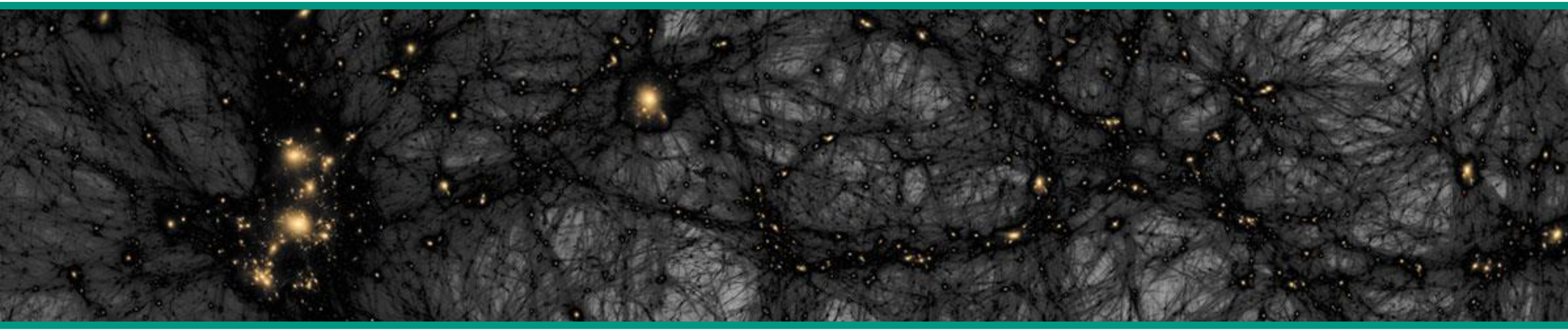
Astroparticle physics *I* – Dark Matter

Winter term 23/24 Lecture 6 Nov. 16, 2023



Recap of Lecture 5

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- **Properties of Cosmic Rays: from the 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 CR – run through outer shock front with β_s
    ⇨ results in **power–law** distribution $N(E) \sim E^{-\gamma}$ (index $\gamma \cong 2.7$)
  - Hillas formula: maximum energy $E_0 \sim \beta_s \cdot Z \cdot B \cdot L$ $\beta_s : 0.03 \ldots 1$
  - galactic CR – propagation: Larmor radius R_L *vs.* galactic disk size (´leaky box´)

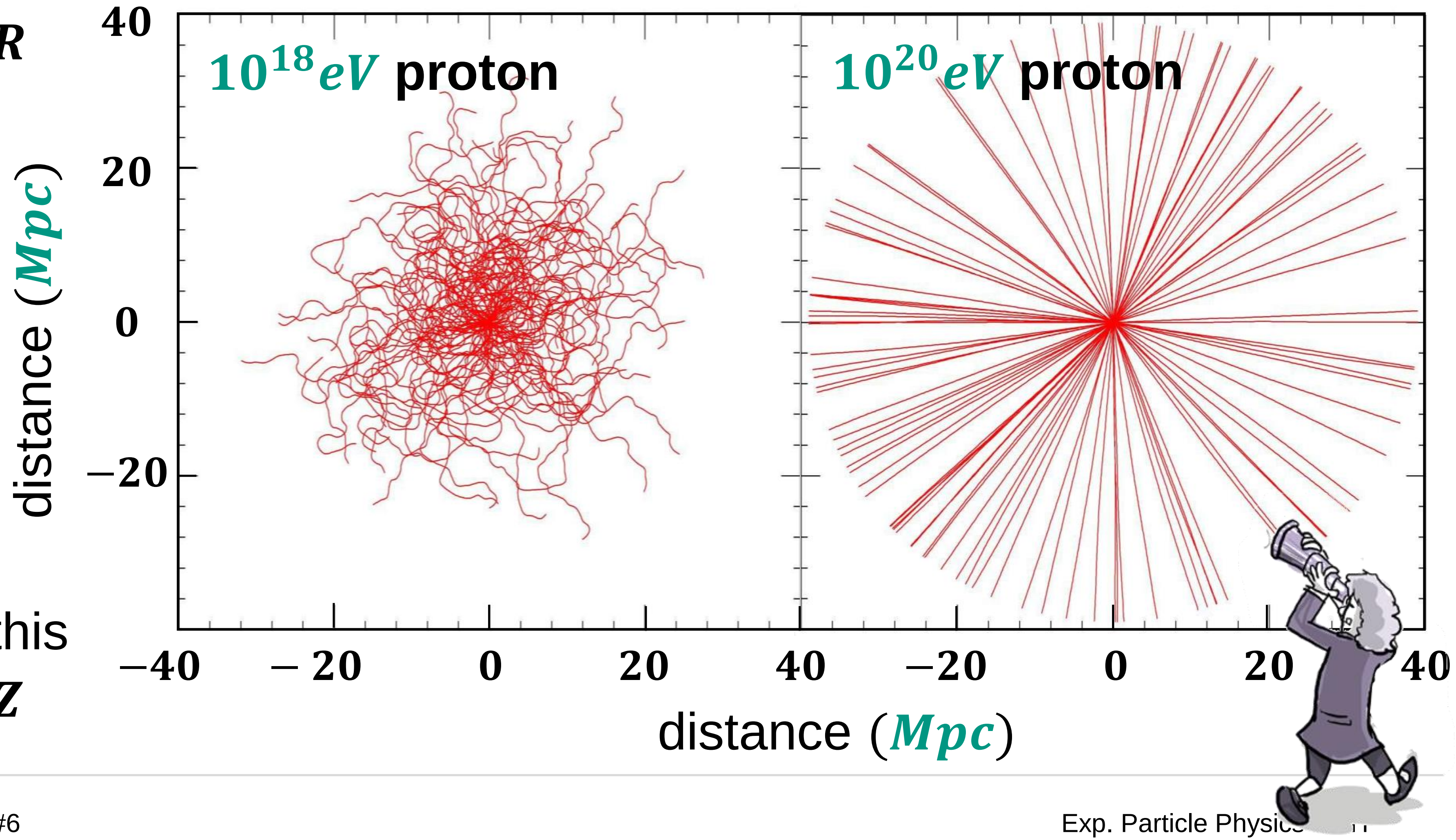
Proton astronomy: seeing wide and clear ?!

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

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

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

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



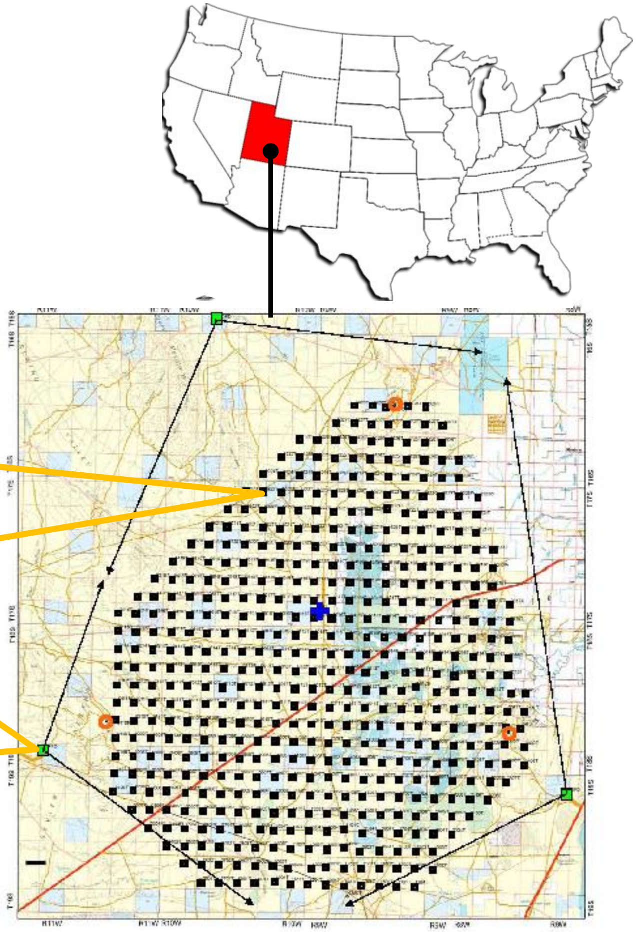
$UHECR$ experiments: $Telescope$ $Array$ (TA)

- **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 $d = 1.2\ km$



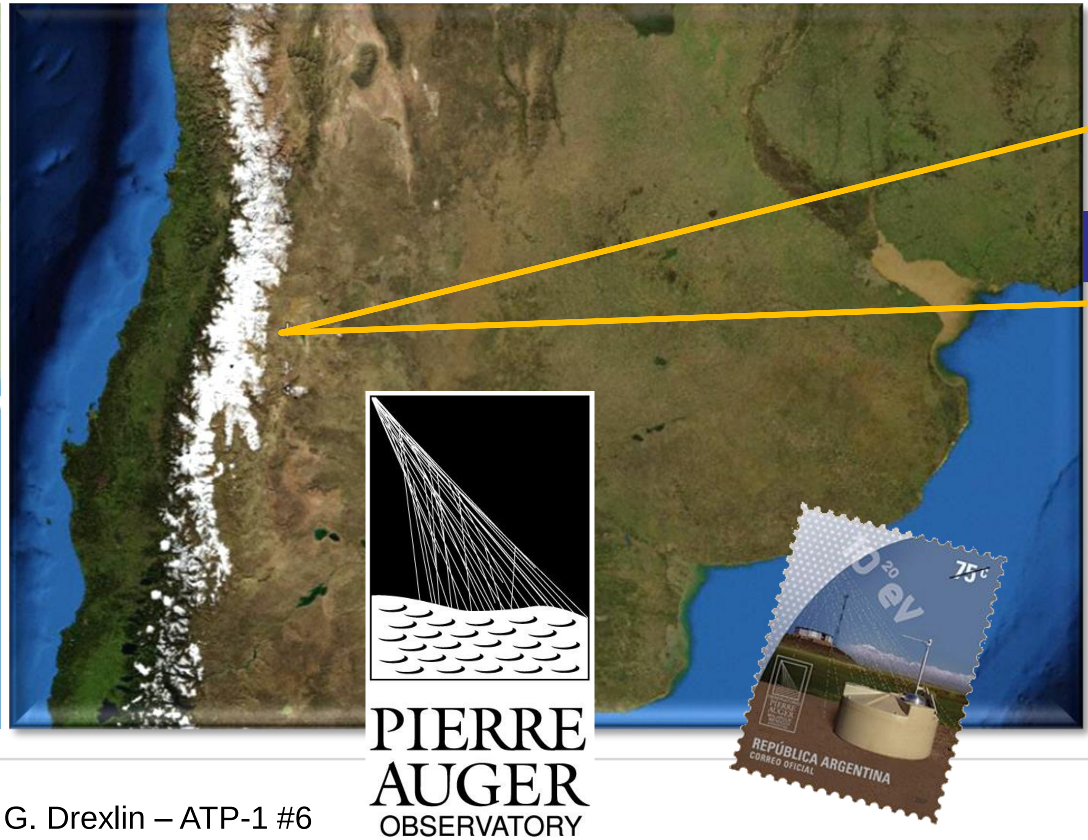
3 fluorescence telescope stations:
$12 \ldots 14$ mirrors & PMT systems each

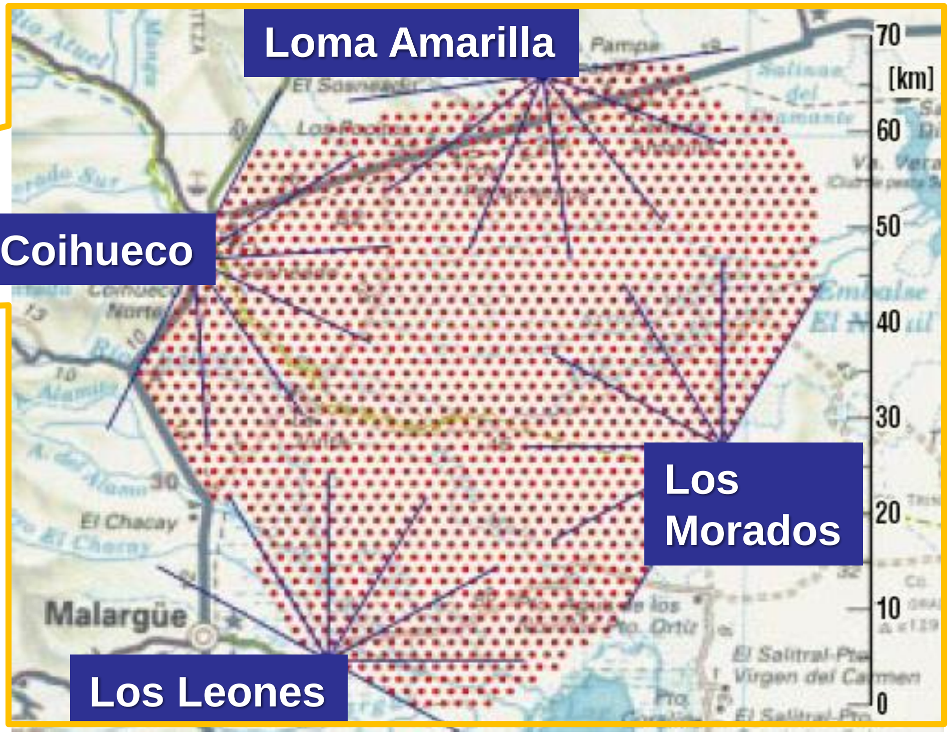
$UHECR$ experiments: Pierre Auger Observatory

- **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

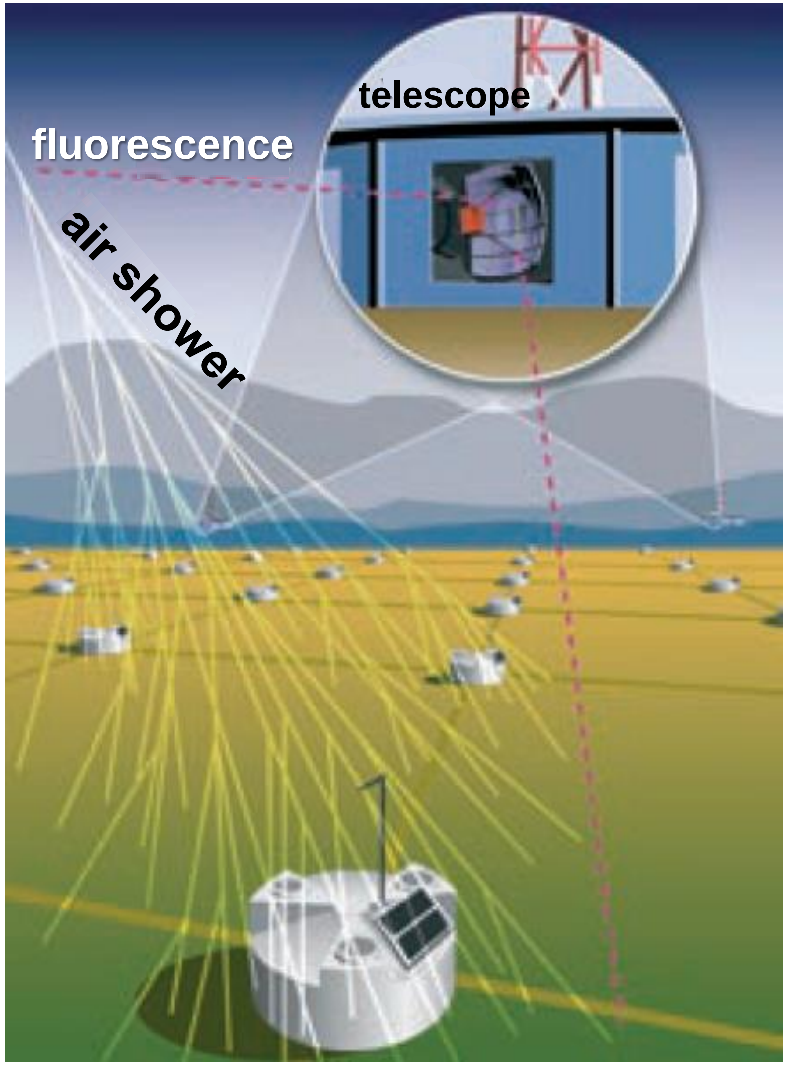
- ***S***urface ***D***etector (***SD***) & ***F***luorescence ***D***etector (***FD***)

4×6 telescopes

elevated sites

1600 H_2O ´tanks´

sampling over $d = 1.5\ km$

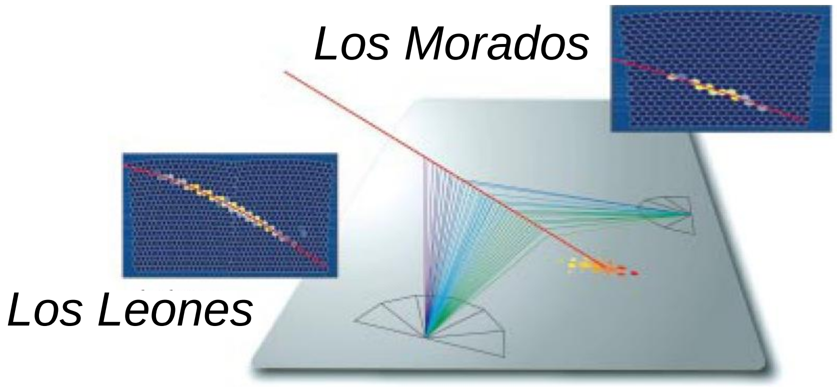


Pierre Auger Observatory: hybrid technology

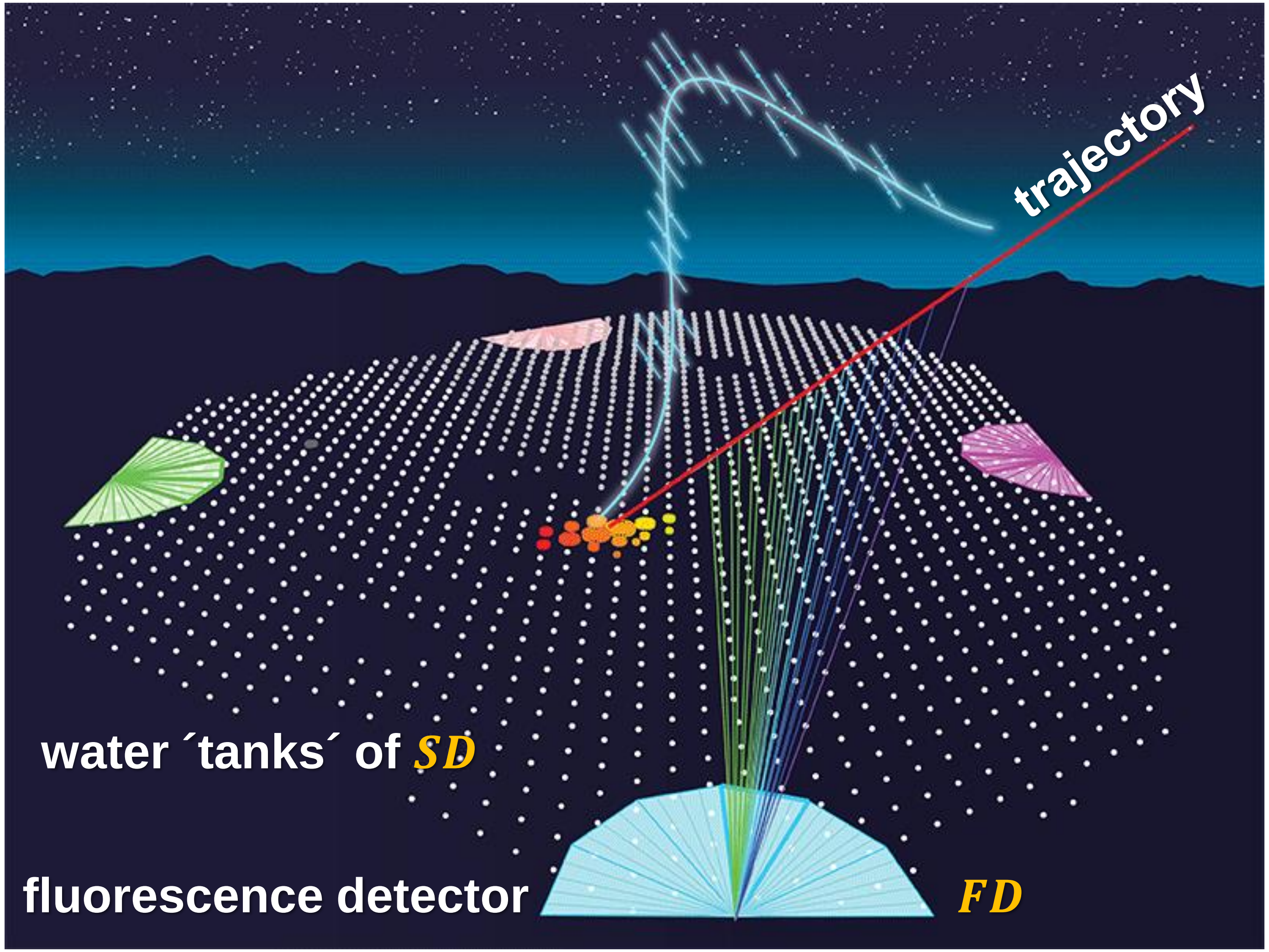
- **Shower observables**

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

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



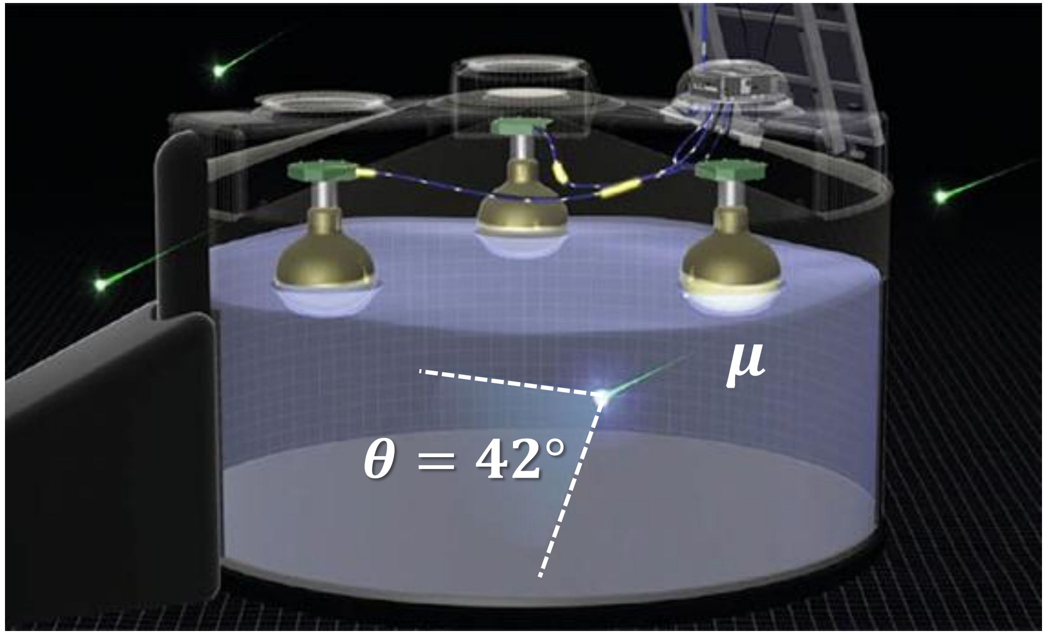
stereo FD event

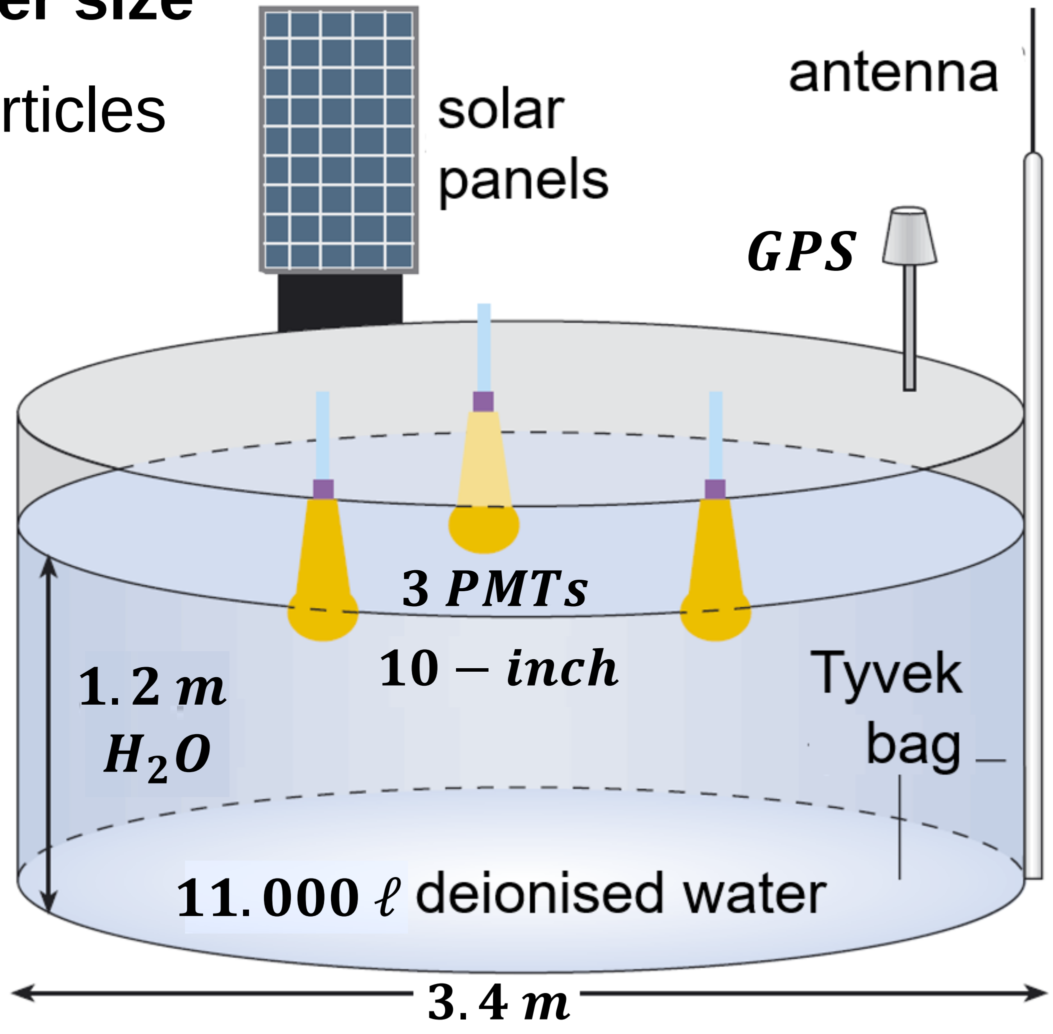


Q: APS

Pierre Auger Observatory: Surface Detector

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



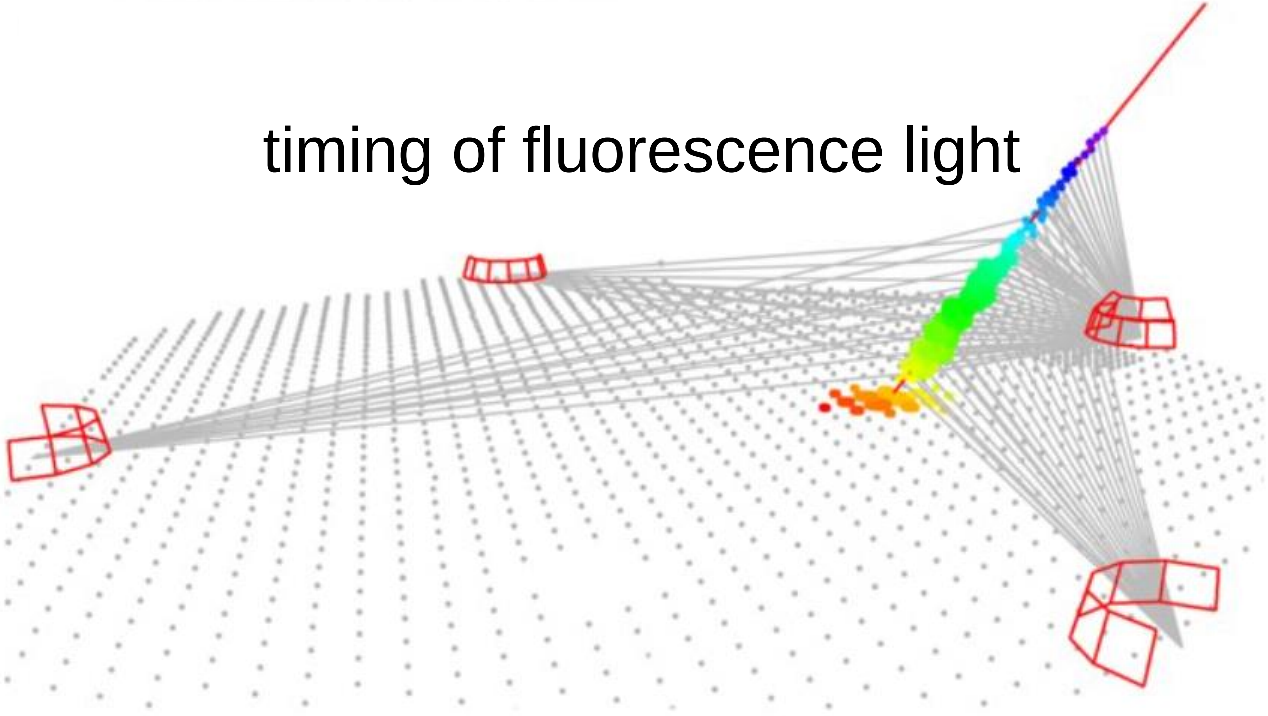


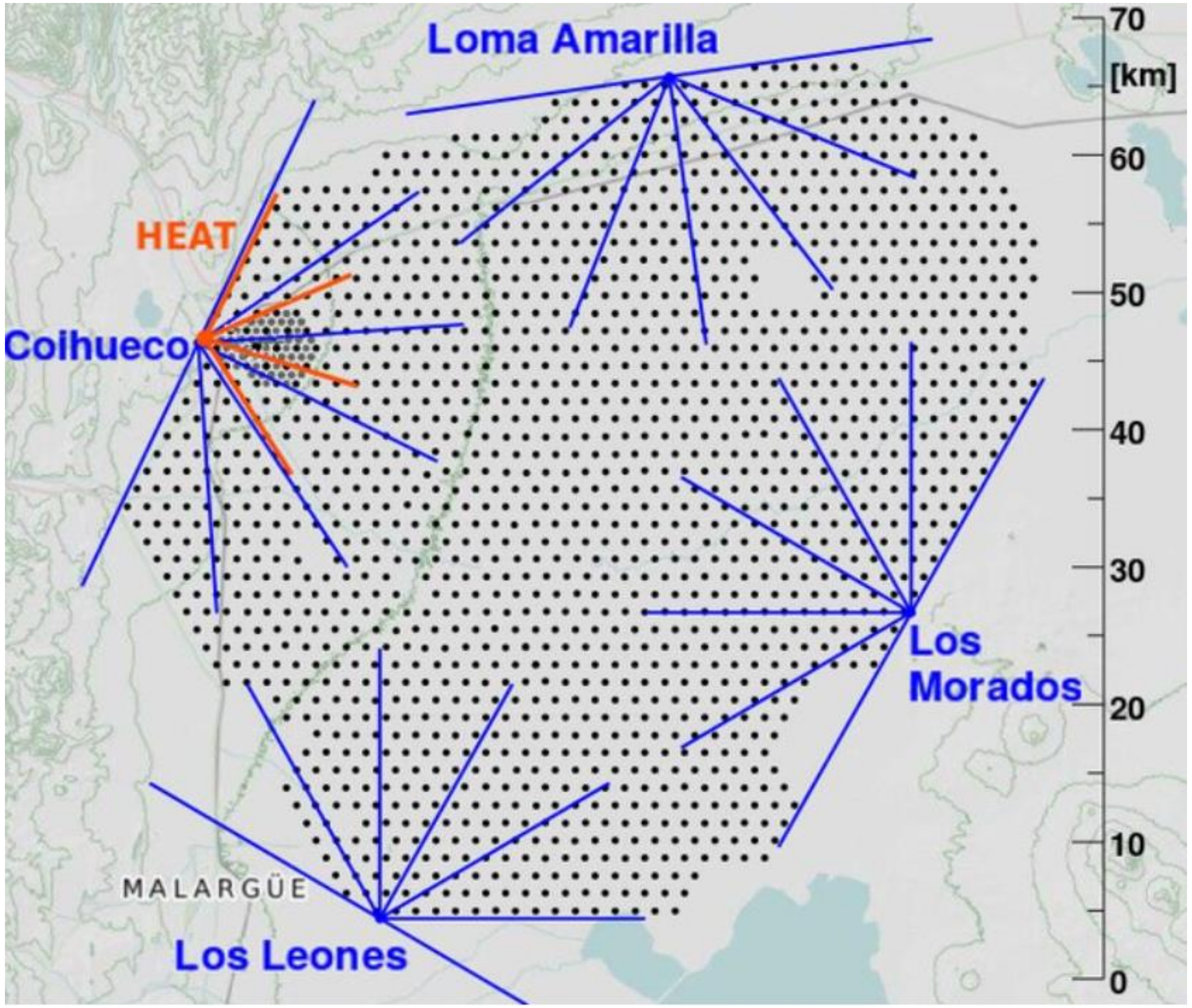
Pierre Auger Observatory: Fluorescence Detector

- **Shower observables via FD**

$$E = 4.7 \cdot 10^{19}\ eV$$

timing of fluorescence light

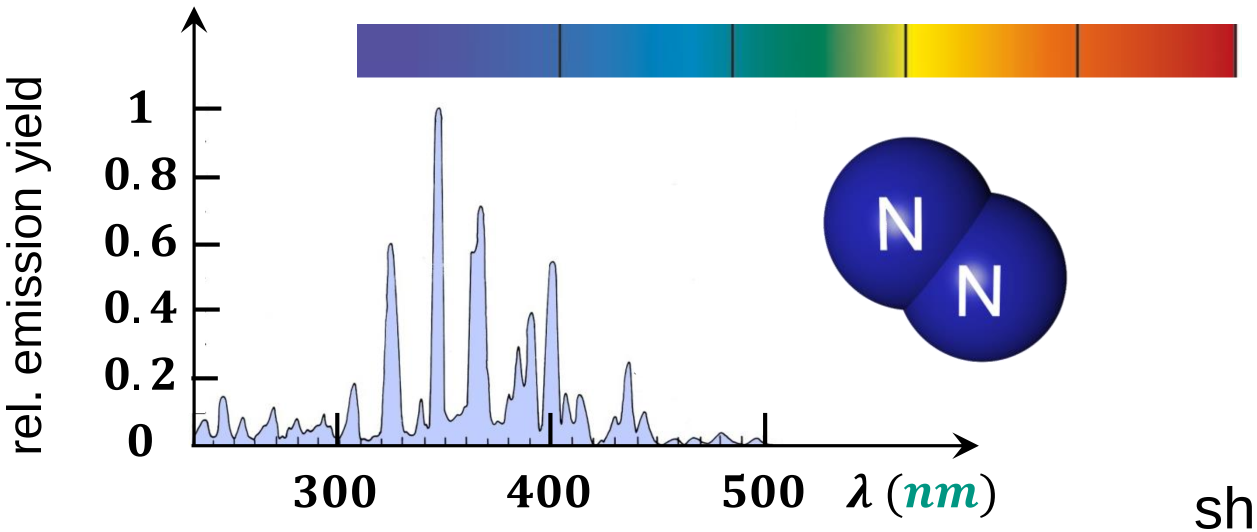


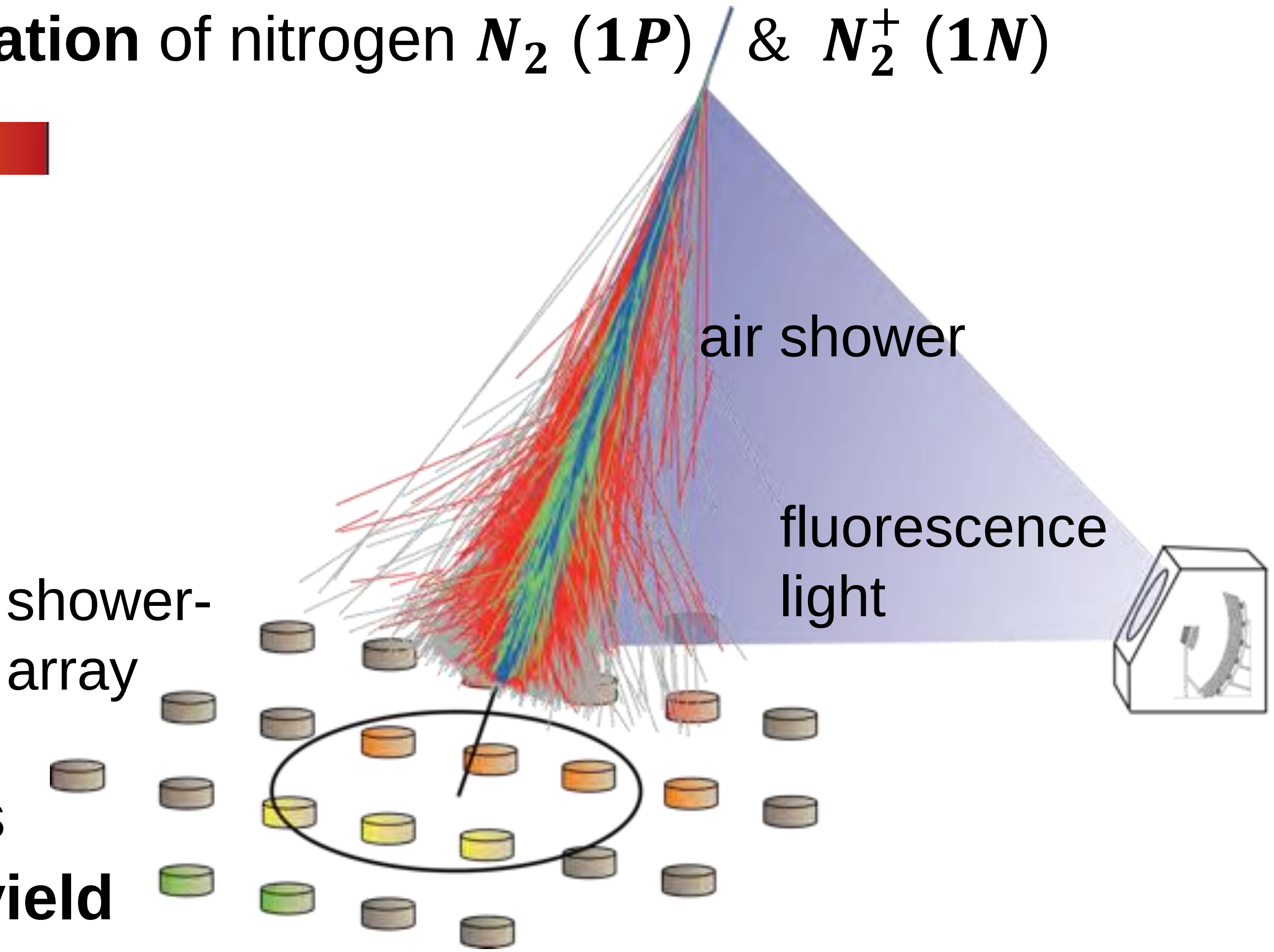


Process of air fluorescence: all due to N_2

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

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





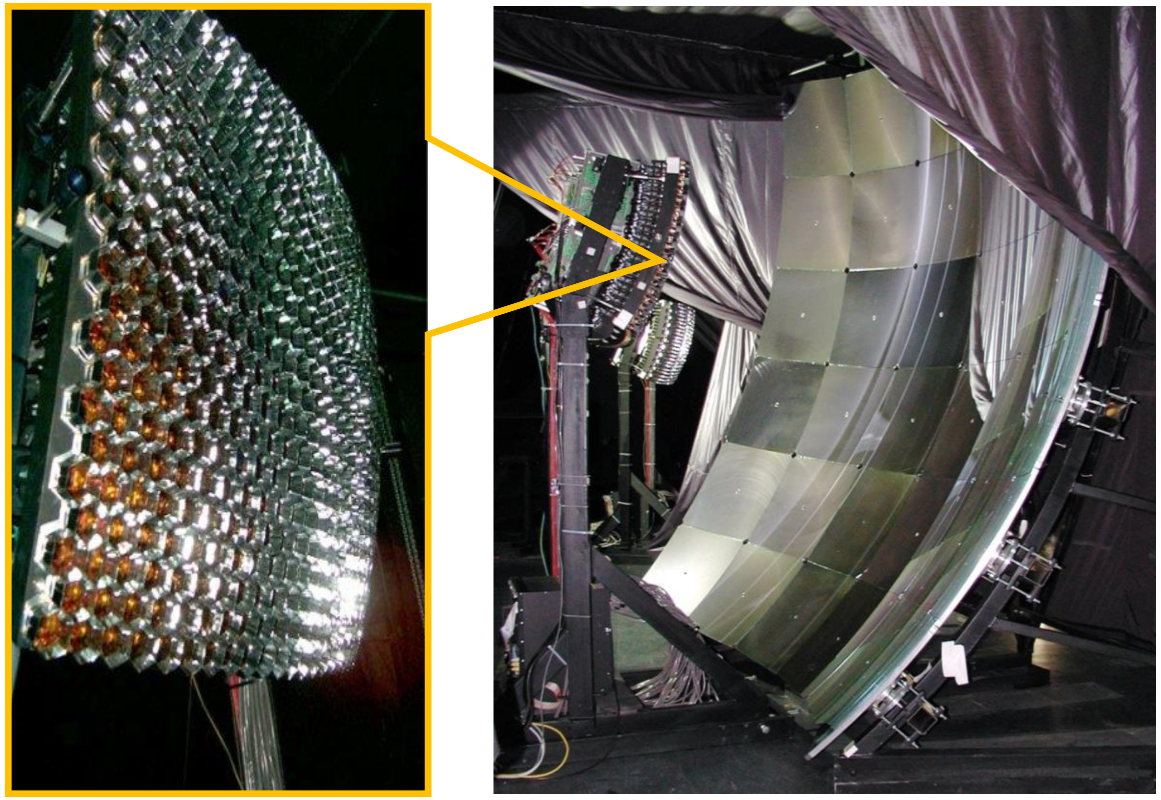
- N_2 fluorescence spectrum (***blue***)

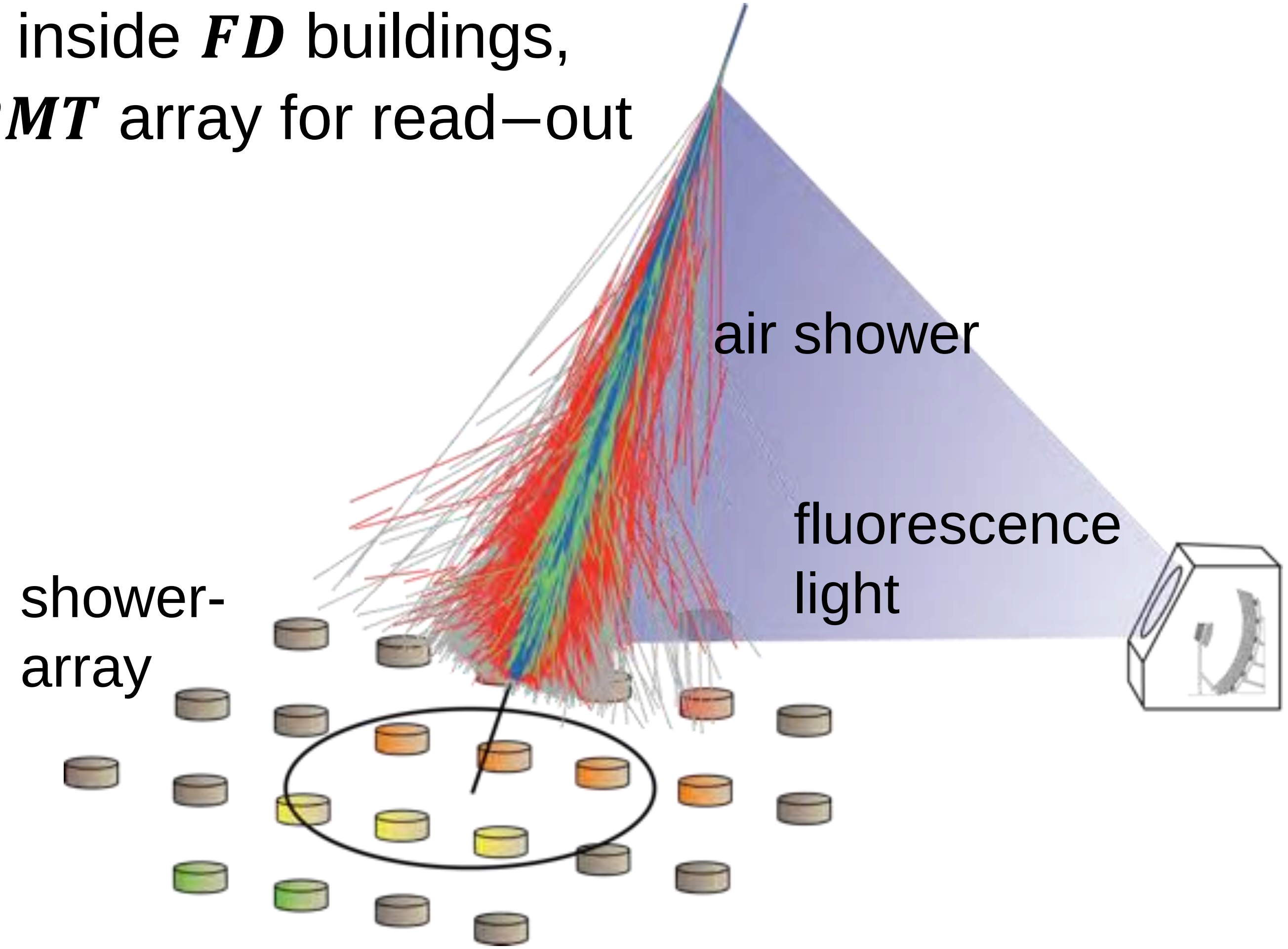
- energy calibration of shower requires precise calibration of **fluorescence yield**

Process of air fluorescence: detection

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

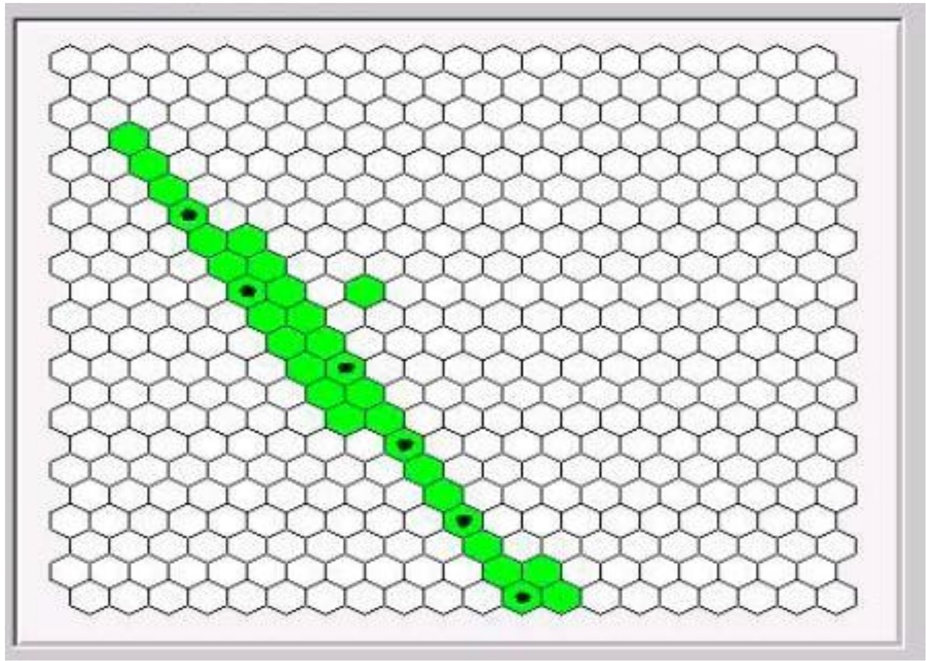
  - large **spherical mirrors** (housed inside FD buildings, secured by daylight shutters) & PMT array for read–out

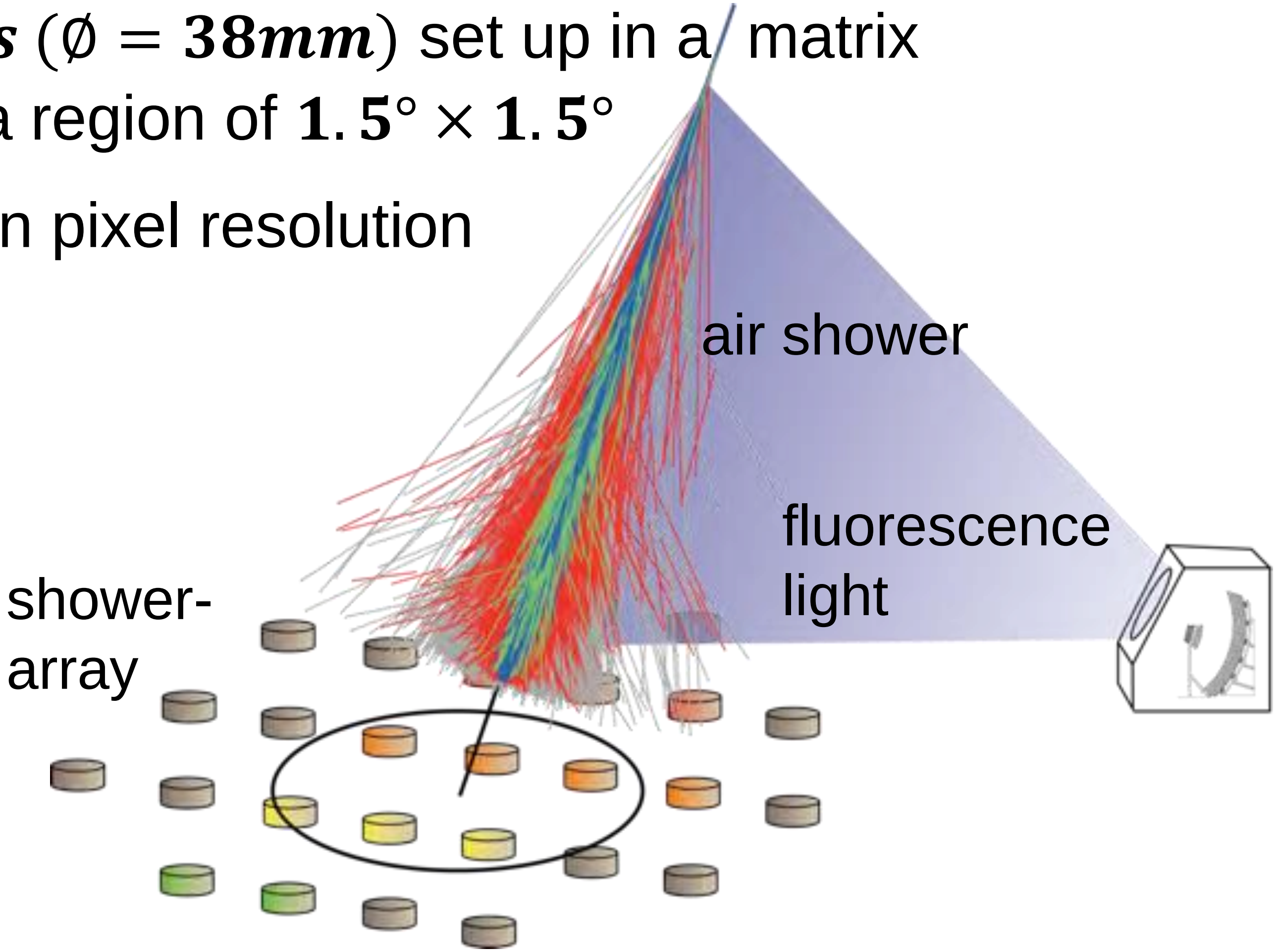




Process of air fluorescence: detection

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





Comparison: Cherenkov light emission in air

- **Air showers also induce 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)

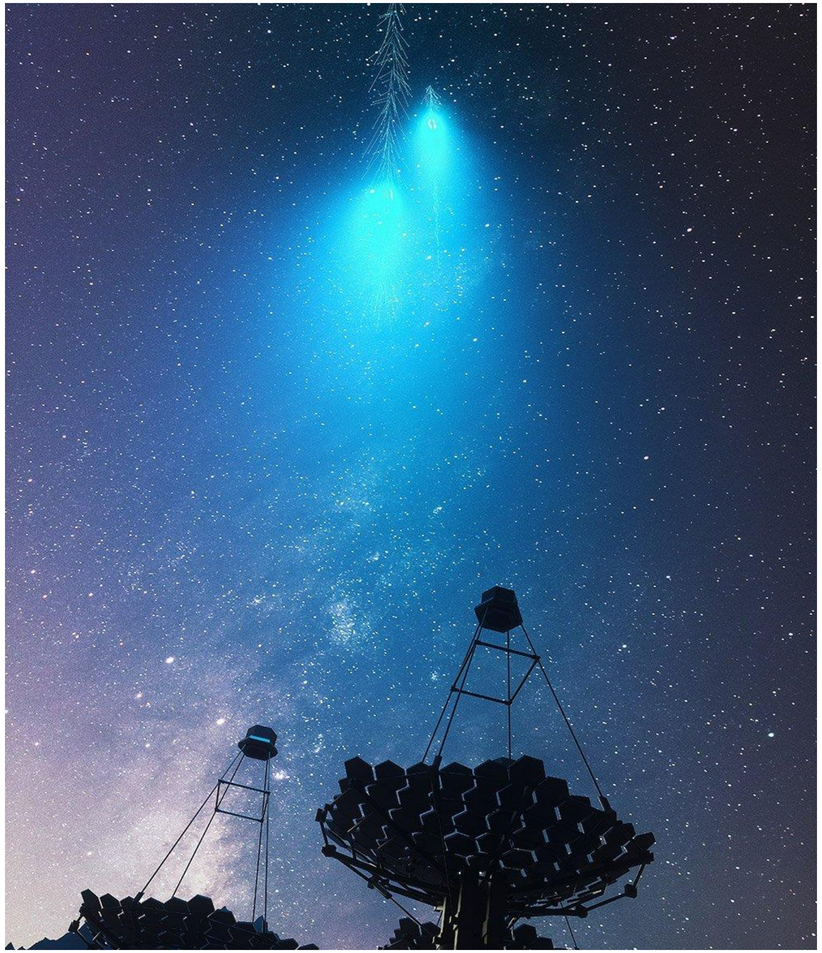
  - after transmission in air of $d = 10\ km$: $\lambda > 300\ nm$

  - **narrow** forward cone

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

opening angle $\Theta \sim 1°$

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

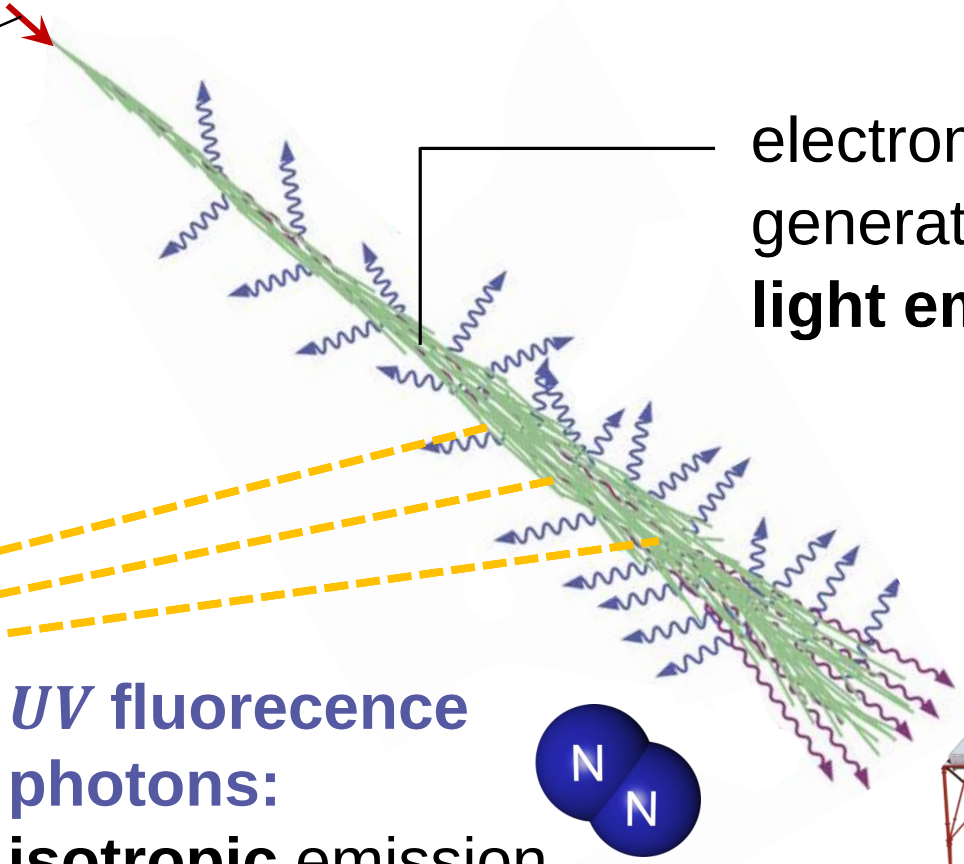


Q: DESY

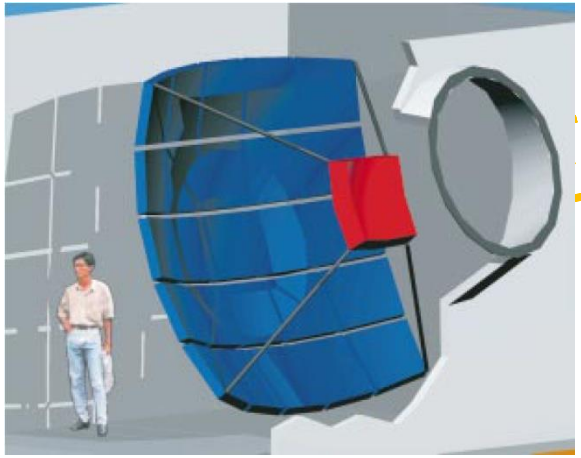
Comparison of fluorescence & Cherenkov light

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

primary particle



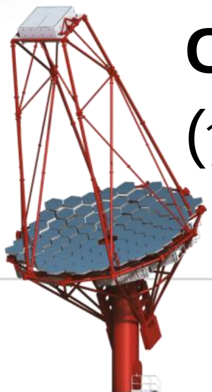
electromagnetic shower with $e^-e^+\gamma$ generates secondaries which induce **light emission** in atmosphere



fluorescence telescope

UV **fluorecence photons:**
isotropic emission

Cherenkov photons:
forward–peaked emission

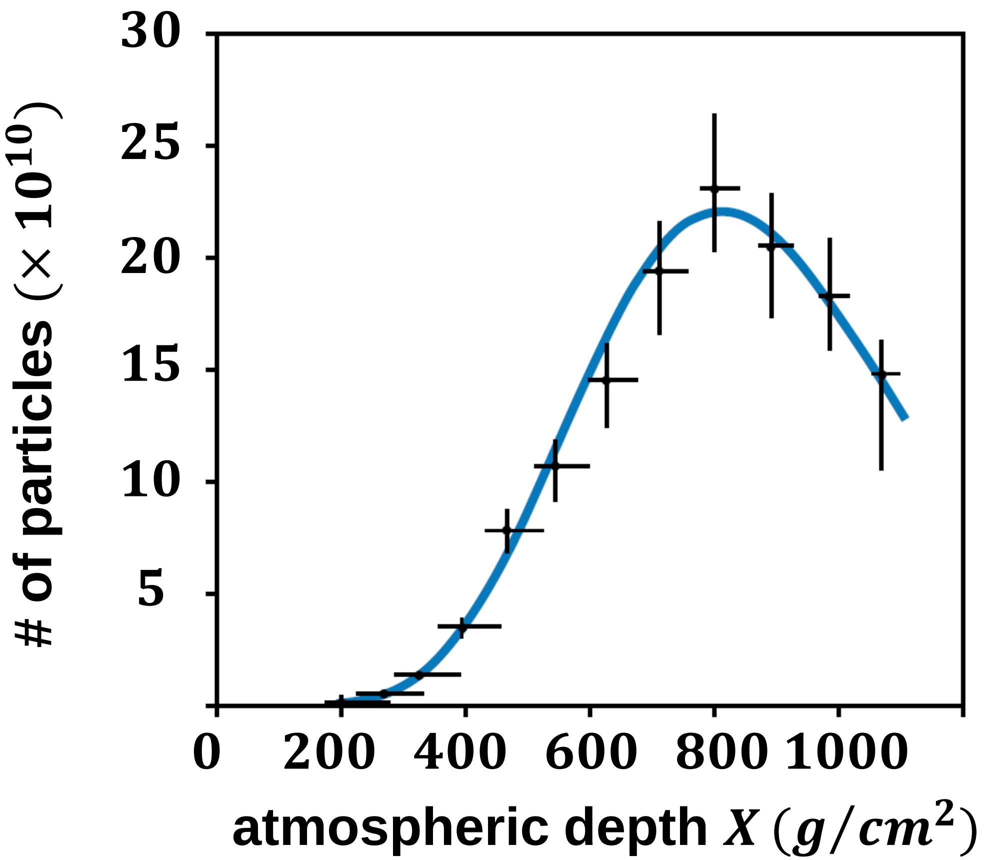


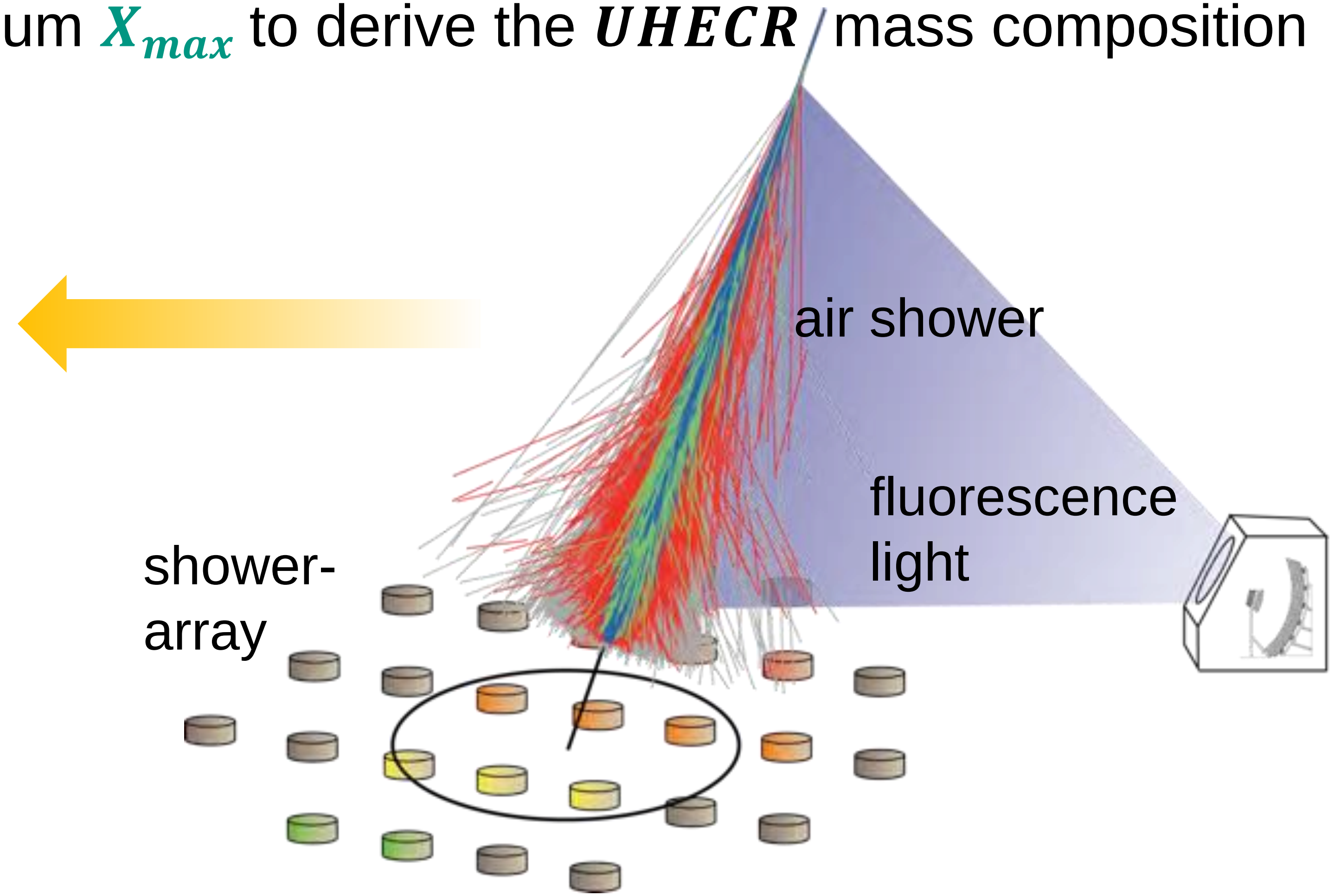
atmospheric **Cherenkov** telescope (γ – astronomy, see lect. **8**)

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

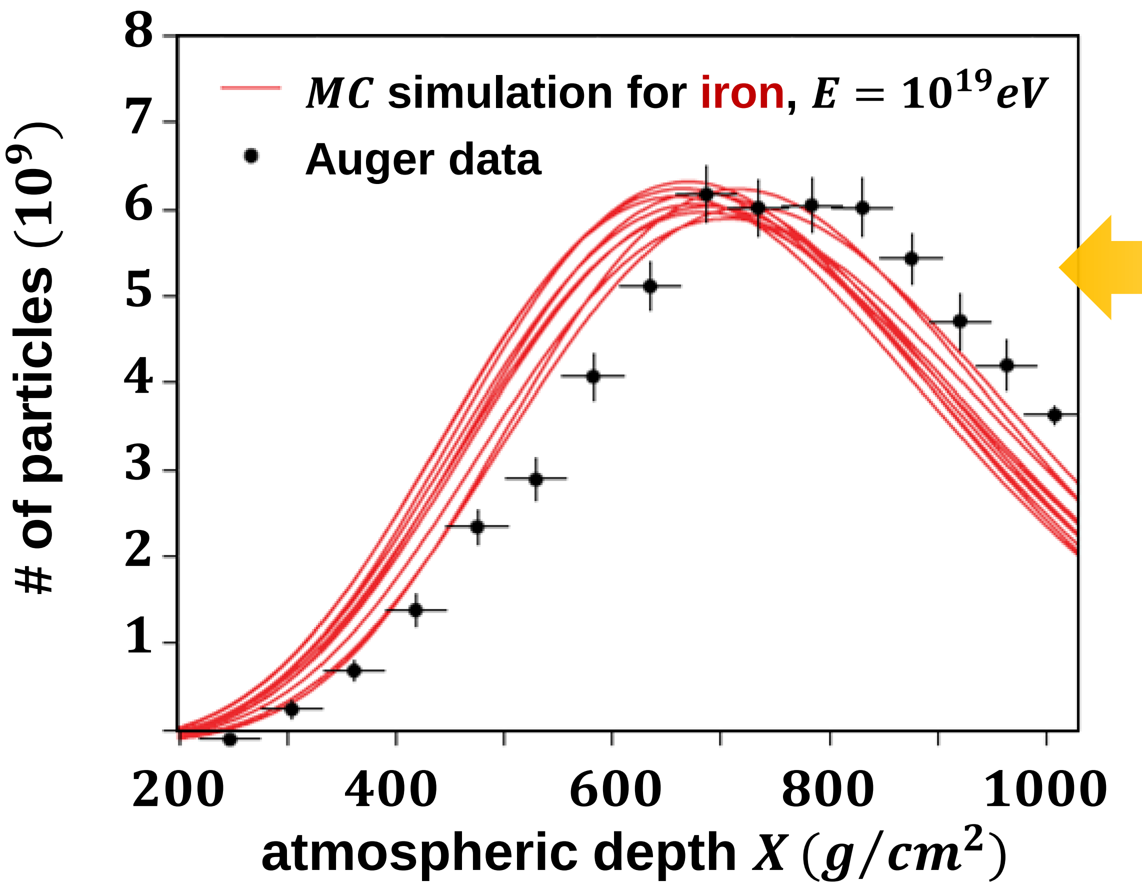


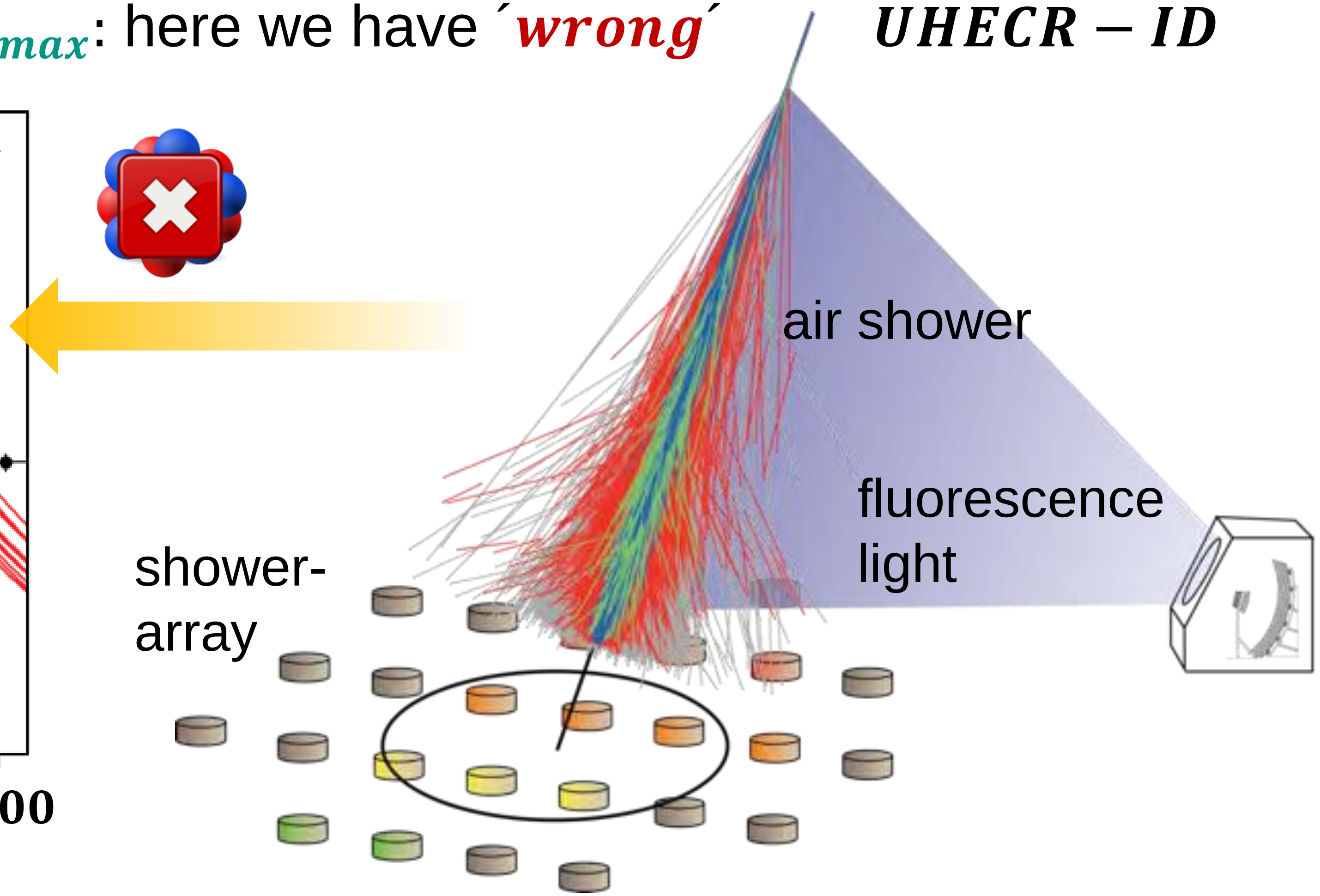


Pierre Auger Observatory: comparison to MC

- $UHECR$ observable: data compared to $MC-$ simulations for a shower by ^{56}Fe

  - comparing shower maximum X_{max}: here we have ´*wrong*´ $UHECR-ID$

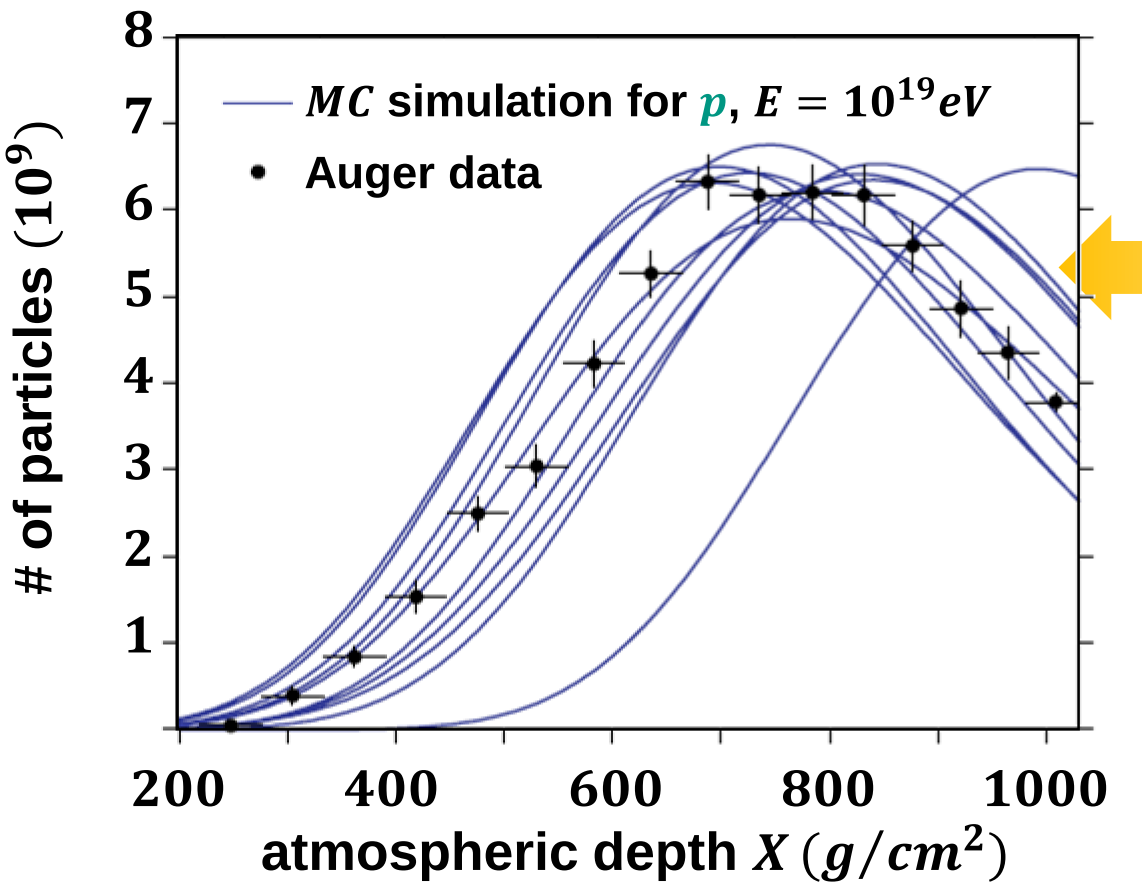


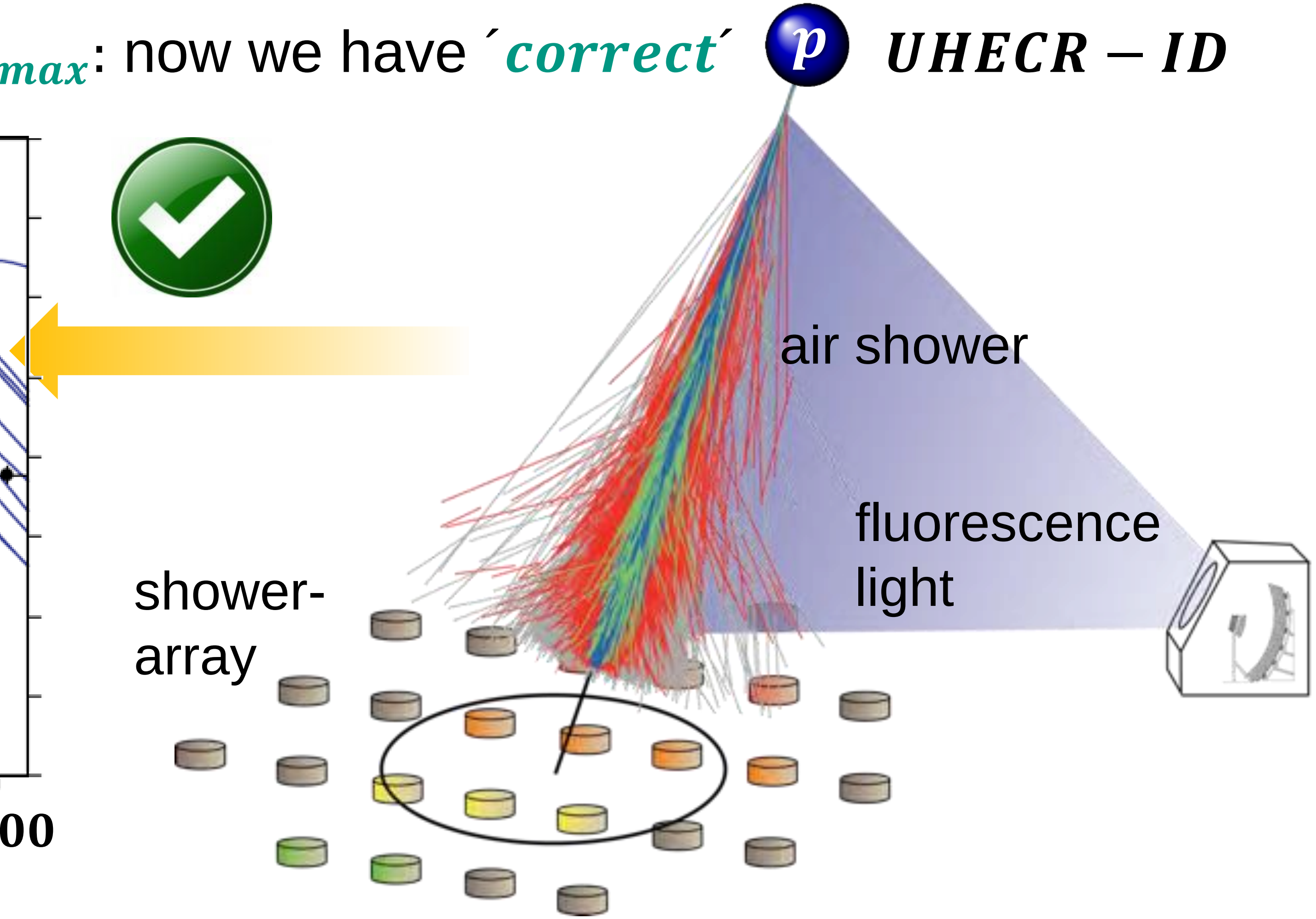


Pierre Auger Observatory: comparison to MC

- $UHECR$ **observable: data compared to** $MC -$ **simulations for a shower by a** p

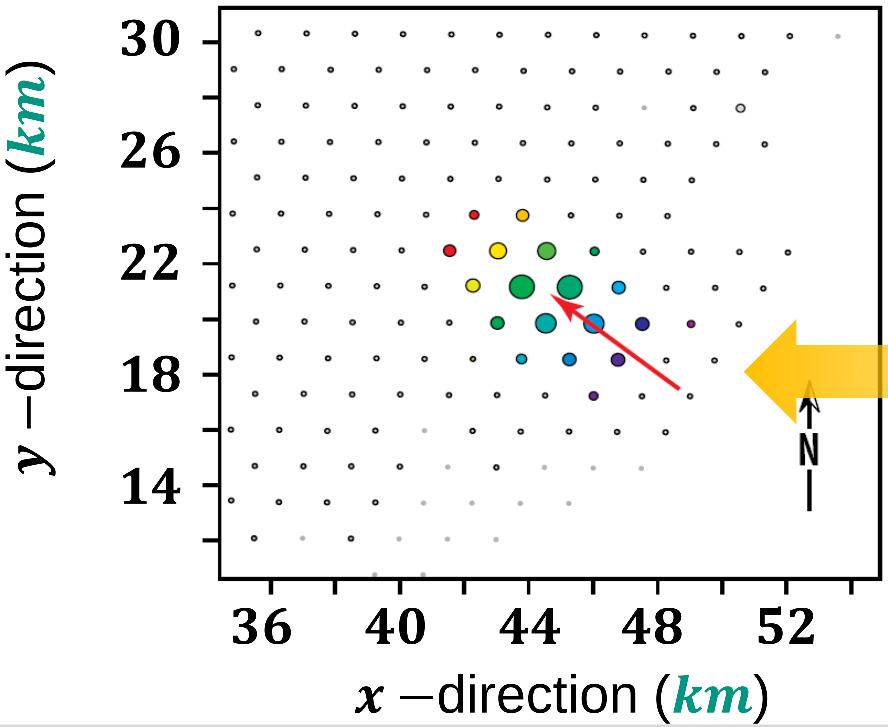
  - comparing shower maximum X_{max}: now we have ´$correct$´ p $UHECR - ID$

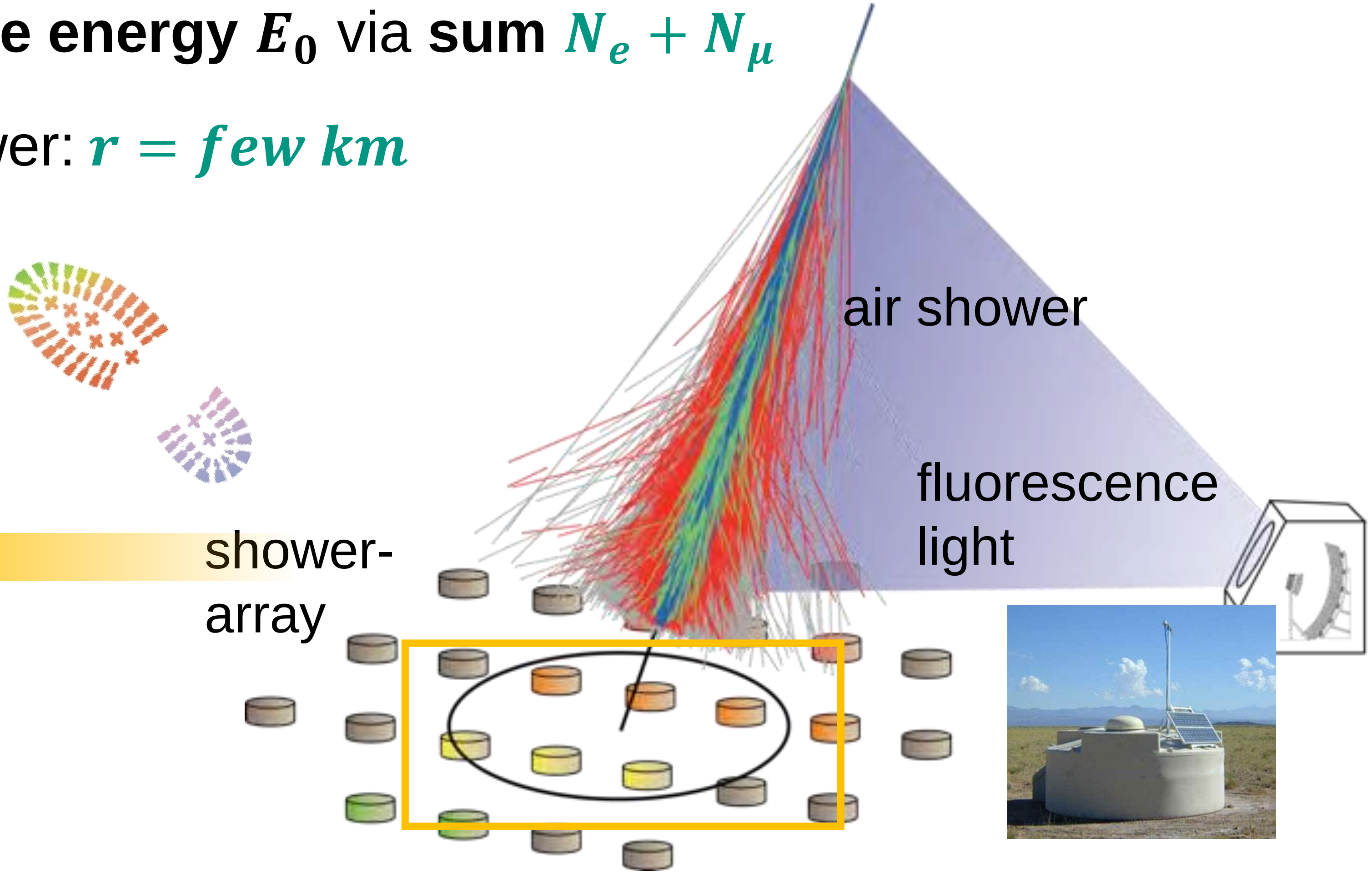




Pierre Auger Observatory: hybrid technology

- **second $UHECR$ observable:** **lateral distribution** (***aka*** **´the footprint´)**
  - determining **primary particle energy E_0** via **sum** $N_e + N_\mu$
  - **lateral size** of $UHECR$ shower: $r = few\ km$



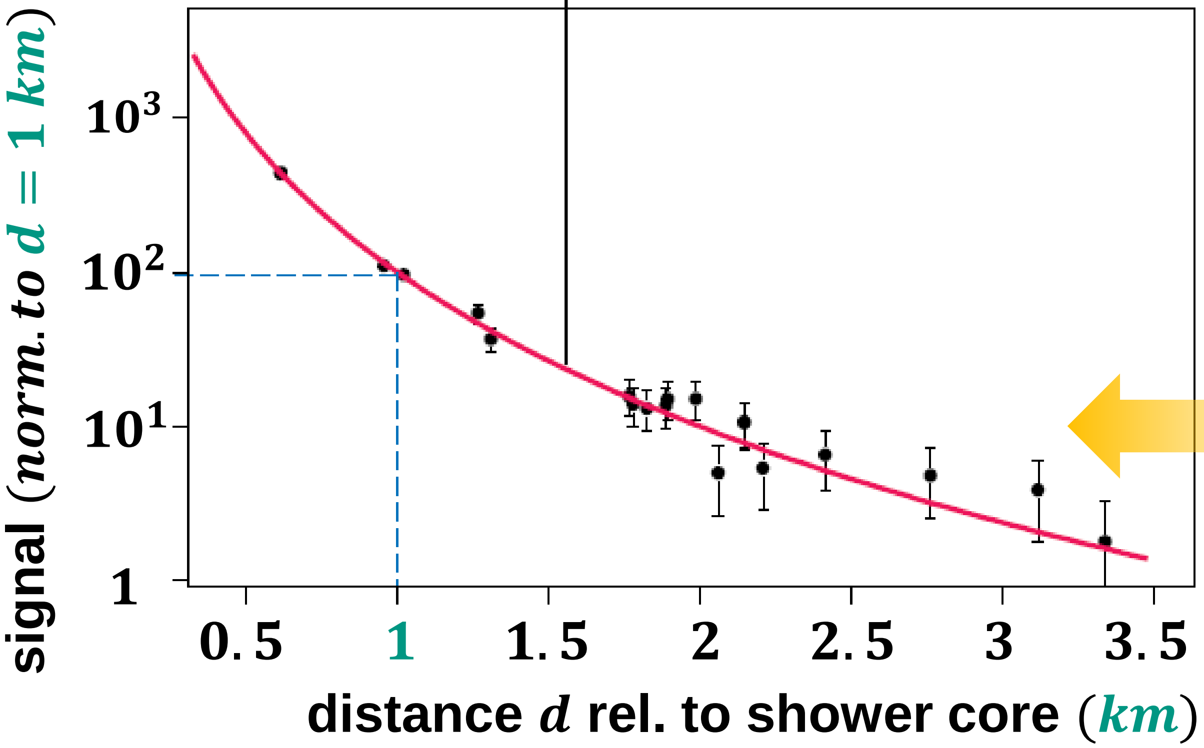


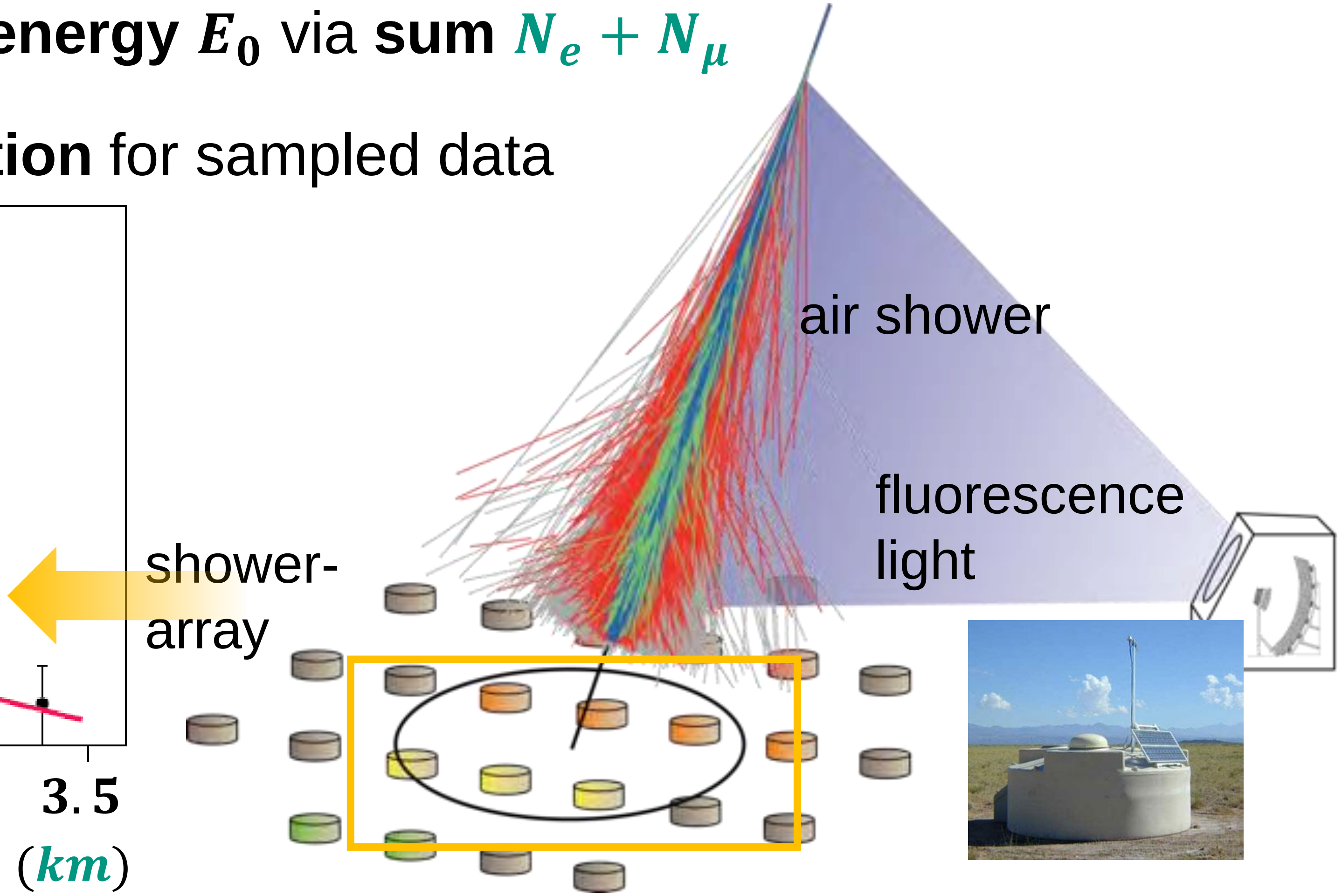
Pierre Auger Observatory: hybrid technology

- **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 data





Results: energy specta at the highest energies

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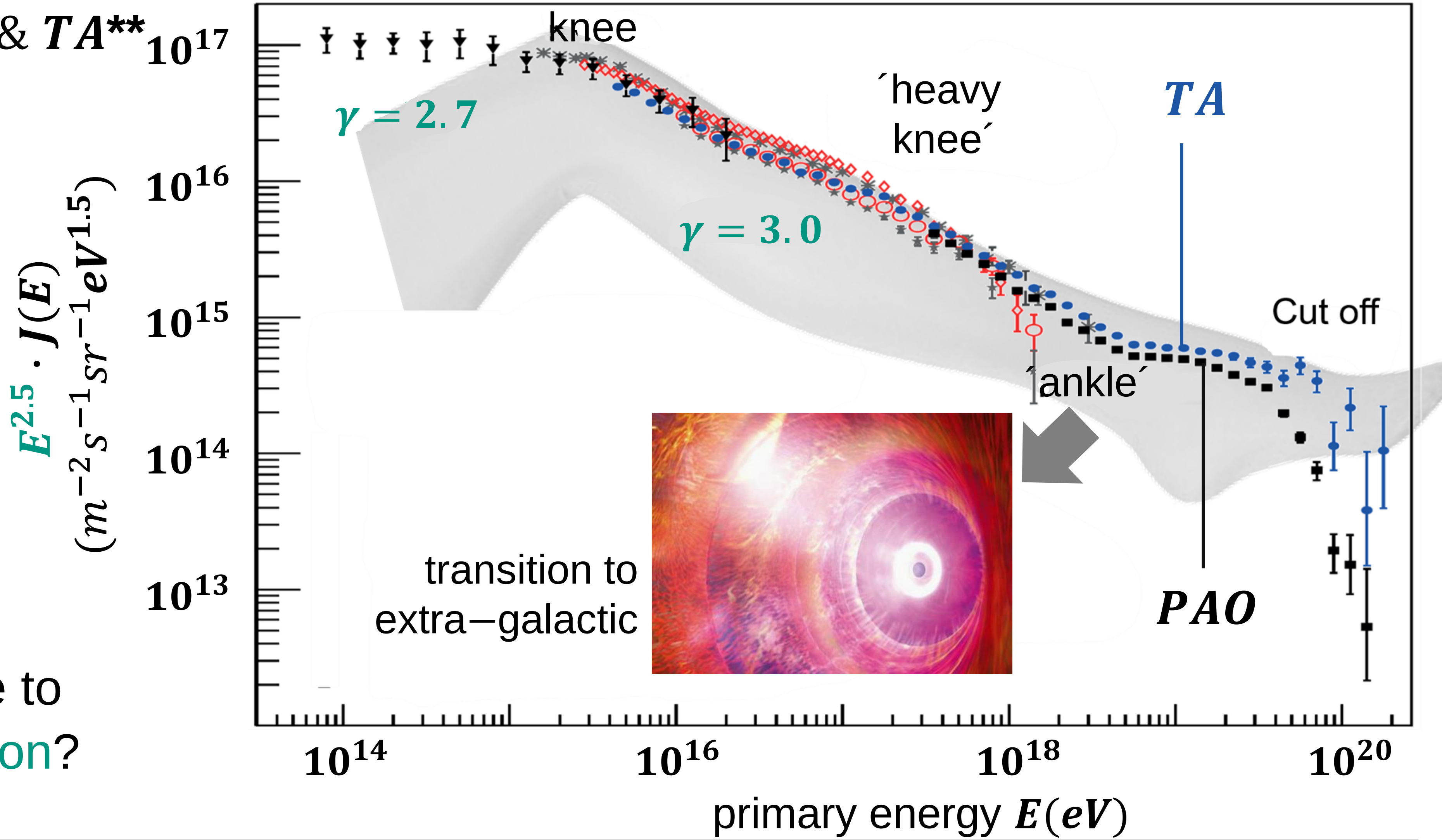
- **Results of PAO* & TA****

  - different energy <u>*energy estimators*</u> (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

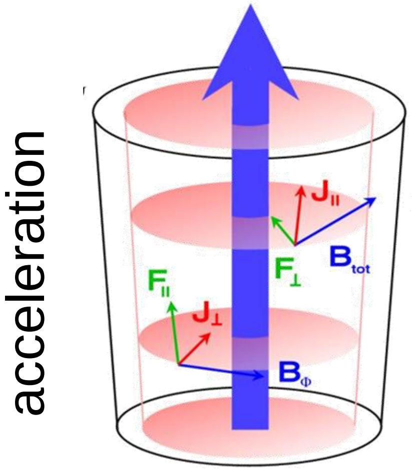
Interpretations for cut off at highest energies

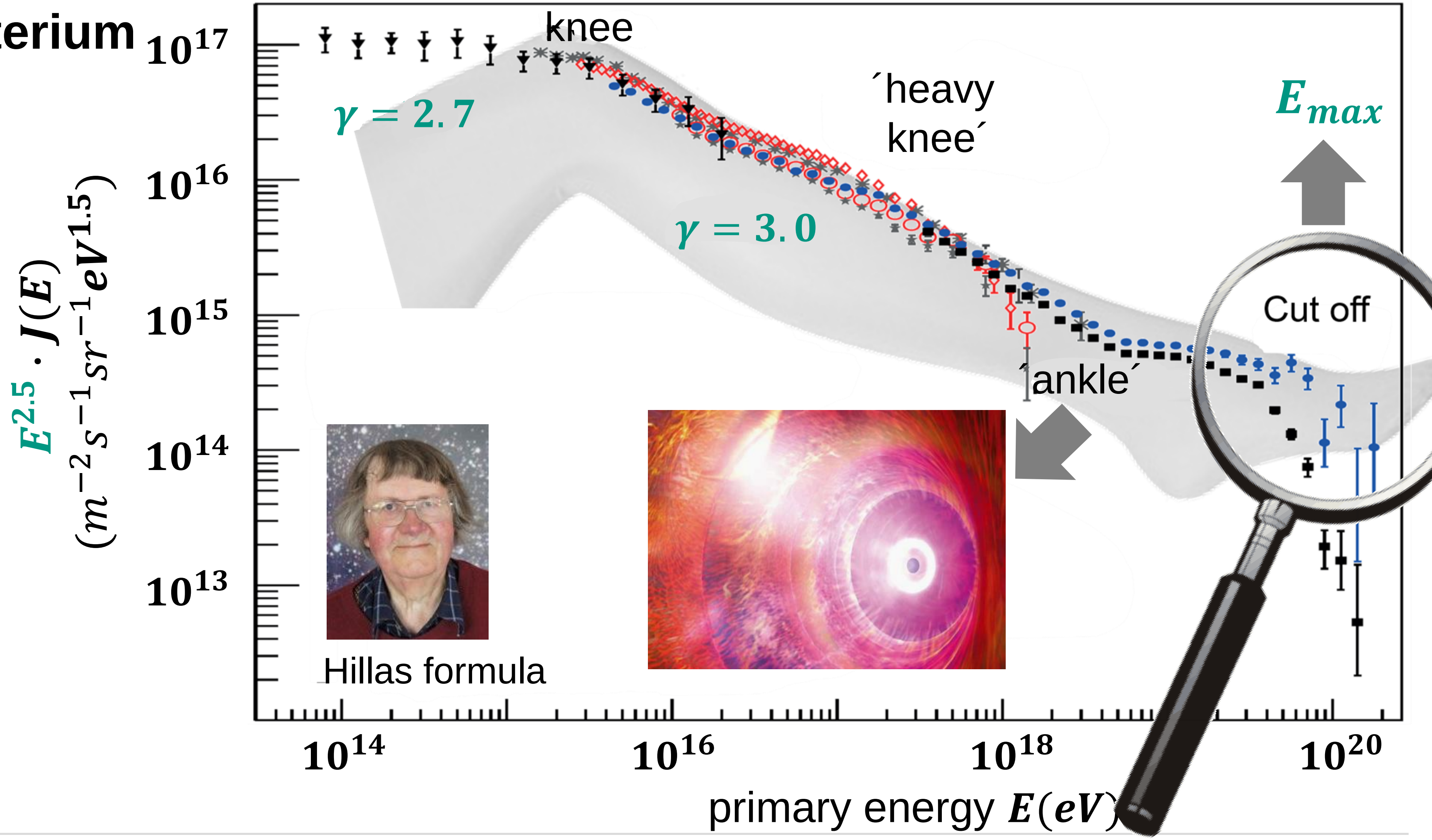
- **Idea 1: Hillas criterium**

- **source is limited**
  key parameters:

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

- here: ***AGN*** jet

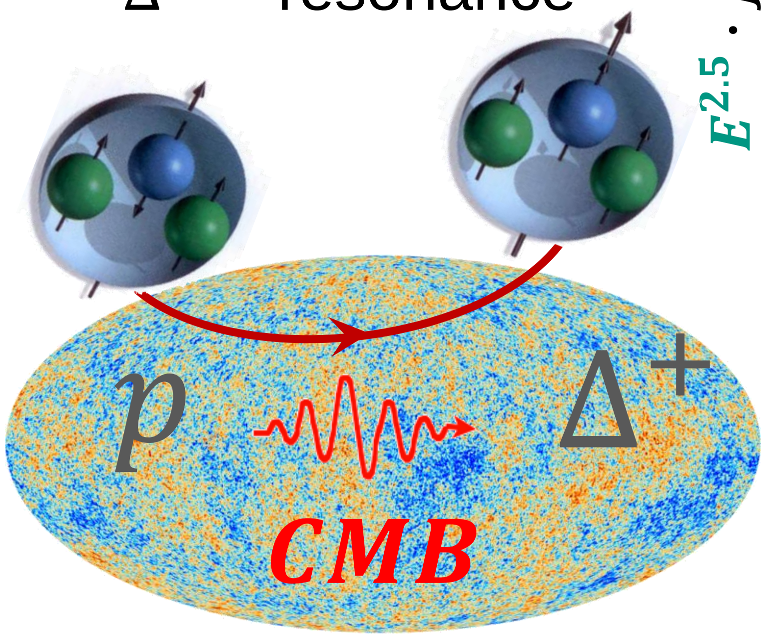


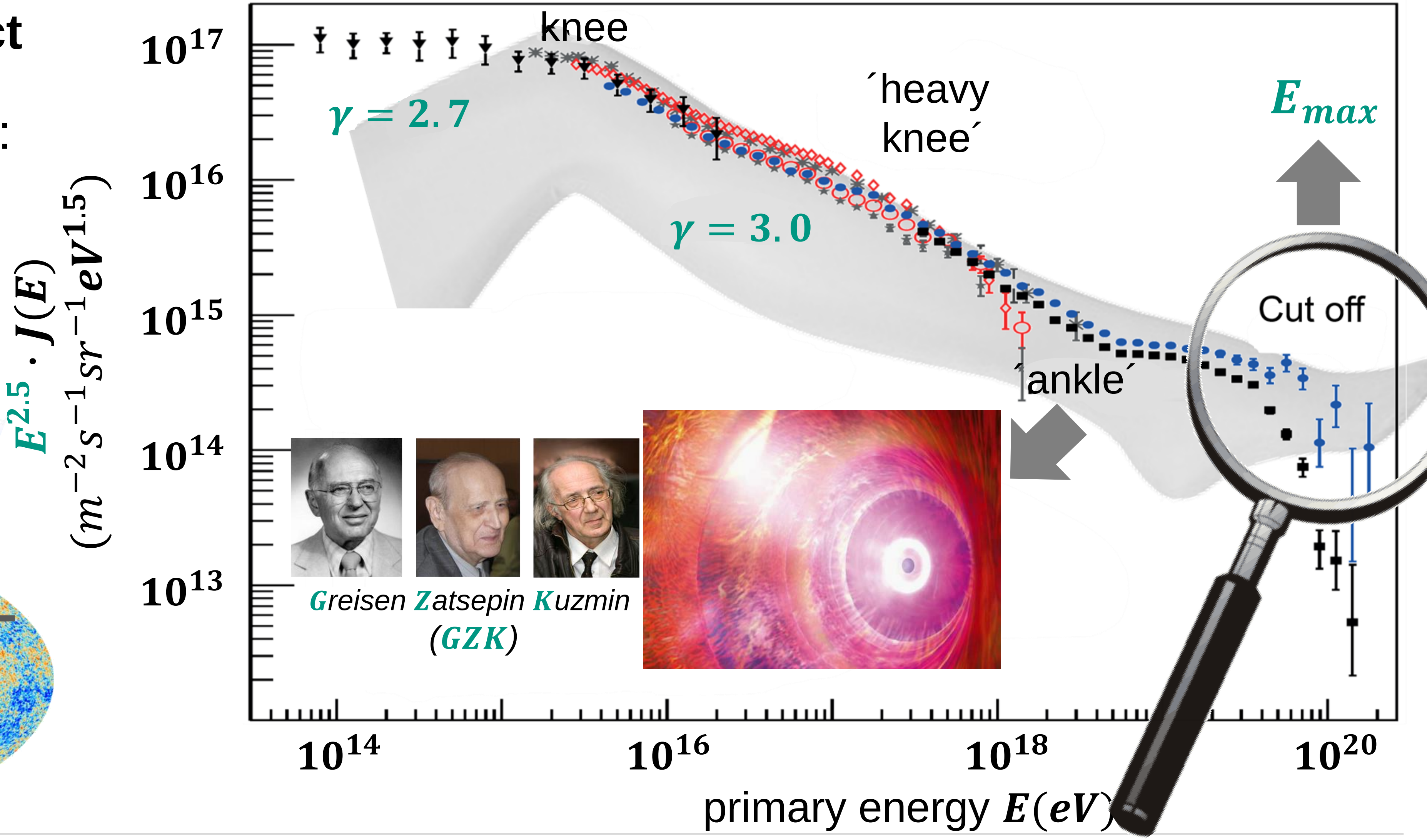


Interpretations for cut off at highest energies

- **Idea 2: GZK effect**

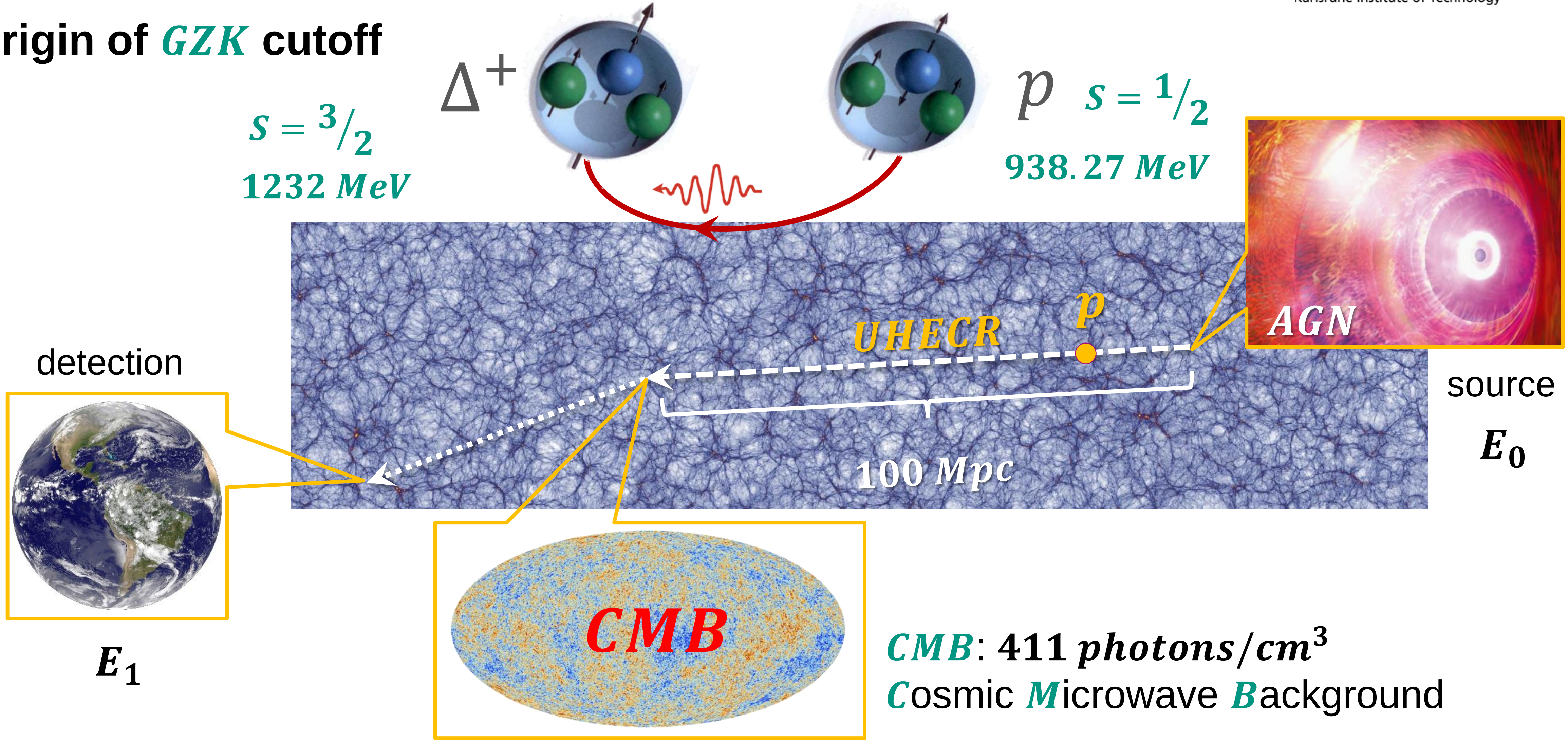
- **propagation effect**: CMB photons
- here: p forms a $\Delta^+ -$ resonance





Scenario 2: GZK – cutoff for $UHECR$ – protons

- Origin of GZK cutoff



CMB: $411\ photons/cm^3$
Cosmic Microwave Background

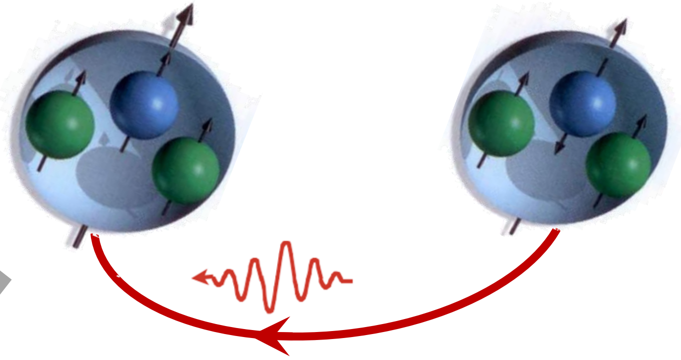
Scenario 2: GZK – cutoff for $UHECR$ – protons

■ **Origin of GZK cutoff**

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) will (above threshold) generate a short–lived Δ^+ – resonance

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

Scenario 2: GZK – cutoff for $UHECR$ – protons

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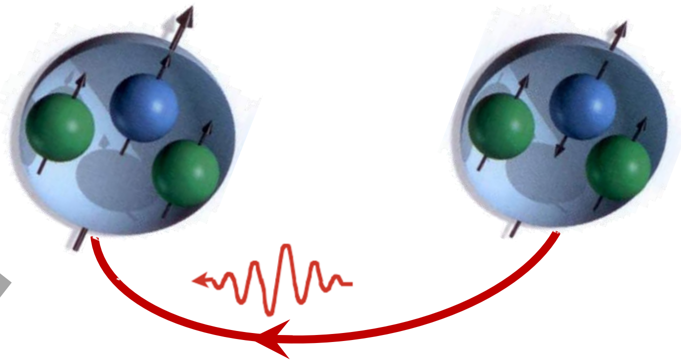
- **Origin of GZK cutoff**

Δ^+ $s = {}^3/_2$ $1232\ MeV$



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: $E_p = 4 \times 10^{19}\ eV$

Greisen

Zatsepin

Kuzmin

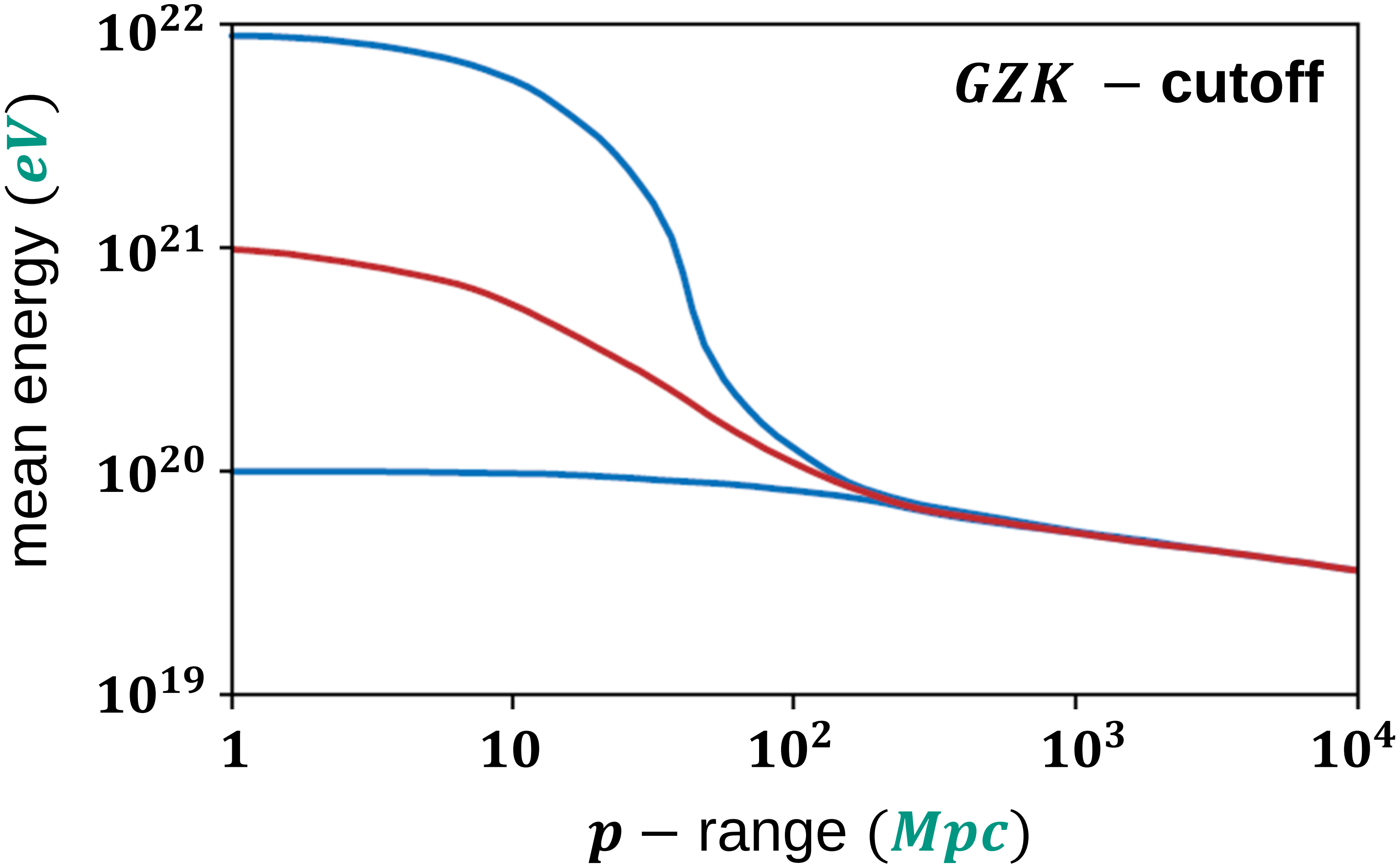
Scenario 2: GZK – cutoff for $UHECR$ – protons

- GZK **effect will severely limit 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 $2.7\ K\ \gamma$´s results in an **energy loss** due to **spallation reactions**

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



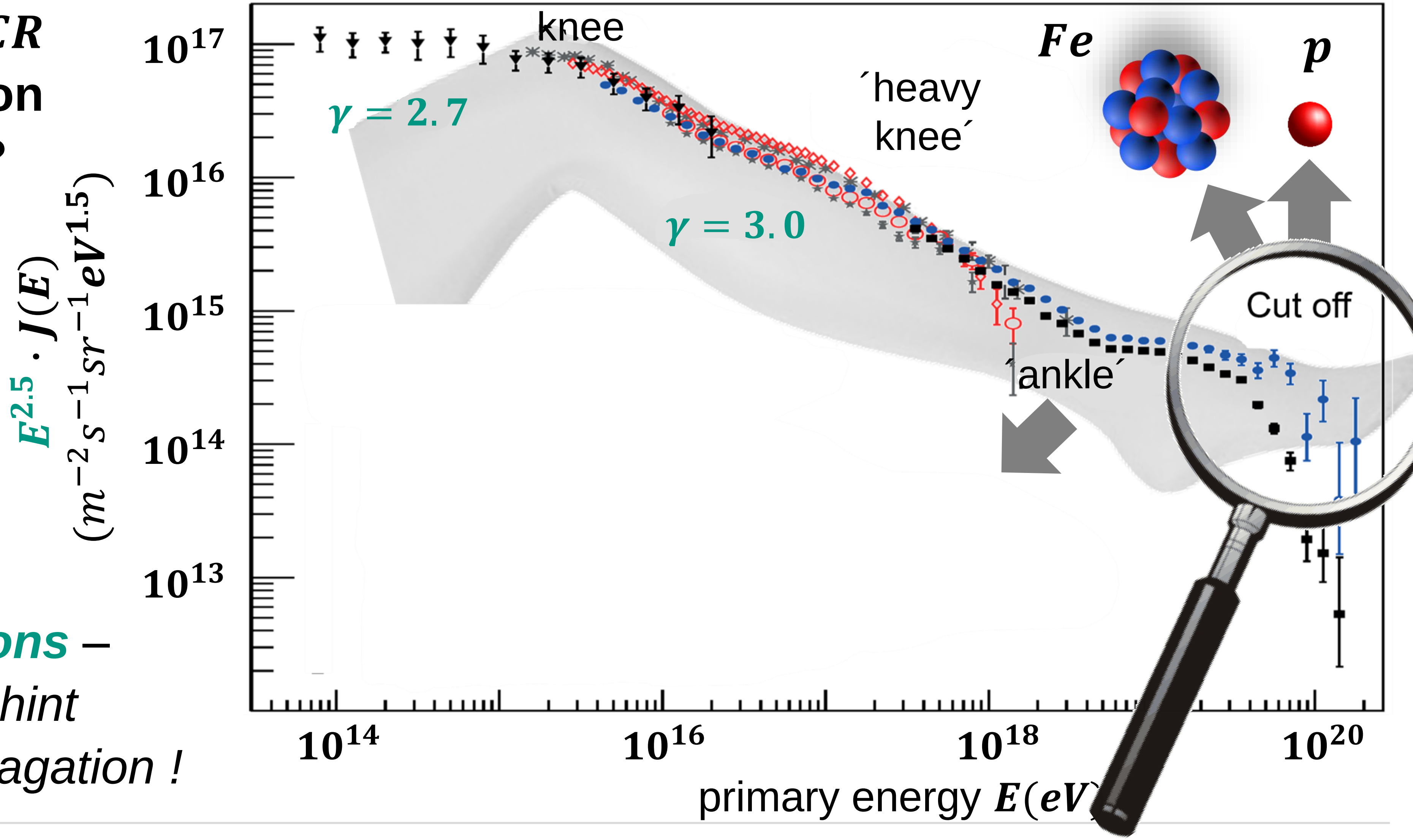
Origin of the $UHECR$ cut off at highest energies

- What´s the $UHECR$ mass composition at the highest E?

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

↕

GZK: *if these are **protons** – that would be a strong hint for a cutoff due to propagation !*



Observed changes of the CR mass composition

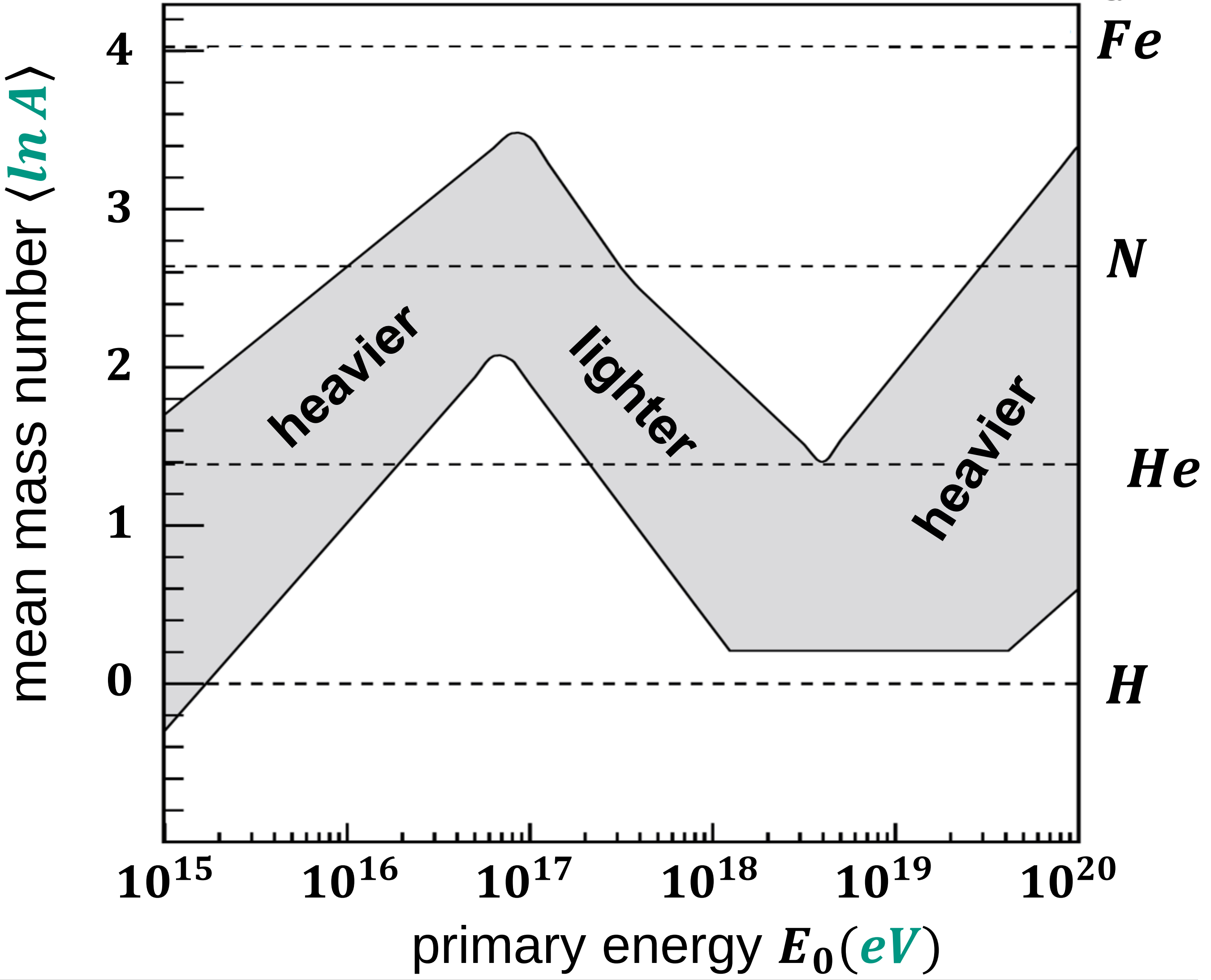
- **Measurements by PAO and other observatories reveal:**

- at $E = 10^{15} \dots 10^{17} eV$:
galactic CRs: heavier nuclei

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

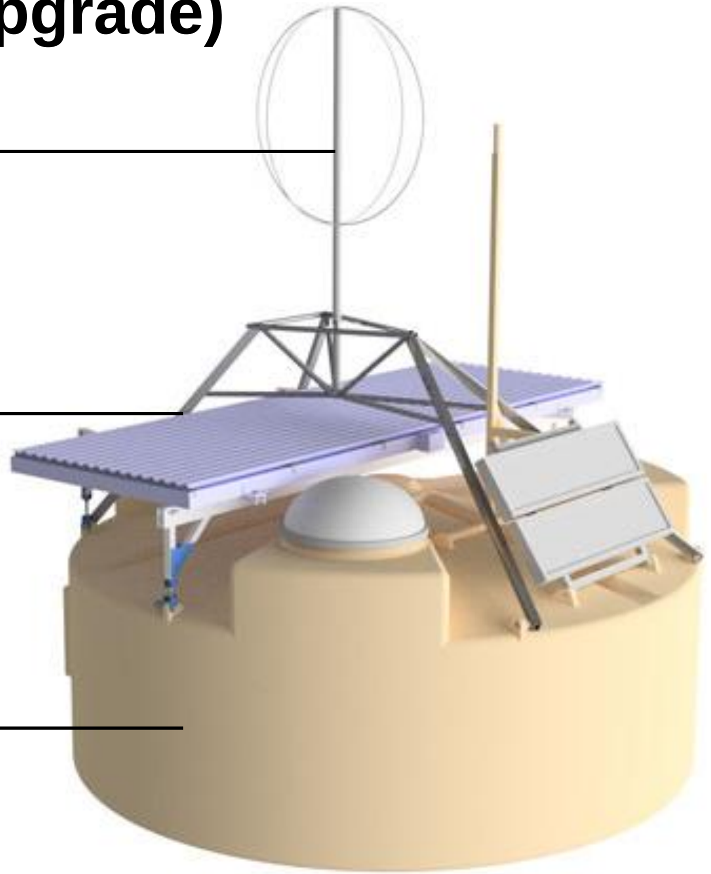
- at $E = 10^{17} \dots few \times 10^{18} eV$:
CRs: lighter nuclei (new sources)

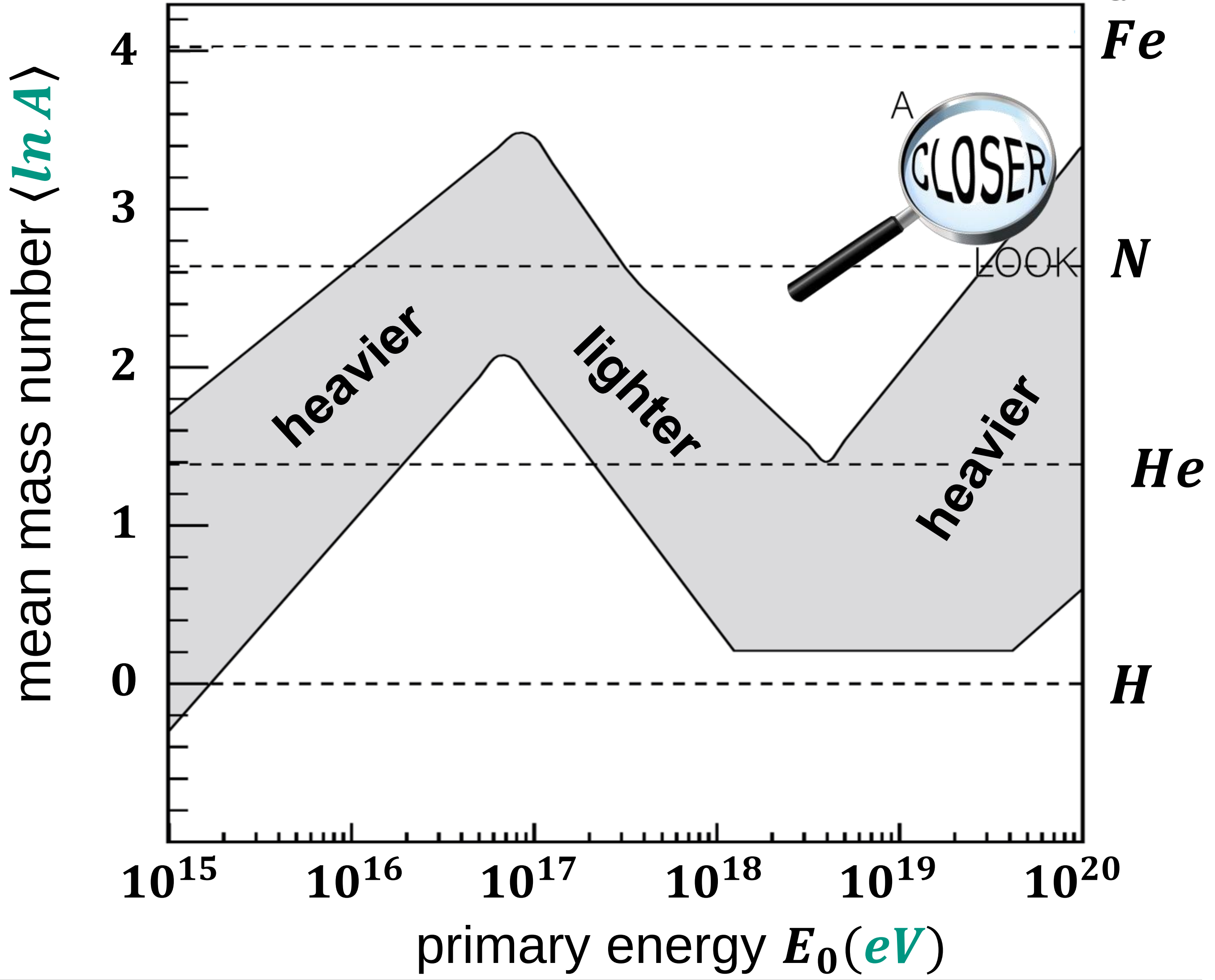
- at $E = few \times 10^{18} eV \dots 10^{20} eV$:
CRs: heavier nuclei (extra−galactic)



Observed changes of the CR mass composition

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





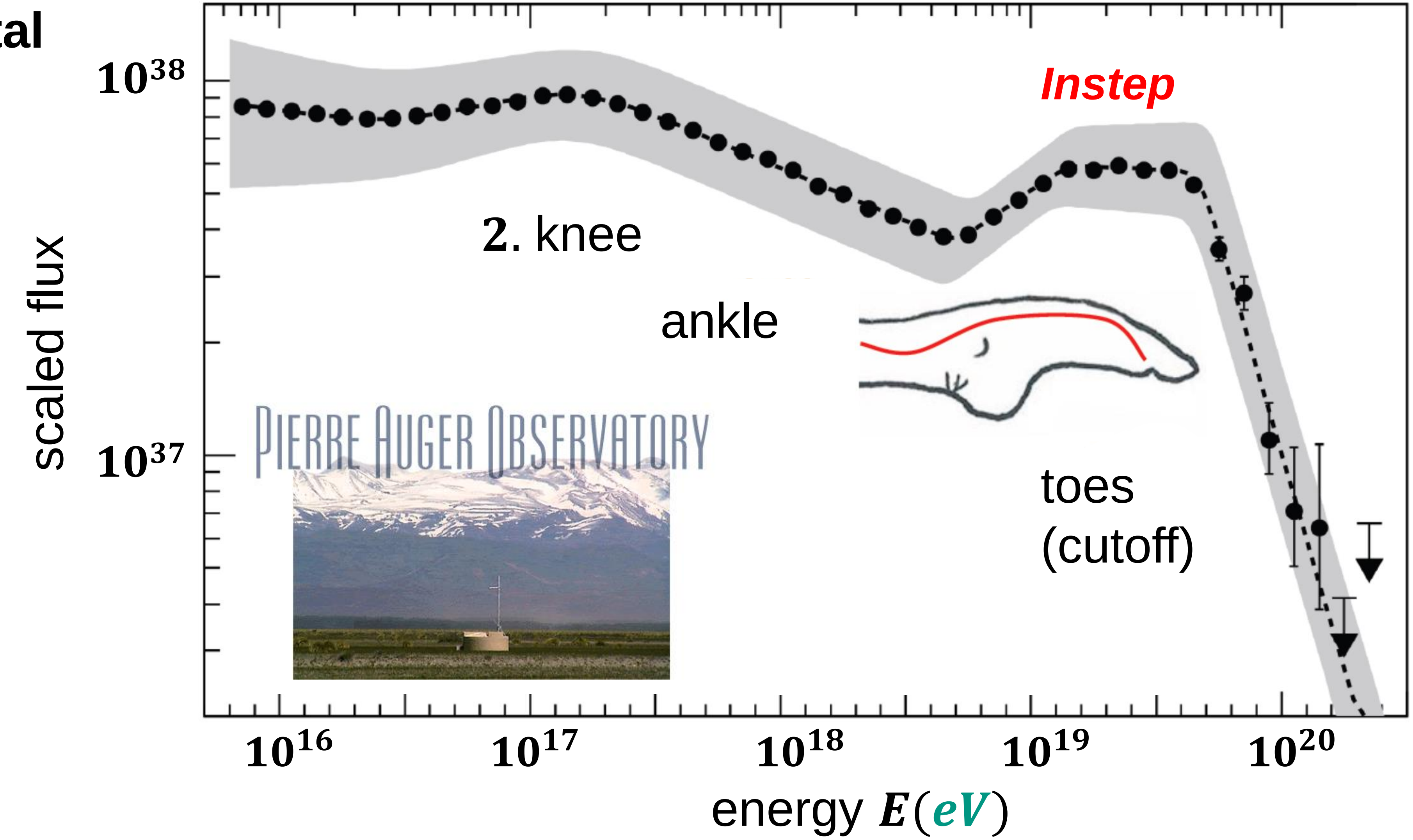
Energy spectrum of $UHECR$: new Auger results

- **Latest experimental results: energy spectrum up to $10^{20} eV$**

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

  a) **not** due to the GZK – effect

  b) accelerators reach their **maximum energy E_{max}**



Arrival direction of $UHECRs$: latest results

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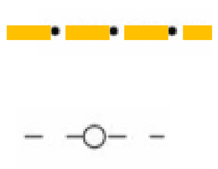
- UHECRs with $E > 40\ EeV$ (PAO) and $E > 53.2\ EeV$ (TA, Telescope Array)

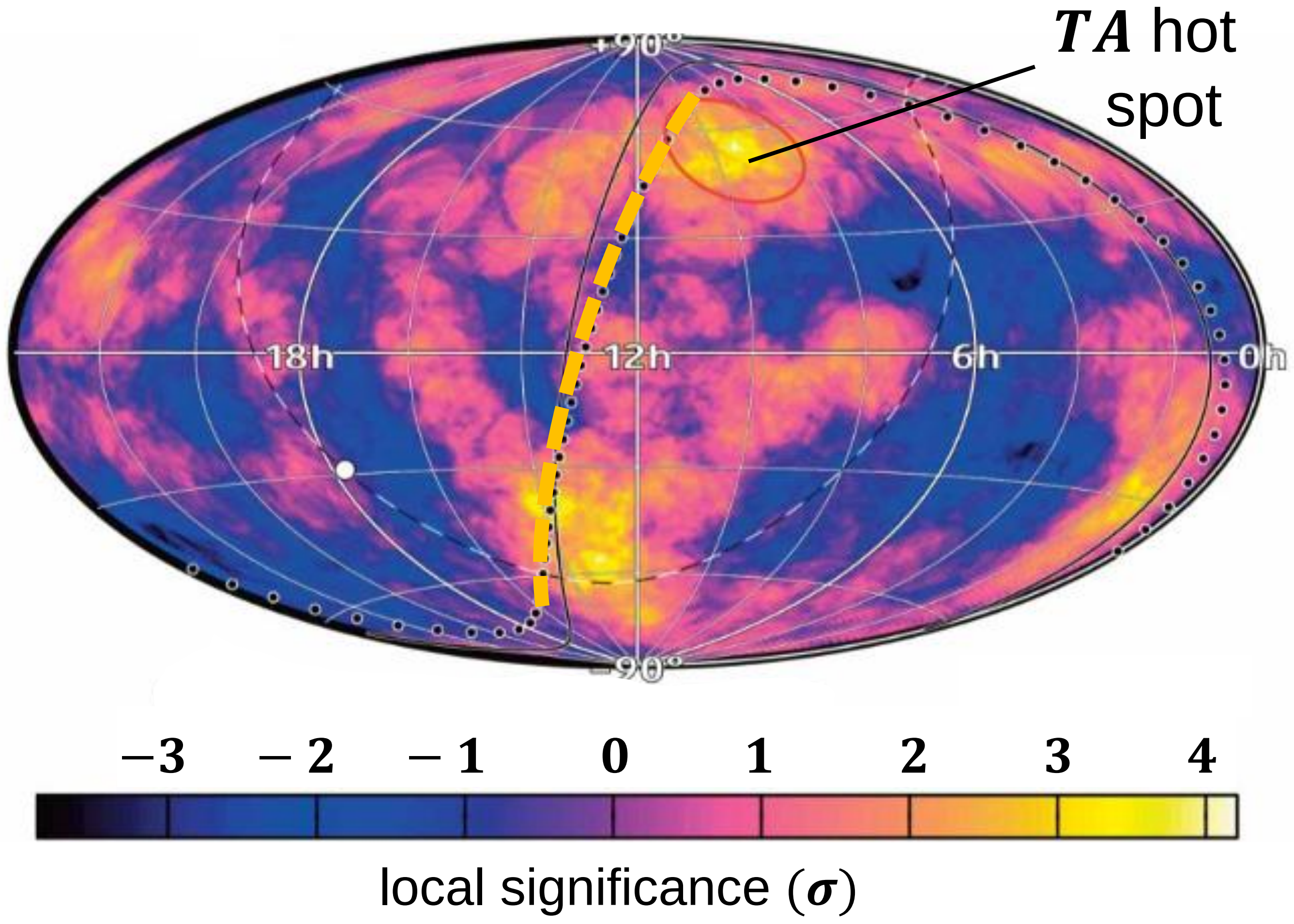
  - **anisotropy** of arrival directions of $UHECRs$ well established

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

  - SGP = plane of local supercluster

  - SGP (by chance) almost ⊥ to galactic plane (GP)





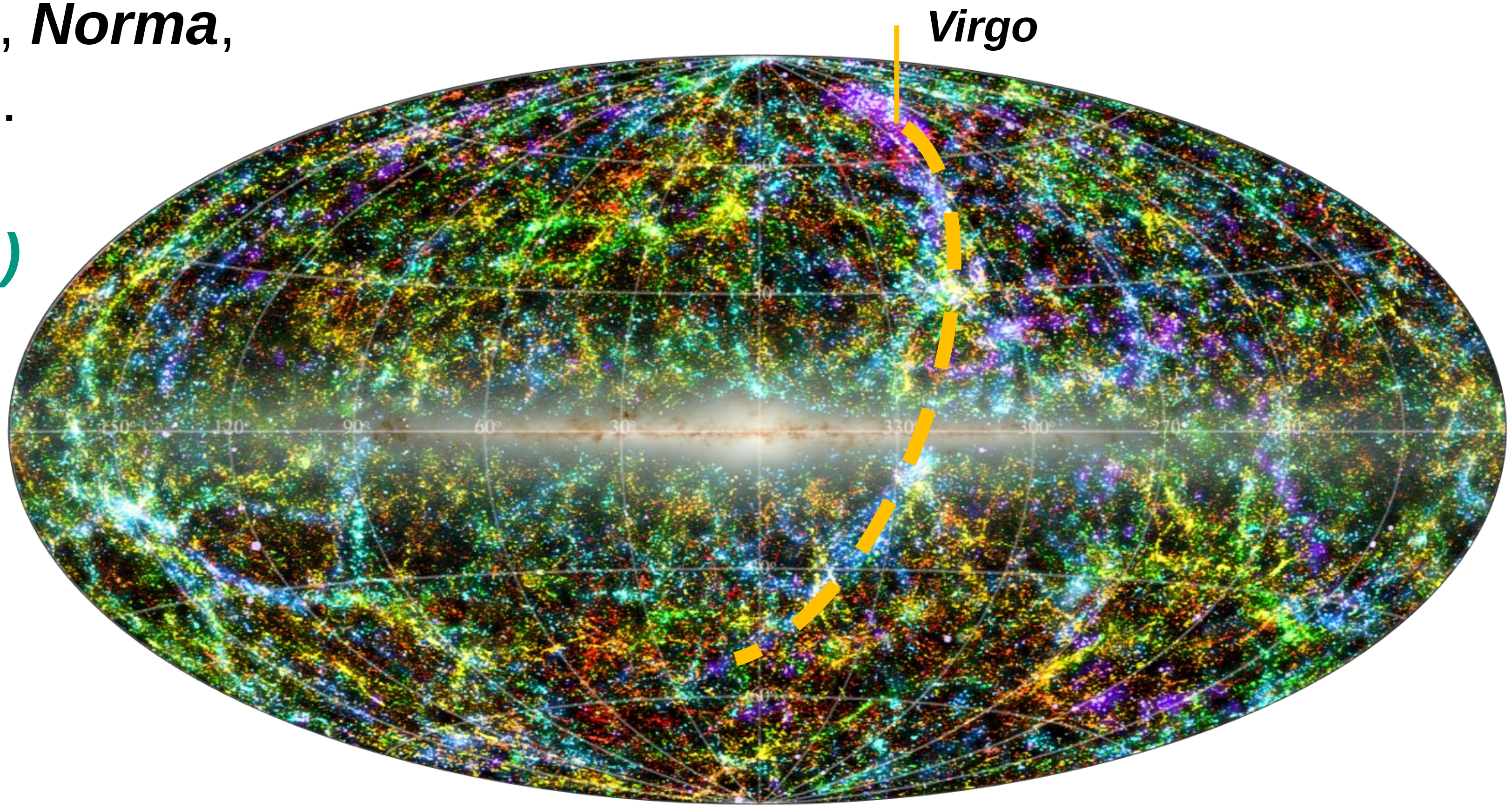
Local universe: supergalactic plane SGP

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 ☑

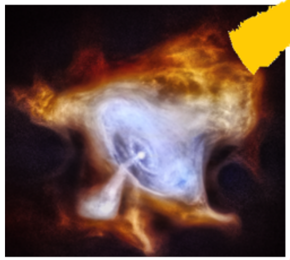


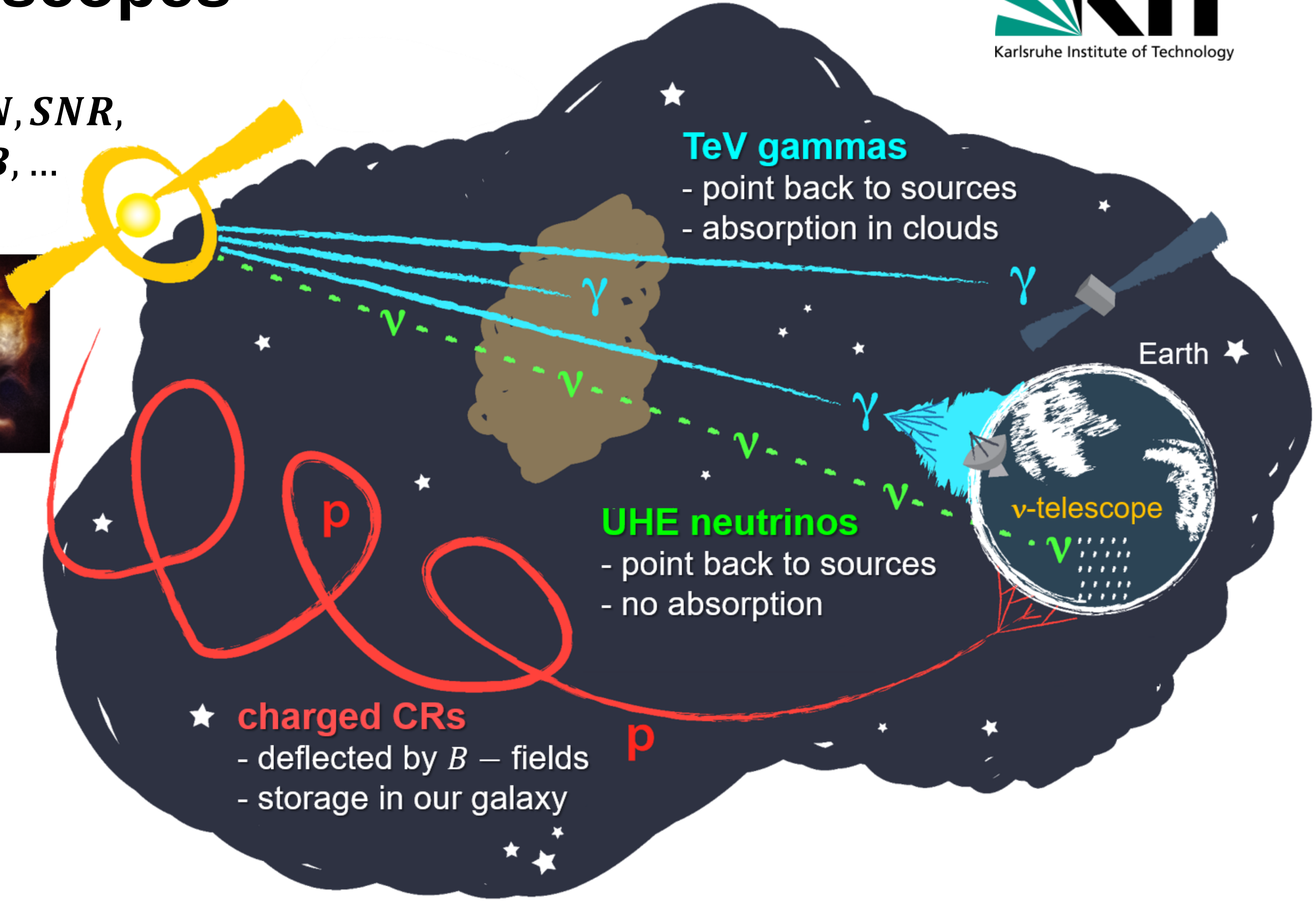
2.1.2 Neutrino Telescopes

- **Science goals**

- identification of **hidden UHE accelerators**

$AGN, SNR,$
$GRB, \ldots$





$2.1.2$ Neutrino Telescopes

Karlsruhe Institute of Technology

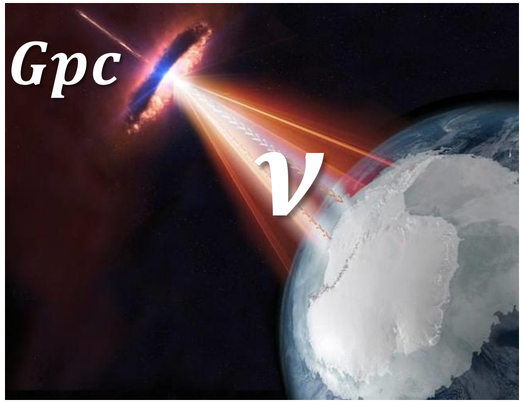
■ Science goals

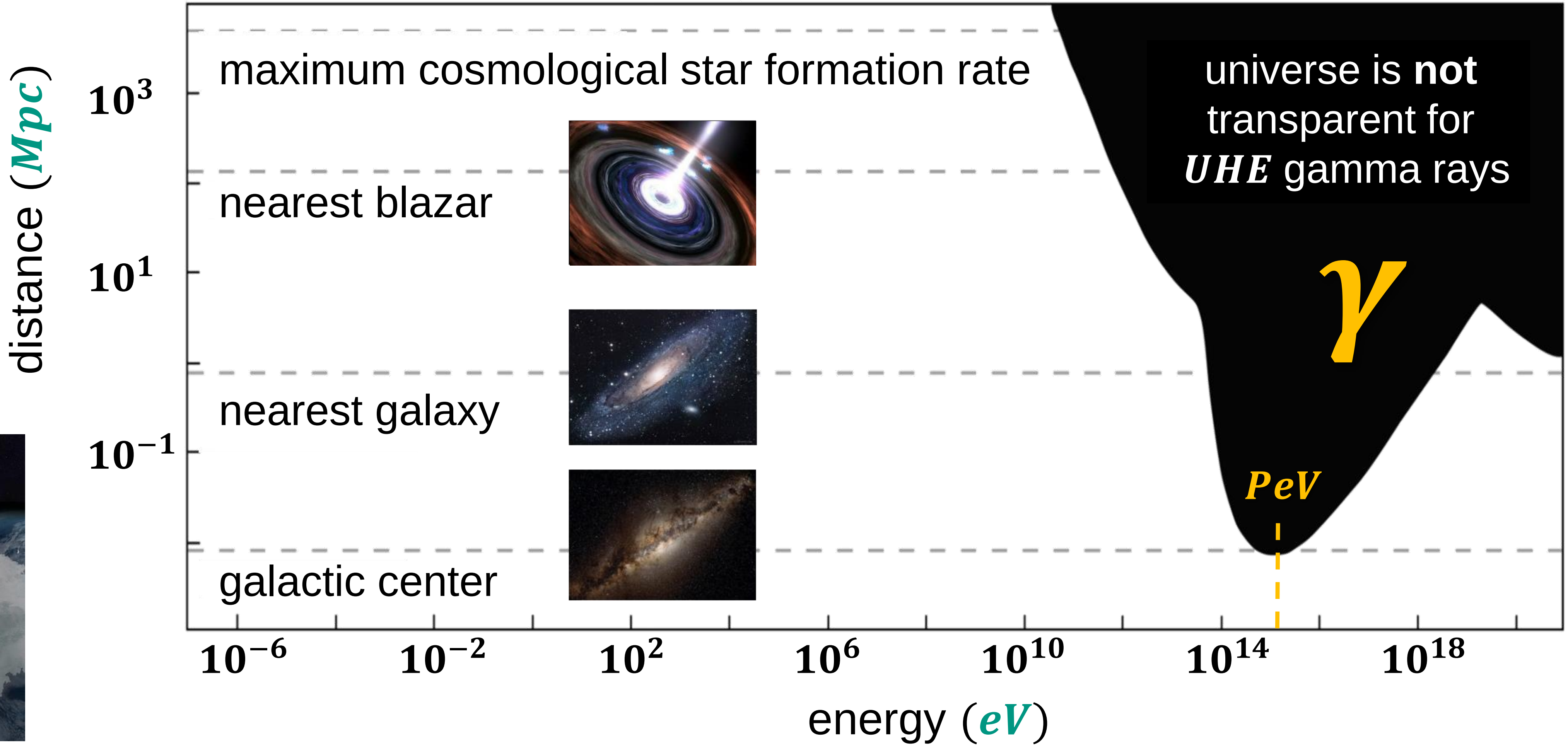
- neutrinos as messengers with many advantages:
  - ⇨ **no** deflection $(\boldsymbol{Z=0})$
  - ⇨ **no** absorption $(\boldsymbol{Gpc})$

Neutrinos as messengers: unlimited range

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

$PeV - \nu$´s
as ideal
messengers

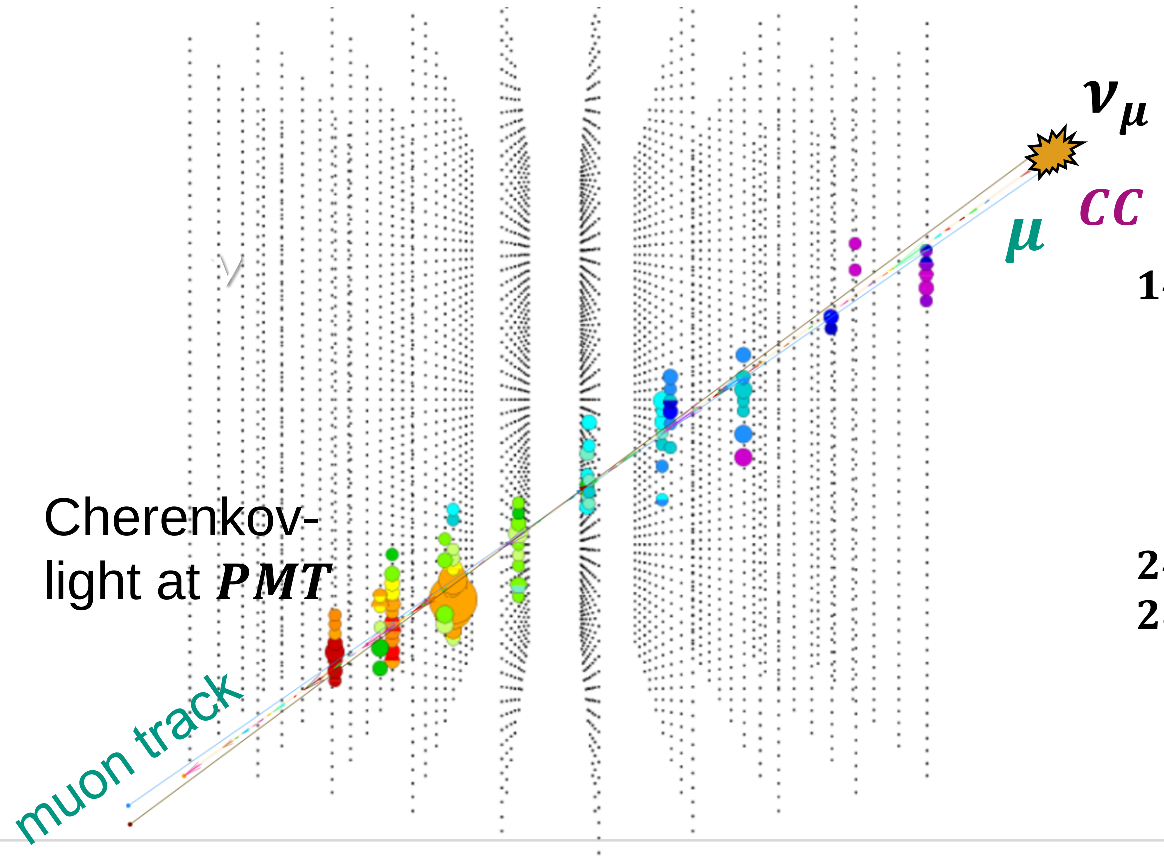


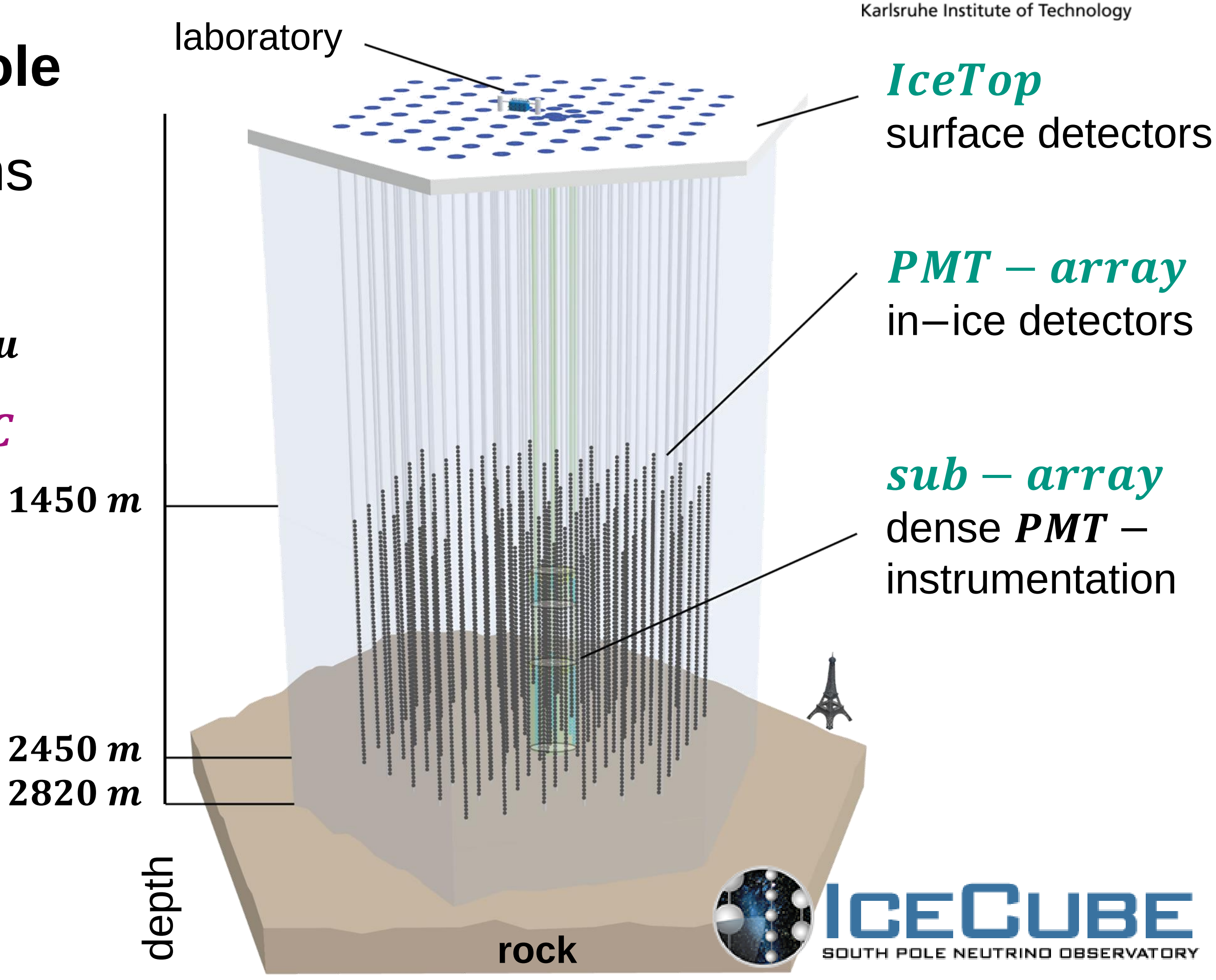


Neutrino telescopes: setup & detection principle

- $\boldsymbol{IceCube}$ **Observatory @ Southpole**

- detection of **muons** from $\boldsymbol{CC}$ reactions

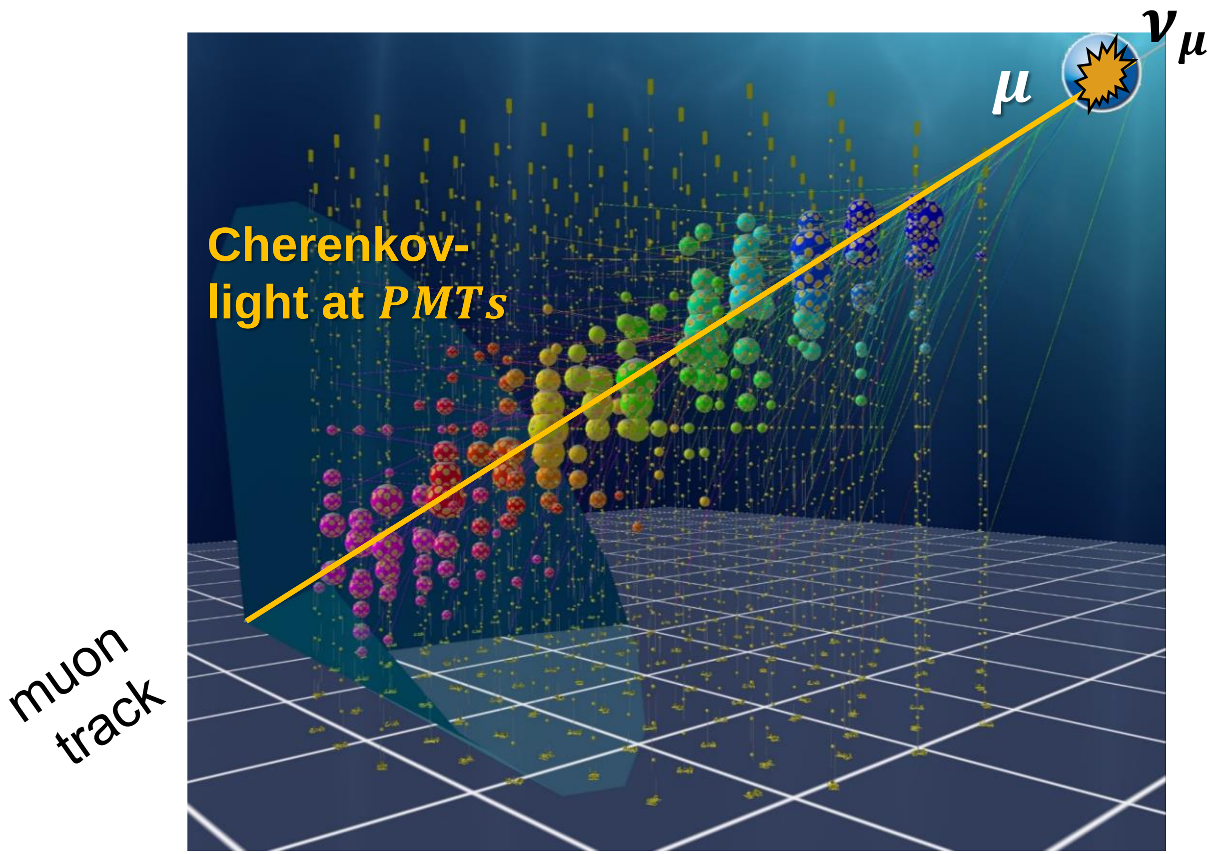


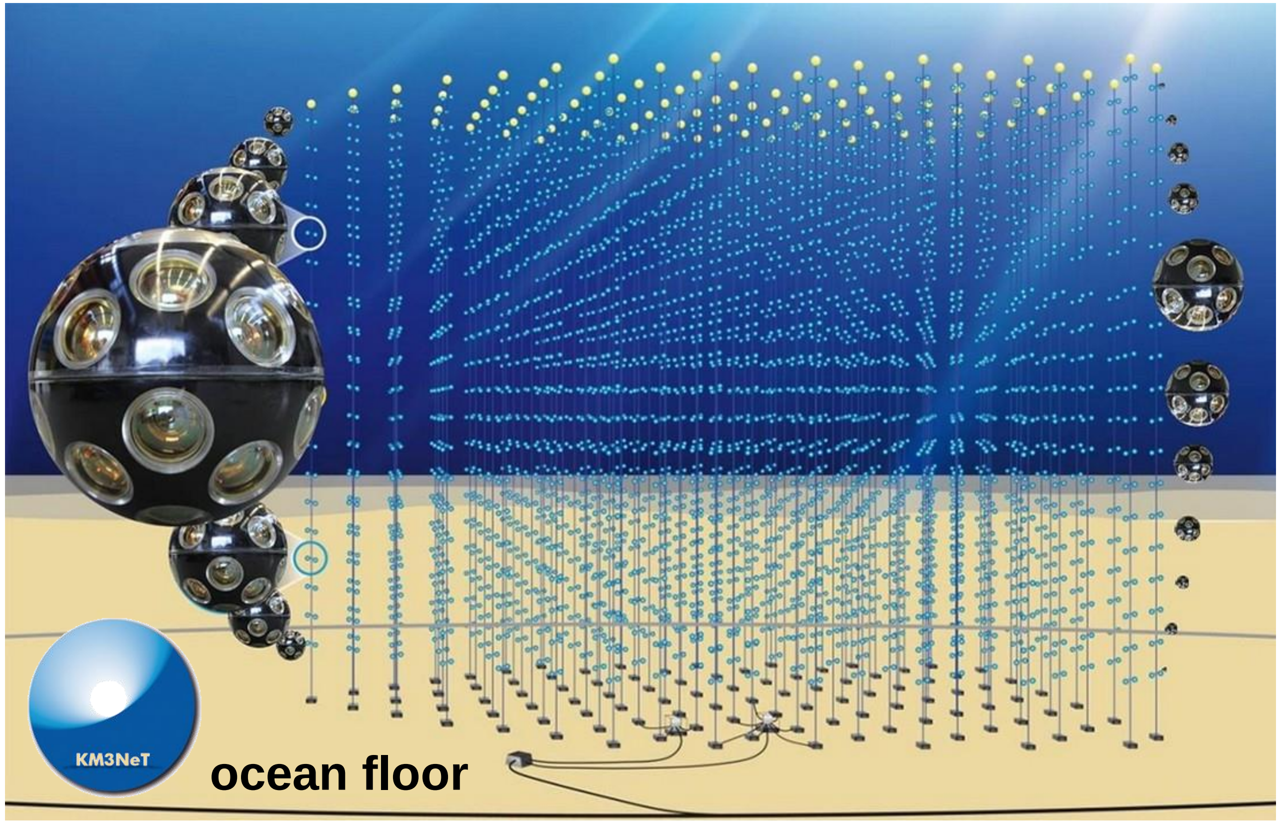


Neutrino telescopes: setup & detection principle

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

  - detection of muons from CC reactions at **2** sites using two large PMT arrays





Neutrino telescopes: setup & detection principle

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

  - $\boldsymbol{\nu_\mu}$ – reactions in matter produce **high–energy** $\boldsymbol{\mu\acute{}s}$ $(\boldsymbol{GeV - TeV - PeV})$ range

  - decay kinematics: $\boldsymbol{E(\mu) \sim 0.5 \ldots 0.7\, E(\nu_\mu)}$

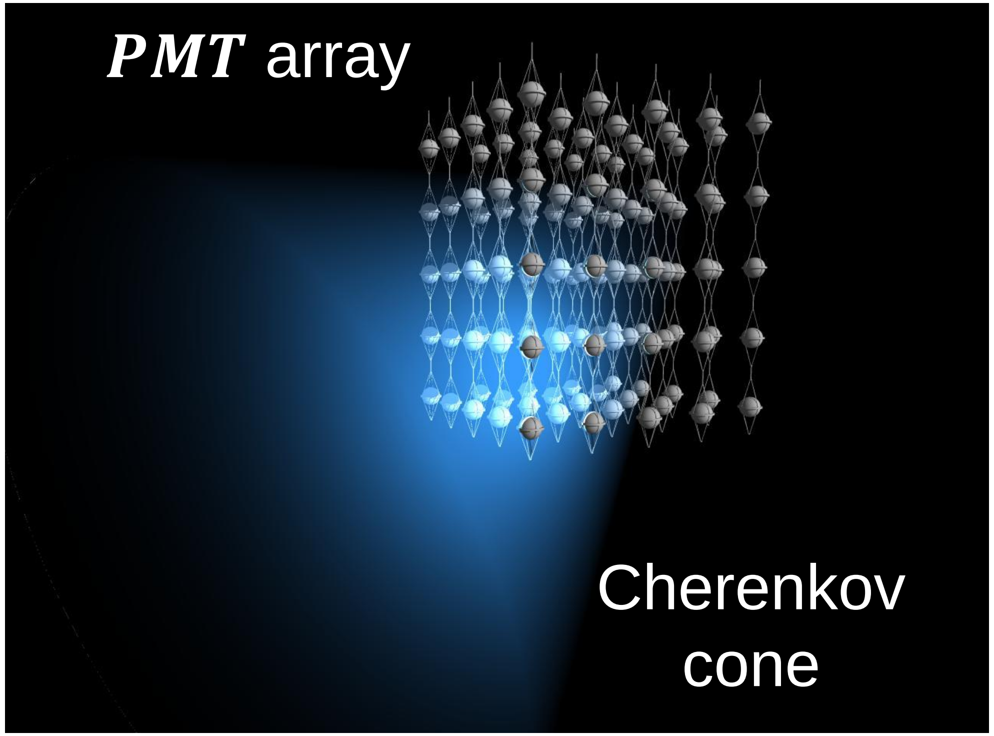
  - muons with large **range** $\boldsymbol{R_\mu}$ in ice / water

$$\mathbf{1}\ \boldsymbol{PeV} : \ \boldsymbol{R_\mu} = \mathbf{1.7}\ \boldsymbol{km}$$
$$\mathbf{10}\ \boldsymbol{PeV} : \ \boldsymbol{R_\mu} = \mathbf{7}\ \boldsymbol{km}$$

  - emission of Cherenkov–light induced by $\boldsymbol{\mu}$ with $\boldsymbol{\Theta_C \sim 43°}$

water: $\boldsymbol{n = 1.33}$

$$\cos \boldsymbol{\Theta_C} = \mathbf{1}/(\boldsymbol{n} \cdot \boldsymbol{\beta})$$



Neutrino telescopes: setup & detection principle

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

  - ν_μ – reactions in matter produce **high–energy** μ´s $(GeV - TeV - PeV)$ range

  - decay kinematics: $E(\mu) \sim 0.5 \ldots 0.7\ E(\nu_\mu)$

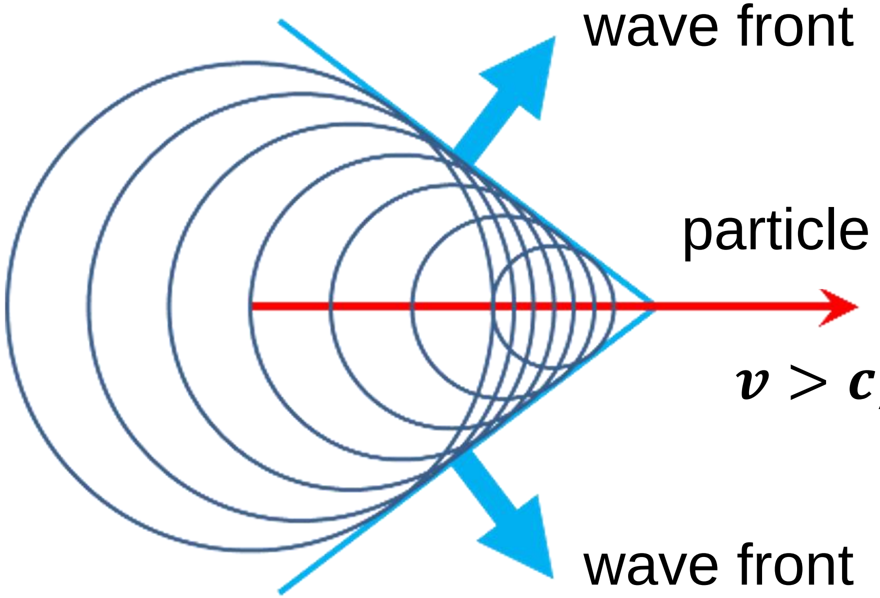
  - muons with large **range** R_μ in ice / water

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

water: $n = 1.33$

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

dielectric medium with index n

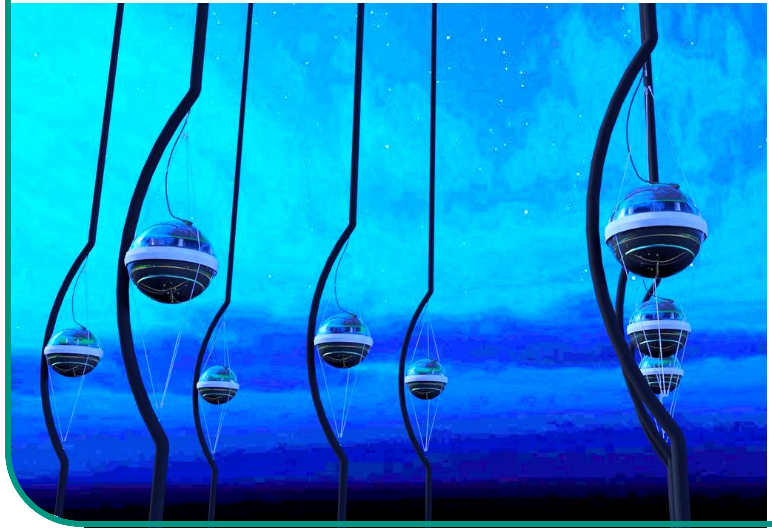


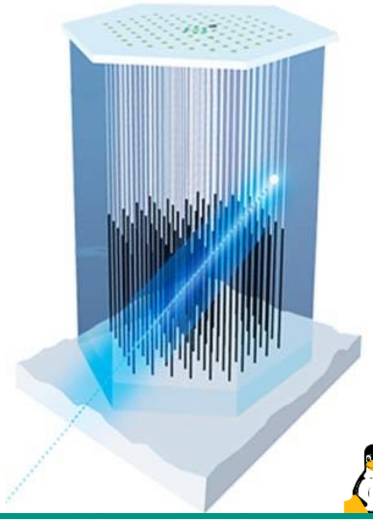
Q: U of Sheffield

Neutrino telescopes in ice & in the deep sea

ν – telescope in the **antarctic ice**

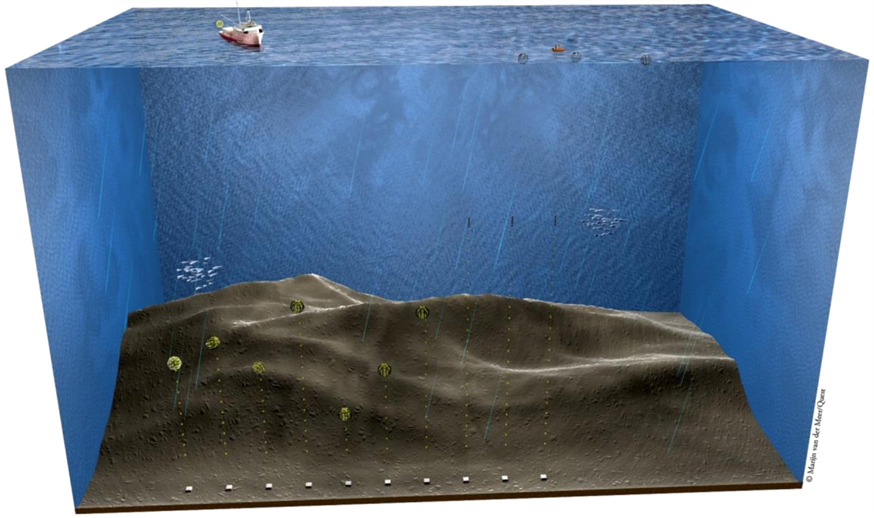
- good optical transparency ☺
- scattering at dust particles ☹
- $\boldsymbol{PMTs}$ with very low noise ☺
- challenging infrastructure 😐
- surface veto ☺





deep-sea ν –telescope: **Mediterranean**

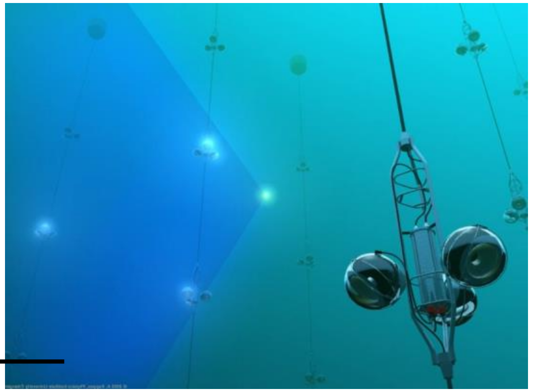
- optical transparency 😐
- motion of $\boldsymbol{PMT}$ –strings (currents) 😐
- $\boldsymbol{PMTs}$ with high background ☹
- challenging infrastructure 😐
- oceanographic studies ☺



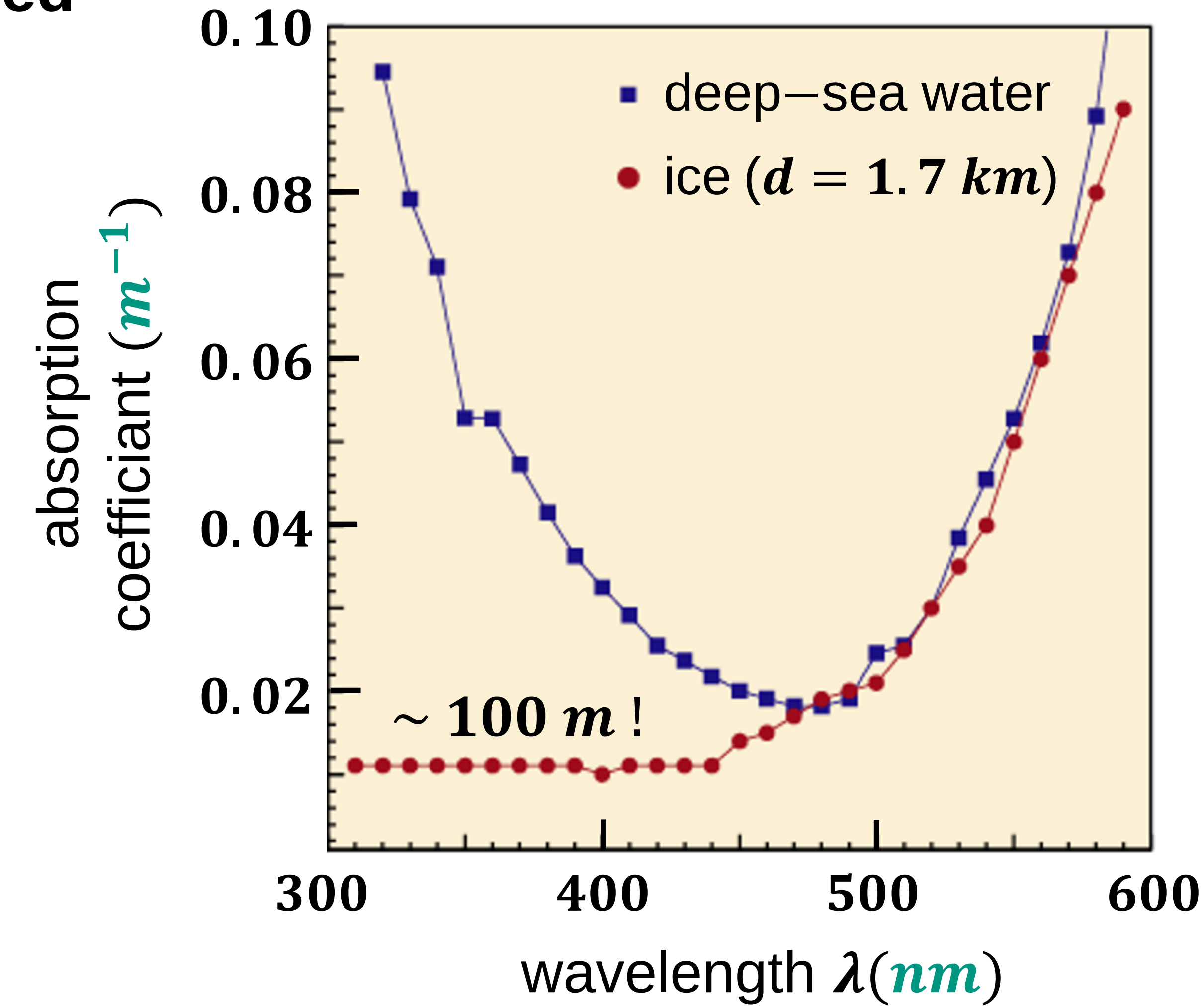
Neutrino telescopes in ice & in the deep sea

- **Ice at the South Pole has an unmatched optical transparency for $\lambda < 470\,nm$**

transparency of medium at **blue wavelengths** of key importance for Cherenkov light detection



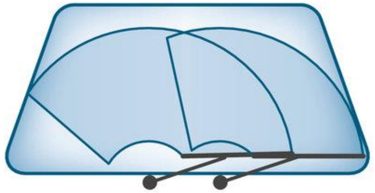
parameter	ice	water
optical transparency	dust	variable
bio−luminescence	none	yes
PMT background rate	**low**	kHz
angular resolution	$0.5\ldots1°$	$< 0.3°$

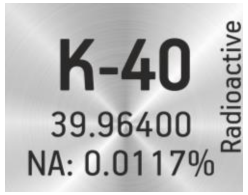


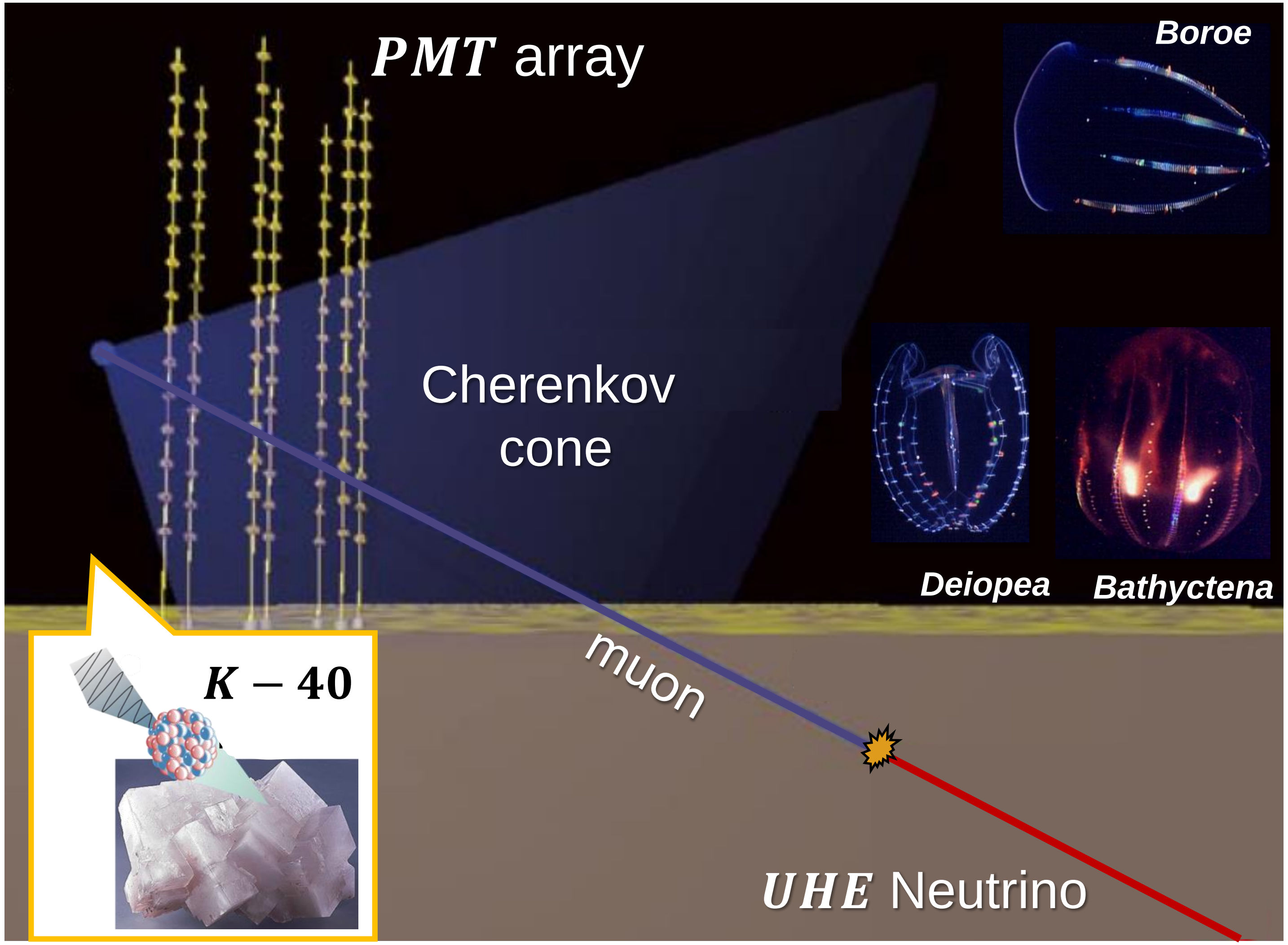
Neutrino telescopes in the deep sea: salt water

Criteria for an optimum site

- low optical scattering
- degree of ocean currents
- bio–luminescence
- sedimentation
- $K-40$ background rate*
- topology of the deep sea floor
- infrastructure on land







*see chapter 2.2 ´search for rare events´

Neutrino telescopes: deep–sea technology

- **technological challenges during PMT installation**

  - deep–sea vessel for PMT – & cable deployment

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

  - **hydrophones** to monitor position

  - deep–sea diving robot for $PMTs$