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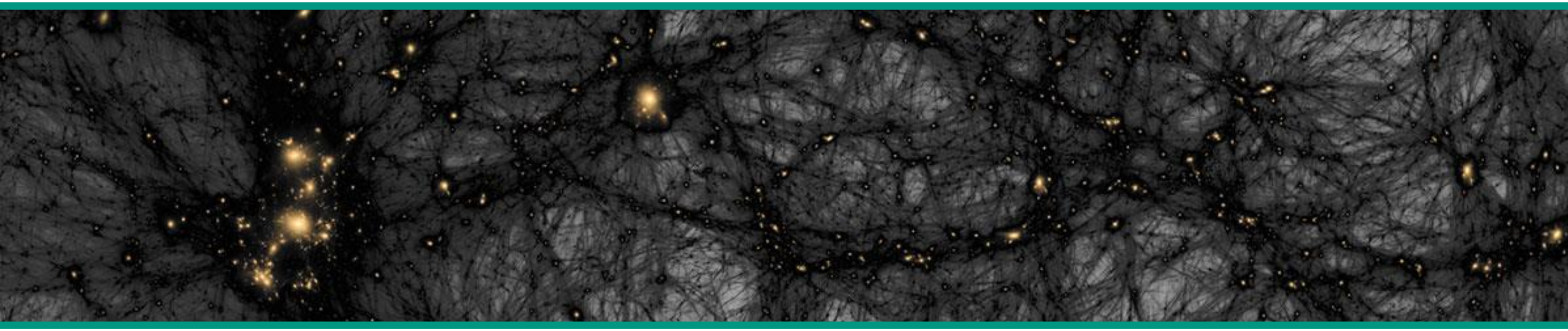
Astroparticle physics I – Dark Matter

WS22/23 Lecture 7 Nov. 23, 2022



Recap of Lecture 6

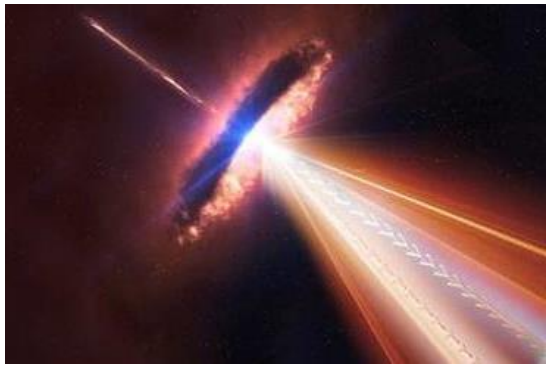
- **UHECRs: modern observations & results at the highest energies**
  - hybrid technology (air fluorescence & $N_e + N_\mu$): CR-observatories PAO & TA
  - measurement of longitudinal distributions via isotropic emission of N_2
  - UHECR-Cutoff at $E \sim 10^{20} eV$: max. energy E_0 (${}^{A}Z$) vs. GZK-Cutoff (p)
- **UHE neutrinos: multi-messengers from afar**
  - ν-telescopes in-ice / deep-sea: PMT-array to detect Cherenkov light
  - CC-reactions of ν_μ at PeV-energies: μ –tracks with range in km – range
  - optical properties of medium (deep-sea water vs. ice) for Cherenkov light

UHE Neutrinos – production mechanisms

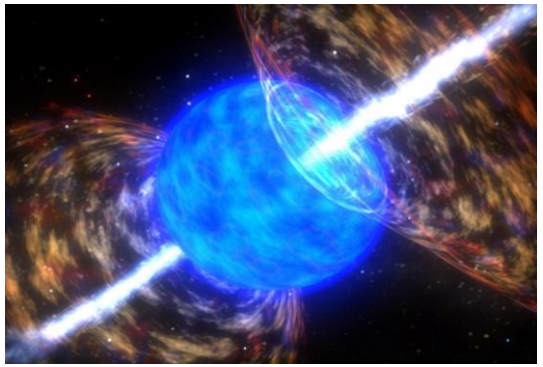
- **expected ν–sources at UHE scales: transient and/or variable accelerators**

  - AGN jets (active galaxies)
  - GRBs (gamma ray bursts)
  - μ-quasars (galactic)

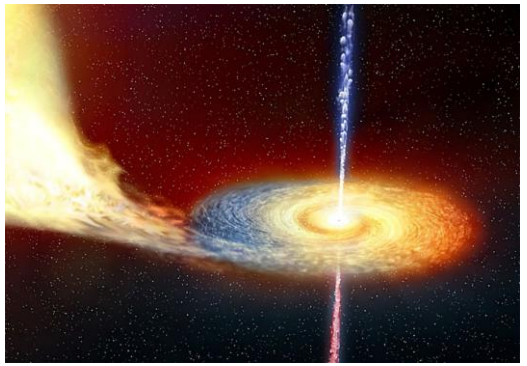
  } Hillas criterium



Active **G**alactic **N**ucleus



Gamma **R**ay **B**urst

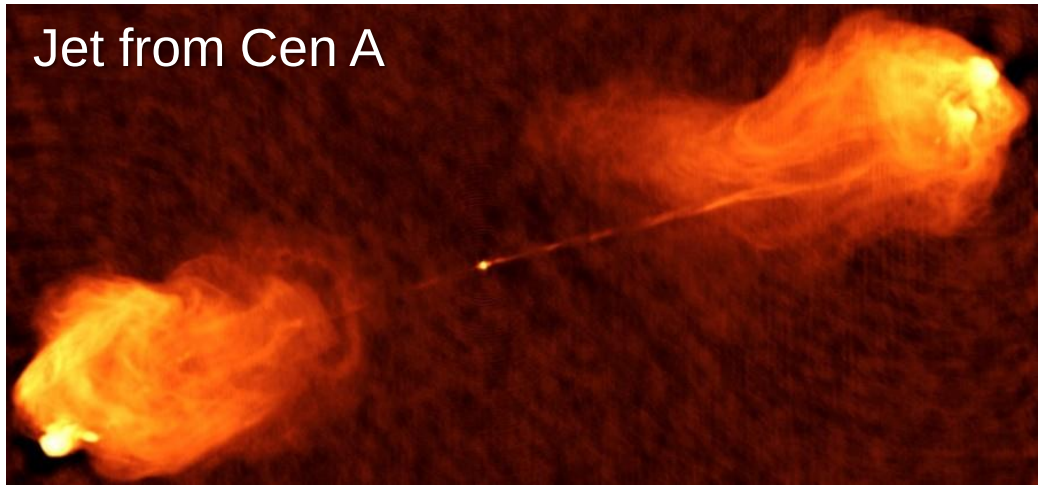


μ-quasar in galaxis

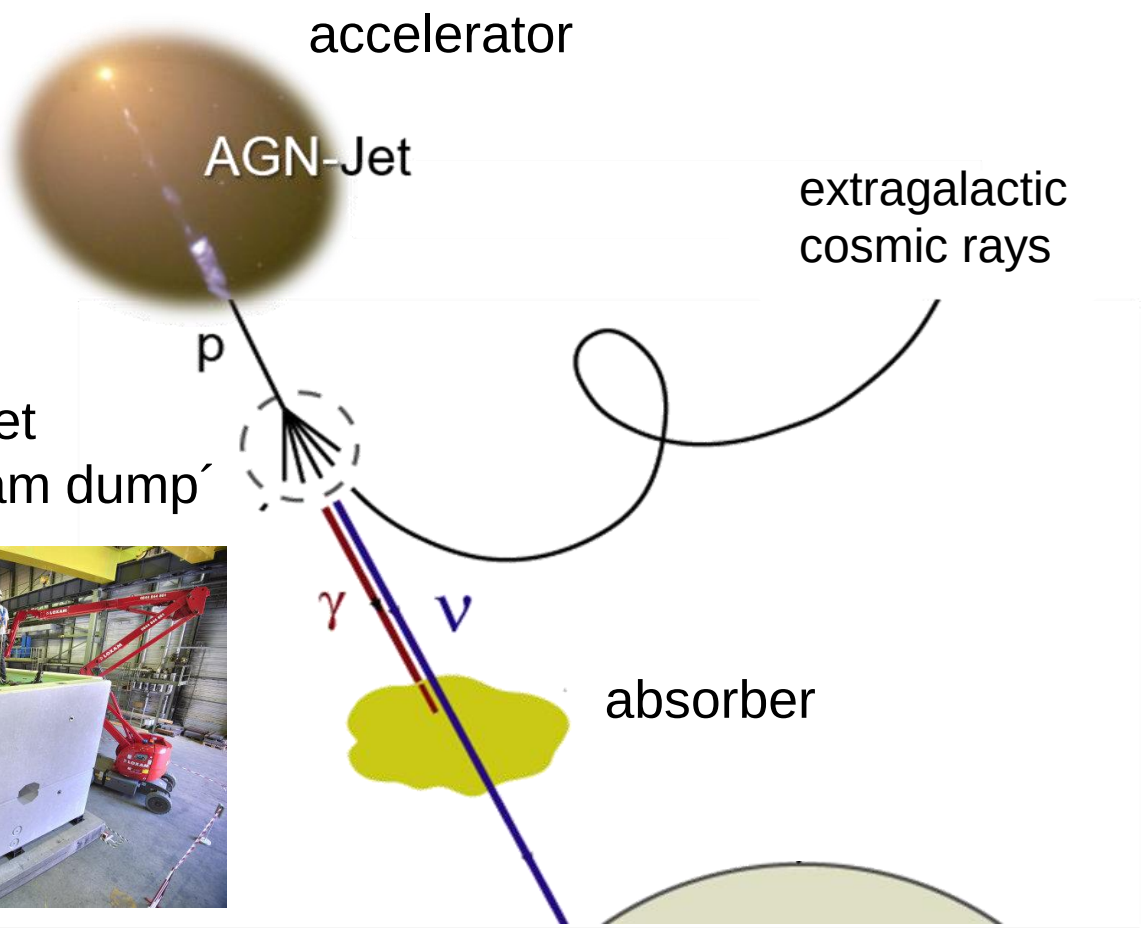
UHE Neutrinos – production at target

- **neutrino production in the ´beam dump´ of a proton accelerator**

  - close analogy to terrestrial proton high-energy accelerators



CERN-SPS



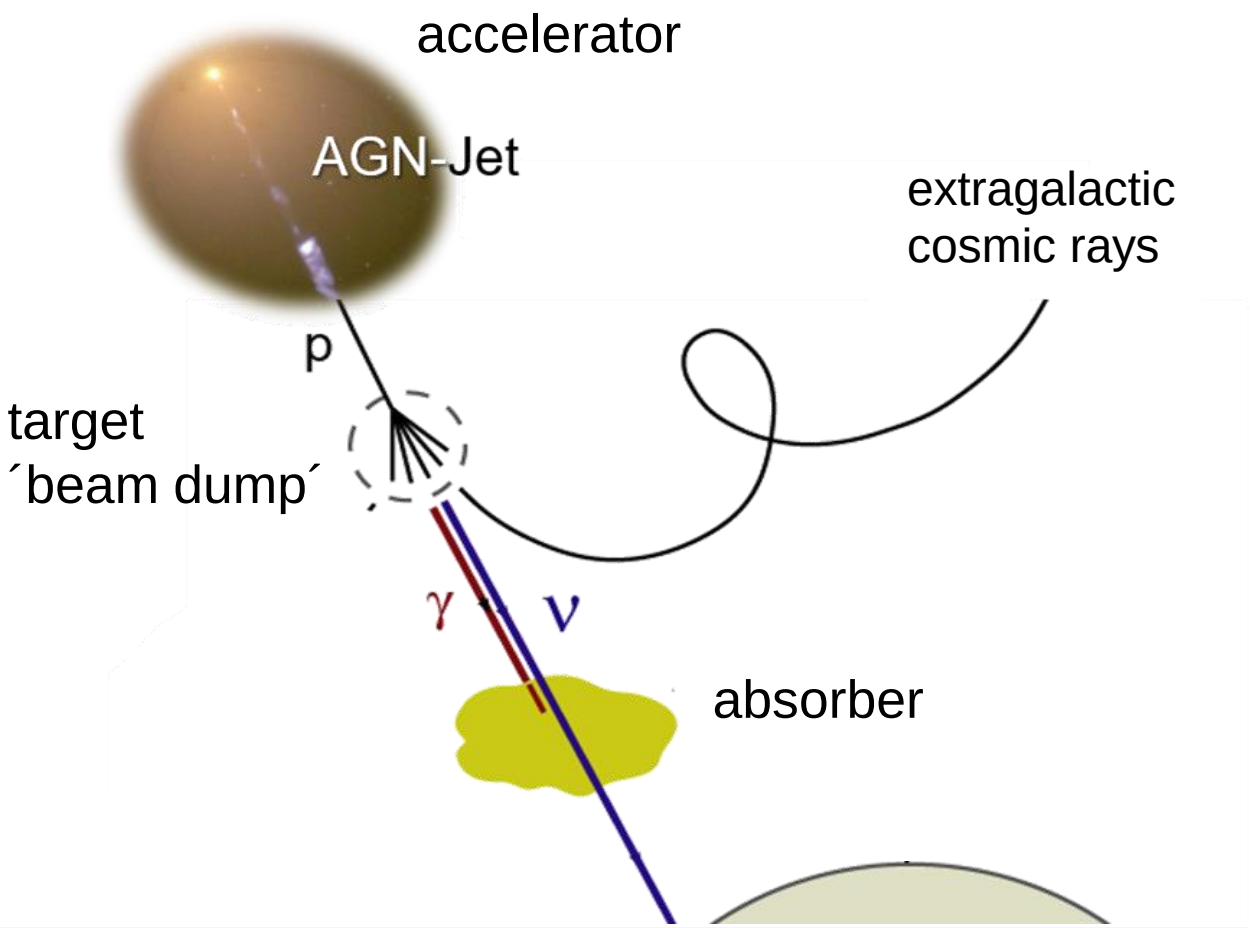
UHE Neutrinos – production at target

- **neutrino production in the ´beam dump´ of a proton accelerator**

  - close analogy to terrestrial proton high-energy accelerators

$$p + p \rightarrow p + p + \pi´s$$

$$\pi^+ \rightarrow \mu^+ + \nu_\mu$$
$$\downarrow$$
$$e^+ + \nu_e + \bar{\nu}_\mu$$



  - flavour composition at source:

$$\nu_e : \nu_\mu : \nu_\tau = 1 : 2 : 0$$

UHE Neutrinos – production at target

- **neutrino production in the ´beam dump´ of a proton accelerator**

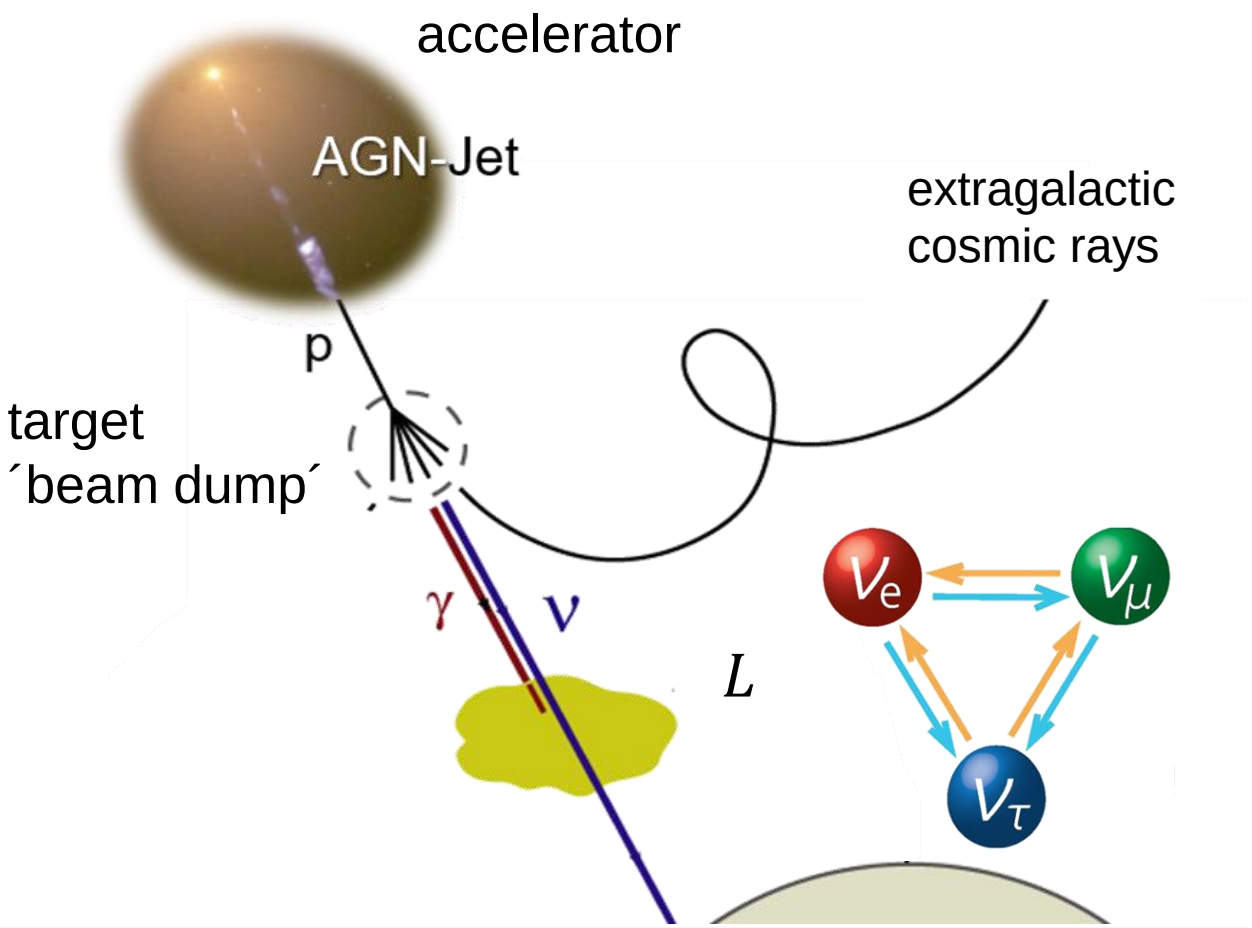
  - propagation effects of neutrinos: extremely long baseline L

  - initially, ν-oscillations $\nu_i \rightarrow \nu_j$ take place

  - due to huge L: decoherence of neutrino wave packets, thus no further flavour oscillations

  - flavour composition at earth:

$$\nu_e : \nu_\mu : \nu_\tau = 1 : 1 : 1$$



Connecting ATP with TP: neutrino beams

- **Neutrino generation allows to investigate flavour oscillations**

protons from SPS

target (beam dump)

p

magnet. horns (focussing)

decay tunnel

absorber

absorber

instrumentation

ν

detector

oscillations

ν_e

accelerator

AGN-Jet

extragalactic cosmic rays

p

target

ν

L

ν_e ν_μ ν_τ

UHE neutrinos – detection reactions of ν_e, ν_μ, ν_τ

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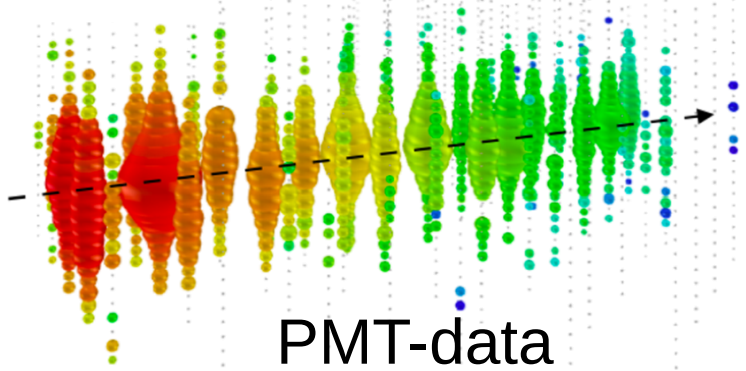
muon neutrino ν_μ

- straight muon track
- energy-dependent R_μ

CC reaction

early late

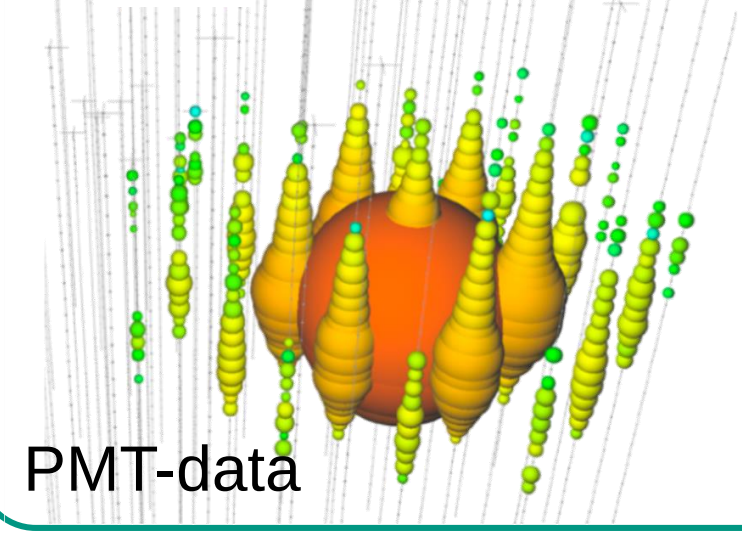


PMT-data

electron neutrino ν_e

- electromagnetic shower
- spherical deposition of E

NC reaction

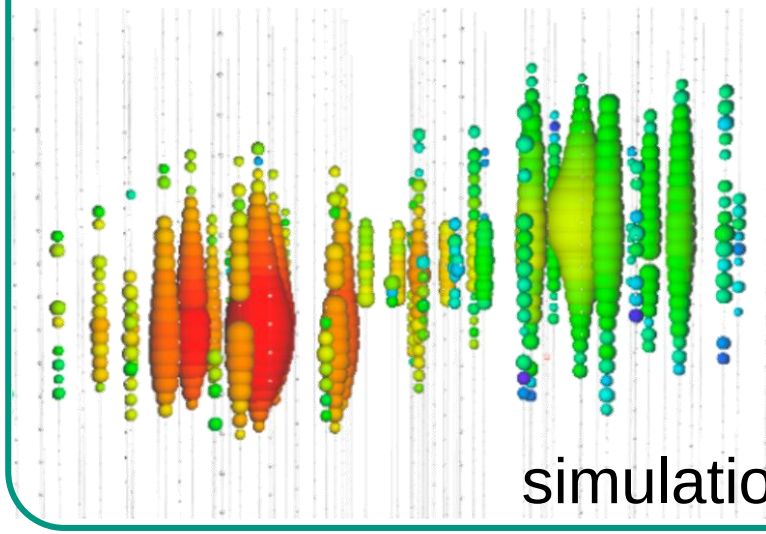


PMT-data

tau neutrino ν_τ

- „double bang“ signal from fast τ-decay

τ-decay after **CC** reaction



simulation

UHE Neutrinos – measured flavour composition

- **neutrino production: test of our models of production & oscillation**

  - propagation effects of neutrinos:
    epected *flavour ratio of the source*

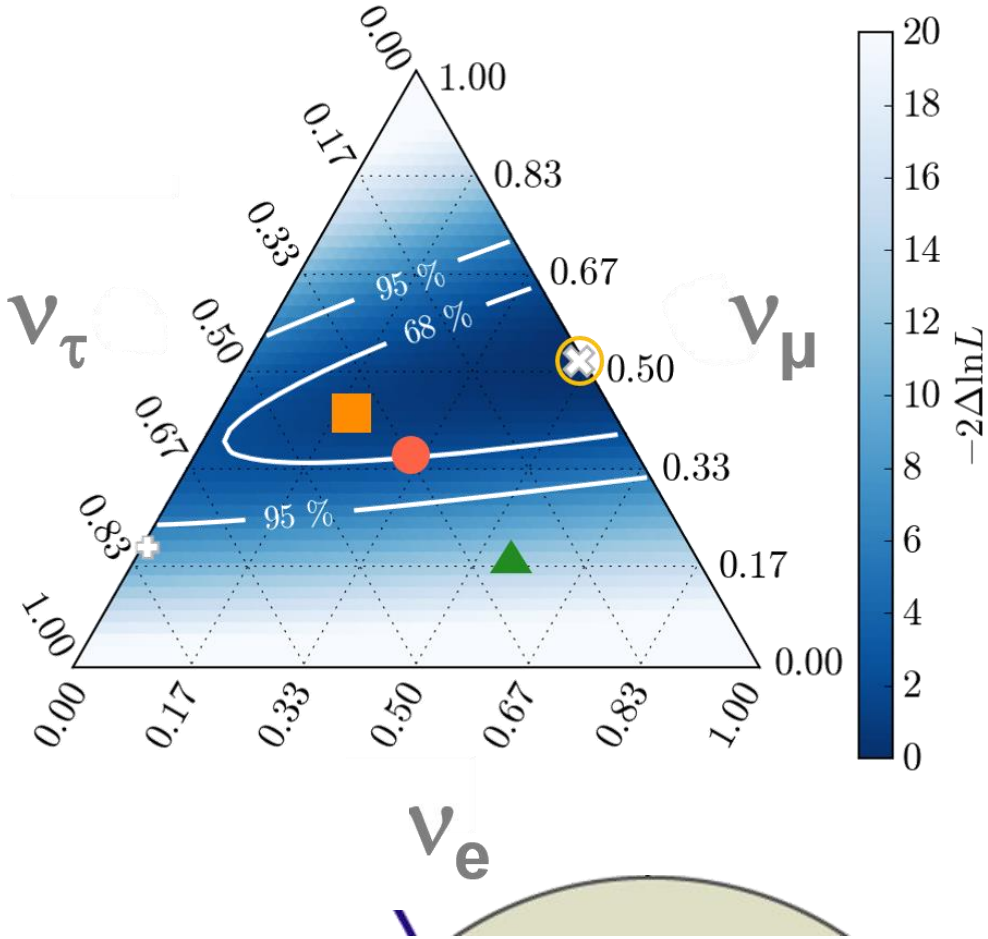
$$\nu_e : \nu_\mu : \nu_\tau = 1 : 2 : 0$$ ●

$$\nu_e : \nu_\mu : \nu_\tau = 0 : 1 : 0$$ ■

$$\nu_e : \nu_\mu : \nu_\tau = 1 : 0 : 0$$ ▲

  - experimental data ⊗

    ⇨ compatible with decay chain ●
    $\pi \to \mu \to e$, but not with n – decay (▲)



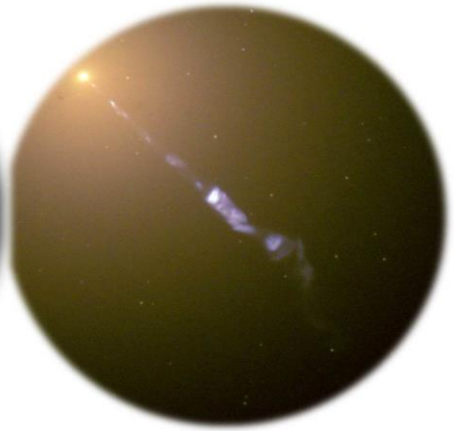
UHE neutrinos – signal of ν_{astro} & background

- **Atmospheric neutrinos as a major background for astrophysical ν-sources**

  - we need to discriminate ν_{atm} (isotropic) from ν_{astro}: go to highest $E_\nu > 10^{14} eV$

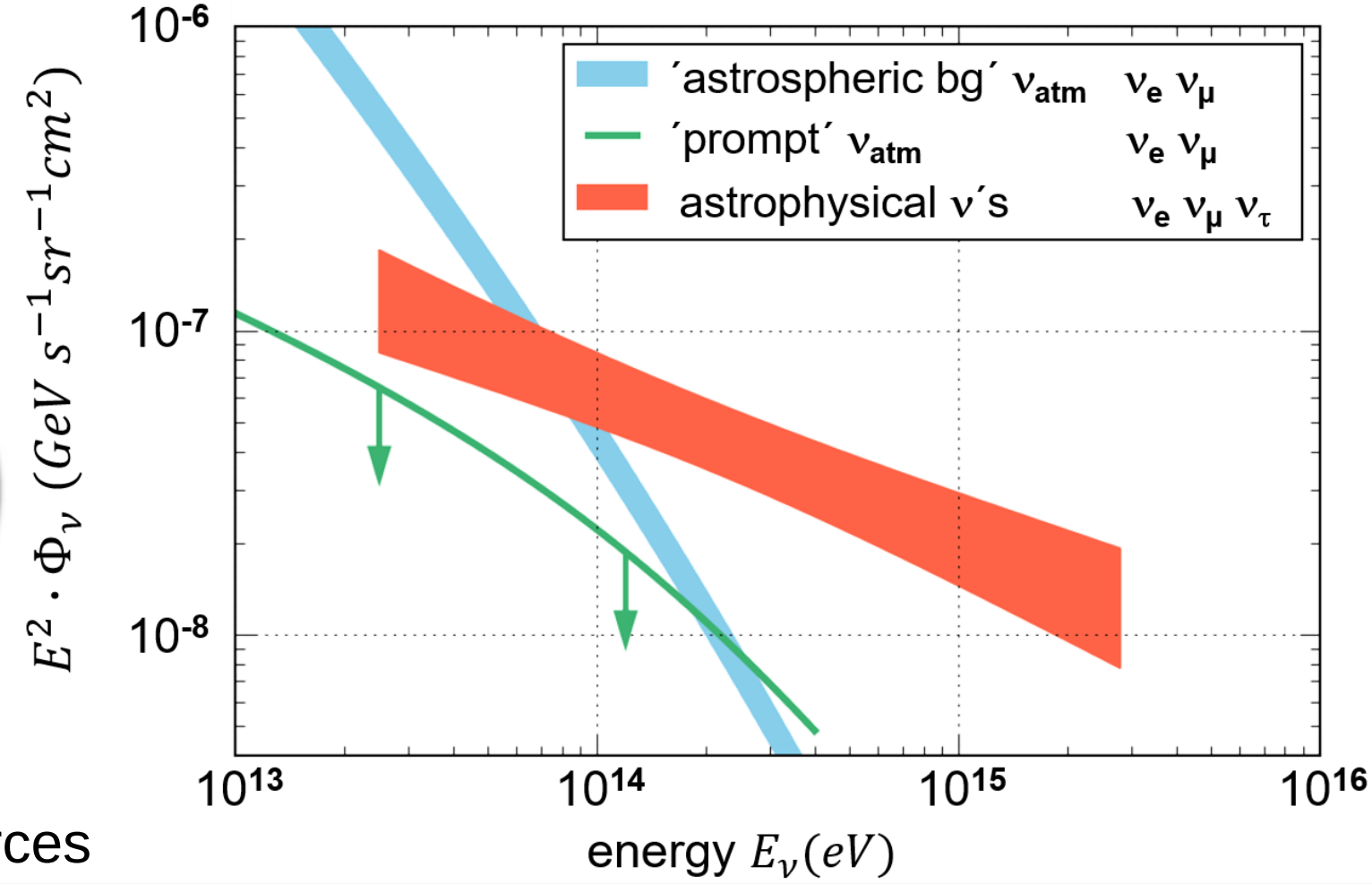
ν_{atm}

from 4π



ν_{astro}

very few ν-sources

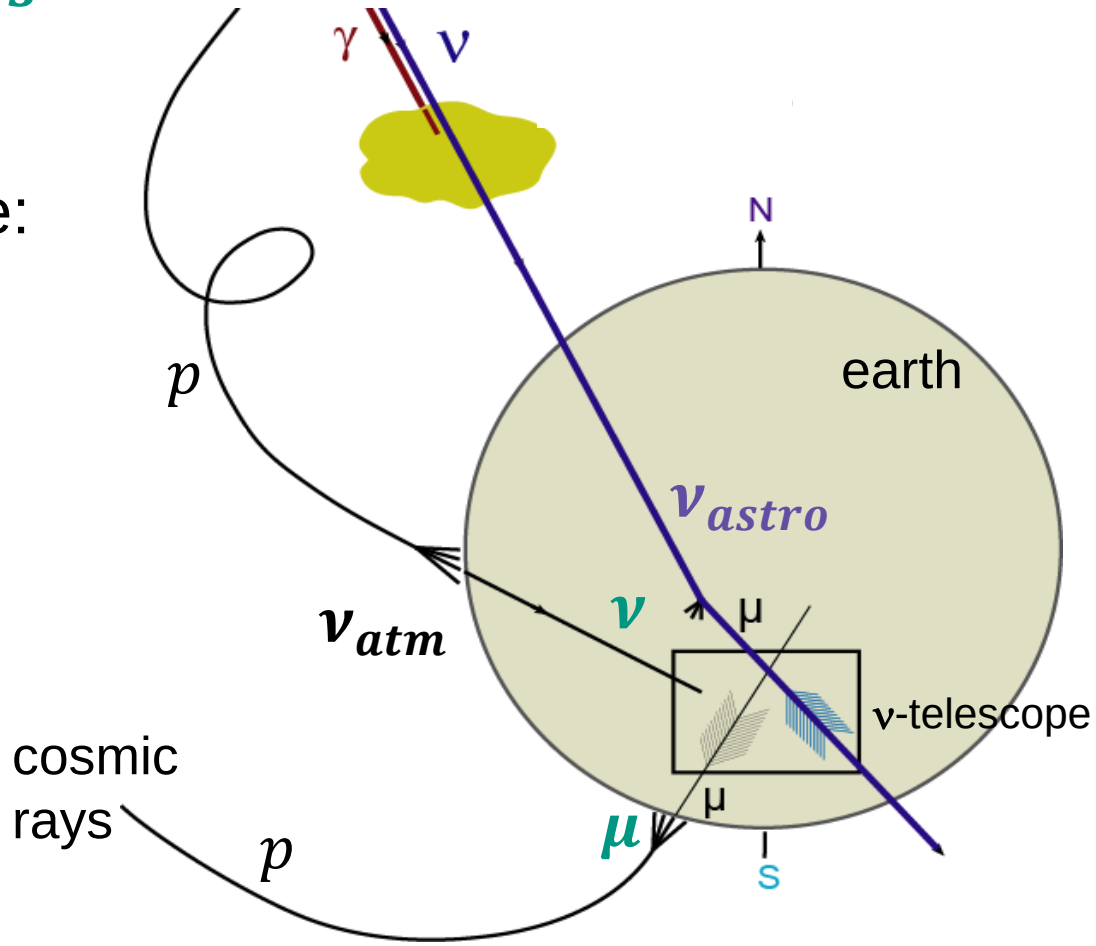


Background sources for astrophysical neutrinos

- **atmospheric muons $\mu's$ & atmospheric $\nu's$**

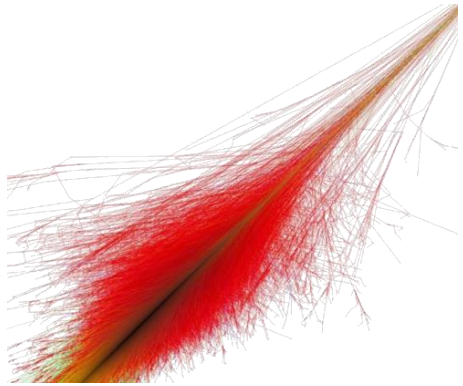
  - **atmospheric neutrinos**:
    generated by CR – p in upper atmosphere:
    neutrinos can travel through Earth
    ⇨ isotropic arrival directions

  - **muons from air showers**
    high-energy muons from the atmosphere have km –scale range in ice & can cross a deep in-ice/under-water ν-telescope
    ⇨ only from ´upper´ hemisphere



Background sources for astrophysical neutrinos

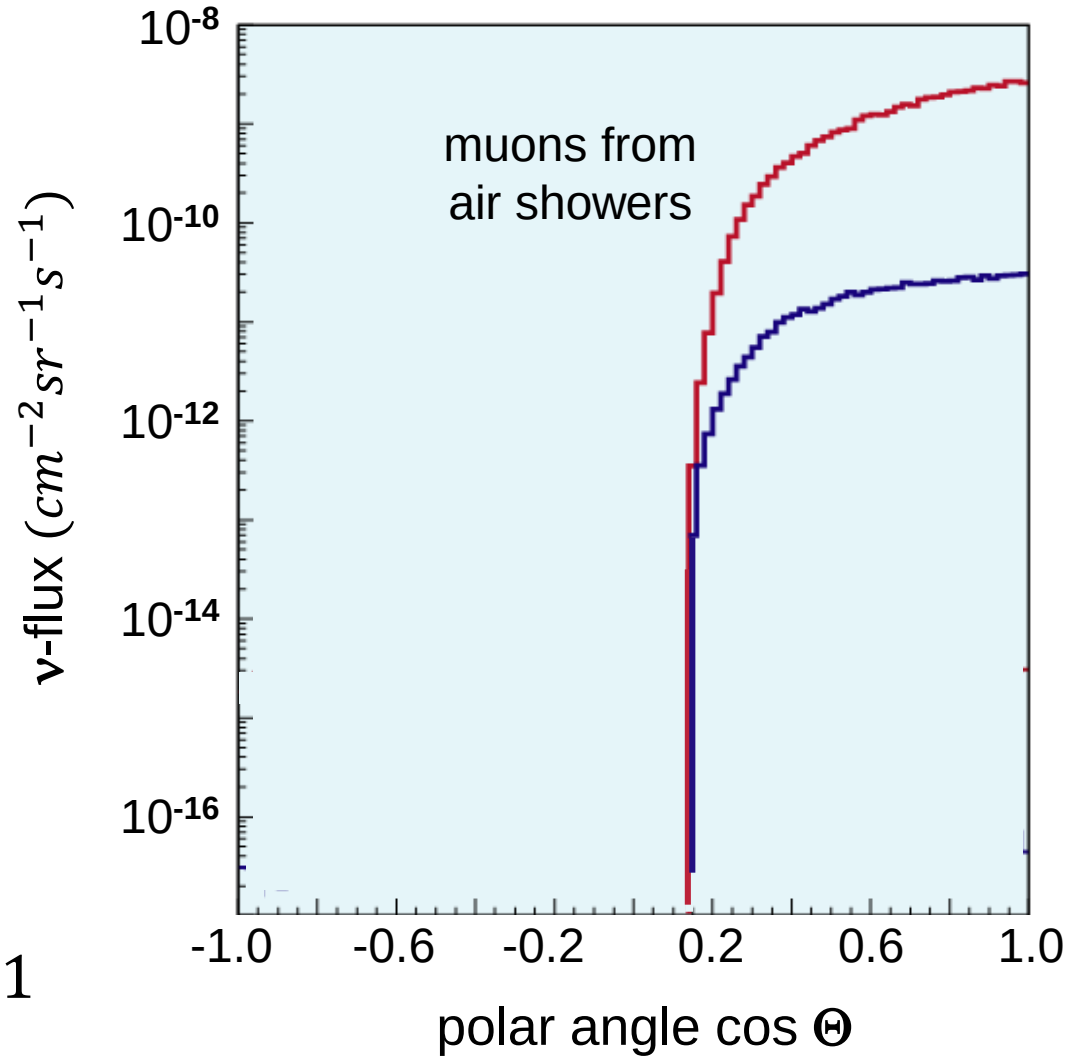
- **Background as function of Θ**



- **muons from air showers**

  high-energy muons from the atmosphere have km –scale range in ice & can cross a deep in-ice/under-water ν-telescope

  ⇨ only from ´upper´ hemisphere $\cos\Theta > 0.1$



Background sources for astrophysical neutrinos

- **Background as function of Θ**

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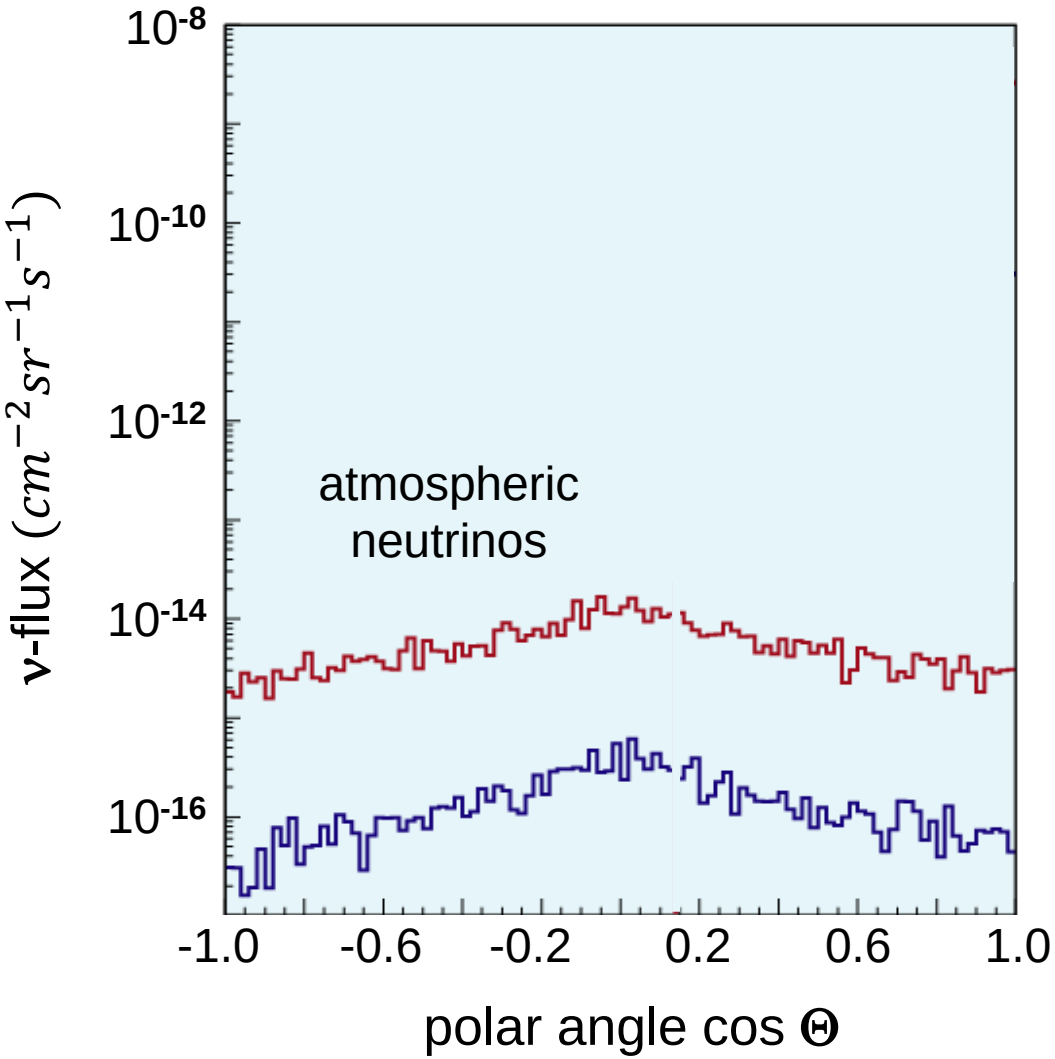
cos Θ :
−1 (from bottom) …
+1 (from top)



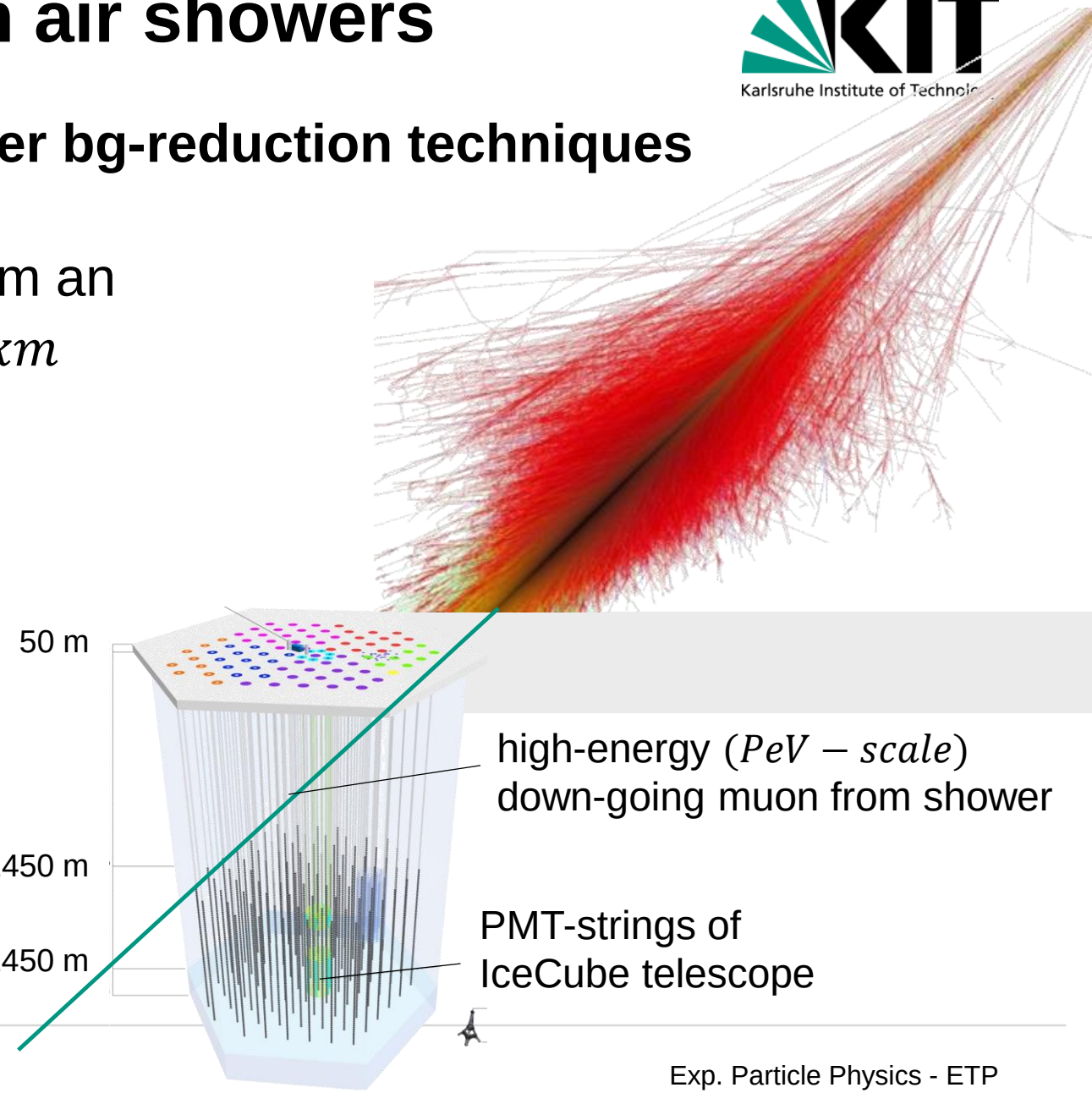
UHE neutrinos – muons from air showers

- **Instrumenting the ice surface & other bg-reduction techniques**

  - muons with the highest energies from an air shower have a range of several km in ice or water

  - μ with large **range** in ice/water
    1 PeV: R_μ = 1.7 km
    10 PeV: R_μ = 7 km

  - discrimination:
    polar angle Θ
    surface-detector-veto

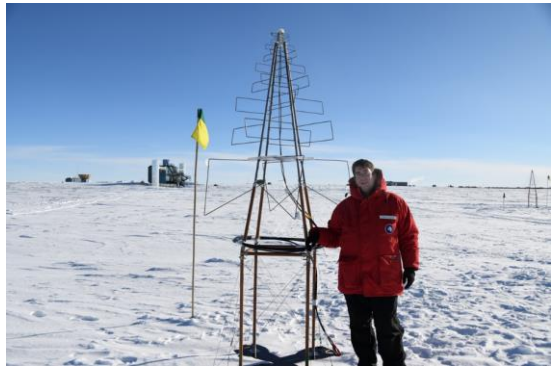


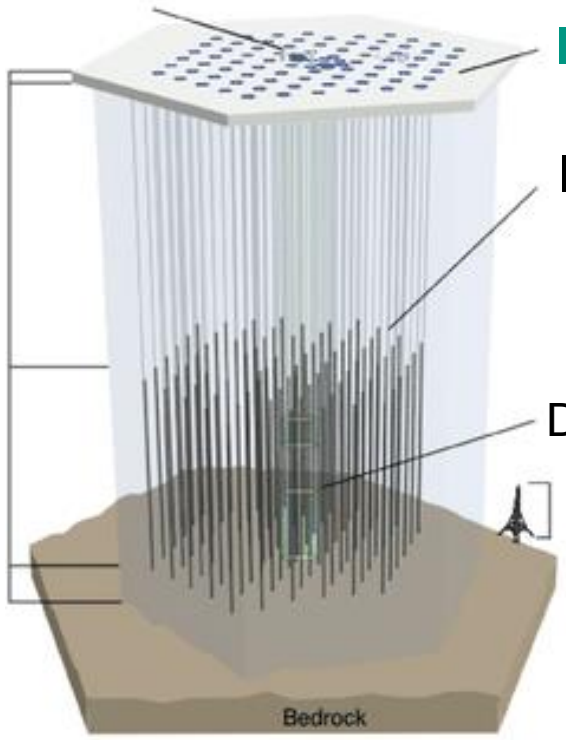
UHE neutrinos – muons from air showers

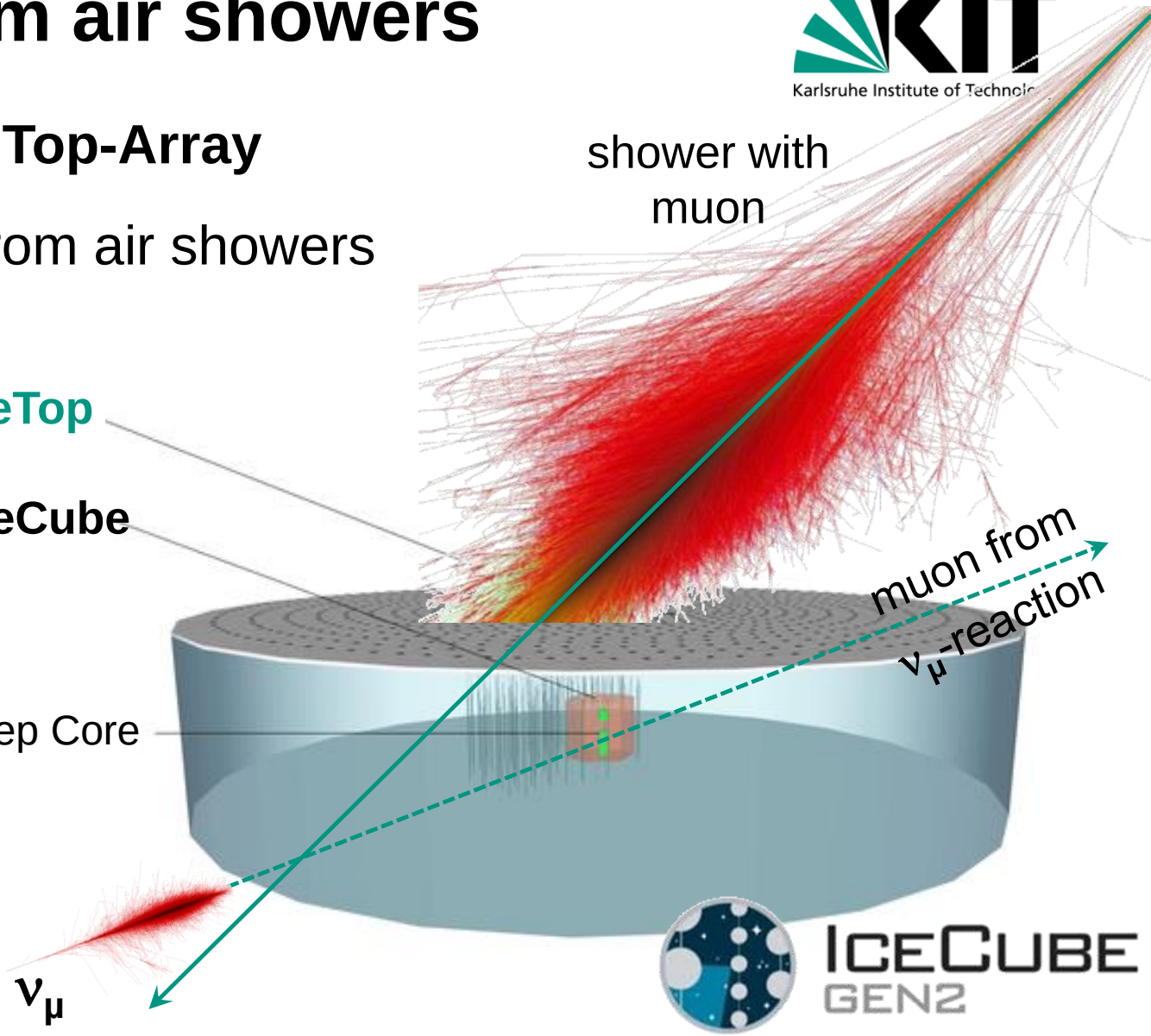
- **Instrumenting the ice surface: Ice Top-Array**

  - IceTop array can veto PeV-muons from air showers

study/veto of showers



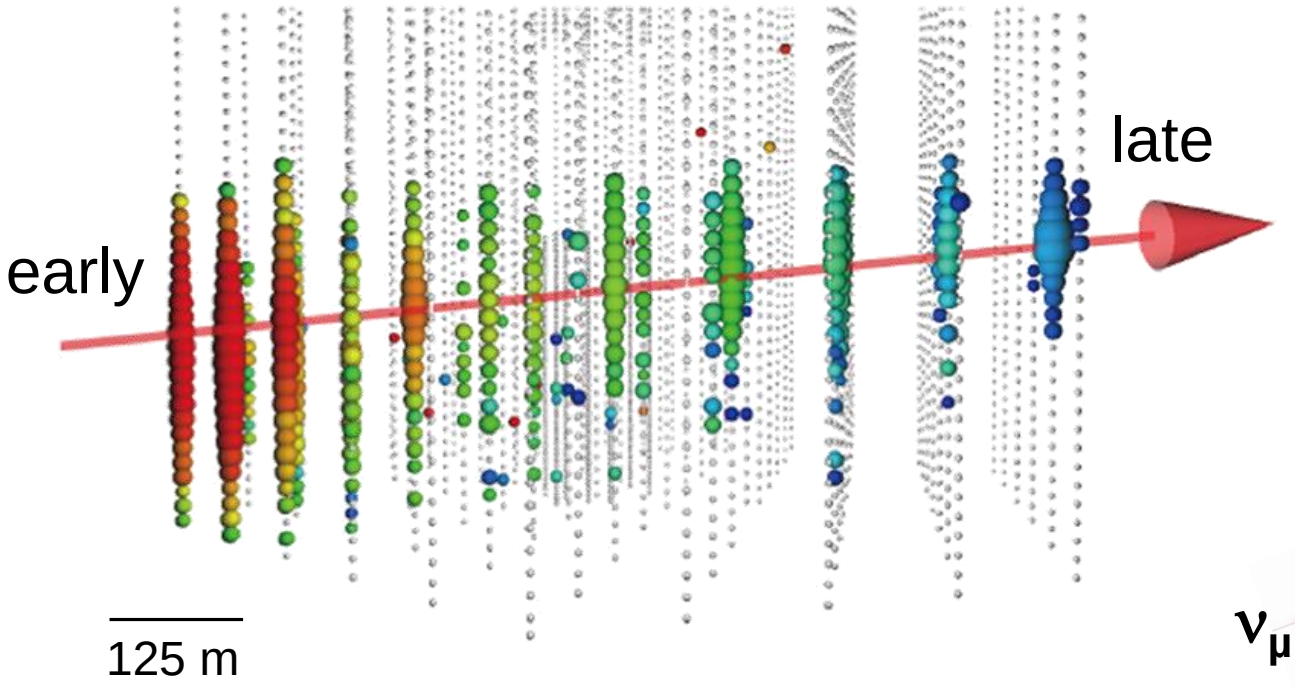


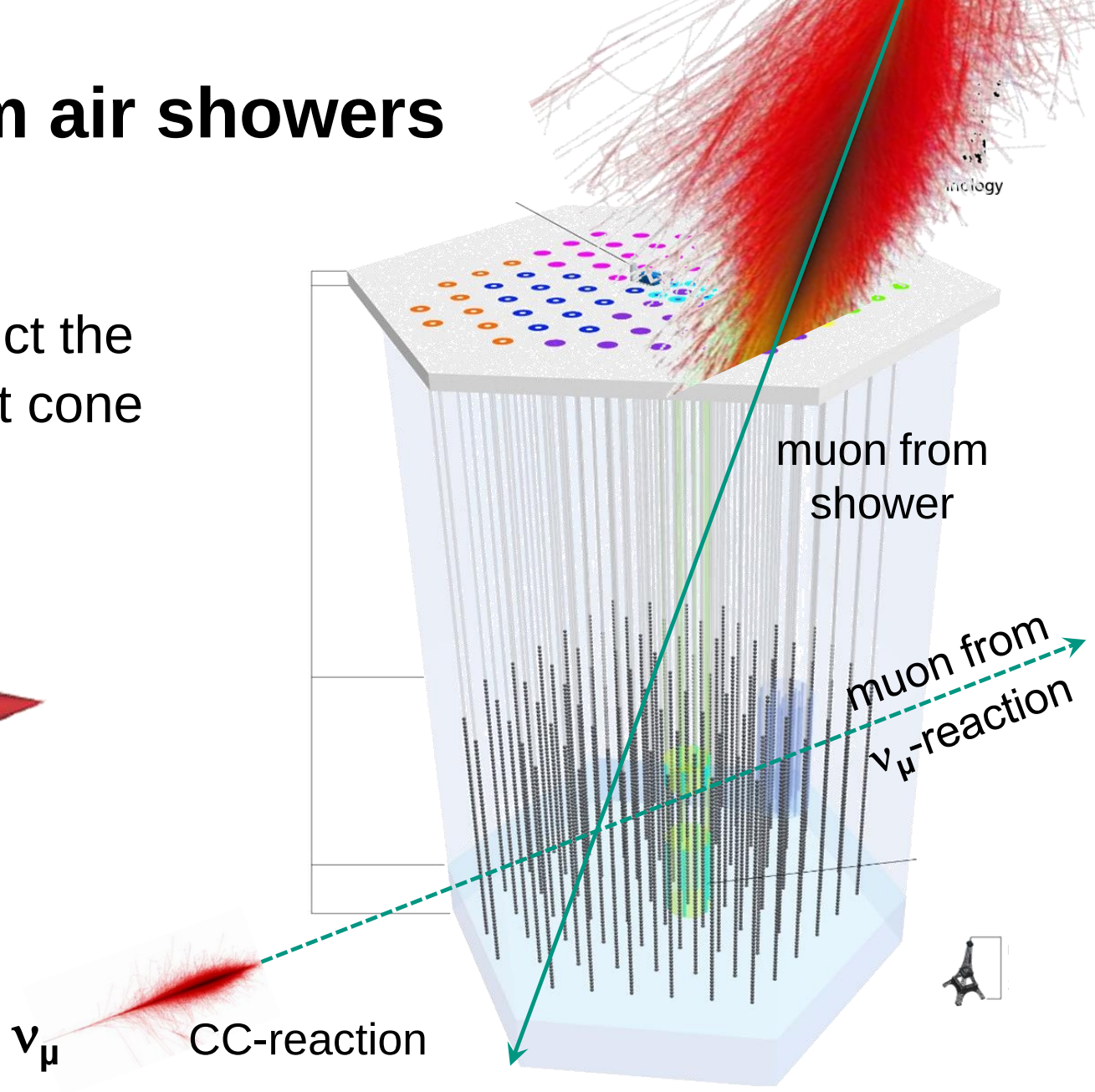


UHE neutrinos – muons from air showers

- **Discrimination via polar angle**

  - timing of PMTs allows to reconstruct the muon track via the Cherenkov light cone





Background sources for astrophysical neutrinos

- **Background as function of Θ**

  - **atmospheric neutrinos**:
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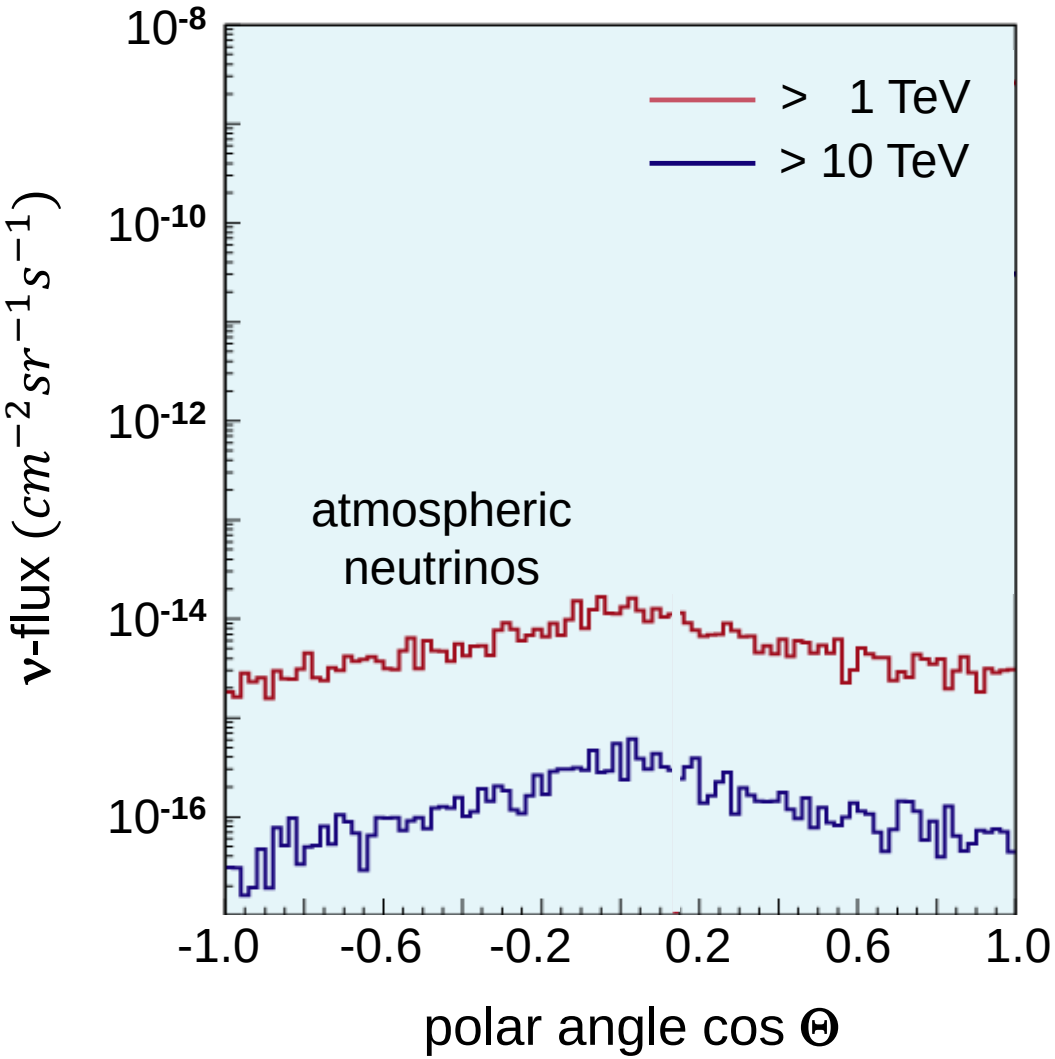
  - energies: typical on GeV –scale
    dominant up to $\sim 10^{14} eV$ $(0.1\ PeV)$

    Φ_{max} at $E_\nu = 0.25\ GeV$
    at higher energies: $\Phi_\nu \sim E^{-2.7}$

    $\Phi_\nu \sim 1\ cm^{-2} s^{-1}$ at sea level



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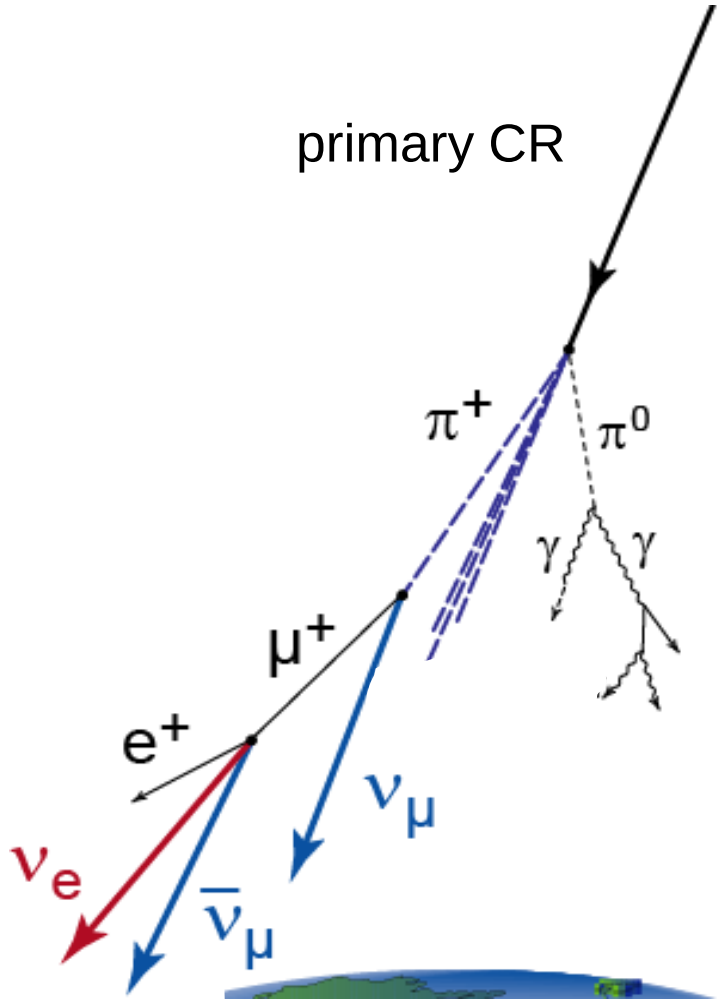


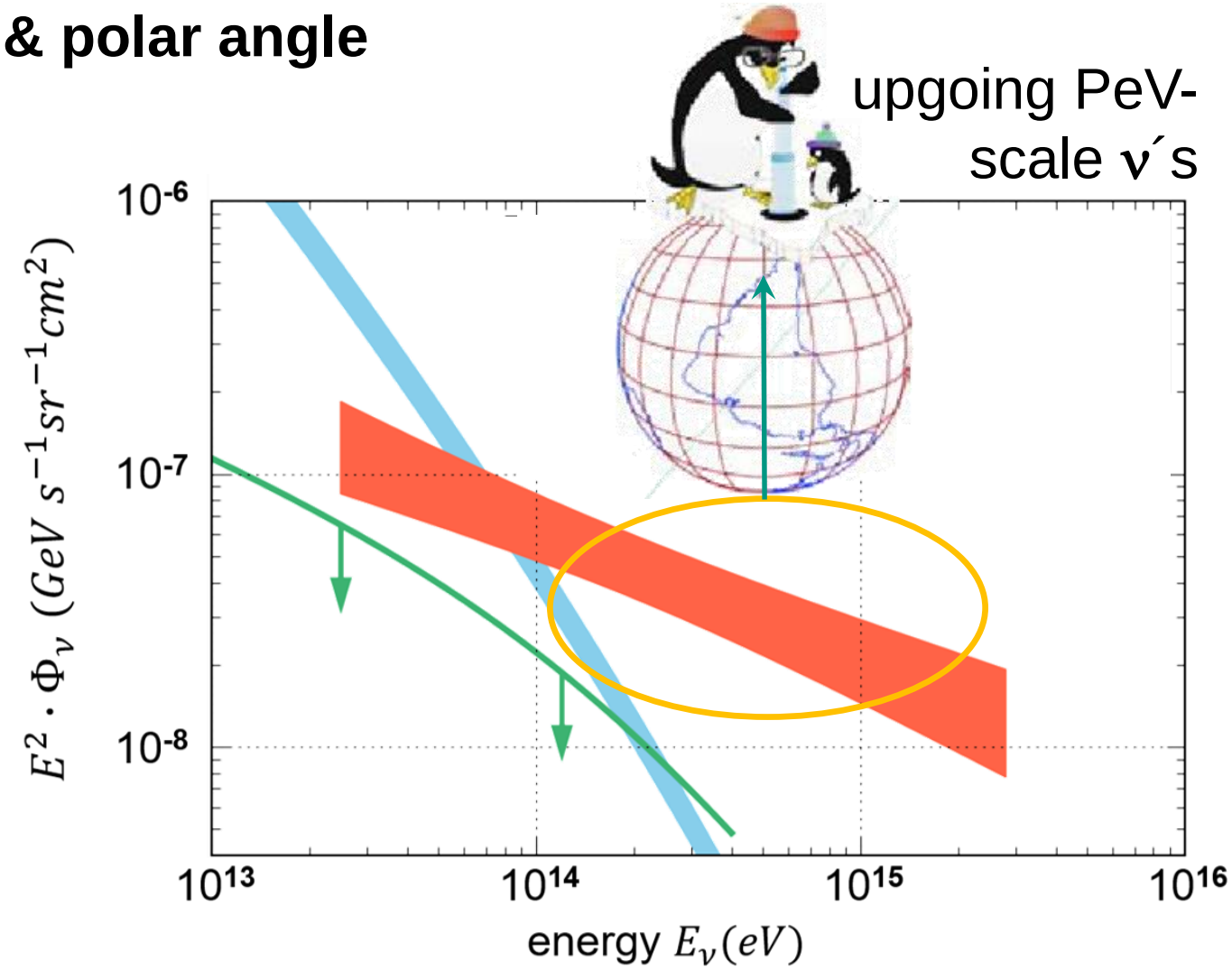
UHE neutrinos from astrophysical sources

- **Discrimination via event energy & polar angle**

  - astrophysical neutrinos dominate event rate at energies $> 10^{14} eV$

  - up-going neutrinos on the PeV-scale have to cross & propagate through the Earth. Is this possible?

  - cross-section of UHE-ν´s in rock/iron-core?



UHE neutrinos – transmission through the Earth?

- **Deep-inelastic scattering processes of UHE-ν´s inside the Earth**

  - ν-cross section increases linearly $\boldsymbol{\sigma_\nu \sim E_\nu}$

    $E_\nu = 100\,TeV \Rightarrow \sigma_\nu = 10^{-7} mbarn$

    ⇨ at $E_\nu \sim 100\,TeV\ (0.1\,PeV)$:

    Earth starts to be opaque for UHE-ν´s

  - transmission probabilities $P(E_\nu)$ for UHE ν´s after travel distance d:

$$P(E_\nu) = e^{-(d/\lambda_\nu)}$$

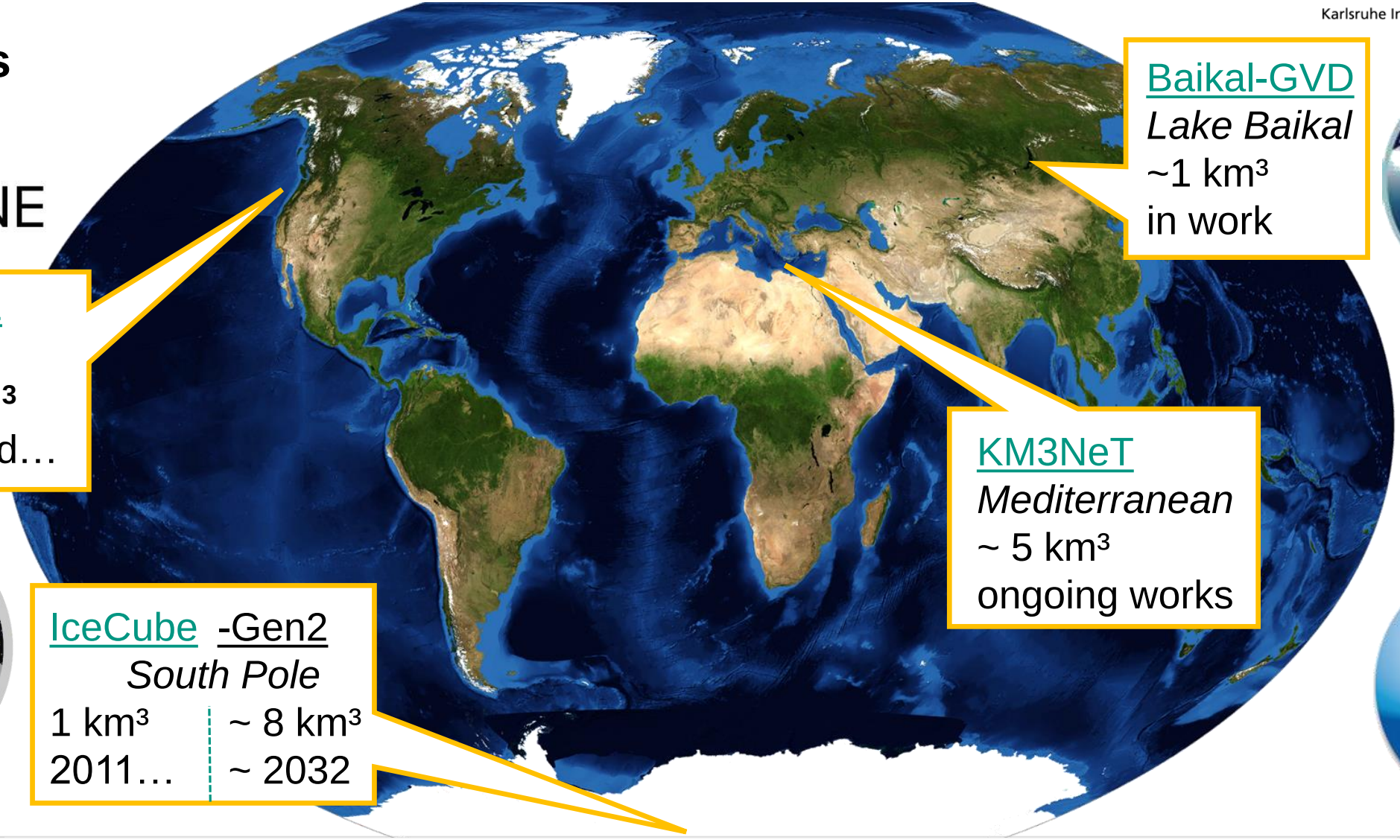
mean free path λ_ν :

$$(1/\lambda_\nu) = \rho_{Earth} \cdot N_A \cdot \sigma_\nu(E_\nu)$$

N_A = Avogadro constant

Existing & planned ν-telescopes: world overview

- **Status**



Baikal-GVD
Lake Baikal
~1 km³
in work

P-ONE
Pacific
few km³
planned…

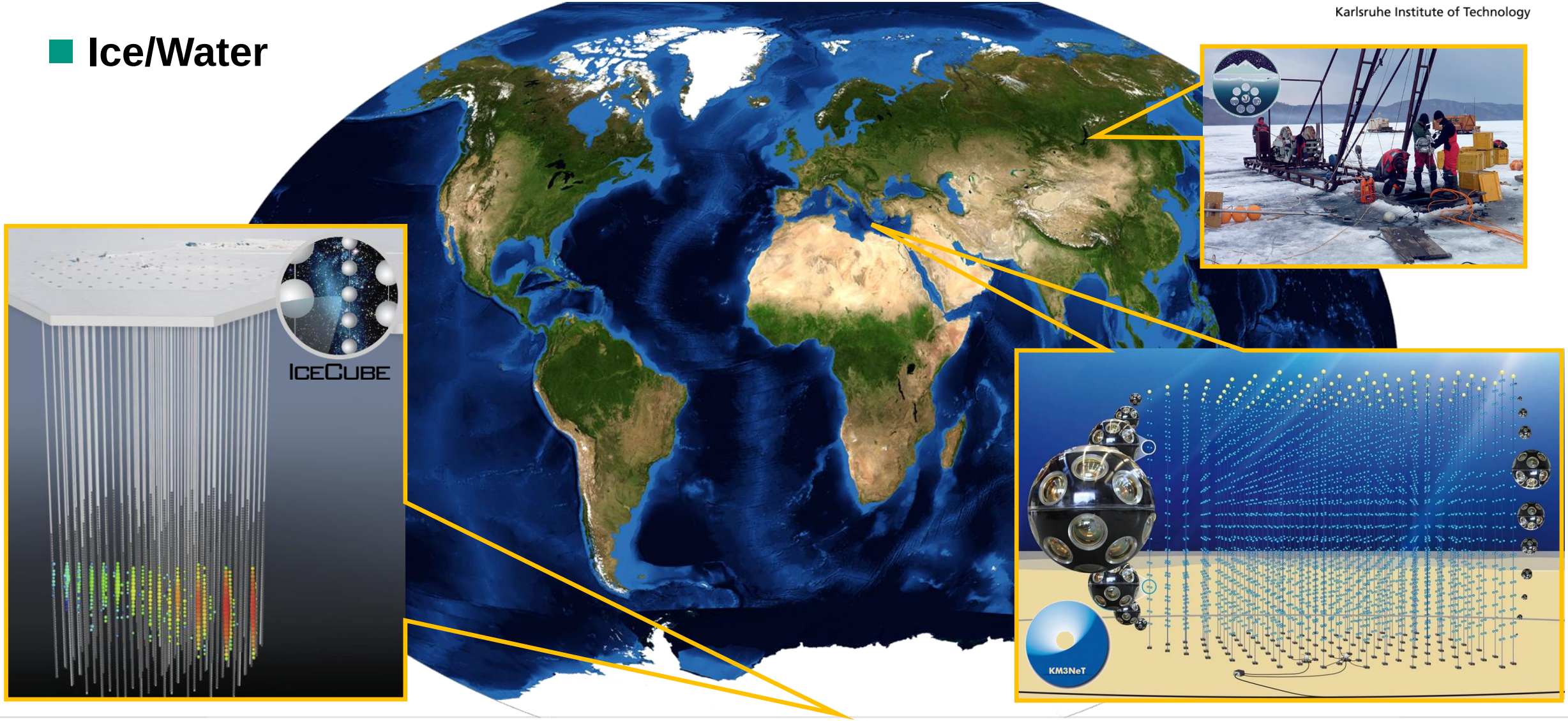
KM3NeT
Mediterranean
~ 5 km³
ongoing works

IceCube -Gen2
South Pole

1 km³	~ 8 km³
2011…	~ 2032

Existing & planned ν-telescopes: world overview

- **Ice/Water**

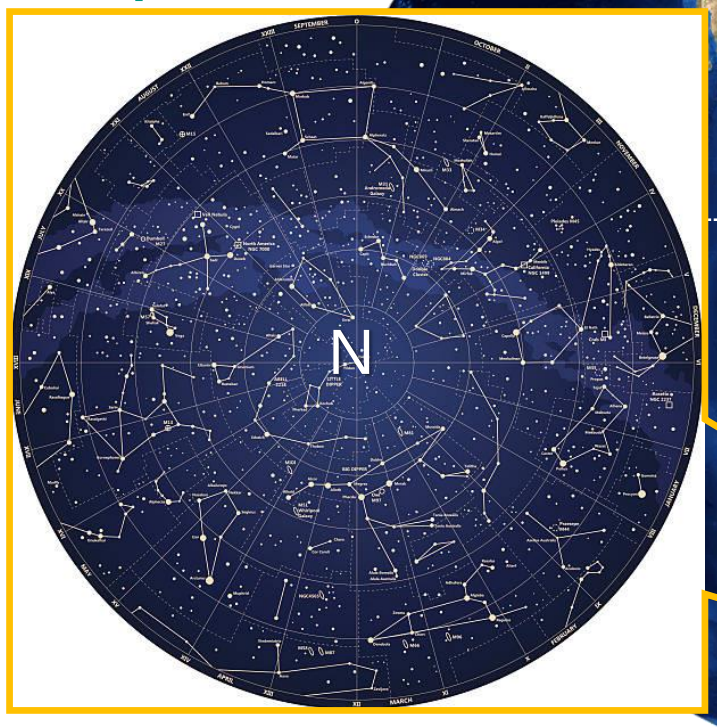


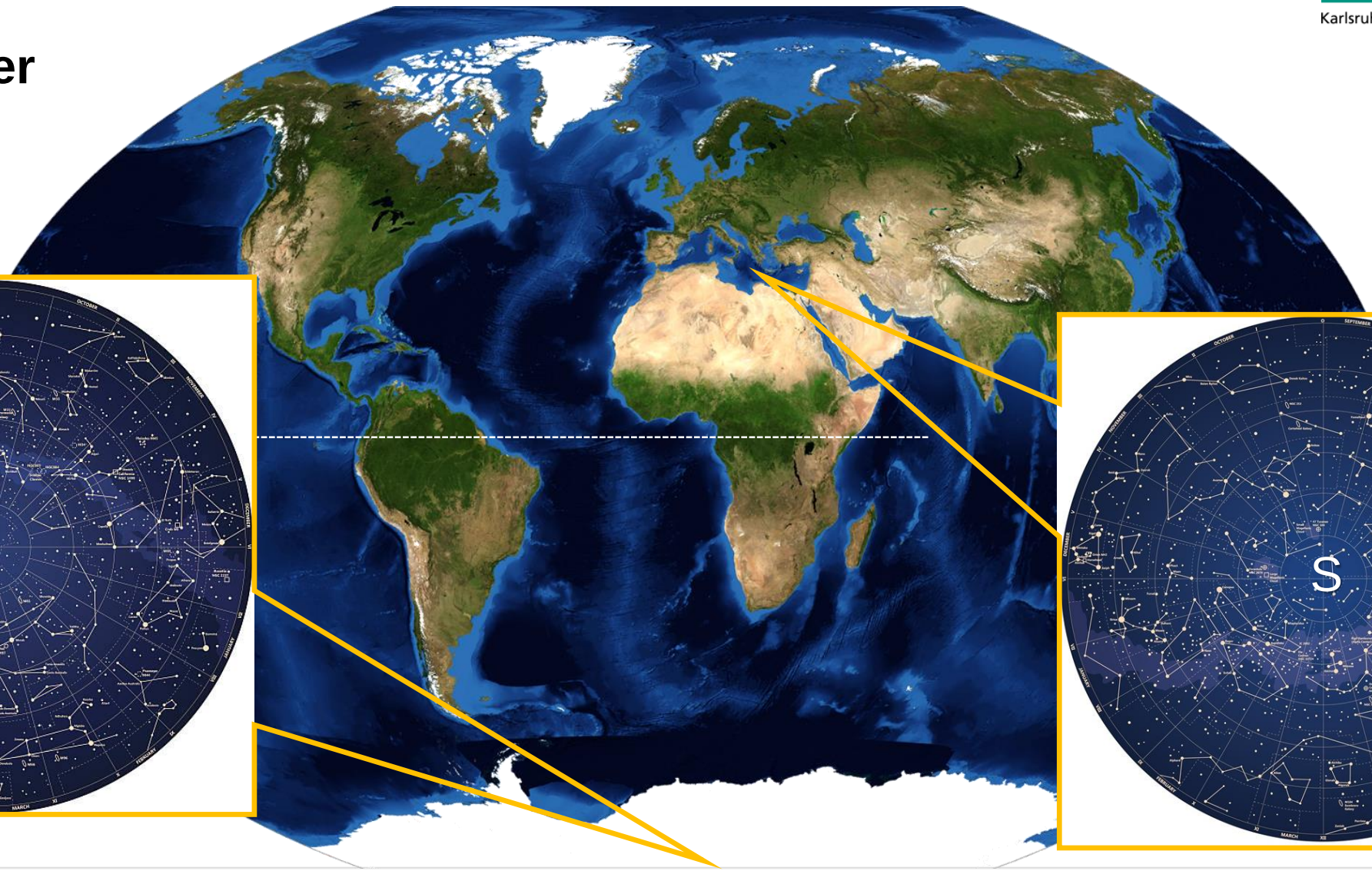
Existing & planned ν-telescopes: sky overview

- **Ice/Water**

observation of **northern hemisphäre**

observation of **southern hemisphäre**





Neutrino Telescopes – KM3NeT

- **Detecting astrophysical & atmospheric ν´s at different sites in the Mediterranean Sea: a European project**

  - European consortium for a $V \sim 5\ km^3$ deep-sea ν-observatory

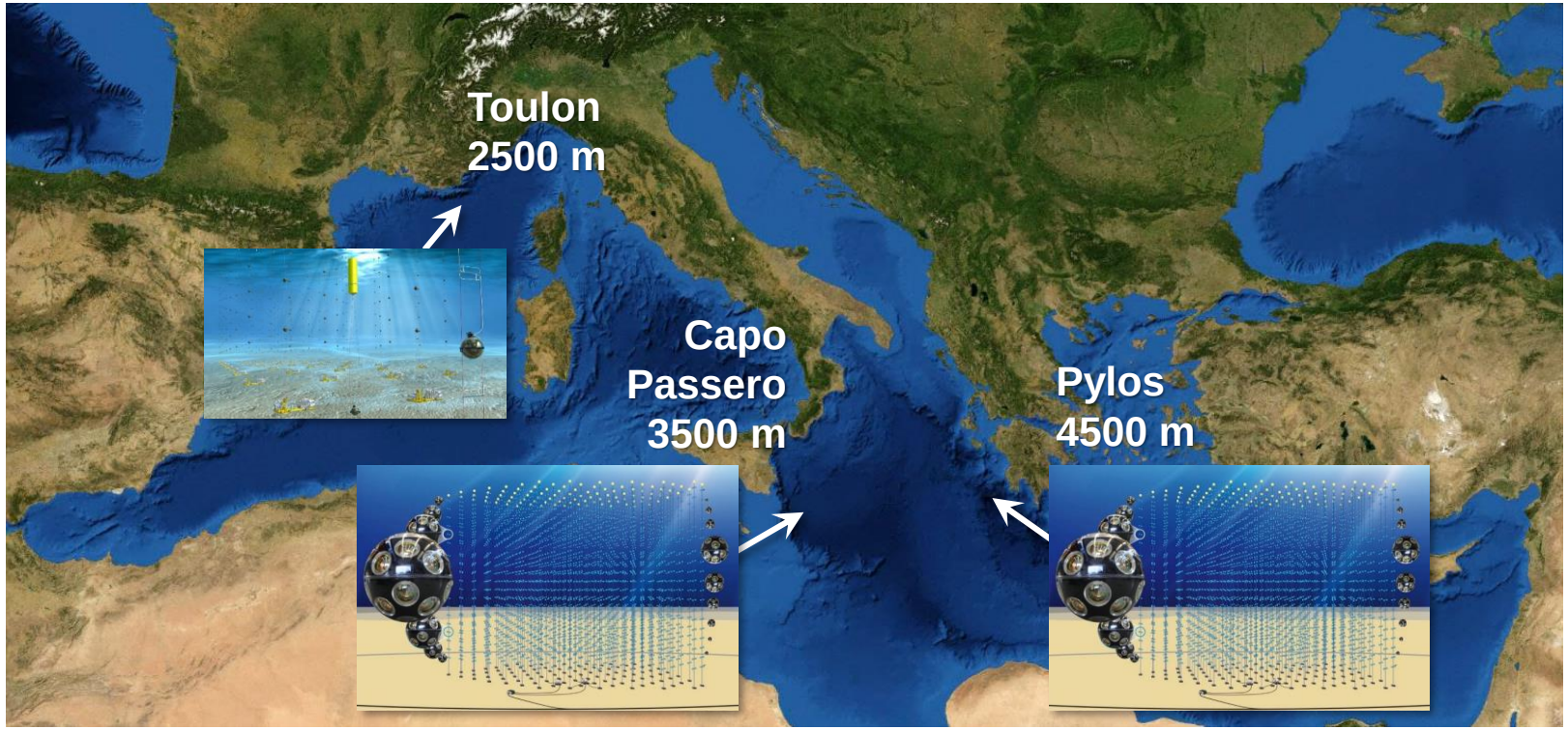
  ~ 200 M€ cost estimate

  - ongoing construction works since 2012(!)

  - three deep-sea sites:

KM3NeT

-Fr -It -Gr



Neutrino Telescopes – KM3NeT

- **Detecting astrophysical & atmospheric ν´s at different sites in the Mediterranean Sea: a European project**
  - KM3NeT is the successor to Antares, Nemo & Nestor
  - R&D works on many new technologies: PMTs, deployment,…
  - three deep-sea sites:

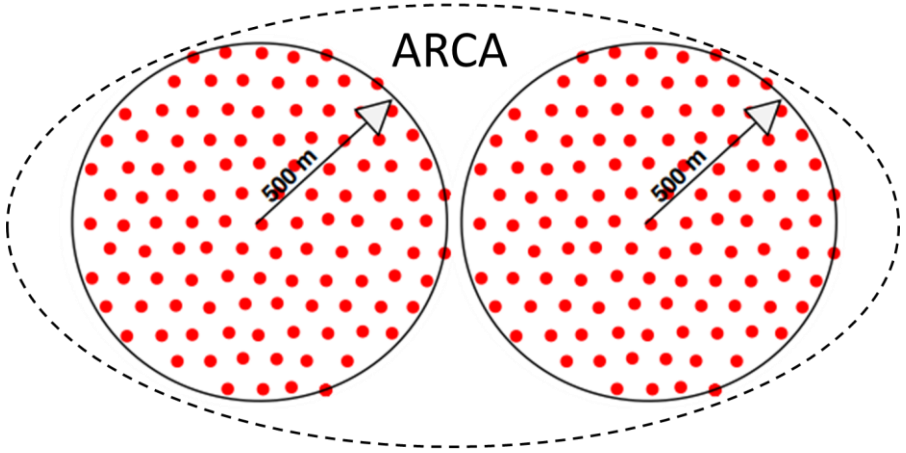
KM3NeT

-Fr -It -Gr

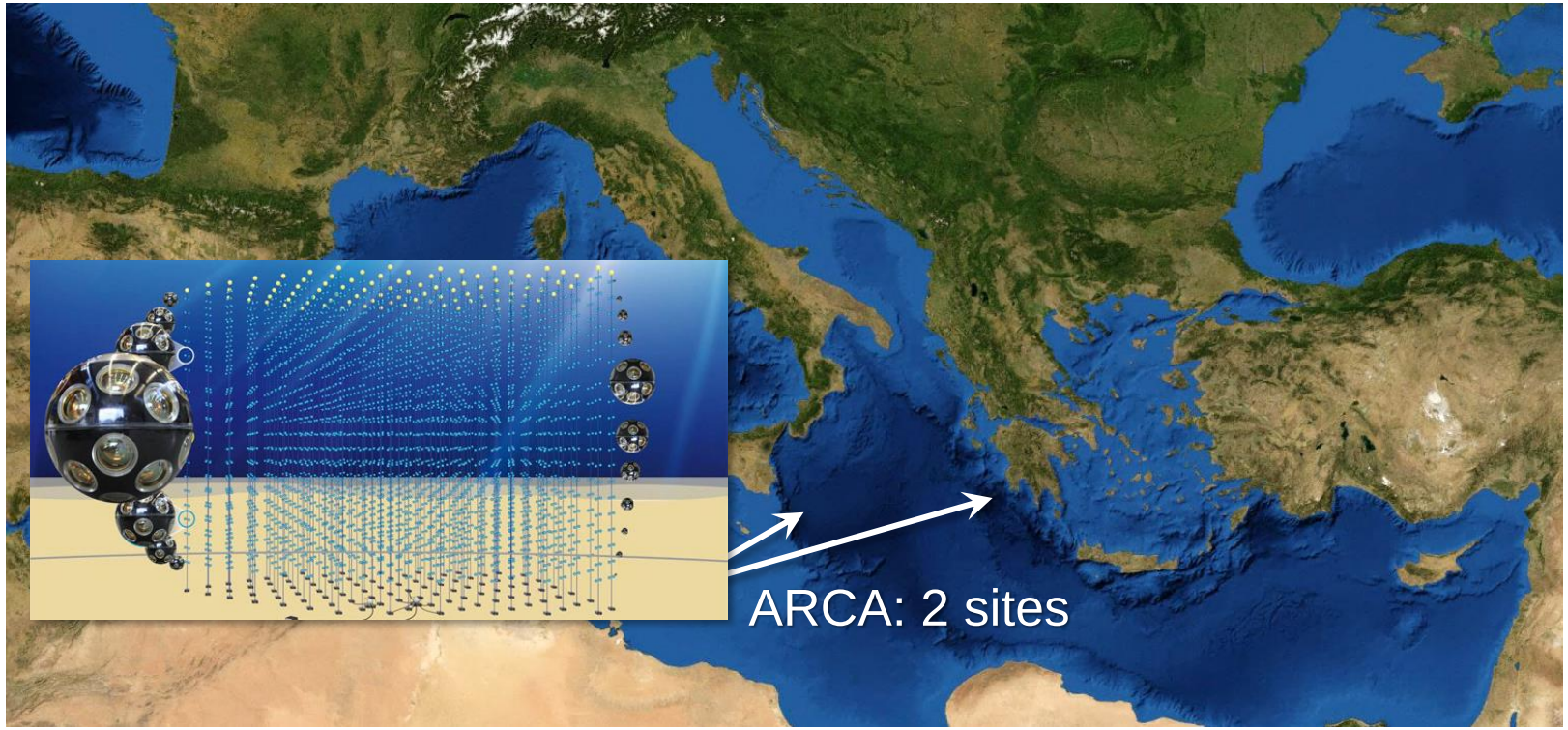
Neutrino Telescopes – ARCA & ORCA

- **KM3NeT subsystems: ARCA (2 sites)** & ORCA (1 site)

  - **ARCA**: **A**stroparticle **R**esearch with **C**osmics in the **A**byss
    hunting astrophysical neutrino sources with a large array



2 neutrino telescopes for
TeV-PeV astrophs. ν´s



Neutrino Telescopes – ARCA & ORCA

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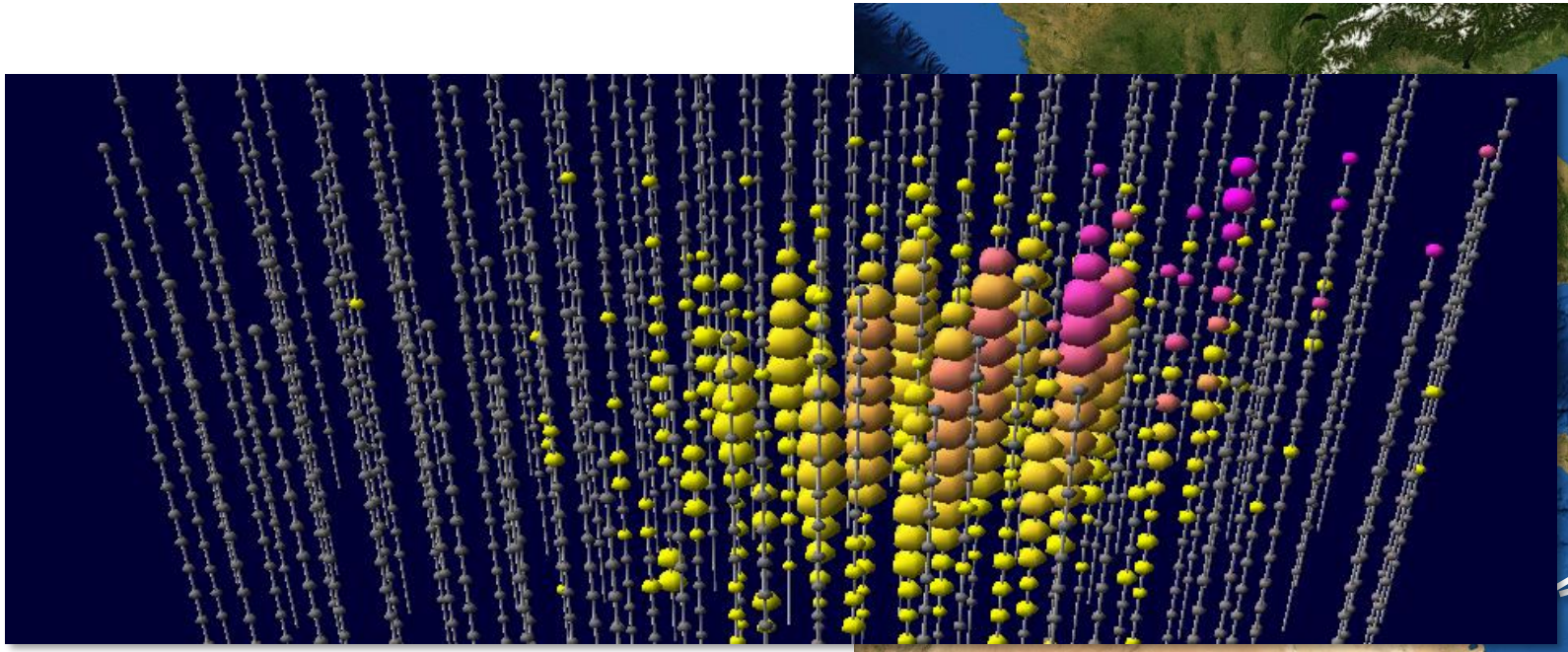
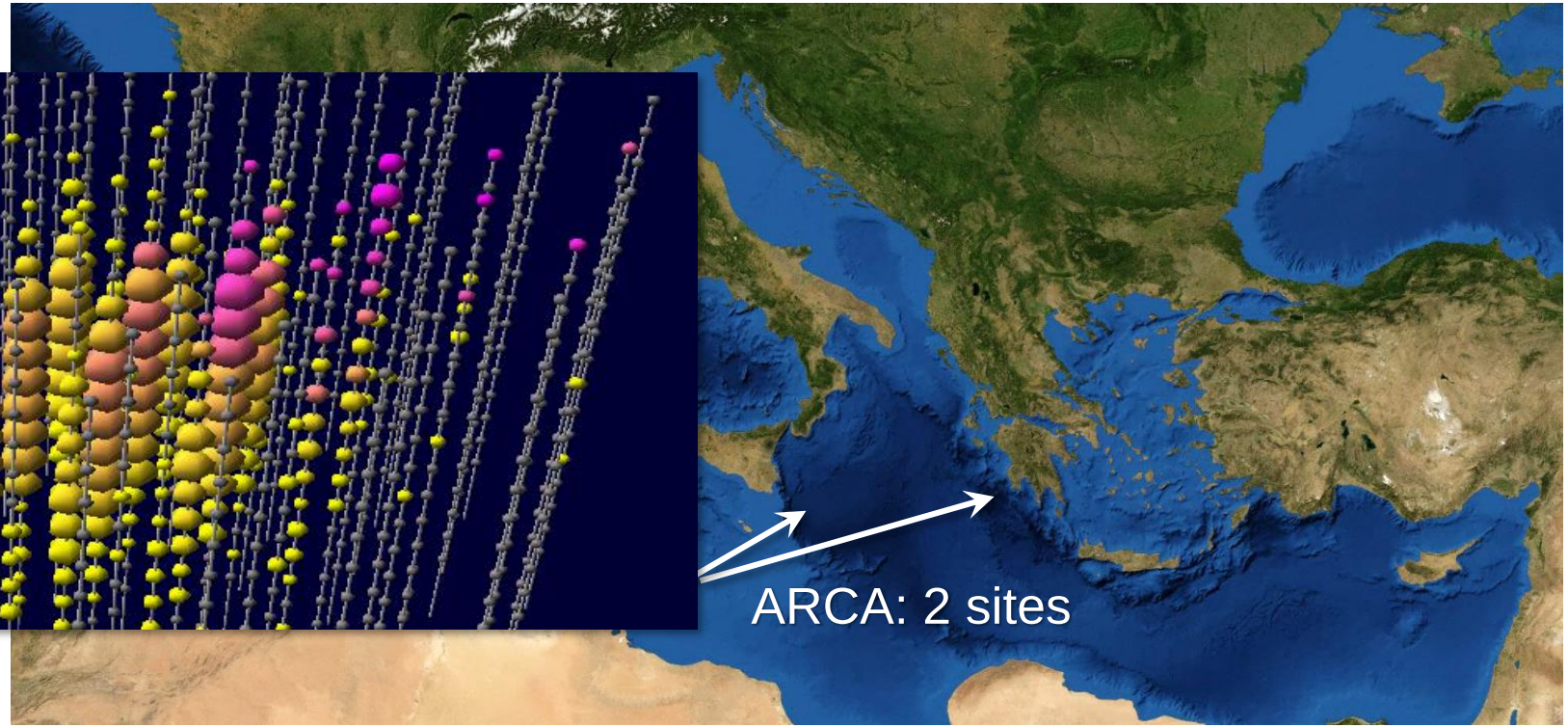


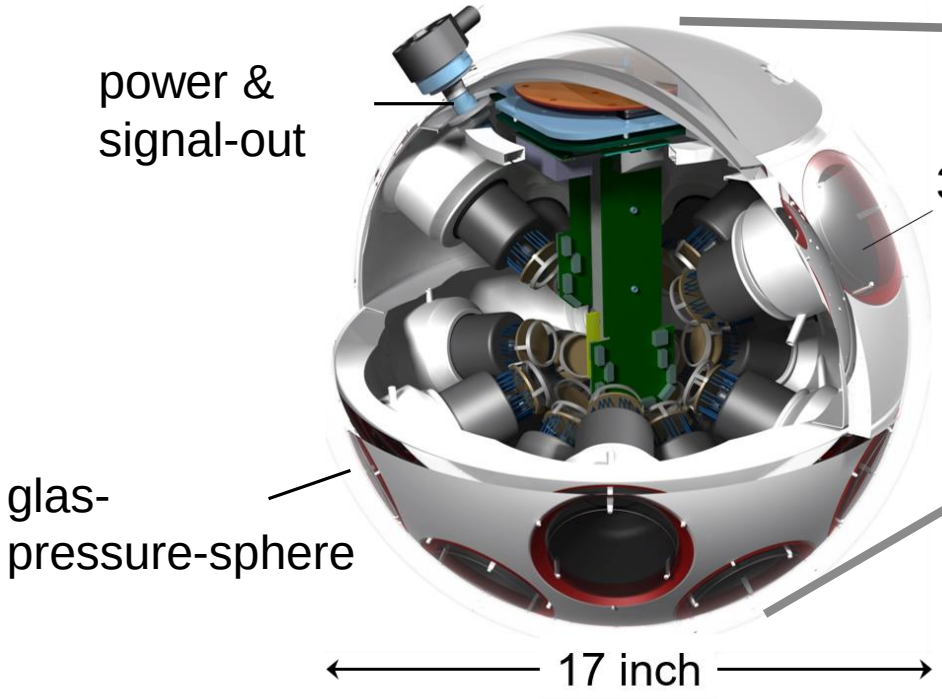
simulated ARCA events

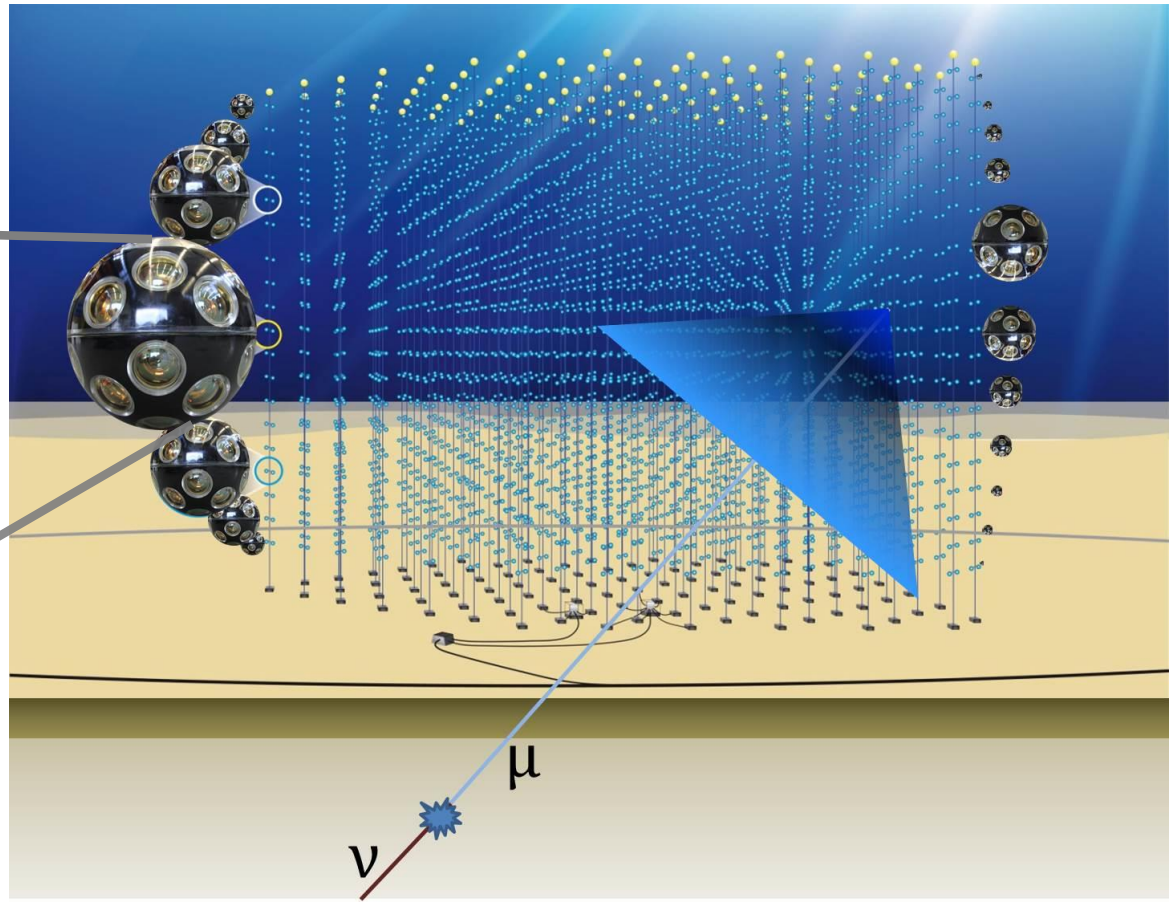


KM3NeT – ARCA design

- **PMT - arrays based on Digital Optical Modules***

- DOMs ($\emptyset = 17\ inch$) instrumented with 31 $3 - inch$ PMTs for light detection



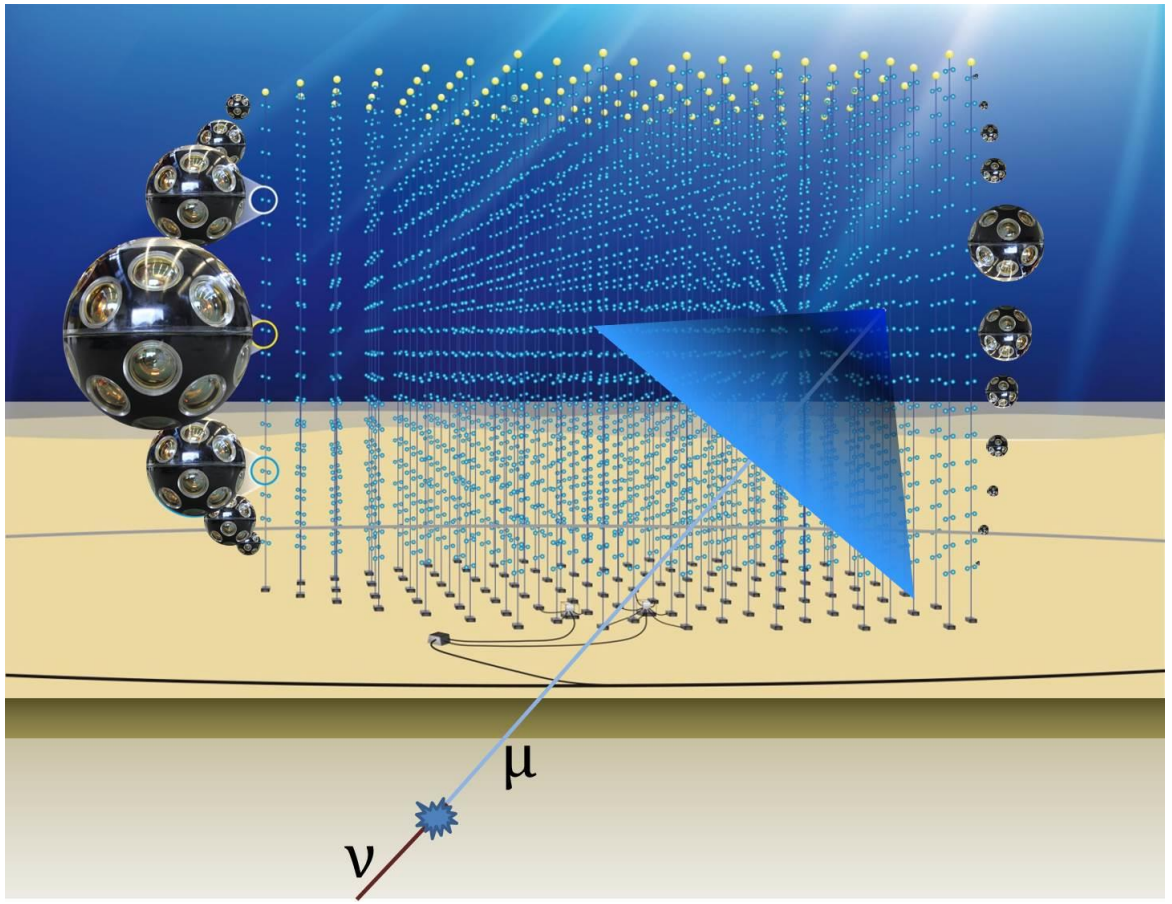


*DOM

KM3NeT – ARCA design

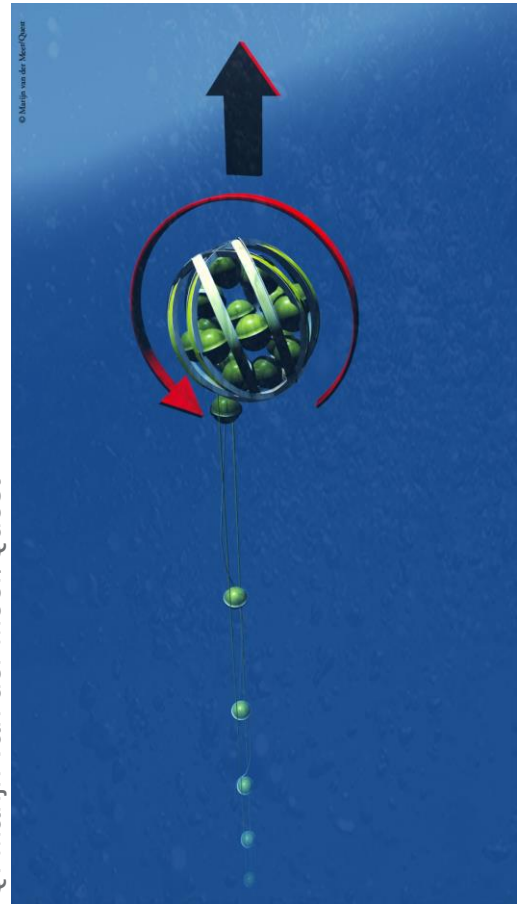
- **ARCA is hunting for ν-point sources with energies on the PeV-scale**

- initial design: full scale size with 600 strings
- present design: 2×115 strings (each with 18 DOM units)
- strings placed in $d = 90\,m$, each with length $l = 650\,m$
- current status (9/2022): 21 strings (deployment since 2015)
- ongoing data-taking

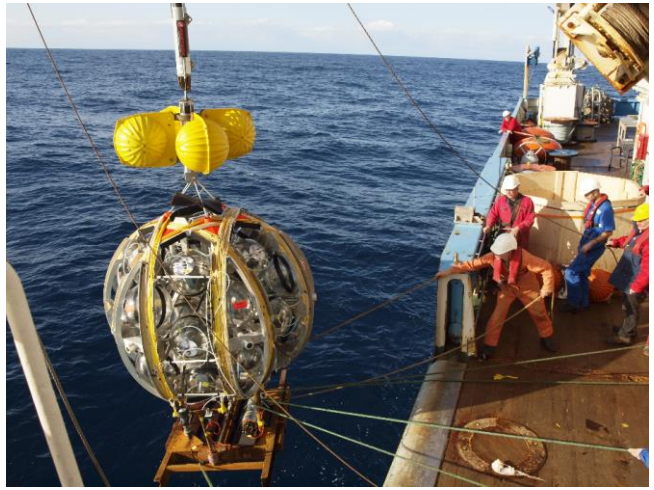


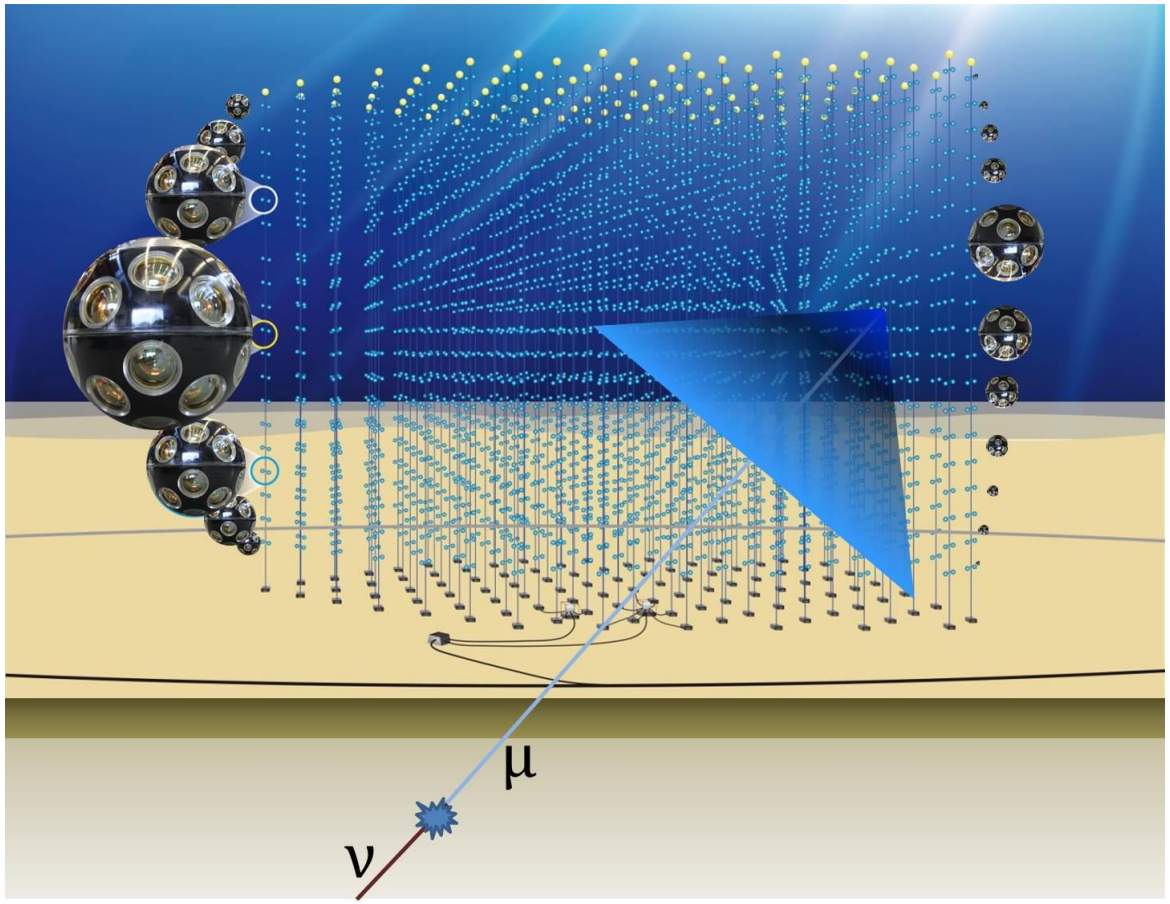
KM3NeT – ARCA deployment

- **ARCA strings deployed in specific campaigns with sea-going vessel**



Q: Marijn van der Meer/Quest

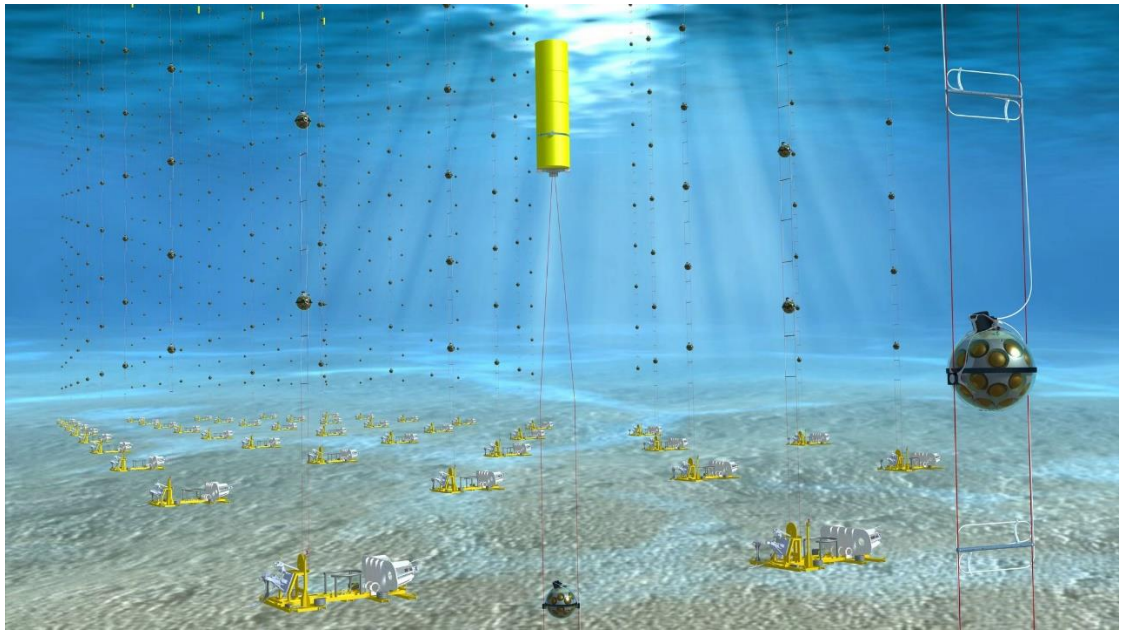




KM3NeT – ORCA studying ν-oscillations

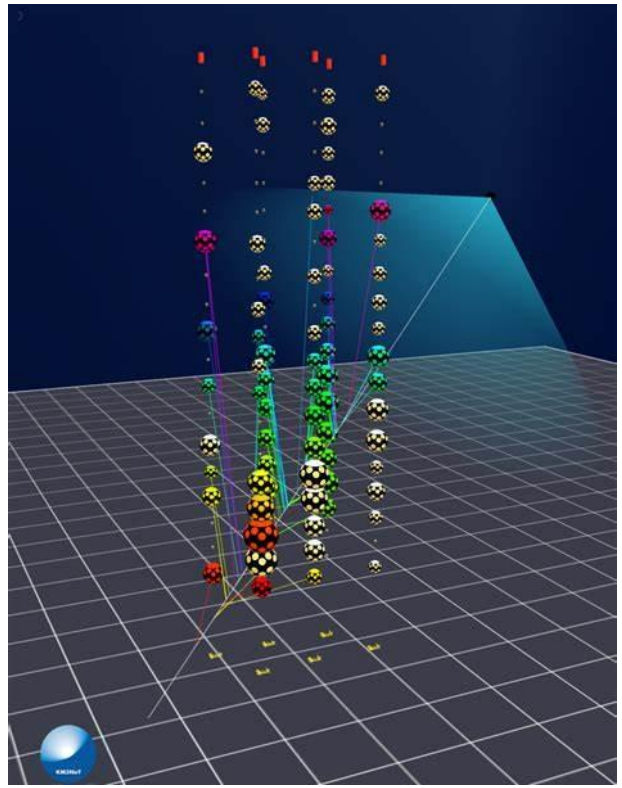
- **KM3NeT subsystems:** ARCA (2 sites) & **ORCA (1 site)**

  - **ORCA**: **O**scillation **R**esearch with **C**osmics in the **A**byss



goal: study of oscillation processes of atmospheric ν´s

- ORCA full scale: 115 strings (ℓ = 150 m, each with 18 DOMs)
- **DOMs with much finer spacing (GeV scale)**
- in a depth $d = 2.5\ km$
- status (as of 9/2022): 12 strings deployed



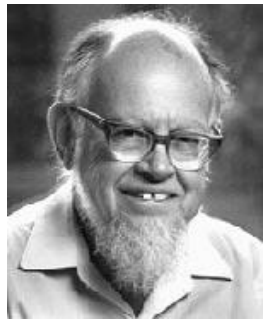
KM3NeT – ORCA studying ν-oscillations

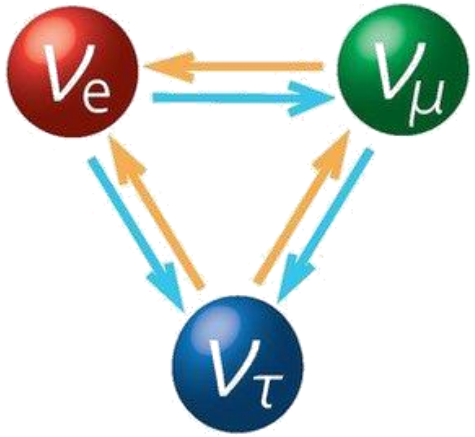
- **ORCA key target: investigate the mass hierarchy of neutrinos**

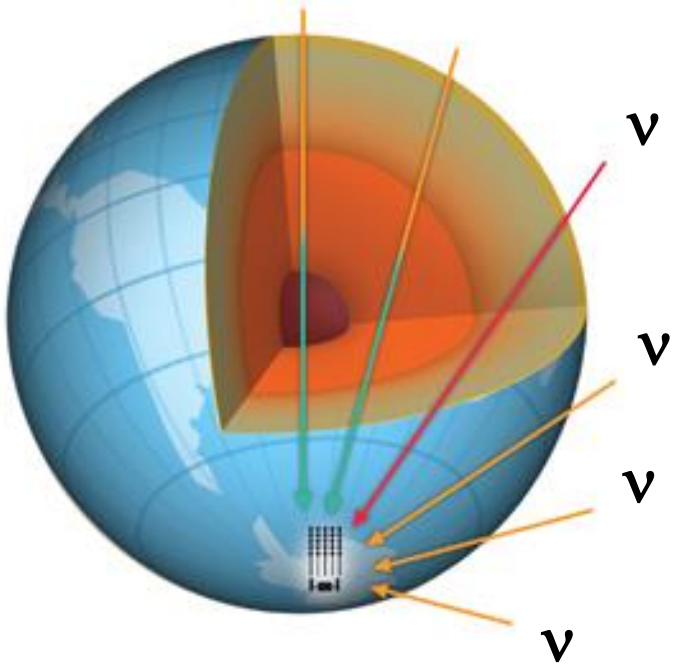
  - ORCA investigates low-energy atmospheric neutrinos on the GeV-scale

  - atmospheric neutrinos **oscillate***!

  - ν_{atm} propagate in the matter of the Earth: matter-induced effects (´MSW effect´)







flight paths of atmospheric ν´s

*see ATP-2 in summer term 2023

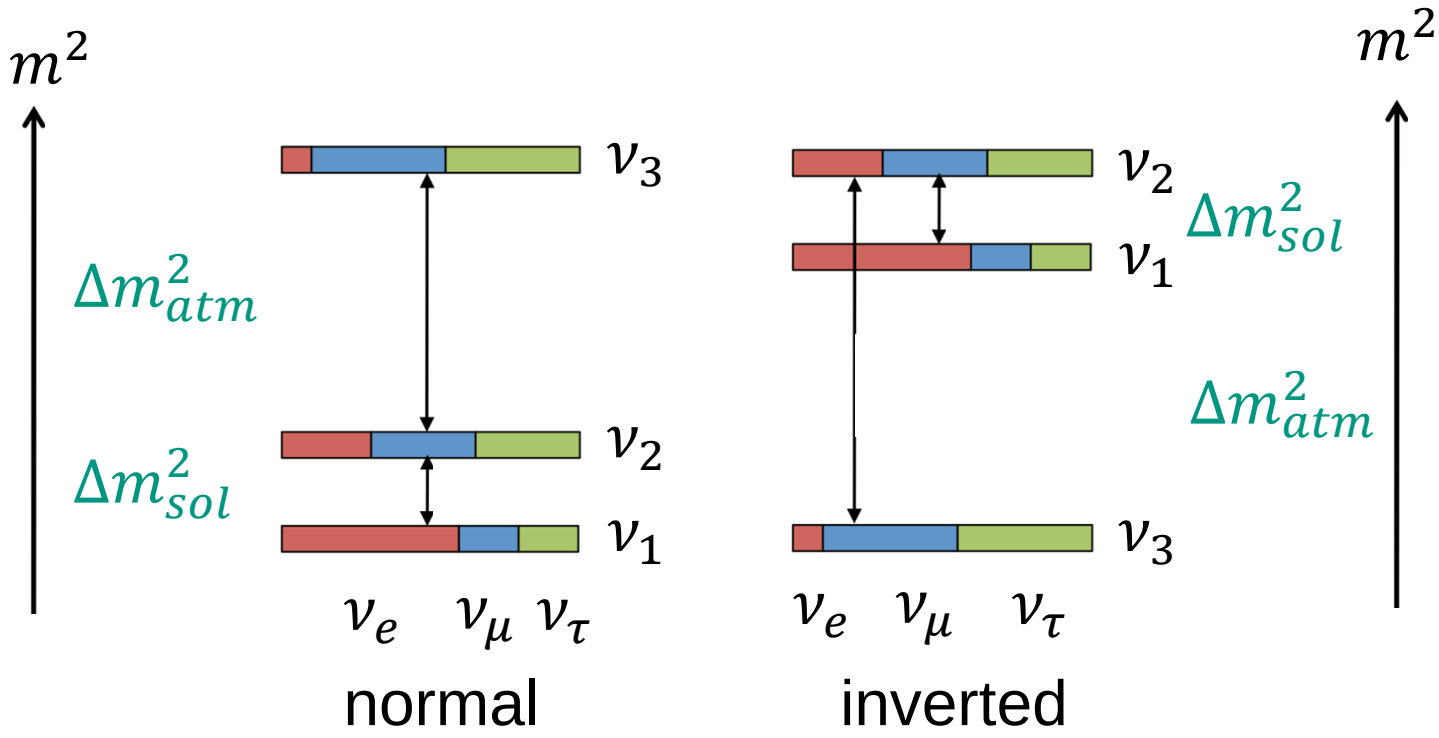
KM3NeT – ORCA studying ν-oscillations

- **ORCA key target: investigate the mass hierarchy of neutrinos**

  - ORCA investigates low-energy atmospheric neutrinos on the GeV-scale

  - atmospheric neutrinos **oscillate***!

  - ν_{atm} may allow to determine the n-mass hierarchy:
    what is the correct ordering of mass eigenstates?
    normal or inverted hierarchy?

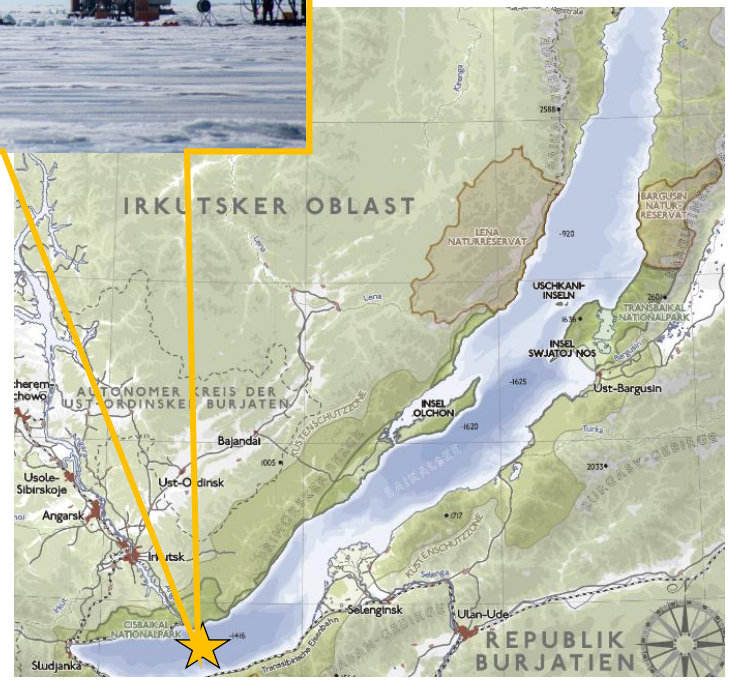


*see ATP-2 in summer term 2023

ν-Telescope Lake Baikal

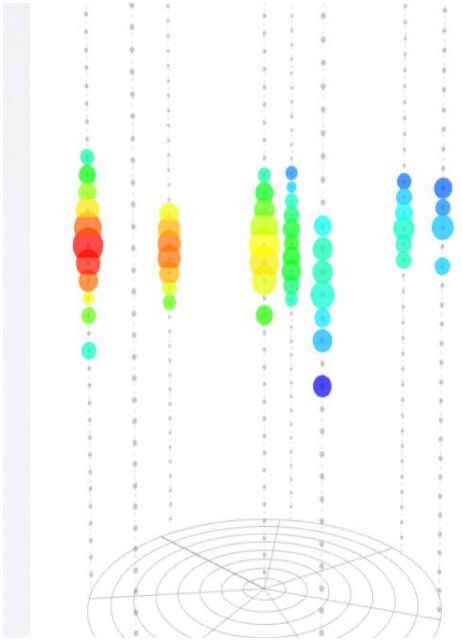
- **deep-sea experiment in the deepest lake on Earth: Baikal**

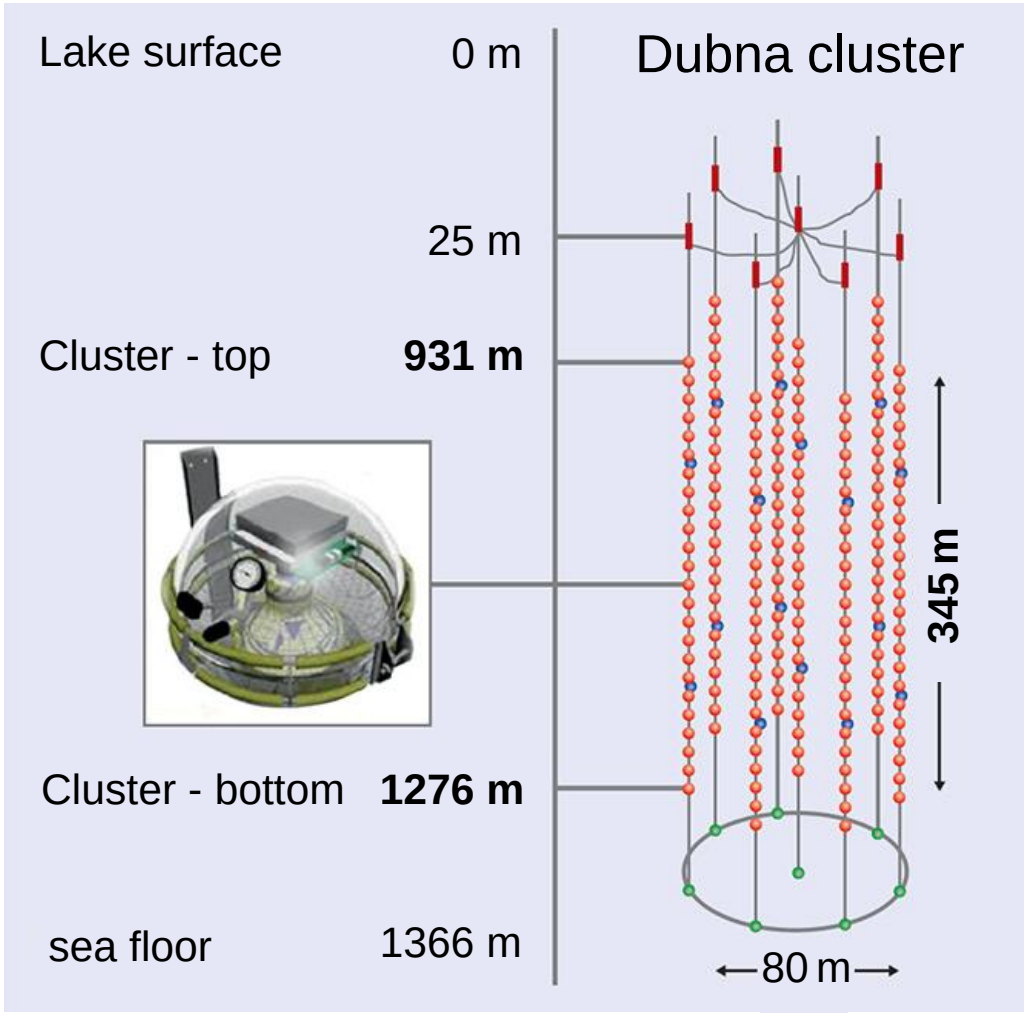
  - pioneering neutrino telescope „Lake Baikal“ in the 80-s/90-s



Baikal – Gigaton Volume Detector (GVD)

- **Extending an existing ν-telescope in Lake Baikal**
  - largest ν-telescope in northern hemisphere
  - full-scale extension to 1 km³ planned
  - present (2021) status
    GVD-I ready ($V \sim 0.5\ km^3$)
  - 8 clusters in operation

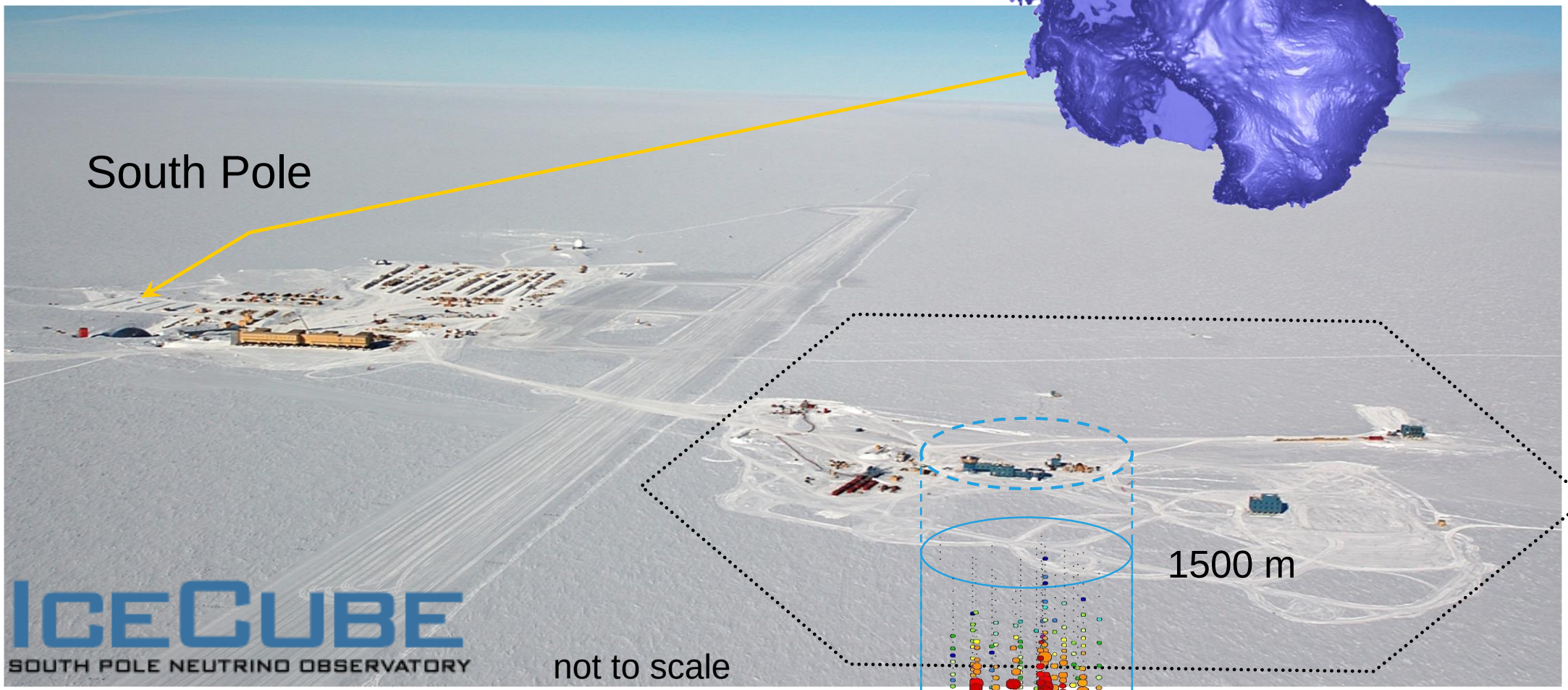




prototype cluster

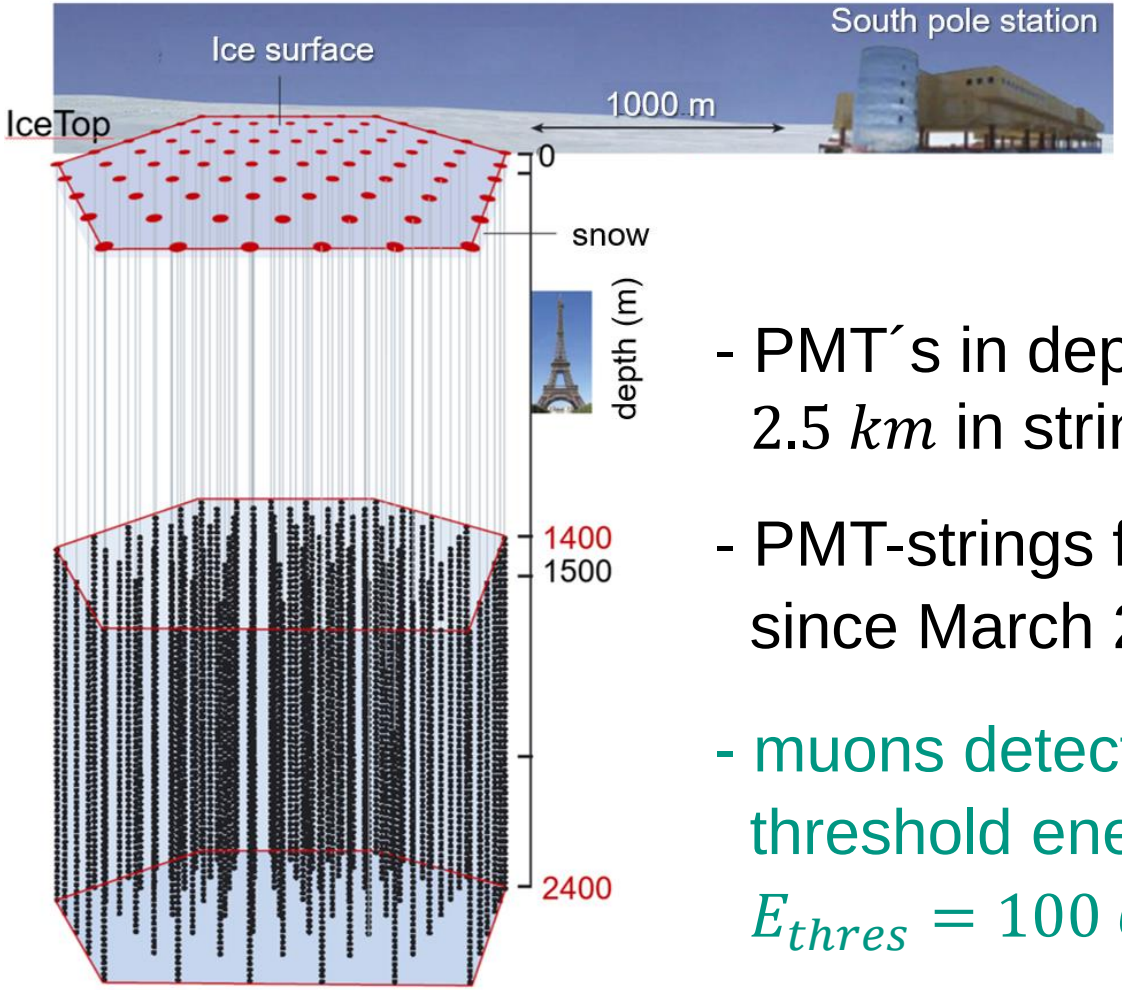
IceCube observatory at the South Pole

- **Amundsen-Scott station**



IceCube observatory at the South Pole

Design of an in-ice neutrino telescope



- 4800 photomultipliers distributed over volume $V = 1\ km^3$ with 80 PMT strings

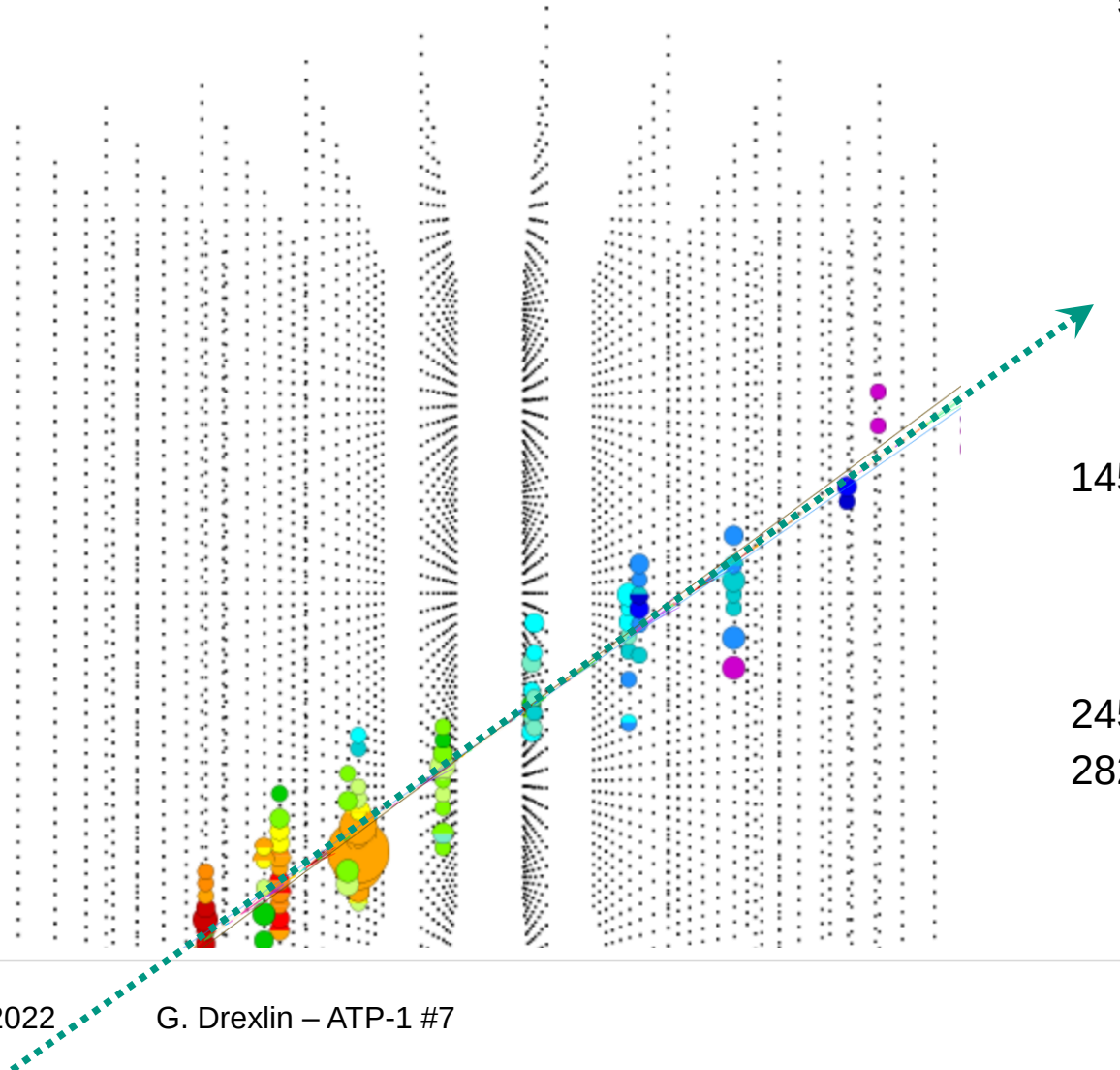
- PMT´s in depth $d = 1.5$ ... $2.5\ km$ in strings of 1 km

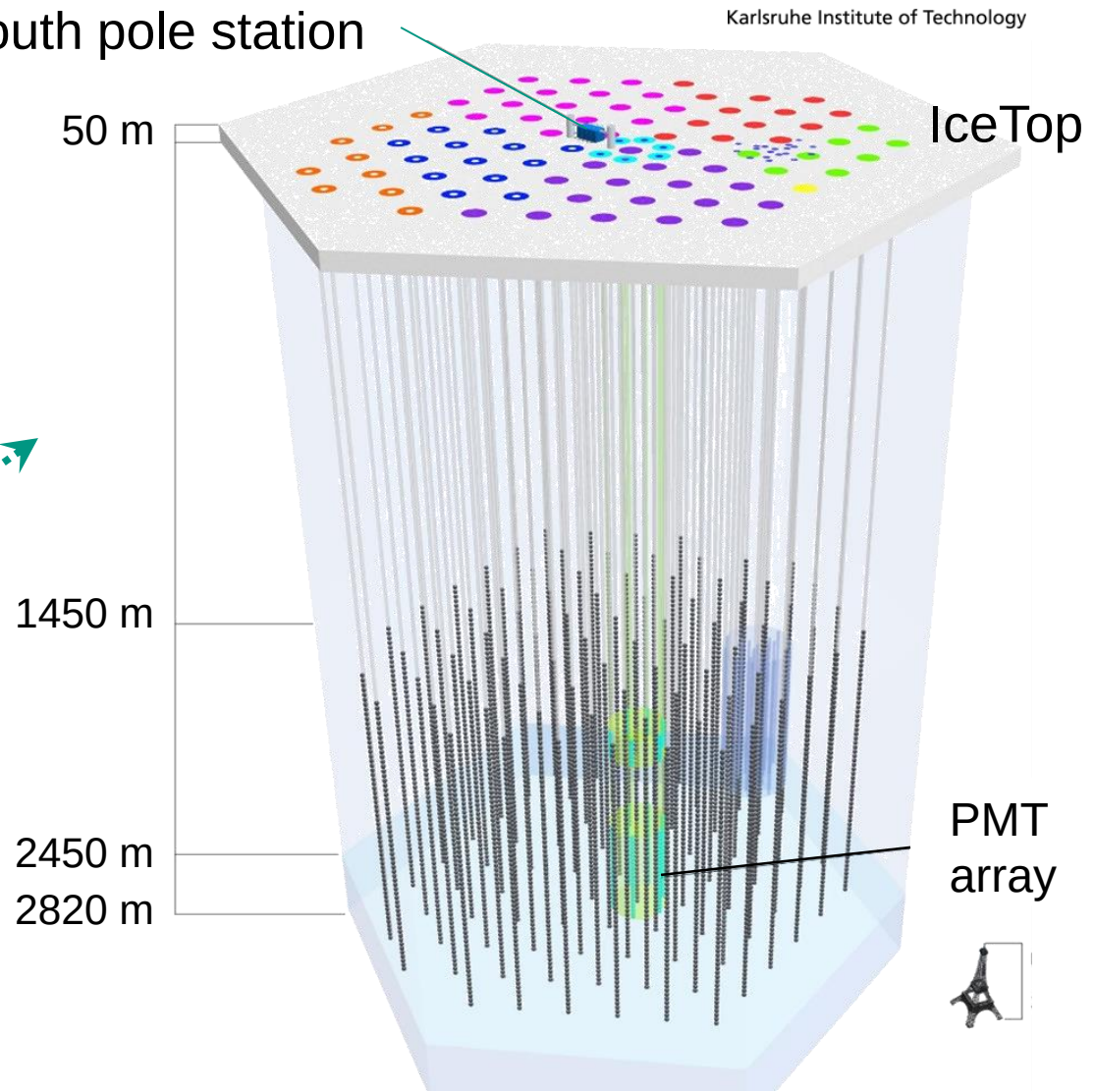
- PMT-strings fully deployed since March 2010

- muons detected from threshold energy $E_{thres} = 100\ GeV$

IceCube observatory: design features

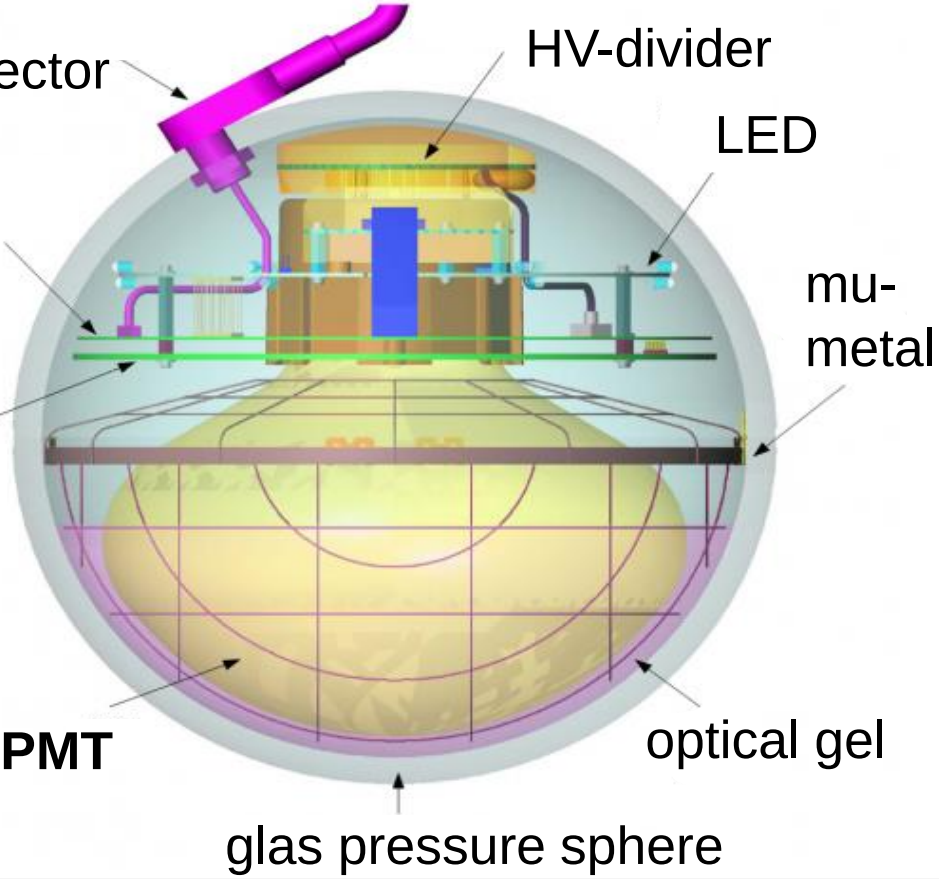
- **Detecting tracks with PMT strings**

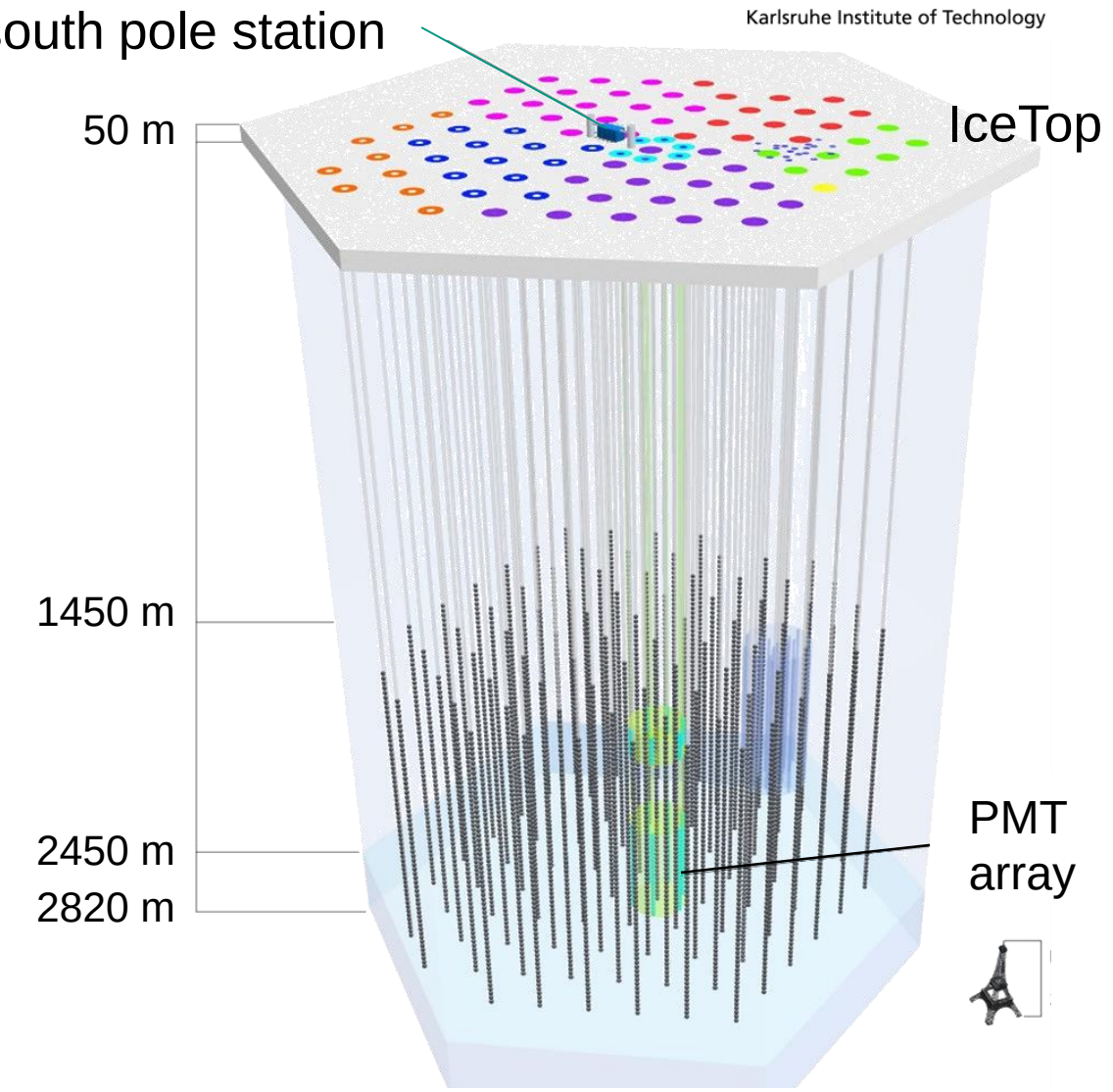




IceCube observatory: design features

- **DOM design for in-ice operation**
  - have to withstand $P = 200\ atm$





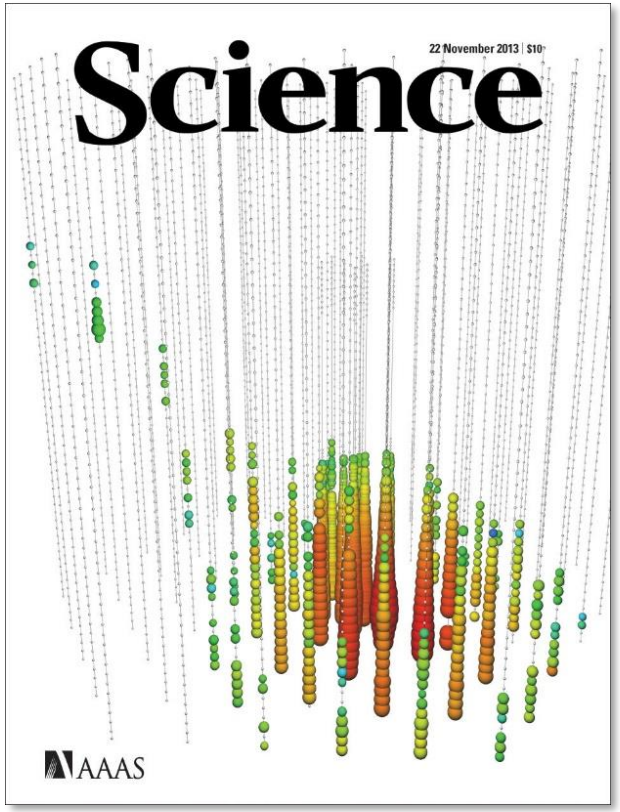
IceCube Observatory: observations

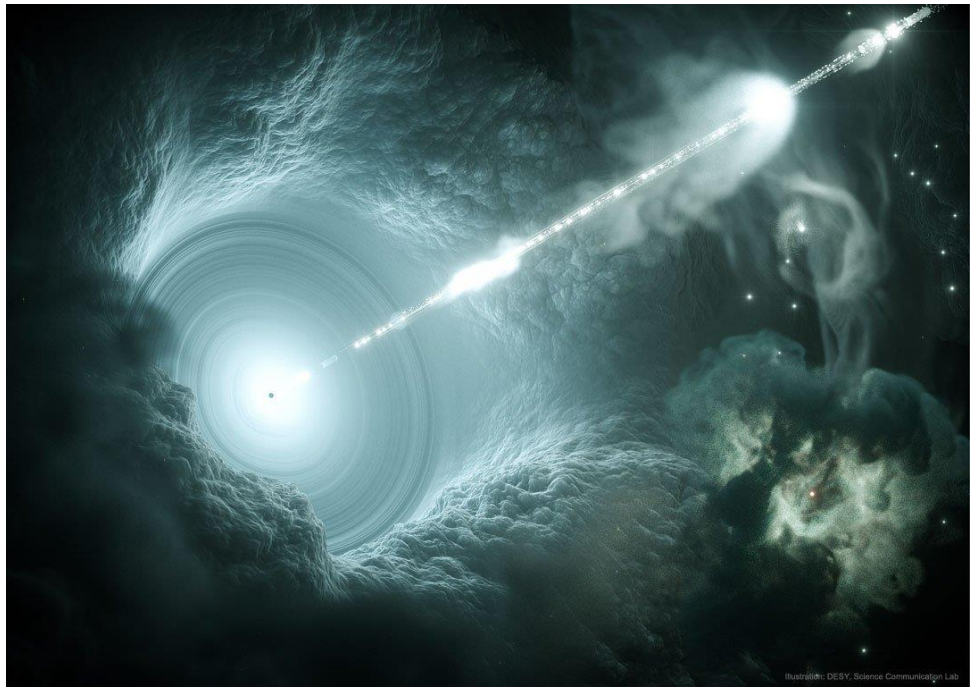
- **Astrophysical neutrinos**

  - from galaxy PKS 1424-418: flare state in a **blazar**

  - a very energetic event (´Big Bird´) observed in 2017: $E(\nu_\mu) = 250\ TeV$!

Big Bird



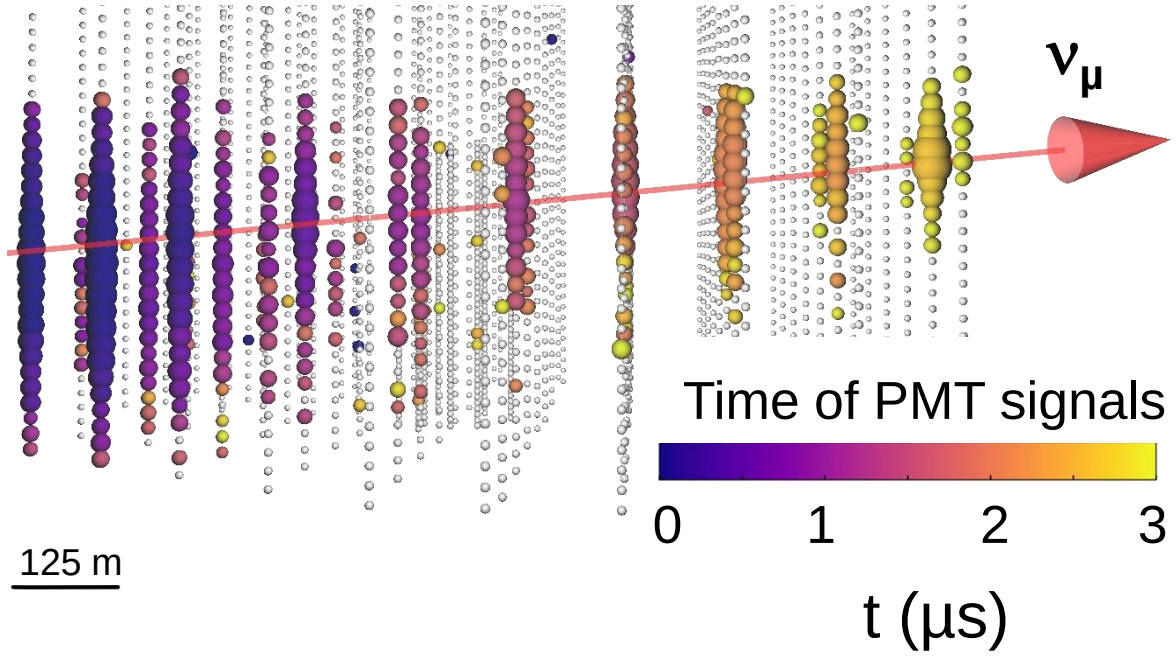


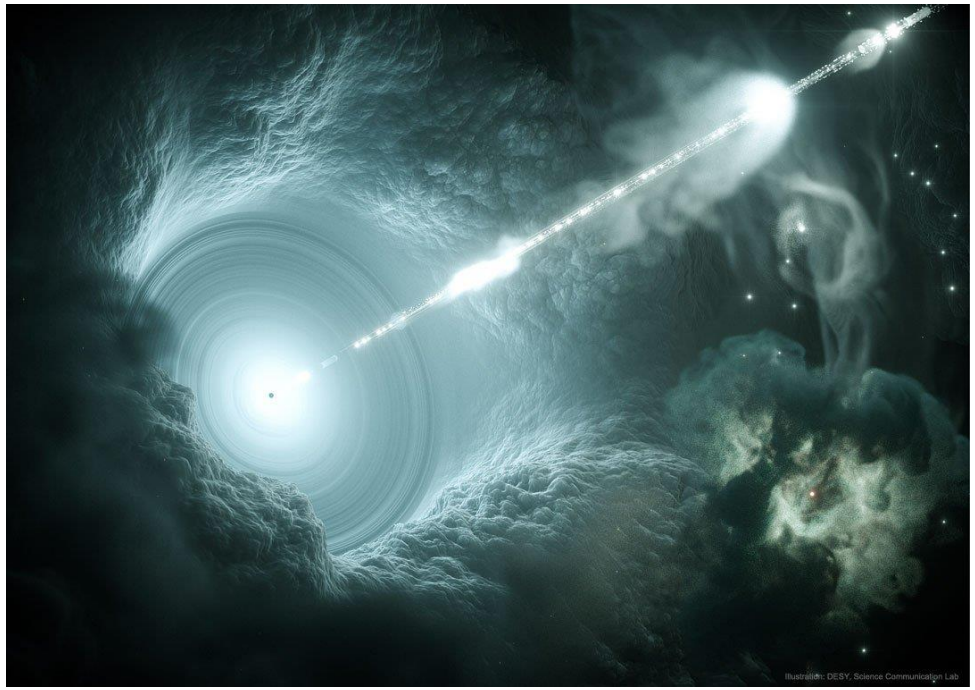
blazar PKS 1424-418

IceCube Observatory: observations

- **Astrophysical neutrinos: an energetic n from an AGN-source in a flare state (enhanced emission of gamma rays)**

  - AGN was in a very active phase: more ν´s!
  - muon direction points back to blazar





blazar PKS 1424-418

IceCube Observatory: observations

- **Astrophysical neutrinos on the PeV −scale**