Neutrino Oscillations

The next 10 years

Personal View from Jenny Thomas world,

Planet UCL

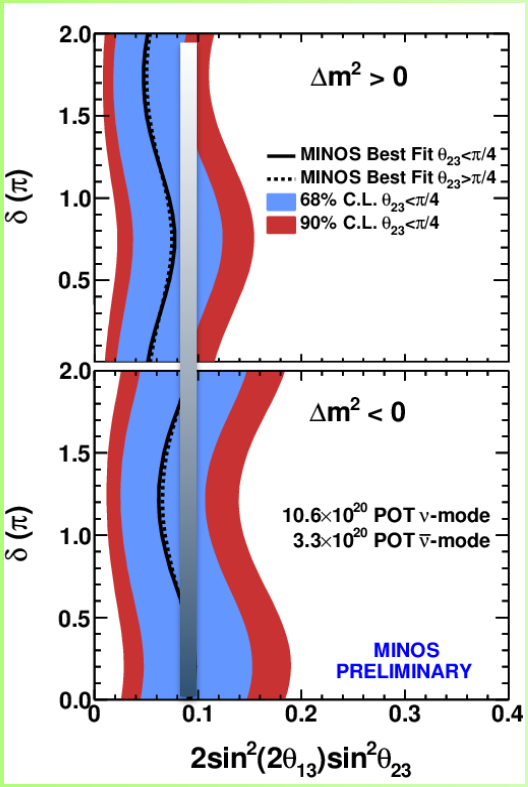
Introduction

- What are the burning questions?
  - Amazingly, we know what they are and how to answer them (some this decade)!
    - **θ_{23} octant : this is now the least well-known angle**
      - MINOS+, NOVA, T2K, ICECUBE!
    - **Mass Hierarchy : which mass eigenstate is smallest?**
      - DBII+LBL, NOVA (40% chance),PINGU
    - **CP violation : and the answer to everything**
      - CHIPS+NOVA+T2K
    - **Number of sterile flavors : and a whole new field**
      - MINOS+,MICROBOONE

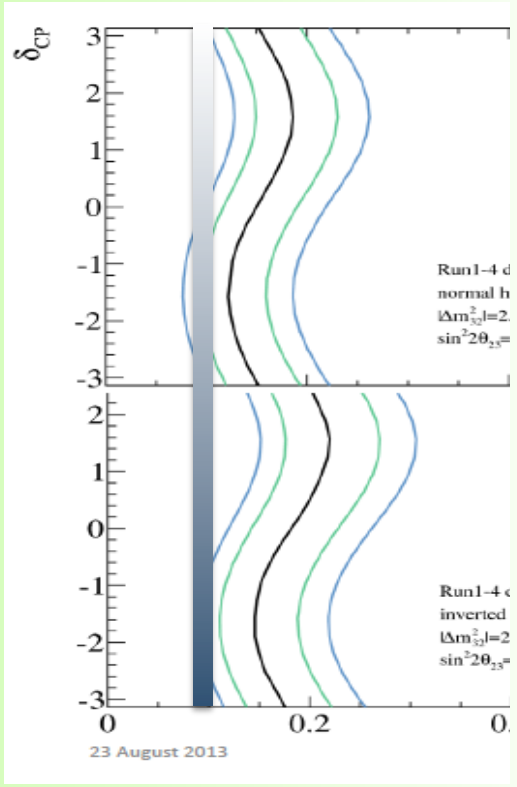
MINOS and T2K on θ_{13}

- MINOS 10.71×10^{20}p.o.t and 3.36×10^{20}p.o.t of antineutrinos
- T2K now really using the power of the L/E choice
- MINOS used ND for background measurements
- Are T2K,MINOS and reactors only consistent with
  - $\delta_{CP}=-\pi/2$?
- Now we know θ13, number of sigma away from 0 less interesting than error bars?
  - MINOS smaller for NH
  - T2K smaller for IH

$(NH,\delta_{CP}=0)\ 0.051^{+0.038}_{-0.030}$



$0.150^{+0.039}_{-0.034}$



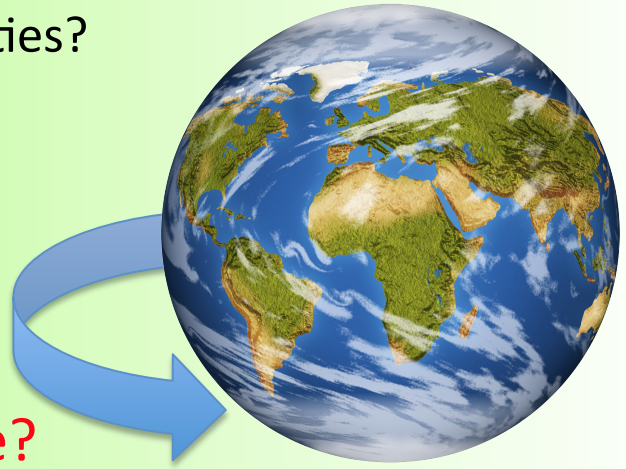
$(IH,\delta_{CP}=0)\ 0.093^{+0.054}_{-0.049}$

$0.182^{+0.046}_{-0.040}$

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

Introduction

- This is the speaker's (subjective) crystal ball about the next decade
- We will dash around the world looking at the experiments taking data
  - NOVA,MINOS+,DAYA BAY, ICECUBE,T2K(?),MicroBOONE
  - What could we learn without any new facilities?
- And at the ones who might take data
  - CHIPS ☺
  - DB-II (JUNO)
  - PINGU
- Where will we be this time, next decade?
  - I will be retired
  - But the measurements will go on…

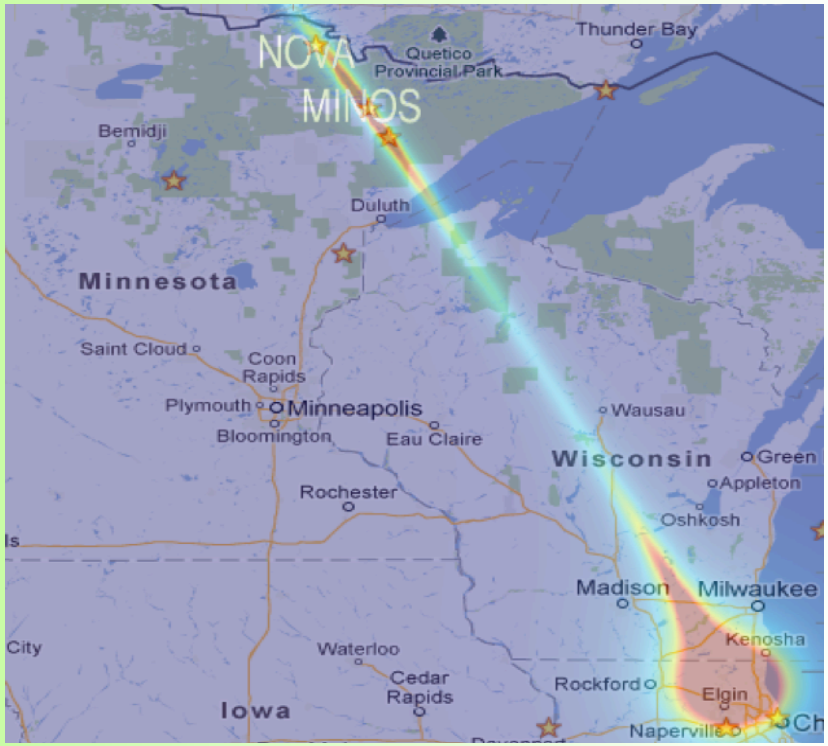


World's premier neutrino oscillation laboratory

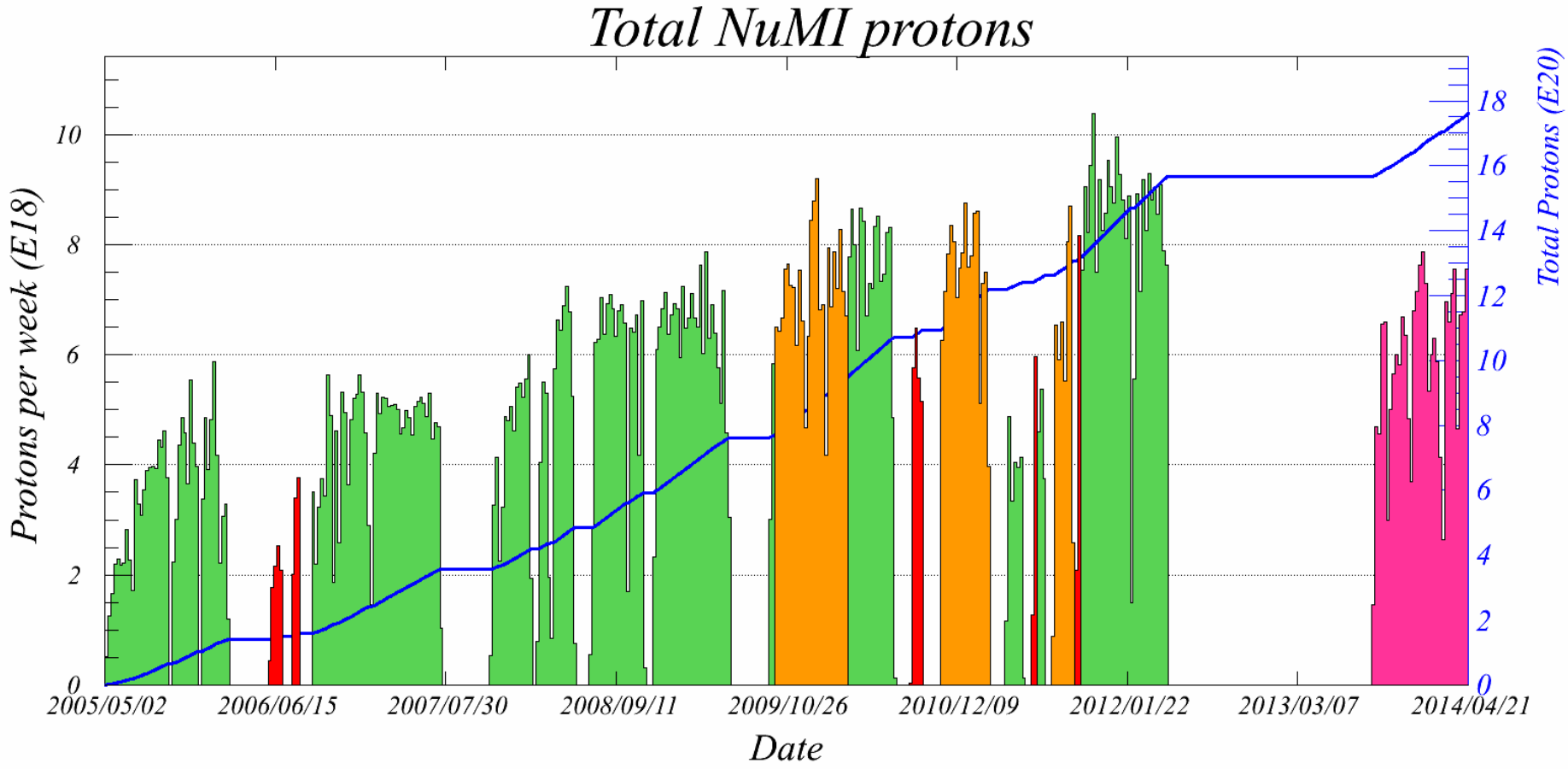
WHAT'S HAPPENING AT FNAL?

FNAL's Neutrino facility

- FNAL is the premier neutrino oscillation laboratory in the world
- Experiments on NuMI beam
  - MINOS+ (θ_{23} octant, Δm^2, steriles)
  - NOνA (MH, θ_{23} octant, Δm^2)
  - CHIPS (δ_{CP})
  - Minerva (x-secs)
- Experiments on the Booster beam
  - MicroBOONE (BOOSTER-steriles)
  - LAr1?
- Plans for the NBT in neutrino physics with LBNE



FNAL's NuMI beam



Party like its 2009 (well 2008 really)

The New Goal Posts (post θ_{13})

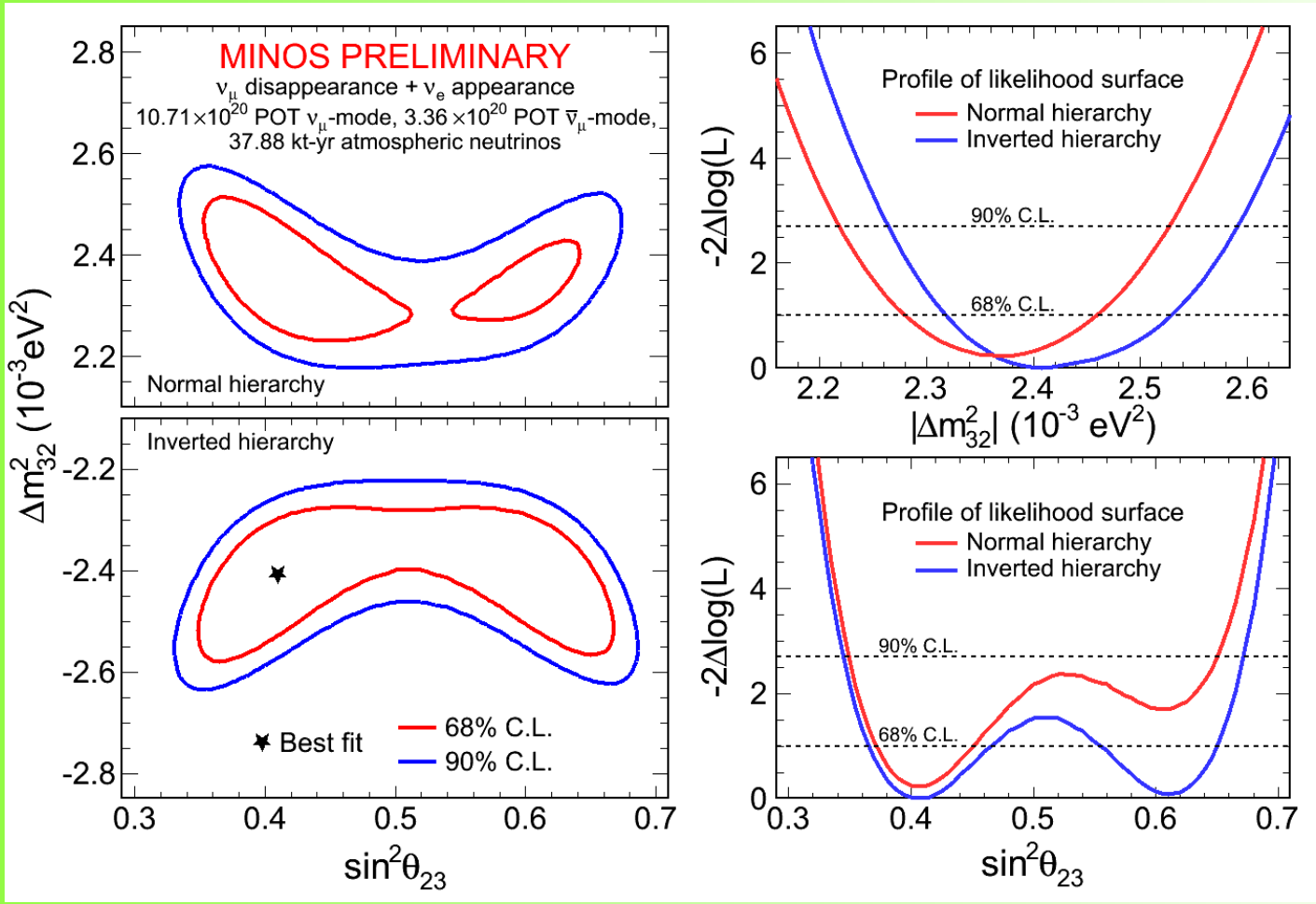
$$\mathcal{P}(\nu_\mu \to \nu_\mu) = 1 - \sin^2(2\theta_{eff}) \sin^2\left(\frac{\Delta m^2_{eff} L}{4E}\right) + \mathcal{O}(\theta^3_{13})$$

$$\sin^2(\theta_{eff}) = |U_{\mu 3}|^2 = \sin^2\theta_{23} \cos^2\theta_{13} \quad (\sin^2 2\theta_{eff} \approx \sin^2 2\theta_{23} : \theta_{13} \approx 0)$$

$$\Delta m^2_{ee} \sim 0.7\Delta m^2_{31} + 0.3\Delta m^2_{32}$$
$$\Delta m^2_{\mu\mu} \sim 0.3\Delta m^2_{31} + 0.7\Delta m^2_{32} + CP$$

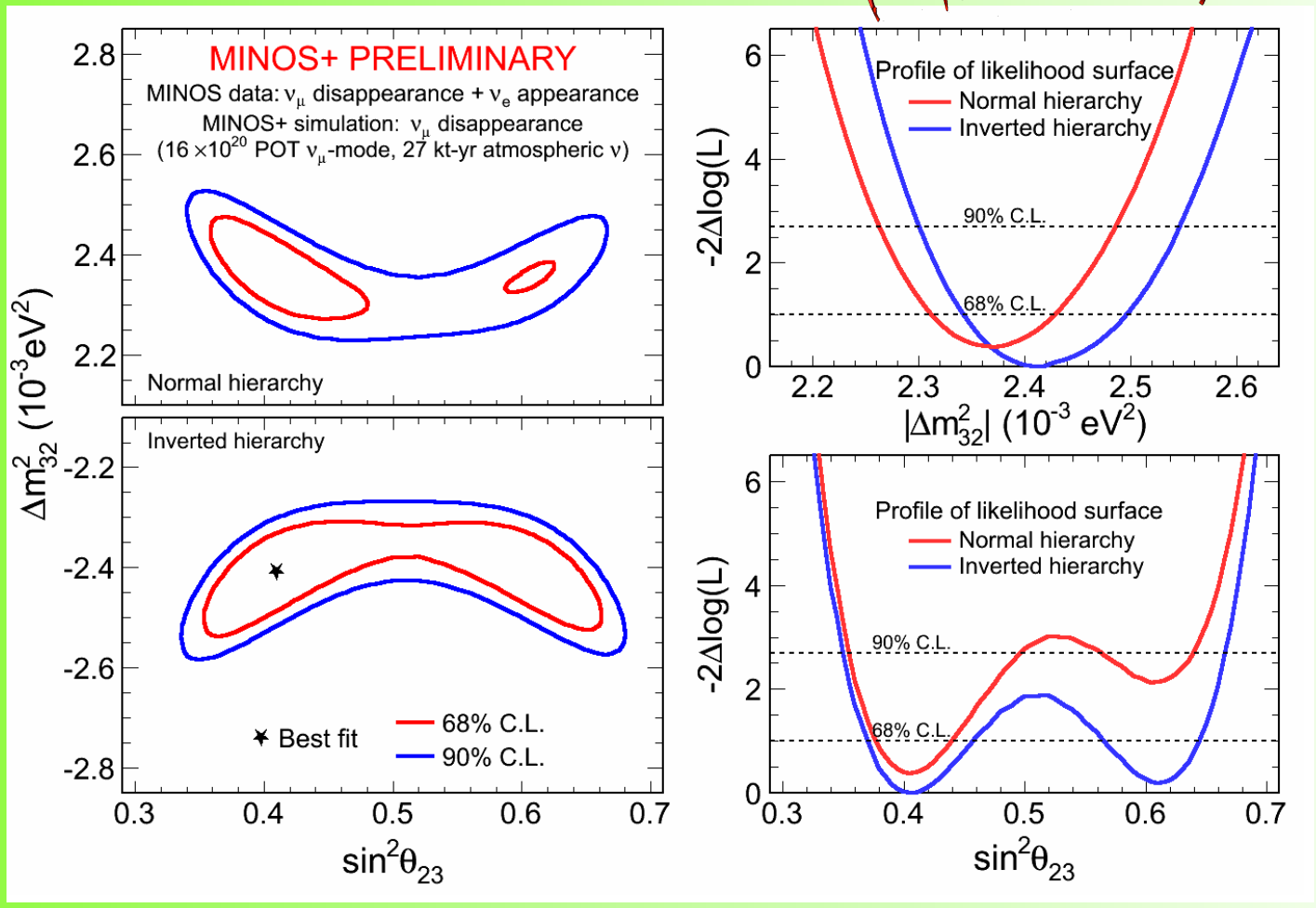
- Disappearance has θ_{13} info embedded in it:
  - 2 flavor analysis is not good enough for large θ_{13}
- 3 flavor fits done to MINOS disappearance data and atmospheric data (has mass hierarchy information)
- Then COMBINED with MINOS ν_e appearance data
- T2K are planning this result also, may be by NEUTRINO 2014

MINOS Alone



- Solar mixing parameters fixed
- θ_{13} fit as nuisance parameter, constrained by reactor results
- δ_{CP}, θ_{23}, Δm^2 unconstrained
- major systematic uncertainties included as nuisance parameters

MINOS+

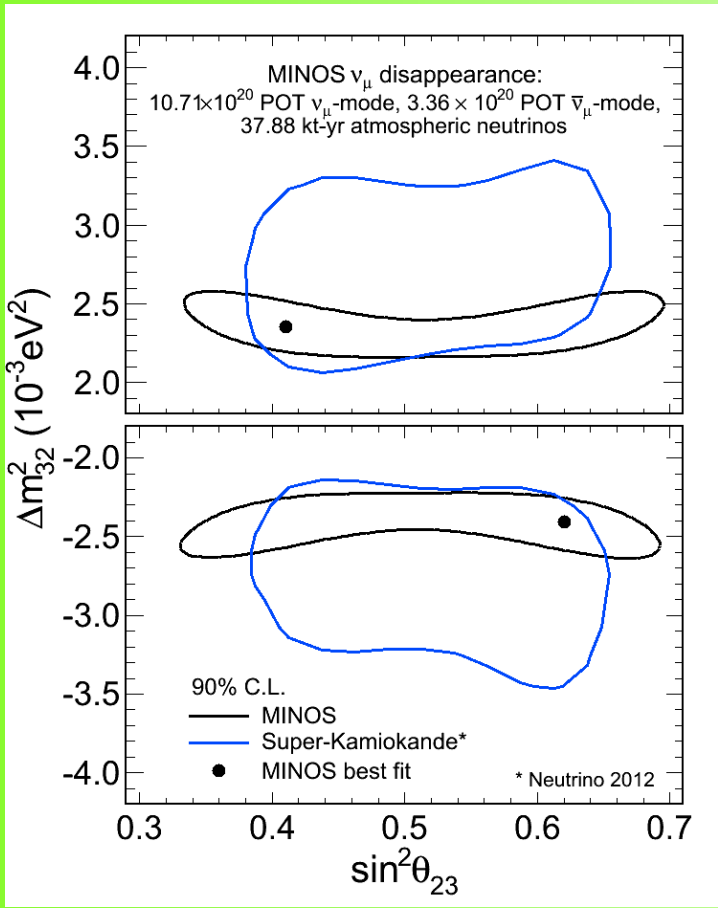


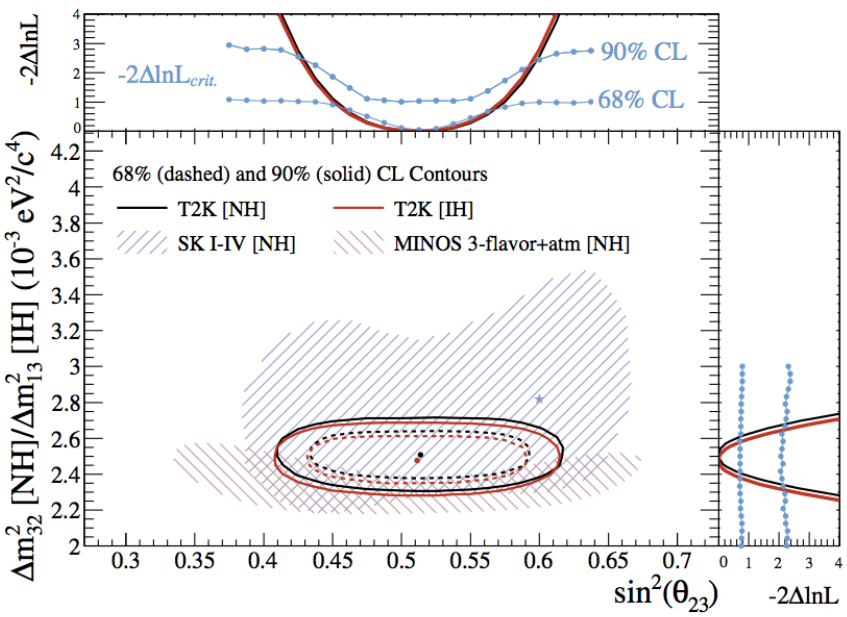
- Preliminary results should be available by NEUTRINO 2014
- Full reach by end 2016 or 2017, depending on beam performance

Look at T2K and Super-K

LETS HEAD TO JAPAN

SuperK and T2K on θ_{23}





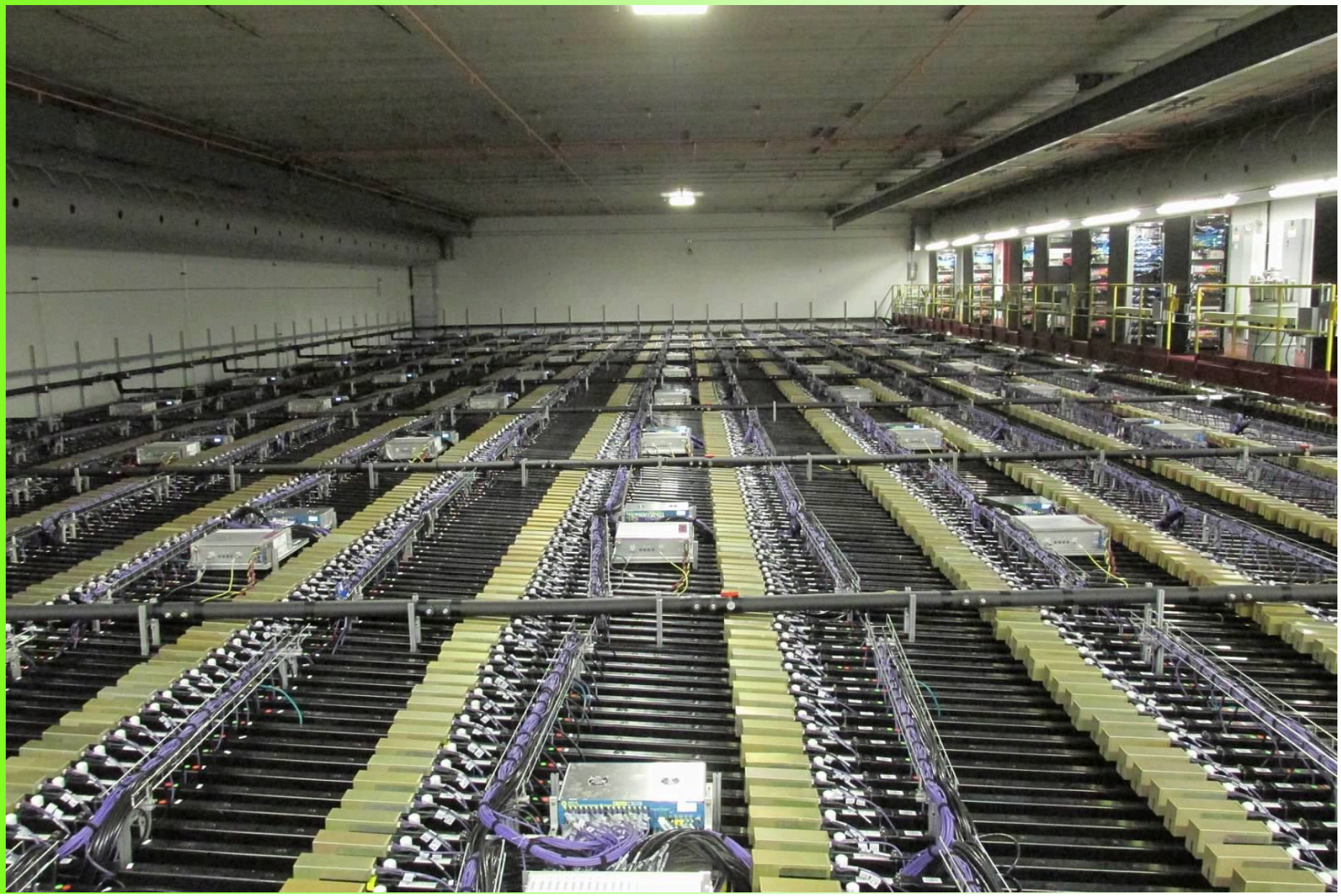
Period	Integ. No. of Proton on Target	Beam Power (kW)	
-Jun.2012	3.1E+20	170	
-Jun.2013	7.8E+20	200	
-Jun.2014	1.2E+21	250	*2
-Jun.2015	1.8E+21	250	
-Jun.2016	2.5E+21	300	
-Jun.2017	3.2E+21	300	
-Jun.2018	3.9E+21	300	
-Jun.2019	5.5E+21	700	*1
-Jun.2020	7.1E+21	700	
-Jun.2021	8.8E+21	700	

- Unlikely to see more precision from T2K (at least soon)
  - 2014 anti-neutrino “pilot” run for 1 month
  - Total POT to be 7.8e21 by 2021
  - T2K cannot tell us their plans presently for running schedule or desires

The land o’ lakes

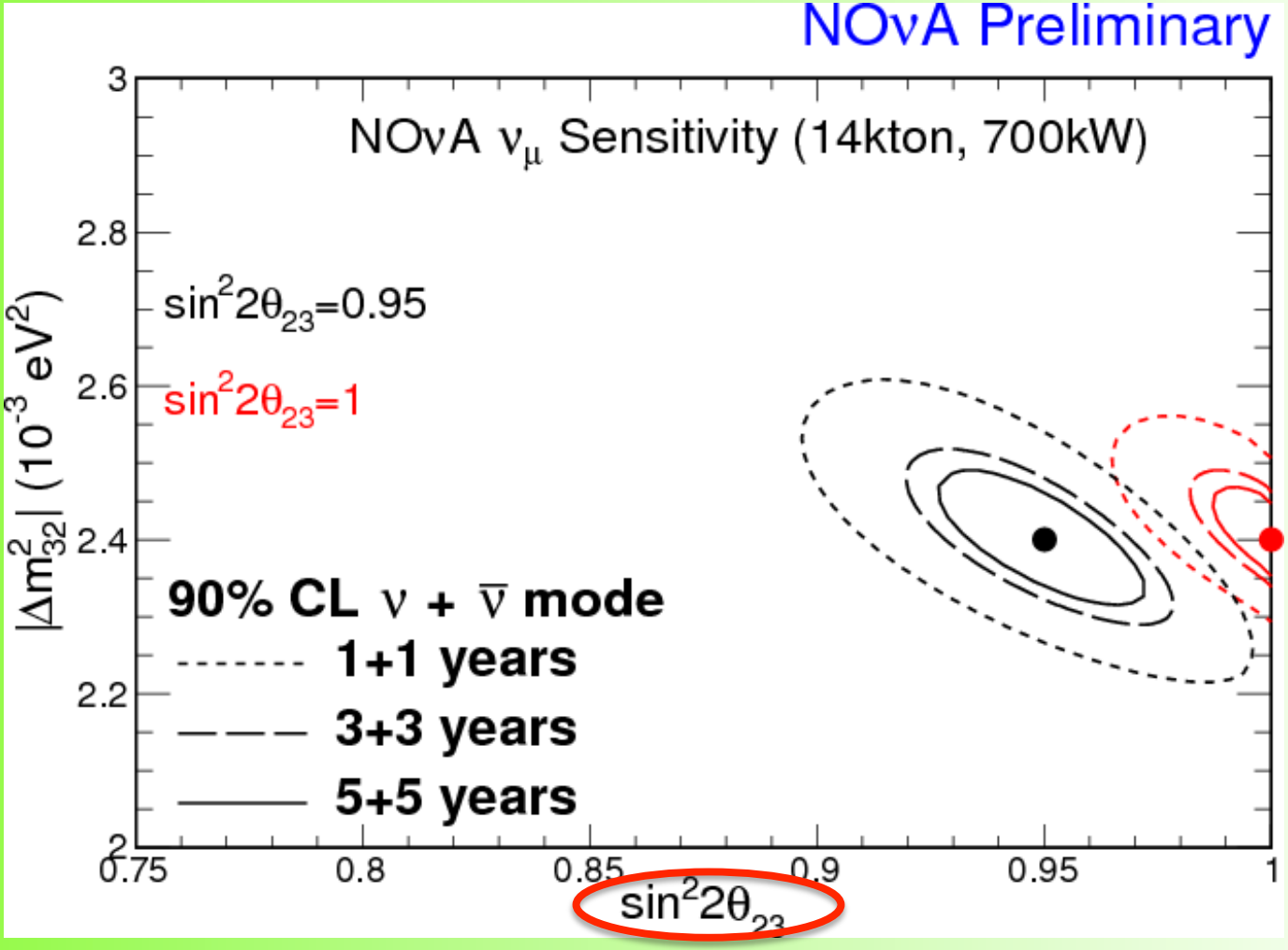
BACK TO FNAL : MINNESOTA TOO!

The NOνA Far Detector

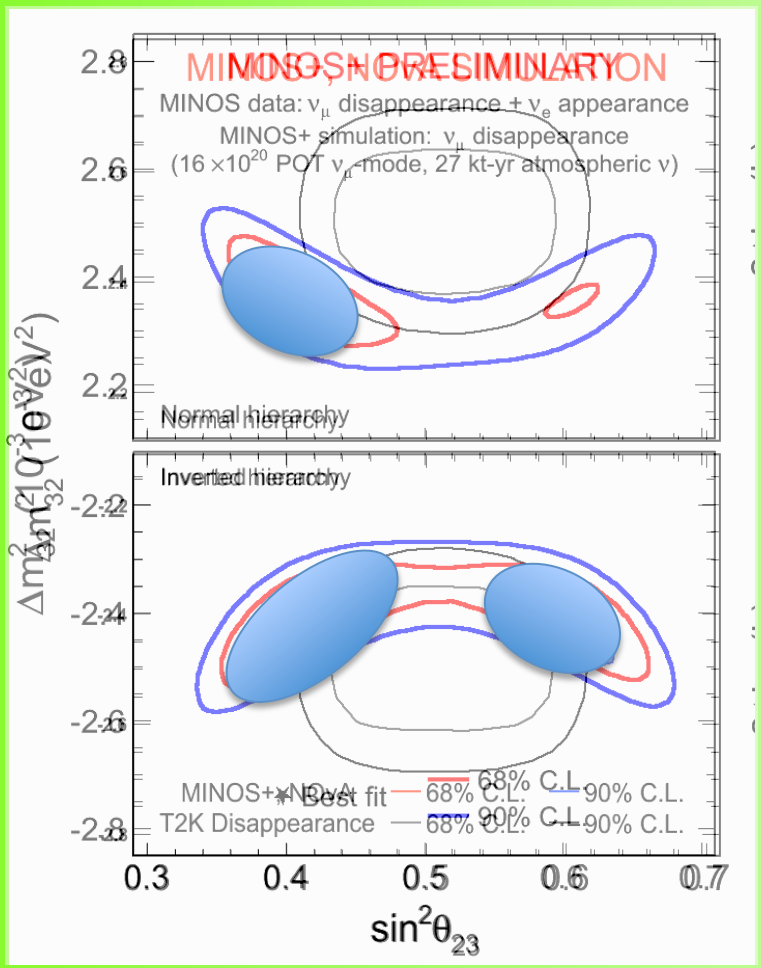


NOνA on Δm^2

- Nova should get 2-3% finally on Δm^2 : energy scale systematic limited



NOVA+MINOS+



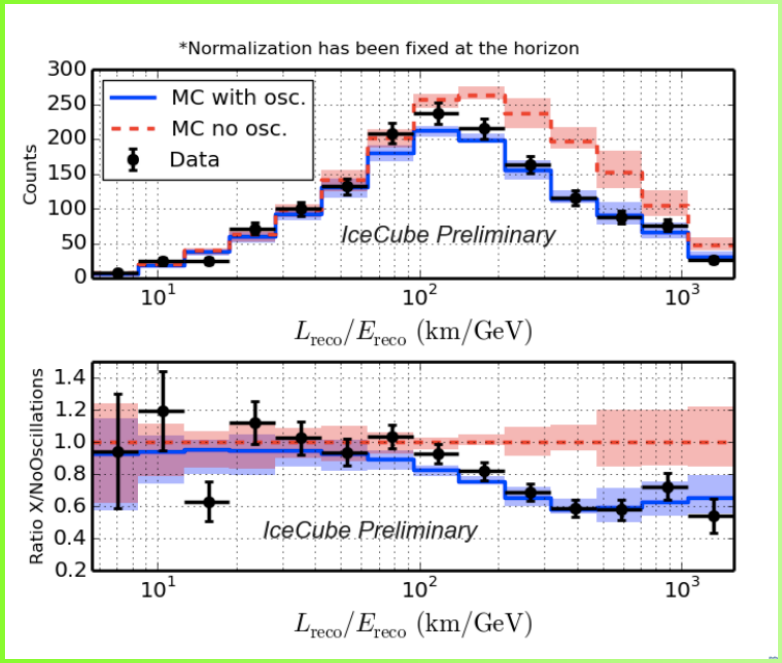
- Back of the envelope
- Combination of NOVA and MINOS+ will give this level of accuracy by 2016 (2σ)
  - MINOS 12e20 NOVA 9e20
- Maybe 1-2% (1σ) by MINOS+ turn off

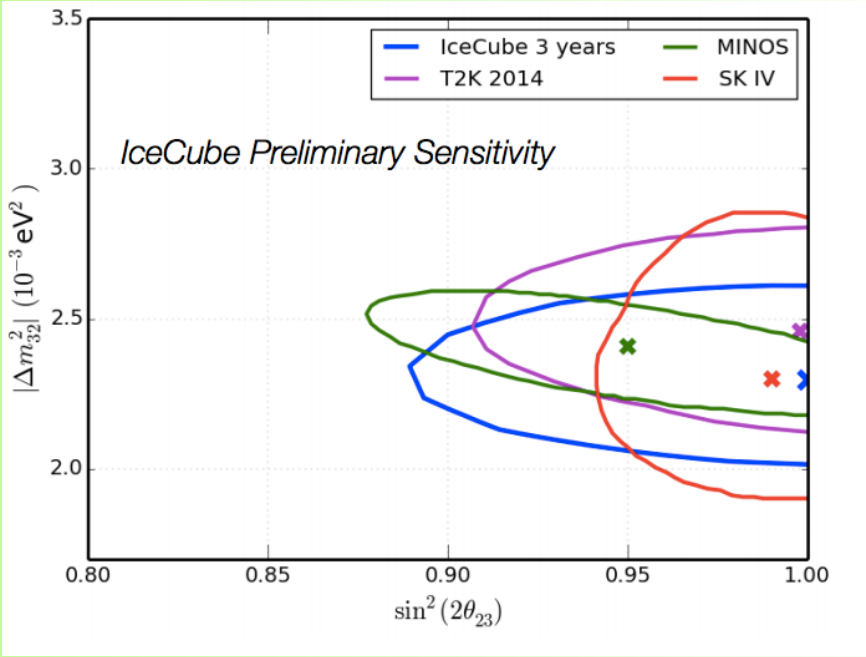
Under the ice

MEANWHILE, AT THE SOUTH POLE..

Ice Cube on θ_{23}

- Another player has joined the θ_{23} game
- Marvellous confirmation of oscillations at completely different neutrino energy and baseline
- Personally very excited about the result ($\theta_{23} \neq 45^{o}$?)

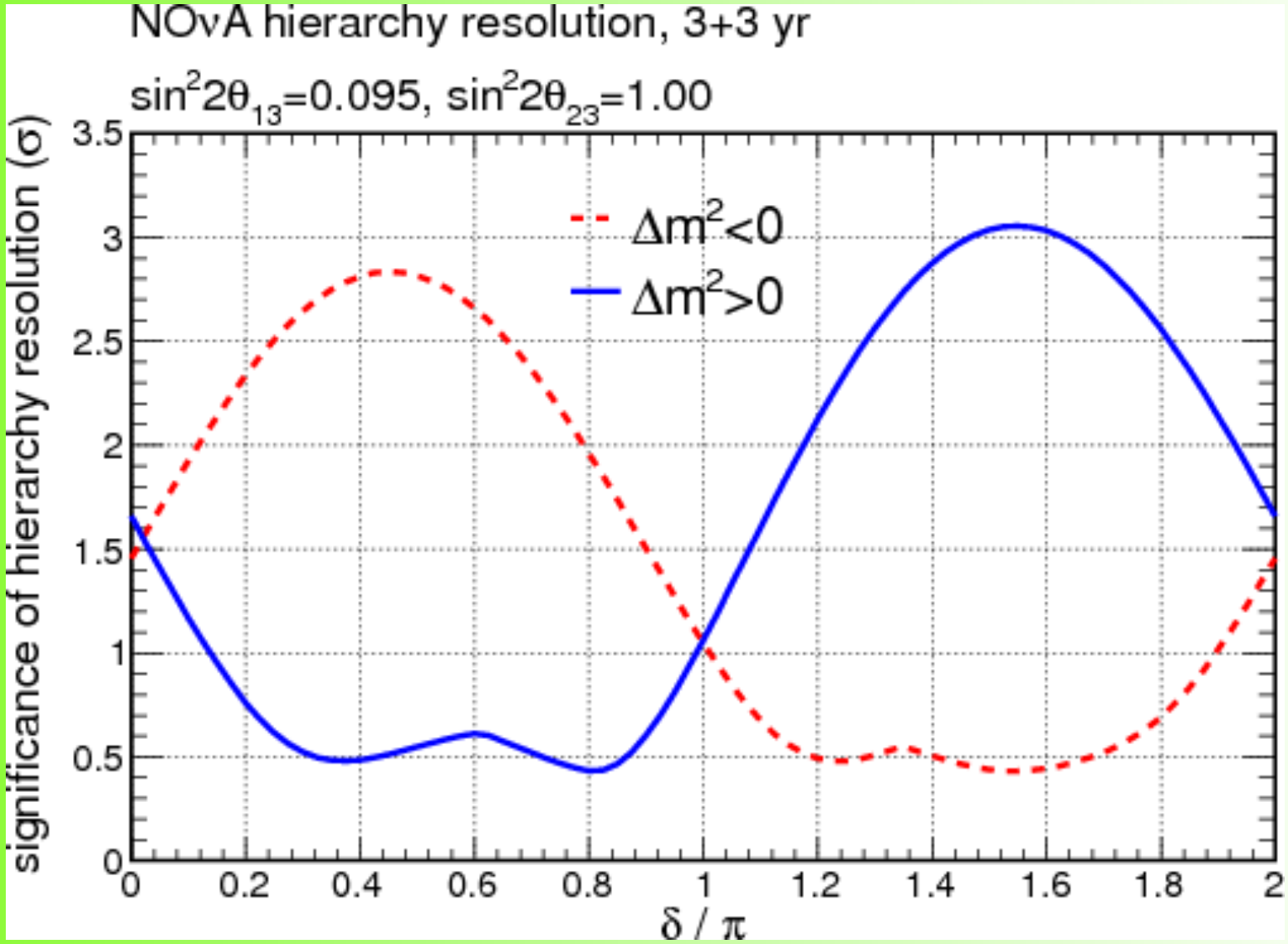




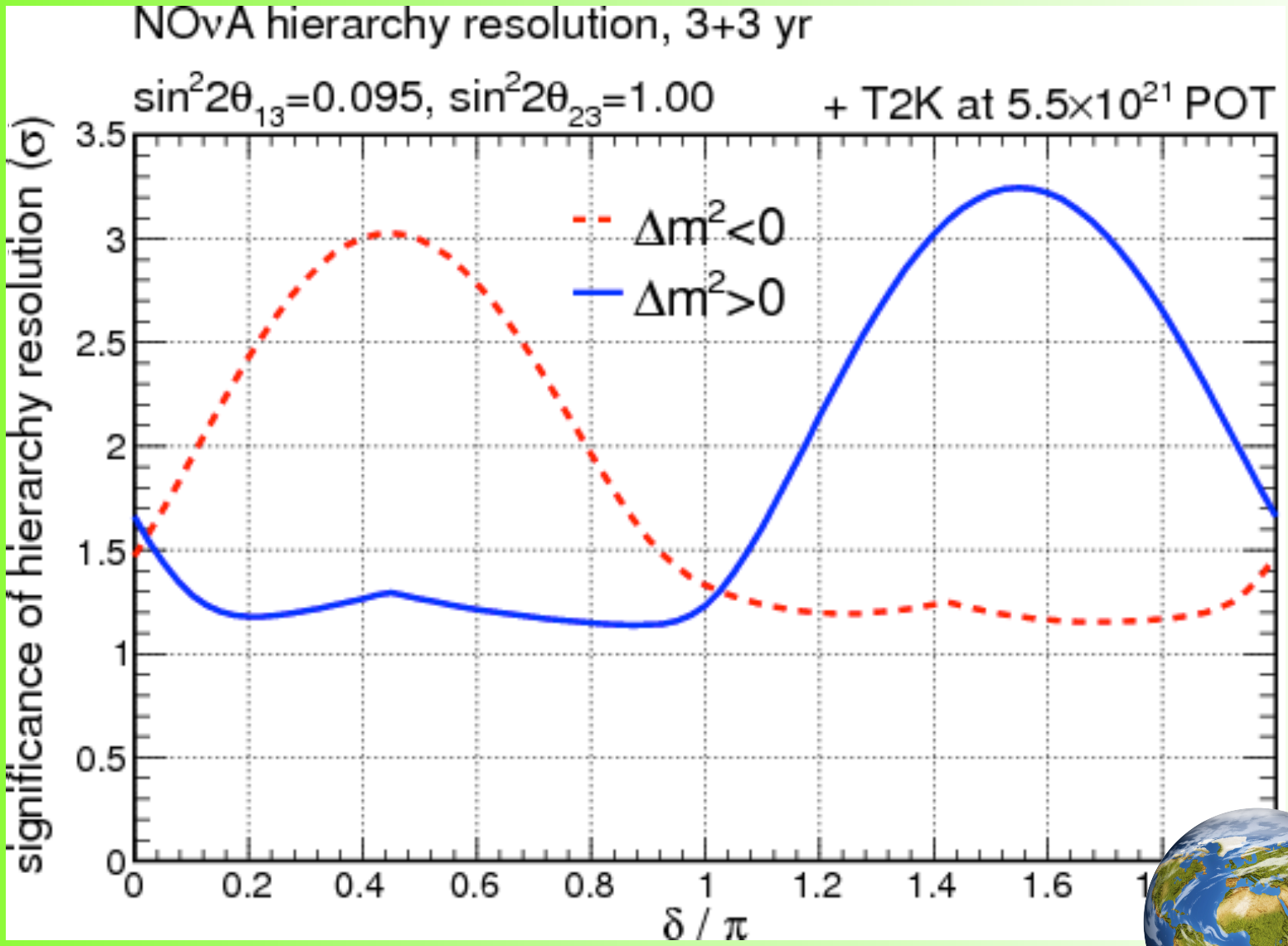
Where the buffalos roam

BACK TO FERMILAB….

NOVA on Mass Hierarchy



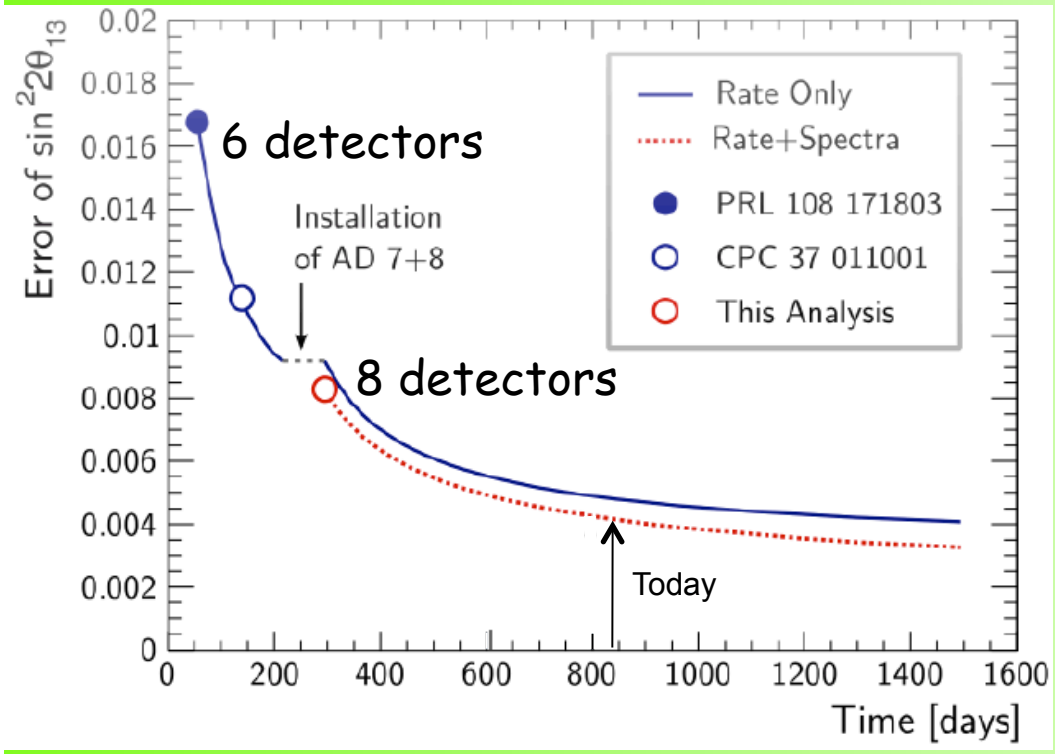
NOVA on Mass Hierarchy



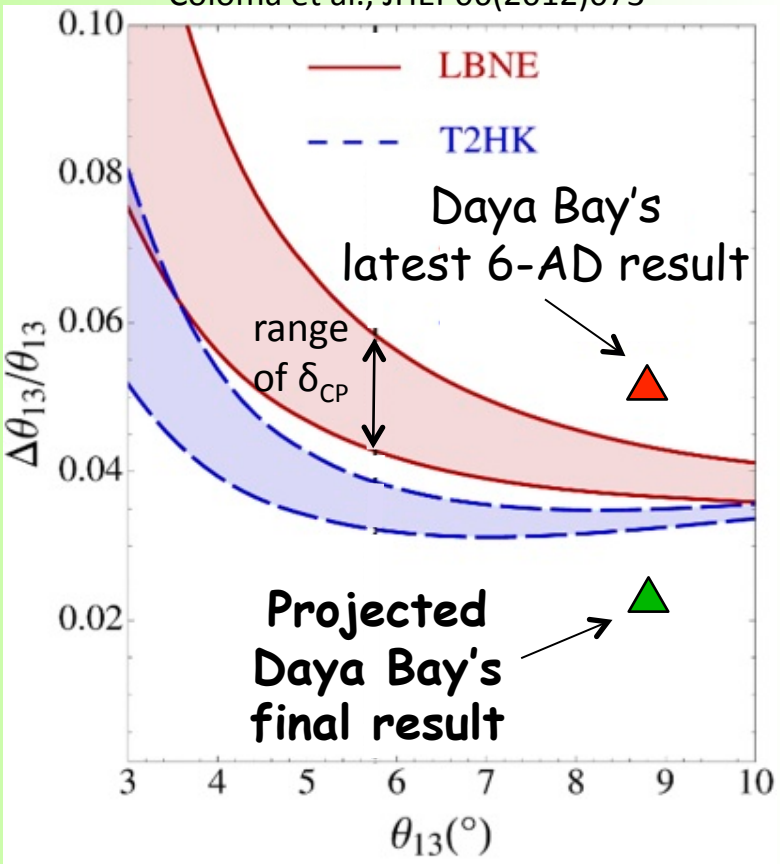
Reactor experimental plans

WHAT WILL HAPPEN IN CHINA?

Daya Bay: Projected Precision of $\sin^2 2\theta_{13}$



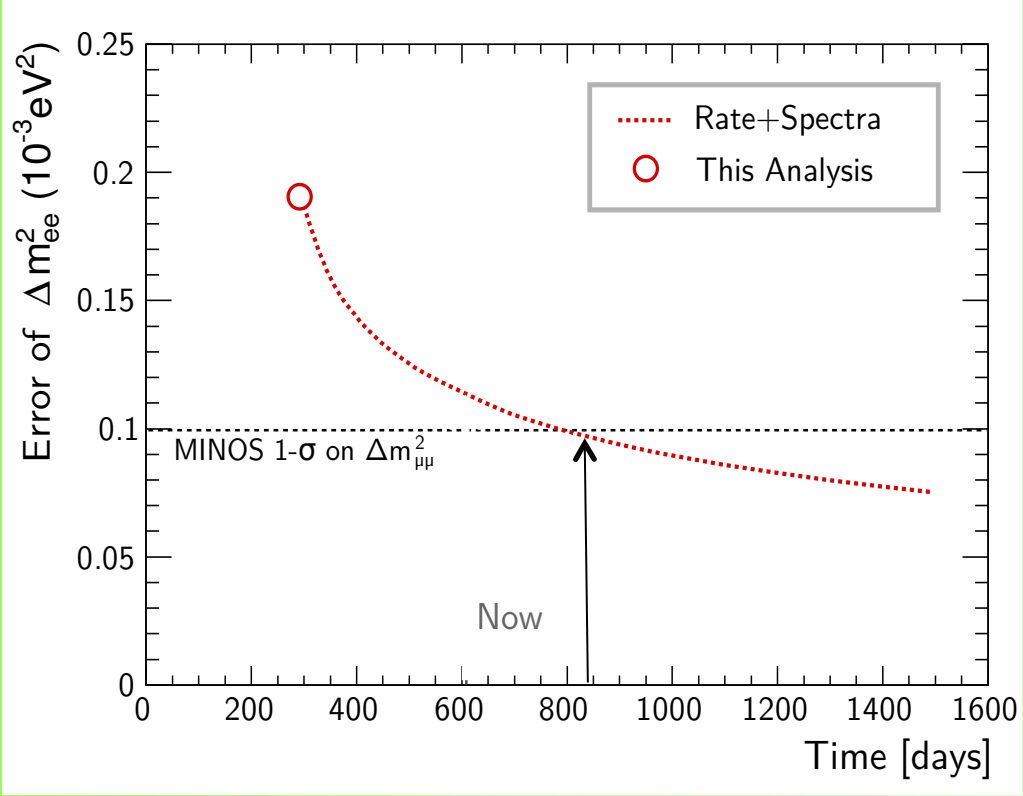
Coloma et al., JHEP06(2012)073



- Final precision, ~0.003, is still dominated by statistics (3%)
- Major systematics: relative efficiencies

Daya Bay: Projected Precision of $|\Delta m^2_{ee}|$

$$\sin^2\left(\frac{\Delta m^2_{ee} L}{4E}\right) = \cos^2\theta_{12}\sin^2\left(\frac{\Delta m^2_{31} L}{4E}\right) + \sin^2\theta_{12}\sin^2\left(\frac{\Delta m^2_{32} L}{4E}\right)$$



← 4% $\sigma\Delta m^2_{\mu\mu}$

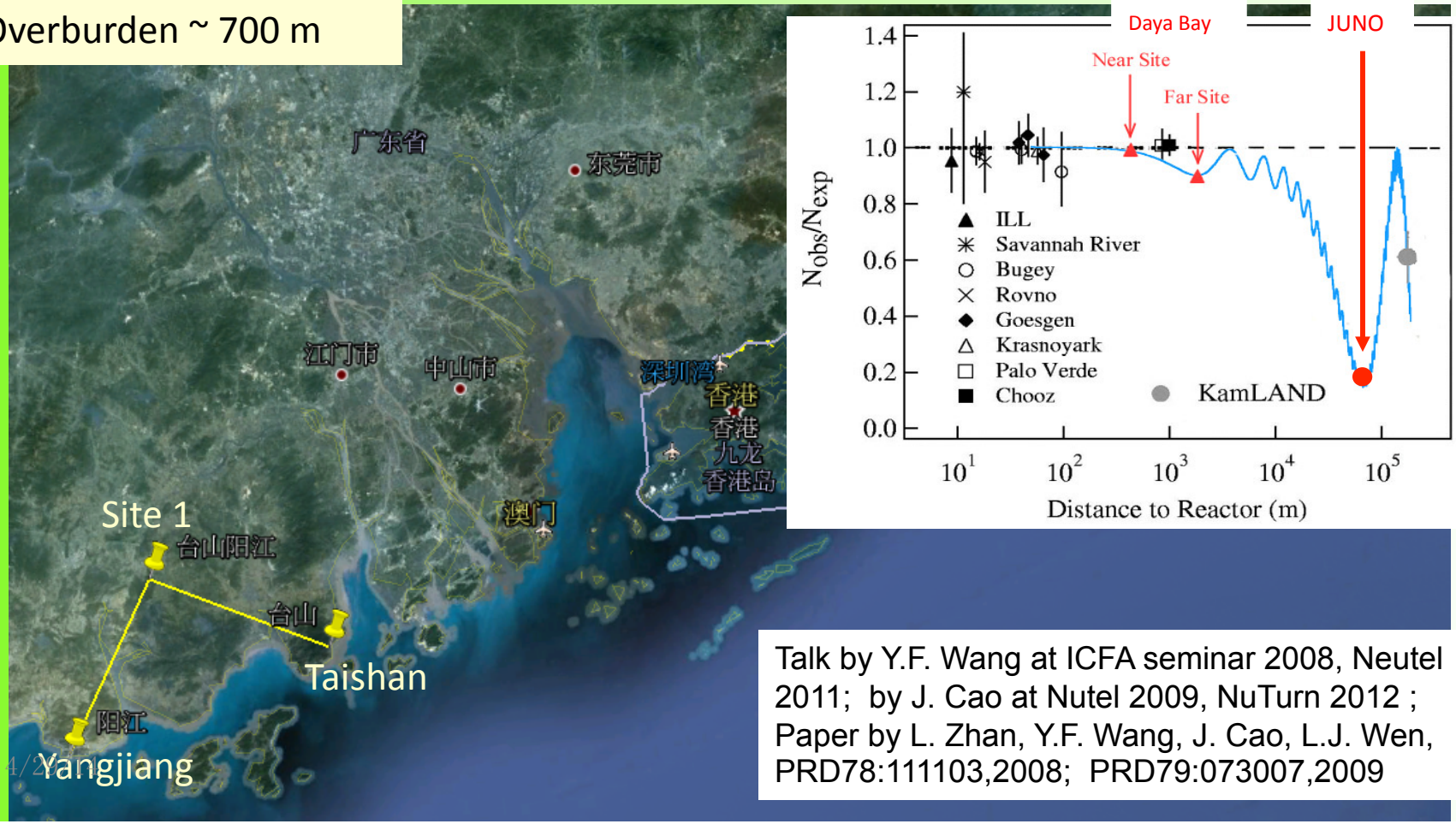
← 2% $\sigma\Delta m^2_{\mu\mu}$

- Final precision of ~0.075 x 10^{-3} eV^2 (3%) is limited by statistics **(in 2017)**
- Major systematics: Relative energy response, relative efficiencies, and background
- Precision of $|\Delta m^2_{ee}|$ is comparable to results obtained with ν_μ

Next Experiment: JUNO

	Daya Bay	Huizhou	Lufeng	Yangjiang	Taishan
Status	Operational	Planned	Planned	Under construction	Under construction
Power	17.4 GW	17.4 GW	17.4 GW	17.4 GW	18.4 GW

Overburden ~ 700 m



Talk by Y.F. Wang at ICFA seminar 2008, Neutel 2011; by J. Cao at Nutel 2009, NuTurn 2012 ; Paper by L. Zhan, Y.F. Wang, J. Cao, L.J. Wen, PRD78:111103,2008; PRD79:073007,2009

Current Status & Brief Schedule

- Project approved by CAS for R&D and design
- Geological survey completed
  - Granite rock, tem. ~ 31 ^{o}C, little water
- Engineering design underway
- Detector design and R&D underway
- International Collaboration: China, Czech, France, Germany, Italy, Russia, US, …

Schedule:

Civil preparation： 2013-2014

Civil construction： 2014-2017

Detector R&D： 2013-2016

Detector component production： 2016-2017

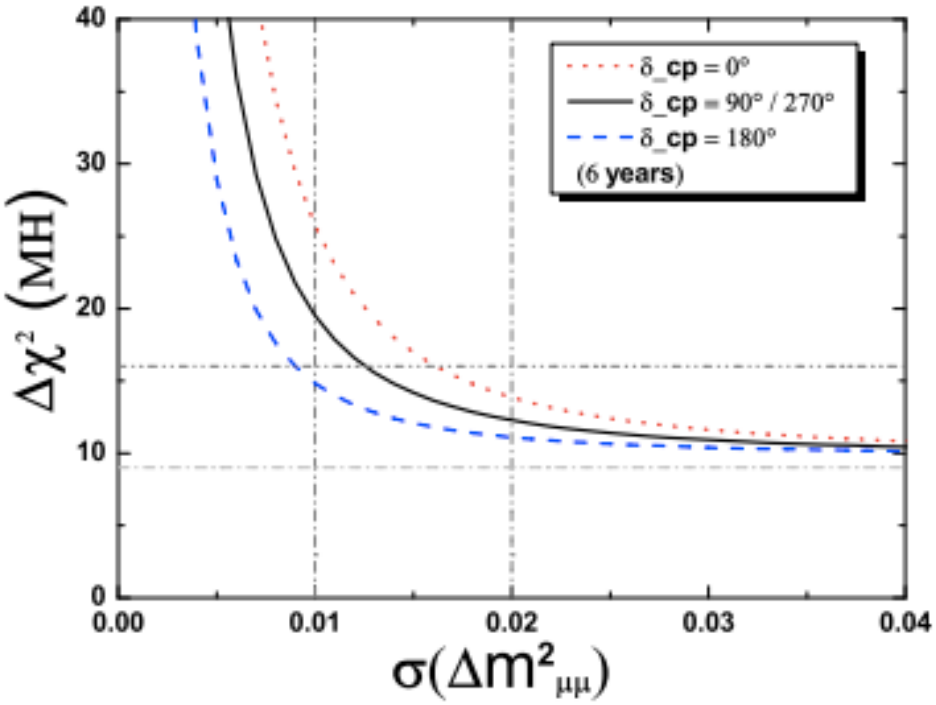
PMT production： 2016-2019

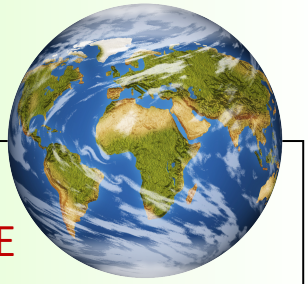
Detector assembly & installation： 2018-2019

Filling & data taking： 2020

4-6 years to Mass Hierarchy result

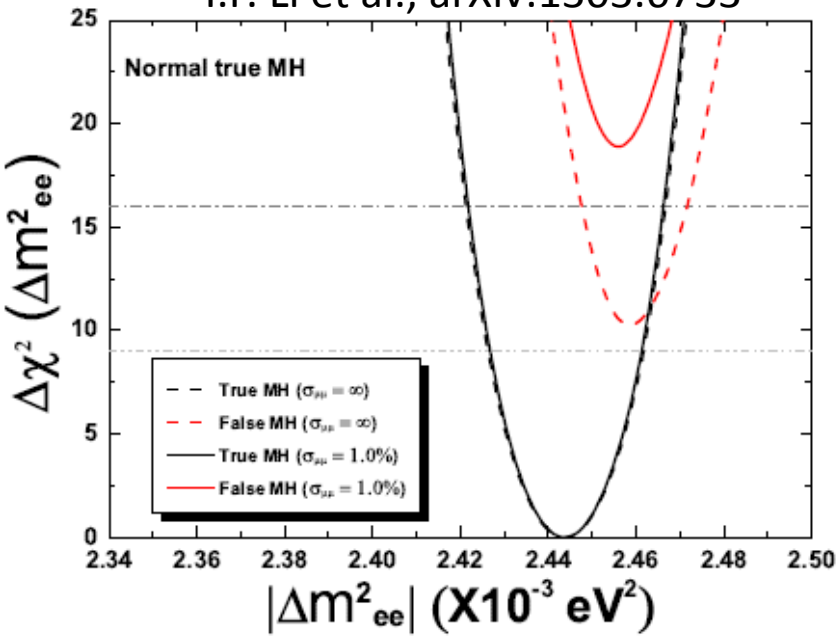
Physics Reach by 2024-6





Detector size: 20kt
Energy resolution: 3%/√E
Thermal power: 36 GW

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



	Current	Daya Bay II
Δm^2_{12}	3%	0.6%
Δm^2_{23}	5%	0.6%
$\sin^2\theta_{12}$	5%	0.7%
$\sin^2\theta_{23}$	5%	N/A
$\sin^2\theta_{13}$	14% ➔ 4%	~ 15%

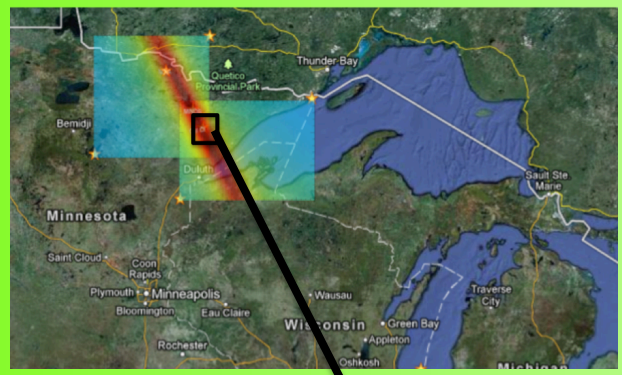
For 6 years, mass hierarchy can be determined at 4σ level, ***if $\Delta m^2_{\mu\mu}$ can be determined at 1% level!***

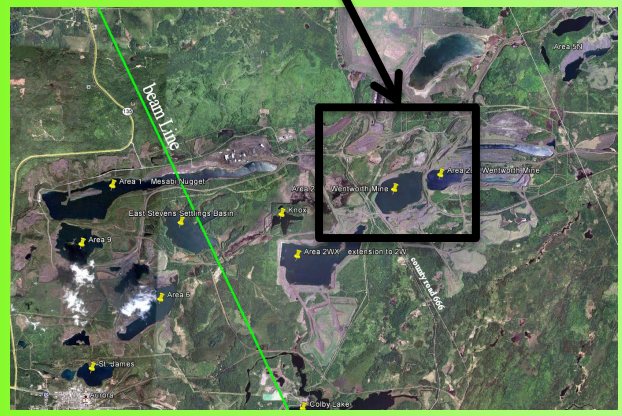
Actually to Middle-of-Nowhere, Minnesota

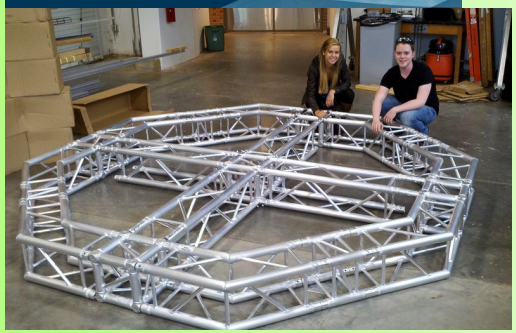
BACK TO FNAL….

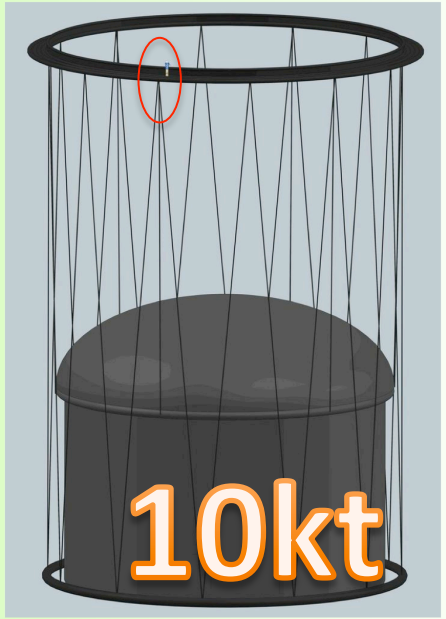
δ_{CP} : CHIPS concept

- Look for a deep water mass in Minnesota intersected by the NuMI beam
- Deploy from floating platform : pit water acts as mechanical support
- Replace nets with roofing liner and will with with cleaned water
- Deployment Idea developed by Madison/PSL groups for LBNE
- Approved by FNAL PAC for 1st year of R&D

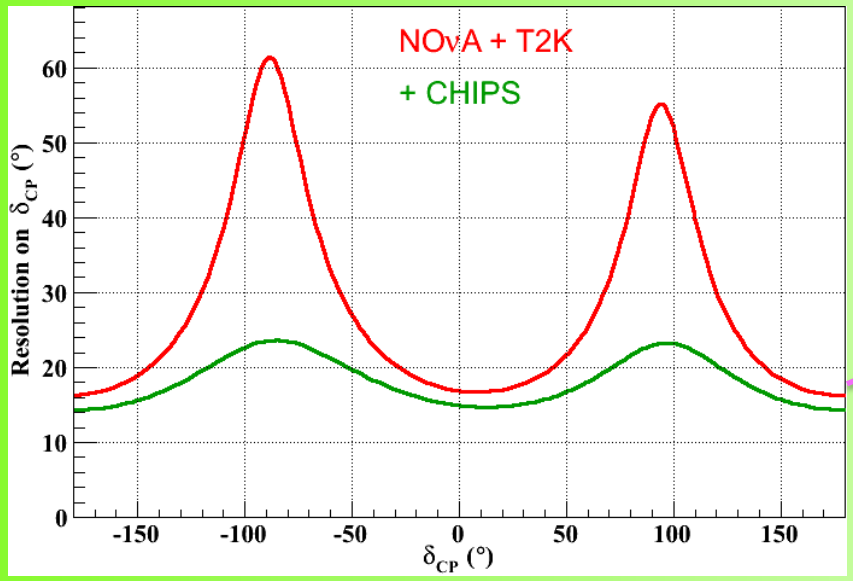


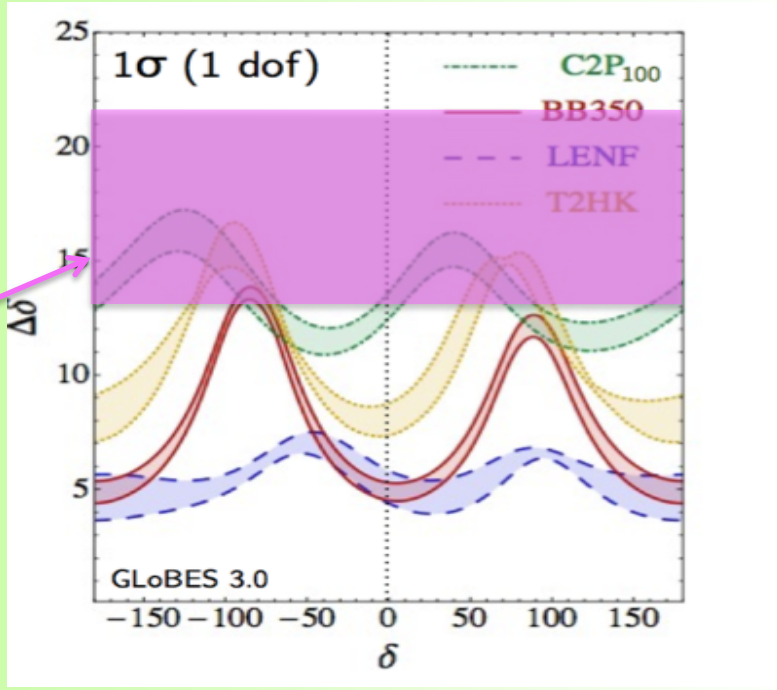


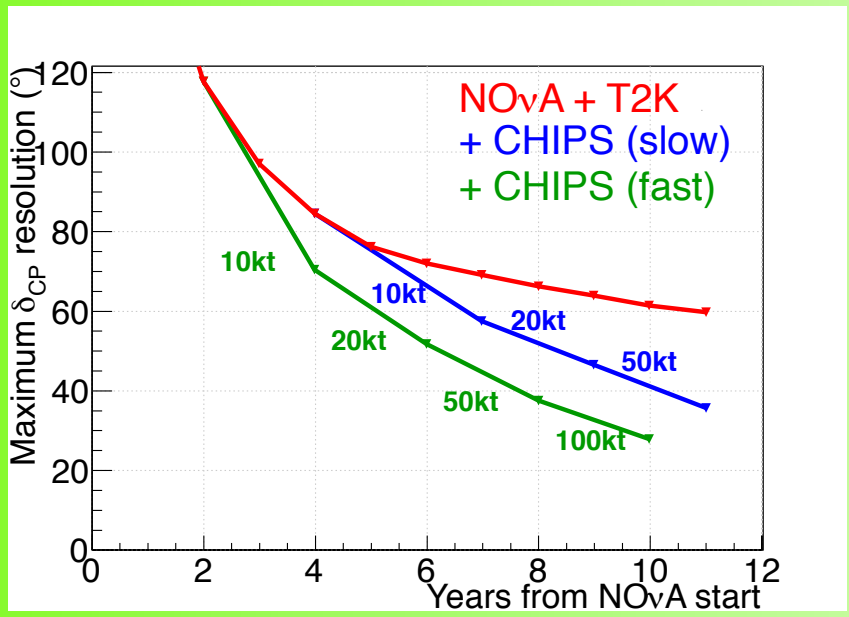




CHIPS@NuMI



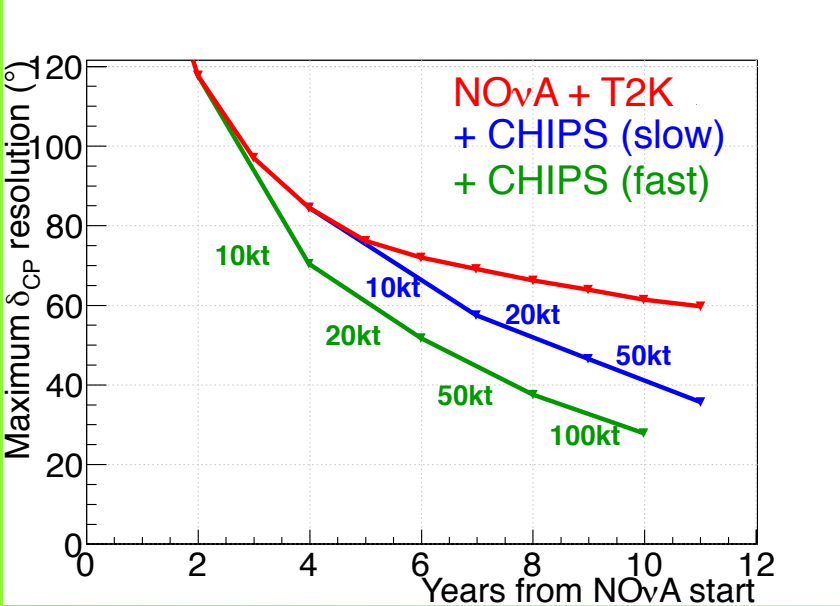




- CHIPS can make very big inroads into δ_{CP}
- Racing against the ticking NuMI / LBNE changeover clock

Getting started fast

- Starting small can yield important results if we are fast



- Slow but continuous detector growth ($3-10M/yr)
- Real costs fully understood using stepwise approach: avoid huge contingencies
- 100kt end result gives impressive gain over NOVA alone

- **Starting at all (!) can allow external money to be applied for**

CHIPS

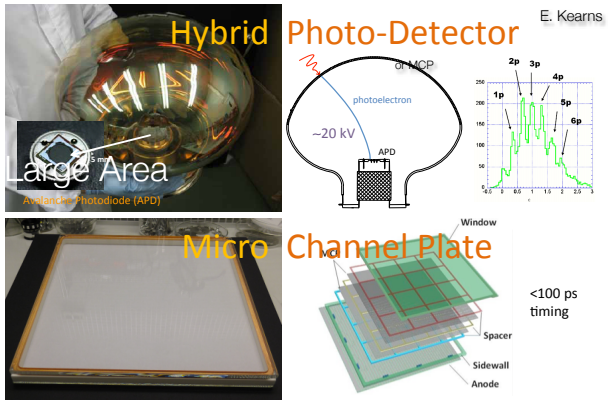
- PMTs are the major cost driver
  - Pushing on PMT technology as well as increasing competition will be a plank of the CHIPS philosophy
- In contact with KM3Net collaboration
  - Electronics developed already for a 31x3”PMT DOM
  - This may actually be better for us than large tubes
  - Have received pieces from NIKEF at UT to benchmark

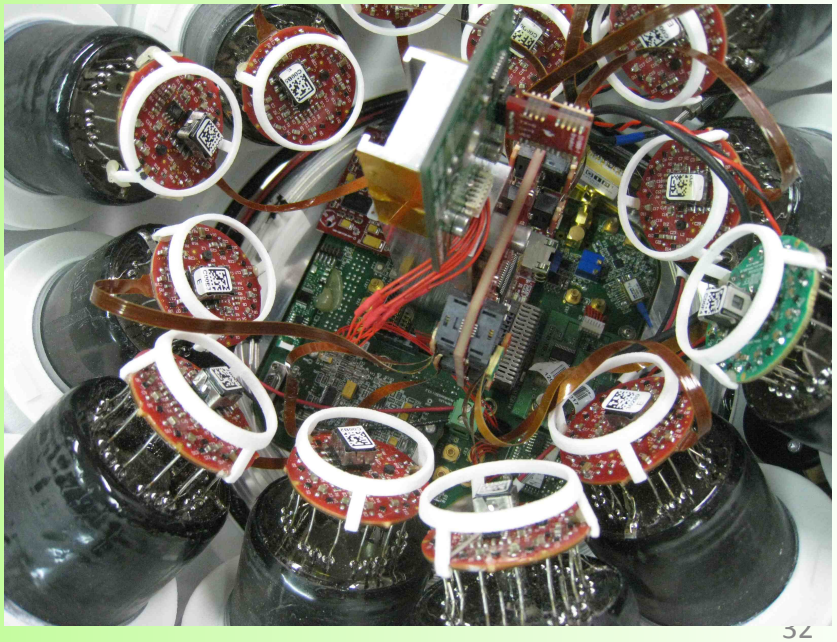
New Photodetector Technologies

- Examples of two promising new large-area photosensors in development are:

Hybrid Photo-Detector : ~ 600 to 2200 psec timing resolution depending on HPD size

Large Area Pico-Second Photodetector : ~100 psec timing + ~1cm spatial res

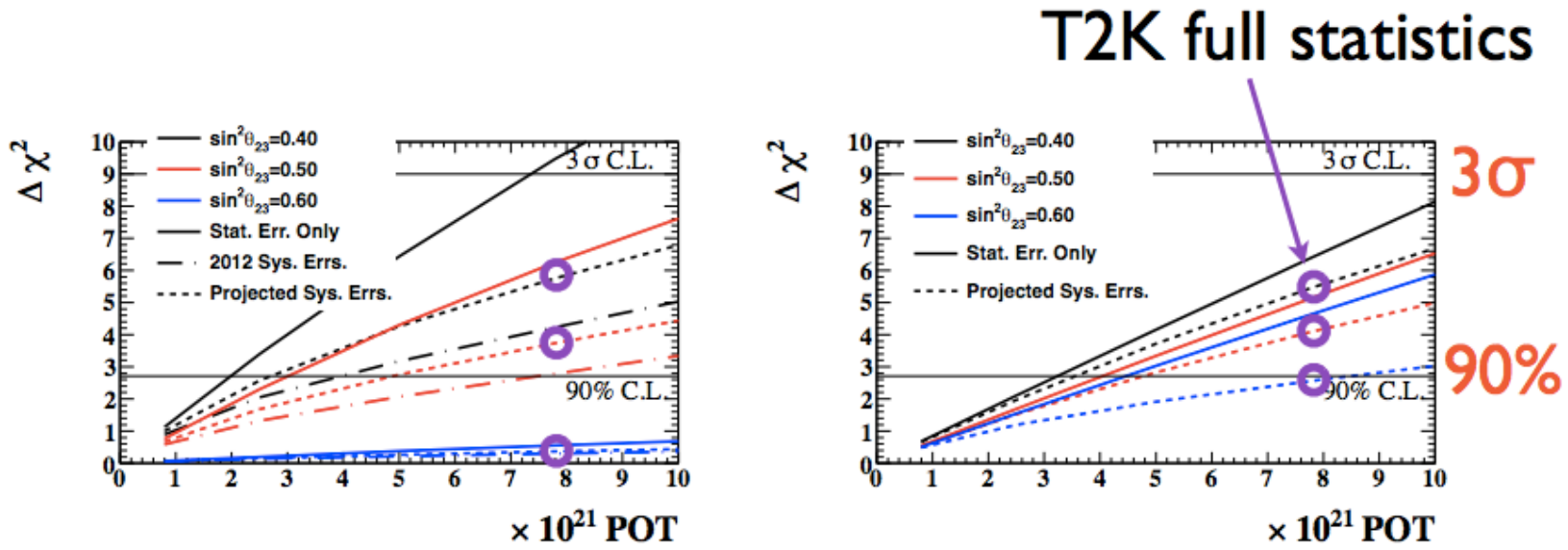




Look at T2K and Super-K

BACK TO JAPAN

CPV w/ T2K



(a) 100% ν-running.

(b) 50% ν-, 50% $\bar{\nu}$ running.

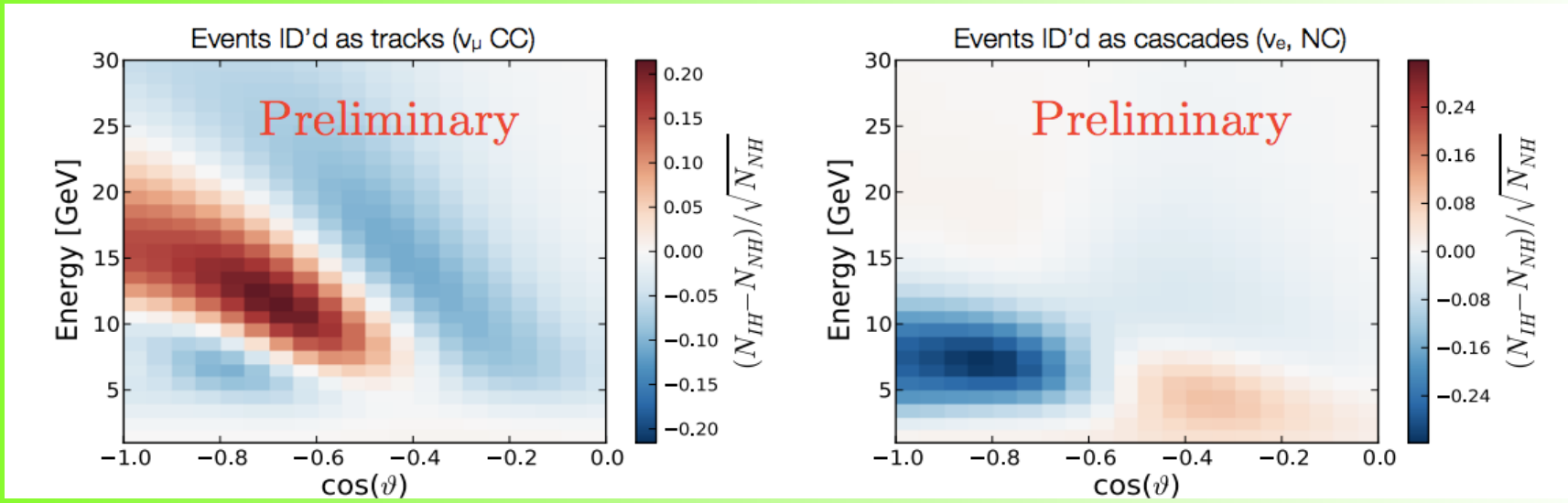
Figure 26: The expected $\Delta\chi^2$ for $\sin\delta_{CP} = 0$ plotted as a function of POT. Plots assume true $\sin^2 2\theta_{13} = 0.1$, $\delta_{CP} = +90°$, inverted MH, and various true values of $\sin^2\theta_{23}$ (as given in the plot legends). The solid curves include statistical errors only, while the dash-dotted (dashed) curves assume the 2012 systematic errors (the projected systematic errors). Note that the sensitivity heavily depends on the assumed conditions, and that the conditions applied for these figures ($\delta_{CP} = +90°$, inverted MH) correspond to the case where the sensitivity for $\sin\delta_{CP} \neq 0$ is maximal.

What next?

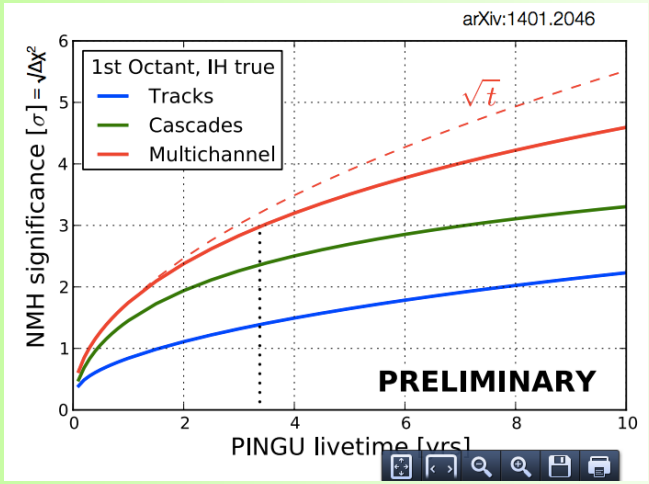
BACK TO THE SOUTH POLE!!

PINGU

- PINGU goal is to start data taking in 2021
- Evidence of Mass Hierarchy in both cascade AND muon events



- Big techno-synergy with CHIPS
  - PMTs, readout
  - Complementary experiment



What about the sterile search

BACK HOME AGAIN TO FNAL

A Staged Multi-LAr TPC Short-Baseline Neutrino Program

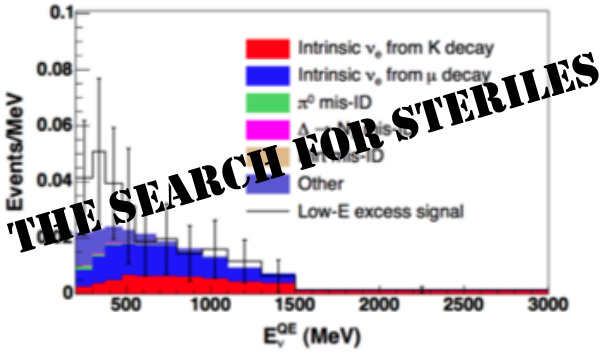
Existing enclosure vacated by SciBooNE detector

Phase 0: MicroBooNE
86 t active volume TPC
L = 470 m
start in 2014

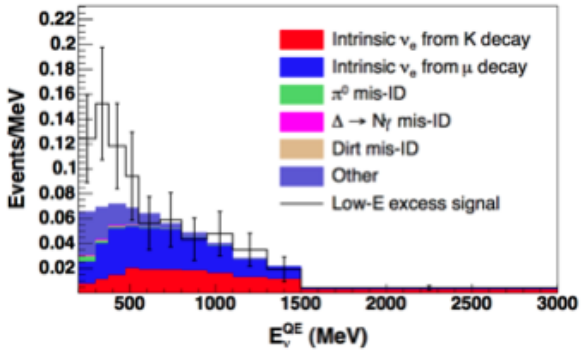
Phase 1: LAr1-ND
82 t active volume TPC
L = 100 m
2017-2018

Phase 2: LAr1-FD
1000 t active volume TPC
L = 700 m
2020+

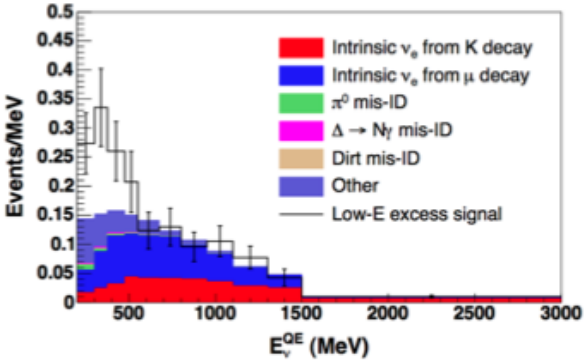
MicroBOONE



1x10^{20} POT
e-like: 2.2σ
γ-like: 1.6σ



3x10^{20} POT
e-like: 3.8σ
γ-like: 2.8σ



6.6x10^{20} POT
e-like: 5.7σ
γ-like: 4.2σ

THE SEARCH FOR STERILES

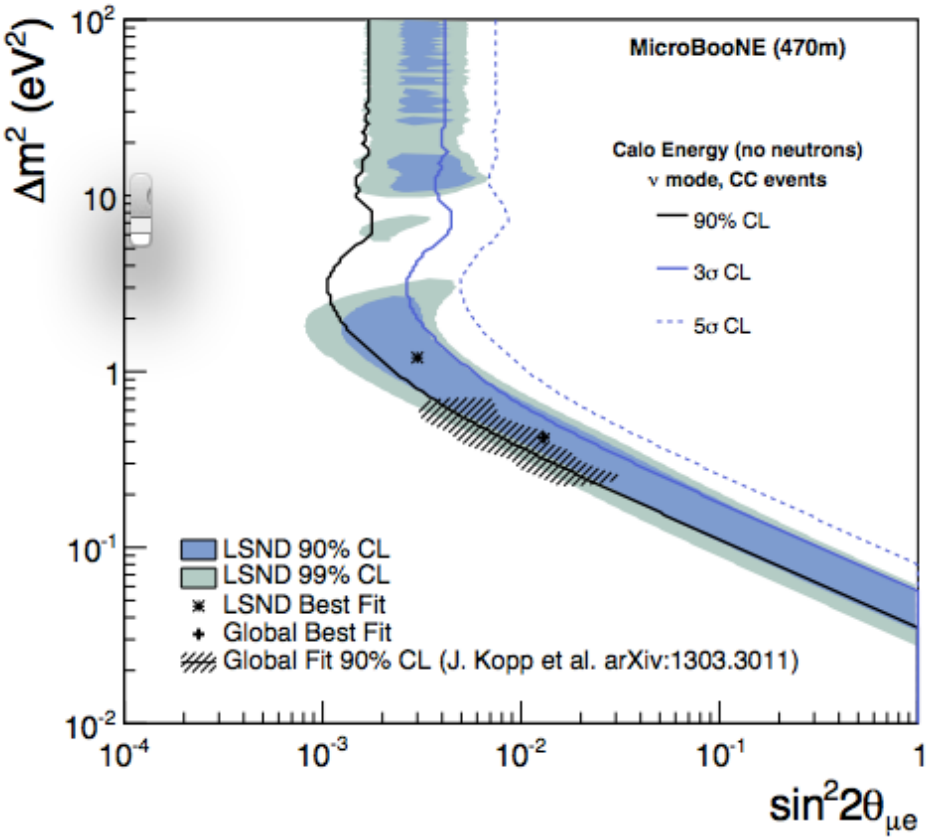
- MicroBooNE is a very small detector (70t)
- It will not have much reach in the sterile limit
- But it will tell us whether the MiniBoone excess is photons or electrons!
- Will we stop looking if they are photons??

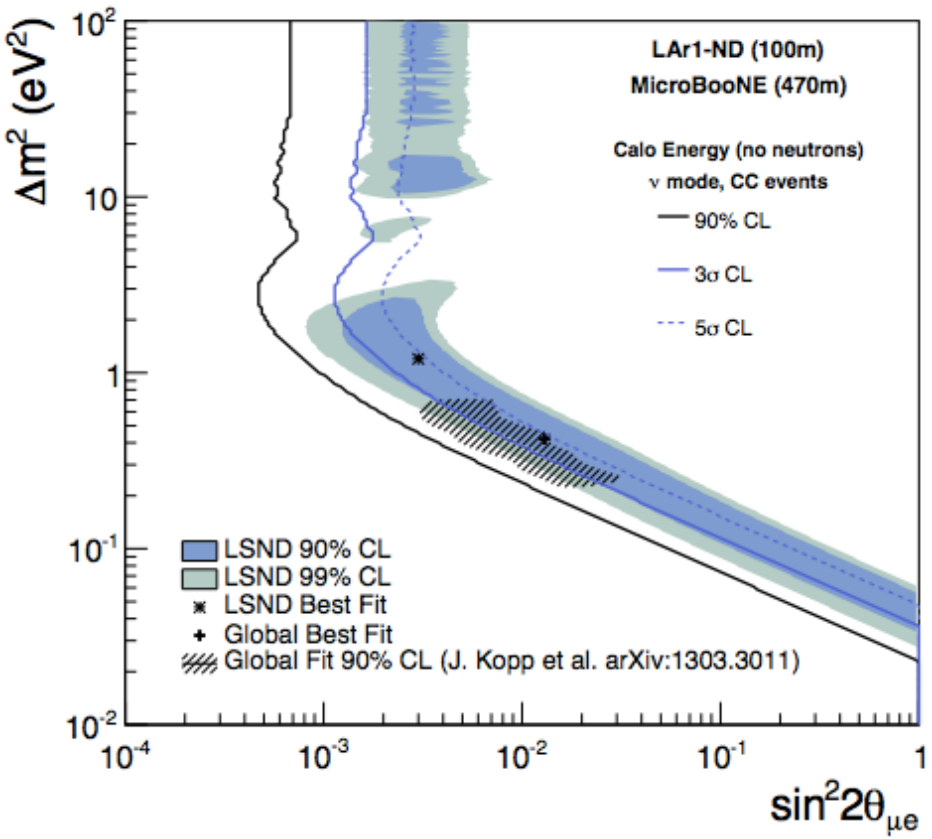
$\nu_\mu \rightarrow \nu_e$ Appearance

6.6×10^{20} POT exposure for MicroBooNE alone, assuming 20% systematic uncertainties on ν_e background prediction

+ND

Same MicroBooNE exposure + 2.2×10^{20} POT exposure for LAr1-ND to constrain background prediction

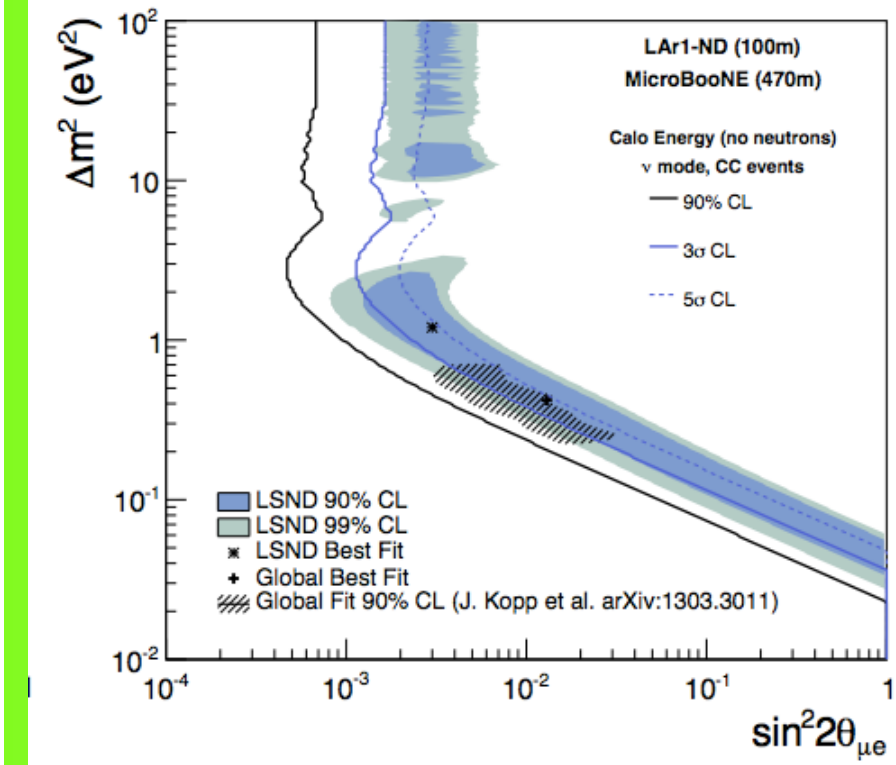




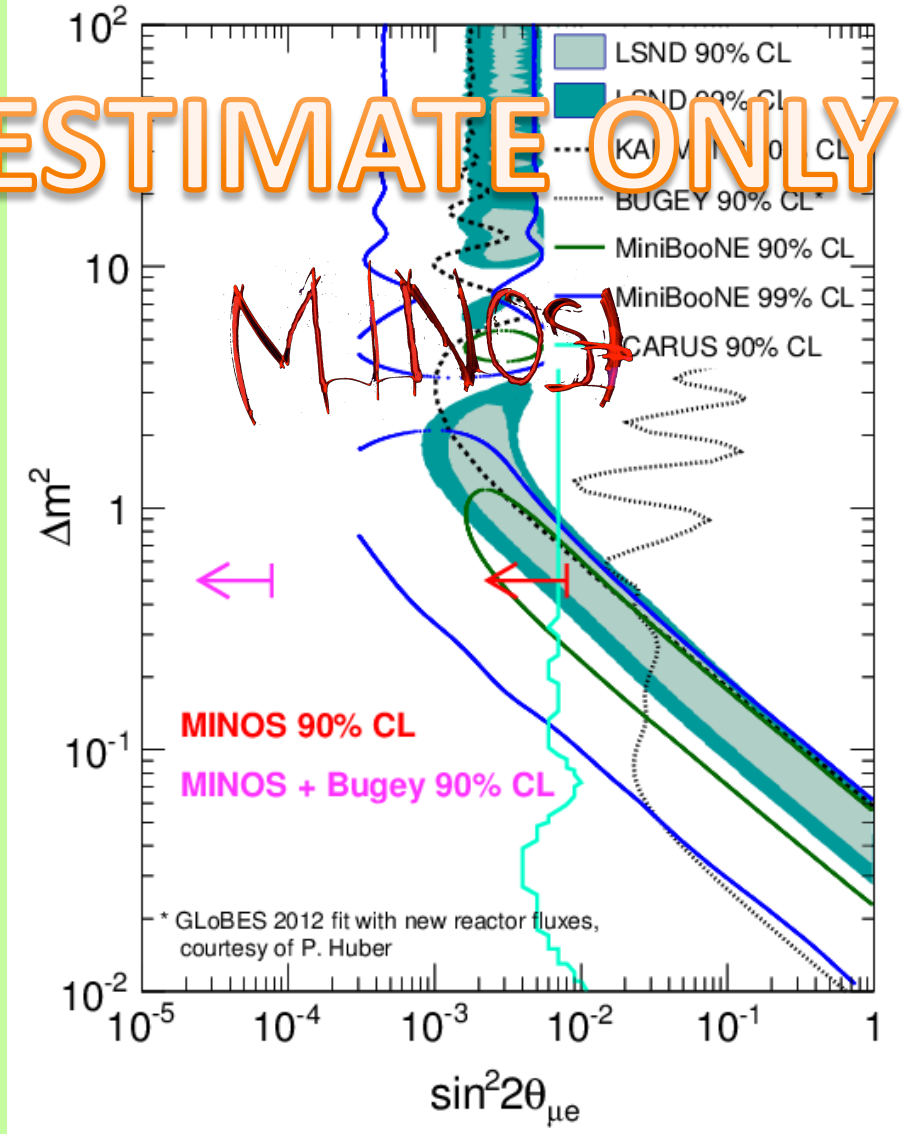
MicroBOONE(6.6e20)+LAr1-ND(2.2e20)

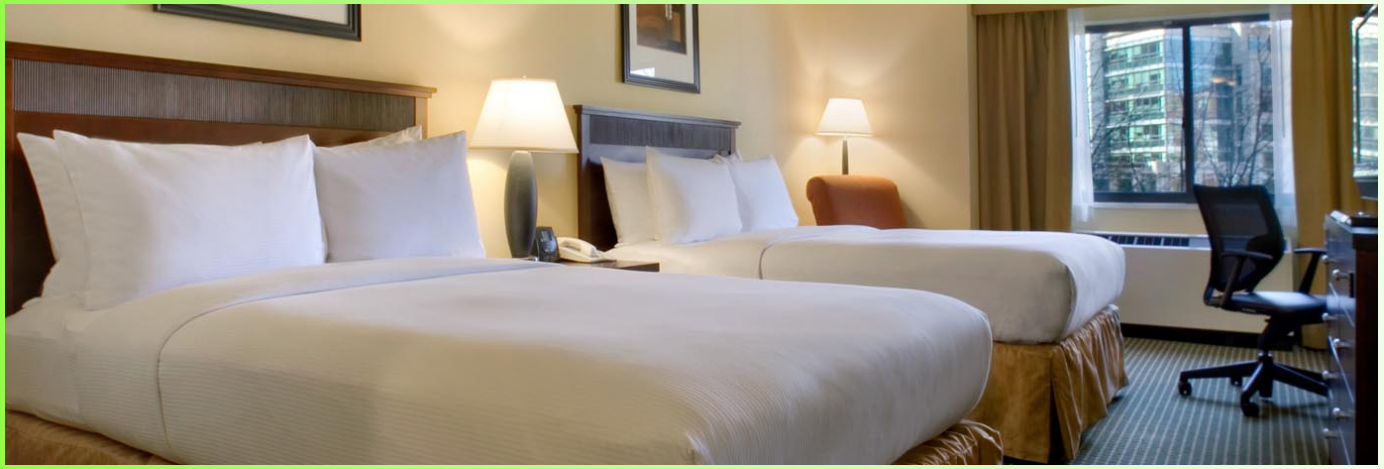
+ND

Same MicroBooNE exposure +
2.2x10^{20} POT exposure for LAr1-ND
to constrain background prediction



ESTIMATE ONLY



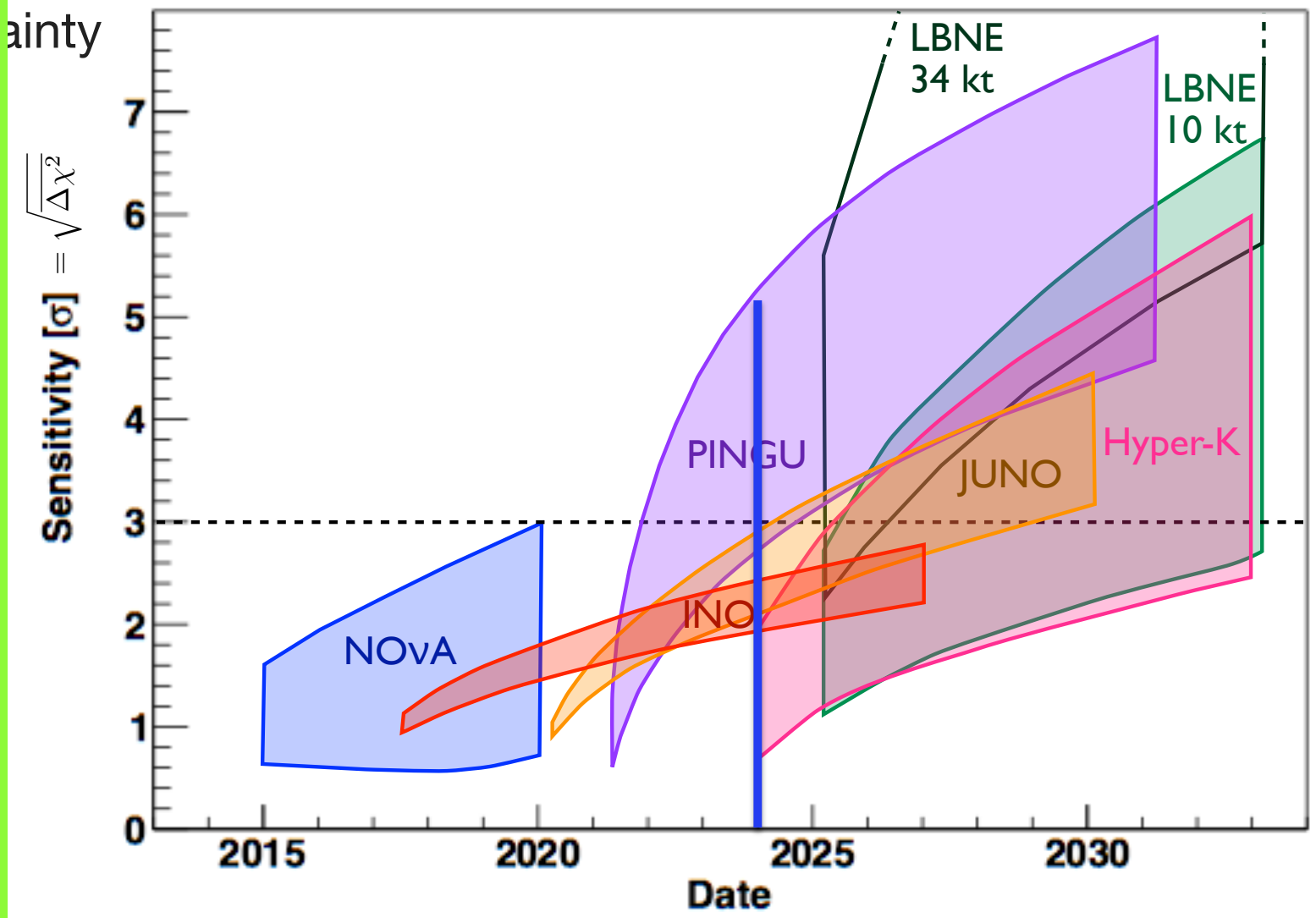


Stop to take stock

MEANWHILE….IN THE ARLINGTON HILTON

Reasonable Synopsis

after Blennow et al., arXiv:1311.1822



Summary

- Probably by the end of the coming decade we will know the mass hierarchy
  - It is not yet a slam dunk
  - PINGU will have the best reach if it can get started soon
  - Daya Bay II could be lucky, they have surprised us before
    - **Two approaches, belts and braces, but no cigar**
- We will know θ_{23} to few % (NOVA)
- We will know θ_{13} to 3% (still stats limited)
- We will know Δm^2_{12} to 0.6% (DBII)
- We will know Δm^2_{13} to 0.6% (DBII)
- We will know Δm^2_{32} to 1-2% (NOVA+MINOS+)
  - The combined data will be hinting about MH …
- We should have strong limits on steriles
- **But what of life after retirement?.....**

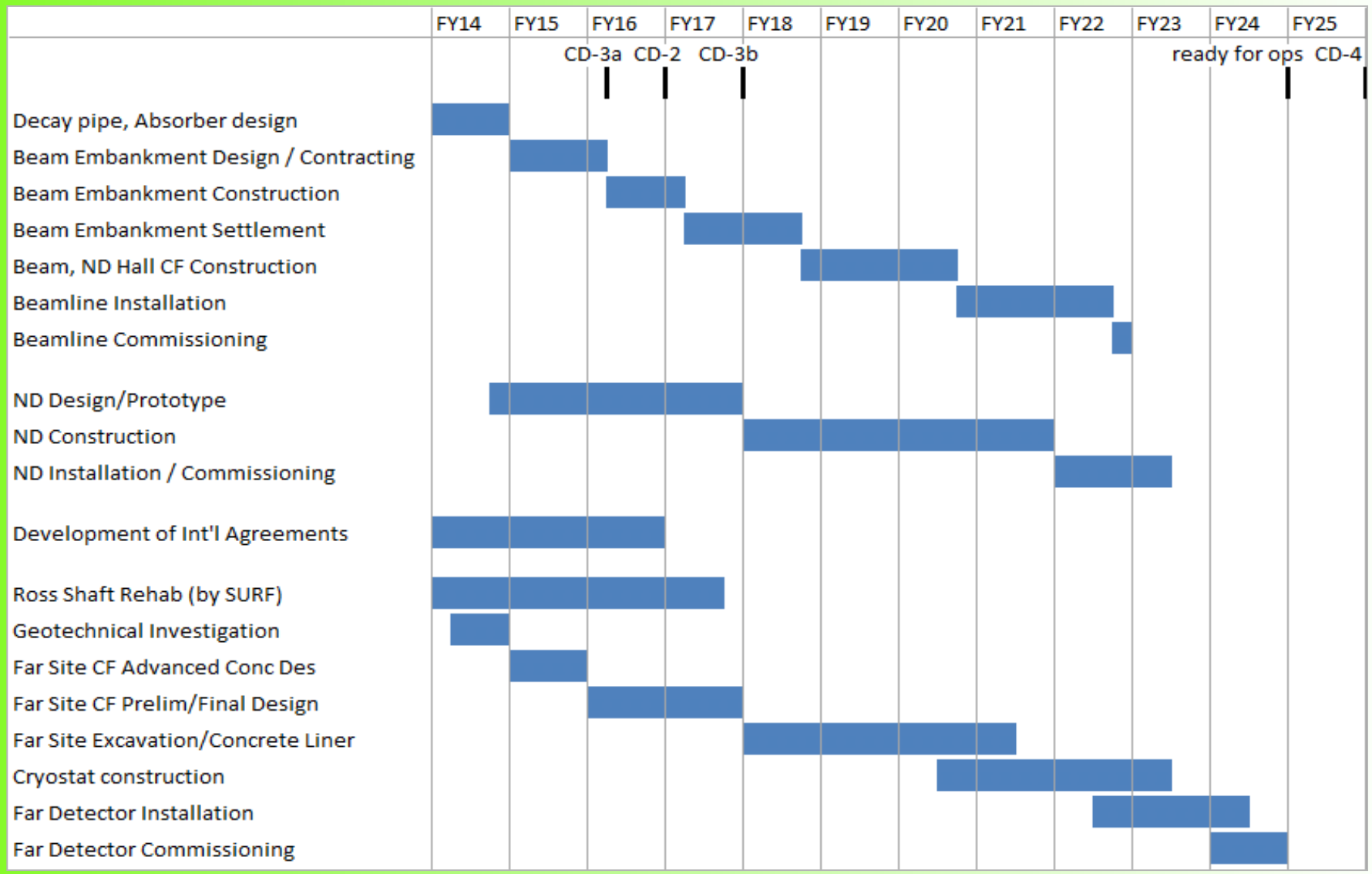
Going forward, the remaining question is:
What is δ_{CP}???
Do we already know it? (T2K, MINOS and Reactors)
Without CHIPS, it could take another 20 years to find out!

The further future

THE NEXT DECADE STARTS AT FNAL!

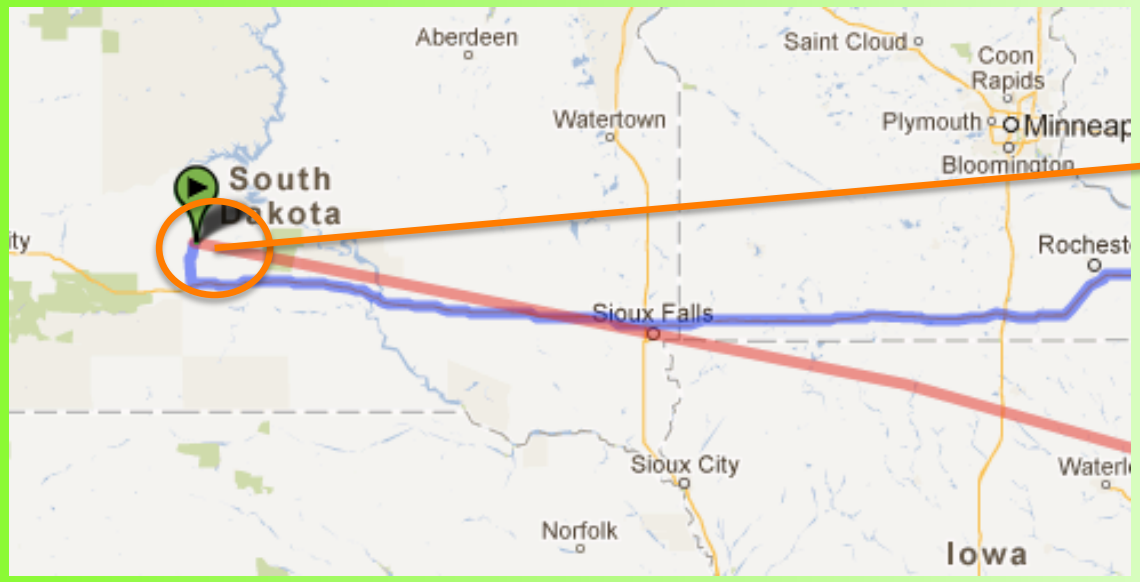
Plausible Schedule for International LBNE

Question 1: "a brief summary of … a notional timeline…"



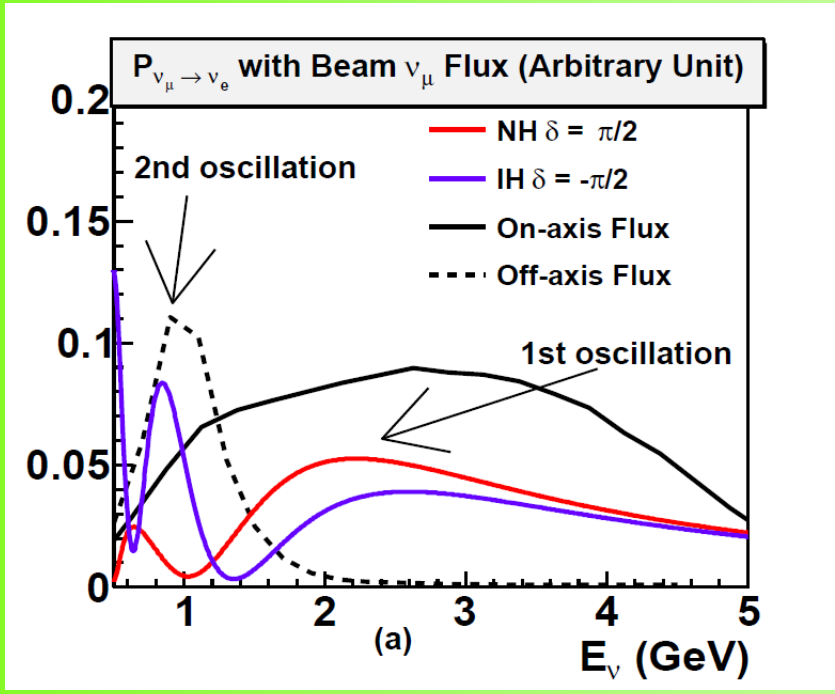
LBNE

- Much longer baseline to measure mass heirarchy
- On-axis Liquid Argon detector (35kt)
- Planned to be operating in 2026
- CHIPS could also provide the complementary off-axis detector
  - After all, we already paid for all those phototubes….

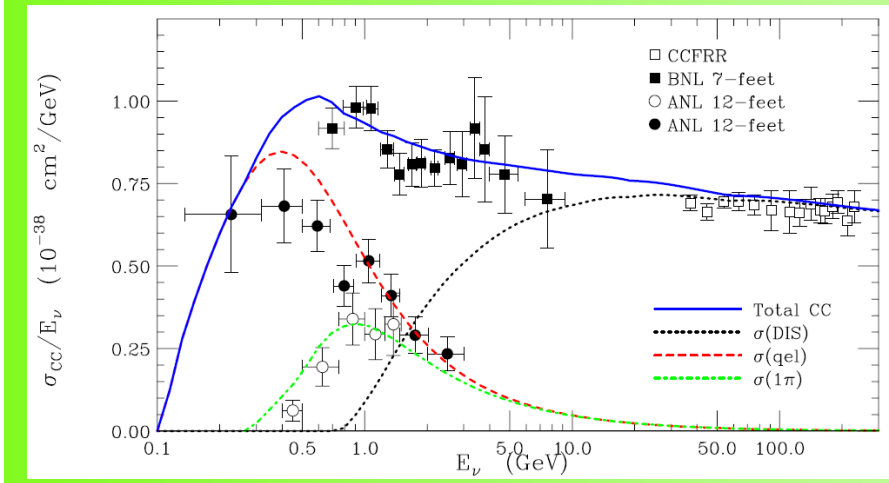


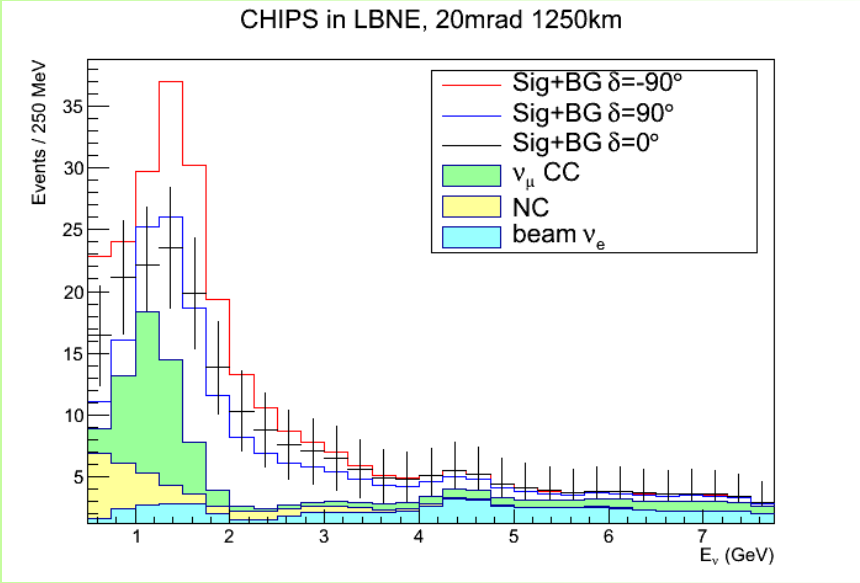
- There is (at least) one (40m depth) reservoir in the beam line @ 20mr (Pactola Resevoir, SD)

CHIPS@LBNE (20mr off axis)

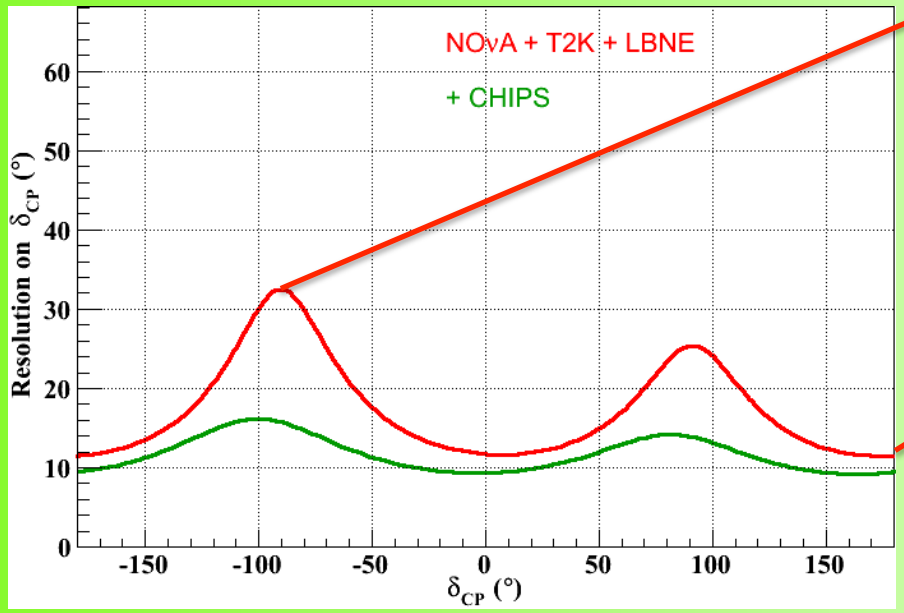


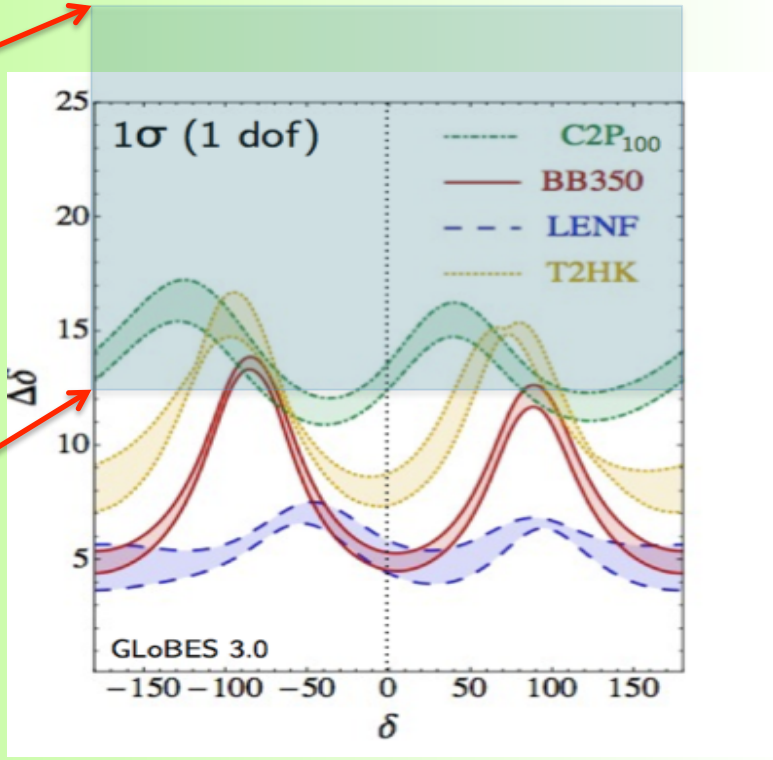
- 2nd oscillation maximum located around 0.8 GeV
- Large quasi-elastic x-section
- Suitable for water Cerenkov detector
  - High efficiency for QE events
- 2nd oscillation maximum is a necessary upgrade/augmentation path for LBNE





NO CHIPS + 10kt LAr

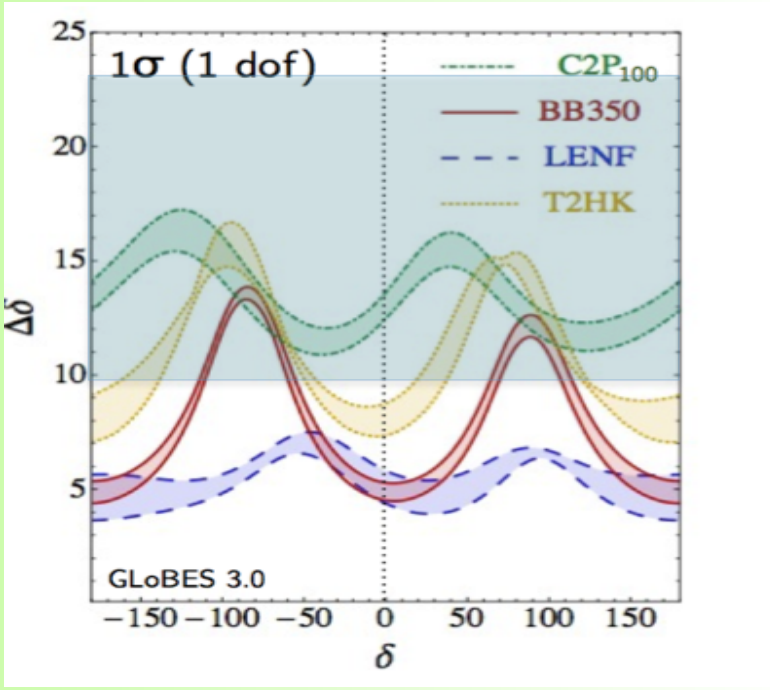




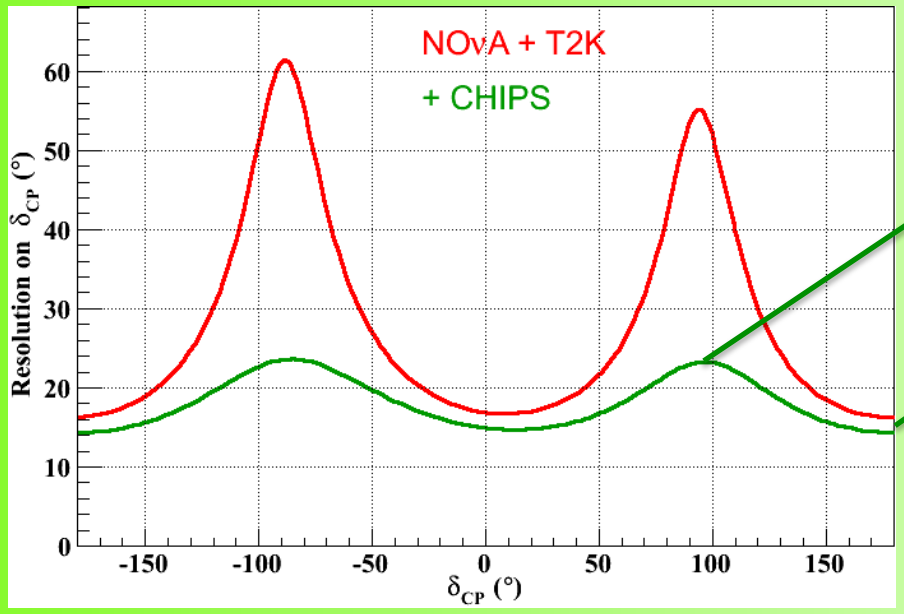
- This is the region of δ_{CP} which we will cover with 10kt LBNE after 10 years (green shaded region)
- Obviously, with 35kt it is better

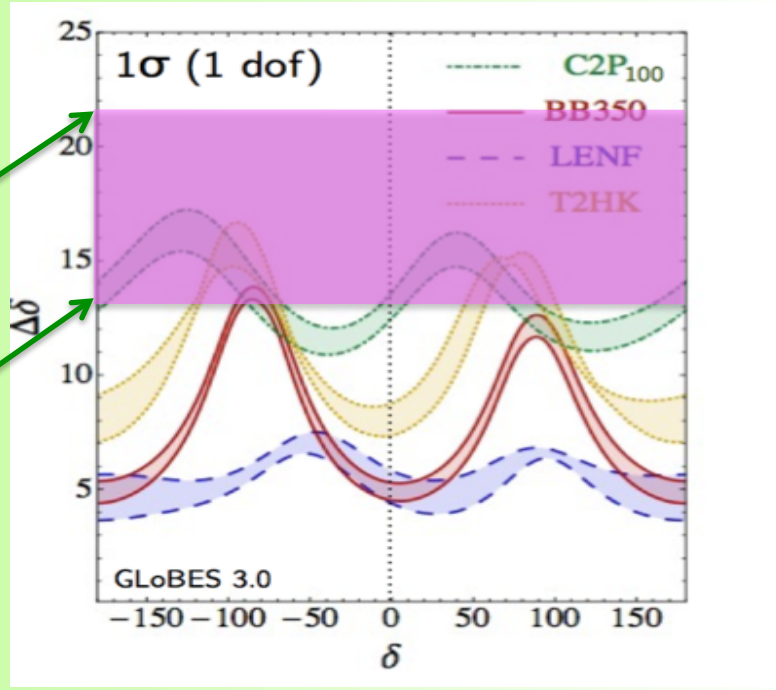
NO CHIPS + 35kt LAr

- IF LBNE is 35kt LAr detector
  - Better at small δ_{CP}
  - Worse at large δ_{CP}



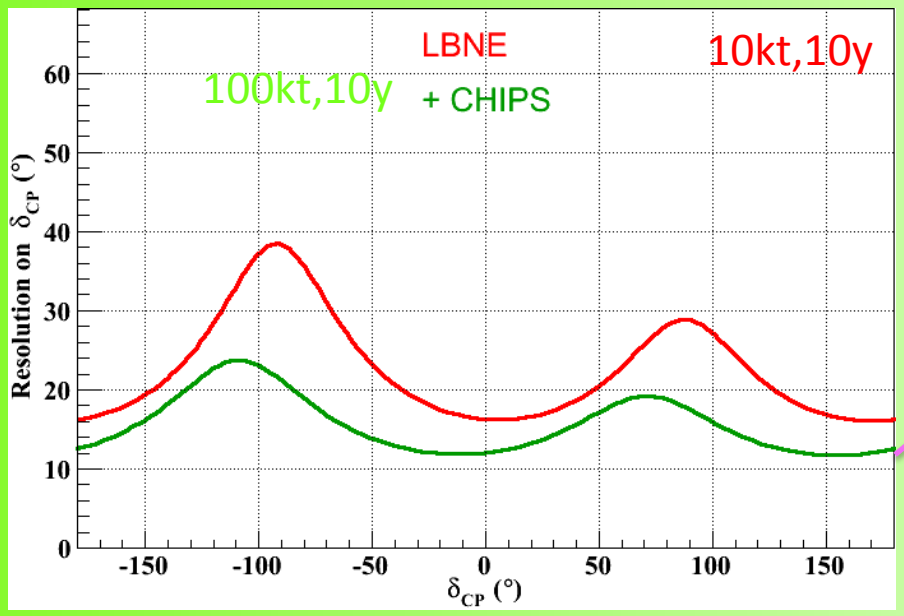
CHIPS@NuMI

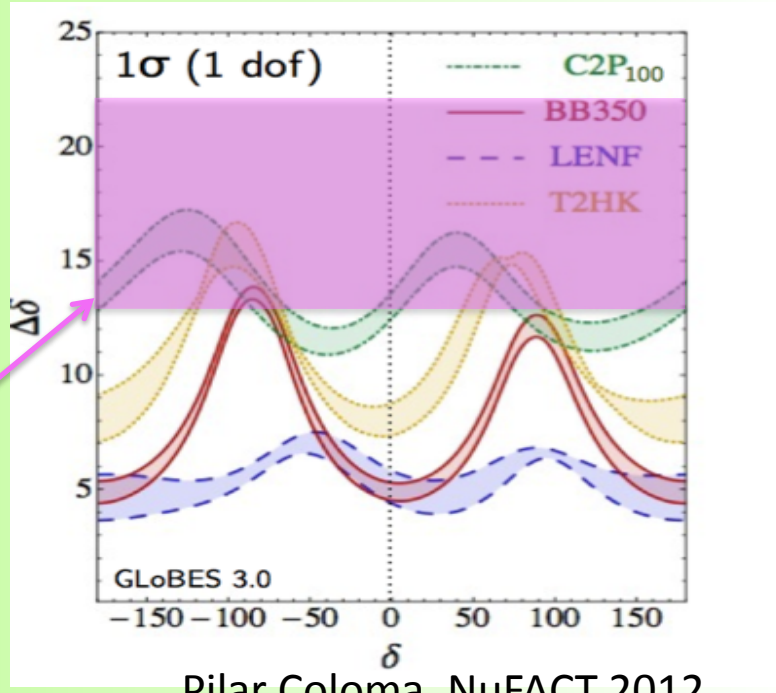




- CHIPS can make very big inroads into δcp
- LBNE could build SUBSTANTIALLY **on** CHIPS@NuMI and together **with** CHIPS@LBNE
- **10kt LAr+100kt CHIPS now on the same page as the NF!**

CHIPS@LBNE+10kt LAr





Pilar Coloma, NuFACT 2012

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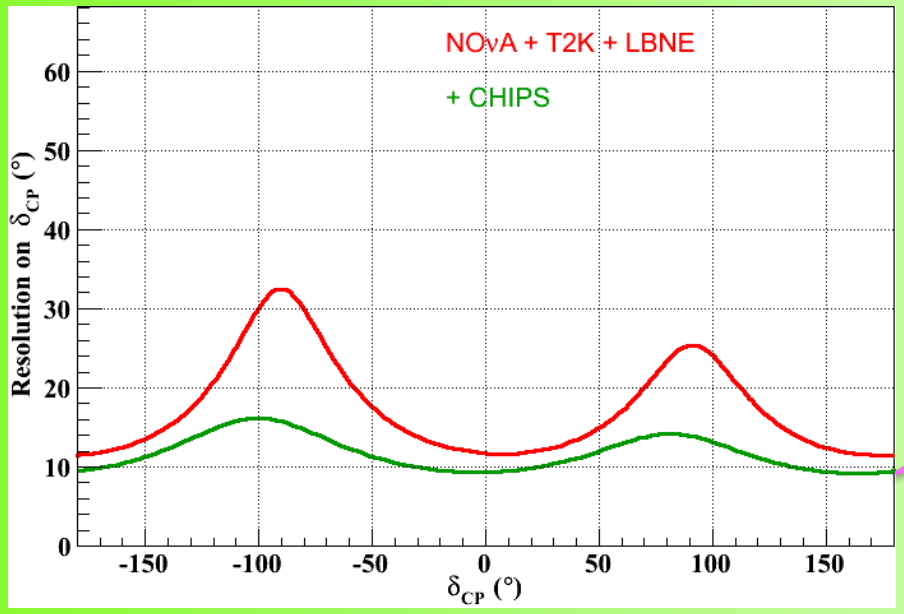
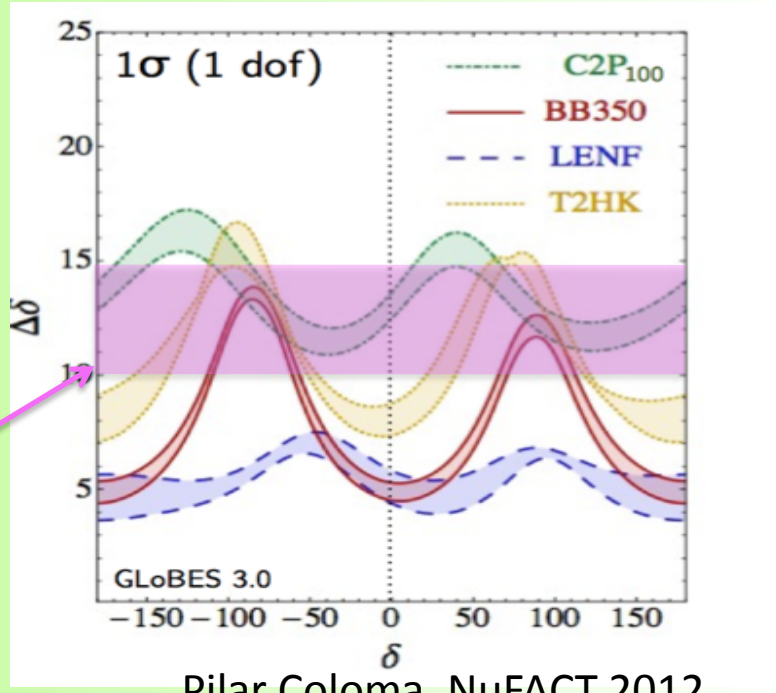
CHIPS@NuMI + CHIPS@LBNE+10kt LAr





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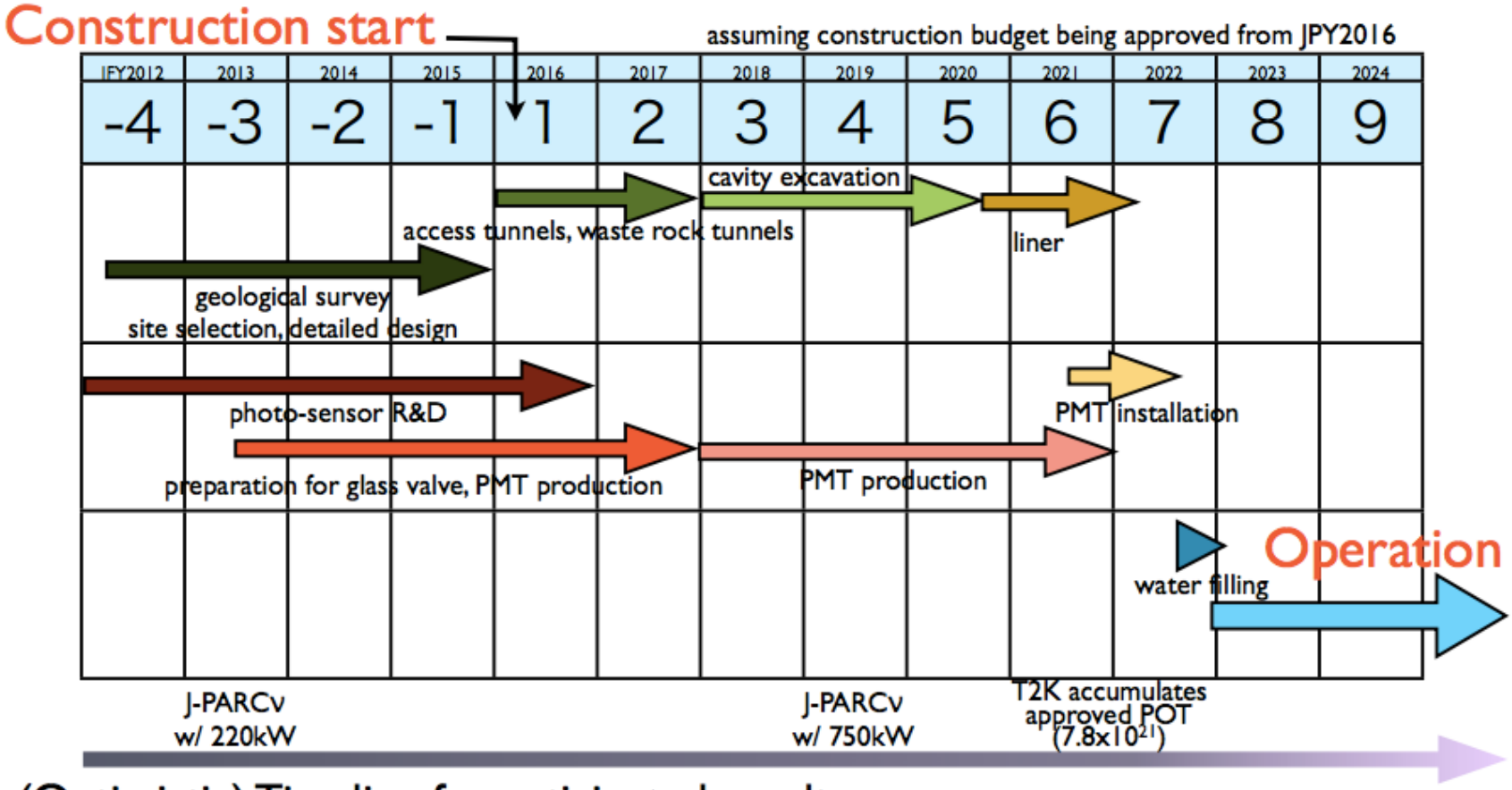
Hyper-K plans : my guess is that data taking does not start until 2024

BACK TO JAPAN

Notional Timeline



(Optimistic) Timeline for anticipated results

- -2022 ~2σ CPV indication (sinδ=1) by T2K+reactors (also in Nova)
- -2023 *Start Hyper-K data taking*
- -2026 Discovery of leptonic CPV w/ >5σ (MH at the same time or earlier)
- -2028 Discovery of proton decays
- -20XX Always ready for Supernova neutrino burst

Cost Estimate

Total	800M USD*	
Cavern	300M USD	
Tank & structure	200M USD	
Photo-sensors	200M USD	High QE HPD
Near Detector	30M USD	@Tokai

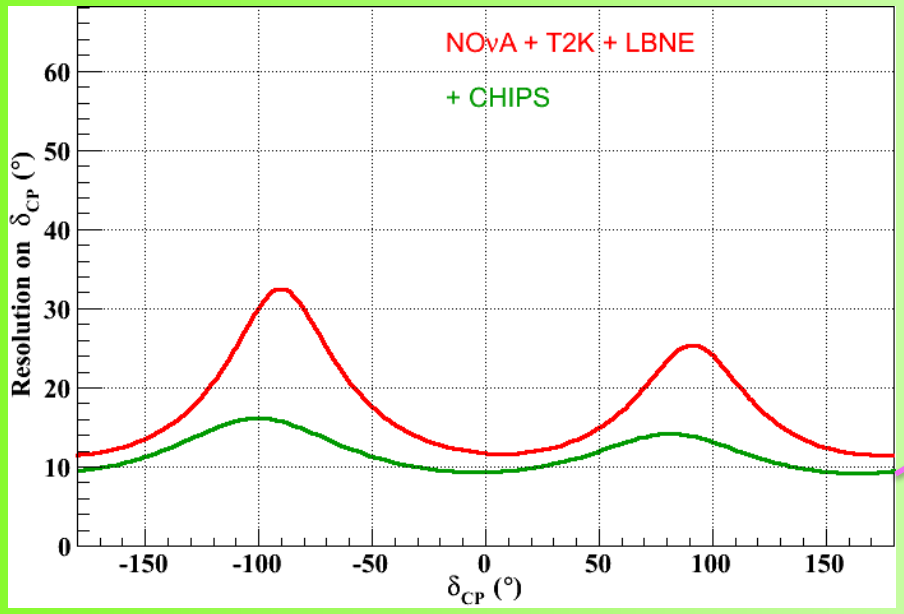
*The cost of rock disposal and water purification system to be added in the future

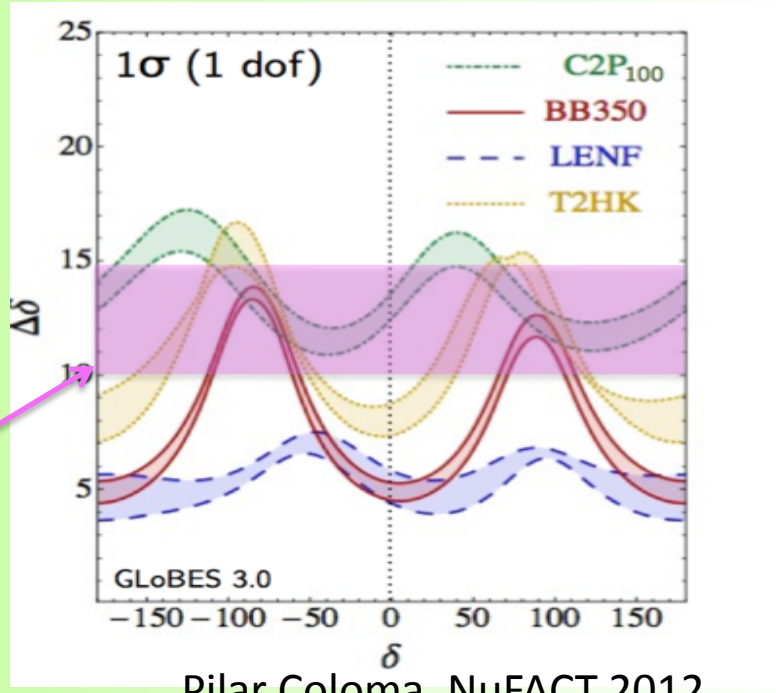
- Contribution from each country is under discussion in the Hyper-K WG
- Proportional sharing in an international project is ideal.
- The target for international contribution is 30% to 50% of the cost.

The last word

FNAL ONE LAST TIME

CHIPS@NuMI + CHIPS@LBNE+10kt LAr





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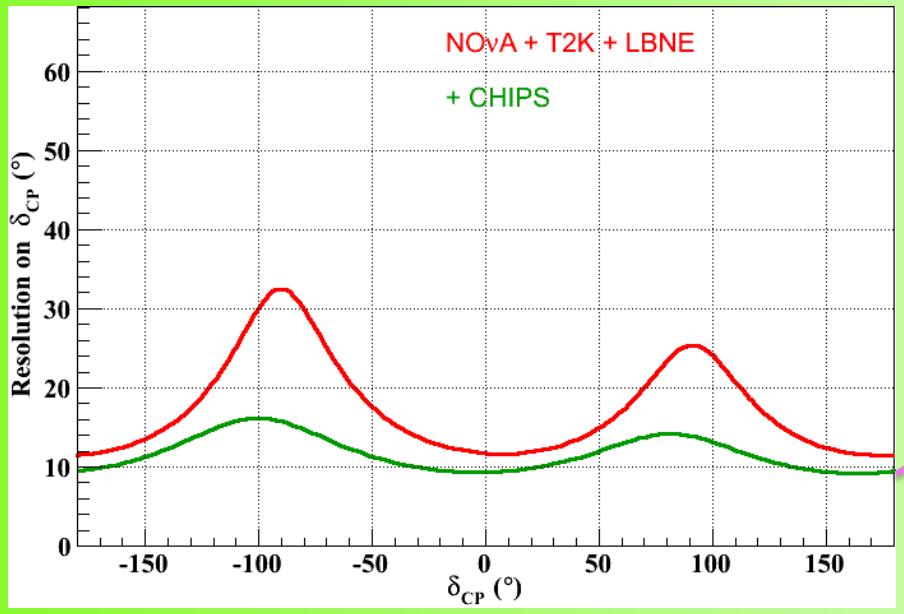
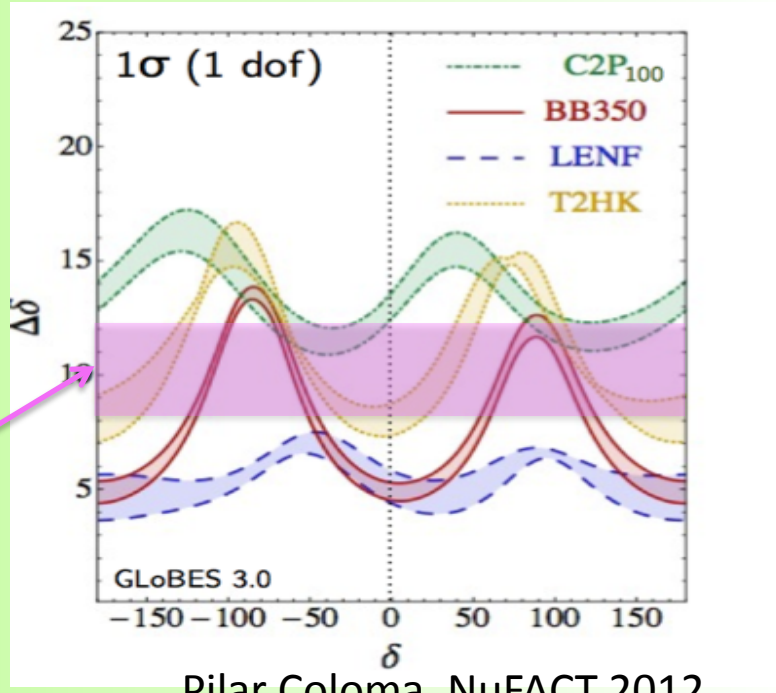
CHIPS@NuMI + CHIPS@LBNE + 35kt LAr





Pilar Coloma, NuFACT 2012

- CHIPS can make very big inroads into δ_{CP}
  - FNAL can be in everyway as good as HK on δ_{CP}
- LBNE could build SUBSTANTIALLY **on** CHIPS@NuMI and together **with** CHIPS@LBNE
- **35kt LAr+100kt CHIPS now on the same page as the NF!**
- **What if it were 200kt…or 500kt**

Thank you for listening

BACK TO EARTH. DINNER.