Neutrinos, towards CP violation ….
and beyond

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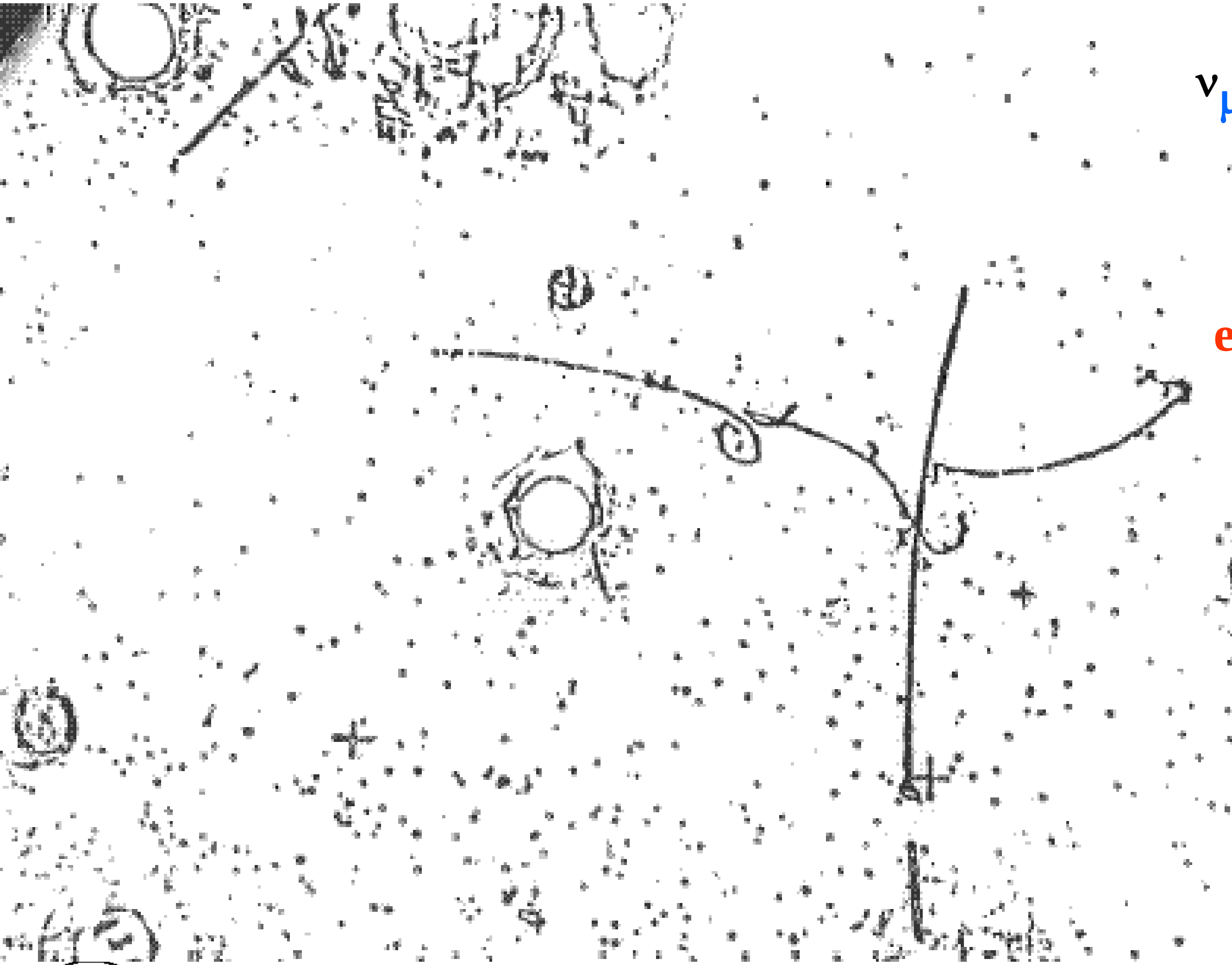
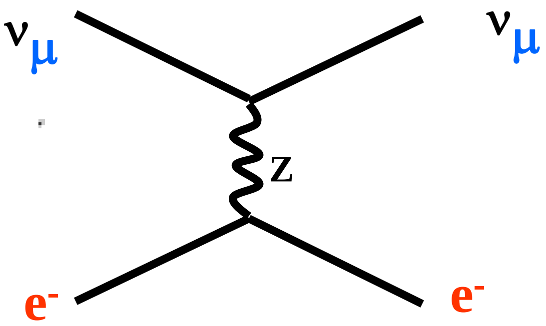
1973 Experimental birth of the Standard model



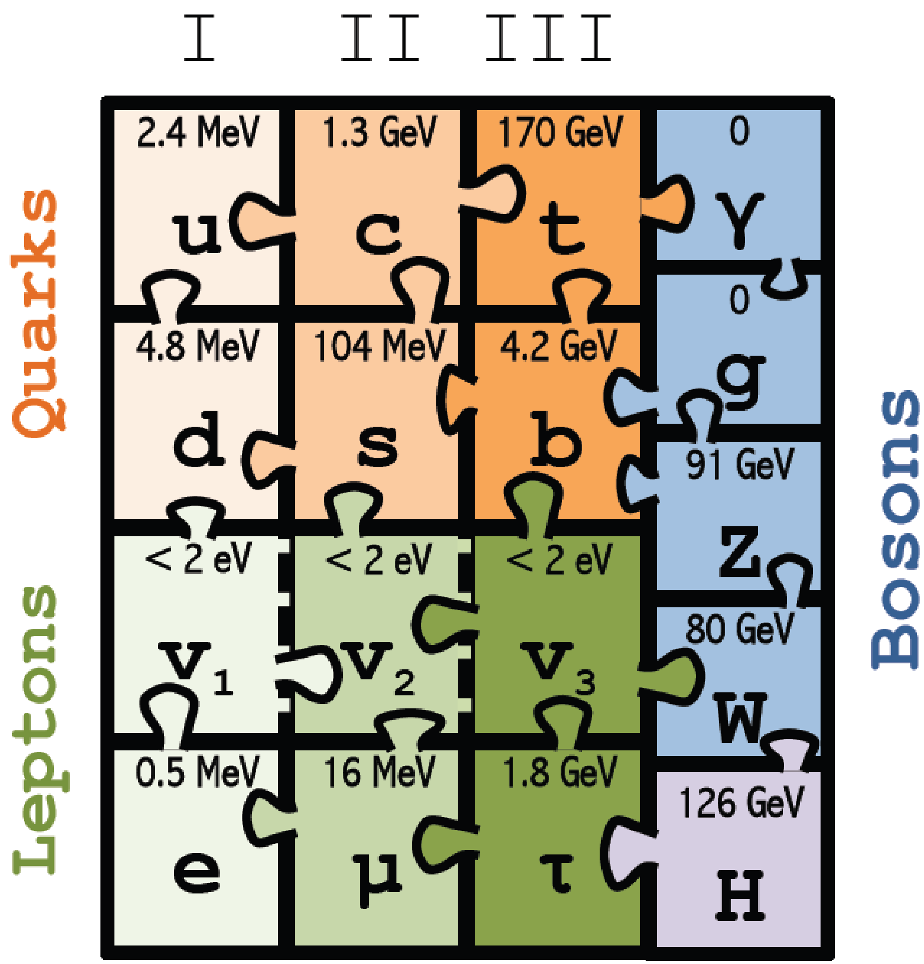


elastic scattering of neutrino off electron in the liquid

1973 Gargamelle

2012 Discovery of the Higgs boson (ATLAS, CMS)

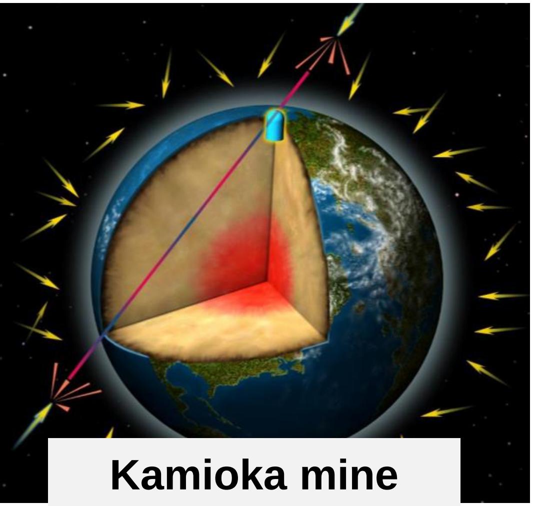
«The Standard Model is complete»



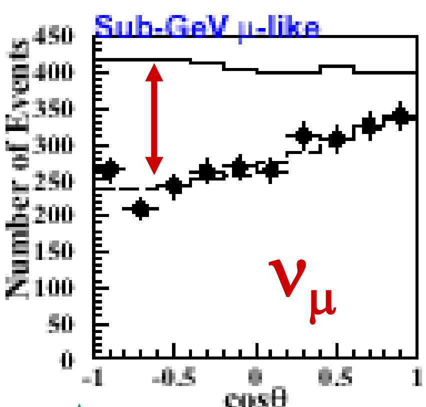
note that these are the mass eigenstates

(c) Sfyrla

Experimental birth of .. Beyond the Standard Model



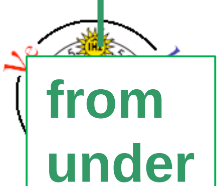
Kamioka mine detectors

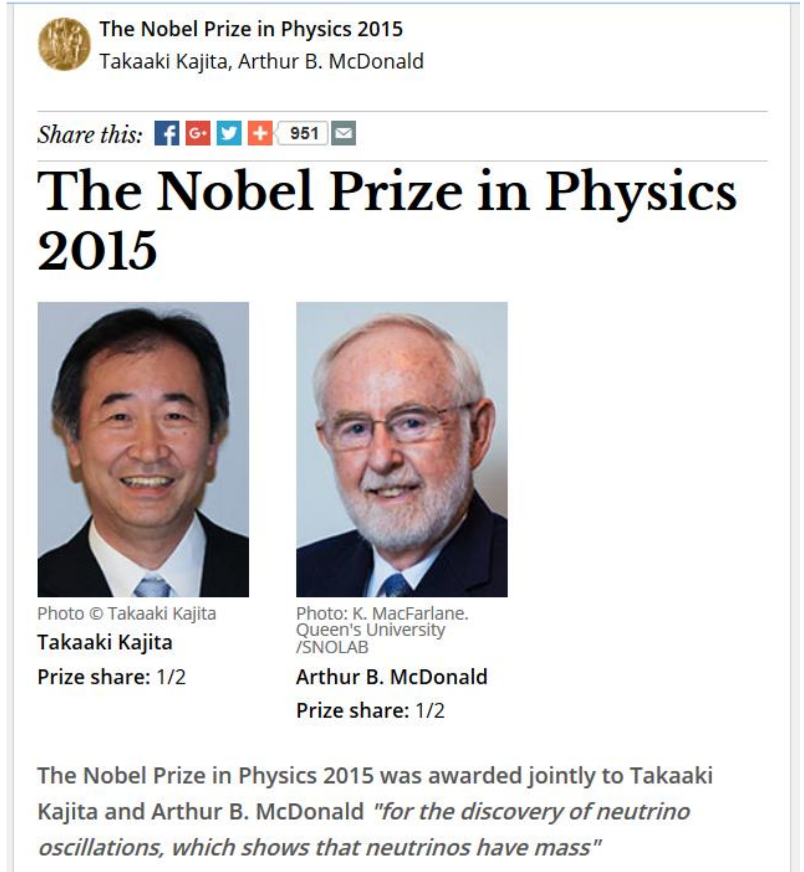


ν_μ

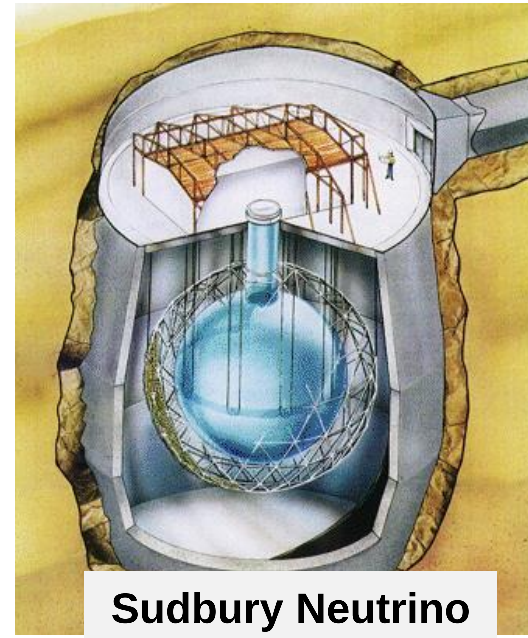
from under

from above





The discovery of neutrino oscillations shows that neutrinos have mass



Sudbury Neutrino Observatory

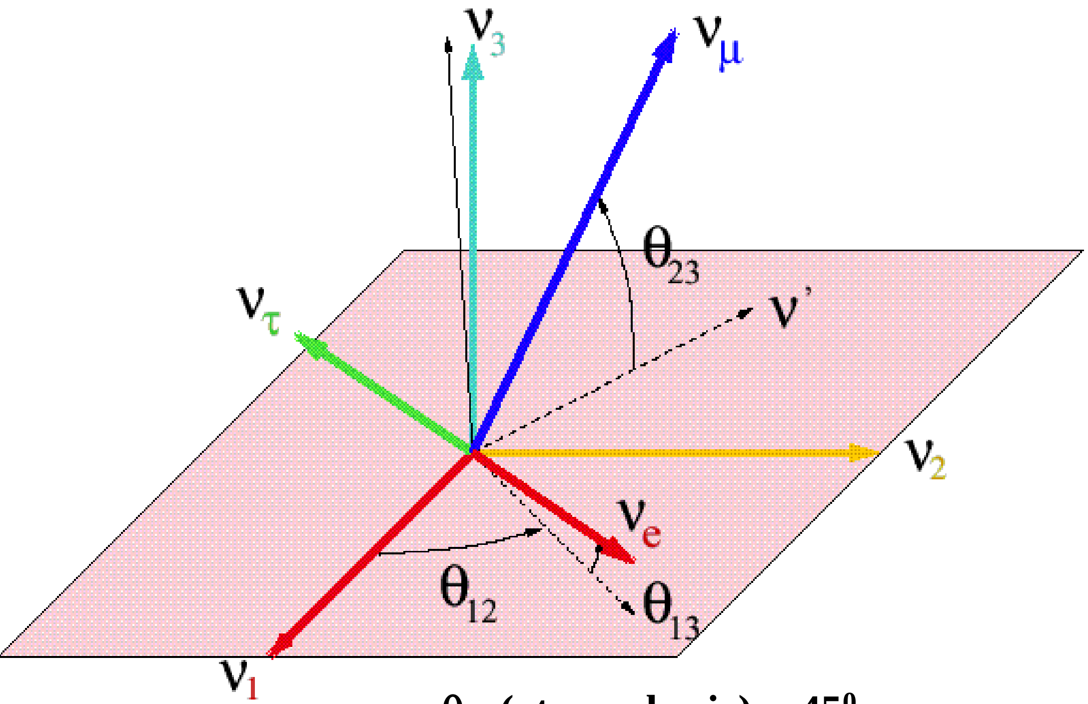
1000 ton of heavy water D_20
12 m diam. 9456 PMTs

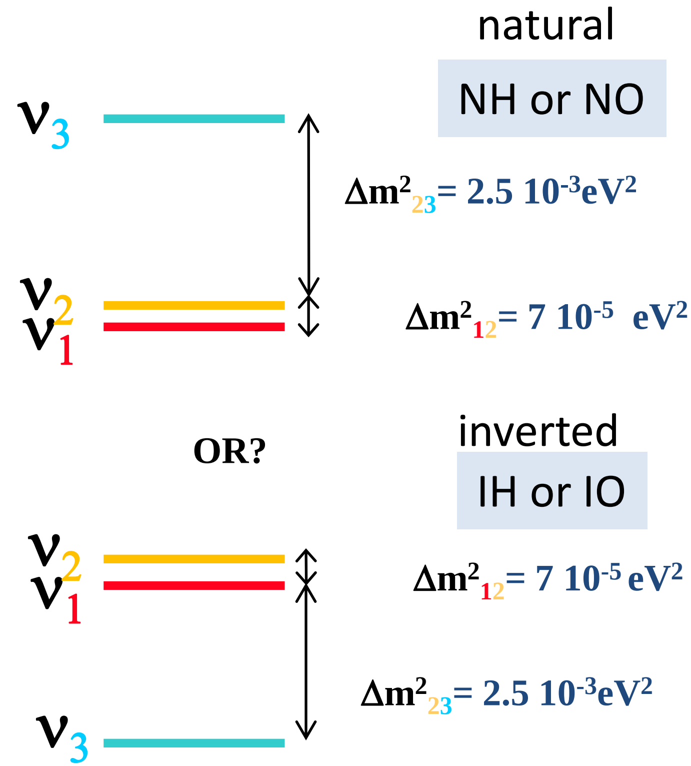
Determine that all neutrinos reach the earth but only 1/3 remain of same flavour as produced in the sun

Neutrinos having mass and mixing…..

1. → there shall be CP violation (just like in quarks)
2. → there should be right-handed neutrinos.

The neutrino mixing matrix: 3 angles and a phase δ



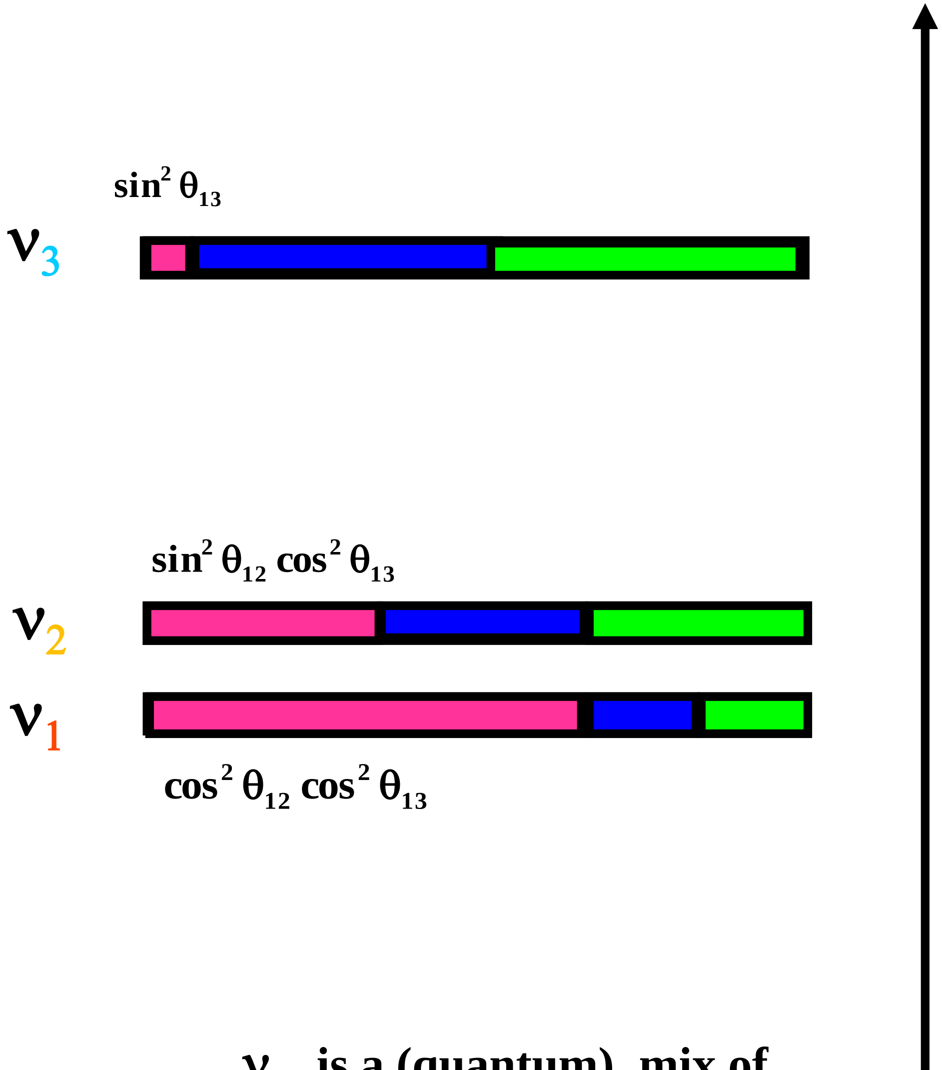


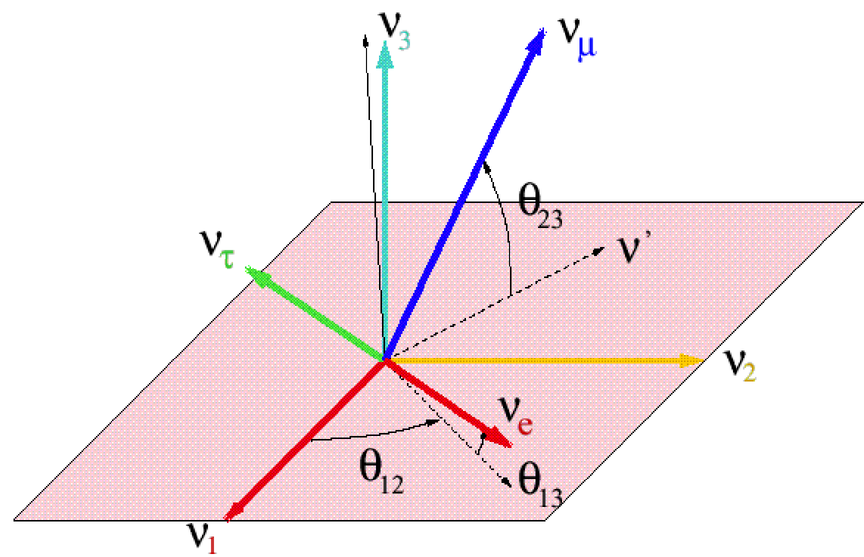
θ_{23} (atmospheric) = 45^0 ,
θ_{12} (solar) = 32^0 ,
θ_{13} (reactors) = 8.5^0

$$U_{MNS}: \begin{pmatrix} \sim \frac{\sqrt{2}}{2} & \sim -\frac{\sqrt{2}}{2} & \sin\theta_{13}\, e^{i\delta} \\ \sim \frac{1}{2} & \sim \frac{1}{2} & \sim -\frac{\sqrt{2}}{2} \\ \sim \frac{1}{2} & \sim \frac{1}{2} & \sim \frac{\sqrt{2}}{2} \end{pmatrix}$$

Unknown or poorly known today:
$\sin^2\theta_{23}$, phase δ, sign of Δm^2_{23}

neutrino mixing (natural hierarchy NH -- or Natural Ordering NO)





$$U_{MNS}: \begin{pmatrix} \sim \frac{\sqrt{2}}{2} & \sim -\frac{\sqrt{2}}{2} & \sin\theta_{13}\, e^{i\delta} \\ \sim \frac{1}{2} & \sim \frac{1}{2} & \sim -\frac{\sqrt{2}}{2} \\ \sim \frac{1}{2} & \sim \frac{1}{2} & \sim \frac{\sqrt{2}}{2} \end{pmatrix}$$

ν_e is a (quantum) mix of

ν_1 (majority, 65%) and ν_2 (minority 30%)

with a small admixture of ν_3 (2.5%)

The situation today

1. We know that there are three families of active, light neutrinos *(LEP, $N_\nu = 2.992 \pm 0.008$)*
2. Solar neutrino oscillations are established *(Homestake+Gallium+Kam+SK+SNO)*
3. Atmospheric neutrino ($\nu_\mu \rightarrow \nu_\mu$, $\nu_\mu \rightarrow \nu_\tau$) oscillations are established *(IMB+Kam+SK+OPERA)*
4. At that frequency, ($\nu_\mu \rightarrow \nu_e$) oscillations have been discovered (T2K)
   and ν_e disappearance has been measured (Daya Bay, Reno, Double Chooz)

This allows a consistent picture with 3-family oscillations

[solar: θ_{12} ~30^0 , $\Delta m_{12}^2 = 7.10^{-5} eV^2$] [atmo: θ_{23} ~45^0 , $\Delta m_{23}{}^2 = \pm 2.5\ 10^{-3} eV^2$] $\theta_{13} = 8^0$
phase δ_{CP} unknown (weakly constrained)

=> experimental program for at least 20 years *) towards mass hierarchy (is $<m_{\nu e}> \ > <m_{\nu\mu,\tau}>$?)
and leptonic CP & T violations

5. Various weak signals might be interpreted as hints of further (right-handed /'sterile') neutrinos
   -- eV region (LSND, Miniboone, reactor anomaly) oscillations
   -- 3.5 keV photons signals as $N \rightarrow \nu\,\gamma$ from galactic centers
   and if confirmed require 'beyond PMNS' physics

*)to set the scale: CP violation in quarks was discovered in 1964
and there is still an important program (K0pi0, B-factories, Neutron EDM, LHCb, NA62…)
to go on for many years…i.e. a total of >60 yrs.
and we have not discovered leptonic CP yet!

1. Towards CP violation

Oscillation maximum $1.27\ \Delta m^2\ L / E = \pi/2$

Atmospheric $\Delta m^2 = 2.5\ 10^{-3}\ eV^2$ $L = 500$ km @ 1 GeV
Solar $\Delta m^2 = 7\ 10^{-5}\ eV^2$ $L = 18000$km @ 1 GeV

Consequences of 3-family oscillations:

I There will be $\nu_\mu \leftrightarrow \nu_e$ oscillation at L_{atm}
(discovered by T2K)

$$P(\nu_\mu \leftrightarrow \nu_e)_{max} =\sim \tfrac{1}{2} \sin^2 2\theta_{13} + \ldots \text{(small)}$$

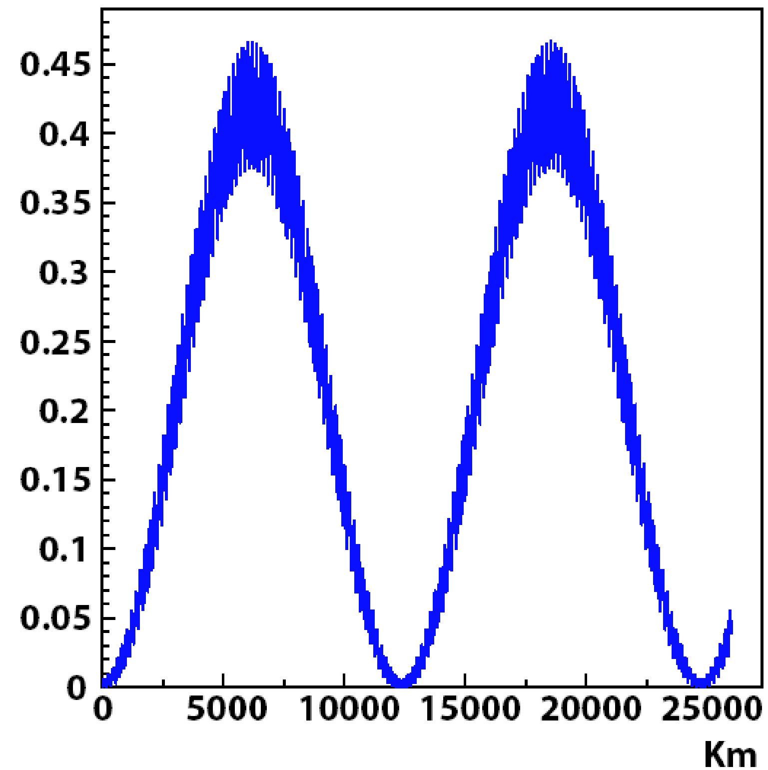
II There will be CP violation

CP: $P(\bar{\nu}_\mu \leftrightarrow \bar{\nu}_e) \neq P(\nu_\mu \leftrightarrow \nu_e)$

III we do not know if the neutrino ν_1 which contains more ν_e is
the lightest one (natural?)
or not (inverted)

Oscillations of 250 MeV neutrinos;

$P(\nu_\mu \leftrightarrow \nu_e)$



Three family oscillations and $\nu_\mu \rightarrow \nu_e$ oscillation

Mezzetto

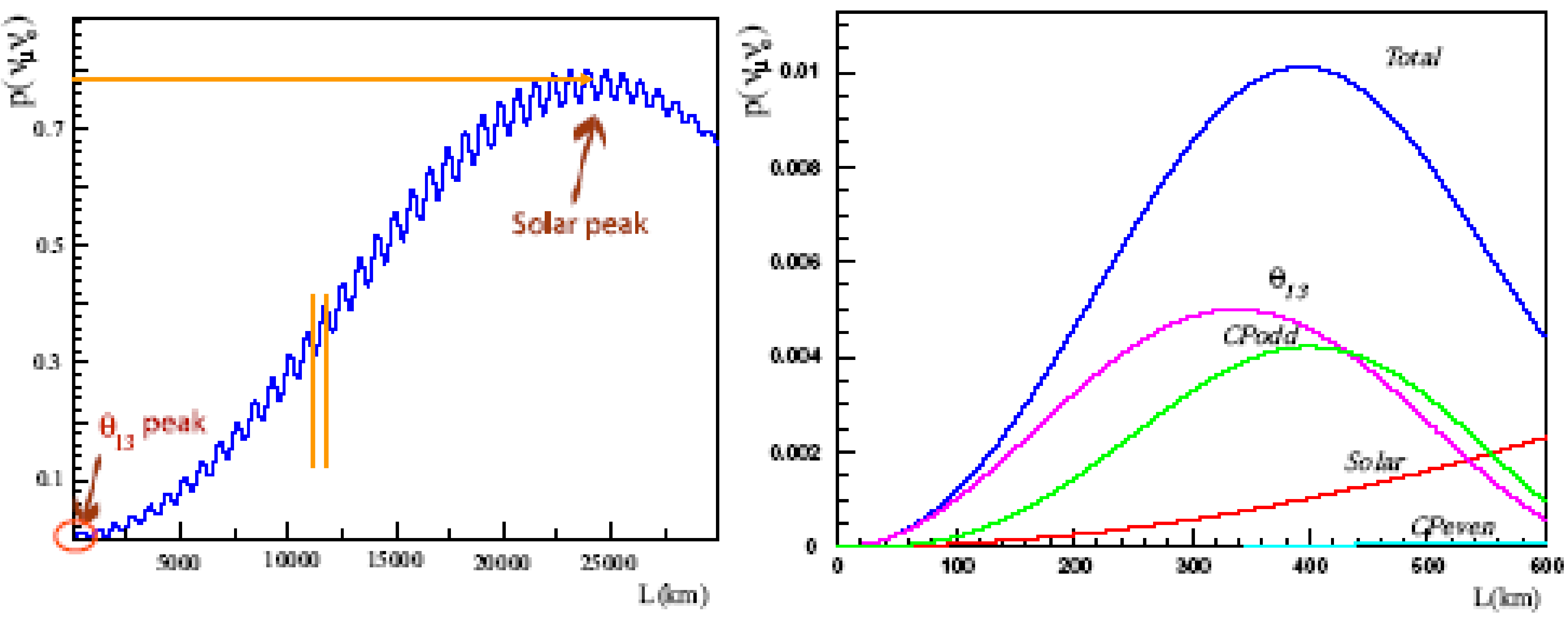


Figure 3: Sketch of $P(\nu_\mu \rightarrow \nu_e)$ as function of the baseline computed for monochromatic neutrinos of 1 GeV in the solar baseline regime for δ_{CP} =0 (left) and in the atmospheric baseline regime for $\delta_{CP} = -\pi/2$ (right), where the different terms of eq. 4 are displayed. The following oscillation parameters were used in both cases: $\sin^2 2\theta_{13} = 0.01$, $\sin^2 2\theta_{12} = 0.8$, $\Delta m^2_{23} = 2.5{\cdot}10^{-3}$ eV^2, $\Delta m^2_{12} = 7{\cdot}10^{-5}$ eV^2.

$$P(\nu_e \to \nu_\mu) = |A|^2 + |S|^2 + 2\,A\,S\ \sin\delta$$

$$P(\bar{\nu}_e \to \bar{\nu}_\mu) = |A|^2 + |S|^2 - 2\,A\,S\ \sin\delta$$

$$\frac{P(\nu_e \to \nu_\mu) - P(\bar{\nu}_e \to \bar{\nu}_\mu)}{P(\nu_e \to \nu_\mu) + P(\bar{\nu}_e \to \bar{\nu}_\mu)} = A_{CP}\ \alpha\ \frac{\sin\delta\ \ \sin(\Delta m^2_{12}\, L/4E)\ \ \sin\theta_{12}\sin\theta_{13}}{\sin^2 2\theta_{13} + \text{solar term}\ldots}$$

… need large values of $\sin\theta_{12}$, Δm^2_{12} (LMA) but *not* large $\sin^2\theta_{13}$

… need APPEARANCE … $P(\nu_e \to \nu_e)$ is time reversal symmetric (reactors or sun are out)

… can be large (30%) for suppressed channel (one small angle vs two large)

… at wavelength at which 'solar' = 'atmospheric' and for $\nu_e \to \nu_\mu$, ν_τ

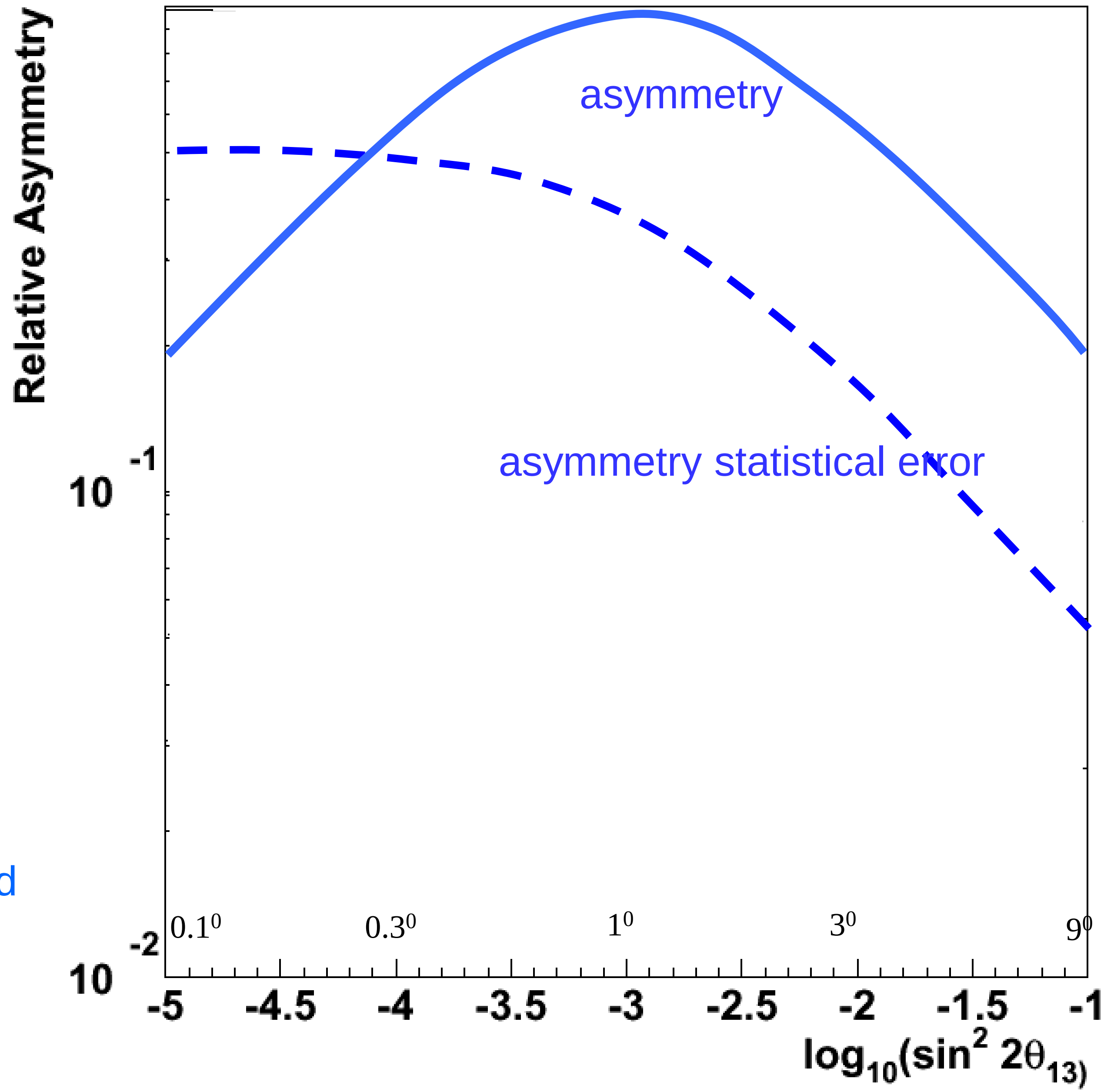
… asymmetry is opposite for $\nu_e \to \nu_\mu$ and $\nu_e \to \nu_\tau$

!

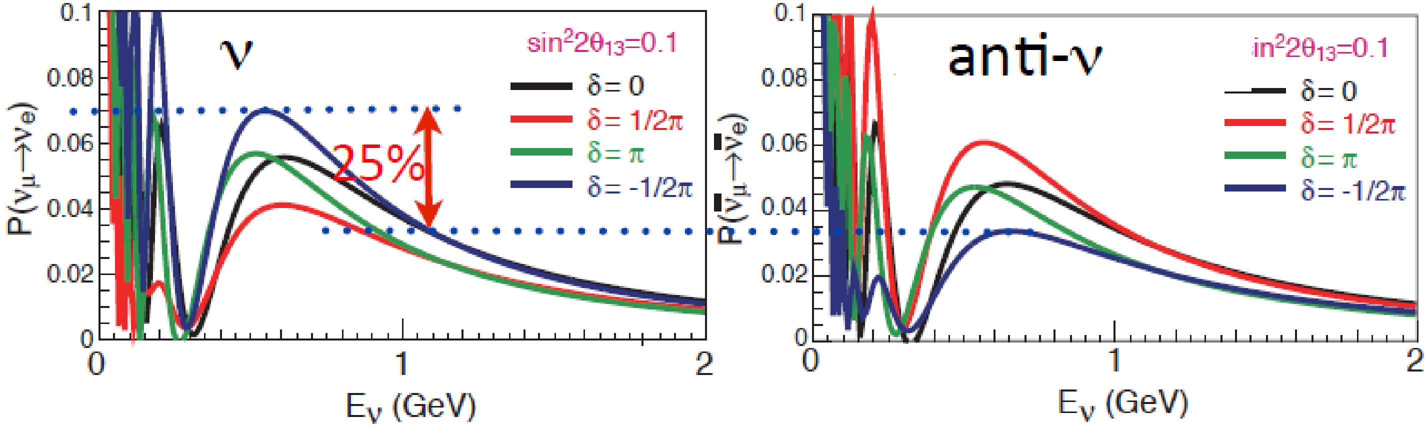
large θ_{13} → asymmetry is a few % and requires excellent flux normalization (neutrino fact., beta beam or excellent near/far detector

NOTE:
This is at first maximum!
Sensitivity at low values of θ_{13} is better for short baselines, sensitivity at large values of θ_{13} may be better for longer baselines (2d max or 3d max.)

T asymmetry for sin δ = 1



ν_e appearance



for $P(\bar{\nu}_\mu \to \bar{\nu}_e)$

- $\delta \to -\delta$
- $a \to -a$

$P(\nu_\mu \to \nu_e) =$

$$4c_{13}^2 s_{13}^2 s_{23}^2 \sin^2\frac{\Delta m_{13}^2 L}{4E}\left(1+\frac{2a}{\Delta m_{13}^2}\left(1-2s_{13}^2\right)\right)$$

θ_{13}(Leading term)

$$+8c_{13}^2 s_{12}s_{13}s_{23}\left(c_{12}c_{23}\cos\delta - s_{12}s_{13}s_{23}\right)\cos\frac{\Delta m_{23}^2 L}{4E}\sin\frac{\Delta m_{13}^2 L}{4E}\sin\frac{\Delta m_{21}^2 L}{4E}$$

CPC

$$-8c_{13}^2 c_{12}c_{23}s_{12}s_{13}s_{23}\sin\delta\sin\frac{\Delta m_{23}^2 L}{4E}\sin\frac{\Delta m_{13}^2 L}{4E}\sin\frac{\Delta m_{21}^2 L}{4E}$$

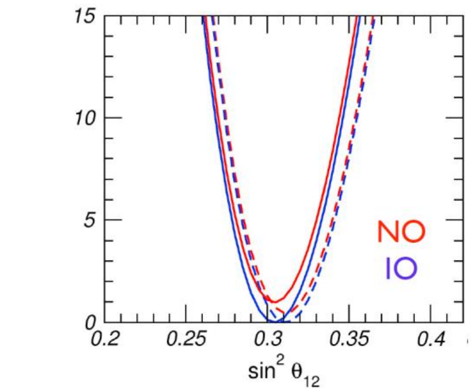
CPV

$$+4s_{12}^2 c_{13}^2\left(c_{12}^2 c_{23}^2 + s_{12}^2 s_{23}^2 s_{13}^2 - 2c_{12}c_{23}s_{12}s_{23}s_{13}\cos\delta\right)\sin\frac{\Delta m_{21}^2 L}{4E}$$

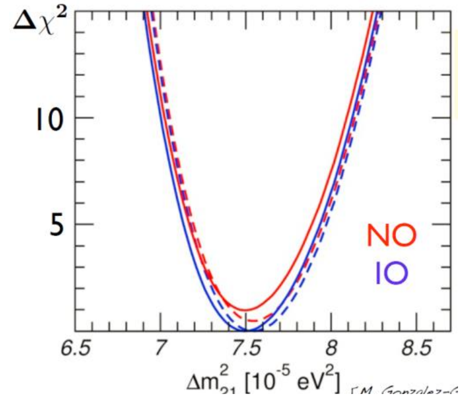
Solar

$$-8c_{13}^2 s_{13}^2 s_{23}^2\cos\frac{\Delta m_{23}^2 L}{4E}\sin\frac{\Delta m_{13}^2 L}{4E}\frac{aL}{4E}\left(1-2s_{13}^2\right)$$

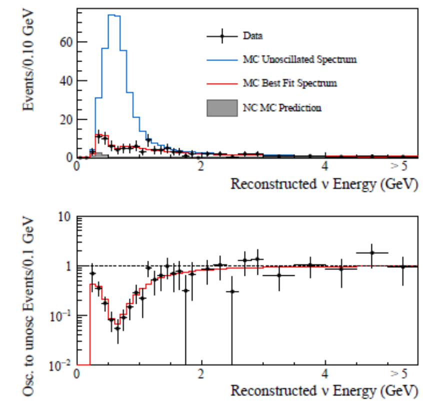
Matter effect



$$\mathbf{0.304 \pm 0.013}$$

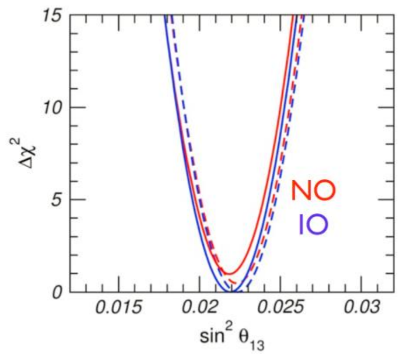


$$(\mathbf{7.50 \pm 0.19}) \times \mathbf{10^{-5}}\mathrm{eV}^2$$

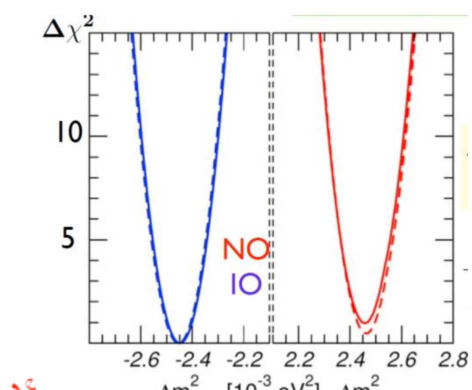


$P(\nu_\mu \rightarrow \nu_\mu) \approx 1 - \sin^2(\mathbf{2}\theta_{23}) \sin^2(\Delta m^2_{23}L/4E)$

Maximum for θ_{23}= 45°

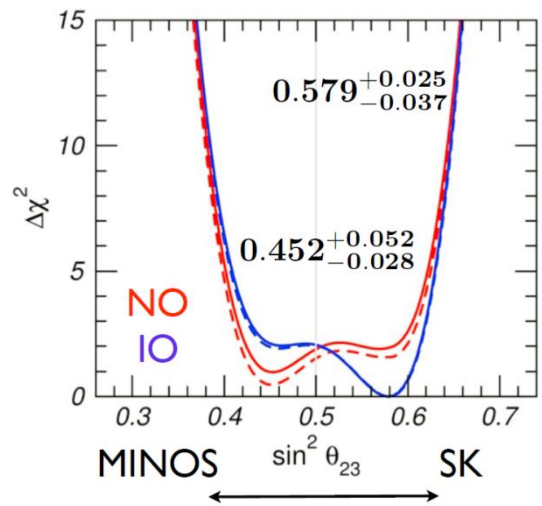


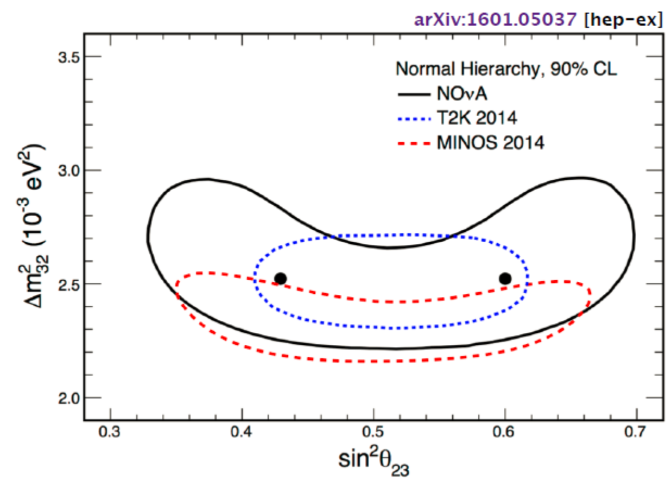
$$\mathbf{0.0218 \pm 0.0010}$$



$$+(\mathbf{2.457 \pm 0.047}) \times \mathbf{10^{-3}}\mathrm{eV}^2$$

$$-(\mathbf{2.449 \pm 0.047}) \times \mathbf{10^{-3}}\mathrm{eV}^2$$





disappearance nearly complete: $\sin^2(2\theta_{23})$ ~1

large error on θ_{23} , two solutions near θ_{23}= 45°

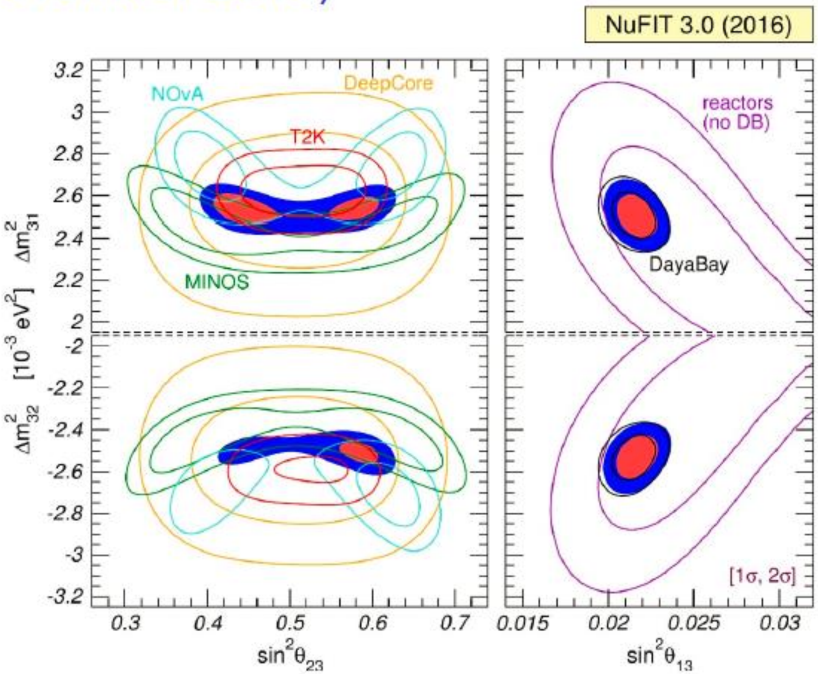
[M. Gonzalez-Garcia et al. arXiv:1409.5439 arXiv:1507.04366]

Status of MNSP oscillation parameters (November 2016)

M. C. Gonzalez-Garcia, M. Maltoni, J. Salvado, T. Schwetz
1512.06856 www.nu-fit.org

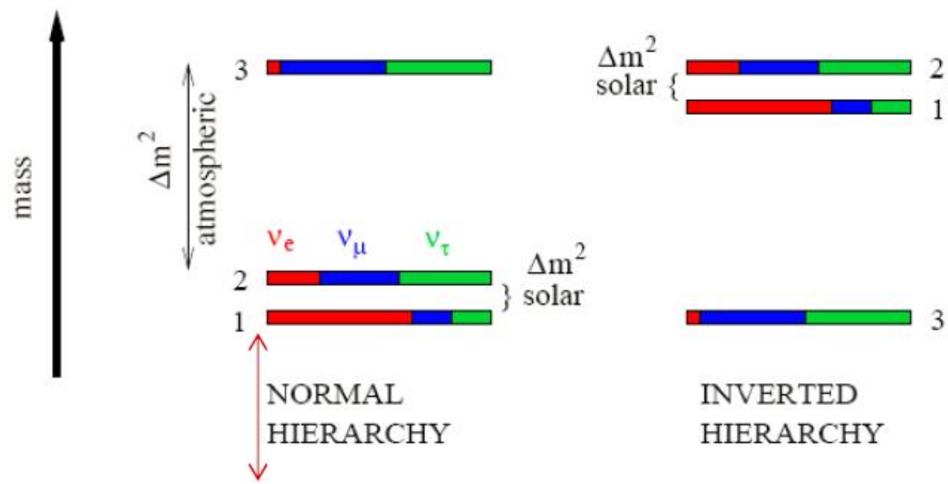
		3σ range
$\sin^2\theta_{12}$	0.306	[0.271 – 0.345]
$\sin^2\theta_{23}$	0.441	[0.385 – 0.638]
$\sin^2\theta_{13}$	0.02166	[0.01934 – 0.02397]

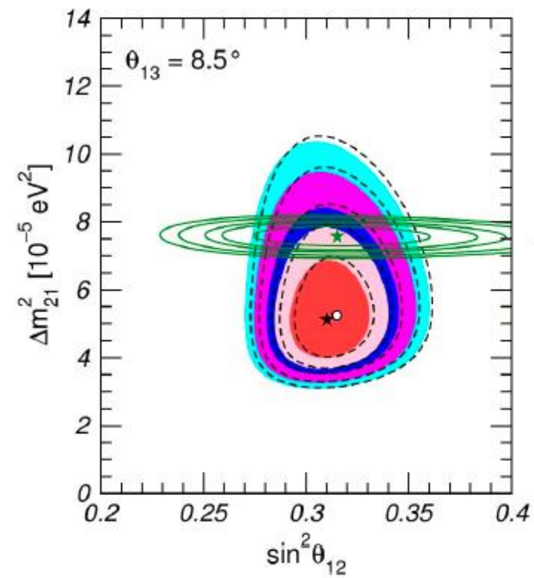
$\delta_{cp} = [-3.13, -0.39](NH), [-2.09, -0.74]\ (IH)$ at 90% CL



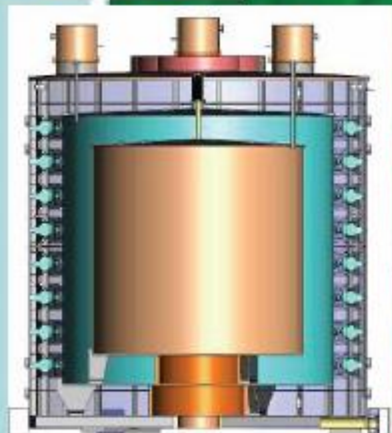
And oscillation measurements give acces to:

Δm^2_{21}	7.50 10^{-5} eV²	[7.03-8.09]
$\lvert\Delta m^2_{31}\rvert$	2.524 10^{-3} eV²	[2.407-2.643]





Daya Bay



inner volume 20 ton each

- Multiple detectors per site cross-check detector efficiency
- Two near sites sample flux from reactor groups
- Civil construction underway

	DYB	LA	Far
DYB cores	363	1347	1985
LA cores	857	481	1618
LA II cores	1307	526	1613

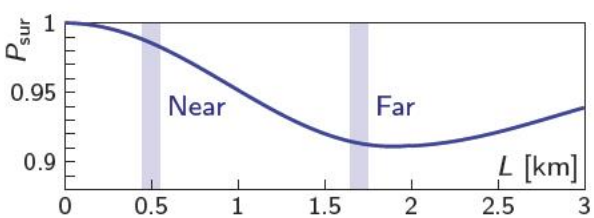
start 2010-2011
sensitivity $\sin^2 2\theta_{13} < 0.03-0.01$

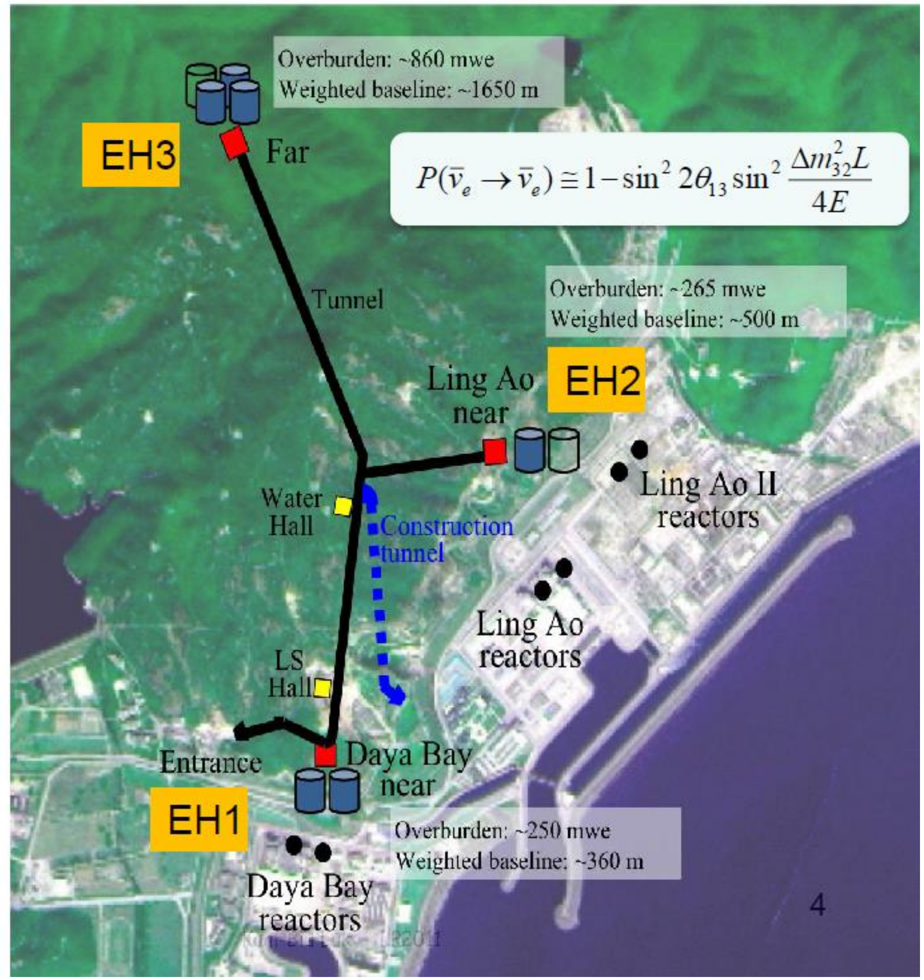
Daya Bay Experiment Layout

- 6 reactor cores, 17.6GW$_{th}$ total power
- Relative measurement
  - 2 near sites, 1 far site
- Multiple detector modules
- Good cosmic ray shielding

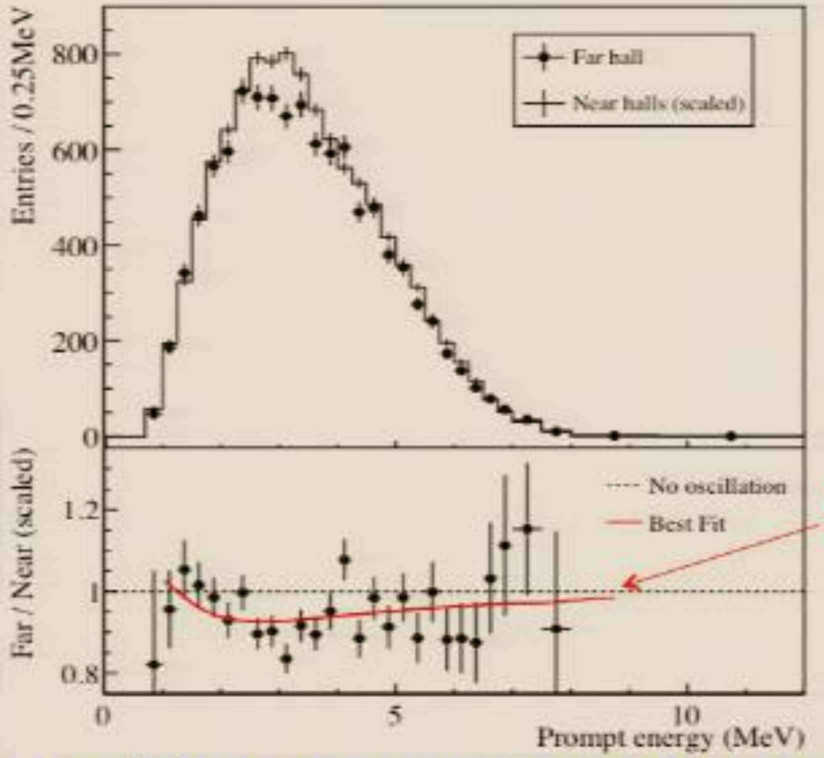
TABLE I. Vertical overburden (m.w.e.), muon rate R_μ (Hz/m^2), and average muon energy E_μ (GeV) of the three EHs, and the distances (m) to the reactor pairs.

	Overburden	R_μ	E_μ	D1,2	L1,2	L3,4
EH1	250	1.27	57	364	857	1307
EH2	265	0.95	58	1348	480	528
EH3	860	0.056	137	1912	1540	1548





Far vs. Near Comparison : Spectrum



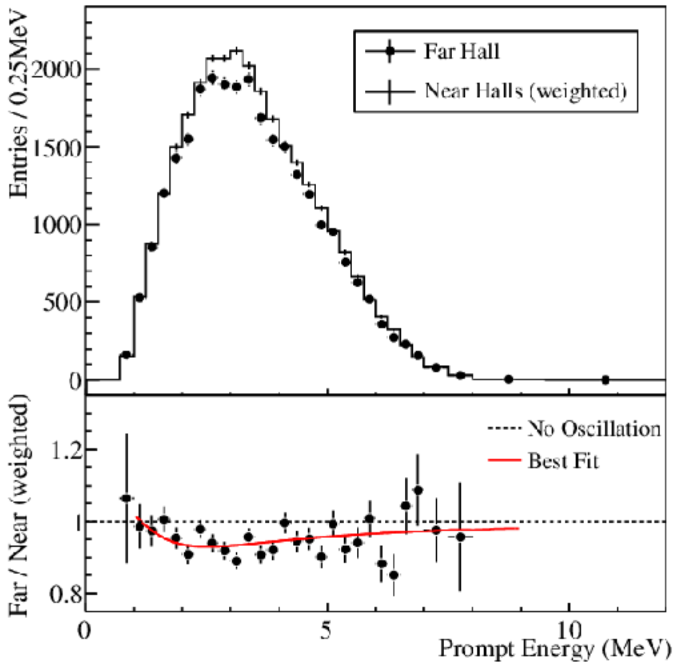
$\sin^2 2\theta_{13} = 0.092$

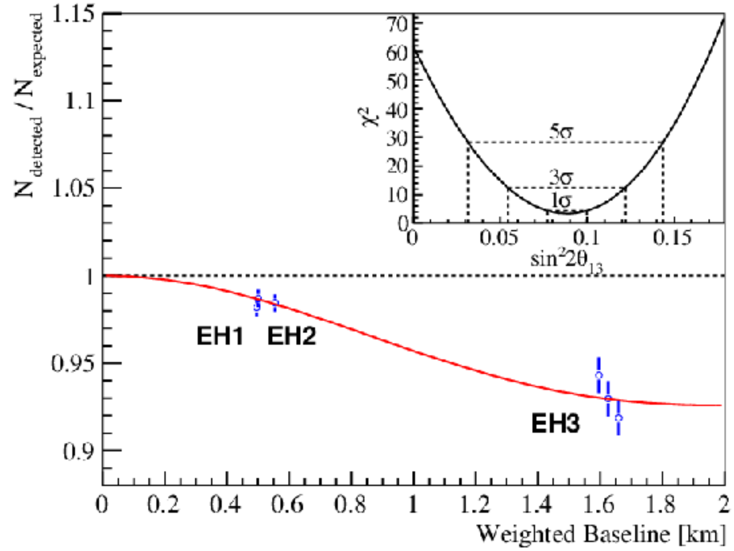
Spectral distortion consistent with oscillation.

$\sin^2 2\theta_{13} = 0.092 \pm 0.016$ (stat) ± 0.005 (syst)

$\sin^2 2\theta_{13} = 0$ excluded at 5.2σ

Anti-neutrino disappearance





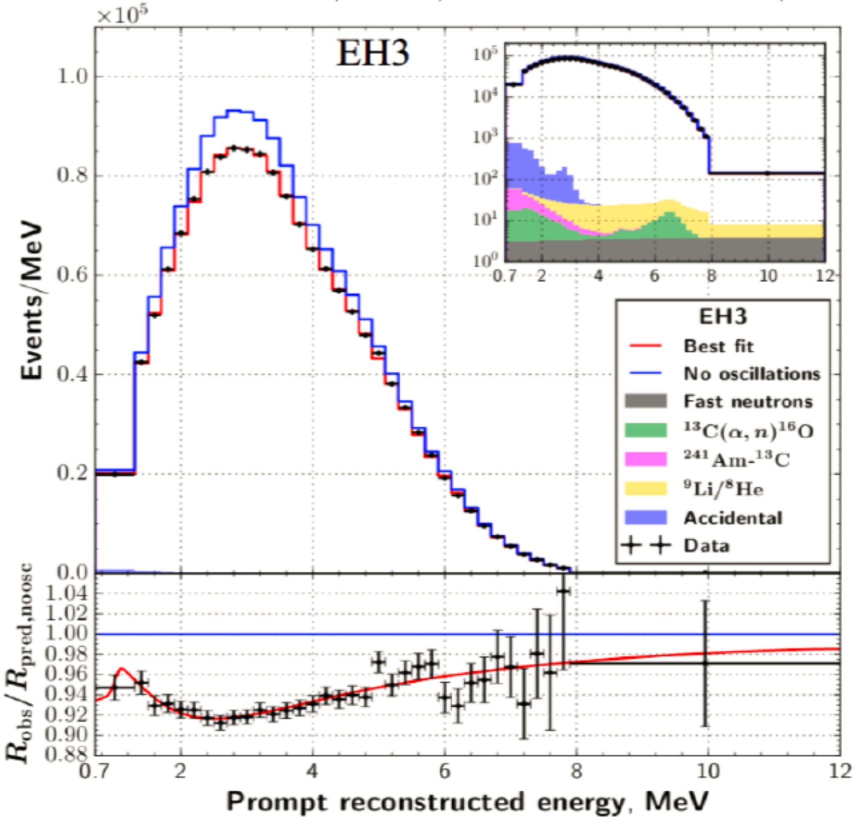
$R = 0.944 \pm 0.007$ (stat) $\pm$ 0.003 (syst)

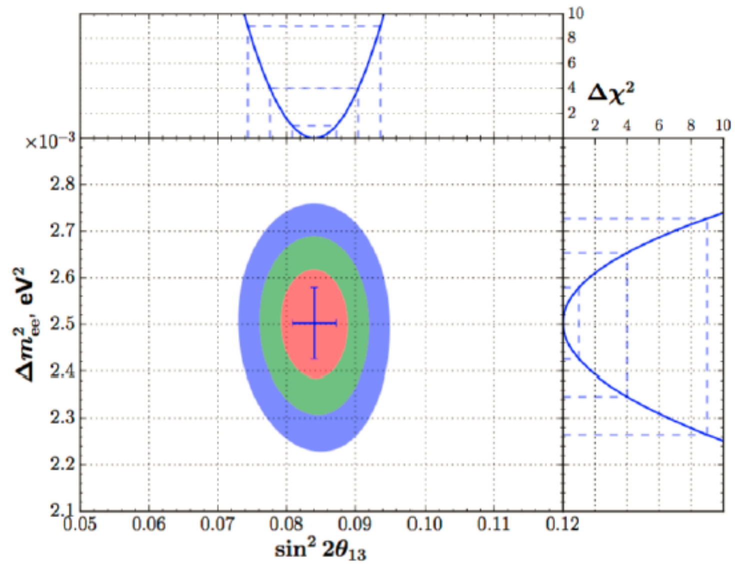
$\sin^2 2\theta_{13} = 0.089 \pm 0.010$(stat)$\pm 0.005$(syst)

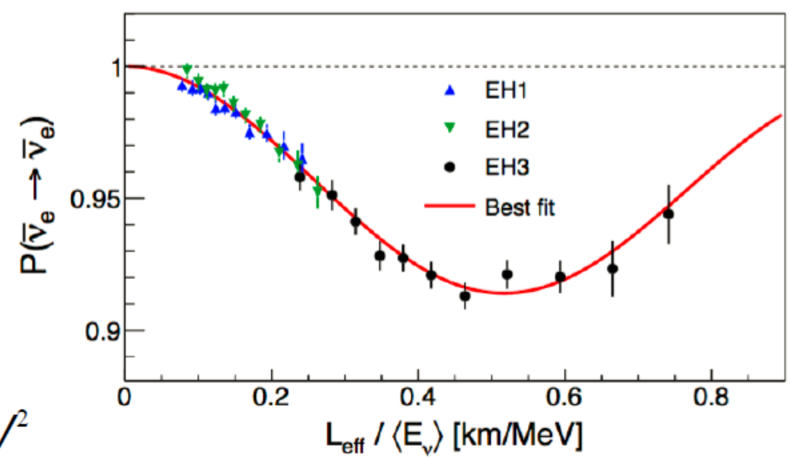
With 2.5x more statistics, an improved measured of θ_{13}

Daya Bay: the Latest Results

$$P_{ee} = 1 - \sin^2 2\theta_{13} \sin^2\left(\frac{\Delta m^2_{ee} L}{4E}\right) - \cos^4\theta_{13} \sin^2 2\theta_{12} \sin^2\left(\frac{\Delta m^2_{21} L}{4E}\right)$$





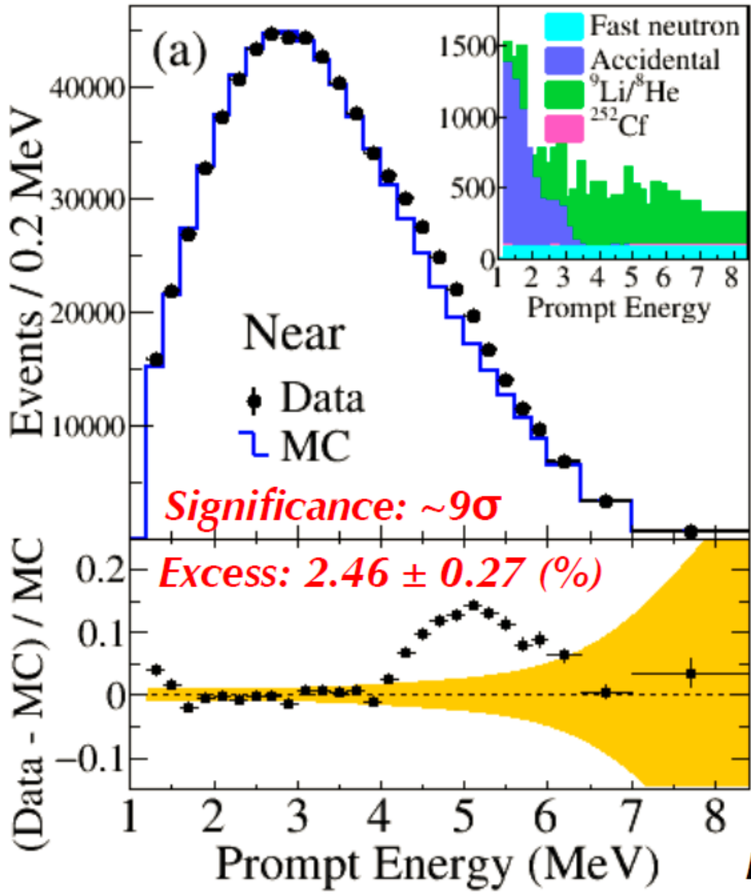


$$\sin^2 2\theta_{13} = 0.0841 \pm 0.0027(stat.) \pm 0.0019(syst.)$$

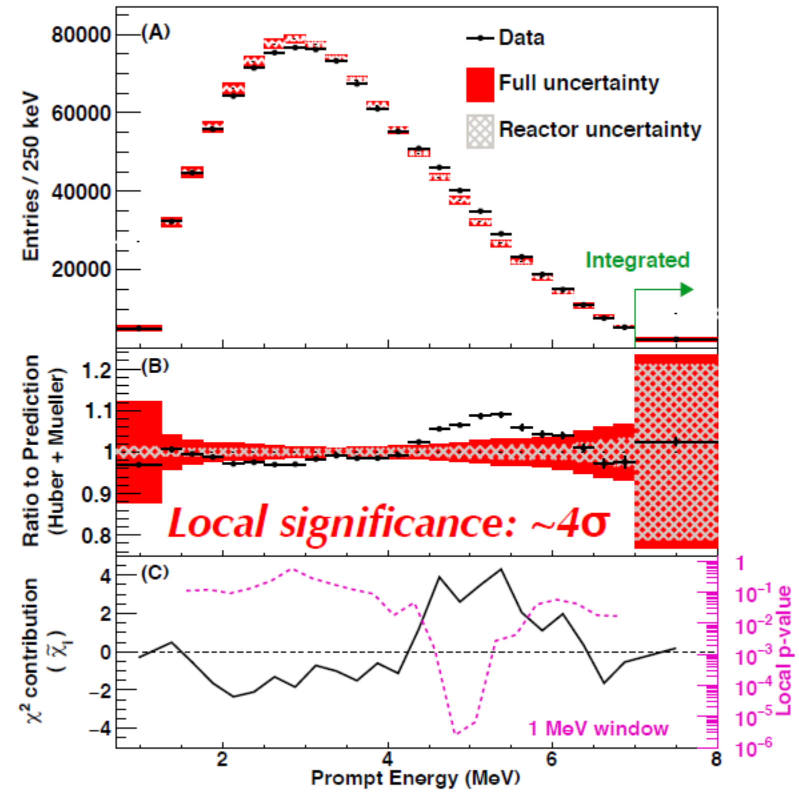
$$|\Delta m^2_{ee}| = [2.50 \pm 0.06(stat.) \pm 0.06(syst.)] \times 10^{-3}\, eV^2$$

The Reactor Flux Spectrum Discrepancy

RENO preliminary



Daya Bay CPC

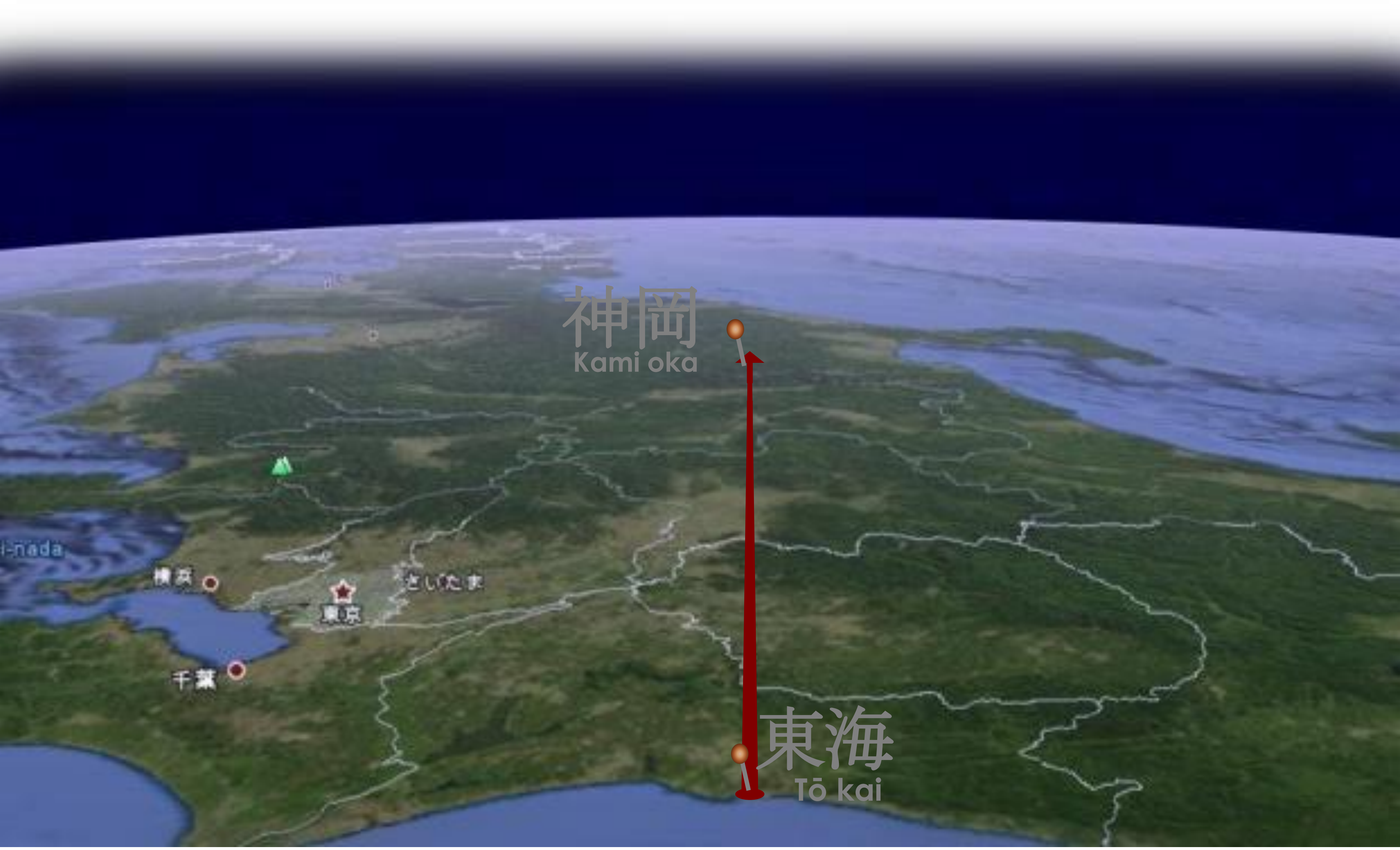


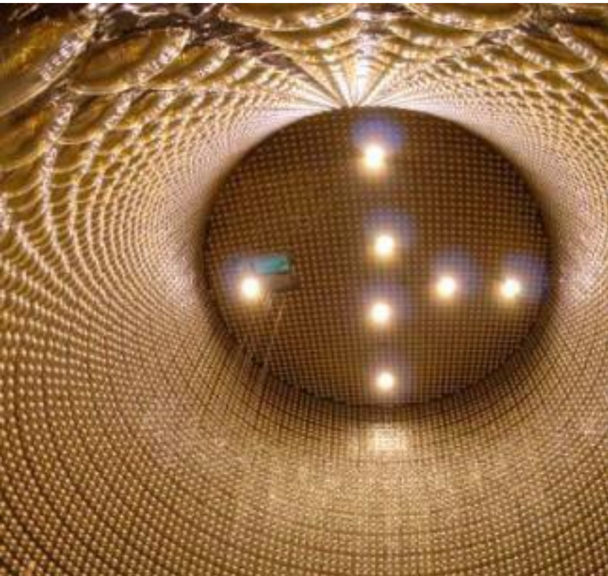
Blaming fission isotope beta decay calculation/data?

For example, see: Dwyer & Langford, PRL114 (2015)012502; Hayes et al, PRL112 (2014) 202501

reactor experiments allow investigation of reactor calculations! (and… badly off) since I am coming back from Japan...

T2K, T2K-II and HyperK



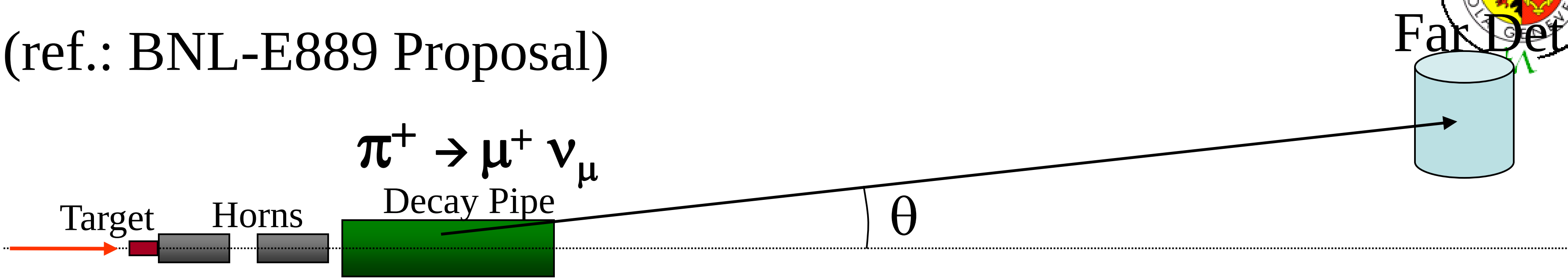


Idea of T2K was born 1999-2001 hep-ex/0106019 combining:

- **-- existing SuperKamiokande detector (50kton W.Č., 22.5 kton fiducial)**
- **-- JAERI-KEK Japanese Proton Accelerator Research Complex (JPARC) at TOKAI including a high power, 0.75MW/30GeV Proton Synchrotron neutrino beam from pion decay $\pi^+ \rightarrow \mu^+ \nu_\mu$**
- **-- baseline 295 km ➔ neutrino energy for first maximum is ~650 MeV achievable by pion-decay beam at 2.5 degrees off-axis**

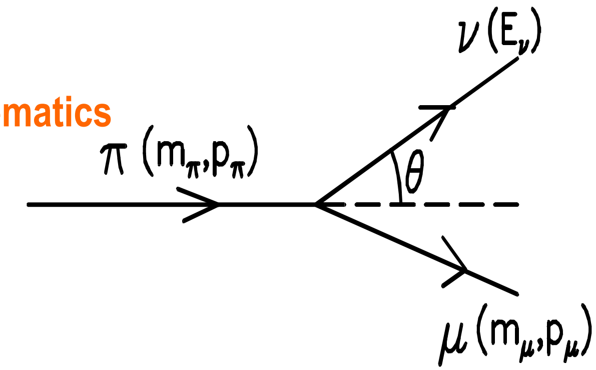
Off Axis Beam (another NBB option)

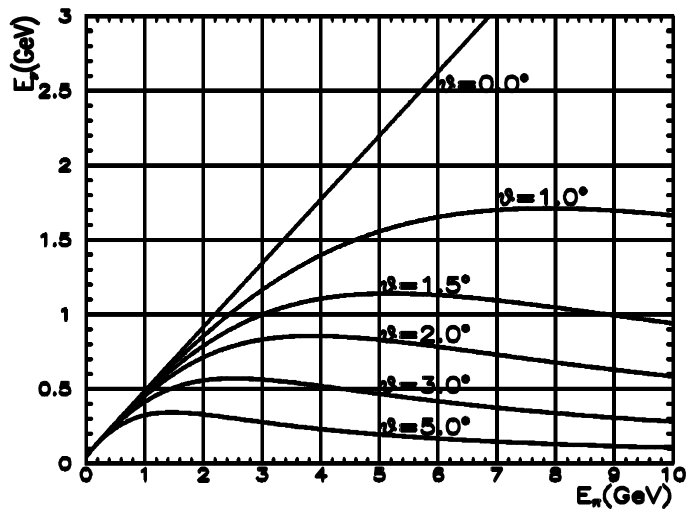
(ref.: BNL-E889 Proposal)



WBB w/ intentionally misaligned beam line from det. axis

Decay Kinematics



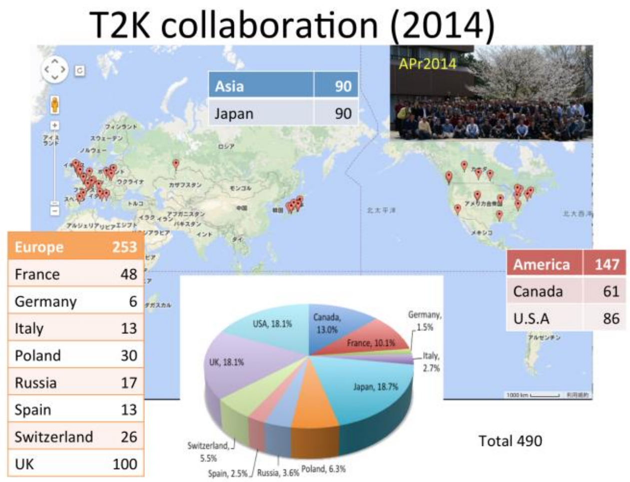


$$E_\nu = \frac{m_\pi^2 - m_\mu^2}{2(E_\pi - p_\pi \cos\theta)}$$

- Quasi Monochromatic Beam
- x2~3 intense than NBB

T2K Long Baseline Neutrino Oscillation Experiment

T2K collaboration (2014)



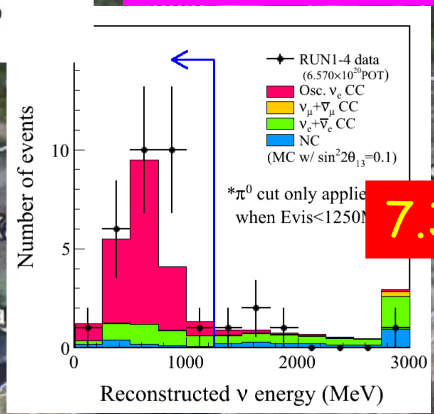
Asia	90
Japan	90

Europe	253
France	48
Germany	6
Italy	13
Poland	30
Russia	17
Spain	13
Switzerland	26
UK	100

America	147
Canada	61
U.S.A	86

$40m^{\phi}$x$40m^{H}$
50kt Water Cherenkov det.

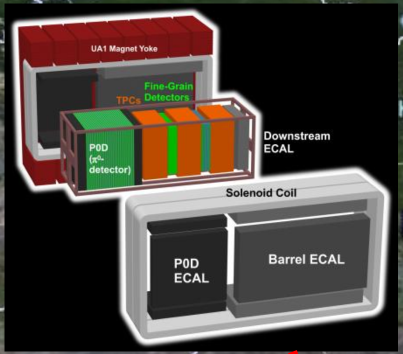
Discovery of appearance of electron neutrino



7.3σ

Muon neutrino beam
295km

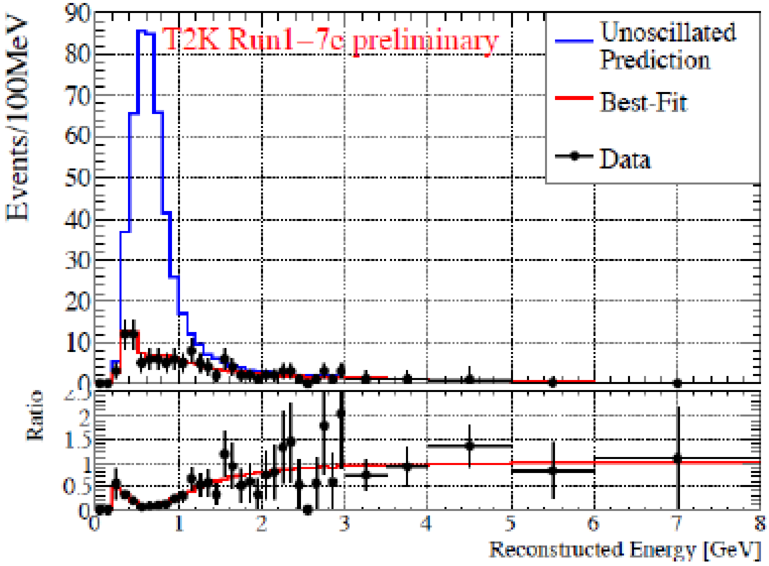
Near neutrino detect



- T2K collaboration ~500 collaborators from 59 institutions, 11 countries
- Funded in FY2004, Started measurements in 2010
- First discovery of ν_e appearance in ν_μ beam
- Best measurement of ν_μ disappearance
- Opens the door for CP violation measurements
  - Could be the key to matter in the universe!

$\nu_\mu \to \nu_\mu$ and $\overline{\nu_\mu} \to \overline{\nu_\mu}$ disappearance

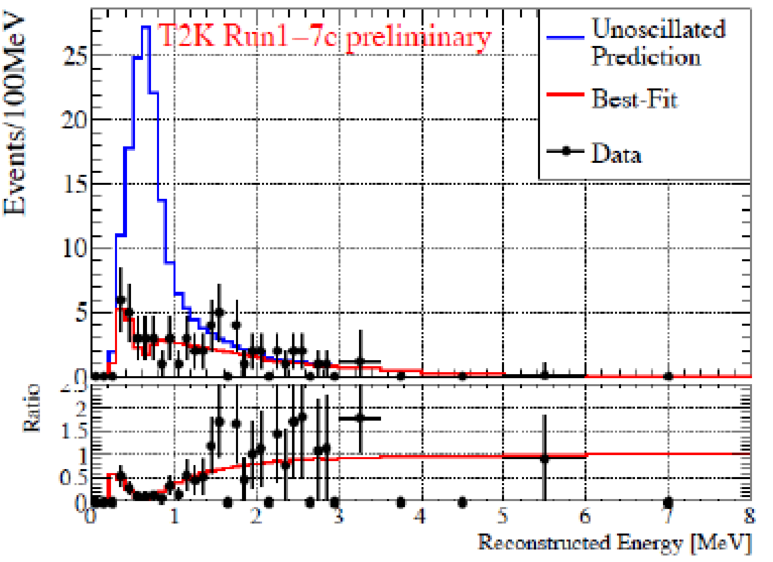
Neutrino



$$\Delta m^2_{32} = [2.34, 2.75]\times 10^{-3} eV^2 (NH) \text{ at 90\% CL}$$

$$\sin^2\theta_{23} = [0.42, 0.61] (NH) \text{ at 90\% CL}$$

Antineutrino



$$\Delta \overline{m}^2_{32} = [2.16, 3.02]\times 10^{-3} eV^2 (NH) \text{ at 90\% CL}$$

$$\sin^2\overline{\theta}_{23} = [0.32, 0.70] (NH) \text{ at 90\% CL}$$

Neutrino and antineutrino parameters are consistent

No evidence of CPT violation, NSI, etc

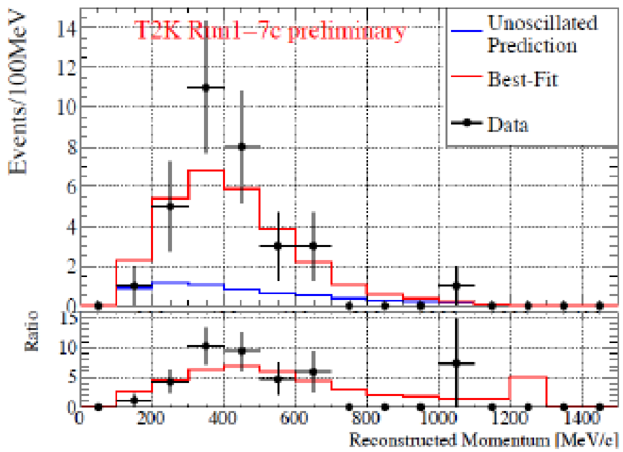
$\nu_\mu \rightarrow \nu_e$ and $\overline{\nu_\mu} \rightarrow \overline{\nu_e}$ appearance

Predictions:

ν_e: 19.6 events (NH, $\delta_{CP} = \pi/2$) to 28.7 events (NH, $\delta_{CP} = -\pi/2$)

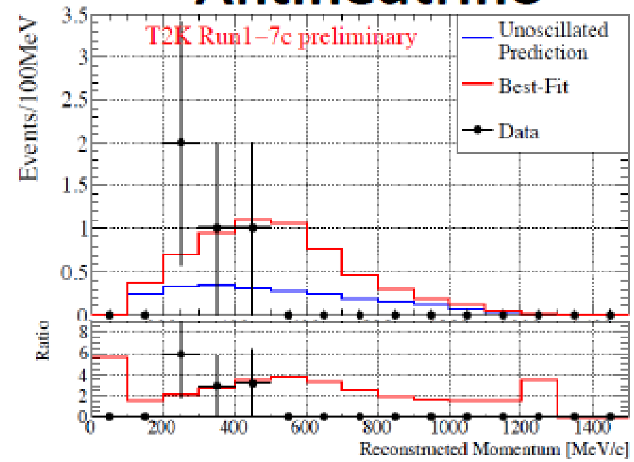
$\overline{\nu_e}$: 7.7 events (NH, $\delta_{CP} = \pi/2$) to 6.0 events (NH, $\delta_{CP} = -\pi/2$)

Neutrino



Observed 32 events

Antineutrino



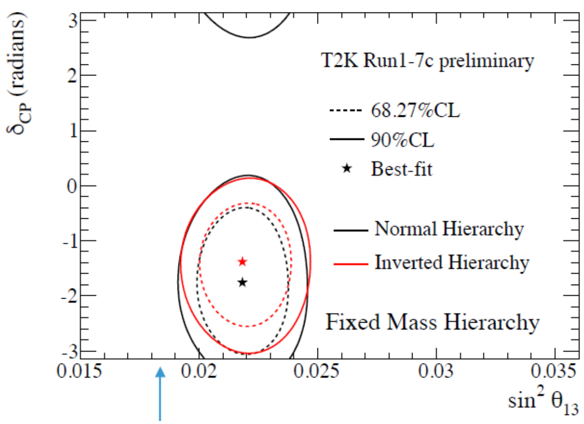
Observed 4 events

Excess of ν_e events above prediction favors NH and $\delta_{CP} = -\pi/2$ ($3\pi/2$)

Deficit of $\overline{\nu}_e$ events below prediction favors NH and $\delta_{CP} = -\pi/2$ ($3\pi/2$)

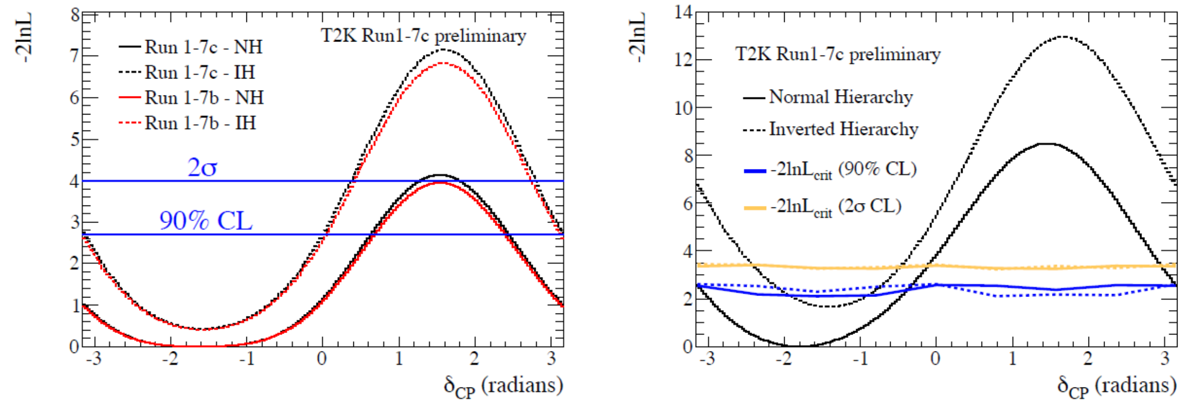
θ_{13} and δ_{cp}

T2K Result with Reactor Constraint
($sin^2 2\theta_{13} = 0.085 \pm 0.005$)



- T2K result with reactor constraint ($\sin^2 2\theta_{13} = 0.085 \pm 0.005$)

Sensitivity (Simulation) **Measurement (Data)**



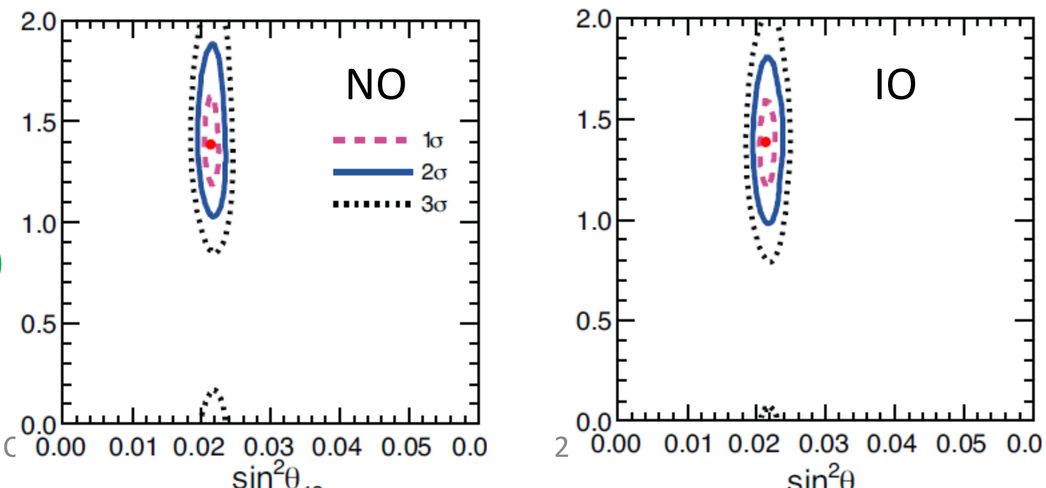
$$\delta_{cp} = [-3.13, -0.39](NH), [-2.09, -0.74]\ (IH) \text{ at } 90\% \text{ CL}$$

Similar (but less significant) effects seen in NOvA and SuperK)

➔ > 2 σ CP violation.

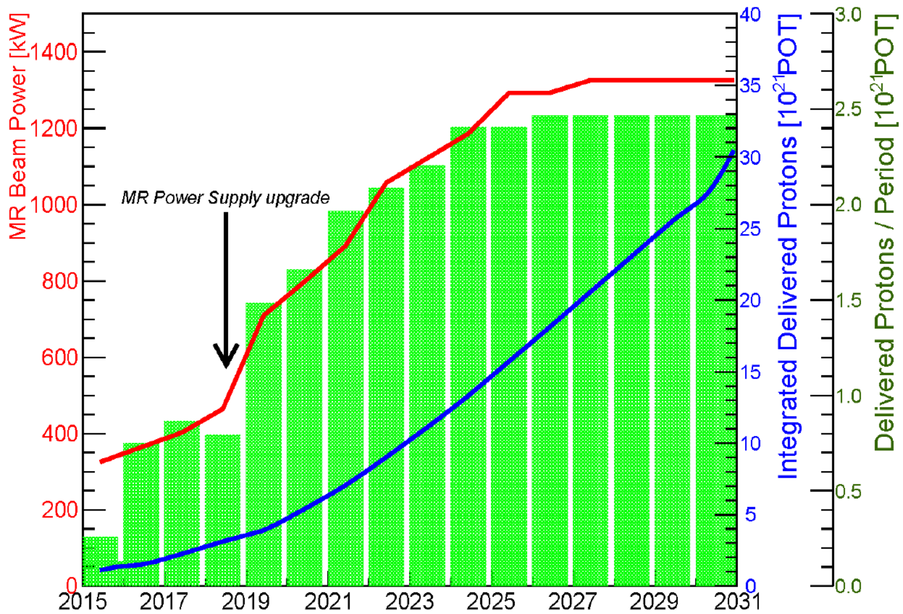
Regardless of Hierarchy

average by Marrone (neutrino2016)

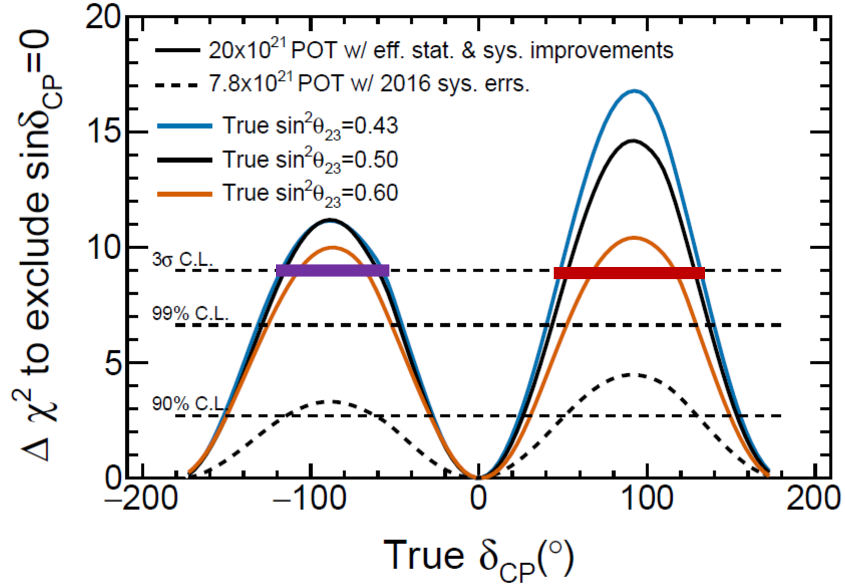


Proposal for an Extended Run of T2K to 20×10^{21} POT

«T2K-II»



Approved upgrade of T2K intensity



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

3σ over 40% of 2π

(will grow with time…)

Obviously need something bigger!

KEK Preprint 2016-21
ICRR-Report-701-2016-1

Hyper-Kamiokande

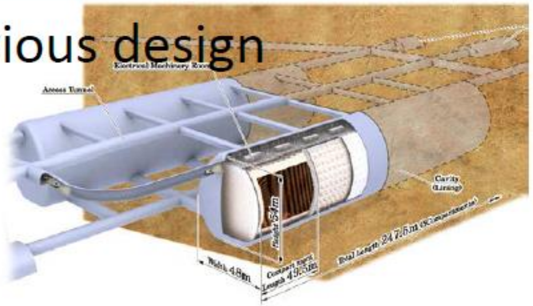
Design Report

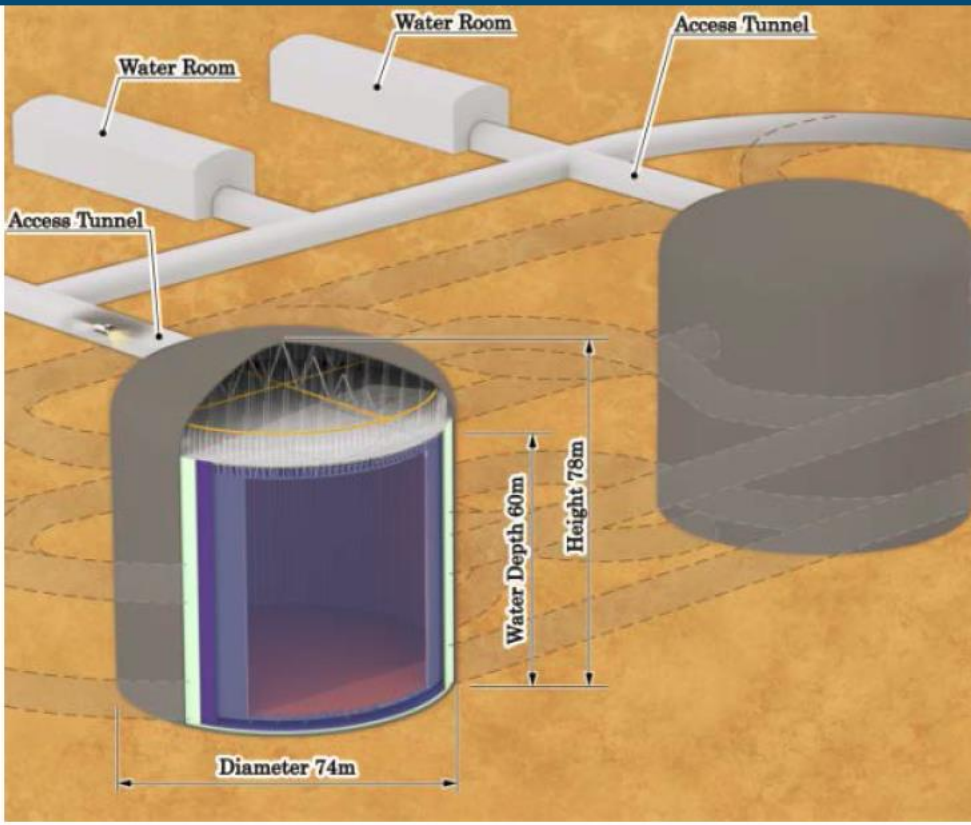
(Februry 7, 2016)

https://lib-extopc.kek.jp/preprints/PDF/2016/1627/1627021.pdf

Present design of Hyper-K

Previous design





✓Super-K-like structure

✓2 tanks with staging
(2nd tank assumed to be ready 6 years later)

✓1 tank will be;
- 60m(H)×74m(D)
- Total volume: 260 kton
- Fiducial volume(FV): 190 kton
  ~10 x Super-K FV
- PMT coverage 40%, 40,000 ID-PMT, 6,700 OD-PMT

✓ The candidate site is ~8km south of SK (2.5 degree off axis beam, L=295km)

Photosensor Improvements

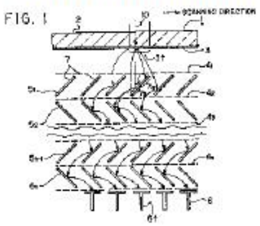
Photo Multipliers (PMTs)

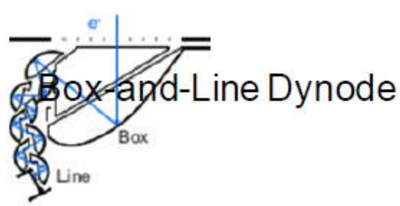
- Efficiency x 2, Timing resolution x 1/2

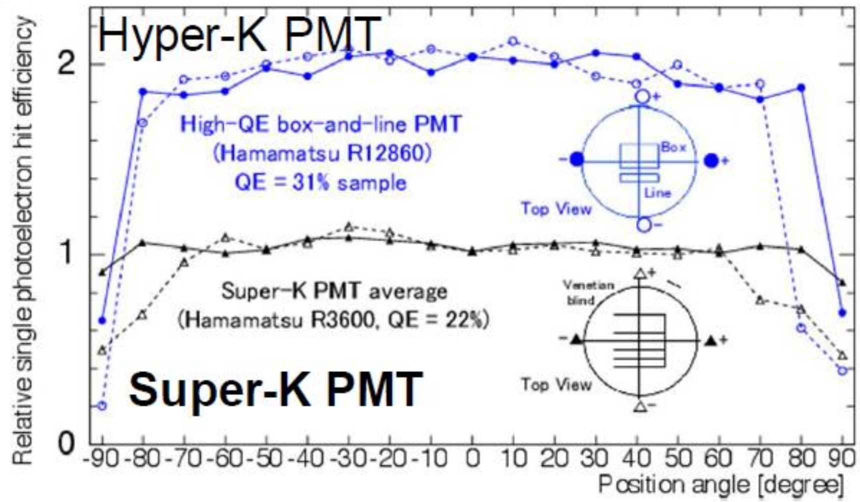
  Pressure tolerance x 2 (>100m)

  Enhance p→$\bar{\nu}K^+$ signal, solar ν, neutron signature of np→d+γ(2.2MeV),..

Venetian Blind

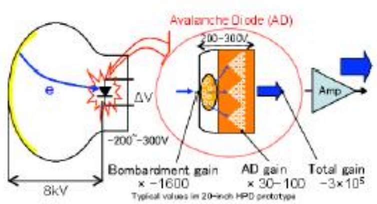






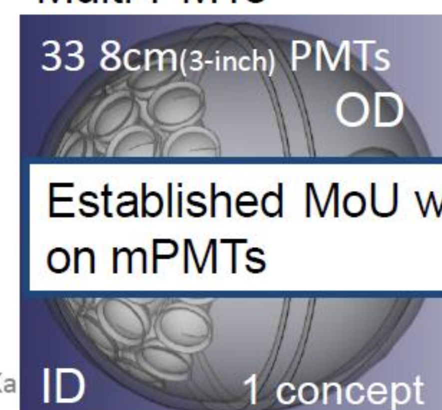
Other Developments:

Hybrid Photo Detectors (HPDs)



Under viability study

Multi-PMTs



Working concept from KM3NeT but:

- peripheral ID/OD
- ultrapure water.

International contribut.

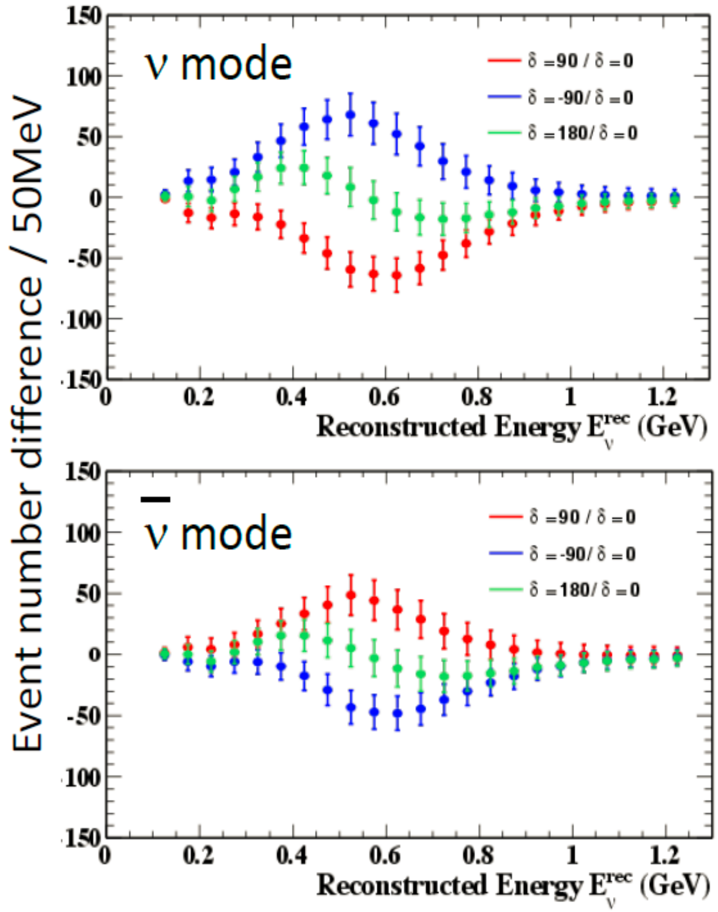
Established MoU with KM3Net to collaborate on mPMTs

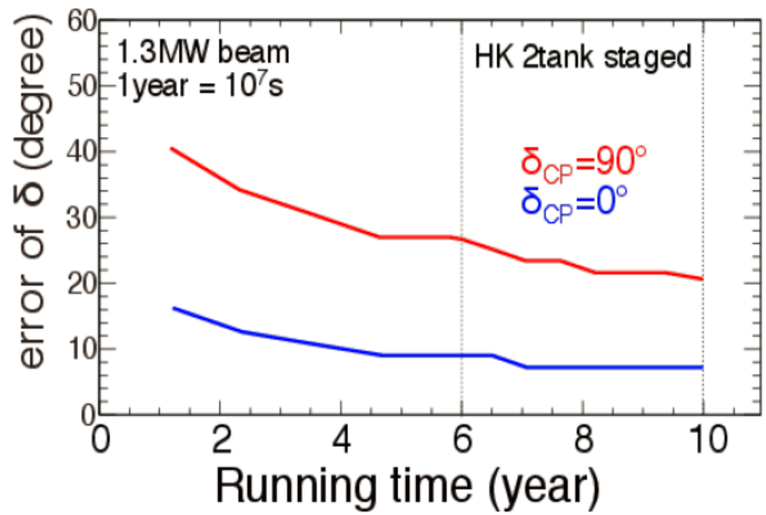
Hamamatsu new plant for mass production

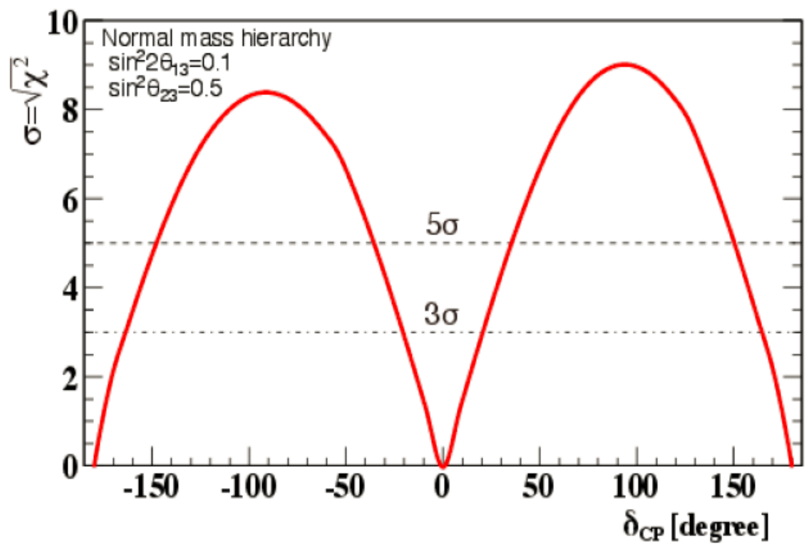
- **New large plant for mass production for HK built by Hamamatsu.**
- The PMT division is moving there.
- Around 6 years for mass production.

δ_{CP} sensitivity

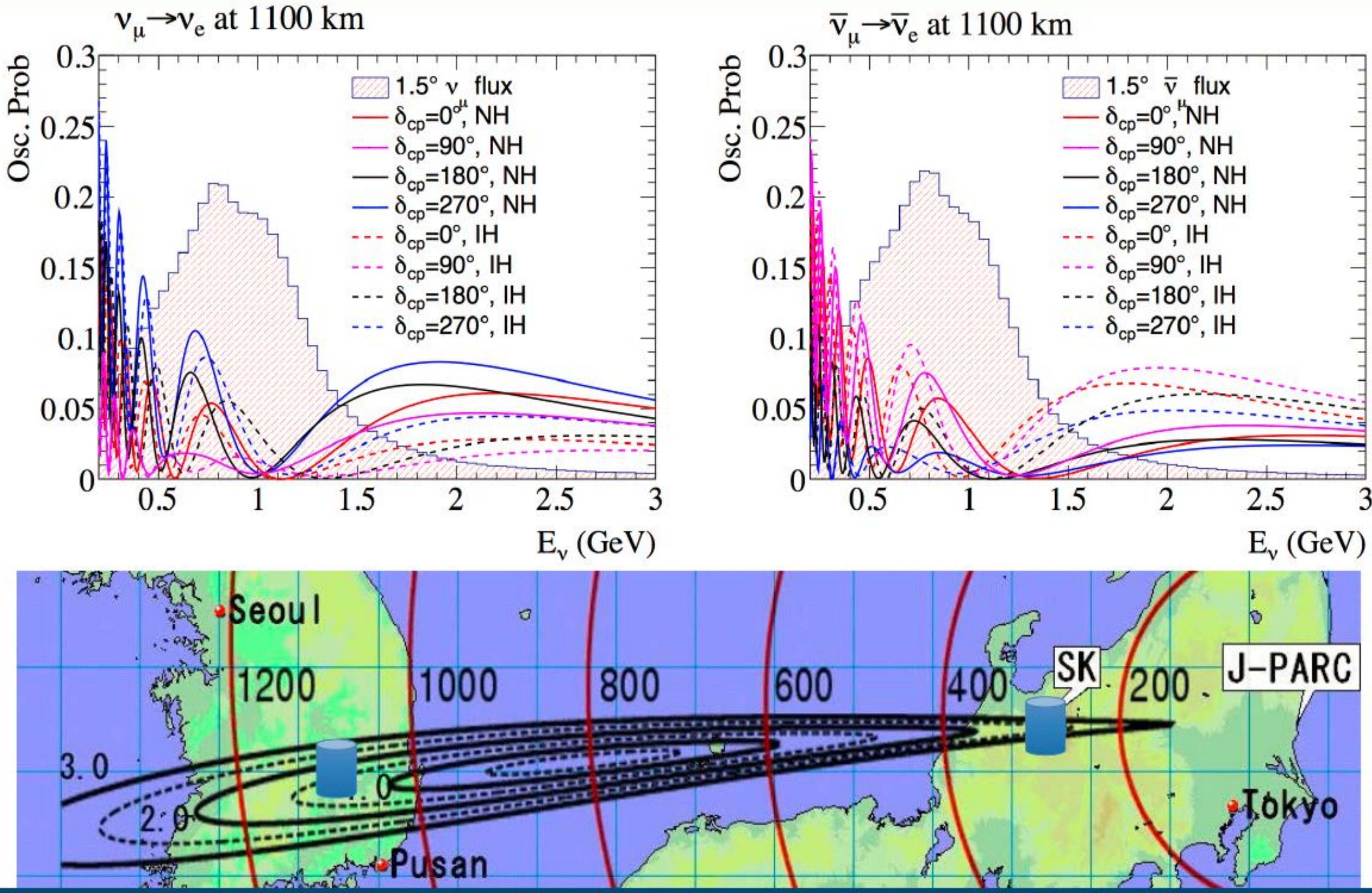
<u>*Difference from δ_{CP}=0*</u>







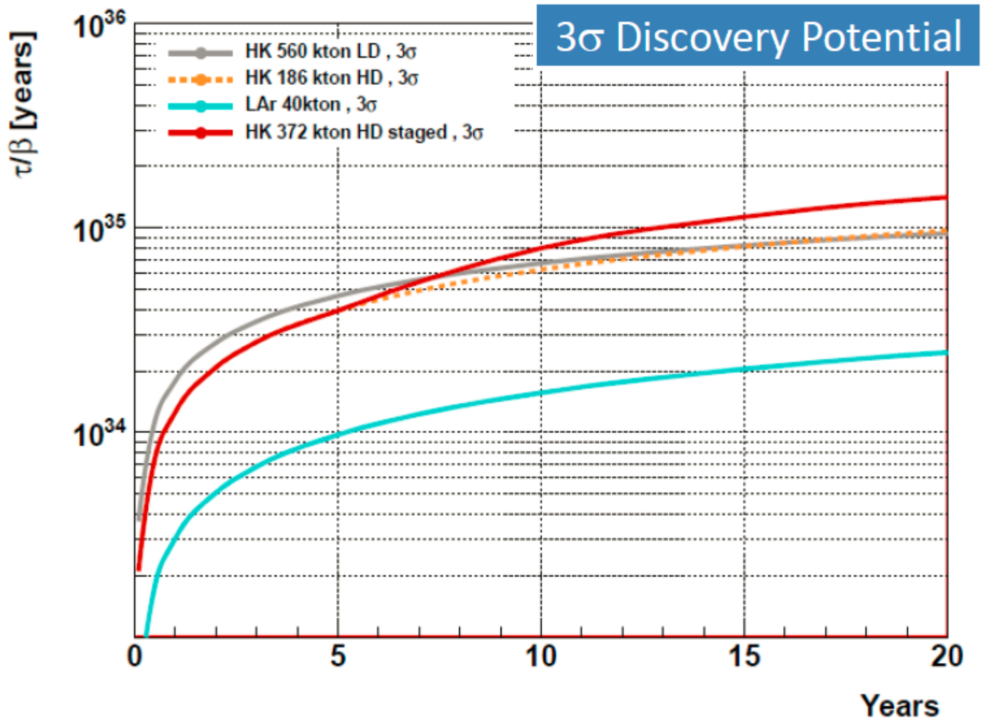
2^{nd} Hyper-K detector in Korea ?

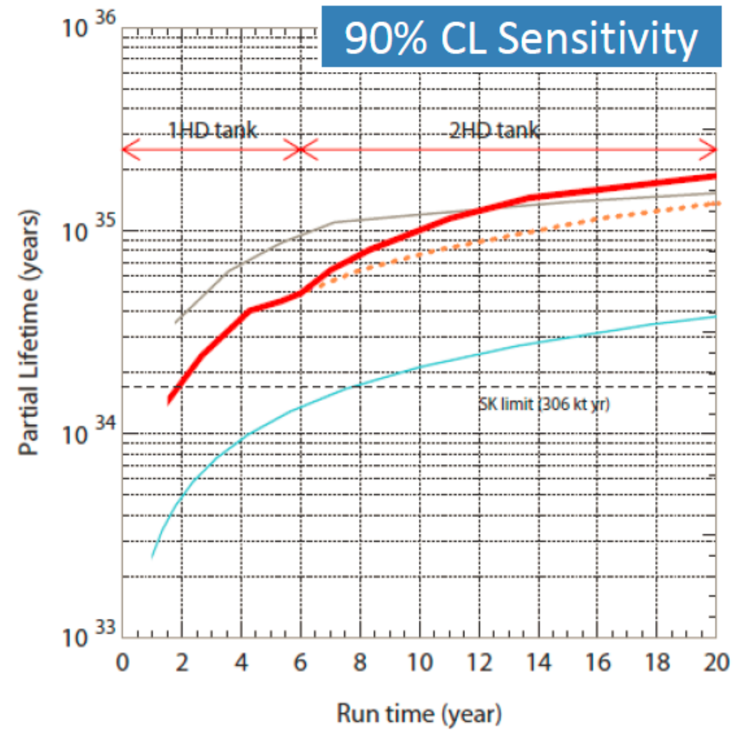


Phys.Rev.D72:033003,2005
Phys.Lett.B637:266-273,2006
Phys. Rev. D81, 093001, 2010

- The 2^{nd} HK tank can be located some other place.
- About 10 years ago, this possibility was discussed.
- Now this possibility is revisited...

$P \rightarrow e^+ \pi^0$: sensitivity



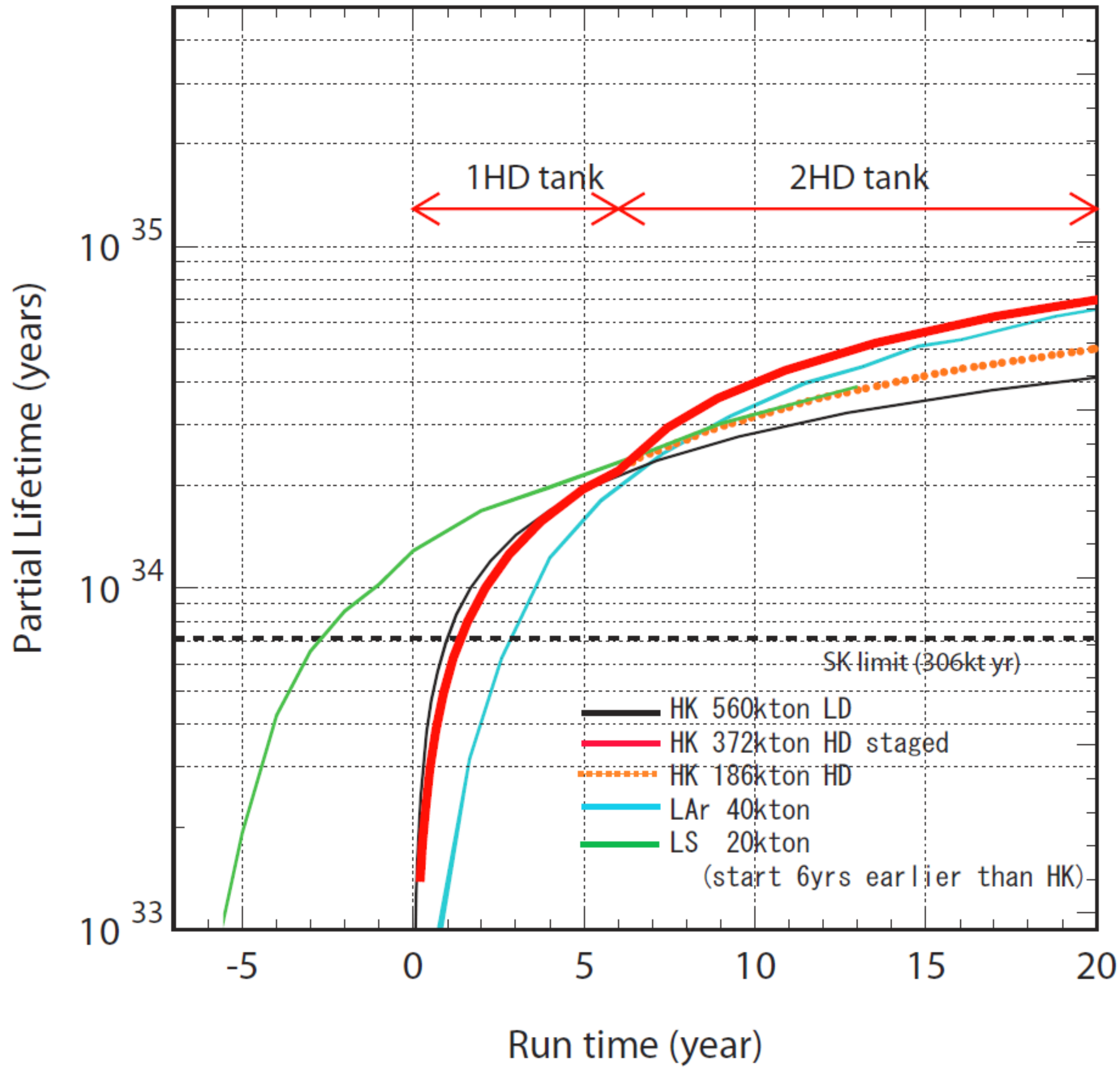


- > 1×10^{35} years after 2.7 Mton yr (90%CL) or 3σ discovery with 4.0 Mtonyr.
- If proton lifetime is near the current Super-K limit of 1.7×10^{34} years Hyper-K will observe a positive signal at 8.9σ in 2.7 Mtonyr exposure.

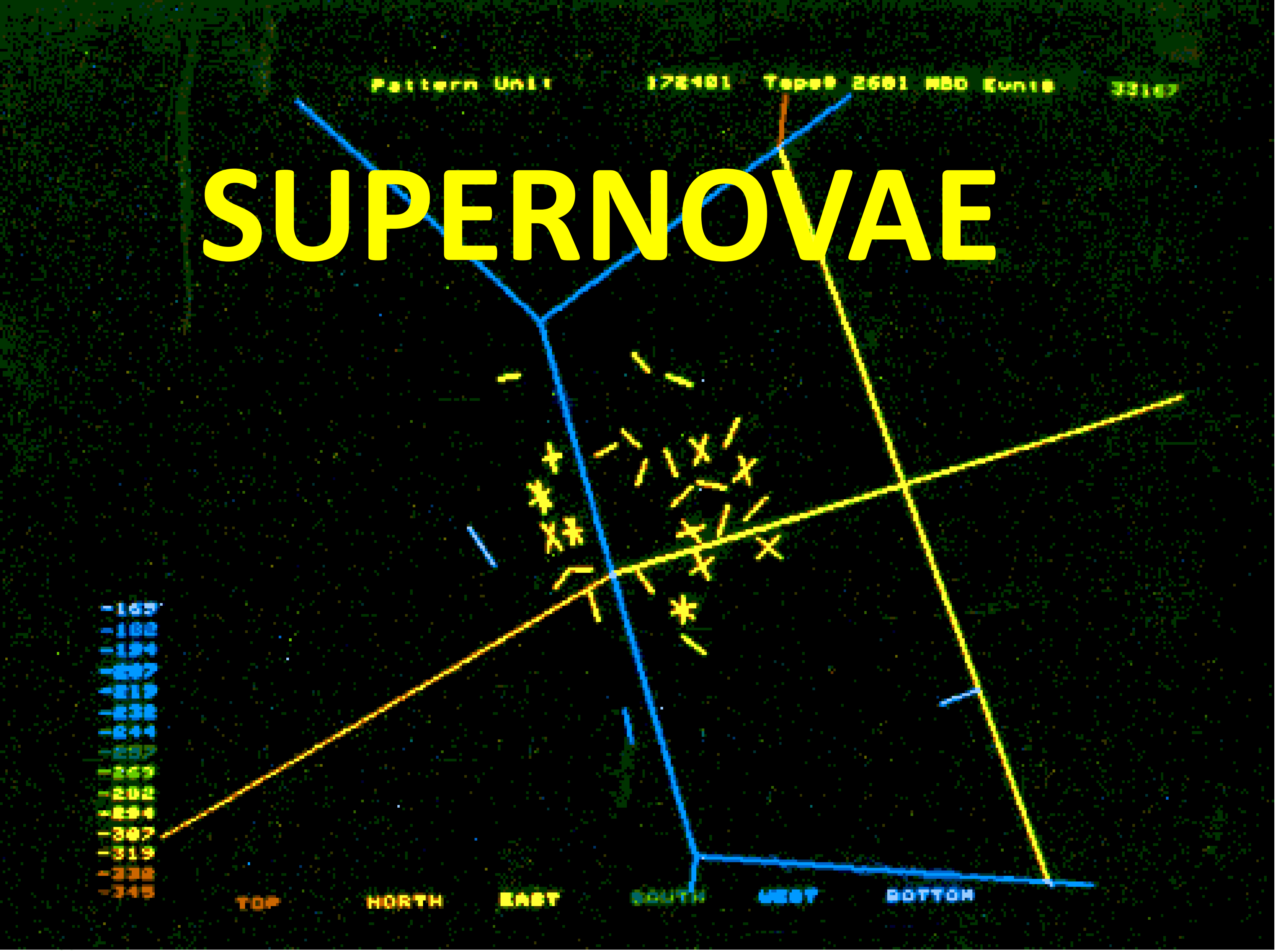
(Lines for the liquid argon experiment have been generated based on numbers in the literature (efficiency: 45% bkg: 1 event/Mtonyr).)

p → K⁺ ν sensitivity

Here, JUNO expt (liquid Scintillator (LS) is competitive and will be earlier.



SUPERNOVAE



Galactic SN Burst Neutrino Events

Neutrino source	1 Tank HD	2 Tank HD	LOI
$\bar{\nu}_e + p$	49,000～68,000	98,000～136,000	165,000～230,000
$\nu_e + e^-$	2,100～2,500	4,200～5,000	7,000～8,000
$\nu_e + {}^{16}O$ CC	80～4,100	160～8,200	300～14,000
$\bar{\nu}_e + {}^{16}O$ CC	650～3,900	1,300～7,800	2,000～13,000
NC γ	～2,500	～5,000	～7,500
$\nu_e + e^-$ (Neutronization)	6～40	12～80	20～130
Total events.	52,000～79,000	104,000～158,000	170,000～260,000

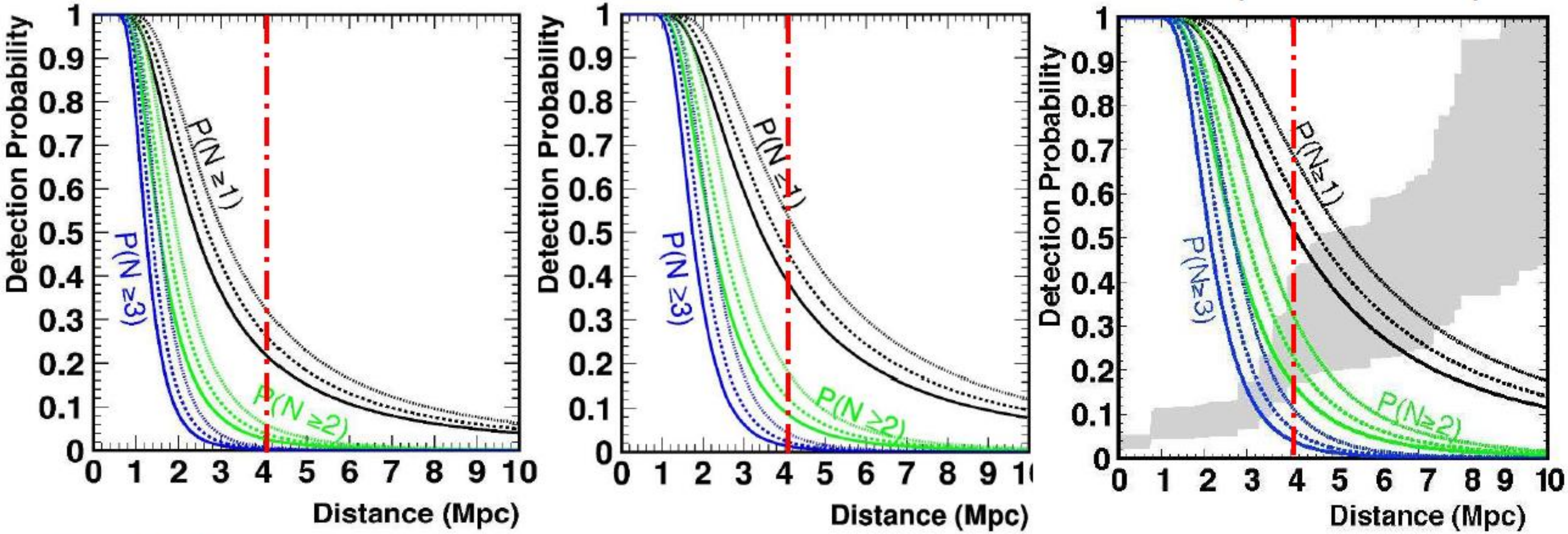
Energy threshold is 5MeV in all cases.
NC is roughly scaled from Langanke et al. PRL 76 2629, 1996

10kpc, Livermore model

Large statistics will make it possible to study SN mechanism in detail

ν detection probability for ~Mpc SN

1 tank (0.19Mt FV) 2tank staged (0.37Mt FV) LOI (0.56Mt FV)



For 4Mpc supernova

3-6% for P(N >= 2) 10-20 % for P(N >= 2) 17-32% for P(N >=2)

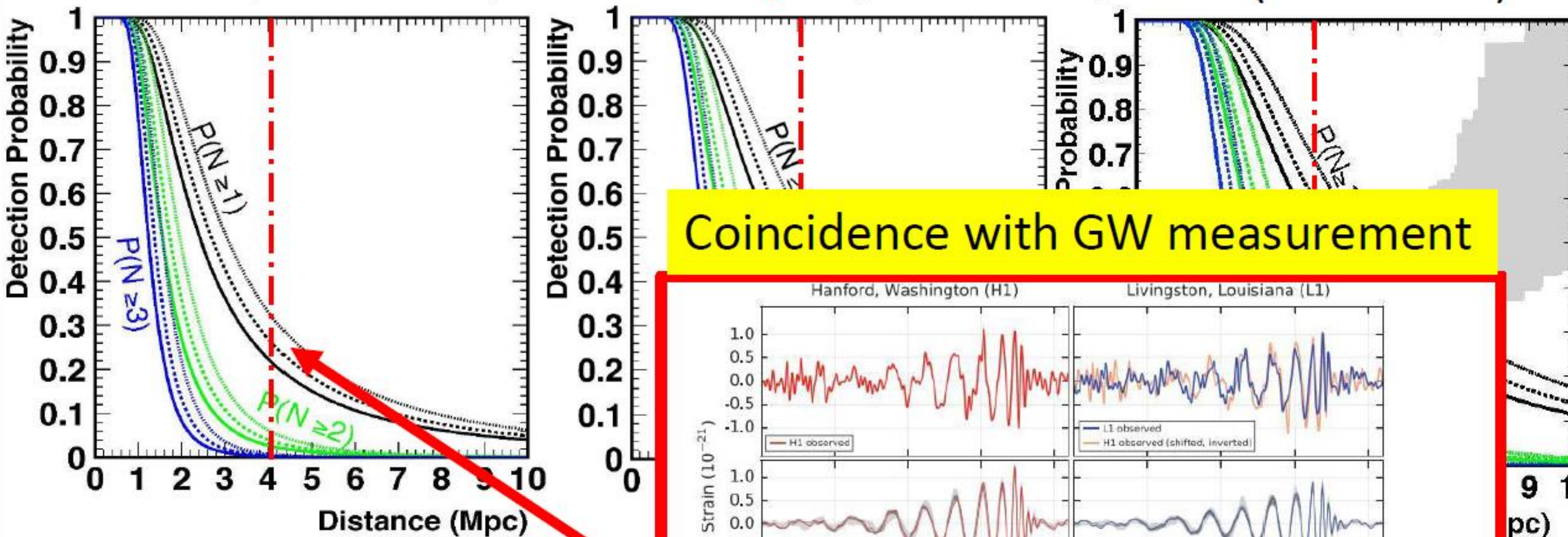
Conditions:

- Livermore simulation
- 10MeV threshold
- # range for no osc., N.H. and I.H.

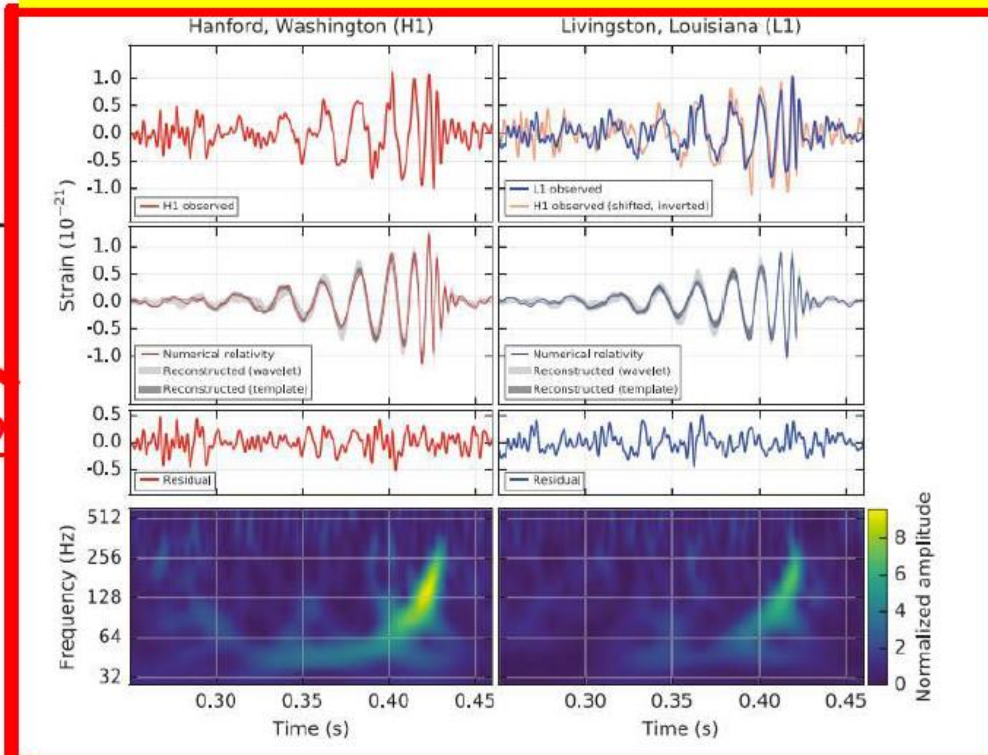
16

ν detection probability for ~Mpc SN

1 tank (0.19Mt FV) 2tank staged (0.37Mt FV) LOI (0.56Mt FV)



Coincidence with GW measurement



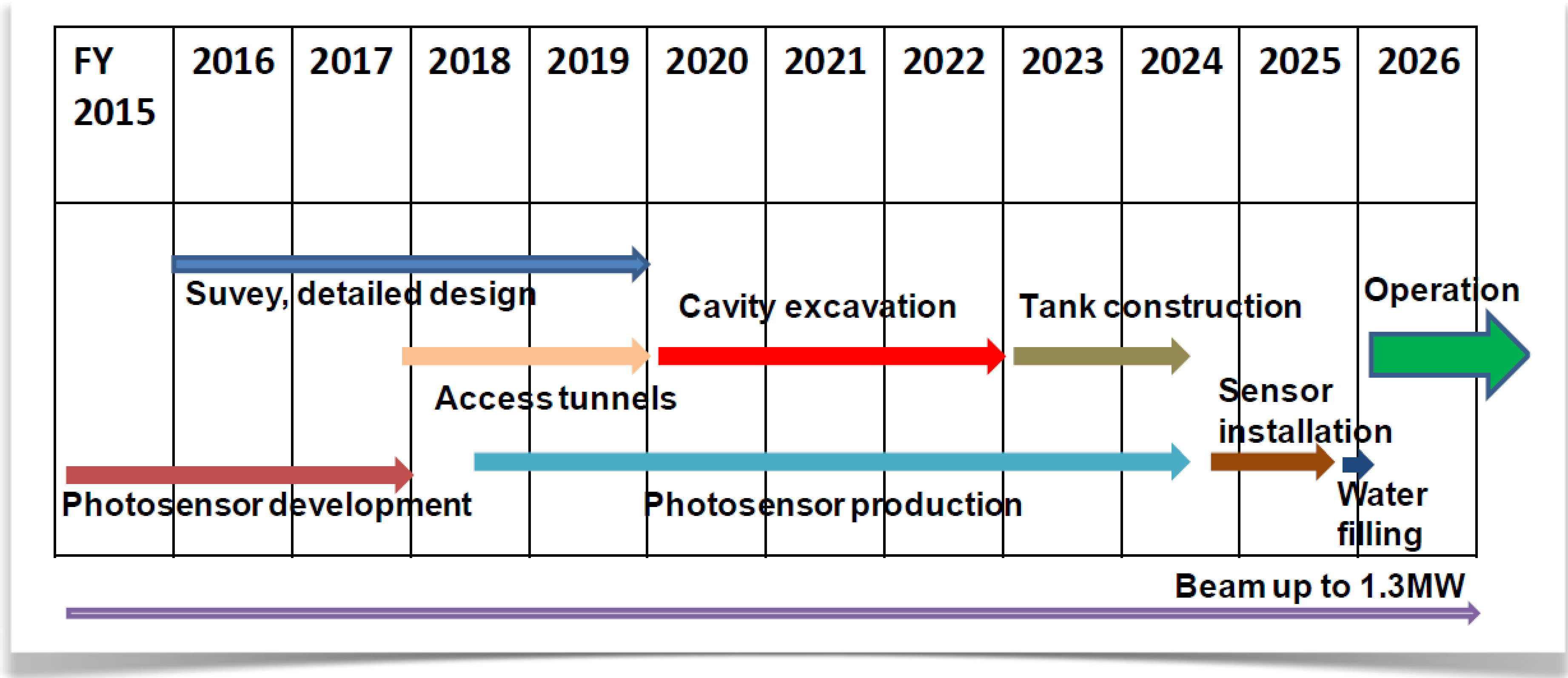
For 4Mpc supernova

3-6% for P(N >= 2) 10-2)

Conditions:

- Livermore simulation
- 10MeV threshold
- # range for no osc., N.H. and I.H.

The Hyper-Kamiokande Timeline



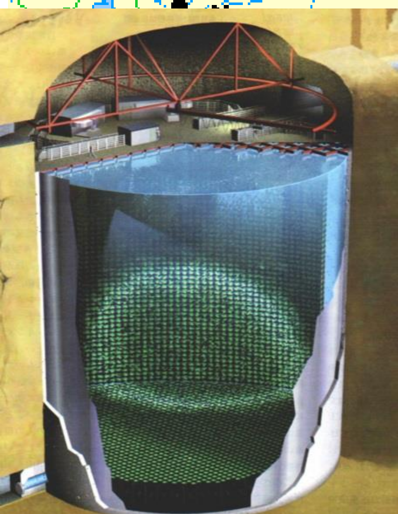
- 2018 - 2025 HK construction
- 2026 onwards CPV study, Atm, Solar, Supernova ν study, Proton decay searches

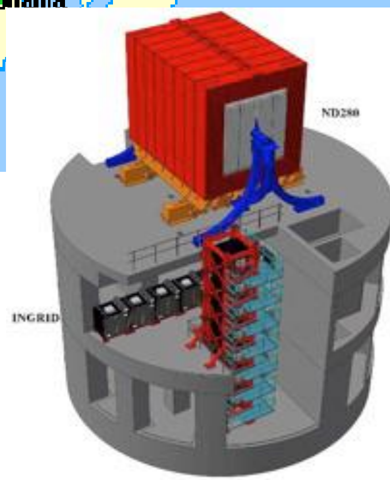
The second (identical) tank start starts operation 6y after the first one.

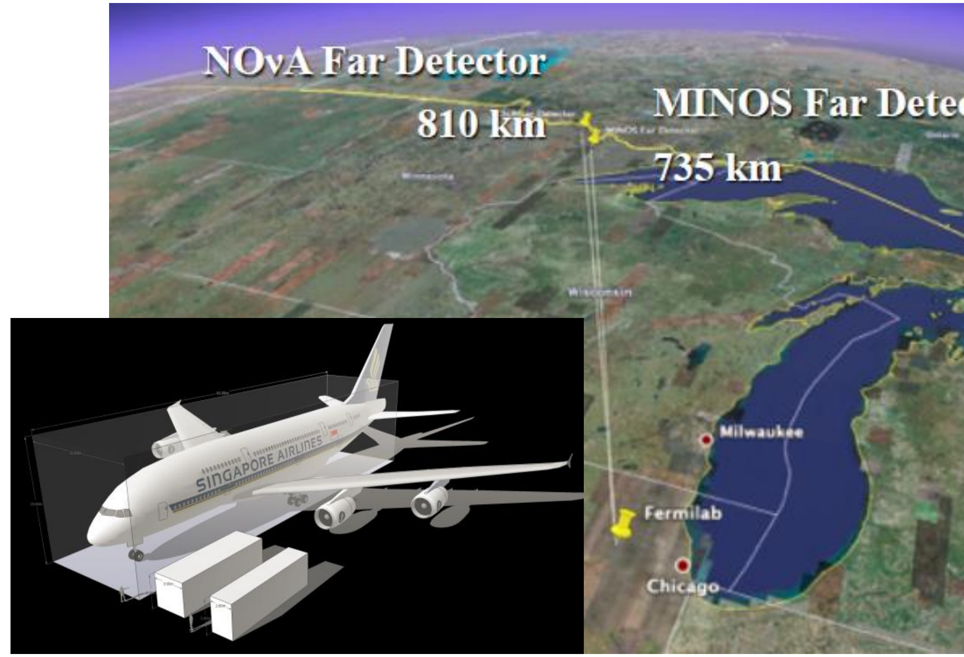
The players -- *approximate* time scales

Experiment	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30	31	32	33	34	35	36	37	38	39	40
Accelerator LBL																									
T2K		running																							
T2K-II							Running																		
NOvA		running					extensions?																		
Atmospheric																									
PINGU		construction					Running ---->								Not approved yet										
ORCA		construction					Running ---->								Not approved yet										
SK-Gd					<----- Running ---->																				
INO(?)																									
Reactor 20km																									
JUNO	construction				<----- Running ----------------->													approved							
RENO 50	?	?	?	?	?	?	?	?	?	?															
Accelerator LBL-II																									
HYPER-K	R&D & Approval												<----- Running ----------------->												
DUNE	R&D&Approval												<----- Running ----------------->												

T2K and NOvA







14 kton (10 fid) far detector on surface with cover.
liq. Scintillator 65% active, 6cm longiitudinal pitch
300ton ND with similar functionality.

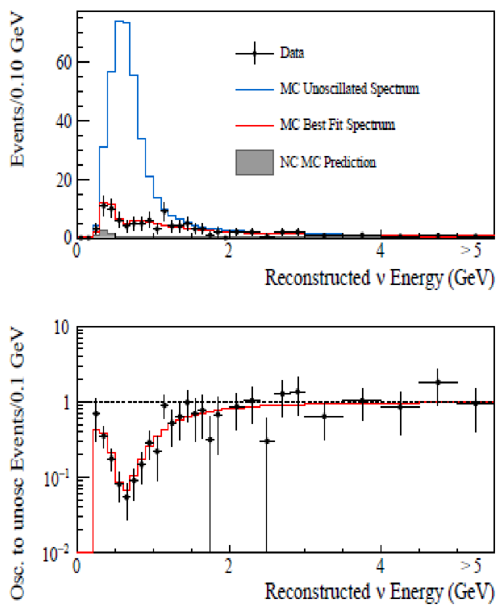
50 kton (22.5 fid) WC SuperK
Suite of near detectors on-axis +
magnetized off-axis ND280
Off axis 2.5° (E_ν = 650 MeV) L=295 km,
Approved for 7.5 10^{21} pot (30 GeV protons)
First run in 2009. Received 14% of it.
Running at 380kW now. T2K-II under consideratio..

810 km, 14 mrad (0.8°)off axis. (E_ν = 1.8GeV)
14 kton fiducial plastic scintillator (6cm pitch).
First run February 2014 to May 2015.
3.45×10^{20}pot 120 GeV 36×10^{20} approved
Running at 420/470 kW now.
Consider physics with 6 years (3 ν, 3 $\bar{\nu}$)
or 72×10^{20} pot

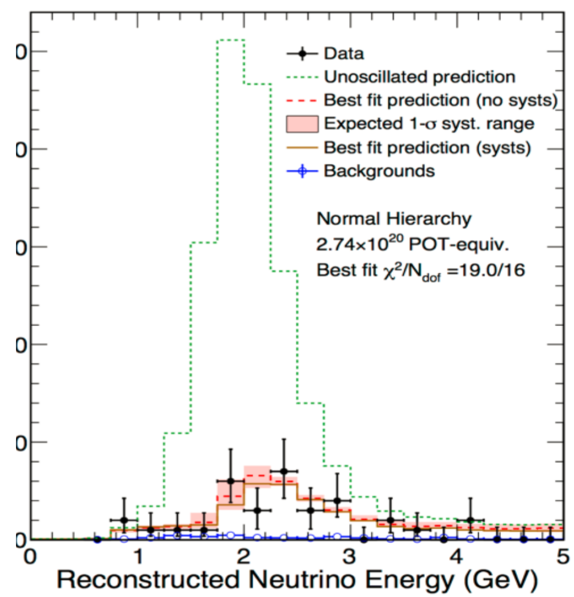
T2K and NOvA

Significant complementarity, with different baselines and different near and far detectors
-- NOvA more sensitive to Mass Ordering
-- T2K directly sensitive to CP violation

Both experiments benefit from off-axis geometry
-- reduction of backgrounds esp. intrinsic ν_e
-- beam energy peak is given by pion decay kinematics → provides reference energy.



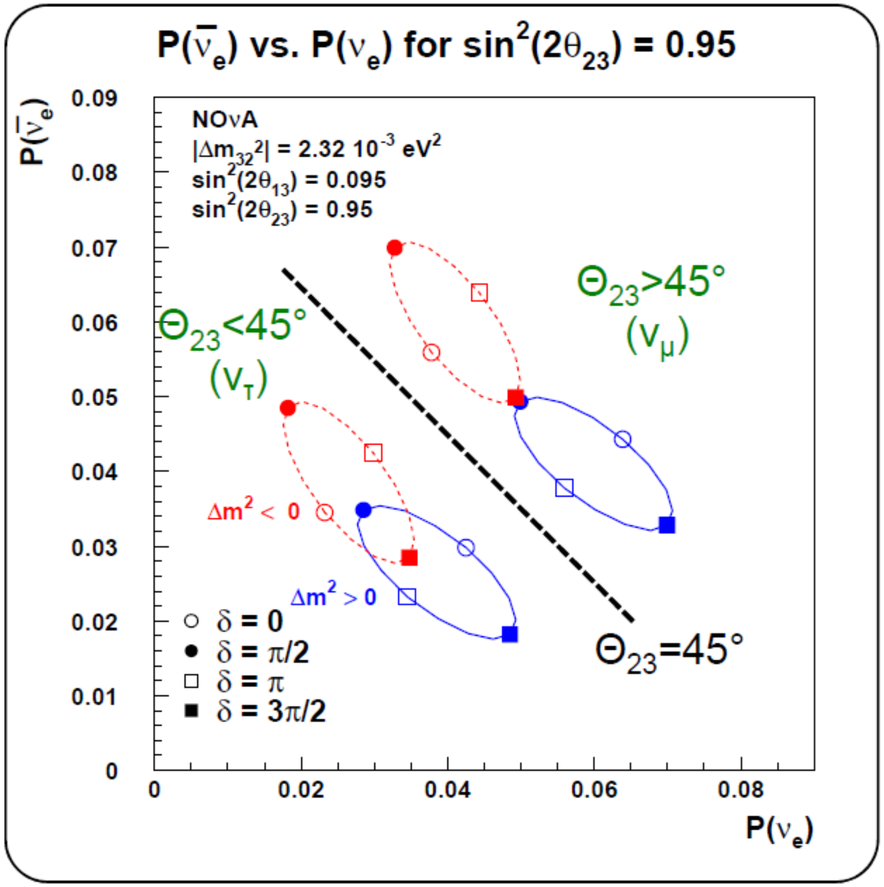
T2K

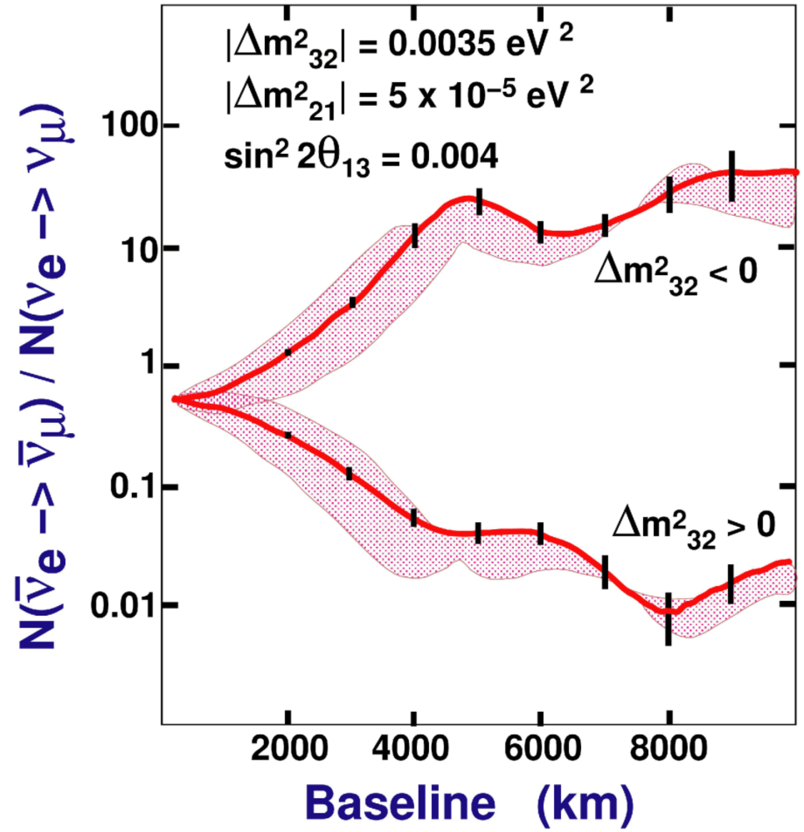


NOvA

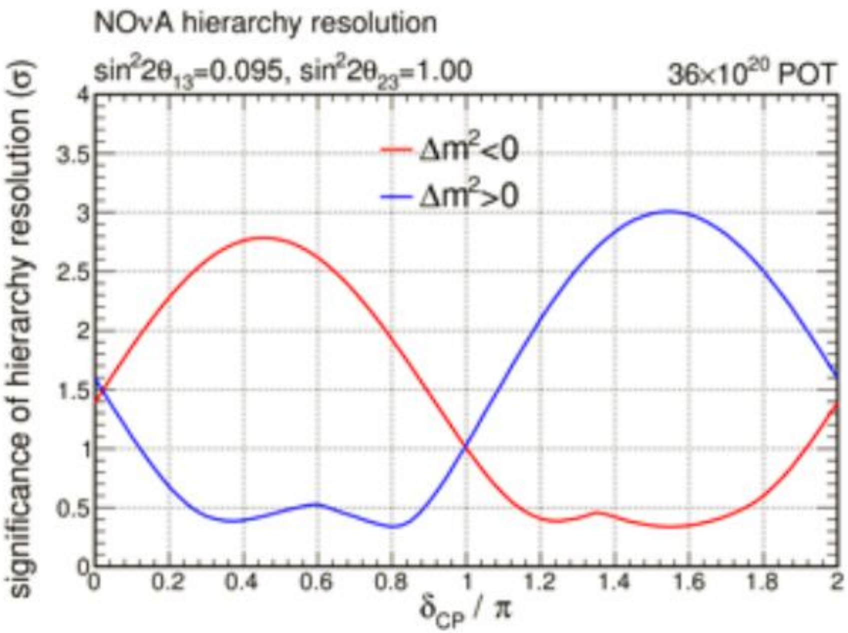
NOVA: Mass ordering, δ_{CP} and θ_{23} octant ambiguity.
T2K mass ordering effect is ~3 times smaller
DUNE mass ordering effect is 1.6 times larger than NOVA

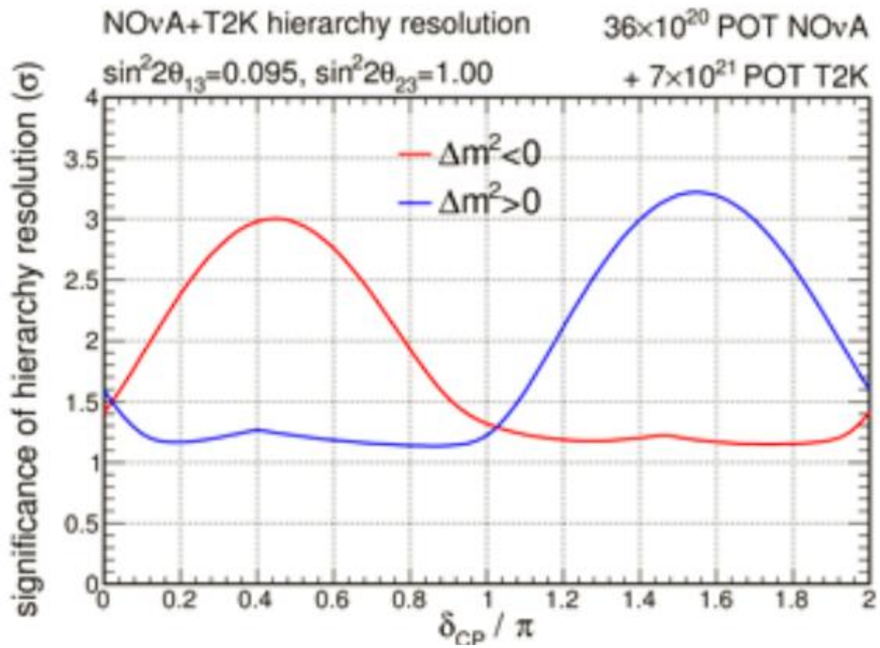
Old plot (CP violation now smaller)!





The CP violation dominates below 500km, matter effect dominates above ~1200 km.

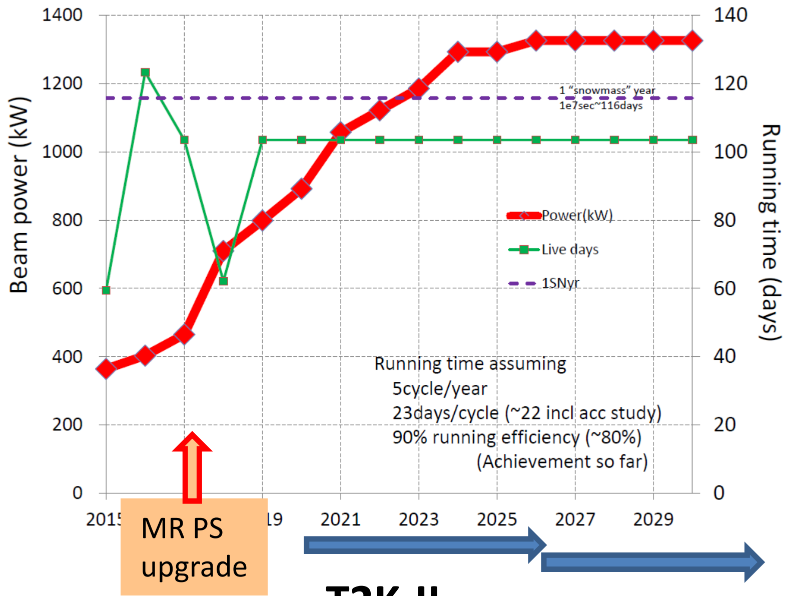




NB combination for T2K-II @ 2x10^{21} and NOvA @ 7.2 10^{21} does not exist,
(indicatively) multiply number of sigma by ~sqrt(2) → determination between 2 and >4 sigma

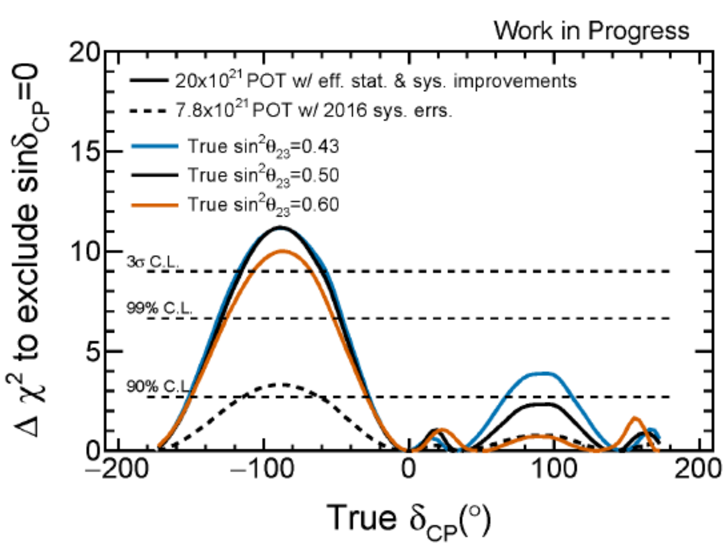
NB If $\delta \sim -\pi/2 \equiv 3\,\pi/2$ as preferred today NOvA could already make significant contribution by summer 2016.

The combination of NOvA and T2K → inform the mass hierarchy at 2 to 4 sigma by 2025.

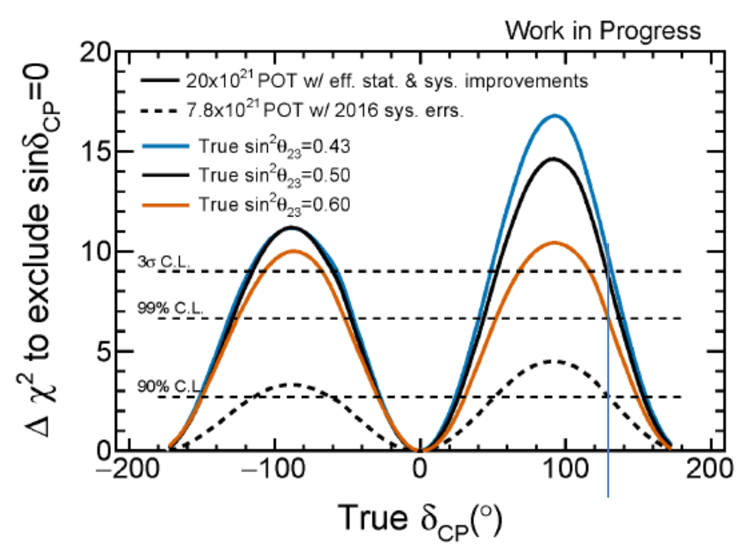


By 2026, T2K-II might obtain evidence for CPV at 3-4 σ for $\delta=\pm\pi/2$
(or measurement at $\pm$<20 degrees precision for $\delta=0$)
+ NOvA → maybe just 5σ for $\delta=\pm\pi/2$

Discovery and study will require more powerful experiments!

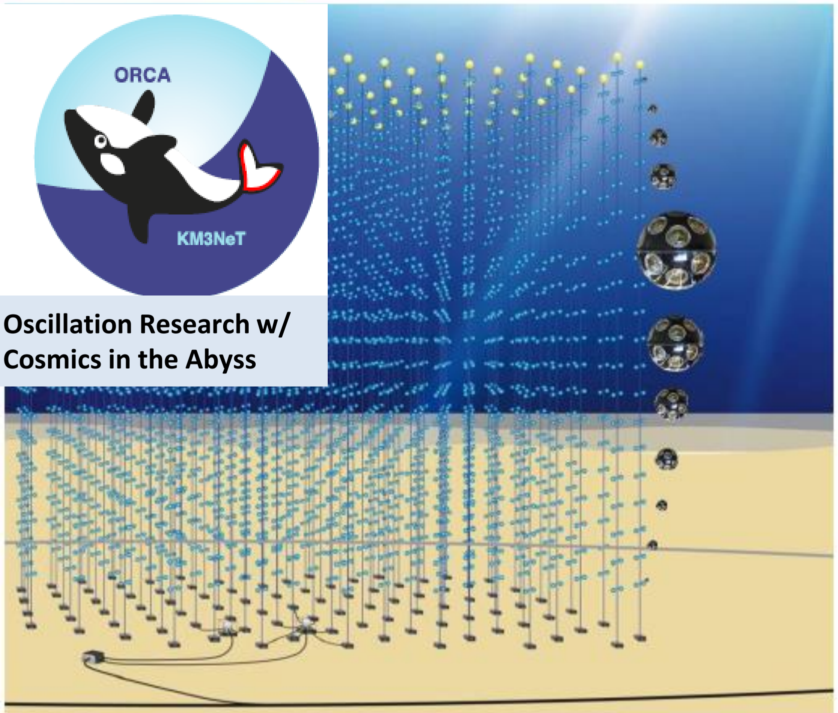


(a) Assuming the MH is unknown.

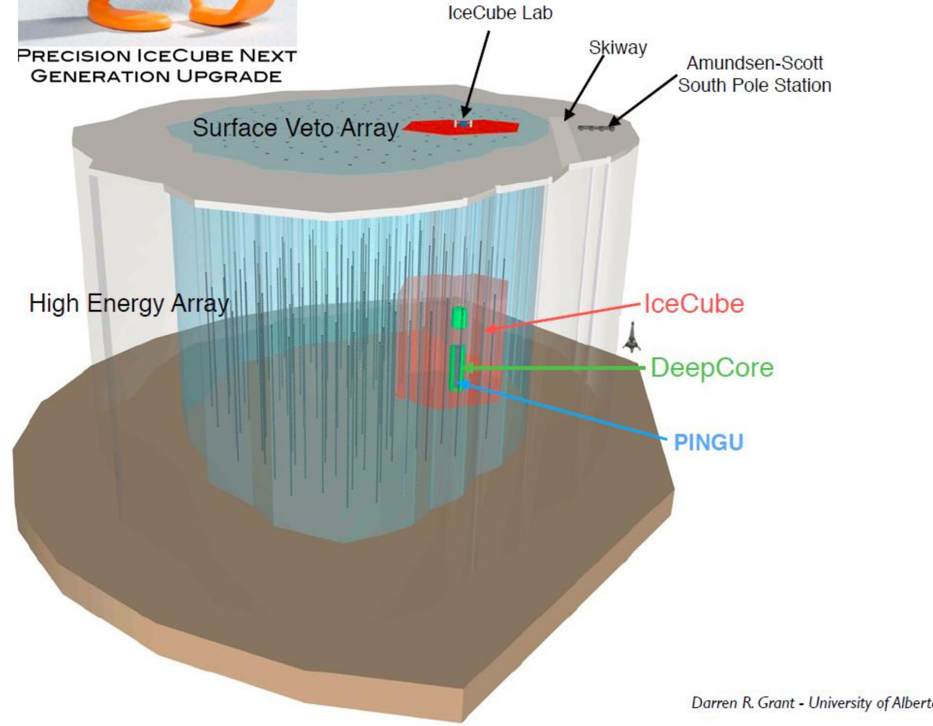


(b) Assuming the MH is known – measured by an outside experiment.

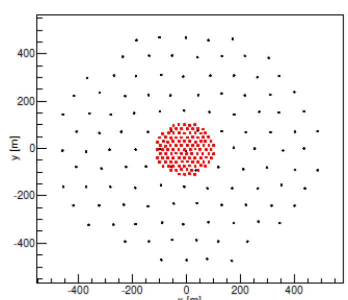
ORCA and PINGU



Artist's impression of a KM3NeT building block: 115 strings of 18 DOMs.



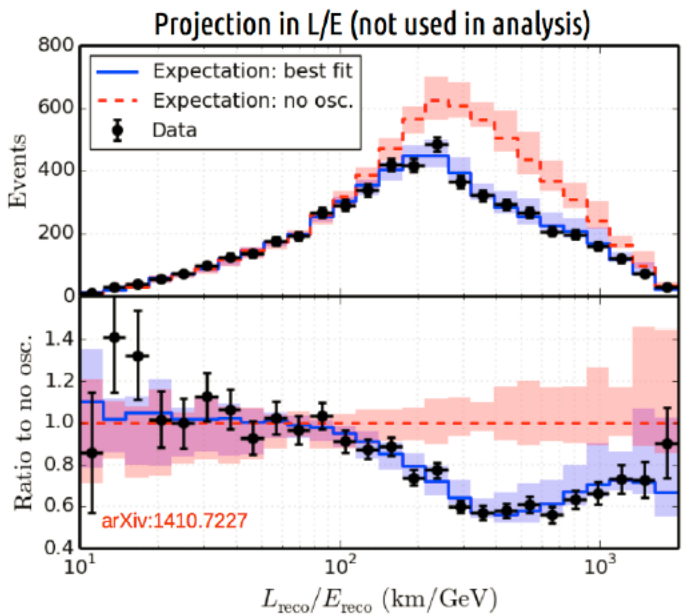
Darren R. Grant - University of Alberta

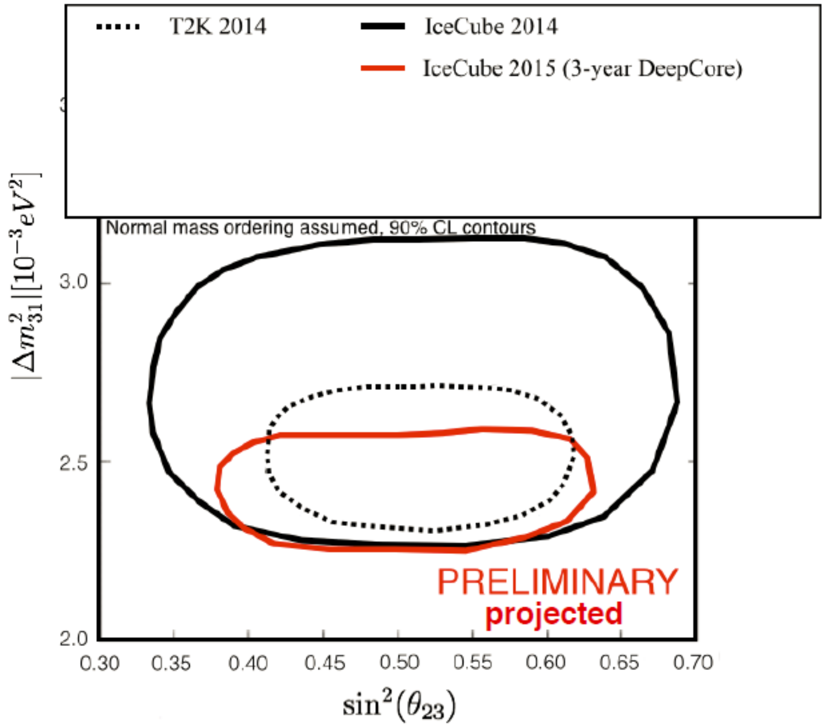


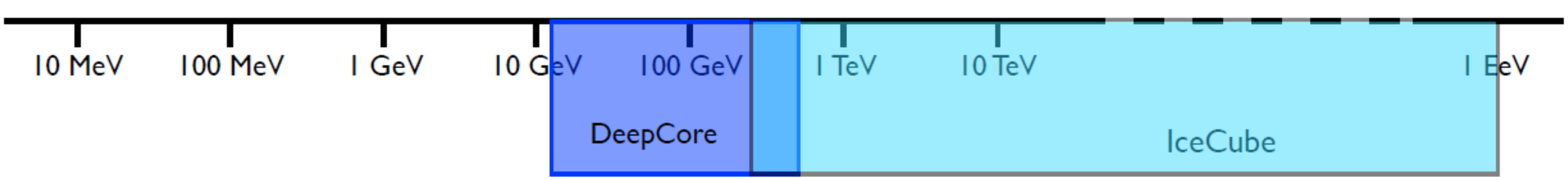
ORCA: 3.8 Mton

Both experiments are in <u>proposal</u> phase.
ORCA: deployment 2017-2020
PINGU: aim at completion in 2021-22.
Both: 4 years for MH determination at 3 sigma

Atmospheric neutrino oscillations with DeepCore





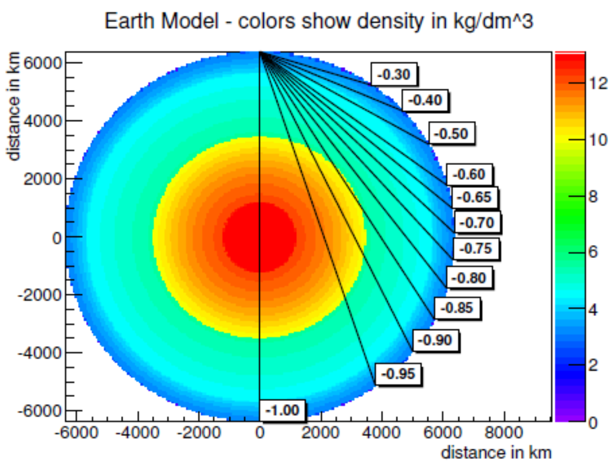


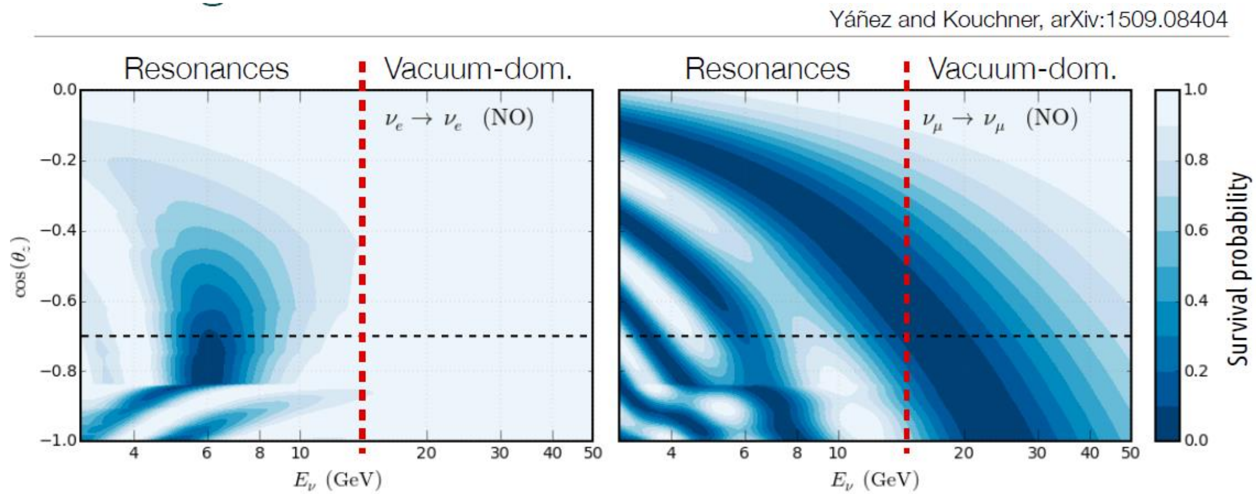
ORCA and PINGU

Determination of mass hierarchy with matter effect

Very large effect : up to ~100% asymmetry $\nu_e \rightarrow \nu_e$ vs. $\bar{\nu}_e \rightarrow \bar{\nu}_e$, different for ν_μ

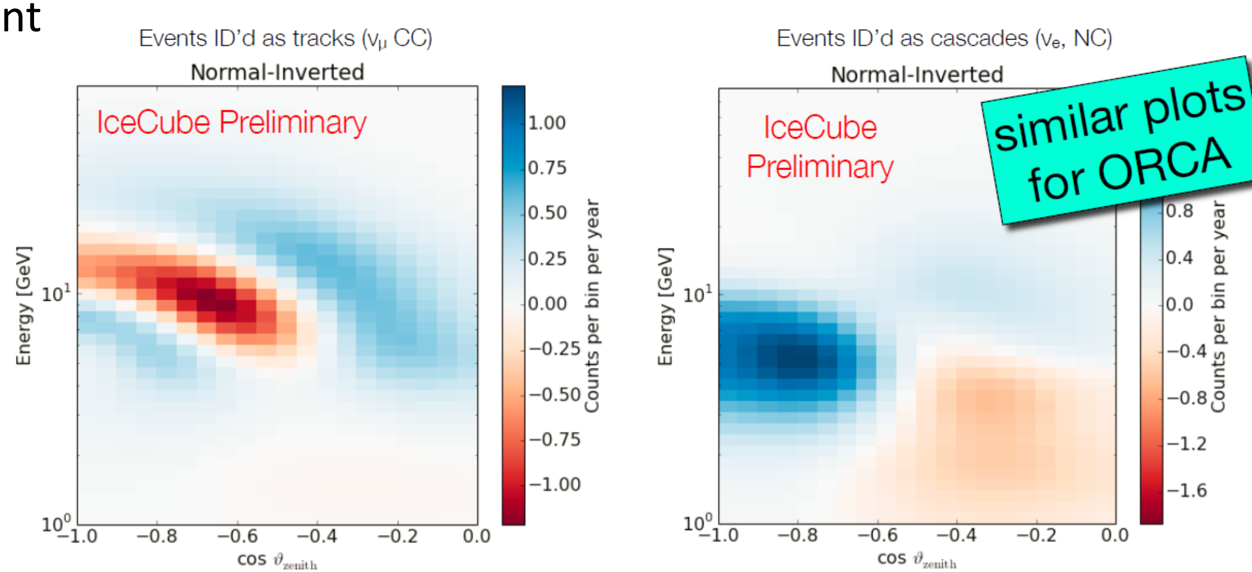
diluted by charge, PID, lepton angle energy reconstruction





Optimum region for measurement
Is around 10 GeV and 7000km

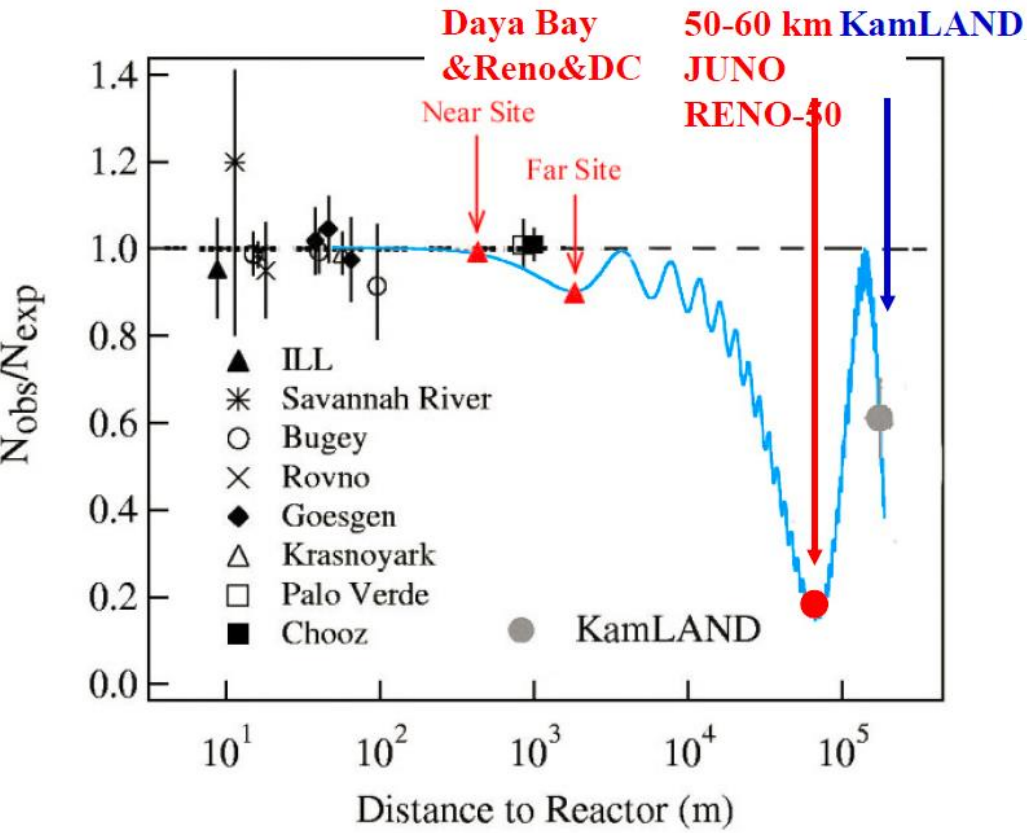
Dilution and systematics due to ν flux, cross-sections and angle smearing… but effect is large; little sensitivity to δ_{CP}

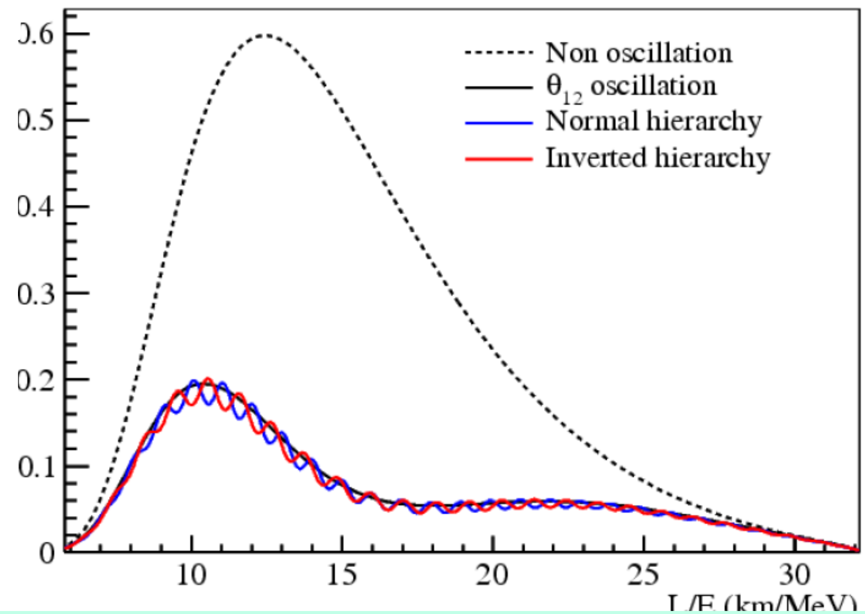


JUNO (RENO50)

$\bar{\nu}_e$ disappearance from reactor.

$$P_{ee}(L/E) = 1 - P_{21} - P_{31} - P_{32}$$
$$P_{21} = \cos^4(\theta_{13})\sin^2(2\theta_{12})\sin^2(\Delta_{21})$$
$$P_{31} = \cos^2(\theta_{12})\sin^2(2\theta_{13})\sin^2(\Delta_{31})$$
$$P_{32} = \sin^2(\theta_{12})\sin^2(2\theta_{13})\sin^2(\Delta_{32})$$





Locate 20kton, 75% coverage liq. scintillator detector at 1st solar disappearance max (50km) use interference between solar and atmospheric terms which is sensitive to the **sign of Δm^2_{23}**

Since disappearance is used, no sensititivity to δ_{CP} .

Challenge from energy scale/linearity/resolution!

Yellow Book

Neutrino Physics with JUNO

The Jiangmen Underground Neutrino Observatory (JUNO), a 20 kton multi-purpose underground liquid scintillator detector, was recently proposed with the determination of the neutrino mass hierarchy as a primary physics goal. The excellent energy resolution and the large fiducial volume anticipated for the JUNO detector offer exciting opportunities for addressing many important topics in neutrino and astro-particle physics. In this document, we present the physics motivations and the anticipated performance of the JUNO detector for various proposed measurements.

arXiv: 1507.05613

- Reactor neutrino physics
  - Mass hierarchy, precision measurements, (geo-neutrino),…
- Astro-particle physics
  - Supernova neutrino, diffused supernova neutrino background, solar neutrino
- High energy events
  - Atmospheric neutrino, nucleon decays, …

1. **Statistical error-->Target Mass: 20 ktons, biggest LS Detector**
2. **Best Energy Resolution for LS Detector: 3%**

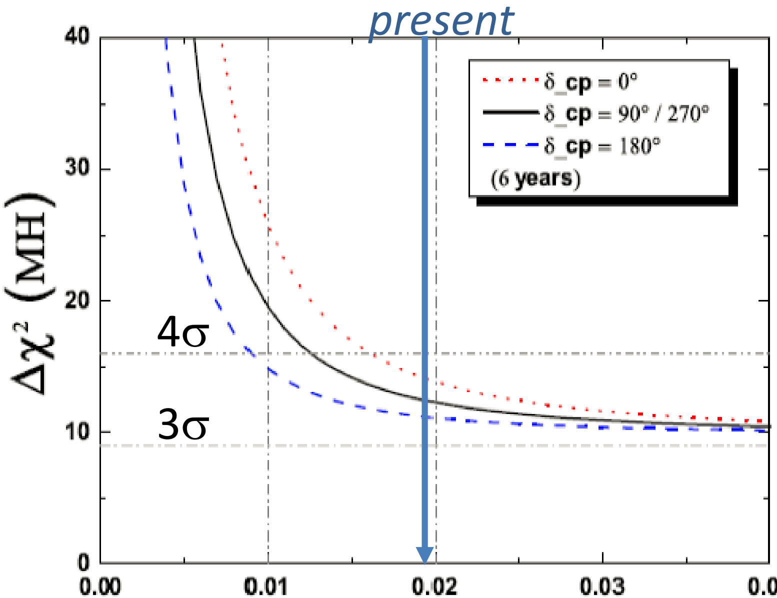
→ ~75% PMT: coverage

→ Photon Detection Efficience double 30% **Quantum Effi. + 90% Collection Efficience of PMT**

→Transparent LS

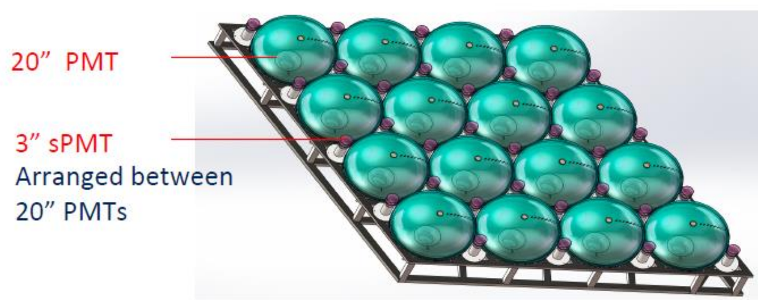
3. **Energy and Vertex reconstruction and correction:**
   symmetrical structure, time and charge measurement by PMT
4. **Energy range and linearity: PMT response and electronics**
5. **Background Radiation Rate, fiducial volume cut, Material, Clean consideration**

JUNO sensitivity to Mass Hierarchy :
«more than 3 σ in 6 years»



Relative error on $\sigma(\Delta m^2_{\mu\mu})$ (external input)

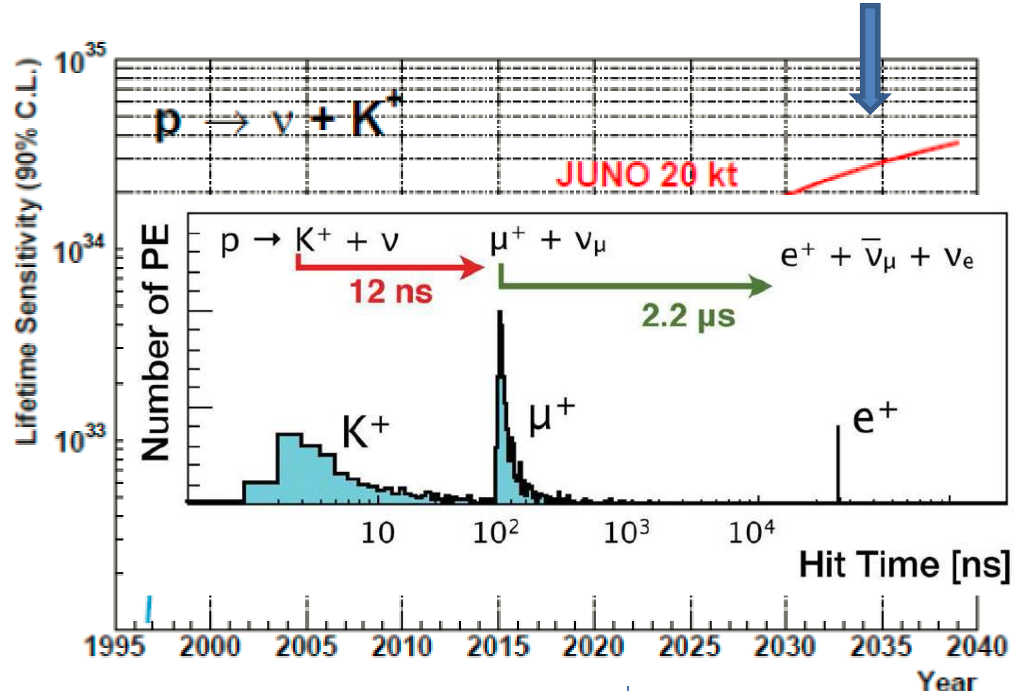
	Current	JUNO
Δm^2_{12}	3%	0.6%
Δm^2_{23}	5%	0.6%
$\sin^2\theta_{12}$	6%	0.7%
$\sin^2\theta_{23}$	20%	N/A
$\sin^2\theta_{13}$	5%	~ 15%
δ_{CP}		N/A



20'000 PMTs 15k from China 5k from Japan
Civil construction underway → complete 2018
Data taking date: early 2020.

JUNO (RENO50)

Crossing point with DUNE & HyperK



Many physics topics

Some overlap with DUNE/HyperK

-- p→ vK →

-- SuperNovae

Some specific

-- geoneutrinos

700m deep

Supernova neutrinos

- Less than 20 events observed so far
- Assumptions:
  - **Distance: 10 kpc (our Galaxy center)**
  - **Energy: 3×10^{53} erg**
  - **L_ν the same for all types**
  - **Tem. & energy**

$T(\bar{\nu}_e)$ = 3.5 MeV, $\langle E(\bar{\nu}_e)\rangle$ = 11 MeV

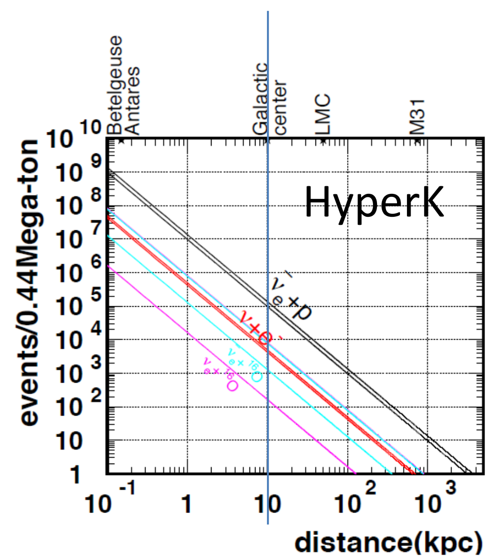
$T(\nu_e)$ = 5 MeV, $\langle E(\nu_e)\rangle$ = 16 MeV

$T(\nu_x)$ = 8 MeV, $\langle E(\nu_x)\rangle$ = 25 MeV

- Many types of events:
  - **$\bar{\nu}_e + p \rightarrow n + e^+$, ~ 3000 correlated events**
  - **$\bar{\nu}_e + {}^{12}C \rightarrow {}^{12}B^* + e^+$, ~ 10-100 correlated eve**
  - **$\nu_e + {}^{12}C \rightarrow {}^{12}N^* + e^-$, ~ 10-100 correlated eve**
  - **$\nu_x + {}^{12}C \rightarrow \nu_x + {}^{12}C^*$, ~ 600 correlated events**
  - **$\nu_x + p \rightarrow \nu_x + p$, single events**
  - **$\nu_e + e^- \rightarrow \nu_e + e^-$, single events**
  - **$\nu_x + e^- \rightarrow \nu_x + e^-$, single events**

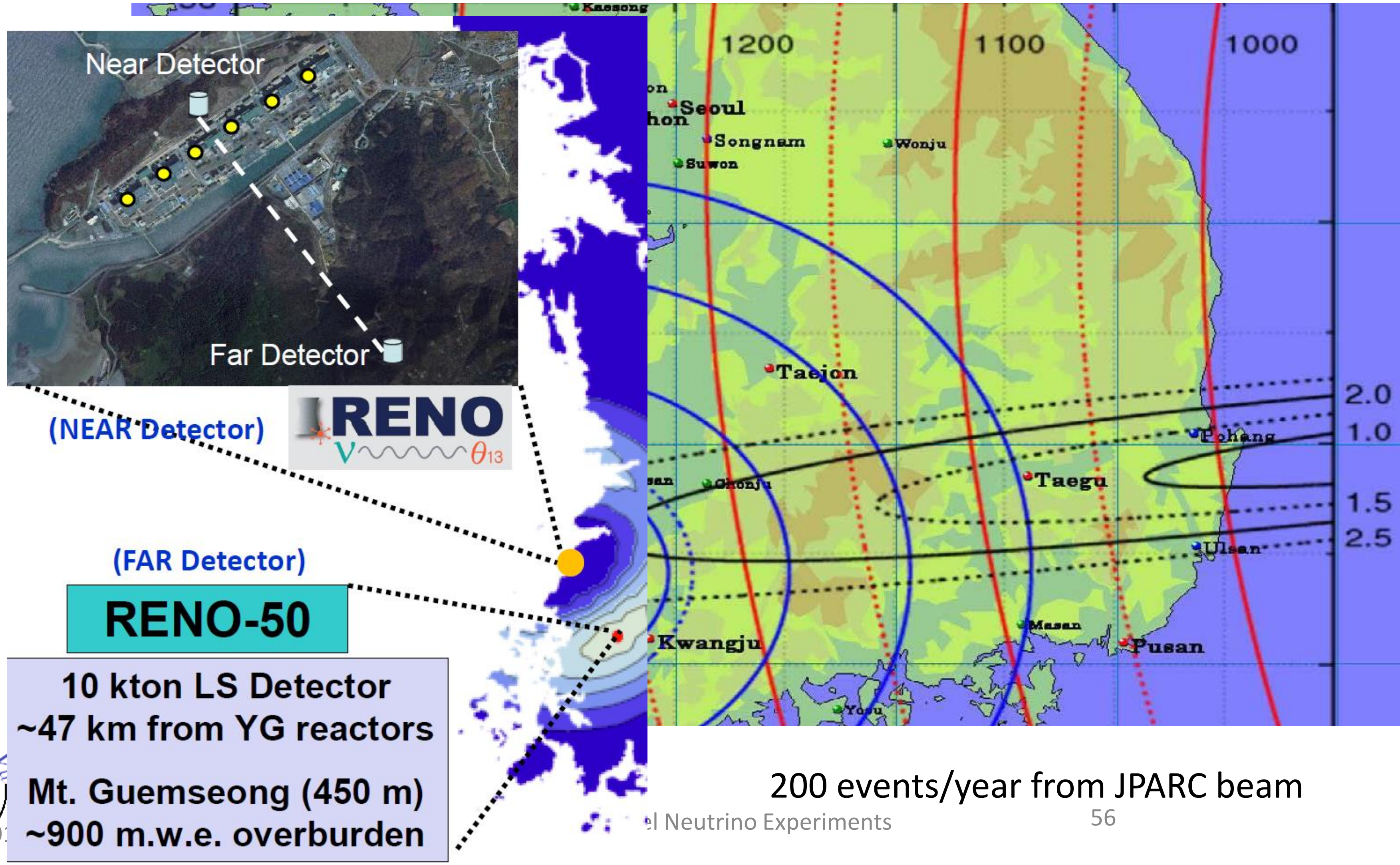
Water Cerenkov detectors can not see these correlated events

Energy spectra & fluxes of all types of neutrinos



A word on RENO50 (17kton, 60% coverage, 100M$)

-- R&D funding (US $2M for 2015-2017)
from the Samsung Science & Technology Foundation.
R&D is in progress to produce TDR.
-- A proposal has been submitted to obtain full funding.

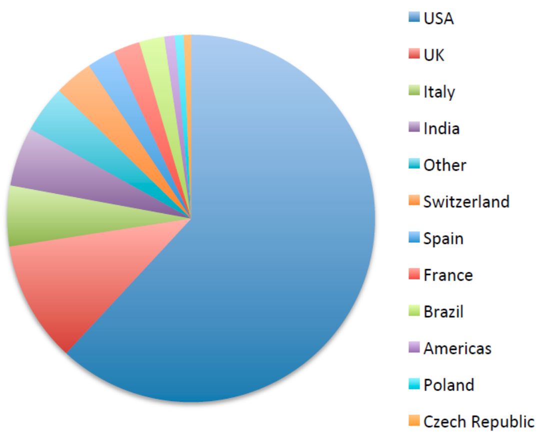


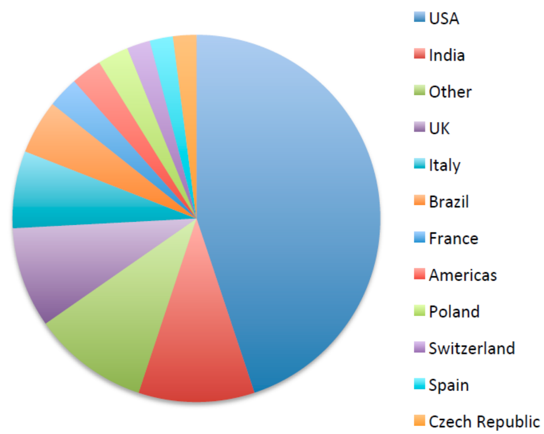
200 events/year from JPARC beam

The DUNE Collaboration

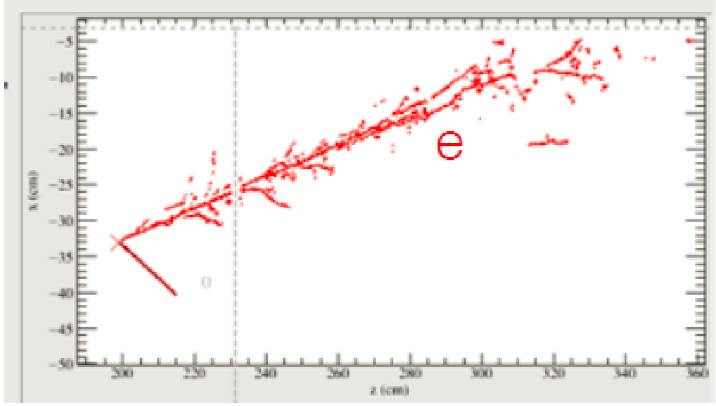
As of today: from

790 Collaborators 144 Institutes





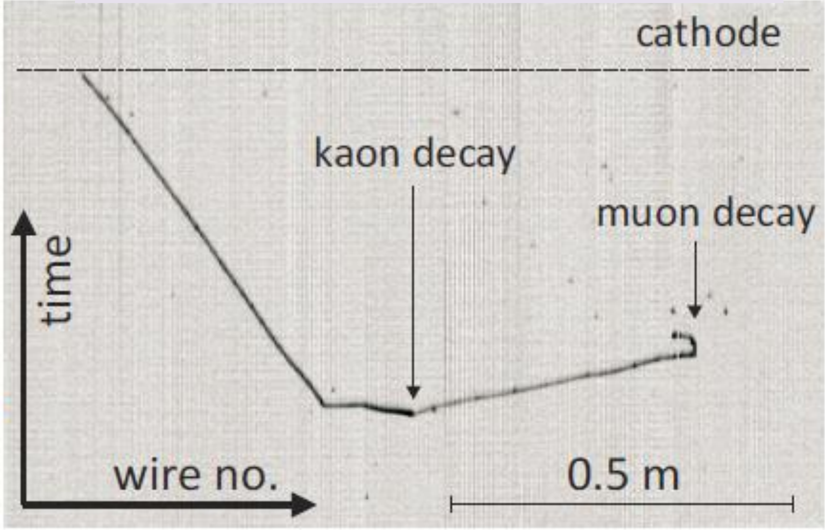
DUNE Primary Science Program



Focus on fundamental open questions in particle physics and astro-particle physics:

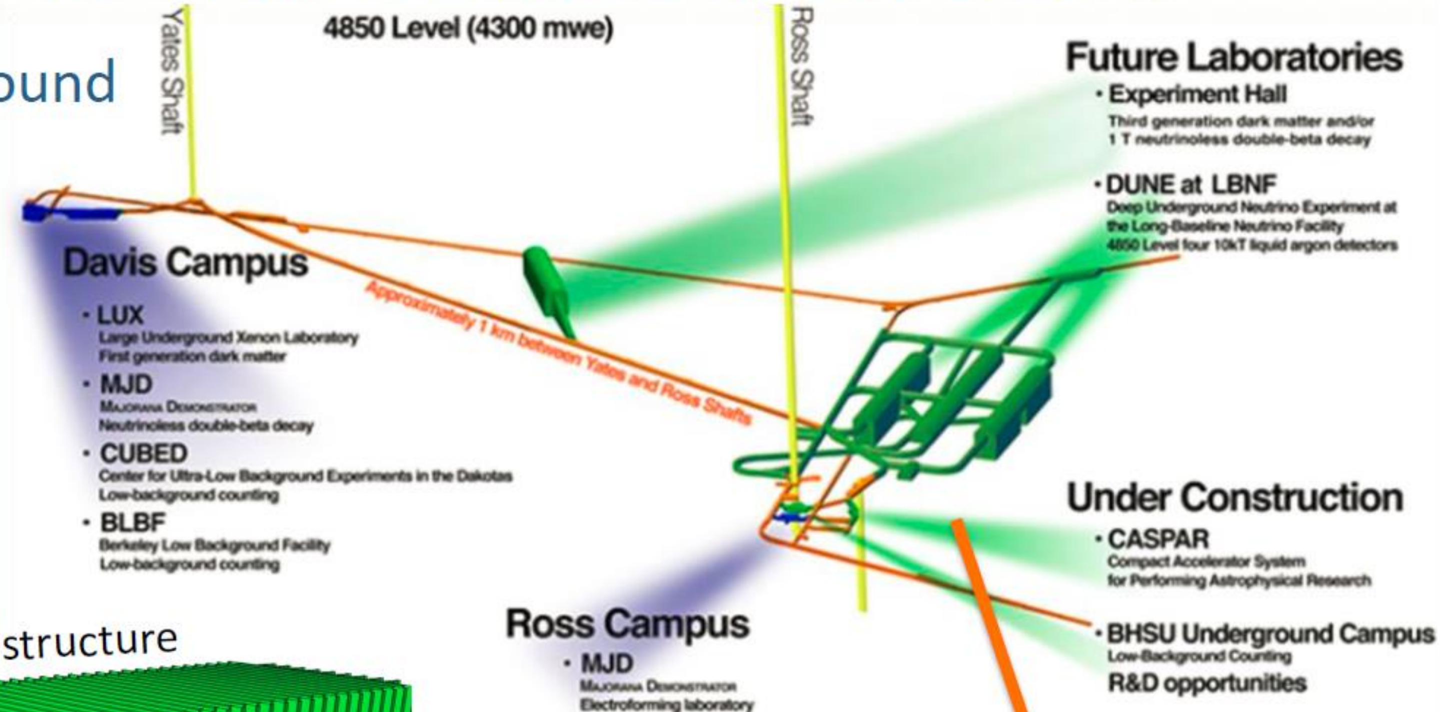
- **1) Neutrino Oscillation Physics**
  - CPV in the leptonic sector
  - Definitive determination of the Mass Hierarchy
  - Precision Oscillation Physics (θ_{23} octant, …) & testing the 3-flavor paradigm
- **2) Nucleon Decay**
  - Targeting SUSY-favored modes, e.g. $p \to K^+\overline{\nu}$
- **3) Supernova burst physics & astrophysics**
  - Galactic core collapse supernova, sensitivity to ν_e

Very clean signals for Kaon decay.

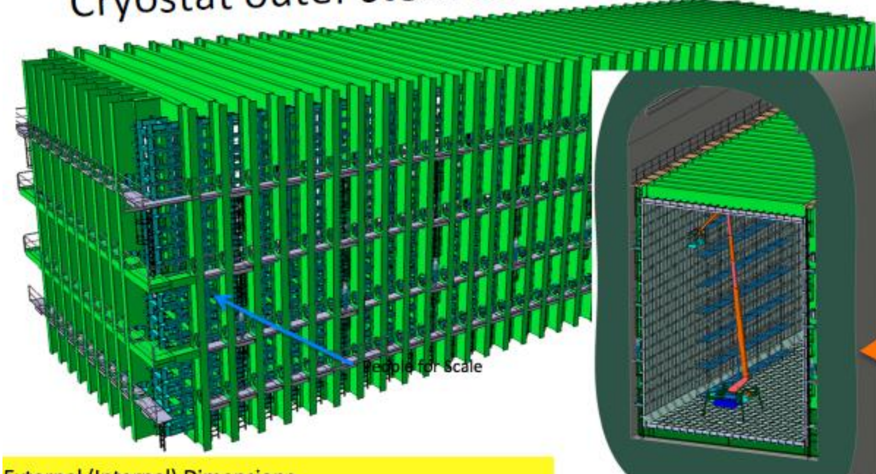


DUNE Far Detector at SURF

Location:
Sanford Underground Research Facility

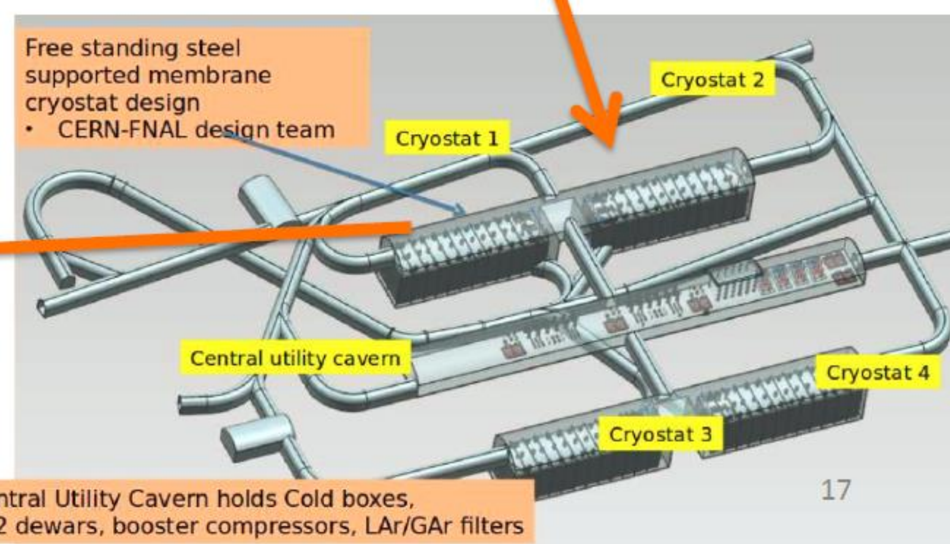


Cryostat outer steel structure



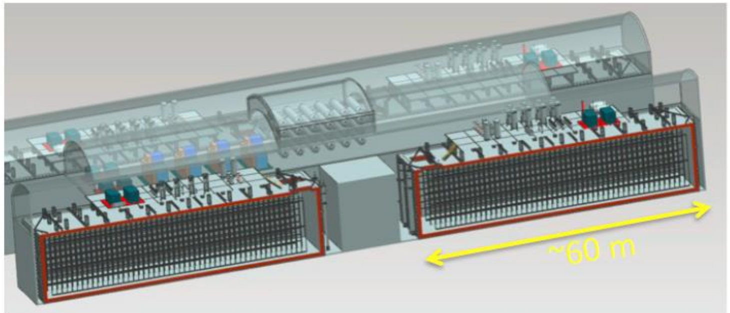
External (Internal) Dimensions
19.1m (16.9m) W x 18.0m (15.8m) H x 66.0m (63.8m) L

Can accommodate single and dual-phase LAr detectors



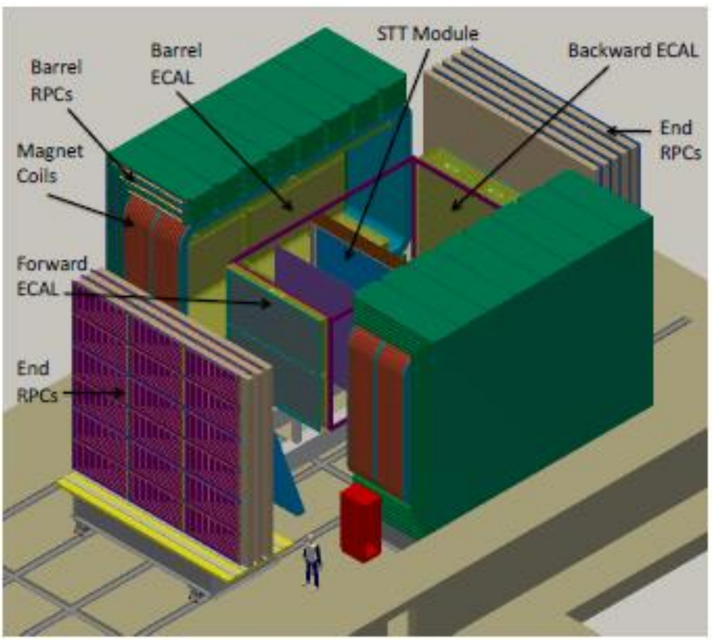
DUNE CDR Design =

Far detector: **40-kt LArTPC**



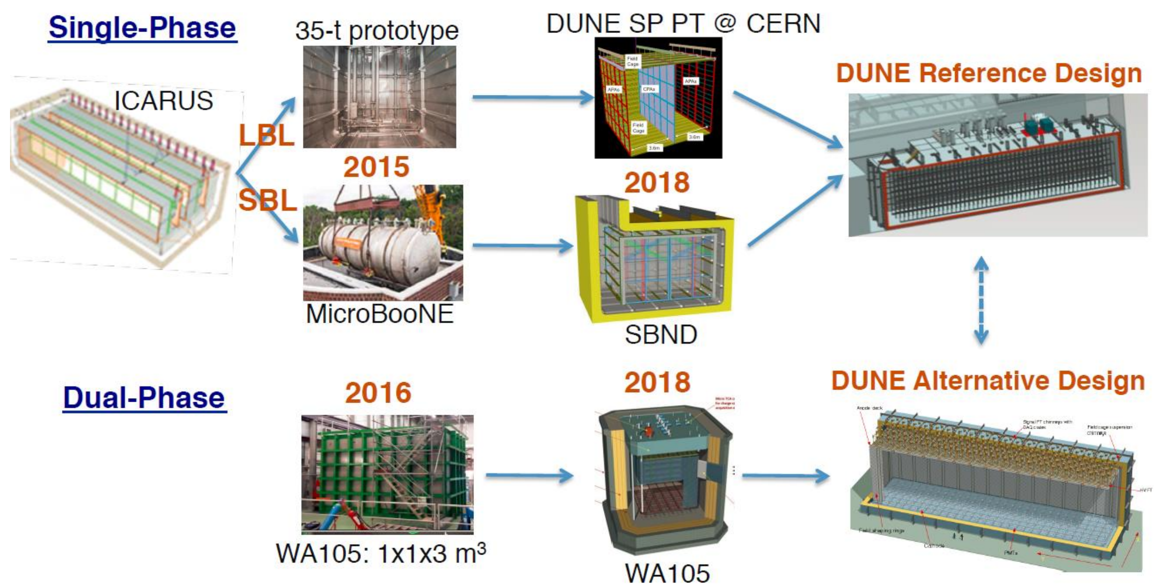
1 mile underground

Near detector : 0.4T straw tube



LArTPC Development Path

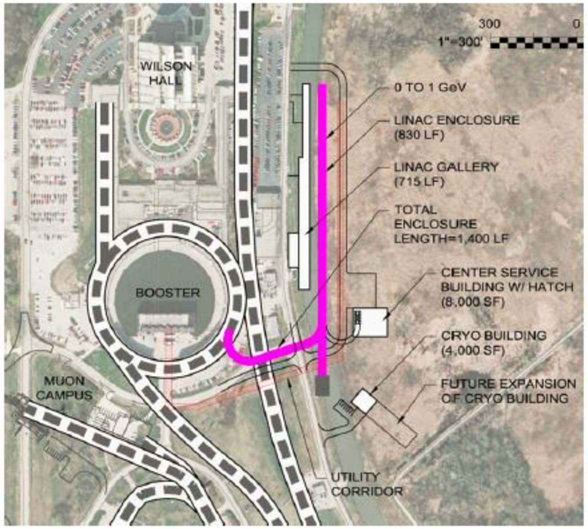
Fermilab SBN and CERN neutrino platform provide a strong **LArTPC** development and prototyping program

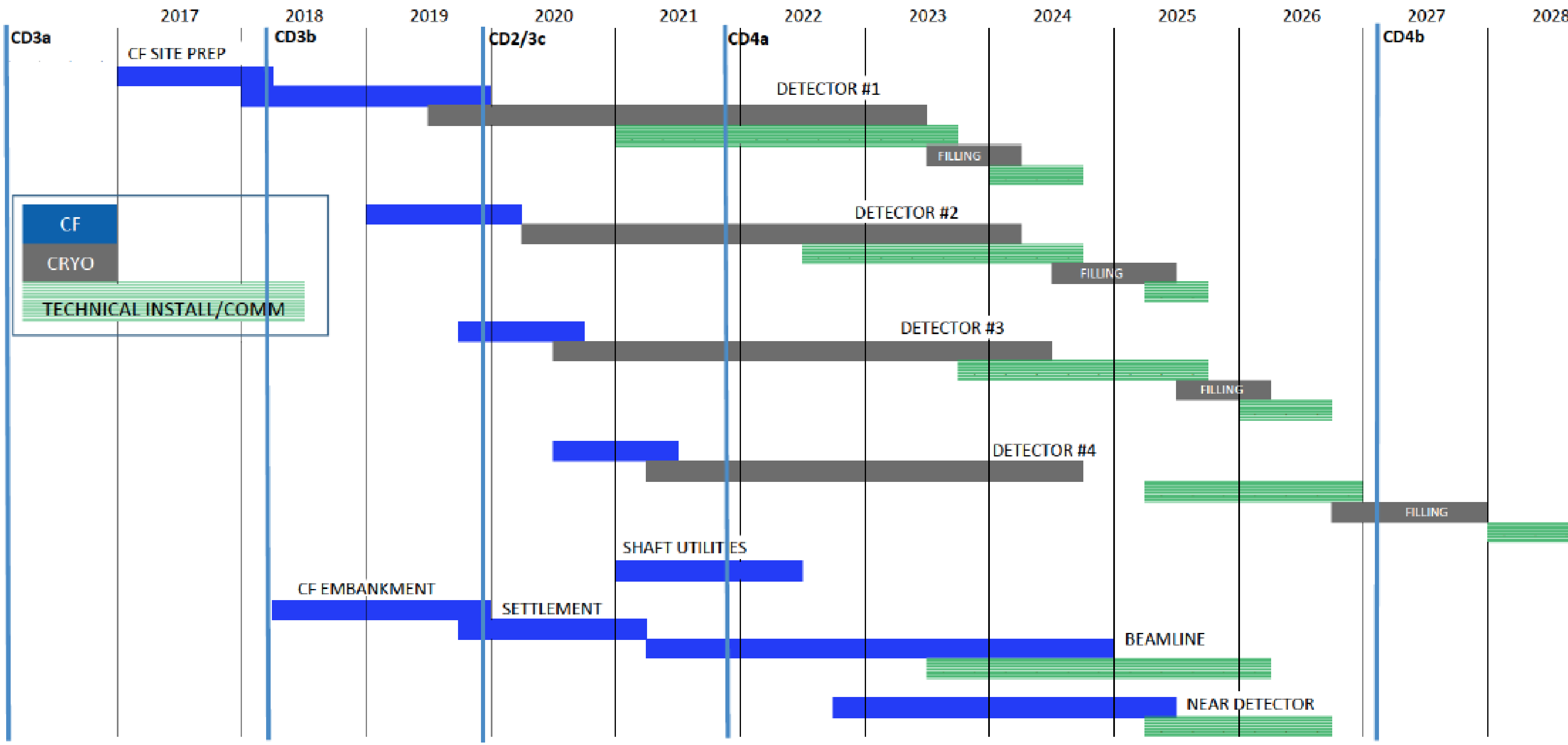


DUNE

LBNF and PIP-II

- ★ In beam-based long-baseline neutrino physics:
  - beam power drives the sensitivity
- ★ LBNF will be the world's most intense high-energy ν beam
  - Build on strong Fermilab track record (BNB & NuMI)
  - 1.2 MW from day one (end 2026)
    - NuMI (MINOS) <400 kW
    - NuMI (NOVA) ultimately ~700 kW
  - upgradable to 2.4 MW After 6 years
- ★ Requires PIP-II (proton-improvement plan)
  - $0.5B upgrade of FNAL accelerator infrastructure
  - Replace existing 400 MeV LINAC with 800 MeV SC LINAC





DUNE Schedule as of CDR http://arxiv.org/abs/1601.05471

Beam starts (with 1.2 MW capability) in 2026 with 2 detectors, upgrade to 2.4Mw ~6 yrs later.

3σ CPV sensitivity over 75% of δ after 13 yrs.

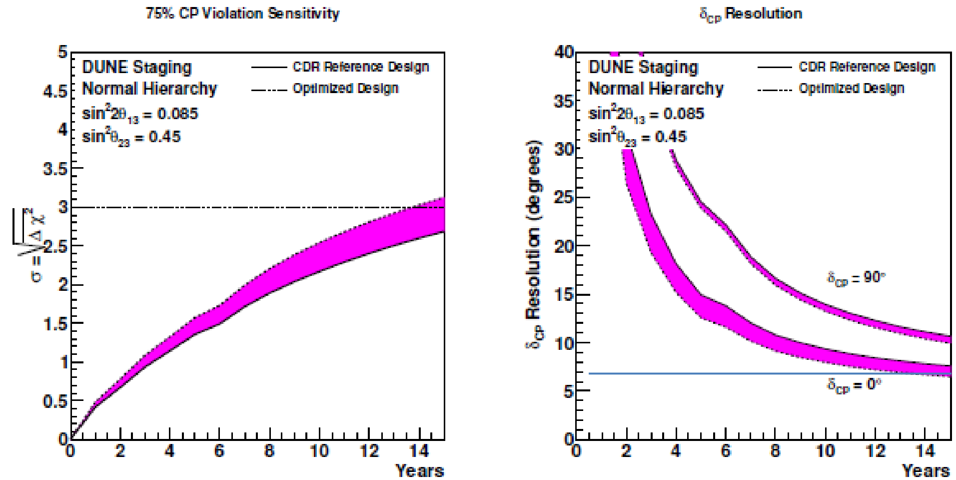
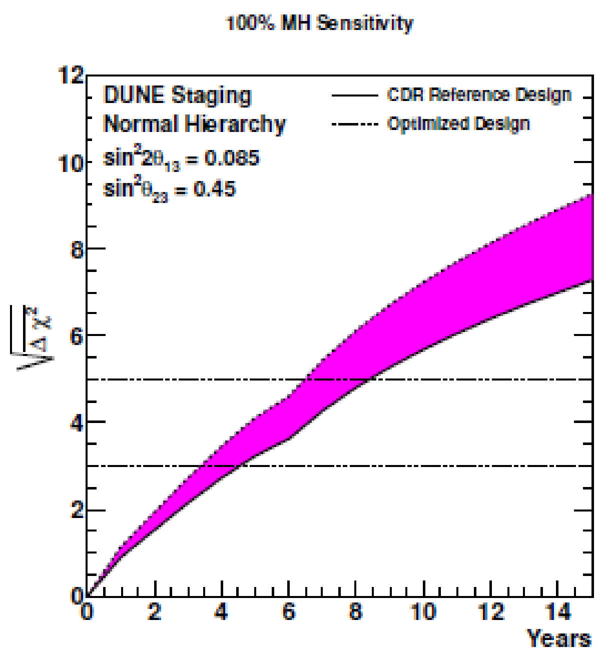
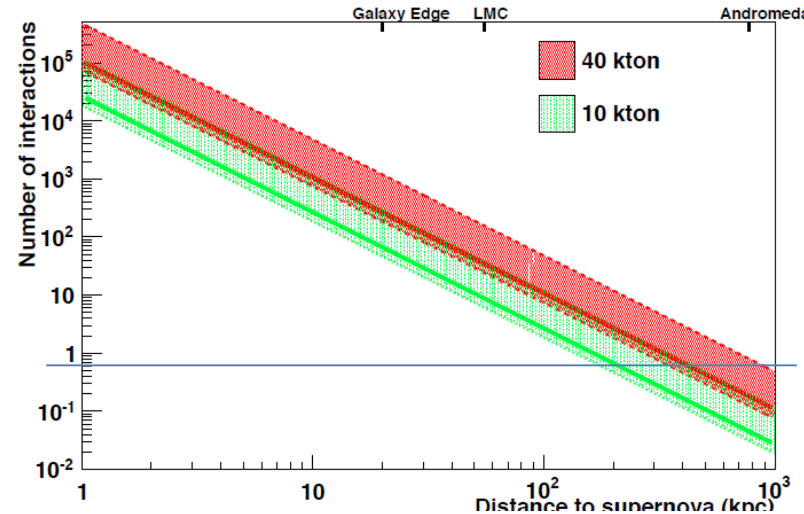
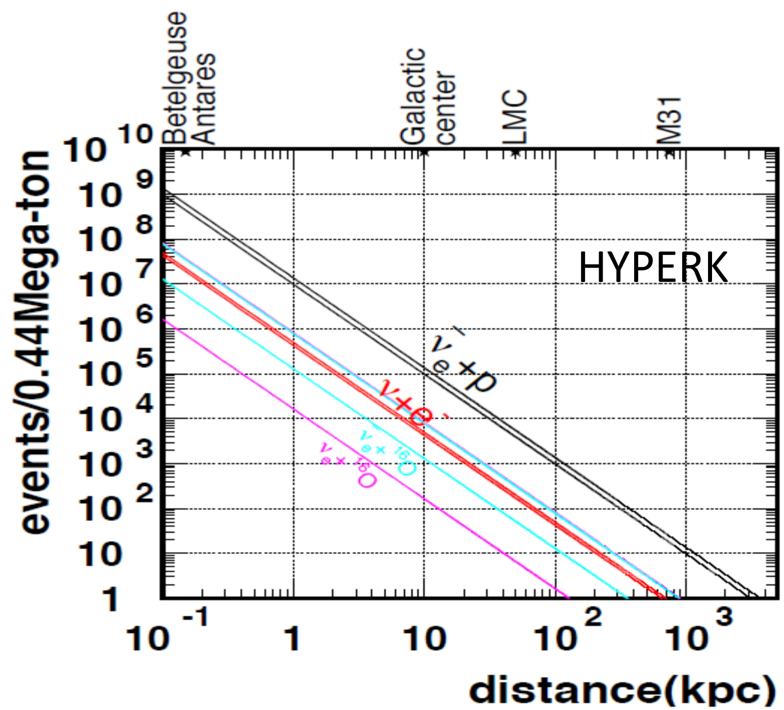


Figure 2.2: The significance with which CP violation can be determined for 75% of δ_{CP} values (left) and the expected 1σ resolution (right) as a function of exposure in years using the proposed staging plan outlined in this chapter. The shaded regions represent the range in sensitivity due to potential variations in the beam design. The plots assume normal mass hierarchy.



SUPERNOVAE $\nu_e + {}^{40}Ar \rightarrow e^- + {}^{40}K^*$



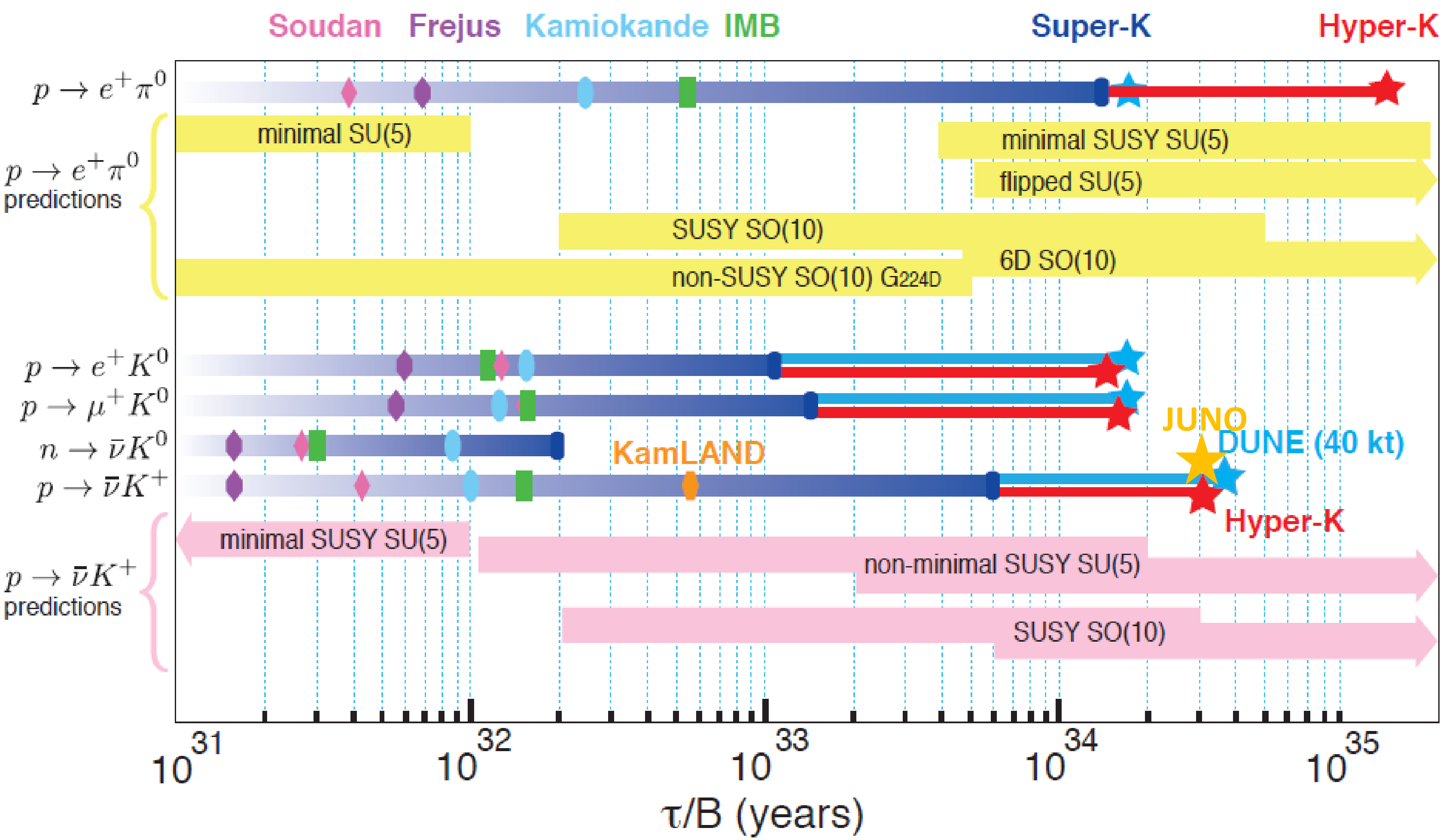


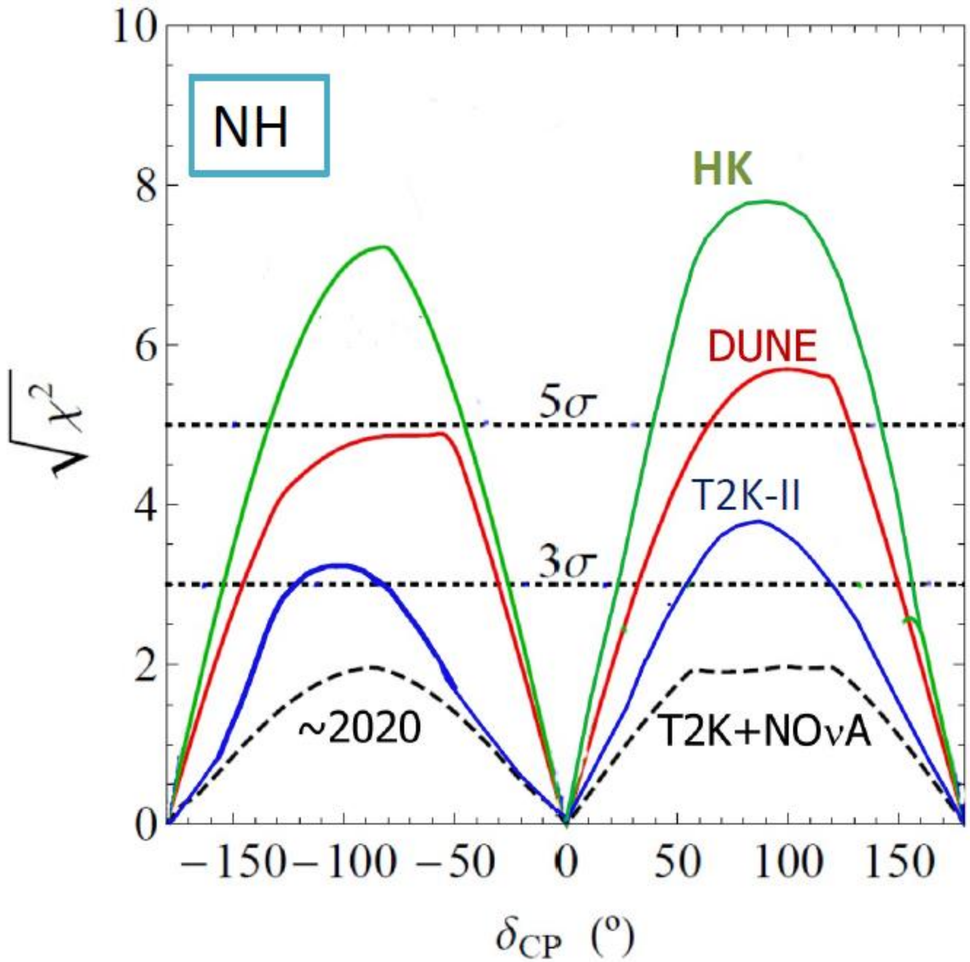
The players   Mass Ordering

Experiment	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30	31	32	33	34	35	36	37	38	39	40
Accelerator LBL																									
T2K																									
T2K-II											}2-4σ														
NOvA																									
Atmospheric																									
PINGU										3σ															
ORCA										3σ															
SK-Gd																									
INO(?)																									
Reactor 20km																									
JUNO											3-4σ														
RENO 50	?	?	?	?	?	?	?	?	?	?					3-4σ										
Accelerator LBL-II																									
HYPER-K																	3.5-5σ								
DUNE																	**5-15σ**								

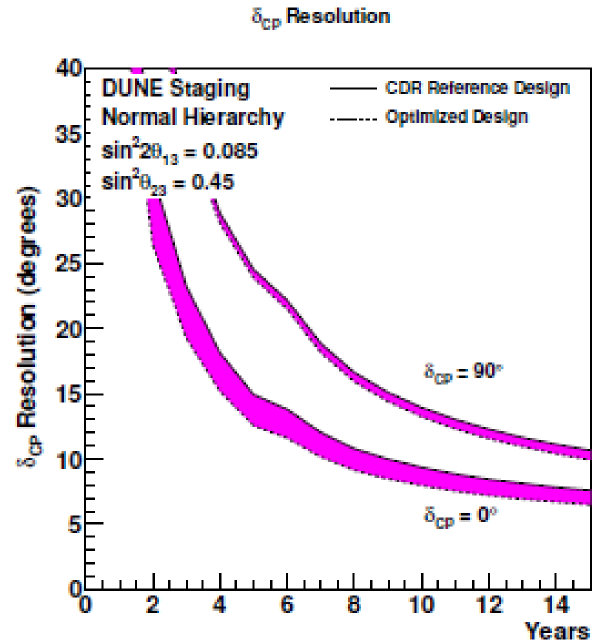
The players CP Violation fraction at 3σ /5σ /(1σ error at δ=0)

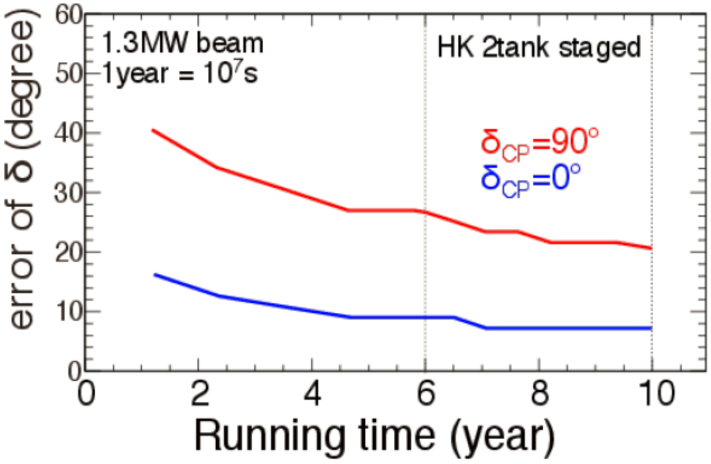
Experiment	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30	31	32	33	34	35	36	37	38	39	40
Accelerator LBL																									
T2K																									
T2K-II									40%/0/<20°																
NOνA																									
Atmospheric																									
PINGU																									
ORCA																									
SK-Gd																									
INO(?)																									
Reactor 20km																									
JUNO																									
RENO 50	?	?	?	?	?	?	?	?	?	?															
Accelerator LBL-II																									
HYPER-K																					78%/62%/7°				
DUNE																									75%/50%/7°


Soudan
Frejus
Kamiokande
IMB
Super-K
Hyper-K
$p \to e^+\pi^0$
$p \to e^+\pi^0$ predictions
minimal SU(5)
minimal SUSY SU(5)
flipped SU(5)
SUSY SO(10)
6D SO(10)
non-SUSY SO(10) G224D
$p \to e^+K^0$
$p \to \mu^+K^0$
$n \to \bar{\nu}K^0$
$p \to \bar{\nu}K^+$
KamLAND
JUNO
DUNE (40 kt)
Hyper-K
$p \to \bar{\nu}K^+$ predictions
minimal SUSY SU(5)
non-minimal SUSY SU(5)
SUSY SO(10)
10^{31}
10^{32}
10^{33}
10^{34}
10^{35}
τ/B (years)



Mezzetto , Neutrino 2016

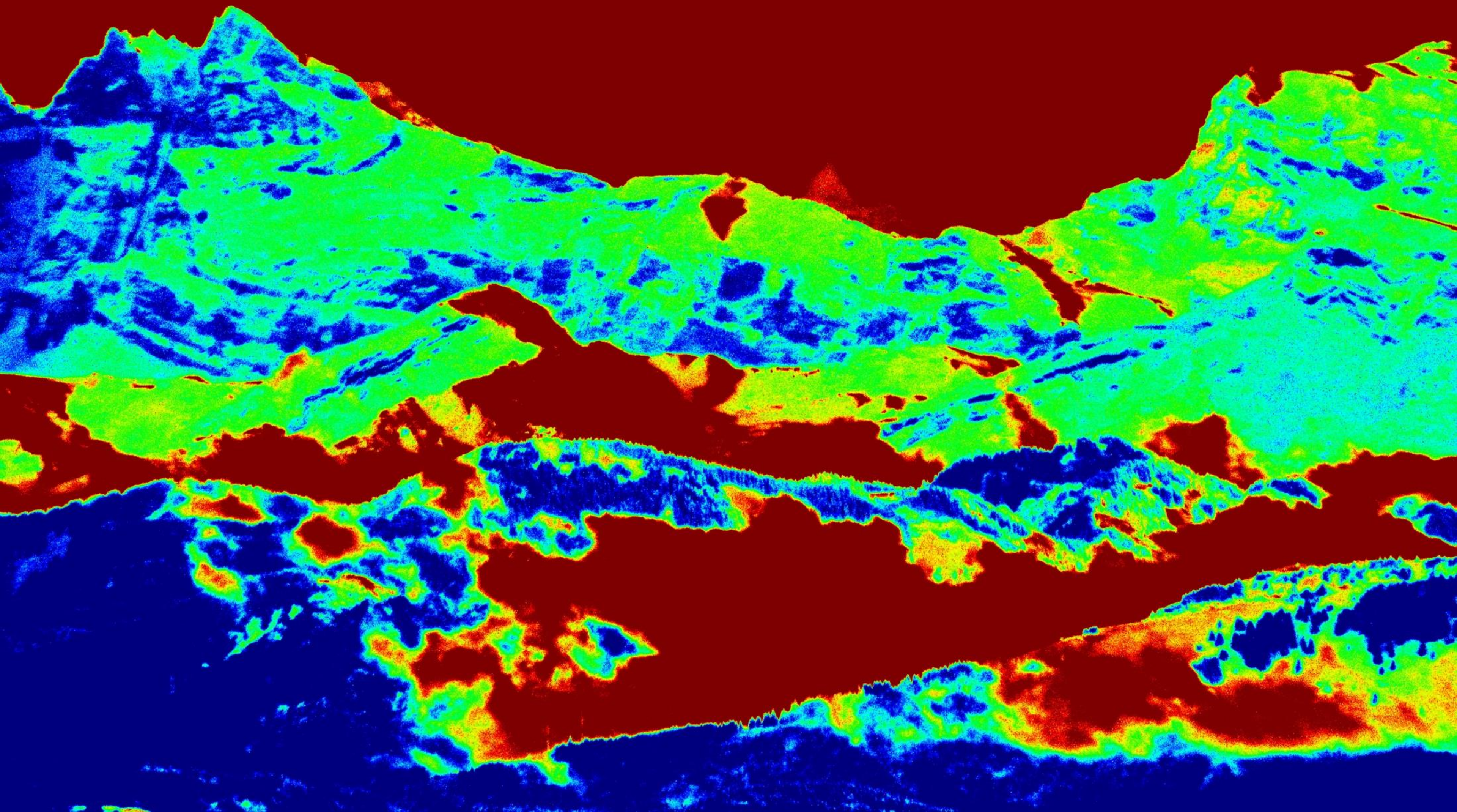




complementarity of DUNE and HYPERK

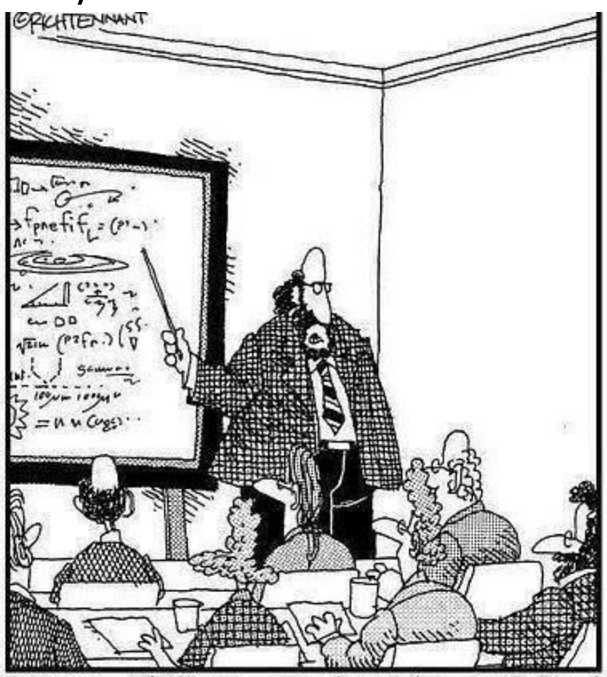
LArg vs WC; 1300km vs 295km; wide-band vs narrow-band

2. The Search for the Right-Handed Neutrinos



Electroweak eigenstates

$\begin{pmatrix} e \\ \nu_e \end{pmatrix}_L$ $\begin{pmatrix} \mu \\ \nu_\mu \end{pmatrix}_L$ $\begin{pmatrix} \tau \\ \nu_\tau \end{pmatrix}_L$	$(e)_R$ $(\mu)_R$ $(\tau)_R$	Q= -1
	$(\nu_e)_R$ $(\nu_\mu)_R$ $(\nu_\tau)_R$	Q= 0
I = 1/2	I = 0	



"Along with 'Antimatter,' and 'Dark Matter,' we've recently discovered the existence of 'Doesn't Matter,' which appears to have no effect on the universe whatsoever."

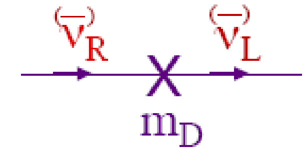
Right handed neutrinos are singlets
no weak interaction
no EM interaction
no strong interaction

can't produce them
can't detect them
-- so why bother? –

Also called 'sterile'

Adding masses to the Standard model neutrino 'simply' by adding a Dirac mass term (Yukawa coupling)

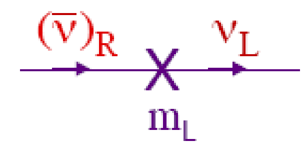
$$m_D \nu_L \overline{\nu_R} \qquad m_D \overline{\nu_L} \nu_R$$



implies adding a right-handed neutrino (new particle)

<u>No SM symmetry</u> prevents adding then a term like

$$m_M \overline{\nu_R}^c \nu_R$$



and this simply means that a neutrino turns into a antineutrino

It is perfectly conceivable ('natural'?) that both terms are present.

Dirac mass term + Majorana mass term ➔ 'see-saw'

B. Kayser, the physics of massive neutrinos (1989)

Mass eigenstates

See-saw type I :

$$\mathcal{L} = \frac{1}{2}(\bar{\nu}_L, \bar{N}^c_R) \begin{pmatrix} 0 & m_D \\ m_D^T & M_R \end{pmatrix} \begin{pmatrix} \nu^c_L \\ N_R \end{pmatrix}$$

$M_R \neq 0$
$m_D \neq 0$
Dirac + Majorana mass terms

$$\tan 2\theta = \frac{2\, m_D}{M_R - 0} \qquad \ll 1$$

$$m_\nu = \tfrac{1}{2}\left[(0 + M_R) - \sqrt{(0 - M_R)^2 + 4\, m_D^2}\right] \qquad \simeq -m_D^2/M_R$$

$$M = \tfrac{1}{2}\left[(0 + M_R) + \sqrt{(0 - M_R)^2 + 4\, m_D^2}\right] \qquad \simeq M_R$$

general formula — if $m_D \ll M_R$

$M_R = 0$
$m_D \neq 0$
Dirac only, (like e- vs e+):

m ↑

ν_L ν_R $\bar{\nu}_L$ $\bar{\nu}_R$
I_{weak}= ½ 0 ½ 0

4 states of equal masses

Some have I=1/2 (active)
Some have I=0 (sterile)

$M_R \neq 0$
$m_D = 0$
Majorana only

m ↑

ν_L $\bar{\nu}_R$
I_{weak}= ½ ½

2 states of equal masses

All have I=1/2 (active)

$M_R > m_D \neq 0$ see-saw

Dirac + Majorana

m ↑

dominantly: ν N $\bar{\nu}$ $\bar{N}$
I_{weak}= ½ 0 ½ 0

4 states , 2 mass levels

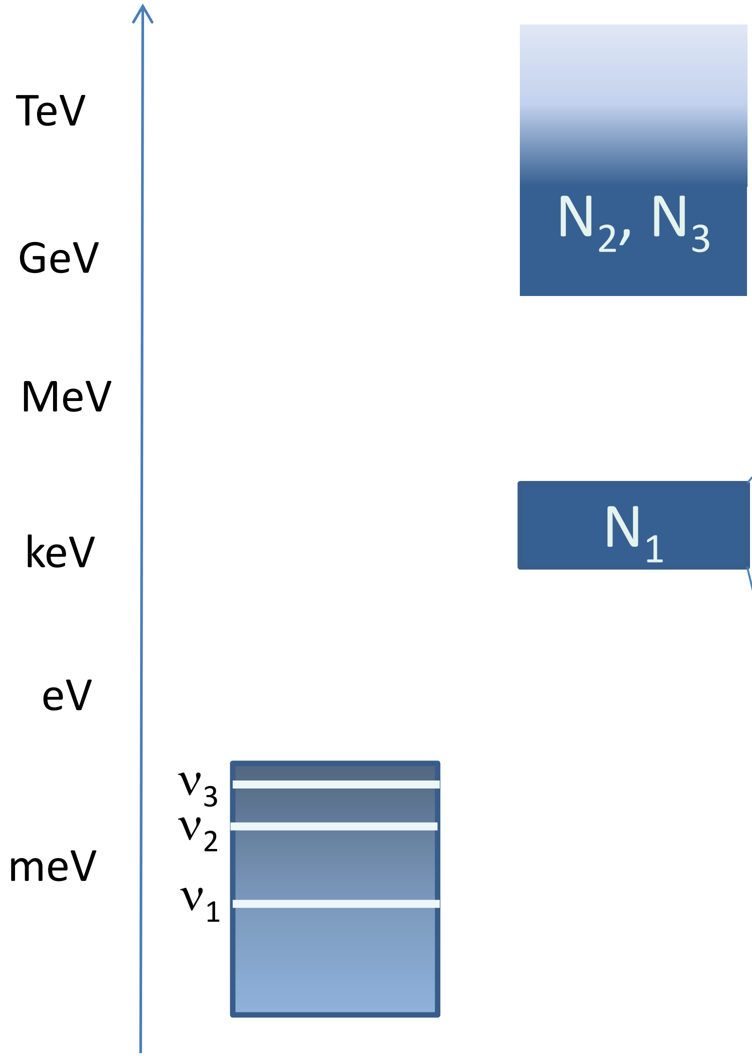
m_1 have ~I=1/2 (~active)
m_2 have ~I=0 (~sterile)

Although it is often considered (GUT) that the heavy neutrinos have masses at energy scale of a fraction of GUT scale, *we actually dont know this.*

It is perfectly plausible that the observed masses of neutrinos (0.05 eV) are consistent with Dirac masses of O(< m_e) and Majorana mass of O(m_W).

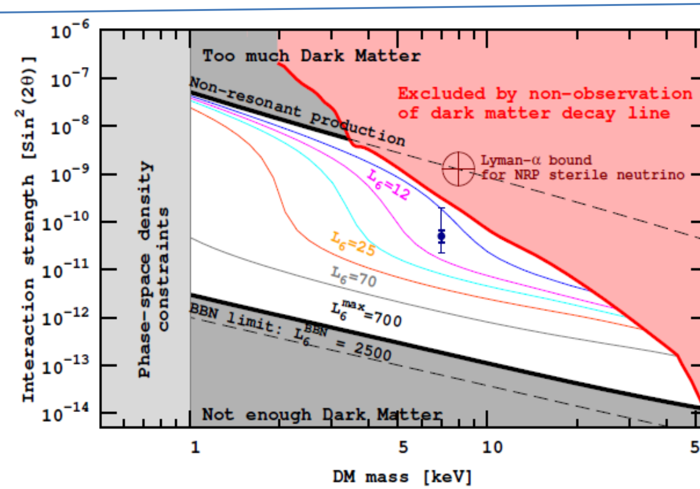
There even exists a scenario that claims to explains everything: the νMSM

Shaphoshnikov et al

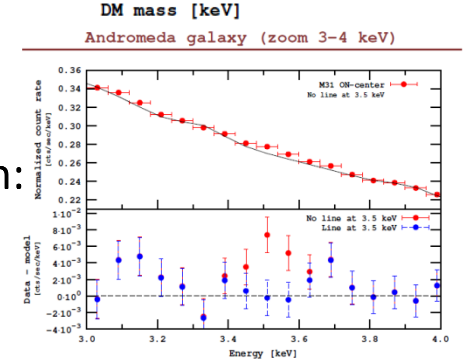


can generate Baryon Asymmetry of Universe if $m_{N2,N3} > 140$ MeV

constrained:
mass: 1-50 keV
mixing : 10^{-7} to 10^{-13}
decay time:
$\tau_{N1} > \tau_{Universe}$



$N_1 \rightarrow \nu \gamma$
may have been seen:
arxiv:1402:2301
arxiv:1402.4119



can be dark matter?

SEARCHING FOR THE 3.5 KEV LINE IN THE DEEP FIELDS WITH CHANDRA: THE 10 MS OBSERVATIONS

Nico Cappelluti[1,2,3], Esra Bulbul[4], Adam Foster[5], Priyamvada Natarajan[1,2,3], Megan C. Urry[1,2,3], Mark W. Bautz[4], Francesca Civano[5], Eric Miller[4], and Randall K. Smith[5]

Draft version January 30, 2017

arXiv:1701.07932v1

ABSTRACT

In this paper we report a 3σ detection of an emission line at $\sim$3.5 keV in the spectrum of the Cosmic X-ray Background using a total of $\sim$10 Ms Chandra observations towards the COSMOS Legacy and CDFS survey fields. The line is detected with an intensity is $8.8 \pm 2.9 \times 10^{-7}$ ph cm^{-2}s^{-1}. Based on our knowledge of *Chandra*, and the reported detection of the line by other instruments, we can rule out an instrumental origin for the line. We cannot though rule out a background fluctuation, in that case, with the current data, we place a 3σ upper limit at 10^{-6} ph cm^{-2}s^{-1}. We discuss the interpretation of this observed line in terms of the iron line background, S XVI charge exchange, as well as arising from sterile neutrino decay. We note that our detection is consistent with previous measurements of this line toward the Galactic center, and can be modeled as the result of sterile neutrino decay from the Milky Way when the dark matter distribution is modeled with an NFW profile. In this event, we estimate a mass $m_s \sim$7.02 keV and a mixing angle $\sin^2(2\theta)$= 0.69–2.29 $\times 10^{-10}$. These derived values of the neutrino mass are in agreement with independent measurements toward galaxy clusters, the Galactic center, and M31.

Manifestations of right handed neutrinos

one family see-saw :
$\theta \approx (m_D/M)$
$m_\nu \approx \frac{m_D{}^2}{M}$
$m_N \approx M$
$|U|^2 \propto \theta^2 \approx m_\nu / m_N$

$$\nu = \nu_L \cos\theta \; - N^c{}_R \; \sin\theta$$

$$N = N_R \; \cos\theta + \; \nu_L{}^c \; \sin\theta$$

what is produced in W, Z decays is:

$$\nu_L = \; \nu \cos\theta \; + N \; \sin\theta$$

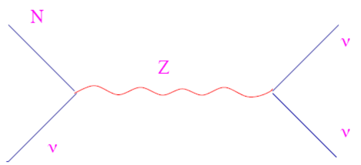
ν = light mass eigenstate
N = heavy mass eigenstate
$\neq \nu_L$, active neutrino
which couples to weak inter.
and $\neq N_R$, which does'nt.

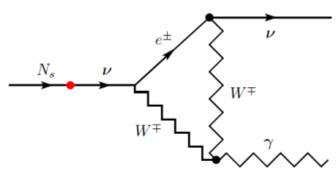
-- mixing with active neutrinos leads to various observable consequences
  -- if very light (eV) , possible effect on neutrino oscillations
  -- if in keV region (dark matter), monochromatic photons from galaxies with $E=m_N/2$
-- possibly measurable effects at High Energy
  If N is heavy it will decay in the detector (not invisible)
  ➔ PMNS matrix unitarity violation and deficit in Z «invisible» width
  ➔ Higgs, Z, W visible exotic decays $H \rightarrow \nu_i \; \bar{N}_i$ and $Z \rightarrow \nu_i \; \bar{N}_i$, $W \rightarrow l_i \; \bar{N}_i$
  ➔ also in K, charm and b decays via $W^* \rightarrow l_i{}^{\pm} \; \bar{N}$, $N \rightarrow l_j{}^{\pm}$
  with any of six sign and lepton flavour combination
  ➔ violation of unitarity and lepton universality in Z, W or τ decays
  -- etc... etc...
-- Couplings are very small (m_ν / m_N) *(but who knows?)* **and generally seem out of reach at high energy colliders.**

Search Processes (I)

m_N Below m_π:

N→ 3ν; N→ νγ w $E_\gamma = m_N/2$





$$\tau_{N_1} = 10^{14}\,\text{years}\left(\frac{10\,\text{keV}}{M_N}\right)^5\left(\frac{10^{-8}}{\theta_1^2}\right)$$

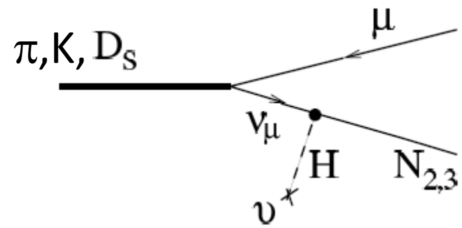
Long life, **dark matter candidate**

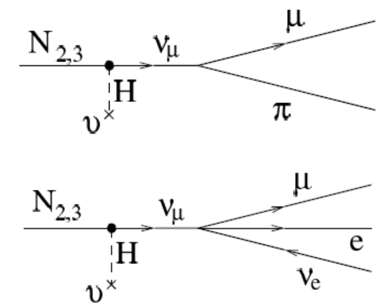
Equilibrium with neutrinos produced in the stars

→ Search for gamma emission line (such as 3.5 keV line)

Drewes et al; arXiv:1602.04816v1

Meson decay (π,K: neutrino beams) examples:





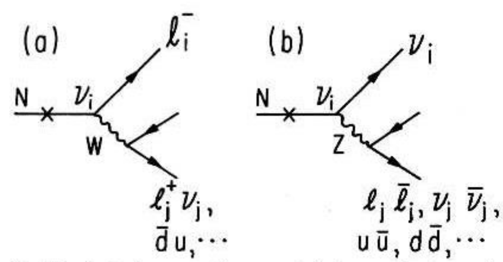


FIG. 2. Typical decays of a neutral heavy lepton via (a) charged current and (b) neutral current. Here the lepton l_i

$$L \approx \frac{3}{|U|^2\ (m_{\nu_m}(\mathrm{GeV}/c^2))^6} \times \frac{P_\nu}{45 GeV/c}$$

Decay via W gives at least two charged particles, and amounts to ~60% of decays.

Searches for long lived decays in neutrino beams PS191, NuTeV, CHARM; SHIP and DUNE proposals

Search for masses < m_c or m_τ

Experiment	PS191	NuTeV	CHARM	SHiP
Proton energy (GeV)	19.2	800	400	400
Protons on target ($\cdot 10^{19}$)	0.86	0.25	0.24	20
Decay volume (m^3)	360	1100	315	1780
Decay volume pressure (bar)	1 (He)	1 (He)	1 (air)	10^{-6} (air)
Distance to target (m)	128	1400	480	80-90
Off beam axis (mrad)	40	0	10	0

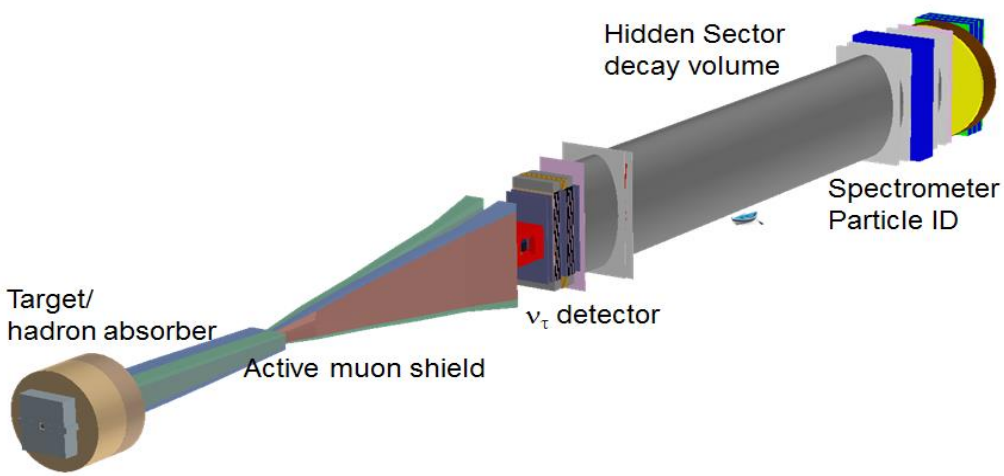
Next generation heavy neutrino search experiment SHIP

-- focuses on neutrinos from charm to cover 0.5 – 2 GeV region

-- uses beam dump to reduce background from neutrino interactions from pions and Kaons and bring the detector as close as possible to source.

-- increase of beam intensity and decay volume

status: proposal, physics report and technical report exist. R&D phase approved at CERN



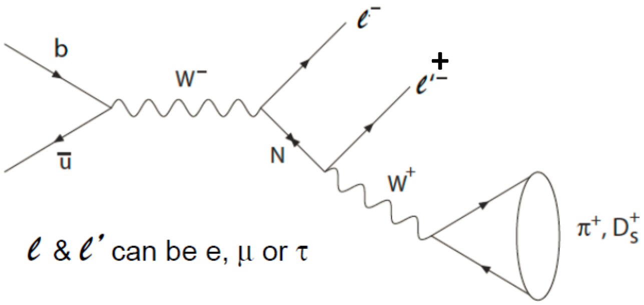
arXiv:1504.04855

arXiv:1504.04956

Processes (II)

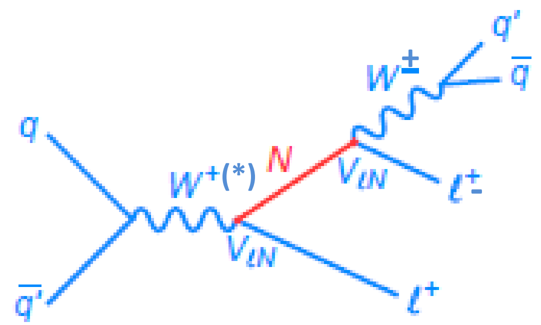
Search for heavy right-handed neutrinos in collider experiments.

B factories



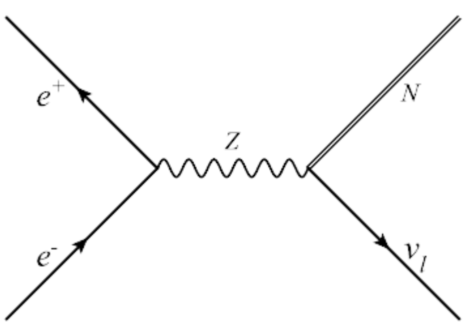
ℓ & ℓ′ can be e, μ or τ

Hadron colliders

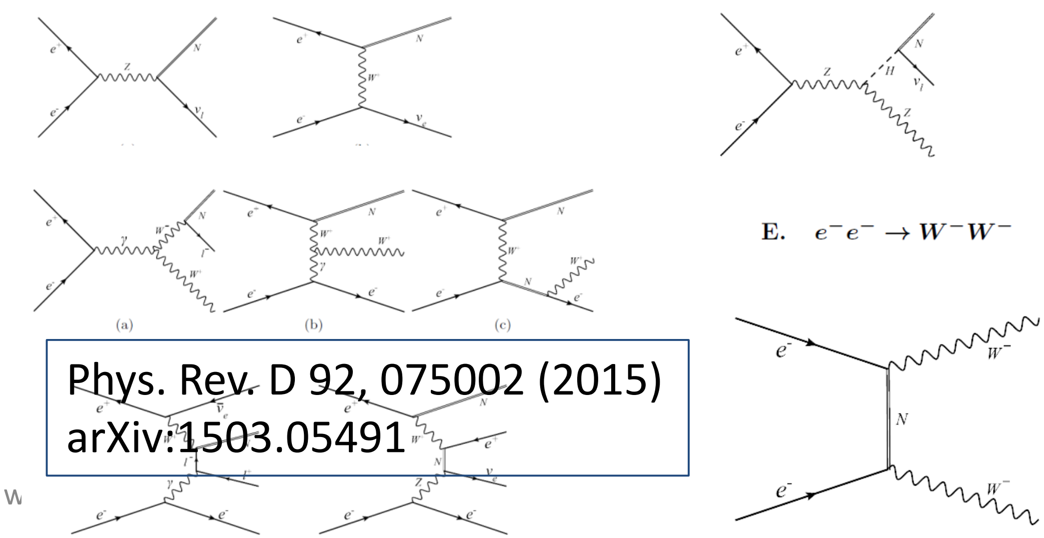


Z factory (FCC-ee, Tera-Z)

arXiv:1411.5230



HE Lepton Collider (LEP2, CEPC, CLIC, FCC-ee, ILC, μμ)



Phys. Rev. D 92, 075002 (2015)
arXiv:1503.05491

Future Circular Collider Study - SCOPE
CDR and cost review for the next ESU (2018)

Forming an international collaboration to study:

- ***pp*-collider (*FCC-hh*)**

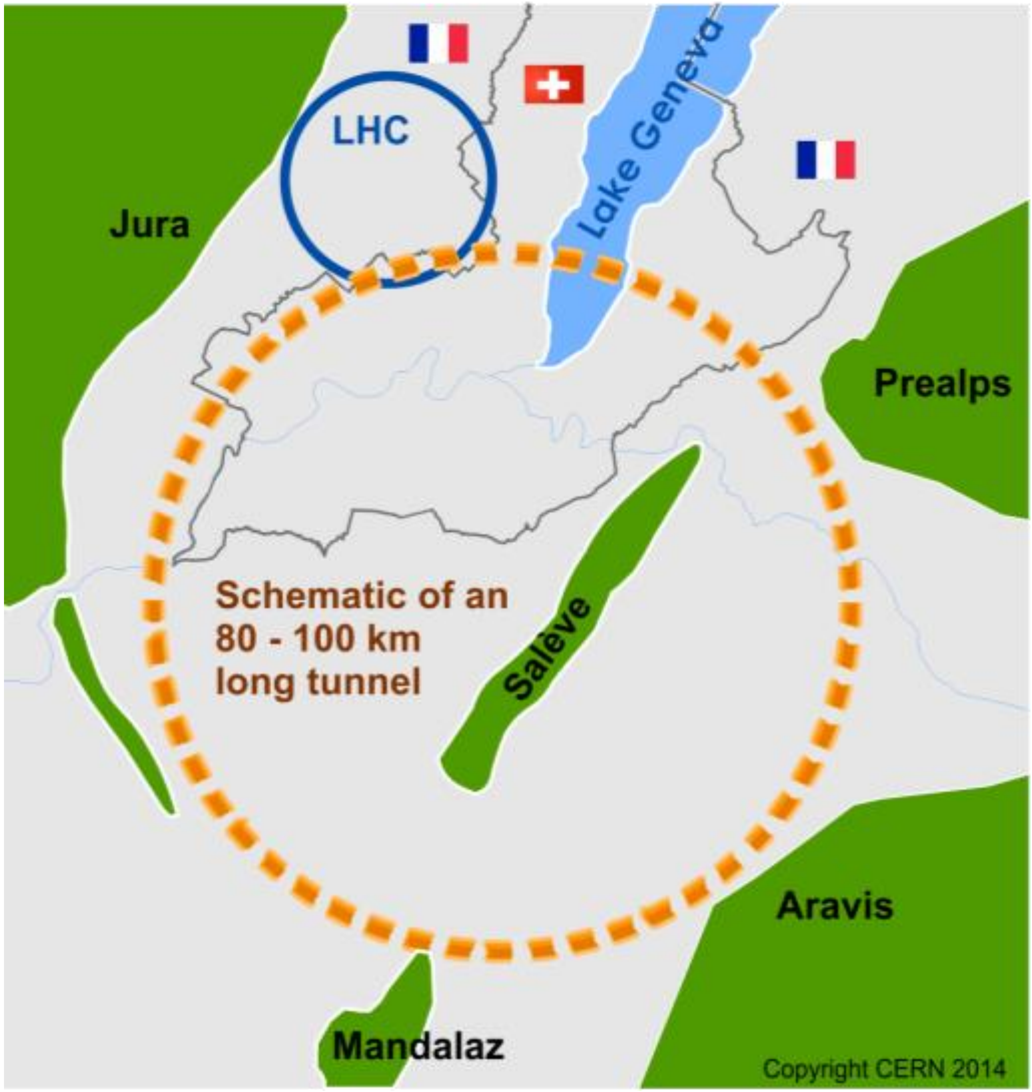
~16 T ⇒ 100 TeV *pp* in 100 km

→ ultimate goal defining infrastructure requirements

- **e^+e^- collider (*FCC-ee*)**
  as potential first step
  ECM=90-400 GeV

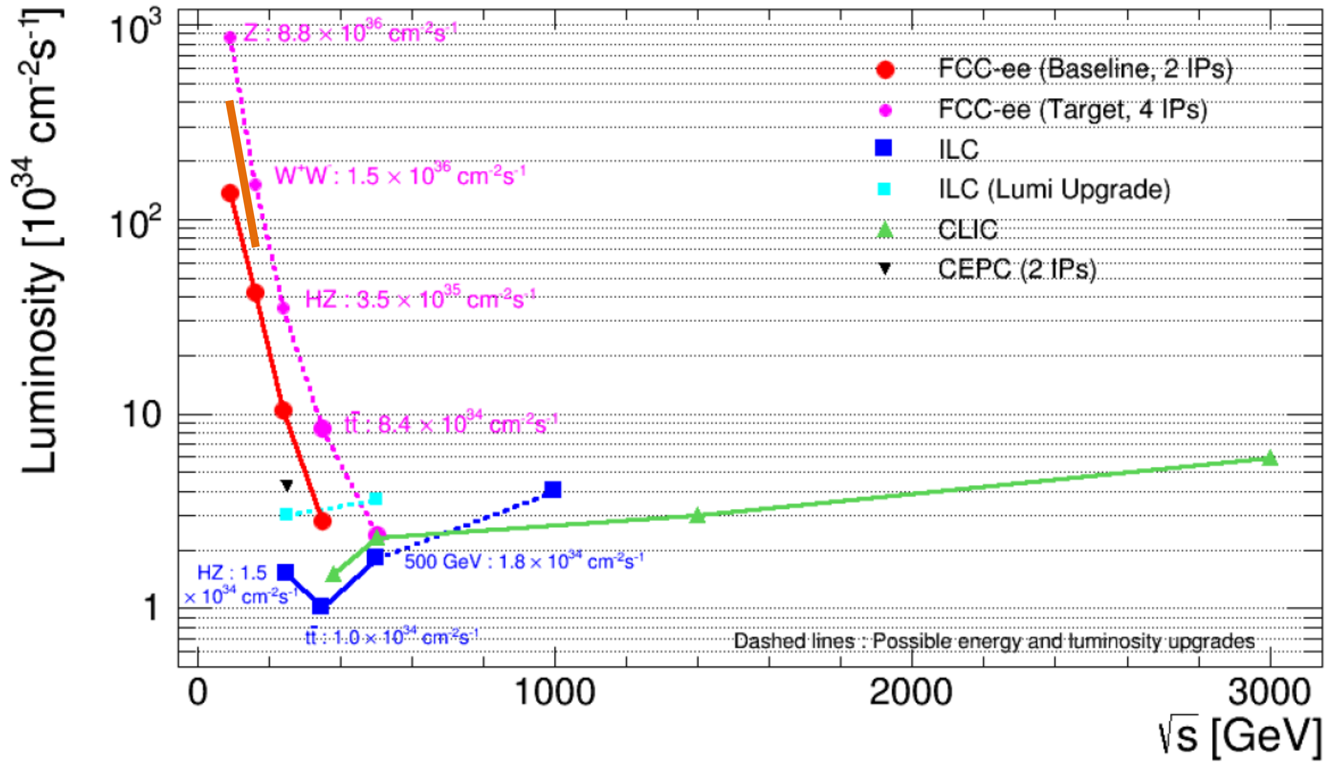
- ***p-e* (*FCC-he*) option**

- **80-100 km infrastructure** in Geneva area



FCC-ee highest possible luminosity from Z to tt by exploiting b-factory technologies:

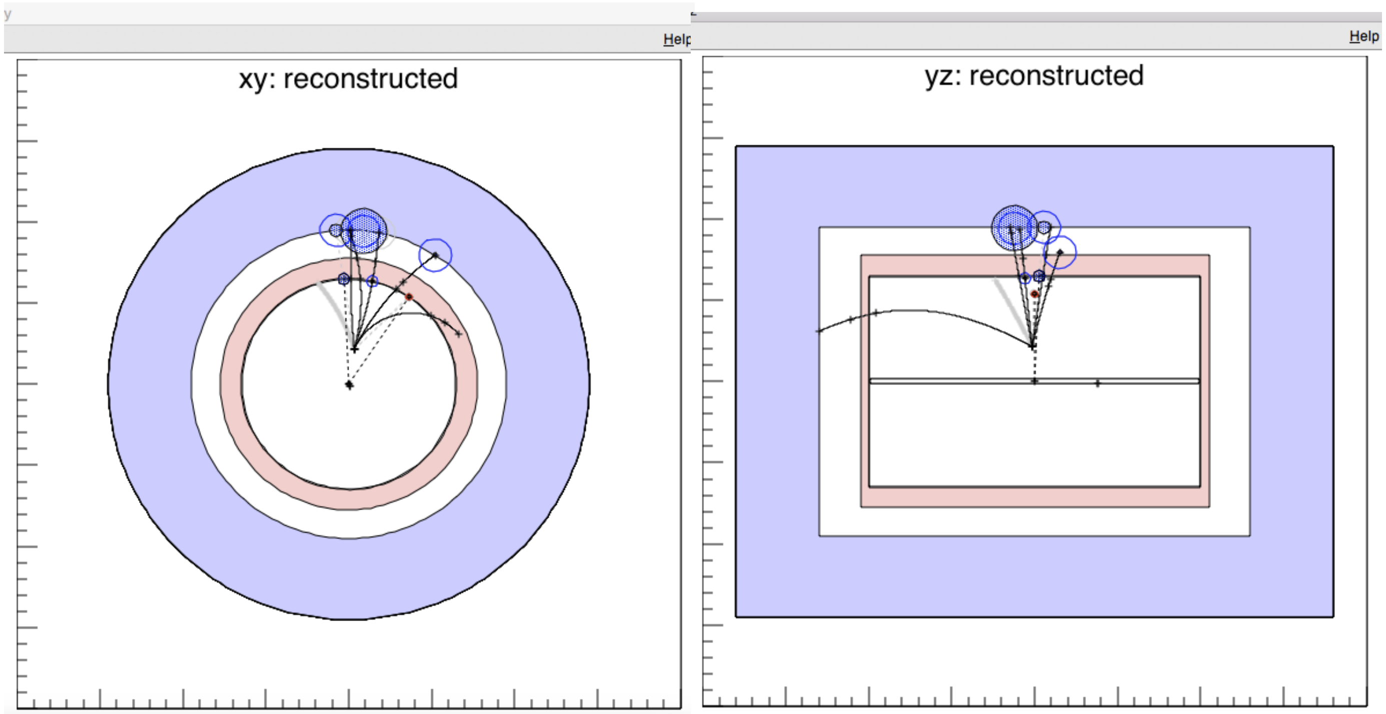
- **separate e- and e+ storage rings**
- **very strong focussing: β*y = 1 - 2 mm (target, baseline -- work in progress!)**
- **top-up injection**
- **crab-waist crossing**



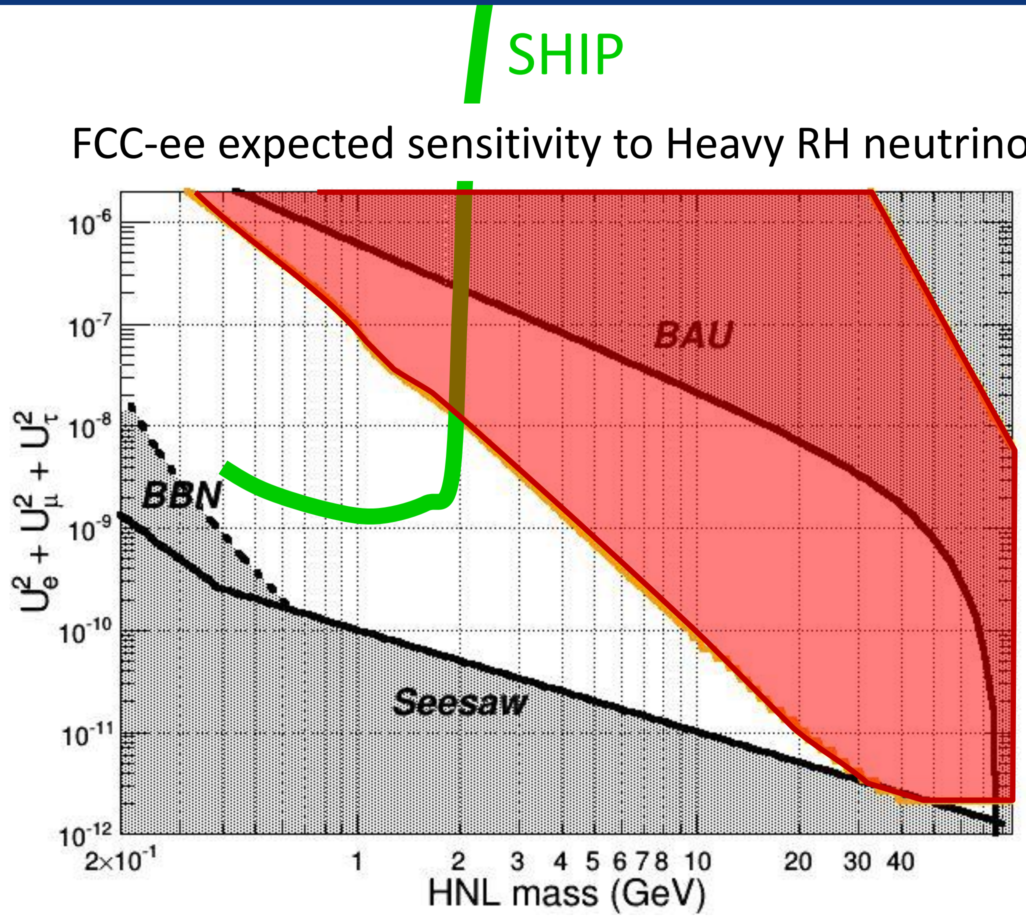
Event statistics :

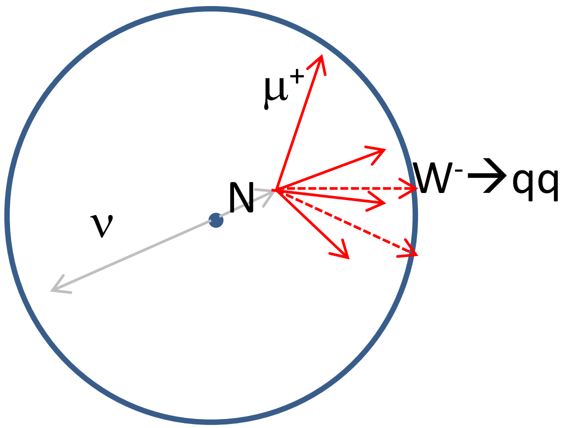
Z peak	E_{cm} : 91 GeV	5 10^{12}	e+e- → Z	LEP x 2.10^5
WW threshold	E_{cm} : 161 GeV	10^8	e+e- → WW	LEP x 2.10^3
ZH threshold	E_{cm} : 240 GeV	10^6	e+e- → ZH	Never done
tt threshold	E_{cm} : 350 GeV	10^6	e+e- → tt	Never done

Simulation of heavy neutrino decay in a FCC-ee detector



FCC-ee expected sensitivity to heavy RH neutrinos





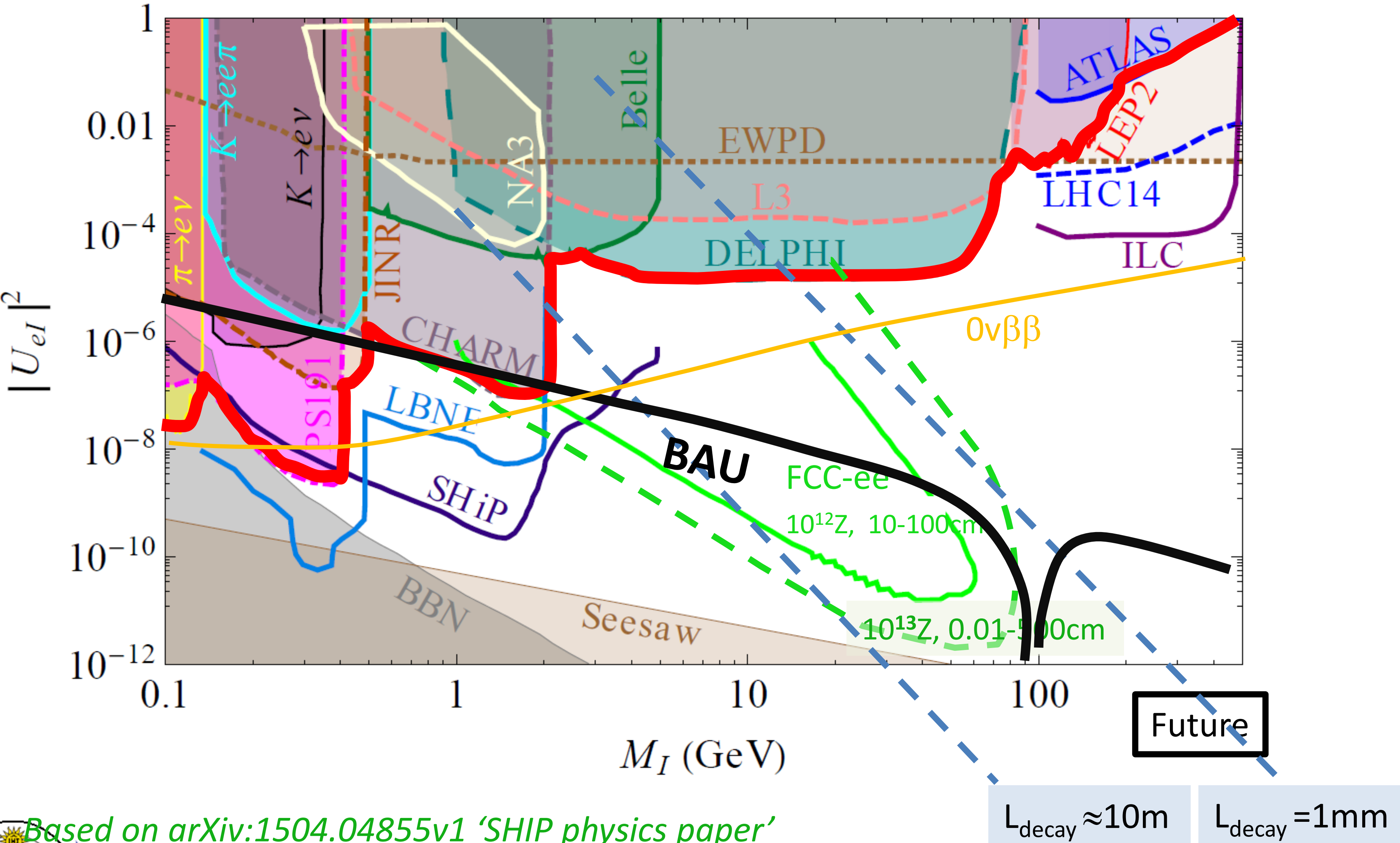
$N_Z = 10^{13}$ $100\mu m < L < 5m$

region of interest

FCC-ee sensitivity

NB: very large detector caverns for FCC-hh may allow for very large FCC-ee detector (R=8 m?) leading to improved reach at lower masses

Present limits



Based on arXiv:1504.04855v1 'SHIP physics paper'
And Pilar Hernandez, HEP-EPS Vienna

The seesaw path to leptonic CP violation

A. Caputo[a,1,2], P. Hernandez [b,1,2], M. Kekic [c,1], J. López-Pavón [d,2], J. Salvado[e,1]

[1]Instituto de Física Corpuscular, Universidad de Valencia and CSIC,
Edificio Institutos Investigación, Catedrático José Beltrán 2, 46980 Spain.
[2]CERN, Theoretical Physics Department, Geneva, Switzerland.

$$|U_{ei}|^2 M_i \simeq A\left[r s_{12}^2 - 2\sqrt{r}\theta_{13}\sin(\delta+\phi_1)s_{12} + \theta_{13}^2 + \mathcal{O}(\varepsilon^{5/2})\right],$$
$$|U_{\mu i}|^2 M_i \simeq A\Big[s_{23}^2 - \sqrt{r}\, c_{12}\sin\phi_1 \sin 2\theta_{23} + r c_{12}^2 c_{23}^2$$
$$+2\sqrt{r}\,\theta_{13}\sin(\phi_1+\delta)s_{12}s_{23}^2 - \theta_{13}^2 s_{23}^2 + \mathcal{O}(\varepsilon^{5/2})\Big]. \quad (6)$$

arXiv:1611.05000v1 (SHIP, B factory, Z factory)

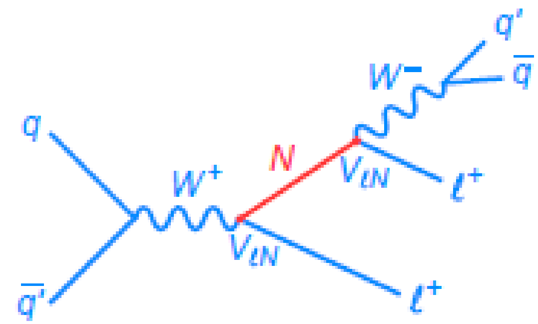
The ratio of decays to muons vs electrons is directlly related to the CP phase (and the known PMNS angles)

➔ the discovery of a massive neutrino and the measurement of its mass and its mixings to electrons and muons can result in a 5σ CL discovery of leptonic CP violation in very significant fraction of the CP-phase parameter space (> 80%/>60%) for IH/NH

for mixings above $O(10^{-8})$ in SHiP and above $O(10^{-10})$ in FCC-ee.

Outlook for FCC-hh

We have seen that the Z factory offers a clean method for detection of Heavy Right-Handed neutrinos
Ws are less abundant at the lepton colliders



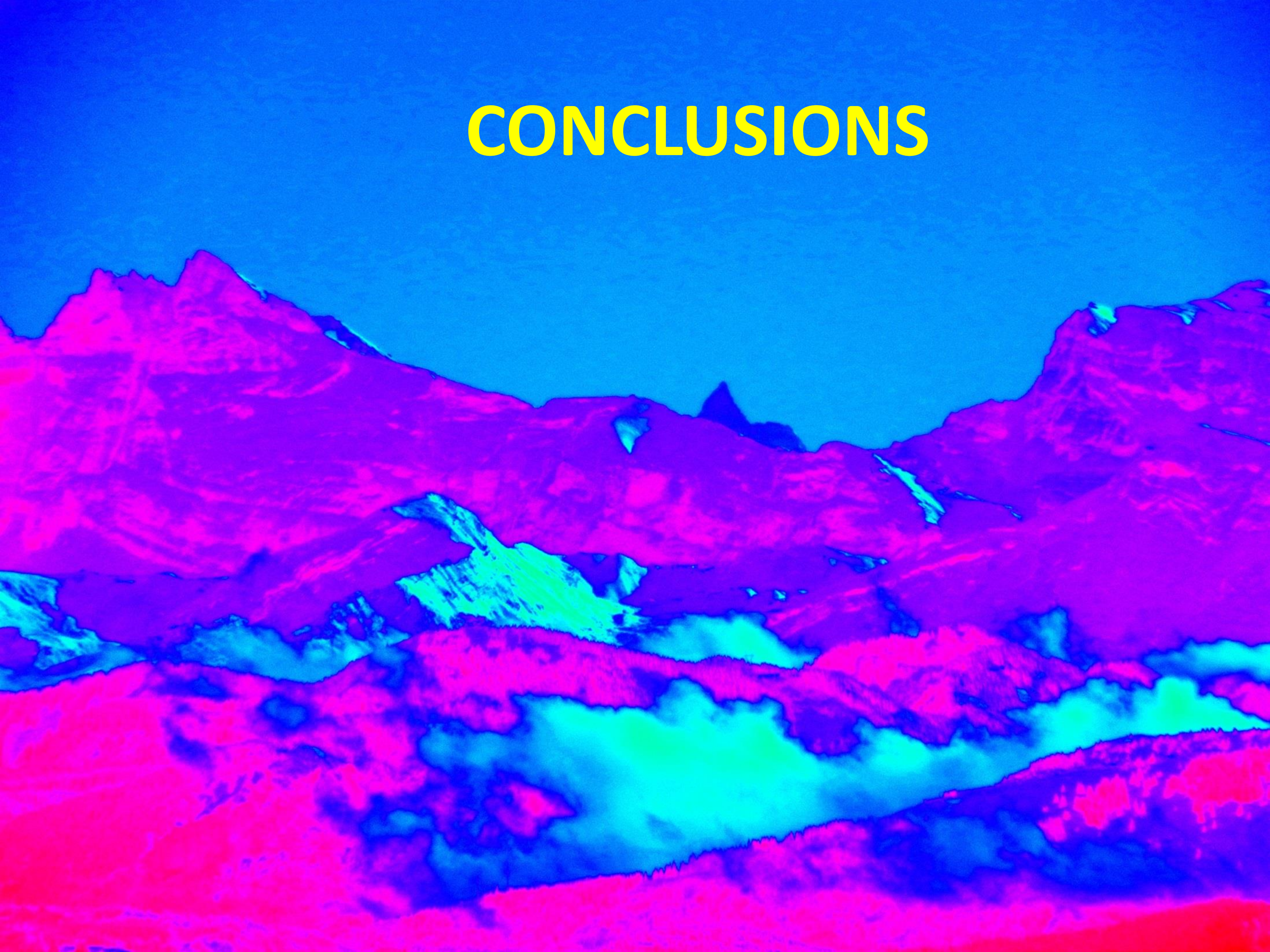
At the 100 TeV pp W is the dominant IVB particle,
Expect 10^{13} real W's.

There is a lot of /pile-up/backgrounds/lifetime/trigger issues which need to be investigated.
BUT.... in the regime of long lived HNLs the simultaneous presence of
-- the initial lepton from W decays
-- the detached vertex with kinematically constrained decay
allows for a significant background reduction.

But it allows also a characterization both in flavour and charge of the produced neutrino, thus information of the flavour sensitive mixing angles and a test of the fermion violating nature of the intermediate (Majorana) particle.

VERY interesting... but the detector needs to be designed for it!

CONCLUSIONS



Conclusions

The discovery that neutrinos have mass opens a new era of experimental investigation

-- Search for CP violation in neutrino oscillations

-- systematic hunt for right handed neutrinos (a.k.a. 'sterile')
-- in high intensity facilities (SHIP, SuperKEKb, LHC)
-- in the Future Circular Colliders (Z factory, W factory)
-- quite possible to observe CP violation (and all the mixing patterns)

-- This will require a different optimization than the 'standard' SuSy searches.

Life is exciting because it is different!

CONCLUSIONS -- II

The fascinating interest of the massive neutrinos become realized in the minimal scenario where neutrinos have both Majorana and Dirac mass terms

→ massive right handed neutrinos mixing with the light ones (almost 'sterile' $|\theta|^2 \propto m_\nu/m_N$

Besides the fact that the mass scale is unknown, this is a very likely scenario

If the mass scale is adequate, they generate either

dark matter

and/or

the baryon asymmetry of the universe

AND

can be observed at SHIP or HL-LHC, FCC-ee, FCC-hh !