

Neutrino Oscillations

Experimental Status and Prospects

CZ+SK HEP Workshop
Prague, Czech Republic

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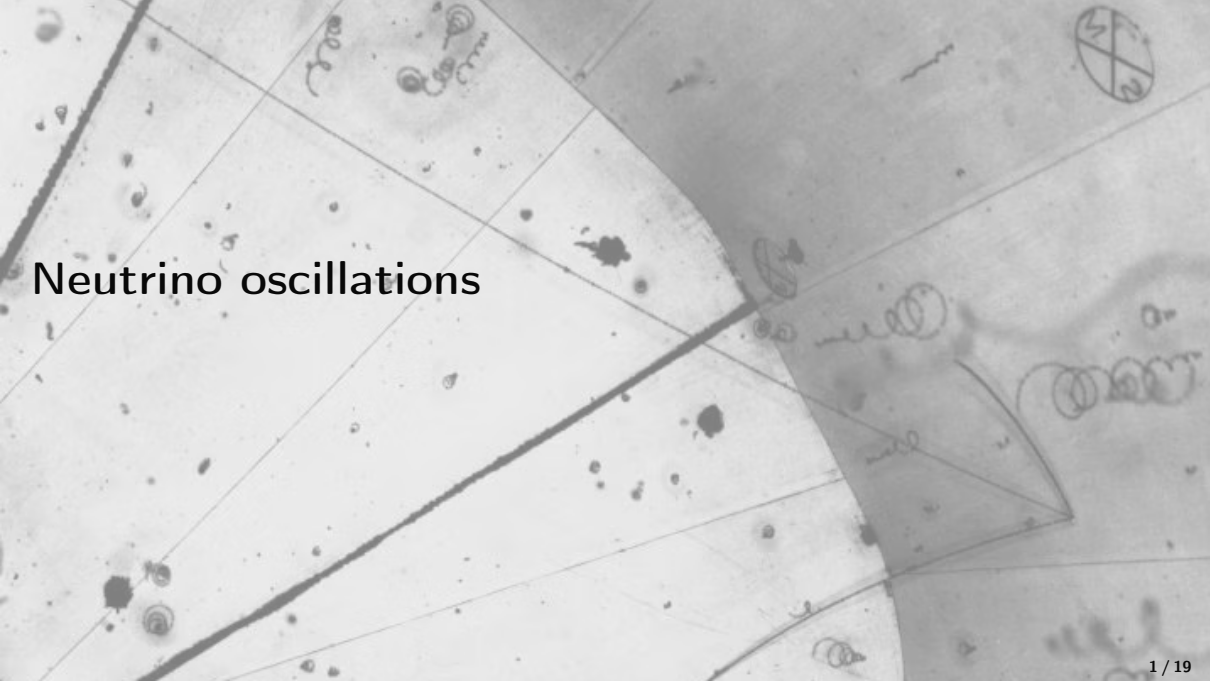
September 11, 2026



Co-funded by
the European Union

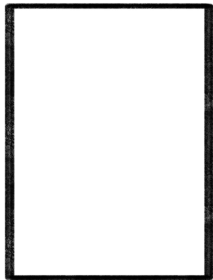


Ministry of Education,
Youth and Sports
of the Czech Republic

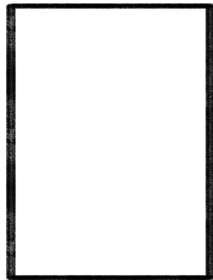


Neutrino oscillations

Neutrino flavor transitions

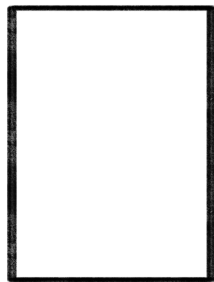
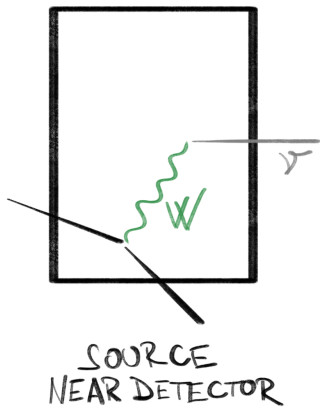


SOURCE
NEAR DETECTOR



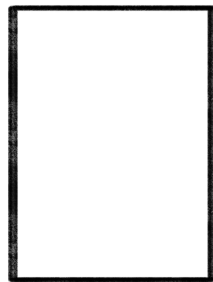
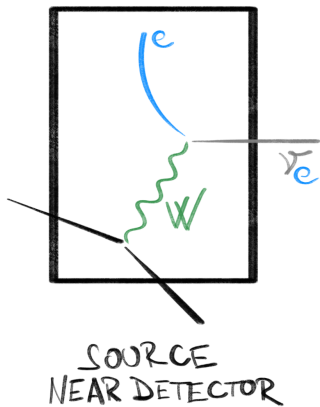
FAR
DETECTOR

Neutrino flavor transitions



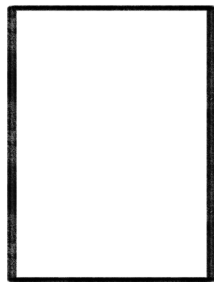
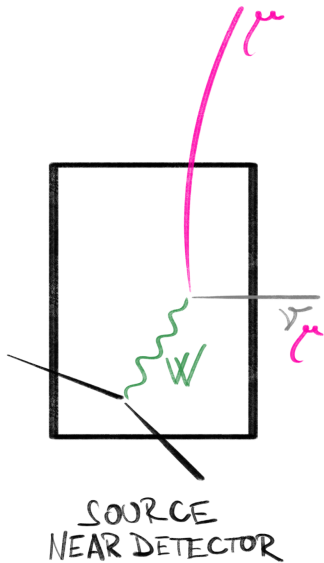
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Neutrino flavor transitions



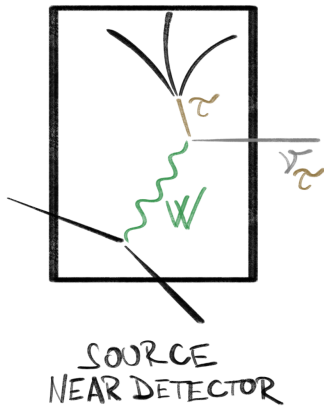
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Neutrino flavor transitions



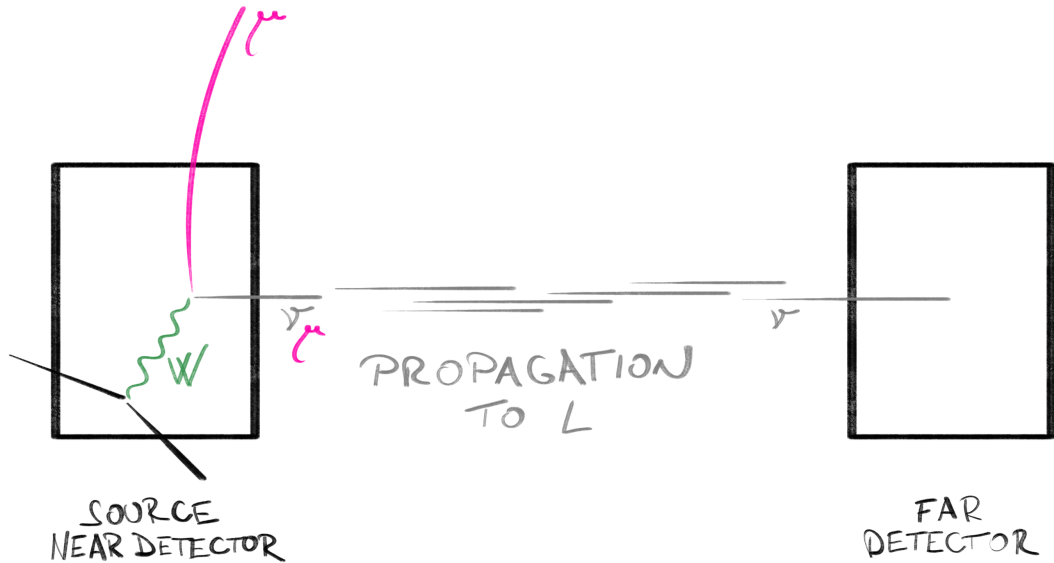
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Neutrino flavor transitions

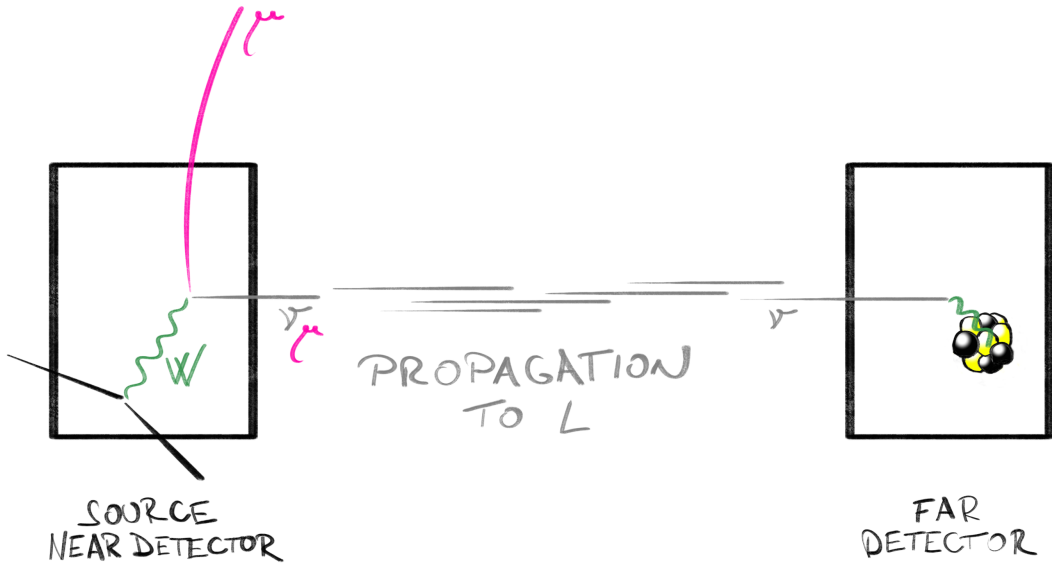


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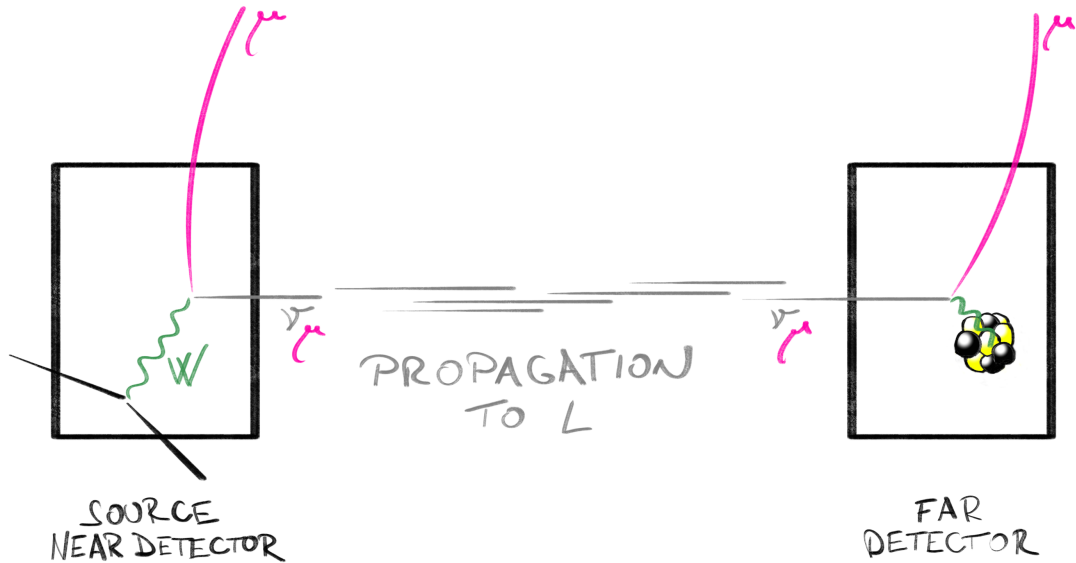
Neutrino flavor transitions



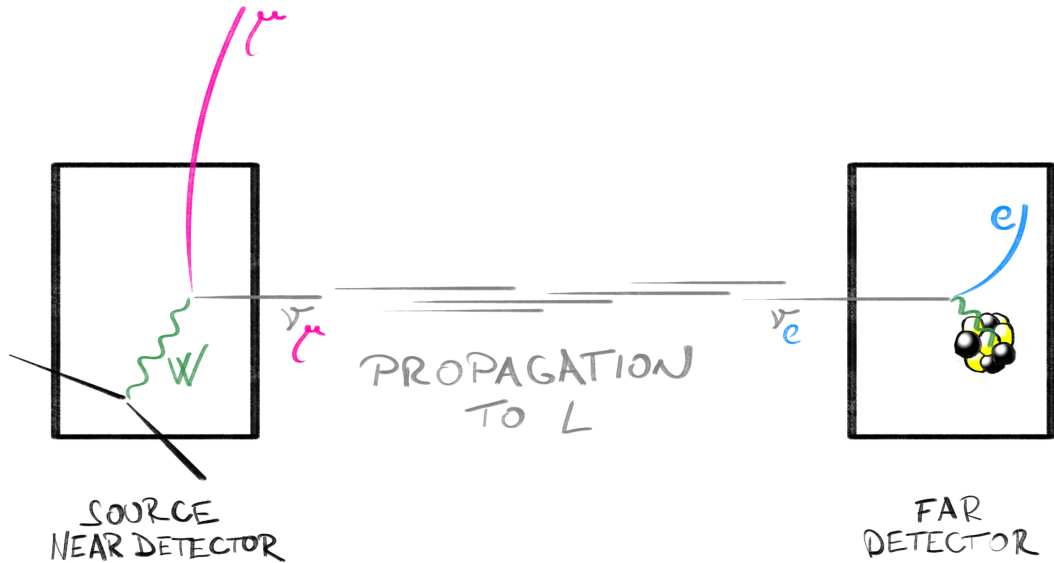
Neutrino flavor transitions



Neutrino flavor transitions

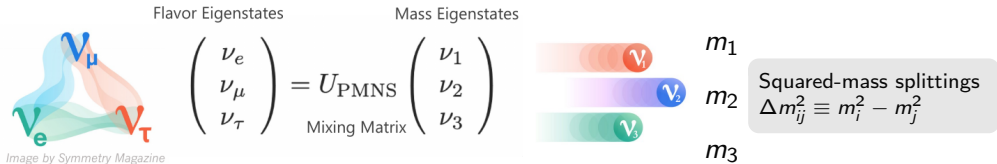


Neutrino flavor transitions



Neutrino (lepton) mixing in 3ν -paradigm

Originally proposed by Bruno Pontecorvo (Sov.Phys.JETP 26 (1968) 984, Zh.Eksp.Teor.Fiz. 53 (1968) 1717)



$$U_{\text{PMNS}} = \begin{bmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{bmatrix} \begin{bmatrix} c_{13} & 0 & s_{13}e^{-i\delta_{\text{CP}}} \\ 0 & 1 & 0 \\ -s_{13}e^{i\delta_{\text{CP}}} & 0 & c_{13} \end{bmatrix} \begin{bmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{bmatrix}$$

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

Measured from
the following
neutrino sources



Atmospheric



Accelerator



Reactor

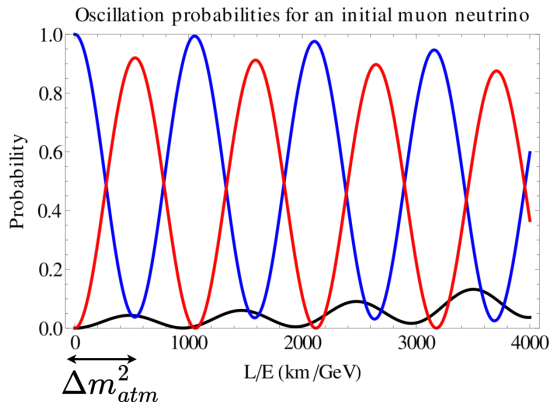
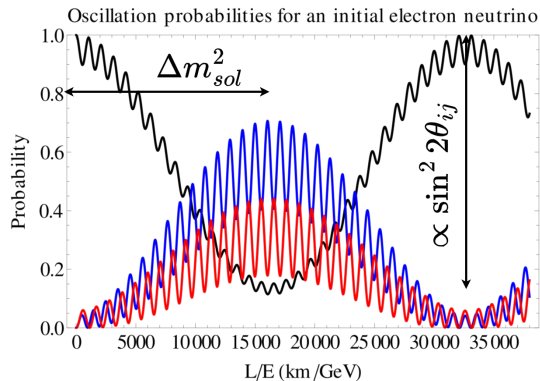


Solar

Image by Symmetry Magazine

Neutrino oscillations

As a consequence of the mixing, neutrino flavor transition probability oscillates with L/E



Two oscillation frequencies corresponding to solar neutrino experiments

$\Delta m_{sol}^2 \approx 7.5 \times 10^{-5} \text{ eV}^2$ and atmospheric neutrino experiments $\Delta m_{atm}^2 \approx 2.5 \times 10^{-3} \text{ eV}^2$

Experimental status of the 3ν -paradigm

The neutrino (oscillation) hunters



Solar



Atmospheric



Reactor



Accelerator

$$\nu_e \rightarrow \nu_e$$

$$\bar{\nu}_{\mu} \rightarrow \bar{\nu}_{\mu/e}$$

$$\bar{\nu}_e \rightarrow \bar{\nu}_e$$

$$\nu_{\mu} \rightarrow \nu_{\mu/e}, \bar{\nu}_{\mu} \rightarrow \bar{\nu}_{\mu/e}$$

E 0.1–10.0 MeV

0.1–10³ GeV

1.8–10.0 MeV

0.2–20.0 GeV

L $\sim 1.5 \times 10^8$ km

10–13000 km

~ 5 –30 m

~ 1 km

$\sim 10^1$ –10² km

10¹–10² m

10²–10³ km

3ν-PMNS

θ_{12}
 Δm_{21}^2

θ_{23}, θ_{13}
 Δm_{32}^2

beyond
3ν-PMNS

θ_{13}
 Δm_{32}^2

θ_{12}
 $\Delta m_{32}^2, \Delta m_{21}^2$

beyond
3ν-PMNS

θ_{23}, θ_{13}
 δ_{CP}
 Δm_{32}^2

Concluded

Homestake,
GALLEX, GNO,
Kamiokande,
SNO, Borexino

Kamiokande,
IMB, Frejus,
NUSEX,
ANTARES

STEREO,
PROSPECT,
NEOS,
SoLid

Daya Bay,
RENO,
D.Chooz

–

LSND,
KARMEN,
MiniBooNE,
MicroBooNE

K2K,
OPERA,
ICARUS,
MINOS

Active

Super-K,
KamLAND,
SAGE, SNO+

Super-K,
KM3NeT,
IceCube,
Baikal-GVD

DANSS

–

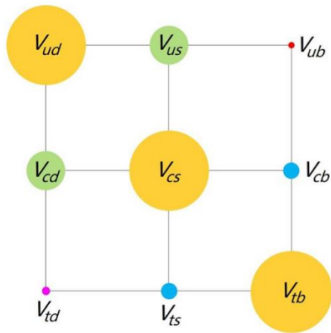
JUNO,
KamLAND

SBND,
ICARUS

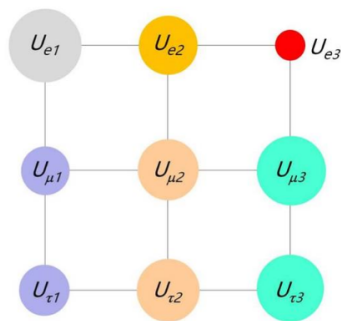
T2K,
NOvA

Neutrino oscillation parameters (excl. JUNO)

12 sector	23 sector	13+CP sector
$\sin^2 \theta_{12} = 0.307 \pm 0.012$	$\sin^2 \theta_{23} = \begin{matrix} 0.523^{+0.031}_{-0.027} \text{ (IO)} \\ 0.533 \pm 0.018 \text{ (NO)} \end{matrix}$	$\sin^2 \theta_{13} = (2.17 \pm 0.07) \times 10^{-2}$
$\Delta m_{21}^2 = (7.60 \pm 0.17) \times 10^{-5} \text{ eV}^2$	$\Delta m_{32}^2 = \begin{matrix} (-2.52 \pm 0.04) \times 10^{-3} \text{ eV}^2 \text{ (IO)} \\ (2.445 \pm 0.023) \times 10^{-3} \text{ eV}^2 \text{ (NO)} \end{matrix}$	$\delta_{\text{CP}} = 1.21^{+0.19}_{-0.17} \pi$

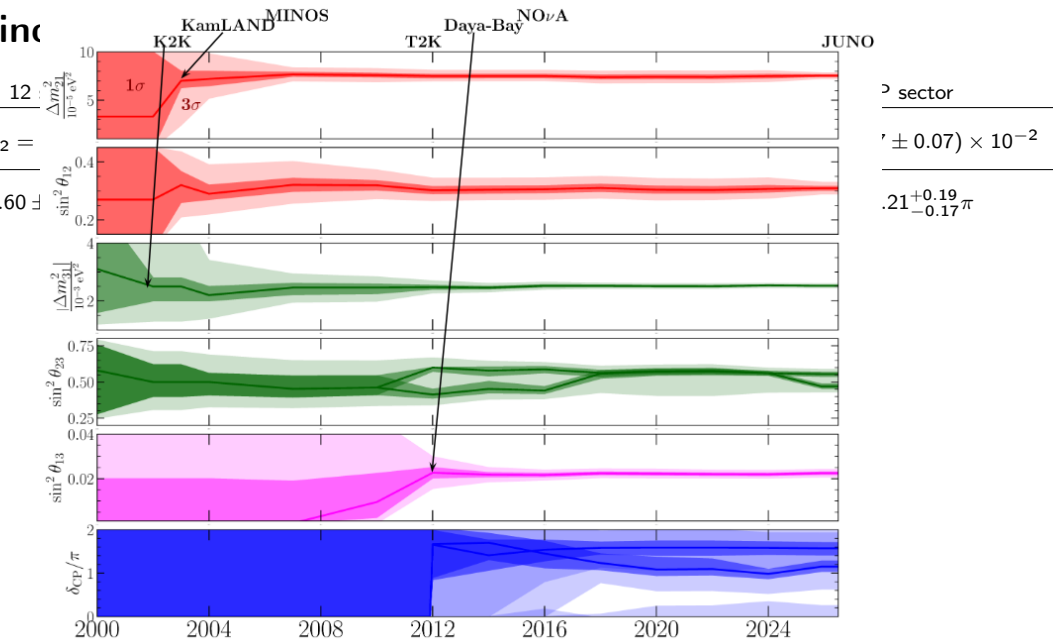


(a) CKM quark flavor mixing



(b) PMNS lepton flavor mixing

Neutrino

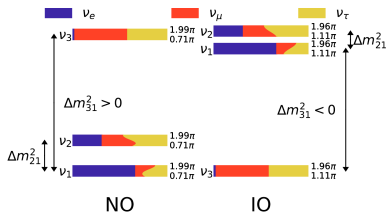


Open questions

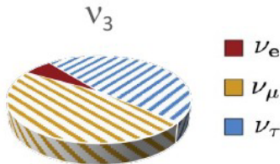
$$\Delta m_{32}^2, \text{ NO/IO}$$

What is the ordering of the ν masses?

Normal (NO) or inverted (IO)?



$$\theta_{23}$$



Is 23 mixing maximal?

$\mu\tau$ symmetry?

Is $\theta_{23} \leq 45^\circ$?

$$\delta_{CP}$$

Is there significant CP violation in the lepton sector?

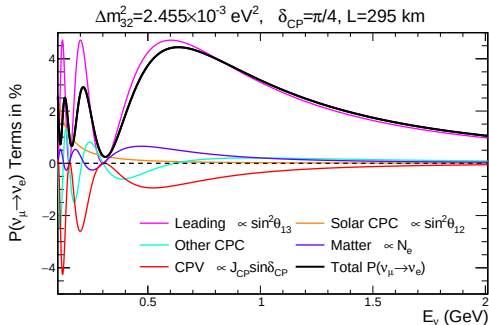


The “my-precious” channel $\nu_\mu \rightarrow \nu_e$

$$P(\nu_\mu \rightarrow \nu_e; L, E, A) \approx$$

- $4c_{13}^2 s_{13}^2 s_{23}^2 \sin^2 \Delta_{31}$ (dominant term)
- $+ 8c_{13}^2 s_{12} s_{13} s_{23} (c_{12} c_{23} \cos \delta_{\text{CP}} - s_{12} s_{13} s_{23}) \cos \Delta_{32} \sin \Delta_{31} \sin \Delta_{21}$ (other CPC)
- $- 8c_{13}^2 c_{12} c_{23} s_{12} s_{13} s_{23} \sin \delta_{\text{CP}} \sin \Delta_{32} \sin \Delta_{31} \sin \Delta_{21}$ (CPV)
- $+ 4s_{12}^2 c_{13}^2 (c_{12}^2 c_{23}^2 + s_{12}^2 s_{23}^2 s_{13}^2 - 2c_{12} c_{23} s_{12} s_{23} s_{13} \cos \delta_{\text{CP}}) \sin^2 \Delta_{21}$ (solar CPC)
- $- 8c_{13}^2 s_{13}^2 s_{23}^2 \frac{AL}{4E_\nu} (1 - 2s_{13}^2) \cos \Delta_{32} \sin \Delta_{31} + 8c_{13}^2 s_{13}^2 s_{23}^2 \frac{A}{\Delta m_{31}^2} (1 - 2s_{13}^2) \sin^2 \Delta_{31}$ (matter)

$$s_{ij} \equiv \sin \theta_{ij}, c_{ij} \equiv \cos \theta_{ij} \quad \Delta_{ij} \equiv \frac{\Delta m_{ij}^2 L}{4E_\nu} \quad A(E_\nu) \equiv 2\sqrt{2}G_F N_e E_\nu, \quad \bar{\nu} : A \rightarrow -A, \delta_{\text{CP}} \rightarrow -\delta_{\text{CP}}$$



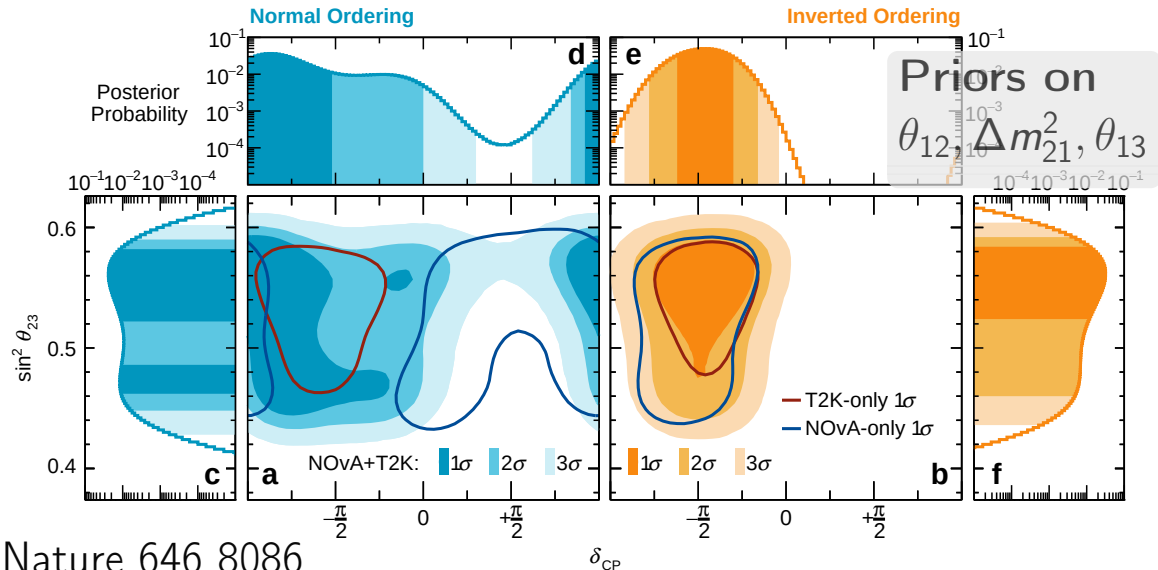
Long-baseline acc.

Atmospheric

Crucial $\sin^2 \theta_{13}$ from reactor $\bar{\nu}_e \rightarrow \bar{\nu}_e$ experiments



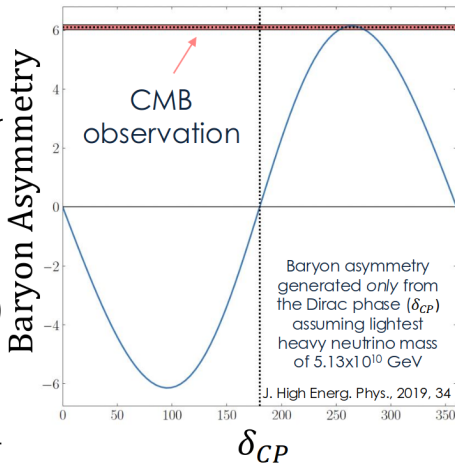
The “my-precious” channel $\nu_\mu \rightarrow \nu_e$ and T2K+NOvA



Nature 646 8086

Why this matters? ...and not anti-matters

- δ_{CP} is a fundamental parameter (even if $\sin \delta_{CP} \rightarrow 0$)
- CPV is a Sacharov's condition for matter-antimatter imbalance in the originally symmetrical universe
 - One of the Standard Model (SM) CPV sources
 - Quark CKM CPV is not strong enough
 - CPV in strong interactions not observed (too small?)
 - Extra CPV requires Majorana neutrinos
- Relic and cosmogenic neutrinos would provide information on the evolution of the universe



Oh, who you gon' call?

Oh, who you gon' call?

2025

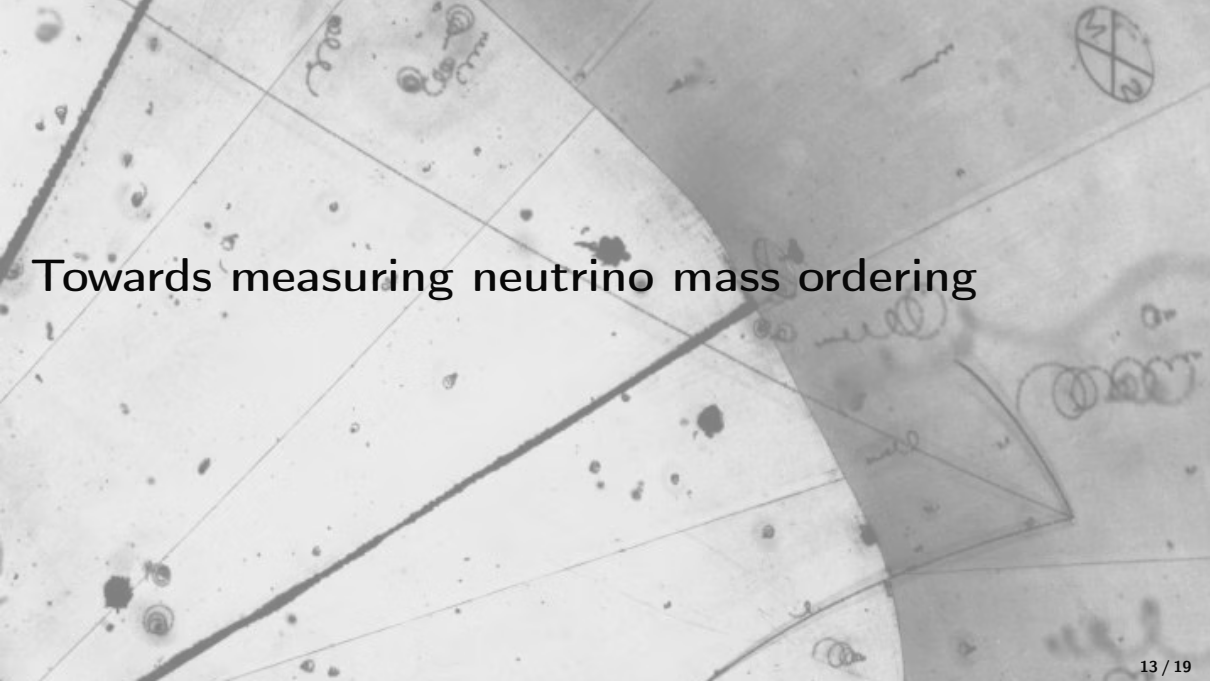


2028



2031



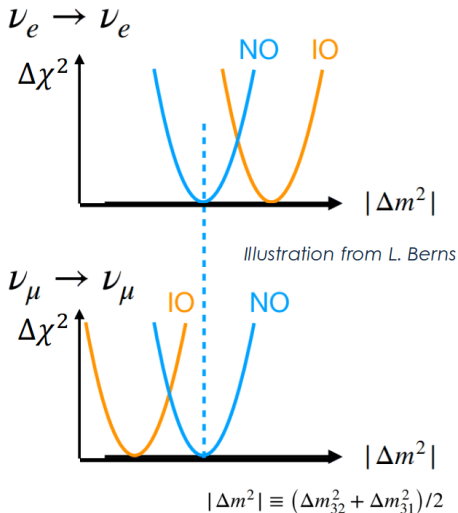


Towards measuring neutrino mass ordering

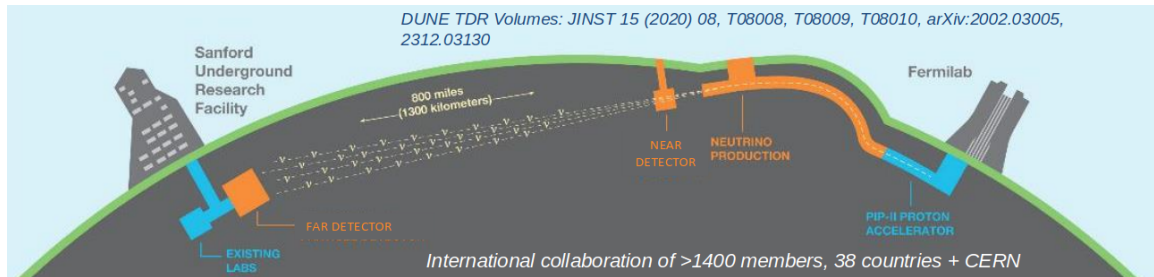
JUNO with LBL+Atm friends

- JUNO reports %-level constraints on Δm_{32}^2 from $\bar{\nu}_e \rightarrow \bar{\nu}_e$
- T2K+NOvA report %-level constraints on Δm_{32}^2 from $\nu_\mu \rightarrow \nu_\mu$ and $\bar{\nu}_\mu \rightarrow \bar{\nu}_\mu$
- The best fit values shift depending on the assumed mass ordering (by a factor of Δm_{21}^2)
- The shift is in the opposite direction for electron and muon neutrino disappearance
- The right mass ordering is the one in which JUNO agrees with long-baseline and atm. measurements

Combinations of high-statistics $\nu_\mu \rightarrow \nu_\mu$ channels with JUNO enable higher sensitivity to neutrino mass ordering. Expect about 3σ for combined measurements.

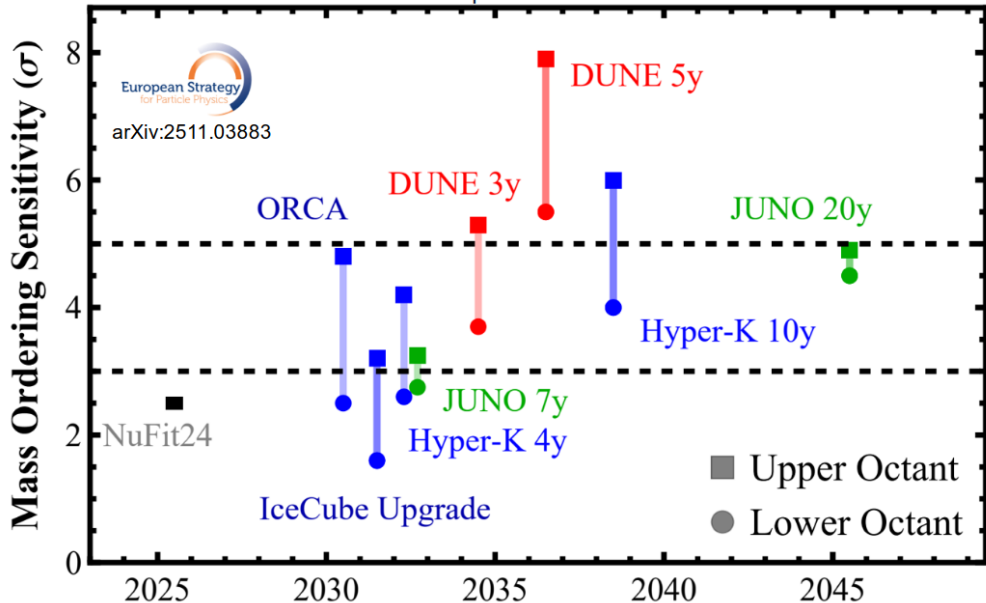


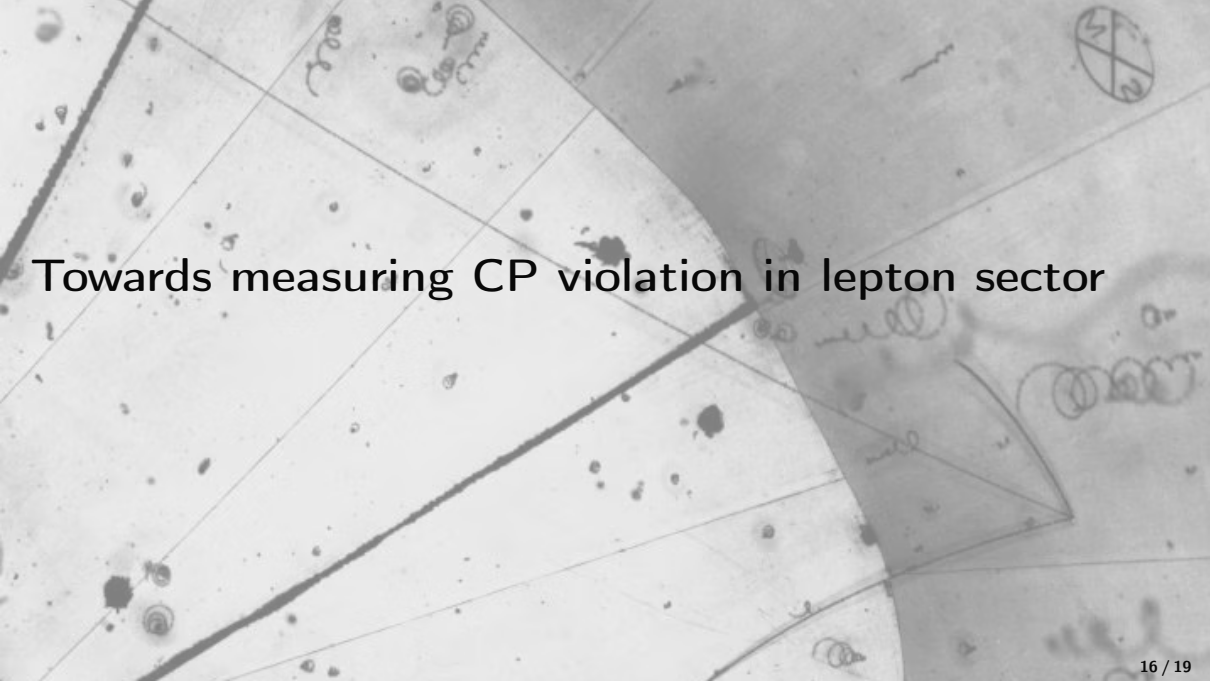
DUNE in the landscape



DU

N.B.: Does not include experiment combinations





Towards measuring CP violation in lepton sector



IPNP Hyper-K team:

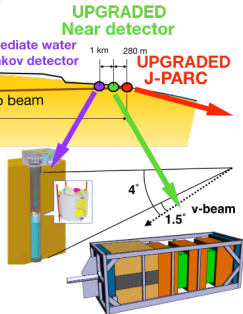
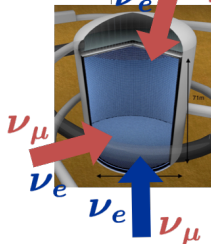
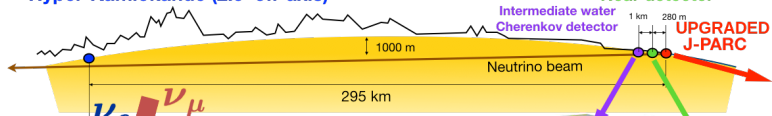
T. Dohnal, R. Leitner, M. Malinský,
T. Nosek, B. Roskovec

- International multipurpose experiment, under construction
- Successor of T2K and Super-K experiments
- Hyper-K (HK) will be the largest neutrino and nucleon decay detector with ~ 260 kt of pure water
- Accelerator, atmospheric, solar, and supernova neutrinos

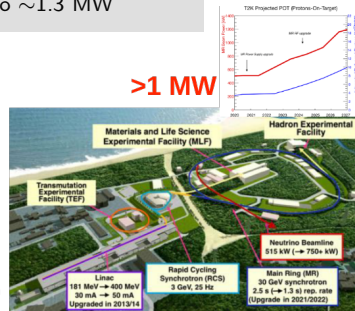
High-stats

- HK is $> 5\times$ the size of SK
- J-PARC upgrades for higher beam intensity up to ~ 1.3 MW

Hyper-Kamiokande (2.5° off-axis)



>1 MW



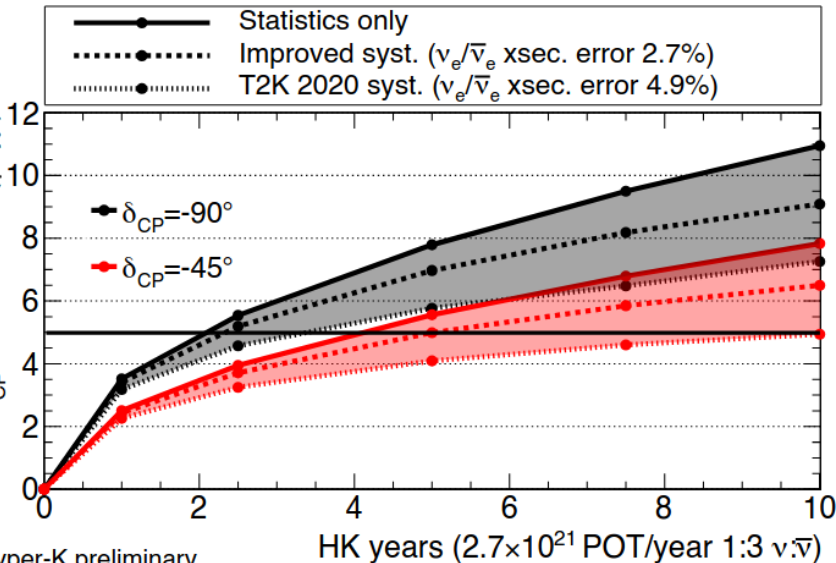
Better ν int. systematics

- Upgraded ND280
- IWCD off-axis detector



- International
- Successor of
- Hyper-K (Hyper-Kamiokande)
- Accelerator, Hyper-Kai

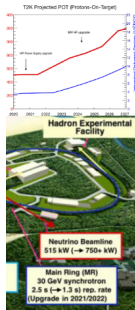
$\sin\delta_{CP}=0$ exclusion ($\sqrt{\Delta\chi^2}$)



Hyper-K preliminary

True normal ordering (known)

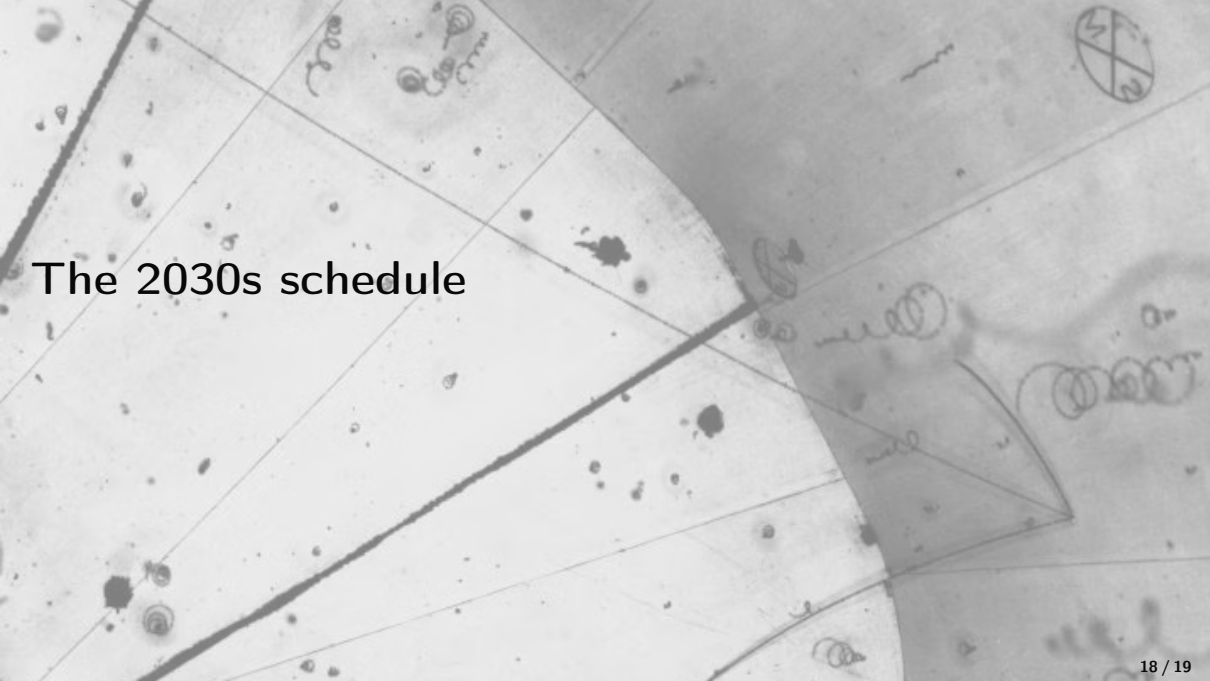
$$\sin^2\theta_{13}=0.0218\pm0.0007, \sin^2\theta_{23}=0.528, \Delta m_{32}^2=2.509\times10^{-3}\text{eV}^2/c^4$$



Systematics

30

detector



The 2030s schedule

A possible 2030s timeline by Stephen Dolan (ed. by TN)

- **2029-30:** Combinations of experiments with JUNO provide 3σ determination of neutrino mass ordering 😊👉😊
- **2031-32:** Hyper-K provides 5σ evidence for leptonic CP-violation 🦄
- **2034-35:** DUNE provides 5σ verification of the neutrino mass ordering 🦄
- **2036-37:** DUNE and Hyper-K PMNS measurements show significant tensions 😞
- **2038:** Turns out to be an issue with the neutrino interaction modelling 😊
- **2039-40:** Oh, it is actually beyond 3ν -PMNS effect... 😊