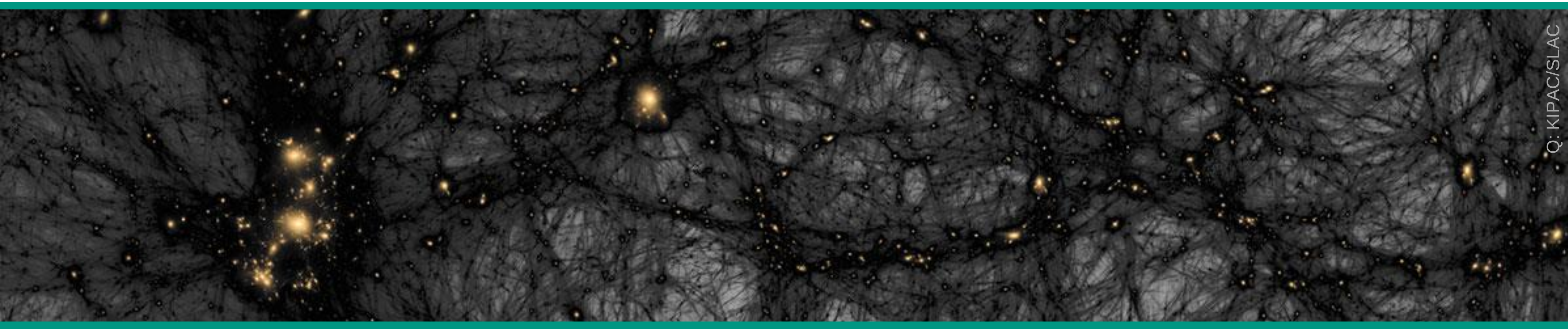
Karlsruhe Institute of Technology

Astroparticle physics I – Dark Matter

Winter term $23/24$ Lecture 3 Nov. $2, 2023$



Recap of Lecture 2

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

  - **thermal universe** (Big Bang, supernovae): order parameter $\boldsymbol{T}$

  - **non−thermal universe** ($\boldsymbol{SNR}$, $\boldsymbol{GRB}$, $\boldsymbol{AGN}$, particle decays):
    order parameters: $\boldsymbol{B}$, **length scale** $\boldsymbol{L}$, **density** $\boldsymbol{\rho}$, **max. energy** $\boldsymbol{E_0}$, …

  - **limitation of range** $\boldsymbol{d}$ **due to photon background fields** $(\boldsymbol{IR}, \boldsymbol{CMB})$

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

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

neutrinos: no direct resonance at propagation ($\boldsymbol{\nu}$ does not couple to $\boldsymbol{\gamma}$)

Lesson by Lecture 2: possible hints for axions ?

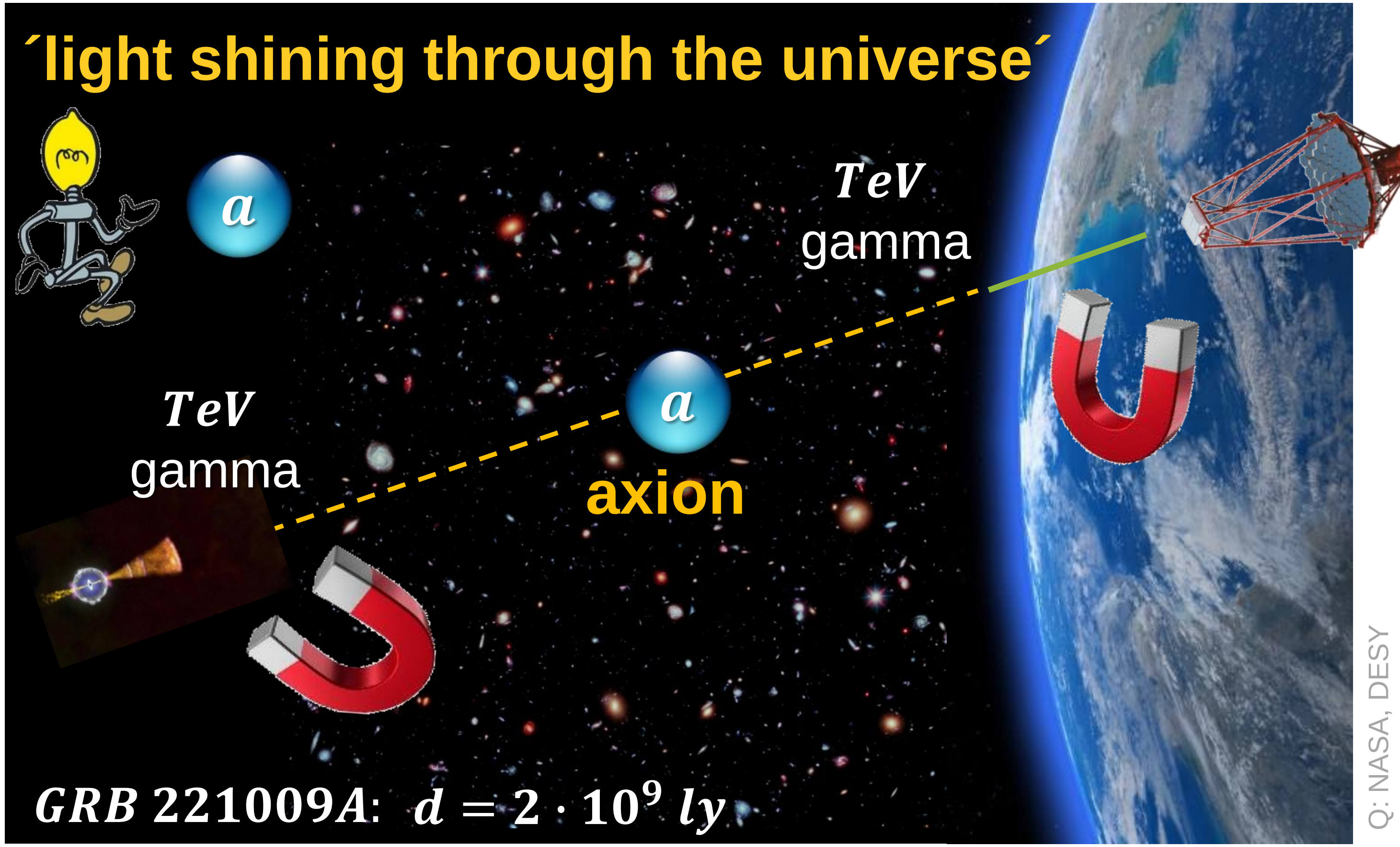
- **tantalizing way to extend γ – range: conversion to axions* & back (B – fields)**

experimental observation:
universe (seemingly) is much **more transparent** for very high–energy γ´s than we expect

an intriguing **theoretical ansatz**:

❶ $TeV - \gamma$ converts in the B – field close to the source into hypothetical **axion**, which will propagate over Gpc

❷ **axion** converts back to γ

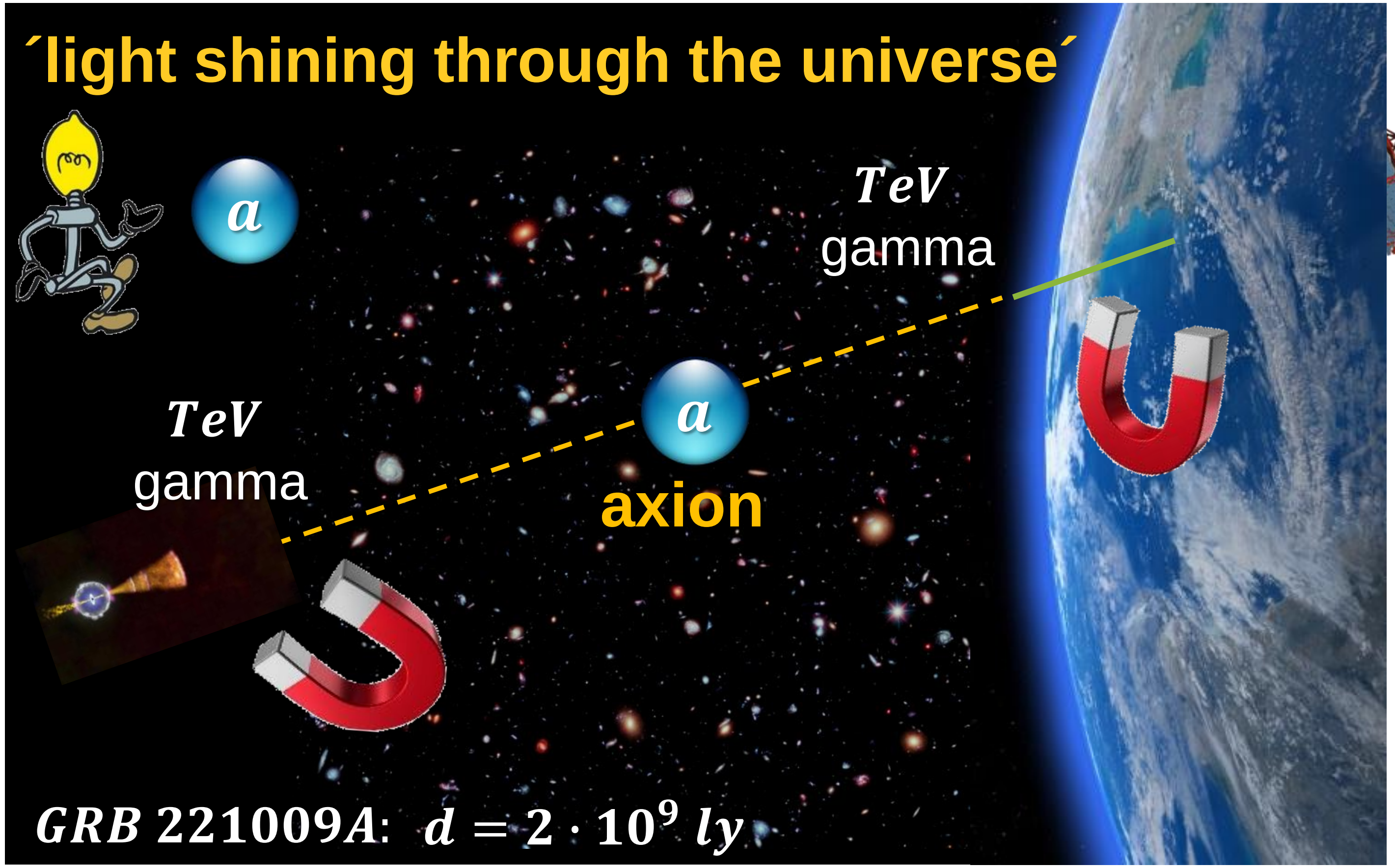


Q: NASA, DESY

*see chapter $4.6.1$ on axions

Lesson by Lecture 2: possible hints for axions ?

- tantalizing way to extend γ – range: conversion to axions* & back (B – fields)



Q: NASA, DESY

*see chapter $4.6.1$ on axions

Lesson by Lecture 2: possible hints for axions ?

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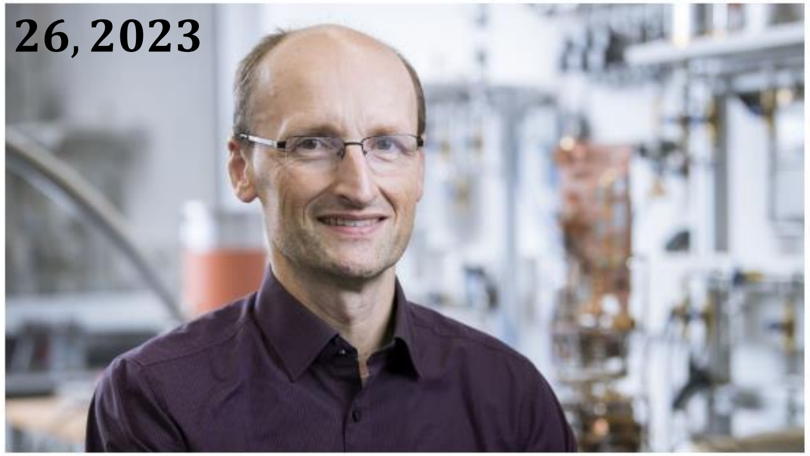
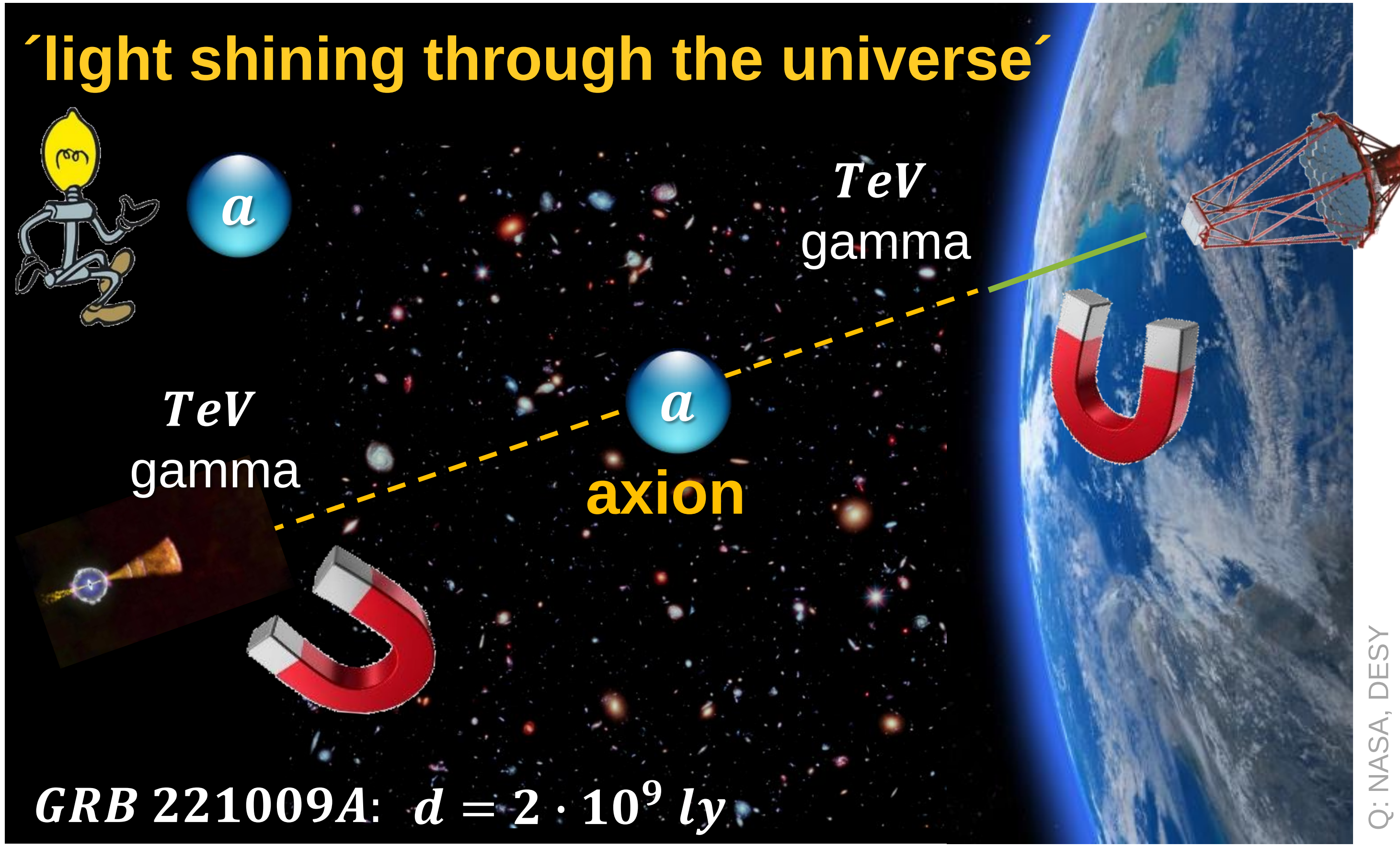
- tantalizing way to measure axions* with **advanced quantum technologies**

Oct. $26, 2023$



Quantum Technologies: A Deep Look into Dark Matter

Wolfgang Wernsdorfer receives ERC Synergy Grant – Six-year international project DarkQuantum uses quantum technologies to prove the existence of axions



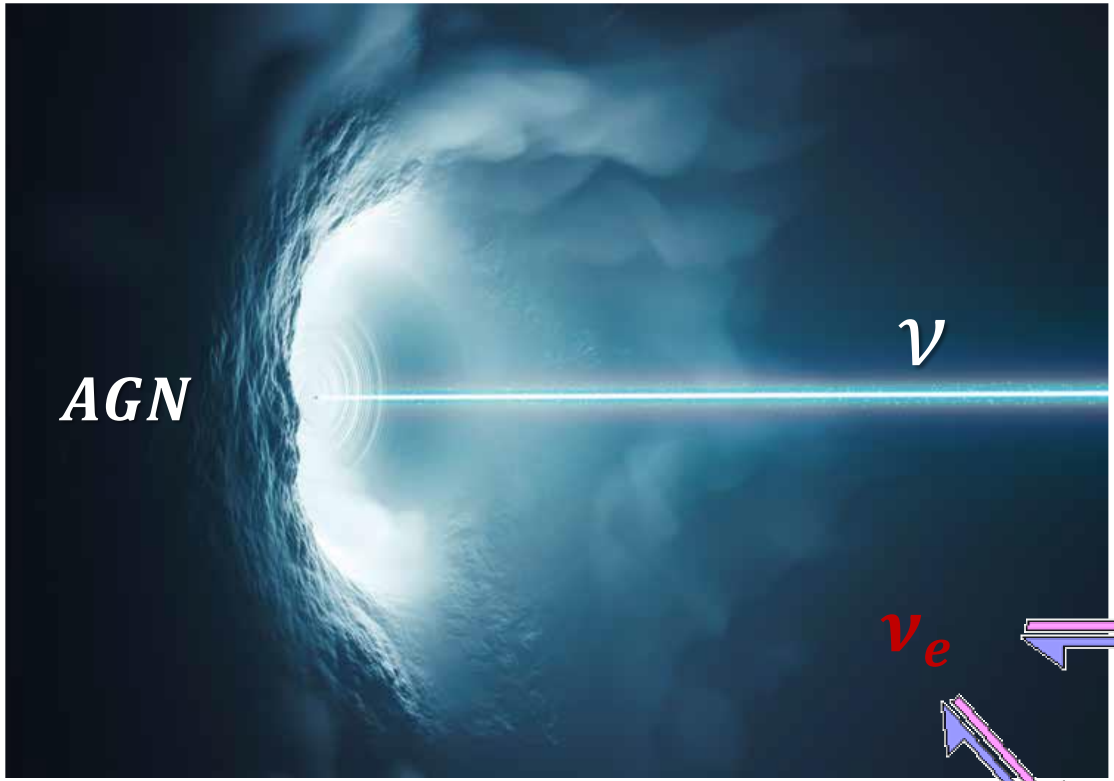
Q: NASA, DESY

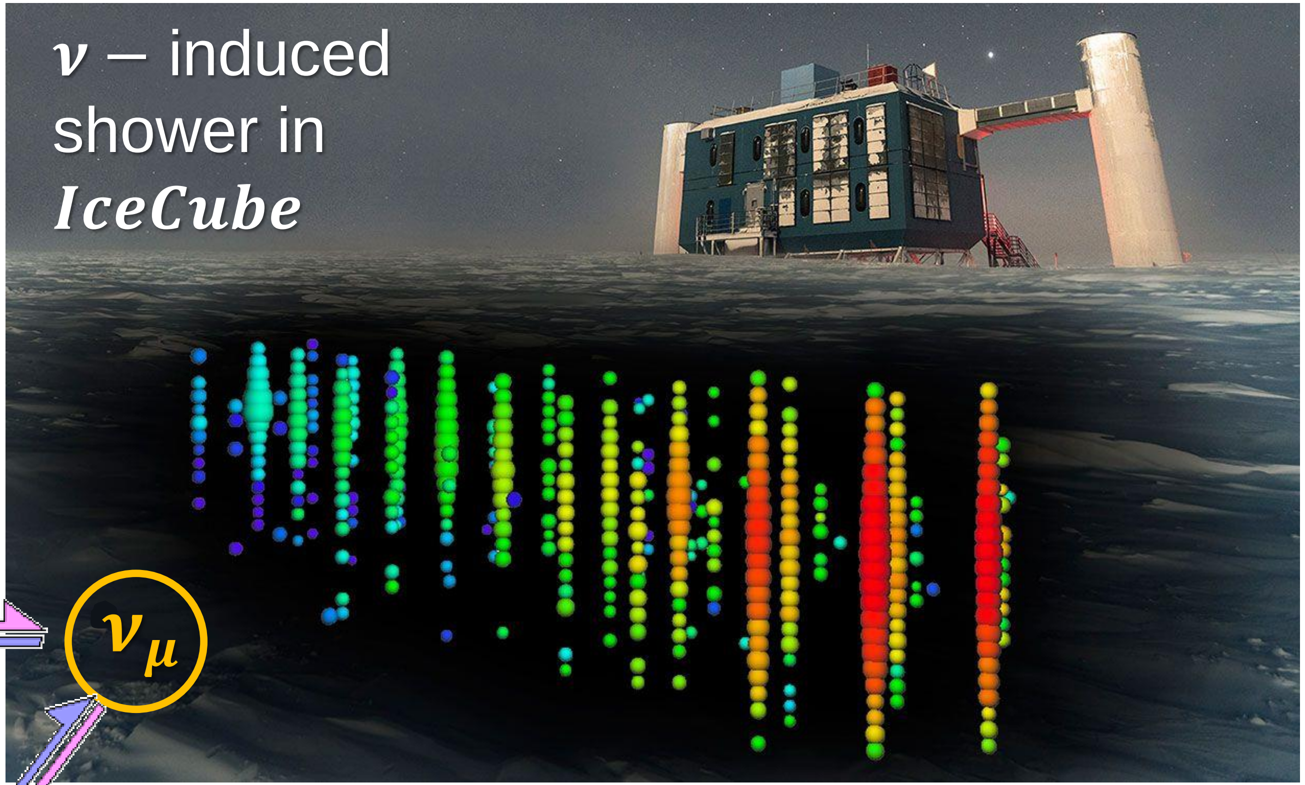
*see chapter $4.6.1$ on axions

Neutrinos: large–volume Cerenkov detectors

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

  - no interactions with photon background fields, but ν – oscillations do occur



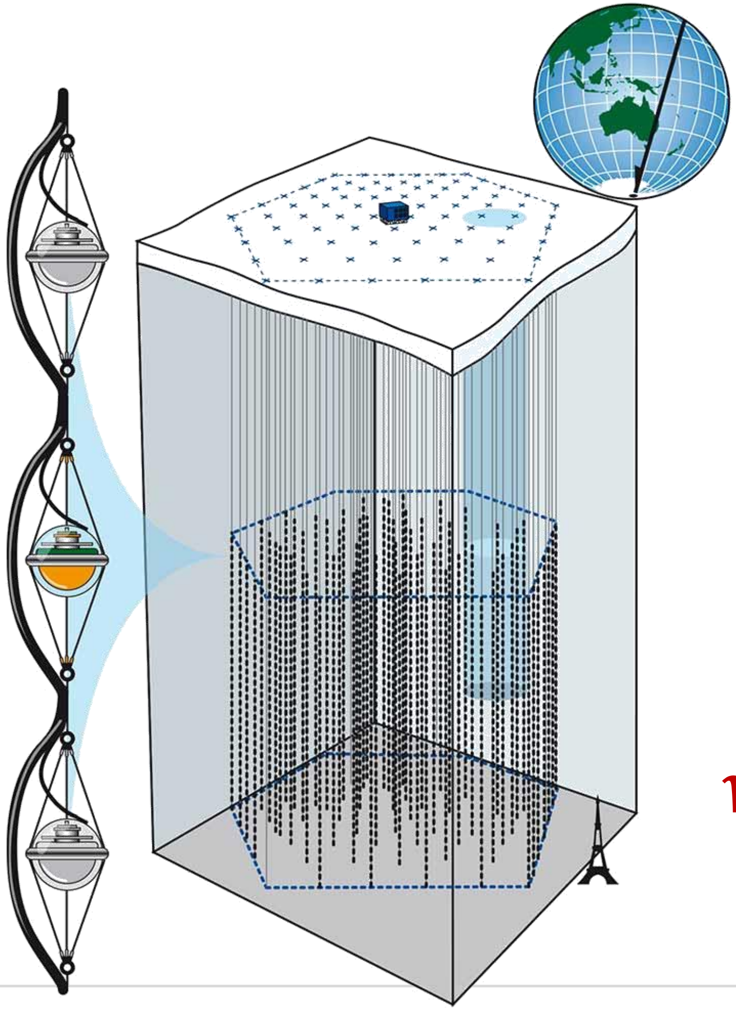


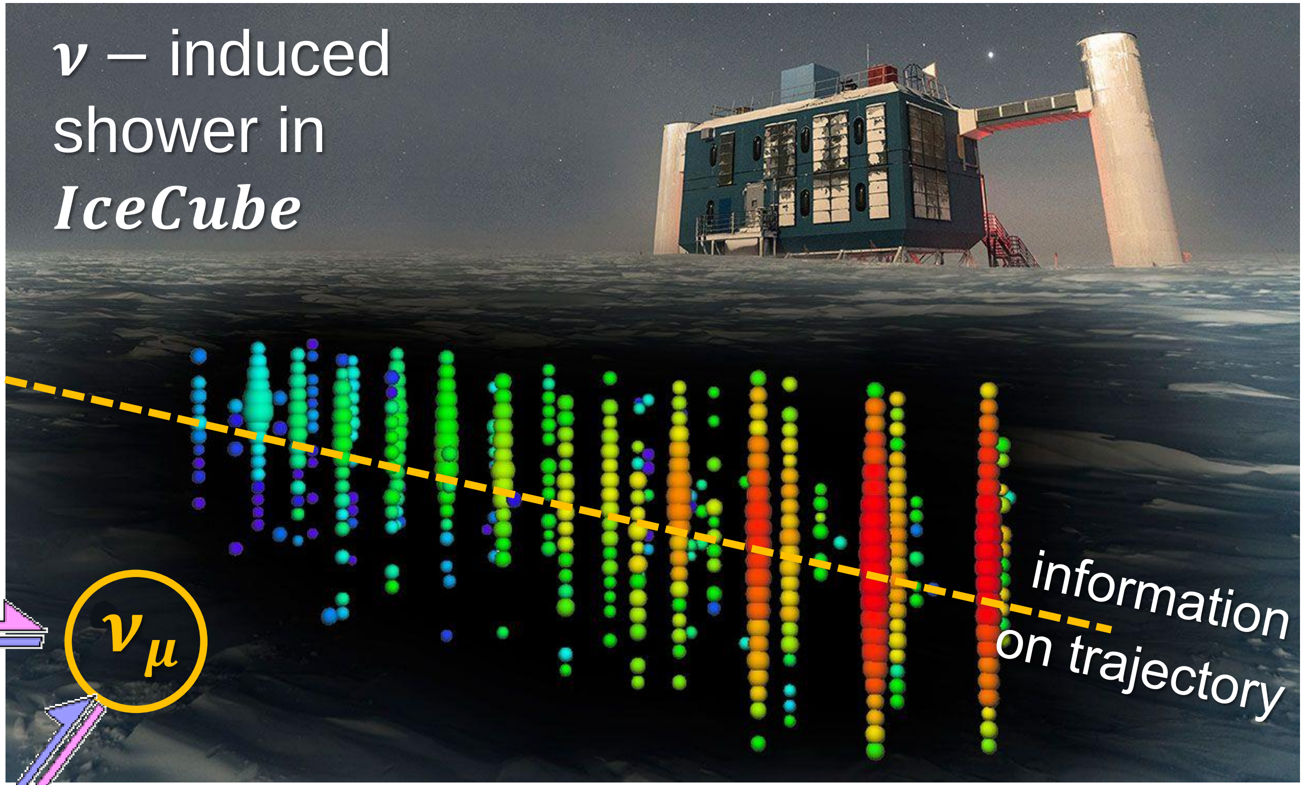
ν_τ

Q: DESY

Neutrinos: large–volume Cerenkov detectors

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



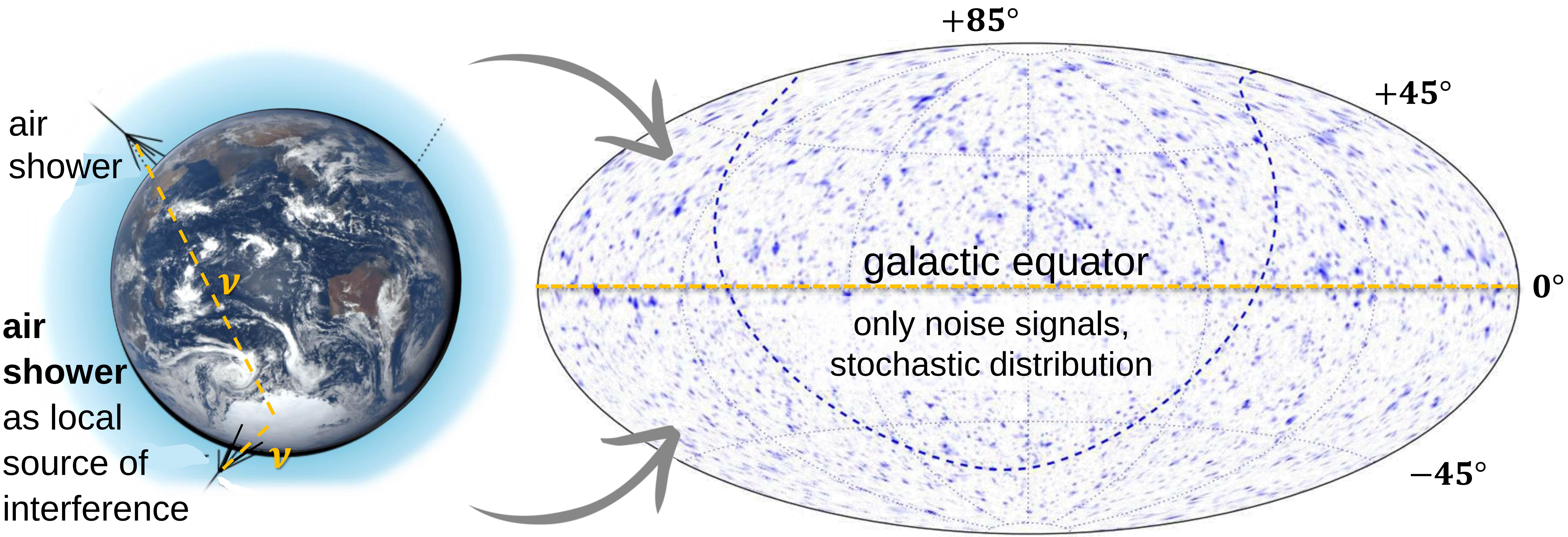


ν_e ν_μ ν_τ

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**

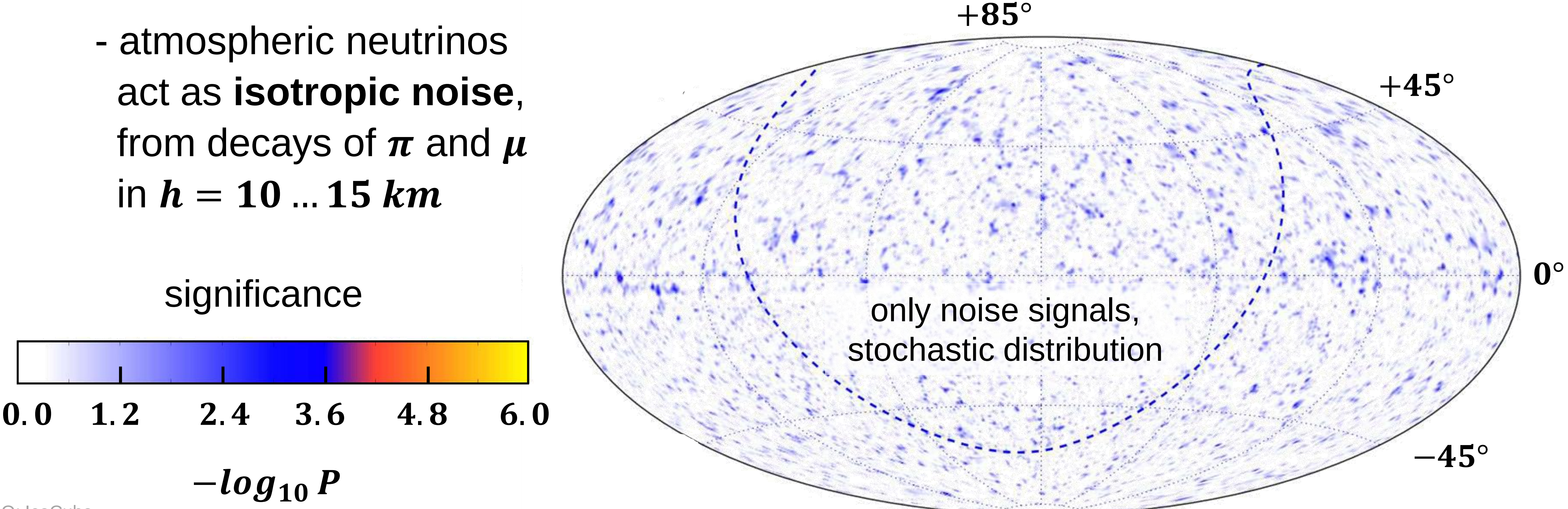


Neutrinos: scanning the northern & southern sky

- Search for point sources of neutrinos at the $TeV \dots PeV$ energy scale

  - isotropic background, very rare $\nu -$ signals from extragalactic sources

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



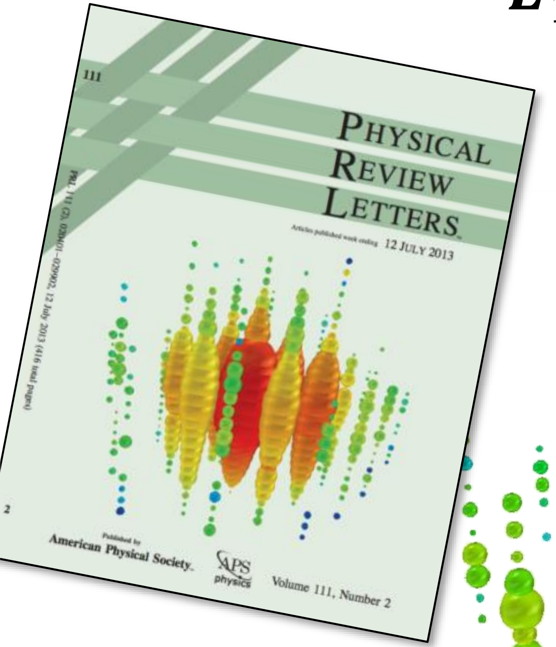
Q: IceCube

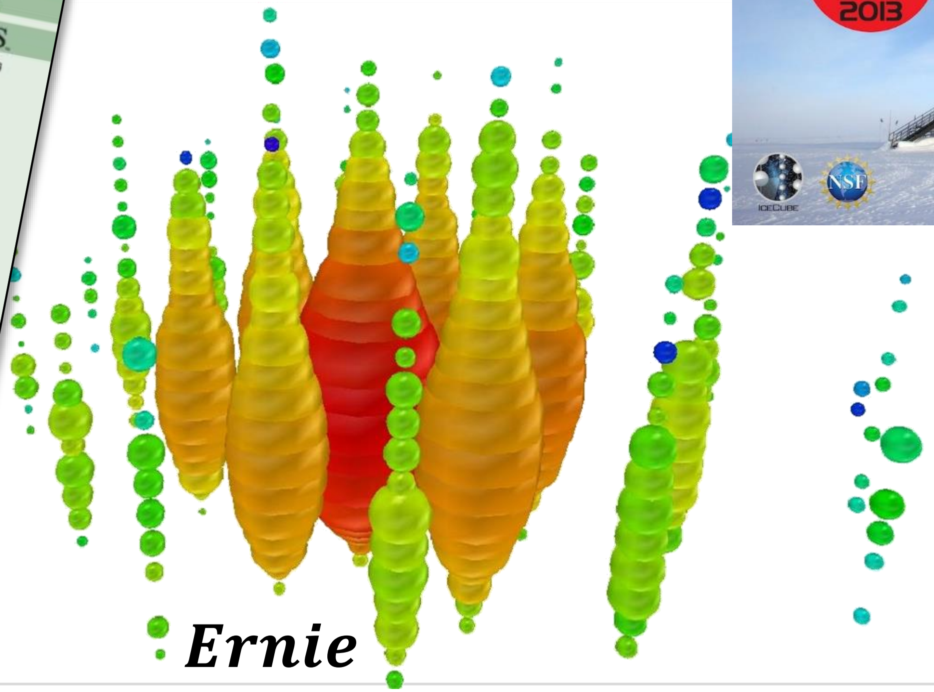
UHE neutrinos – first detection in April 2013

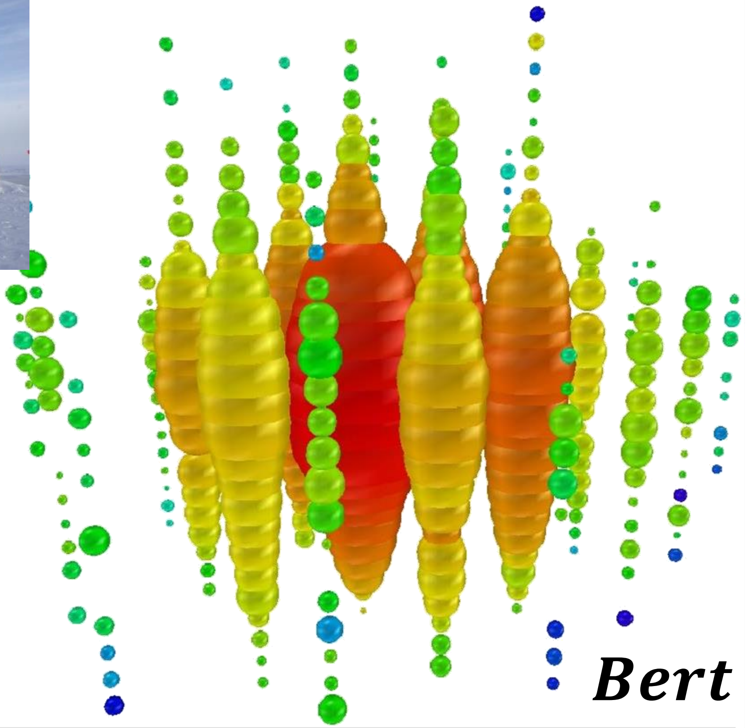
- First breakthrough in neutrino astronomy with $IceCube$ $(2.8\,\sigma)$

$E_1 = (1.04 \pm 0.16)\,PeV$

$E_2 = (1.14 \pm 0.17)\,PeV$







$Ernie$

$Bert$

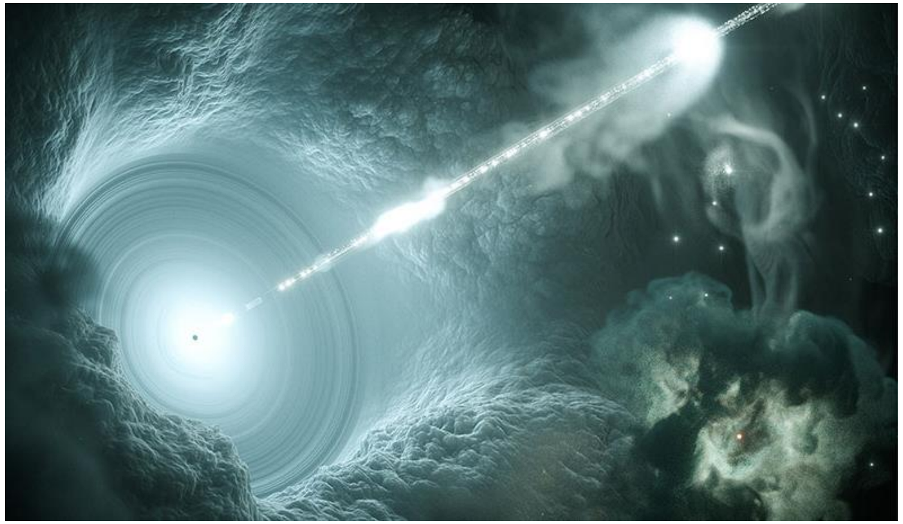
Q: IceCube

UHE neutrinos – November 2019 sky map

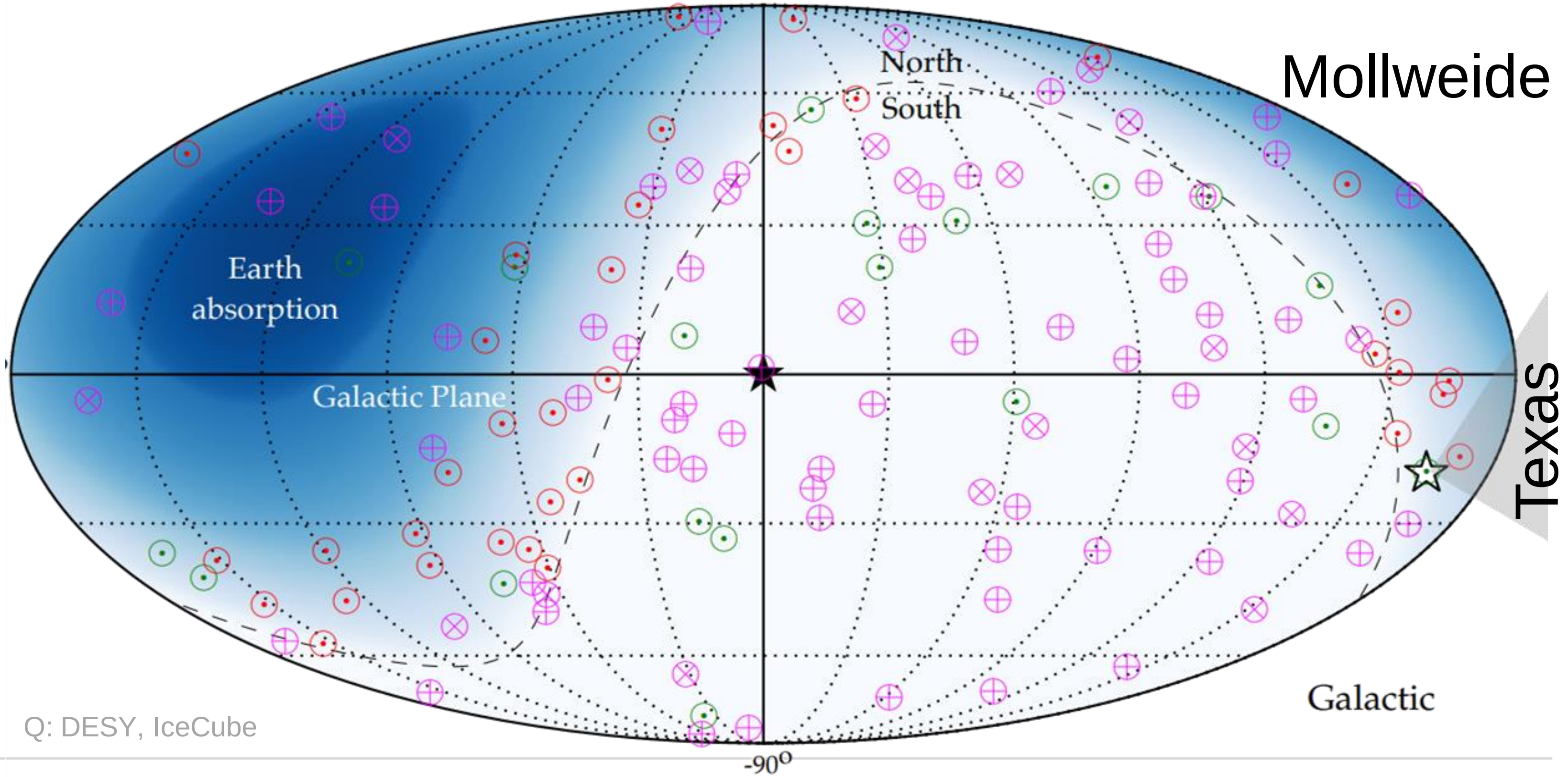
- **distribution of UHE neutrinos is isotropic – no identified sources, but…**

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

$\boldsymbol{TXS\ 0506+056}$: the active ´$\boldsymbol{TEXAS}$´ blazar



Mollweide



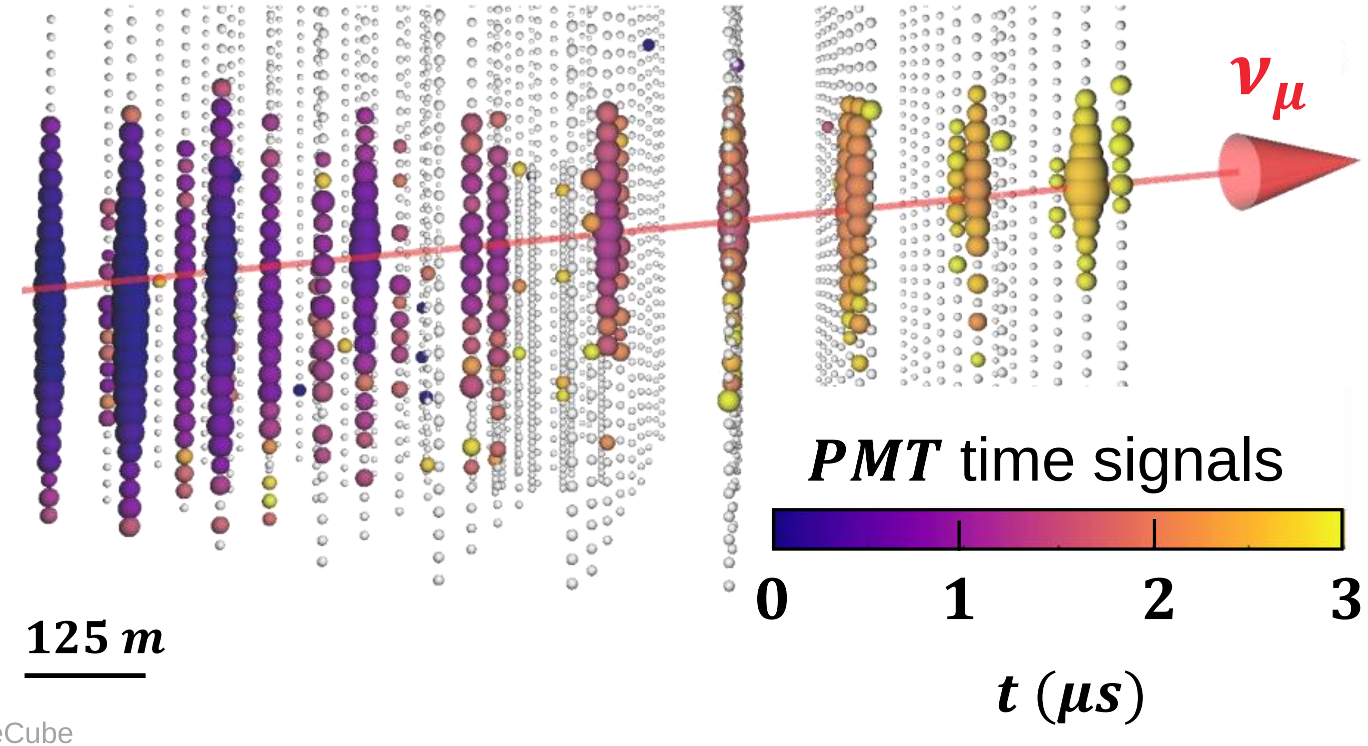
Q: DESY, IceCube

*$\boldsymbol{blazar = AGN}$ 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



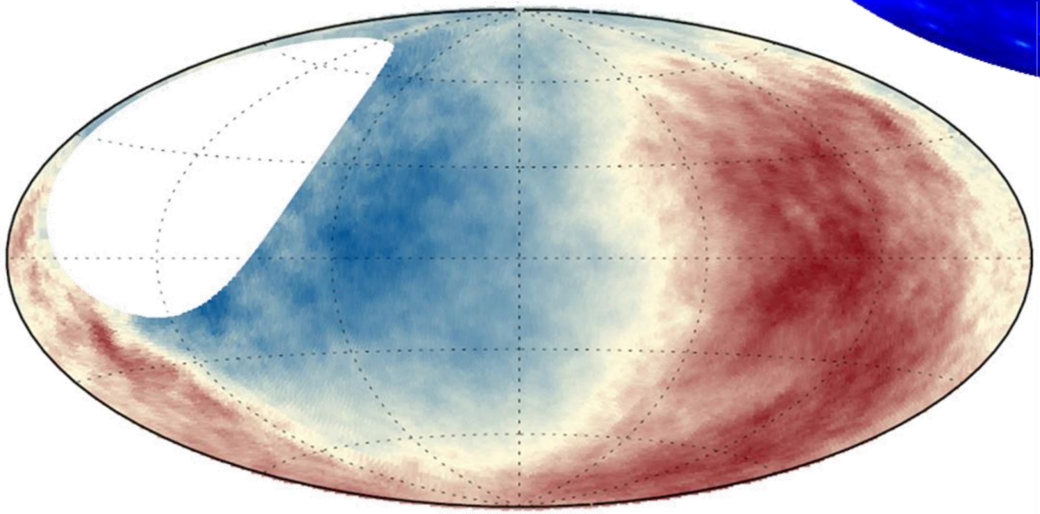
Q: DESY, IceCube

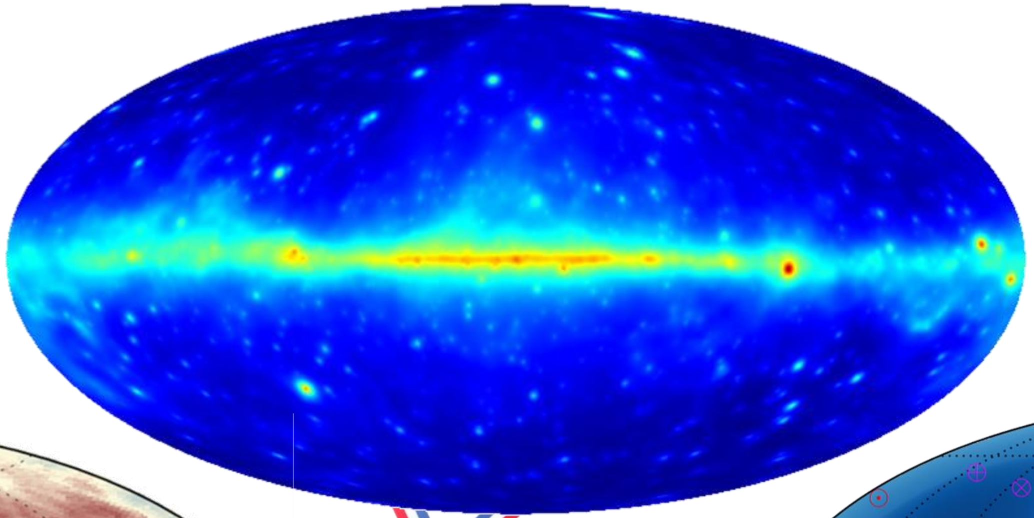
Multimessenger astronomy – a comparison

- all−sky−maps für $GeV \ldots TeV$ gammas, PeV neutrinos & $UHECR´s$ at EeV

CR

anisotropy $> \; 8\; EeV$





γ

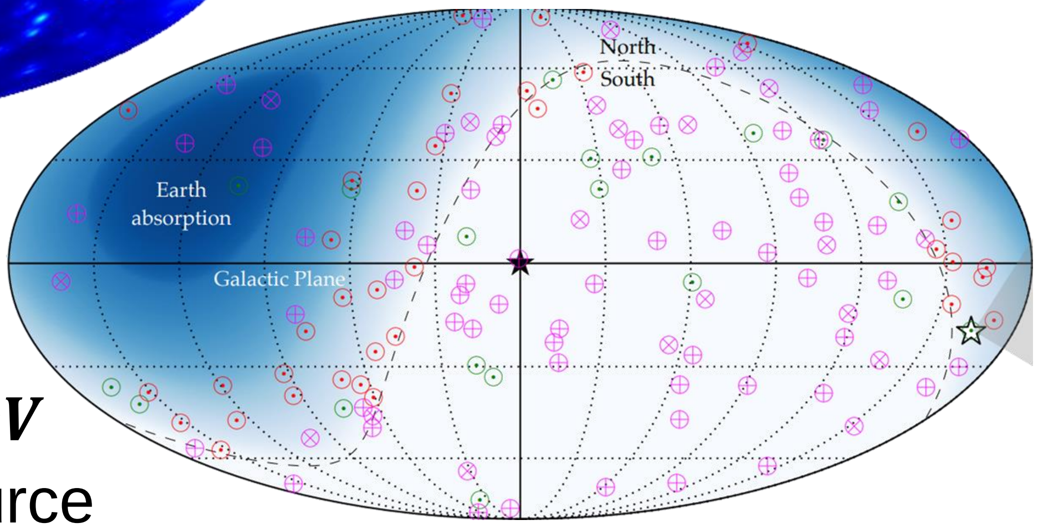
$>$ **500** sources

$> \mathbf{10}\; GeV$

ν

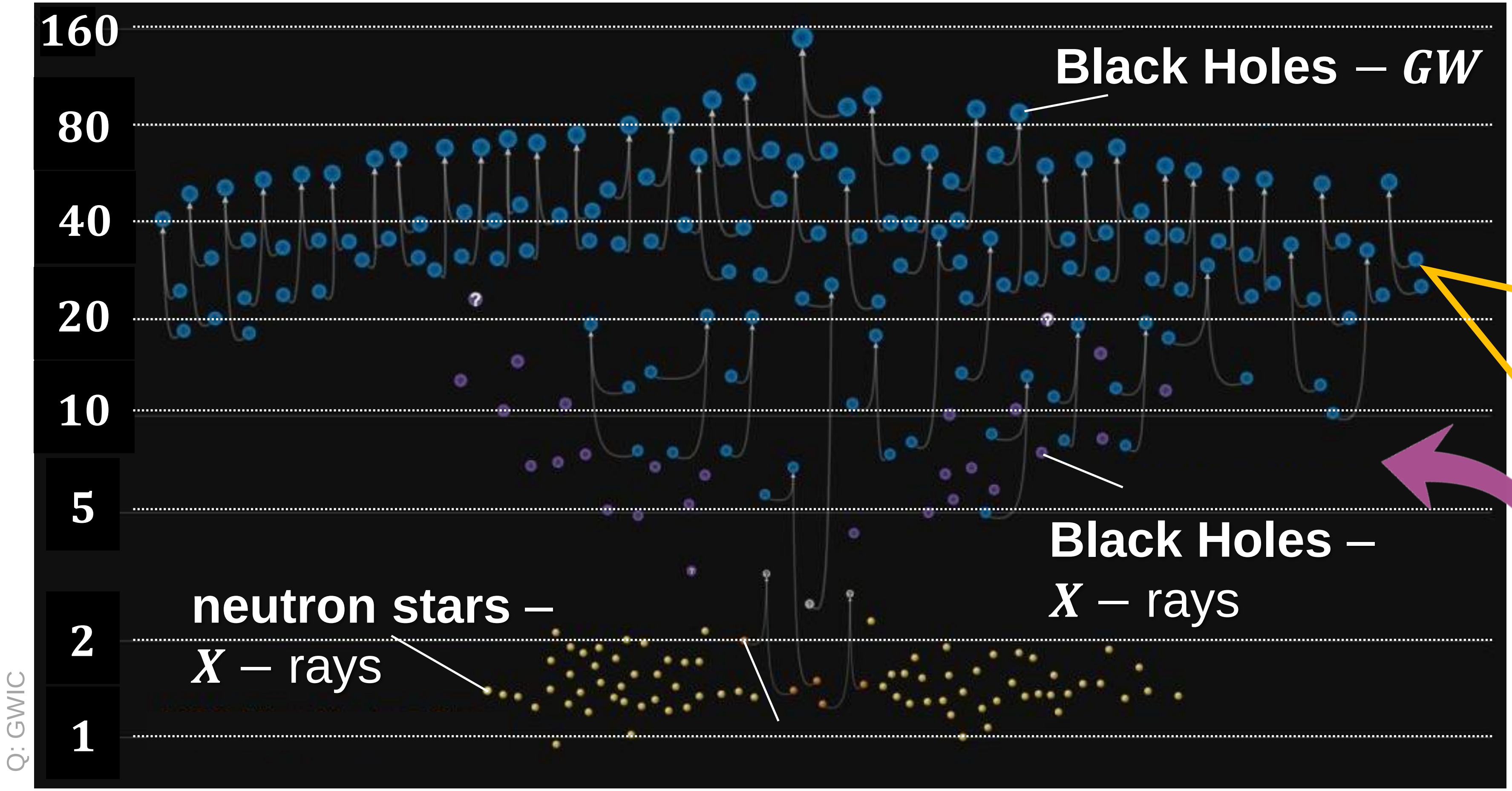
$E \; > \; 30\, TeV$

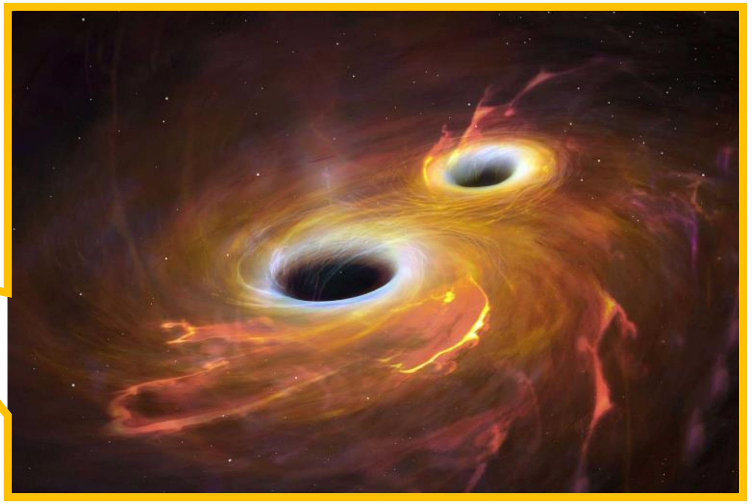
$+\, TEXAS$ source



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

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



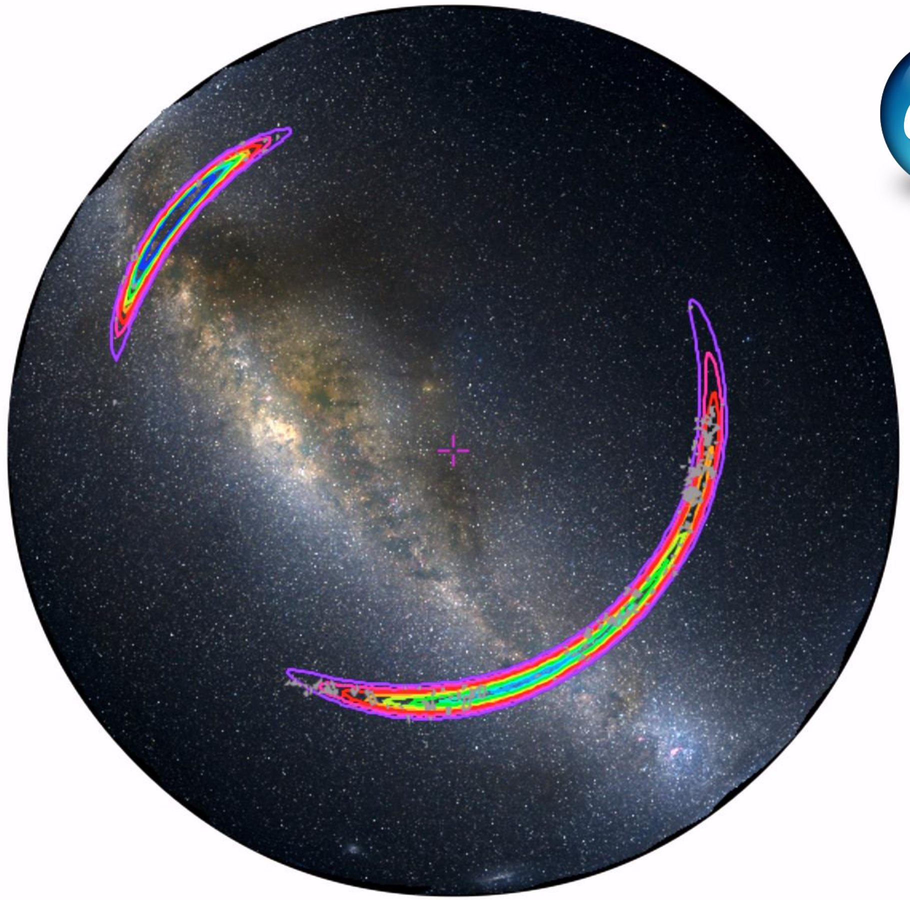


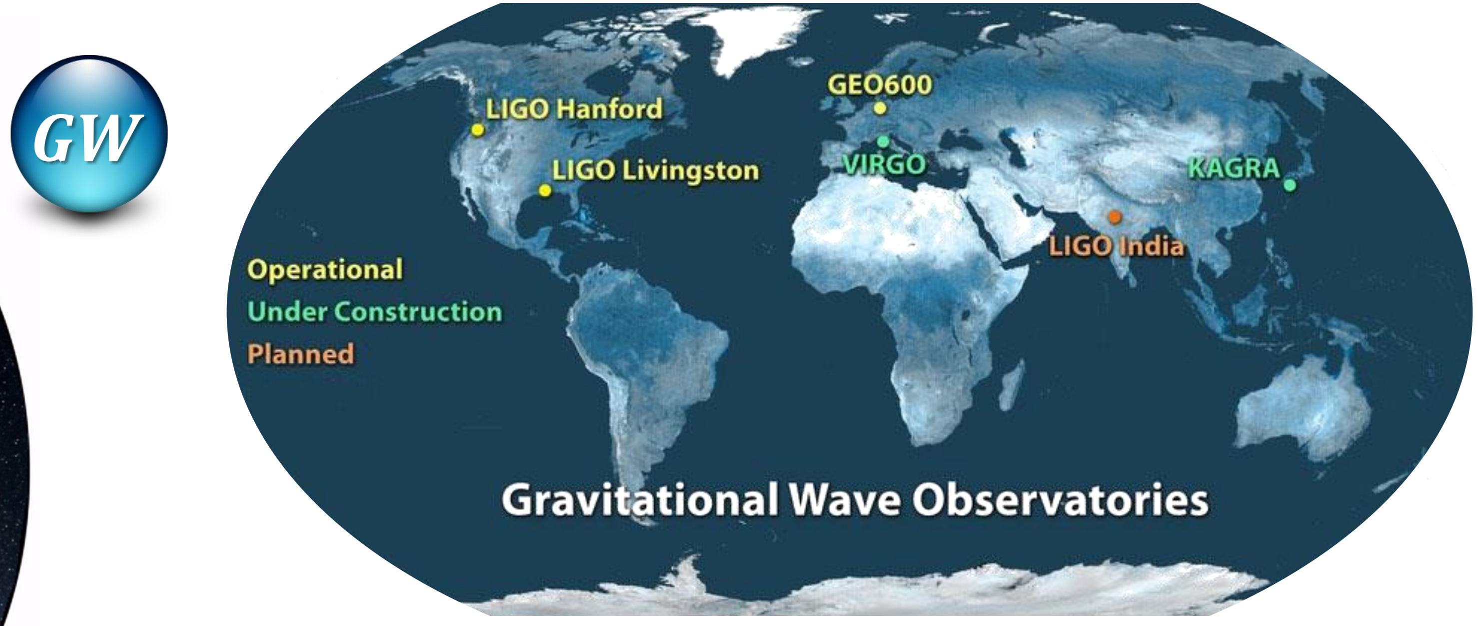
merger process of two Black Holes

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

BH merger process: reconstructing the GW origin

- GW allow to **reconstruct the merger site**, if data from observatories combined





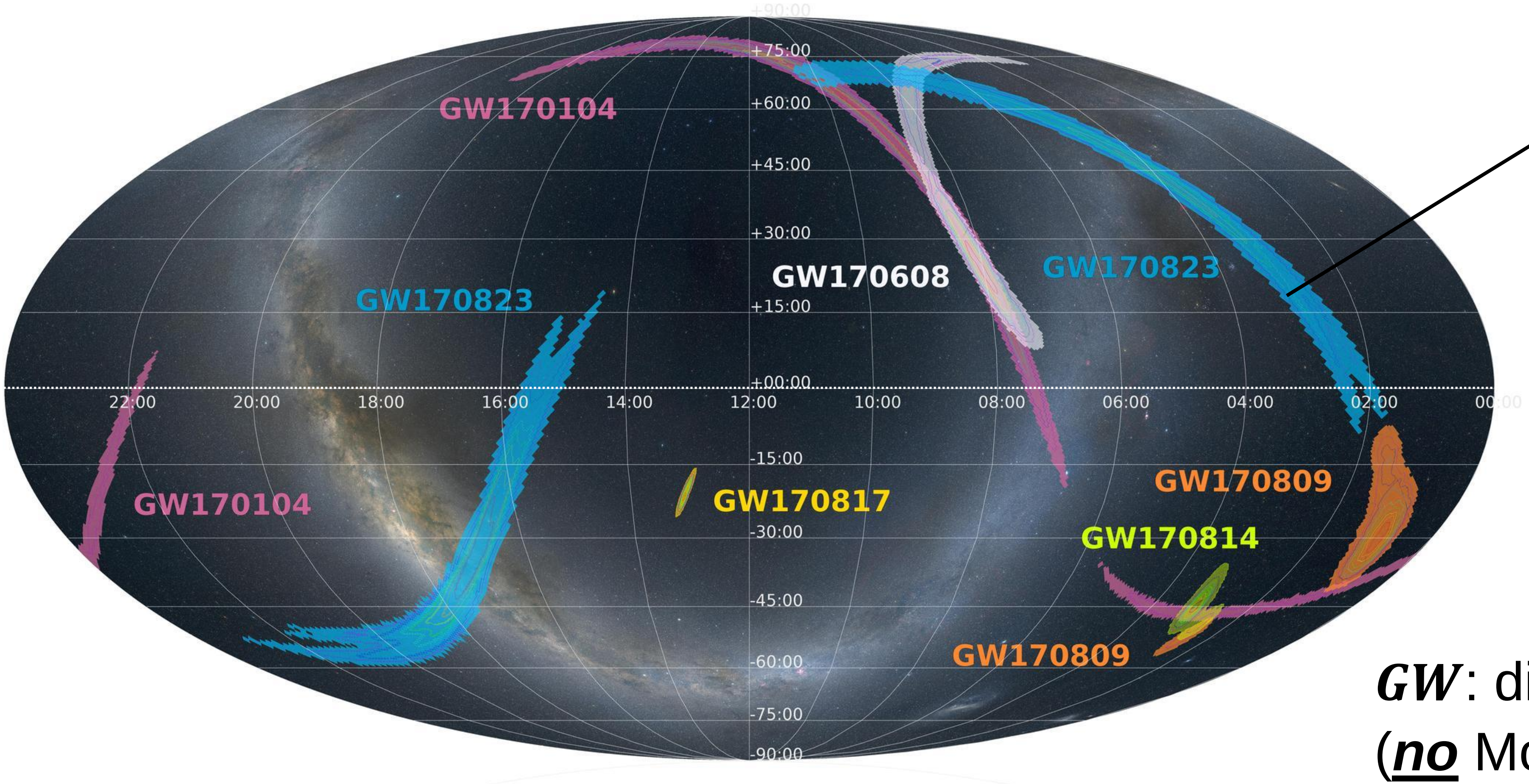
- detection in only one GW experiment:
  large uncertainties to determine the origin

- **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

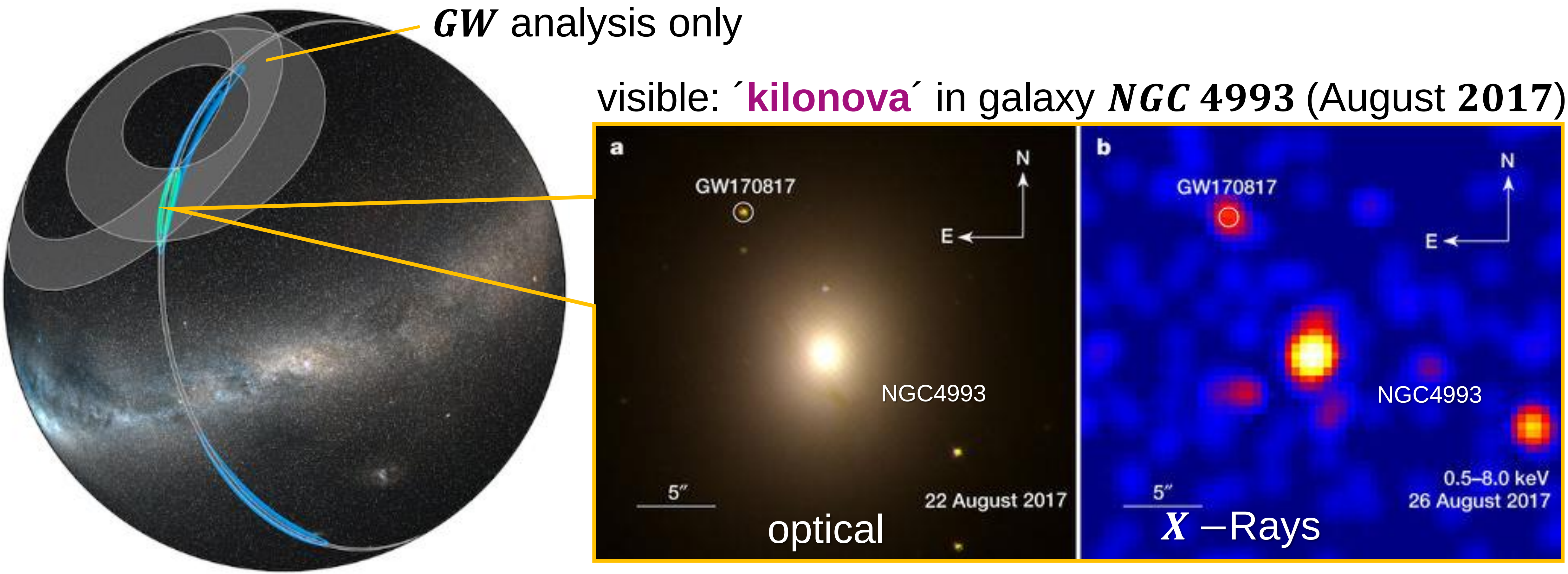
GW: displayed in $ICRS$*
(**<u>no</u>** Mollweide projection !)

Q: LIGO

*International Celestial Reference System

BH merger process: using an optical afterglow

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

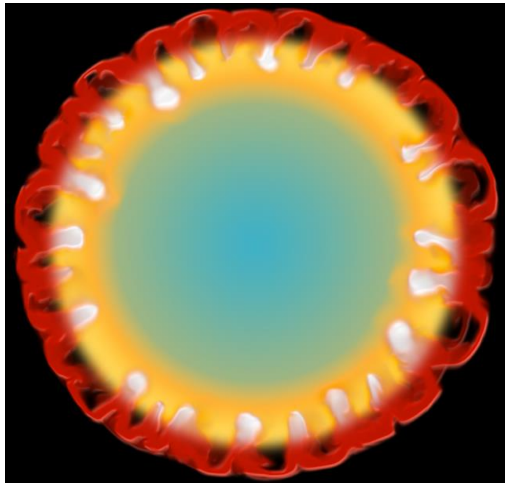


Q: LIGO

2.1.1 Cosmic air shower experiments

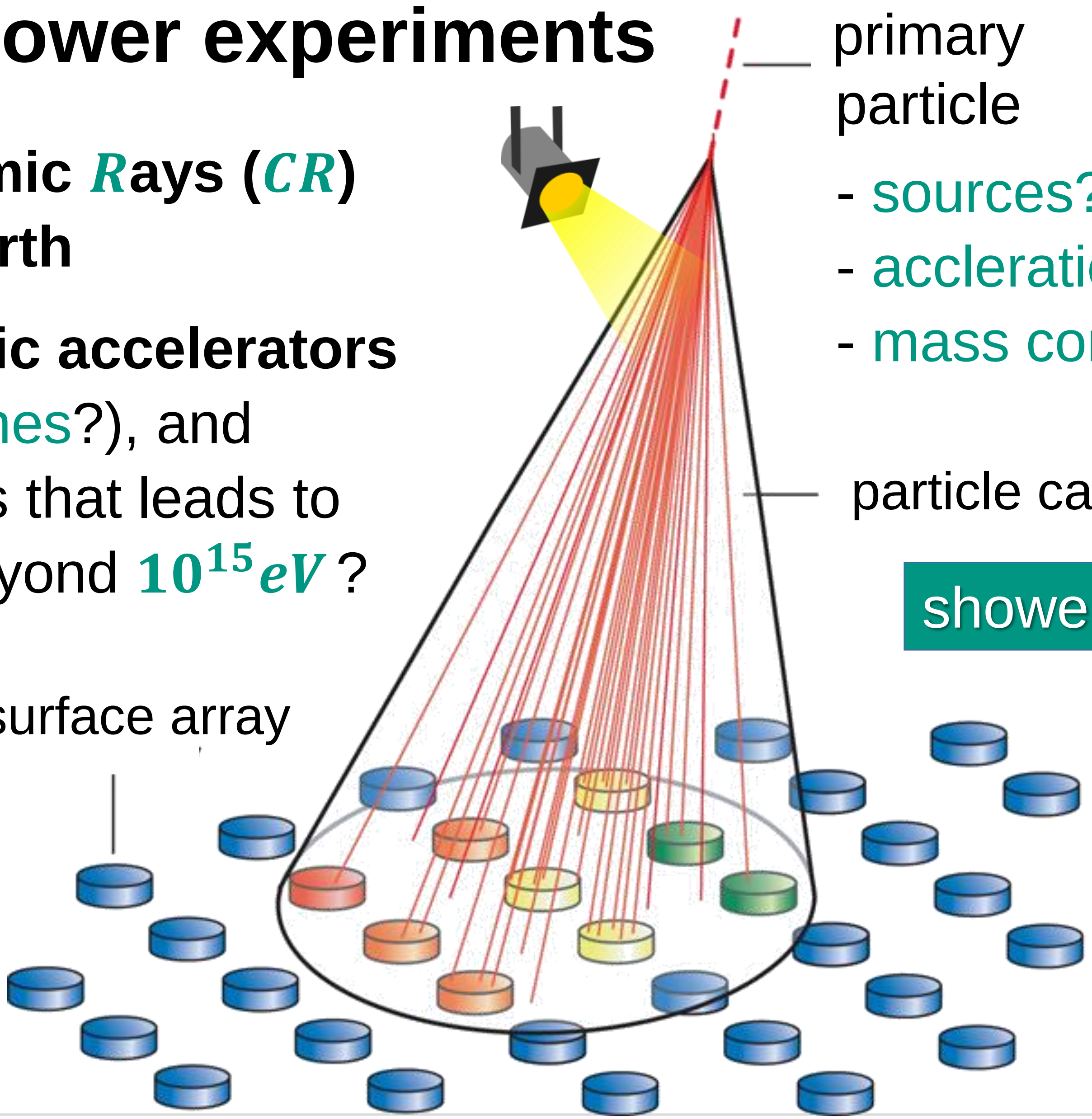
- **detecting charged *C*osmic *R*ays (*CR*) at the surface of the Earth**

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



Q: scientific am.

SNae as sources?



- sources?
- accleration processes?
- mass composition?

shower processes

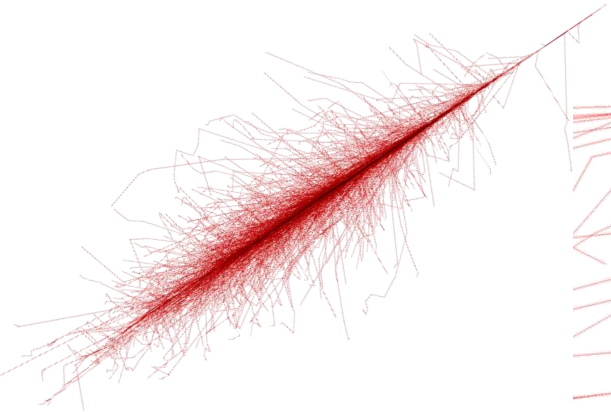
detectors

Q: KH Kampert

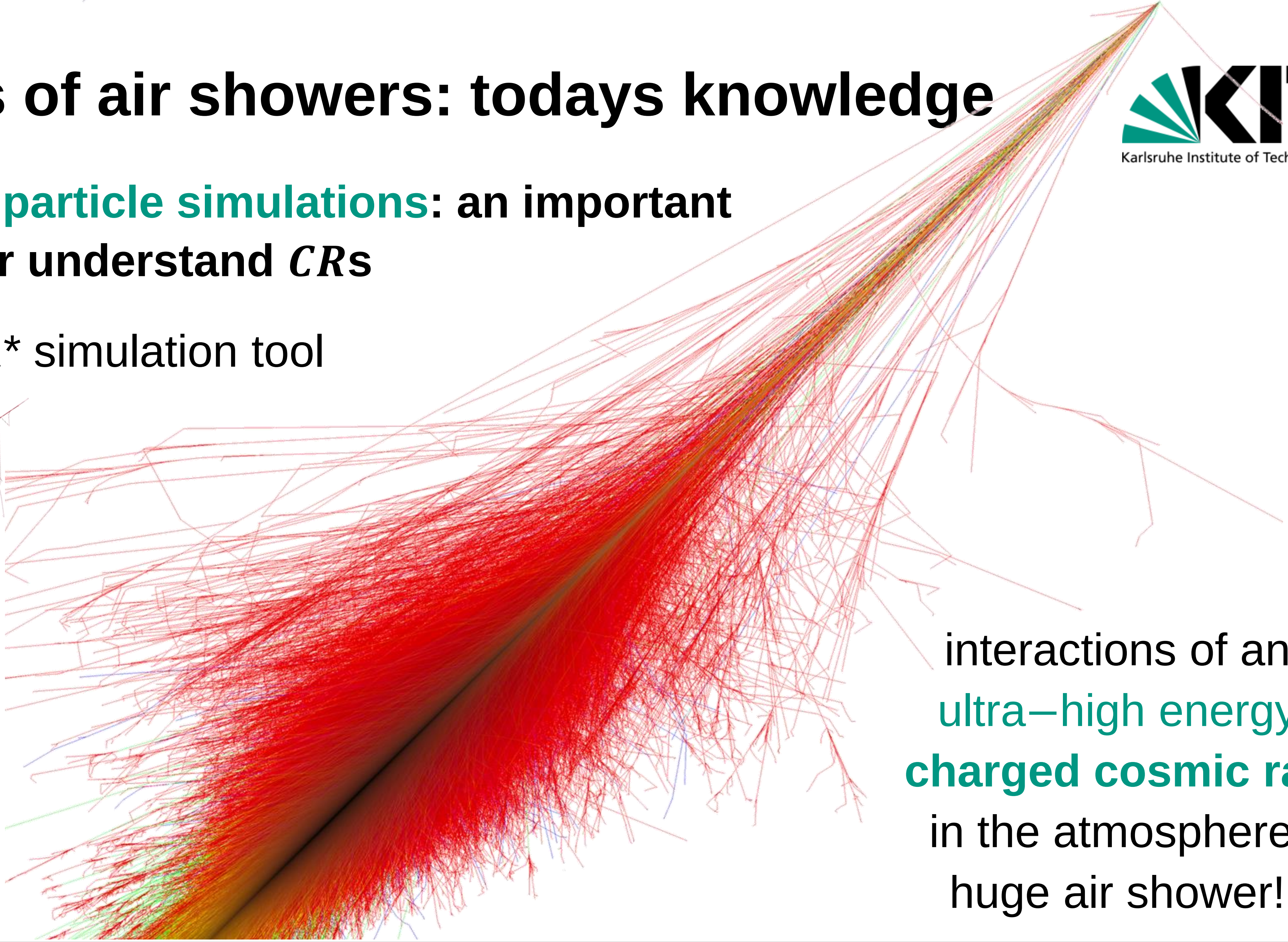
the physics of air showers: todays knowledge

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

  - $\boldsymbol{CORSIKA}$* simulation tool



photon induced shower



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

Q: CORSIKA, KIT

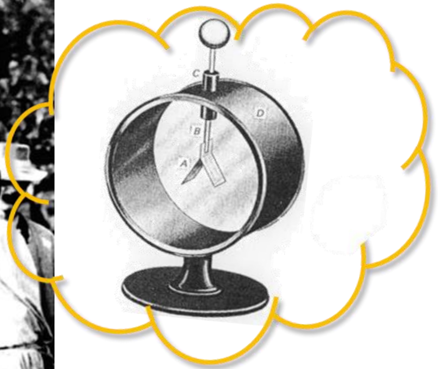
* KIT - CORSIKA - CORSIKA

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*

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

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

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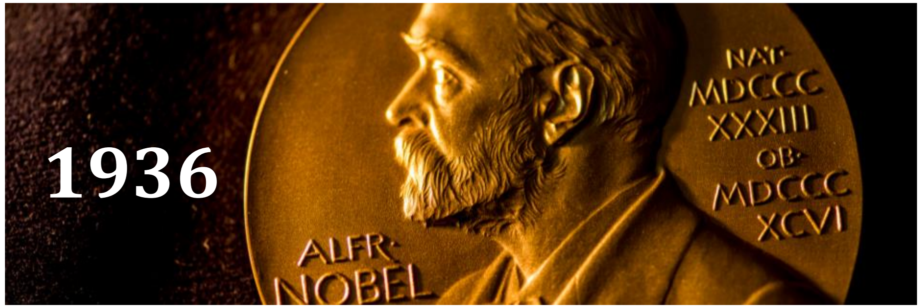
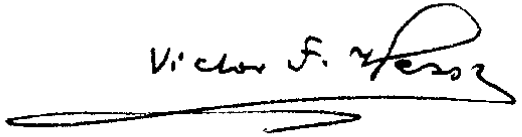
Q: nobelprize



´for his discovery of cosmic radiation´

Viktor Hess
$1883 - 1964$



Q: österreichische Post

112 years: $1911 - 2023$

The discovery of cosmic rays by *Hess* & $\boldsymbol{H.E.S.S.}$

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

in honour of ***V. Hess***, an air Cherenkov array, $\boldsymbol{H.E.S.S.}$, has been named, which has given us important insights into the $\boldsymbol{GeV}$ ... $\boldsymbol{TeV}$ **gamma ray sky** (see $\mathbf{2.1.2}$)

H.E.S.S.

Q: österreichische Post

$\boldsymbol{H.E.S.S.}$ – ***H***igh ***E***nergy ***S***tereoscopic ***S***ystem (Namibia)

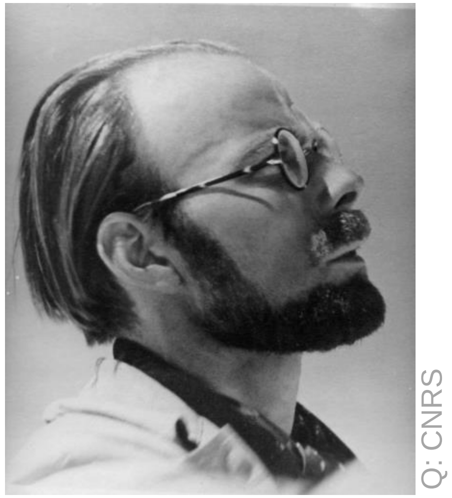
Discovery of extended air showers by *P. Auger*

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

coincidence technique:

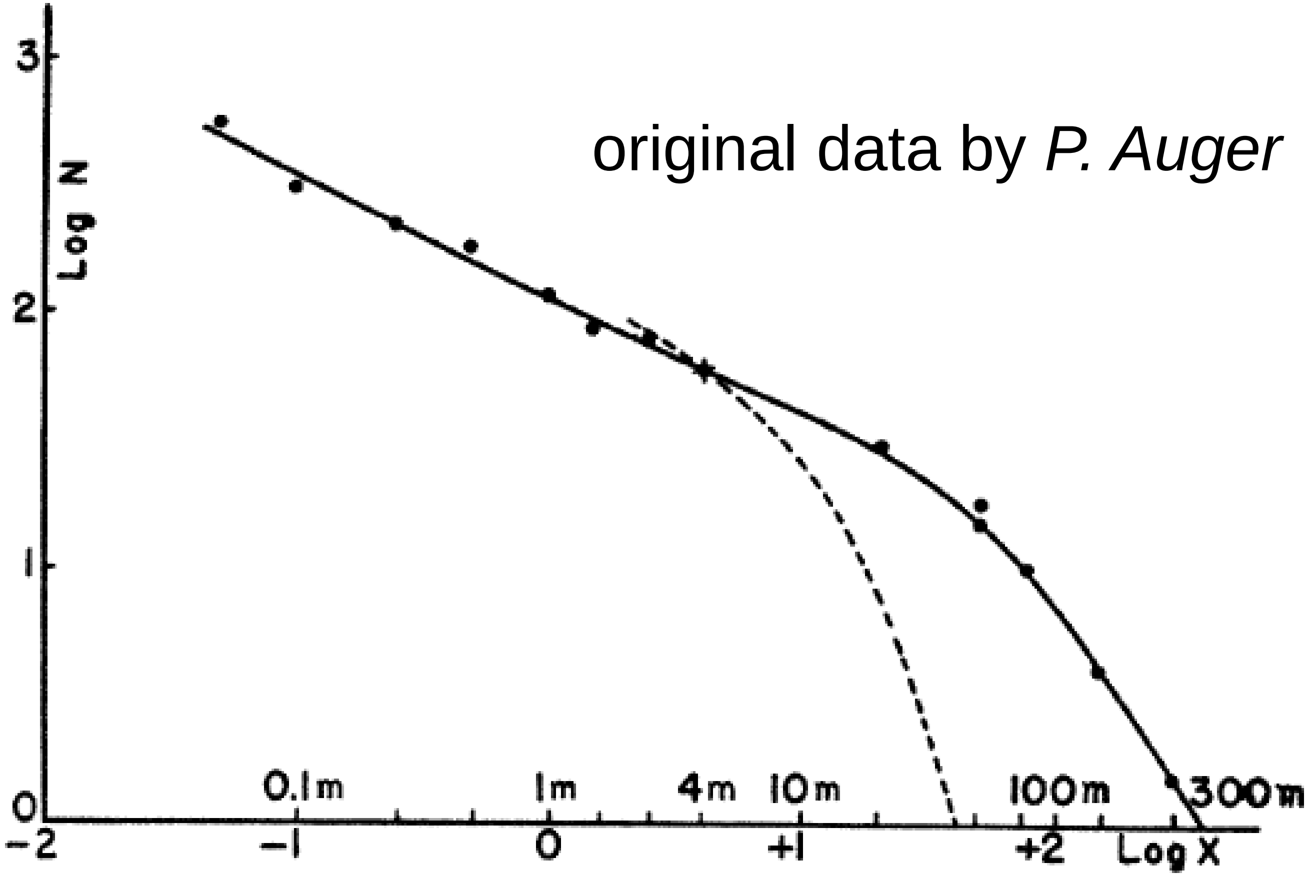
$\mathbf{2}$ Geiger counters operated at distances of up to $\boldsymbol{d = 300\,m}$

Jungfraujoch



Pierre Auger
$\mathbf{1899 - 1993}$

original data by *P. Auger*



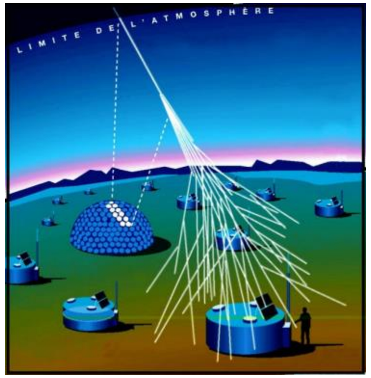
Discovery of extended air showers by *P. Auger*

- ***Pierre Auger***: **series of coincidence measurements at the Jungfraujoch $\mathbf{1939}$**

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

  - primary energies far beyond the $\boldsymbol{LHC}$ scale (highly efficient $\boldsymbol{CR}$ acclerators!)

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



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 $10^{20} eV$

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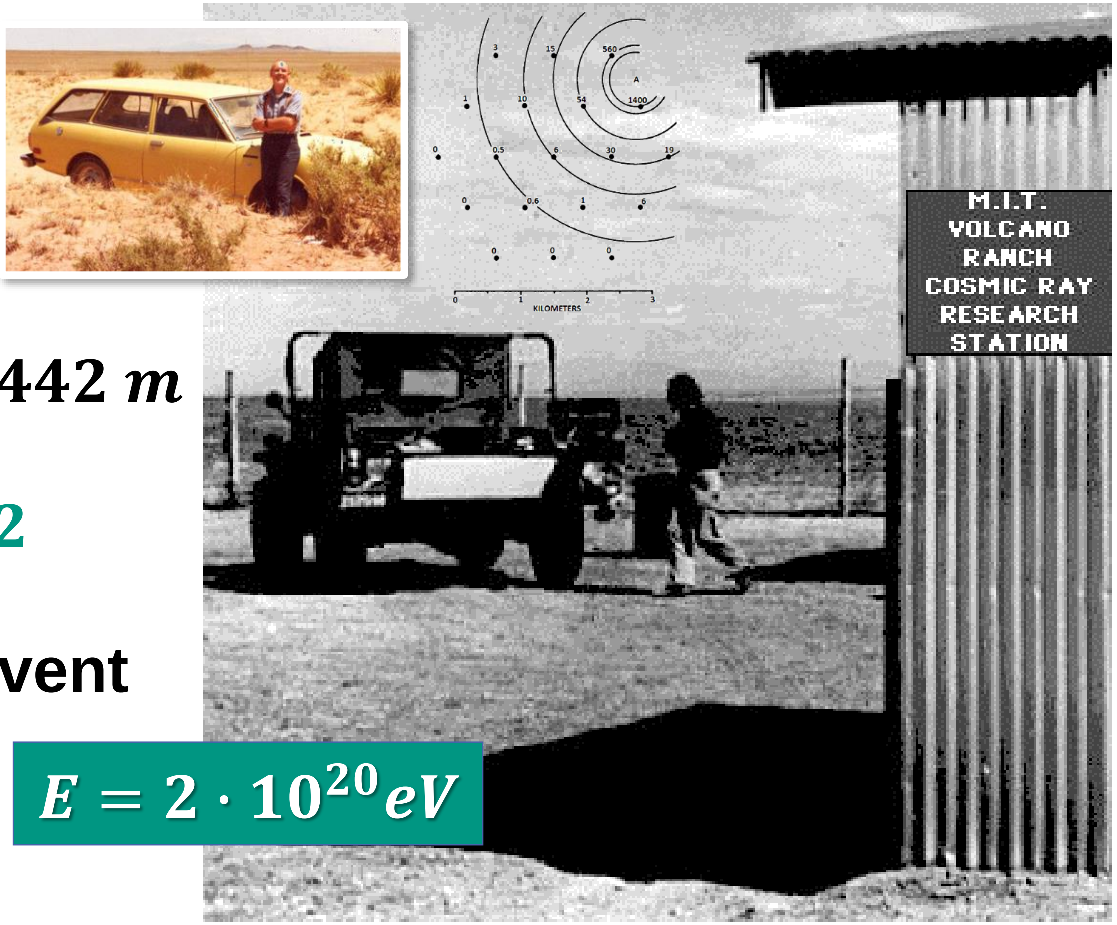
- ***John Linsley***: **pioneering measurements at Volcano Ranch, NM (USA)**

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



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

Q: Fermilab

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

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

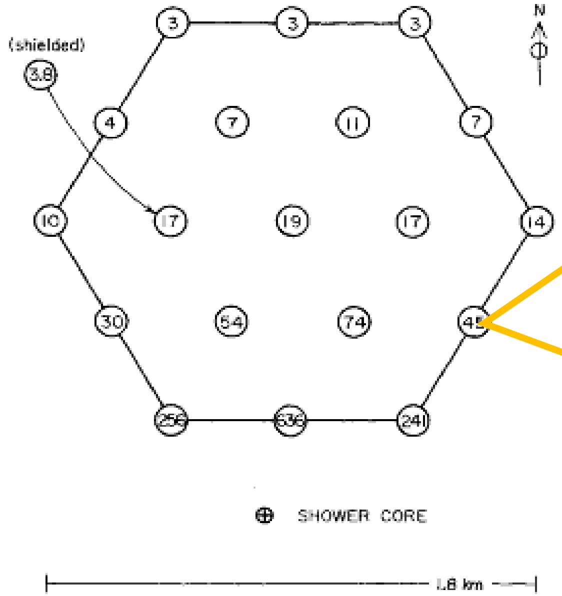
EXTREMELY ENERGETIC COSMIC-RAY EVENT*

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 m^2, and the spacing of adjacent detectors was 442 m. The area enclosed by the array was 2 km^2, 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/m^2) 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-

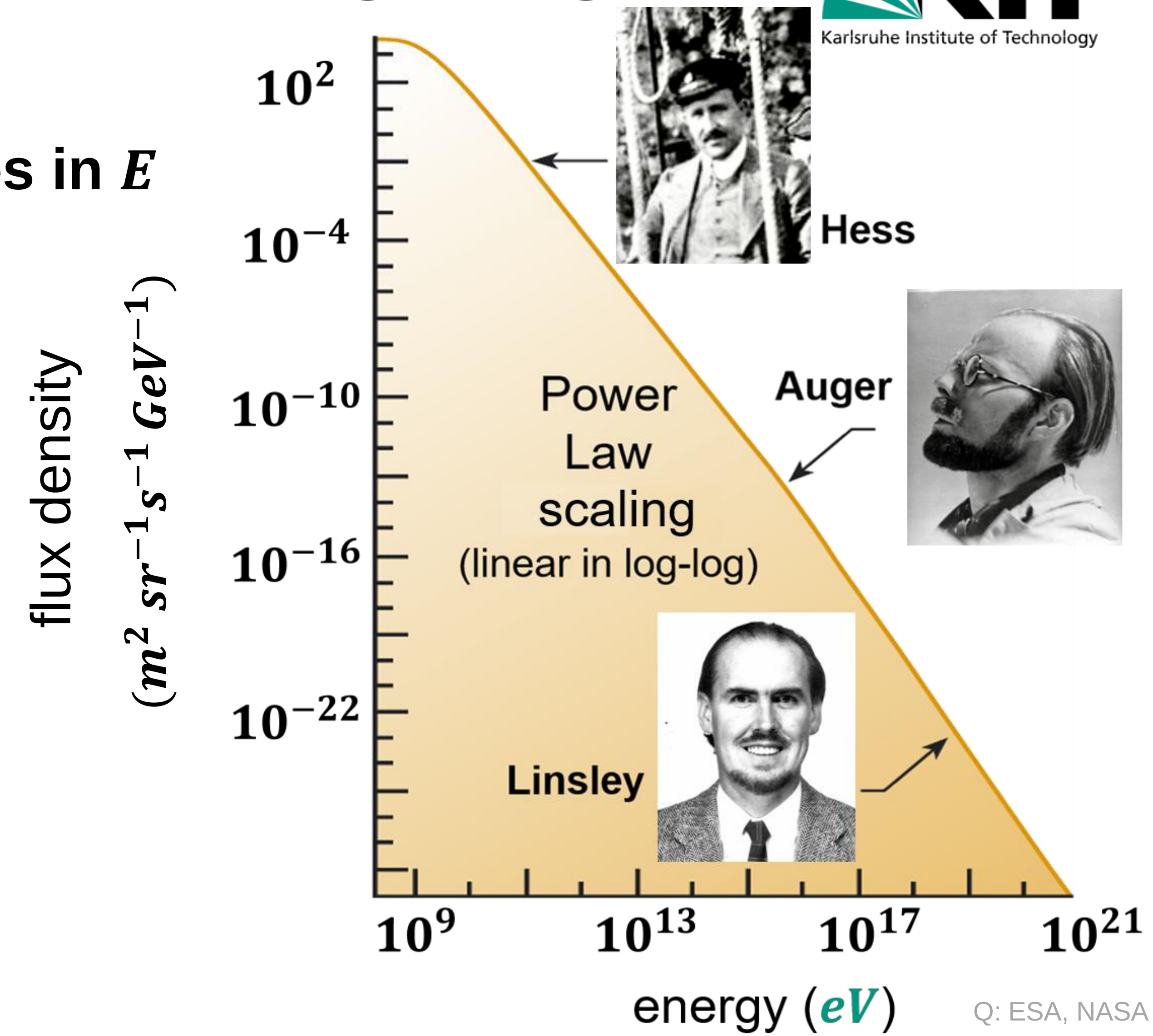


Energy spectrum of cosmic rays in $log - log$

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

- frequency of primaries:

$E = 10^{11} eV$ (V. Hess)
$1\ event\ /\ m^2\ /\ s$
$E = 10^{15} eV$ (P. Auger)
$1\ event\ /\ m^2\ /\ yr$
$E = 10^{19} eV$ (D. Linsley)
$1\ event\ /\ km^2\ /\ yr$



Q: ESA, NASA

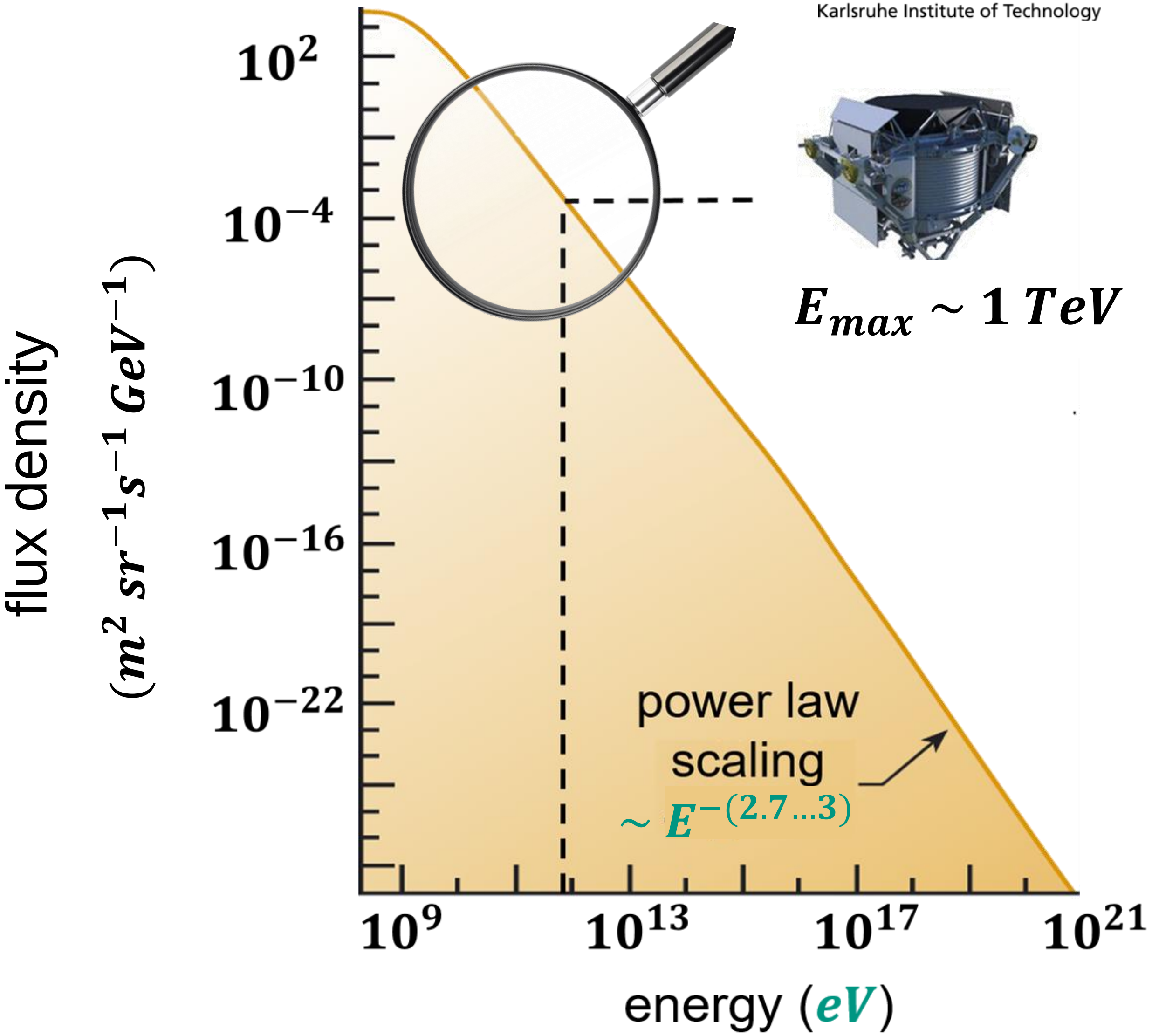
Energy spectrum of cosmic rays

- CR **spectrum: low–energy region**

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

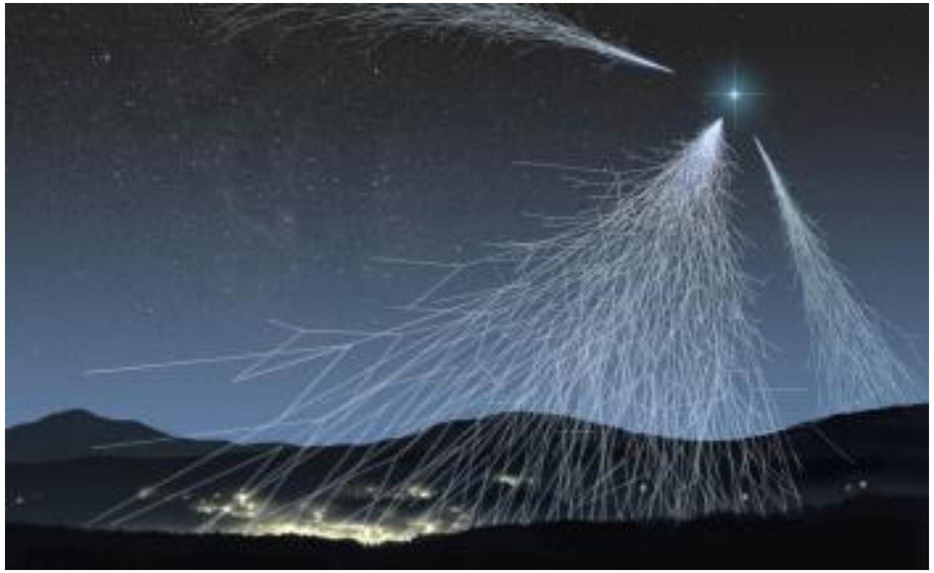
  - measurement of the **primary particle**

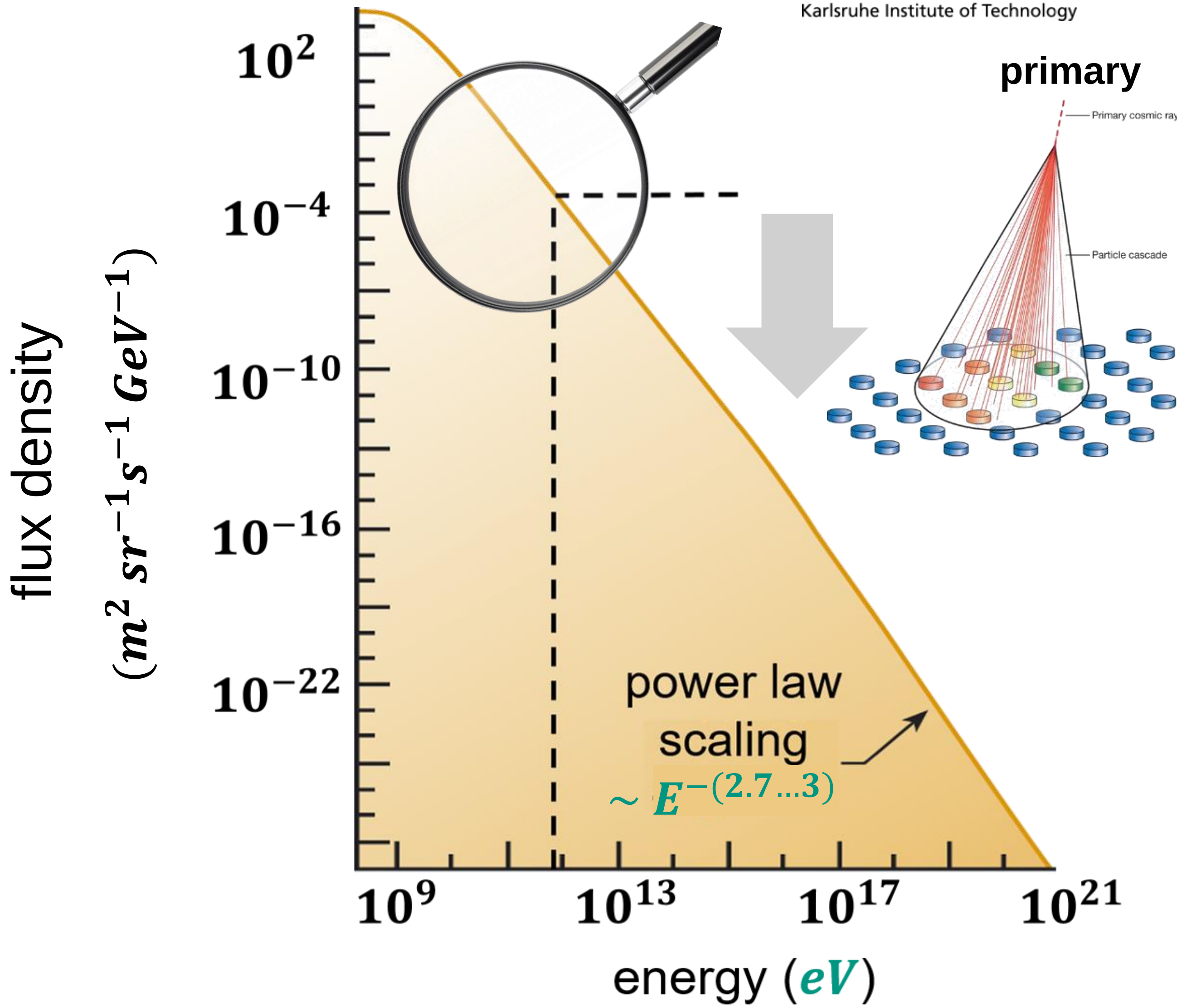
Q:NASA



Energy spectrum of cosmic rays

- CR **spectrum: high–energy region**
  - accessible via **indirect methods**: large air shower arrays at the surface (from $E \sim 10^{13} eV$)
  - measurement of **secondaries**





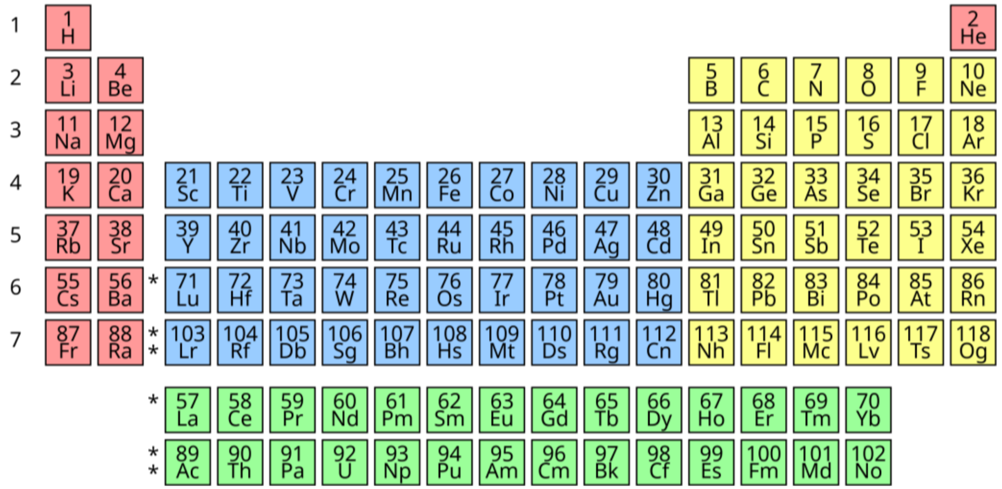
Q: spektrum

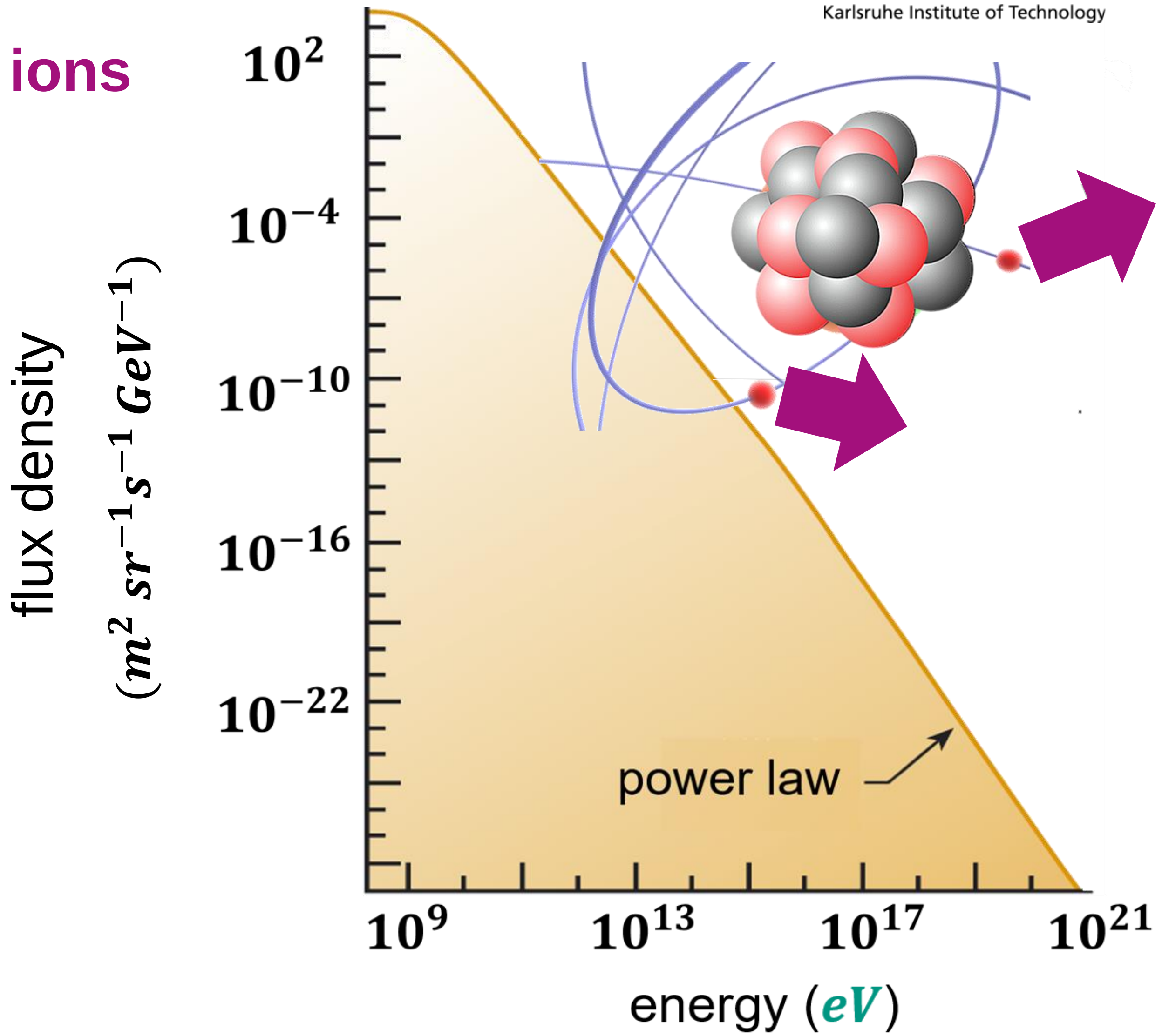
mass composition of cosmic rays

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

    protons $(Z = 1,\ \ A = \ \ 1)$, ...

    iron nuclei $(Z = 26, A = 56)$
  - CR chemical composition ?

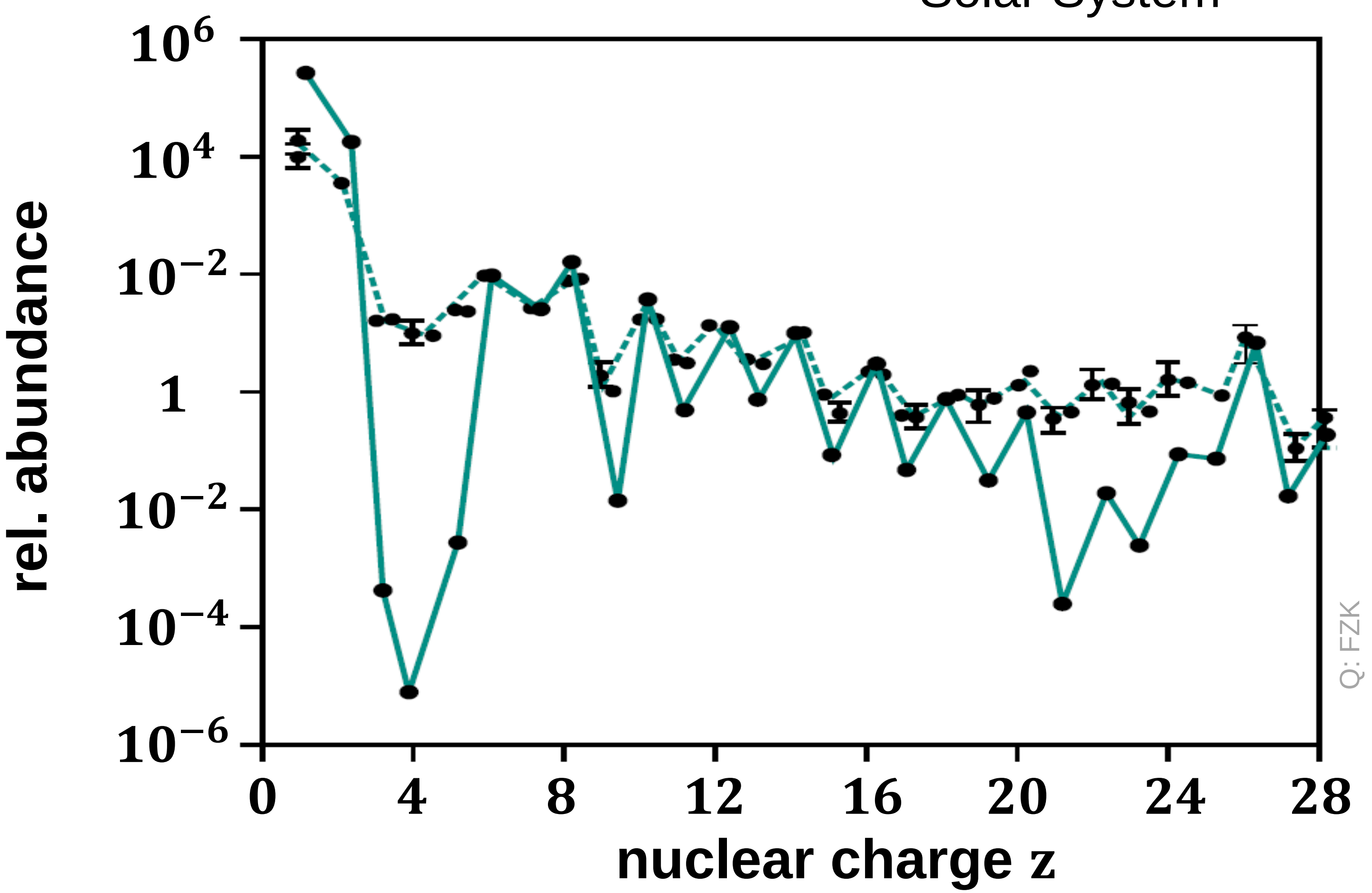




mass composition of Cosmic Rays – results

- 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^-)

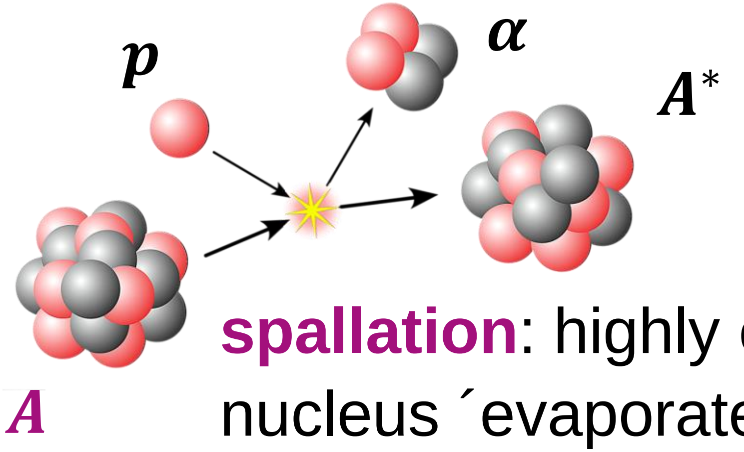


mass composition of cosmic rays – spallation!

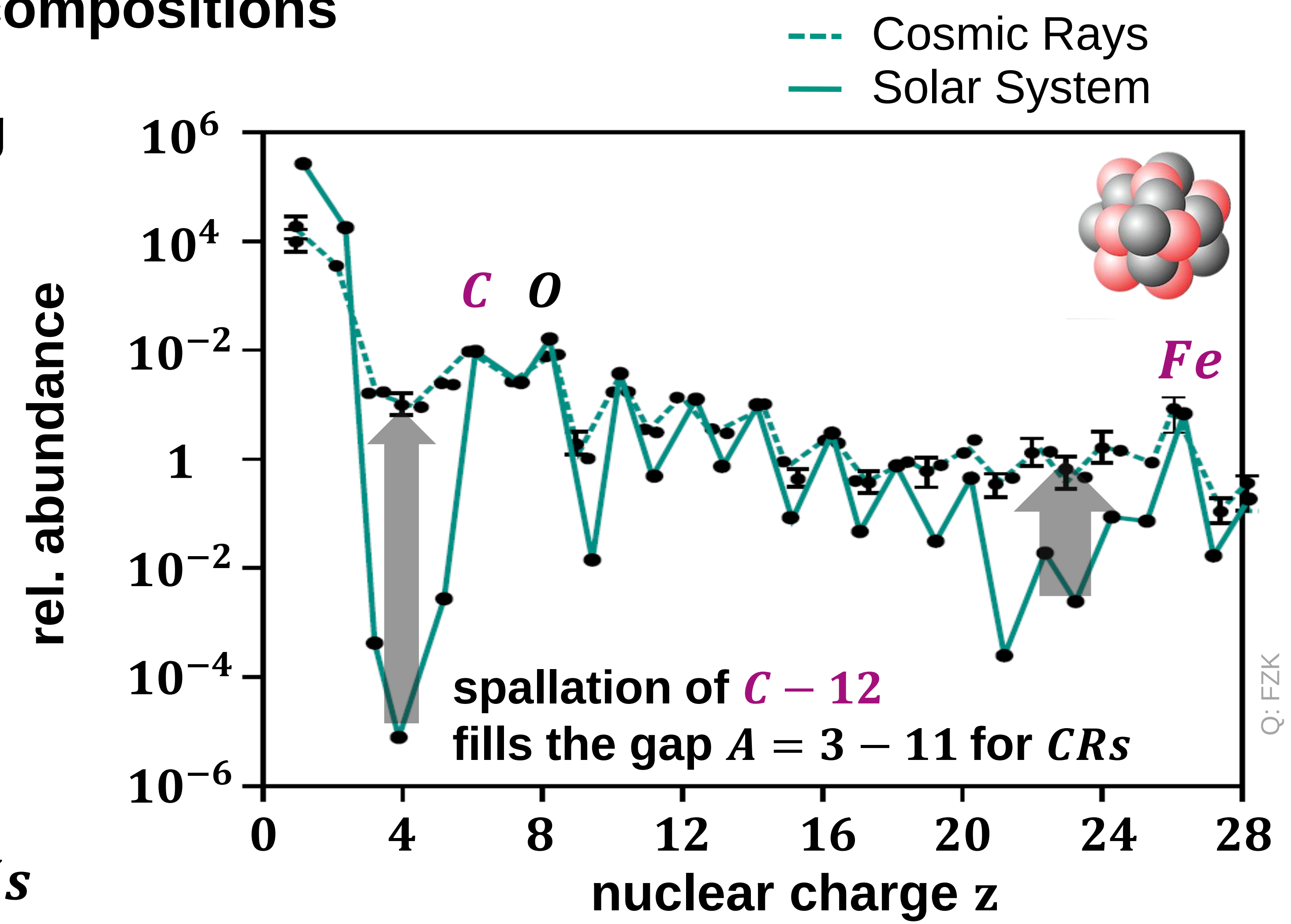
- differences in the two mass compositions

- CR – nuclei propagate over long distances & time scales in our galaxy: spallation reactions

- important CR ´seed nuclei´: ^{56}Fe, ^{16}O, ^{12}C

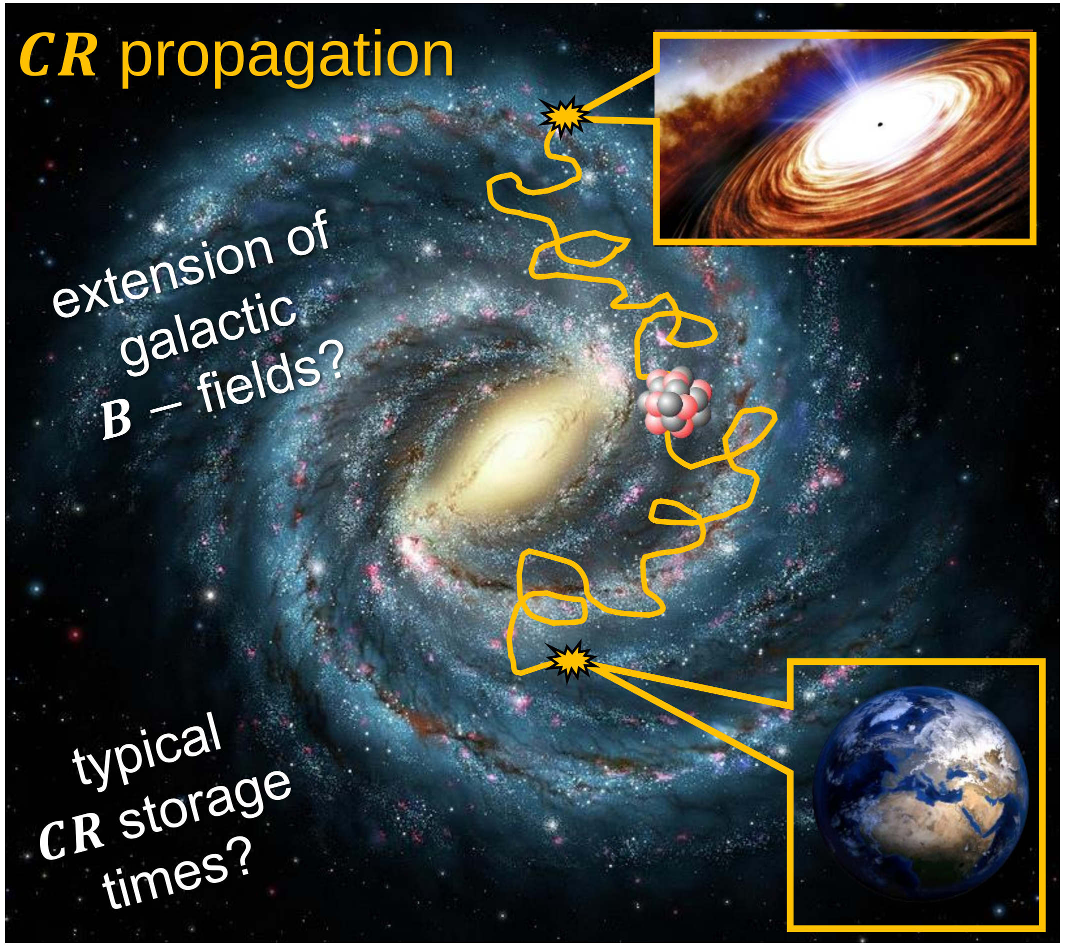


spallation: highly excited nucleus ´evaporates´ α´s / n´s

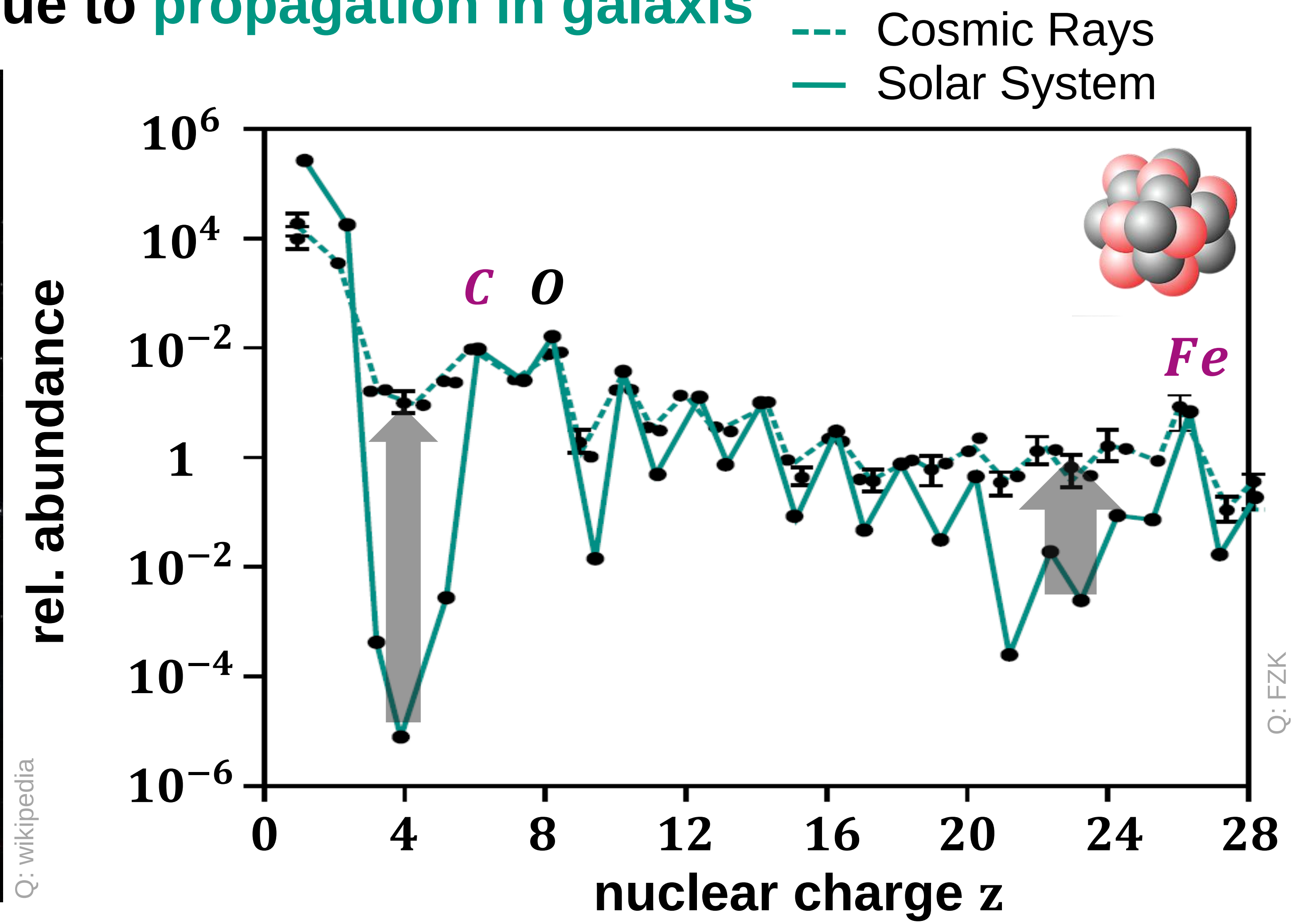


mass composition of Cosmic Rays – spallation !

- spallation reactions on CRs due to propagation in galaxis



Q: wikipedia



Q: FZK

mass composition of CRs – balloon missions

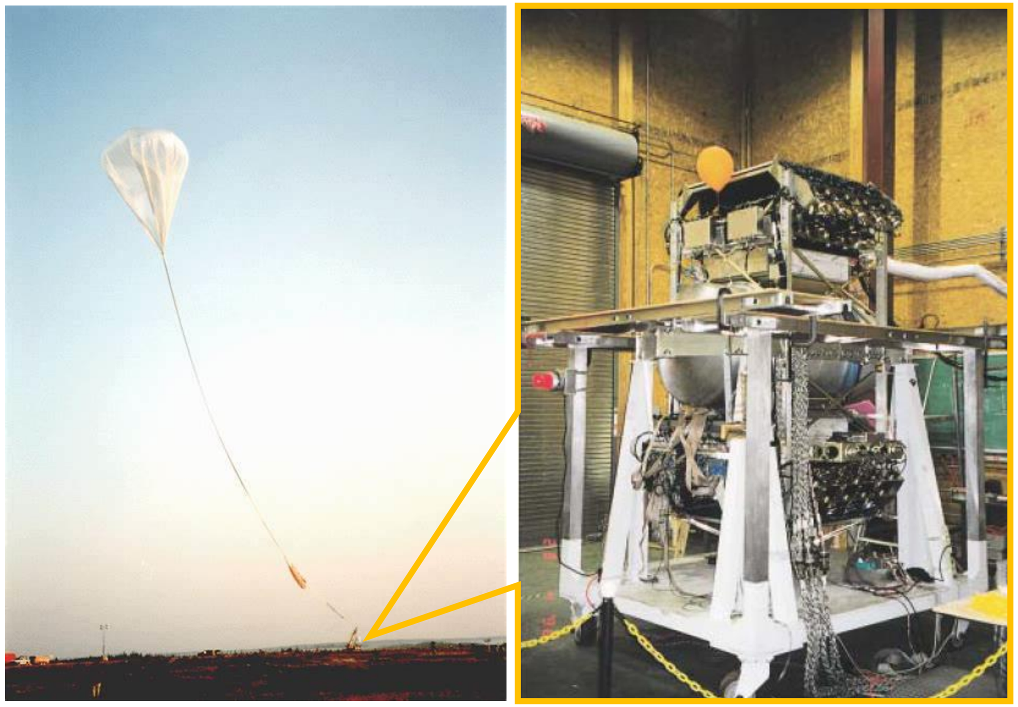
Karlsruhe Institute of Technology

experiment	scientific goals	energy range
detection of antimatter		
$HEAT$ - High Energy Antimatter Telescope	e^+, e^- / anti–protons	$5 \ldots 50\ GeV$ / $0.2 \ldots 30\ GeV$
$CAPRICE$ - Cosmic Anti$P$article Ring Imaging Cherenkov Experiment	e^+, e^- / anti–protons atmospheric muon spectra	$0.5 \ldots 50\ GeV$
$BESS$ – Ballone Borne Experiment with Superconducting Solenoidal Spectrometer	anti–protons anti–helium	$0.25 \ldots 3\ GeV$ $0.25 \ldots 100\ GeV$
element– and isotope composition		
$ISOMAX$ - Isotope Magnet E$x$periment	$Be-10$, isotopes with $2 < Z < 8$	$0.2 \ldots 3\ GeV$ / 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	$20 \ldots 200\ GeV$ / nucleon
$JACEE$ - Japanese–American Collaborative Emulsion Experiment	spectra from $1 < Z < 26$	$1 \ldots 100\ TeV$
$TRACER$ - Transition Radiation Array for Cosmic Energetic Radiation	spectra $8 < Z < 26$	$< 10\ TeV$ / nucleon

Example: $ISOMAX$ mission – start (& abrupt end)

- **Science goals of $ISOMAX$ (Isotope Magnet E$x$periment)**

  - measurement of **light isotopes** of CRs,
  special focus on: $^{9}Be/^{10}Be$ ratio (study spallation during long CR propagation in our galaxy) up to nucleon energies of GeV/n



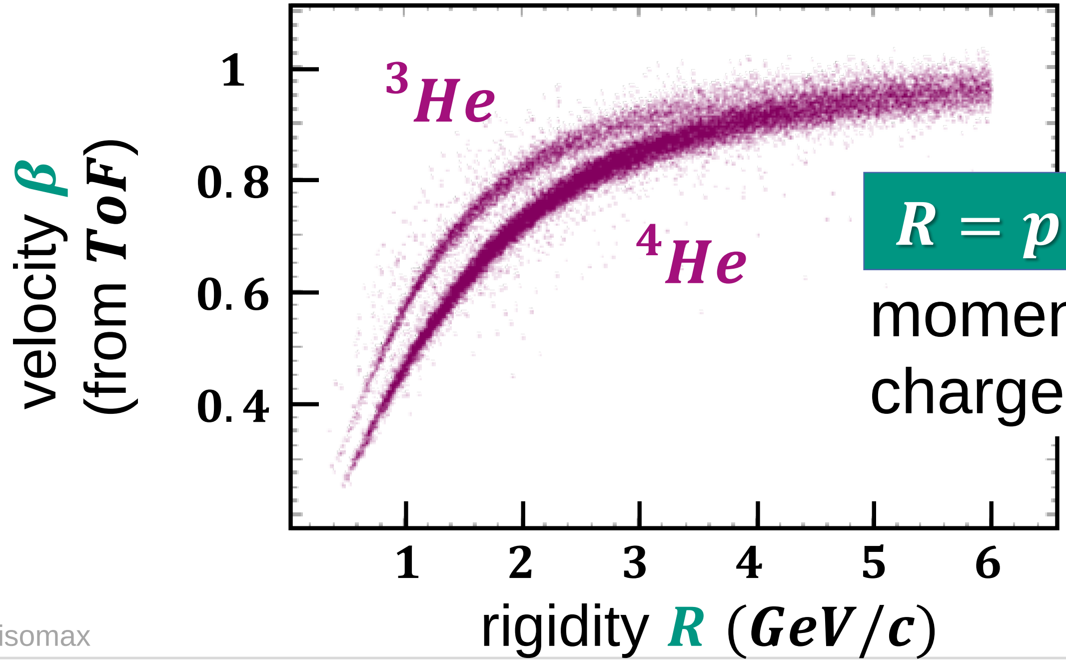
detector:
$h = 2.5\, m$
$m = 2\, t$

hard landing of $ISOMAX$

Q: isomax

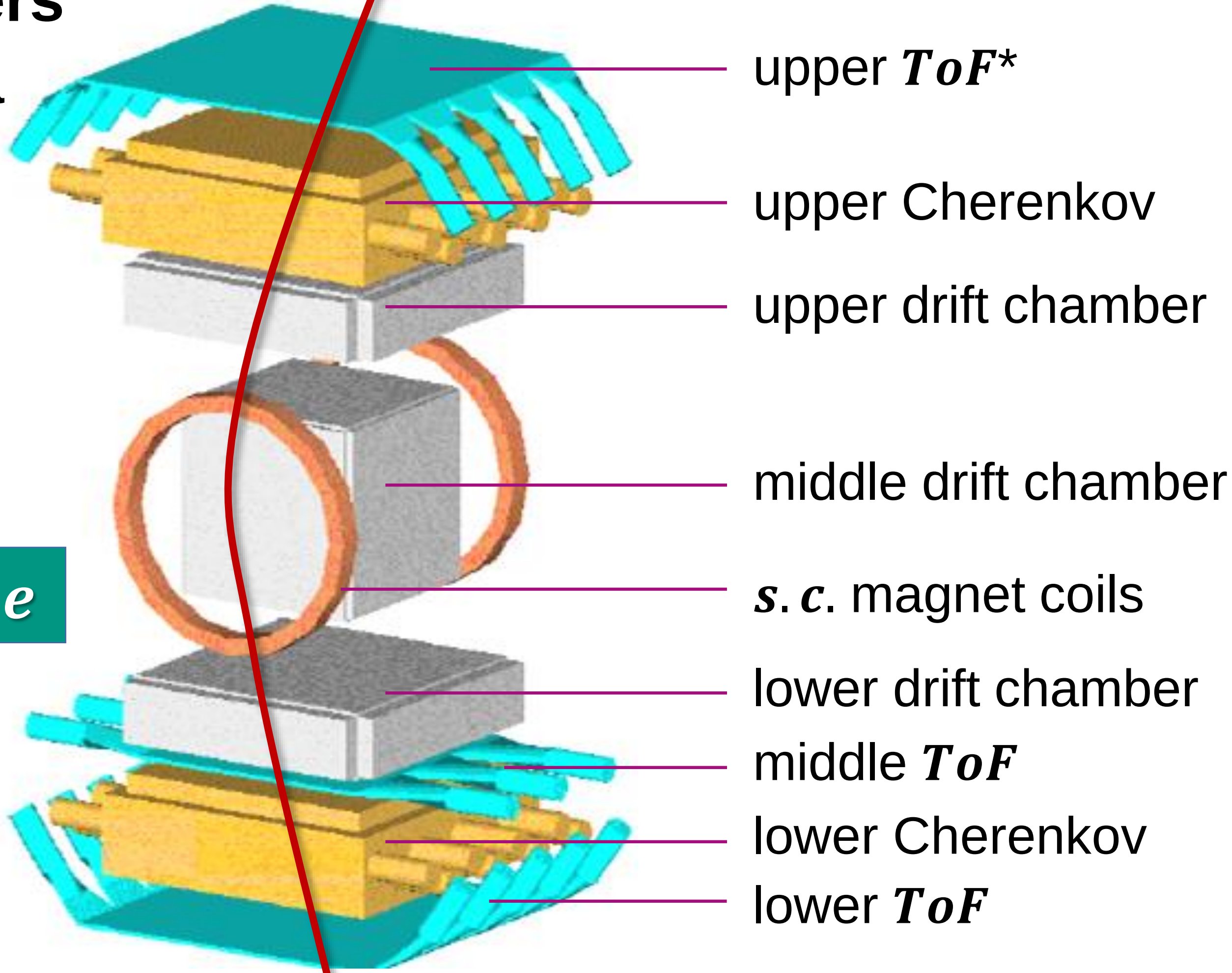
Example: $ISOMAX$ mission – key principles

- **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

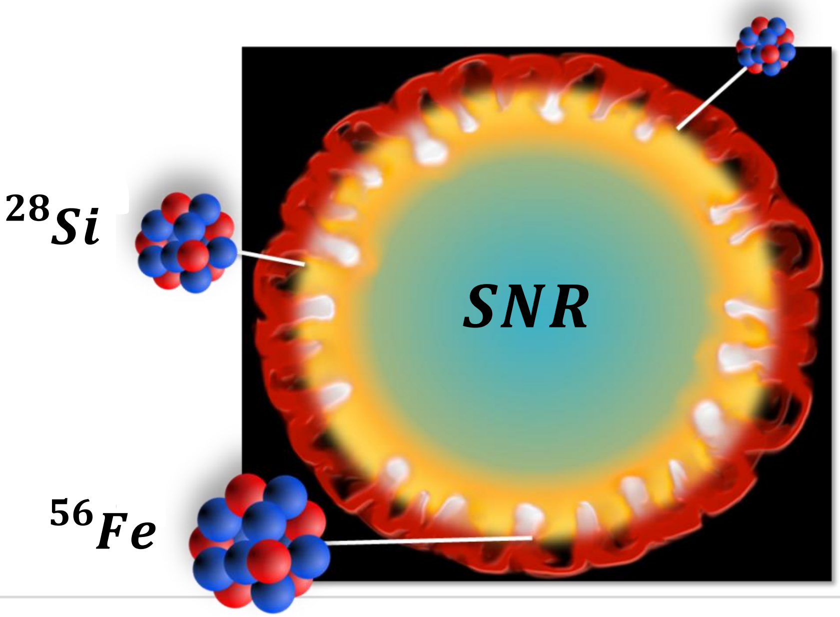
*Time–of–Flight

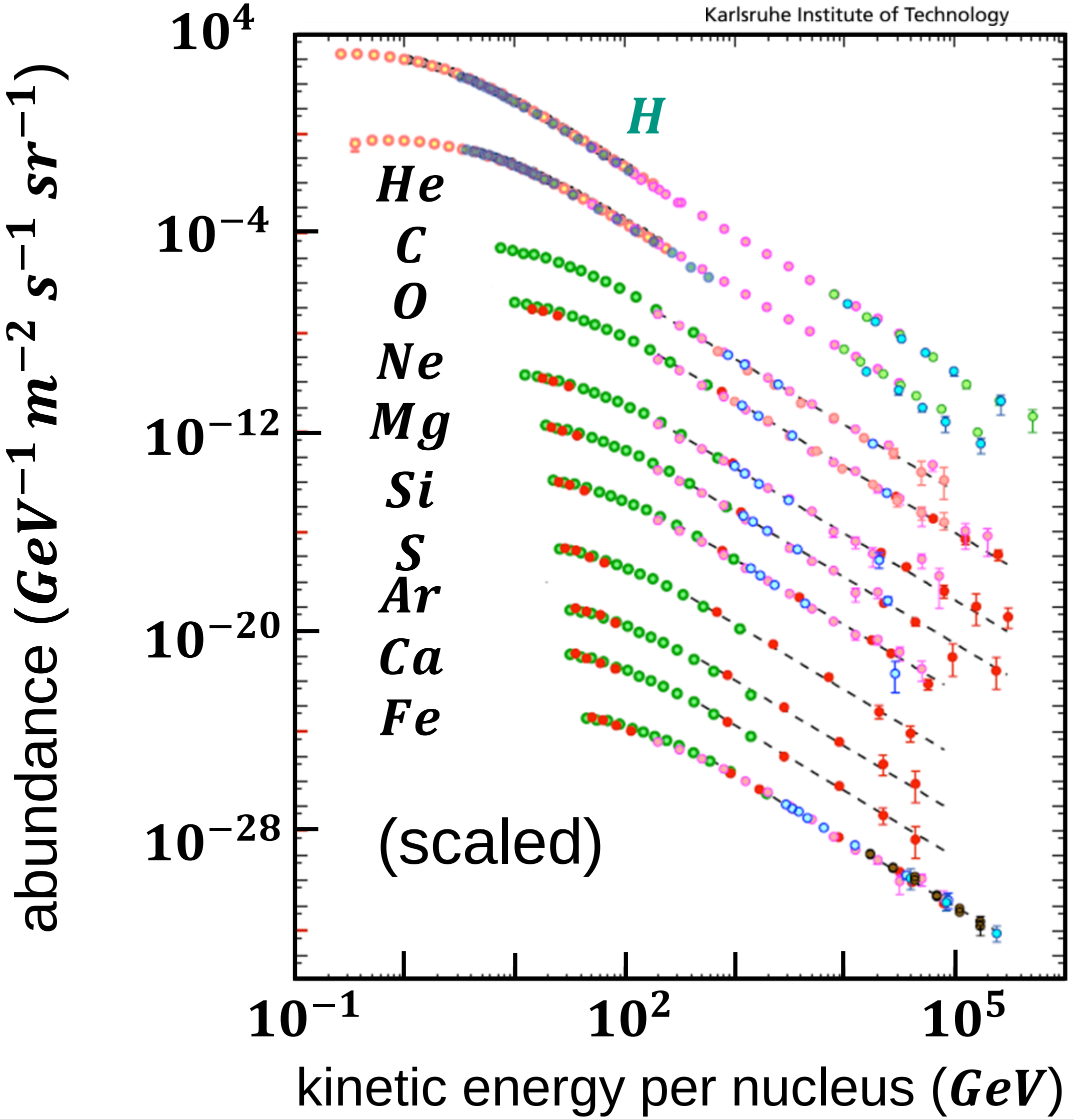
Energy spectrum of single CR species

- **direct data: up to a few hundred TeV**

  - all elements show the **same spectral index** as function of their kinetic energy

    ⇨ **only 1 acceleration mechanism is relevant for CRs up to this E – scale**



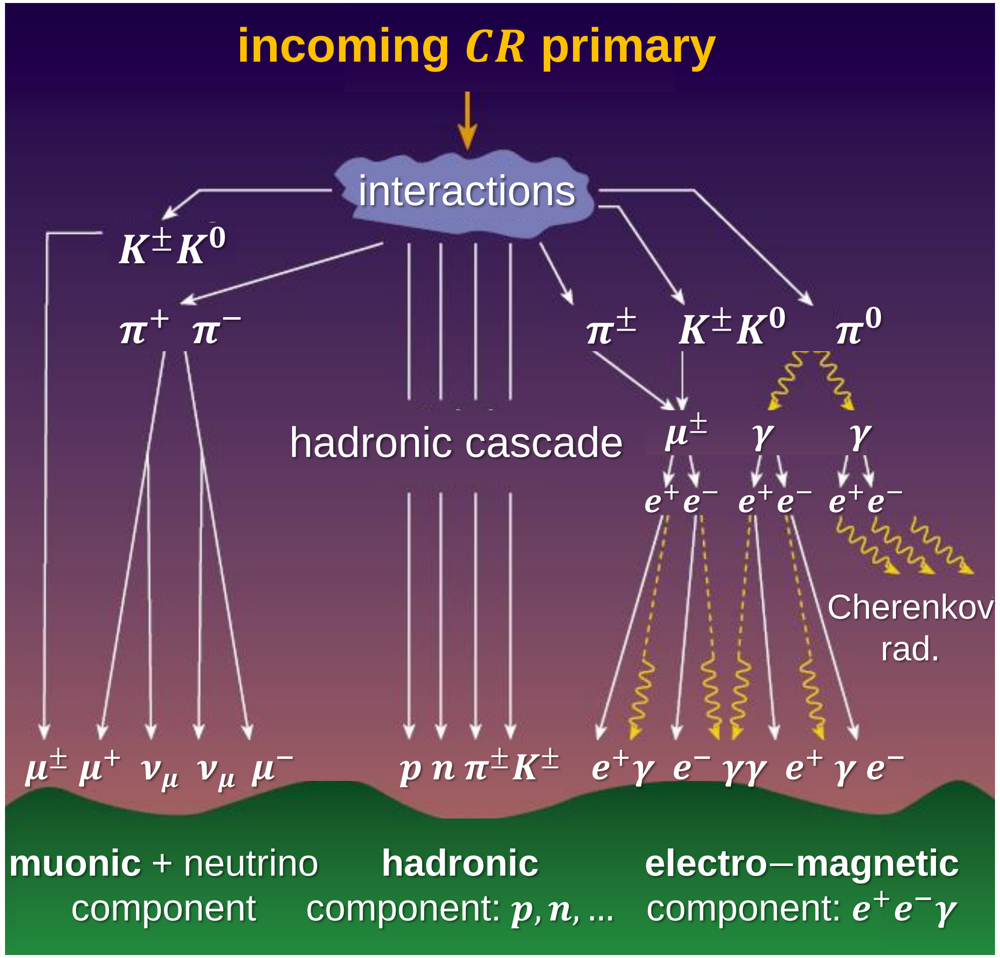


Q: sciam

the physics of large air showers – first overview

Karlsruhe Institute of Technology

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



⇨ secondaries via **cascade** & **decay** processes

3 COMPONENTS

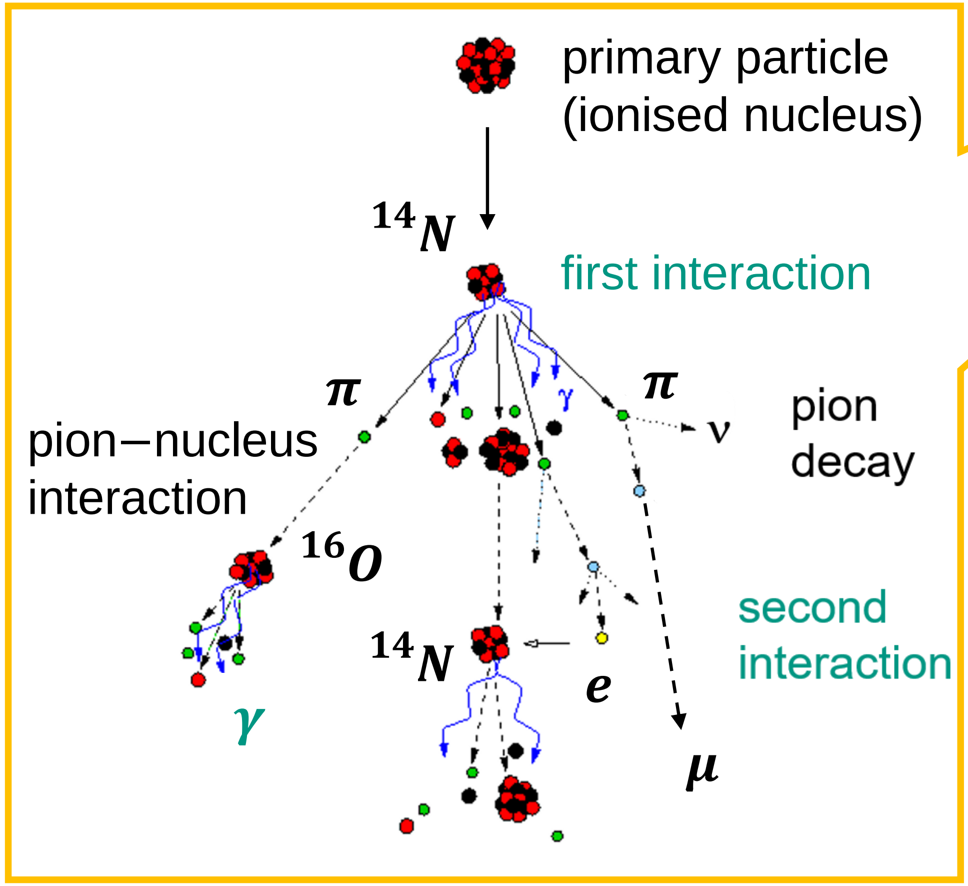
electro−magnetic component
- electrons, positrons & photons
- cascade processes, ´**soft**´ part

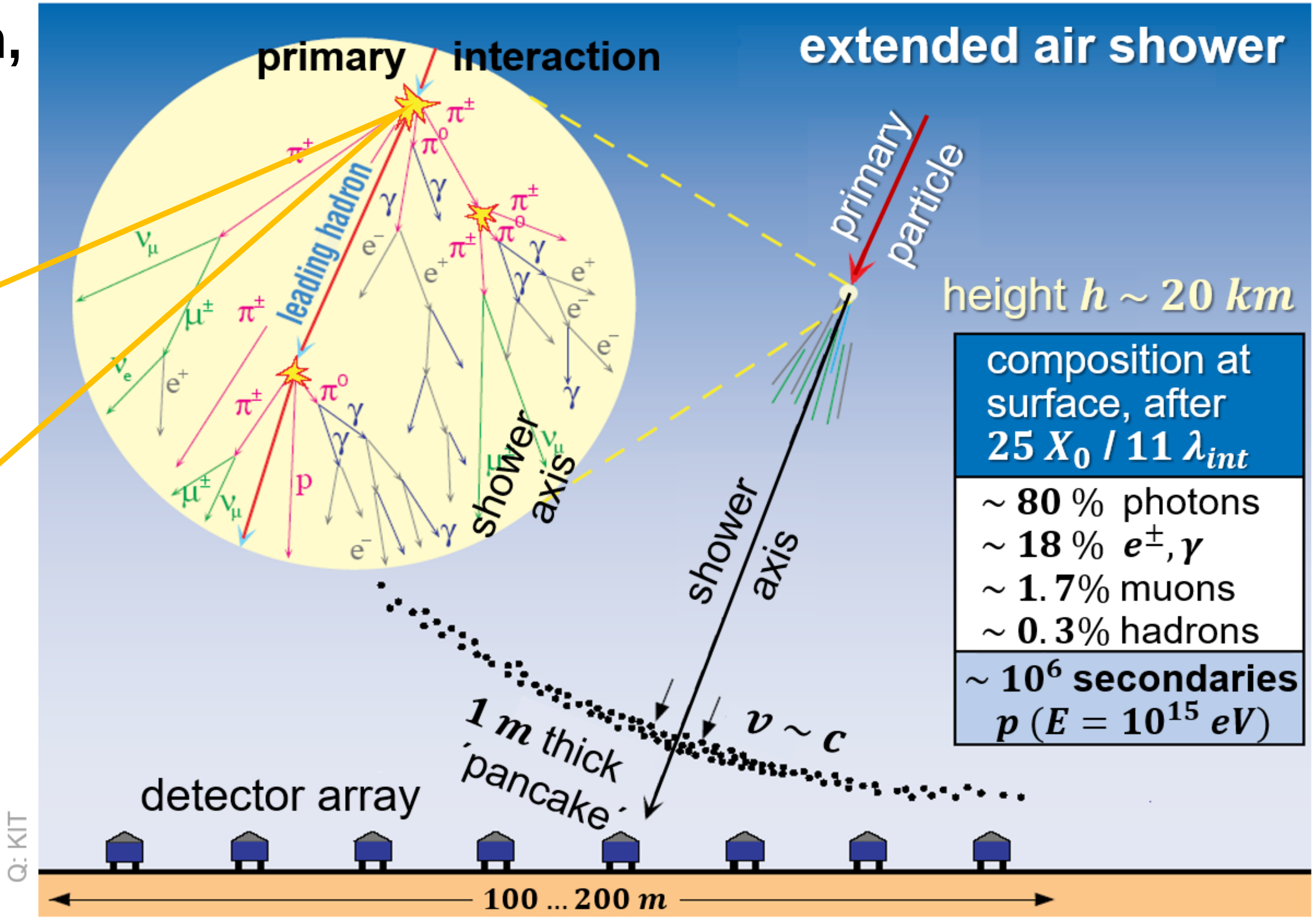
muonic component
- $\mu^{+}\mu^{-}$ with strong penetration power
- ´**hard**´ CR component

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

Large air showers: modelling of all processes

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





composition at surface, after $25\ X_0\ /\ 11\ \lambda_{int}$
$\sim$ **80 %** photons
$\sim$ **18 %** $e^{\pm}, \gamma$
$\sim$ **1.7%** muons
$\sim$ **0.3%** hadrons
$\sim 10^6$ **secondaries** $p\ (E = 10^{15}\ eV)$

CR air showers & jets at hadron colliders ($CERN$)

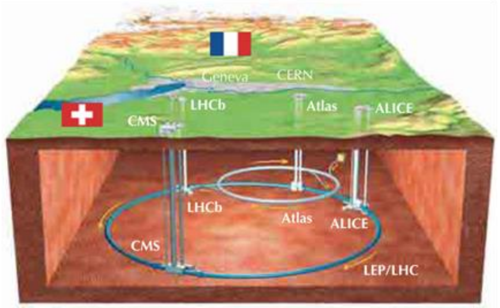
- **Common topics:**

- analysis of **jets** & of particle interactions

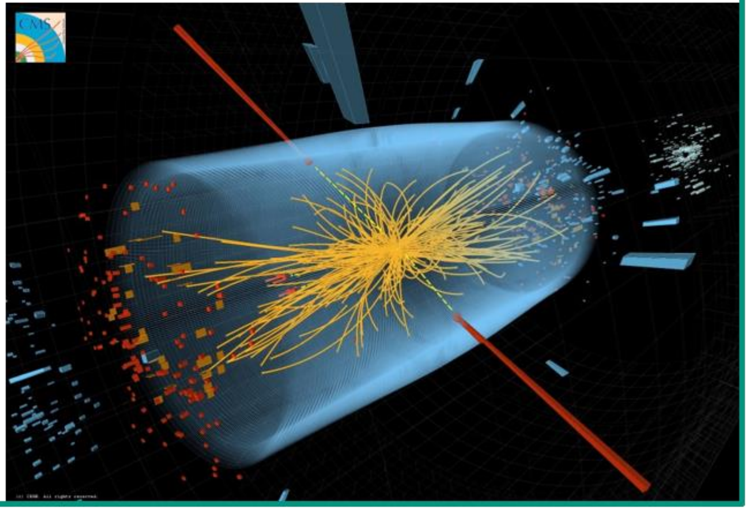
ATP & TP!

shower physics at the LHC

- accelerators: protons up to $E_p = 7\,TeV$ ($\sqrt{s}$ well known)



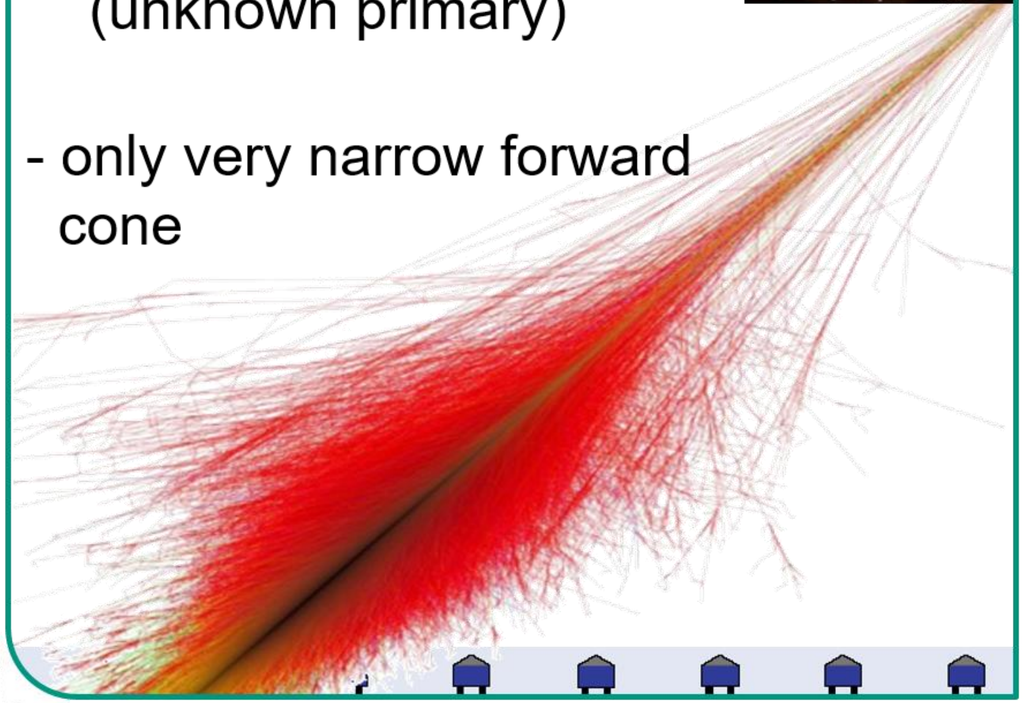
- CMS coverage over 4π – geometry



showers from AGN – accelerators

- AGN – site: protons up to $E_p = 10^{20}\,eV$ or nuclei (unknown primary)

- only very narrow forward cone



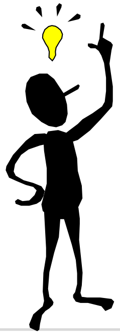
Q: CERN, CMS

CR air showers & jets at hadron colliders ($CERN$)

■ **Common topics:**

- analysis of **jets** & of particle interactions

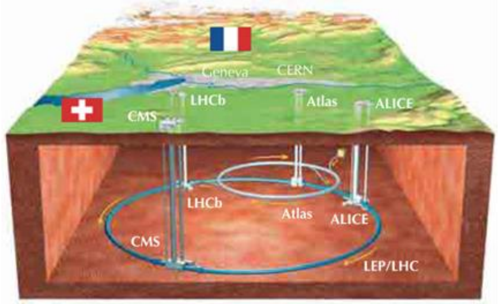
ATP & TP!



shower physics at the LHC

- accelerators:

highest luminosity
well–known
time structure



showers from AGN – accelerators

- AGN – site:

very low luminosity
unknown, irregular
time structure

collider experiment

4π geometry

proton
$7\ TeV$

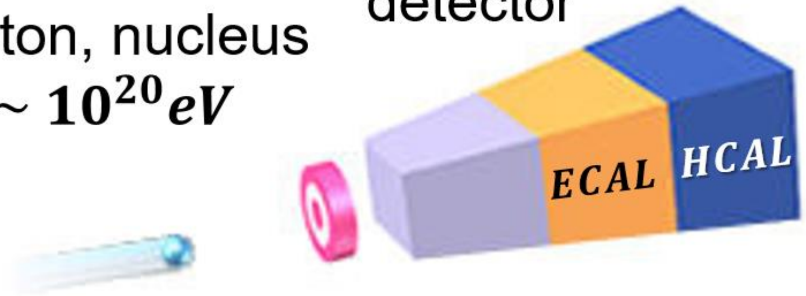
proton
$7\ TeV$

$ECAL$ detector

fixed–target experiment

proton, nucleus
$\sim 10^{20} eV$

detector



target (atmosphere)

Q: CERN, CMS