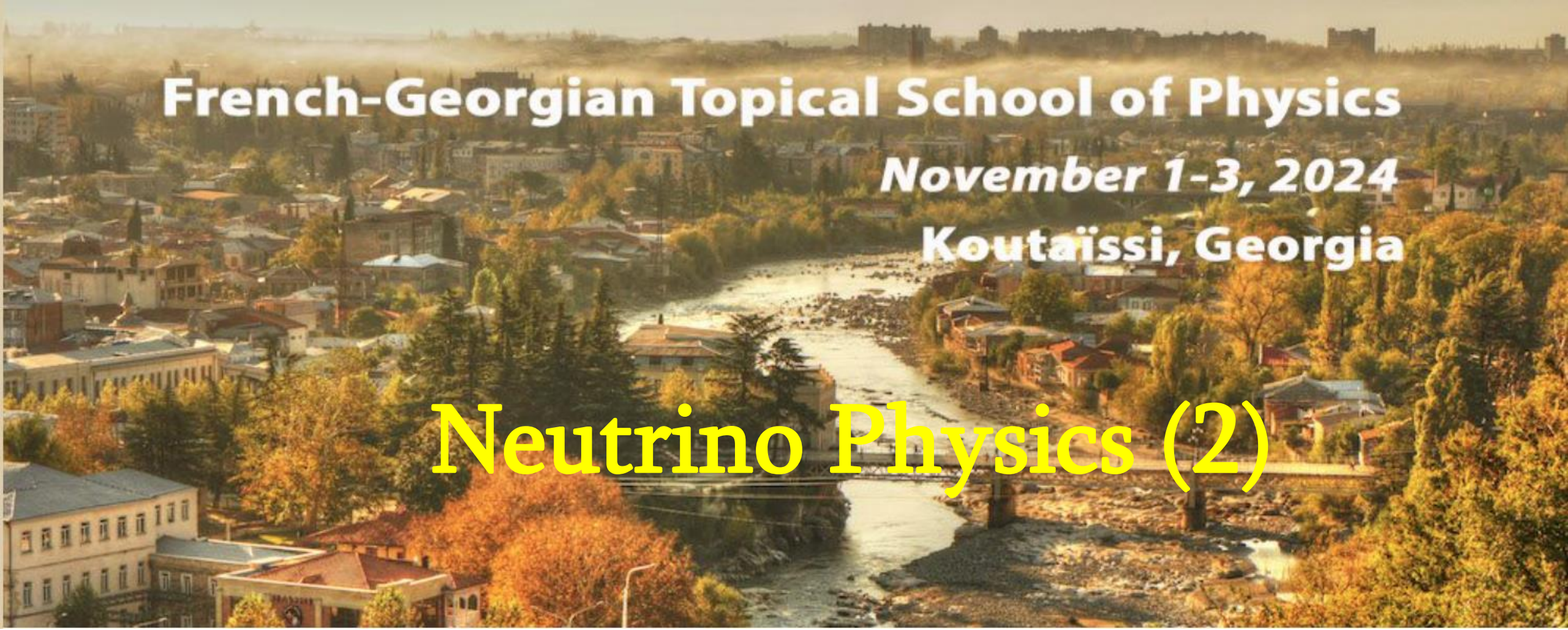


Neutrino Physics (2)

Rezo Shanidze
Kutaisi International University
Tbilisi State University

Content

- Introduction
  - From Pauli and Fermi theory to discovery of neutrino.
  - Neutrinos in the Standard Model

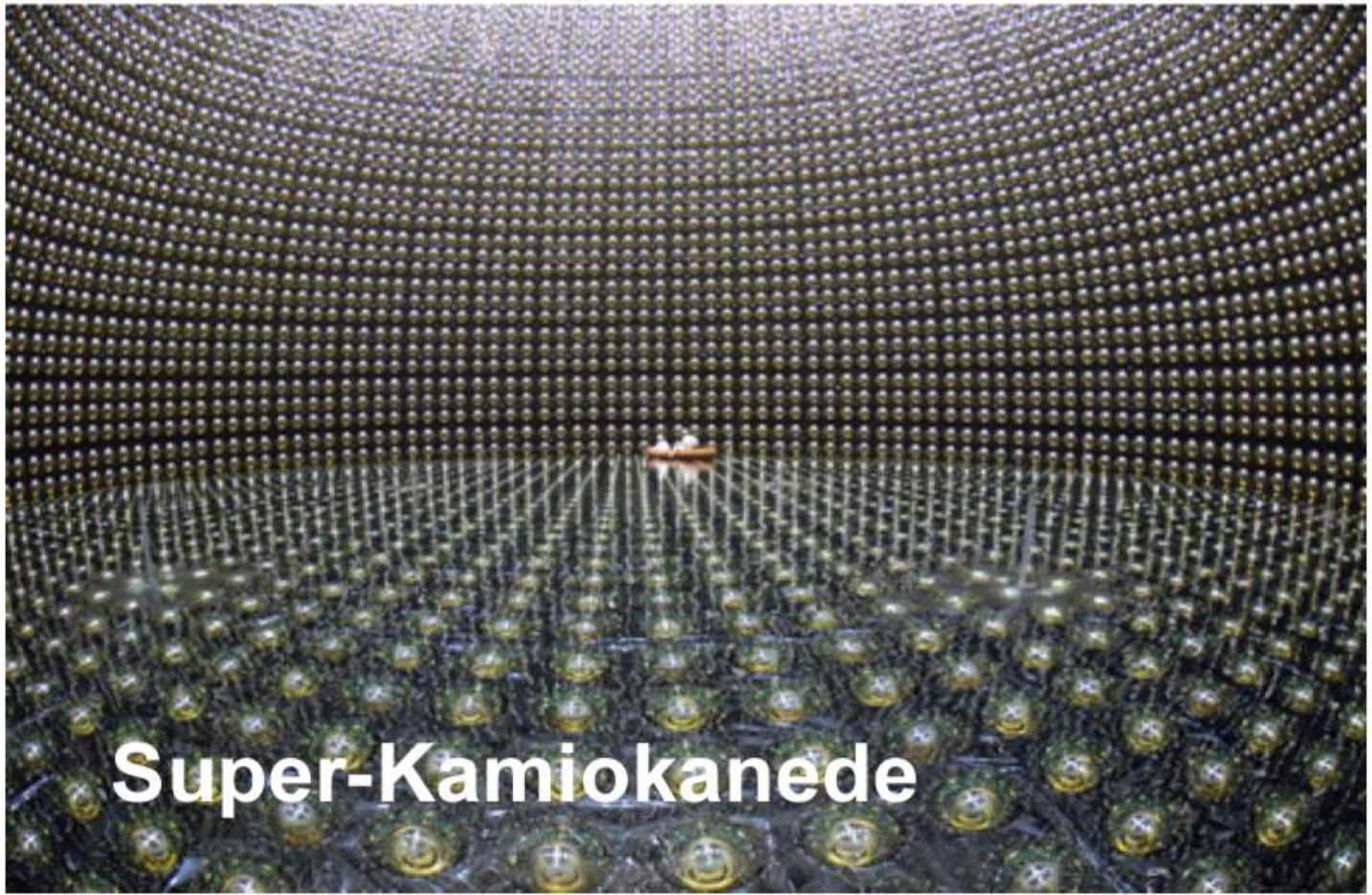
- Neutrino Oscillations
  - Solar and atmospheric neutrino problem.
  - Discovery of neutrino oscillations and consequences.

- Neutrino Astronomy/astrophysics
  - Solar and Supernova neutrinos
  - High Energy Neutrino Astronomy

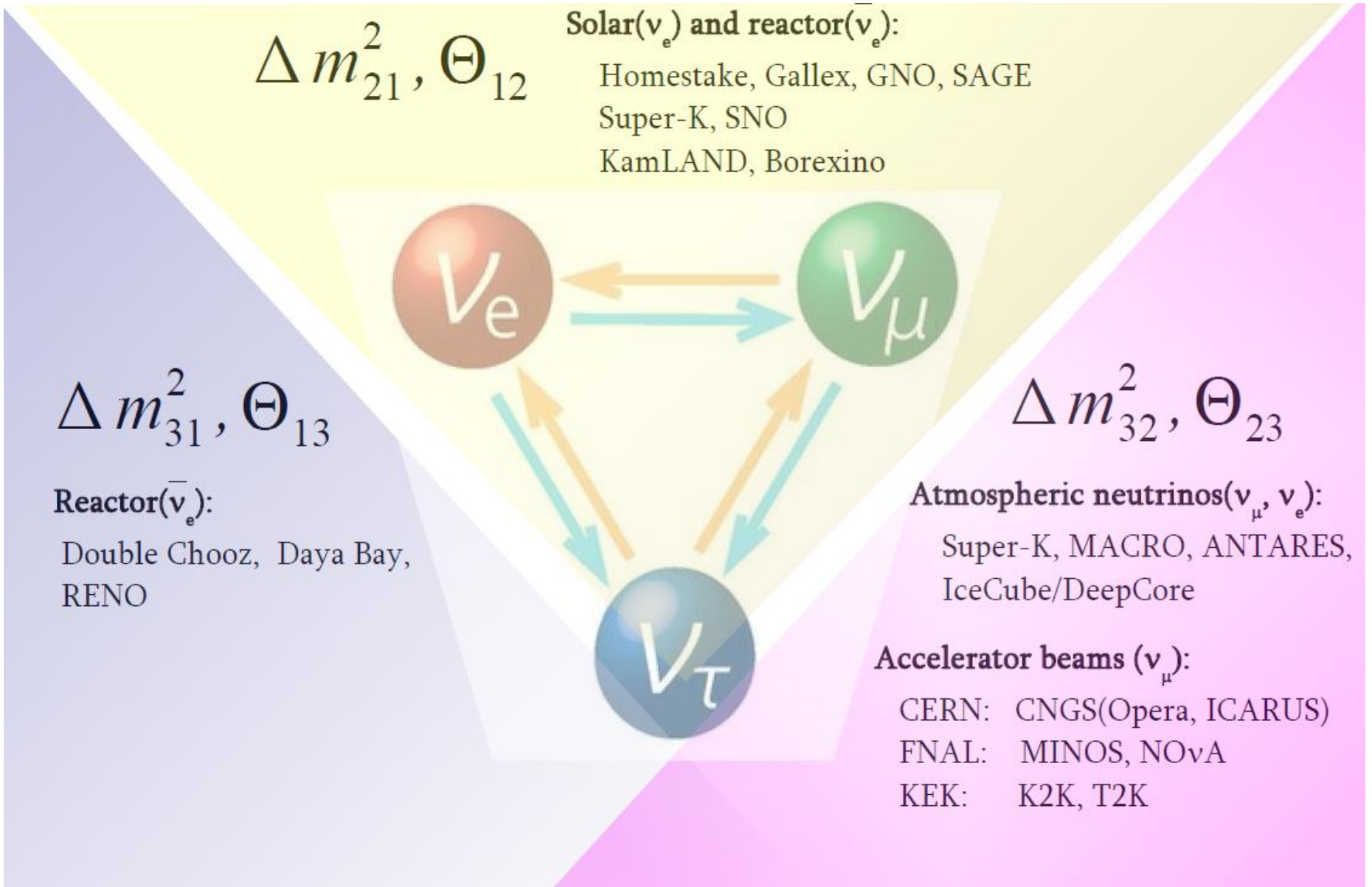
Solution of Solar Neutrino Problem

Takaaki Kajita (1959) and Arthur McDonald (1943)

2015



Neutrino Oscillation Experiments



Under construction:

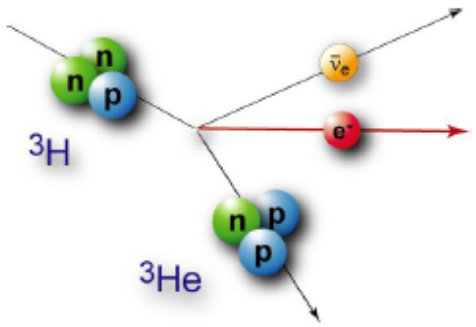
KM3NeT/ORCA
(data taking: 2020)
with full det. 2027

JUNO (2025)

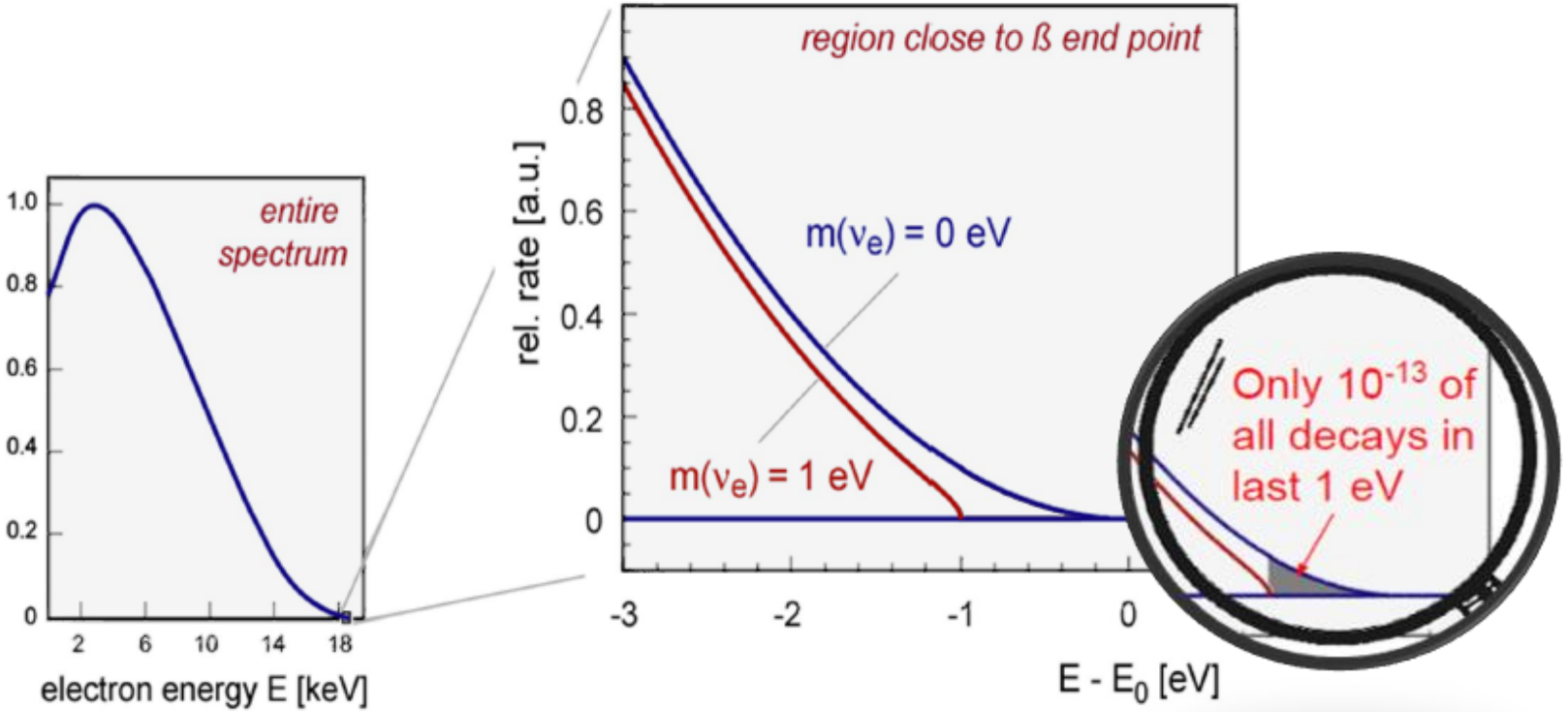
Hyper-K (2027)

DUNE (2030 ?)

Direct Neutrino Mass Measurement



- Independent of cosmology
- Independent of neutrino nature



Key requirements:

- Strong β-source

^{3}H: 12.3 y, E_0 = 18.6keV

- Excellent energy resolution (1 eV)

- Low background

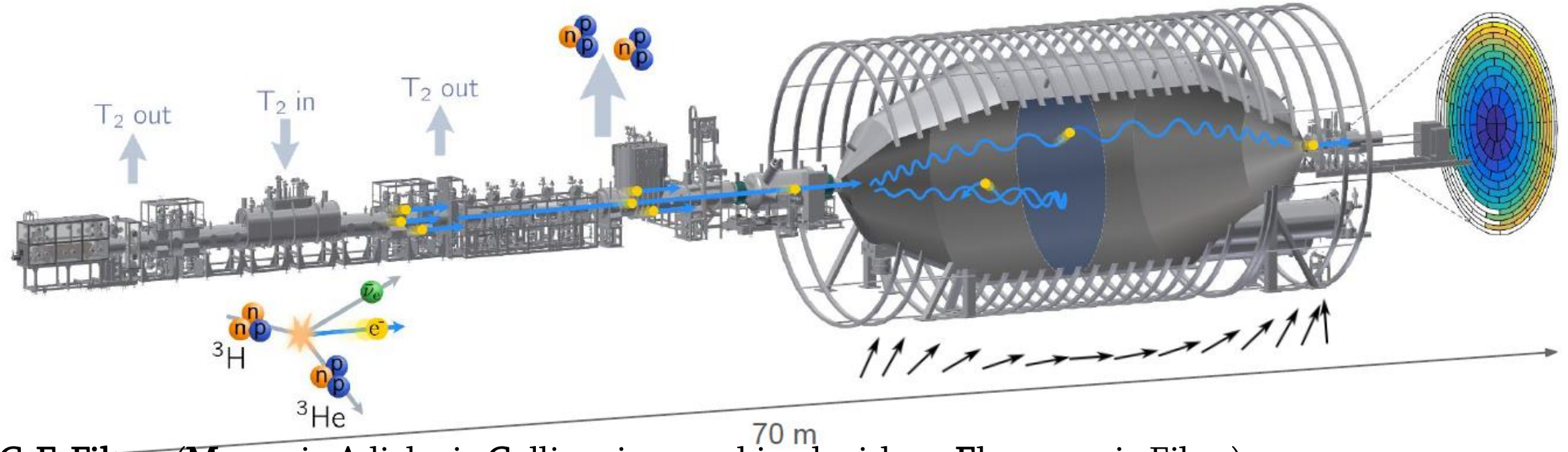
Karlsruhe Tritium Neutrino **Experiment** (KATRIN)

Windowless gaseous tritium source
- 30 µg molecular tritium in closed loop
- **10^{11} T_2 decay/s**

Transport section
- Tritium gas/ion removal > **10^{14}**

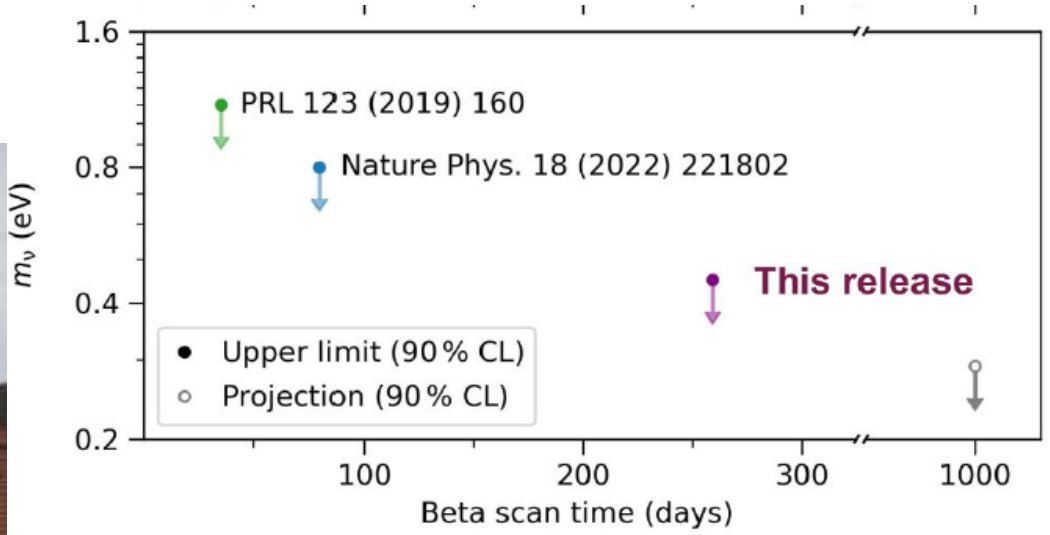
Spectrometer
- MAC-E filter principle
- High resolution: **O(1) eV**

Detector
- Focal plane detector, **148 pixel** PIN-diode
- Counts electrons



MAC-E-Filters (Magnetic Adiabatic Collimation combined with an Electrostatic Filter).

KATRIN Results



New KATRIN release improves direct neutrino-mass bound by a factor of 2:

$m_\nu < 0.45$ eV (90% CL)

Expected final result (2025, 1000 days):

$m_\nu < 0.3$ eV (90% CL)

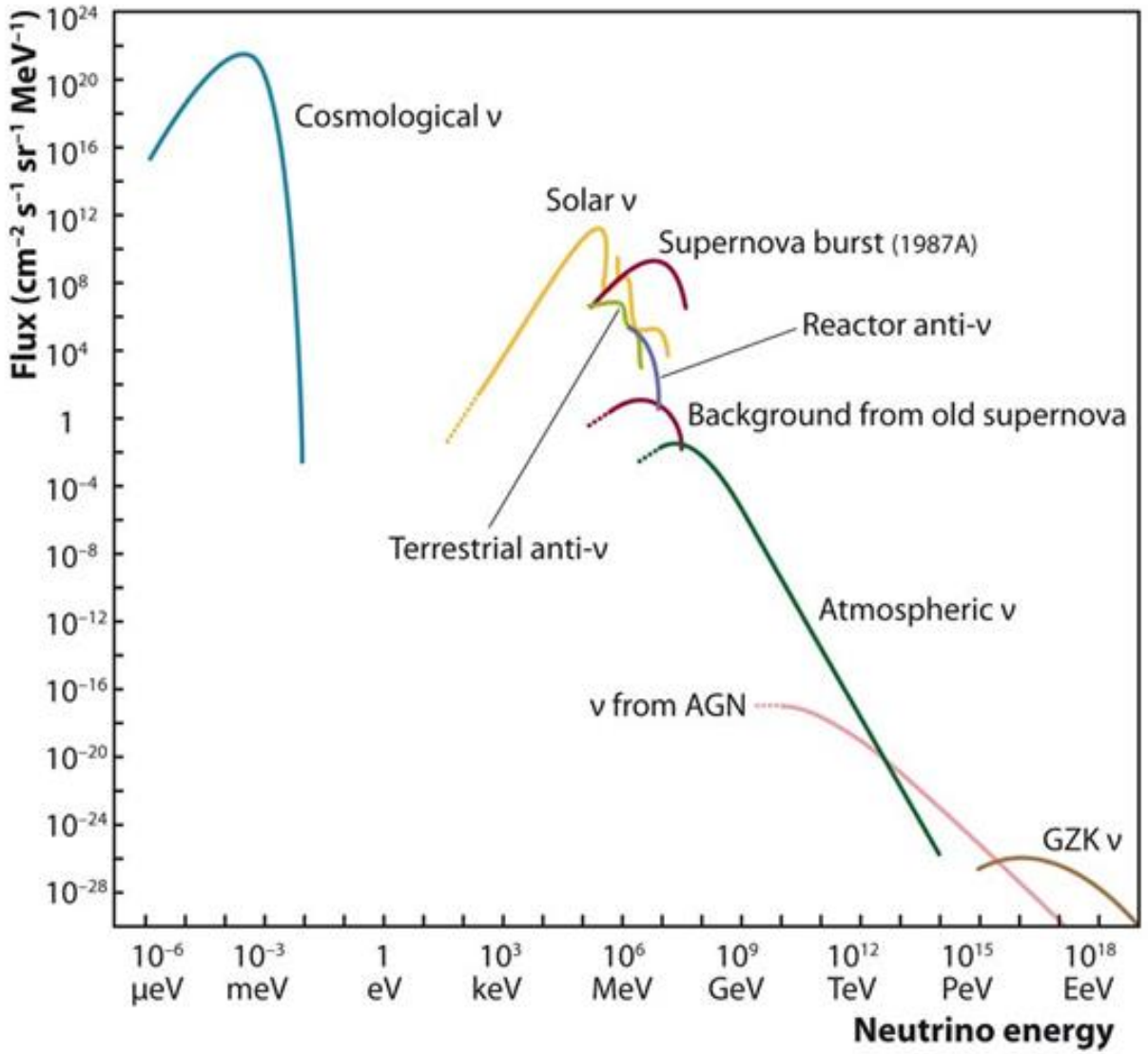
Christoph Köhler (TUM), PIC 2024

Neutrino Astronomy/astrophysics

Solar and Supernova neutrinos

High Energy Neutrino Astronomy

Neutrinos in Nature



- ✓ Cosmological neutrinos (CνB)
- ✓ Neutrinos produced in the fusion reactions in the stars
- ✓ Neutrinos from the supernova explosion of massive stars
- ✓ Neutrinos from astrophysical objects (AGN, GRB,...) produced by cosmic rays, CR)
- ✓ Neutrinos from UHECR interactions with CMBR (GZK ν)

Borexino Solar Neutrino Experiment

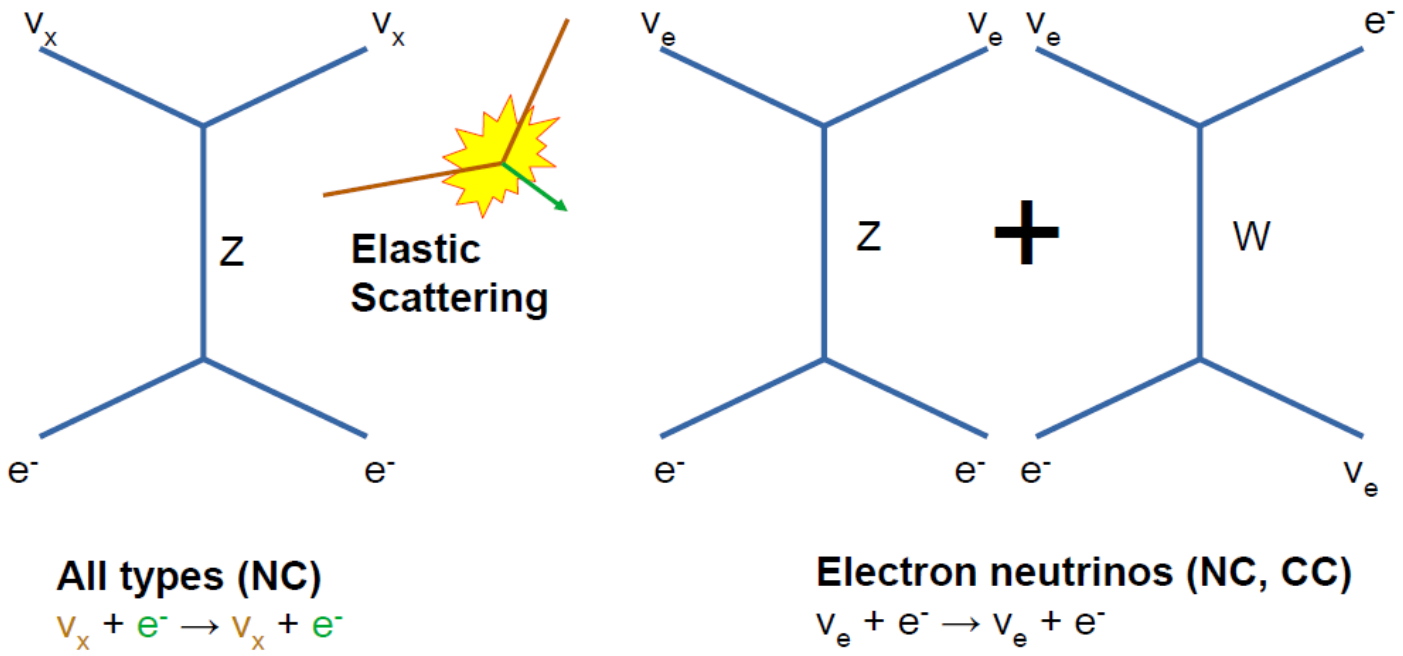
1990: idea of a real time neutrino detection for a sub Mev solar neutrinos

Measure of the neutrino–electron elastic scattering rates

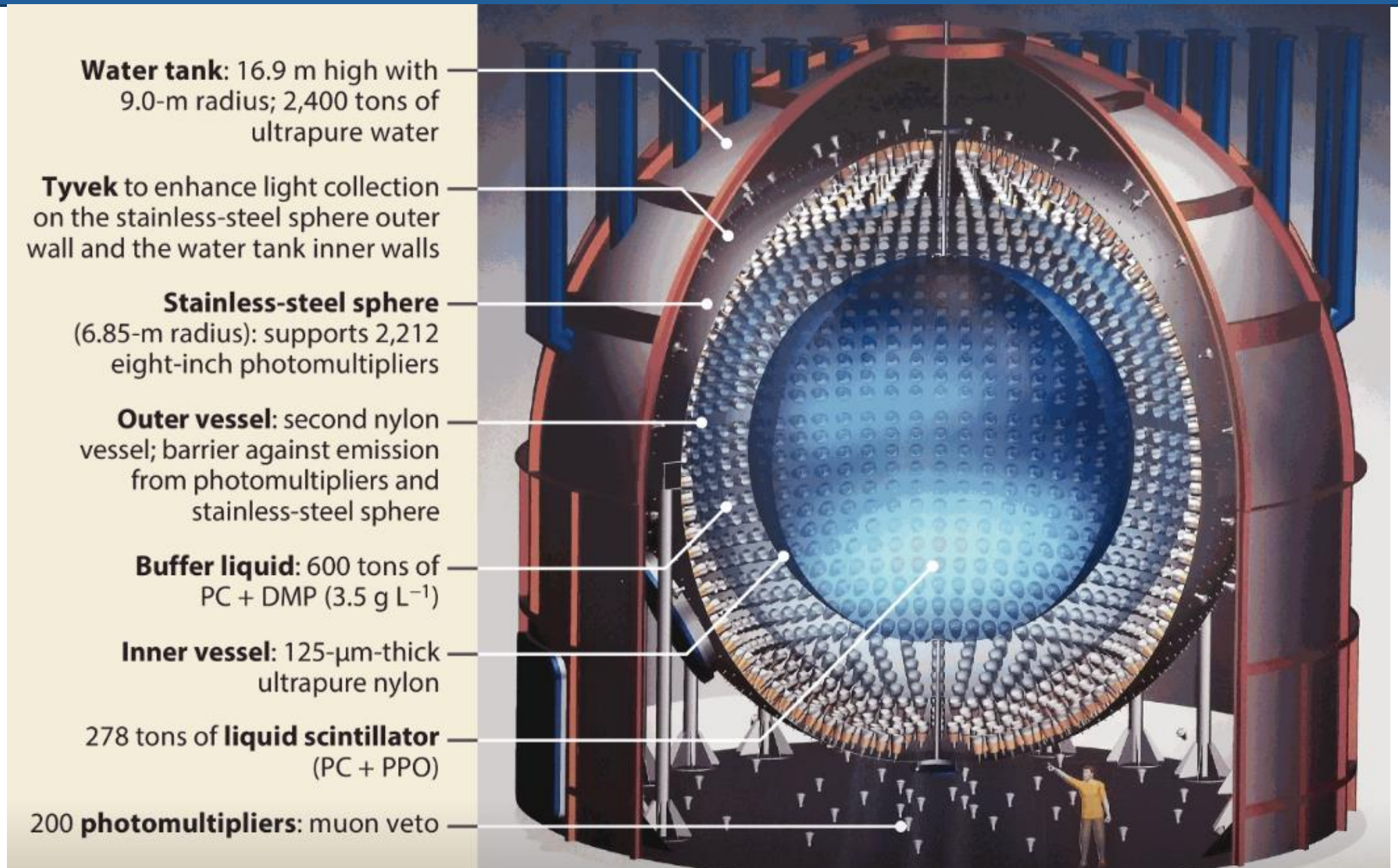
1995: testing the record radiopurity ^{238}U, $^{232}Th < 10^{-16}$ g/g & $^{14}C/^{12}C < 10^{-18}$

1996-1997 : Approval

2007-2021: Data taking



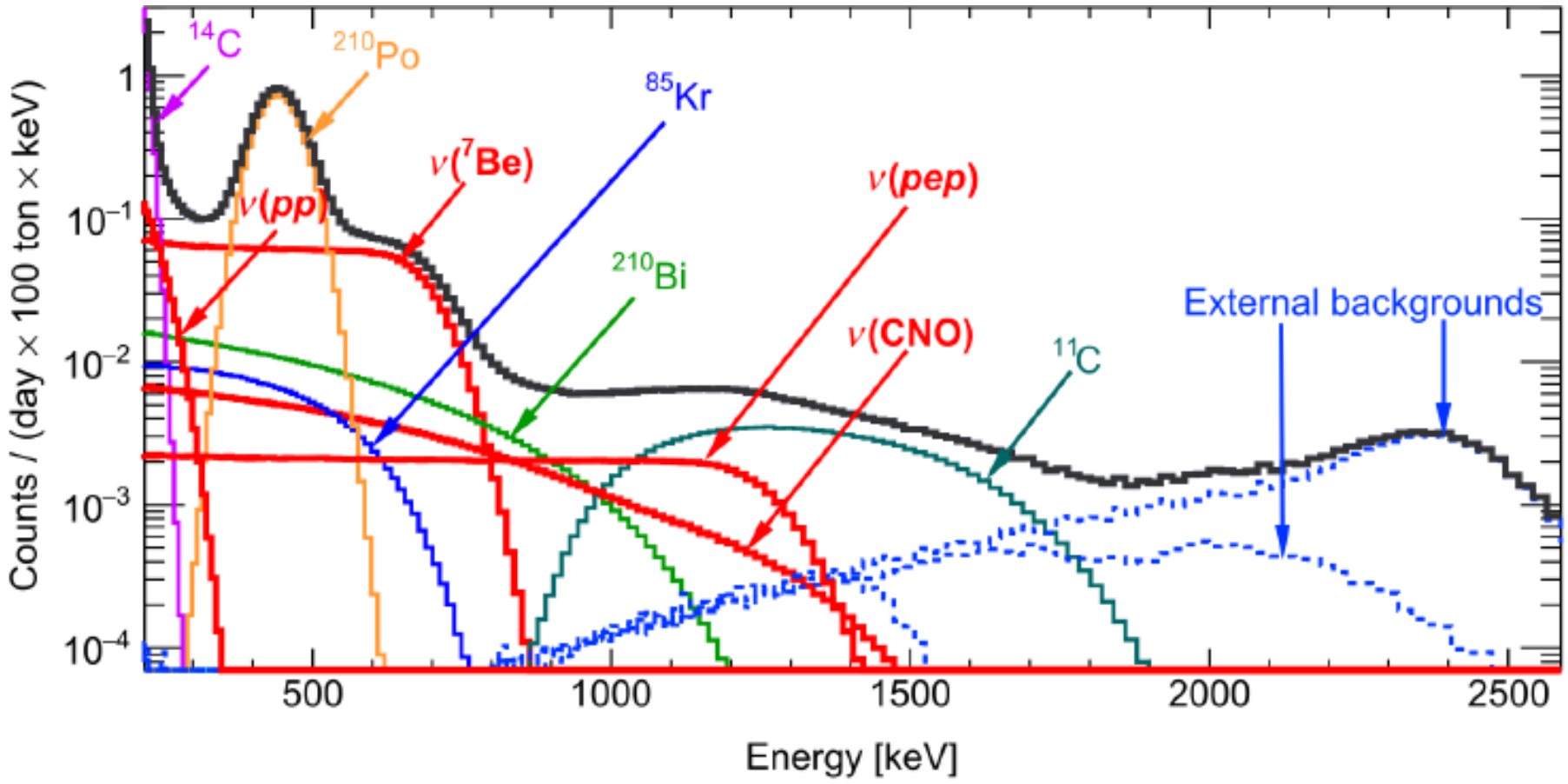
Borexino Solar Neutrino Experiment at LNGS



Compehensive Measurement of Solar Neutrinos

BOREXINO Collaboration, Comprehensive measurement of *pp*-chain solar neutrinos, Nature 562(2018), 505–510

neutrinos produced by 4 reactions of the Sun pp chain:
-initial pp;
7Be;
pep;
8B



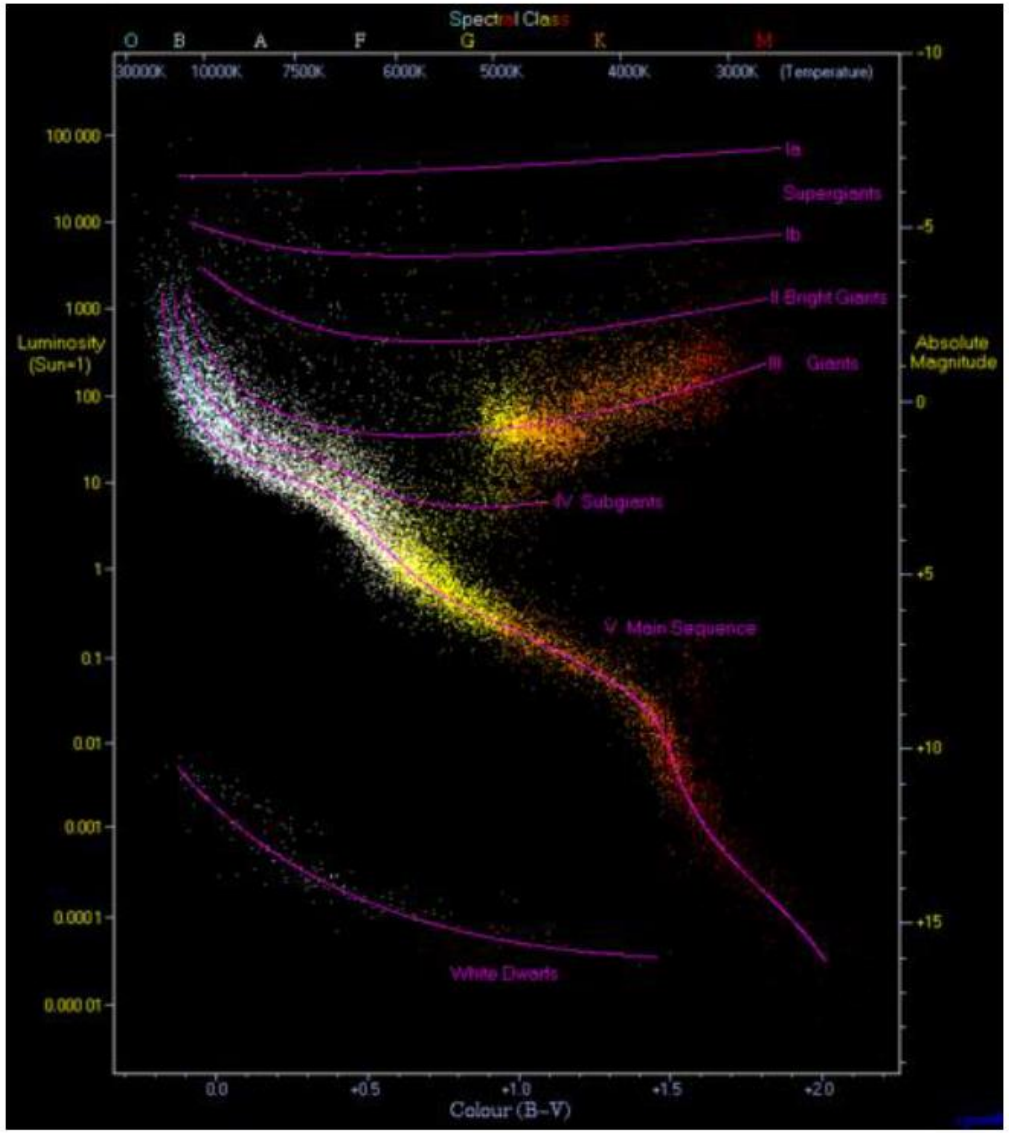
BOREXINO Results

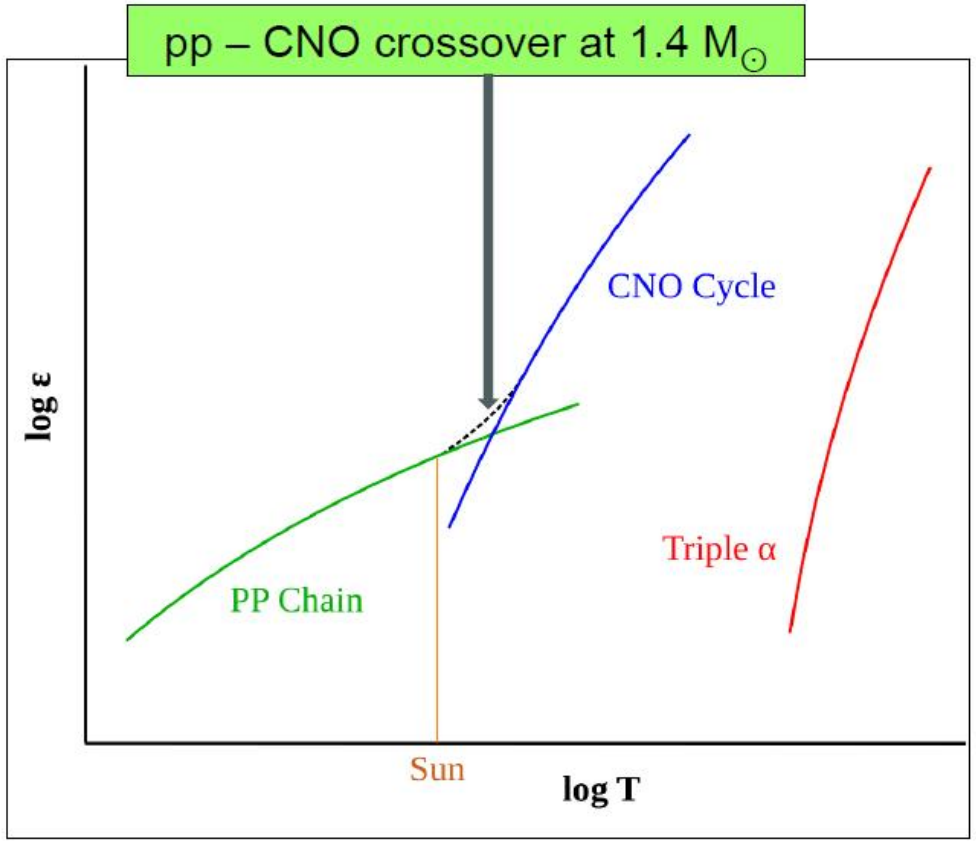
Fundamental step to the understanding and the experimental demonstration of the working principle of all stars in the Main Sequence

Neutrinos	References	Rate [cpd/100t]	Flux [$cm^{-2}s^{-1}$]
pp	Nature 2014, Nature 2018, PRD 2019	$(134\pm10)_{-10}^{+6}$	$(6.1\pm0.5)_{-0.5}^{+0.3}\times10^{10}$
^{7}Be	PLB 2008, PRL 2011, Nature 2018, PRD 2019	$(48.3\pm1.1)_{0.7}^{+0.4}$	$(4.99\pm0.11)_{-0.08}^{+0.06}\times10^{9}$
pep	PRL 2012, Nature 2018 PRD 2019	$(2.65\pm0.36)_{-0.24}^{+0.15}$ [HZ]	$(1.27\pm0.19)_{-0.12}^{+0.08}\times10^{8}$[HZ]
^{8}B	PRD 2010, Nature 2018, PRD 2020	$0.223_{-0.022}^{+0.021}$	$5.68_{-0.41-0.03}^{+0.39+0.03}\times10^{6}$
hep	Nature 2018, PRD 2020	<0.002 (90% CL)	$<1.8\times10^{5}$ (90% CL)
CNO	Nature 2020	$6.7_{-0.8}^{+2.0}$	$6.6_{-0.9}^{+2.0}\times10^{8}$

Marco Giammarchi, "Borexino and the SUN", PIC2024

BOREXINO Results

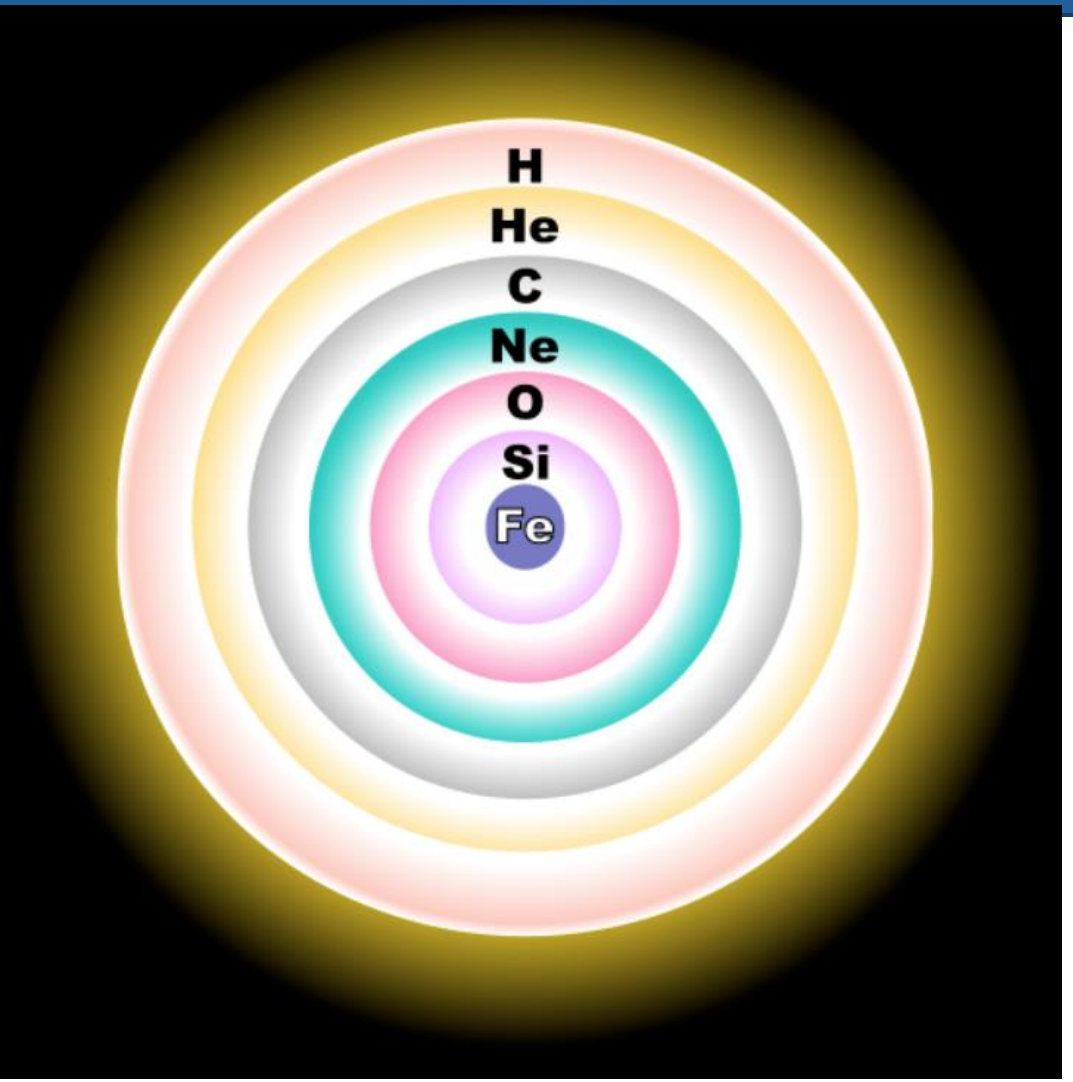




BOREXINO measurements are relevant to all Main Sequence stars

(22,000 stars in the Hipparchos catalog)

Neutrinos from SN1987A



The onion-like layers of a massive, evolved star just before core collapse. (Not to scale.)

Core Collapse Supernova (CCSN) /
Supernova type II (SN II)

Massive stars (8-40 solar masses) - explode as after the core is formed from Fe/Ni.

99% of gravitation collapse energy is released by Neutrinos

SN II very rare event: few per Galaxy per century

Very active field of research since SN1988A

Bethe, H. A. Supernova mechanisms. *Rev. Mod. Phys*. **62(1990)**, 801–866 (1990)..

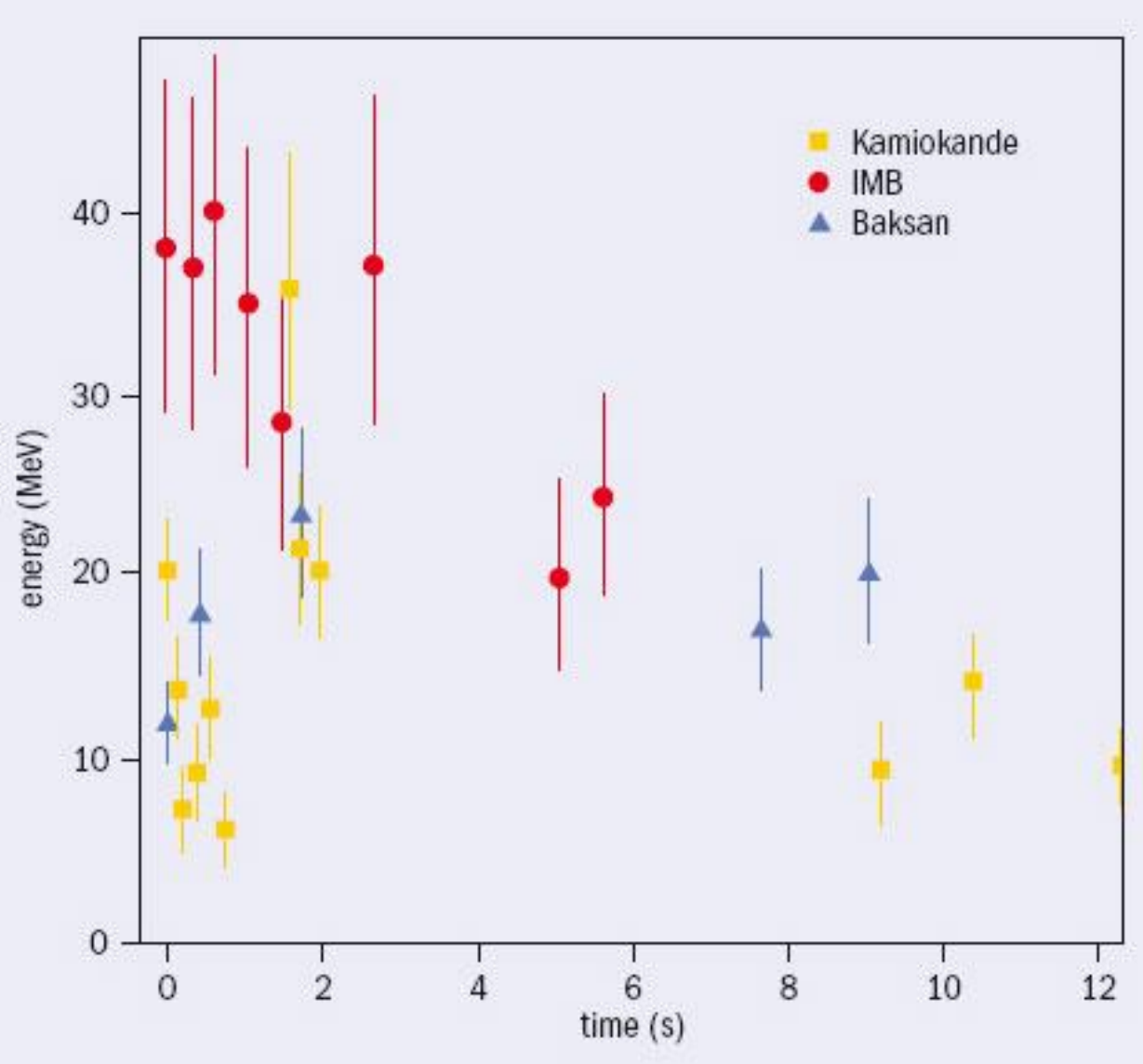
SN1987A

Closest observed supernova 1604 (Kepler's Supernova)

The progenitor star: Sanduleak –69 202 (Sk -69 202)

SN1987A (SN II) explosion in the LMC satellite galaxy of Milky Way about 51.4 kpc (168 000 light-year) away. Observed on Feb 23, 1987 (photo by

Neutrino Burst from SN1987A



SN neutrino flux:

$$e^- + p \longrightarrow n + \nu_e$$

$$n \longrightarrow p + e^- + \nu_e$$

weak interactions of electron-positron pairs:

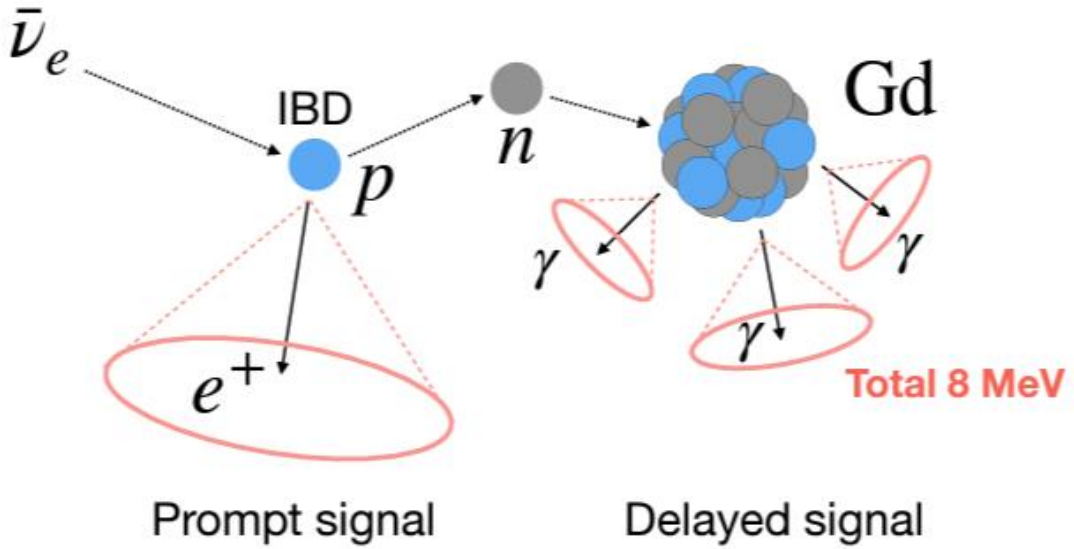
$$e^+ + e^- \longrightarrow \nu_x + \nu_x \quad x = e, \mu, \tau$$

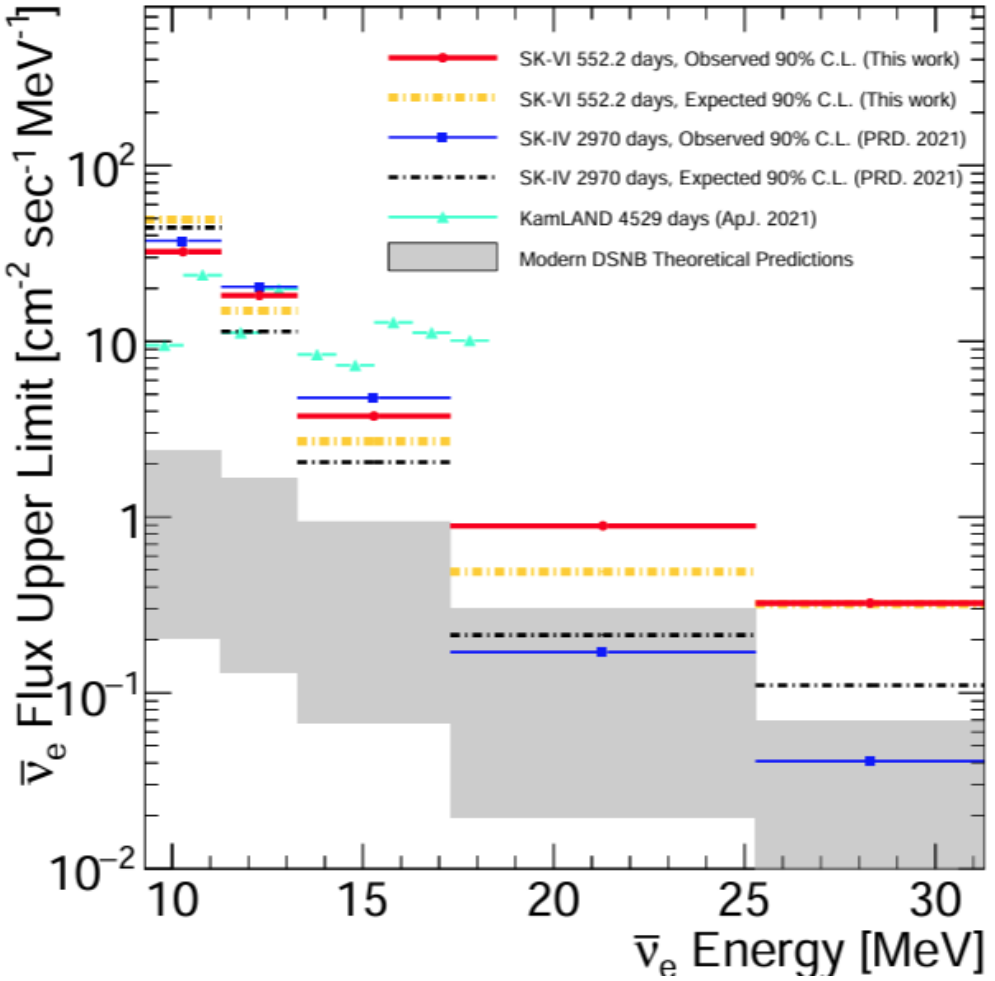
25 neutrinos were detected from SN1986A in a time interval of about 10 sec by 3 neutrino detectors:

Kamiokande (12 events)
IMB (8 events)
Baksan (5 events)

Diffuse Supernova Neutrino Background (DSNB)

DSNB is an integrated flux of neutrinos emitted from all past supernovae in the universe.





SK Collaboration, "First result of a search for Diffuse Supernova Neutrino Background in SK-Gd experiment", *PoS* ICRC2023 (2023) 117

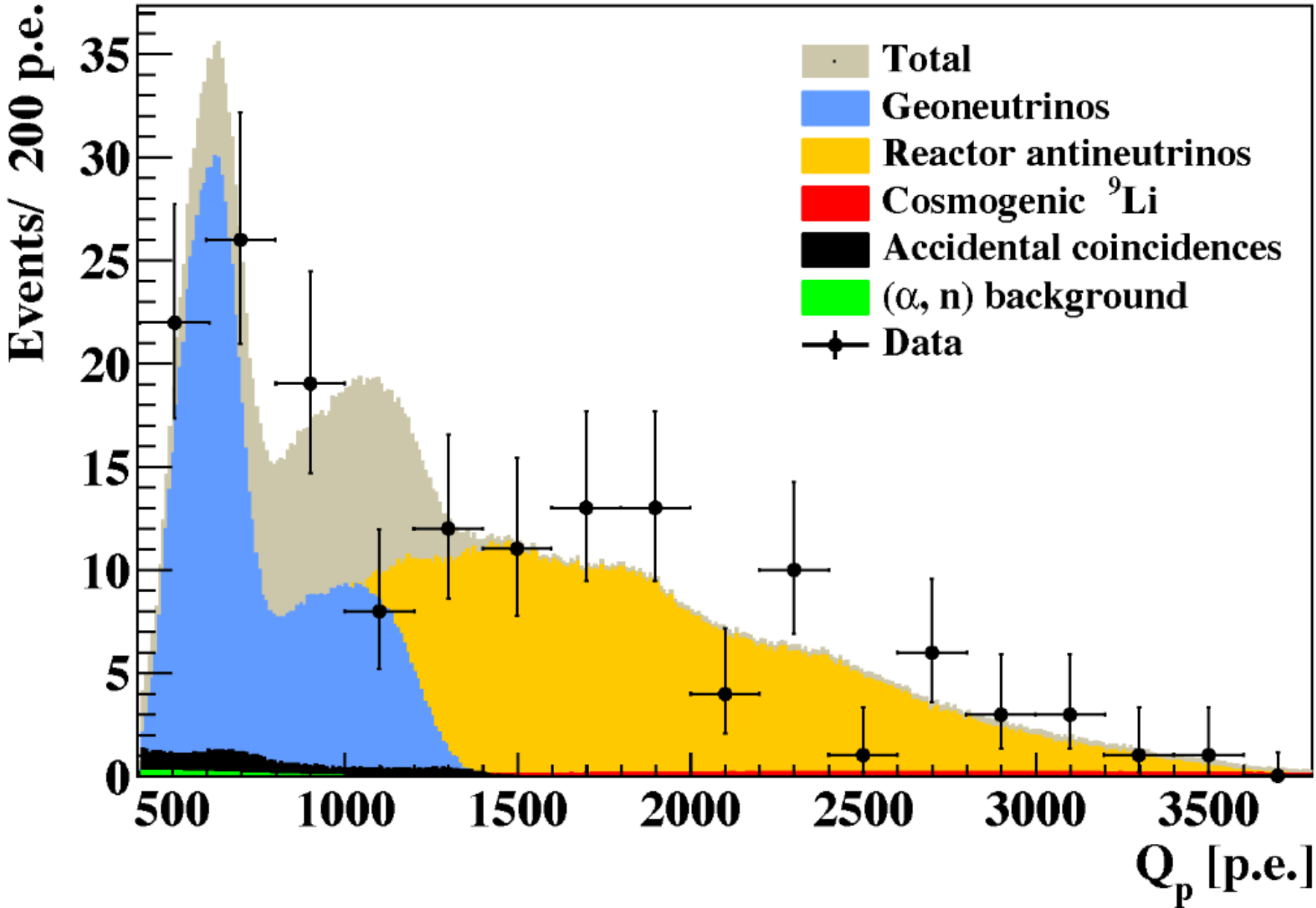
Terrestrial Neutrinos (Geoneutrinos)

^{40}K, ^{232}Th, ^{238}U

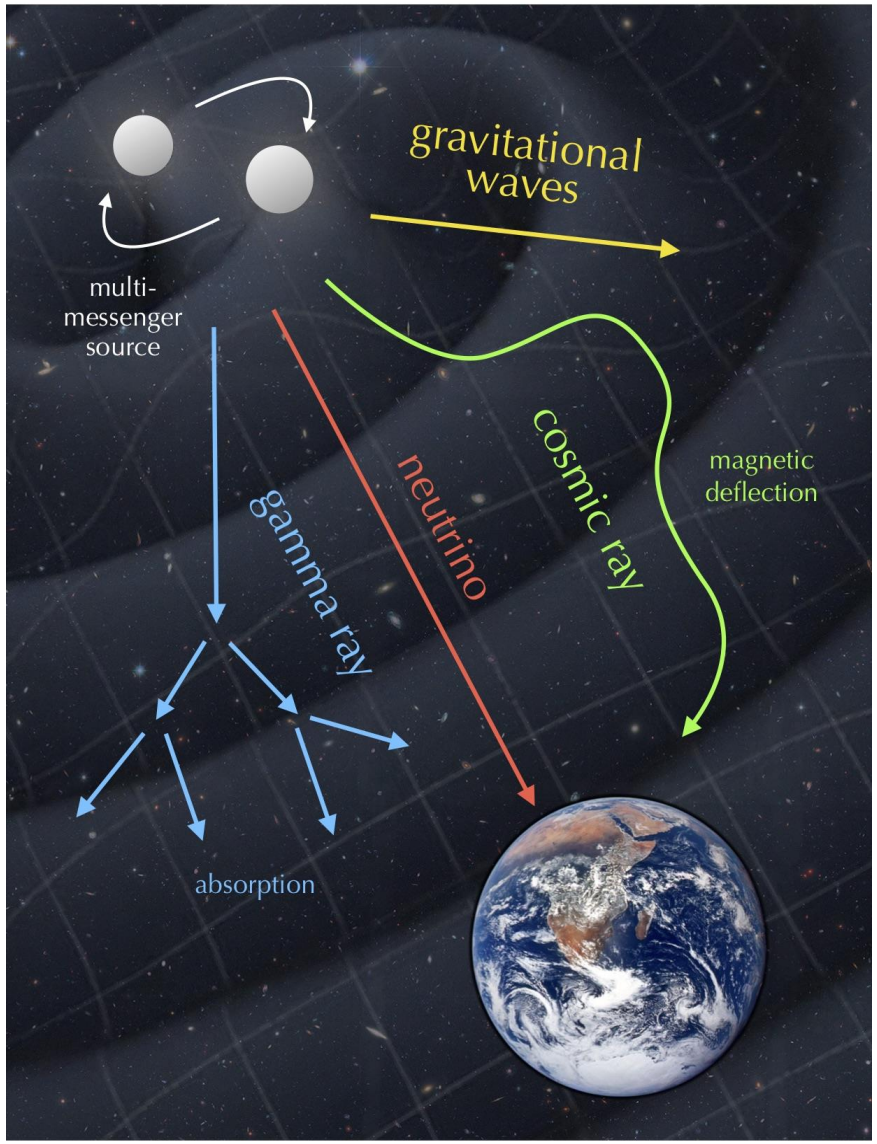
Earth composition models:
16 TW

Electron antineutrinos produced by the decay of ^{238}U and ^{232}Th within the Earth.

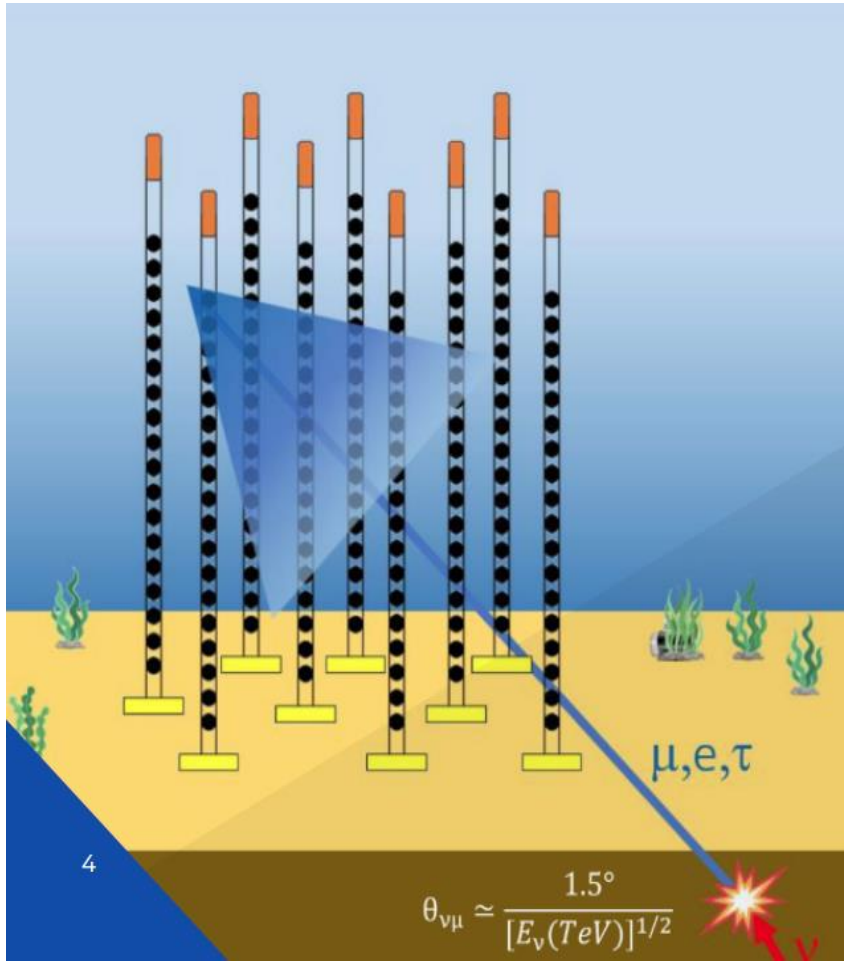
Measurements by KamLAND and BOREXINO



High Energy Neutrino Astronomy



Moisey Markov
1908-1994



First attempt:

Deep Underwater Muon And NeutrinDetector (DUMAND)

First Generation Neutrino Telescopes

AMANDA: South Pole, Amundsen-Scott Station

Polar ice: high transparent environment, short scattering length, no background

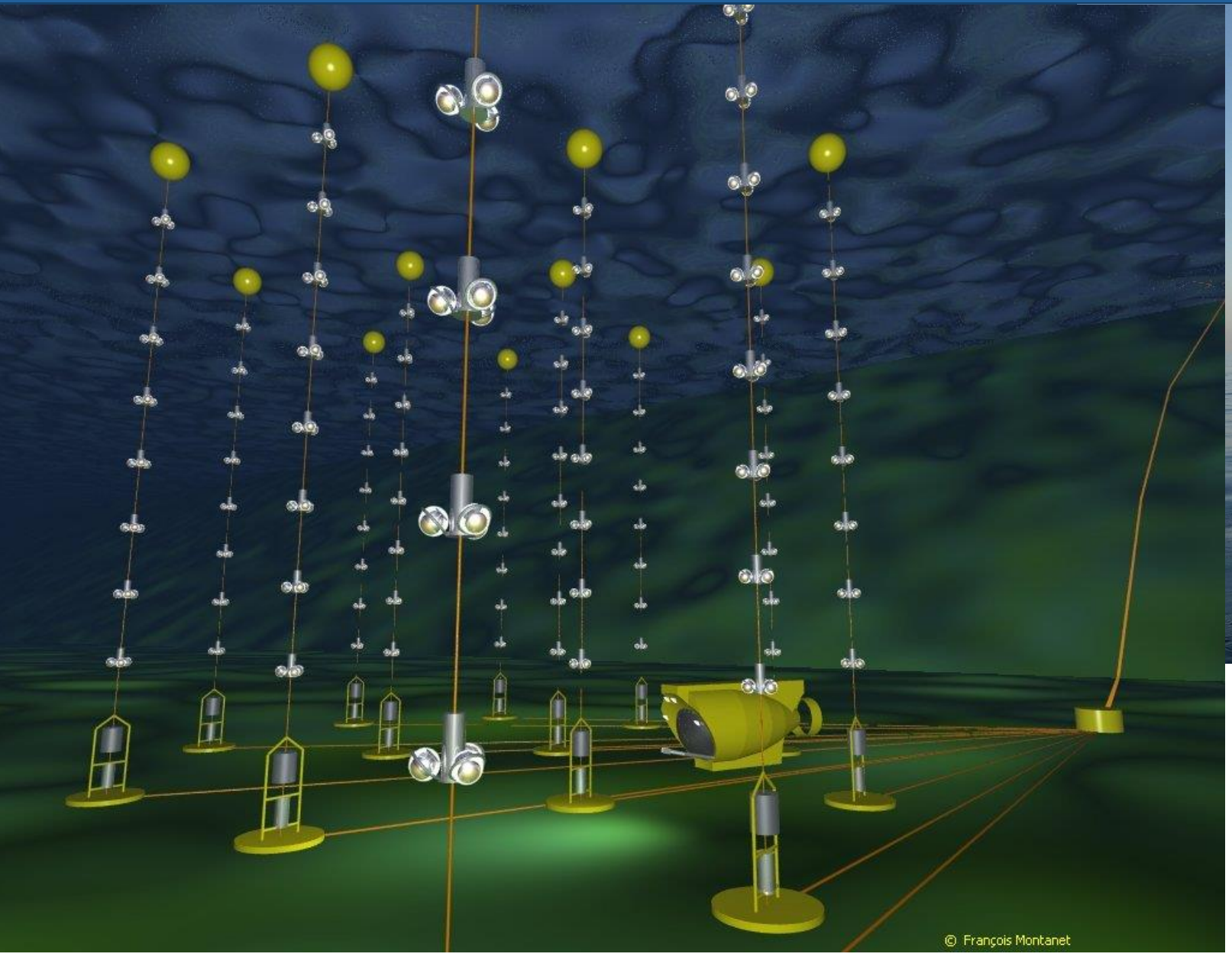
Remote location: high transportation and energy supply costs

ANTARES: first deep-sea neutrino telescope (near Toulon, France)

Deep-sea environment: short absorption and longer scattering lengths, Optical background from 40K and bioluminescence,

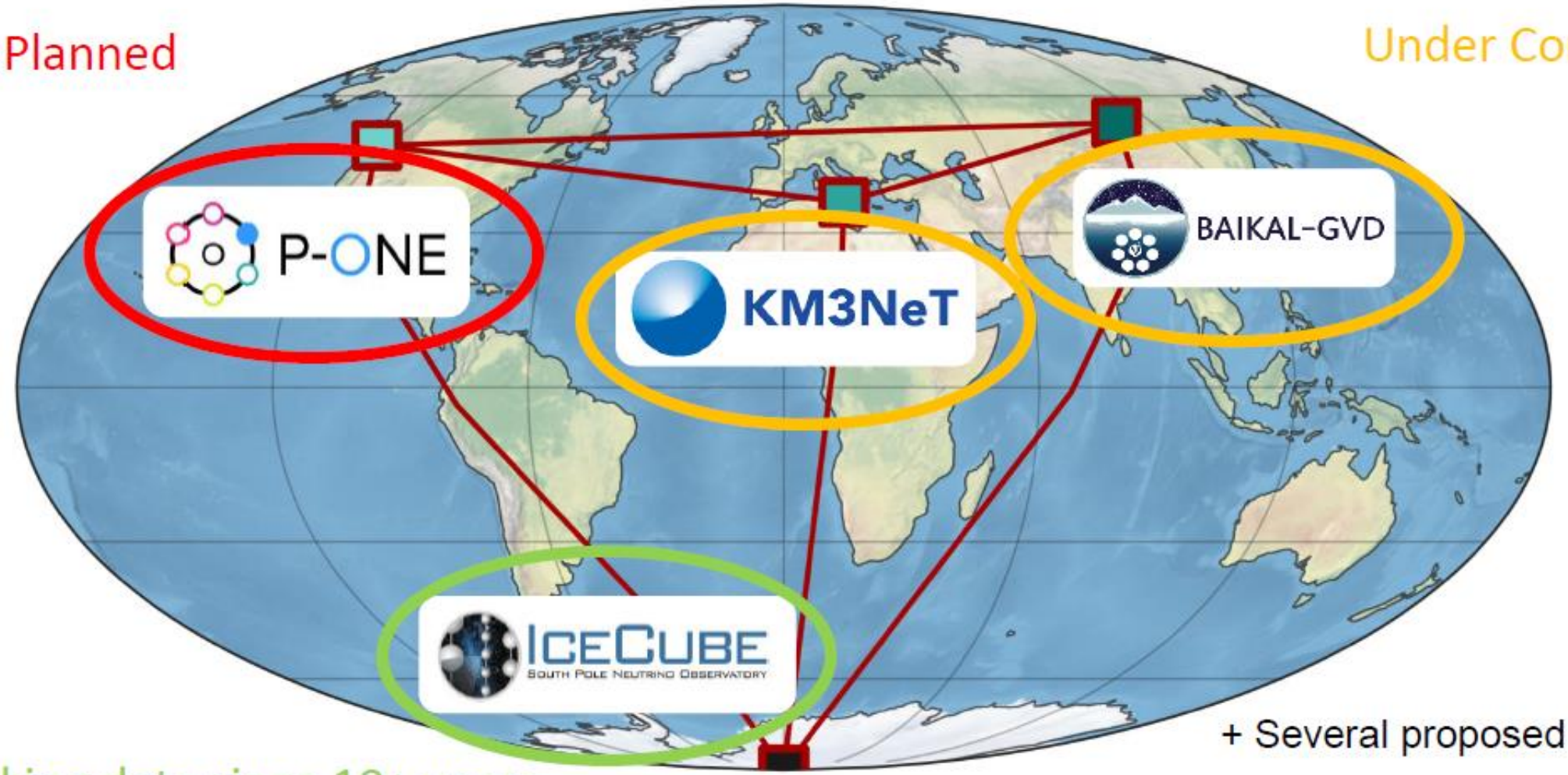
Baikal telescope in the lake Baikal

ANTARES Neutrino Telescope

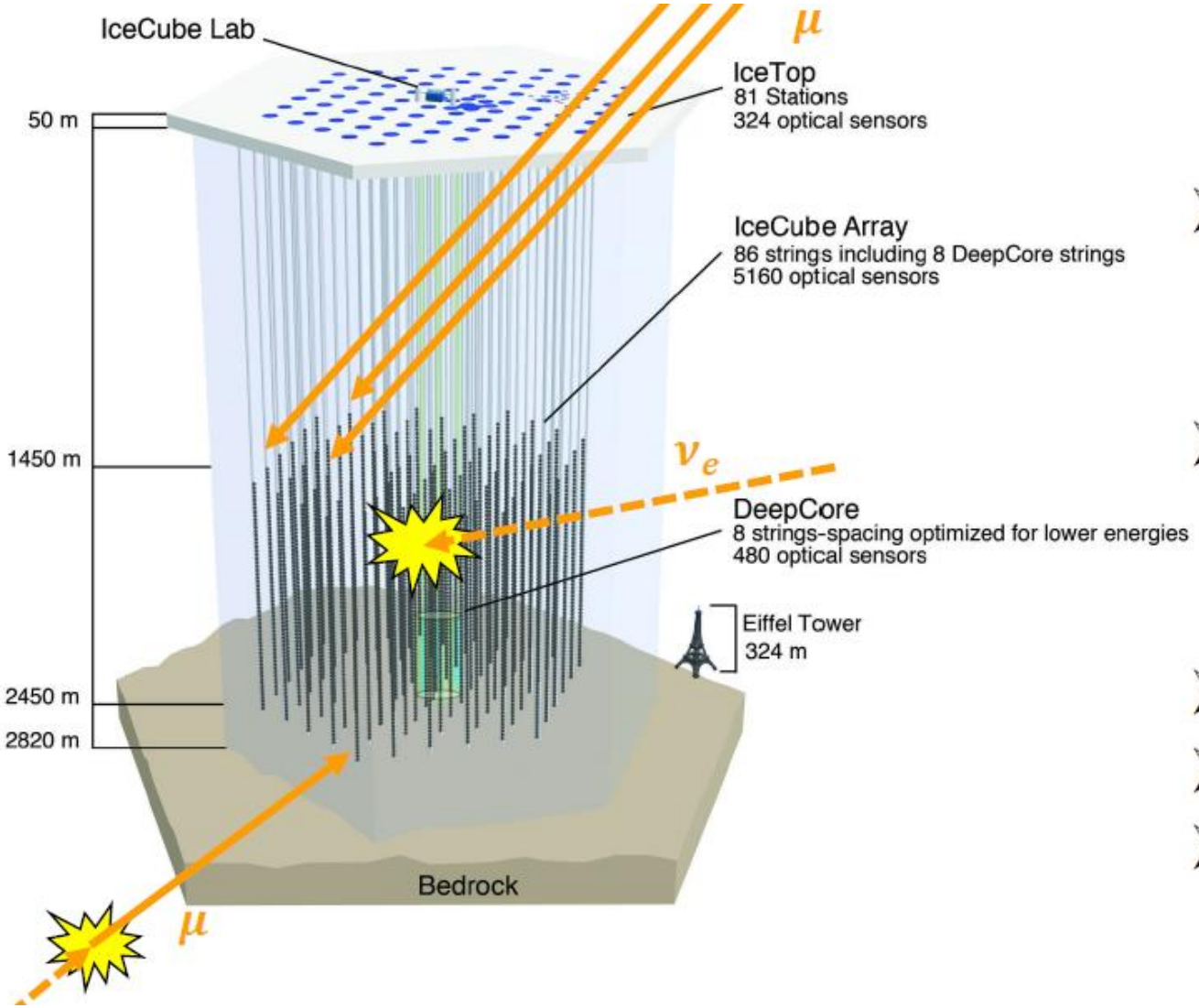


ANTARES Neutrino telescope.
(data taking: 2007-2022)

Current Projects of High Energy Neutrino Astronomy



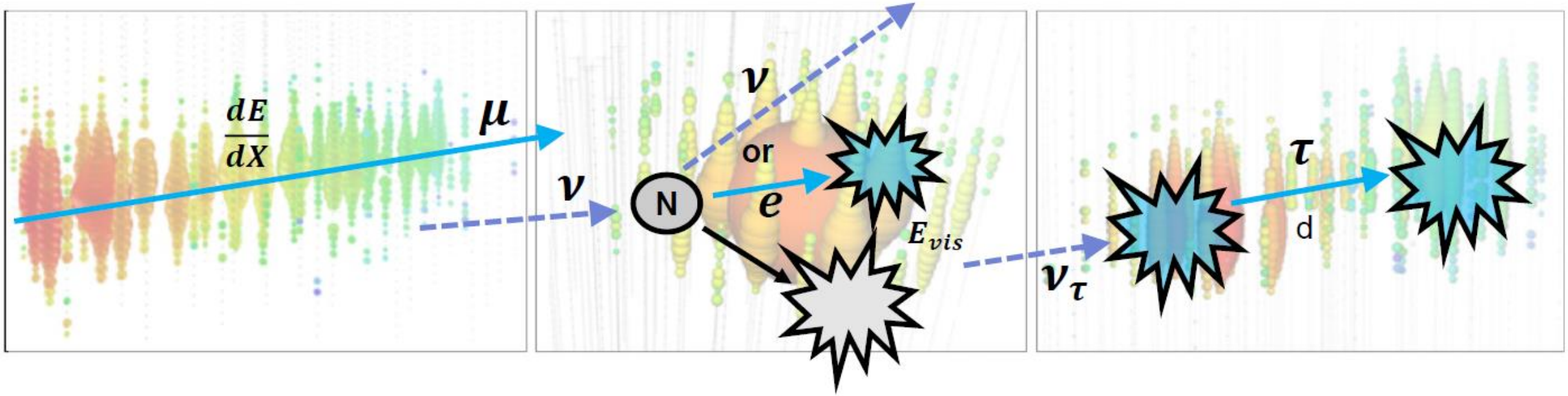
IceCube: First km^3 Scale Neutrino Telescope



- 86 Strings with 60 Digital Optical Modules (DOMs)
- Full configuration running with > 99% uptime since 2011
- 3000 atmospheric μ per second
- 1 atmospheric ν per minute
- 1 astrophysical ν per day

Cristian Haak, Current State of Neutrino Astronomy, PIC2024

Neutrino Sugnatures in IceCube



"**Tracks**":

- Good directional resolution $< 1°$
- Poor energy resolution via $\frac{dE}{dX}$ of muon

"**Cascades**":

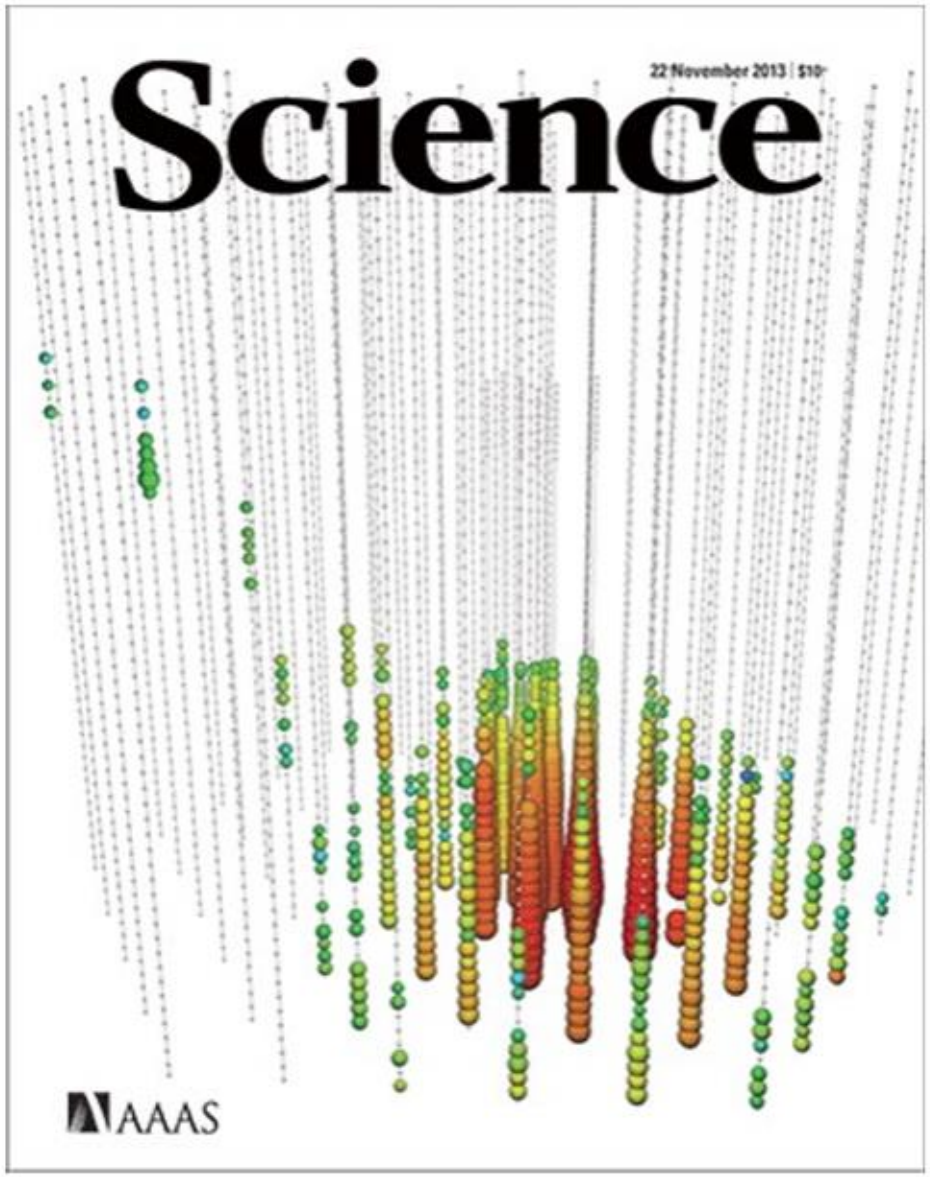
- CC ν_e & ν_τ interactions + NC all-flavor
- Directional resolution $\sim 5 - 15°$
- Good resolution of visible energy: $\sim 10\%$ for CC ν_e

"**Double Bang**":

- CC ν_τ interactions + τ decay
- Atmospheric ν_τ production strongly surpressed
- τ decay length:

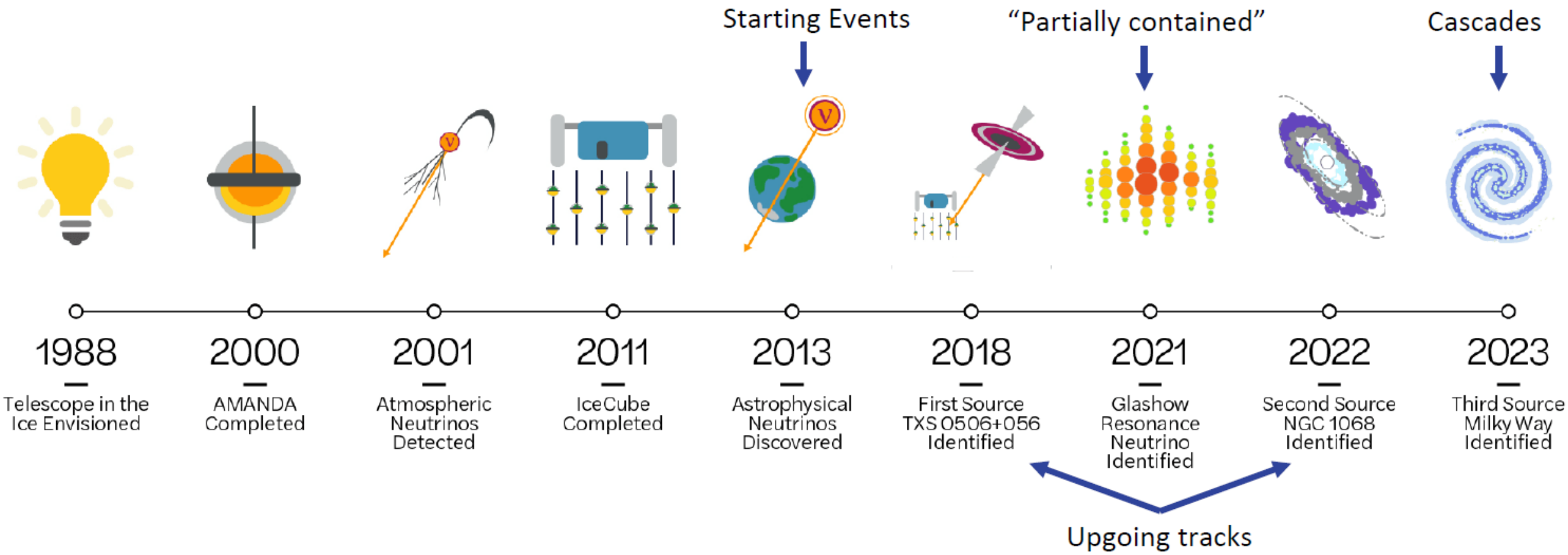
$$\mathrm{d} \sim 50\mathrm{m} \cdot \left(\frac{E}{\mathrm{PeV}}\right)$$

ORCA (Oscillation Research with Cosmics in Abyss)

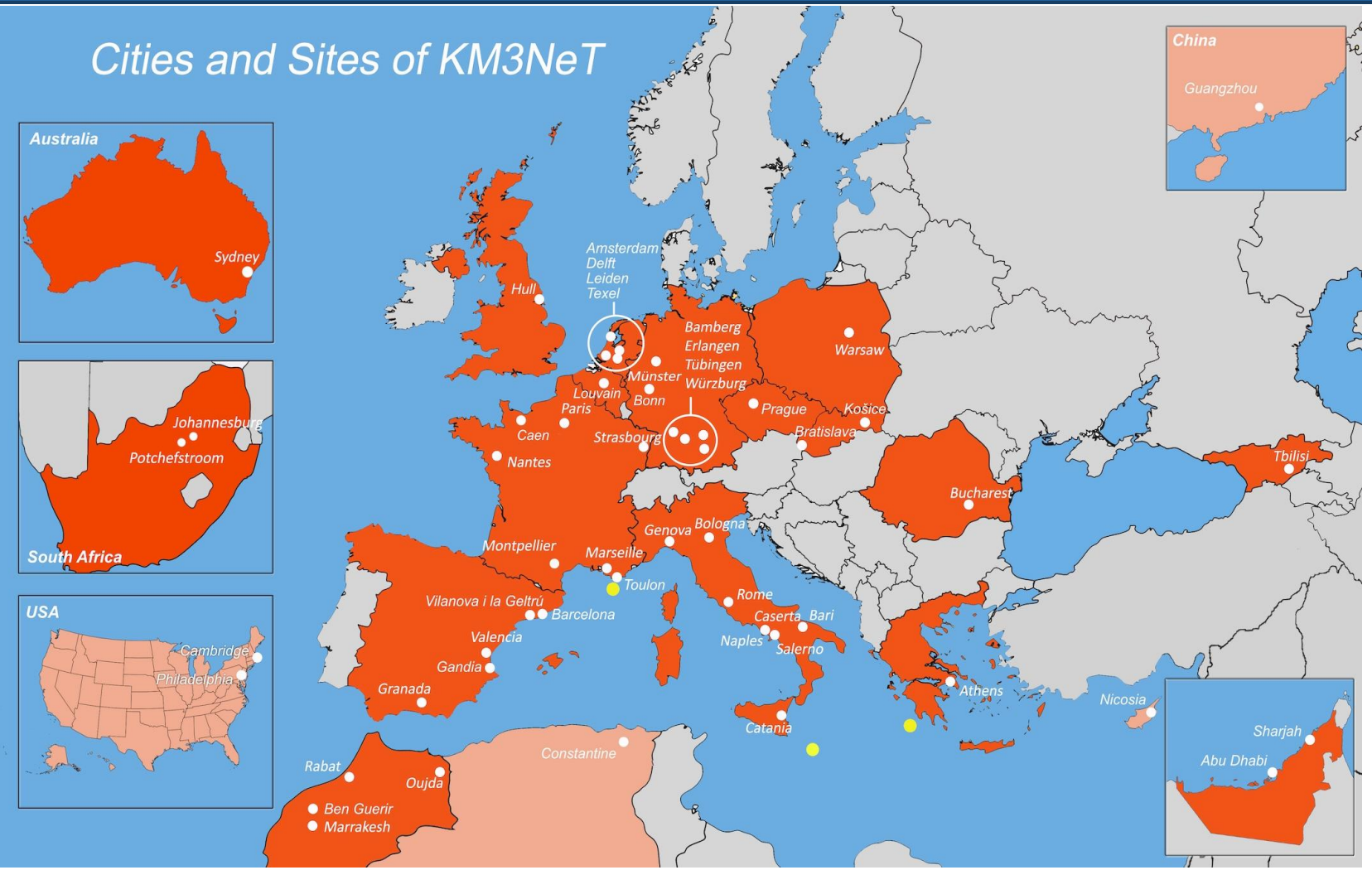


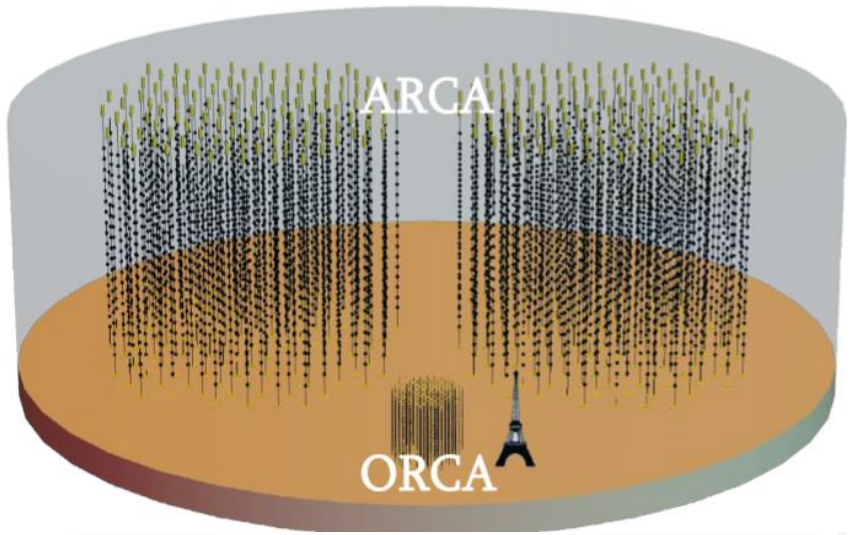
IceCube Collaborartion, Evidence for High-Energy Extraterrestrial Neutrinos at the IceCube Detector, Science 342 (2013), 1242856

History of Neutrino Astronomy in Antarctica



KM3NeT Project





ARCA

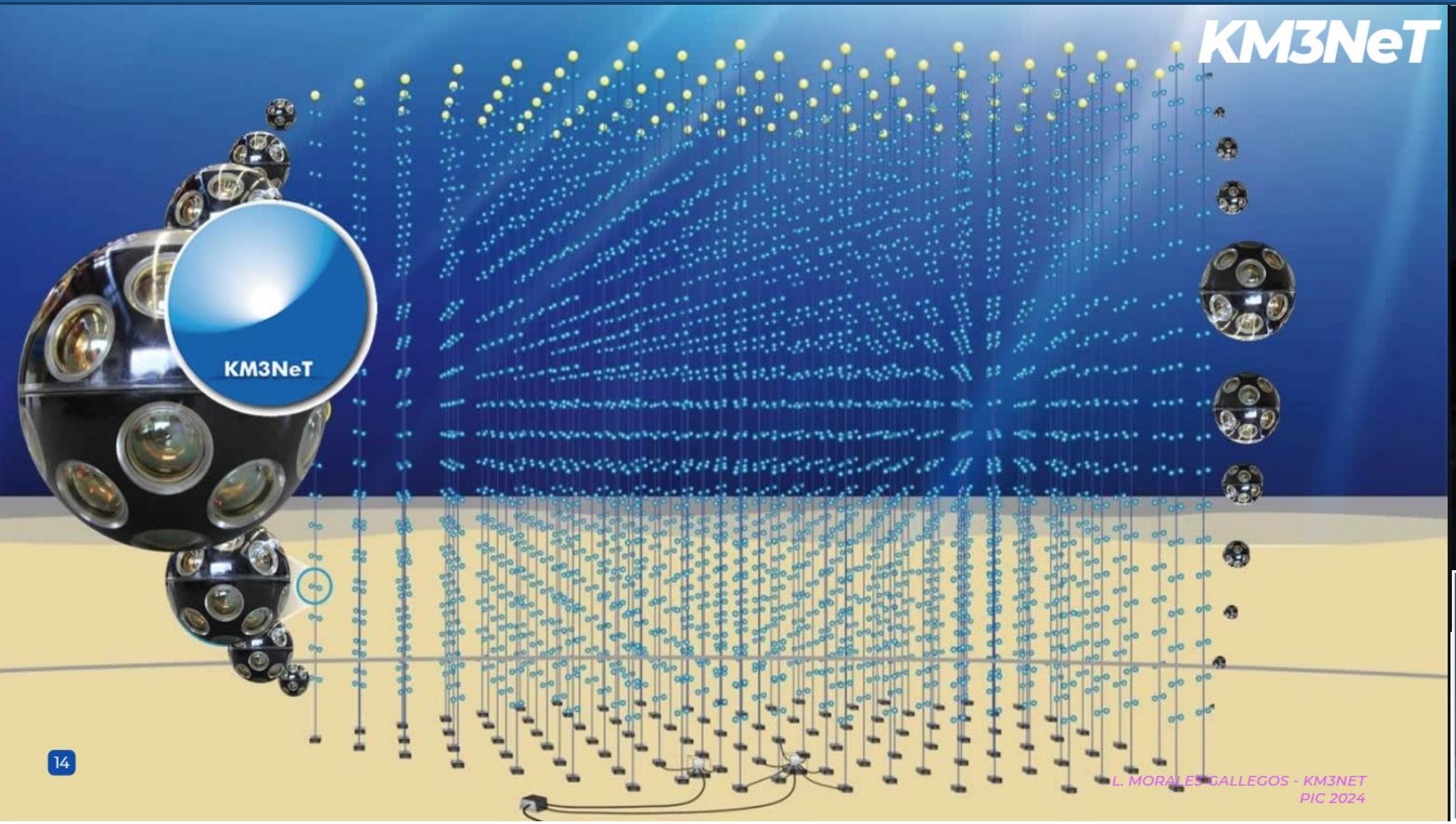
Depth ~3500 m
2 blocks of 115 Detection Units (DU)
Distance between DU ~90 m
Distance between DOMs ~36 m
Volume (0.5 × 2) km3

ORCA

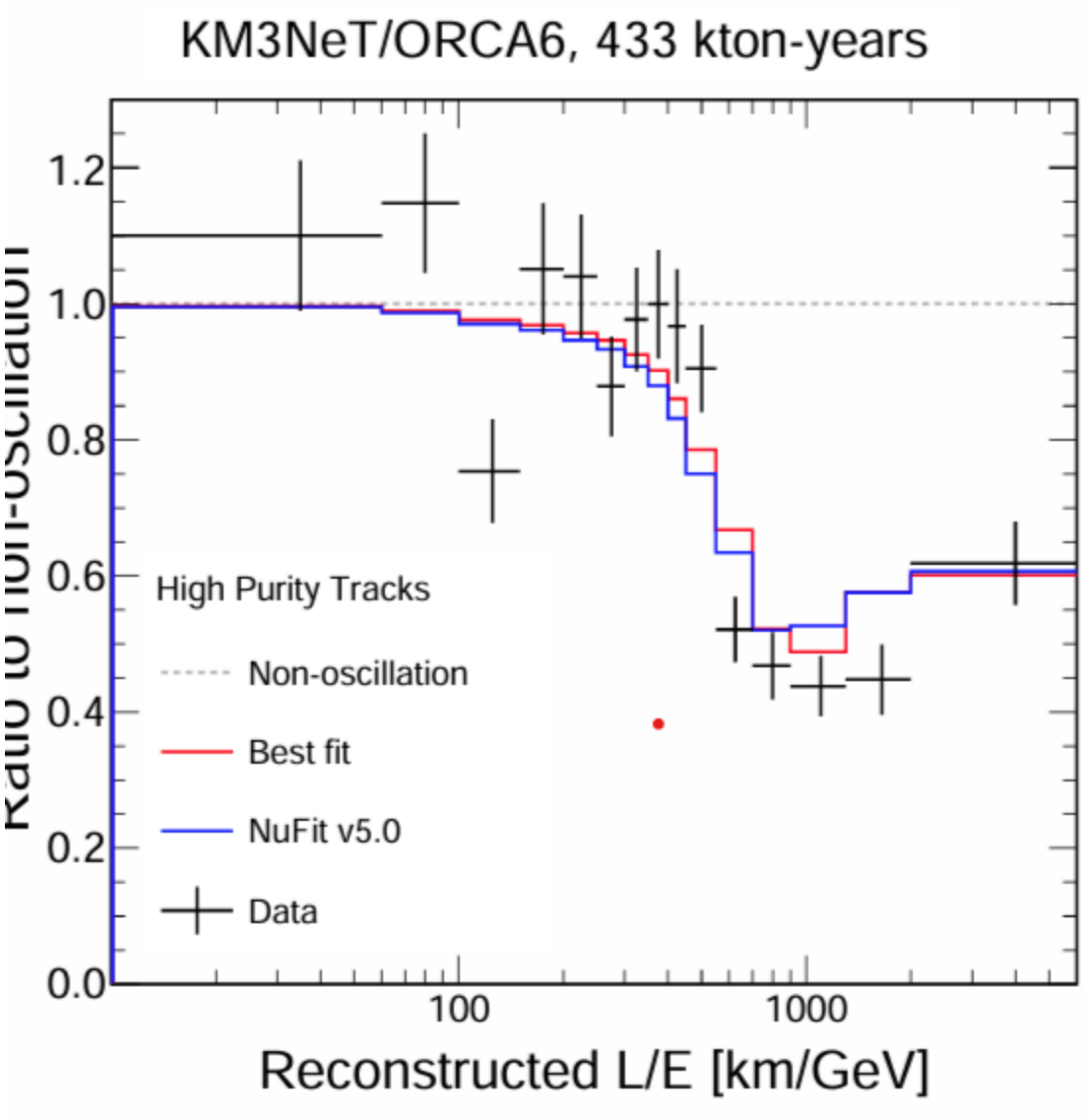
Depth ~2500 m
One block of 115 Detection Units
Distance between DU ~20 m
Distance between DOMs ~9 m
Colume ≈8 Mton

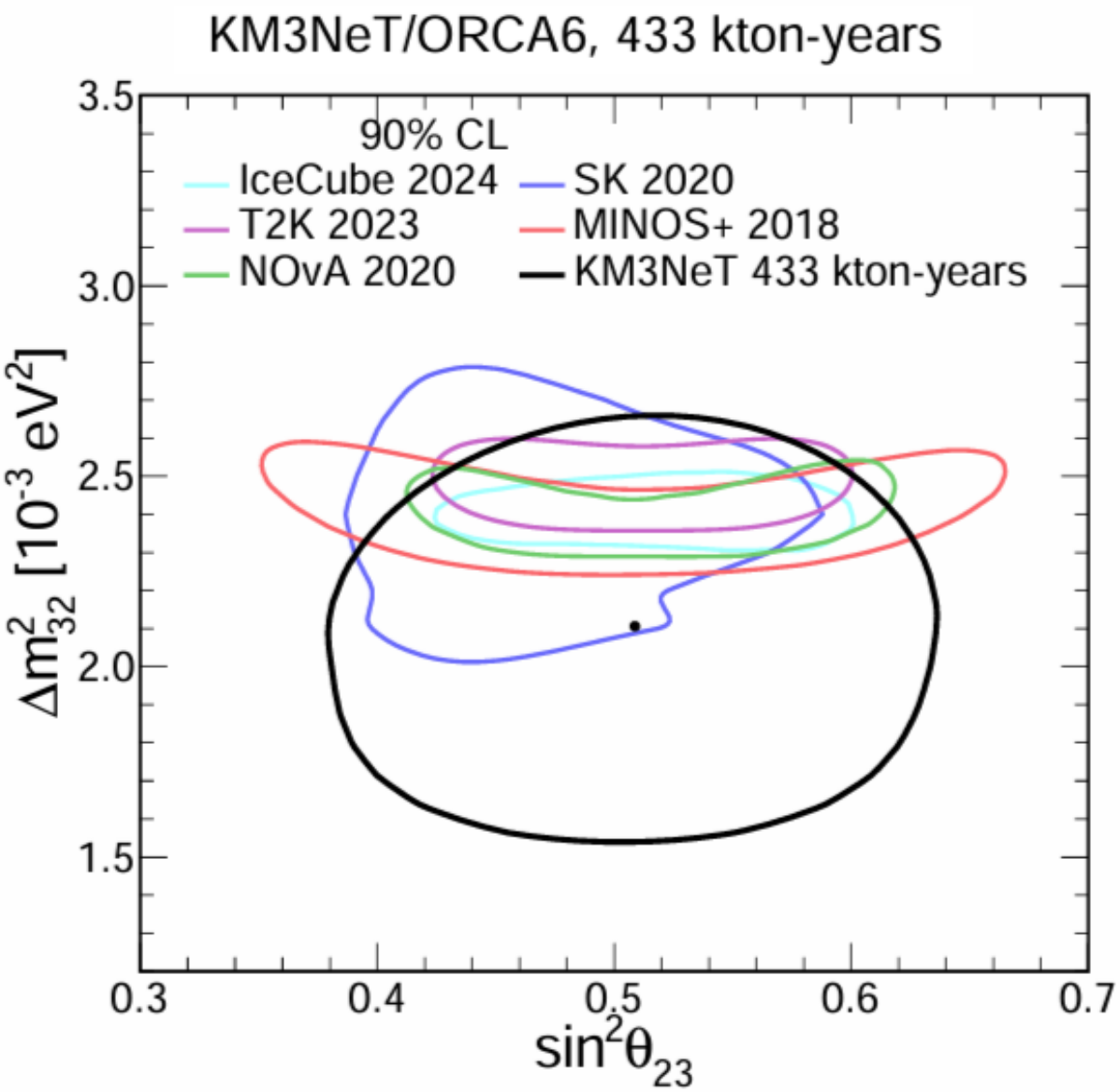
The KM3NeT Collaboration (62 institutes, 22 countries)

KM3NeT Detector

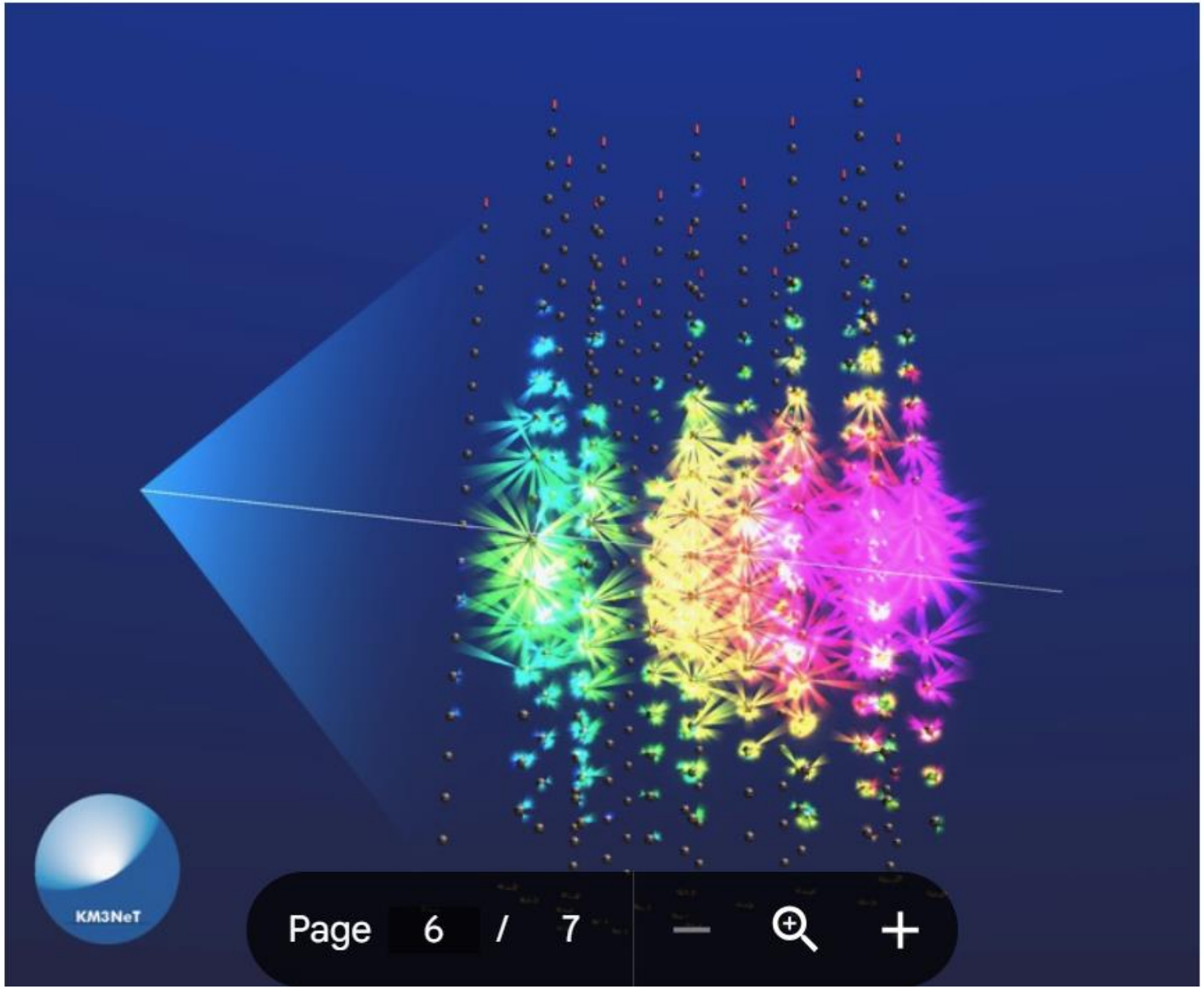


Neutrino Oscillations in KM3NeT/ORCA6





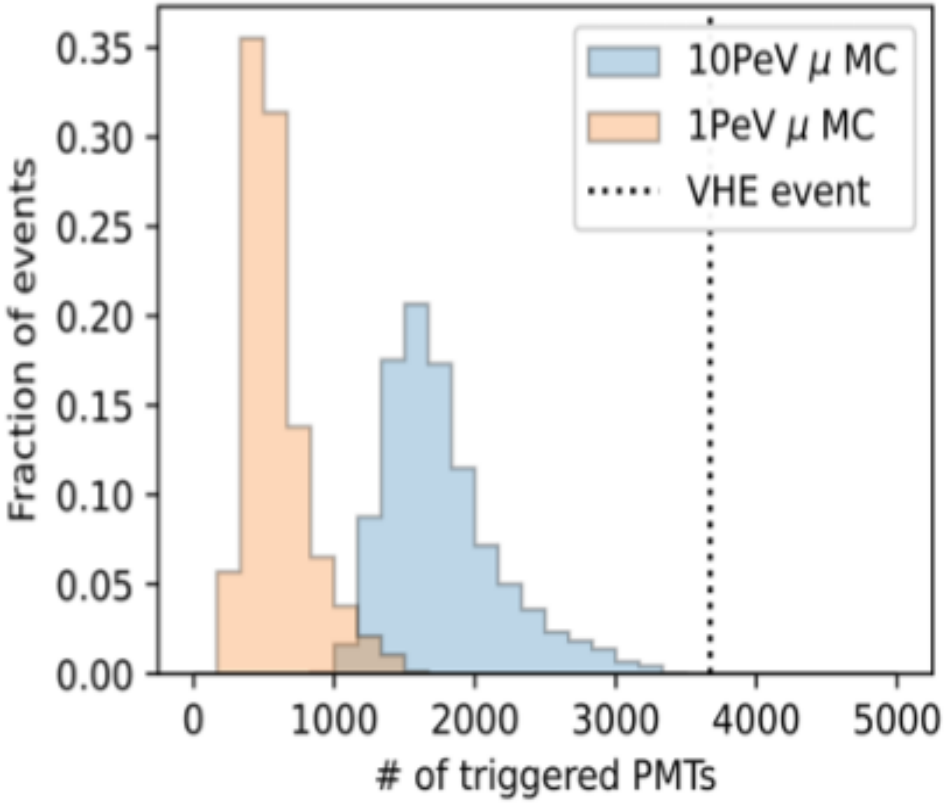
VHE Neutrino Events in ARCA21



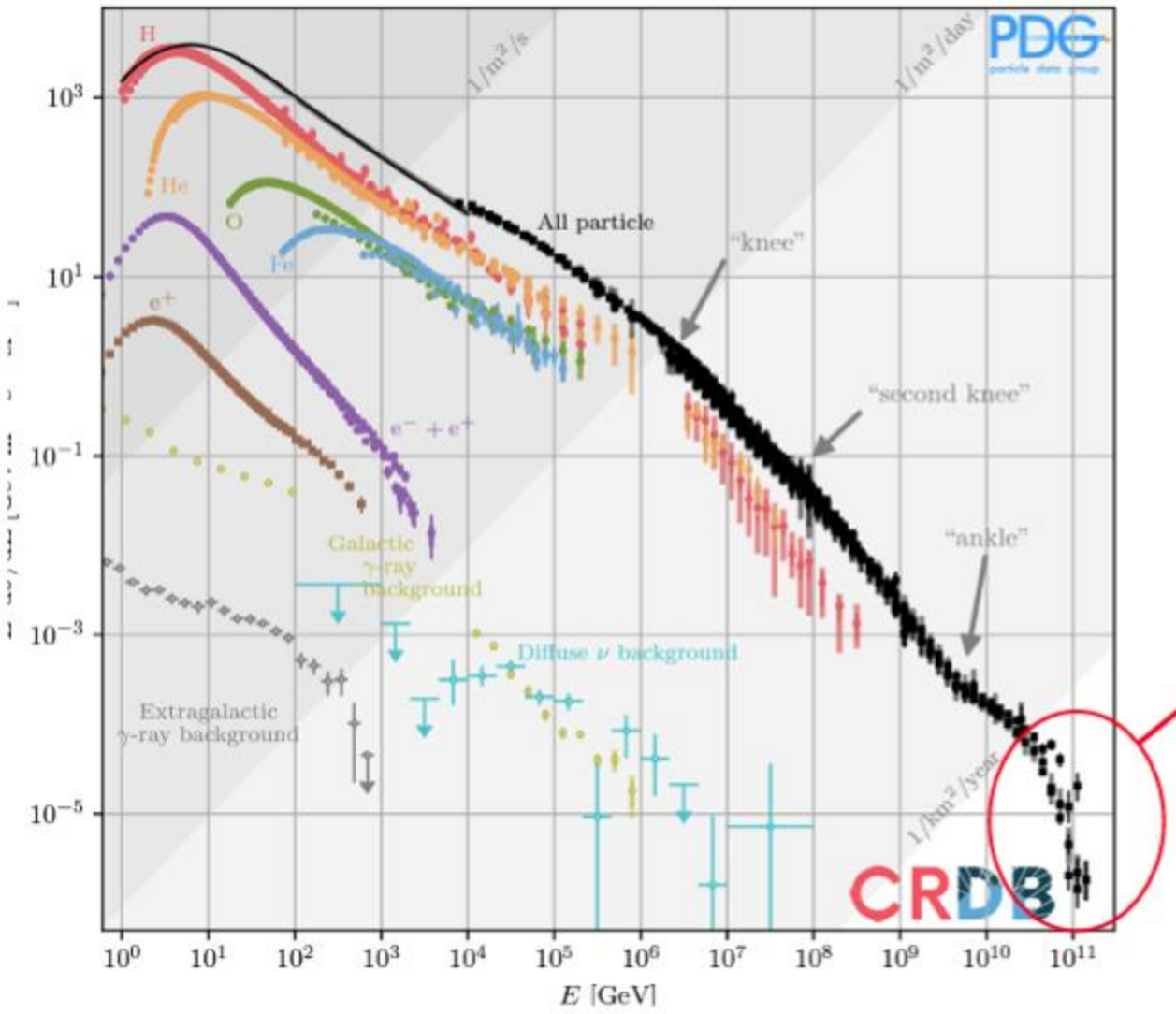
ARCA21: VHE event

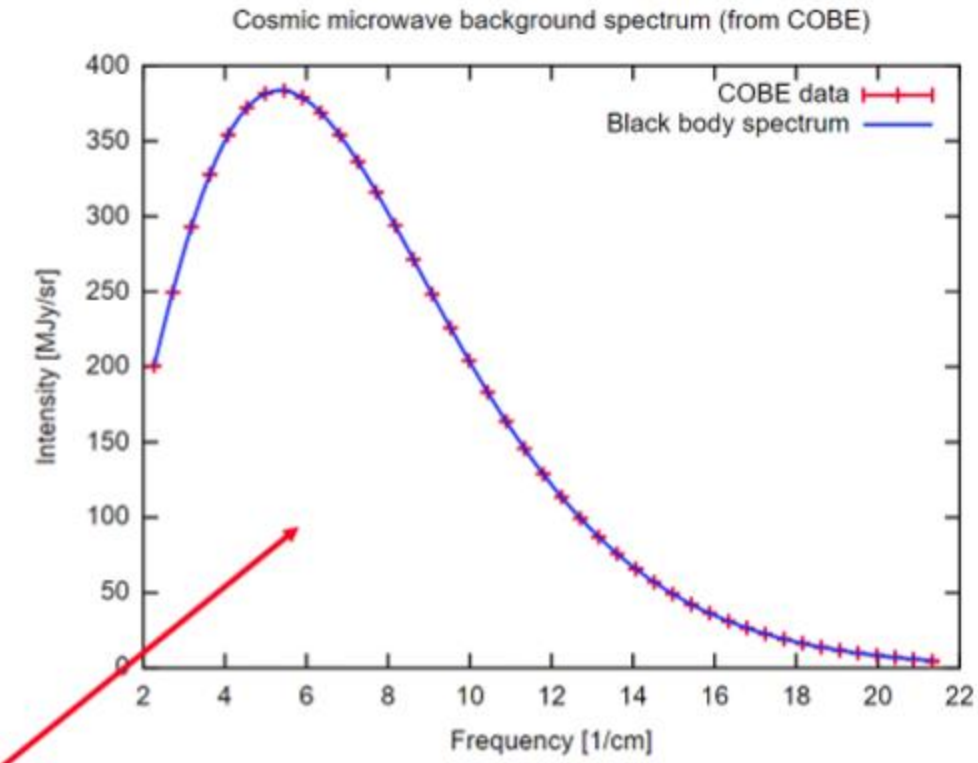
3672 PMTs (35%) triggered

Energy: > 100 PeV



KM3NeT VHE-Event: GZK Neutrino?





GZK process (cutoff):

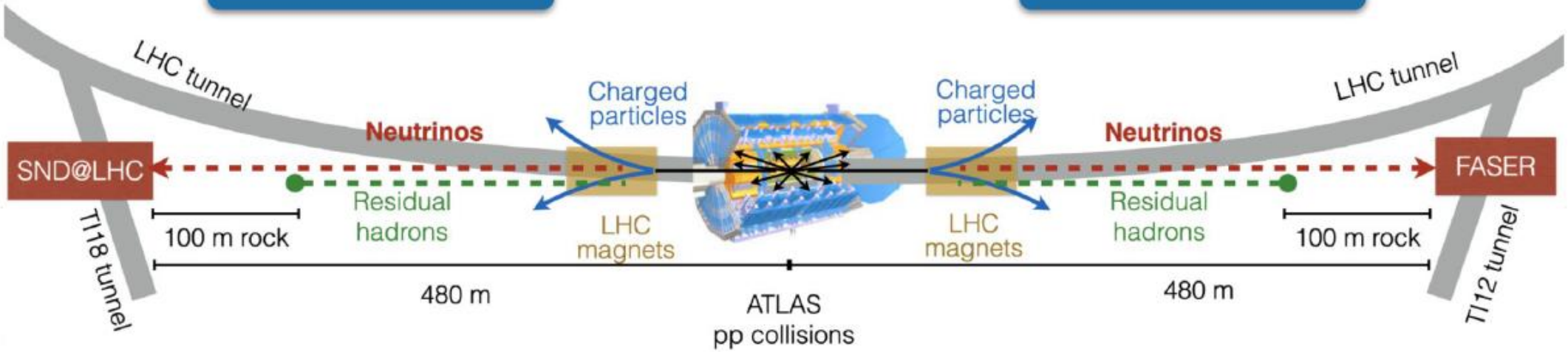
$$p + \gamma_{CMB} \rightarrow n + \pi^+ \; (p\pi^0)$$

$$\pi^+ \rightarrow \mu^+ + \nu_\mu$$

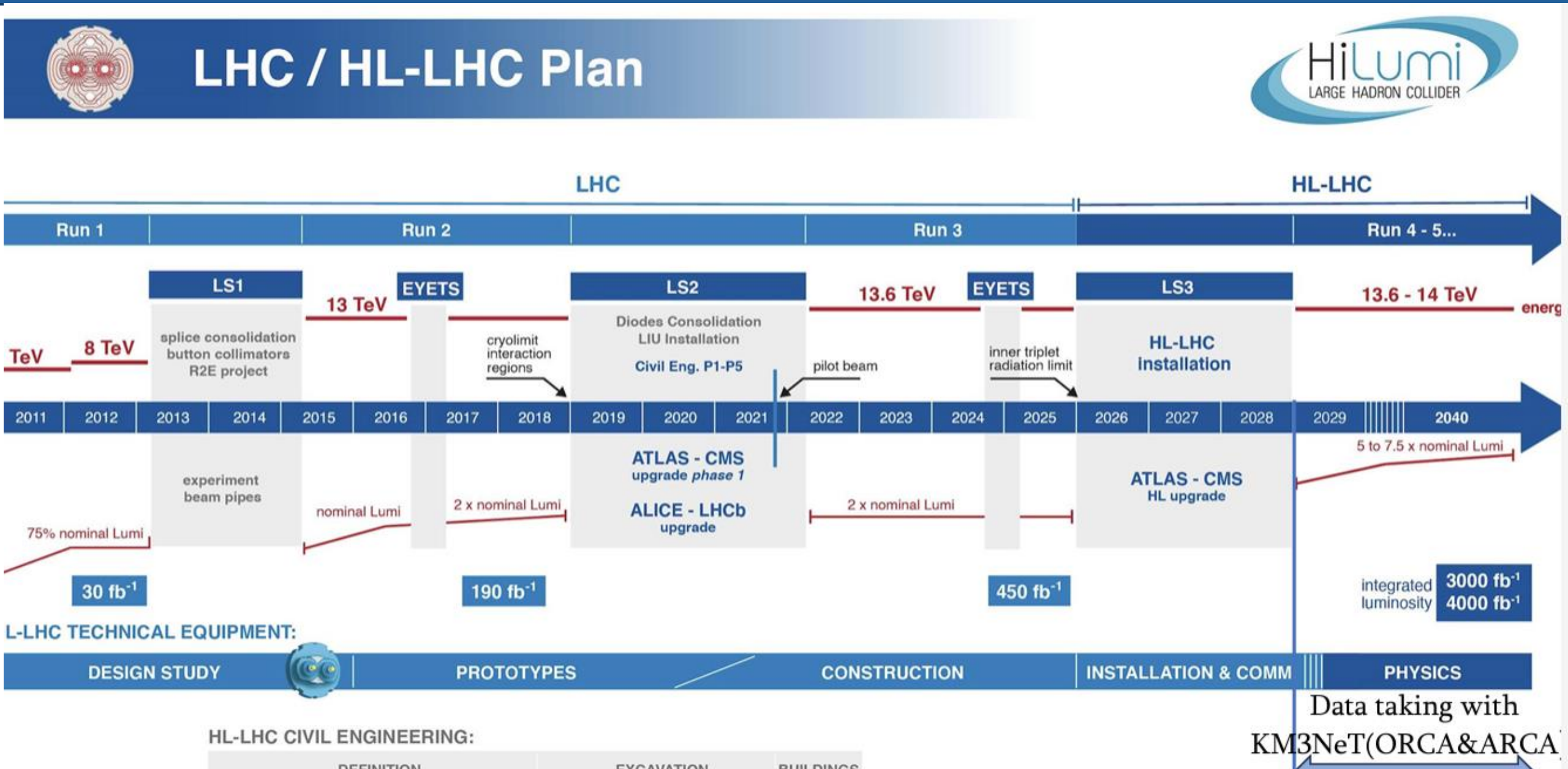
LHC Neutrino Detectors

SND@LHC in TI18

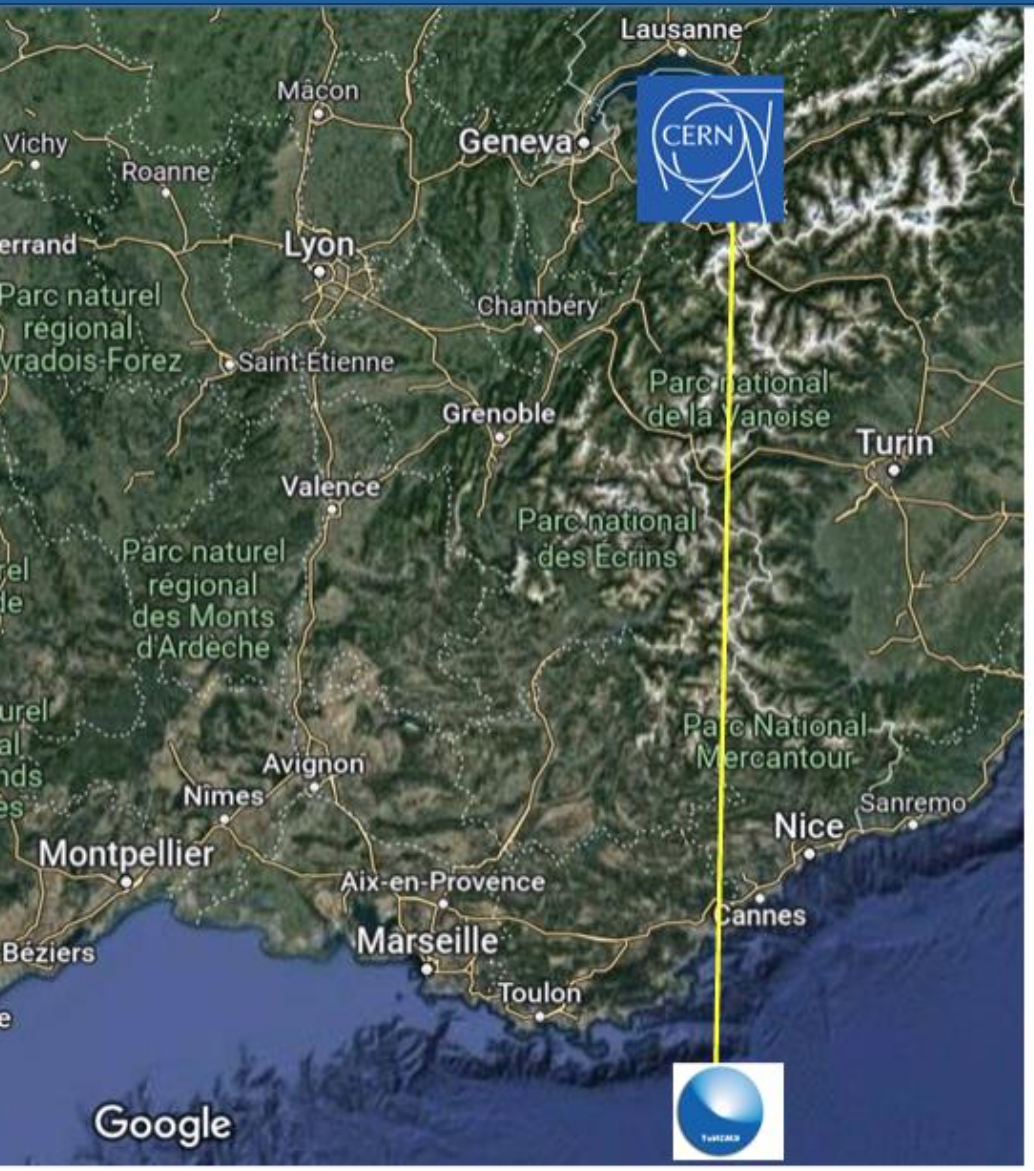
FASER in TI12



LHC Neutrinos in the KM3NeT ?



LHC Neutrinos in the KM3NeT ?



CERN (46.2330° N, 6.0557° E)

KM3NeT/ORCA (42°48' N, 6°02' E)
(42.8° N, 6.0333° E)

CERN experiments:

ATLAS (46.235° N, 6.053° E)

CMS (46.3098° N, 6.0764° E)

LHCb (46.2412° N, 6.0969° E)

Distances:

ATLAS - KM3NeT/ORCA: 382 km

CMS - KM3NeT/ORCA: 390 km

KM3NeT/ORCA

Summary

Neutrino physics is very active field of research: linking Standard Model and New Physics?

Neutrino oscillation research:

- precision measurement of 5 PMNS parameters
- defining NMO and δ_{CP}

Measurement of neutrino mass

Unanswered questions:

- are massive neutrinos Dirac or Majorana particles? ($0\nu\beta\beta$)
- are there sterile neutrinos?
- are there non-standard neutrino interactions?

New neutrino experiments: DUNE, Hyper-K, JUNO, KM3NeT, . . .

End of Lecture II