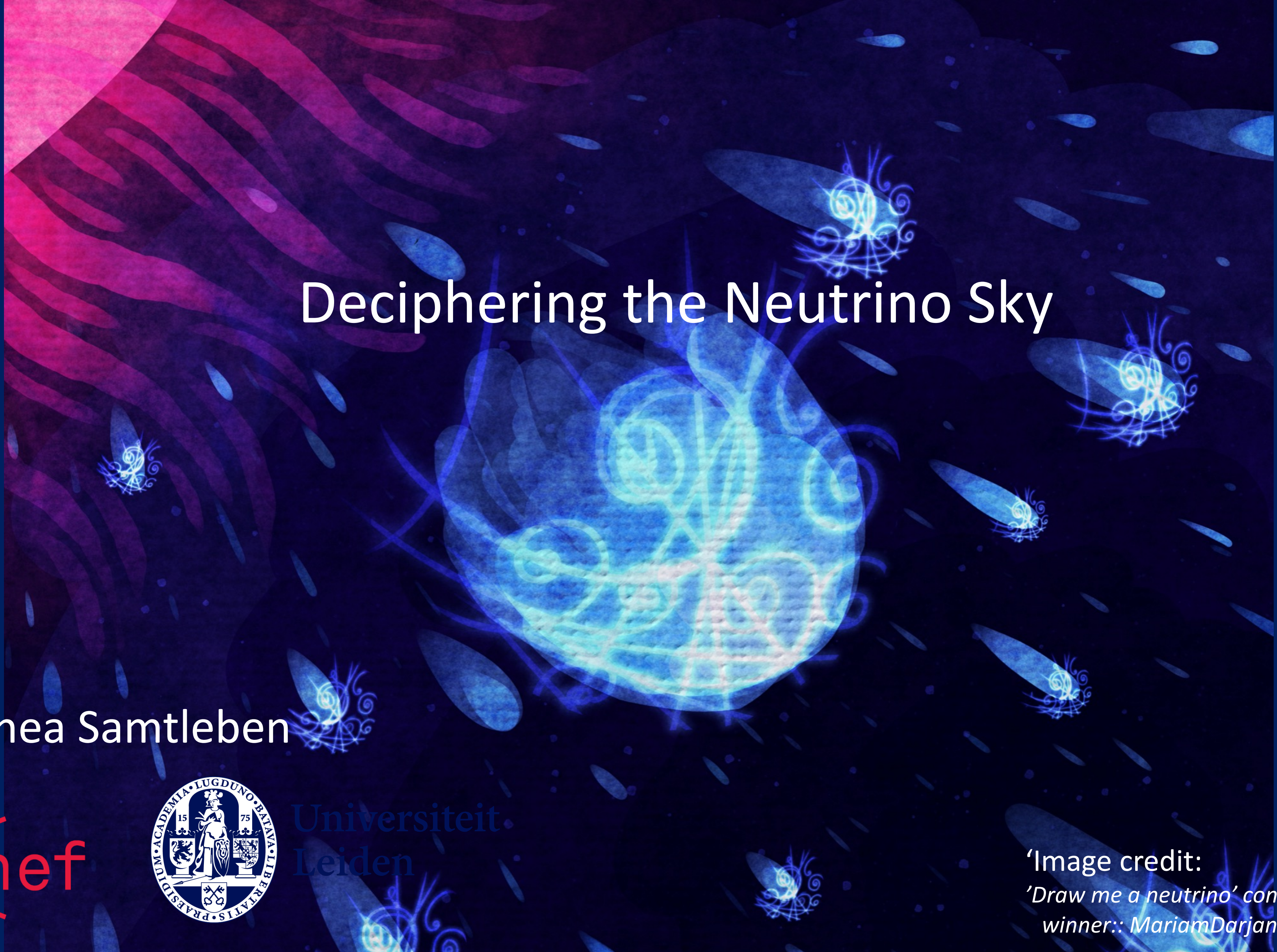


Deciphering the Neutrino Sky

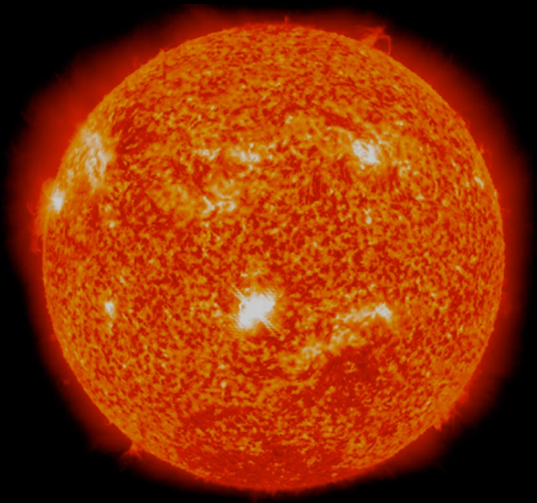
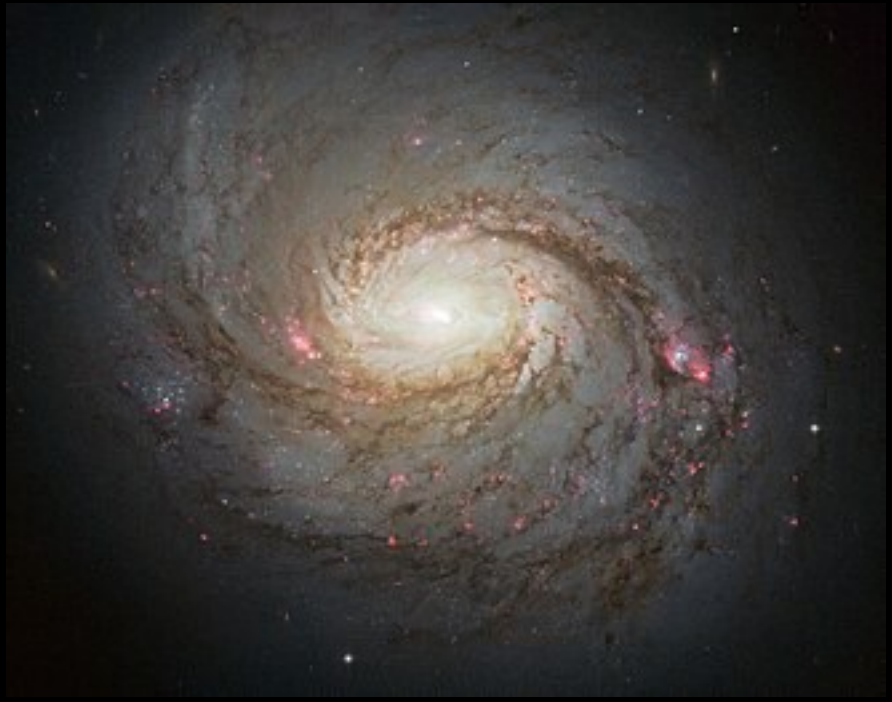
Dorothea Samtleben

Nikhef

Universiteit Leiden

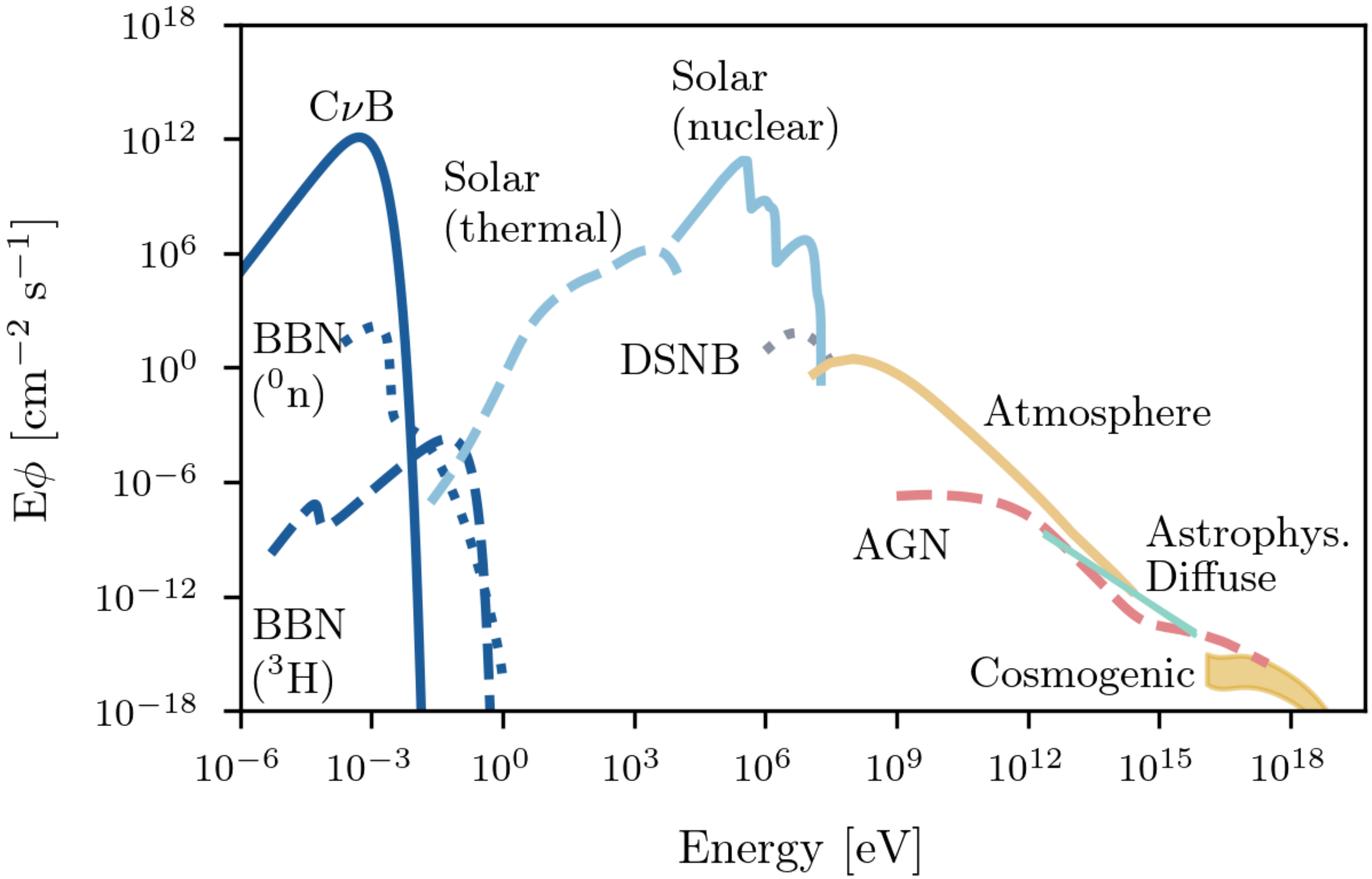
'Image credit:
'Draw me a neutrino' contest 2020 winner:: MariamDarjania



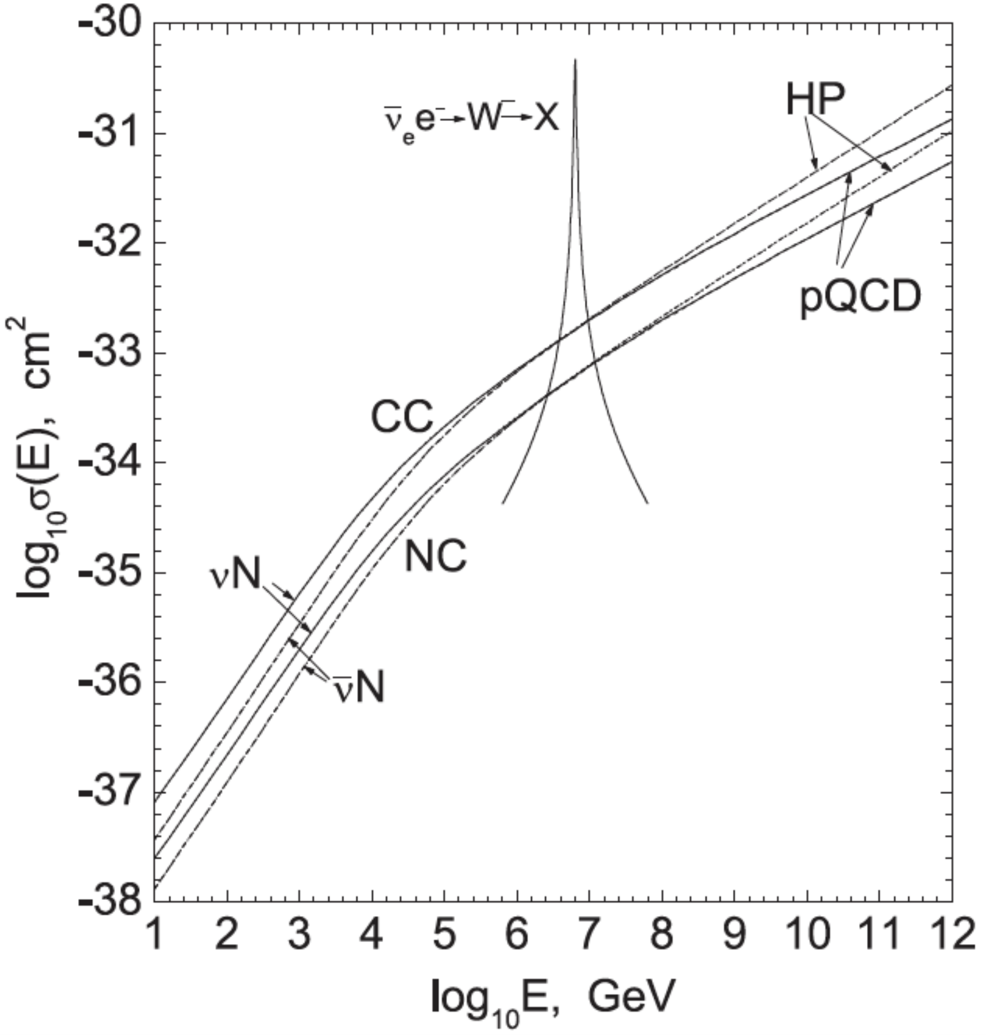



Neutrino energy spectrum

updated by Bellenghi & Kerscher ‘24 from Vitagliano, Tamborra, Raffelt ‘19

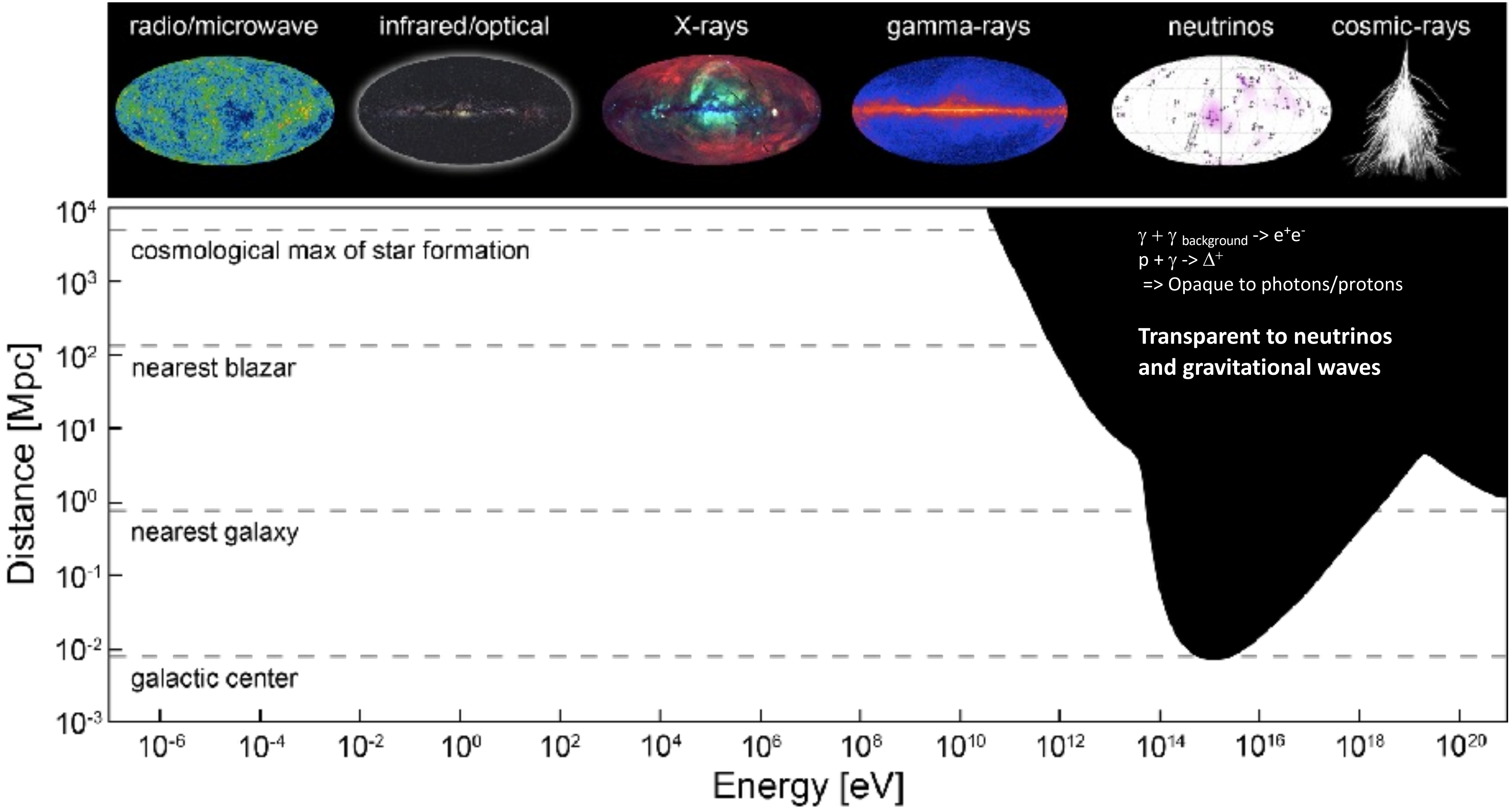


Neutrino cross sections



- Probability for a neutrino to interact rises with energy
- Antineutrinos have lower probabilities to interact
- At lower energies Neutral-Current (NC) and Charged-Current (CC) interactions have slightly different probabilities to interact

Gazizov, Kowalski Comput. Phys. Commun. 172 (2005)



Large part of high-energy Universe only accessible with neutrinos and gravitational waves

What makes the neutrinos special?

Introduction & some history

How can we detect them?

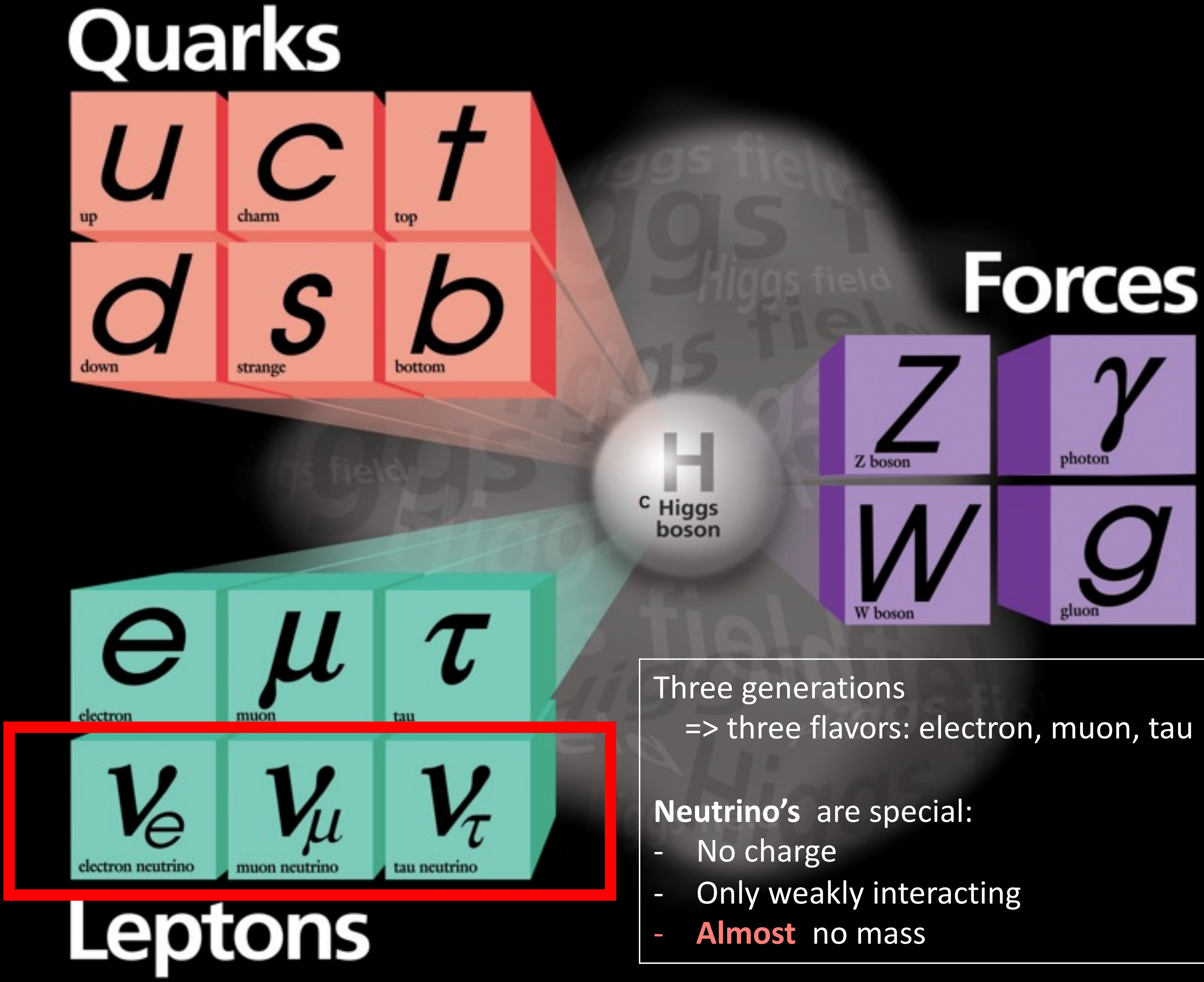
Meet the neutrino telescopes

What do we know so far of cosmic neutrinos?

Highlights of the cosmic discoveries

What makes the neutrinos special?

Introduction & some history



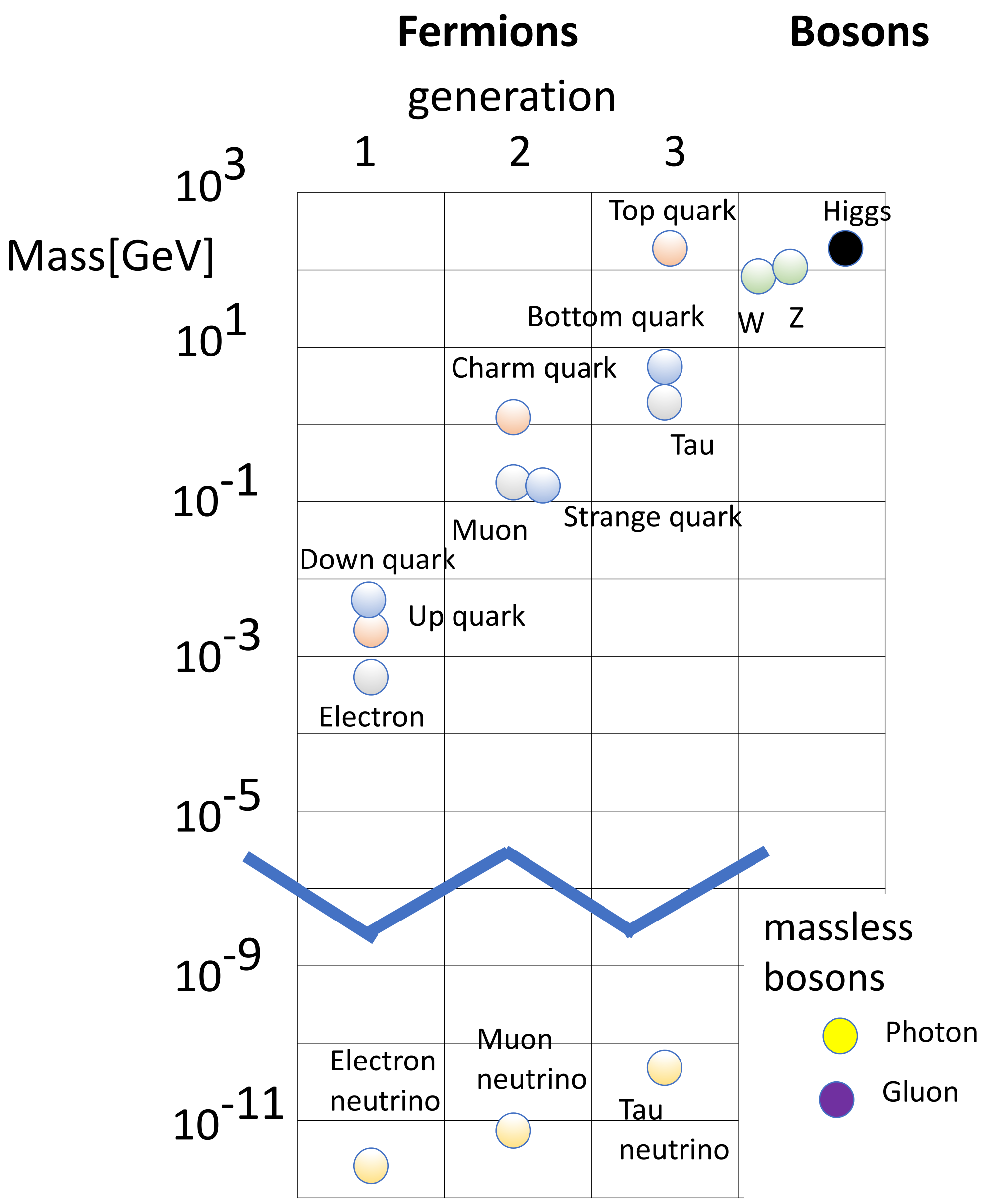
Three generations

=> three flavors: electron, muon, tau

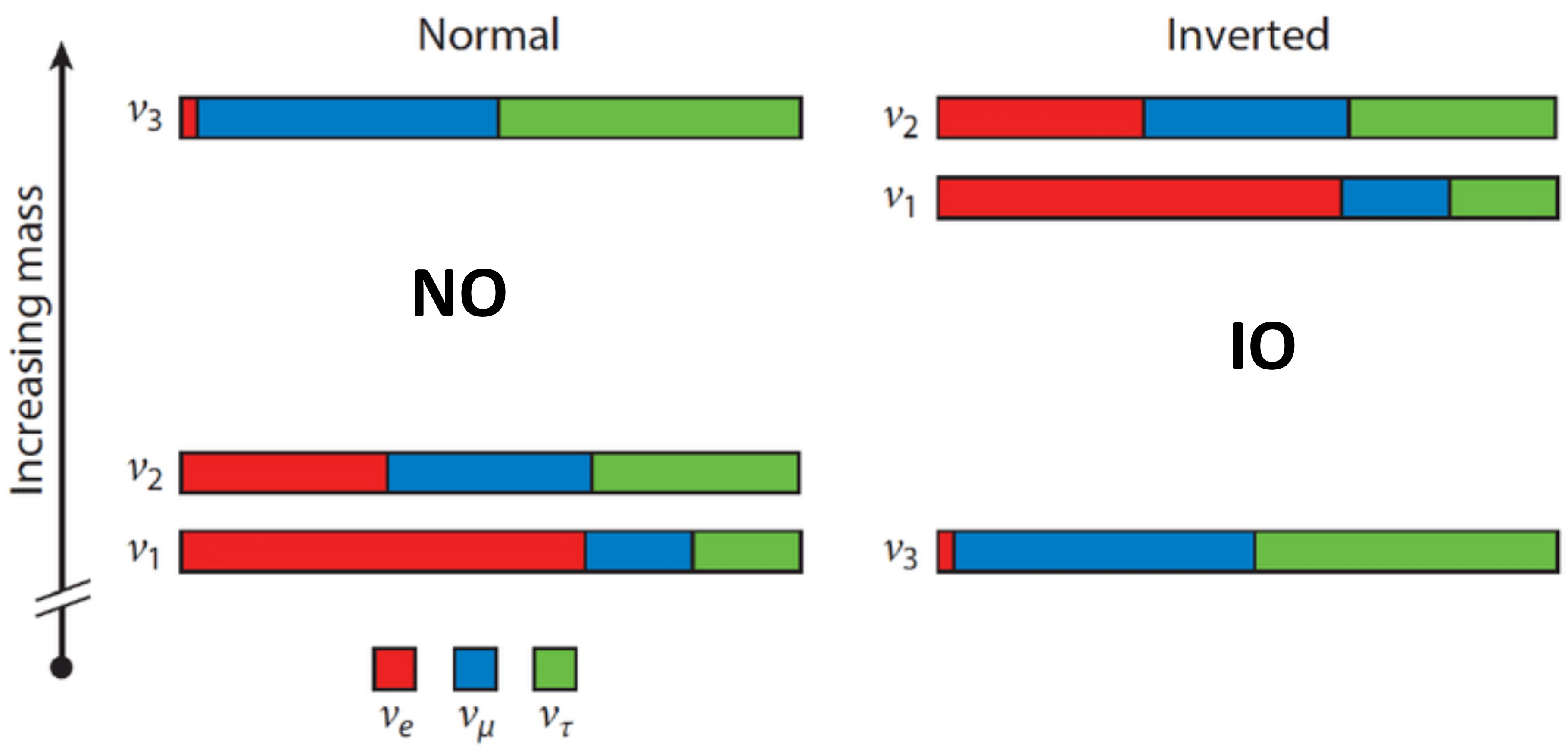
Neutrino's are special:

- No charge
- Only weakly interacting
- **Almost** no mass

Particle masses



Neutrino mass ordering



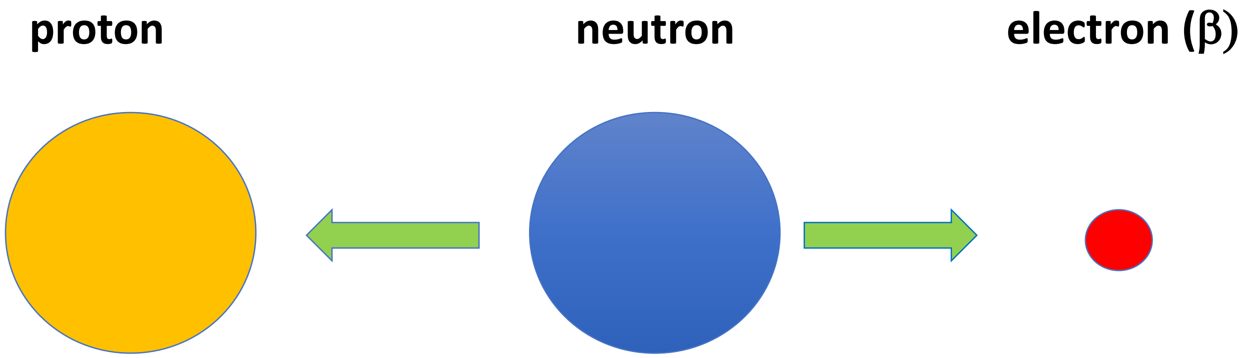
Open questions

What are the masses of the neutrinos and why are they so small?

Do neutrinos and antineutrinos behave the same? (CP)

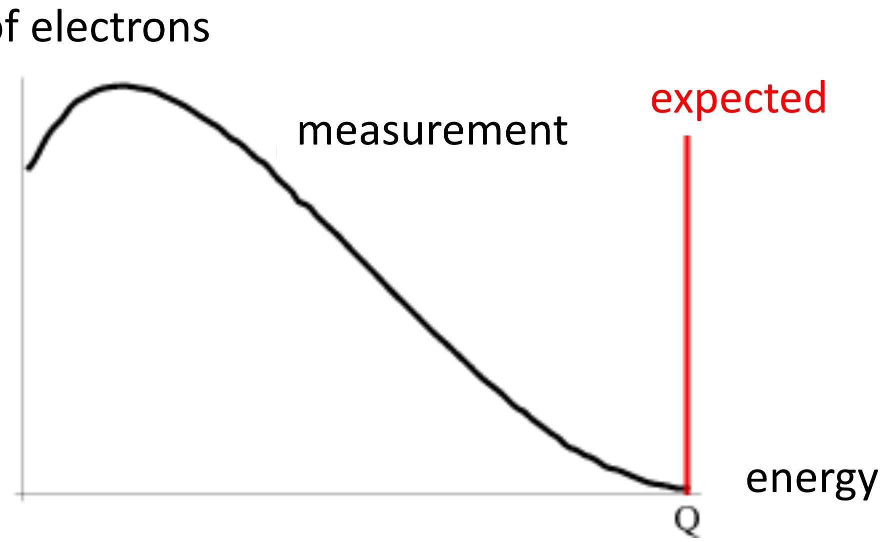
Is the neutrino its own antiparticle?

Radioactive β decay

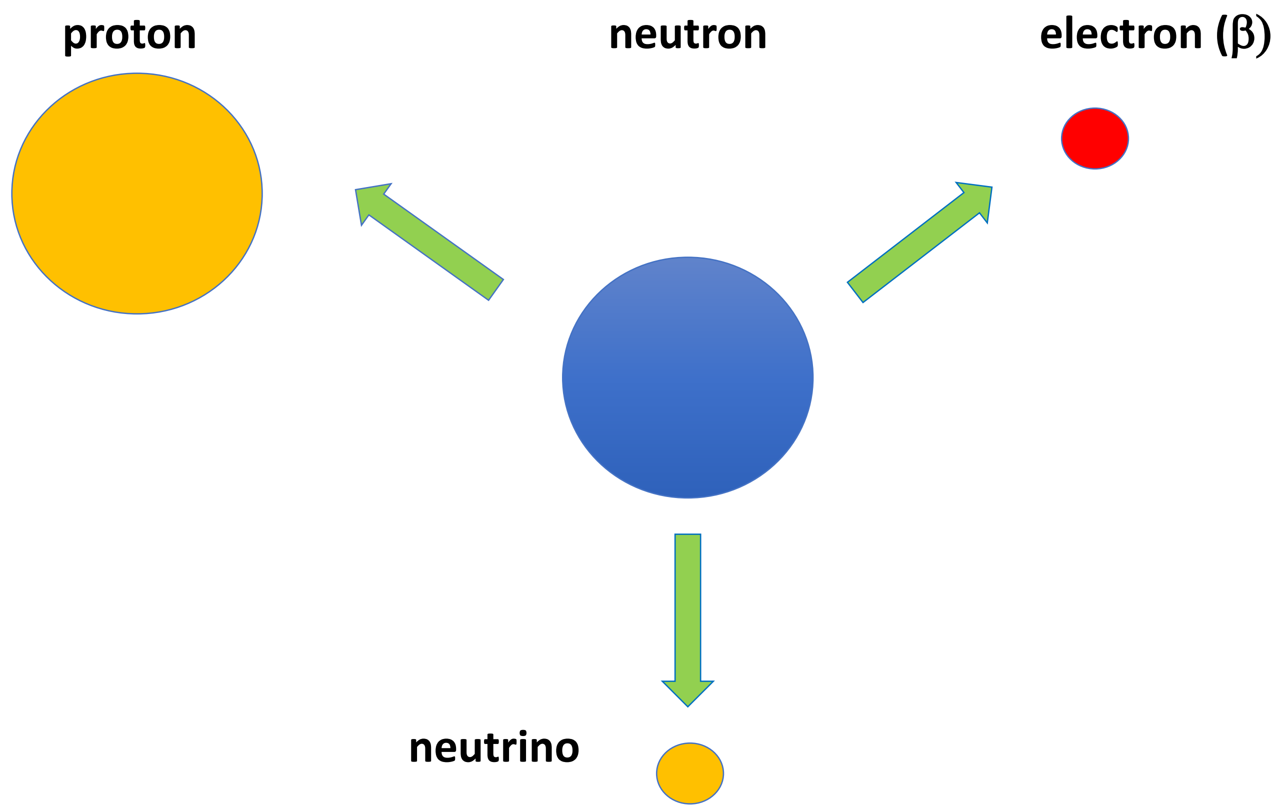


Energy/momentum conservation => energy of electron fixed

But:



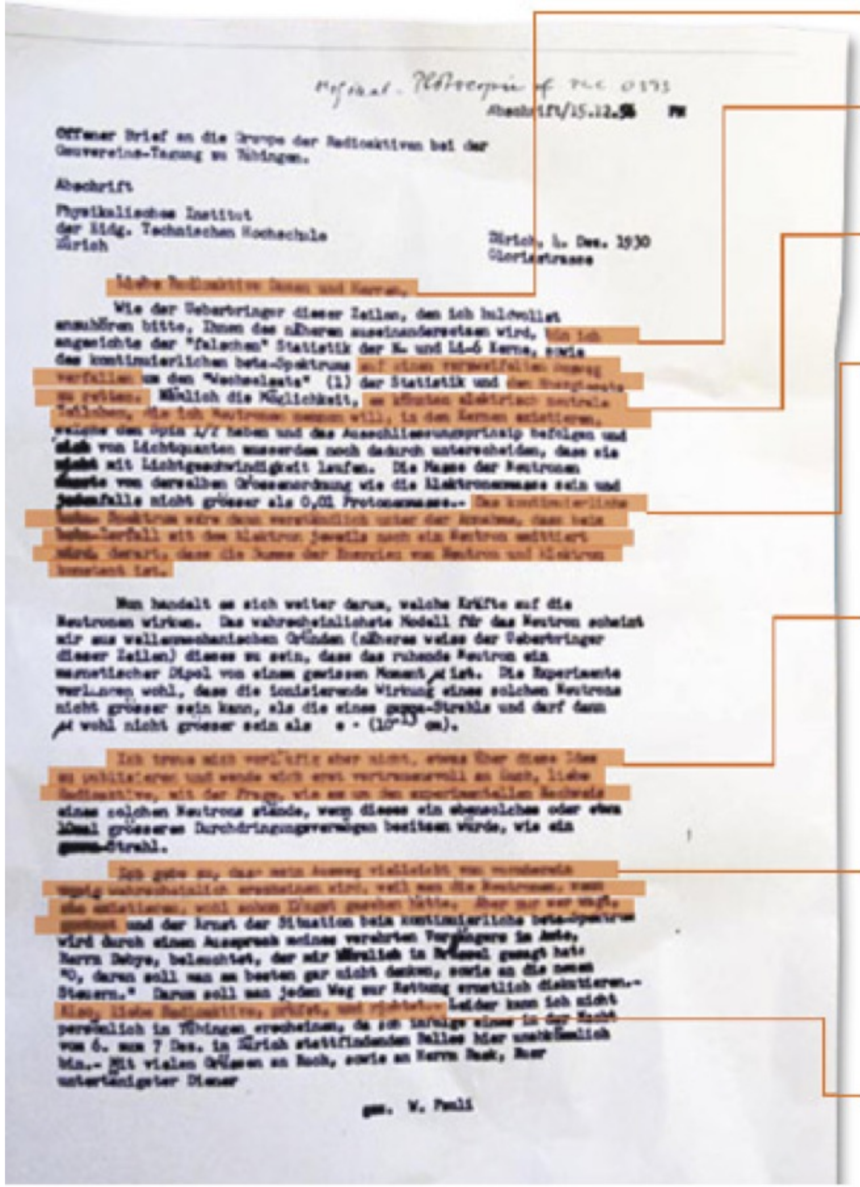
Radioactive β decay



1930: Wolfgang Pauli: New, invisible particle

Wolfgang Pauli, 4 December 1930

95 years ago!



Offener Brief an die Gruppe der Radioaktiven bei der Gauvereins-Tagung zu Tübingen.

Abschrift

Physikalisches Institut
der Eidg. Technischen Hochschule
Zürich

Zürich, 4. Dez. 1930
Gloriastrasse

Dear radioactive ladies and gentlemen,

I may have found a solution to the energy crisis in radioactive decays.

… the existence of electrically neutral particles –which I call neutrons– in the atomic nucleus.

The measured spectrum can be understood if such a neutral particle escapes together with the electron such that the total energy is conserved.

But until now I did not dare to publish this idea and I ask you –radioactive people– whether it is possible to detect this particle experimentally.

I admit that this idea is unlikely because the neutrons –if they exist– would have been found already.

So, dear radioactive people, think about this idea and judge.

26 years later: Discovery of neutrino

70 years ago!

1956 Clyde Cowan and Frederick Reines performed the project ‘Poltergeist’
1995 Nobel Prize

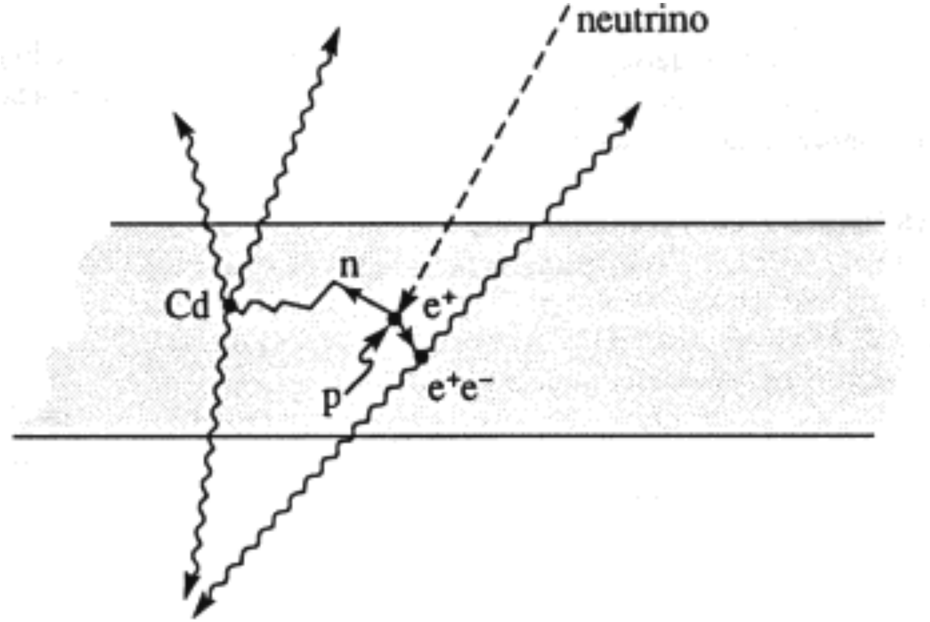
Measuring antineutrinos from nuclear reactor

Antineutrino + proton -> Neutron + positron

$$\overline{\nu} + p \rightarrow n + e^+$$

Detectable by γ flashes in capture on nucleus

Detectable by γ flashes in annihilation



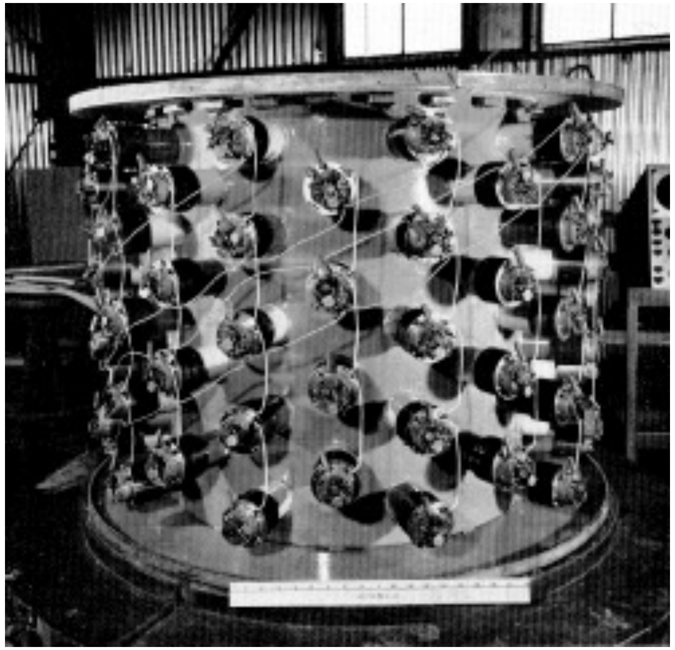
26 years later: Discovery of neutrino

70 years ago!

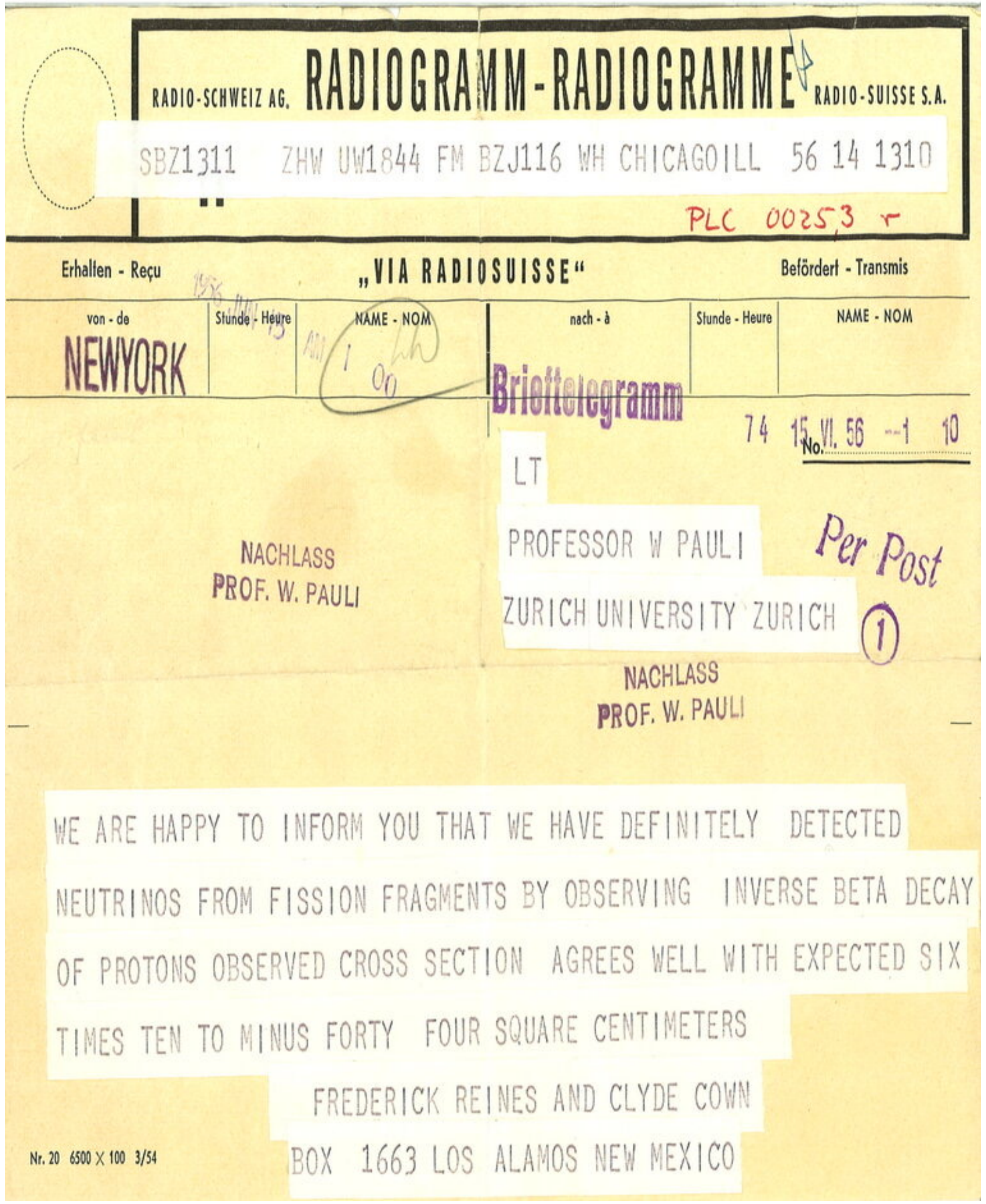
1956 Clyde Cowan and Frederick Reines performed the project 'Poltergeist'
1995 Nobel Prize

- 200 l Water tank with Cd Cl_2 solution
- Monitored by sensitive light detectors (Photomultipliers)
- Improved version moved underground to better reject backgrounds
  => 3 events/hour (1 background)

'Herr Auge'



Cowan & Reines telegram



RADIO-SCHWEIZ AG. RADIOGRAMM-RADIOGRAMME RADIO-SUISSE S.A.

SBZ1311 ZHW UW1844 FM BZJ116 WH CHICAGOILL 56 14 1310

PLC 00253

Erhalten - Reçu „VIA RADIOSUISSE" Befördert - Transmis

von - de	Stunde - Heure	NAME - NOM	nach - à	Stunde - Heure	NAME - NOM
NEWYORK			Brieftelegramm		

74 15 VI. 56 --1 10

LT

PROFESSOR W PAULI

ZURICH UNIVERSITY ZURICH

Per Post

NACHLASS PROF. W. PAULI

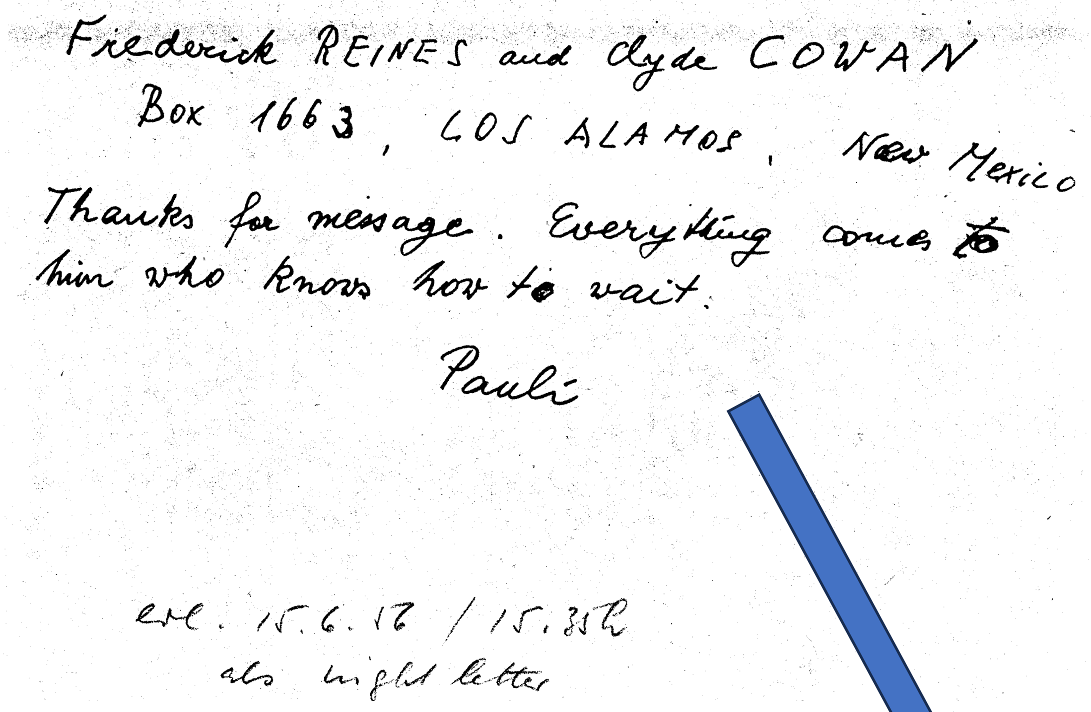
WE ARE HAPPY TO INFORM YOU THAT WE HAVE DEFINITELY DETECTED NEUTRINOS FROM FISSION FRAGMENTS BY OBSERVING INVERSE BETA DECAY OF PROTONS OBSERVED CROSS SECTION AGREES WELL WITH EXPECTED SIX TIMES TEN TO MINUS FORTY FOUR SQUARE CENTIMETERS

FREDERICK REINES AND CLYDE COWN

BOX 1663 LOS ALAMOS NEW MEXICO

Nr. 20 6500 X 100 3/54

Pauli's drafted answer



Frederick REINES and Clyde COWAN

Box 1663, LOS ALAMOS, New Mexico

Thanks for message. Everything comes to him who knows how to wait.

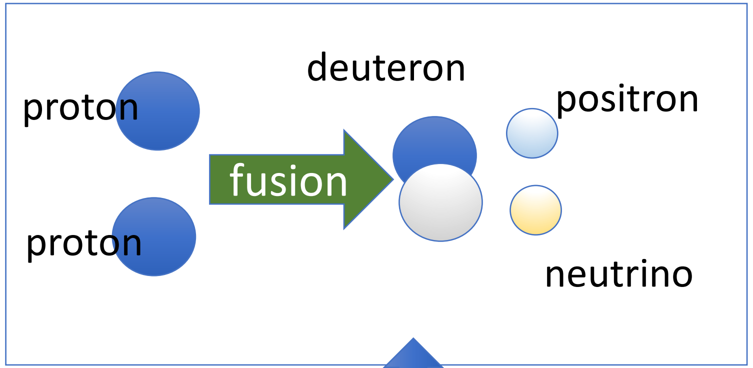
Pauli

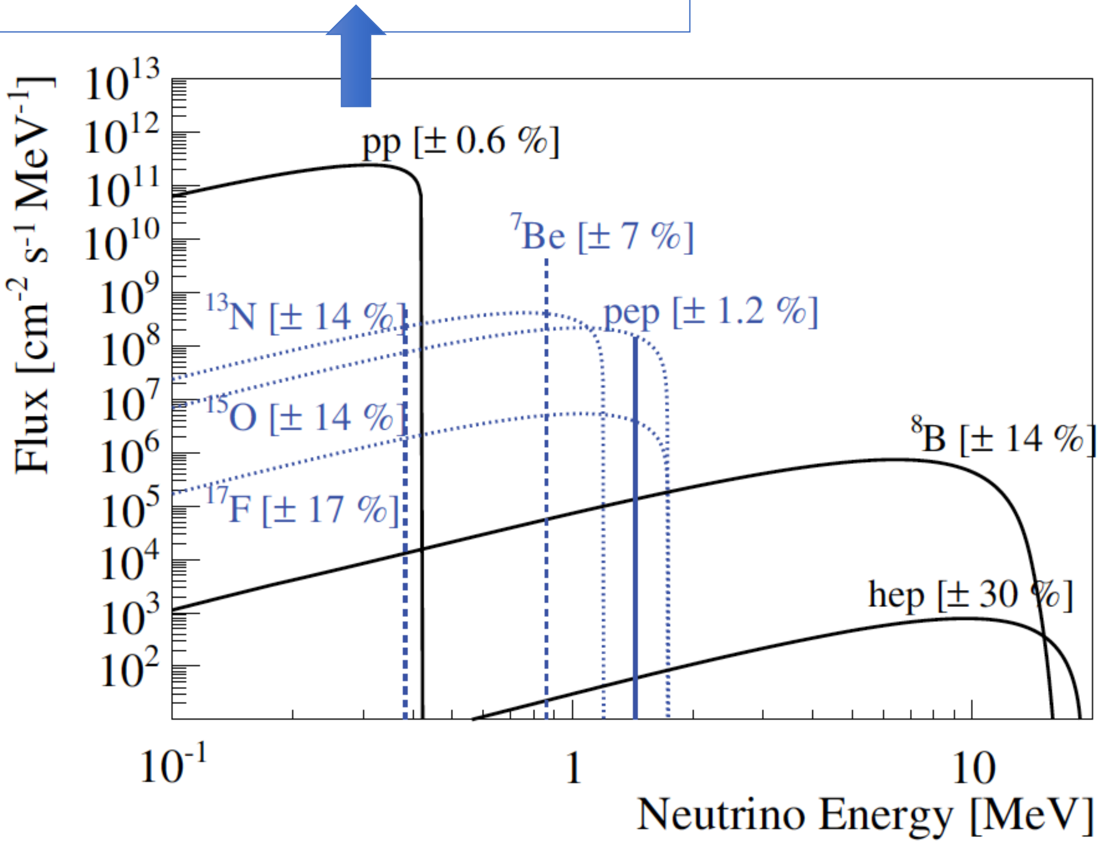
erl. 15.6.56 / 15.35h

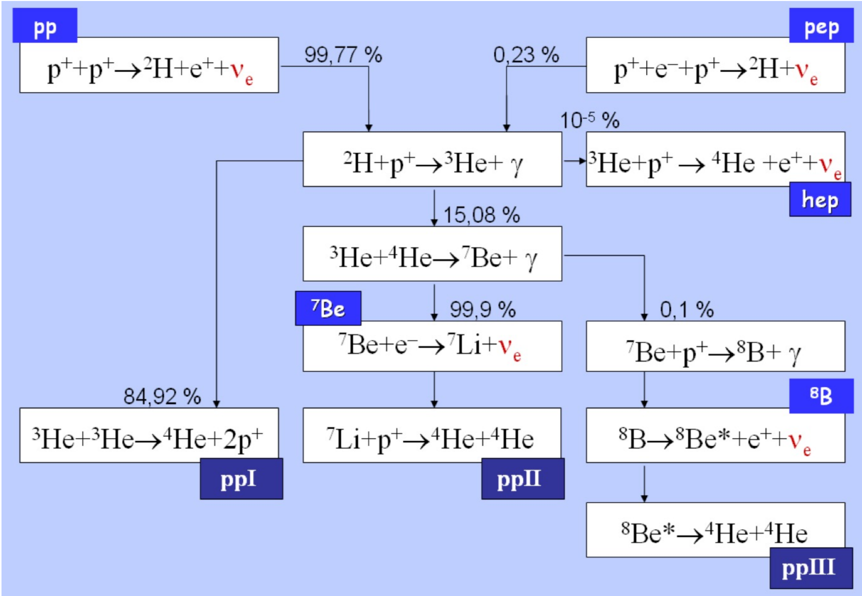
als night letter

Thanks for the message.
Everything comes to him who knows how to wait

Energy spectrum of solar neutrinos







https://www-sk.icrr.u-tokyo.ac.jp/en/sk/about/research/

First solar neutrino measurement

~60 years ago!

From 1967 on experiment of **Raymond Davis**

Homestake gold mine (South Dakota), 1478m deep

Tank with $380m^3$ perchloroethylene

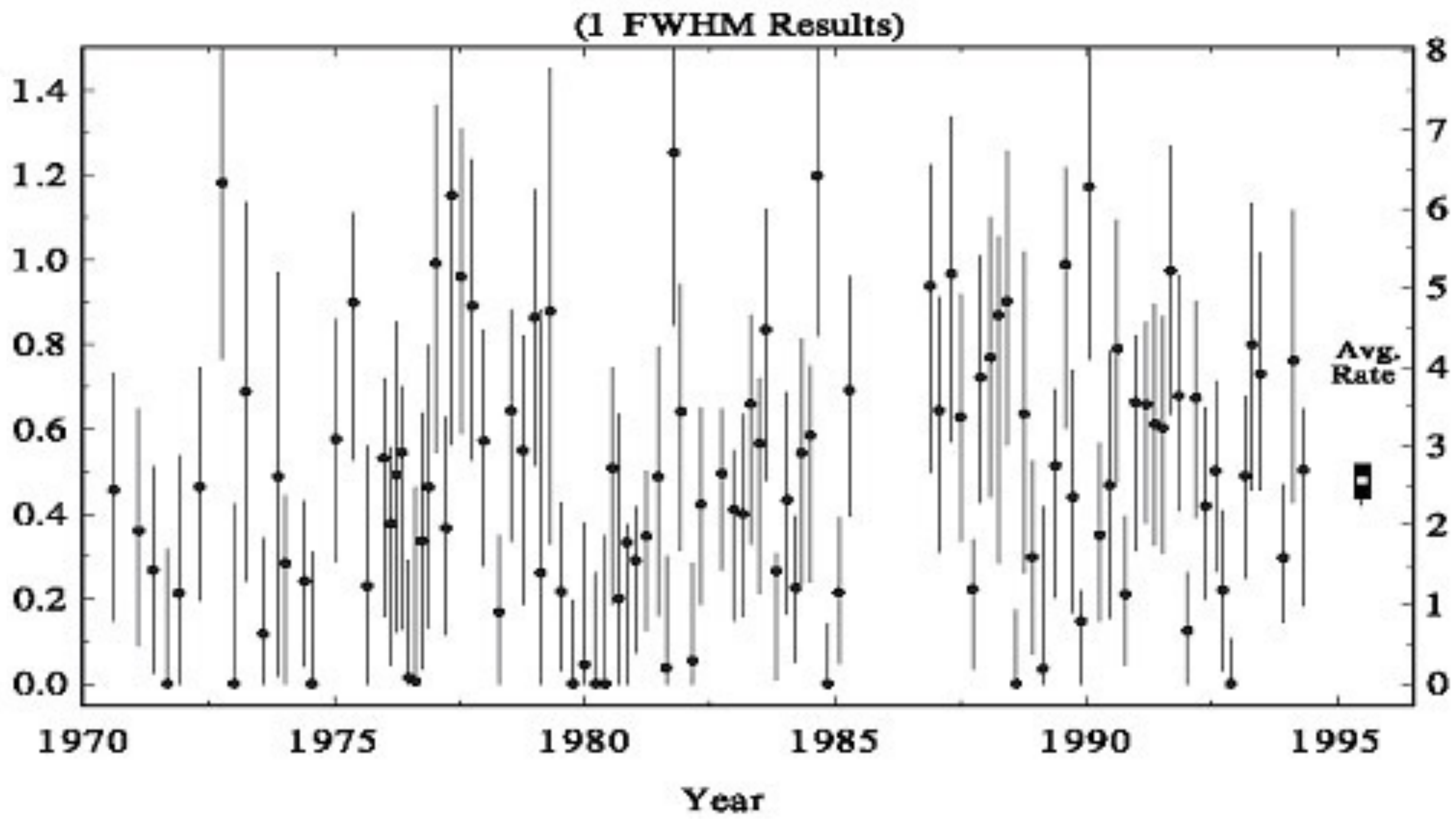
$$\nu_e + {}^{37}Cl \rightarrow {}^{37}Ar + e^-$$

Neutrinos absorbed by Chlorine
-> Argon produced
-> Counting of single Argon atoms

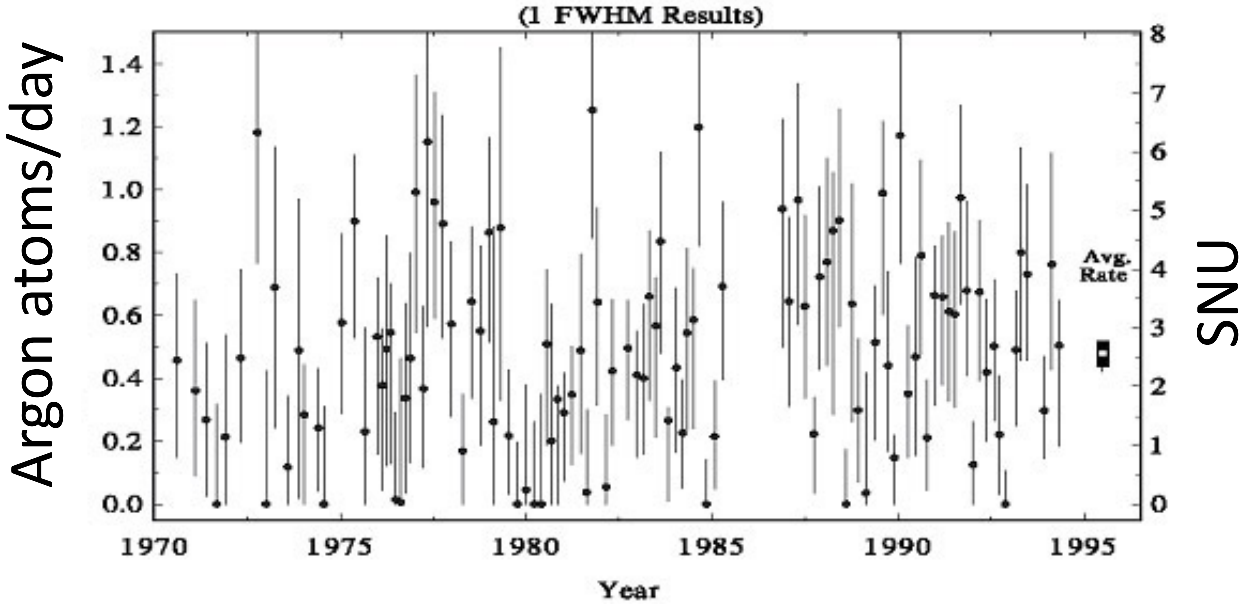
Extraction of Argon with the help of helium

=> Extraction of a few 10 atoms from ~10^{30} in tank!
=> Counting by measurements of radioactive decay

Measurements 1970-1995



The missing neutrinos



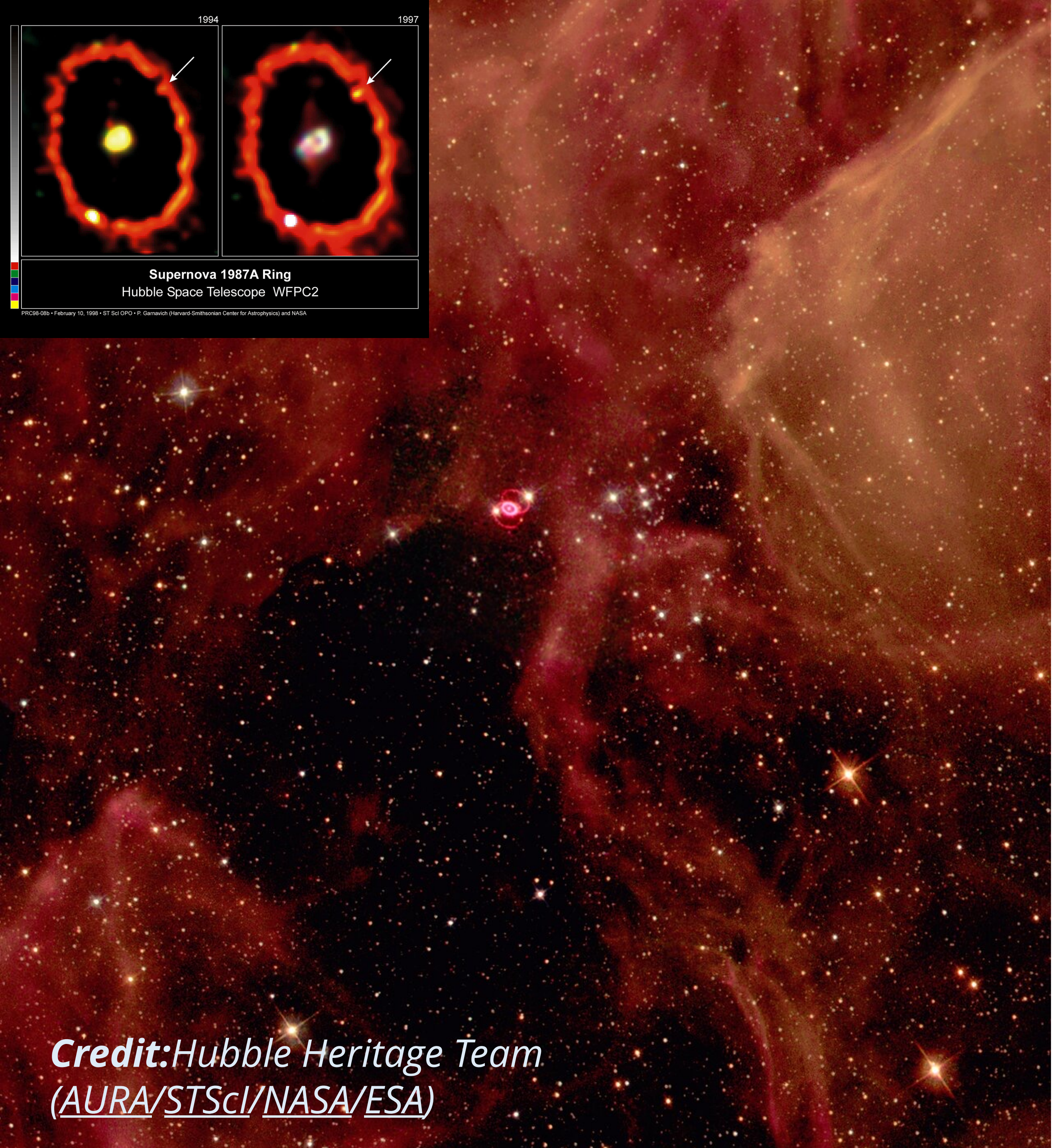
Expectation: 6.4-9.3 SNU
Measurement: 2.6 SNU

What's wrong?
- Model of solar processes?
- Experimental flaw?
- …?

designed Kamiokande
(successor Super-Kamiokande)

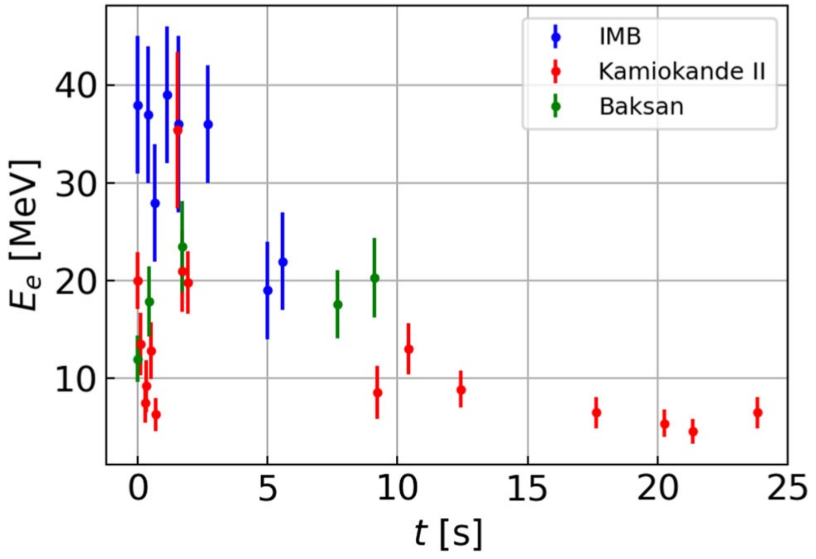
Nobelprijs 2002: Raymond Davis Jr. and **Masatoshi Koshiba**

"for pioneering contributions to astrophysics, in particular for the detection of cosmic neutrinos"



***Credit:**Hubble Heritage Team*
(AURA/STScI/NASA/ESA)

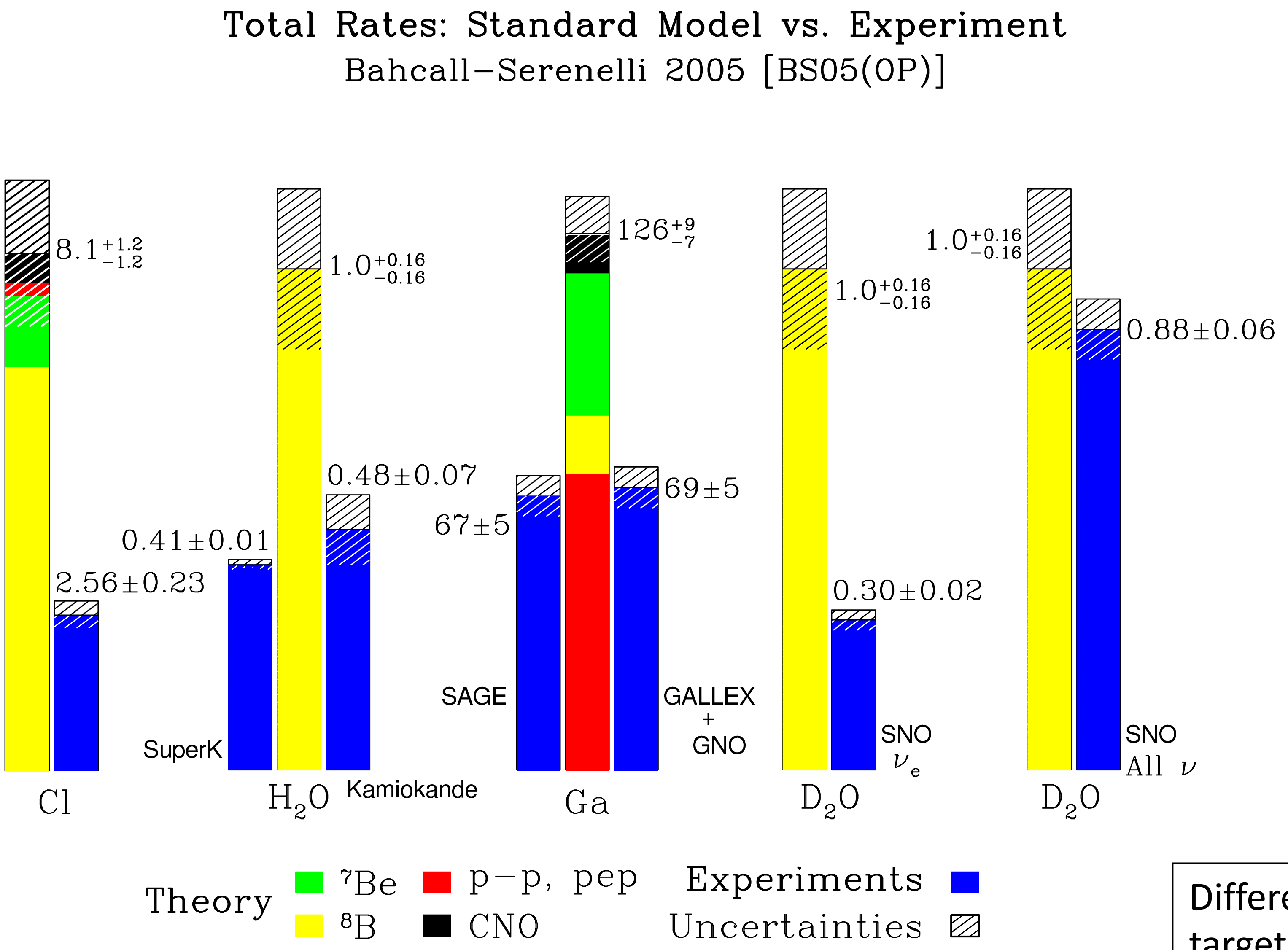
Supernova 1987a



- Supernova 168000 light years away in the Large Magellanic Cloud
- A handful of MeV energy neutrinos detected in 3 detectors

~40 years ago

The mystery of missing neutrinos



experiment
theorie
theorie
theorie
theorie

Different experimental methods, targeting different energies

Mystery:

Far too little electron neutrino interactions detected

But:

Total number of neutrino interactions (all flavors) agrees with expectation

Conclusion:

Neutrinos change their flavor with travelling
=> only possible if they have mass

Nobelprijs 2002: Takaaki Kajita and **Arthur B. McDonald**

" for the discovery of neutrino oscillations, which shows that neutrinos have mass"

Solution for the missing neutrinos: Neutrino Oscillations

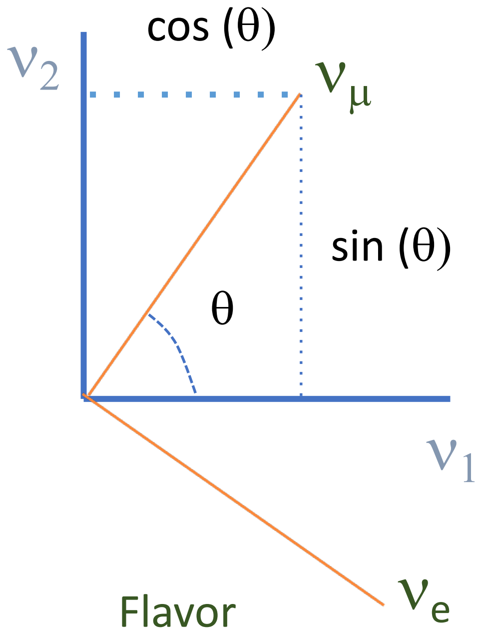
Flavor eigenstates are not equal to mass eigenstates

Flavor eigenstate		Mass eigenstate
νe	*Mixing matrix* →	$\nu 1$
$\nu\mu$		$\nu 2$
$\nu\tau$		$\nu 3$

Example with 2 flavors (electron, muon)

$\nu_\mu = \cos(\theta)\, \nu_1 + \sin(\theta)\, \nu_2$

θ has to be measured



Neutrino Oscillations

Flavor eigenstates are not equal to mass eigenstates

Flavor eigenstate → *Mixing matrix* → **Mass eigenstate**

νe → $\nu 1$

$\nu\mu$ → $\nu 2$

$\nu\tau$ → $\nu 3$

Pontecorvo–Maki–Nakagawa–Sakata (PMNS) matrix

$$\begin{bmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{bmatrix} \begin{bmatrix} c_{13} & 0 & s_{13}e^{-i\delta_{CP}} \\ 0 & 1 & 0 \\ -s_{13}e^{i\delta_{CP}} & 0 & c_{13} \end{bmatrix} \begin{bmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{bmatrix}$$

$$= \begin{bmatrix} c_{12}c_{13} & s_{12}c_{13} & s_{13}e^{-i\delta_{CP}} \\ -s_{12}c_{23} - c_{12}s_{23}s_{13}e^{i\delta_{CP}} & c_{12}c_{23} - s_{12}s_{23}s_{13}e^{i\delta_{CP}} & s_{23}c_{13} \\ s_{12}s_{23} - c_{12}c_{23}s_{13}e^{i\delta_{CP}} & -c_{12}s_{23} - s_{12}c_{23}s_{13}e^{i\delta_{CP}} & c_{23}c_{13} \end{bmatrix}.$$

c_x: $\cos(\theta_x)$

s_x: $\sin(\theta_x)$

Neutrino Oscillations

- Neutrino is created in single flavor eigenstate (superposition of different mass eigenstates)
- Propagation of the different mass eigenstates depends on energy and **mass**

$\Longrightarrow$ **Leads to differences in the composition of the superposition**

$\Longrightarrow$ **Leads to flavor changes, depending on travel length/energy/mass differences**

- Flavor changes ONLY if neutrinos have mass
- Oscillation pattern determined by mass differences (thus no mass measurement)
- Flavor distribution at astrophysical source (and at the atmosphere) is different from detected flavors on Earth

Oscillation probability

$$P_{\nu_e \to \nu_\mu} = \left[\sin 2\theta \sin\left(\frac{({m_2}^2 - {m_1}^2)c^3}{4\hbar E} L\right)\right]^2$$

Often shown in simplified form ($\hbar = c = 1$). *Be mindful with restoring in calculations*

$$P_{\nu_e \to \nu_\mu} = \left[\sin 2\theta \;\sin(\Delta m_{12}^2 \frac{L}{E})\right]^2$$

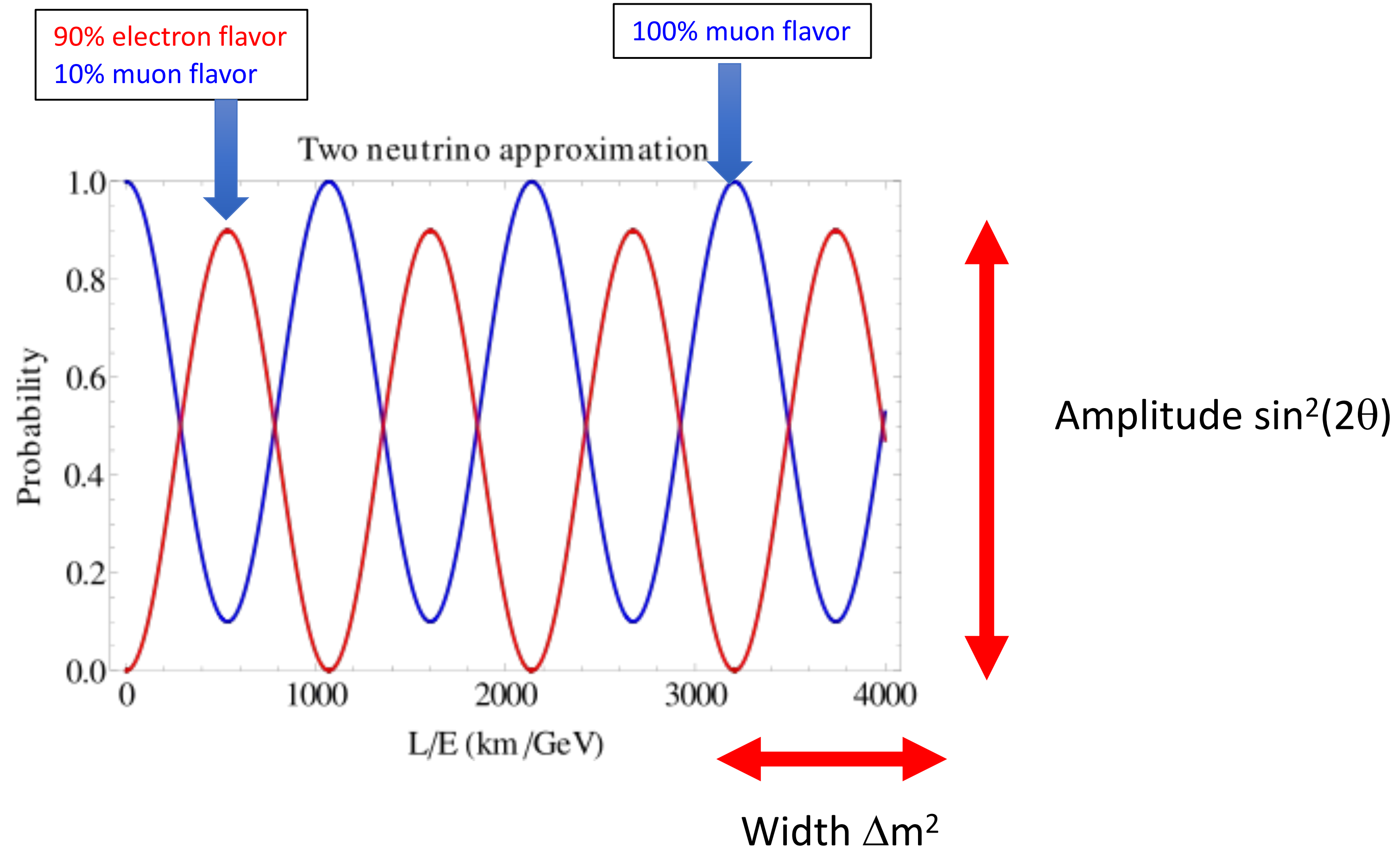
Characteristic oscillation length: L/E

Probability of flavor change depends on

- Mass differences of mass eigenstates
- Mixing angle
- Travel time (distance)
- Energy of neutrino

Oscillation probability of a muon neutrino

muon flavor
electron flavor



Start with 100% Muon neutrinos

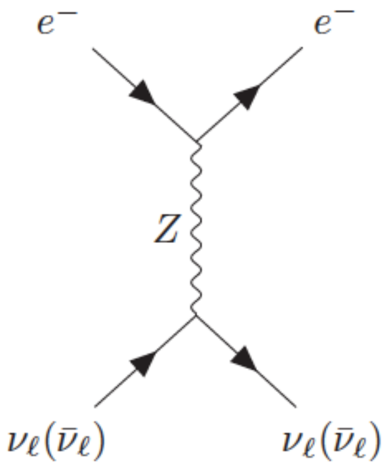
Probability to detect a muon (electron) neutrino changes depending on travel length and energy

Neutrino oscillations in matter

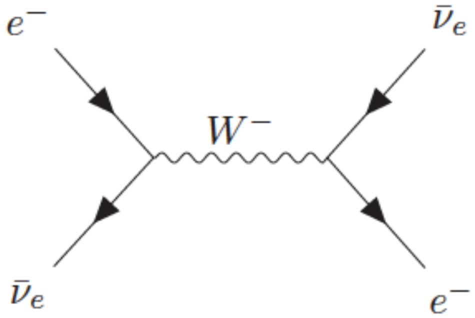
- Propagation of electron (anti-)neutrinos in matter:
- Electron (anti-)neutrinos sense a potential from coherent forward-scattering with the electrons

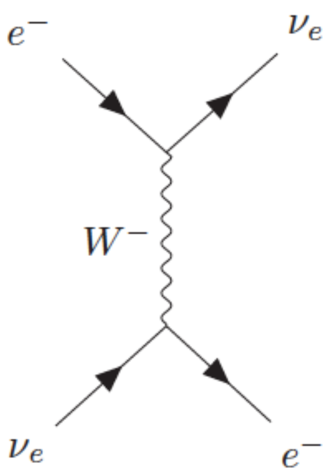
Mikheyev-Smirnov-Wolfenstein (MSW) effect

=> Sensitive to Neutrino Mass ordering

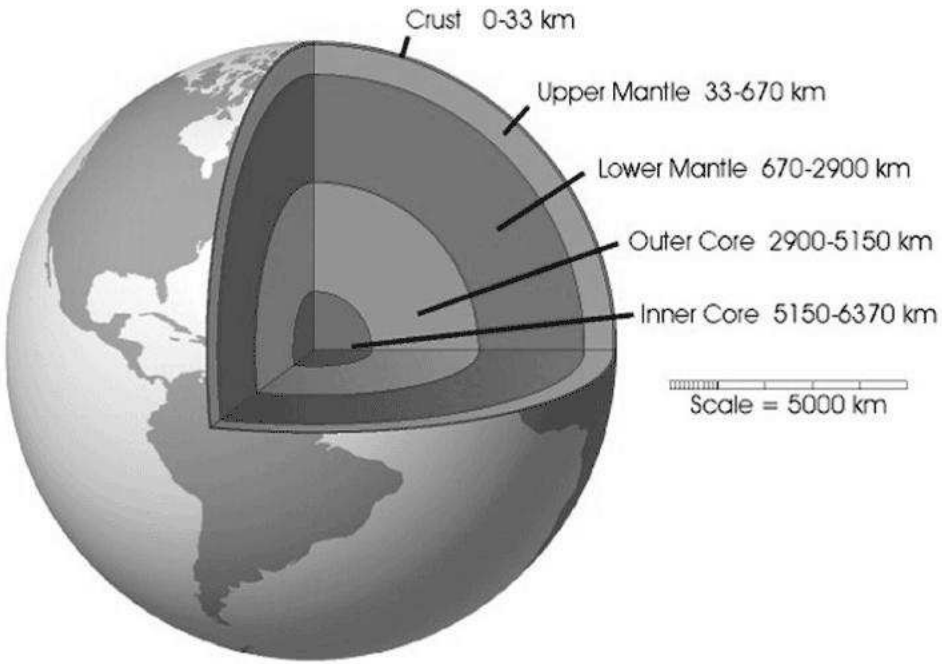


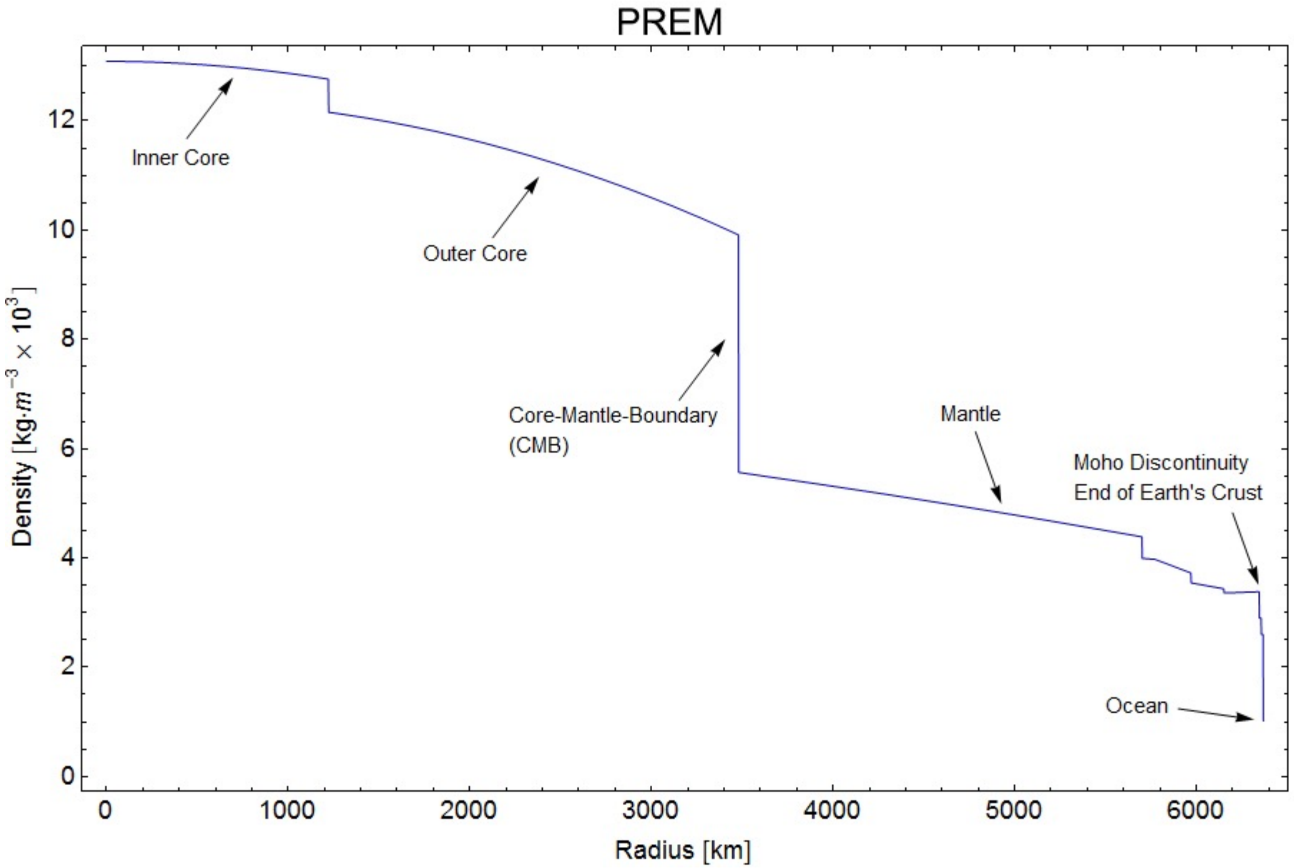
- Dependent on electron density
- Happening in dense media,
  -> Supernovae, Sun, Earth
- Dependent on mass ordering



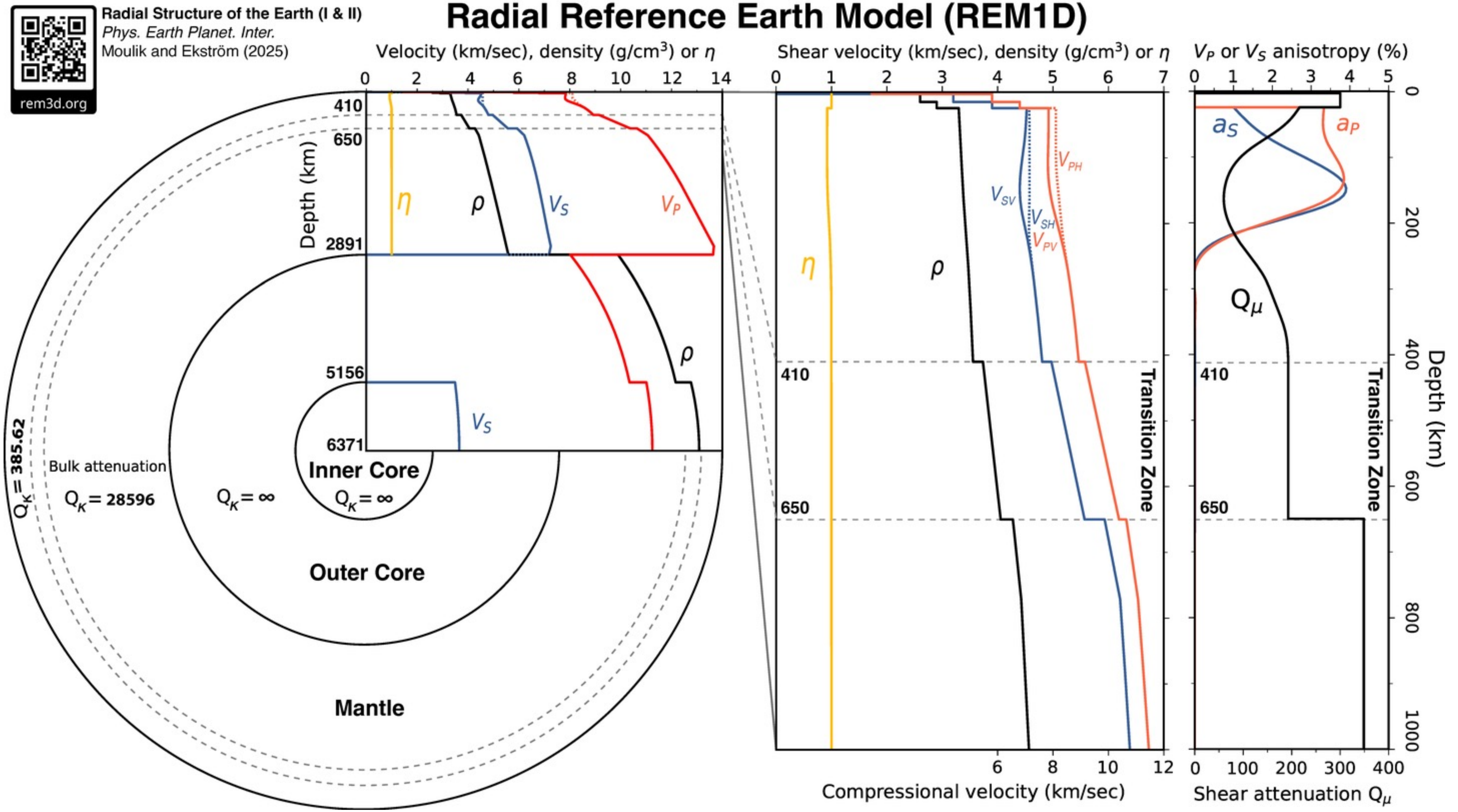


‘Preliminary’ Reference Earth Model (PREM)

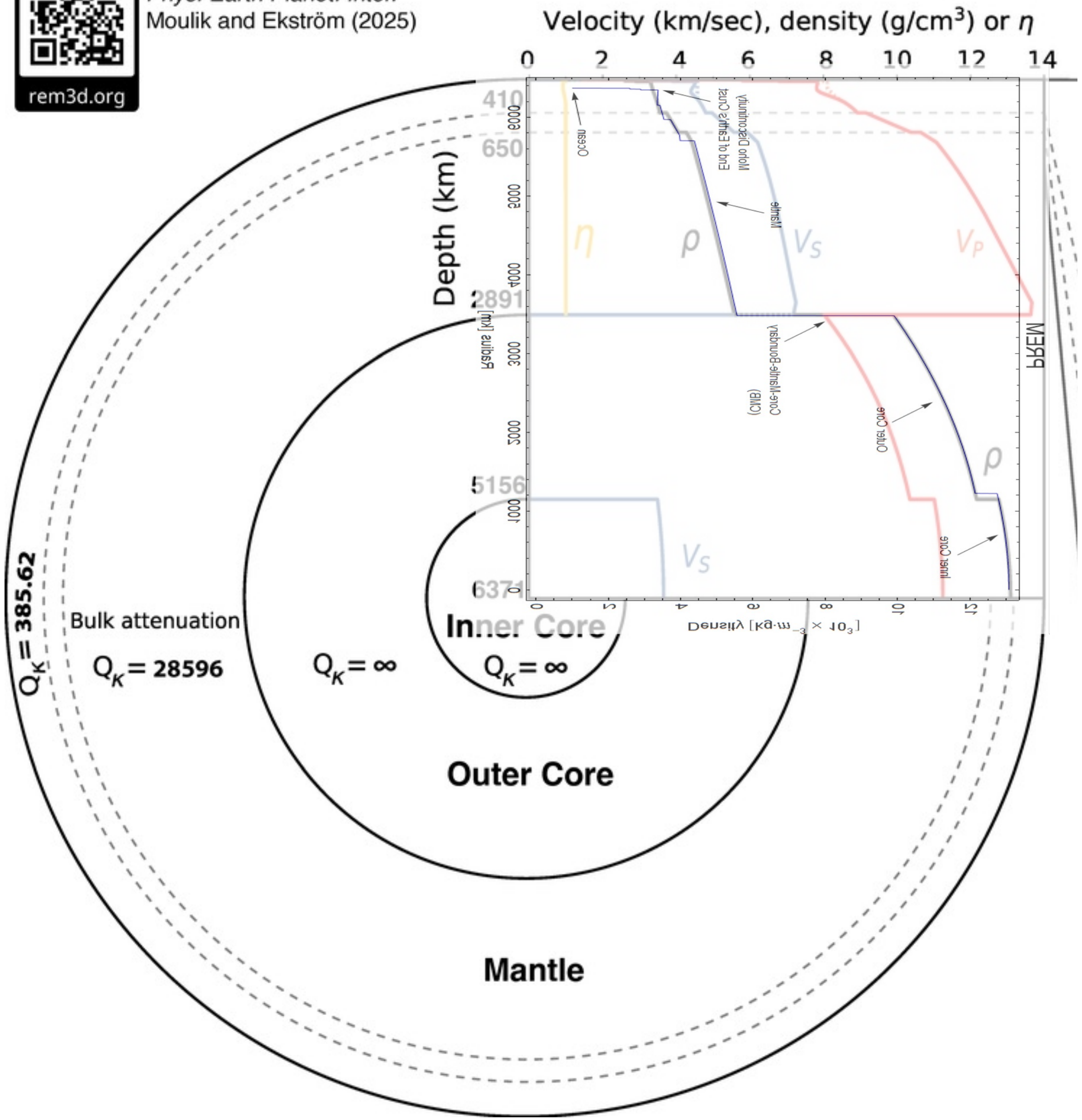




Reference Earth Model (2025)



Radial Reference Earth Model (REM1D)



Similar to ‘preliminary Earth model’

Matter effect for neutrino oscillations in Earth

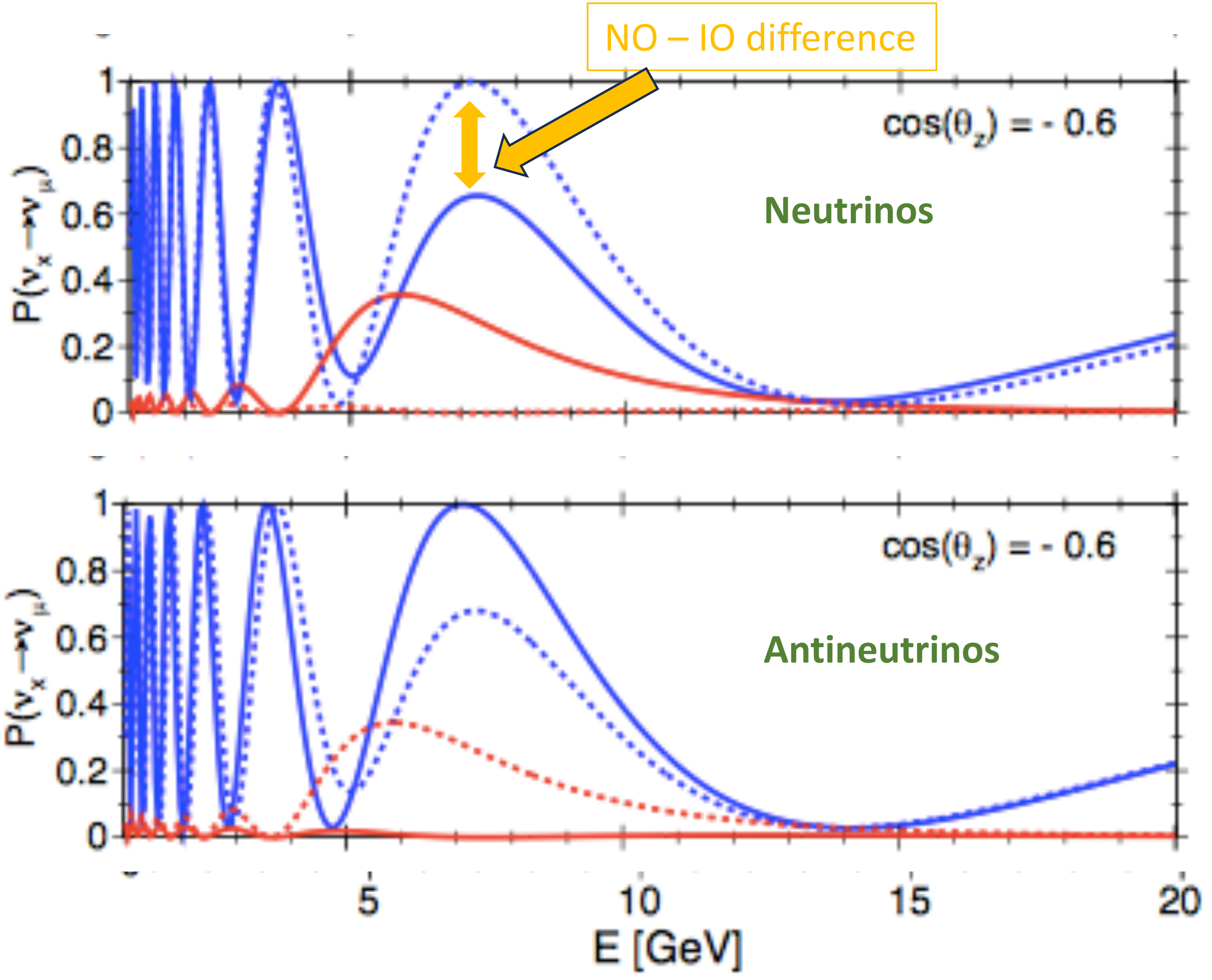
ν_μ -> ν_μ
ν_e -> ν_e

Solid: Normal Ordering (NO)
Dashed: Inverted Ordering (IO)

- Inverted Ordering (IO) and Normal Ordering (NO) lead to different flavor distributions for neutrinos travelling through Earth

  => Mass ordering measurement possible

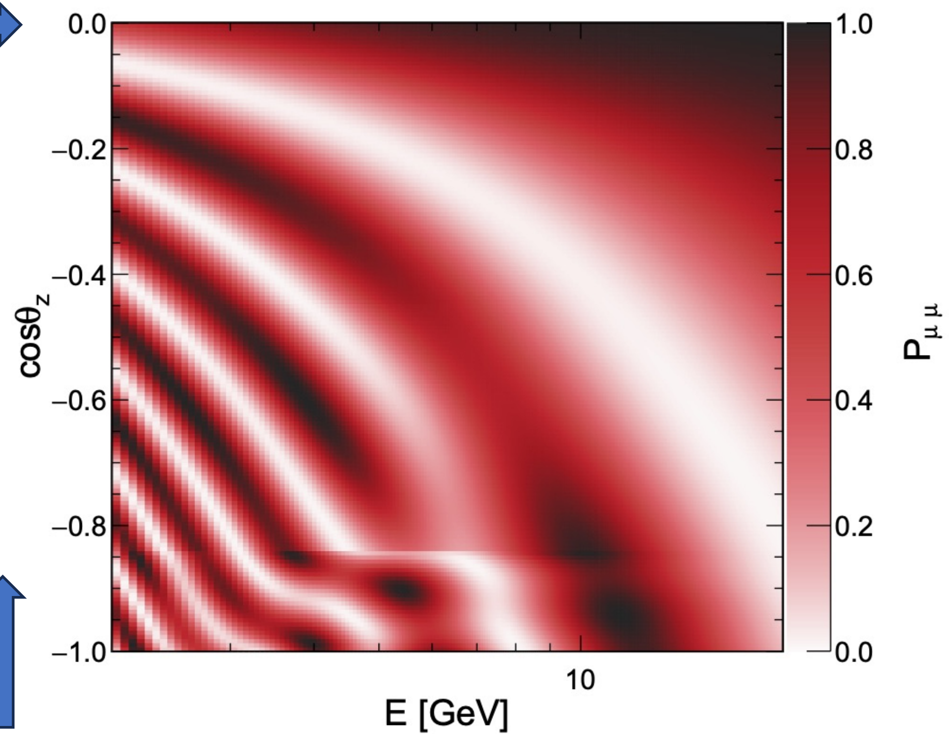
- Neutrinos IO pattern corresponds to antineutrinos NO pattern
- Neutrino telescopes do not distinguish neutrinos and antineutrinos
  => Effect would cancel with equal neutrino/antineutrino rates

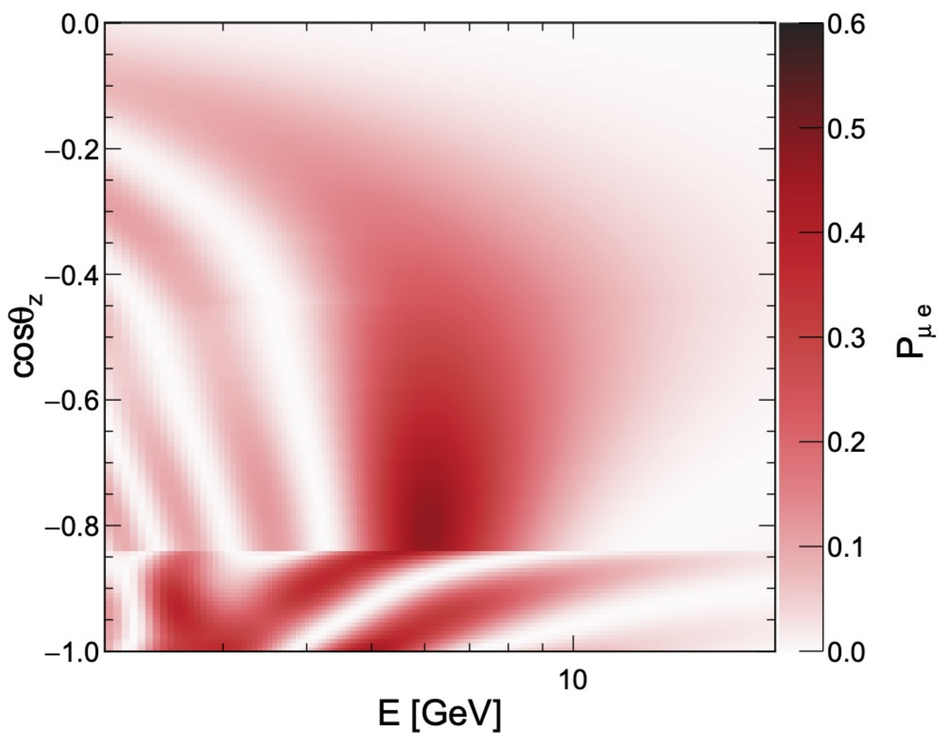


Probability for a muon neutrino
to be measured as muon neutrino

Probability for a muon neutrino
to be measured as electron neutrino

horizontal





Angle -> Travel distance

upward. going

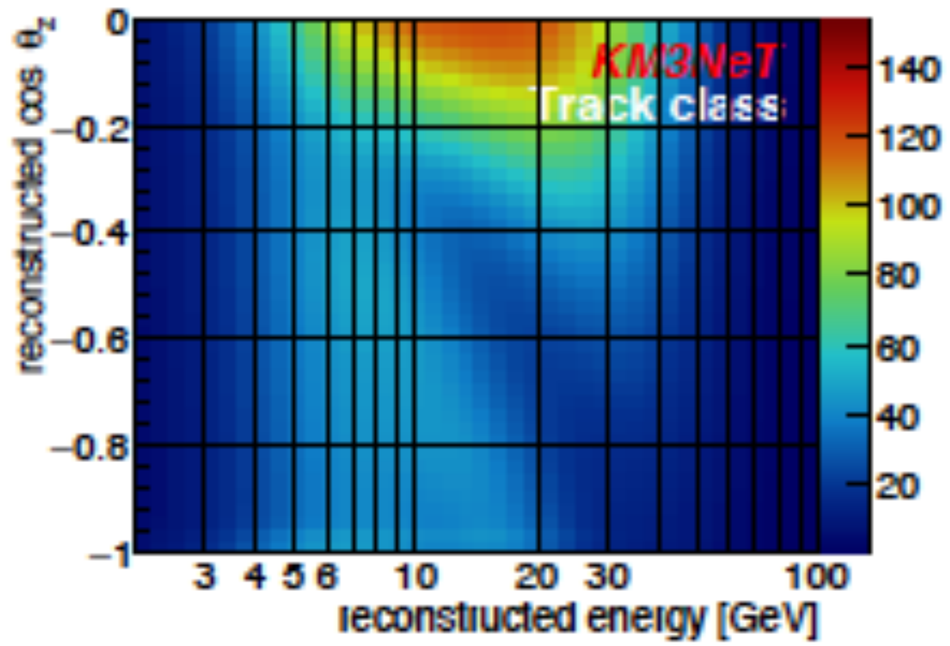
Energy

Probabilities depend on
neutrino mixing parameters (angles)
and mass differences
and Earth structure (matter effects)

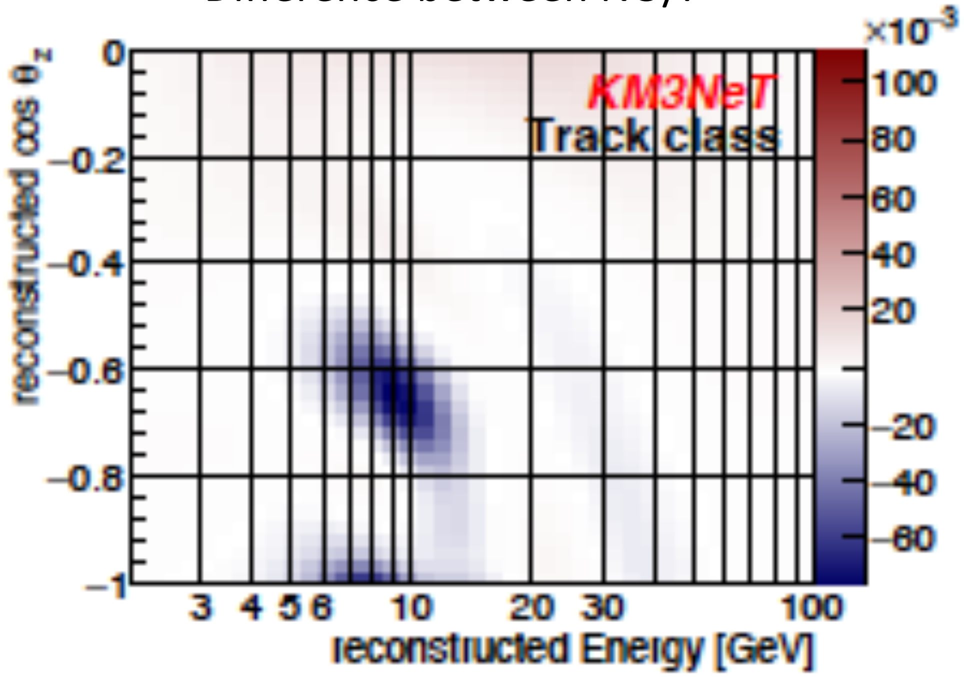
Projection of muon measurement in KM3NeT

Angle -> Travel distance

Track events



Difference between NO/I



Energy

Probabilities depend on
neutrino mixing parameters (angles)
and mass differences
and Earth structure (matter effects)

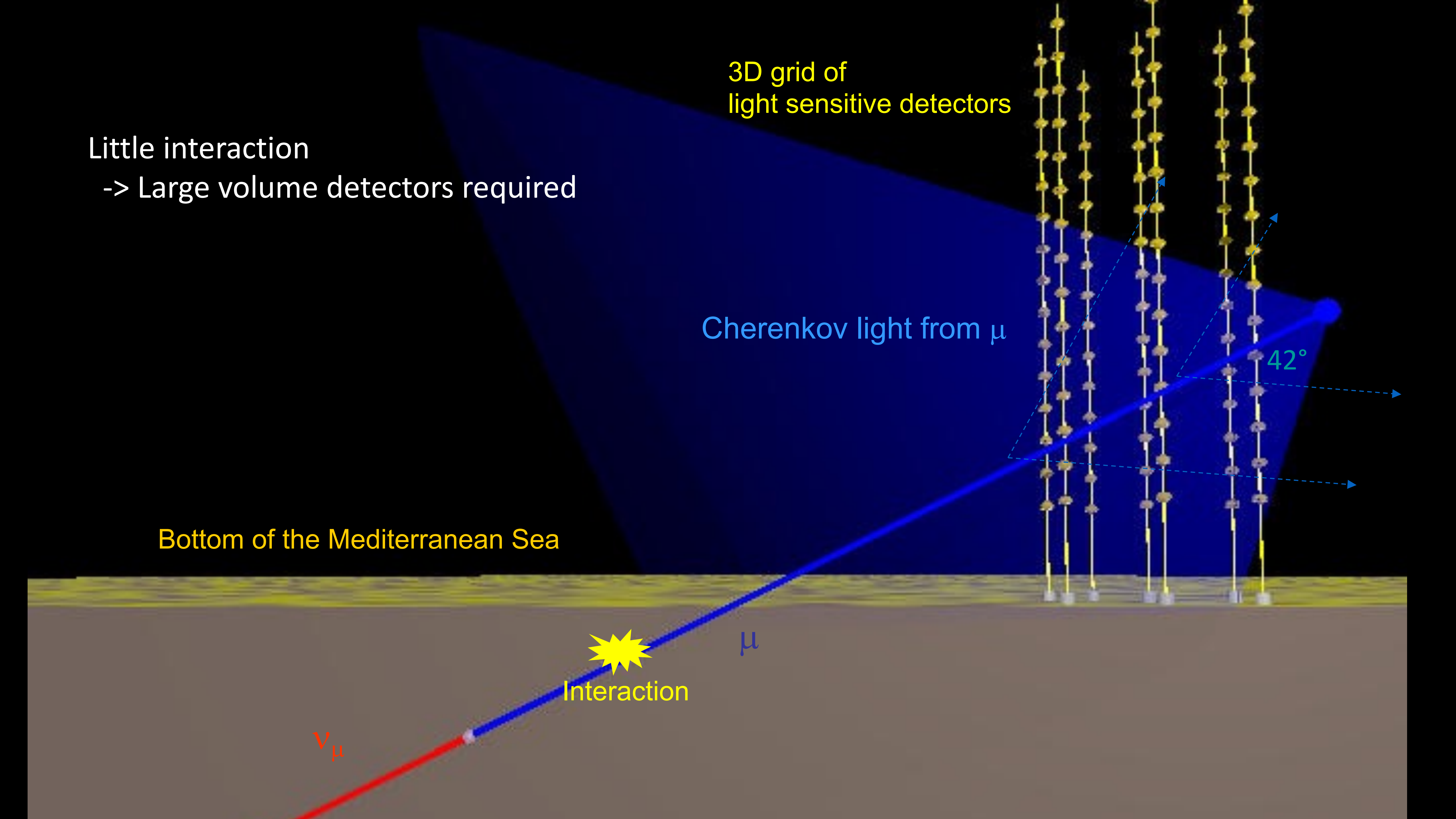
Measured pattern in detector expected as:
- pattern folded with atmospheric muon flux
- pattern folded with detector response

How can we detect the neutrinos?

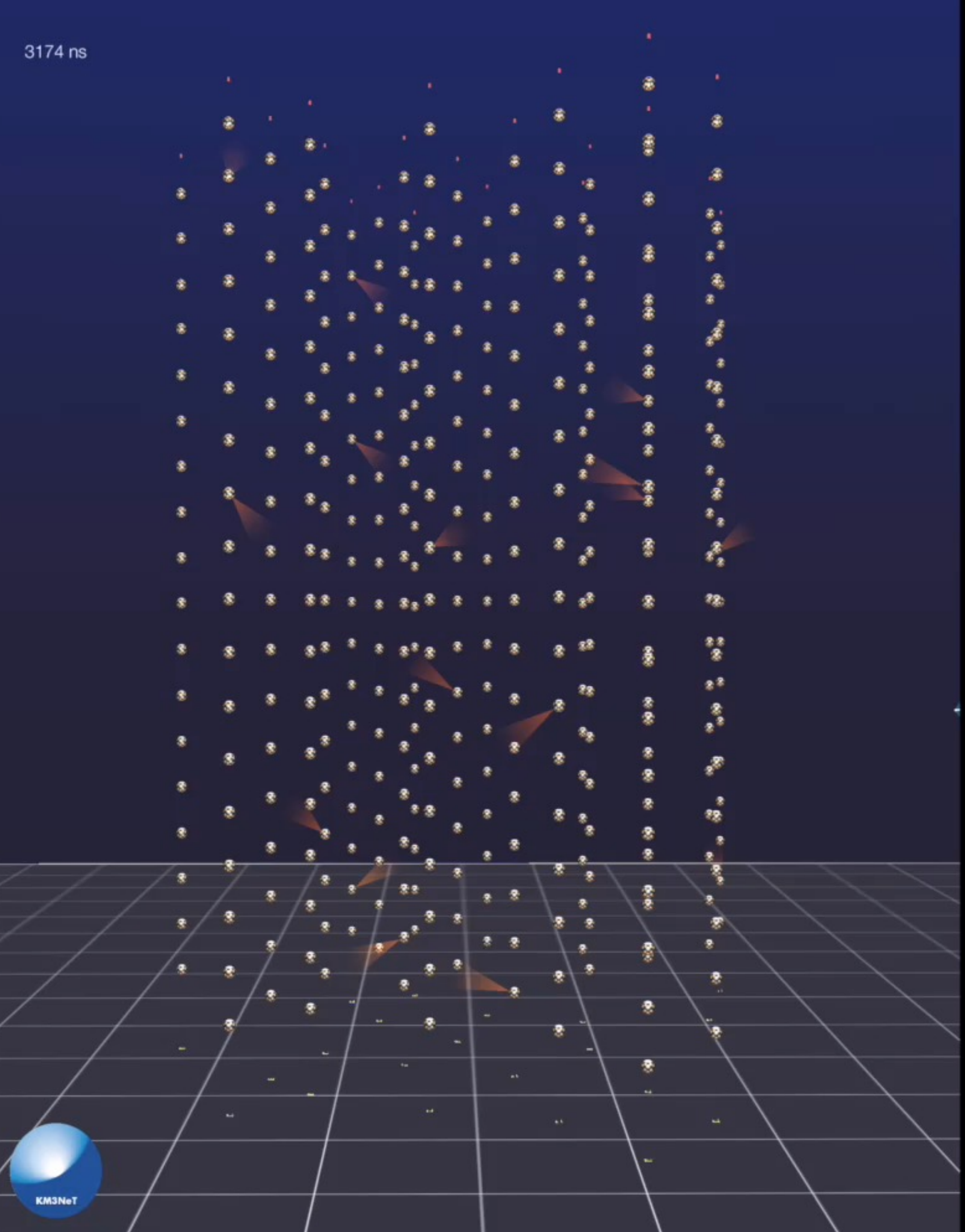
Meet the neutrino telescopes

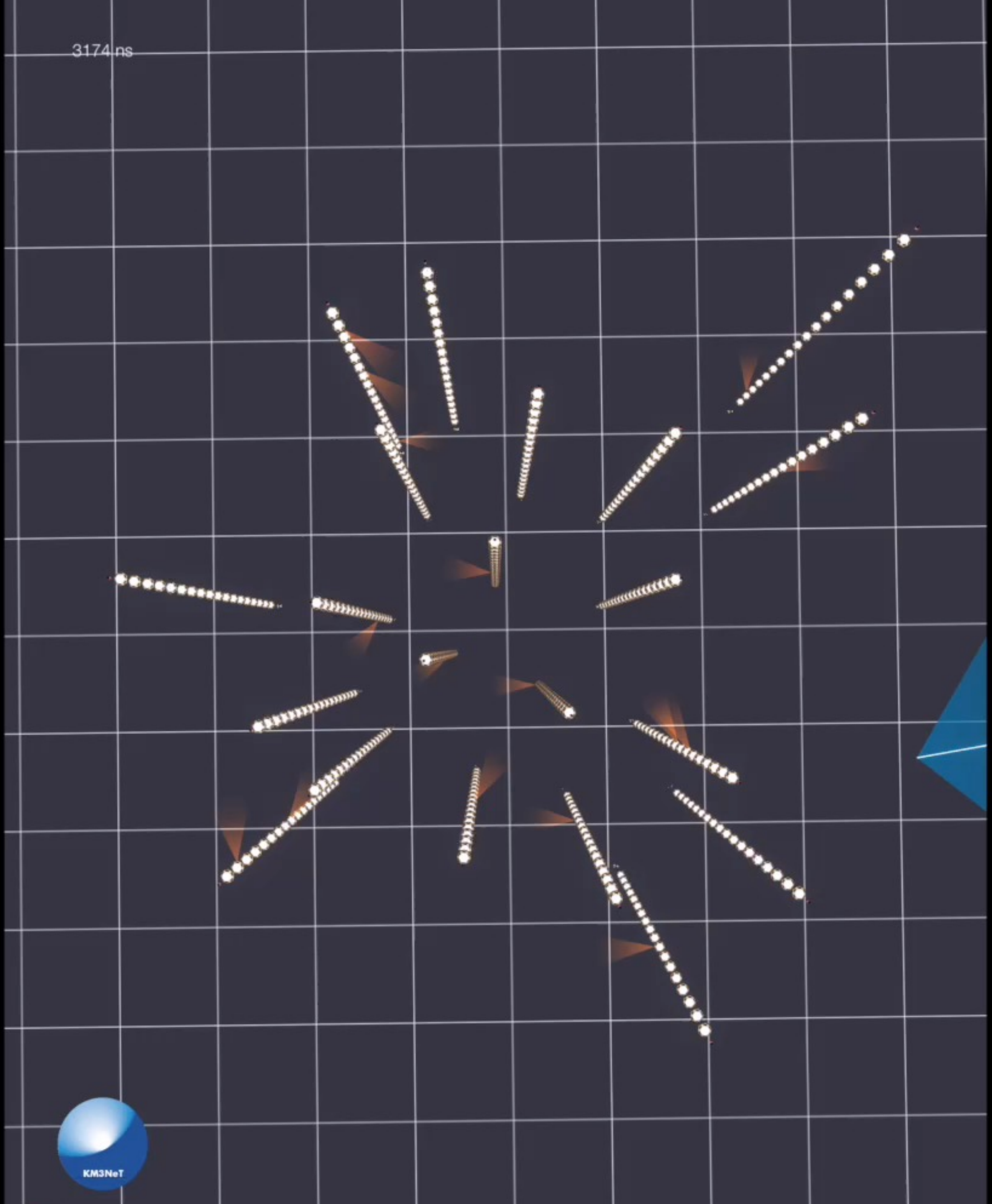
Neutrino detection

Interaction with matter
-> production of charged high energy particles
-> charged particle is faster than light in medium
-> production of Cherenkov light

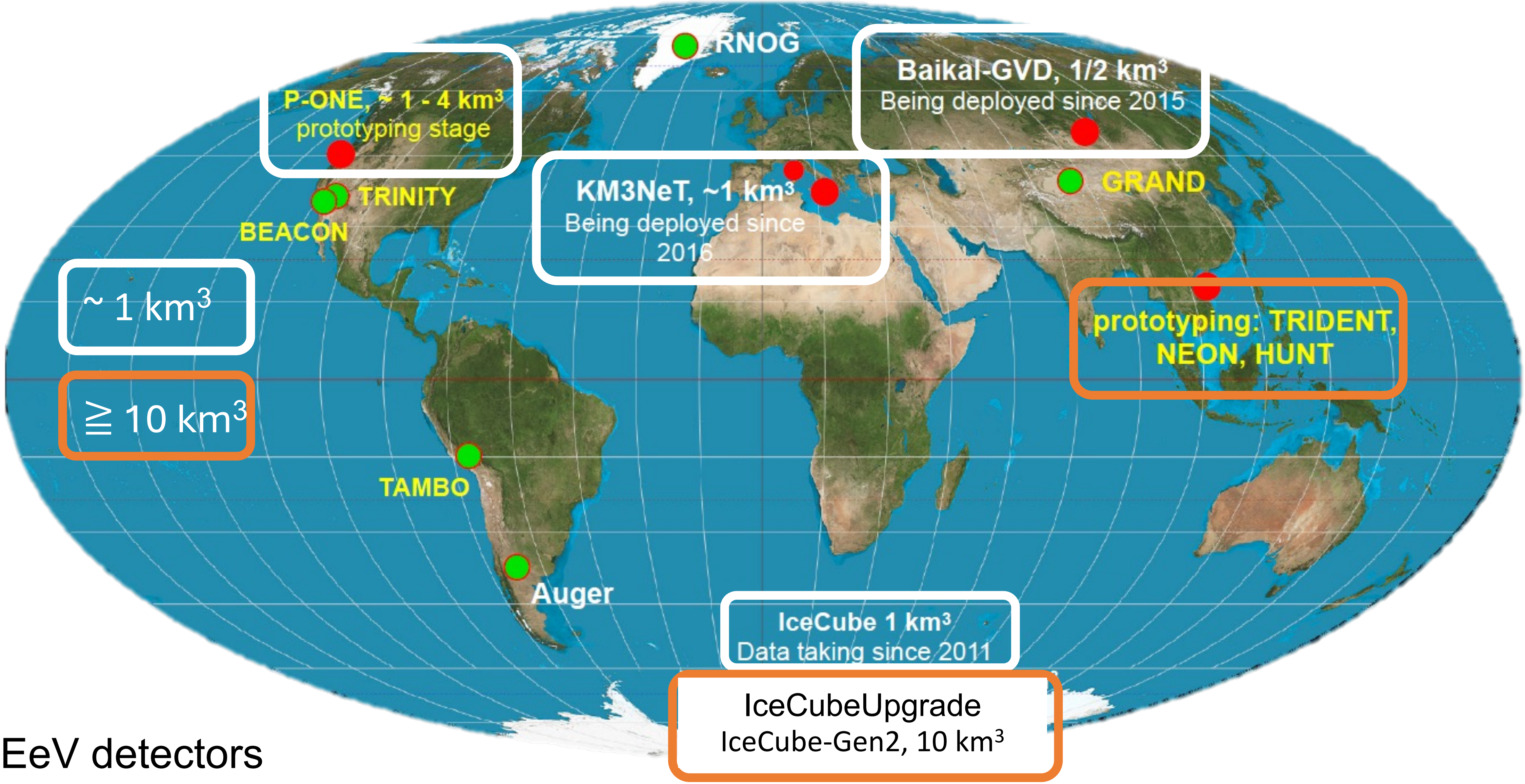


Little interaction
-> Large volume detectors required
3D grid of
light sensitive detectors
Cherenkov light from μ
42°
Bottom of the Mediterranean Sea
μ
Interaction
ν_μ


3174 ns
KM3NeT


3174 ns
KM3NeT

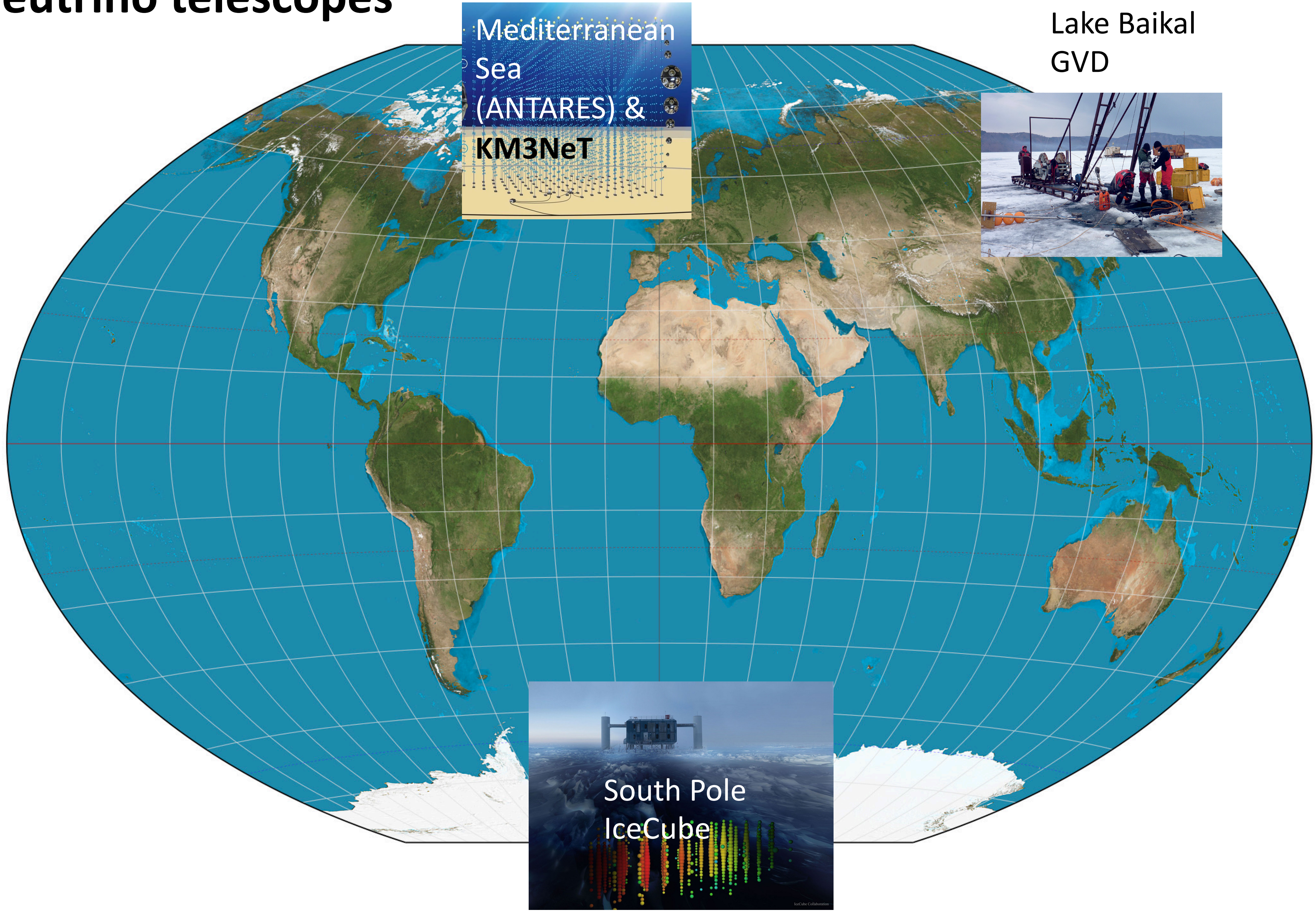
Current (and future) neutrino telescope landscape (optical and radio)



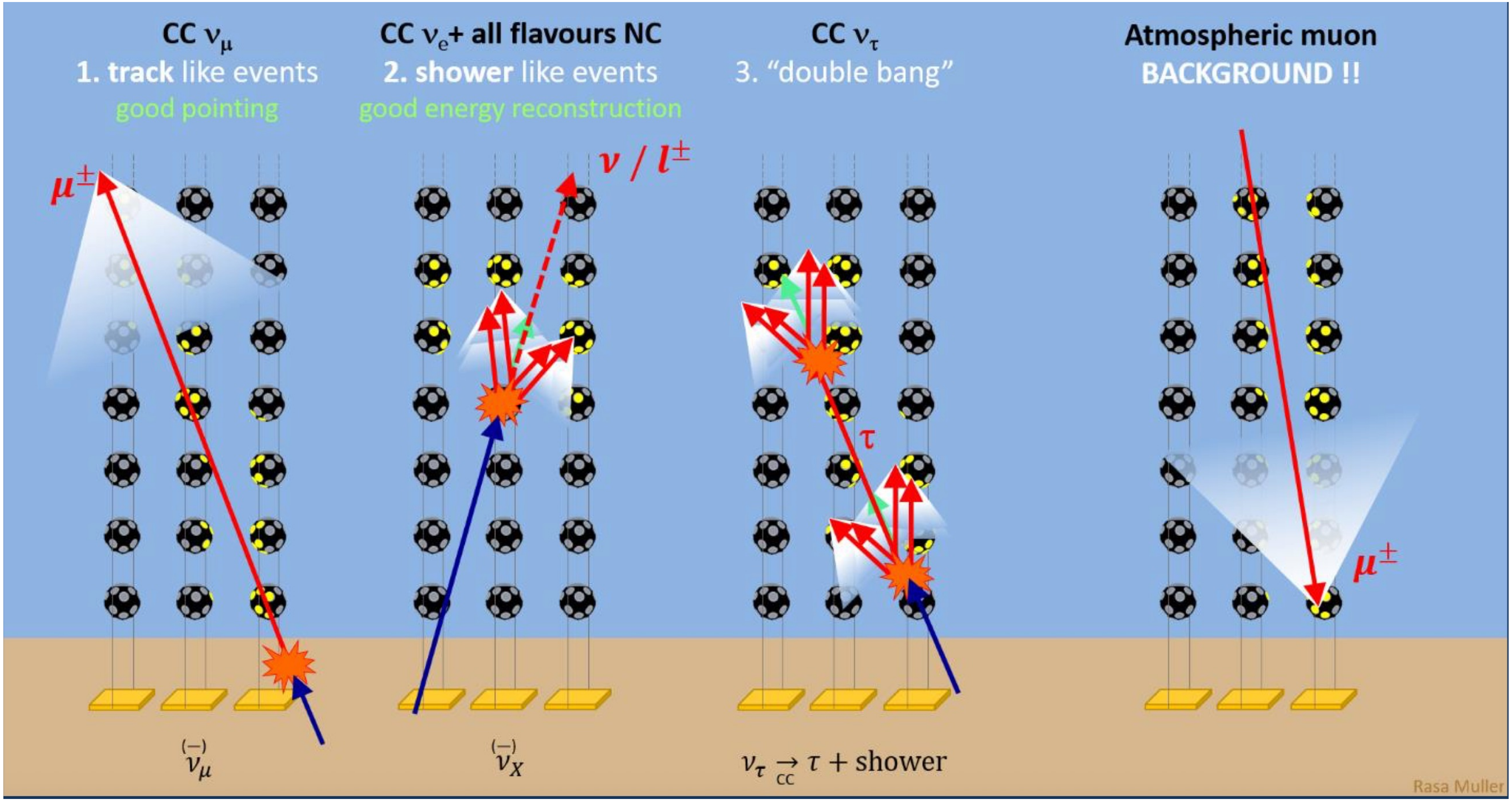
- EeV detectors
- megaton GeV detectors: IceCube Upgrade, ORCA, HUNT

F. Halzen, NeuTel 2025

Current neutrino telescopes

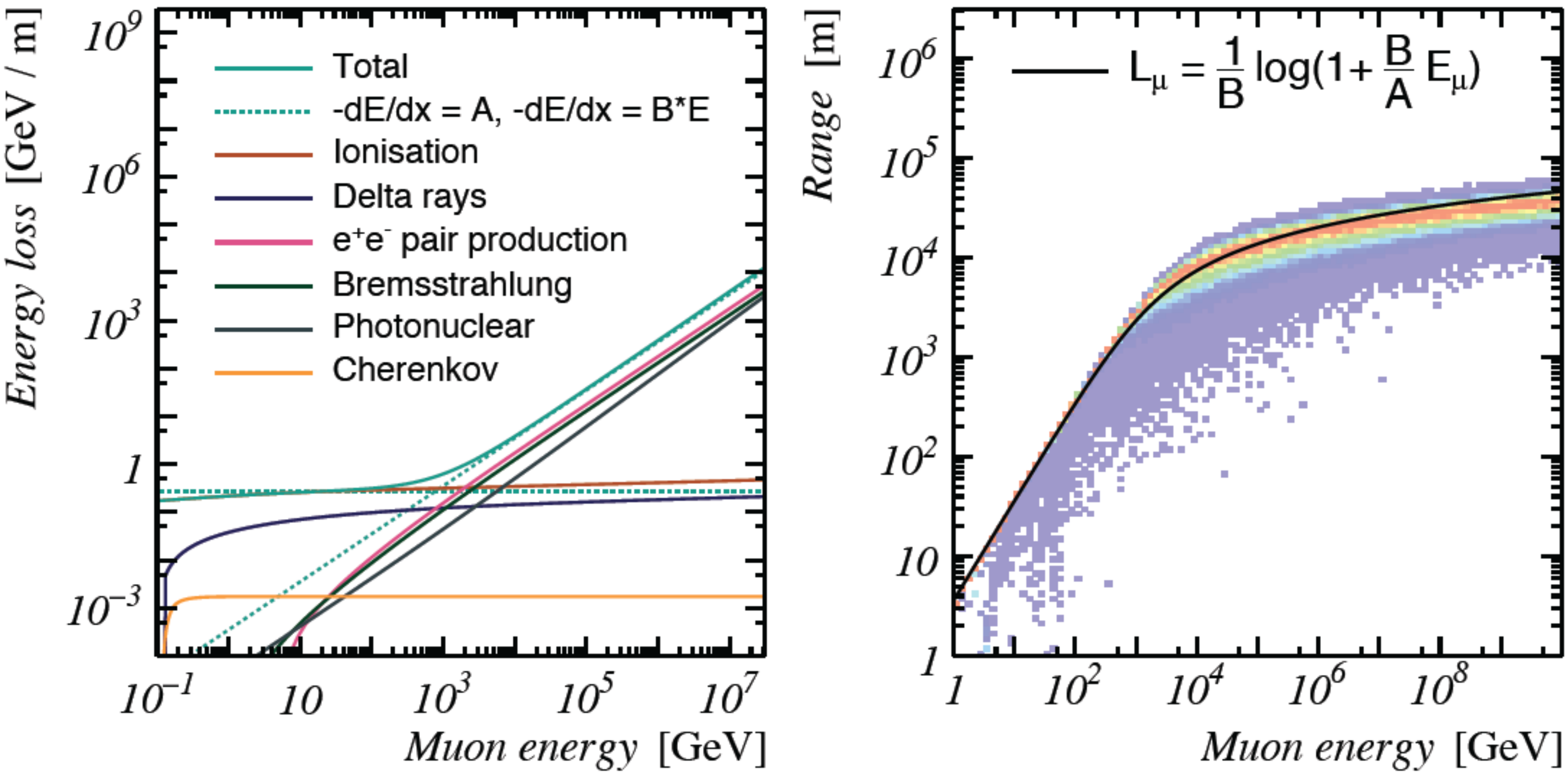


Different signatures in the detector – from different neutrino flavors



Energy loss and range of muons in water

TeV muons travel several kilometers through water

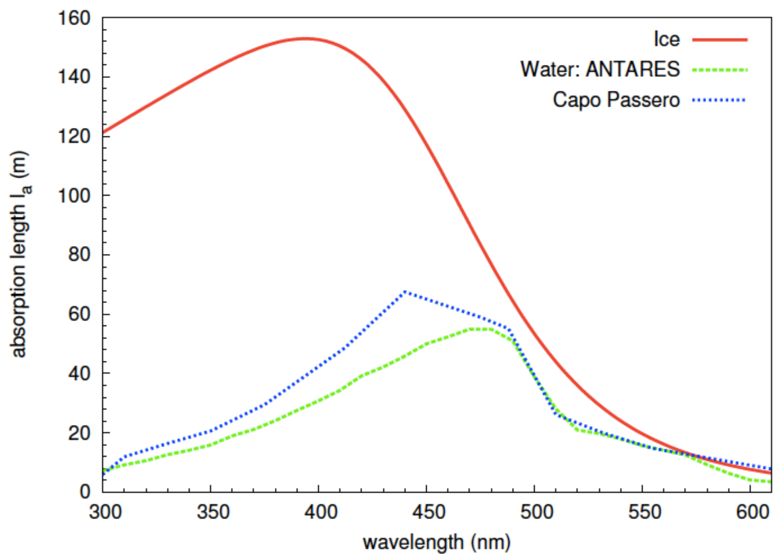


K. Melis, PhD thesis

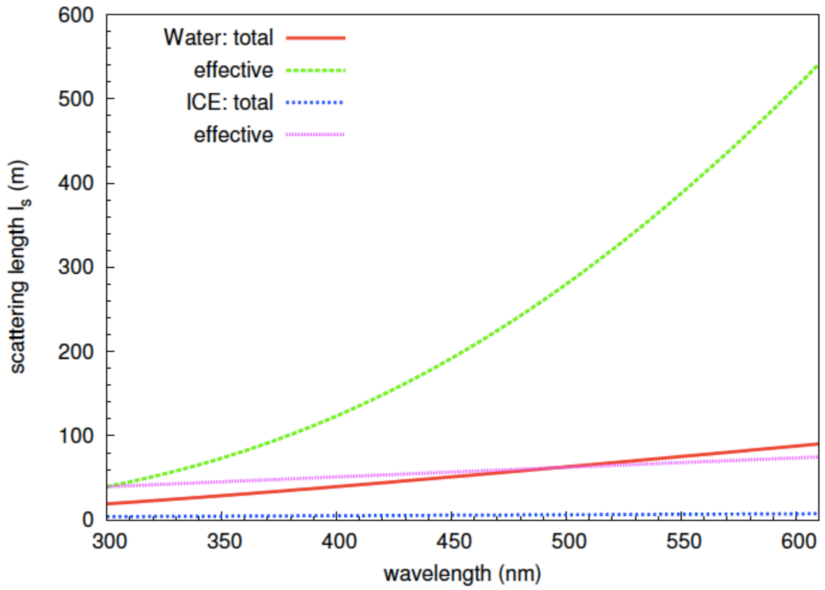
Impact of the medium (water/ice)

Light contains information on the direction/energyof event -> absorption/scattering impact event reconstruction

absorption



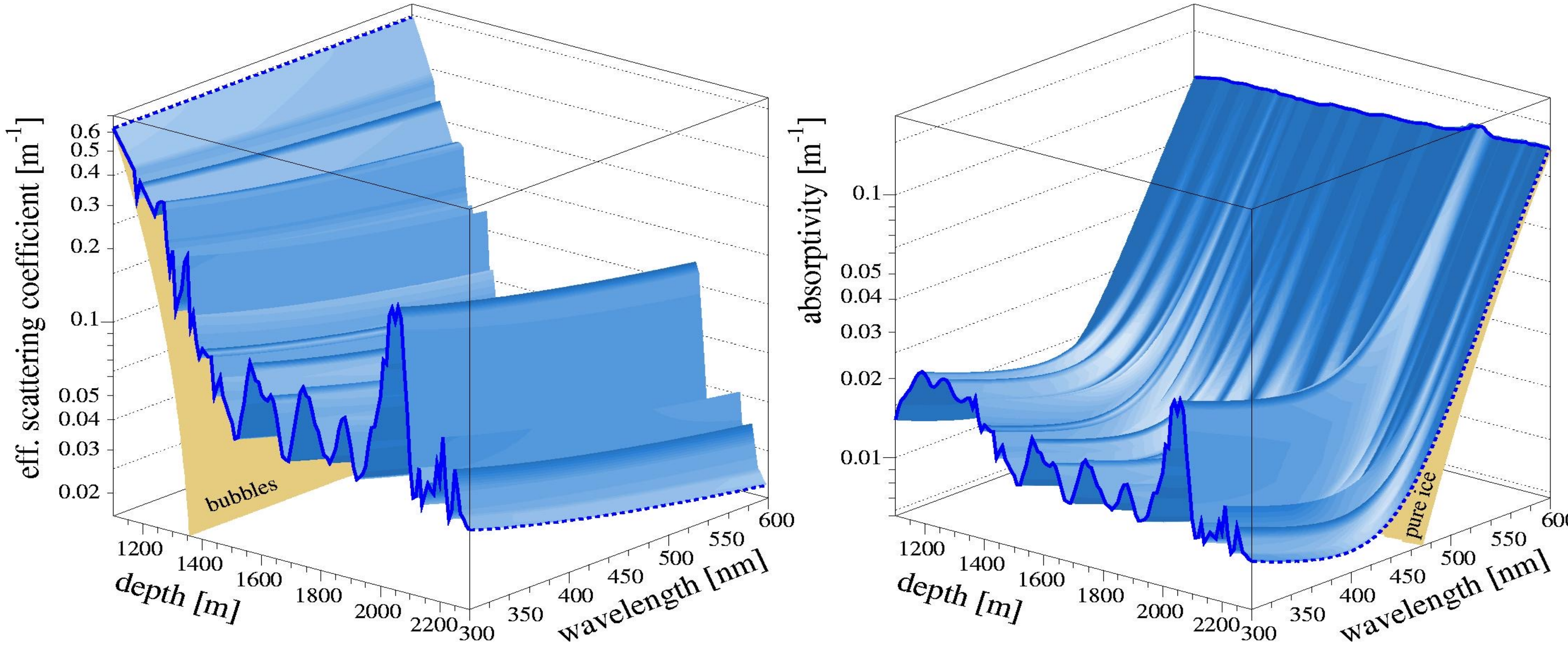
scattering



For Ice properties are depth dependent
-> different dust layers

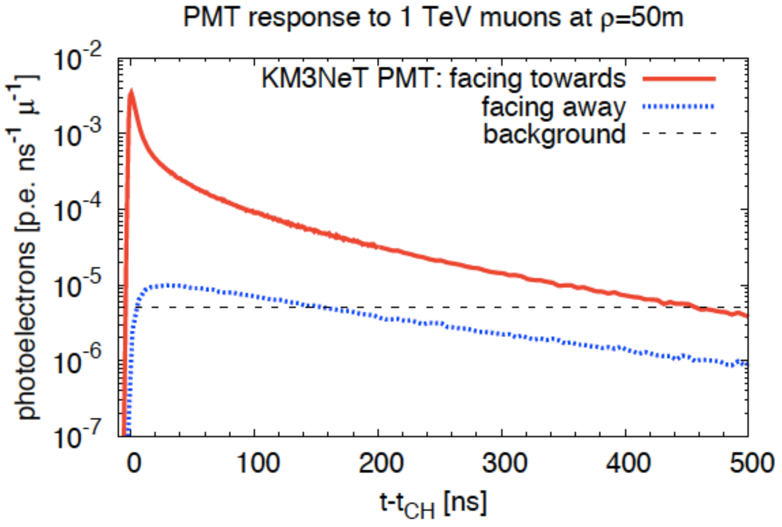
For Lake Baikal significantly lower absorption/scattering lengths than in Mediterranean water (~20m)

Ice dust layers impact optical properties



Time residuals for muon light in water/ice

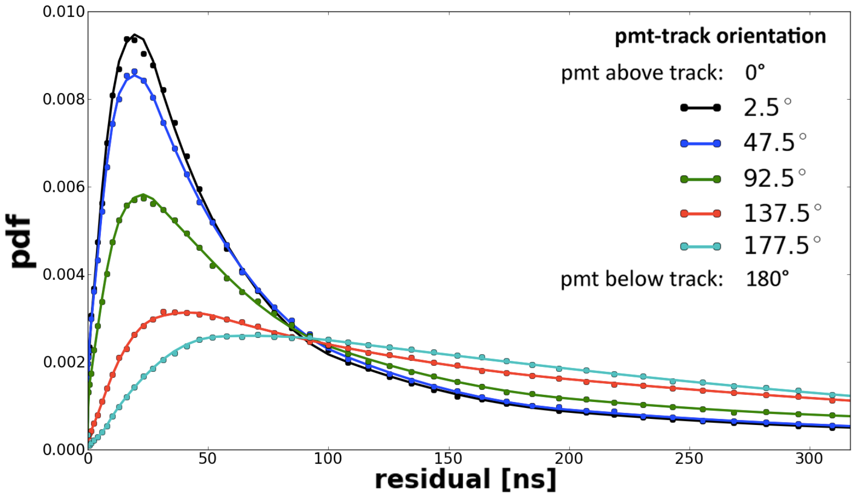
KM3NeT (water)



Large scattering length
=> at 50m still extremely precise time information (logarithmic y-scale)

IceCube (ice)

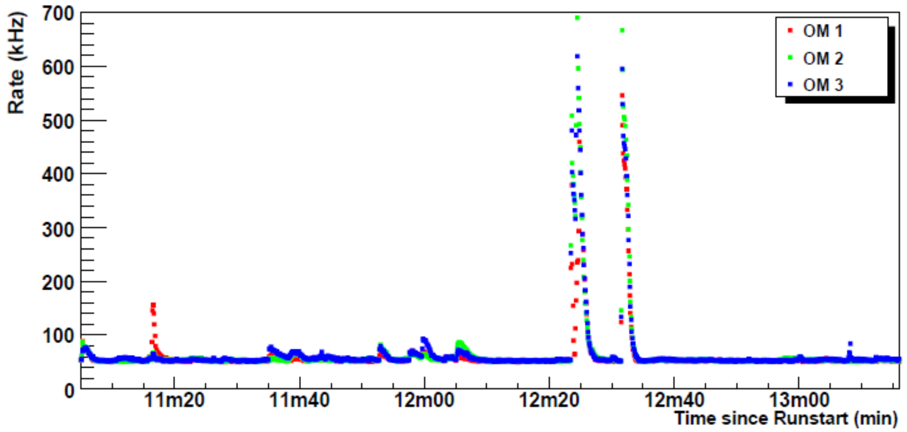
45 meter distance



Scattering and time residuals
are depth dependent (here at 2310m)

Timing determines angular reconstruction accuracy (important for point source search) and reconstruction of event topology (signatures of different flavors)

Optical backgrounds in the Sea

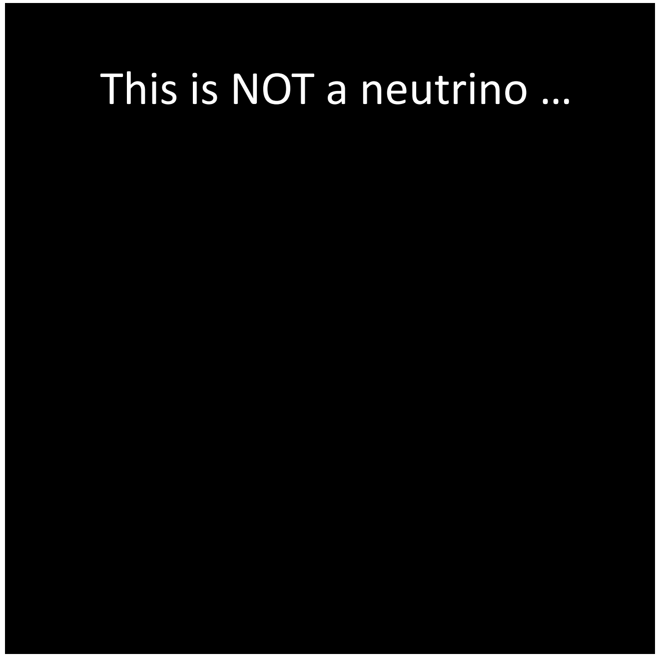


Optical background in ANTARES due to

- ^{40} K decay (salt in water)
  -> can be used for calibration

- bioluminescent organisms
  (e.g. megaplankton, pyrosoma, size 0.2-2000mm)

Baseline hit rate 50-120kHz
Short bursts/flashes with higher rates



Video from biocam installed 2010

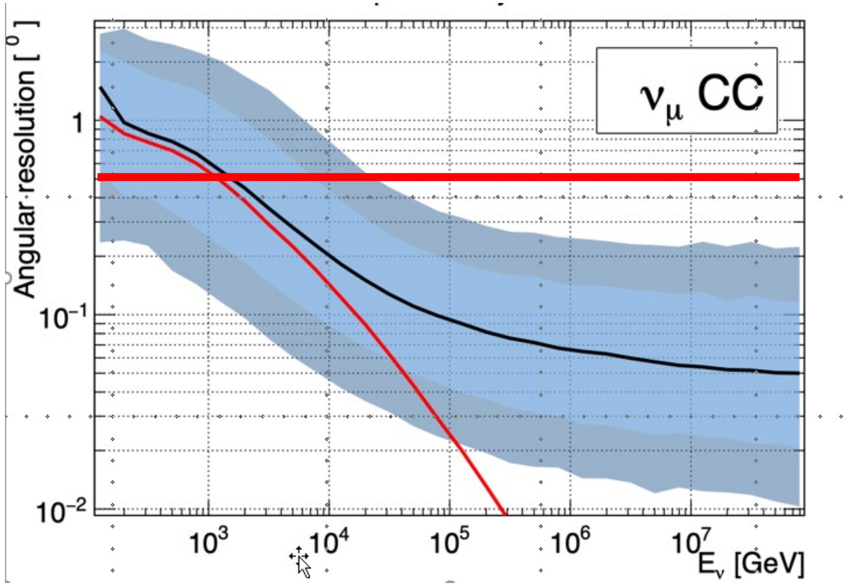
Angular resolution on the sky

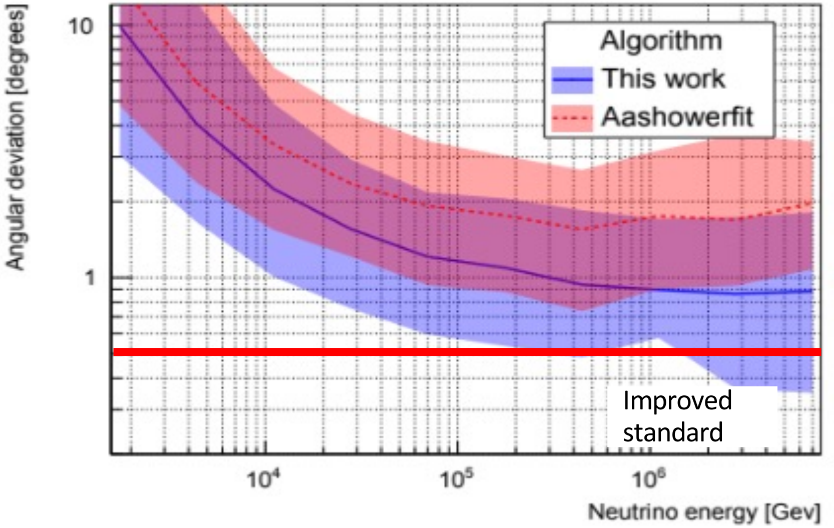
Red line:
Diameter of moon

Tracks

Cascades

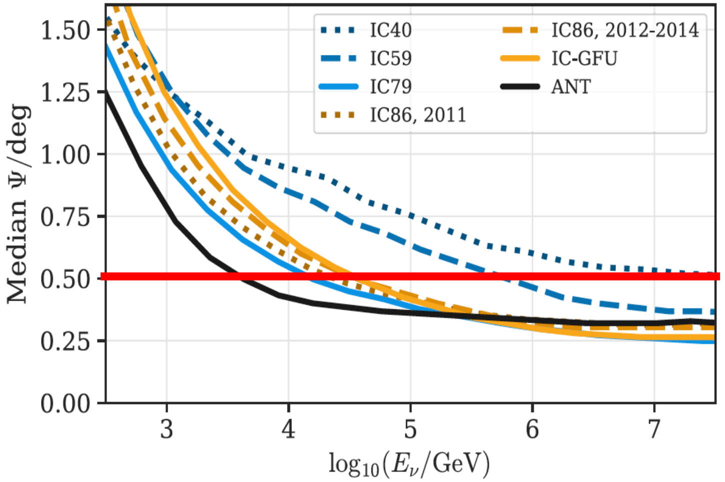
KM3NeT

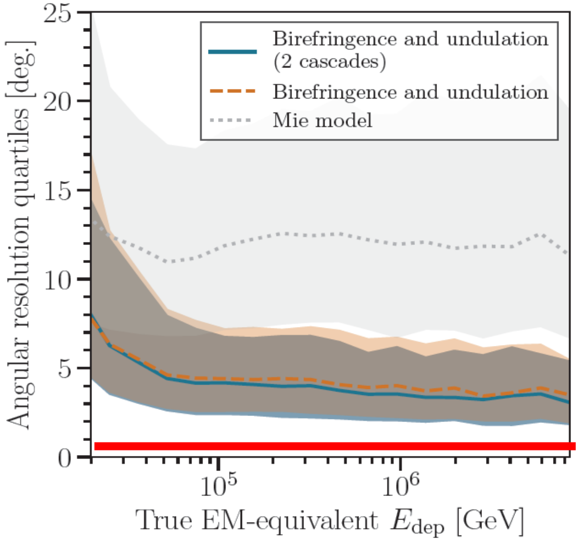




- Resolution gets better with increasing energy
- Tracks provide sub=degree angular resolution at high energies
- Cascades provide resolutions of a few degrees at high energies

IceCube





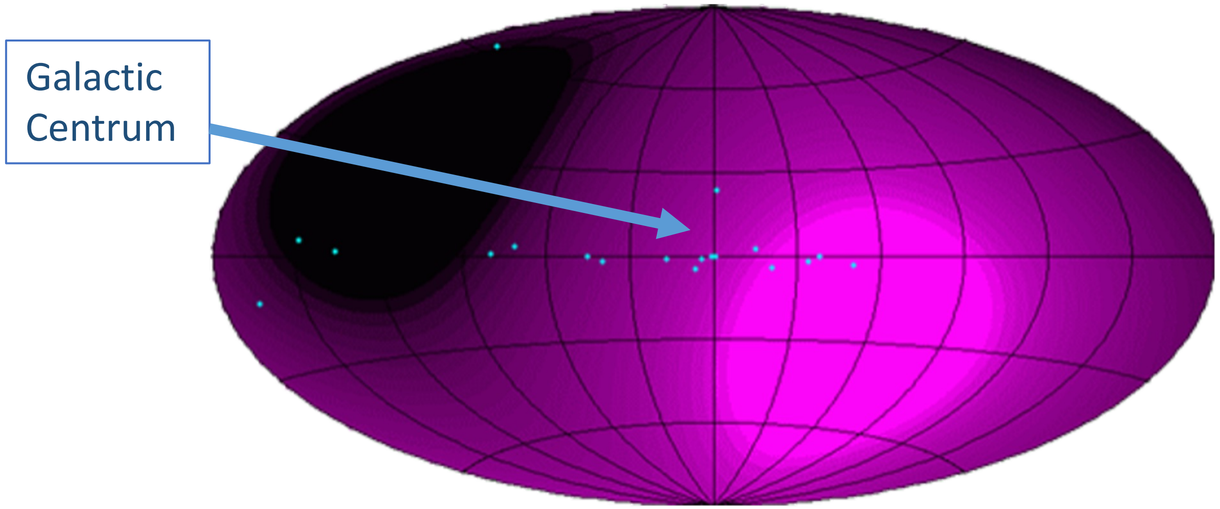
Field of view

Neutrino telescopes are sensitive to all directions

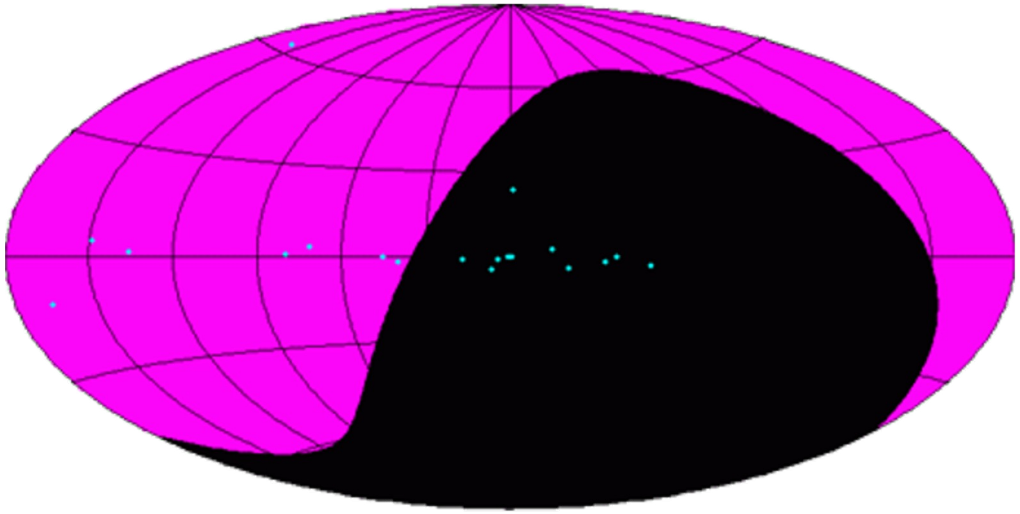
BUT

Atmospheric muons from above form sizable background
-> constrain (mostly) to upwards going events

Galactic coordinates: field of view looking ‚through the Earth‘

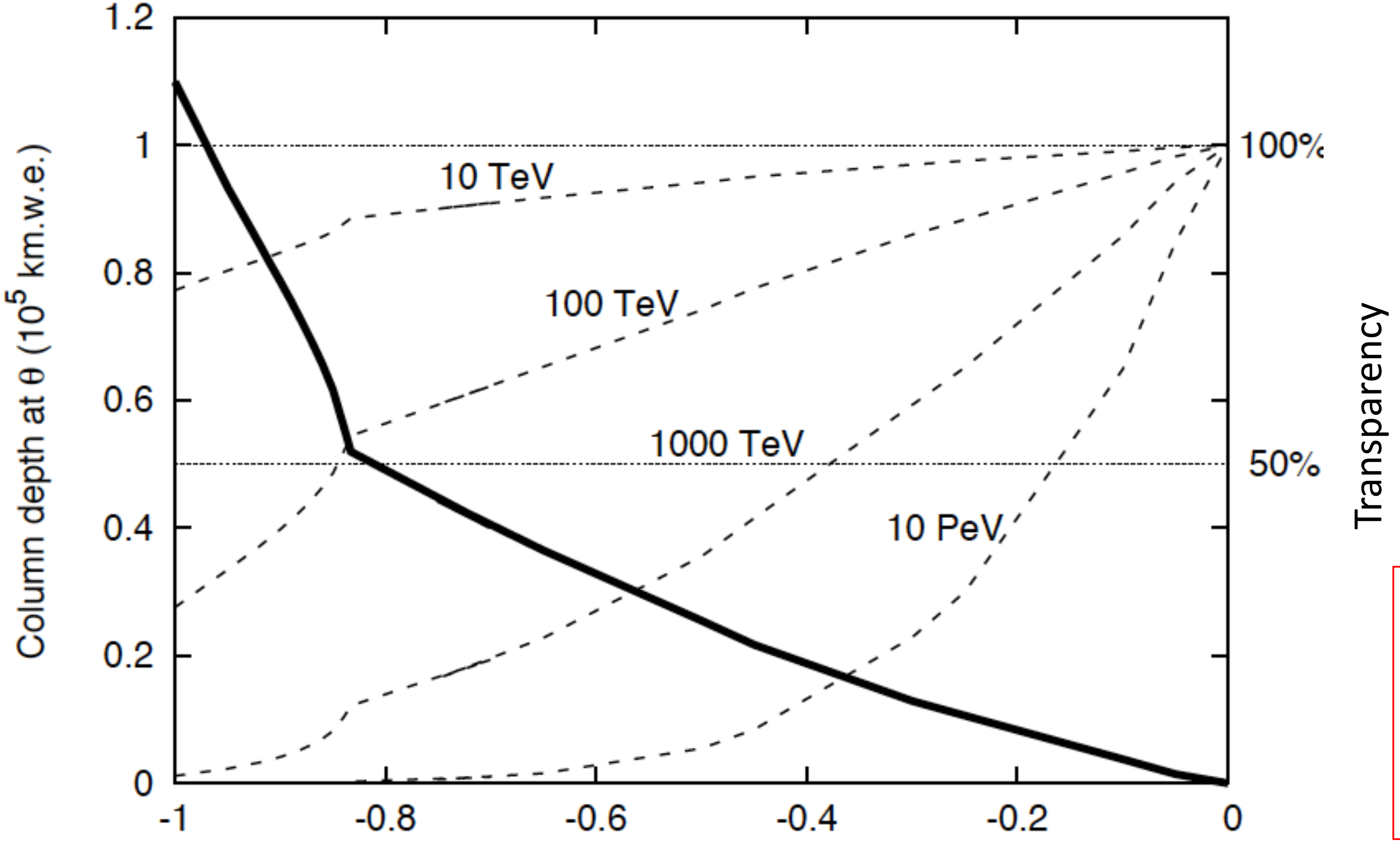


Mediterranean Sea (~43deg North)



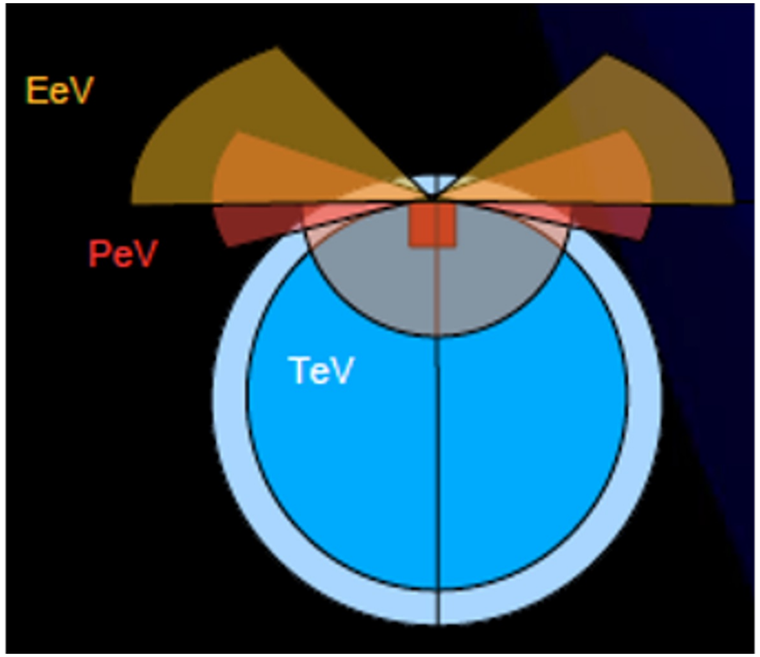
South Pole

Transparency of the Earth



Upward path

Horizontal path



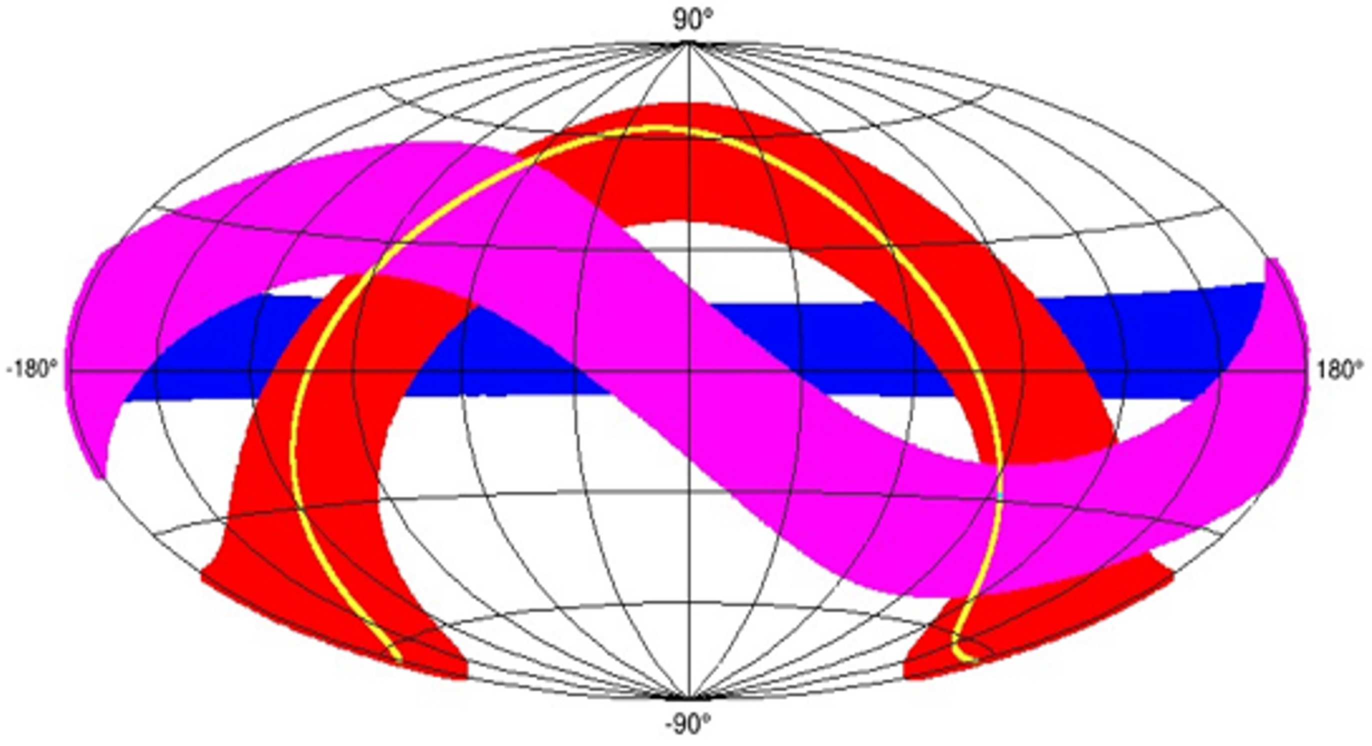
Earth is opaque for very high energy Neutrinos

=>. At high energies main field of view: horizon

Gaisser, 2019

Very high energy (>PeV) neutrinos

PeV neutrinos: instantaneous field of view
(equatorial coordinates)



Instantaneous sky coverage depends on location

For observatories not at a pole the field of view changes over the day

Lake Baikal

South Pole

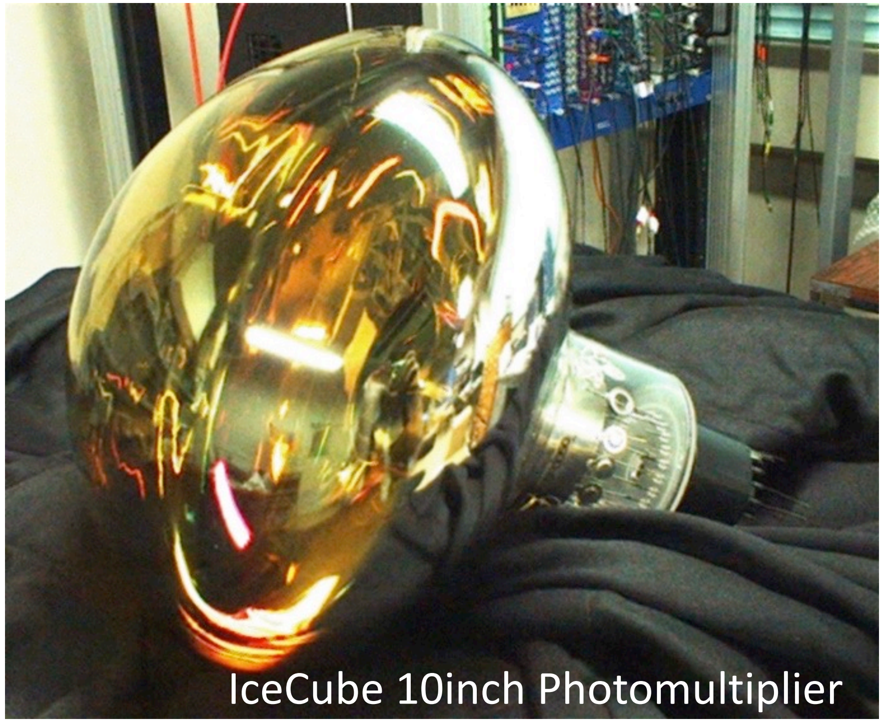
Mediterranean

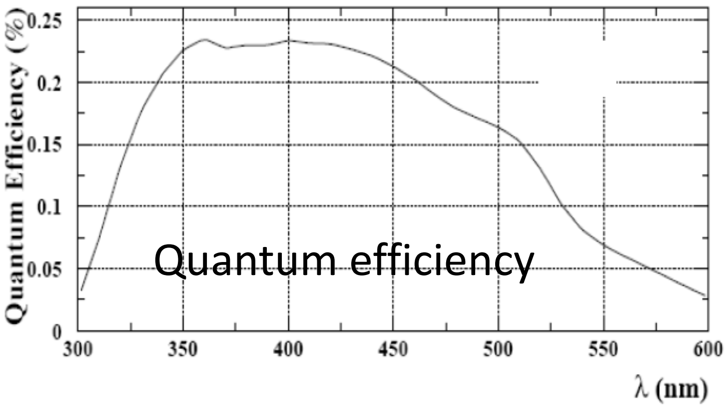
Photomultipliers

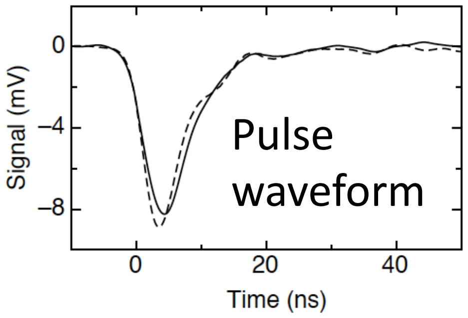
Relevant characteristics:
- Quantum Efficiency
- Dark Count
- Time spread

Glass sphere surrounds PMTs as pressure housing

Large PMTs require also shielding from Earth magnetic field
-> mu metal grid

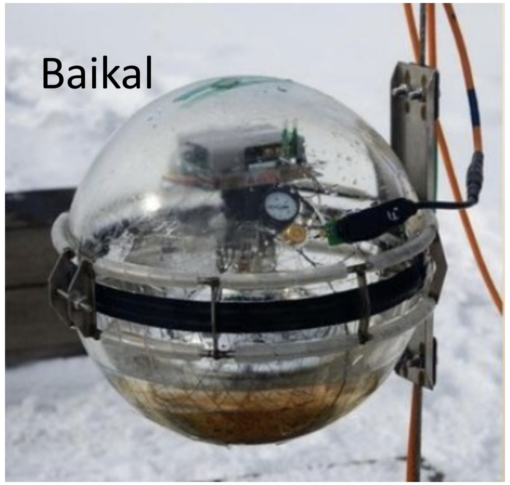






Typical gain 10^7
Quantum efficiency ~25%
Noise rate ~500Hz
~2ns time precision

Optical Modules



D-Egg

Multi-PMT module pioneered by KM3NeT

Small PMTs:
-> Photon counting
-> Directional resolution

Baikal: NT200(+) -----> **G**igaton **V**olume **D**etector (GVD)

Lake with 1.3km depth

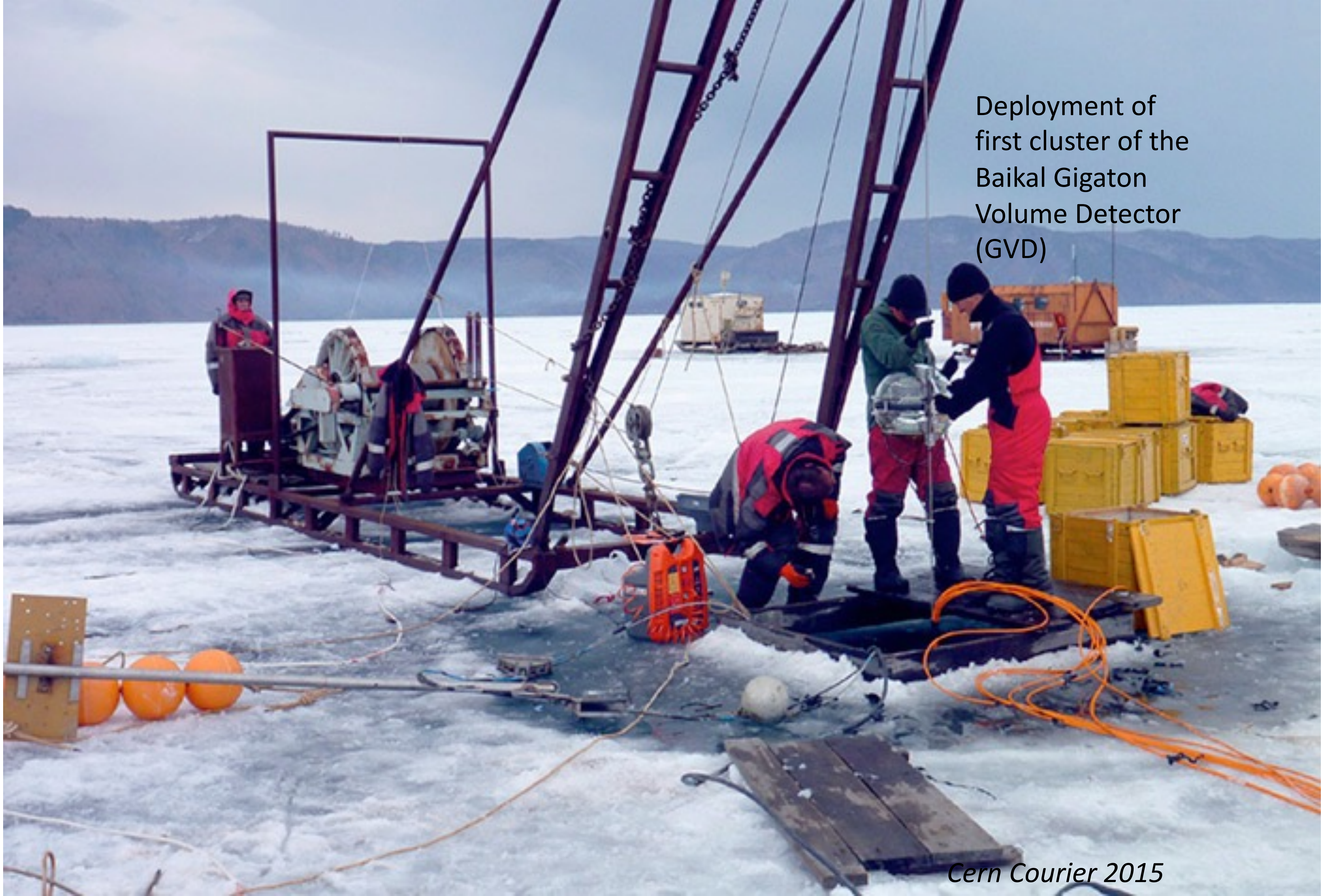
1981: Start of first underwater neutrino telescope in the Baikal Lake (1 string)

Since 1998 NT200 (8 strings)

2005: +3 strings (NT200+)

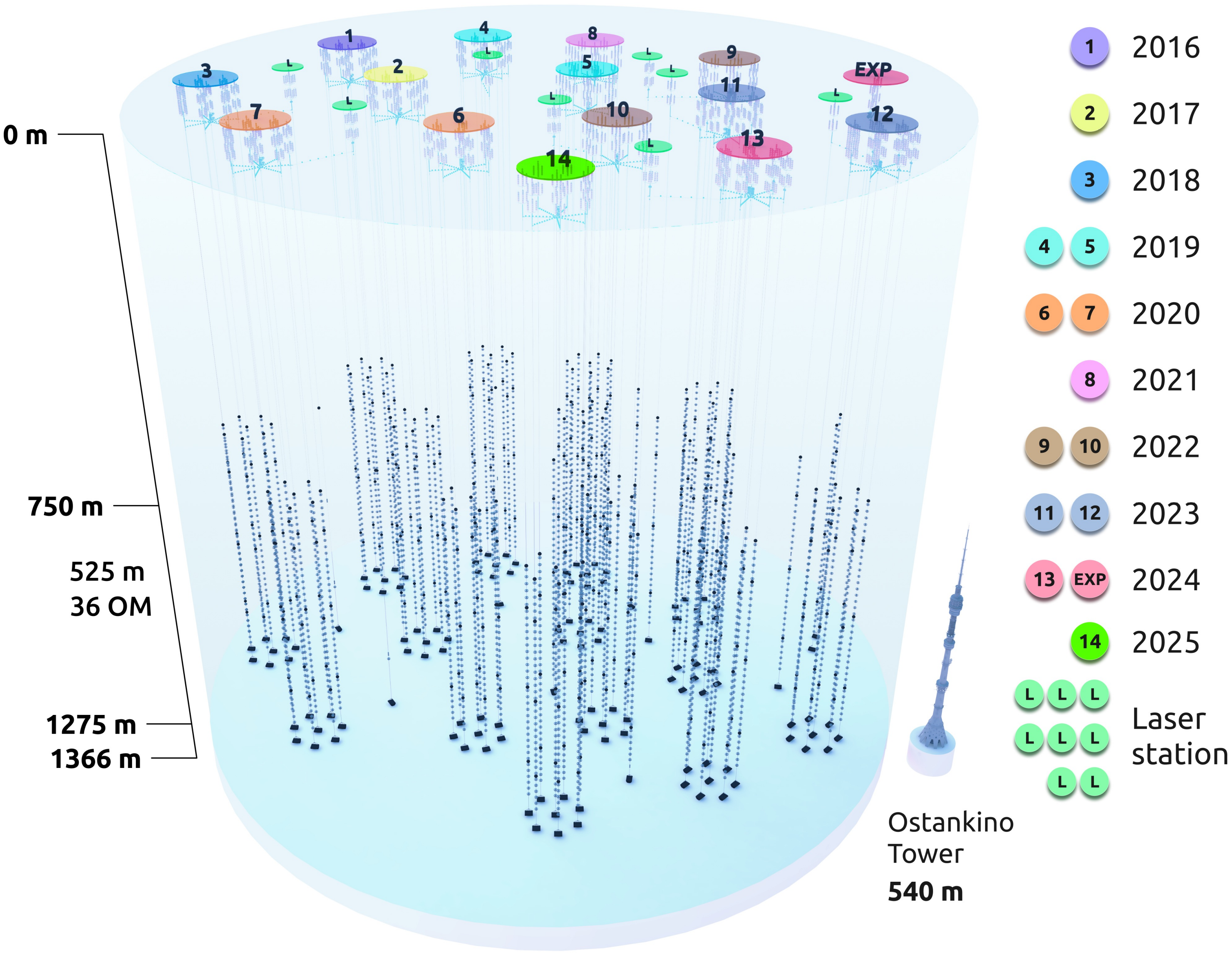
Since 2011: Upgrade to GVD

Picture: Cern Courier 2005



Deployment of first cluster of the Baikal Gigaton Volume Detector (GVD)

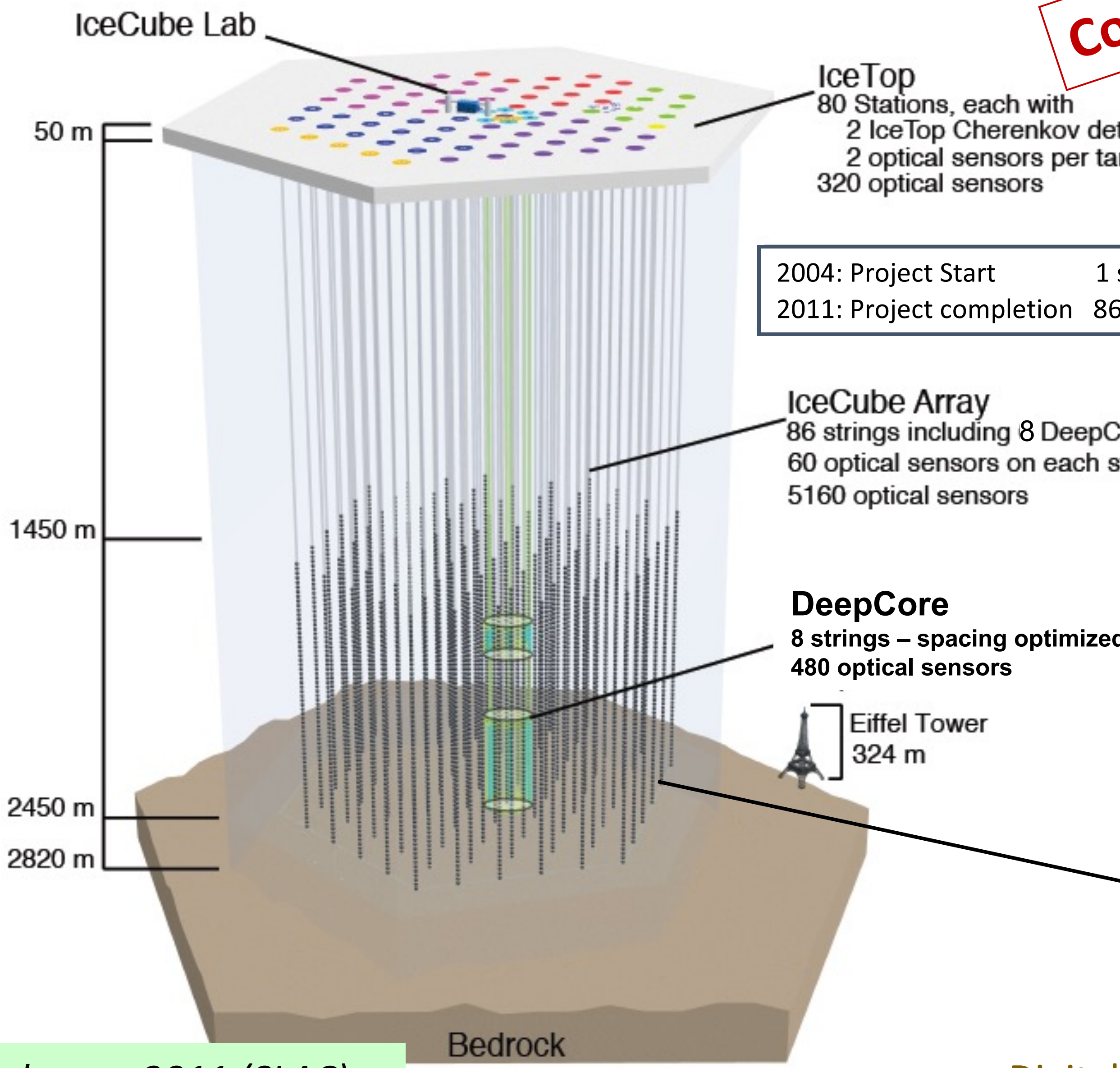
Cern Courier 2015



0 m
750 m
525 m
36 OM
1275 m
1366 m
1 2016
2 2017
3 2018
4 5 2019
6 7 2020
8 2021
9 10 2022
11 12 2023
13 EXP 2024
14 2025
L L L L L L L L
Laser station
Ostankino Tower
540 m

The IceCube Neutrino Observatory

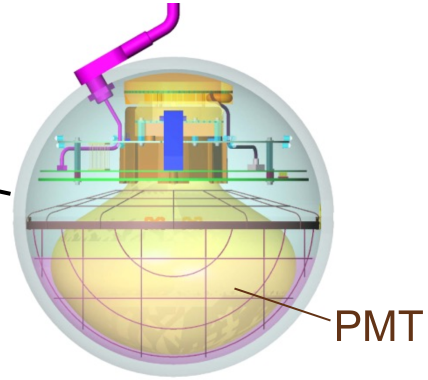
Completed: Dec 2010



2004: Project Start	1 string
2011: Project completion	86 strings

Configuration chronology

2006: IC9
2007: IC22
2008: IC40
2009: IC59
2010: IC79
2011: IC86



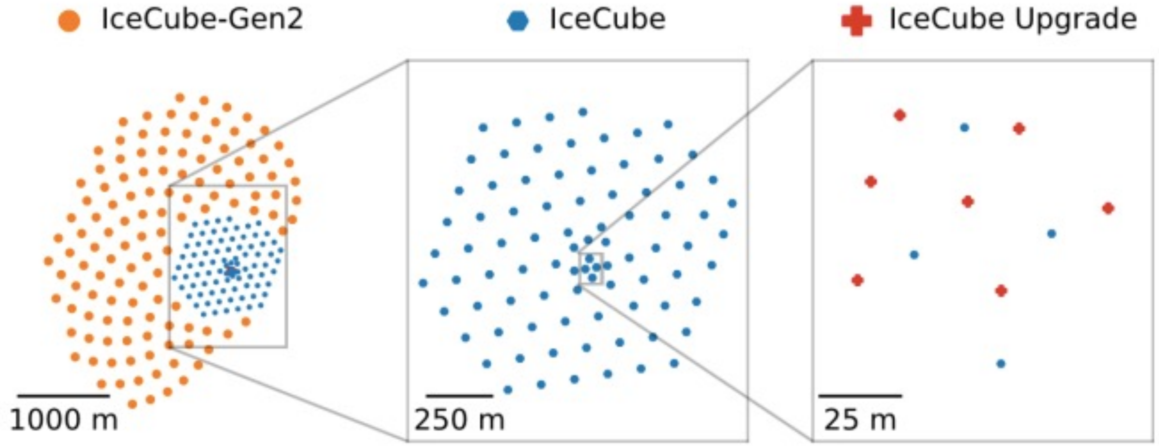
Digital Optical Module (DOM)

Woschnagg 2011 (SLAC)

7 new strings

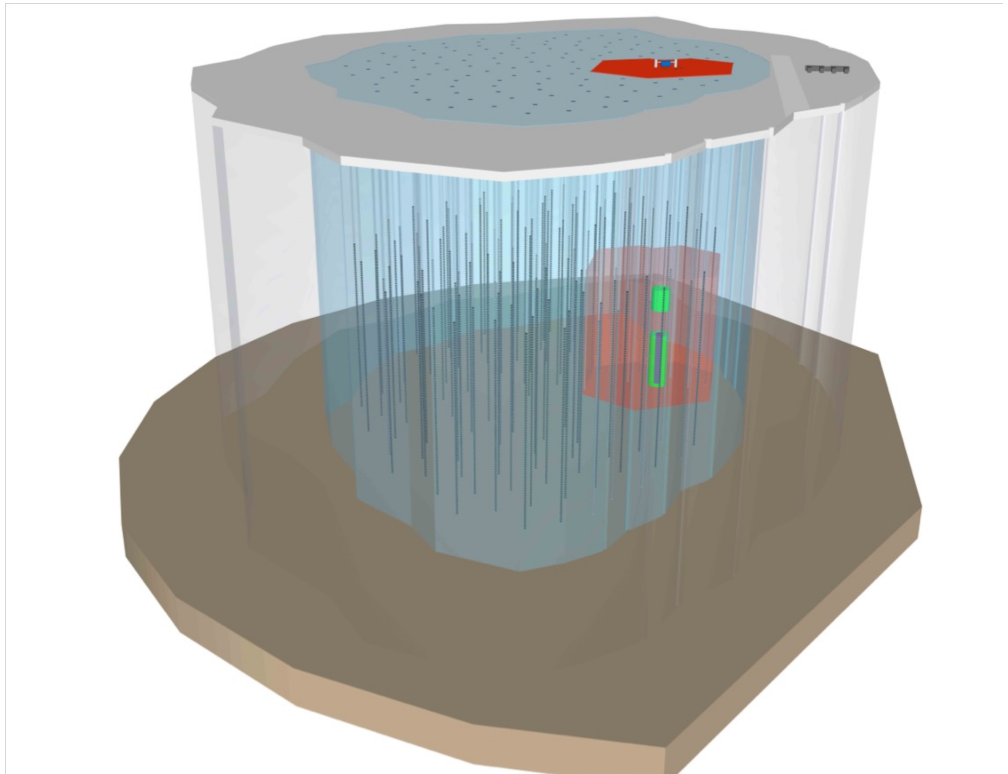
Just now 6 deployed

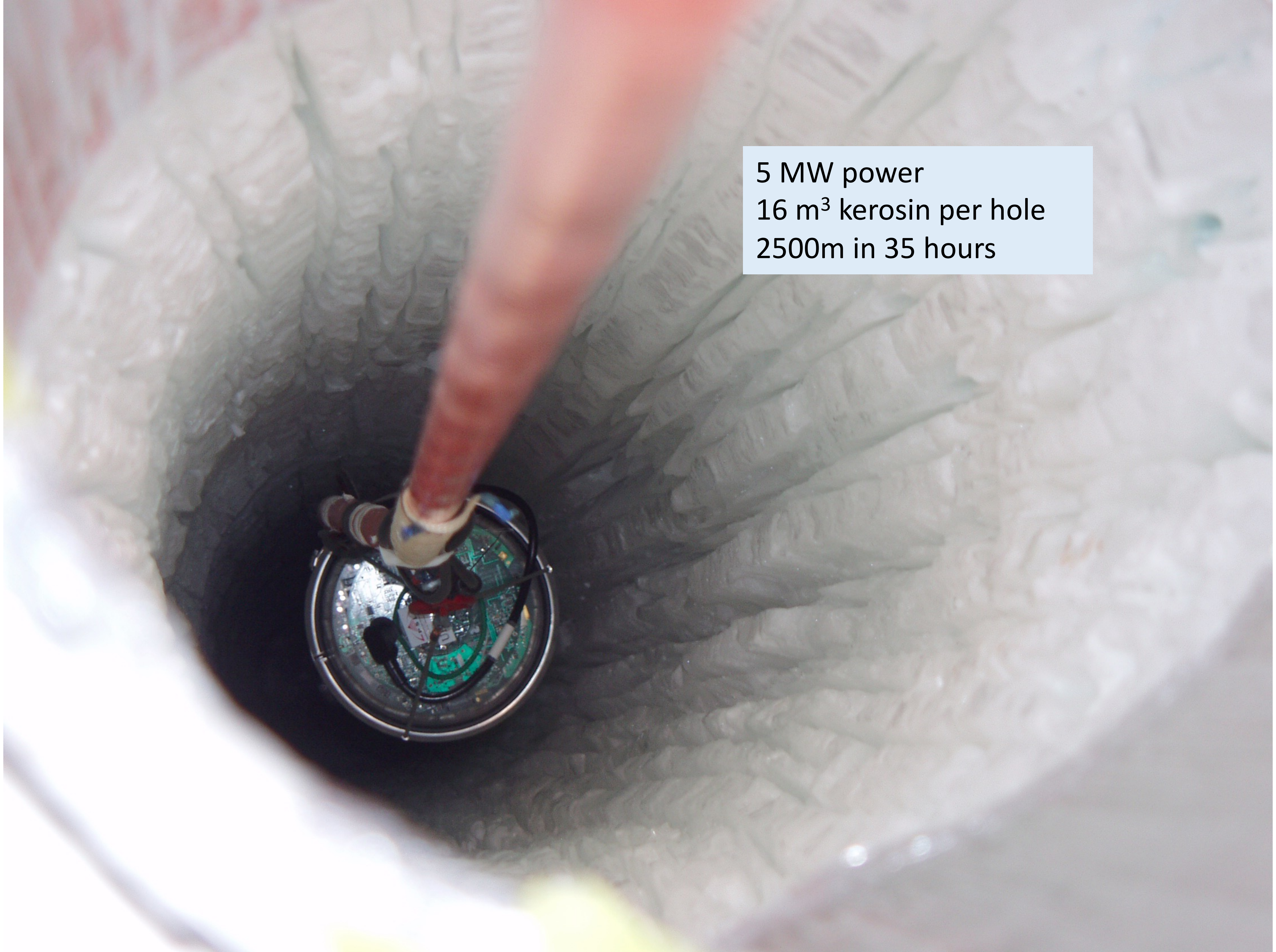
IceCube Gen2



- Plans for extending IceCube with sparse array, complement with radio array
- 10km^3 volume

-> Increased very high energy sensitivity




5 MW power
16 m³ kerosin per hole
2500m in 35 hours

Hot off the press: IceCube Upgrade deployment

KM3NeT/ARCA (Italian site)

Astroparticle **R**esearch with **C**osmics in the **A**byss

KM3NeT/ORCA (French Site)

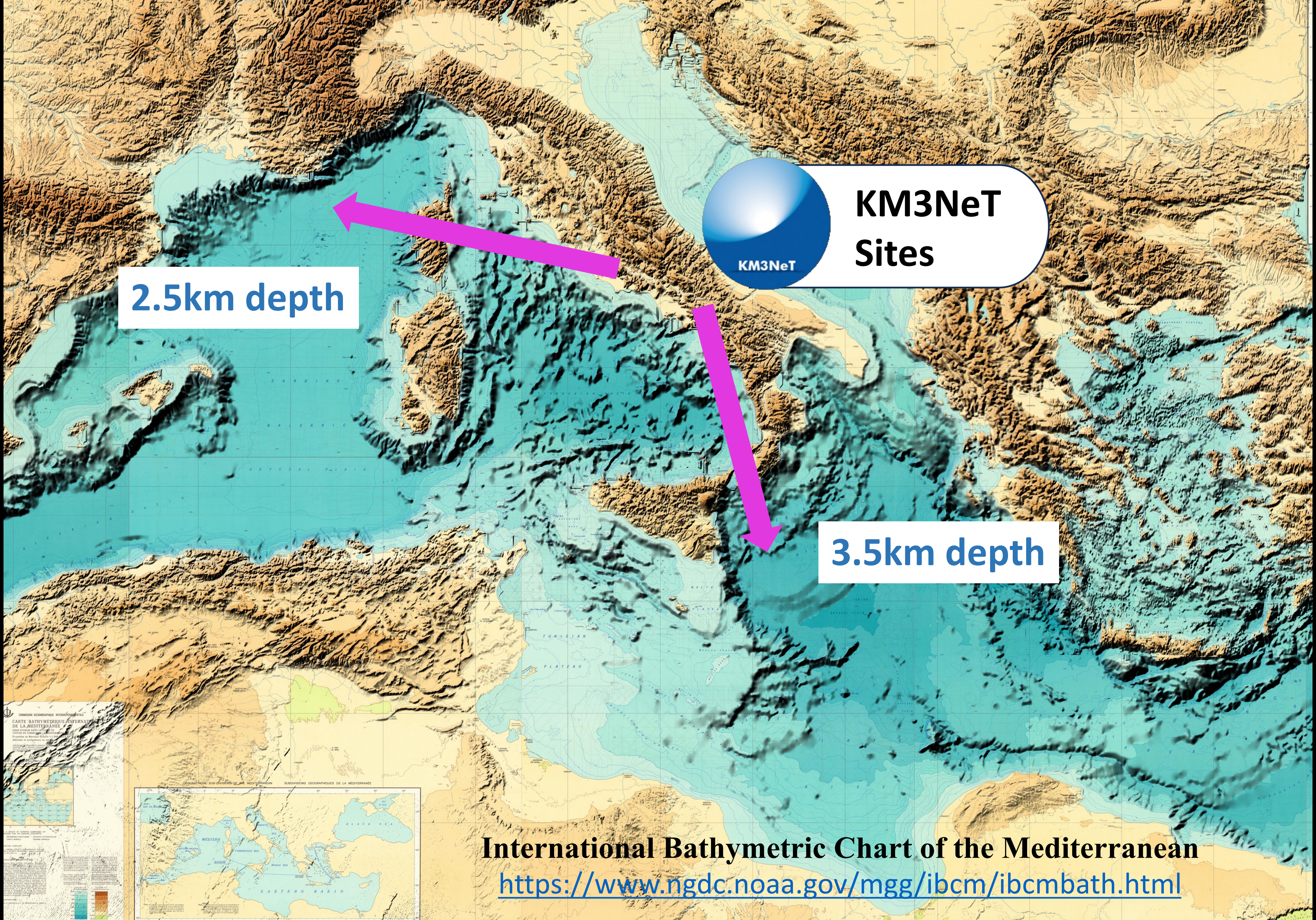
Oscillation **R**esearch with **C**osmics in the **A**byss

KM3NeT

Planned:

ARCA: 2x115 strings (51 already deployed)

ORCA: 108 strings (31 already deployed)



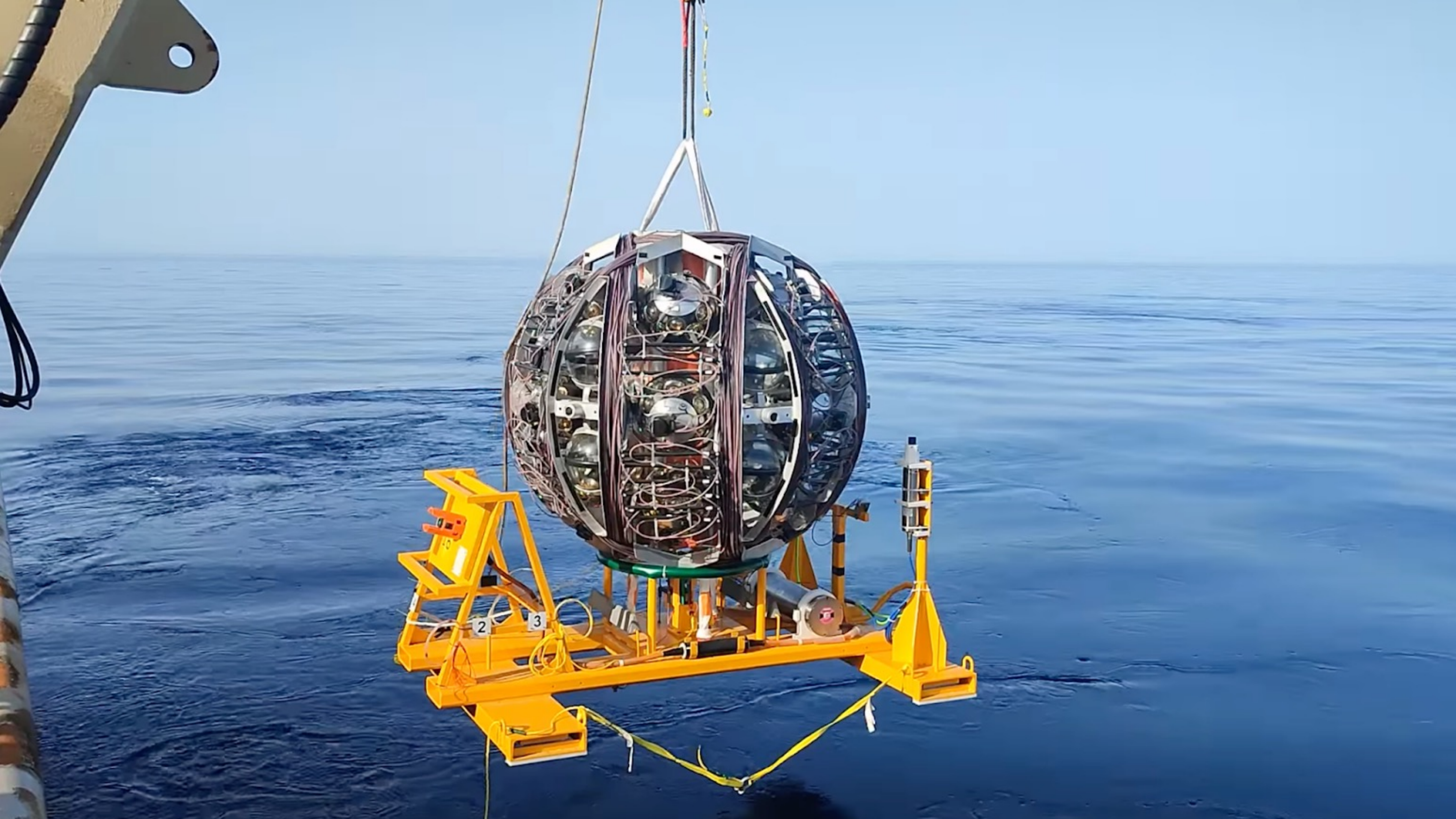
International Bathymetric Chart of the Mediterranean
https://www.ngdc.noaa.gov/mgg/ibcm/ibcmbath.html

~ 40 cm

- 31 3” PMTs
- Light reflector rings
- LED beacon
- acoustic piezoelectric
- Tiltmeter/compass
- Gbit/s fibre DWDM for data transmission
- White Rabbit for time synchronization

Aside from light sensitive devices
also several calibration devices

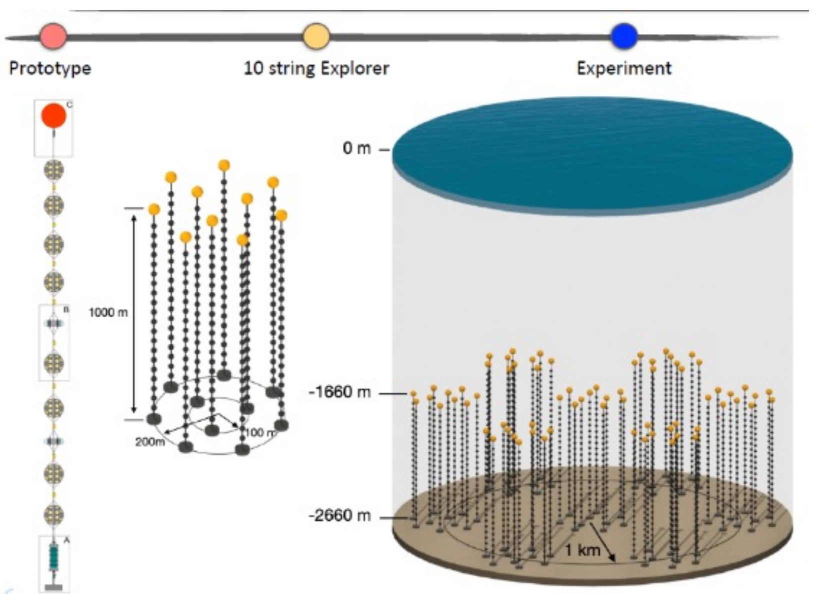

KM3NeT


2
3

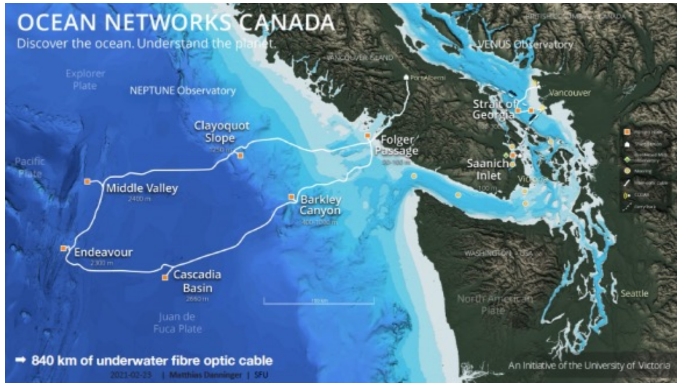

aggreko
aggreko
FUGRO
FUGRO
FUGRO
RESCUE ZONE

348. The Pacific Ocean Neutrino Experiment
Ignacio Taboada (Georgia Institute of T...)
05/11/2025, 15:30
Neutrinos Talk Neutrinos

P-One



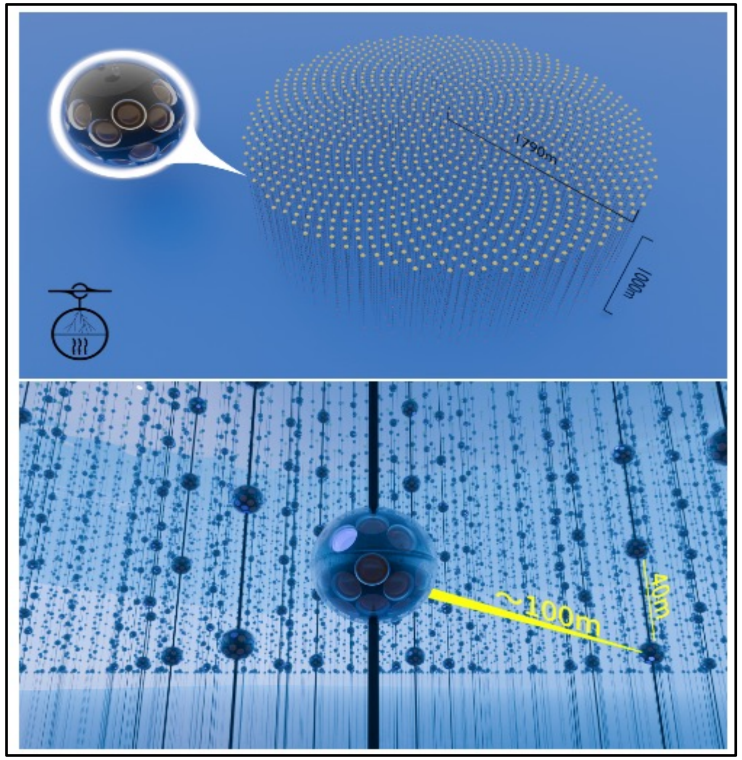
- Use Canadian deep sea network
- Aim for multi-km^3
- Explorer under construction



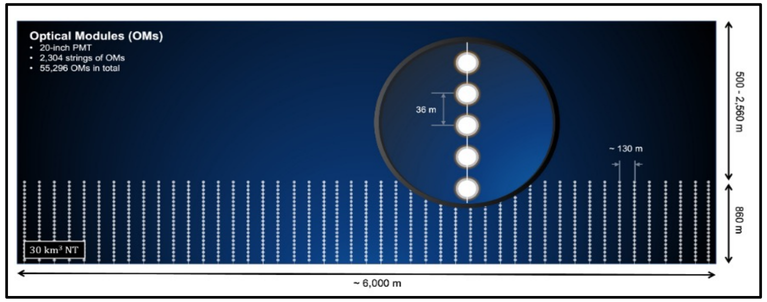
Km-long string with 20 DOMs

Heijboer, TevPa2025

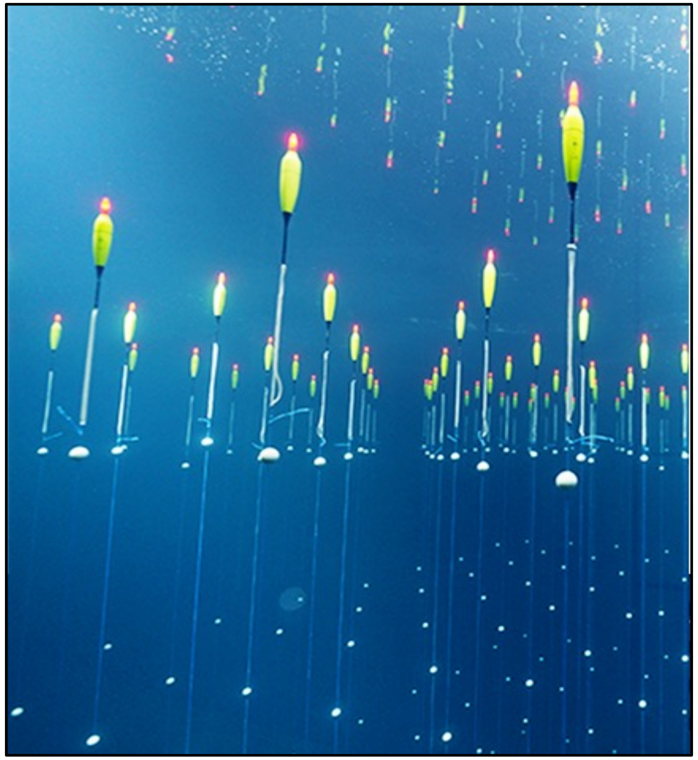
Chinese initiatives



Neon South China Sea
https://arxiv.org/html/2408.05122v3



HUNT, South China Sea/Lake Baikal
ICRC '23 (1080)



Trident, South China Sea
Nature Astronomy **7**, 1497 (2023)

Detector	Volume $[km^3]$	Number of Strings	Number of OMs	Type of OM
TRIDENT	7.5	1,211	24,000	**31** × *3″* PMTs & SiPM
HUNT	30	2,304	55,000	**1** × *20″* PMT
NEON	10	1,200	21,600	**31** × *3″* PMTs

Heijboer, TevPa2025