Neutrinos!

Present Understanding & Future Prospects

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CERN, Geneva, Switzerland
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CERN-FERMILAB
HADRON COLLIDER PHYSICS
Summer School

Pion event in the ProtoDUNE at CERN

Electron neutrino event in the
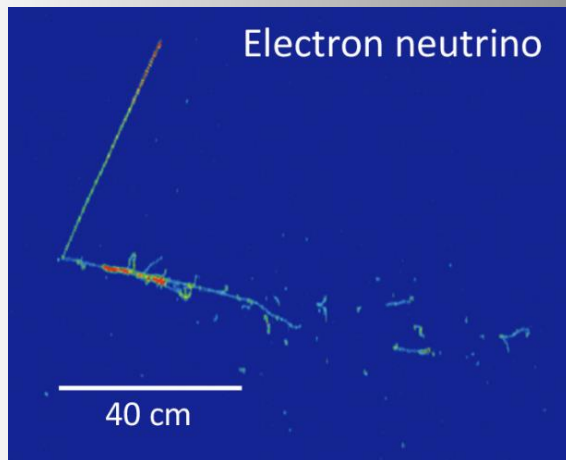ICARUS detector at FNAL

Outline

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

Neutrinos

- Neutrinos at the CERN-Fermilab Hadron Collider Physics Summer School?
  - No neutrino collider any time soon ☺ (vv collisions do happen plentifully in supernova explosions…). Neutrino factory..?
- Fermilab has a strong ongoing program on neutrino physics
  - Eg DONUT, MINOS, MINERvA, MicroBooNE, MiniBooNE, NOvA…
  - And recently/future: ICARUS, SBND, DUNE…
- CERN is coming back "on-line" in neutrino physics. Significant investment with the Neutrino Platform
  - ProtoDUNEs, participating in DUNE, SBN, T2K, ...
- The LHC is also becoming a place to study neutrinos, via searches for new or heavy neutrinos, or more recently via news experiments that measure high energy neutrino interactions (FASER(-Nu), SND@LHC)
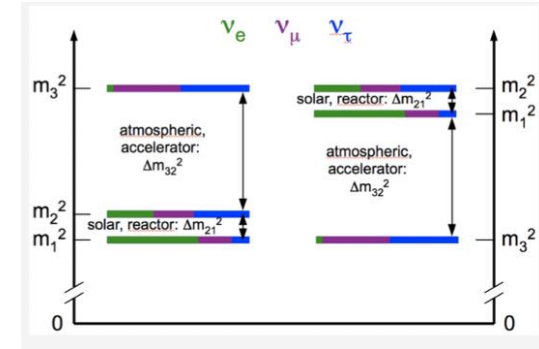
Neutrinos

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

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? -> LNV processes

- 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

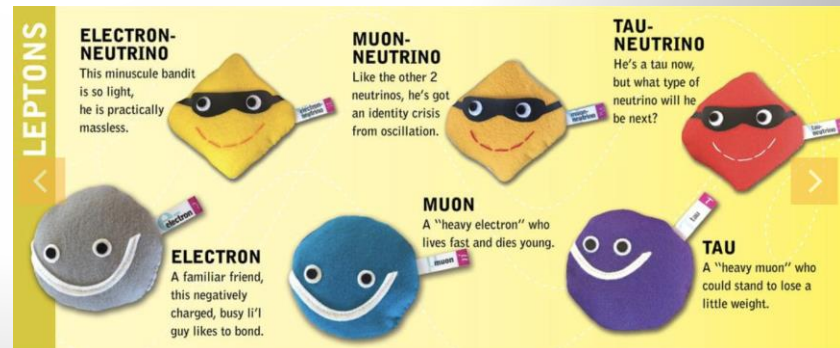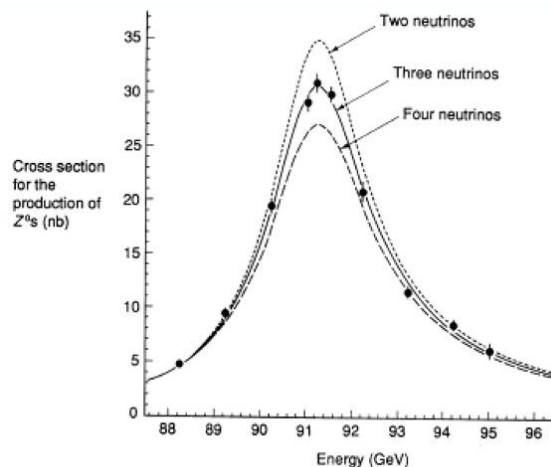# Neutrinos come in 3 Flavors

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

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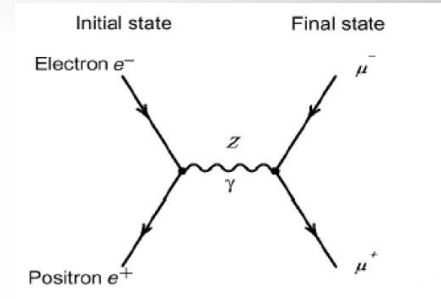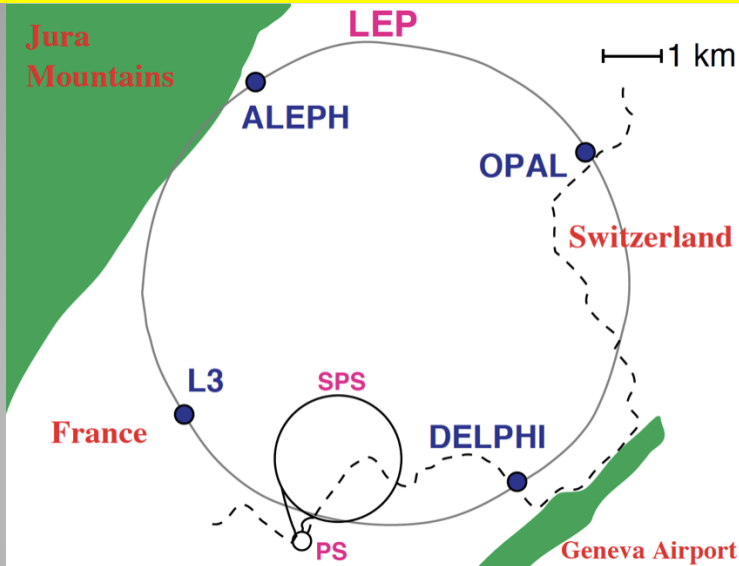
The width of the Z-boson gives the number of neutrinos

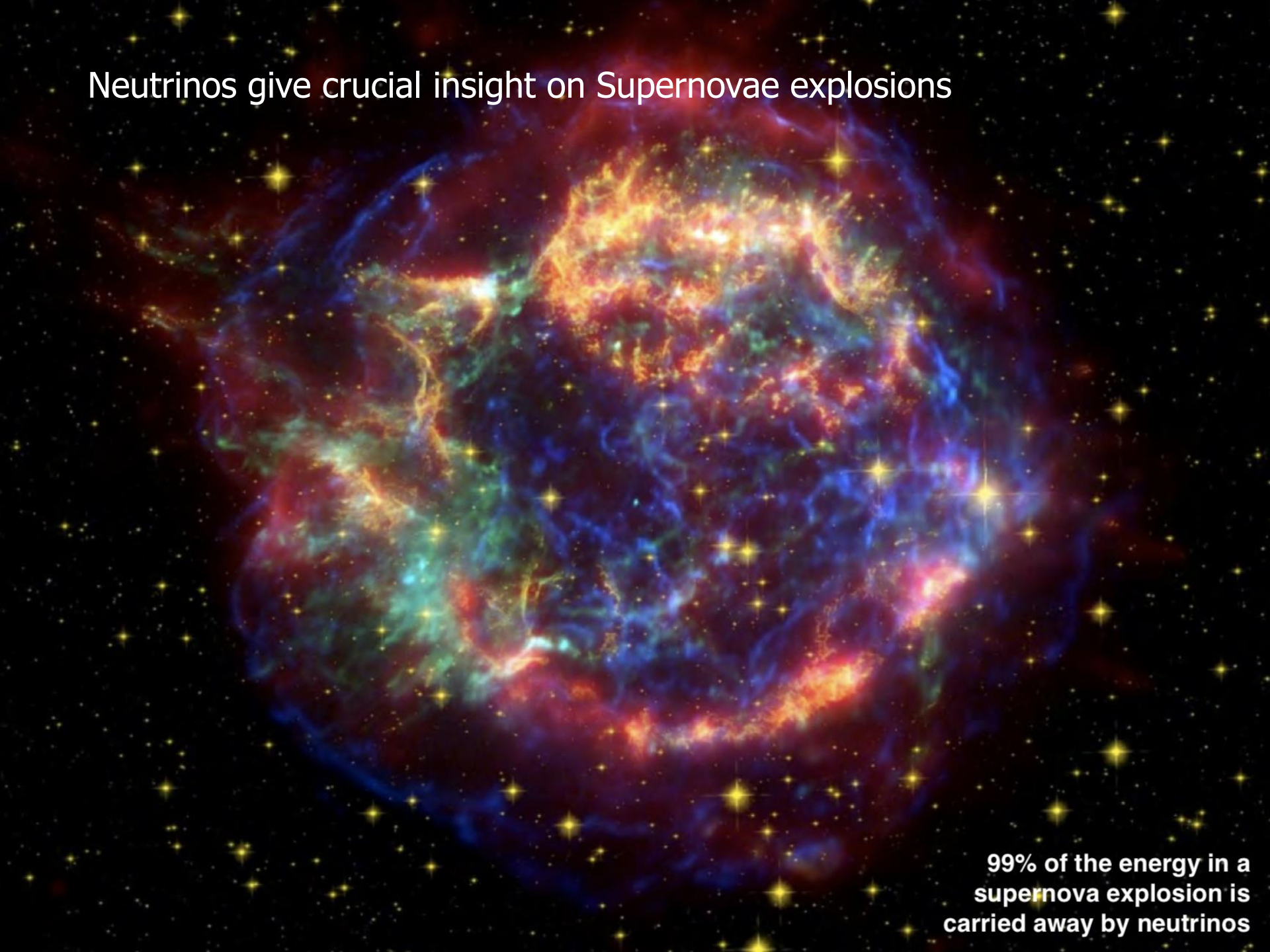$$\Gamma_Z = \Gamma_{had} + 3\Gamma_l + N_\nu \Gamma_\nu$$

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

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

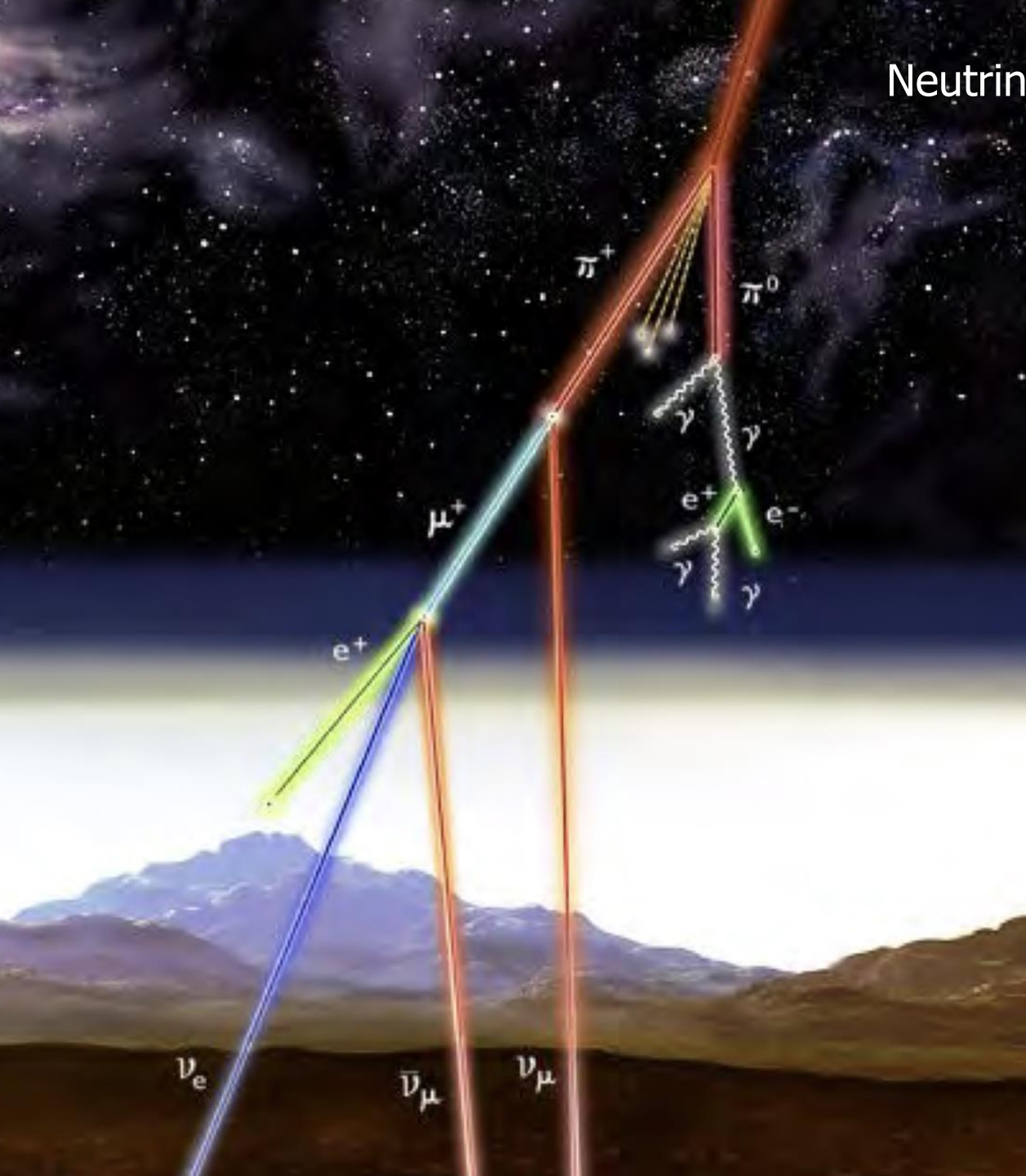99% of the energy in a supernova explosion is carried away by neutrinos

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 ~10^{11}/cm^2/sec at the Earth)
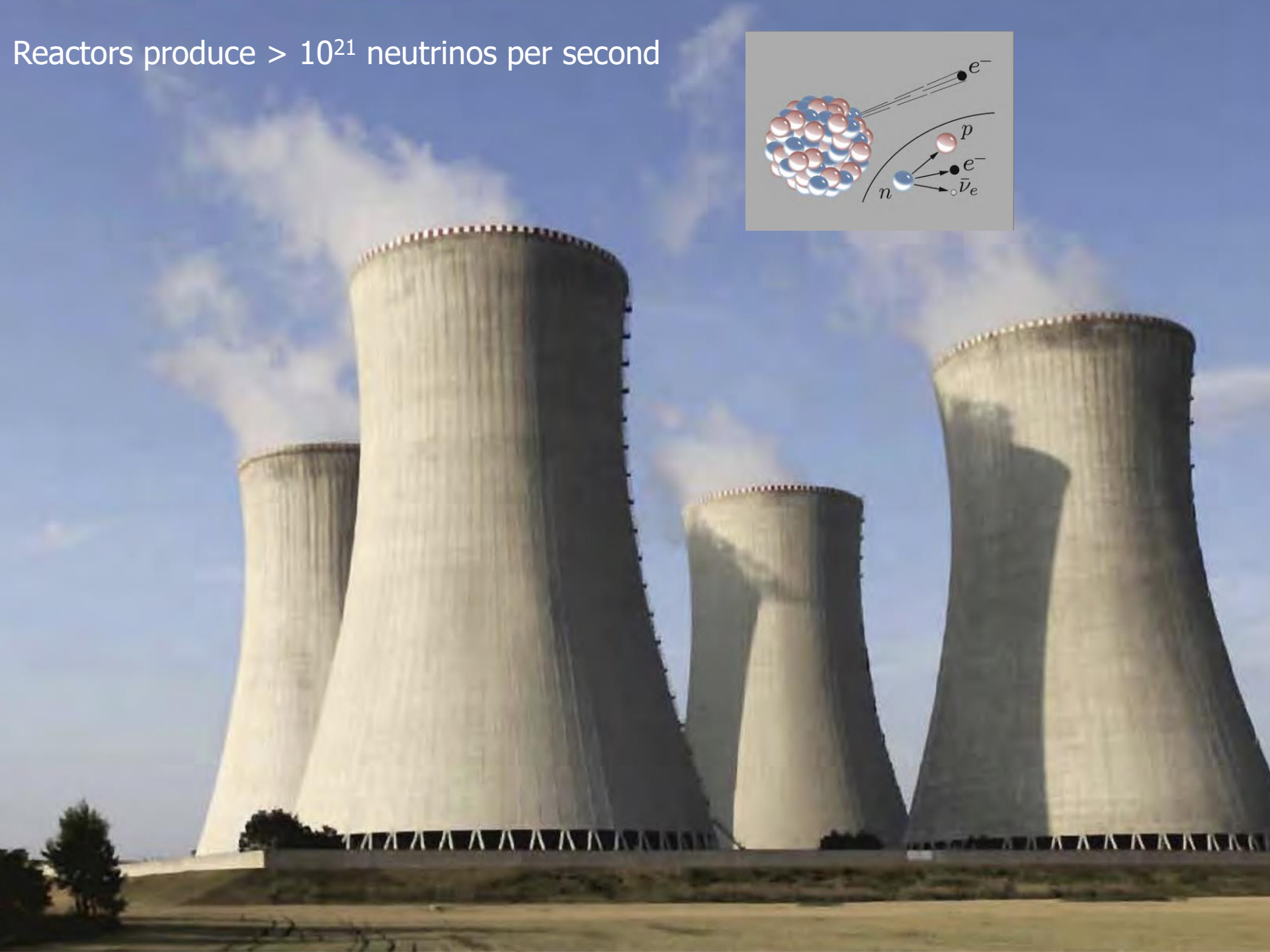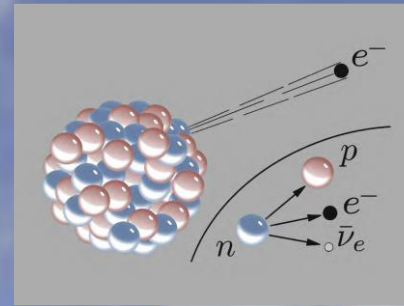
Neutrinos from cosmic rays

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
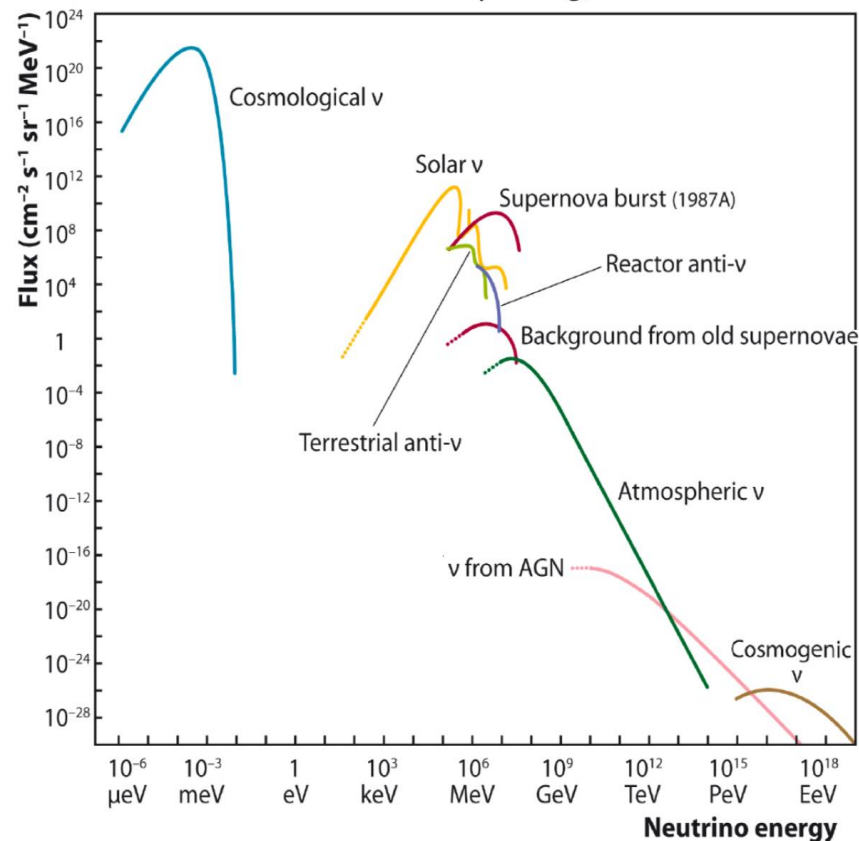
Neutrinos are Forever !!!!
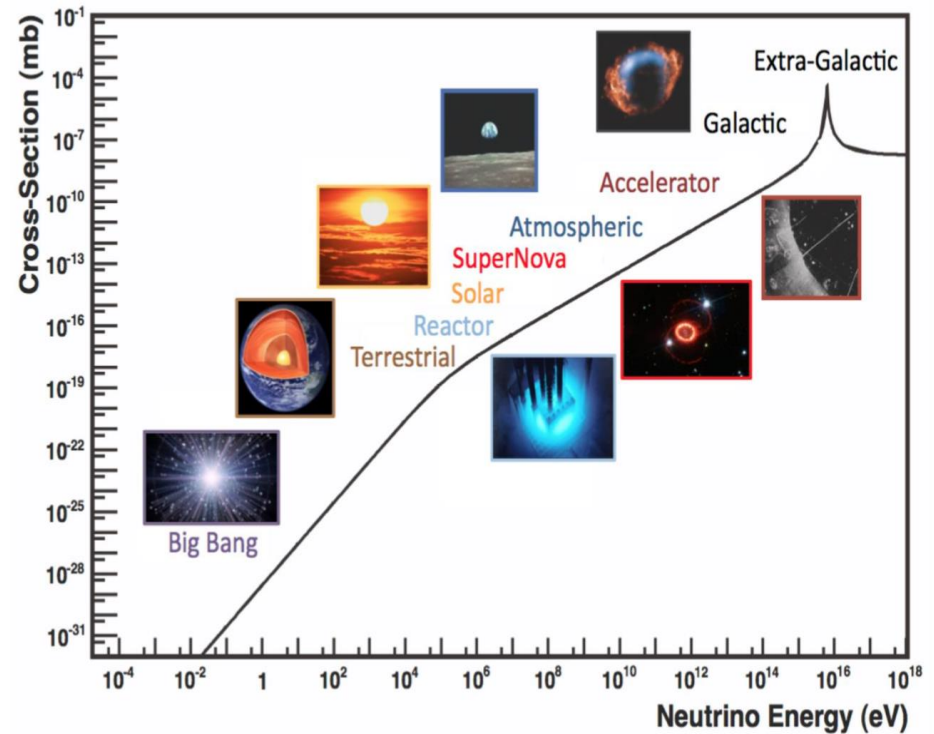
(except for the highest energy neutrino's)

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

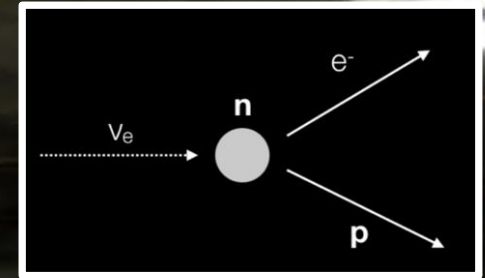# Neutrino Sources, Flux and Cross Sections

C. Spiering, arXiv:1207.4952
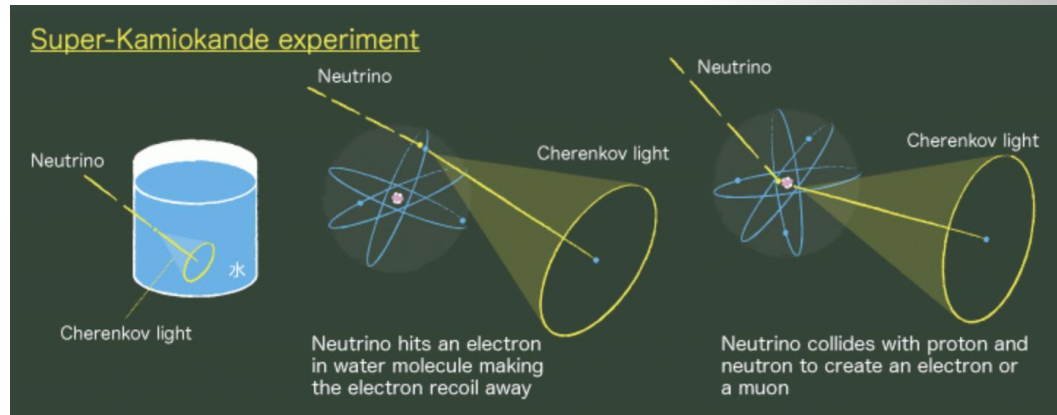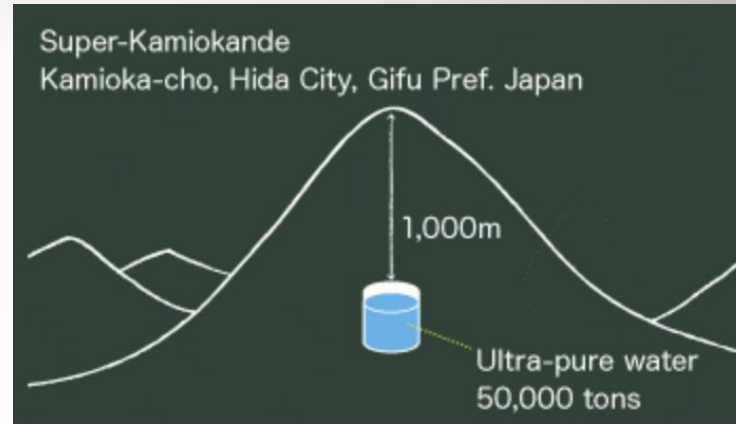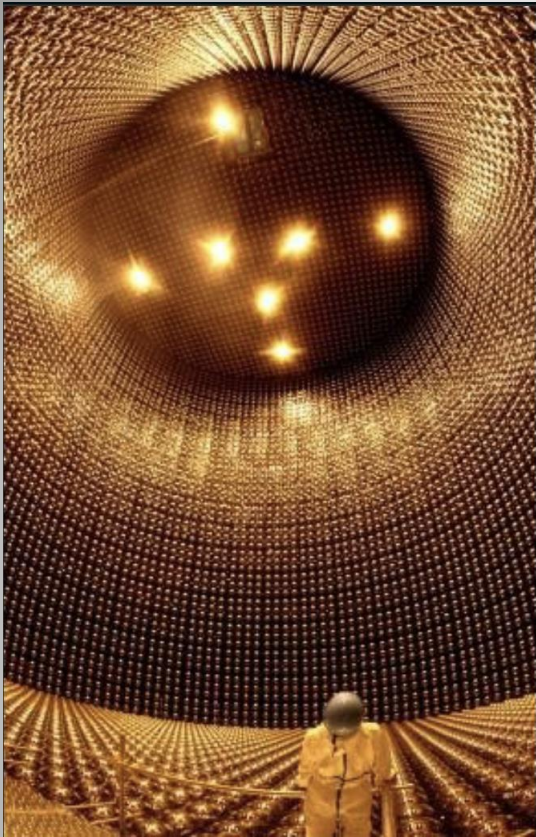
J. Formaggio, G.P. Zeller, arXiv:1305.7513

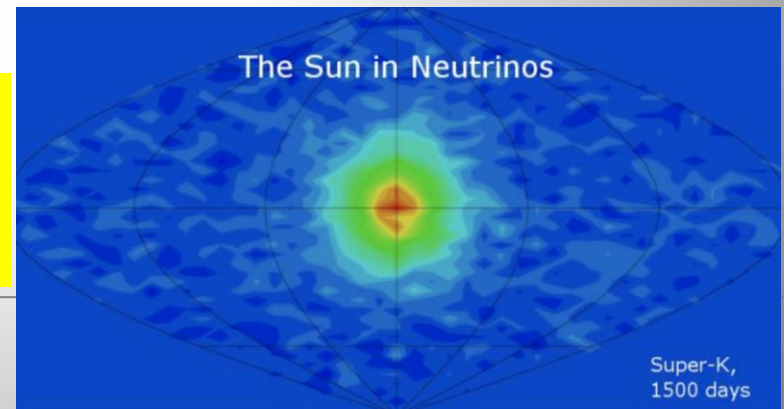Cosmological and background from old supernovae neutrinos not yet observed!

Detecting neutrinos is challenging
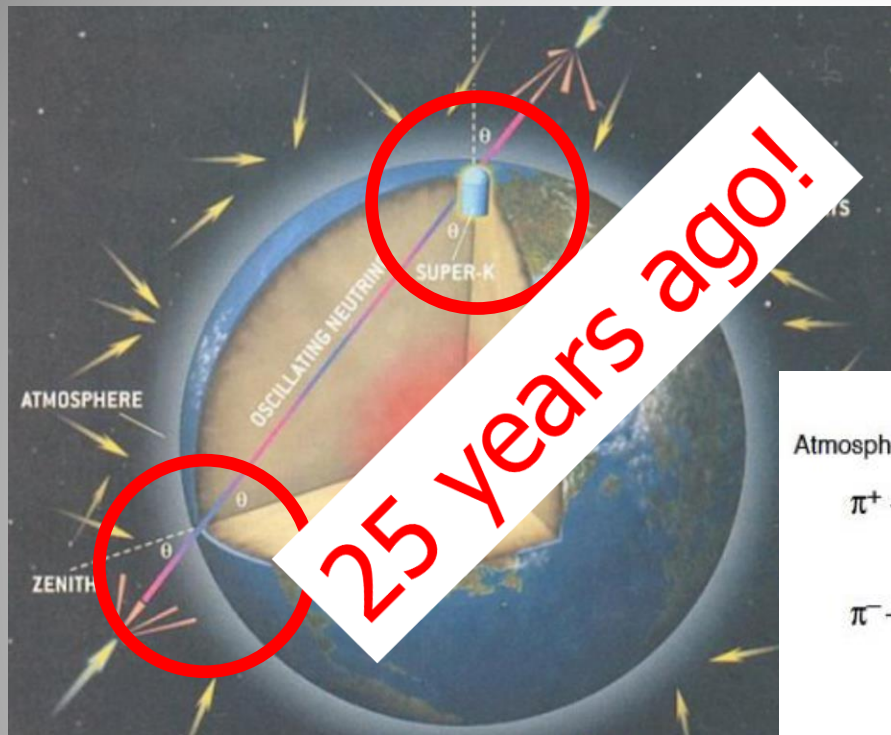**Very large detectors are needed**

NOvA detector (US)

SuperKamiokande

Super-Kamiokande
Kamioka-cho, Hida City, Gifu Pref. Japan

1,000m

Ultra-pure water
50,000 tons

Super-Kamiokande experiment

Neutrino

Neutrino

Neutrino

Cherenkov light

Cherenkov light

Cherenkov light

水

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

The Sun in Neutrinos

Super-K, 1500 days

Neutrinos Oscillate! (1998)

25 years ago!

ATMOSPHERE

ZENITH

θ

SUPER-K

OSCILLATING NEUTRINO

Atmospheric neutrino source

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

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

— The expected number of events without neutrino oscillation
— The expected number of events with neutrino oscillation
—+— The observed number of events in Super-Kamiokande

The number of observed muon neutrinos

1000

500

0

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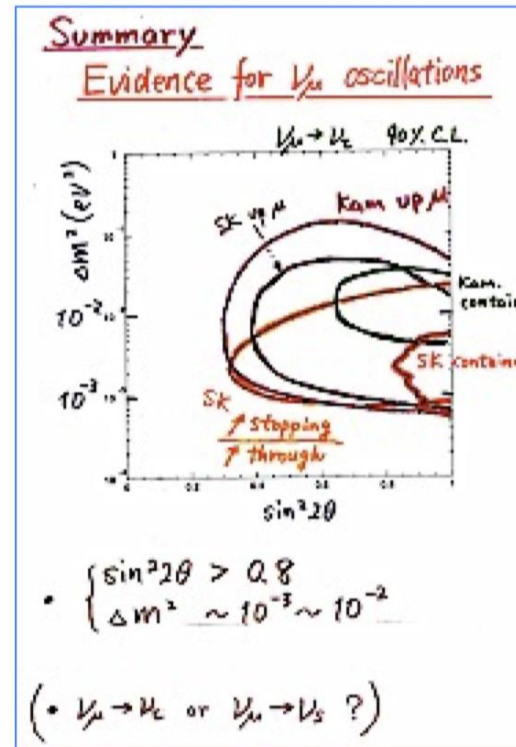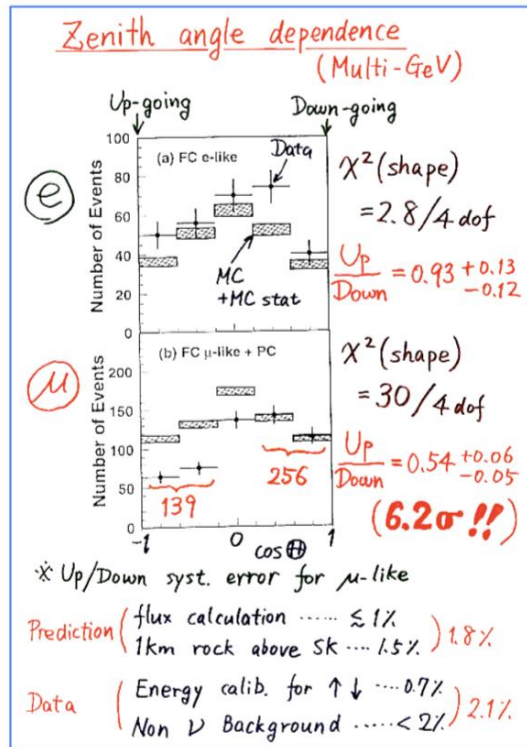
E. Lisi
Re-interpretation
Workshop
17/2/2021

Initial interpretation in terms of simple 2ν ($\nu_\mu \rightarrow \nu_\tau$) 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!!

ν_μ

hundreds of kilometers

ν_μ
ν_τ
ν_e
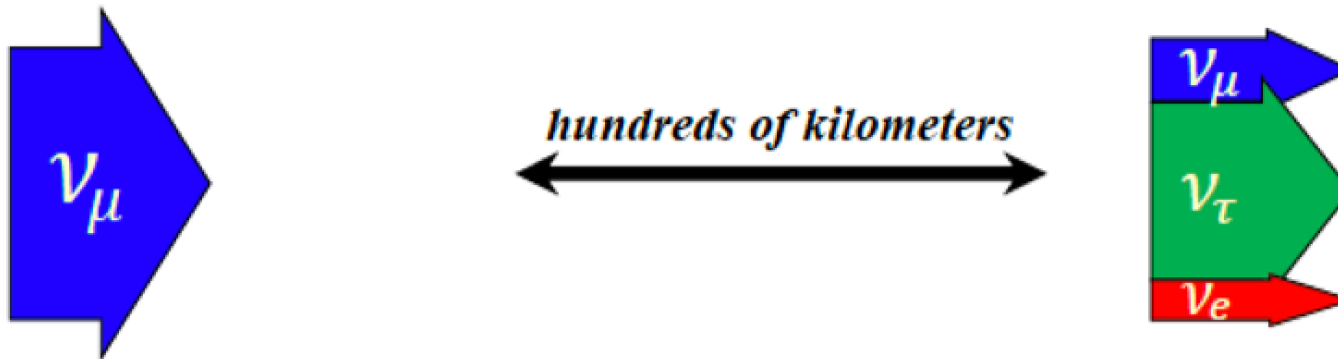
Neutrino oscillations

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
$i = 1, 2, 3$

Flavor states

(*) Pontecorvo-Maki-Nakagawa-Sakata Matrix

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)

length or time
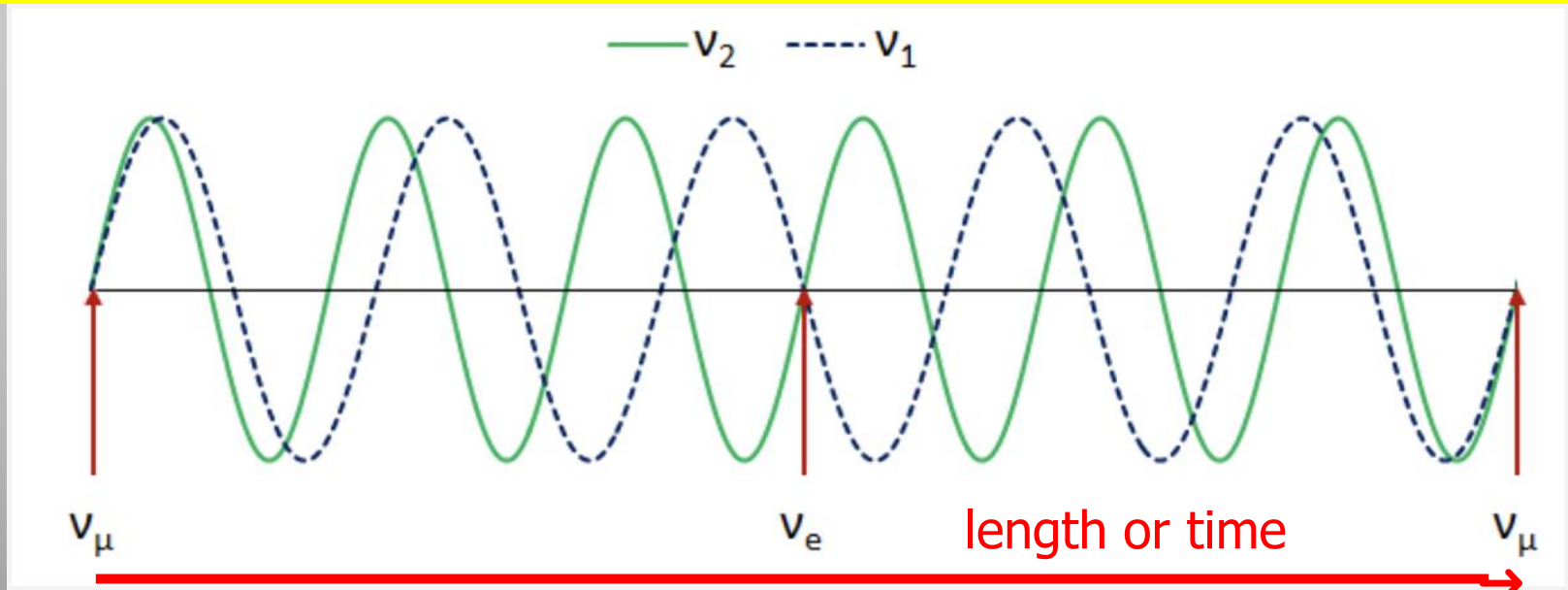
The neutrinos change identity (flavor) along the way...!!

Two Flavour Oscillations

Flavour states   "Rotation Matrix"   Mass states

$$
\begin{pmatrix} \nu_\alpha \\ \nu_\beta \end{pmatrix} = \begin{pmatrix} \cos\theta & \sin\theta \\ -\sin\theta & \cos\theta \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \end{pmatrix}
$$
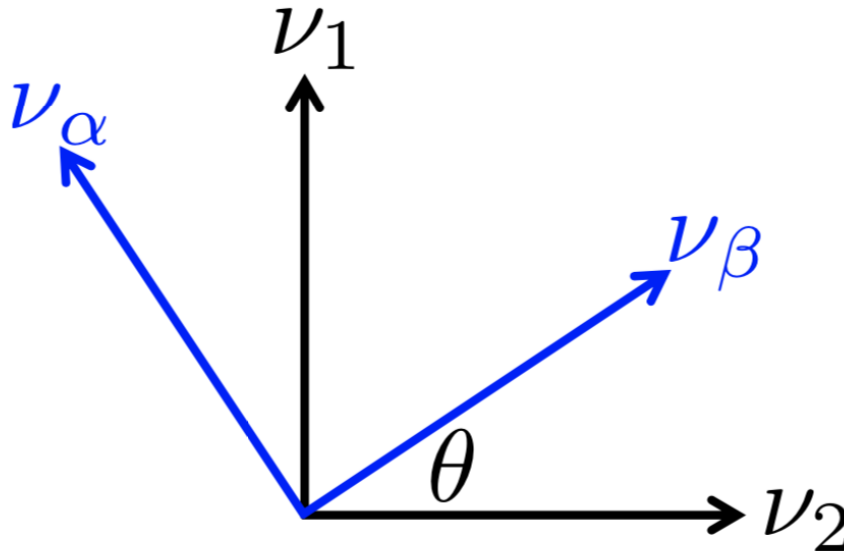
$$
|\nu(t=0)\rangle = |\nu_\alpha\rangle = \cos\theta\,|\nu_1\rangle + \sin\theta\,|\nu_2\rangle
$$

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

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

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

ultra-relativistic

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

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

Neutrino Oscillations

Neutrino oscillations is a pure Quantum Mechanical effect
The effect depends on the mass difference between flavor states

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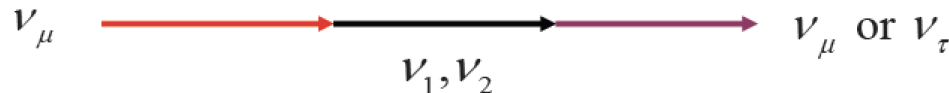
$$\begin{pmatrix} \nu_\mu \\ \nu_\tau \end{pmatrix} = \begin{pmatrix} \cos\theta & \sin\theta \\ -\sin\theta & \cos\theta \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \end{pmatrix} \qquad P(\nu_\mu \to \nu_\tau) = \sin^2(2\theta)\sin^2\left(\frac{1.27\Delta m^2 L}{E_\nu}\right)$$

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

$\Delta m^2 = 3 \times 10^{-3} \text{eV}^2$
$\sin^2(2\theta) = 1$
$L = 735 \text{ km}$

Survival Probability vs E (GeV)
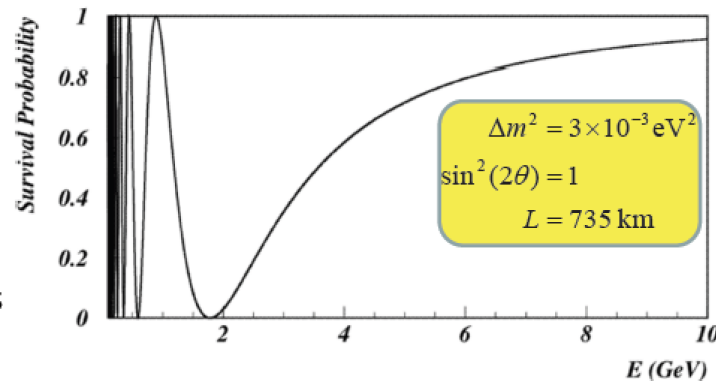
- $\Delta m^2_{21} = m^2_2 - m^2_1 \approx 8 * 10^{-5} \text{ eV}^2$ => wavelength of ~100km
- $|\Delta m^2_{31}| \approx |\Delta m^2_{32}| \approx 2 * 10^{-3} \text{ eV}^2$ => wavelength of ~1km

Absolute mass values?   Mass hierarchy?

Neutrino Oscillations

Neutrino mixing: Pontecorvo-Maki-Nakagawa-Sakata (PMNS) matrix
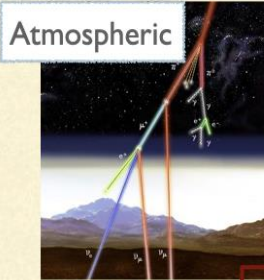
Atmospheric | Accelerator | Reactor | Solar
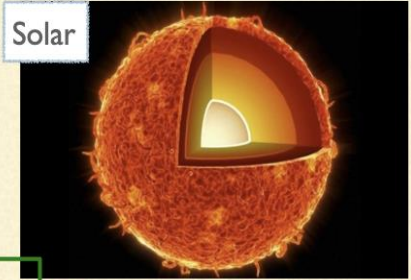
$$c_{ij} = \cos\theta_{ij}$$
$$s_{ij} = \sin\theta_{ij}$$

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

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

Oscillations governed by   * PDG 2022

- three mixing angles:
  - $\theta_{12} \approx 34°$, $\theta_{13} \approx 9°$, $\theta_{23} \approx 48°$ (41-51 within 3σ)
- two mass squared differences:
  - $\Delta m_{21}^2 \approx 7.4\times10^{-5}\,eV^2$ and $|\Delta m_{32}^2| \approx 2.5\times10^{-3}\,eV^2$
- source-detector baseline and neutrino energy

In total 6 parameters to determine:

-3 angles
-2 mass differences
-1 CP violation phase

Neutrino Oscillations

Mixings and phases: CKM→ PMNS (Pontecorvo-Maki-Nakagawa-Sakata)

$$U_{\alpha i} = \begin{bmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{bmatrix} \begin{bmatrix} c_{13} & 0 & s_{13}e^{-i\delta} \\ 0 & 1 & 0 \\ -s_{13}e^{i\delta} & 0 & c_{13} \end{bmatrix} \begin{bmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{bmatrix}$$

θ_{23} rotation $\qquad$ θ_{13} rotation $\; c_{ij} = \cos\theta_{ij}; \, s_{ij} = \sin\theta_{ij}$

+ CPV "Dirac" phase δ

Mass [squared] spectrum $\qquad$ (E ~ p + m²/2E + "interaction energy")

"Normal" Ordering N.O.

$+\Delta m^2$

δm^2 — 3

δm^2 — 2, 1

$-\Delta m^2$

2, 1 — δm^2

3

"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

		$\sin^2 2\theta_{13}$	
Daya Bay	nGd		8.53 ± 0.24
RENO	nGd		8.96 ± 0.67
Daya Bay	nH		7.1 ± 1.1
Double CHOOZ			10.5 ± 1.4
T2K	NO	IO	$11.64^{+2.20}_{-1.89}$

$\sin^2 2\theta_{13},\ 10^{-2}$
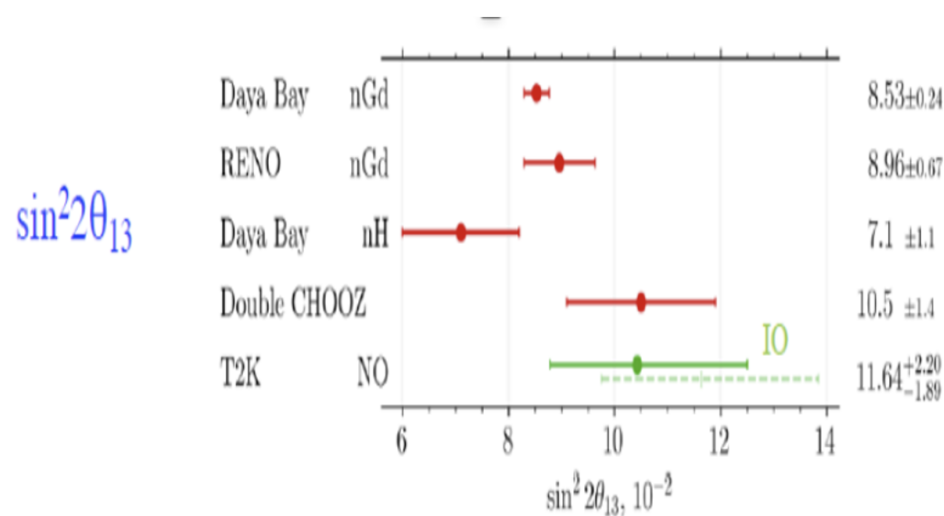
Phys. Rev. Lett. 130, 161802 (2023

• New results from Daya Bay nGd capture:

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

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

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

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

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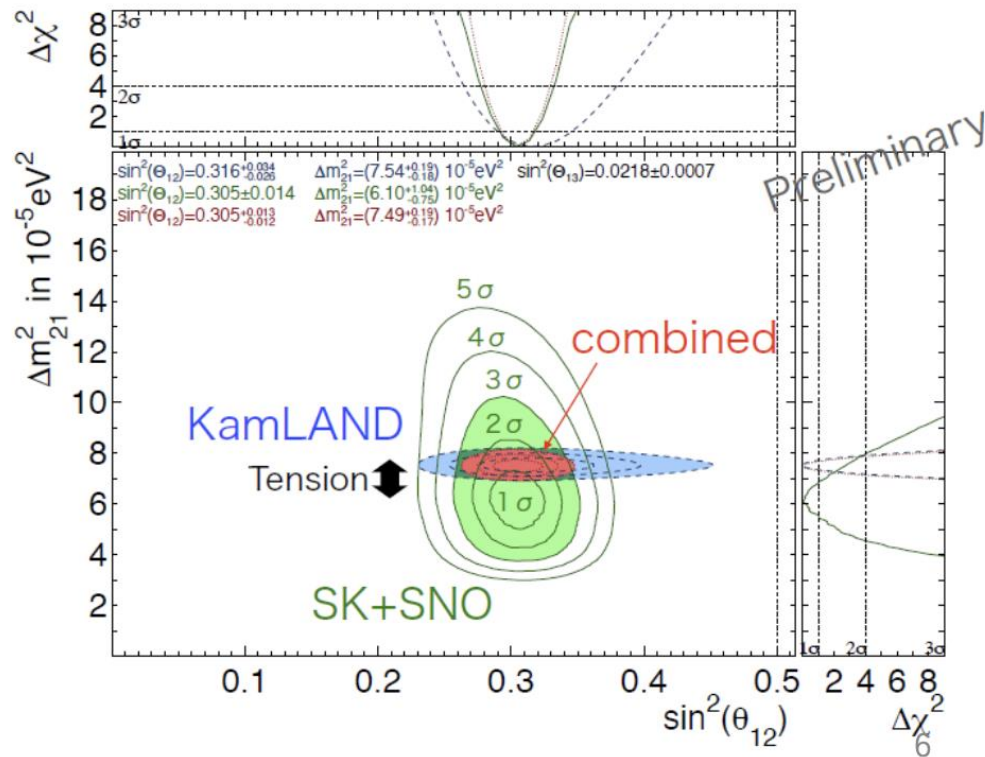
$$\sin^2(\theta_{12}) = 0.316^{+0.034}_{-0.026}$$

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

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

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

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

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

- 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
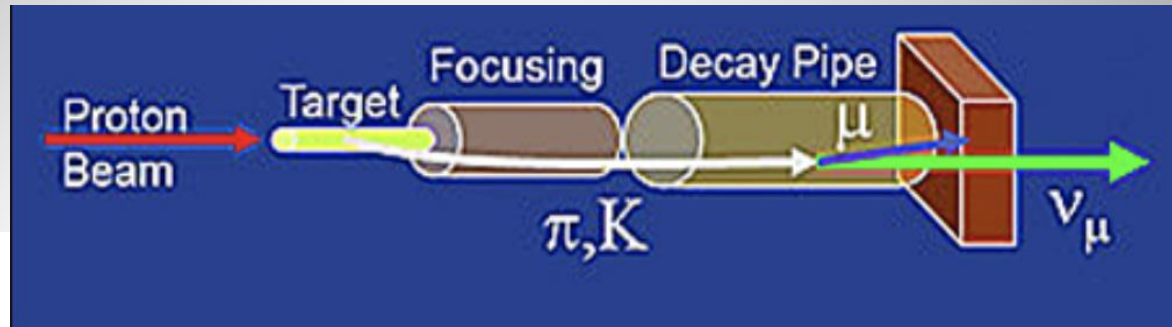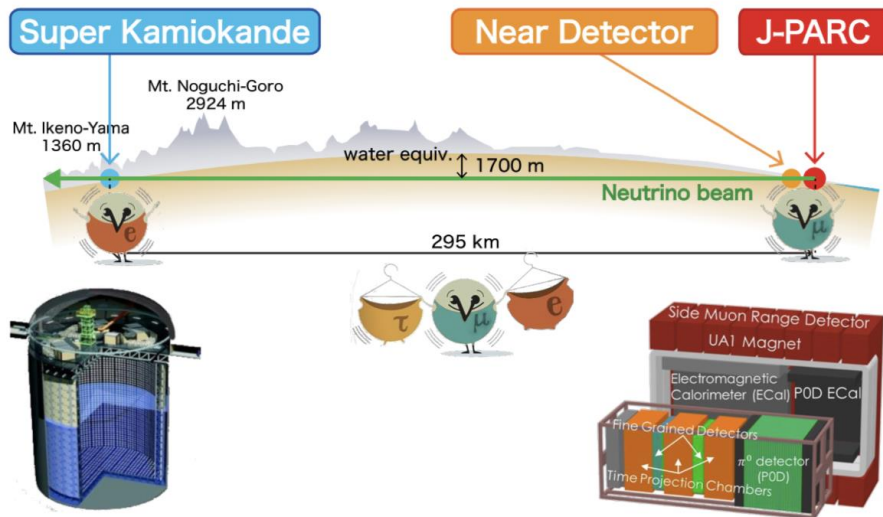
NOvA

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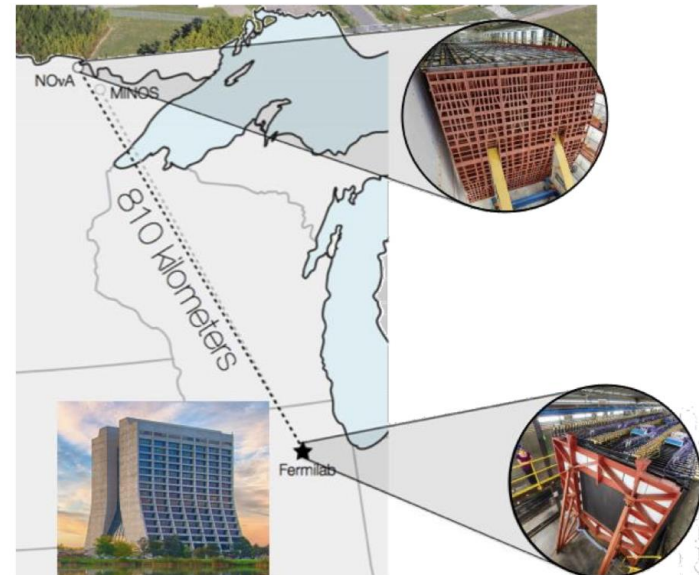
- Baseline: 810 km
- Peak E_ν: ~2 GeV (off-axis)
- Near detector: Scintillator tracker (300 T)
- Far detector: Scintillator tracker (14 kT)

Muon Neutrino Disappearance
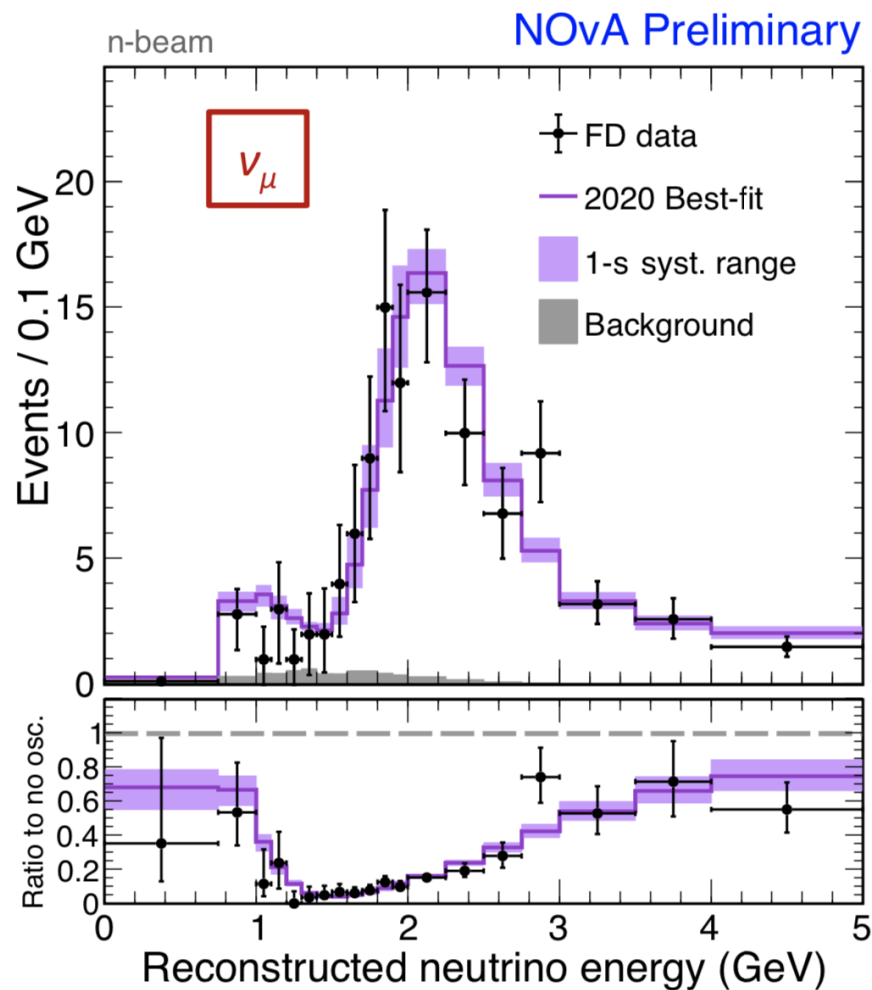
211 events, 8.2 background
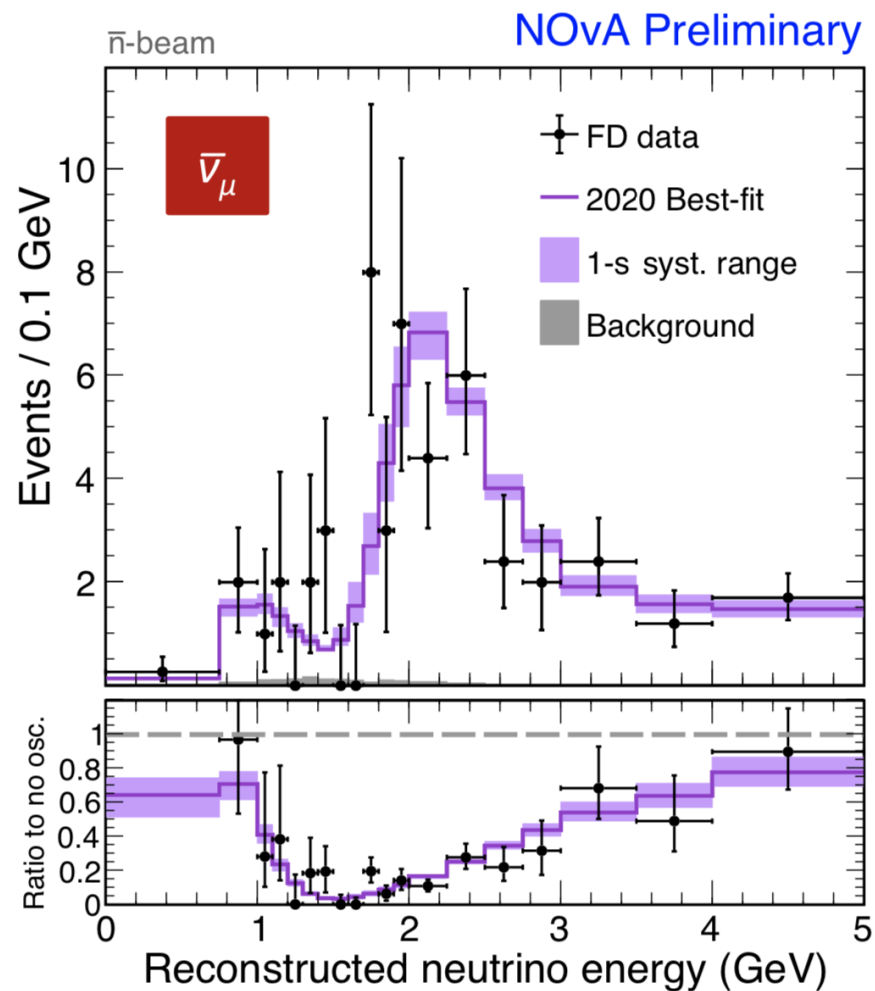
105 events, 2.1 background
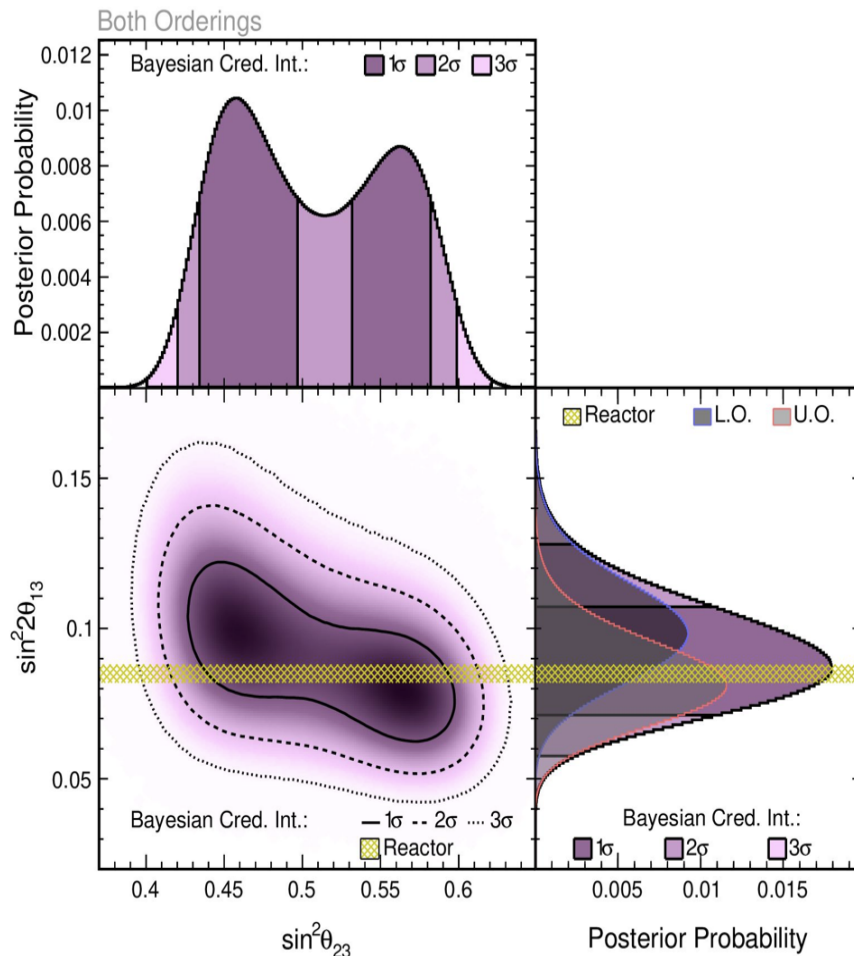
Measurement of θ_{13}

- The results so far all use a constraint on θ_{13} from reactor experiments.
- The Bayesian interpretation of our data allows us to drop this constraint and make a NOvA measurement of θ_{13}.

$$\sin^2(2\theta_{13}) = 0.085^{+0.020}_{-0.016}$$

- Consistent with the measurements from reactor experiments.
- Good test of PMNS consistency → NOvA measurement uses a very different strategy to reactor experiments.

Open Questions: CP Violation?

Do neutrinos and anti-neutrinos oscillate differently ?

Charge-Parity (CP) violation

2020 news: T2K exp.
$\sin\delta$ = 0 excluded at 3σ !!
-> Appeared in Nature

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!

Leptogenesis[1] is a workable solution for the baryon asymmetry, but need to first **find *any* leptonic (neutr**
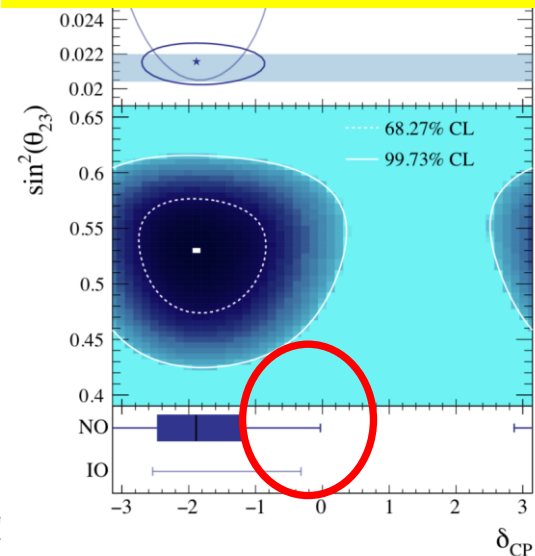
$\sin\delta \neq 0$?
Leptonic CP violation?

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 $\delta=0$	Expectation	
		$\delta_{CP} = -90°$	$\delta_{CP} = +90°$
Electron neutrino	70	82	56
Electron antineutrino	20	17	22
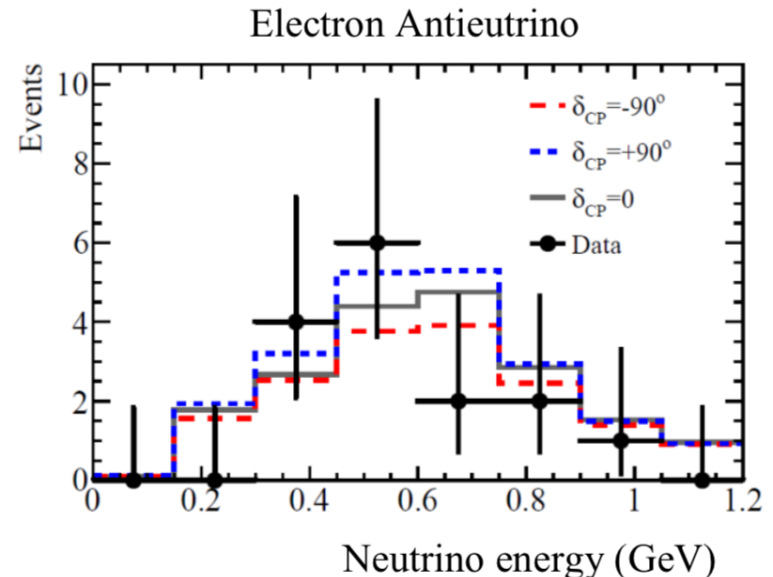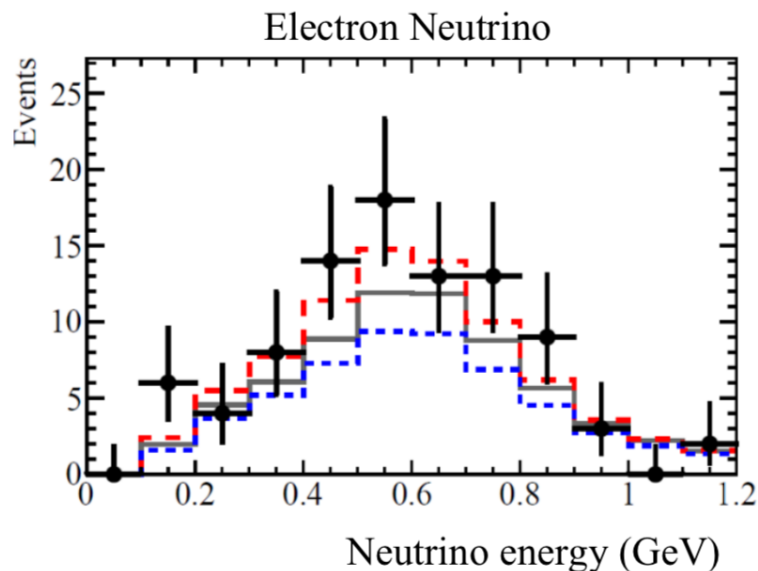
CP Violation: T2K Result

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

Determination of δ_{CP}
Appearance of ν_e events
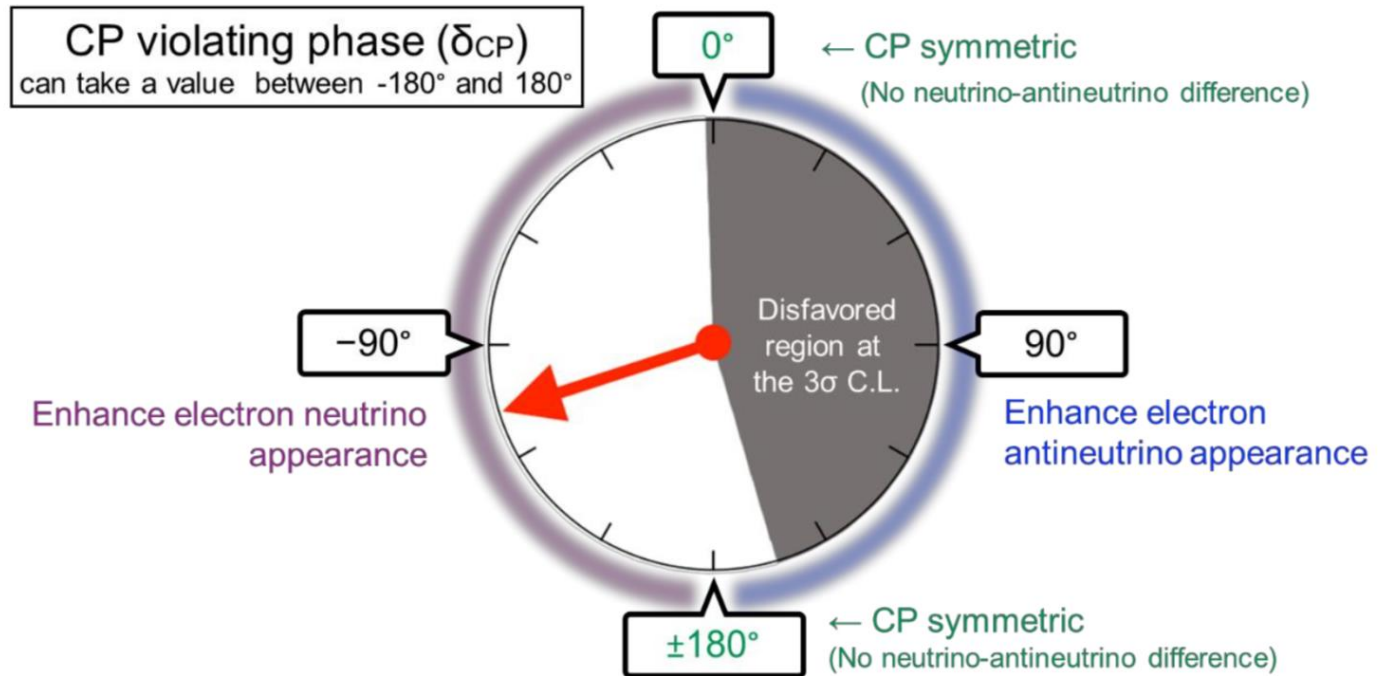
The gray region is disfavored by 99.7% (3σ) CL
The values 0 and 180 degrees are disfavoured at 95% CL

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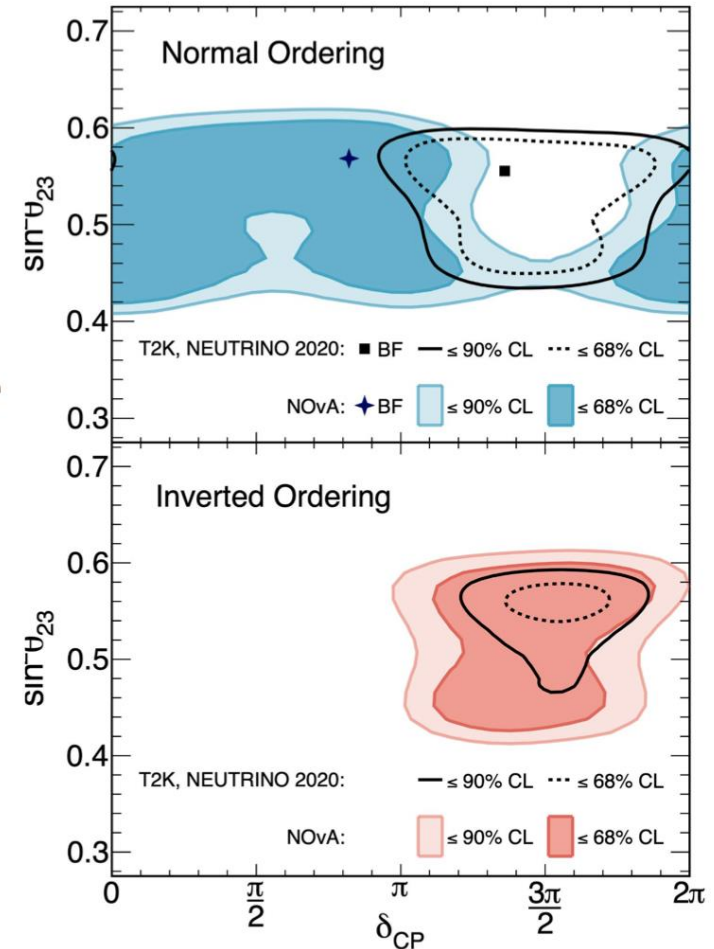
NOvA/T2K will continue to take data till 2026/2027
-> double the statistics of present analyses, reduce systematics

T2K Future

- Gadolinium now added to SK water: not yet used in analysis but neutron signal seen
- Significant enhancement in neutron capture: anti-neutrino events tagging
- Also the T2K neutrino beamline upgrade on-going

Accumulate more data in the next years
- Reduce systematics uncertainties
- Replica of the beam target has been put proton beam of NA61 this summer
- Reach 3σ for non-CPV rejection prior to Hyper-Kamiokande
- T2K+HK atmospheric joint fit

+ upgrade of the ND280 near detector
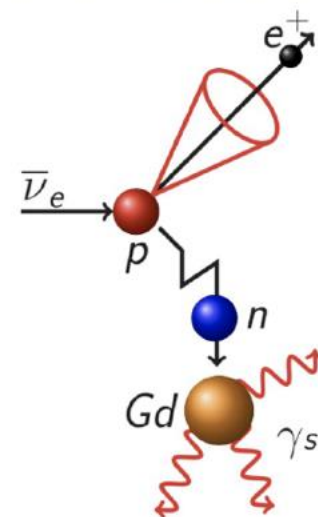
8 MeV γ cascade
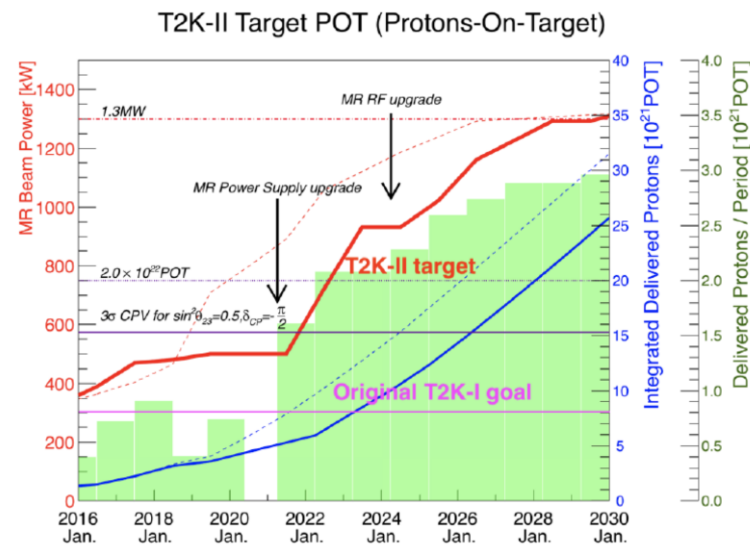
Neutrino Experiments

- Atmospheric parameter determinations by several experiments
- Results are consistent
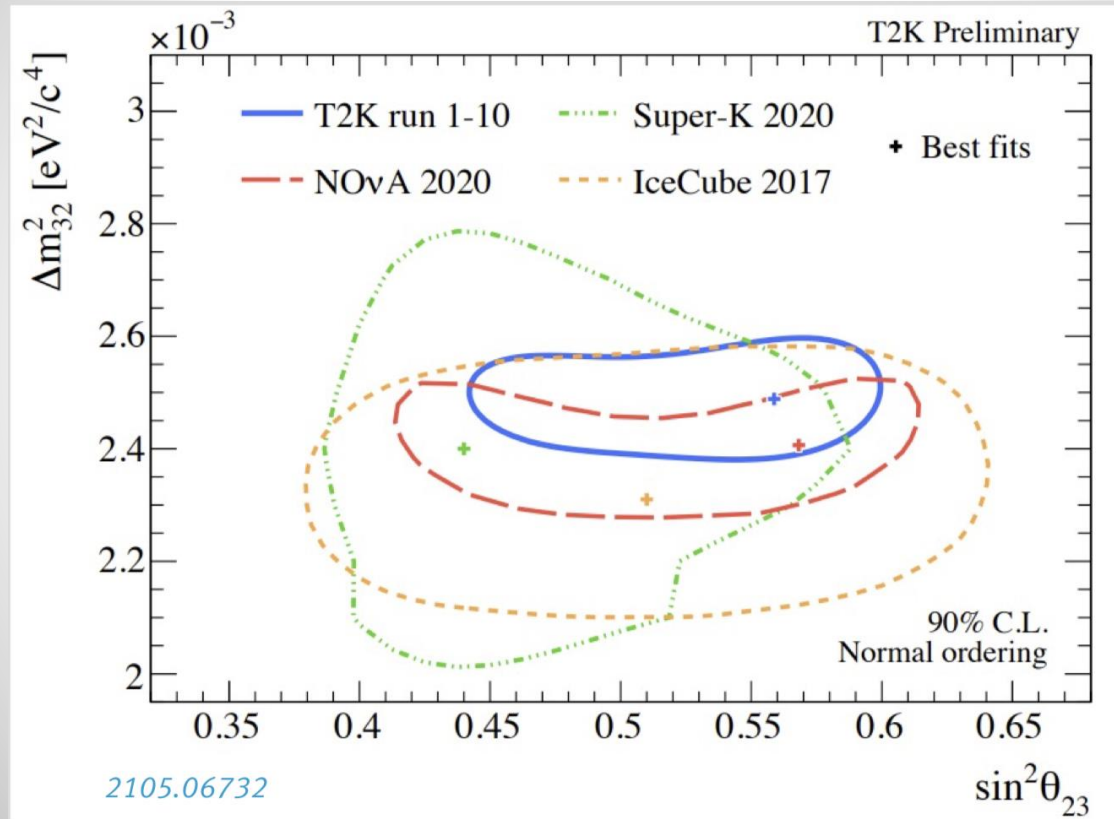
2105.06732

- Δm^2_{32} -vs- $\sin^2\theta_{23}$: at 90% CL, θ_{23} contours overlap. T2K and NOvA favour upper octant while Super-K prefers lower

Recent Global Neutrino Data Fits

Recent 3-neutrino global analysis

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	$\sin^2\theta_{12}$	$0.304^{+0.012}_{-0.012}$	$0.269 \to 0.343$	$0.304^{+0.013}_{-0.012}$	$0.269 \to 0.343$
	$\theta_{12}/°$	$33.45^{+0.77}_{-0.75}$	$31.27 \to 35.87$	$33.45^{+0.78}_{-0.75}$	$31.27 \to 35.87$
	$\sin^2\theta_{23}$	$0.450^{+0.019}_{-0.016}$	$0.408 \to 0.603$	$0.570^{+0.016}_{-0.022}$	$0.410 \to 0.613$
	$\theta_{23}/°$	$42.1^{+1.1}_{-0.9}$	$39.7 \to 50.9$	$49.0^{+0.9}_{-1.3}$	$39.8 \to 51.6$
	$\sin^2\theta_{13}$	$0.02246^{+0.00062}_{-0.00062}$	$0.02060 \to 0.02435$	$0.02241^{+0.00074}_{-0.00062}$	$0.02055 \to 0.02457$
	$\theta_{13}/°$	$8.62^{+0.12}_{-0.12}$	$8.25 \to 8.98$	$8.61^{+0.14}_{-0.12}$	$8.24 \to 9.02$
	$\delta_{CP}/°$	230^{+36}_{-25}	$144 \to 350$	278^{+22}_{-30}	$194 \to 345$
	$\dfrac{\Delta m^2_{21}}{10^{-5}\ \text{eV}^2}$	$7.42^{+0.21}_{-0.20}$	$6.82 \to 8.04$	$7.42^{+0.21}_{-0.20}$	$6.82 \to 8.04$
	$\dfrac{\Delta m^2_{3\ell}}{10^{-3}\ \text{eV}^2}$	$+2.510^{+0.027}_{-0.027}$	$+2.430 \to +2.593$	$-2.490^{+0.026}_{-0.028}$	$-2.574 \to -2.410$

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

General Picture

Approximate flavor compostion of the mass eigenstates and mass differences (squared)
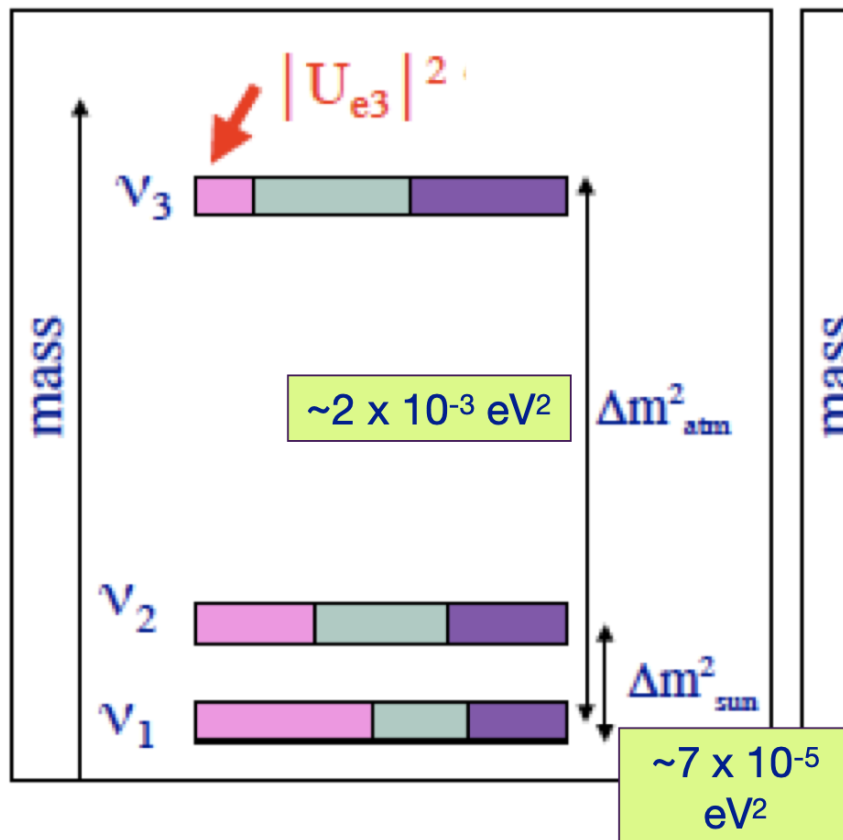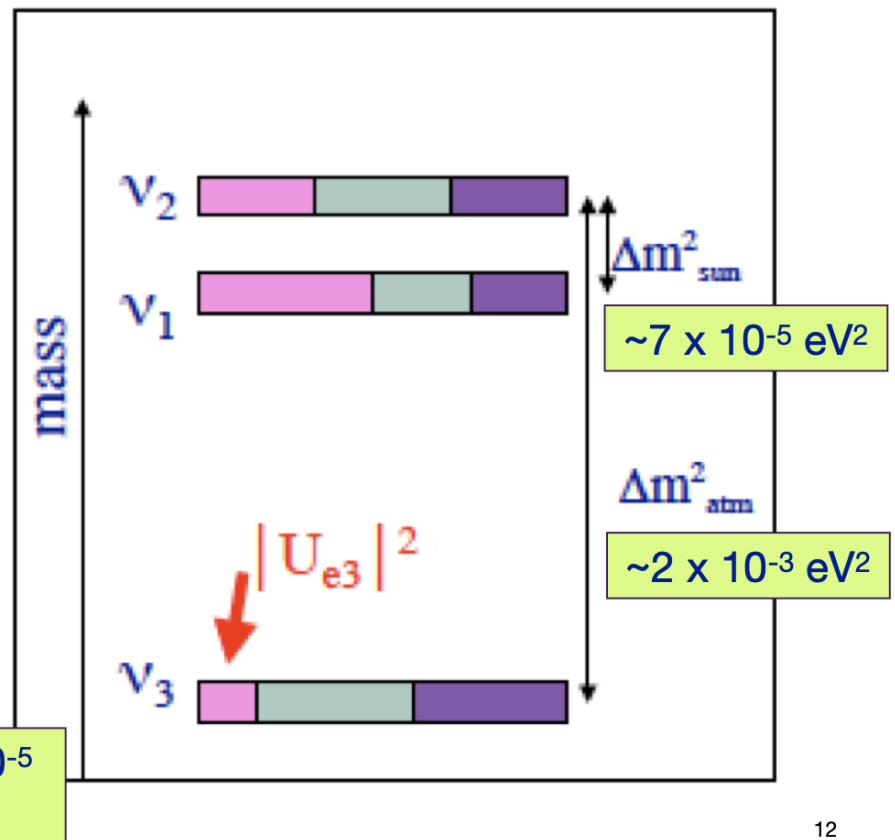
Neutrino Parameter Evolution

Towards precision physics
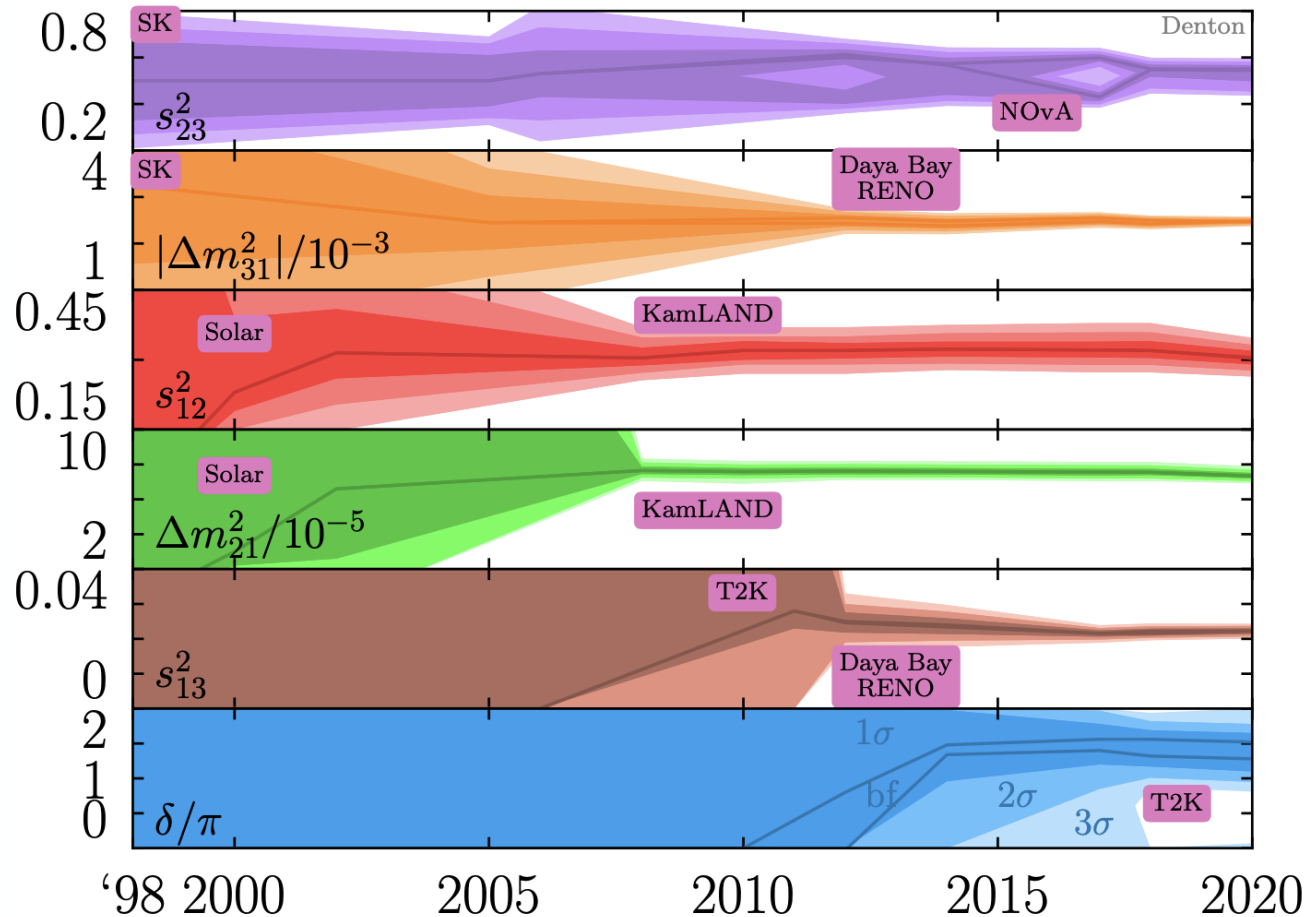
The past 20 years have seen a remarkable progress in determining neutrino properties!

CMK vs PMNS

Why is neutrino mixing so different from quark mixing?
What does that tell us?

CKM
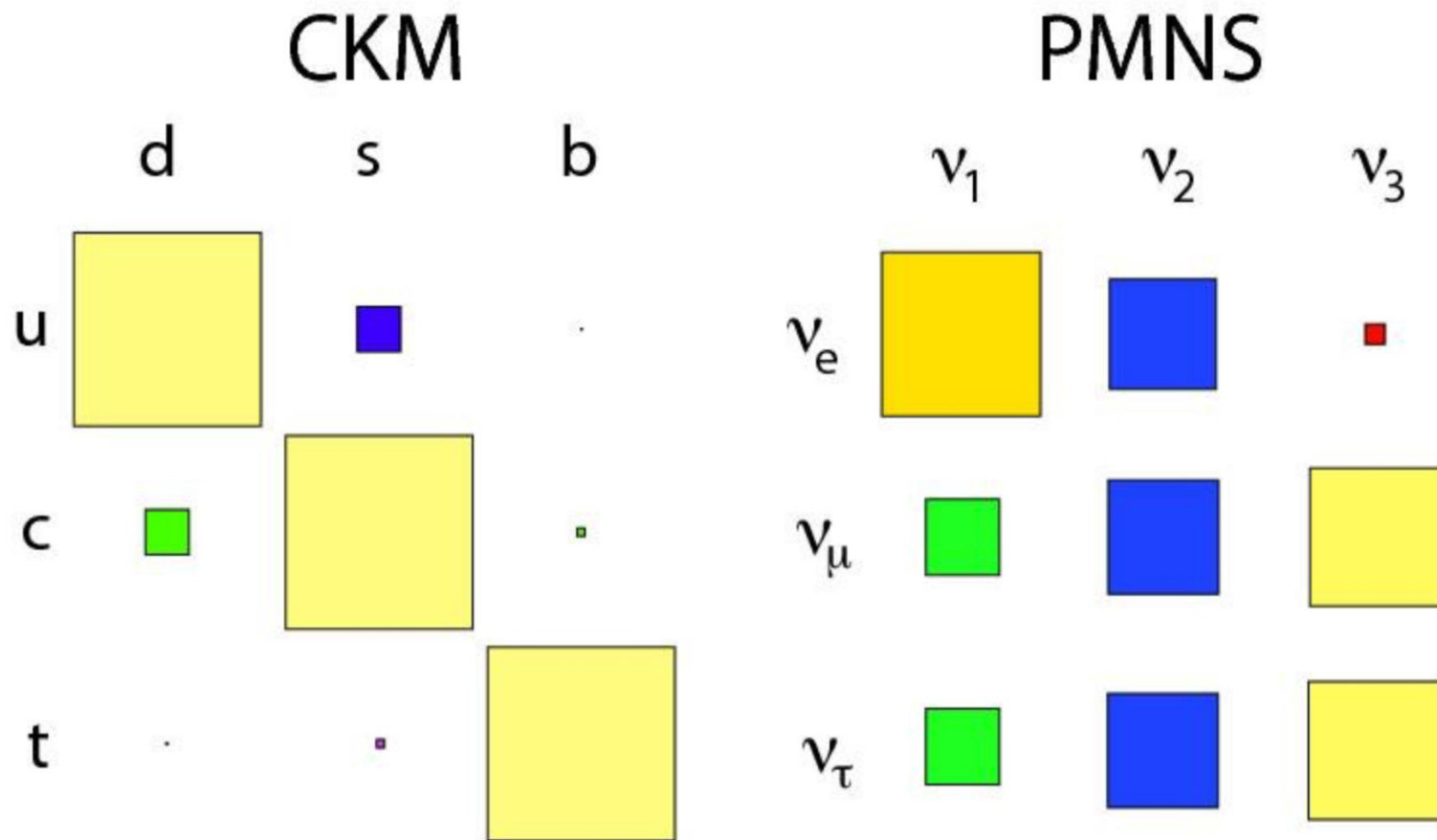
PMNS

The CKM matrix is almost diagonal, while the PMNS matrix is almost uniform.

Neutrino Oscillations

Neutrino Mass EigenStates or Propagation States:

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

ν_1
most ν_e **68%**

ν_2
30 % ν_e

ν_3
least ν_e **2%**
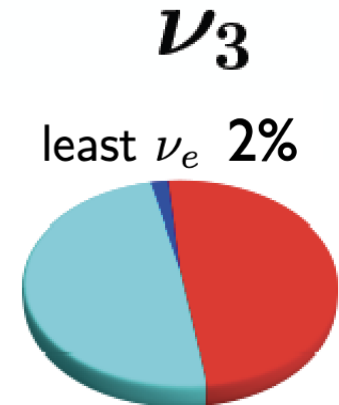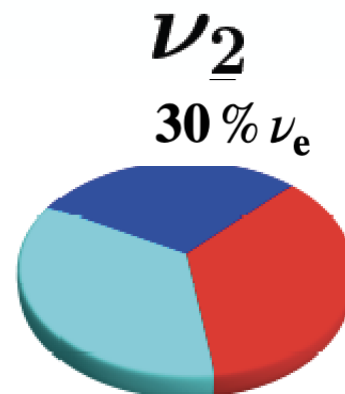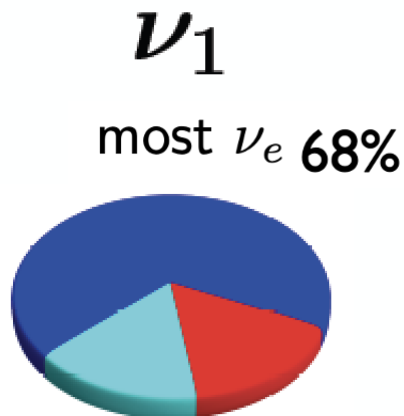
$\nu_e =$
Solar Exp, SNO
KamiLAND
Daya Bay, RENO, …

$\nu_\mu =$
SuperK, K2K, T2K
MINOS, NOvA
ICECUBE

$\nu_\tau =$
Unitarity
SK, Opera
ICECUBE ?

Neutrino Properties

Neutrino Mass

The smallness of the neutrino mass $m_\nu \ll m_{e, u, d}$
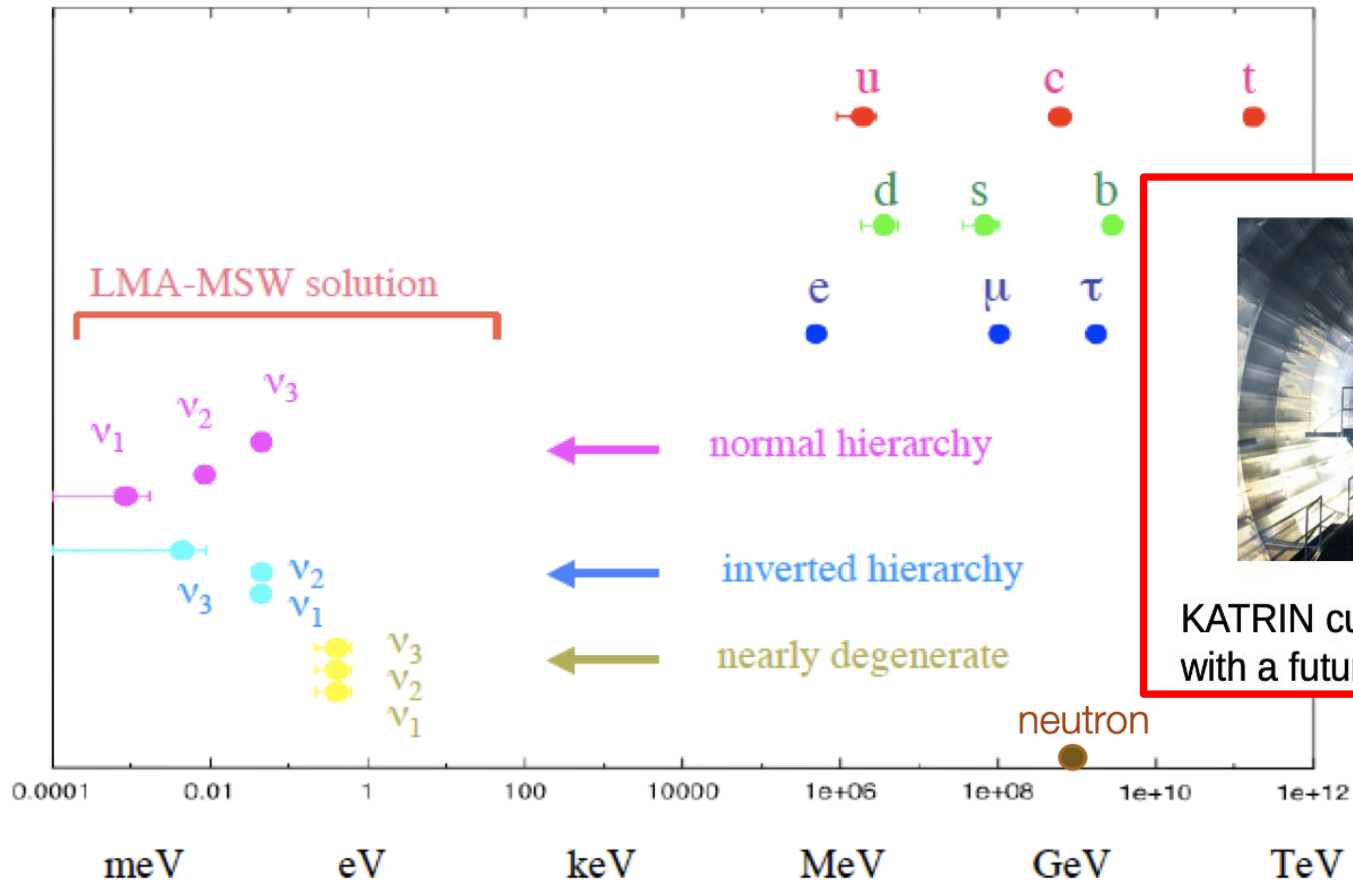
KATRIN current limit is 0.8eV
with a future sensitivity of 0.2eV

Neutrino Mass Measurents

Complementary paths to the ν mass scale
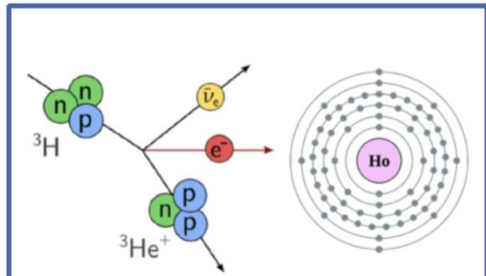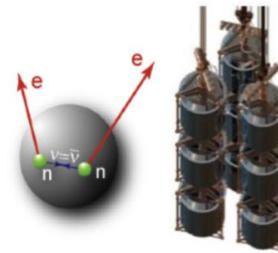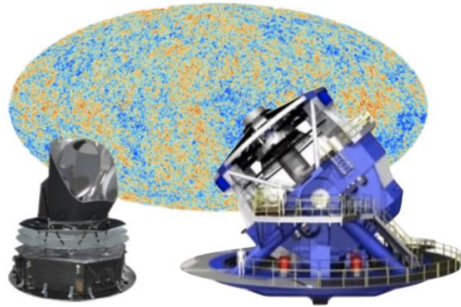
	Cosmology	Search for 0νββ	Kinematics of weak decays
Method	Structure of Universe at early and evolved stages	ββ-decay of ^{76}Ge, ^{130}Te, ^{136}Xe, …	β-decay of ^{3}H, EC of ^{163}Ho
Observable	$M_\nu = \sum_i m_i$	$m^2_{\beta\beta} = \left\| \sum_i U^2_{ei} m_i \right\|^2$	$m^2_\beta = \sum_i \left\| U_{ei} \right\|^2 m^2_i$
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
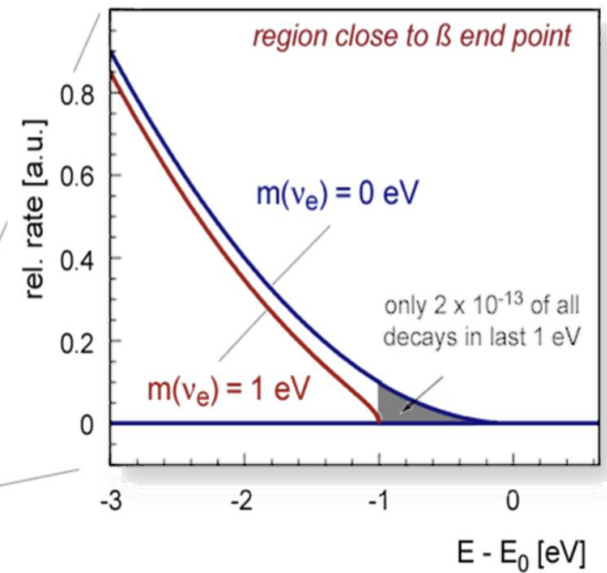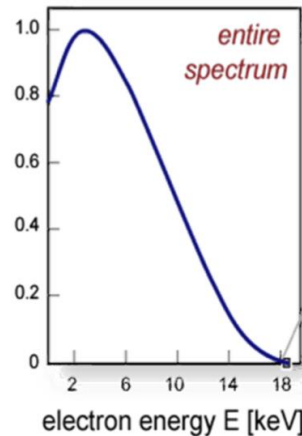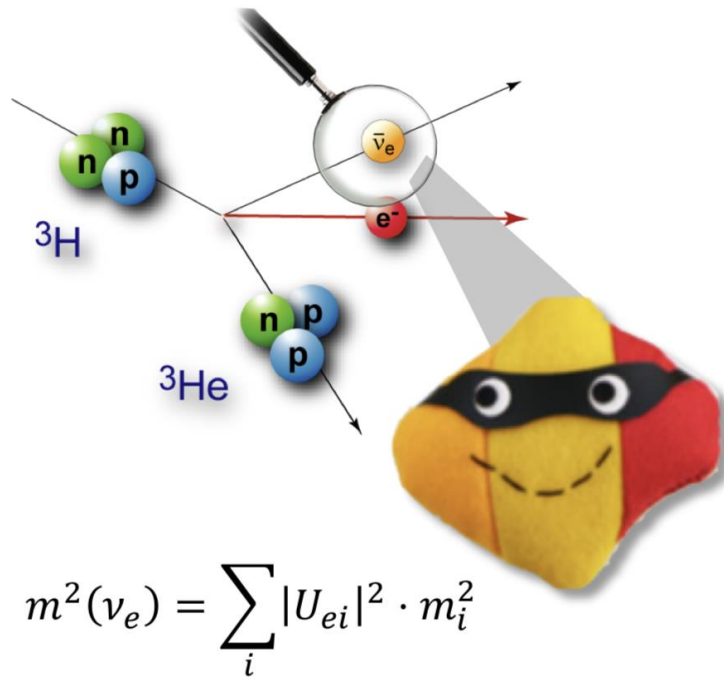
What is measured really in this experiment is the effective electron anti-neutrino mass defined by $m^2(\nu_e) = \sum_i |U_{ei}|^2 \cdot m_i^2$ with U_{ei} the PMNS mixing elements

KATRIN Experiment: the Mass of ν_e
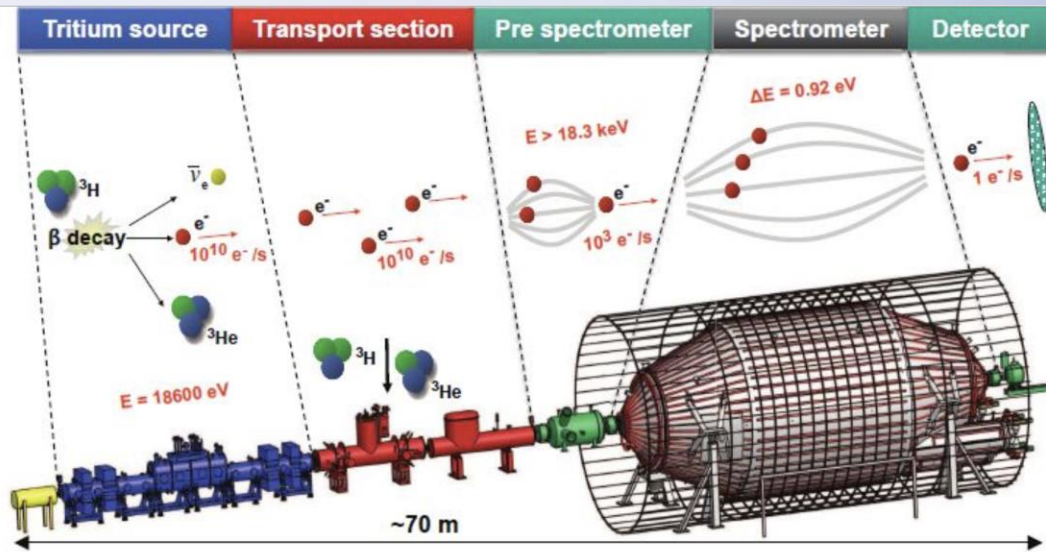
The KArlsruhe TRItium Neutrino experiment (KATRIN) is designed to measure the mass up to projected sensitivity of 0.2eV
To achieve this, KATRIN will perform high-precision spectroscopy of the endpoint region of the tritium beta-decay spectrum.

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!
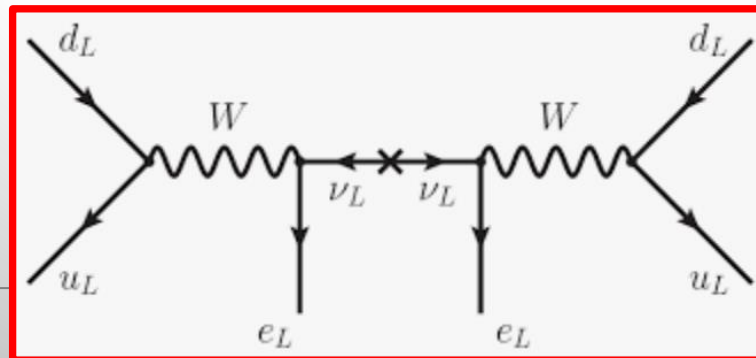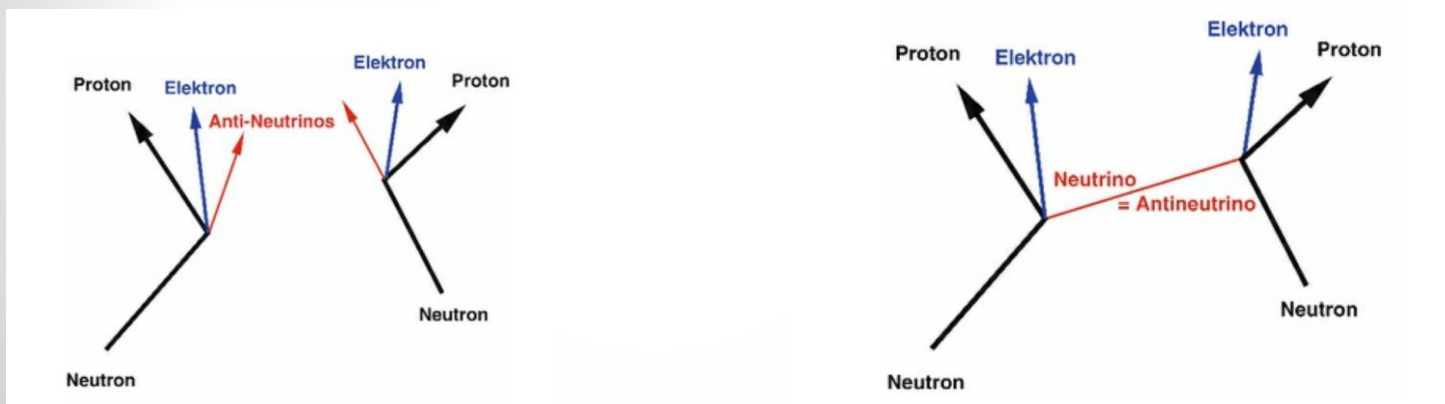
Neutrinoless Double Beta Decay

Final results: arXiv:2009.06079

127.2 kg.year exposure between 2011-2019

Experiment now completed
No $0\nu\beta\beta$ signal observed ☹
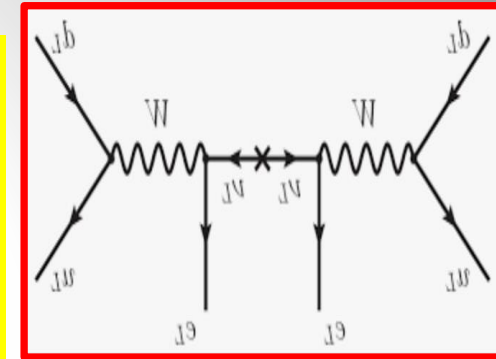
upper mass limit: $m_{\beta\beta} < 79 - 180$ meV

- Present best limits:
  - ^{136}Xe (KamLAND-Zen): $T_{1/2} > 10^{26}$ yrs
  - ^{76}Ge (GERDA): $T_{1/2} > 10^{26}$ yrs
  - ^{130}Te (CUORE): $T_{1/2} > 3 \times 10^{25}$ yrs

- Future goal:
  ~2 OoM improvement in $T_{1/2}$
  - Covers IO
  - Up to 50% of NO
  - Factor of ~few in Λ
  - An aggressive experimental goal

$$\frac{1}{T_{1/2}} = G_{01}\, g_A^4 \left(M^{0\nu} + \frac{g_\nu^{NN} m_\pi^2}{a_\Lambda^2} M^{0\nu}_{cont} \right)^2 \frac{m_{\beta\beta}^2}{m^2}$$

Best so far: $T_{1/2} > 10^{26}$ yr

GERDA
KZ
Exo-200

inverted mass ordering

normal mass ordering

$m_{\beta\beta}$ [eV]

m_{light} [eV]
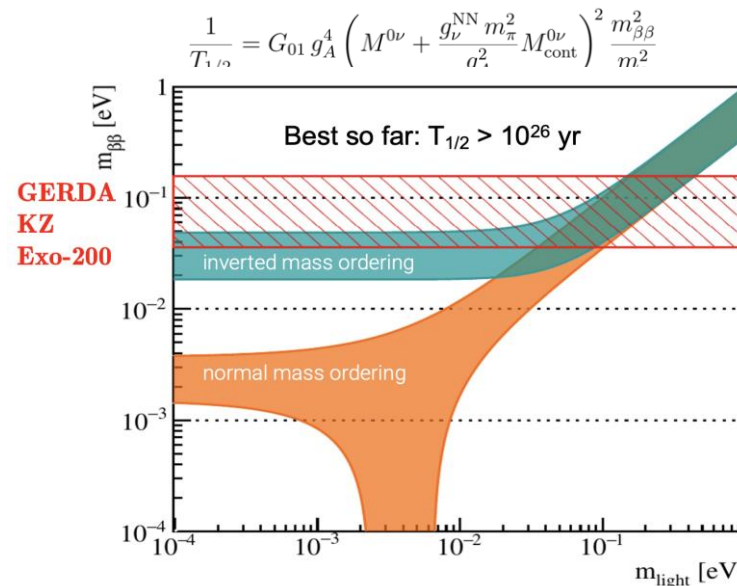
Anomalies

search for sterile neutrino

with $\Delta m^2 \sim 1 \text{ eV}^2$

Sterile Neutrinos

Several anomalies around in the community since some years...
Additional sterile neutrinos as a possible candidate explanation

☑ Very generic extension of SM

  ○ can be leftover of extended gauge multiplet

☑ Useful phenomenological tool

  ○ can explain **v** masses (seesaw mechanism, m ~ TeV...M$_{Pl}$)

  ○ can explain cosmic baryon asymmetry (leptogenesis, m≫100 GeV)

  ○ can explain dark matter (m ~ keV)

  ○ can explain oscillation anomalies (m ~ eV)
     Promote mixing matrix to 4 x 4, oscillation formula unchanged:

$$P_{\alpha \to \beta} = \sum_{j,k} U^*_{\alpha j} U_{\beta j} U_{\alpha k} U^*_{\beta k} \exp\left[-i(E_j - E_k)T\right]$$

J. Kopp, Neutrino 2022
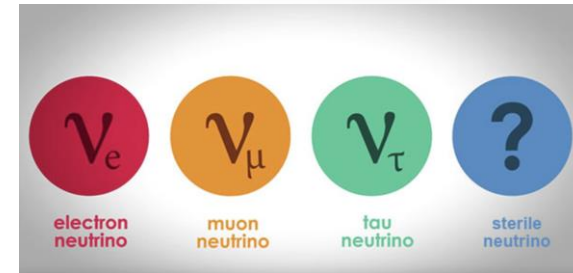
Anomalies
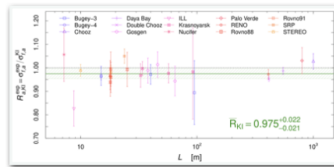
reactor flux anomaly
resolved with new input data
to flux calculation
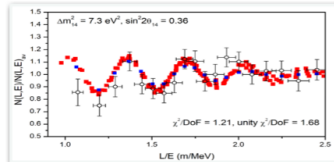
reactor spectra
is there really an anomaly?
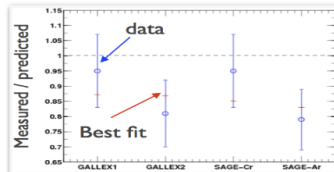
gallium anomaly
unresolved, recently reinforced
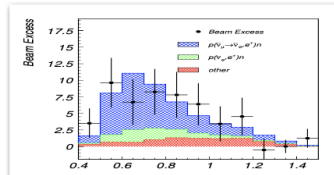
LSND
unresolved
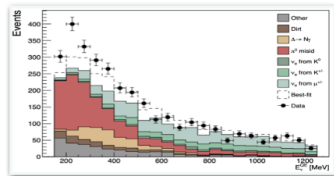
MiniBooNE
unresolved
resolvable by next-gen. SBL experiments

– Most anomalies at ~3-4 σ level
– Simplest 3+1 model seems in tension to cover all anomalies
  • Some anomalies seems real, but maybe not related to sterile neutrinos

Neutrino Anomalies
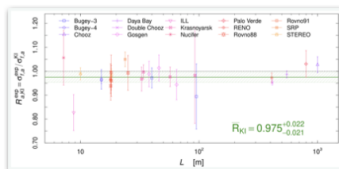
reator flux anomaly
resolved with new input data
to flux calculation ✔
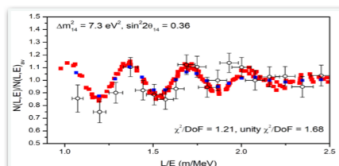
reactor spectra
is there really an anomaly? -> DANSS ?
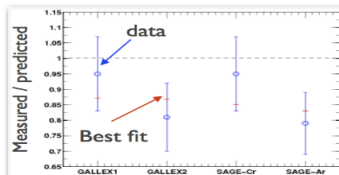
gallium anomaly
unresolved, recently reinforced BEST ?
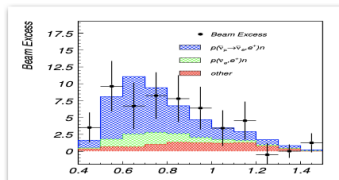
LSND
unresolved ?
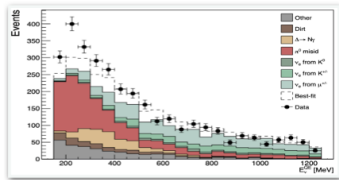
MiniBooNE
unresolved μBooNe excluded some explanations
resolvable by next-gen. SBL experiments ?

More details in the backup

- Jury still out on many of these anaomalies. No clear picture emerging yet.
- Simple sterile neutrino would not fit all the data. Tensions on all sides...
- Future: Reactor experiments continuing or new ones (eg JSNS²) or new experiments at the FNAL short neutrino baseline... (ICARUS, SBND)

New Short Baseline Experiments will check!

Experiments at reactors, eg the SoLid experiment @BR2 reactor in Belgium
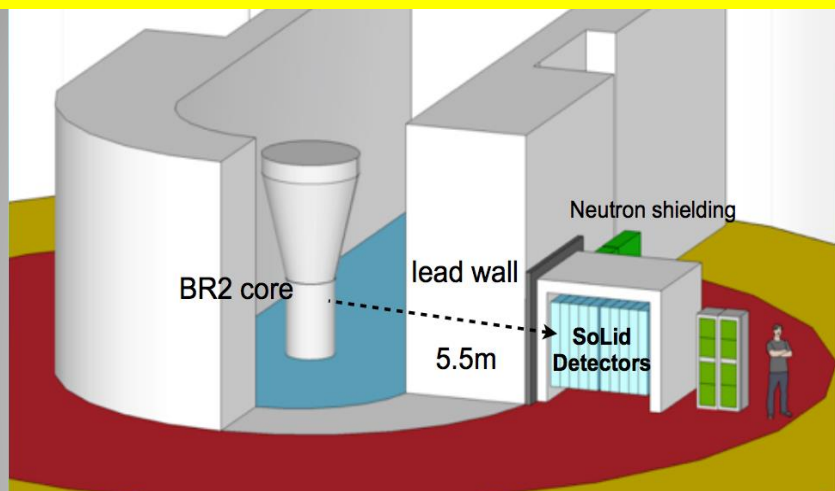
$$\bar{\nu}_e + p \rightarrow e^+ + n$$
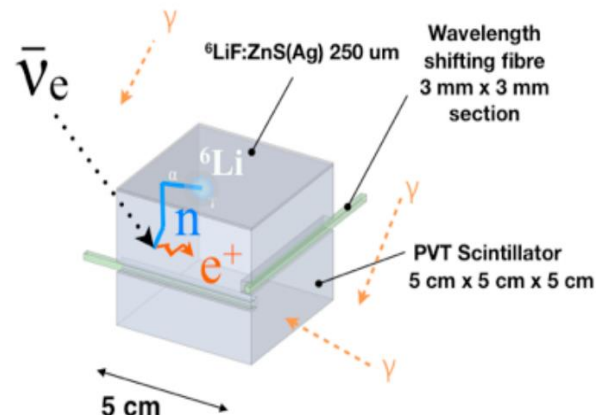
Also: Prospect, STEREO, NEOS…
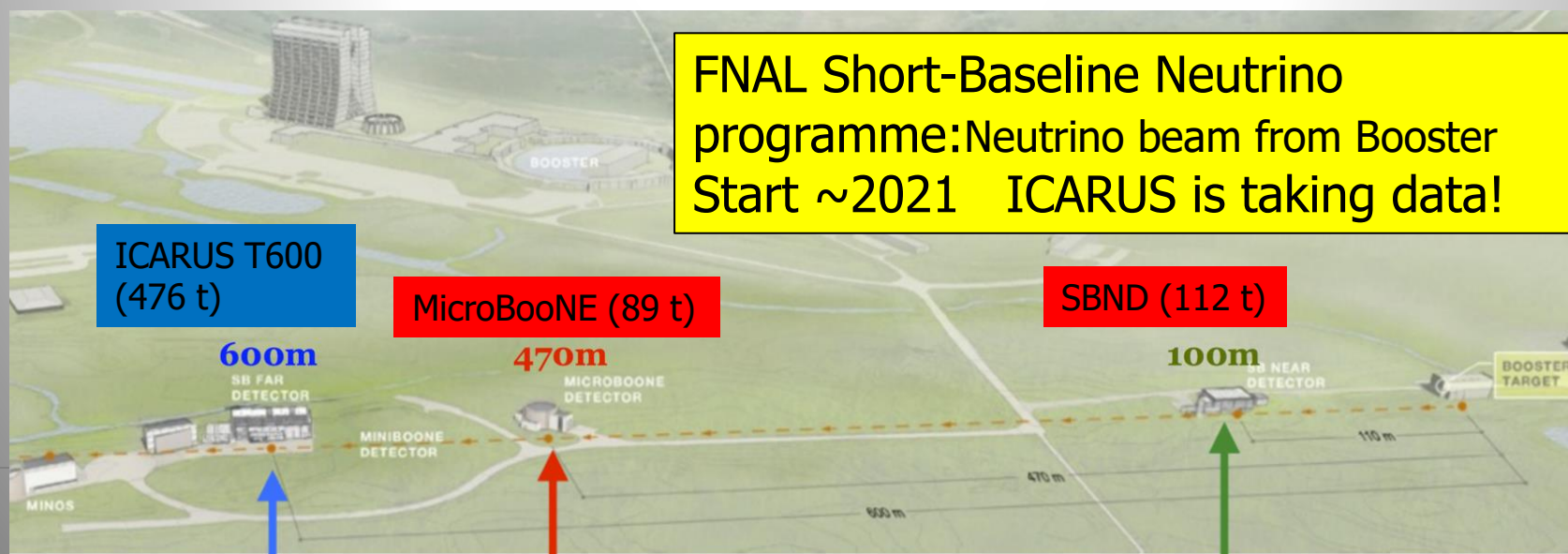
FNAL Short-Baseline Neutrino programme: Neutrino beam from Booster
Start ~2021   ICARUS is taking data!

ICARUS T600 (476 t)

MicroBooNE (89 t)

SBND (112 t)

600m

470m

100m

Astrophysical Sources of Neutrinos

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

Neutrino Astronomy

Gigantic detectors 1 km³ of size and beyond...
Use the resources of planet Earth
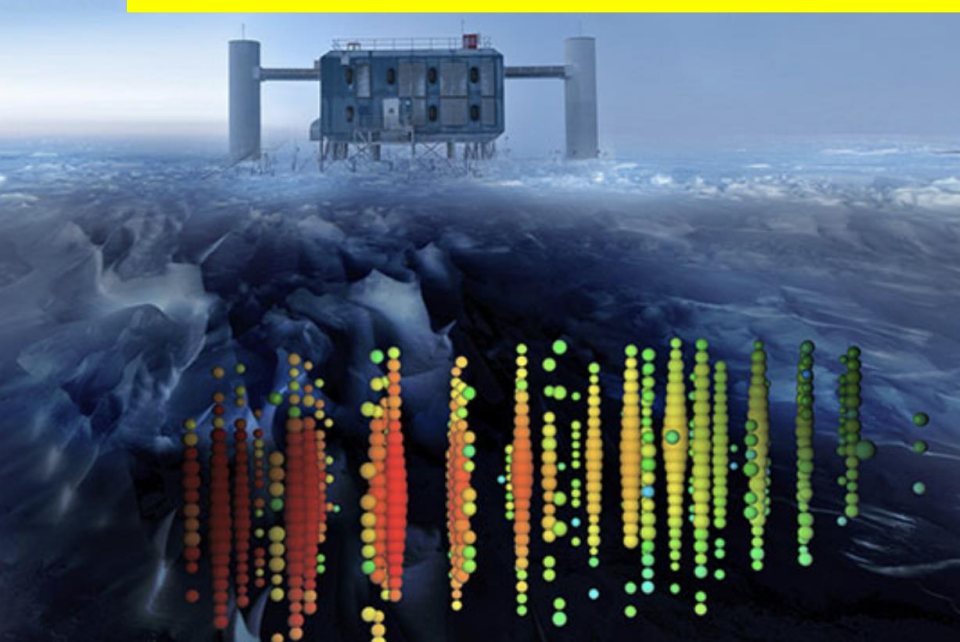
The IceCube Experiment: operational
-> In the ice of Antarctica

The KM3NET Experiment: >30 DU
strings now/ full detector by 2026
-> In the Mediterranean sea...
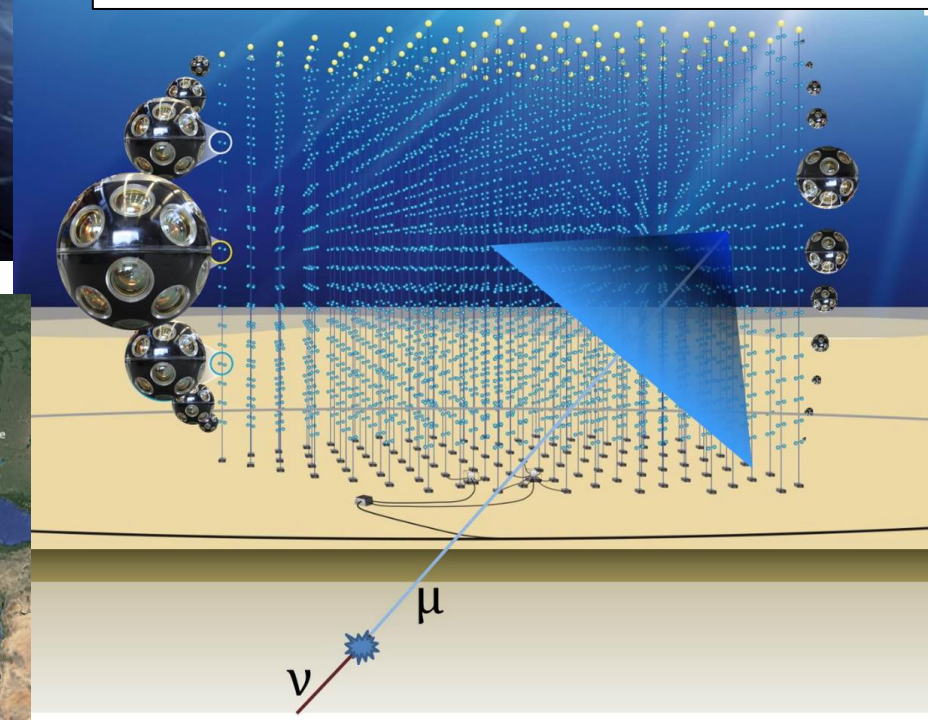
ANTARES
retired this
summer after
14 years

The IceCube Experiment

Result from 8 year data collection with DeepCore
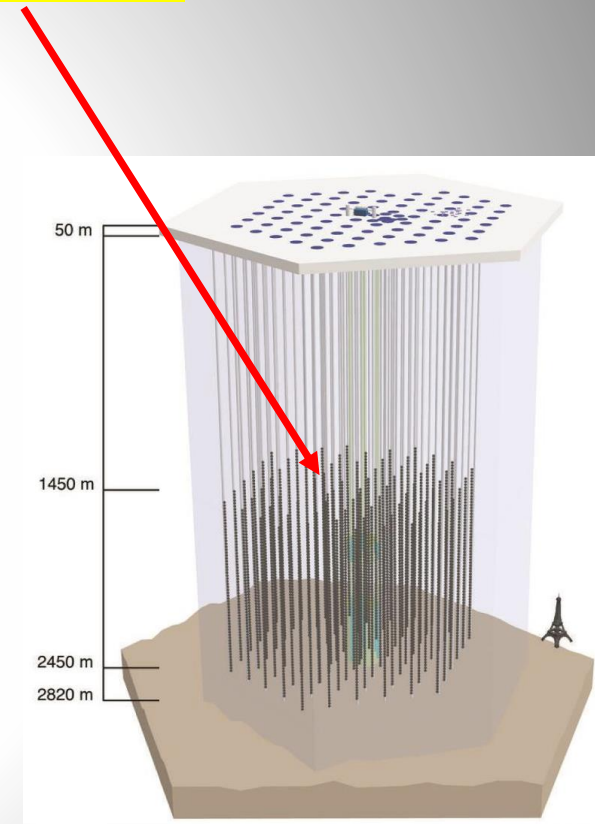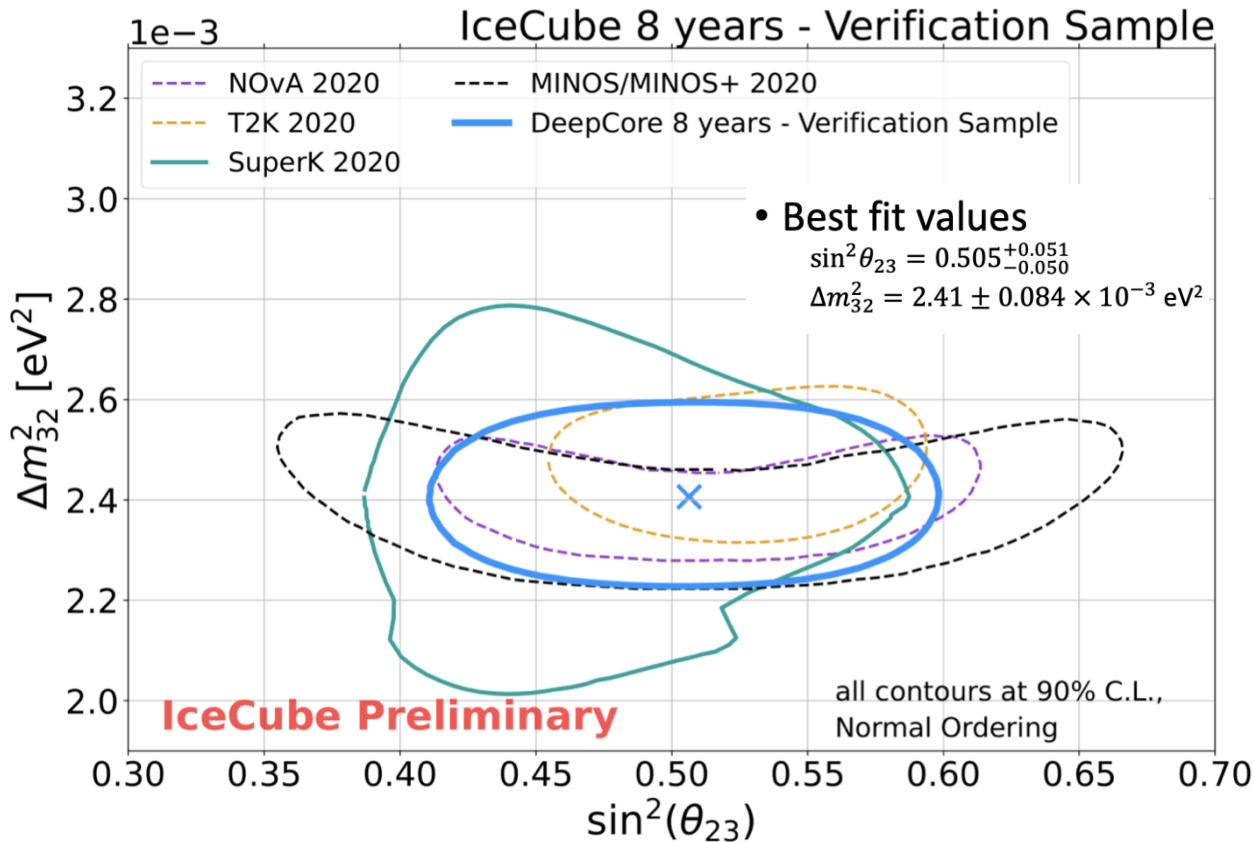
Very competitive measurement....

Baikal-GVD Gigaton Volume Detector

Dzhilkibaev

Projects: Baikai-GVD

- Largest neutrino telescope in the Northern Hemisphere and still growing

- Outlook:

  - 2025/2026 – ~ 1km^3 GVD with total of 16-18 clusters
  - 2022-2024 – "Conceptual Design Report" for next generation neutrino telescope in Lake Baikal

Optical module

Section control module

Deployment schedule

Year	Number of clusters	Number of OMs
2016	1	288
2017	2	576
2018	3	864
2019	5	1440
2020	7	2016
2021	8	2304
2022	10	2880
2023	12	3456
2024	14	4032
2025	16	4608
2026	18	5184

Shore DAQ center

36
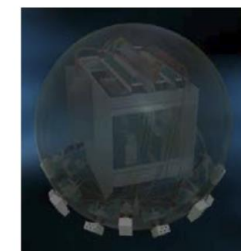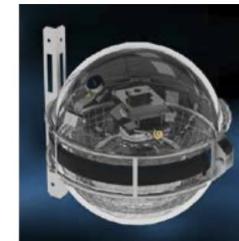
The P-ONE Proposal

The Pacific Ocean Neutrino Experiment

A multi-km^3 neutrino telescope; the first to be hosted by an existing oceanographic infrastructure.

P-ONE

2111.13133
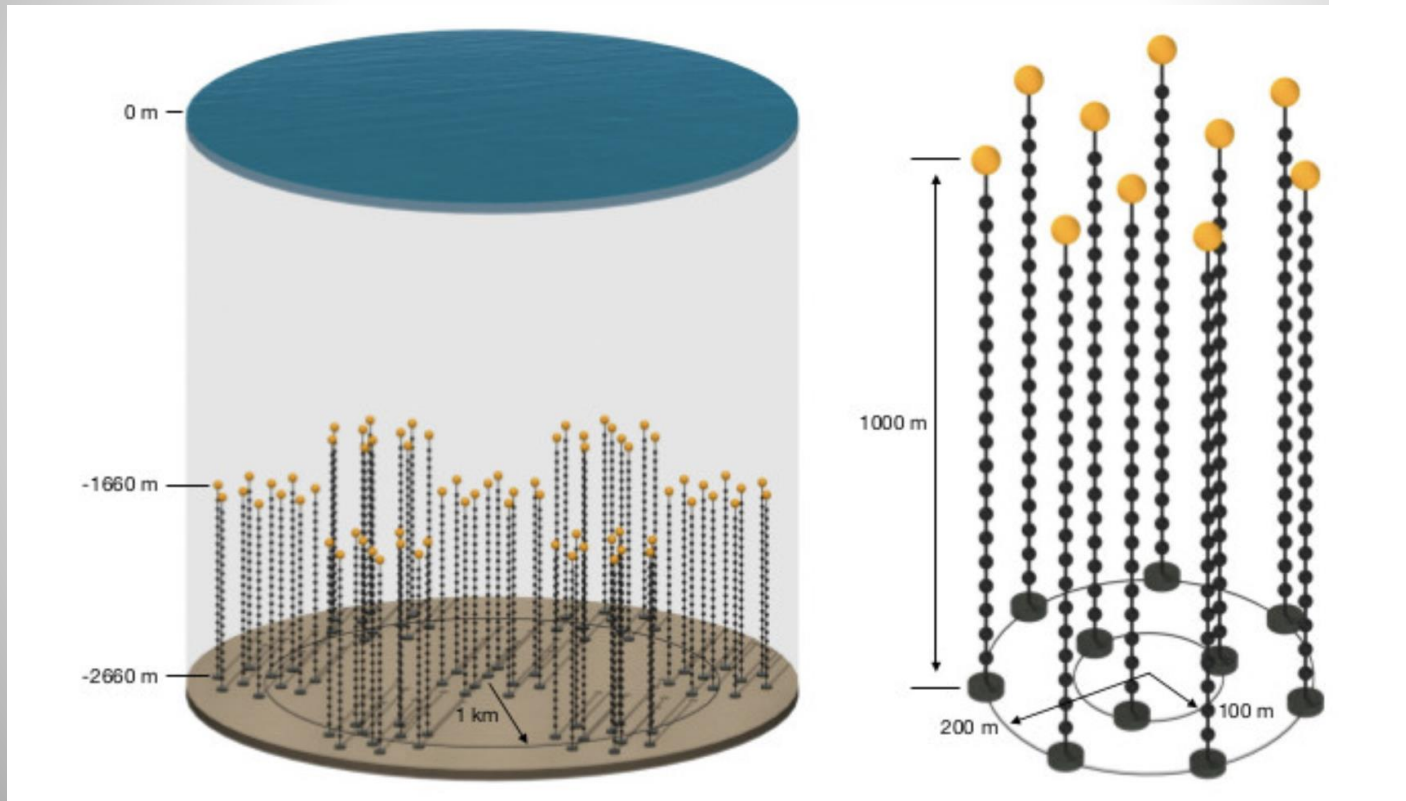
Experiment for energies above 50 TeV. A first segment is planned to be installed in a four weeks sea operation in 2023/24

Large Neutrino Observatories
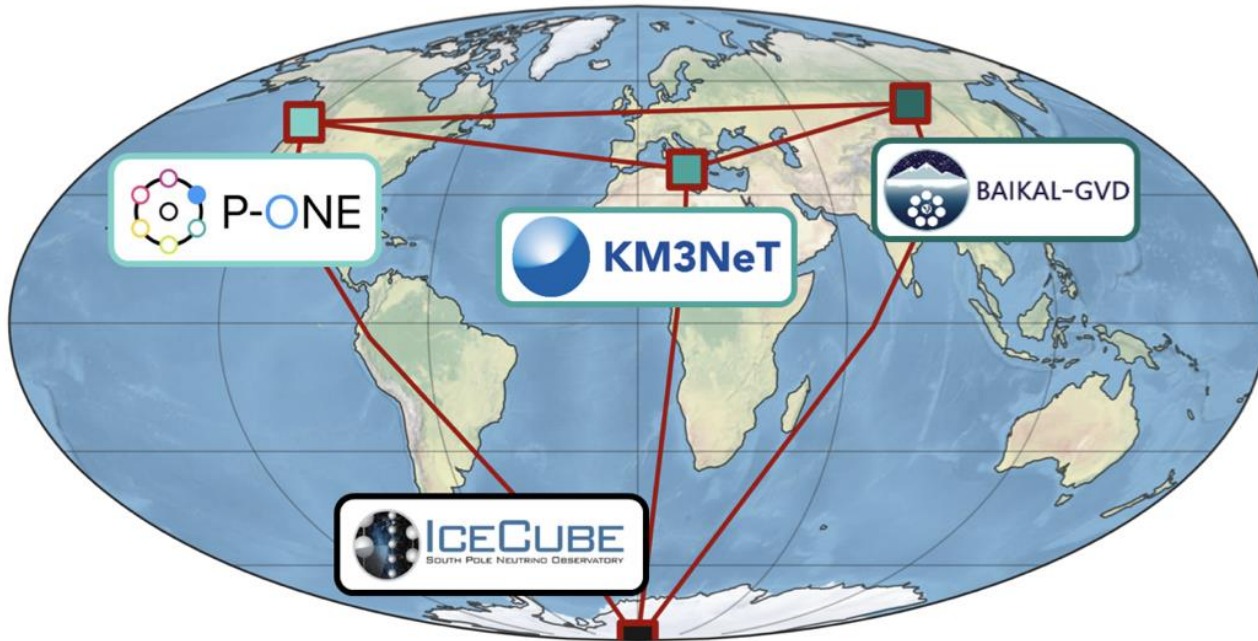
IceCube GEN-2
10 km³
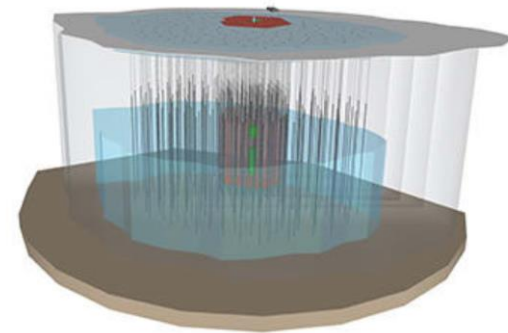
When combined and used as a single distributed planetary instrument (Planetary Neutrino Monitoring System (PLEnUM)), it would cover almost the entire sky
Huge increase of the detection probability for > 50 TeV neutrinos

Multi Messenger Astronomy…

Neutrinos? Perfect Messenger

p

e⁺

e⁻

ν

- electrically neutral
- essentially massless
- essentially unabsorbed
- tracks nuclear processes
- reveal the sources of cosmic rays

- … but difficult to detect

Now:
neutrinods +photons
Next?
neutrinos and
gravitational waves?
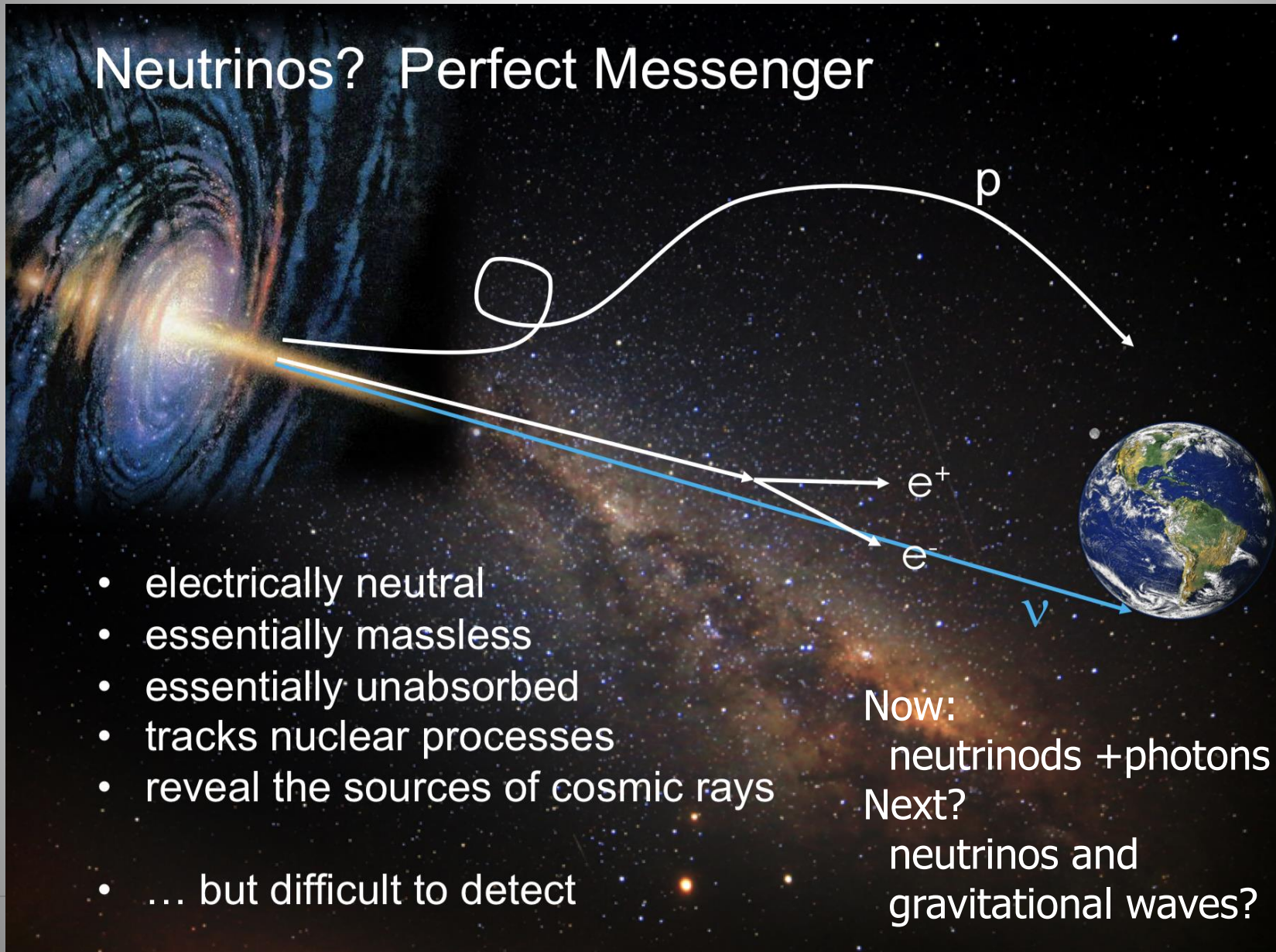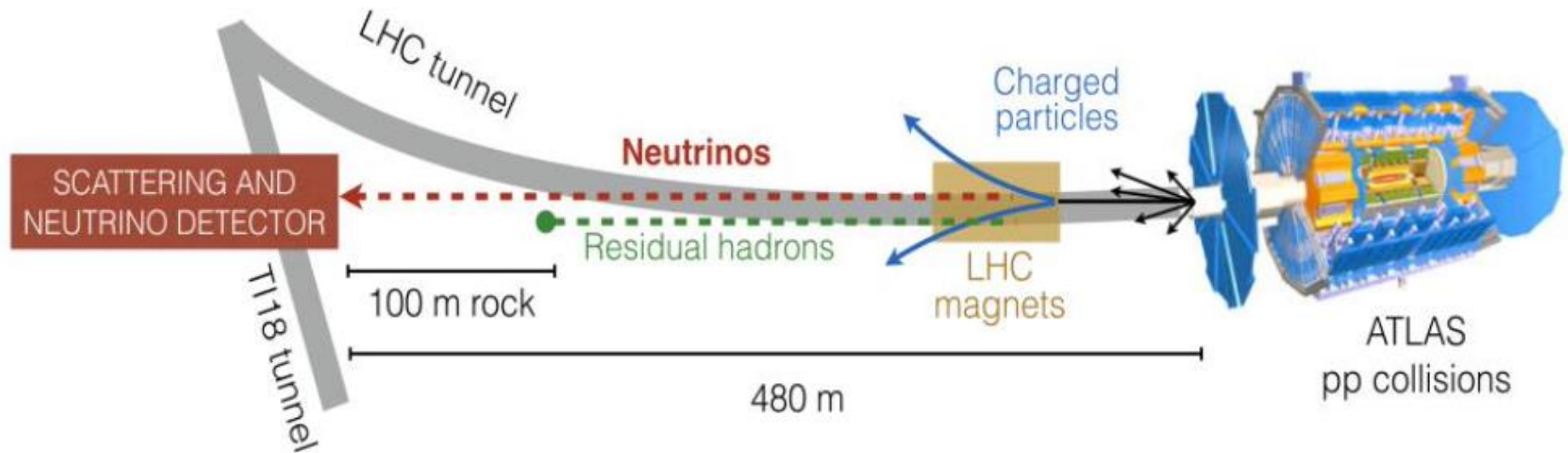
Neutrinos at the LHC!

Neutrinos @ the LHC: Examples

νMSM (Neutrino Minimal Standard Model)

TeV scale right handed Neutrinos
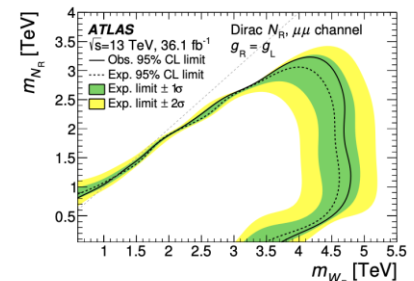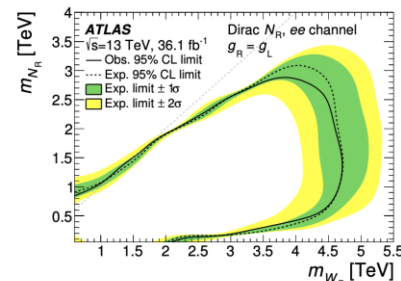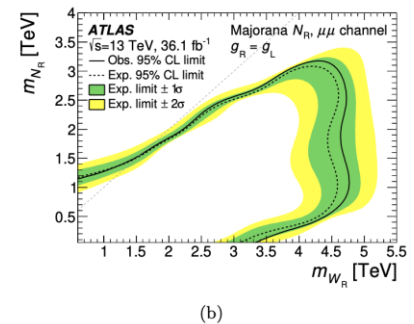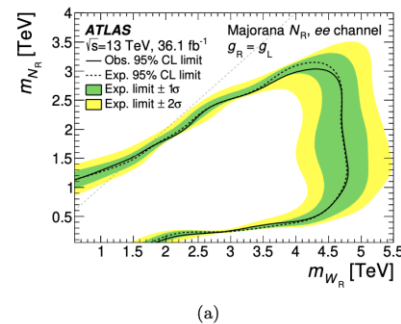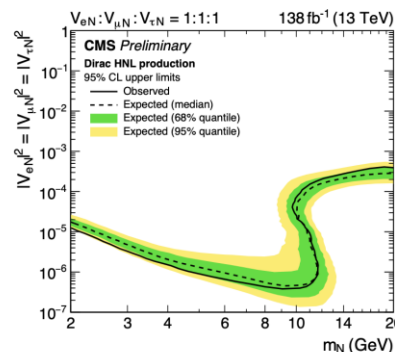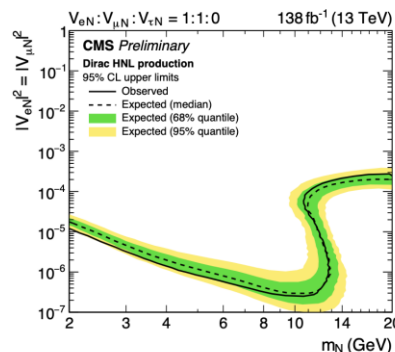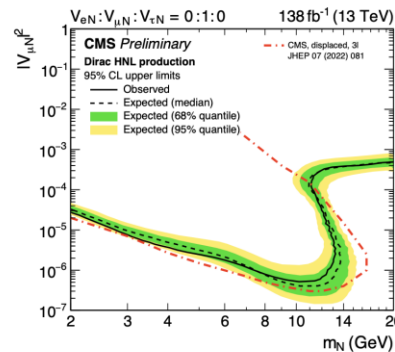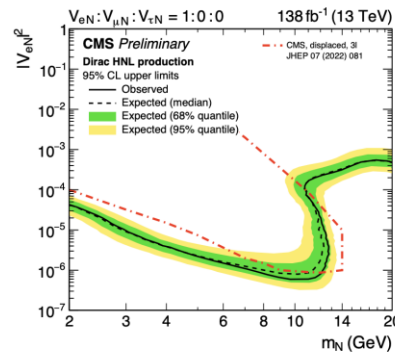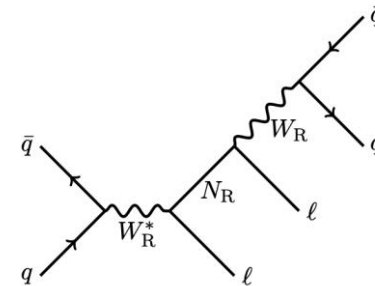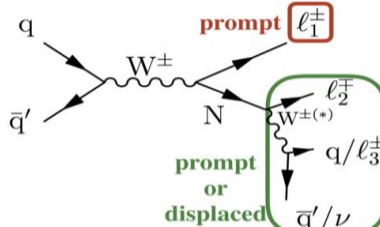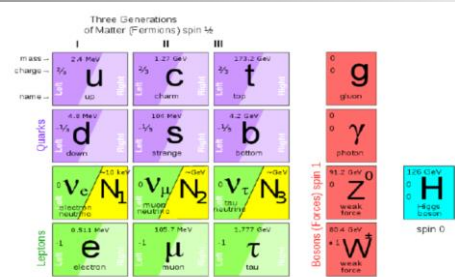
Measuring Neutrino Interactions @ LHC

SND@LHC and FASERν are 480m forward of the IPs 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

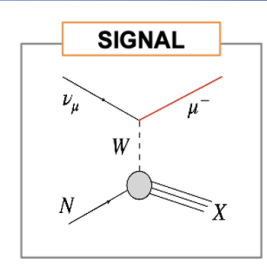SND@LHC/FASERν are 480m forward and can study TeV-neutrinos with emulsion and tracking+muon/calo detectors

SND@LHC

FASER(ν)

ν

FASERν will come

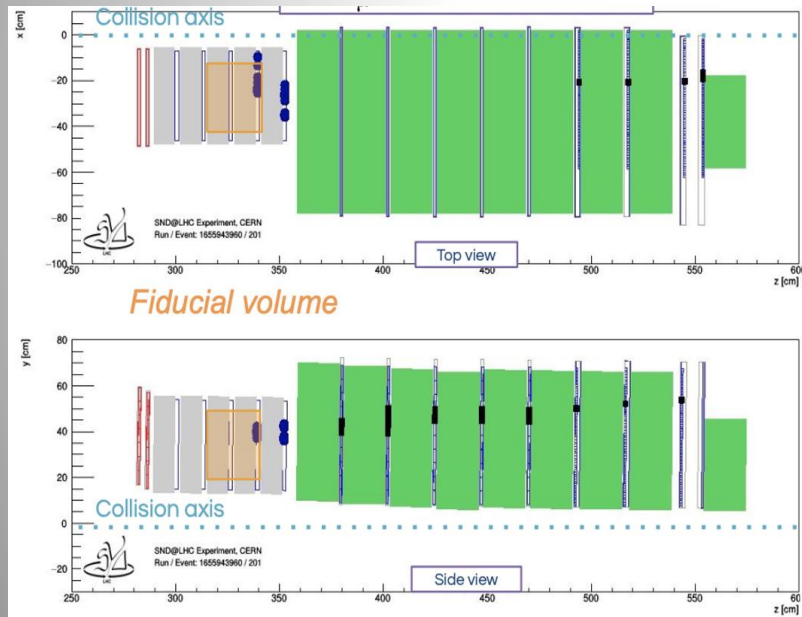FASER spectrometer with 0.55T magnets

Calorimeter
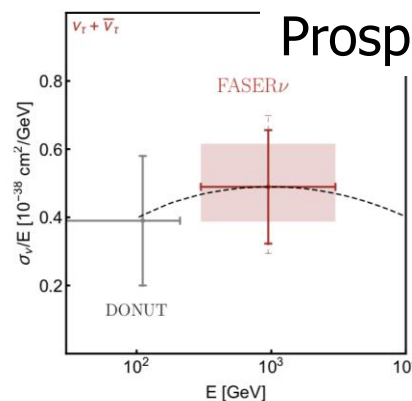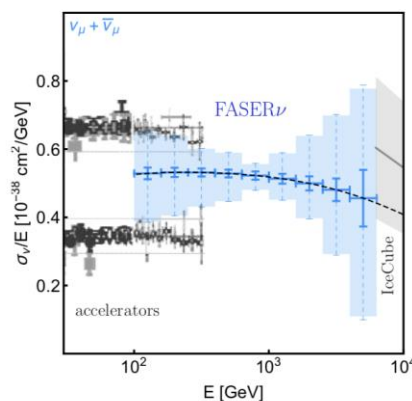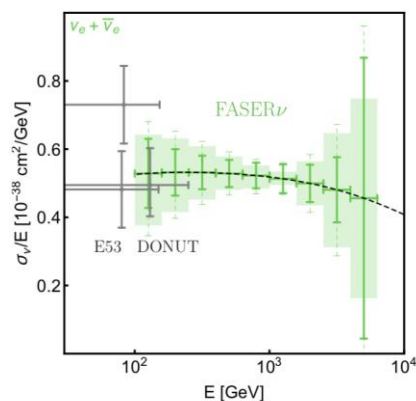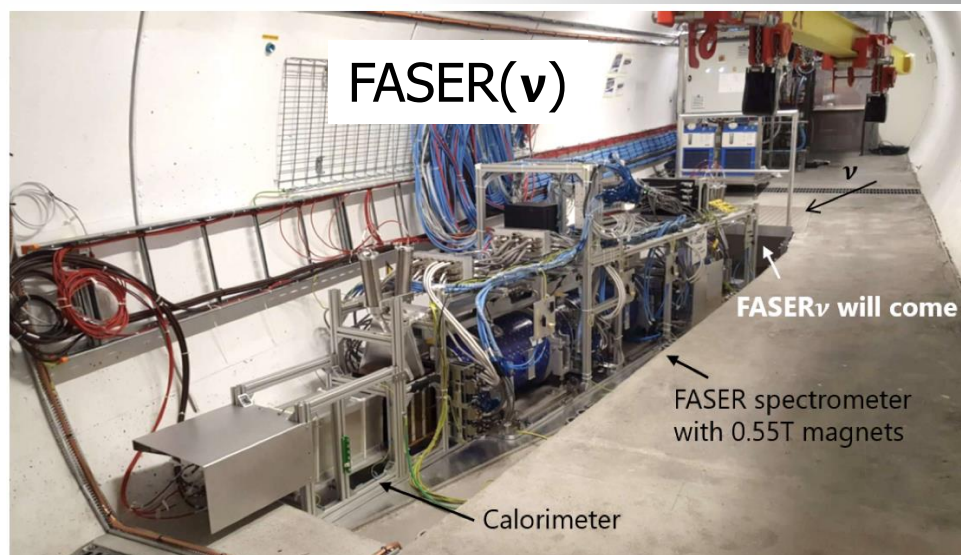
Prospects for Run 3

First Results from FASER and SND@LHC

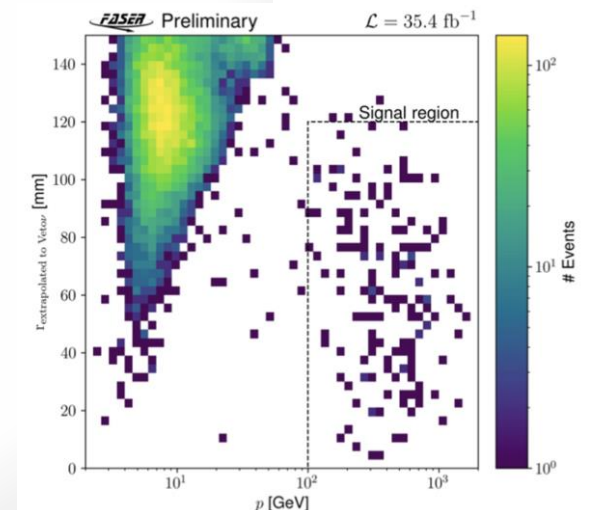Direct observation of neutrinos produced at the LHC in the charged current muon channel

SND@LHC (off-axis)   2305.09383

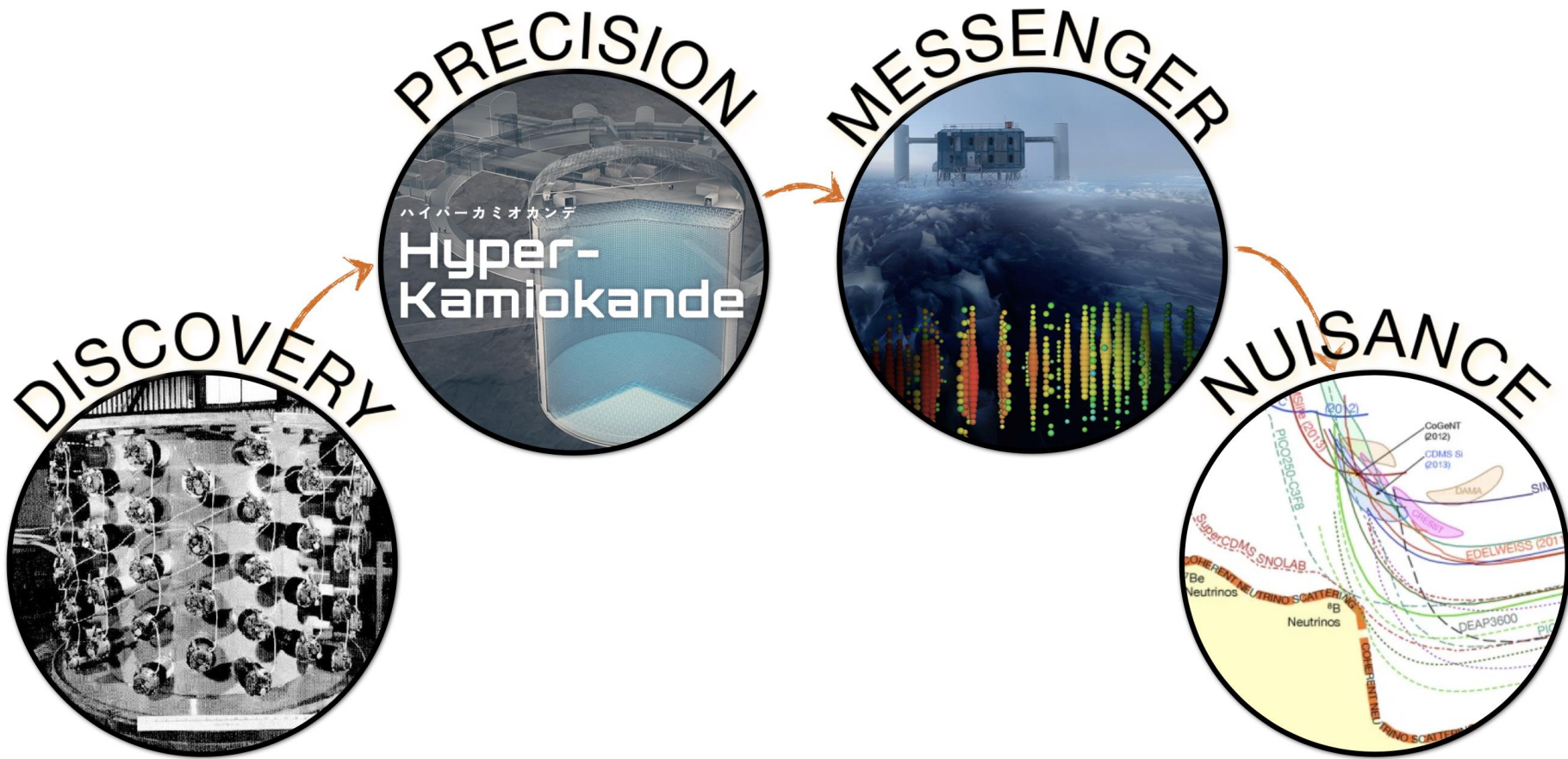FASER (on-axis)

2303.14185

- Observed ν_μ **candidates**: 8 (expected 5)
- Preliminary estimate of background yield: 0.2

153 observed events in signal region

Near Future Neutrino Experiments

Ongoing Neutrino History

PRECISION

Hyper-Kamiokande

ハイパーカミオカンデ

MESSENGER

DISCOVERY

NUISANCE
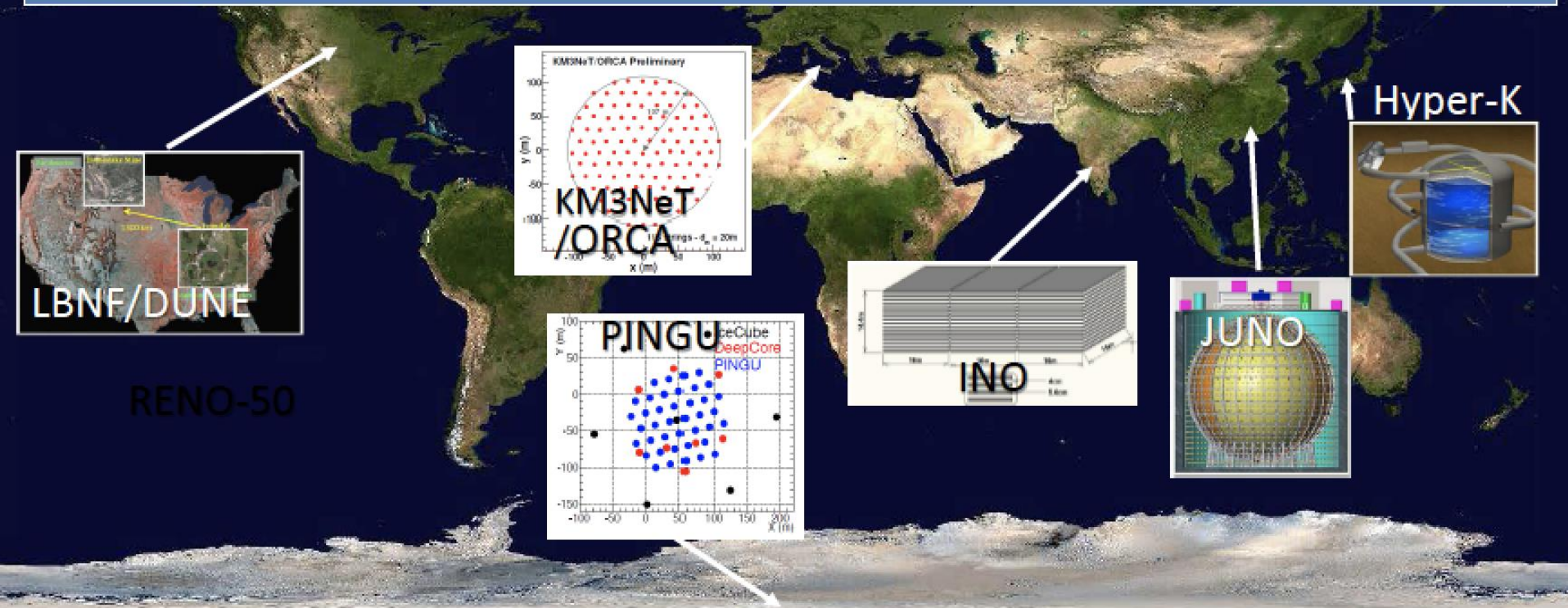
Future Neutrino Experiments

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.

KM3NeT/ORCA

LBNF/DUNE

RENO-50

PINGU
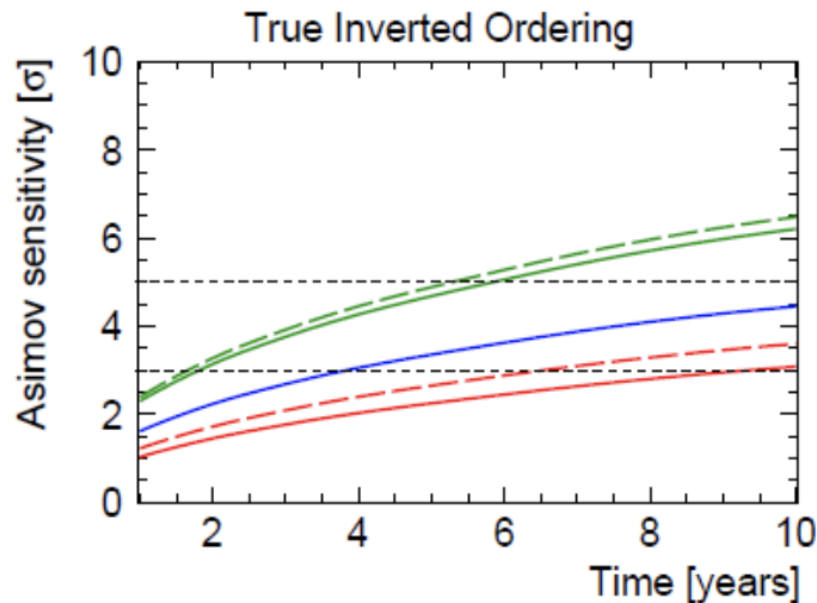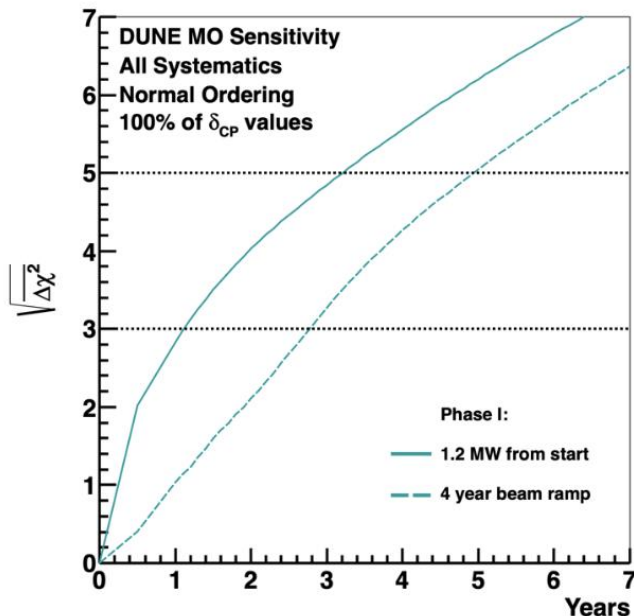
INO

JUNO

Hyper-K

JUNO in 2024   T2HK/DUNE start in 2028-2030

Mass Hierarchy/Ordering

- No concrete evidence of MO from individual experiment (T2K, Nova and SuperK)

- Global fit seems slightly prefer NO($<3\sigma$)

- Definite answer will come from DUNE, JUNO, HyperK, ORCA and Icecube.
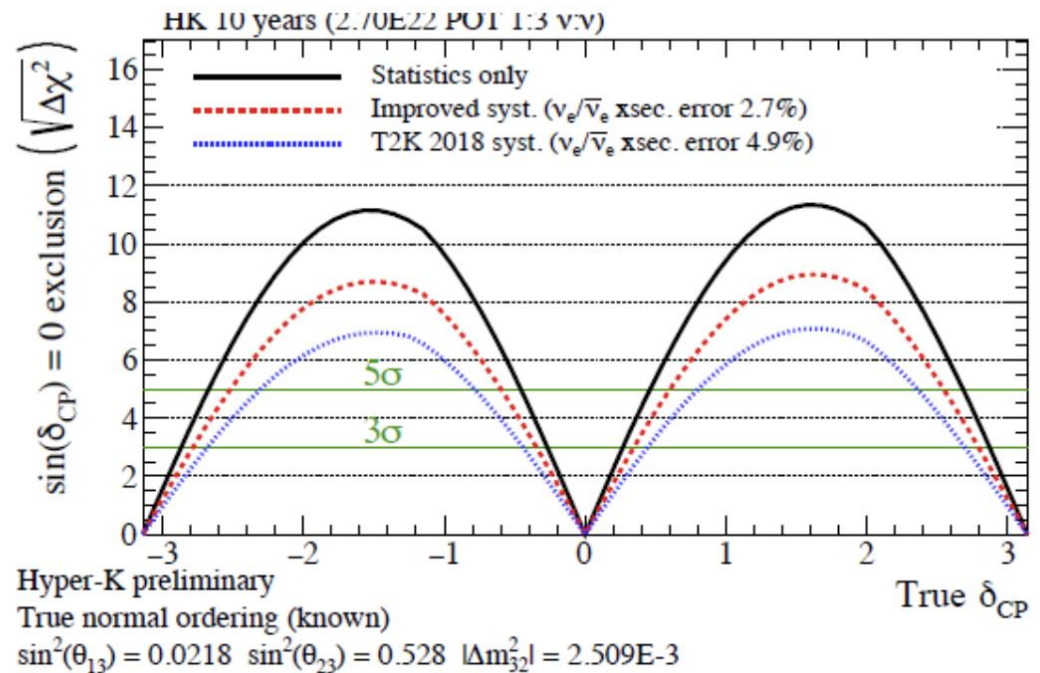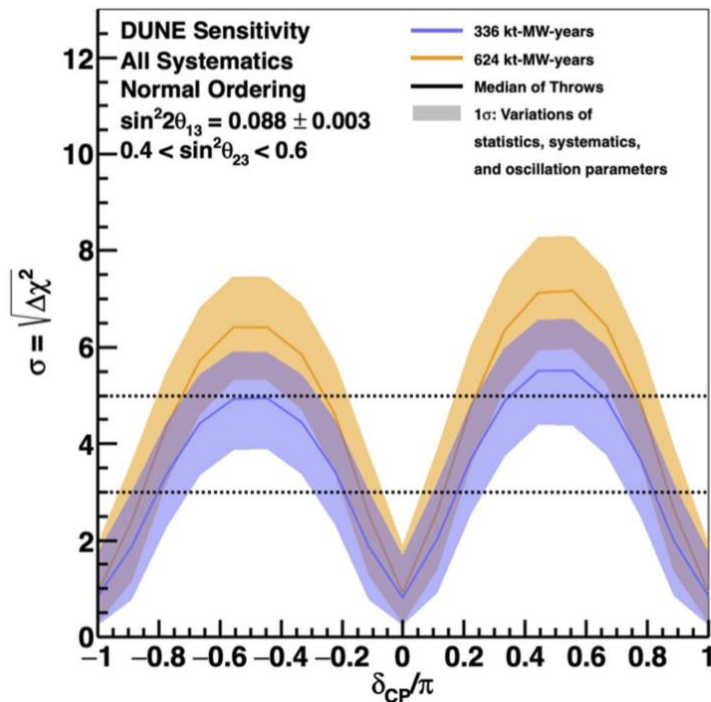
DUNE

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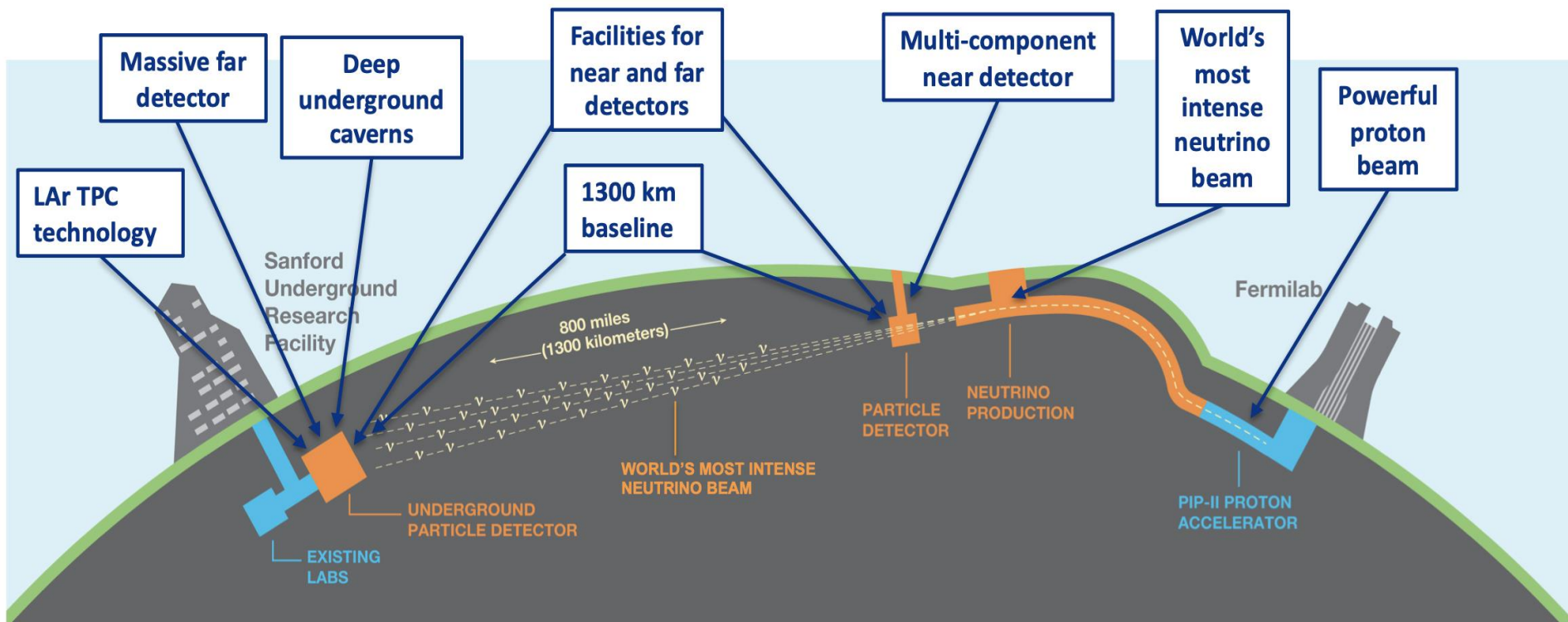
- The Hyper-Kamiokande detector is the next generation water Cherenkov detector in Kamioka, Japan, with an accelerator and near detector complex at J-PARC in Tokai
- Size: 258 kton, with fiducial mass ~8 times larger than Super-K,
- Baseline: 20,000 50-cm photomultiplier tubes (PMT), ~2,000 multi-PMT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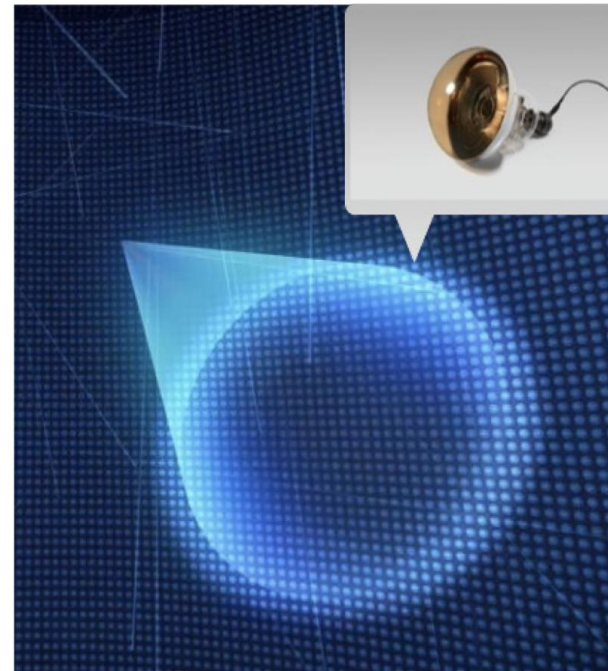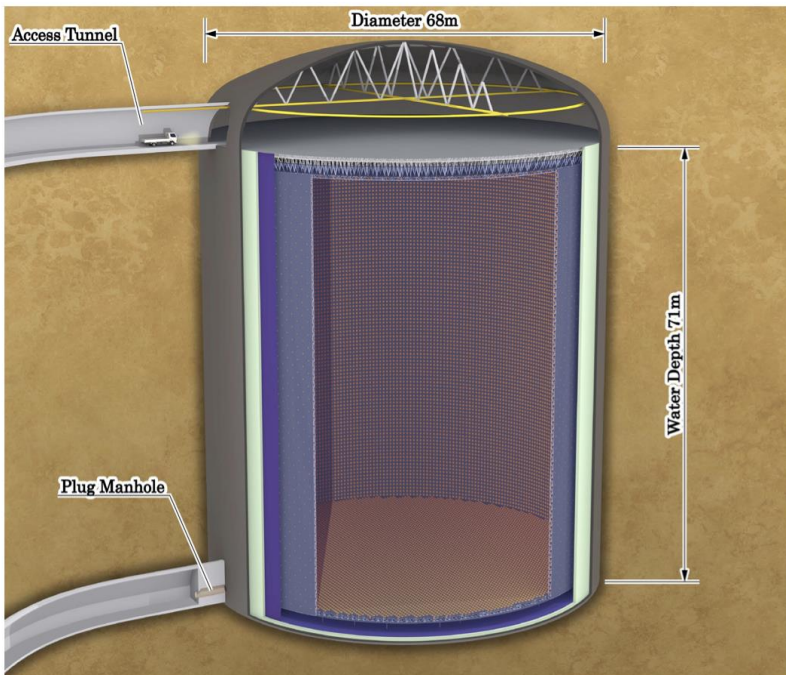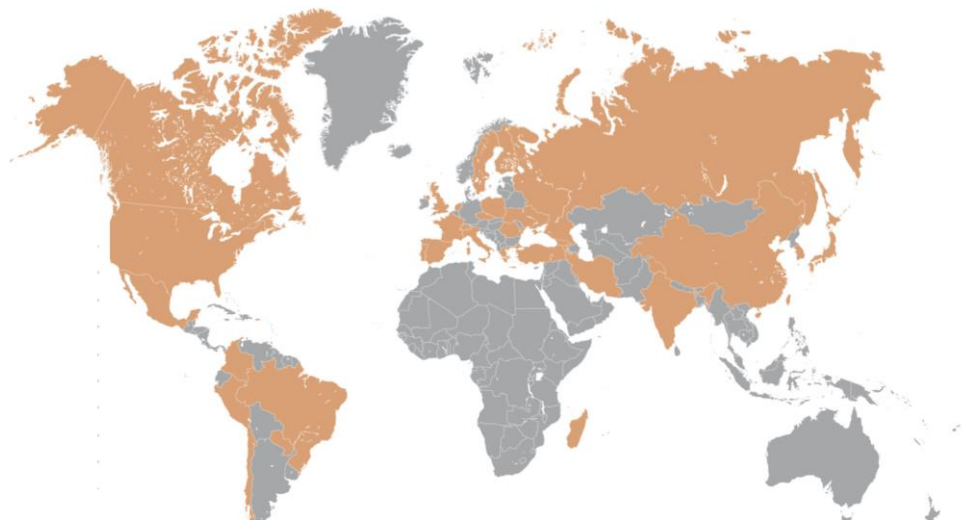
LNBF/DUNE

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

Sanford Underground Research Facility

Fermilab

800 miles (1300 kilometers)

PARTICLE DETECTOR

NEUTRINO PRODUCTION

WORLD'S MOST INTENSE NEUTRINO BEAM

UNDERGROUND PARTICLE DETECTOR

PIP-II PROTON ACCELERATOR

EXISTING LABS

DUNE – a global collaboration

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

Still more groups joining

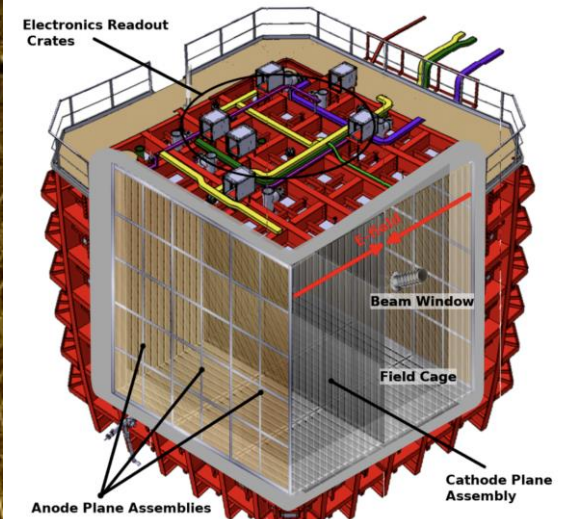**DUNE Jan 2023** Collaboration meeting at CERN

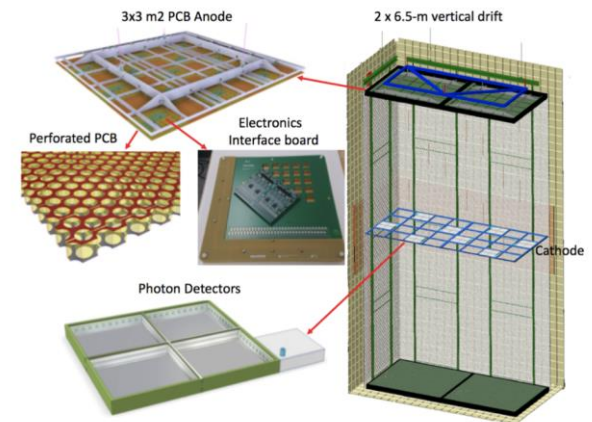**Total participants : 581 In person: 354 (largest on record) Zoom:227**

The CERN Neutrino Platform

CERN strongly involved in DUNE Far Detector R&D

FD1 Horizontal Drift
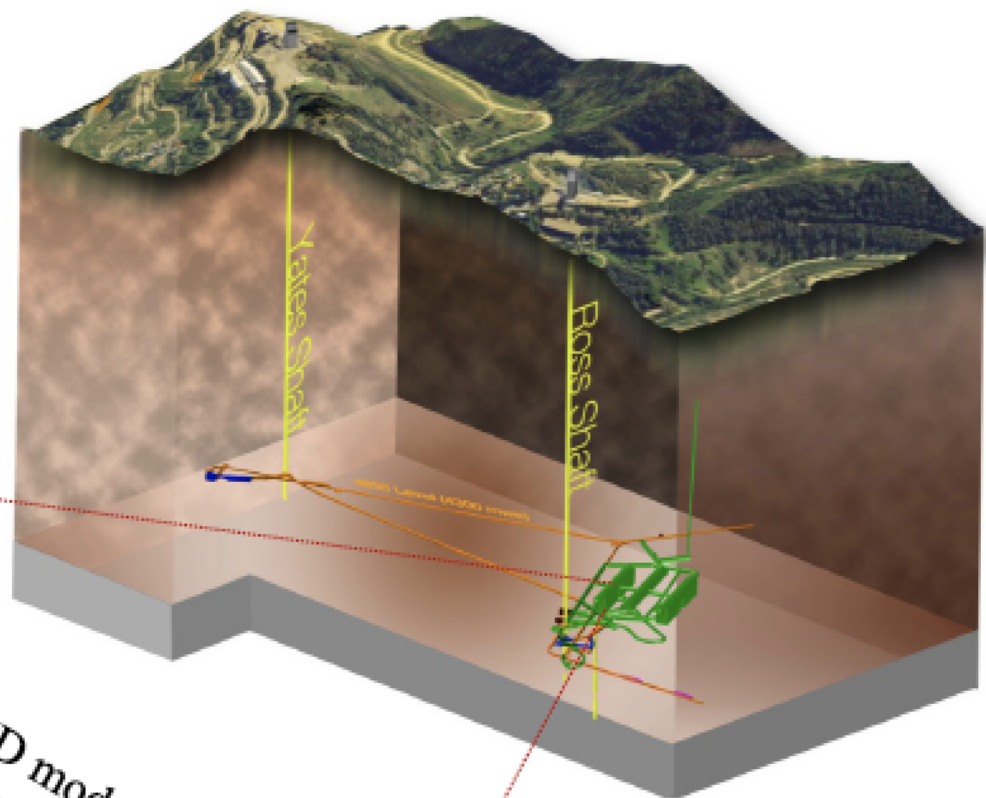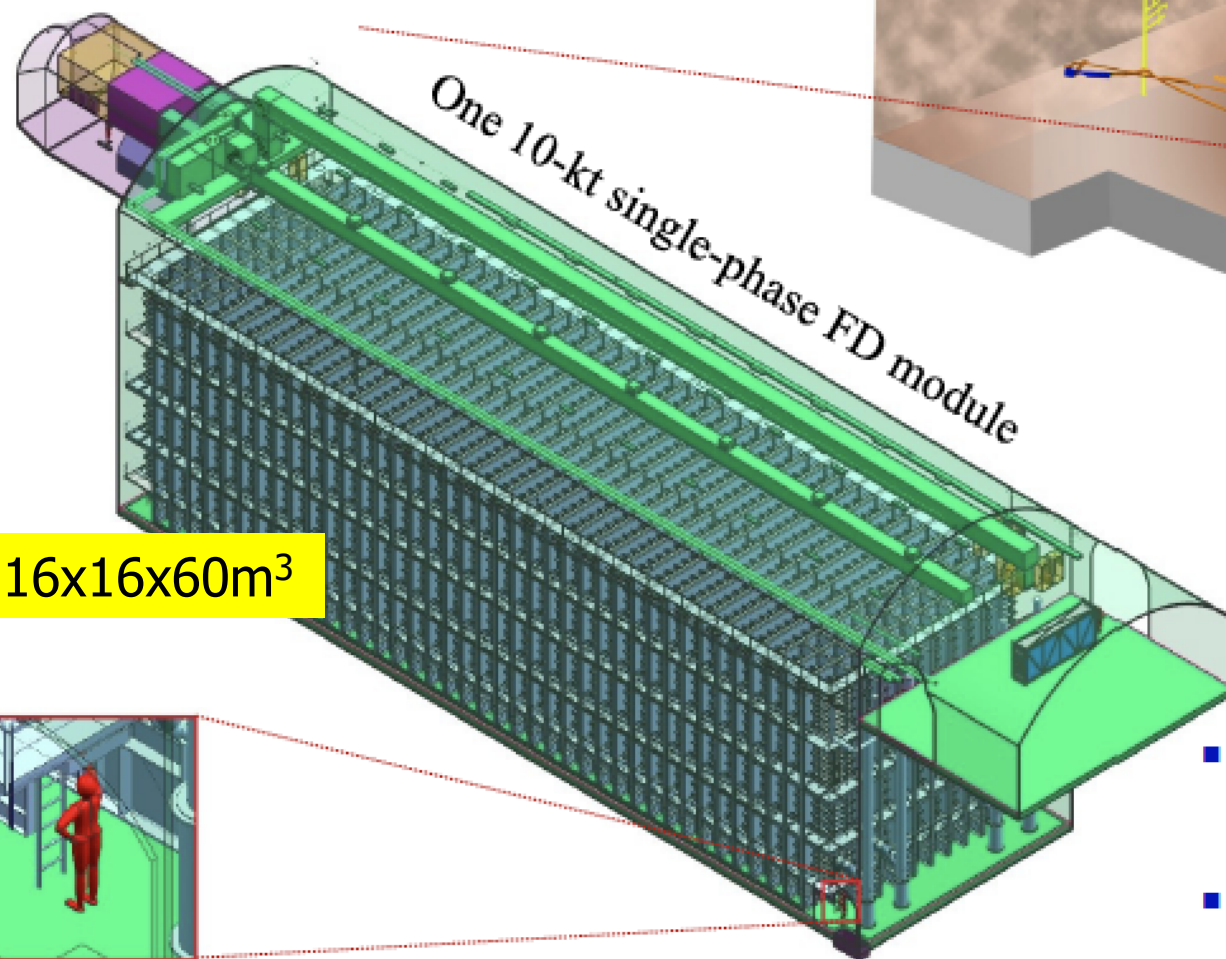

FD2 vertical Drift (NEW)

CRPs

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

16x16x60m³

1.5 km underground

Sanford Underground Research Facility (SURF)

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

The EHN1 Hall at CERN

Next step : ~800 ton LAr prototypes

External cryogenics

SPS : new EHN1-1 experimental area

NP04 proximity cryogenics

NP02 proximity racks

DAQ & computing rooms

NP04 SP

NP02 DP

H2 beam line

H4 beam line

NP04 proximity racks

NP02 proximity cryogenics

The Neutrino Platform hall
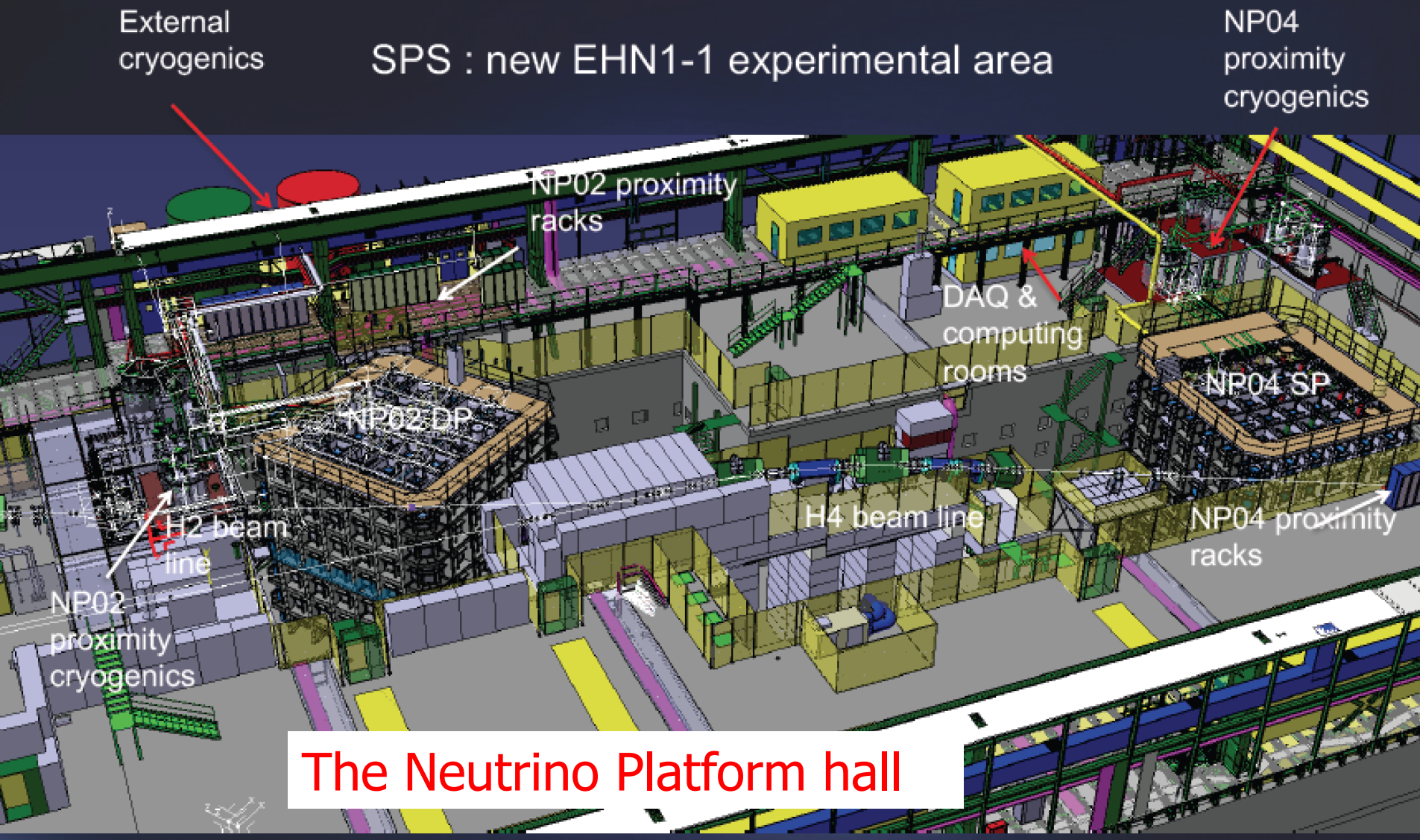
SUMMARY: Neutrinos

- 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??
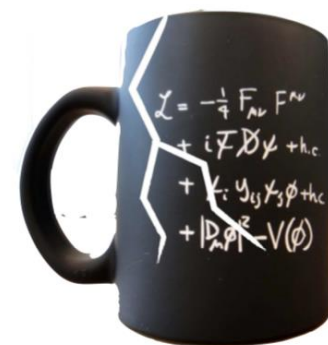
Snowmass Neutrino Frontier Report

Frontier Conveners: Patrick Huber,[1] Kate Scholberg,[2] Elizabeth Worcester,[3]

Topical Group Conveners: Jonathan Asaadi,[4] A. Baha Balantekin,[5] Nathaniel Bowden,[6] Pilar Coloma,[7] Peter B. Denton,[8] André de Gouvêa,[9] Laura Fields,[10] Megan Friend,[11] Steven Gardiner,[12] Carlo Giunti,[13] Julieta Gruszko,[14,15] Benjamin J.P. Jones,[4] Georgia Karagiorgi,[16] Lisa Kaufman,[17] Joshua R. Klein,[18] Lisa W. Koerner,[19] Yusuke Koshio,[20] Jonathan M. Link,[1] Bryce R. Littlejohn,[21] Ana A. Machado,[22] Pedro A.N. Machado,[23] Kendall Mahn,[24] Alysia D. Marino,[25] Mark D. Messier,[26] Irina Mocioiu,[27] Jason Newby,[28] Erin O'Sullivan,[29] Juan Pedro Ochoa-Ricoux,[30] Gabriel D. Orebi Gann,[31,32] Diana S. Parno,[33] Saori Pastore,[34] David W. Schmitz,[35] Ian M. Shoemaker,[1] Alexandre Sousa,[36] Joshua Spitz,[37] Raimund Strauss,[38] Louis E. Strigari,[39] Irene Tamborra,[40] Hirohisa A. Tanaka,[41] Wei Wang,[42] Jaehoon Yu,[4]

Liaisons: K S. Babu,[43] Robert H. Bernstein,[44] Erin Conley,[2] Albert De Roeck,[45] Alexander I. Himmel,[46] Jay Hyun Jo,[47] Claire Lee,[48] Tanaz A. Mohayai,[46] Kim J. Palladino,[49] Vishvas Pandey,[46] Mayly C. Sanchez,[50] Yvonne Y.Y. Wong,[51] Jacob Zettlemoyer,[46] Xianyi Zhang,[52] and

arXiv:2211.08641