How to catch a neutrino?

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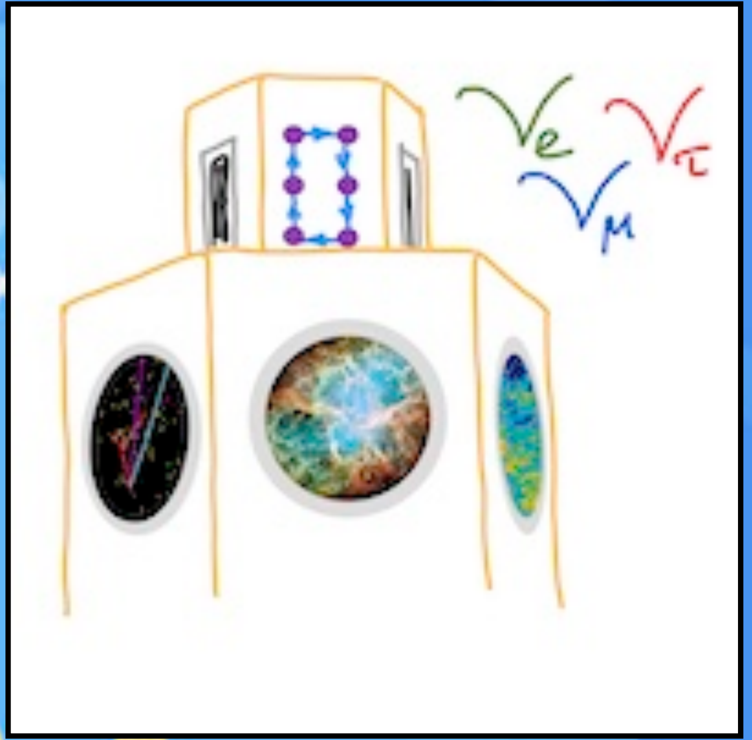

Neutrinos and New Physics
High School Physics Teachers' Conference at KITP
26 March 2022

Artwork by Sandbox Studio

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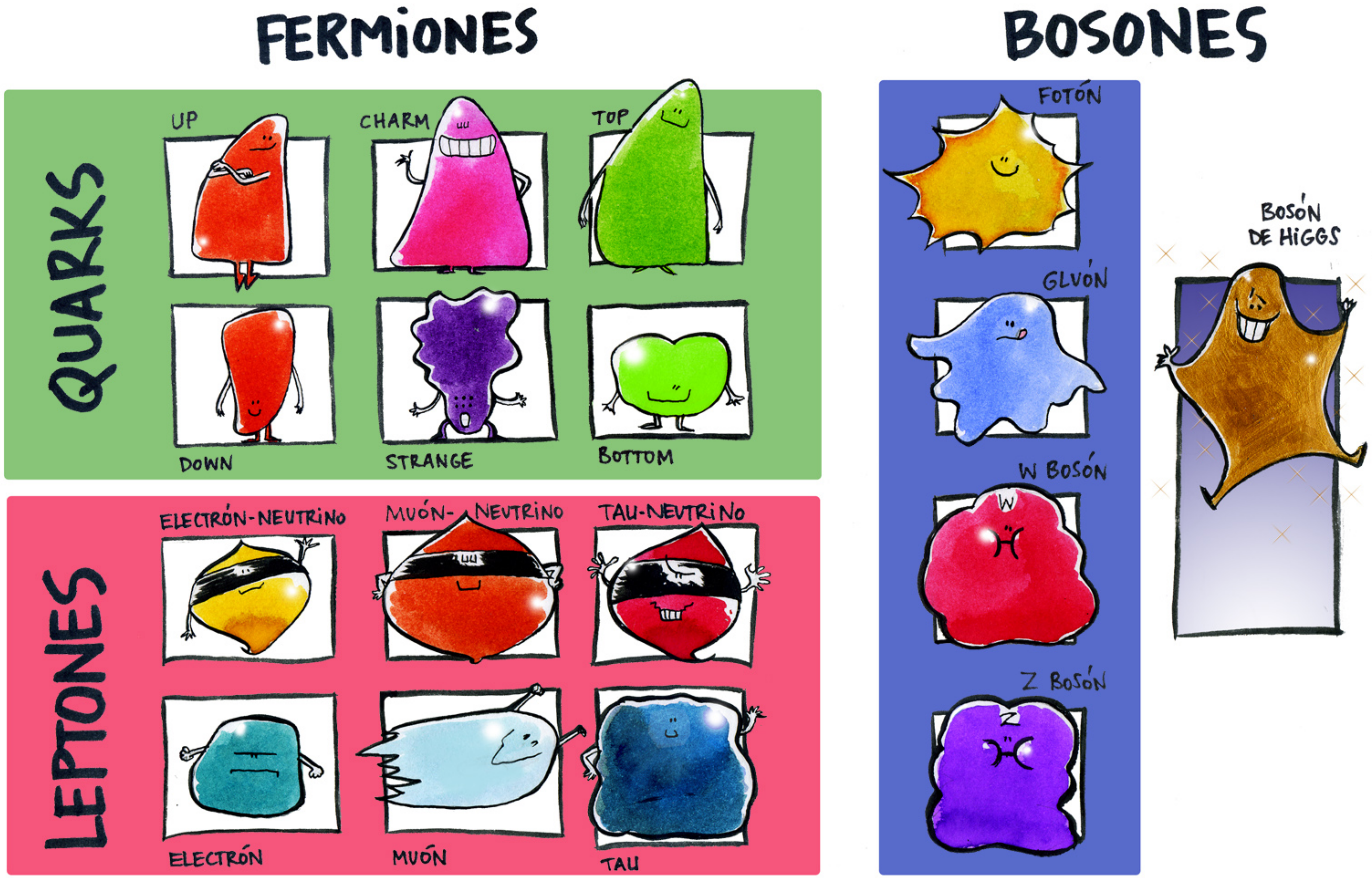
FERMIONES
BOSONES
QUARKS
UP
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BOTTOM
LEPTONES
ELECTRÓN-NEUTRINO
MUÓN-NEUTRINO
TAU-NEUTRINO
ELECTRÓN
MUÓN
TAU
FOTÓN
GLUÓN
W BOSÓN
Z BOSÓN
BOSÓN DE HIGGS

Neutrinos

1


4000 neutrinos per second

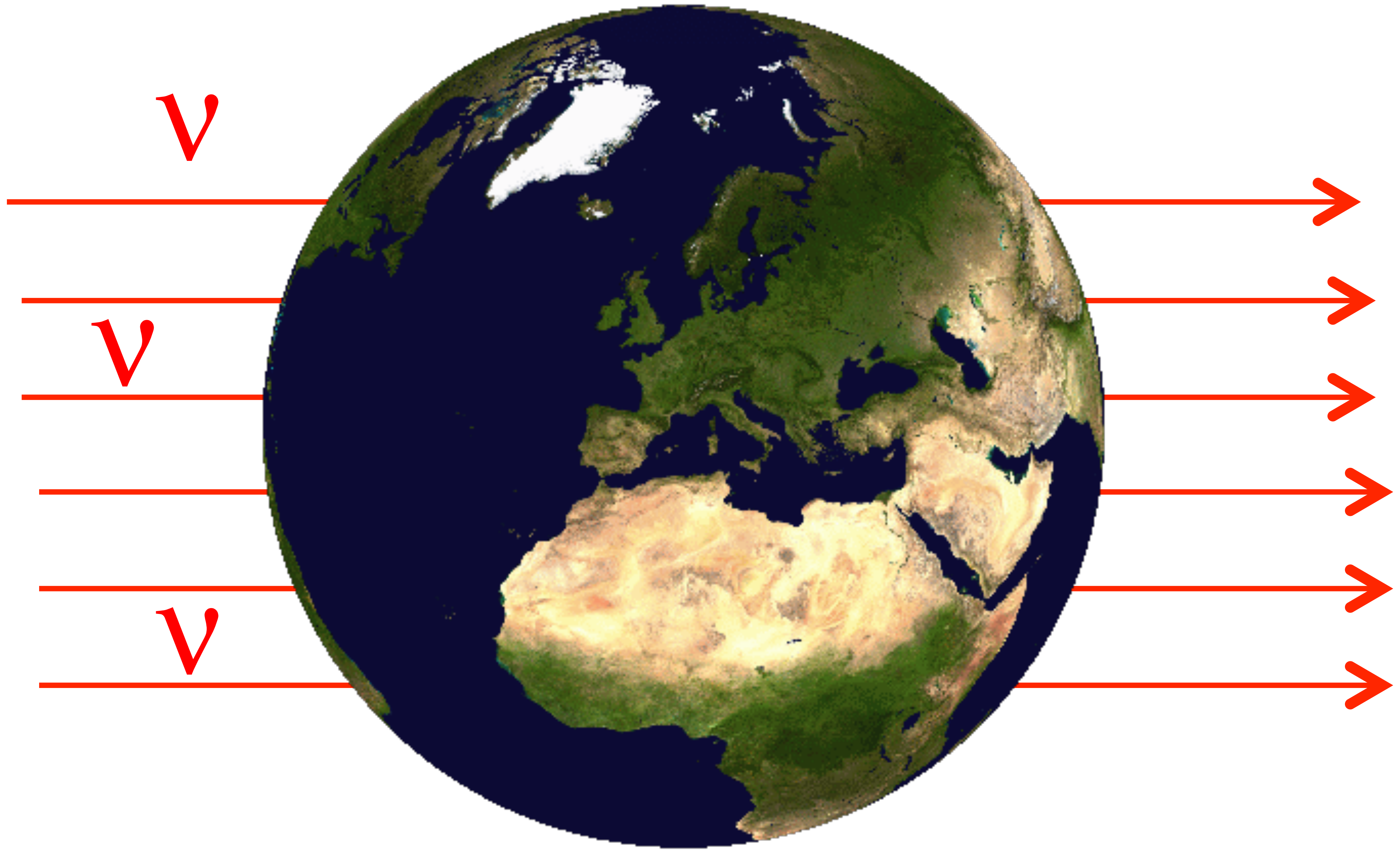

65 billion neutrinos
per cm² per second


Several billion neutrinos
in 10 seconds


300 relic neutrinos per cm3

Neutrinos constantly bombard us...

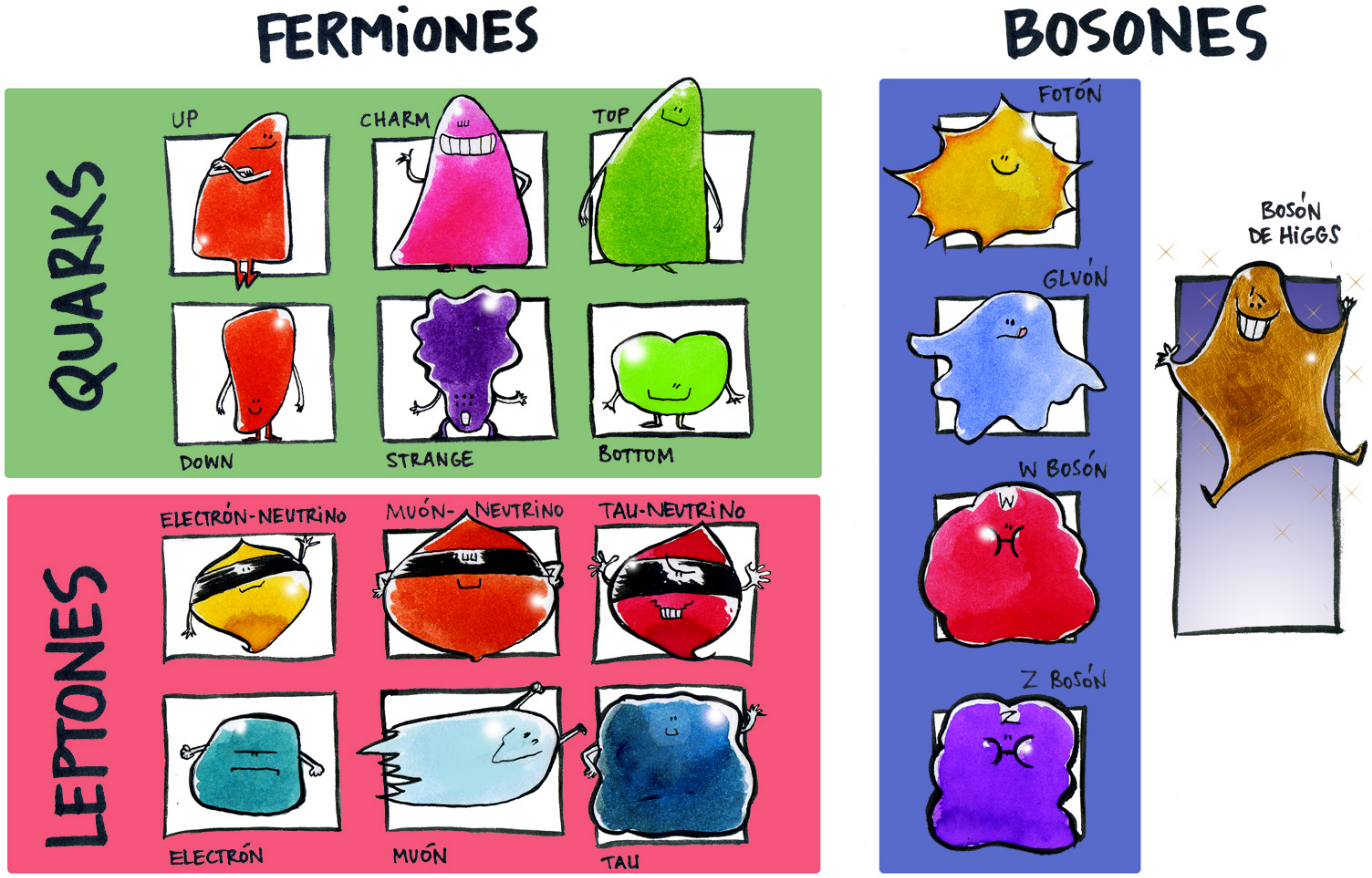
...BUT... they are harmless...



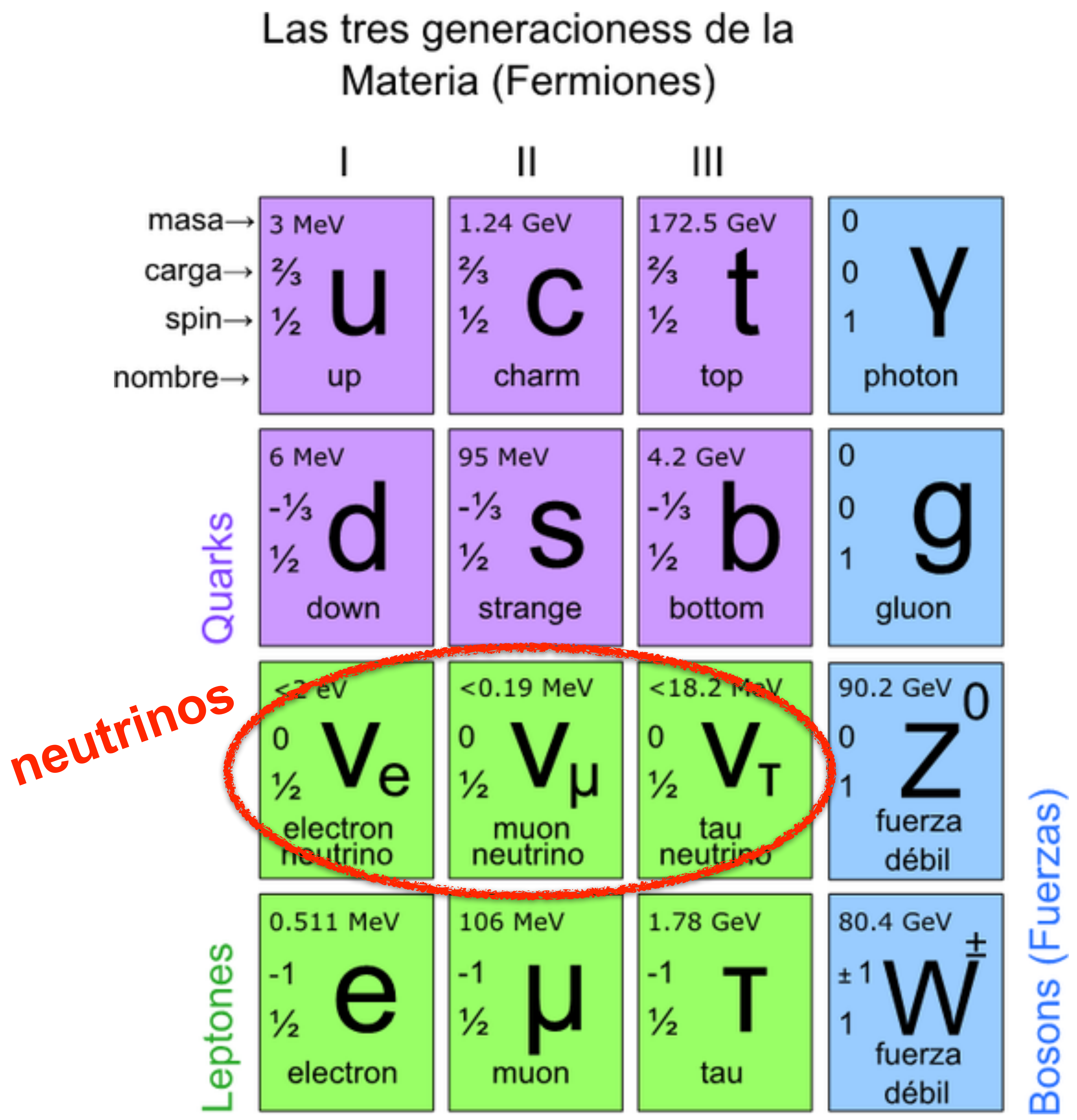
Only 1 neutrino in several billions is intercepted when traversing the Earth

Neutral particles, almost impossible to catch them, traverse all media and they are extremely abundant

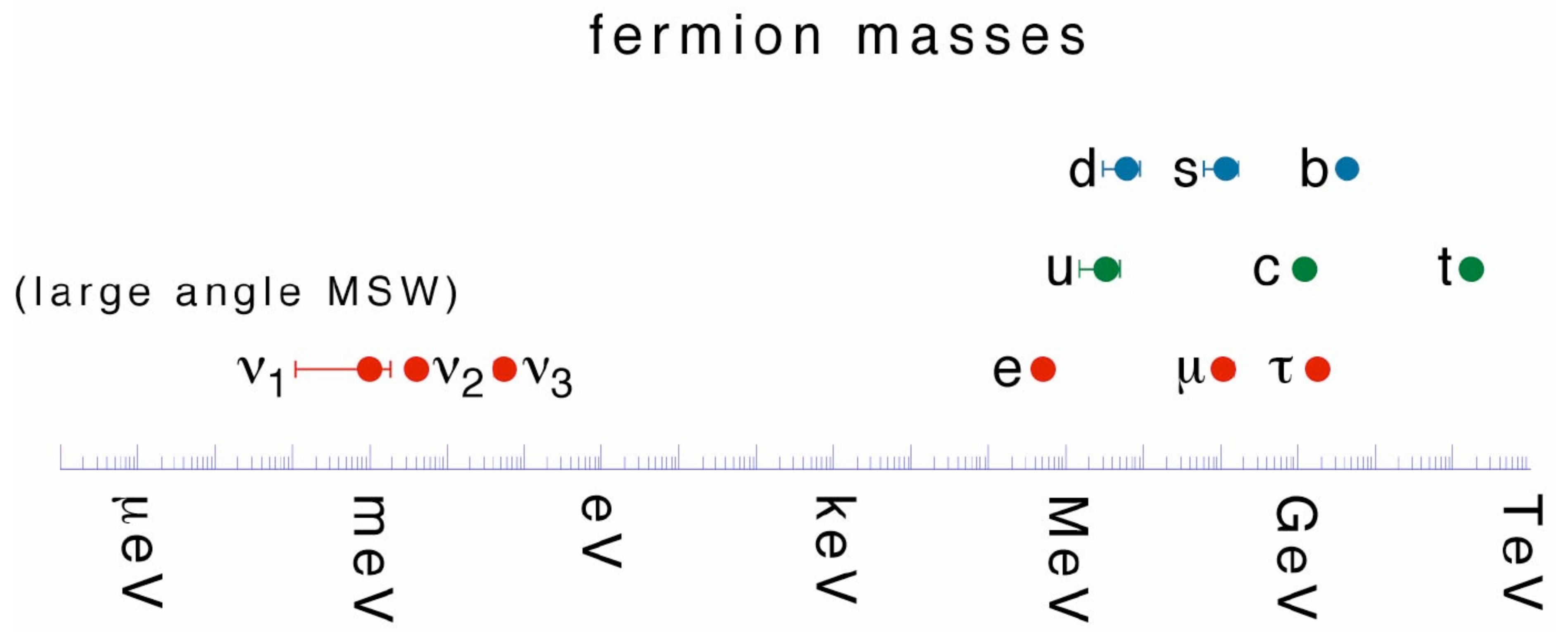
Standard Model of Particles



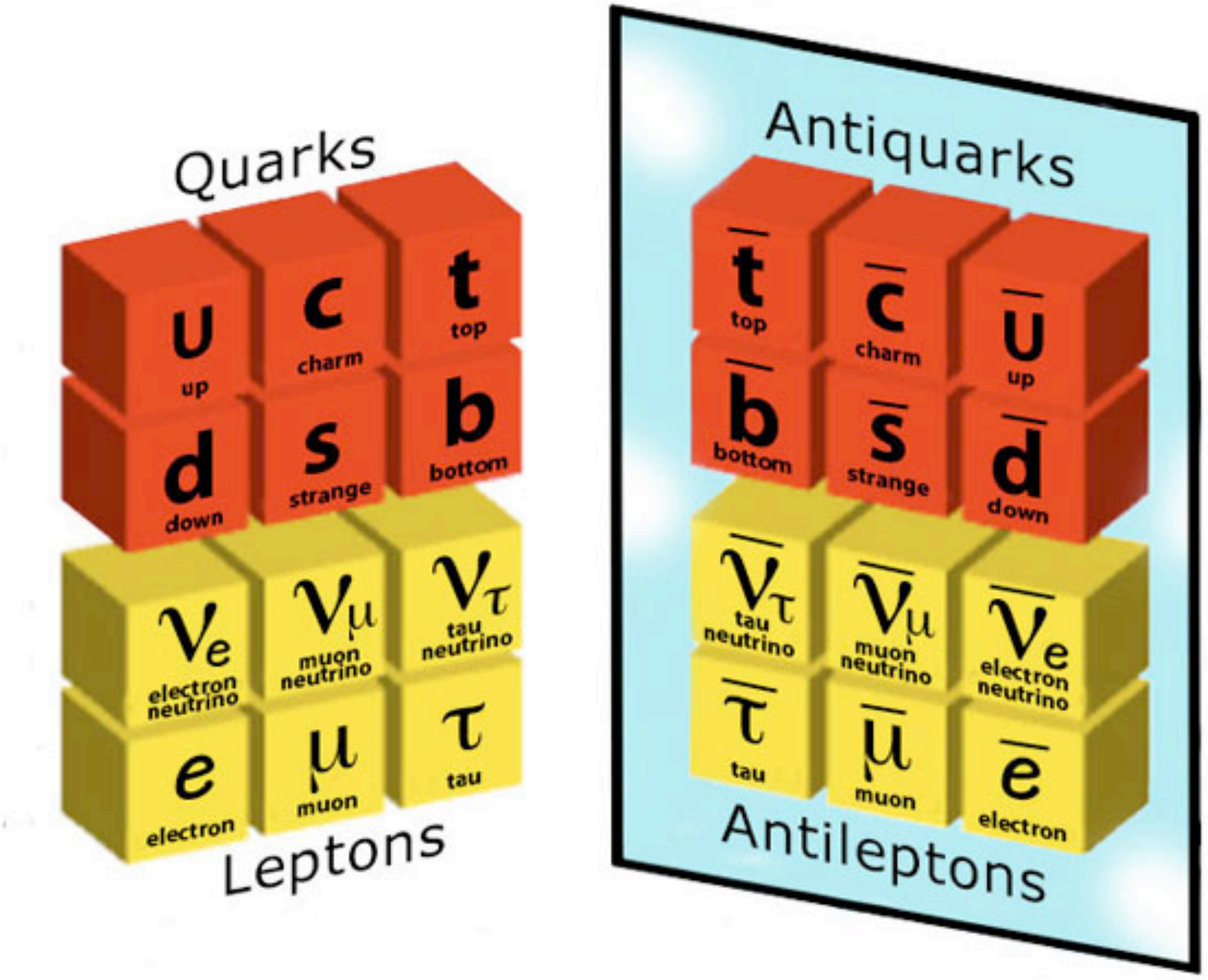
Neutrinos in the Standard Model



- **3 types** of neutrinos (although extra sterile neutrinos beyond the SM could exist)
- They are electrically **neutral** particles
- Much **lighter** than their charged leptonic partners
- **Very weak interaction** with matter
- Together with photons, they are the most **abundant** elementary particles in the Universe



Antiparticles

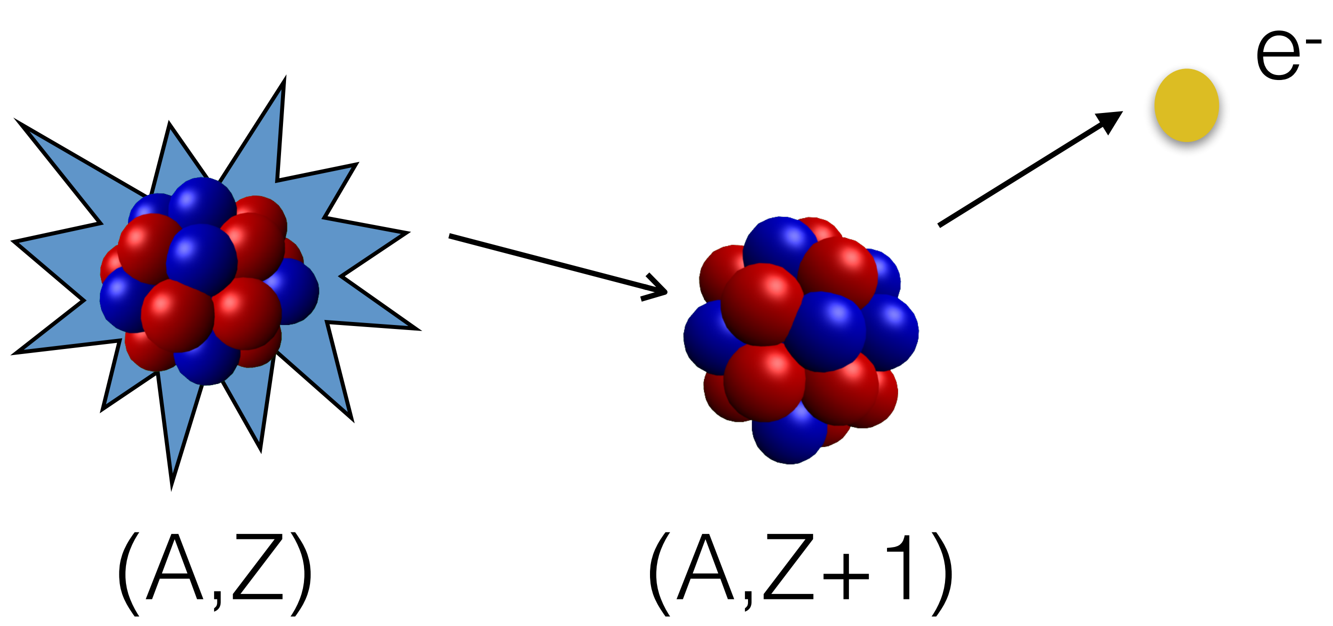


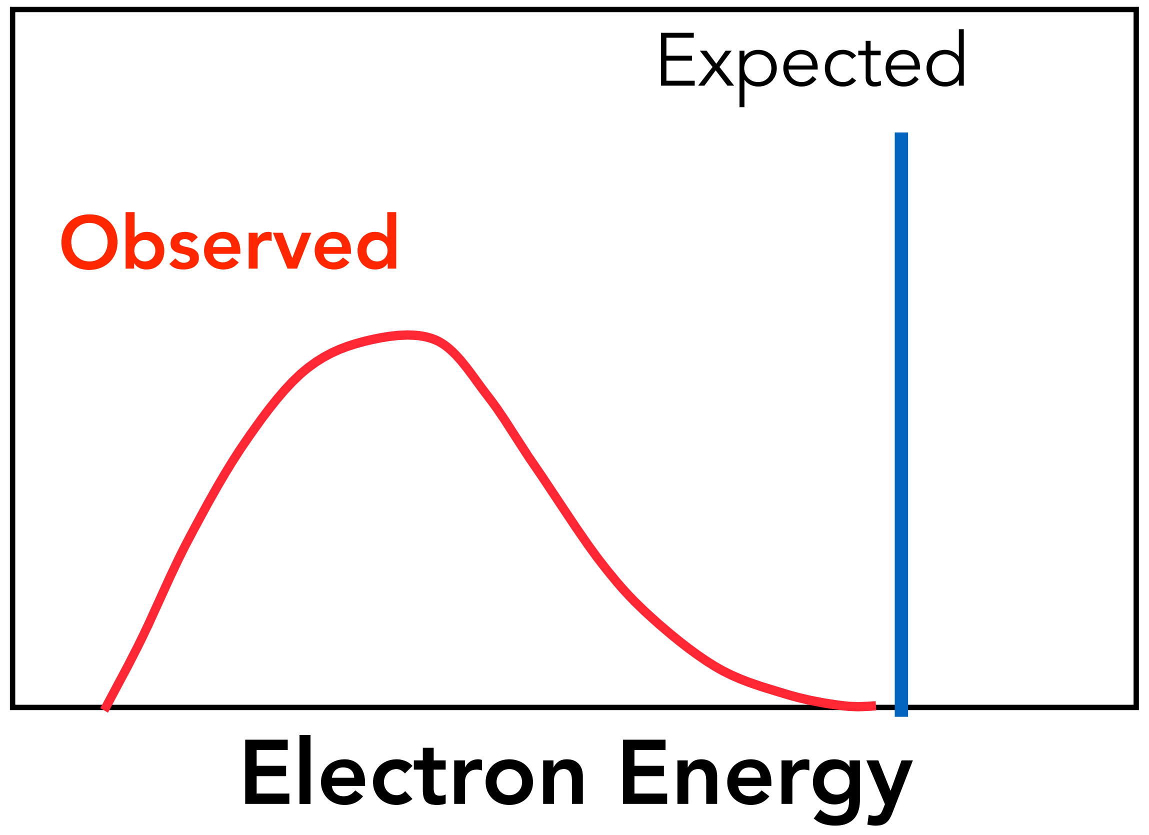
- Dirac neutrinos: particle ≠ antiparticle
- Majorana neutrinos: particle = antiparticle

- For each particle, there is an associated **antiparticle** with **the same mass** and **opposite charge**
- Antiparticles are produced in natural processes (as radioactive decays) and particle accelerators
- Neutrinos **could be their own antiparticles**
- Equals amounts of particles and antiparticles were created after the Big Bang
  - Where are the antiparticles?
  - Why are we made of matter?

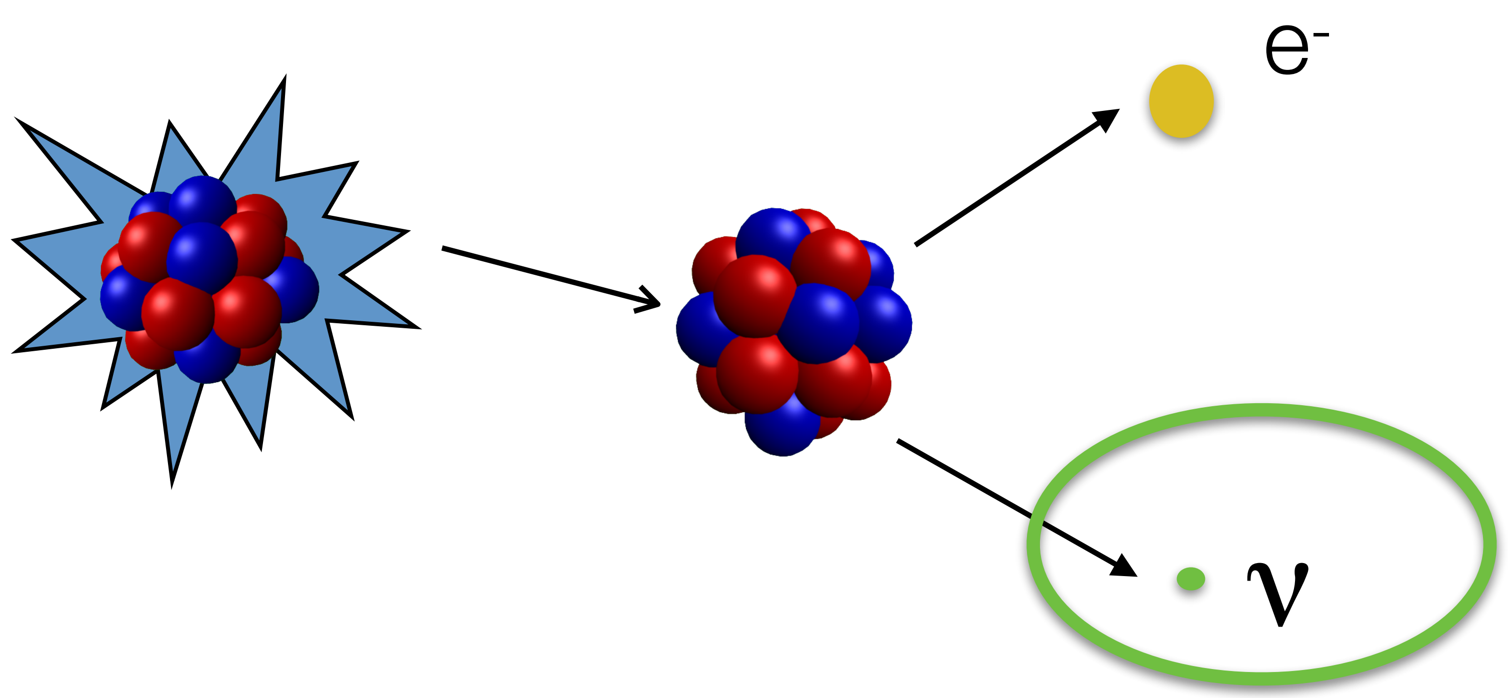
How were they discovered?

- Pauli proposed the existence of neutrinos in 1930 as a *desperate remedy* to solve the beta radioactivity "problem"
- In a **two-body emission**, the **electron energy** has a **fixed value** (energy conservation)



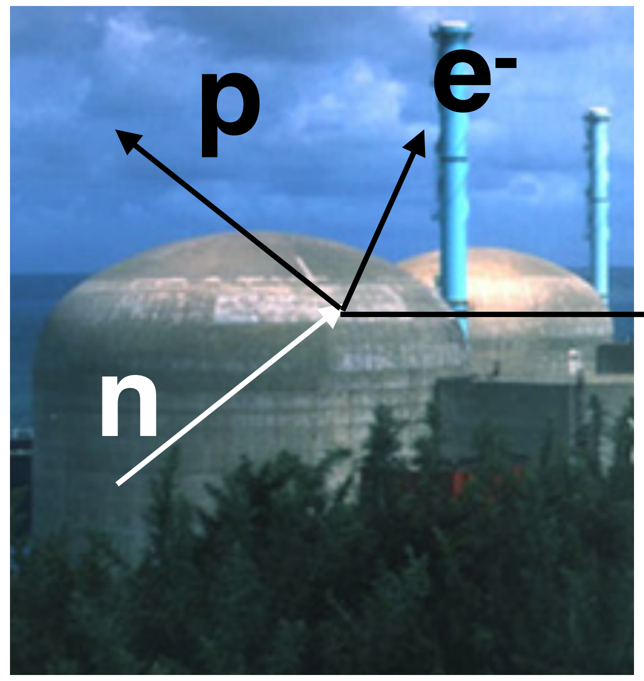


- The beta radioactivity presents an **anomaly**
- **Pauli**: "There is a neutral particle able to cross all detectors without leaving any trace and carrying all the missing energy"
- In 1934 **Fermi** builds a new theory to explain the beta decay and names the new particle "neutrino"



The neutrino discovery (1956)

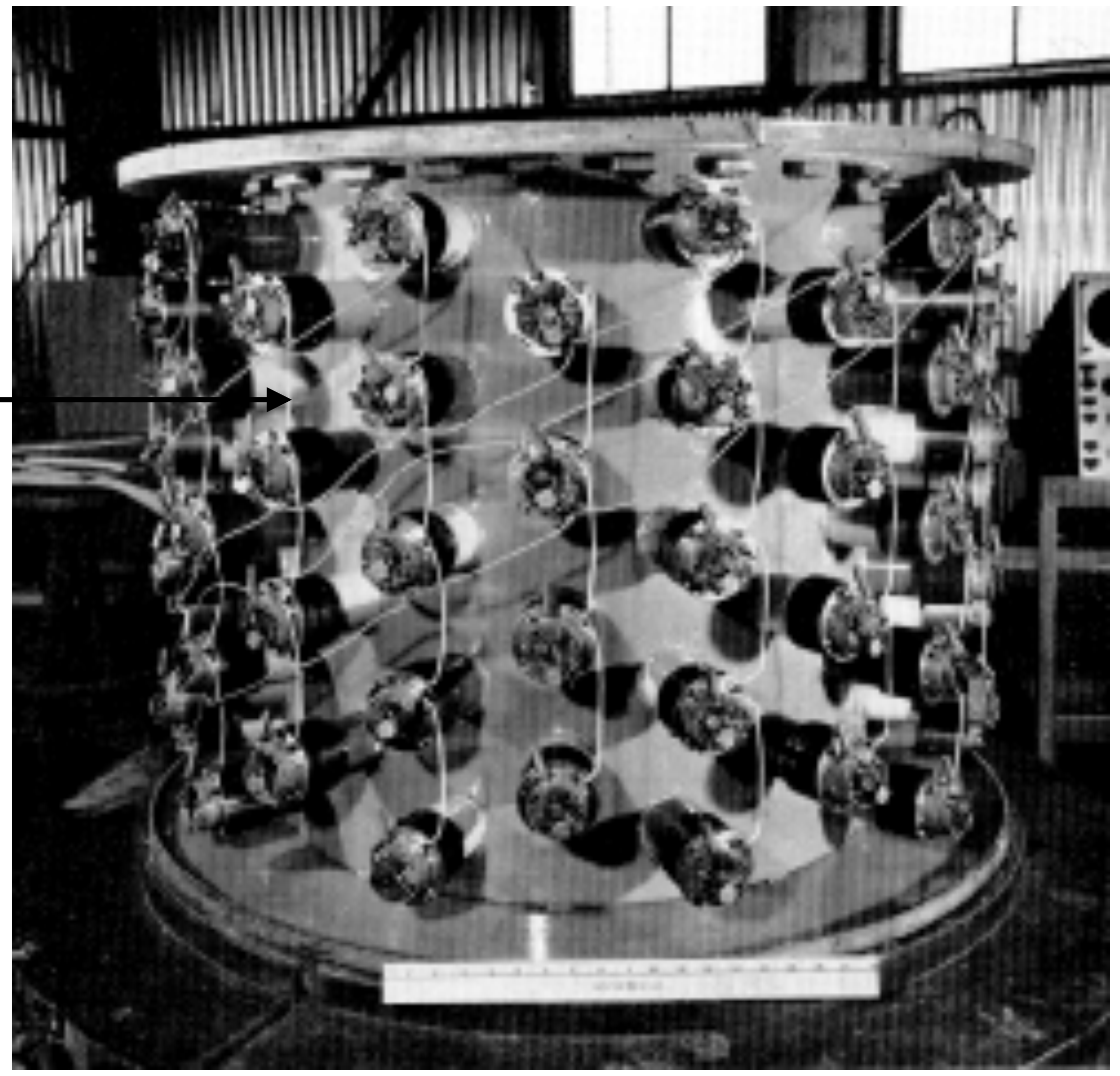
Savannah River reactor (US)



$\bar{\nu}_e$

distance traveled = ~meters

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

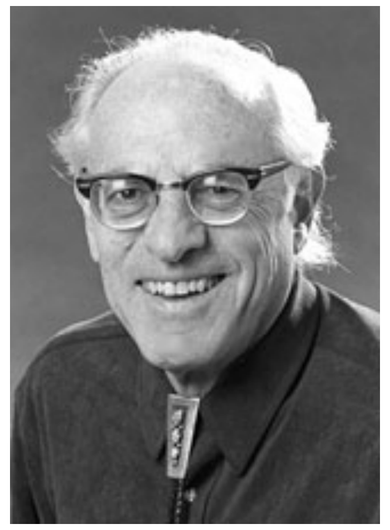


$$^{235}U + n_{th} \rightarrow X + Y \rightarrow \beta - decay$$

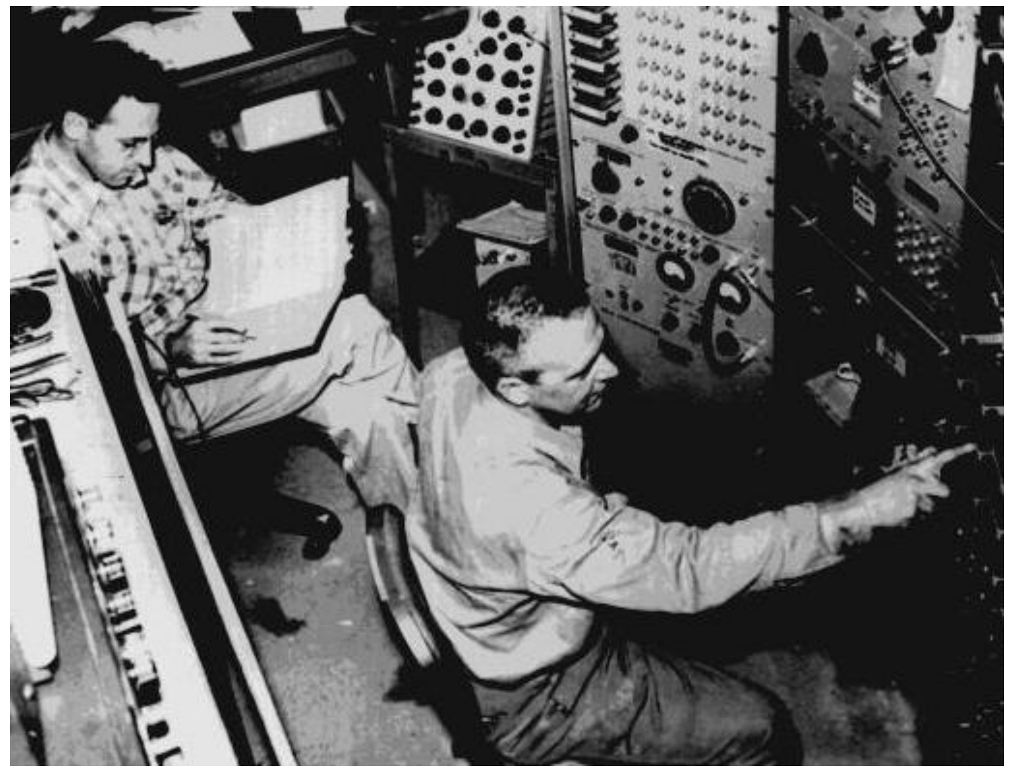
Neutrino production in the nuclear reactor cores

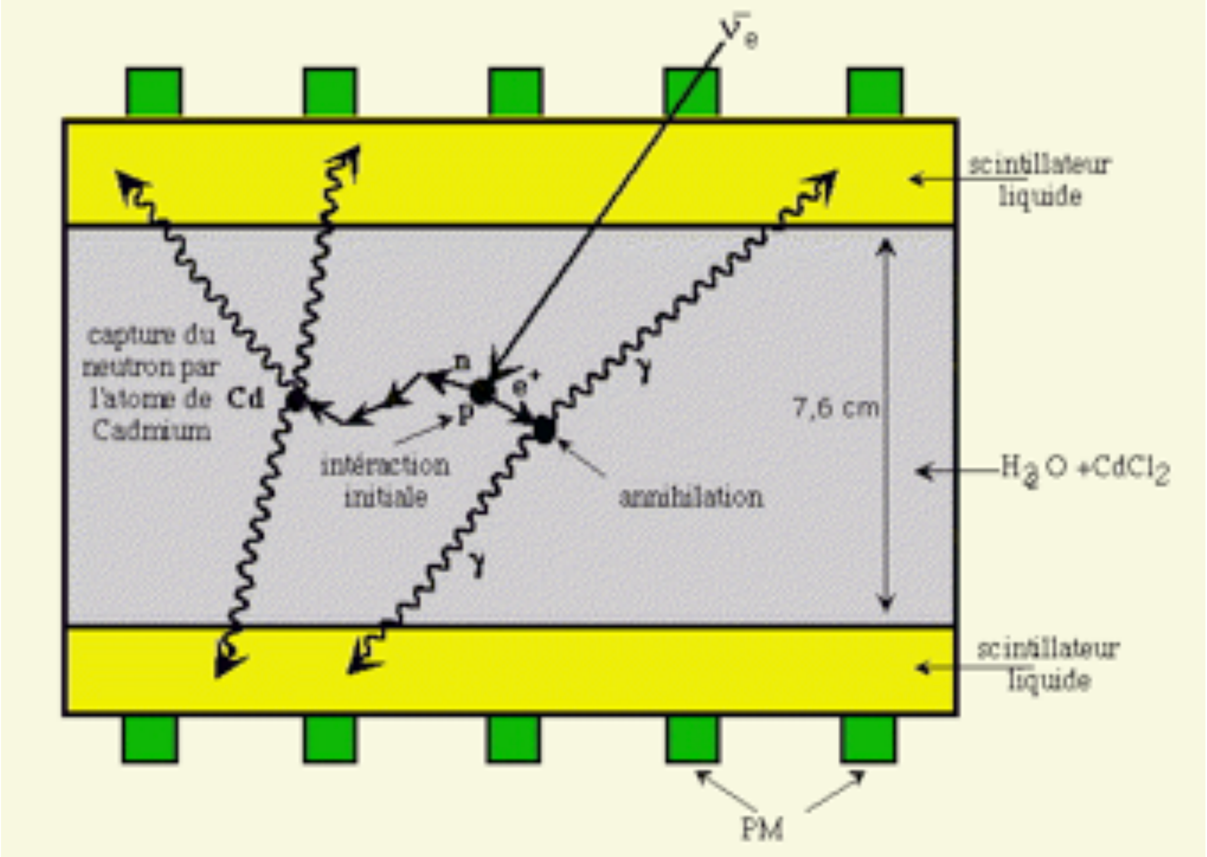
Neutrino detection in 1 m³ liquid scintillator (~3 ν/h)

Cowan **Reines**



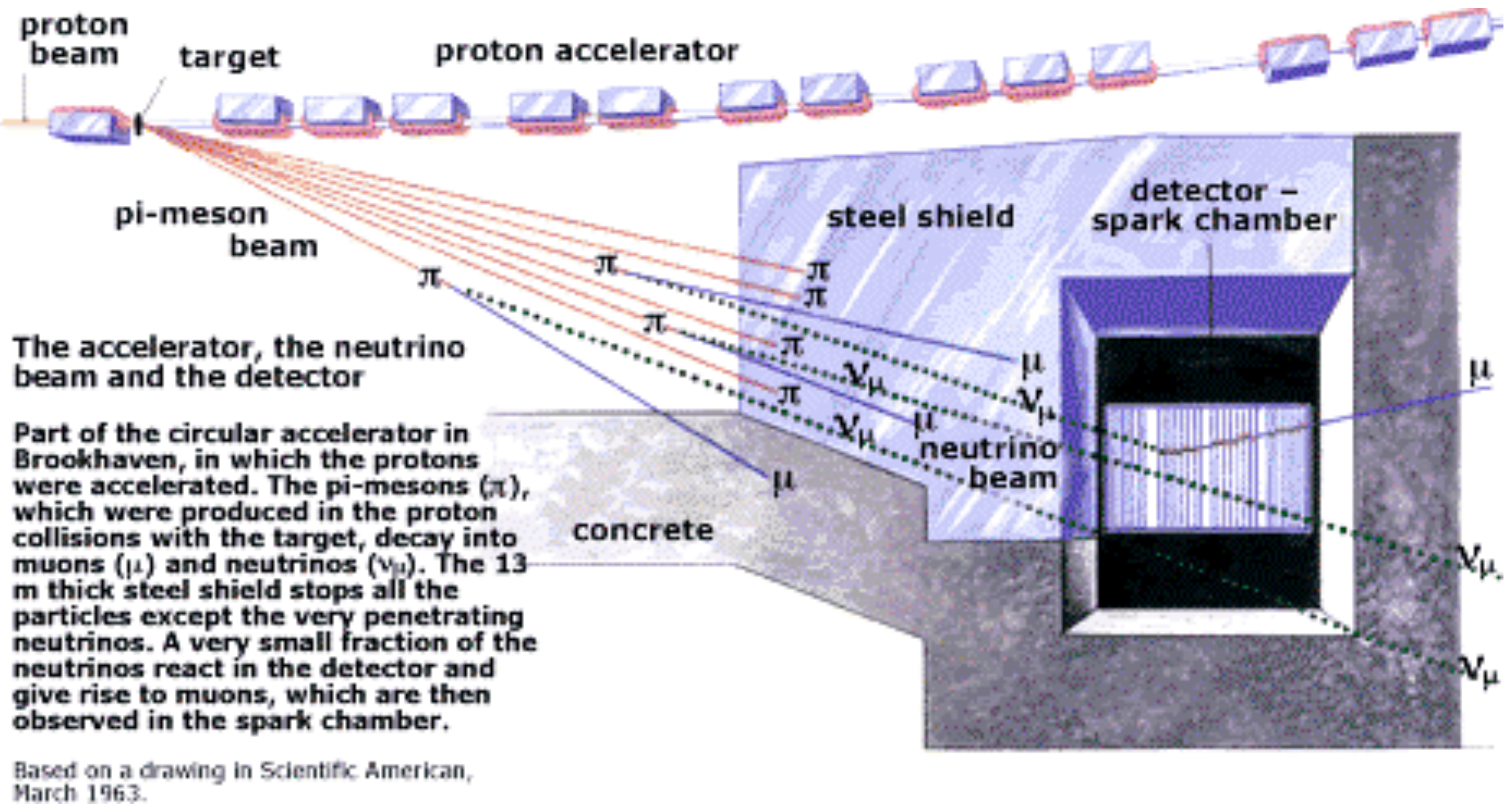
Nobel Prize in Physics in 1995





Later discoveries

- **1962: ν_μ observed in Brookhaven (US)**
  - First accelerator neutrino experiment
  - Discovery of a *second type of neutrino* (muon)

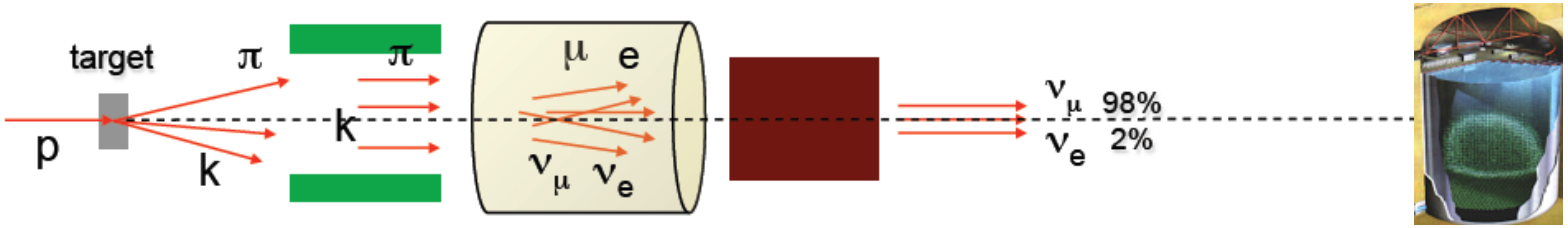


Lederman *Schwartz* *Steinberger*

Nobel Prize in Physics in 1988

- Much later, in **2000**, the *third type of neutrino* $\boldsymbol{\nu_\tau}$ (tau) was discovered by the DONUT experiment at Fermilab (US)

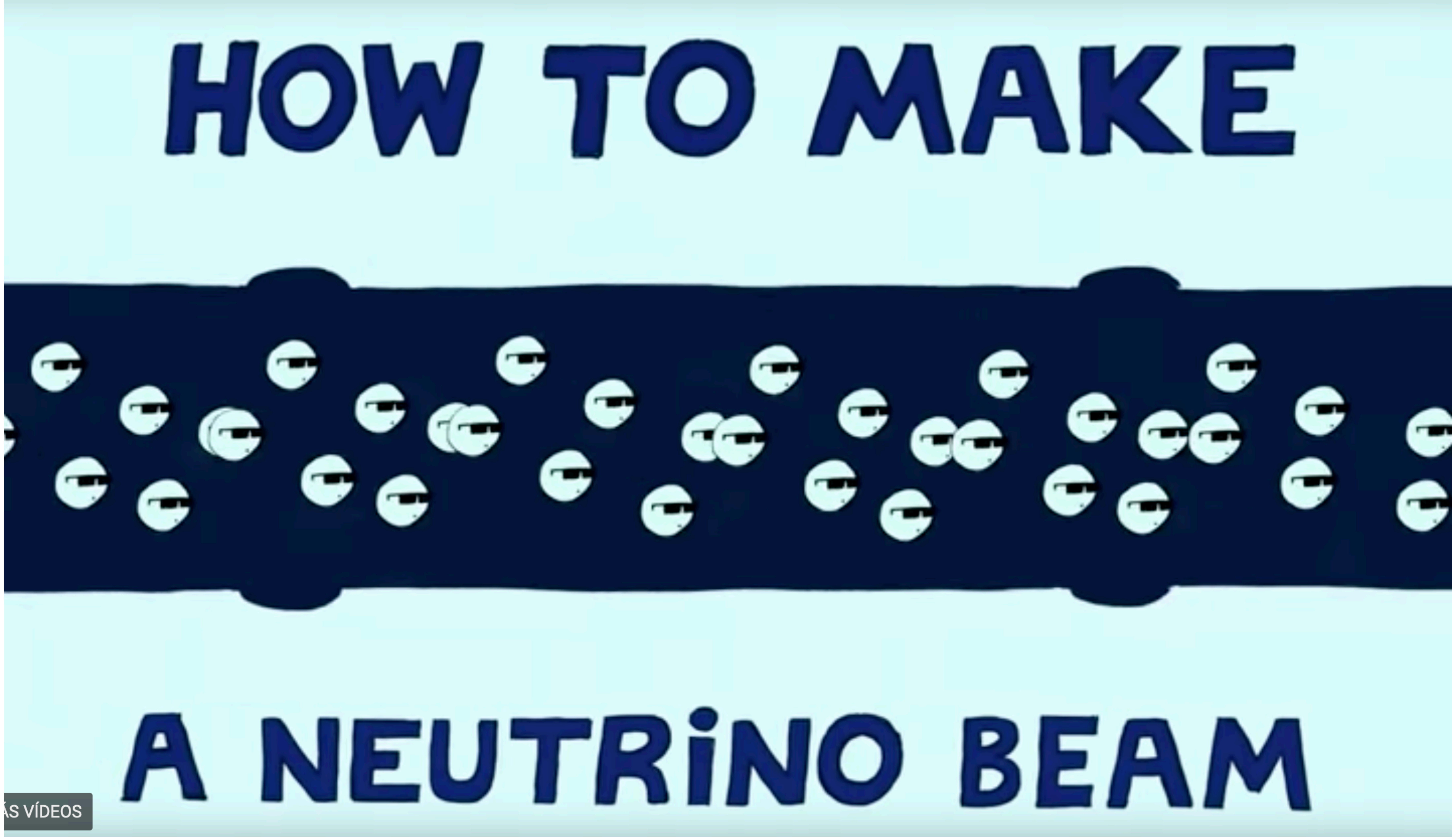
Neutrino from accelerators



- It is possible to create an **intense beam of neutrinos** from an **intense beam of protons**

- ***Advantages:***
  - the beam can be *switched on and off* to know when we have neutrinos and when not (signal over background events)
  - the neutrino energy can be selected (within a certain range)

- ***Disadvantages:***
  - the neutrino beam is not pure (several types of neutrinos are produced)
  - the flux is not very large
  - it is expensive!



https://youtu.be/U_xWDWKq1CM

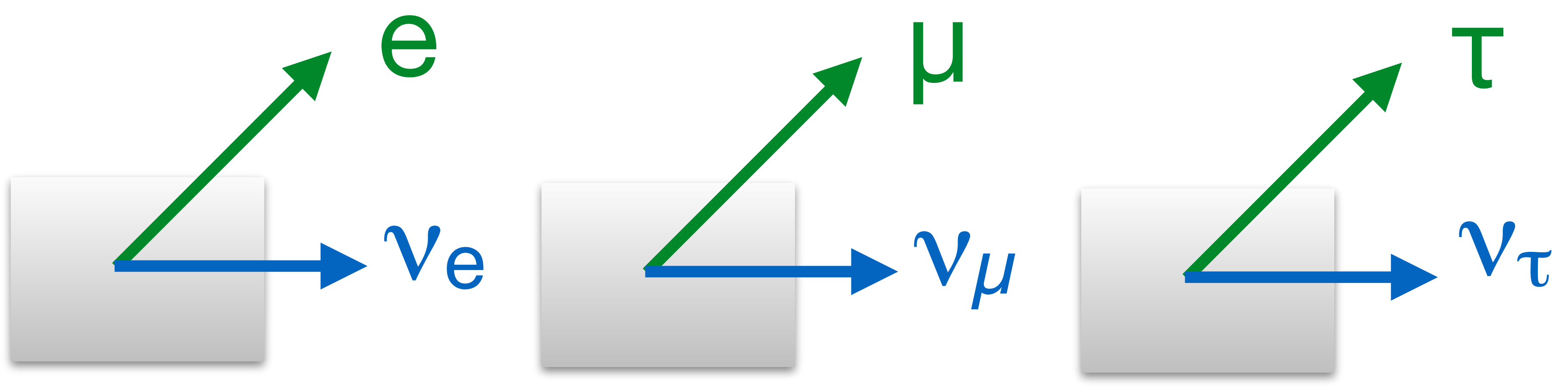
What do neutrinos look like?

Neutrino interactions

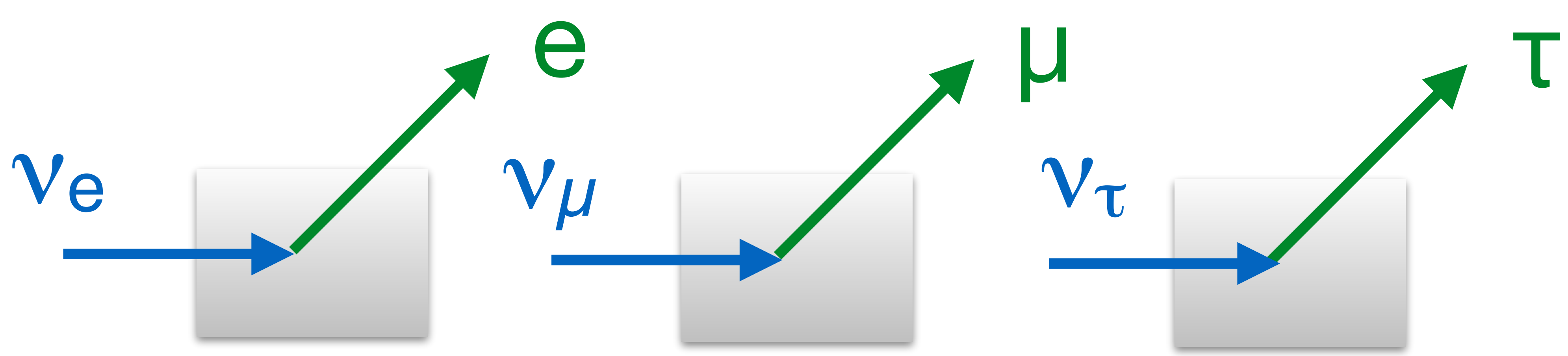
- ***Magnitud:***
  - A GeV **proton** travels **10 cm in lead**!!
  - Neutrinos produced by accelerators (~GeV) travel (on average) **1.5 x 10^{12} m in lead** before interacting
  - Neutrinos produced by the Sun (~1000 times less energetic ~MeV) travel (on average) **1.5 x 10^{16} m in lead** before interacting

I	II	III
e	μ	τ
ν_e	ν_μ	ν_τ

- Neutrinos only interact with ***members of their own family*** (electron, muon or tau)
- The identification of the partner charged particle allows us to know the type (flavor) of the neutrino

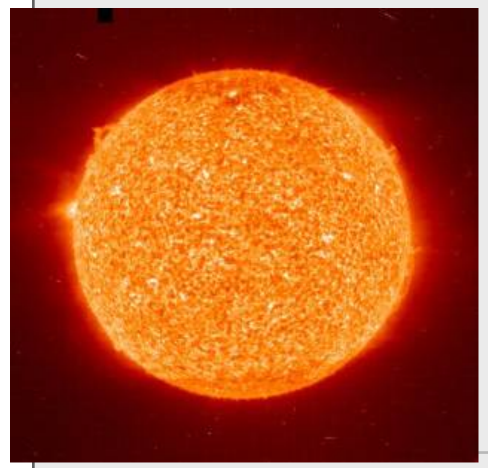
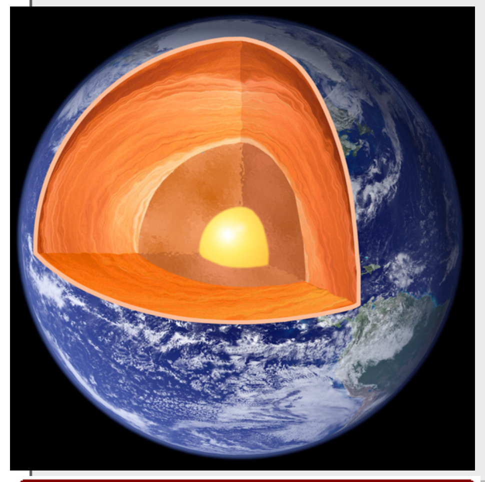
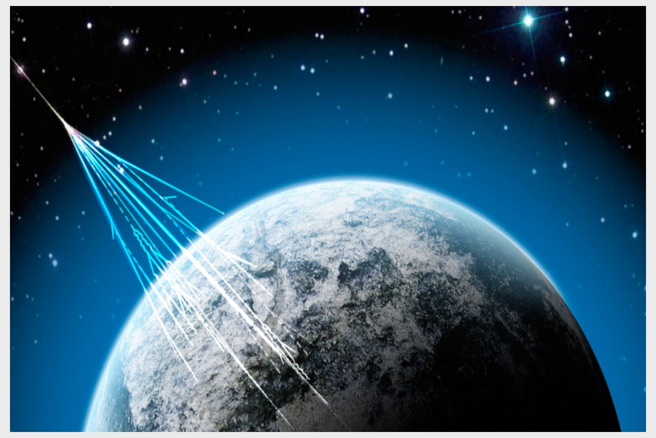
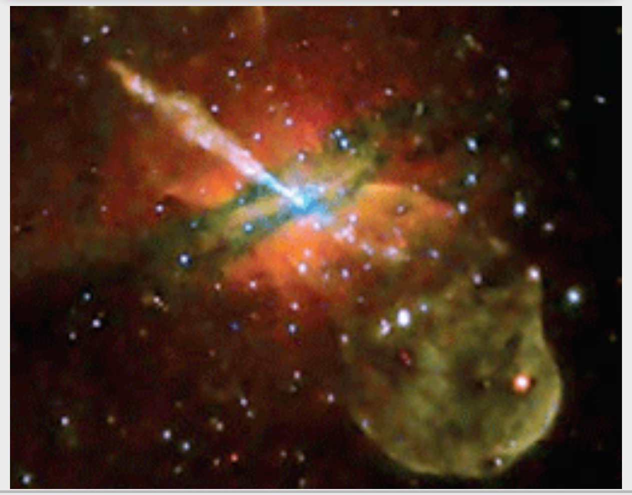


Neutrino appearance

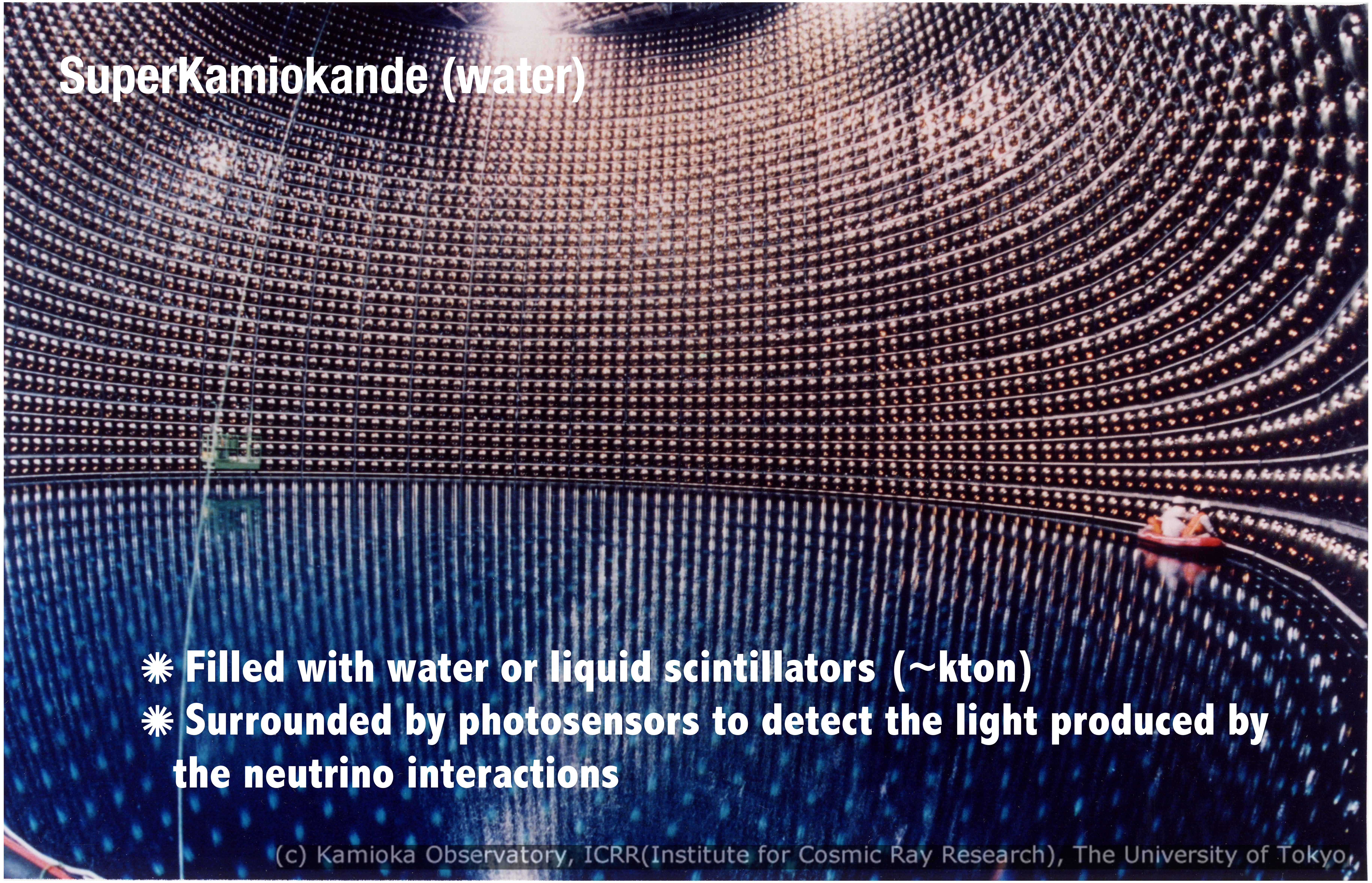


Neutrino disappearance

Neutrino sources

NATURAL		The Sun	ϕ_ν ~65 billion /cm^2 s	E ~ MeV	L ~ 10^8 km
NATURAL		Earth	ϕ_ν ~10^6 /cm^2 s	E ~ MeV	L ~ 10 - 10^3 km
NATURAL		Big Bang	ϕ_ν ~300 /cm^3	E ≲ meV	L ~ Mpc
NATURAL		Atmosphere	ϕ_ν ~ 10^{-2} - 10^{-9} /GeV cm^2 sr s	E ~ GeV-TeV	L ~ 10 - 10^4 km
NATURAL		Supernovae	ϕ_ν ~several billions in 10 sec	E ~ MeV	L ~ kpc- Mpc
NATURAL		Cosmic accelerators		E ~ TeV-PeV	L ~ kpc- Mpc
ARTIFICIAL		Nuclear reactors	ϕ_ν ~2 x 10^{20} /s GW$_{th}$	E ~ MeV	L ~ 1-100 km
ARTIFICIAL		Particle accelerators		E ~ GeV	L ~ 100-1000 km

Neutrino traps: (I) Big detectors



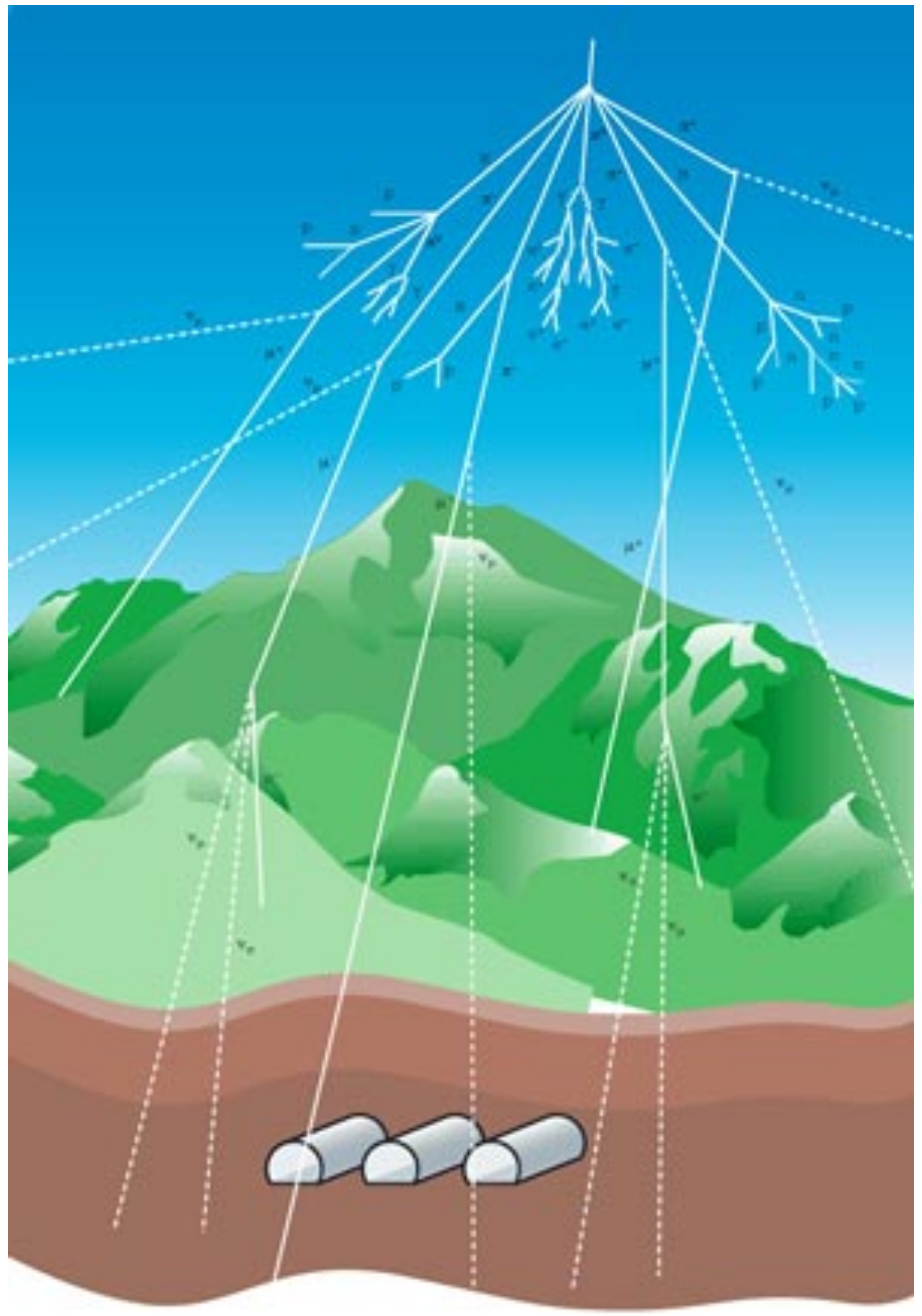
Double Chooz (liquid scintillator)

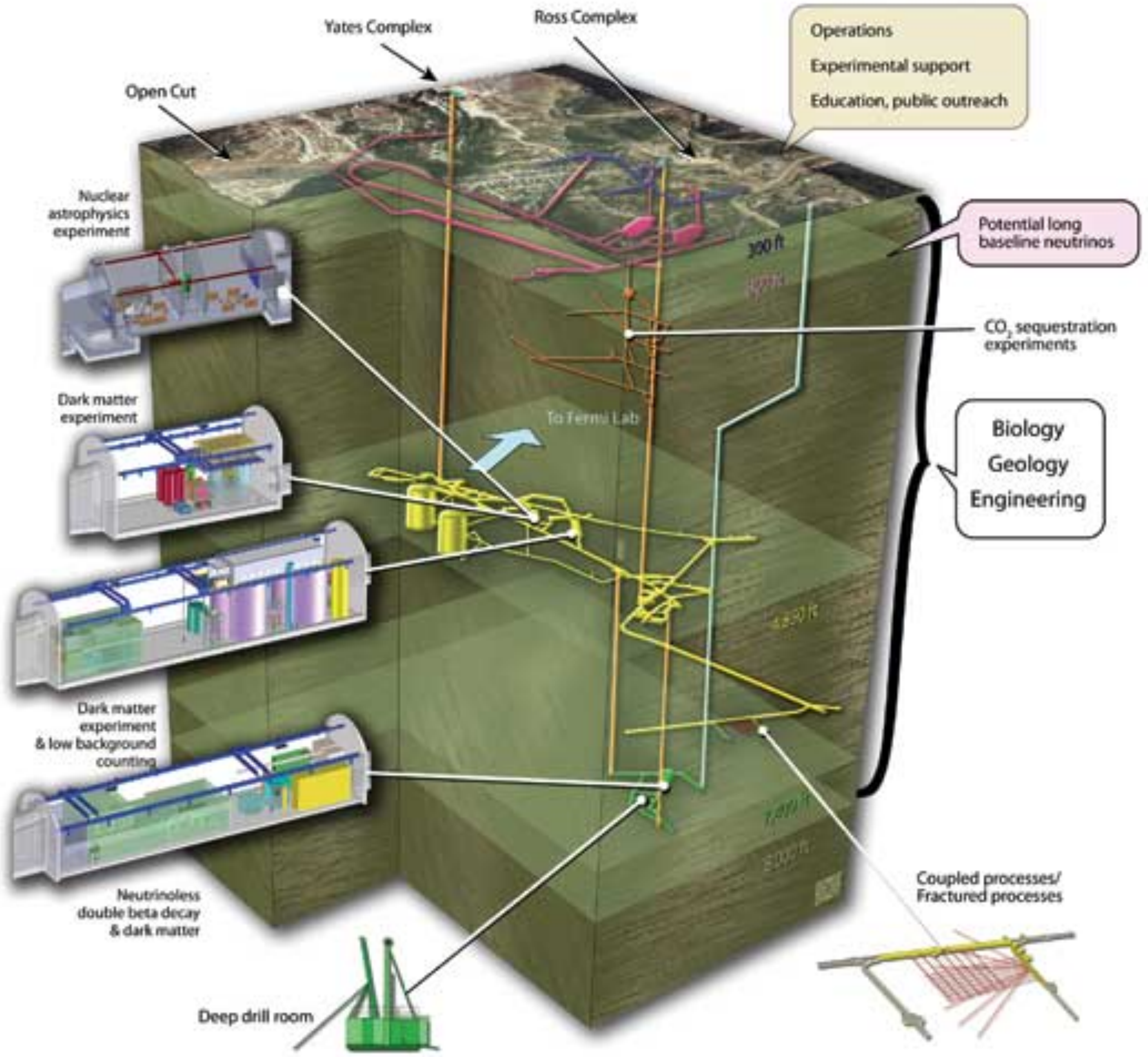
ICARUS (liquid Argon)

IceCube (ice)

Neutrino traps: (II) Underground laboratories

Underground detectors installed in the most deepest mines to be protected from the cosmic rays continuously traversing the Earth





Pictures of real neutrinos

1) Neutrinos in ATLAS/CMS

2) Cherenkov rings

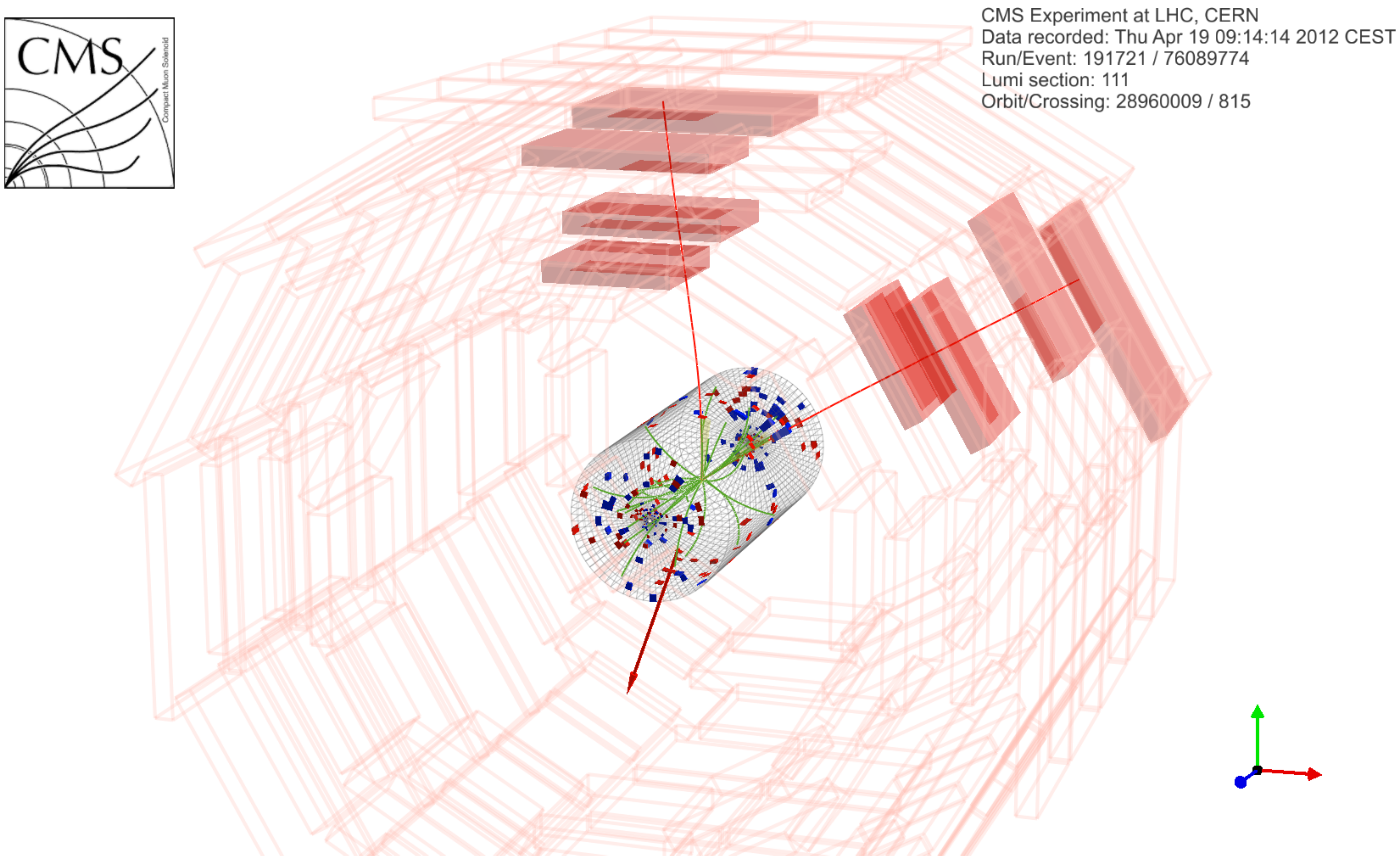
3) PMT hits in liquid scintillators

4) Tracks in T2K

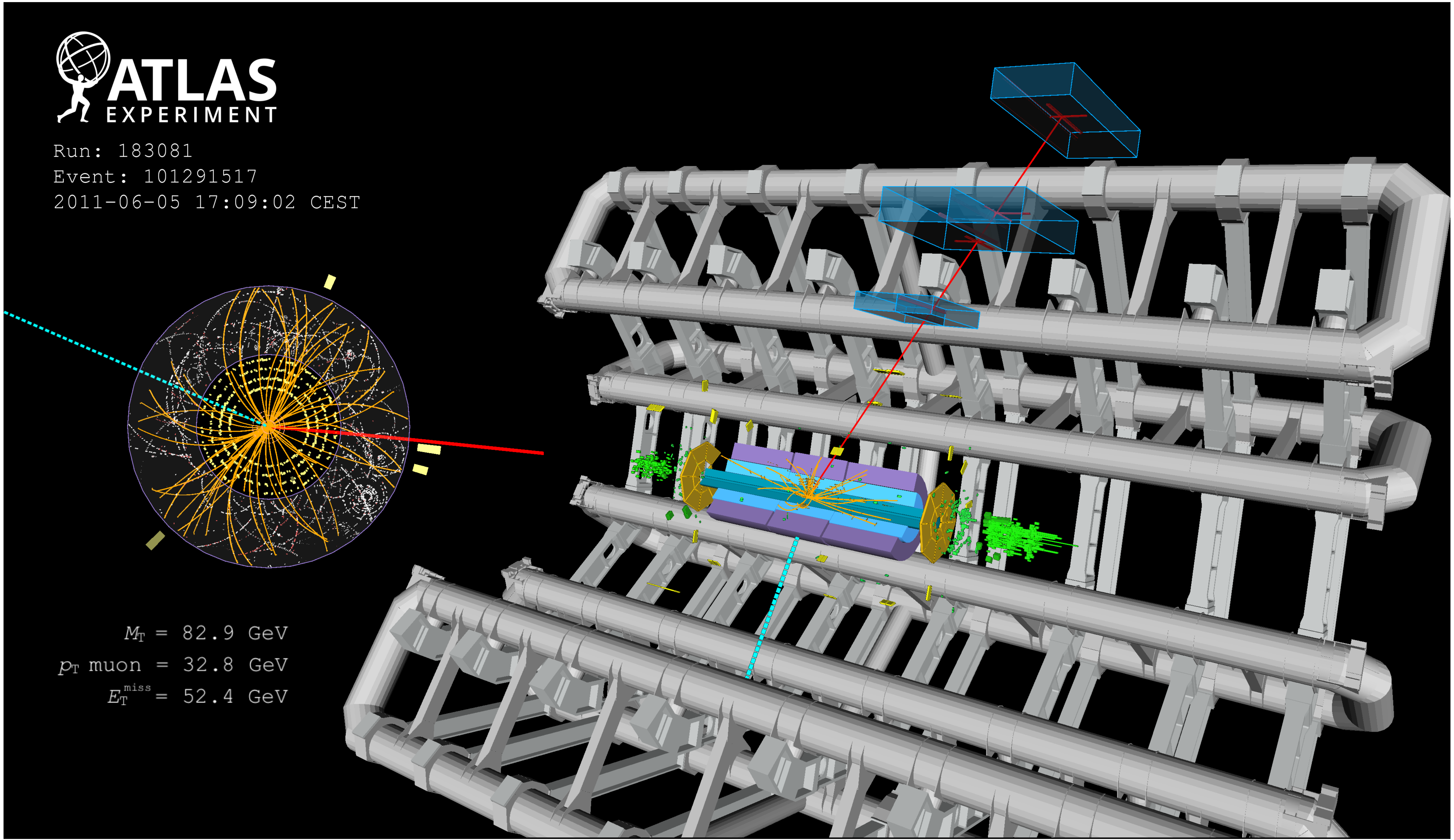
5) Tracks in LAr TPCs

6) Ultra-energetic neutrinos

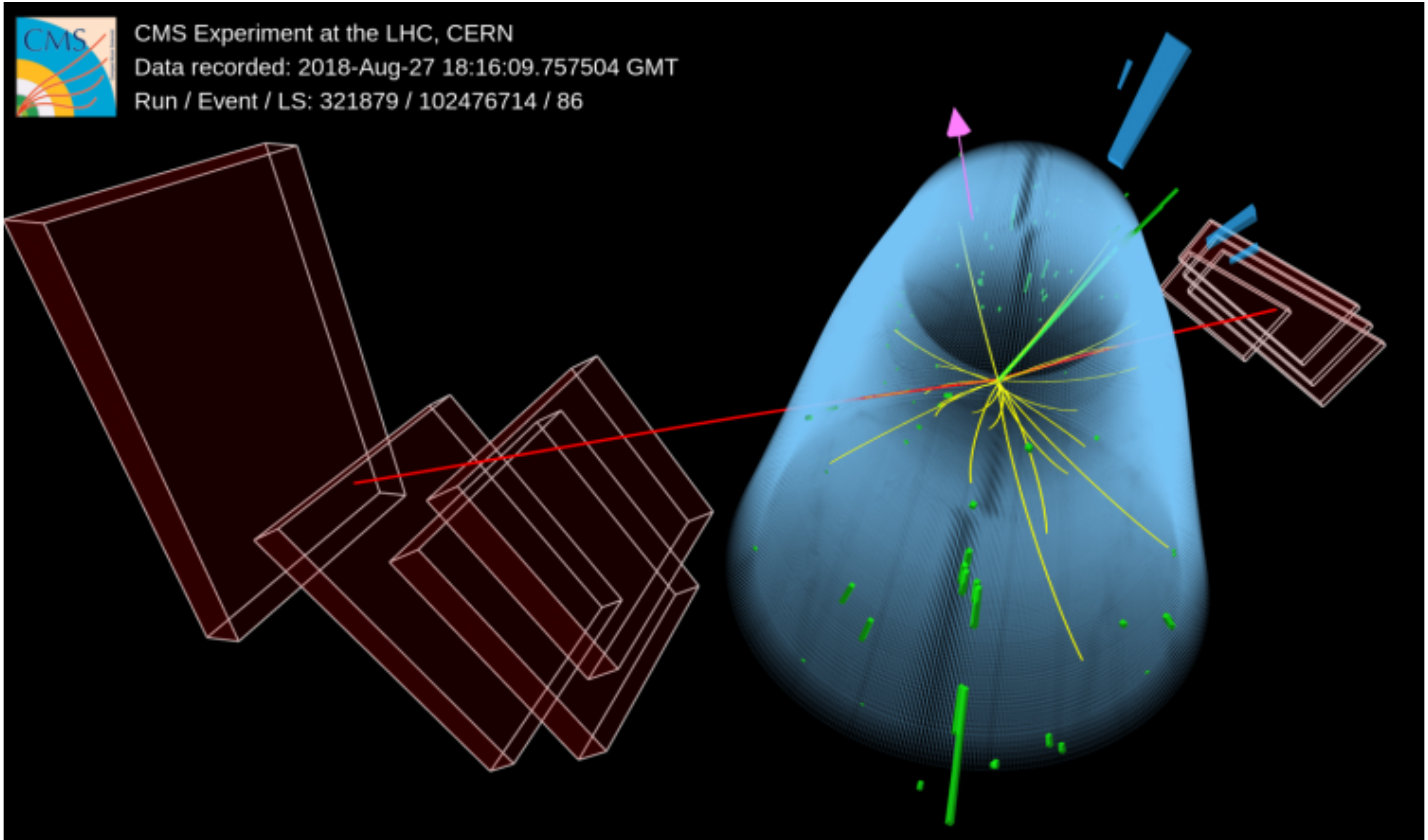
Neutrinos in CMS → INVISIBLES



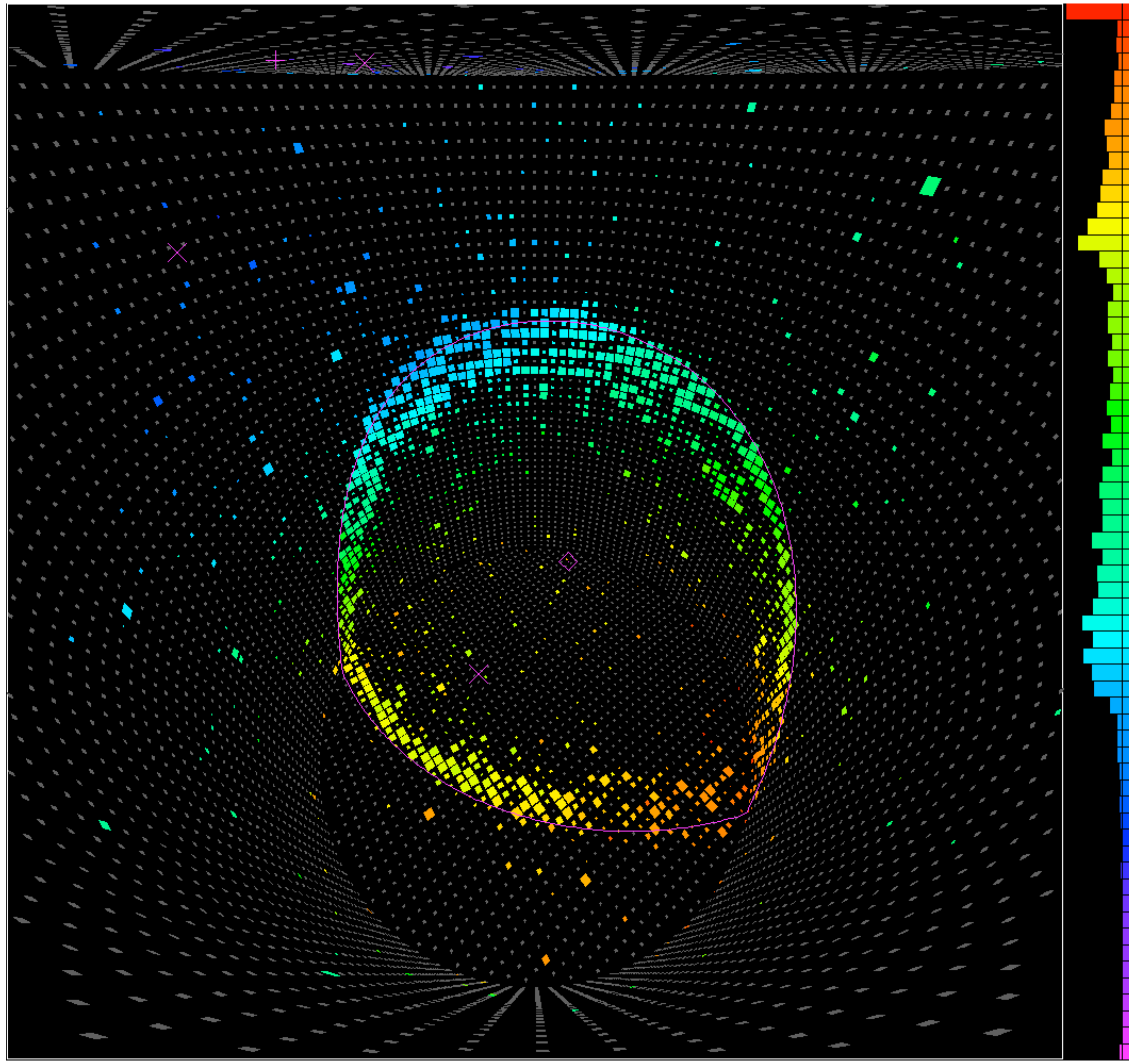
Neutrinos in ATLAS → INVISIBLES



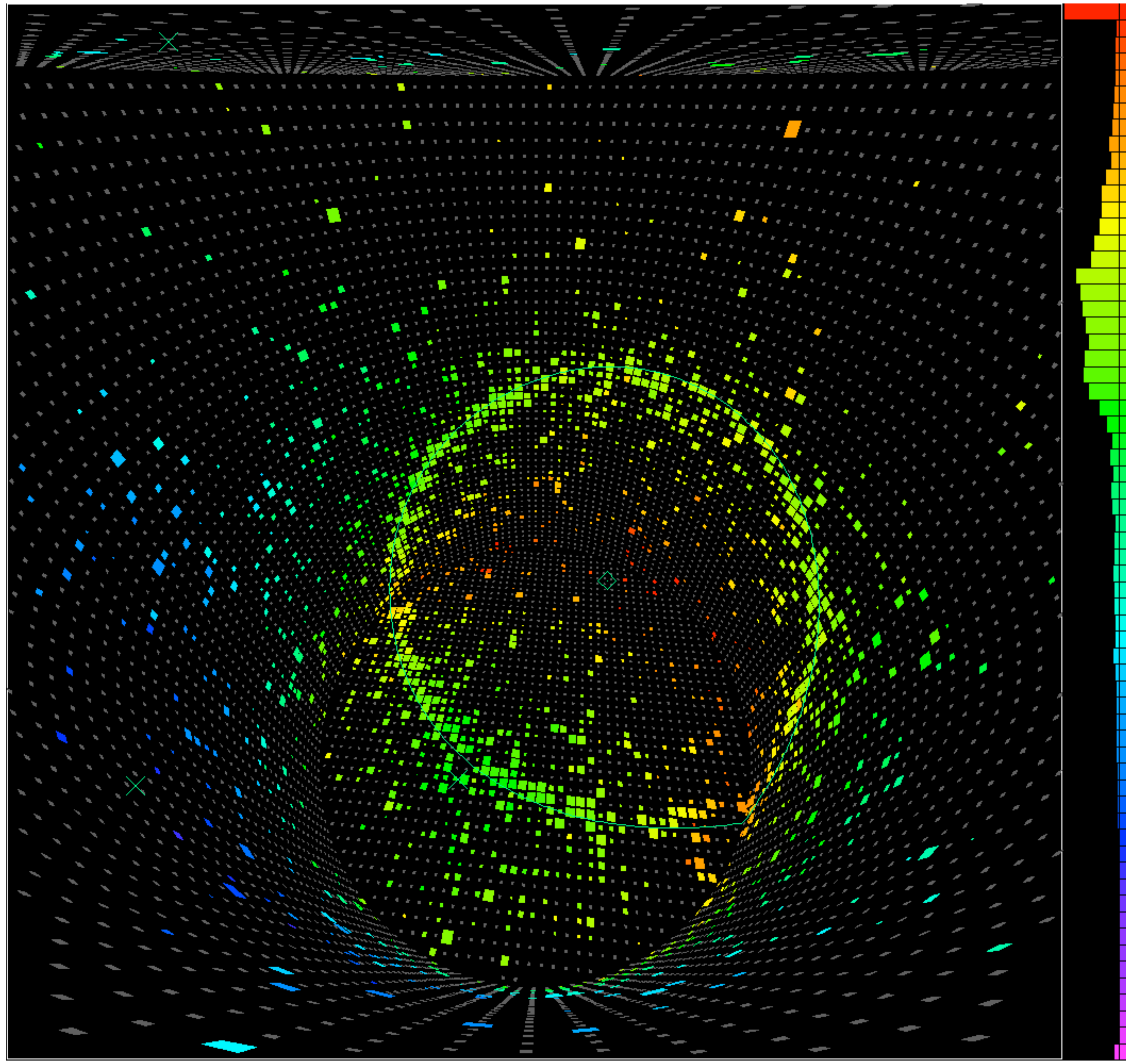
Neutrinos in CMS → INVISIBLES



Cherenkov rings

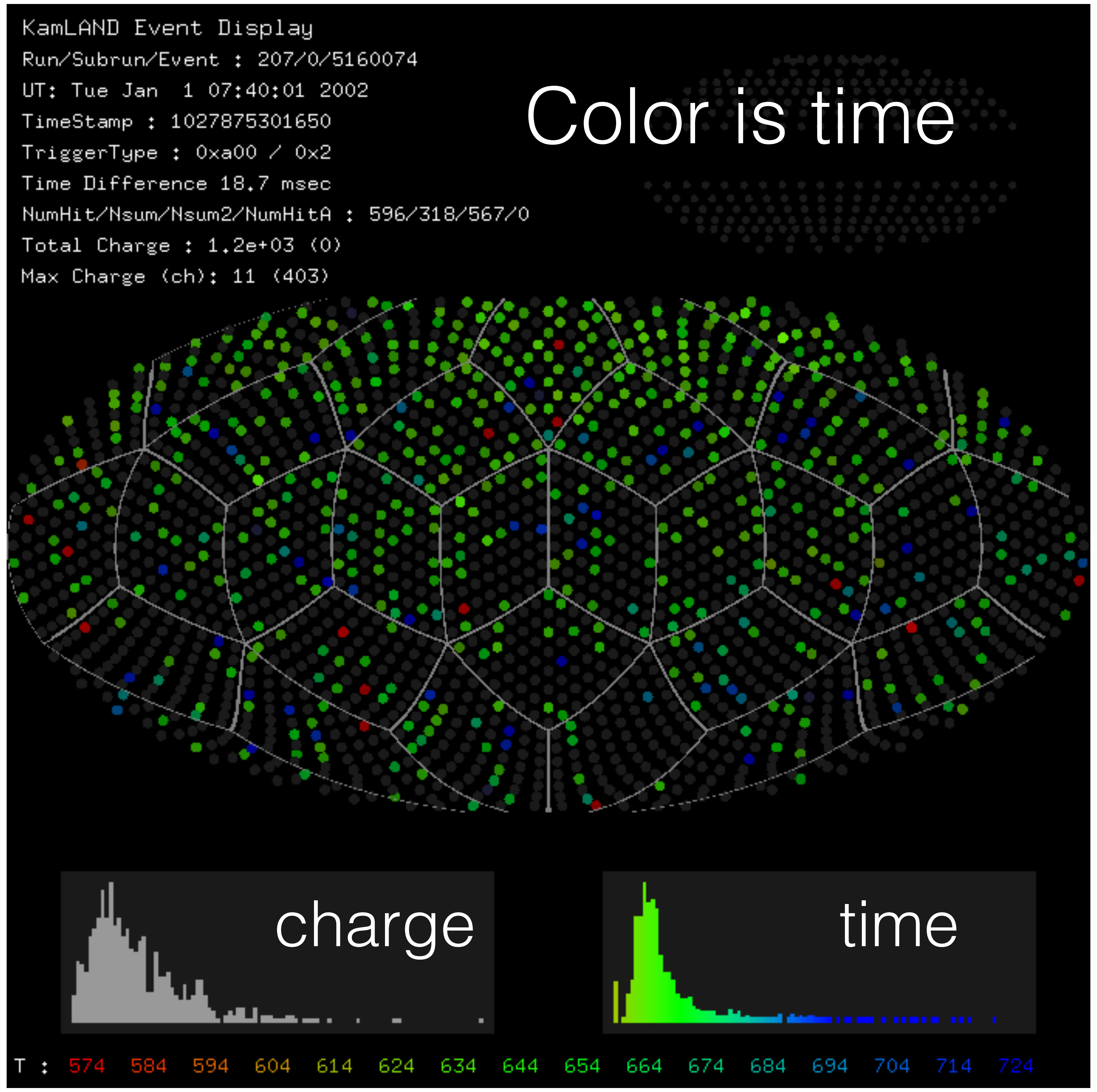


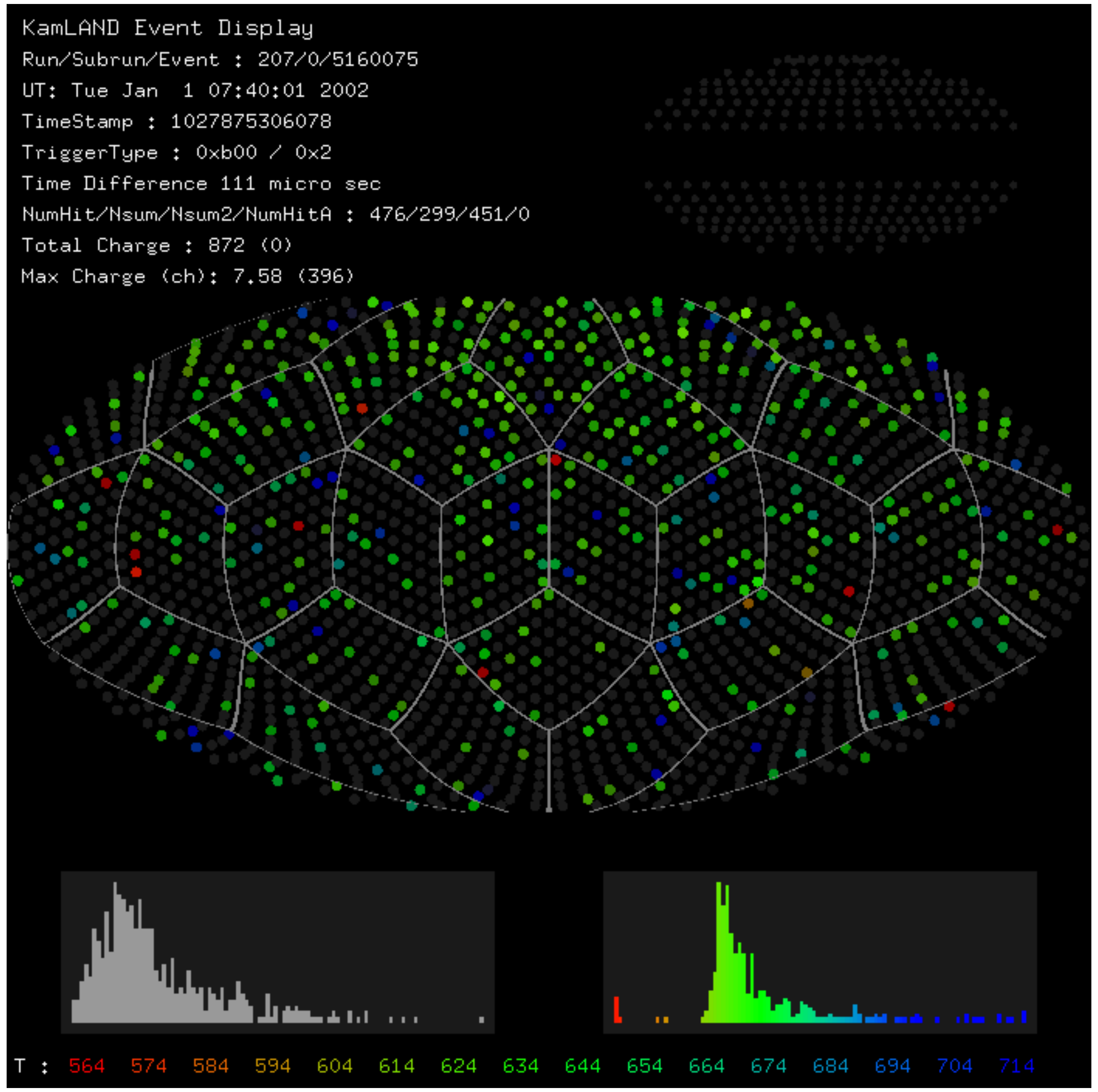
p_μ = 603 MeV



p_e = 492 MeV

Neutrinos in liquid scintillators



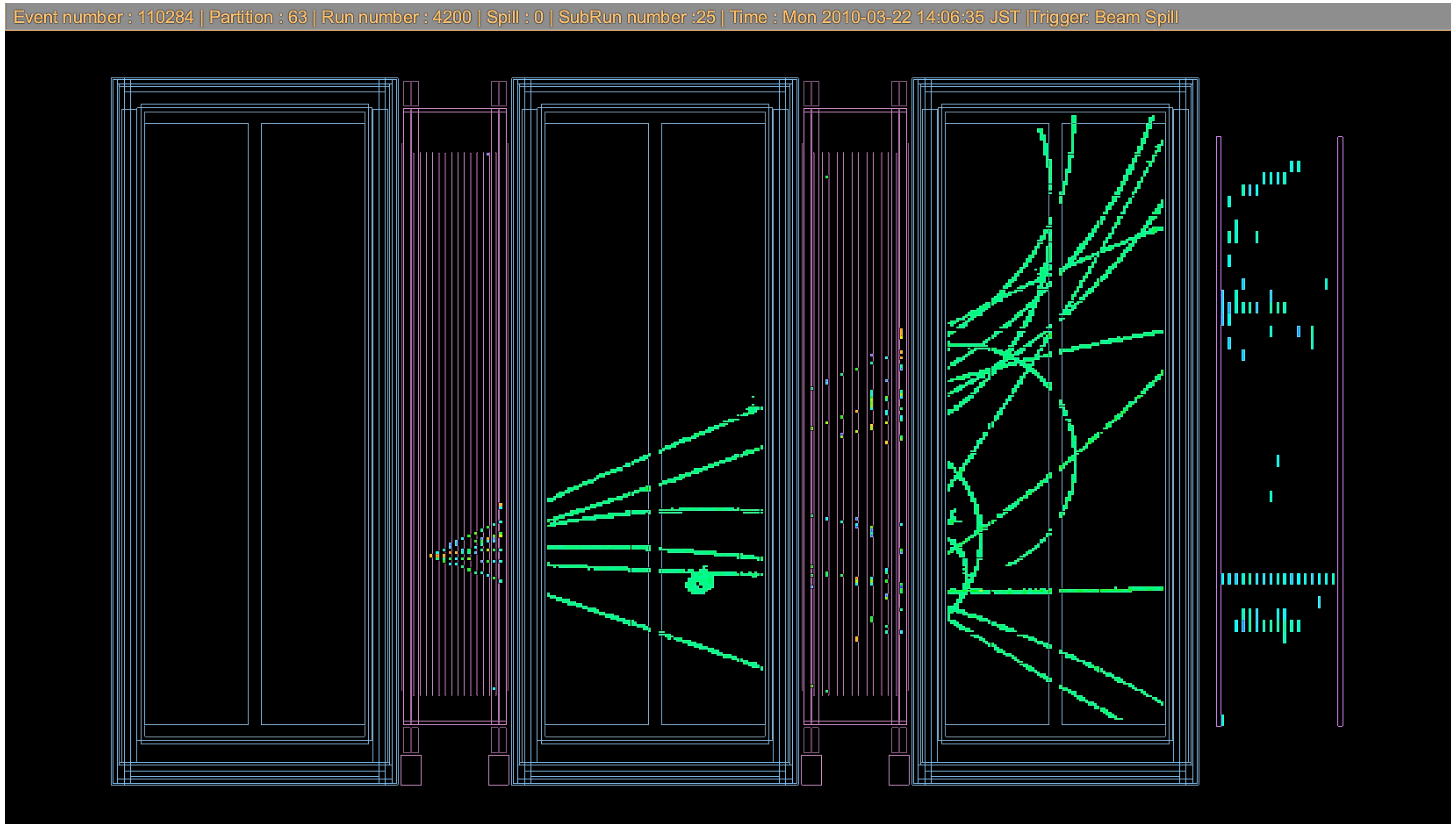


Prompt signal
E = 3.20 MeV

$\Delta T = 111\ \mu s$
$\Delta R = 34\ cm$

Delayed signal
E = 2.22 MeV

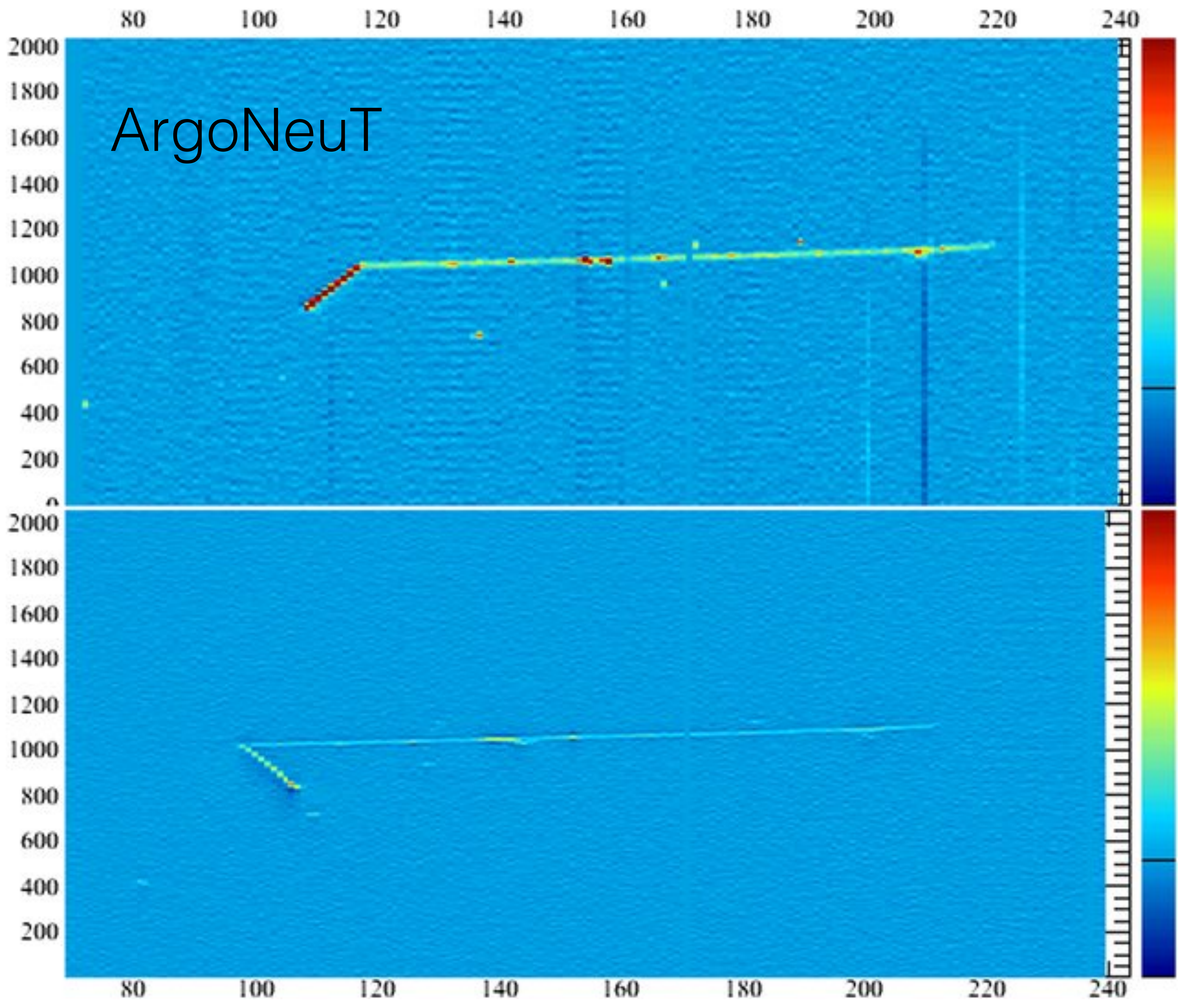
Neutrinos in T2K ND



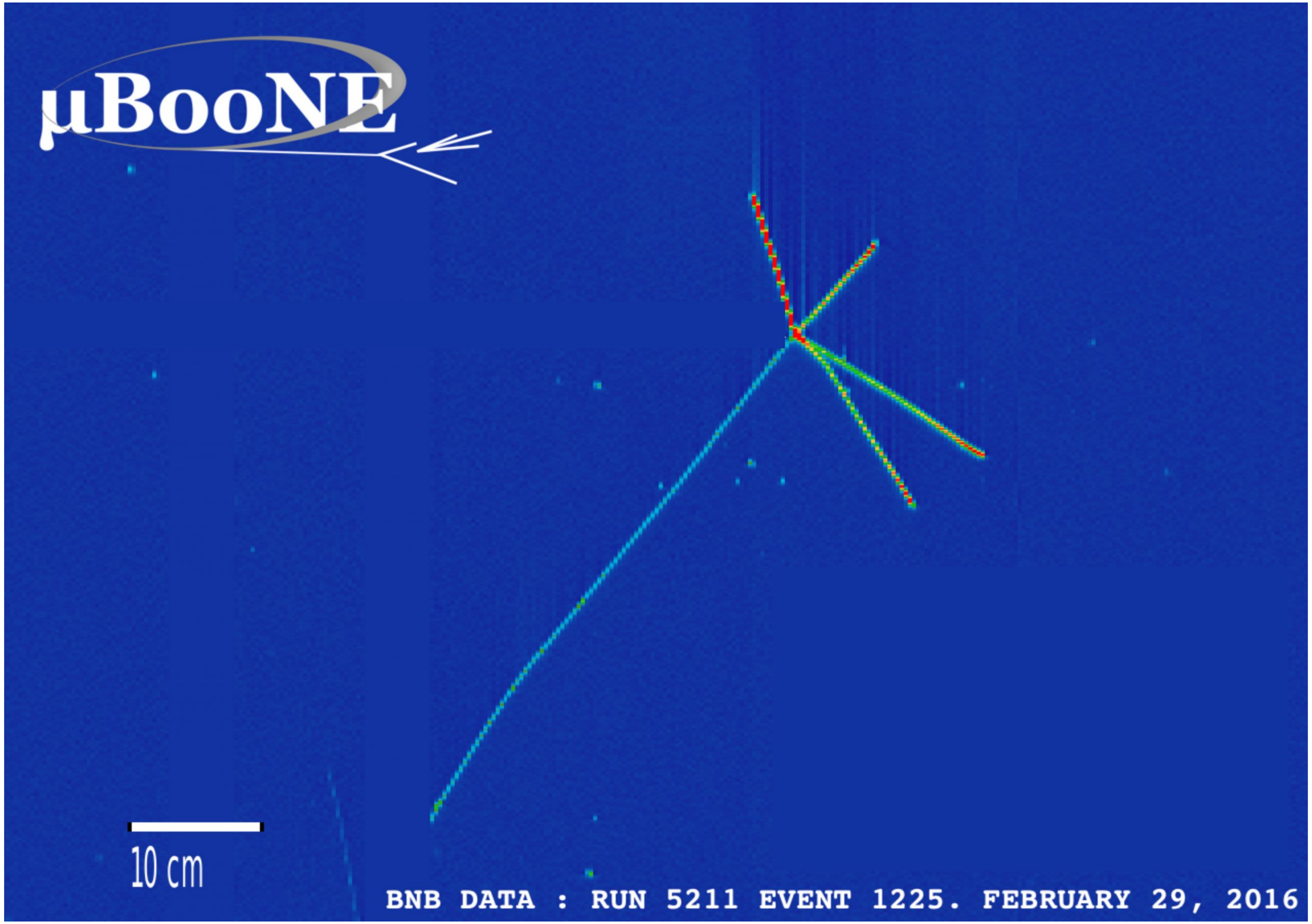
Tracks of charged particles produced by a neutrino interaction in the T2K near detector

Neutrinos in LAr detectors

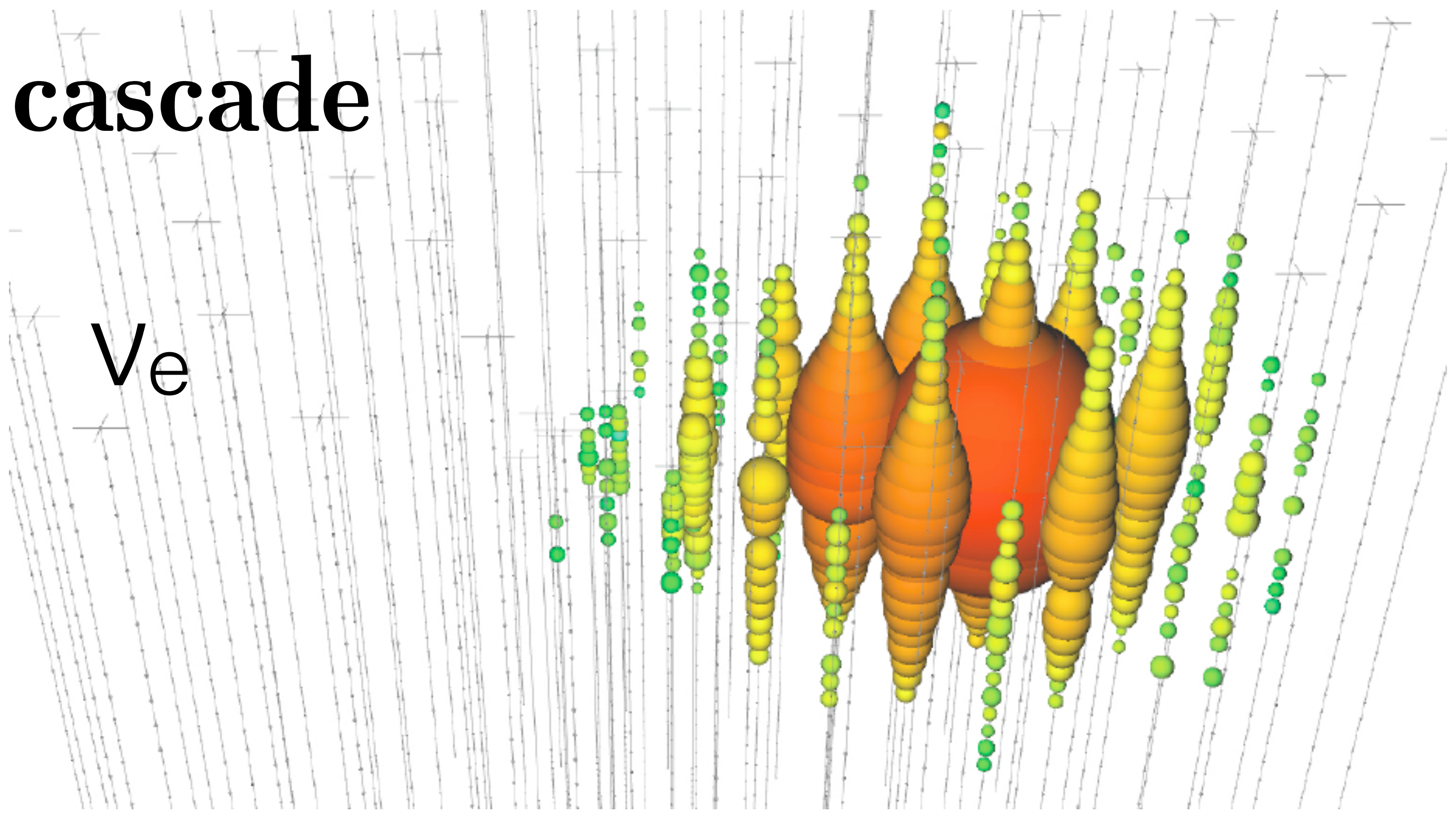
CCQE event: $\nu_\mu\, n \rightarrow \mu\, p$

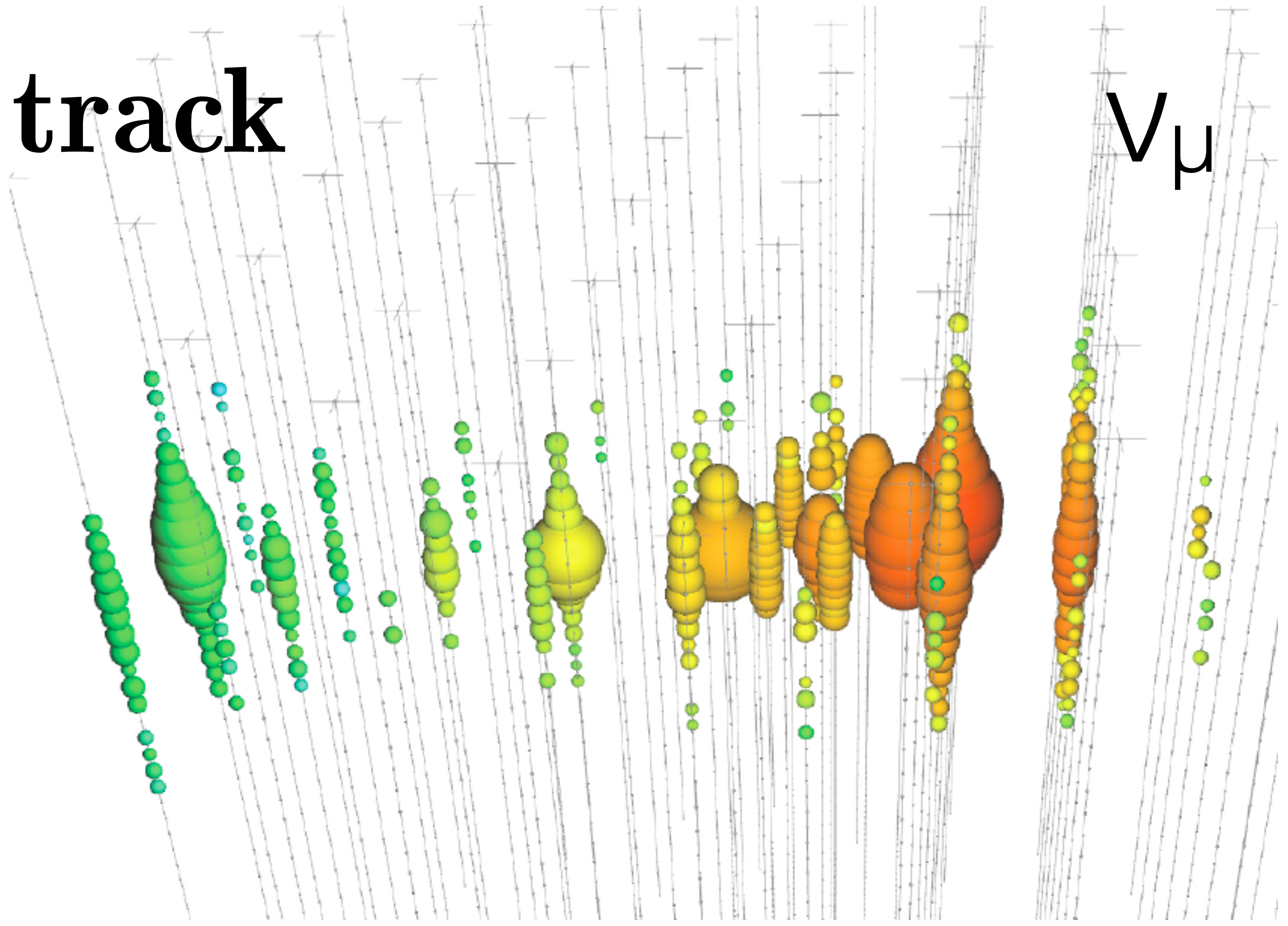


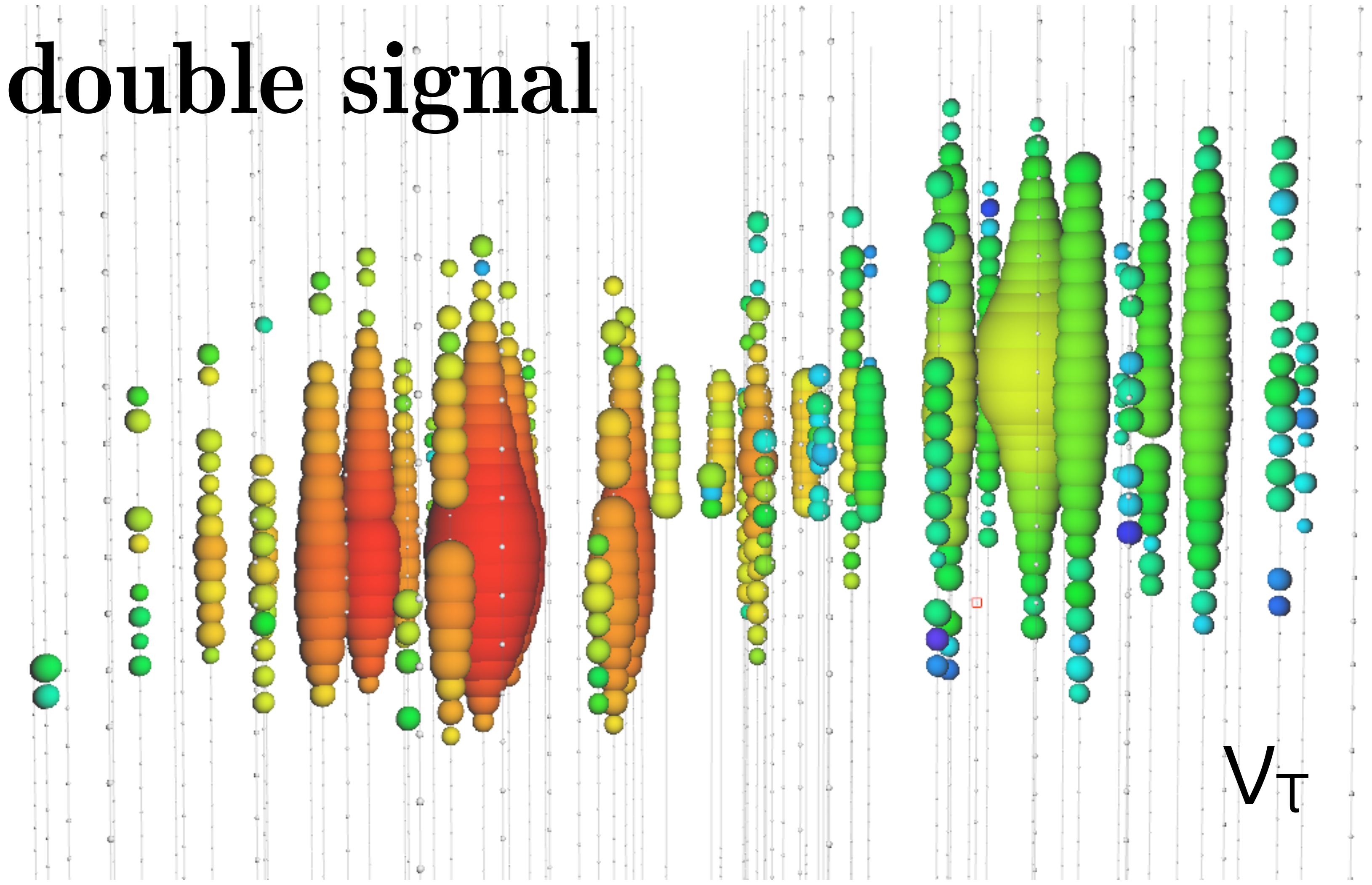
Neutrinos in LAr detectors



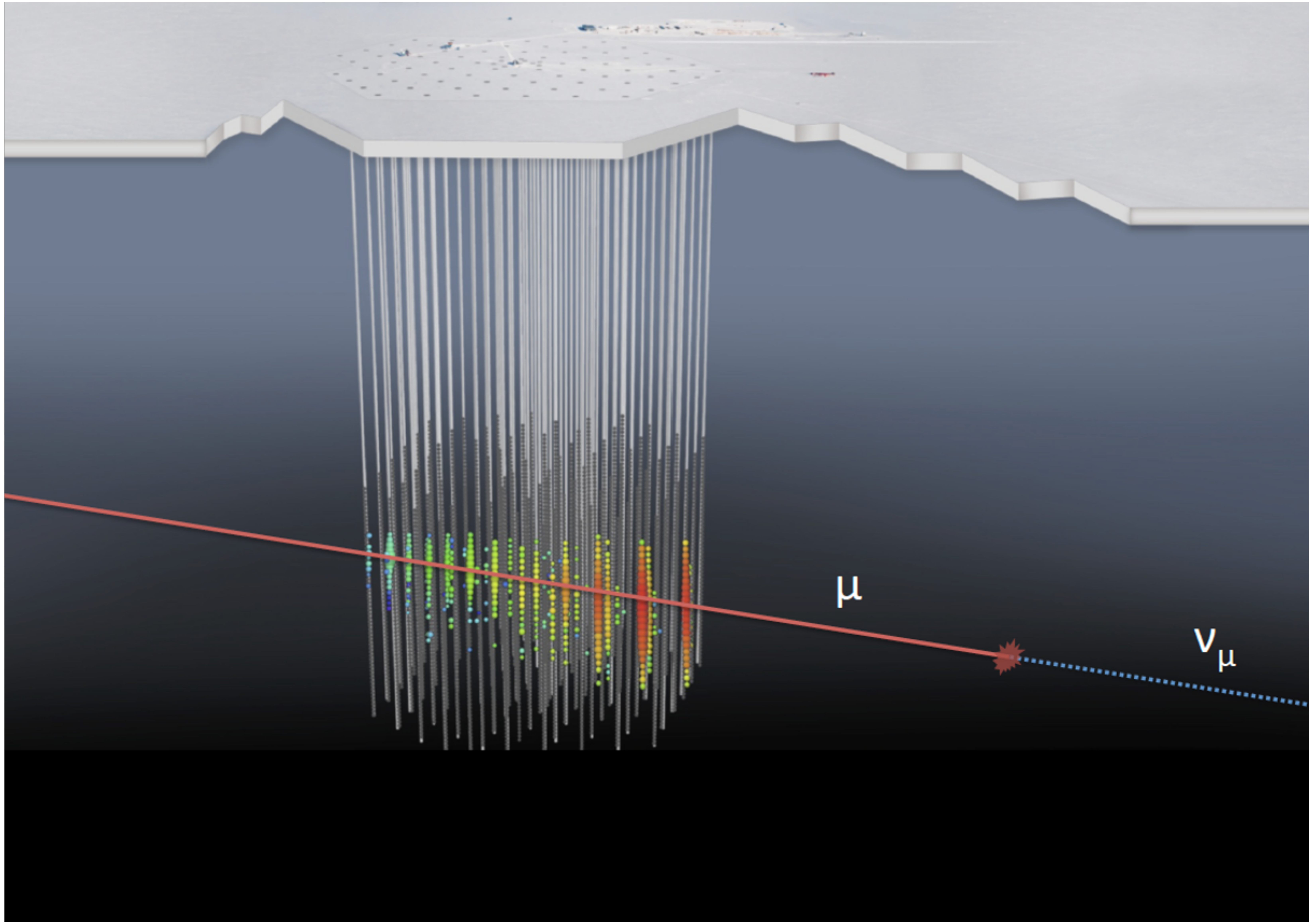
Very high energy neutrinos

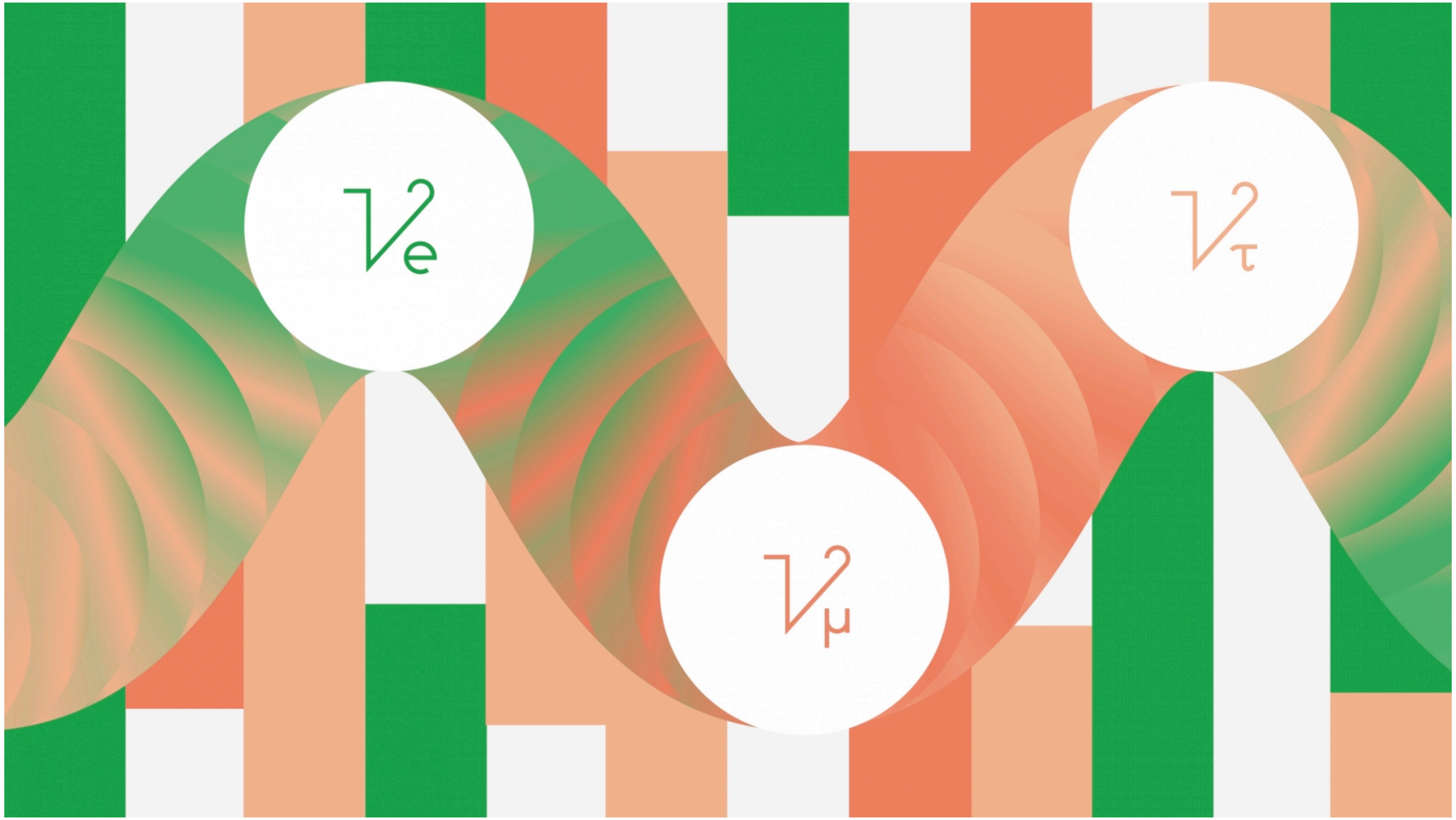






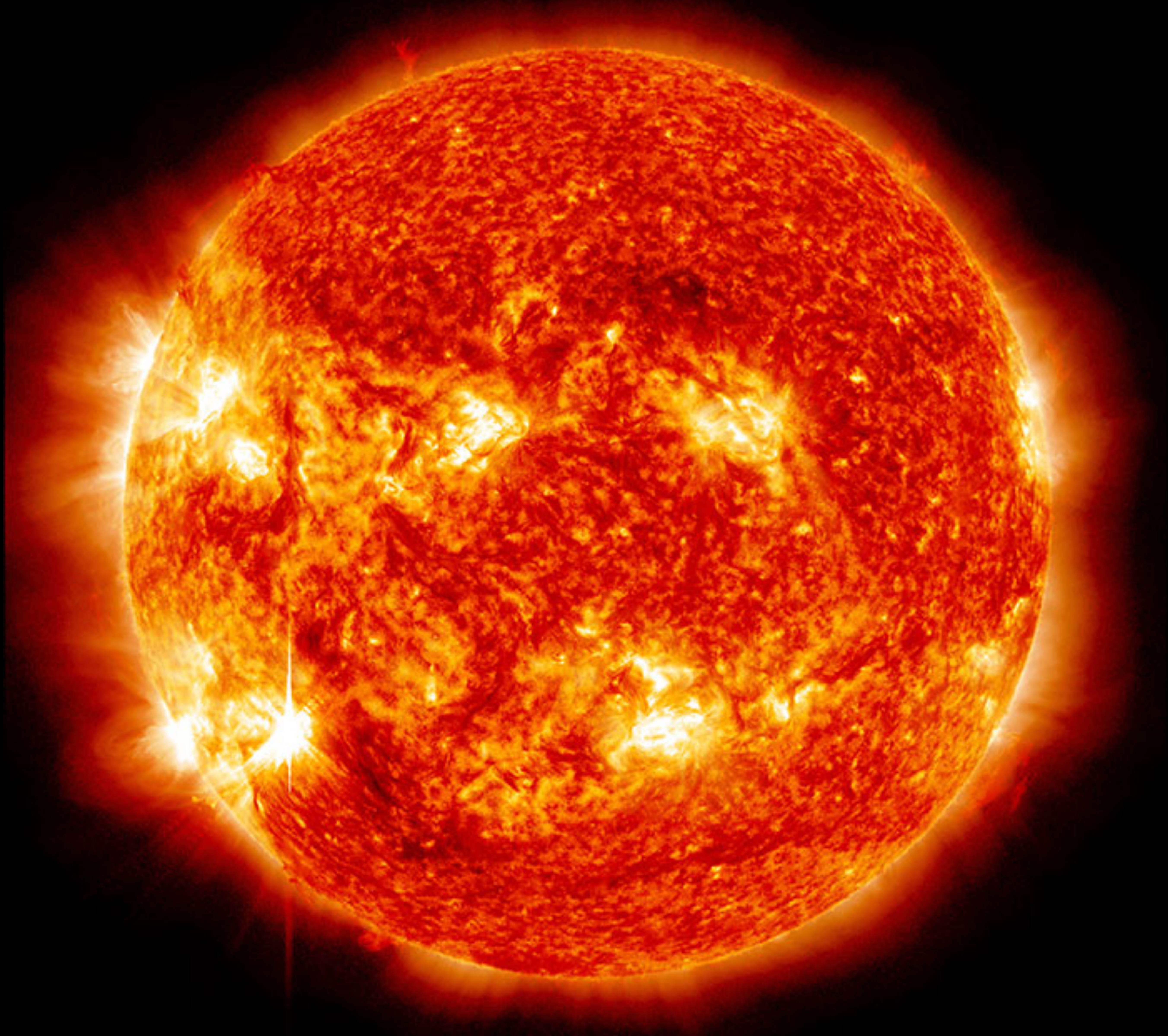
Neutrinos in ice



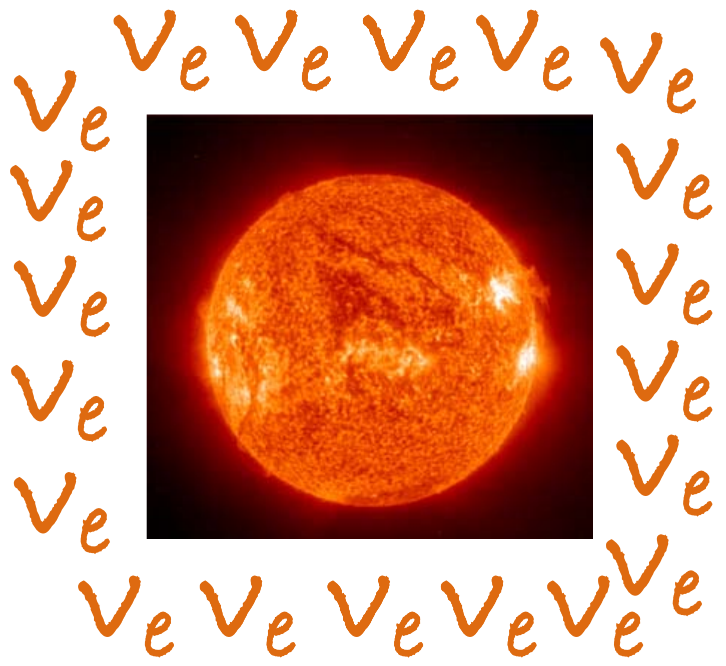


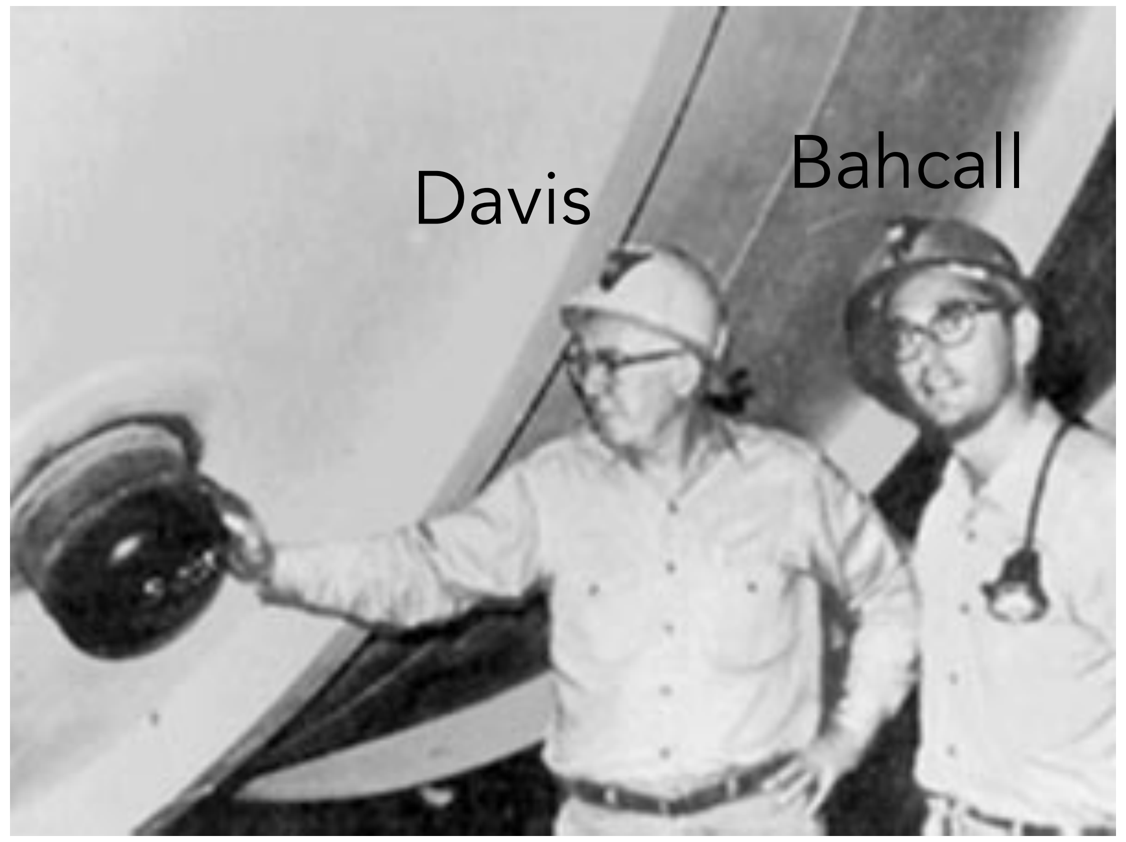
The journey of neutrinos

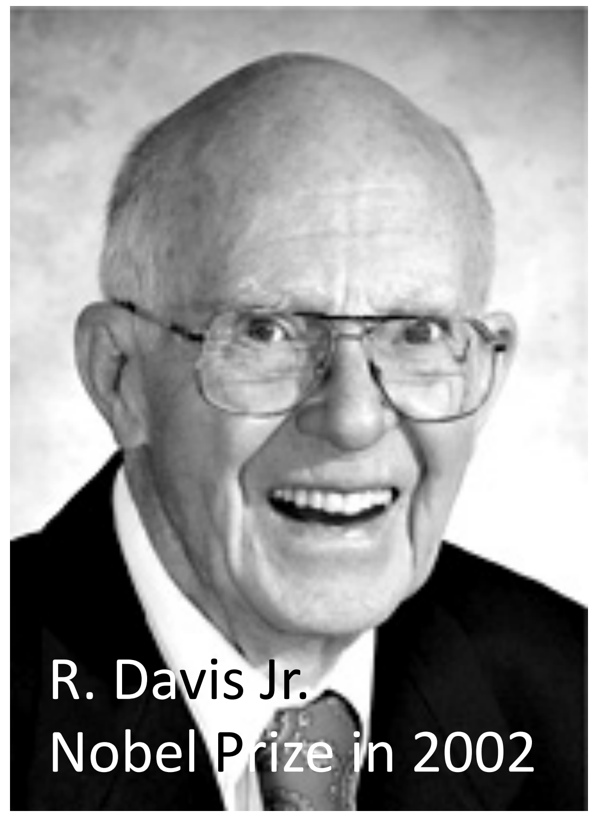
3

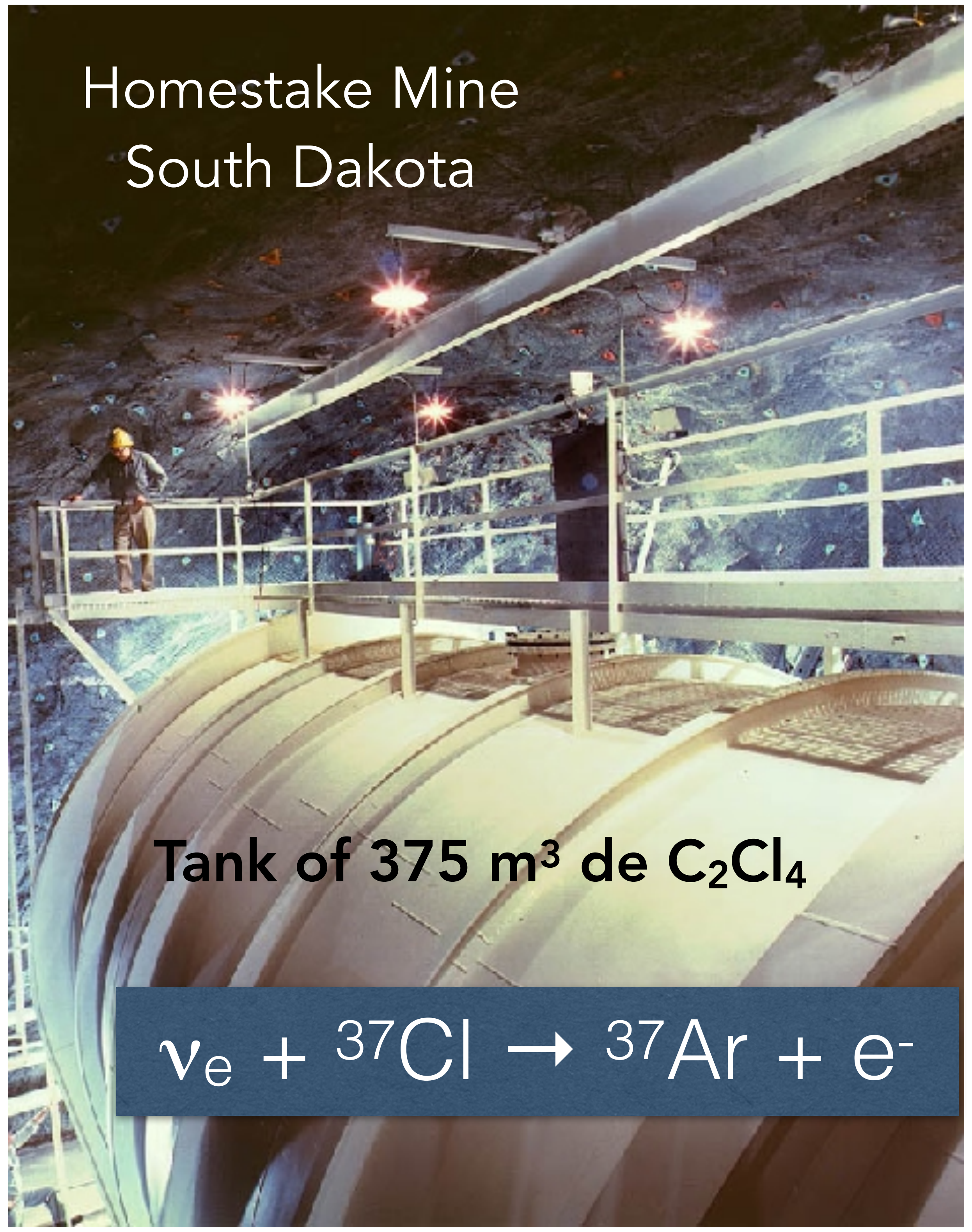


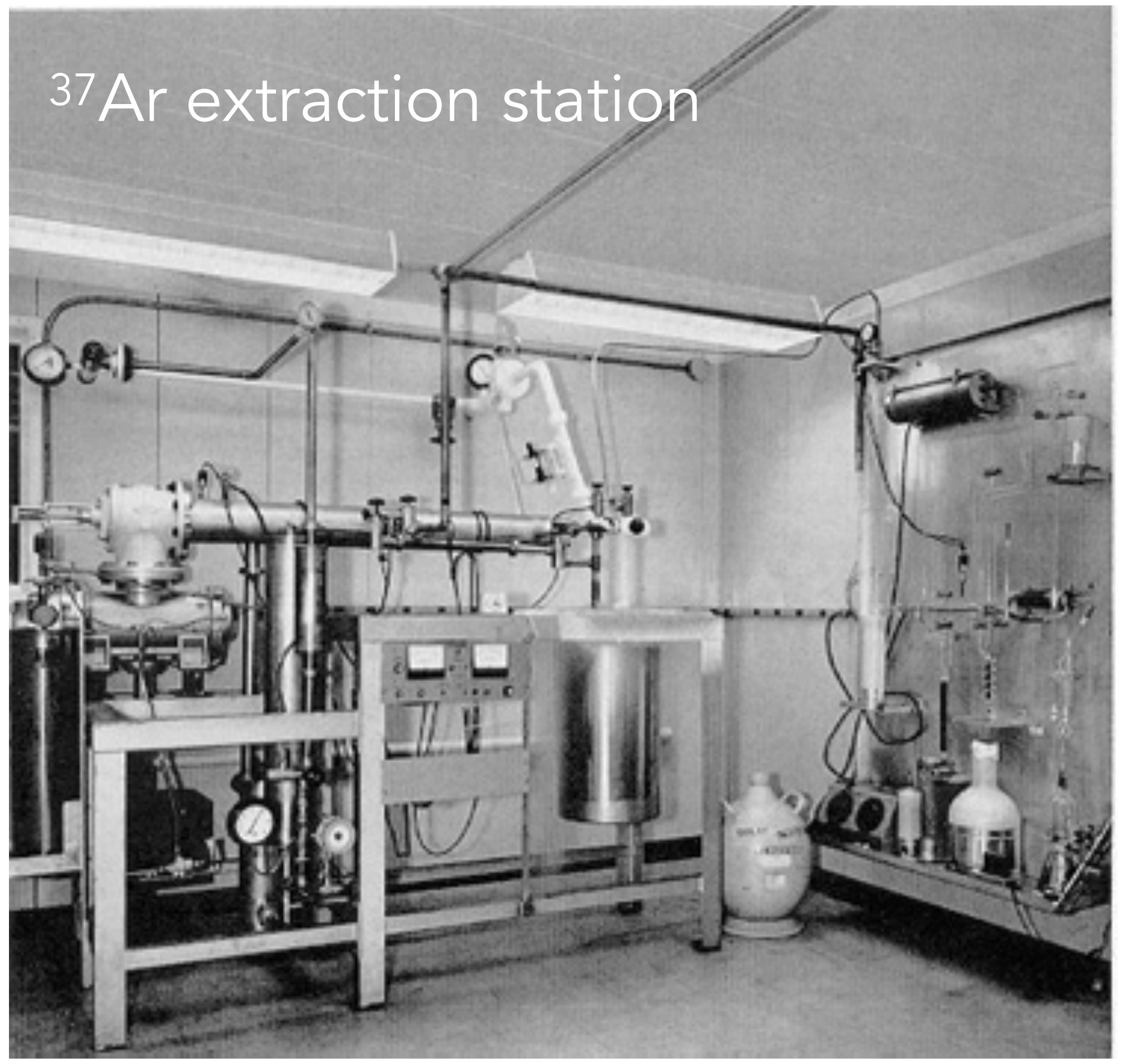
Solar neutrinos











Prediction (J. Bahcall): 1 Ar atom per day

Measurement (R. Davis): 1/3 of prediction!!

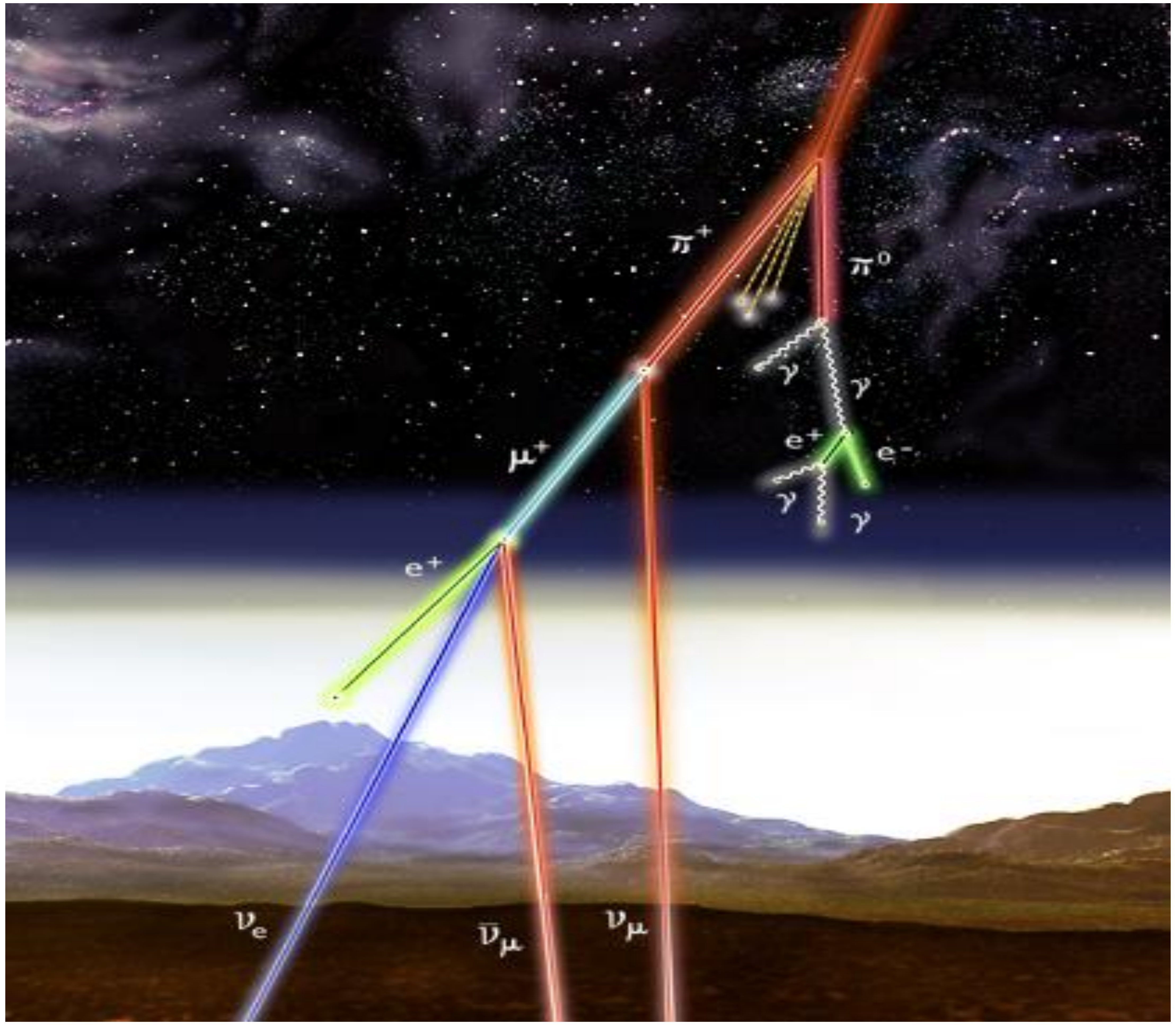
2/3 of neutrinos are missing!!

The discrepancy would go without explanation for more than 30 years

(1968-2001)

Atmospheric neutrinos

Kamiokande and IMB detected atmospheric neutrinos in the 80's



- **Expected:** 2 times more ν_μ than ν_e

  $$2\nu_\mu \sim \nu_e$$

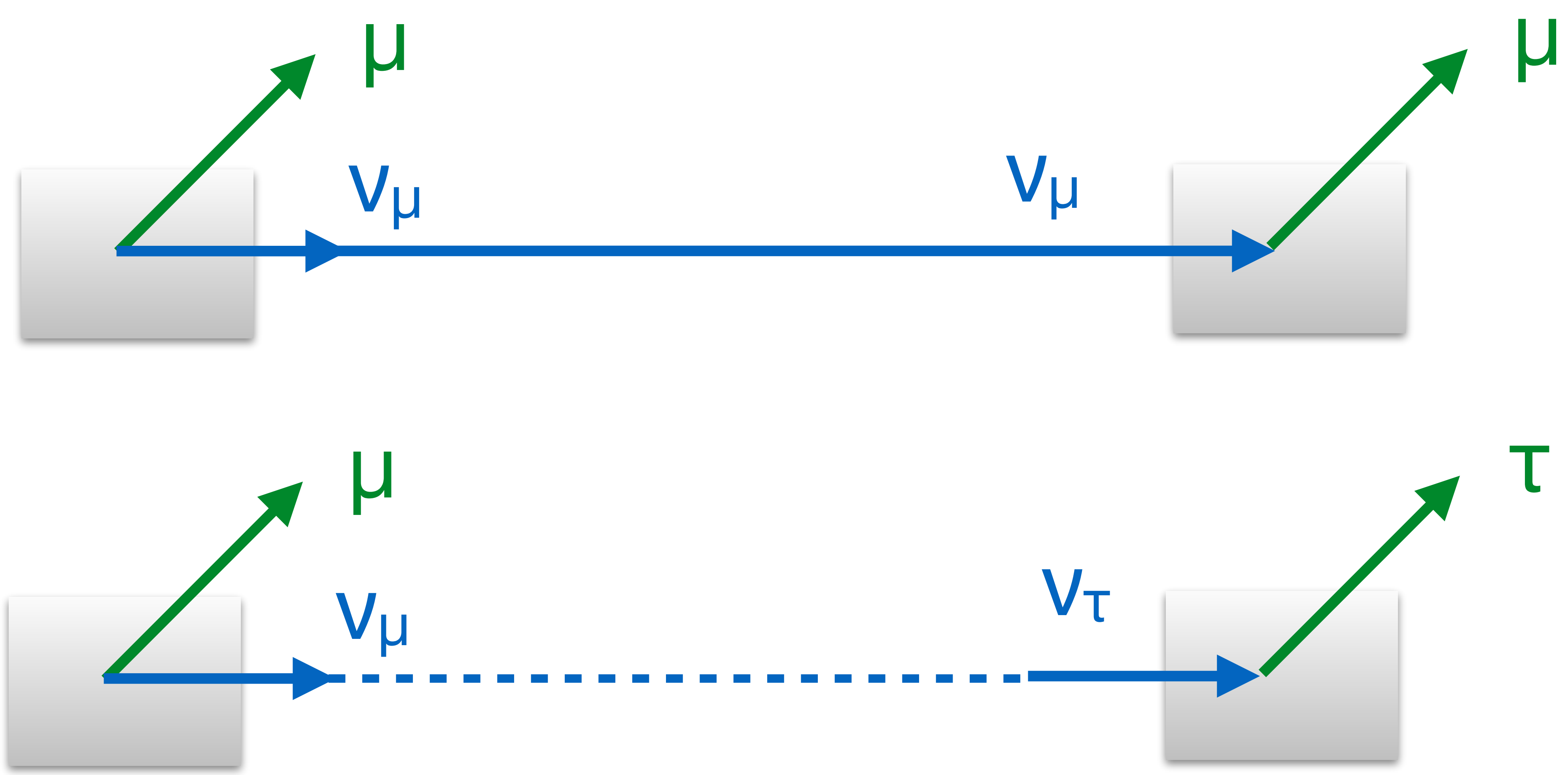
- **Found:**

  $$\nu_\mu \sim \nu_e$$

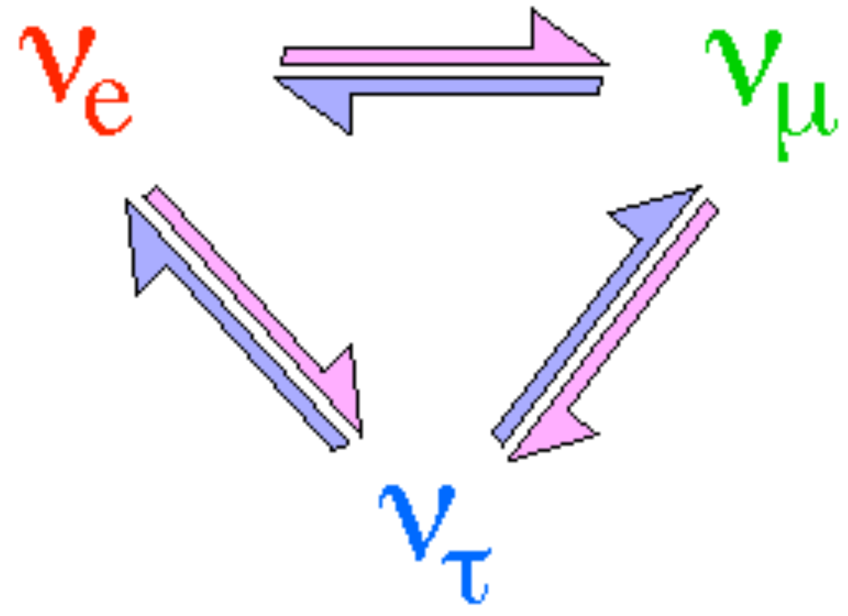
Where are the neutrinos going?

The idea of oscillations

Quantum interference phenomenon in which a neutrino of a certain flavor is transformed into a neutrino of a different flavor



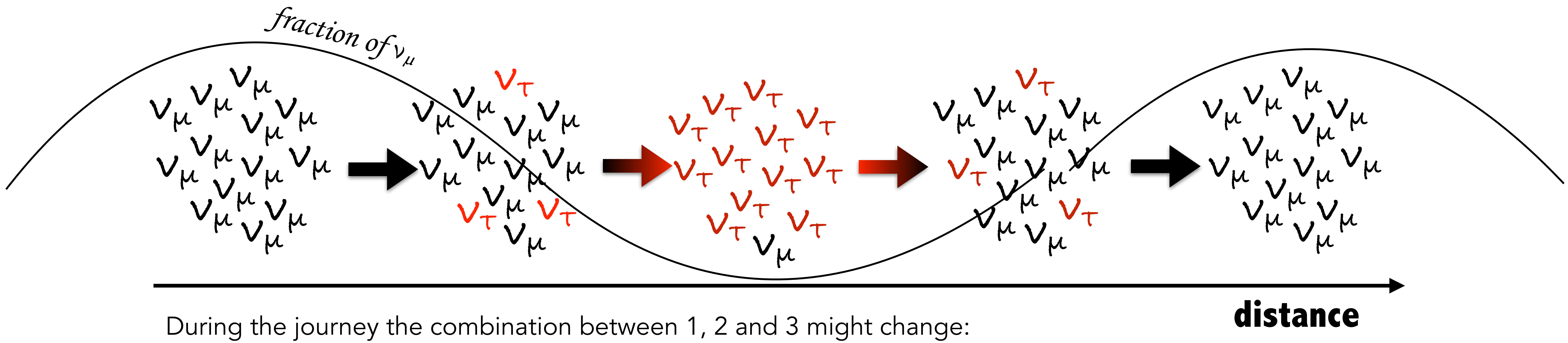
B. Pontecorvo (1957)



This phenomenon is only possible if neutrinos have different masses

Combination of 3 waves

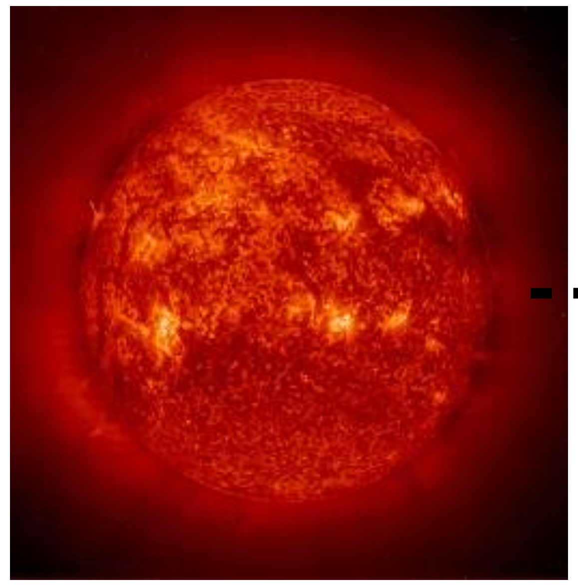
- In the SM neutrinos are 3 distinct particles but when they propagate they are a **combination of 3 different "waves" (1,2,3)**
- As a neutrino travels through space, the waves combine in different ways depending on the **distance** the neutrino has travelled and its **energy**



During the journey the combination between 1, 2 and 3 might change:

- Sometimes the combination might look like a ν_μ
- Then later, the waves might combine to look like a ν_τ

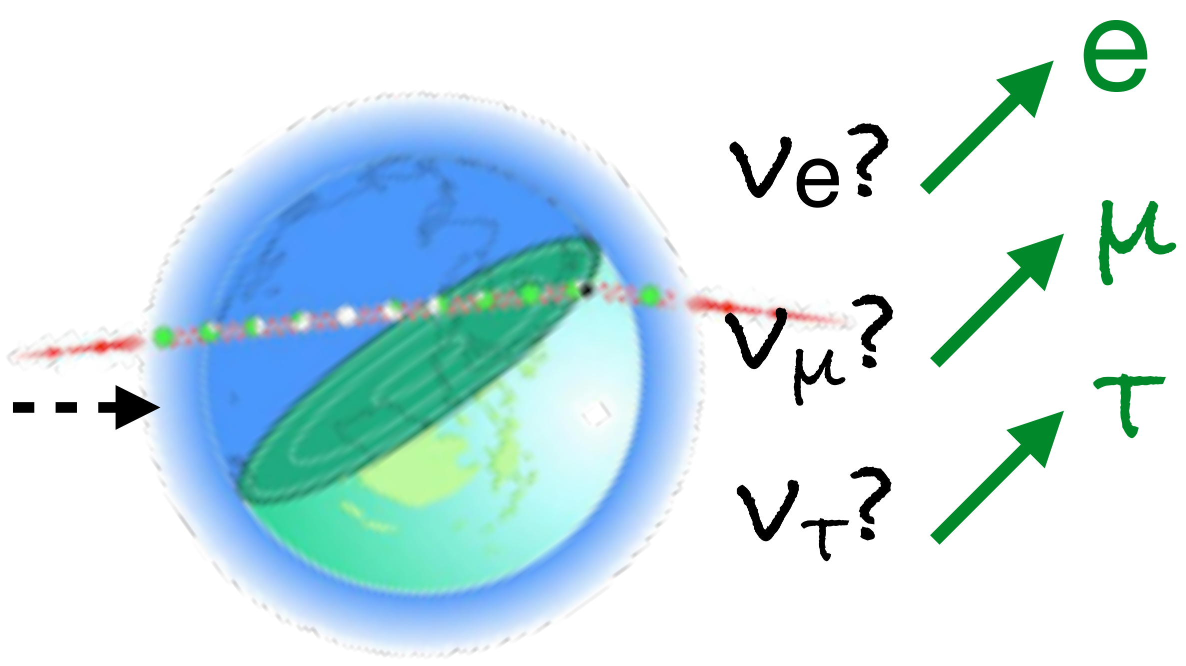
Detection of neutrino oscillations



ν_e

E_ν

L = distance



production

- Weak interaction produces neutrinos of a certain flavor
- We know which kind of neutrino is by detecting its associated particle

propagation

Neutrinos travel a distance and mix

Oscillation Probability

$$P(\nu_\alpha \rightarrow \nu_\beta) = \sin^2 2\theta \cdot \sin^2\left(\frac{\Delta m^2 \cdot L}{4 \cdot E_\nu}\right)$$

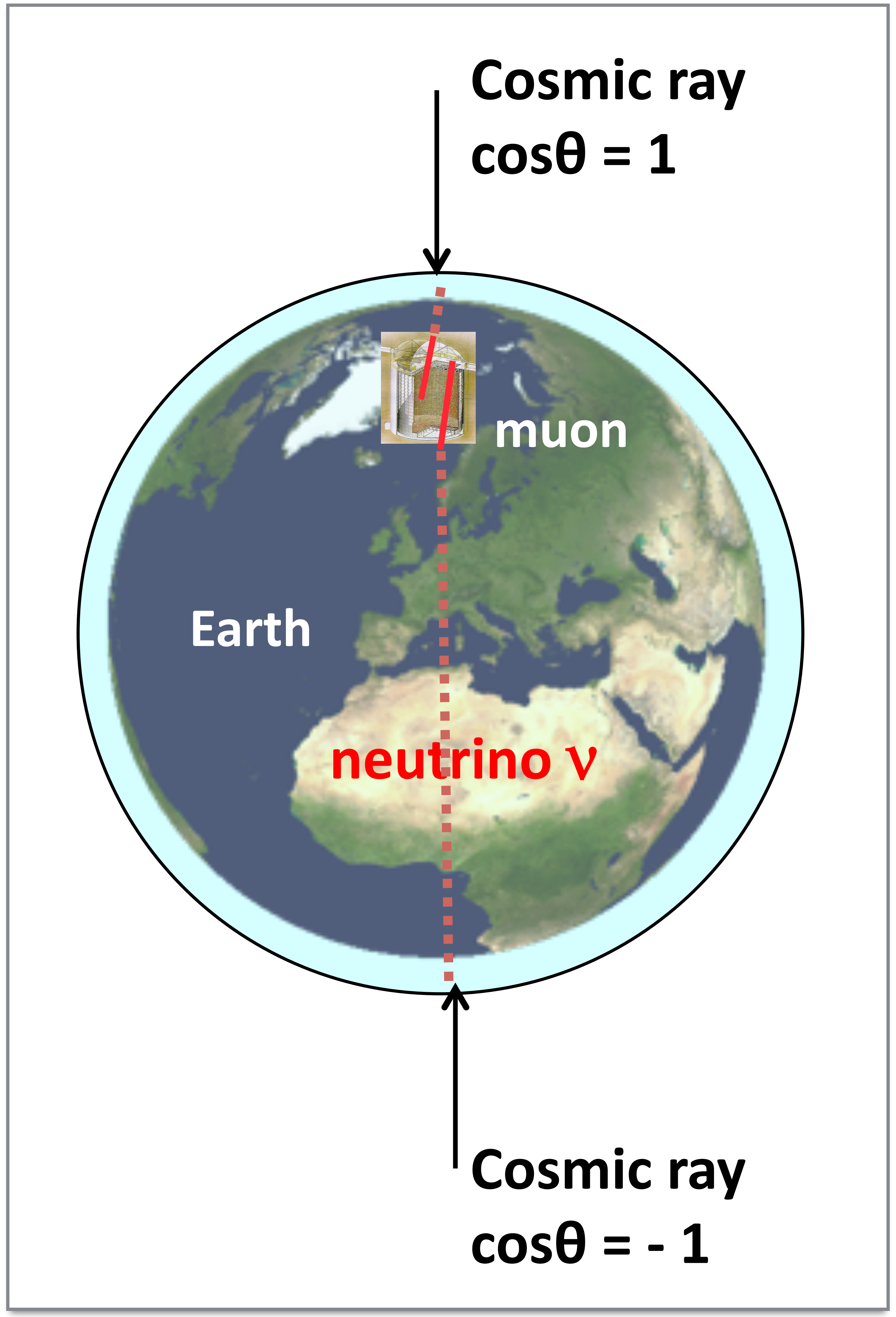
For 3 neutrinos:

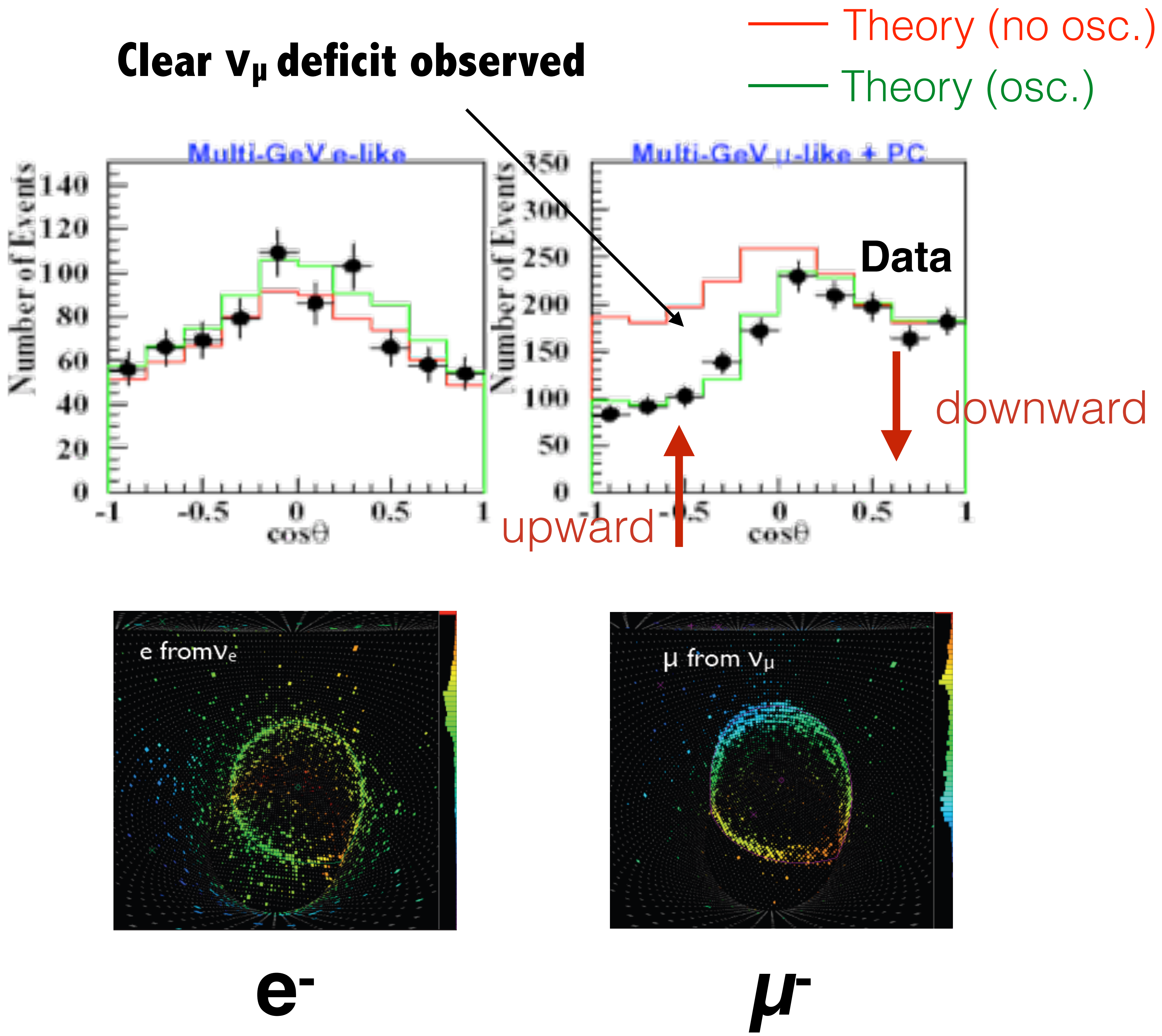
2 values of Δm^2 (Δm^2_{21}, Δm^2_{32})
3 values of θ (θ_{12}, θ_{23}, θ_{13})

detection

- Neutrinos interact in the detector
- We know which kind of neutrino is by detecting its associated particle
- Comparison of observations with predictions (theory) or expectations coming from measurements at short distances (no osc.)

The discovery of neutrino oscillations (1998): Super-Kamiokande (Japan)

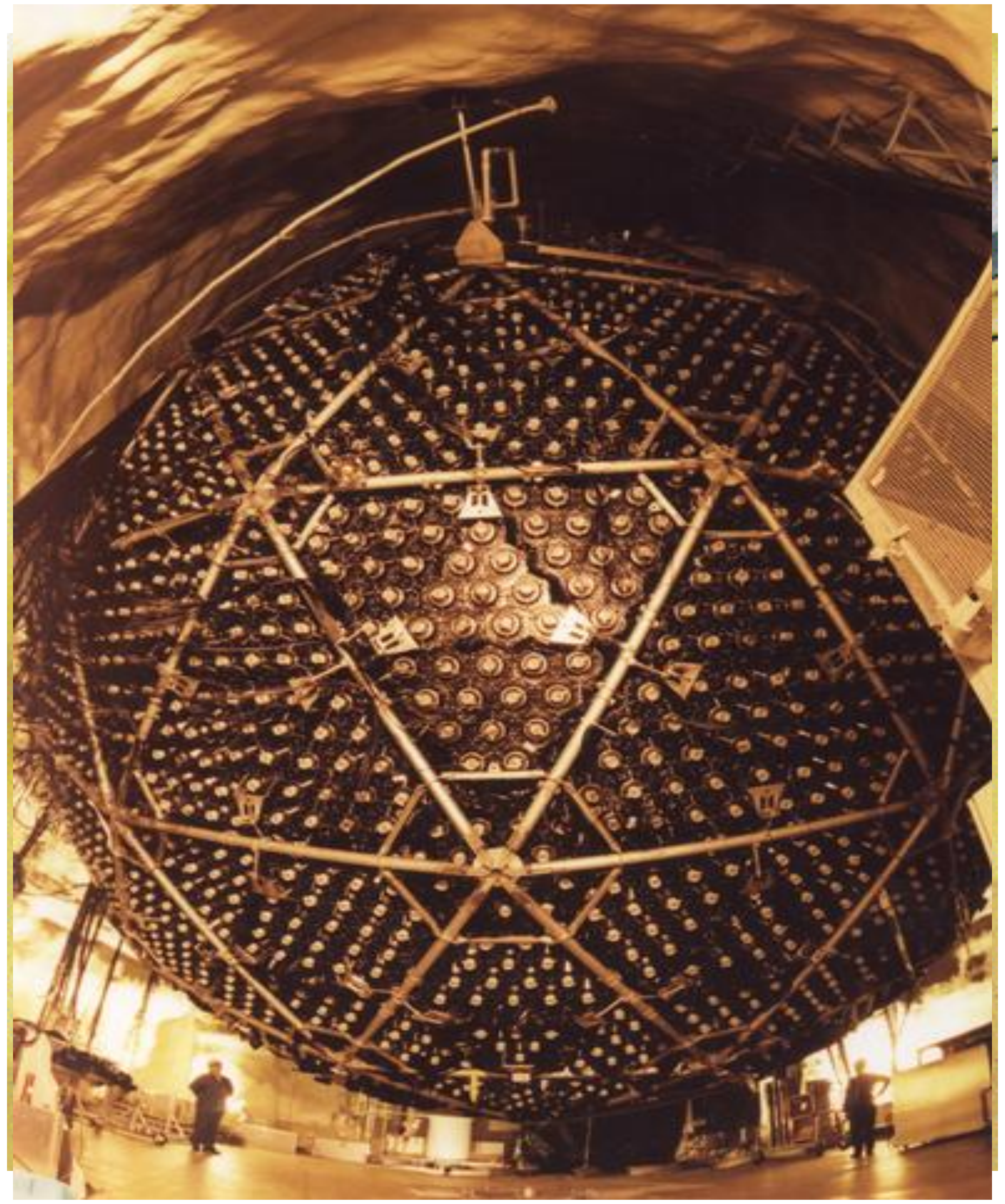




Atmospheric neutrino oscillations

$\nu_\mu \rightarrow \nu_\tau$

Solar neutrino anomaly solved (2001)



- **SNO**: 1000 ton heavy water (D_2O) in the Sudbury mine (Canada)
- Able to measure *all types of neutrinos* from the Sun
- Reaction sensitive to all types of neutrinos (NC)

$$\boxed{\nu_x + d \Rightarrow p + n + \nu_x}$$

- Reaction only sensitive to electron neutrinos (CC)

$$\boxed{\nu_e + d \Rightarrow p + p + e^-}$$

- In case of no oscillations: $\Phi_{NC} = \Phi_{CC}$
- If neutrinos oscillate: $\Phi_{NC} \neq \Phi_{C}$

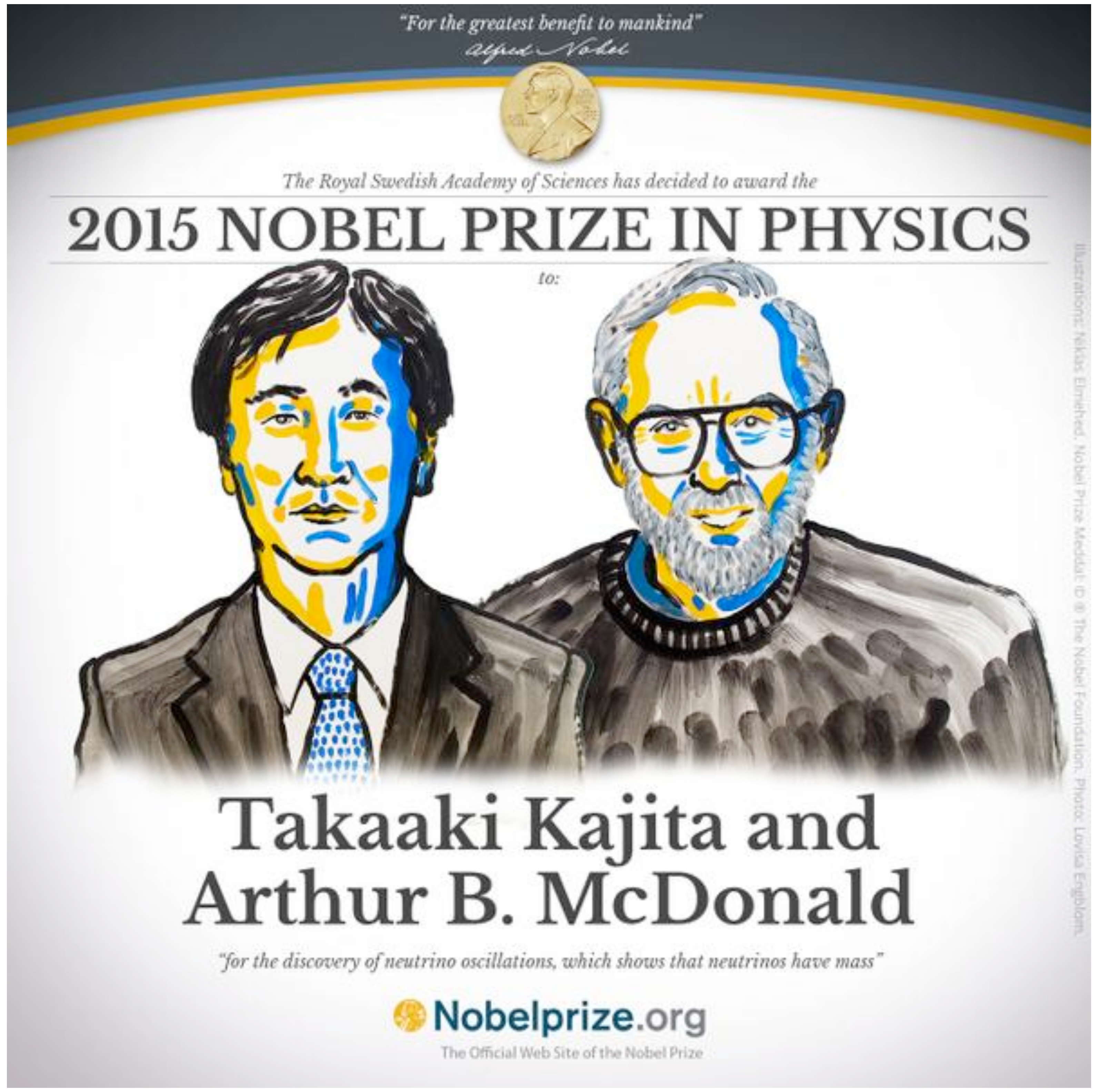
Only ν_e are emitted from the Sun by fusion reactions

Result: $\mathbf{\Phi_{CC} / \Phi_{NC} = 0.301 \pm 0.033}$

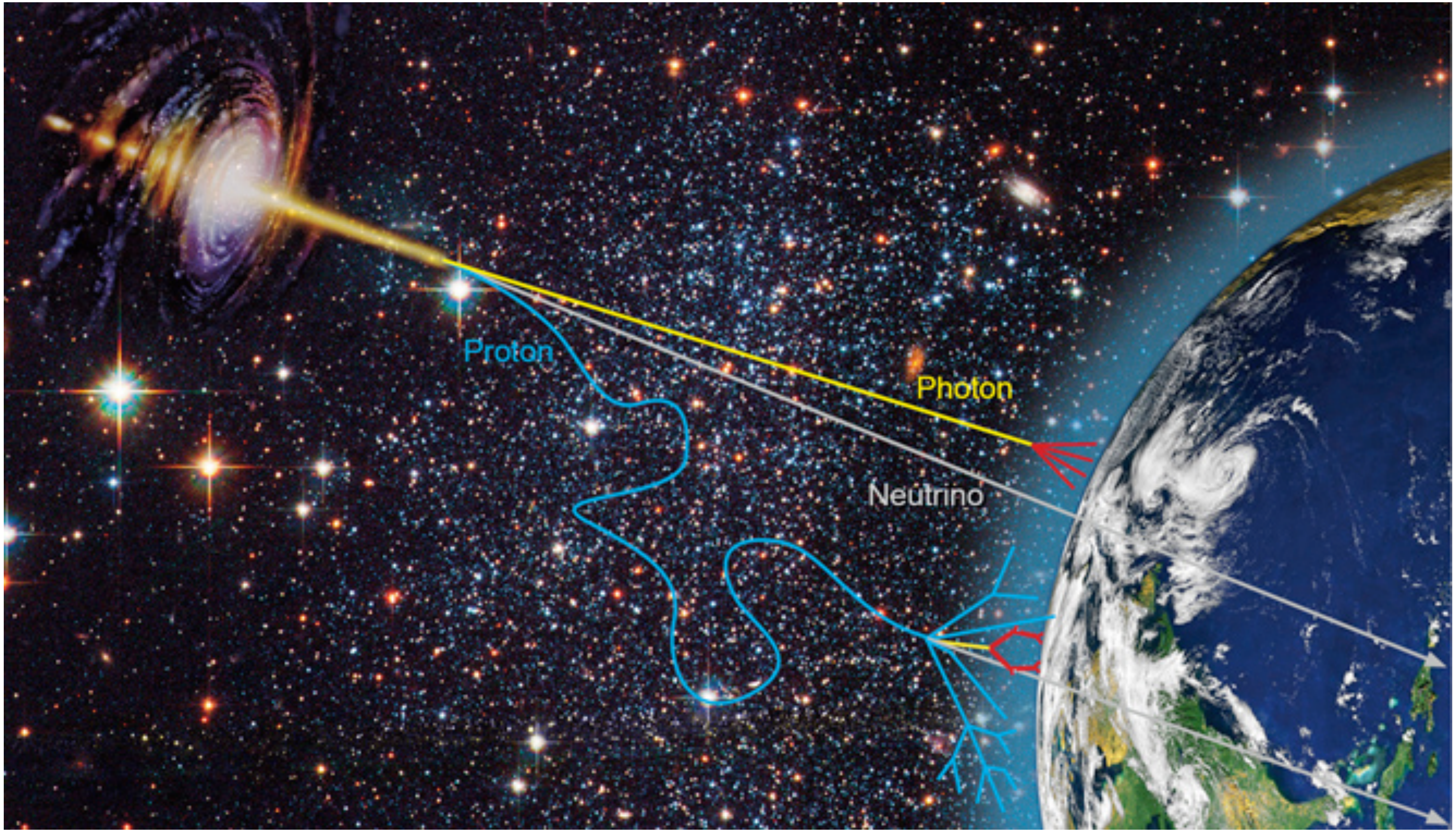
Φ_{NC} in agreement with SSM

Part of ν_e **converted into ν_μ and/or ν_τ**

Neutrinos have mass!!



- Evidence that the **Standard Model of Particles is not complete**
- Can this observation open the door to new Physics beyond the SM?



Cosmic messengers

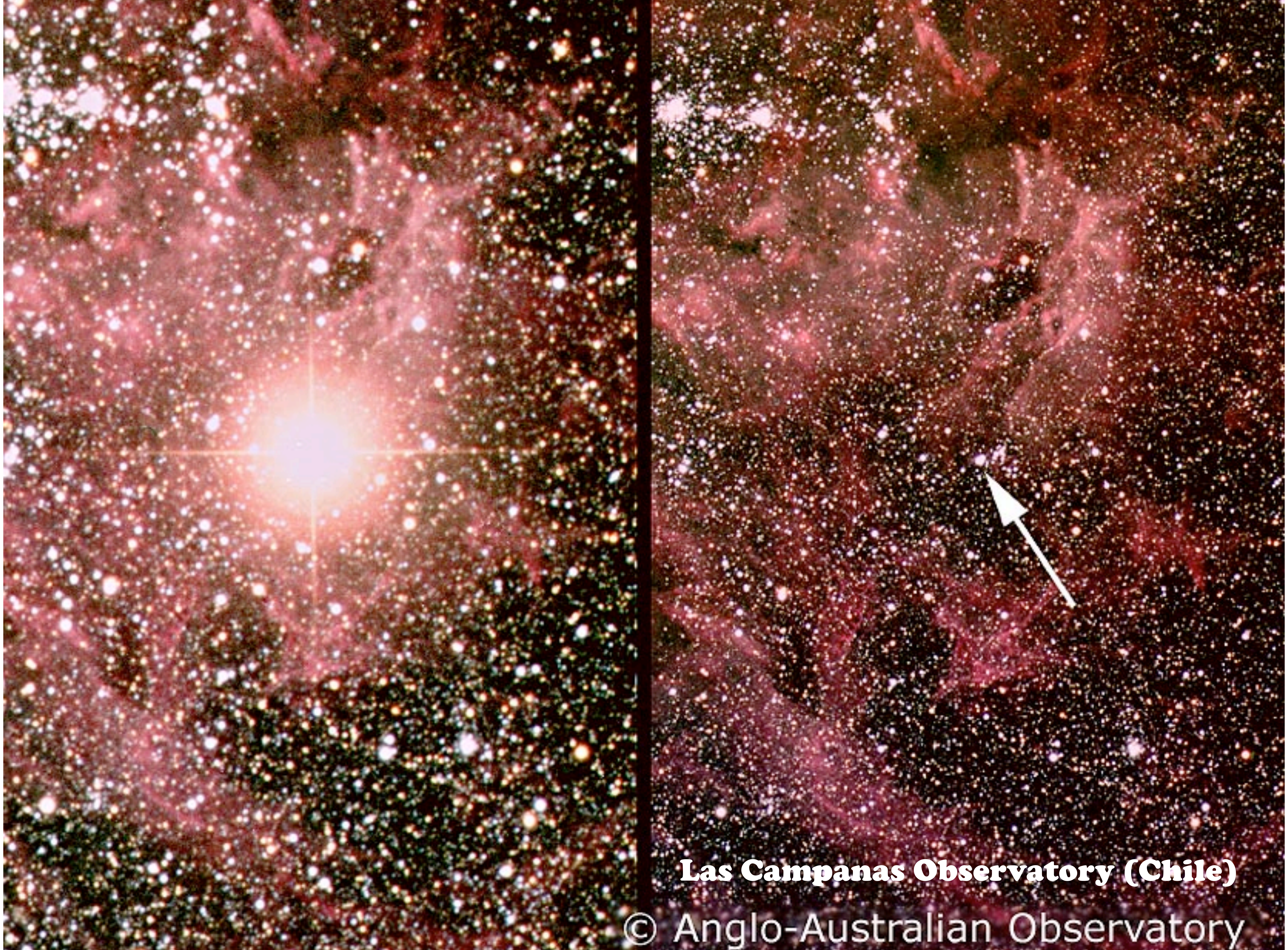
News from far away…

SN1987A

Large Magellanic Cloud

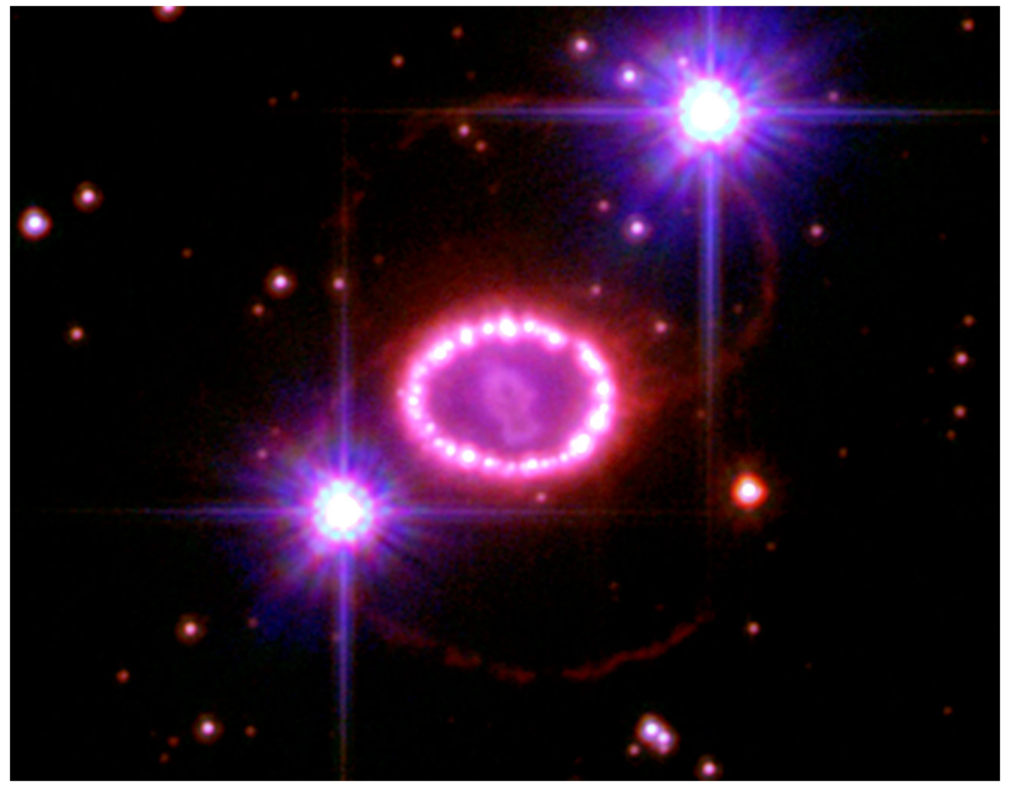
160.000 light-years

23 February 1987
The explosion was visible to the naked eye


Las Campanas Observatory (Chile)
© Anglo-Australian Observatory

SN1987A: 1st detection of extragalactic neutrinos

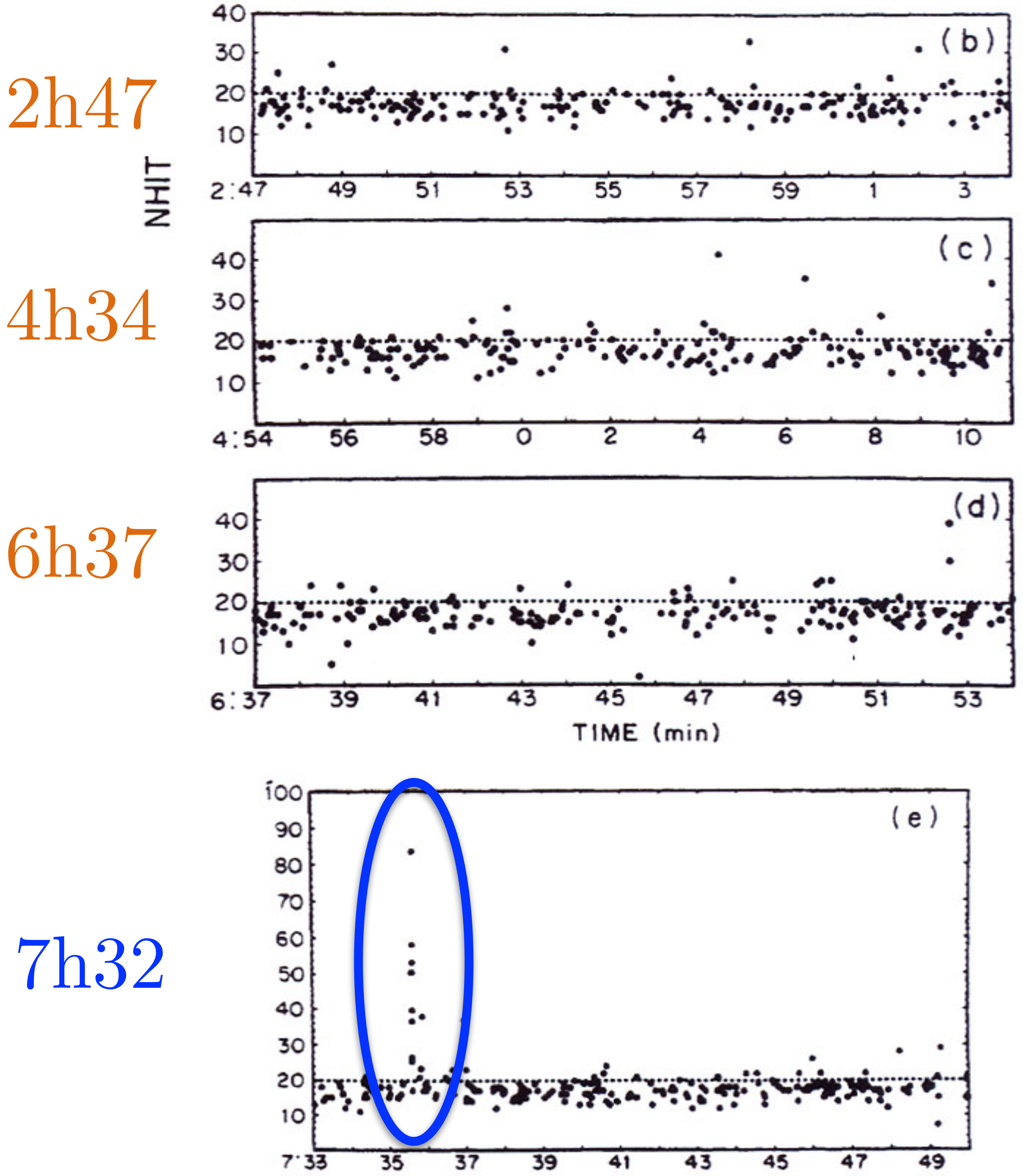
- 10^{58} neutrinos were emitted from the Supernova 1987A 160.000 years ago
- About 5×10^{17} crossed the Kamiokande detector
- **10 neutrinos detected!!**



Koshiba

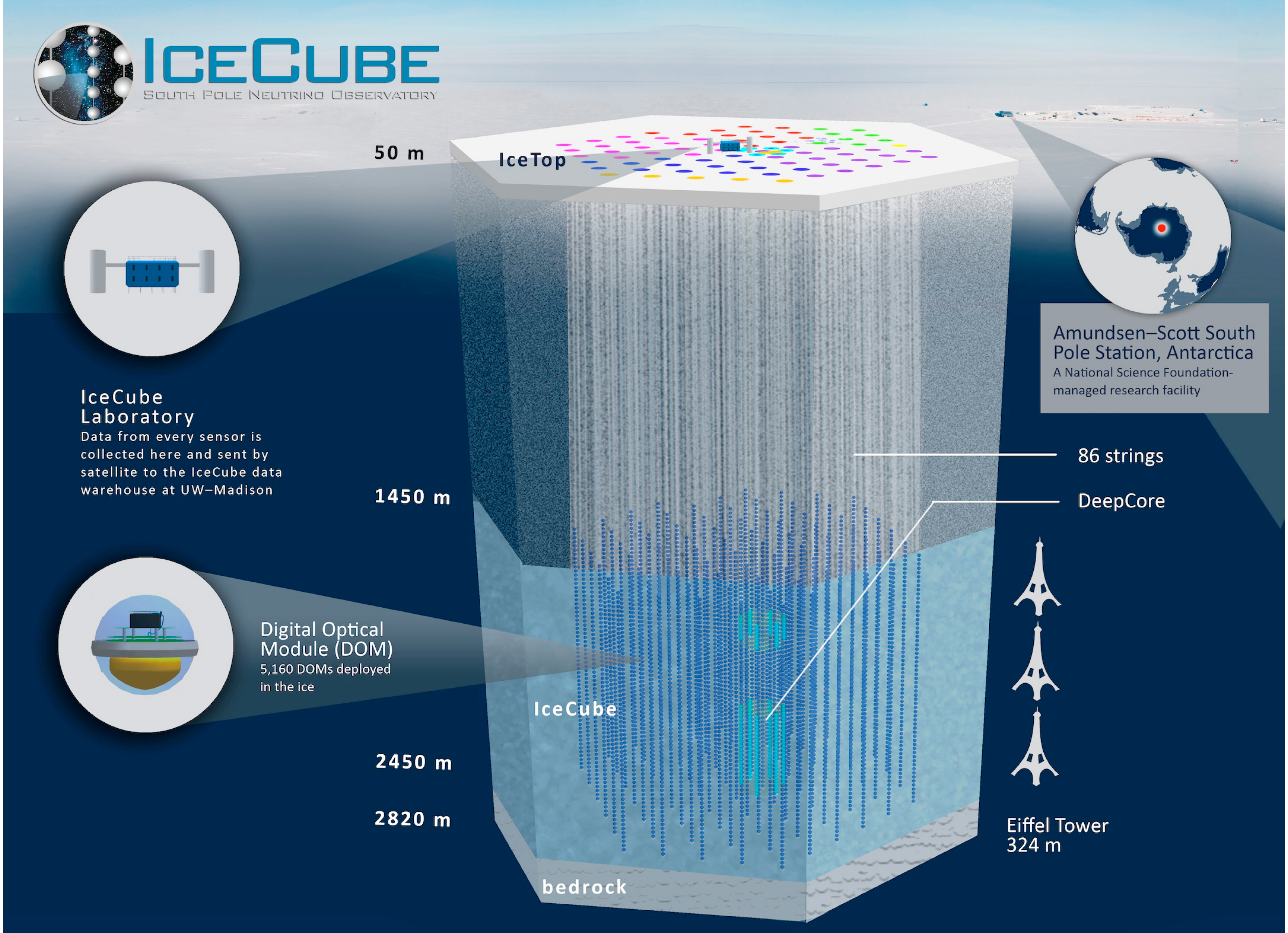
Nobel Prize in Physics 2002

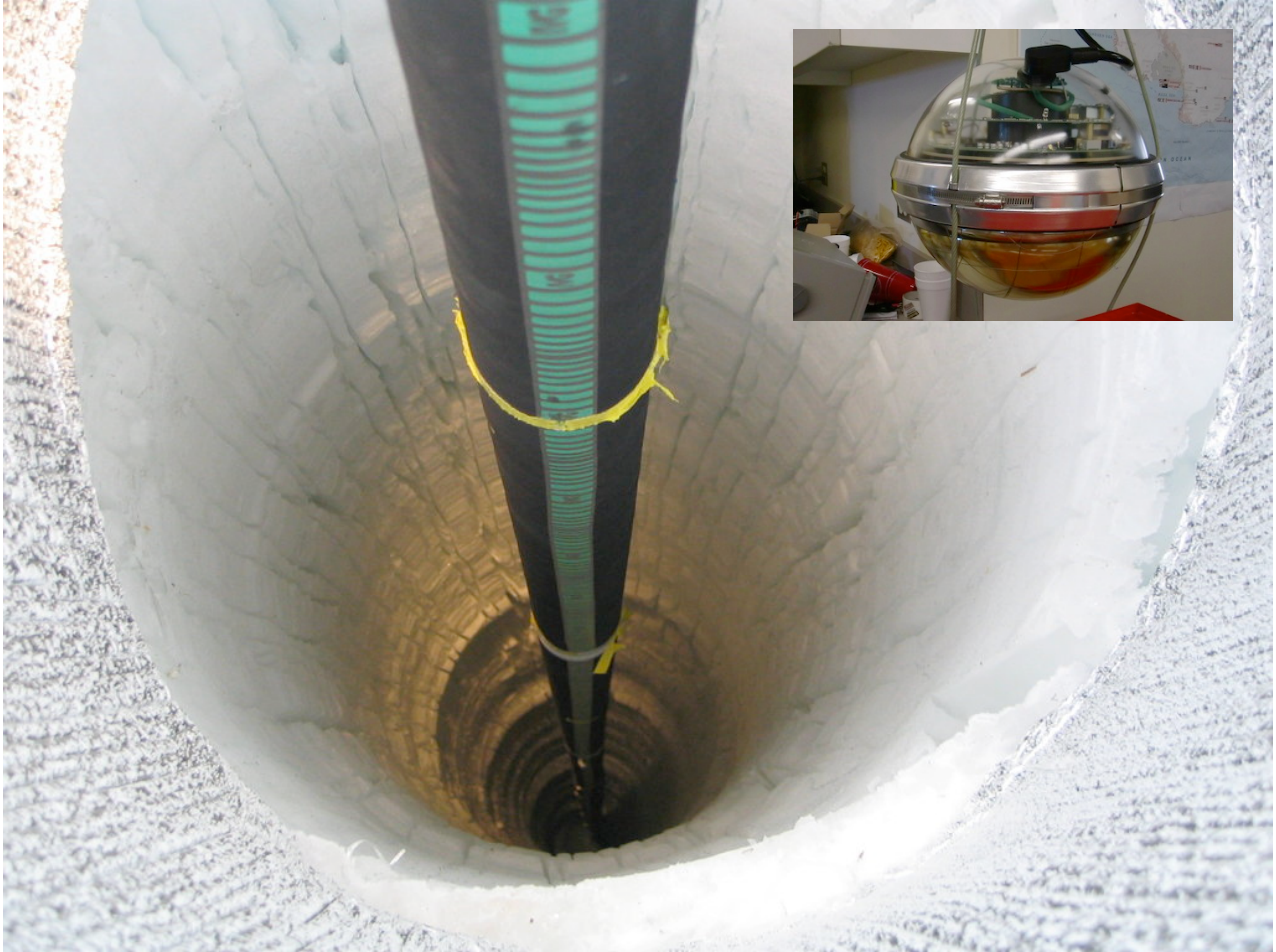
Kamiokande



High energy neutrinos

Multimessenger era


IceCube
South Pole Neutrino Observatory
50 m
IceTop
IceCube Laboratory
Data from every sensor is collected here and sent by satellite to the IceCube data warehouse at UW–Madison
1450 m
Digital Optical Module (DOM)
5,160 DOMs deployed in the ice
IceCube
2450 m
2820 m
bedrock
Amundsen–Scott South Pole Station, Antarctica
A National Science Foundation-managed research facility
86 strings
DeepCore
Eiffel Tower
324 m



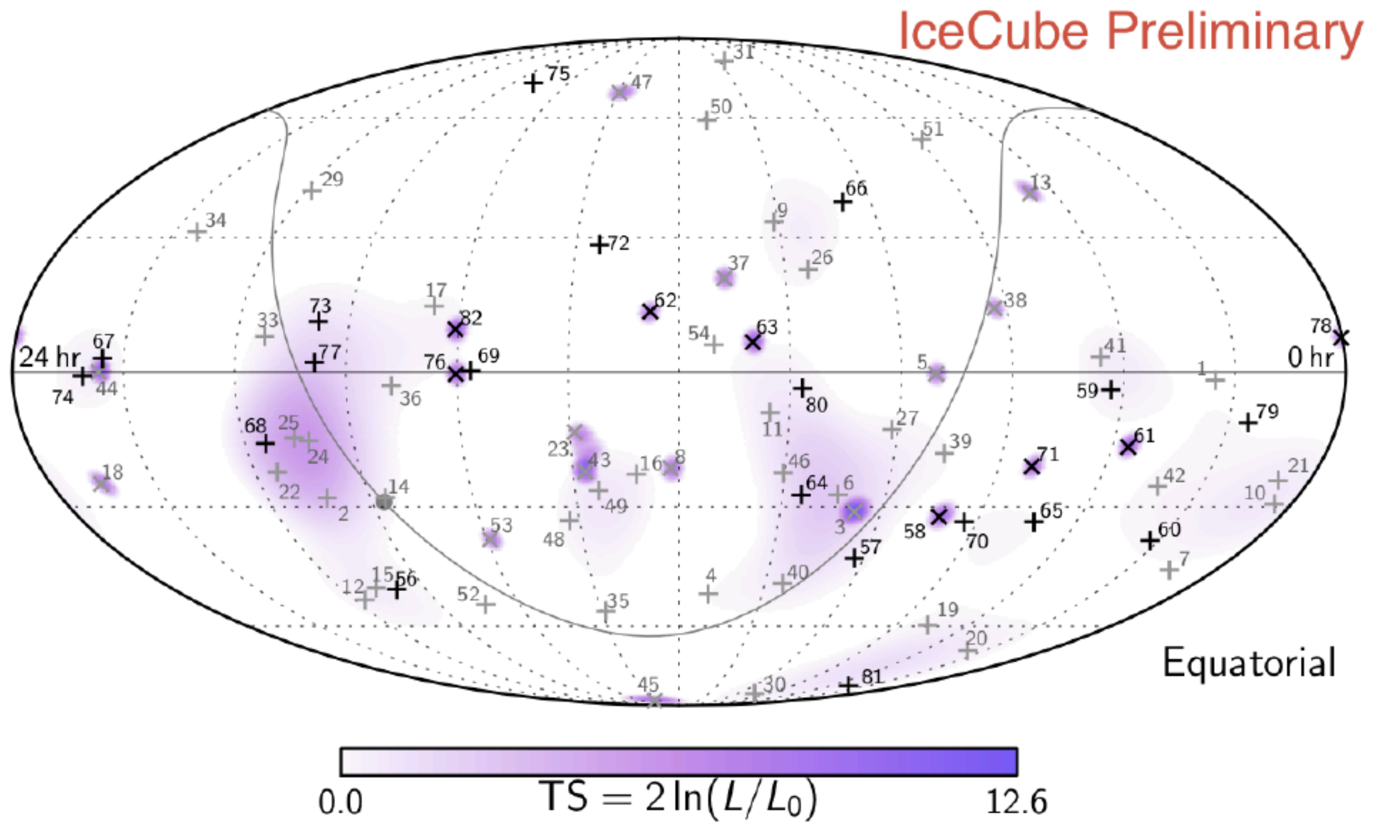
Very HE neutrinos observed in IceCube

- IceCube has detected >**100 very high energy neutrino events** in **10 years of data taking**. This is a solid evidence of astrophysical neutrinos from a cosmic source.

- IceCube has observed a **diffuse flux of astrophysical neutrinos**. After 10 years of data, IceCube points to the possibility that the neutrino sky map might not be isotropic.

- More data are needed to understand the source of this astrophysical flux

- IceCube continues collecting more data



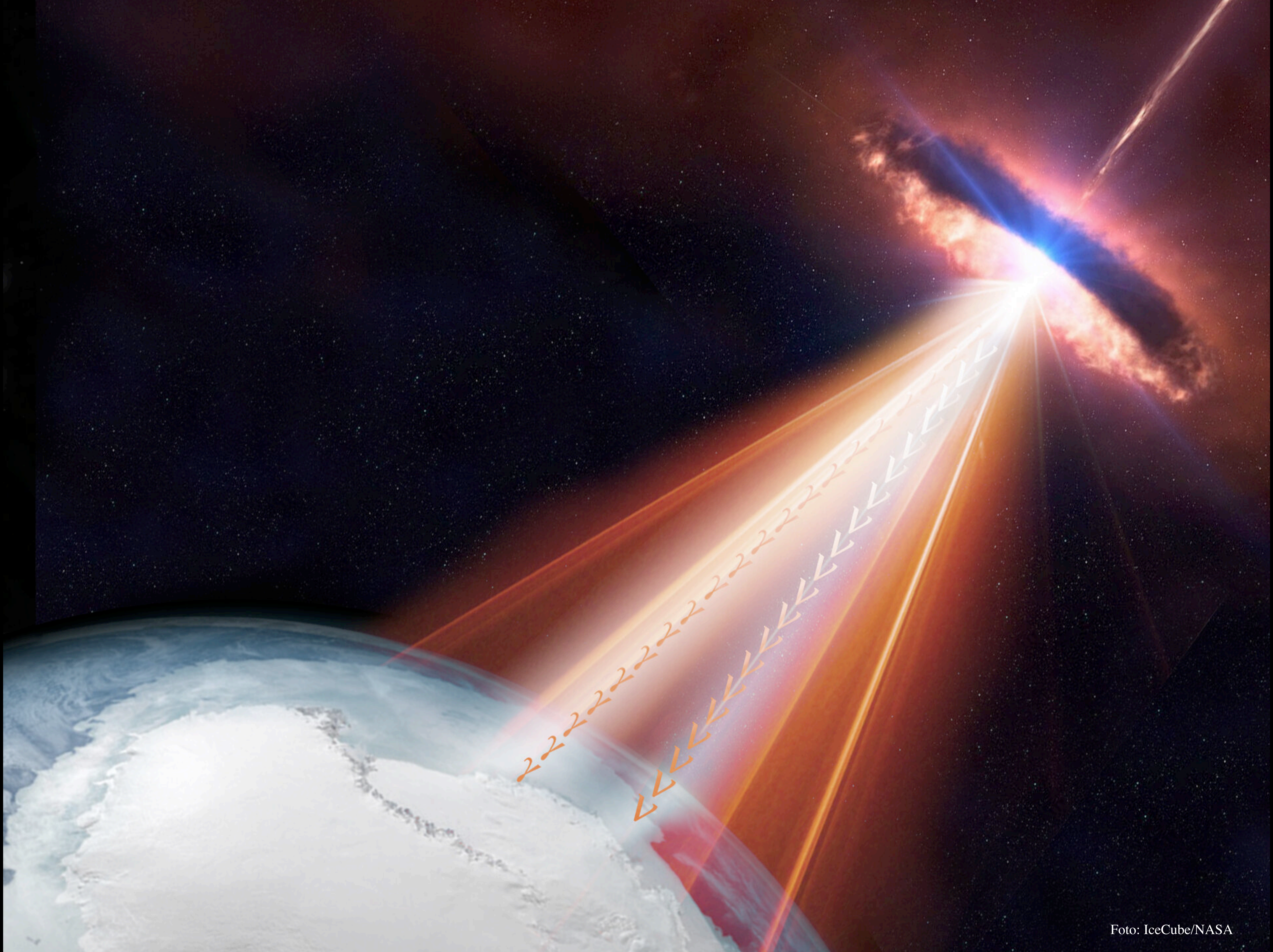
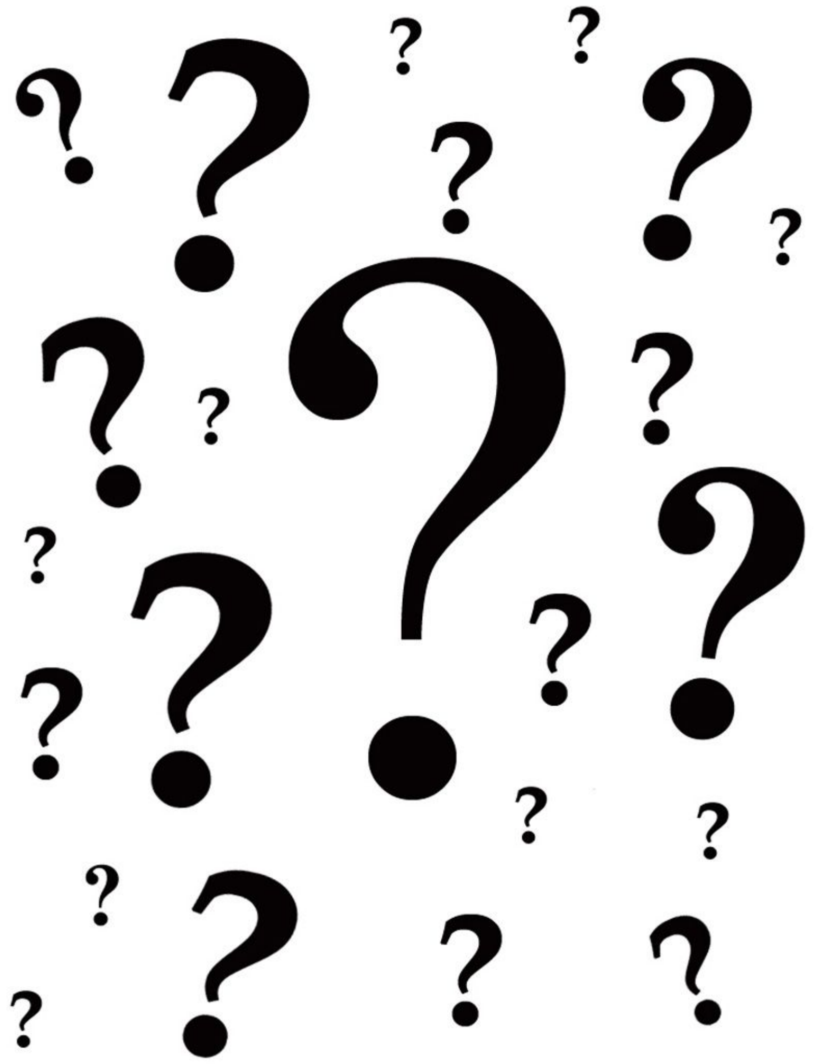


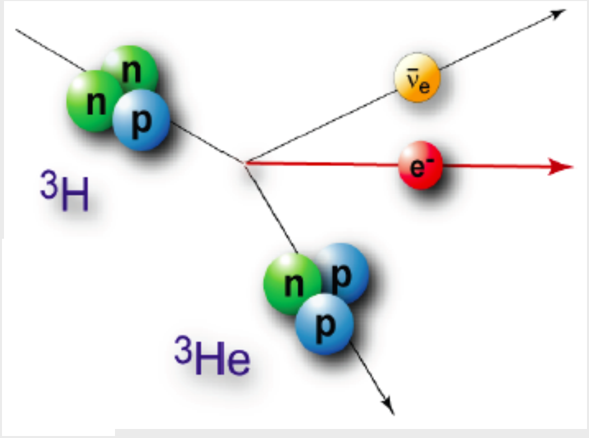
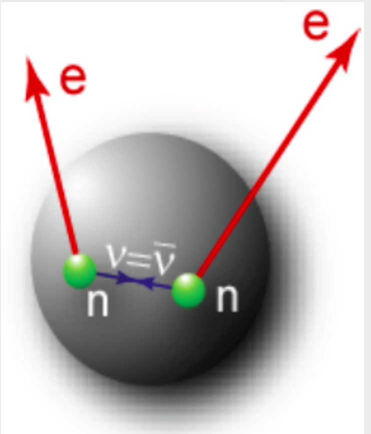
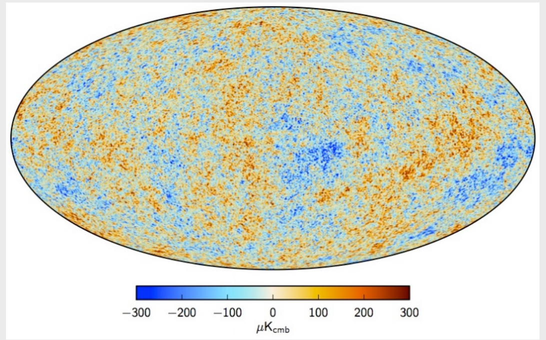
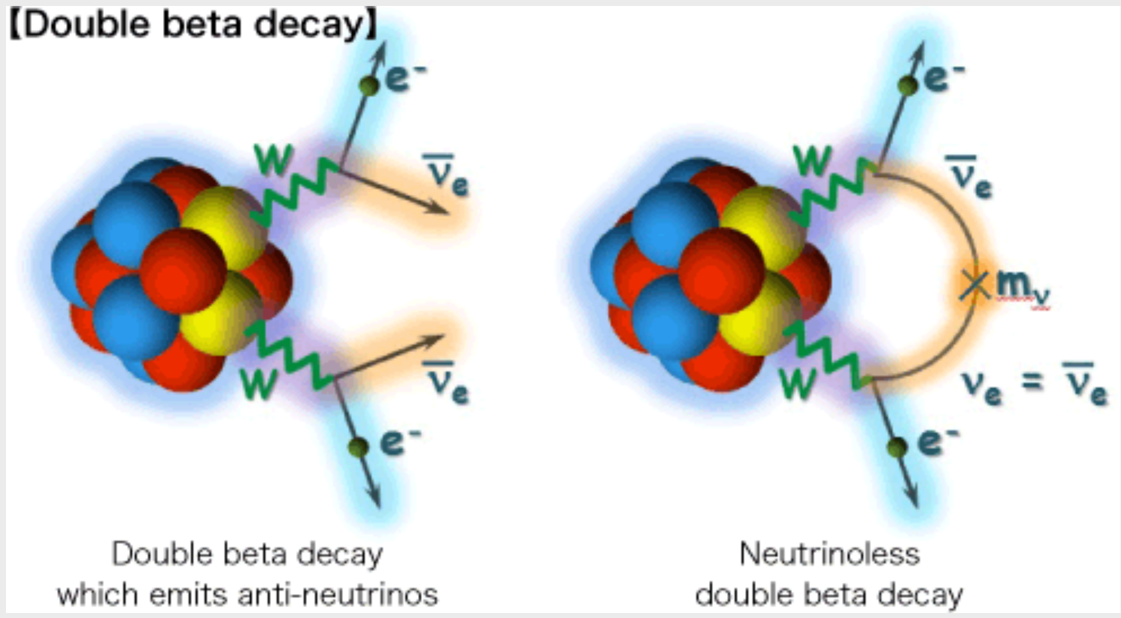
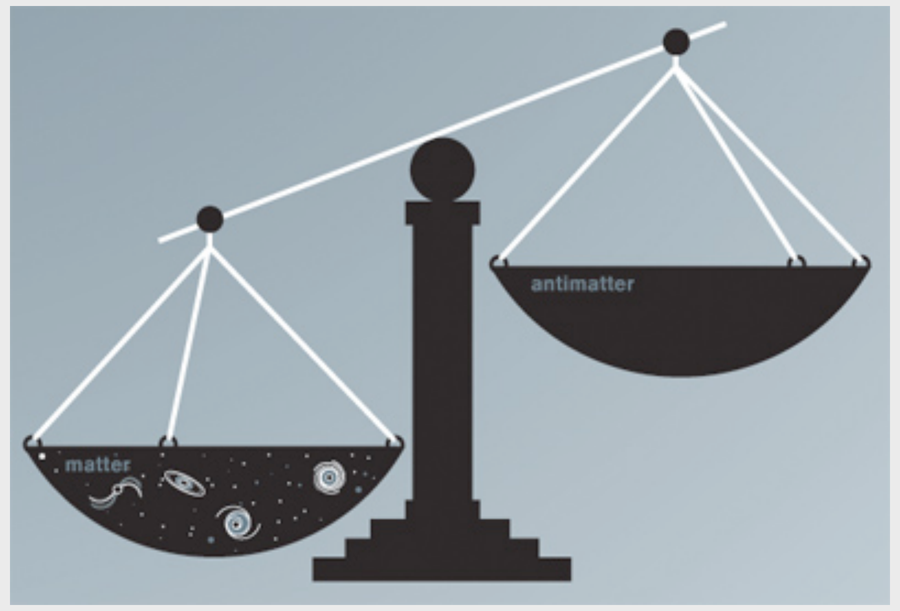
Foto: IceCube/NASA

IceCube 170922
22 sept 2017
The MAGIC telescope detects gamma ray emission of E > 90 GeV
290 TeV neutrino
The FERMI satelite detects gamma rays from blazar TXS 0506+056 with 0.1° precision
B
Declination
Right Ascension
MAGIC significance [σ]
TXS 0506+056
PKS 0502+049
MAGIC PSF
A
original GCN Notice Fri 22 Sep 17 20:55:13 UT
refined best-fit direction IC170922A
IC170922A 50% - area: 0.15 square degrees
IC170922A 90% - area: 0.97 square degrees
3FHL
3FGL
Fermi-LAT Counts/Pixel

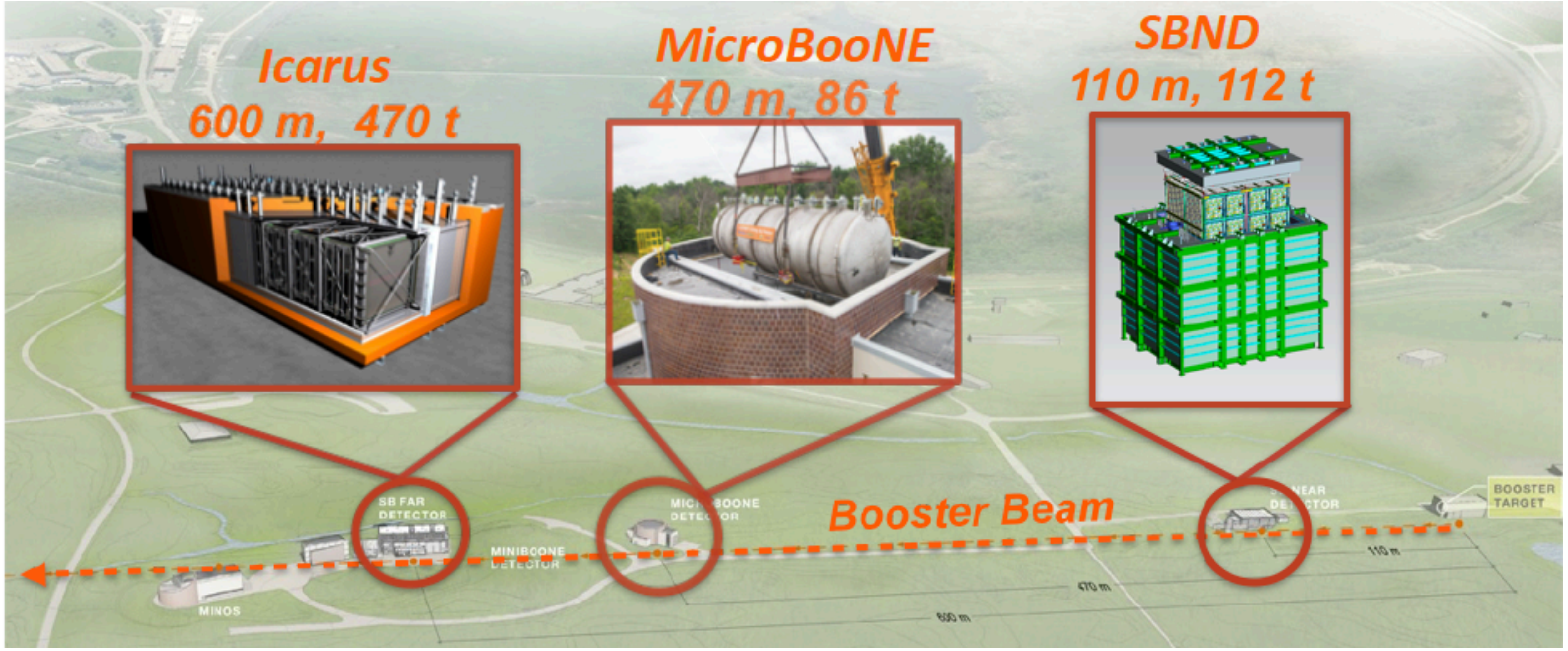


Big questions to be answered

Big questions

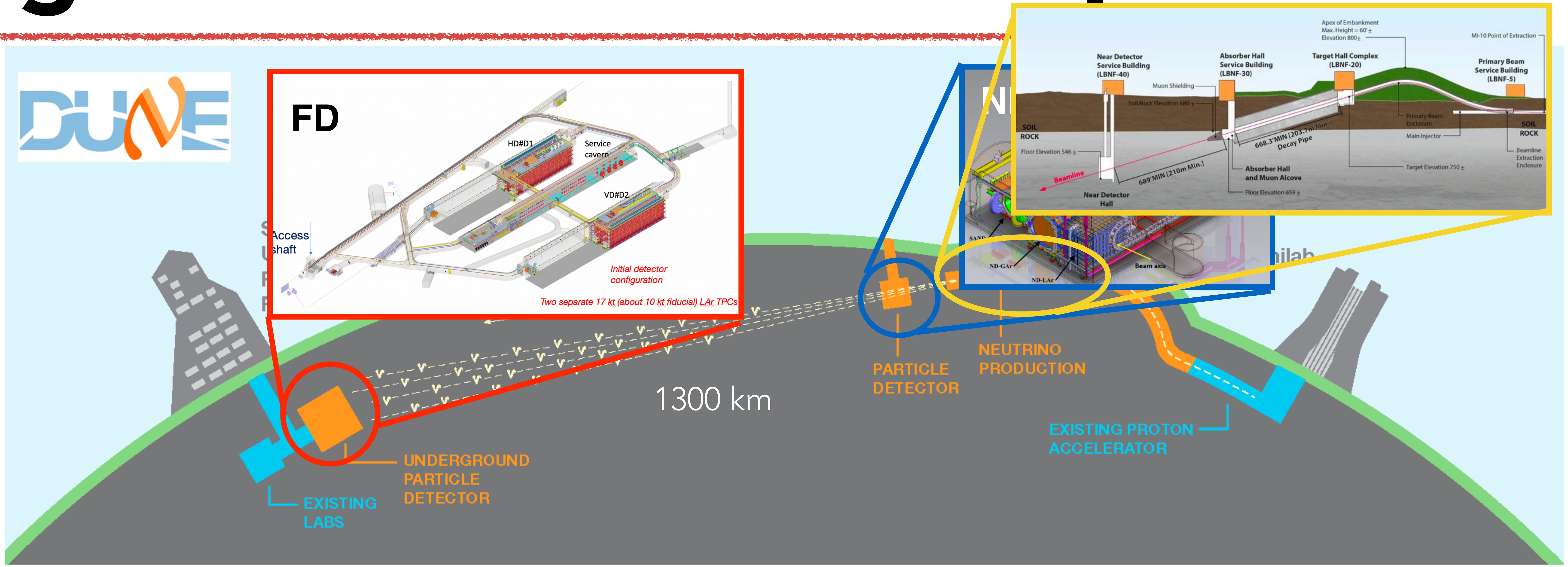
Mass value and origin?	Type of particle: Dirac o Majorana?
  	
More than 3? **Sterile** neutrinos?	Neutrinos ≠ Antineutrinos? Is CP symmetry violated?
	

Short-baseline neutrino experiments



- **Short-baseline Neutrino (SBN) Program** at the Booster neutrino beam in Fermilab
  - Liquid argon detectors at different distances from the neutrino source
- **Goals:**
  - Understand neutrino **oscillation anomalies** found in other experiments (like MiniBooNE): sterile neutrinos
  - Measure cross-sections in Ar (**ν-Ar interactions**)
  - **Beyond the Standard Model** searches

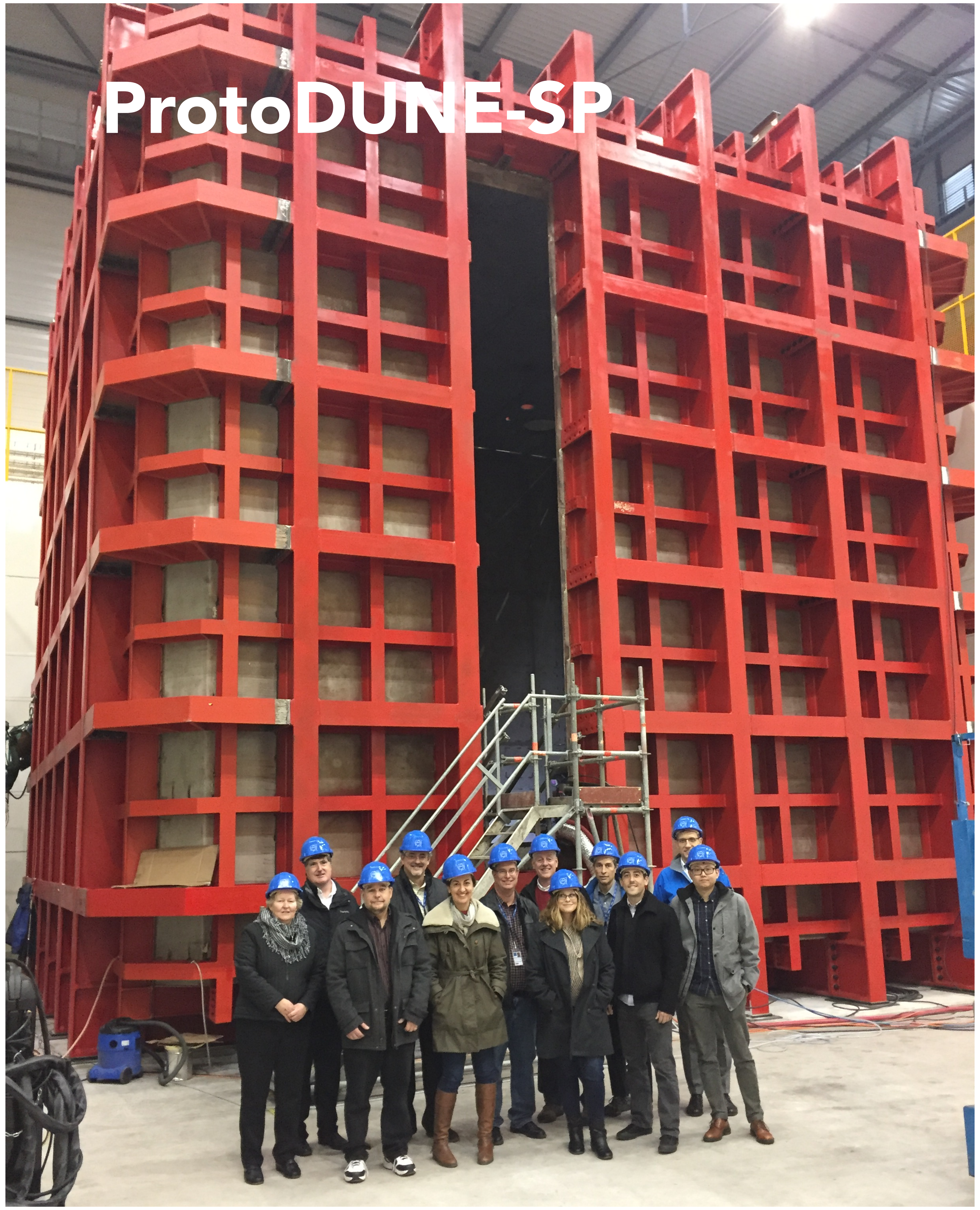
Long-baseline neutrino experiments



- The most powerful **neutrino beam** in the world will be sent from **Fermilab** (Chicago) to **SURF** (South Dakota) along **1300 km** distance to be detected by huge liquid argon modules (**70000 LAr ton**) at 1.5 km deep underground
- **Goals**:
  - Precise measurement of **neutrino oscillations** (mass ordering, differences between neutrinos and antineutrinos - CP violation)
  - Detection of **supernova neutrinos**
  - **Beyond the Standard Model** searches (proton decay, sterile neutrinos, non-standard interactions, dark matter…)

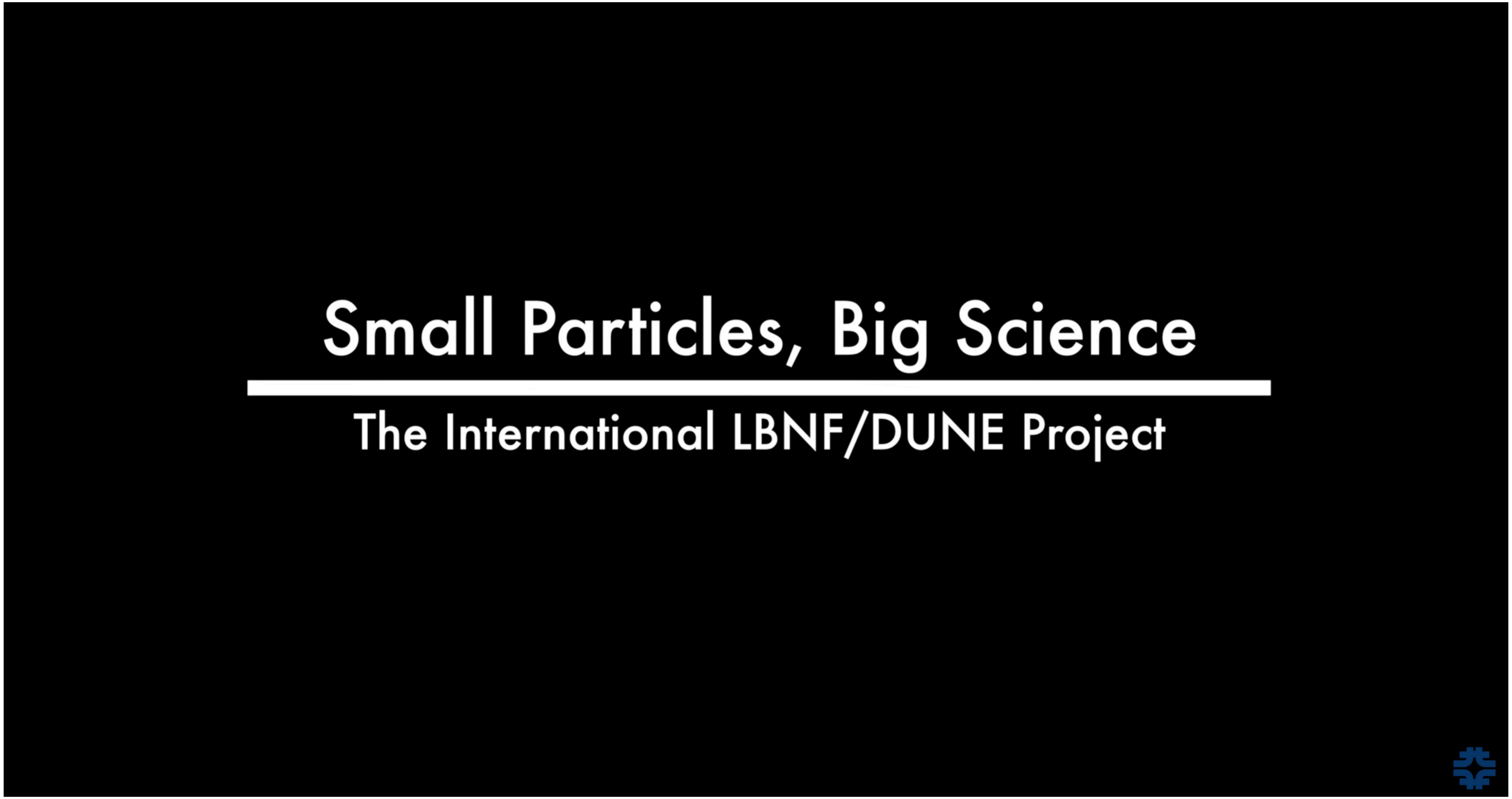
CERN Neutrino Platform

Cryostats built at CERN




Genie
Genie
Genie AWP-20S


JLG
20MVL



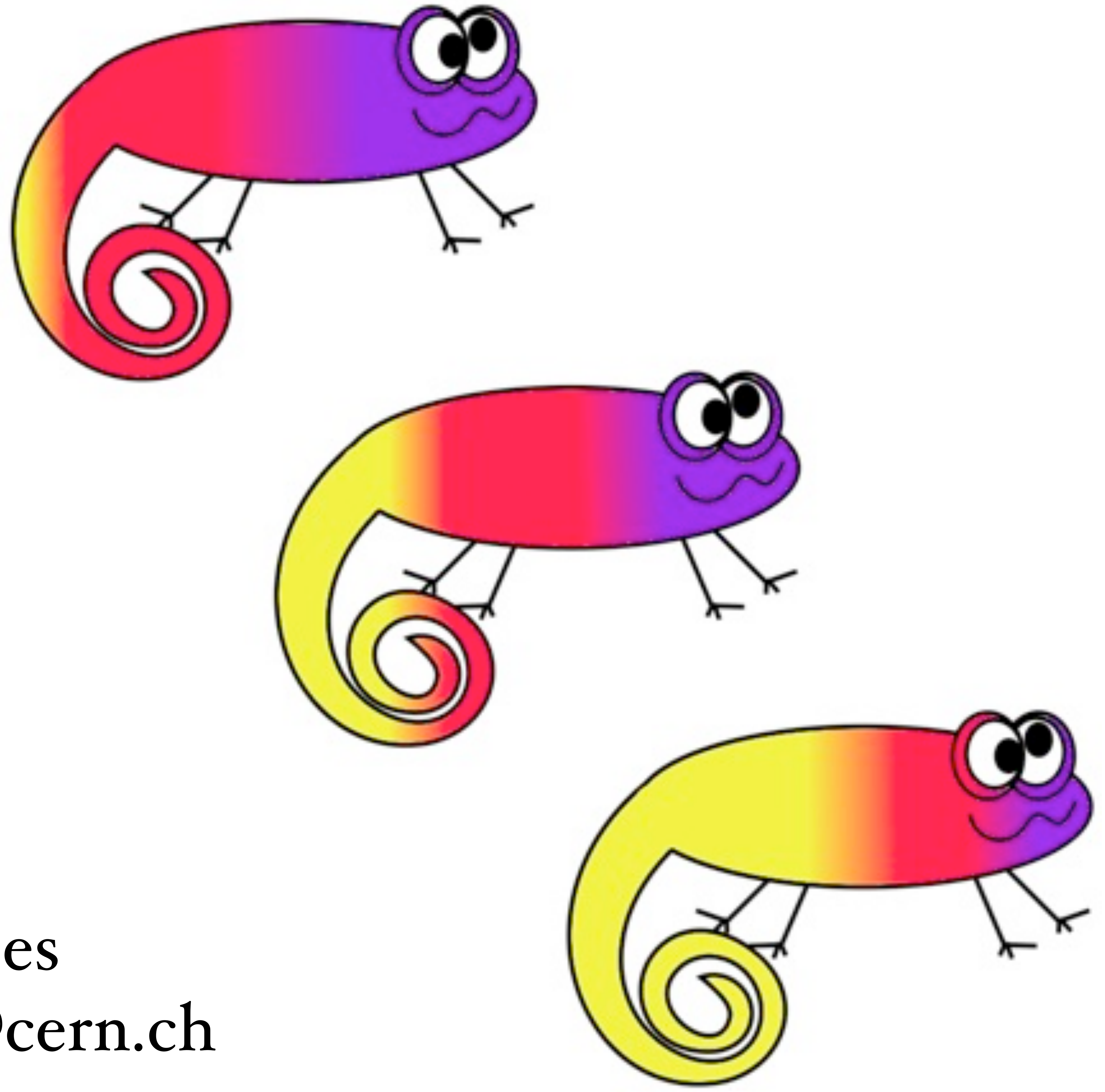
https://www.youtube.com/watch?v=AYtKcZMJ_4c

Conclusions

Wrap-up

- Neutrinos are **extremely abundant** in the Universe
- They carry crucial **information about the phenomena in the Cosmos**
- Neutrinos have **mass** but it is **extremely small** (the exact value is unknown)
- They **mix flavors** (oscillation)
- They **interact** very **weakly with matter** →. very difficult to catch them!
- There could be **more than 3 neutrinos**
- Neutrinos could explain the **excess of matter in the Universe**

Neutrinos still have surprises for us!



Thank you!
Gracias!

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