Neutrino physics (4-1)

Evgeny Akhmedov

Max-Planck Institute für Kernphysik, Heidelberg

Coherent elastic neutrino-nucleus scattering

Coherent elastic neutrino-nucleus scattering

NC – mediated neutrino-nucleus scattering:

$$\nu + A \to \nu + A$$

Incoherent scattering – Probabilities of scattering on individual nucleons add:

$\diamondsuit$ $\sigma \propto (\#$ of scatterers$)$

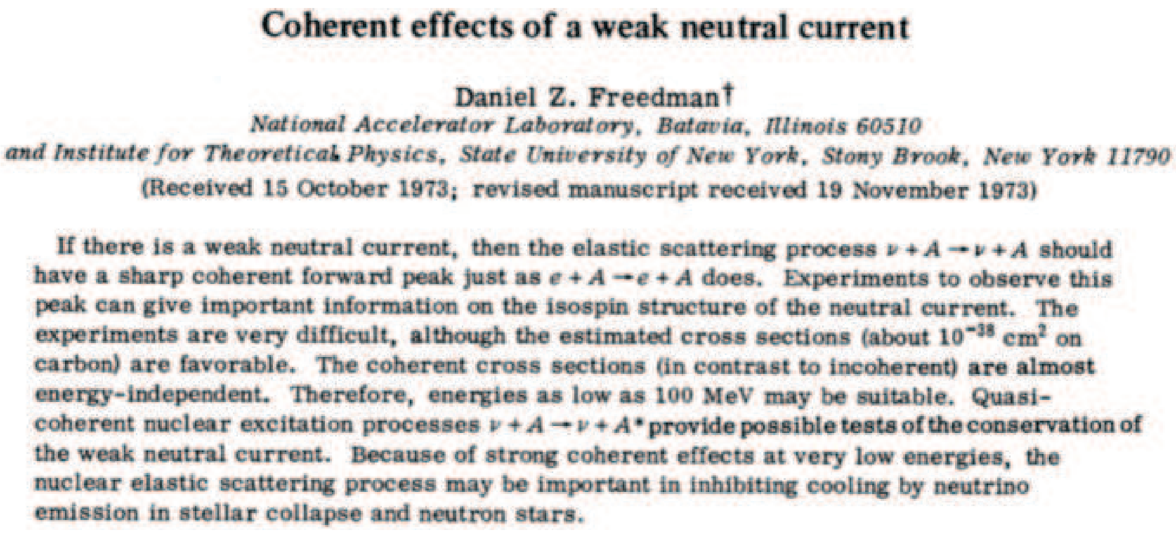
Coherent scattering on nucleus as a whole – Amplitudes of scattering on individual nucleons add

$\diamondsuit$ $\sigma \propto (\#$ of scatterers$)^2$

Significant increase of the cross sections (but requires small momentum transfer, $q \lesssim R^{-1}$)

(D.Z. Freedman, 1974)

Coherent neutrino nucleus scattering: Predictions & Implications



Coherent effects of a weak neutral current

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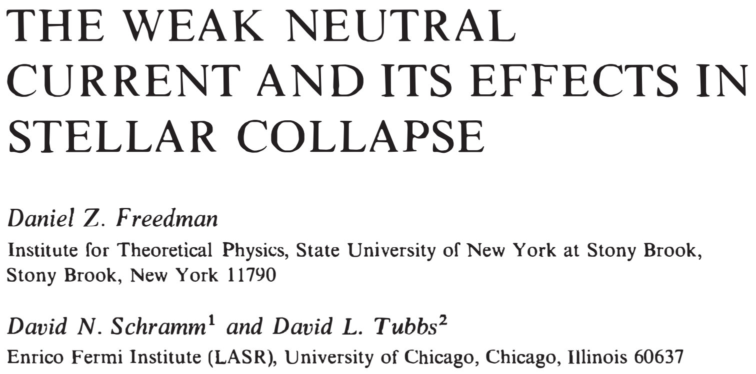
(Received 15 October 1973; revised manuscript received 19 November 1973)

If there is a weak neutral current, then the elastic scattering process $\nu + A \to \nu + A$ should have a sharp coherent forward peak just as $e + A \to e + A$ does. Experiments to observe this peak can give important information on the isospin structure of the neutral current. The experiments are very difficult, although the estimated cross sections (about 10^{-38} cm^2 on carbon) are favorable. The coherent cross sections (in contrast to incoherent) are almost energy-independent. Therefore, energies as low as 100 MeV may be suitable. Quasi-coherent nuclear excitation processes $\nu + A \to \nu + A^*$ provide possible tests of the conservation of the weak neutral current. Because of strong coherent effects at very low energies, the nuclear elastic scattering process may be important in inhibiting cooling by neutrino emission in stellar collapse and neutron stars.

- Implications for neutrino transport in supernovae

- Large cross section important for understanding how neutrinos emerge from supernovae



THE WEAK NEUTRAL CURRENT AND ITS EFFECTS IN STELLAR COLLAPSE

Daniel Z. Freedman
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David N. Schramm^1 *and David L. Tubbs*^{2}
Enrico Fermi Institute (LASR), University of Chicago, Chicago, Illinois 60637

NC-induced neutrino-nucleus scattering: flavour blind.

♢ $$\left[\frac{d\sigma_{\nu A}}{d\Omega}\right]_{\mathrm{coh}} \simeq \frac{G_F^2}{16\pi^2} E_\nu^2 [Z(4\sin^2\theta_W - 1) + N]^2 \, (1+\cos\theta) |F(\vec{q}^{\,2})|^2$$

$F(\vec{q}^{\,2})$ is nuclear formfactor:

$$F_{N(Z)}(\vec{q}^{\,2}) = \frac{1}{N(Z)} \int d^3x \rho_{N(Z)}(\vec{x}) e^{i\vec{q}\vec{x}}, \qquad \vec{q} = \vec{k} - \vec{k}'.$$

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For $q \ll R^{-1} \quad \Rightarrow \quad F(\vec{q}^{\,2}) = 1, \qquad \left[d\sigma_{\nu A}/d\Omega\right]_{\rm coh} \propto N^2$.

For $q \gg R^{-1}$: $\qquad F(\vec{q}^{\,2}) \ll 1$.

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By Heisenberg uncertainty relation: for $q \lesssim R^{-1}$ the uncertainty of the coordinate of the sctatterer $\delta x \gtrsim R \quad \Rightarrow$ it is in principle impossible to find out on which nucleon the neutrino has scattered. Also: neutrino waves scattered off different nucleons of the nucleus are in phase with each other.

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The necessary conditions for coherent scattering!

$$R \simeq 1.2\ \mathrm{fm}\, A^{1/3}; \quad A \sim 130 \quad \Rightarrow \quad R^{-1} \sim 30\ \mathrm{MeV}.$$

Recoil energy of the nucleus:

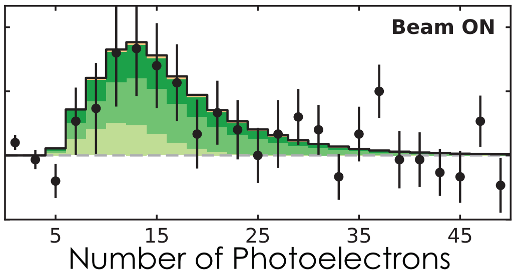
$$E_{rec} \simeq \frac{\vec{q}^{\,2}}{2M_A}, \qquad E_{rec}^{max} = \frac{2E_\nu^2}{M_A + 2E_\nu} \simeq \frac{2E_\nu^2}{M_A}.$$

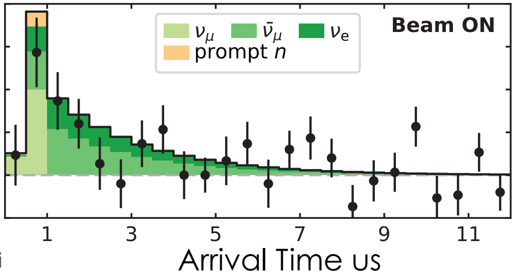
For $q \sim 30\ \mathrm{MeV}$: $\quad E_{rec} \sim 5\ \mathrm{keV}$.

Need to detect very low recoil energies $\Rightarrow$ requires

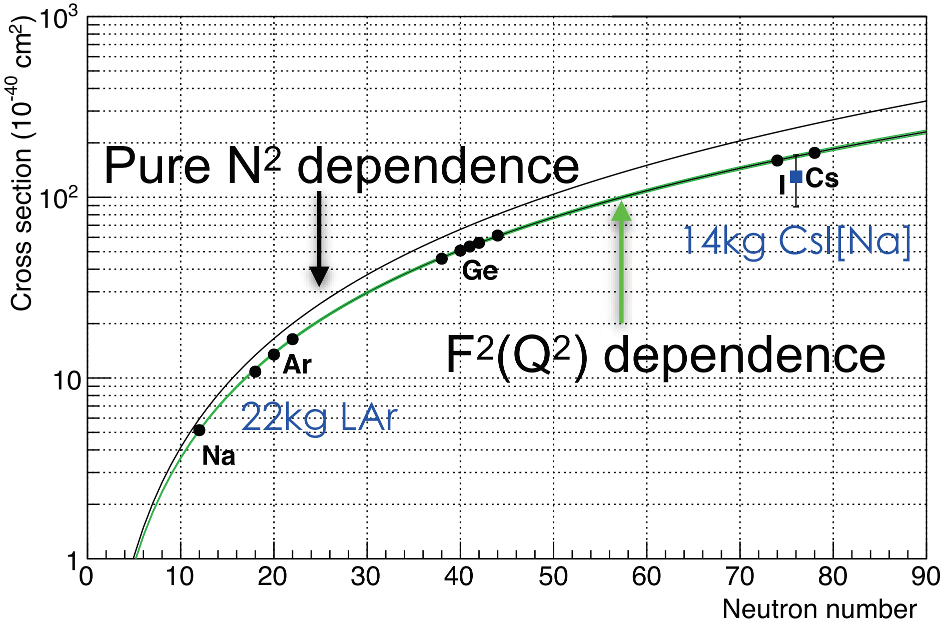
- Very low detection thresholds
- Low backgrounds
- Intense neutrino fluxes

First Observation of CEvNS





Akimov et al. *Science*
Vol 357, Issue 6356
15 September 2017



First light detectors deployed to measure neutron-squared dependence. (Na, Ge in 2019)

High precision measurements enable the full potential of CEvNS scientific impact.

Jason Newby, Magnificent CEvNS Workshop 2018

COHERENT experiment

Neutrino energies: $E_\nu \sim 16 - 53\ \mathrm{MeV}$. Nuclear recoil energy: keV - scale.

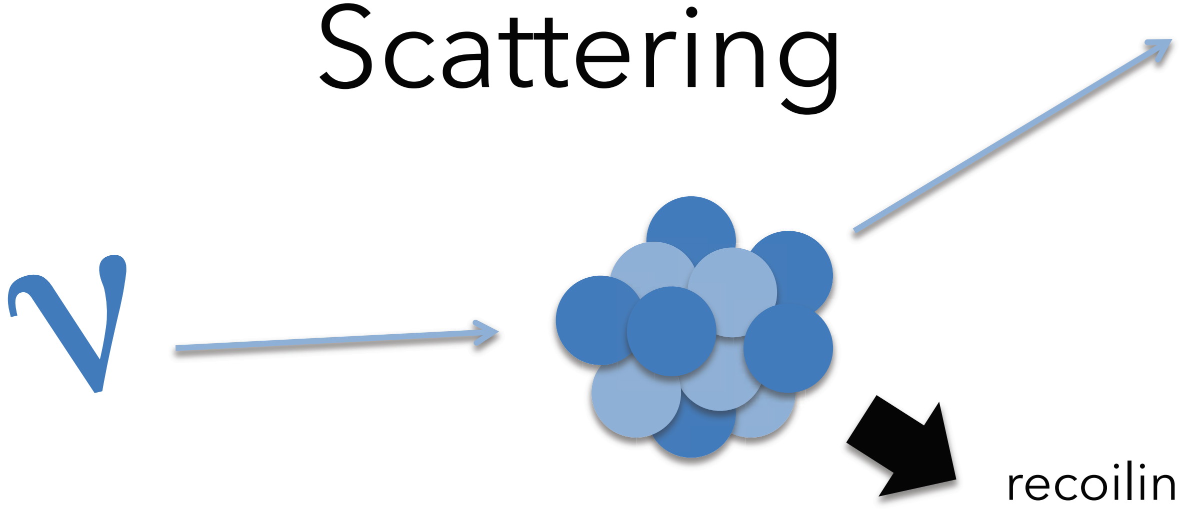
# of events expected (SM): 173 $\pm$ 48

# of events detected: 134 $\pm$ 22

“We report a 6.7 sigma significance for an excess of events, that agrees with the standard model prediction to within 1 sigma”
$\sim 2 \times 10^{23}$ POT; $\sigma \sim 10^{-38}$ cm^2.

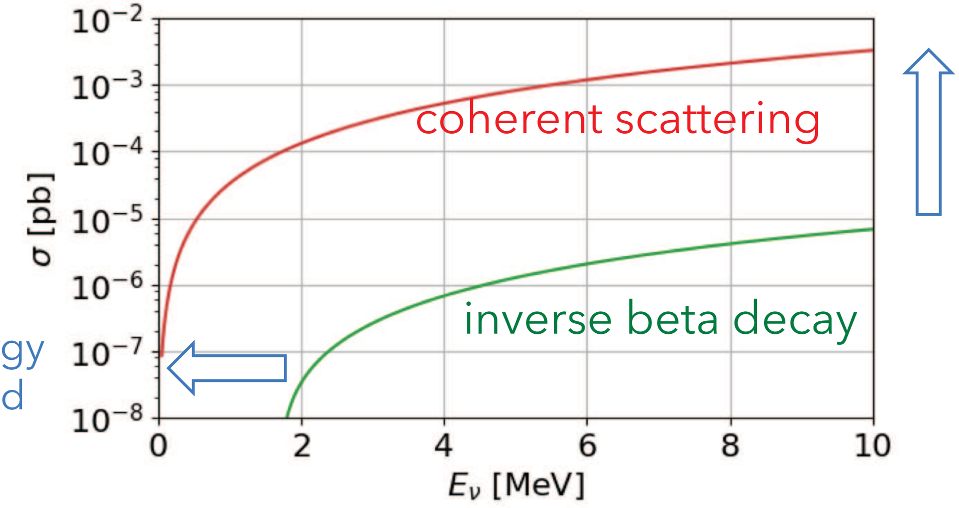
D. Akimov et al., Science 10.1126/science.aao0990 (2017).

Coherent Neutrino-Nucleus Scattering



recoiling nucleus

Neutrino cross sections

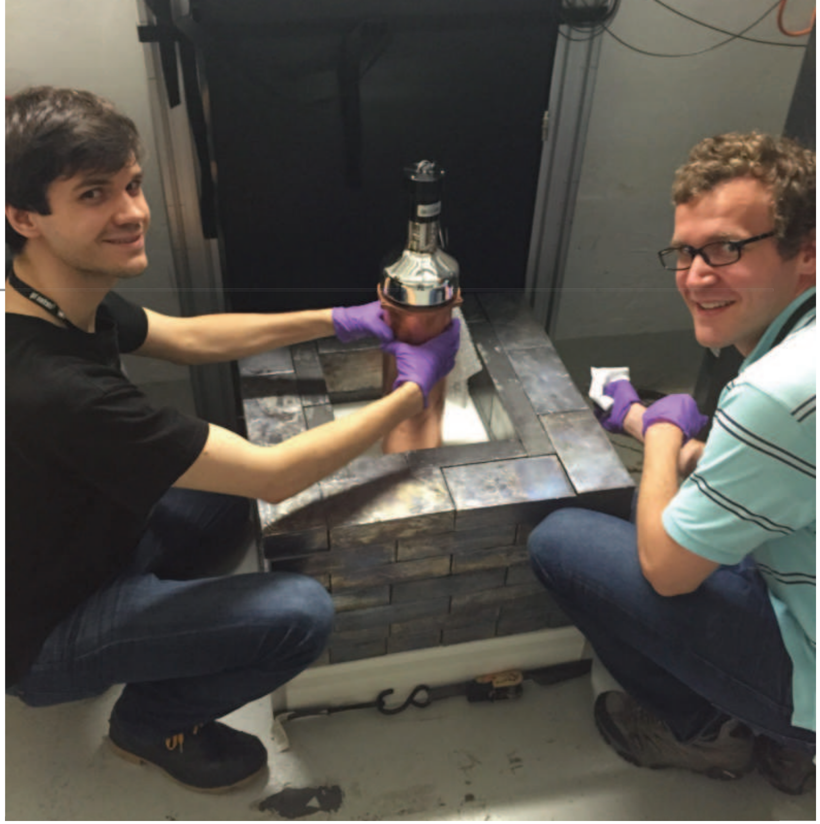


Strongly enhanced cross-section

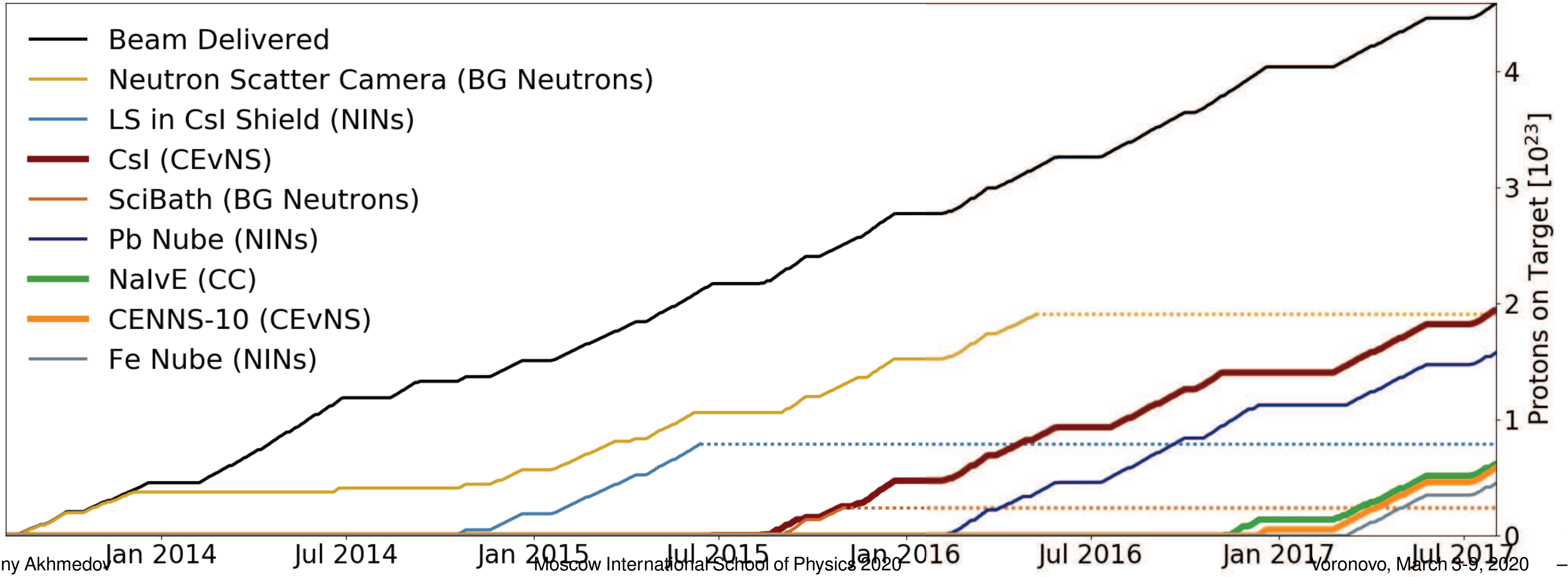
No energy threshold

Magnificent CEvNS, Raimund Strauss

A hand-held neutrino detector



- 14.6 kg low-background CsI[Na] detector deployed to a basement location of the SNS in the summer of 2015
- ~ 2×10^{23} POT delivered and recorded since CsI began taking data



Why is CEvNS interesting?

- Large cross sections – small detectors
- Very clean SM predictions for cross sections – sensitivity to NSI
- Sensitivity to μ_ν and $\langle r_\nu^2\rangle$
- Possibility to measure $\sin^2\theta_W$ at low energies
- Masurements of neutron formfactors (nuclear structure)
- Nuclear reactor monitoring (non-proliferation)
- Precision flavor-independent neutrino flux measurements for oscillation experiments
- Sterile neutrino searches
- Energy transport in SNe
- SN neutrino detection
- Input for DM direct detection (neutrino floor)
- Detection of solar neutrinos

Why is CEvNS interesting?

Many experiments planned or under way – CONUS, TEXONO, Ricochet, Connie, ν-cleus, RED100, MINER, νGEN, ...

Many theoretical studies

A very active field!

Atmospheric neutrinos

Atmospheric neutrinos

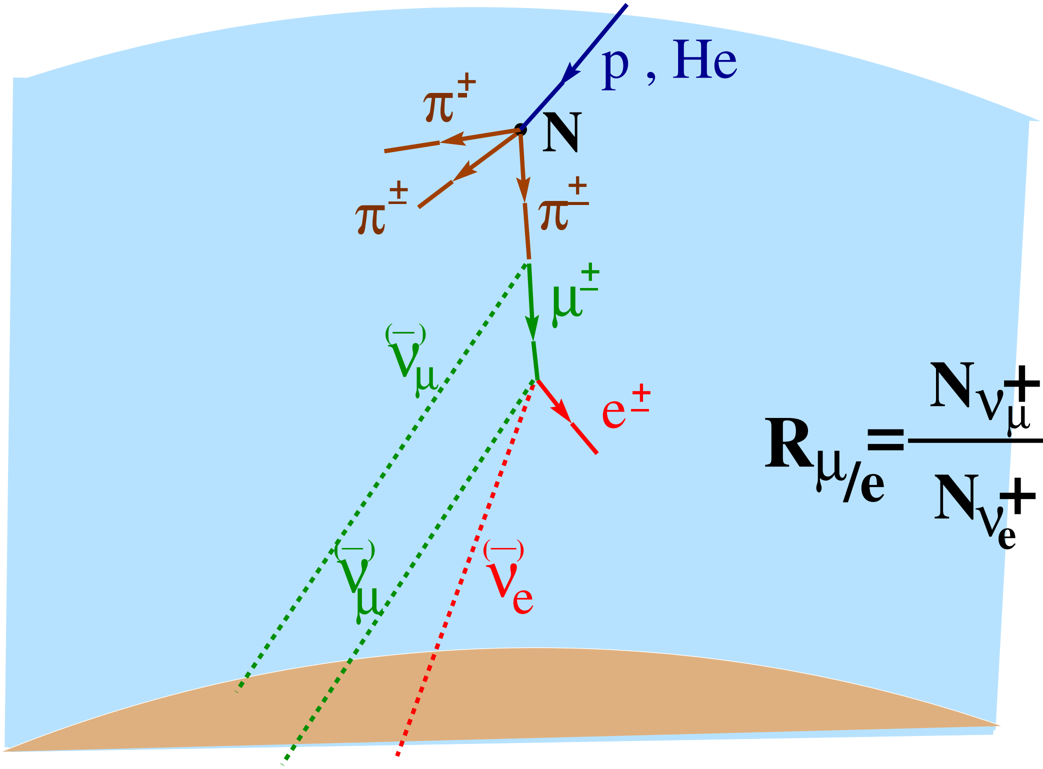
- Atmospheric neutrinos are produced by the interaction of *cosmic rays* (p, He, …) with the Earth's atmosphere:

$\boxed{1}$ $A_{\rm cr} + A_{\rm air} \to \pi^{\pm}, K^{\pm}, K^{0}, \ldots$

$\boxed{2}$ $\pi^{\pm} \to \mu^{\pm} + \nu_{\mu}\,,$

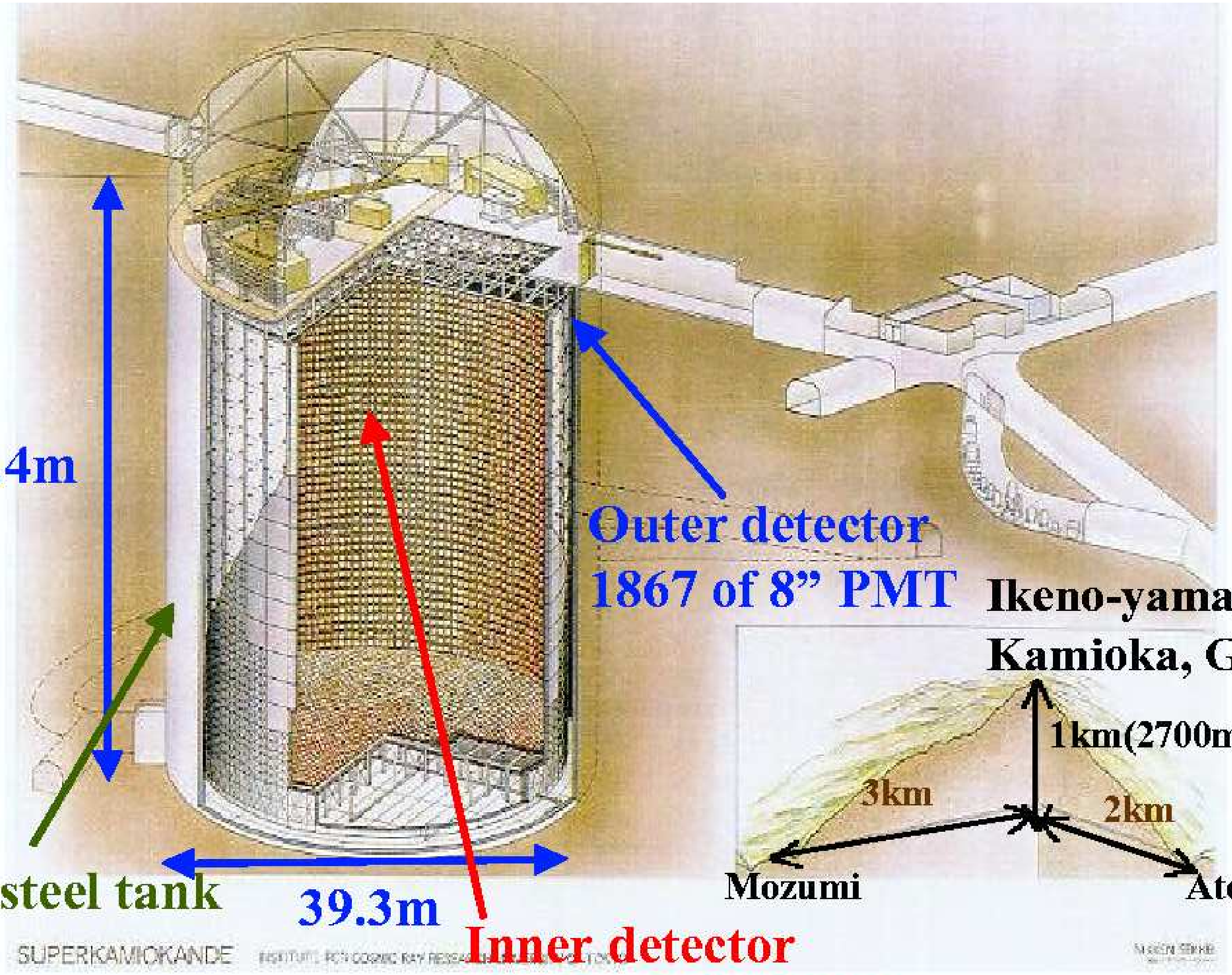
$\boxed{3}$ $\mu^{\pm} \to e^{\pm} + \nu_{e} + \nu_{\mu}\,;$

- at the detector, some ν interacts and produces a **charged lepton**, which is observed.



$$R_{\mu/e} = \frac{N_{\nu_\mu} + N_{\bar{\nu}_\mu}}{N_{\nu_e} + N_{\bar{\nu}_e}} \sim 2$$

Super-Kamiokande detector



41.4m

Outer detector
1867 of 8” PMT

Ikeno-yama
Kamioka, Gifu

1km(2700mwe)

3km

2km

Mozumi

Atotsu

50kton
stainless steel tank

39.3m

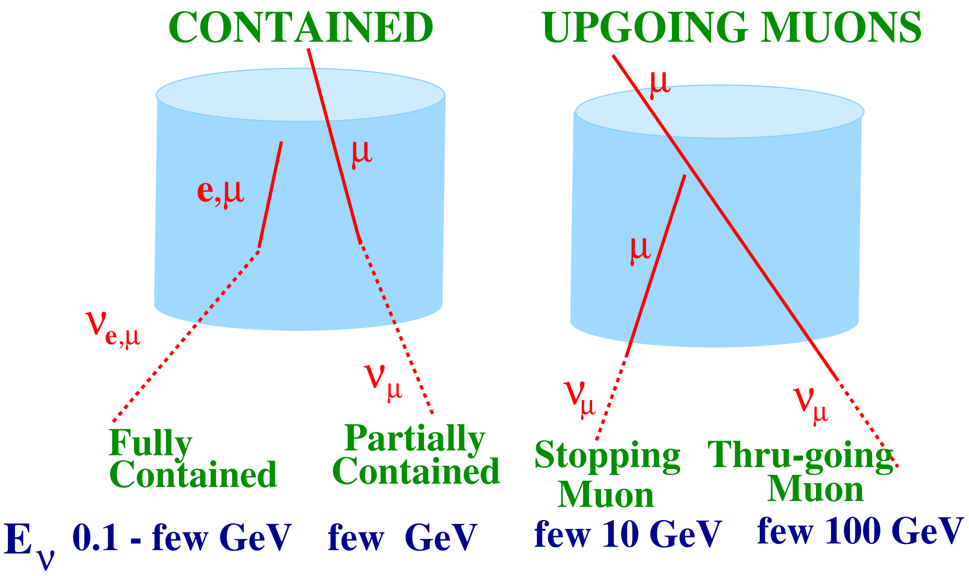
Inner detector
11146 of 20” PMT

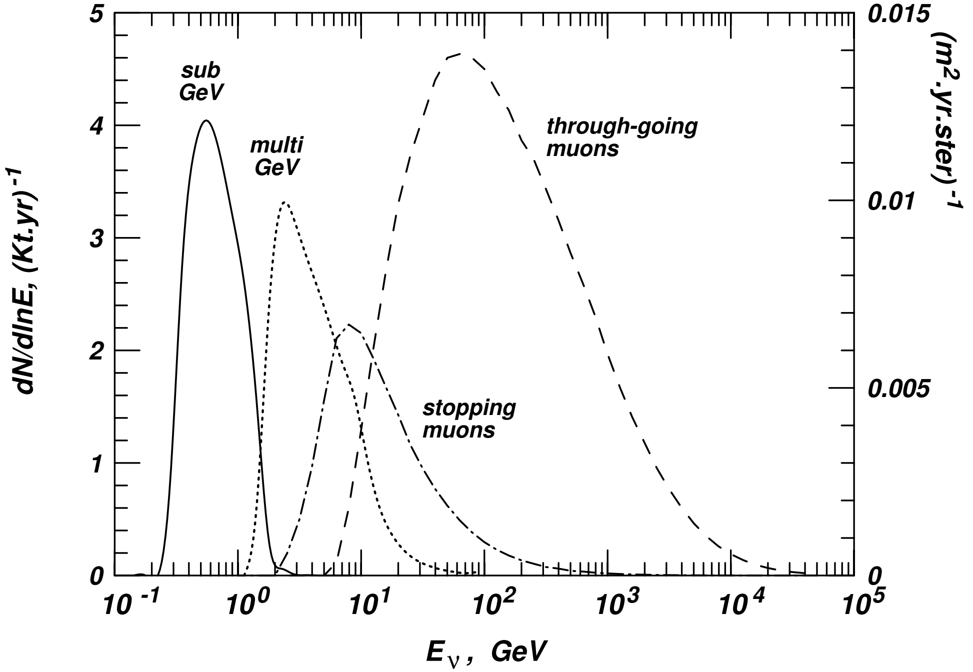
Classification of atmospheric neutrino events

- Neutrino events are classified according to whether the track of the charged lepton **begins** and **ends** **inside** or **outside** the detector:

	end inside	**end outside**
begin inside	fully contained	partially contained
begin outside	stopping μ	thru-going μ

- **contained events** are further divided into **sub-GeV** and **multi-GeV** data, depending on the reconstructed lepton energy.





Zenith angle distributions

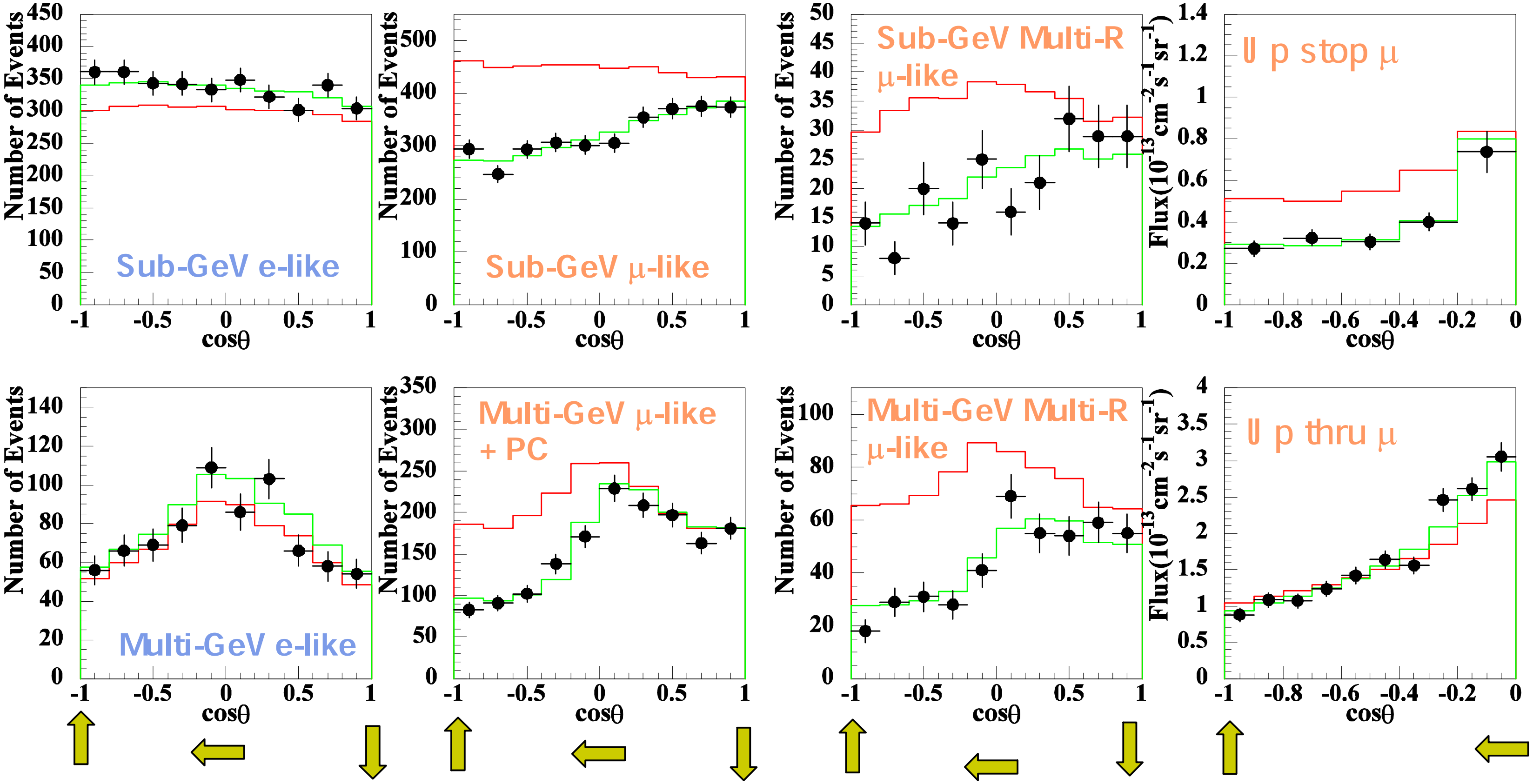
$\nu_\mu \leftrightarrow \nu_\tau$

2-flavor oscillations

🟩 **Best fit**

$\sin^2 2\theta = 1.0$, $\Delta m^2 = 2.0 \times 10^{-3}$ eV^2

🟥 **Null oscillation**



~13000km ~500km ~15km

~13000km ~500km

Oscillations of atmospheric ν_e

- ◇ $\Delta m^2_{21} \to 0$ (E.A., Dighe, Lipari & Smirnov, 1998) :

$$\frac{F_e - F_e^0}{F_e^0} = P_2(\Delta m^2_{31},\, \theta_{13}, V_{\rm CC}) \cdot (r\, s^2_{23} - 1)$$

- ◇ $s_{13} \to 0$ (Peres & Smirnov, 1999) :

$$\frac{F_e - F_e^0}{F_e^0} = P_2(\Delta m^2_{21},\, \theta_{12}, V_{\rm CC}) \cdot (r\, c^2_{23} - 1)$$

At low energies $r \equiv F_\mu^0/F_e^0 \simeq 2$; also $s^2_{23} \simeq c^2_{23} \simeq 1/2$ –
a conspiracy to hide oscillation effects on e-like events!
Reason: a peculiar flavour composition of the atmospheric ν flux.

(Because of $\theta_{23} \simeq 45°$, $P_{e\mu} \simeq P_{e\tau}$; but the original ν_μ flux is ~ 2 times larger than ν_e flux $\Rightarrow$ compensation of transitions from and to ν_e state).

Atmospheric neutrinos:

- Consistent with $\nu_\mu \leftrightarrow \nu_\tau$ oscillations. SK results confirmed by accelerator ν_μ disapperance experiments K2K, Minos, T2K and NoνA. Also seen in MACRO and IceCube DC expts.

$$|\Delta m^2_{31}| \sim 2.5 \times 10^{-3}\,\mathrm{eV}^2\,, \qquad \theta_{23} \sim 45^\circ$$

- Evidence for ν_τ appearance in SK and OPERA.

- Oscillations of ν_e may also be present at some level.

  Suppression of the observed ν_e signal due to the composition of the original ν_{atm} flux and value of θ_{23}.

  Broken by 3f effects and possible deviation θ_{23} from 45° (as follows from the latest global fits).

Summary

- Atmospheric neutrino experiments led to the first unambiguous evidence for neutrino oscillations
- About a half of atmospheric neutrinos traverse the Earth on their way to the detector
- Matter can strongly affect ν oscillations inside the Earth through the MSW and parametric resonance effects
- Study of atmsopheric neutrino oscillations in the Earth may bring a wealth of information both on neutrinos and the Earth

LBL accelerator experiments

Long-baseline beam experiments: taming the source

Past — Current — Future

K2K
KEK to Kamioka
250 km, 5 kW

MINOS (+)
FNAL to Soudan
734 km, 400 kW

CNGS
CERN to LNGS
730 km, 400 kW

NOνA
FNAL to Ash River
810 km, 700 kW

T2K
J-PARC to Kamioka
295 km, 380-750 kW

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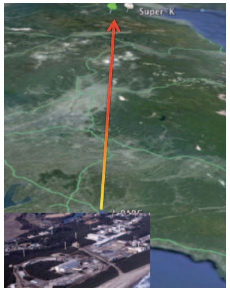
295 km, 380-750 kW

LBNF/DUNE
FNAL to Homestake
1300 km, 1.2 MW (➔2.3 MW)

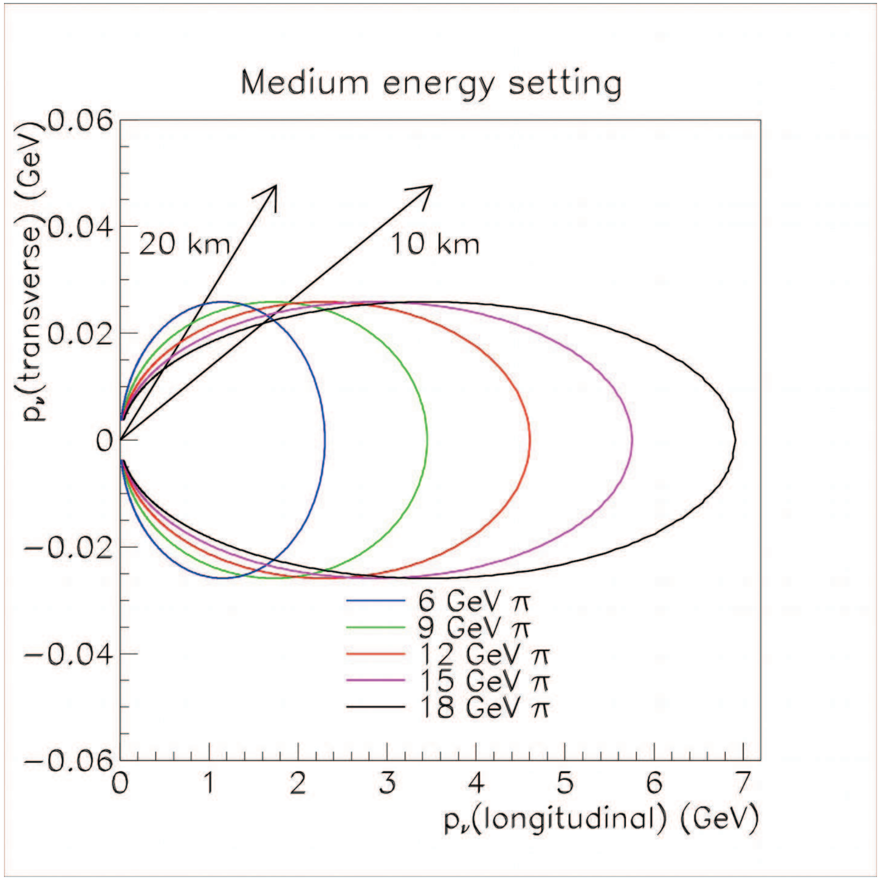


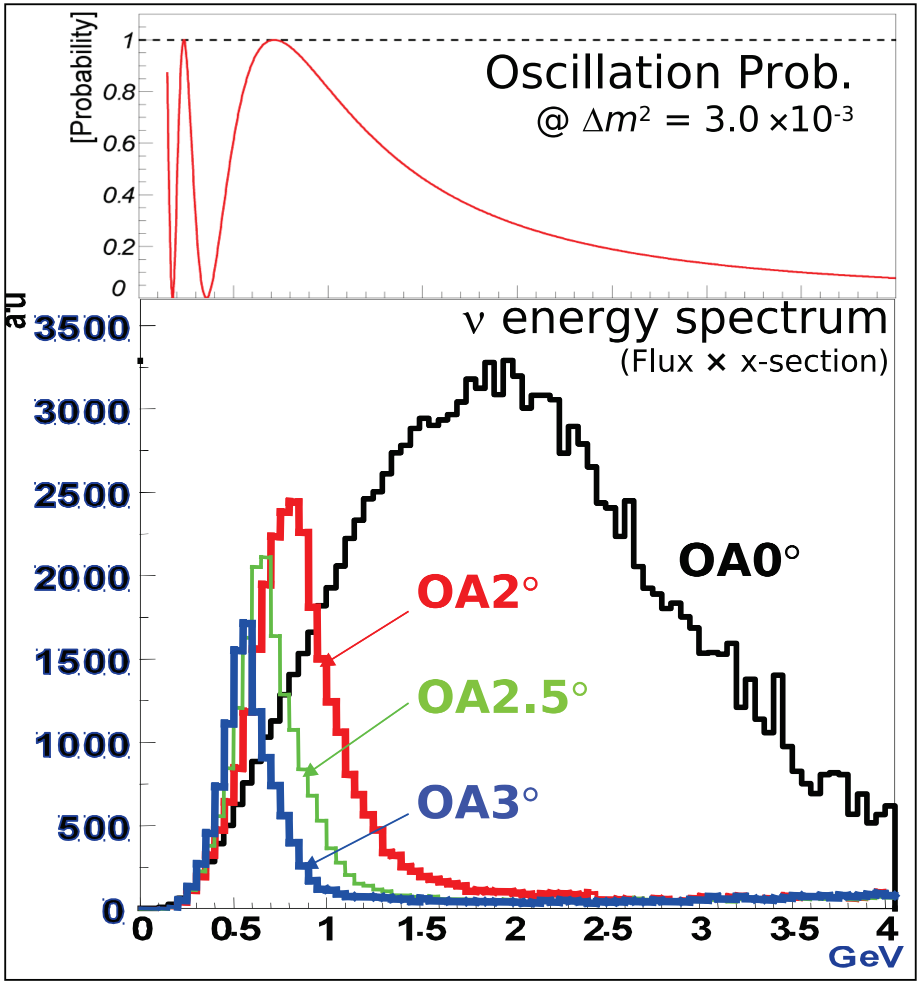
Hyper-K
J-PARC to Kamioka
295 km, 750 kW
(➔..)

And beyond...
ESSnuB,
neutrino factories

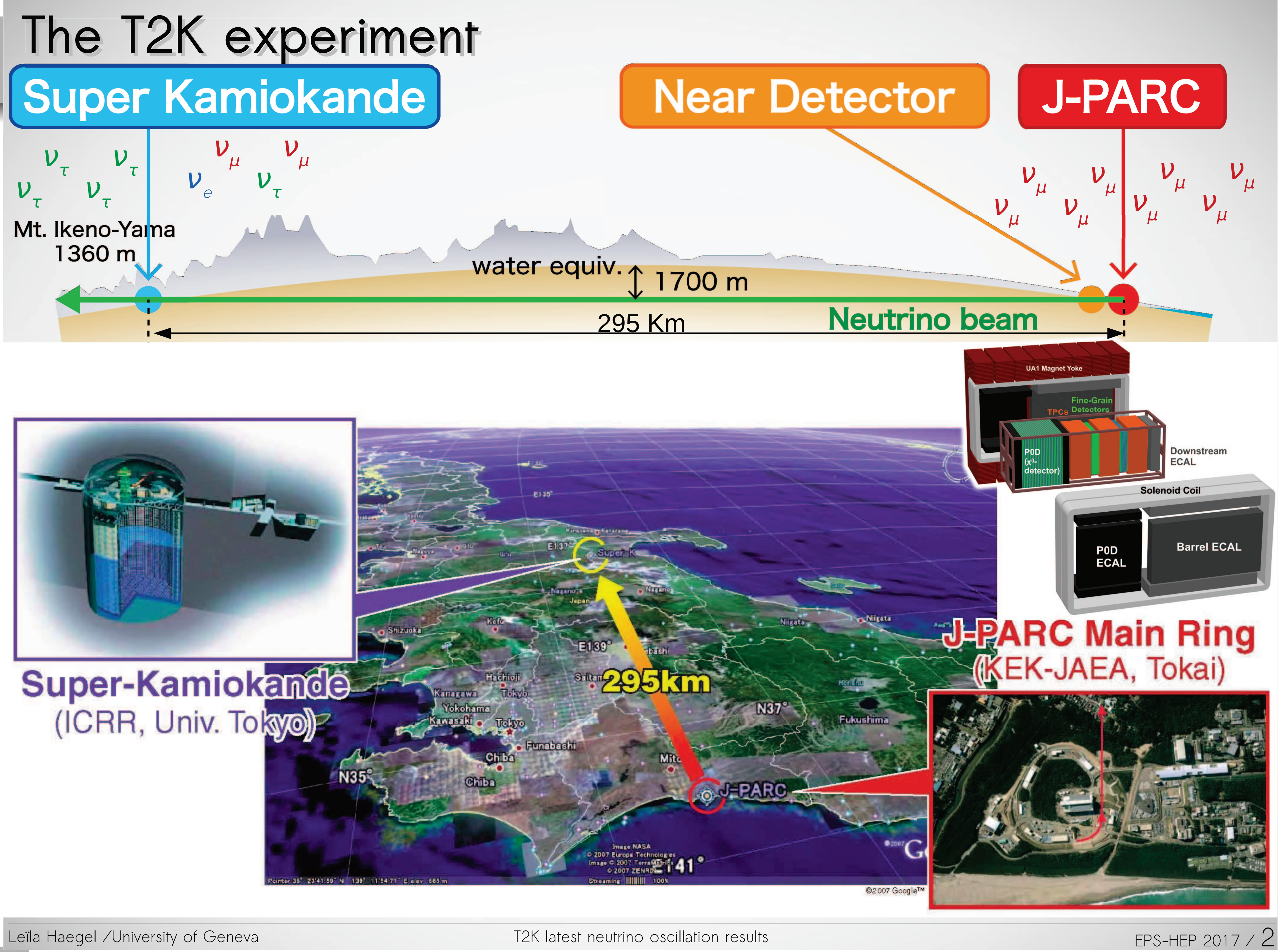
See sessions Neutrino-4,5,8

Off-Axis ν_μ Beam





Off-axis beam: more flux near peak oscillation energy, less flux at higher energies where ν_e backgrounds are produced.



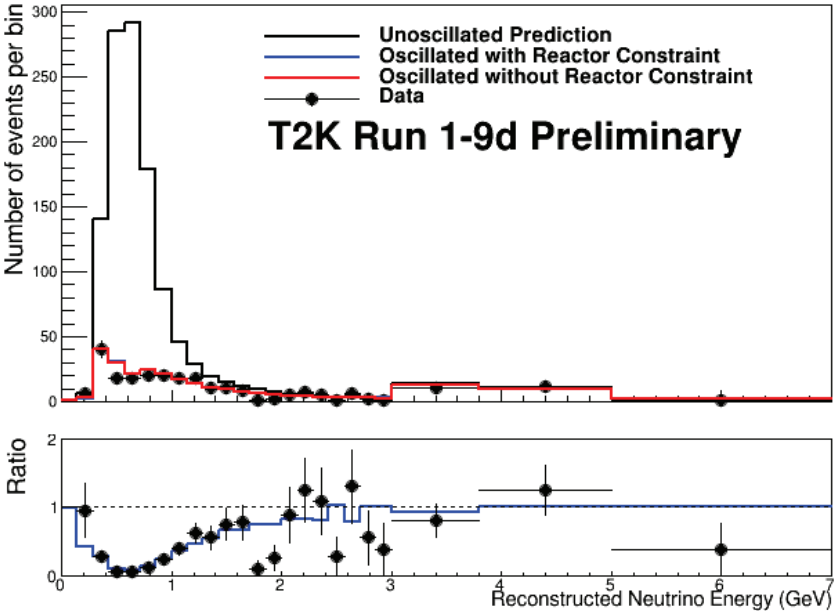
The T2K experiment

Leïla Haegel / University of Geneva

T2K latest neutrino oscillation results

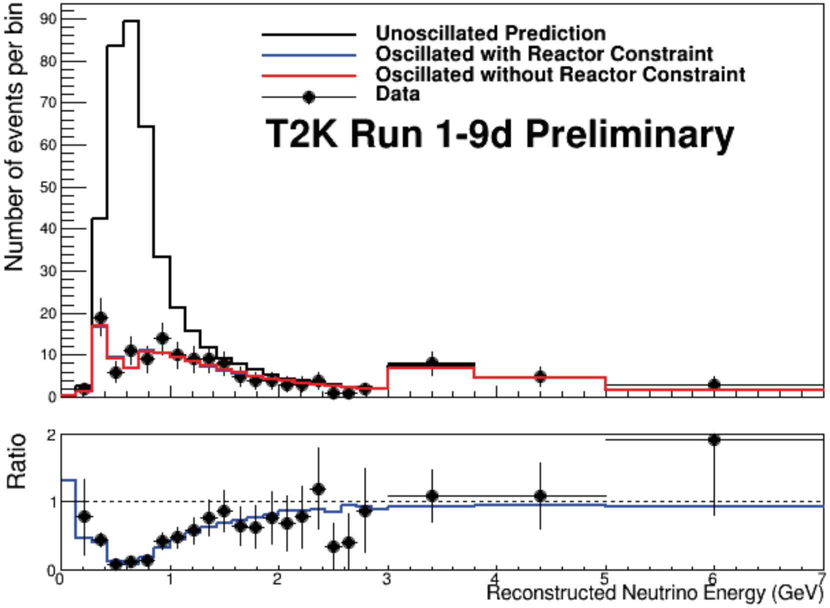
EPS-HEP 2017 / 2

Disappearance

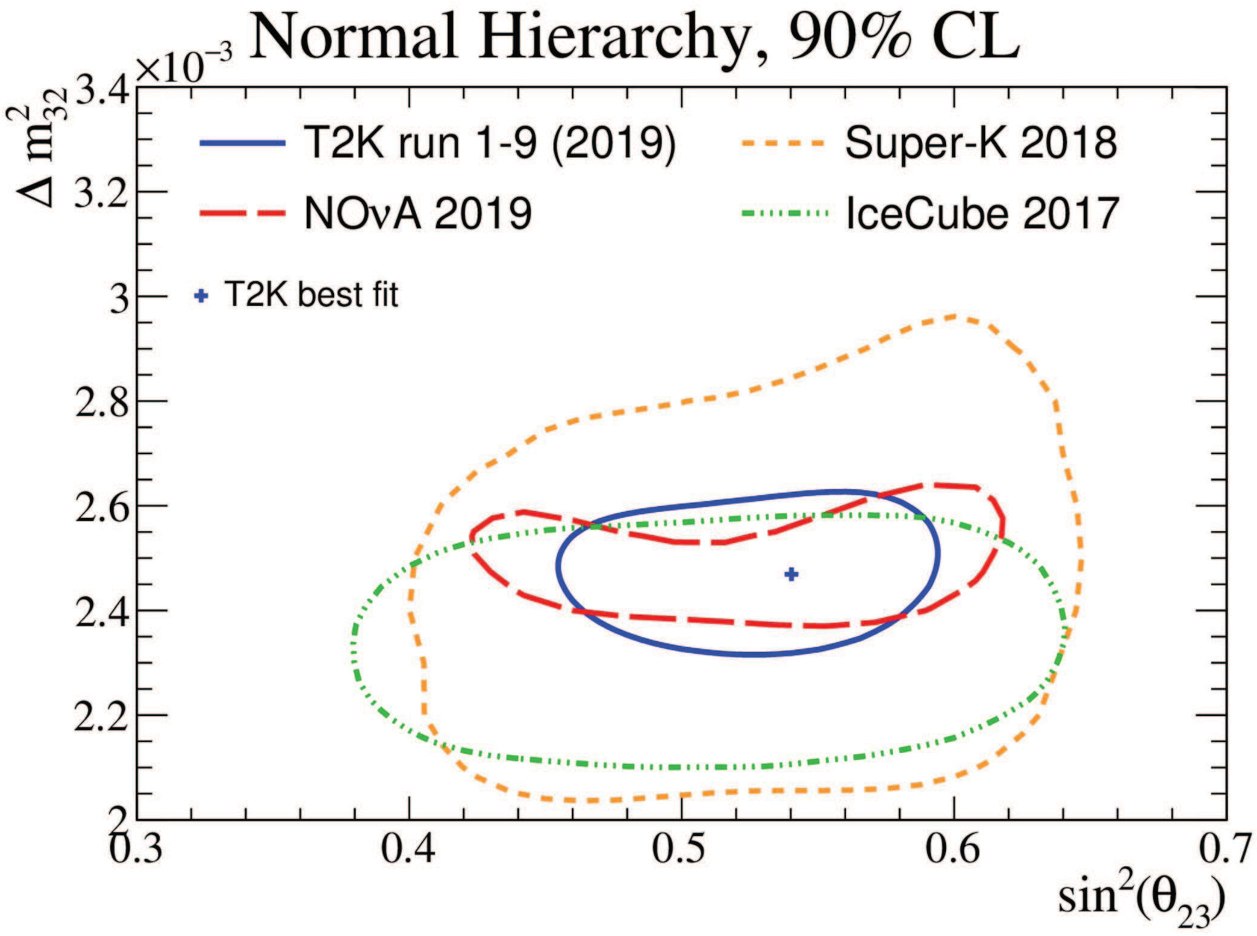


muon neutrino disappearance

muon antineutrino disappearance



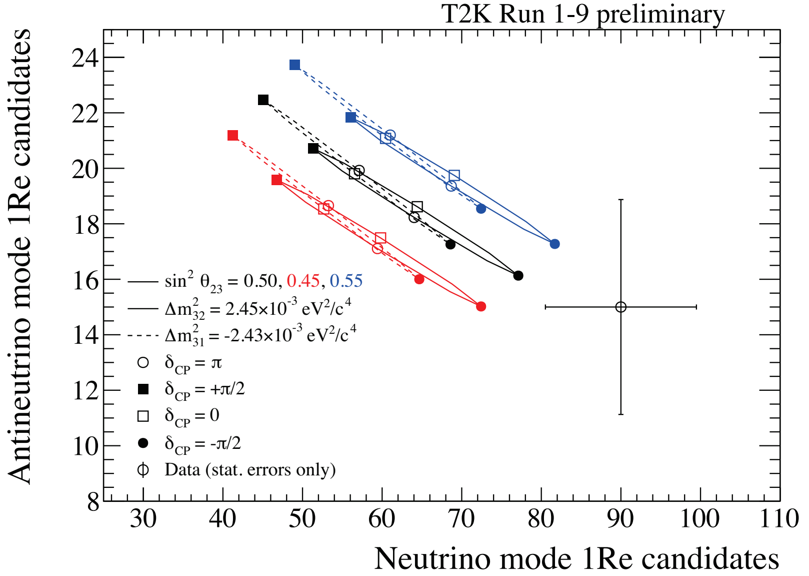
$\sin^2 2\theta_{23}$, Δm^2



ν_e vs $\bar{\nu}_e$ appearance

- **Comparison of # of ν_e and $\bar{\nu}_e$ appearance candidates**

	Obs.	Expectation			
		$\delta=-\pi/2$	$\delta=\pi$	$\delta=\pi/2$	$\delta=0$
$\nu_\mu \to \nu_e$ candidates	**90**	81.4	68.6	55.5	68.3
$\bar{\nu}_\mu \to \bar{\nu}_e$ candidates	**15**	17.1	19.3	21.7	19.4
		CPV	CPC	CPV	CPC



oscillation parameters are extracted using all event samples (not only ν_e samples but also ν_μ samples)

Summary

- The accelerator-based neutrino oscillation program in Japan, founded by Koichiro Nishikawa, is continuing evolution K2K → T2K → T2HK
- δ_{CP} 2σ confidence interval[−3.966, −0.628] (NO) [−1.799, −0.979] (IH)

  CP-conserving case ($\delta_{CP} = 0, \pi$) is outside 2σ (95%) region

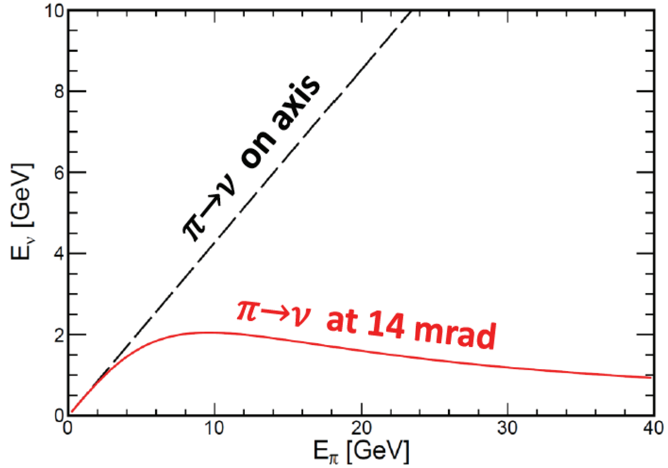
  $[-2°, 165°]$ is outside 3σ region

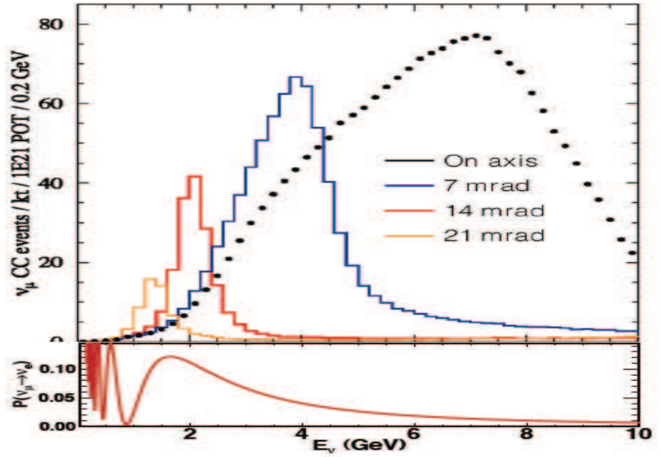
  Normal ($m_3 > m_2 > m_1$): 88.9% vs. Inverted ($m_2 > m_1 > m_3$): 11.1%
- Timeline from now

  2020 Super-Kamiokande upgrade by dissolving Gd to 0.01% concentration

  2021 Upgrade of beam intensity(750 kW) & ND280
  2023~2025 Second beam upgrade to reach 1.3 MW
  Aiming to collect 1~2x 10^{22} POT with 3σ sensitivity to CPV if CPV is ~maximal

NuMI Off-Axis ν_e Appearance Experiment

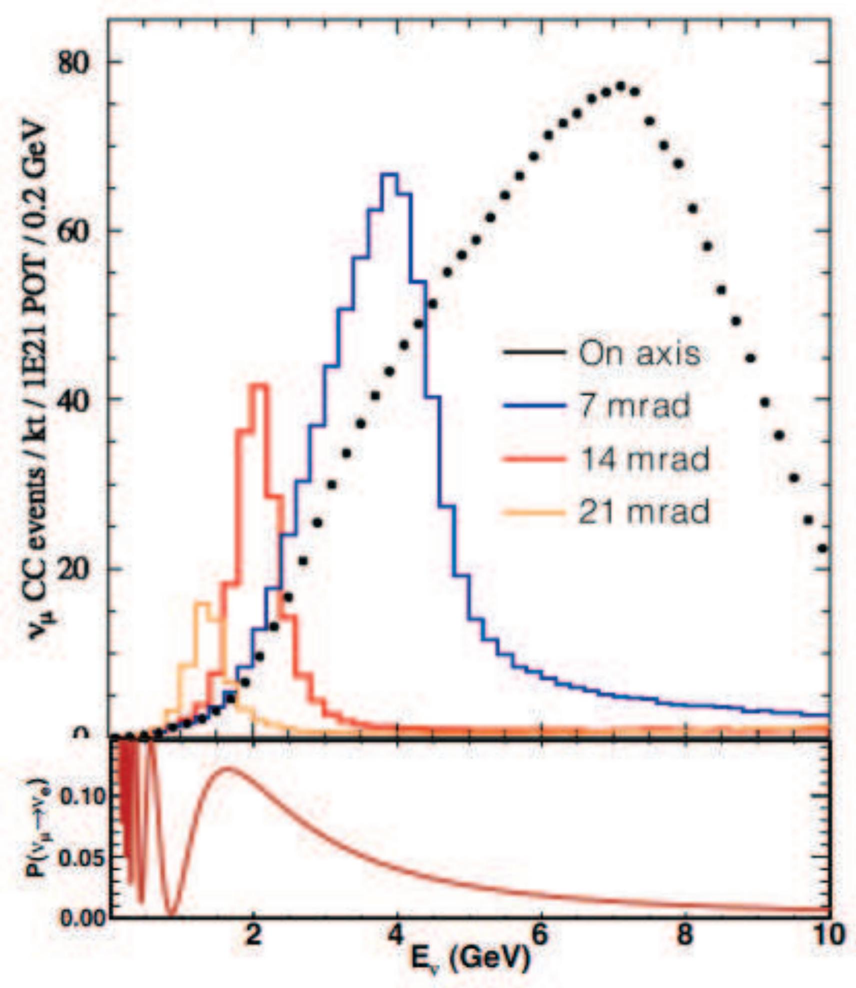




- Upgraded NuMI muon neutrino beam at Fermilab (700 kW design goal achieved)
- Longest baseline in operation (810 km), large matter effect (±30%), sensitive to mass hierarchy
- Far/Near detector sited 14 mrad off-axis, narrow-band beam around oscillation maximum, small wrong sign components ($\bar{\nu}$ in ν beam or ν in $\bar{\nu}$ beam)

The NOvA experiment

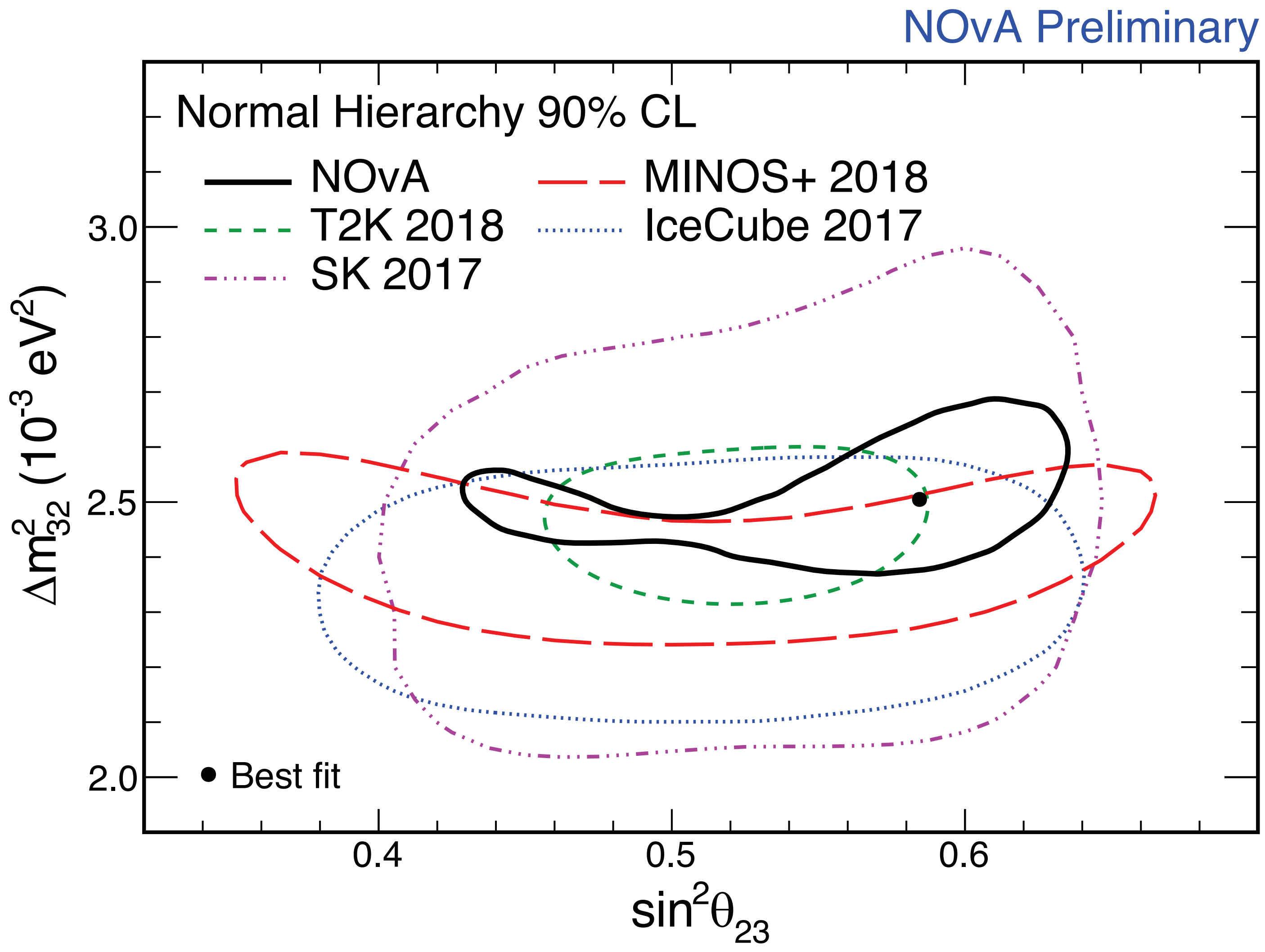
- NuMI Off-Axis ν_e Appearance, the leading neutrino oscillation experiment in the NuMI beam
- Two highly active scintillator detectors:
  - Far Detector: 14 kT, on surface
  - Near Detector: 300 T, 105 m underground
- 14 mrad off-axis narrowly peaked muon neutrino flux at 2 GeV, L/E ~ 405 km/GeV
- ν_μ disappearance channel: θ_{23}, Δm^2_{32}
- ν_e appearance channel: mass hierarchy, δ_{CP}, θ_{13}, θ_{23} and octant degeneracy



Also: neutrino cross sections at the ND, sterile neutrinos, supernovae…

Joint Appearance and Disappearance

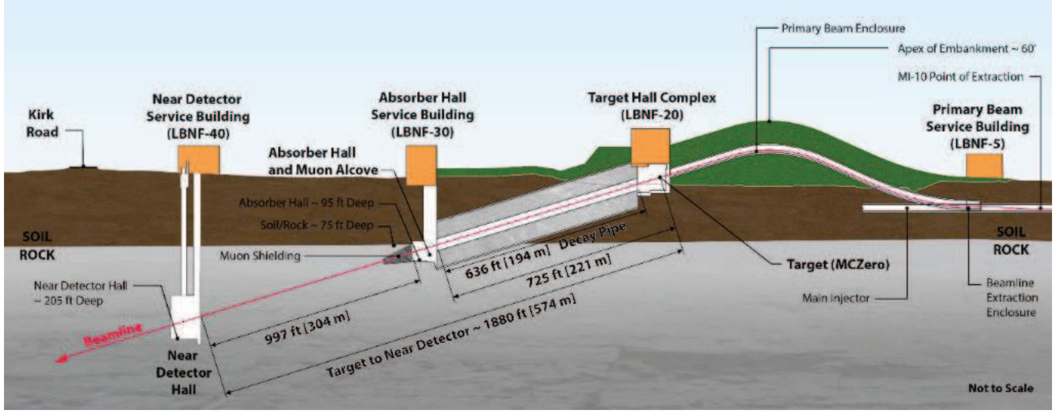
NOvA's allowed 90% C.L. regions are compatible to other experiments

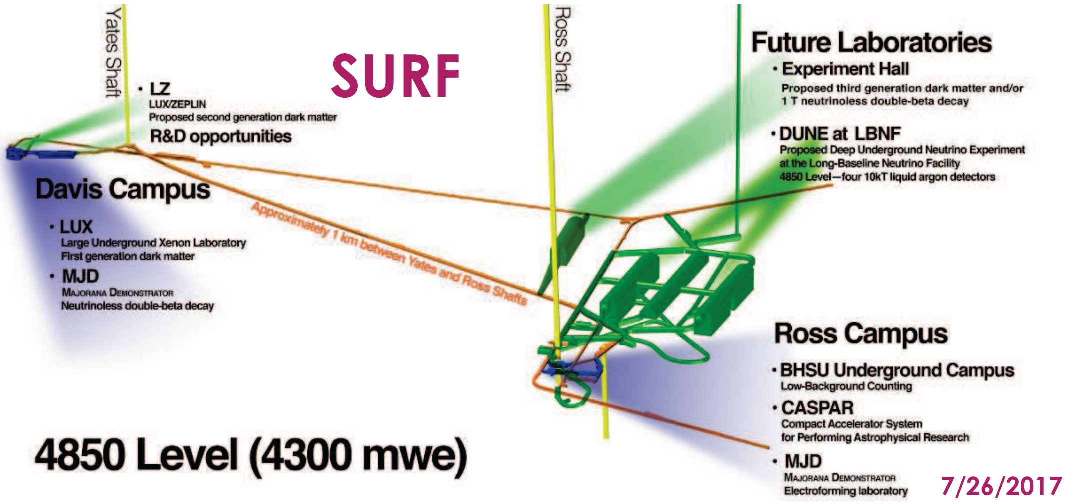


Future LBL projects

DUNE (**D**eep **U**nderground **N**eutrino **E**xperiment)

- Muon neutrino beam from from Fermilab (LBNF – Long Baseline Neutrino Facility)
  - On-axis broadband beam
  - Beam intensity 1.2 MW, upgradable to 2.4 MW (120 GeV primary protons)
- Far detector at SURF in South Dakota
  - 1300 km baseline
  - 4300 mwe overburden





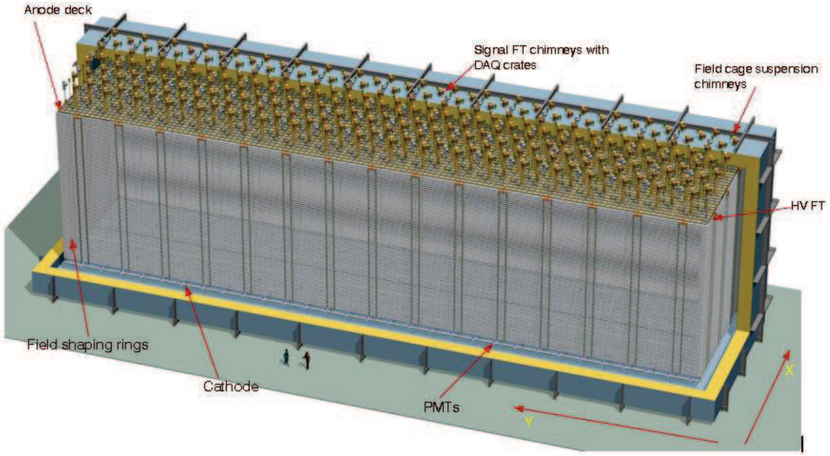
DUNE CDR arXiv:1512.06148
E. Worcester, APS April 2017

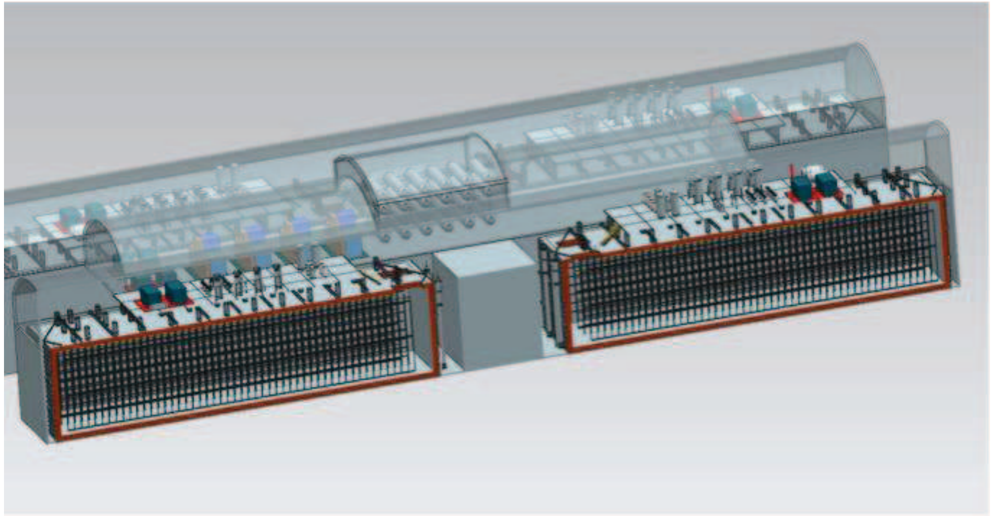
DUNE Far Detector

40 kt liquid argon (LAr) TPC
4 x 10 kt modules
(Modules not necessarily identical)

Dual-phase TPC

(single module with amplification in gas phase)





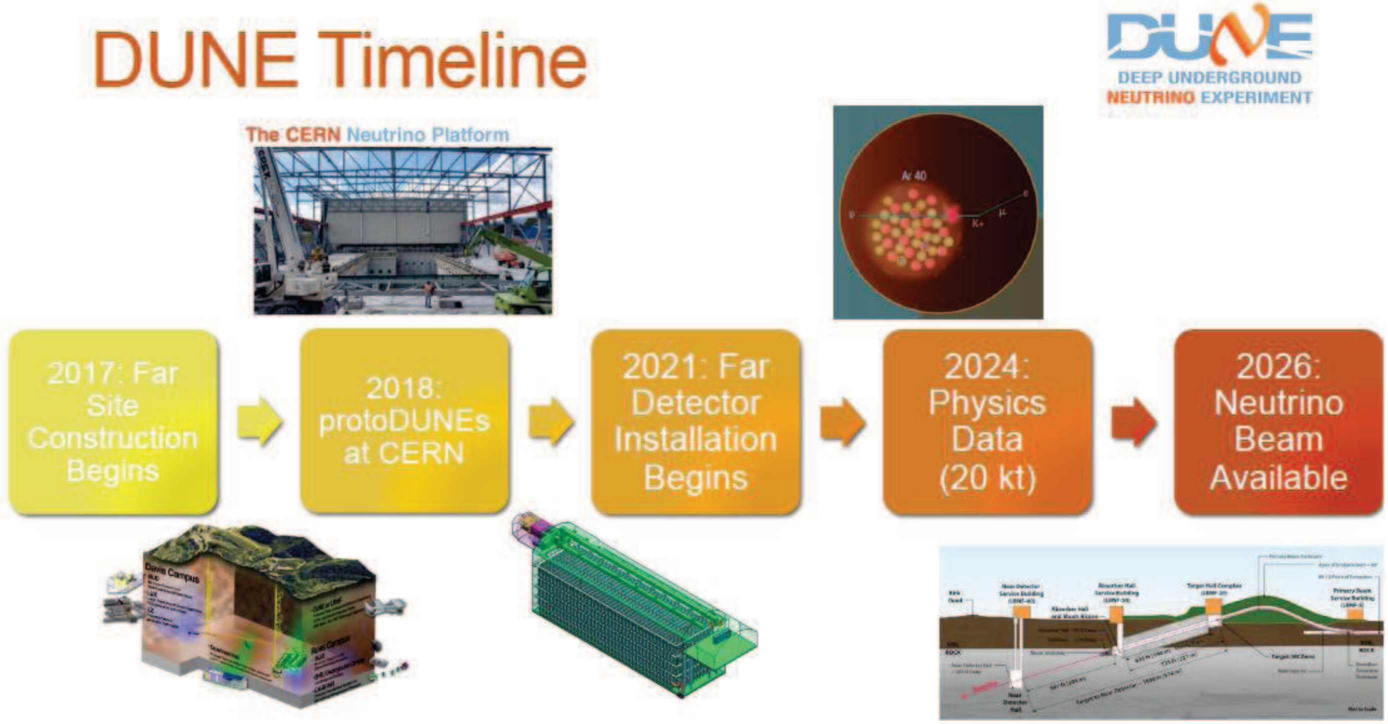
Single-phase TPC

Suspended anode (APA) and cathode (CPA) assemblies – 3.6 m spacing

L.W. Koerner, University of Houston

7/26/2017

DUNE Status and Timeline



DUNE Timeline

DEEP UNDERGROUND NEUTRINO EXPERIMENT

The CERN Neutrino Platform

2017: Far Site Construction Begins

2018: protoDUNEs at CERN

2021: Far Detector Installation Begins

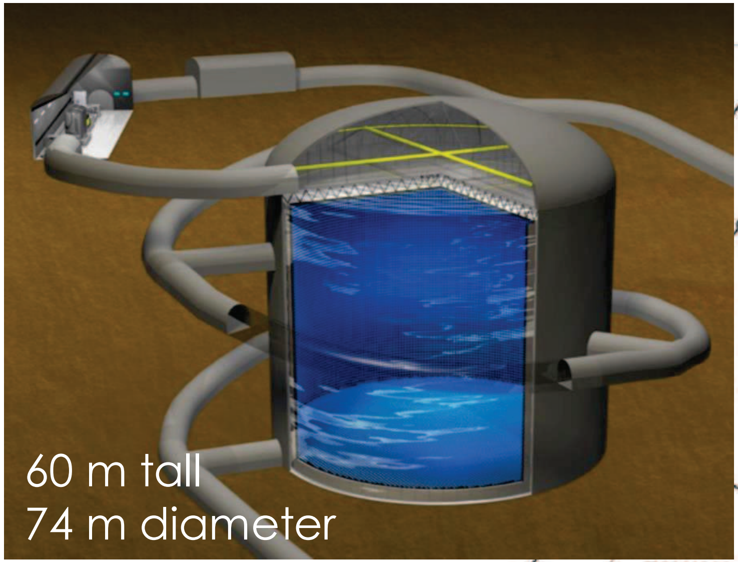
2024: Physics Data (20 kt)

2026: Neutrino Beam Available

- International collaboration
  - Began in 2015
  - Nearly 1000 collaborators from 30 countries
- Far site ground breaking ceremony July 21!

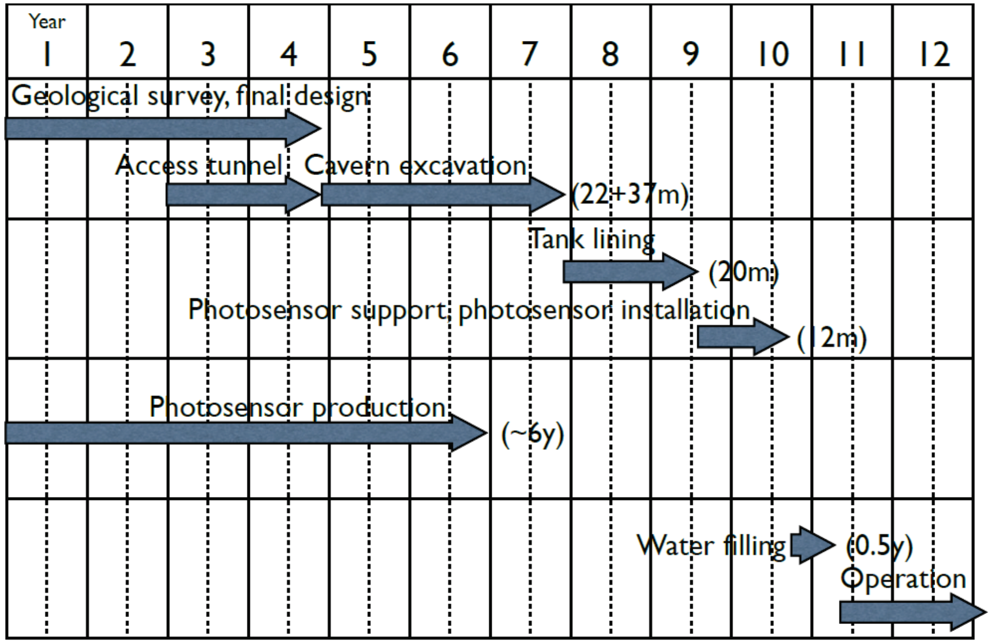
Hyper-Kamiokande Detector

- Water Cherenkov detector
  - 260 kton ultra pure water (Fiducial mass 187 kton)
  - New 50 cm photo sensors with improved single photon deection efficiency (2x Super-K PMTs)
  - 40% photocathode coverage
  - 650 m (1750 mwe) depth
- Aiming for a quick start with one tank
  - Second tank under consideration (time, design, location…)



S. Nakayama WIN 2017
"Hyper-Kamiokande Design Report"
https://lib-extopc.kek.jp/preprints/PDF/2016/1627/1627021.pdf

Hyper-K Status and Timeline



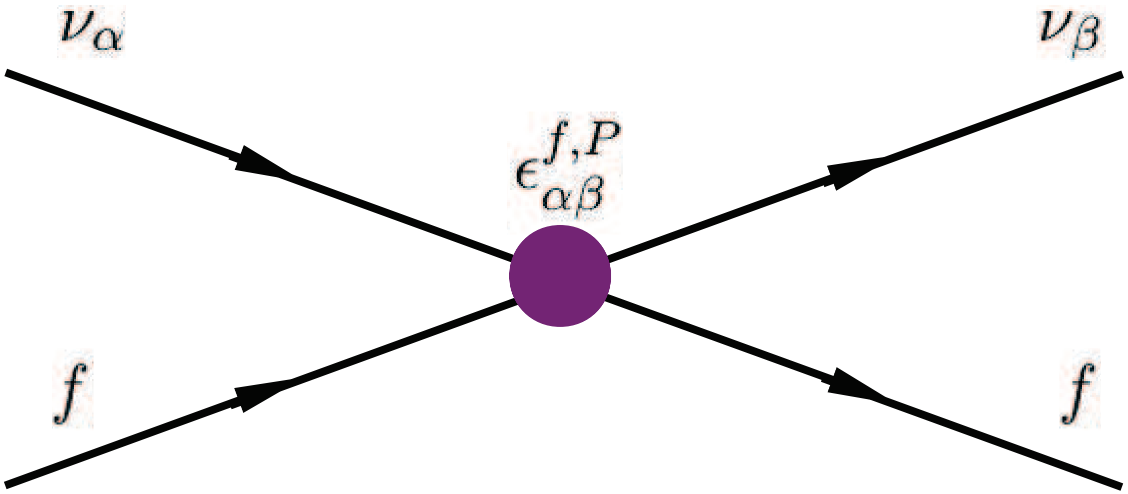
- International Collaboration
  - Began in 2015
  - As of April 2017, 300 members from 15 countries
- Just last week, a draft of the MEXT (funding agency) Roadmap for Large Projects was released and includes Hyper-K as an important component
- Budget request to start construction in JFY2018
  - Aim to begin operation in 2026

Backup slides

NSI parameterization

P. Coloma. P.B. Denton, M.C. Gonzalez-Garcia, M. Maltoni, T. Schwetz,
”Curtailing the Dark Side in Non-Standard Neutrino Interactions”, arXiv:1701.04828

$$\mathcal{L}_{\mathrm{NSI}} = -2\sqrt{2}G_F \sum_{f,P,\alpha,\beta} \epsilon^{f,P}_{\alpha\beta} (\bar{\nu}_\alpha \gamma^\mu P_L \nu_\beta)(\bar{f}\gamma_\mu P f)$$



Assuming heavy NSI mediators

CEvNS cross section and NSI

J. Barranco, O.G. Miranda, T.I. Rashba,
”Probing new physics with coherent neutrino scattering off nuclei”, arXiv:hep-ph/0508299

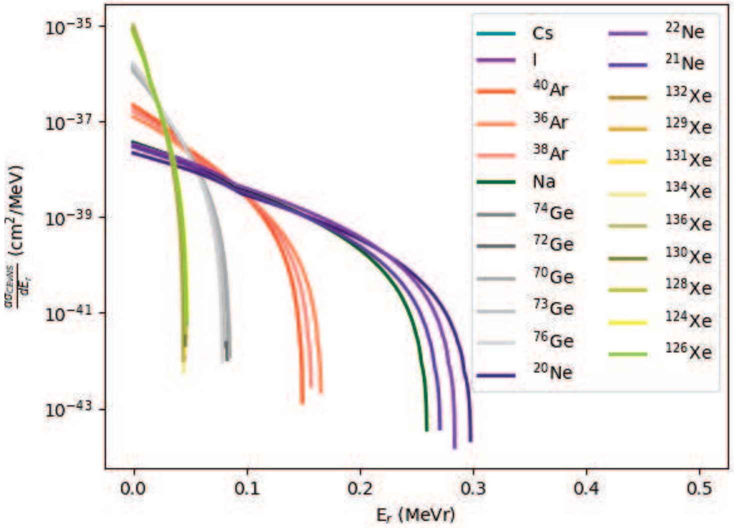
$$\frac{d\sigma}{dT} = \frac{G_F^2 M}{2\pi} F^2(Q) \left[(G_V + G_A)^2 + (G_V - G_A)^2 \left(1 - \frac{T}{E_\nu}\right)^2 - (G_V^2 - G_A^2)\frac{MT}{E_\nu^2} \right]$$

$$G_V = (g_V^p + \boxed{2\varepsilon_{ee}^{uV} + \varepsilon_{ee}^{dV}})Z + (g_V^n + \boxed{\varepsilon_{ee}^{uV} + 2\varepsilon_{ee}^{dV}})N$$

NSI terms

$$G_A = (g_A^p + 2\varepsilon_{ee}^{uA} + \varepsilon_{ee}^{dA})(Z_+ - Z_-) + (g_A^n + \varepsilon_{ee}^{uA} + 2\varepsilon_{ee}^{dA})(N_+ - N_-) \approx 0$$

- Modification = $\dfrac{\sigma(\varepsilon)}{\sigma^{SM}}$

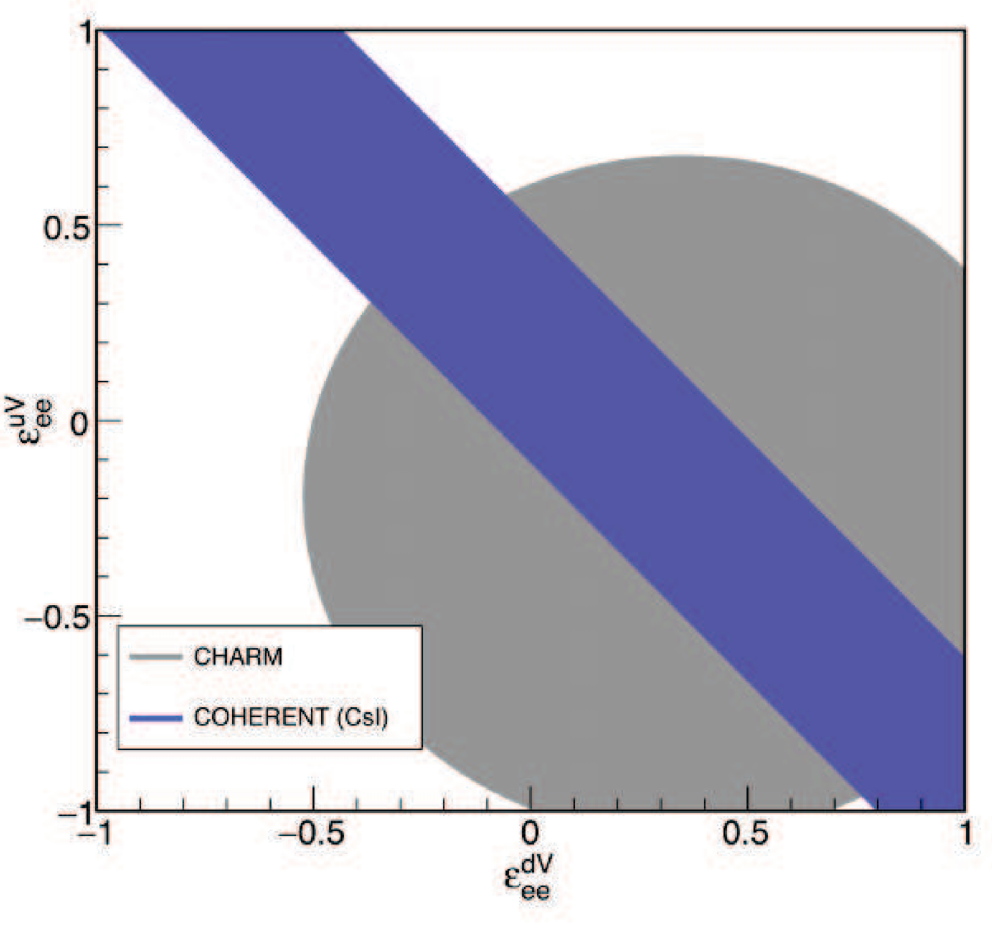


SM diff σ weighted by piDAR spectra

D. Akimov, J.B. Albert, P. An, et al.,
”Observation of Coherent Elastic Neutrino-Nucleus Scattering”, arXiv:1708.01294

COHERENT NSI constraint

- August 2017 result
- 14.6 kg CsI[Na]
- ~2 years running
  - 308.1 live-days
- Events
  - 134 ± 22 observed
  - 173 ± 48 predicted



Why straight lines for SM rate?

J. Barranco, O.G. Miranda, T.I. Rashba,
”Probing new physics with coherent neutrino scattering off nuclei”, arXiv:hep-ph/0508299

$$\frac{d\sigma}{dT} = \frac{G_F^2 M}{2\pi} F^2(Q) \left[(G_V + G_A)^2 + (G_V - G_A)^2 \left(1 - \frac{T}{E_\nu}\right)^2 - (G_V^2 - G_A^2)\frac{MT}{E_\nu^2} \right]$$

$$G_V = (g_V^p + 2\varepsilon_{ee}^{uV} + \varepsilon_{ee}^{dV})Z + (g_V^n + \varepsilon_{ee}^{uV} + 2\varepsilon_{ee}^{dV})N \qquad G_A \approx 0$$

SM rate: $G_V^{SM} = g_V^p Z + g_V^n N$

$$\frac{d\sigma^{SM}}{dT} = \frac{d\sigma}{dT}(G_V^{SM}) \quad \rightarrow \quad {G_V^{SM}}^2 = G_V^2$$

$$(g_V^p + 2\varepsilon_{ee}^{uV} + \varepsilon_{ee}^{dV})Z + (g_V^n + \varepsilon_{ee}^{uV} + 2\varepsilon_{ee}^{dV})N = \pm (g_V^p Z + g_V^n N)$$

Generating two straight lines in NSI-coupling space with SM rate

Including magnetic moment scattering

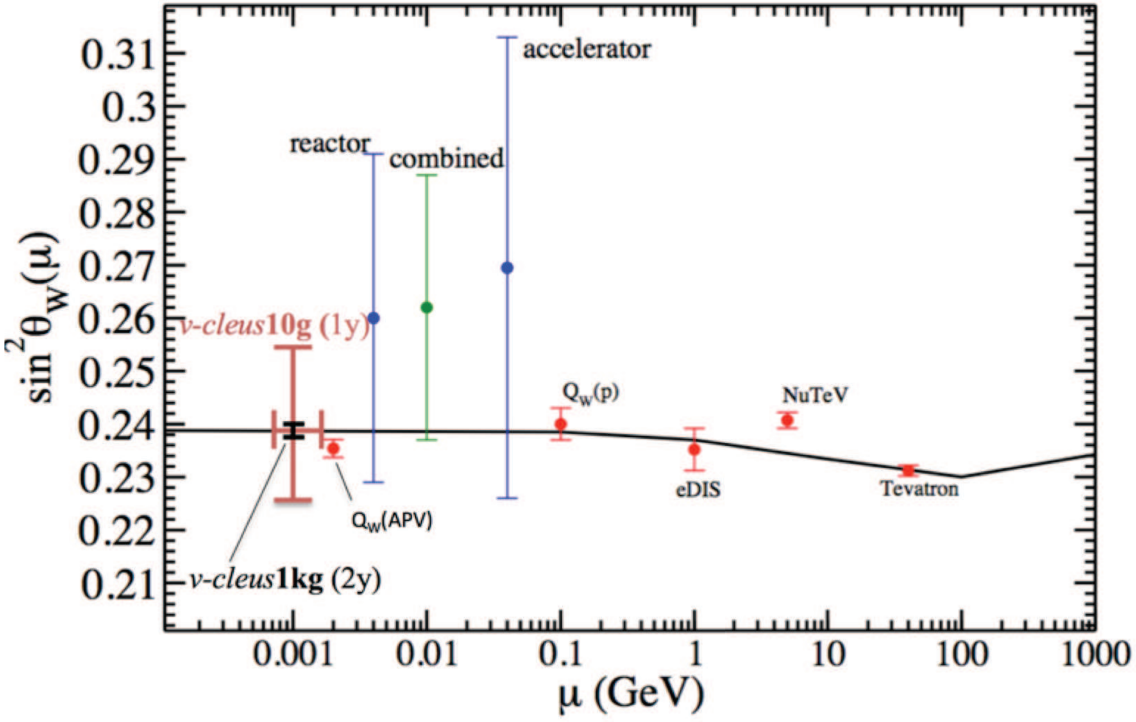
$$\frac{d\sigma}{dT} = \frac{G_F^2}{8\pi} M \left[2 - \frac{2T}{T_{max}} + \left(\frac{T}{E}\right)^2\right] Q_W^2 [F_Z(Q^2)]^2 + \frac{\pi\alpha^2\mu_{\mathrm{eff}}^2 Z^2}{m_e^2}\left[\frac{1}{T} - \frac{1}{E}\right][F_\gamma(Q^2)]^2$$

$$\mu_{\mathrm{eff}}^2 = \sum_i \left|\sum_j U_{(e\ \mathrm{or}\ \mu)j}\ e^{-iE_jL}\mu_{ji}\right|^2$$

Note that this is a different combination at CEνNS than what is measured at reactors or solar neutrino experiments!

Weinberg Angle

“Running” of Weinberg Angle



$$\left(\frac{d\sigma}{dE}\right)_{\nu_\alpha A} = \frac{G_F^2 M}{\pi} F^2(2ME)\left[1 - \frac{ME}{2k^2}\right] \times$$
$$\{[Z(g_V^p + 2\varepsilon_{\alpha\alpha}^{uV} + \varepsilon_{\alpha\alpha}^{dV}) + N(g_V^n + \varepsilon_{\alpha\alpha}^{uV} + 2\varepsilon_{\alpha\alpha}^{dV})]^2$$

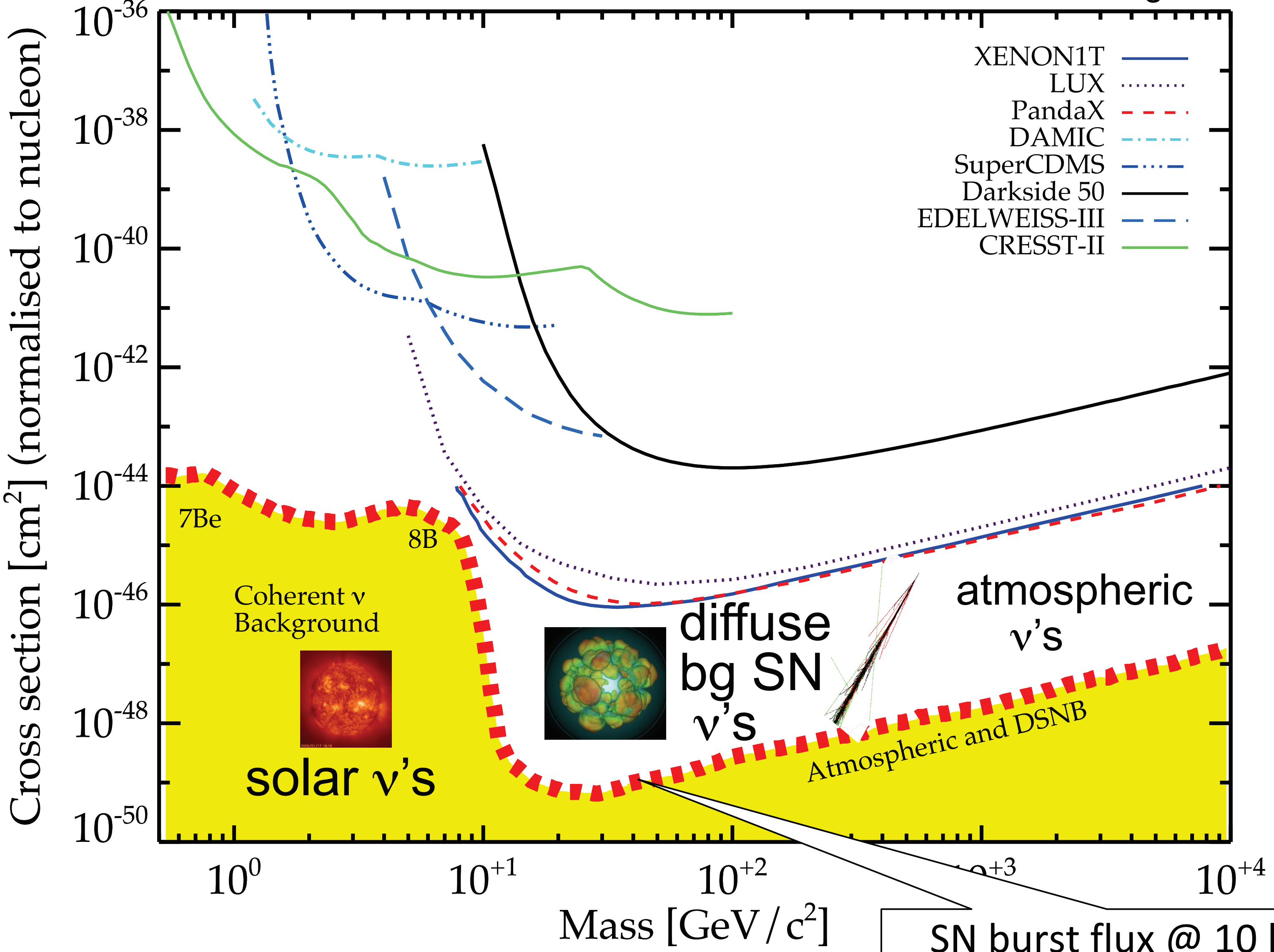
With $g_V^p = (\frac{1}{2} - 2\,\underline{\sin^2\theta_W})$ and $g_V^n = -\frac{1}{2}$

First determination of the Weinberg angle at q = 1MeV/c after 2-3 weeks of measurement with 10g!

The so-called “**neutrino floor**” for DM experiments

J. Billard, E. Figueroa-Feliciano, and L. Strigari, arXiv:1307.5458v2 (2013).

L. Strigari

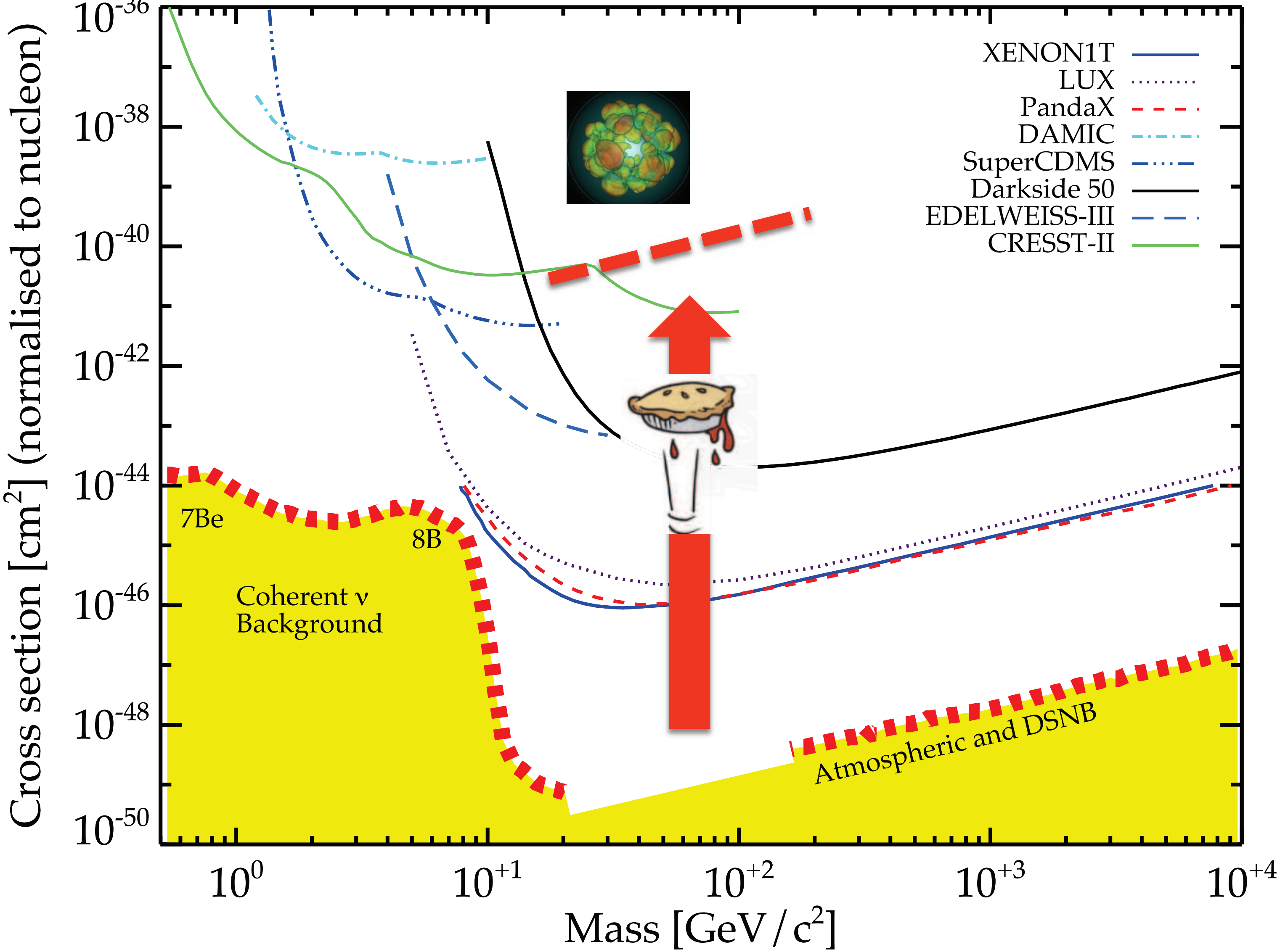


SN burst flux @ 10 kpc is 9-10 orders of magnitude greater than DSNB flux

Think of a SN burst as "**the ν floor coming up to meet you**"

J. Billard, E. Figueroa-Feliciano, and L. Strigari, arXiv:1307.5458v2 (2013).

L. Strigari



More backup slides

Sensitivity Assumptions

DUNE

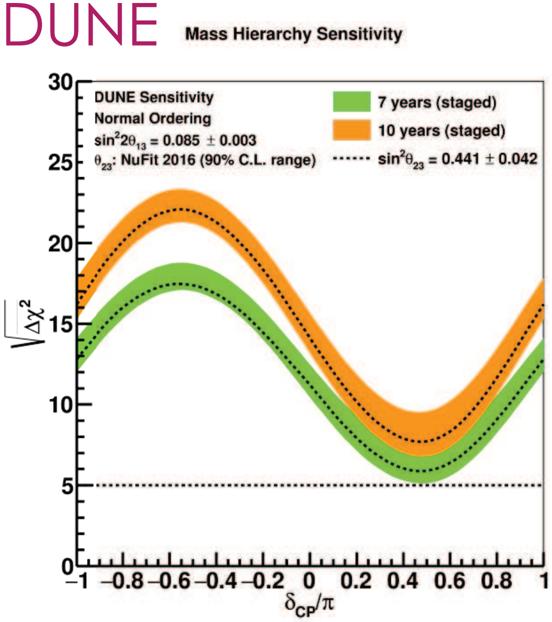
- Staging: Begin with 20 kton, 1.07 MW beam; 40 kton in year 4, 2.14 MW in year 7
- Neutrino: Antineutrino = 1:1
- θ_{23} from global fit (non-maximal)

Hyper-K

- Staging: Begin with single 187 kton fiducial tank and 1.3 MW beam; second tank in year 7
- Neutrino: Antineutrino = 1:3
- θ_{23} maximal

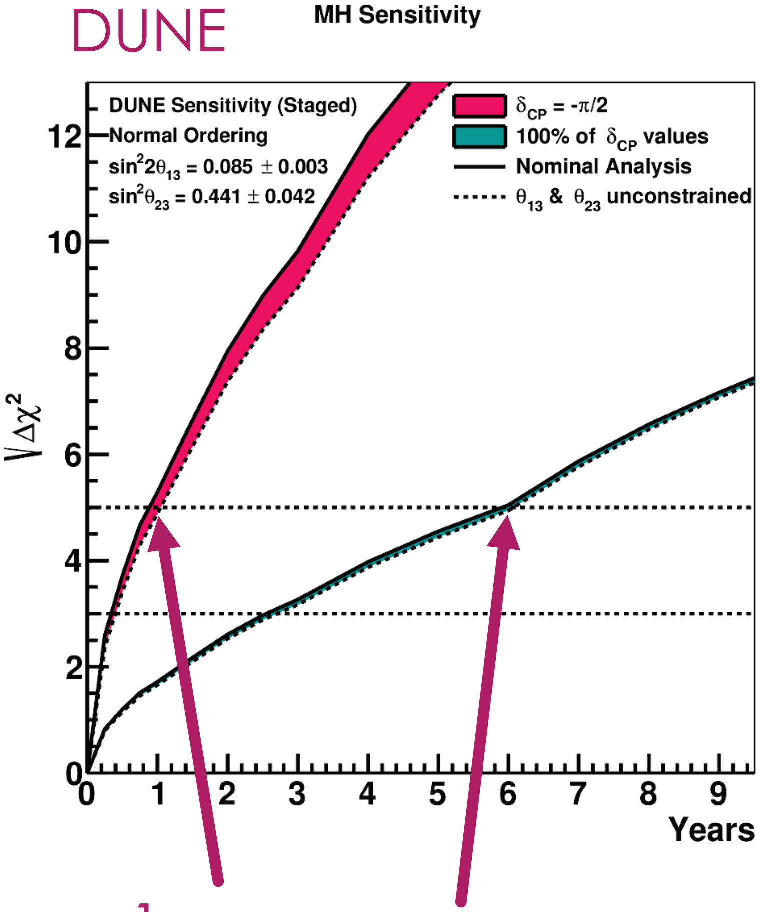
Mass Hierarchy

DUNE



Width of band indicates variation in sensitivity for θ_{23} values in the NuFit 2016 90% C.L. range

DUNE



~1 yr

~6 yrs

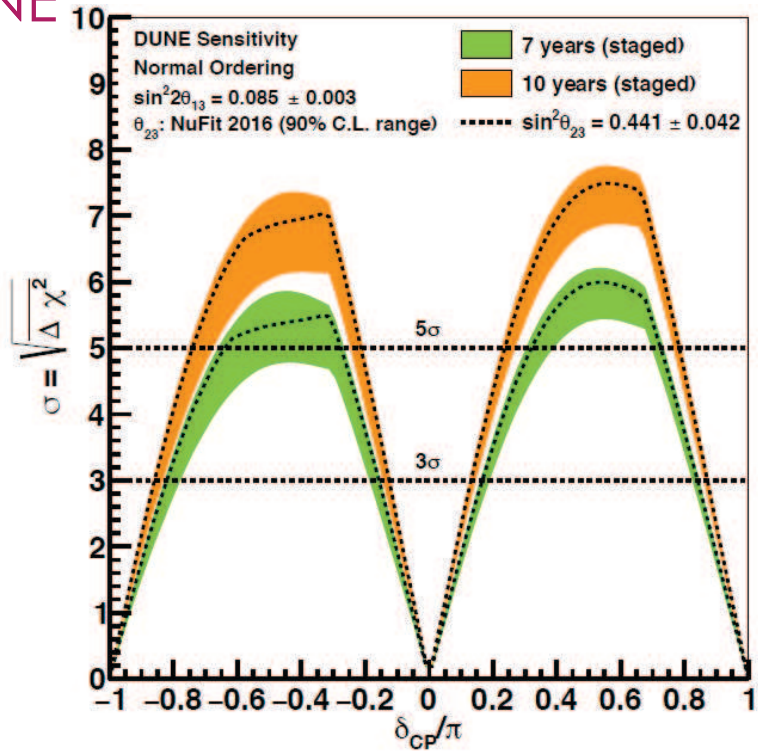
- DUNE should be able to make a relatively quick determination of the mass hierarchy
- Hyper-K is less sensitive due to the shorter baseline
  - Combined analysis with beam and atmospheric neutrinos leads to >3σ determination in about 5 years with one tank Hyper-K

L.W. Koerner, University of Houston

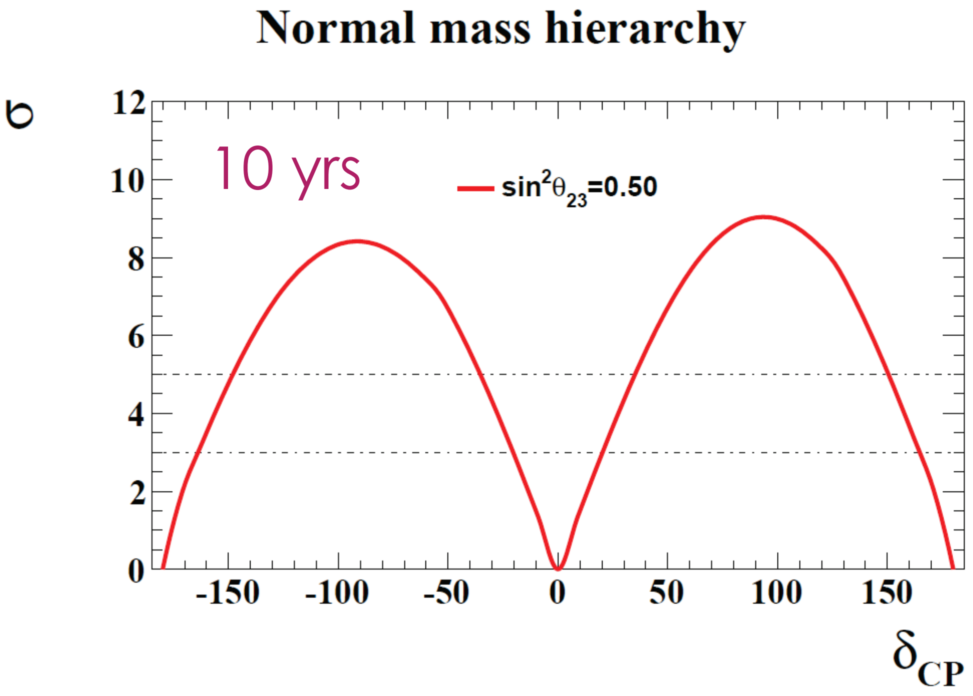
7/26/2017

CP Violation

DUNE



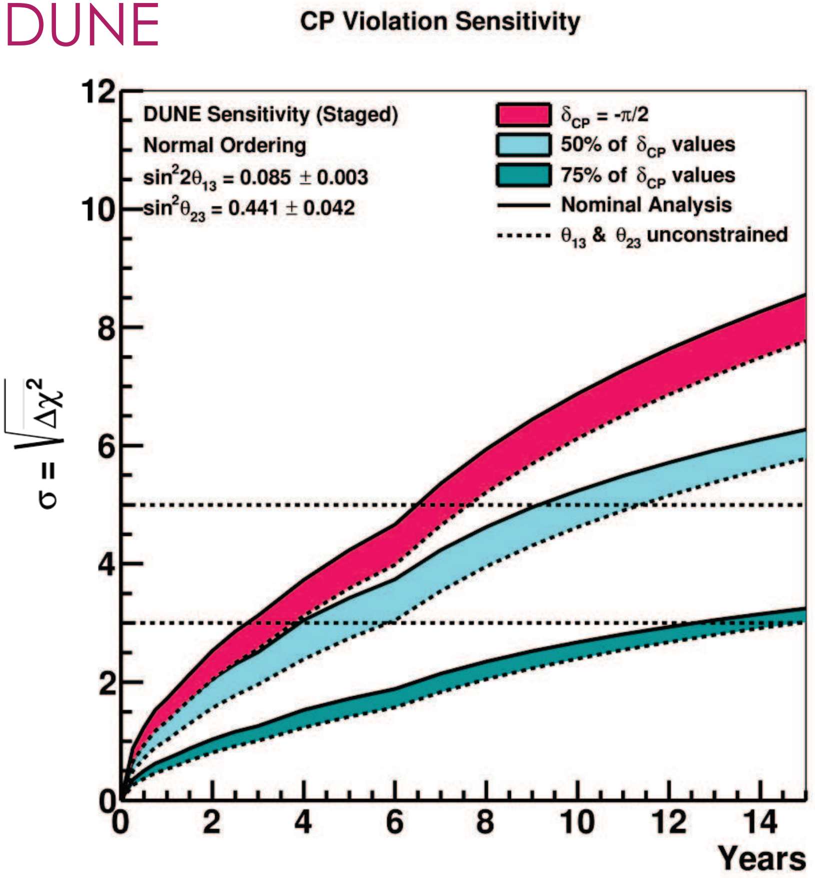
Hyper-K



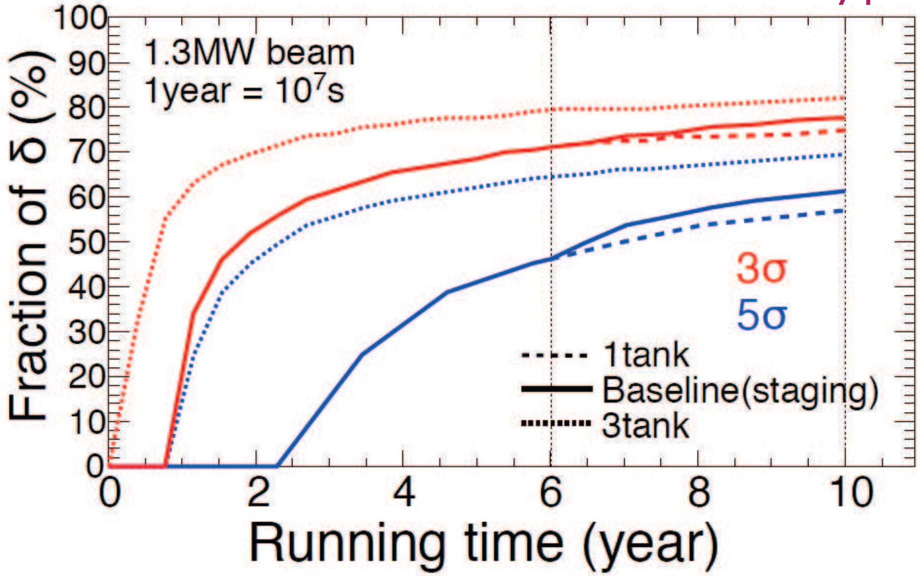
Width of band indicates variation in sensitivity for θ_{23} values in the NuFit 2016 90% C.L. range

CP Violation

DUNE



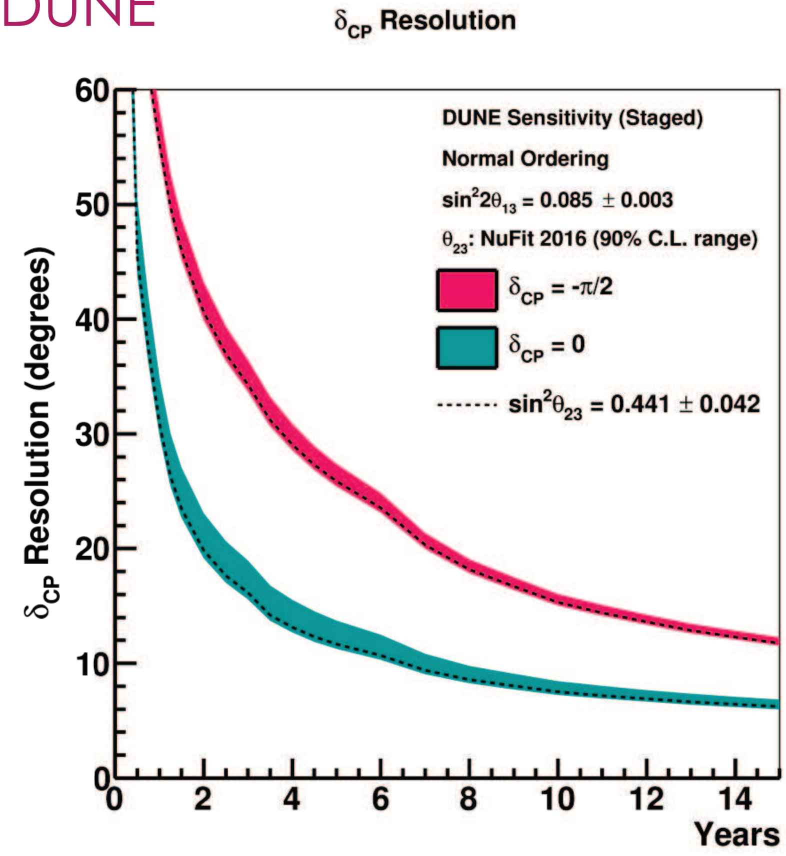
Hyper-K



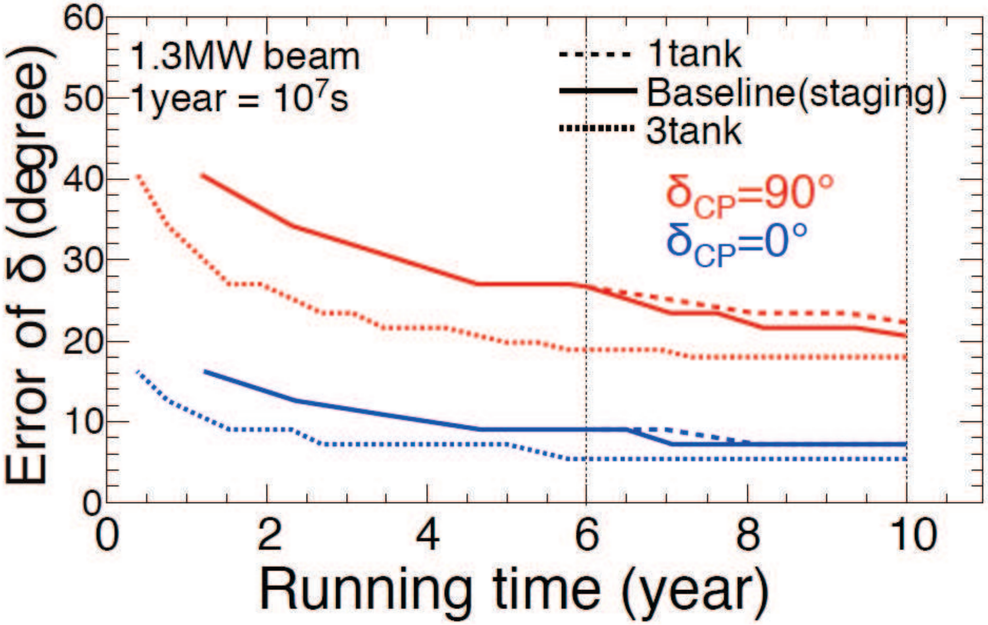
- Ultimately sensitivities of 5σ with 50% CP coverage and 3σ 75% CP coverage

CP Phase

DUNE



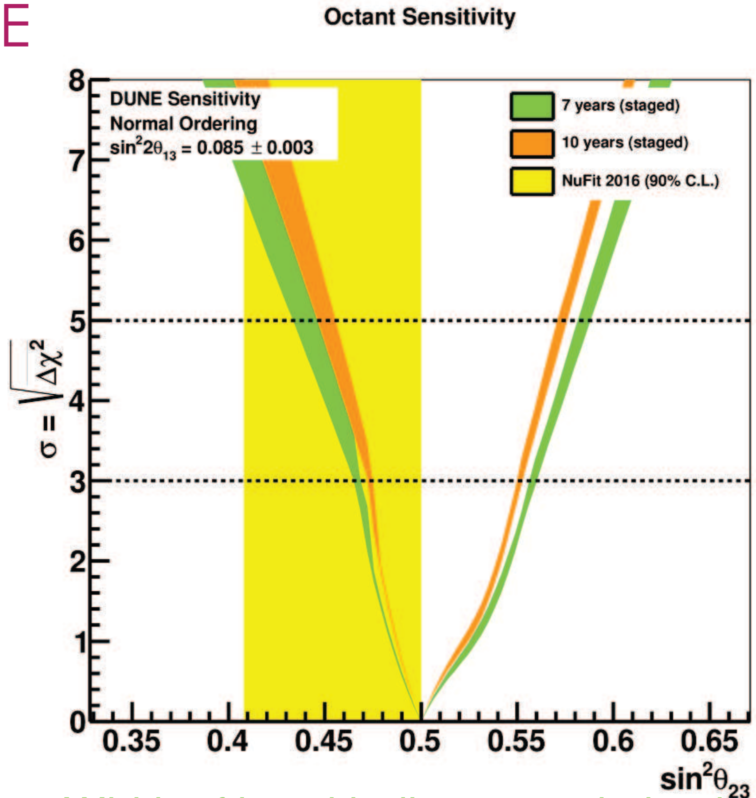
Hyper-K



- Resolution on measurement of δ_{CP} of ~10-20°

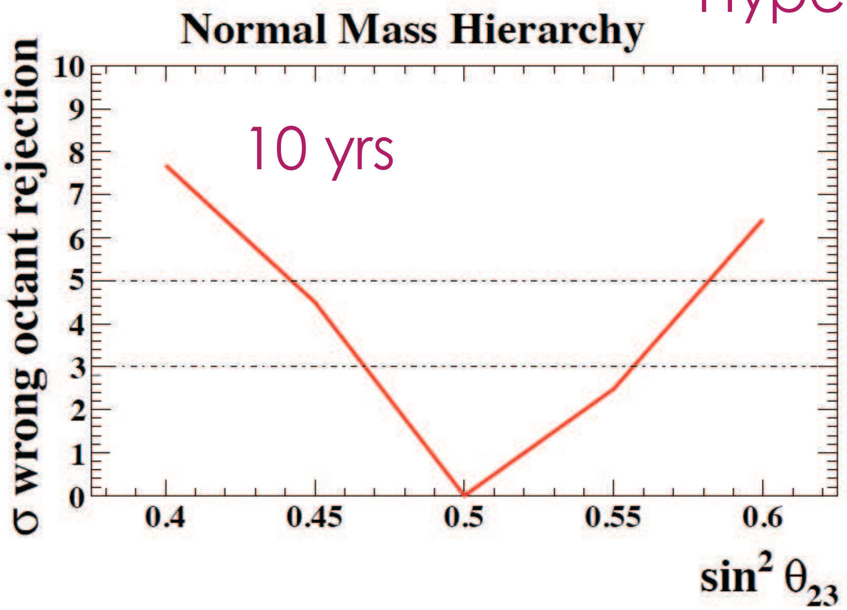
Octant

DUNE



Width of band indicates variation in sensitivity for different δ_{CP} values

Hyper-K



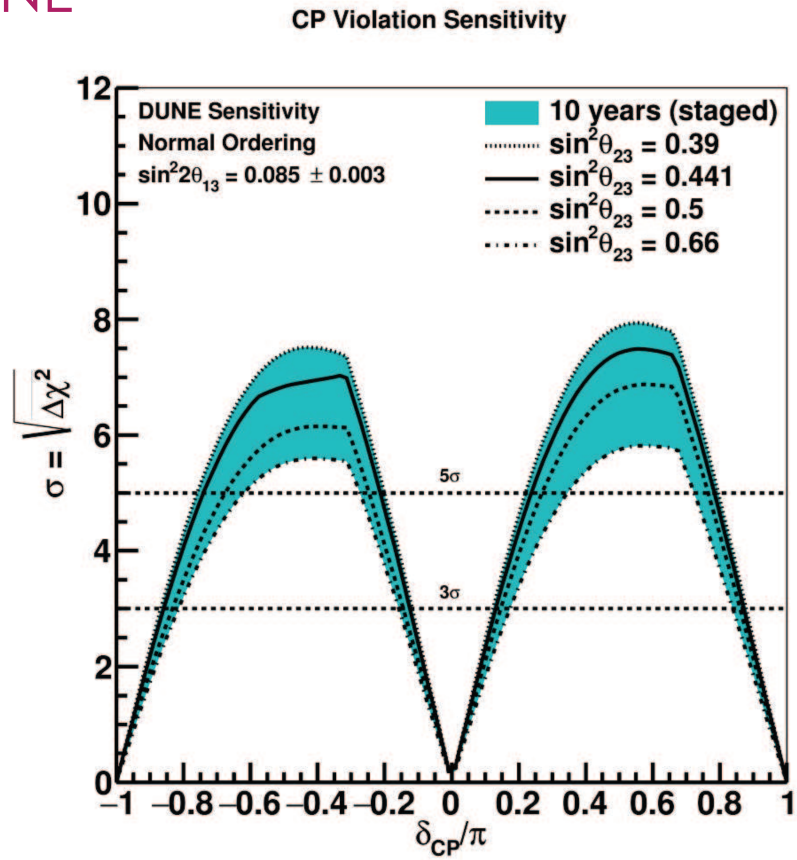
- Potential to reject maximal mixing at 3σ or 5σ in the range of the current global best fit
- Enhanced sensitivity with combined beam and atmospheric neutrino data

L.W. Koerner, University of Houston

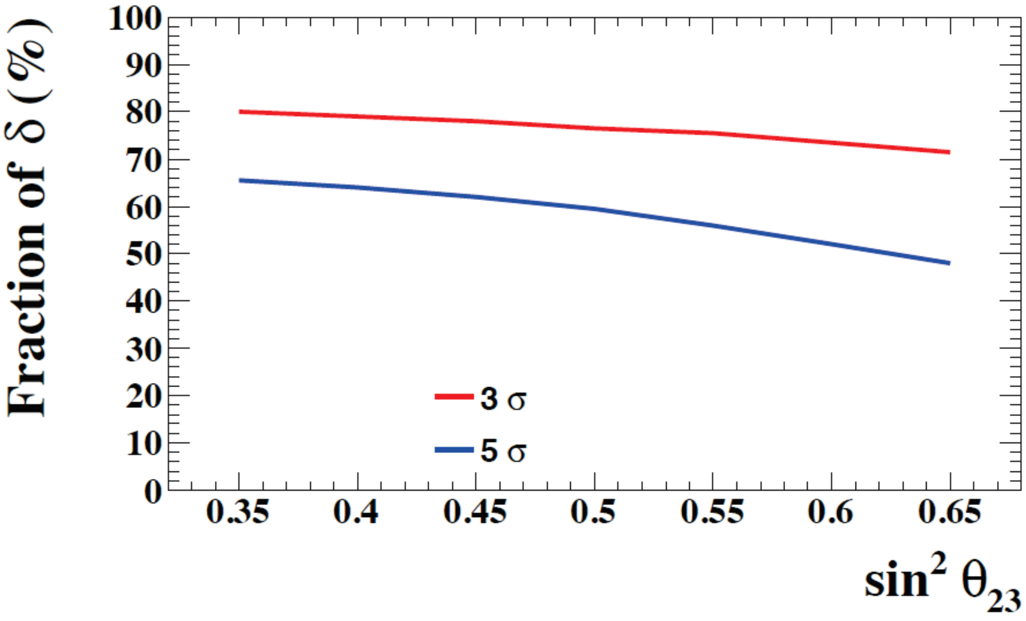
7/26/2017

Effect of θ_{23} on CP

DUNE

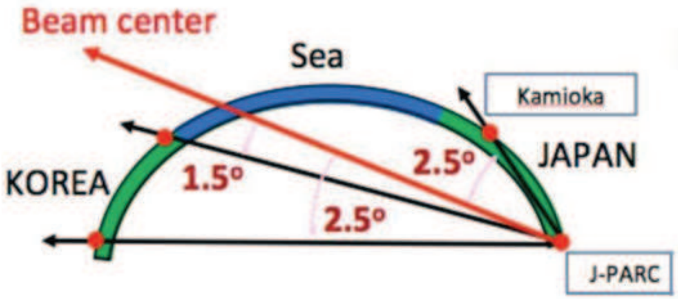


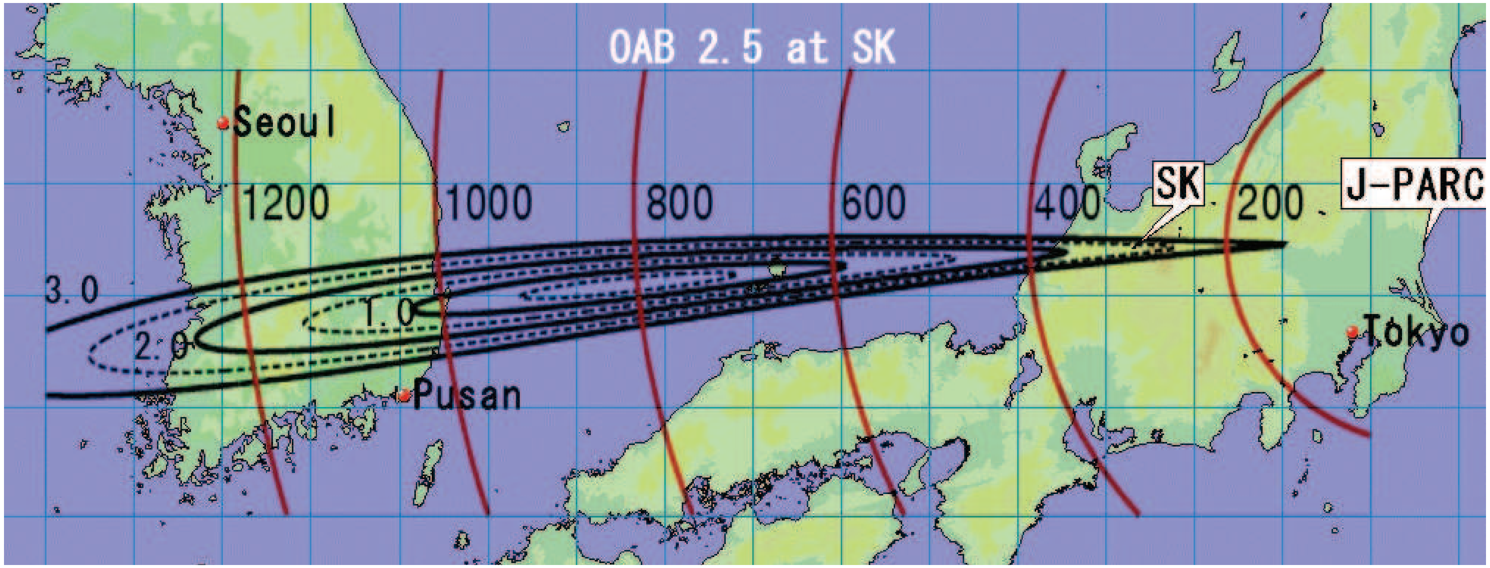
Hyper-K



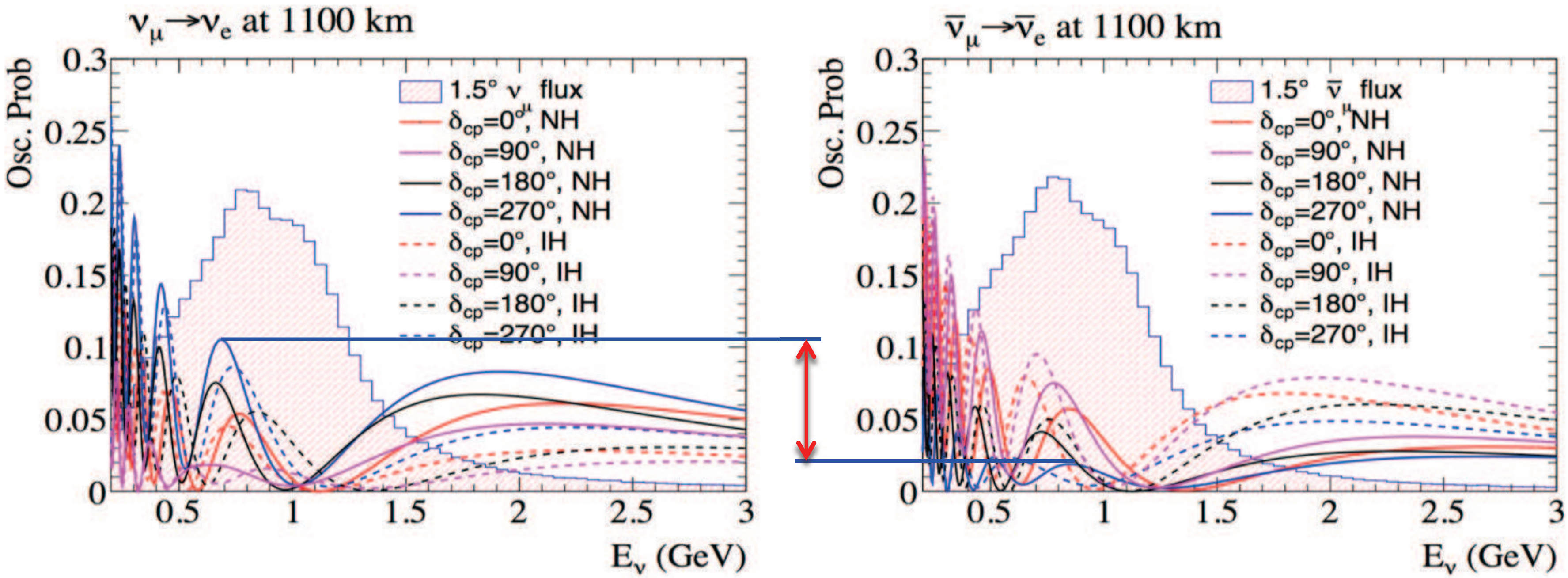
T2HKK: Tokai to Hyper-K and Korea

- Build second tank in Korea to enhance mass hierarchy and δ_{CP} sensitivities
  - 1000 – 1200 km baseline
  - $1.3^0 - 3.0^0$ off axis beam direction





ν_e appearance at the Korean site

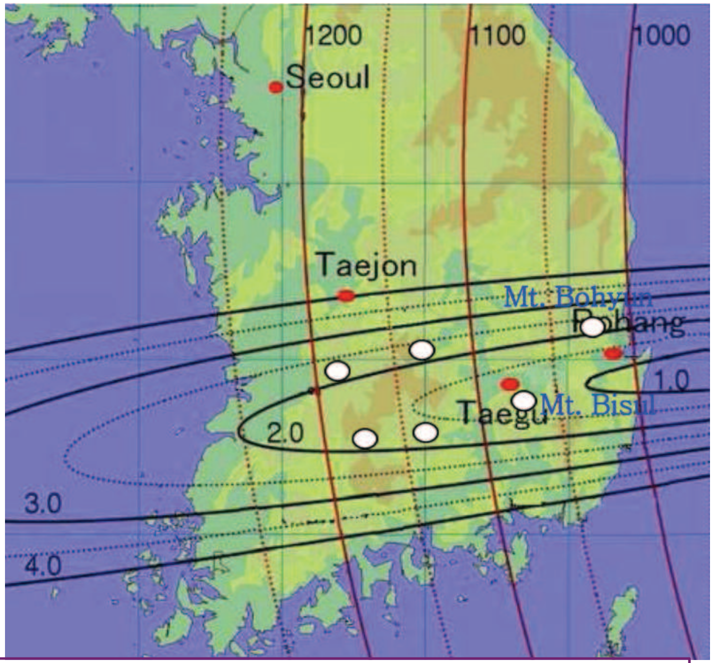


- ☐ Covers the 2nd oscillation maximum where the CP asymmetry between ν and anti-ν is 3 times larger than the 1st oscillation maximum
- ☐ Less sensitive to systematics errors due to larger CP effect
  - Lower statistics due to flux reduction
- ☐ Longer baseline(1100km) leads to larger matter effects
  - MH better determination

Additional benefits of the Korean site

- ☐ >1000 m high mountains with hard granite rocks
- ☐ Smaller background due to its larger overburden (> 800m)
- ☐ Improved sensitivity in solar neutrino physics
  - Day/night asymmetry due to MSW matter effect in Earth
  - HEP solar neutrinos
  - Energy spectrum upturn
- ☐ Supernova relic neutrino detection capability below 20 MeV improves
  - Detection efficiency is more than twice HK site in16-18 MeV range

Site	OAB	Baseline [km]	Height [m]
Mt. Bisul	~1.3°	1088 km	1084 m
Mt. Hwangmae	~1.8°	1140 km	1113 m
Mt. Sambong	~1.9°	1180 km	1186 m
Mt. Bohyun	~2.2°	1040 km	1126 m
Mt. Minjuii	~2.2°	1140 km	1242 m
Mt. Unjang	~2.2°	1190 km	1125 m



K. Abe *et al.*, "Physics Potentials with the Second Hyper-Kamiokande Detector in Korea", November 2016, arXiv:1611.06118

Summary of physics potential

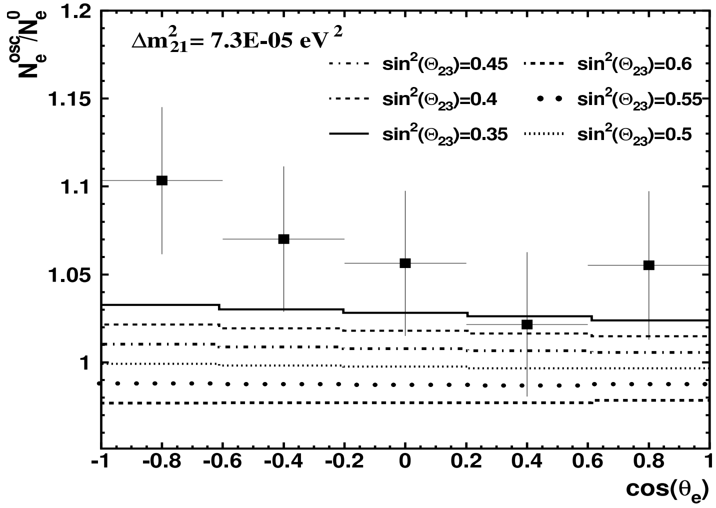
		HK (2TankHD w/ staging)
LBL (13.5MWyr)	δ precision	7°-21°
	CPV coverage (3/5 σ)	78%/62%
	$\sin^2\theta_{23}$ error (for 0.5)	±0.017
ATM+LBL (10 years)	MH determination	$>5.3\sigma$
	Octant ($\sin^2\theta_{23}=0.45$)	5.8σ
Proton Decay (10 years)	$e^+\pi^0$ 90%CL	1.2×10^{35}
	ν K 90%CL	2.8×10^{34}
Solar (10 years)	Day/Night (from 0/from KL)	$6\sigma/12\sigma$
	Upturn	4.9σ
Supernova	Burst (10kpc)	104k-158k
	Nearby	2-20 events
	Relic (10 yrs)	98evt/4.8σ

** for DM search see backup slides

Breaking the conspiracy – 3f effects

$$\begin{aligned}\frac{F_e - F_e^0}{F_e^0} \simeq\ & P_2(\Delta m_{31}^2,\,\theta_{13})\cdot(r\,s_{23}^2-1)\\ +\ & P_2(\Delta m_{21}^2,\,\theta_{12})\cdot(r\,c_{23}^2-1)\\ -\ & 2 s_{13}\,s_{23}\,c_{23}\,r\,\mathrm{Re}(\tilde{A}_{ee}^{*}\,\tilde{A}_{\mu e})\end{aligned}$$

Interference term not suppressed by the flavour composition of the $\nu_{\rm atm}$ flux; may be (partly) responsible for observed excess of upward-going sub-GeV e-like events

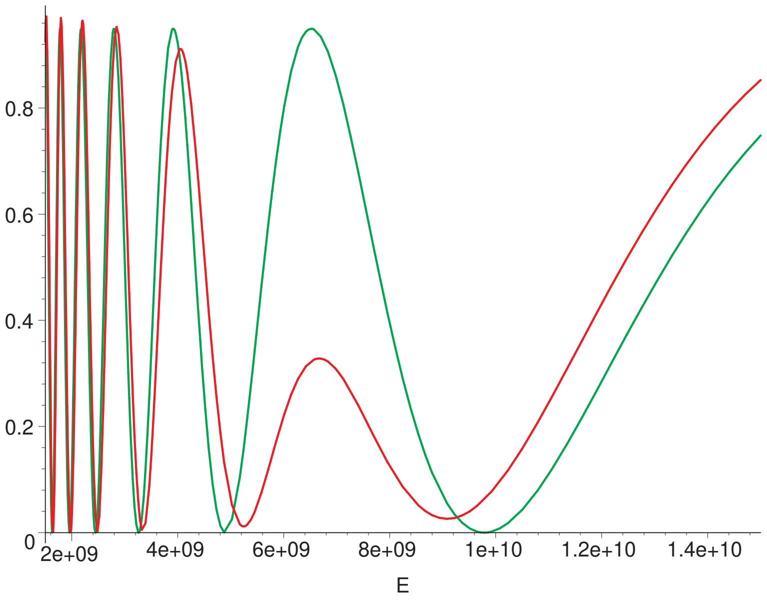


Interf. term may not be sufficient to fully explain the excess of low-E e-like events – a hint of $\theta_{23} \neq 45°$? (Peres & Smirnov, 2004)

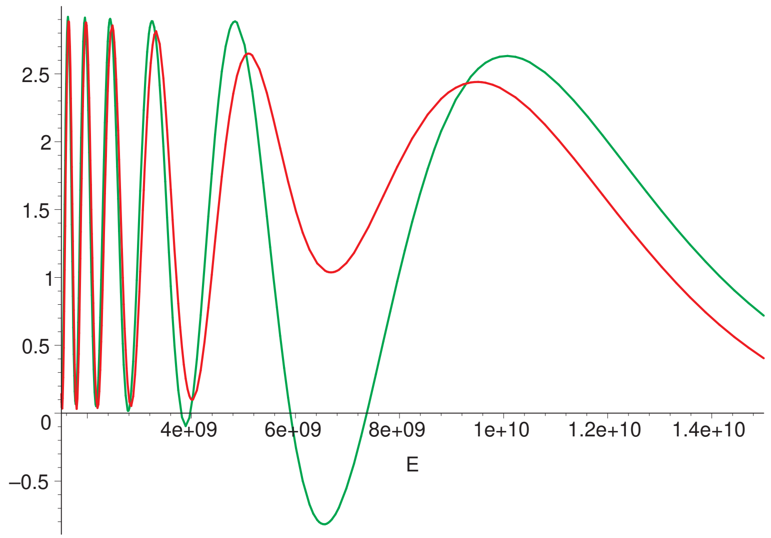
Matter effects on $\nu_\mu \leftrightarrow \nu_\tau$ oscillations

In 2f approximation: no matter effects on $\nu_\mu \leftrightarrow \nu_\tau$ oscillations $[V(\nu_\mu) = V(\nu_\tau)$ modulo tiny rad. corrections].

Not true in the full 3f framework! (E.A., 2002; Gandhi et al., 2004)



$P_{\mu\tau}$



Oscillated flux of atm. ν_μ

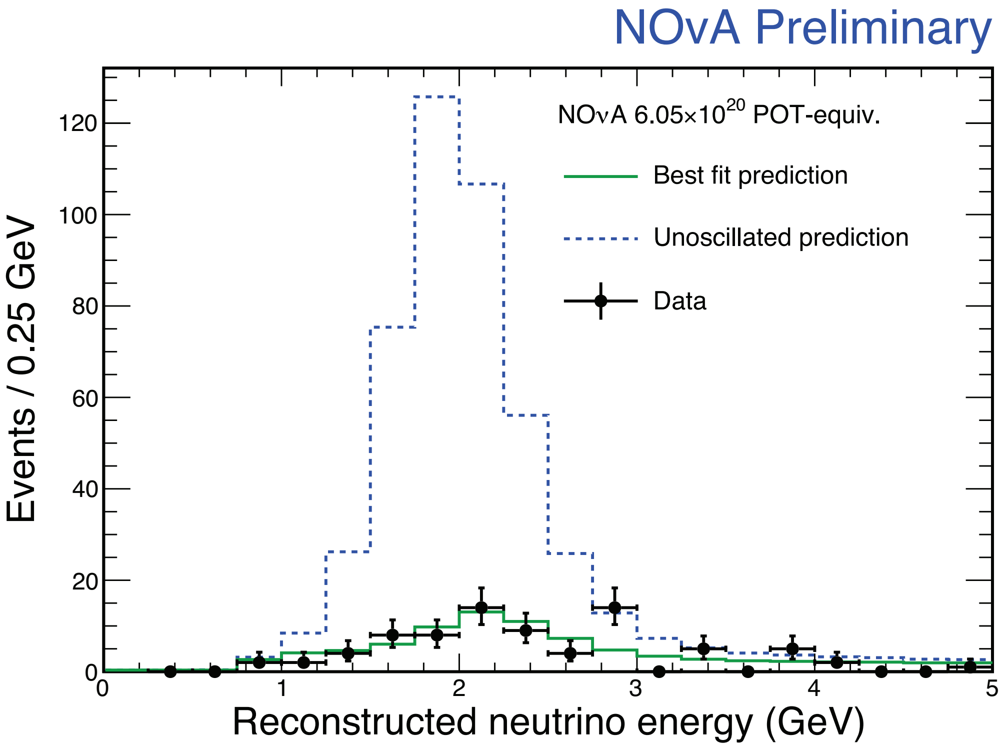
$\Delta m_{31}^2 = 2.5 \times 10^{-3}$ eV^2, $\sin^2\theta_{13} = 0.026$, $\theta_{23} = \pi/4$, $\Delta m_{21}^2 = 0$, $L = 9400$ km

Red curves – w/ matter effects, green curves – w/o matter effects on $P_{\mu\tau}$

Muon-Neutrino Disappearance

arXiv:1701.05891

- Using 6.05×10^{20} POT equivalent
- 473 +/- 30 events predicted in the absence of oscillations
- Observed 78 events
- 82 events predicted at the best fit point including 3.7 beam background and 2.9 cosmic induced events



ν_μ —> ν_e Appearance channel

Following presentation by Nunokawa, Parke, Valle, in “CP Violation and Neutrino Oscillations”, Prog.Part.Nucl.Phys. 60 (2008) 338-402. arXiv:0710.0554 [hep-ph]

$$P(\nu_\mu \to \nu_e) \approx \left|\sqrt{P_{atm}}\, e^{-i(\Delta_{32}+\delta)} + \sqrt{P_{sol}}\right|^2$$

$$= P_{atm} + P_{sol} + 2\sqrt{P_{atm}P_{sol}}\,(\cos\Delta_{32}\cos\delta \mp \sin\Delta_{32}\sin\delta)$$

$$\sqrt{P_{atm}} = \sin\theta_{23}\sin 2\theta_{13}\frac{\sin(\Delta_{31}-aL)}{\Delta_{31}-aL}\Delta_{31}$$

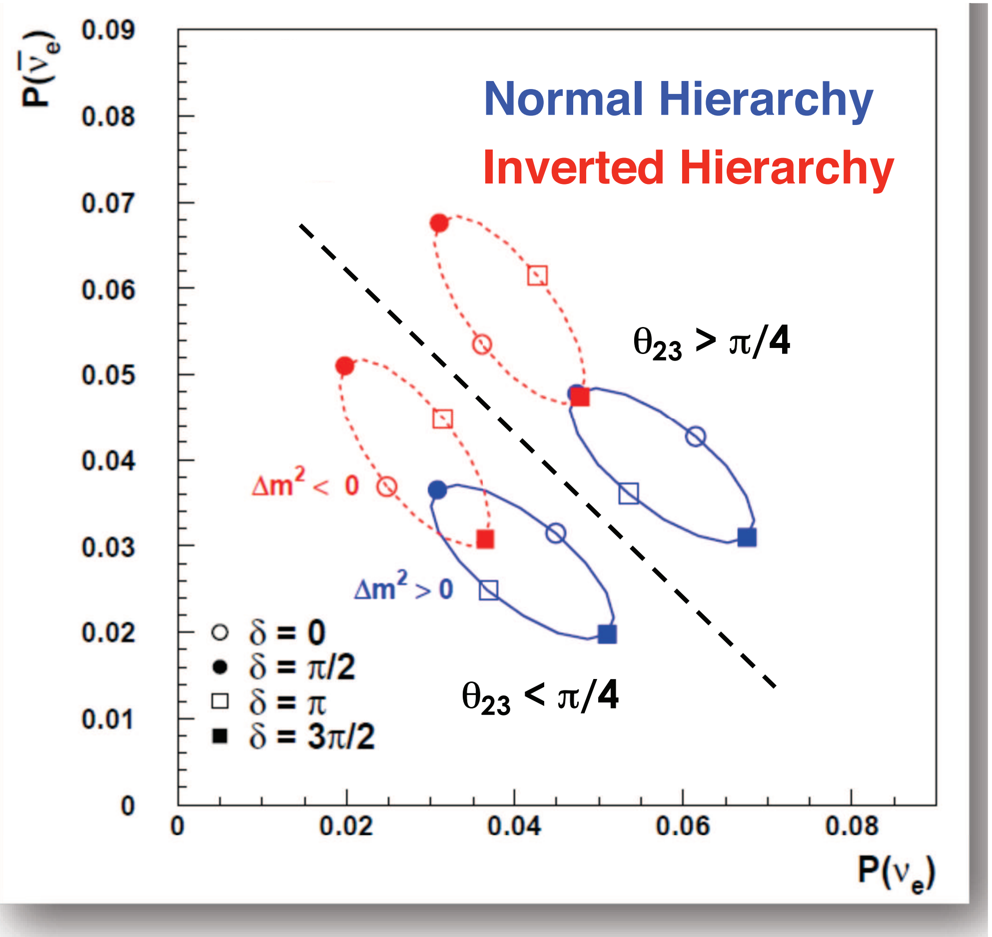
Depends on relative sign of “a” and Δ_{31}

$$\sqrt{P_{sol}} = \cos\theta_{23}\sin 2\theta_{12}\frac{\sin(aL)}{aL}\Delta_{21}$$

$$a = \frac{G_F N_e}{\sqrt{2}} \approx \frac{1}{3500km}$$

aL=0.08 for L=295km T2K baseline

aL=0.23 for L=810km NOvA baseline



Oscillation probability is sensitive to: mass ordering, CP violating phase, and θ_{23} octant.