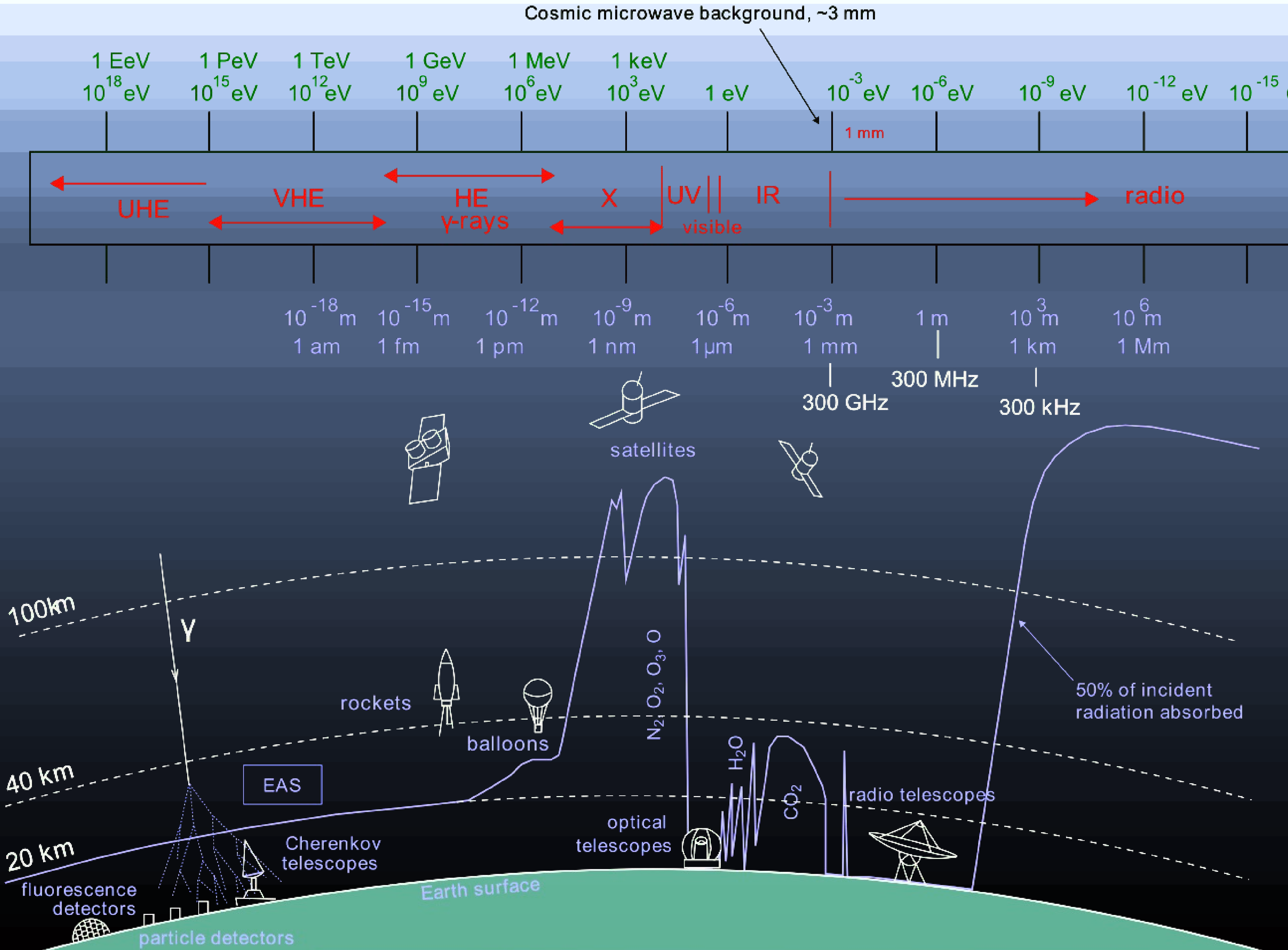
However, charged particles are deflected by magnetic fields all over the Universe and their origin cannot be reconstructed

But they emit electromagnetic radiation over a large spectral range

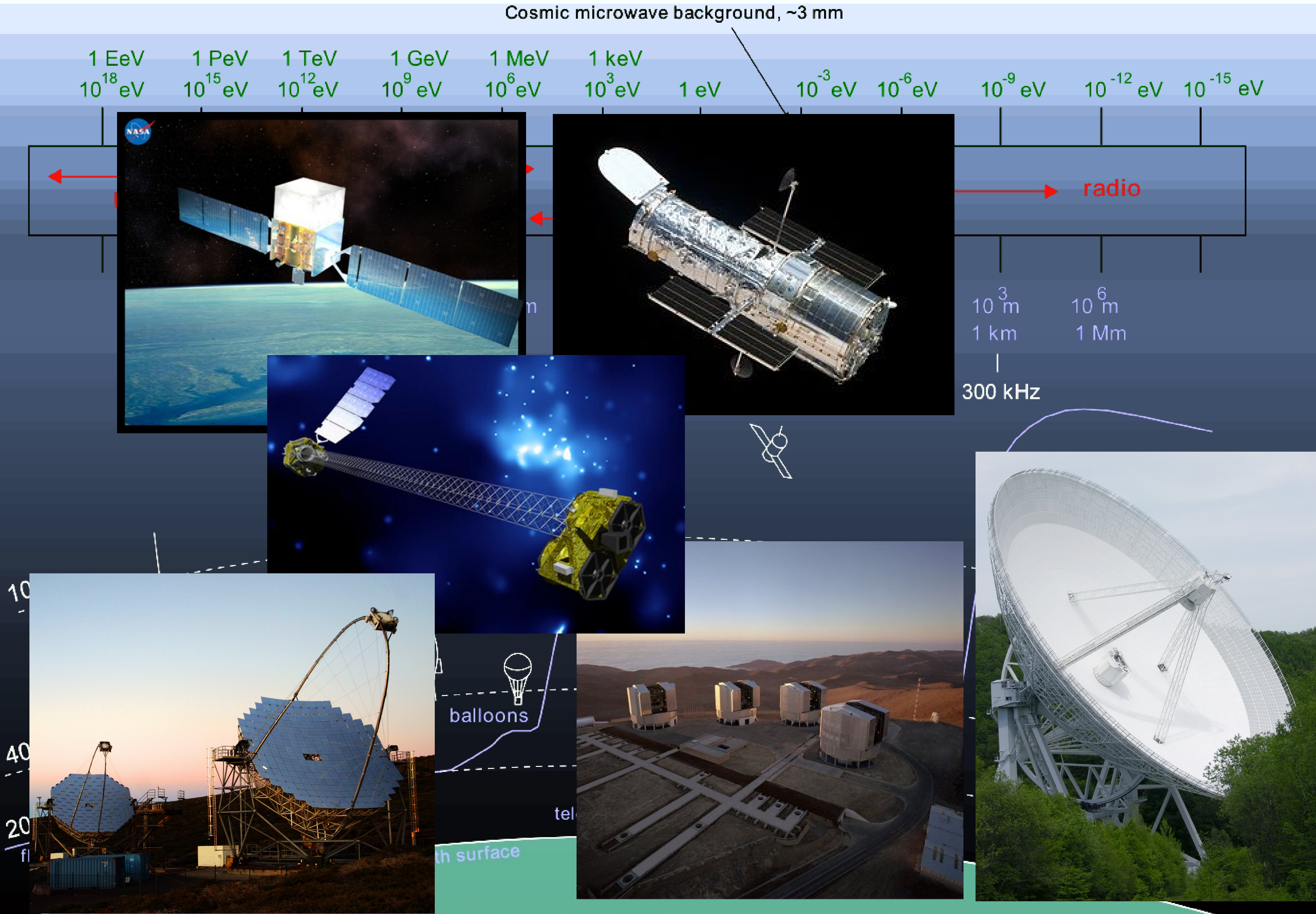
Radiation mechanisms are:

- Synchrotron radiation
- Inverse Compton scattering
- Curvature radiation
- $\pi 0$ decay from hadronic interactions

Electromagnetic radiation as probe



Different detection techniques for different energies



Different detection techniques for different energies

- Some parts of the electromagnetic spectrum are directly accessible (mainly Radio, Optical and some near IR)

- Other wavelengths demand for going to space (microwave, IR, X-ray, Gamma)

- For X-ray it is still possible to build optics (Chandra, NuSTAR)

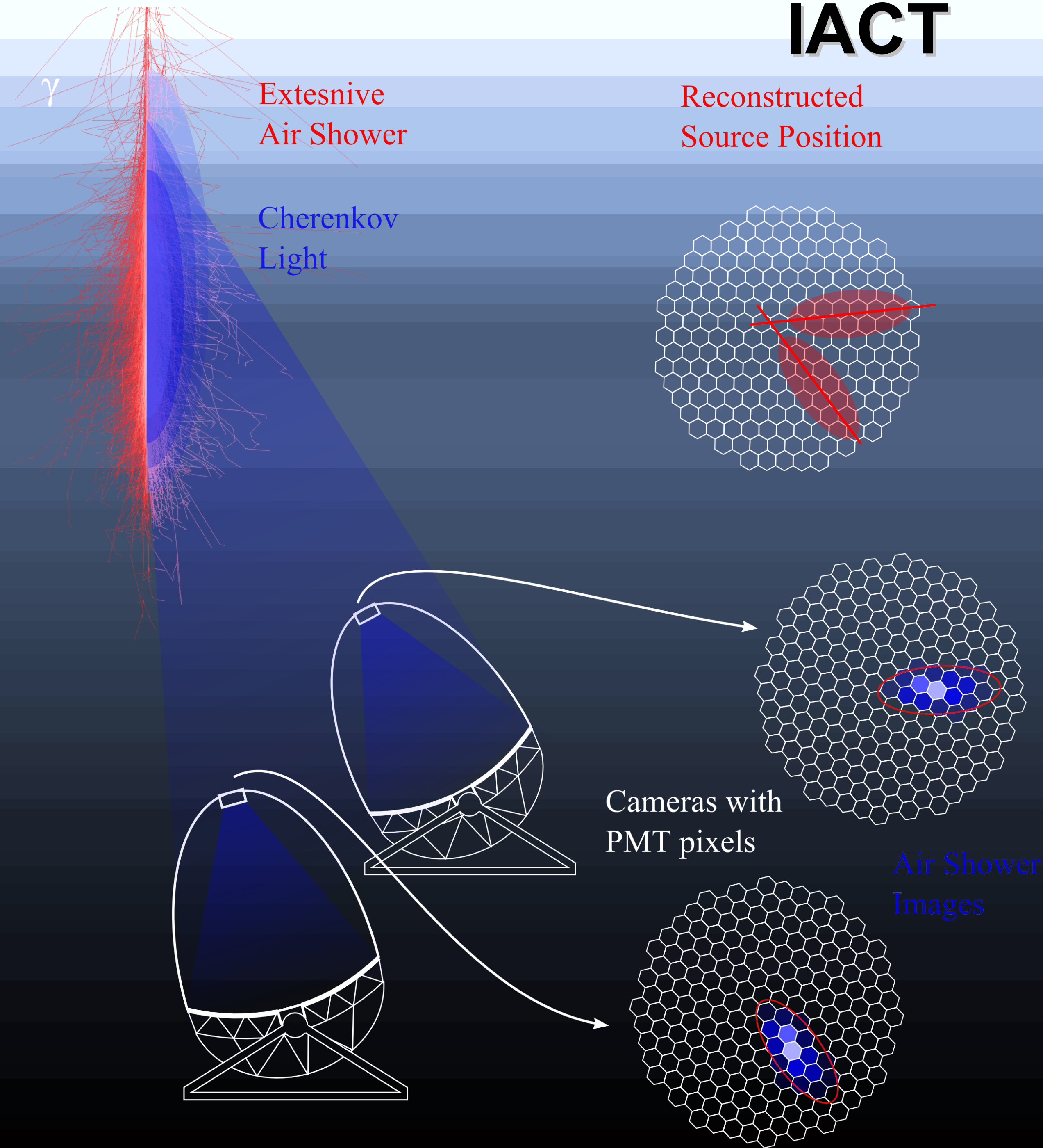
- Gamma-rays are detected with trackers and calorimeters like in particle physics experiments

- For VHE-Gamma radiation one needs:

  - bigger calorimeter
  - larger collection areas

- Not anymore possible in space

Imaging Airshower Cherenkov Technique IACT



Air serves as Calorimeter

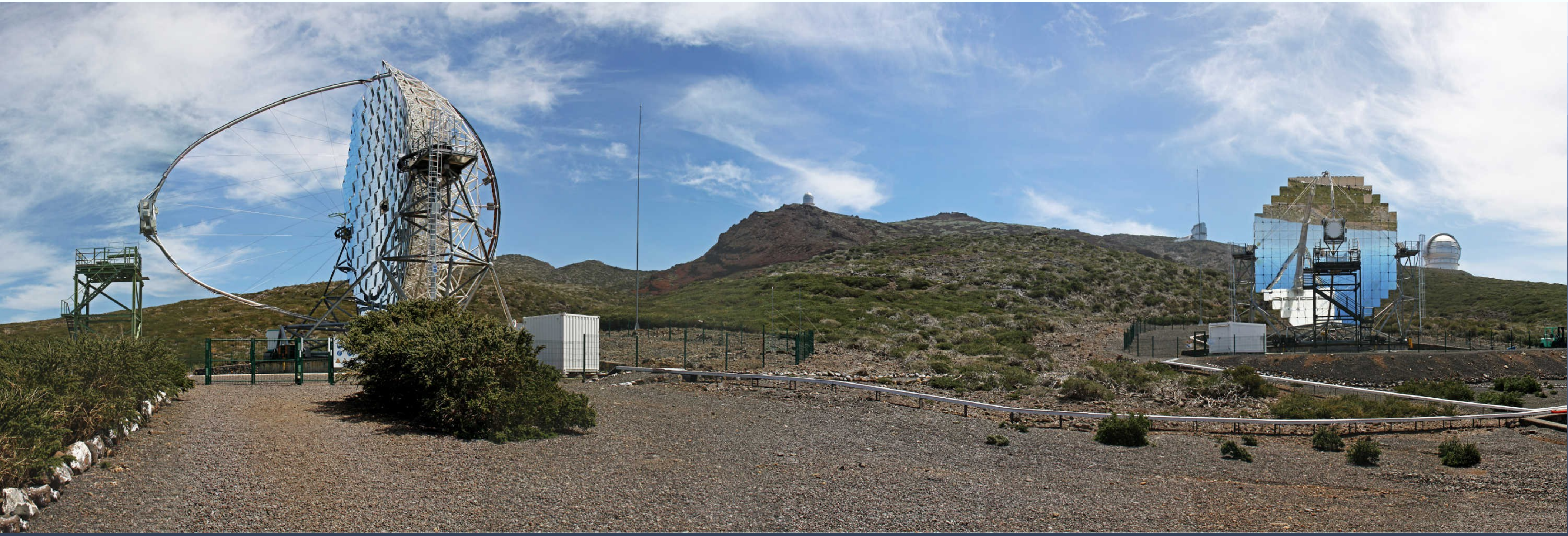
Huge detection areas
~1E5 m²

Direction reconstruction via image parametrization and stereo observations

Cherenkov light flashes are ultra fast (~3ns) and very faint phenomenon
(1 photon/m² at low energies)

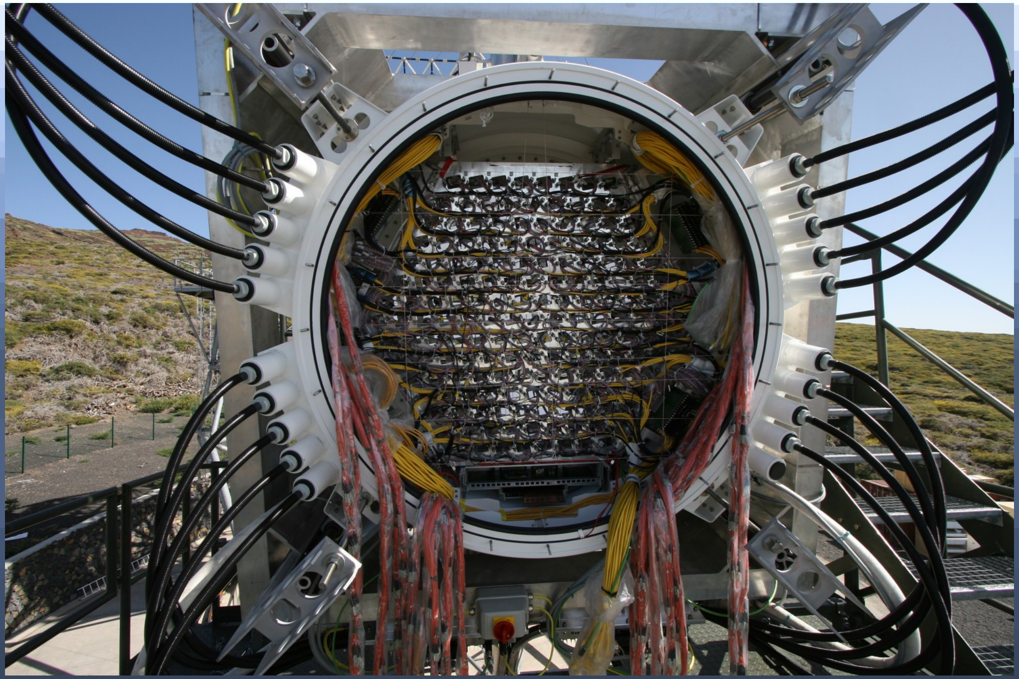
Using photomultiplier cameras and selective triggering

The Major Atmospheric Gamma Imaging Cherenkov Telescopes



- two 17m diameter instruments with only one optical element
- located at 2225m a.s.l. on the Roque de los Muchachos on La Palma
- overall mirror shape is parabolic to conserve arrival times
- 964 0.5m x 0.5m (M1) 247 1m x 1m spherical mirror facets
- lightweight structure from carbon fiber tubes for fast movement

The cameras



- 1039 photomultiplier pixels using Winston cones for optimizing acceptance angle and fill factor

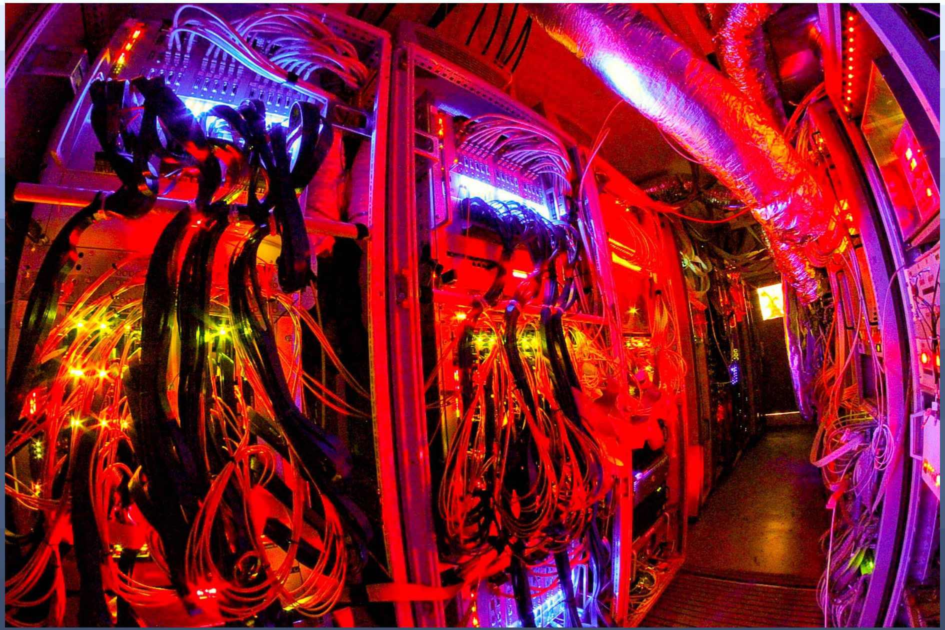
- signal is pre-amplified and transformed into a laser pulse for transmission to the counting house for triggering and digitization via optical fiber

- camera also housed the HV supply and cooling for the detectors/electronics

Trigger and readout

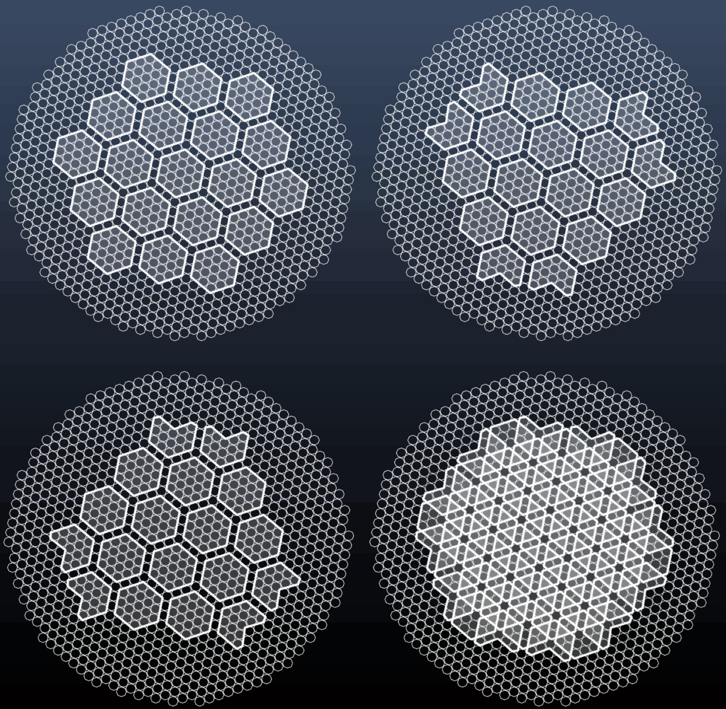
The telescope is equipped with two different trigger systems:

- digital 3 / 4 n.n. digital trigger
- analog sum trigger

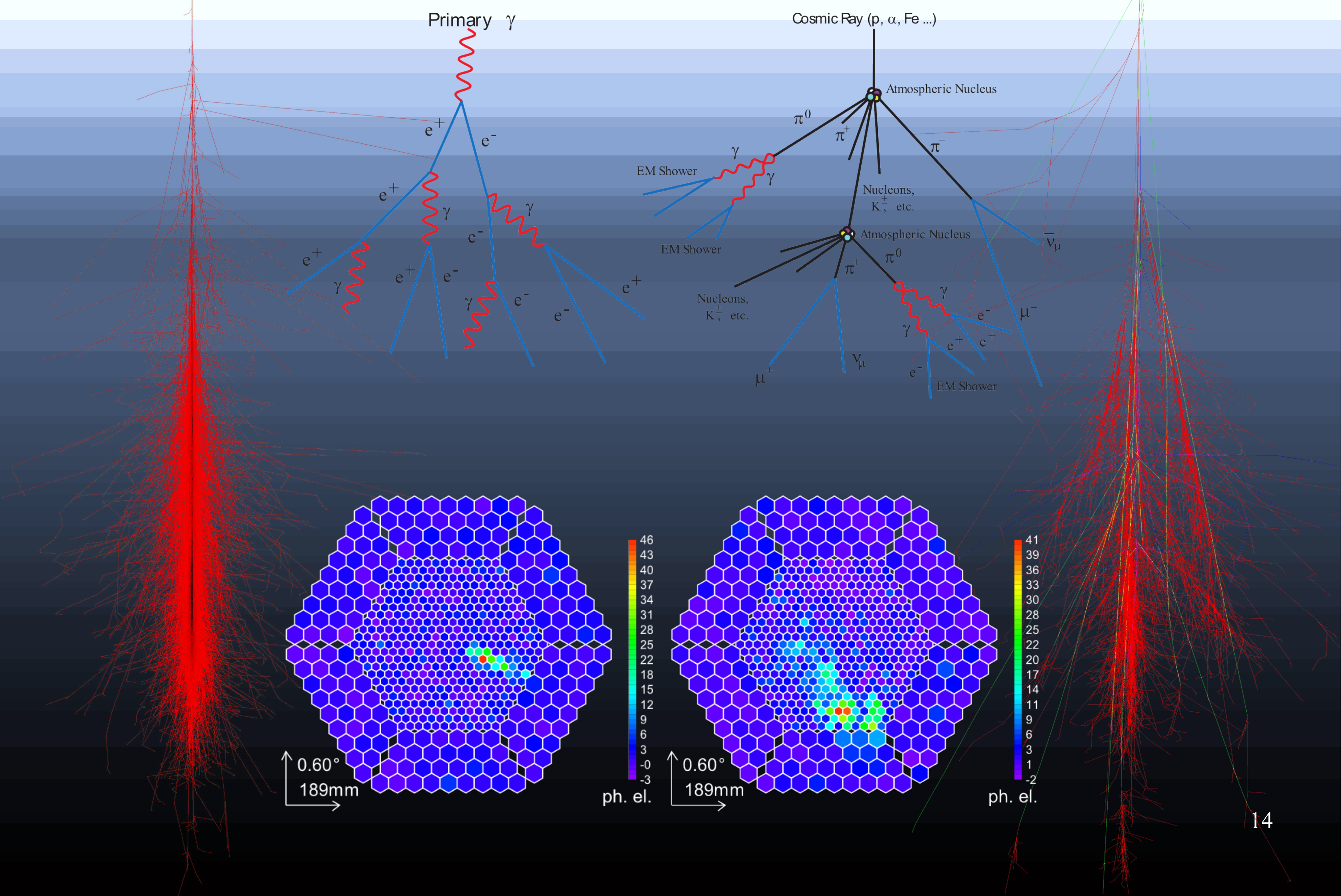


The digitization is done using DRS4 analog ring-buffers:

- signal is stored on a chain of capacitors with 2GHz sampling rate
- the sampling is interrupted if a trigger occurs and read out at a lower frequency
- fast readout of many channels at comparably low cost



EM / hadron separation



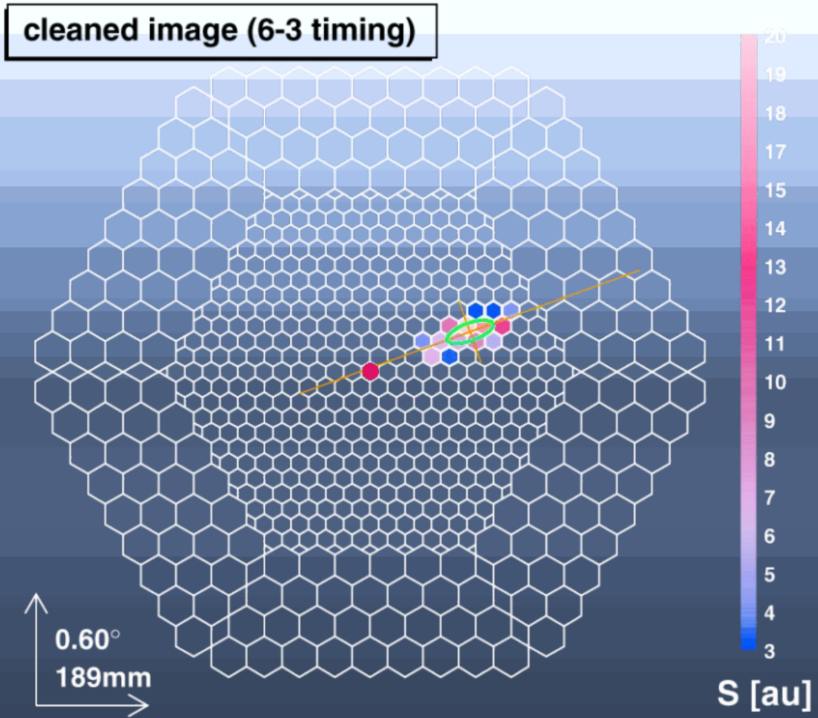
Data analysis

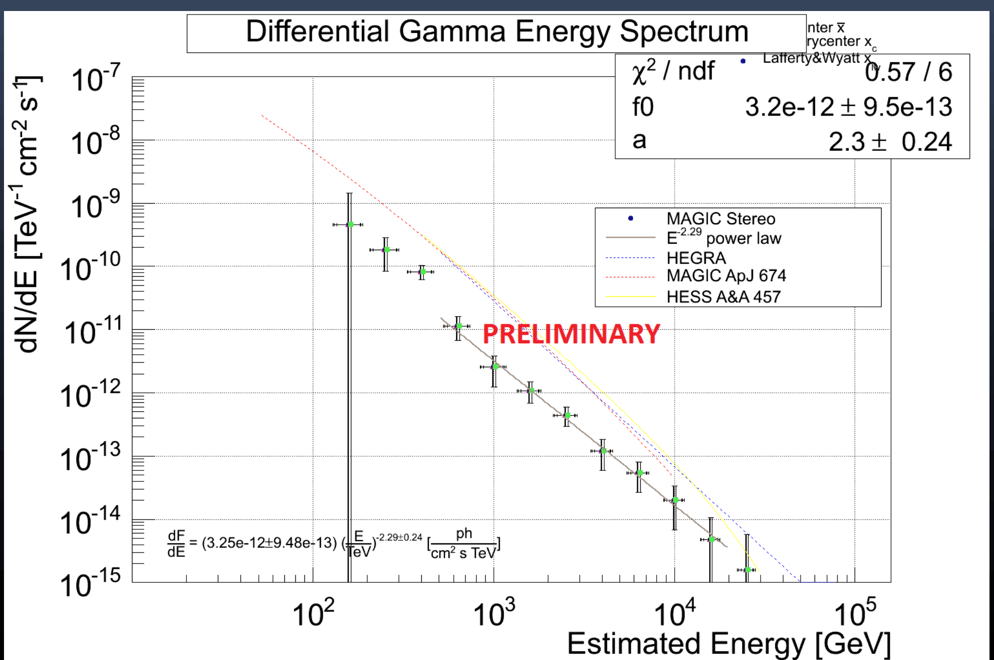
Image is first cleaned to reduce the effect of background light

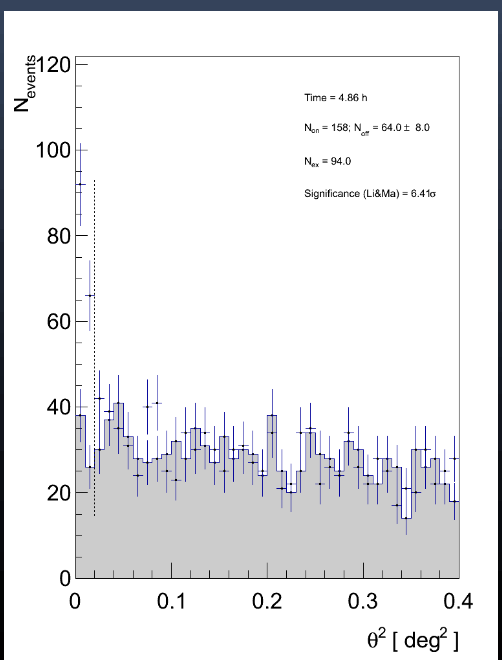
Then image is parametrized. Image parameters are: length, width, size, angle of fitted ellipse as well as timing and number of islands

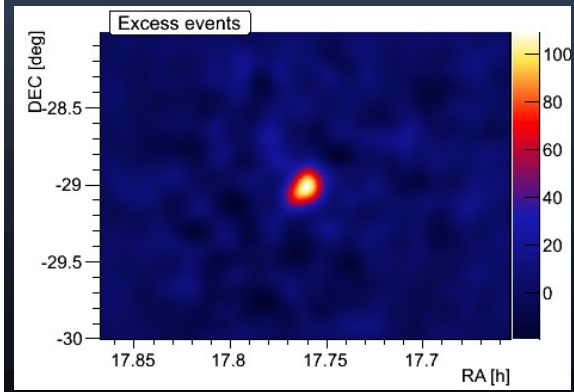
Random forests are trained wit MC data for γ-hadron separation and energy estimation

There is always background data subtracted from the signal in order to determine the excess events





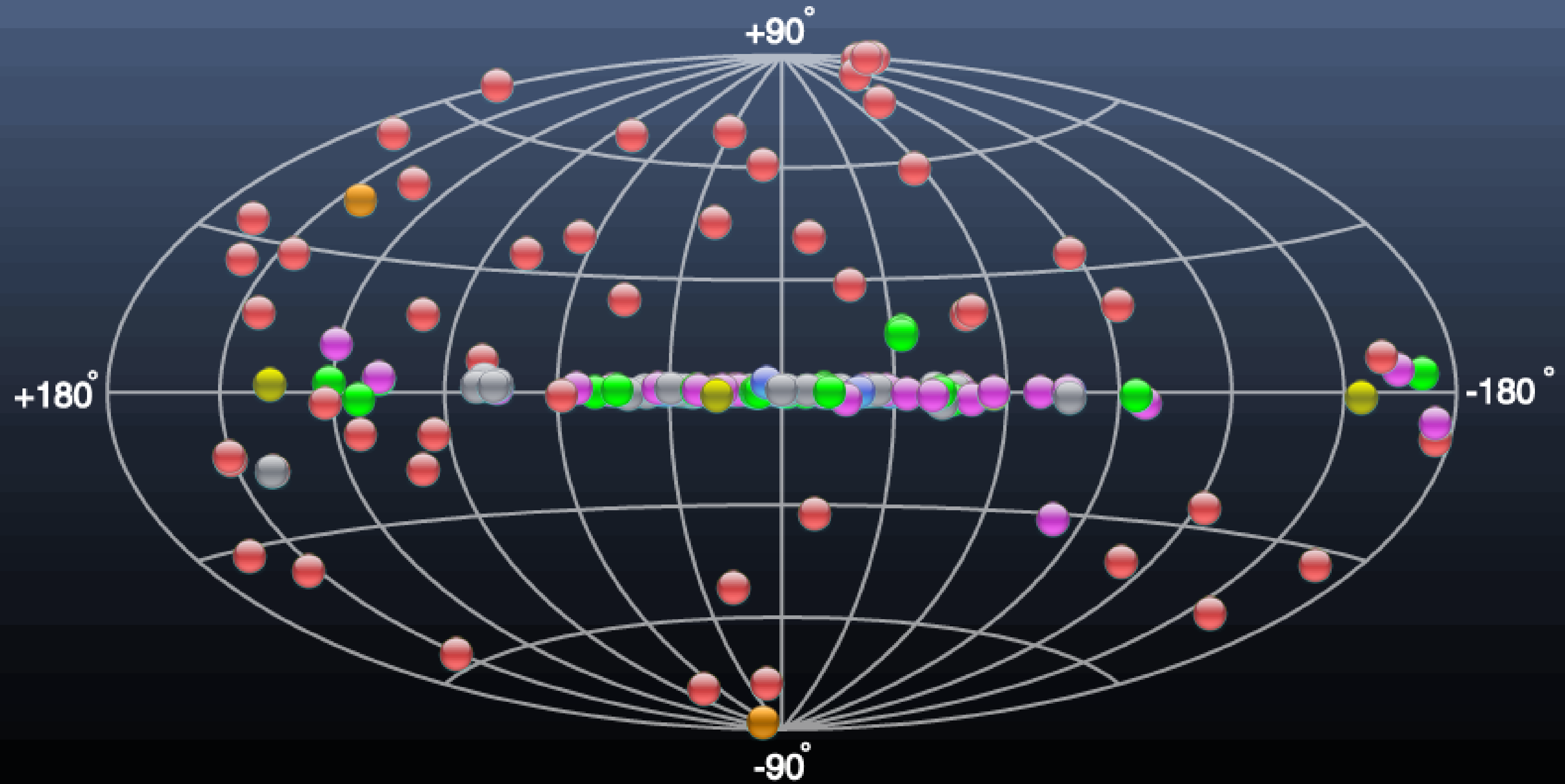




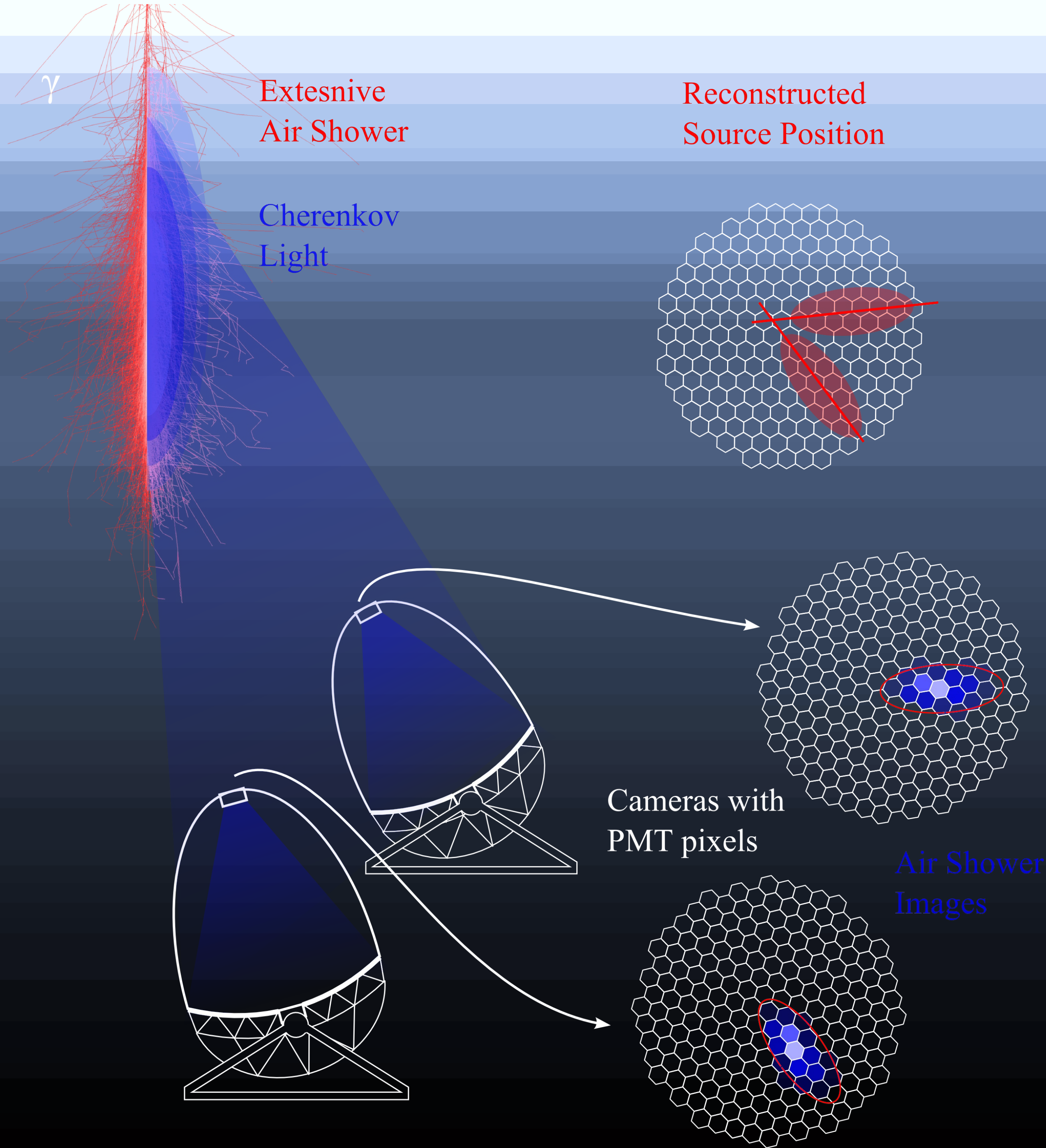
Sources detected with IACTs

Today over 130 sources of VHE-gamma radiation

Red: AGN
Pink: PWN
Orange: Starburst Galaxies
Green: Shell type SNR
Yellow: Gamma Ray Binary



The importance of atmosphric conditions



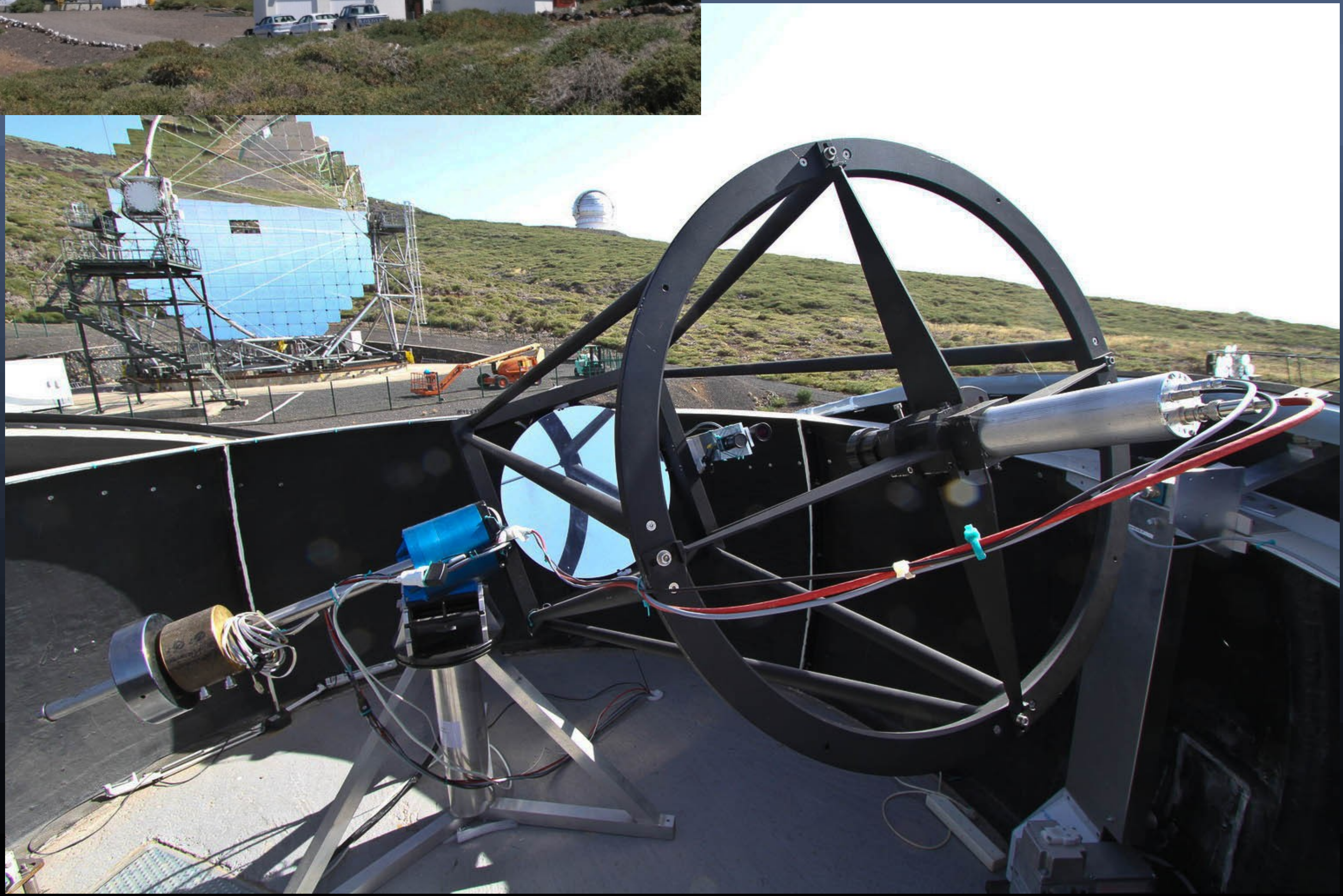
Cherenkov light is emitted on different altitudes

Weather conditions influencing the transparency of the atmosphere are very important for our systematics

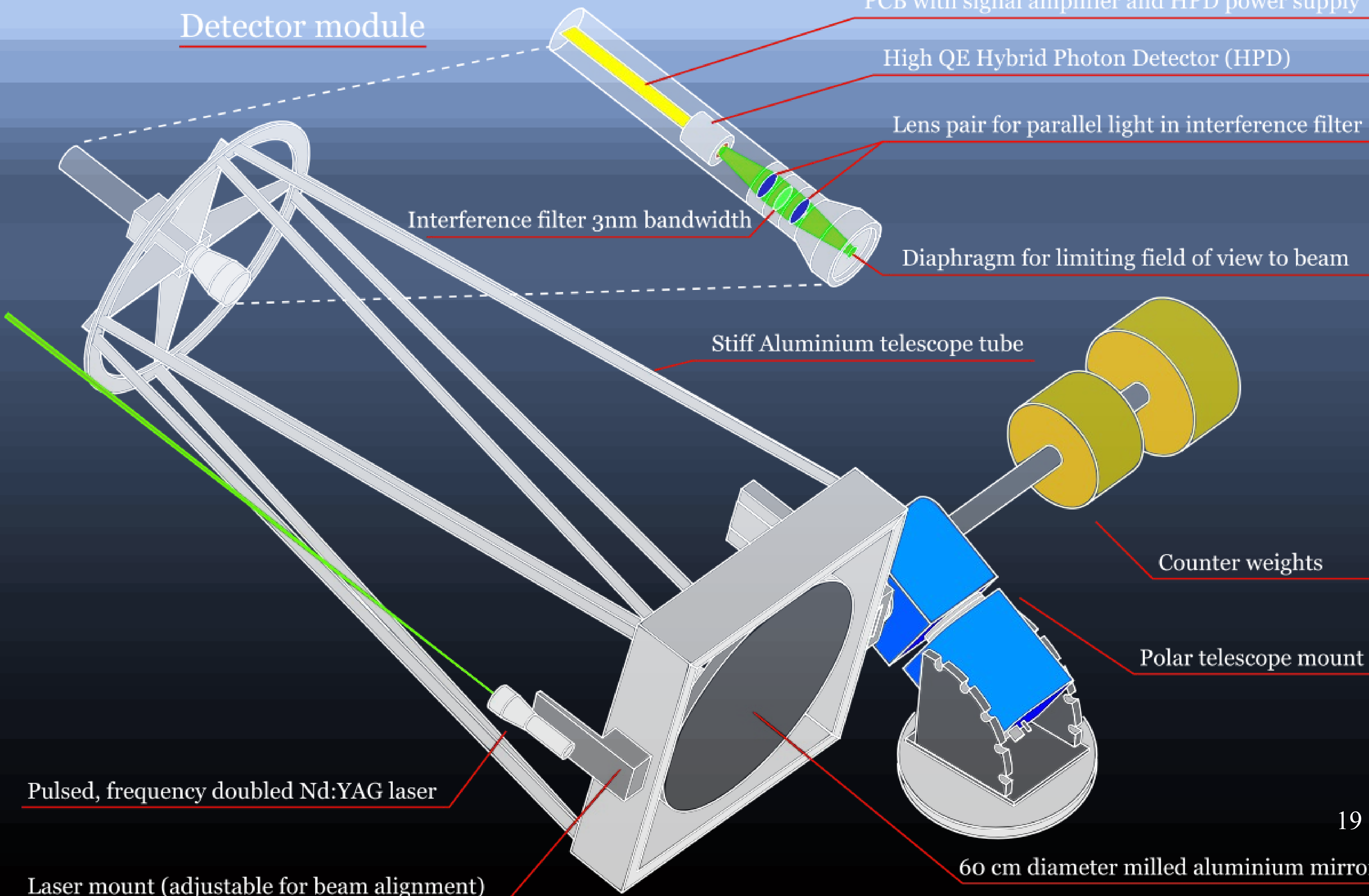
Need real-time information about the differential atmospheric transmission

LIDAR can provide such information!

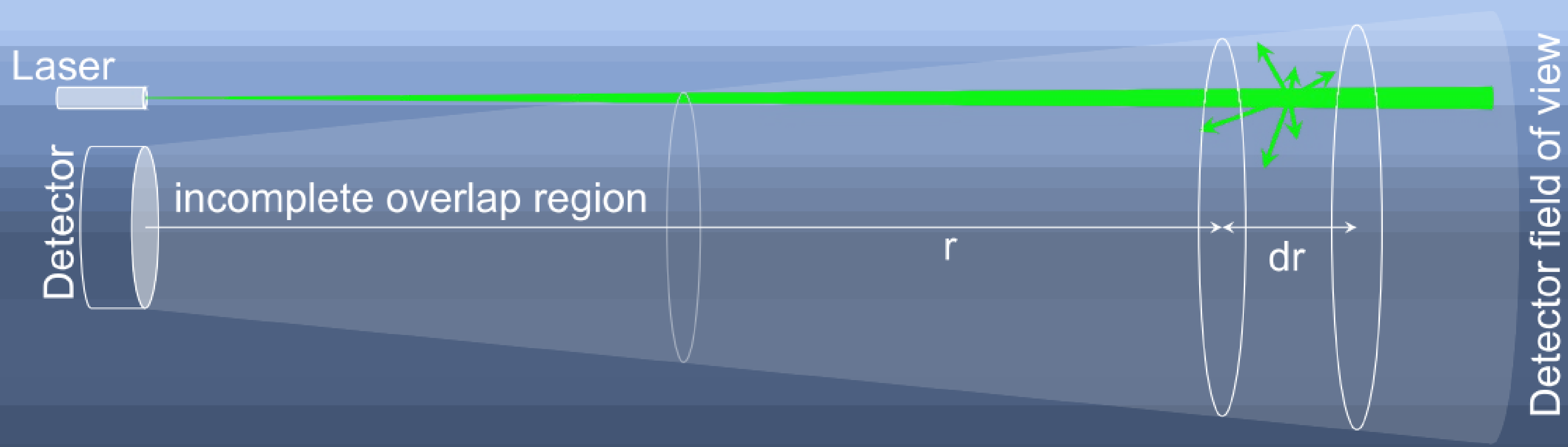
The MAGIC LIDAR system



The MAGIC LIDAR system



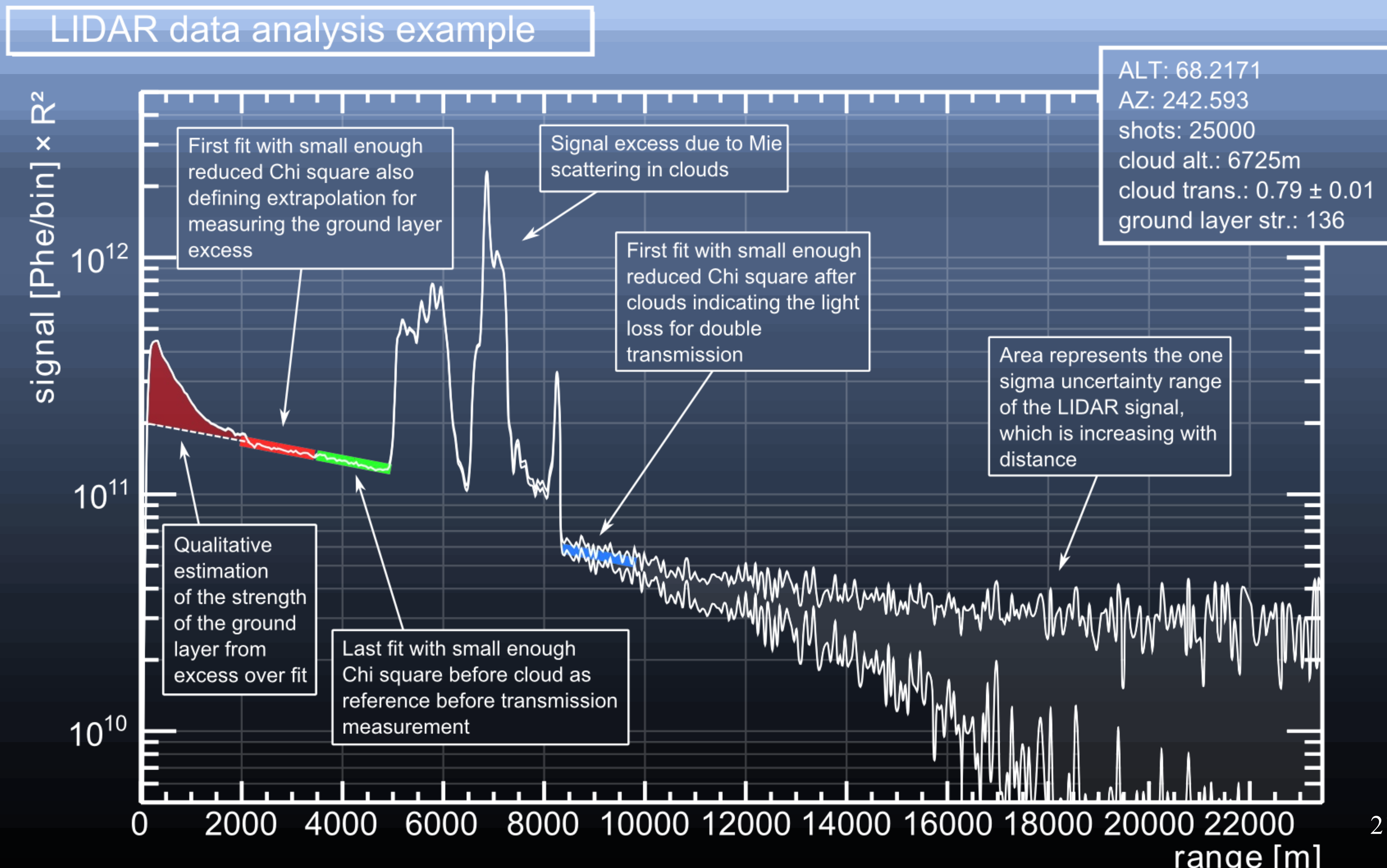
LIDAR (Light Detection And Ranging)



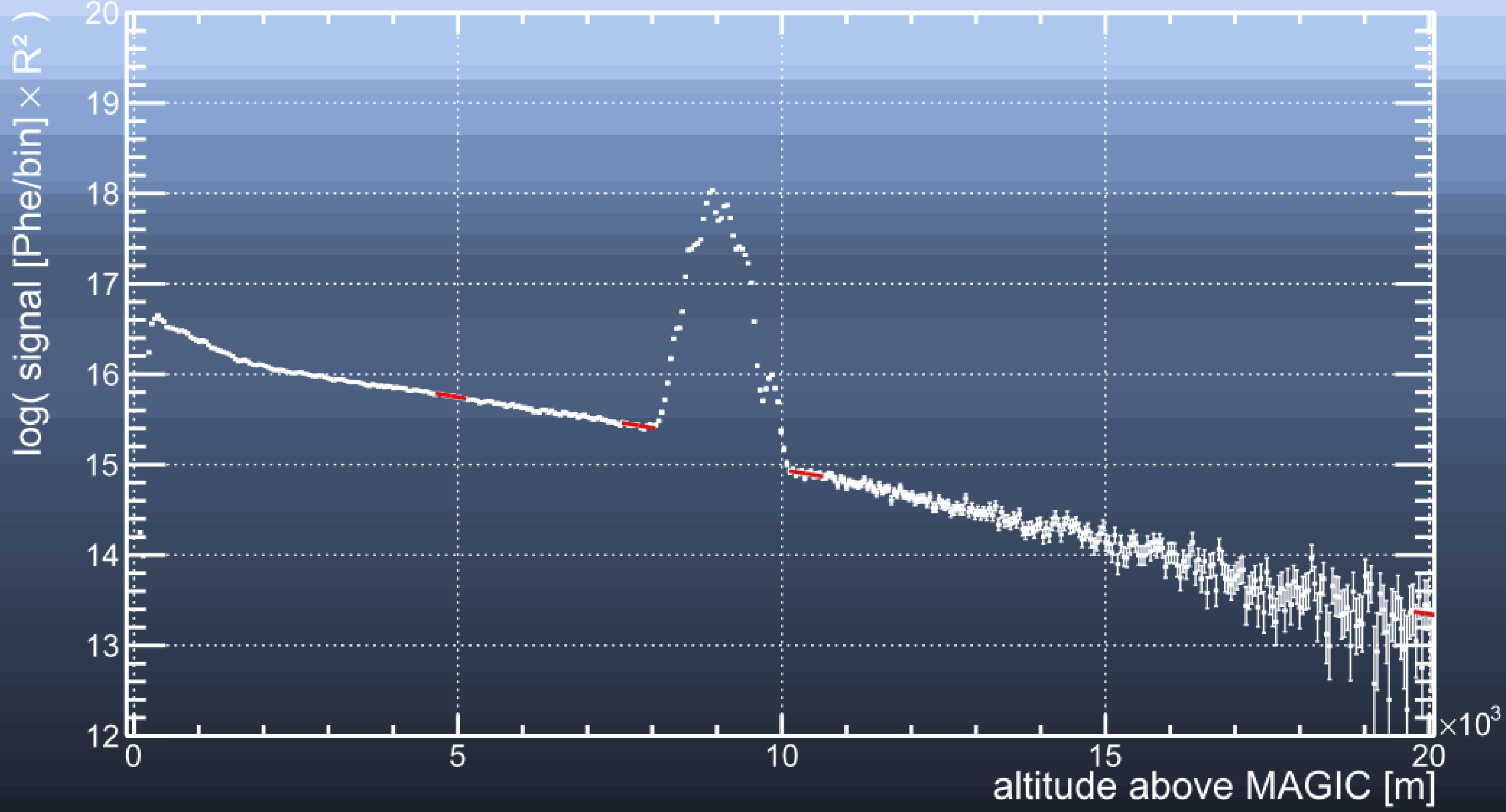
$$dN(r) = N_0 \; C \; G(r) \; \frac{A}{r^2} \; \beta(r) dr \; \exp\left(-2 \int_0^r \sigma(r') dr'\right)$$

- N_0,$dN(r)$: photons: in laser pulse, in range bin
- C,$G(r)$: overall efficiency, overlap (laser-FOV) and focus effects
- $\frac{A}{r^2}$: solid angle (detector seen from location of scattering)
- $\beta(r)dr$: volume backscattering coefficient times range bin length
- $\exp\left(-2 \int_0^r \sigma(r') dr'\right)$ total attenuation on the way
- two unknown functions: $\beta(r)$ and $\sigma(r)$

Typical LIDAR signal

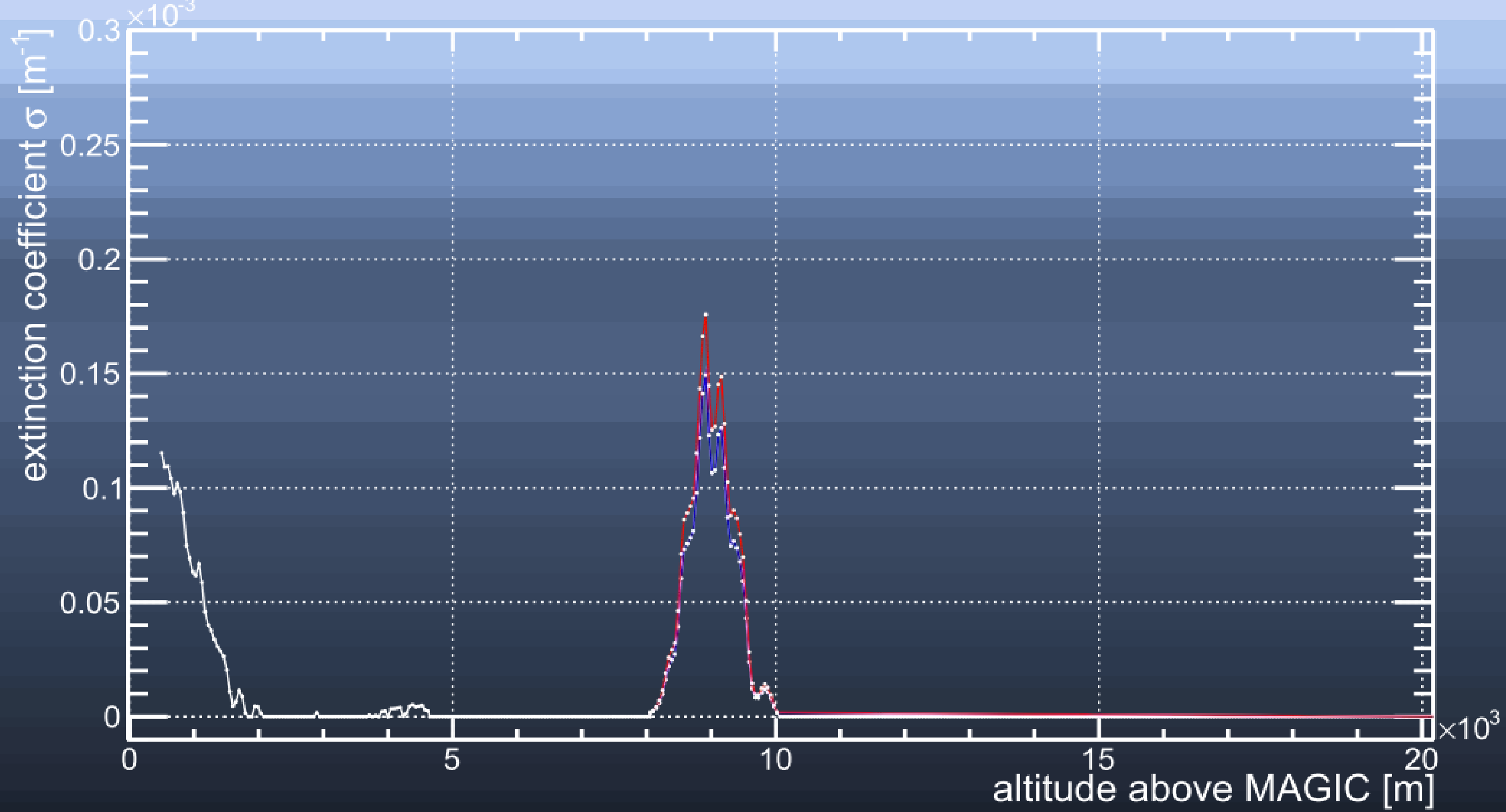


LIDAR data analysis



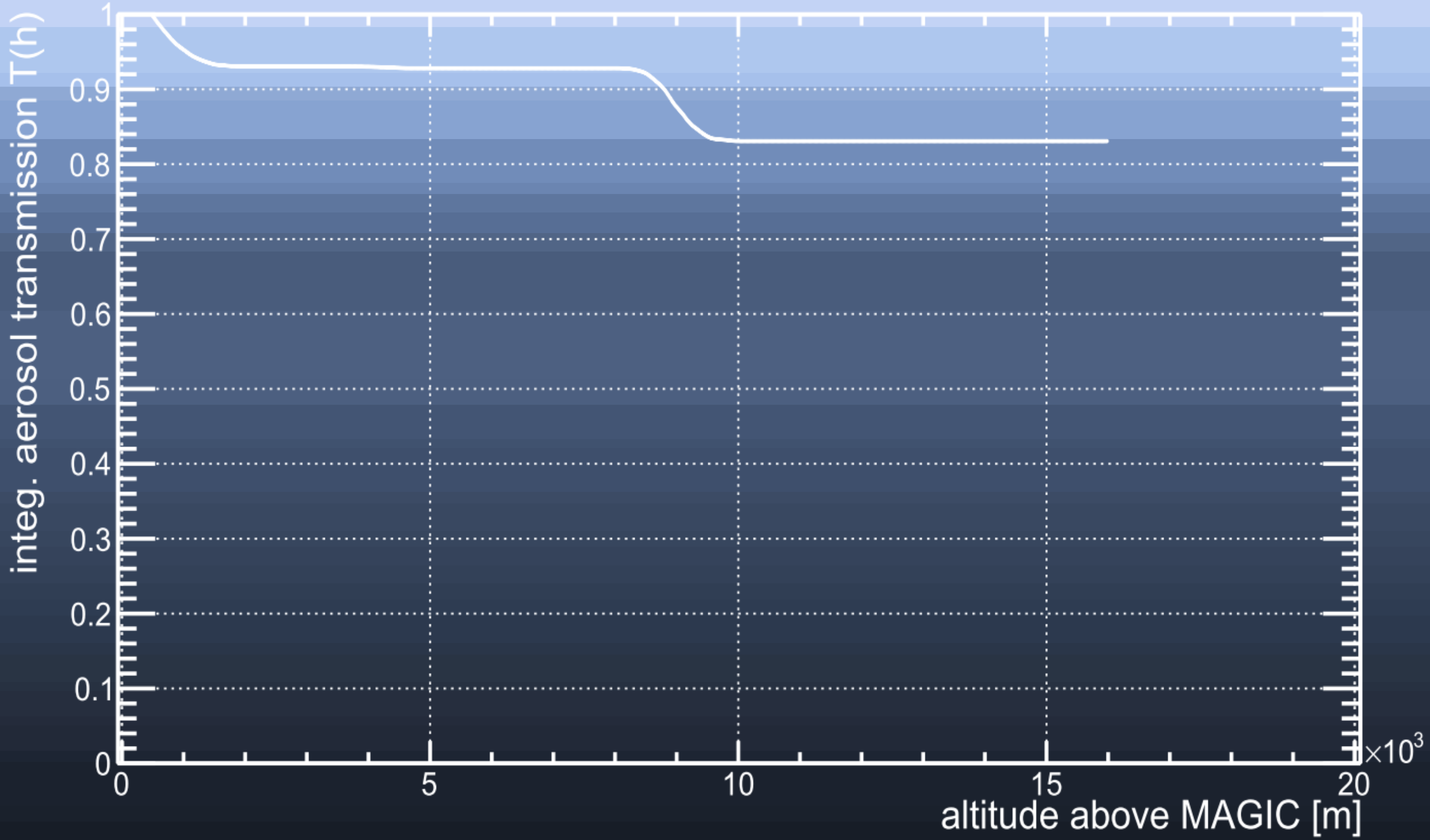
$$\sigma_a(h) = \frac{\sqrt{\frac{S_2}{S_1}}}{\int_{h_1}^{h_2} ex(h)\mathrm{d}h} \cdot ex(h)$$

LIDAR data analysis



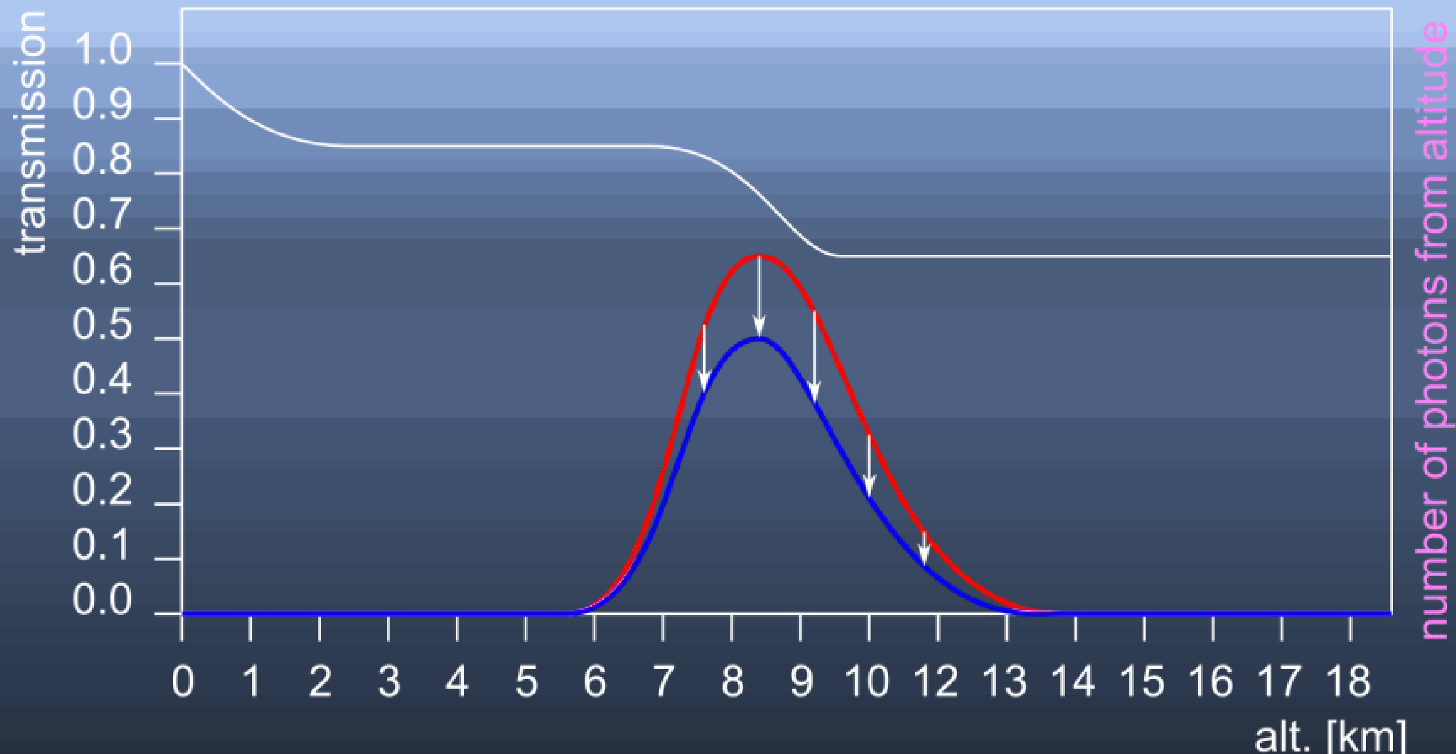
$$\sigma_a(h) = \frac{\sqrt{\frac{S_2}{S_1}}}{\int_{h_1}^{h_2} ex(h)\,\mathrm{d}h} \cdot ex(h)$$

LIDAR data analysis



$$T_a(h) = \int_{h_0}^{h} \sigma_a(h) \mathrm{d}h$$

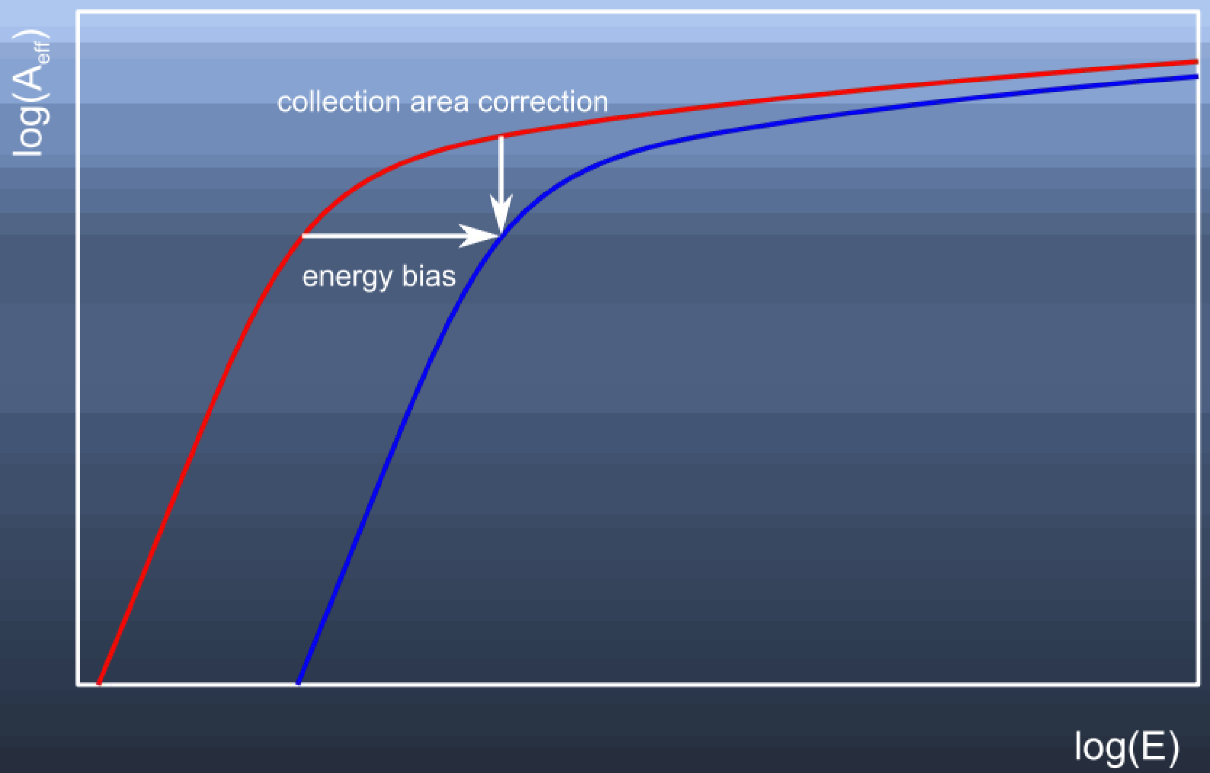
Event-wise energy correction for MAGIC



$$\overline{\tau} = \int_0^{h_{max}} \epsilon(h) \cdot T_a(h)\, \mathrm{d}h$$

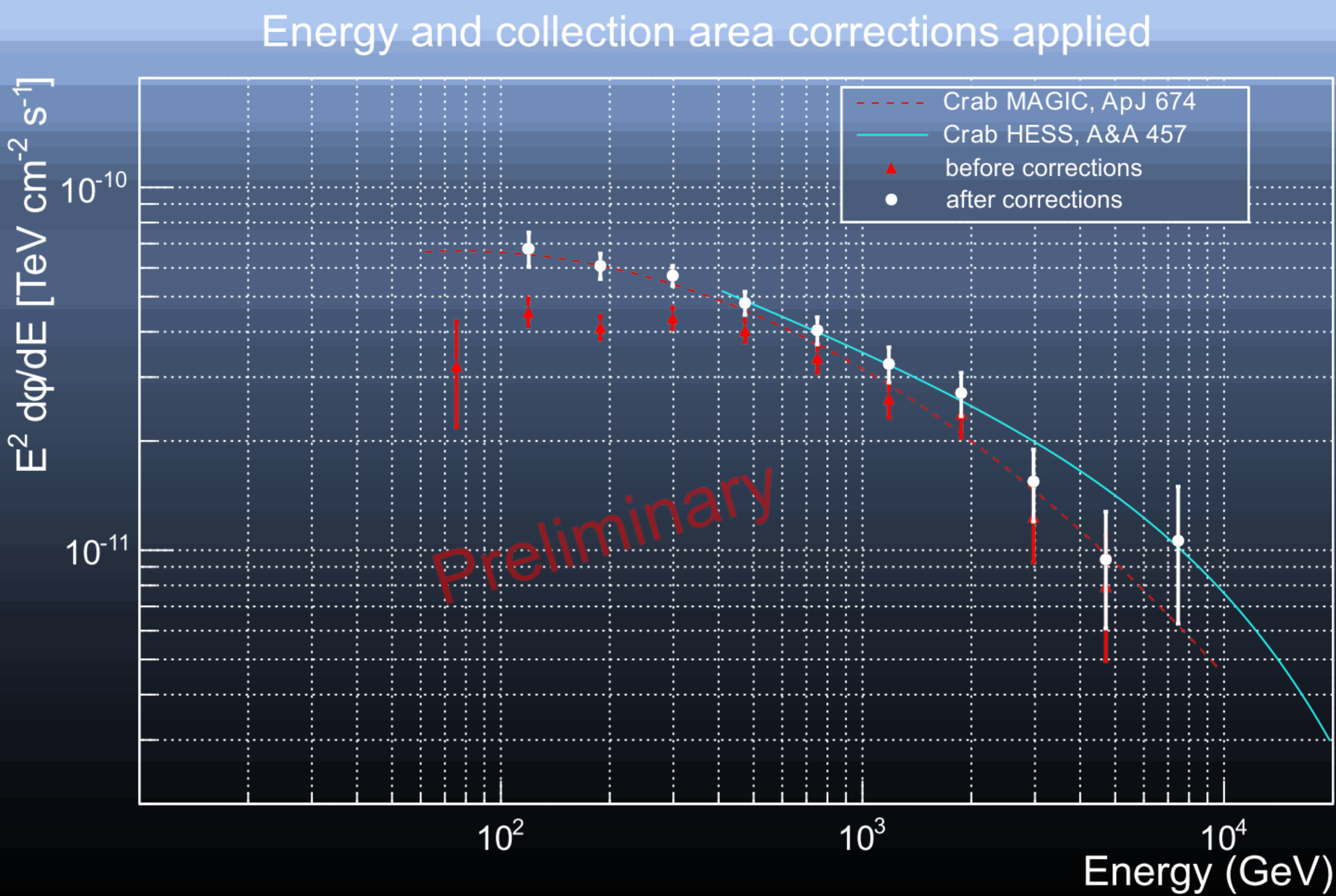
$$E_{true} = \frac{E_{est}}{\overline{\tau}}$$

Event-wise energy correction for MAGIC



- Wrongly reconstructed energy also leads to error in A_{eff}
- Event migrates to higher energy bin (Energy correction)
- A_{eff} for this bin is higher but real trigger efficiency is decreased
- Can assume that "An event that is affected by atmospheric extinction looks like an event of lower energy to the telescopes"

Event-wise energy correction for MAGIC



Summary and outloock

The MAGIC telescopes are still the largest Cherenkov telescopes working as a stereoscopic array

Covers a large spectral range in the VHE gamma regime including an overlap with space-borne telescopes

But the future is already approaching with CTA:
~ 50 telescopes with sizes from 8-24m diameter working as a stereoscopic array

Thanks for your attention!
Questions?