UNIVERSITY OF Cincinnati

PLANNING FOR FUTURE NEUTRINO EXPERIMENTS

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University of Cincinnati

Intensity Frontier Seminar
Fermilab
March 20, 2014

Unanswered Neutrino Questions

1) What is the value of θ_{13}, the mixing angle between first- and third-generation neutrinos for which, so far, experiments have only established limits? Determining the size of θ_{13} has critical importance not only because it is a fundamental parameter, but because its value will determine the tactics to best address many other questions in neutrino physics.

2) Do neutrino oscillations violate CP? If so, how can neutrino CP violation drive a matter-antimatter asymmetry among leptons in the early universe (leptogenesis)? What is the value of the CP violating phase, which is so far completely unknown? Is CP violation among neutrinos related to CP violation in the quark sector?

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4) Is θ_{23} maximal (45 degrees)? if so, why? Will the pattern of neutrino mixing provide insights regarding unification of the fundamental forces? Will it indicate new symmetries or new selection rules?

5) Are neutrinos their own antiparticles? Do they give rise to lepton number violation, or leptogenesis, in the early universe? Do they have observable laboratory consequences such as the sought-after neutrinoless double beta decay in nuclei?

6) What can we learn from observation of the intense flux of neutrinos from a supernova within our galaxy? Can we observe the neutrino remnants of all supernovae that have occurred since the beginning of time?

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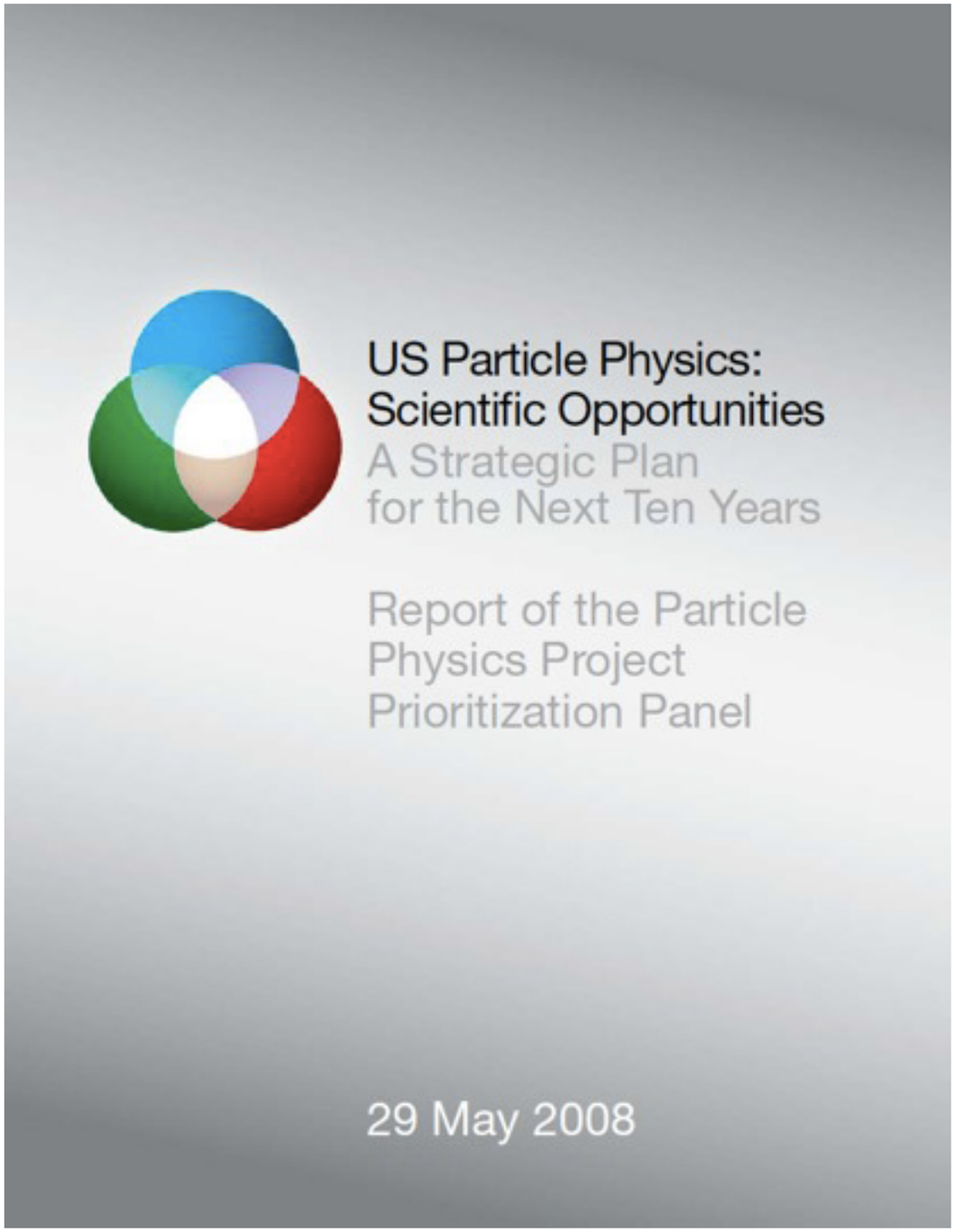

from US Particle Physics: Scientific Opportunities. A Strategic Plan for the Next Ten Years. Report of the Particle Physics Project Prioritization Panel (2008)

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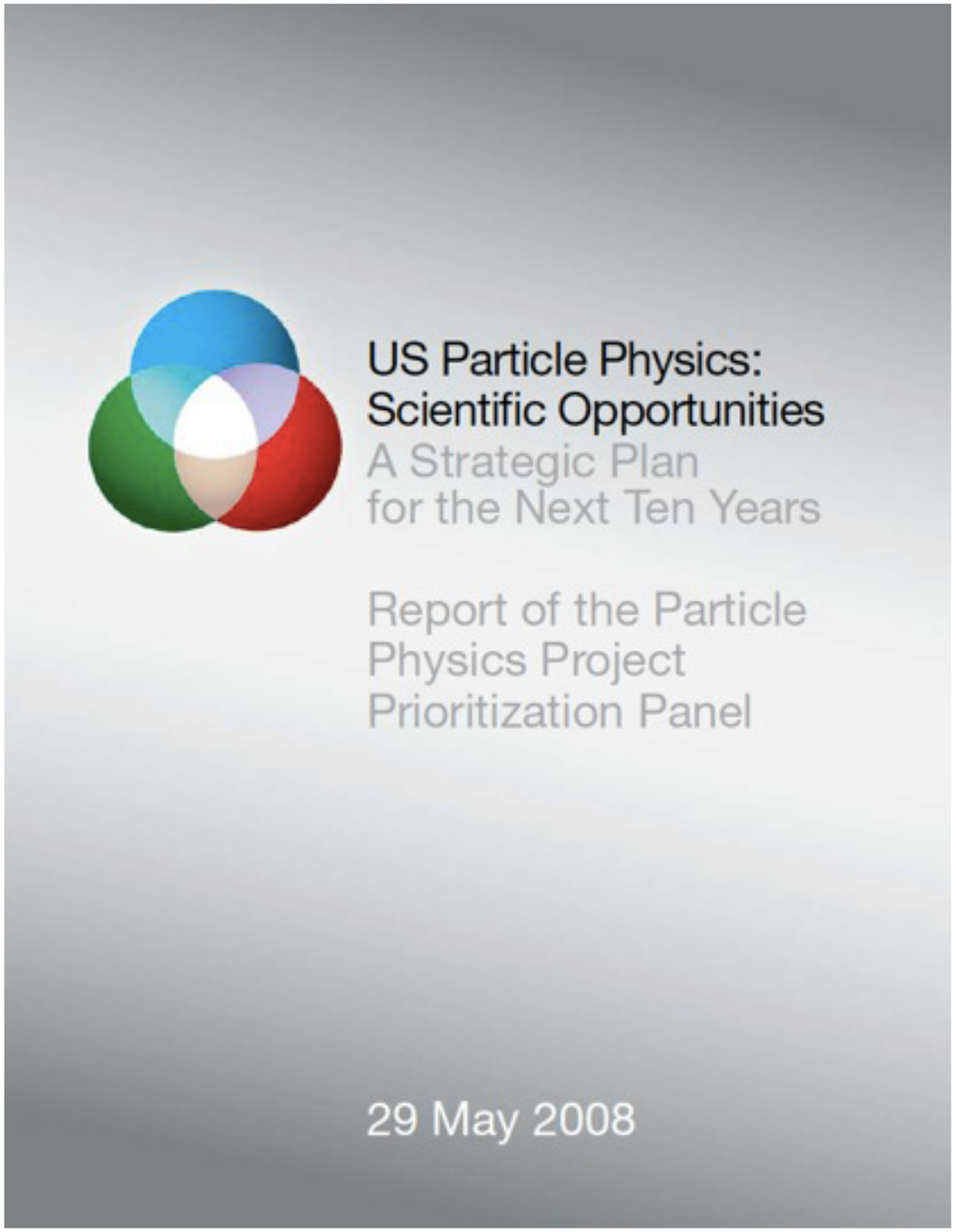

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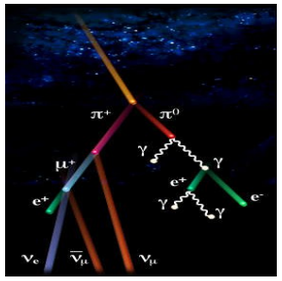
Do neutrino oscillations violate CP?

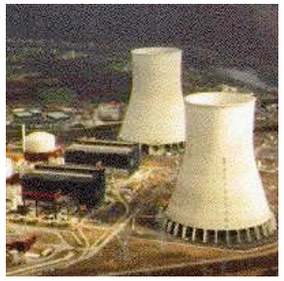
What are the relative masses of the three known neutrinos

Is θ_{23} maximal?

Accelerator



Atmospheric



Reactor

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Do sterile neutrinos exist? (…) New physics beyond the Standard Model?

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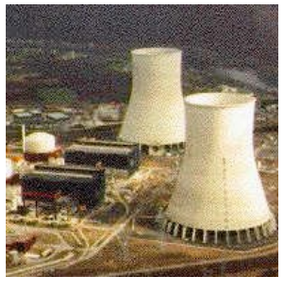

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Radioactive Sources

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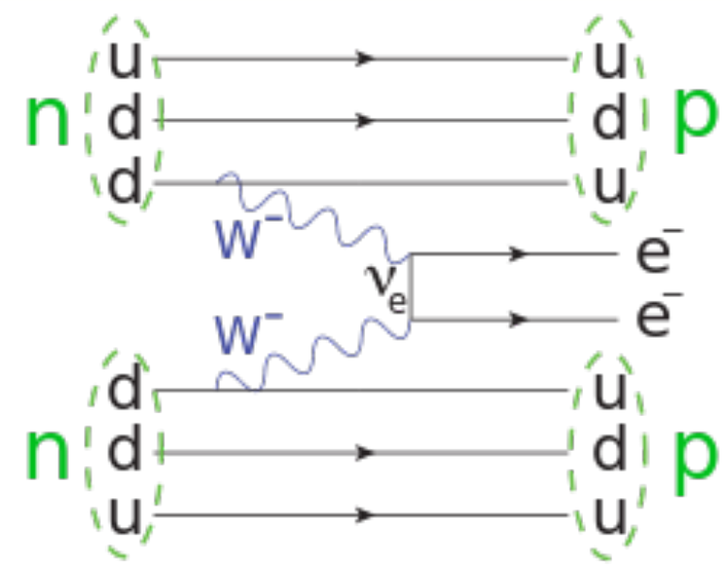
Are neutrinos Majorana particles?



Neutrinoless double-beta decay

What are the absolute values of neutrino masses?

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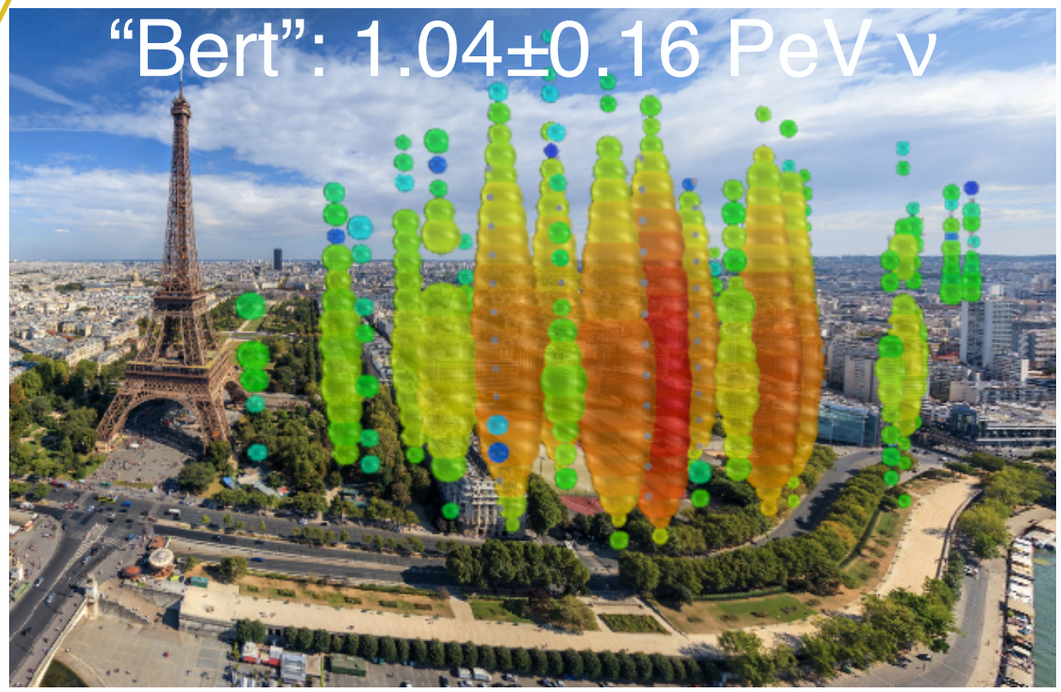
What can we learn from (…) neutrinos from a supernova?

What can neutrinos reveal about other astrophysical phenomena?

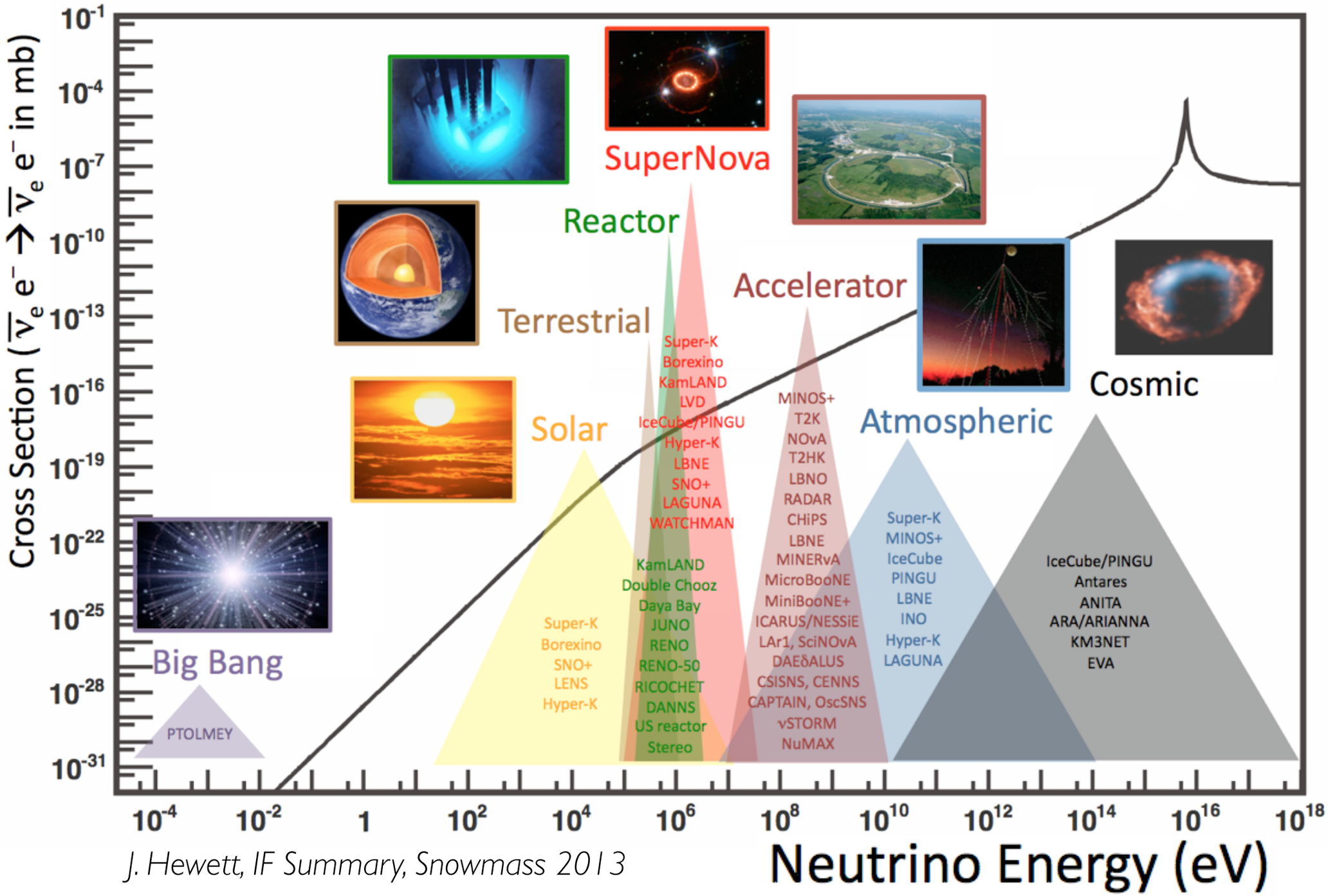


Doug Cowen, UC Colloquium on Ice Cube (2013)

from US Particle Physics: Scientific Opportunities. A Strategic Plan for the Next Ten Years. Report of the Particle Physics Project Prioritization Panel (2008)

Running and Future Experiments

- Many new neutrino projects proposed during Community Summer Study (Snowmass) 2013 process. Will cover a representative fraction.



J. Hewett, IF Summary, Snowmass 2013

Current Three ν Picture

- Neutrinos undergo flavor oscillations

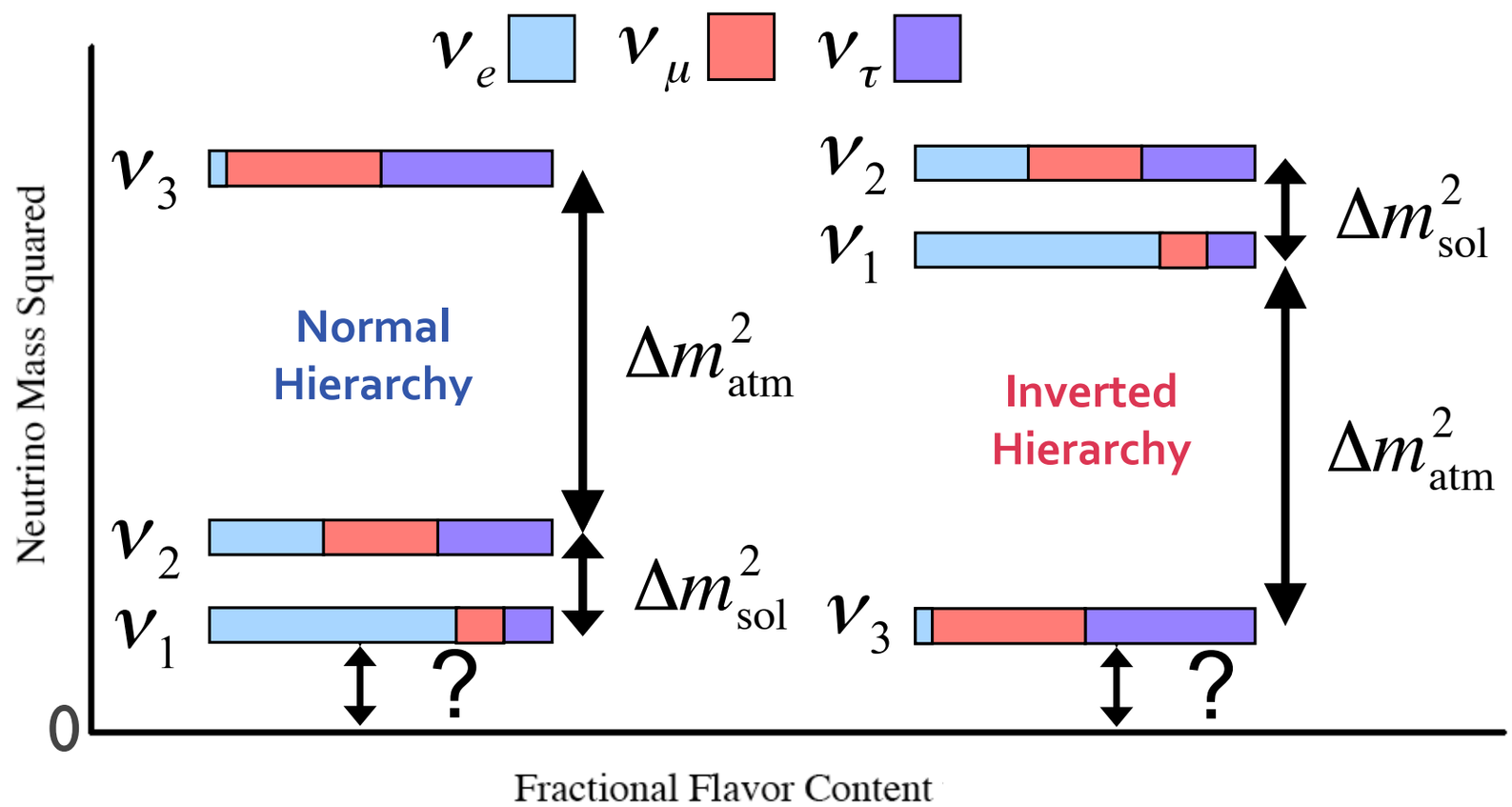
$$|\nu_\alpha\rangle = \sum_{i=1}^{3} U^*_{\alpha i}|\nu_i\rangle \quad (\alpha = e, \mu, \tau)$$

Atmospheric + Accelerator | Reactor+Accelerator | Solar+Reactor

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

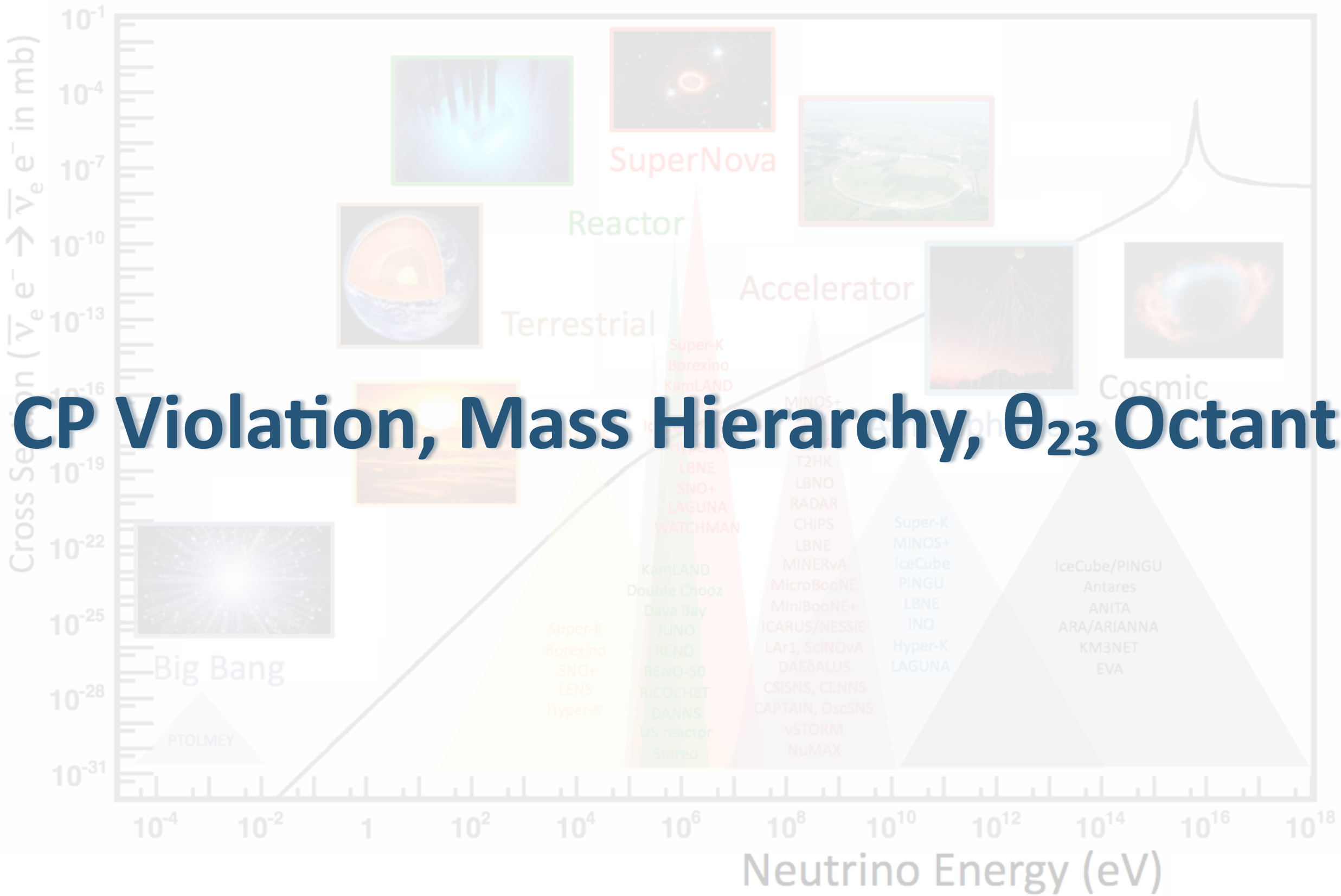
$c_{lk} = \cos\theta_{lk}$
$s_{lk} = \sin\theta_{lk}$

- Two mass splittings
  - **Atmospheric: $\Delta m^2_{atm} \approx \Delta m^2_{32} \approx 2.4\times10^{-3}$ eV^2**
  - **Solar: $\Delta m^2_{sol} \approx \Delta m^2_{21} \approx 7.5\times10^{-5}$ eV^2**
- Large atmospheric mixing
  - **θ_{23}~45°**
- Non-maximal solar mixing
  - **θ_{12}~34°**
- (13) sector
  - **θ_{13}~9°**
  - **δ_{CP}** Unknown $\delta_{CP} \neq 0\,? => P(\bar{\nu}_\mu \to \bar{\nu}_e) \neq P(\nu_\mu \to \nu_e)$



- **Neutrino mass hierarchy unknown; Absolute neutrino mass unknown; Majorana/Dirac nature of neutrino unknown; More than 3 neutrinos?**

CP Violation, Mass Hierarchy, θ_{23} Octant



CP Violation, Mass Hierarchy, θ_{23} Octant

- Why do we want to measure these?

- $\sin\delta_{CP}$ determines the size of CP violation in the lepton sector
  - May be sufficient to explain the matter-antimatter asymmetry of the universe through leptogenesis by decay of heavy seesaw neutrino partner
- Measuring δ_{CP} precisely also needed to understand structure of PMNS matrix and underlying symmetries

- Mass Hierarchy is a good model discriminator
  - Important to interpret results from neutrinoless double-beta decay experiments

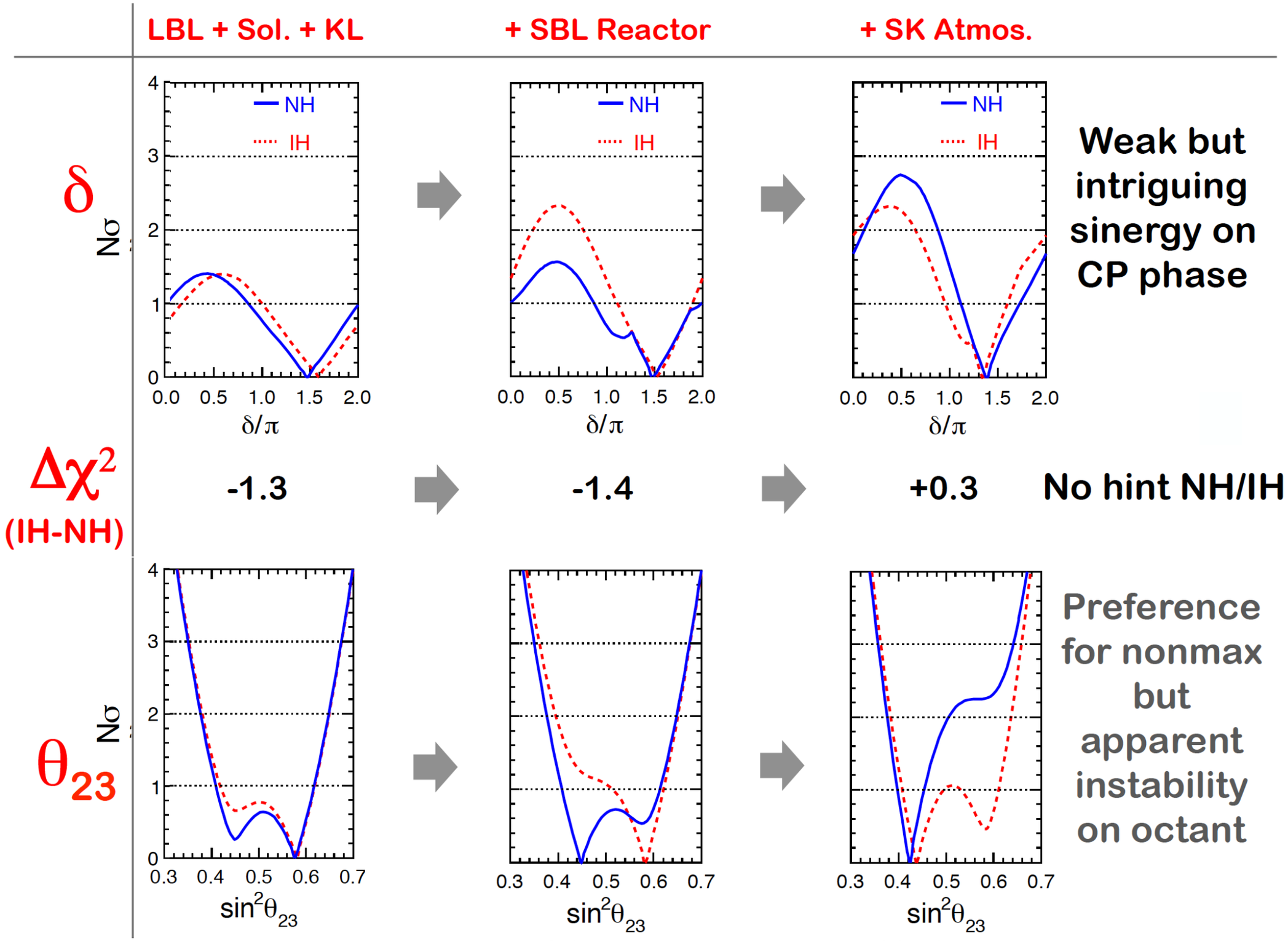
- Maximal θ_{23} could be a hint for a not yet understood symmetry
  - Precision measurements of θ_{23} are important for testing PMNS unitarity and for model building, e.g. $\mu \leftrightarrow \tau$ symmetry, *A4* flavor symmetry, and quark-lepton complementarity

Reference		Hierarchy
Anarchy Model:		
dGM	[18]	Either
$L_e - L_\mu - L_\tau$ Models:		
BM	[35]	Inverted
BCM	[36]	Inverted
GMN1	[37]	Inverted
GL	[38]	Inverted
PR	[39]	Inverted
S_3 and S_4 Models:		
CFM	[40]	Normal
HLM	[41]	Normal
		Normal
KMM	[42]	Inverted
MN	[43]	Normal
MNY	[44]	Normal
MPR	[45]	Normal
RS	[46]	Inverted
		Normal
TY	[47]	Inverted
T	[48]	Normal
A_4 Tetrahedral Models:		
ABGMP	[49]	Normal
AKKL	[50]	Normal
Ma	[51]	Normal
SO(3) Models:		
M	[52]	Normal
Texture Zero Models:		
CPP	[53]	Normal
		Inverted
		Inverted
WY	[54]	Either
		Either
		Either

Albright, Chen, arXiv:hep-ph/0608137(2006)

CP Violation, Mass Hierarchy, θ_{23} Octant

- What does the existing neutrino data tell us?



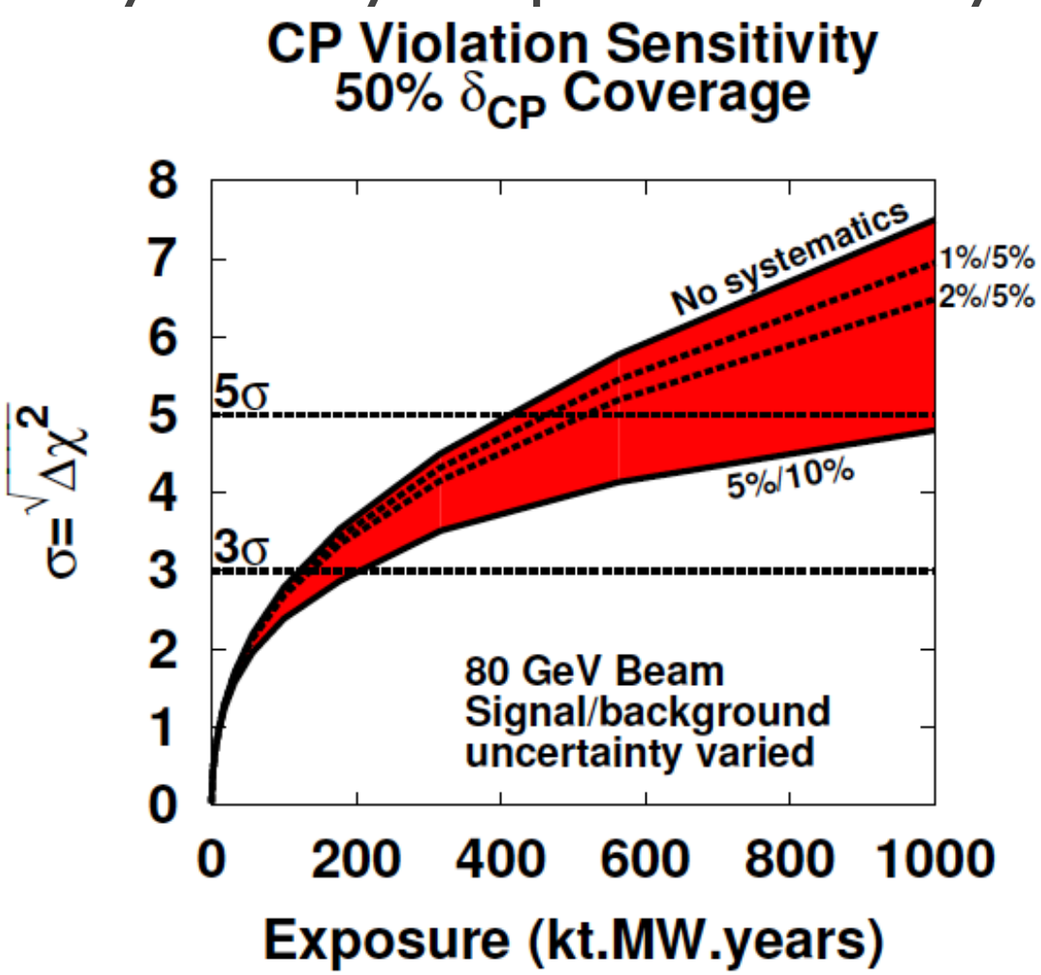
E. Lisi, ICFA Neutrino Panel, Paris (Jan. 2014)

A Note on Systematics

- Size of CP asymmetry is inversely proportional to size of θ_{13}

$$\frac{P(\nu_\alpha \to \nu_\beta) - P(\bar{\nu}_\alpha \to \bar{\nu}_\beta)}{P(\nu_\alpha \to \nu_\beta) + P(\bar{\nu}_\alpha \to \bar{\nu}_\beta)} \propto \frac{1}{\sin 2\theta_{13}}$$

- Need to measure $P(\nu_\mu \to \nu_e), P(\bar{\nu}_\mu \to \bar{\nu}_e)$ or $P(\nu_e \to \nu_\mu), P(\bar{\nu}_e \to \bar{\nu}_\mu)$
- Relatively large θ_{13} means we will have large signal statistics, but also a small asymmetry => percent level systematics to measure leptonic CP violation

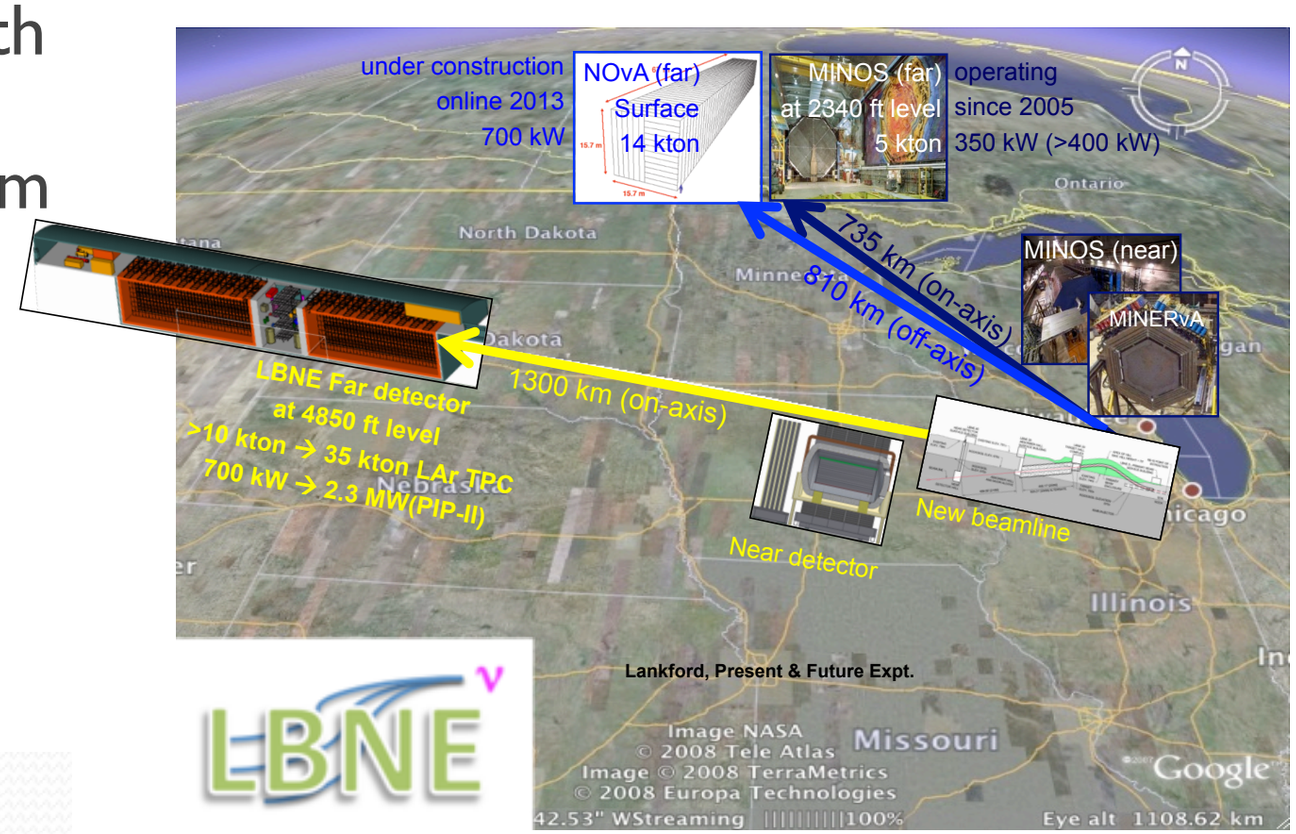


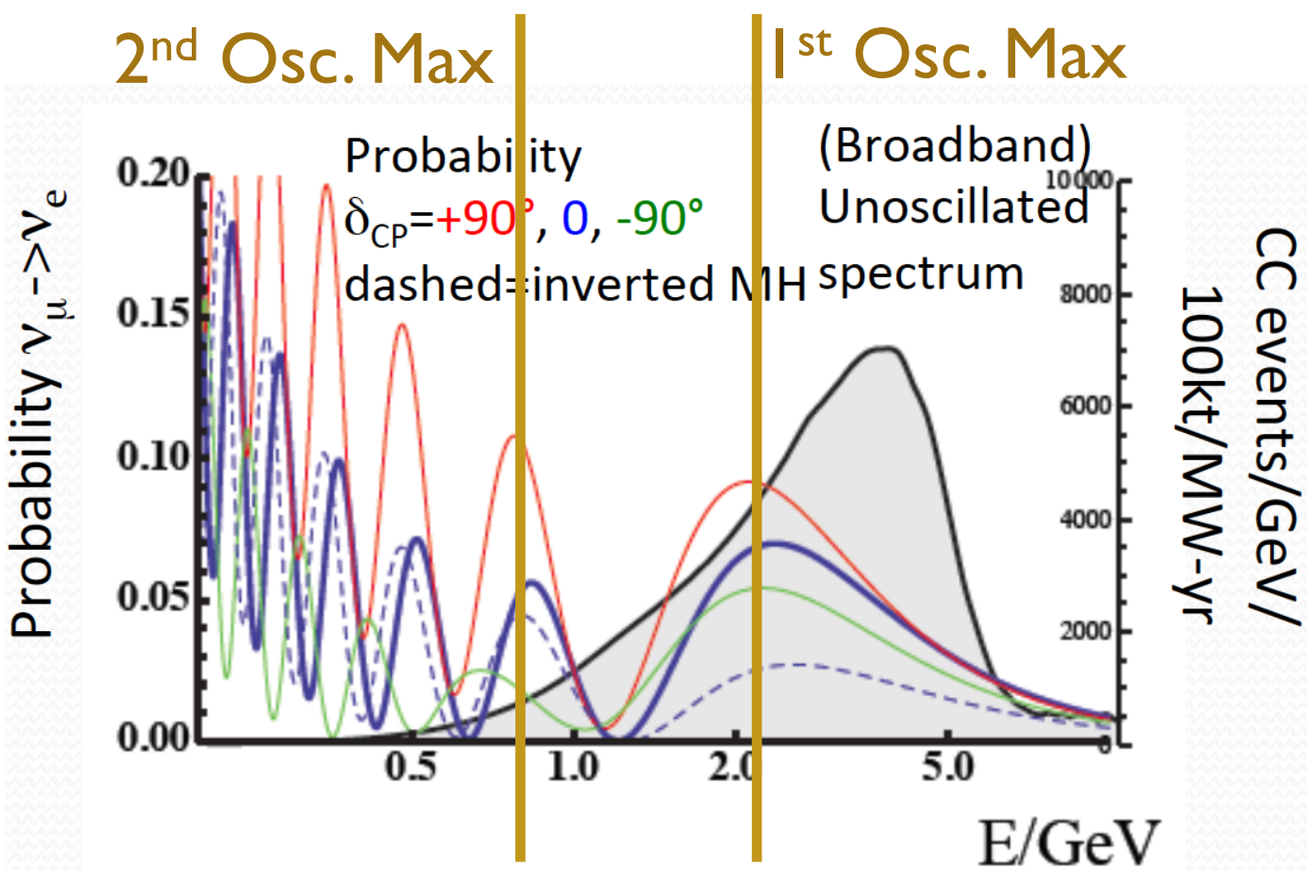
- In long-baseline appearance experiments, signal at FD is ν_e (for a ν_μ beam), so cross-section uncertainties do not cancel out between ND and FD
  - Need precise measurements of ν_e, ν_μ, $\bar{\nu}_e$, $\bar{\nu}_\mu$ cross-sections, nuSTORM, CAPTAIN, …
  - See Sam Zeller's talk in this seminar series
- Also hadron production experiments like NA61, test beams like LArIAT

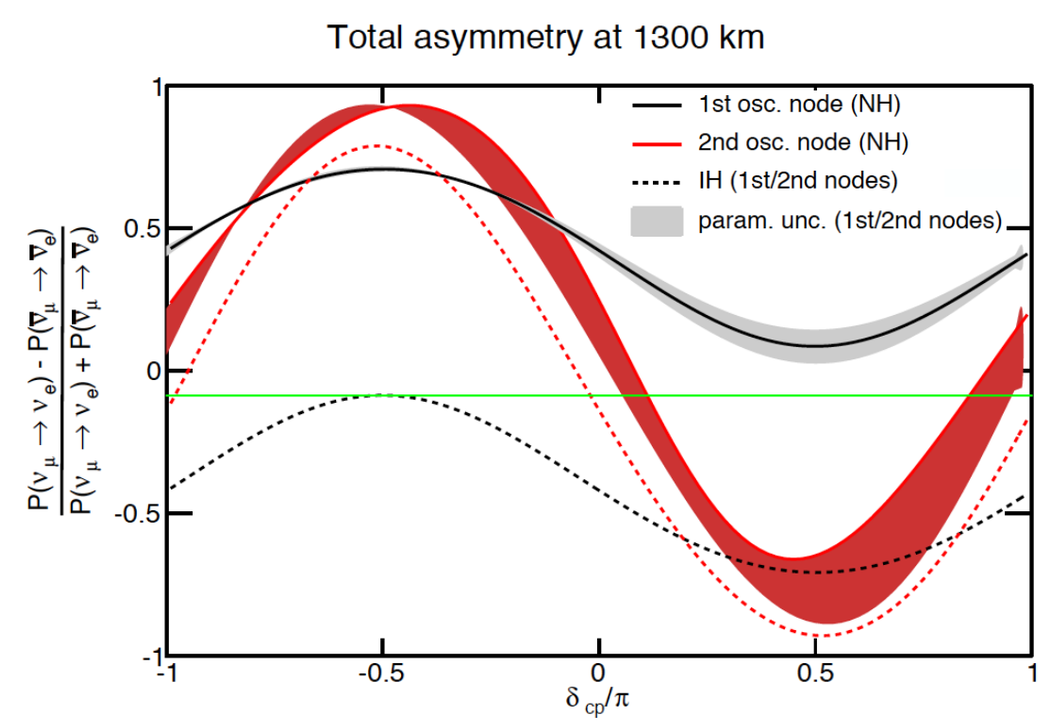
P. Huber, NuFact 2013, Beijing (Aug. 2013)

CP Violation, Mass Hierarchy, θ_{23} Octant

- **LBNE (Long-Baseline Neutrino Experiment) in the US**
- Pion decay-in-flight on-axis ν_μ beam with 1300 km baseline from Fermilab, IL to Homestake, SD. Projecting 1.2 MW beam power (PIP-II) at LBNE start
- Far Detector will be a 35 kton fiducial volume LAr TPC at 4850 ft depth. Configuration to be achieved in phased manner depending on funding



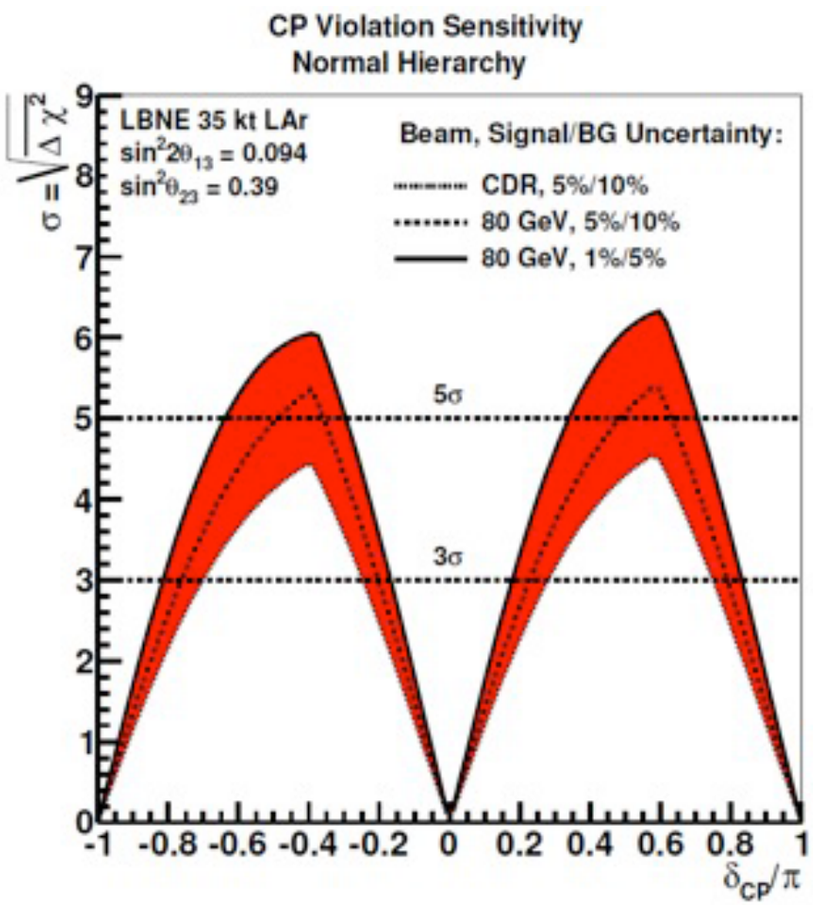


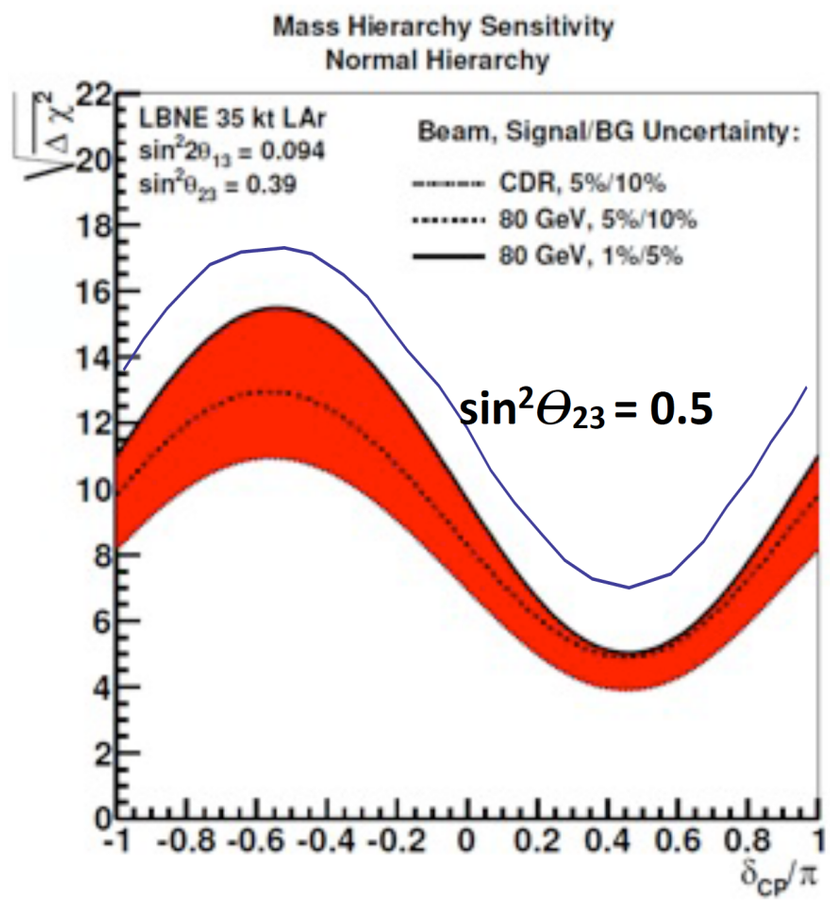


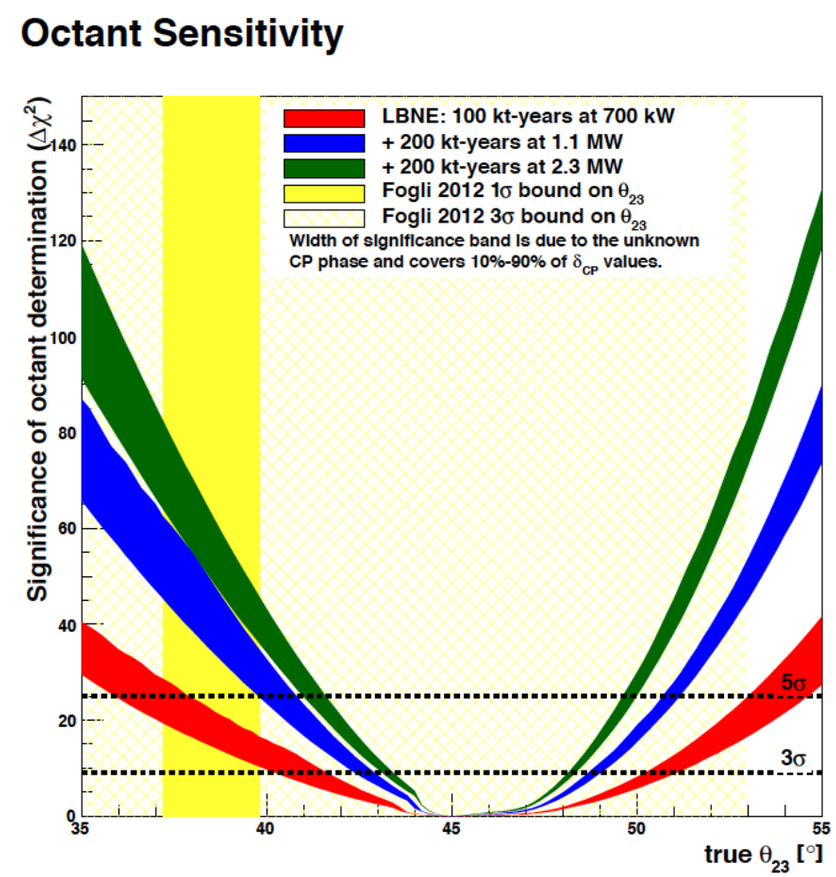
CP Violation, Mass Hierarchy, θ_{23} Octant

- **LBNE (Long-Baseline Neutrino Experiment) in the US**
  - 35 kton FD sensitivities

median sensitivity to reject IH







M. Diwan, ICFA Neutrino Panel, Paris (Jan. 2014)

Assumptions:
35 kt LArTPC
1.2 MW operation at 80 GeV.
~3 yrs for each polarity.
Normal Hierarchy
δ_{CP}= 0
Rest of the parameters are at best fit from 2012

Exposure 245 kt.MW.yr
1.2 MW x 35 kt x(3ν+3$\bar{\nu}$) yr

80 GeV Beam	ν mode	$\bar{\nu}$ mode
Signal: $\nu_e + \bar{\nu}_e$	777	189
BG: NC	67	39
BG: $\nu_\mu + \bar{\nu}_\mu$ CC	84	39
BG: Beam $\nu_e + \bar{\nu}_e$	147	81
BG: $\nu_\tau + \bar{\nu}_\tau$ CC	49	32

CP Violation, Mass Hierarchy, θ_{23} Octant

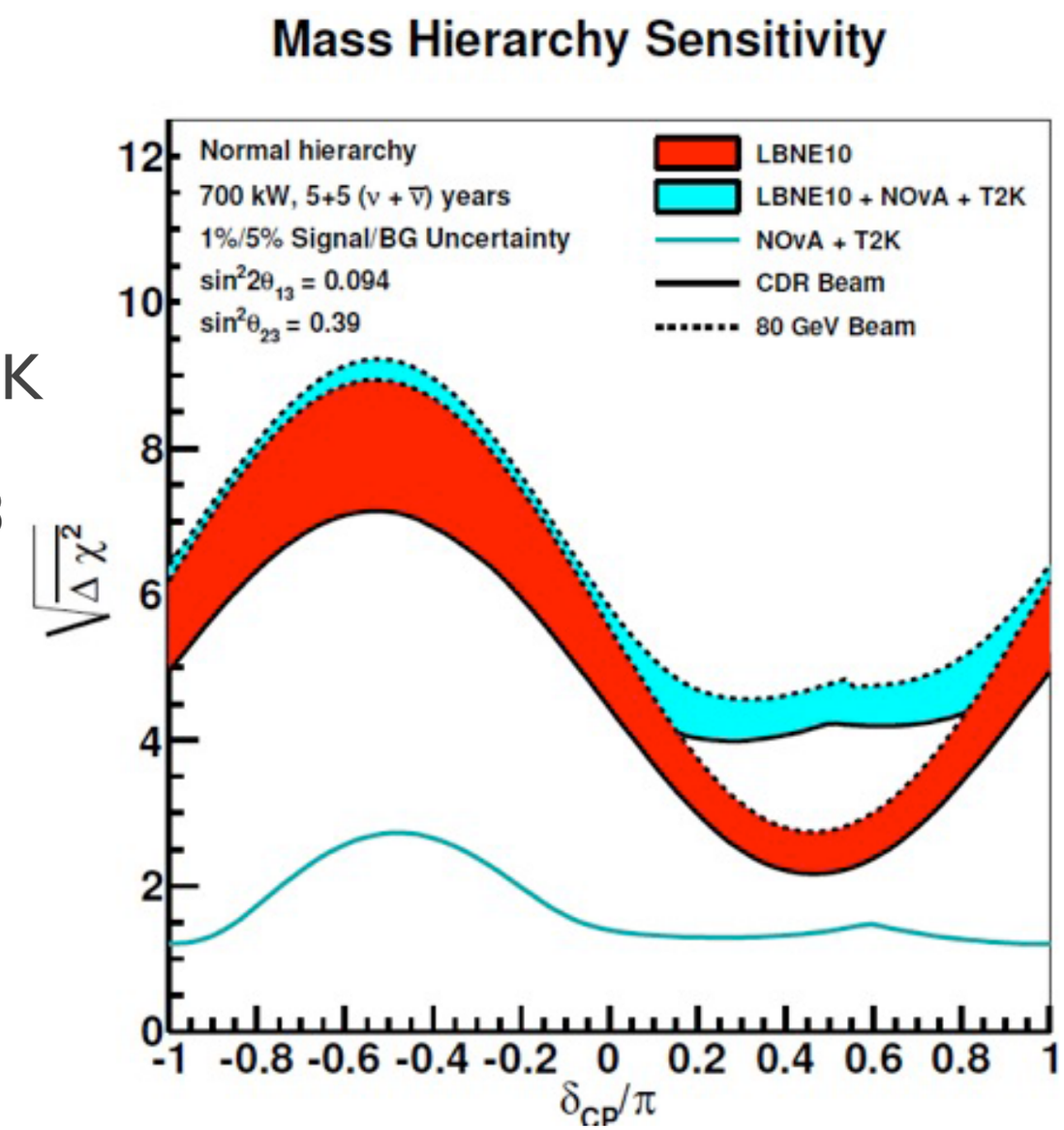
- **LBNE (Long-Baseline Neutrino Experiment) in the US**
  - Status and phased approach with 15 kton Far Detector at 4850 ft

- DOE granted CD-1(critical decision on conceptual design with site decision) with$867M commitment with flexible scope in December of 2012.
- To get the full scope of LBNE, need significant international partnerships - 5 institutions from UK (5 already members), 7 from Italy and 6 from Brazil joined collaboration since September 2013

Possible Timeline

- **2025-2030**
  Detector mass: 15 kt (fid.)
  Proton beam power: 1.2 MW
- **Exposure: 90 kt.MW.yr**

- **2030-2035**
  Add 20 kt = 35 kt
  Proton beam power: 2.3 MW
- **Total Exposure: 490 kt.MW.yr**



- Snowmass detailed-whitepaper arXiv:1307.7335

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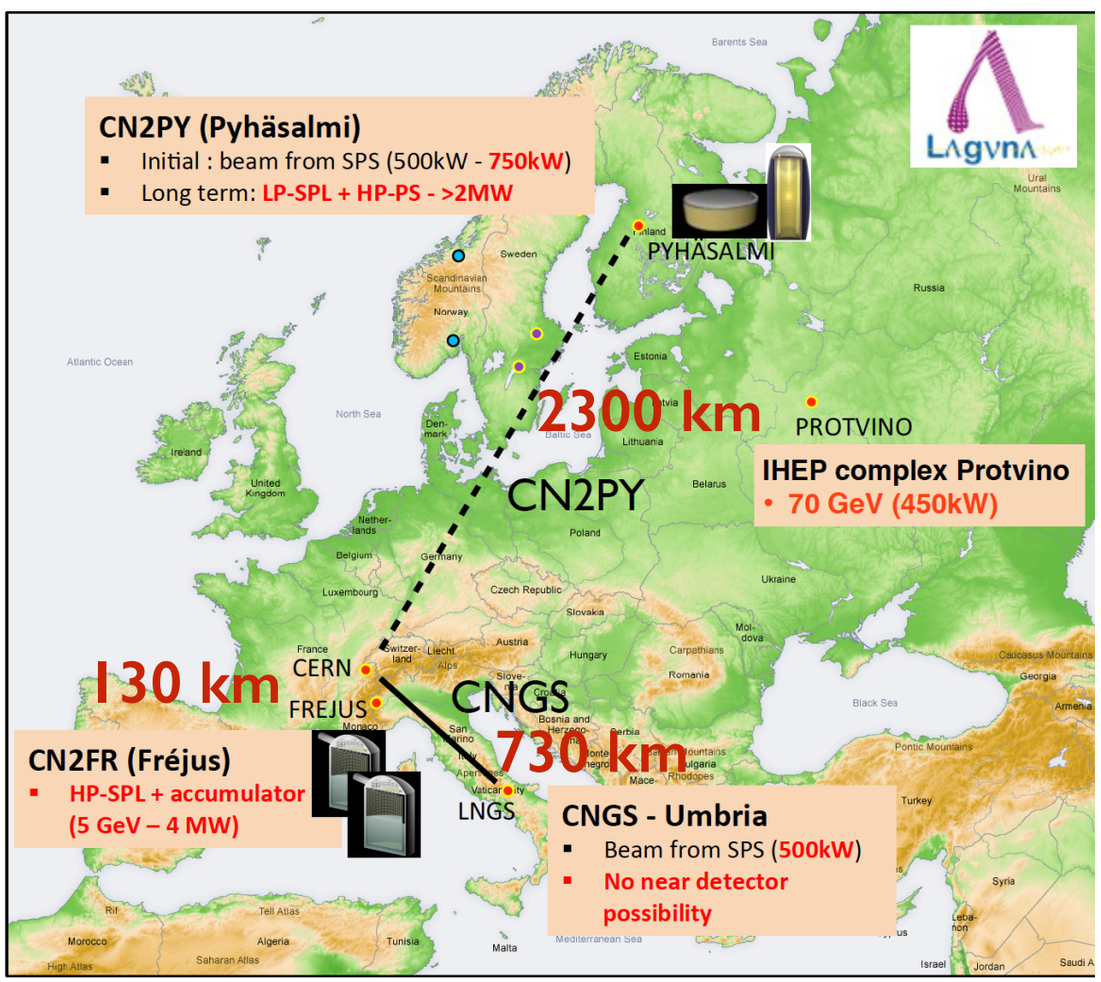
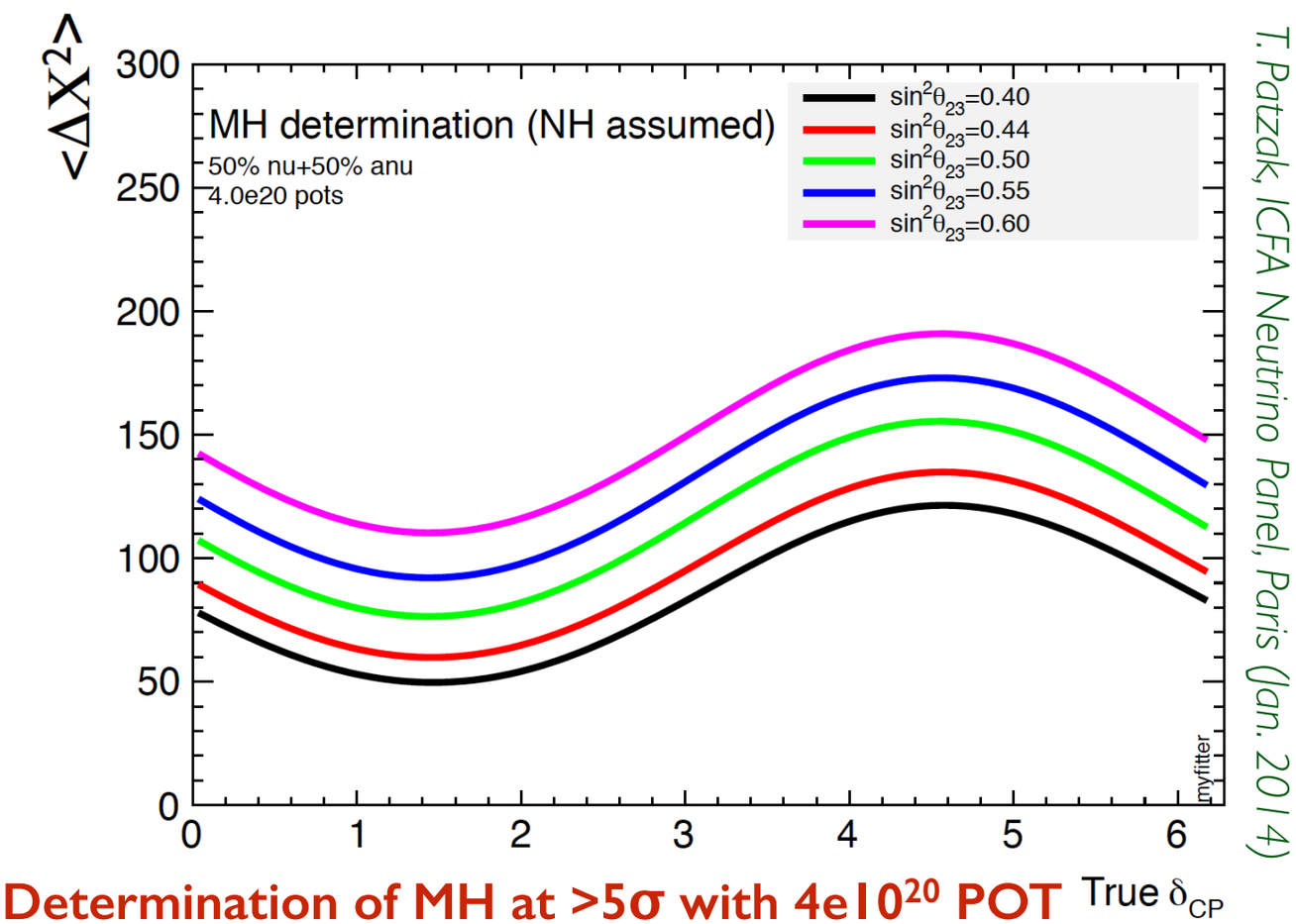
- **LBNO (Long-Baseline Neutrino Oscillations) in Europe**
- Following LAGUNA design study, LBNO produced an EOI (arXiv:1003.1921) proposing:
  - Pion decay-in-flight on-axis ν_μ beam with 500 kW power, 400 GeV protons and 2300 km baseline from CERN (SPS) to Pyhäsalmi, Finland with 20 kton fiducial LAr TPC
  - In later phase, would upgrade to 2 MW beam power and 70 kton det. mass





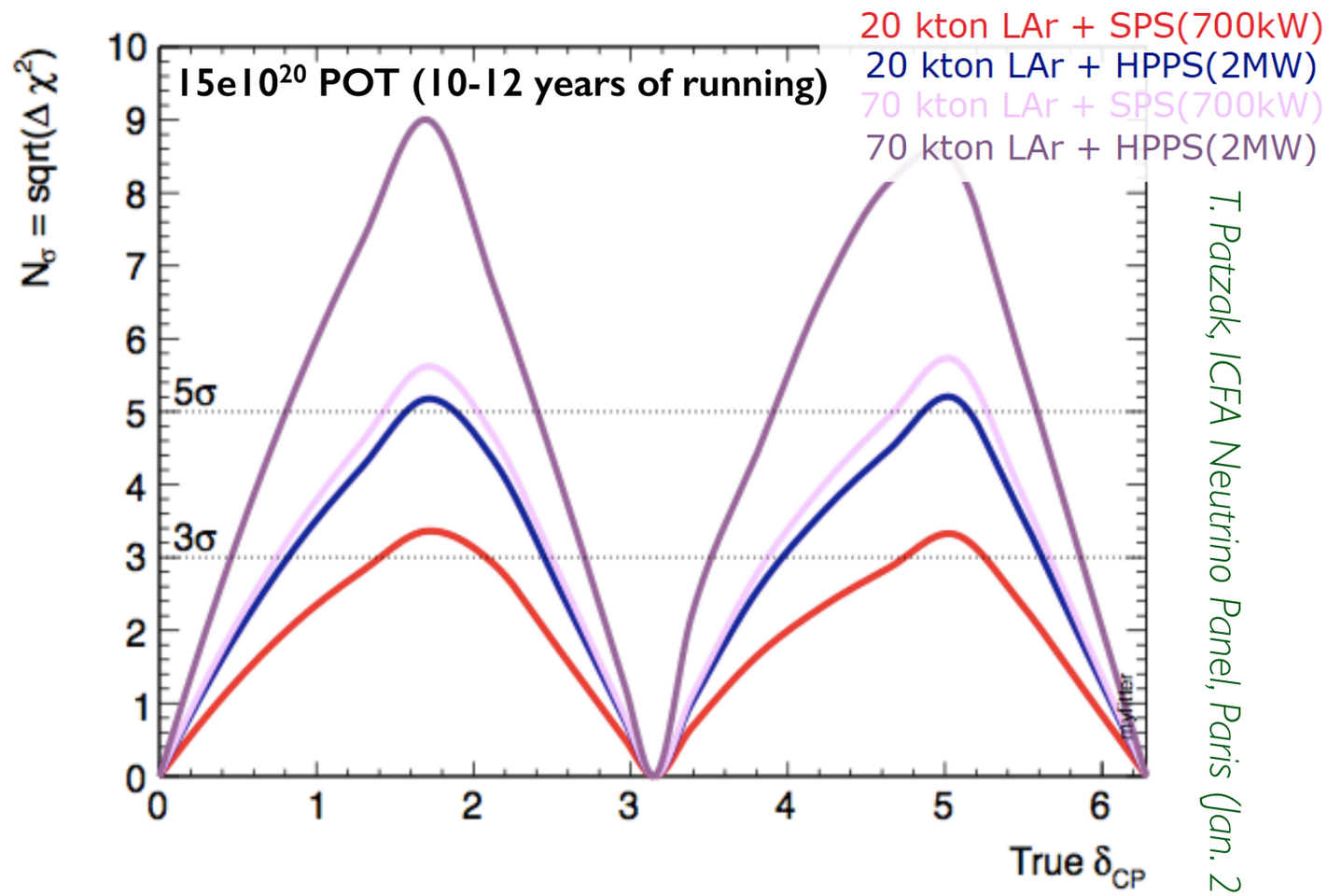
T. Patzak, ICFA Neutrino Panel, Paris (Jan. 2014)

Determination of MH at >5σ with 4e10^{20} POT (5 years of running) and 20 kton detector

CP Violation, Mass Hierarchy, θ_{23} Octant

- **LBNO (Long-Baseline Neutrino Oscillations) in Europe**
- For CP violation probing, after determining MH, adjust beam to enhance statistics in 2nd maximum, move to 2 MW beam power, 50-75 GeV protons and 70 kton det. mass
- LBNO status:
  - In August 2013 the CERN Research Board approved WA104 (formerly ICARUS-NESSIE) and WA105 (LBNO prototype). Approval is for R&D, but no neutrino beam granted.
  - Finland officially pulled out of project, but dialogue is continuing regarding use of Pyhasälmi mine

Science Document, LAGUNA-LBNO, arXiv:1312.6520

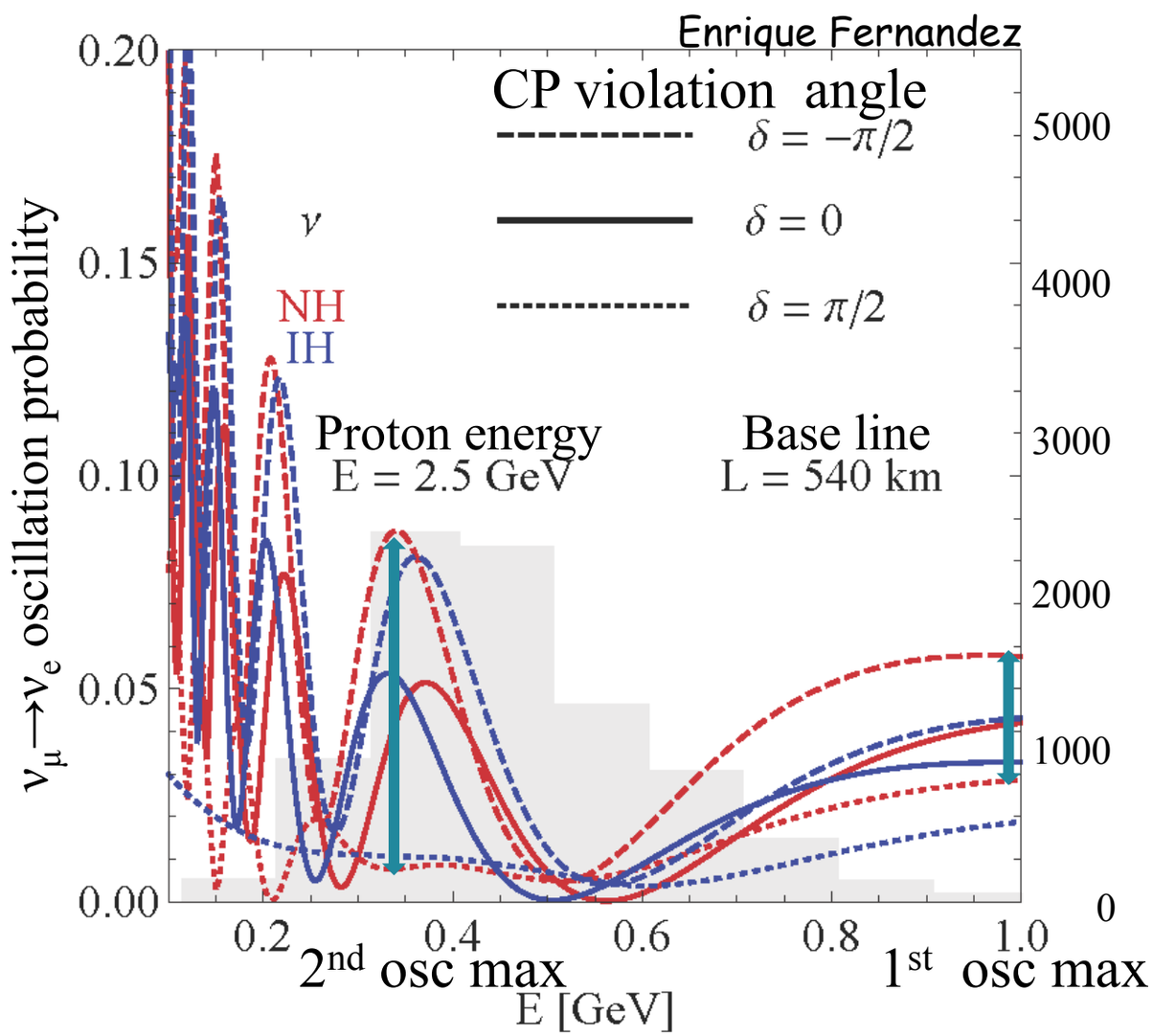


T. Patzak, ICFA Neutrino Panel, Paris (Jan. 2014)

- LBNE and LBNO have created a joint task force to identify synergies between the two projects, both in developing science strategy and in carrying out detector R&D

CP Violation, Mass Hierarchy, θ_{23} Octant

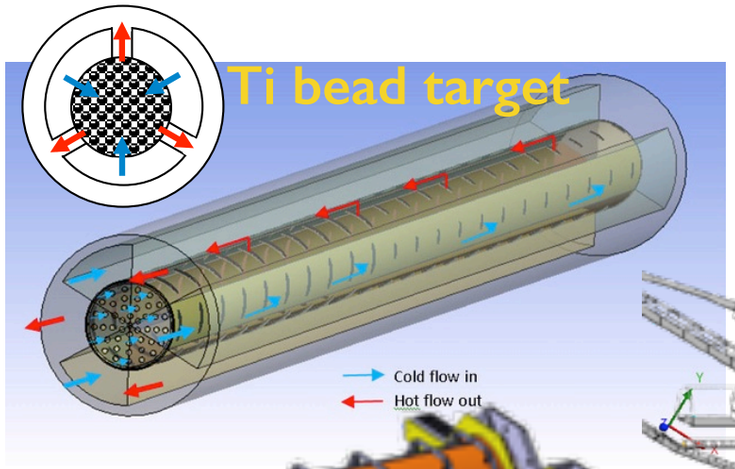
- **ESSνSB (European Spallation Source ν SuperBeam) in Europe**
- Pion decay-in-flight on-axis ν_μ beam with 5 MW power with 2 or 2.5 GeV protons and 1.6×10^{16} protons-on-target/second
- Low-energy, but very intense neutrino beam allows exploration of 2nd osc. maximum, with best results at 540 km baseline. Requires large Water Cherenkov Far Detector (~500 kton)

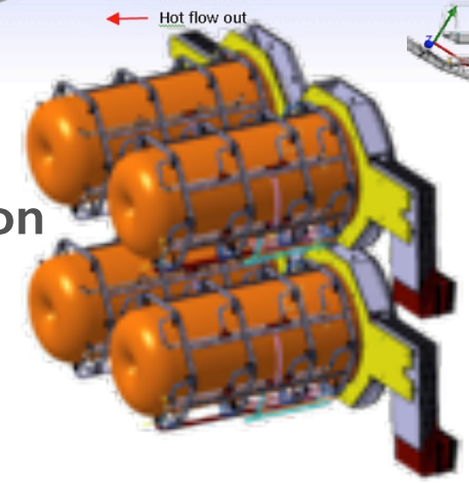


T. Ekelof, ICFA Neutrino Panel, Paris (Jan. 2014)

CP Violation, Mass Hierarchy, θ_{23} Octant

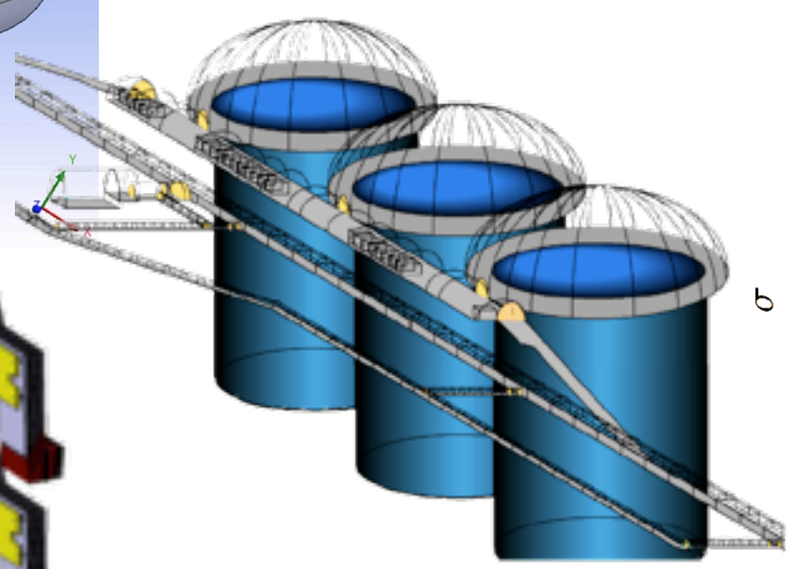
- **ESSνSB (European Spallation Source ν SuperBeam) in Europe**
- Creating high-intensity beam poses technical challenges. Studying use of He-cooled packed titanium bead target and multiple parallel horns
- With 2.5 GeV protons and 540 km baseline, cover >50% of CP space at 5σ in 10 years of running

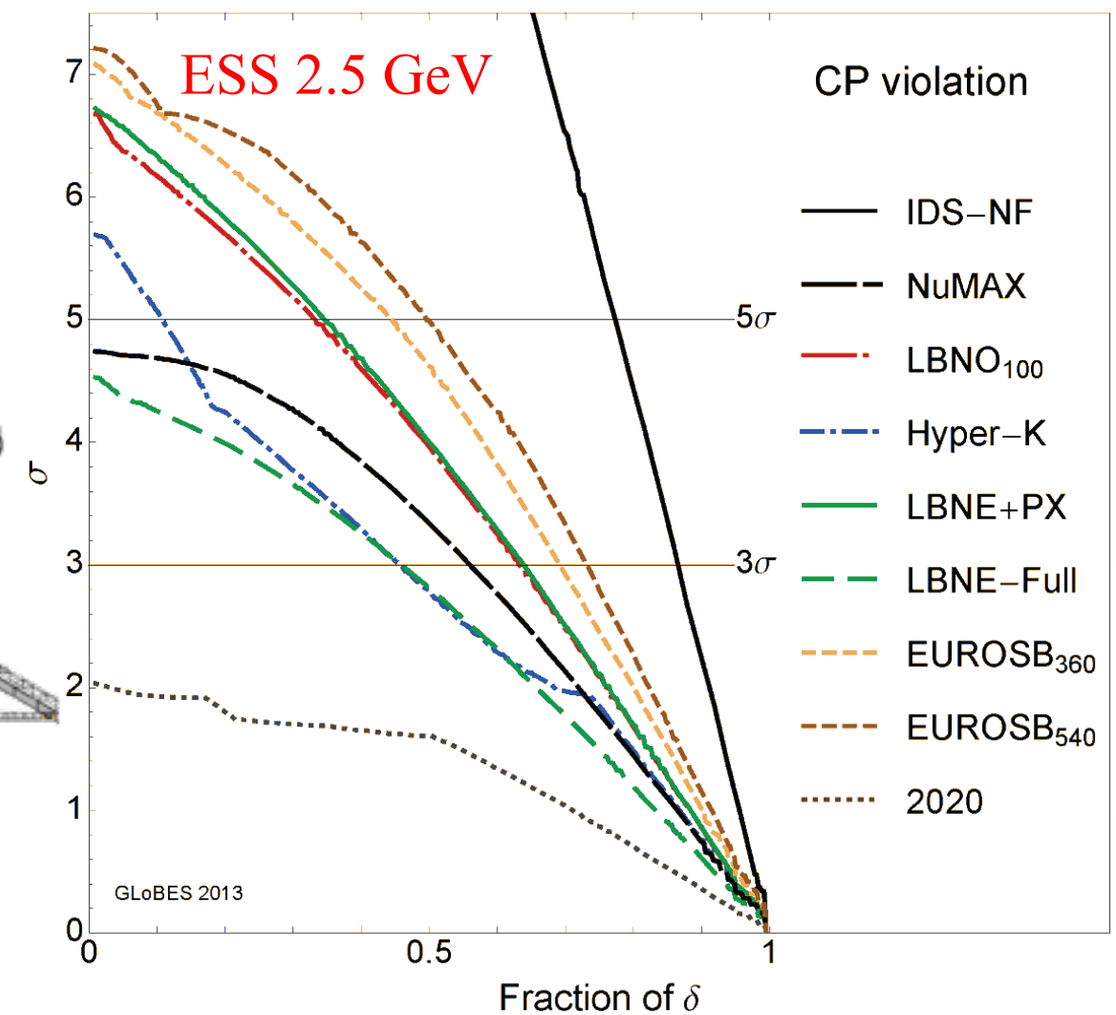




Horn configuration

MEMPHYS
500 kt W.Ch detector
EUR 700M cost



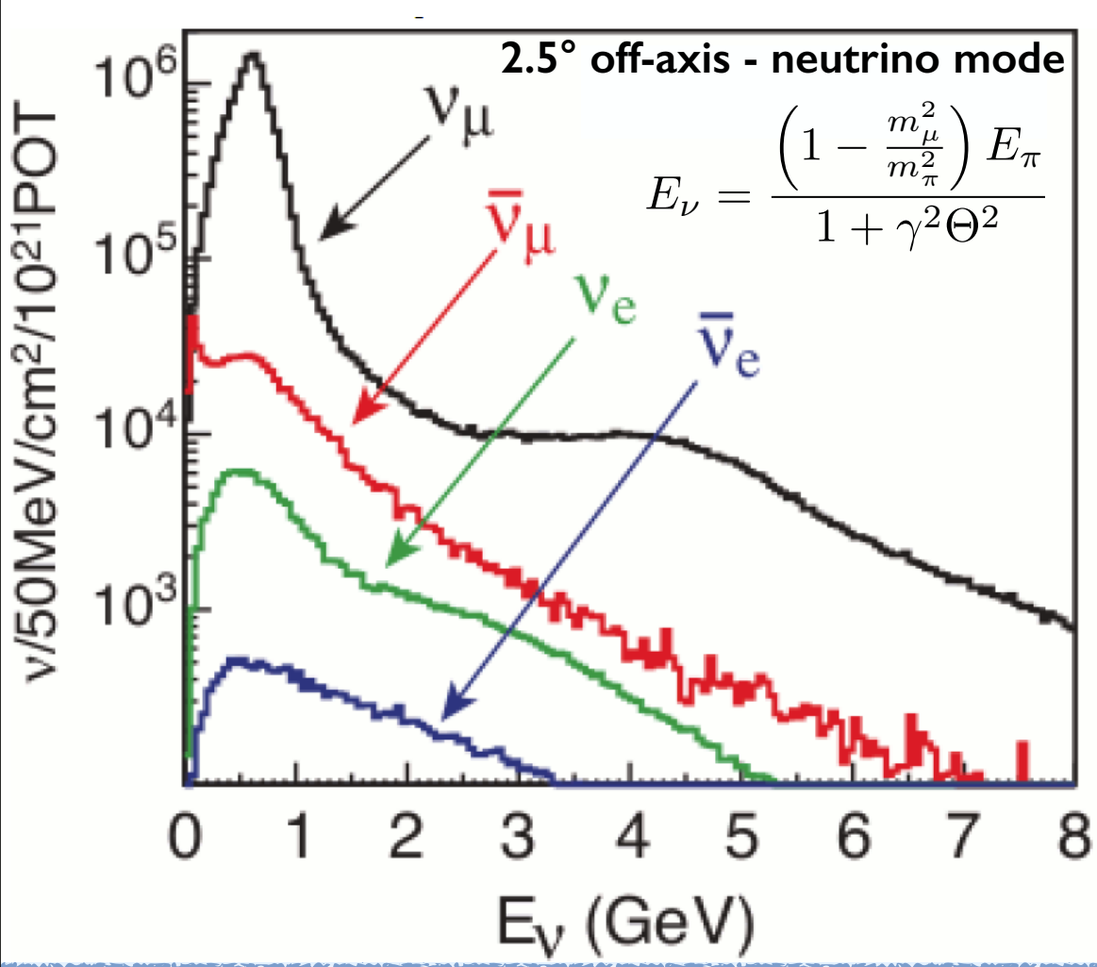


- Operations would start circa 2026
- Estimating EUR1.2 billion total cost

T. Ekelof, ICFA Neutrino Panel, Paris (Jan. 2014)

CP Violation, Mass Hierarchy, θ_{23} Octant

- **T2HK (Tokai to Hyper-Kamiokande) in Japan**
- Pion decay-in-flight off-axis ν_μ beam with >1 MW power and 295 km baseline from Tokai to Hyper-Kamiokande, a new 0.99 Mton (0.56 Mton fiducial) Water Cerenkov tank (25x Super-Kamiokande)
- J-PARC beam peaked at $\nu_\mu \rightarrow \nu_e$ oscillation maximum at 295 km (E~0.6 GeV)

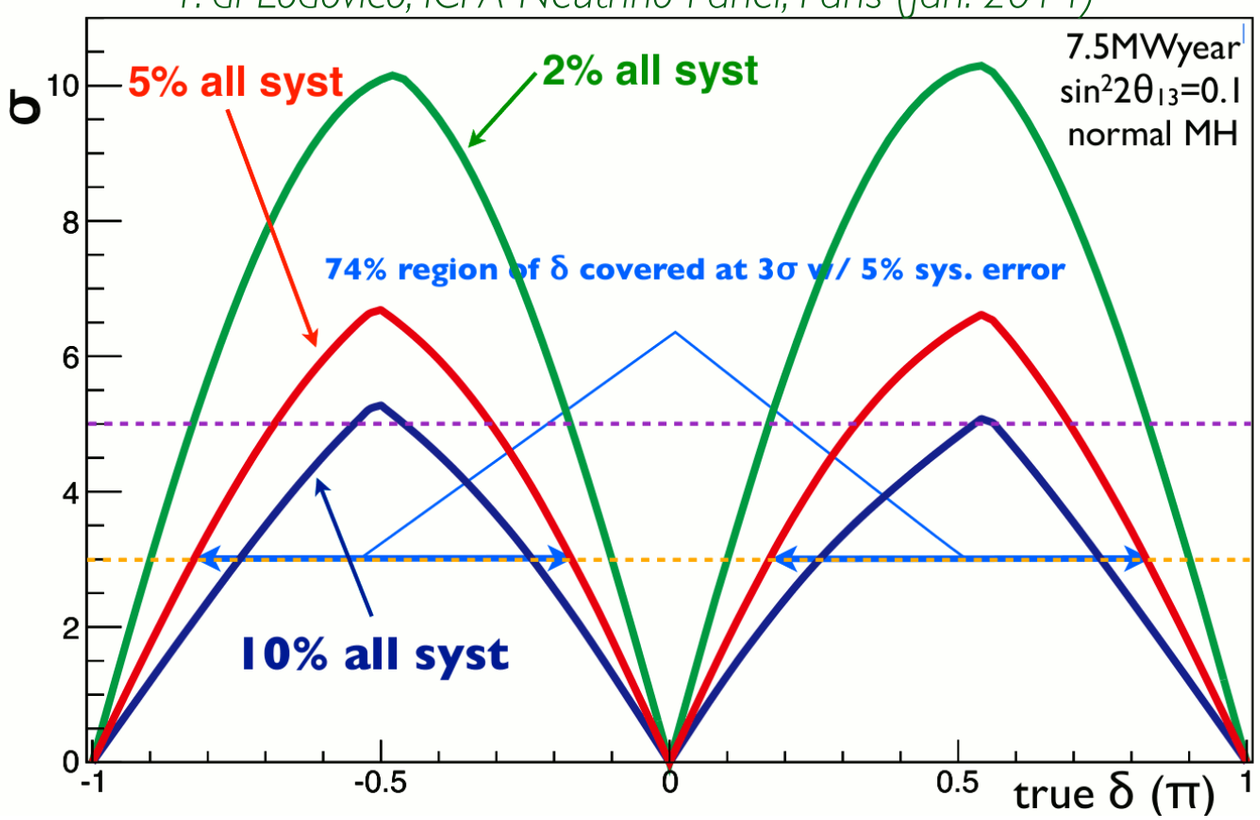


F. di Lodovico, ICFA Neutrino Panel, Paris (Jan. 2014)

CP Violation, Mass Hierarchy, θ_{23} Octant

- **T2HK (Tokai to Hyper-Kamiokande) in Japan**

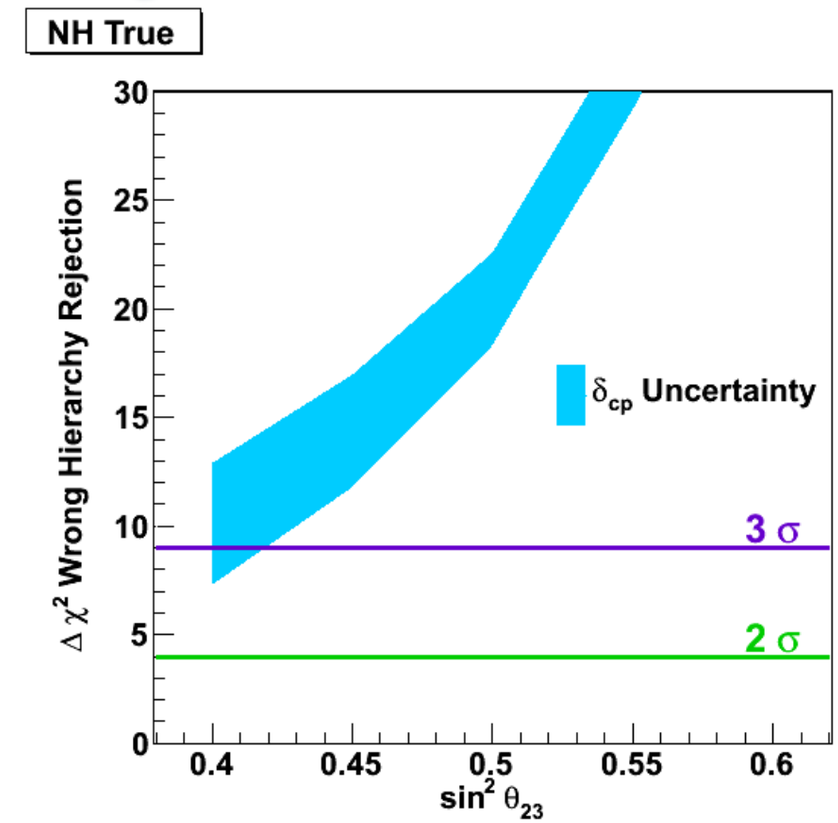
F. di Lodovico, ICFA Neutrino Panel, Paris (Jan. 2014)

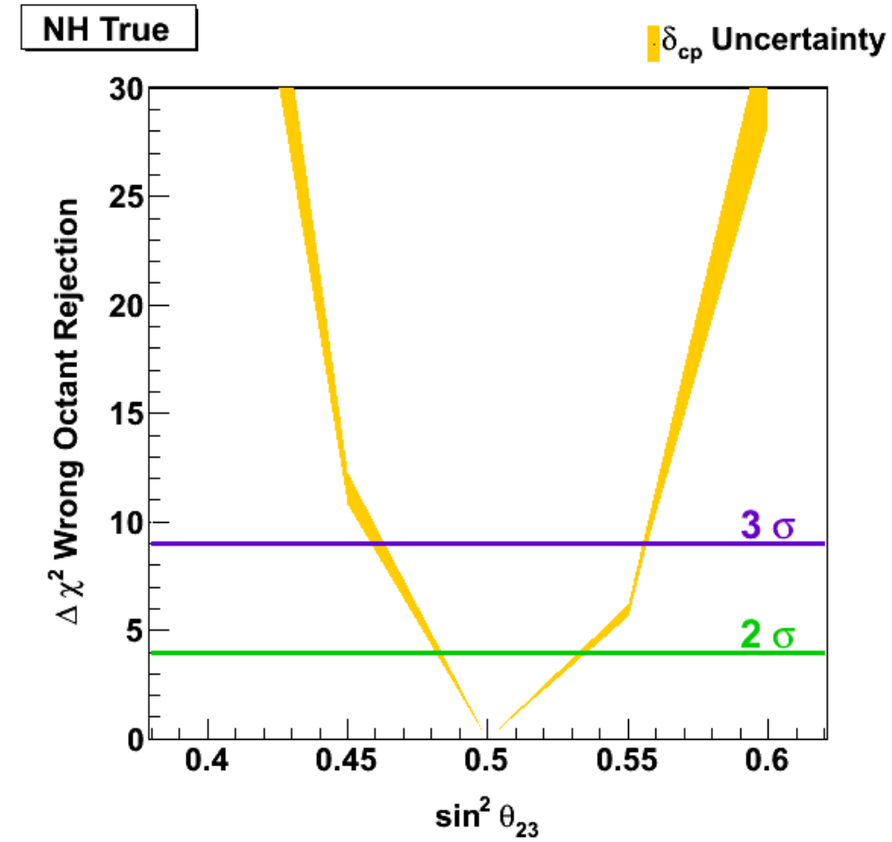


Cover 74% (55%) of δ parameter space at 3σ (5σ) assuming MH known, 5% sys.error with 10 years of running (750 kW beam), or 5 years (1.5 MW beam)

Determination of MH at >3σ for 10 years of running (using atmospheric neutrinos)

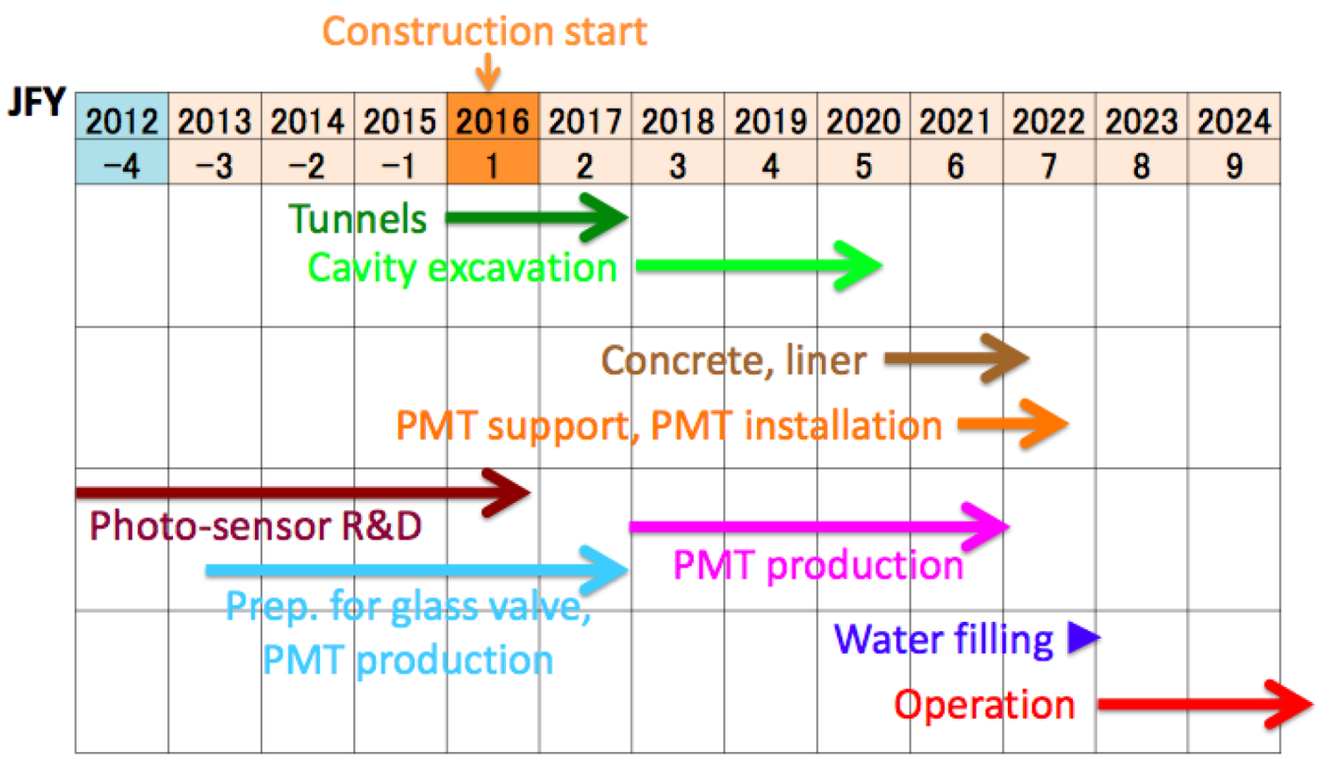
Can distinguish octant of θ_{23} at > 3σ for $\theta_{23} < 42°$ or $\theta_{23} > 48°$





CP Violation, Mass Hierarchy, θ_{23} Octant

- **T2HK (Tokai to Hyper-Kamiokande) in Japan**
- Status:
  - Hyper-K Collaboration formed in 2012
  - R&D funding, including detector prototype, approved in 2013
  - Waiting from feedback from Japan's Science Council. If positive, will submit report to Japan's MEXT (Ministry of Education, Culture, Sports, Science and Technology) during 2014



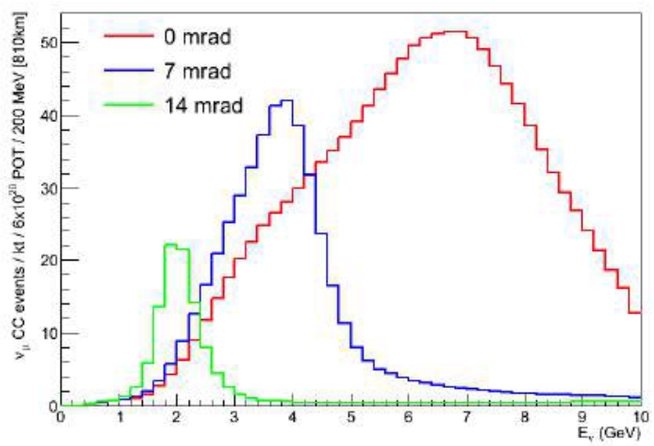
- "Should a new particle such as a Higgs boson with a mass below approximately 1 TeV be confirmed at LHC, Japan should take the leadership role in an early realization of an e+e- linear collider."
- "Should the neutrino mixing angle θ_{13} be confirmed as large, Japan should aim to realize a large-scale neutrino detector through international cooperation"

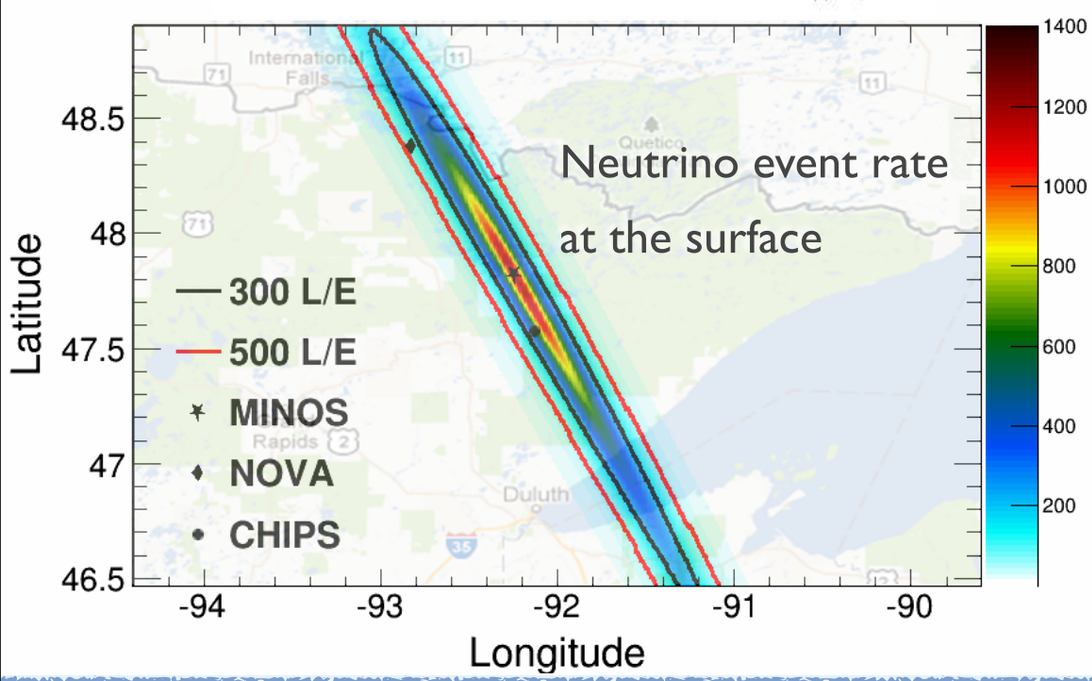
Recommendations of the Final Report of the Subcommittee on Future Projects of High Energy Physics, Japan (2012)

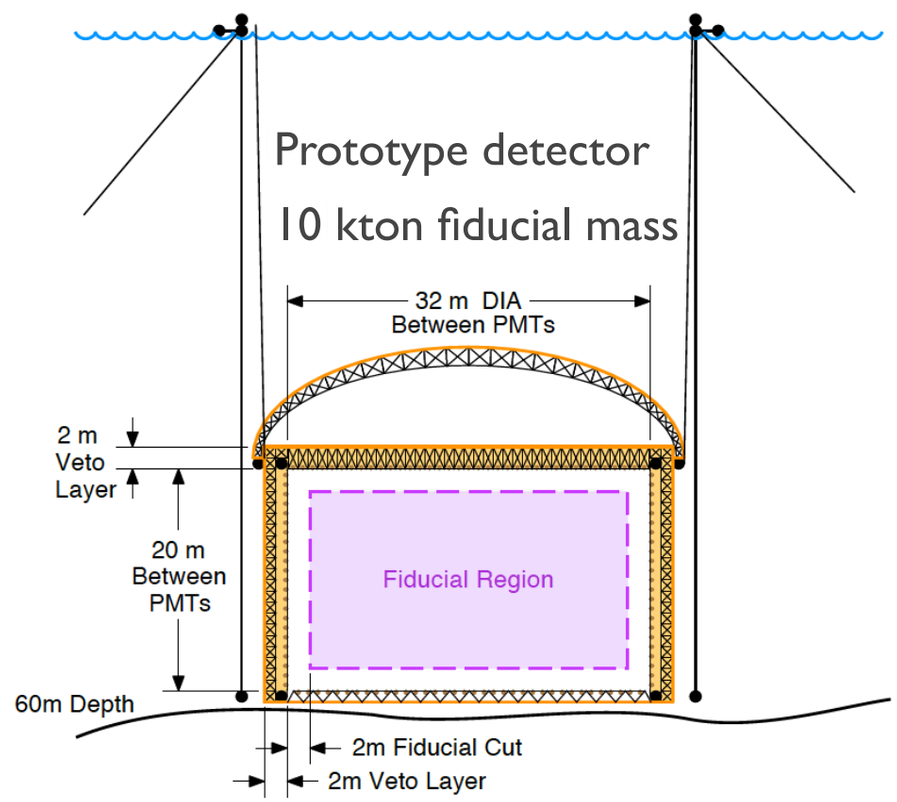
Can Japan fund both the ILC and Hyper-K?

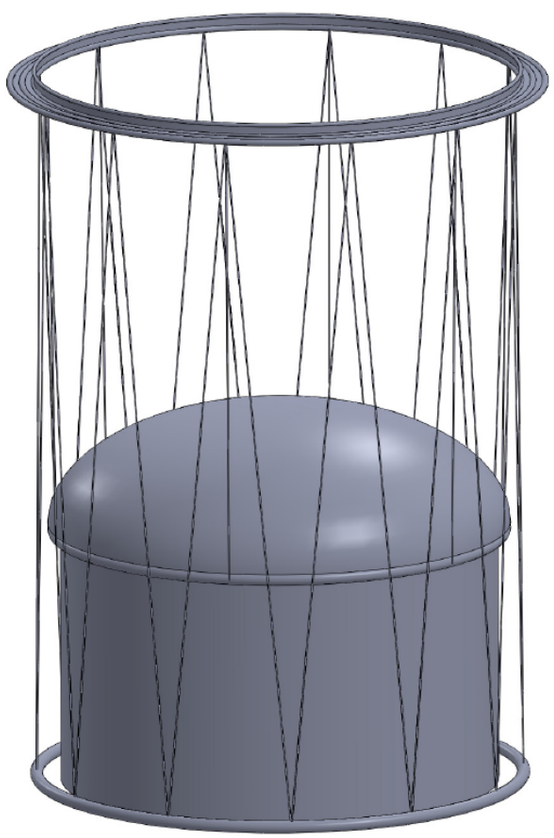
CP Violation, Mass Hierarchy, θ_{23} Octant

- **CHIPS (Cherenkov detectors In Mine PitS) in the US**
- Uses existing NuMI beam — Pion decay-in-flight off-axis (7 mrad) ν_μ beam with 700 kW power and 712 km baseline to Wentworth Pit in Minnesota
- Plan to instrument up to 100 kton of water to measure CP violation at 0.2-0.5M/kton cost







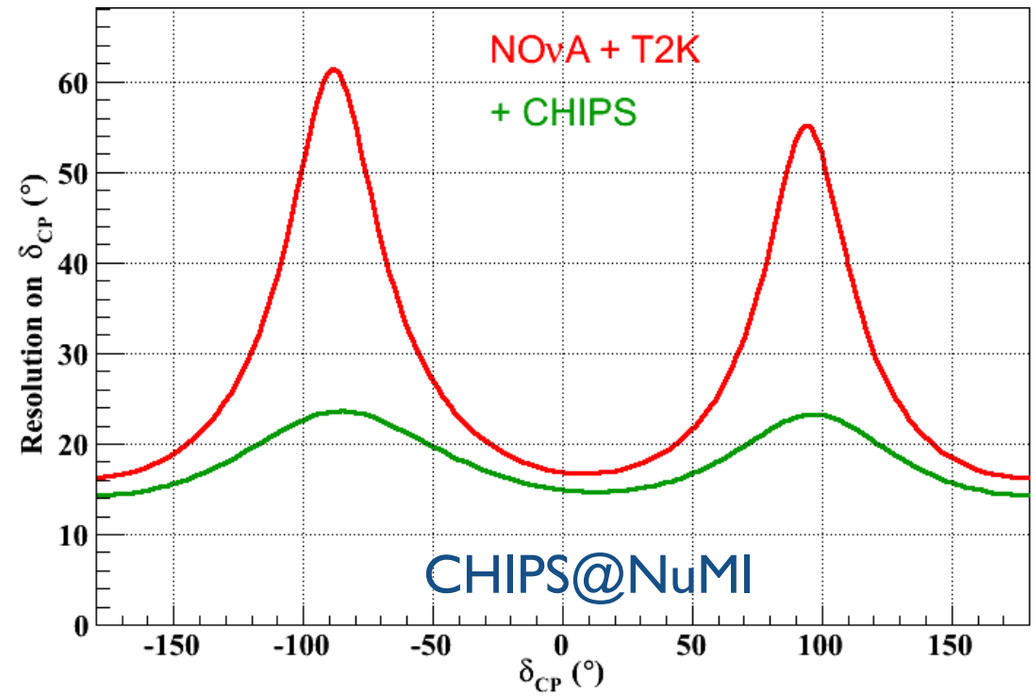


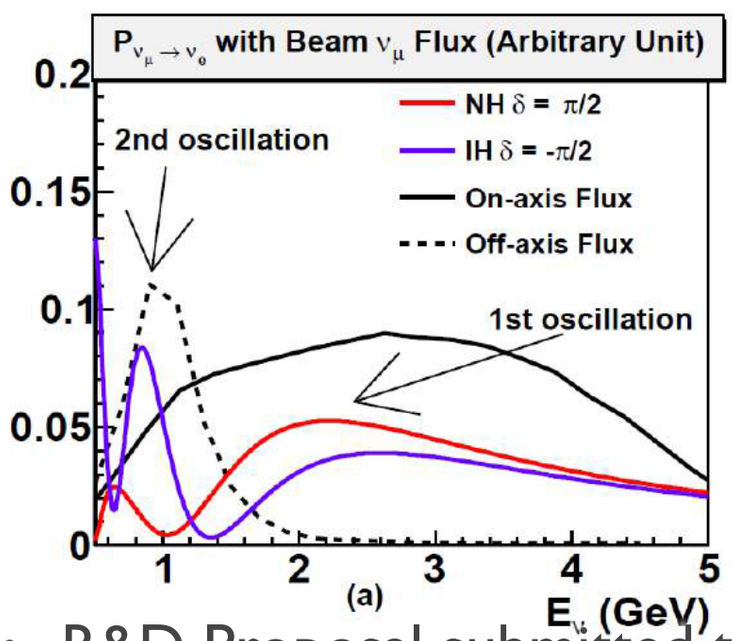
J. Thomas, ICFA Neutrino Panel, Paris (Jan. 2014)

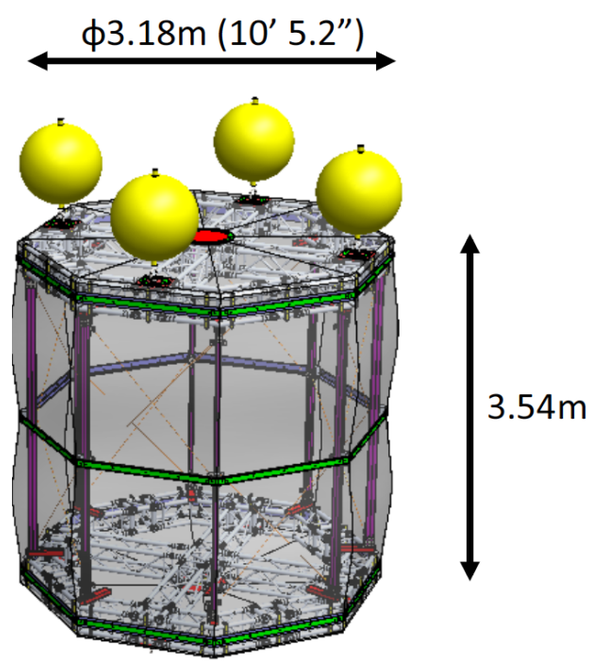
CP Violation, Mass Hierarchy, θ_{23} Octant

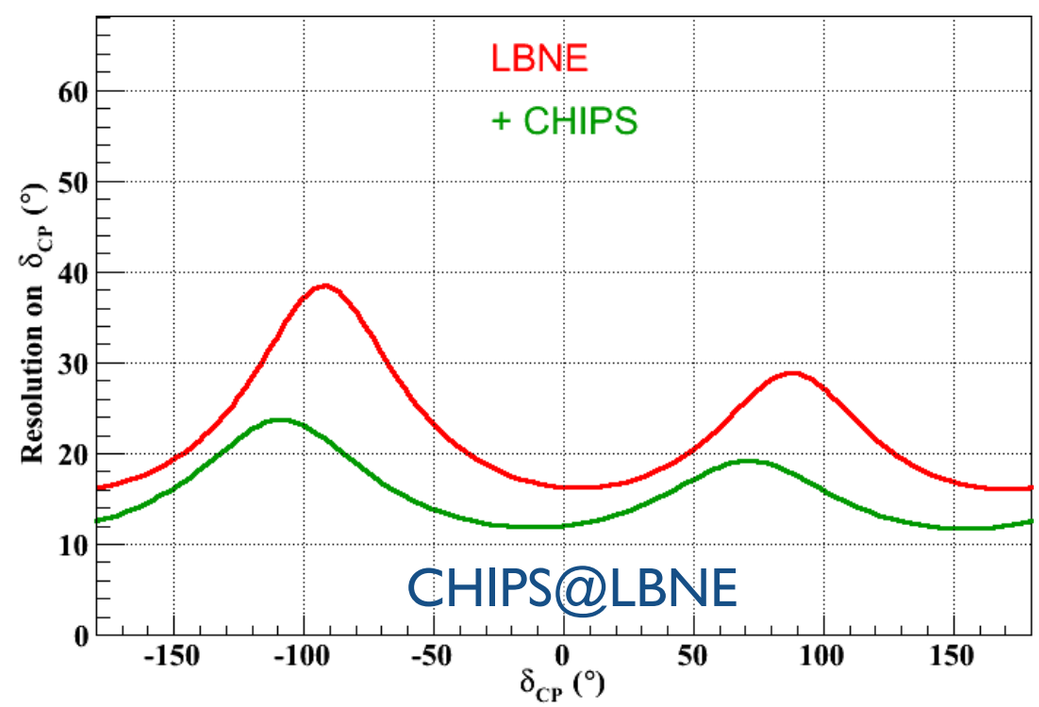
- **CHIPS (Cherenkov detectors In Mine PitS) in the US**

- Assuming 6 years of running with a 100 kton detector in NuMI, CHIPS can improve significantly sensitivity to CP violation from NOvA+ T2K
- In second phase, running 20 mrad off-axis from LBNE beam with 1250 km baseline, would help LBNE measurement





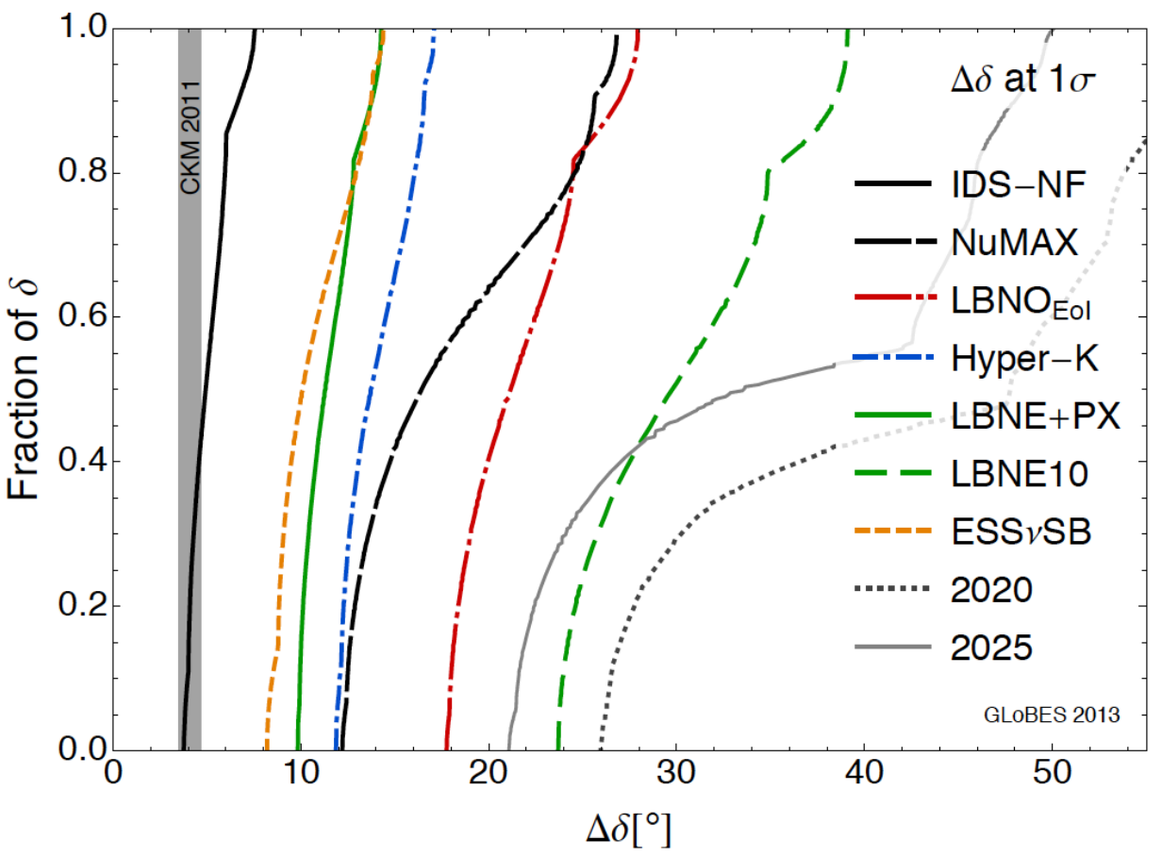




- R&D Proposal submitted to PAC and encouraged.
- 10 ton proof-of-principle detector to be deployed at Wentworth Pit this Summer
- LOI to Snowmass: arXiv:1307.5918

CP Violation, Mass Hierarchy, θ_{23} Octant

- **Other Proposed Experiments**
  - RADAR - 5 kton LAr TPC in NOνA Far Detector Hall using the NuMI beam, arXiv:1307.6507
  - DAEAδALUS - Pion decay-at-rest ν beam produced by 100 kW cyclotron. Use multiple baselines (1-20 km) to measure δ_{CP}. Hyper-K as detector would be ideal, arXiv:1307.2949
  - NuMAX - Low-energy neutrino factory, muon storage ring to produce muon decay-in-flight $\bar{\nu}_\mu$, ν_e, $\bar{\nu}_e$, ν_μ beam, use 1 MW PIP-II 5 GeV protons, and magnetized LBNE Far Detector, arXiv:1308.0494
  - IDS-NF - High-energy neutrino factory, 4 MW beam, muon cooling, 100 kton magnetized Fe detector arXiv:1112.2853



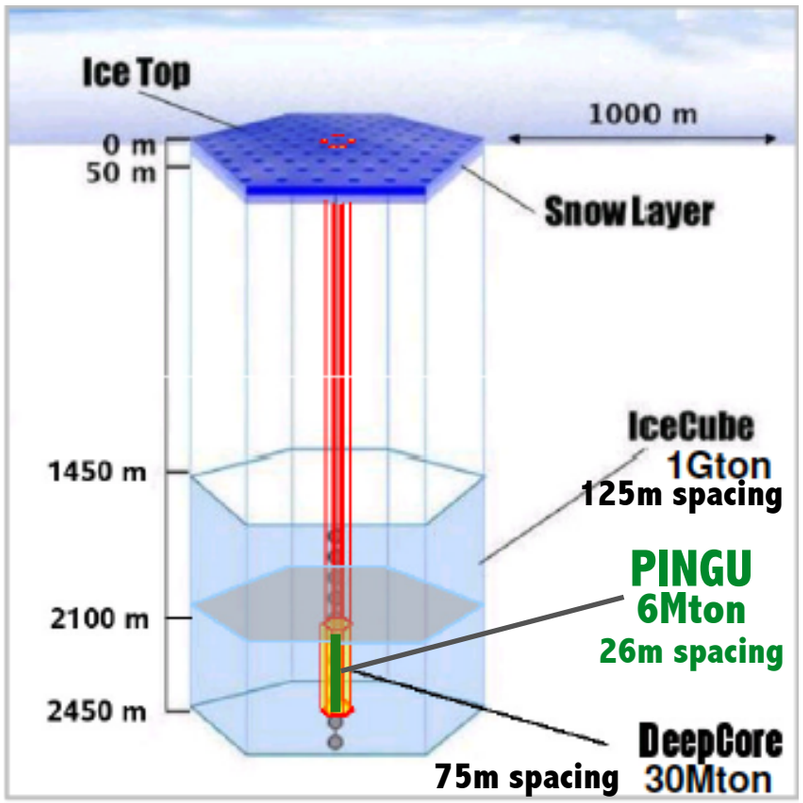
	detector vol. (kt)/type	dist. (km)	power (MW)	proton driver energy (GeV)	years $\nu/\bar{\nu}$
ESSνSB-360	500/WC	360	5	2.0/3.0	2/8
ESSνSB-540	500/WC	540	5	2.0/3.0	2/8
Hyper-K	560/WC	295	0.75	30	3/7
LBNE-10	10/LAr	1290	0.72	120	5/5
LBNE-PX	34/LAr	1290	2.2	120	5/5
LBNO-EoI	20/LAr	2300	0.7	400	5/5
IDS-NF	100/MIND	2000	4	10*	10**
NuMAX	10/LAr (magnetized)	1300	1	5*	5/5

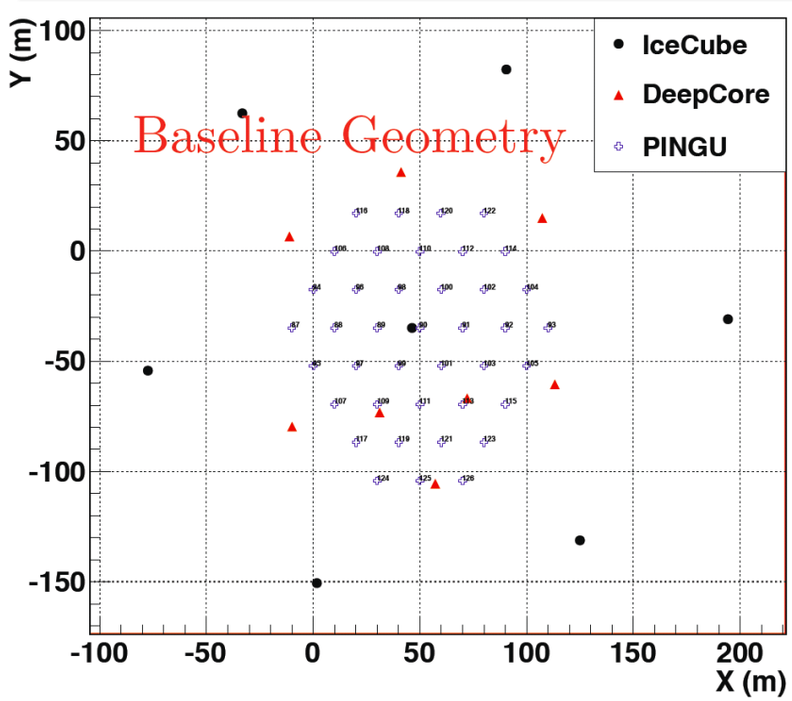
E. Baussan et al., arXiv:1309.7022

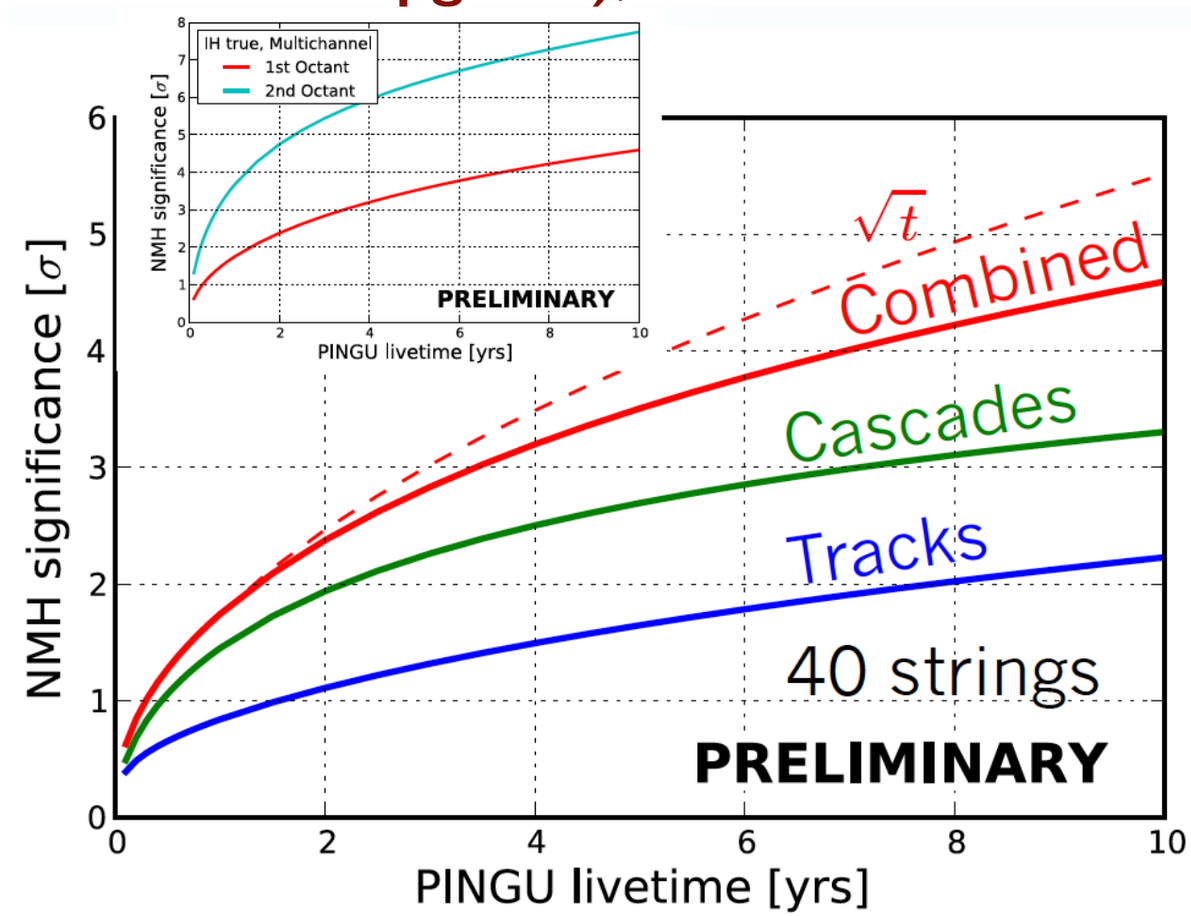
CSS 2013 (Snowmass) Neutrino Report, arXiv:1310.4340 (2013), based on P. Coloma, P. Huber, J. Kopp, W. Winter: Phys. Rev. D 87, 033004 (2013)

Mass Hierarchy, θ_{23} Octant

- **Dedicated Atmospheric Experiments:**
  - **PINGU (Precision IceCube Next Generation Upgrade), at the South Pole**



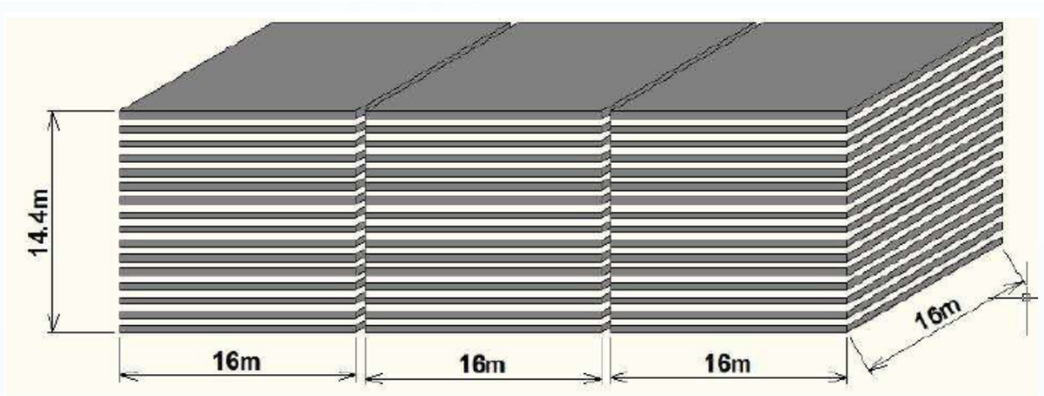




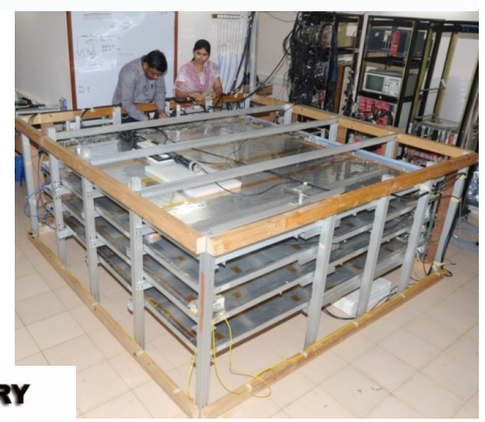
- Can reach 3σ resolution of mass hierarchy in 3-4 years running, planning to start in 2020-21
- Status
  - Still working on optimizing design, number of strings, optical module spacing, etc.
  - LOI in *arXiv.org:1401.2046*. Could become part of a larger NSF facility at the South Pole

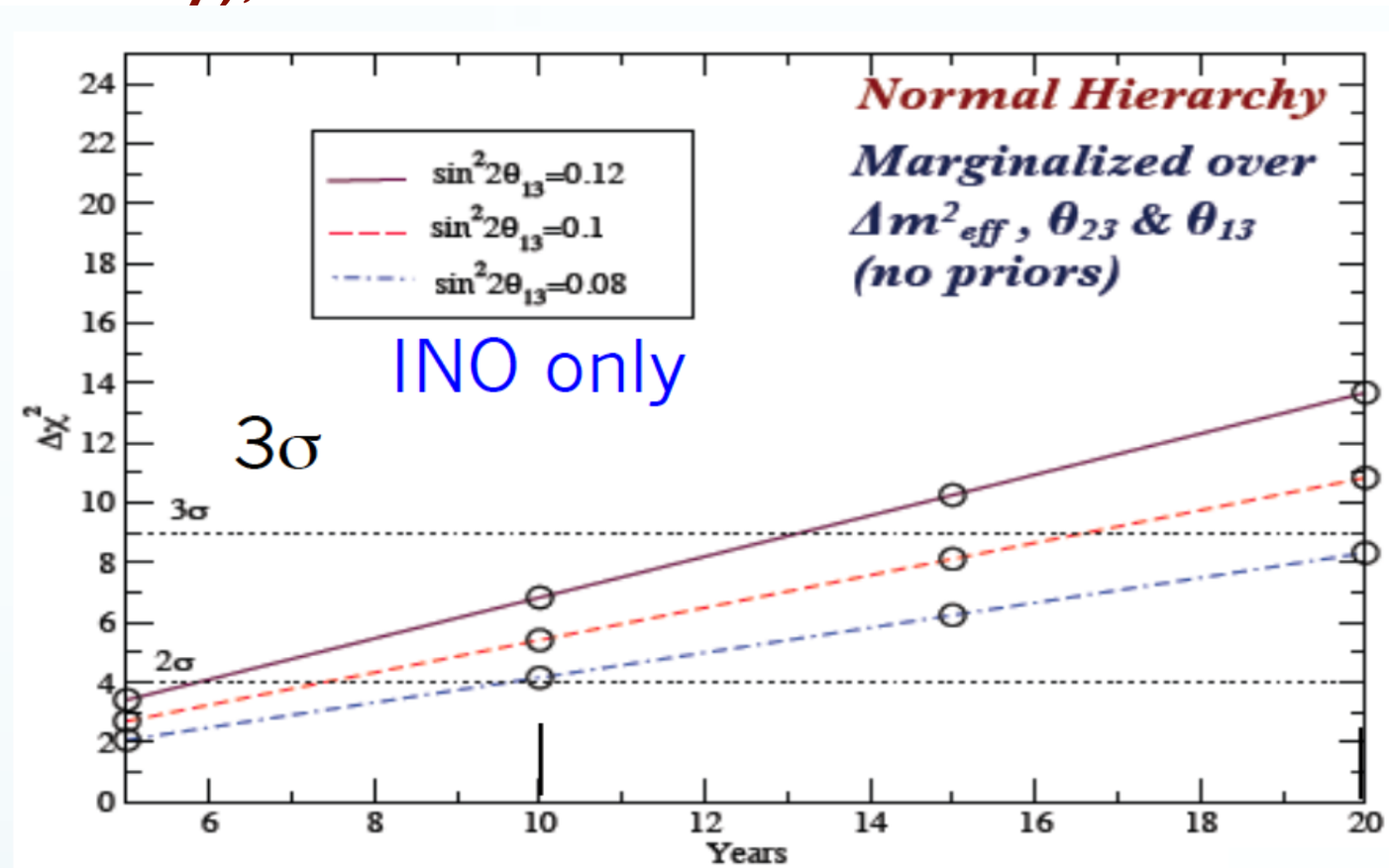
Mass Hierarchy, θ_{23} Octant

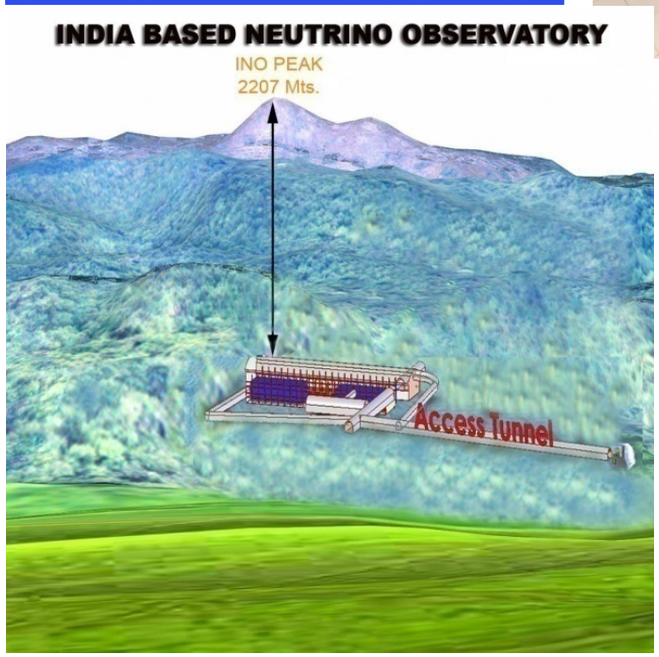
- **Dedicated Atmospheric Experiments:**
  - **INO (India-based Neutrino Observatory), in India**



- ✓ *50Kton Fe-RPC Detectors*
- ✓ *# of layers = 140*
- ✓ *Fe thickness = 5.6 cm*
- ✓ *Magnetic Field ~ 1.3T*
- ✓ *# of RPCs ~ 27K*
- ✓ *# of channels ~ 3.6M*







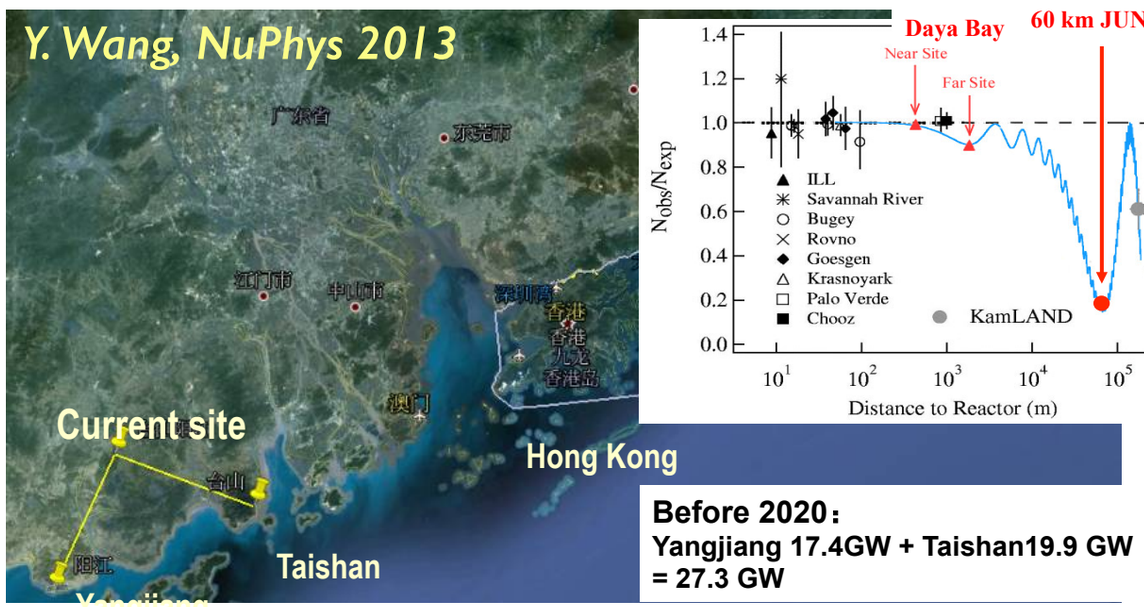
- Need over 10 years of running to reach 3σ resolution of mass hierarchy, but complementary to other measurements
- Status
  - Location chosen in Pottipuran, 100 km west of Madurai
  - Work started on facilities in Madurai HEP Center
  - Waiting for full approval by Indian government. Operations to start circa 2018

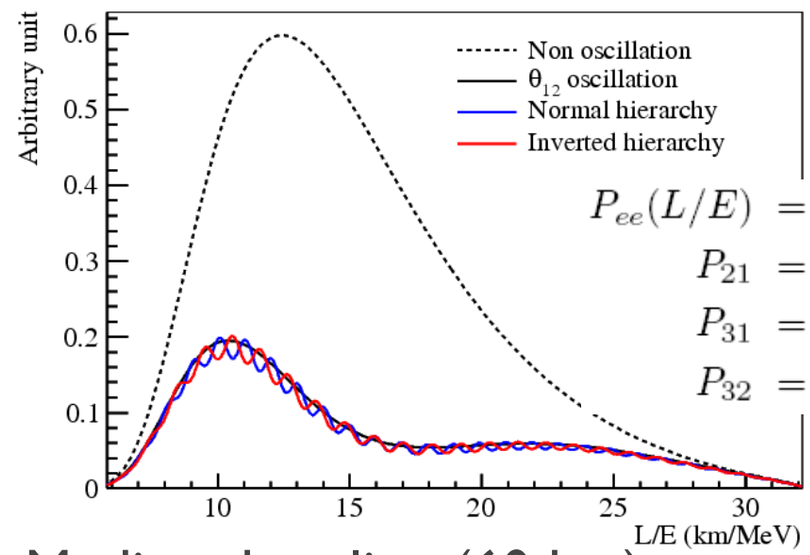
- **NB: Also sensitivity from atmospherics in LBNE, LBNO, Hyper-K**

Mass Hierarchy

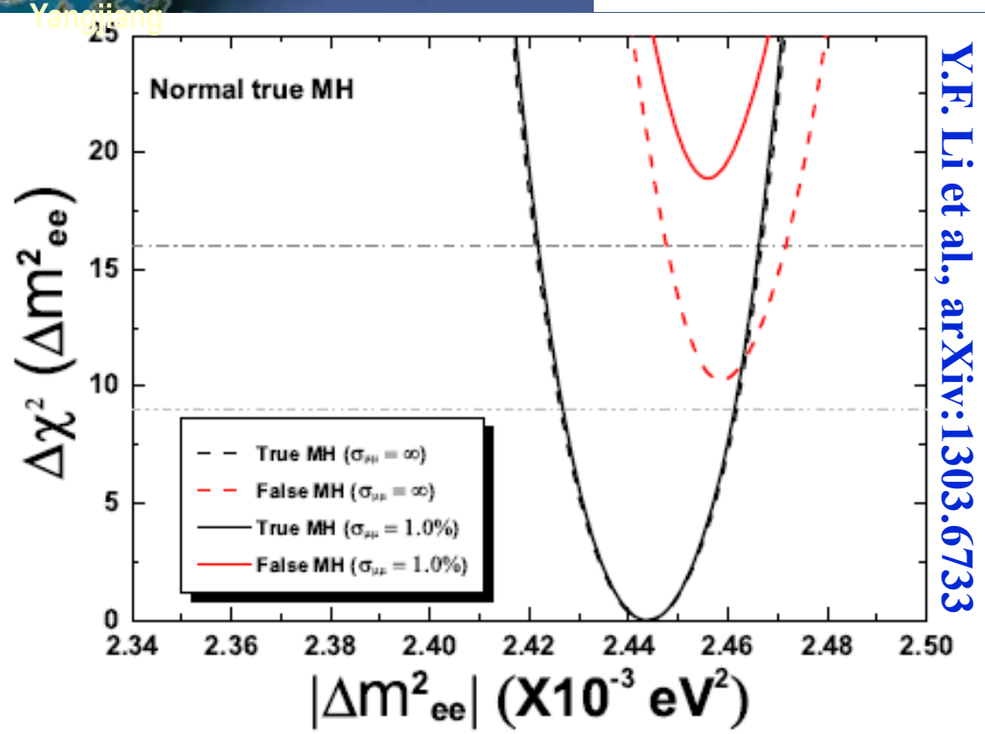
- **Reactor Experiments:**
  - **JUNO (Jiangmen Underground Neutrino Observatory), in China**

	Daya Bay	Huizhou	Lufeng	Yangjiang	Taishan
Status	running	planned	approved	Construction	construction
power/GW	17.4	17.4	17.4	17.4	18.4





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

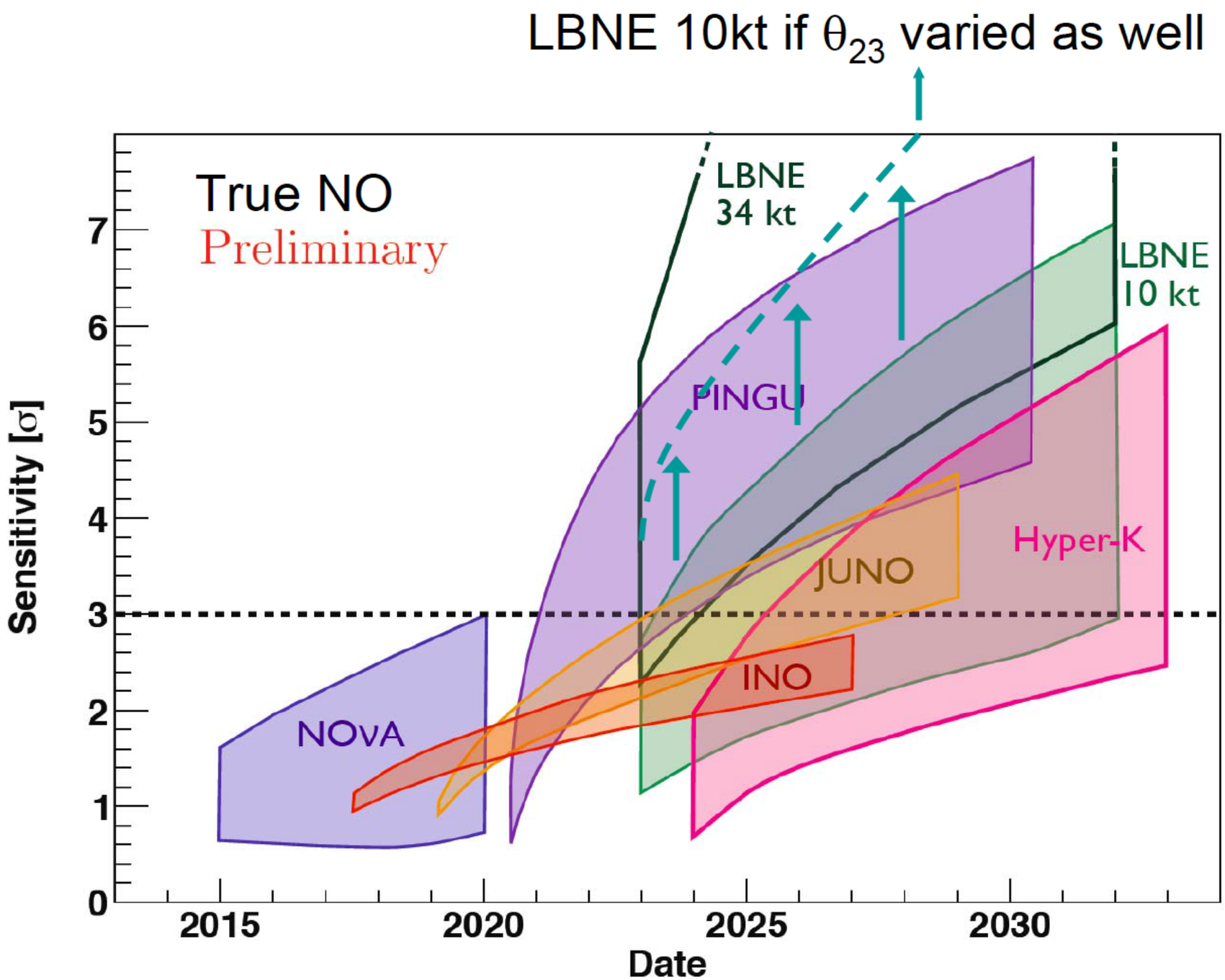


Y.F. Li et al., arXiv:1303.6733

- Medium-baseline (60 km) reactor experiment
- Need to distinguish between NH and IH in rapid oscillations in $P(\bar{\nu}_e \rightarrow \bar{\nu}_e)$ driven by Δm^2_{31-2}
- Requires 20 kton liquid scintillator det. with 3% /$\sqrt{E}$ energy resolution, and reactors with 36 GW power
- Can determine MH at 4σ level with 6 years of running if Δm^2 can be determined with 1% precision; < 2% precision measurement of θ_{12} and Δm^2_{21}
- Status: Detector design underway, prototype to be started by end of the year, R&D funding approved, construction approval in progress
  - First data expected in 2020
- **Also RENO-50 proposal, in Korea, with same concept and same challenges**

Mass Hierarchy Summary

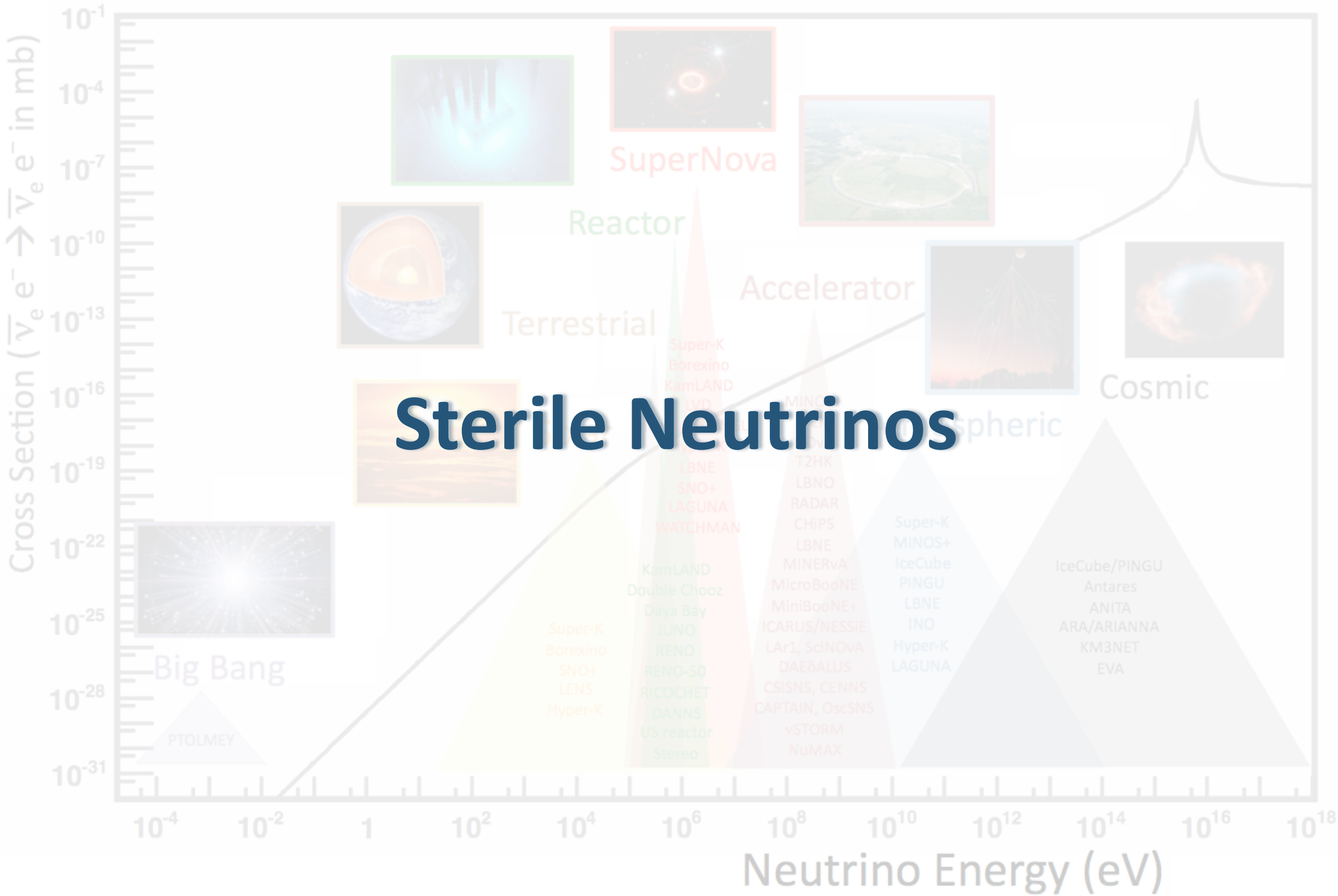
- Comparison of reach in determining the mass hierarchy for current and future experiments



- Bands cover maximum sensitivity differences due to variation of δ_{CP} (NOνA, LBNE), θ_{23} (PINGU, INO, HyperK), and energy resolution (JUNO)
- Expected LBNE sensitivity for most favorable θ_{23} values also included.

W. Winter, Frontiers in HEP 2014, Aspen, based on Blennow, Coloma, Huber, Schwetz, arXiv:1311.1822

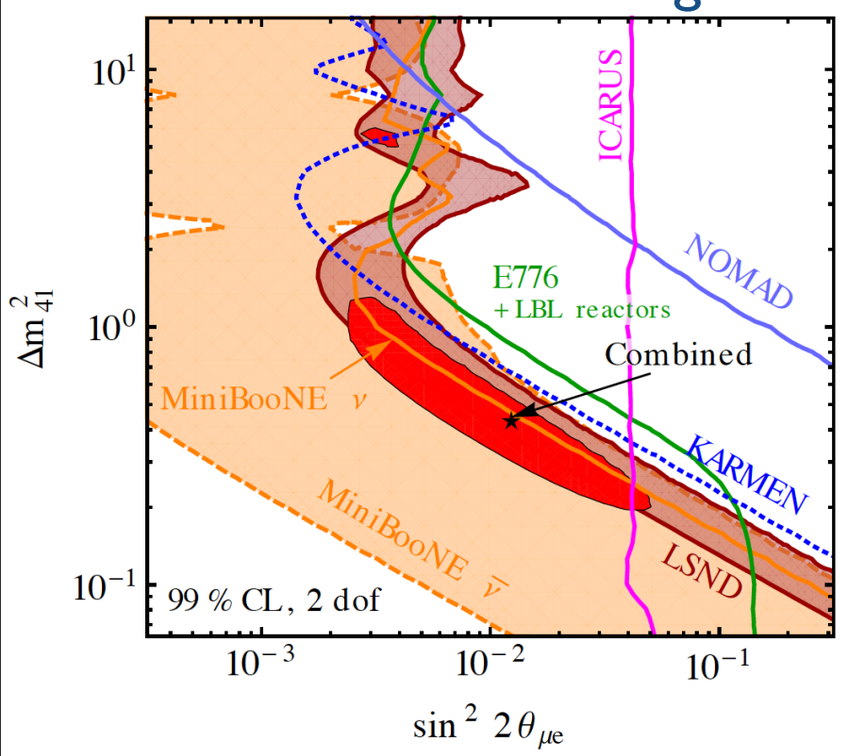
Sterile Neutrinos



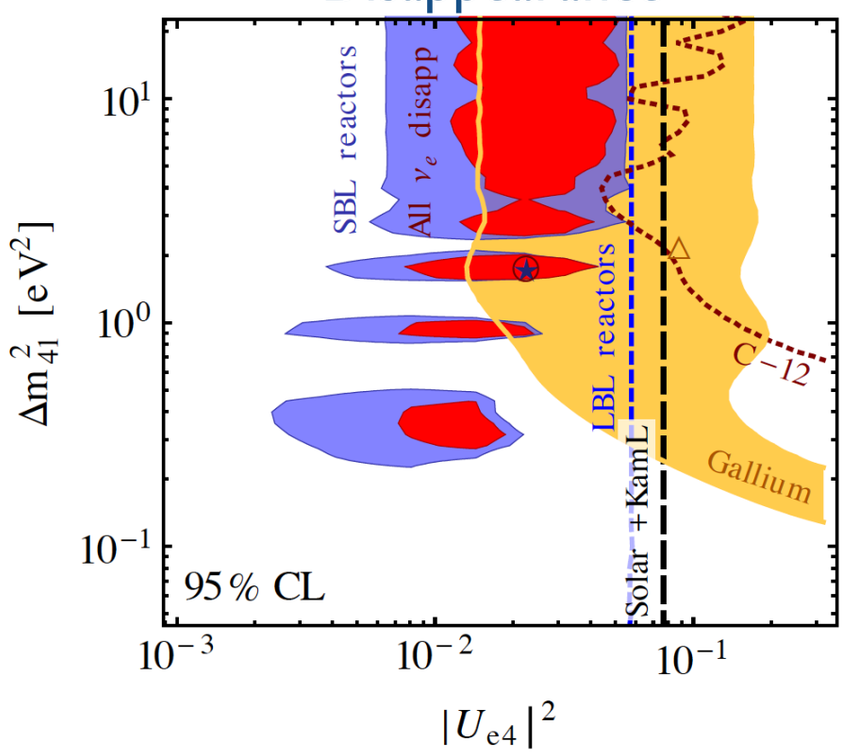
Sterile Neutrinos

- Oscillations into light sterile neutrinos are a proposed explanation for anomalies seen in short-baseline accelerator experiments, reactor experiments (following re-evaluation of $\bar{\nu}_e$ reactor flux to be 3.5% higher), and from gallium anomaly
- Severe tension between appearance, and disappearance measurements or appearance measurements that see no signal

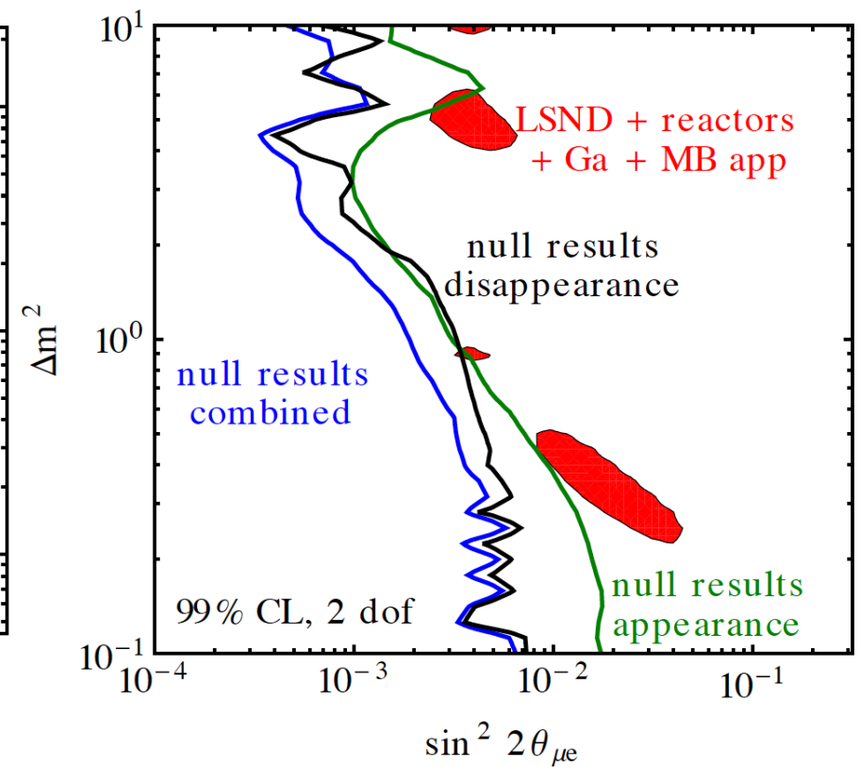
3+1 $\bar{\nu}_e$, ν_e SBL Appearance LSND/MiniBooNE Signal



3+1 $\bar{\nu}_e$, ν_e Reactor, Gallium Disappearance



3+1 Evidence vs No-Evidence

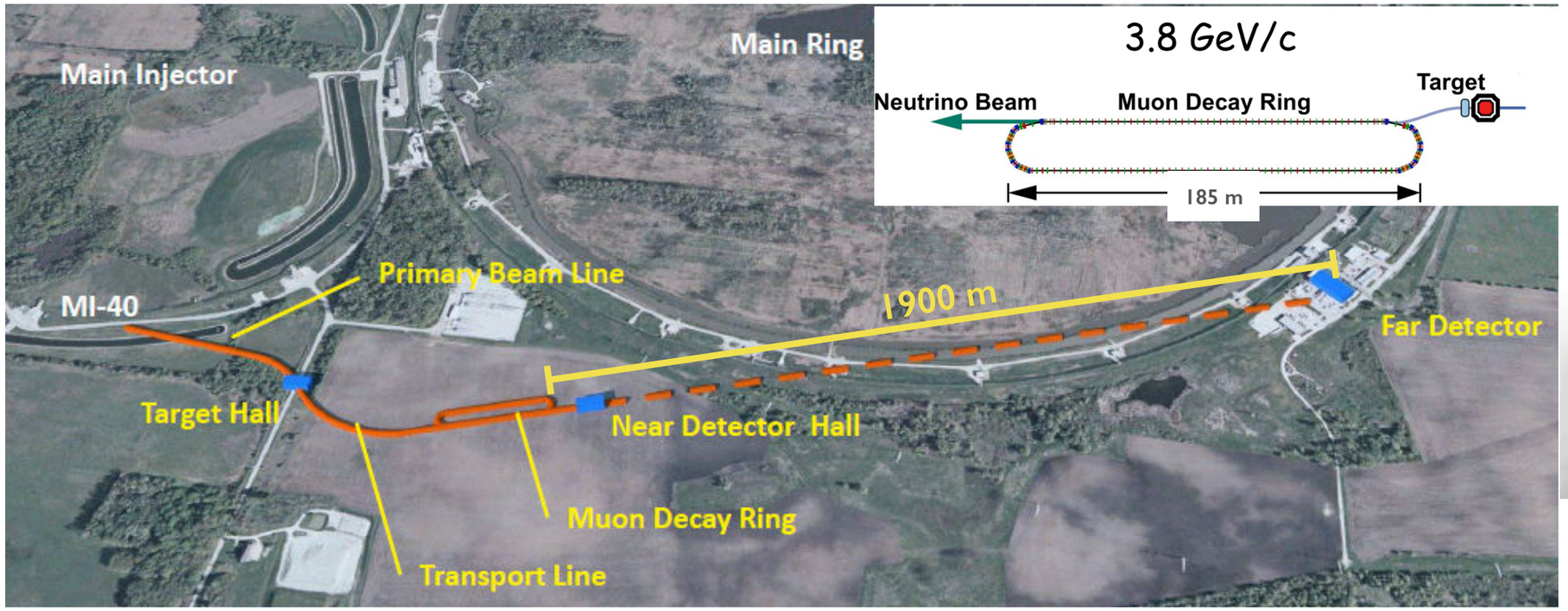


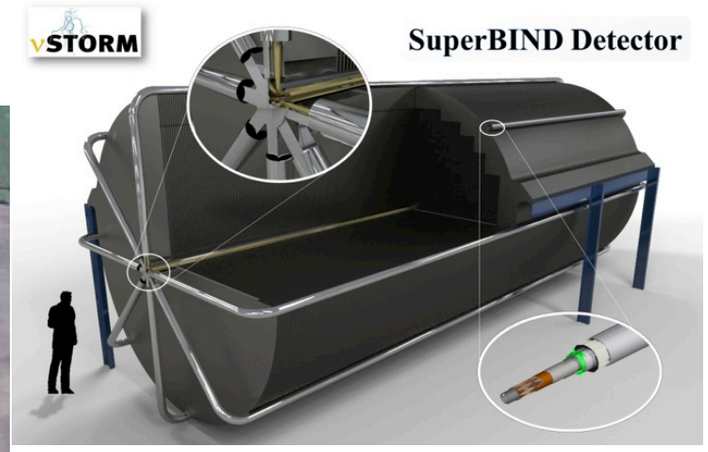
Kopp, Machado, Maltoni, Schwetz, arXiv:1303.3011

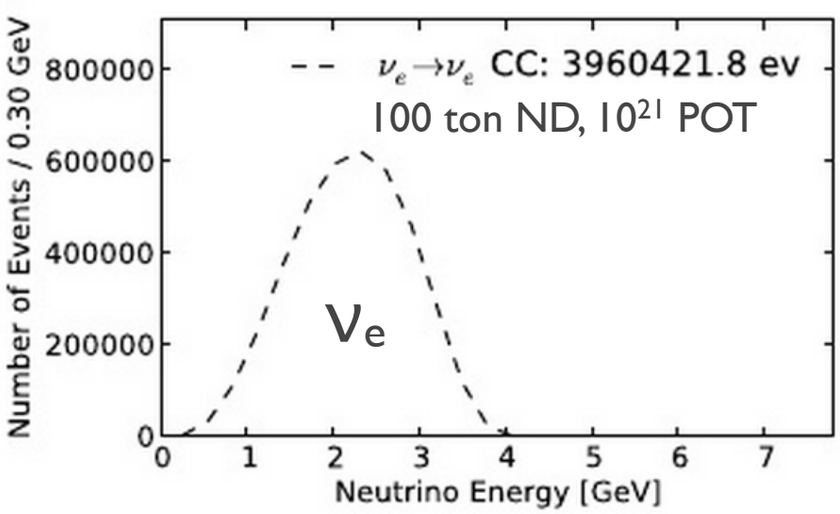
- Short and long-baseline accelerator, reactor, radioactive, and atmospherics experiments planned to resolve these anomalies over next 10-15 years

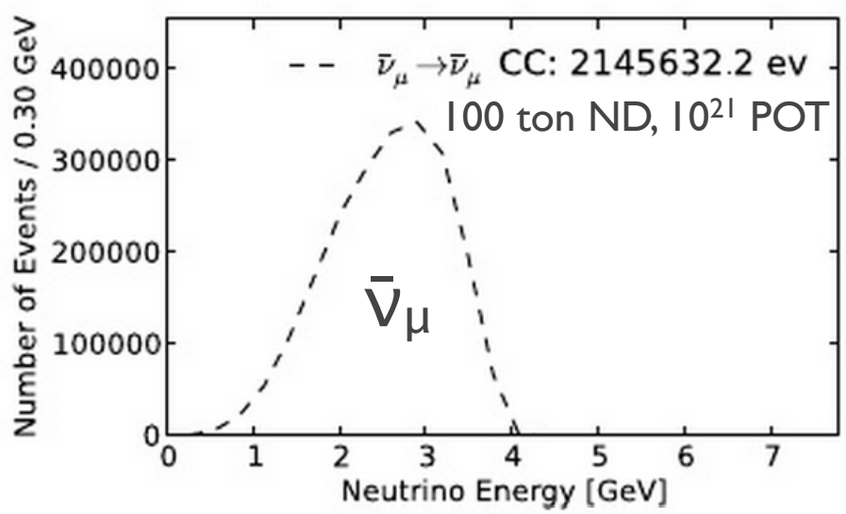
Sterile Neutrinos

- **Short-Baseline Accelerator Experiments**
  - **nuSTORM (Neutrinos from STORed Muons), to be hosted at Fermilab or CERN**
- $\bar{\nu}_\mu$, ν_e, $\bar{\nu}_e$, ν_μ beams from muon decay-in-flight in muon storage ring. 3.8 GeV/c muons from 100 kW 120 GeV/c proton beam incident in graphite target







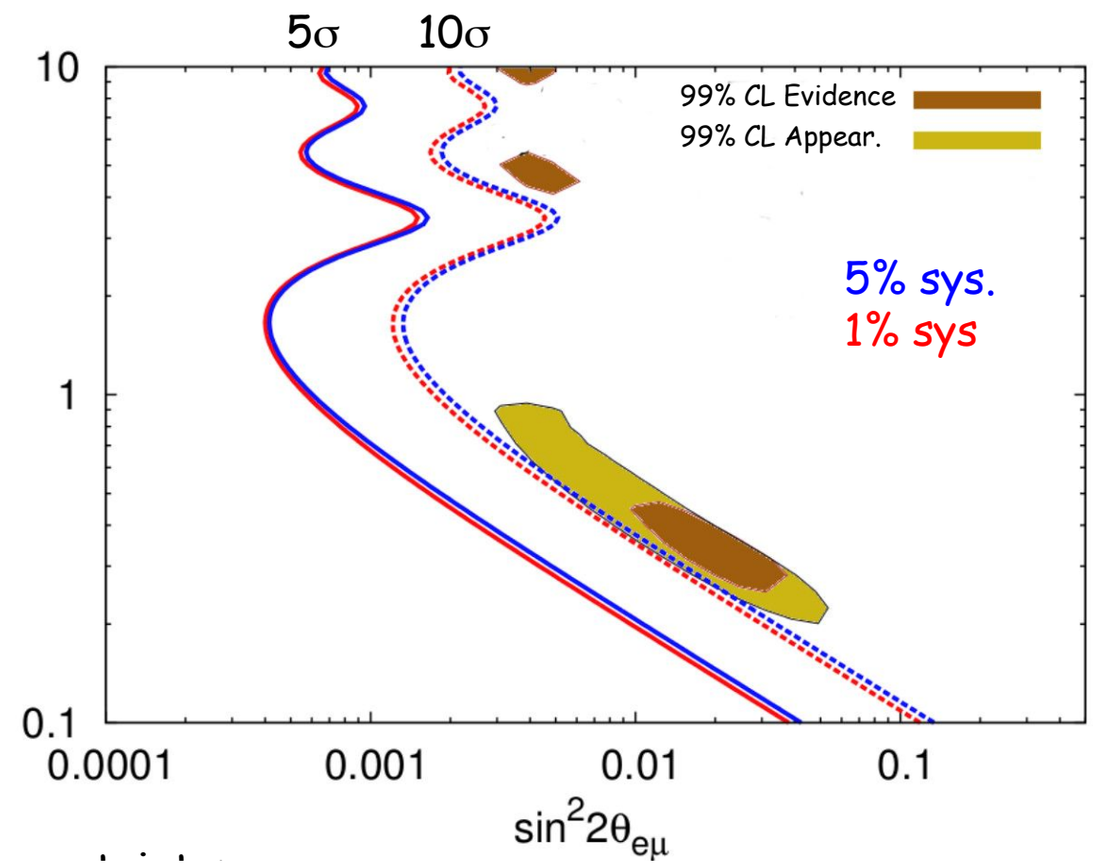


- Proposed FD is a 1.3 kton iron-scintillator tracking calorimeter similar to MINOS, but ~2.3 T B field is generated by a superconducting transmission line

Sterile Neutrinos

- **Short-Baseline Accelerator Experiments**
  - **nuSTORM (Neutrinos from STORed Muons), to be hosted at Fermilab or CERN**
  - Experimental setup has access to 8 of 12 possible channels from stored μ^+ or μ^-
  - Using the very large statistics in the CPT invariant mode of LSND, $\nu_e \rightarrow \nu_\mu$, can rule out sterile neutrino allowed regions at 10σ
  - With Near Detector(s), can potentially measure ν_e, $\bar{\nu}_e$ cross-sections to ~1-2%, essential for future long-baseline experiments

$\mu^+ \rightarrow e^+ \nu_e \overline{\nu}_\mu$	$\mu^- \rightarrow e^- \overline{\nu}_e \nu_\mu$	
$\overline{\nu}_\mu \rightarrow \bar{\nu}_\mu$	$\nu_\mu \rightarrow \nu_\mu$	disappearance
$\overline{\nu}_\mu \rightarrow \bar{\nu}_e$	$\nu_\mu \rightarrow \nu_e$	appearance (challenging)
$\overline{\nu}_\mu \rightarrow \bar{\nu}_\tau$	$\nu_\mu \rightarrow \nu_\tau$	appearance (atm. oscillation)
$\nu_e \rightarrow \nu_e$	$\bar{\nu}_e \rightarrow \bar{\nu}_e$	disappearance
$\nu_e \rightarrow \nu_\mu$	$\bar{\nu}_e \rightarrow \bar{\nu}_\mu$	appearance: "golden" channel
$\nu_e \rightarrow \nu_\tau$	$\bar{\nu}_e \rightarrow \bar{\nu}_\tau$	appearance: "silver" channel



nuSTORM paper submitted to PRD(RC), arXiv:1402.5250 (2014)

- Status: Full proposal submitted to Fermilab PAC in June 2013, granted Stage I approval, expecting to produce Technical Design Report in 2 years; LOI to Snowmass
- EOI to CERN in April 2013: support to study where to site the facility at CERN, and also define decisive european contributions

Sterile Neutrinos

- **Short-Baseline Accelerator Experiments**
  - **Multi-LAr TPC program (MicroBooNE, LAR1-ND, and LAr1) at Fermilab, in the US**

- Recast of 2012 LAr1 proposal to probe LSND anomaly into a phased program

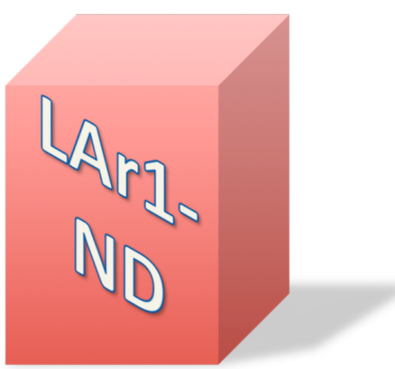
- Provide R&D stepping stones towards LBNE's large far detector

D. Schmitz, P5 Face-to-Face at FNAL (2013)

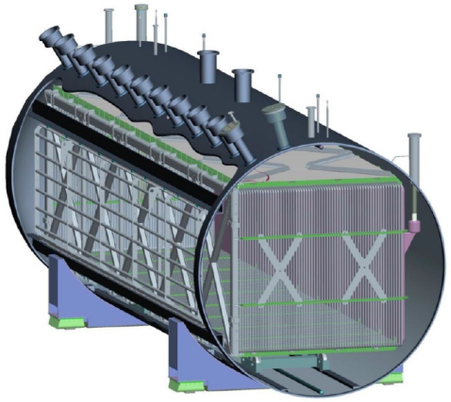
Phase 1:
LAr1-ND as Near Detector to MicroBooNE*
Run ~2016-2017
Estimated ~100 collaborators
*MicroBooNE begins running in 2014

Phase 2:
1 kton-scale Far Detector to complete 3 detector configuration
Run ~2020-
Estimated 100-150 collaborators

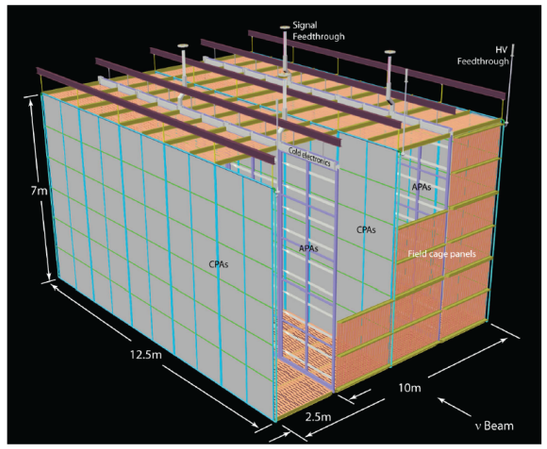
LAr1-ND
(40ton fiducial) at 100 m



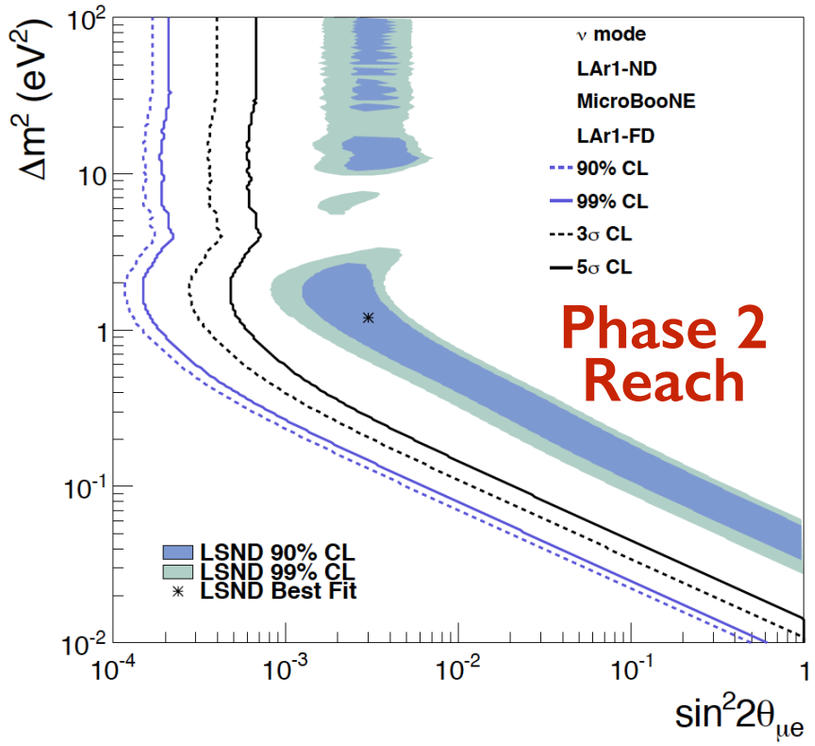
MicroBooNE
(61ton fiducial) at 470 m



LAr1-FD Far detector
(1kton fiducial) at 700 m



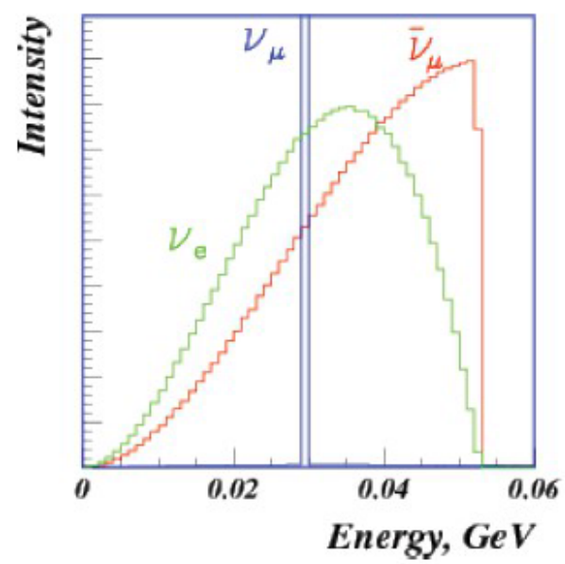
Neutrino mode: 6.6×10^{20} POT exposure

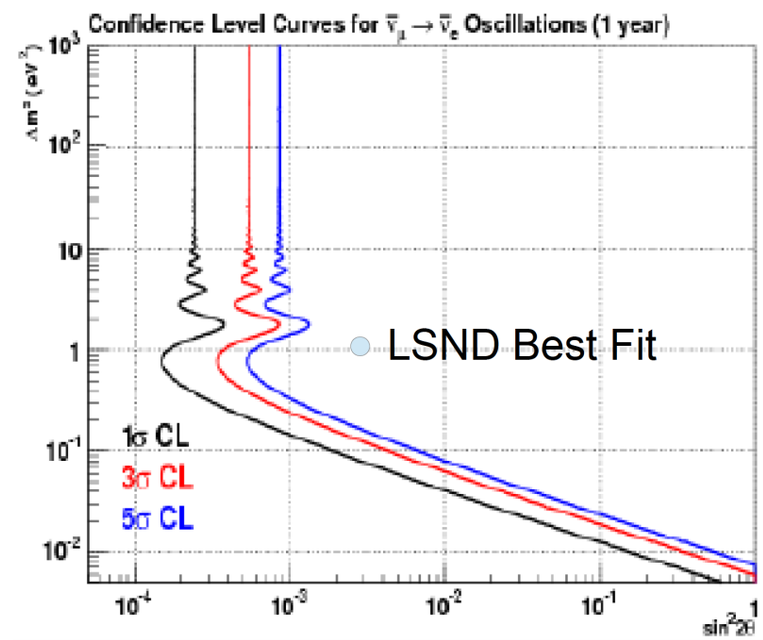


- LAr1 presented to FNAL PAC in 2012
- LAr1-ND Snowmass LOI in arXiv/1309.7987

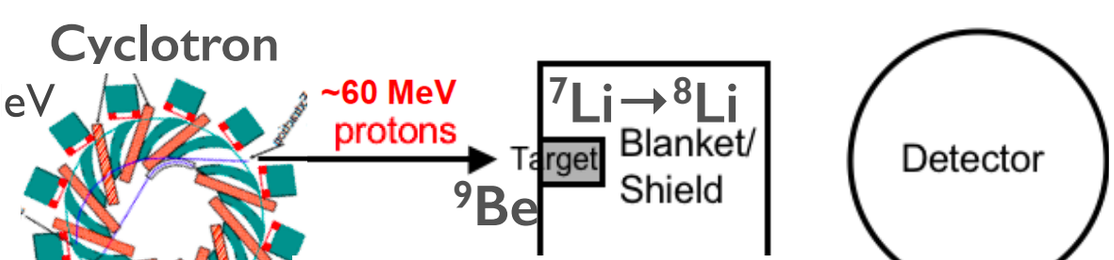
Sterile Neutrinos

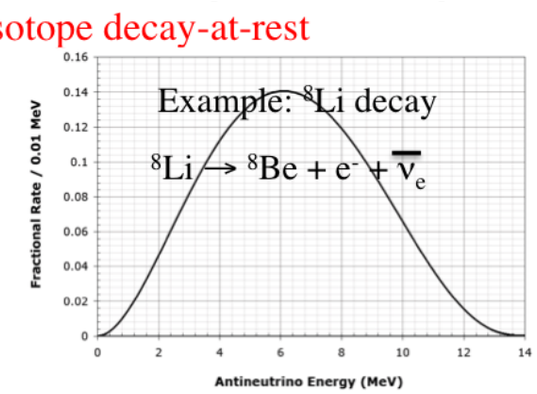
- **Short-Baseline Accelerator Experiments**
  - **OscSNS (Oscillations at the Spallation Neutrino Source), at Oak Ridge Nat. Lab, US**
- Redo LSND experiment with a more intense and well understood pion decay-at-rest beam (1 GeV protons on Hg target) with 1.4 MW power
- Use 450 ton fiducial detector with same type of mineral oil as LSND, but better electronics (200 MHz vs 10 MHz)
- LOI submitted to Snowmass

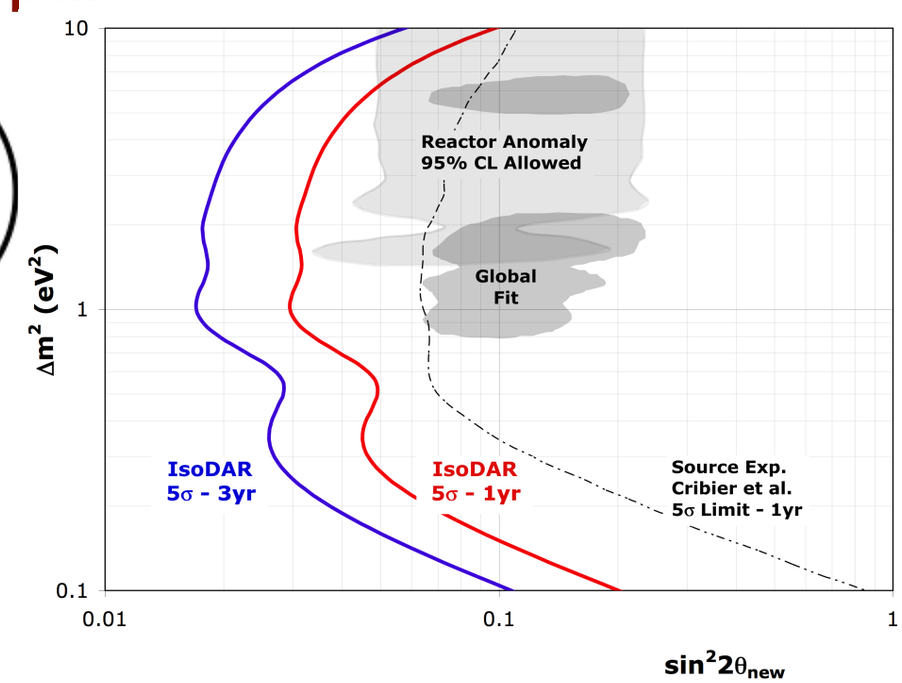




- **IsoDAR (Isotope Decay-At-Rest Experiment), at KamLAND, Japan**
- Mean $\bar{\nu}_e$ energy of 6.5 MeV
- Neutrino source placed 16 m from center of KamLAND
- Look for changes in inverse beta decay rate as a function of L/E inside detector to look for sterile neutrinos
- Proposal in arXiv:1205.4419







Sterile Neutrinos

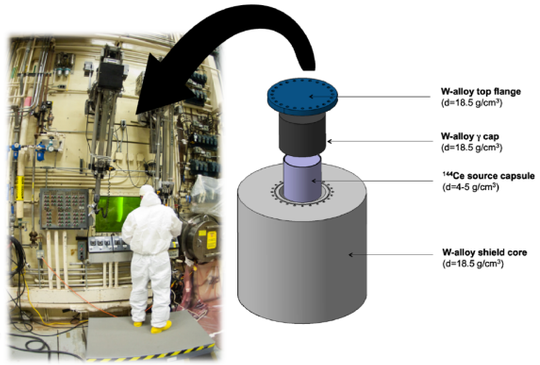
- **Radioactive Sources**
  - **CeLAND (Cerium source at KamLAND), also Ce@Daya Bay and SOX@Borexino**

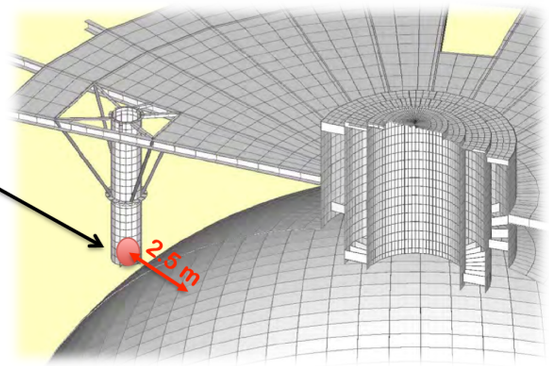
erc

- 75 kCi of ^{144}Ce-^{144}Pr (CeO_2)

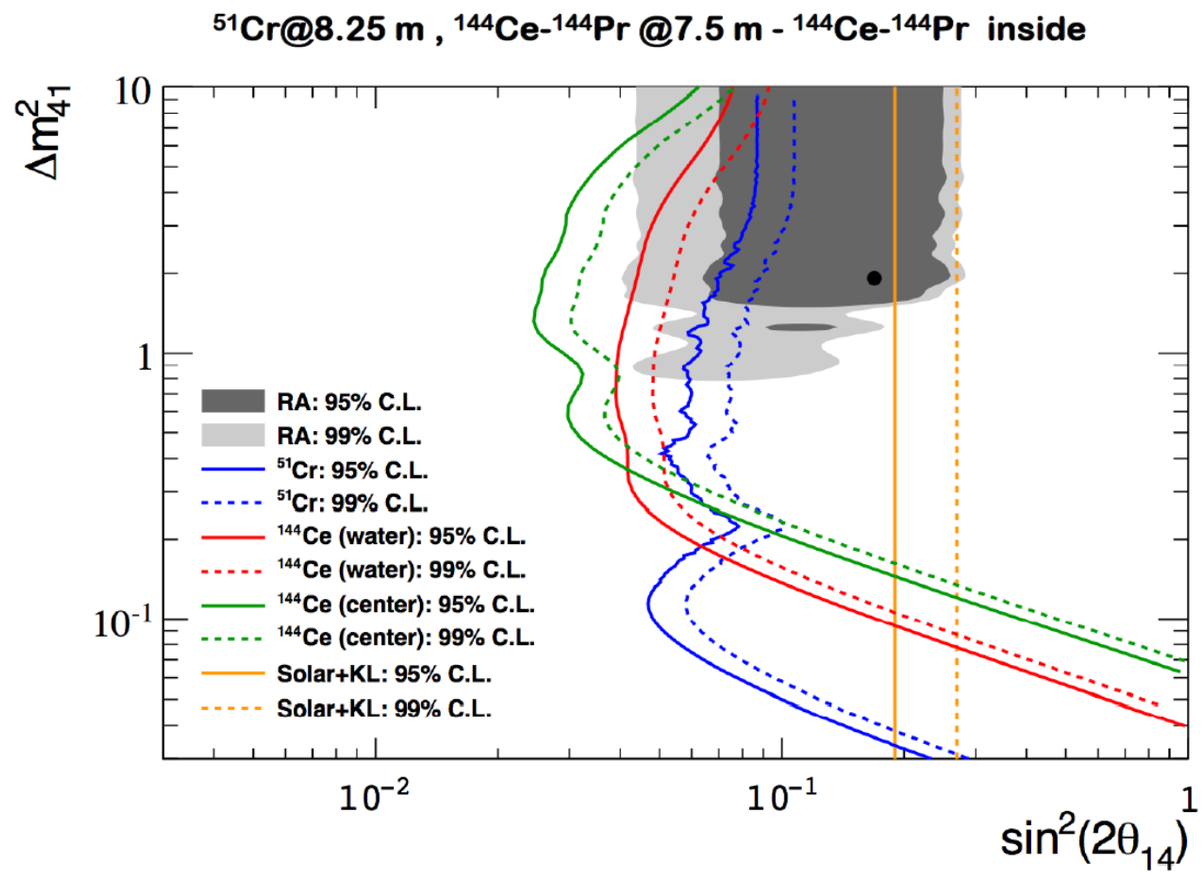
E_ν~2 MeV, L=9.3 m to center of det.

- Production feasible at Mayak Facility (RU) in 2014 (1 y)
  - Standard SNF reprocessing
  - Ce extraction through displacement chromatography
- Need 16 cm tungsten-shield
- KamLAND being prepared
  - Deployment
    - in water veto (3-16 m)
    - In Xenon Room (5-18 m)
  - Run in // with KamLAND-zen
- Deployment in 2015/16

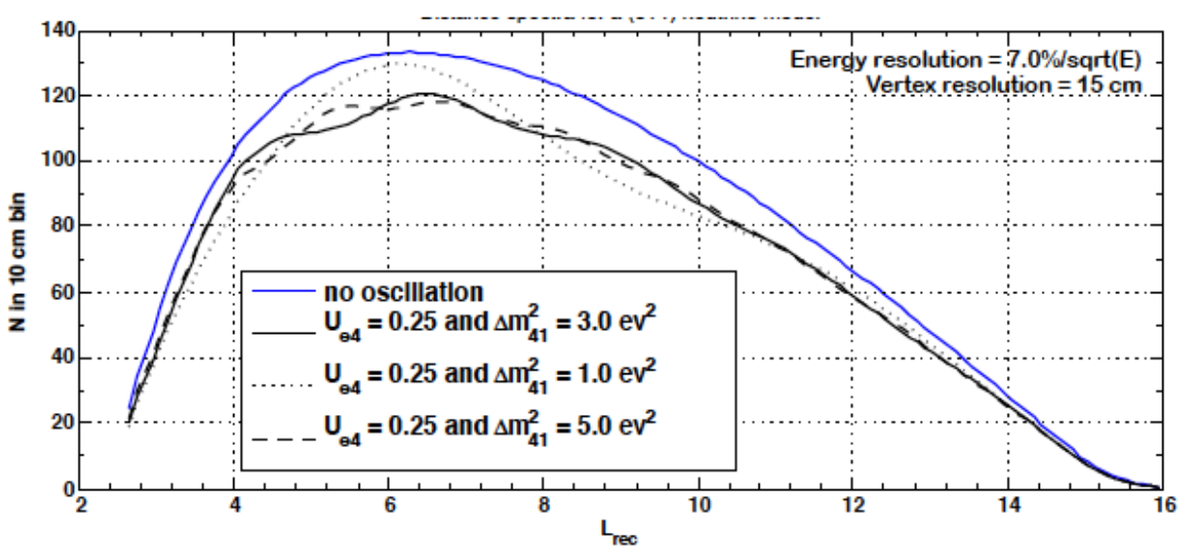


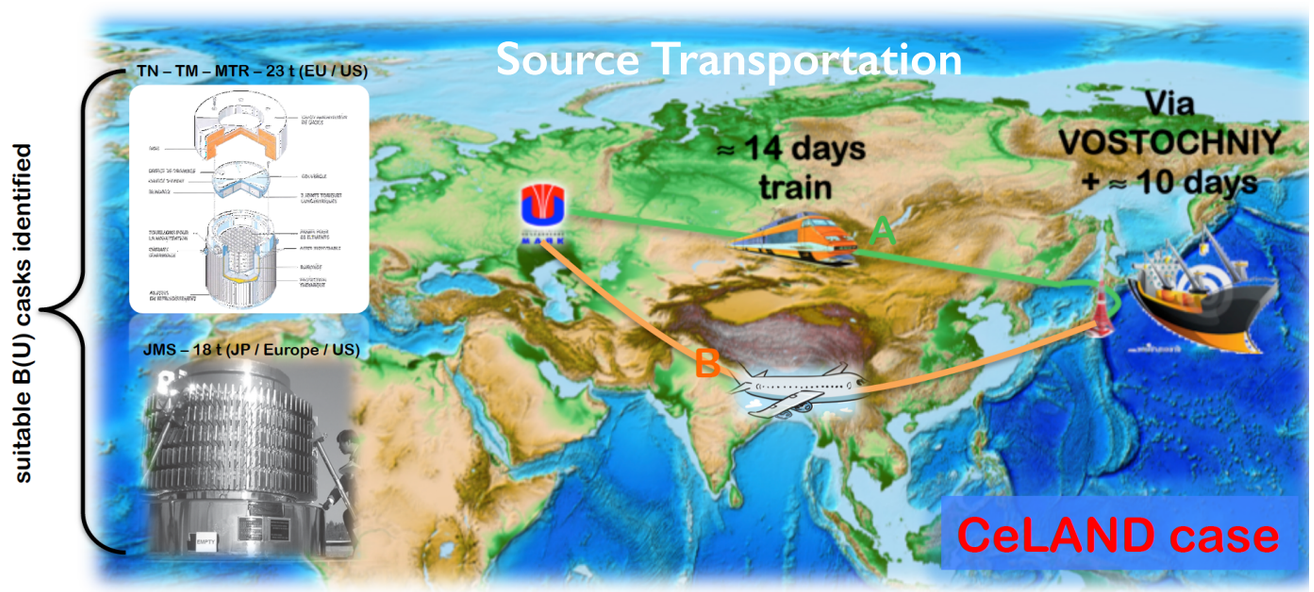


Th. Lasserre – ICFA-ν 2014



- Look for $\bar{\nu}_e \rightarrow \bar{\nu}_s$ oscillations within detector volume



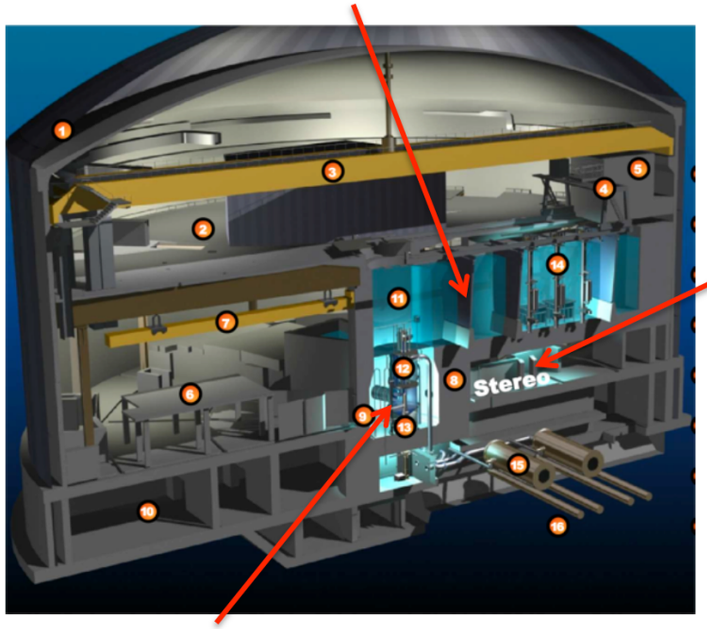


Sterile Neutrinos

- **Very short-baseline reactor experiments**

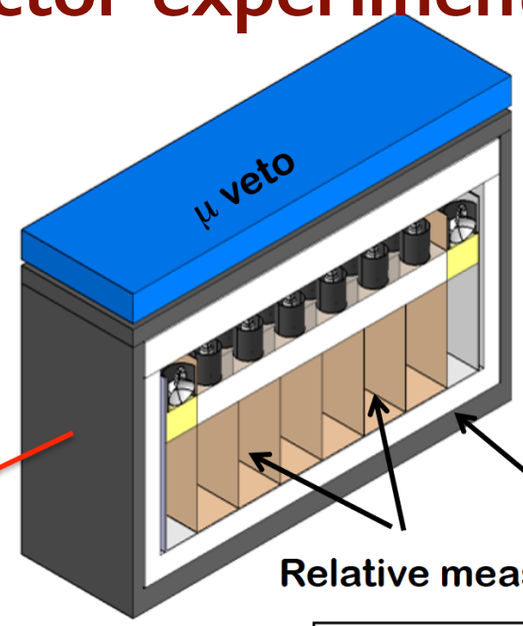
G. Mention et al., Phys. Rev. D 83, 073006 (2011)

Stéréo@ILL, France
factor 4 attenuation of vertical flux from water pool



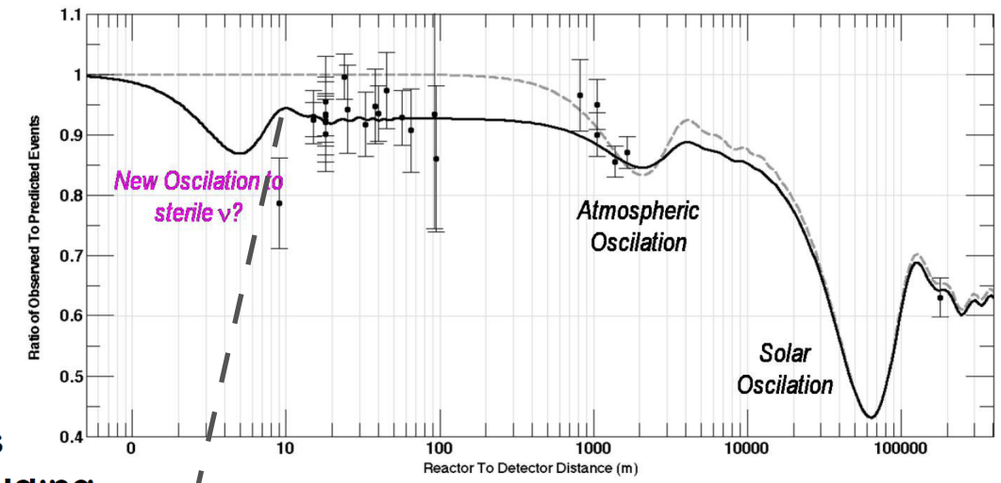
50 MW core
h=80cm, Φ=40cm

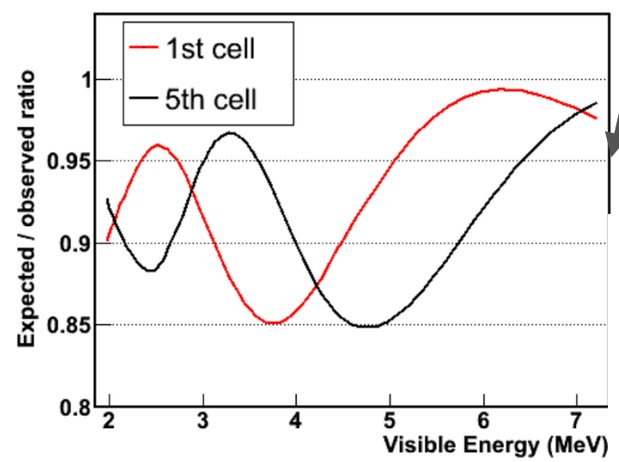
[8.5-11] m
baseline range

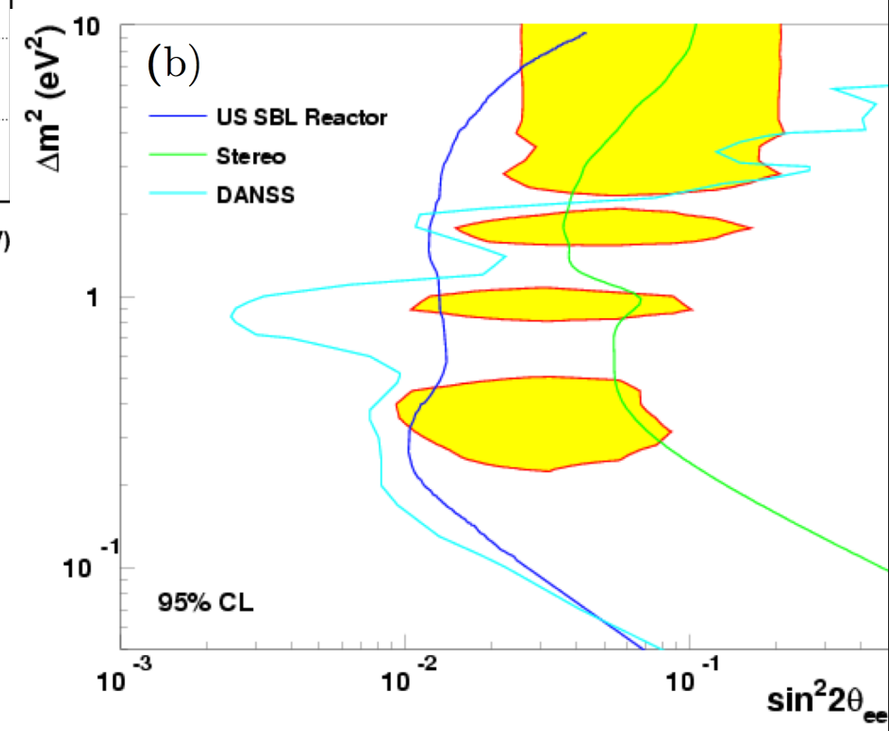


70 tons shielding

Relative measurement in 6 cel







Experiment Type	Projects	P_{Th}	M_{det}	L	Depth
Mature Gd-doped LS detector Technology	Nucifer (FRA)	70 MW	0.7 tons	7 m	Few mwe
	Stéréo (FRA)	50 MW	2 tons	[8-11] m	10 mwe
	Neutrino 4 (RU)	100 MW	2 tons	[6-12] m	Surf.
Highly segmented detector for background reduction	DANSS (RU)	1 GW	1 ton	[10-12] m	50 mwe
	SoLid (UK)	45-80 MW	3 tons	8 m	10 m
Enhanced neutron Tagging					
	Hanaro (KO)	30 MW	0.5 t	6 m	Few mwe
2 detector complex or Moving detector	US project	20-120 MW	-	4m & 15m	Surf.
	China project	-			
	DANSS/Neutrino4	Movable detector			

- Place small detector as close to reactor core as possible, look for very rapid oscillations within detector volume

Sterile Neutrino Summary

CSS 2013 (Snowmass) Neutrino Report, arXiv:1310.4340 (2013)

	Experiment	ν Source	ν Type	Channel	Host	Cost Category[1]
radioactive	CeLAND [259]	^{144}Ce-^{144}Pr	$\bar{\nu}_e$	disapp.	Kamioka, Japan	small[2]
	Daya Bay Source [260]	^{144}Ce-^{144}Pr	$\bar{\nu}_e$	disapp.	China	small
	SOX [261]	^{51}Cr	ν_e	disapp.	LNGS, Italy	small[2]
		^{144}Ce-^{144}Pr	$\bar{\nu}_e$	disapp.		
	BEST [64]	^{51}Cr	ν_e	disapp.	Russia	small
reactor	PROSPECT [262]	Reactor	$\bar{\nu}_e$	disapp.	US[3]	small
	STEREO	Reactor	$\bar{\nu}_e$	disapp.	ILL, France	N/A[4]
	DANSS [263]	Reactor	$\bar{\nu}_e$	disapp.	Russia	N/A[4]
π-DAR	OscSNS [205]	π-DAR	$\bar{\nu}_\mu$	$\bar{\nu}_e$ app.	ORNL, U.S.	medium
π-DIF	LAr1 [264]	π-DIF	$\overset{(-)}{\nu}_\mu$	$\overset{(-)}{\nu}_e$ app.	Fermilab	medium
	LAr1-ND [264]	π-DIF	$\overset{(-)}{\nu}_\mu$	$\overset{(-)}{\nu}_e$ app.	Fermilab	medium
	MiniBooNE+ [203]	π-DIF	$\overset{(-)}{\nu}_\mu$	$\overset{(-)}{\nu}_e$ app.	Fermilab	small
	MiniBooNE II [265]	π-DIF	$\overset{(-)}{\nu}_\mu$	$\overset{(-)}{\nu}_e$ app.	Fermilab	medium
	ICARUS/NESSiE [266]	π-DIF	$\overset{(-)}{\nu}_\mu$	$\overset{(-)}{\nu}_e$ app.	CERN	N/A[4]
Other DAR	IsoDAR [111]	^{8}Li-DAR	$\bar{\nu}_e$	disapp.	Kamioka, Japan	medium
μ-storage ring	nuSTORM [192]	μ Storage Ring	$\overset{(-)}{\nu}_e$	$\overset{(-)}{\nu}_\mu$ app.	Fermilab/CERN	large

[1] Rough recost categories: small: <$5M, medium: $5M-$50M, large: $50M-$300M.

- Also constraints on sterile neutrino mixing from long-baseline experiments (à la MINOS/MINOS+) and atmospheric experiments like PINGU
- SBL accelerator experiments will also contribute to improving ν cross sections knowledge

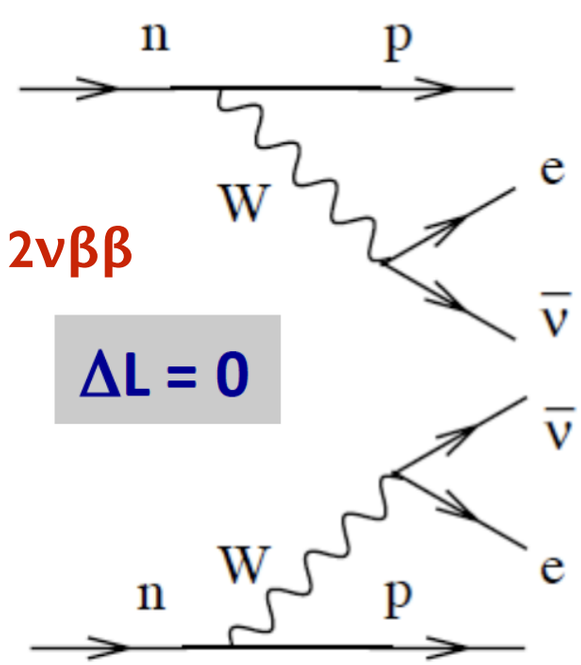
Neutrinoless Double Beta Decay

Neutrino Mass from β-decay

Neutrino Mass from Cosmology

Neutrinoless Double Beta Decay

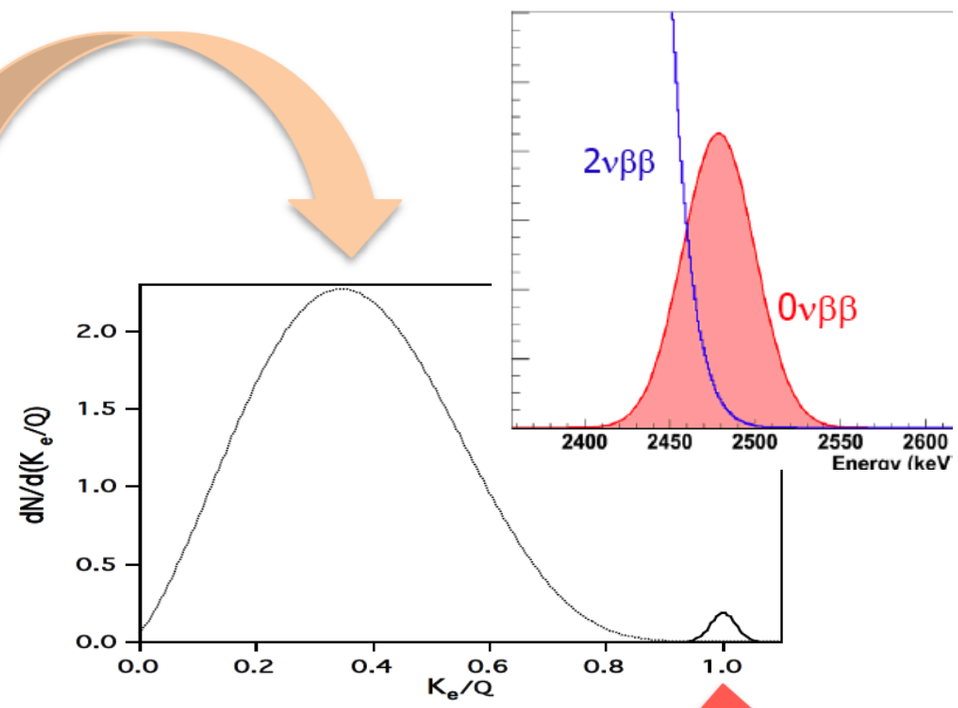
- Observation of 0νββ decay would establish:
  - Neutrinos are Majorana particles
  - Lepton number violation
  - Neutrino mass scale
- *Majorana neutrinos are required in seesaw mass models and leptogenesis*



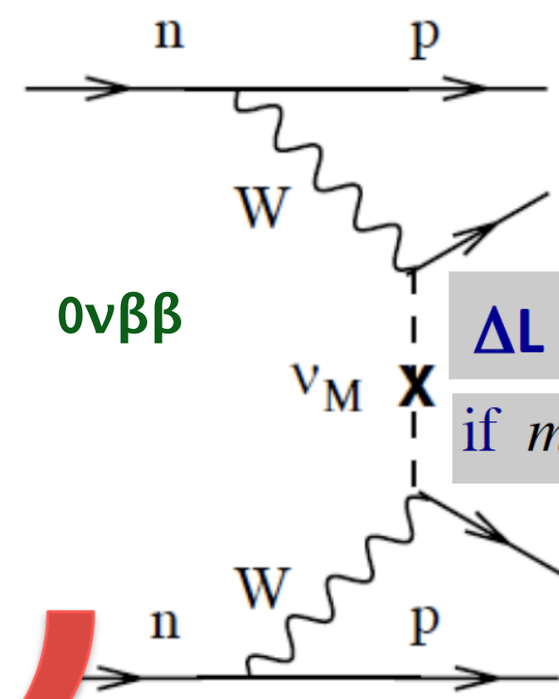
2νββ

ΔL = 0

$$(Z,A) \rightarrow (Z+2,A) + 2e^- + 2\bar{\nu}$$
$$(2\nu\beta\beta)$$



K. Lang, SILAFAE 2010



0νββ

ΔL = 2

if $m_\nu \neq 0$

$$(Z,A) \rightarrow (Z+2,A) + 2e^-$$
$$(0\nu\beta\beta)$$

Neutrinoless Double Beta Decay

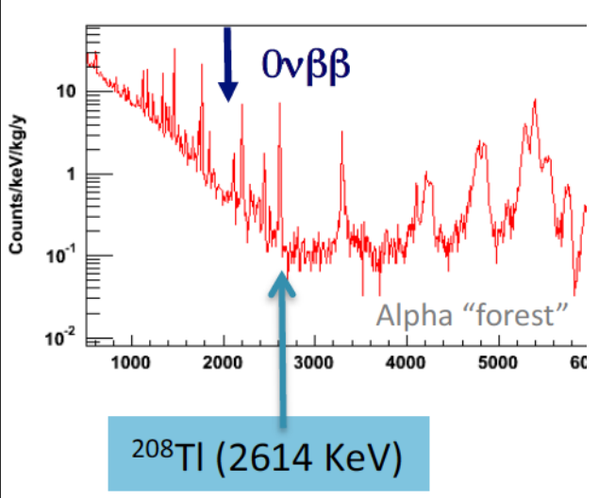
- Sensitivity to Majorana mass is a compromise between statistics, background rejection and detector energy resolution

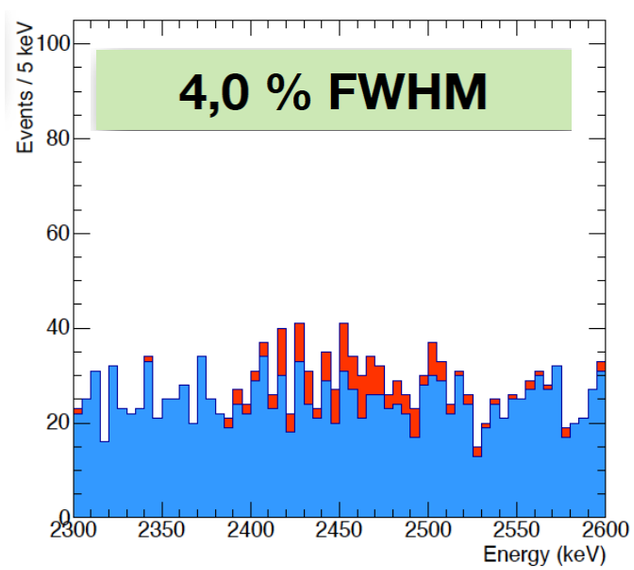
$$m_{\beta\beta} = K\sqrt{1/\epsilon}\left(\frac{b\ \Delta E}{Mt}\right)^{1/4}$$

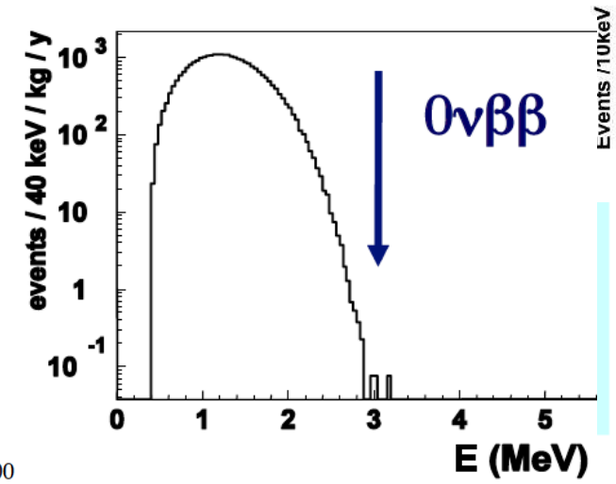
$K \rightarrow$ isotope yield
$\varepsilon \rightarrow$ detection efficiency
$M \rightarrow$ isotope mass
$t \rightarrow$ running time
$b \rightarrow$ background rate
$\Delta E \rightarrow$ energy resolution

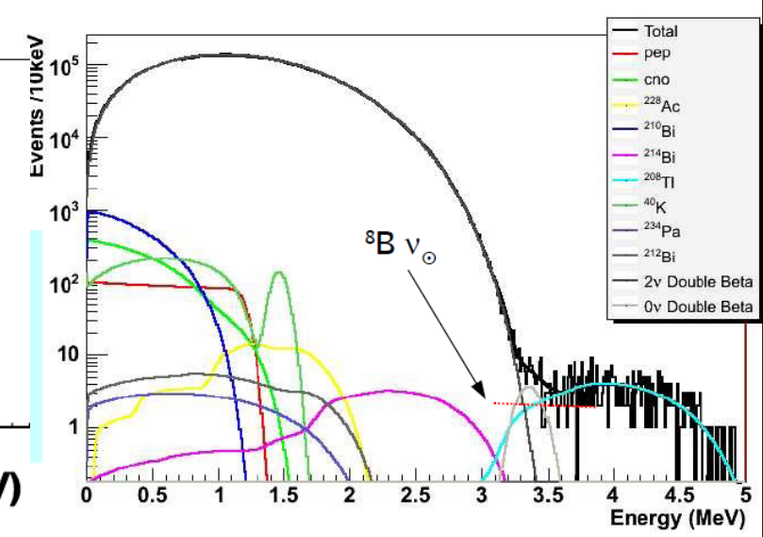
- **Different approaches and technologies in next generation experiments:**

- **Calorimeter/bolometer high energy resolution and efficiency**
- **TPC (Xe) high efficiency, large mass**
- **Tracking calorimeter good bg rejection, multiple isotope choices**
- **Liquid scintillator + isotope - high efficiency, large mass**









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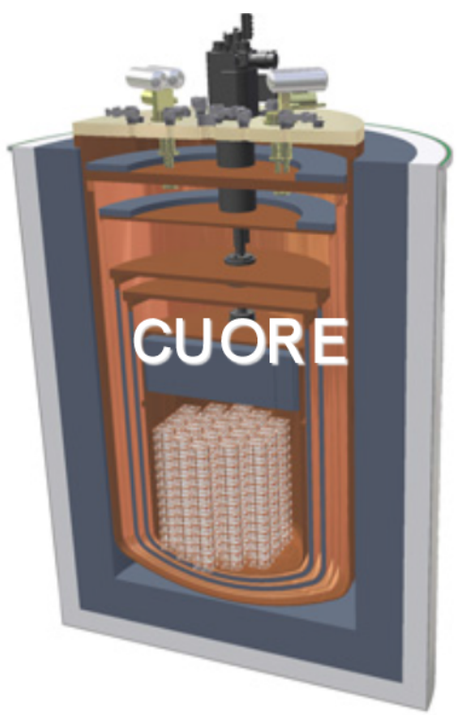
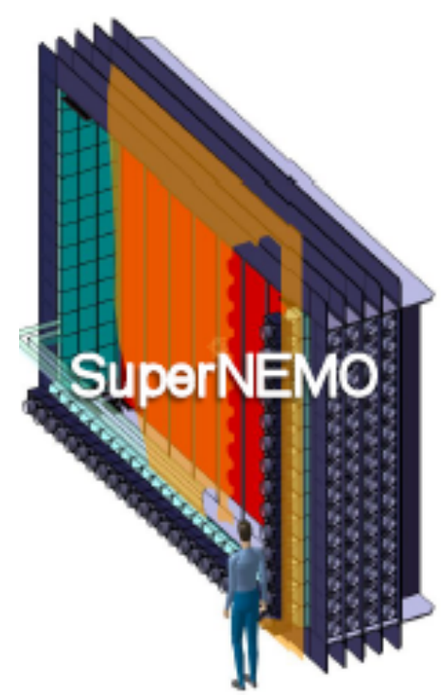


- **TPC (Xe) high efficiency, large mass**

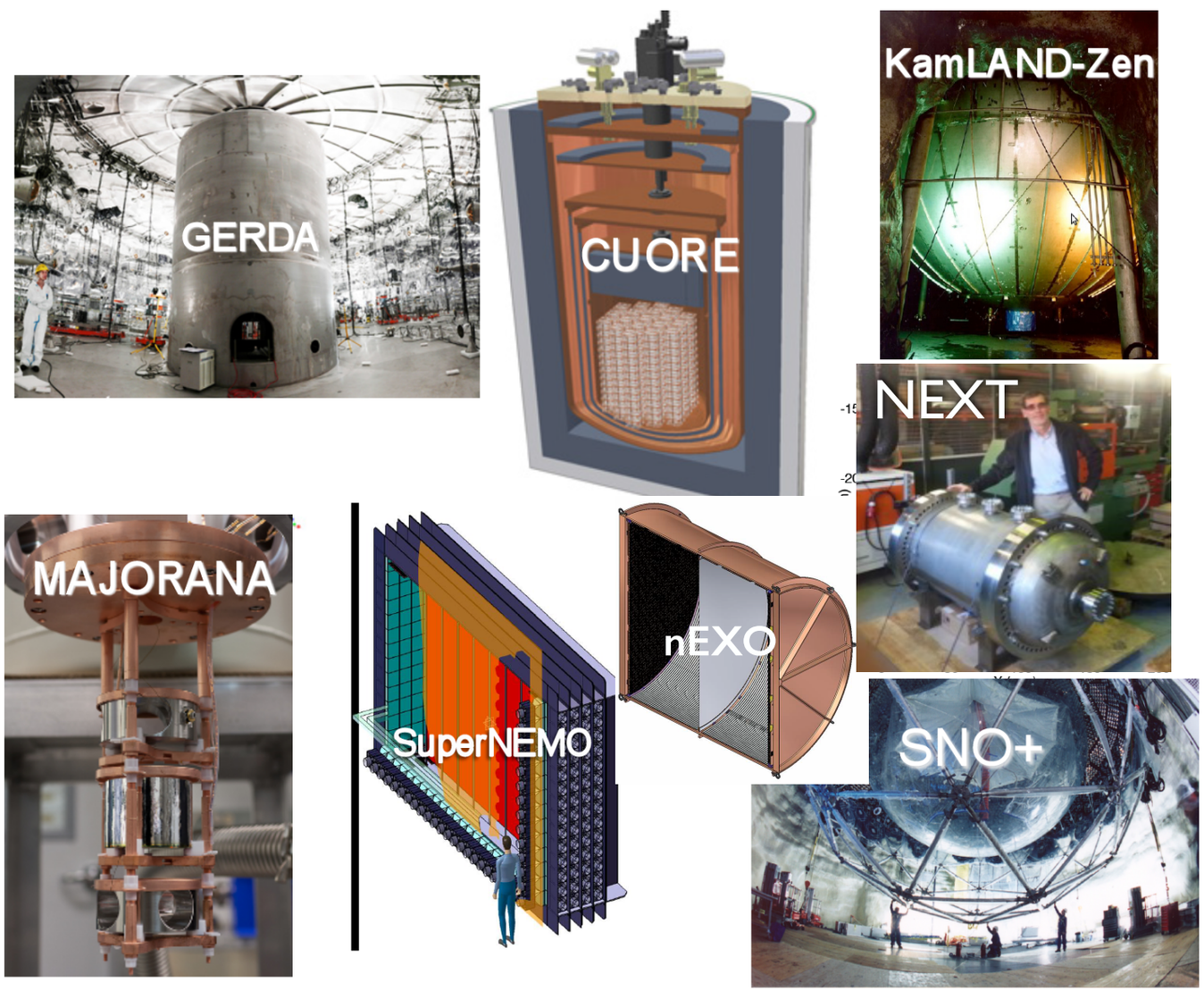
- **Tracking calorimeter good bg rejection, multiple isotope choices**



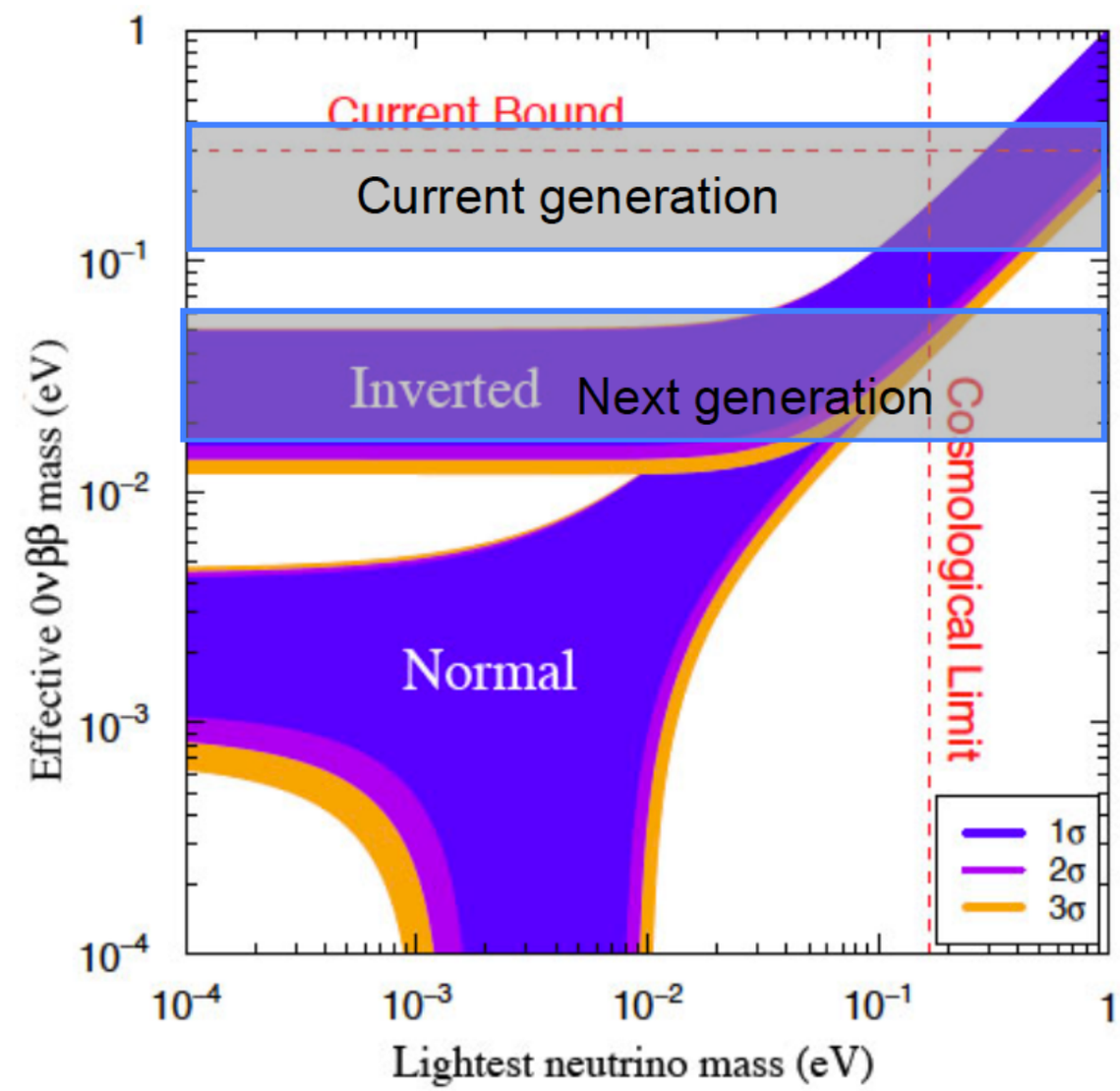
- **Liquid scintillator + isotope - high efficiency, large mass**

Neutrinoless Double Beta Decay

- Next-generation experiments will probe the inverted hierarchy region (2020-2030?)
- If inverted hierarchy is established, next generation of $0\nu\beta\beta$ decay experiments may determine neutrinos are Majorana particles
  - Conversely if no signal is seen down to $m_{\beta\beta}$~20 eV, neutrinos are unlikely to be Majorana particles [modulo scenarios with sterile neutrinos, *cf. Lopez-Pavon, Pascoli, Wong, PRD 87, 093007 (2013)*]



L. Yang, NuFact 2013

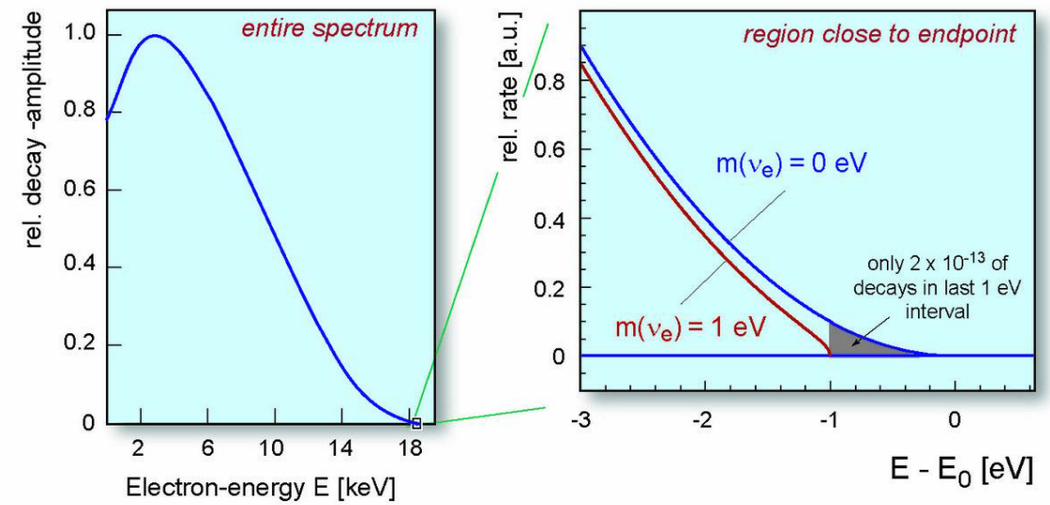


arXiv:1203.5250v1

Neutrino Mass from β-decay

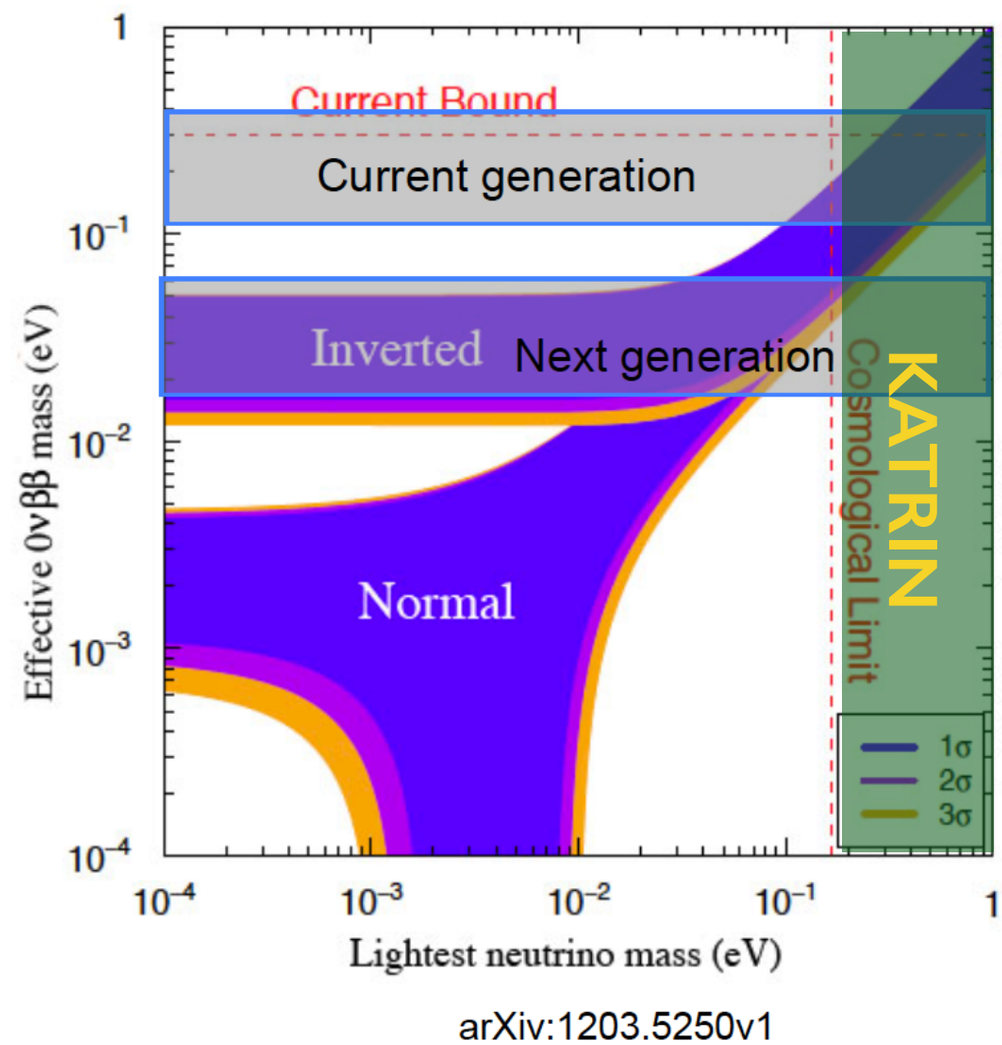
- Measure deviation from $m(\nu_e)=0$ eV in endpoint of β-decay spectrum
- KATRIN β spectrometer currently the main effort
  - Full tritium run in 2015
  - Reach of $m_\beta=0.25$ eV at 95% C.L.

KATRIN Spectrometer on the way to Karlsruhe



- Present limit: $m_\beta < 2$ eV

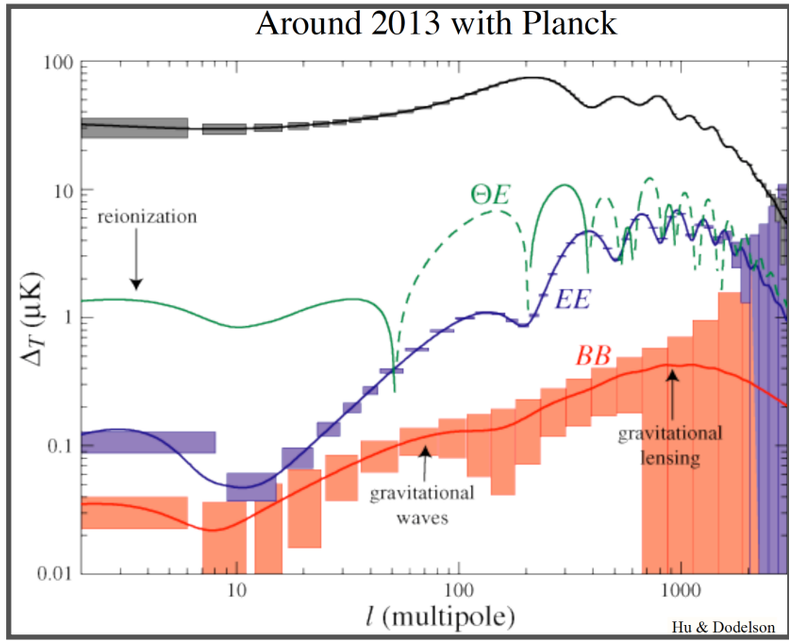
Aseev et al. Phys. Rev D 84 112003 (2011)

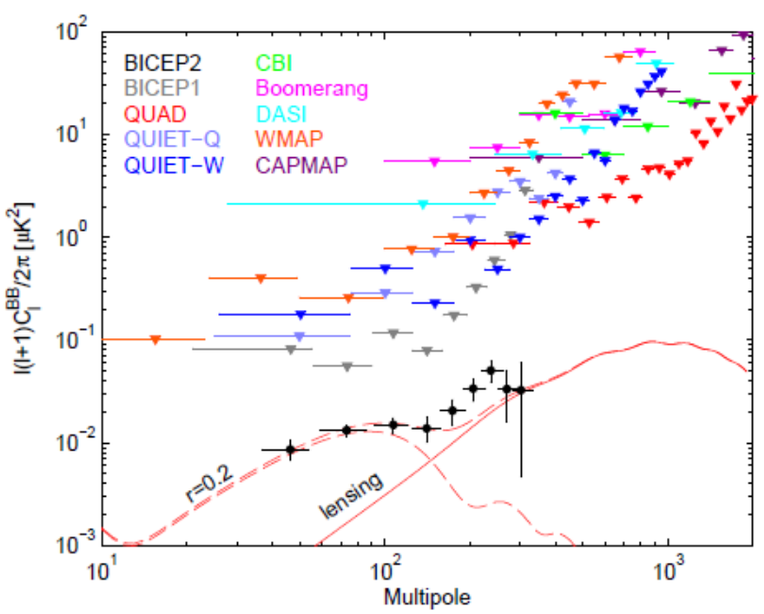


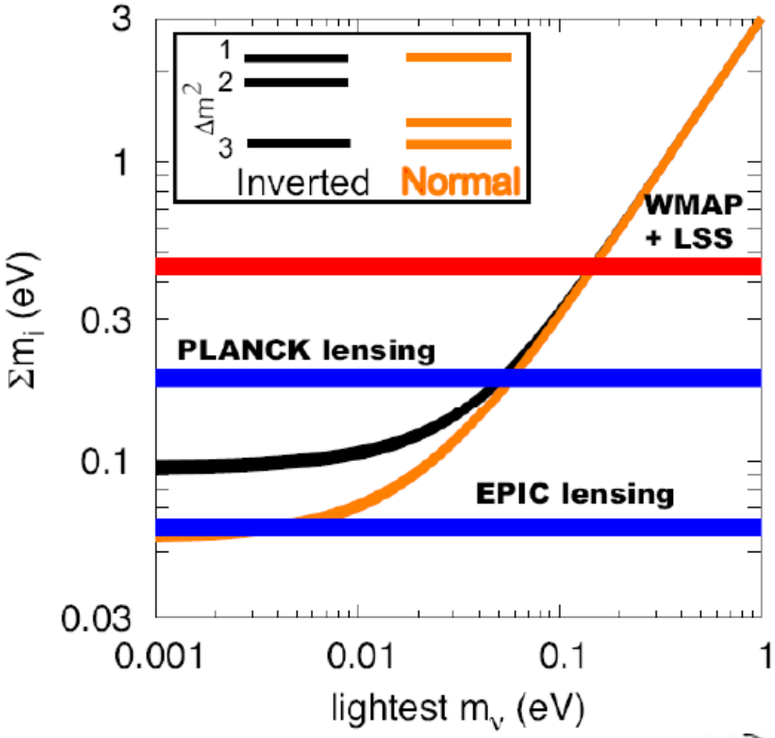
- Several other experiments in R&D phase
  - MARE - thermal microcalorimeters with absorbers containing ^{187}Re operating at 0.1K
    Gatti et al. MARE proposal, 2006
  - ECHO/HOLMES - Same principle as MARE but using ^{163}Ho isotope as absorber
    L. Gastaldo et al, arxiv:1206.5647
  - Project 8 - Construct β-decay spectrum by measuring cyclotron frequency of trapped electrons *B. Monreal and J Formaggio, PRD 80, 051301 2009*

Neutrino Mass from Cosmology

- Cosmological limits on neutrino mass are obtained by combination of CMB anisotropy, CMB lensing, and baryon acoustic oscillation (BAO) measurements
  - Best limit from PLANCK+lensing+BAO: $\sum m_\nu < 0.26\,eV\,(95\%C.L.)$ *Planck Collaboration, arXiv:1311.1657*
- Neutrino mass will contribute to CMB fluctuations caused by gravitational lensing. These can be precisely measured through CMB polarization B-modes
- EPIC (Experimental Probe of Inflationary Cosmology) can probe 0.05 eV neutrino masses by 2022

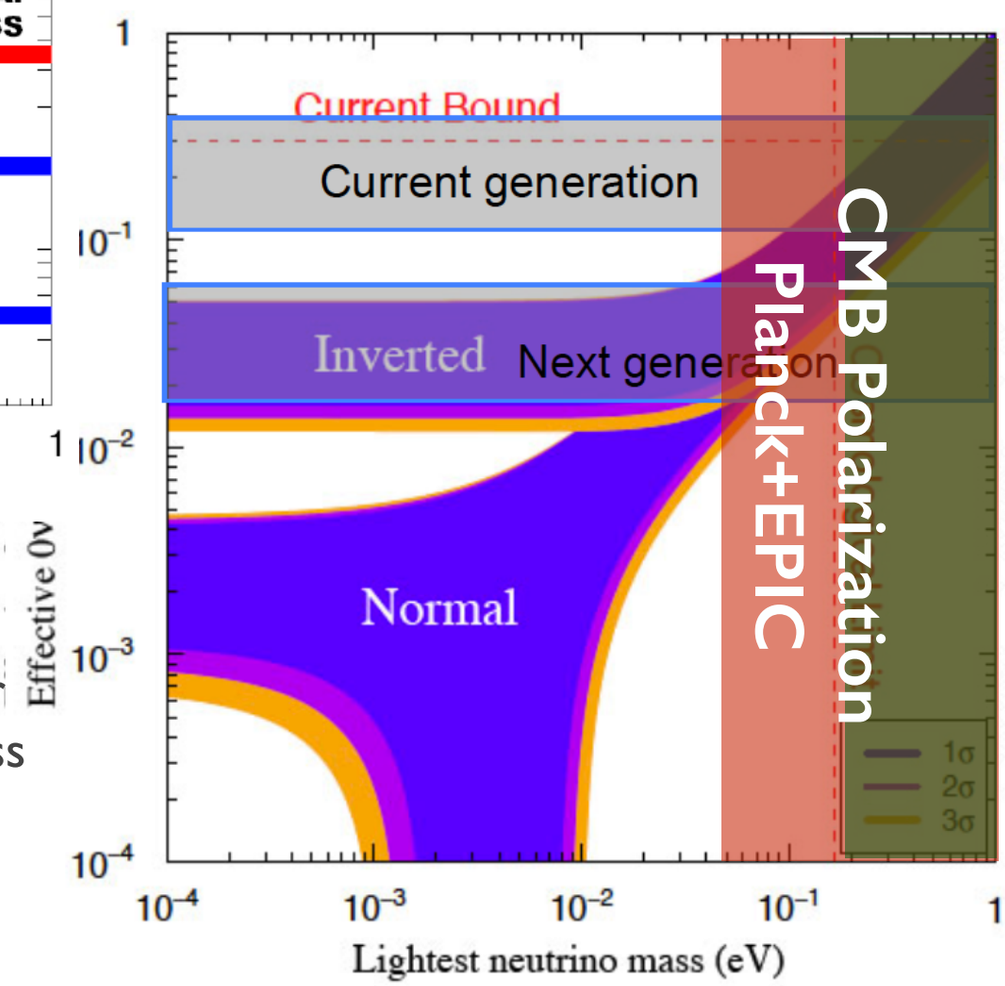






A. Cooray, NOW2010

- Also, if sum of the neutrino masses is lower than 0.1 eV, inverted mass hierarchy would be excluded



arXiv:1203.5250v1

Final Thoughts

- Large quantity and breadth of proposed future neutrino experiments may answer all of the pressing neutrino questions and will likely raise new ones

- Beyond determining the mass hierarchy, and whether CP violation occurs in the lepton sector, oscillation experiments will greatly increase precision of the PMNS mixing matrix measurements, potentially uncovering new symmetries
  - Test unitarity of PMNS matrix, Non-Standard Interactions, Lorentz/CPT violation, etc.
  - Will also extend proton decay probes and Supernovae detection

- Funding is finite, coordination between proponents of large facilities is essential

- US is playing a leading role in a highly active field, need to seize opportunity to make very significant neutrino discoveries.

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Thank You!

Supplements

Current Three ν Picture

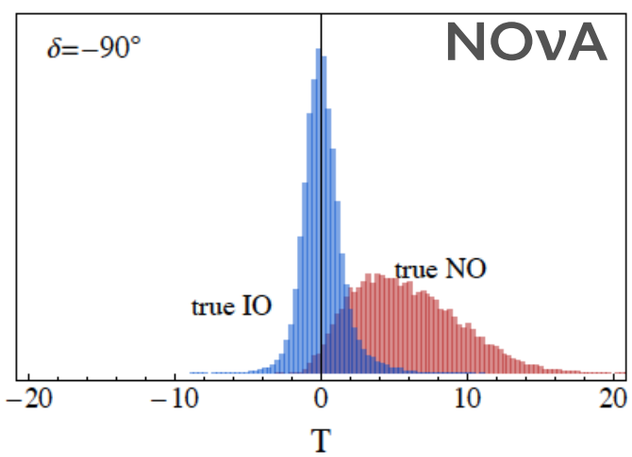
Gonzalez-Garcia, Maltoni, Salvado, Schwetz, JHEP 1212 (2012) 123

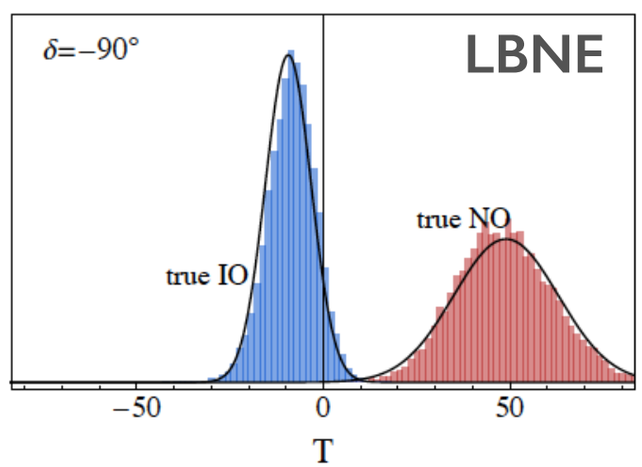
NuFIT 1.2 (2013)

	bfp $\pm 1\sigma$	3σ range	
$\sin^2\theta_{12}$	$0.306^{+0.012}_{-0.012}$	$0.271 \to 0.346$	± 2%
$\theta_{12}/^\circ$	$33.57^{+0.77}_{-0.75}$	$31.38 \to 36.01$	
$\sin^2\theta_{23}$	$0.446^{+0.007}_{-0.007} \oplus 0.587^{+0.032}_{-0.037}$	$0.366 \to 0.663$	± 4% (or better)
$\theta_{23}/^\circ$	$41.9^{+0.4}_{-0.4} \oplus 50.0^{+1.9}_{-2.2}$	$37.2 \to 54.5$	
$\sin^2\theta_{13}$	$0.0229^{+0.0020}_{-0.0019}$	$0.0170 \to 0.0288$	± 4%
$\theta_{13}/^\circ$	$8.71^{+0.37}_{-0.38}$	$7.50 \to 9.78$	
$\delta_{CP}/^\circ$	265^{+56}_{-61}	$0 \to 360$	
$\frac{\Delta m^2_{21}}{10^{-5}\ \mathrm{eV}^2}$	$7.45^{+0.19}_{-0.16}$	$6.98 \to 8.05$	± 3%
$\frac{\Delta m^2_{31}}{10^{-3}\ \mathrm{eV}^2}$ (N)	$+2.417^{+0.013}_{-0.013}$	$+2.247 \to +2.623$	± 3%
$\frac{\Delta m^2_{32}}{10^{-3}\ \mathrm{eV}^2}$ (I)	$-2.410^{+0.062}_{-0.062}$	$-2.602 \to -2.226$	

A Note on Mass Hierarchy Statistics

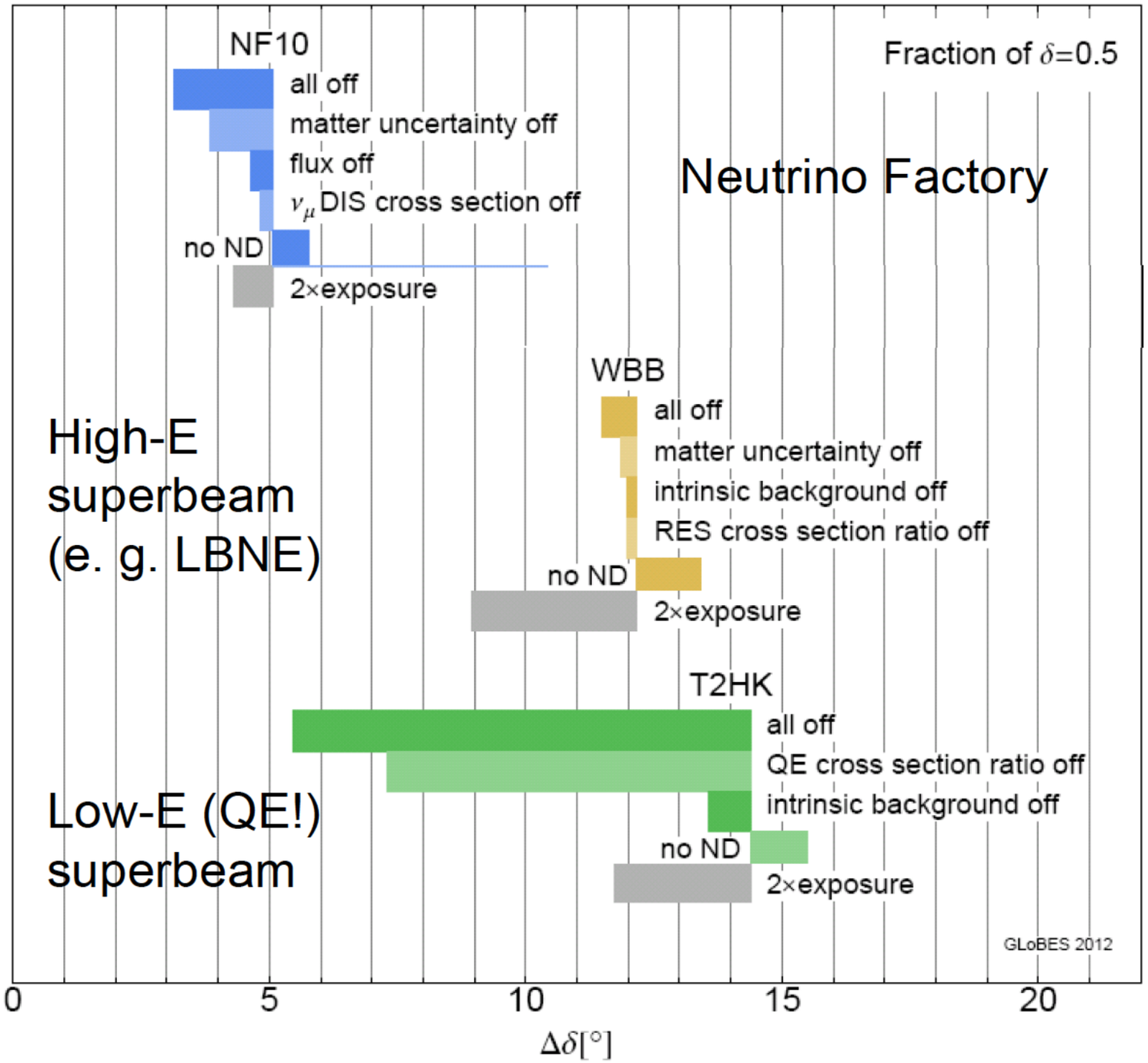
- Each experiment will produce a test of two discrete hypotheses (instead of measuring a continuous range of parameter values)
  - The $T = \Delta\chi^2(\theta)$ test metric we typically use does not follow a χ^2 distribution for mass ordering (*i.e.* Wilks' theorem not valid)
  - Instead, T is approximately gaussian, with mean T_0 and width $2(T_0)^{1/2}$, where T_0 is the value for the data set without statistical fluctuations
- see: Qian et al., PRD 86, (2012) 113011, arXiv:1210.3651; Ciuffoli et al, arXiv:1305:5150; Blennow et al, arXiv: 1311.1822; Cousins et al, JHEP 0511, (2005) 046; Capozzi et al, arXiv: 1309.1638. Also see talk by Blennow at European ICFA: https://indico.in2p3.fr/conferenceOtherViews.py?view=standard&confId=8974
- Need to check gaussianity using MC for each experiment. Quote median sensitivity instead of sqrt(T_0)
- Difference in quoted significance w.r.t. to conventional approach is small





T_0	std. sens.		median sens.	
9	99.73%	(3.0σ)	99.87%	(3.2σ)
16	99.9937%	(4.0σ)	99.9968%	(4.2σ)
25	99.999943%	(5.0σ)	99.999971%	(5.1σ)

More on Systematics



(Coloma, Huber, Kopp, Winter, arXiv:1209.5973)

Robust wrt systematics

Main impact:
Matter density uncertainty

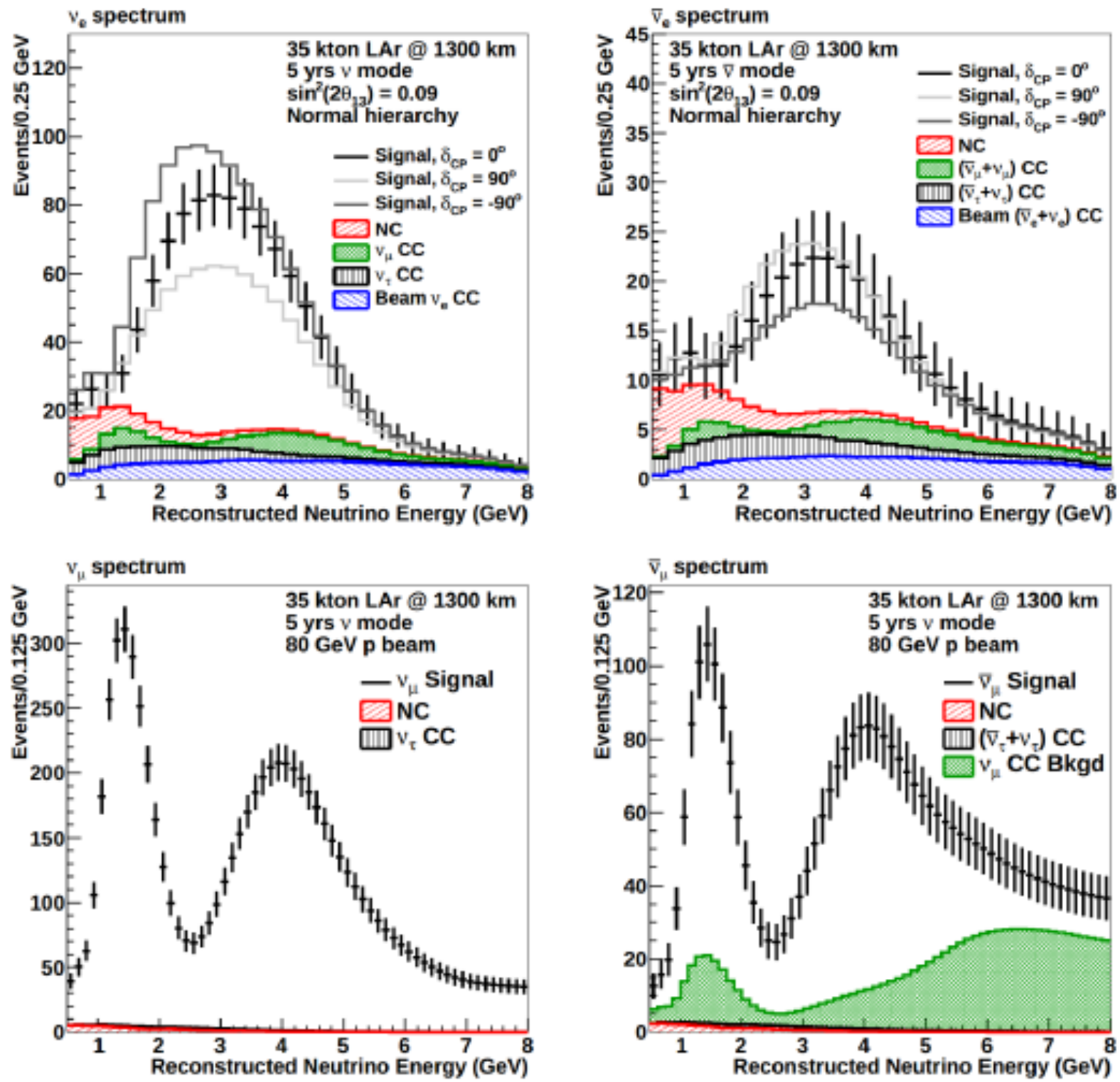
Operate in statistics-limited regime

Exposure more important than near detector

QE ν_e X-sec critical: cannot be measured in near detector

Theory: ν_e/ν_μ ratio?
Experiment: νSTORM

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

CP Violation, Mass Hierarchy, θ_{23} Octant

- **LBNE (Long-Baseline Neutrino Experiment)**
  - Event rate and spectra expectation
  - At 1300 km, full oscillation structure visible in the energy spectra. A combined spectral fit can resolve all oscillation parameter ambiguities with a single experiment