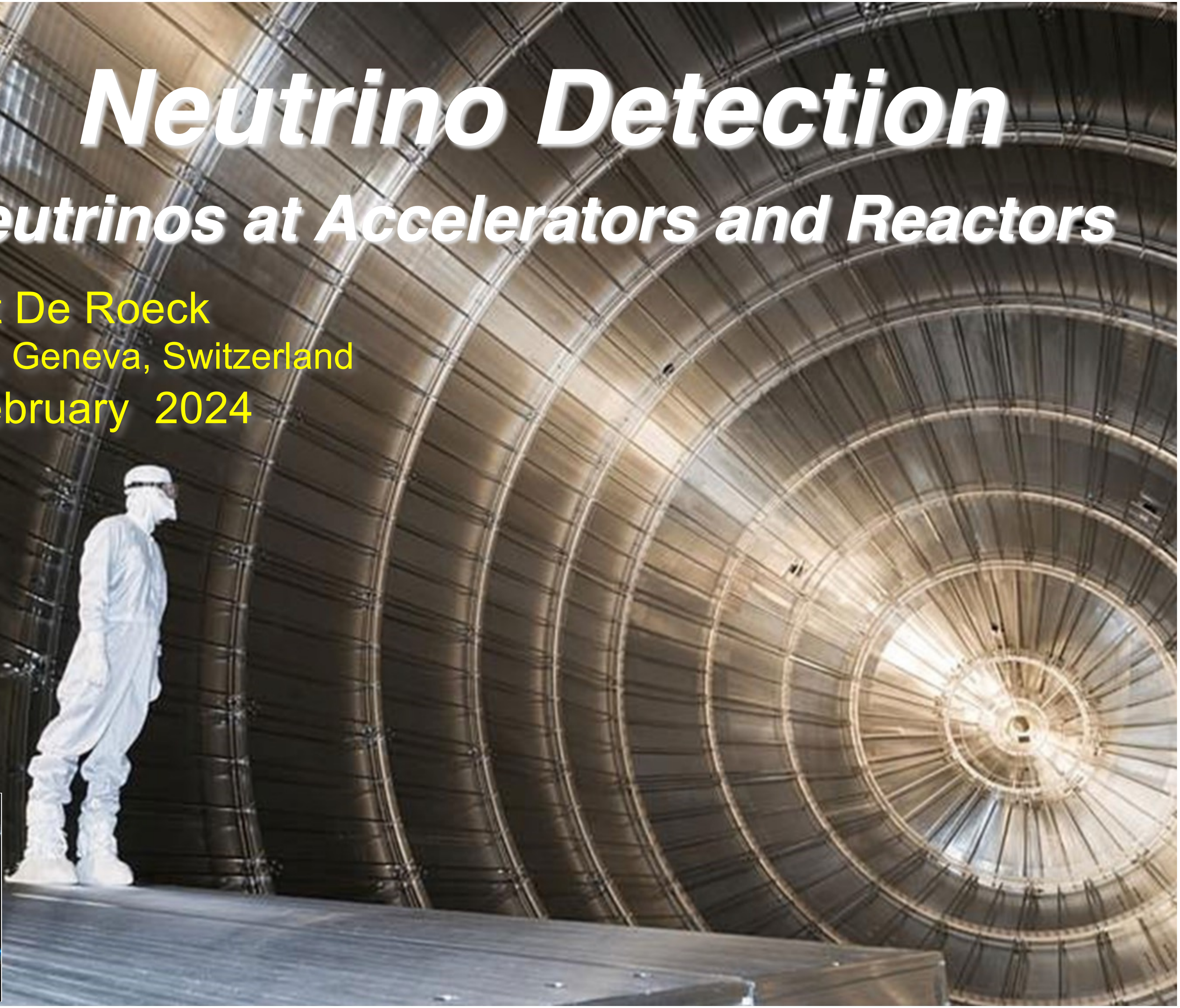
Neutrino Detection

Neutrinos at Accelerators and Reactors



Albert De Roeck
CERN, Geneva, Switzerland

17 February 2024

PARTICLE DETECTION: FROM GROUND TO SPACE AND SPACE WEATHER IMPACTS

WORKSHOP

TOPICS:

- GNSS observation and Space Weather Research in Thailand
- Measuring High Energy Cosmic Rays and Neutrino from IceCube Neutrino Observatory
- Substorms in Near-Earth Space
- Cosmic Rays Payload for Thai Space Consortium Project
- Neutrino Detection at Large Hadron Collider
- Ionosphere and Equatorial plasma bubble
- Hands-on Activities: Cosmic Rays Payload
- Hands-on Activities: On-Demand Analysis Tools for Space Science
- Emulsion scan from Scattering Neutrino Detector (SND) @ LHC CERN
- Hands-on Activities: Ionosphere and Equatorial plasma bubble with computer analysis
- Low Energy Cosmic Rays Detections and Application at Space Weather War Room

SPEAKERS :

Chayanit Asawatangtrakuldee
Jirapoom Budtho
Kullapha Chaiwongkhot
Paul Evenson
Lin Min Min Myint
Yukinaga Miyashita
Waraporn Nuntiyakul
Albert De Roeck
David Ruffolo
Sirawit Saeung
Achara Seripienlert
Pornchai Supnithi

16-19 FEB 2024

IMPORTANT DATES:

REGISTRATION OPEN	JAN 12, 2024
REGISTRATION DEADLINE	JAN 26, 2024 (23:59 BANGKOK TIME)
PARTICIPANT NOTIFICATION	JAN 31, 2024
CONFIRMATION OF ATTENDANCE	FEB 5, 2024
OFFICIAL ACCEPTANCE LETTERS	FEB 7, 2024

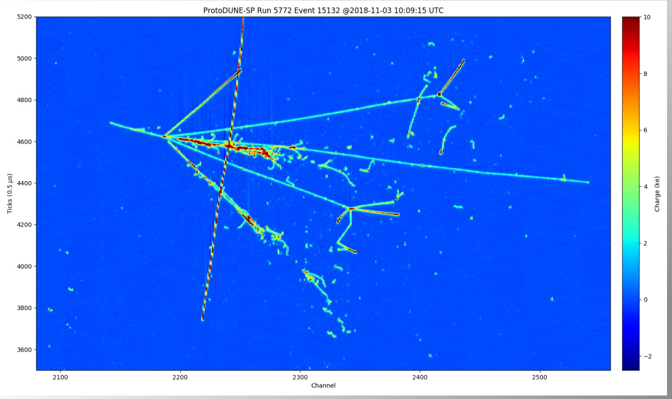
FREE
NO REGISTRATION FEE
FREE ACCOMMODATIONS

IBIS STYLES CHIANG MAI

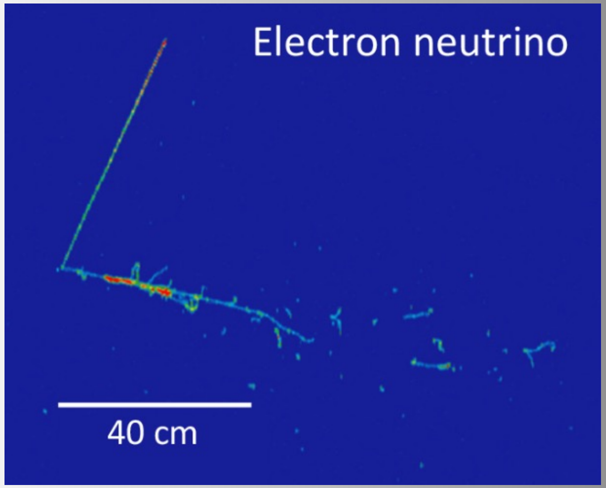
MORE DETAILS

REGISTER NOW

Outline



Pion event in the ProtoDUNE at CERN



Electron neutrino event in the ICARUS detector at FNAL

- Introduction to neutrinos
- Results from oscillation experiments
- (Neutrino properties: mass and Majorana/Dirac nature)
- Neutrino experiments at the LHC
- Next generation of experiments
- Summary

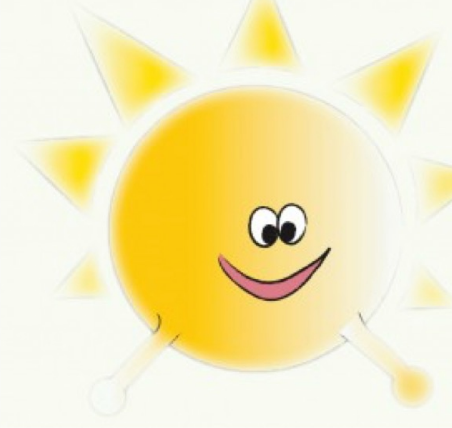
Neutrinos

Neutrinos are still mysterious particles

- Have only (left handed) weak interactions
- Are mass-less in the (minimal) SM .. untill 1998
- Are the only neutral fermions in the SM
- Could be Majorana or Dirac fermions
- Neutrinos are produced everywhere
  - Solar neutrinos
  - Atmospheric neutrinos
  - Neutrinos from supernova explosions
  - Primordial neutrinos from the Big Bang
  - Nuclear reactor created neutrinos
  - Accelerator created neutrinos
  - Geoneutrinos, Radioactive decay, even from your body…

Neutrinos

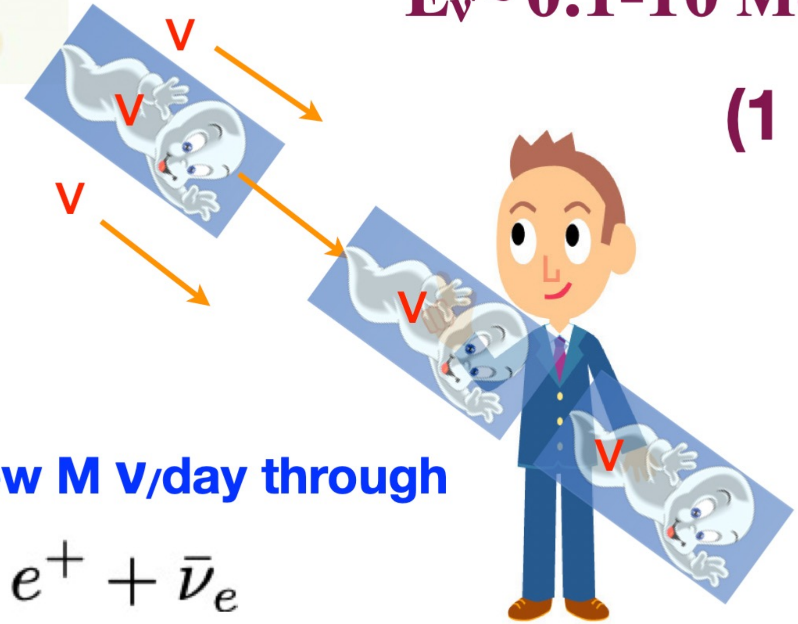
Interaction of neutrinos with matter is very weak!



~ 1trillion (10^{12}) of ν_{solar} per second are passing through our body but we do not feel them at all!

E_{ν}~ **0.1-10 MeV = 10^5 eV**

(1 MeV = 10^6 eV)

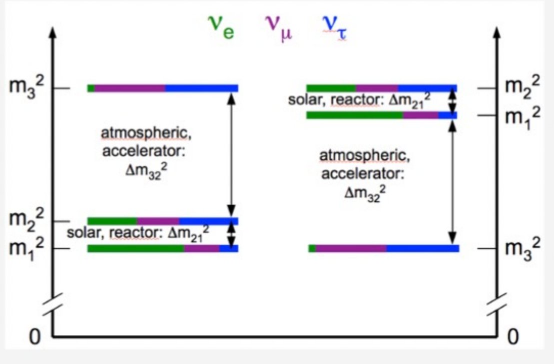


And all of us also emit ~a few M ν/day through

$$^{40}\mathrm{K} \rightarrow ^{40}\mathrm{Ca} + e^{+} + \bar{\nu}_e$$

Neutrinos

Neutrino experiments today -> Open Questions!

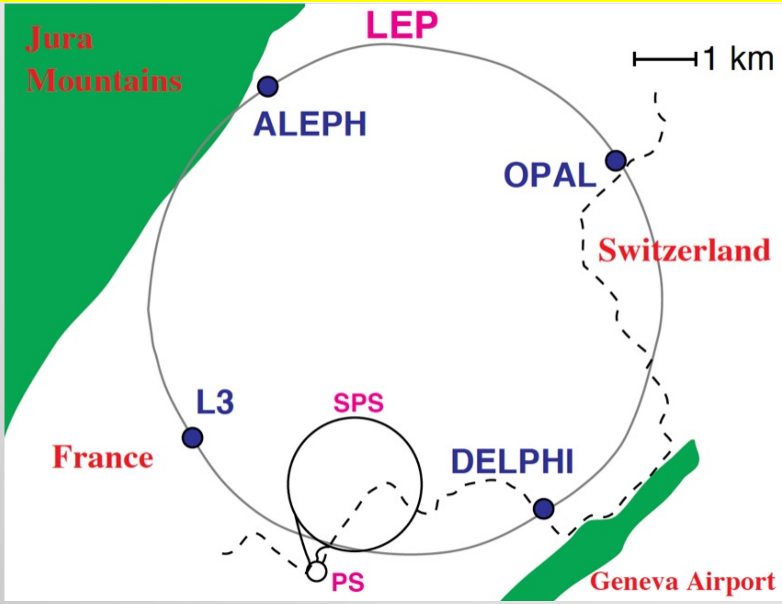


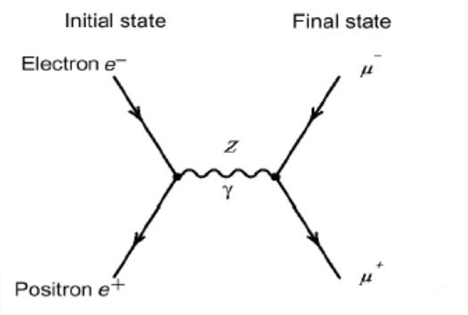
- Neutrino mass values? Origin of the Masses?
- Neutrino mass hierarchy? Normal or Inverted?
- CP violation in the lepton sector? Are neutrinos key the baryon asymmetry in the Universe?
- Are neutrinos their own antiparticles? -> Lepton Number Violation!
- Do right-handed/sterile/heavy neutrinos exist?
- Are there non-standard neutrino interactions?
- Neutrinos and Dark Matter?
- Testing of CPT..
- Neutrinos are Chameleons:
  They can change flavour!!

Neutrinos are an essential part of our Universe and our very existence, and can provide answers to some of the key fundamental questions today

Neutrinos come in 3 Flavors

LEP e+e- collider at CERN (1988-2000)



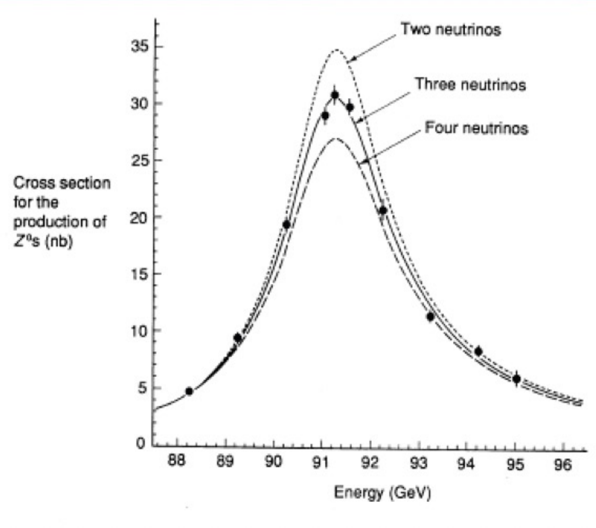


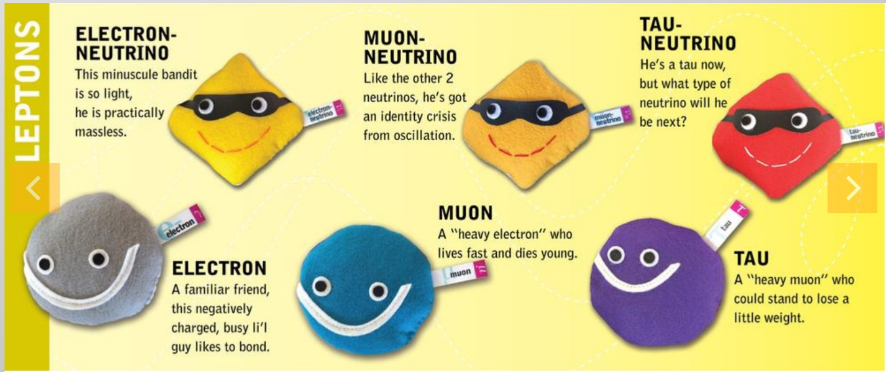
The width of the Z-boson gives the number of neutrinos

$$\Gamma_Z = \Gamma_{had} + 3\Gamma_l + N_\nu \Gamma_\nu$$

$$N_\nu = 2.99 \pm 0.02$$

Detailed study of the Z-boson





ELECTRON-NEUTRINO
This minuscule bandit is so light, he is practically massless.

MUON-NEUTRINO
Like the other 2 neutrinos, he's got an identity crisis from oscillation.

TAU-NEUTRINO
He's a tau now, but what type of neutrino will he be next?

ELECTRON
A familiar friend, this negatively charged, busy li'l guy likes to bond.

MUON
A "heavy electron" who lives fast and dies young.

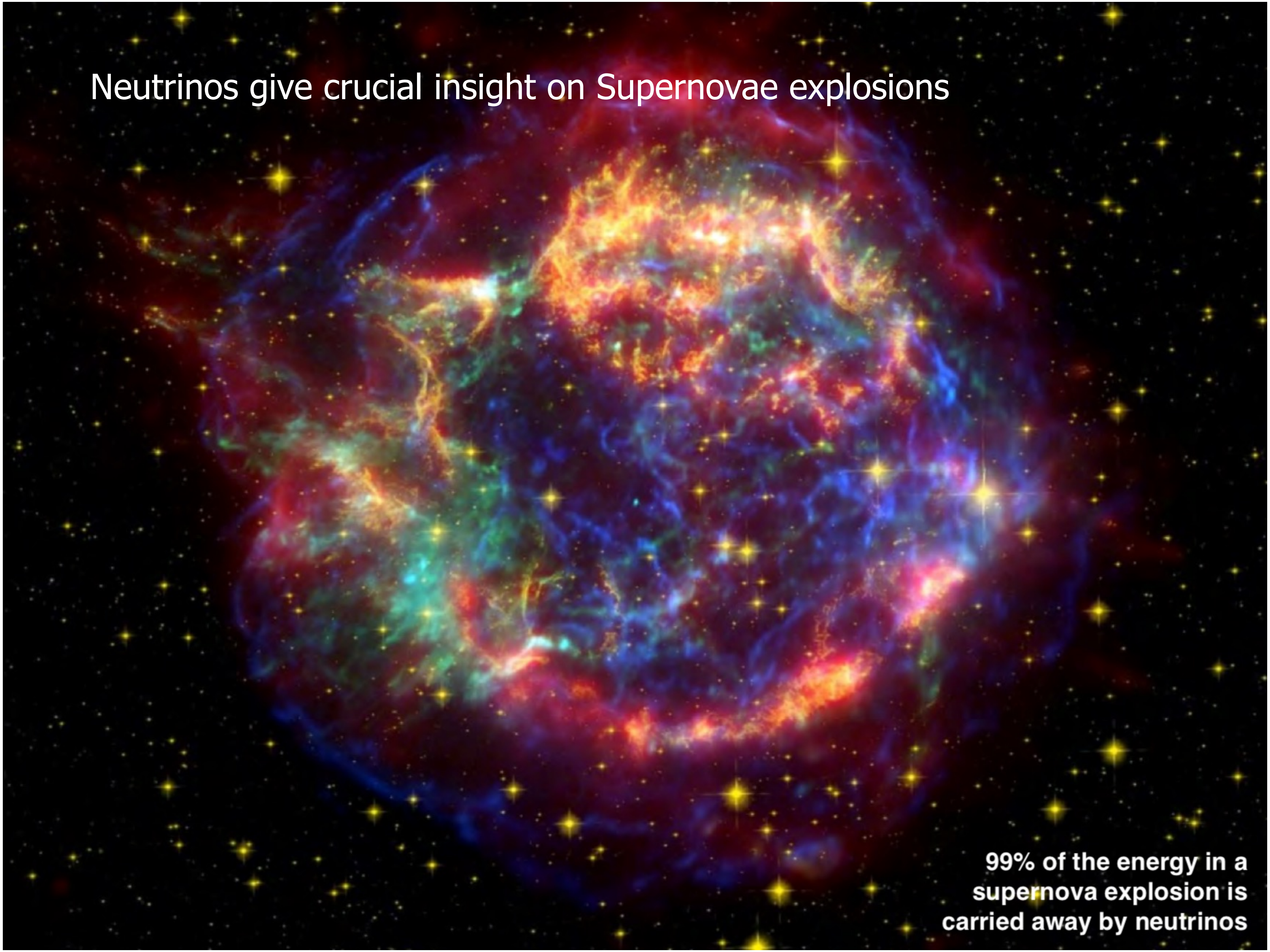
TAU
A "heavy muon" who could stand to lose a little weight.

LEP: three active neutrinos with mass<45 GeV

Plenty of neutrinos in the Universe

For every proton/neutron/electron the Universe contains a billion of neutrinos from the Big Bang

Neutrinos give crucial insight on Supernovae explosions



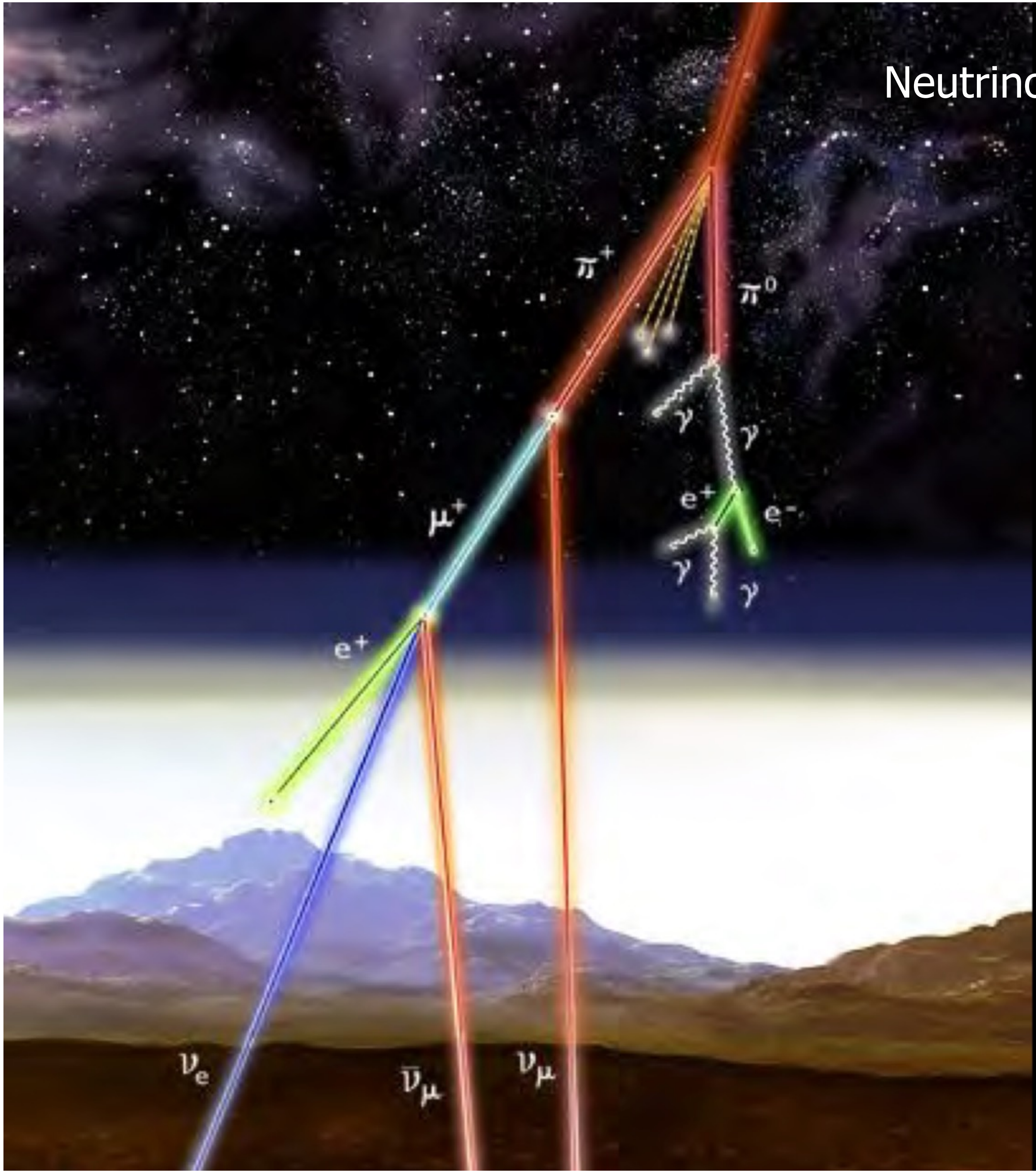
99% of the energy in a supernova explosion is carried away by neutrinos

Neutrinos allow us to to look into the heart of the sun

10^{38} neutrinos per second
are produced by the Sun

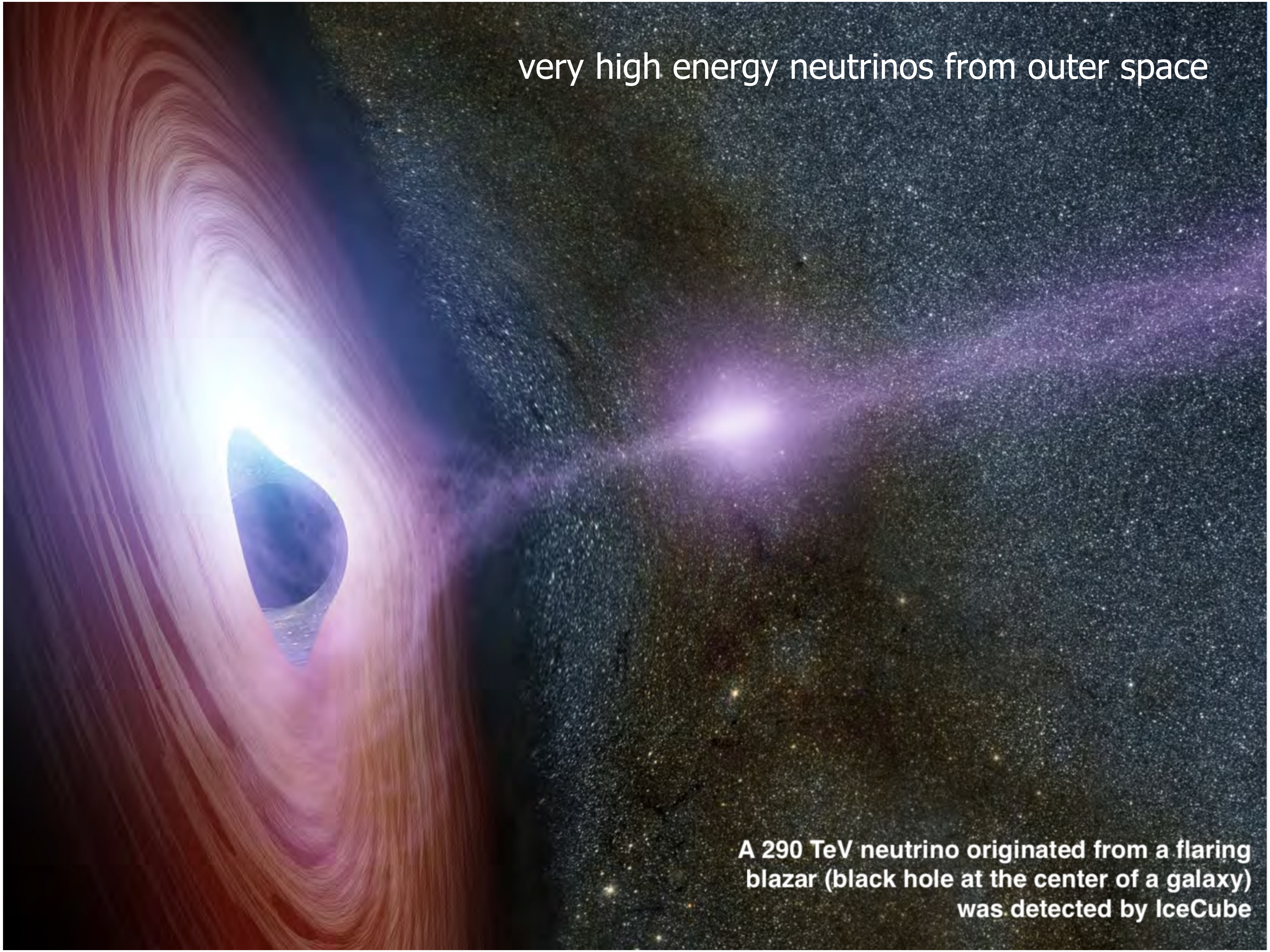
(with a flux of $\sim 10^{11}/\text{cm}^2/\text{sec}$ at the Earth)

Neutrinos from cosmic rays



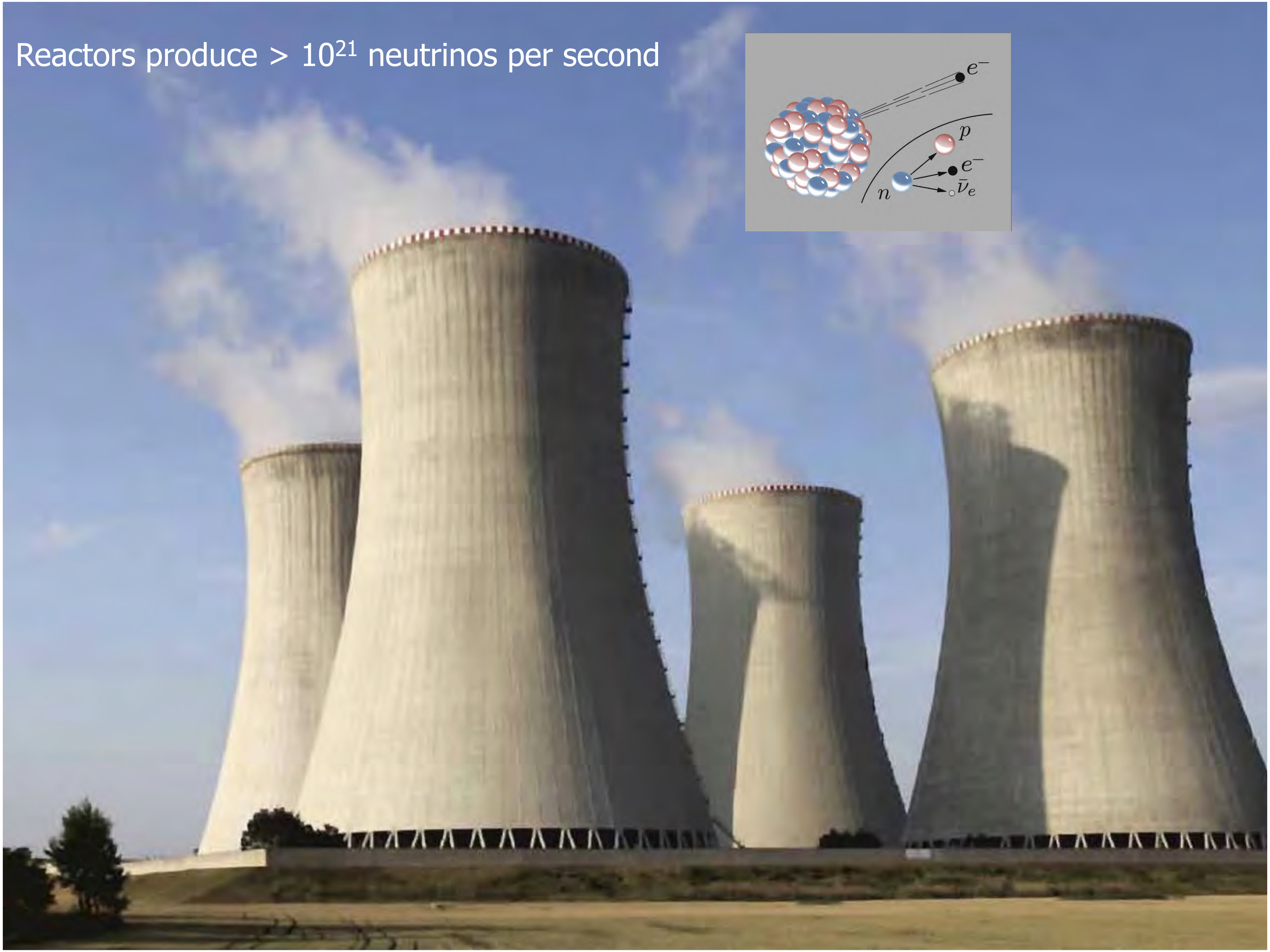
Neutrinos are also produced in the atmosphere

very high energy neutrinos from outer space

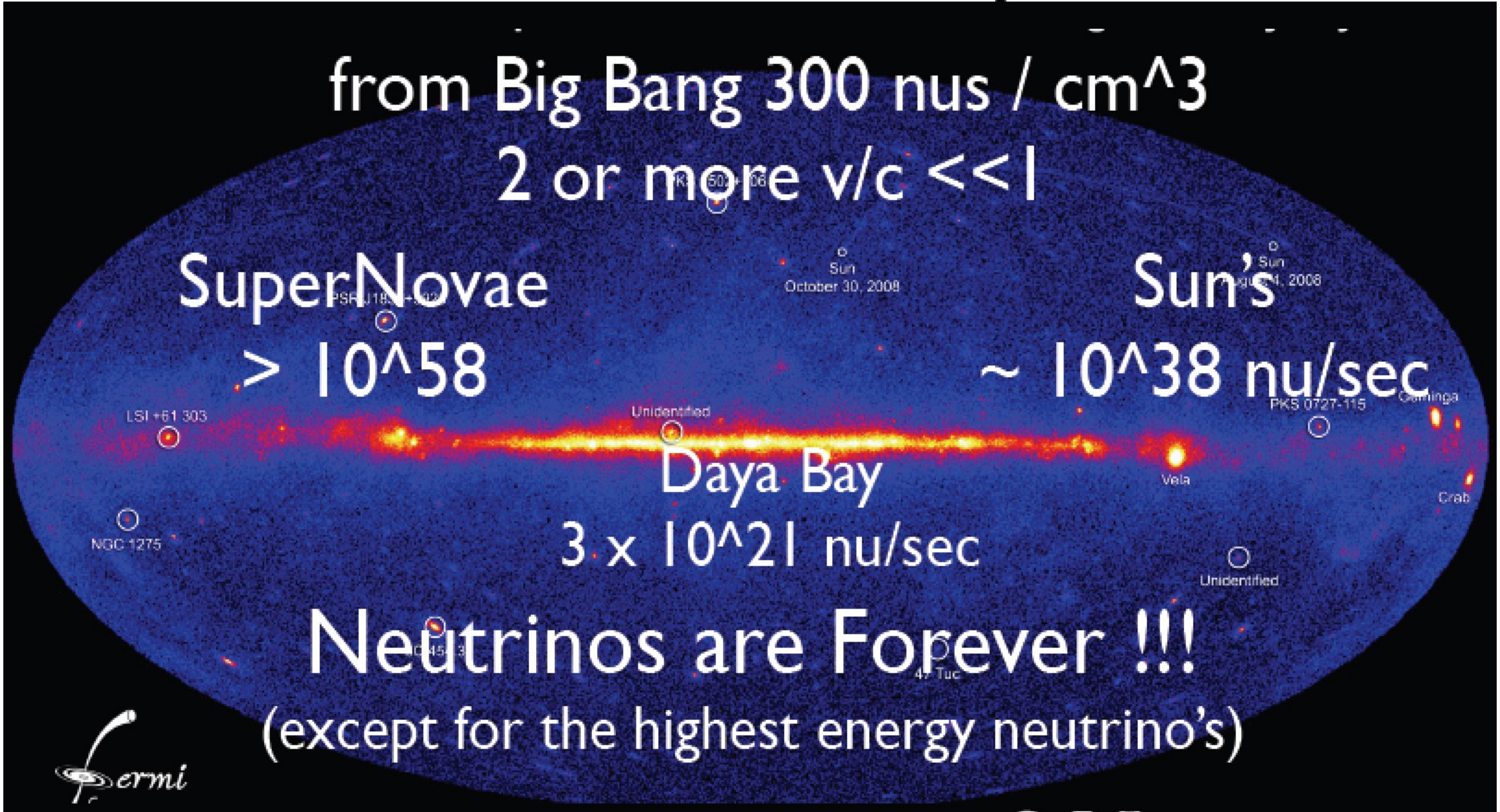


A 290 TeV neutrino originated from a flaring blazar (black hole at the center of a galaxy) was detected by IceCube

Reactors produce > 10^{21} neutrinos per second



Neutrinos are Everywhere !



from Big Bang 300 nus / cm^3

2 or more v/c <<1

SuperNovae

> 10^58

Sun's

~ 10^38 nu/sec

Daya Bay

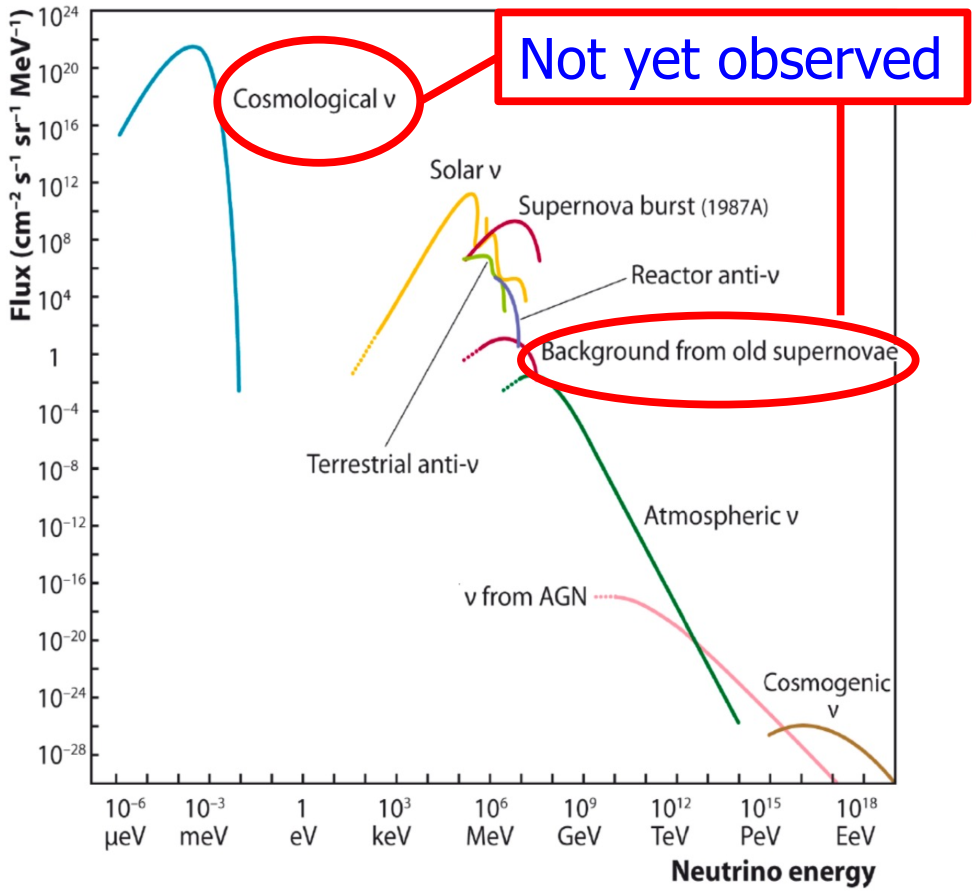
3 x 10^21 nu/sec

Neutrinos are Forever !!!

(except for the highest energy neutrino's)

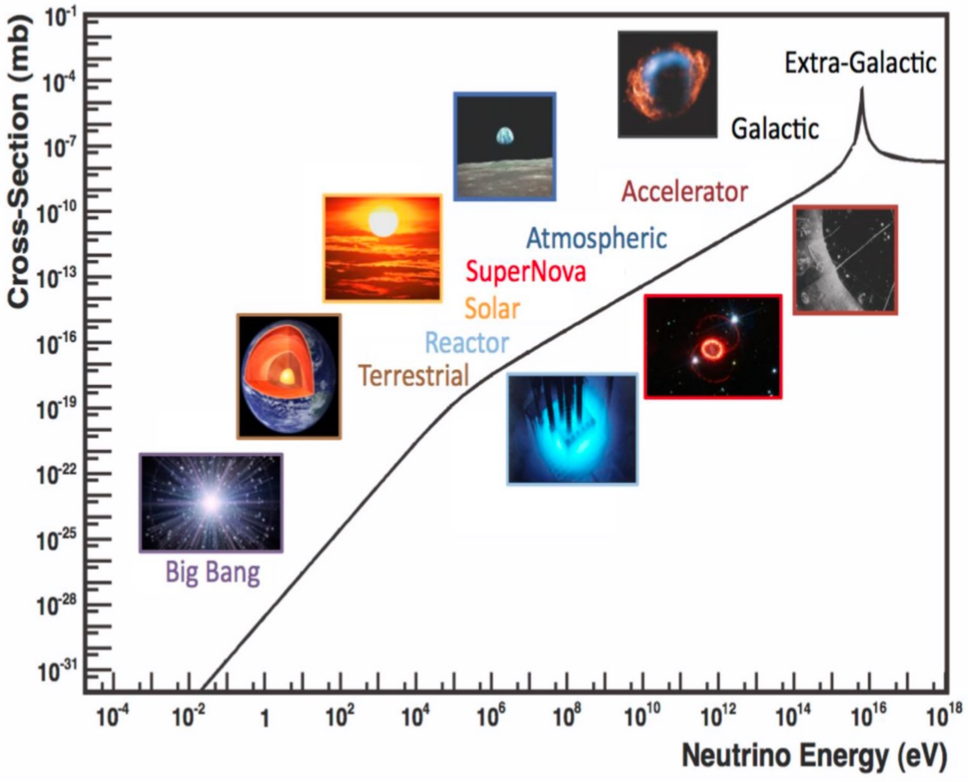
therefore in the Universe: $\frac{\partial N_\nu}{\partial t} > 0$

Neutrino Sources, Flux and Cross Sections



C. Spiering, arXiv:1207.4952

Not yet observed

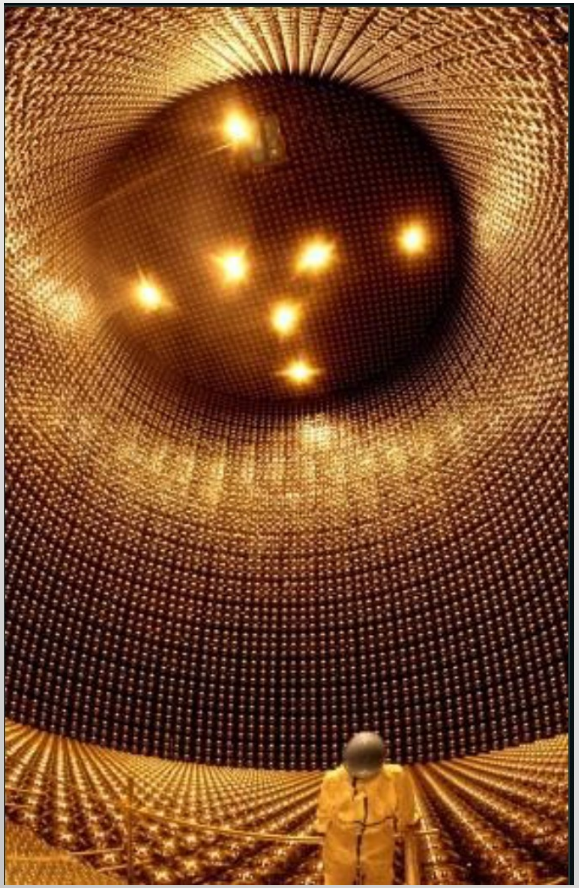


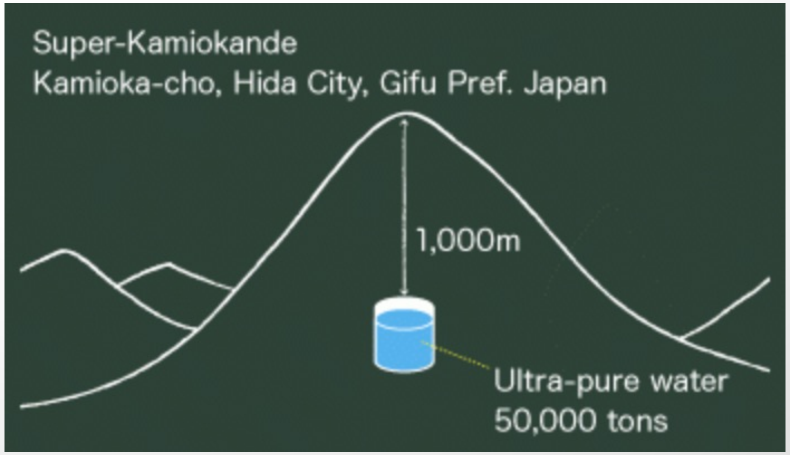
J. Formaggio, G.P. Zeller, arXiv:1305.7513

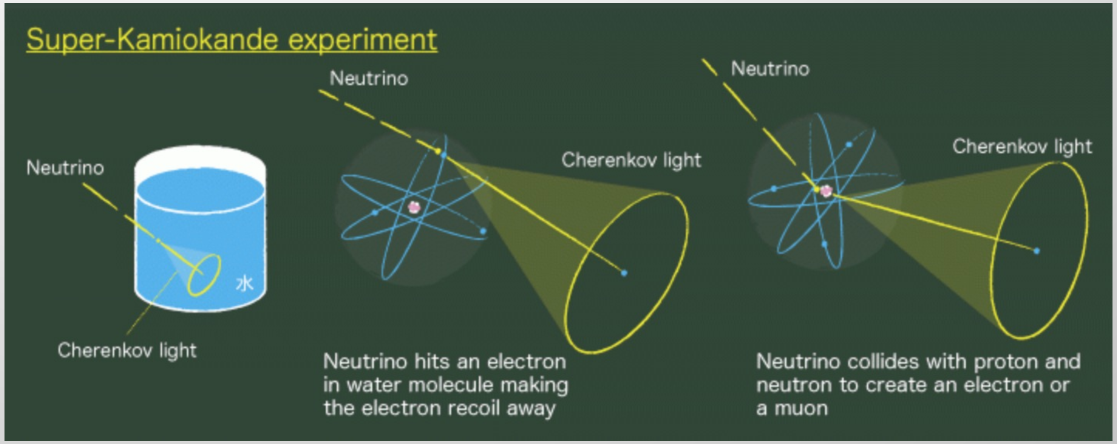
Cosmological and background from old supernovae neutrinos not yet observed!

Detecting neutrinos is challenging
Very large detectors are needed

SuperKamiokande



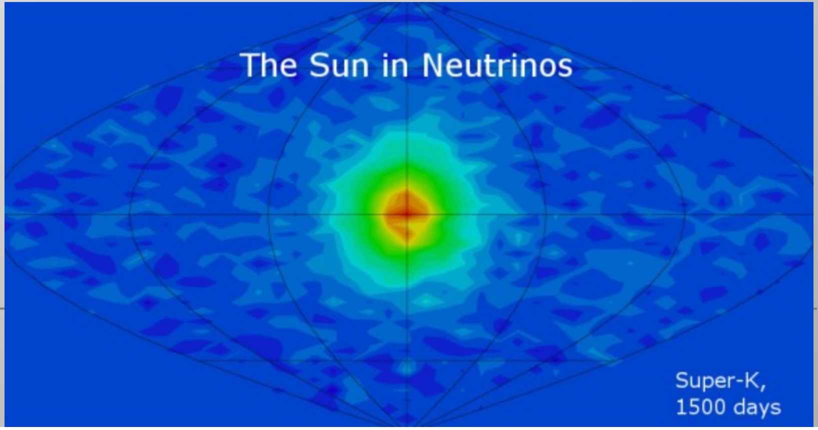




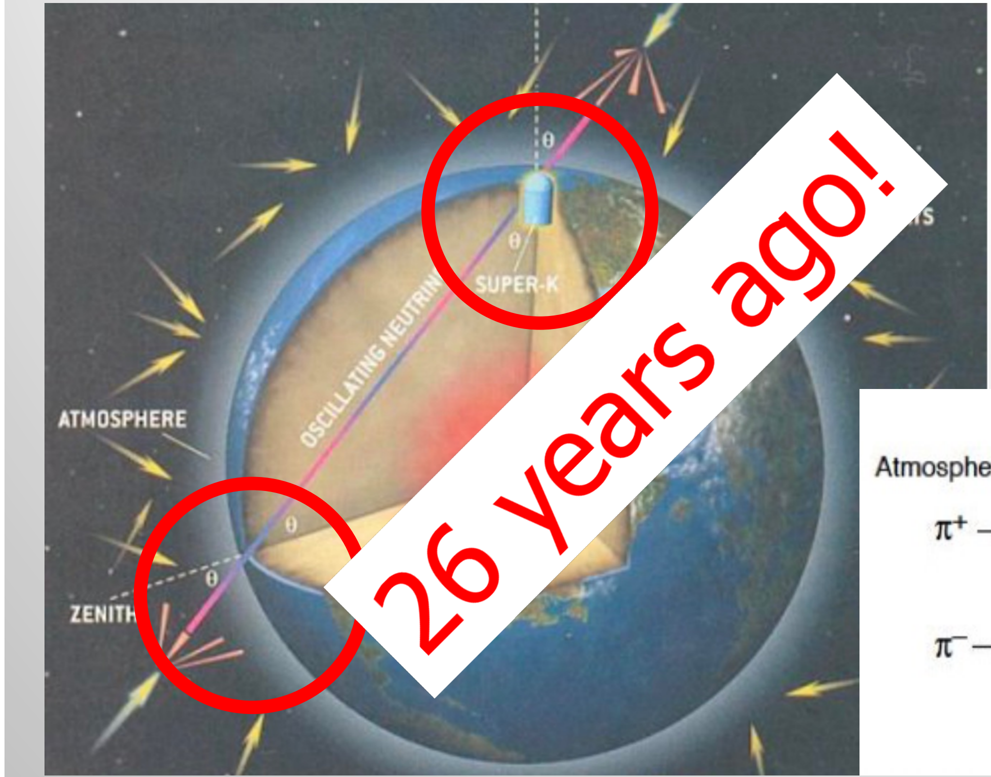
Neutrino hits an electron in water molecule making the electron recoil away

Neutrino collides with proton and neutron to create an electron or a muon

50,000 tons of ultra-pure water, watched by 13,000 photomultipliers



Neutrinos Oscillate! (1998)



26 years ago!

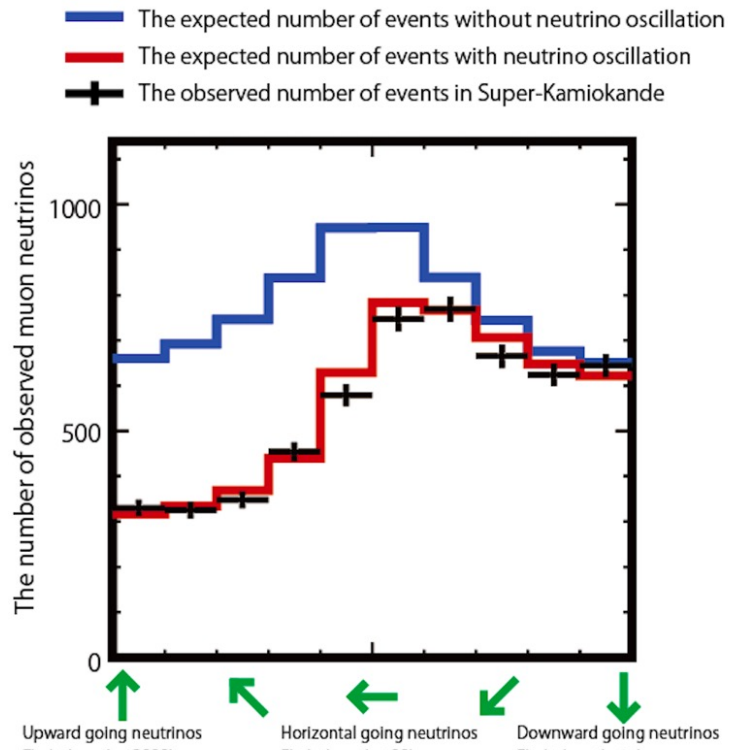
Atmospheric neutrino source

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

$\hookrightarrow e^+ + \nu_e + \bar{\nu}_\mu$

$\pi^- \rightarrow \mu^- + \bar{\nu}_\mu$

$\hookrightarrow e^- + \bar{\nu}_e + \nu_\mu$



Upward going neutrinos
Flight length: 12800km
Only a half of the expected number(blue line) was observed

Horizontal going neutrinos
Flight length: 500km
Only 80% of the expected number was observed

Downward going neutrinos
Flight length: 15km
Consistent with the expected number.

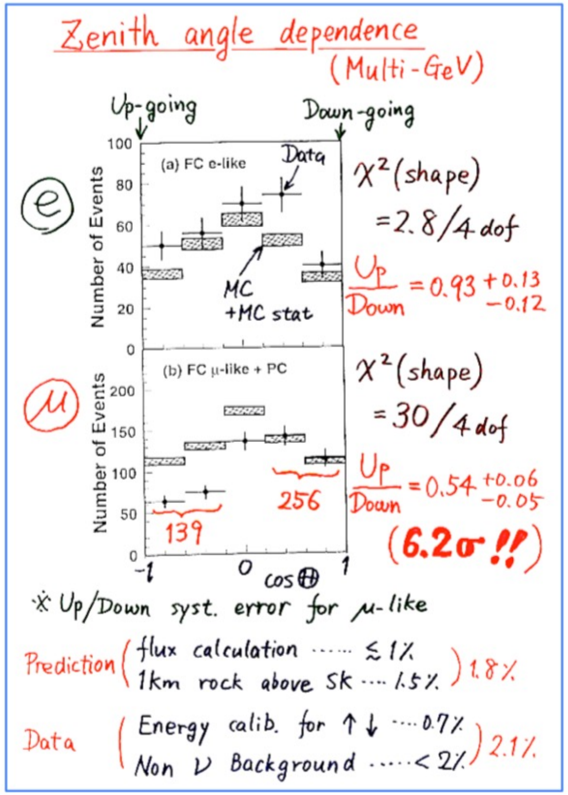
1998: The Super-Kamiokande experiment in Japan used a massive underground detector filled with ultrapure water.

They announced first evidence of neutrino oscillations. The experiment showed that muon neutrinos disappear as they travel through the earth to the detector It also offered an explanation for the observed solar neutrino discrepancy.

Neutrinos Oscillate! (1998)

1998: Nobel-worth discovery of oscillation effects

[Takaaki Kajita for Super-Kamiokande, slides at Neutrino '98 conference]



Zenith angle dependence
(Multi-GeV)

χ^2(shape) = 2.8/4 dof

$\frac{\mathrm{Up}}{\mathrm{Down}} = 0.93^{+0.13}_{-0.12}$

χ^2(shape) = 30/4 dof

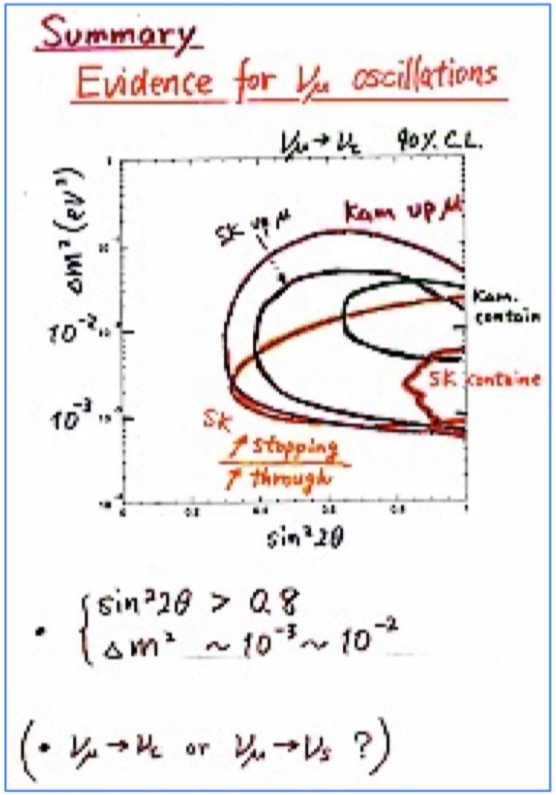
$\frac{\mathrm{Up}}{\mathrm{Down}} = 0.54^{+0.06}_{-0.05}$

(**6.2σ !!**)

※ Up/Down syst. error for μ-like

Prediction (flux calculation …… ≲ 1% ; 1km rock above SK …. 1.5%) 1.8%

Data (Energy calib. for ↑↓ …. 0.7% ; Non ν Background ….. < 2%) 2.1%



Summary

Evidence for ν_μ oscillations

- $\begin{cases} \sin^2 2\theta > 0.8 \\ \Delta m^2 \sim 10^{-3} \sim 10^{-2} \end{cases}$

(• $\nu_\mu \to \nu_\tau$ or $\nu_\mu \to \nu_s$?)

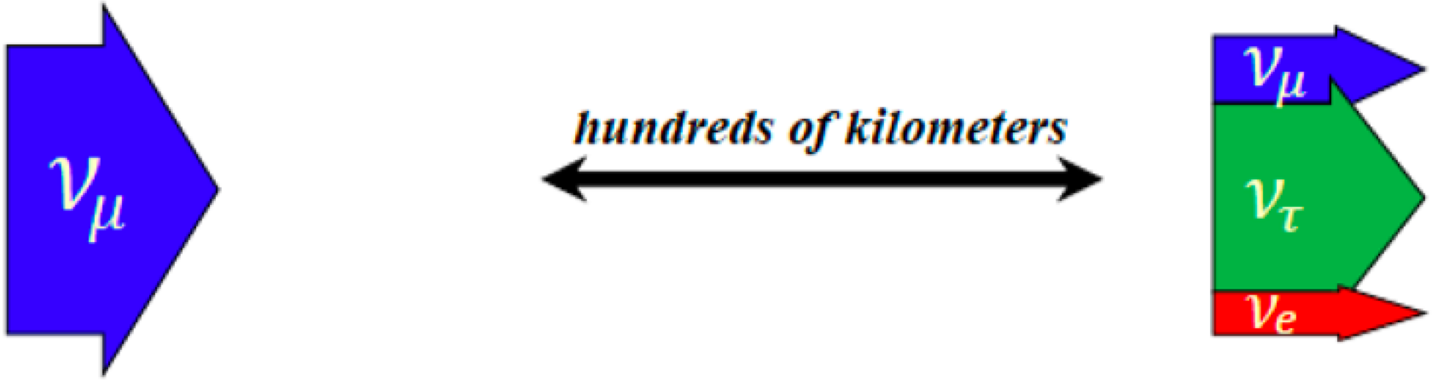
E. Lisi
Re-interpretation
Workshop
17/2/2021

Initial interpretation in terms of simple 2ν ($\nu_\mu \to \nu_\tau$) oscillations

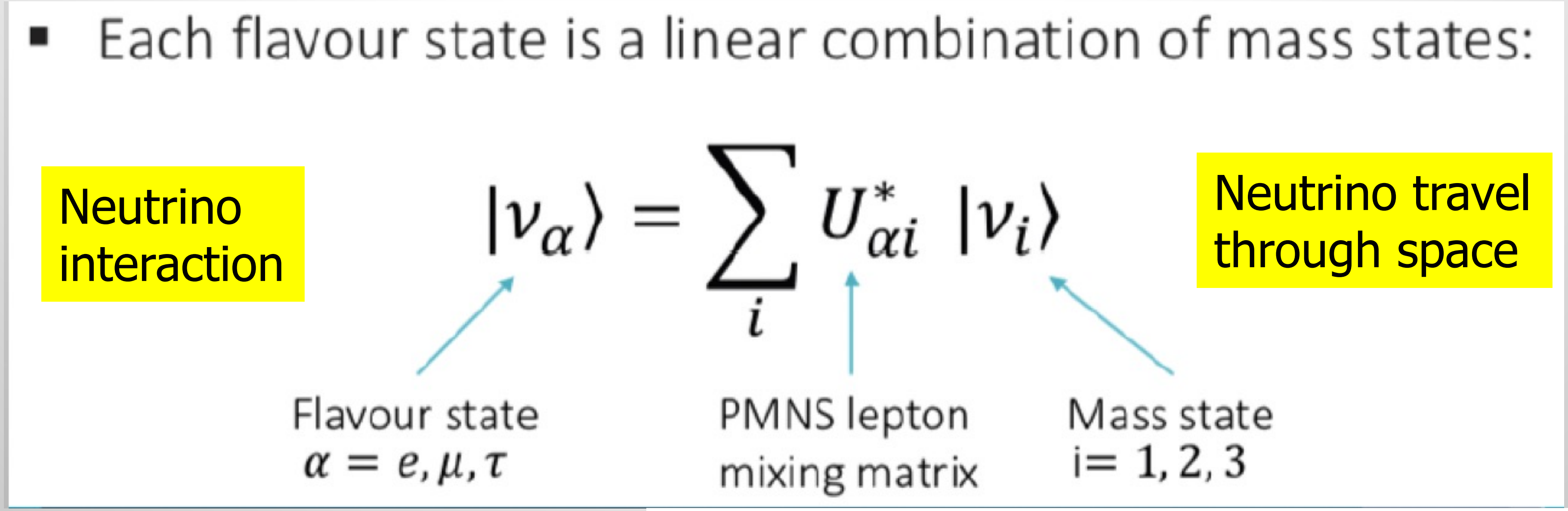
Neutrino Oscillations first firmly established with atmospheric neutrinos

Neutrino Oscillations

- Important discovery in 1998: neutrino oscillations
- Neutrino oscillation is a quantum mechanical phenomenon whereby a neutrino created with a specific lepton flavor (electron, muon, or tau) can later be measured to have a different flavor. The probability of measuring a particular flavor for a neutrino varies between 3 known states as it propagates through space
- Neutrino oscillations only possible if neutrinos have a non-zero mass! Neutrino oscillations -> Neutrinos have mass!!



Neutrino oscillations



- Each flavour state is a linear combination of mass states:

$$|\nu_\alpha\rangle = \sum_i U^*_{\alpha i} \; |\nu_i\rangle$$

Neutrino interaction

Neutrino travel through space

Flavour state
$\alpha = e, \mu, \tau$

PMNS lepton mixing matrix

Mass state
i= 1, 2, 3

(*) Pontecorvo-Maki-Nakagawa-Sakata Matrix

Flavor states

ELECTRON-NEUTRINO
This minuscule bandit is so light, he is practically massless.

MUON-NEUTRINO
Like the other 2 neutrinos, he's got an identity crisis from oscillation.

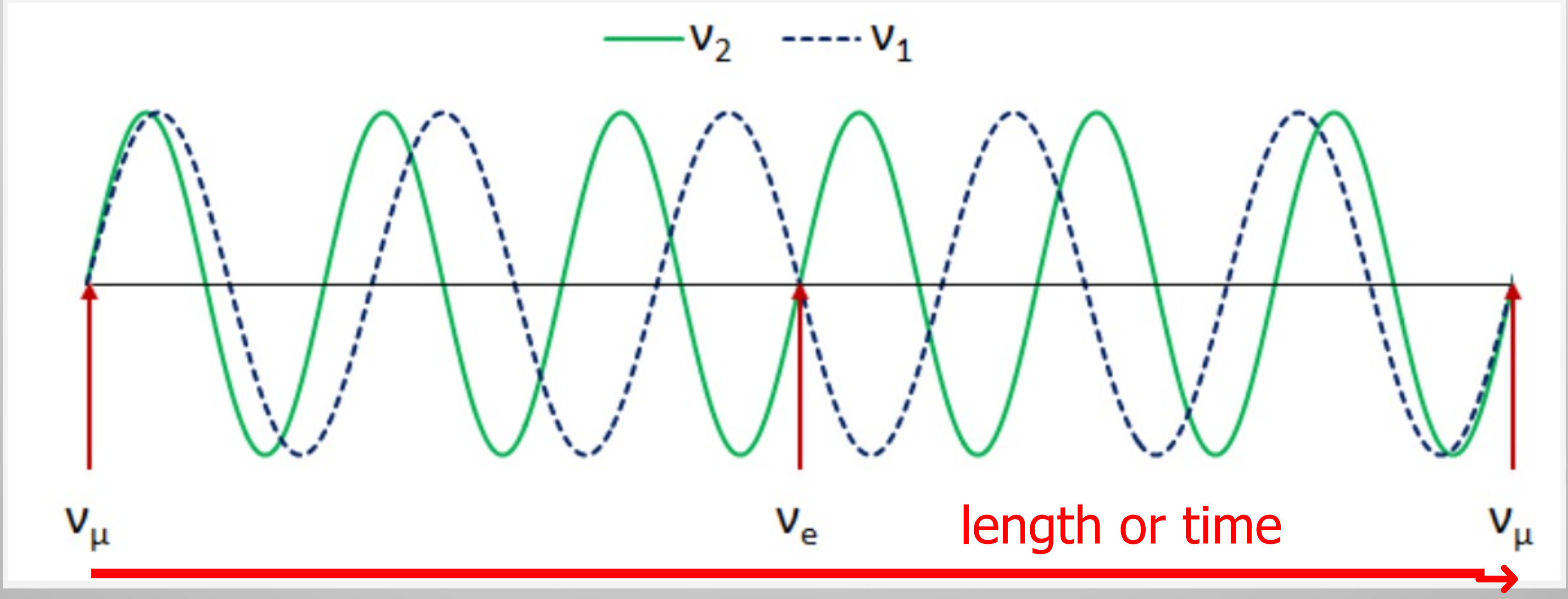
TAU-NEUTRINO
He's a tau now, but what type of neutrino will he be next?

Neutrino Oscillations

The bizarre world of Quantum Mechanics: particles and waves

Take that the neutrino particle is a hybrid of two mass states v1 and v2 as it travels through space the associated waves of these mass states advance at a different rate

Hence the picture looks as follows: (propagation as a superposition of two masses)

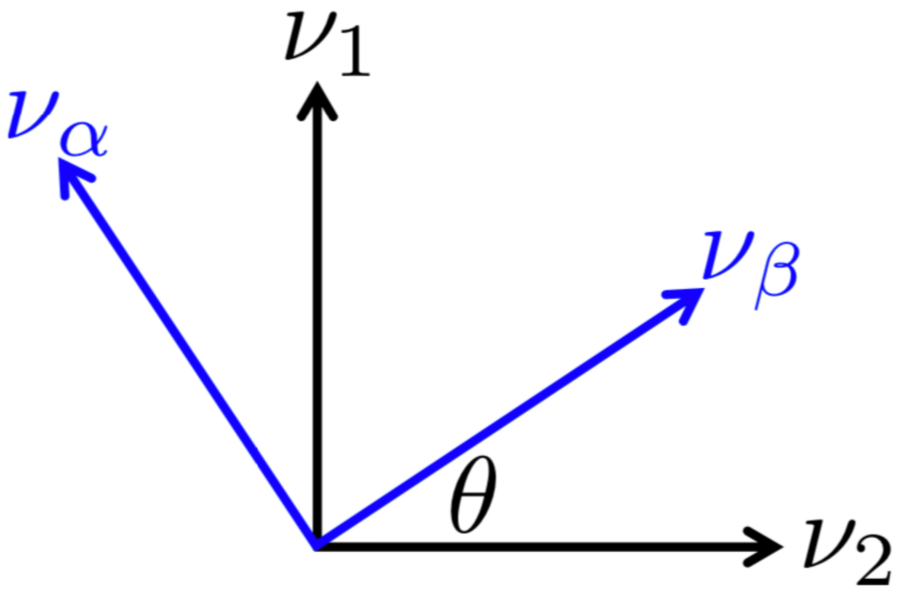


The neutrinos change identity (flavor) along the way…!!

Two Flavour Oscillations

Flavour states	"Rotation Matrix"	Mass states

$$\begin{pmatrix} \nu_\alpha \\ \nu_\beta \end{pmatrix} = \begin{pmatrix} \cos\theta & \sin\theta \\ -\sin\theta & \cos\theta \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \end{pmatrix}$$



$$|\nu(t=0)\rangle = |\nu_\alpha\rangle = \cos\theta\,|\nu_1\rangle + \sin\theta\,|\nu_2\rangle$$

Two Flavour Oscillations

$$|\nu(t)\rangle = e^{i(E_1 t - pL)}\cos(\theta)|\nu_1\rangle + e^{i(E_2 t - pL)}\sin(\theta)|\nu_2\rangle$$

plane wave

$$\boxed{\langle\nu_\beta|\nu(t)\rangle = \sin(\theta)\cos(\theta)(e^{i(E_2 t - pL)} - e^{i(E_1 t - pL)})}$$

$$E \approx p + \frac{m_i^2}{2E} \quad \text{and} \quad t = \frac{L}{c}$$

ultra-relativistic

$$\langle\nu_\beta|\nu(t)\rangle = \sin(\theta)\cos(\theta)(e^{i\frac{m_2^2 L}{2E}} - e^{i\frac{m_1^2 L}{2E}}) = \sin(\theta)\cos(\theta)e^{i\frac{\Delta m_i^2 L}{2E}}$$

$$\boxed{P(\nu_\alpha \to \nu_\beta) = \langle\nu_\beta|\nu(t)\rangle^2 = \sin^2(2\theta)\sin^2\left(\frac{\Delta m_i^2 L}{2E}\right)}$$

L: distance travelled

E: energy of the neutrino

Neutrino Oscillations

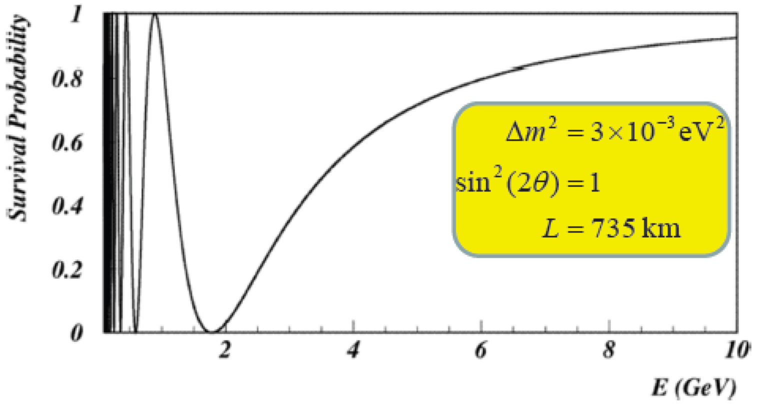
Neutrino oscillations is a pure Quantum Mechanical effect

The effect depends on the mass difference between flavor states

$$\nu_\mu \xrightarrow{\hspace{2em}} \underset{\nu_1,\nu_2}{\xrightarrow{\hspace{4em}}} \xrightarrow{\hspace{2em}} \nu_\mu \text{ or } \nu_\tau$$

$$\begin{pmatrix} \nu_\mu \\ \nu_\tau \end{pmatrix} = \begin{pmatrix} \cos\theta & \sin\theta \\ -\sin\theta & \cos\theta \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \end{pmatrix} \qquad P(\nu_\mu \to \nu_\tau) = \sin^2(2\theta)\sin^2\left(\frac{1.27\Delta m^2 L}{E_\nu}\right)$$

- Measure prob.
  - Survival
  - Appearance
- Result
  - Mixing angle
  - Mass differences

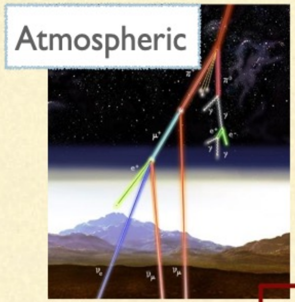


- $\Delta m^2_{21} = m^2_2 - m^2_1 \approx 8 * 10^{-5}\ \mathrm{eV}^2$ => wavelength of ~100km
- $|\Delta m^2_{31}| \approx |\Delta m^2_{32}| \approx 2 * 10^{-3}\ \mathrm{eV}^2$ => wavelength of ~1km

Absolute mass values? Mass hierarchy?

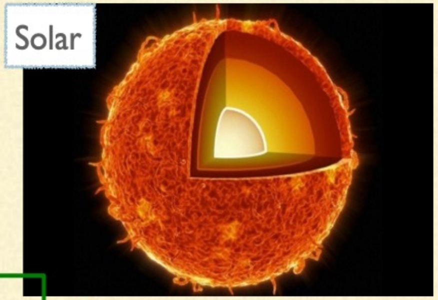
Neutrino Oscillations

Neutrino mixing: Pontecorvo-Maki-Nakagawa-Sakata (PMNS) matrix


Atmospheric


Accelerator


Reactor


Solar

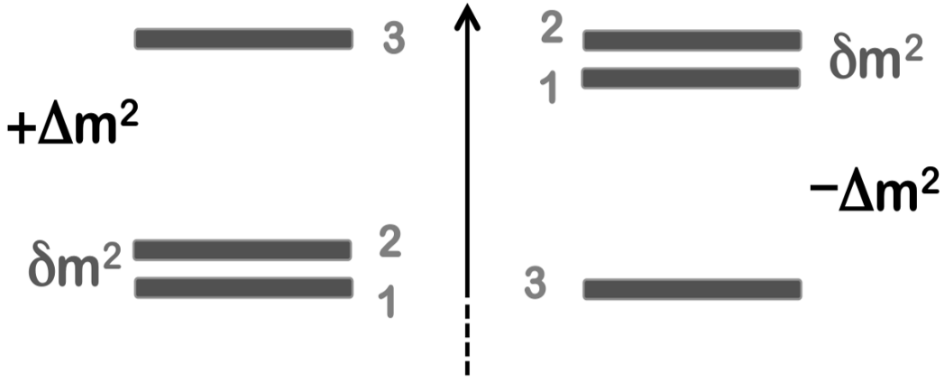
$c_{ij} = \cos\theta_{ij}$

$s_{ij} = \sin\theta_{ij}$

$\Delta m^2_{ij} = m_i^2 - m_j^2$

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

"Normal"
Ordering
N.O.



"Inverted"
Ordering
I.O.

+ interactions in matter → effective terms ~ $G_F \cdot E \cdot$ density

Neutrino Oscillations

- Since >20 years an active field of study and data from many experiments collected:
  - Long baseline accelerator experiments (LBL)
  - Short baseline reactor experiments
  - Atmospheric neutrinos
  - Solar Neutrinos
  - Neutrinoless double beta decay experiments

LBL experiments in the US and Japan
SuperKamiokande, Icecube

Short Baseline Experiments

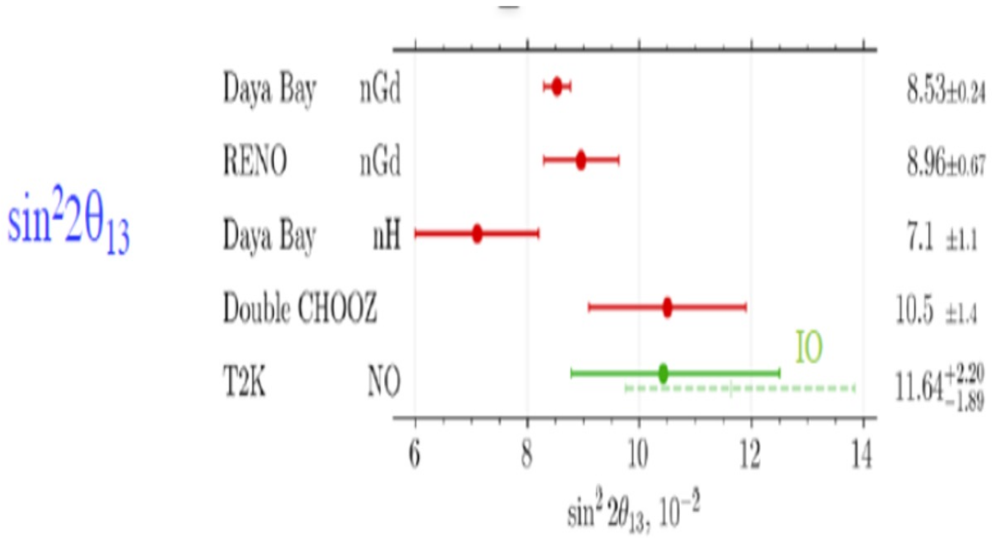
Measuring the mixing angle θ_{13}

Daya Bay (China)
Eight anti-neutrino detectors
(liquid scintillator based)
within 2 km of 6 reactors

RENO (South Korea)
Two anti-neutrino detectors
(liquid scintillator based)
~up to 1.5 km of 6 reactors

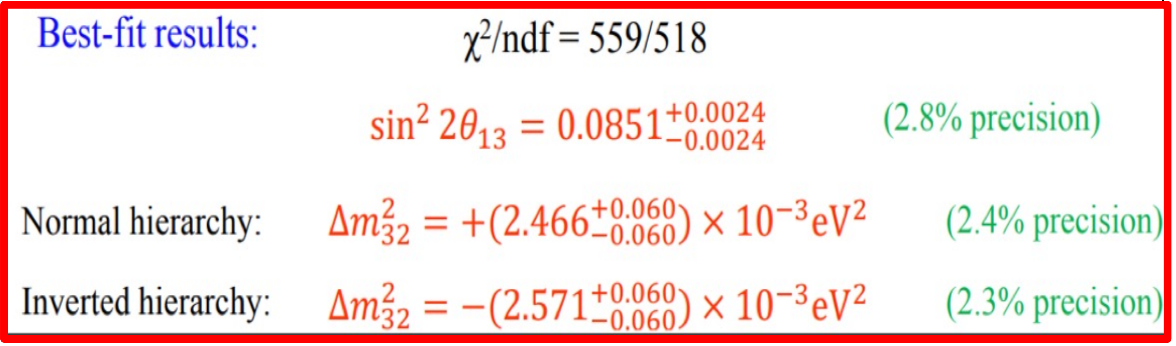
Double Chooz (France)
Two anti-neutrino detectors
(liquid scintillator based)
within 0.4-1 km of the reactors

Results



Phys. Rev. Lett. 130, 161802 (2023

- New results from Daya Bay nGd capture:



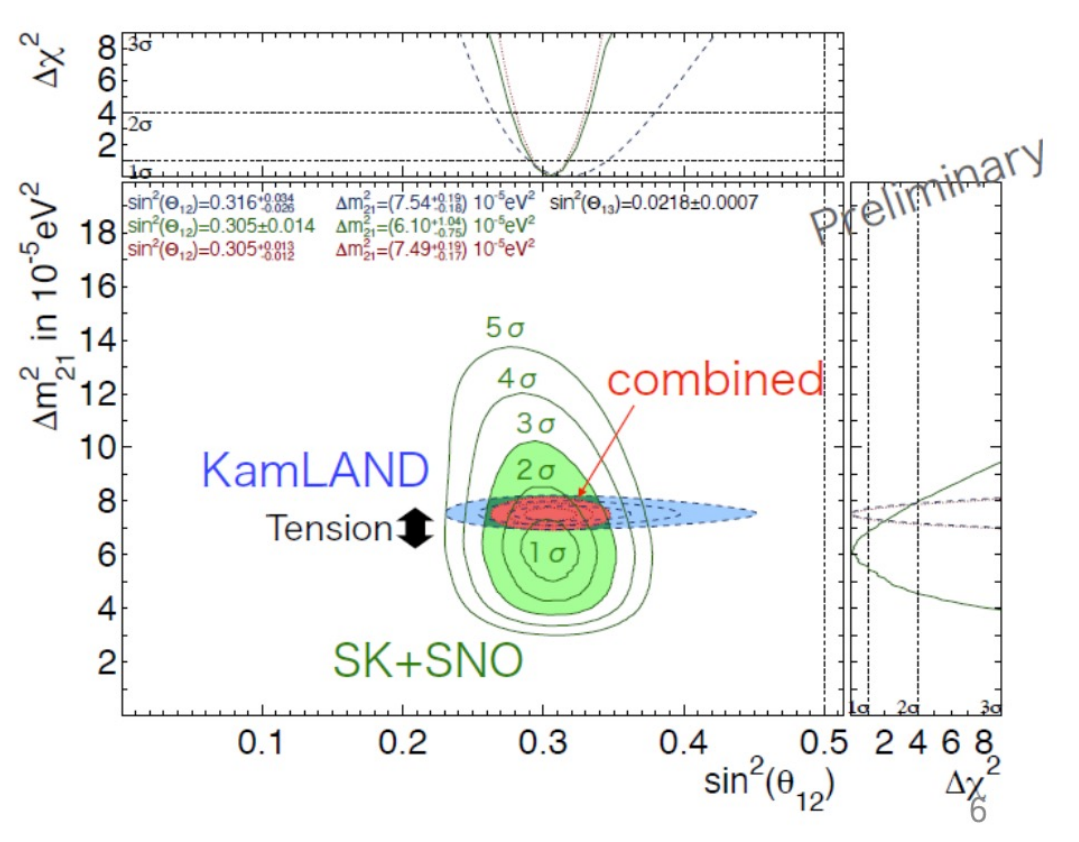
Best-fit results: $\chi^2/\mathrm{ndf} = 559/518$

$$\sin^2 2\theta_{13} = 0.0851^{+0.0024}_{-0.0024}$$ (2.8% precision)

Normal hierarchy: $\Delta m^2_{32} = +(2.466^{+0.060}_{-0.060}) \times 10^{-3}\mathrm{eV}^2$ (2.4% precision)

Inverted hierarchy: $\Delta m^2_{32} = -(2.571^{+0.060}_{-0.060}) \times 10^{-3}\mathrm{eV}^2$ (2.3% precision)

Solar Neutrino Parameters



$$\sin^2(\theta_{12}) = 0.316^{+0.034}_{-0.026}$$

$$\Delta m^2_{21} = 7.54^{+0.19}_{-0.18} \times 10^{-5} eV^2$$

$$\sin^2(\theta_{12}) = 0.305 \pm 0.014$$

$$\Delta m^2_{21} = 6.10^{+1.04}_{-0.75} \times 10^{-5} eV^2$$

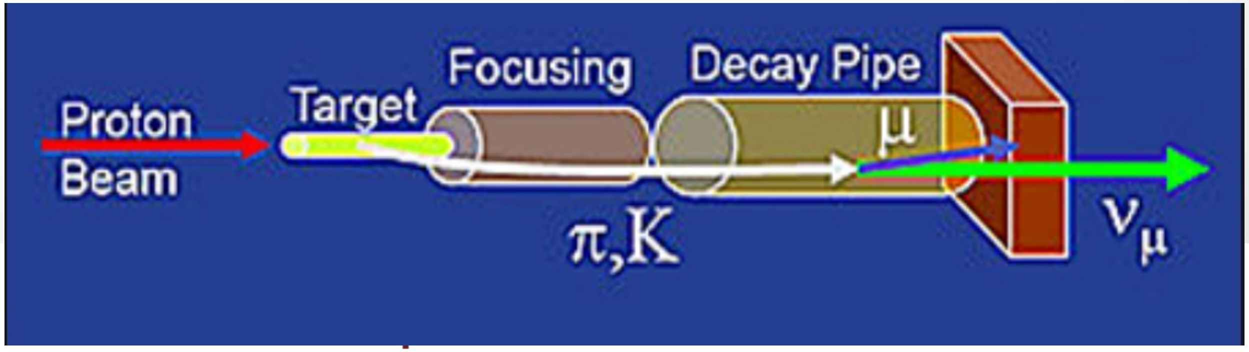
$$\sin^2(\theta_{12}) = 0.305^{+0.013}_{-0.012}$$

$$\Delta m^2_{21} = 7.49^{+0.19}_{-0.17} \times 10^{-5} eV^2$$

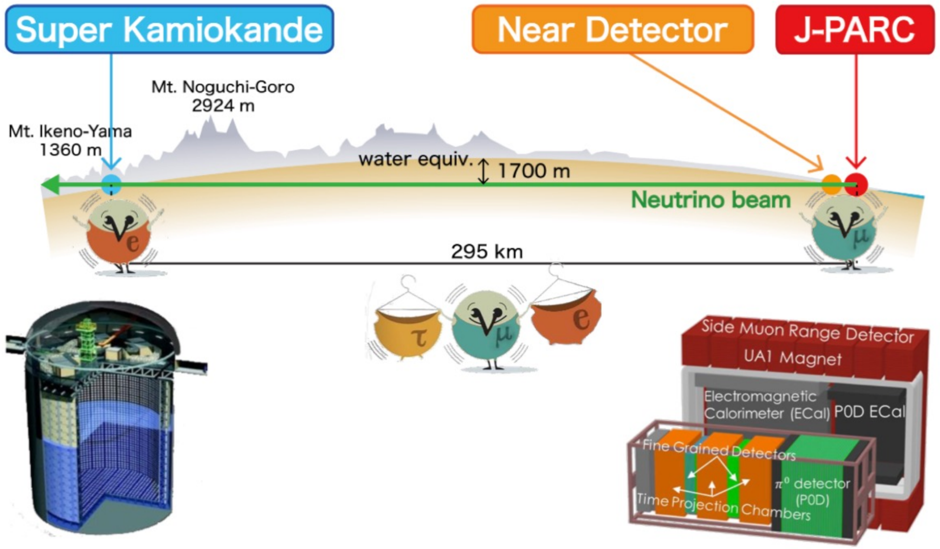
- Tension between solar & reactor result still there, 1.5σ.
- JUNO can simultaneously measure Δm^2_{21} and θ_{12} using reactor antineutrinos and solar neutrinos with a great precision.
- HyperK will improve the solar neutrino result

Accelerator Based Neutrino Experiments

Neutrinos from accelerators

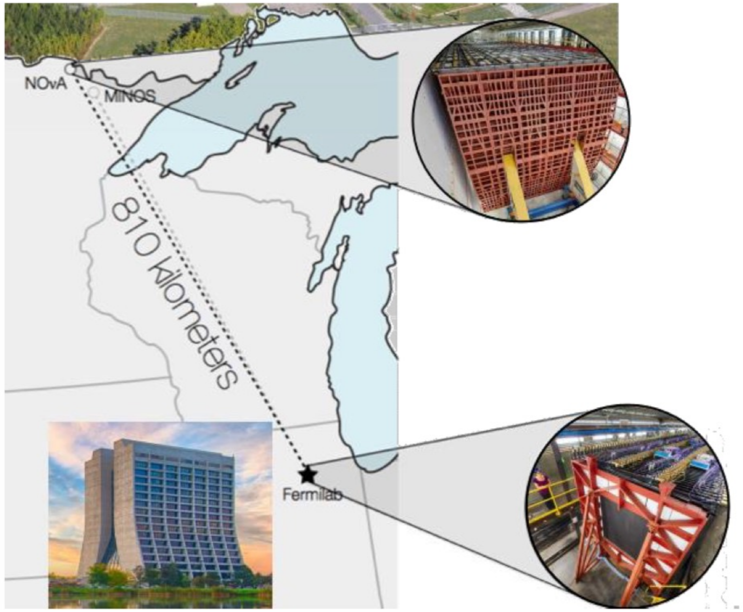


T2K



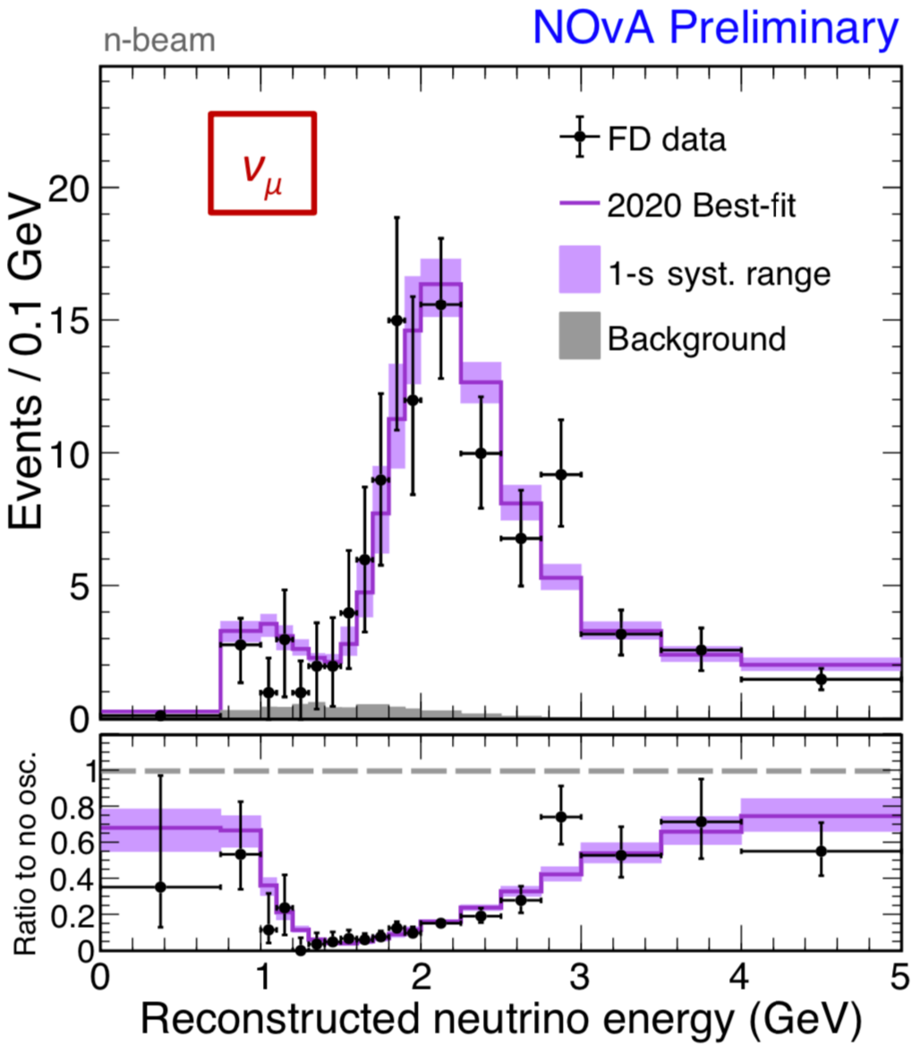
Baseline: 295 km
Peak E_ν: ~0.6 GeV (off-axis)
Near detector: ND280 (~2 T C/O targets, TPC tracking, magnetised)
Far detector: Super-K, 50 kT, Water-Cherenkov

NOvA

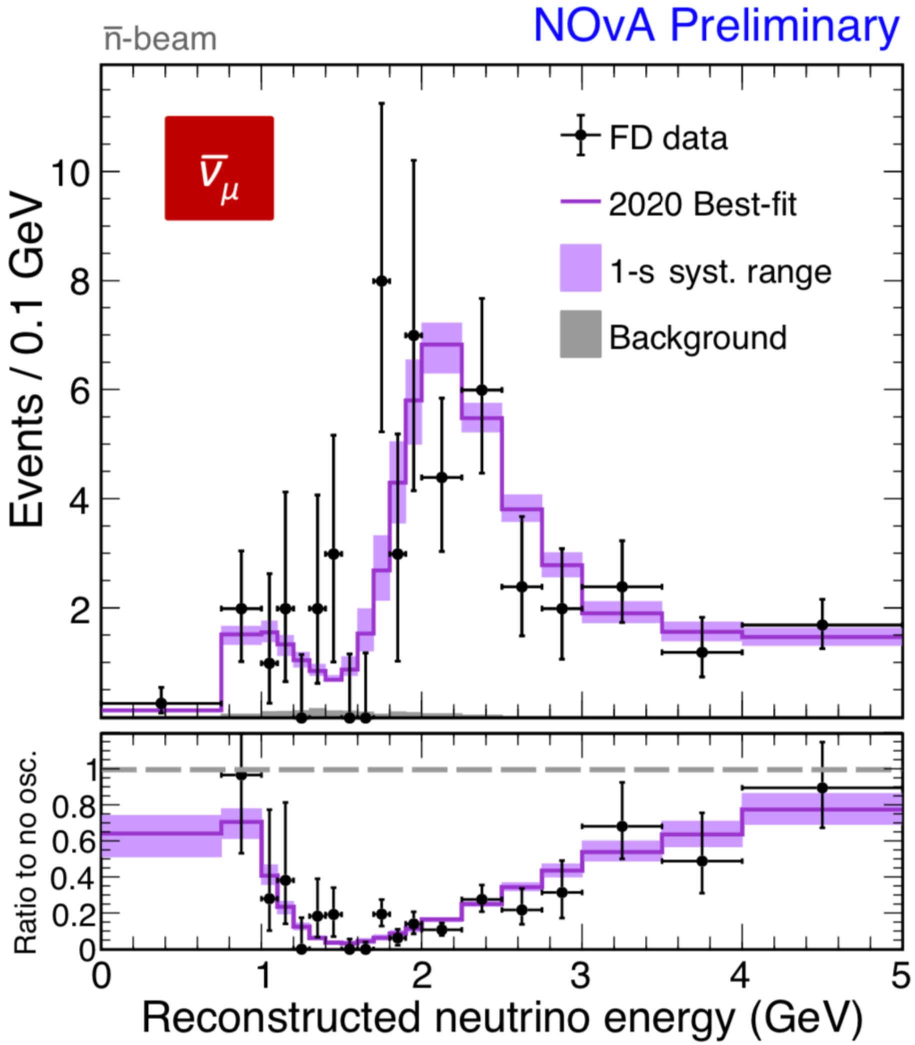


- Baseline: 810 km
- Peak E_ν: ~2 GeV (off-axis)
- Near detector: Scintillator tracker (300 T)
- Far detector: Scintillator tracker (14 kT)

Muon Neutrino Disappearance



211 events, 8.2 background



105 events, 2.1 background

Open Questions: CP Violation?

Do neutrinos and anti-neutrinos oscillate differently ?

Charge-Parity (CP) violation

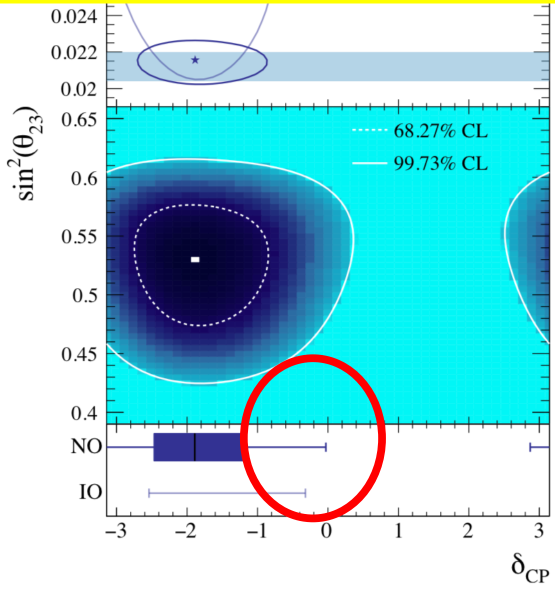
New source of *CP* violation required to explain baryon asymmetry of universe

part-per-billion level of matter/antimatter asymmetry in early universe

Neutrino *CP*v **allowed in νSM**, but not yet observed

…due so far to the experimental challenge, not physics!

2020 news: T2K exp.
sin**δ**= 0 excluded at 3**σ** !!
-> Appeared in Nature



Leptogenesis[1] **is a workable solution** for the baryon asymmetry, but need to first **find *any* leptonic (neutr**

☆ $\sin\delta \neq 0$?

Leptonic CP violation?

Neutrinos could be the key to one of the most important questions today:
Where is the anti-matter in our Universe?

---

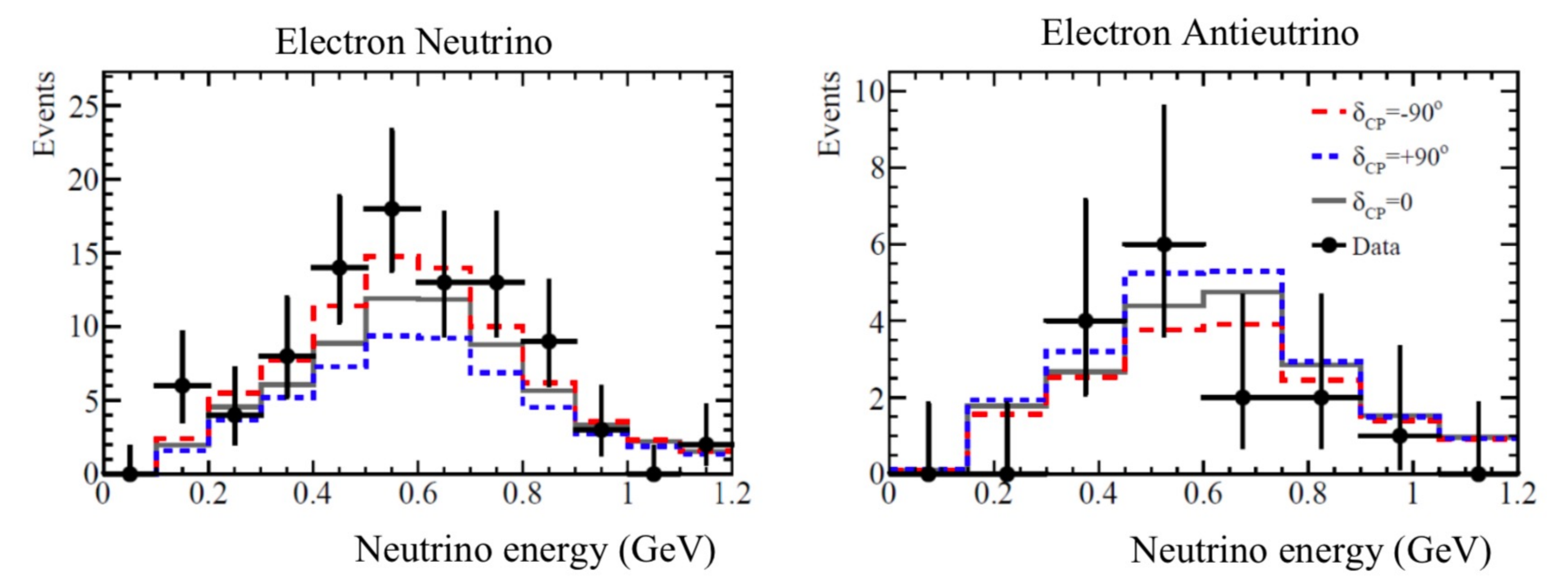
[1] M. Fukugita and T. Yanagida (1986); rich history since then.

CP Violation: T2K Measurement

Do neutrinos and anti-neutrinos oscillate differently ?

Measured versus expected electron-(anti)neutrino events in SK as function of the assumed CP- angle

	Expected If δ=0	Expectation	
		$\delta_{CP} = -90°$	$\delta_{CP} = +90°$
Electron neutrino	70	82	56
Electron antineutrino	20	17	22

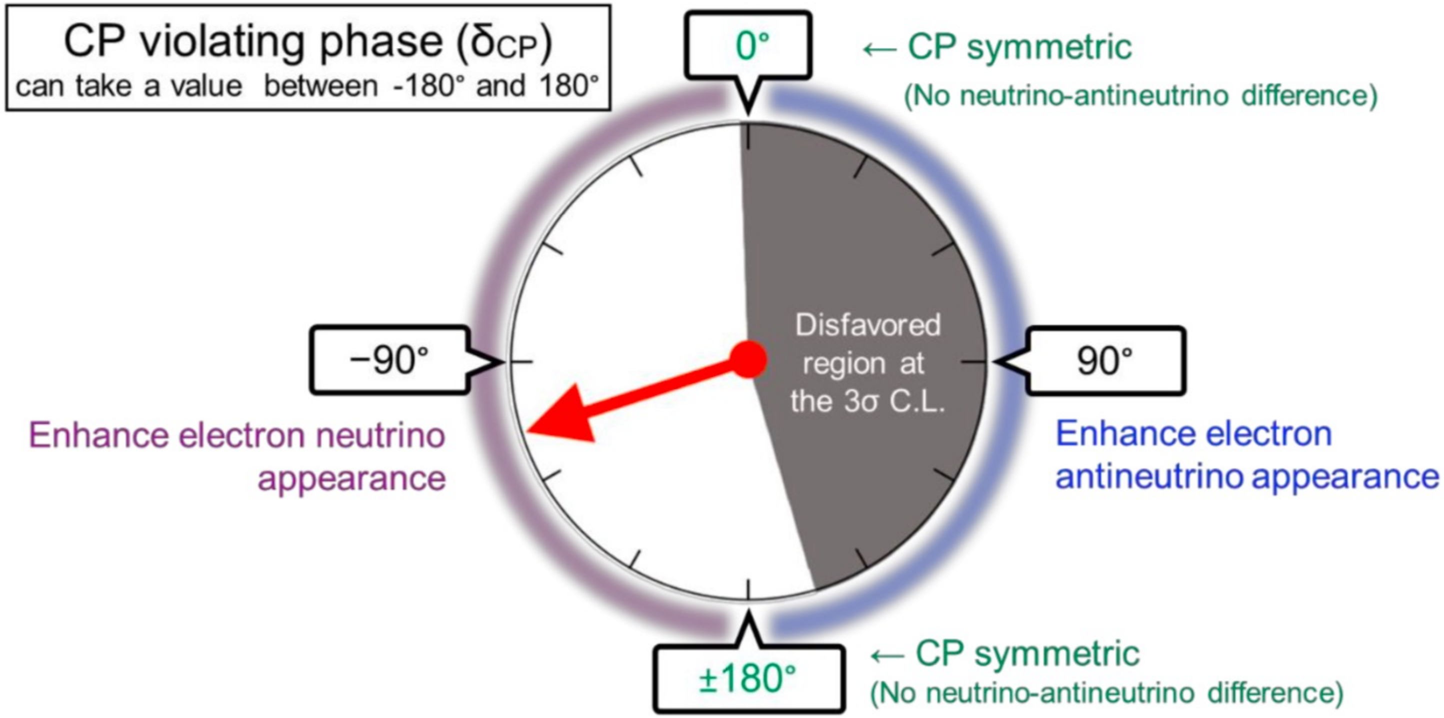

Electron Neutrino

Electron Antieutrino

CP Violation: T2K Result

Nature Magazine April 16/4/2020
and arXiv:: 1910.03887

Determination of $\boldsymbol{\delta}_{CP}$
Appearance of $\boldsymbol{\nu}_e$ events

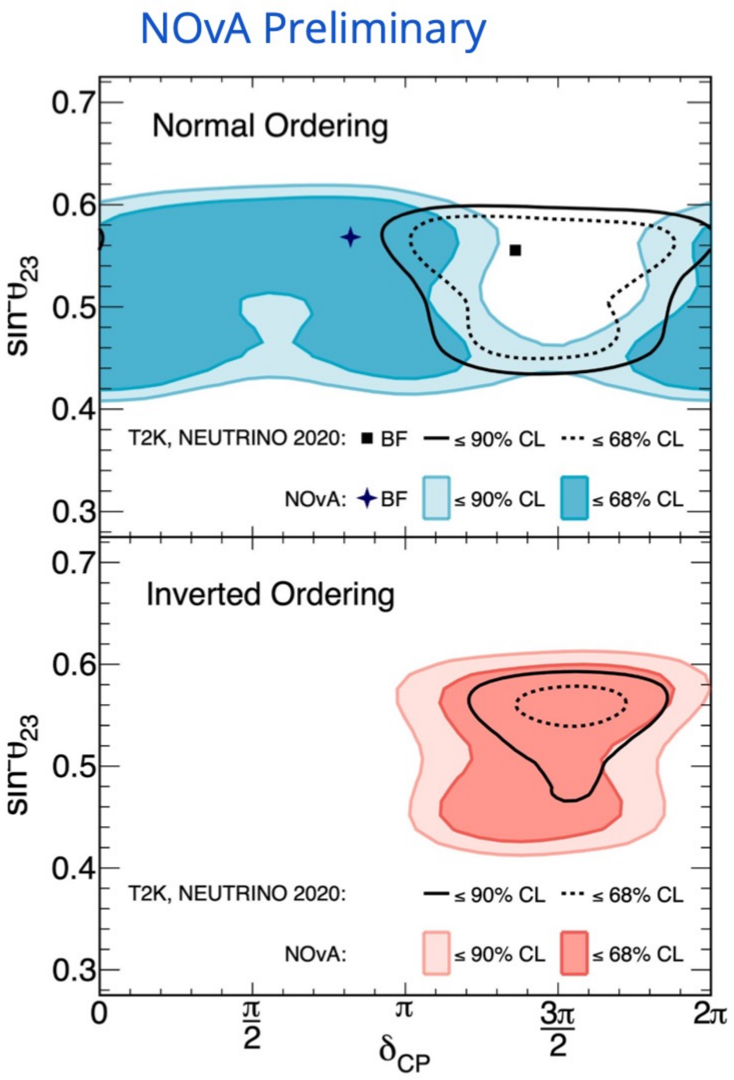


The gray region is disfavored by 99.7% (3σ) CL
The values 0 and 180 degrees are disfavoured at 95% CL

NOvA Results

Comparison with T2K

- Frequestist contours.
- Some tension between preferred regions for the Normal Ordering.
    - Agree on the preferred region in the Inverted Ordering.
- A joint fit of the data from the two experiments is needed to properly quantify consistency.
    - Significant progress made on a joint-fit → coming this year!



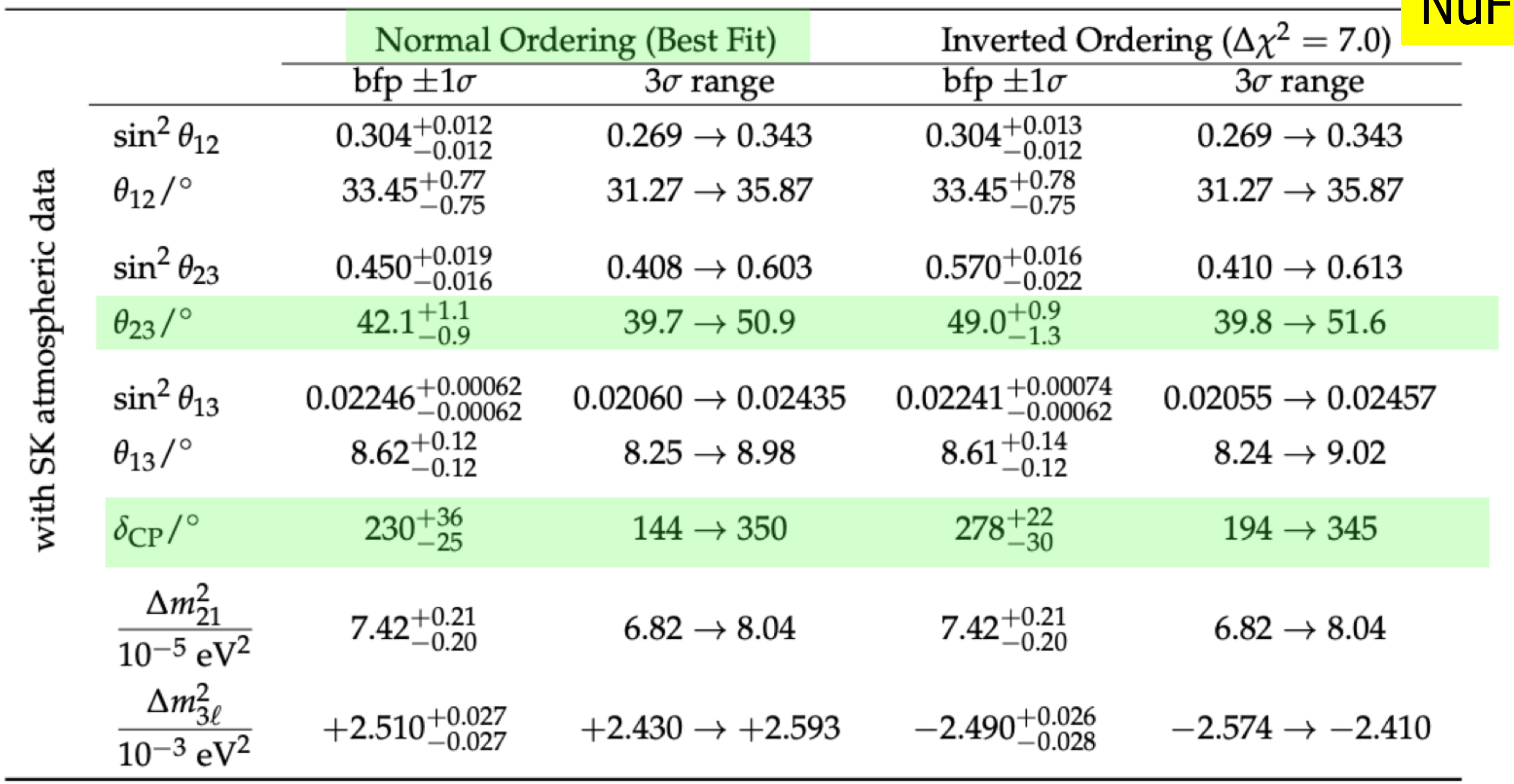
NOvA/T2K will continue to take data till 2026/2027
-> double the statistics of present analyses, reduce systematics

Recent Global Neutrino Data Fits

Recent 3-neutrino global analysis

Gonzalez-Garcia, Maltoni, Schwetz (NuFIT), 2111.03086

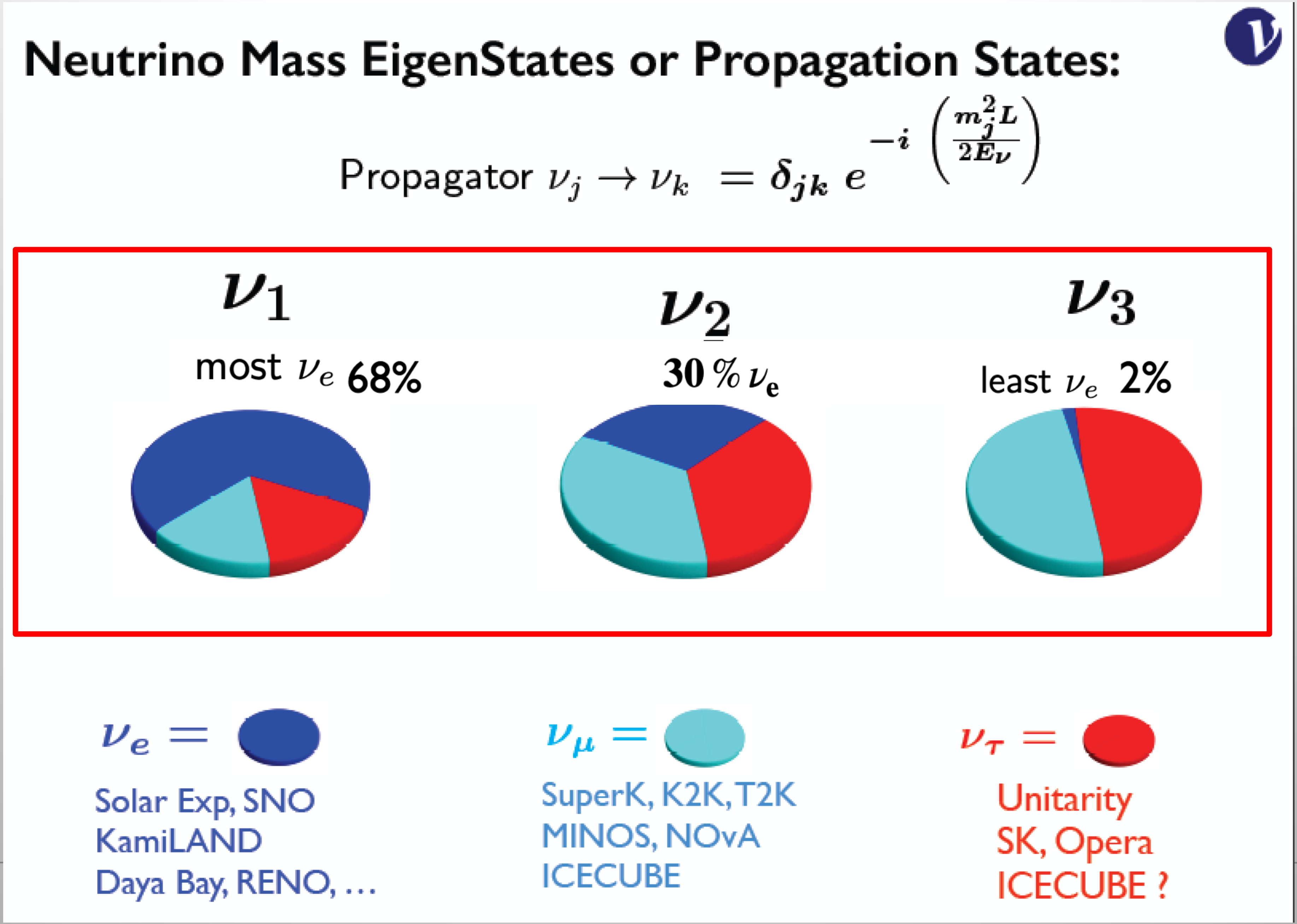
NuFIT group



		Normal Ordering (Best Fit)		Inverted Ordering ($\Delta\chi^2 = 7.0$)	
		bfp $\pm 1\sigma$	3σ range	bfp $\pm 1\sigma$	3σ range
with SK atmospheric data	$\sin^2\theta_{12}$	$0.304^{+0.012}_{-0.012}$	$0.269 \to 0.343$	$0.304^{+0.013}_{-0.012}$	$0.269 \to 0.343$
	$\theta_{12}/^\circ$	$33.45^{+0.77}_{-0.75}$	$31.27 \to 35.87$	$33.45^{+0.78}_{-0.75}$	$31.27 \to 35.87$
	$\sin^2\theta_{23}$	$0.450^{+0.019}_{-0.016}$	$0.408 \to 0.603$	$0.570^{+0.016}_{-0.022}$	$0.410 \to 0.613$
	$\theta_{23}/^\circ$	$42.1^{+1.1}_{-0.9}$	$39.7 \to 50.9$	$49.0^{+0.9}_{-1.3}$	$39.8 \to 51.6$
	$\sin^2\theta_{13}$	$0.02246^{+0.00062}_{-0.00062}$	$0.02060 \to 0.02435$	$0.02241^{+0.00074}_{-0.00062}$	$0.02055 \to 0.02457$
	$\theta_{13}/^\circ$	$8.62^{+0.12}_{-0.12}$	$8.25 \to 8.98$	$8.61^{+0.14}_{-0.12}$	$8.24 \to 9.02$
	$\delta_{CP}/^\circ$	230^{+36}_{-25}	$144 \to 350$	278^{+22}_{-30}	$194 \to 345$
	$\frac{\Delta m^2_{21}}{10^{-5}\ \mathrm{eV}^2}$	$7.42^{+0.21}_{-0.20}$	$6.82 \to 8.04$	$7.42^{+0.21}_{-0.20}$	$6.82 \to 8.04$
	$\frac{\Delta m^2_{3\ell}}{10^{-3}\ \mathrm{eV}^2}$	$+2.510^{+0.027}_{-0.027}$	$+2.430 \to +2.593$	$-2.490^{+0.026}_{-0.028}$	$-2.574 \to -2.410$

- Hints for **$\theta_{23} \neq \pi/4$**
- Mild hints for a Dirac CP phase **δ**
- Mild hint in favor of Normal Ordering

Neutrino Oscillations



Neutrino Mass EigenStates or Propagation States:

Propagator $\nu_j \to \nu_k \;=\; \delta_{jk}\, e^{-i\left(\frac{m_j^2 L}{2E_\nu}\right)}$

ν_1

most ν_e 68%

ν_2

30 % ν_e

ν_3

least ν_e 2%

$\nu_e =$ ●

Solar Exp, SNO
KamiLAND
Daya Bay, RENO, …

$\nu_\mu =$ ●

SuperK, K2K, T2K
MINOS, NOvA
ICECUBE

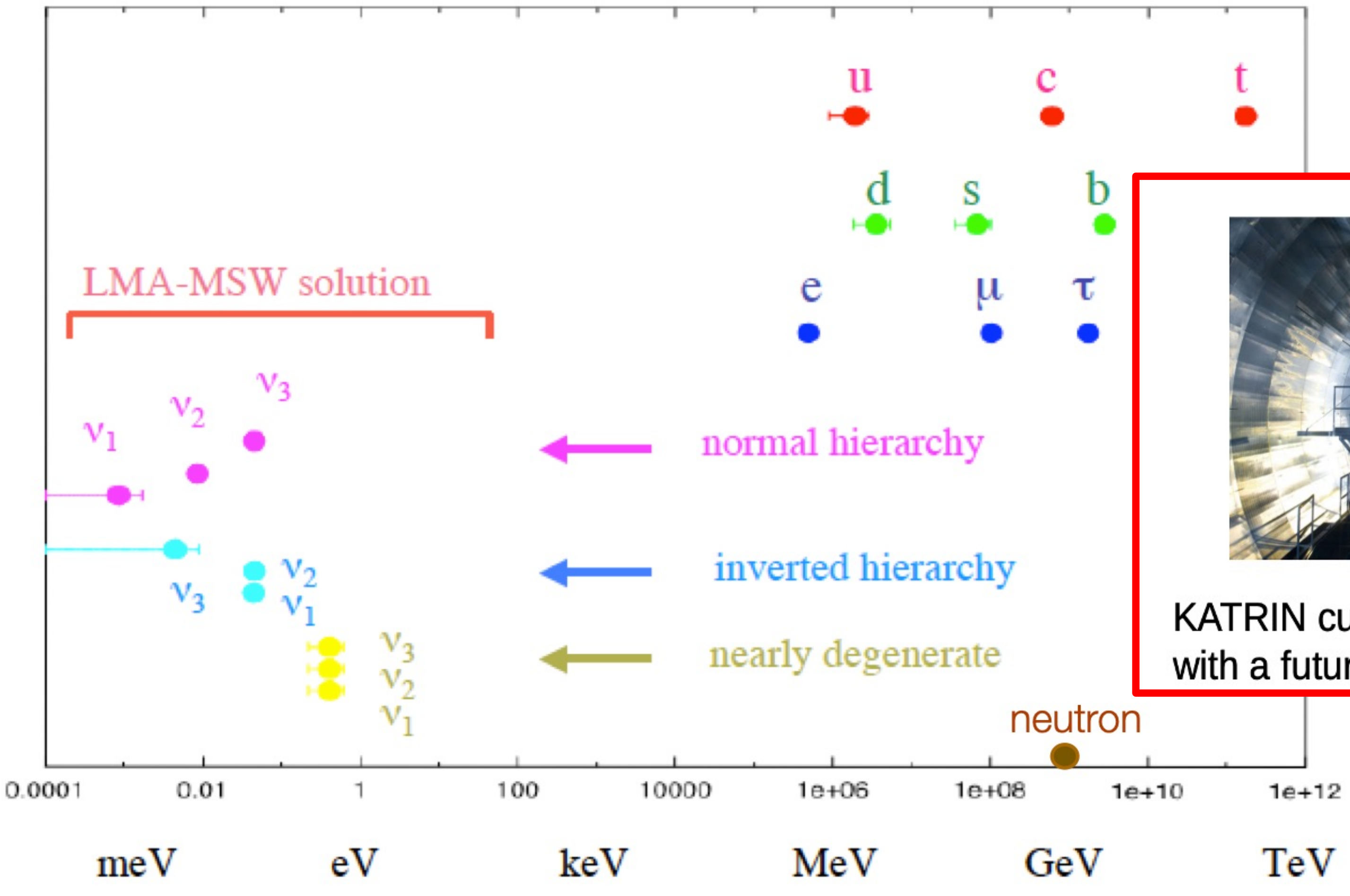
$\nu_\tau =$ ●

Unitarity
SK, Opera
ICECUBE ?

Neutrino Properties

Neutrino Mass

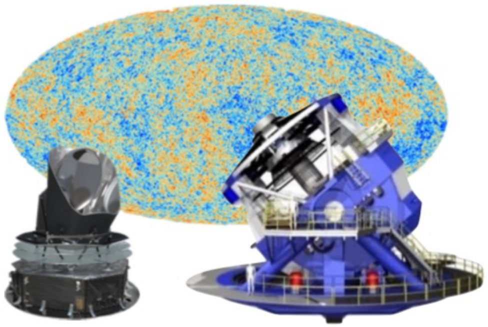
The smallness of the neutrino mass $m_\nu \ll m_{e,\,u,\,d}$

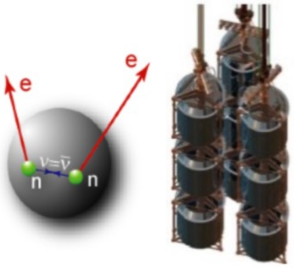


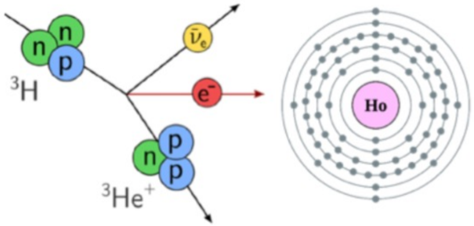
KATRIN current limit is 0.8eV
with a future sensitivity of 0.2eV

Neutrino Mass Measurents

Complementary paths to the ν mass scale



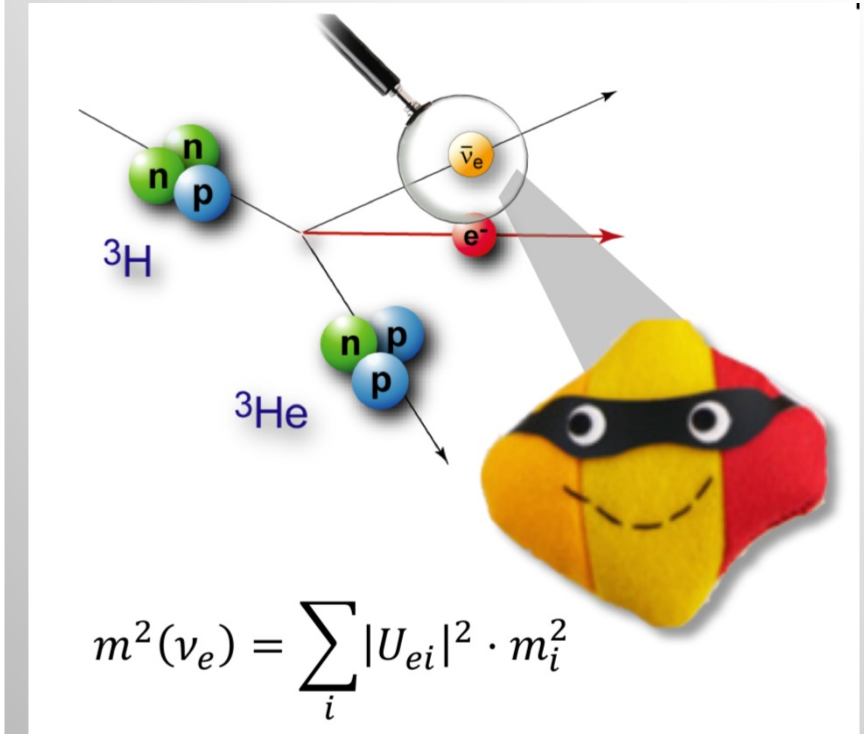




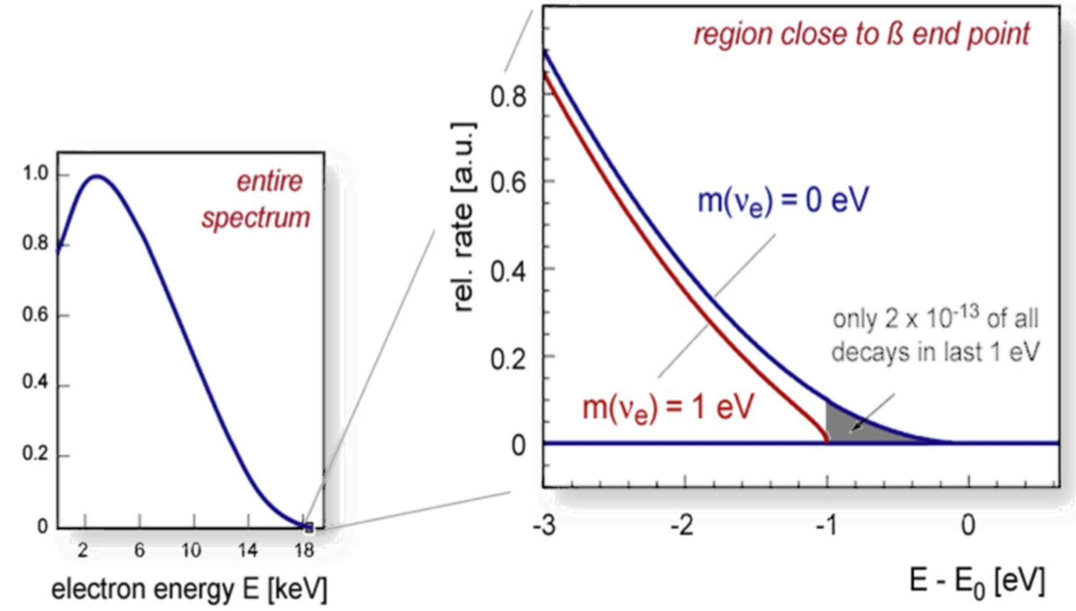
	Cosmology	Search for 0νββ	Kinematics of weak decays
Method	Structure of Universe at early and evolved stages	ββ-decay of ^{76}Ge, ^{130}Te, ^{136}Xe, …	β-decay of ^{3}H, EC of ^{163}Ho
Observable	$M_\nu = \sum_i m_i$	$m^2_{\beta\beta} = \left\lvert\sum_i U^2_{ei}\, m_i\right\rvert^2$	$m^2_\beta = \sum_i \lvert U_{ei}\rvert^2\, m^2_i$
Model assumptions	Multi-parameter cosmological model (ΛCDM)	- Majorana nature of neutrinos? - No BSM contributions other than m(ν)?	Only kinematics; "**direct**" measurement

Neutrino Mass Measurents

The KATRIN experiment: endpoint measurement of tritium decay

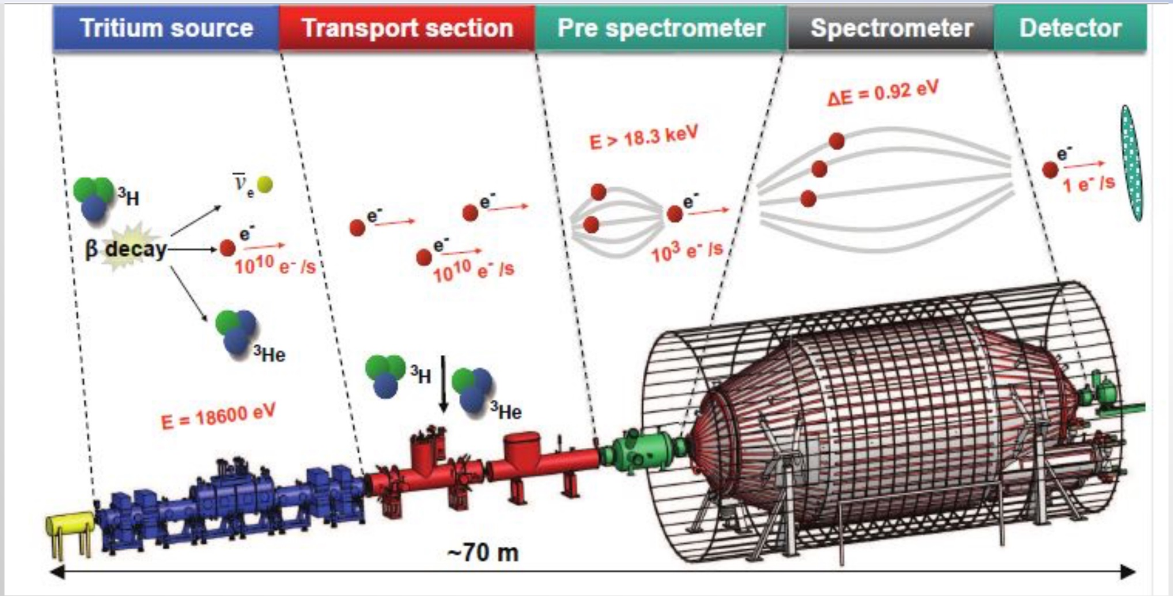


$$m^2(\nu_e) = \sum_i |U_{ei}|^2 \cdot m_i^2$$



What is measured really in this experiment is the effective electron anti-neutrino mass defined by $m^2(\nu_e) = \sum_i |U_{ei}|^2 \cdot m_i^2$ with U_{ei} the PMNS mixing elements

KATRIN Experiment: the Mass of ν_e



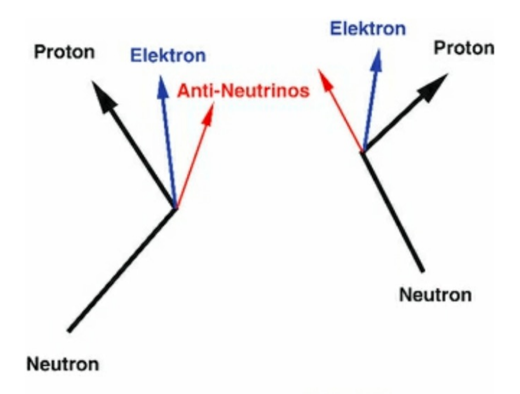
The KArlsruhe TRItium Neutrino experiment (KATRIN) is designed to measure the mass up to projected sensitivity of 0.2eV

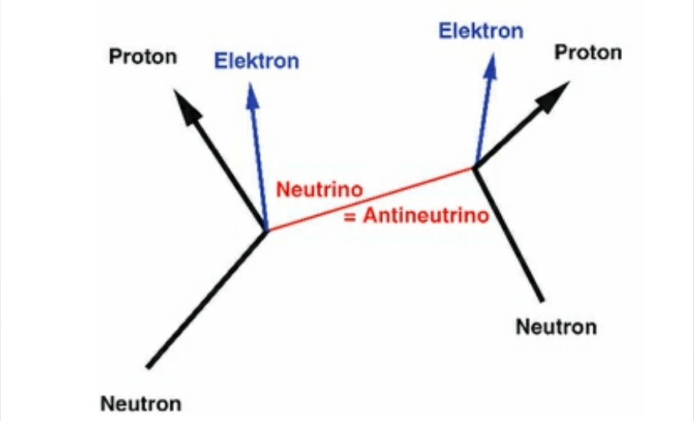
To achieve this, KATRIN will perform high-precision spectroscopy of the endpoint region of the tritium beta-decay spectrum.

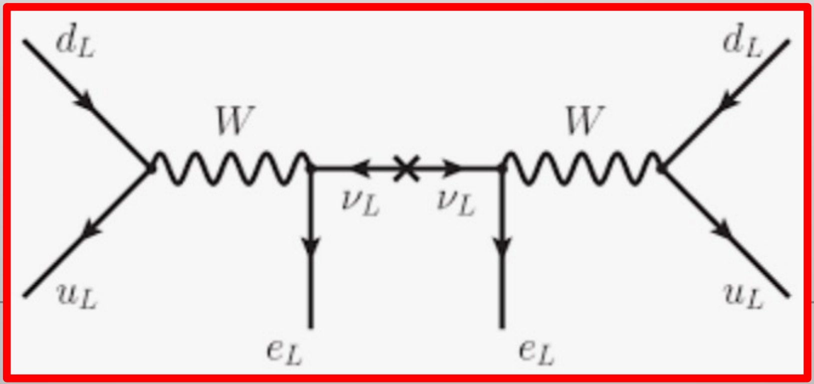
Recent result $M\nu_e < 0.8$ eV (May 2021)

Neutrinoless Double Beta Decay

- Are neutrinos their own antiparticle? We do not know this yet!
- The highly anticipated experimental test is the observation of neutrino-less double beta decay, ie two simultaneous beta-decays within one nucleons, without neutrino emission
- This would be the first evidence of lepton number violation!



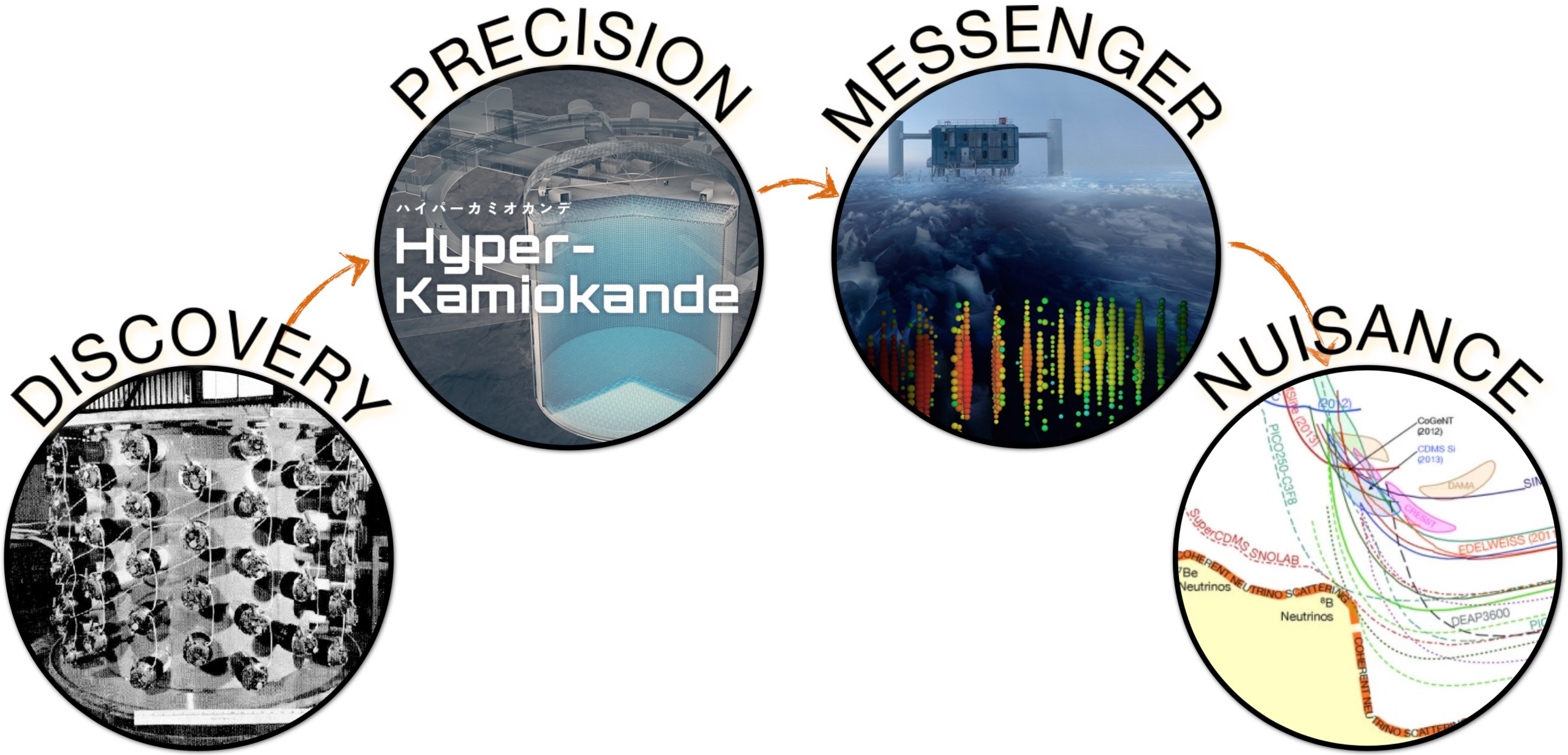




So far no signal yet… ☹

Near Future Neutrino Experiments

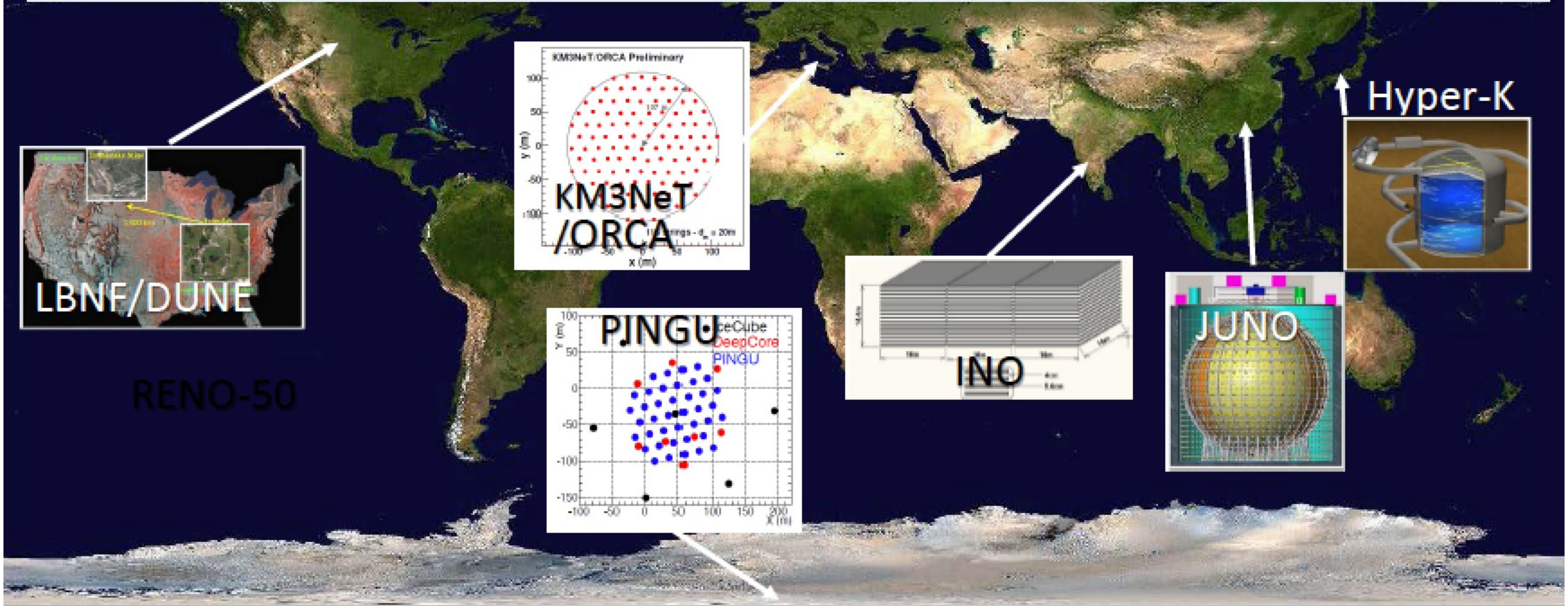
Ongoing Neutrino History



Future Neutrino Experiments

Eg. experiments that will contribute to the mass ordering question

We would like to be convinced the neutrino mass ordering by consistent results from several different technologies/methods with > 3 σ CL from each exp.

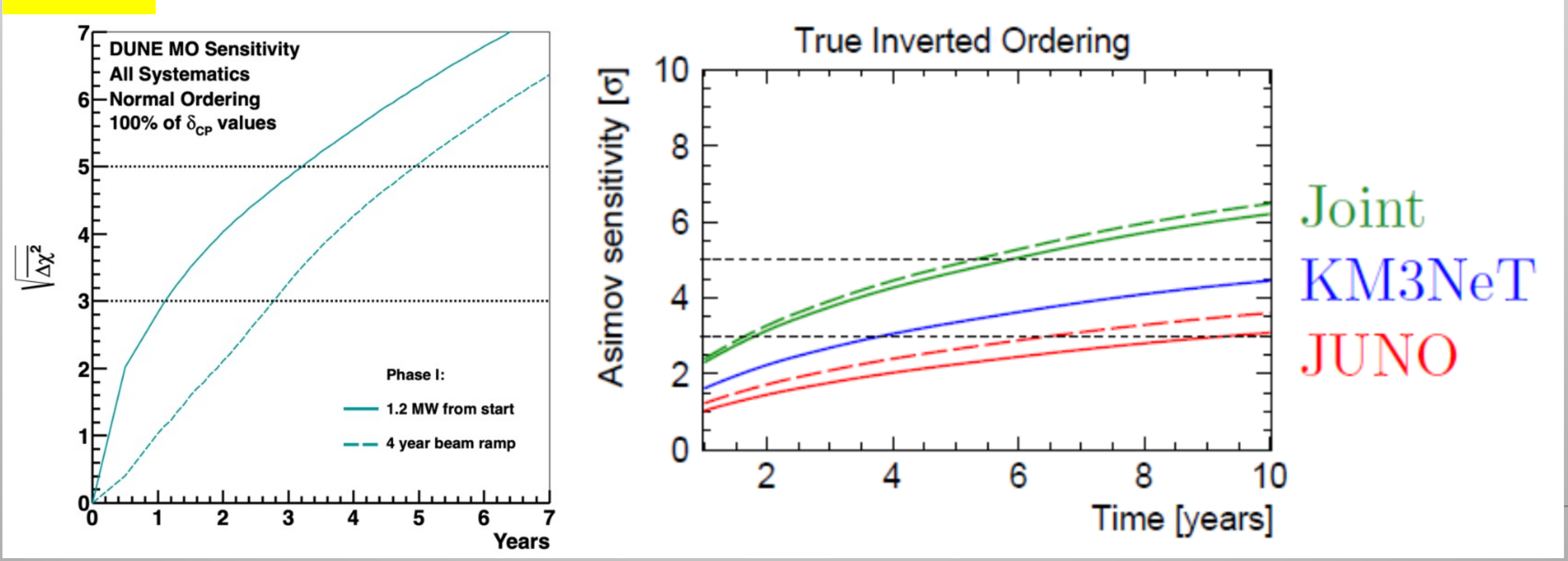


JUNO in 2024 T2HK/DUNE start in 2027-2030

Mass Hierarchy/Ordering

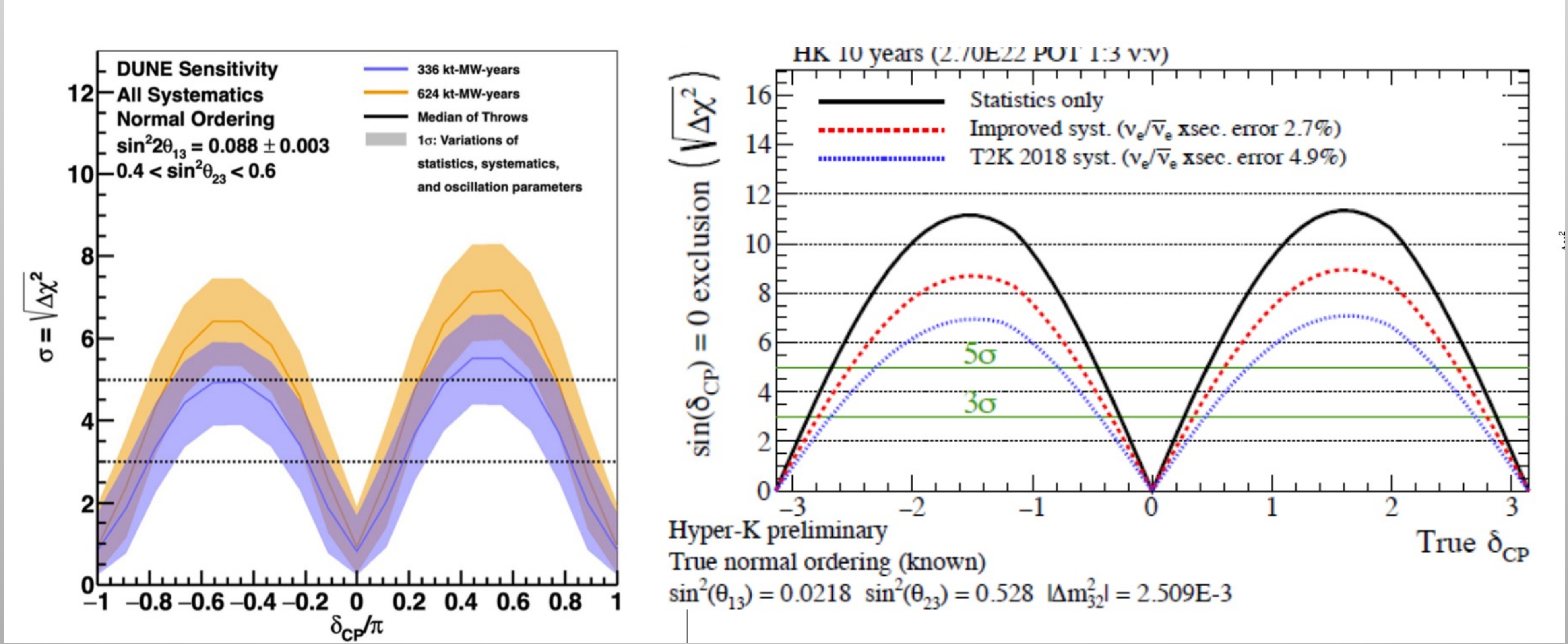
- No concrete evidence of MO from individual experiment (T2K, Nova and SuperK)
- Global fit seems slightly prefer NO(<3σ)
- Definite answer will come from DUNE, JUNO, HyperK, ORCA and Icecube.

DUNE



CP Phase

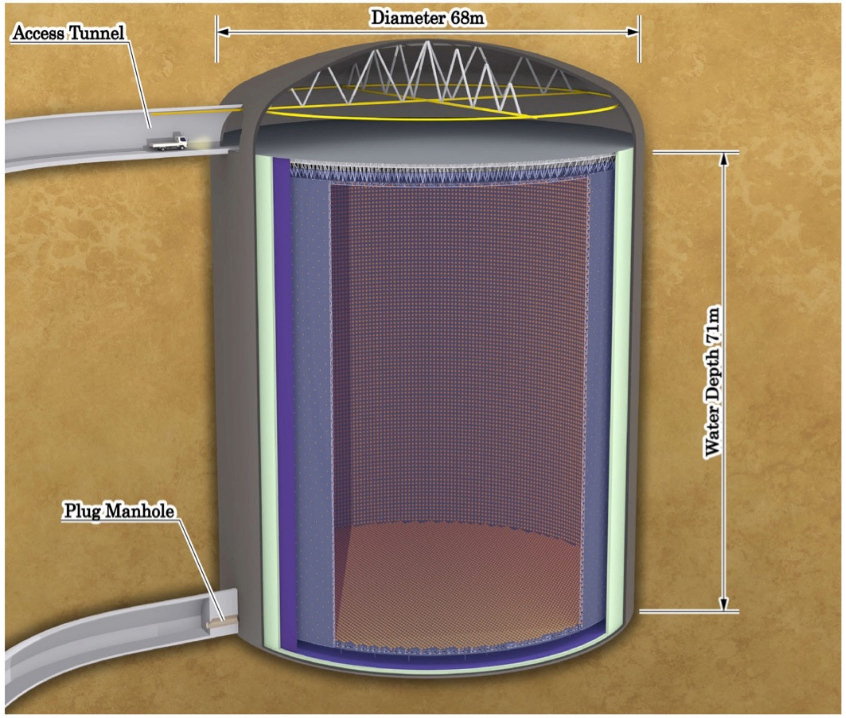
- ~270° (-90°) seems slightly favored
- Combined analysis may give more preference, but not stable yet
- DUNE & HyperK can give a more definite answer
- Further improvement may come from KNO, ESSnuSB, and THEIA

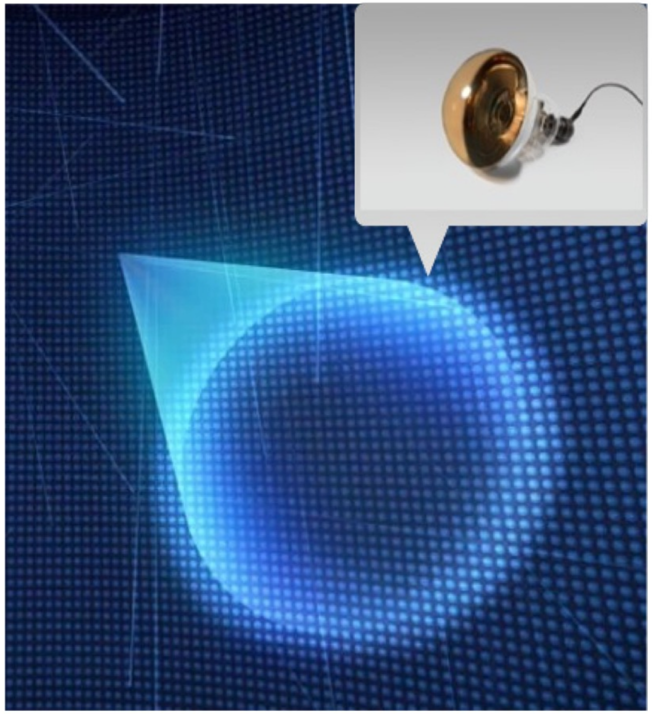


The T2HK Experiment

Hyper-Kamiokande Detector

- The Hyper-Kamiokande detector is the next generation water Cherenkov detector in Kamioka, Japan, with an accelerator and near detector complex at J-PARC in Tokai
- Size: 258 kton, with fiducial mass ~8 times larger than Super-K,
- Baseline: 20,000 50-cm photomultiplier tubes (PMT), ~2,000 multi-PMT modules and 7,200 outer detector 8-cm PMTs with wavelength shifting (WLS) panels

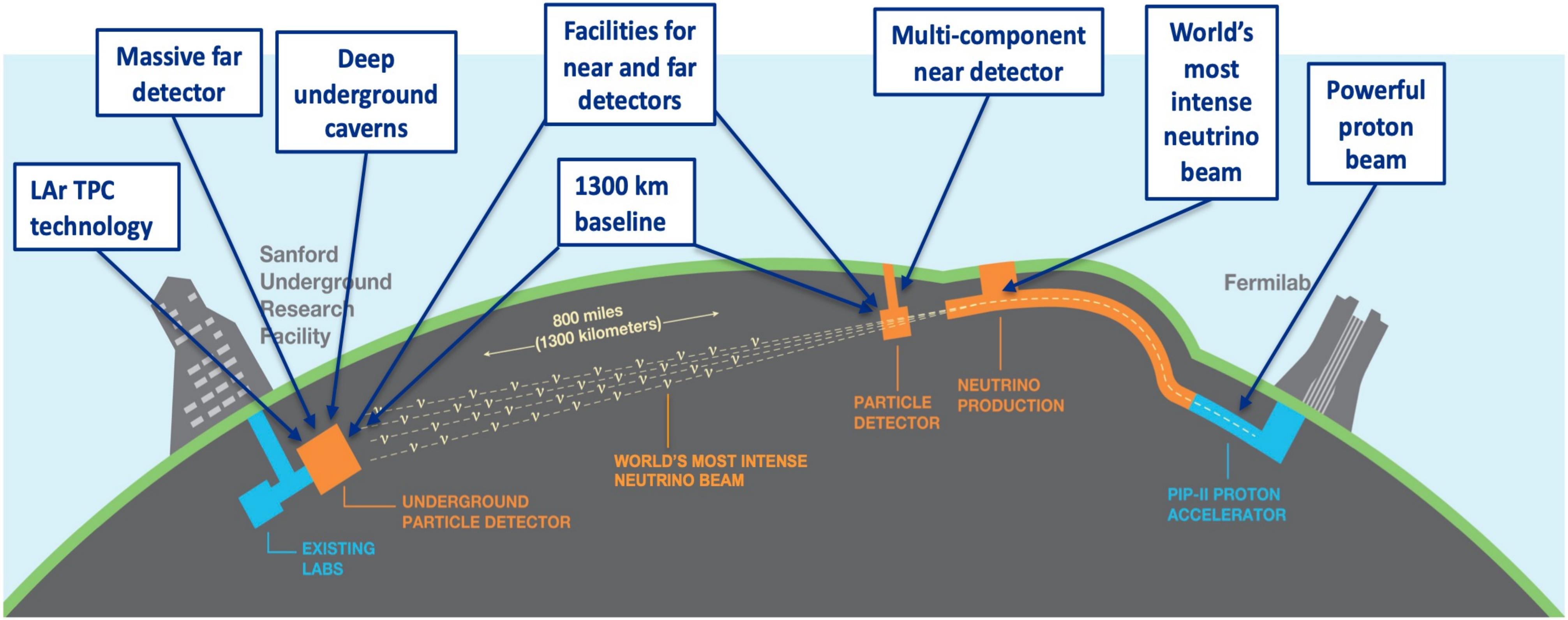




LNBF/DUNE

LBNF/DUNE

- Unambiguous, high precision measurements of Δm^2_{32}, δ_{CP}, $\sin^2\theta_{23}$, $\sin^2 2\theta_{13}$ in a single experiment
- Discovery sensitivity to CP violation, mass ordering, θ_{23} octant over a wide range of parameter values
- Sensitivity to MeV-scale neutrinos, such as from a galactic supernova burst
- Low backgrounds for sensitivity to BSM physics including baryon number violation



Massive far detector

Deep underground caverns

Facilities for near and far detectors

Multi-component near detector

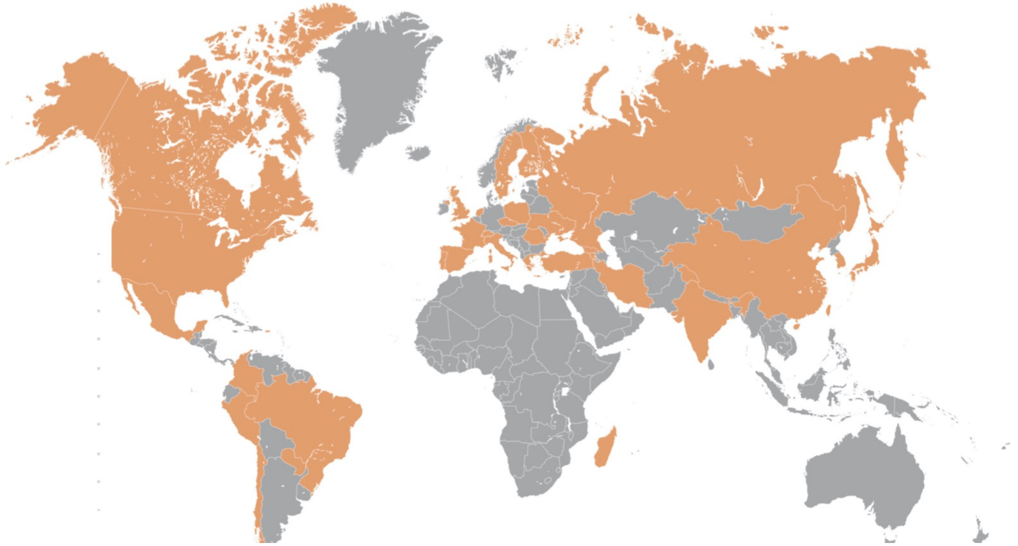
World's most intense neutrino beam

Powerful proton beam

LAr TPC technology

1300 km baseline

DUNE – a global collaboration



- 1400+ collaborators from
- 200+ institutions in
- 31 countries + CERN

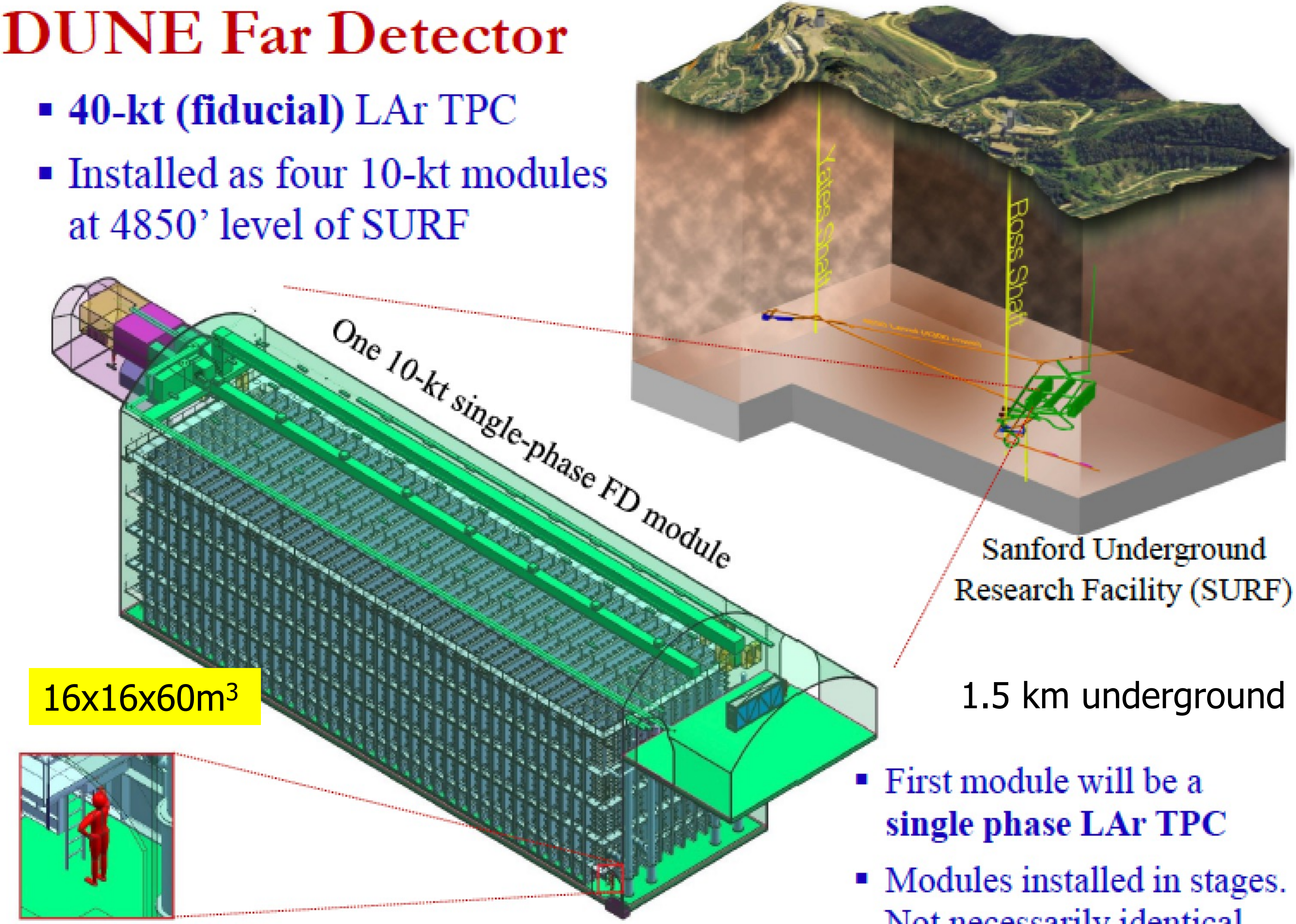
Still more groups joining

DUNE Jan 2023 Collaboration meeting at CERN

Total participants : 581 In person: 354 (largest on record) Zoom:227

DUNE Far Detector

- **40-kt (fiducial)** LAr TPC
- Installed as four 10-kt modules at 4850' level of SURF



One 10-kt single-phase FD module

Sanford Underground Research Facility (SURF)

16x16x60m^3

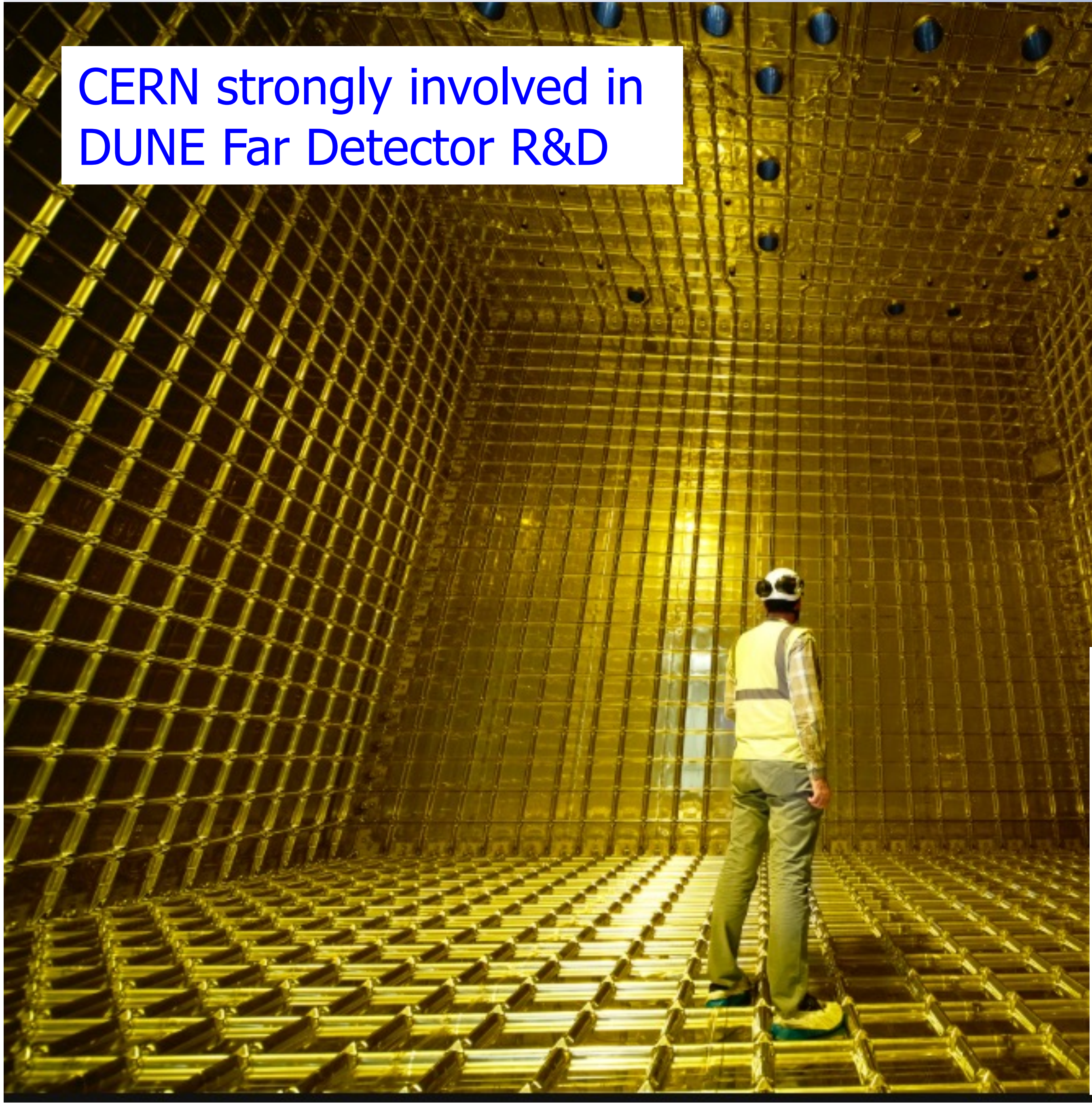
1.5 km underground

- First module will be a **single phase LAr TPC**
- Modules installed in stages. Not necessarily identical

Liquid Argon Time Projection Chamber

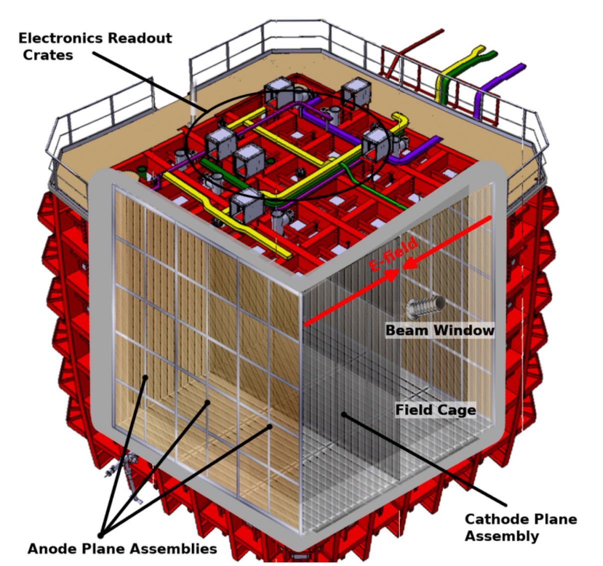
The ‘electronic’ bubble chamber for neutrino experiments

The CERN Neutrino Platform

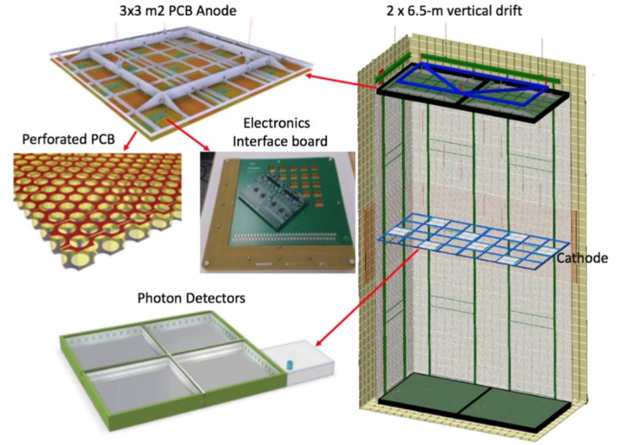


CERN strongly involved in DUNE Far Detector R&D

FD1 Horizontal Drift



FD2 vertical Drift (NEW)



CRPs

The EHN1 Hall at CERN

Next step : ~800 ton LAr prototypes

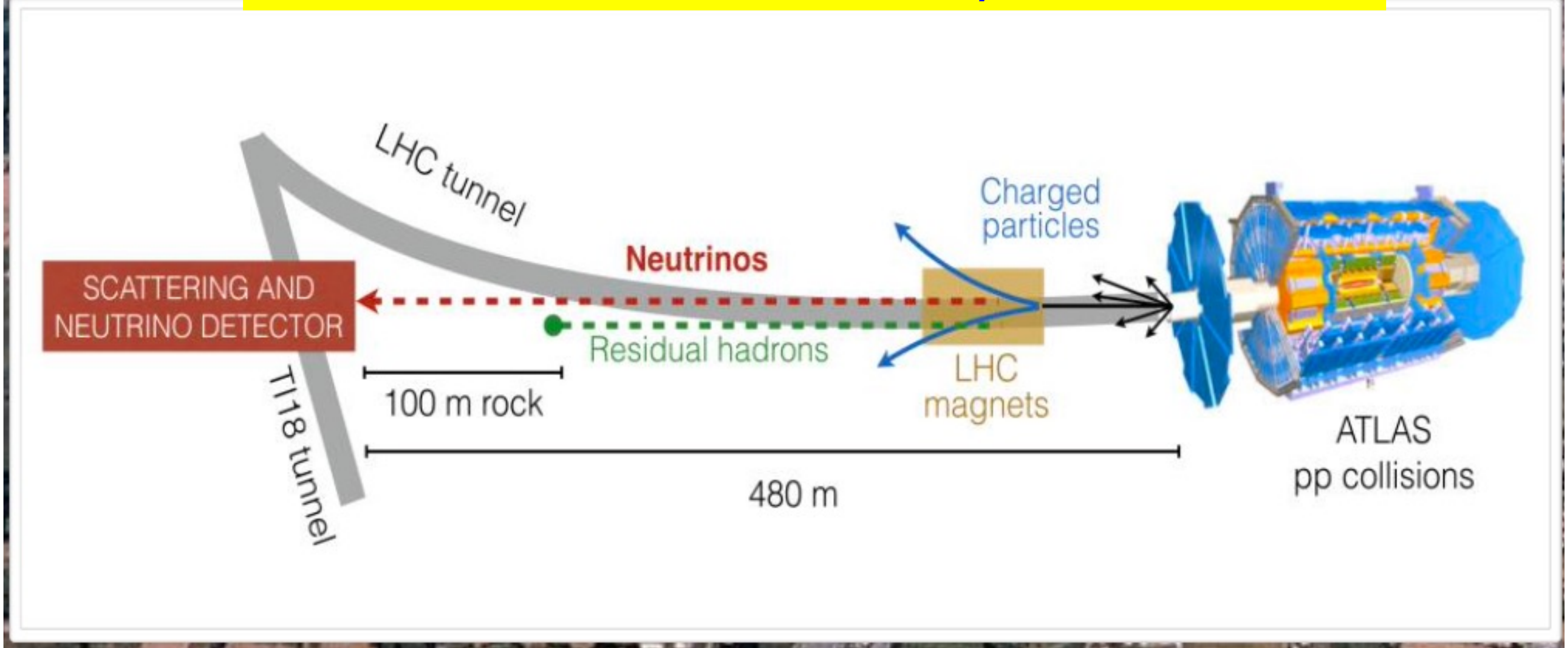
SPS : new EHN1-1 experimental area

The Neutrino Platform hall

Neutrinos at the LHC!

Measuring Neutrino Interactions @ LHC

SND@LHC and FASERν are 480m forward of the Interaction Points and can study TeV-neutrinos



FASER was approved in 2019. FASERν (extension with emulsion) in 2020.
SND@LHC was proposed in 2020 and approved in 2021.
Both experiments take now data with the start of the Run-3 at the LHC

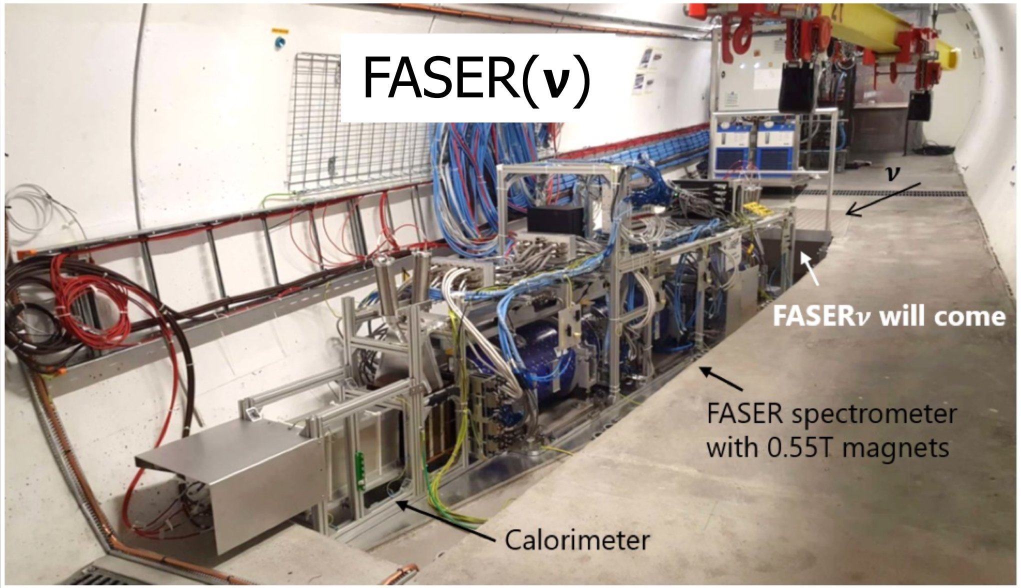
Neutrinos @ the LHC: SND@LHC & FASERν

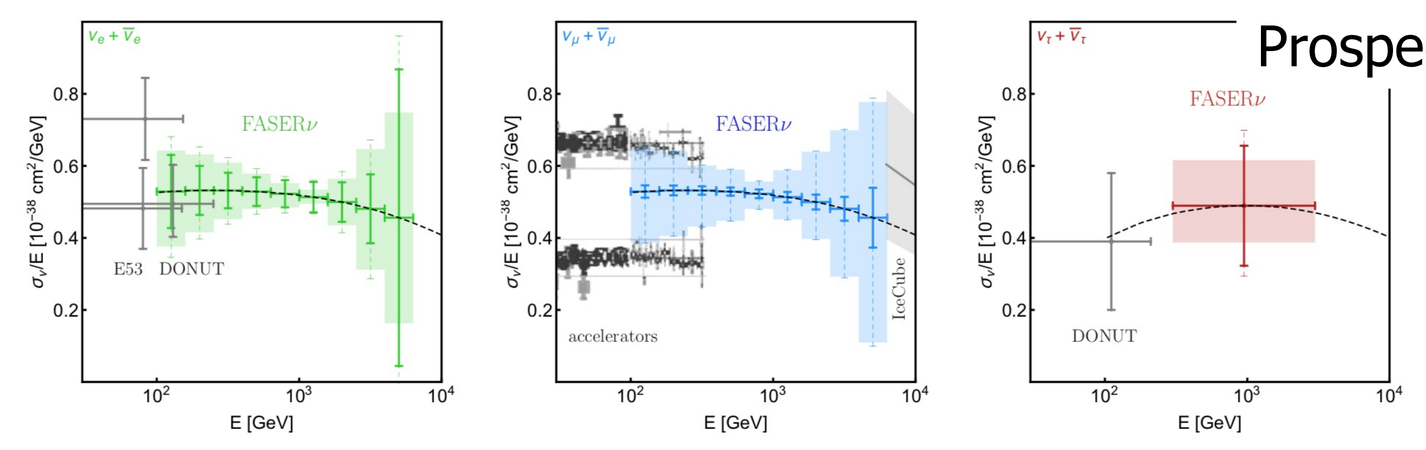
SND@LHC: approved March ‘21

SND= Scattering and Neutrino Detector

SND@LHC/FASERν are 480m forward and can study TeV-neutrinos with emulsion and tracking+muon/calo detectors

Thailand is involved!





Prospects for 2026

Physics with LHC neutrinos

Neutrino interactions

- Measure **ν interactions** in unexplored ~TeV energy range.
- Large yield of ν_τ will more than double existing data.
  - About 20 events observed by DONuT and OPERA.
- First observation of $\overline{\nu}_\tau$.

QCD

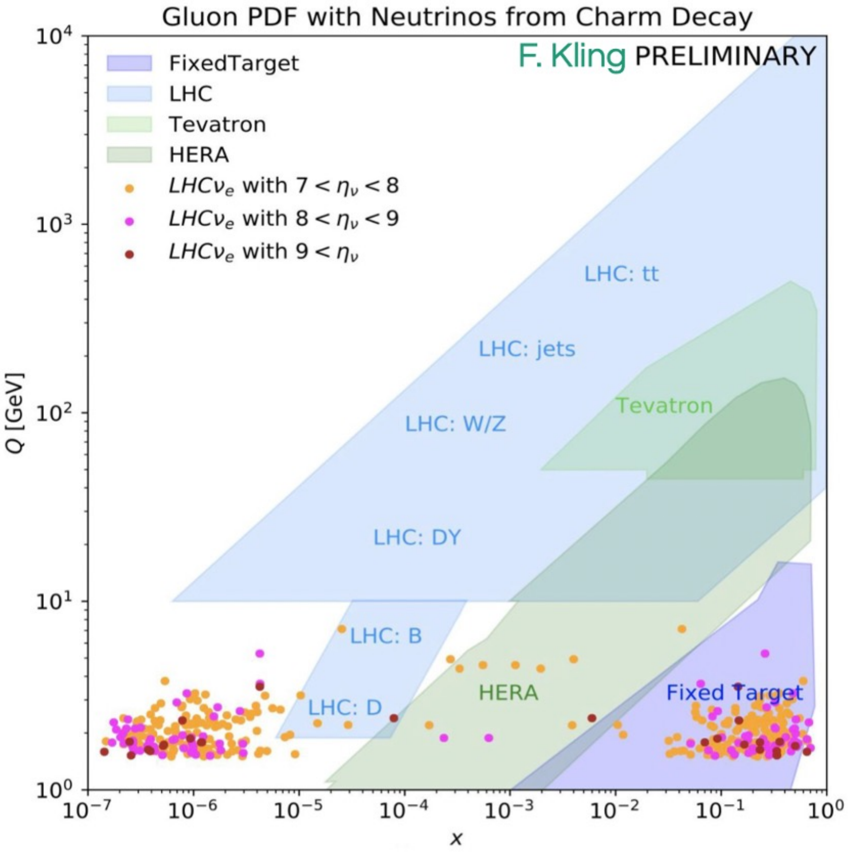
- Decays of **charm** hadrons contribute significantly to the neutrino flux.
  ⇒ Measure **forward charm production** with neutrinos.
  ⇒ Constrain **gluon PDF** at very **small x.**

Flavour

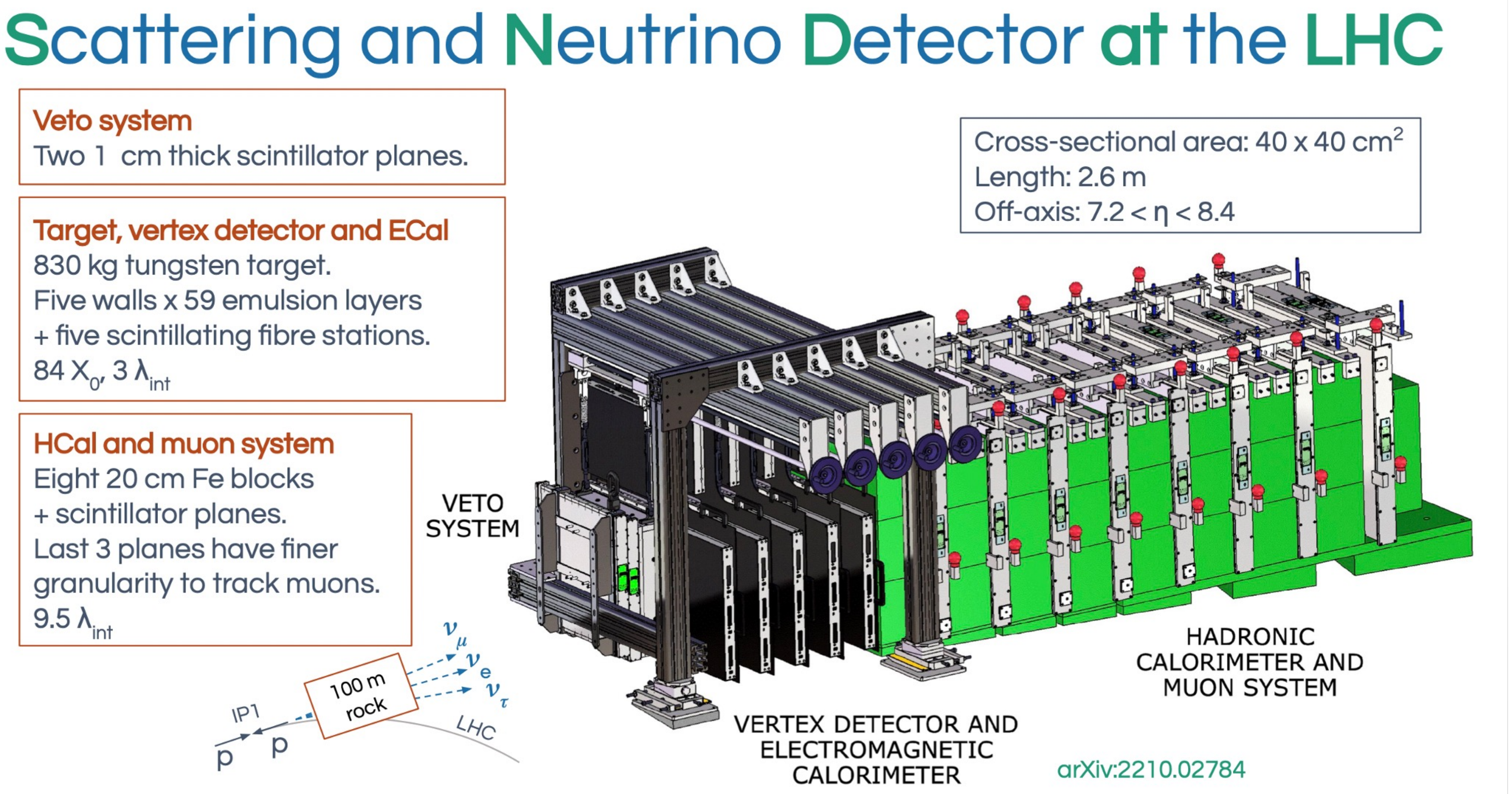
- Detection of all **three types of neutrinos** allows for tests of **lepton flavour universality**.

Beyond the Standard Model

- Search for **new**, feebly interacting, **particles decaying** within the detector or **scattering** off the target.



SND@LHC



Scattering and Neutrino Detector at the LHC

Veto system
Two 1 cm thick scintillator planes.

Target, vertex detector and ECal
830 kg tungsten target.
Five walls x 59 emulsion layers
+ five scintillating fibre stations.
$84\ X_0$, $3\ \lambda_{int}$

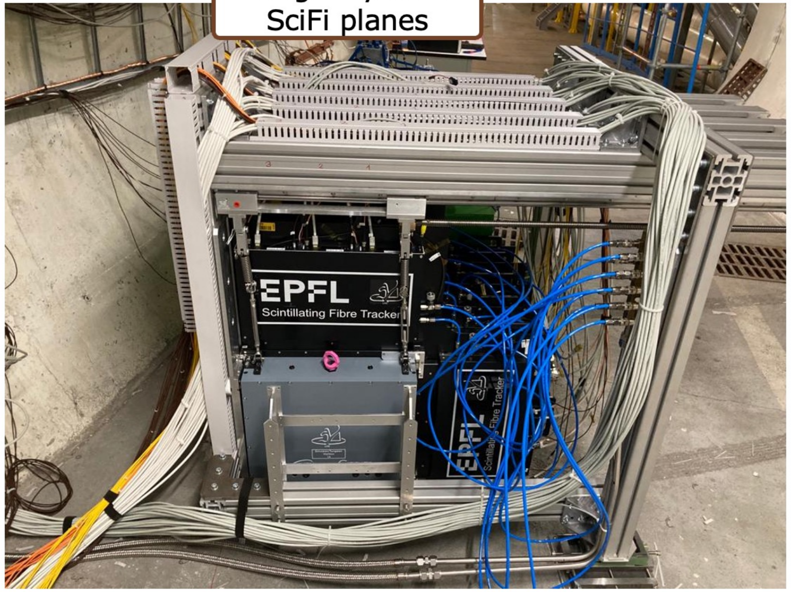
HCal and muon system
Eight 20 cm Fe blocks
+ scintillator planes.
Last 3 planes have finer granularity to track muons.
$9.5\ \lambda_{int}$

Cross-sectional area: 40 x 40 cm^2
Length: 2.6 m
Off-axis: $7.2 < \eta < 8.4$

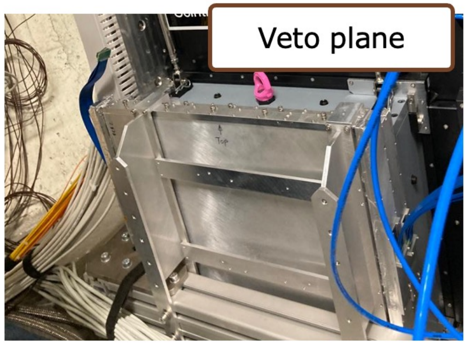
arXiv:2210.02784

DETECTOR INSTALLATION IN TI18


Target wall


Target system
SciFi planes

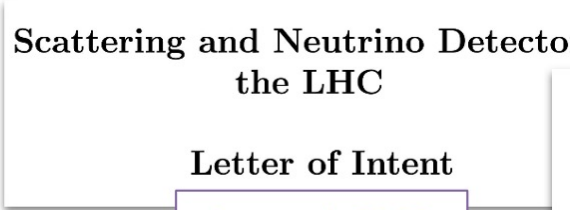

Muon system


Veto plane

- Installation in TI18 started on November 1st 2021
- Electronic detector installation completed on December 3rd 2021
- Installation of the neutron shield completed on March 15th 2022

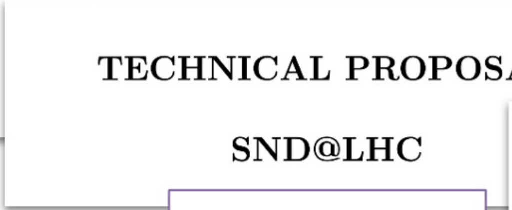
Experiment timeline

LHC
Scattering and Neutrino Detector
at the LHC


Scattering and Neutrino Detector at the LHC

Letter of Intent

August 2020


TECHNICAL PROPOSAL

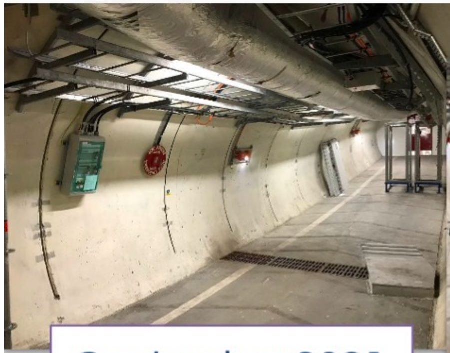
SND@LHC

January 2021

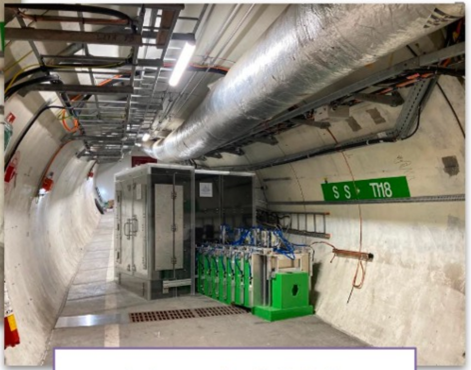

CERN approves new LHC experiment

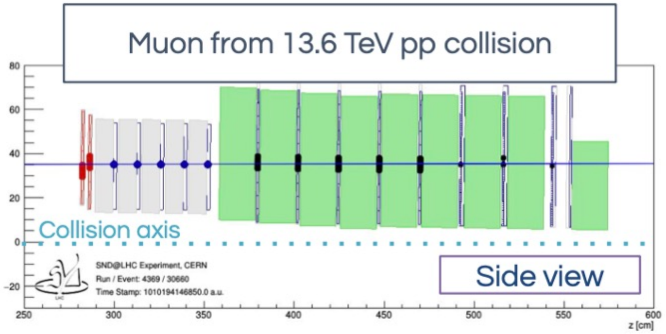
SND@LHC, or Scattering and Neutrino Detector at the LHC, will be the facility's ninth experiment

March 2021


September 2021

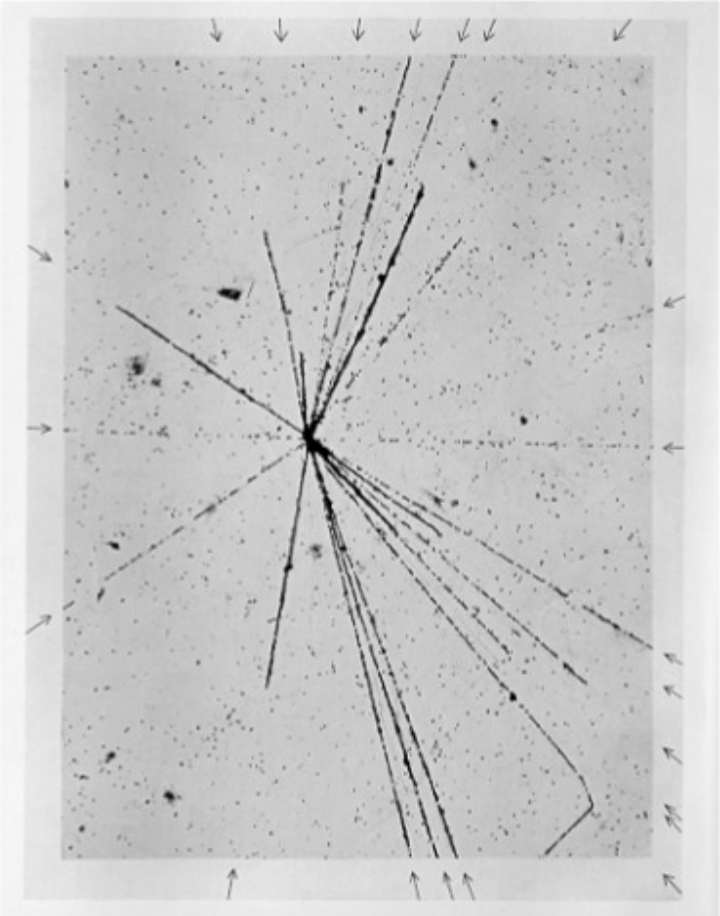

December 2021


March 2022

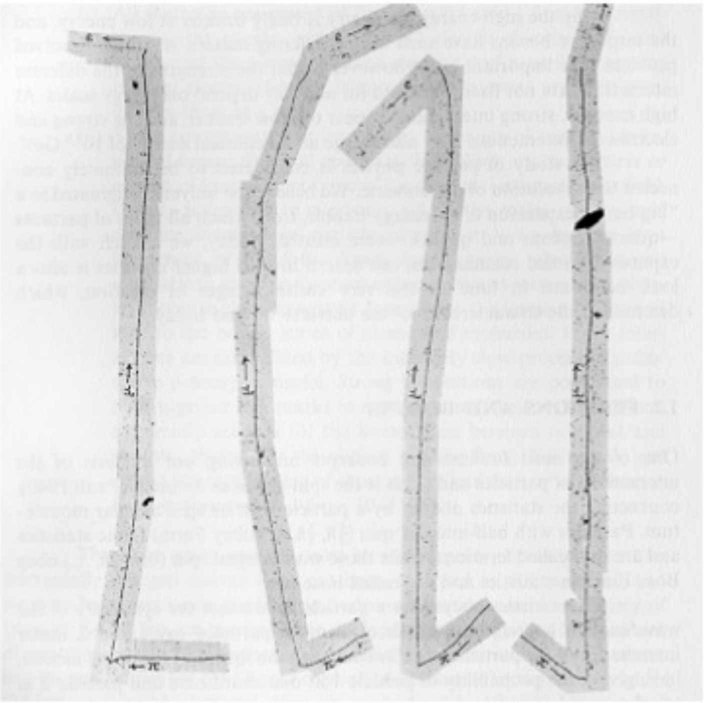


July 2022

Emulsion Detectors for Precision Tracking



'EXPLOSIVE' DISINTEGRATION OF A NUCLEUS



Discovery of muon and pion

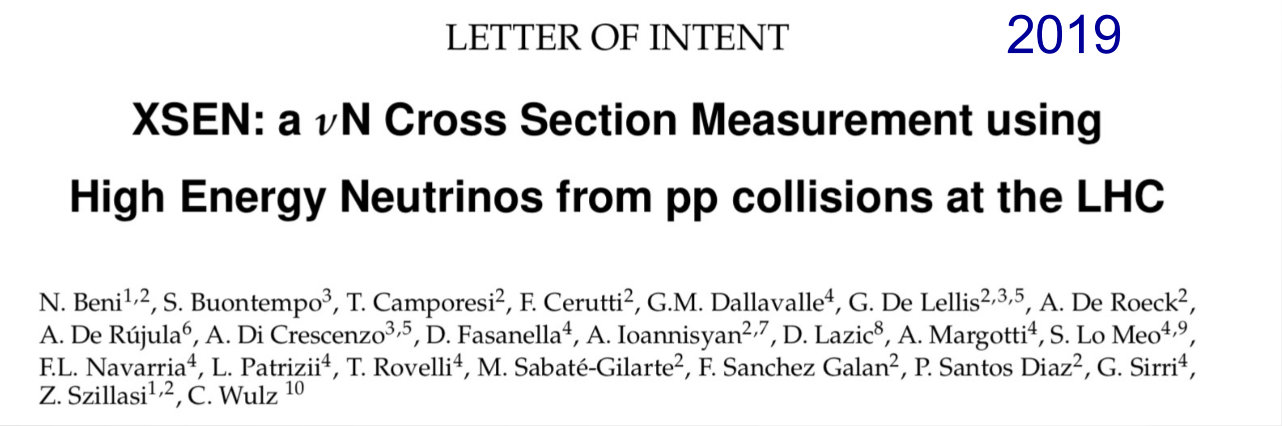
Emulsion detectors are still used today: Opera experiment at Gran Sasso for the identification of tau decays.

2000-2015

Photographic emulsion consist of chemical grains (often Ag doped) that react to the ionization of passing particles. Spatial resolution can be better than 1 μm!

Proposal for Neutrino Detection at the LHC

Detection of neutrinos at the LHC with energy 0.5-1 TeV
3 tons of emulsion/lead stacks

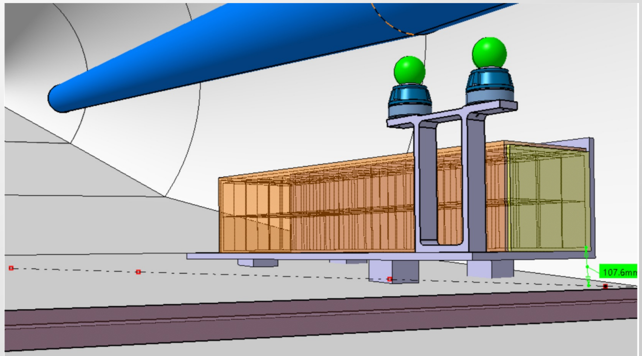


LETTER OF INTENT

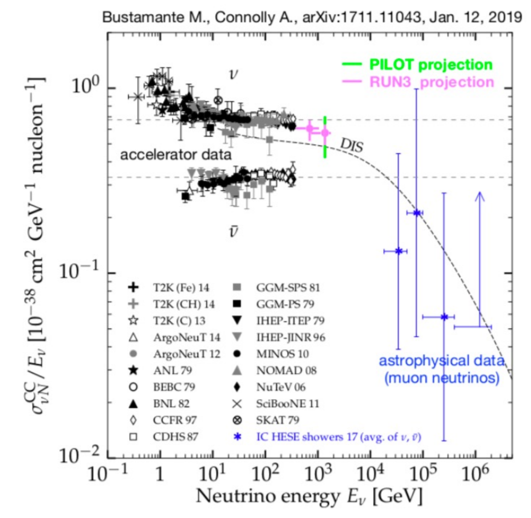
XSEN: a νN Cross Section Measurement using
High Energy Neutrinos from pp collisions at the LHC

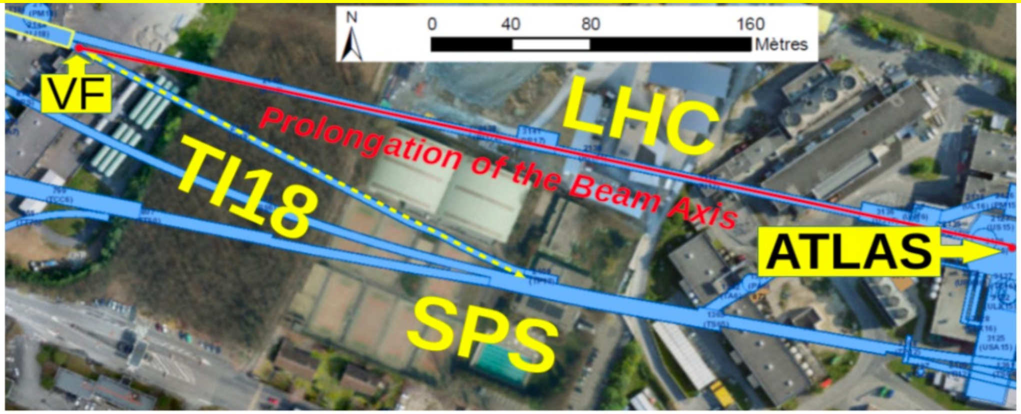
N. Beni[1,2], S. Buontempo[3], T. Camporesi[2], F. Cerutti[2], G.M. Dallavalle[4], G. De Lellis[2,3,5], A. De Roeck[2], A. De Rújula[6], A. Di Crescenzo[3,5], D. Fasanella[4], A. Ioannisyan[2,7], D. Lazic[8], A. Margotti[4], S. Lo Meo[4,9], F.L. Navarria[4], L. Patrizii[4], T. Rovelli[4], M. Sabaté-Gilarte[2], F. Sanchez Galan[2], P. Santos Diaz[2], G. Sirri[4], Z. Szillasi[1,2], C. Wulz [10]

2019



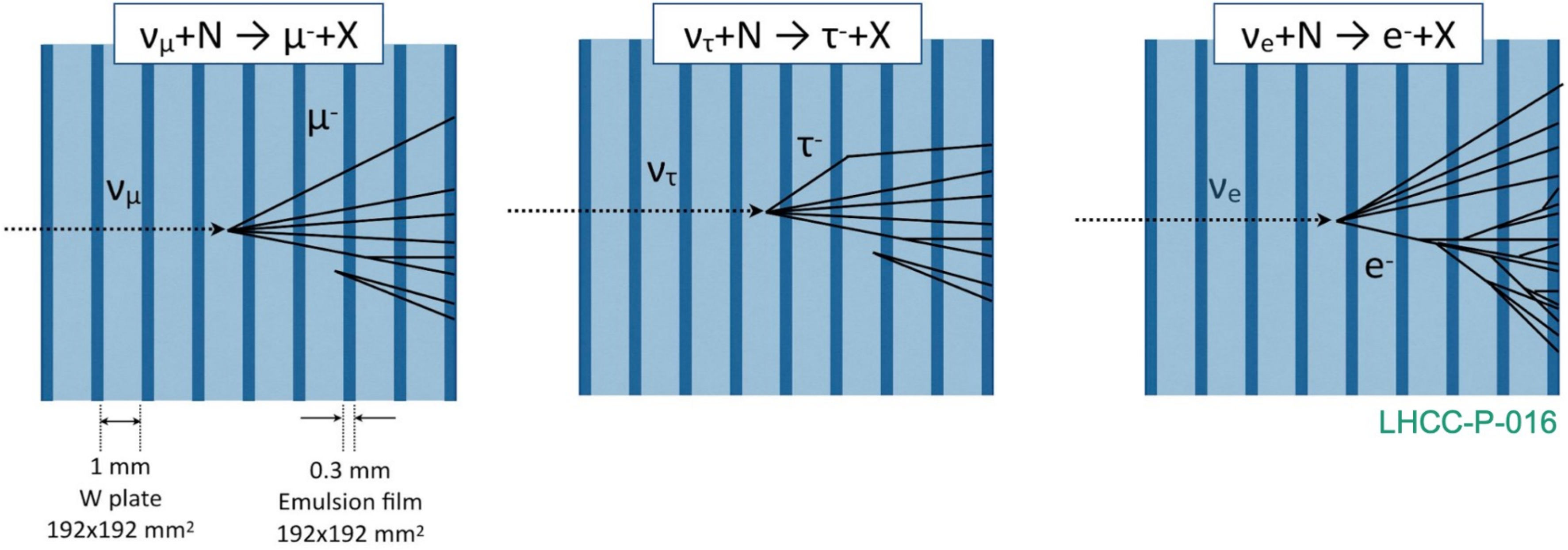
The experiment now called SND@LHC got approved in April 2021 and is now constructed and taking data!!!





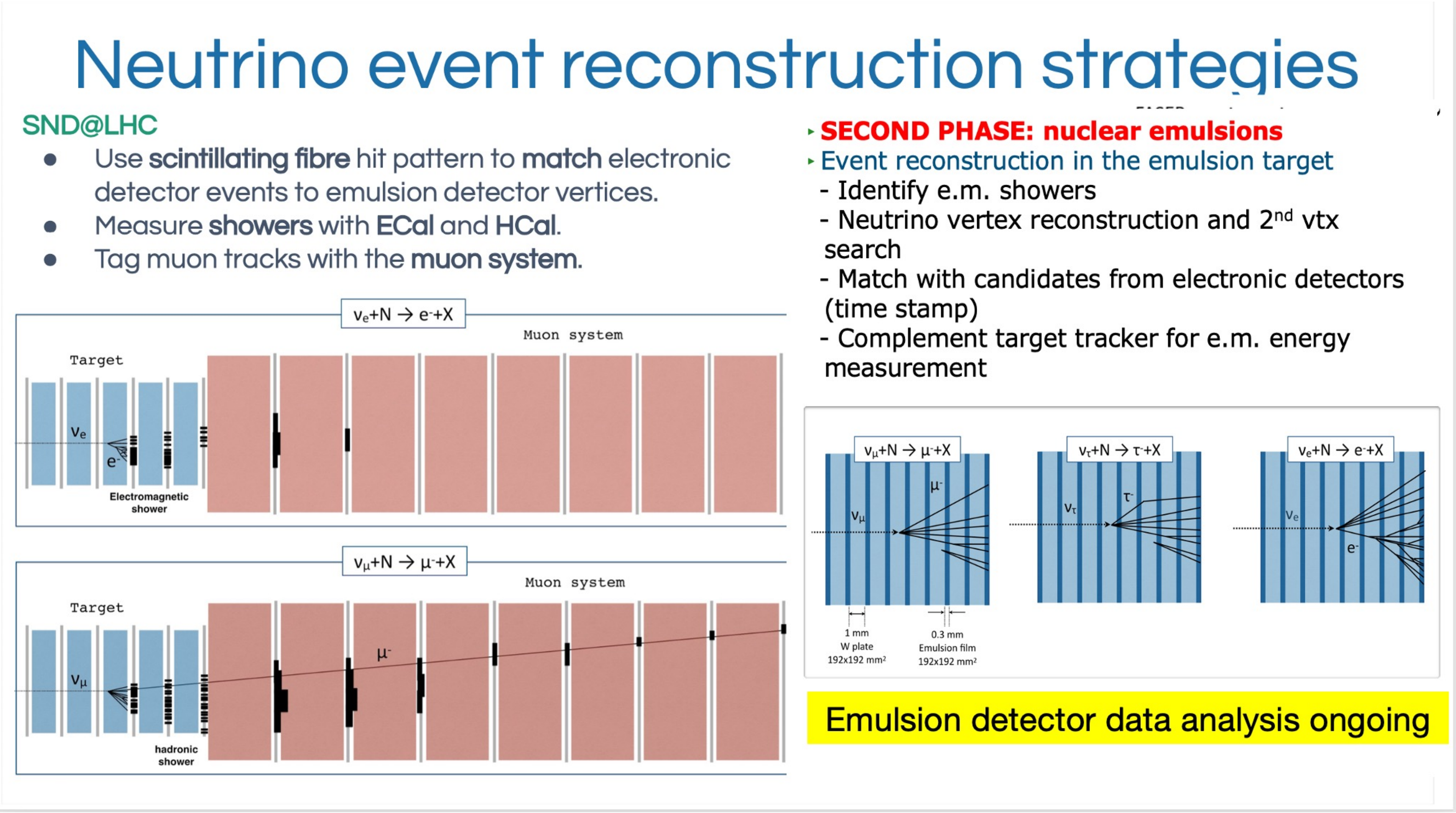
Neutrino identification with emulsions

- **Micrometric resolution** of emulsion detectors allows for **excellent neutrino identification.**
  - **Essential** for the identification of the **secondary vertex** associated to ν_τ,
- However:
  - **No timing** information (emulsions integrate ~months of data).
  - Limited ability to identify **muon tracks.**
  - Limited ability to measure **hadronic showers.**
- Must be complemented with **electronic detector data.**



LHCC-P-016

SND@LHC



Neutrino event reconstruction strategies

SND@LHC

- Use **scintillating fibre** hit pattern to **match** electronic detector events to emulsion detector vertices.
- Measure **showers** with **ECal** and **HCal**.
- Tag muon tracks with the **muon system**.

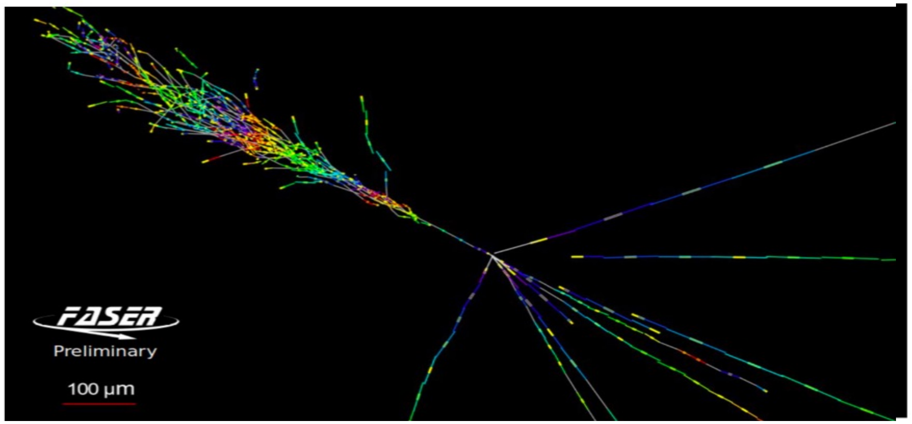
- **SECOND PHASE: nuclear emulsions**
- Event reconstruction in the emulsion target
  - Identify e.m. showers
  - Neutrino vertex reconstruction and 2nd vtx search
  - Match with candidates from electronic detectors (time stamp)
  - Complement target tracker for e.m. energy measurement

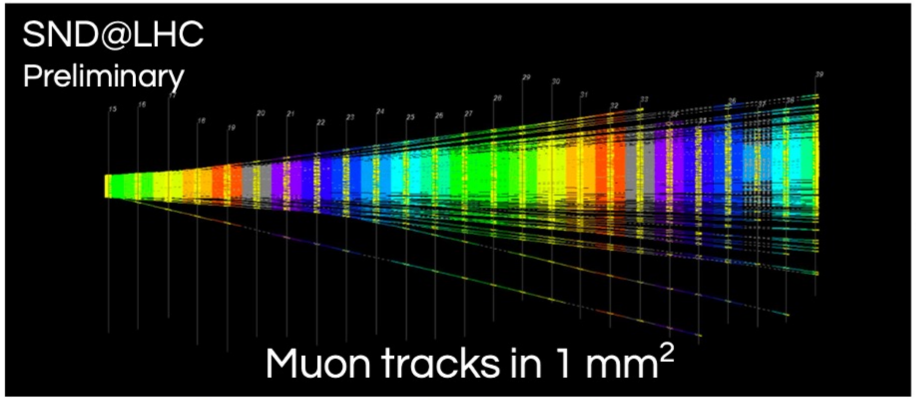
Emulsion detector data analysis ongoing

SND@LHC

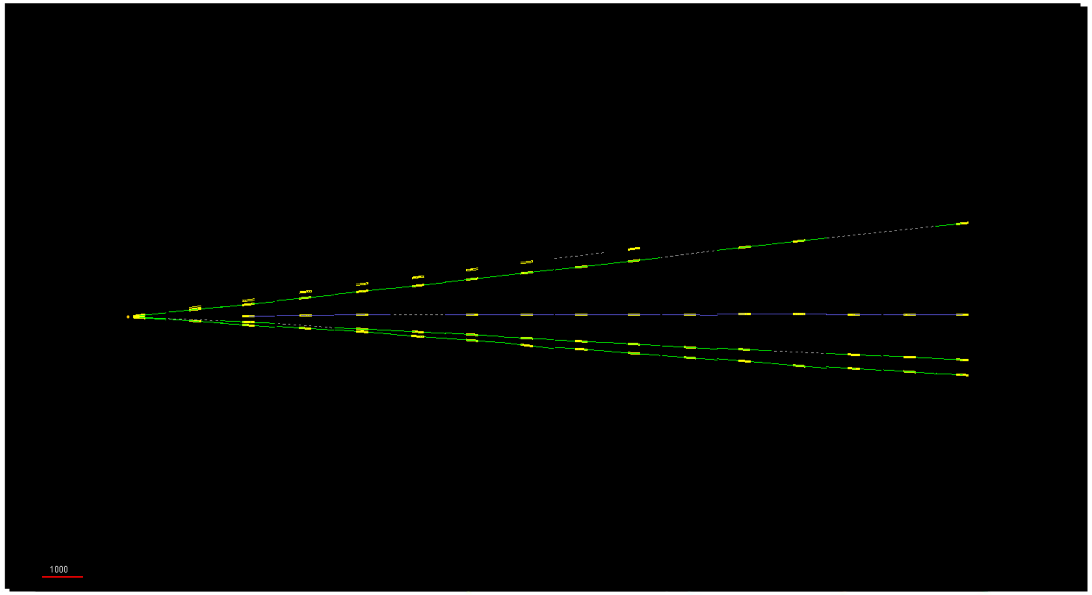
Emulsion detector analyses

Analysis of emulsion detector data is ongoing





10^5 tracks/cm^2 in 10 fb^{-1} exposure



- Significant parts from 2022 data have been already scanned. 2023 data to start
- Examples of vertices found based on predictions from electron detectors

SND@LHC event selection

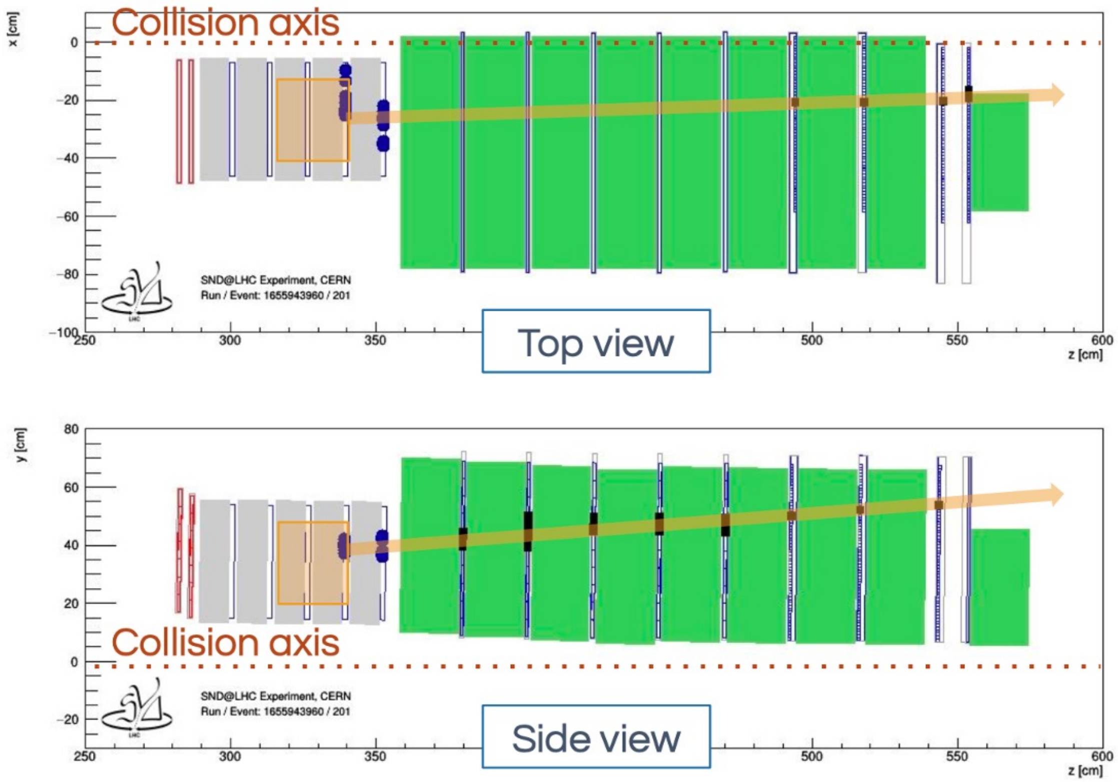
Fiducial volume

- Neutral vertex 3th or 4th wall.
- Reject side-entering backgrounds.
- Signal acceptance: 7.5%

Muon neutrino identification

- Large scintillating fibre detector activity.
- Large HCal activity.
- One muon track associated to the vertex.
- Signal selection efficiency: 36%

Number of ν_μ CC events expected in 36.8 fb^{-1} after cuts: 4.2

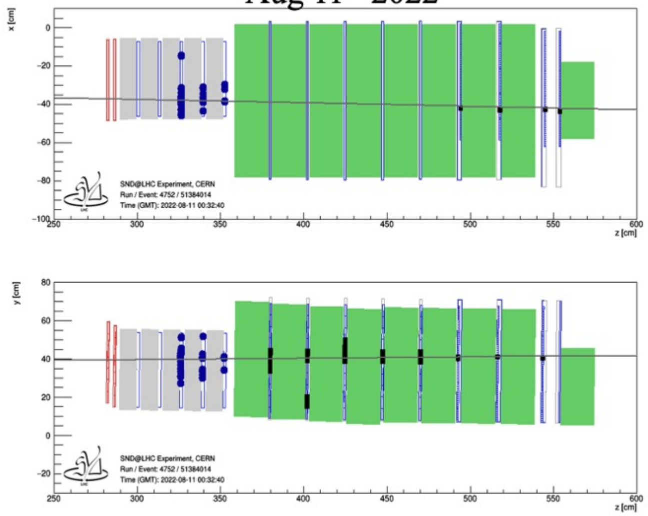


ν_μ CC simulation

SND@LHC

Observation of collider muon neutrinos with 2022 data

Aug 11th 2022



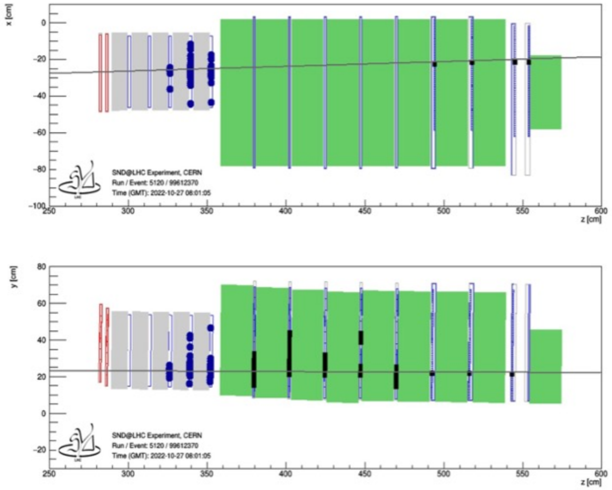
Editors' Suggestion

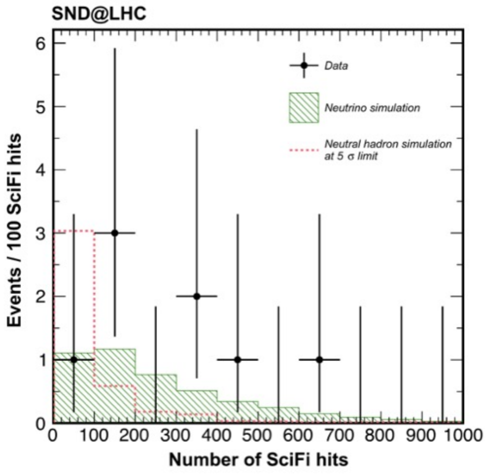
Observation of Collider Muon Neutrinos with the SND@LHC Experiment

R. Albanese *et al.* (SND@LHC Collaboration)

Phys. Rev. Lett. **131**, 031802 (2023) – Published 19 July 2023

Oct 27th 2022





Distribution of SciFi hits for ν_μ candidates with the MC expectation for ν events and background (augmented to the 5 sigma level)

https://journals.aps.org/prl/abstract/10.1103/PhysRevLett.131.031802

8 observed events and an expected background

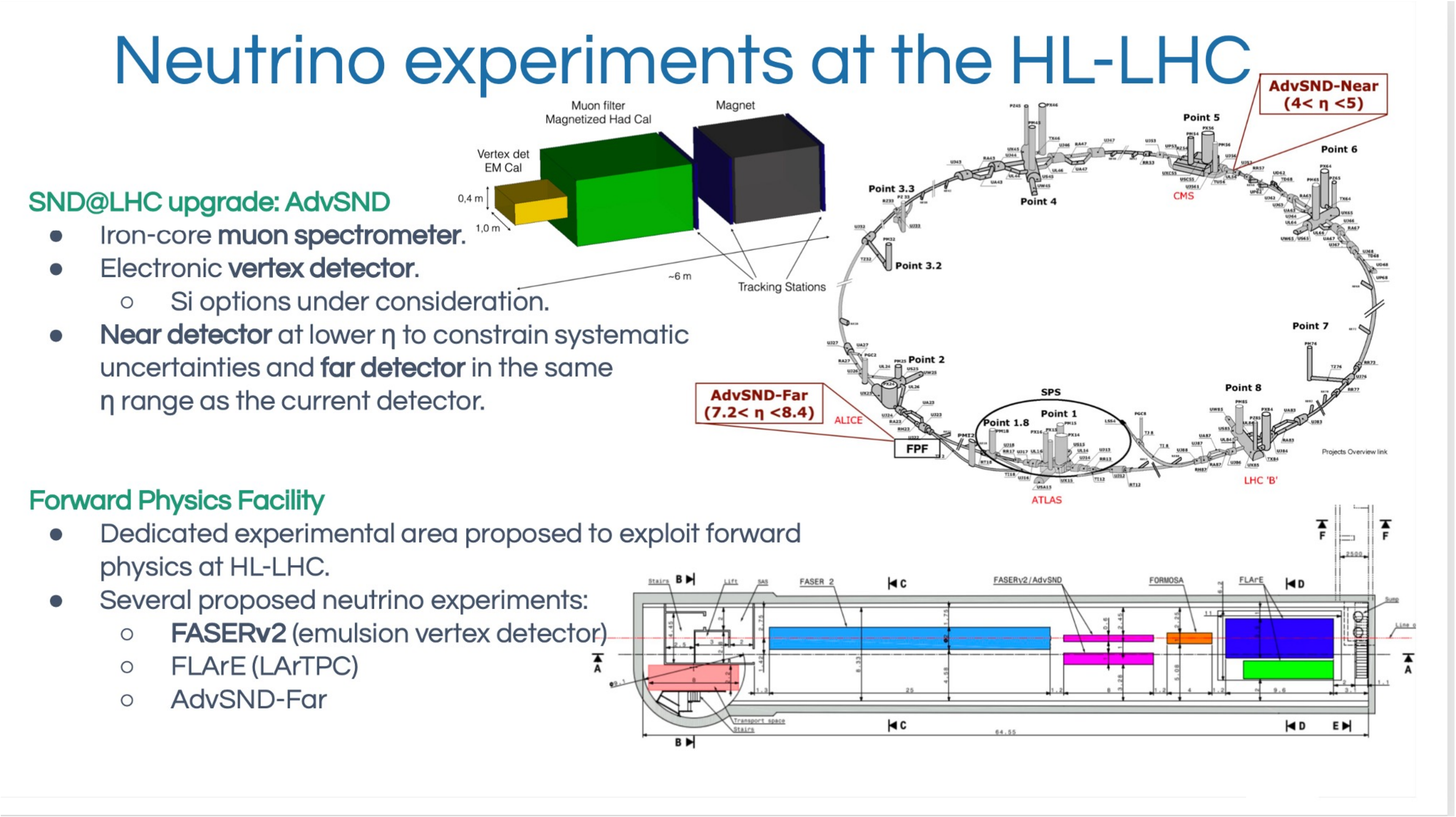
$$(8.6 \pm 3.8) \times 10^{-2}$$

Background only hypothesis probability:

$$P = 7.15 \times 10^{-12}$$

6.8 σ observation

SND@LHC



Neutrino experiments at the HL-LHC

SND@LHC upgrade: AdvSND

- Iron-core **muon spectrometer**.
- Electronic **vertex detector**.
    - Si options under consideration.
- **Near detector** at lower η to constrain systematic uncertainties and **far detector** in the same η range as the current detector.

Forward Physics Facility

- Dedicated experimental area proposed to exploit forward physics at HL-LHC.
- Several proposed neutrino experiments:
    - **FASERv2** (emulsion vertex detector)
    - FLArE (LArTPC)
    - AdvSND-Far

SUMMARY: Neutrinos

- Neutrino studies is a vibrant field of research, and has still many open questions! Right-handed partners? Large CP violation? More than 3 neutrinos? Non Standard Interactions? Are neutrinos their own anti-particle?
- Now comes the age of neutrino precision physics with DUNE & T2HK and neutrino astronomy: look inside the sun, understand supernovae explosions, multi-messenger astronomy…
- Detailed study of PMNS oscillation parameters by experiments is key to the understanding
- Large experiments are really “observatories”
- The history of neutrino research showed many surprises. What surprise is waiting for us next??