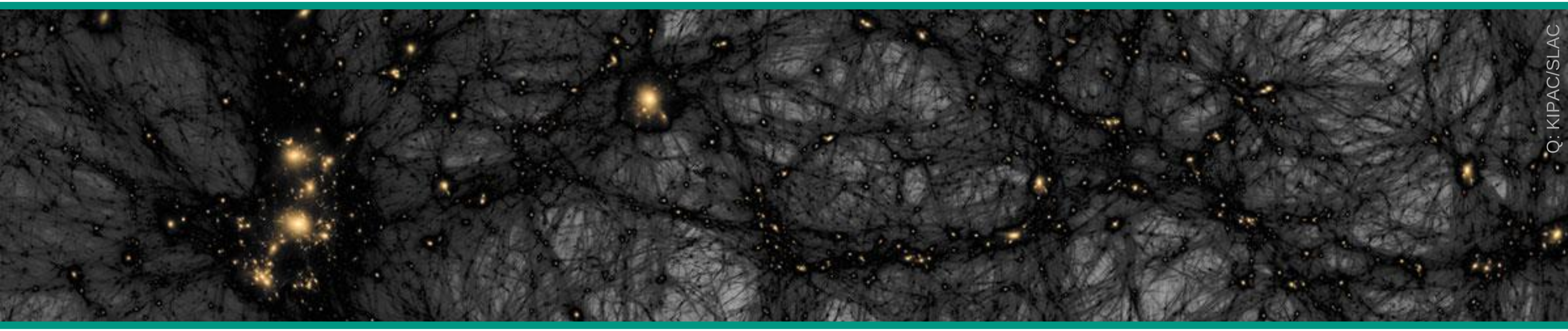
Karlsruhe Institute of Technology

Astroparticle physics I – Dark Matter

WS22/23 Lecture 3 Nov. 3, 2022



Recap of Lecture 2

- **Multi-messenger physics: charged cosmics, gammas, neutrinos**

  - **thermal universe** (Big Bang, supernovae): order parameter **T**
  - **non-thermal universe** (SNR, GRB, AGN, particle decays):
    order parameters: **B, length scale L, density ρ, max. energy E_0, …**
  - **limitation of range due to photon background fields (IR, CMB)**

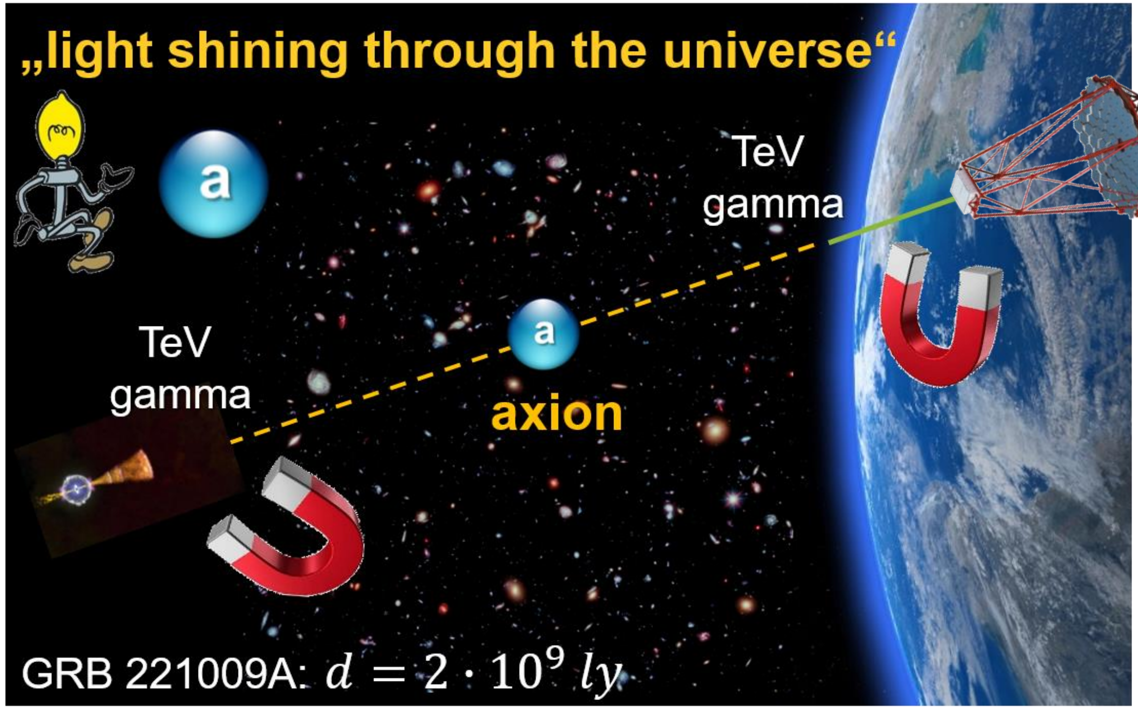
gammas: e^+e^- resonance with IR light for $E(\gamma) \sim 10^{15}$ eV
way out: „*light shining through universe*“ via axion conversion

protons: Δ^+ resonance for p with CMB for $E(p) \sim 10^{20}$ eV (GKZ-Cutoff)

neutrinos: no direct resonance at propagation (ν does not couple to γ)

Application of Lectures 1, 2

- **limited range of high-energy gammas (TeV-scale) from super energetic GRBs***



Q: NASA, DESY

possible way out: „***light shining through universe***“ via axion conversion

Brightest-Ever Space Explosion Reveals Possible Hints of Dark Matter

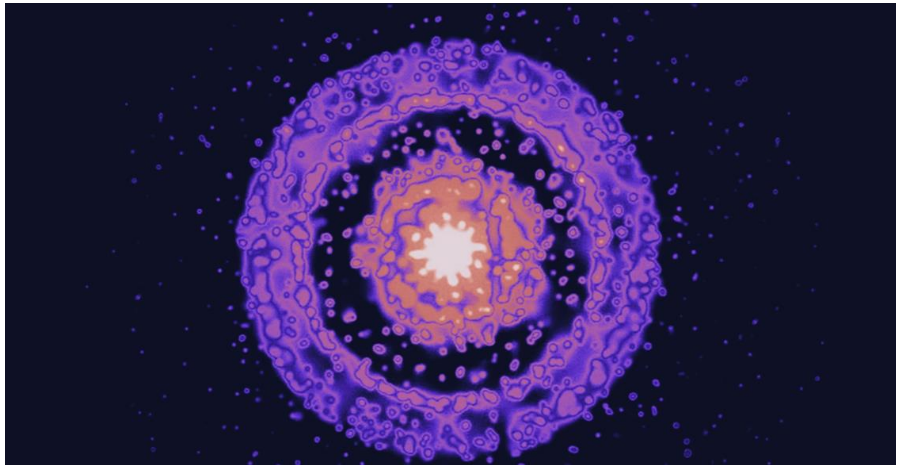
By JONATHAN O'CALLAGHAN

October 26, 2022

HOT TOPIC

A recent gamma-ray burst known as the BOAT — “brightest of all time” — appears to have produced a high-energy particle that shouldn’t exist. For some, dark matter provides the explanation.

Quantamagazine

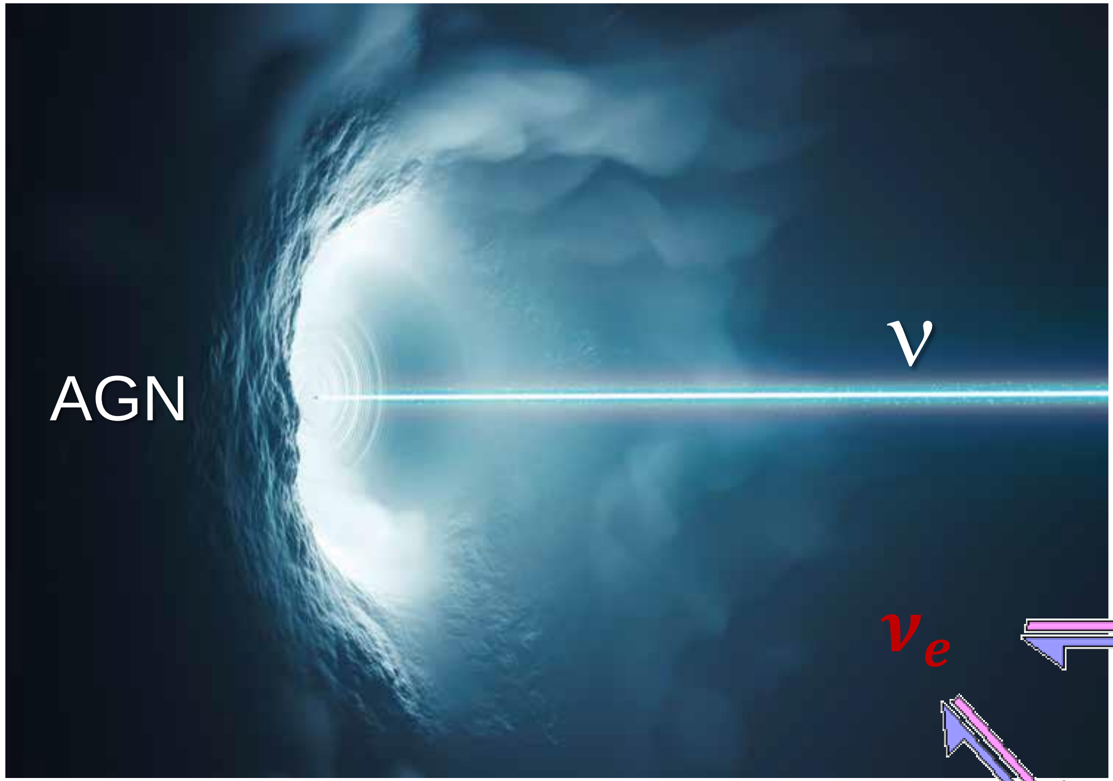


*see Lecture 1 (Oct. 26) p. 17

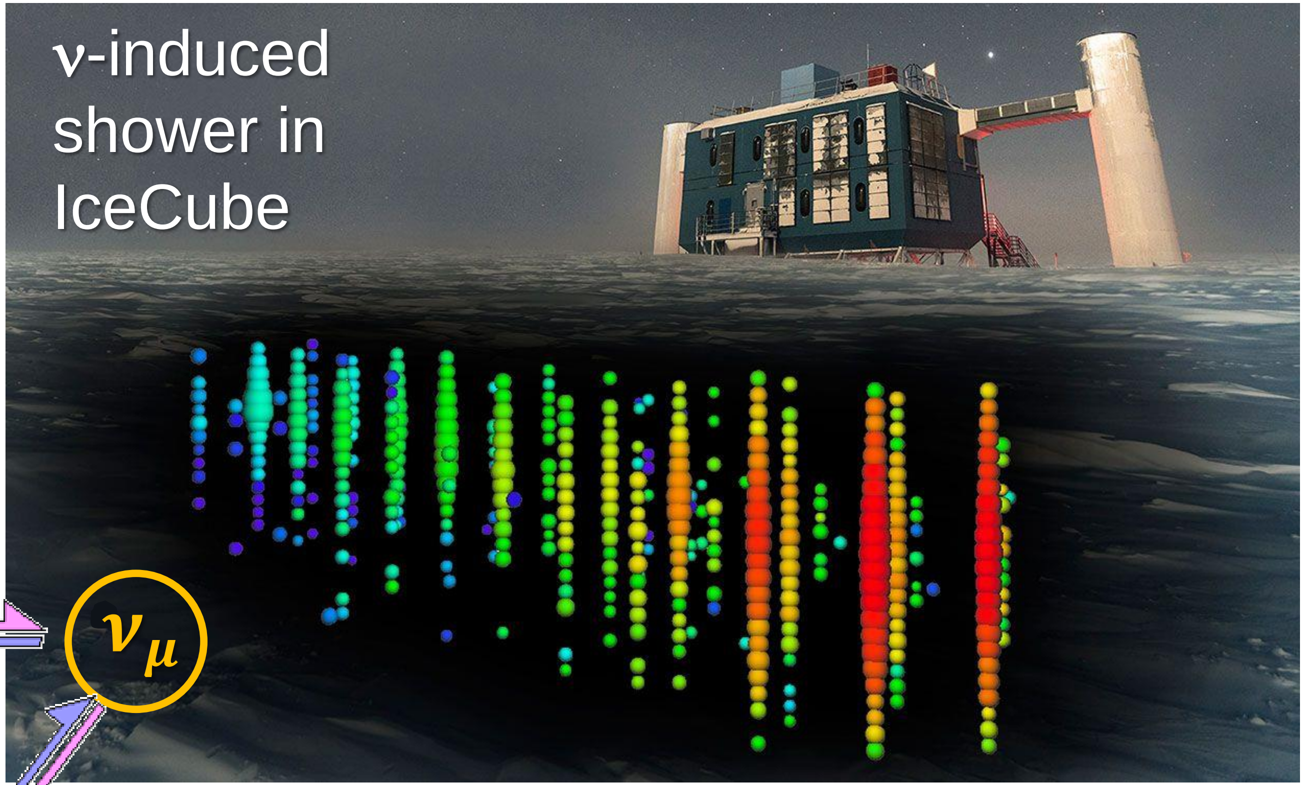
Neutrinos – large-volume Cerenkov detectors

- **Search for point sources of neutrinos at the TeV…PeV energy scale**

  - no interaction with photon background fields, but ν-oscillations



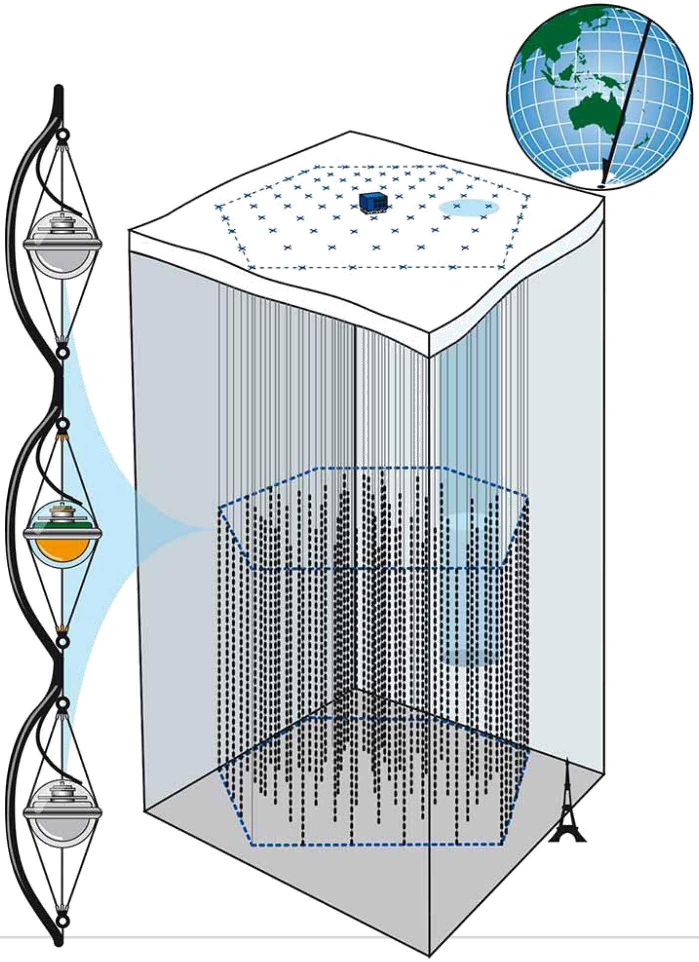
Q: DESY

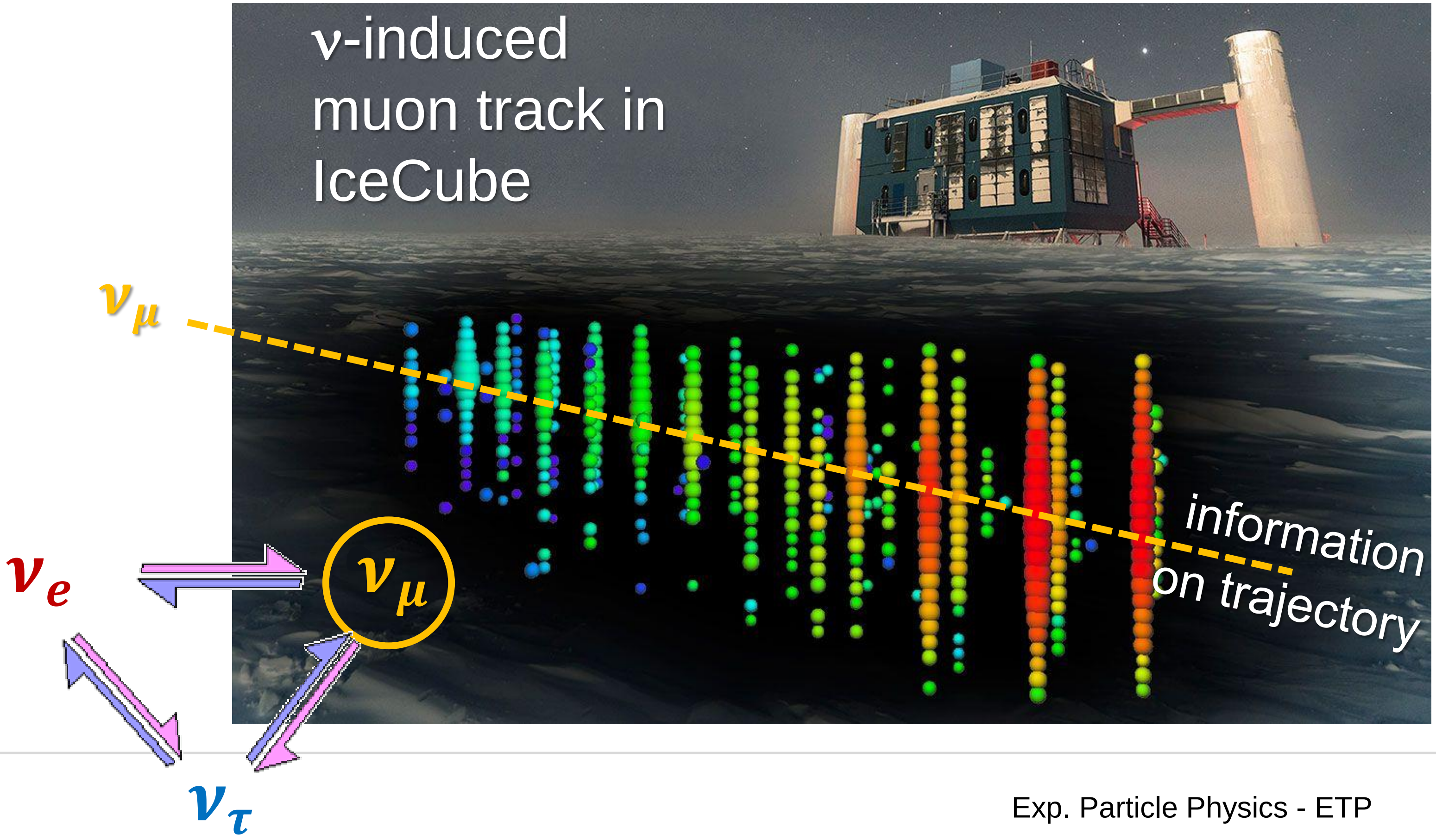


ν_τ

Neutrinos – large-volume Cerenkov detectors

- Search for point sources of neutrinos at the TeV…PeV energy scale



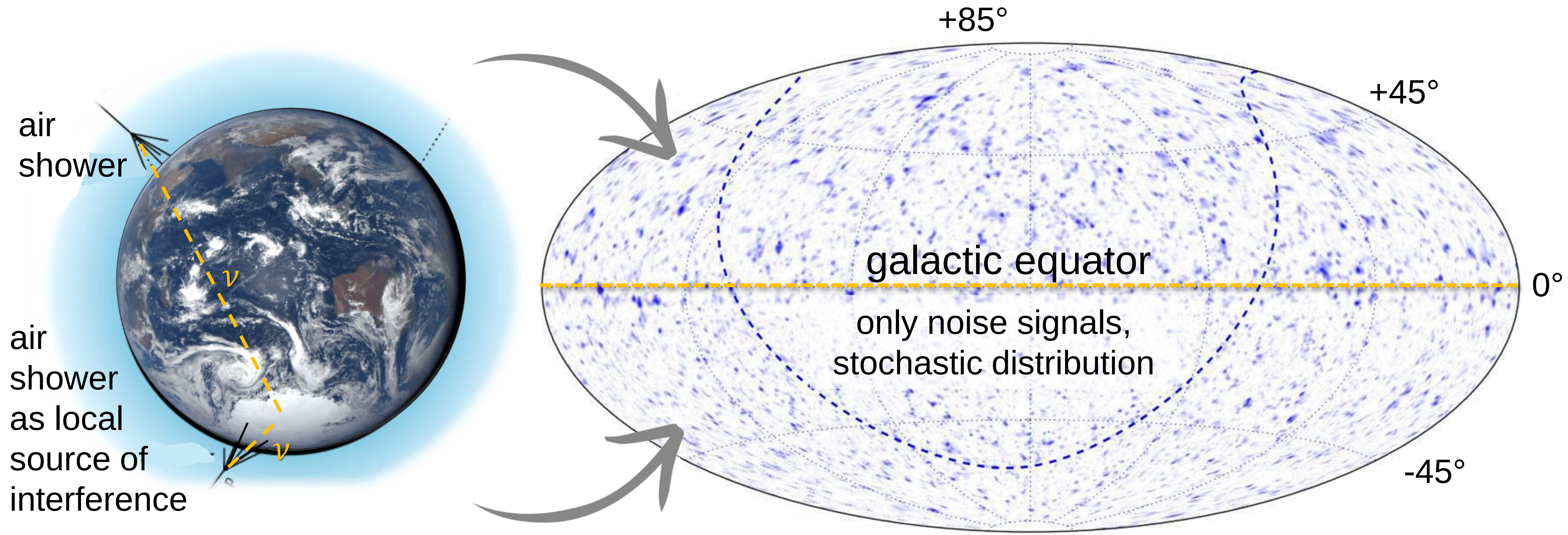


Q: DESY

Neutrinos – scanning the northern & southern sky

- **Search for point sources of neutrinos at the TeV…PeV energy scale**

  - **isotropic background, very rare ν-signals from extragalactic sources**

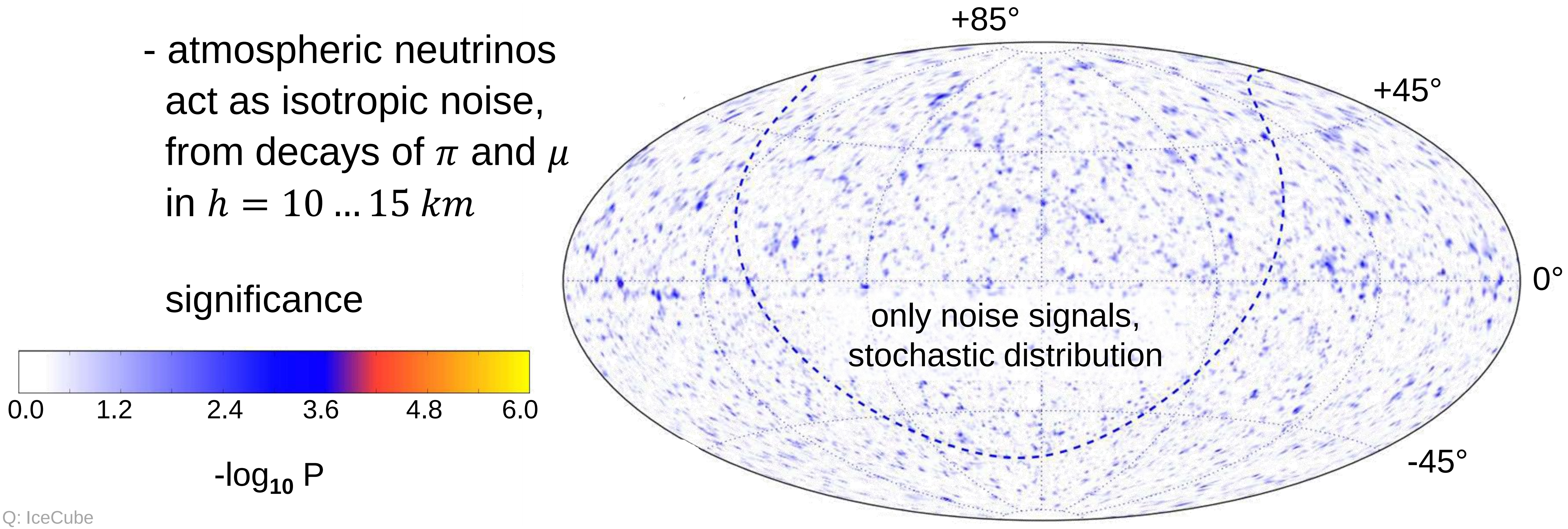


Neutrinos – scanning the northern & southern sky

- Search for point sources of neutrinos at the TeV…PeV energy scale

  - isotropic background, very rare ν-signals from extragalactic sources

  - atmospheric neutrinos act as isotropic noise, from decays of π and μ in $h = 10 \ldots 15\ km$



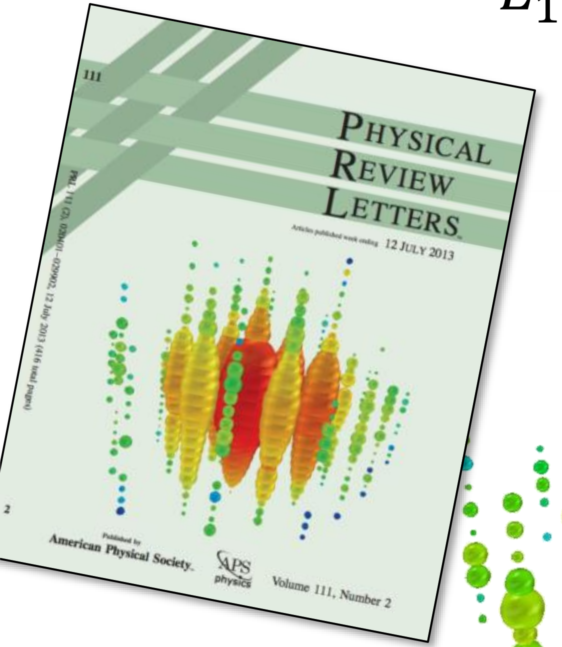
Q: IceCube

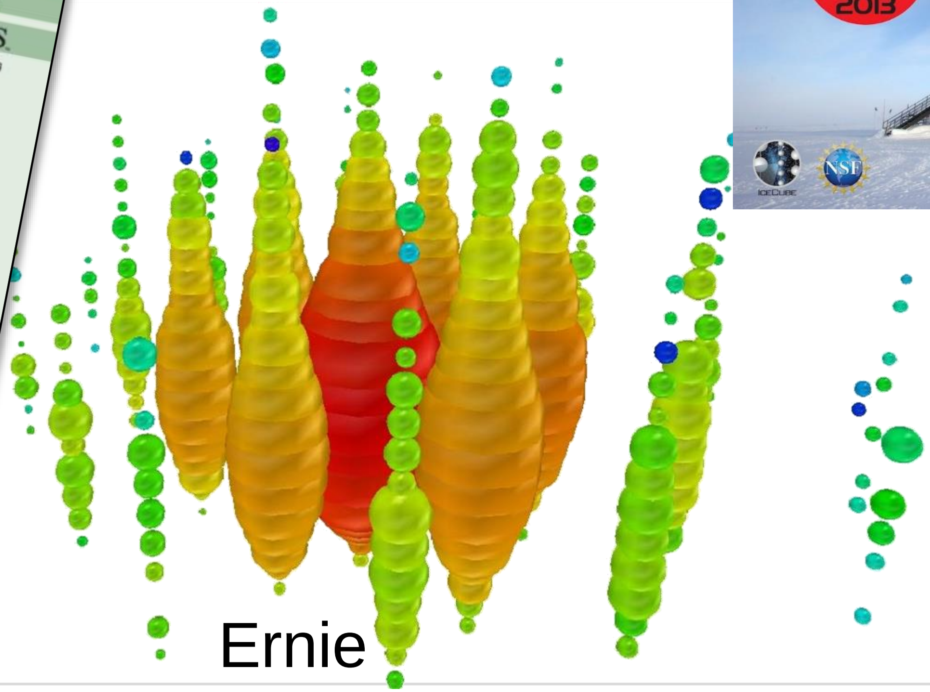
UHE neutrinos – first detection in April 2013

- **First an breakthrough in neutrino astronomy with IceCube (2.8 σ)**

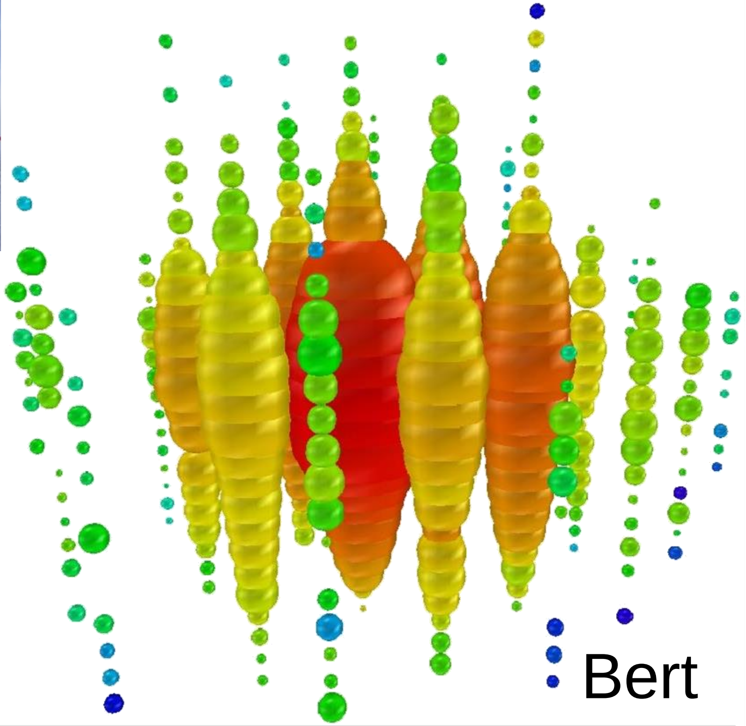
$E_1 = (1.04 \pm 0.16) PeV$

$E_2 = (1.14 \pm 0.17) PeV$





Ernie



Bert

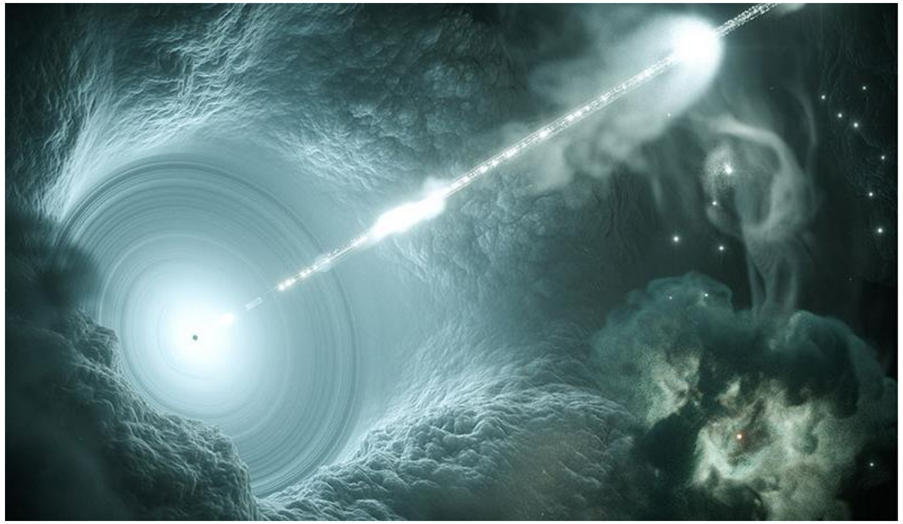
Q: IceCube

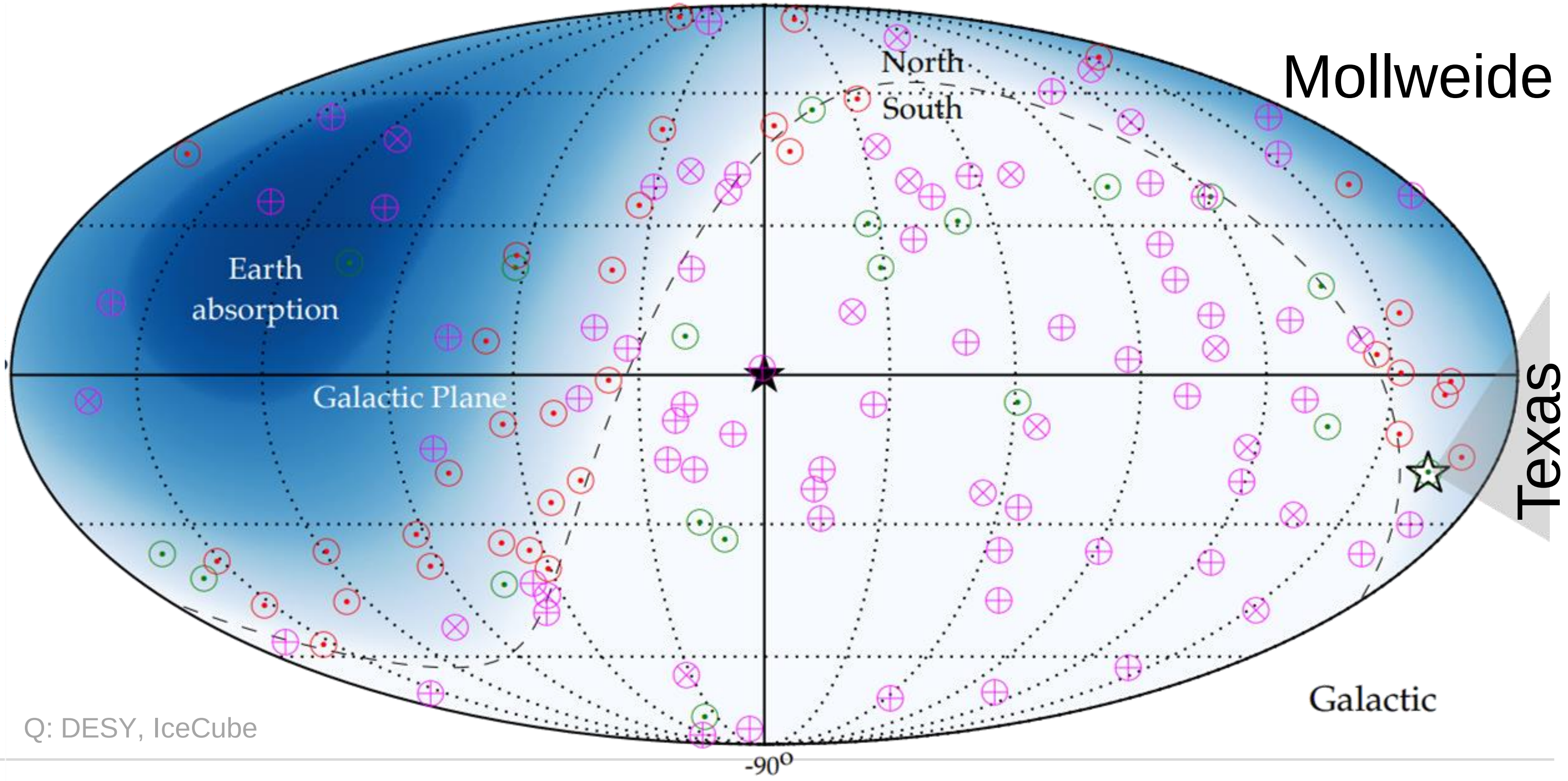
UHE neutrinos – November 2019 sky map

- **distribution of UHE neutrinos is isotropic – no identified sources, but…**

  - then luck strikes: first identified source – **an active blazar*** in a flare state!!

TXS 0506+056: the active ´TEXAS´ blazar





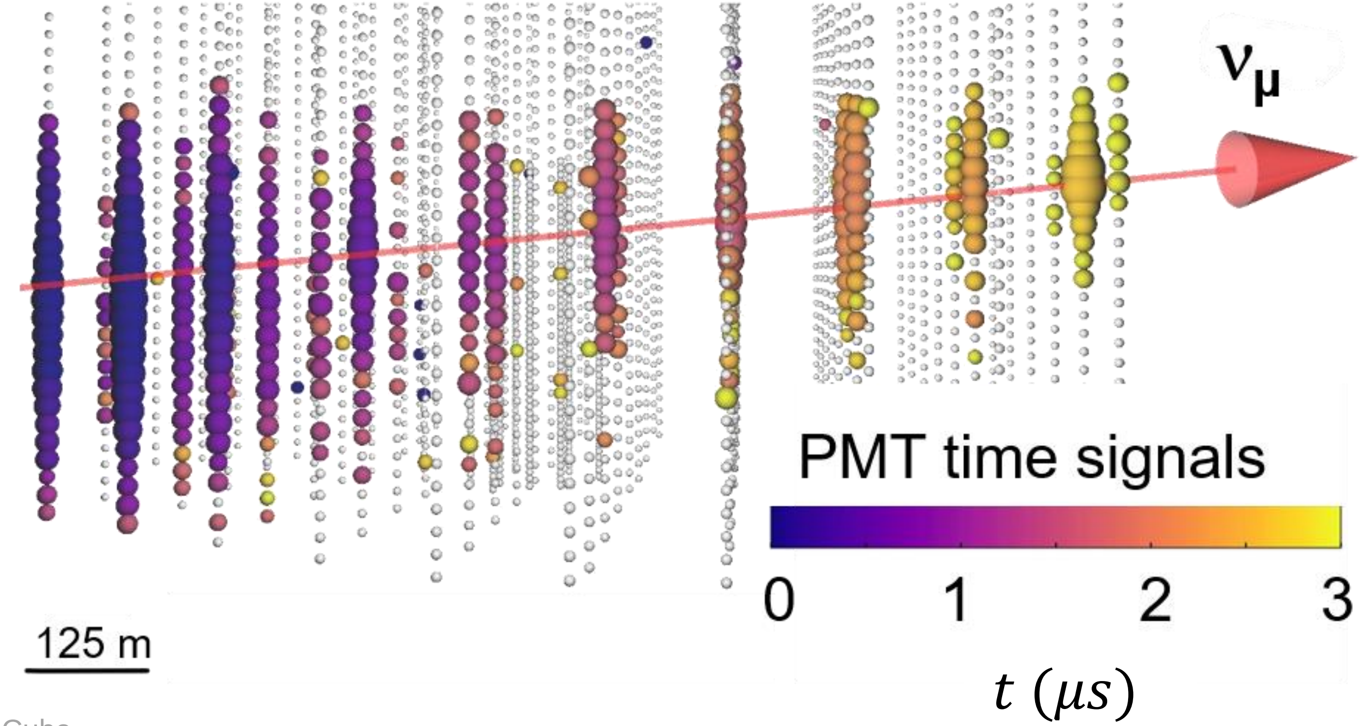
Q: DESY, IceCube

*blazar = AGN with relativistic jet

the first UHE neutrino source: the TEXAS blazar

- **a UHE neutrino from an active blazar in $d = 5.7 \cdot 10^9\ ly$**

Sept. 22, 2017 – IceCube observes a ν_μ with $E = 290\ TeV$ from an active AGN in a ´flare´ state (i.e. enhanced emission of gammas):
a known, variable γ-source



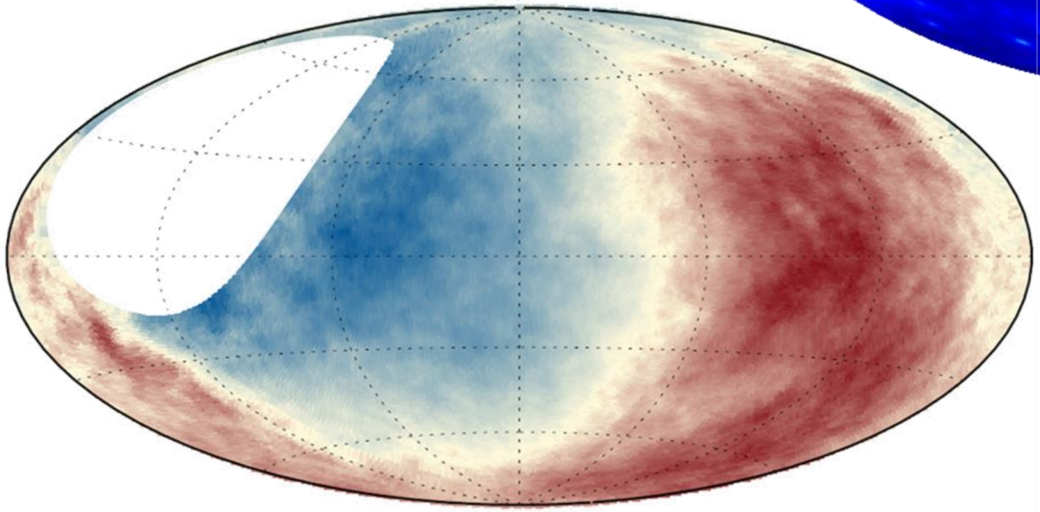
Q: DESY, IceCube

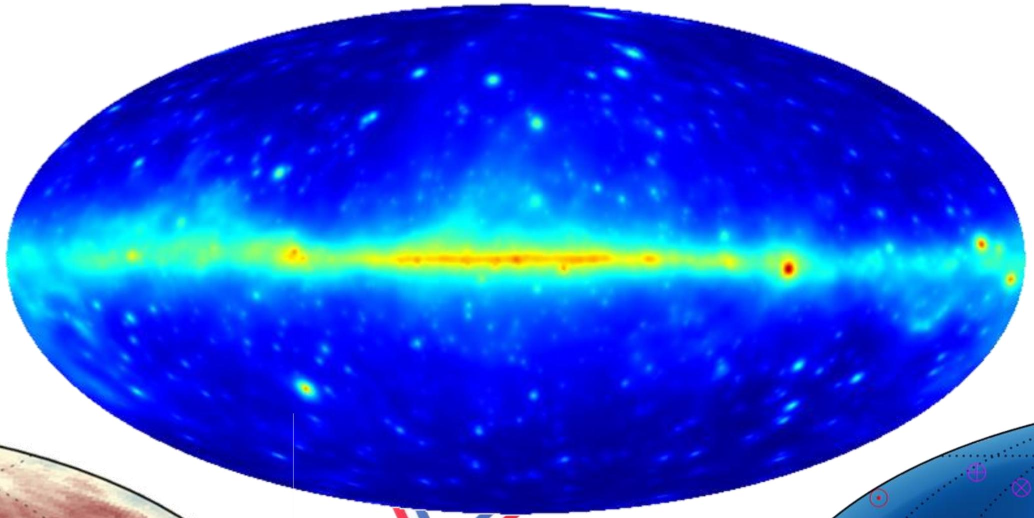
Multimessenger astronomy – a comparison

- **all-sky-maps für GeV/TeV gammas, PeV neutrinos & UHECR´s at EeV**

CR

anisotropy > 8 EeV



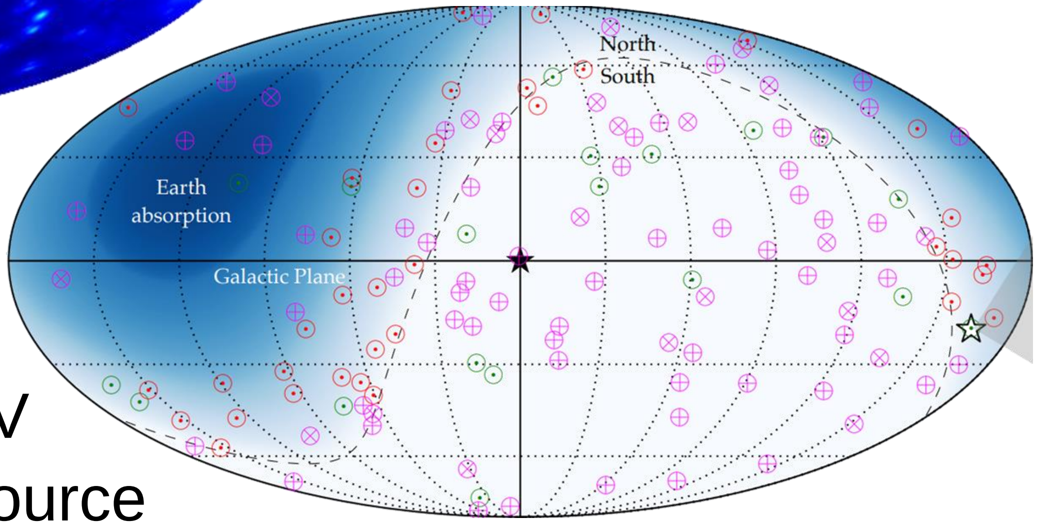


γ

> 500 sources > 10 GeV

ν

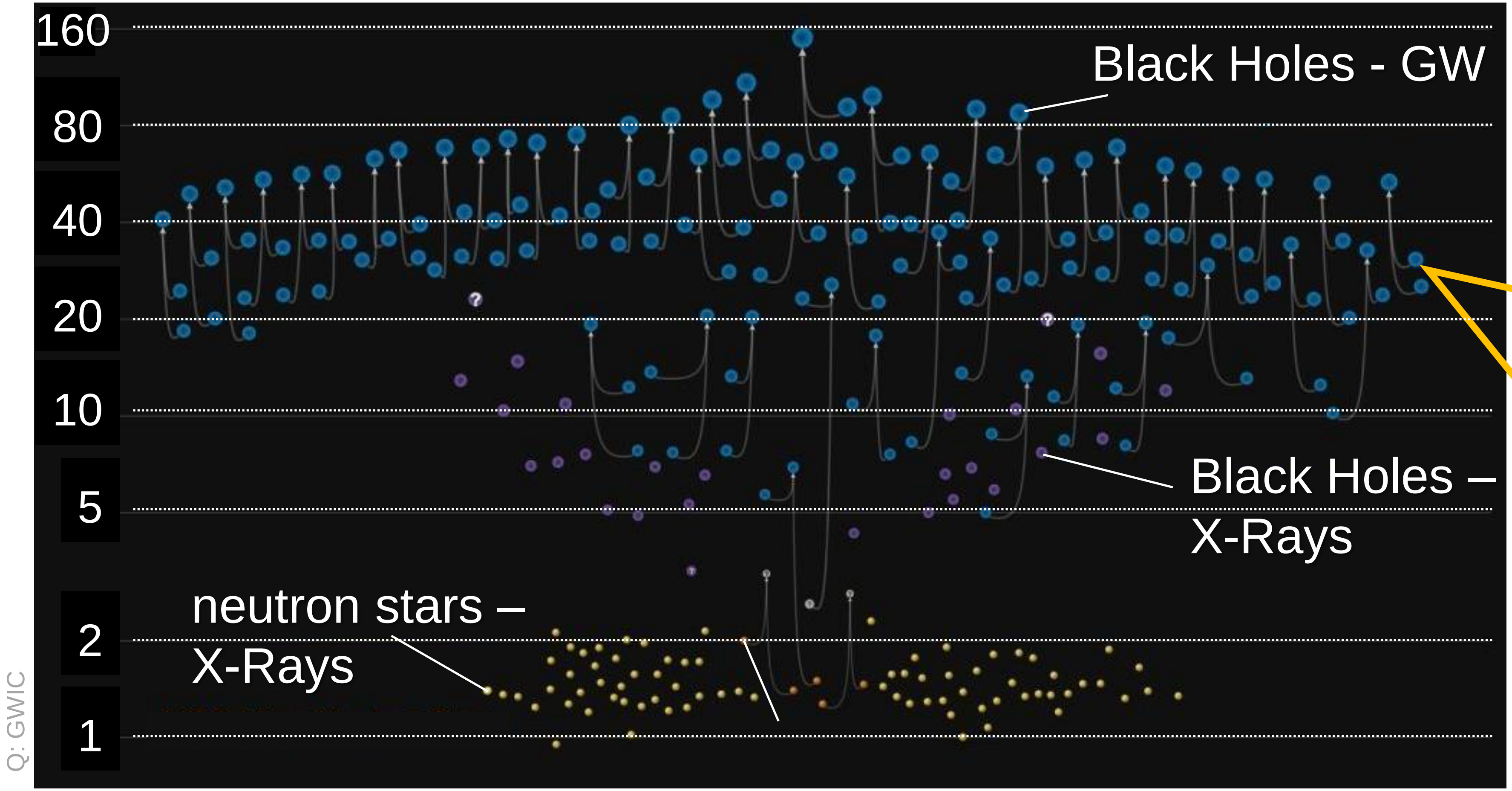
E > 30 TeV
+ Texas source

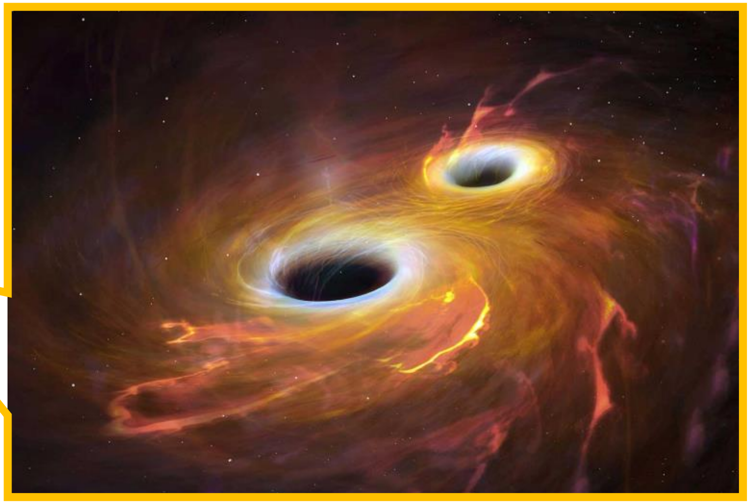


Multimessengers – GW, the new ´kid on the block´

Karlsruhe Institute of Technology

- **Gravitational waves (GW): detection of merger processes of compact objects**



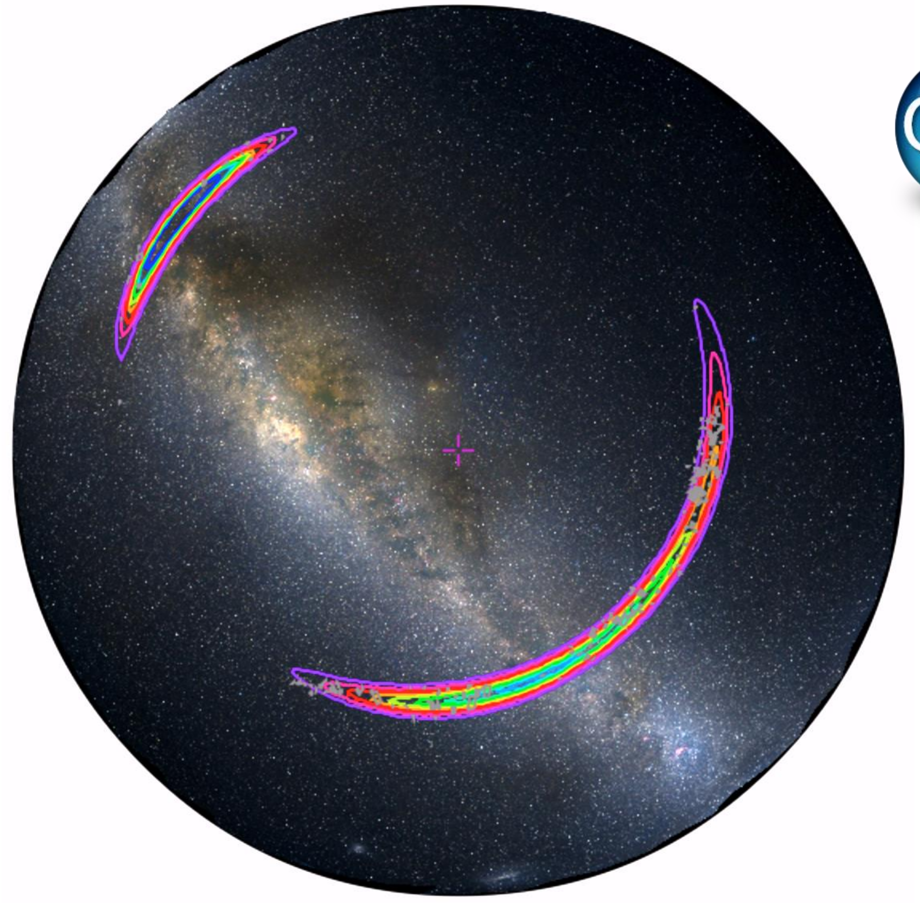


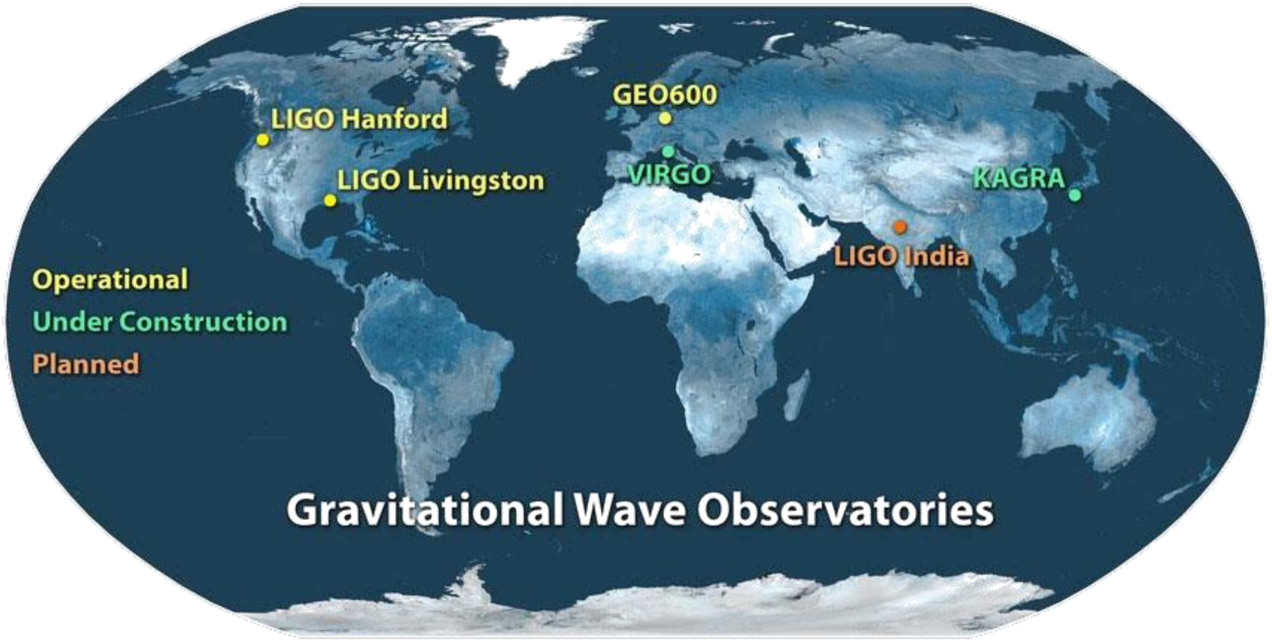
merger process of two Black Holes

masses $[1 - 160\ M_\odot]$ of merging compact objects

BH merger process: reconstructing the GW origin

- Gravitational waves allow to reconstruct the merger place, if combined





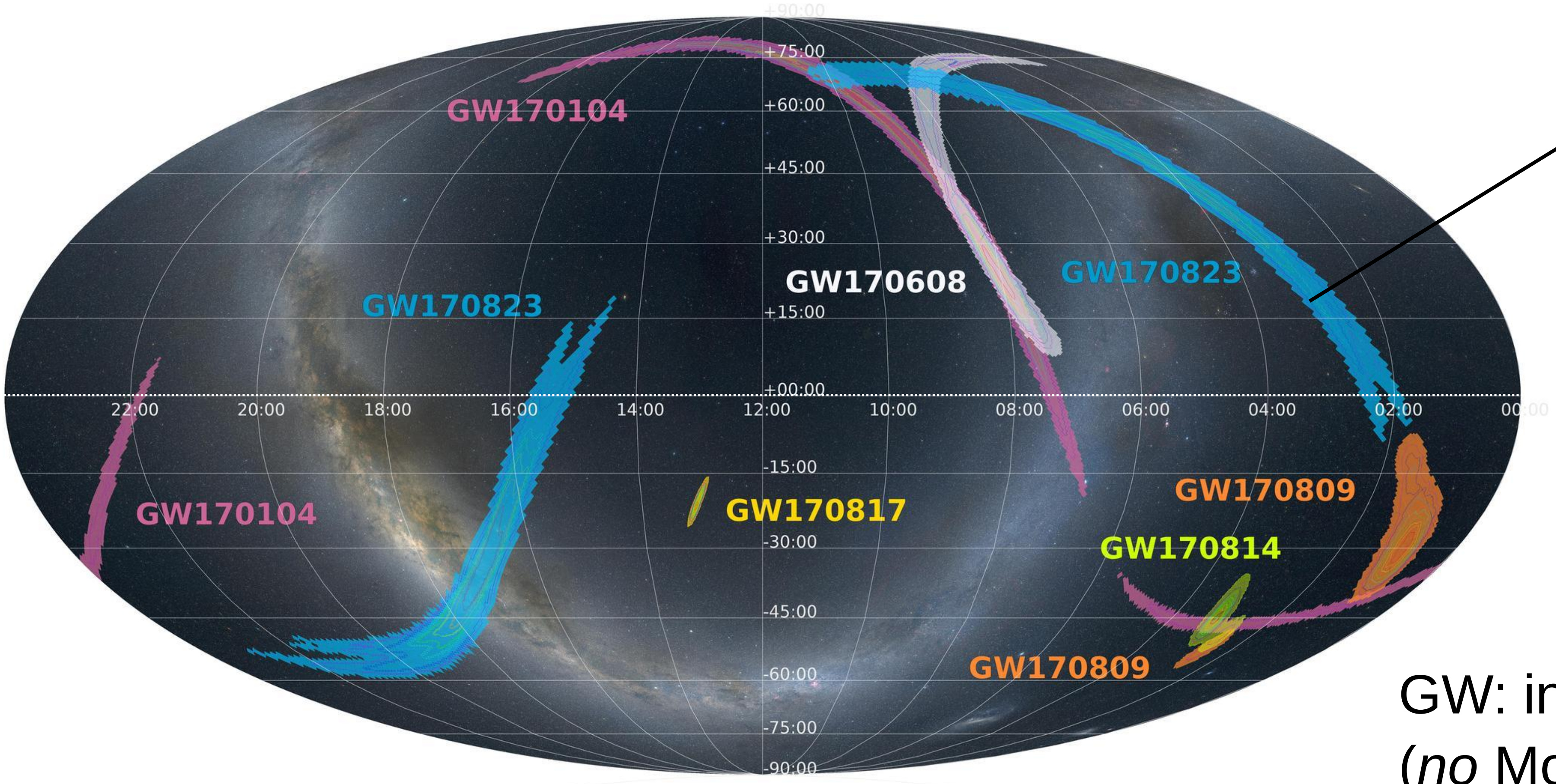
- detection in only one GW experiment:
  large uncertainties to determine the origin

- triangulation allows to improve reconstruction

Q: LIGO

BH merger process: reconstructing the GW origin

- **Status of reconstructing the merger place by combining GW data**



90% CL region of localisation from *offline* analysis

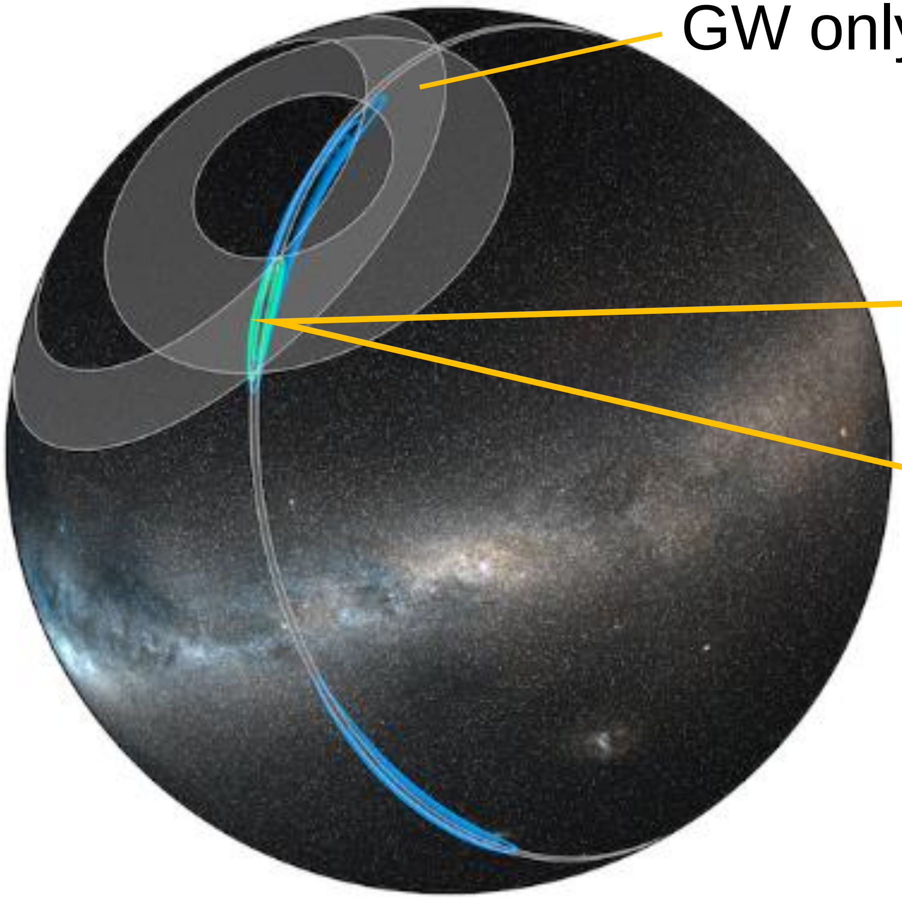
GW: in ICRS*
(<u>no</u> Mollweide projection!)

Q: LIGO

*International Celestial Reference System

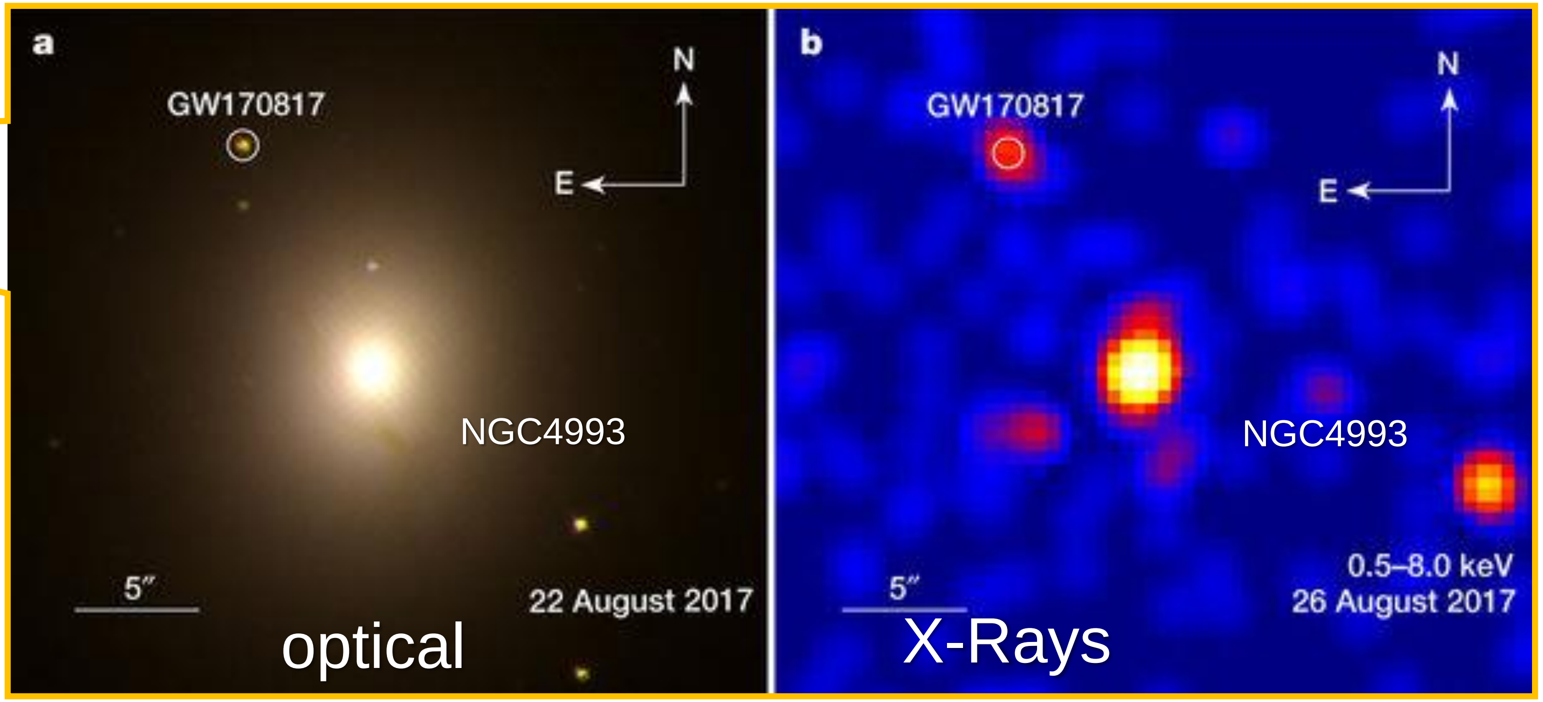
BH merger process: reconstructing the GW origin

- **Precision reconstruction requires identification of an optical ´afterglow´**



GW only

visible: ´kilonova´ in galaxy NGC 4993 (August 2017)

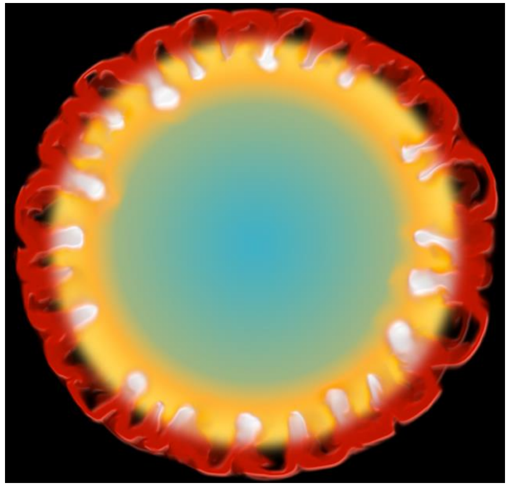


Q: LIGO

2.1.1 Cosmic air shower experiments

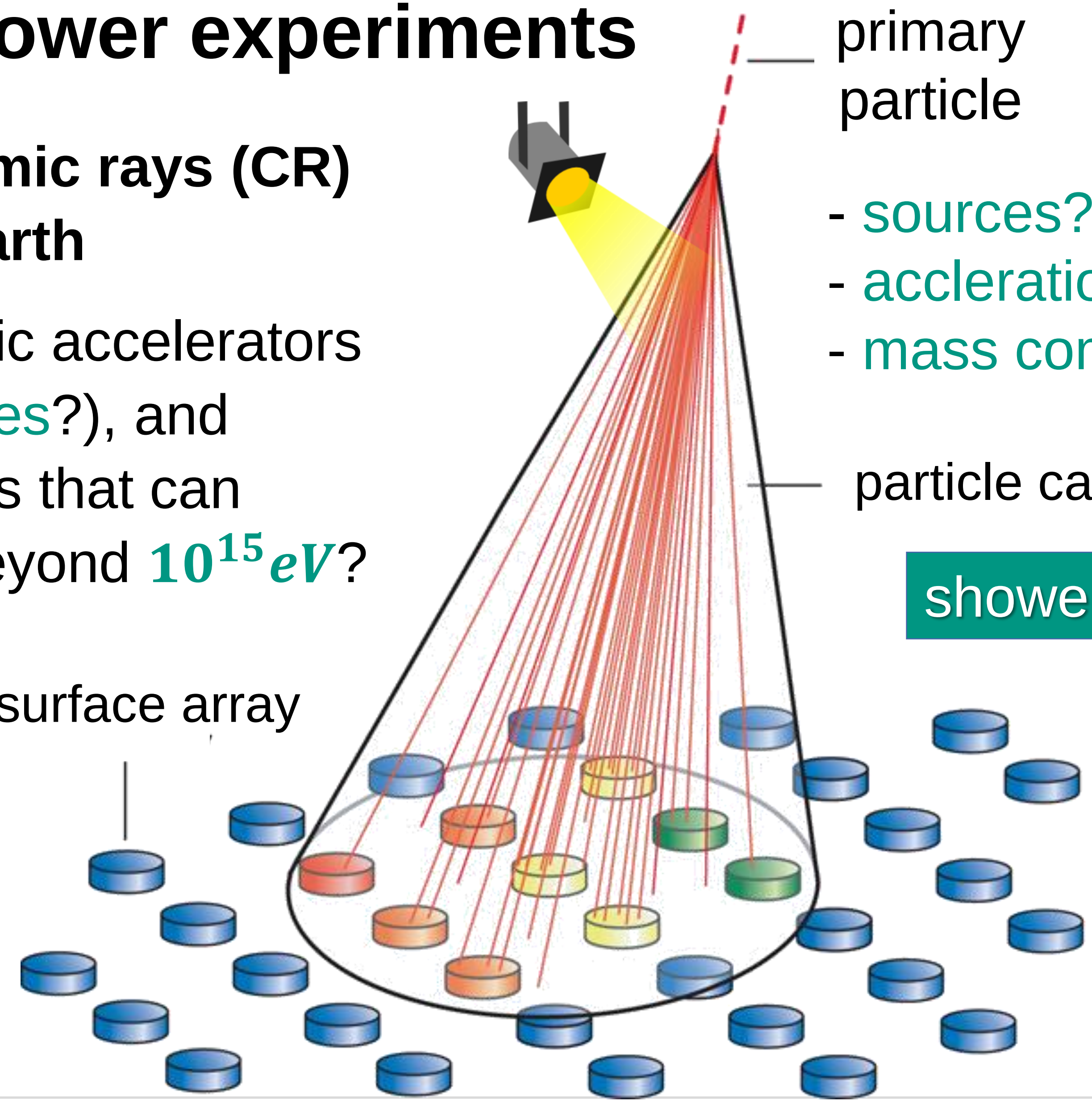
- **detecting charged cosmic rays (CR) at the surface of the Earth**

  - what types are the cosmic accelerators (proton or lepton machines?), and what are the mechanisms that can accelerate particles to beyond $10^{15} eV$?



Q: scientific am.

SNae as sources?



- sources?
- accleration processes?
- mass composition?

shower processes

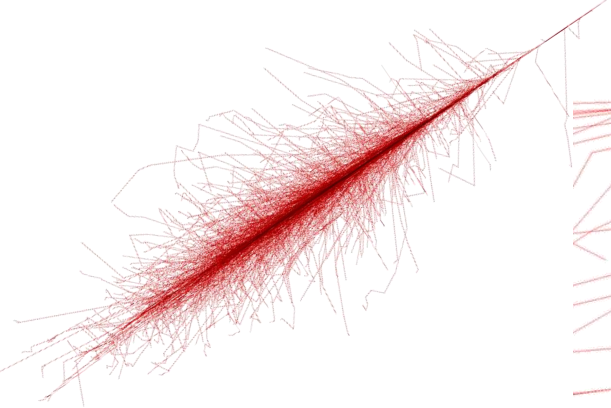
detectors

Q: KH Kampert

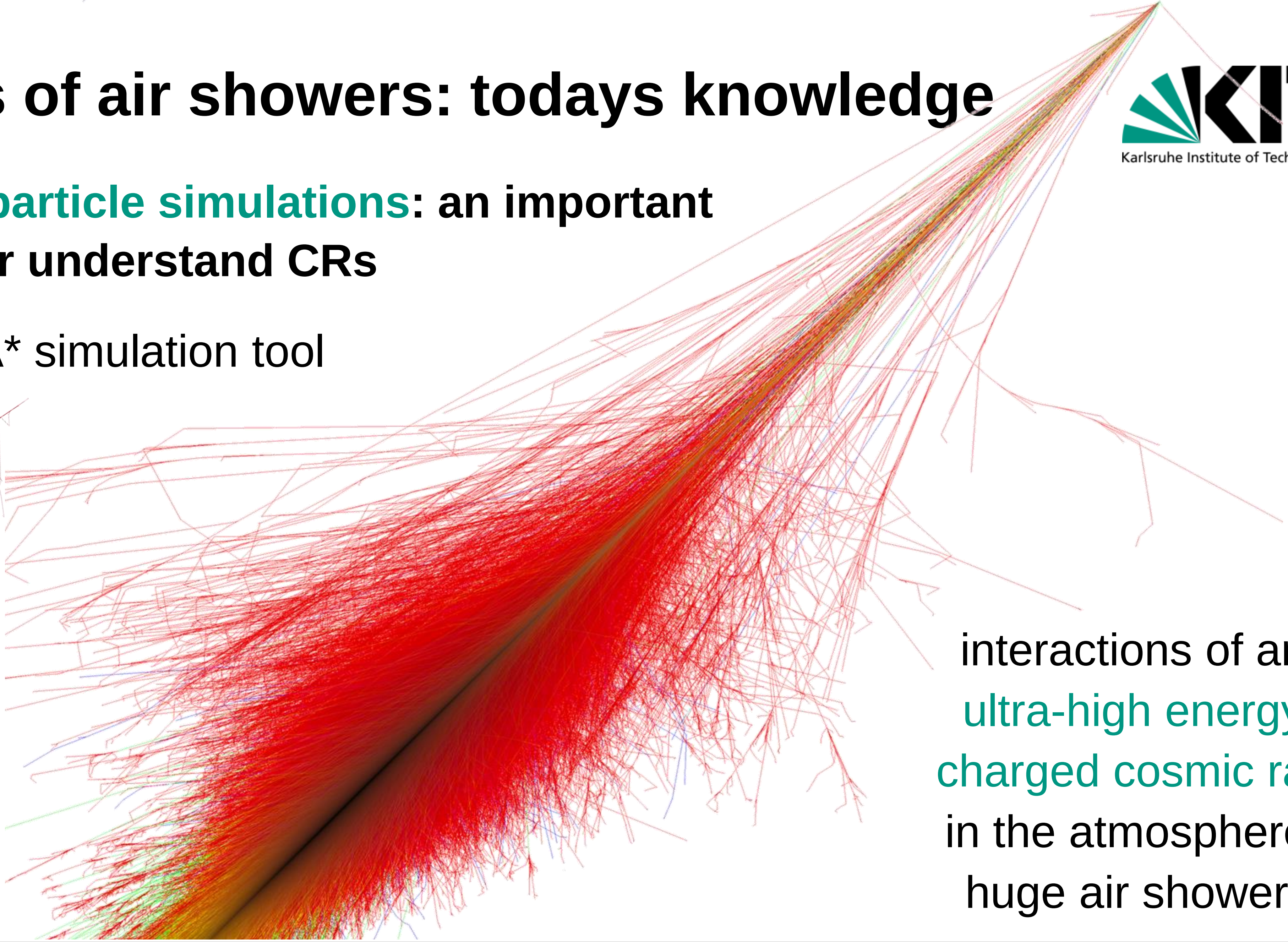
the physics of air showers: todays knowledge

- **large-scale particle simulations: an important tool to better understand CRs**

  - CORSIKA* simulation tool



photon induced shower



interactions of an ultra-high energy charged cosmic ray in the atmosphere: huge air shower!

Q: CORSIKA, KIT

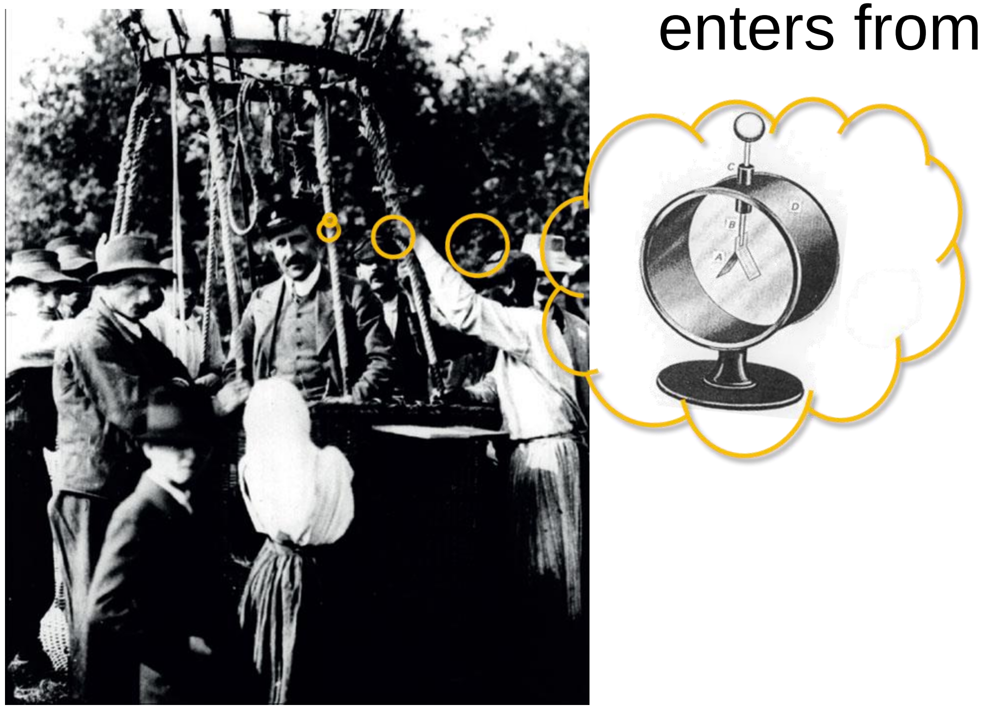
* KIT - CORSIKA - CORSIKA

The discovery of cosmic rays by V. Hess

- **Victor Hess & his series of balloon ascents, starting at the Vienna Prater**

results: ionisation of the air does not decrease with height (h = 5 km)

explanation: there is a radiation form with great penetrating power, which enters from the top of the atmosphere, not correlated to the sun



Q: APS

83. Naturforscherversammlung Karlsruhe (Sept. 1911)

The observed too low decrease of ionisation in a closed vessel as function of altitude could be caused by two effects:

" ... First, there could be (beyond the radioactive substances of the Earth) another **unknown ionisator being effective in the atmosphere**"

Karlsruhe

The discovery of cosmic rays by V. Hess

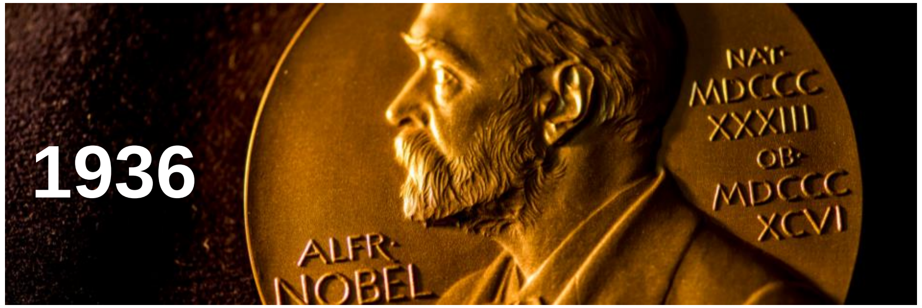
Karlsruhe Institute of Technology

- **Victor Hess & his series of balloon ascents, starting at the Vienna Prater**

results: ionisation of the air does not decrease with height (h = 5 km)

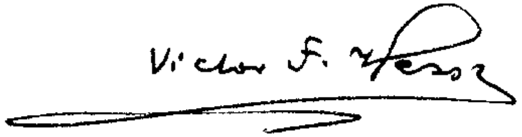
explanation: there is a radiation form with great penetrating power, which enters from the top of the atmosphere, not correlated to the sun

Q: nobelprize



´for his discovery of cosmic radiation´

Viktor Hess
1883-1964



Q: österreichische Post

111 years: 1911-2022

The discovery of cosmic rays by Hess & H.E.S.S.

- **Victor Hess & his series of balloon ascents, starting at the Vienna Prater**

in honour of V. Hess, an air cherenkov array, **H.E.S.S.**, has been named,
which has given us important insight into the GeV-TeV gamma ray sky (see 2.1.2)

Q: österreichische Post

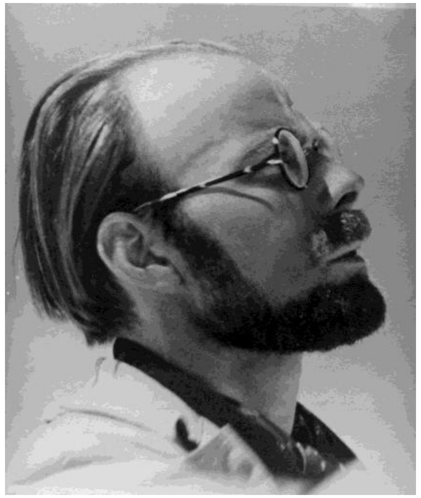
H.E.S.S. - **H**igh **E**nergy **S**tereoscopic **S**ystem (Namibia)

Discovery of extended air showers by P. Auger

- **Pierre Auger: series of coincidence measurements at the Jungfraujoch**

coincidence technique:
2 Geiger counters at distances of up to $d = 300\ m$

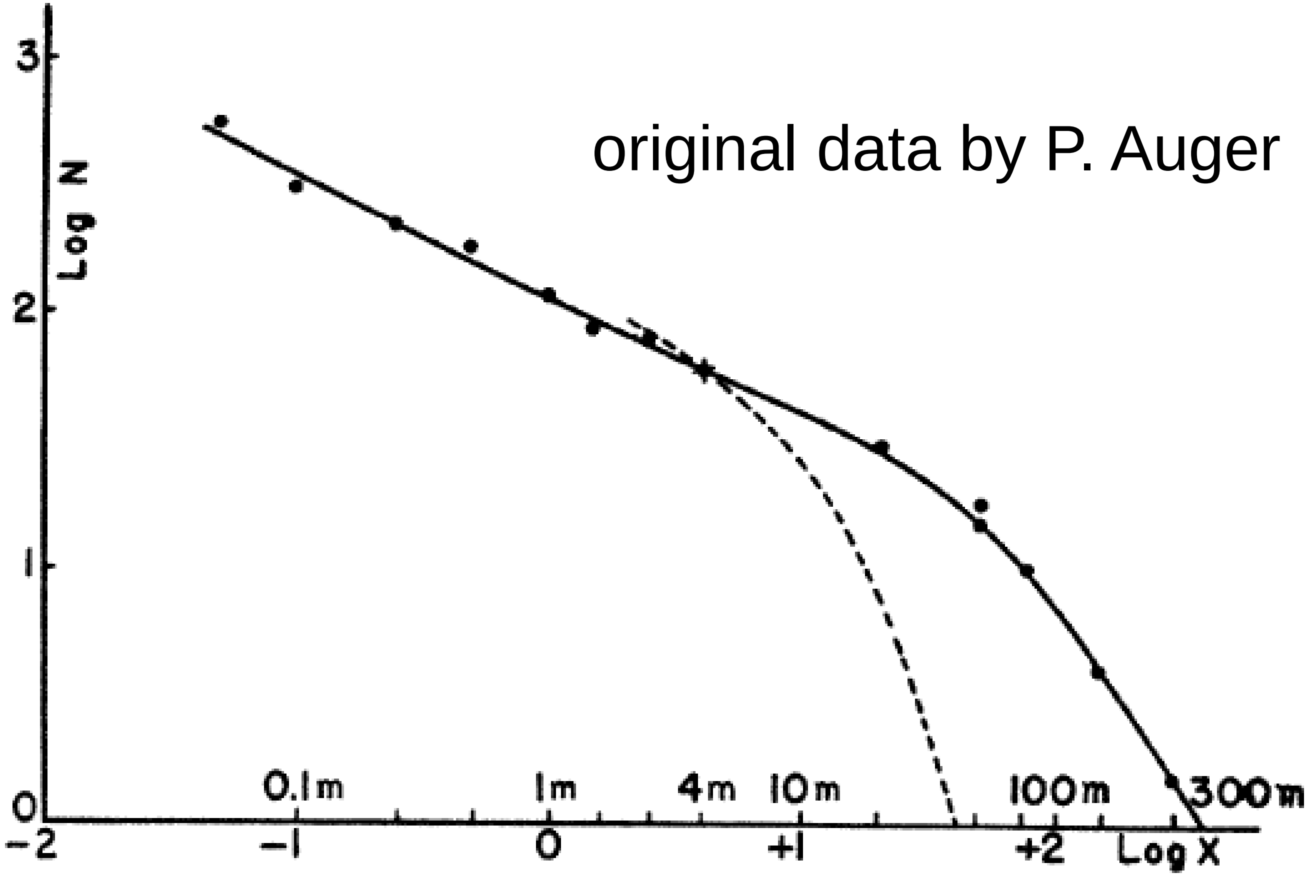
Jungfraujoch



Q: CNRS

Pierre Auger
1899-1993

original data by P. Auger



Discovery of extended air showers by P. Auger

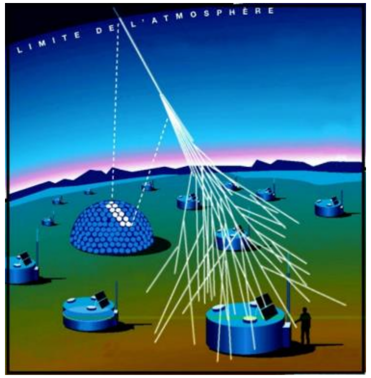
Karlsruhe Institute of Technology

- **Pierre Auger: series of coincidence measurements at the Jungfraujoch 1939**

  - first estimates of the primary CR-energy: $E > 10^{15} eV$!!

  - primary energies far beyond the LHC scale (highly efficient CR acclerators!)

in honour of P. Auger, an air shower array, the **PAO**, has been named, which has given us important insight into CRs at the highest energies (see 2.1.1)



PIERRE AUGER OBSERVATORY

CONCLUSION

One of the consequences of the extension of the energy spectrum of cosmic rays up to 10^{15} ev is that it is actually impossible to imagine a single process able to give to a particle such an energy. It seems much more likely that the charged particles which constitute the primary cosmic radiation acquire their energy along electric fields of a very great extension.

Air showers at the highest energies of $10^{20} eV$

Karlsruhe Institute of Technology

John Linsley: pioneering measurements at Volcano Ranch, NM (USA)

- 2 km² remote set-up close to Albuquerque
- air shower array with 19 scintillator units
- each 3.3 m² area, at average distance $d = 442\, m$
- long-term measurements from 1958 - 1972
- 1961: observation of a very **high-energy event**
- 1970: pionieering investigations of the then new **fluorescene technique**

$$E = 2 \cdot 10^{20} eV$$

Q: Fermilab

Air showers at the highest energies of $10^{20} eV$

- **John Linsley: pioneering measurements at Volcano Ranch, NM (USA)**

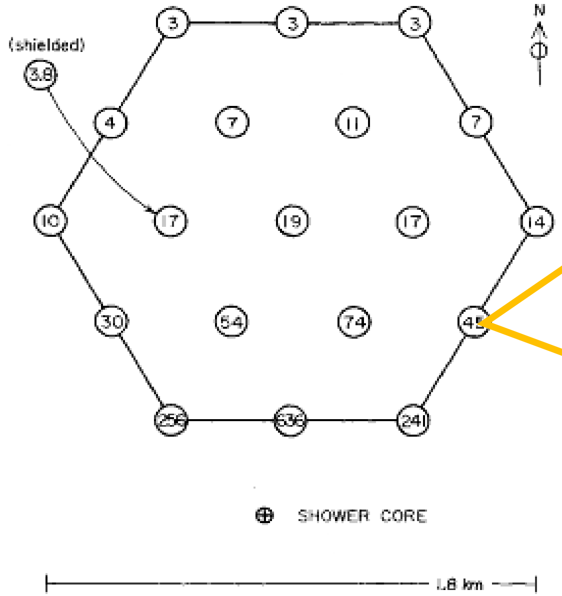
EXTREMELY ENERGETIC COSMIC-RAY EVENT*

John Linsley, Livio Scarsi,† and Bruno Rossi
Laboratory for Nuclear Science, Massachusetts Institute of Technology, Cambridge, Massachusetts
(Received April 12, 1961)

This note is a preliminary report on an extremely large cosmic-ray air shower. The event was observed at the M.I.T. Volcano Ranch station, elevation 5800 ft, near Albuquerque, New Mexico. An array of scintillation counters was used to detect and measure air showers by the technique used in the earlier M.I.T. Agassiz experiment.[1] The main array was made up of 19 detectors arranged in a pattern of triangles as shown in Fig. 1. The area of each detector was 3.3 m², and the spacing of adjacent detectors was 442 m. The area enclosed by the array was 2 km², but the sensitive area for detecting very large showers was considerably greater. An additional detector shielded by 10 cm of lead sampled the penetrating component of showers.

The event to be described was one of two, nearly equal in size, which were the largest observed in the period of operation September, 1959, to May, 1960. The total on-time of the equipment during that interval was about 180 days. The particle densities (particles/m²) registered at the various points of the array are given in Fig. 1. The shower core struck

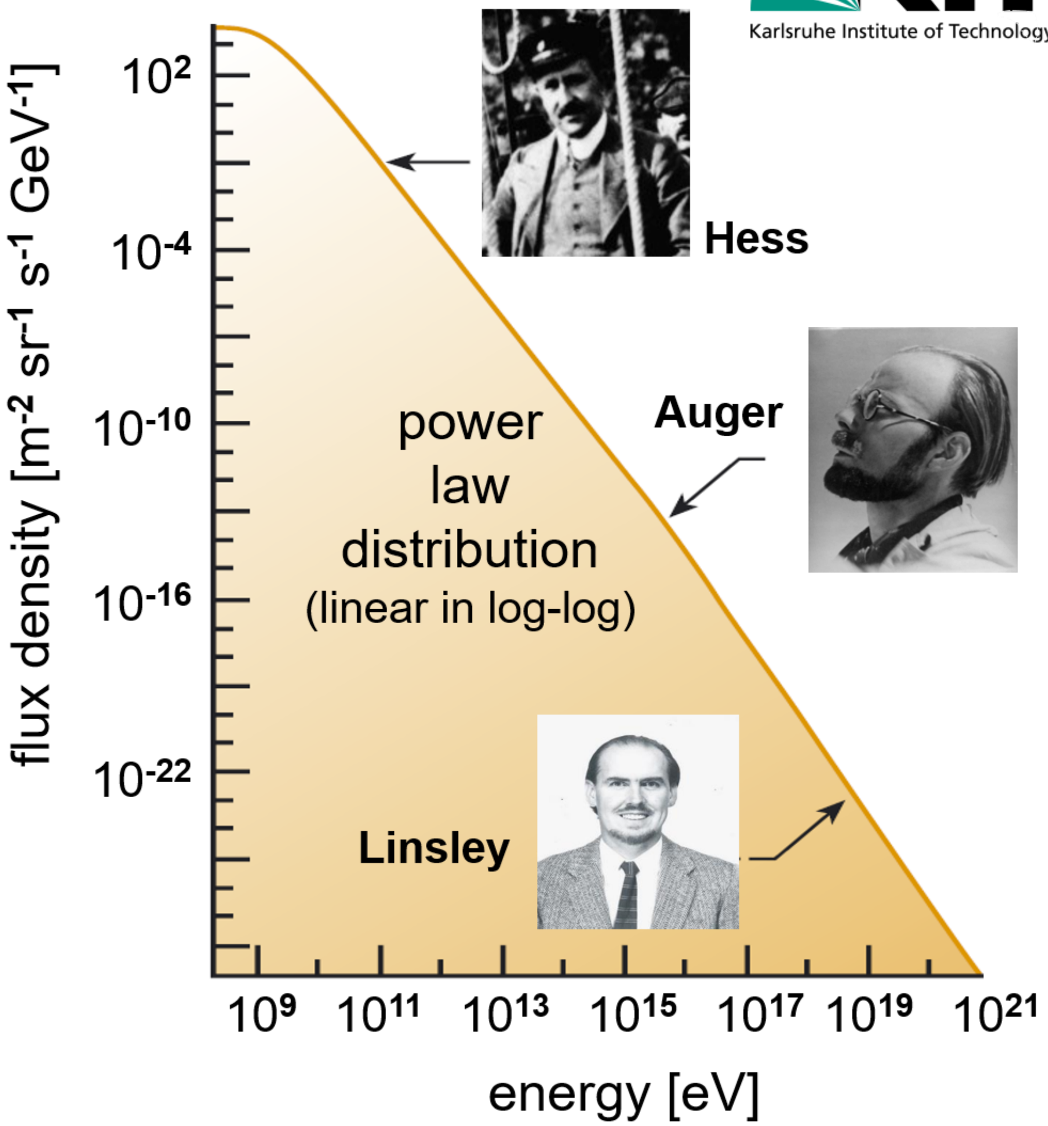
front. The values 41°, 41°, and 70° were found for the zenith angle, declination, and right ascension, respectively. The deviations of the ob-



Energy spectrum of cosmic rays in $log - log$

- CR spectrum displays a **power-law distribution** over many decades in E

■ frequency of primaries:
$E = 10^{11} eV$ (V. Hess)
1 event / m² / s
$E = 10^{15} eV$ (P. Auger)
1 event / m² / a
$E = 10^{19} eV$ (D. Linsley)
1 event / km² / a



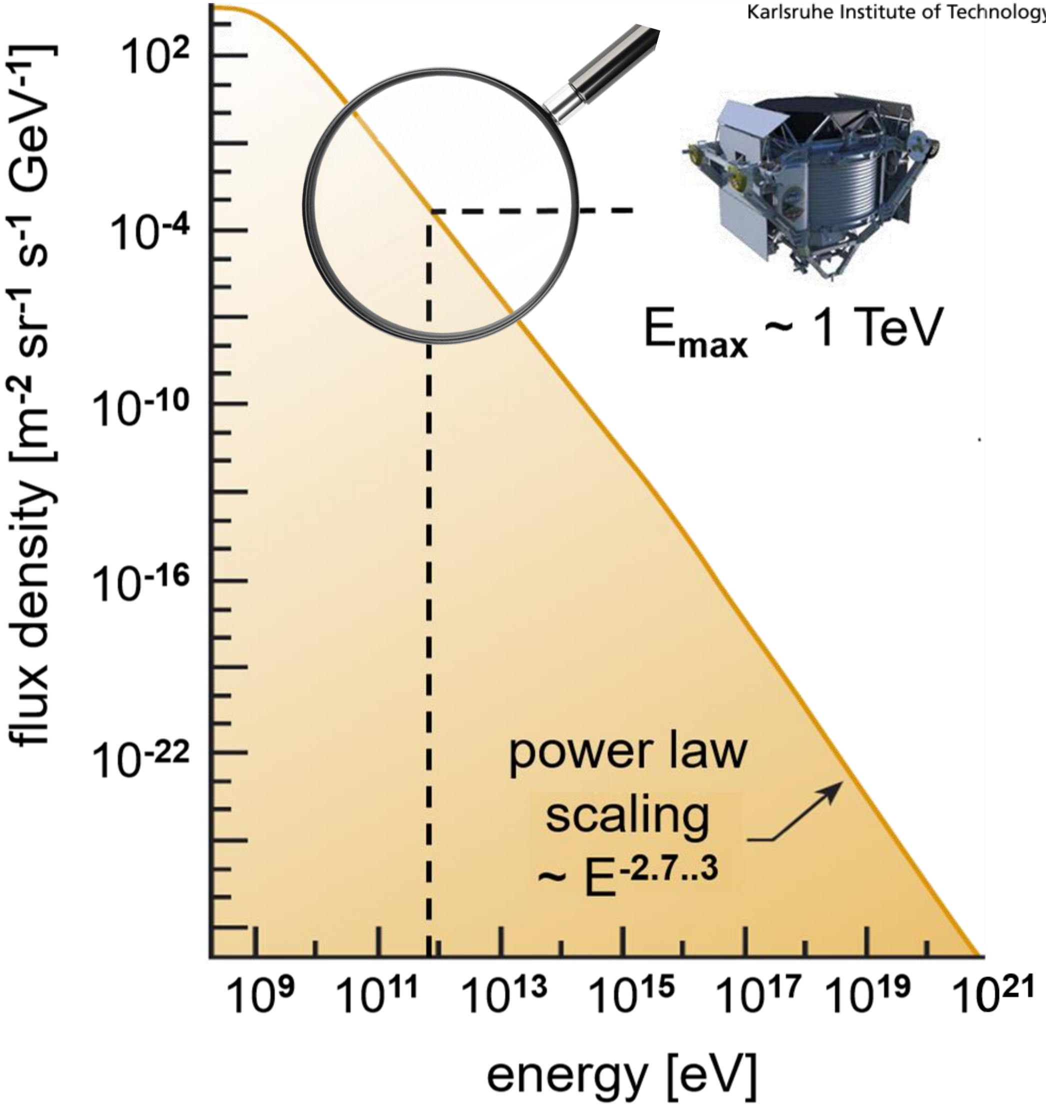
Energy spectrum of cosmic rays

- **CR spectrum: low-energy region**

  - accessible via **direct methods:** balloon- & satellite-based experiments (up to $E \sim 10^{14} eV$)

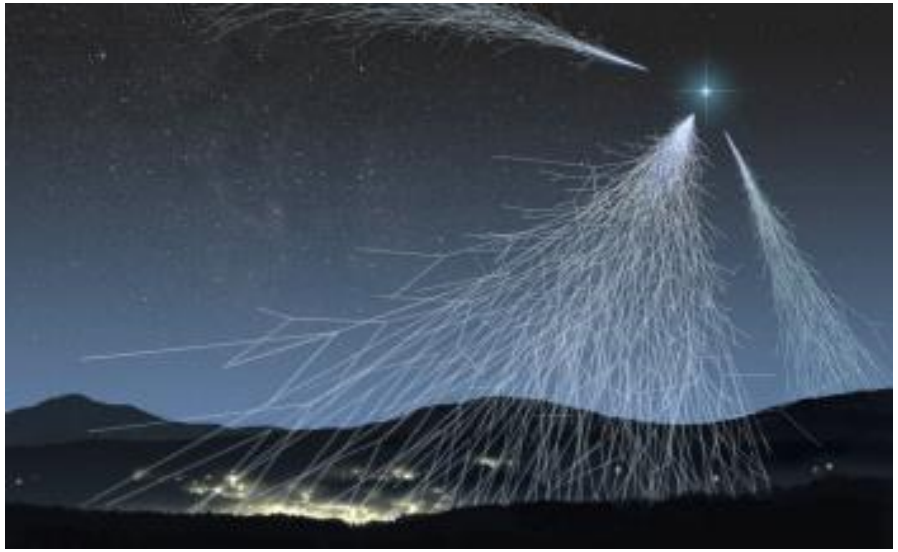
  - measurement of the primary particle

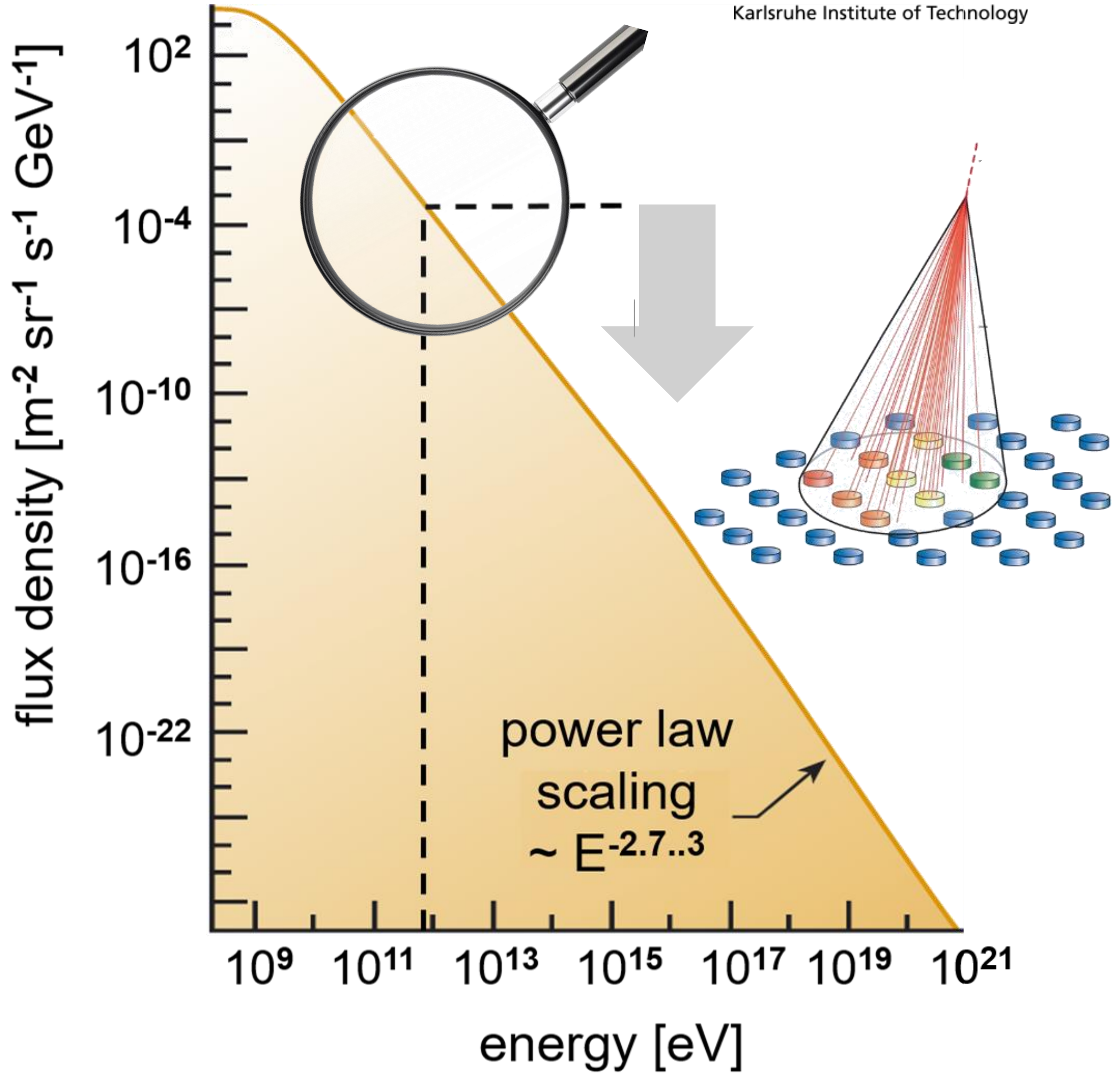
Q:NASA



Energy spectrum of cosmic rays

- **CR spectrum: high-energy region**
  - accessible via **indirect methods:** large air shower arrays at the surface (from $E\sim10^{13}eV$)
  - measurement of secondary particles





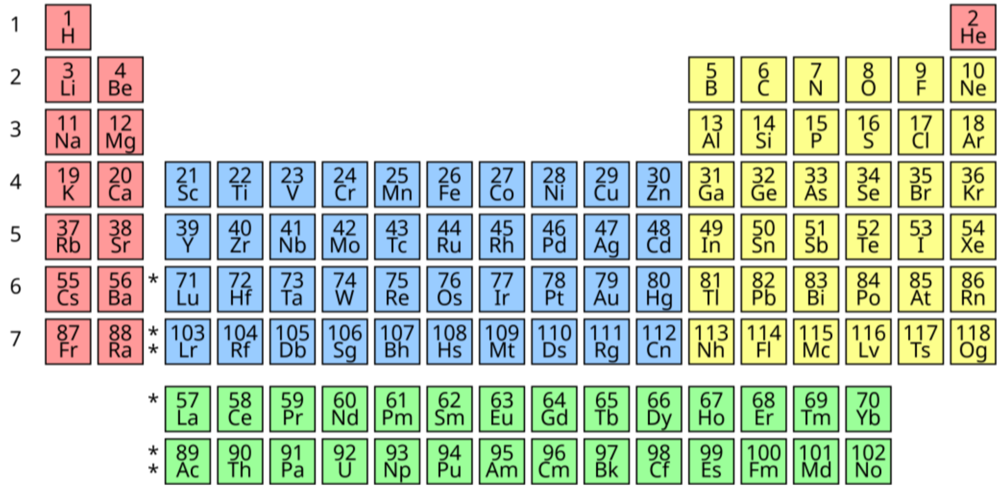
Q: spektrum

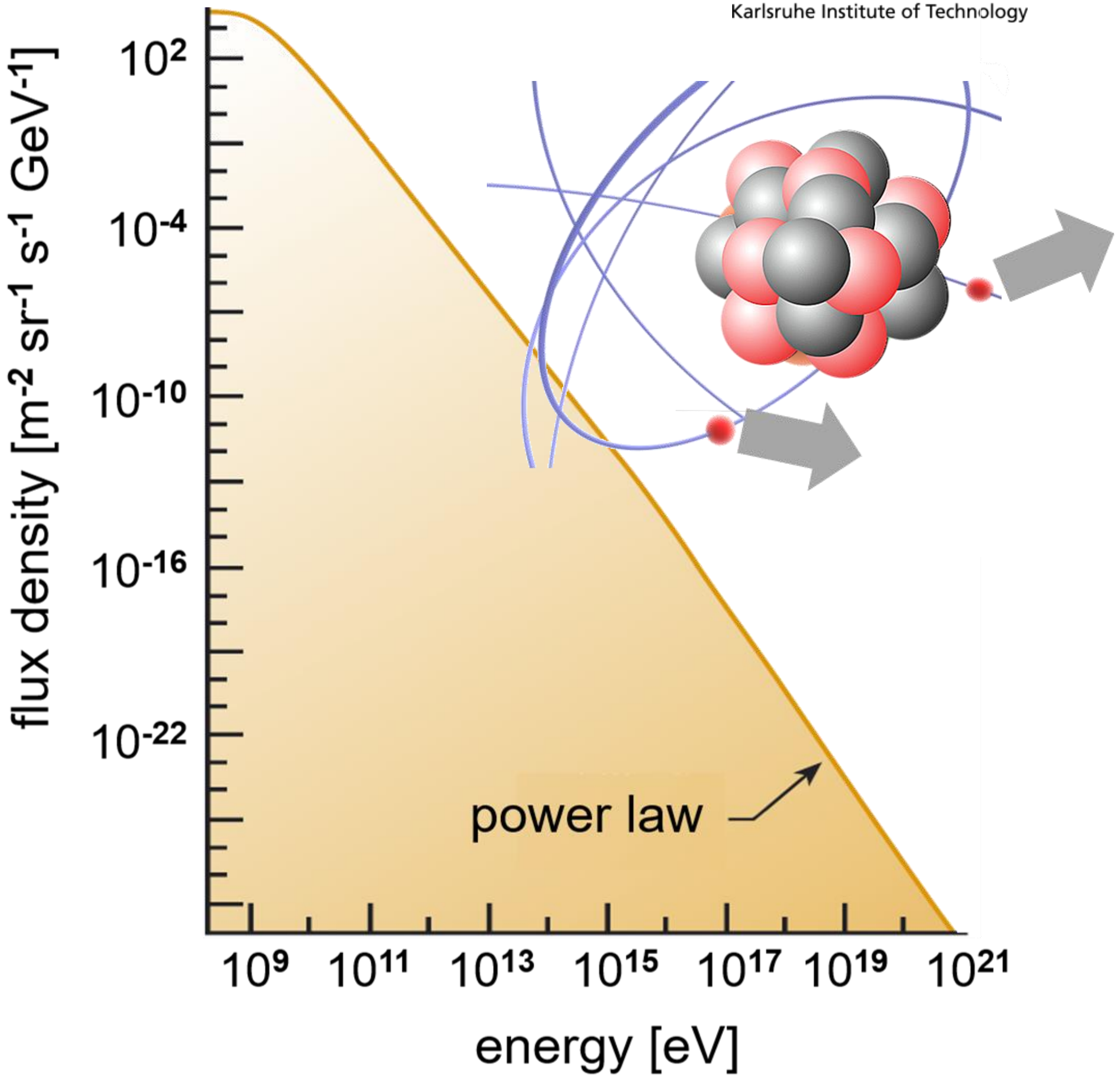
mass composition of cosmic rays

- **CR-acceleration via fully stripped ions**
  - **CR-nuclei are *fully* ionised:**
    nuclear charge Z is important

    protons $(Z = 1, A = 1), \ldots$
    iron nuclei $(Z = 26, A = 56)$

  - CR chemical compostion?





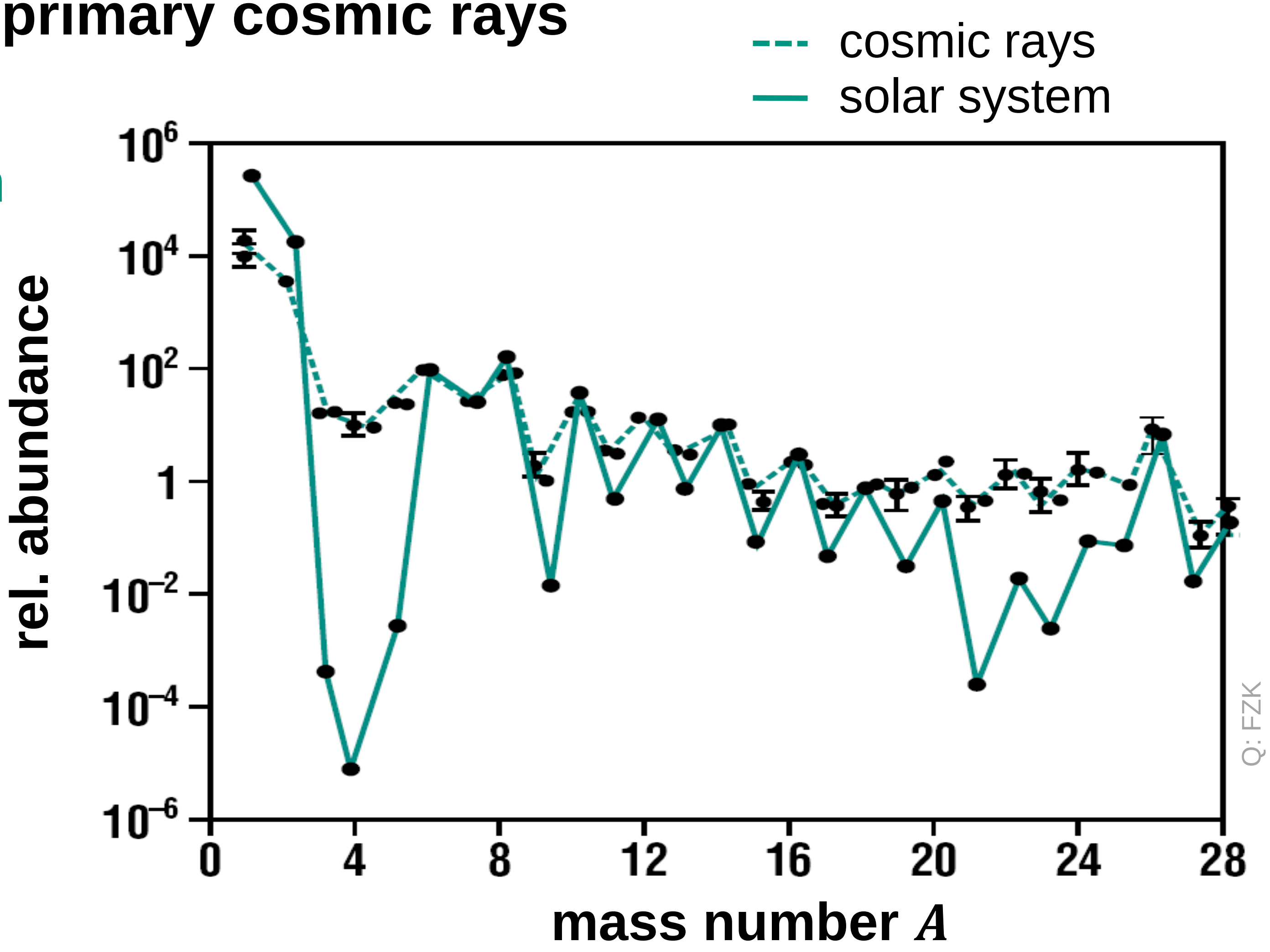
mass composition of cosmic rays – results

- **observed mass composition of primary cosmic rays**

  - **comparison of CR distribution with the solar abundance**

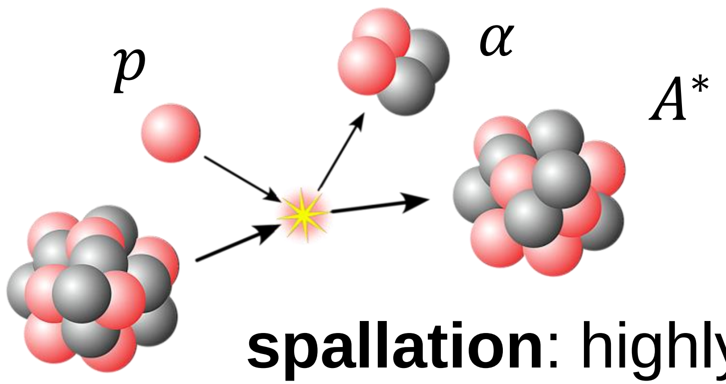
  - observation: a very similiar element composition

  - 86 % protons (p)
    11 % alpha-particles (α)
    1 % heavy nuclei (^{A}Z)
    2 % electrons (e^{-})

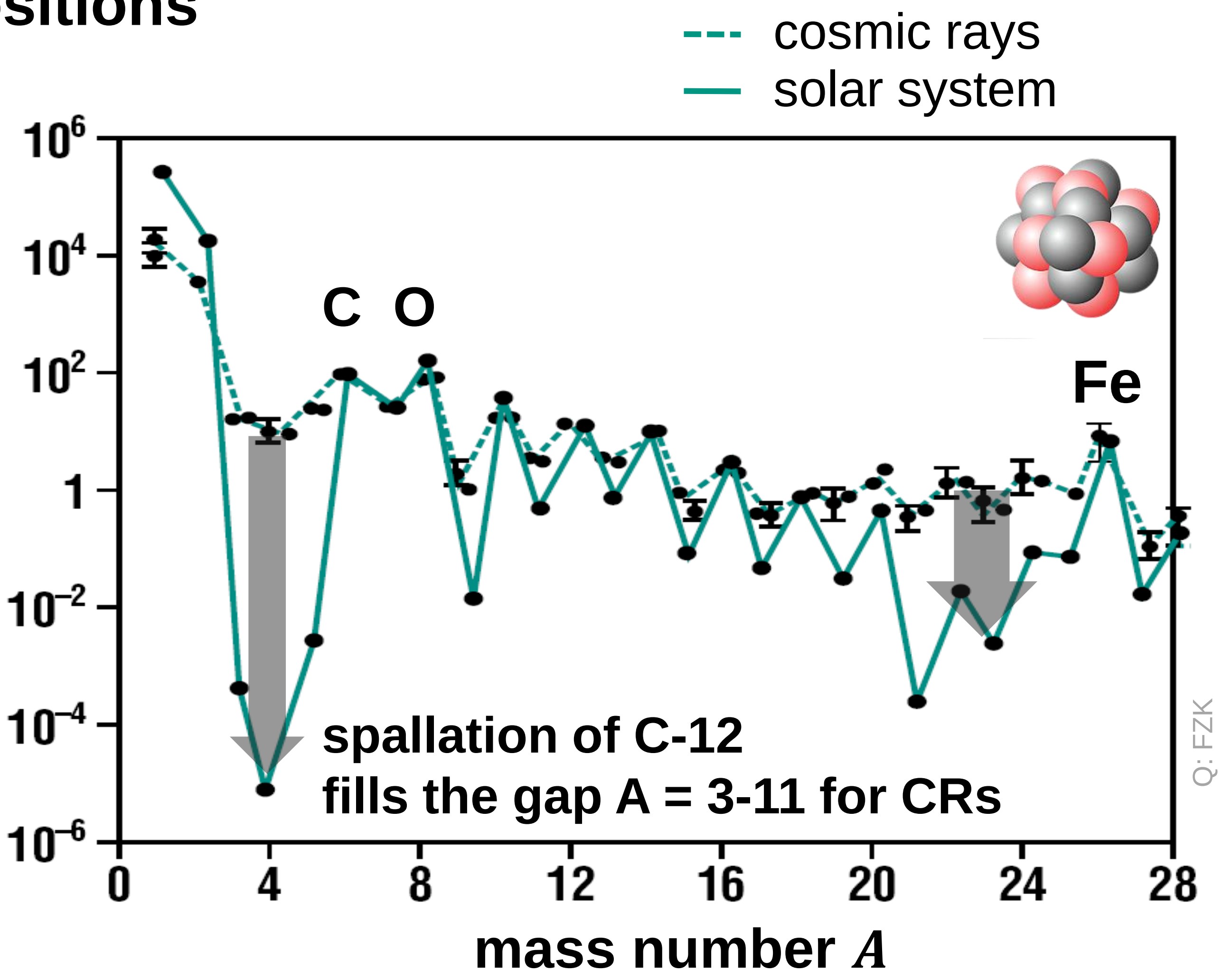


mass composition of cosmic rays – spallation!

- **differences in the two mass compositions**
  - **CR-nuclei propagate over long distances & time scales in our galaxy: spallation reactions**
  - important CR ´seed nuclei´: $^{56}Fe, ^{16}O, ^{12}C$

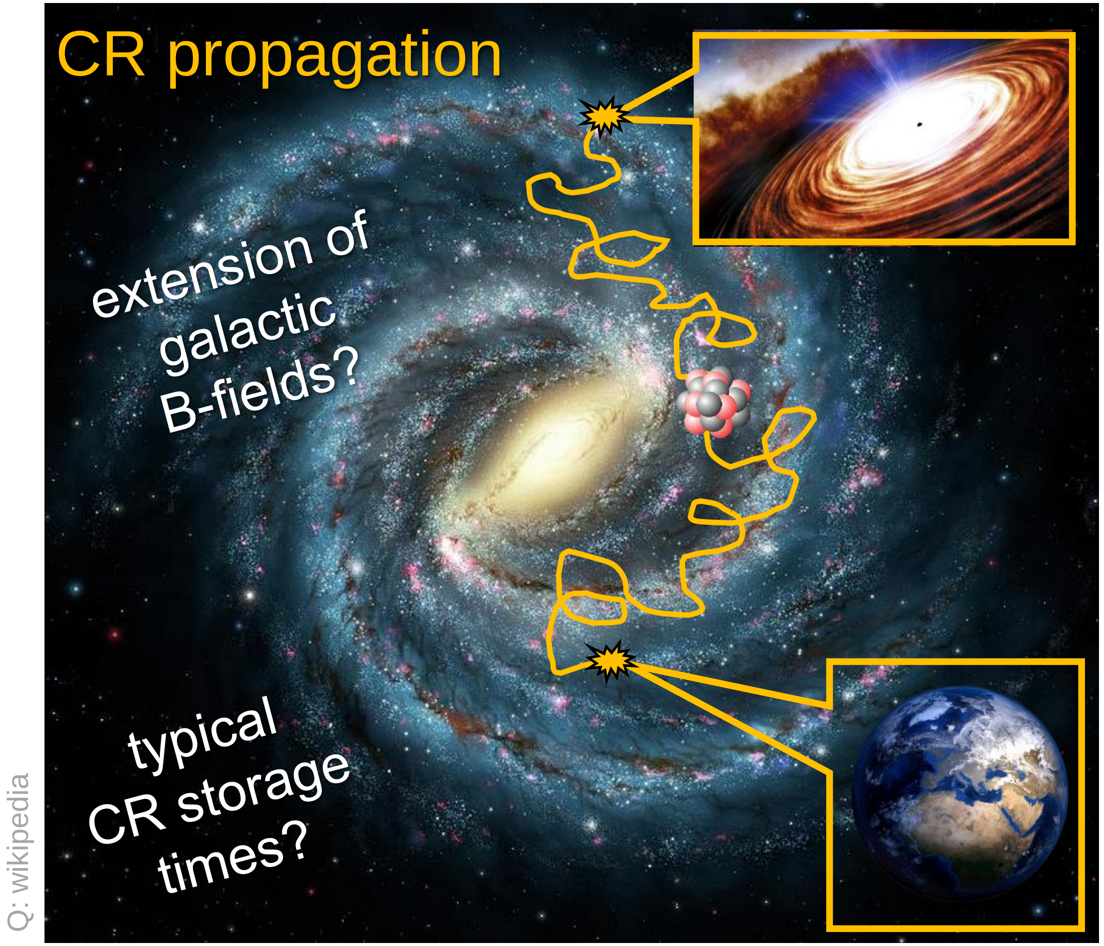


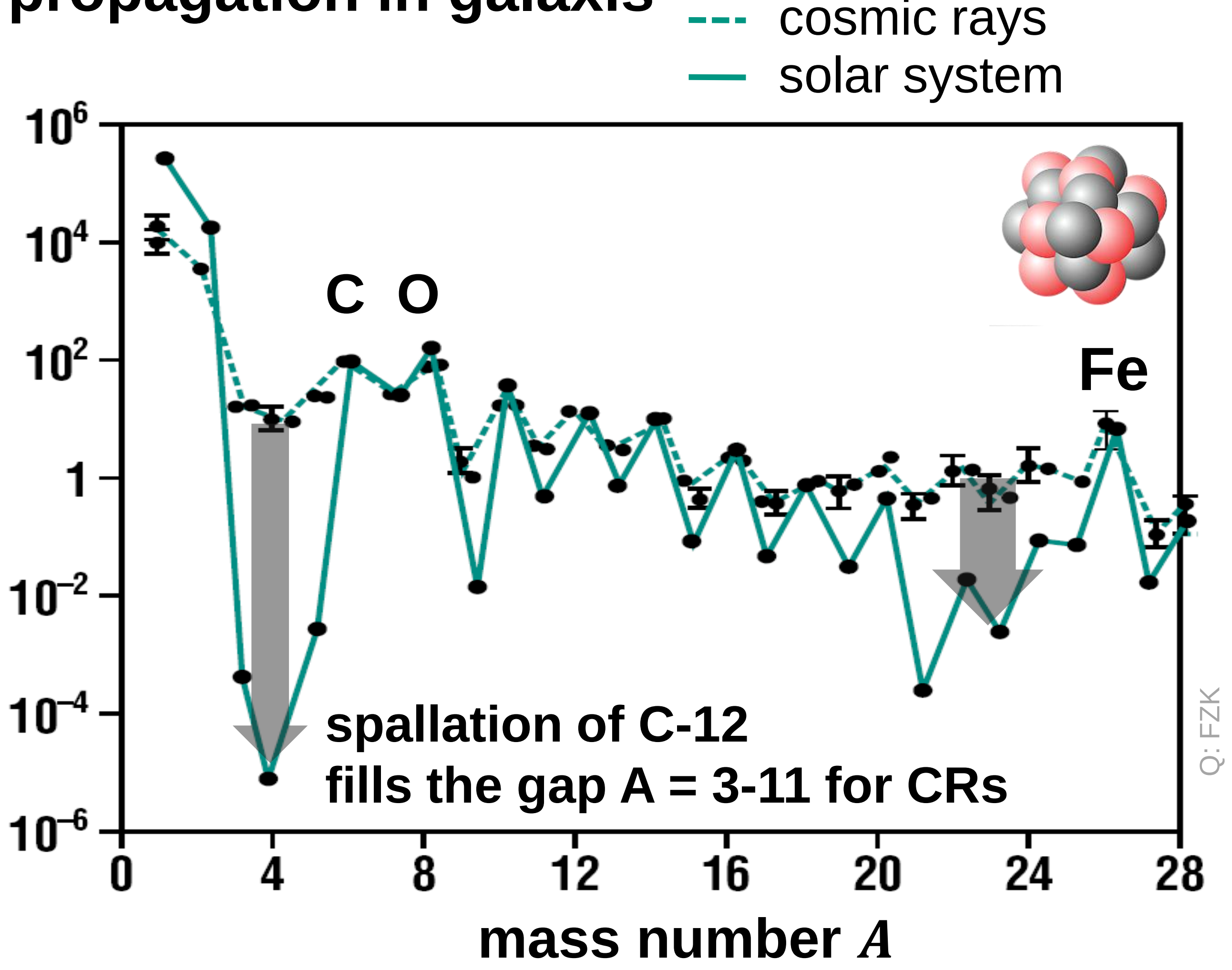
spallation: highly excited nucleus ´evaporates´ α´s / *n*´s



mass composition of cosmic rays – spallation!

- spallation reactions on CRs due to propagation in galaxis





mass composition of CRs – balloon missions

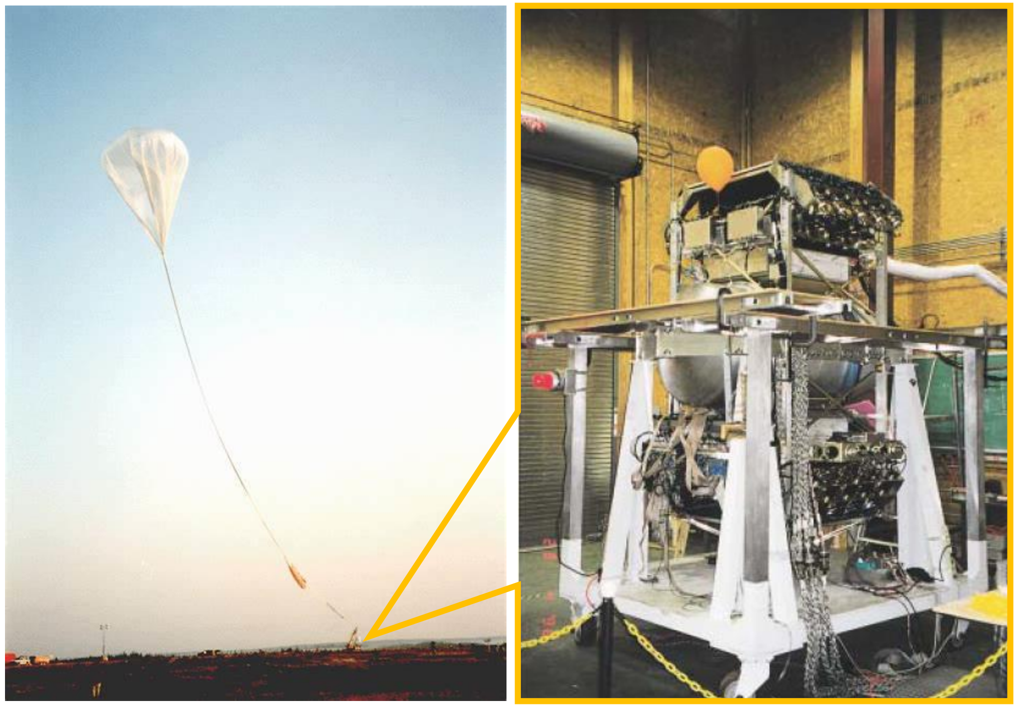
Karlsruhe Institute of Technology

experiment	scientic goals	energy range
detection of antimatter		
HEAT - High Energy Antimatter Telescope	e^+, e^- / antiprotons	5 - 50 GeV / 0.2 - 30 GeV
CAPRICE - Cosmic AntiParticle Ring Imaging Cherenkov Experiment	e^+, e^- antiprotons atmospheric muon spectra	0.5 - 50 GeV
BESS - Ballone Borne Experiment with Superconducting Solenoidal Spectrometer	Antiprotonen Antihelium	0.25 - 3 GeV 0.25 - 100 GeV
element- and isotope composition		
ISOMAX - Isotope Magnet Experiment	beryllium-10, isotopes with 2 < Z < 8	0.2 - 3 GeV / nucleon
TIGER – Trans - Iron Galactic Element Recorder	elements 30 < Z < 40	> 0.5 GeV / nucleon
energy spectra		
RICH - Ring-Imaging Cherenkov	proton- and helium spectra	20 - 200 GeV / nucleon
JACEE - Japanese-American Collaborative Emulsion Experiment	spectra from 1 < Z < 26	1 - 100 TeV
TRACER - Transition Radiation Array for Cosmic Energetic Radiation	spectra 8 < Z < 26	< 10 TeV / nucleon

Q: LIC

Example: ISOMAX mission – start to abrupt end

- **Science goals of ISOMAX (Isotope Magnet Experiment)**
  - measurement of **light isotopes** of CRs, special focus on: ^{9}Be / ^{10}Be ratio (spallation during long CR propagation) up to nucleon energies of GeV/n



detector:

$h = 2.5\,m$

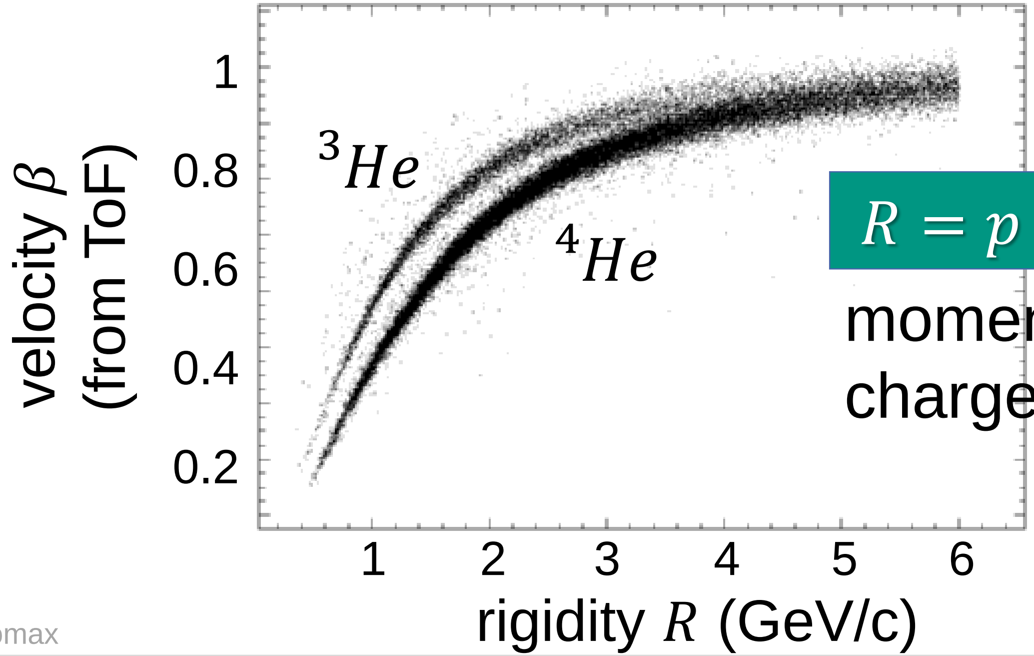
$m = 2\,t$

hard landing of ISOMAX

Q: isomax

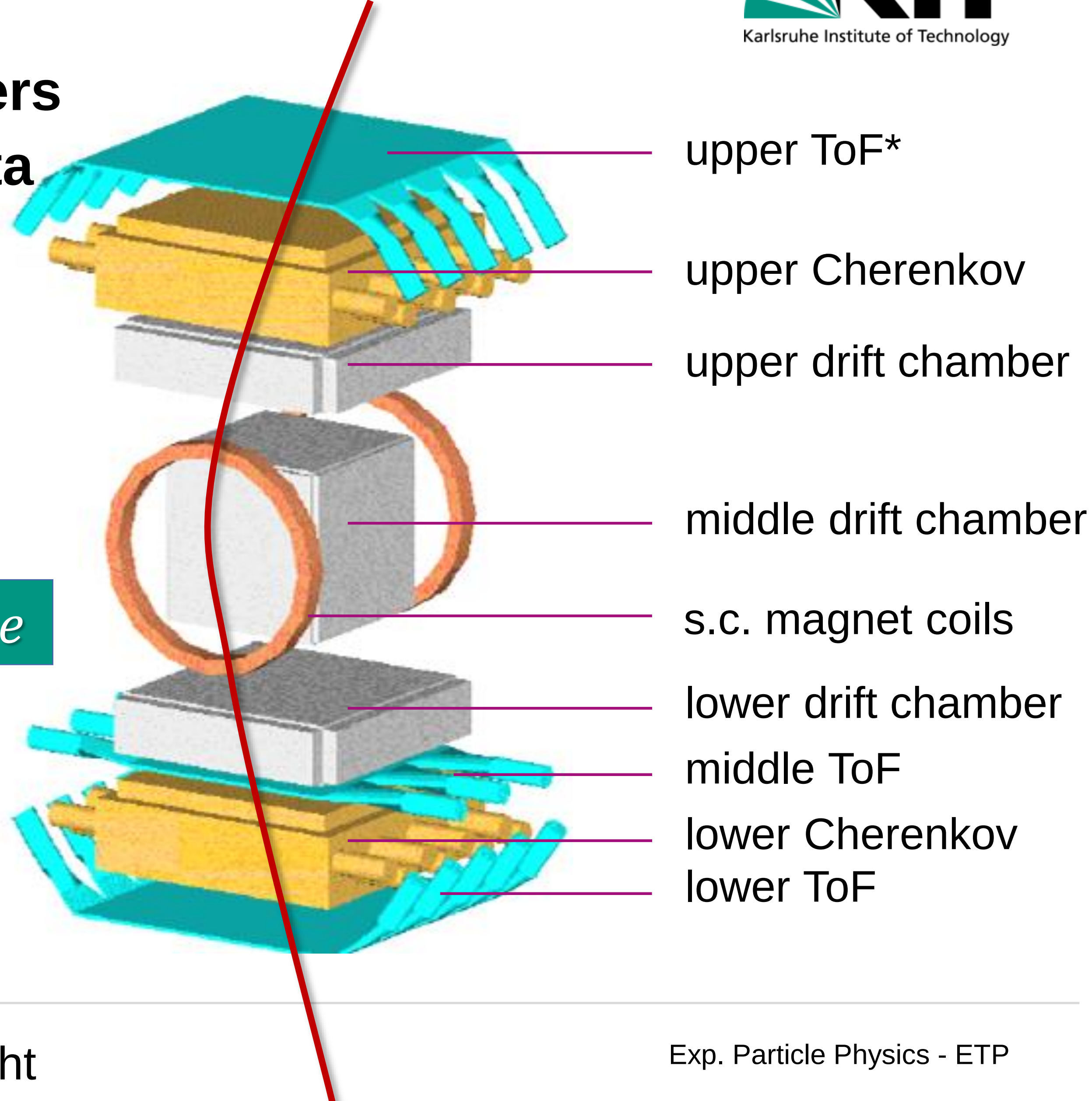
Example: ISOMAX mission – key principles

- **determination of kinematic parameters (rigidity R) & ISOMAX $^3He - {}^4He$ data**
  - mass separation of CRs via precise determination of particle parameters: charge z, momentum p, velocity β



$R = p \cdot c / z \cdot e$

momentum / charge

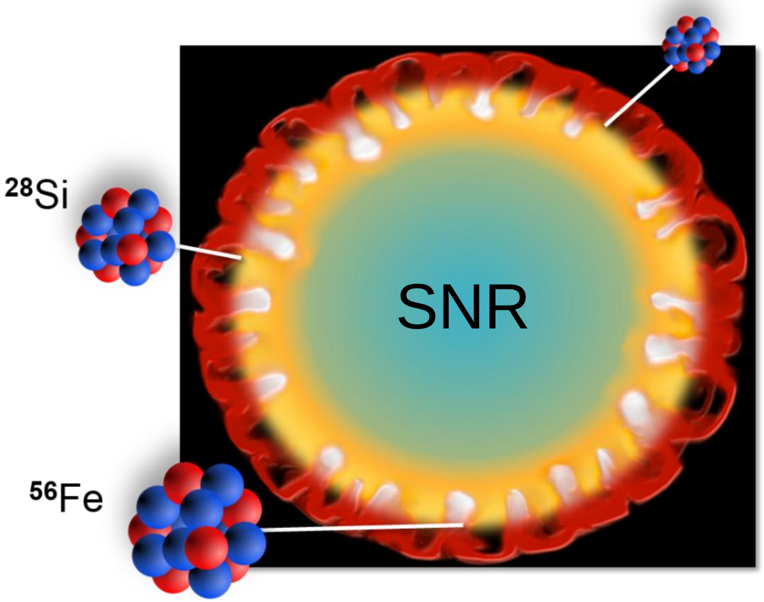


Q: isomax

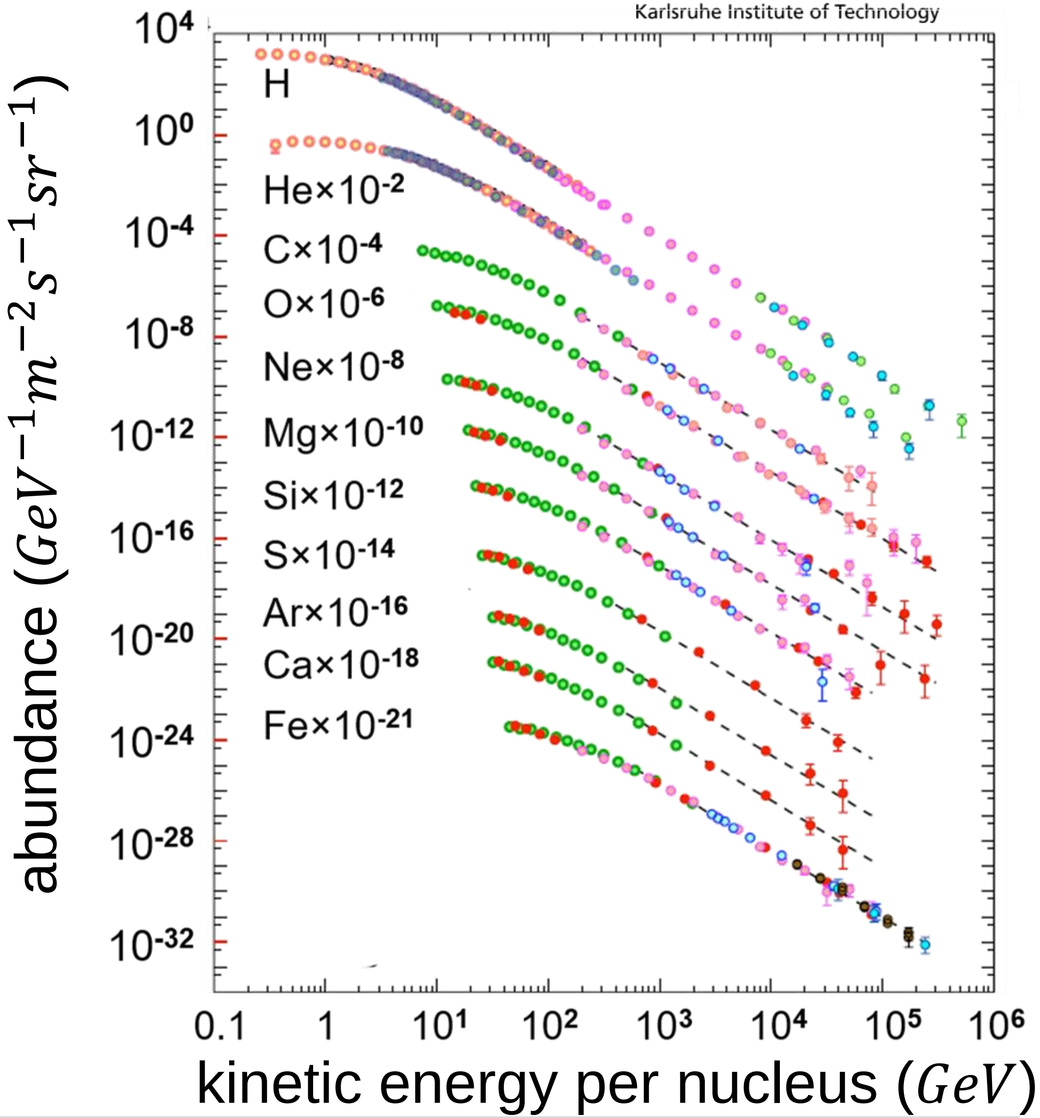
*Time-of-Flight

Energy spectrum of single CR species

- **direct data: up to a few hundred TeV**
  - all elements show the **same spectral index** as function of their kinetic energy
  - ⇨ **only one acceleration mechanism is relevant for CRs up to this E-scale**

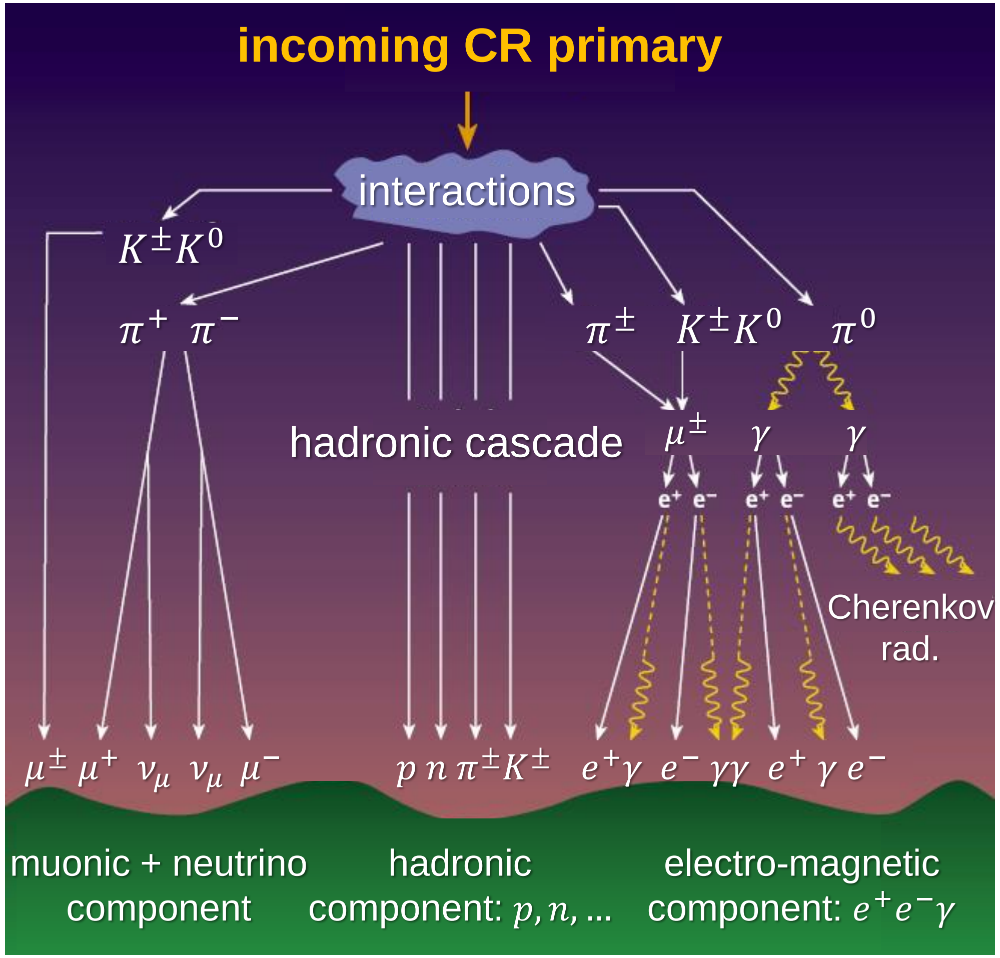


Q: sciam



the physics of large air showers – first overview

- **interactions of a high-energy primary CR particle in the upper atmosphere**



⇨ secondaries via cascade & decay processes

electromagnetic component
- electrons, positrons & photons
- cascade processes, „soft" part

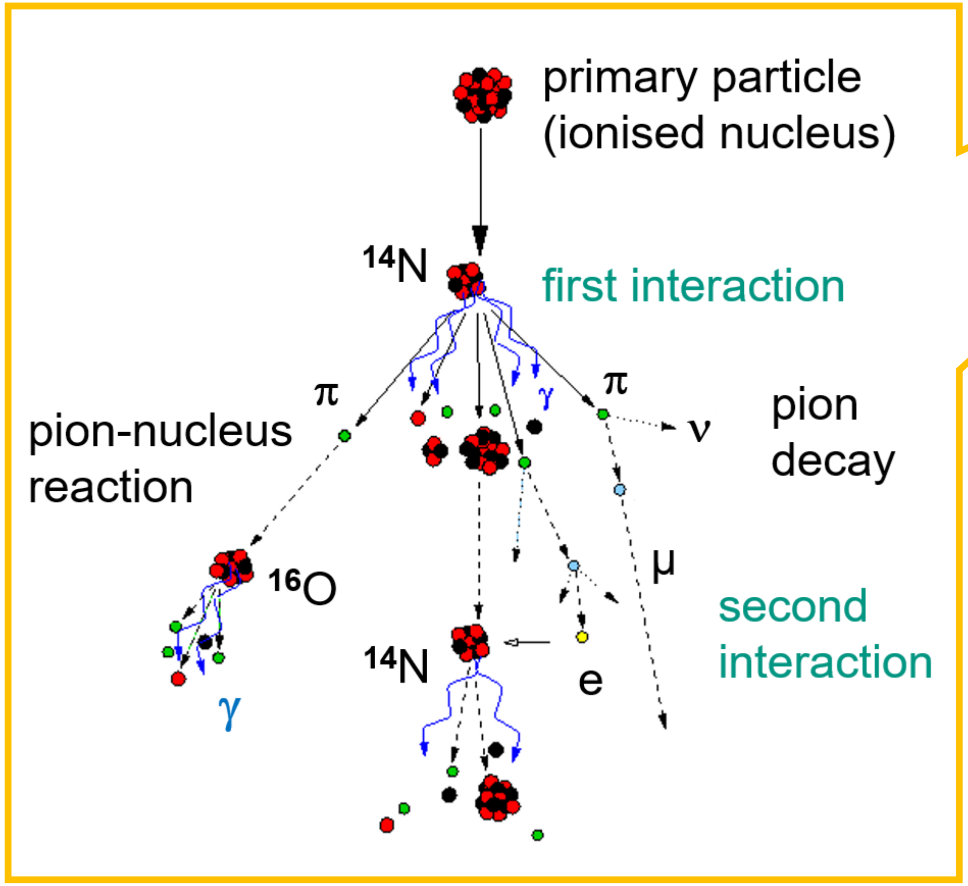
myonic component
- $\mu^+\mu^-$ with strong penetration power
- „hard" CR component

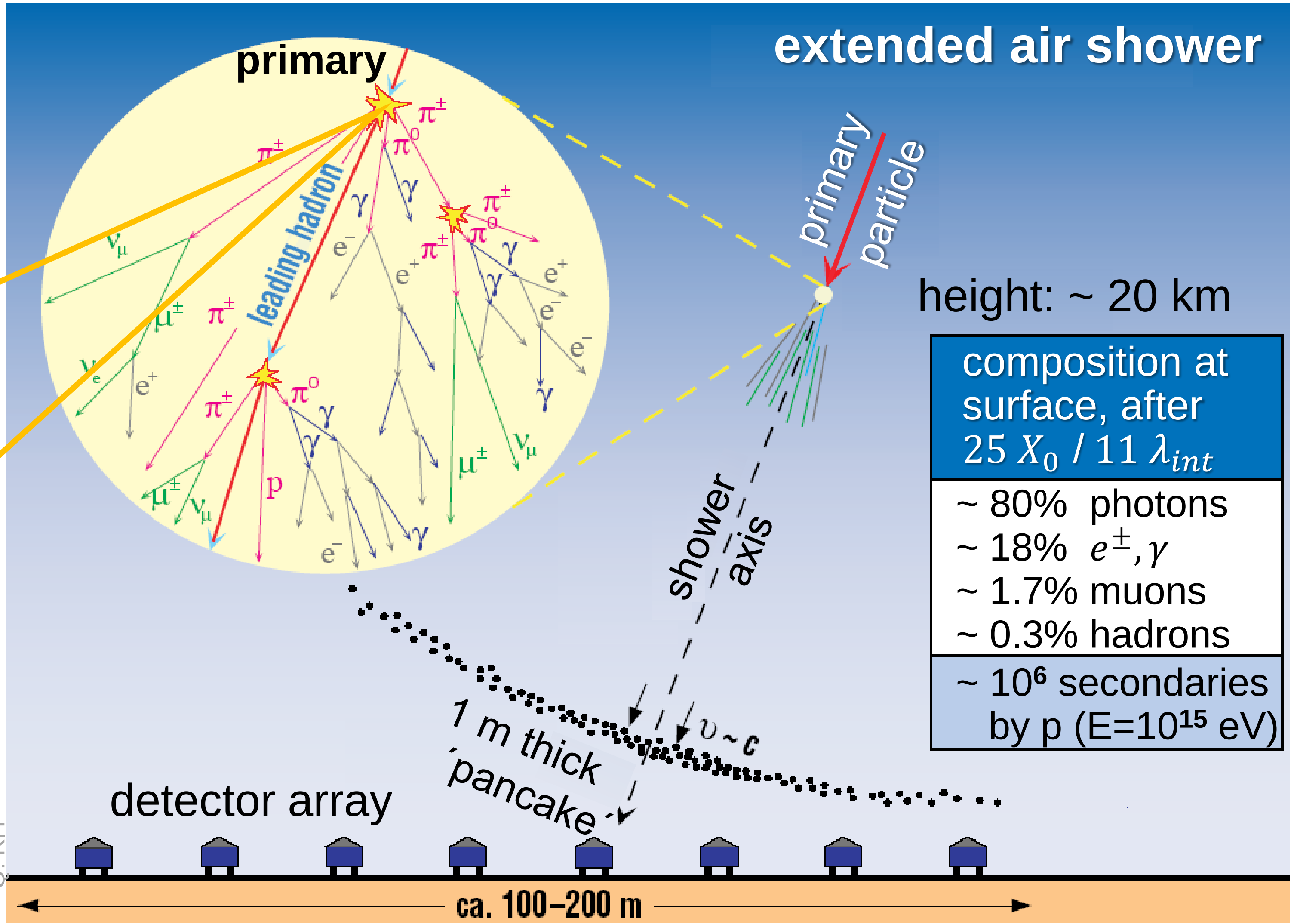
hadronic component
- hadrons: $p, n,$ pions $\pi^{\pm}$, kaons $K^{\pm}$
- very large ionisation rate dE/dx

3 COMPONENTS

Large air showers: modelling of all processes

- **detailed shower simulation, starting at first interaction**



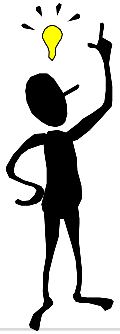


CR air showers & jets at hadron colliders (CERN)

- **Common topics:**

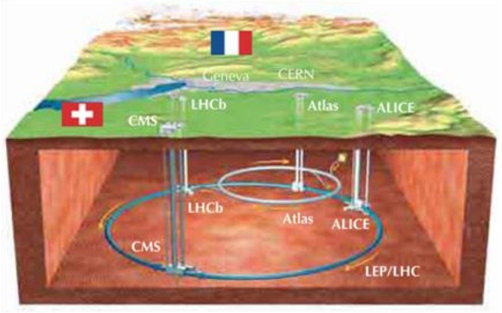
  - analysis of jets & of particle interactions

ATP & TP!

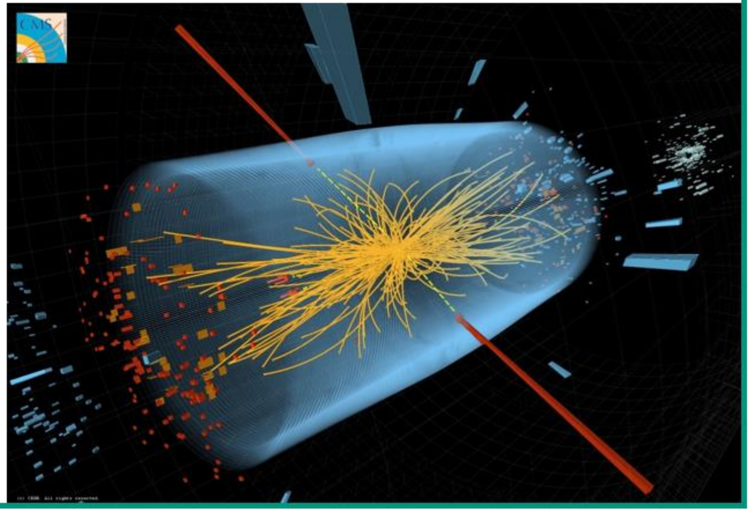


shower physics at LHC

accelerators: protons with up to 7 TeV ($\sqrt{s}$ known)

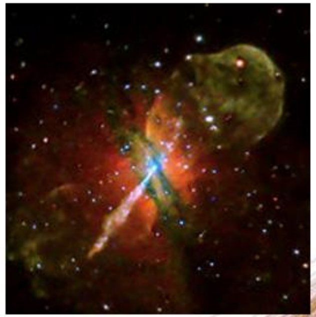


CMS - coverage in a 4π-geometry

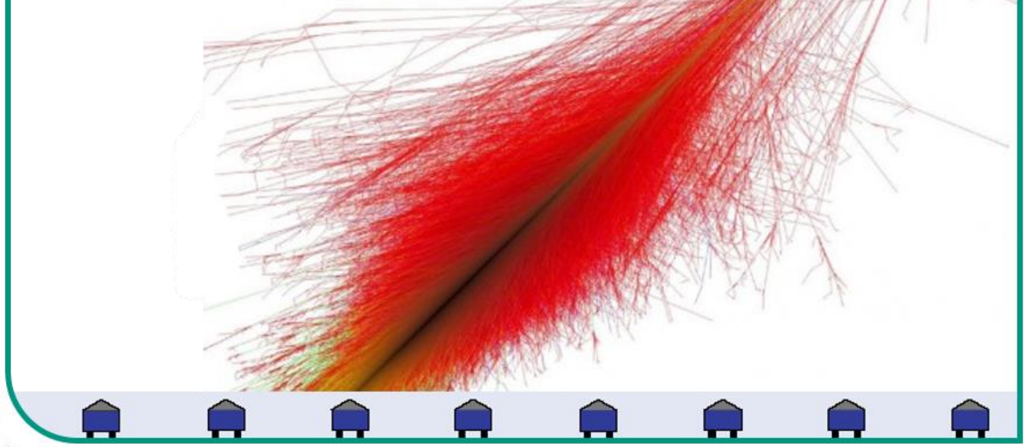


showers from AGN accelerators

accelerators: protons with up to 10^{20} eV or nuclei (primary particle is unknown)



coverage only in narrow forward cone



Q: CERN, CMS

CR air showers & jets at hadron colliders (CERN)

Karlsruhe Institute of Technology

- **Common topics:**

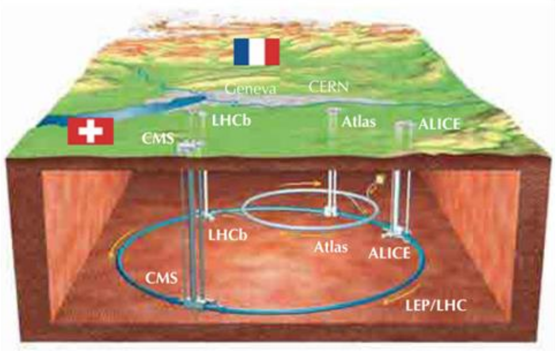
- analysis of jets & of particle interactions

ATP & TP!

Q: Spektrum

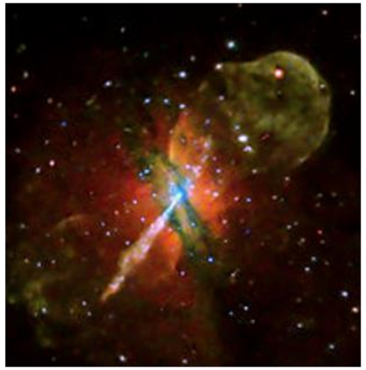
shower physics at LHC

accelerator:
- very high luminosity
- well-known time structure



showers from AGN accelerators

AGN accelerator:
- extremely low luminosity
- unknown, irregular time structure (flare)



collider experiment

4π geometry

proton 7 TeV

ECAL

detector

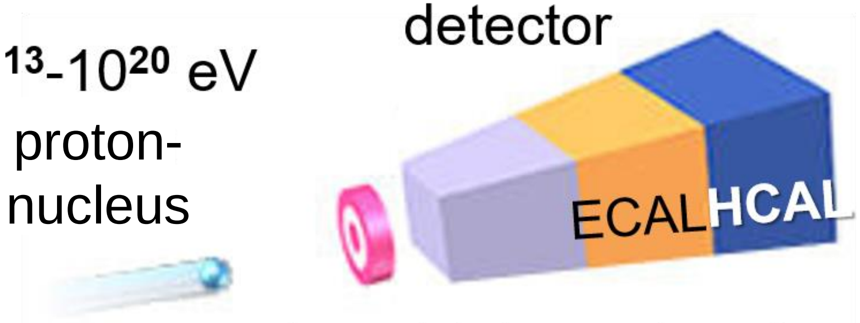
7 TeV proton

fixed target experiment

detector

10^{13}-10^{20} eV

proton-nucleus



target (atmosphere)