Neutrino physics (4-1)

Evgeny Akhmedov

Max-Planck Institute für Kernphysik, Heidelberg

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Plan of the lectures

- Introduction.
- Brief overview of experimental results
- Weyl, Dirac and Majorana fermions
- Neutrino masses in simplest extensions of the Standard Model. The seesaw mechanism(s).
- Neutrino oscillations in vacuum
  - Same E or same p ?
  - QM uncertainties and coherence issues
  - Wave packet approach to neutrino oscillations
  - Lorentz invariance of oscillation probabilities
  - 2f and 3f neutrino mixing schemes and oscillations
  - Implications of CP, T and CPT

Plan of the lectures – contd.

- Neutrino oscillations in matter – the MSW effect
  - Evolution equation
  - Adiabaticity condition and adiabatic evolution
  - Non-adiabatic regime
  - Graphical interpretation and mechanical analogy
  - Earth matter effects on $\nu_\odot$ (day-night asymmetry)
- Neutrino oscillations in matter – parametric resonance
- Direct neutrino mass measurement experiments
- Neutrinoless double β-decay
- Neutrino electromagnetic properties
- Subtleties of the theory of neutrino oscillations
  - Do charged leptons oscillate?
  - Oscillations of Mössbauer neutrinos
- Neutrinos and the baryon asymmetry of the universe

Plan of the lectures – contd.

- Exptl. results: Solar neutrino oscillations and KamLAND
- Oscillations of atmospheric and accelerator neutrinos
- Discovery of θ_{13} in reactor and accelerator expts.
- Future: What's next?

What is left out:

– Oscillations of SN neutrinos (incl. non-linear collective effects)

– Cosmological bounds on # of neutrino species and $\sum m_\nu$

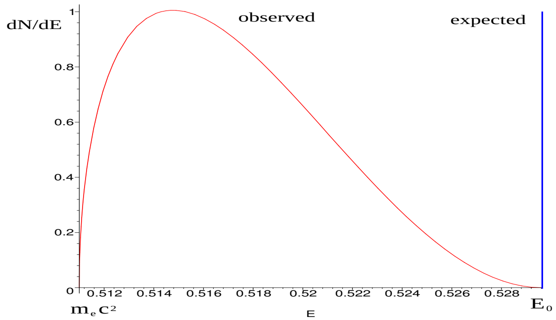
– keV sterile neutrinos as Dark Matter

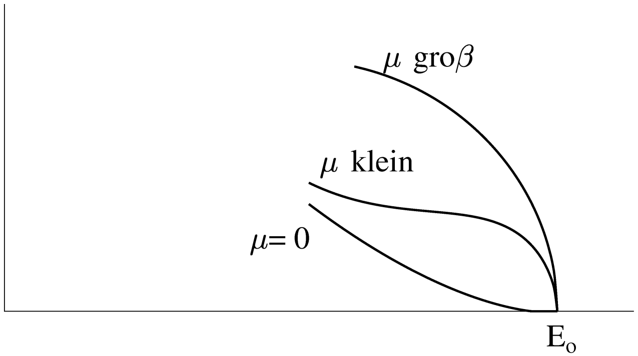
– Geoneutrinos

. . .

Direct neutrino mass measurements

Electron spectrum in β decay





E. Fermi, Z. Phys. 1934

Electron spectrum in allowed β decays:

$$N_e(E_e)dE_e \propto F(Z,E_e)\sqrt{E_e^2 - m_e^2}\, E_e(E_0 - E_e)^2\, dE_e\,, \quad (m_\nu = 0);$$

$$N_e(E_e)dE_e \propto F(Z,E_e)\sqrt{E_e^2 - m_e^2}\, E_e(E_0 - E_e)\sqrt{(E_0 - E_e)^2 - m_\nu^2}\, dE_e\,, \quad (m_\nu \neq 0)$$

For n mixed neutrinos:

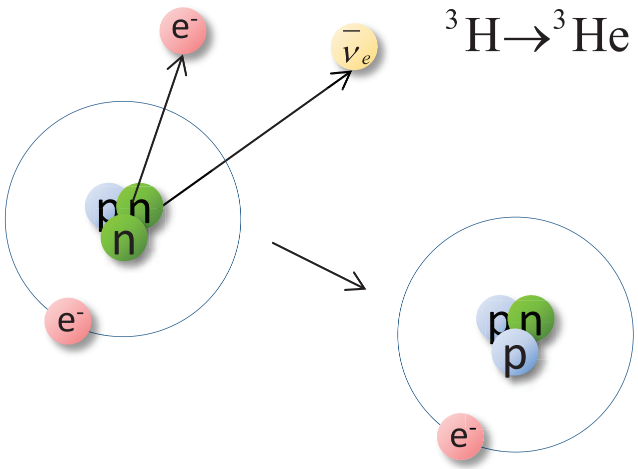
$$m_\nu^2 \to m_\beta^2 \equiv \sum_{i=1}^{n} |U_{ei}|^2 m_i^2$$

Troitsk & Mainz expts. ($^3\mathrm{H} \to ^3\mathrm{He} + e^- + \bar{\nu}_e$): $m_\beta^2 < (2.2\ \mathrm{eV})^2$ (95% C.L.)

KATRIN (expected sensitivity): $m_\beta < 0.2\ \mathrm{eV}$ (90% C.L.).

Discovery potential: $m_\beta = 0.35\ \mathrm{eV}$ (5σ).

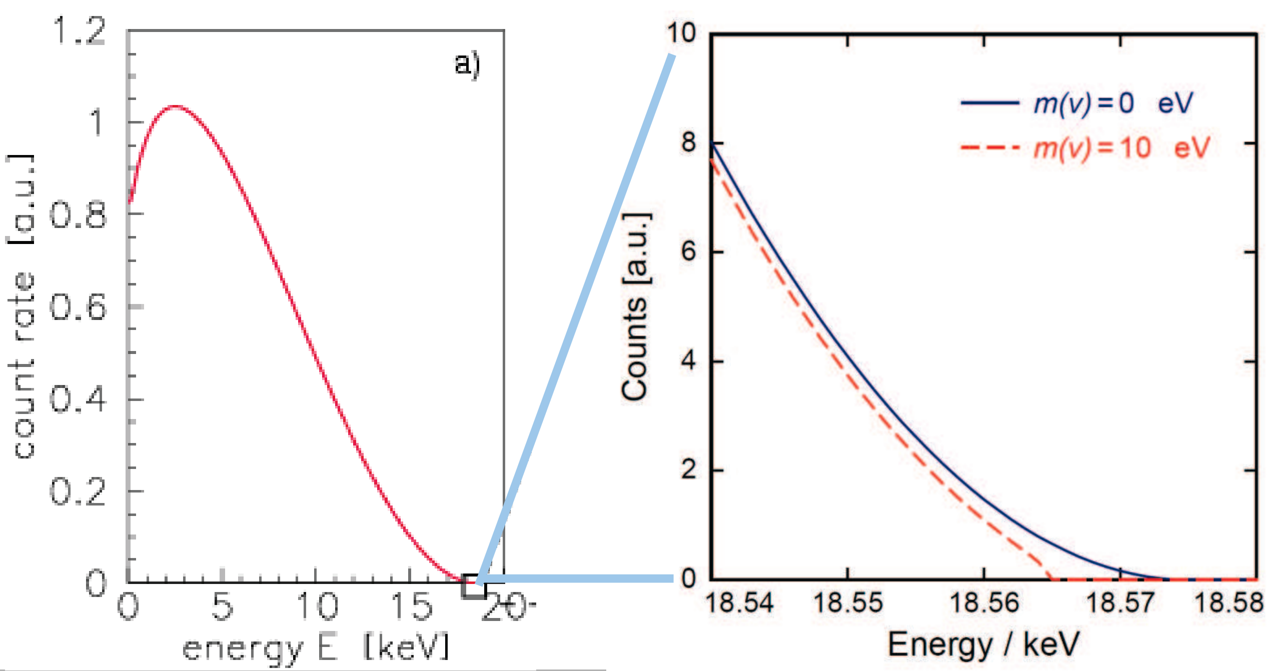
Beta decay of ^{3}H



$$^3\text{H} \rightarrow {}^3\text{He} + e^- + \bar{\nu}_e$$

Precision on the neutrino mass determination relies on

- ✓ Precise modelling of the atomic and molecular final state
- ✓ Background reductions

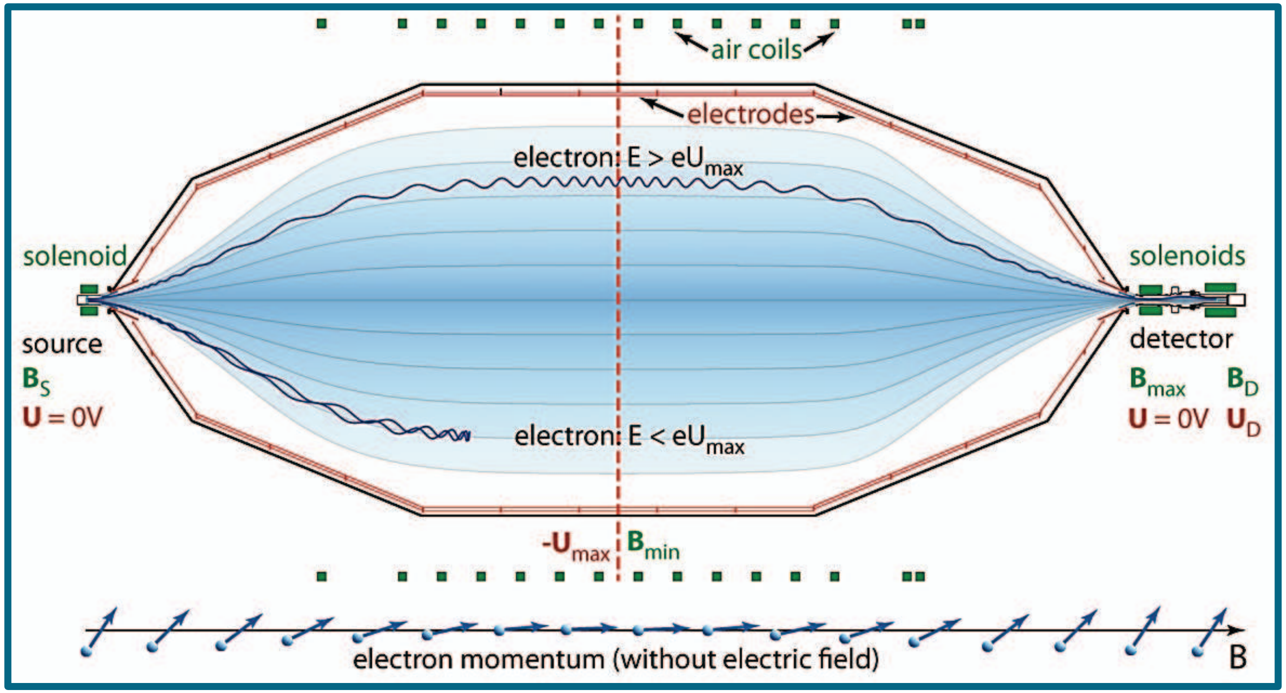


Only a small fraction of events in the last eV below the endpoint: **$2 * 10^{-13}$**

Triutium is present as **bi-atomic molecules**

High resolution β-spectroscopy: MAC-E-Filter

Magnetic **A**diabatic **C**ollimation and **E**lectrostatic Filter:



Magnetic guiding and collimation of e⁻

- Transform $E_\perp$ to $E_{||}$

$$\mu = \frac{E_\perp}{B} = \text{const.}$$

Electrostatic field for energy analysis

- Sharp transmission depending on:
  - Emission angle
  - Radius at B_{min}

Integrated energy resolution:

$$\Delta E = qU_{\max}\frac{B_{\min}}{B_{\max}}$$

e.g. A. Picard et al., NIM-B63(1992) 345-358

KATRIN experiment in Karlsruhe

main spectrometer: transport

End of the 8800 km voyage

Different technologies

Magnetic calorimeters

e^- capture (^{163}Ho – ECHo, HOLMES, NuMECS...)

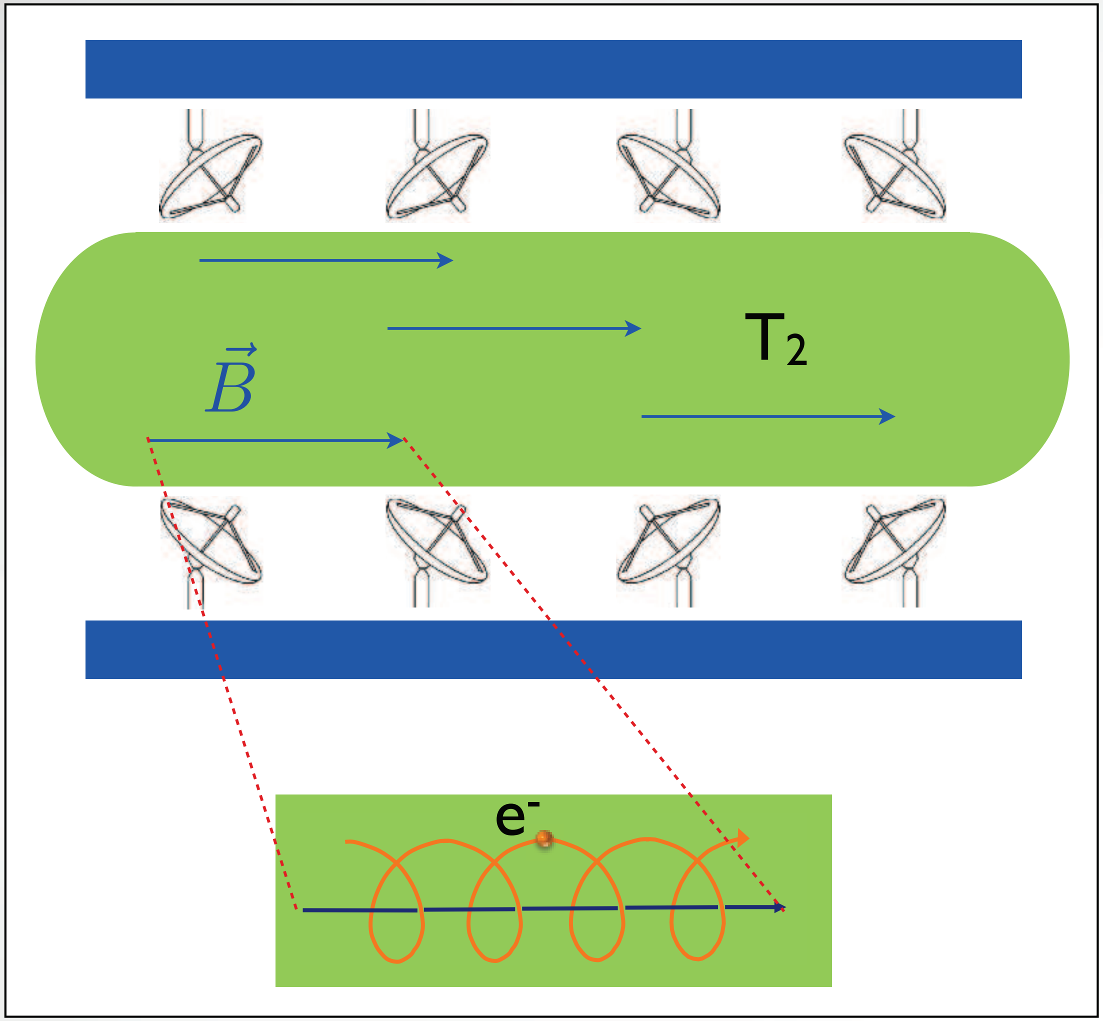
Electron synchrotron radiation (Project 8)

Novel Technique: CRES

Cyclotron Radiation Emission Spectroscopy

Pacific Northwest NATIONAL LABORATORY
Proudly Operated by Battelle Since 1965

- Enclosed volume
- Fill with tritium gas
- Add a magnetic field



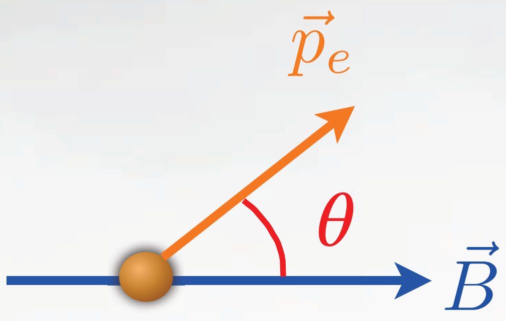
- Decay electrons spiral around field lines
- Add antennas to detect the cyclotron radiation

B. Monreal and J. Formaggio, Phys. Rev. D80 051301 (2009)

Pitch Angle

Pacific Northwest NATIONAL LABORATORY
Proudly Operated by Battelle Since 1965

The angle between
the electron momentum
and the magnetic field



- Correction term for the cyclotron frequency

$$\omega_\gamma = \frac{\omega_0}{\gamma} = \frac{eB}{K + m_e}\left(1 + \frac{\cot^2\theta}{2}\right)$$

- Power emitted

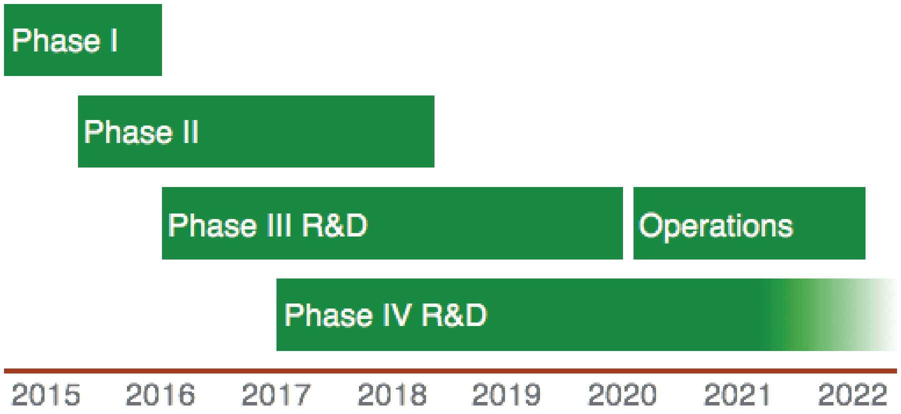
$$P_{\rm tot} = \frac{1}{4\pi\epsilon_0}\frac{2q^2\omega_c^2}{3c}\frac{\beta^2\sin^2\theta}{1-\beta^2}$$

Project 8 Experiment

A phased tritium beta endpoint experiment to measure the electron neutrino mass

> **Phase I (Complete)**
  - First demonstration of CRES technique with ^{83m}Kr

> **Phase II (2015-2018)**
  - First tritium measurement with CRES
  - Endpoint determination to ~30 eV
  - *see also Mathieu Guigue, Thurs. parallel*



> **Phase III (2016-2022)**
  - CRES demonstration in 200 cm^3 free space volume
  - Neutrino mass sensitivity of ~2 eV

> **Phase IV (2017+)**
  - Atomic tritium endpoint measurement with m_ν ~ 40 meV projected sensitivity

Cosmological constraints

Cosmology: constraints on $\sum m_\nu$. Strongly depend on what is taken into account.

- Typically range from $\sum m_\nu < 0.32$ eV (Planck, . . .)
  down to $\sum m_\nu < 0.12$ eV (Planck + Lyman α) (95% C.L.).
- In a foreseeable future may start probing hierarchical neutrino masses.
- eV - range sterile neutrinos ruled out (if thermalized).
- keV - scale sterile neutrino (warm dark matter) allowed

2β decay

Decay modes for Double Beta Decay

Double Beta Decay is a very rare, second-order weak nuclear transition which is possible for a few tens of even-even nuclides

Two decay modes are usually discussed:

① $(A,Z) \to (A,Z+2) + 2e^- + 2\bar{\nu}_e$ ← 2ν Double Beta Decay allowed by the Standard Model already observed – $\tau \geq 10^{19}$ y

② $(A,Z) \to (A,Z+2) + 2e^-$ ← neutrinoless Double Beta Decay (0ν-DBD) never observed (except a discussed claim) $\tau > 10^{25}$ y

Process ② would imply new physics beyond the Standard Model

violation of lepton number conservation

Observation of **0ν-DBD** → $m_\nu \neq 0$, $\bar{\nu} \equiv \nu$

2β decay

Is possible for $A(Z,N)$ when the decay into the "neighbouring" nucleus $A(Z\pm1, N\mp1)$ is energetically forbidden, but decay into the next nucleus $A(Z\pm2, N\mp2)$ is allowed. ^{82}Se, ^{76}Ge, ^{100}Mo, ^{130}Te, ^{96}Zr, ^{48}Ca, ^{136}Xe, ...

Extremely rare decays $(\Gamma \propto G_F^4)$, $T_{1/2}(2\beta 2\nu) > 10^{19}$ yr.

Usually $2\beta^-$ decays (only few canidates for $2\beta^+$ decays known, expected $T_{1/2}$ very large due to small Q values).

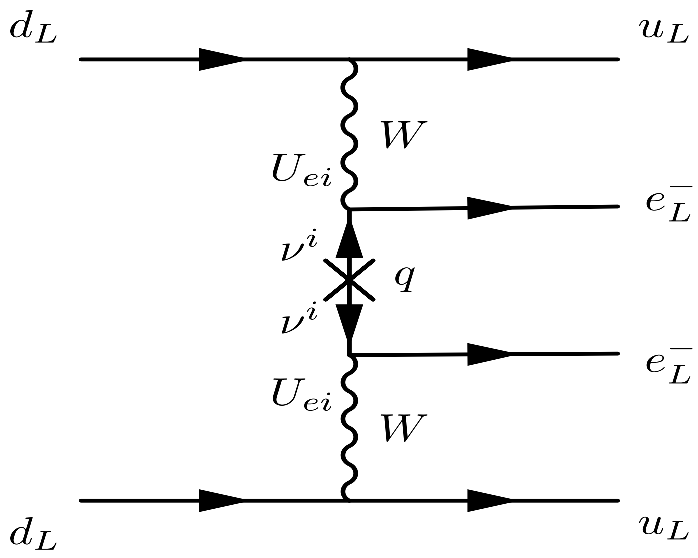
Neutrinoless 2β decay – $\Delta L = 2$ process; would be an unambiguous evidence for Majorana nature of neutrino!

$2\beta 0\nu$ decay not yet experimentally established (only lower bounds on $T_{1/2}(2\beta 0\nu)$ exist). Only one (controversial) claim by part of Heidelberg-Moscow collavoration (Kalpdor-Kleingrothaus et al.). – contradicts data of GERDA expt.

Main uncertainty in the interpretation of the results related to inaccuracy in the theoretciacal calculations of the nuclear matrix elements.

Mechanisms of $2\beta 0\nu$ decay

The standard mechanism with a light Majorana neutrino:



$\diamondsuit \quad \mathcal{A}_{2\beta 0\nu} \propto \sum_i m_i U_{ei}^2 \equiv m_{\beta\beta}$

In the basis where m_l is diagonalized $m_{\beta\beta}$ is the ee entry of m_ν: $m_{\beta\beta} = m_{ee}$

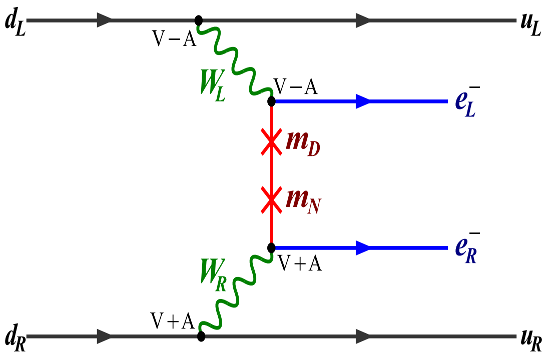
Depends on Majorana-type $\not{C}\not{P}$ phases! In the 3f case:

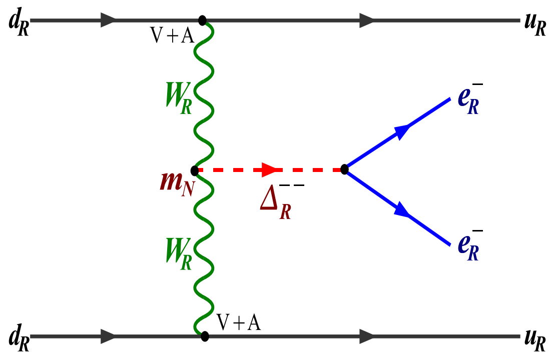
$$\diamondsuit \quad \boxed{m_{\beta\beta} = c_{13}^2 c_{12}^2 m_1 + c_{13}^2 s_{12}^2 e^{2i\sigma_1} m_2 + s_{13}^2 e^{2i(\sigma_2 - \delta_{CP})} m_3.}$$

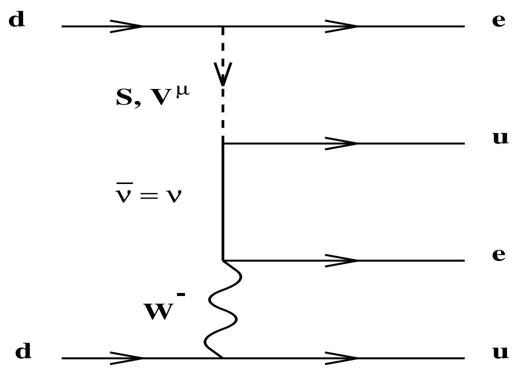
In the case of NH, cancellation possible!

Other mechanisms in extensions of the SM

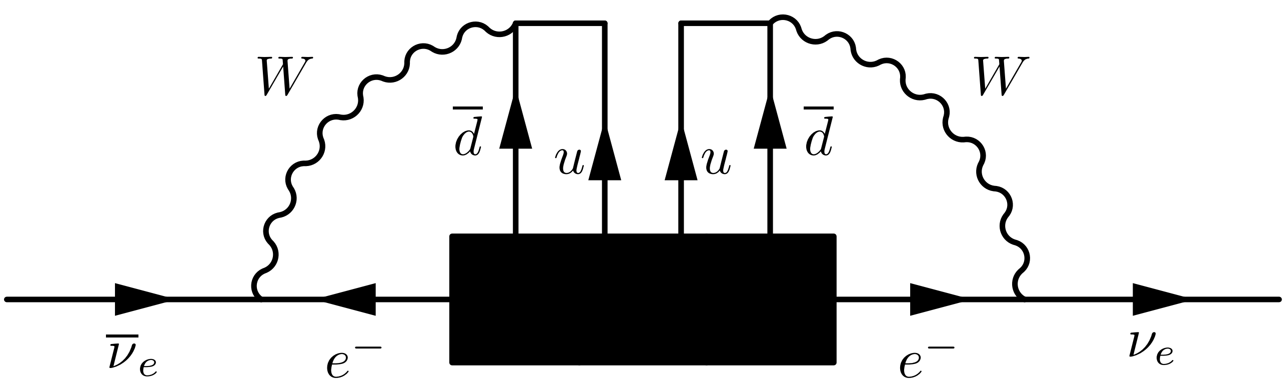
Contributions of W_R, N_R, triplet Higgses, SUSY particles, leptoquarks, ...





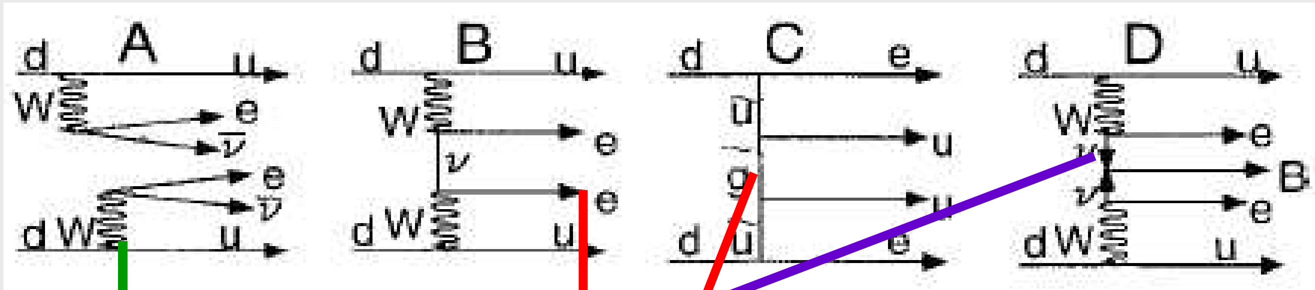


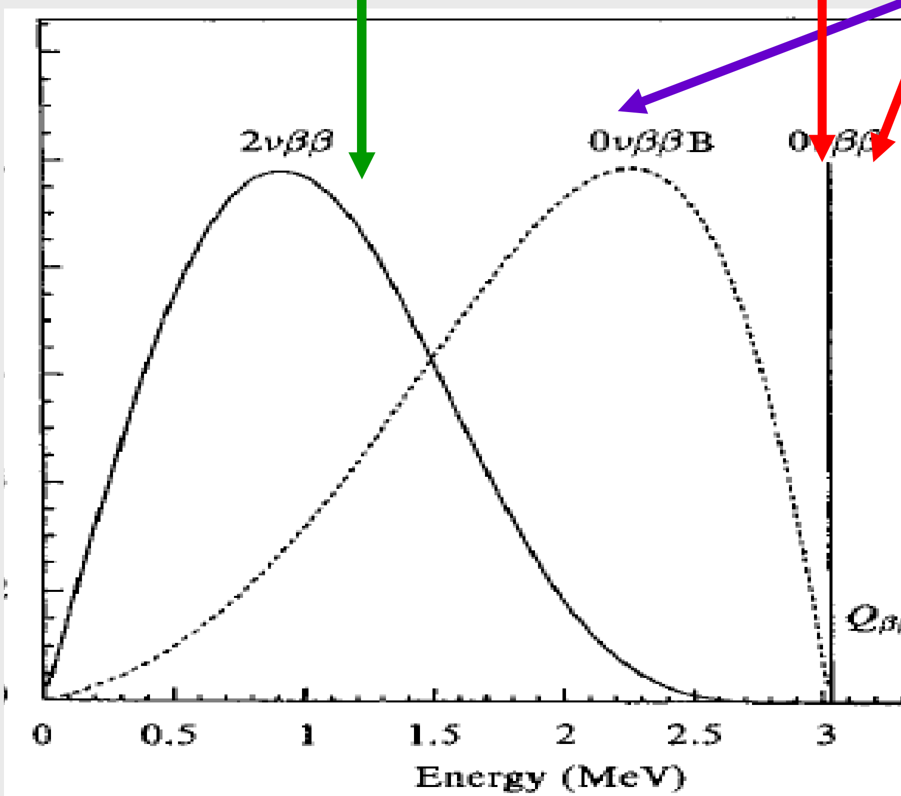
Independently of the $2\beta0\nu$ decay mechanism, neutrino gets Majorana mass term $\Rightarrow$ ν's are Majorana particles! The black box argument:



(Schechter & Valle, 1982)

$0\nu\beta\beta$ by RHC, Heavy ν, SUSY, and others





$A^{0\nu}$ = LHC + RHC

<m> +SUSY $\langle\lambda\rangle \sim k(M_L/M_R)^2$

LHC / RHC

Θ_{21} and E_{12} correlations

LHC m_ν / SUSY

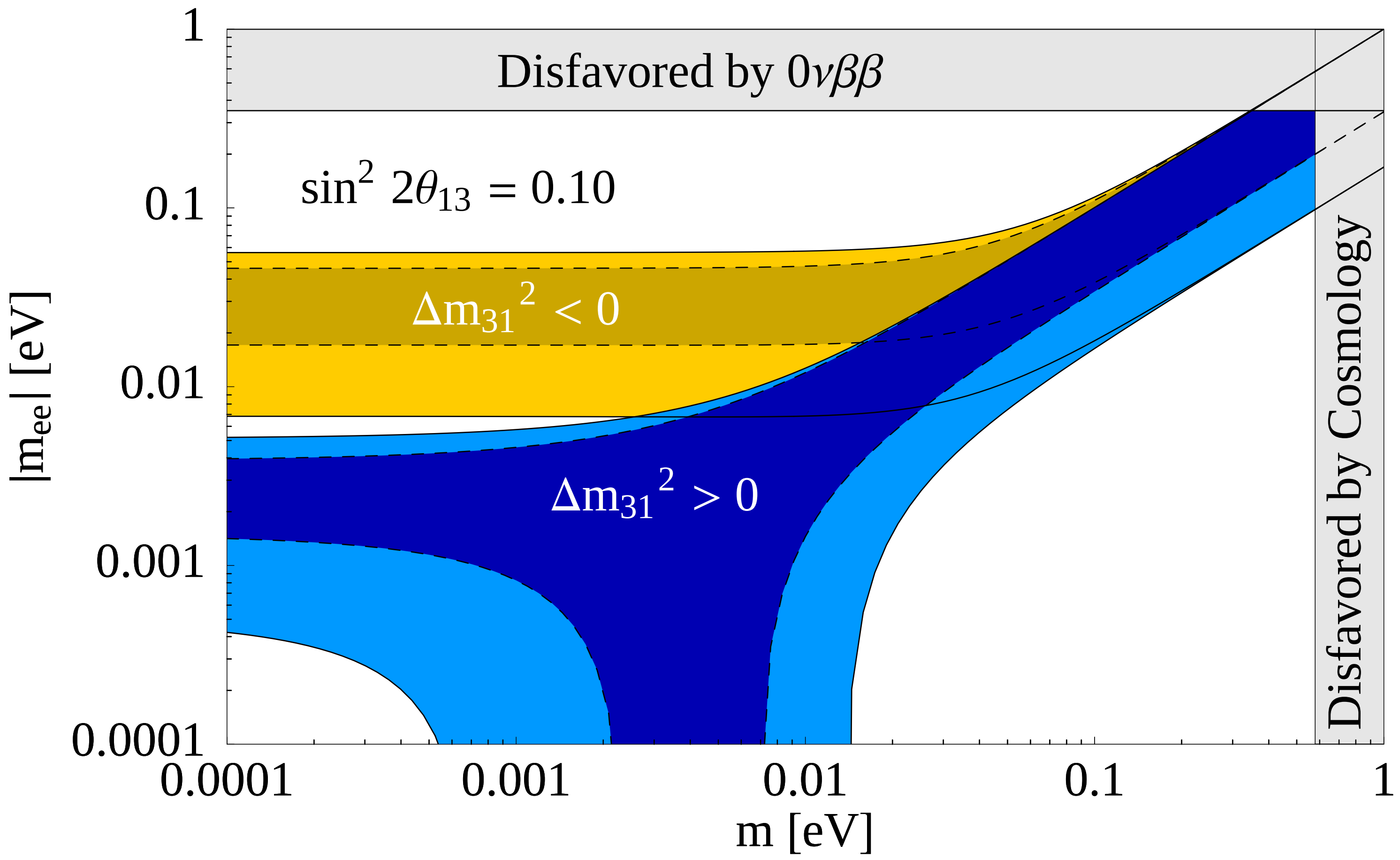
$m_\nu M^{0\nu} + kM^S$

different isotopes and states with different M

$A^{2\nu} = GM^{2\nu}$ $A^M = \langle g_M \rangle M$

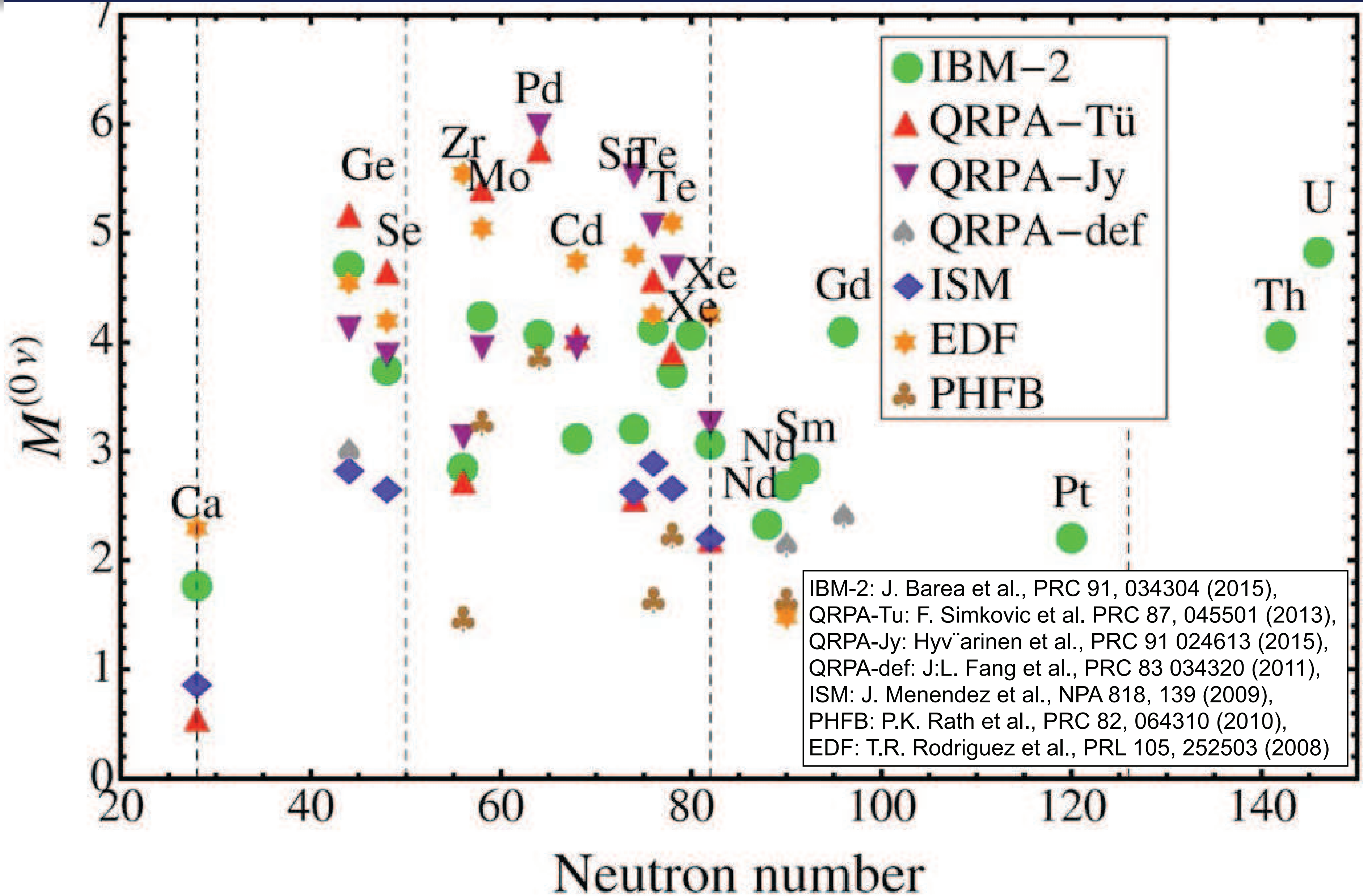
Energy spectra 4,3,2 body

$m_{\beta\beta}$ as a function of $m_{lightest}$



Blue – normal mass ordering, yellow – inverted mass ordering

NME status



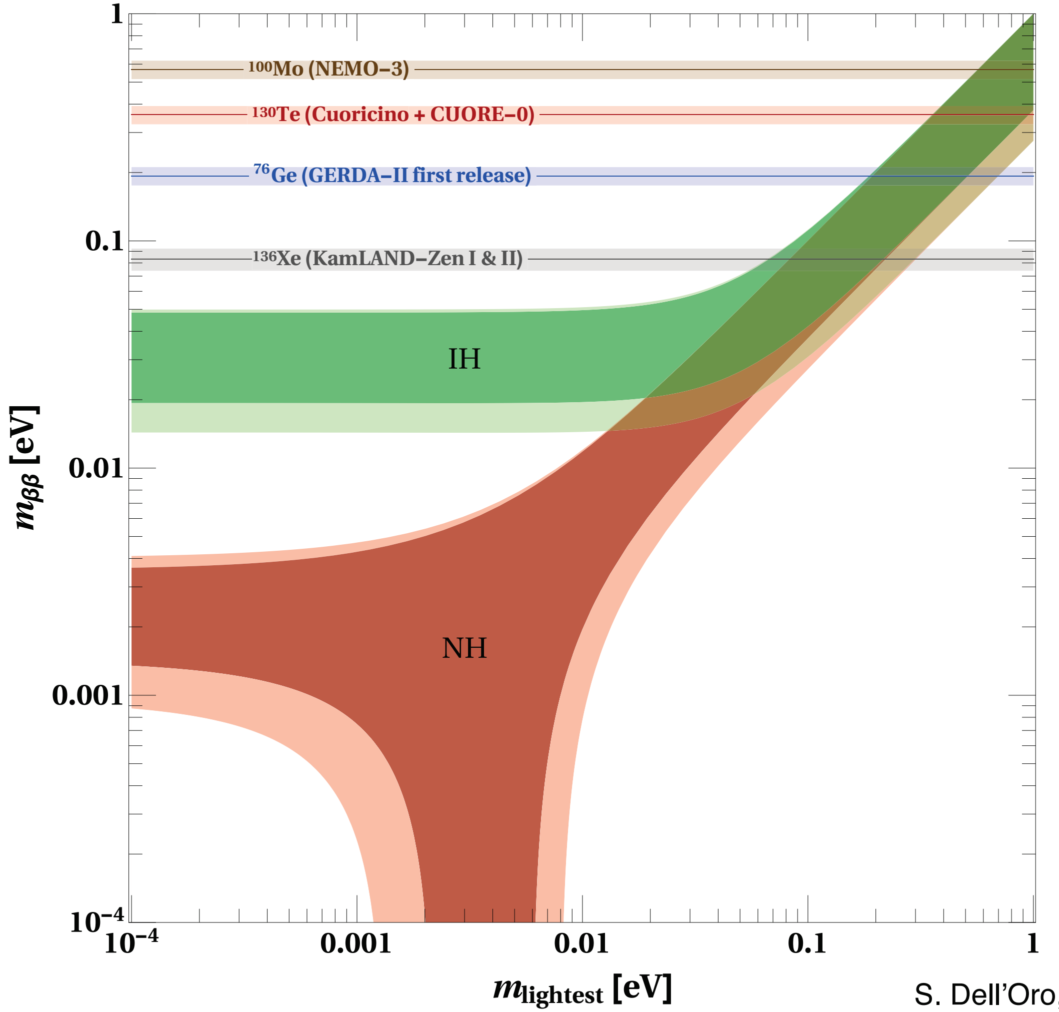
IBM−2
QRPA−Tü
QRPA−Jy
QRPA−def
ISM
EDF
PHFB
Ca
Ge
Se
Zr
Mo
Pd
Cd
Sn
Te
Te
Xe
Xe
Nd
Nd
Sm
Gd
Pt
Th
U
IBM-2: J. Barea et al., PRC 91, 034304 (2015),
QRPA-Tu: F. Simkovic et al. PRC 87, 045501 (2013),
QRPA-Jy: Hyv¨arinen et al., PRC 91 024613 (2015),
QRPA-def: J:L. Fang et al., PRC 83 034320 (2011),
ISM: J. Menendez et al., NPA 818, 139 (2009),
PHFB: P.K. Rath et al., PRC 82, 064310 (2010),
EDF: T.R. Rodriguez et al., PRL 105, 252503 (2008)
$M^{(0\nu)}$
0
1
2
3
4
5
6
7
20
40
60
80
100
120
140
Neutron number

ββ(0ν) ongoing efforts

Experiment	Isotope	Technique	Mass ββ(0ν) isotope	Status
CUORICINO	130Te	TeO2 Bolometer	10 kg	Complete
NEMO3	100Mo/82Se	Foils with tracking	6.9/0.9 kg	Complete
GERDA I	76Ge	Ge diodes in LAr	15 kg	Complete
EXO200	136Xe	Xe liquid TPC	160 kg	Operating
KamLAND-ZEN	136Xe	2.7% in liquid scint.	380 kg	Operating
CUORE-0	130Te	TeO2 Bolometer	11 kg	Operating
GERDA II	76Ge	Point contact Ge in LAr	30+35 kg	Commissioning
Majorana D	76Ge	Point contact Ge	30 kg	Commissioning
CUORE	130Te	TeO2 Bolometer	206 kg	Construction
SNO+	130Te	0.3% natTe suspended in Scint	55 kg	Construction
NEXT-100	136Xe	High pressure Xe TPC	80 kg	Construction
SuperNEMO D	82Se	Foils with tracking	7 kg	Construction
CANDLES	48Ca	305 kg of CaF2 crystals - liq. scint	0.3 kg	Construction
LUCIFER	82Se	ZnSe scint. bolometer	18 kg	Construction
1TGe (GERDA+MJ)	76Ge	Best technology from GERDA and MAJORANA	~ tonne	R&D
CUPID	-	Hybrid Bolometers	~ tonne	R&D
nEXO	136Xe	Xe liquid TPC	~ tonne	R&D
SuperNEMO	82Se	Foils with tracking	100 kg	R&D
AMoRE	100Mo	CaMoO4 scint. bolometer	50 kg	R&D
MOON	100Mo	Mo sheets	200 kg	R&D
COBRA	116Cd	CdZnTe detectors	10 kg/183 kg	R&D
CARVEL	48Ca	48CaWO4 crystal scint.	~ tonne	R&D
DCBA	150Nd	Nd foils & tracking chambers	20 kg	R&D

Present experiments ($m_{\beta\beta}$)

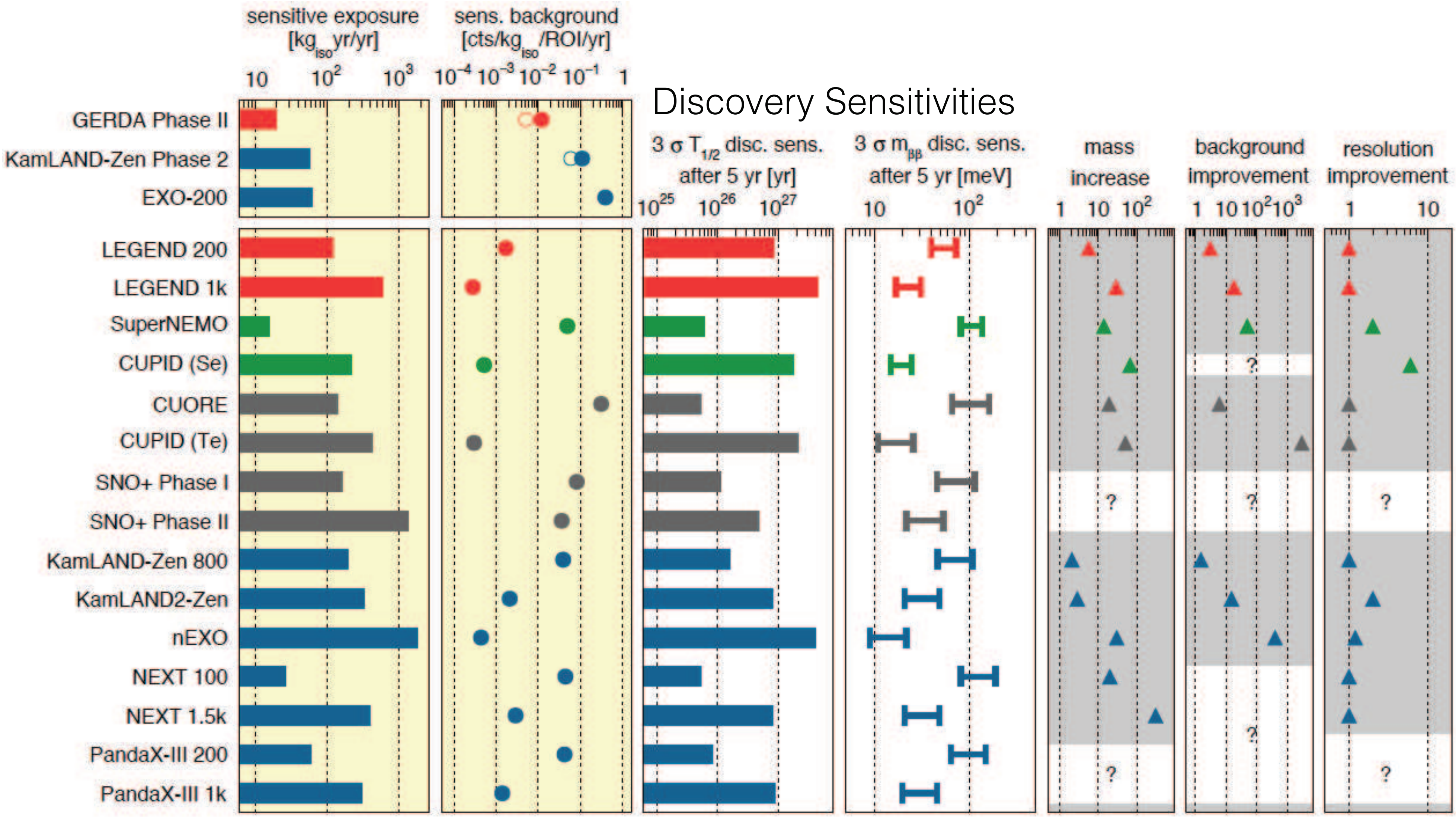
Presently best available published limits for each isotope



S. Dell'Oro, Presentation at NuFact 2016

NOW 2016 - Neutrino Oscillation Workshop Otranto (Lecce, Italy), September 4-11, 2016

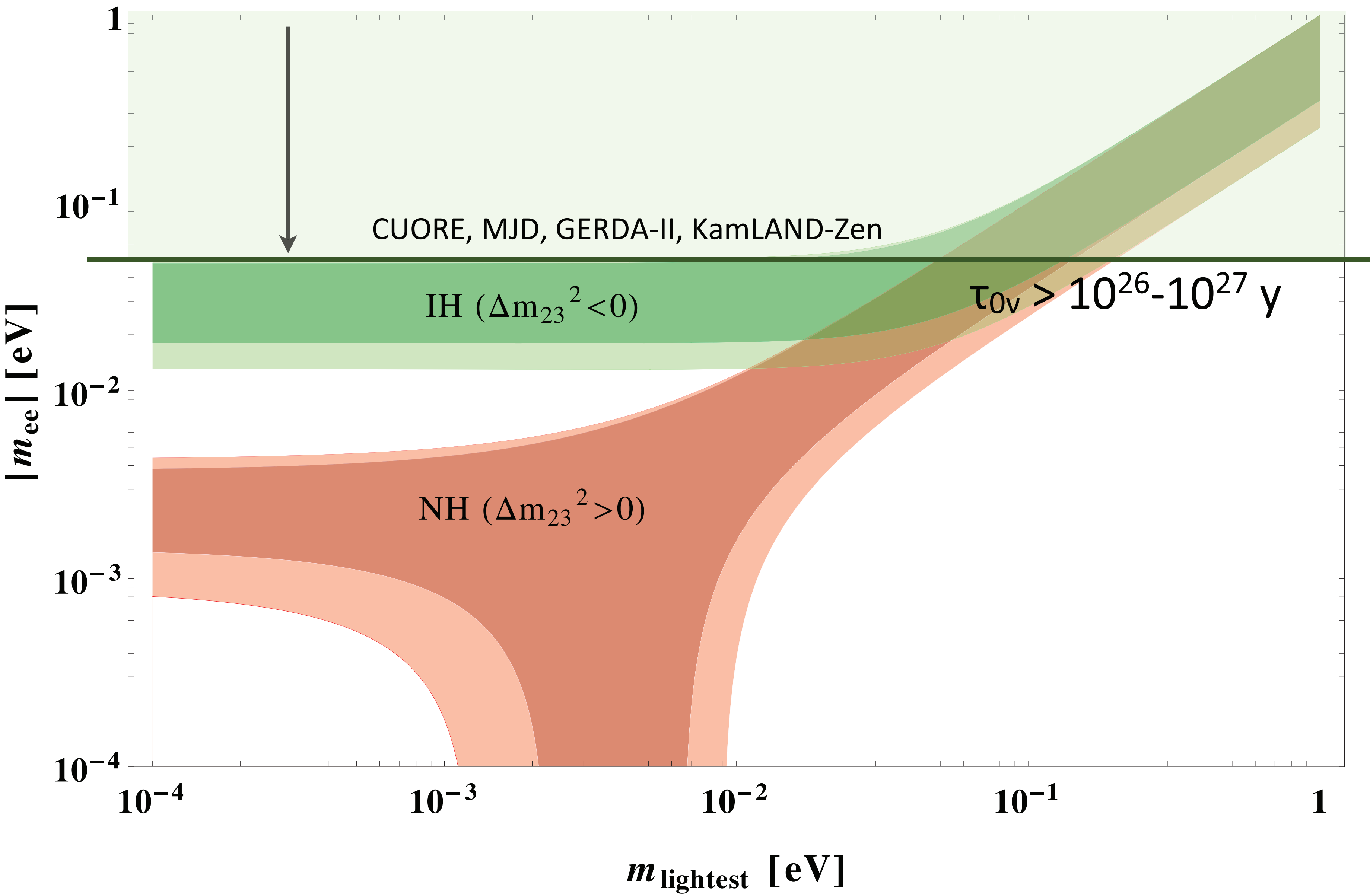
Comparison of Experiments



S. Schönert | TUM
Double Beta Decay
TAUP2017

Adopted from Agostini, Benato, Detwiler arXiv:1705.02996

Status: near future



O. Cremonesi - September 10, 2015 - TAUP 2015, Turin, Italy 29

Atmospheric neutrinos

Atmospheric neutrinos

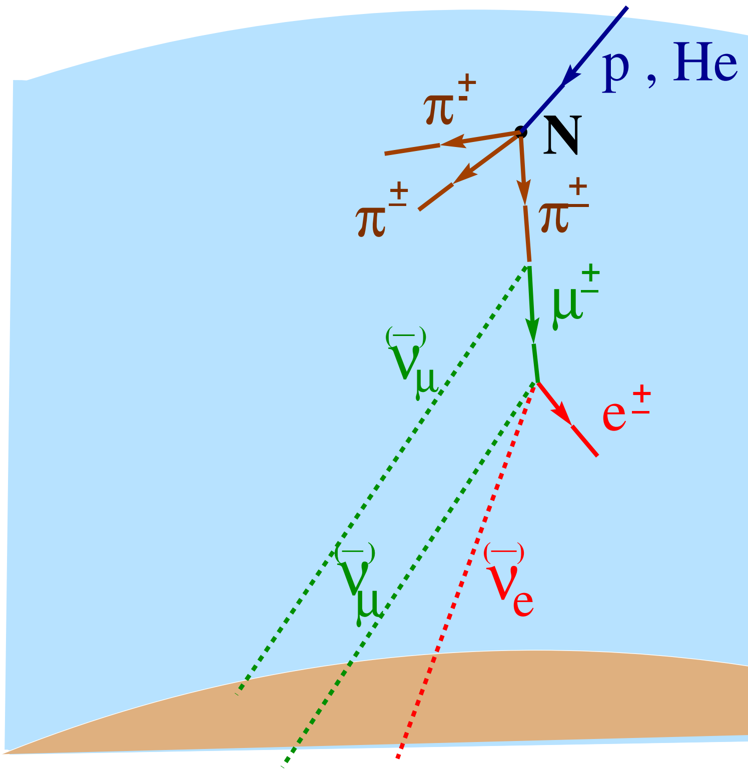
- Atmospheric neutrinos are produced by the interaction of *cosmic rays* (p, He, ...) with the Earth's atmosphere:

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

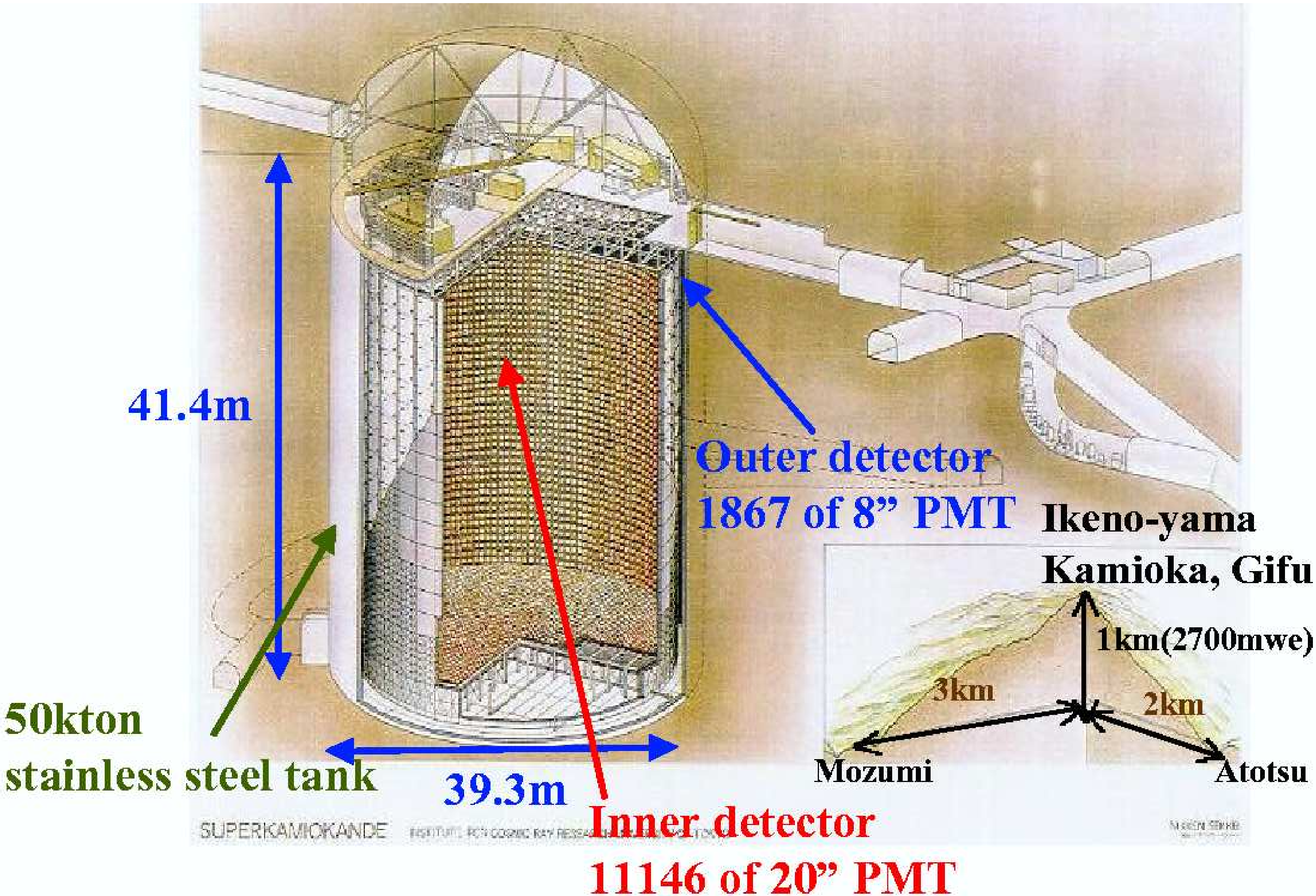
$$\boxed{2}\quad \pi^{\pm}\to\mu^{\pm}+\nu_{\mu},$$

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

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



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

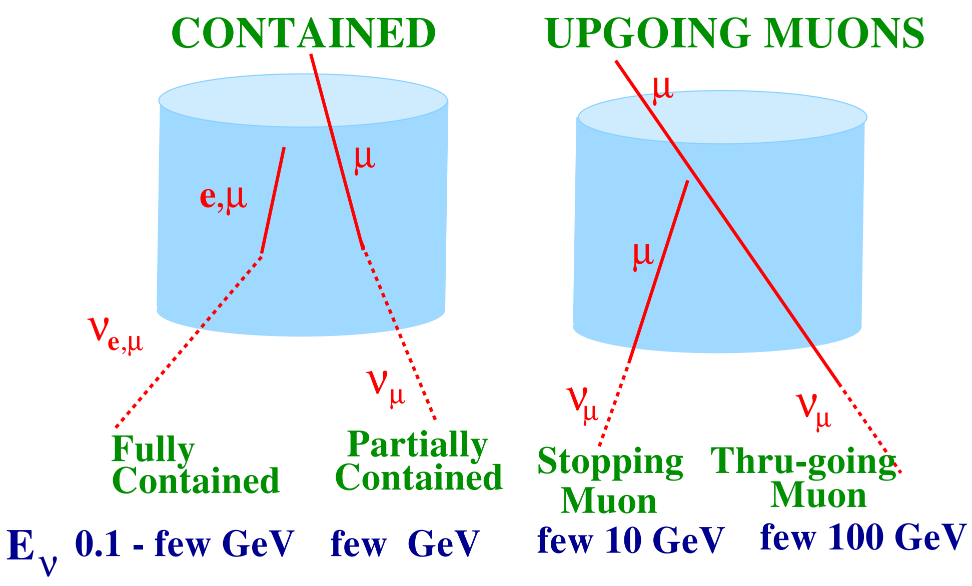

41.4m
Outer detector
1867 of 8" PMT
Ikeno-yama
Kamioka, Gifu
1km(2700mwe)
3km
2km
Mozumi
Atotsu
50kton
stainless steel tank
39.3m
SUPERKAMIOKANDE
Inner detector
11146 of 20" PMT

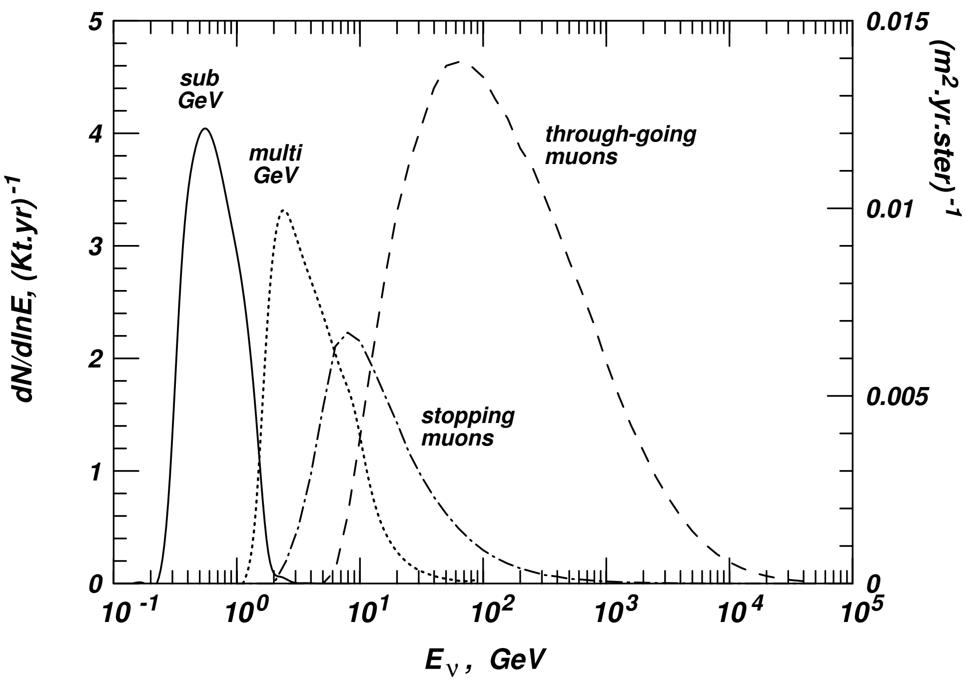
Classification of atmospheric neutrino events

- 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.





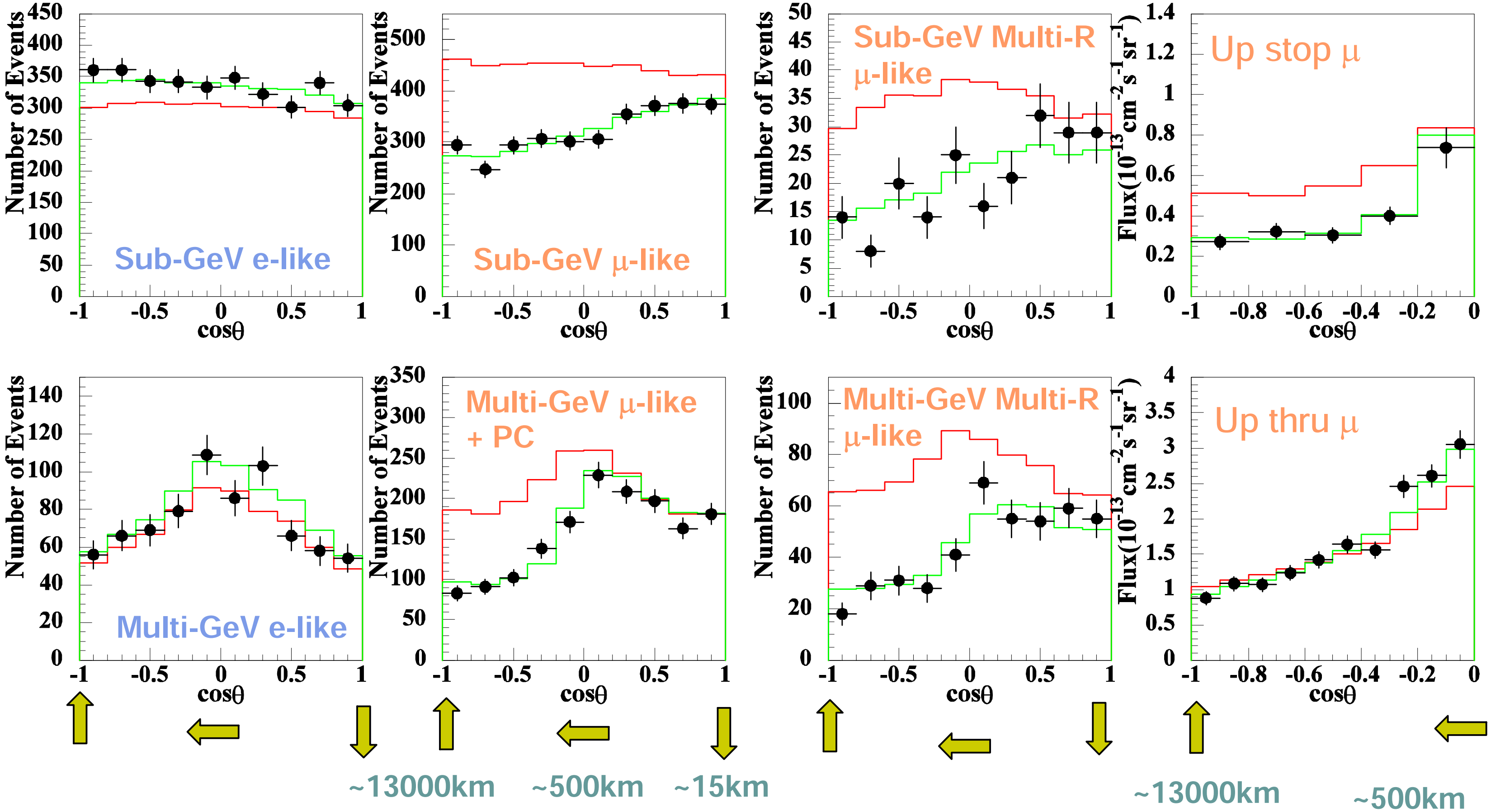
Zenith angle distributions

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

2-flavor oscillations

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

Null oscillation



Oscillations of atmospheric ν_e

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

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

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

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

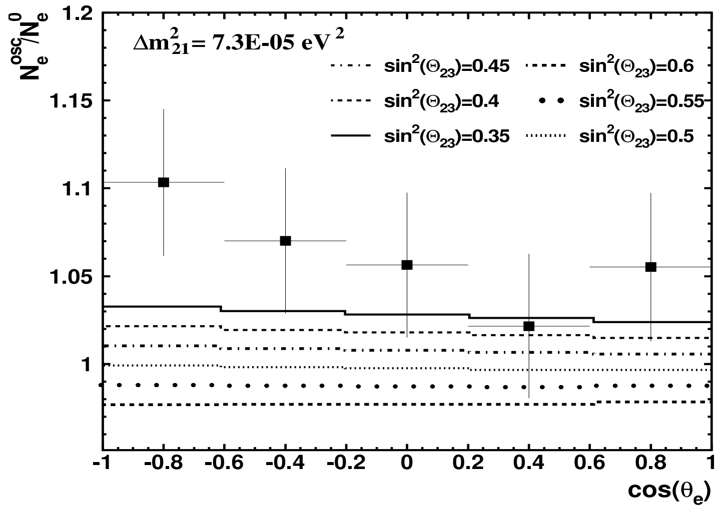
At low energies $r \equiv F_\mu^0/F_e^0 \simeq 2$; also $s_{23}^2 \simeq c_{23}^2 \simeq 1/2$ –
a conspiracy to hide oscillation effects on e-like events!
Reason: a peculiar flavour composition of the atmospheric ν flux.

(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).

Breaking the conspiracy – 3f effects

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

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

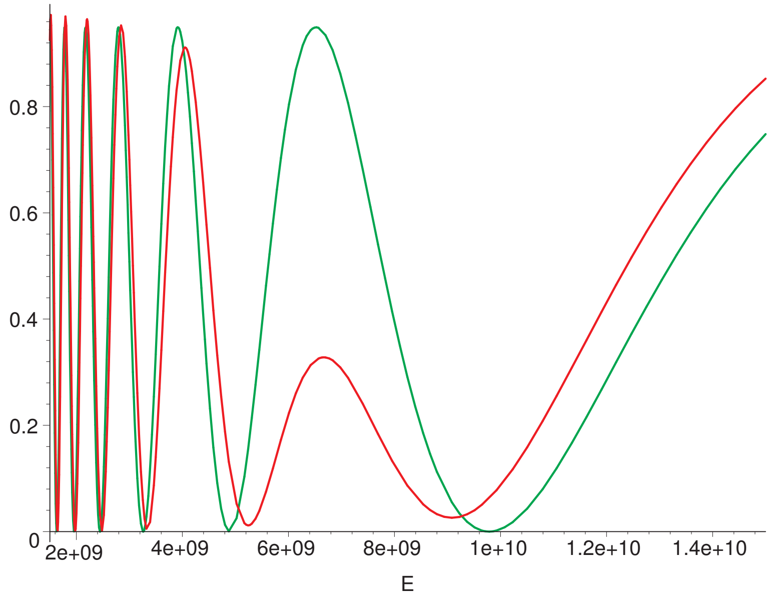


Interf. term may not be sufficient to fully explain the excess of low-E e-like events – a hint of $\theta_{23} \neq 45^\circ$? (Peres & Smirnov, 2004)

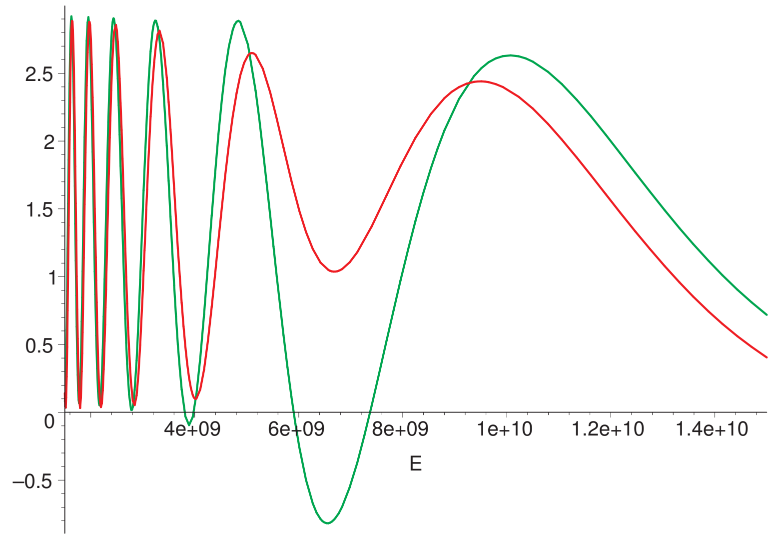
Matter effects on $\nu_\mu \leftrightarrow \nu_\tau$ oscillations

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)



$P_{\mu\tau}$

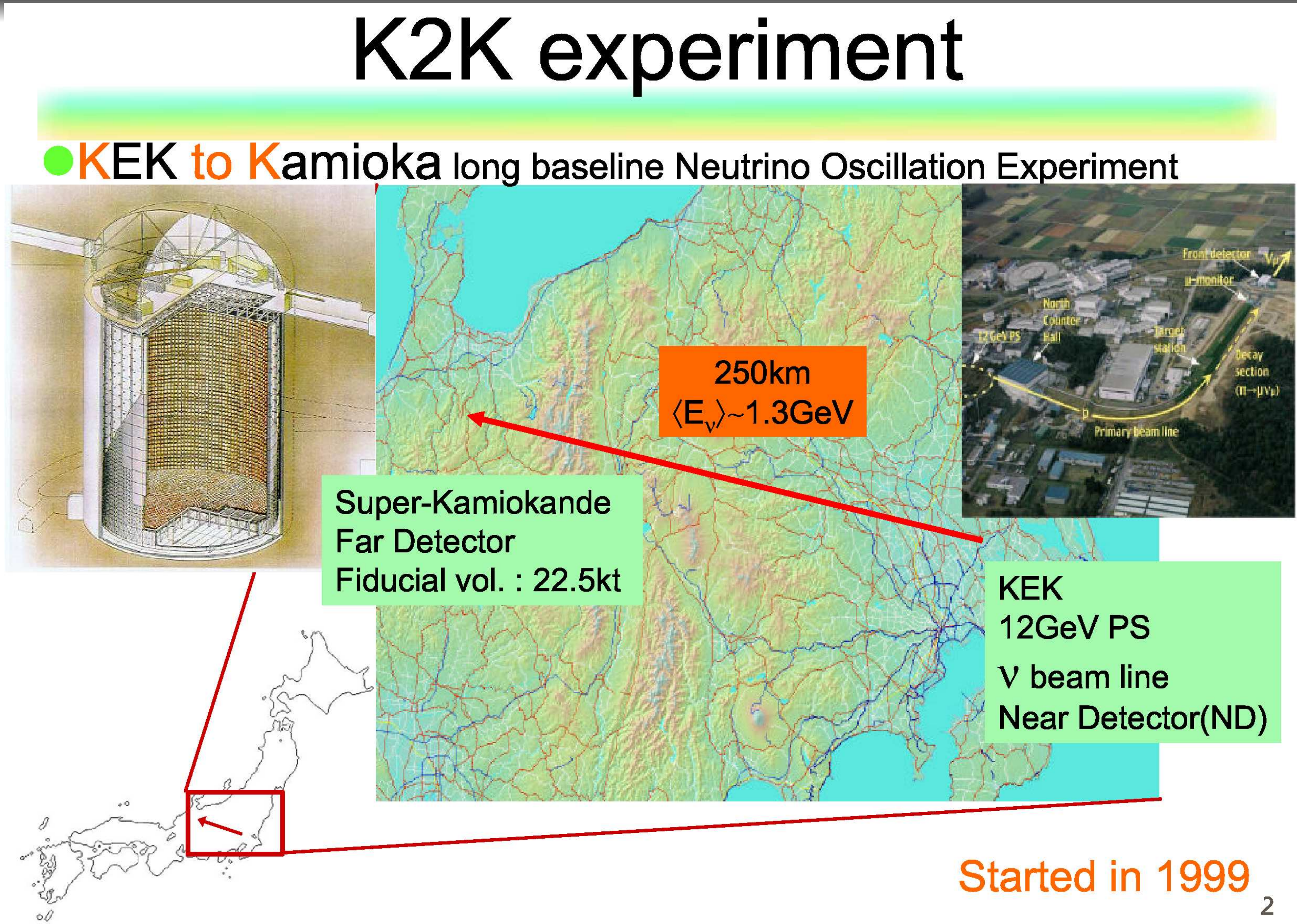


Oscillated flux of atm. ν_μ

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

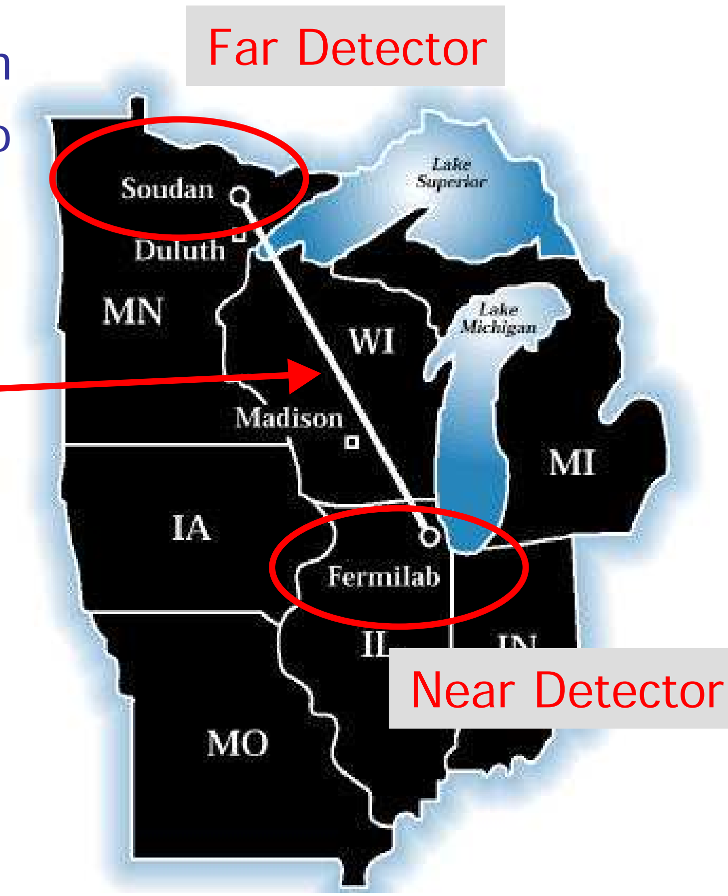
Red curves – w/ matter effects, green curves – w/o matter effects on $P_{\mu\tau}$

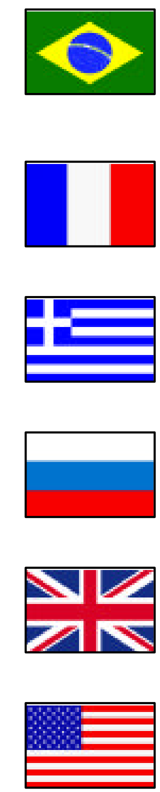
ν_μ disappearance: confirmed by accel. expts.

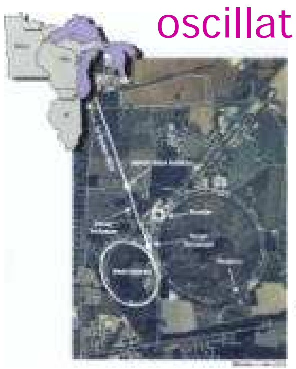


The MINOS Experiment

- Main Injector Neutrino Oscillation Search
- Accelerator-based long-baseline neutrino experiment
- Precision experiment at the atmospheric Δm^2
- One ν_μ beam: NuMI
  - 120 GeV protons from Fermilab Main Injector
- Two detectors
  - Near Detector: measure beam composition and spectrum
  - Far Detector: search for evidence of oscillations







Atmospheric neutrinos:

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

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

- 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



Long-baseline beam experiments: taming the source

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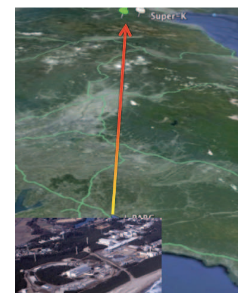
J-PARC to Kamioka
295 km, 380-750 kW

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



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

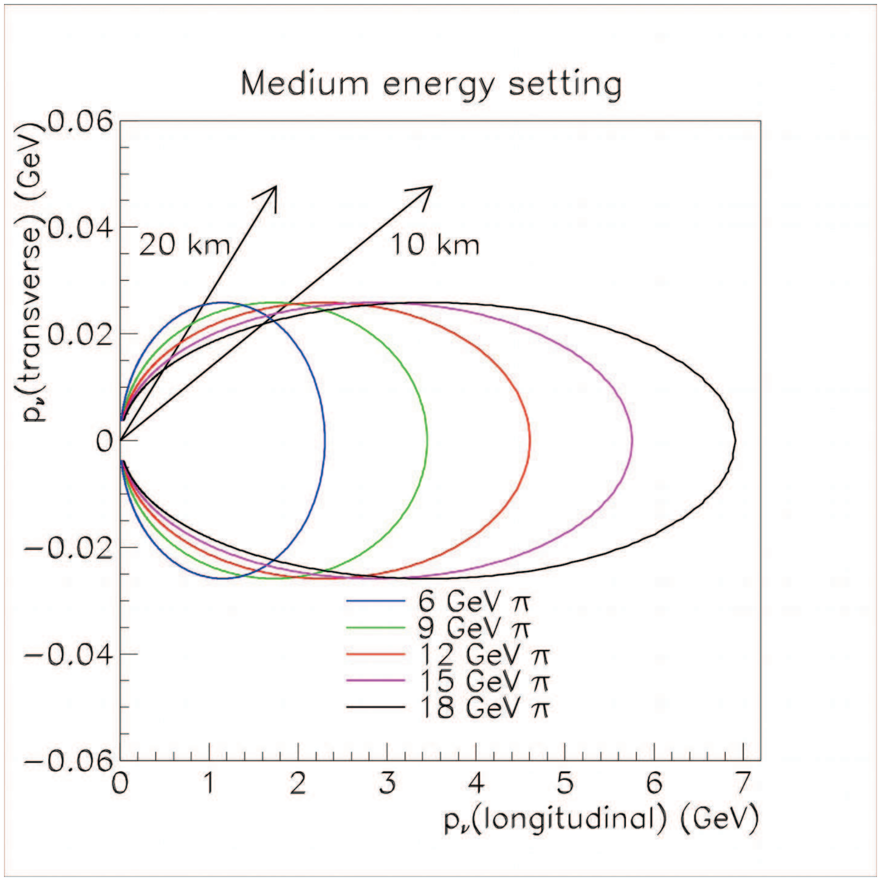
And beyond...
ESSnuB,
neutrino factories

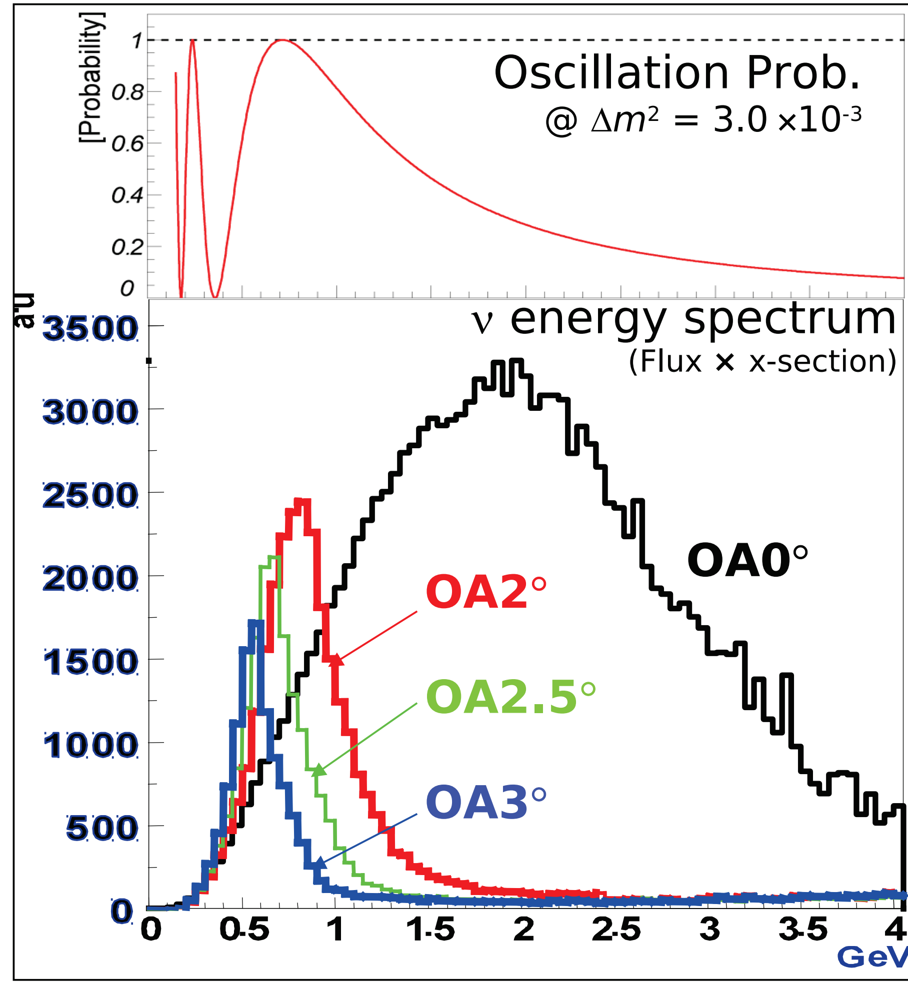




See sessions Neutrino-4,5,8

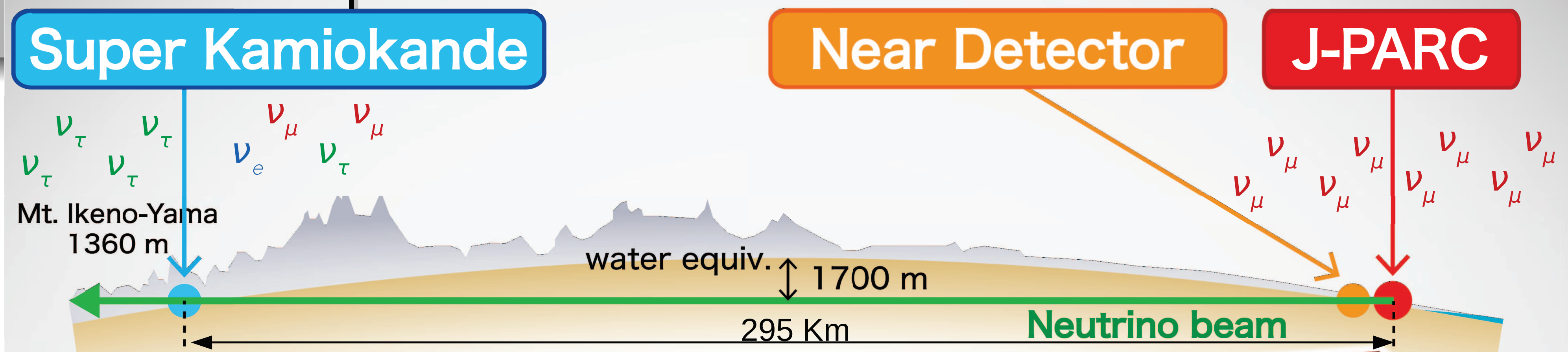
Off-Axis ν_μ Beam





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

The T2K experiment



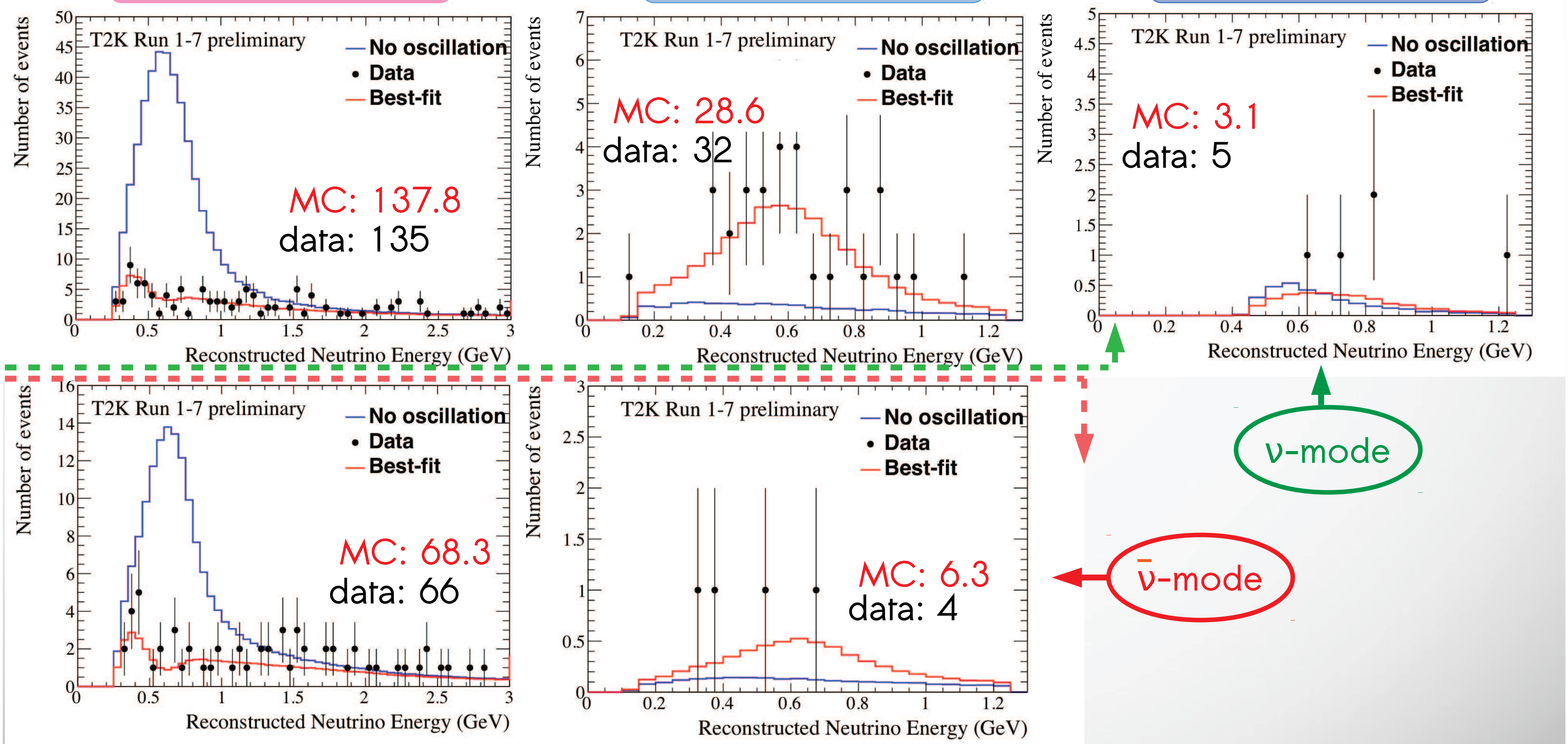
Super-K samples

5 samples of charged-current (CC) ν interactions:

determination of oscillation parameters

new e^- rings CC-1π^+ sample since ICHEP 2016

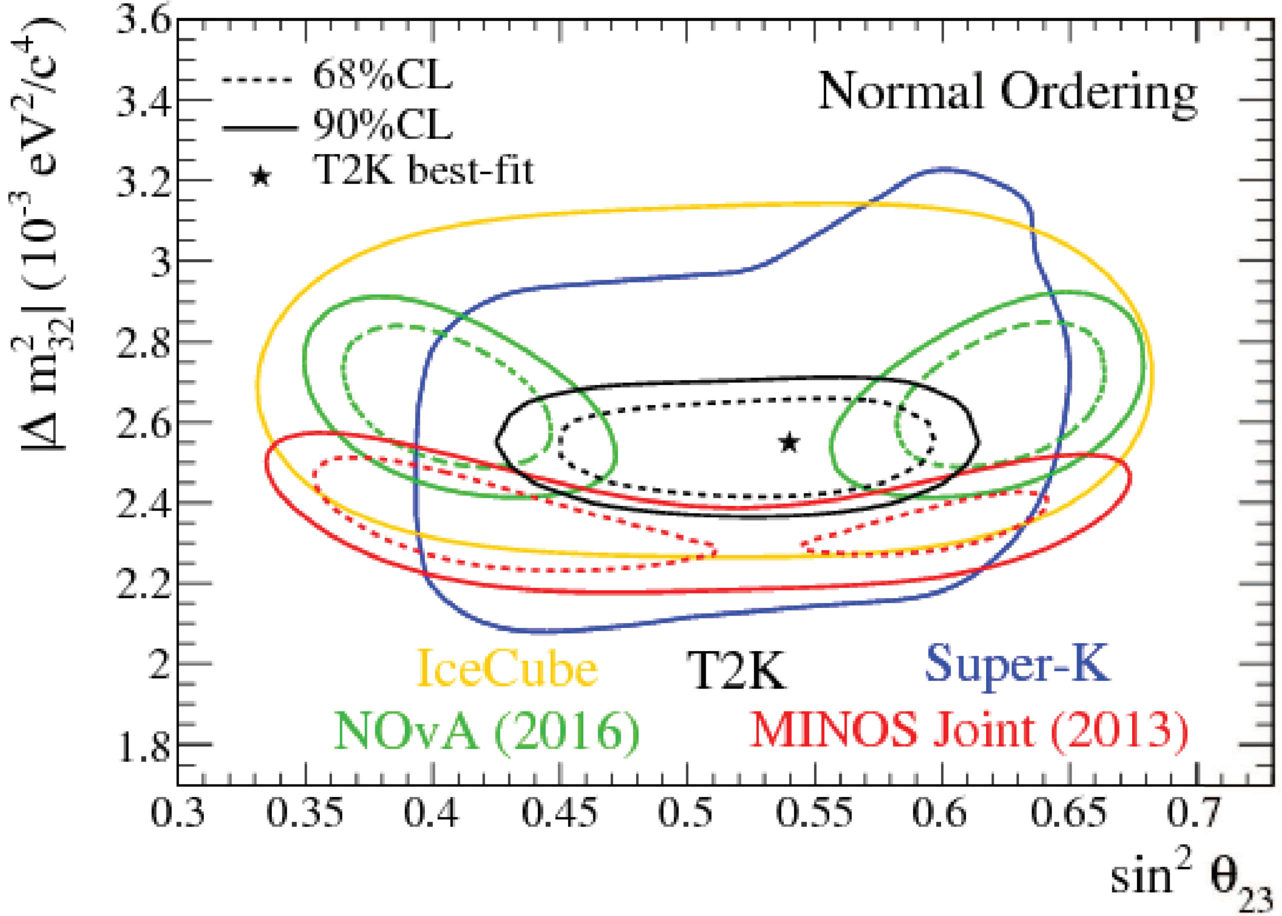
$\mu^{+/-}$ rings CC-0π | $e^{+/-}$ rings CC-0π | e^- rings CC-1π^+



Results v.s. other experiments (frequentist analysis)

T2K data + $\sin^2\theta_{13}$ from reactor (PDG 2015)

Normal mass ordering assumed



90% confidence levels (CL) have the true value falling inside 90% of times the experiment is repeated

Conclusion and prospects

- T2K analysed data in ν - mode ($7.482 \cdot 10^{20}$ POT) and $\overline{\nu}$ - mode ($7.531 \cdot 10^{20}$ POT) → 90% credible intervals exclude CP-conserving values $\delta_{CP} = 0, +/-\pi$

paper soon to be published

arXiv:1707.01048

T2K only

Parameter	Best-fit	$\pm 1\sigma$
δ_{CP}	-1.815	[-2.275; -0.628]
$\sin^2\theta_{13}$	0.0254	[0.0210; 0.0350]
$\sin^2\theta_{23}$	0.513	[0.460 ; 0.550]
Δm^2_{32}	$2.539 \times 10^{-3} eV^2/c^4$	$[-2.628; -2.544] \times 10^{-3} eV^2/c^4$ $[2.436; 2.652] \times 10^{-3} eV^2/c^4$

T2K + reactor

Parameter	Best-fit	$\pm 1\sigma$
δ_{CP}	-1.789	[-2.450; -0.880]
$\sin^2\theta_{13}$	0.0219	[0.0208; 0.0233]
$\sin^2\theta_{23}$	0.534	[0.490 ; 0.580]
Δm^2_{32}	$2.539 \times 10^{-3}\ \mathrm{eV}^2/c^4$	$[-3.000; -2.952] \times 10^{-3} eV^2/c^4$ $[2.424; 2.664] \times 10^{-3} eV^2/c^4$

Conclusion and prospects

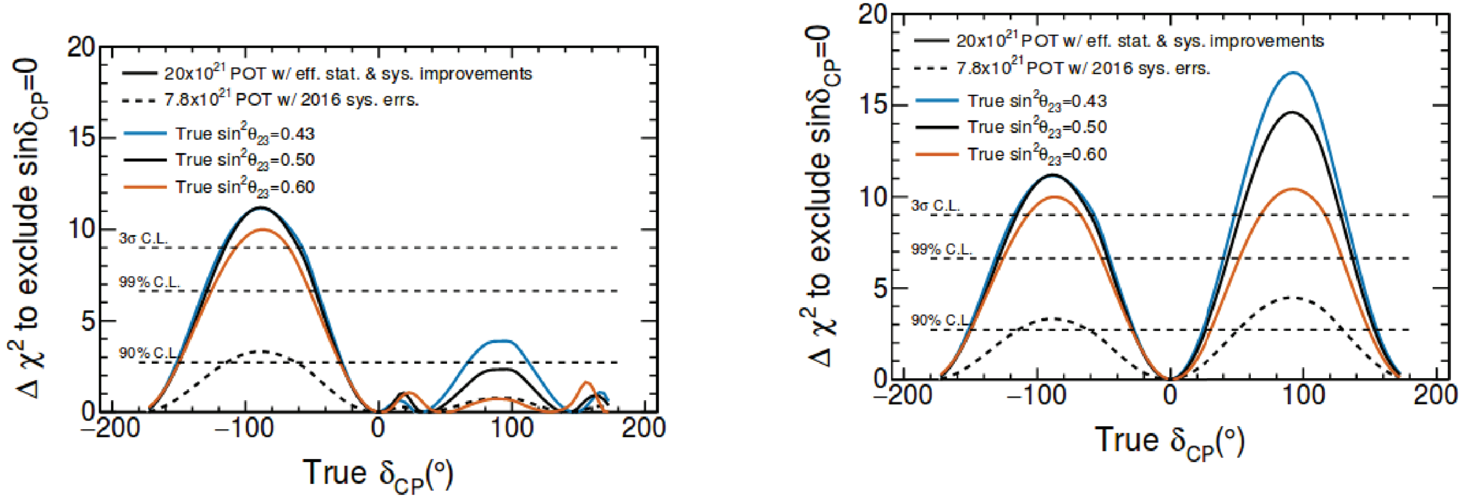
- T2K analysed data in ν - mode ($7.482 \cdot 10^{20}$ POT) and $\overline{\nu}$ - mode ($7.531 \cdot 10^{20}$ POT) ⇒ 90% credible intervals exclude CP-conserving values δ_{CP} = 0, +/-π

- New results with run 8 will be released this Summer.

- More data will be taken in 2017/18, including $\overline{\nu}$ - mode runs.

- T2K entering the T2K-II phase (after collecting current goal $7.8 \cdot 10^{20}$ POT): $20 \cdot 10^{20}$ POT

arxiv 1609.04111

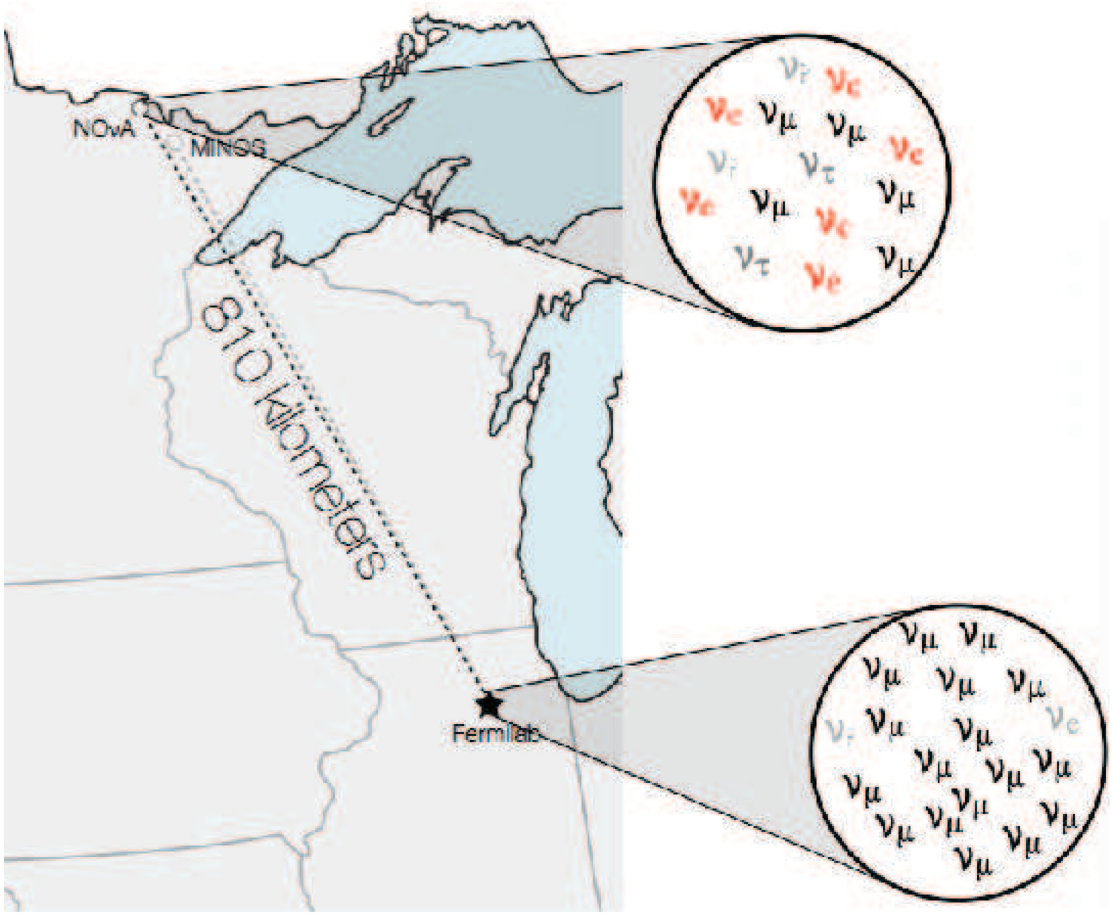


(a) Assuming the MH is unknown.

(b) Assuming the MH is known – measured by an outside experiment.

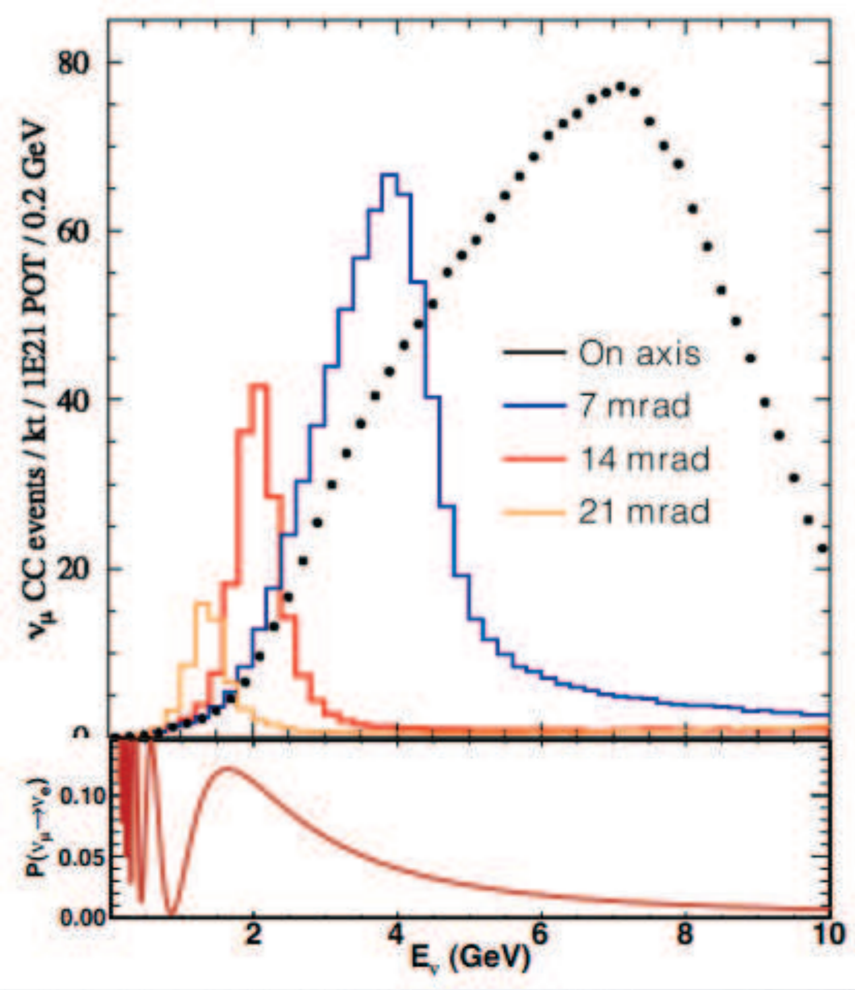
NOvA Experiment

- Longest baseline accelerator neutrino search
  - NuMI is a beam of mainly muon-neutrinos created at Fermilab
  - Two functionally identical detectors
- Measured muon-neutrino disappearance and electron-neutrino appearance
  - And starting to do the same with anti-neutrinos
- Sensitive to PMNS matrix, mass hierarchy, CP violation, sterile neutrinos, interaction physics, supernova, …



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

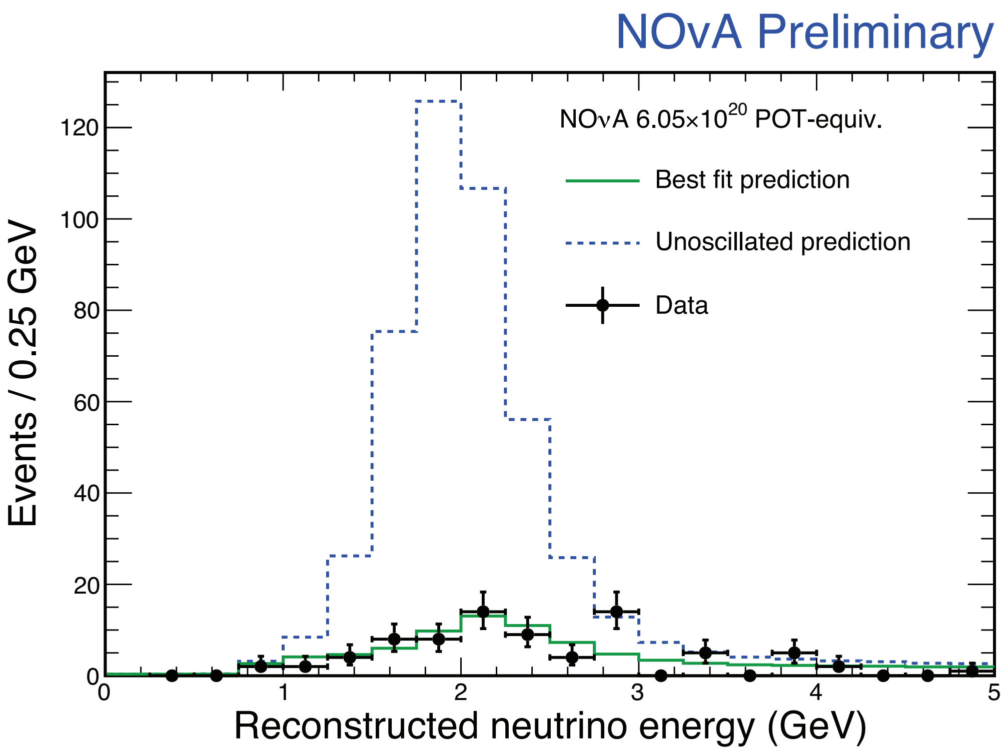


Also: neutrino cross sections at the ND, sterile neutrinos, supernovae…

Muon-Neutrino Disappearance

arXiv:1701.05891

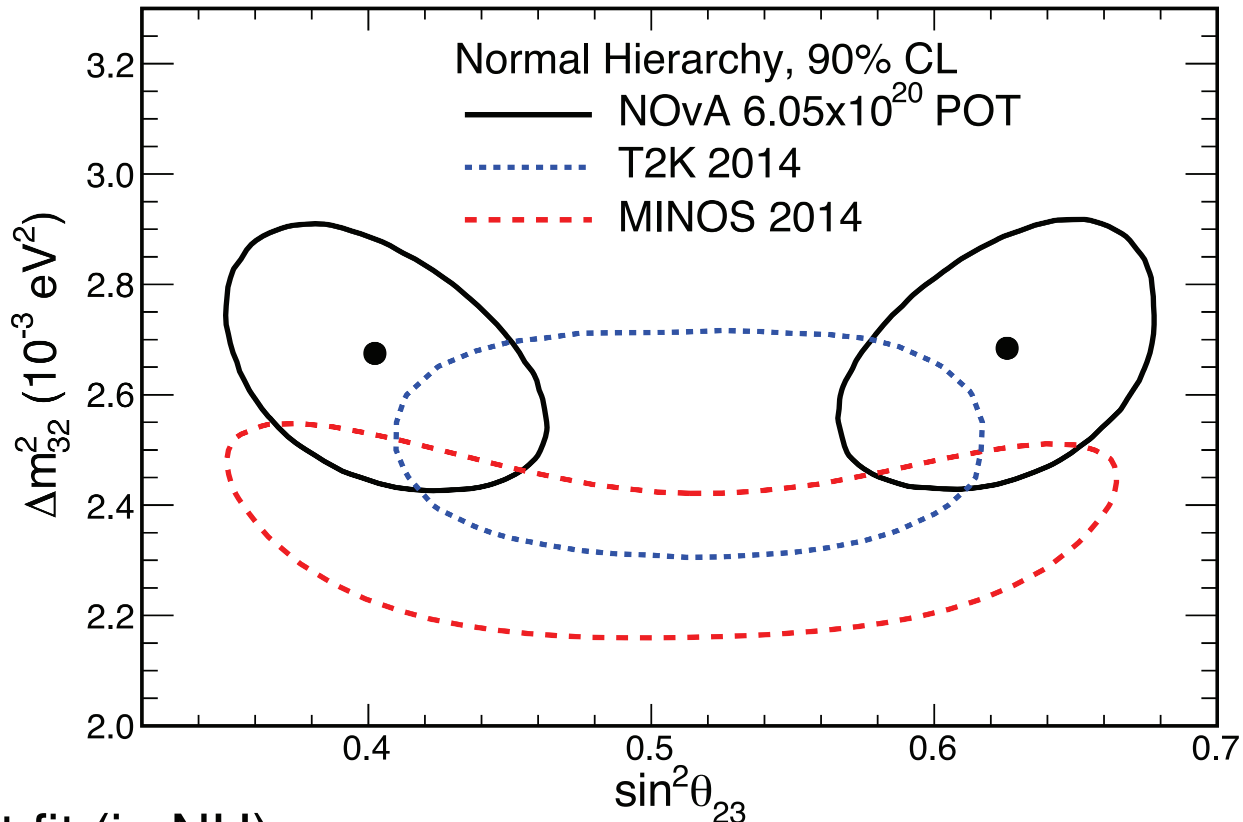
- Using 6.05x10^{20} POT equivalent
- 473 +/- 30 events predicted in the absence of oscillations
- Observed 78 events
- 82 events predicted at the best fit point including 3.7 beam background and 2.9 cosmic induced events



18 NOvA @ NeuTel, Ryan Nichol

Muon-Neutrino Disappearance

arXiv:1701.05891



Best fit (in NH):

$$|\Delta m^2_{32}| = 2.67 \pm 0.11 \times 10^{-3}\mathrm{eV}^2$$

$$\sin^2\theta_{23} = 0.404^{+0.030}_{-0.022}(0.624^{+0.022}_{-0.030})$$

- Maximal-mixing disfavoured at 2.6 sigma
- Interesting tension between NOvA and T2K, new results eagerly anticipated

$\nu_\mu \longrightarrow \nu_e$ 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]

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

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

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

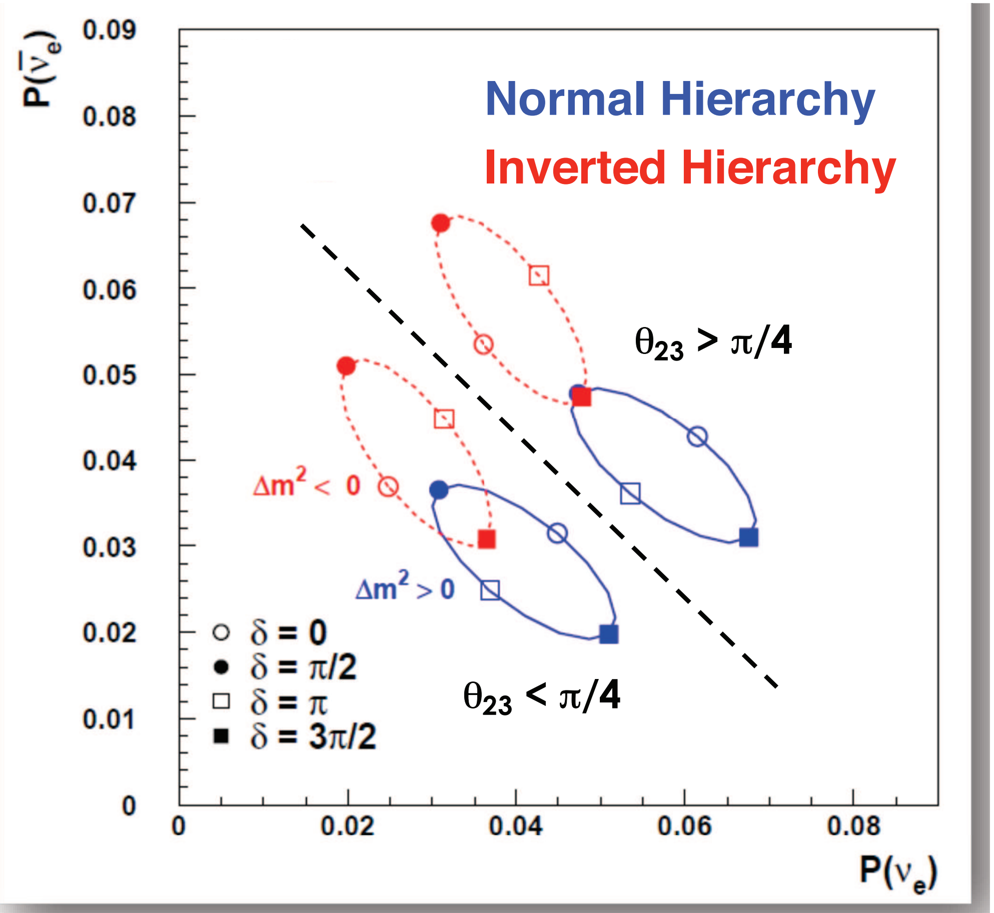
Depends on relative sign of "a" and Δ_{31}

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

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

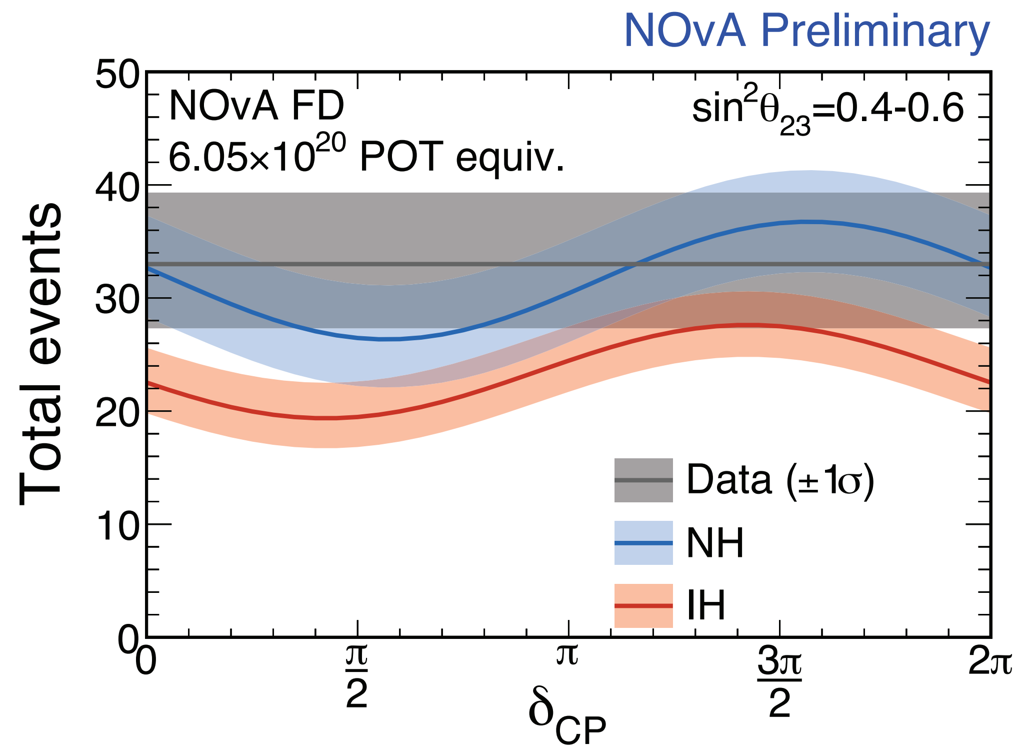
aL=0.08 for L=295km T2K baseline
aL=0.23 for L=810km NOvA baseline

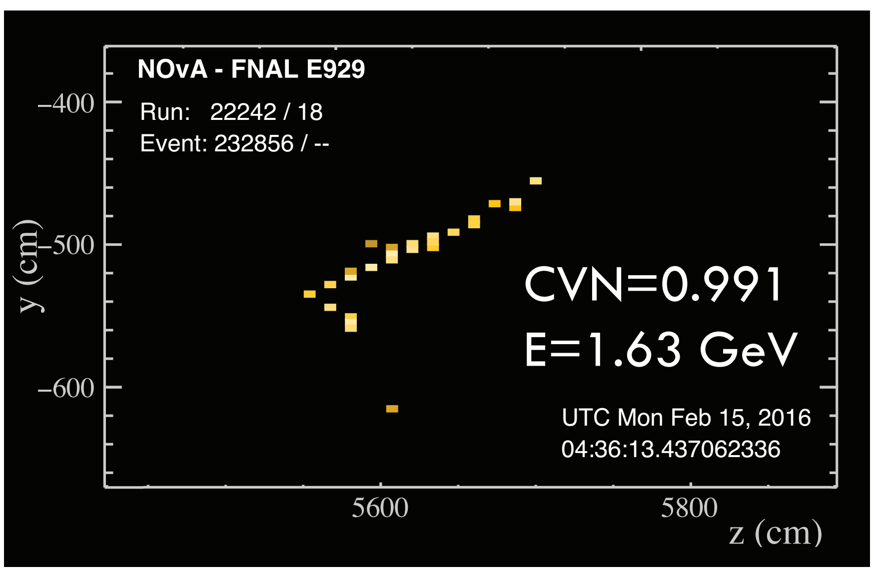
Oscillation probability is sensitive to: mass ordering, CP violating phase, and θ_{23} octant.

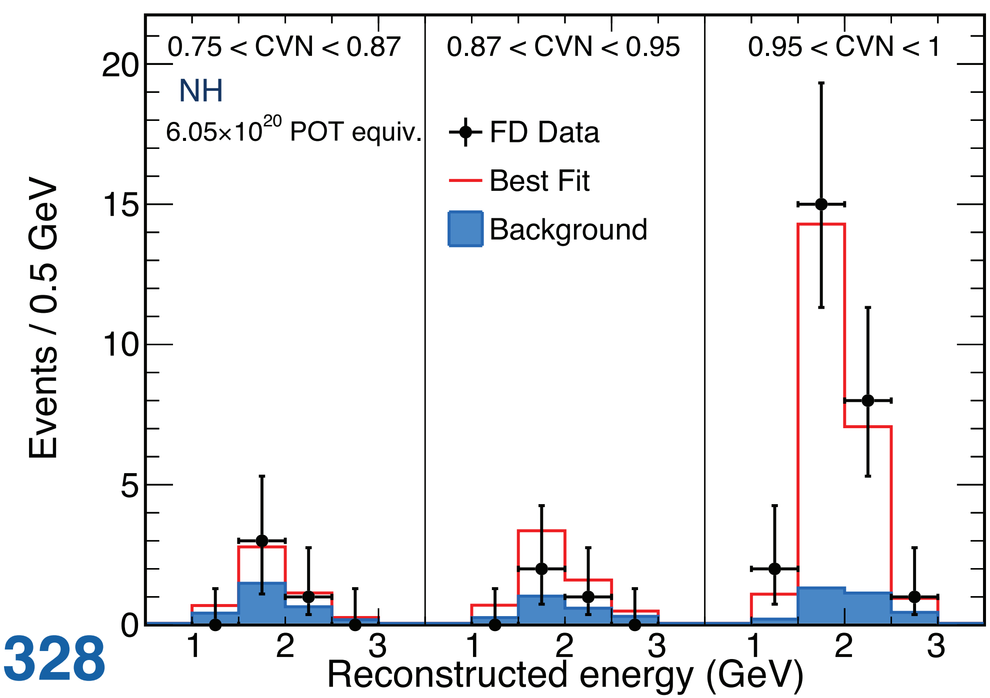


Electron-neutrino appearance

- Observe 33 events on background of 8.2 +/- 0.8 events
- Over 8σ significance of electron-neutrino appearance







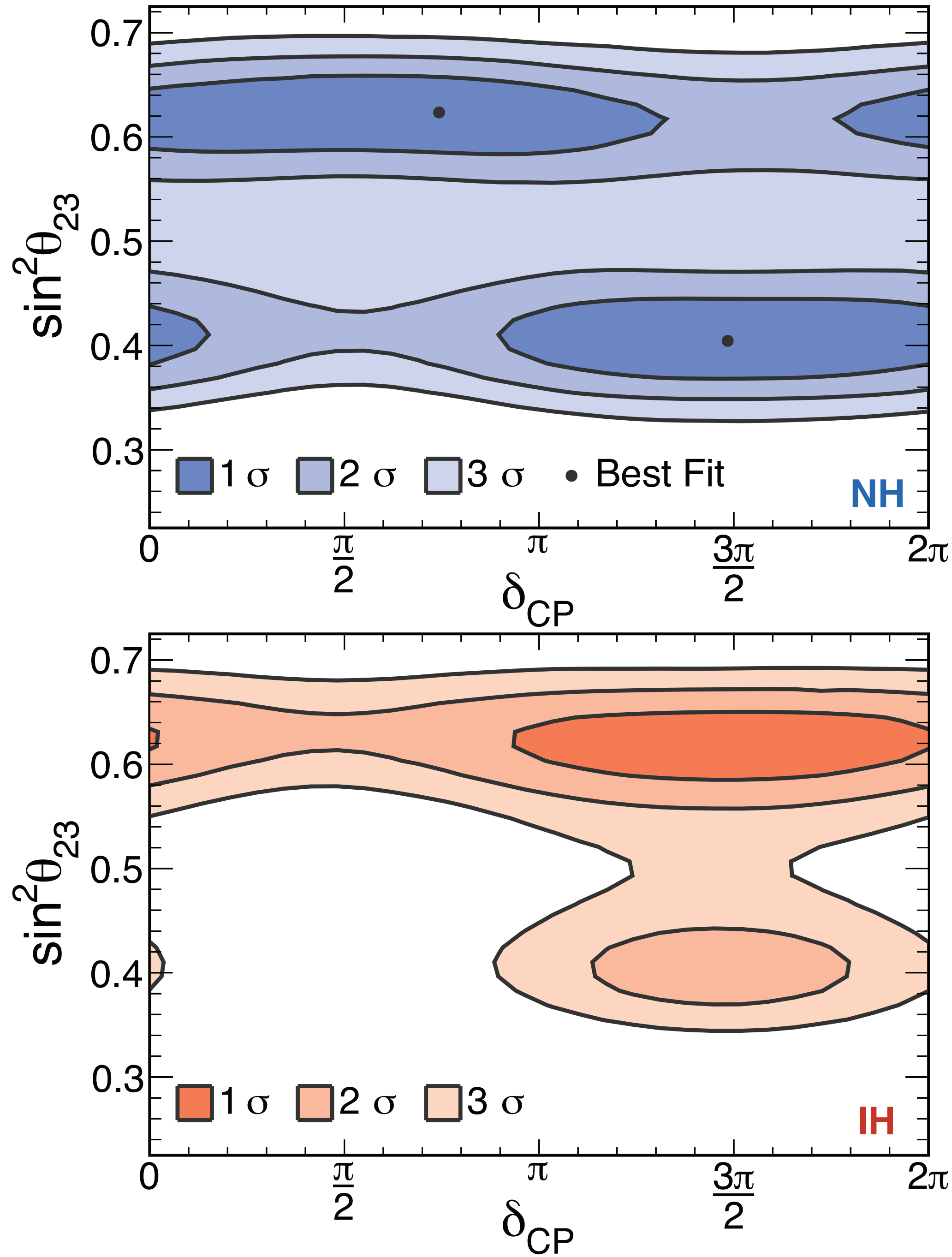
arXiv:1703.03328

$\nu_\mu \to \nu_e$ Oscillation Results

- Fit for hierarchy, δ_{CP}, $\sin^2\theta_{23}$
  - Constrain $\sin^2 2\theta_{13} = 0.085 \pm 0.005$ from reactor experiments
  - Simultaneous fit NOvA disappearance data
- Global best fit, two degenerate points in Normal Hierarchy

$$\delta_{cp} = 1.48\pi, \sin^2(\theta_{23}) = 0.404$$
$$\delta_{cp} = 0.74\pi, \sin^2(\theta_{23}) = 0.623$$

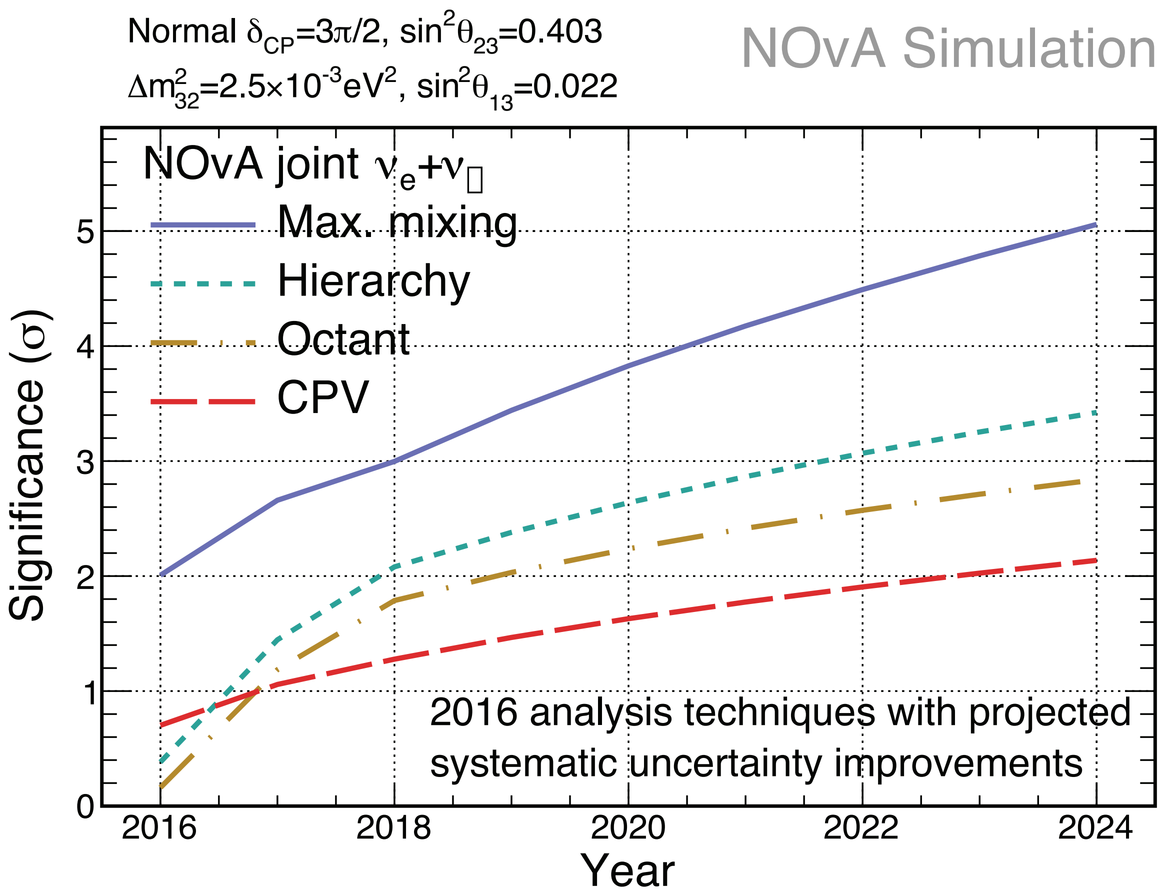
  - best fit IH-NH, $\Delta\chi 2$=0.47
  - Lower octant, IH is disfavoured at greater than 93% C.L for all values of δ_{CP}



30 NOvA @ NeuTel, Ryan Nichol

arXiv:1703.03328

Looking Forward



- Switched to anti-neutrino running in February 2017
- Run 50% neutrino, 50% anti-neutrino after 2018
  - 3 σ sensitivity to maximal mixing of θ_{23} in 2018
  - 2 σ sensitivity to mass hierarchy and θ_{23} octant in 2018-2019

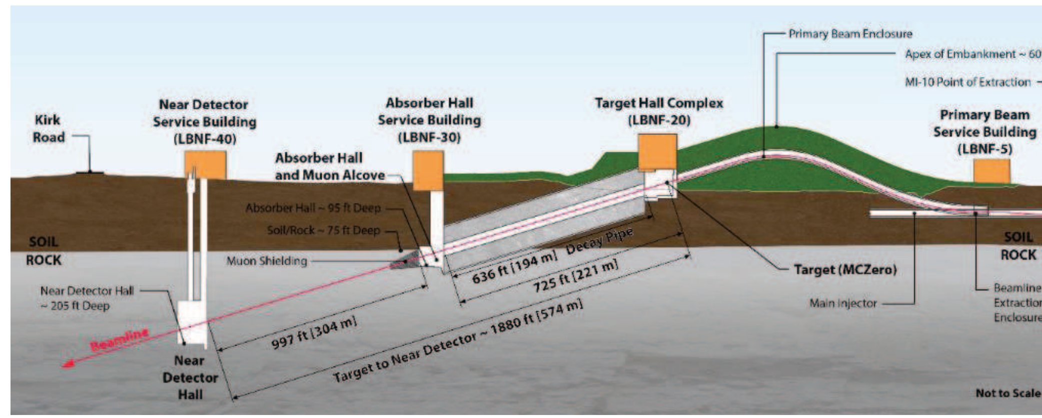
Conclusions

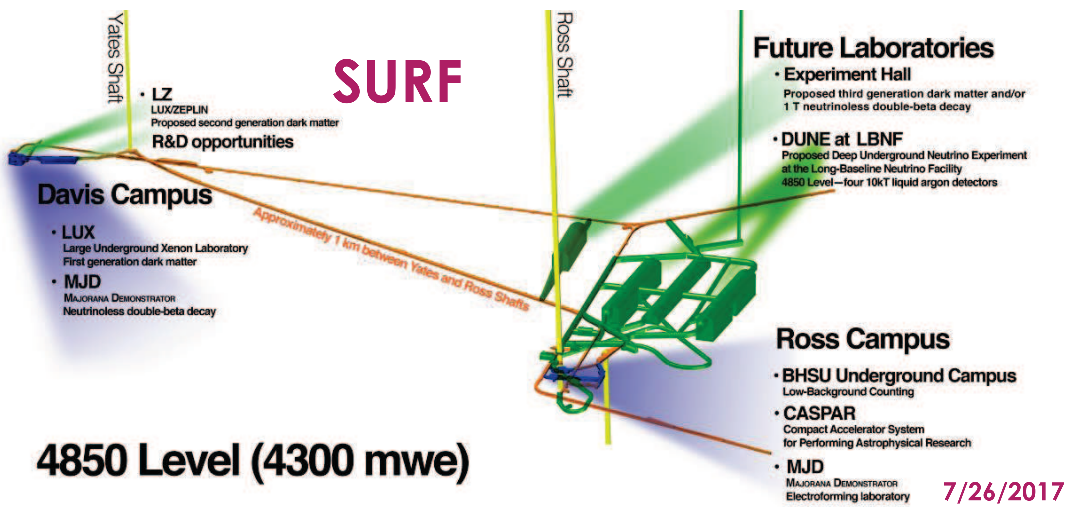
- Analysis of 6.05×10^{20} POT of NOvA data (1 nominal year)
- Muon-neutrino disappearance (arXiv:1701.05891)
  - Best fit is non-maximal value of θ_{23}, maximal mixing disfavoured at 2.5σ
- Electron neutrinos appearance (arXiv:1703.03328)
  - First joint fit of NOvA appearance and disappearance data
  - Weak preference for normal hierarchy
  - Inverted hierarchy, lower octant is disfavoured at > 93% C.L.
- Didn't mention sterile neutrino search, neutrino interaction, supernova, monopoles, and a lot more
- Switched to anti-neutrino running just a few weeks ago

Future projects

DUNE (Deep Underground Neutrino Experiment)

- 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

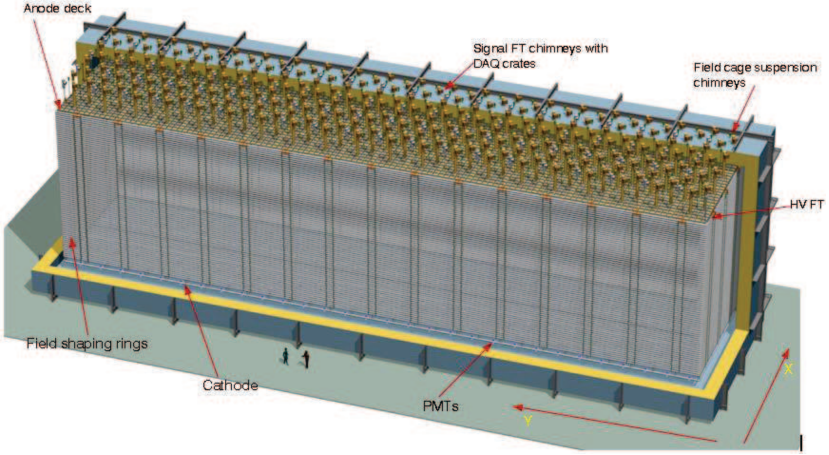
L.W. Koerner, University of Houston 7/26/2017

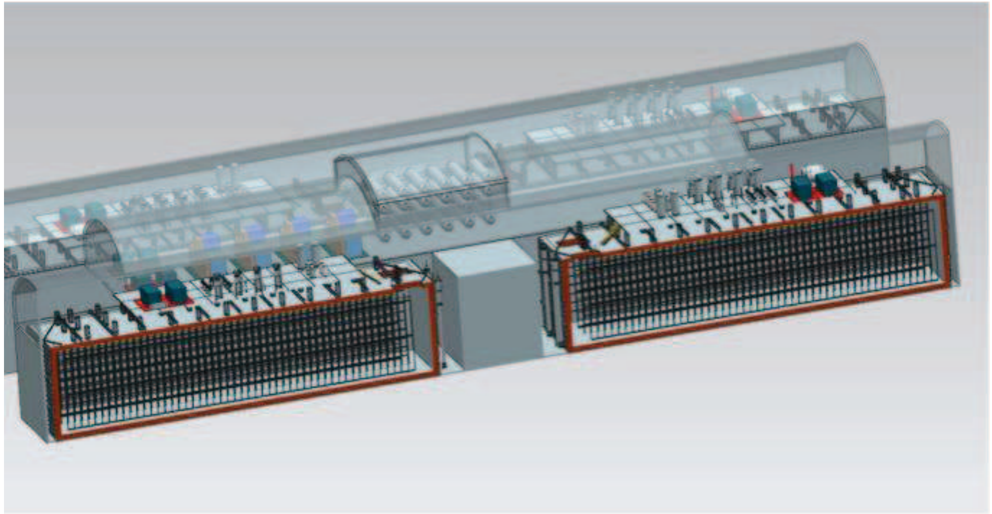
DUNE Far Detector

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)



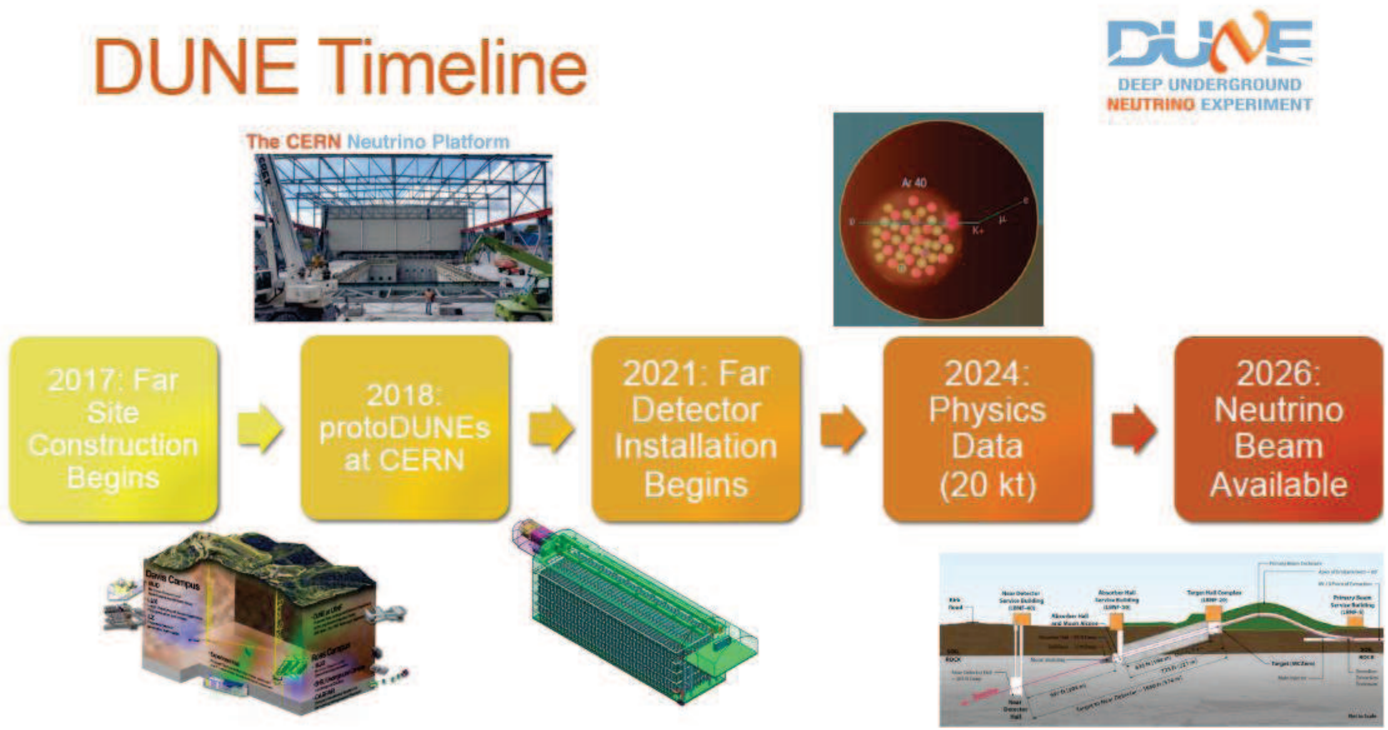


Single-phase TPC

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

L.W. Koerner, University of Houston 7/26/2017

DUNE Status and Timeline



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

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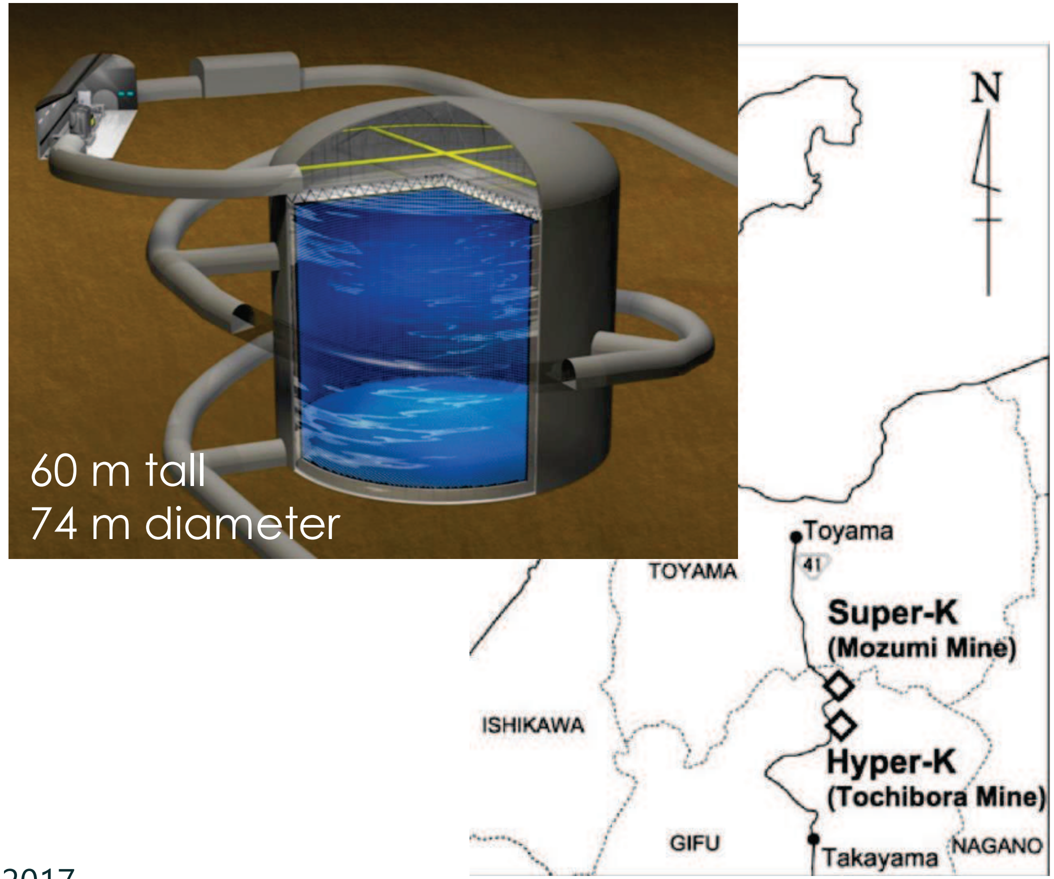
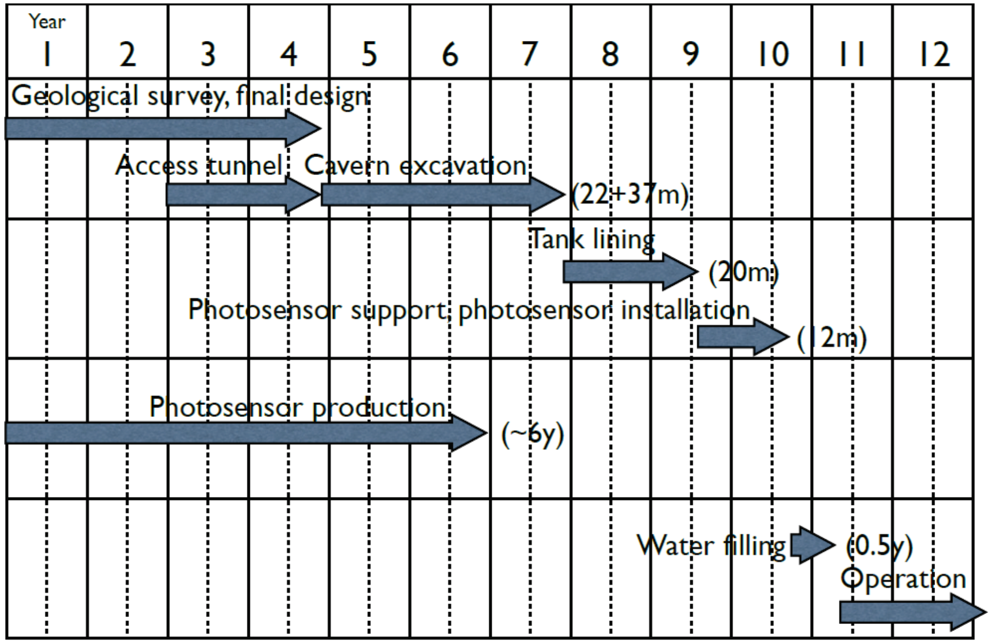
Hyper-Kamiokande Detector

- 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

Sensitivity Assumptions

DUNE

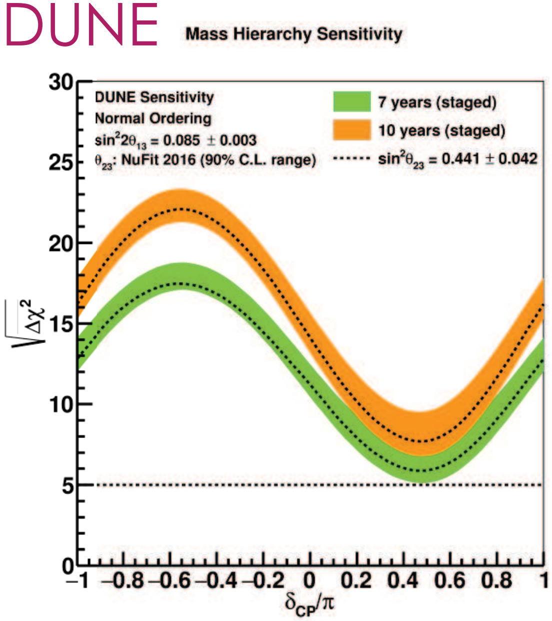
- Staging: Begin with 20 kton, 1.07 MW beam; 40 kton in year 4, 2.14 MW in year 7
- Neutrino: Antineutrino = 1:1
- θ_{23} from global fit (non-maximal)

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

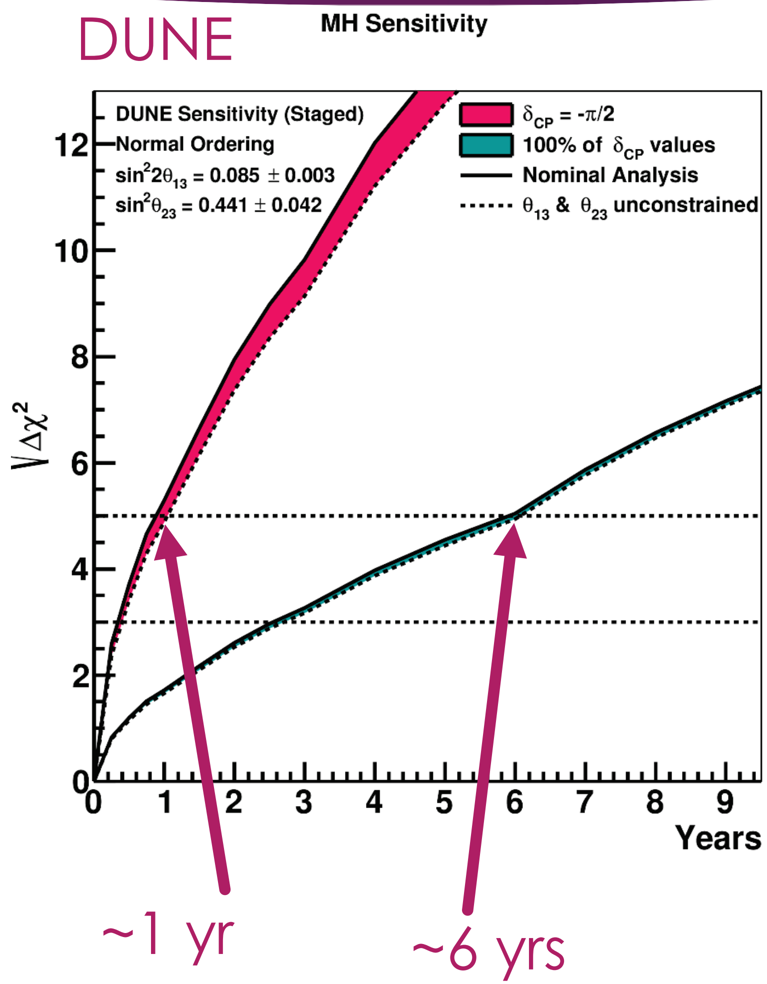
Mass Hierarchy

DUNE



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

DUNE



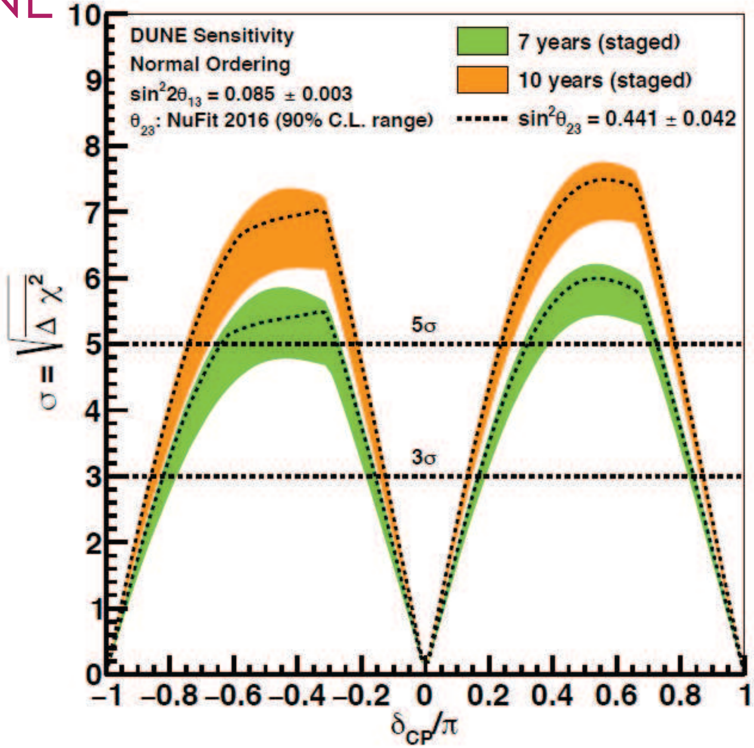
- DUNE should be able to make a relatively quick determination of the mass hierarchy
- Hyper-K is less sensitive due to the shorter baseline
  - Combined analysis with beam and atmospheric neutrinos leads to >3σ determination in about 5 years with one tank Hyper-K

L.W. Koerner, University of Houston

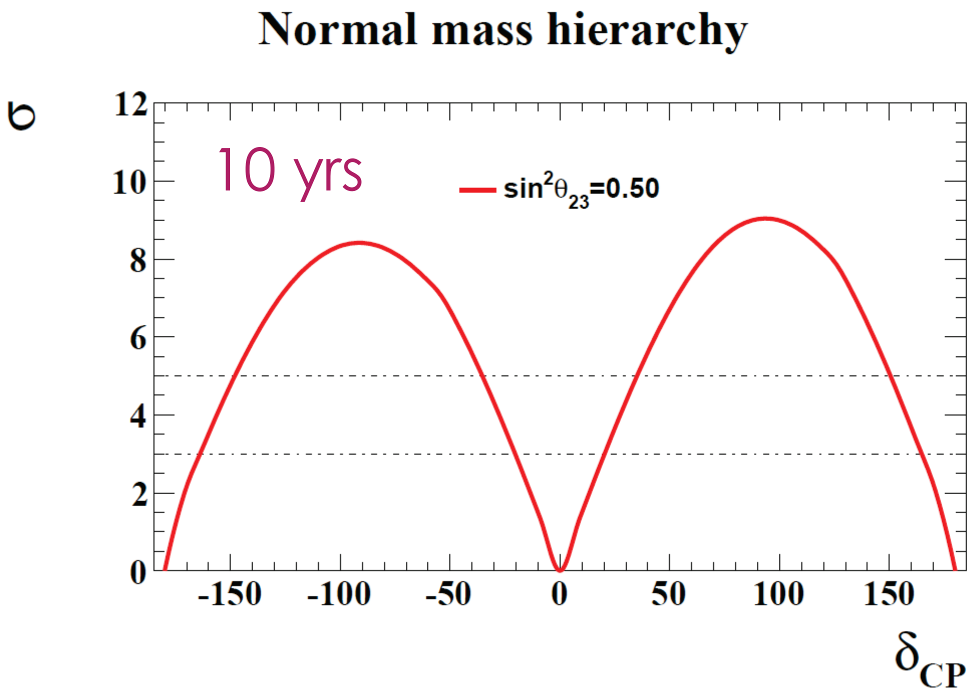
7/26/2017

CP Violation

DUNE



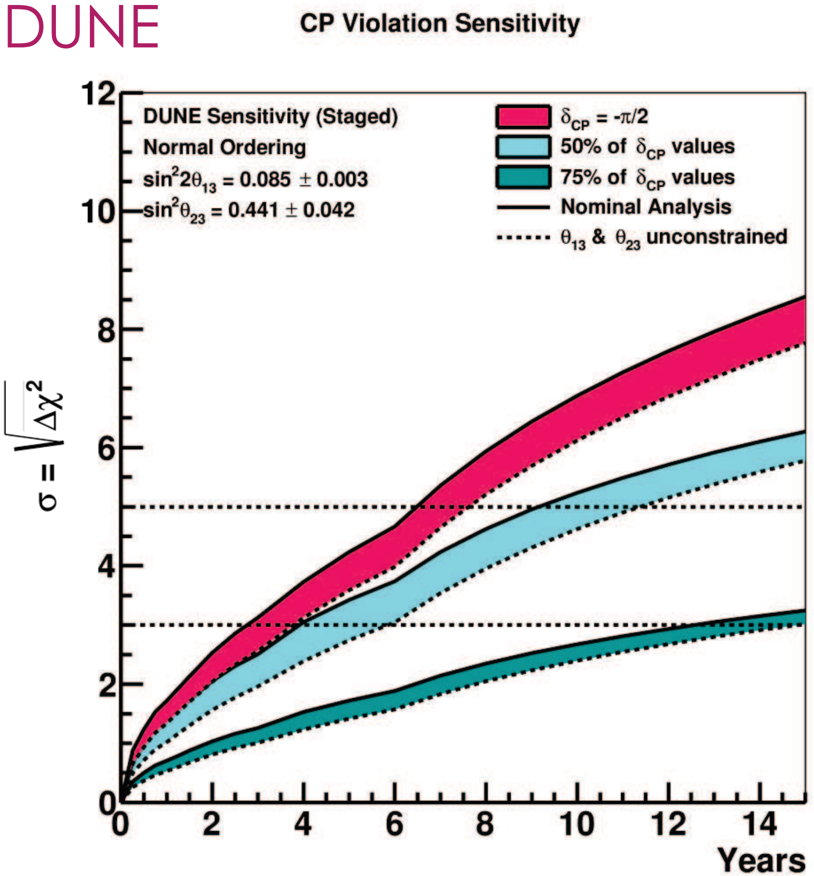
Hyper-K



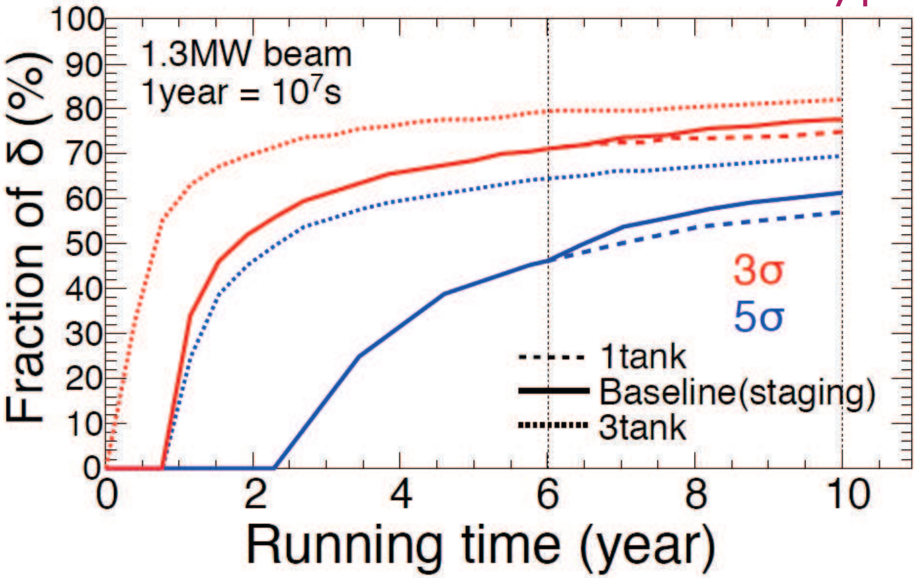
Width of band indicates variation in sensitivity for θ_{23} values in the NuFit 2016 90% C.L. range

CP Violation

DUNE



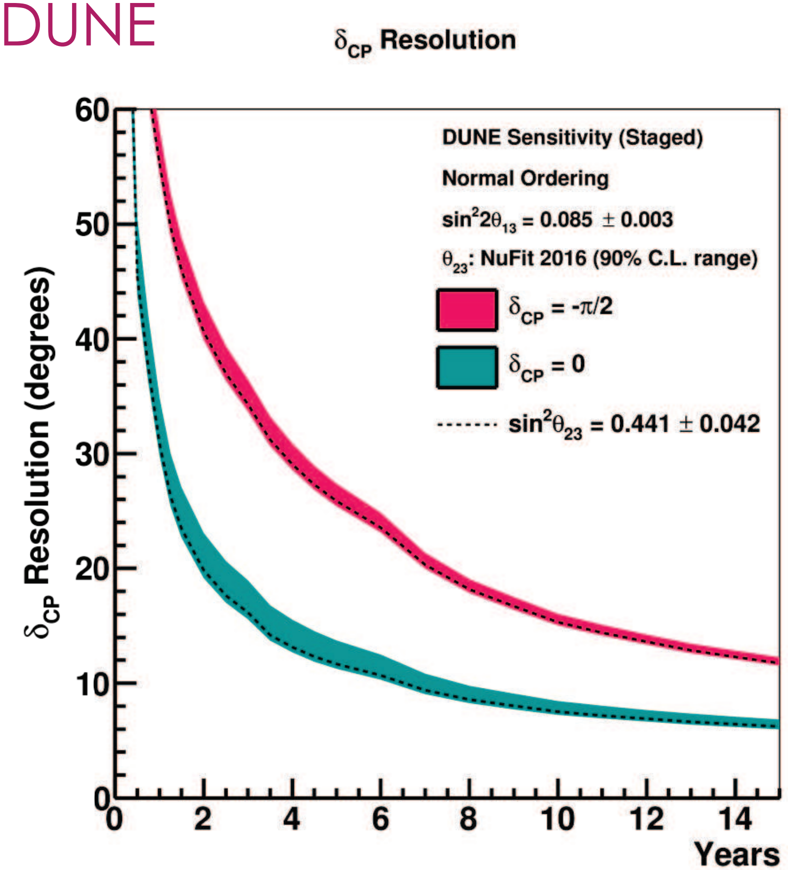
Hyper-K



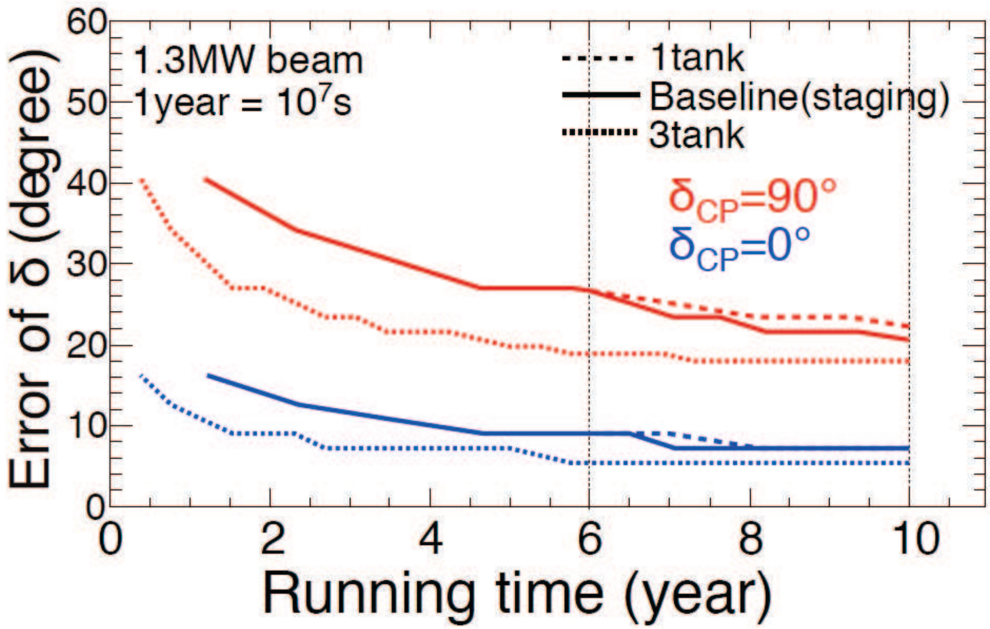
- Ultimately sensitivities of 5σ with 50% CP coverage and 3σ 75% CP coverage

CP Phase

DUNE



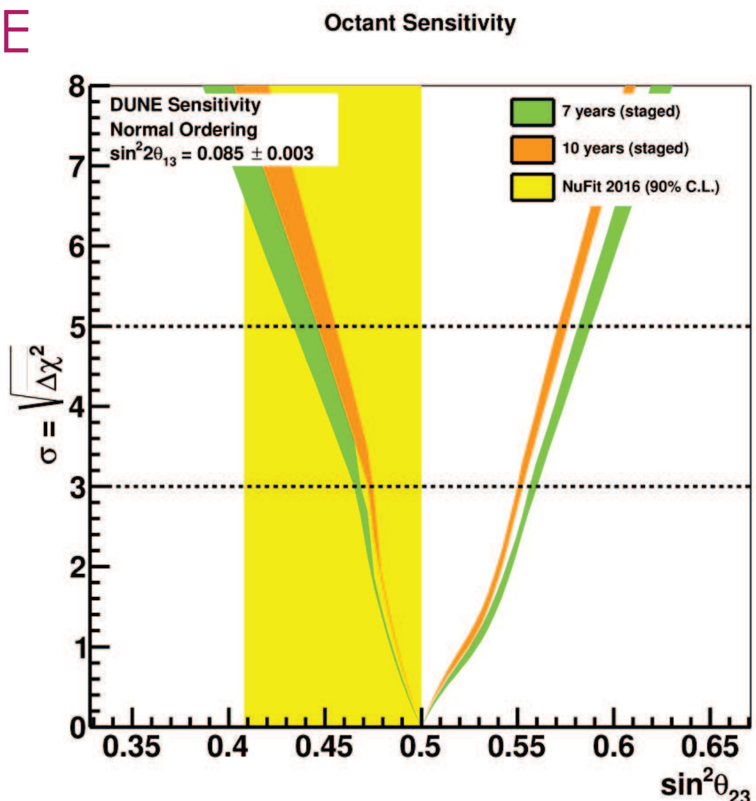
Hyper-K



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

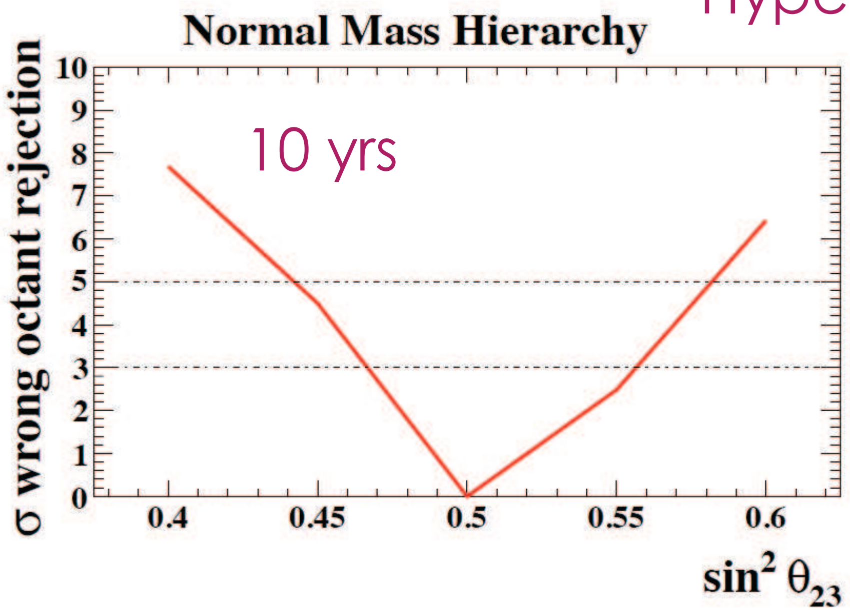
Octant

DUNE



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

Hyper-K

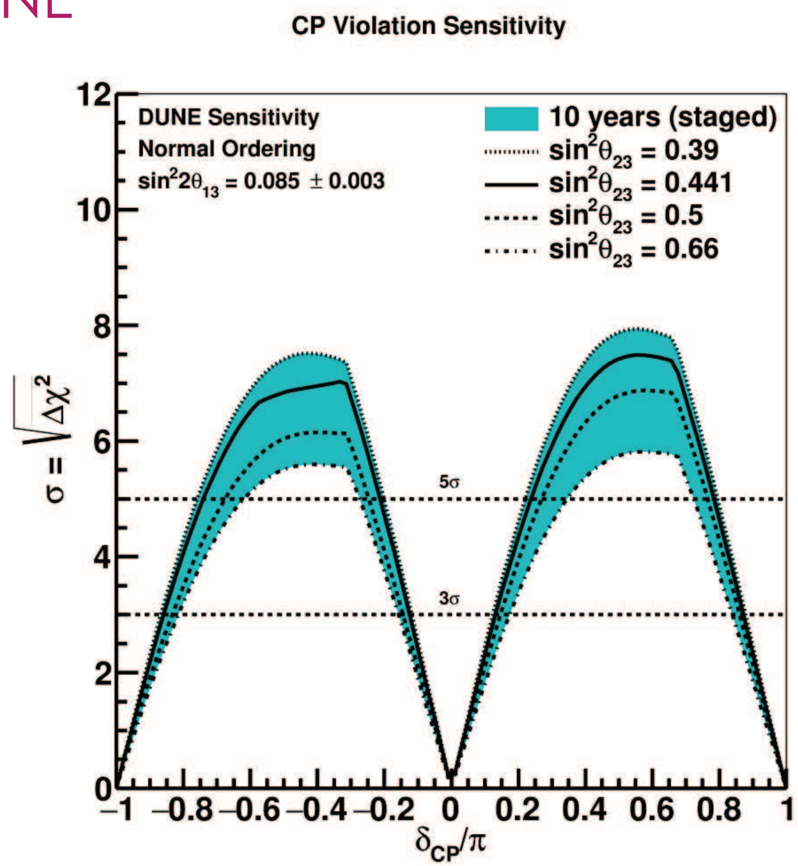


- Potential to reject maximal mixing at 3σ or 5σ in the range of the current global best fit
- Enhanced sensitivity with combined beam and atmospheric neutrino data

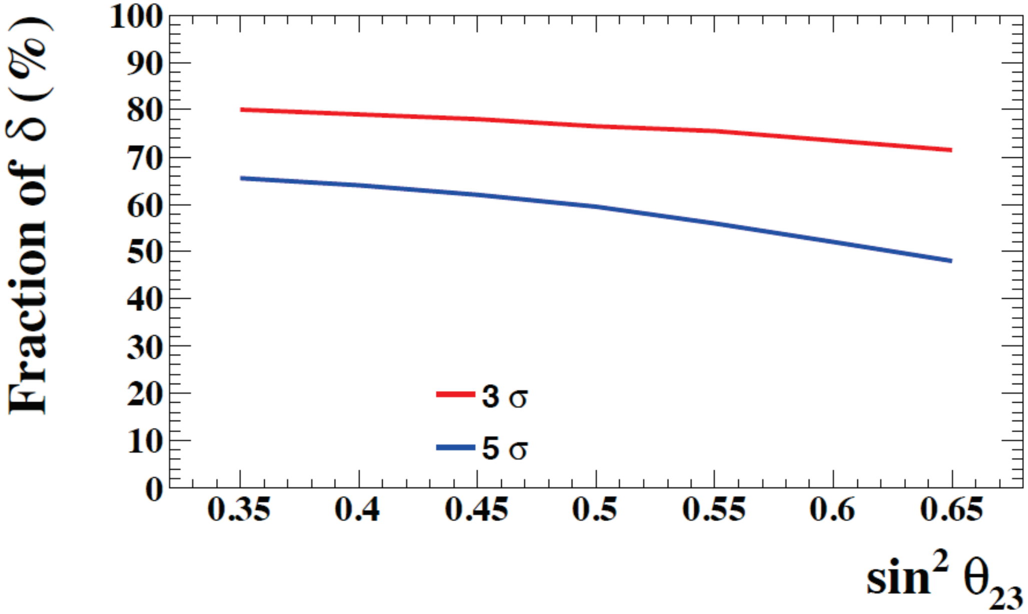
L.W. Koerner, University of Houston 7/26/2017

Effect of θ_{23} on CP

DUNE



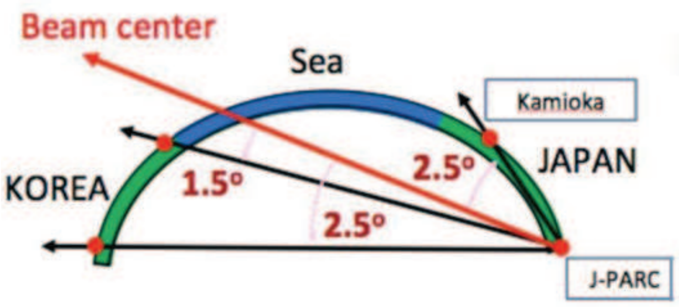
Hyper-K

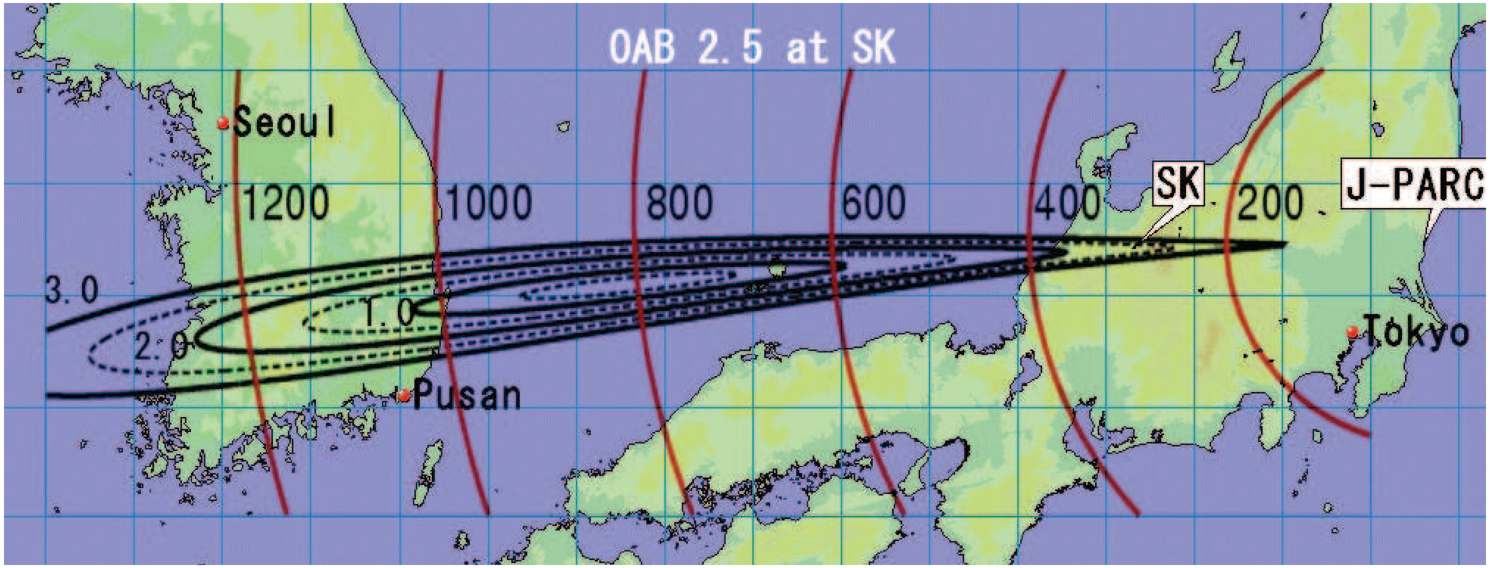


T2HKK: Tokai to Hyper-K and Korea

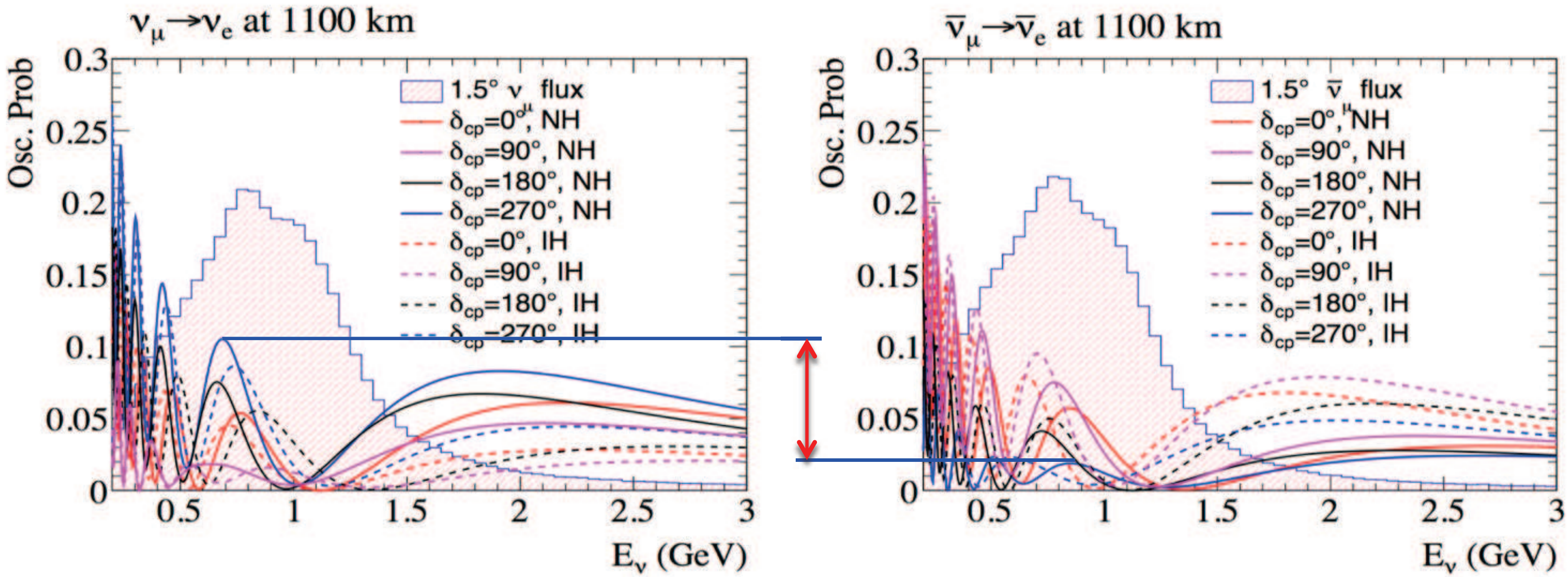
23

- 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

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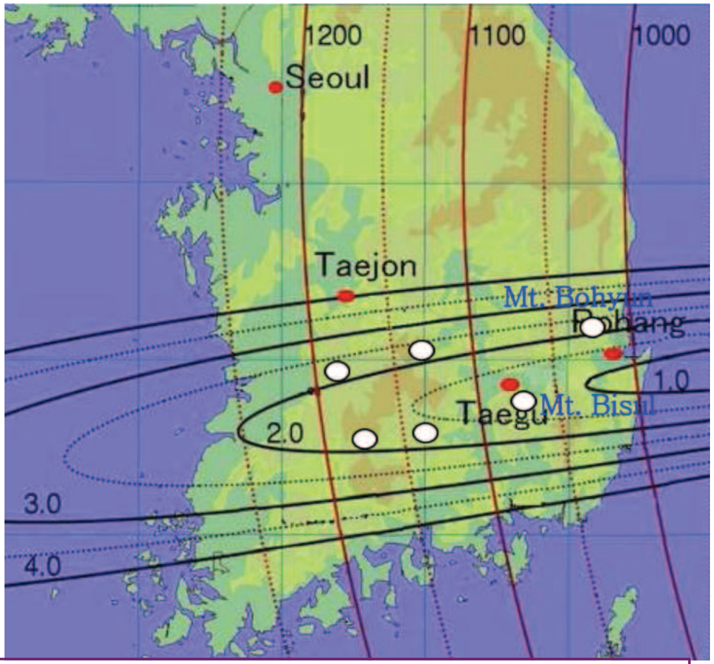
- >1000 m high mountains with hard granite rocks
- Smaller background due to its larger overburden (> 800m)
- Improved sensitivity in solar neutrino physics
  - Day/night asymmetry due to MSW matter effect in Earth
  - HEP solar neutrinos
  - Energy spectrum upturn
- Supernova relic neutrino detection 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	~1.3º	1088 km	1084 m
Mt. Hwangmae	~1.8º	1140 km	1113 m
Mt. Sambong	~1.9º	1180 km	1186 m
Mt. Bohyun	~2.2º	1040 km	1126 m
Mt. Minjuii	~2.2º	1140 km	1242 m
Mt. Unjang	~2.2º	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

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		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 σ
	Octant ($\sin^2\theta_{23}$=0.45)	5.8 σ
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 σ/12 σ
	Upturn	4.9 σ
Supernova	Burst (10kpc)	104k-158k
	Nearby	2-20 events
	Relic (10 yrs)	98evt/4.8 σ

** for DM search see backup slides