Università degli Studi di Napoli Federico II - Dipartimento di
Fisica "Ettore Pancini"

Understanding the Universe with neutrinos

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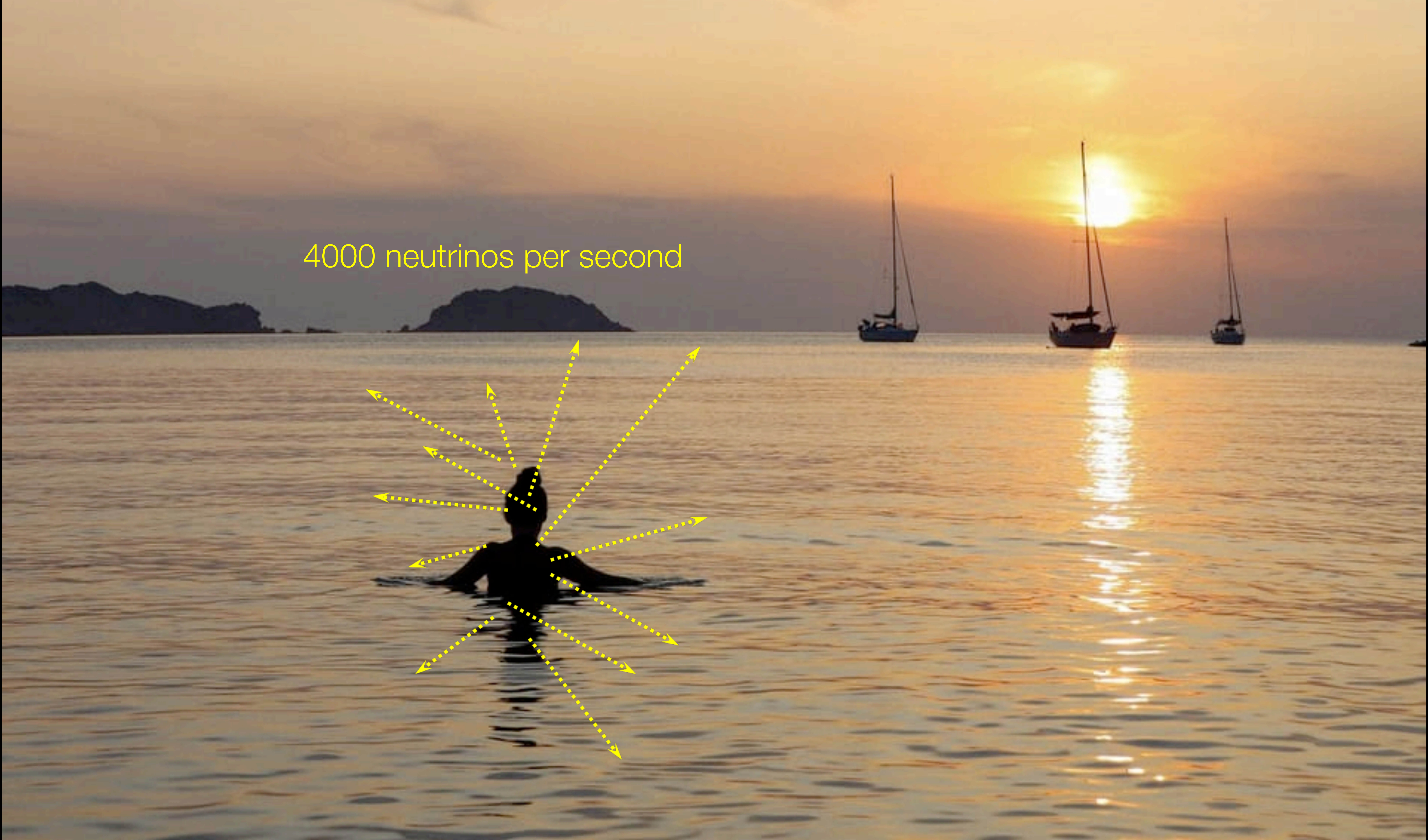
Ciemat
Centro de Investigaciones Energéticas, Medioambientales y Tecnológicas

Outline

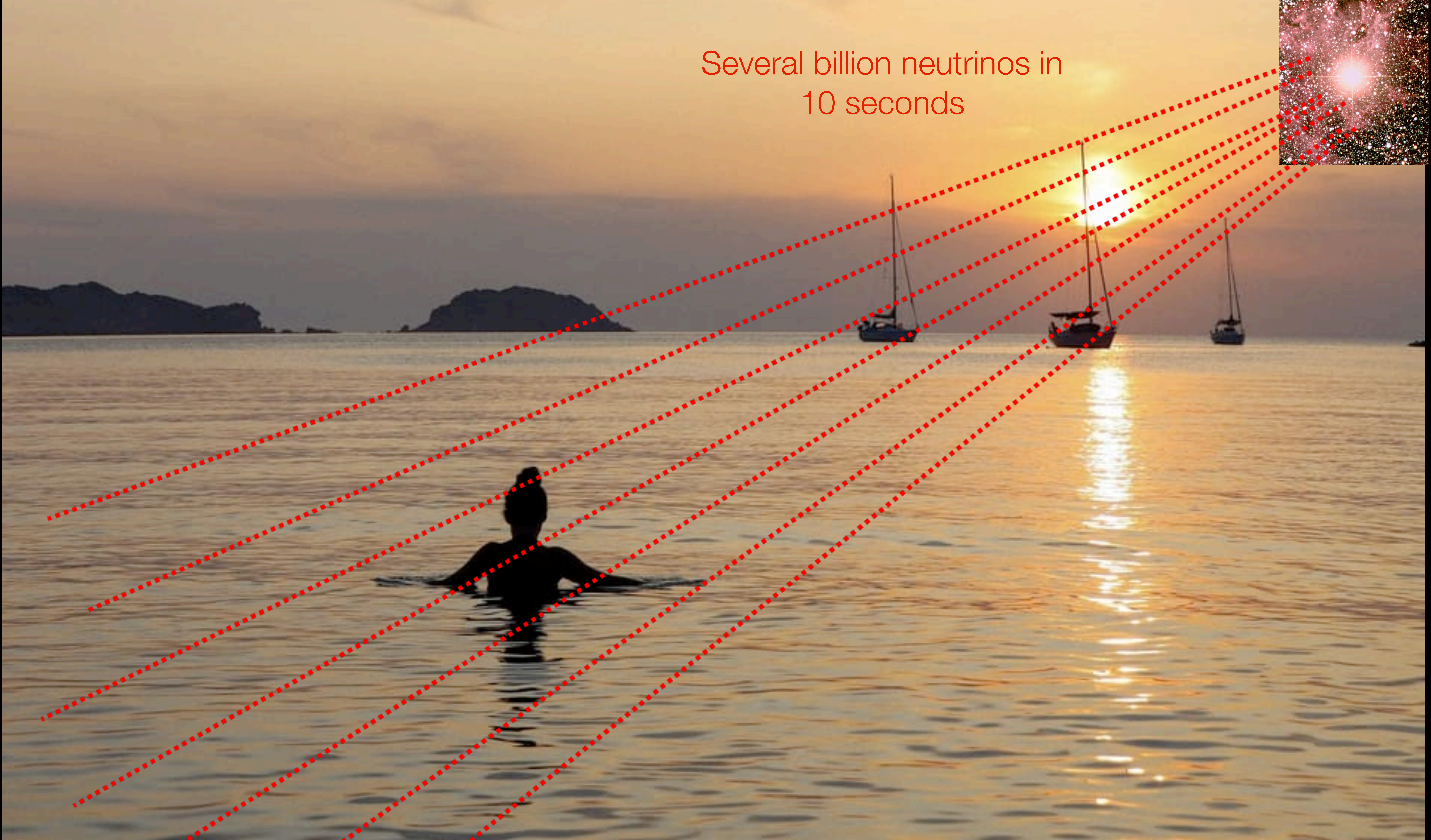
1. Neutrinos and Particle Physics
2. Neutrino detection
3. Messengers of the Universe
4. Major challenges and future discoveries
5. Conclusions

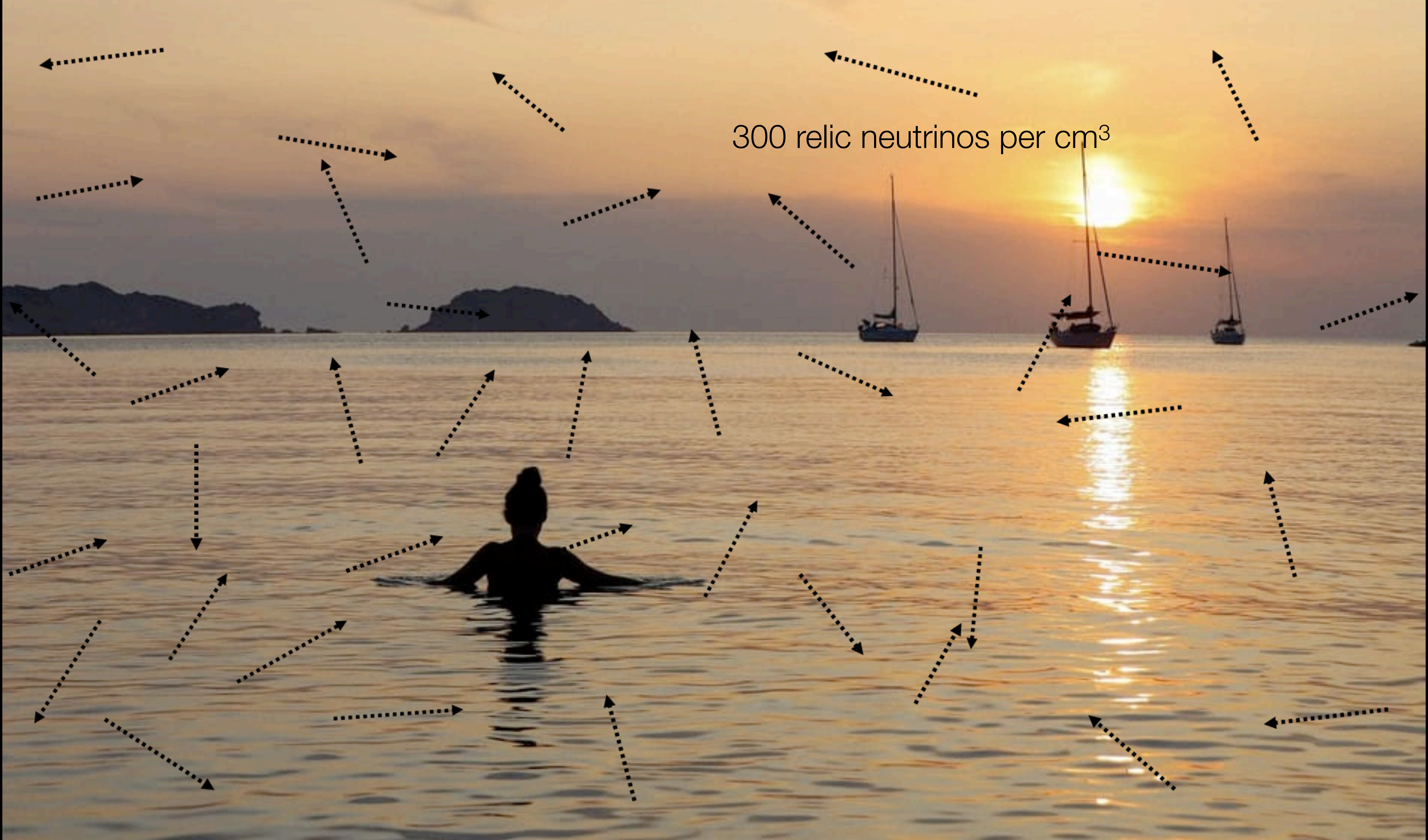
Artwork by Sandbox Studio

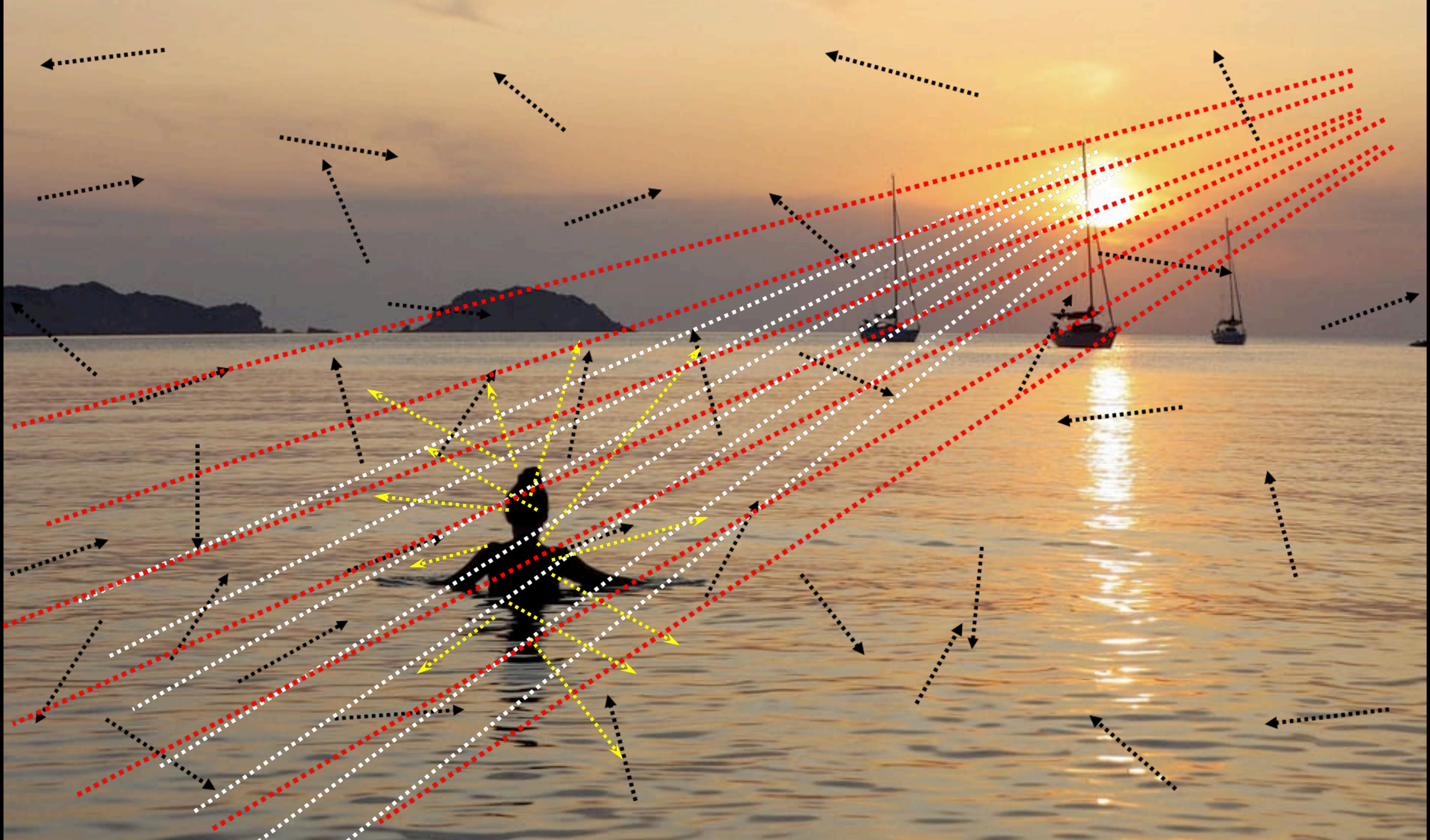
- The visible is only a small part of the energy and mass of the Universe
- For every electron, proton and neutrino in the Universe, there are **1 000 000 000 neutrinos!!**
- To understand the Universe, we have to understand neutrinos


4000 neutrinos per second


65 billion neutrinos
per cm² per second

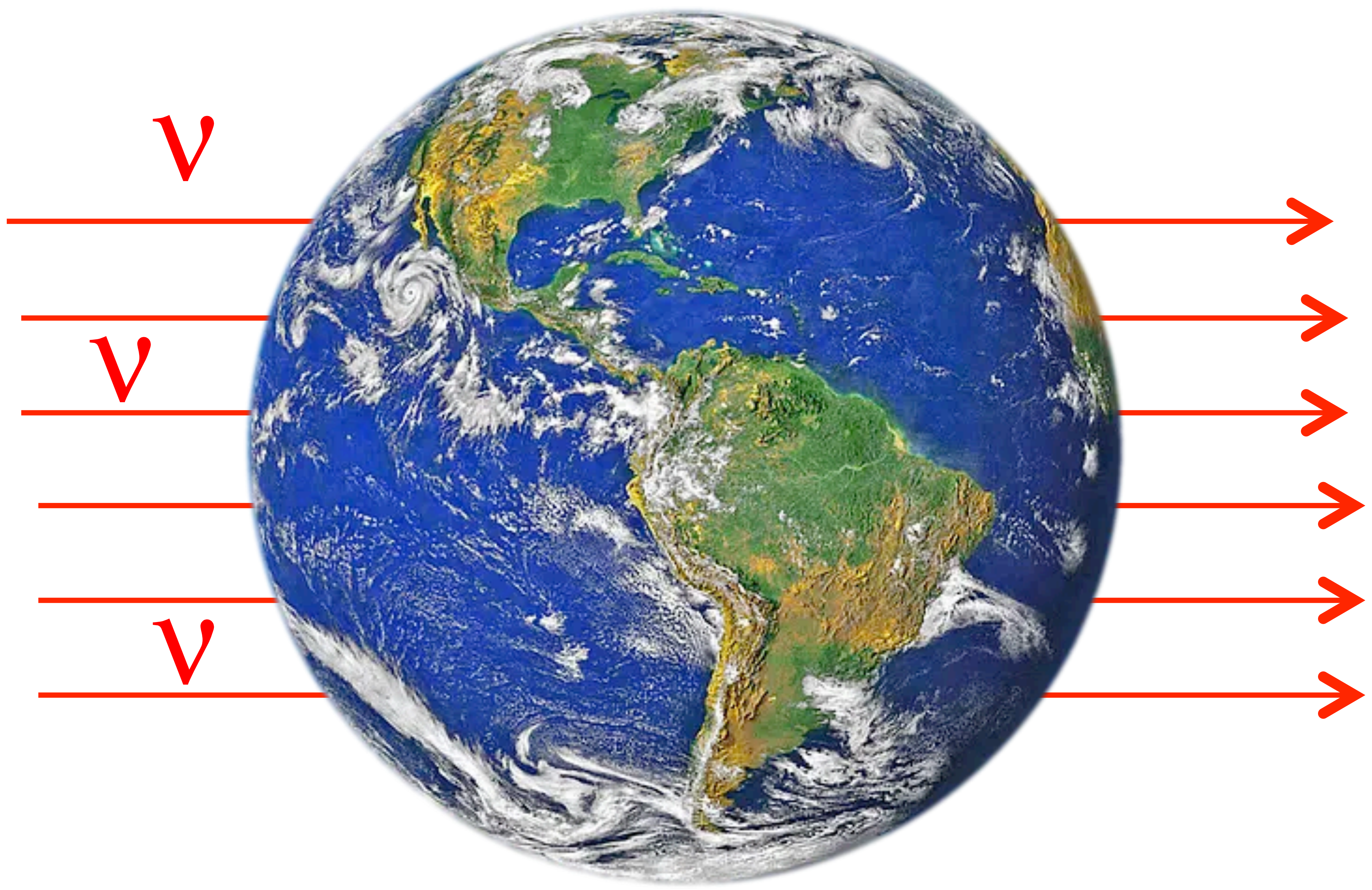

Several billion neutrinos in
10 seconds


300 relic neutrinos per cm^3



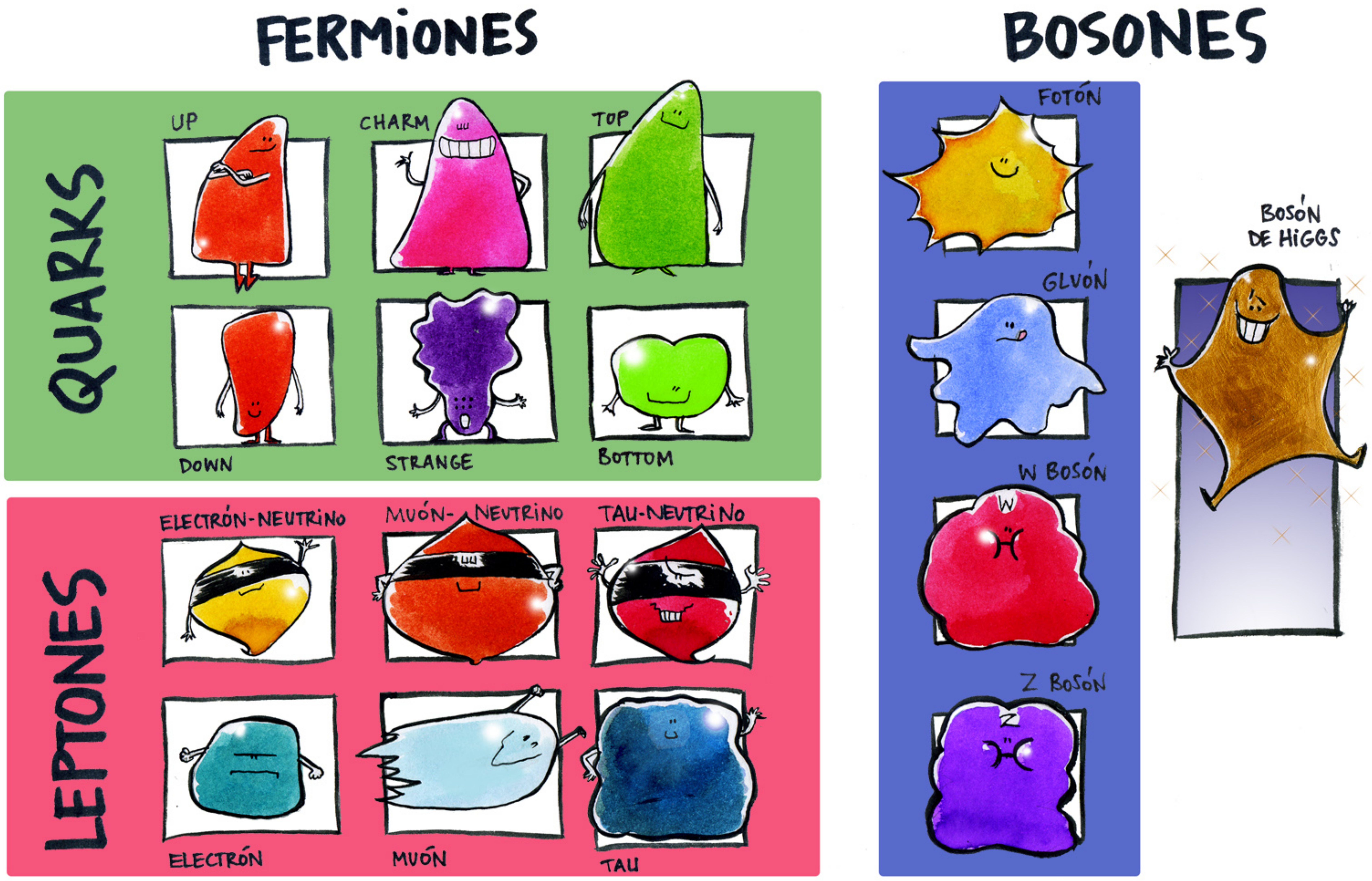
Neutrinos are constantly bombarding us...

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



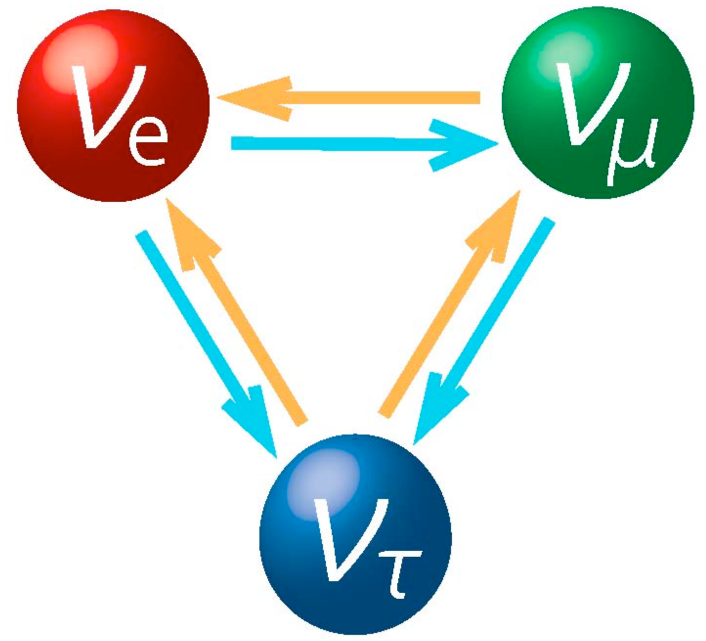
Only 1 neutrino in several billions is intercepted when traversing the Earth

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

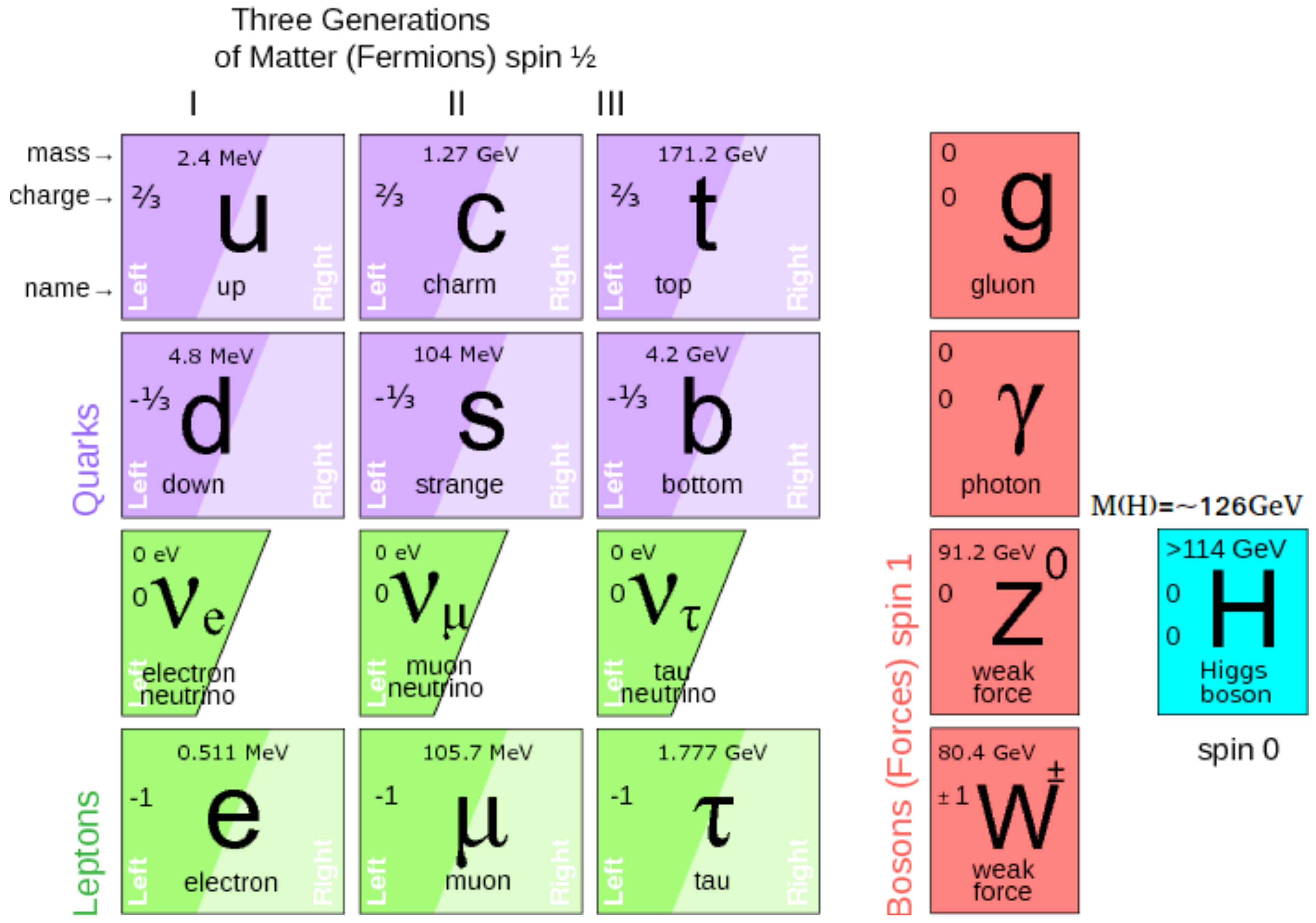


1 Neutrinos and Particle Physics

Neutrinos and the Standard Model

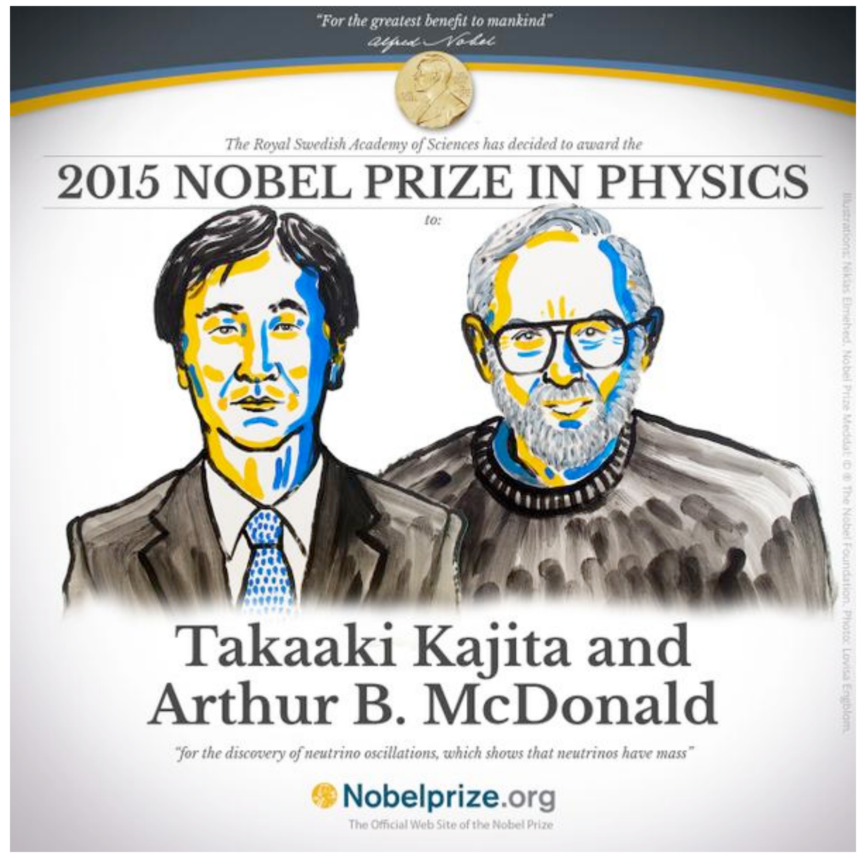


- The last 20 years have been a **revolution for neutrino physics**



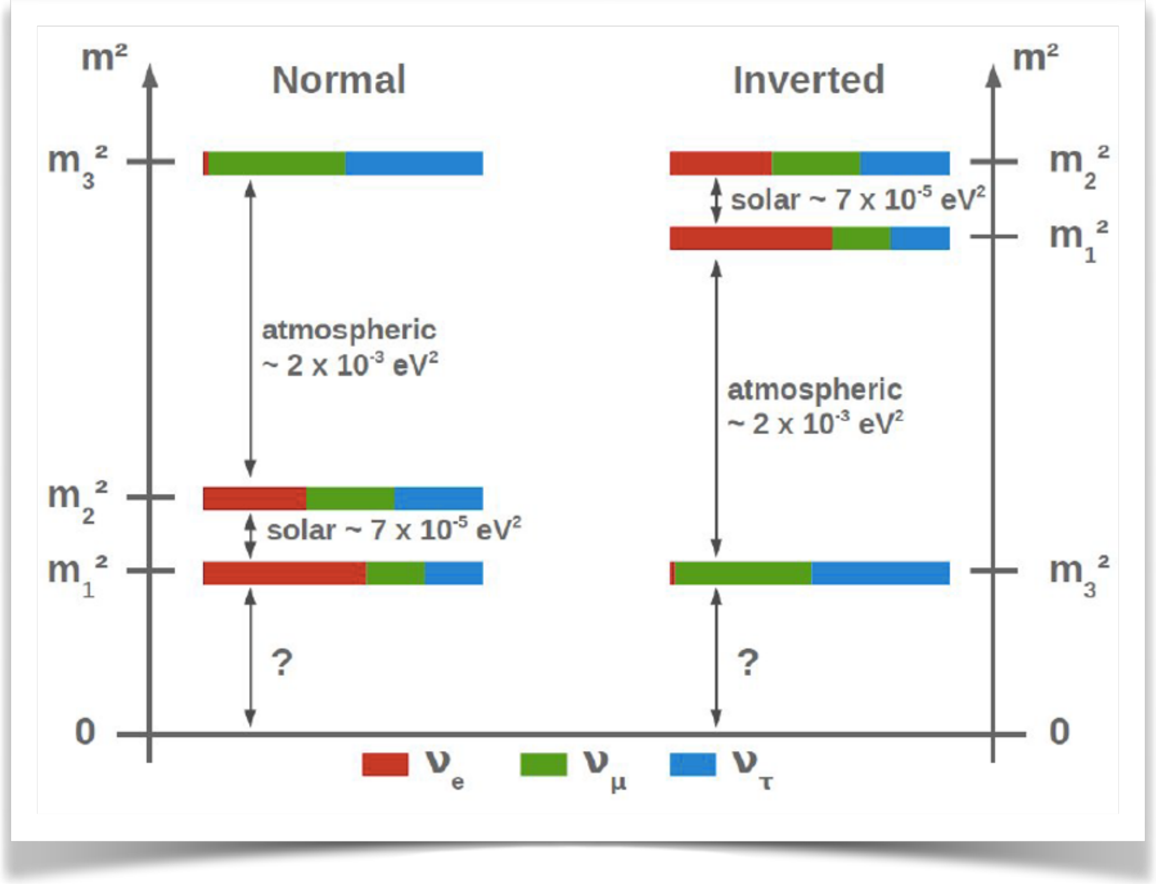
- The only neutral fermion in the SM
- Very weak interaction with matter
- 3 types of neutrinos
- Only left-handed neutrinos have been detected
- Much lighter than their charged leptonic partners (in the SM they are massless)
- Together with photons, they are the most abundant elementary particles in the Universe

- Observation of neutrino oscillations → **non-vanishing neutrino mass** (flavor mixing)
- First evidence of physics beyond the Standard Model

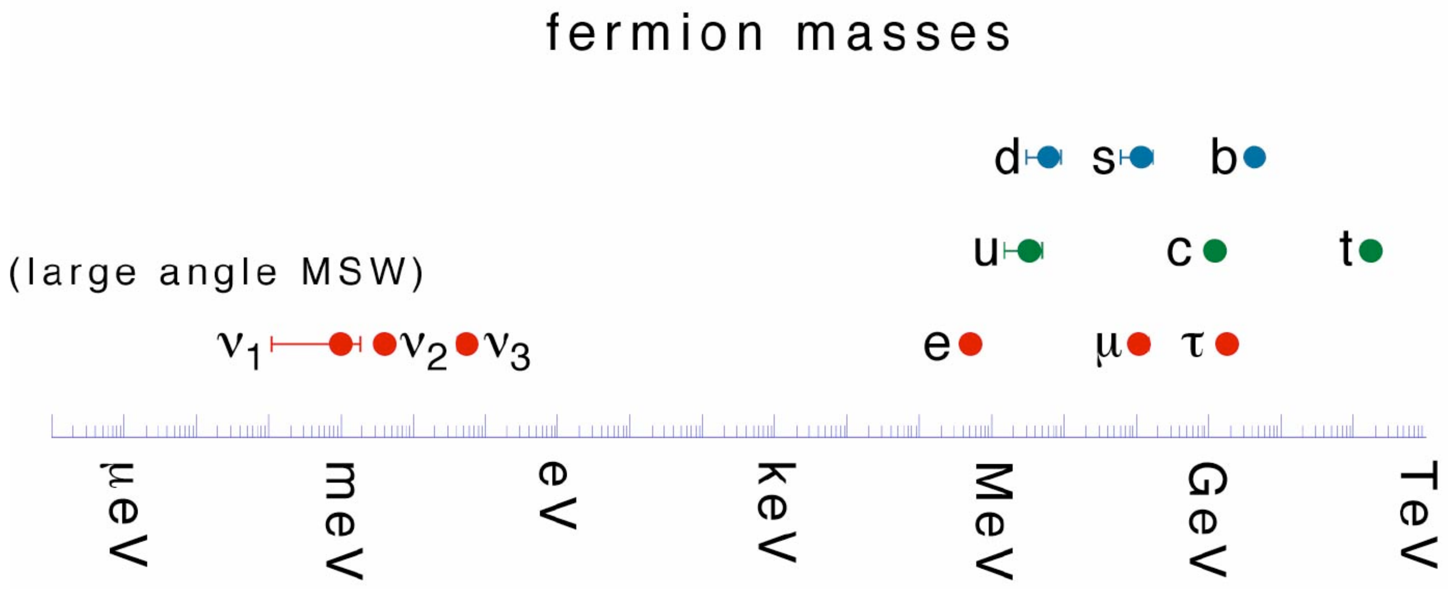


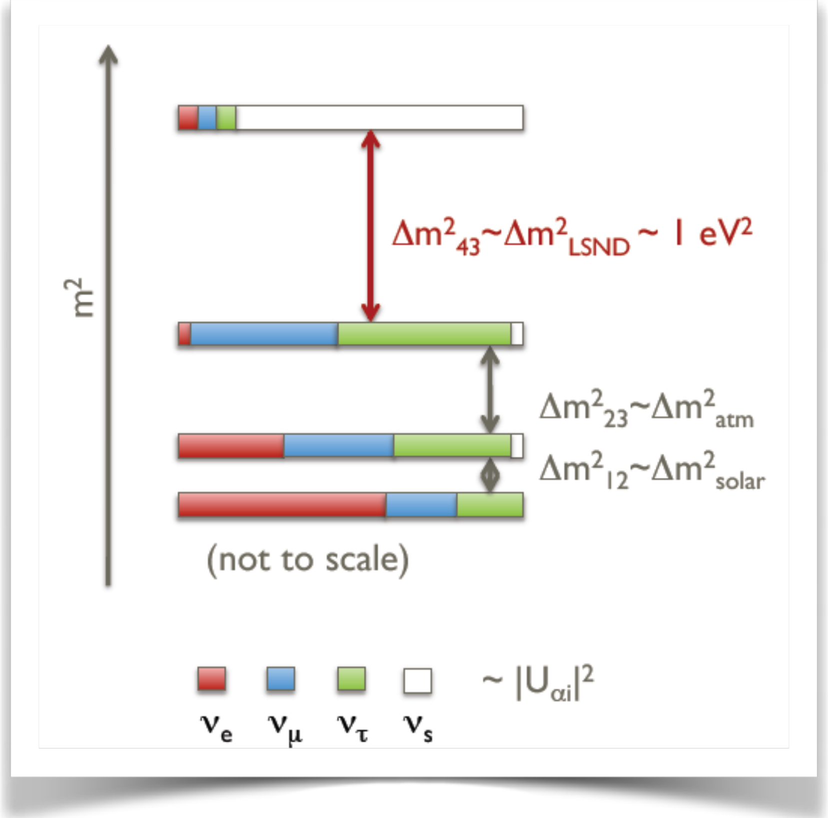
Main open questions

However, there are **fundamental unanswered questions**:



- ✦ What is the mass of neutrinos?
- ✦ Are neutrinos their own antiparticle? Dirac or Majorana?
- ✦ Why are neutrinos much lighter than the other fermions?
- ✦ What is the neutrino mass ordering?
- ✦ Is there CP violation in the lepton sector? CP-phase value?
- ✦ Are there any sterile neutrino states? If so, what are their masses?
- ✦ Deviations from unitarity of the PMNS matrix?

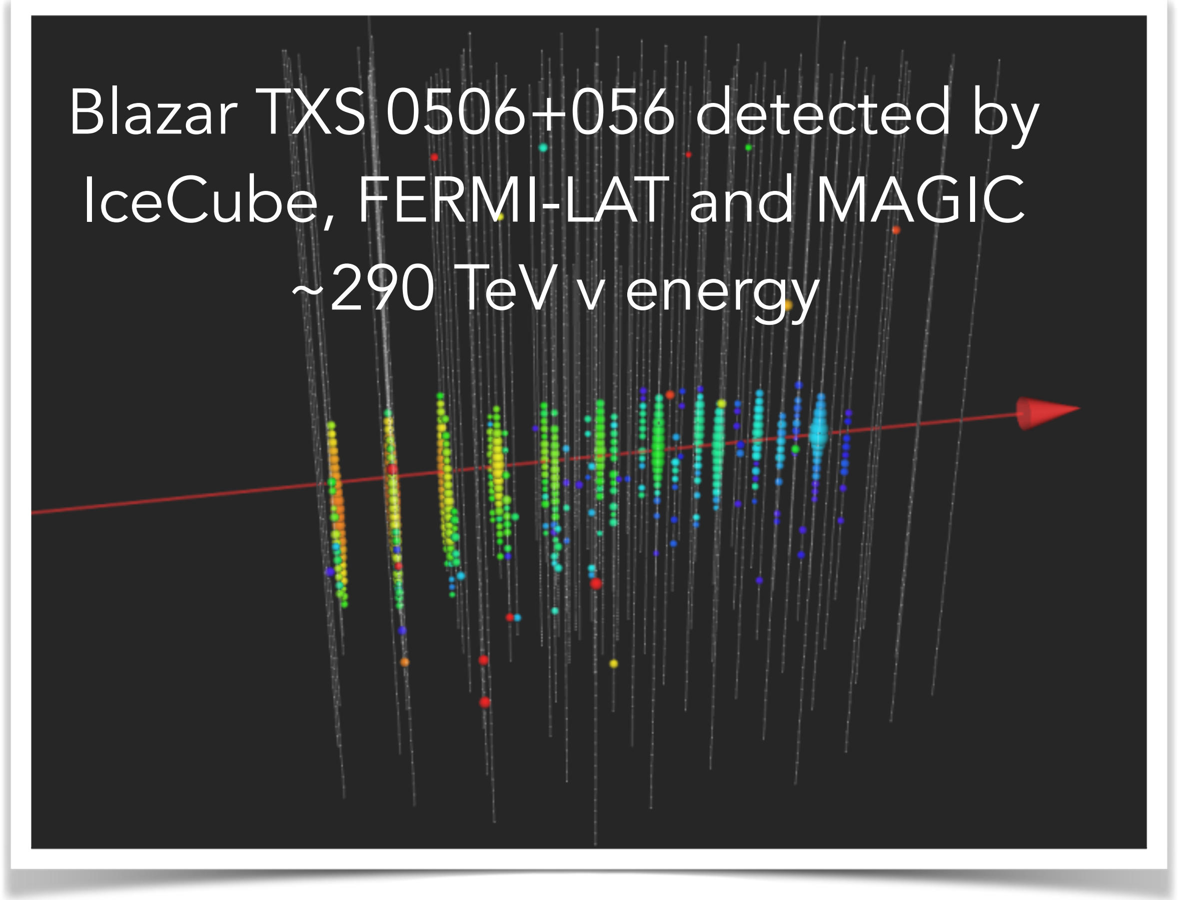


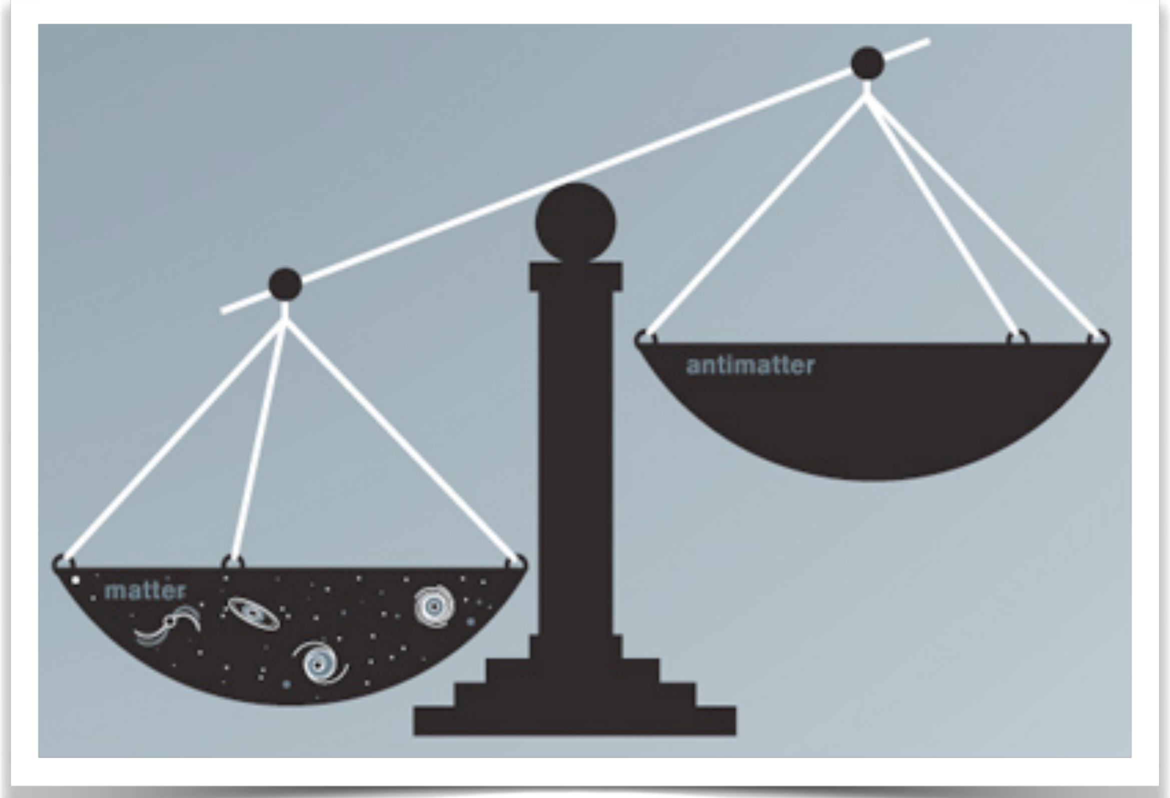


Connection with astrophysics and cosmology

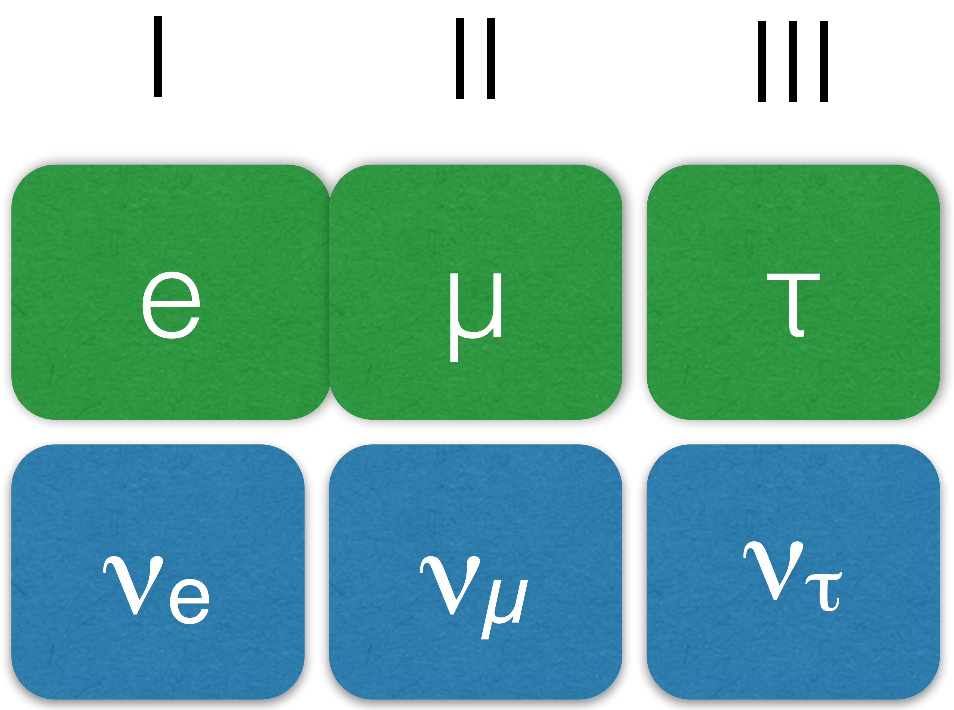
Neutrinos as **probes of the Universe**:

- ✦ High-energy neutrino physics
- ✦ New astrophysical sources
- ✦ Core-collapse supernova and diffuse SN neutrino background
- ✦ Relic neutrinos from early Universe
- ✦ Matter-antimatter asymmetry relation
- ✦ Sterile neutrinos as dark matter?

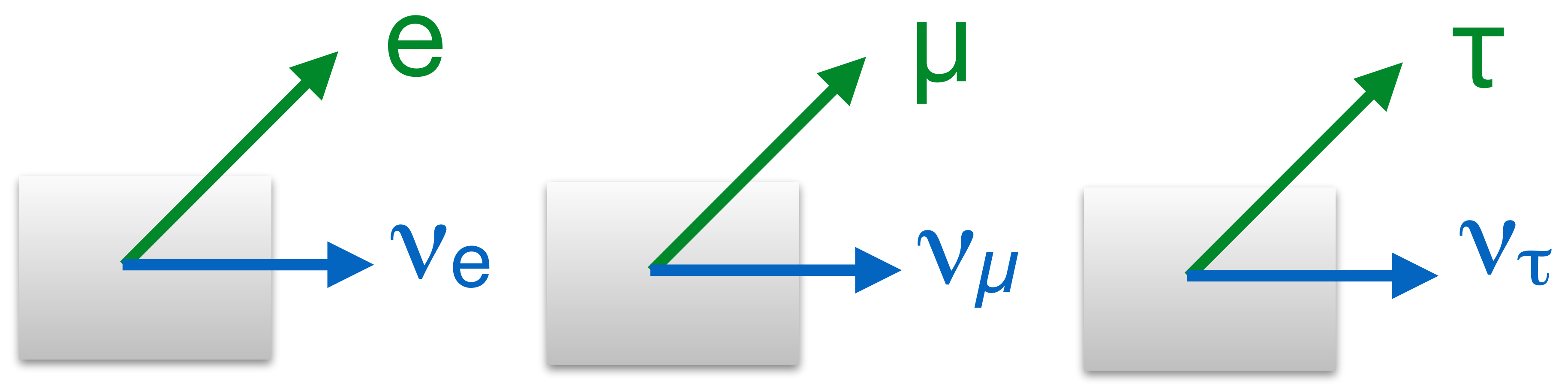




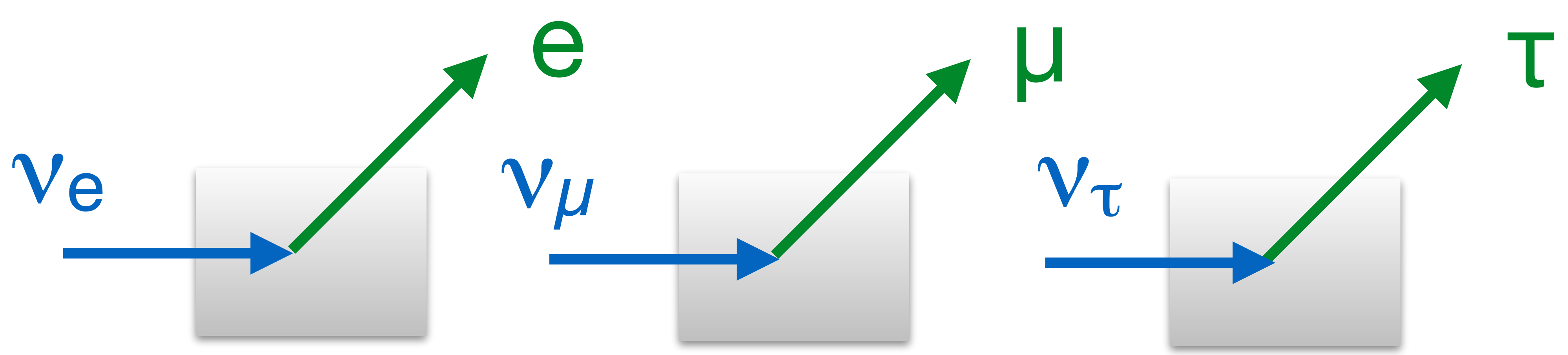
Neutrino interactions



- Magnitud:
  - A GeV **proton** travels **10 cm in lead**!!
  - **Neutrinos** produced by accelerators (~GeV) travel (on average) **1.500 millions of km in lead** before interacting
  - **Neutrinos** produced by the Sun (~1000 times less energetic ~MeV) travel (on average) **1.5 light-years in lead** before interacting



Neutrino appearance



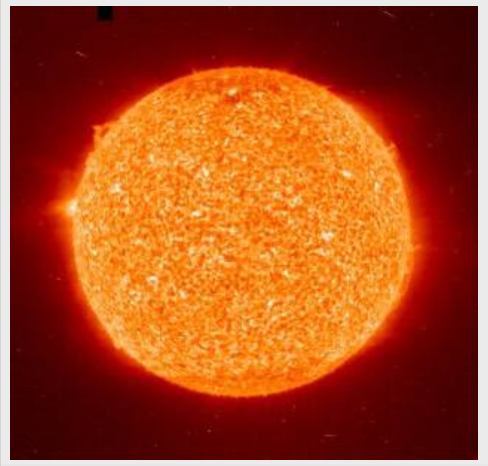
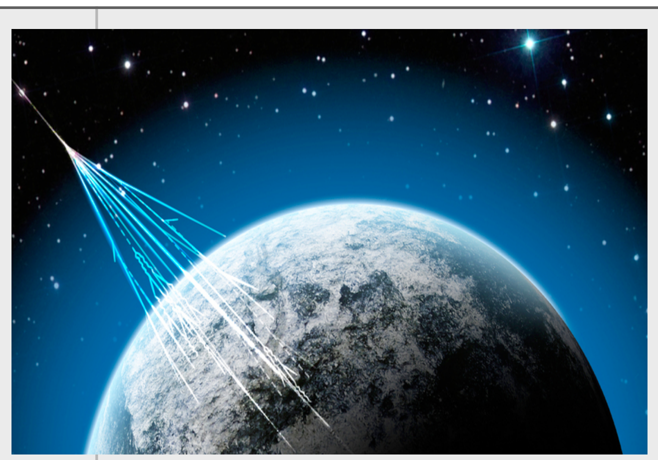
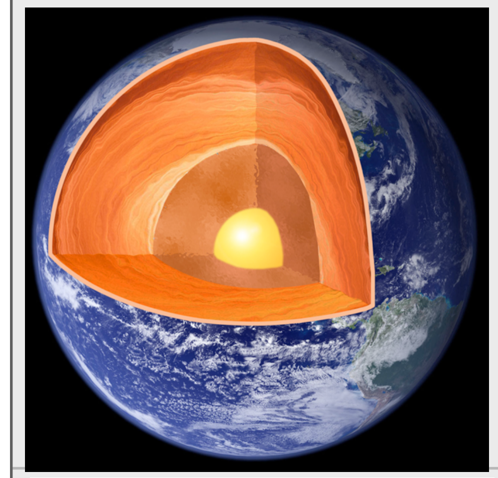
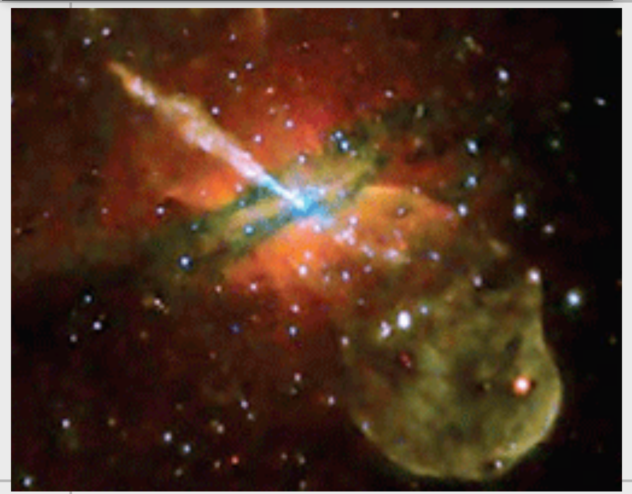
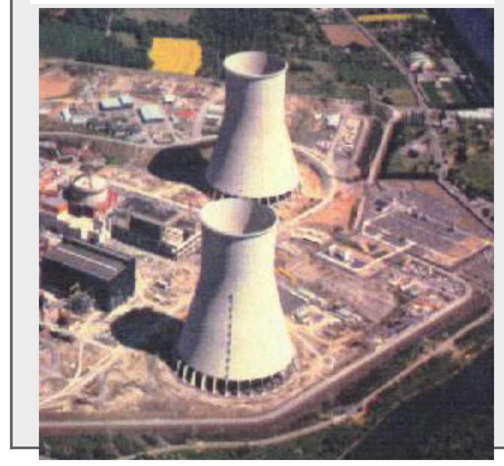
Neutrino disappearance

- 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

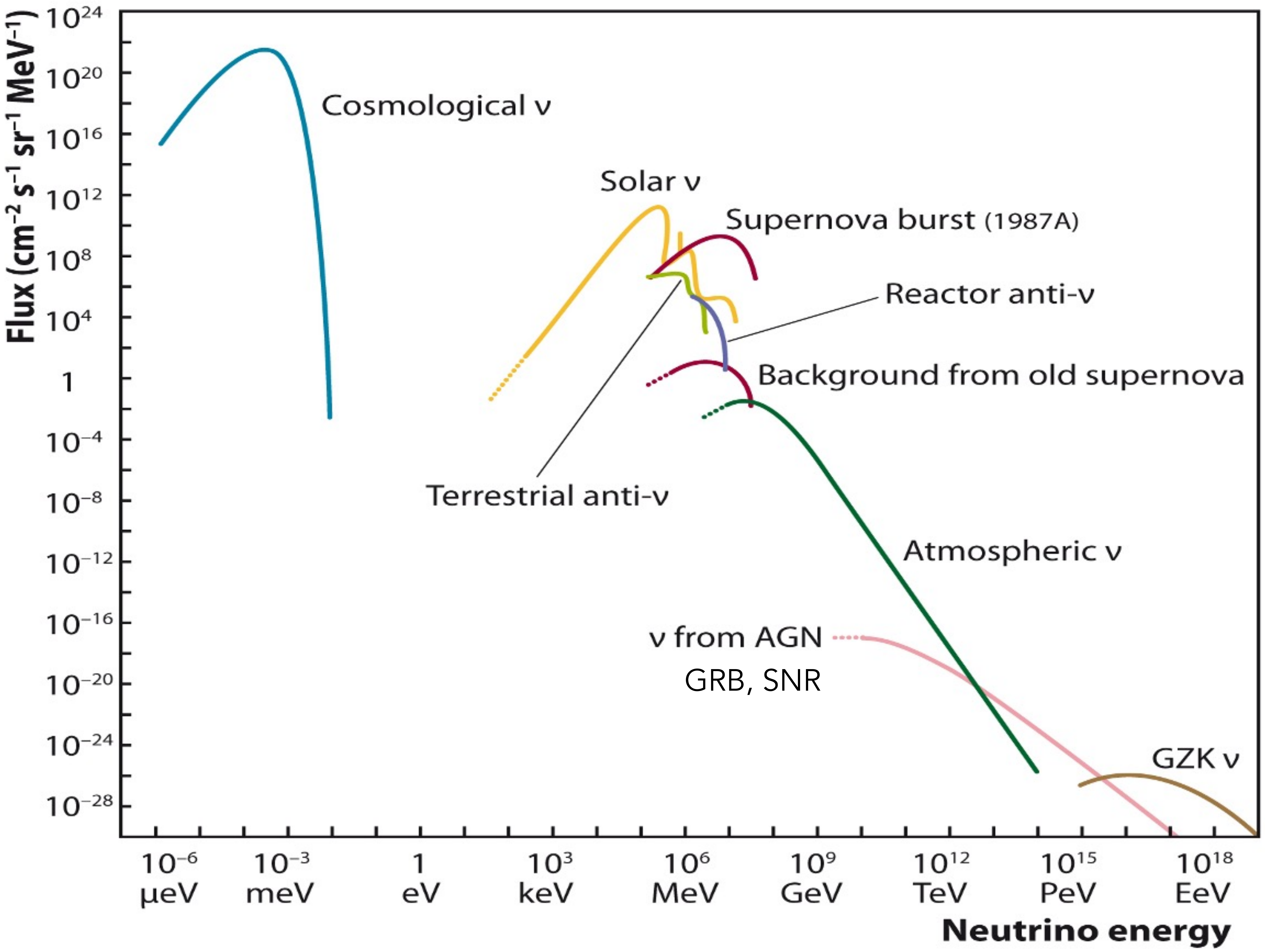
Neutrino sources

NATURAL

ARTIFICIAL

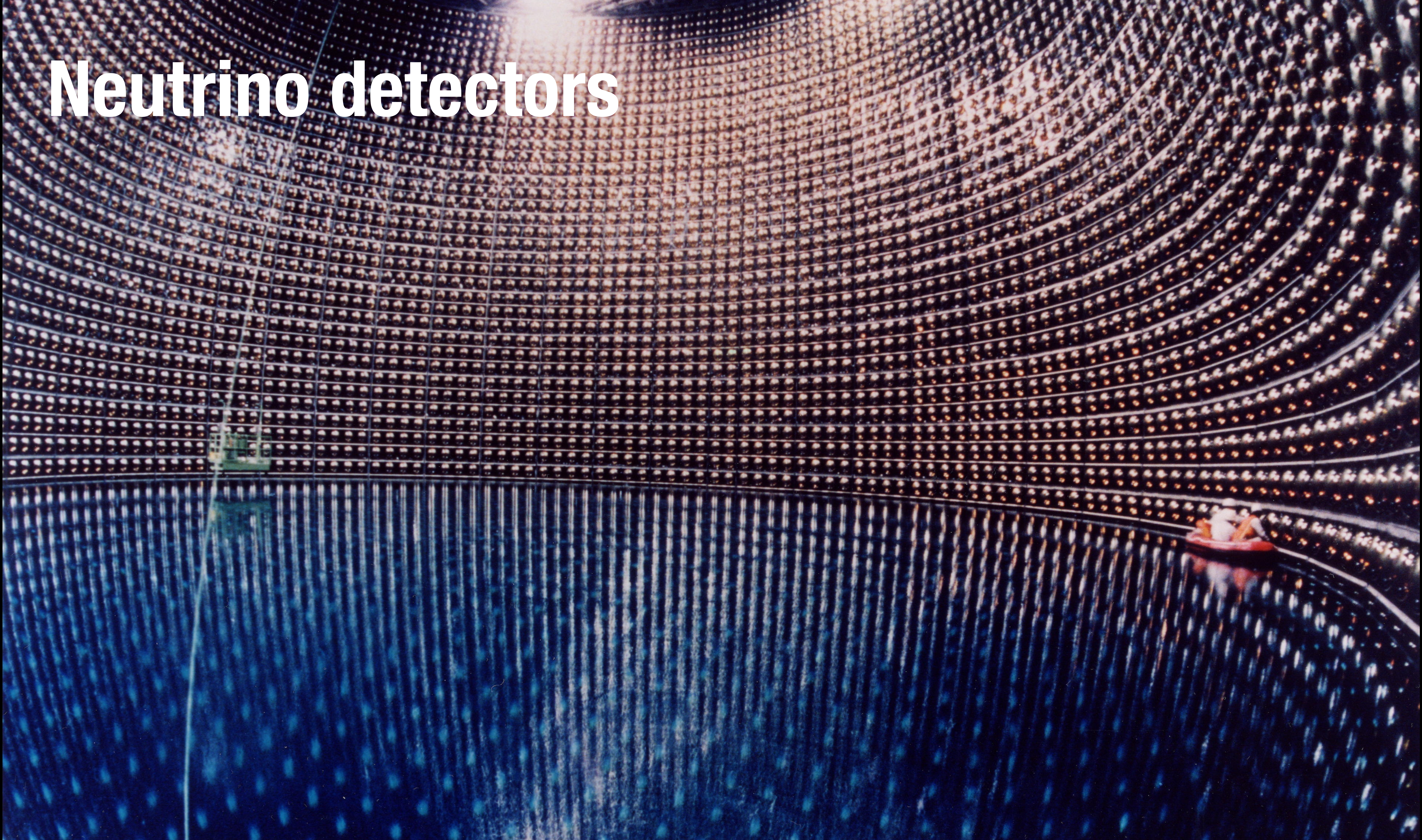
	Sun	ϕ_ν ~65 x 10^9 /cm² s	E ~ MeV	L ~ 10^8 km
	Atmosphere	ϕ_ν ~10^2 - 10^9 /GeV cm² sr s	E ~ GeV-TeV	L ~ 10 - 10^4 km
	Earth	ϕ_ν ~10^6 /cm² s	E ~ MeV	L ~ 10 - 10^3 km
	Supernovae		E ~ MeV	L ~ kpc- Mpc
	Big Bang	ϕ_ν ~300 /cm³	E ≲ meV	L ~ Mpc
	Astrophysics Accelerators		E ~ TeV-PeV	L ~ kpc- Mpc
	Nuclear Reactors	ϕ_ν ~2 x 10^{20} /s GW_{th}	E ~ MeV	L ~ 1-100 km
	Particle Accelerators		E ~ GeV	L ~ 100-1000 km

Neutrino fluxes at Earth

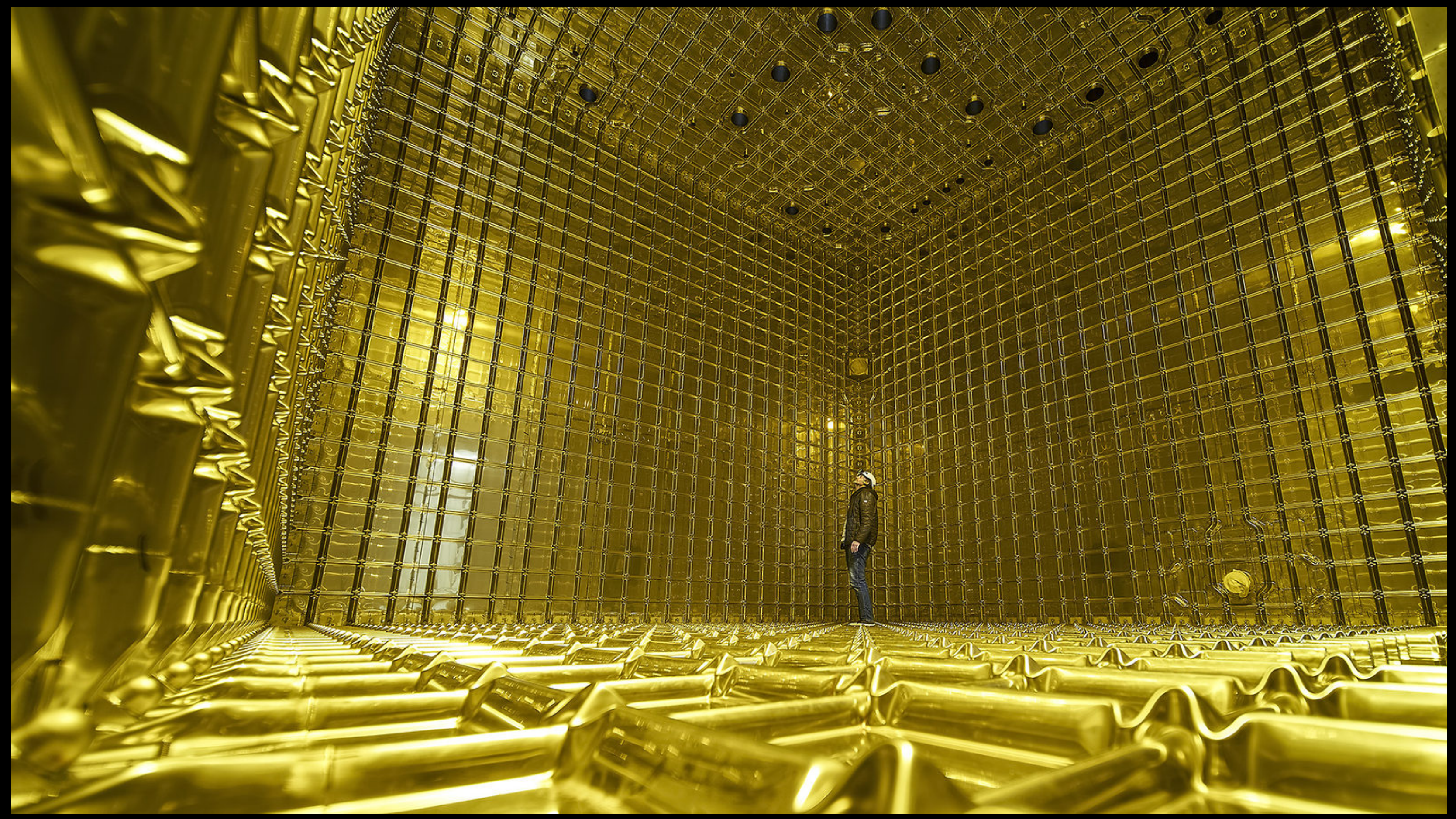
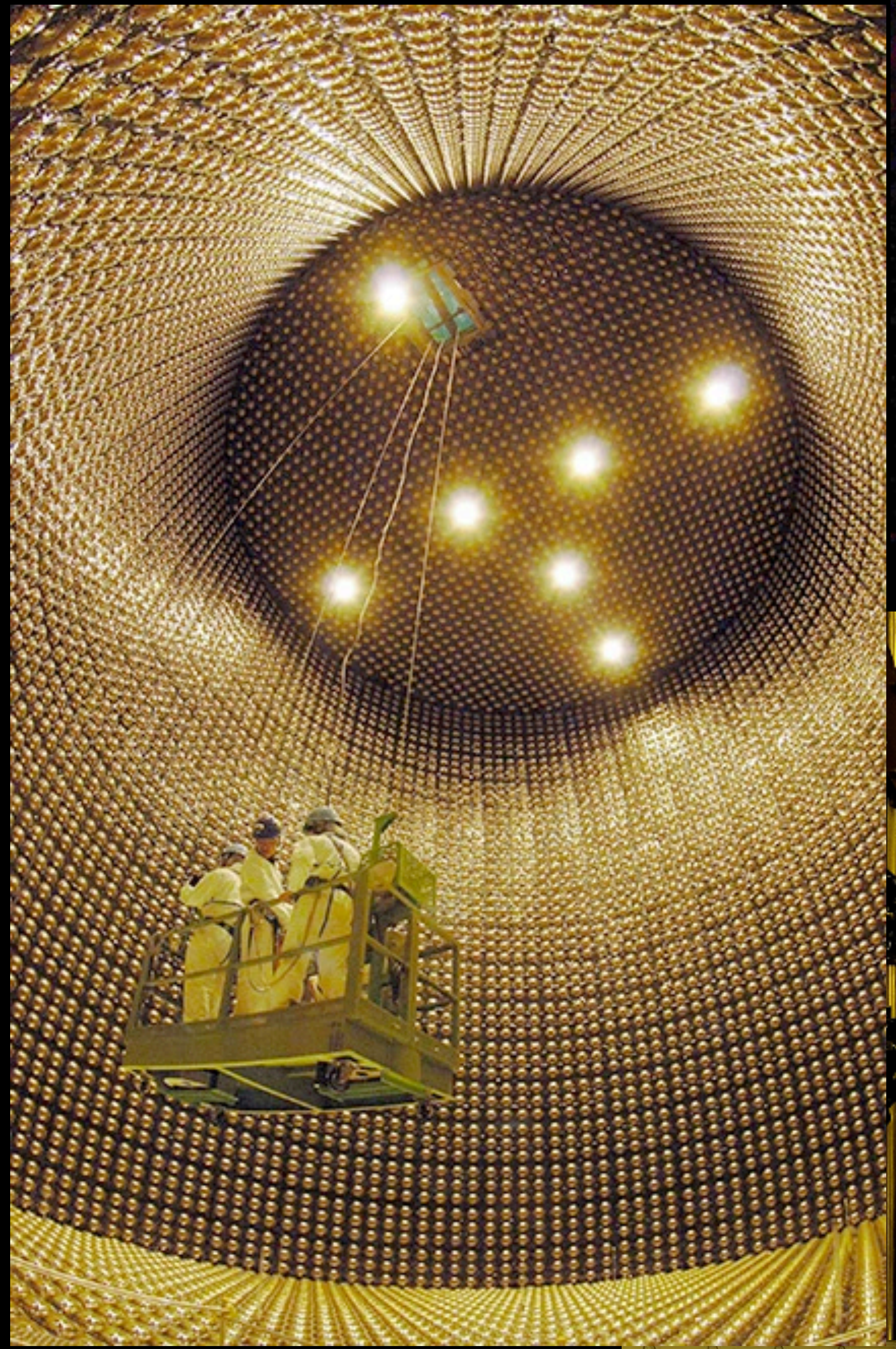
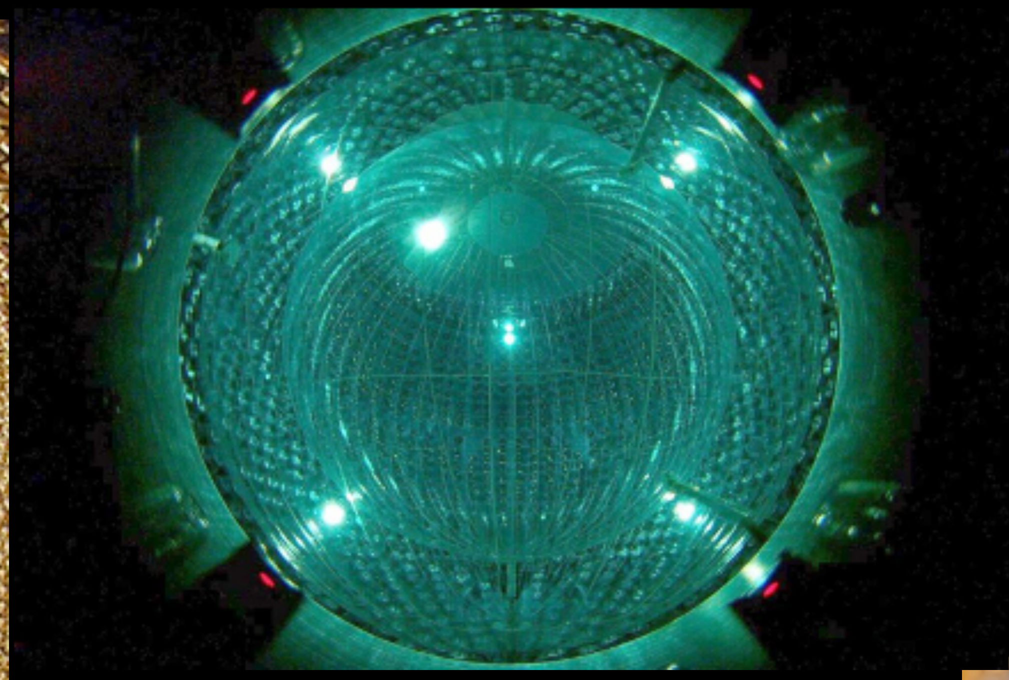
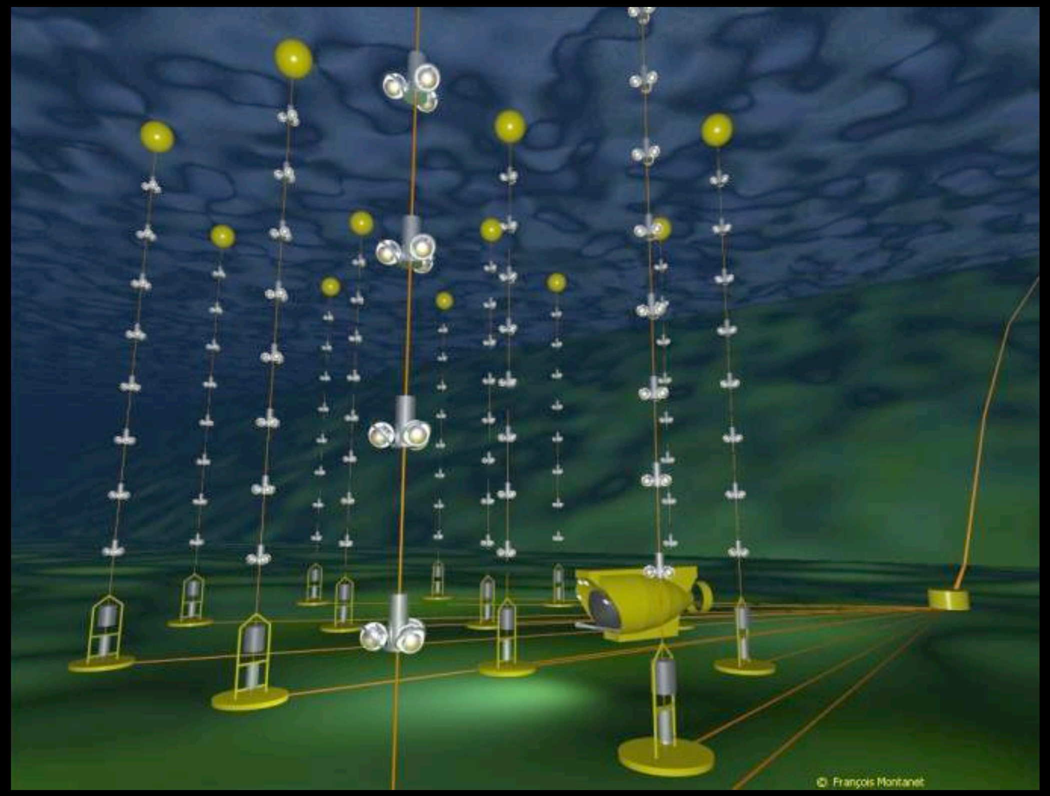


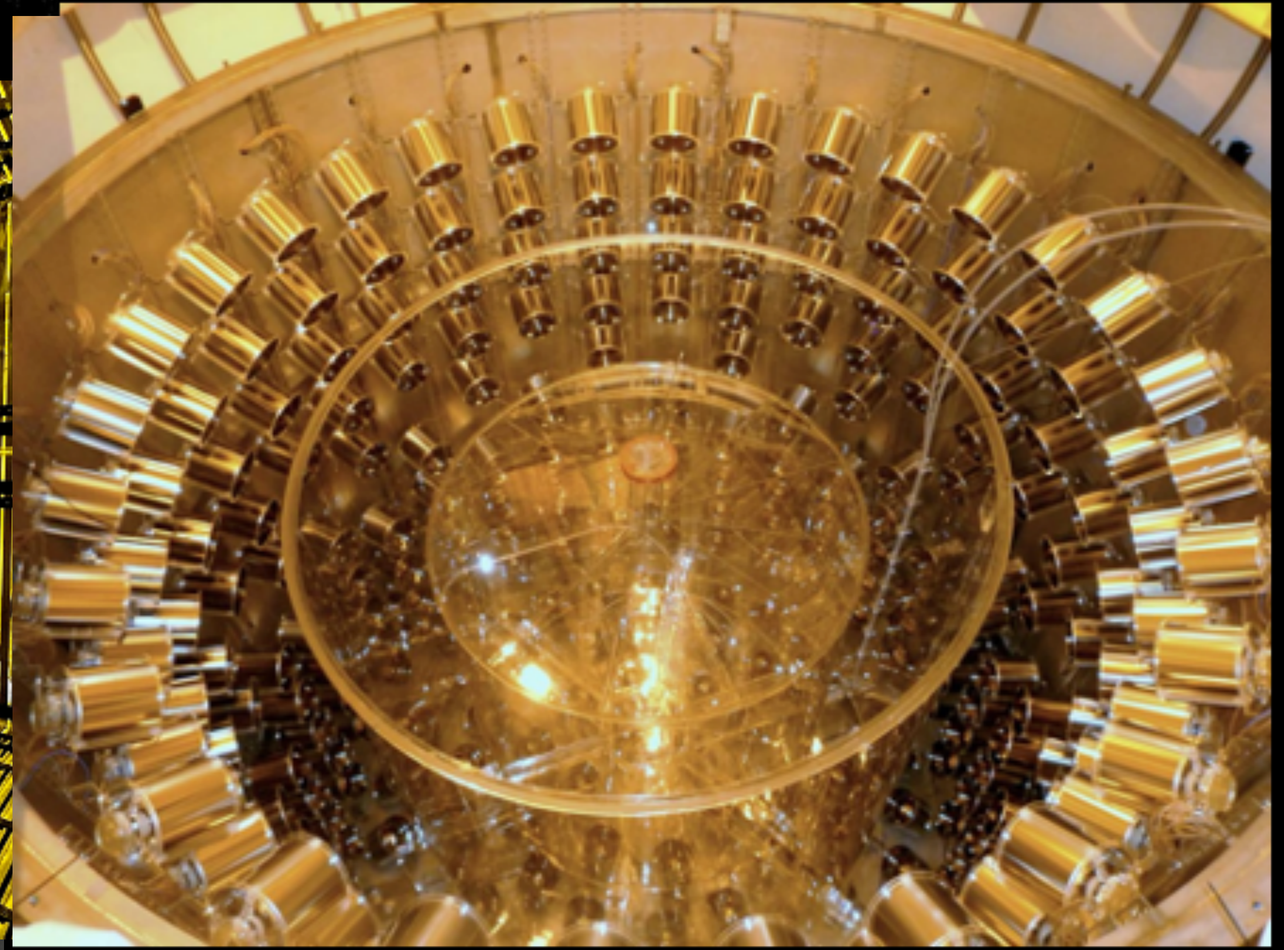
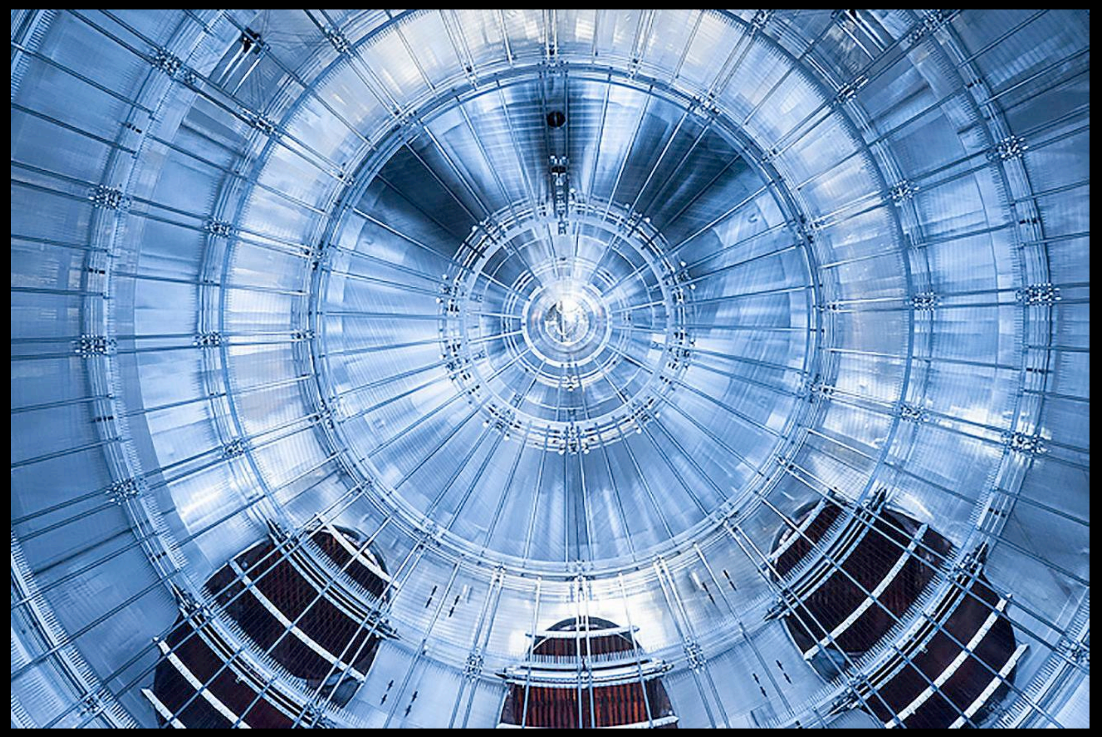
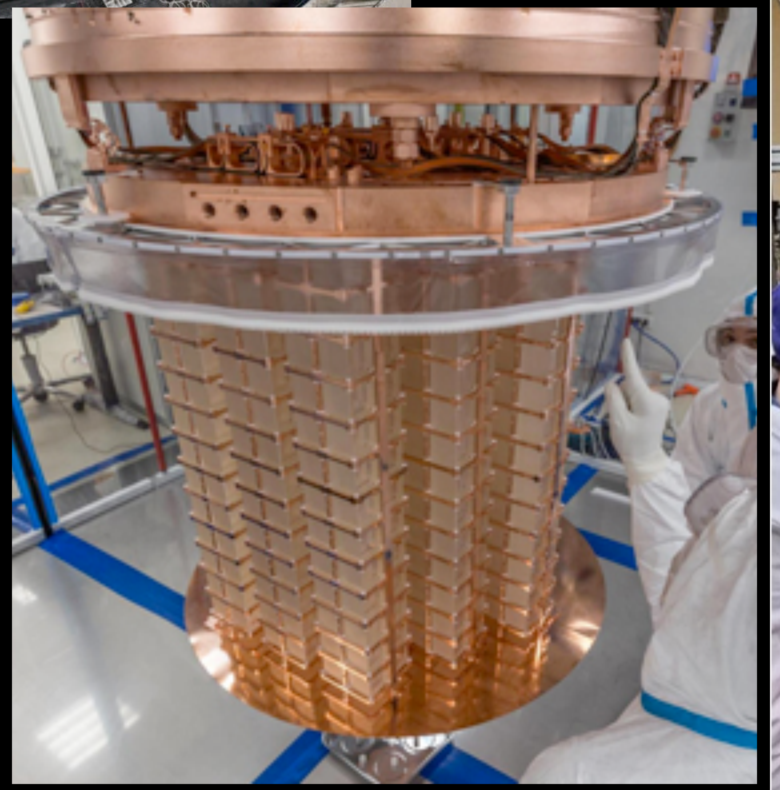
2 Neutrino detection

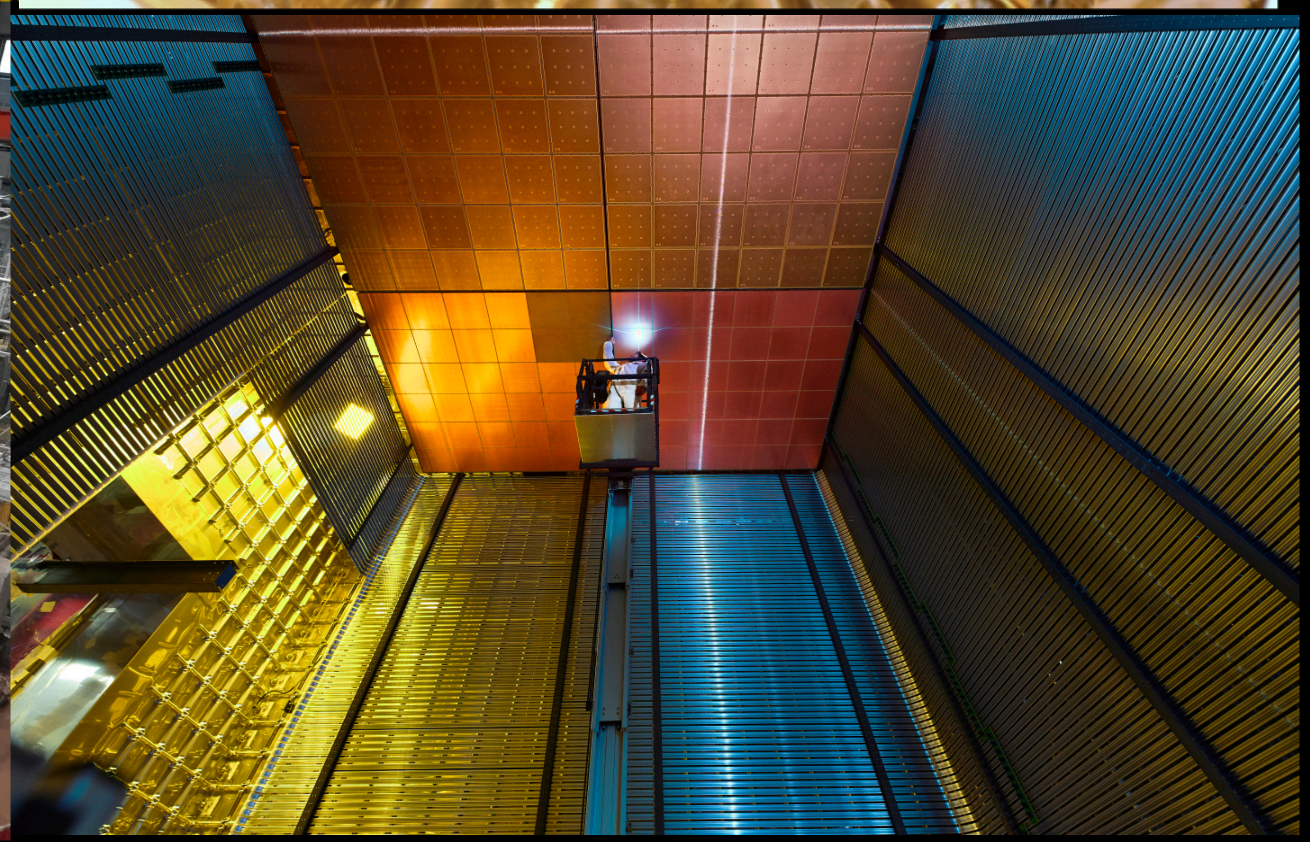
Neutrino detectors



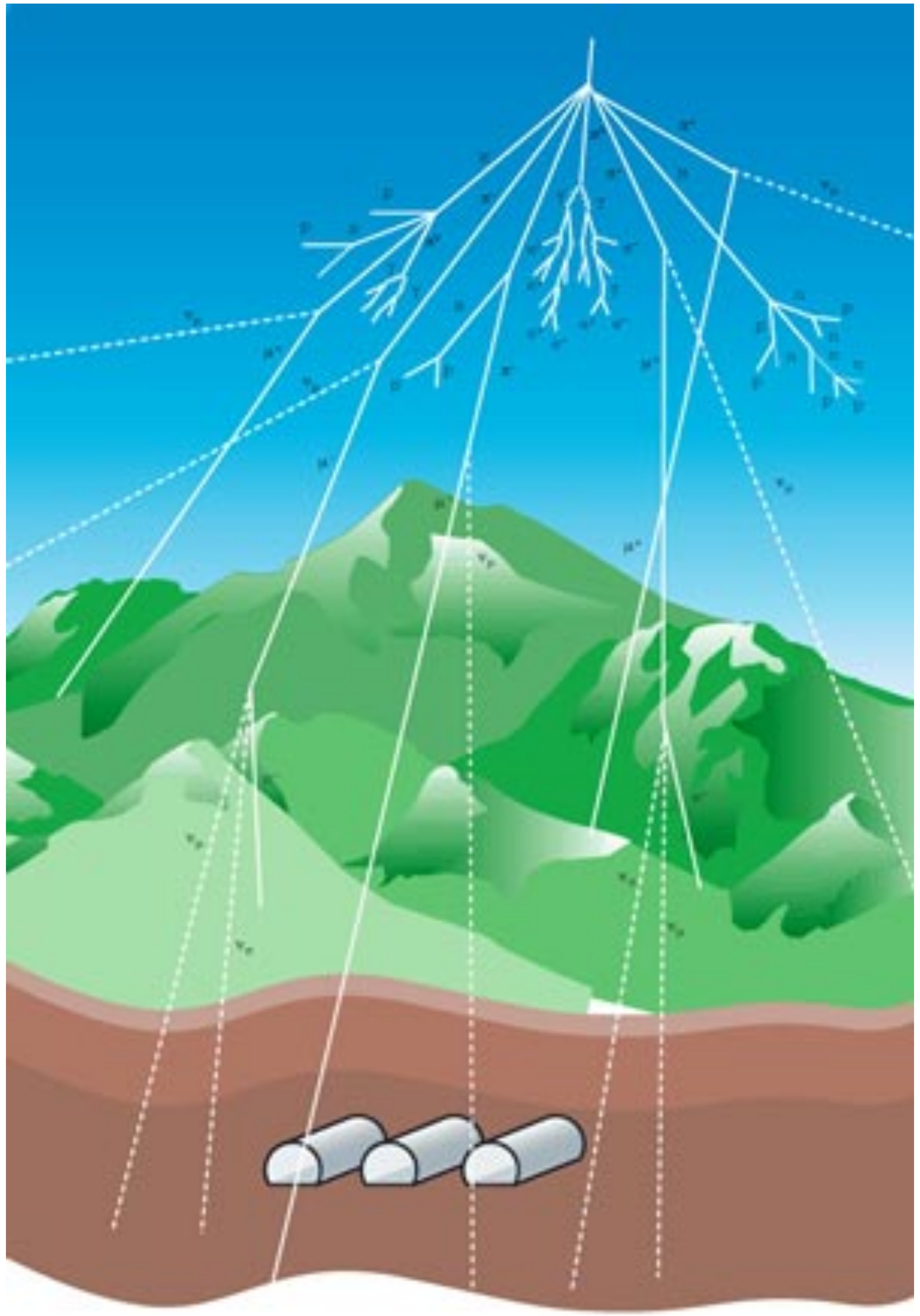
Neutrino detectors

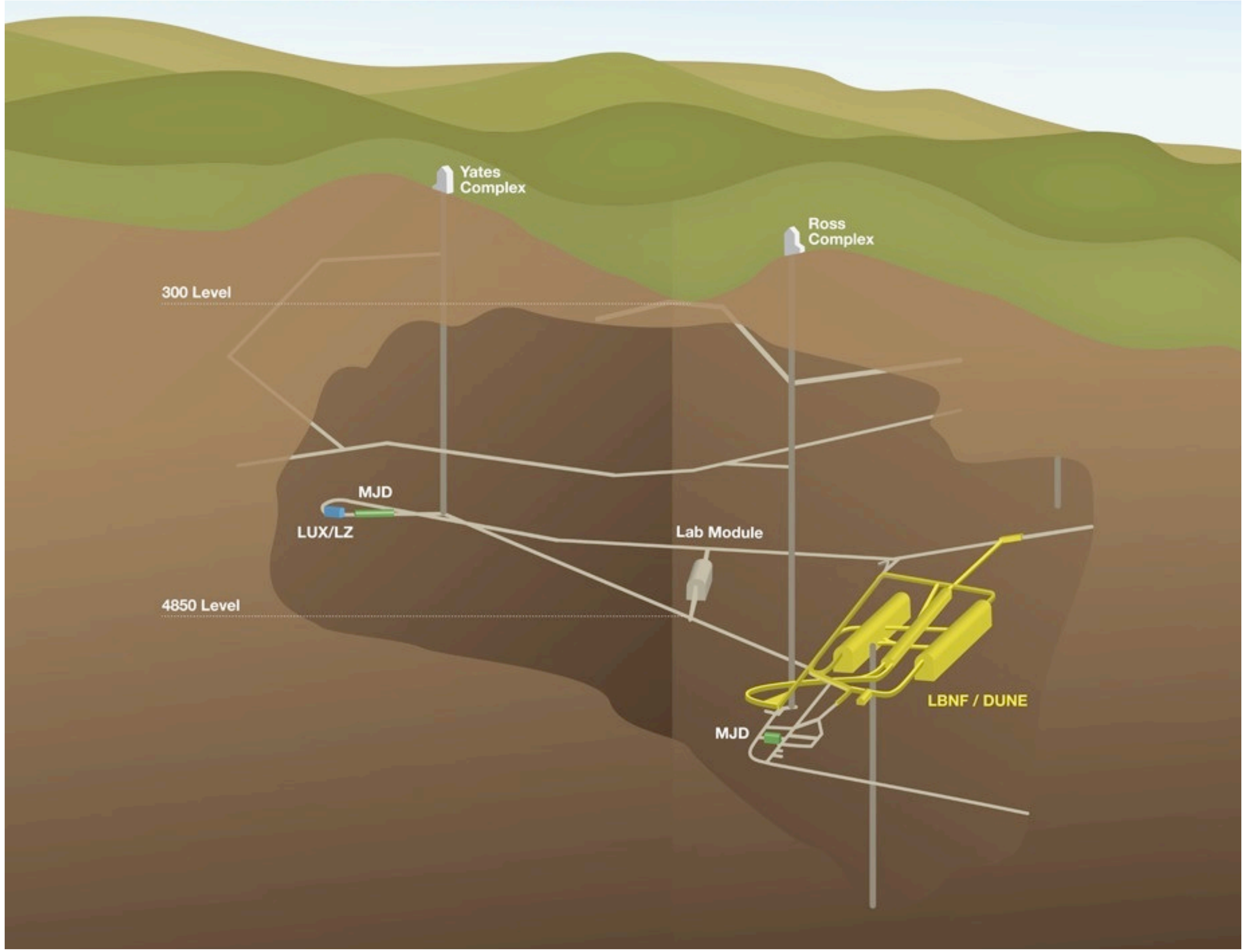





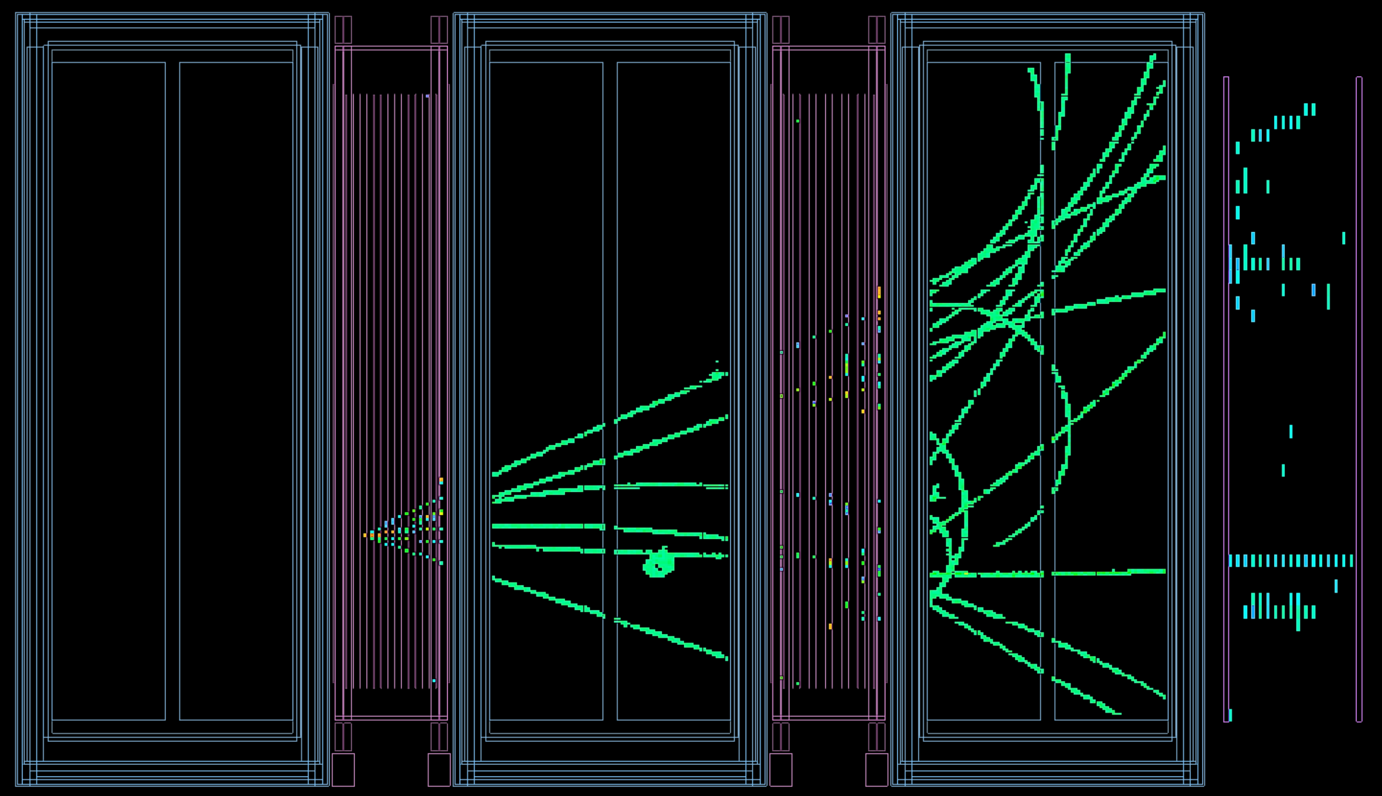



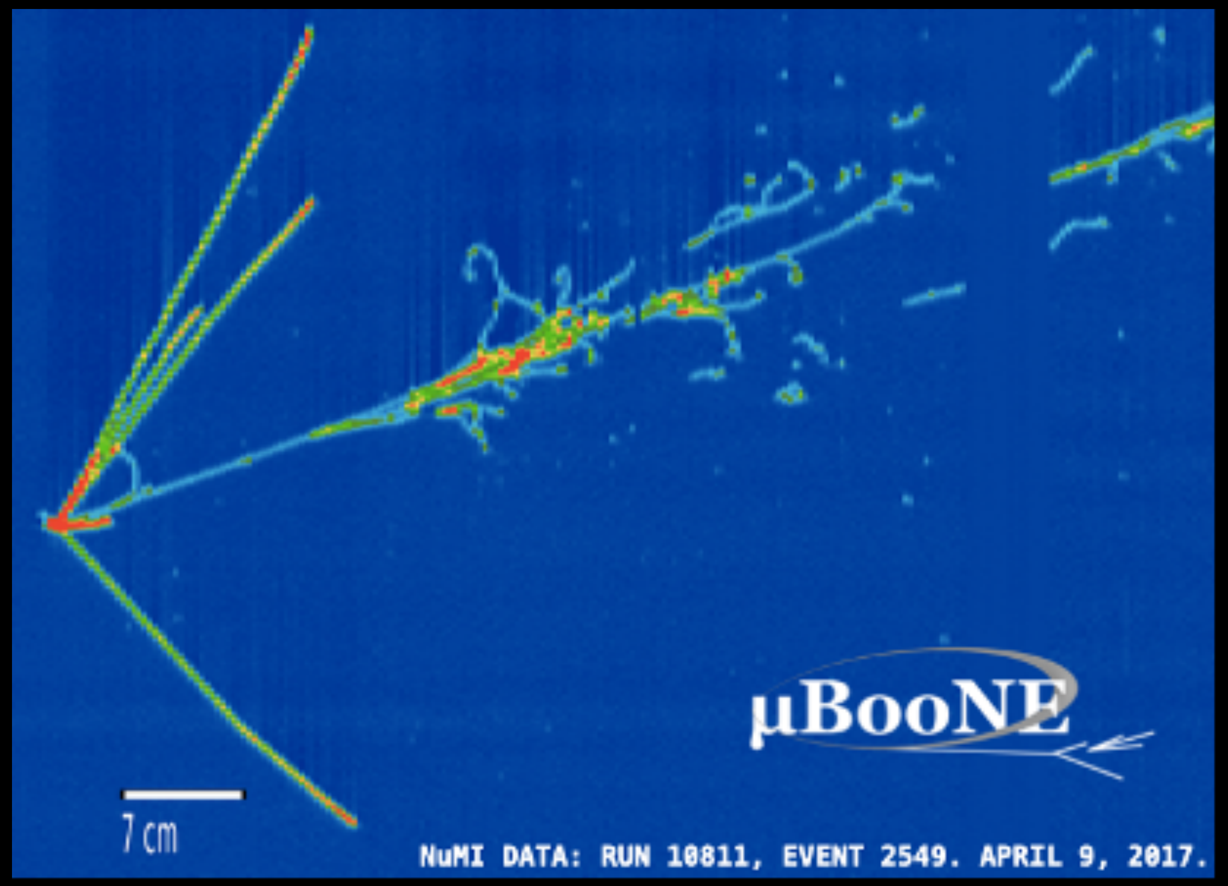
Underground laboratories

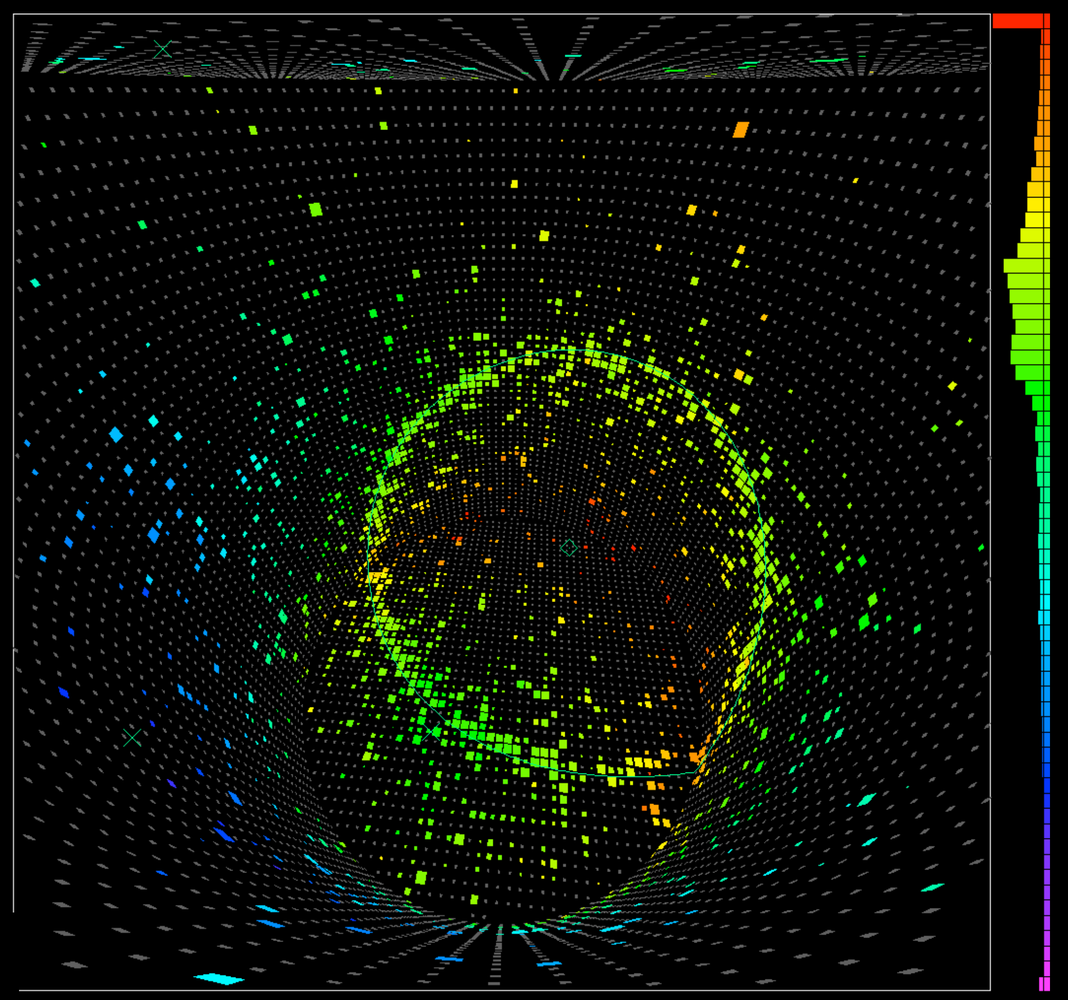


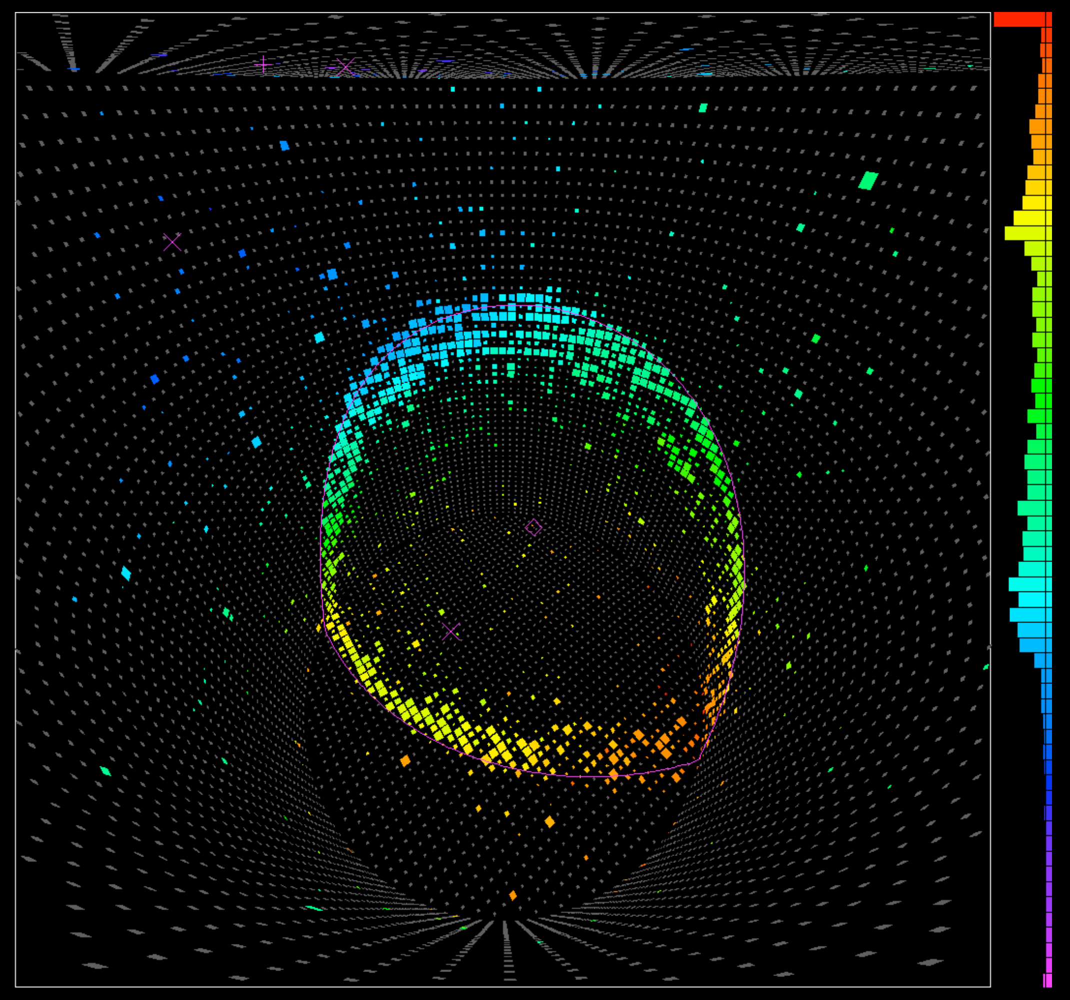


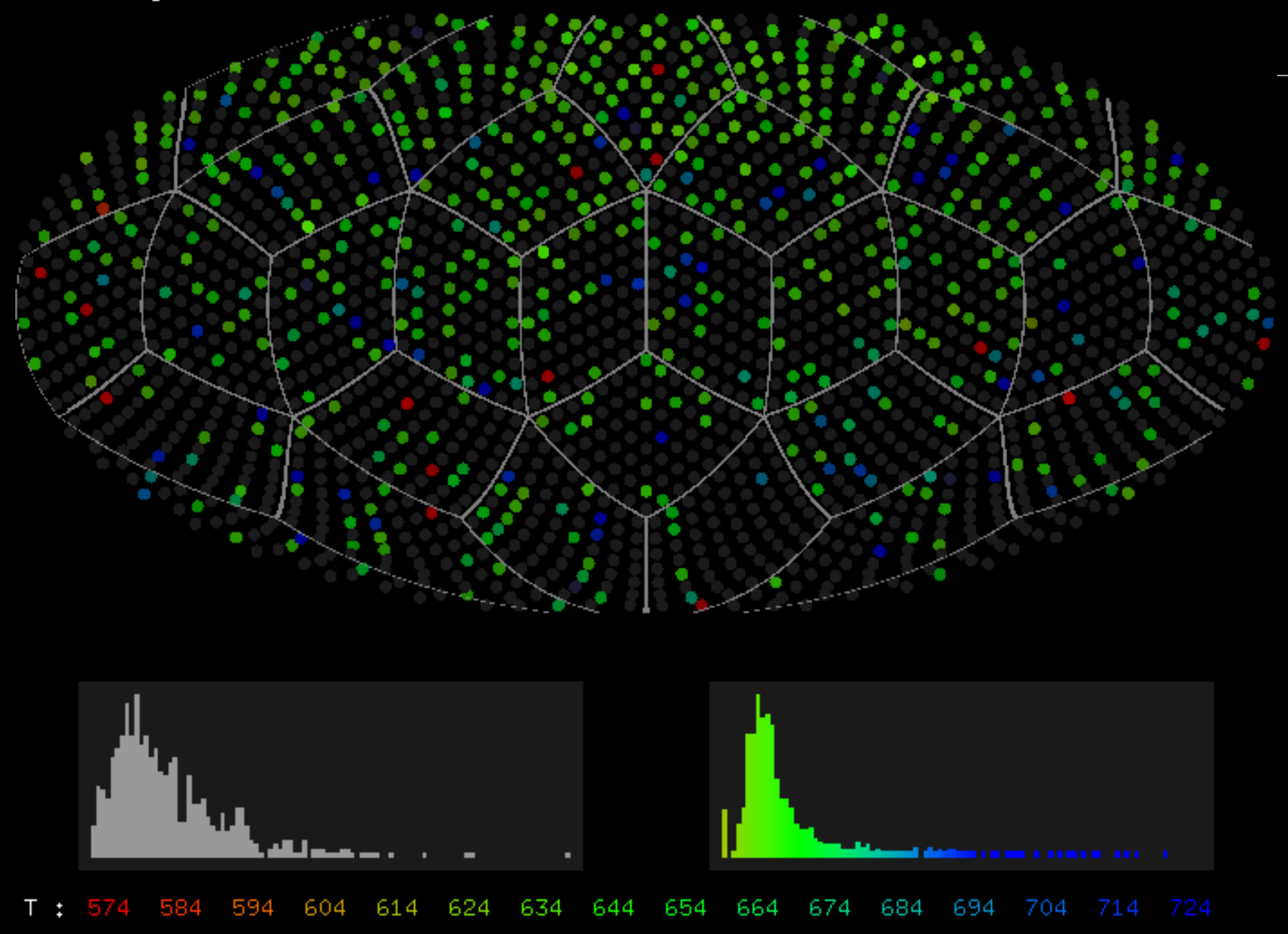
Neutrinos

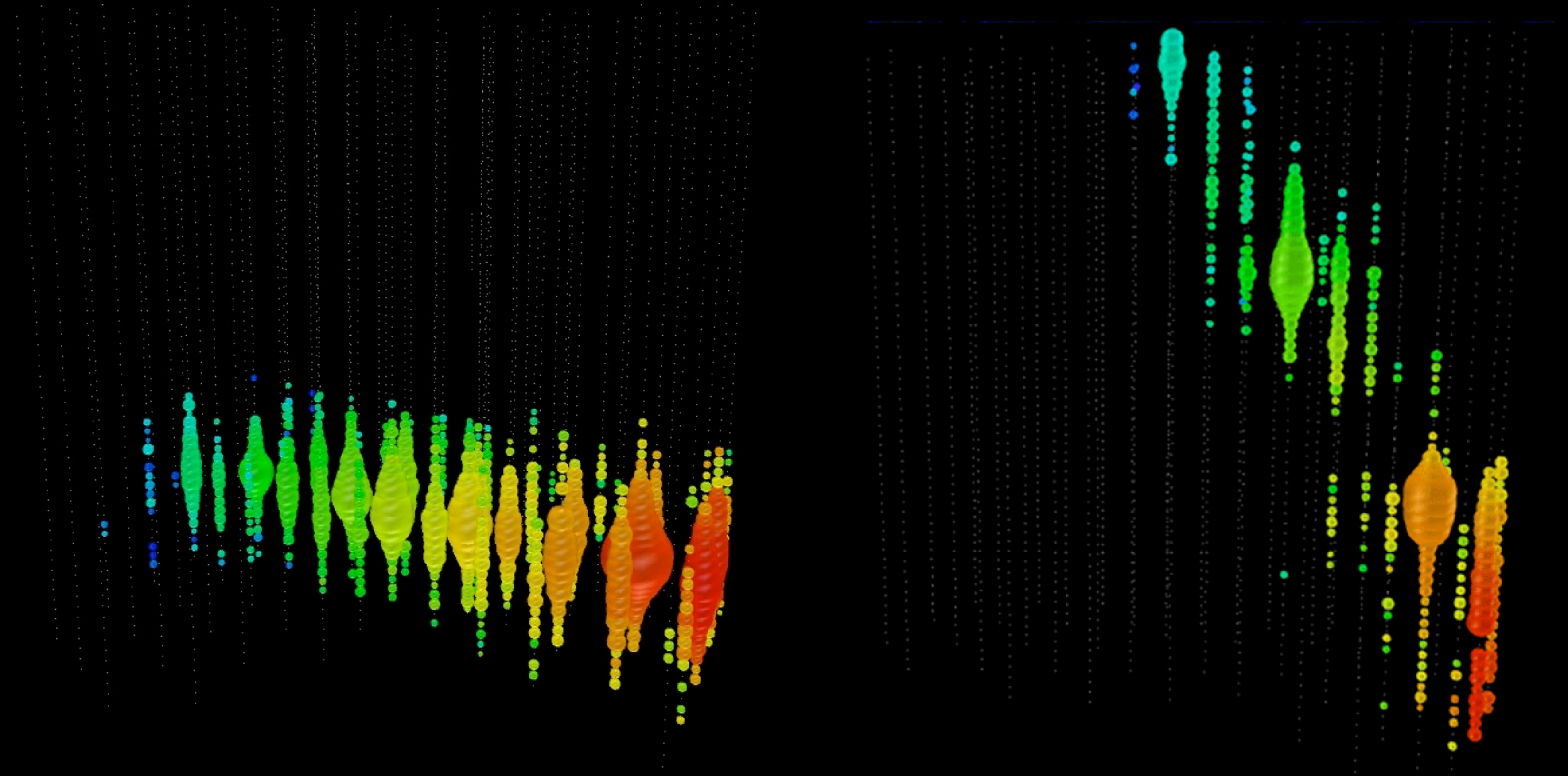


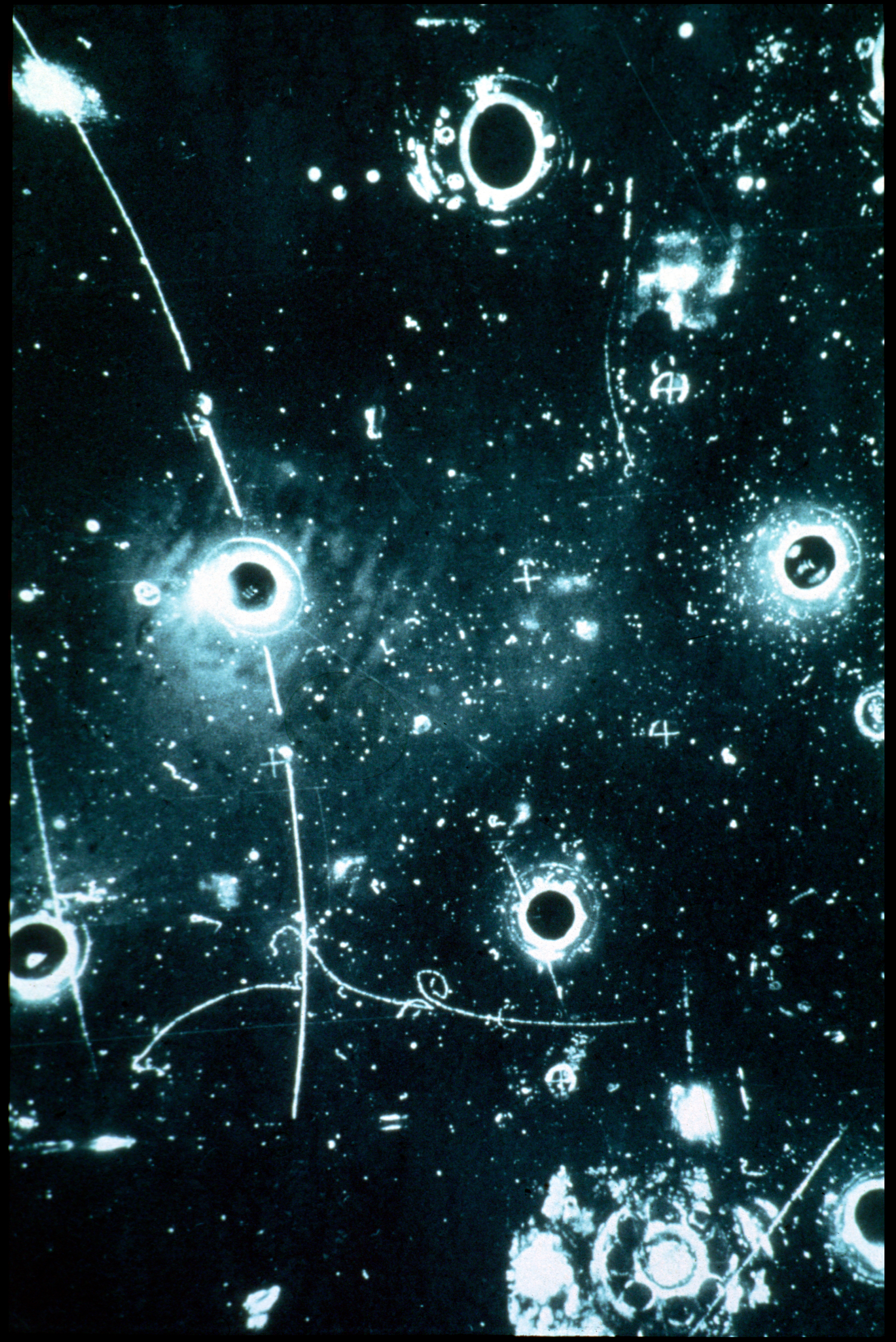

μBooNE
7 cm
NuMI DATA: RUN 10811, EVENT 2549. APRIL 9, 2017.

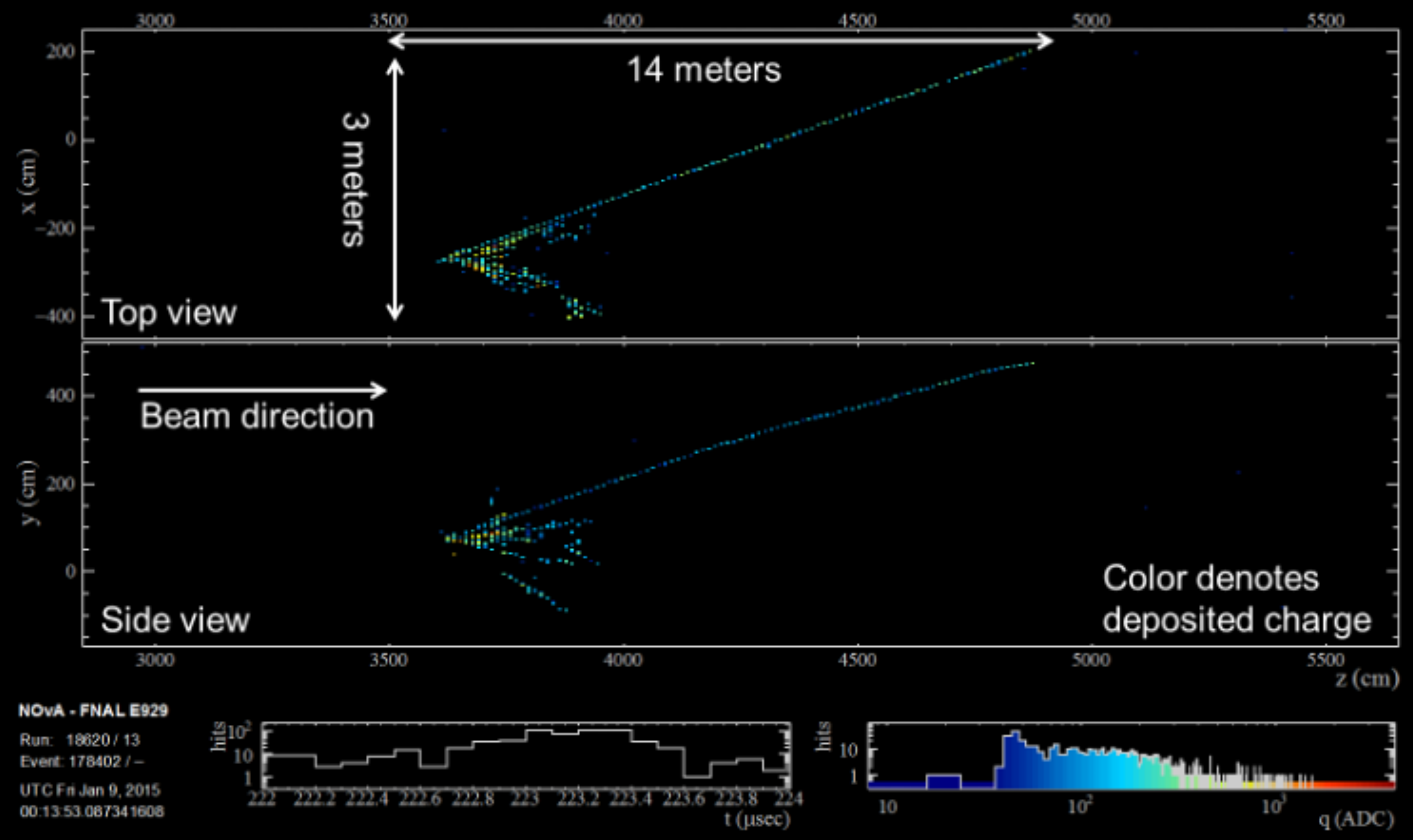




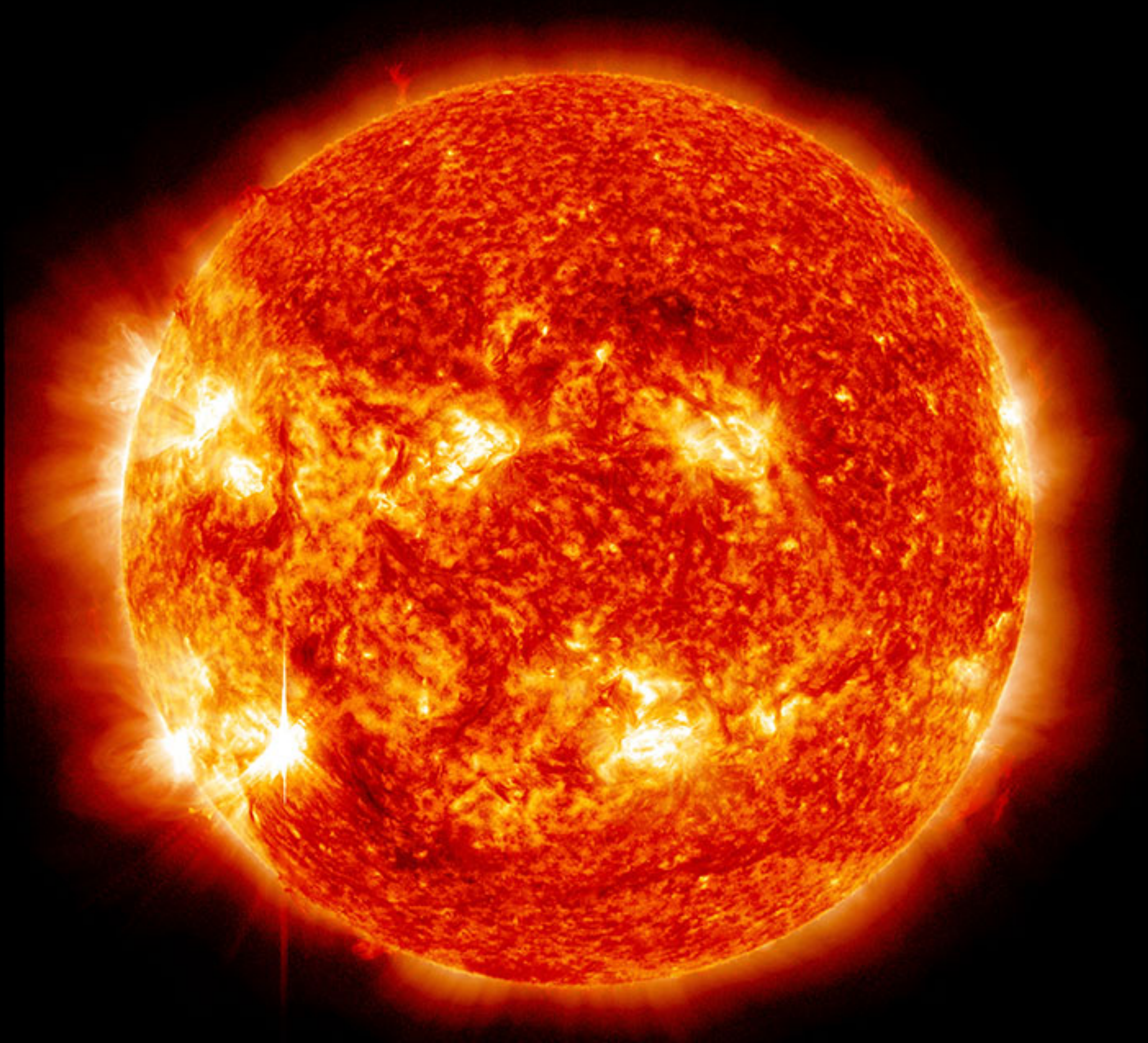

T : 574 584 594 604 614 624 634 644 654 664 674 684 694 704 714 724



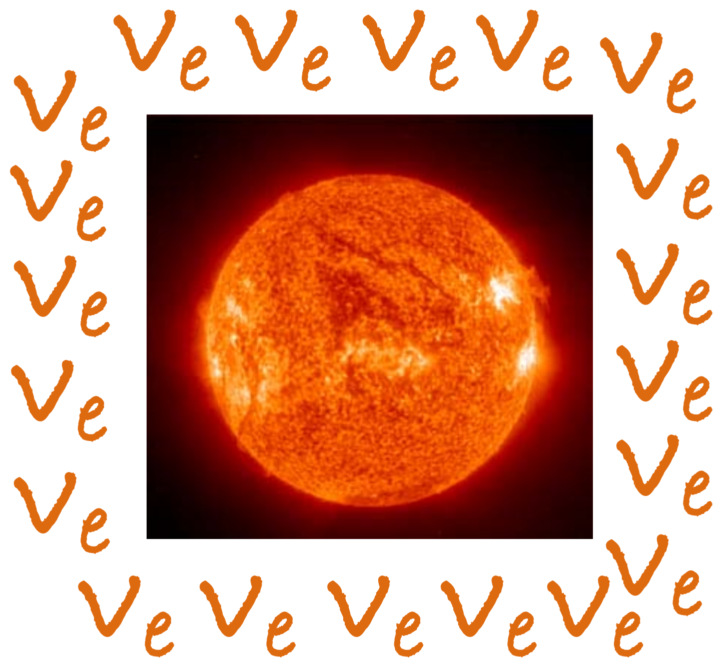


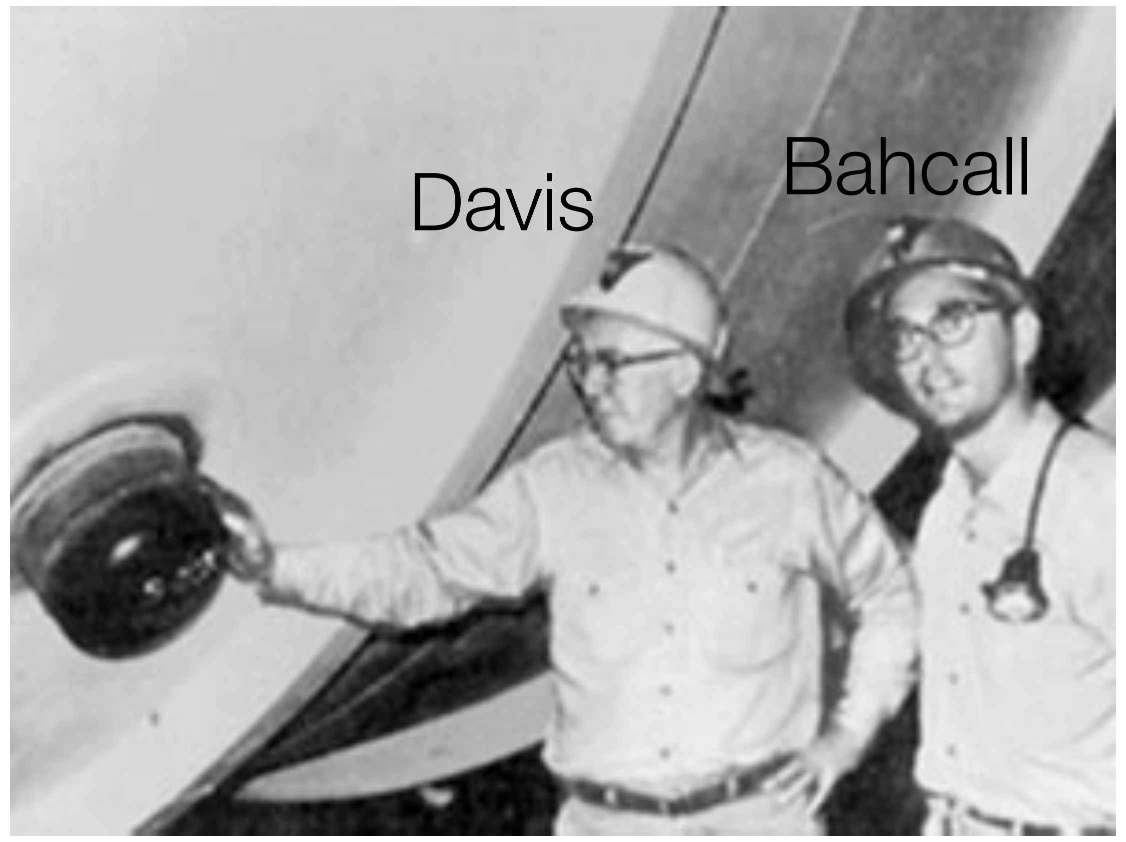

14 meters
3 meters
Top view
x (cm)
Beam direction
Side view
y (cm)
Color denotes
deposited charge
z (cm)
NOvA - FNAL E929
Run: 18620 / 13
Event: 178402 / --
UTC Fri Jan 9, 2015
00:13:53.087341608
t (μsec)
q (ADC)

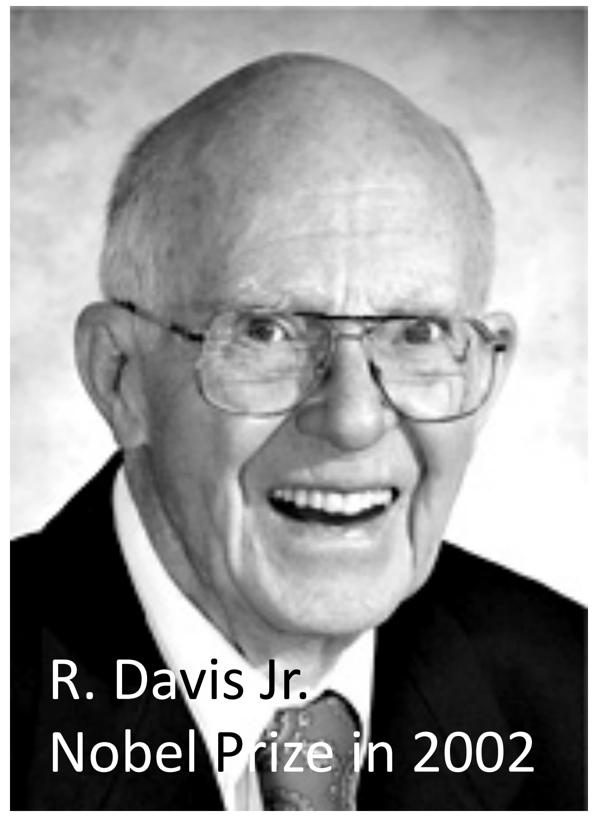

μBooNE
10 cm
BNB DATA : RUN 5211 EVENT 1225. FEBRUARY 29, 2016

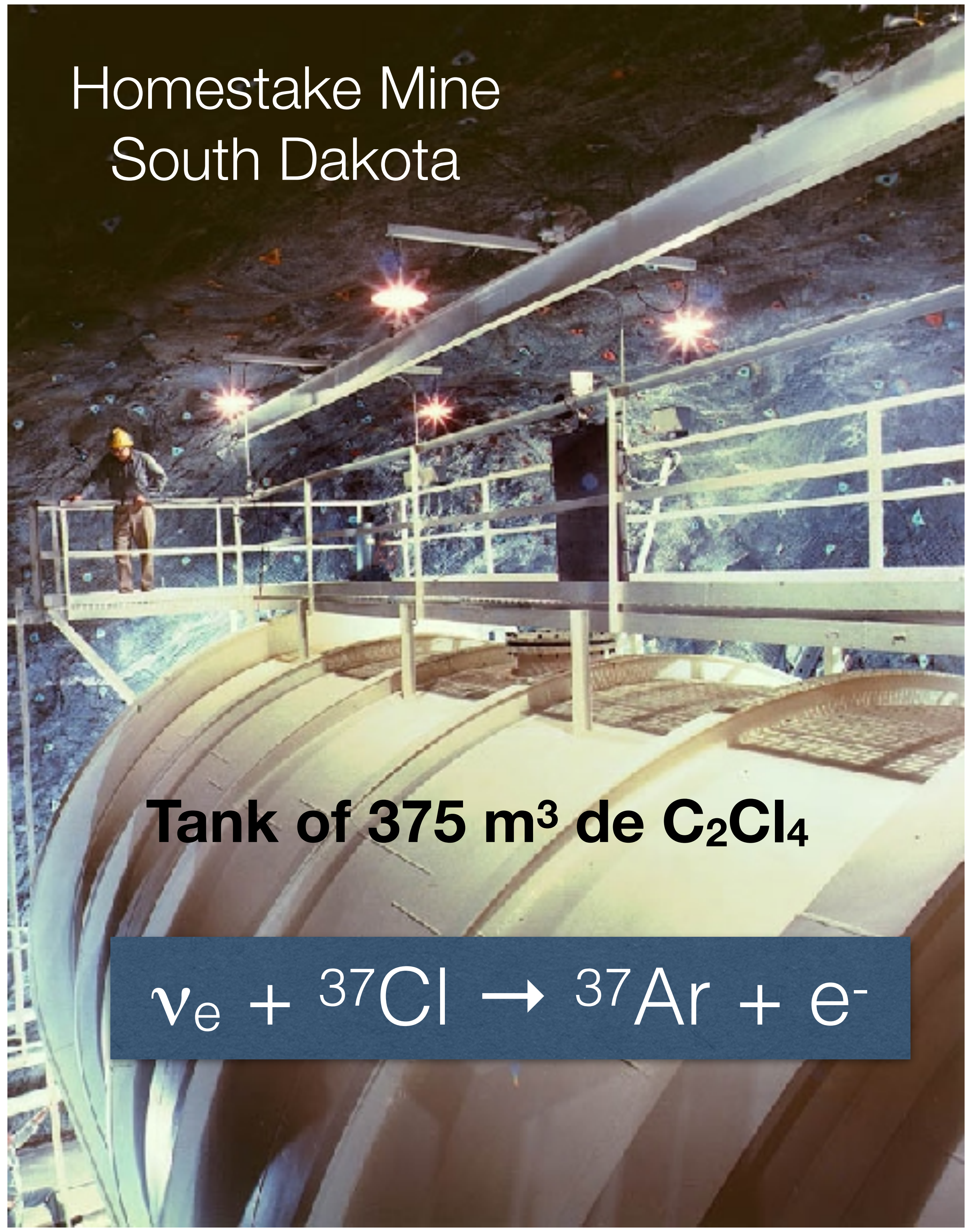


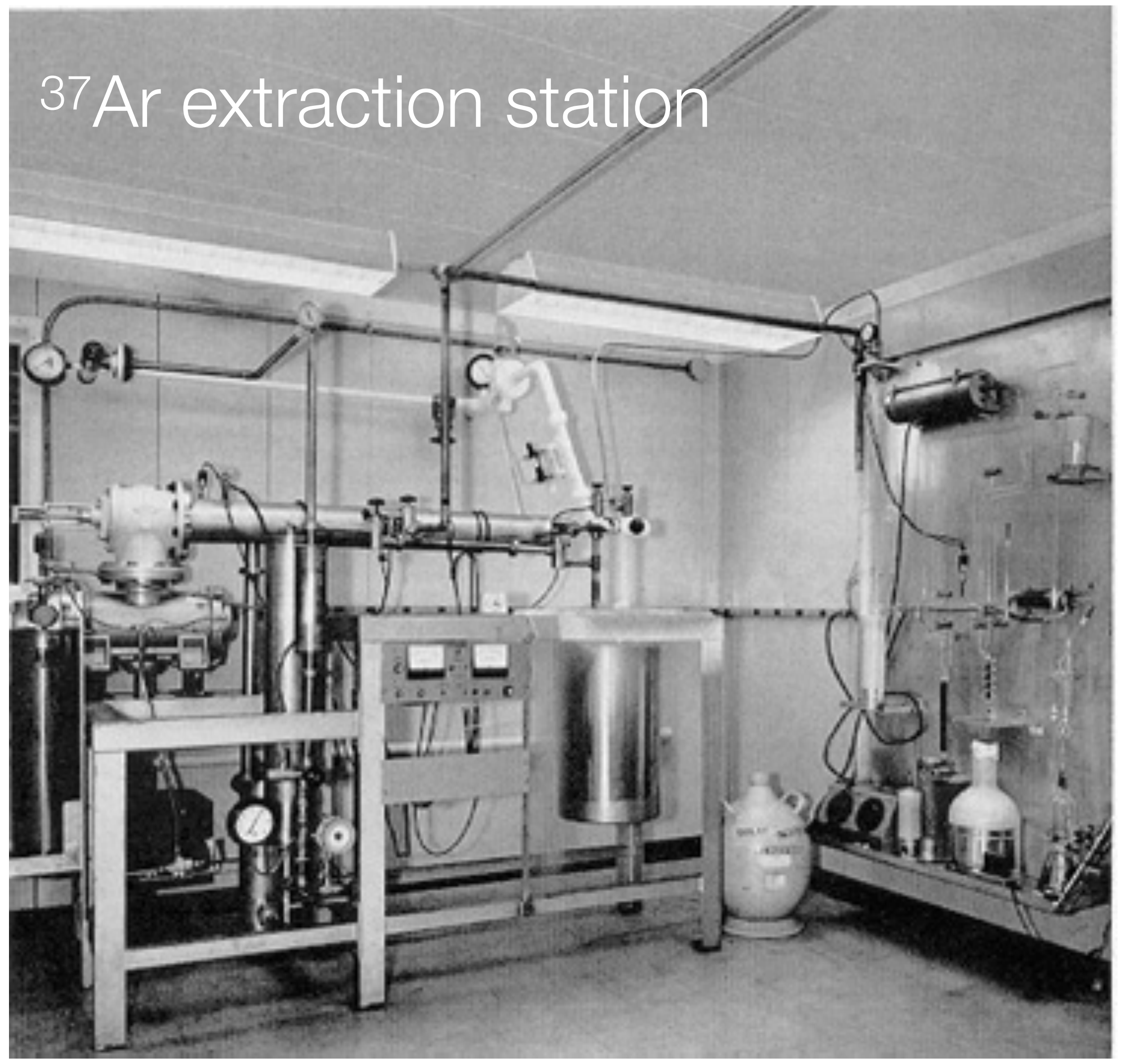
Solar neutrinos











No explanation over 30 years

(1968-2001)

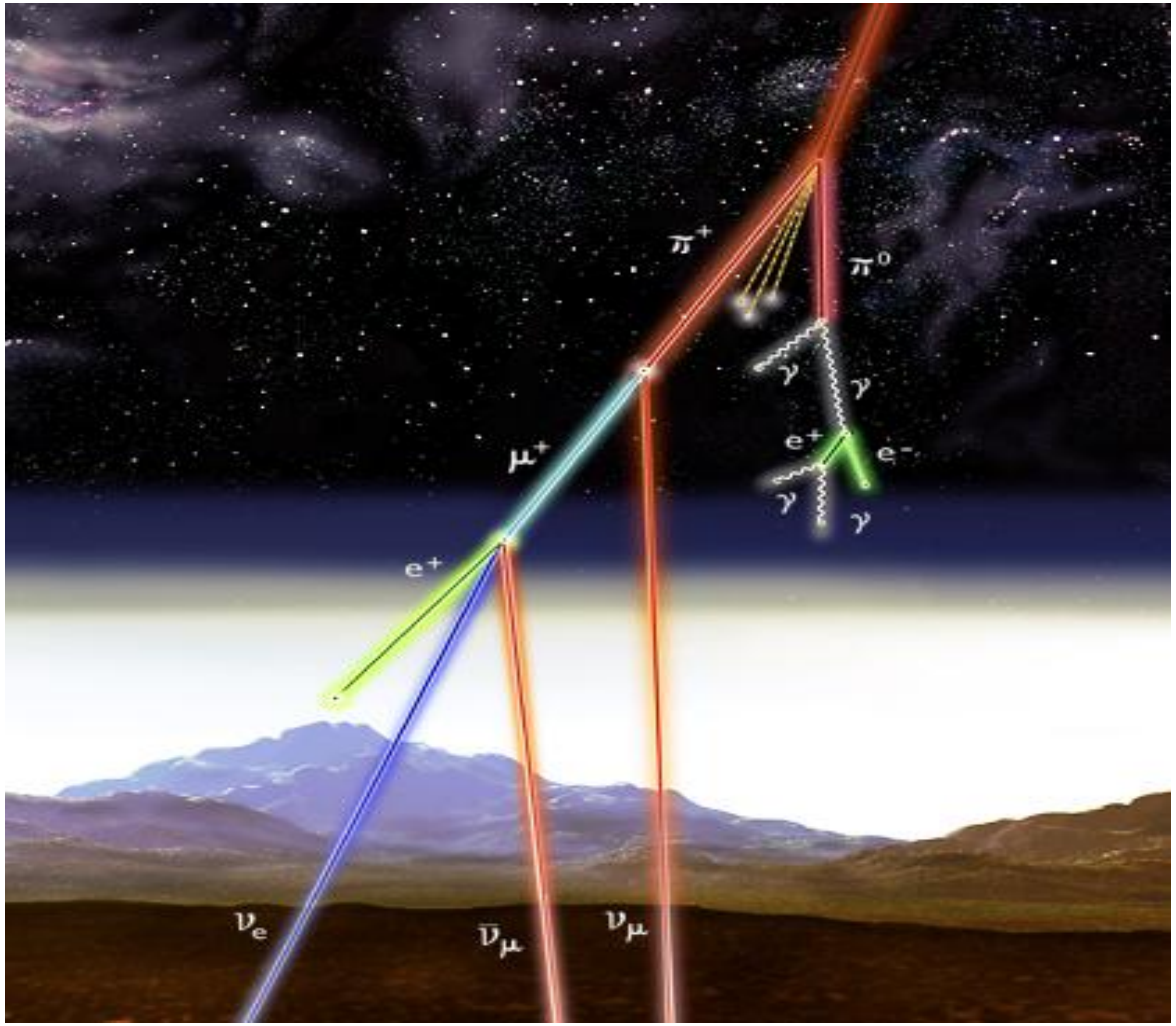
Prediction (J. Bahcall): 1 Ar atom per day

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

2/3 OF NEUTRINOS ARE MISSING !!

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:**

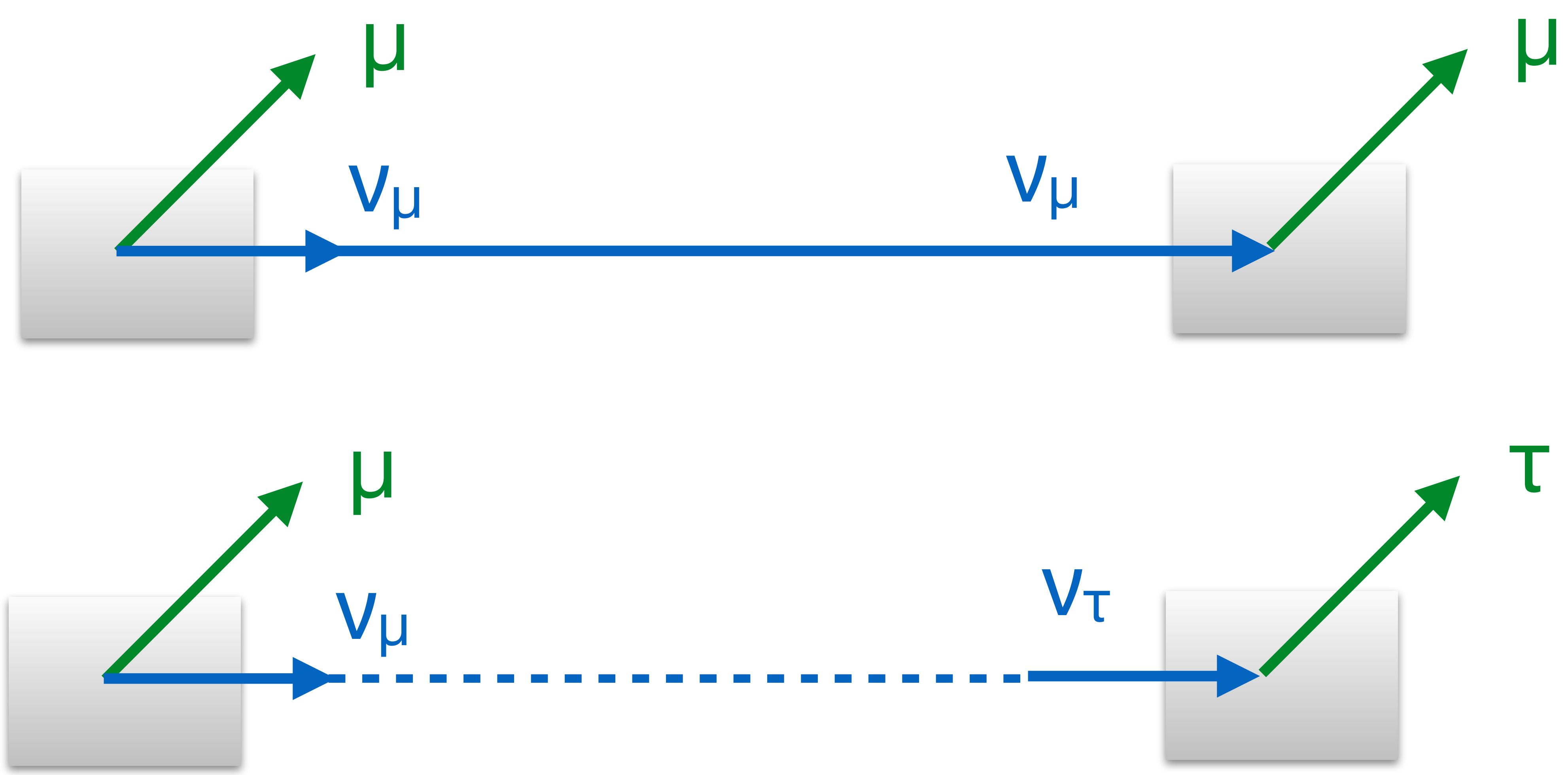
$$\nu_\mu \sim \nu_e$$

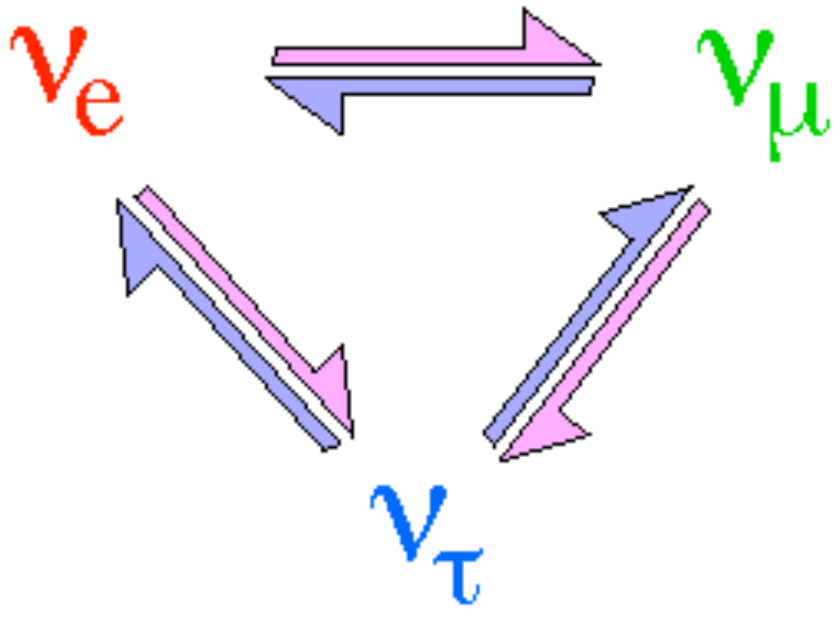
WHERE ARE THE NEUTRINOS GOING?

The idea of oscillations

B. Pontecorvo (1957)

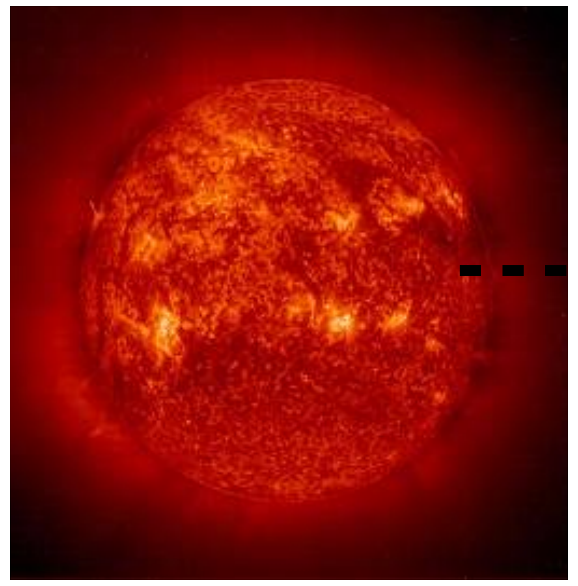
Quantum interference phenomenon in which a neutrino of a certain flavor is transformed into a neutrino of a different flavor





This phenomenon is only possible if neutrinos have different masses

Detection of neutrino oscillations



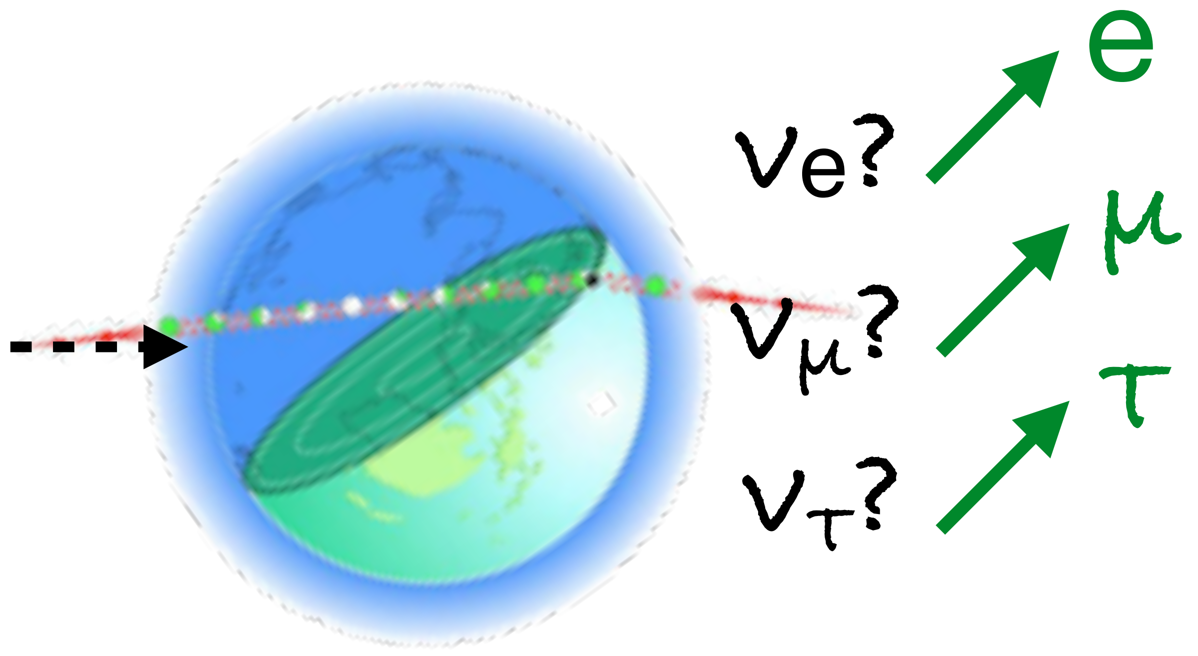
ν_e

E_ν

Production

L = distance

Propagation



Detection

Oscillation probability

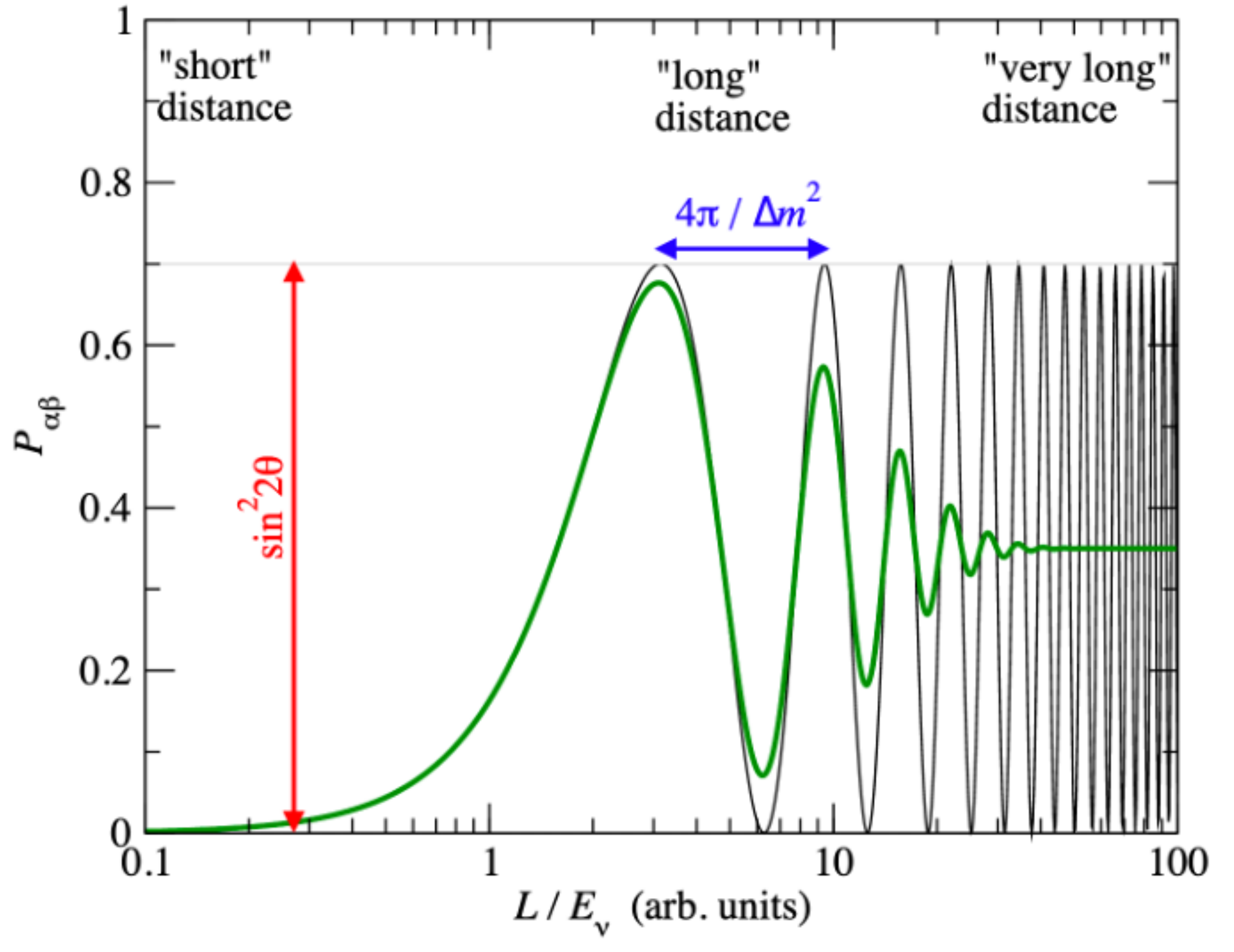
$$P(\nu_\alpha \to \nu_\beta) = \sin^2 2\theta \cdot \sin^2\left(\frac{\Delta m^2 L}{4E_\nu}\right)$$

Frequency

Distance

Amplitude

Neutrino energy



For 3 neutrinos:

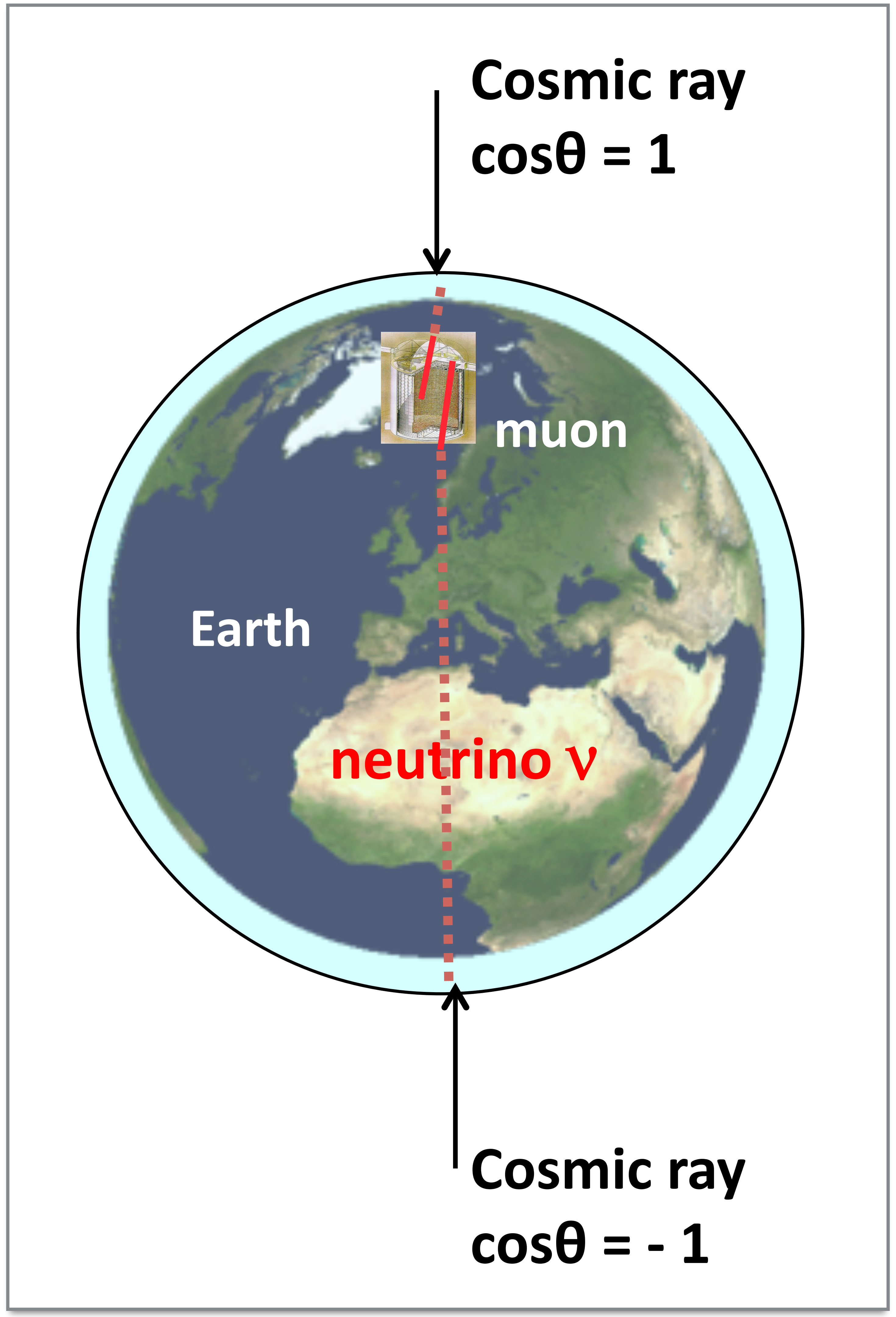
2 values of Δm^2 (Δm^2_{21}, Δm^2_{32})

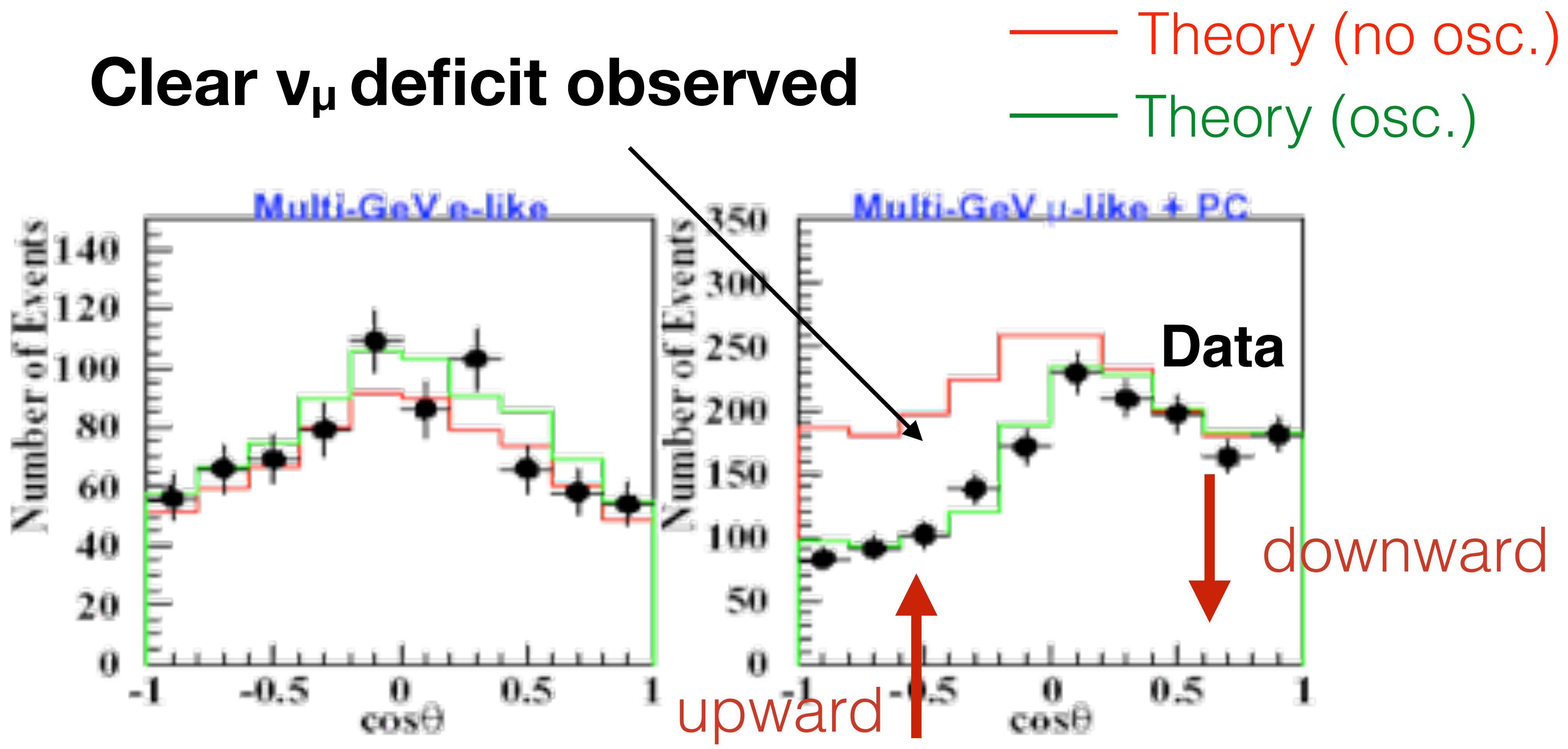
3 values of θ (θ_{12}, θ_{23}, θ_{13})

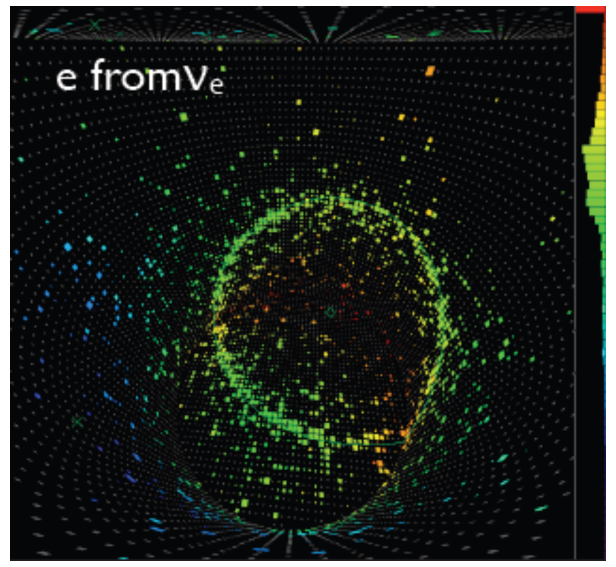
$$\Delta m^2 = m_2^2 - m_1^2$$

Squared mass difference

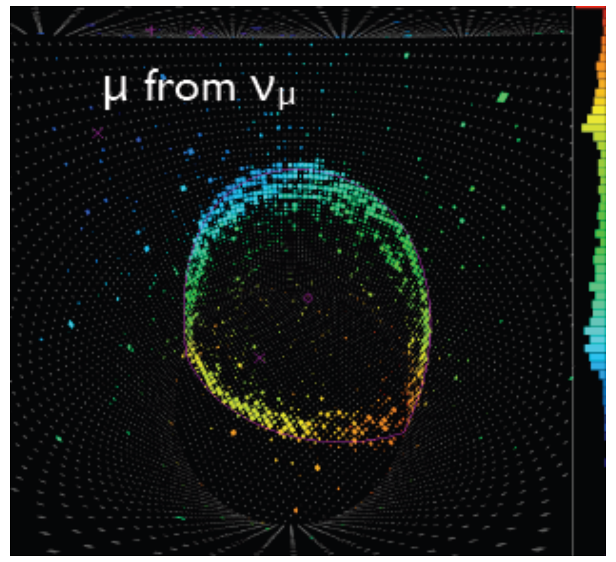
The discovery of neutrino oscillations (1998)







e^-

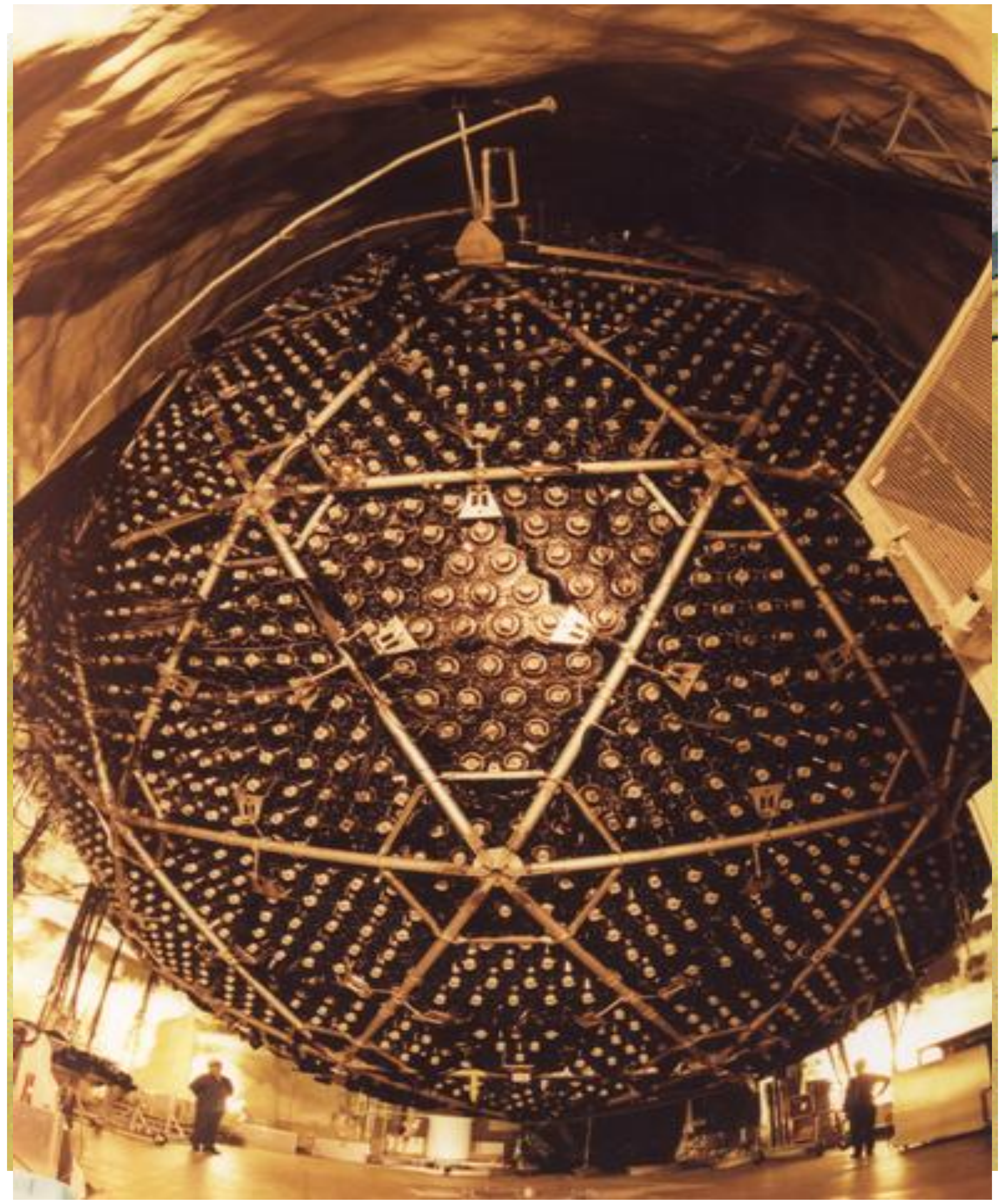


μ^-

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)

$$\nu_x + d \Rightarrow p + n + \nu_x$$

- Reaction only sensitive to **electron neutrinos** (CC)

$$\nu_e + d \Rightarrow p + p + e^-$$

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

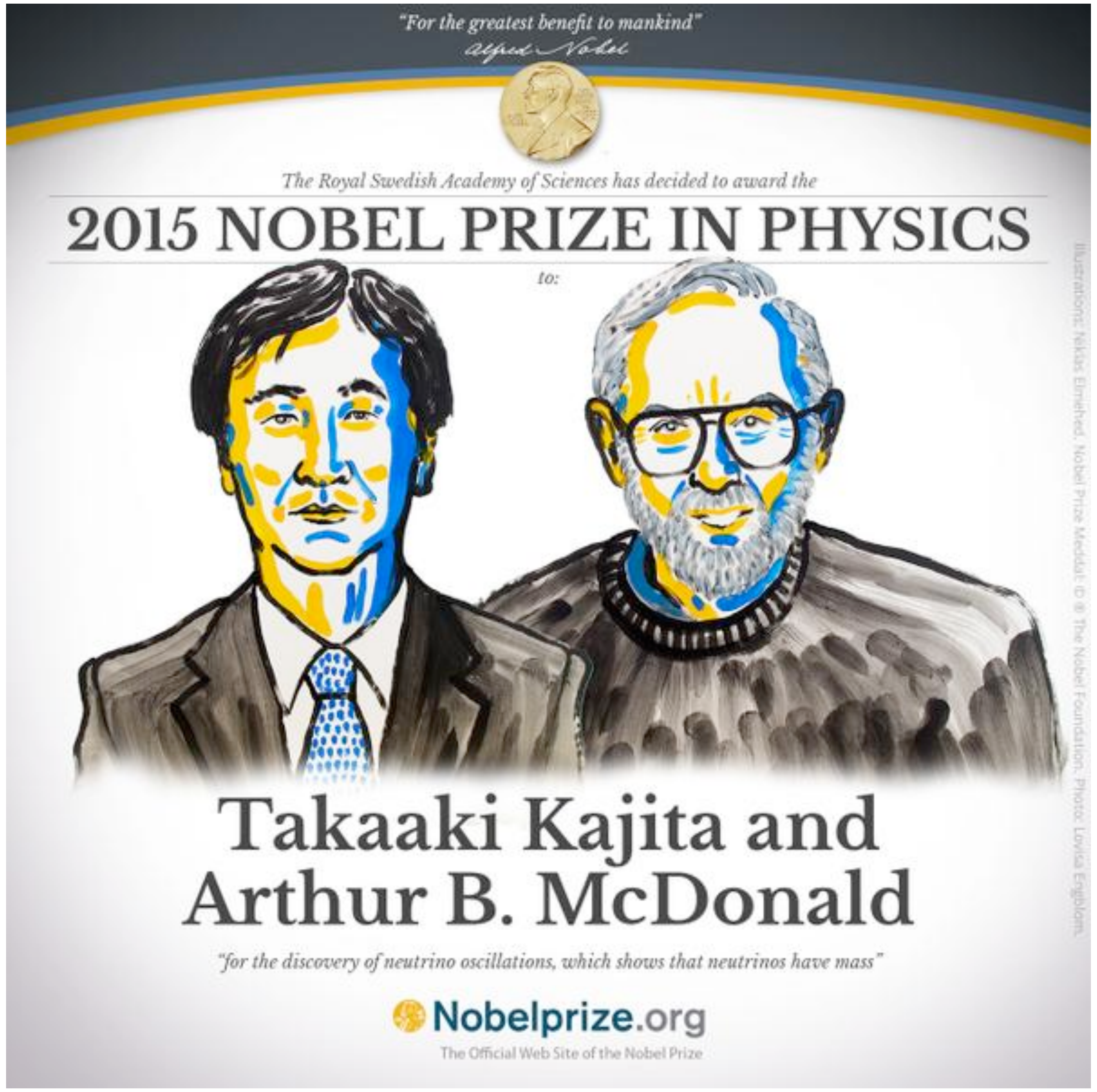
Only ν_e are emitted from the Sun by fusion reactions

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

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?

Neutrino mass measurements

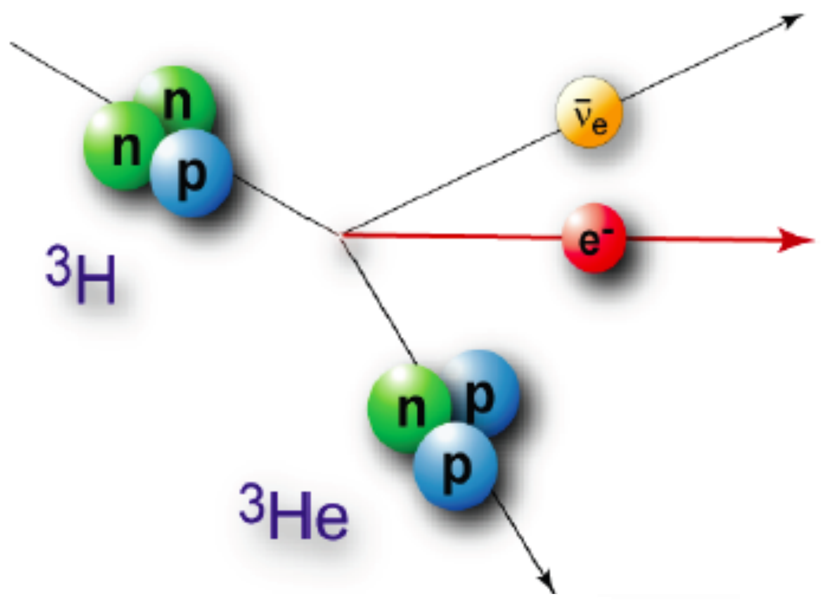
From oscillations:
$m_\nu > 0.05$ eV

- **Direct measurements**:

  Tritium beta decay experiments:

  ✦ KATRIN 2022: **m < 0.8 eV (90% CL)**

  ✦ KATRIN (goal): m < 0.3 eV (90% CL) in 2026



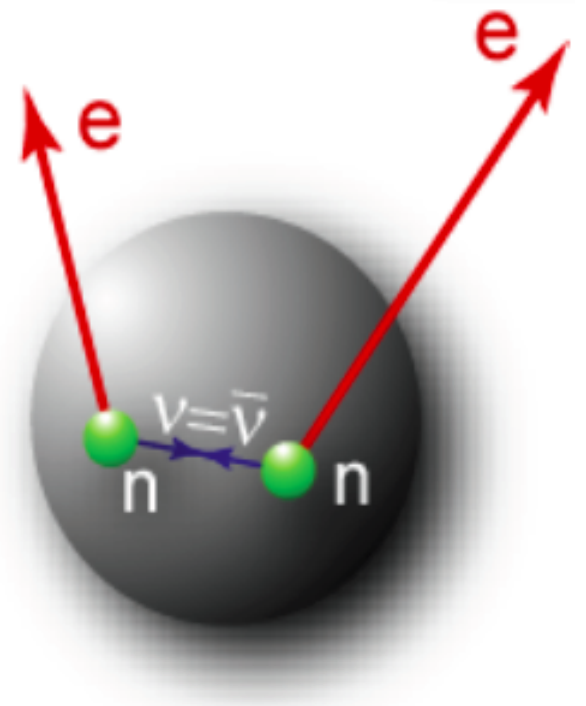
$$m_{\nu_e}^2 = \sum_i |U_{ei}|^2 \cdot m_{\nu_i}^2$$

- **Neutrinoless double beta decay**:

  ✦ If measured, neutrinos are Majorana particles

  ✦ GERDA, EXO, CUORE, CUPID, NEMO-3, KamLAND-Zen: **$m_{\beta\beta}$ < 28-122 meV (90% CL)**

  ✦ Future ton scale: $m_{\beta\beta}$ < 10 meV (only IO)



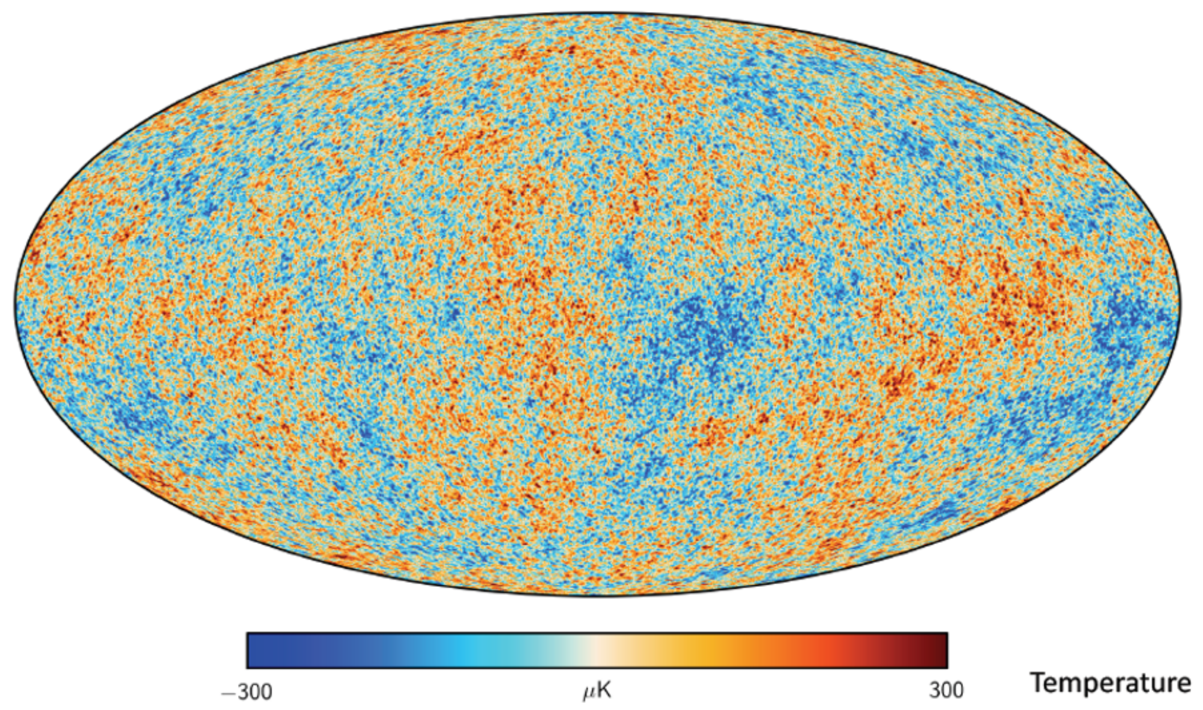
$$m_{\beta\beta} = \left| \sum_i U_{ei}^2 \cdot m_{\nu_i} \right|$$

- **Indirect measurements (Cosmology)**:

  PLANCK 2018: A&A 641 (2020) A6

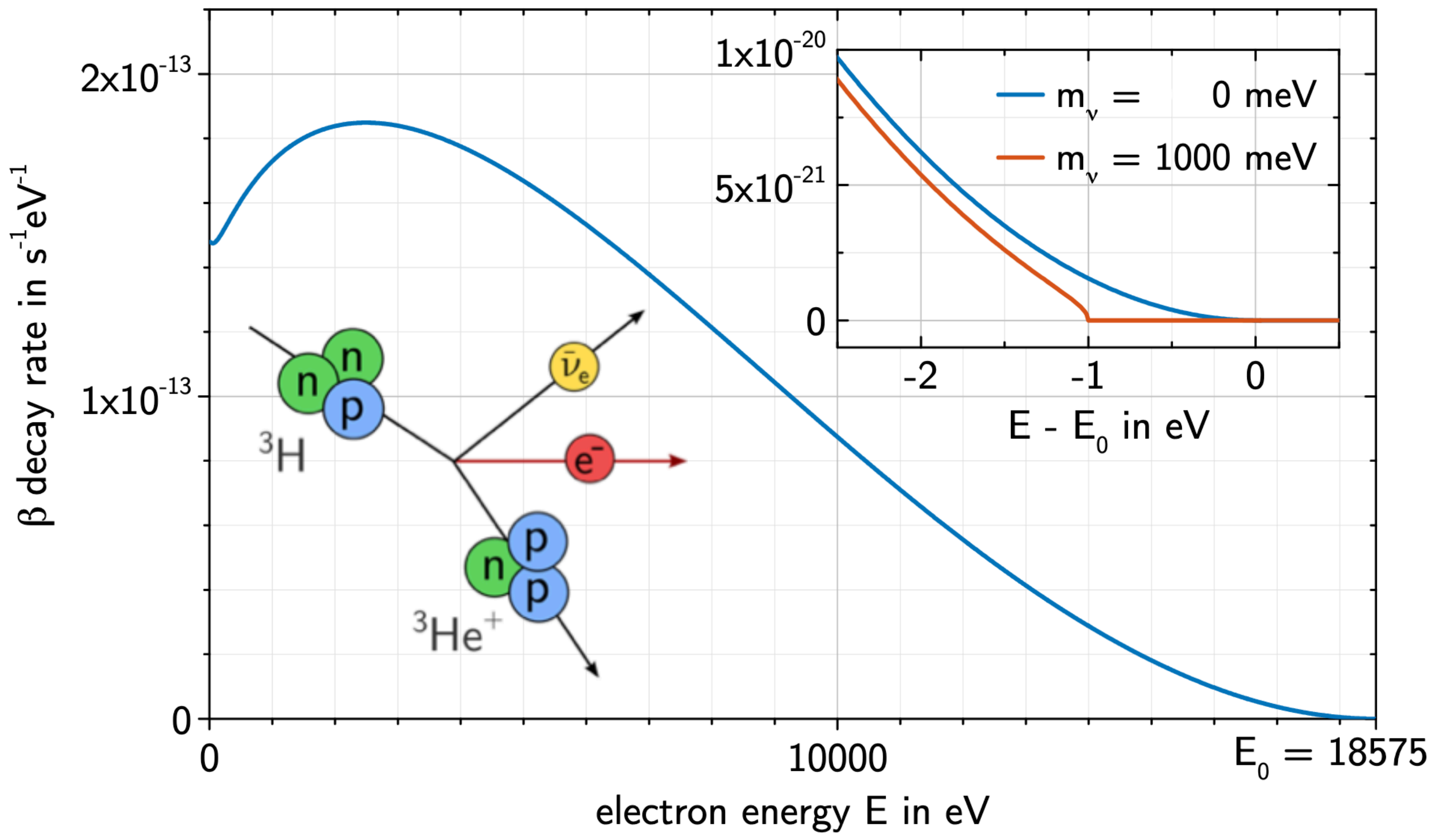
  ✦ **$\sum m_\nu$ < 0.12 eV** (Planck TT,TE,EE +low E +lensing +BAO)

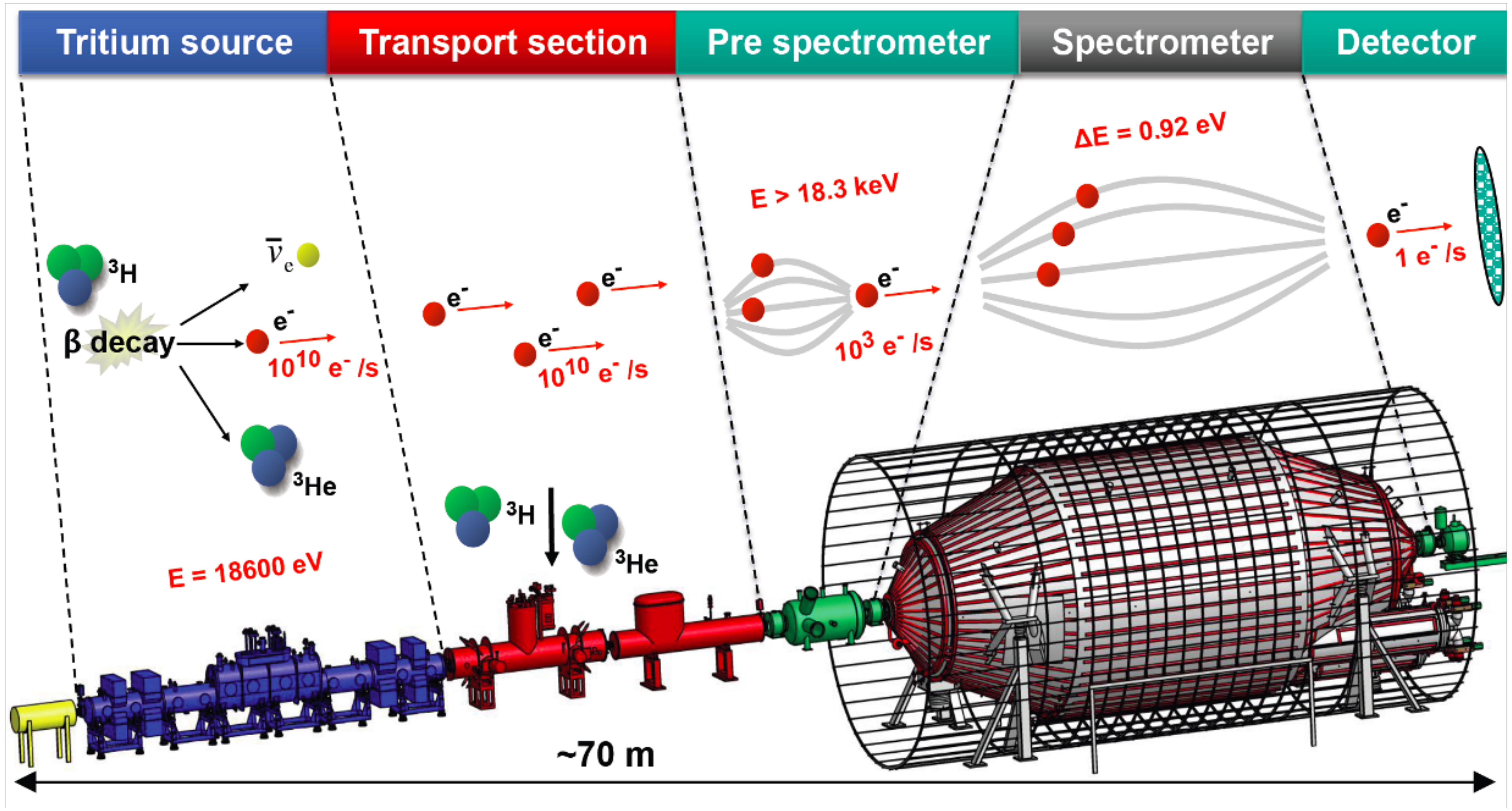
  ✦ $N_{eff} = 2.99^{+0.34}_{-0.33}$ (Planck TT,TE,EE +low E +lensing +BAO)



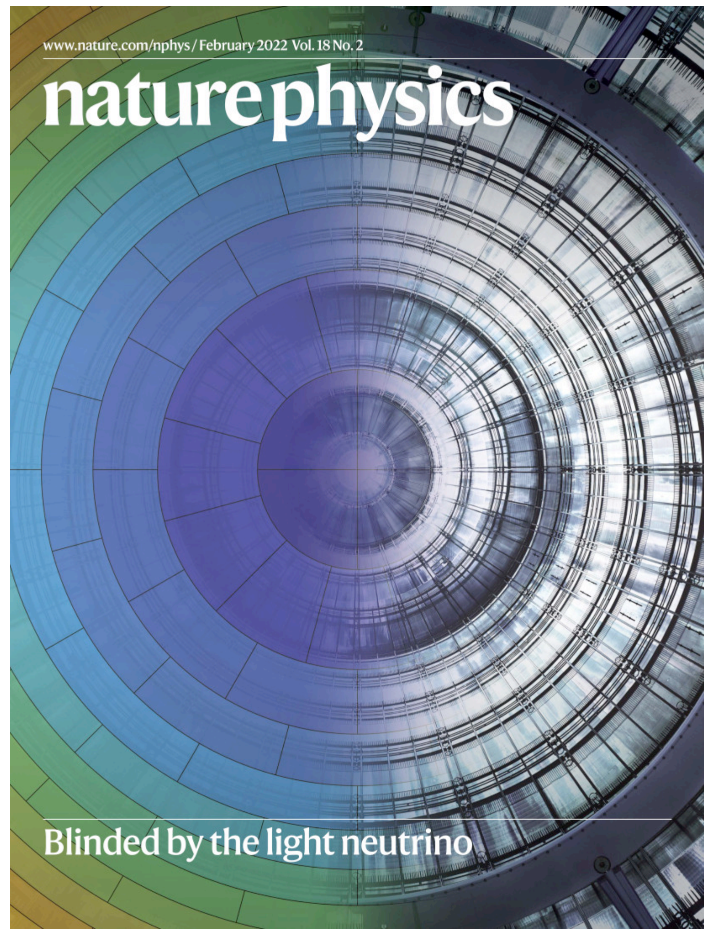
$$m = \sum_i m_{\nu_i}$$

KATRIN


β decay rate in s⁻¹eV⁻¹
2x10⁻¹³
1x10⁻¹³
0
0
10000
E₀ = 18575
electron energy E in eV
³H
³He⁺
n
p
e⁻
1x10⁻²⁰
5x10⁻²¹
-2
-1
E - E₀ in eV
m_ν = 0 meV
m_ν = 1000 meV

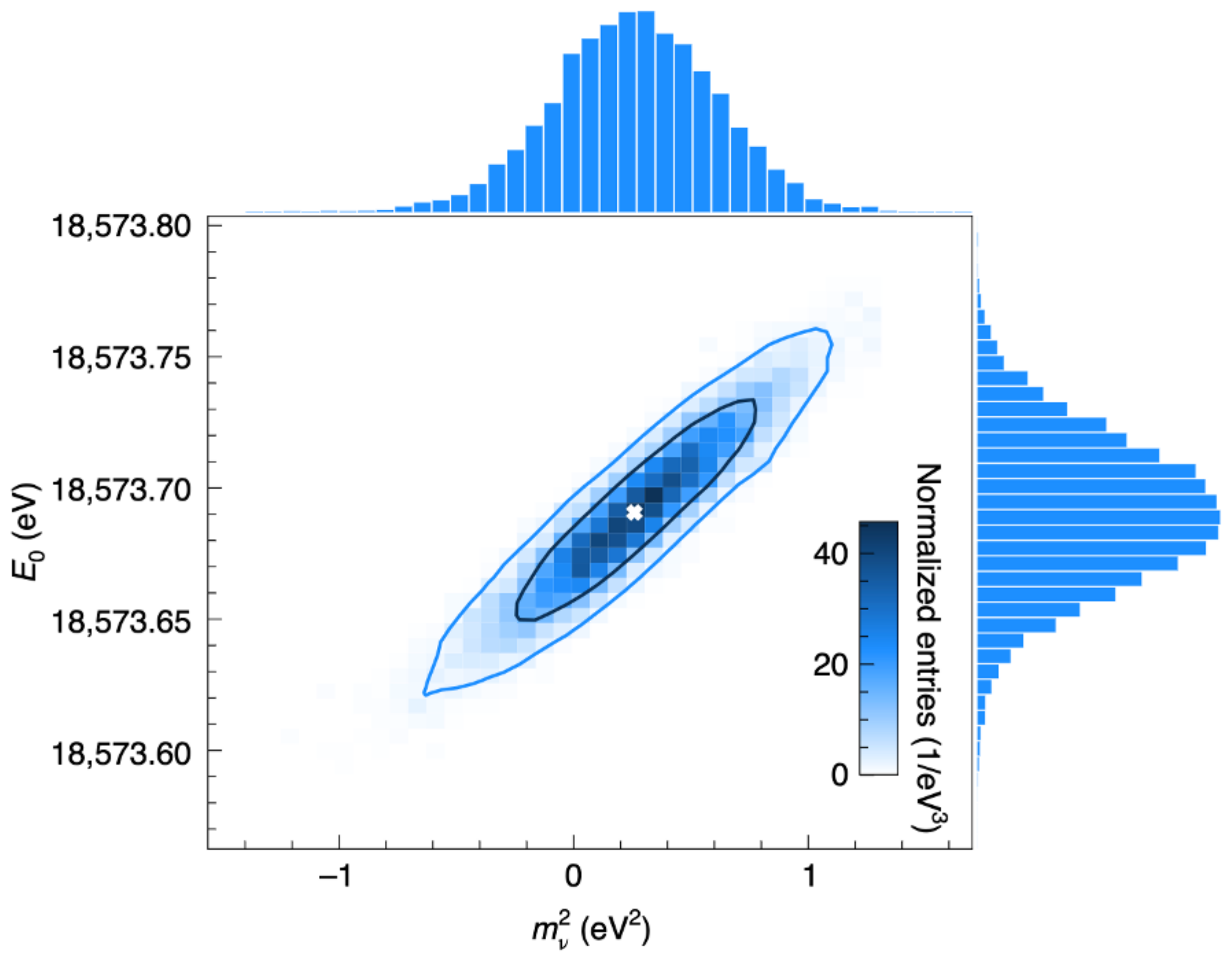

Tritium source
Transport section
Pre spectrometer
Spectrometer
Detector
³H
β decay
e⁻
10¹⁰ e⁻/s
³He
E = 18600 eV
E > 18.3 keV
10³ e⁻/s
ΔE = 0.92 eV
1 e⁻/s
~70 m

New KATRIN result (2024)

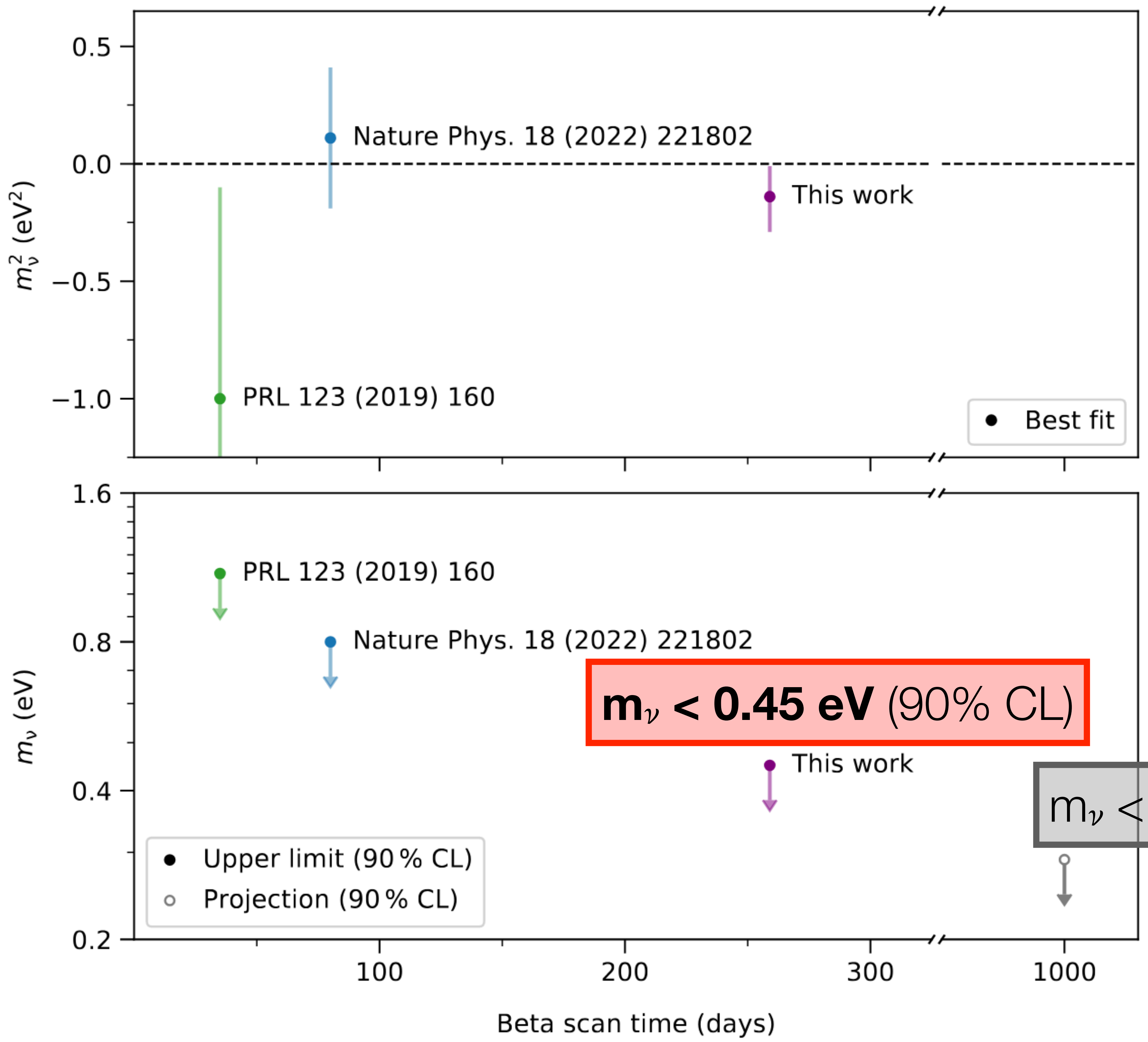


Nature Physics 18, 160-166 (2022)

m_ν < 0.8 eV (90% CL)



KATRIN arXiv:2406.13516 (2024)



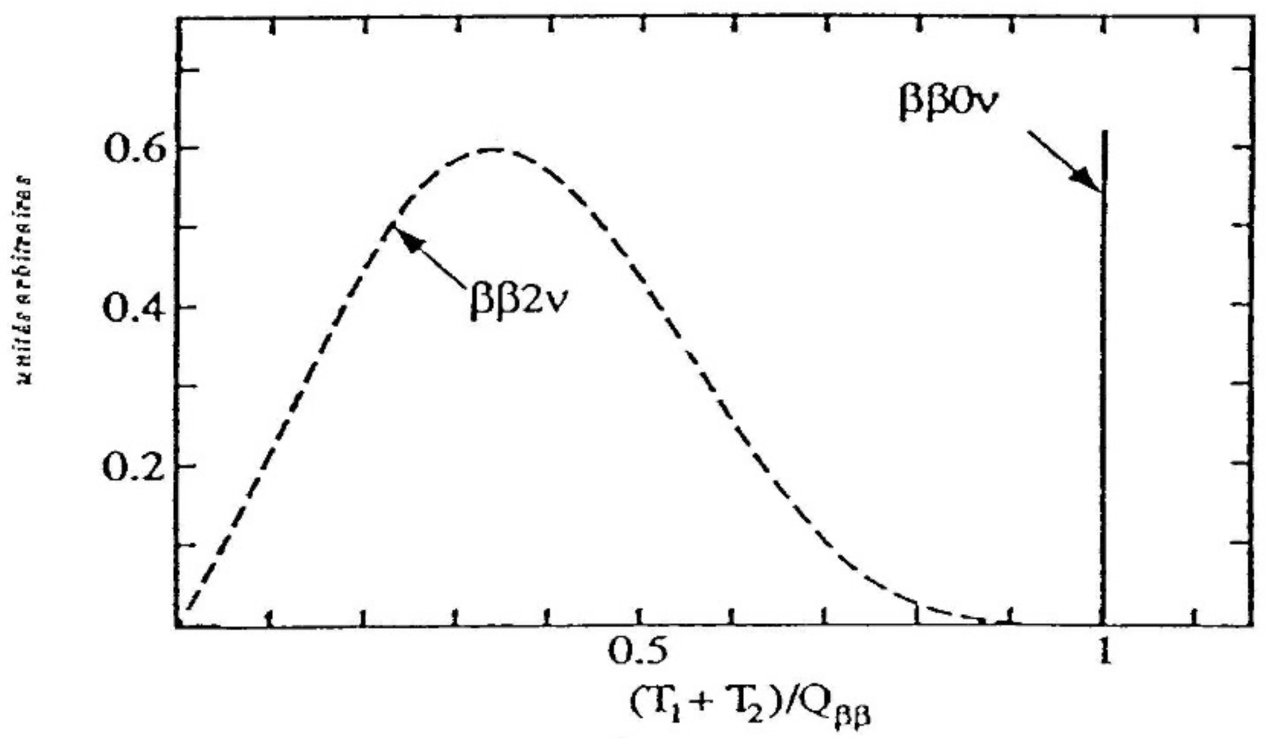
m_ν < 0.45 eV (90% CL)

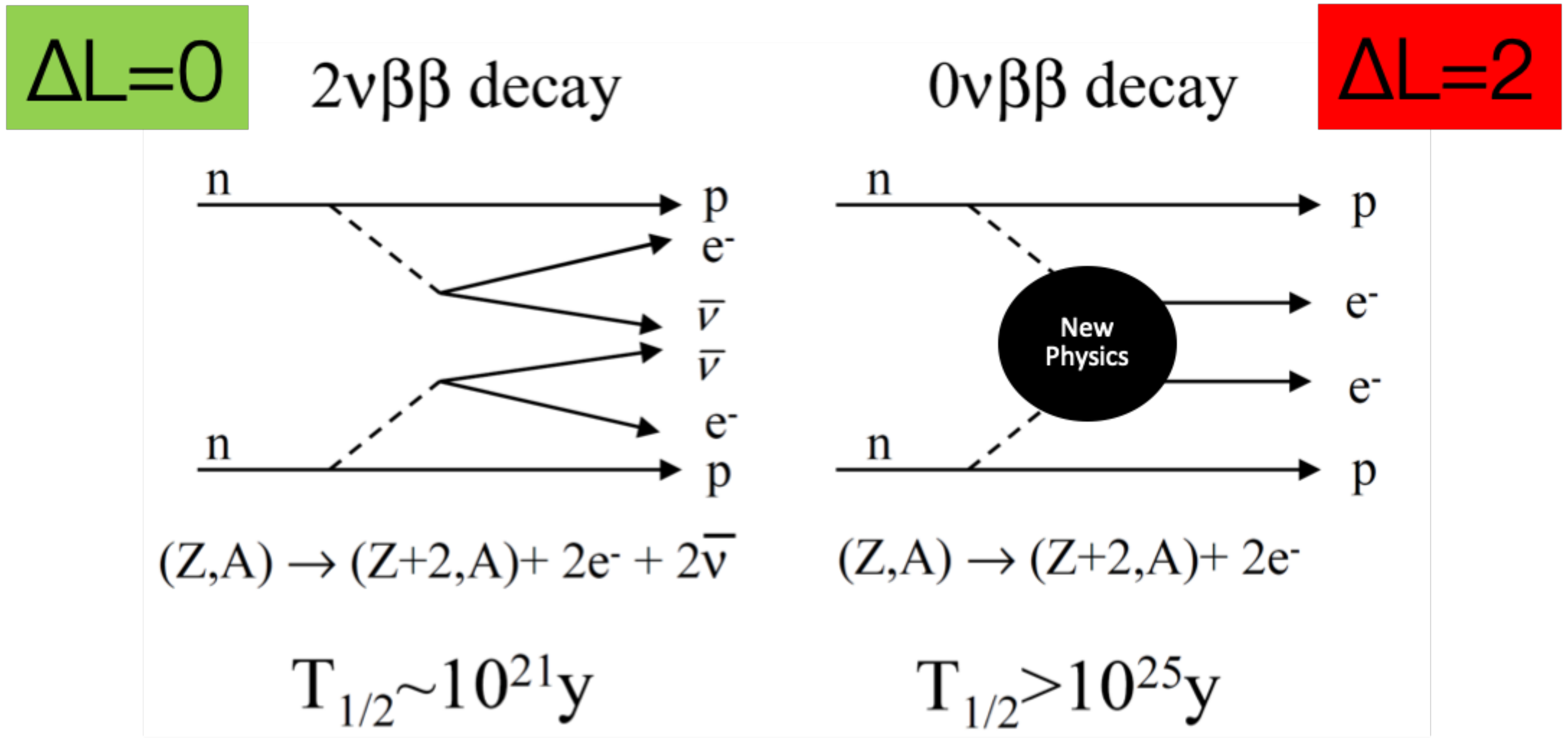
Final goal

m_ν < 0.3 eV (90% CL)

Other technologies (cyclotron radiation: Project-8; micro-calorimetry with holmium: ECHo, Holmes) **under development**

Neutrinoless double beta decay





In the light-neutrino exchange model,
$0\nu\beta\beta$ decay half-life:

$$T_{1/2}^{0\nu} = \left(G\,|\mathcal{M}|^2\,\langle m_{\beta\beta}\rangle^2\right)^{-1}$$

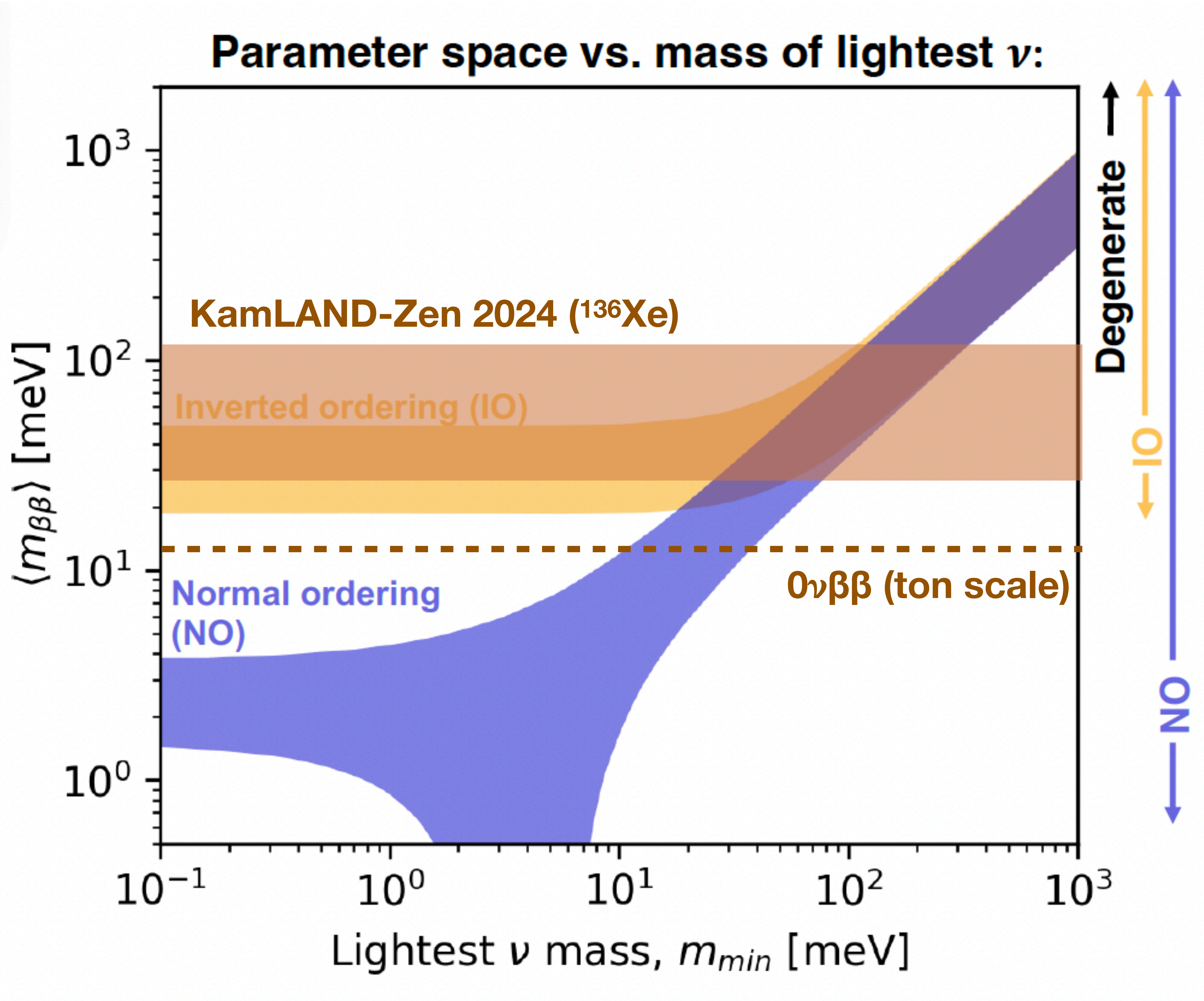
Phase space — Nuclear matrix elements — Effective Majorana neutrino mass

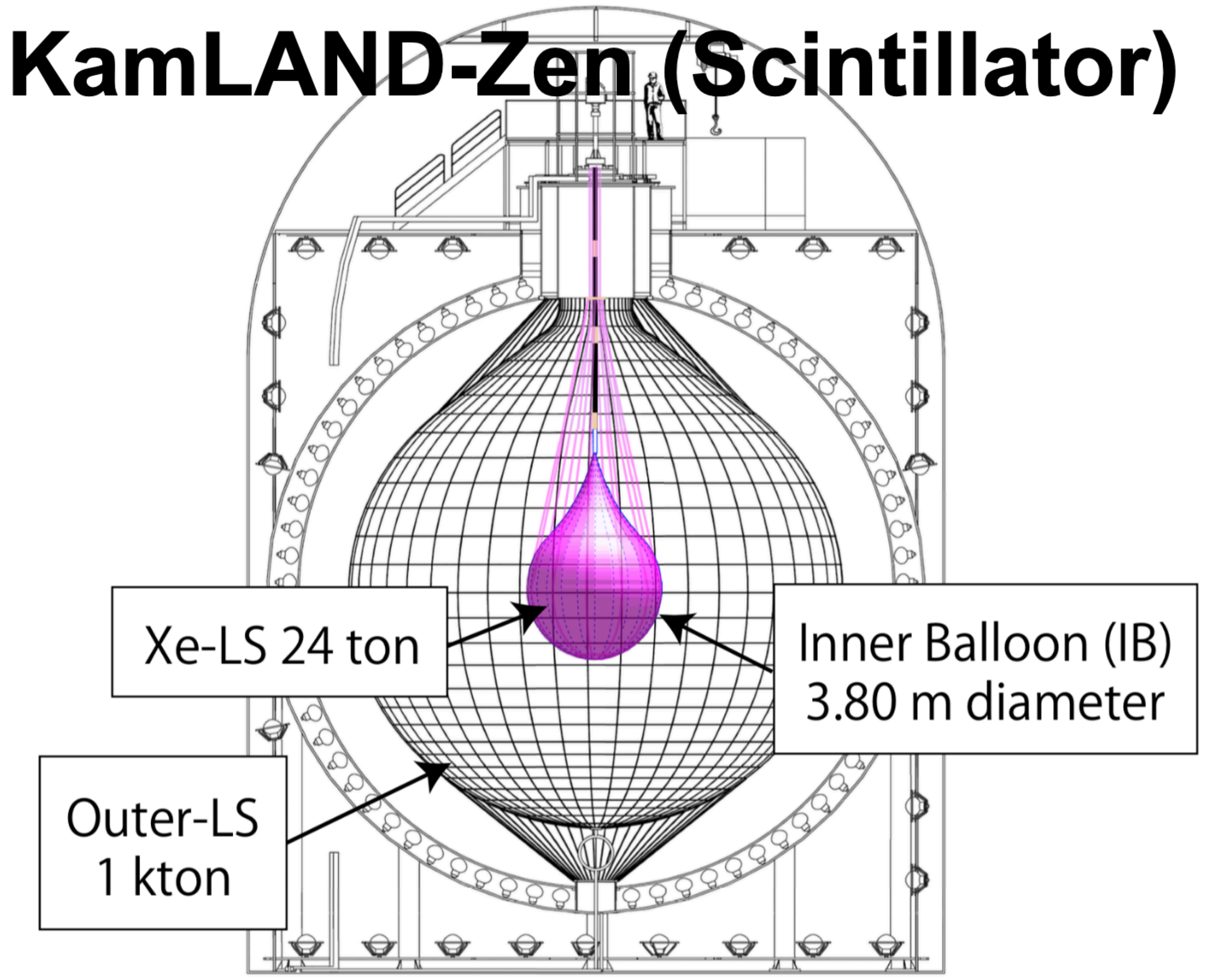
$$m_{\beta\beta} = \left|\sum_i U_{ei}^{\;2} \cdot m_{\nu_i}\right|$$

$$m_{\beta\beta} \equiv |m_1 c_{12}^2 c_{13}^2 + m_2 s_{12}^2 c_{13}^2 e^{i\alpha_{21}} + m_3 s_{13}^2 e^{i(\alpha_{31}-\delta)}|$$

- **2νββ** has been observed in more than 10 isotopes (lifetimes 10^{18} – 10^{21} y)
- **0νββ** has not been observed yet (lifetimes > 10^{25} – 10^{26} y):
  - ✦ It would imply **total lepton number violation** (LNV) and **neutrino Majorana mass**
  - ✦ Different mechanisms are possible: SUSY, leptoquarks, extradimensions, Majorons, …
  - ✦ Most discussed mechanism: **light Majorana neutrino exchange**

Current status of 0νββ searches





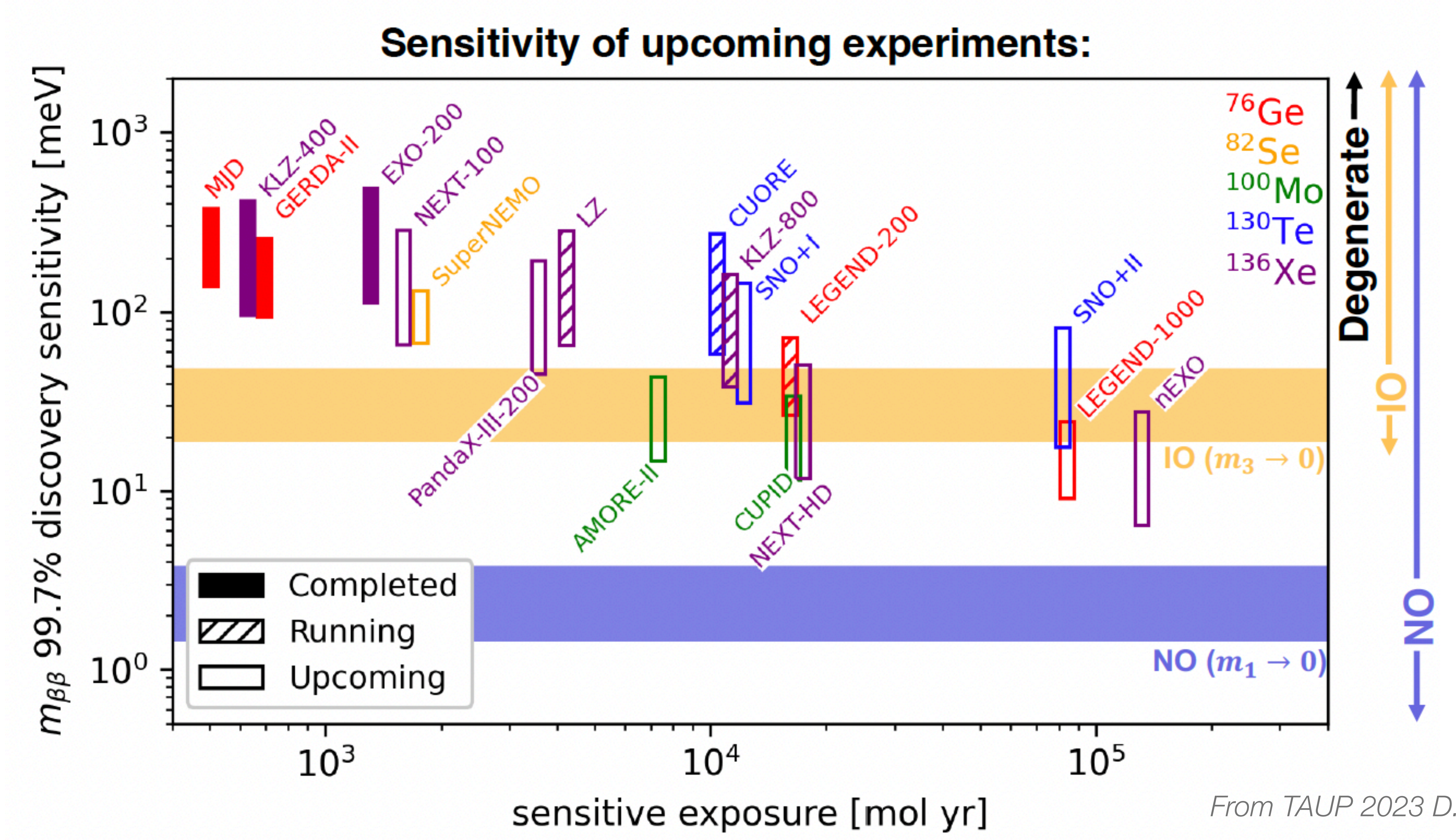
KamLAND-Zen

$\langle m_{\beta\beta} \rangle$ < 28-122 meV

$m_{lightest}$ < 84 - 353 meV

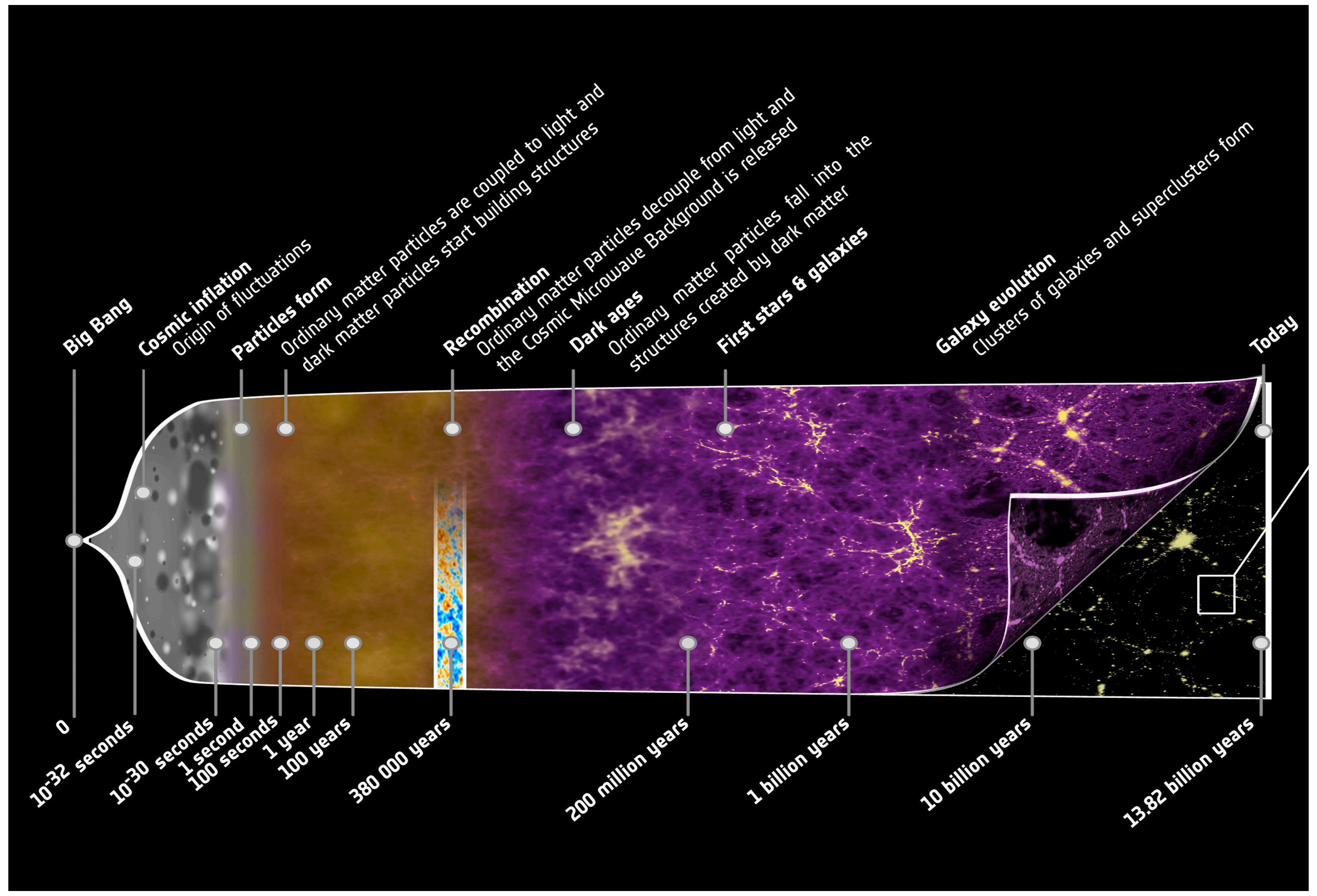
The most sensitive search to date for 0νββ

Current and future sensitivity

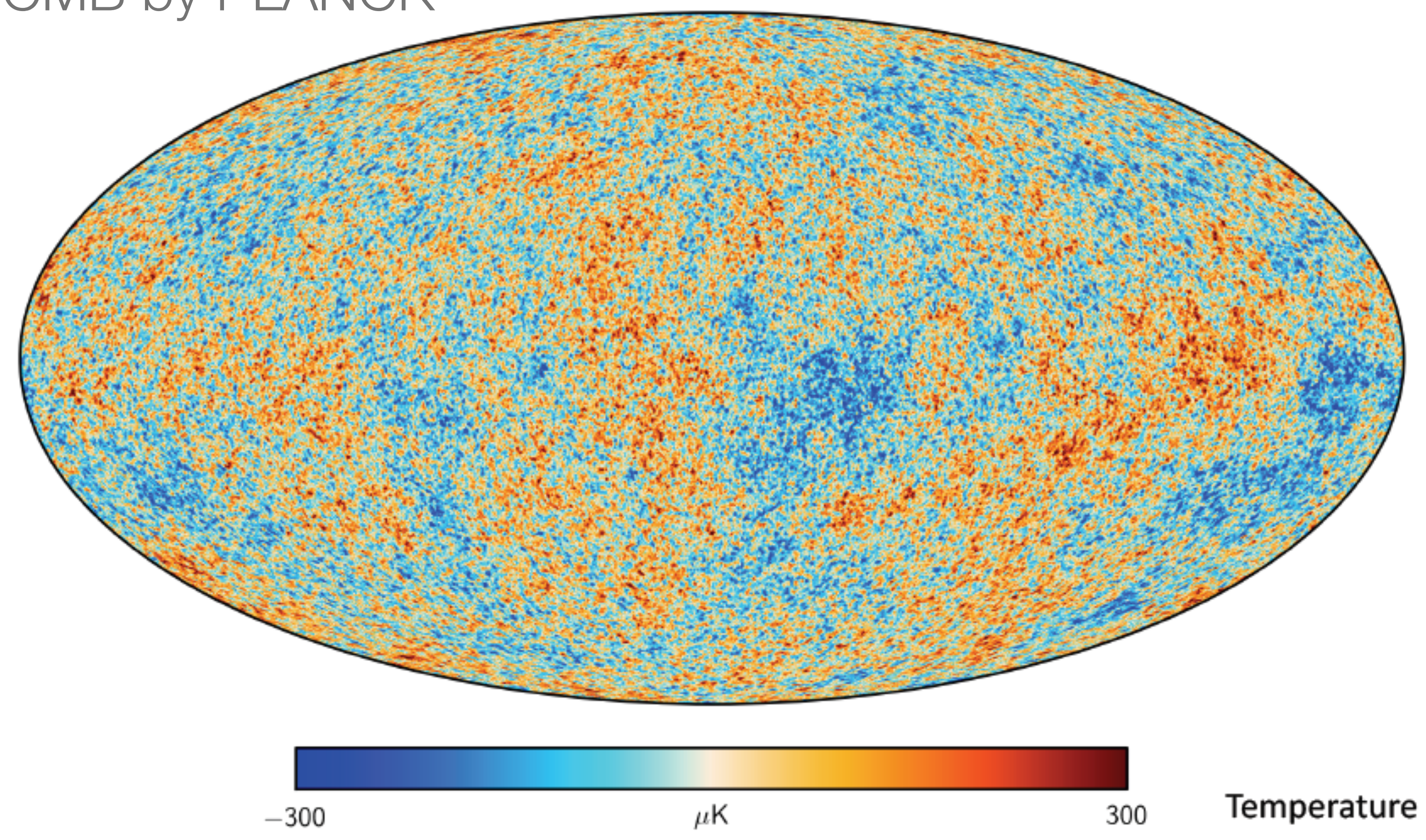


From TAUP 2023 D. Moore

Cosmology



CMB by PLANCK



- Neutrinos are everywhere in the Universe and their presence and interactions must be **incorporated into astrophysical and cosmological models**.
- **Cosmological neutrinos are very abundant**
  - ✦ They contribute to radiation at early times and to matter at late times
  - ✦ Cosmological observables can be used to test standard or non-standard properties
- Neutrino parameters: **sum of neutrino masses** ($\sum m_\nu$) & **effective number of neutrinos** (N_{eff})

$$\sum m_\nu > \begin{cases} 0.058\,\text{eV} & (\text{NO}) \\ 0.10\,\text{eV} & (\text{IO}) \end{cases} \text{ from osc.}$$

$$\sum m_\nu < 0.21\,\text{eV} \quad (\text{CMB})$$

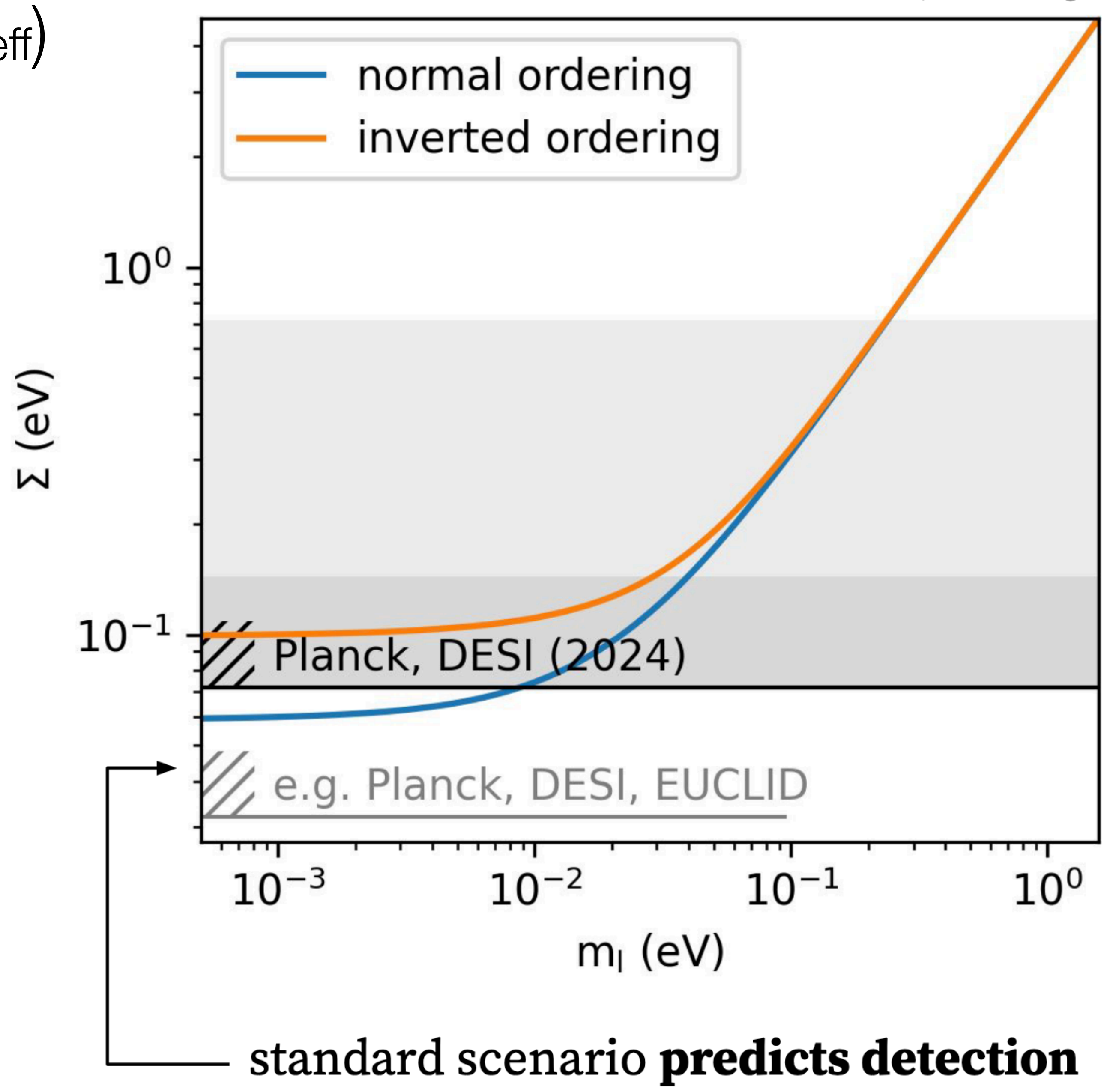
$$N_\nu = 2.9963 \pm 0.0074 \text{ from LEP}$$

$$N_{\text{eff}} = 2.98 \pm 0.20 \quad (\text{CMB})$$

New result from **CMB** + **DESI BAO** (2024), 95%:

$$\sum m_\nu < 0.072\ \text{eV}$$

[NuFIT 5.3, nu-fit.org]



3 Messengers of the Universe

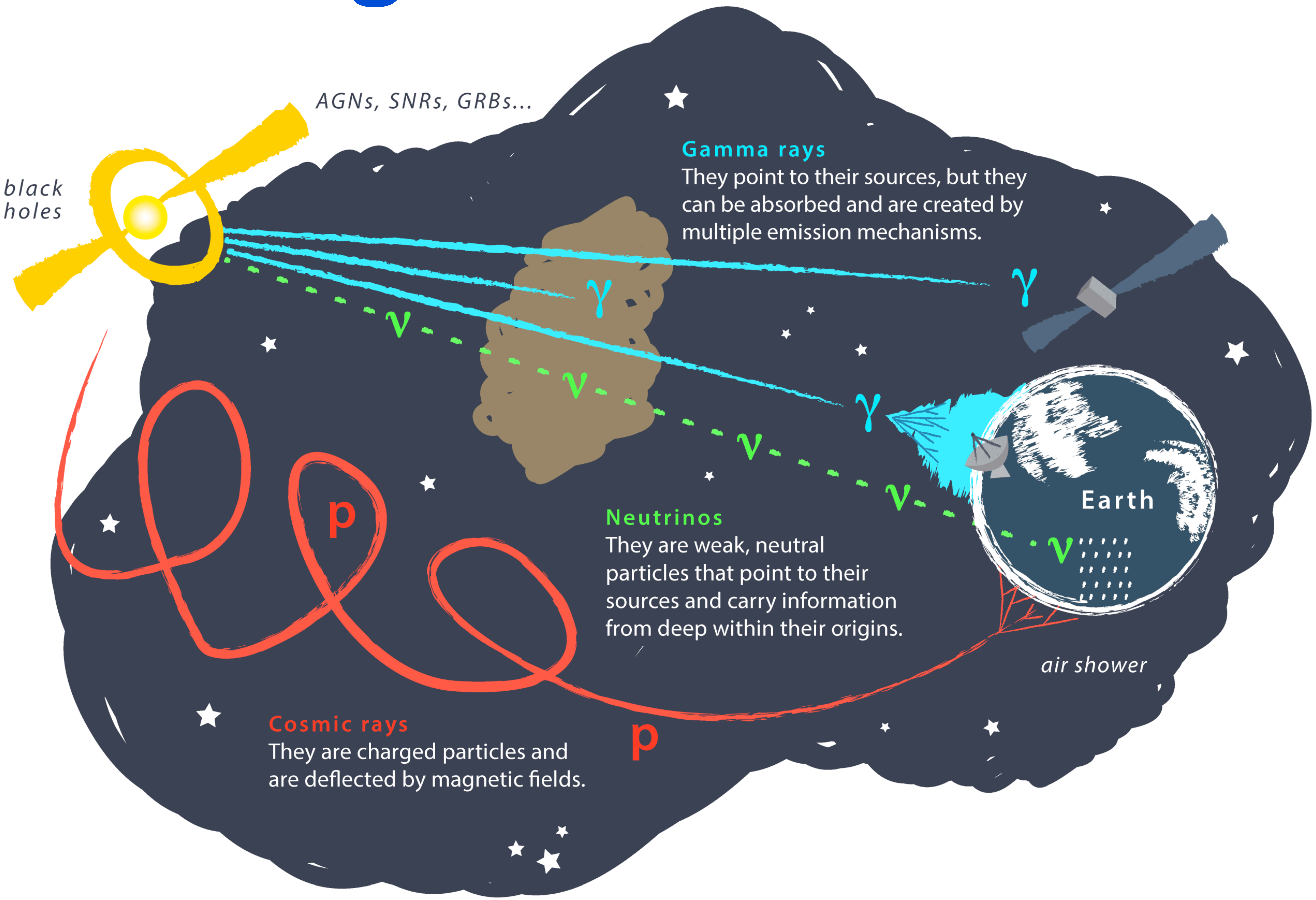
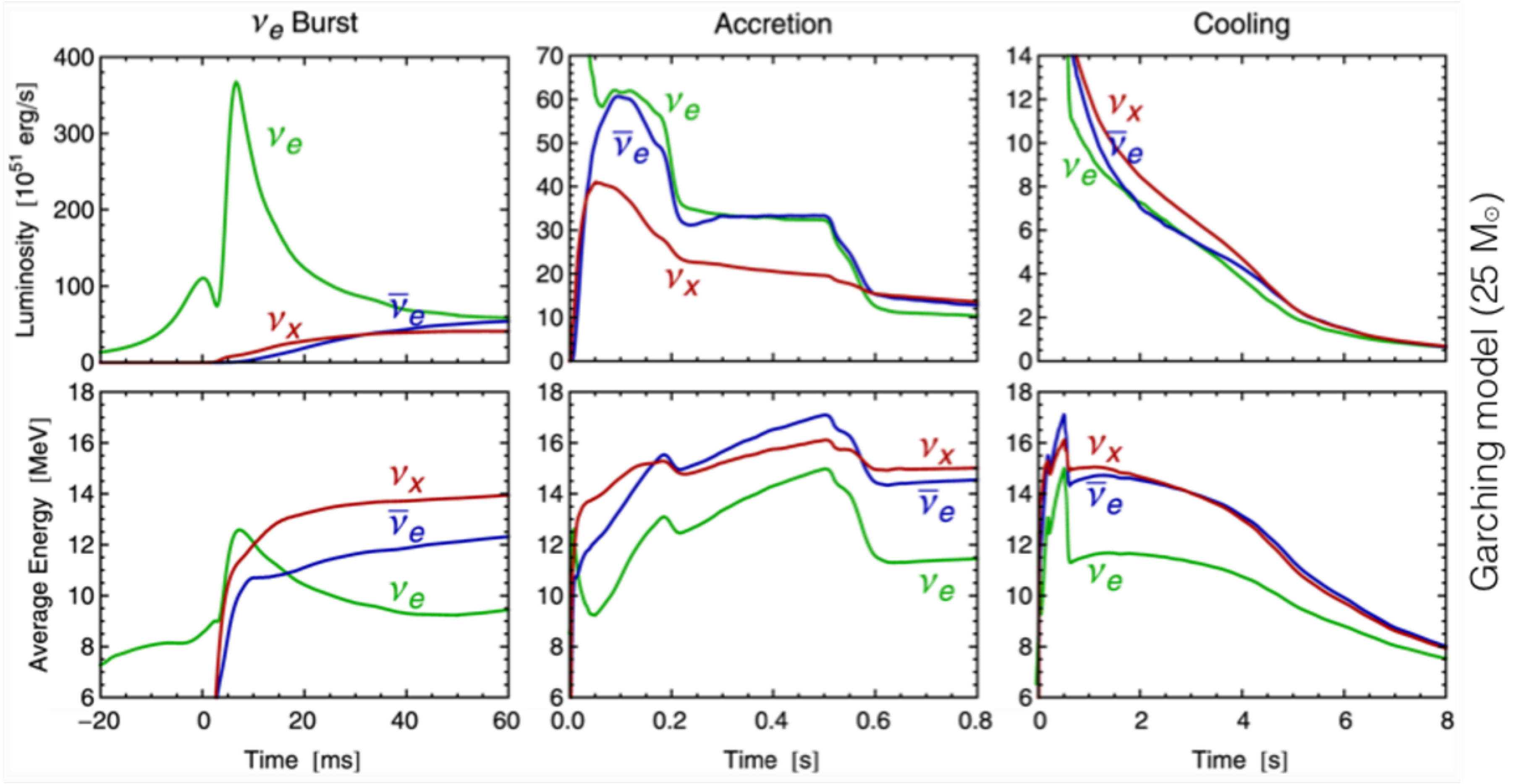


Image: Juan Antonio Aguilar and Jamie Yang. IceCube/WIPAC

Neutrinos from core-collapse supernovae and DSNB

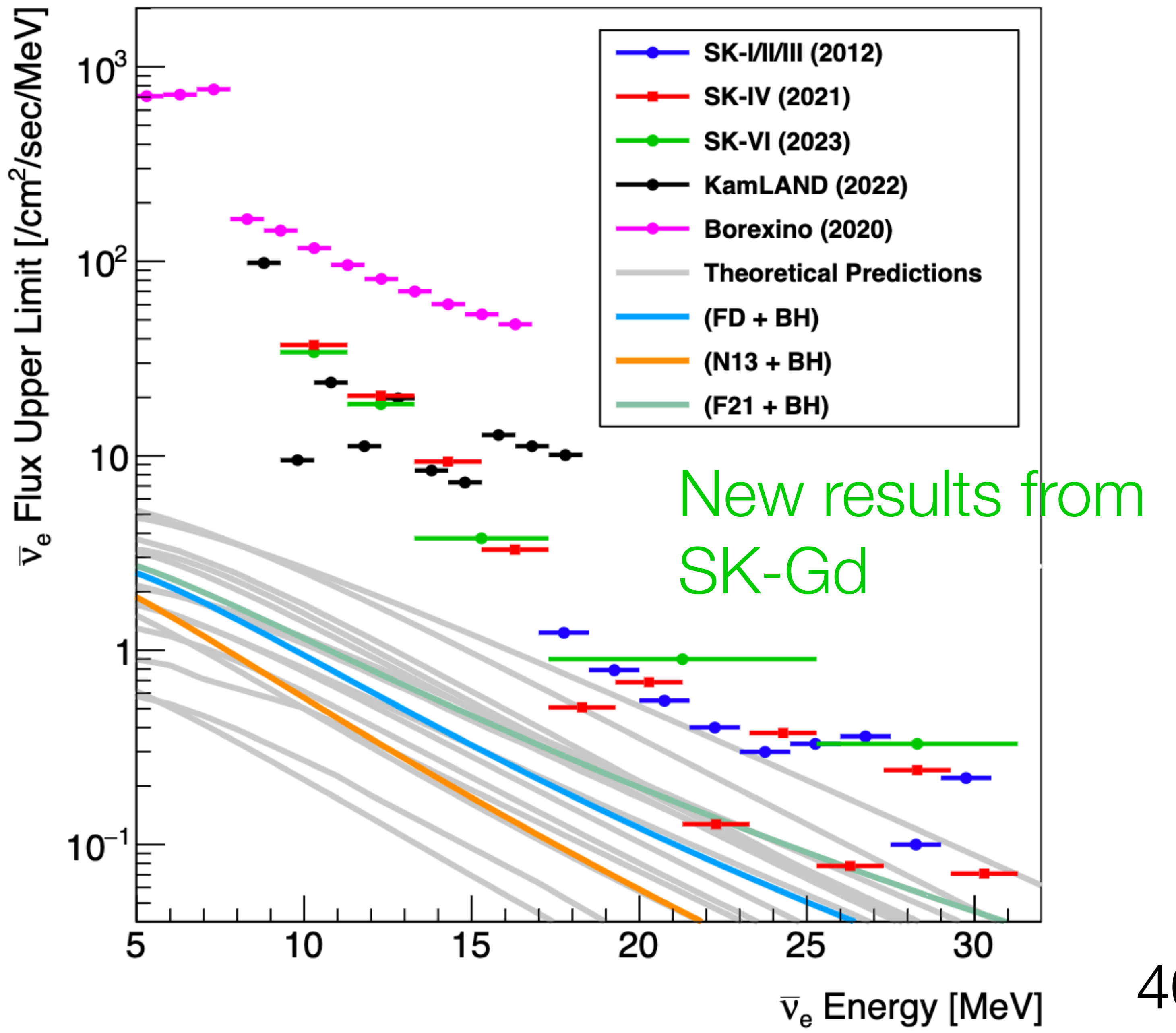
Detection of **core-collapse supernova neutrinos** (99% SN binding energy emitted in ~10 seconds by neutrinos) provides information about:

- ✦ Core-collapse explosion mechanism
- ✦ Neutrino properties

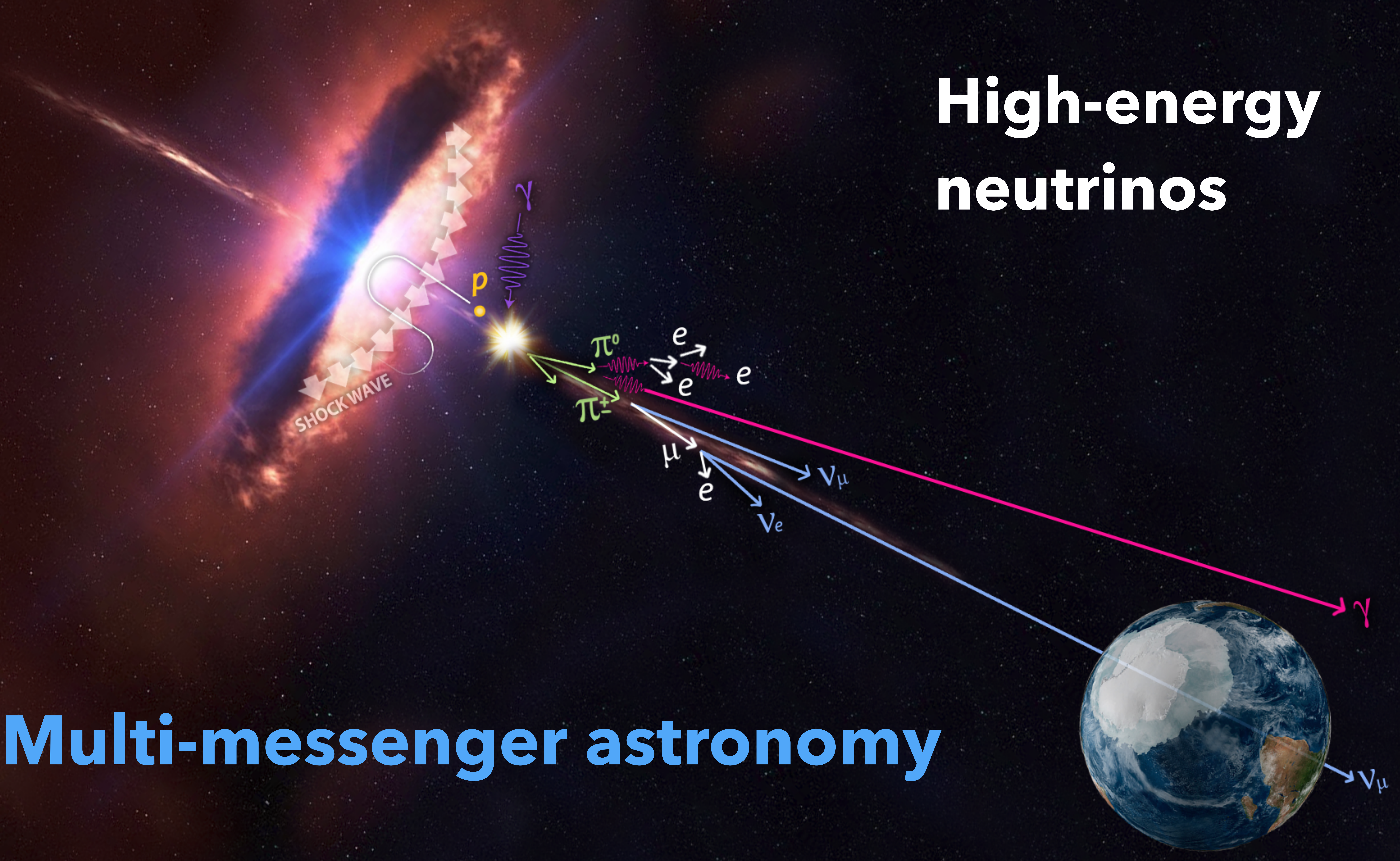


Detection of **diffuse supernova neutrino background** (averaged neutrino flux from all supernovae)

- ✦ No detected yet
- ✦ Best upper limits from Super-K

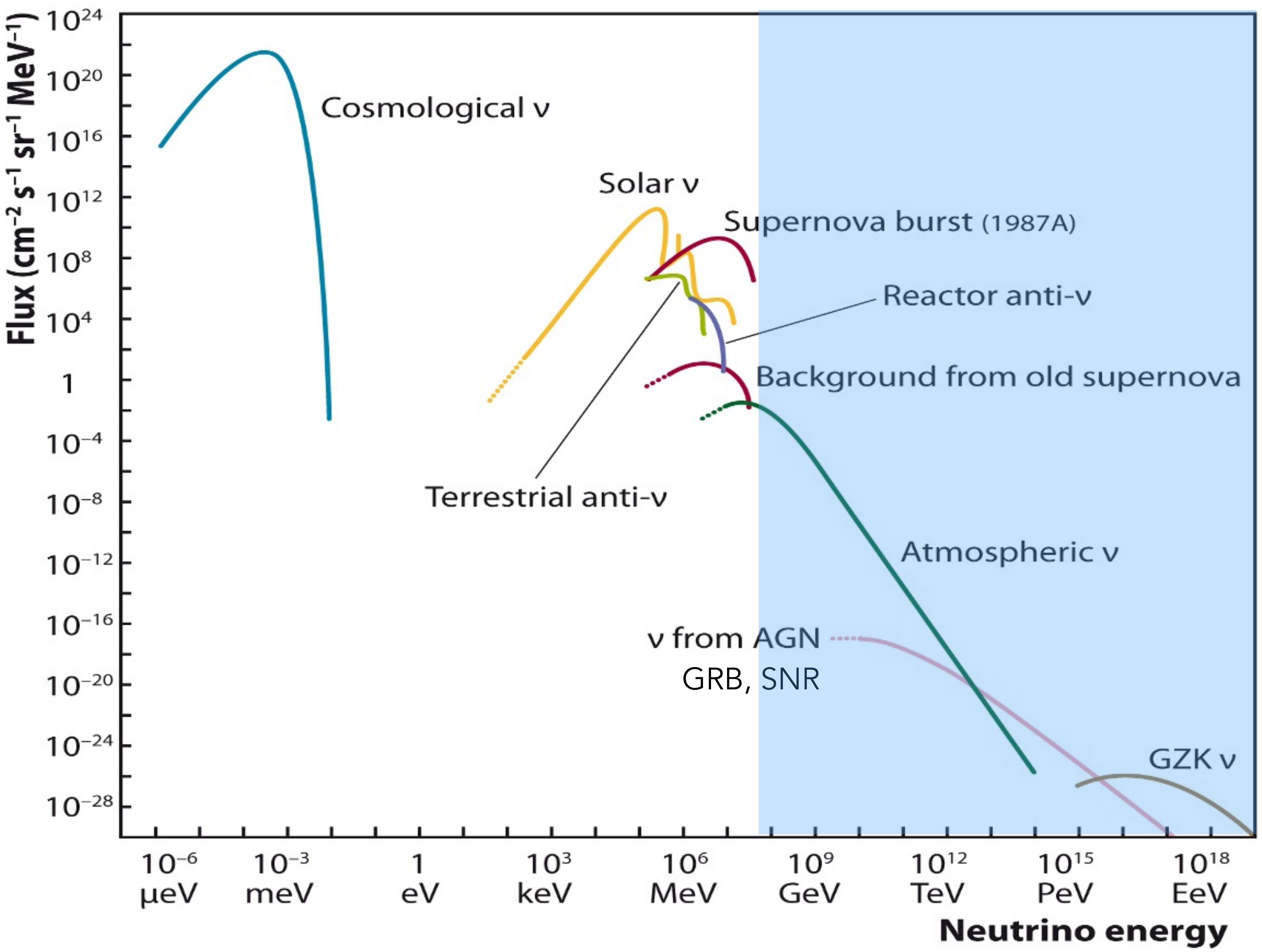


High-energy neutrinos



Multi-messenger astronomy

Astrophysical neutrinos - high-energy neutrinos

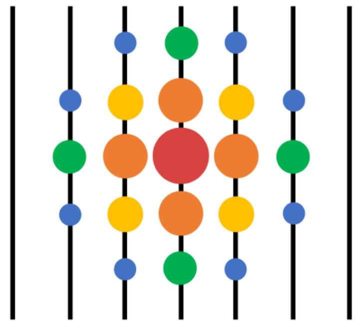


- **Atmospheric** neutrinos
  - ✦ Up to 100 TeV
- **Cosmic** neutrinos (~TeV-PeV)
  - ✦ From AGN, GRB, SNR
- **Cosmogenic** neutrinos (PeV-EeV)
  - ✦ From cosmic ray interactions with CMB photons (not detected yet)
- Production: $p + \gamma \rightarrow n + \pi^+$

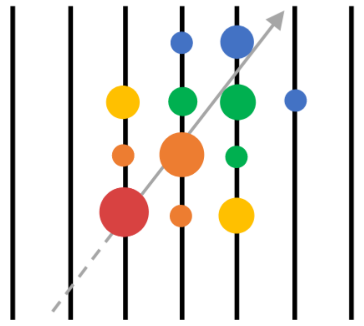
$$\pi^+ \rightarrow \mu^+ + \nu_\mu$$
$$\mu^+ \rightarrow e^+ + \nu_e + \bar{\nu}_\mu$$

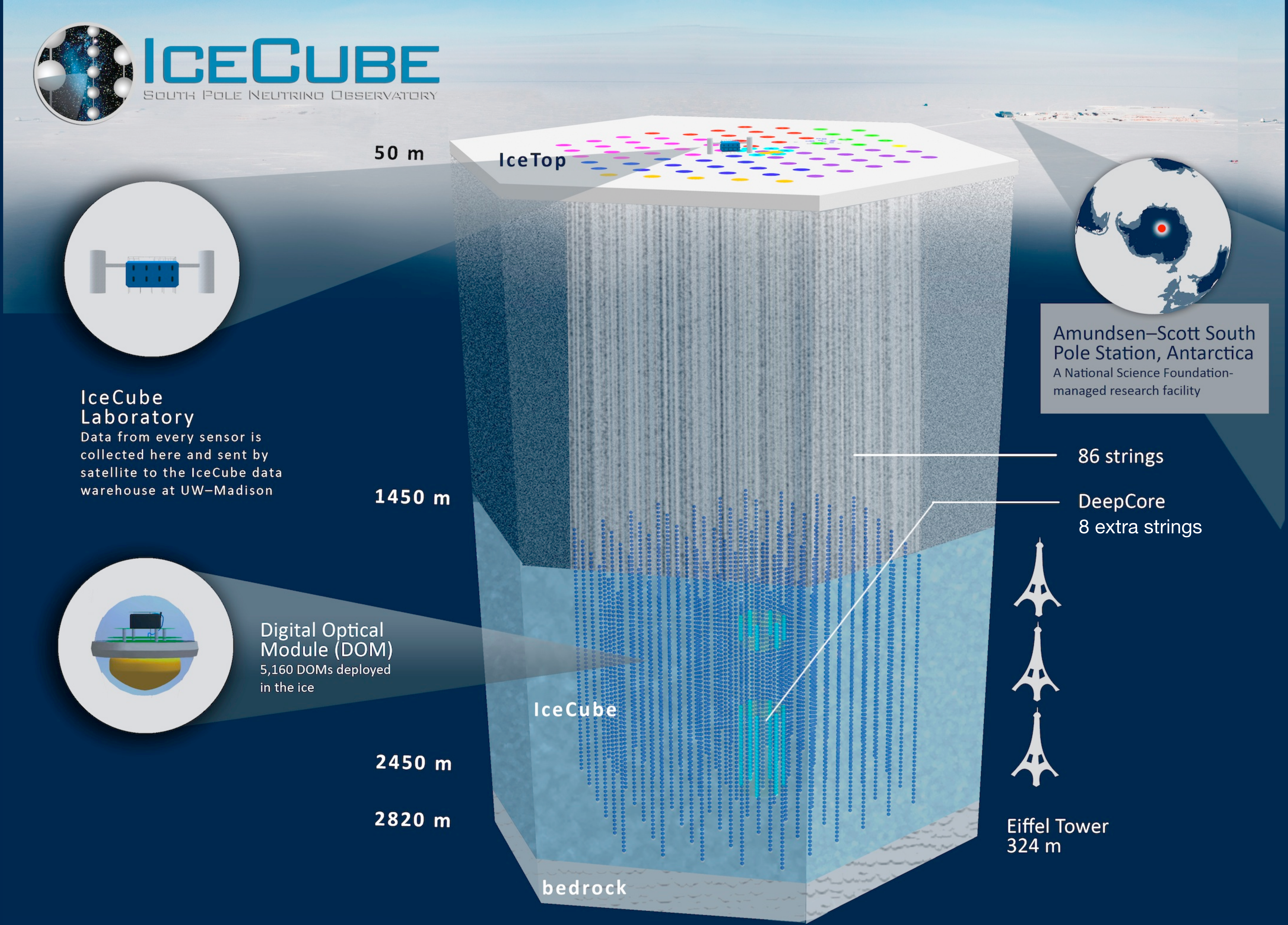
- Detection of astrophysical neutrinos
  - ✦ Interaction with water/ice producing Cherenkov photons (shower vs tracks)

ν_eCC, ν_τCC, NC



ν_μCC

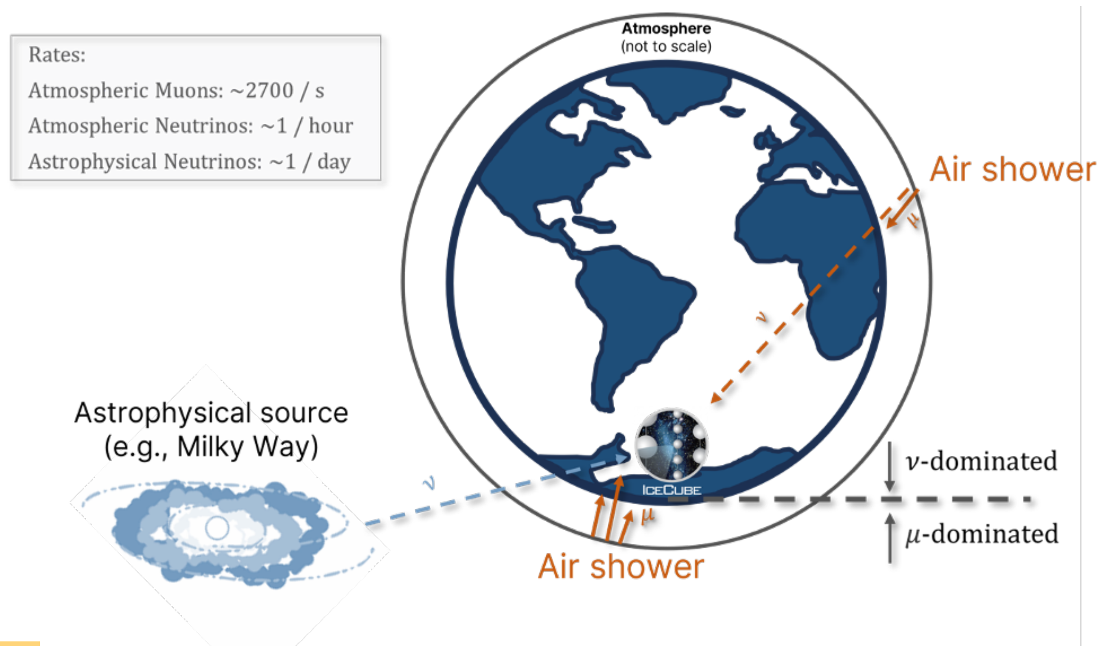


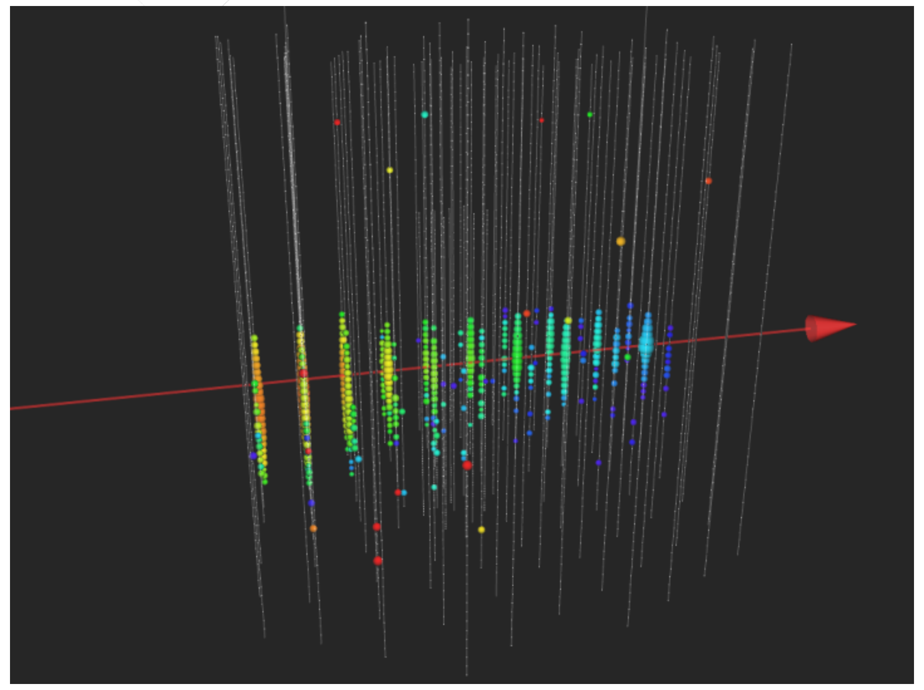


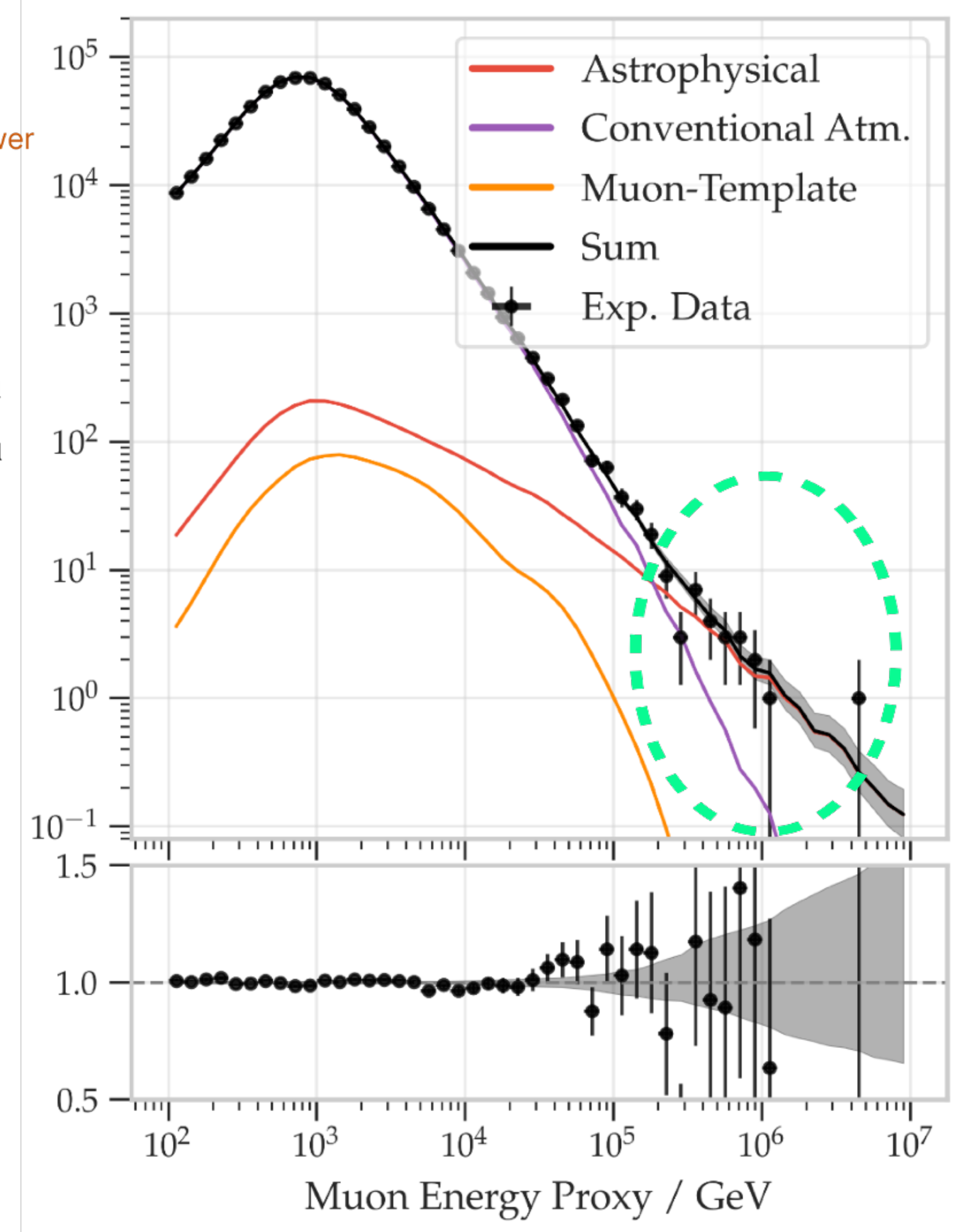
IceCube
South Pole Neutrino Observatory
50 m
IceTop
IceCube
Laboratory
Data from every sensor is
collected here and sent by
satellite to the IceCube data
warehouse at UW–Madison
Amundsen–Scott South
Pole Station, Antarctica
A National Science Foundation-
managed research facility
86 strings
DeepCore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

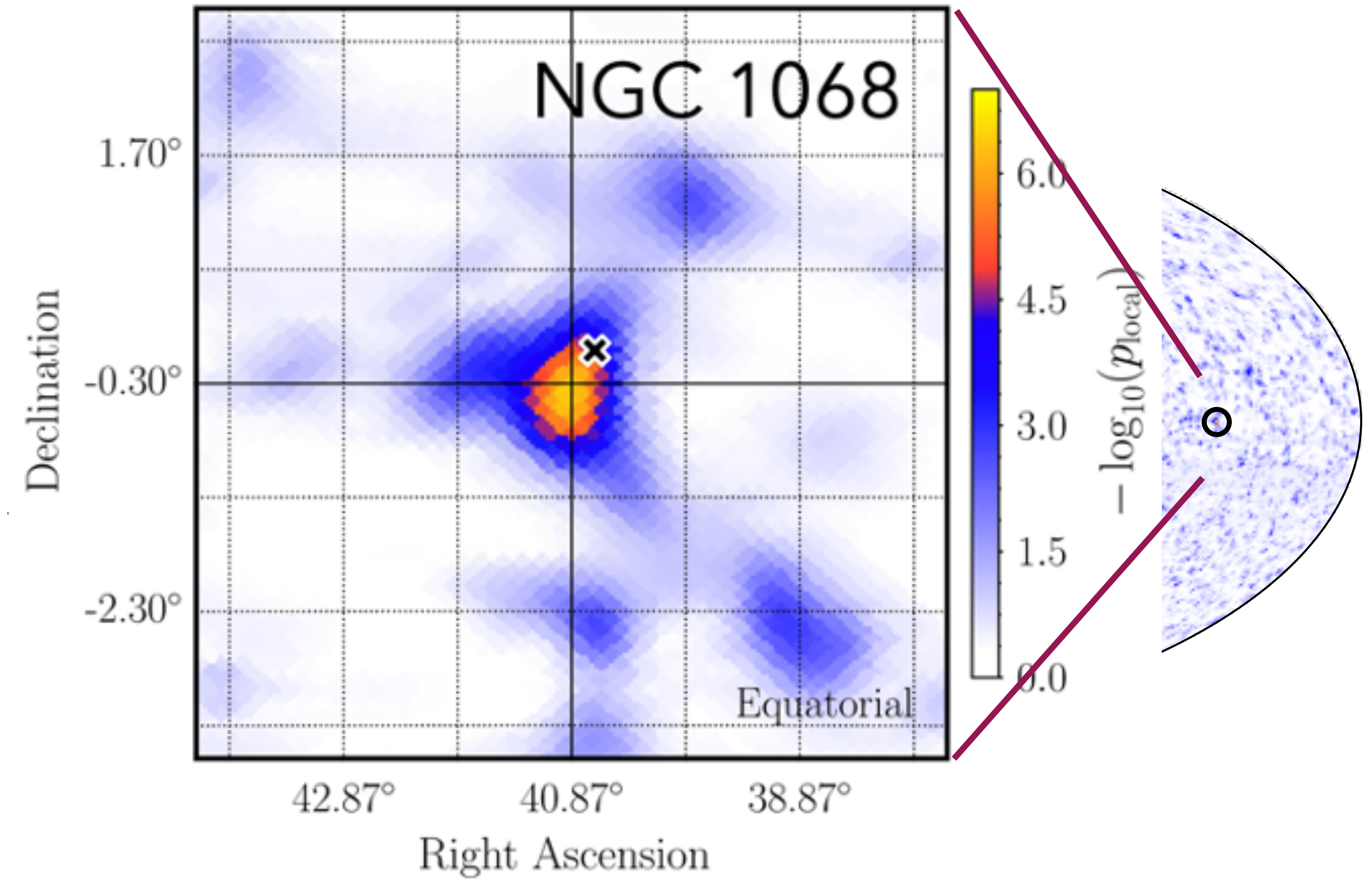
IceCube results

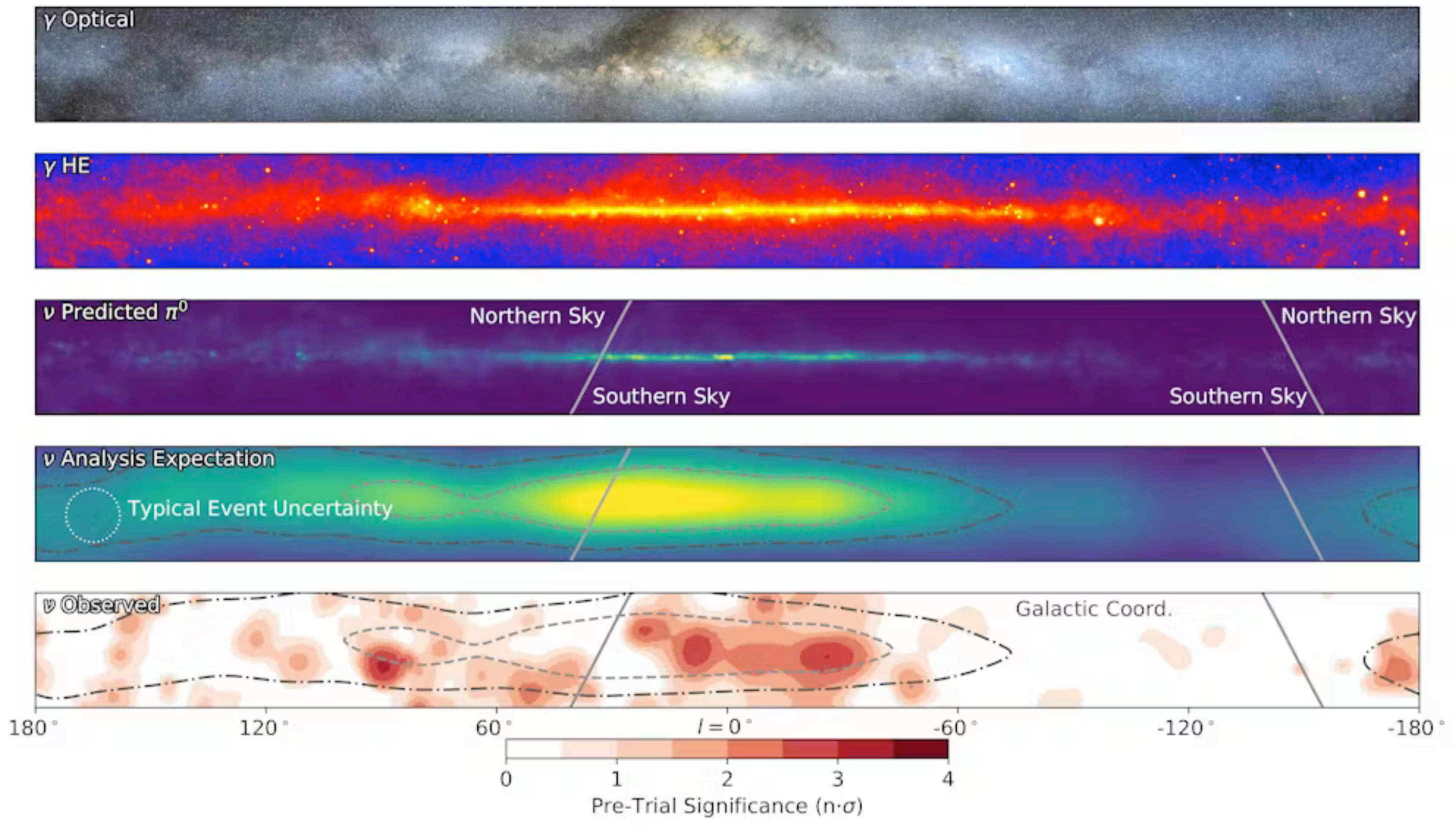
- 2013: Discovery of high-energy astrophysical neutrino flux
- 2017: Neutrino emission from **blazar TXS 0506+056**
- 2022: Neutrino emission from the **active galaxy NGC1068**
- 2023: Evidence of neutrinos from the **Galactic plane**







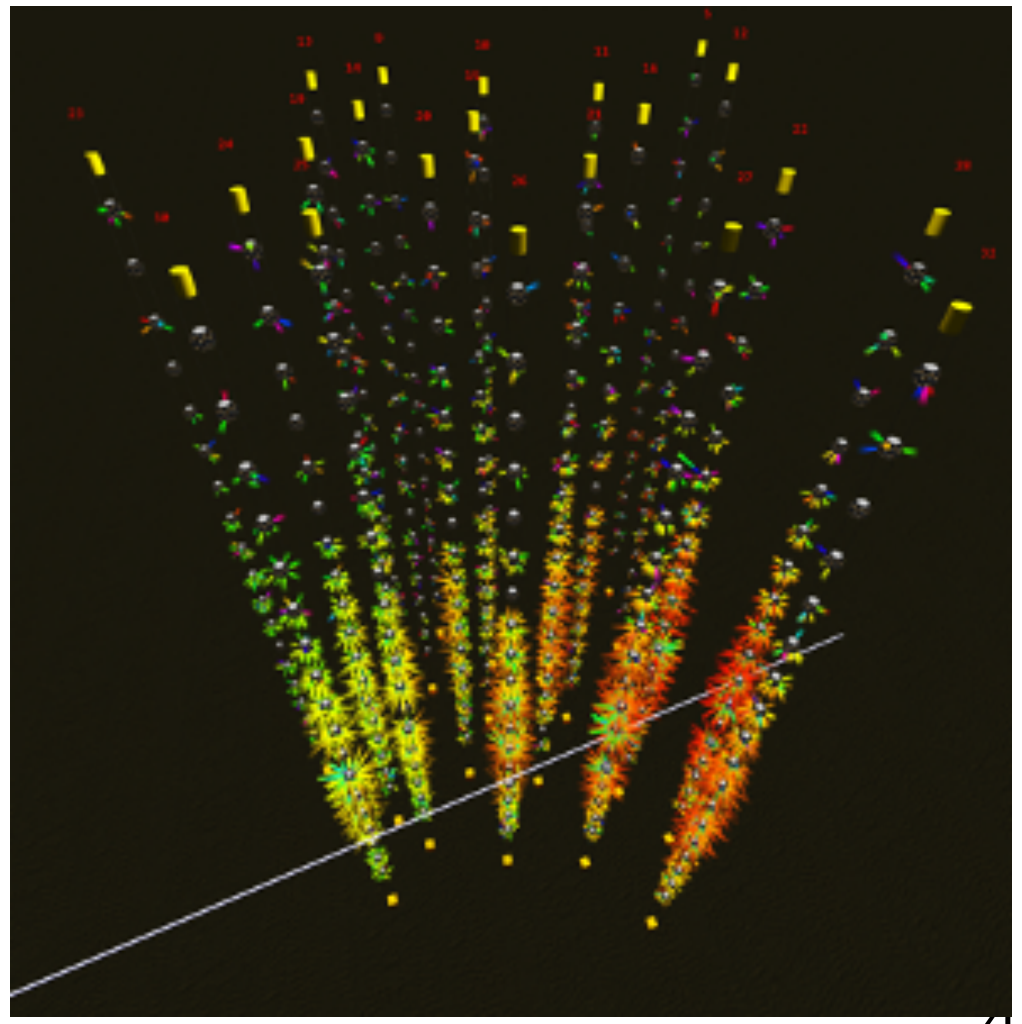




Neutrino astronomy is an exciting field

KM3NeT also taking data!

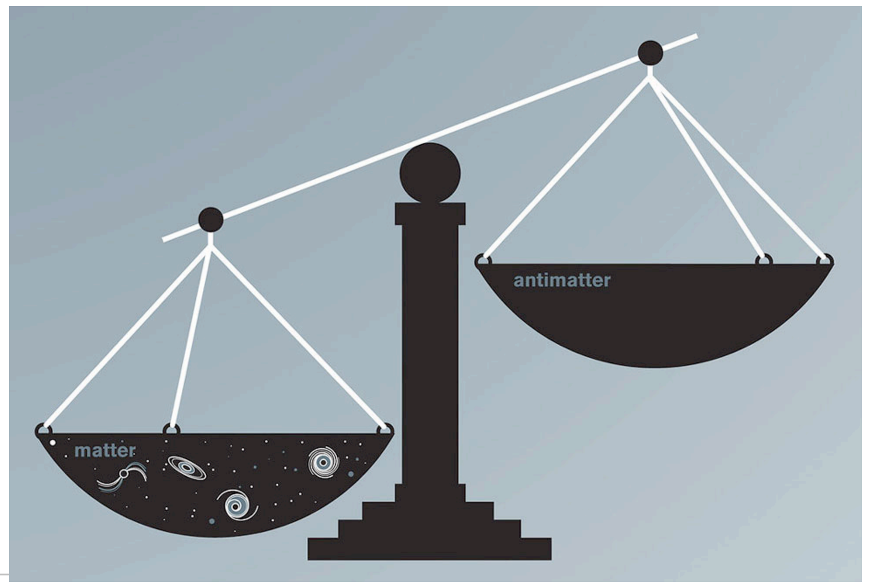
Event (likely 10's of PeV) detected by KM3NeT

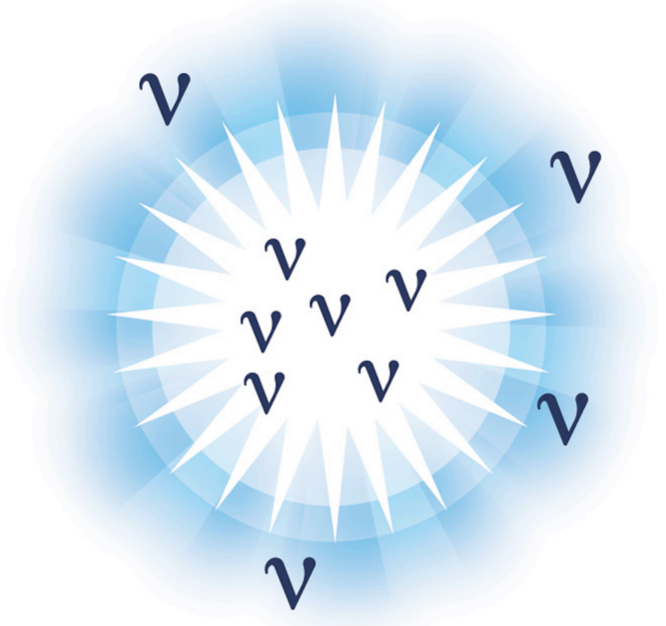


4 Future challenges and discoveries

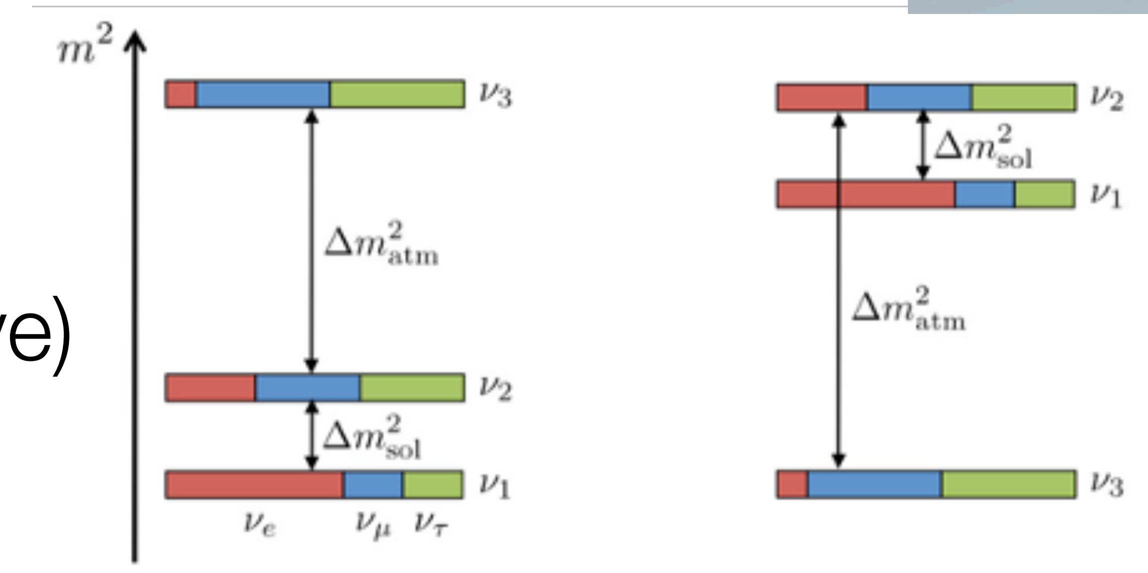
Discovery opportunities in LBL experiments

- **CP violation**
  - ✦ T2K and NOvA could reach 3σ sensitivity to CPV over the next years
  - ✦ To reach discovery and precise measurement, larger detectors and (upgraded or new) beams are needed

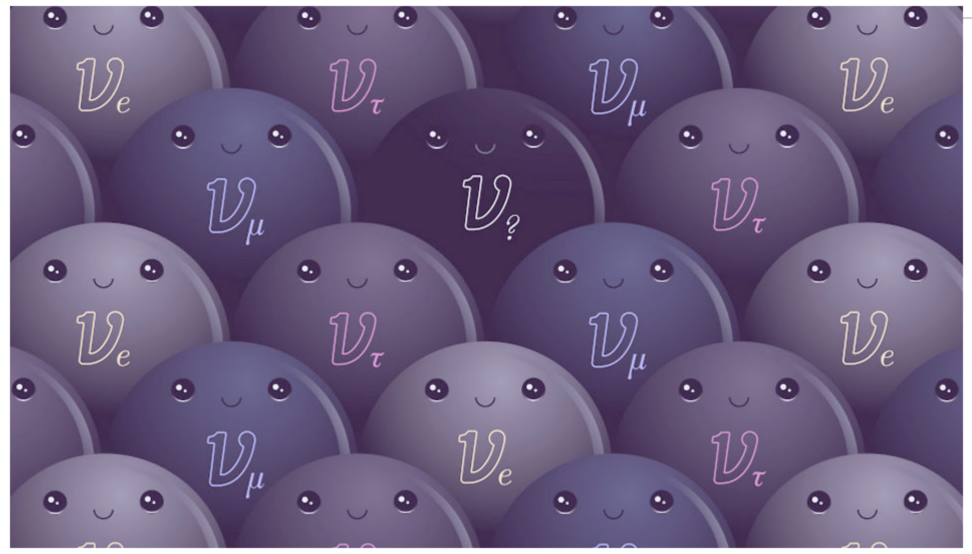




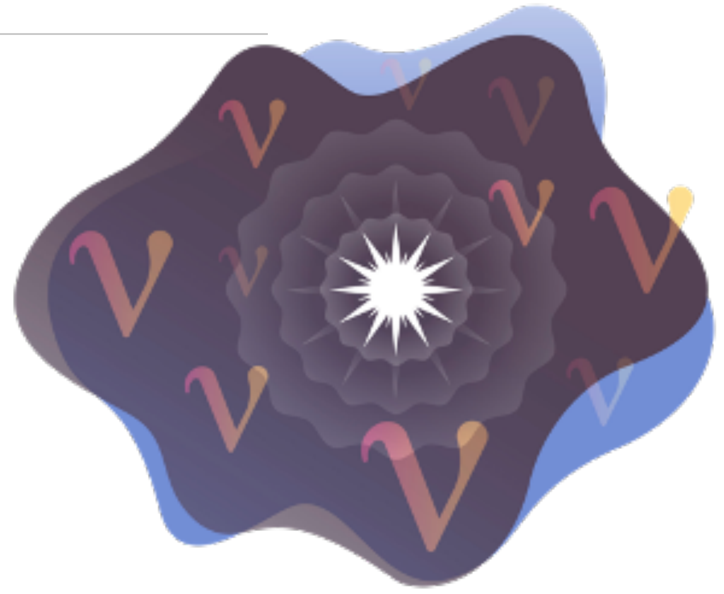
- Neutrino **mass ordering**
  - ✦ Small preference for NO with current data (not conclusive)



- **Octant** of θ_{23}
  - ✦ Maximal? $\nu_\mu \leftrightarrow \nu_\tau$ mixing symmetric? If so, why?



- Neutrino anomalies: **sterile neutrinos**?
- **Solar** neutrinos: hep neutrino flux



- **Supernova** burst and Diffuse SN Neutrino Background detection
- **Beyond the Standard Model**: nucleon-decay, testing the 3-neutrino flavor paradigm

Neutrino oscillations

3 neutrino mixing: $|\nu_\alpha> = \sum_{i=1}^{3} U_{\alpha i} |\nu_i>$

Pontecorvo, Maki, Nakagawa, Sakata (PMNS) 3x3 mixing matrix

$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = \begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix} \begin{pmatrix} c_{13} & 0 & s_{13}e^{-i\delta} \\ 0 & 1 & 0 \\ -s_{13}e^{i\delta} & 0 & c_{13} \end{pmatrix} \begin{pmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix}$$

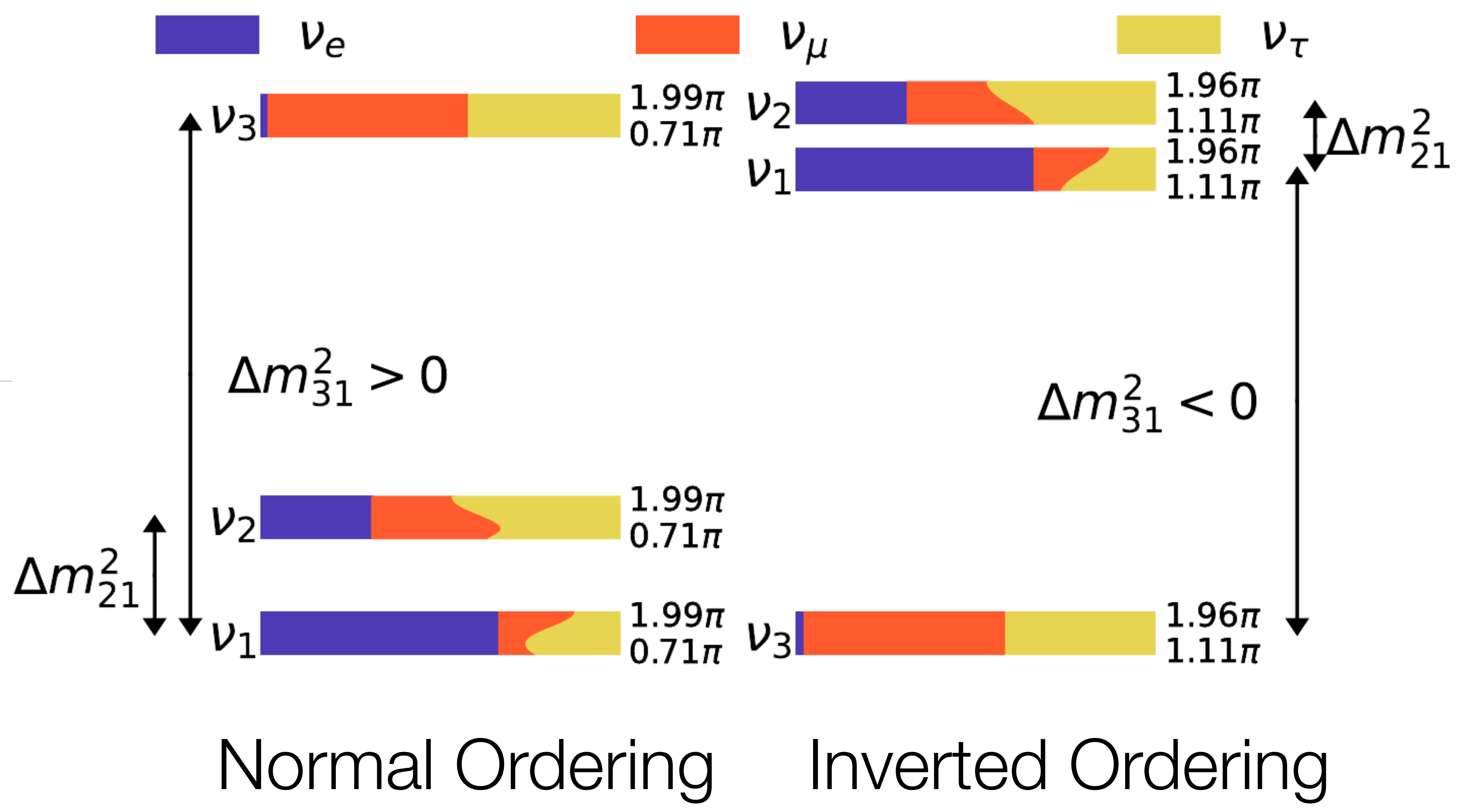
θ_{23}	θ_{13}, δ_{CP}	θ_{12}
Atmospheric + LBL acc.	SBL reactors + LBL acc.	Solar + KamLAND

Oscillation probability

$$P_{\nu_\alpha \to \nu_\beta}(L,E) = \delta_{\alpha\beta} - 4\sum_{i>j} Re\left[U^*_{\alpha i}U_{\beta i}U_{\alpha j}U^*_{\beta j}\right] \sin^2\left(\frac{\Delta m^2_{ij} L}{4E}\right)$$
$$- 2\sum_{i>j} Im\left[U^*_{\alpha i}U_{\beta i}U_{\alpha j}U^*_{\beta j}\right] \sin\left(\frac{\Delta m^2_{ij} L}{2E}\right)$$

Neutrino mass spectrum

$\Delta m^2_{ij} = m^2_i - m^2_j$

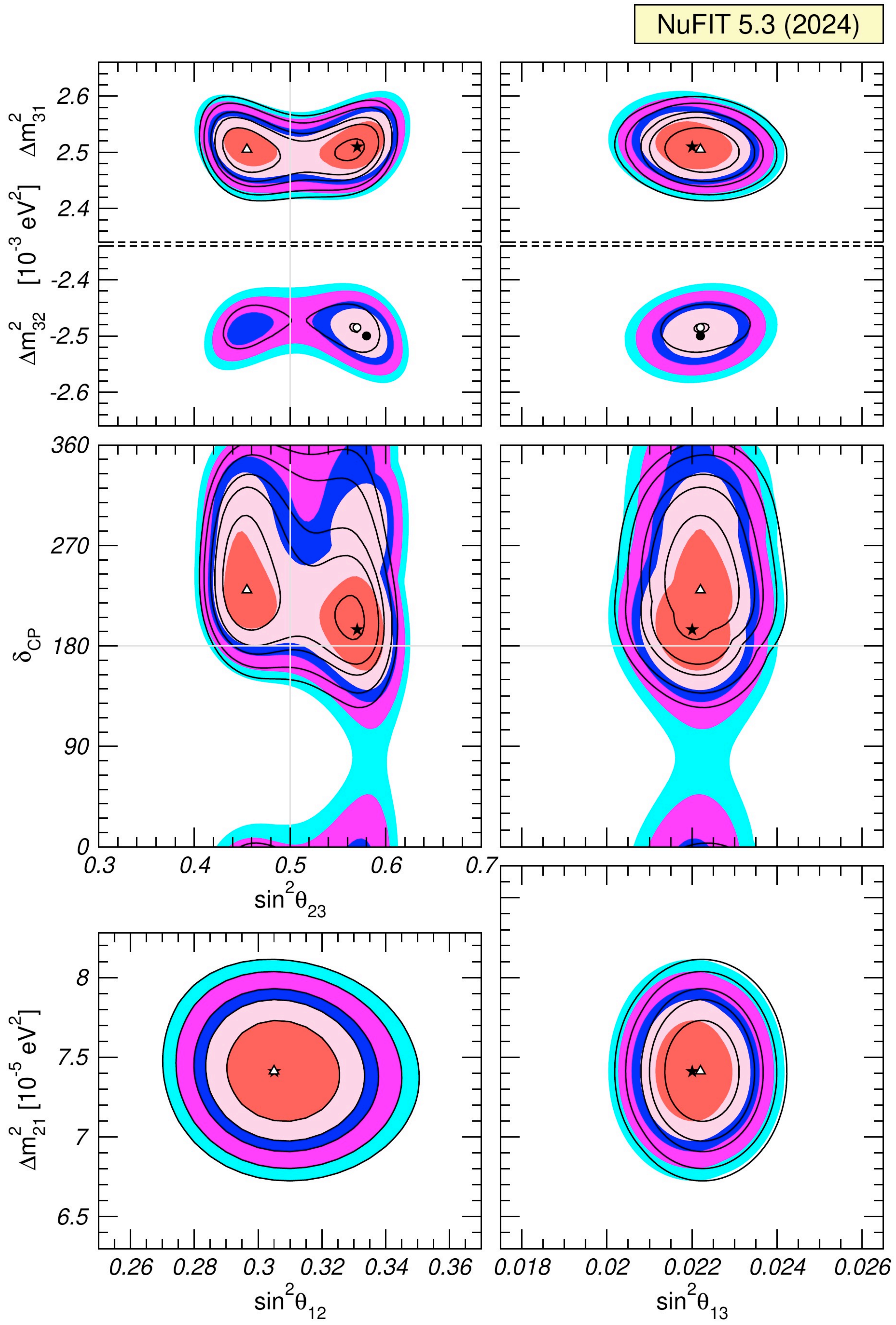


Unknown parameters: mass ordering (sign of Δm^2_{31}), δ_{CP}, octant of θ_{23}

Global fit information

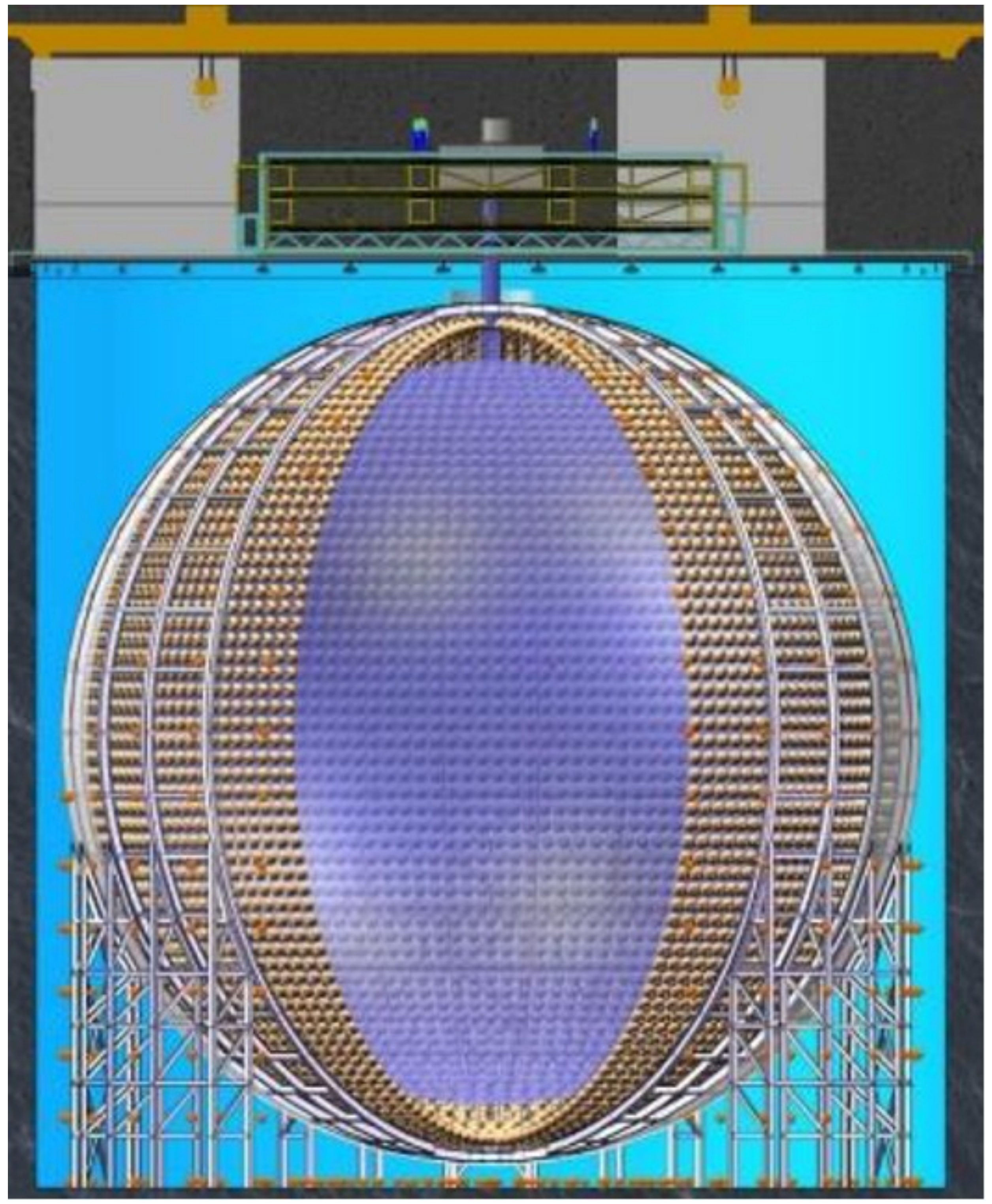
- Global 6-parameter fit (including δ_{CP}):
  - **Solar**: Cl + Ga + SK(1–4) + SNO-full (I+II+III) + BX(1–3);
  - **Atmospheric**: SK(1–4) + DeepCore;
  - **Reactor**: KamLAND + Dbl-Chooz + Daya-Bay + Reno;
  - **Accelerator**: Minos + T2K + NOvA;

- θ_{23} **octant** is **not resolved** yet (slight preference for the second octant)
- The sign of Δm^2_{32} is **unknown** (Normal Ordering is preferred)
- δ_{CP} **unknown**: Tension between T2K and NOvA experiments for NO. CP-violation for IO at ~3σ

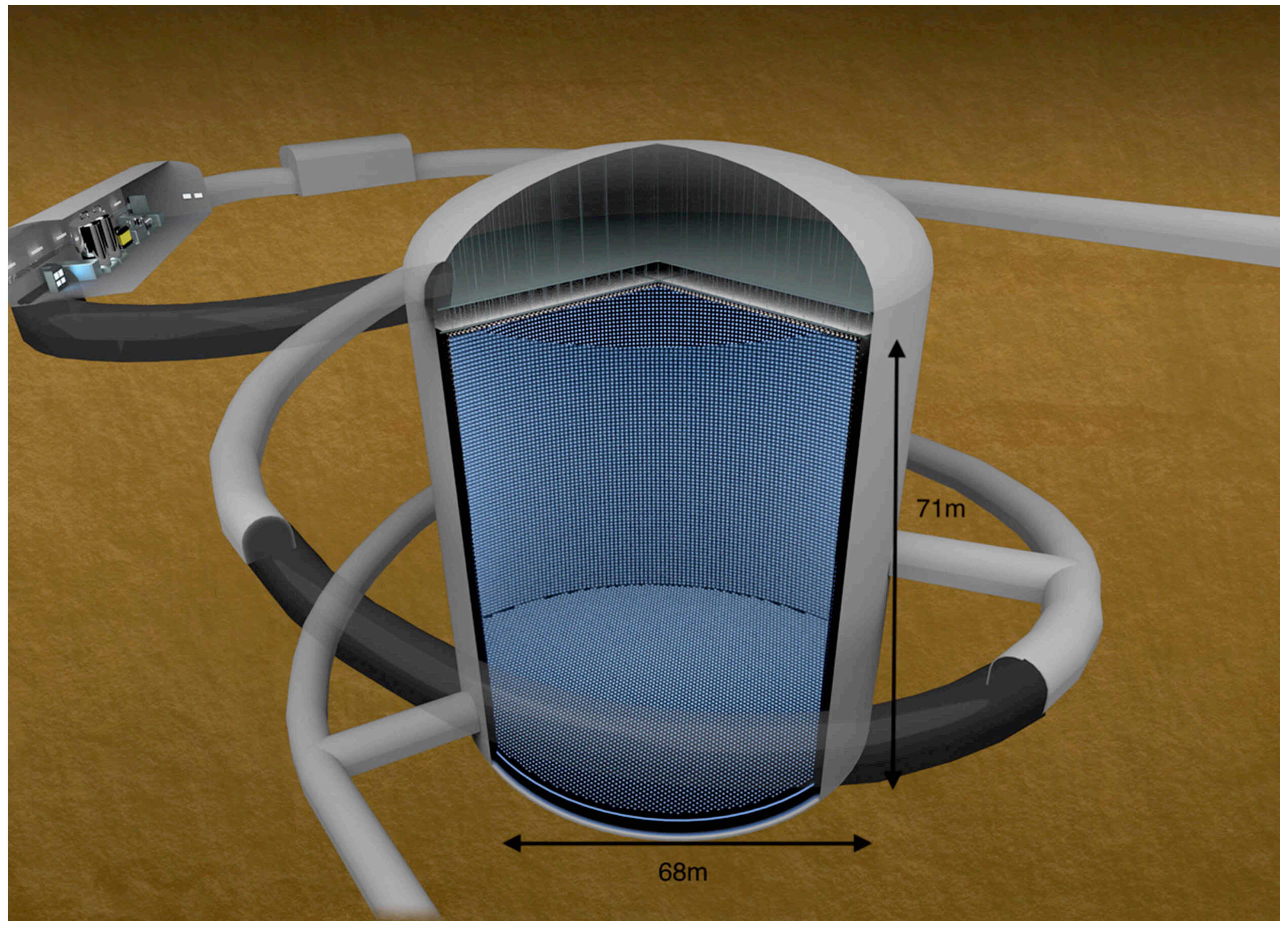


Three large-scale projects under construction

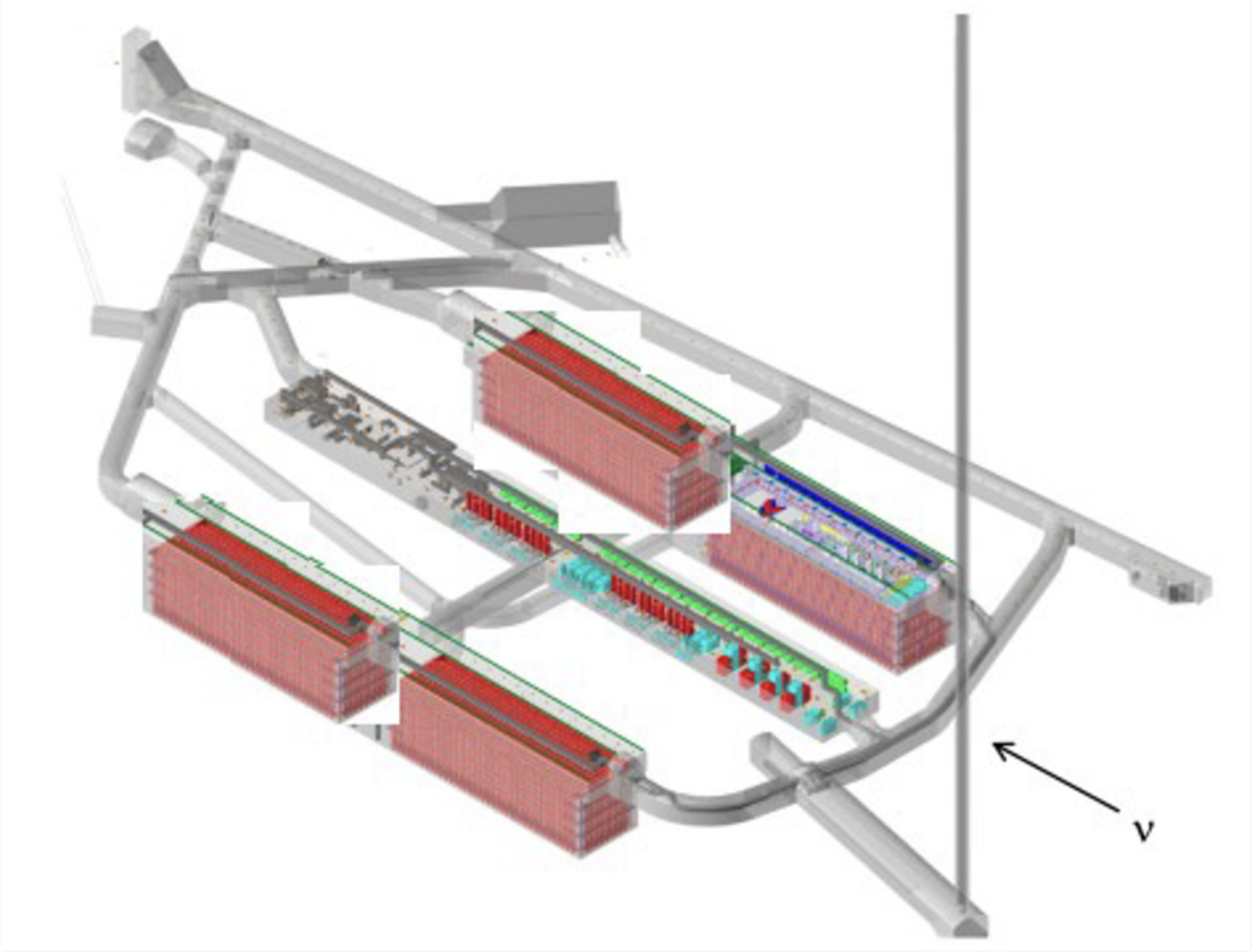
JUNO



Hyper-K

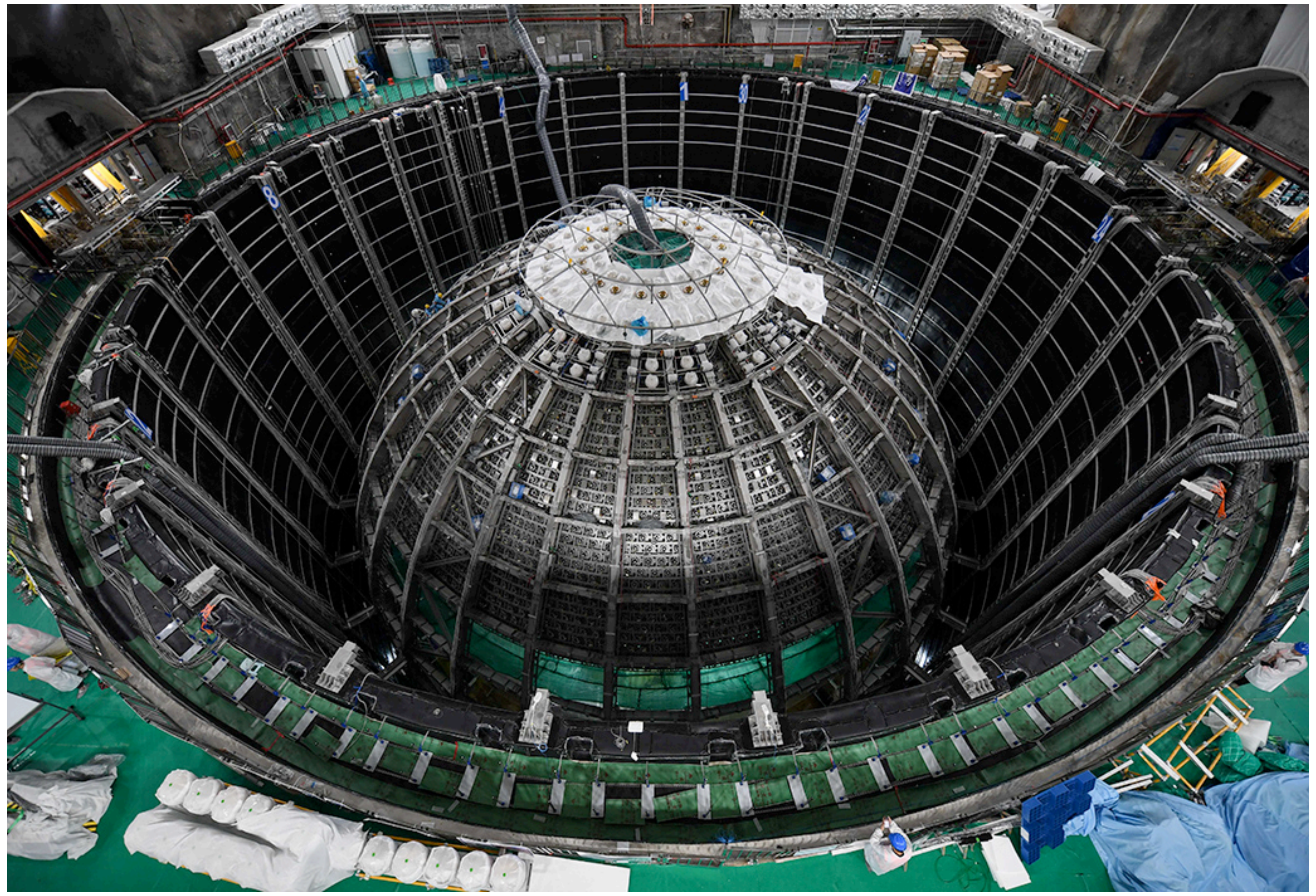


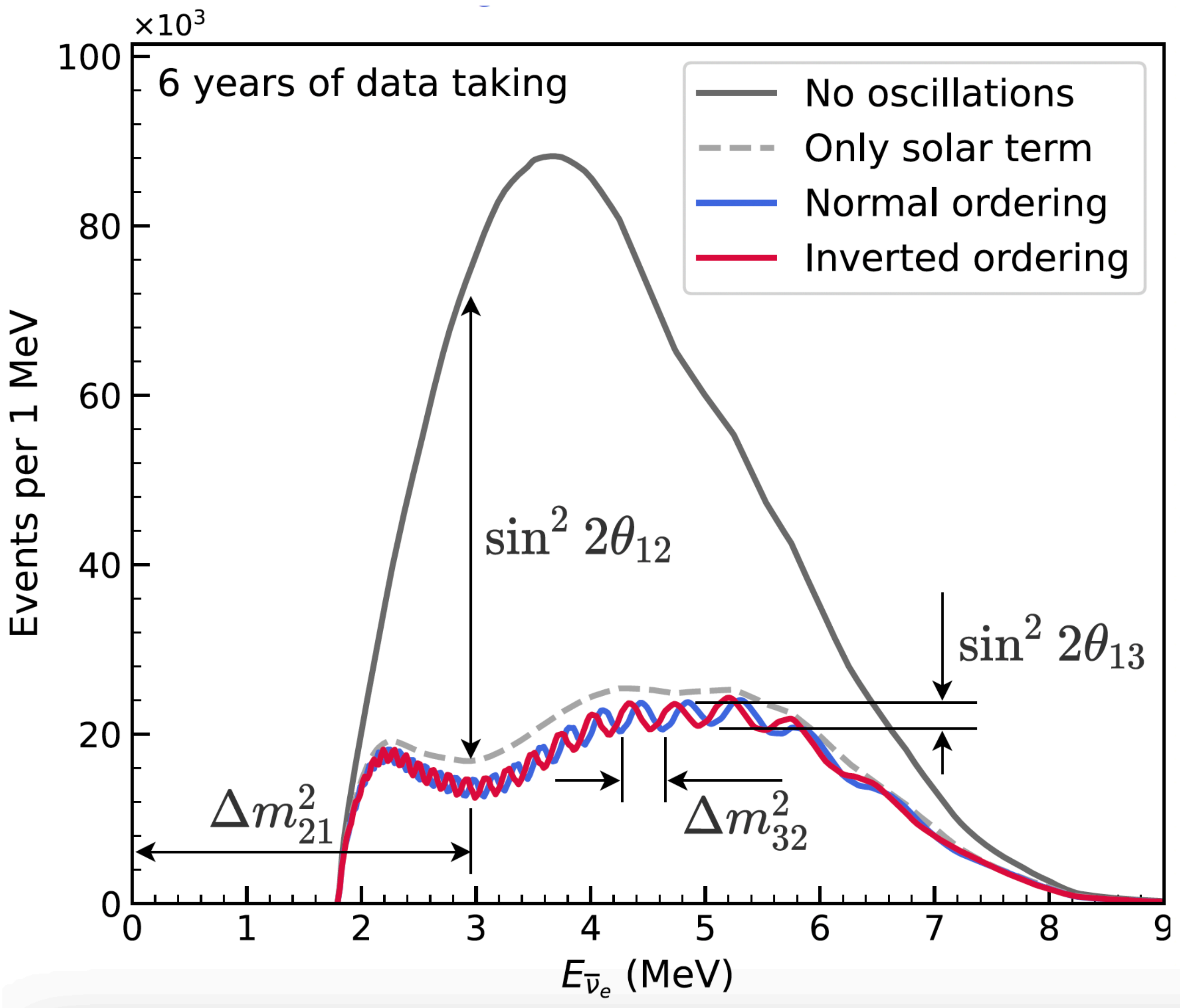
DUNE
DEEP UNDERGROUND
NEUTRINO EXPERIMENT



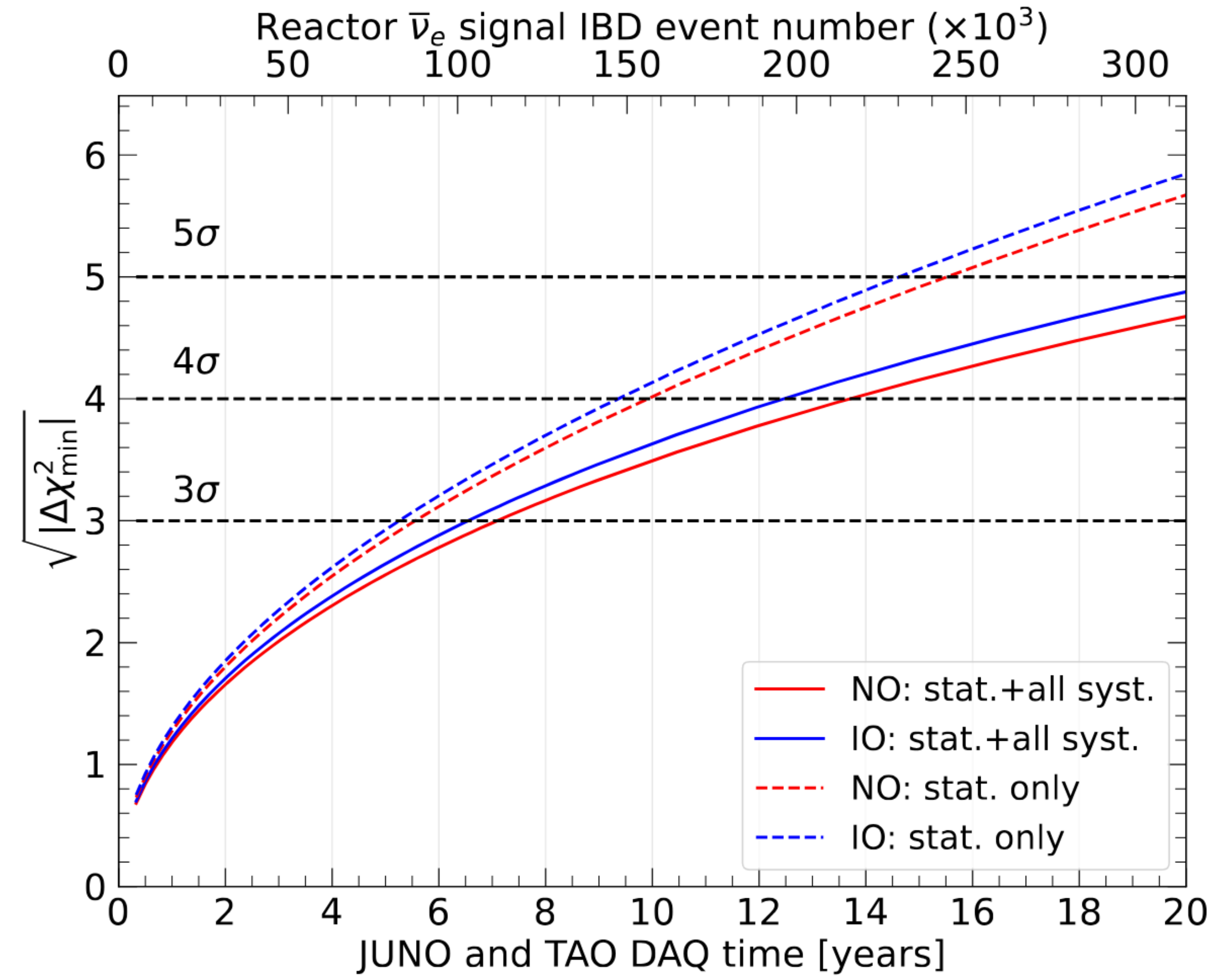
JUNO (Jiangmen Underground Neutrino Observatory)

- Next-generation Large Liquid Scintillator detector (20 kton)
  - ✦ Medium baseline **reactor experiment** (<L>=50 km) in China
  - ✦ Aim at much improved light yield and energy resolution ≈3%/√E(MeV)
  - ✦ Relatively shallow depth (700m overburden)
  - ✦ Expect to start data taking in 2025!
- Design to reach 3σ precision on **mass ordering** determination after 6y + precise **solar oscillation parameters** (<0.5%) in 7y + other low-E physics





Reactor antineutrino spectrum



Mass ordering sensitivity

arXiv:2405.18008

Long-baseline neutrino accelerator experiments

Oscillation probability in matter

$$P(\overset{(-)}{\nu_\mu} \to \overset{(-)}{\nu_e}) \approx \sin^2\theta_{23}\sin^2 2\theta_{13}\frac{\sin^2(\Delta_{31}-aL)}{(\Delta_{31}-aL)^2}\Delta_{31}^2$$
$$+ \sin 2\theta_{23}\sin 2\theta_{13}\sin 2\theta_{12}\frac{\sin(\Delta_{31}-aL)}{(\Delta_{31}-aL)}\Delta_{31}\frac{\sin(aL)}{(aL)}\Delta_{21}\cos(\Delta_{31}\pm\delta_{CP})$$
$$+ \cos^2\theta_{23}\sin^2 2\theta_{12}\frac{\sin^2(aL)}{(aL)^2}\Delta_{21}^2$$

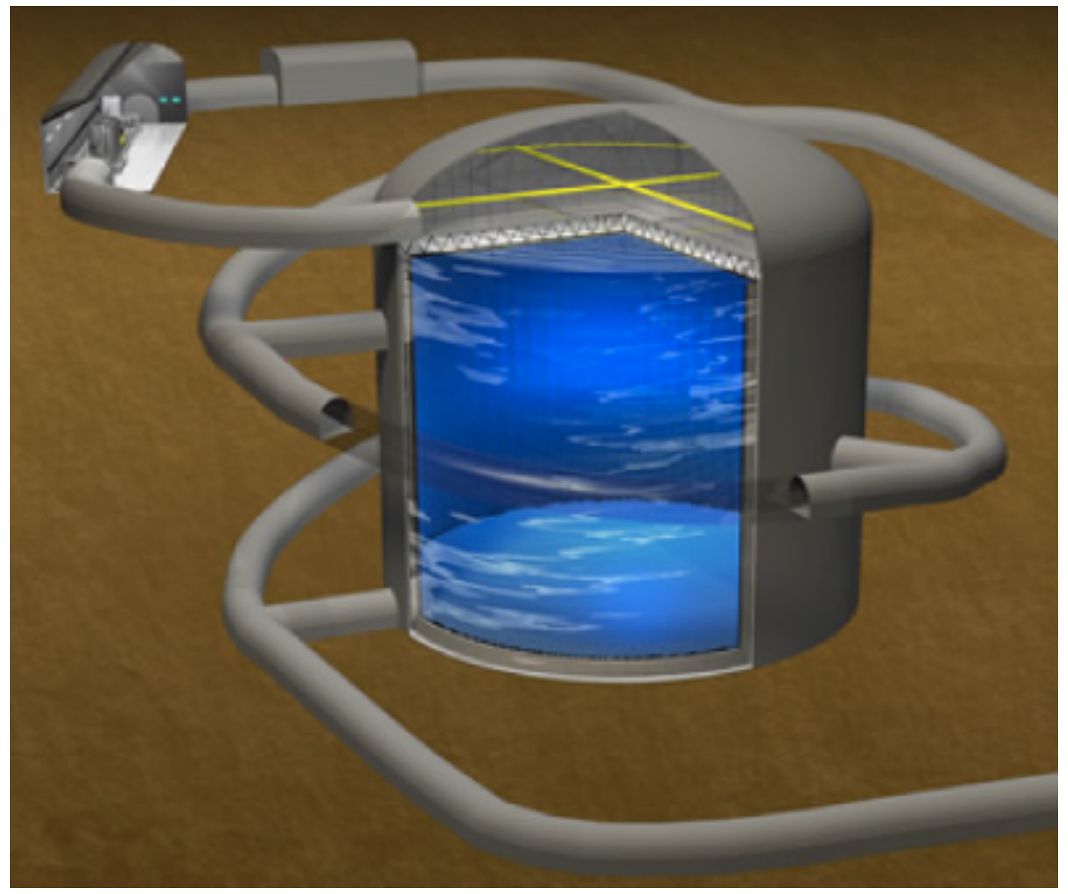
$$\Delta_{ij} = \Delta m^2_{ij}L/4E_\nu$$
$$a = \pm G_F N_e/\sqrt{2}$$

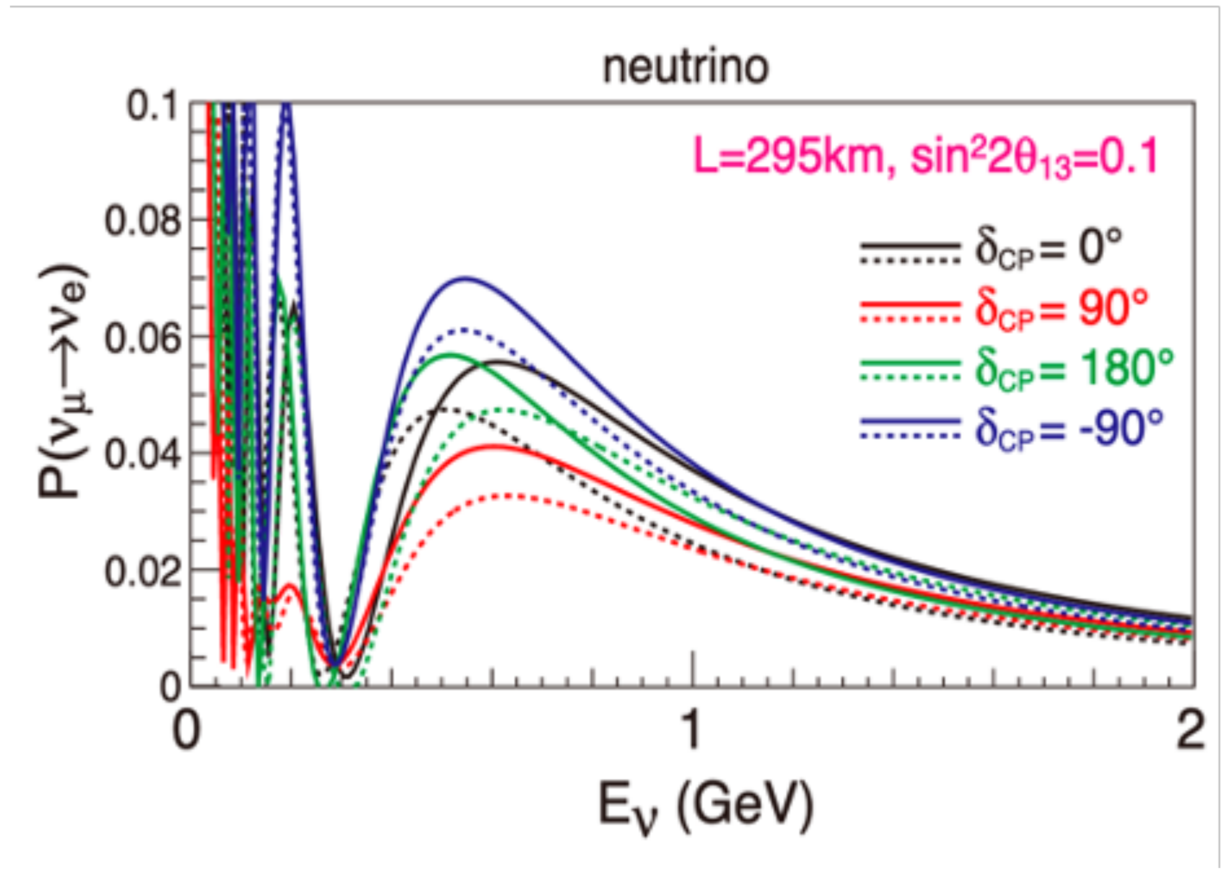
T2HK: Tokai to HyperK

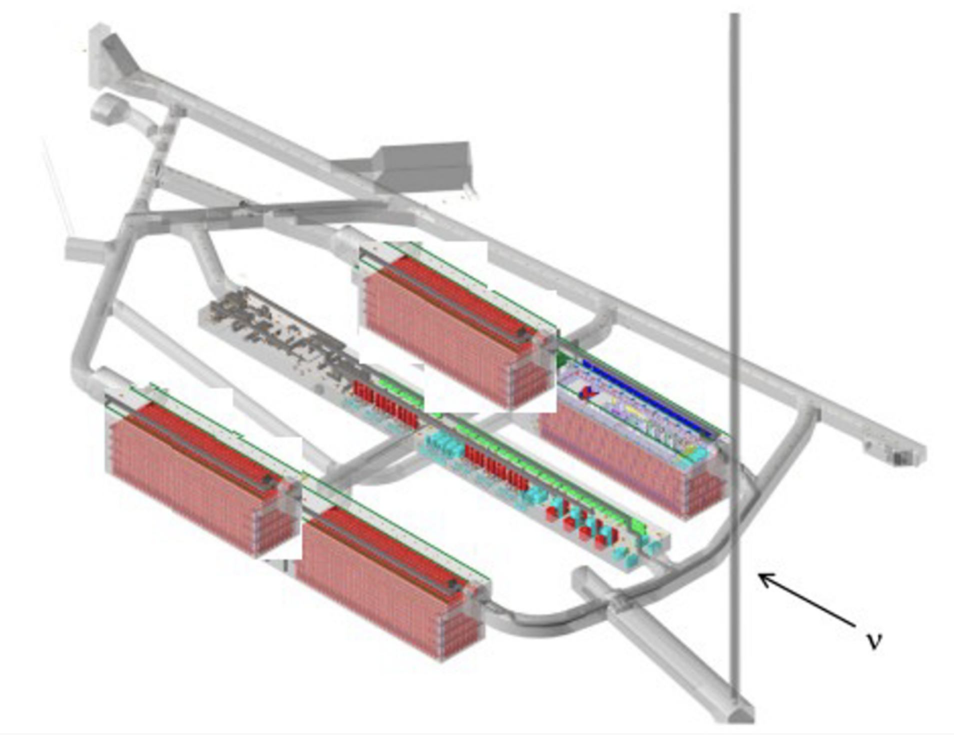
- ✦ Minimize matter effects and maximize statistics to focus on <u>CPV discovery</u> (MO and other parameters must be known by other means) + non-beam physics program
- ✦ Narrow-band beam (~0.6 GeV; 500 kW → 1.3 MW) and Water-Cerenkov detector (190 kt fiducial)

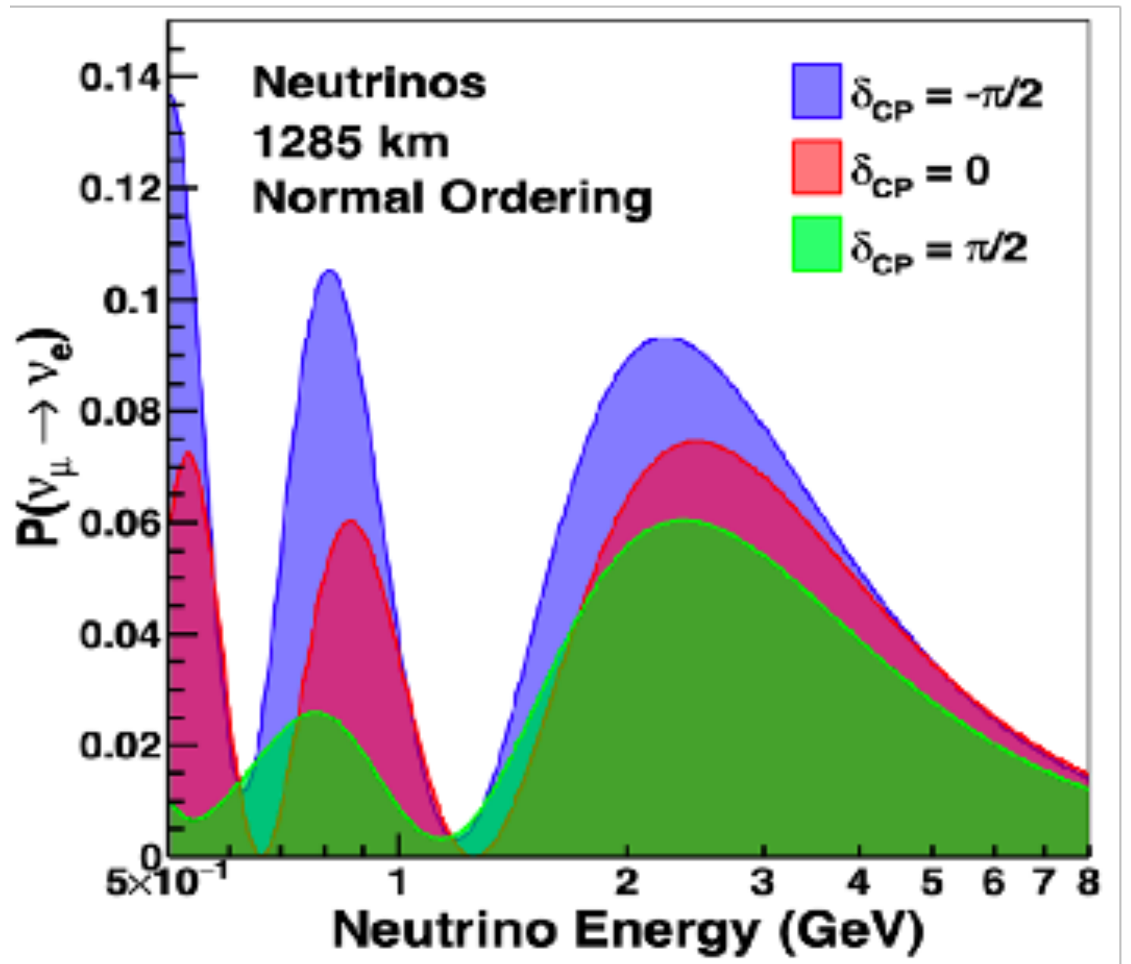
DUNE: FNAL to SURF

- Measure first and second oscillation maxima to disentangle <u>CPV and matter effects</u> and access to <u>all neutrino oscillation parameters</u> + non-beam physics program
- Wide-band beam (0.5-5 GeV; 1.2 → >2 MW) and liquid Argon TPC (>40 kt fiducial)



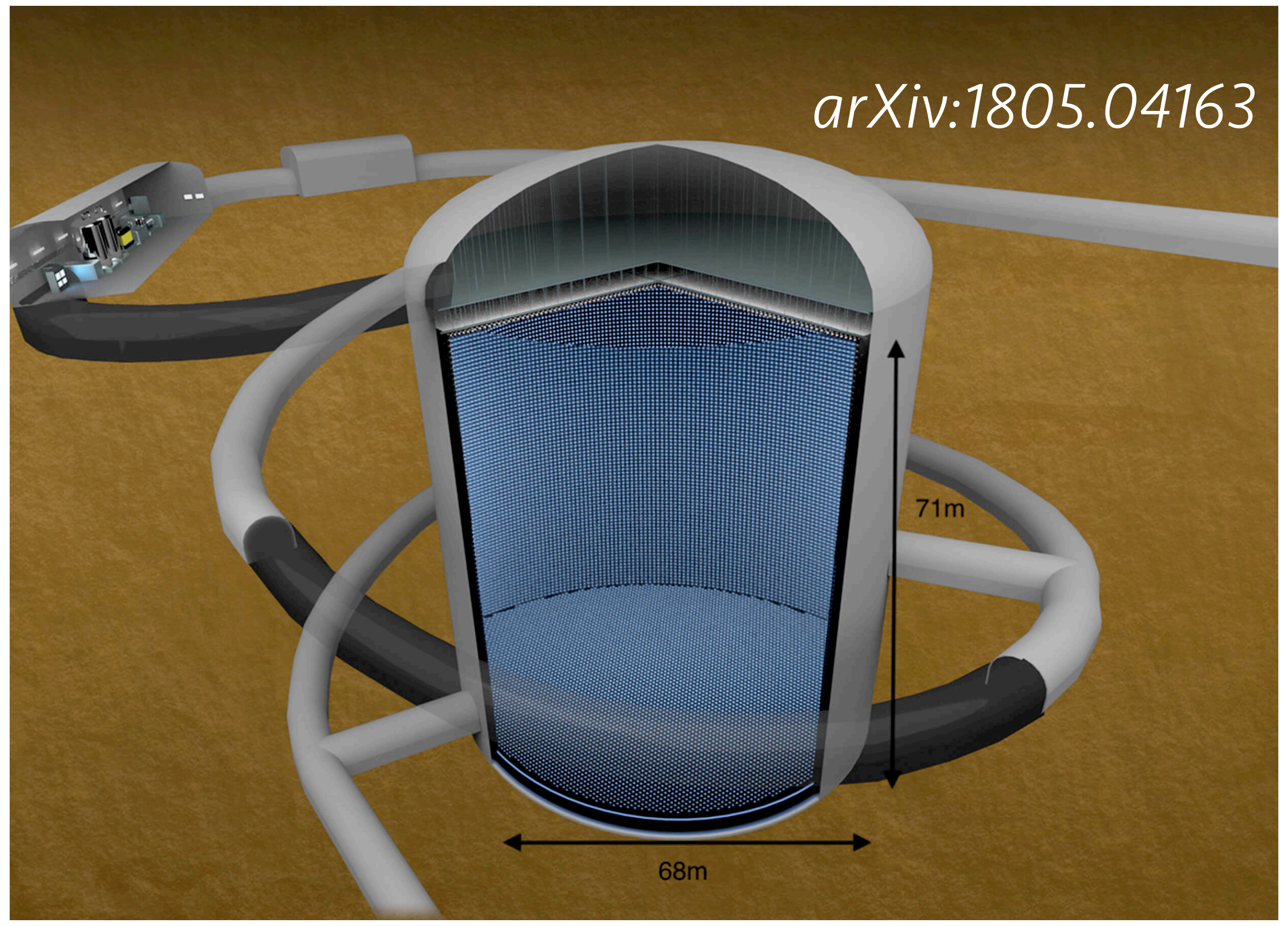






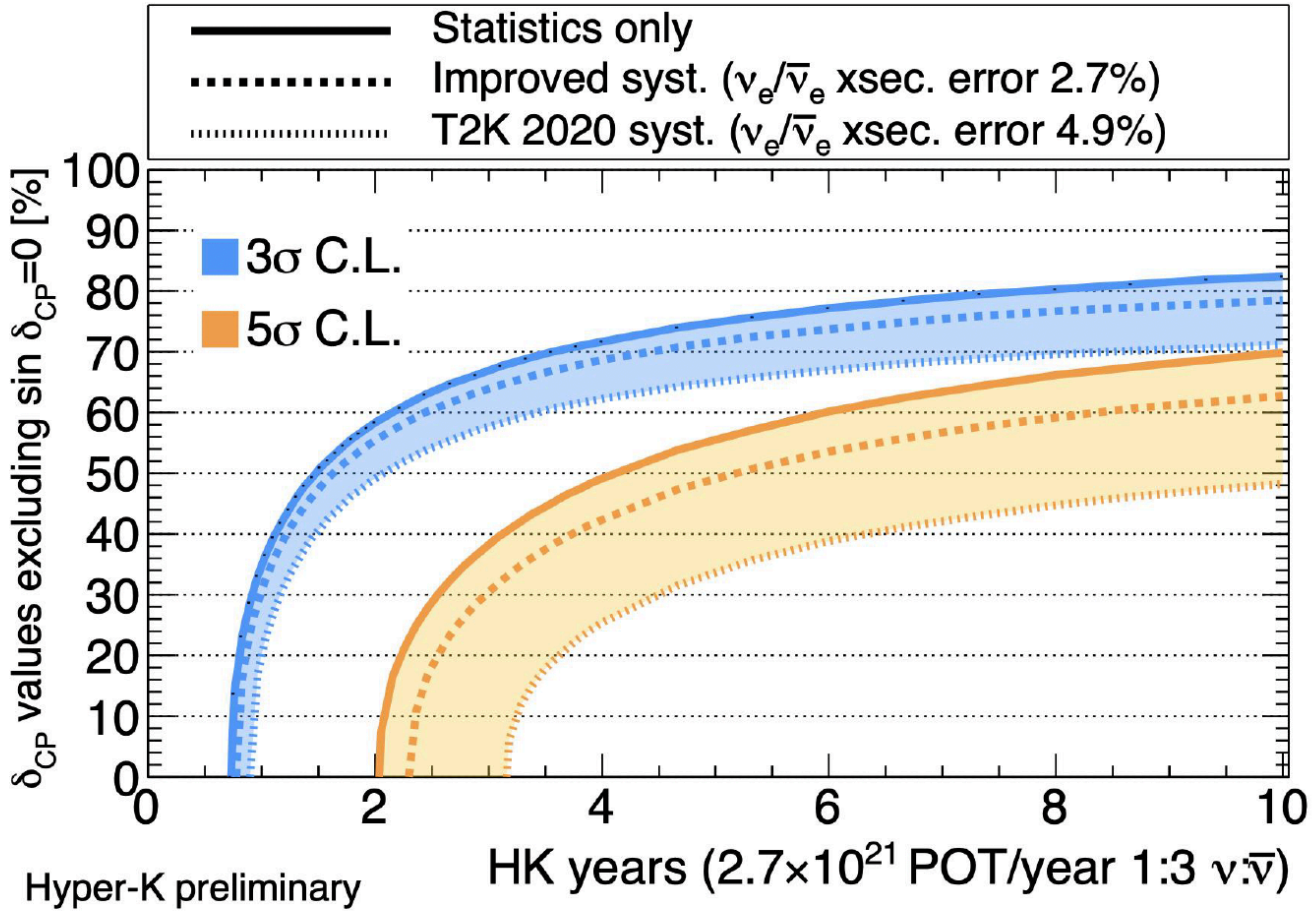
Hyper-Kamiokande

- Upgrade J-PARC neutrino beam with expected power 1.3 MW, 2.5^{o} off-axis angle
- Baseline: 295 km
- WC Total mass: 260 kton pure water, Inner detector: 216 kton, Fiducial mass: **~200 kton (x 8 SK)**
- Between 20-40% photocathode coverage
- New cavern in a different part of Kamioka mine under construction (600 m rock overburden)
- Aiming to start operation in 2027

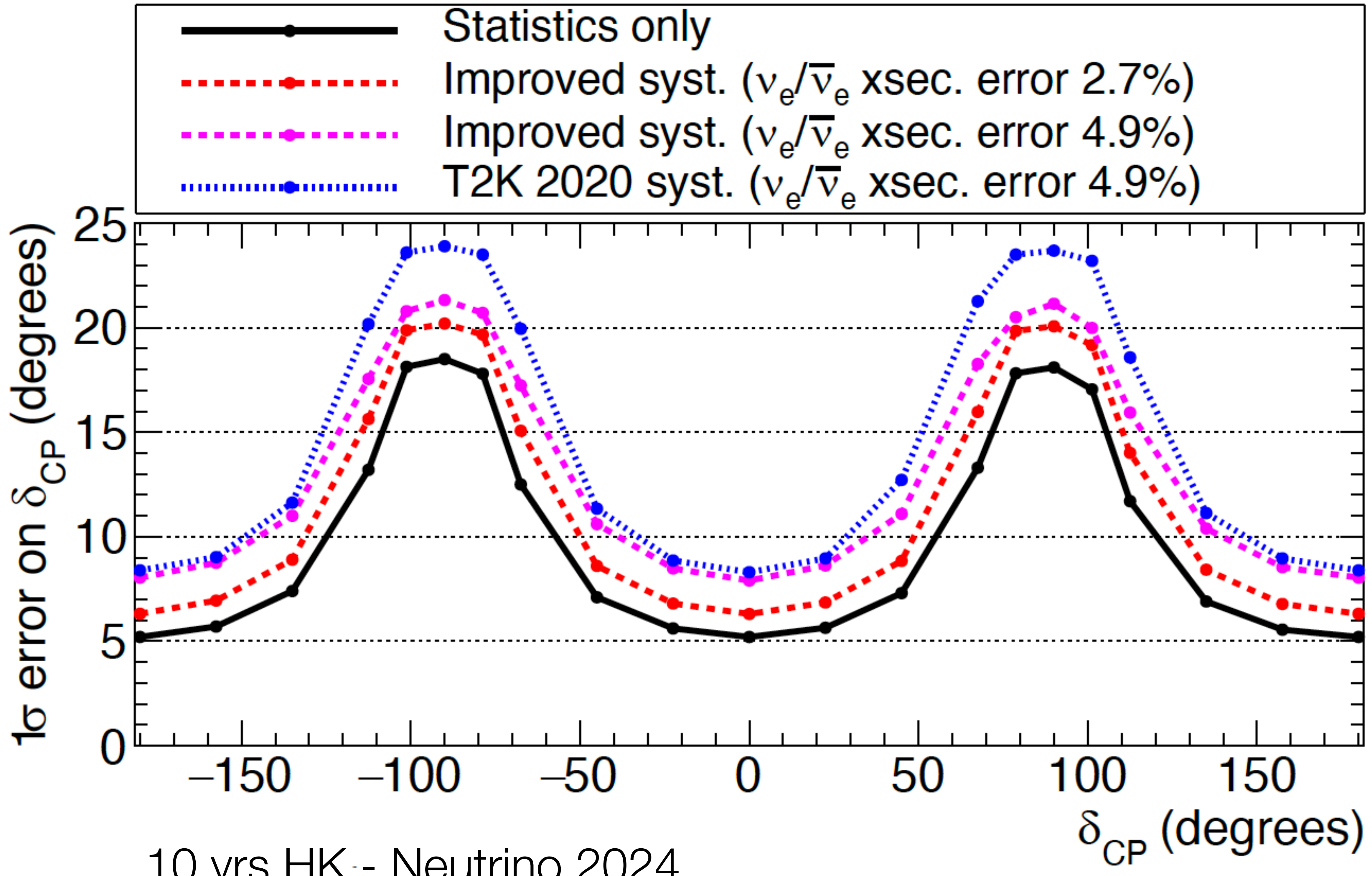


Hyper-Kamiokande sensitivity

- Able to exclude **CP** conservation at 5σ for 60% of δ_{CP} values (if MO known) in 10 years for nominal power
- 1σ resolution of δ_{CP} in 10 yrs ~20° (6°) for δ_{CP} = -90° (0°)
- 4-6σ **MO** determination depending on $\sin^2\theta_{23}$ for 10y of data taking combining beam and atmospheric neutrinos

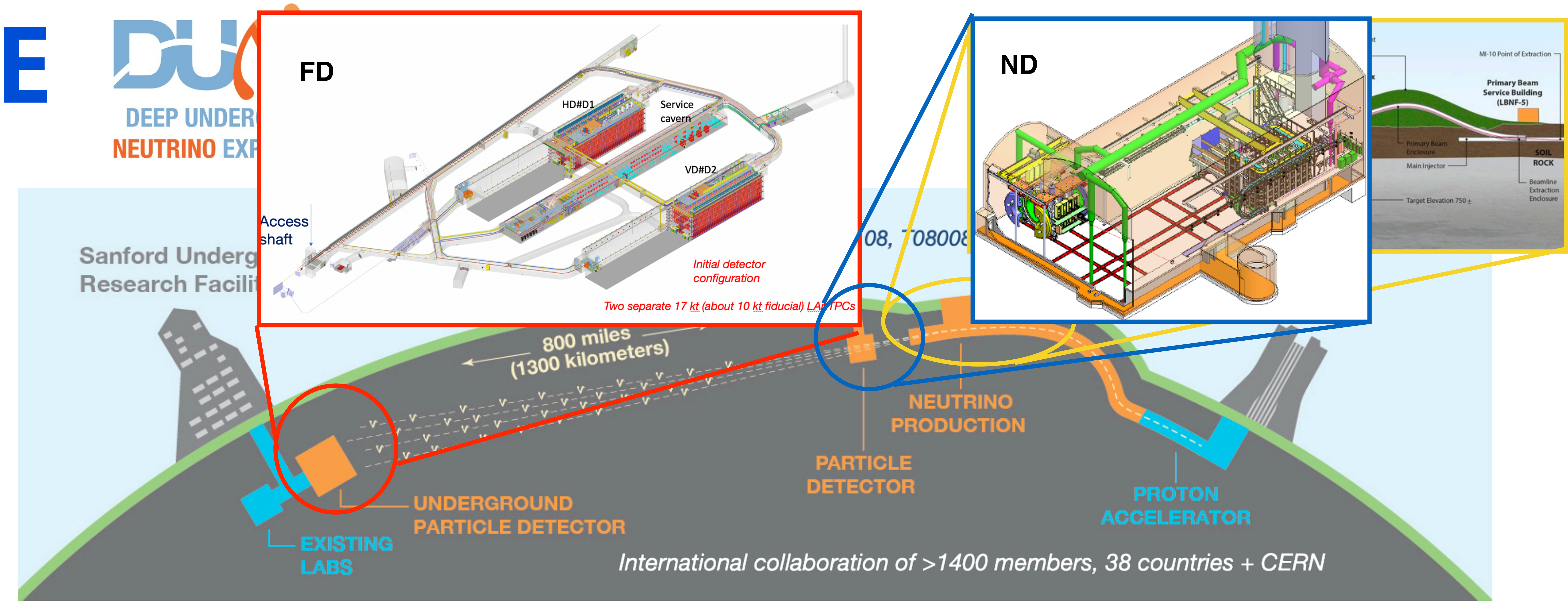


Neutrino 2024



10 yrs HK - Neutrino 2024

DUNE



- 70 kton (4 x 10 kt fiducial) **LAr TPC far detectors** at 1480 m depth (4300 mwe) at SURF measuring neutrino spectra at 1300 km in a wide-band high purity ν_μ beam with peak flux at 2.5 GeV operating at ~1.2 MW and upgradeable to >2 MW
- **Near detector** (*CDR: arXiv:2103.13910*) at 560 m from the neutrino source: LArTPC, TMS/magnetized GAr TPC & magnetized beam monitor
- **Physics goals**: LBL oscillations (MO and CP violation), precise osc. measurements, SN burst neutrinos, solar neutrinos, nucleon decay, Beyond Standard Model searches, non-standard interactions…

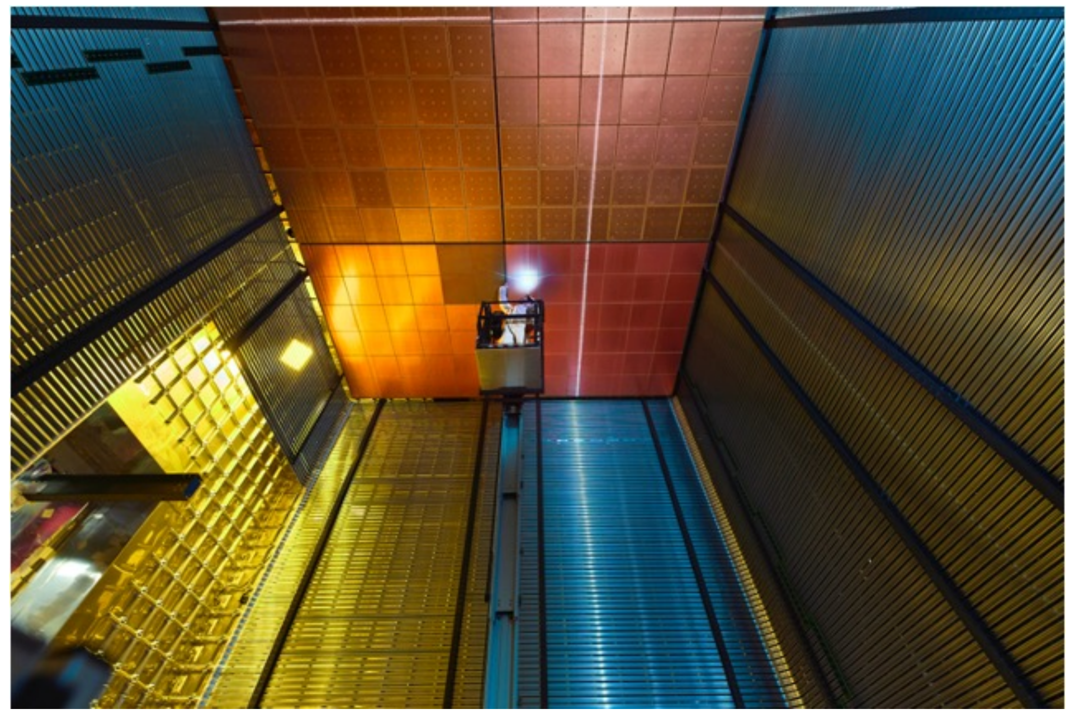
CERN Neutrino Platform

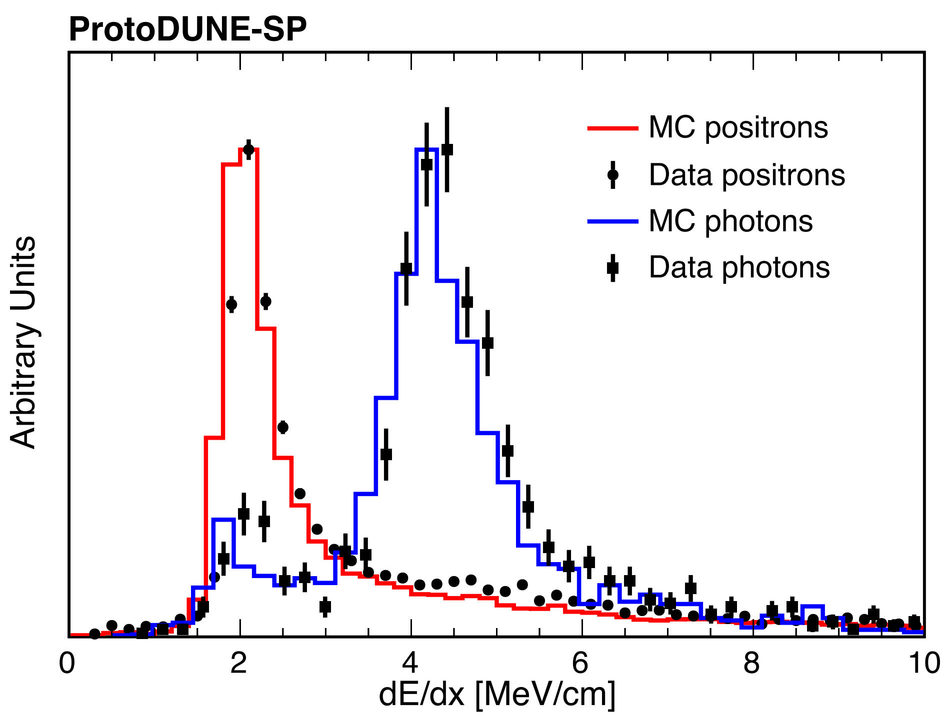
ProtoDUNE/DUNE ~1/20
Full scale DUNE FD components

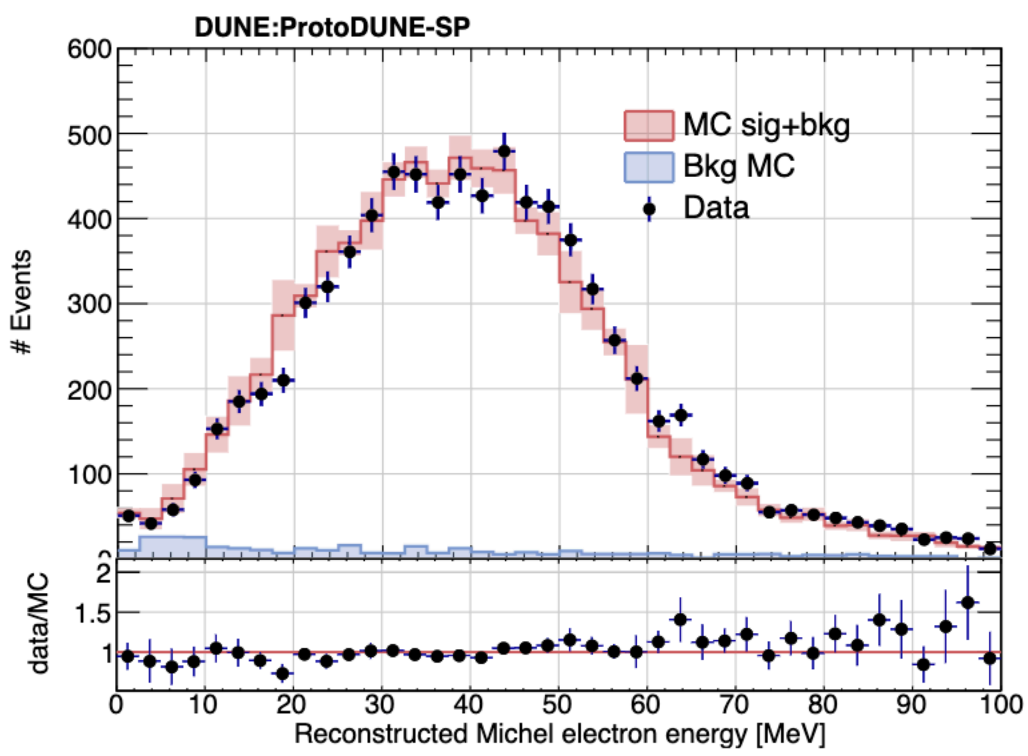
ProtoDUNEs operation at CERN

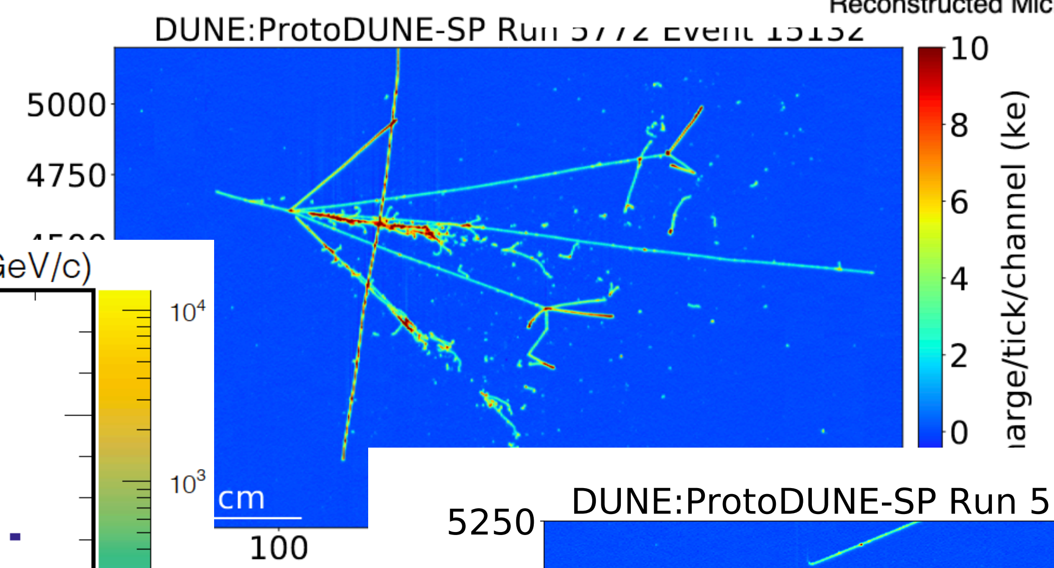
FIRST PHASE PROTODUNEs

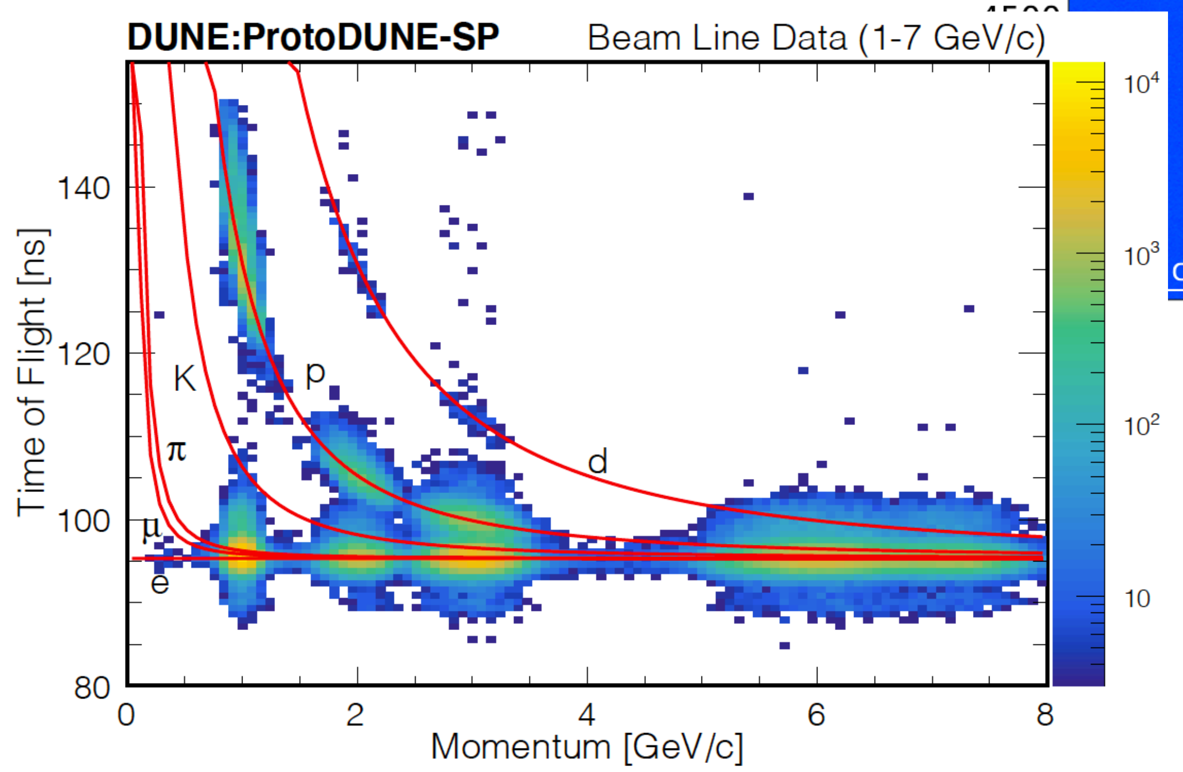
- Construction and operation of ProtoDUNEs at CERN (2018 - 2020)
- Successful demonstration of the DUNE LAr TPC performance
- Several ongoing analyses (hadron-Ar cross sections…)

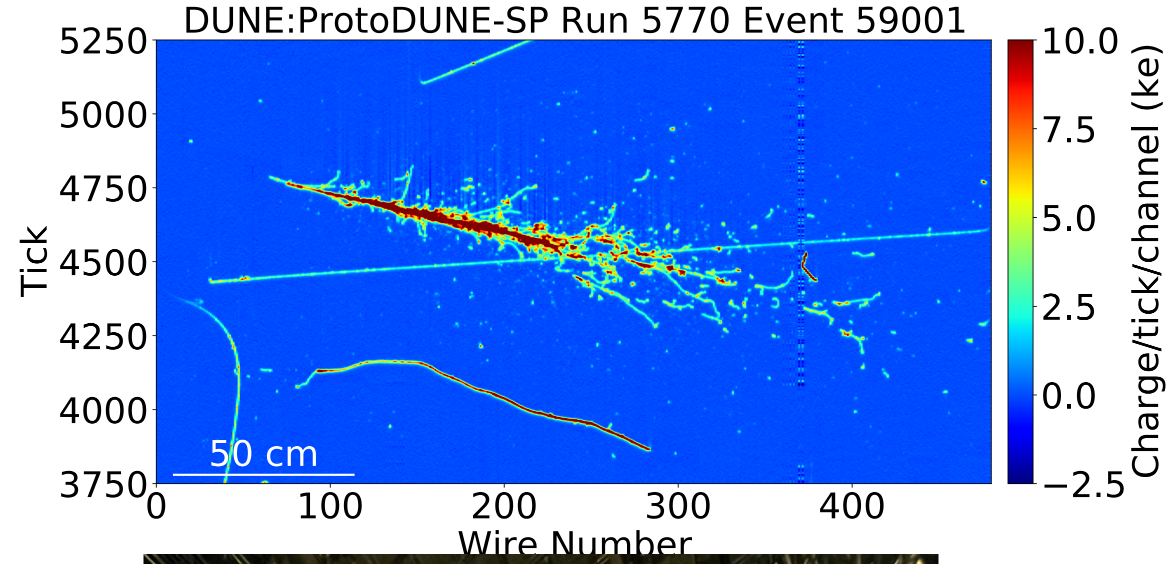






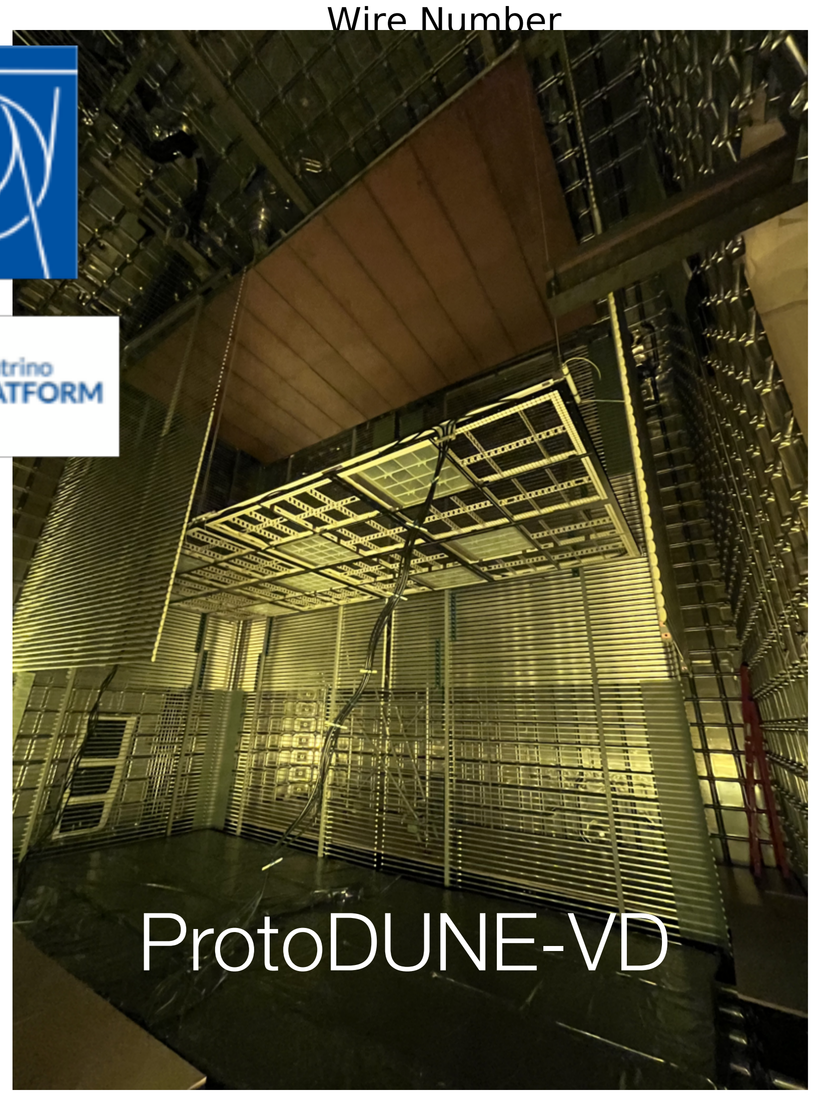






SECOND PHASE PROTODUNEs (2020-2023 construction + operation ≥2024)

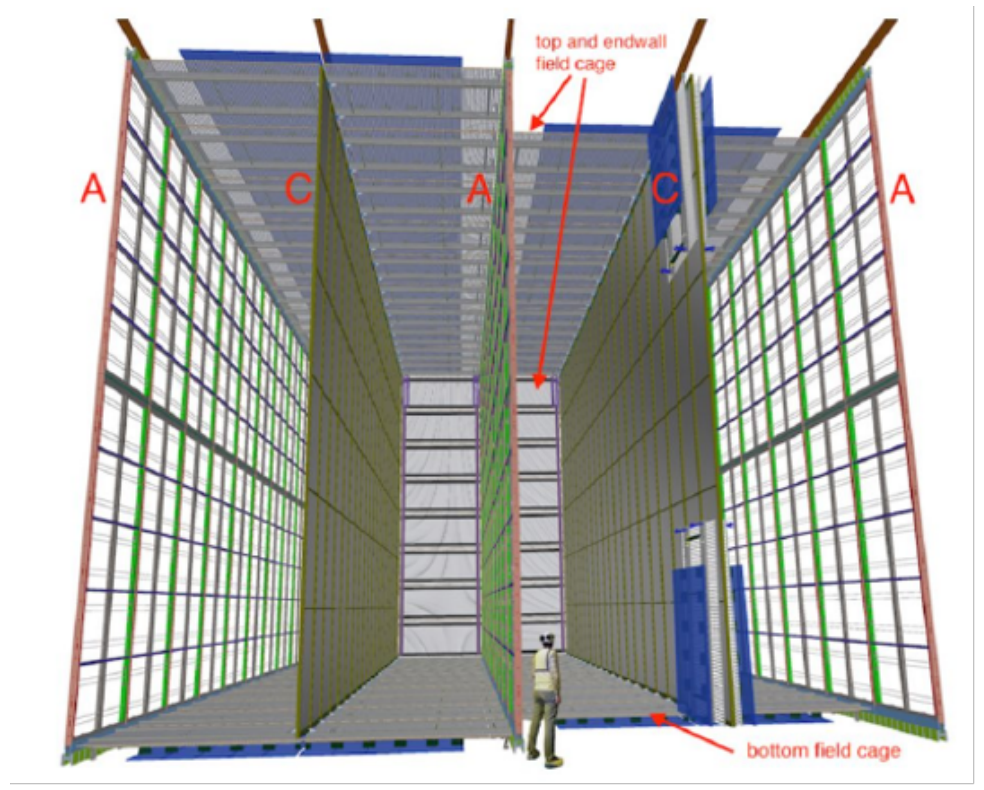
- ProtoDUNE-HD
  - ✦ Final technical solutions for all FD-HD subdetectors
  - ✦ Detector filled and currently taking data with charged-particle test-beam and cosmic muons at CERN
- ProtoDUNE-VD
  - ✦ Realization of a Module-0 detector in 2022-2023; LAr will be transferred to ProtoDUNE-VD in October for running starting in early 2025

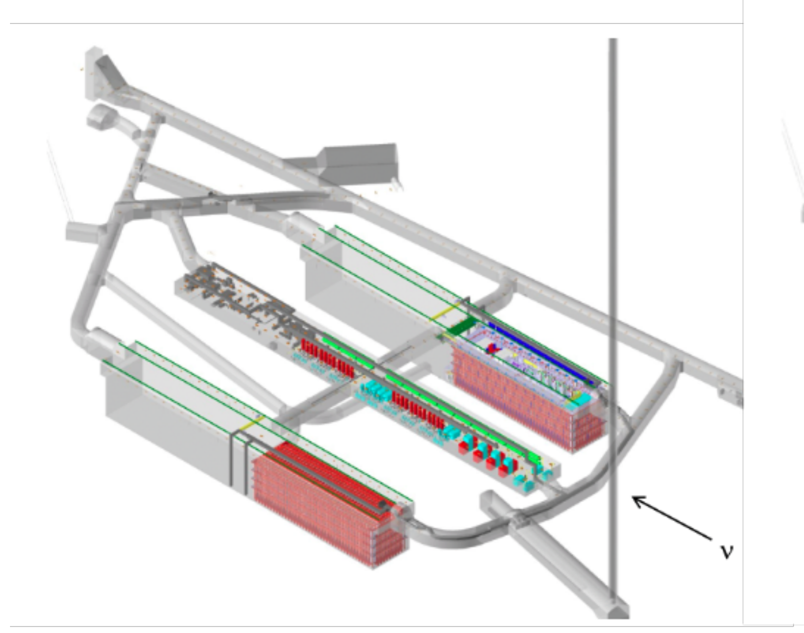


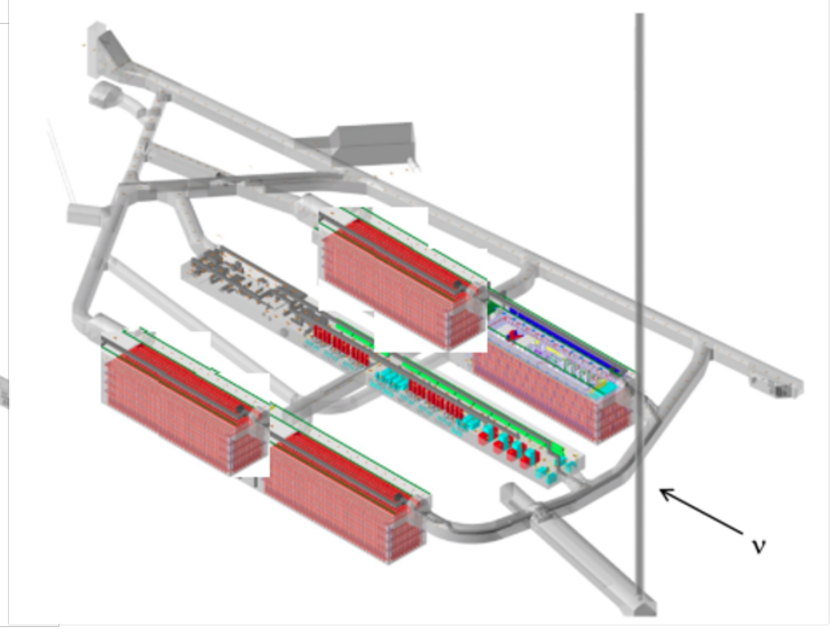
DUNE Phases

- **DUNE Phase I** (2026 start inst; 2029 physics; 2031 beam+ND)
  - ✦ Full near + far site facility and infrastructure
  - ✦ Two 17 kt LArTPC modules
  - ✦ Upgradeable 1.2 MW neutrino beamline
  - ✦ Movable LArTPC near detector with muon catcher
  - ✦ On-axis near detector
- **DUNE Phase II**:
  - ✦ Two additional FD modules (≥40 kt fiducial in total)
  - ✦ Beamline upgrade to >2 MW
  - ✦ More capable Near Detector (ND-GAr)

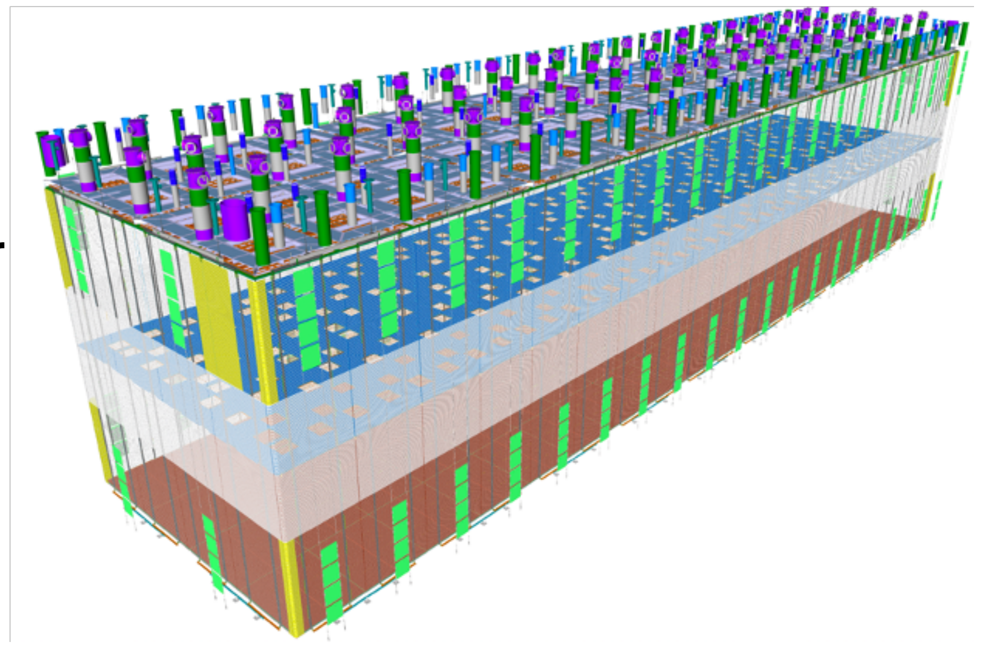
FD-HD: *JINST 15 T08010 (2020)*

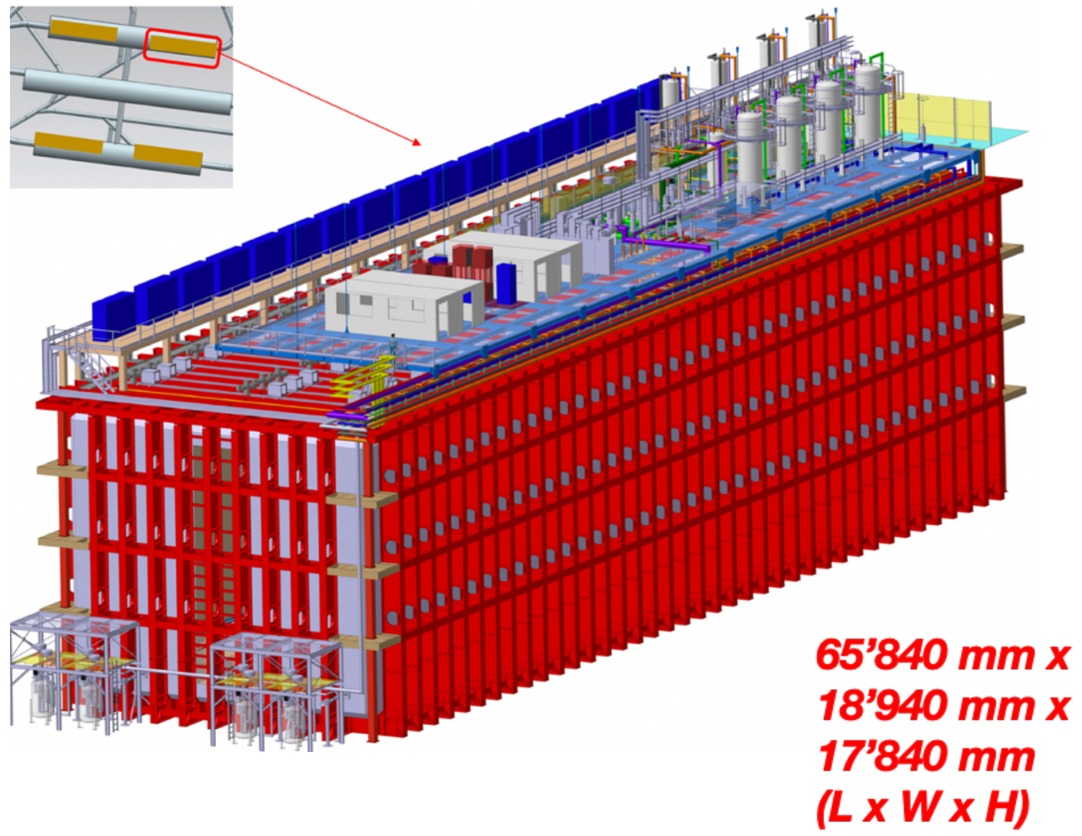


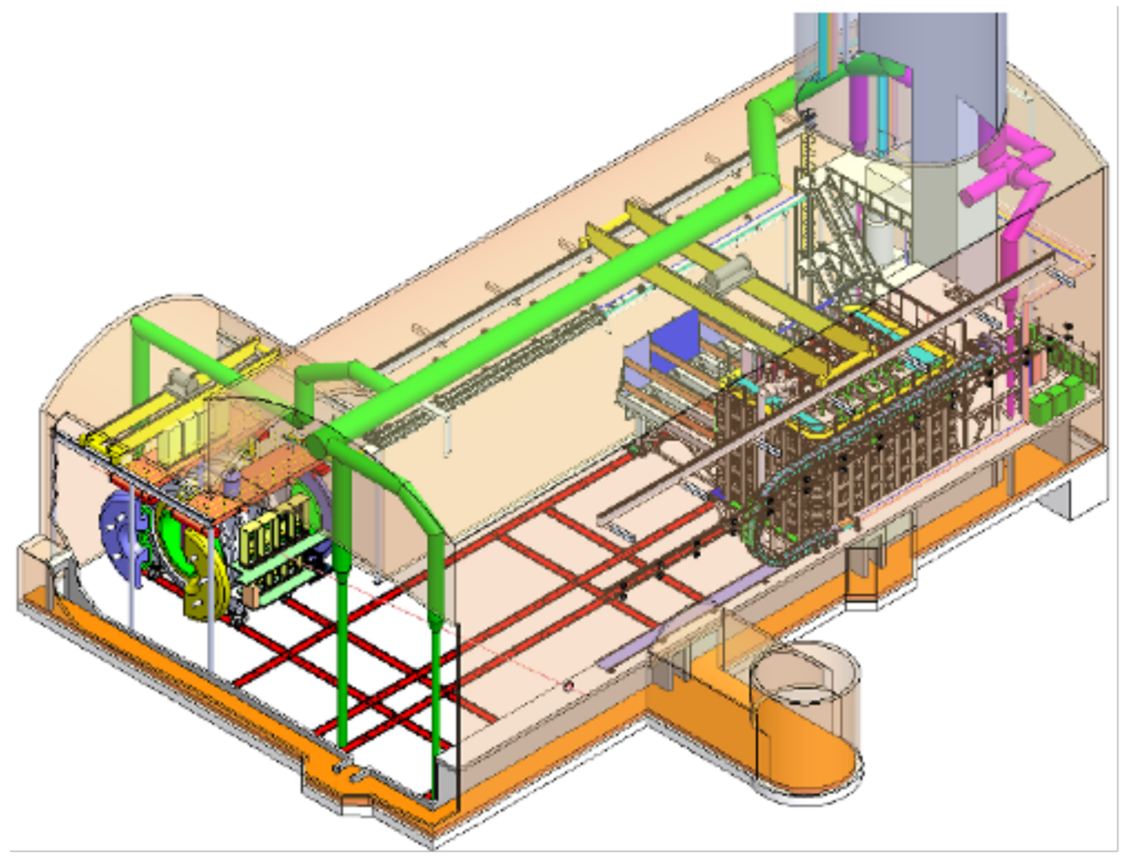




FD-VD: *arXiv:2312.03130 (2023)*

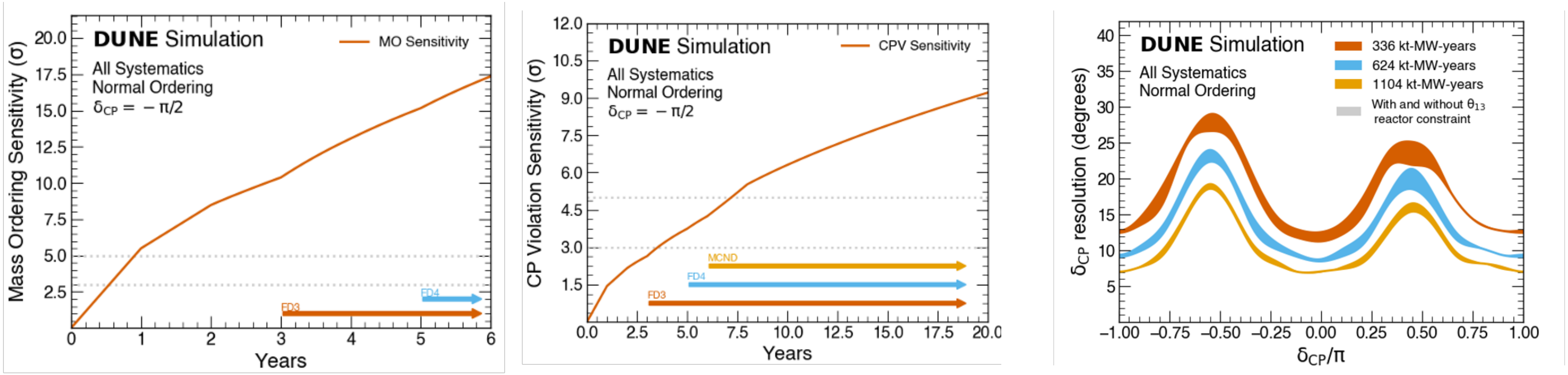






DUNE Physics Program

- DUNE can determine the neutrino **mass ordering** at 5σ in 1-3 years of data (depending on δ_{CP} value)
- Excellent resolution to θ_{23}
- **CP violation**: if maximal, 3σ (5σ) observation in 3.5y (7.5y); in long-term >3σ CPV for 75% of δ_{CP}; 6º-16º resolution
- Precise measurement of all oscillation parameters
- Supernova and solar neutrinos + BSM (NSI, non-unitary mixing, dark matter, sterile neutrinos, nucleon decay,…)



5 Conclusions

- Neutrinos are **massive** particles - breakthrough in Particle Physics → SM needs to be extended (how do neutrinos acquire their mass?)
- Neutrino **oscillations** are still one of the most important topics/priorities in Particle and Astroparticle Physics (beyond the Standard Model)
- Neutrino oscillations are under intense study, but **next generation** of experiments with more capable detectors and powerful (anti-)neutrino beams are needed to discover CP violation, determine the neutrino mass ordering and measure with precision all neutrino oscillation parameters
- More precise **solar** and **supernova** neutrino measurements will be provided by bigger and complementary detectors
- Many opportunities for **Beyond SM** with neutrinos (heavy neutrinos, NSI, …)
- Neutrino **mass** measurement is hopefully around the corner (in the lab and in cosmology)
- **Majorana or Dirac** neutrinos: intensive neutrinoless double beta experimental campaign trying to cover the IO range → an important technological step will be needed to explore lower masses
- The beginning of a golden era for **high-energy neutrino** detection (and multi-messenger astronomy)

Exciting neutrino physics program!

Grazie