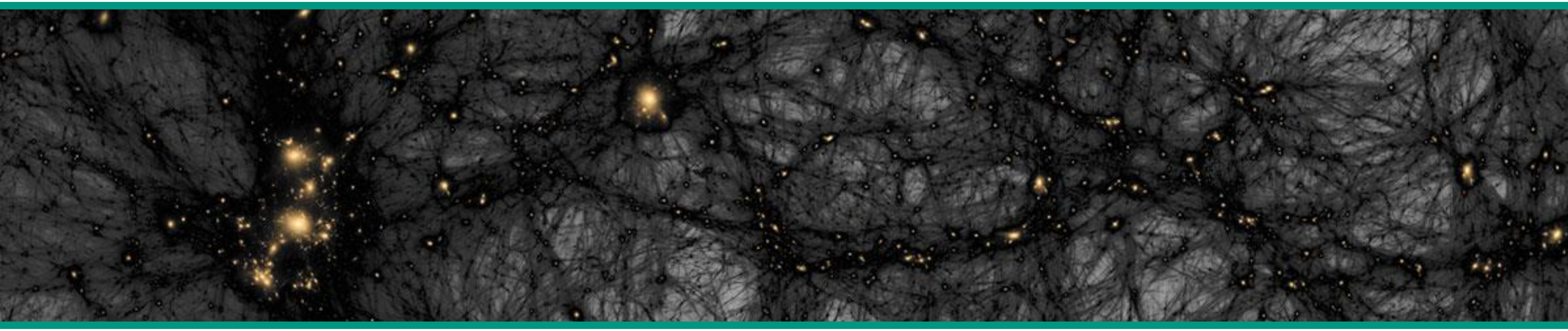
Astroparticle physics I – Dark Matter

WS22/23 Lecture 6 Nov. 17, 2022



Recap of Lecture 5

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- **Properties of Cosmic Rays: from galactic up to the UHECR-scale**

  - spectral features: ´**knee**´ - a change of power law index for protons ($E \sim 4\ PeV$) & iron nuclei $(E \sim 100\ PeV)$
  - galactic accelerators (**SNR**, pulsar wind nebula): quasi-isotropic
  - extra-galactic accelerators (**AGN**, radio galaxies …): hot spots for UHECRs
  - energy-density: efficiency for CR-acceleration of a few-% in case of SNRs
  - Fermi acceleration: repeated run through of outer shock front with β_s
    ⇨ results in power law distribution $\boldsymbol{N(E) \sim E^{-\gamma}}$ (index $\gamma \cong 2.7$)
  - Hillas formula: maximum energy $\boldsymbol{E_0 \sim \beta_s \cdot Z \cdot B \cdot L}$ $\beta_s: 0.03 \ldots 1$
  - galactic CR-propagation: Larmor radius R_L vs. galactic disk (´leaky box´)

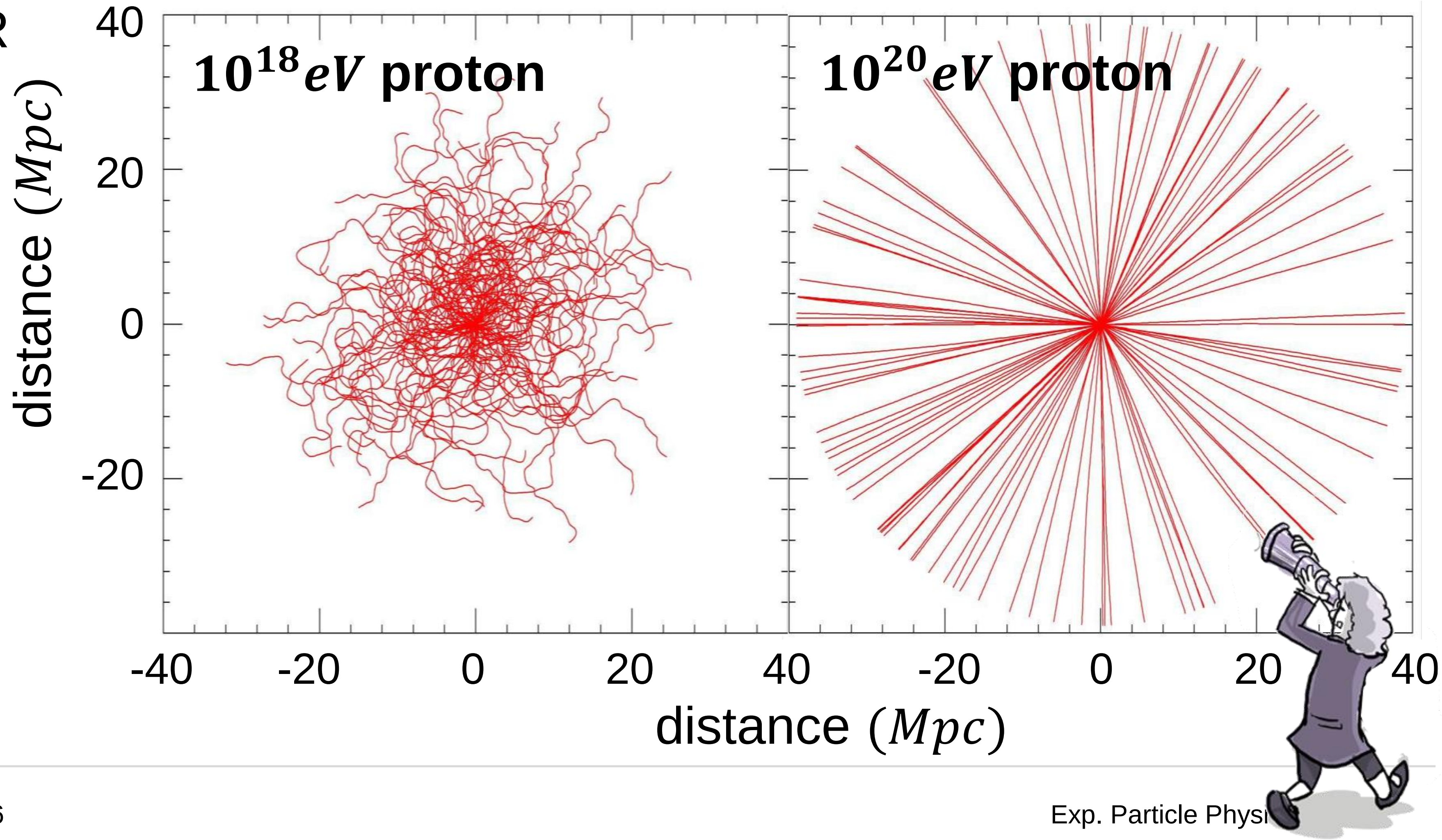
Proton astronomy: seeing wide and clear?!

- **Proton astronomy would be possible above $E \sim 10^{20}\ eV$**

- task: identifying UHECR sources, despite inter-galactic $B -$ fields

- MC-simulation of the propagation of $\boldsymbol{p}$ at UHECR energies in $B_{intergal.} \sim 10^{-9} G$

- but: CR nuclei at this E are deflected due to Z

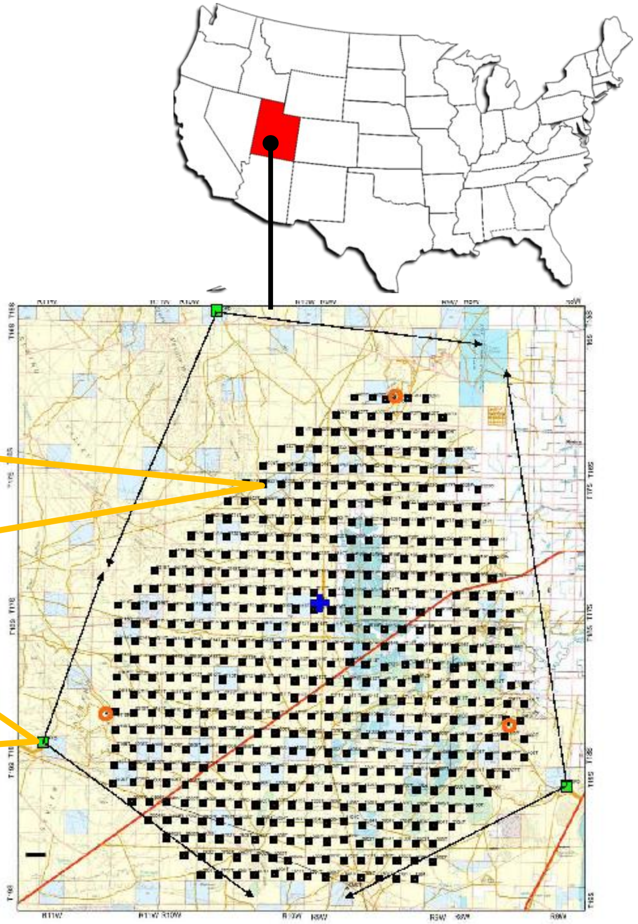


UHECR experiments: the Telescope Array (TA)

- **Investigating UHECRs at a site in the northern hemisphere (*nh*)**

  - site: Delta, Utah (US) – access to UHECR sources in *nh*

  $A = 700\ km^2$ large array with ´**hybrid technology**´



500 **scintillation detector** stations, $3\ m^2$ area each, distance $d = 1.2\ km$

3 **fluorescence telescope** stations, 12-14 mirrors & PMT systems each

UHECR experiments: Pierre Auger Observatory

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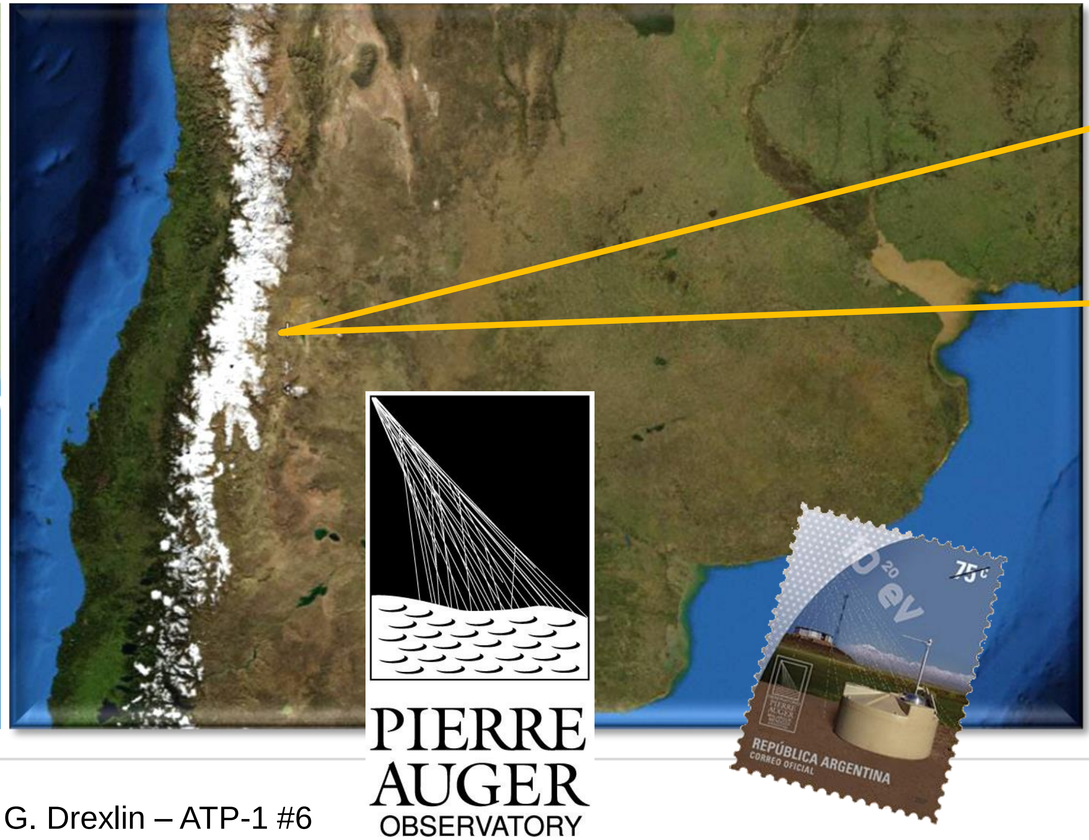
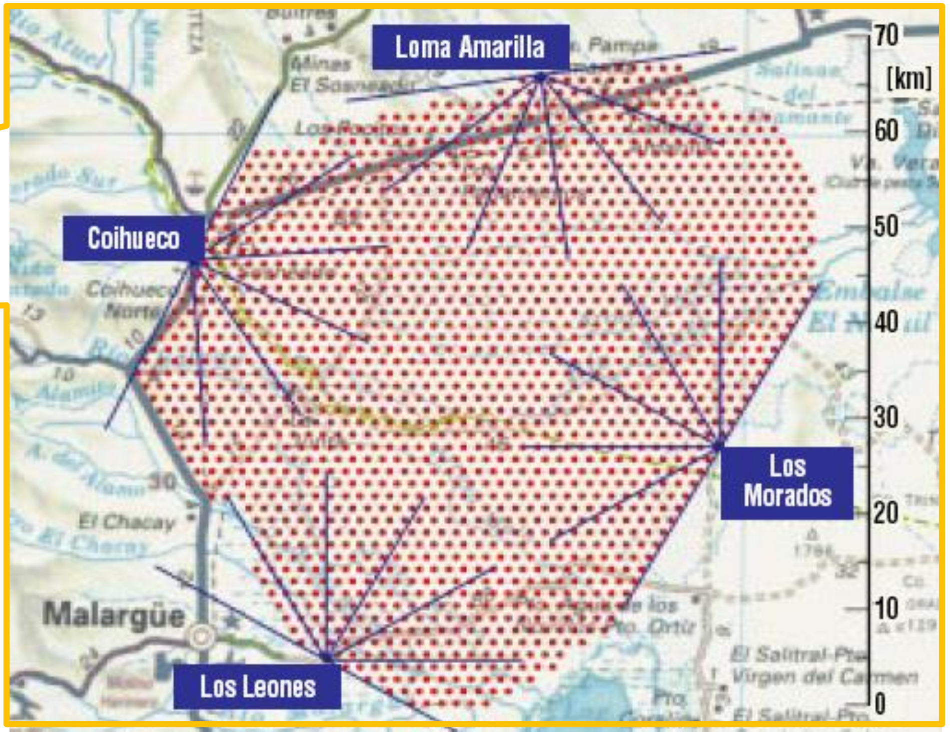
- **Investigating UHECRs at a site in the southern hemisphere (*sh*)**

  - site: Pampa Amarilla, Malargüe (Argentina) – access to UHECR sources in *sh*

  $A = 3000\ km^2$ large array with ´**hybrid technology**´





PIERRE AUGER OBSERVATORY

Pierre Auger Observatory: hybrid technology

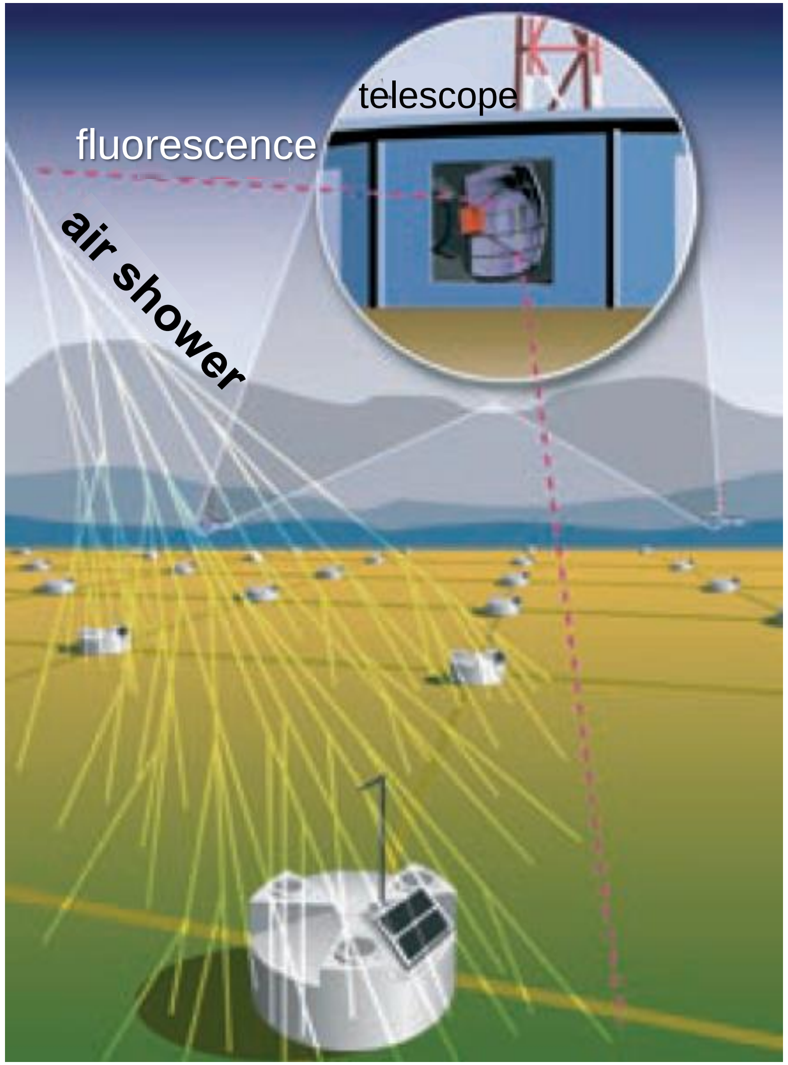
- **Surface Detector (SD) & Fluorescence Detector (FD)**

4 × 6 telescopes

elevated sites

$1600\ H_2O$ ´tanks´

sampling
in $d = 1.5\ km$



Pierre Auger Observatory: hybrid technology

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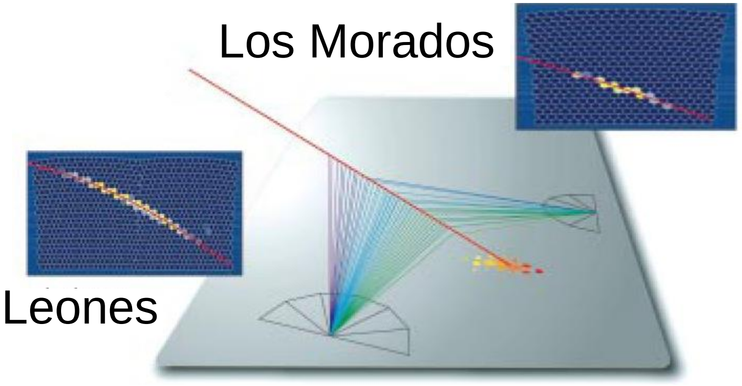
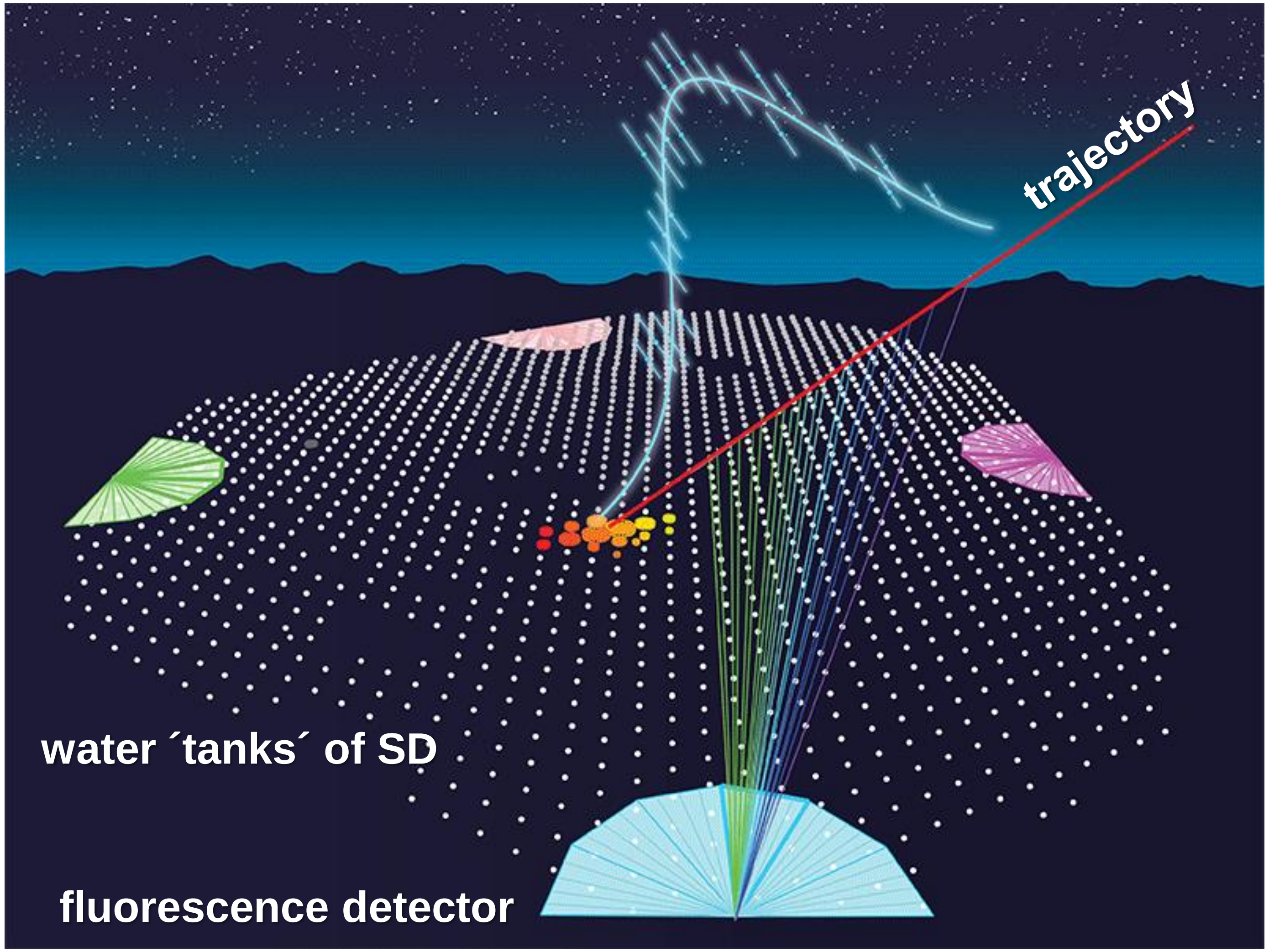
- **Shower observables**

  - longitudinal distribution (FD)
  - lateral distribution (SD)

  - FD data available only in clear moonless nights $(\varepsilon = 10\%)$ to avoid scattered light (PMTs)



stereo FD event

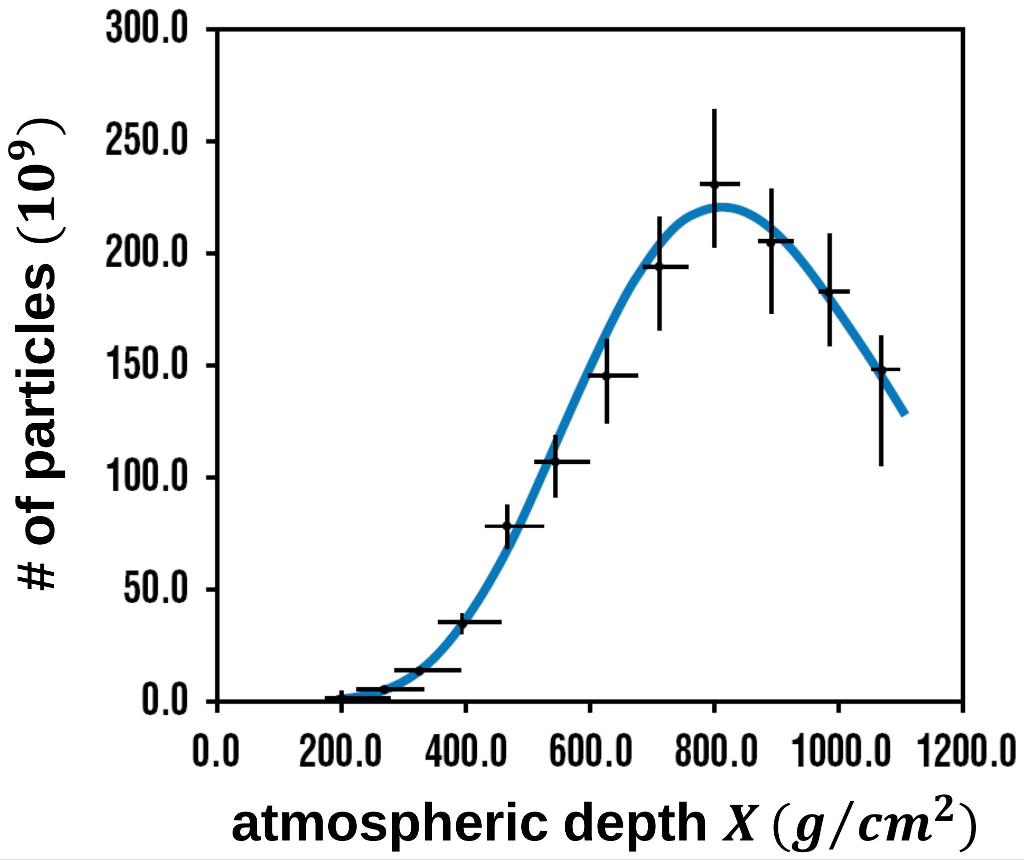


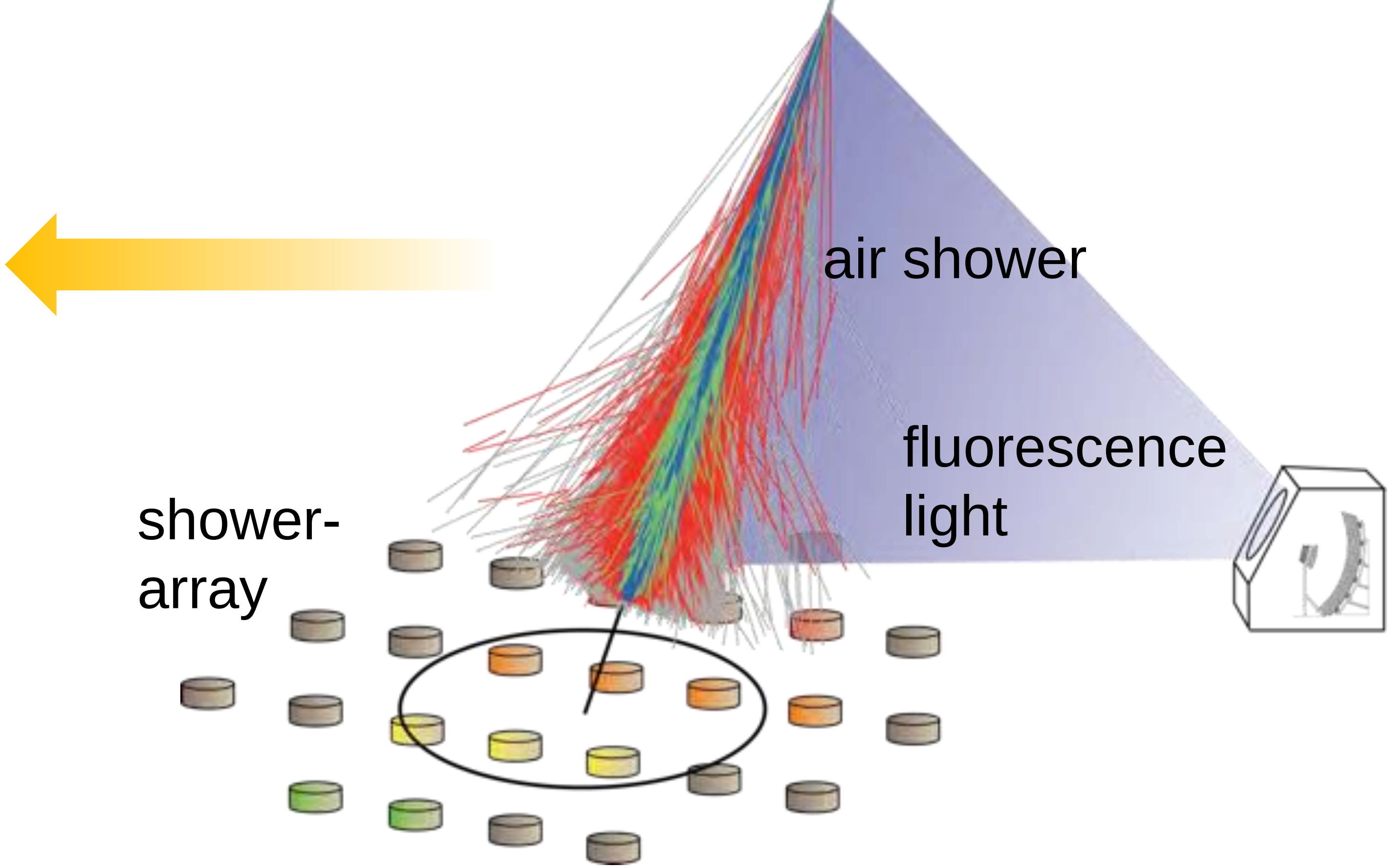
Q: APS

Pierre Auger Observatory: hybrid technology

- **UHECR observable: longitudinal distribution (height profile of a CR shower)**

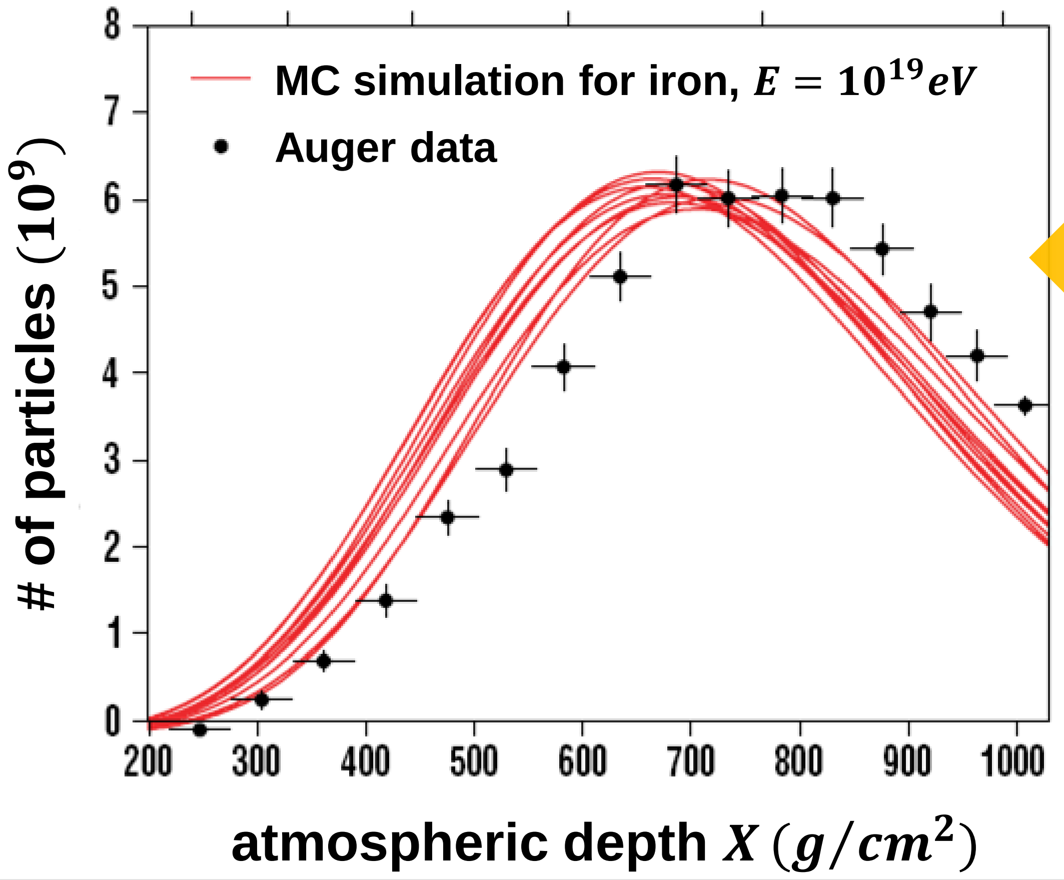
  - measuring the shower maximum X_{max} to derive the UHECR mass composition

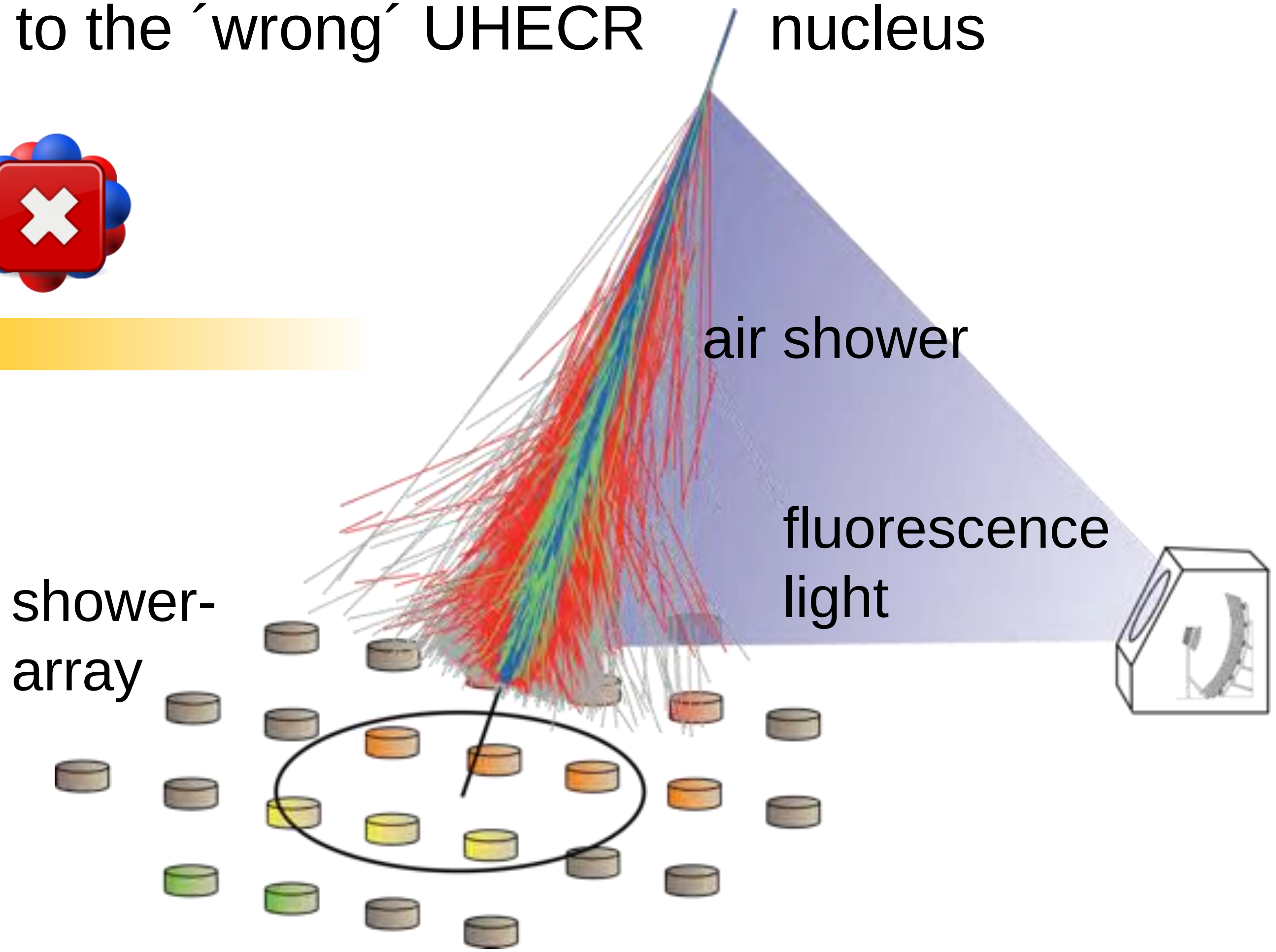




Pierre Auger Observatory: comparison to MC

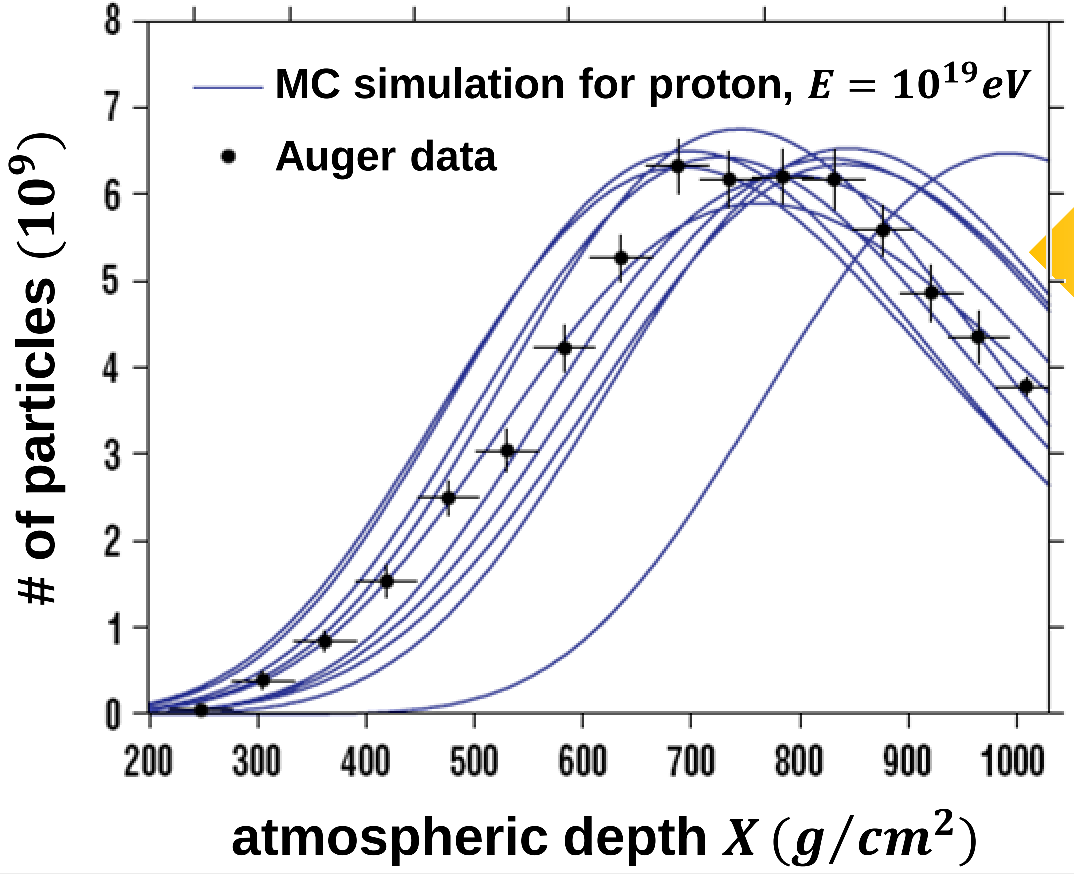
- **UHECR observable: data compared to MC-simulations for a shower by ^{56}Fe**
  - comparing shower maximum X_{max} to the ´wrong´ UHECR nucleus

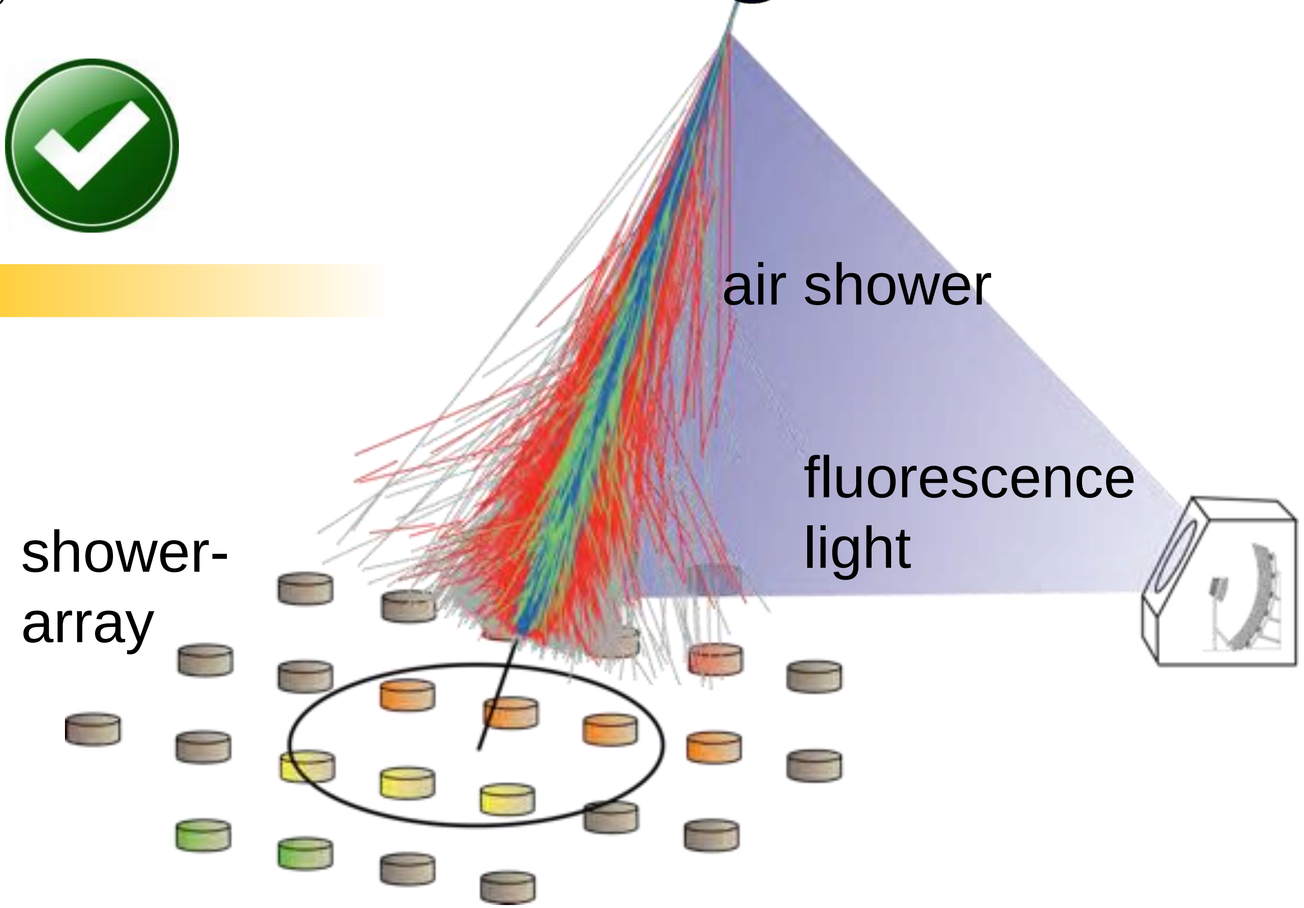




Pierre Auger Observatory: comparison to MC

- **UHECR observable: data compared to MC-simulations for a shower by a p**
  - comparing shower maximum X_{max} to the ´correct´ UHECR p nucleus

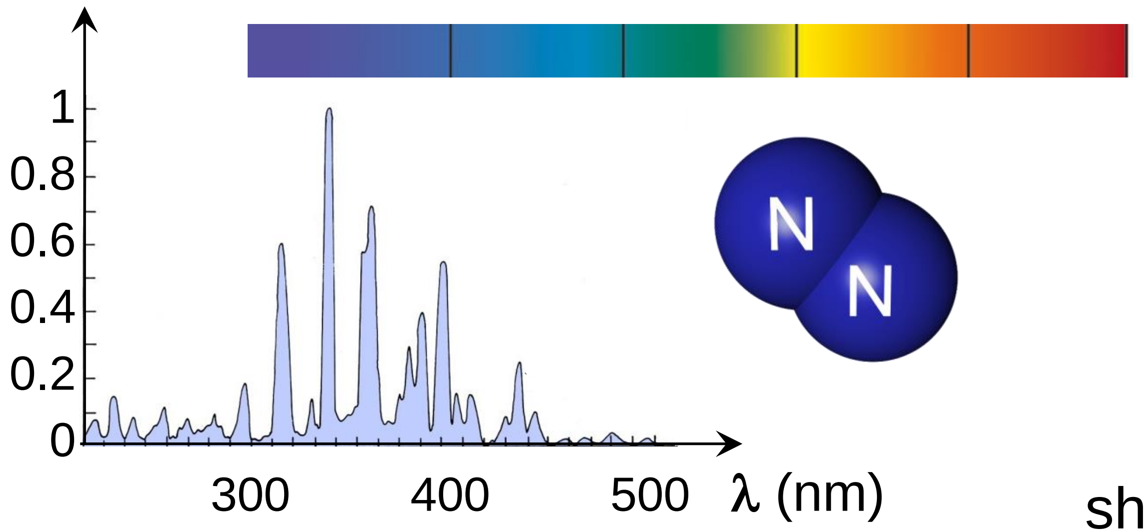


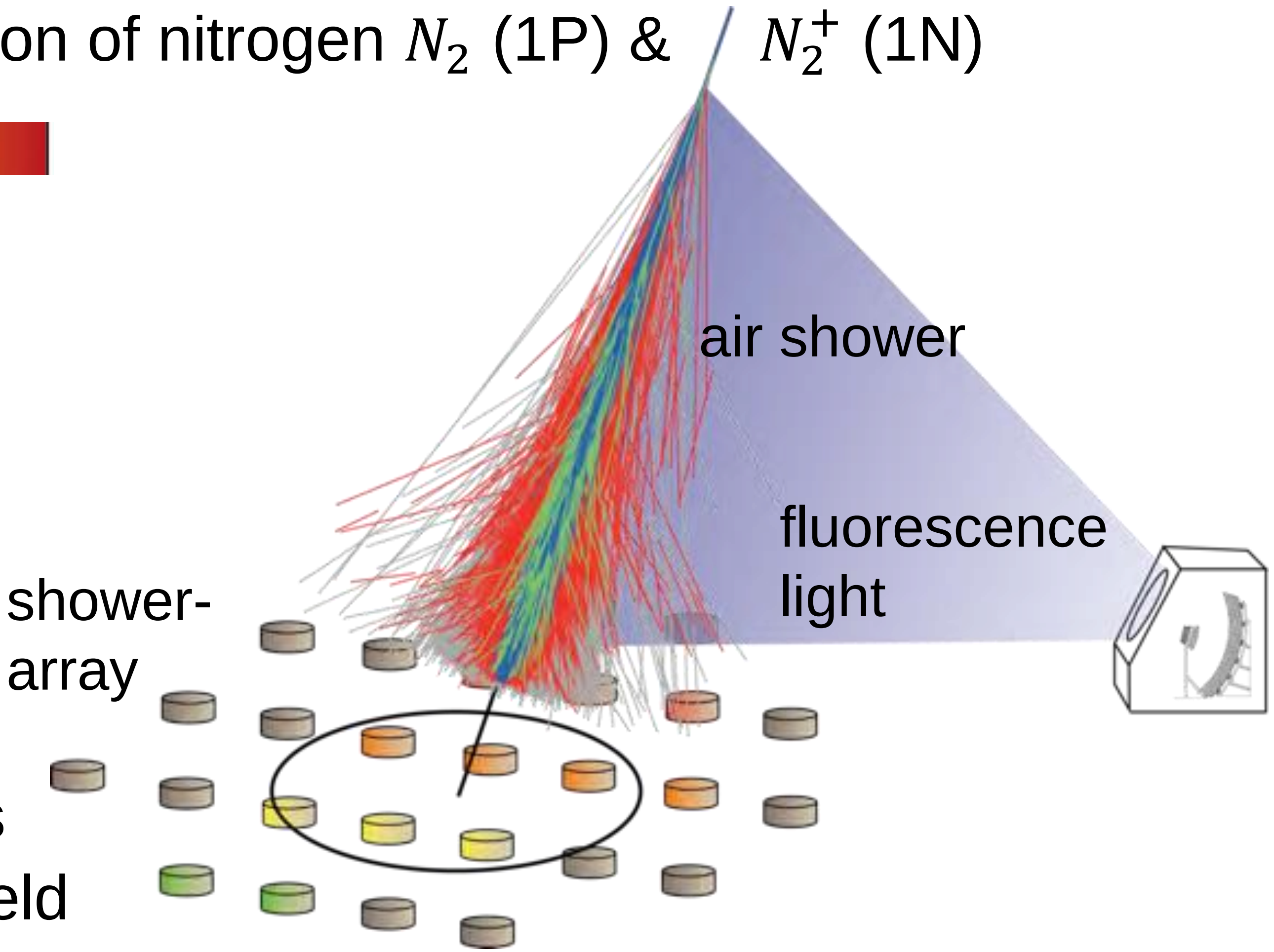


Process of air fluorescence: all due to N_2

- **Air showers induce the isotropic emission of fluorescence light**

  - light in near-UV due to de-excitation of nitrogen N_2 (1P) & N_2^+ (1N)





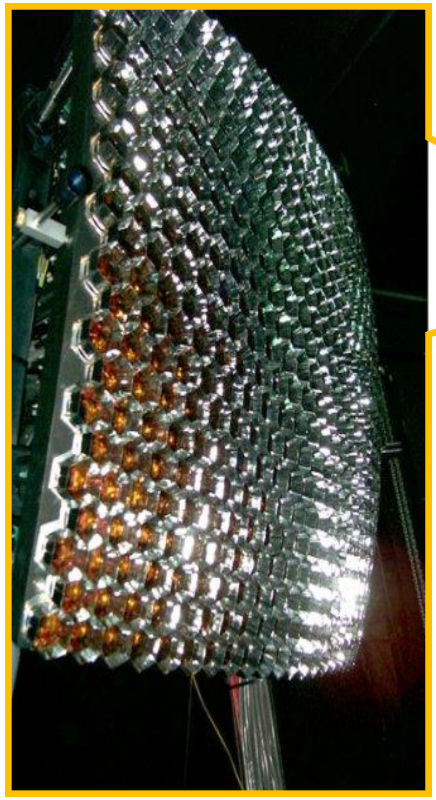
- N_2 fluorescence spectrum (blue)

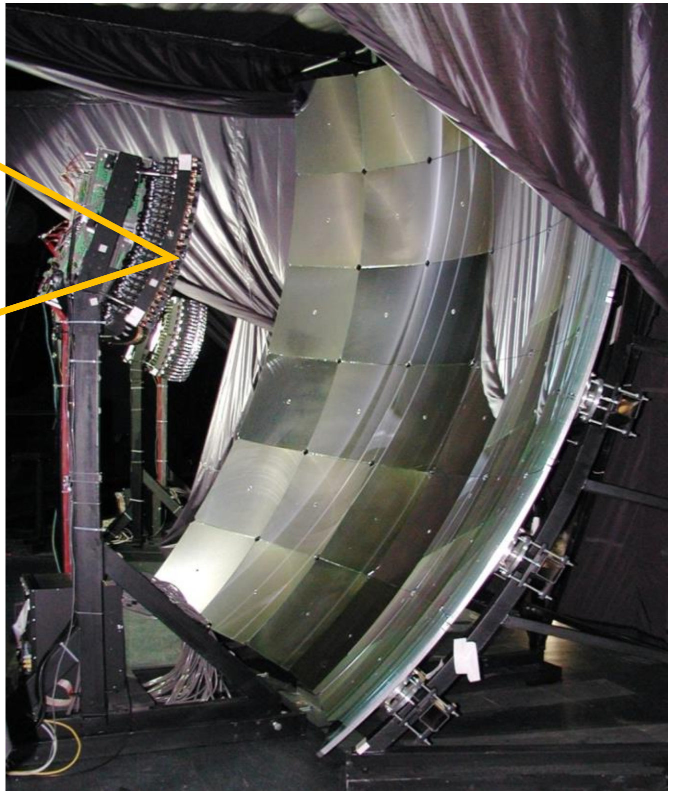
- energy calibration of shower requires precise calibration of fluorescence yield

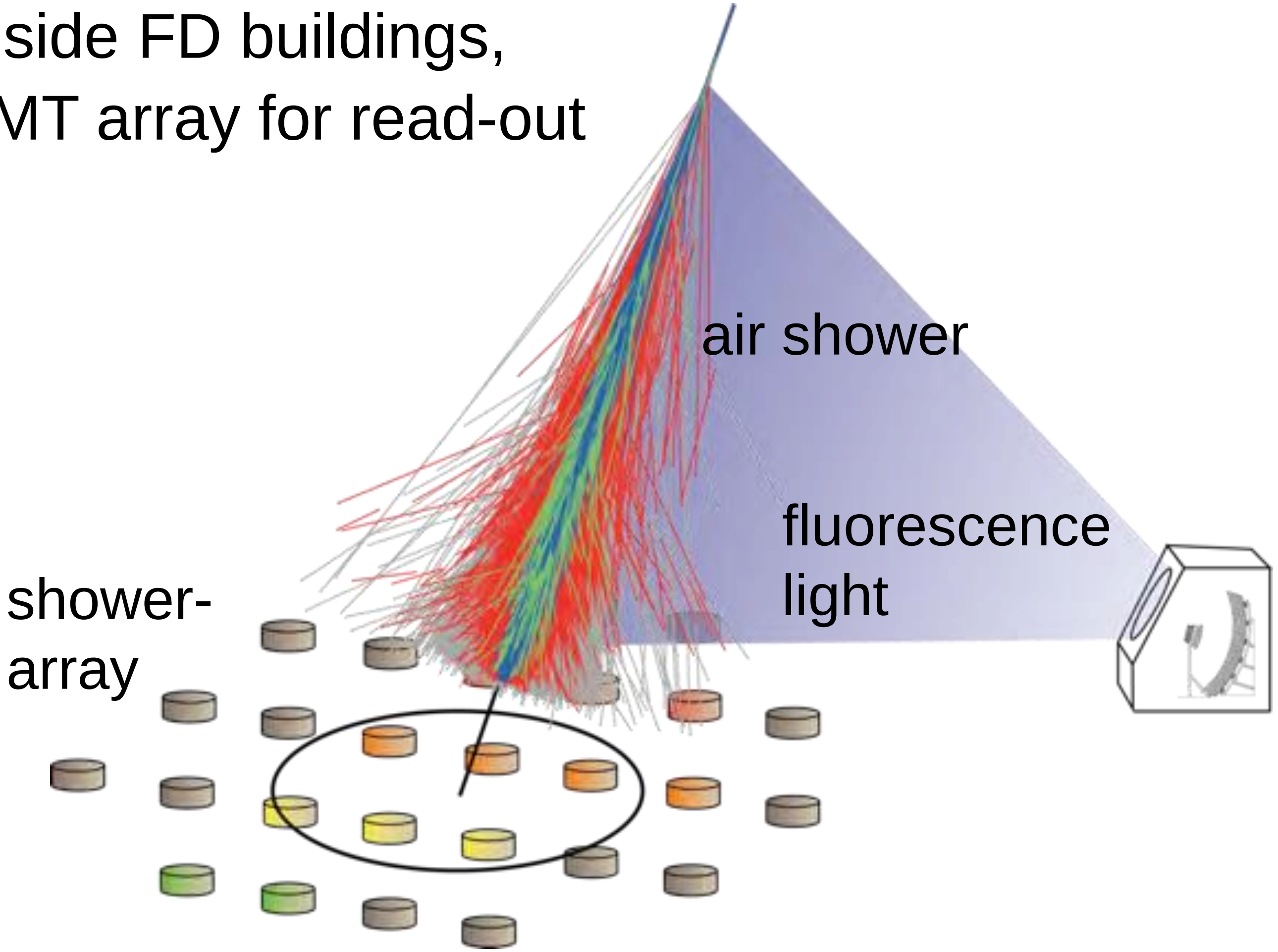
Process of air fluorescence: detection

- **fluorescence light is collected by large mirrors & focused onto PMTs**

  - large spherical mirrors (housed inside FD buildings, secured by daylight shutters) & PMT array for read-out

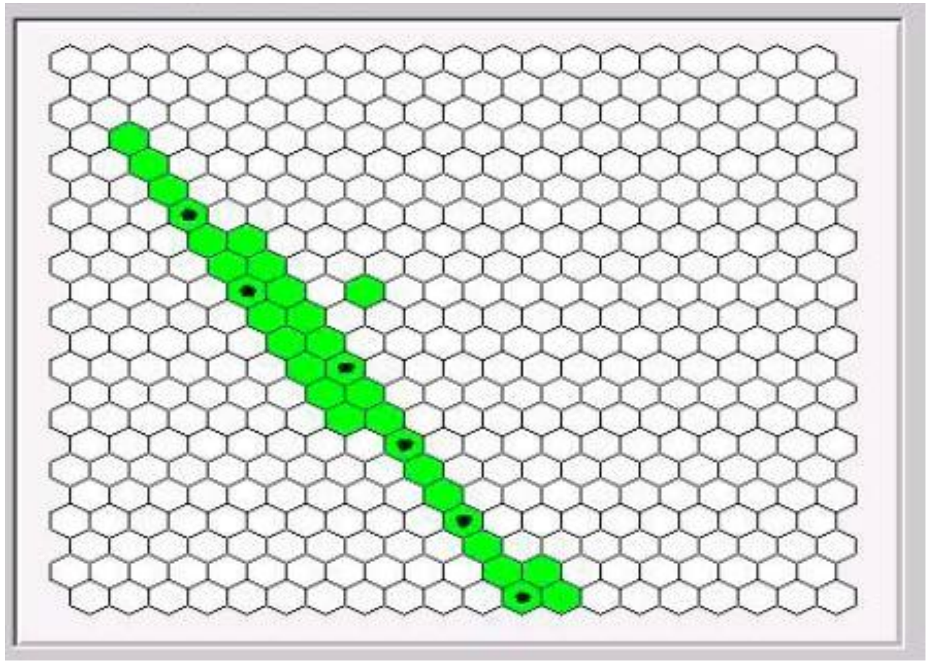


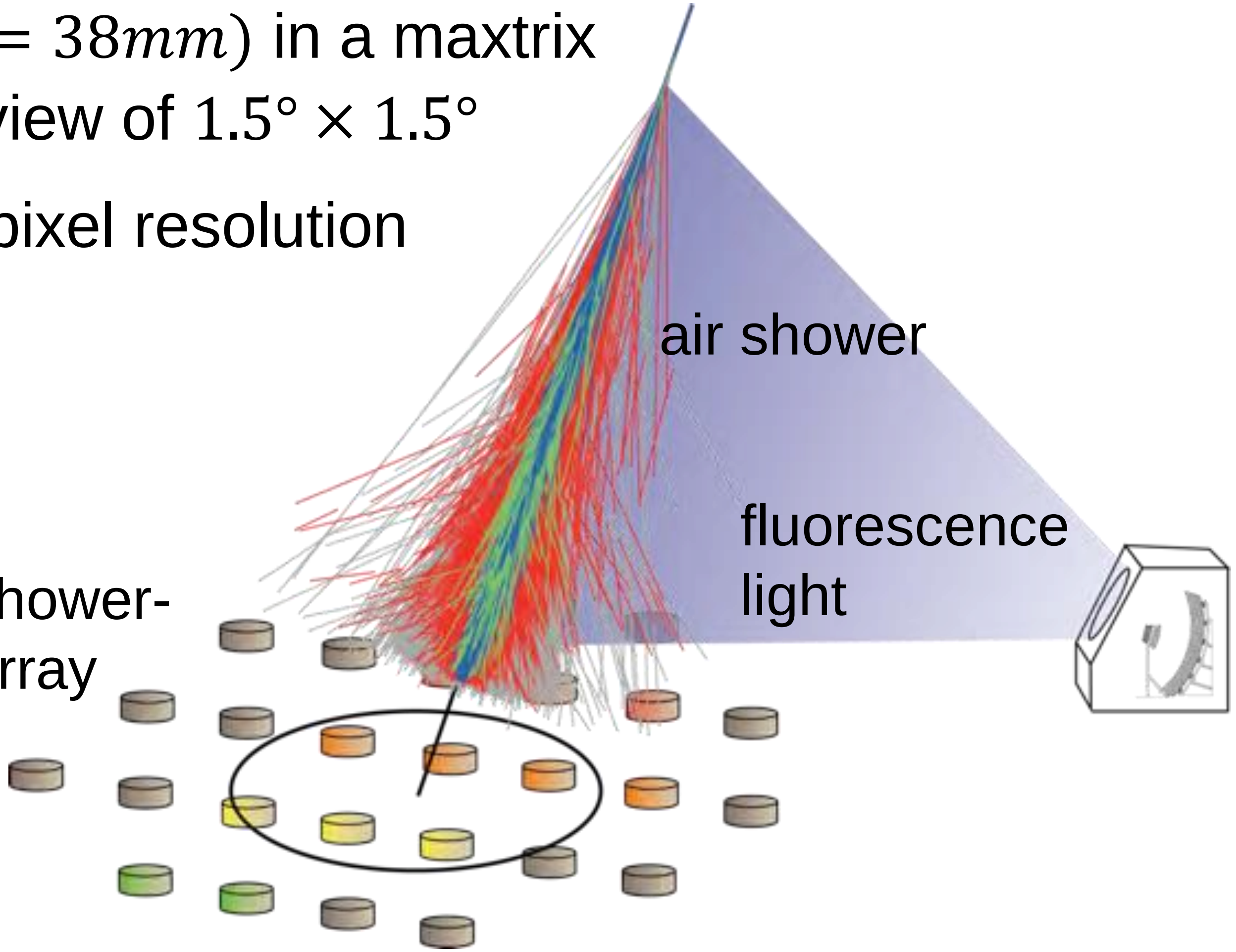




Process of air fluorescence: detection

- **fluorescence light is collected by large mirrors & focused onto PMTs**
  - PMT-camera image: $440\ PMTs\ (\emptyset = 38mm)$ in a maxtrix of 20×22 pixels, each covering a view of $1.5° \times 1.5°$
  - FD: side view of a shower track in pixel resolution





Process of Cherenkov light emission in air

- **Air showers induced the forward peaked emission of Cherenkov light**

  - $\Delta t = 2 - 3\ ns$ short light signal due to fast-moving shower particles (polarisation effect of medium)

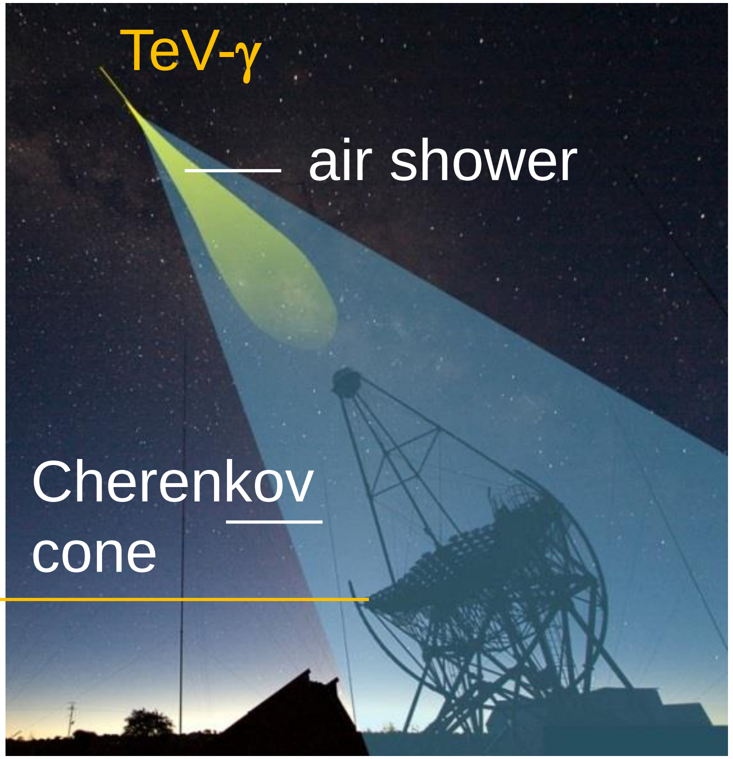
  - after transmission in air of $d = 10\ km$: $\lambda > 300$ nm

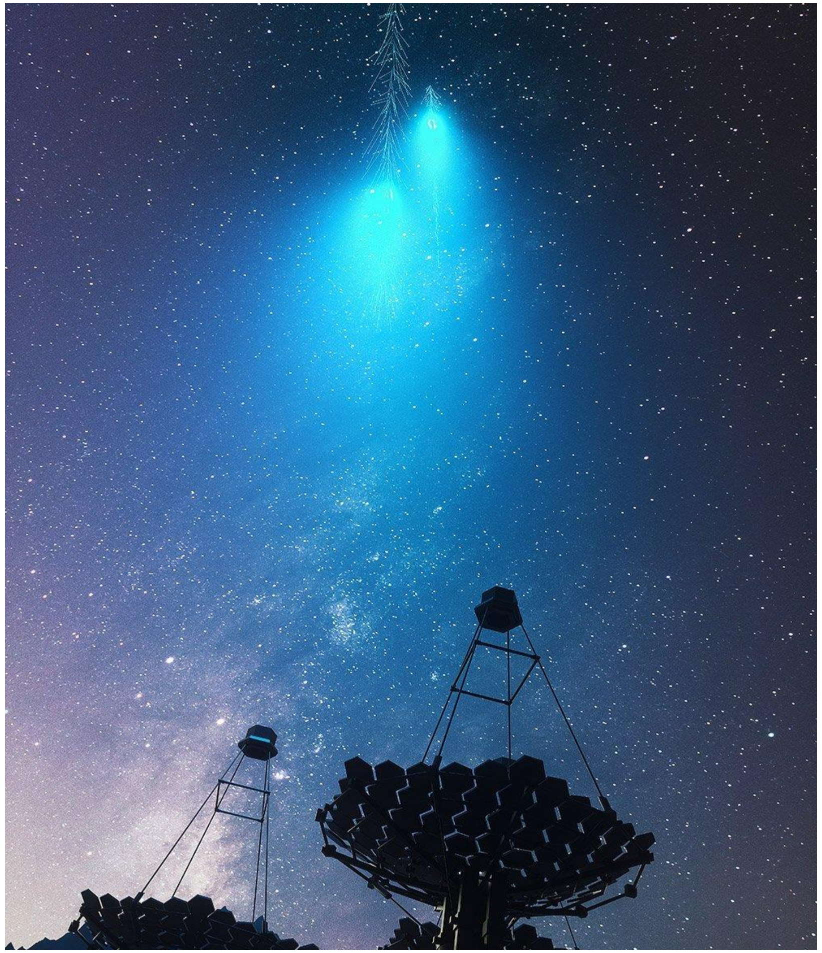
  - narrow forward cone

$$\cos\Theta = 1/(n \cdot \beta)$$

opening angle $\boldsymbol{\Theta \sim 1°}$

$0.066\ \gamma\text{´}s\ m^{-2} GeV^{-1}$



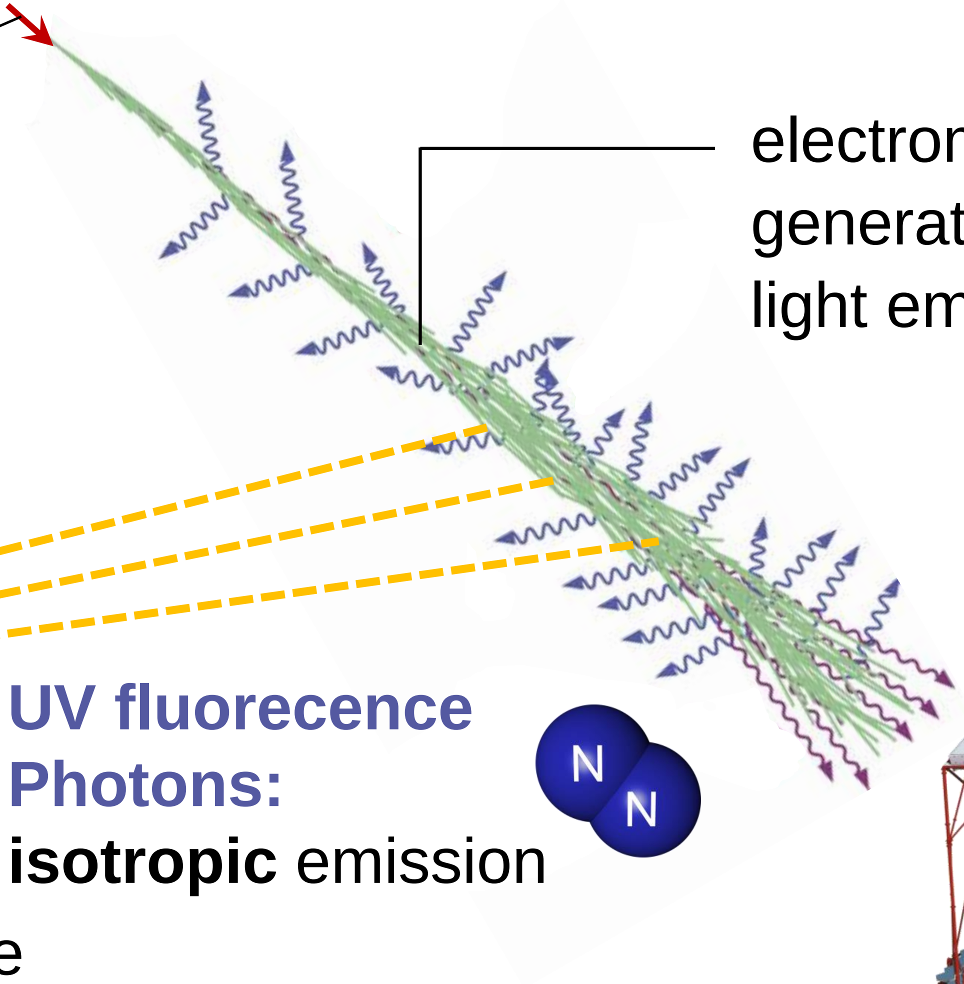


Q: DESY

Comparison of fluorescence & Cherenkov light

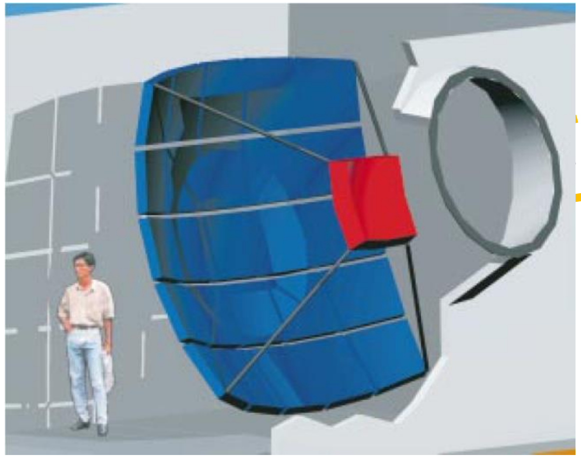
- **Air showers induce 2 light-emitting processes with different characteristics**

primary particle



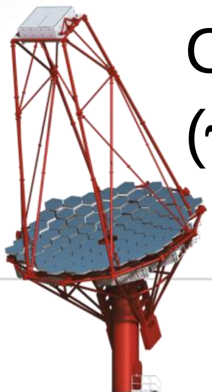
electromagnetic shower with $e^- e^+ \gamma$ generates secondaries which induce light emission in atmosphere

Cherenkov photons:
forward-peaked emission



UV fluorecence Photons:
isotropic emission

fluorescence telescope



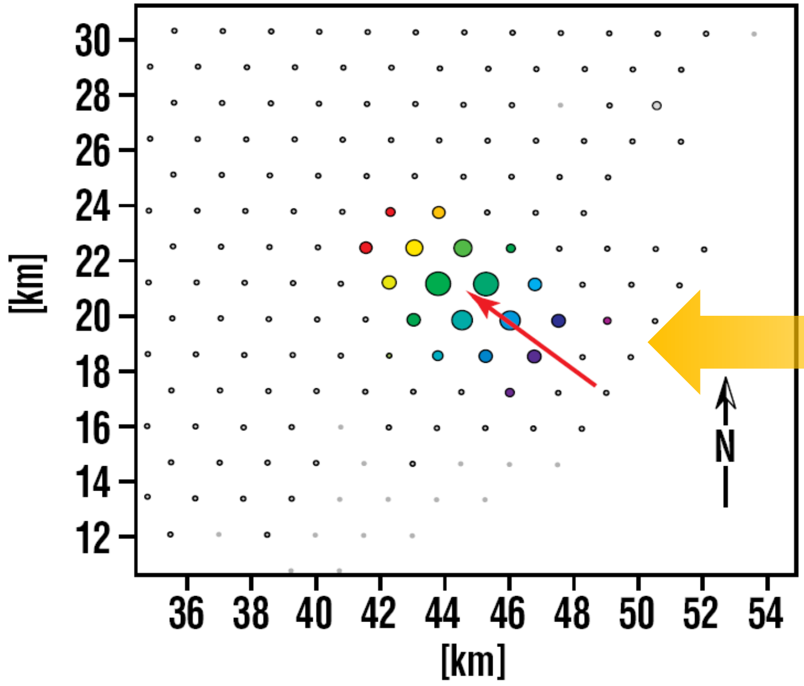
atmospheric Cherenkov telescope (γ-astronomy, see lect. 8)

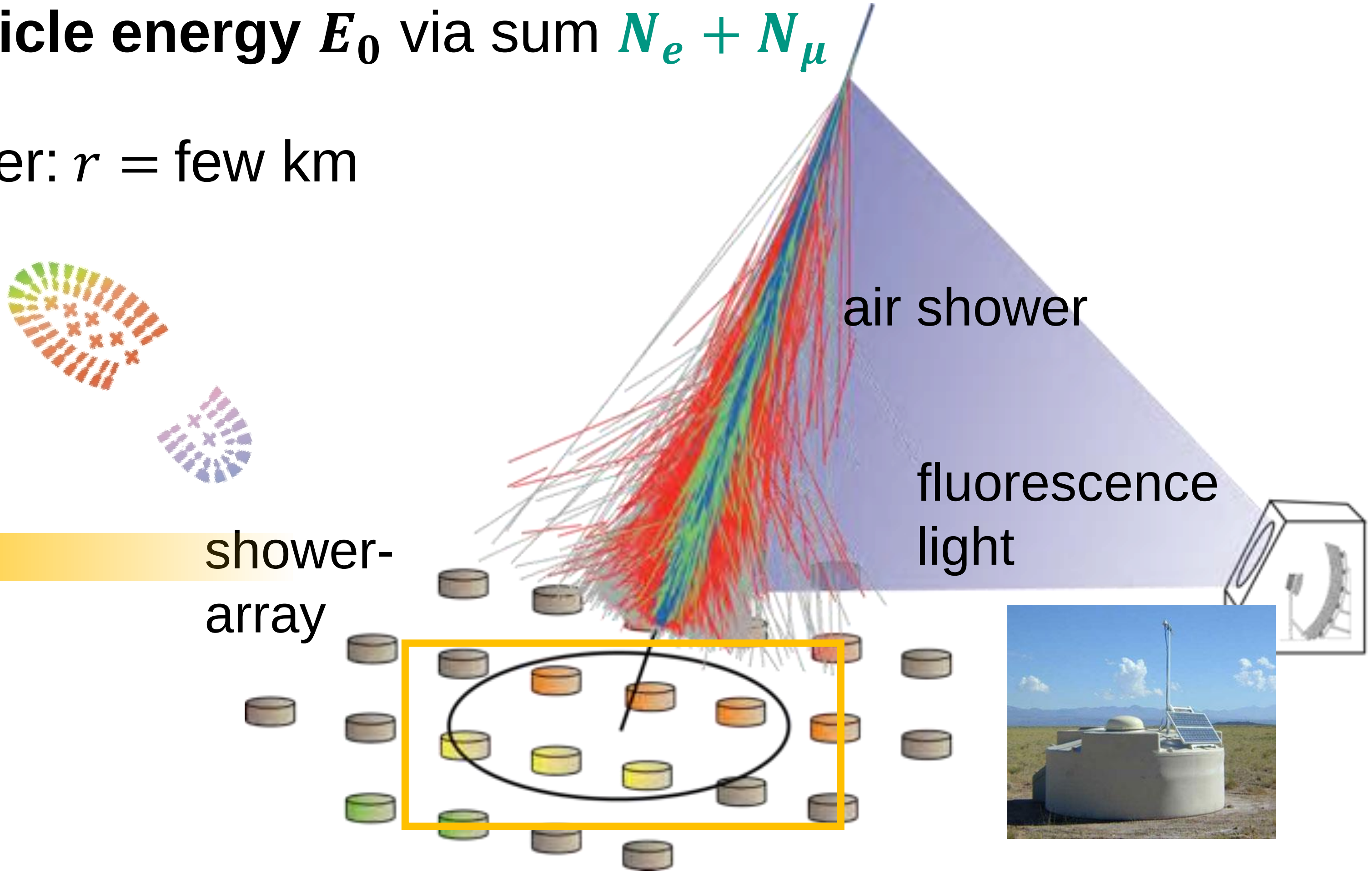
Pierre Auger Observatory: hybrid technology

- **second UHECR observable:** **lateral distribution** **(aka ´the footprint´)**

  - determining **primary particle energy** $\boldsymbol{E_0}$ via sum $\boldsymbol{N_e + N_\mu}$

- lateral size of UHECR shower: $r =$ few km



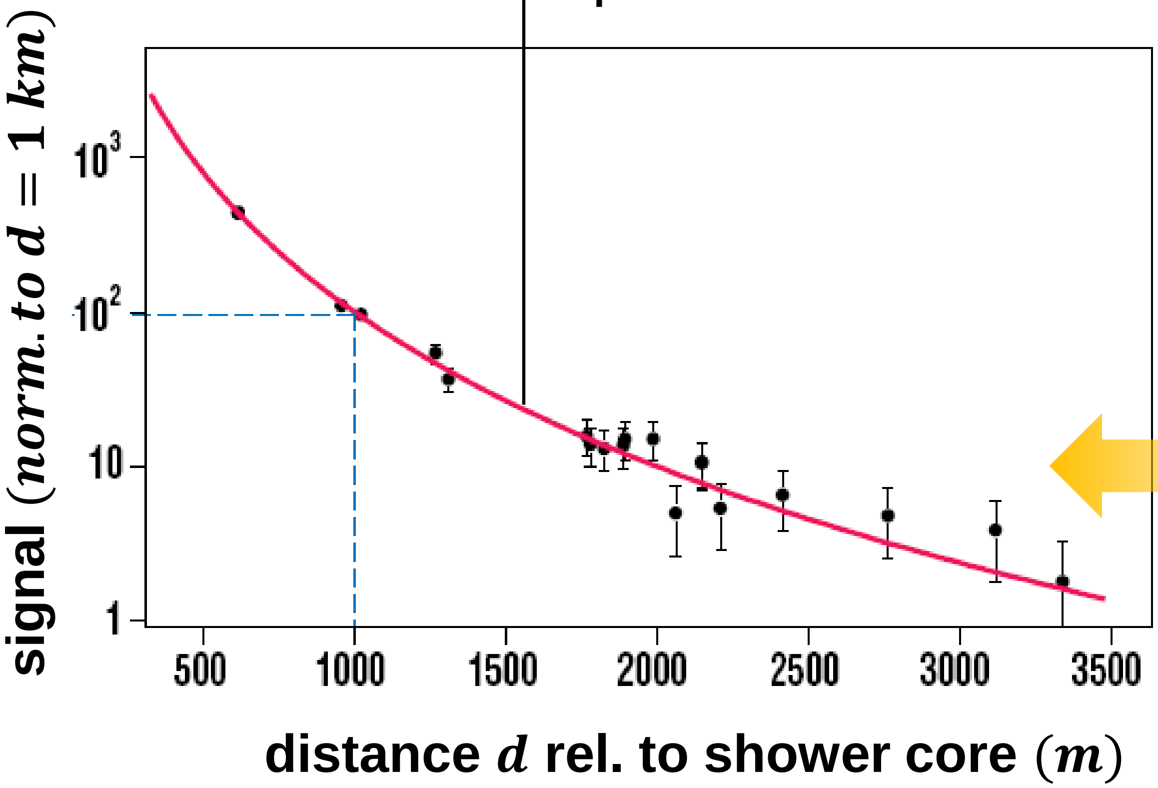


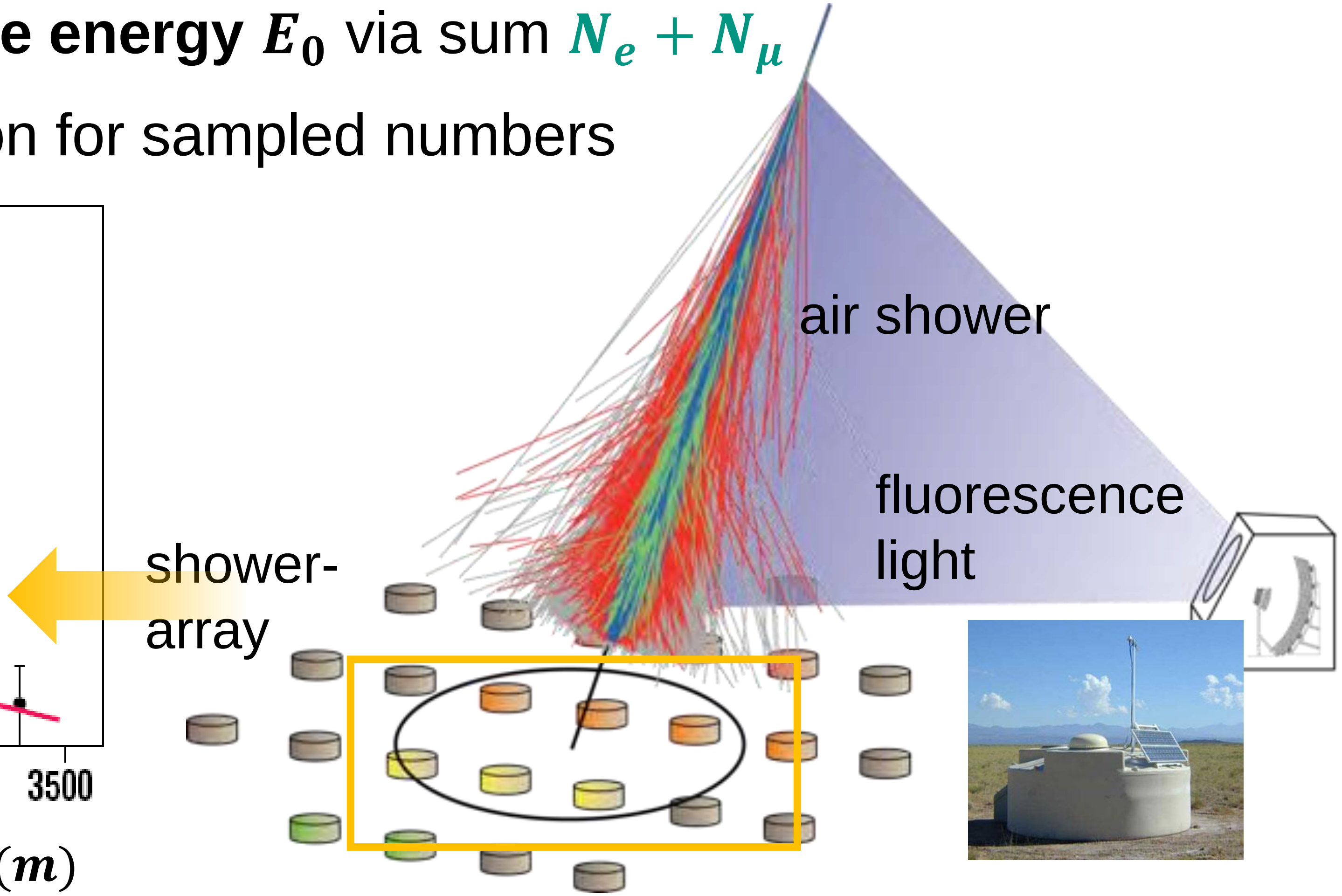
Pierre Auger Observatory: hybrid technology

- **second UHECR observable: lateral distribution (aka ´the footprint´)**

  - determining **primary particle energy E_0** via sum $N_e + N_\mu$

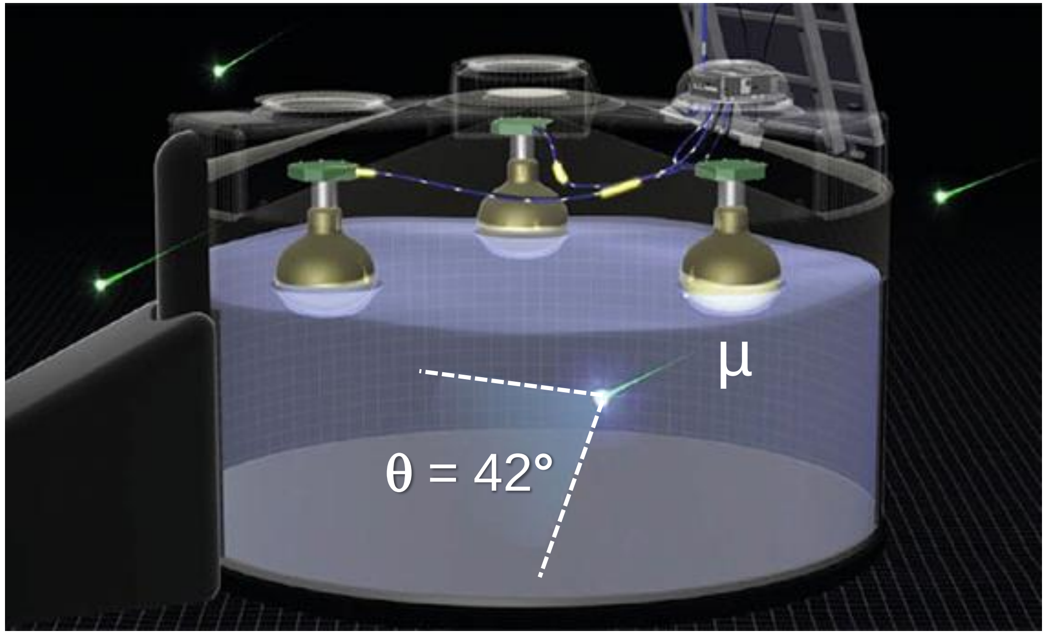
specific fit function for sampled numbers

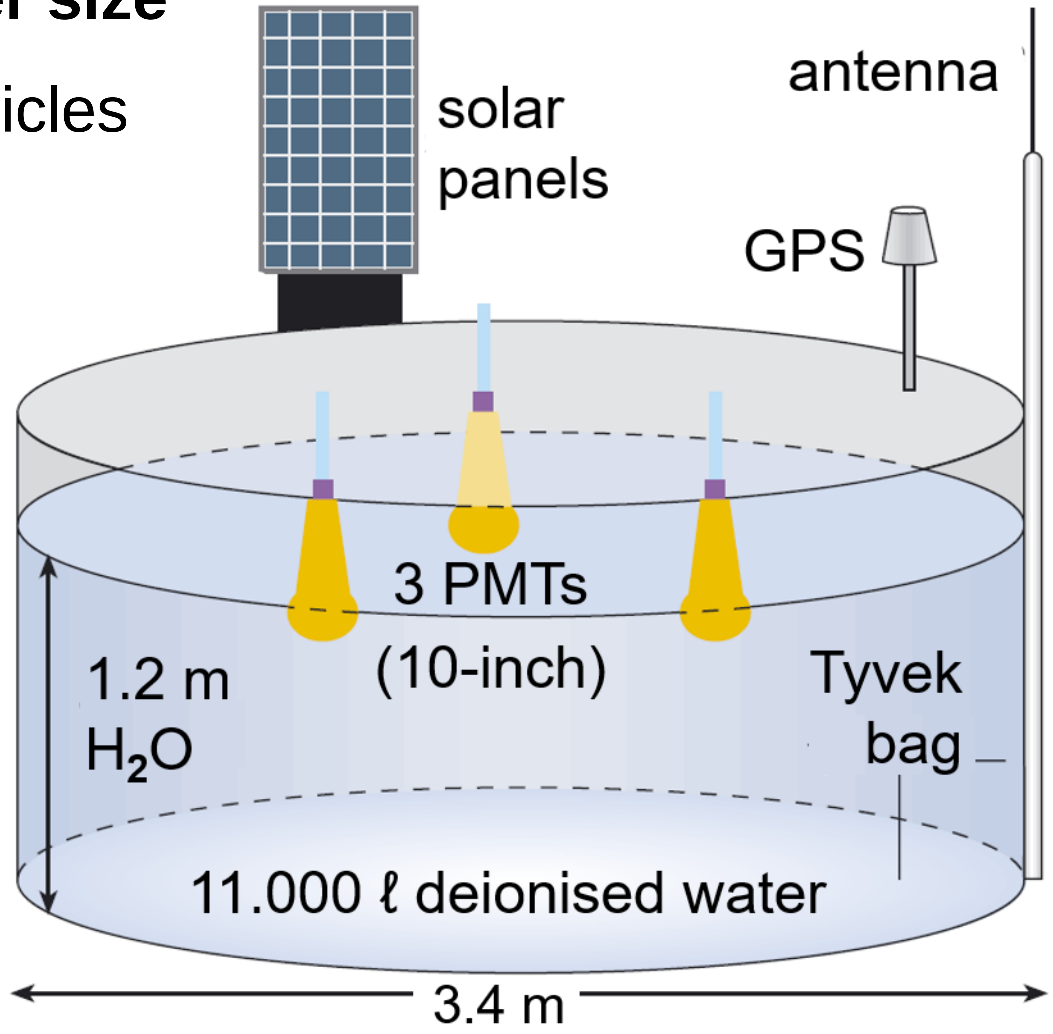




Pierre Auger Observatory: Surface Detector

- **Water-Cherenkov detector stations: shower size**
  - register Cherenkov light of all charged particles
  - Trigger: $5\ H_2O$ –´tanks´ in $\Delta T = 20\ ms$
    ⇘ $\boldsymbol{\varepsilon} = \mathbf{98}\ \%$ at $E = 10^{19} eV$



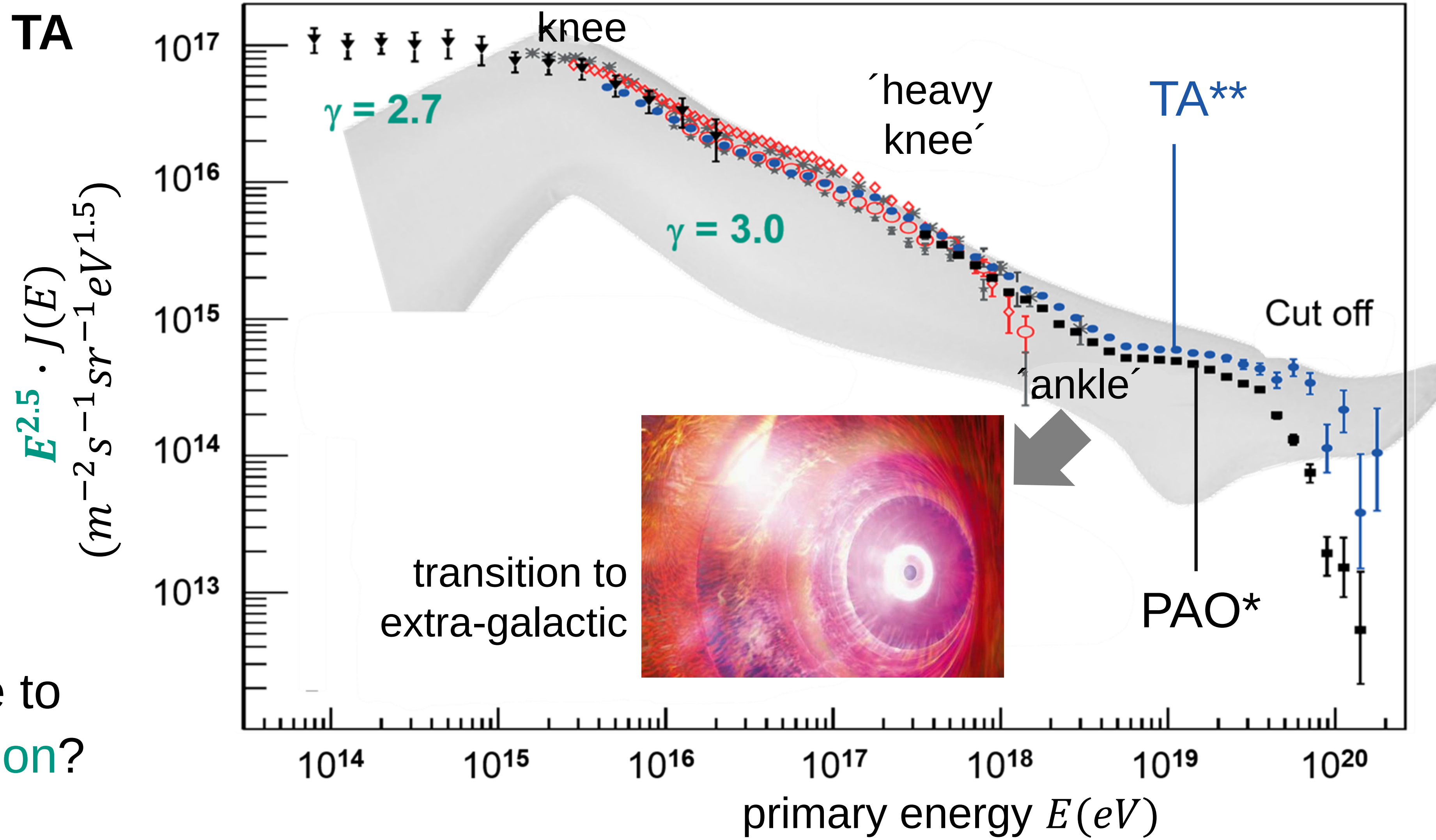


Results: energy specta at the highest energies

Results of PAO & TA

- different energy *energy estimators* (calibrations) for UHECR energies

- common feature: at $E \sim 10^{20}\ eV$ one observes a sharp **cut off** of the rate
  ⇨ E_{max} or effect due to UHECR propagation?

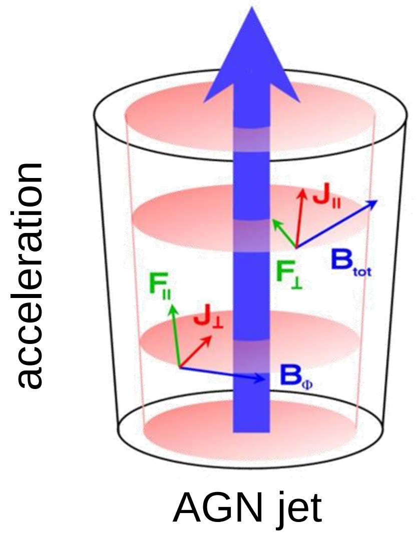


* Pierre Auger Observatory
** Telescope Array

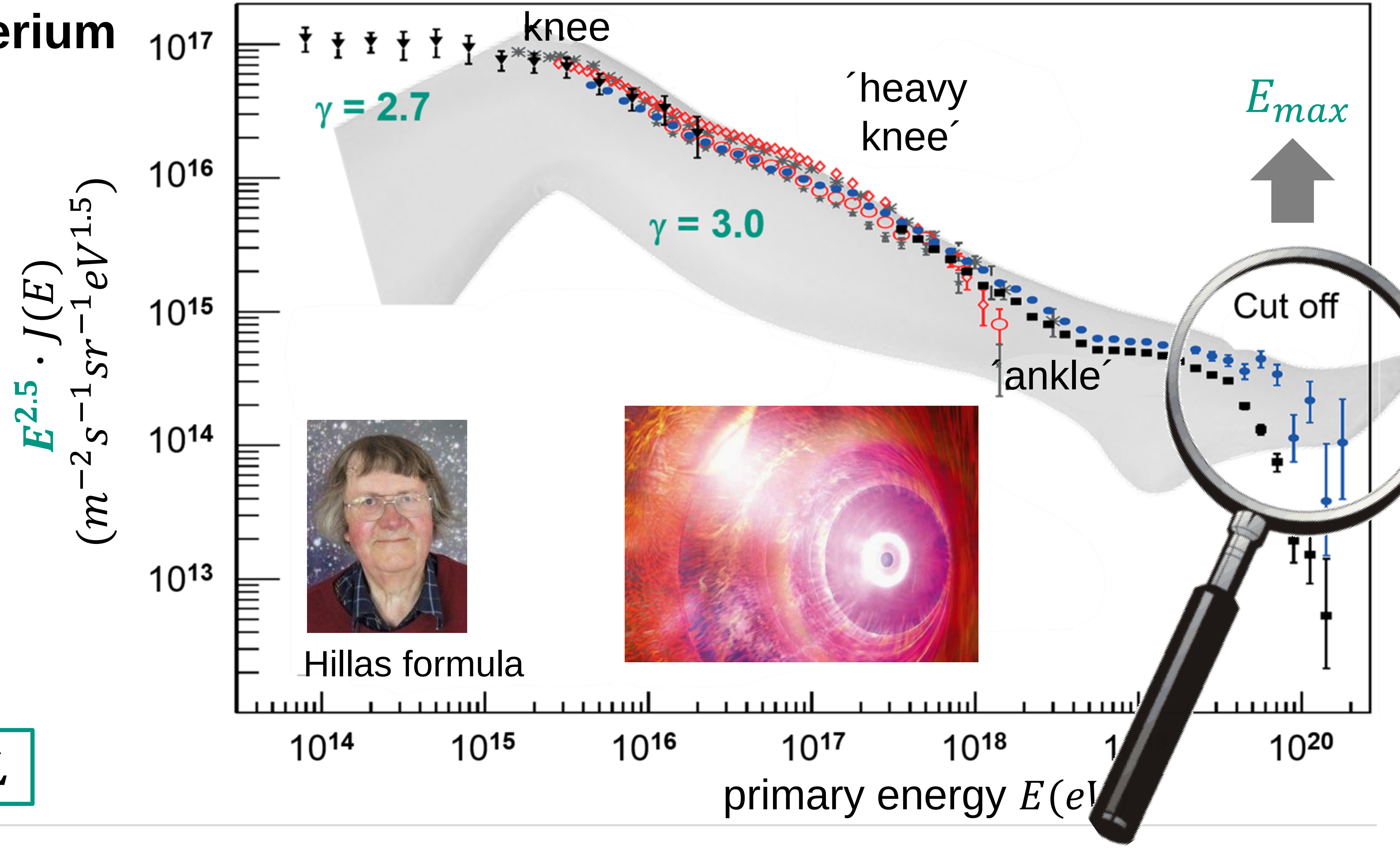
Recap: cut-off of UHECR at specific energy

- **Idea 1: Hillas criterium**

- **source is limited**:
  parameters B, L, β_s
- here: AGN jet



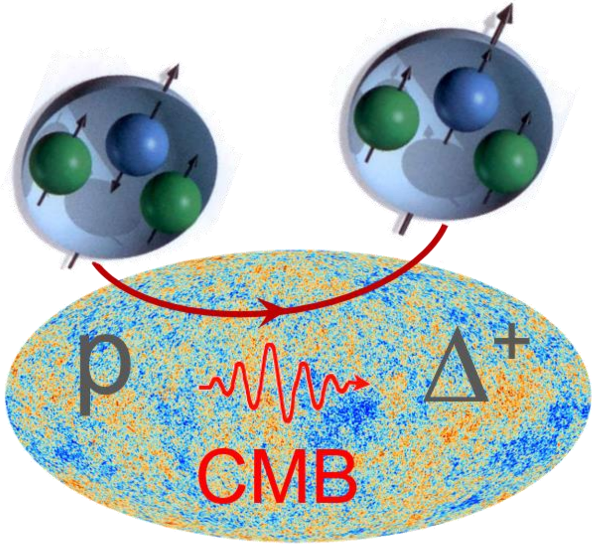
$$E_{max} \sim \beta_S \cdot Z \cdot B \cdot L$$

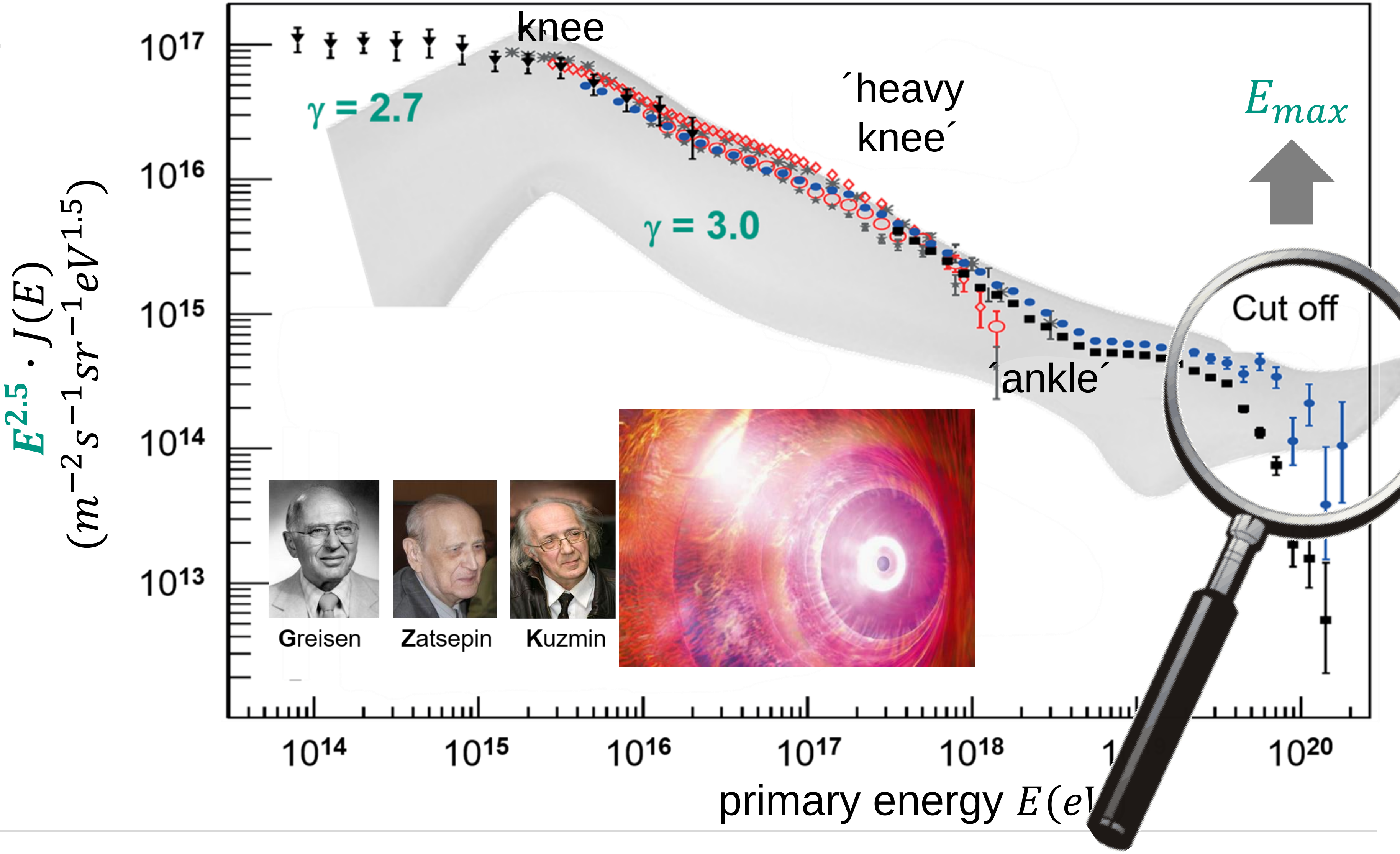


Recap: cut-off of UHECR at specific energy

- **Idea 2: GZK effect**

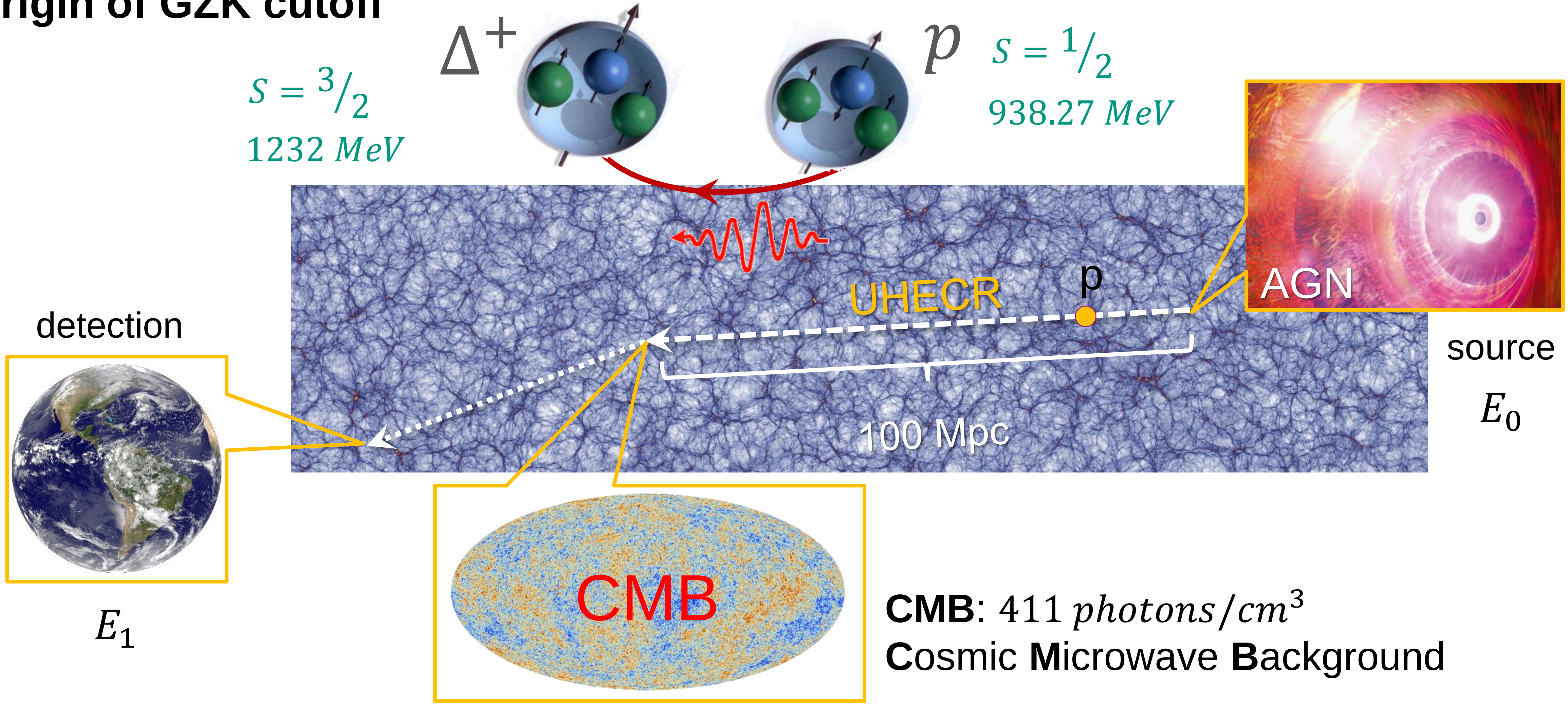
- **propagation effect**: CMB photons
- here: p forms a Δ^+ – resonance





Scenario 2: GZK-cutoff for UHECR-protons

- **Origin of GZK cutoff**

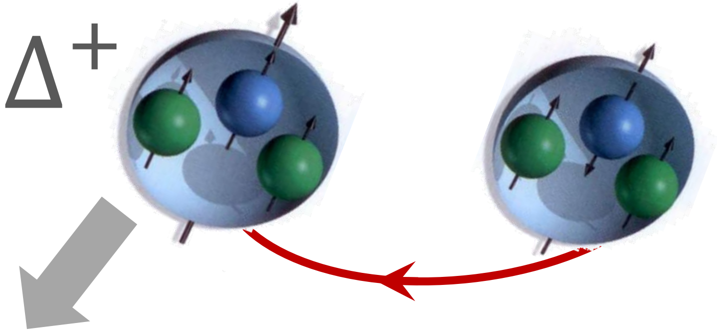


CMB: $411\ photons/cm^3$
Cosmic **M**icrowave **B**ackground

Scenario 2: GZK-cutoff for UHECR-protons

- **Propagation effect**

Δ^+ $s = {}^3/_2$ $1232\ MeV$



p $s = {}^1/_2$ $938.27\ MeV$

decay

$$\Delta^+ \rightarrow p + \pi^0$$
$$\rightarrow n + \pi^+$$

$$p + \gamma(2.7K) \rightarrow \Delta^+ \rightarrow p + \pi^0$$

$$\sigma_{tot} \sim 10^{-28} cm^2$$

- resonant scattering of UHECR protons off CMB photons ($2.7\ K$ background-radiation) generates a short-lived Δ^+ – resonance

- production & decay of Δ^+ – resonance is well understood (measured)

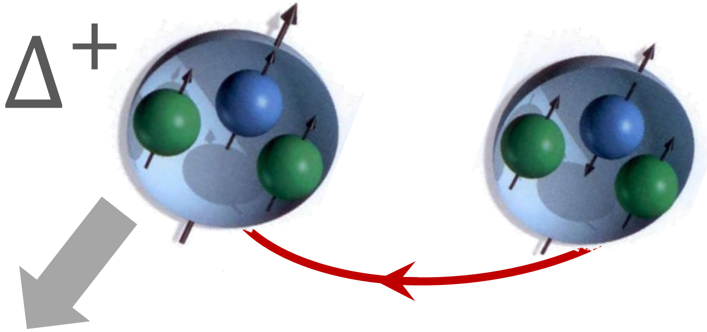
Scenario 2: GZK-cutoff for UHECR-protons

- **threshold effect**

$s = {}^{3}/_{2}$

$1232\ MeV$

Δ^+



p

$s = {}^{1}/_{2}$

$938.27\ MeV$

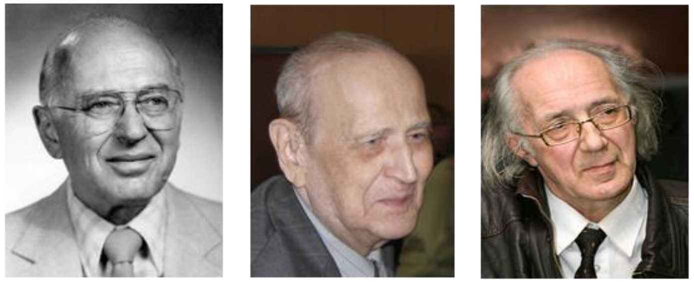
decay

a photo-hadronic interaction!

$$\Delta^+ \rightarrow p + \pi^0$$
$$\rightarrow n + \pi^+$$

$$cms^* - energy:\ \ s > (m_p + m_\pi)^2$$

threshold energy for protons: $\boldsymbol{E_p = 4 \times 10^{19}\ eV}$



Greisen **Zatsepin** **Kuzmin**

*center-of-mass system

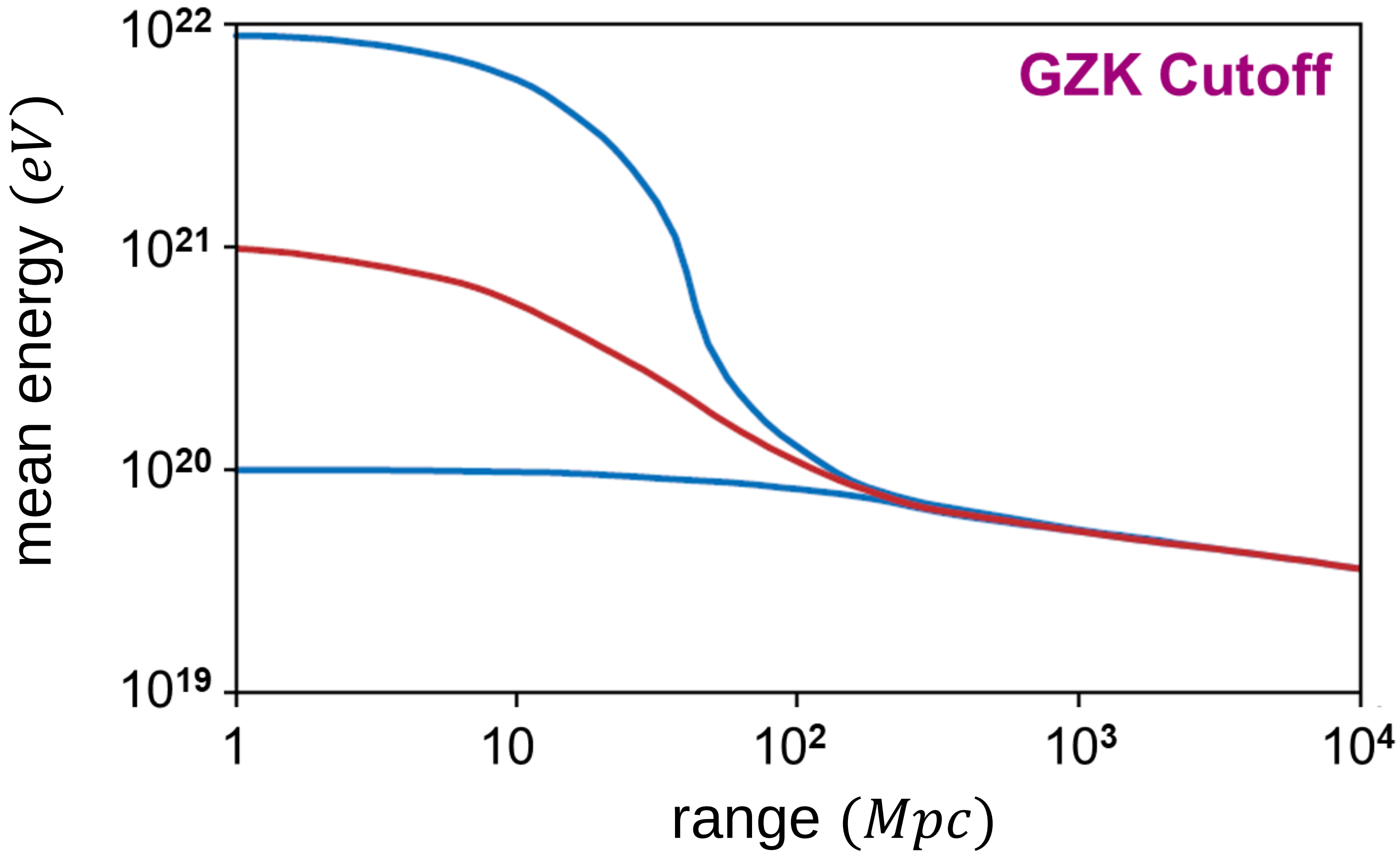
Scenario 2: GZK-cutoff for UHECR-protons

- **GZK effect severely limits the range of protons with energy $E > 10^{20} eV$**

- photo-hadronic interactions of **protons** above the GZK cutoff will result in a very strong **energy loss of p**

- for **heavy nuclei**, an inter-action with the $2.7\ K\ \gamma\text{´}s$ results in an **energy loss** due to **spallation reactions**

- only ´nearby´ UHECR sources are visible in both PAO & TA

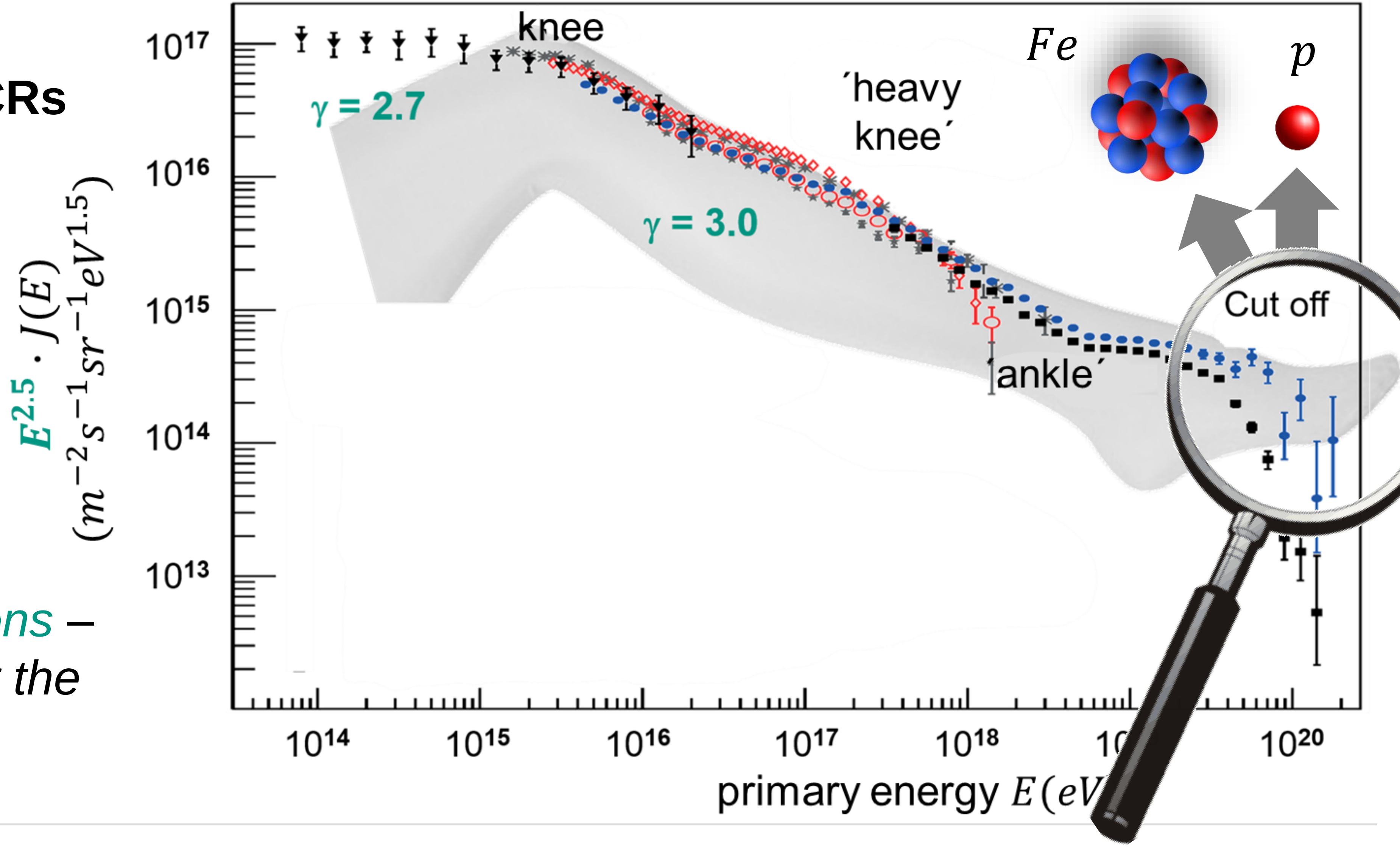


Energy spectrum of UHECRs

- **What is the mass composition of CRs at the highest energies?**

Hillas: *heavy nuclei (large Z) – can be accelerated to much higher energies !*

GZK: *if these are protons – This is a strong hint for the GZK-cutoff !*



Observed changes of the CR mass composition

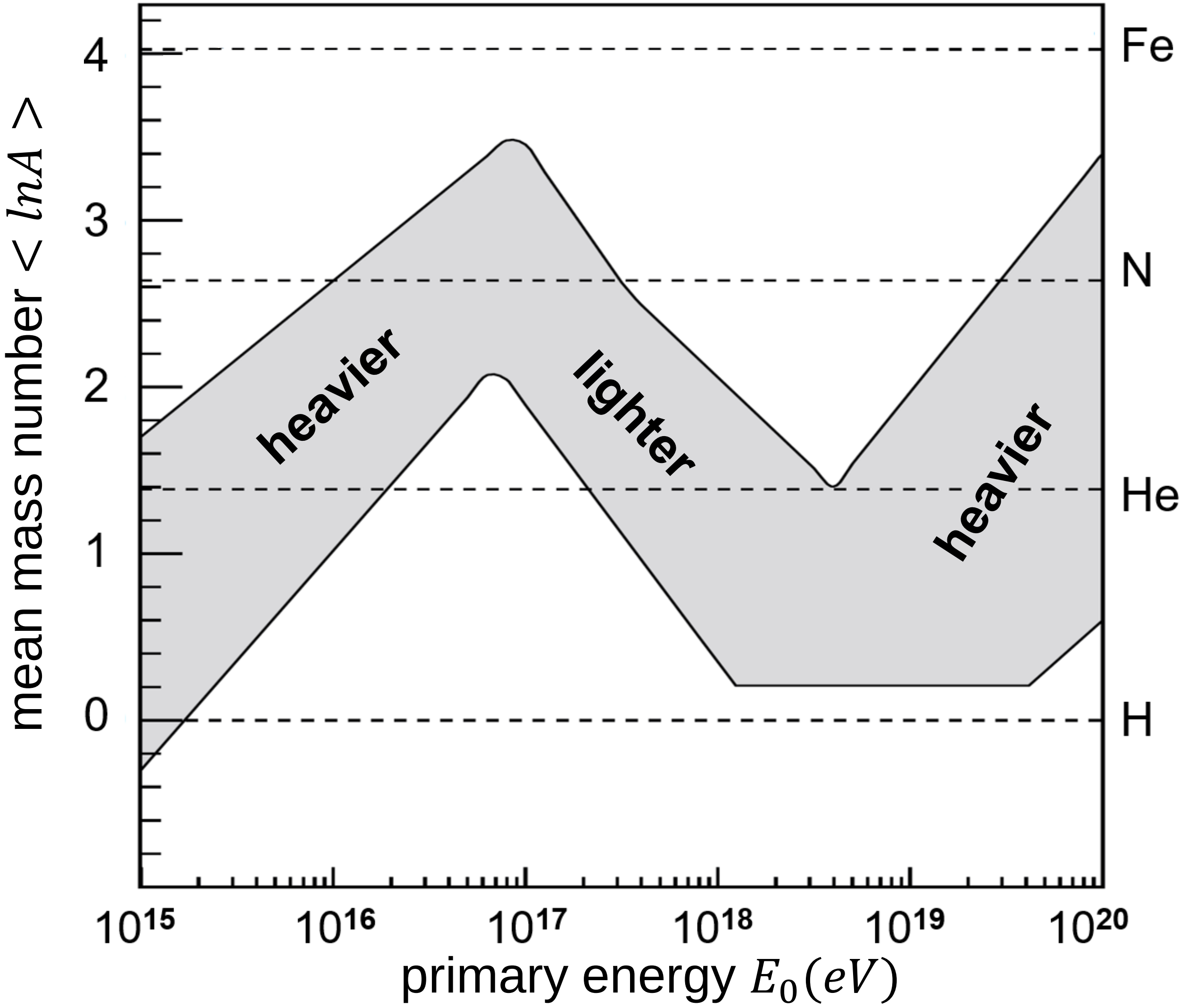
- **Measurements by Auger and other observatories**

  - at first: $E = 10^{15} \ldots 10^{17} eV$ (galactic CRs) nuclei get heavier

$$E_{max} \sim \beta_S \cdot Z \cdot B \cdot L$$

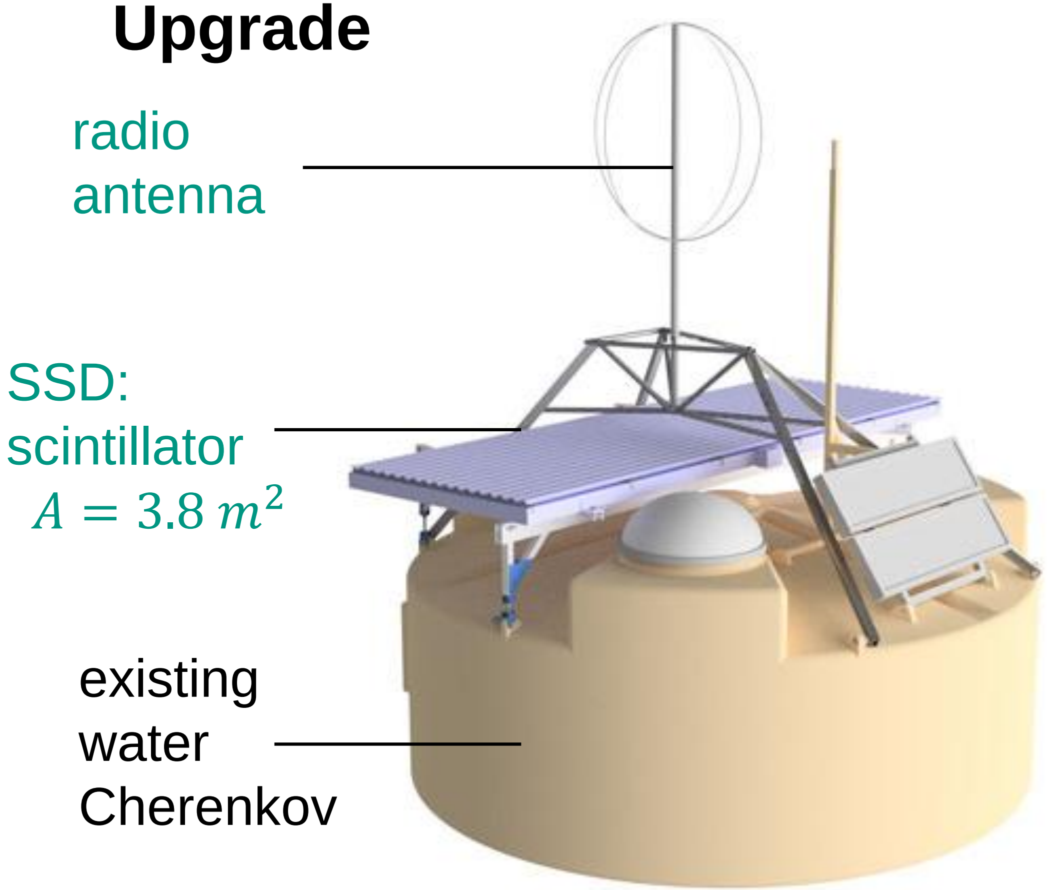
  - then: $E = 10^{17} \ldots few \times 10^{18} eV$ CRs get lighter: new sources

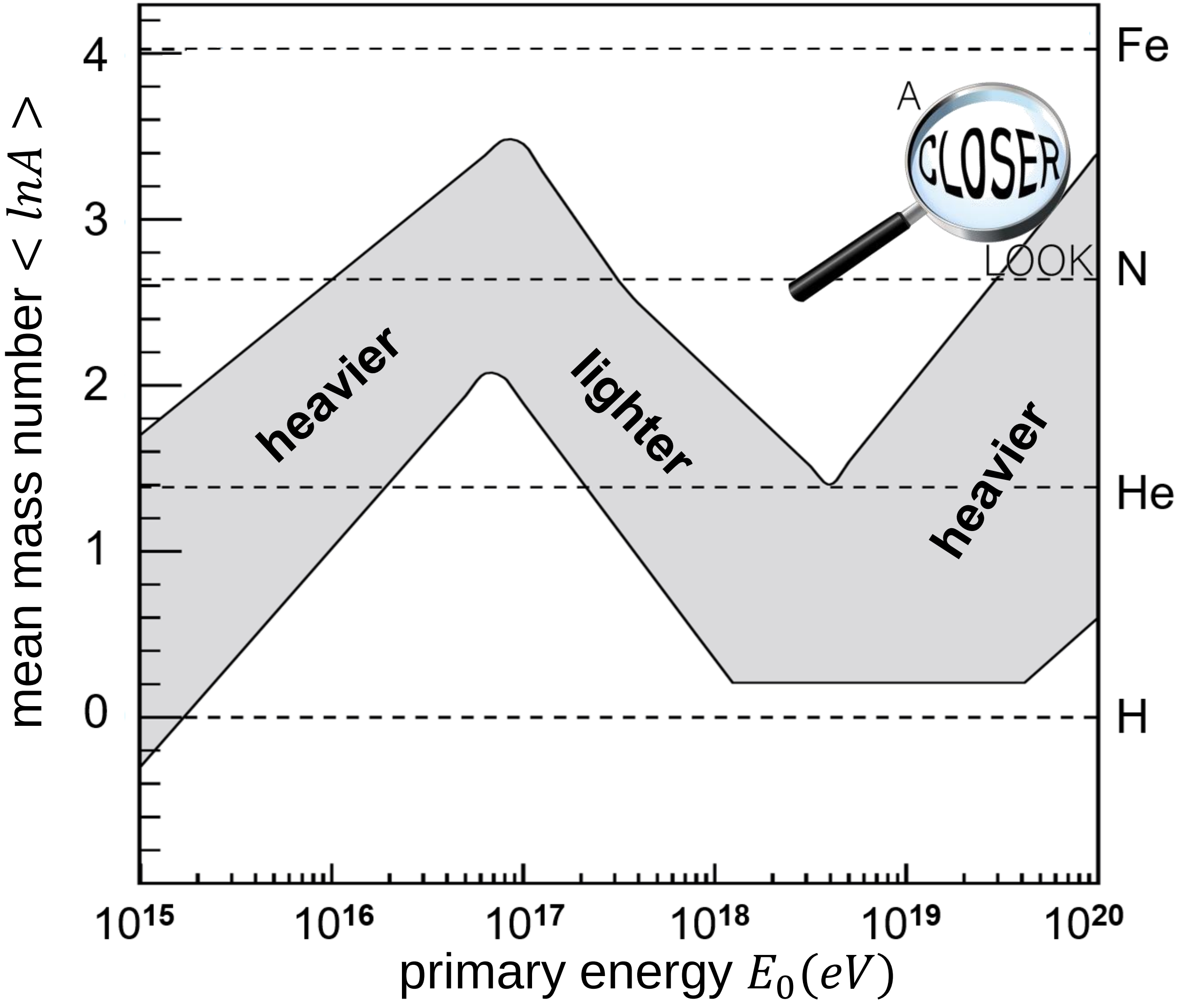
  - finally: $E = few \times 10^{18} eV \ldots 10^{20} eV$ CRs get heavier (extra-galactic)



Observed changes of the CR mass composition

- **Future measurements:**
  AugerPrime – more precise data
  Upgrade





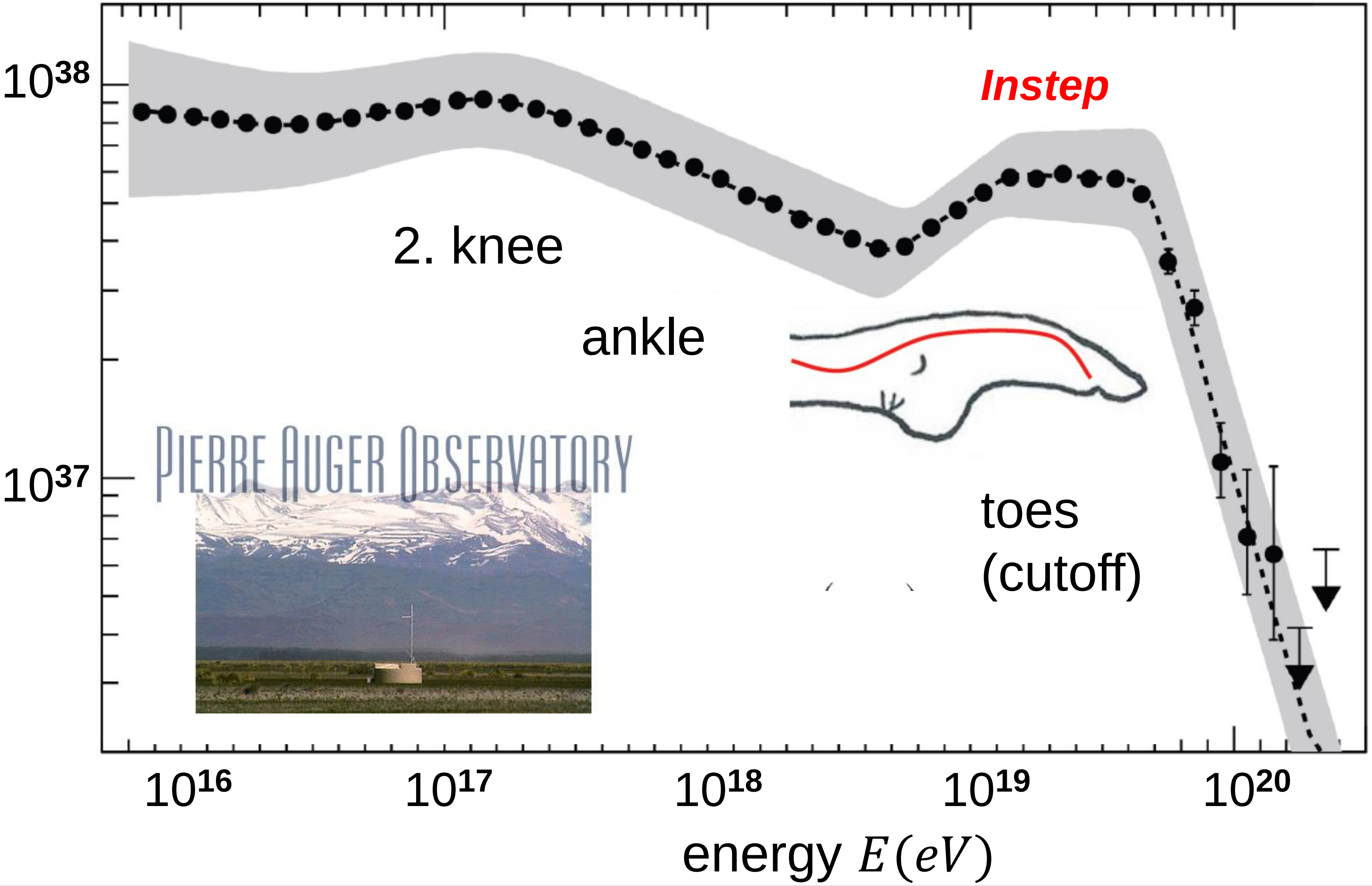
Energy spectrum of UHECR: new Auger results

- **Latest experimental results of the energy spectrum up to $\mathbf{10^{20} eV}$**

- cut-off of energies above $E = 10^{20} eV$:

- not due to GZK-effect

- accelerator reach the maximum energy $\boldsymbol{E_{max}}$



Arrival direction of UHECRs: latest results

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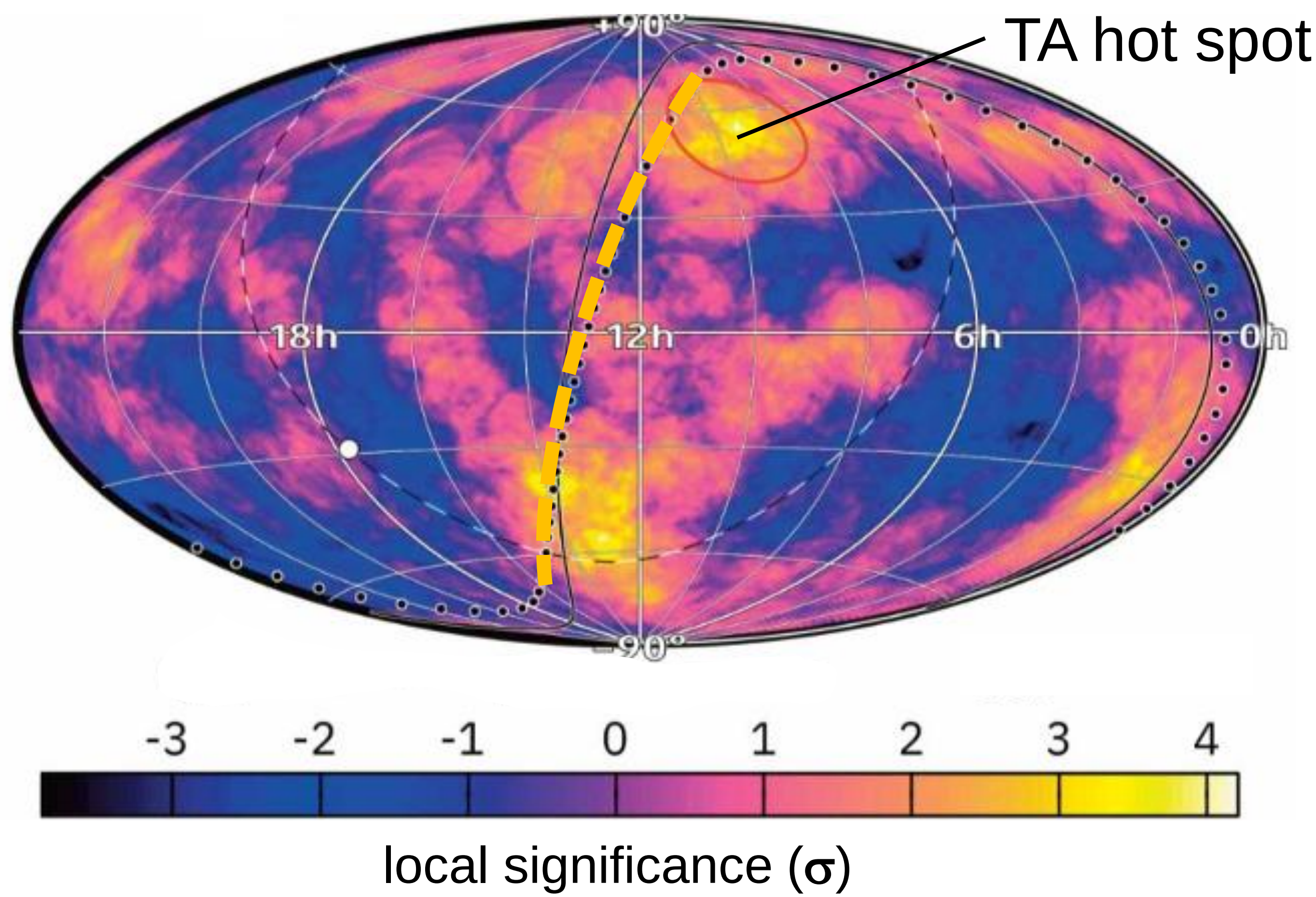
- **UHECRs with $E > 40\ EeV$ (Auger) and $E > 53.2\ EeV$ (Telescope Array)**

- anisotropy of arrival directions of UHECRs well established

- hot spots along the socalled **supergalactic plane (SGP)**

- SGP = plane of local supercluster

- SGP almost perpendicular to galactic plane (GP)



SGP

GP

Local universe: supergalactic plane

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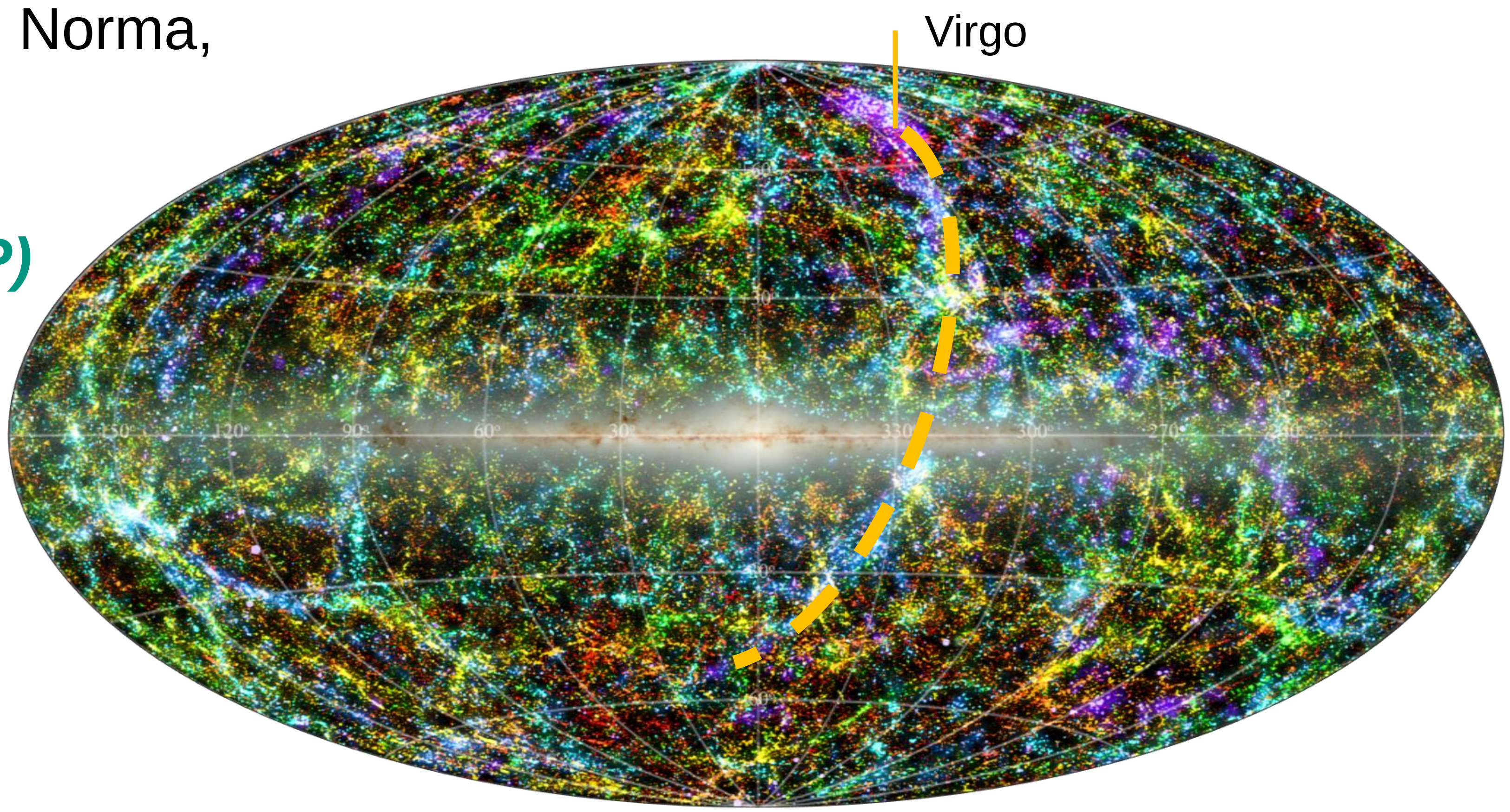
■ Distribution of galaxy clusters in the local universe

- local galaxy clusters Virgo, Norma, Coma, Pisces, Shapley,… are aligned along a thin ***supergalactic plane (SGP)*** (⊥ to galactic plane)

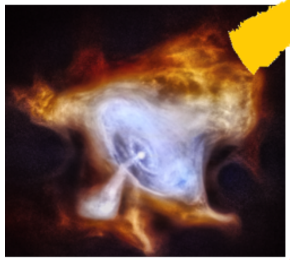
- UHECRs are expected to start in local universe (limited range)

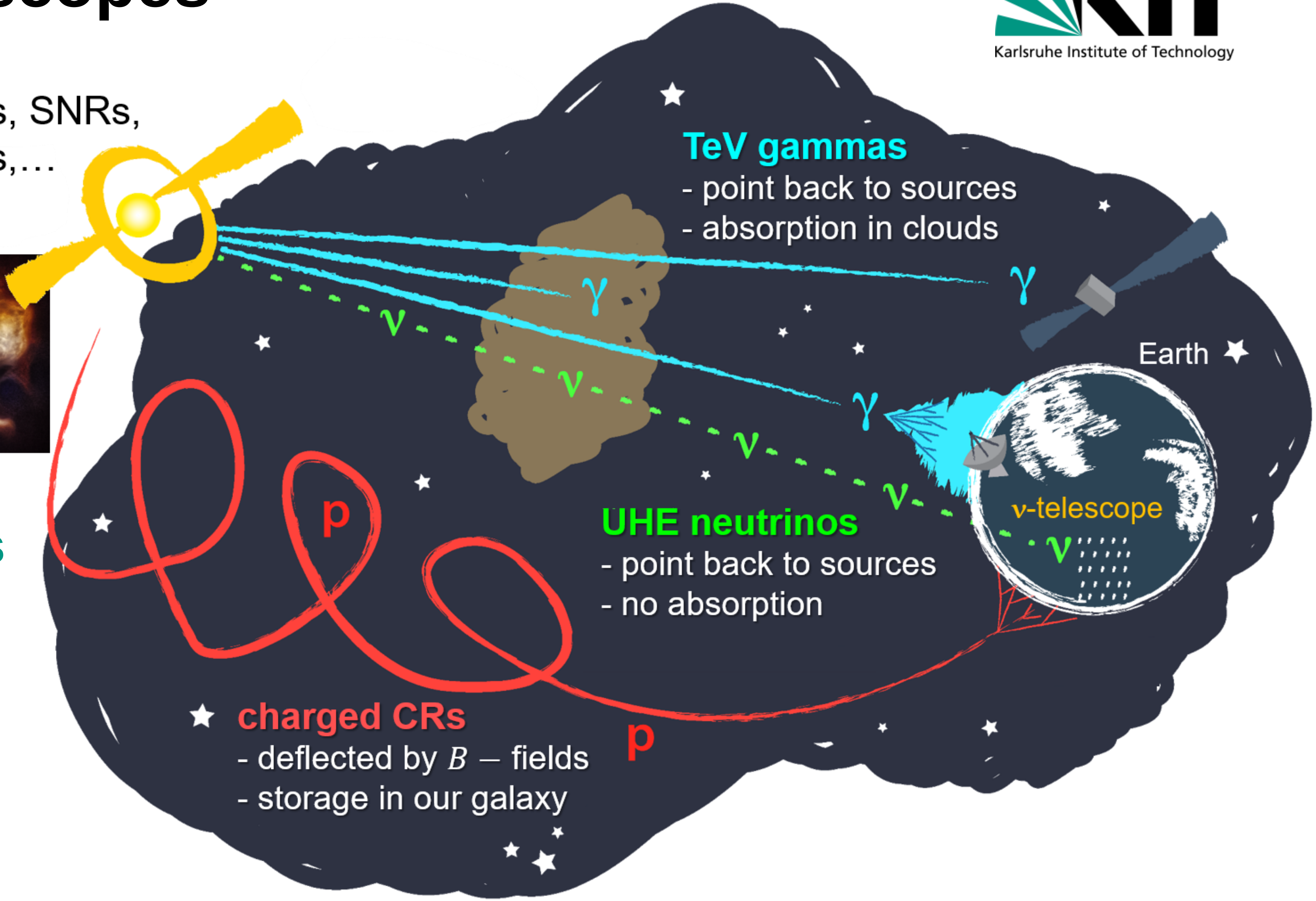
⇨ arrival directions of UHECRs from SGP ☑



2.1.2 Neutrino Telescopes

- **Science goals**



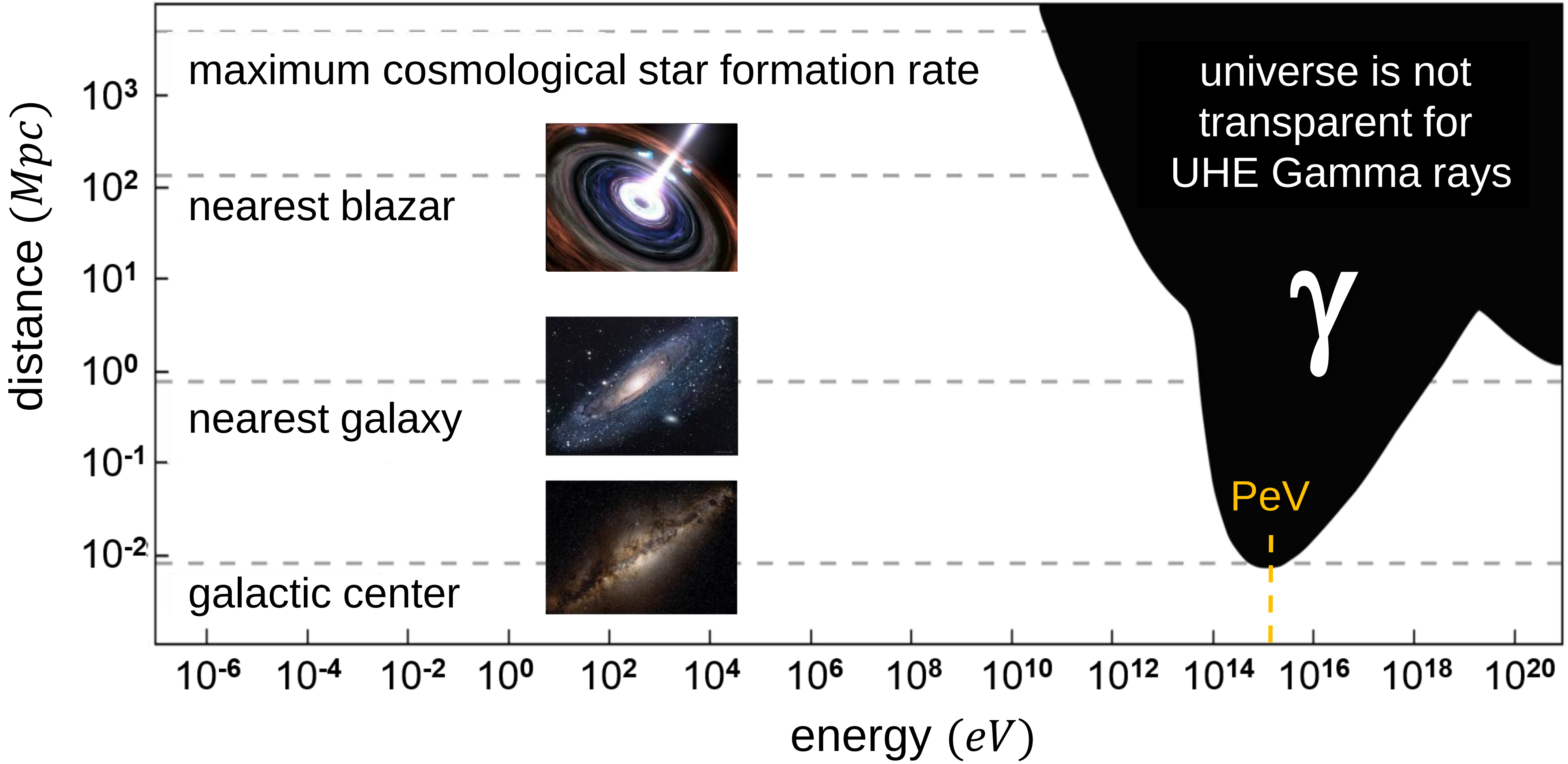


- identification of **hidden UHE accelerators**
- neutrinos as messengers with many advantages:
  - ⇨ no deflection $(Z = 0)$
  - ⇨ no absorption (Gpc)

Neutrinos as messengers: unlimited range

- **Neutral messengers: gammas vs. neutrinos**

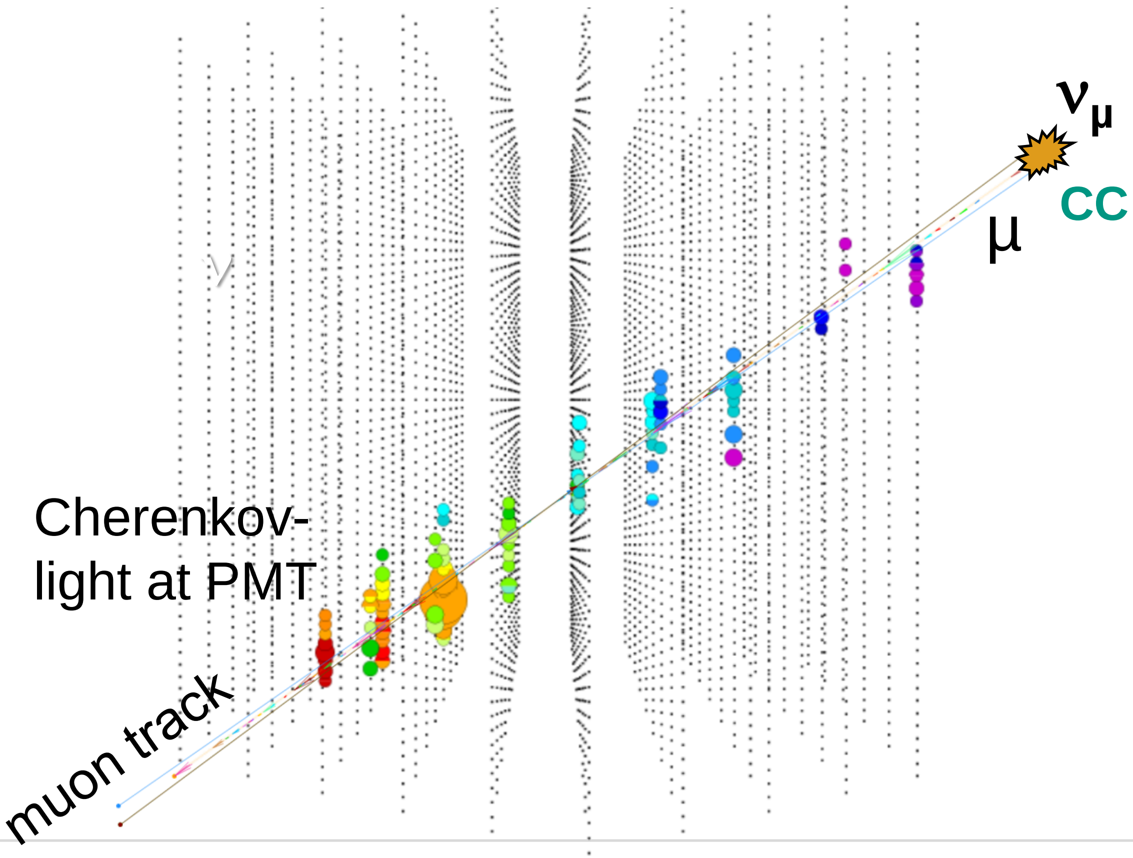
PeV-neutrinos as ideal messengers

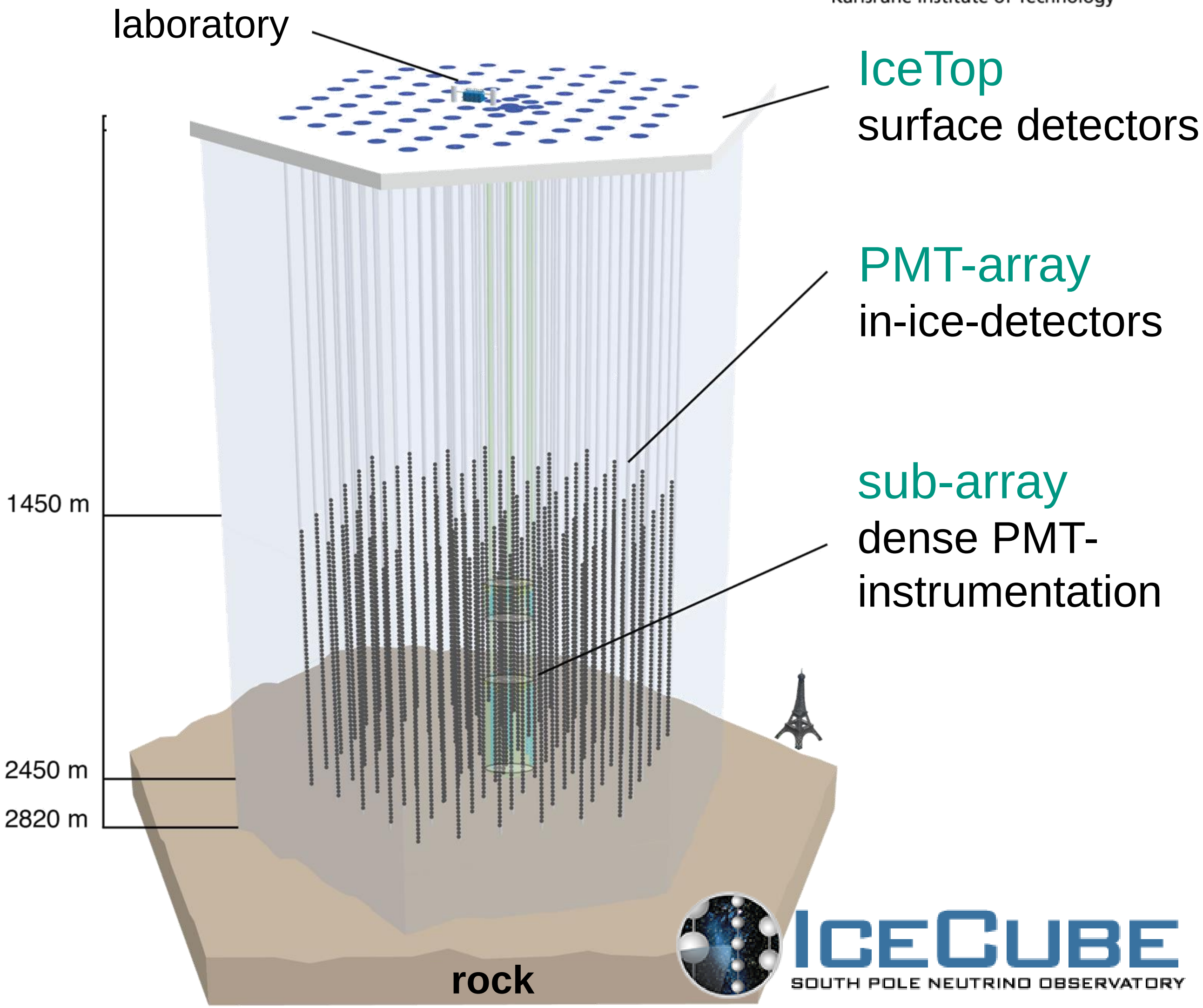


Neutrino telescopes: setup & detection principle

- **IceCube Observatory @ Southpole**

- detection of muons from **CC** reactions

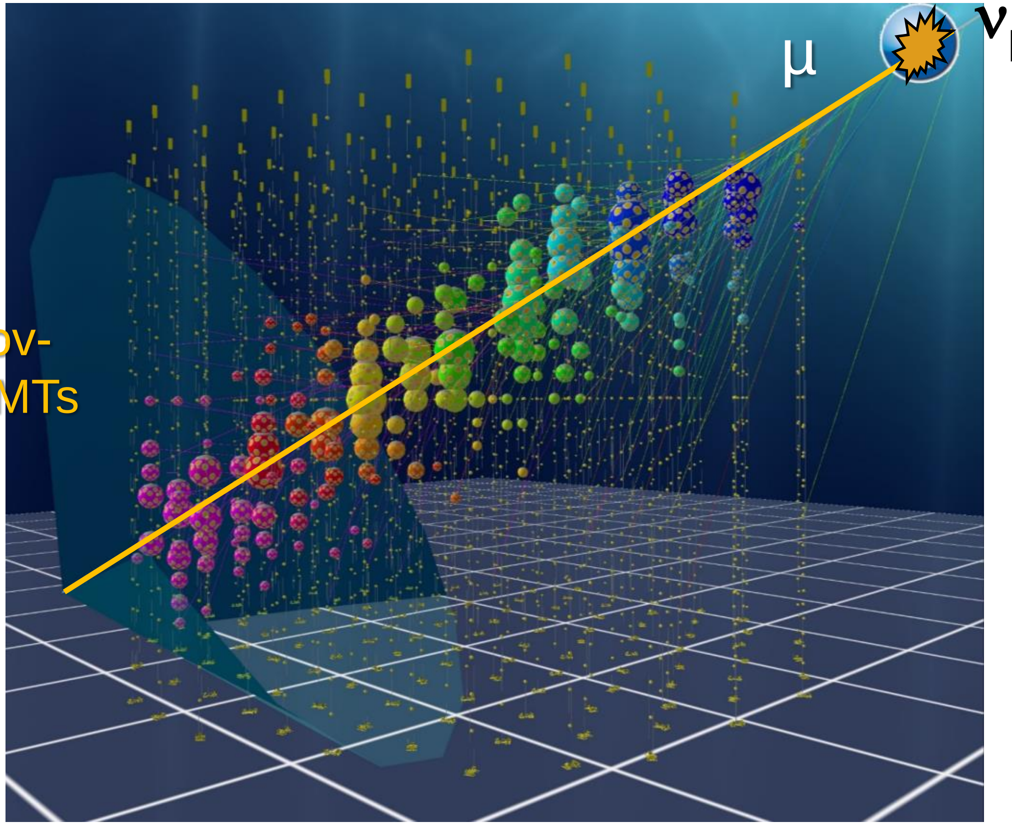


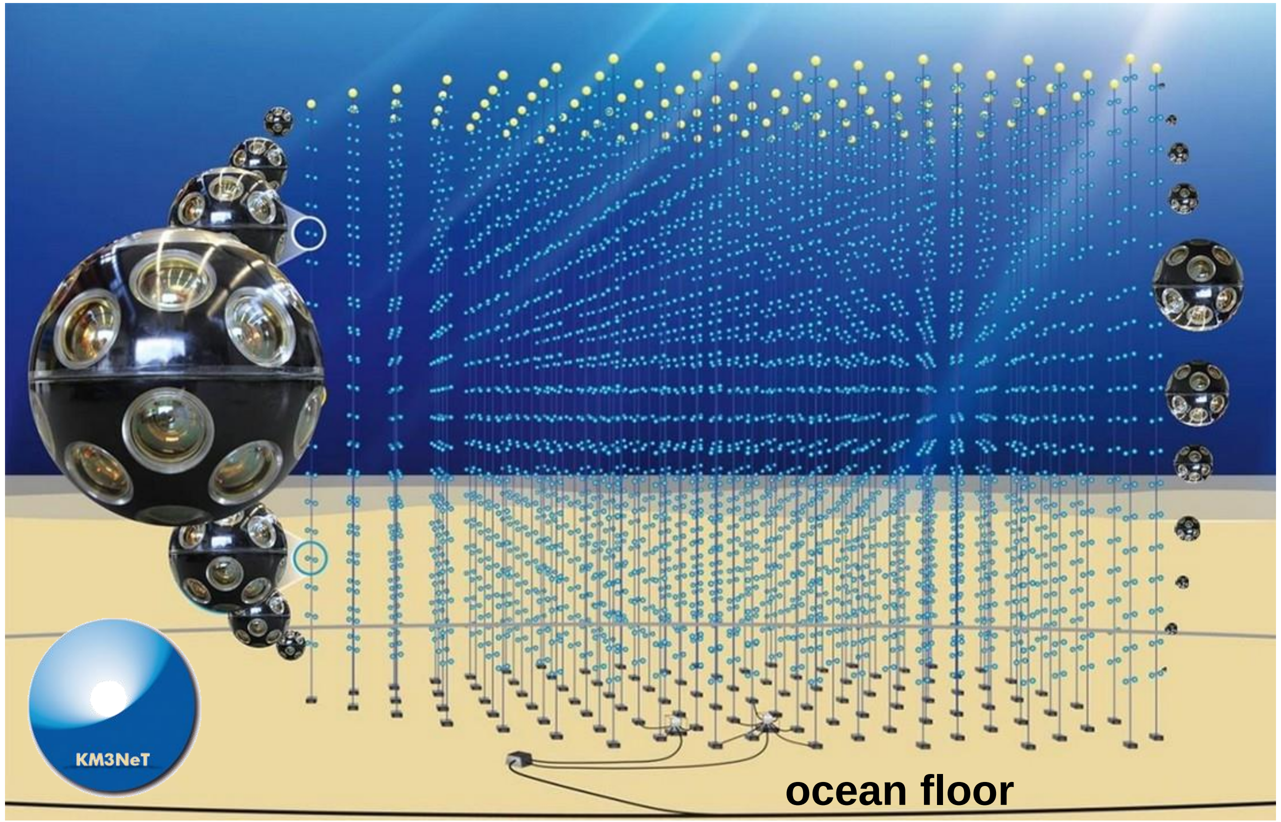


Neutrino telescopes: setup & detection principle

■ **Deep-sea eutrino observatories: KM3Net in the Mediterranean abyss**

- detection of muons from **CC** reactions in a planned $1 \times 1 \times 1\ km^3$ PMT array





Neutrino telescopes: setup & detection principle

- **UHE neutrino detection via charged current (CC) reaction:** $\nu_\mu \rightarrow \mu^- \quad \overline{\nu}_\mu \rightarrow \mu^+$

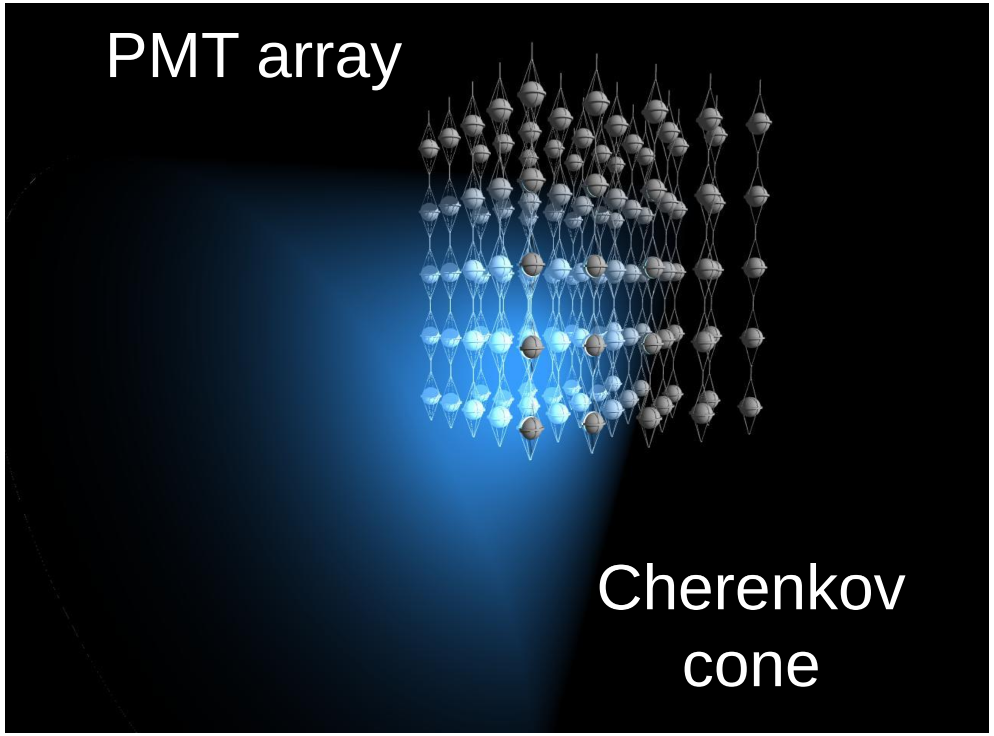
  - ν_μ reactions in matter produce high-energy muons $(GeV - TeV - PeV)$ range
  - decay kinematics: $E(\mu) \sim 0.5 \ldots 0.7\, E(\nu_\mu)$
  - muons with large **range** in ice / water

$$1\,PeV: \; R_\mu = 1.7\,km$$
$$10\,PeV: \; R_\mu = 7\,km$$

  - emission of Cherenkov-light with $\boldsymbol{\Theta_C \sim 43°}$

(water: $n = 1.33$)

$$\cos\Theta = 1/(n\cdot\beta)$$



Neutrino telescopes: setup & detection principle

Karlsruhe Institute of Technology

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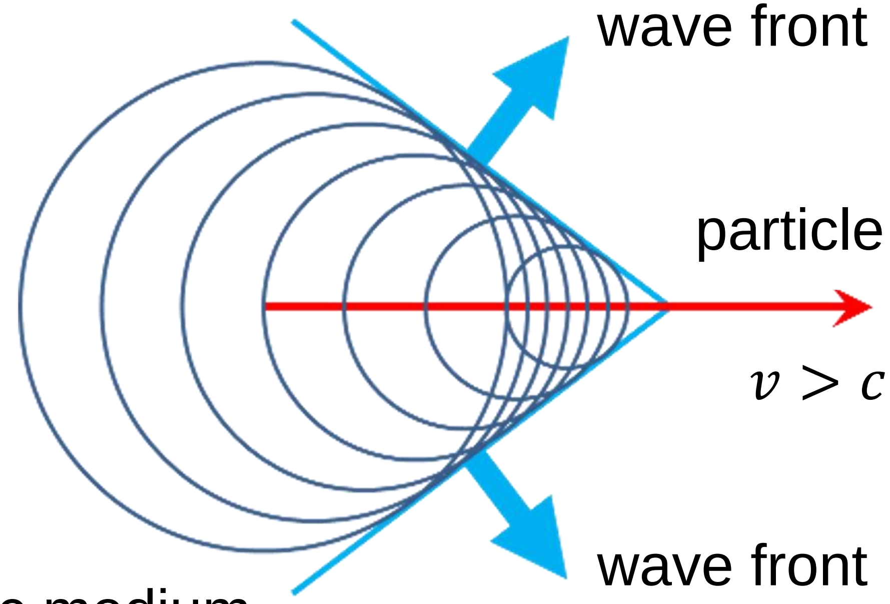
water: $n = 1.33$

$$\gamma_{thres} = 1.52$$
$$\beta_{thres} = 0.75$$



Q: U of Sheffield

Neutrino telescopes in ice & in the deep sea

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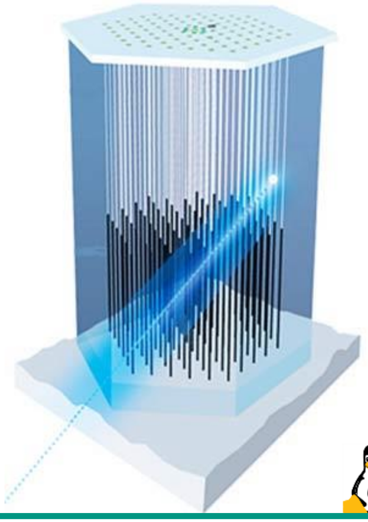
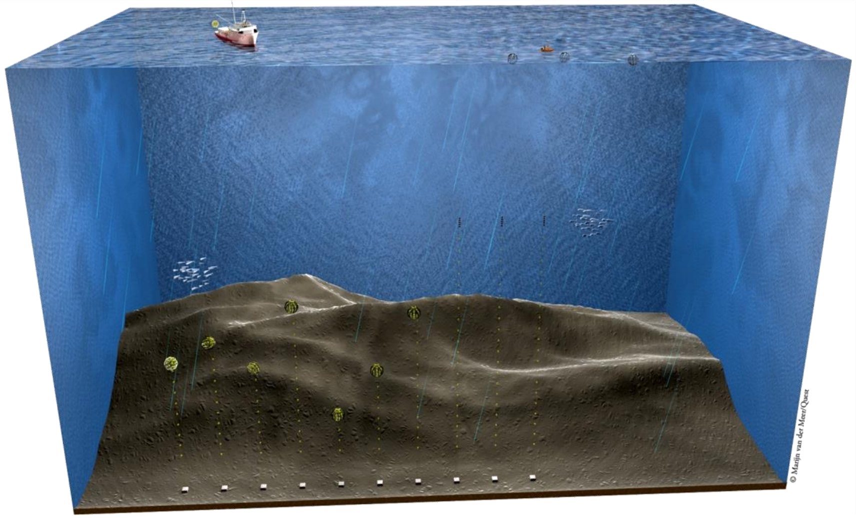
ν-telescope in the antarctic ice

- good optical transparency ☺
- scattering at dust particles ☹
- PMTs with very low noise ☺
- challenging infrastructure 😐
- surface veto ☺



deep-sea-ν-telescope in Mediterranean

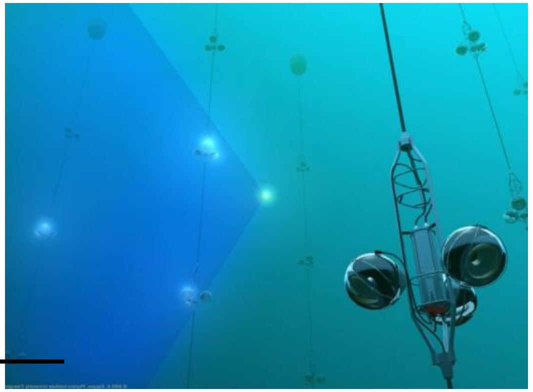
- optical transparency 😐
- motion of PMT-strings (currents) 😐
- PMTs with high background ☹
- challenging infrastructure 😐
- oceanographic studies ☺



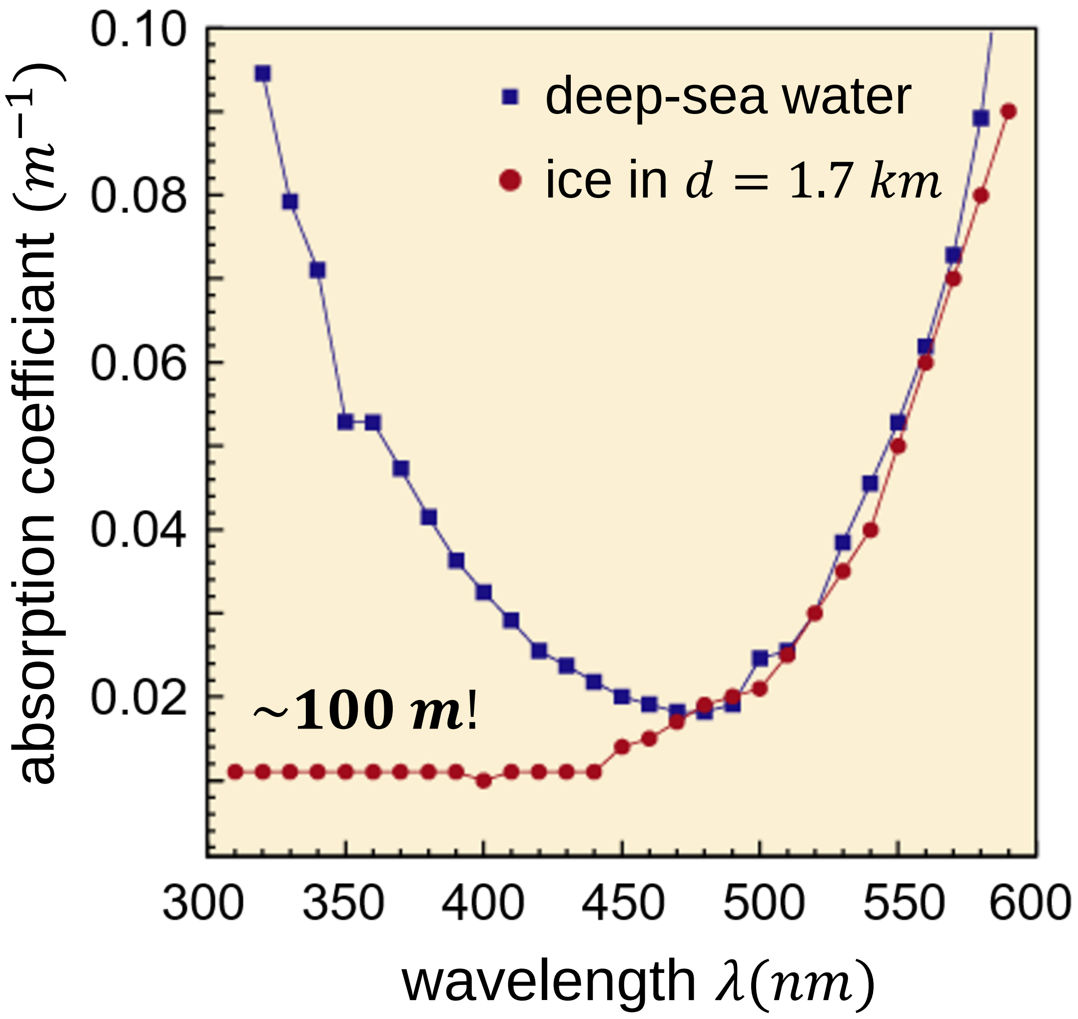
Neutrino telescopes in ice & in the deep sea

- **Ice at the South pole has a much better transparency for $\lambda < 470\ nm$**

transparency at blue wavelengths very important for Cherenkov light



parameter	ice	water
optical transparency	dust	variable
bioluminescence	none	yes
PMT backgroundrate	low	kHz
angular resolution	$0.5 - 1°$	$< 0.3°$



Neutrino telescopes in the deep sea

Karlsruhe Institute of Technology

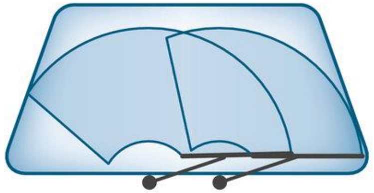
- **Criteria for an optimum site**

- optical scattering

- degree of ocean currents

- bioluminescence

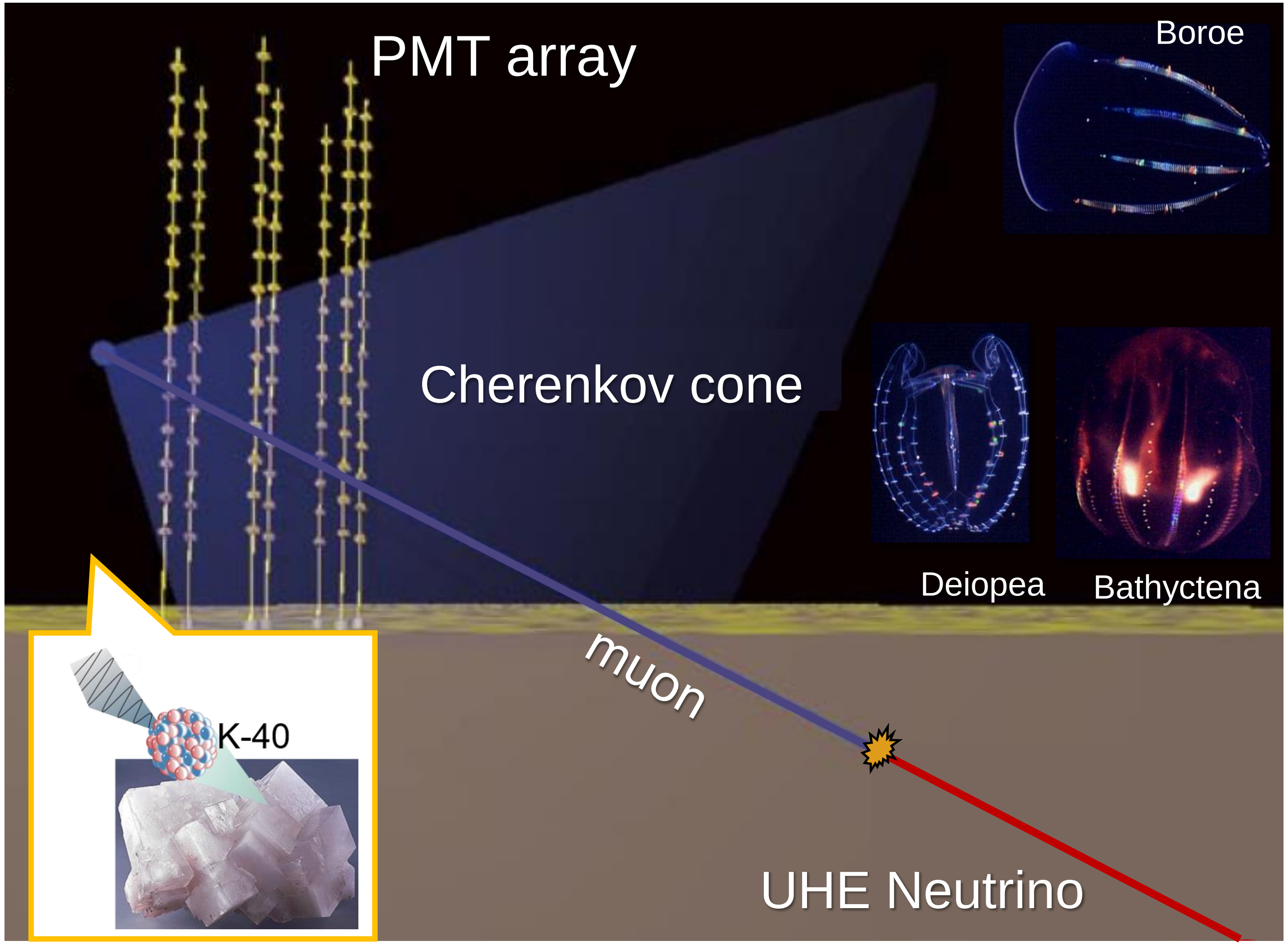
- sedimentation



- K-40 background rate

- topology of deep sea floor

- infrastrucute on land



Neutrino telescopes: deep-sea technology

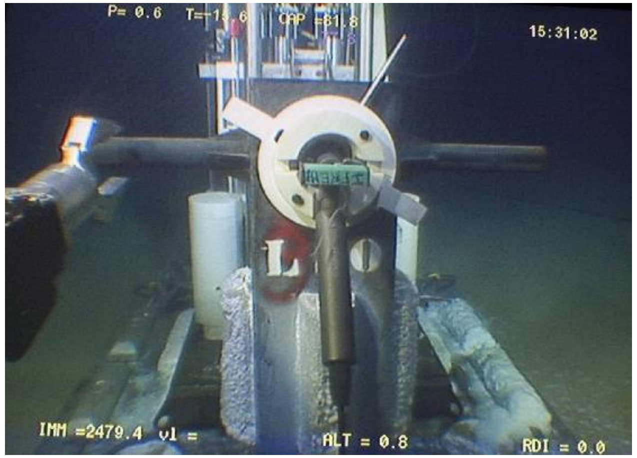
- **technological challenges during PMT installation**

  - deep-sea vessel for PMT- & cable deployment

  - electro-optical cable $(L = 20 - 100\ km)$
    distribution box, $P = 50\ kW$ for 10000 PMTs
    signal bandwidth $< 100\ Gb/s$

  - hydrophones to
    monitor position

  - deep-sea diving
    robot for PMTs



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