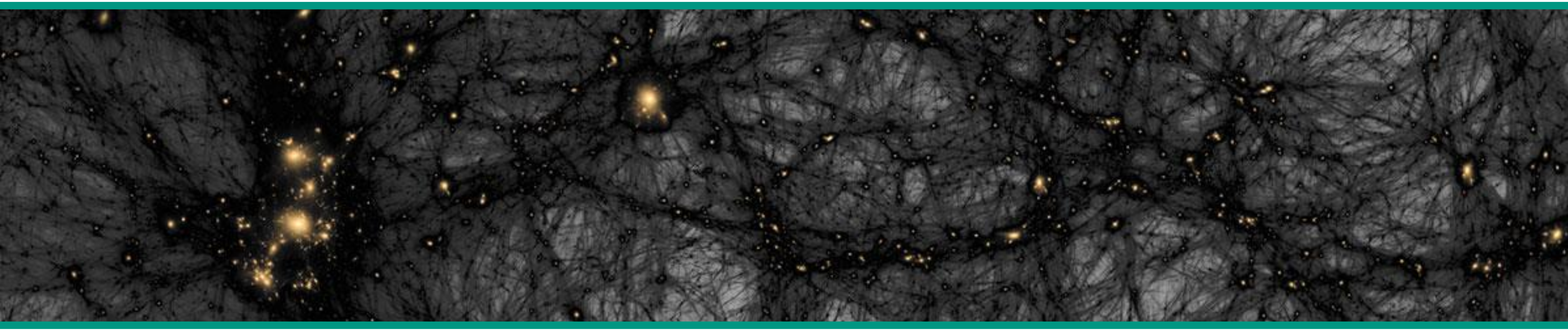
Astroparticle physics *I* – Dark Matter

Winter term 23/24 Lecture 7 Nov. 22, 2023



Recap of Lecture 6

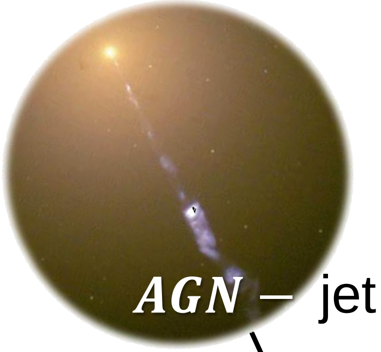
- $UHECRs$: **modern observations & results at the highest energies**
  - hybrid technology (air fluorescence & $N_e + N_\mu$): CR – observatories PAO & TA
  - measurement of **longitudinal distributions** via isotropic emission of N_2
  - $UHECR$ – **cutoff** at $E \sim 10^{20} eV$: due to **Hillas** (^{A}Z), not GZK – resonance (p)
- UHE **neutrinos: multi–messengers from afar**
  - ν – telescopes **in–ice / deep–sea**: PMT – arrays to detect **Cherenkov** light
  - CC – reactions of ν_μ at PeV – energies: μ – tracks over km – range
  - **properties** of medium (deep–sea water vs. ice) key to particle reconstruction

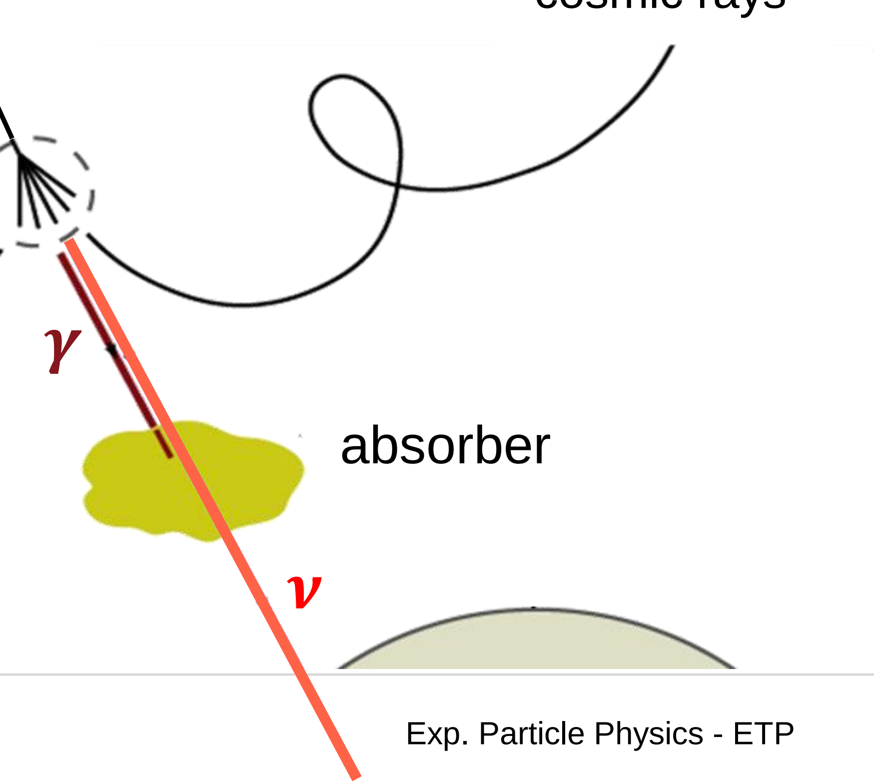
UHE neutrinos – production mechanisms

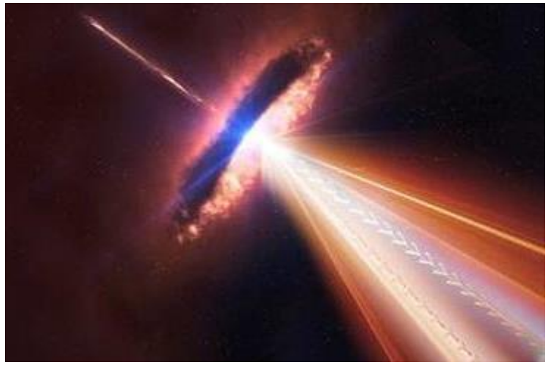
- **expected $\nu -$ sources at UHE scale: transient and/or variable accelerators**

  - AGN jets (active galaxies)
  - $GRBs$ (gamma ray bursts)
  - $\mu -$ quasars (galactic)

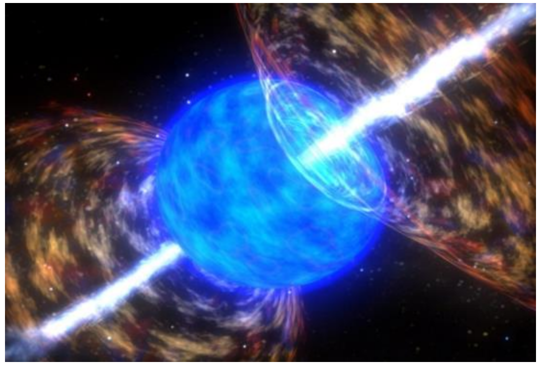
  Hillas criterium



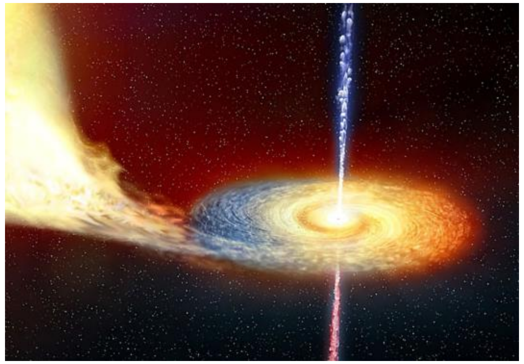




Active Galactic Nucleus



Gamma Ray Burst

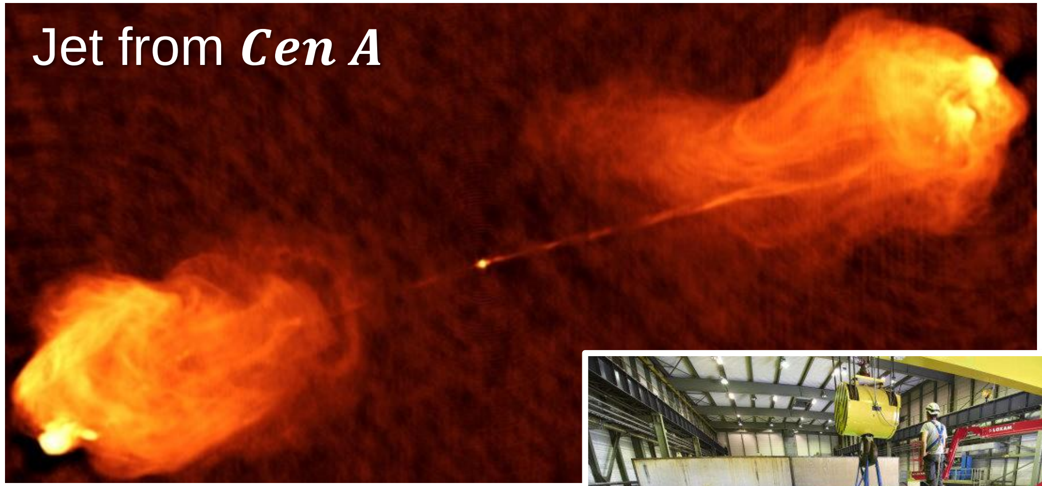


$\mu -$ (micro) quasar in galaxis

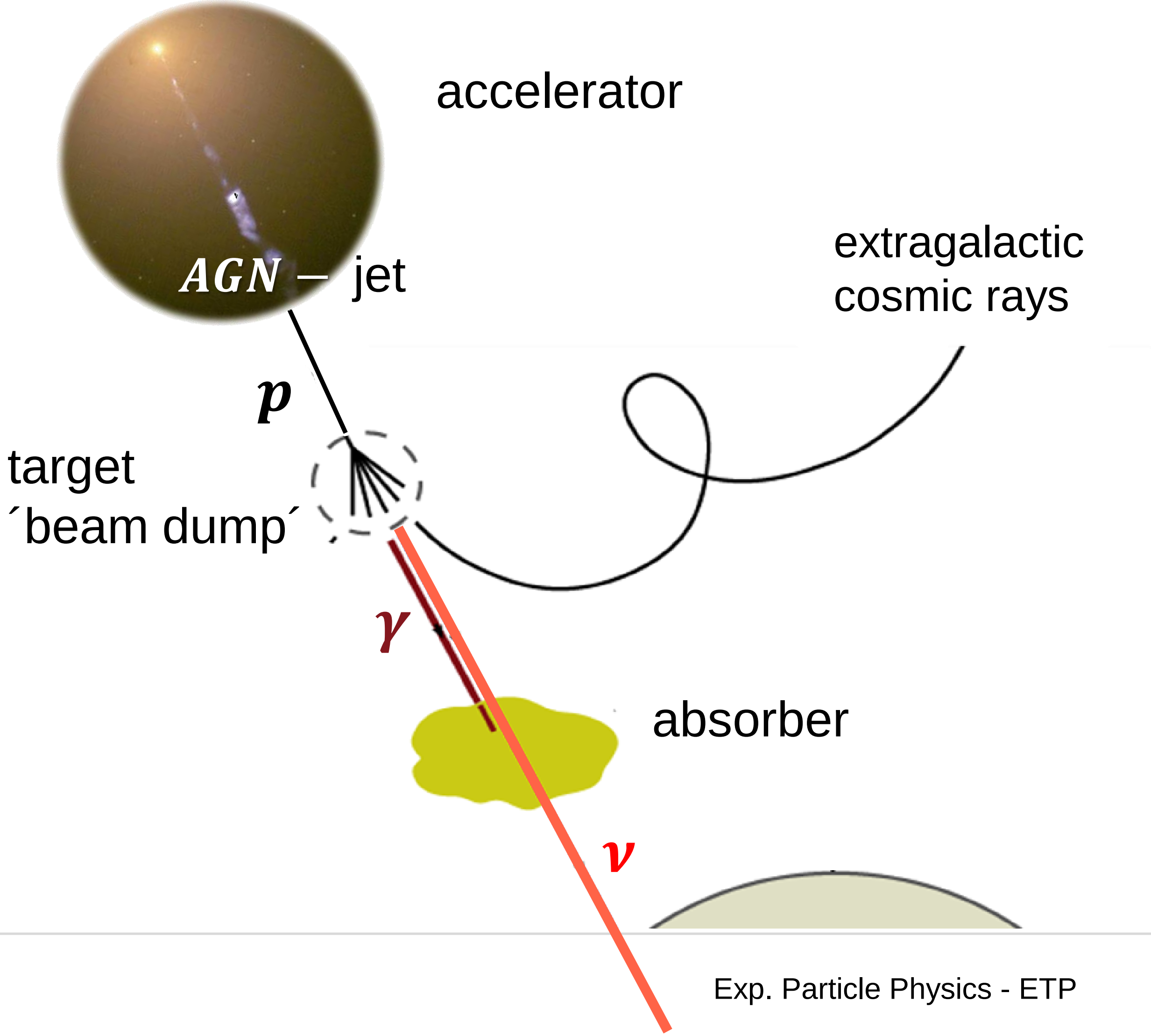
UHE neutrinos – production at target

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

  - close analogy to terrestrial high–energy proton accelerators



$CERN – SPS$



UHE neutrinos – pion processes at target

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

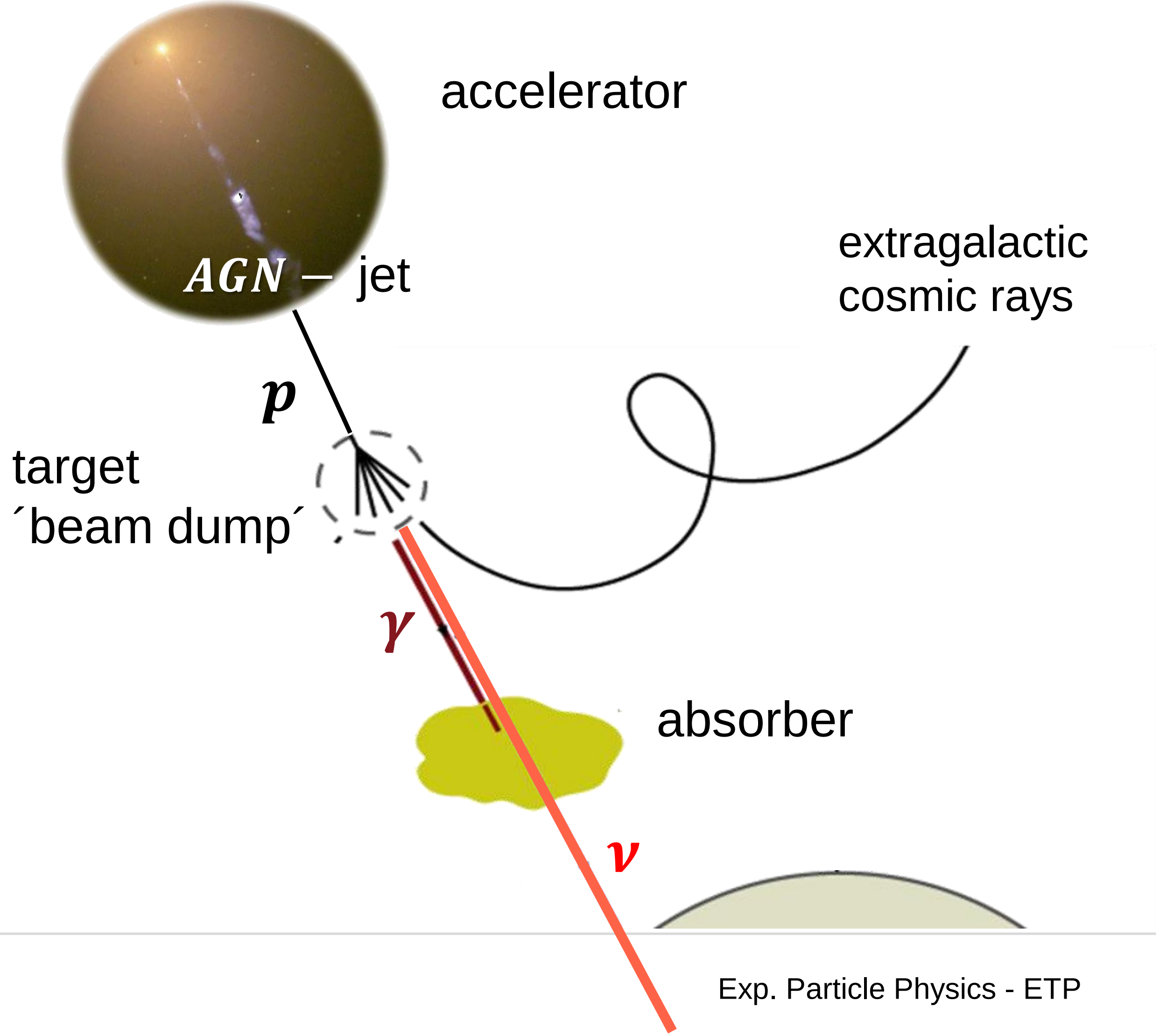
  - production & decay of **pions** at high–energy proton accelerators

$$p + p \rightarrow p + p + \pi´s$$

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

  - **flavour** composition at source:

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

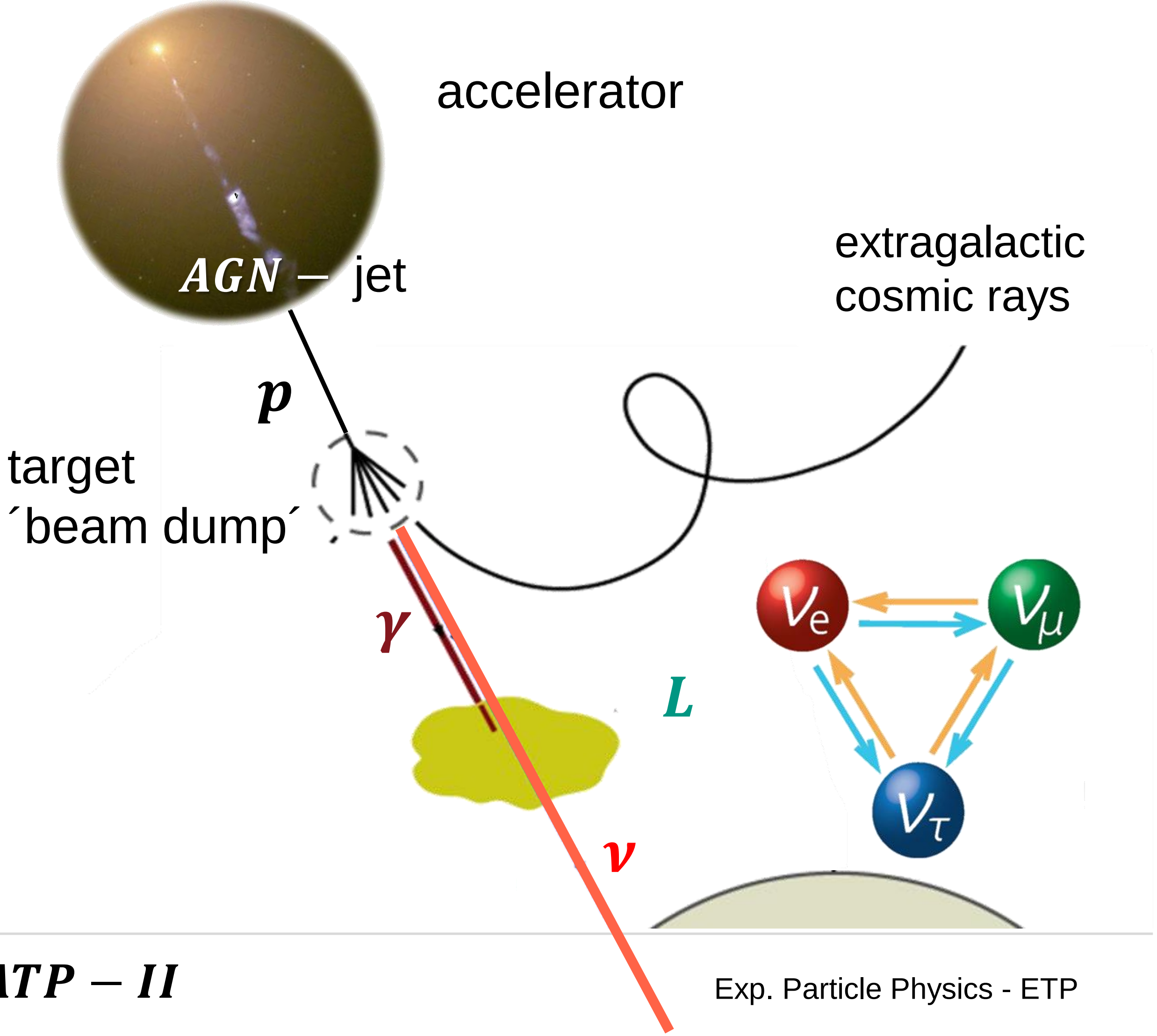


UHE neutrinos – propagation effects

Neutrino propagation: flavour *vs.* mass eigenstates

- propagation effects of neutrinos: **extremely long baseline L**
- initially, ν –**oscillations** $\nu_i \rightarrow \nu_j$ are taking place locally ($\ell_{osc} \ll L$)*
- due to **huge L**: **decoherence** of neutrino wave packets, thus **no** further flavour oscillations
- **flavour** composition here on Earth:

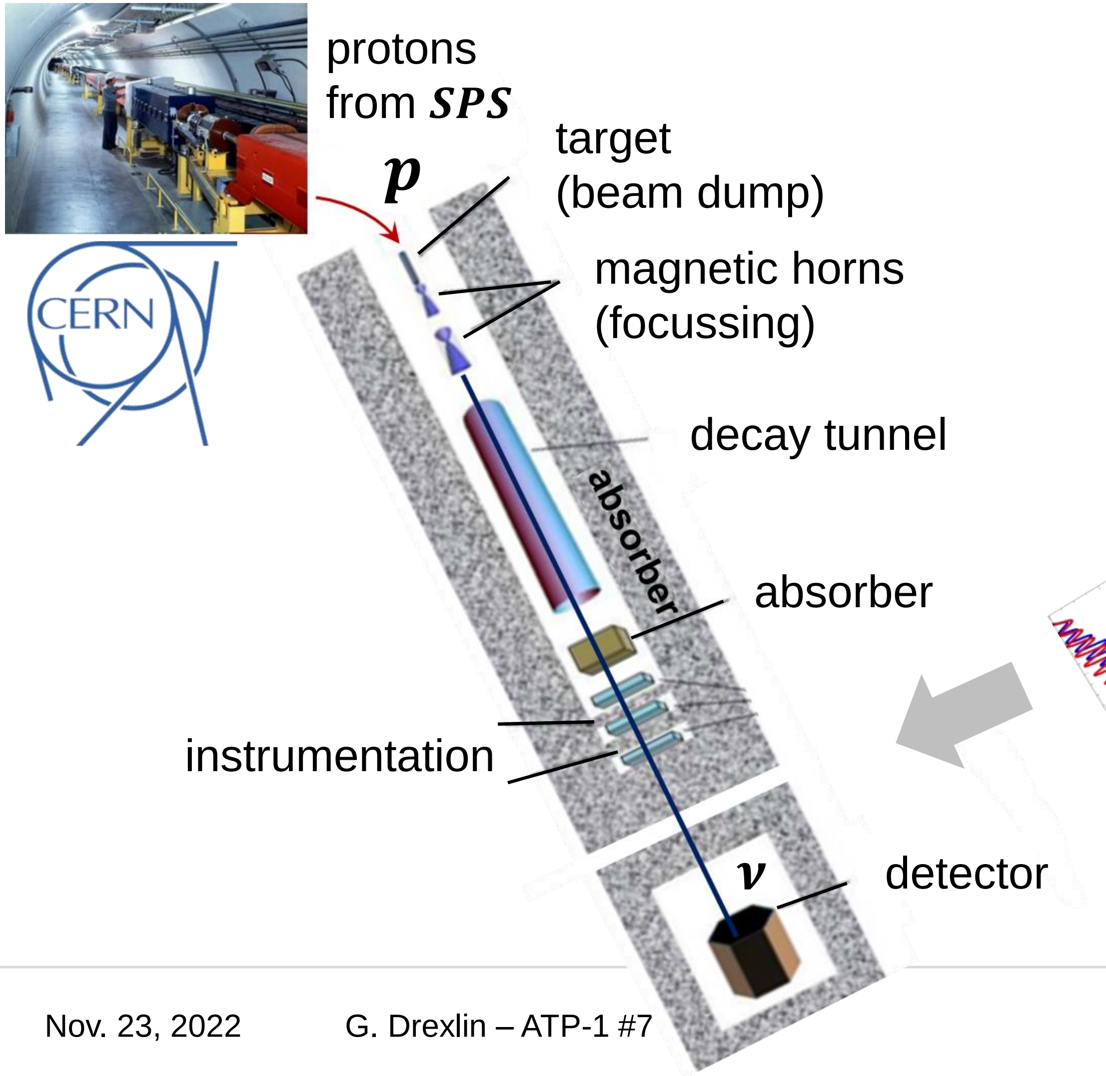
$$\nu_e : \nu_\mu : \nu_\tau = 1 : 1 : 1$$

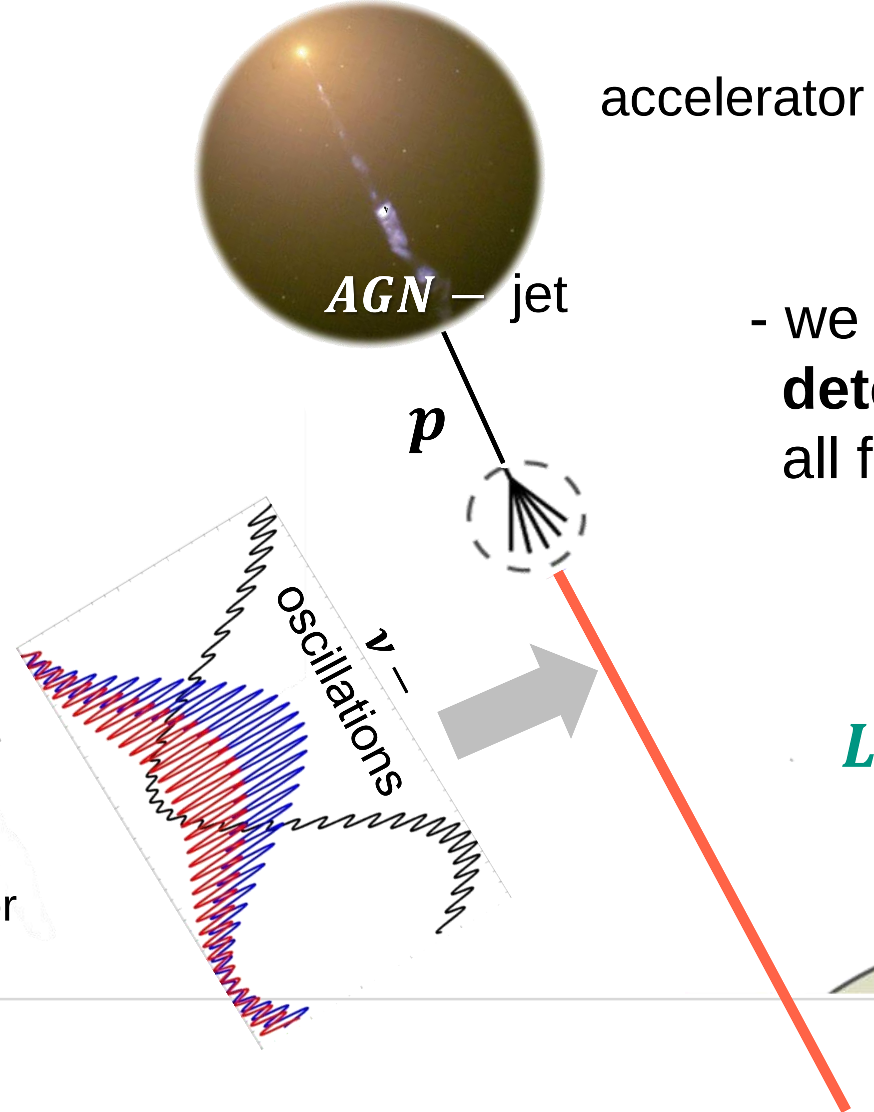


*for details see $ATP-II$

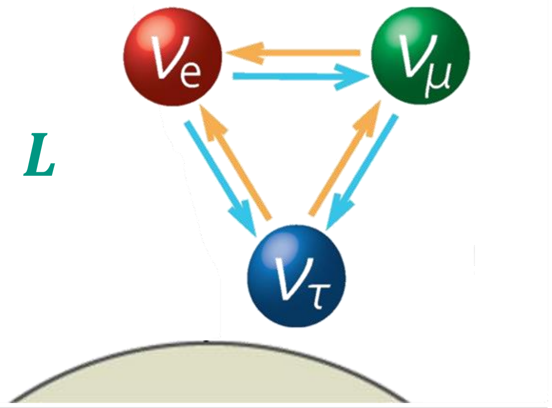
Neutrino beams: connecting ATP and TP

- **neutrino beams from $p-$ accelerators allow to investigate flavour oscillations**





- we need **specific detection** methods for all flavours ($\nu_e\ \nu_\mu\ \nu_\tau$)



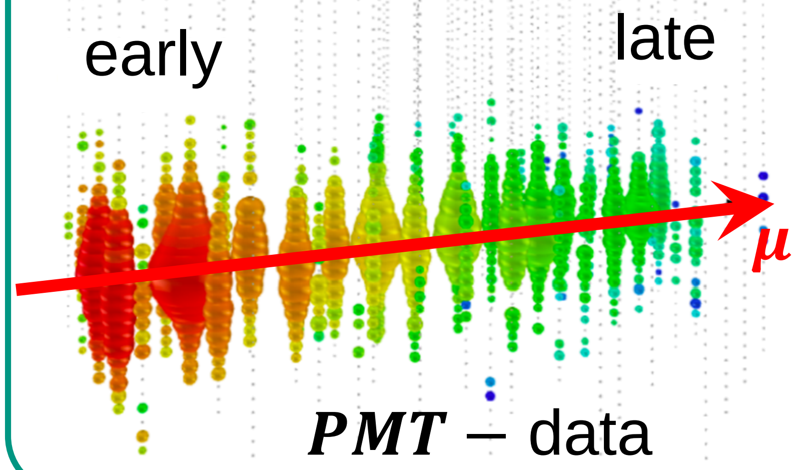
UHE neutrinos – detection reactions for ν_e, ν_μ, ν_τ

Karlsruhe Institute of Technology

muon neutrino ν_μ

- **straight muon track**
- energy–dependent R_μ

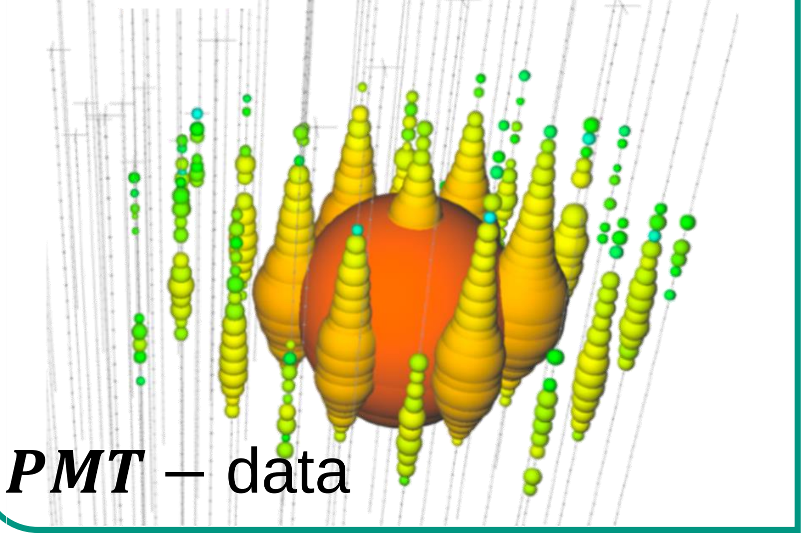
CC reaction



electron neutrino ν_e

- electromagnetic shower (**cascade** signature)
- spherical deposition of E

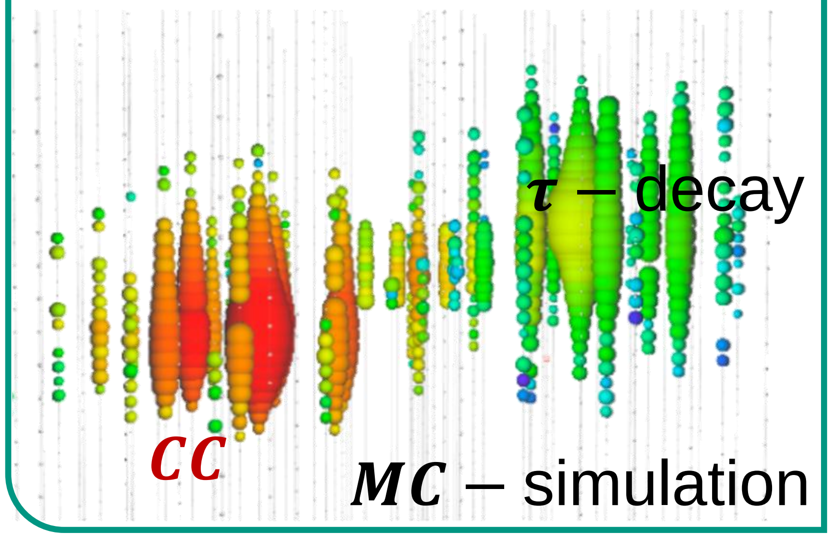
NC reaction



tau neutrino ν_τ

- ´**double bang**´ signal from fast τ – decay

τ – decay after CC reaction



UHE Neutrinos – measured flavour composition

Karlsruhe Institute of Technology

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

- propagation effects of neutrinos & expected *flavour ratio of the source:*

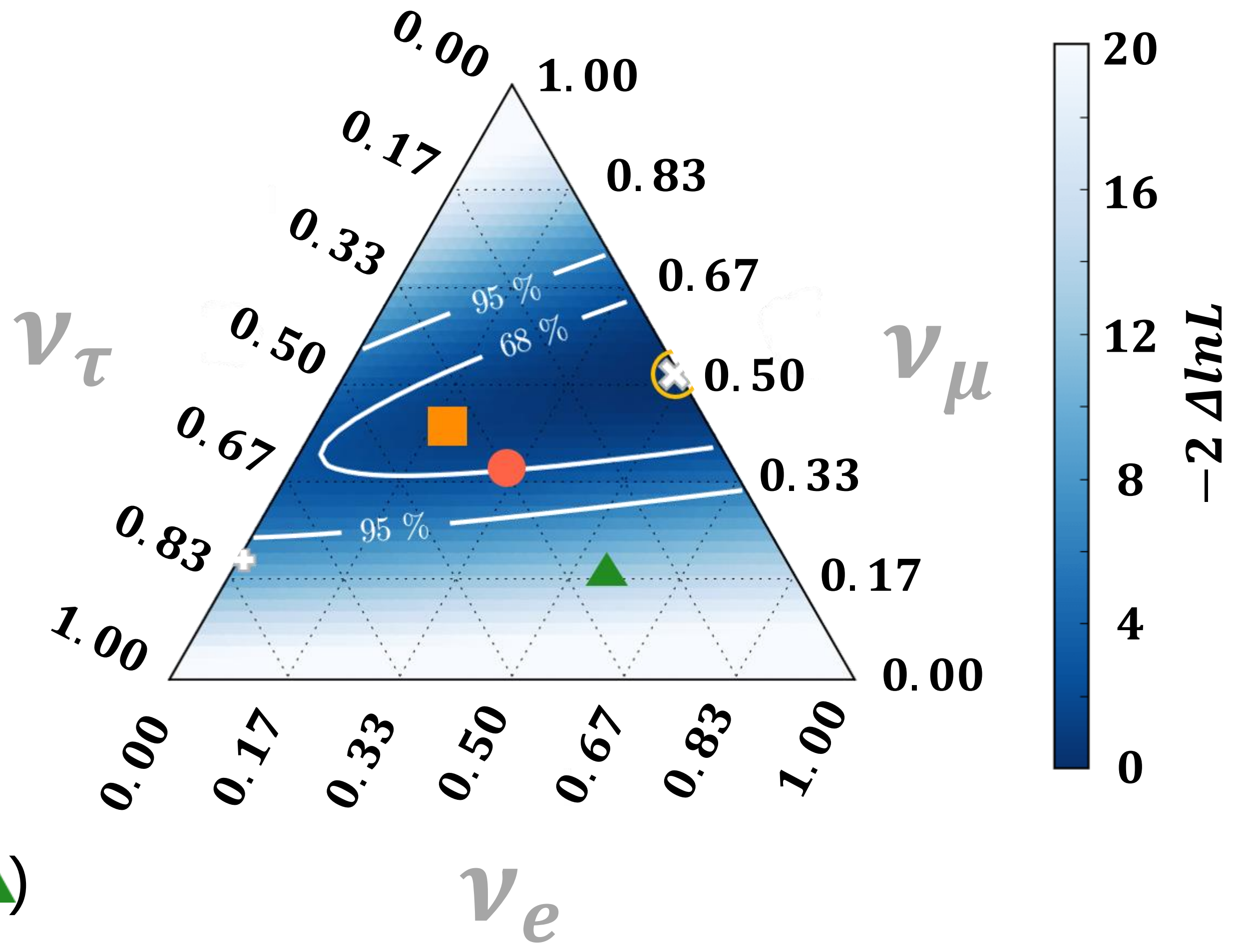
$\nu_e : \nu_\mu : \nu_\tau = 1 : 2 : 0$ ●

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

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

- **experimental data** ⊗

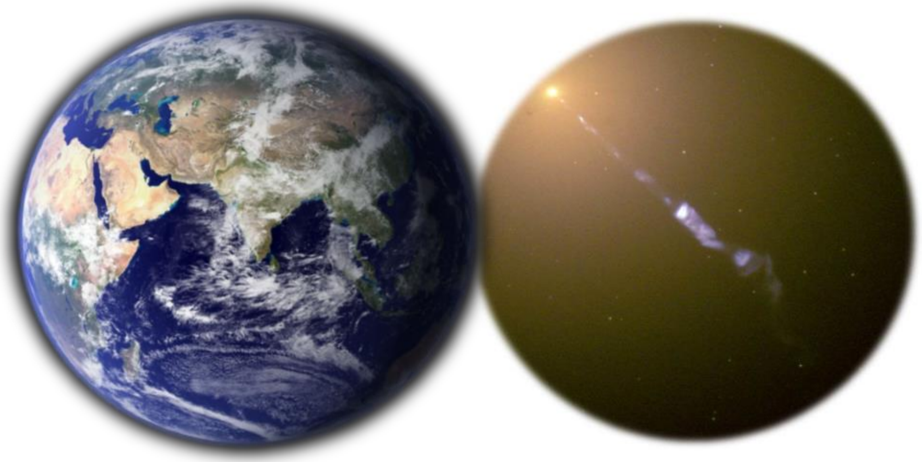
⇨ compatible with decay chain ● $\pi \to \mu \to e$, but not with n – decay (▲)



UHE neutrinos – signal of ν_{astro} & background

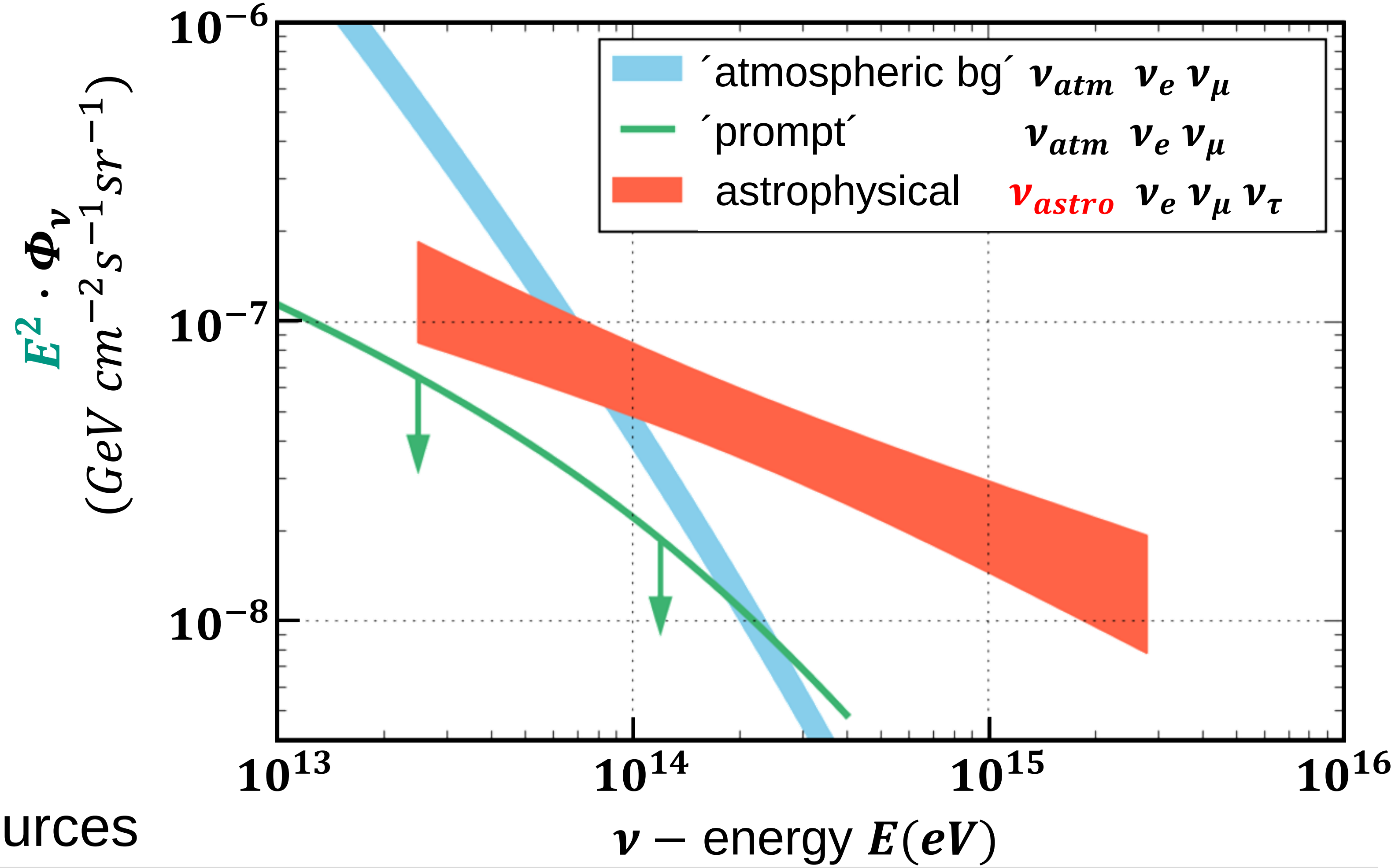
- **Atmospheric neutrinos as key background for astrophysical ν – sources**

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



ν_{atm} from 4π

ν_{astro} very few ν – sources

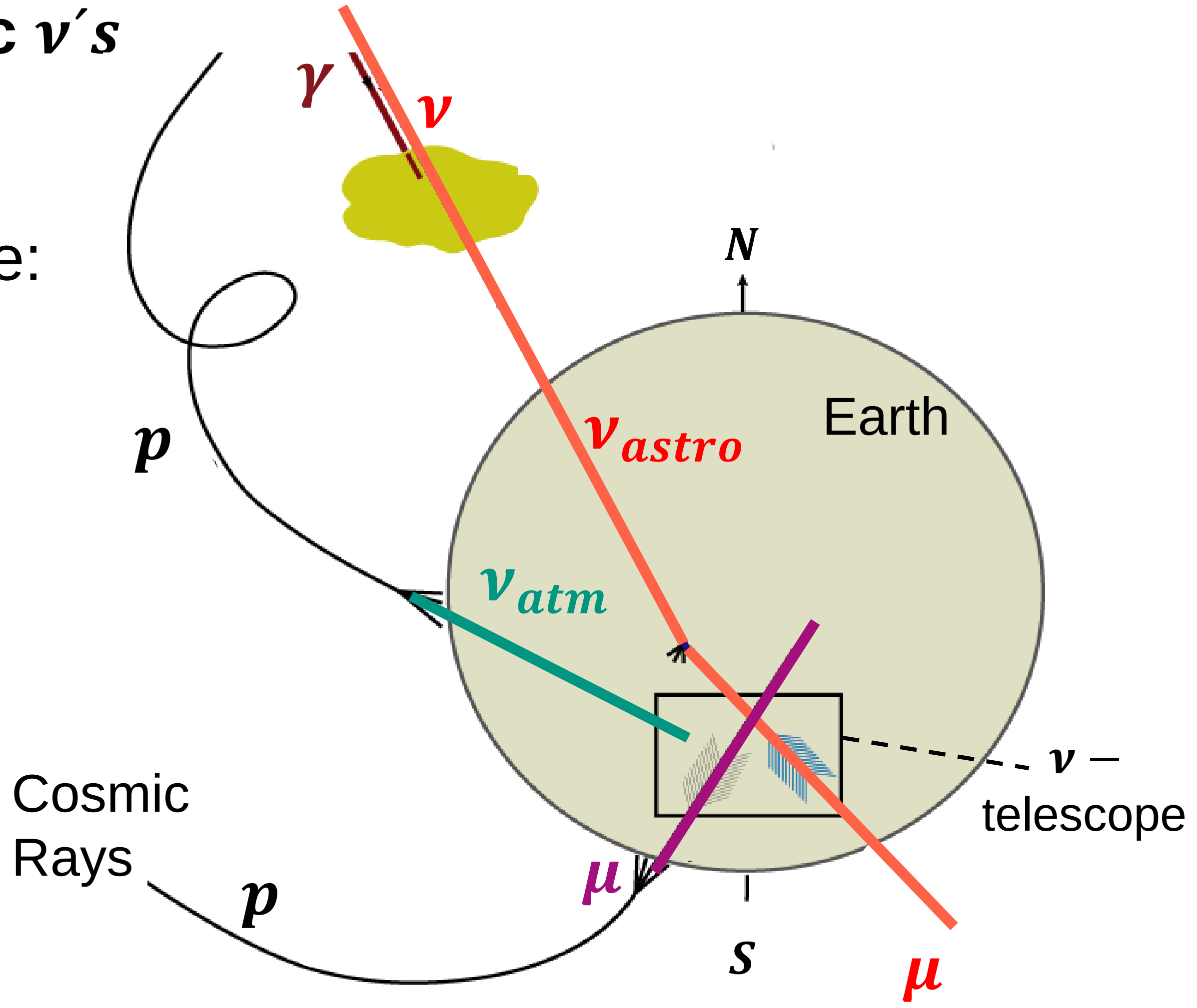


Background sources for astrophysical neutrinos

- **atmospheric muons** μ´s & **atmospheric** ν´s

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

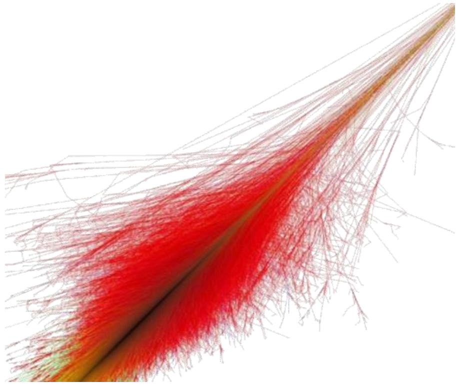
\- **muons from air showers**
high–energy muons from the atmosphere have km – scale range in ice & can cross a deep in–ice/under–water ν – **telescope**
⇨ only from ´upper´ hemisphere



Background sources for astrophysical neutrinos

Karlsruhe Institute of Technology

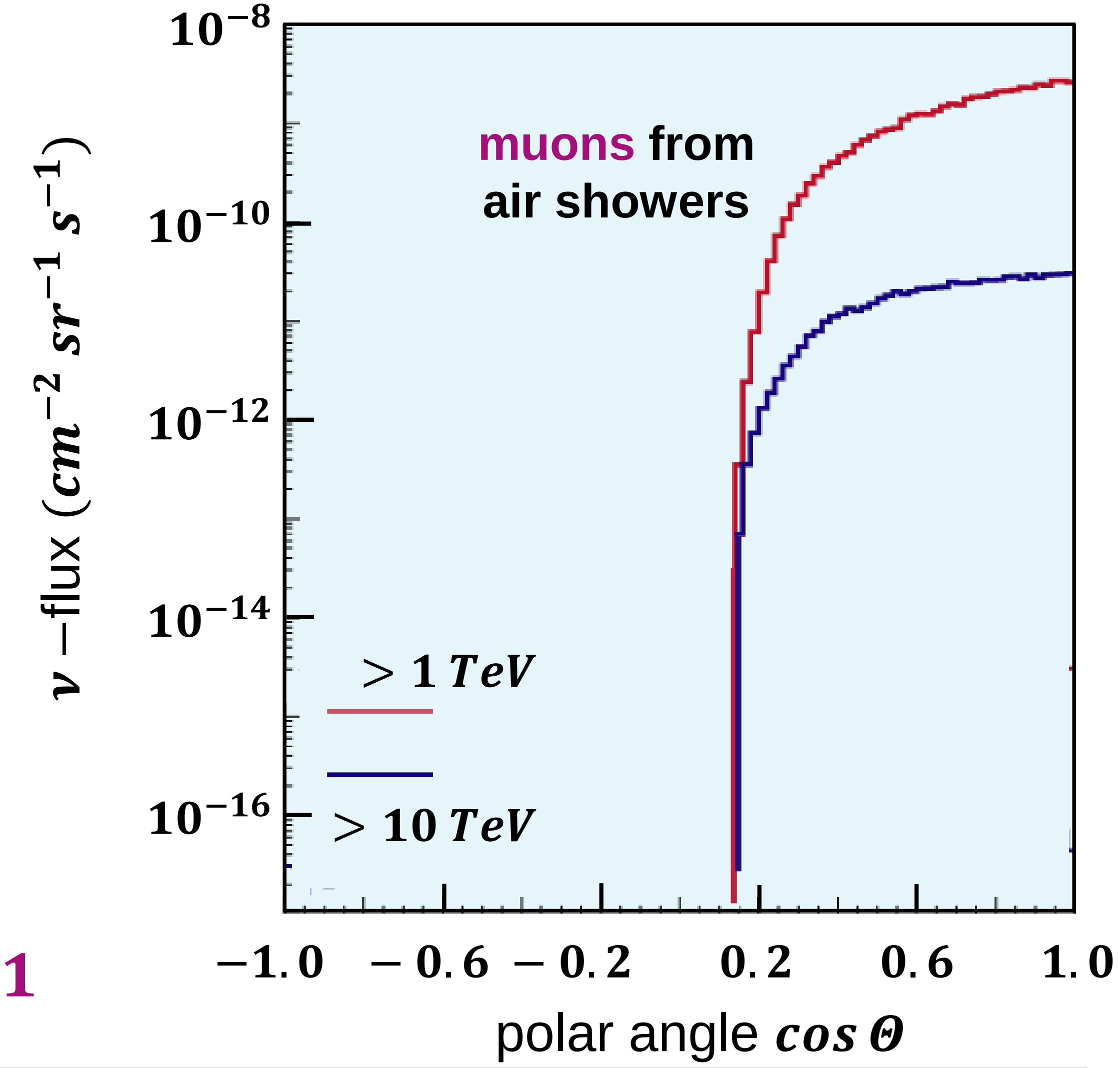
- **Background as function of Θ**



\- **muons from air showers**

high–energy muons from the atmosphere have $\boldsymbol{km}$ – scale range in ice & can cross a deep in–ice/under–water $\boldsymbol{\nu}$ – **telescope**

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



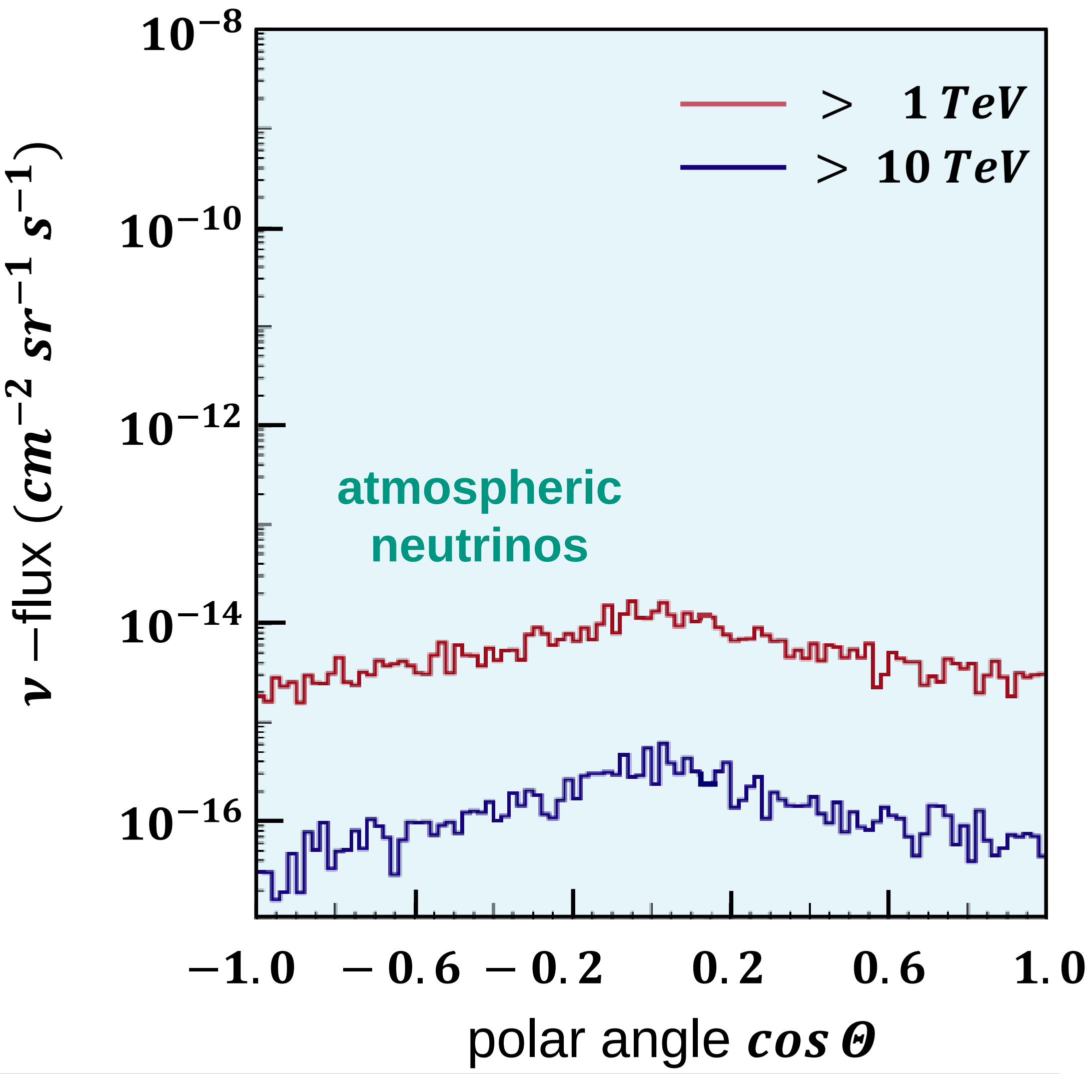
Background sources for astrophysical neutrinos

- **Background as function of Θ**

- **atmospheric neutrinos**:

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

$\cos\Theta$:
-1 (from **bottom**) …
$+1$ (from **top**)



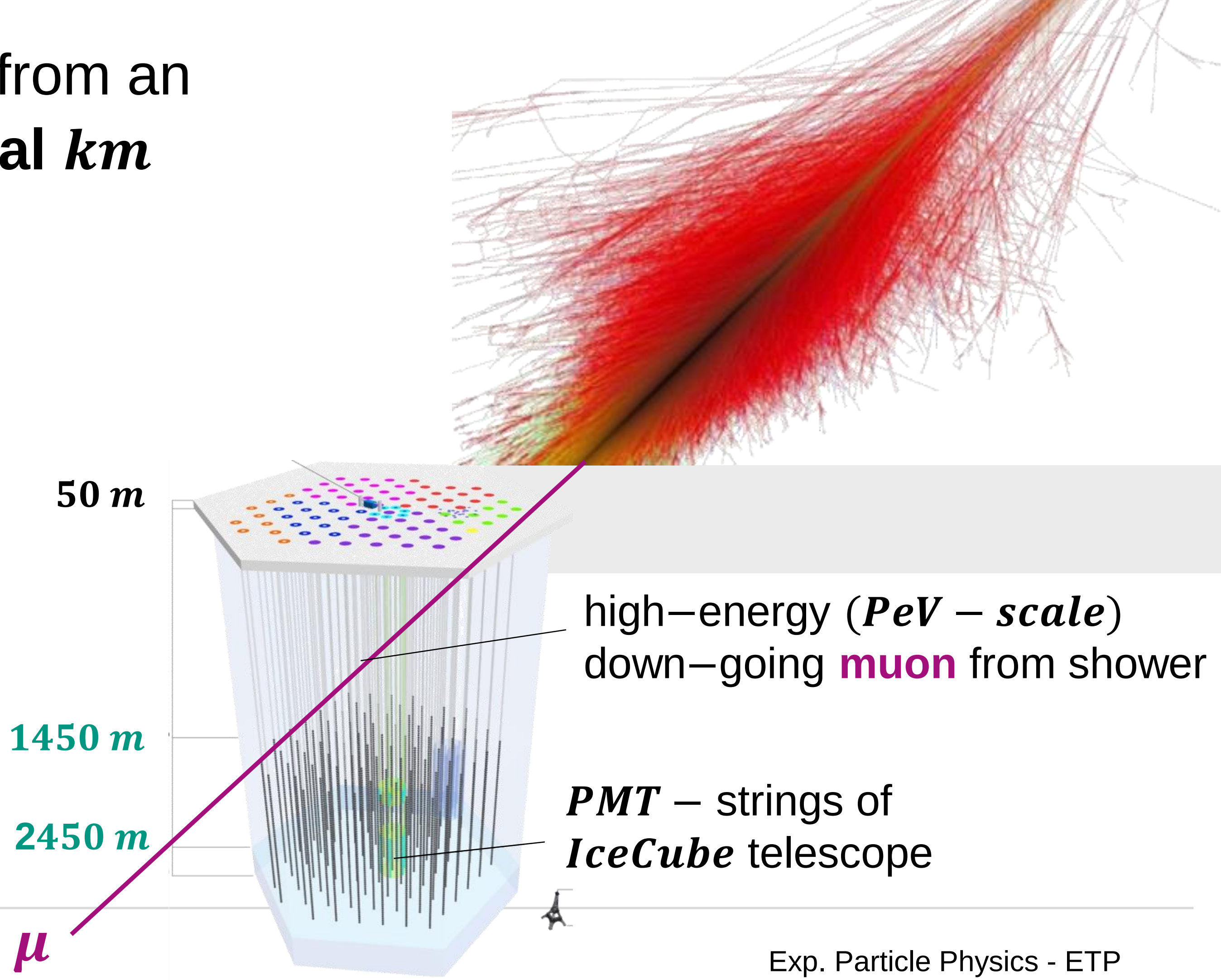
Background – penetrating muons

- **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

  - **muon range R_μ** in ice / water
    $1\ PeV$: $\quad R_\mu = 1.7\ km$
    $10\ PeV$: $\quad R_\mu = \quad 7\ km$

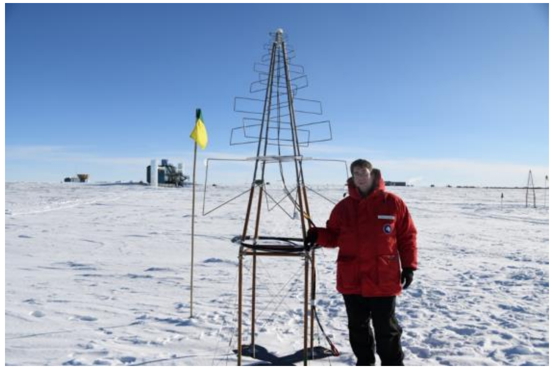
  - discrimination:
    polar angle Θ
    surface detector veto

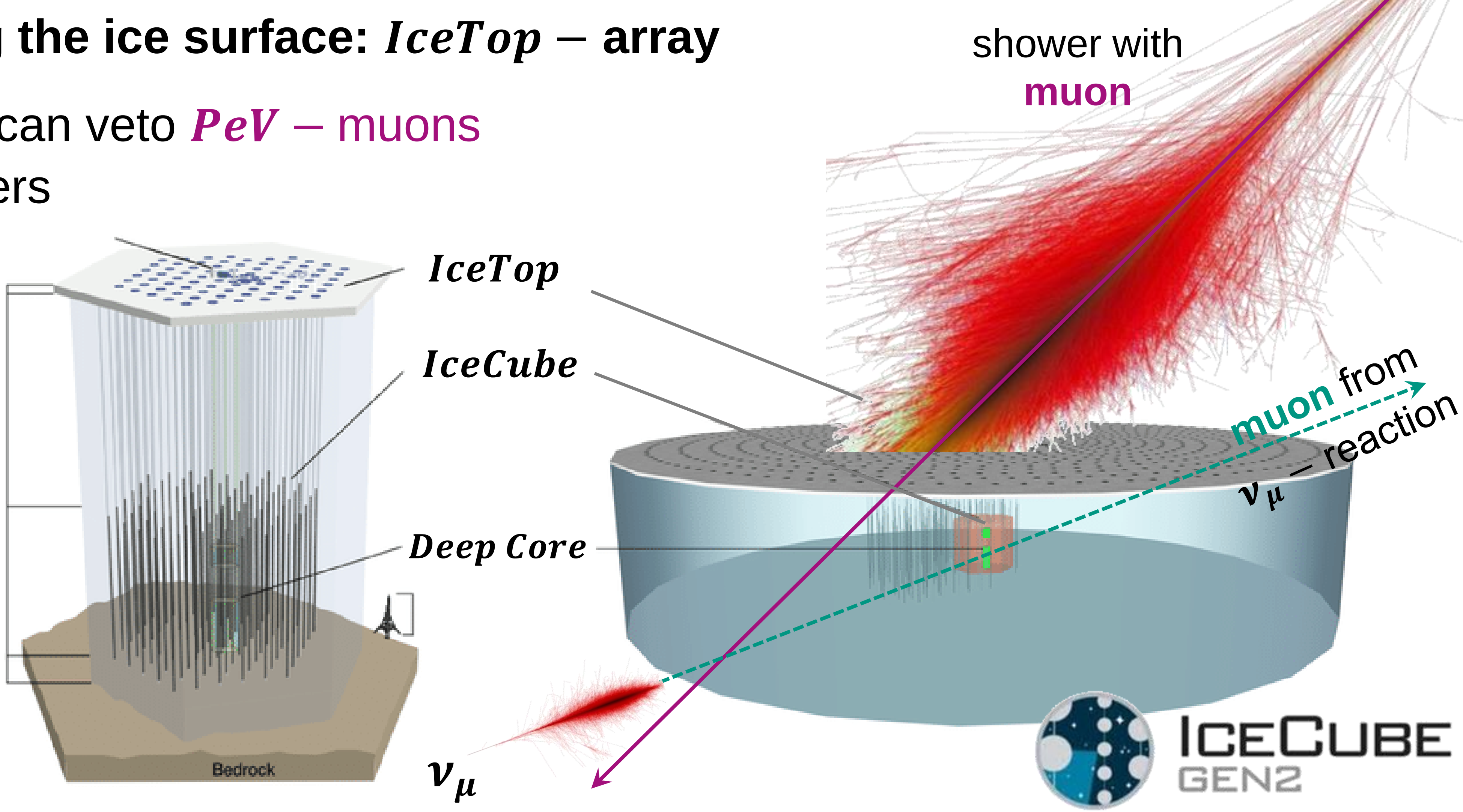


Background reduction via top CR array

- **Instrumenting the ice surface: $IceTop$ – array**
  - $IceTop$ array can veto PeV – muons from air showers

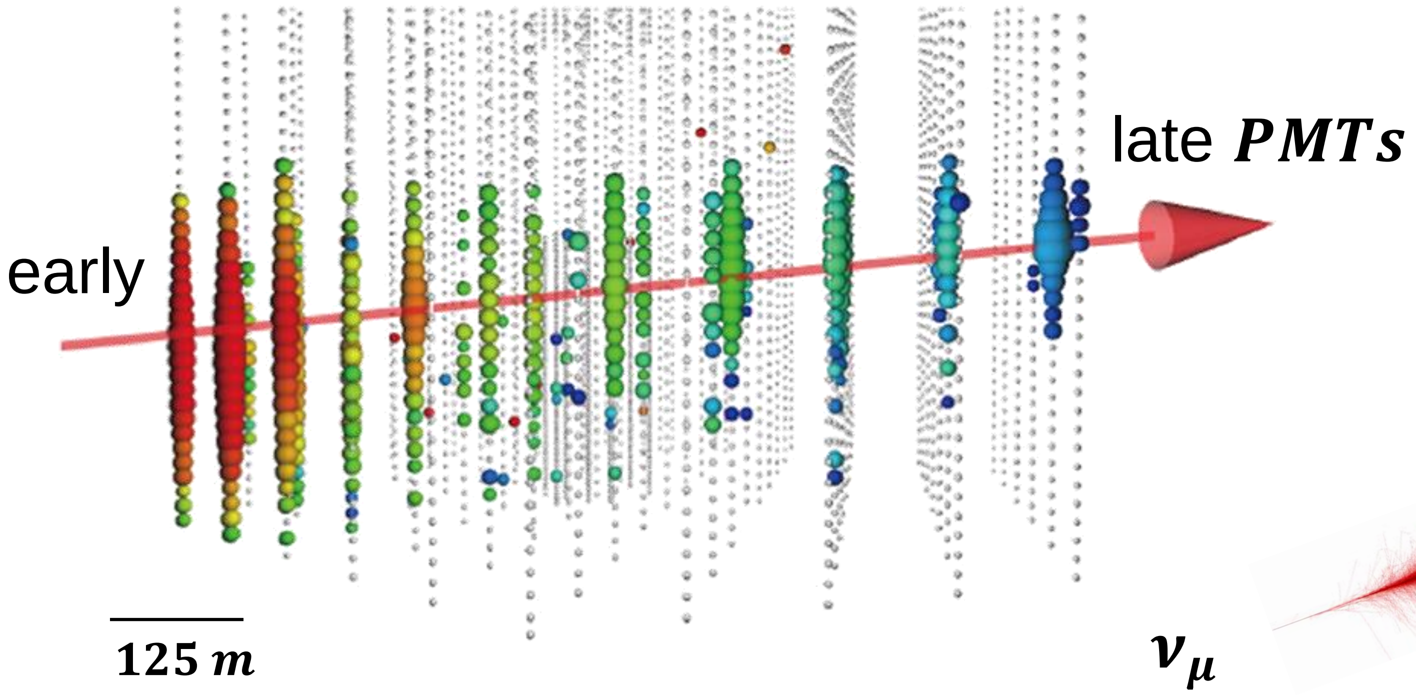
study / veto of showers

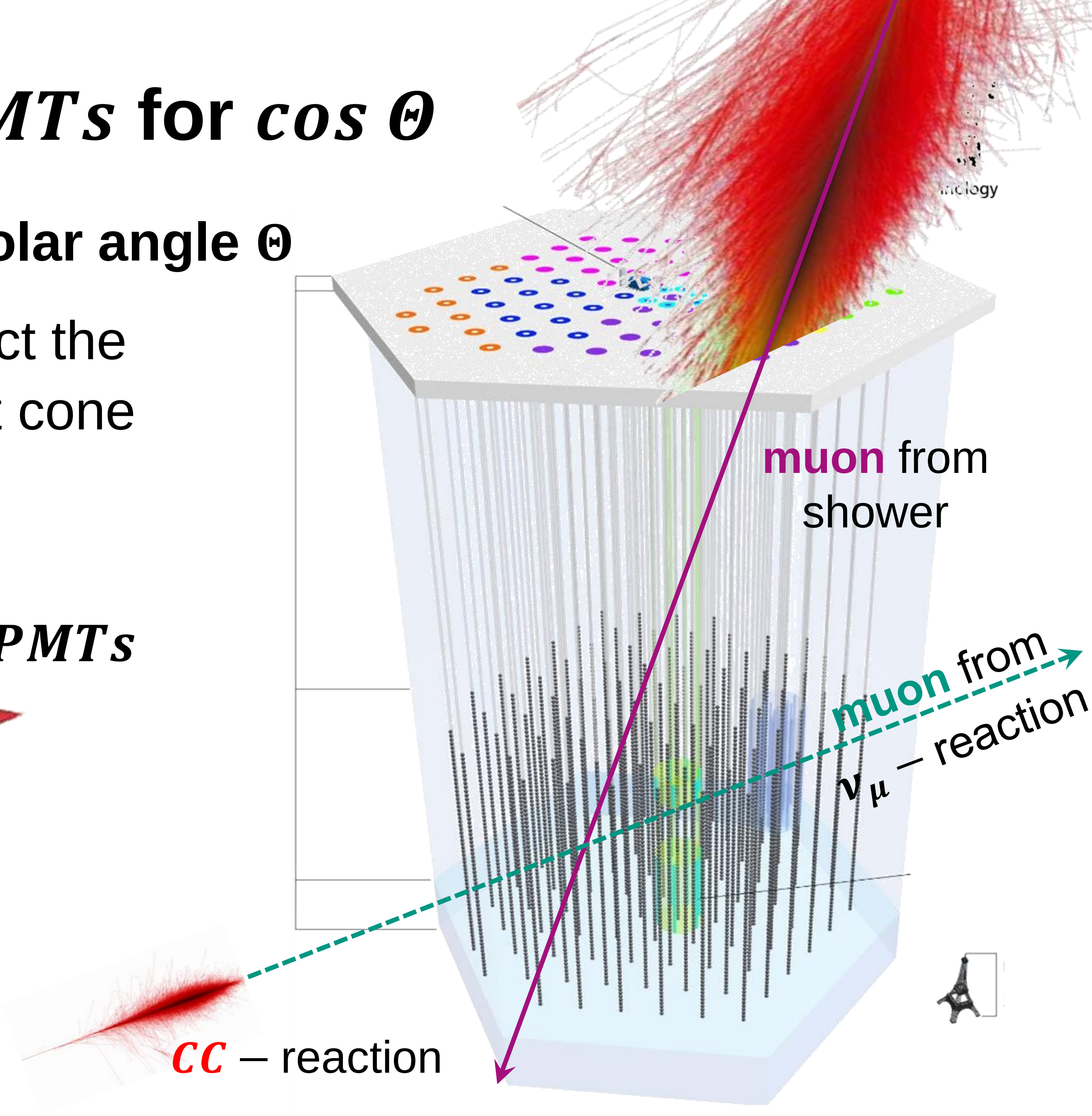




UHE neutrinos – timing of $PMTs$ for $cos\ \Theta$

- **Main discrimination via observed polar angle Θ**
  - timing of $PMTs$ allows to reconstruct the **muon** track via the Cherenkov light cone





Properties of atmospheric neutrinos

■ Atmospheric neutrinos: production in upper atmosphere

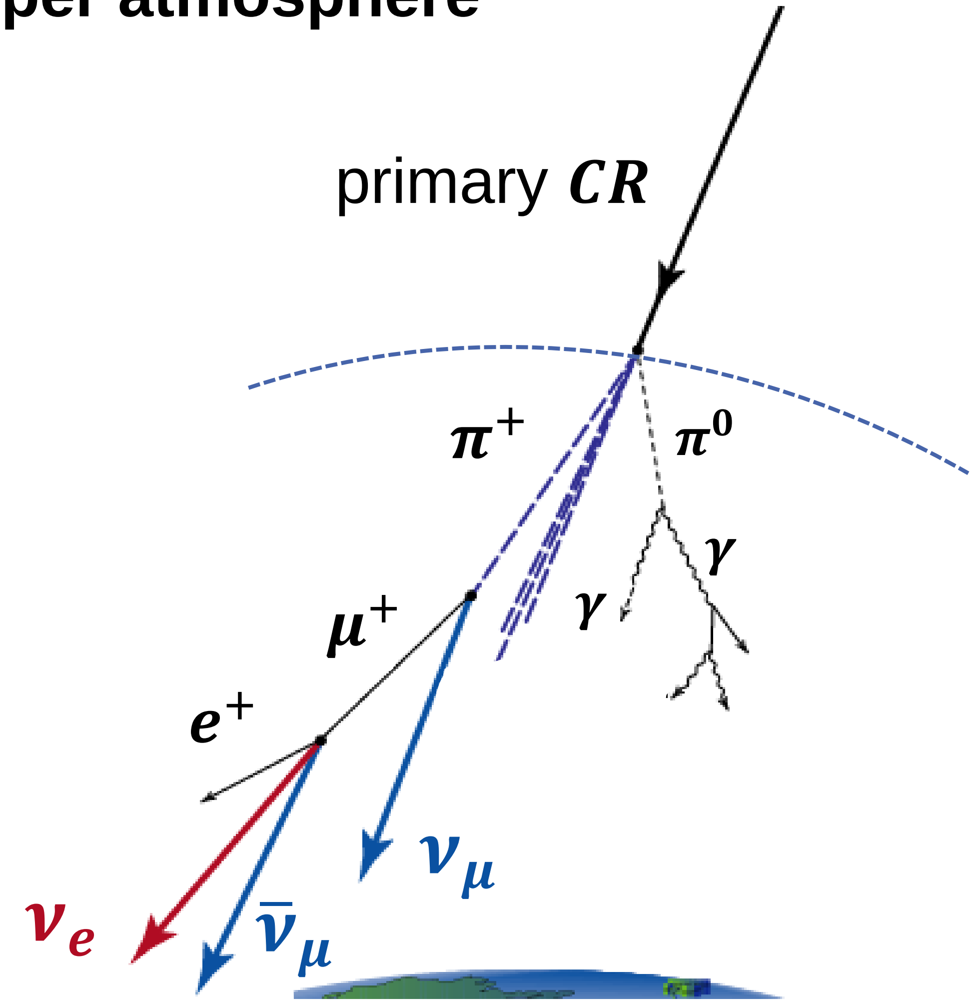
- energies: typical on GeV – scale
  dominant up to $\sim 10^{14}\ eV\ (0.1\ PeV)$

- maximum flux and **power–law**:

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

- integral flux:

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



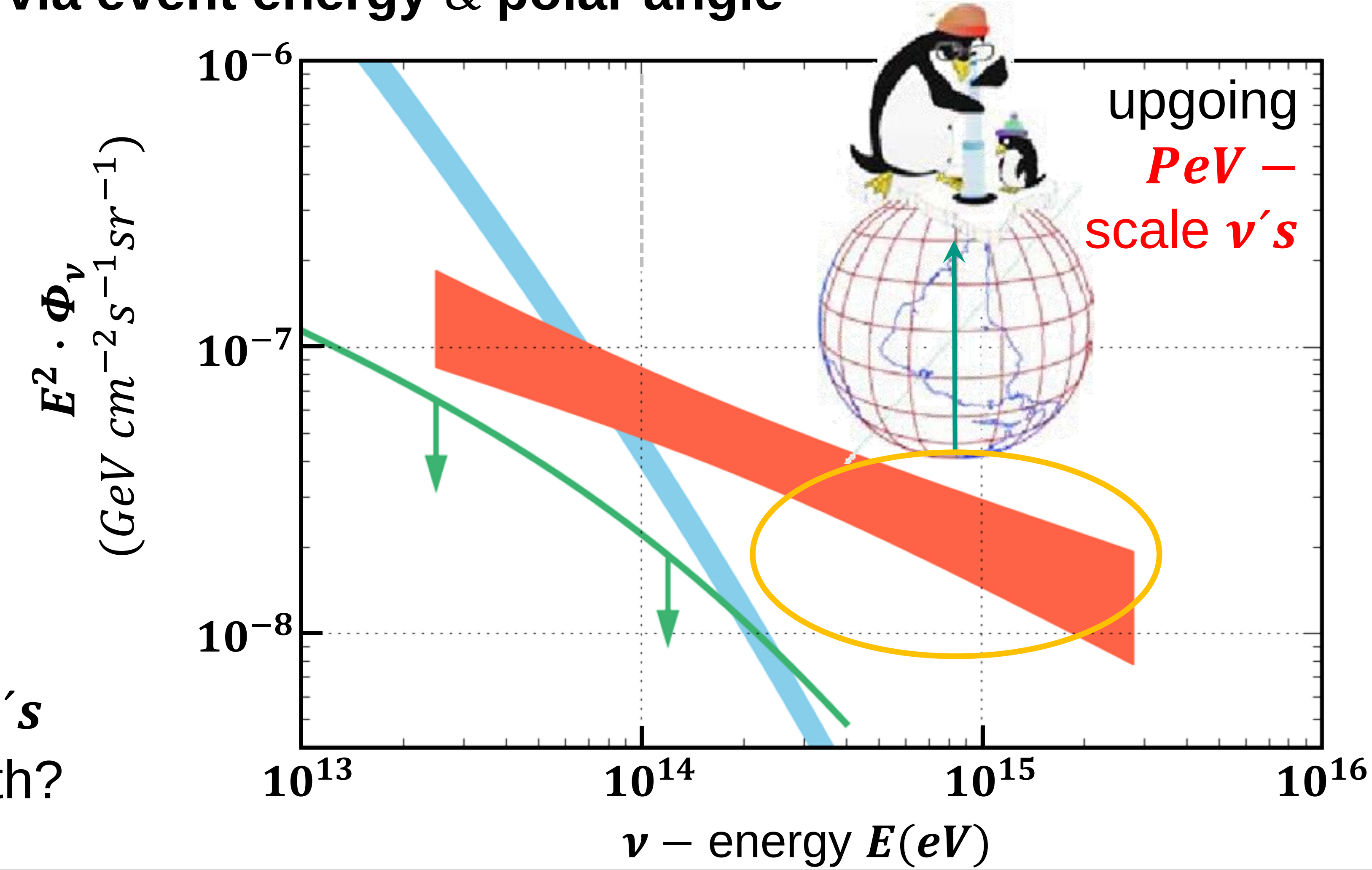
UHE neutrinos from astrophysical sources & bg

- **Discrimination of ν_{astro} via event energy & polar angle**

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

- up−going neutrinos at PeV – scale have to cross & propagate through the Earth: is this possible?

- **cross−section** of $UHE - \nu´s$ in mantle / iron−core of Earth?



UHE neutrinos – Earth starts to become opaque !

- **Deep–inelastic scattering processes of $UHE-\nu's$ inside the Earth limit field of view & observable sources for ν – telescopes**

  - ν – cross section increases linearly $\sigma_\nu \sim E_\nu$

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

    ⇨ at $E_\nu \sim 100\ TeV\ (0.1\ PeV)$:
    Earth starts to become **opaque** for $UHE-\nu's$

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

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

mean free path λ_ν :

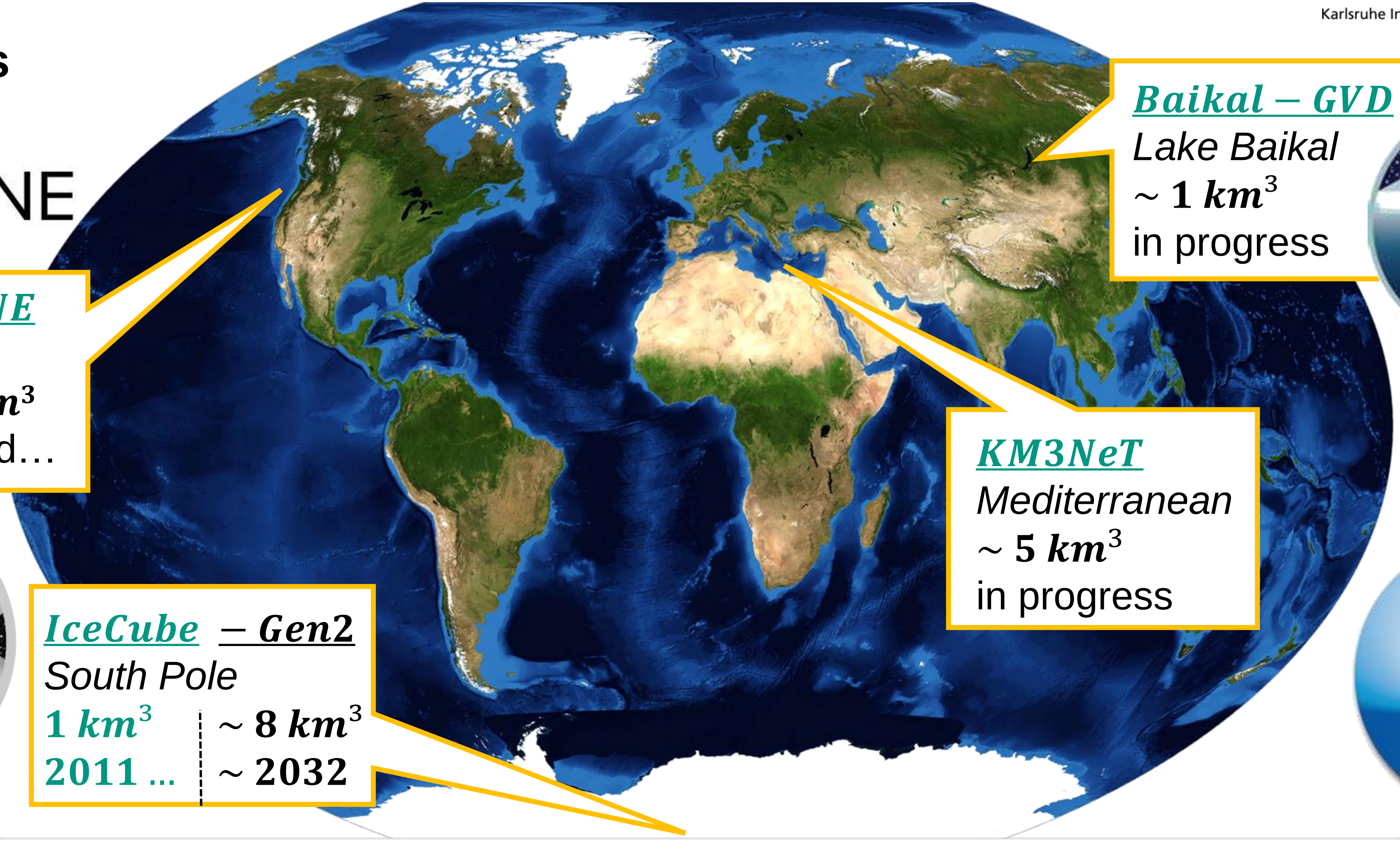
$$(1/\lambda_\nu) = \rho_{Earth} \cdot N_A \cdot \sigma_\nu$$

ρ_{Earth}

N_A = Avogadro constant

Existing & planned ν – telescopes: global overview

- **Status**



P-ONE

$\underline{P - ONE}$
Pacific
$few\ km^3$
planned…

$\underline{Baikal - GVD}$
Lake Baikal
$\sim 1\ km^3$
in progress

$\underline{KM3NeT}$
Mediterranean
$\sim 5\ km^3$
in progress

$\underline{IceCube}$ $\underline{- Gen2}$
South Pole

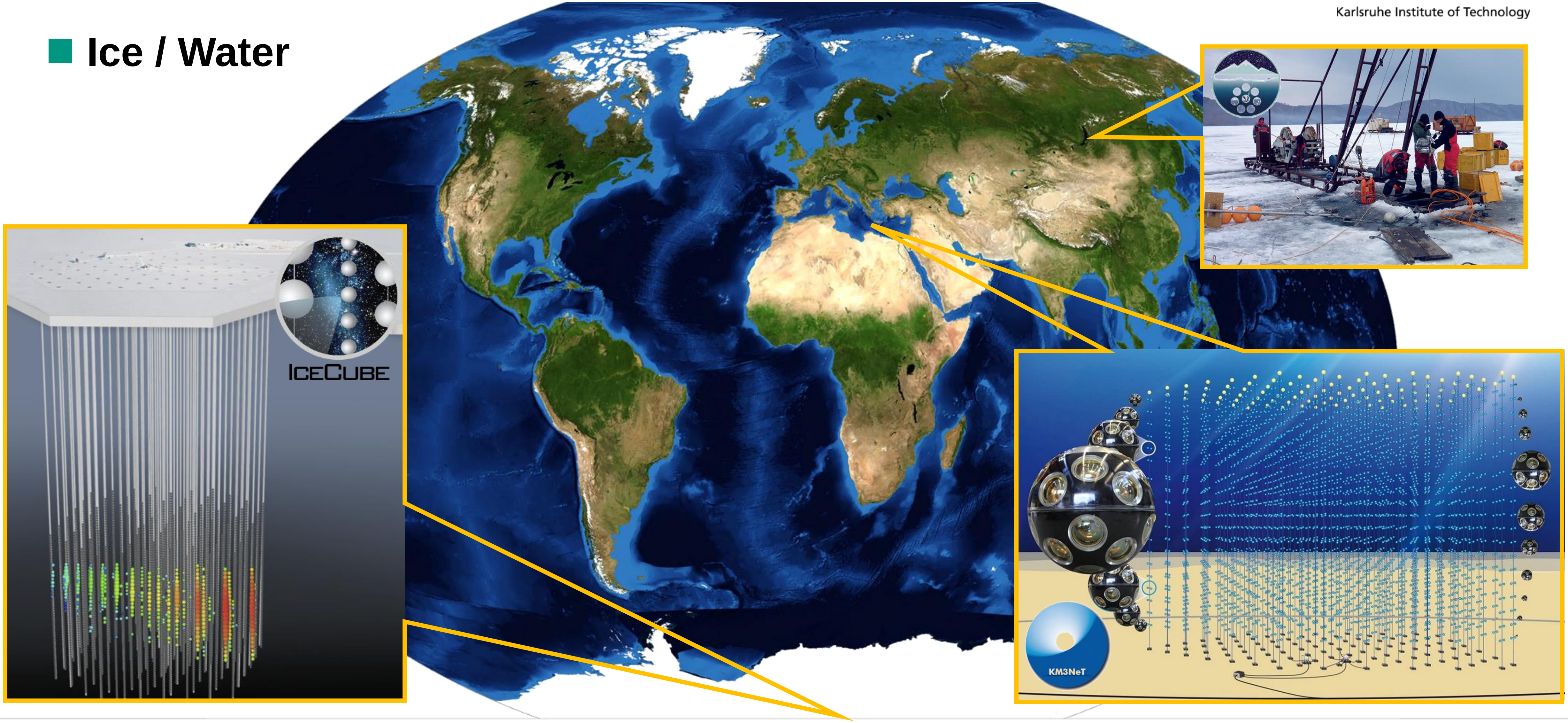
$1\ km^3$	$\sim 8\ km^3$
2011 …	~ 2032

ICECUBE

KM3NeT

Existing & planned ν – telescopes: global overview

- Ice / Water

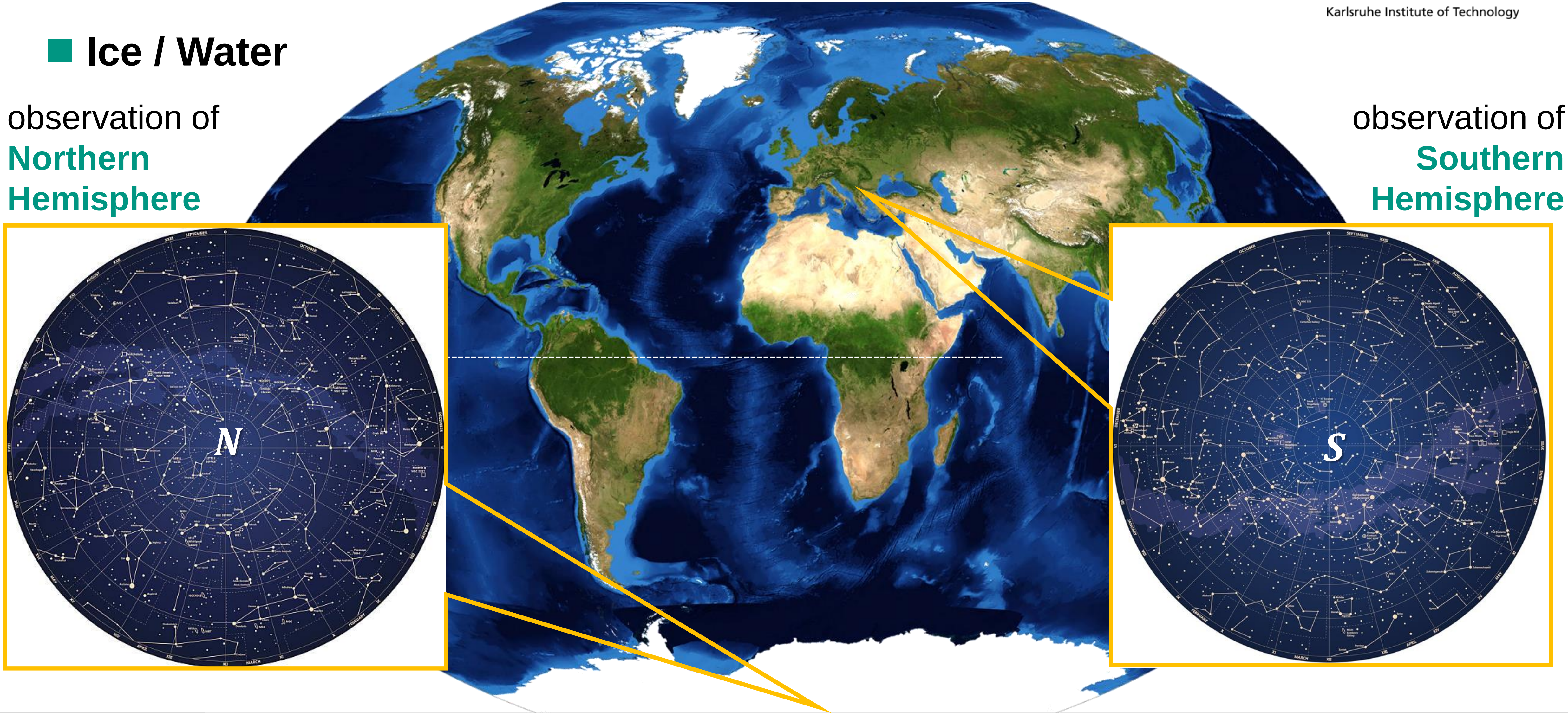


Existing & planned ν – telescopes: sky overview

- Ice / Water

observation of **Northern Hemisphere**

observation of **Southern Hemisphere**



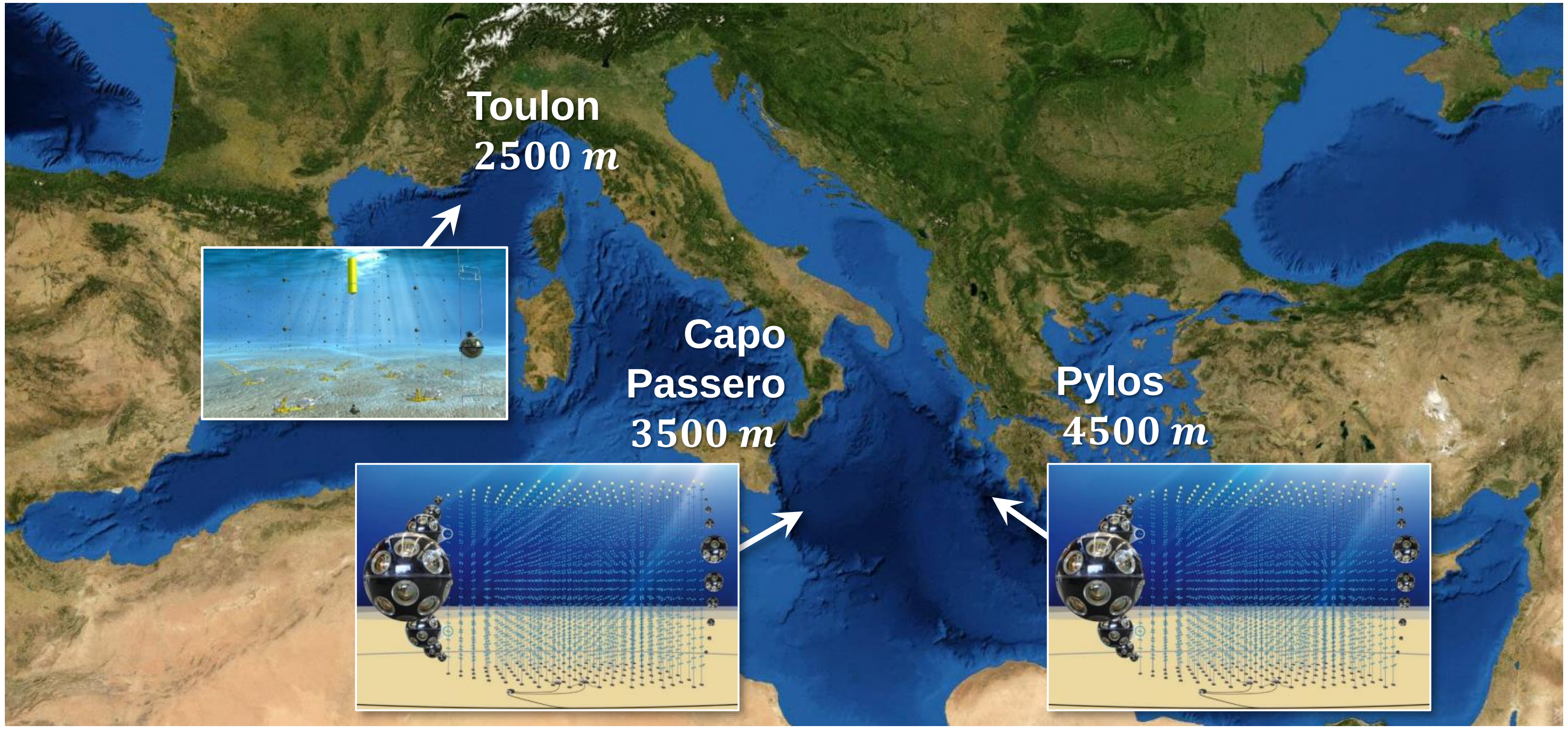
Neutrino Telescopes – $KM3NeT$

- **Detecting astrophysical & atmospheric $\nu's$ at different sites in the deep Mediterranean Sea: a European project**

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

  ~ $\mathbf{200}\ M$€ cost estimate

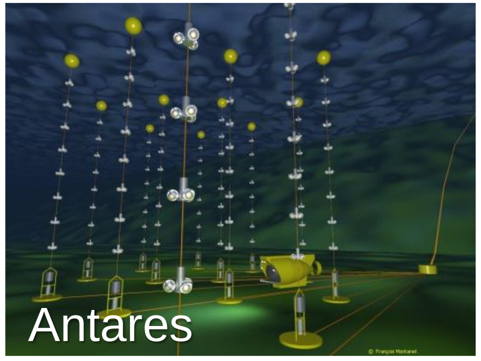
  - ongoing construction works since $\mathbf{2012}$ (!)



Neutrino Telescopes – *KM3NeT*

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

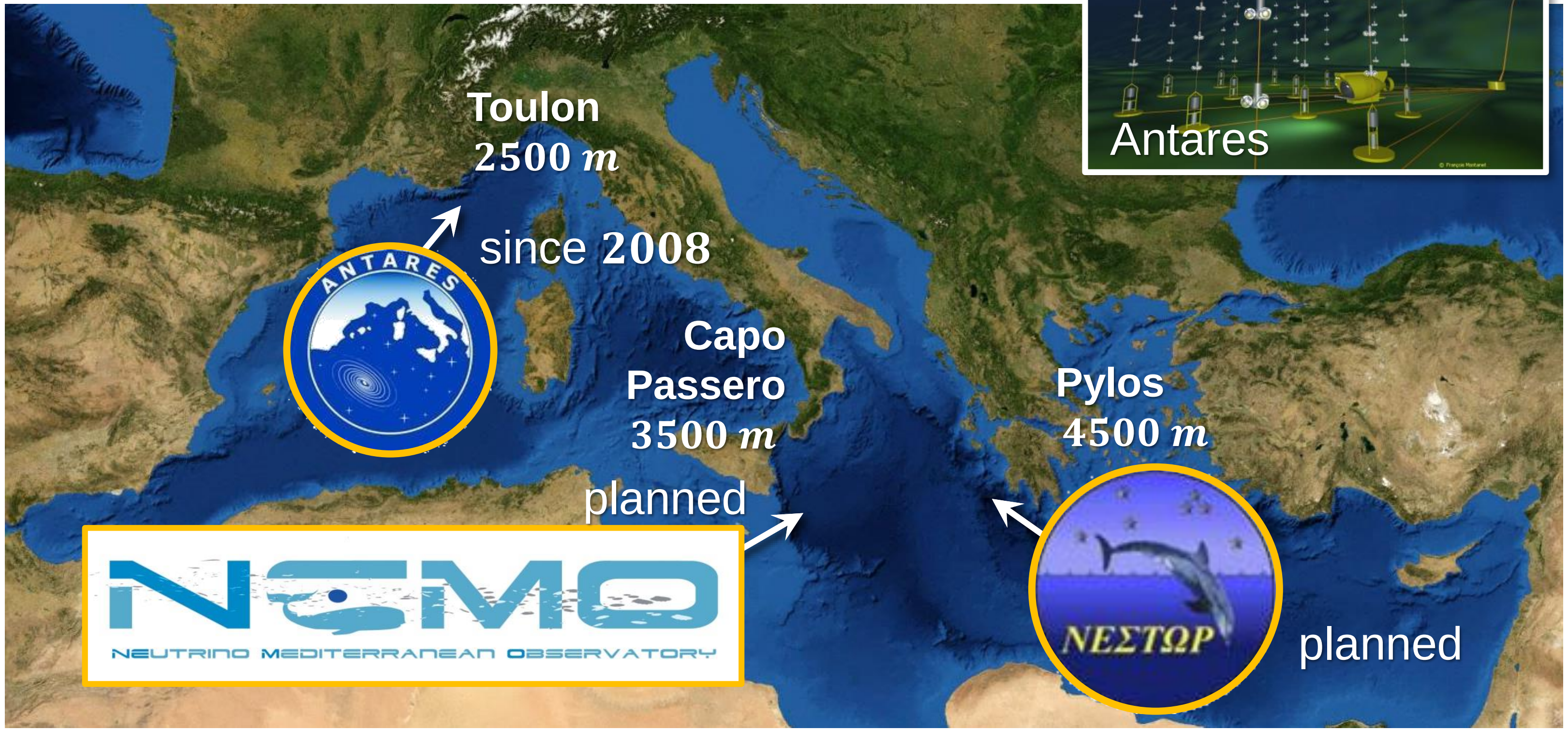
  - ***KM3NeT***: the successor to ***Antares***, ***Nemo*** & ***Nestor***



  - ***R&D****** works on many new technologies: ***PMTs***, deployment, signal read–out

  - historically: three **deep–sea** sites:

–Fr ***– It*** ***– Gr***

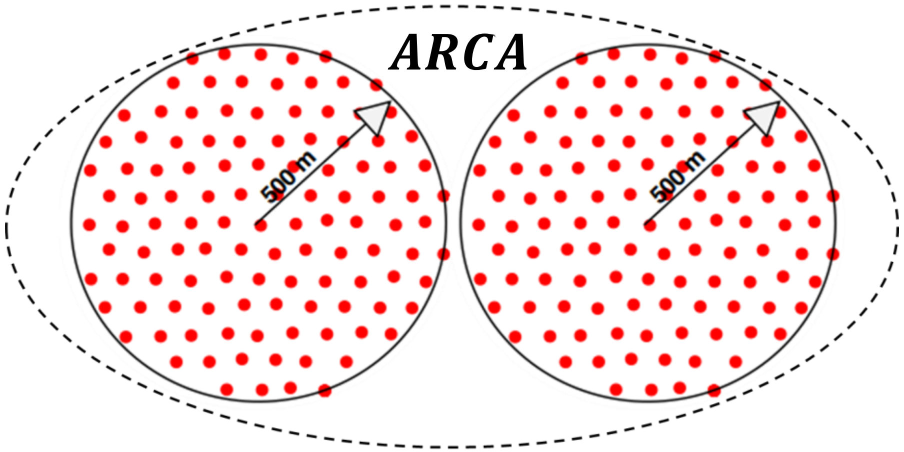


****R****esearch **&** ***D****evelopment

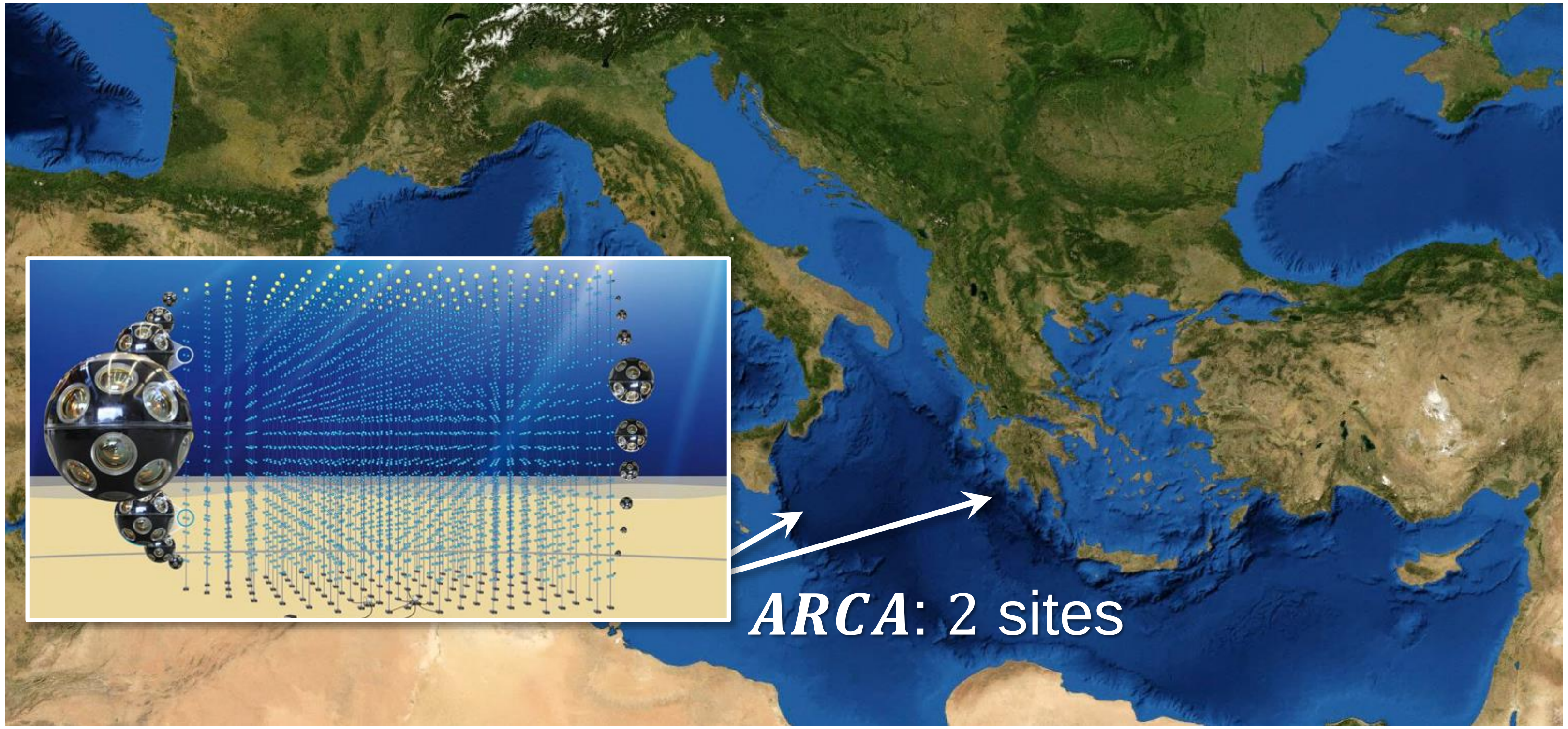
Neutrino Telescopes – $ARCA$ & $ORCA$

- $KM3NeT$ **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



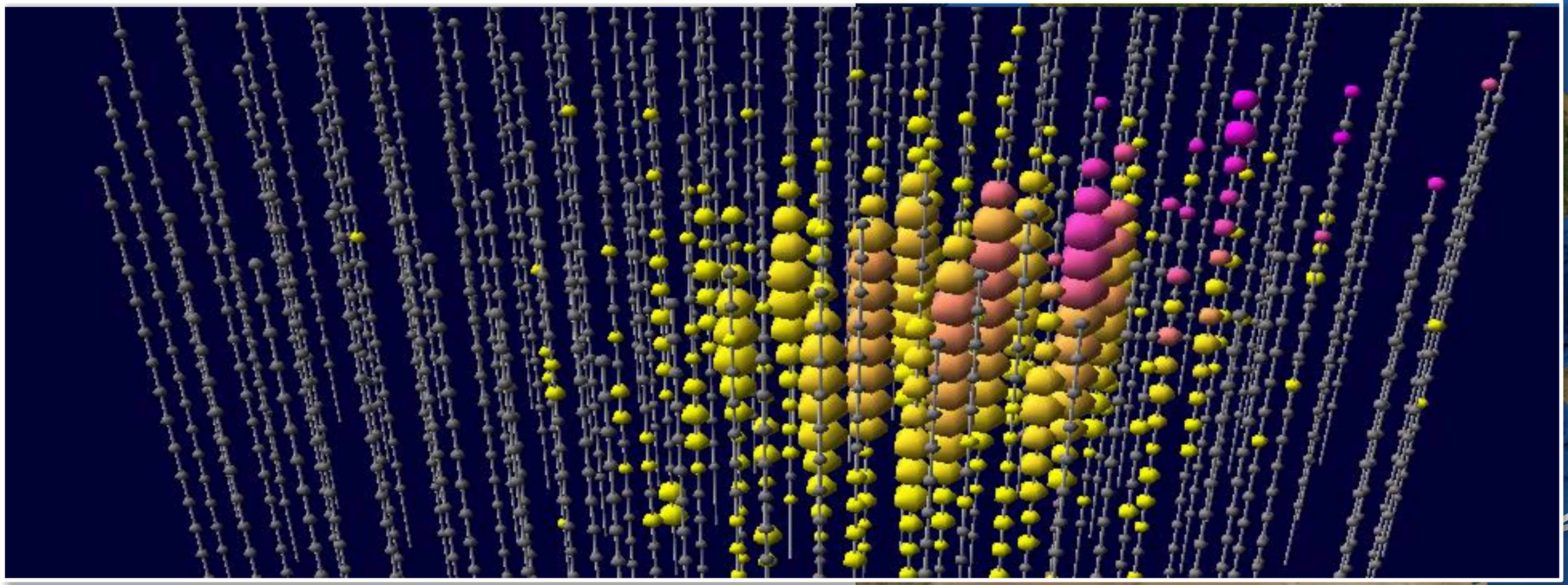
2 neutrino telescopes for
TeV ... PeV astrophys. ν´s



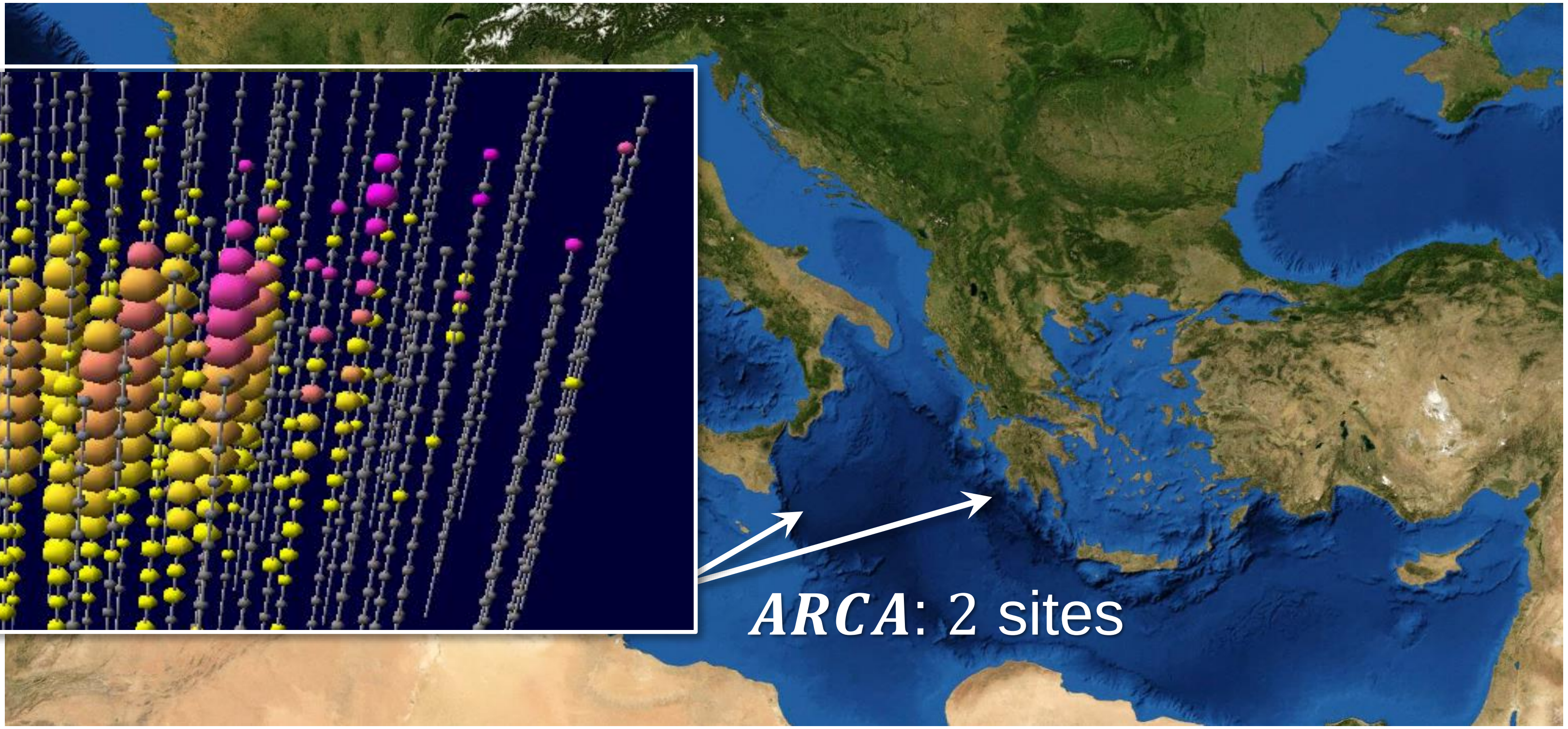
Neutrino Telescopes – *ARCA* & *ORCA*

- ***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



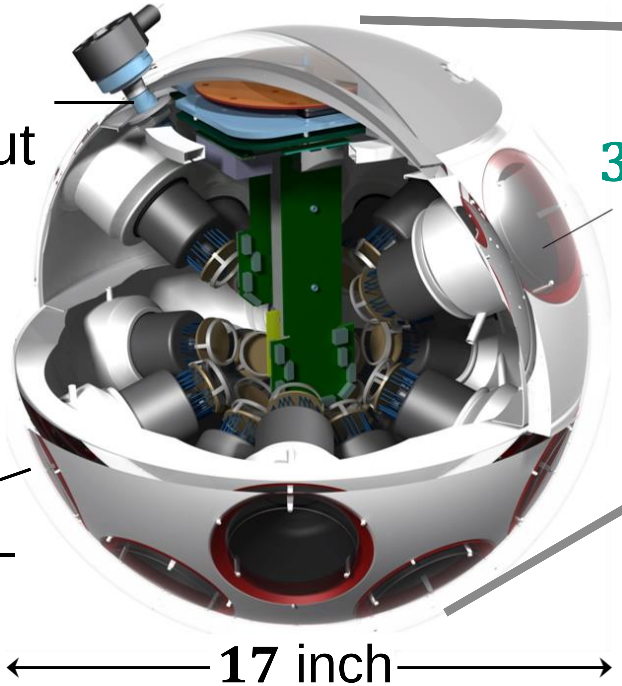
simulated *ARCA* events

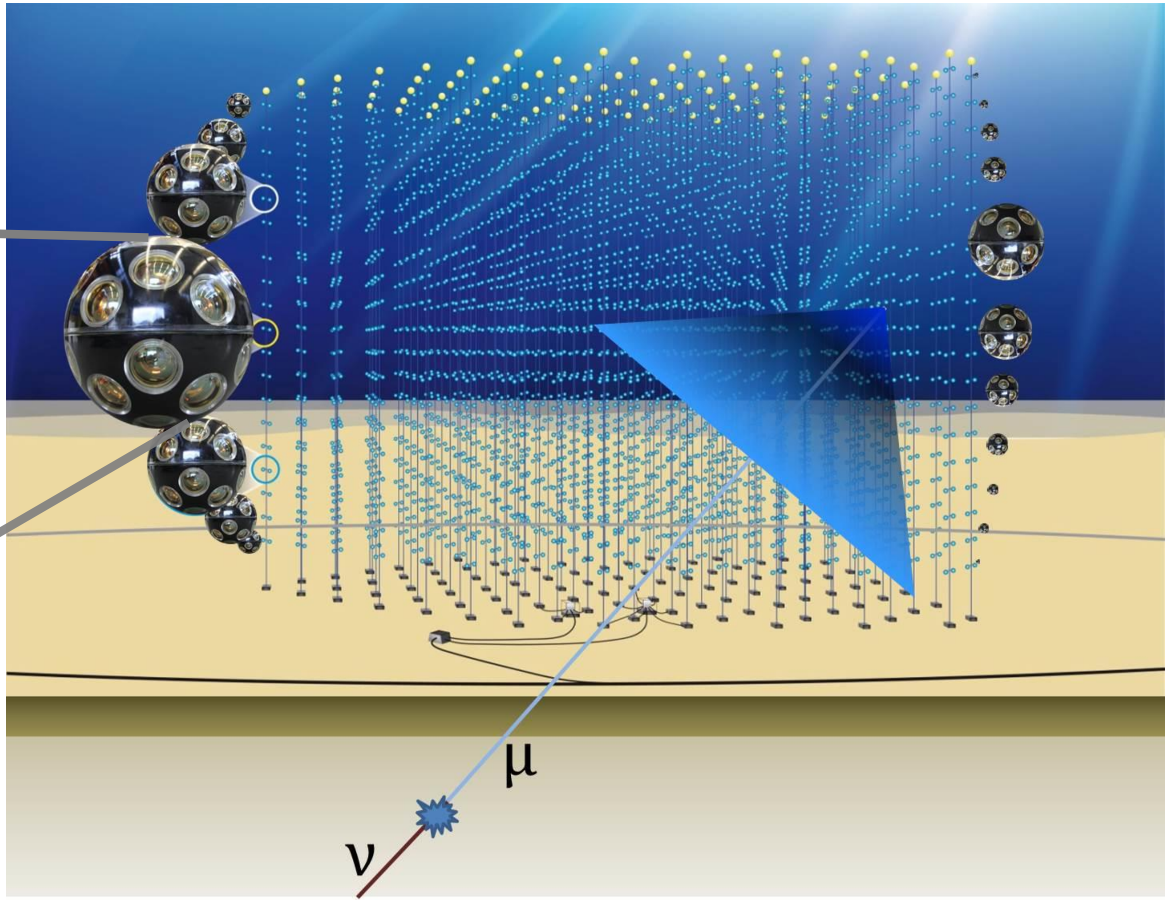


$KM3NeT$ – $ARCA$ design

- PMT – arrays based on novel concept of Digital Optical Modules*

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



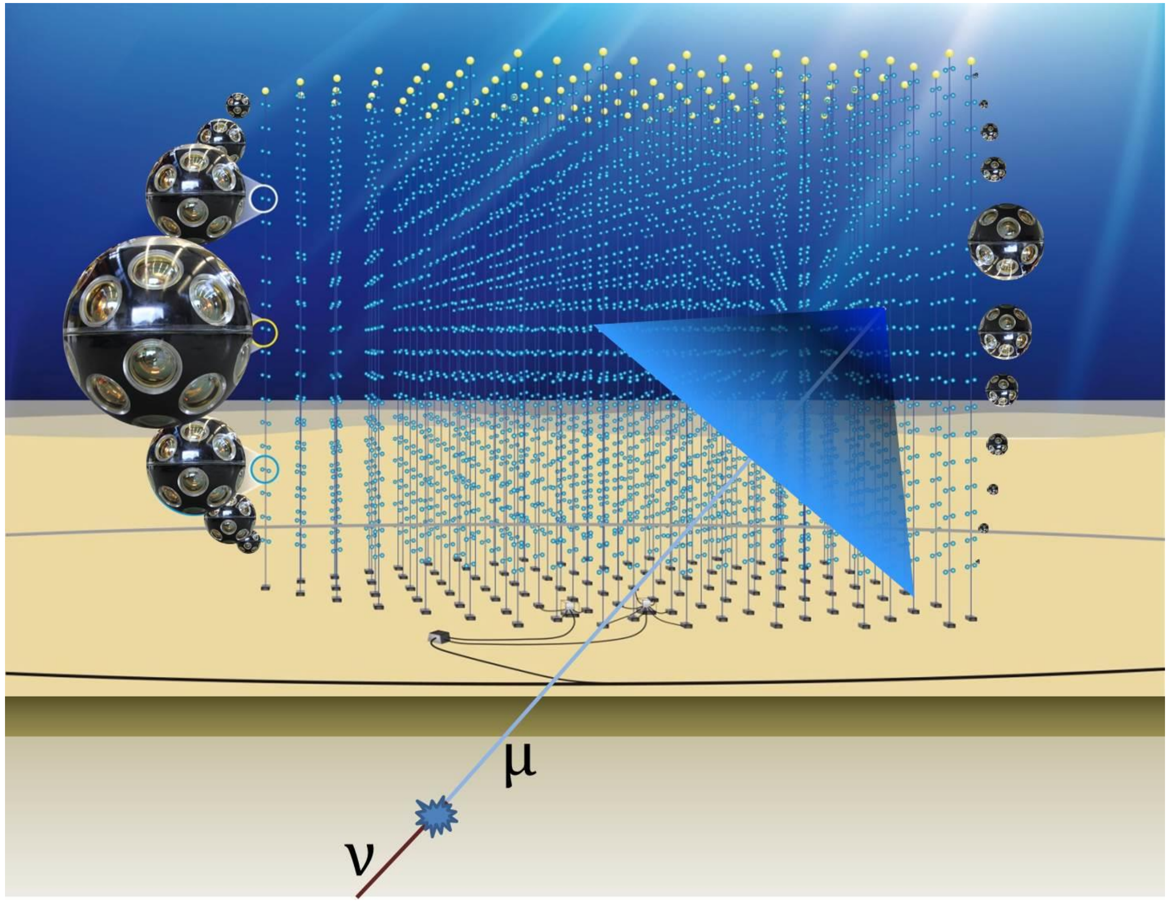


*DOM

$KM3NeT$ – $ARCA$ design & status

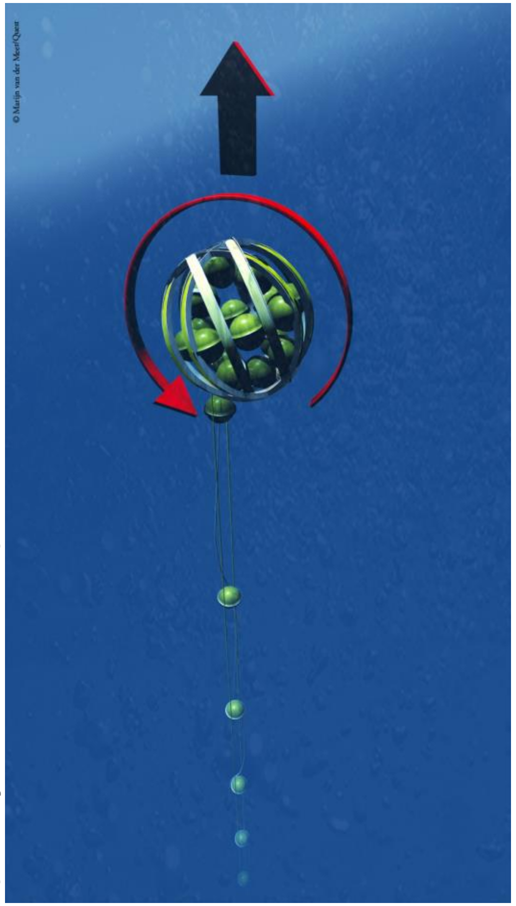
- $ARCA$ is hunting for ν – point sources with energies on the PeV – scale

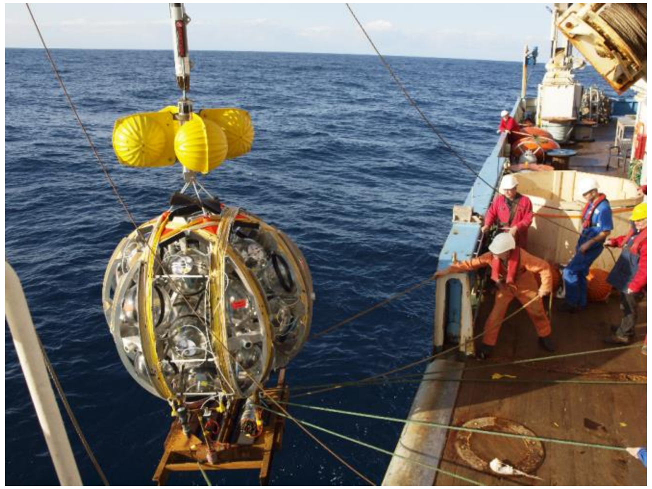
- initial design: full scale size with **600 strings**
- present design: 2×115 strings (each with $18\ DOM$ units)
- strings spaced at $d = 90\ m$, each with length $l = 650\ m$
- status ($10/2023$): 28 units are deployed (start was in 2015) with $504\ DOMs$ deployed therein
- ongoing data–taking

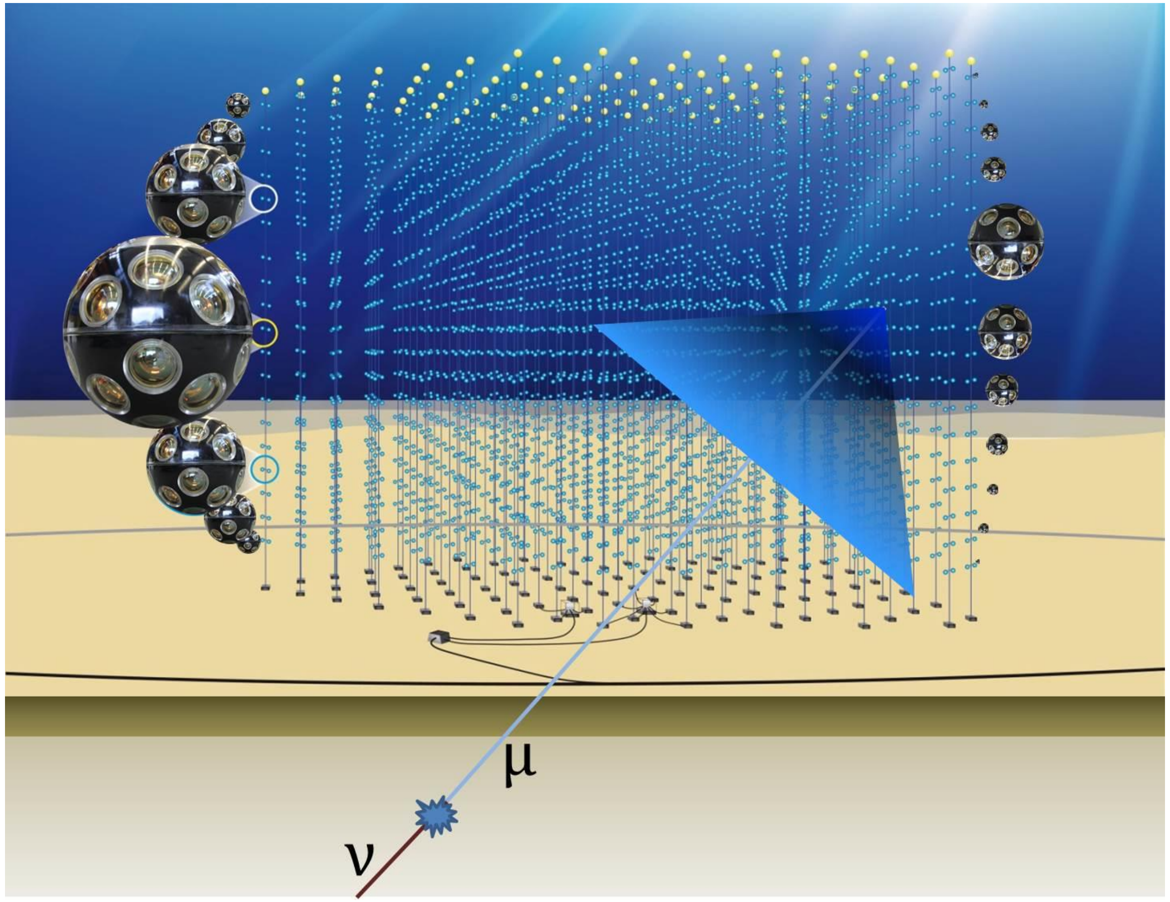


KM3NeT – *ARCA* deployment

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







Q: Marijn van der Meer/Quest

[Trailer: KM3NeT ORCA line deployment - YouTube]

Topical: Interesting article on $KM3NeT$

- A ´deep dive´ into the Mediterranean´s dark abyss

NEUTRINOS OUT OF THE BLUE

More than 17,000 photomultipliers for KM3NeT are already transmitting data from the Mediterranean seabed, opening a new vista on the neutrino's properties. Paschal Coyle, Antoine Kouchner and Gwenhaël De Wasseige take a deep dive.

In the dark abysses of the Mediterranean Sea, what promises to be the world's largest neutrino telescope, KM3NeT, is rapidly taking shape. Using transparent sea-water as the detection medium, its large three-dimensional arrays of photosensors will instrument a volume of more than one cubic kilometre and detect the faint Cherenkov light induced by the passage of charged particles produced in nearby neutrino interactions. The main physics goals of KM3NeT are to detect high-energy cosmic neutrinos and identify their astrophysical origins, as well as to study the fundamental properties of the neutrino itself.

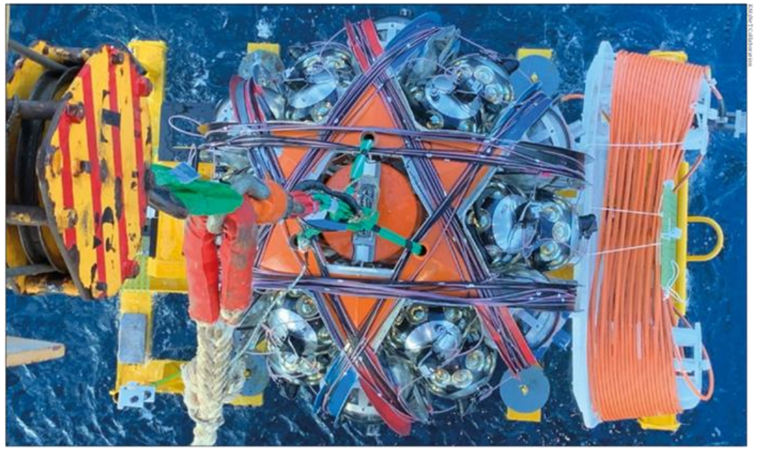
KM3NeT (the Cubic Kilometre Neutrino Telescope) is the successor to the ANTARES neutrino telescope, which operated continuously from 2008 and has recently been decommissioned (see "The ANTARES legacy" panel, p32). KM3NeT comprises two detectors: ARCA (Astroparticle Research with Cosmics in the Abyss), located at a depth of 3500 m offshore from Sicily, and ORCA (Oscillation Research with Cosmics in the Abyss), located at a depth of 2450 m offshore from southern France. ARCA is a sparse detector of about 1 km^3 that is optimised for the detection of TeV–PeV neutrinos, while ORCA is a 7 Mt-dense detector optimised for sub-TeV neutrinos. The KM3NeT collaboration comprises more than 250 scientists from 16 countries.

The key technology is the digital optical module (DOM) – a pressure-resistant glass sphere hosting 31 three-inch photomutiplier tubes, various calibration devices and the readout electronics (see "Modular" image). A total of 18 DOMs are hosted on a single detection line, and the lines are anchored to the seafloor and held taut by a submerged buoy. The ORCA detector will comprise around 100 lines and the ARCA detector will have twice as many. The bases of the lines are connected via cables on the seafloor to junction boxes, from which electro-optical cables many tens of kilometres long bring the data to shore along optical fibres. Information on every single photon is transmitted to the shore stations, where trigger algorithms are applied to select interesting events for offline analysis.

From the light pattern recorded by the DOMs, the energy and the direction of a neutrino can be estimated. Furthermore, the neutrino flavour can also be distinguished; muon neutrino charged-current (CC) interactions produce an extended track-like signature (see "Subsea shower" image) whereas electron- and tau-neutrino CC interactions, as well as neutral-current interactions, produce more compact shower-like events. By selecting up-going neutrinos, i.e. those that have travelled from the other side of Earth, the large background from down-going atmospheric muons can be rejected and a clean sample of neutrinos obtained.

The first KM3NeT detection line was connected in 2016 and currently a total of 32 lines are operating at the two sites. The first science results with these partial detectors have already been obtained.

THE AUTHORS
Paschal Coyle *Centre de Physique des Particules de Marseille, CNRS, Aix-Marseille University, France;* **Antoine Kouchner** *Laboratoire Astroparticule et Cosmologie, Université Paris Cité, CNRS, France; and* **Gwenhaël De Wasseige** *Centre for Cosmology, Particle Physics and Phenomenology, UCLouvain, Belgium.*



First descent *One of the KM3NeT lines bundled up before being unwound and lowered into position.*

Modular *The assembly room for the KM3NeT optical modules, with a photo of the first prototype module visible as a screen saver.*

Fundamental neutrino properties

Sixty-six years after their discovery, neutrinos remain the most mysterious of the fermions. As they whiz through the universe, barely interacting with any other particles, they have the unique ability to oscillate between their three different types or flavours (electron, muon and tau). The observation of neutrino oscillations in the late 1990s implies that neutrinos have a non-zero mass, contrary to the Standard Model expectation. Understanding the origin and order of the neutrino masses could therefore unlock a path to new physics. Numerous neutrino experiments around the world are closing in on the neutrino's properties, using both artificial (accelerator and reactor) and natural (atmospheric and extraterrestrial) neutrino sources.

Sixty-six years after their discovery, neutrinos remain the most mysterious of the fermions

The KM3NeT/ORCA array is optimised for the detection of atmospheric neutrinos, produced when cosmic rays strike atomic nuclei at an altitude of around 15 km. Such interactions produce a cascade of particles on Earth's surface, mostly pions and kaons, which decay to neutrinos capable of traversing the entire planet. About two thirds of these are muon neutrinos and antineutrinos, and the remainder are electron neutrinos and antineutrinos.

Measuring the directions and energies of the detected atmospheric neutrinos allows the oscillatory behaviour of neutrinos to be studied, and thus elements of the leptonic "PMNS" mixing matrix to be determined. The measured direction is used as a proxy for the distance the atmospheric neutrino has travelled through Earth between its points of production and detection. First preliminary results with six ORCA lines and one year of data clearly show the expected disappearance of muon neutrinos with increasing baseline/energy. The corresponding constraints on θ_{23} (the mixing angle between the m_2 and m_3 states) and Δm^2_{32} (the mass difference of the squared masses) already start to be competitive with multi-year results from the current long-baseline accelerator experiments (see "Physics debut" figure, p33).

A longer-term physics goal of KM3NeT is to determine the neutrino mass ordering, i.e. whether the third neutrino

HOT TOPIC

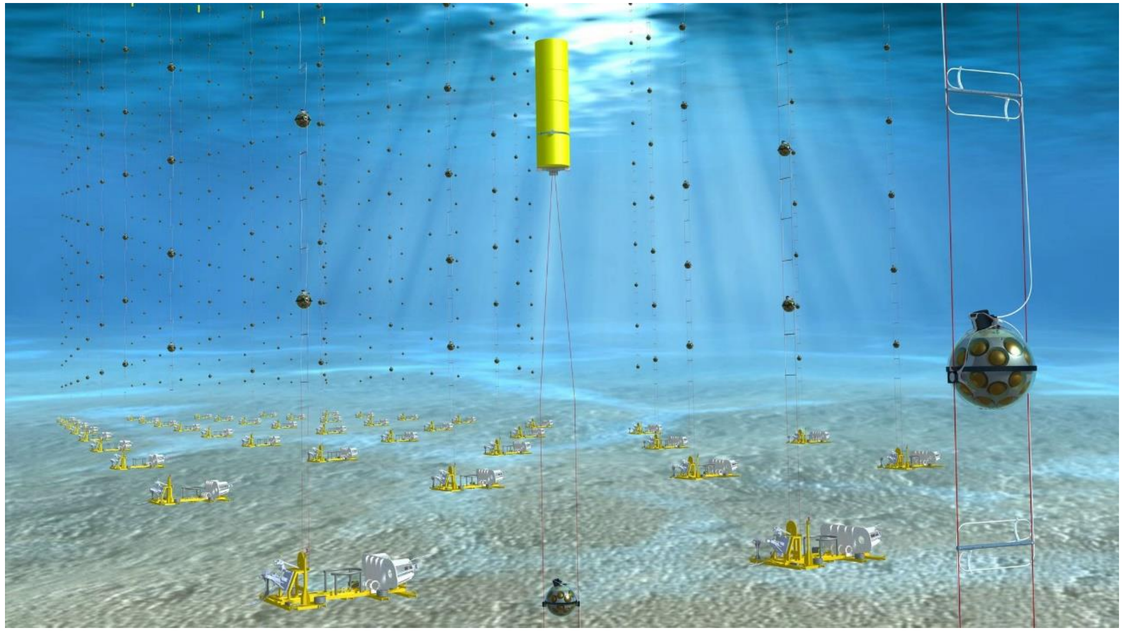
CERNCourier2022NovDec-digitaledition.pdf

$KM3NeT - ORCA$: study of ν – oscillations

Karlsruhe Institute of Technology

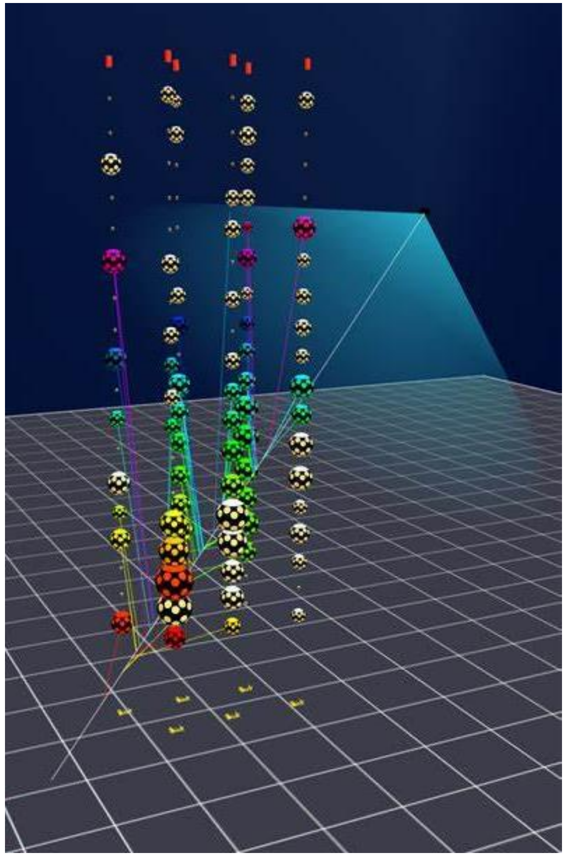
- **$KM3NeT$ subsystems: $ARCA$ (2 sites) & $ORCA$ (1 site)**

  - $ORCA$: Oscillation Research with Cosmics in the Abyss



goal: study of **oscillation processes** of atmospheric $\nu ´s$

- $ORCA$ full scale: 115 strings ($\ell = 150\ m$, each with $18\ DOMs$)
- **$DOMs$ with much finer spacing (GeV scale)**
- at a depth $d = 2.5\ km$
- status (as of $3/2023$): 14 strings deployed



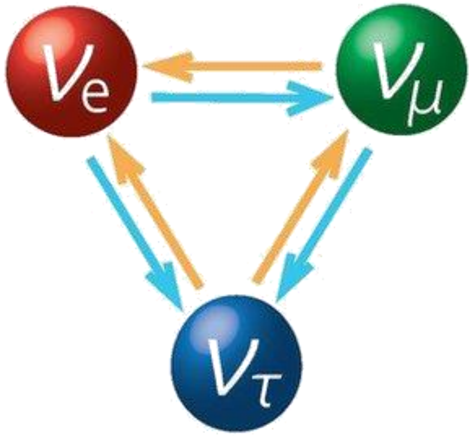
$KM3NeT - ORCA$: study of ν – oscillations

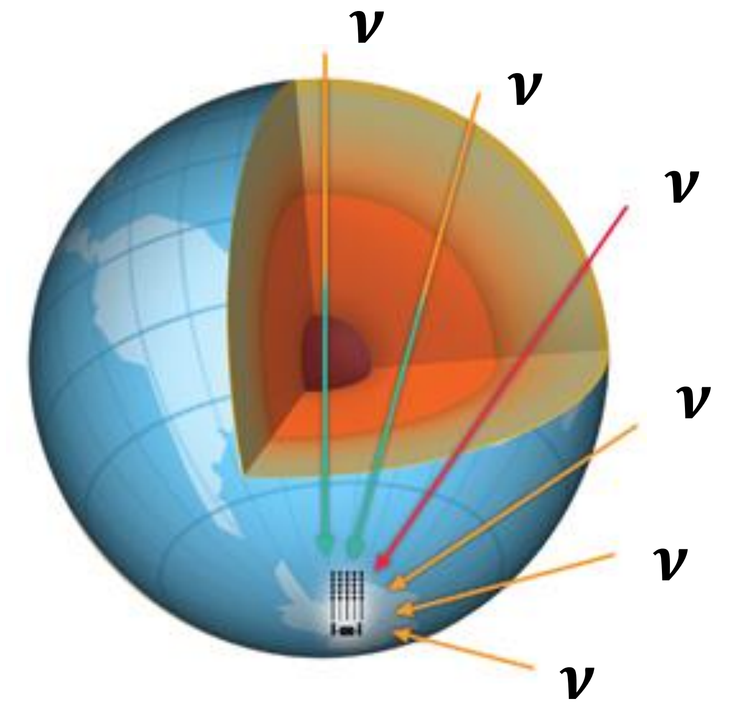
- $ORCA$ key target: investigate the mass hierarchy of neutrinos

  - $ORCA$ investigates low–energy atmospheric neutrinos at the GeV – scale

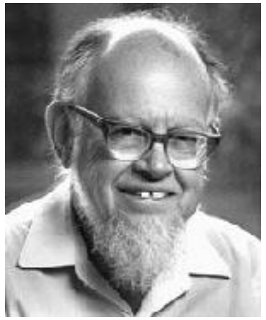
  - atmospheric neutrinos do **oscillate***! (Nobel prize)

  - ν_{atm} are propagating in the matter of the Earth: **matter–induced effects** (´MSW **effect**´)





flight paths of atmospheric ν´s



L. Wolfenstein

*see $ATP - 2$ in summer term 2024

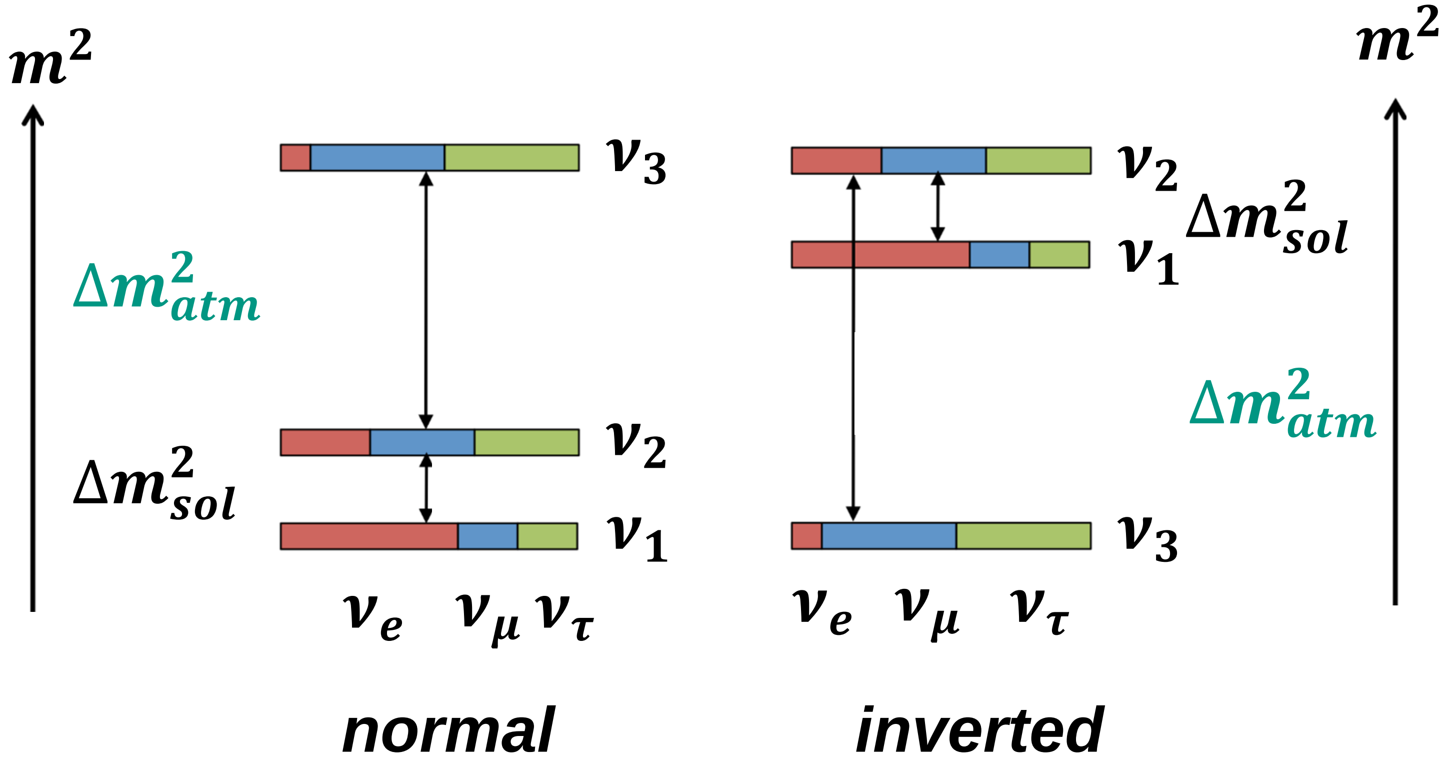
$KM3NeT - ORCA$: studying ν – oscillations

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

  - $ORCA$ investigates **low–energy atmospheric neutrinos** at the GeV – scale

  - atmospheric neutrinos **oscillate** at scale Δm^2_{atm}

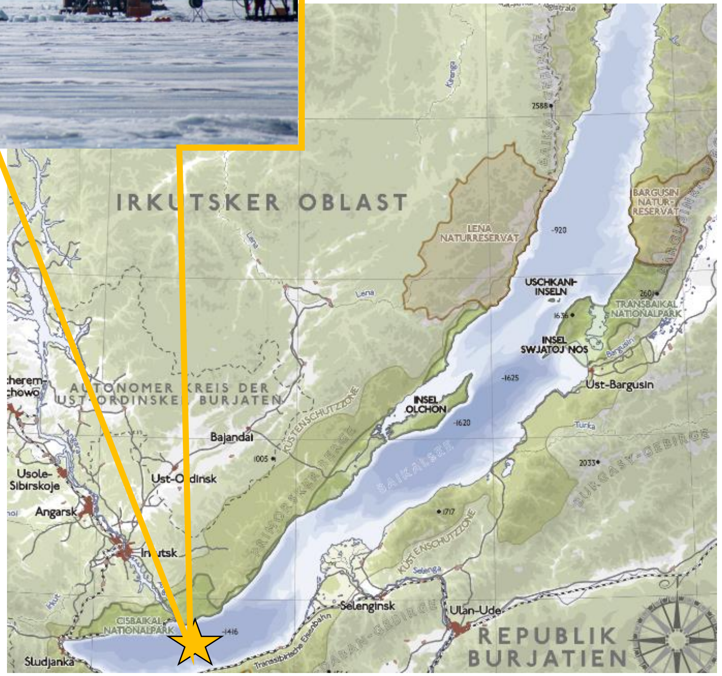
  - ν_{atm} may allow to determine the **ν – mass hierarchy:** what is the correct ordering of mass eigenstates ν_i? ***normal*** / ***inverted*** scheme?



ν –Telescope *Lake Baikal*

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

  - pioneering neutrino telescope *´Lake Baikal´* in the **$80s/90s$**



#StandWithUkraine

$\boldsymbol{Baikal}$ – $\boldsymbol{G}$igaton $\boldsymbol{V}$olume $\boldsymbol{D}$etector ($\boldsymbol{GVD}$)

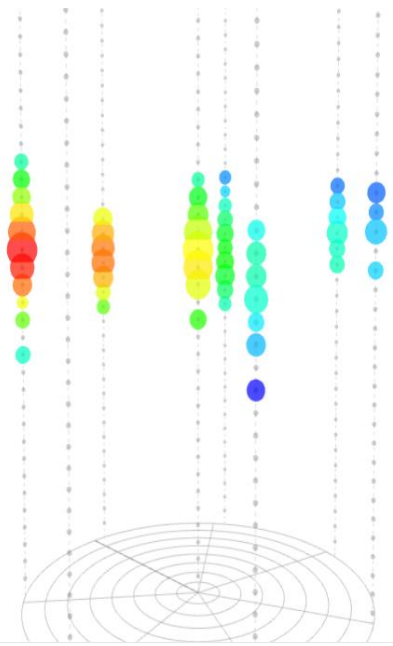
- **Extending an existing $\boldsymbol{\nu}$ – telescope at Lake Baikal**

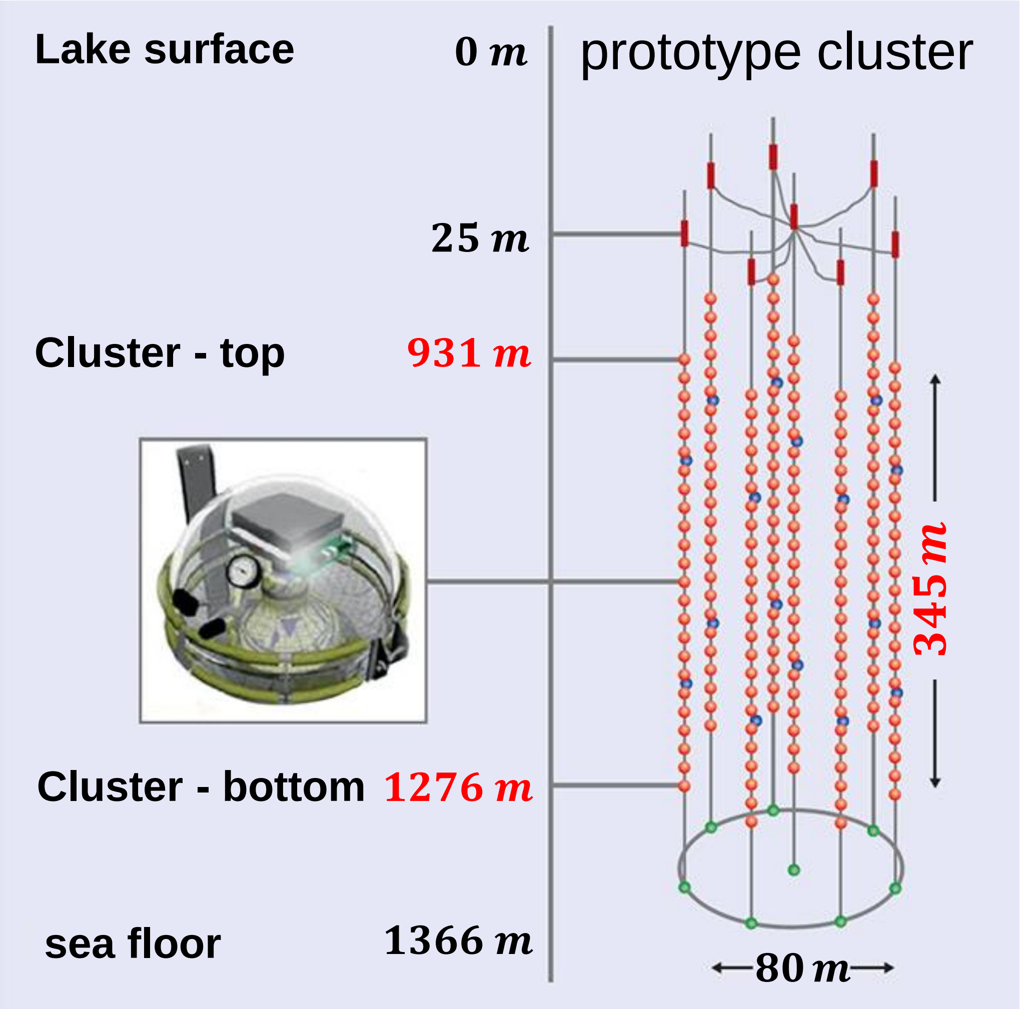
- largest $\boldsymbol{\nu}$ – telescope in Northern Hemisphere

- full–scale extension to $\mathbf{1}\ \boldsymbol{km^3}$ in progress

- present $(\mathbf{9/2023})$ status
  $\boldsymbol{GVD - I}$ ready ($\boldsymbol{V \sim 0.5\ km^3}$)

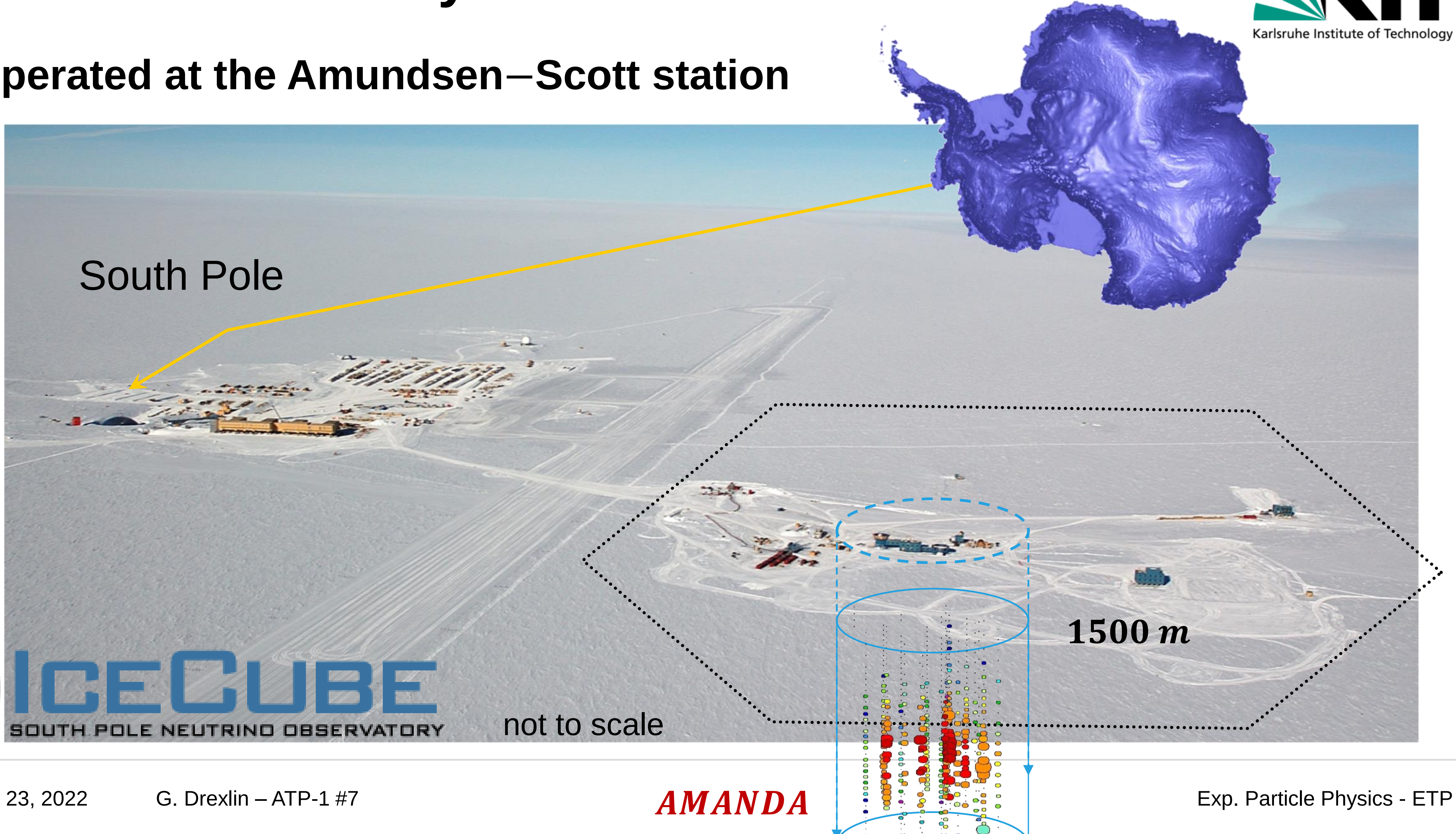
- $\mathbf{12}$ clusters in operation





IceCube observatory at the South Pole

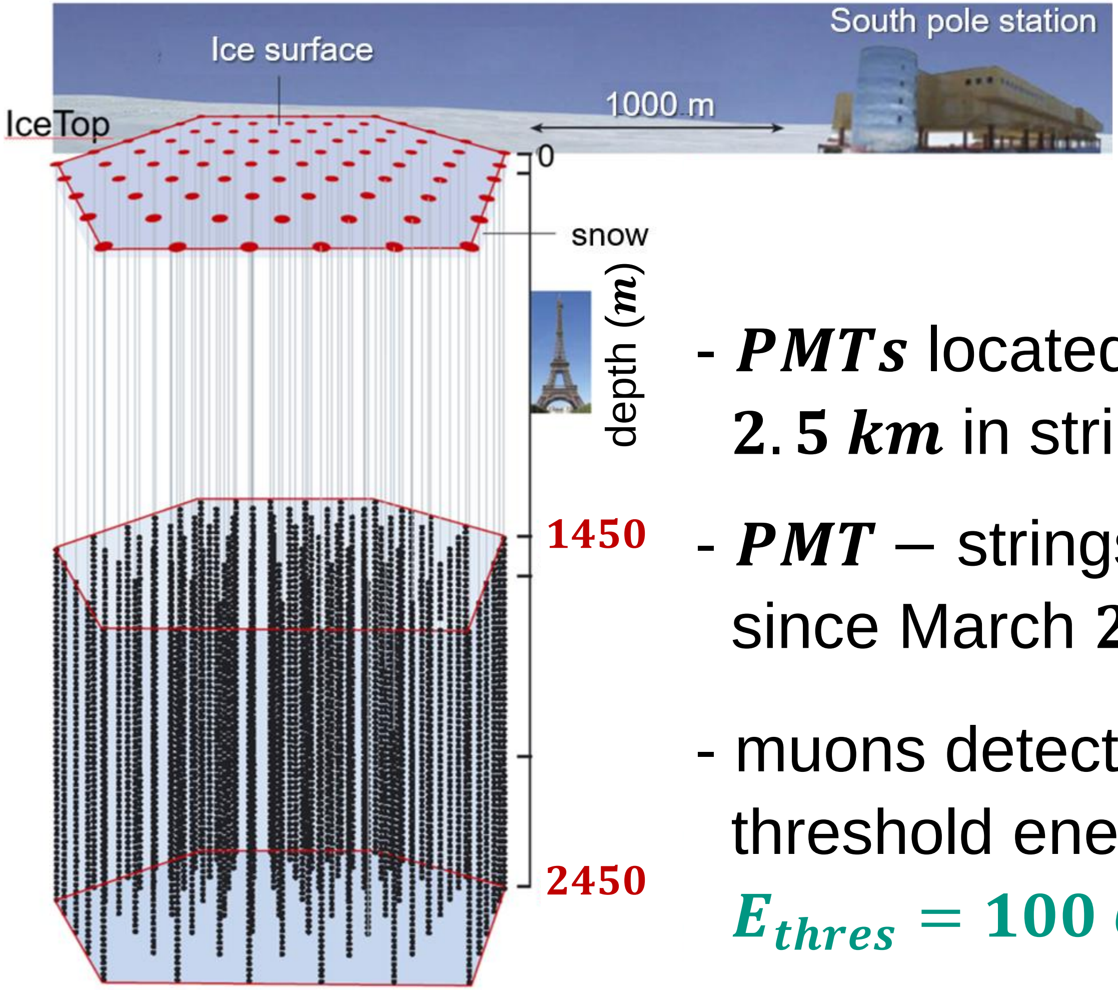
- **Operated at the Amundsen–Scott station**



ICECUBE
SOUTH POLE NEUTRINO OBSERVATORY

IceCube observatory at the South Pole

- Design of a very large in−ice neutrino telescope



- $\mathbf{4800}$ $\boldsymbol{PMTs}$ distributed over volume $\boldsymbol{V = 1\ km^3}$ with $\mathbf{80}$ $\boldsymbol{PMT}$ strings

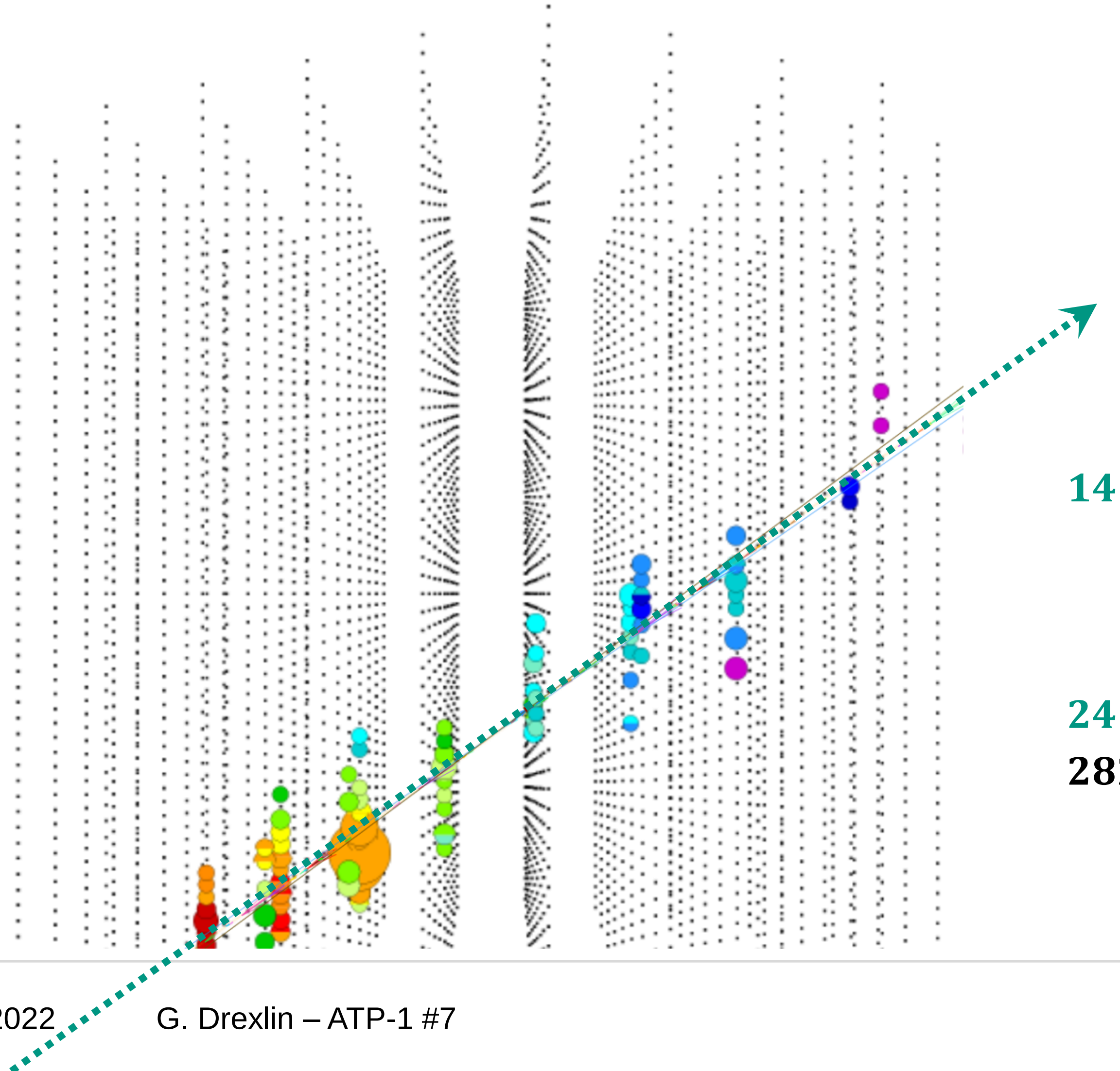
- $\boldsymbol{PMTs}$ located at $\boldsymbol{d = 1.5 \ldots 2.5\ km}$ in strings of $\boldsymbol{1\ km}$

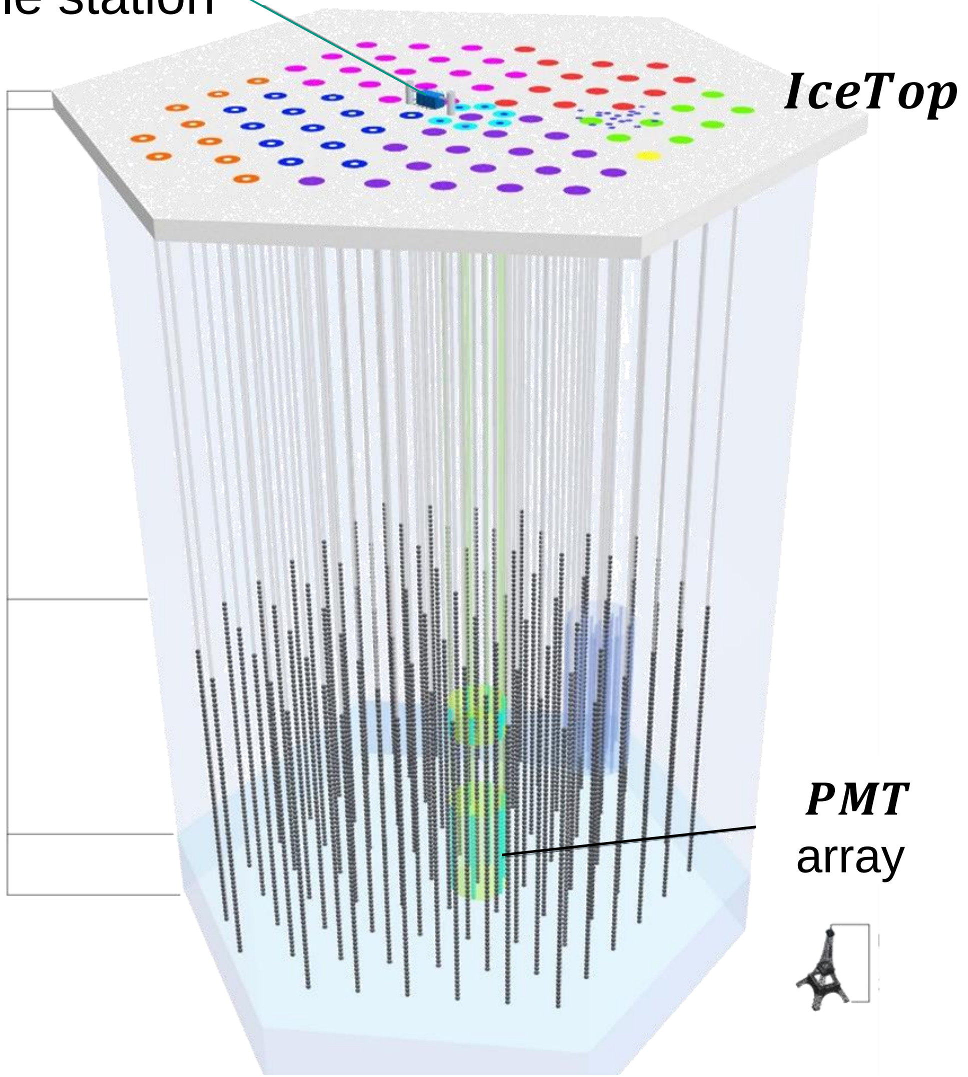
- $\boldsymbol{PMT}$ – strings fully deployed since March $\mathbf{2010}$

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

IceCube observatory: design features

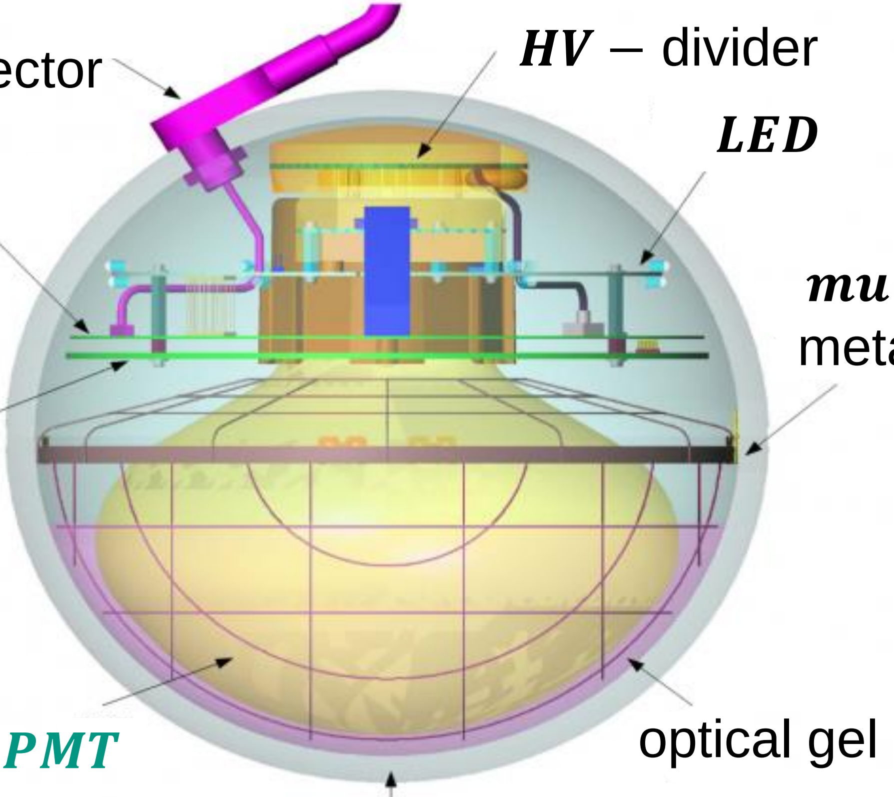
- **Detecting tracks with *PMT* strings**

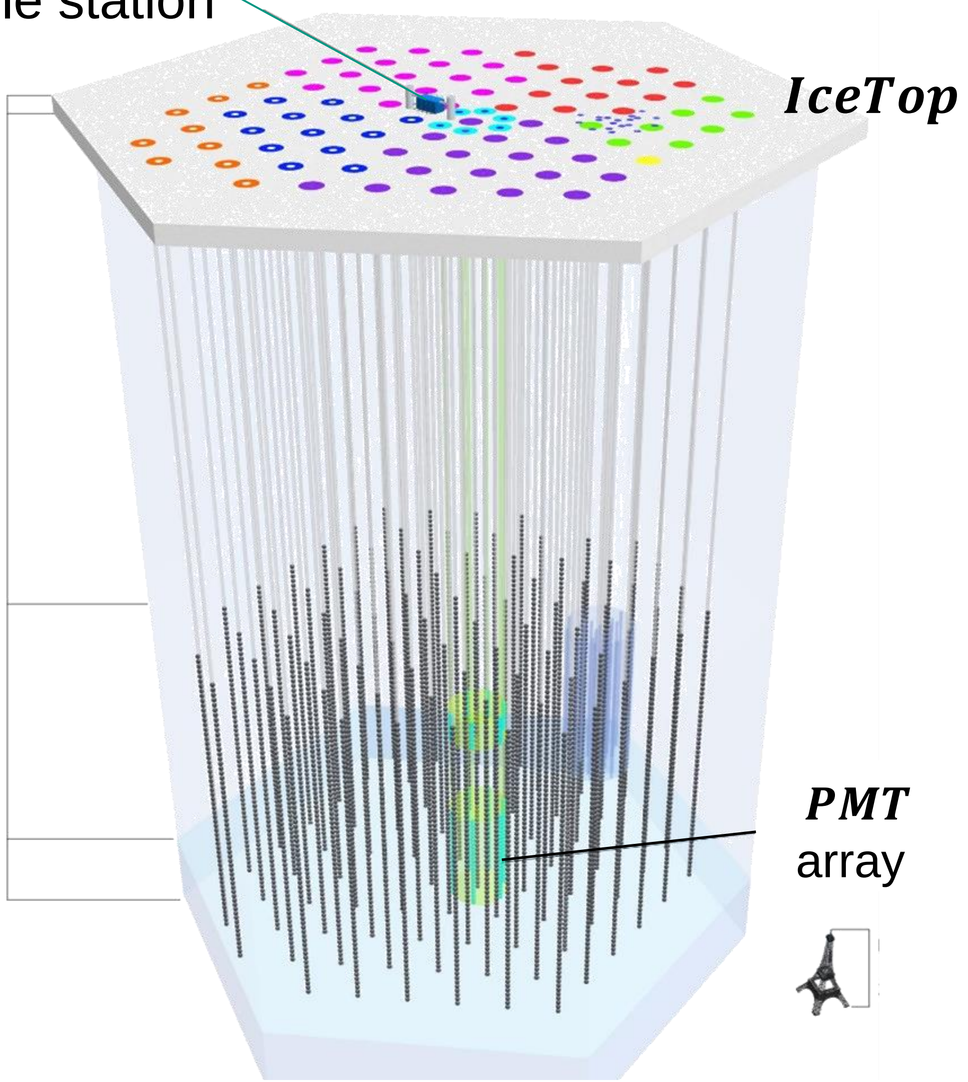




$IceCube$ observatory: design features

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





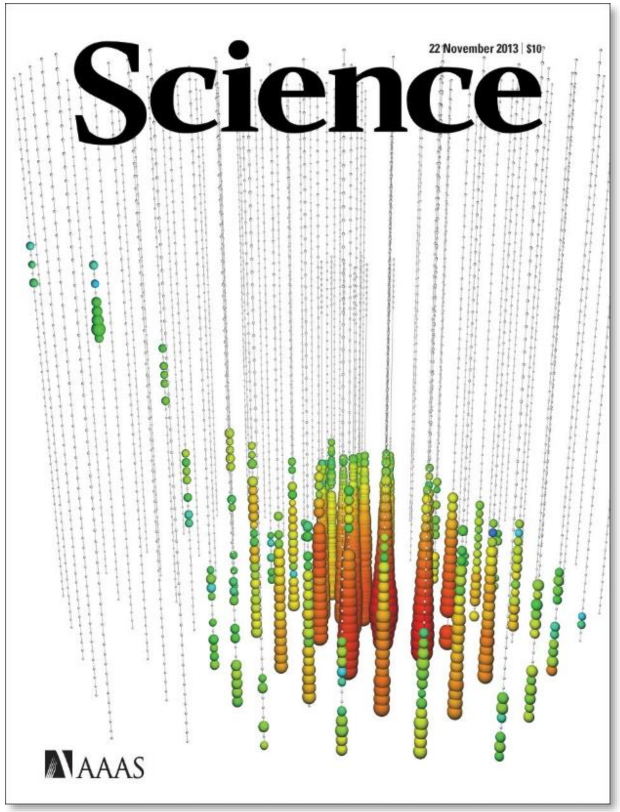
IceCube Observatory: initial observations

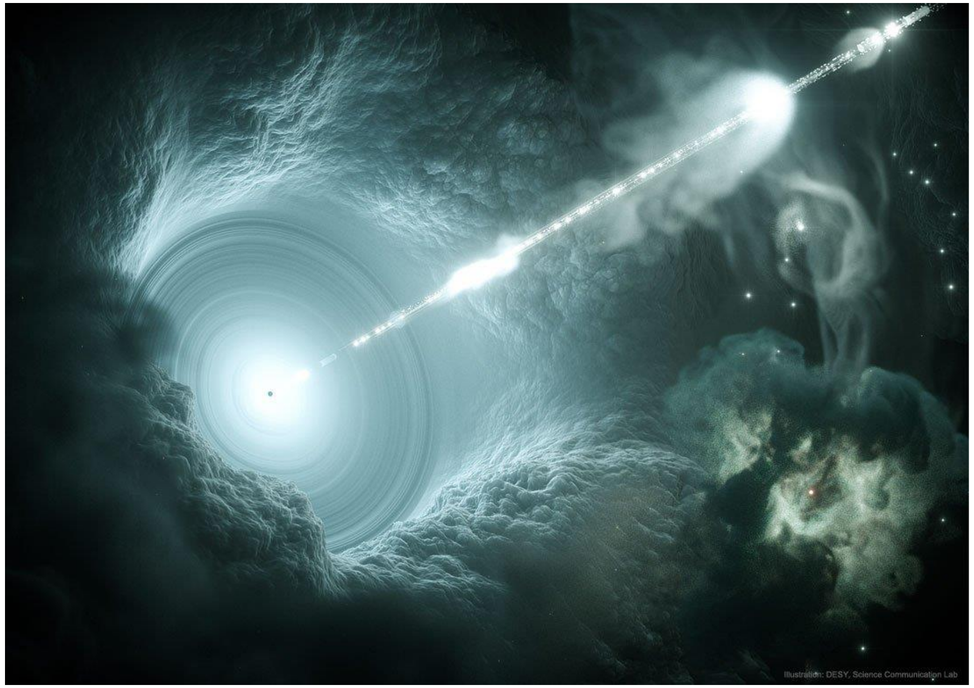
- **Astrophysical neutrinos: an extragalactic source is observed!**

- origin: from galaxy $\boldsymbol{PKS\ 1424-418}$:
  flare state in a **blazar**

- a very energetic
  event (´**Big Bird**´)
  observed in $\mathbf{2013}$:
  $\boldsymbol{E(\nu_\mu) = 250\ TeV}$!

Big Bird



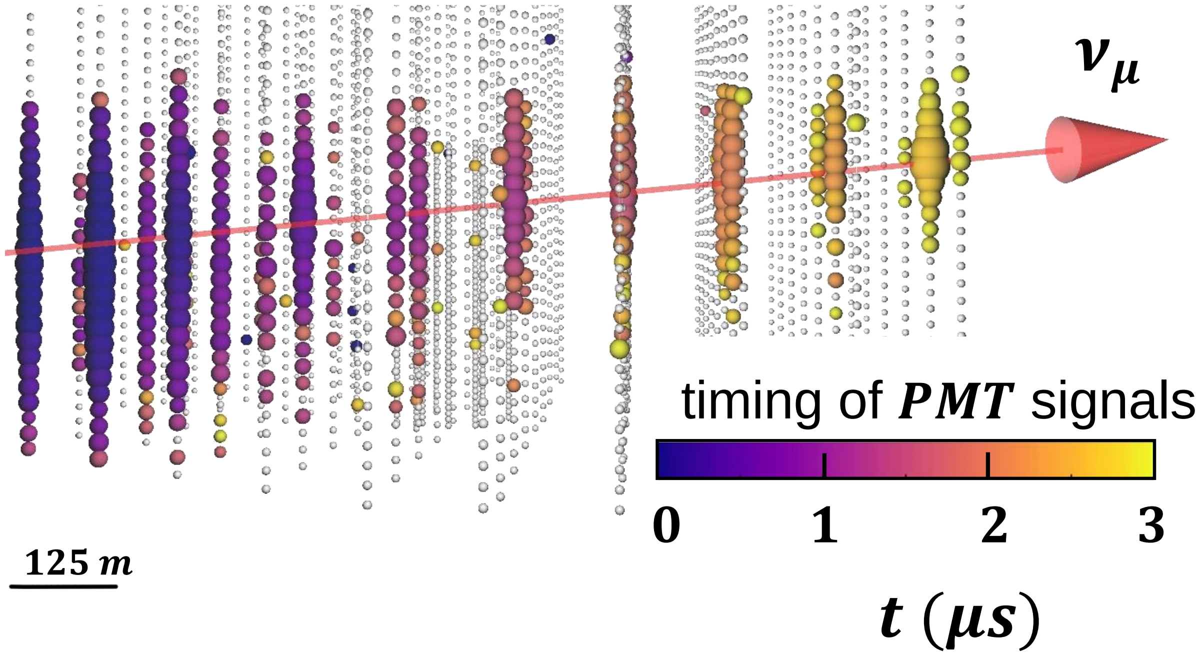


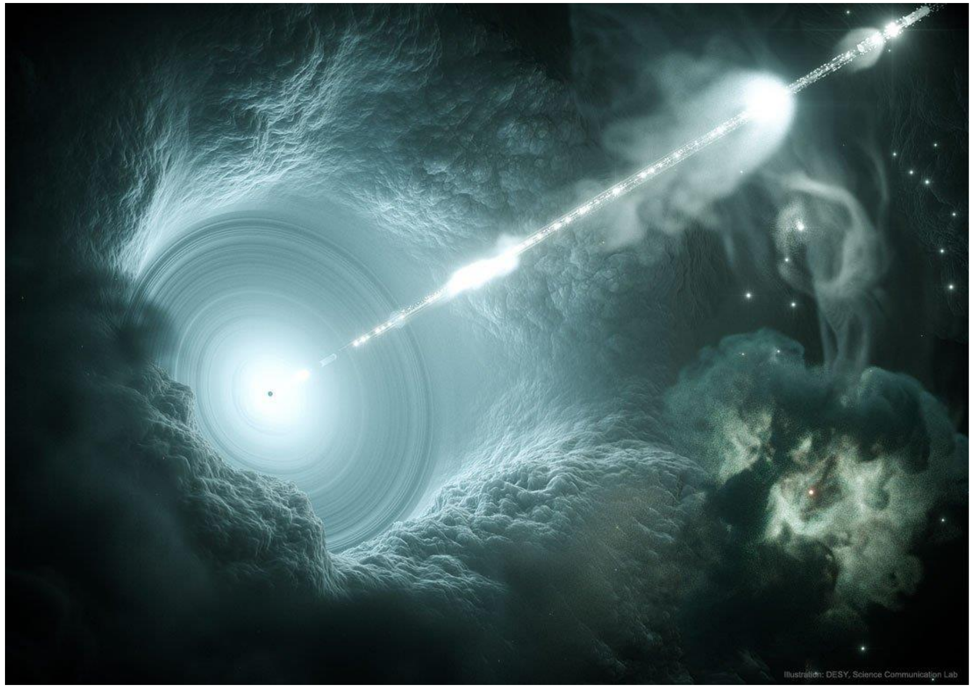
blazar $\boldsymbol{PKS\ 1424-418}$

$IceCube$ Observatory: initial observations

- **Astrophysical neutrinos: an energetic ν 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 directly points back to **blazar**

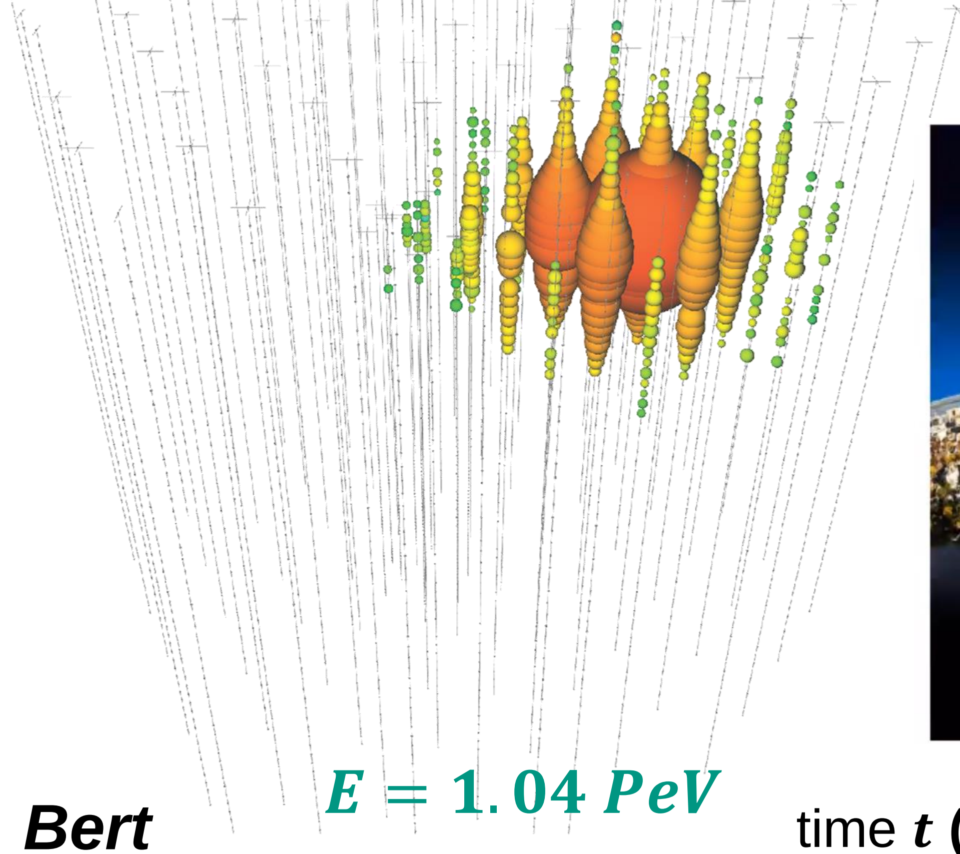


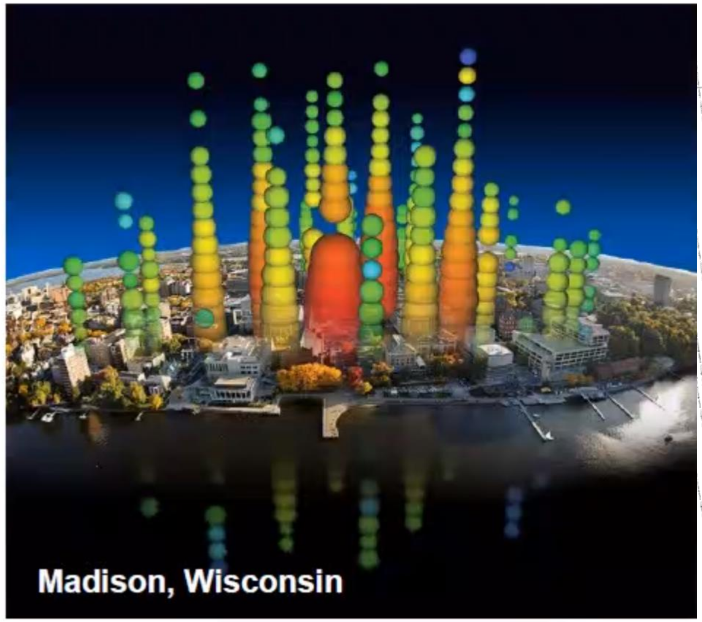


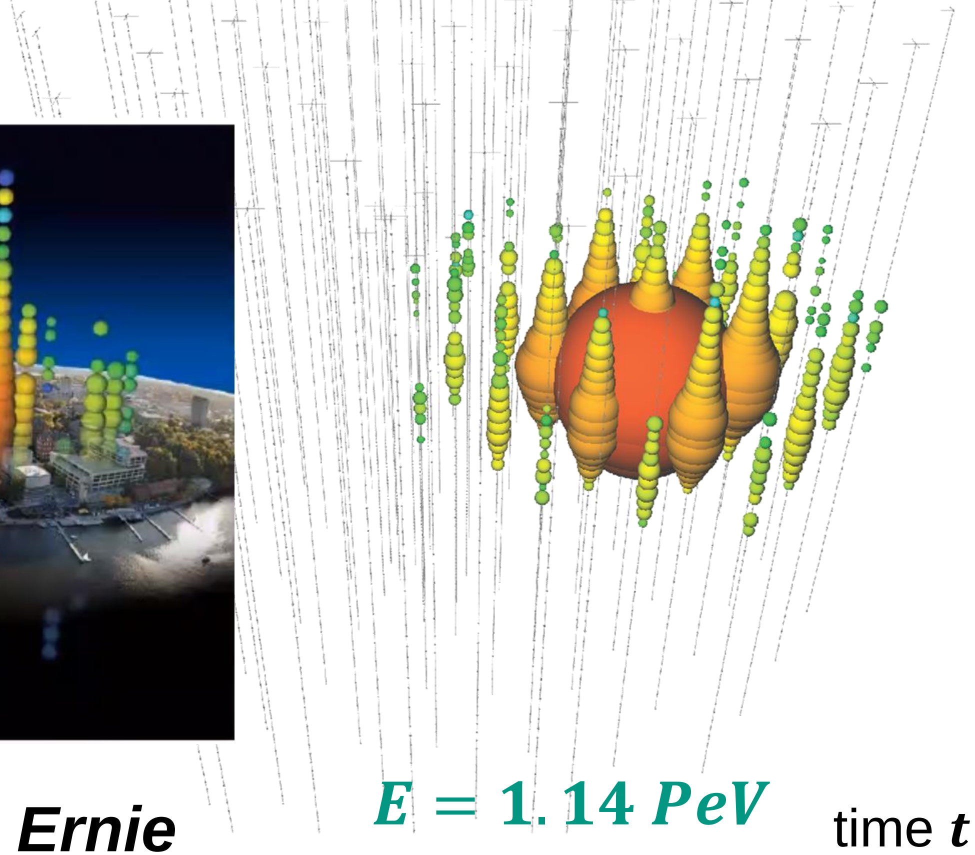
blazar $PKS\ 1424 - 418$

IceCube Observatory: ν – events *Ernie* & *Bert*

- **Astrophysical ν´s now at the PeV – scale: cascade (NC) events**







Bert $E = 1.04\ PeV$ time t (μs)

0.0 0.8 1.6 2.4 3.2 4.0 4.8 5.6

Ernie $E = 1.14\ PeV$ time t (μs)

0.0 0.8 1.6 2.4 3.2 4.0 4.8 5.6