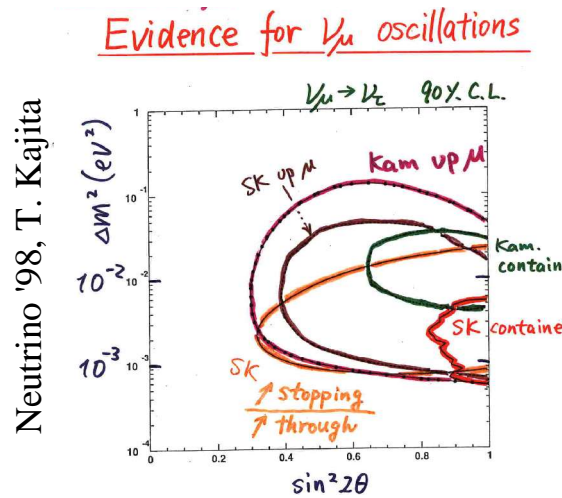


B.T.Fleming  
P5 Meeting, FNAL  
January 31, 2008

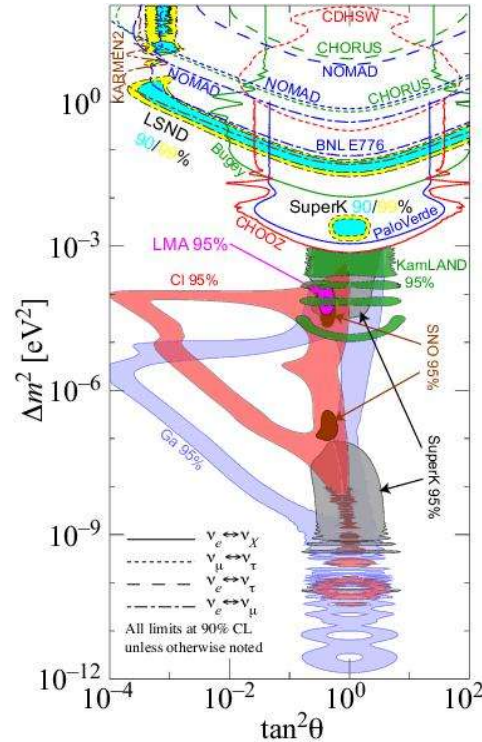


Experimental Strategy:  
Neutrino Oscillations

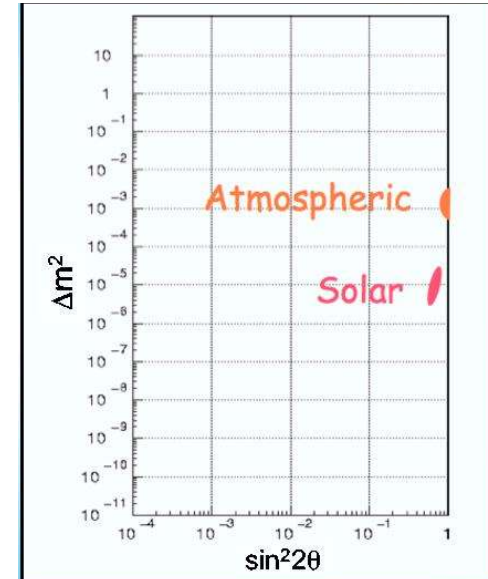
# The last decade revolutionized neutrino physics



1998



2004



2008

The Standard Model is incomplete.... Neutrinos mix and have mass!

The next decade: Move beyond measuring neutrino properties

↓  
 Use neutrinos to tell us about the universe...

*CP Violation in the neutrino sector:  
 Are neutrinos the reason we exist?*

The US is home to the two highest intensity neutrino beams in the world, the Booster Neutrino Beam and the NuMI Beam

- Running: MINOS, MiniBooNE, SciBooNE
- Under construction: MINERvA
- CD-2 stage: NOvA -- expected to start its construction in FY08, but being delayed due to the FY08 budget crisis.

We have an opportunity in the US to build on these investments:

Visionary, world class program with incredible discovery potential

Staged in

—► physics reach, beams, detectors  
practical way to build the program

How do we get there?

Staged approach in measuring  $\sin^2 2\theta_{13}$ , mass hierarchy, CP Violation

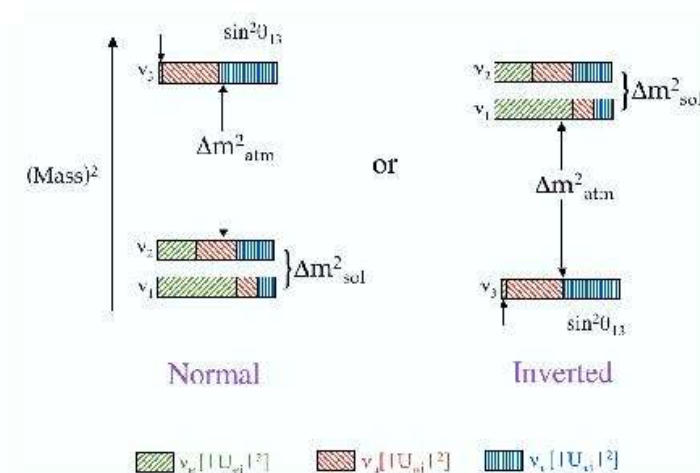
Three Neutrino Mixing Matrix:

$$U = \begin{pmatrix} c_{12}c_{13} & s_{12}c_{13} & s_{13}e^{-i\delta} \\ -s_{12}c_{23} - c_{12}s_{23}s_{13}e^{i\delta} & c_{12}c_{23} - s_{12}s_{23}s_{13}e^{i\delta} & s_{23}c_{13} \\ s_{12}s_{23} - c_{12}c_{23}s_{13}e^{i\delta} & -c_{12}s_{23} - s_{12}c_{23}s_{13}e^{i\delta} & c_{23}c_{13} \end{pmatrix}$$

$$= \begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix} \begin{pmatrix} c_{13} & 0 & s_{13}e^{-i\delta} \\ 0 & 1 & 0 \\ -s_{13}e^{i\delta} & 0 & c_{13} \end{pmatrix} \begin{pmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix}$$

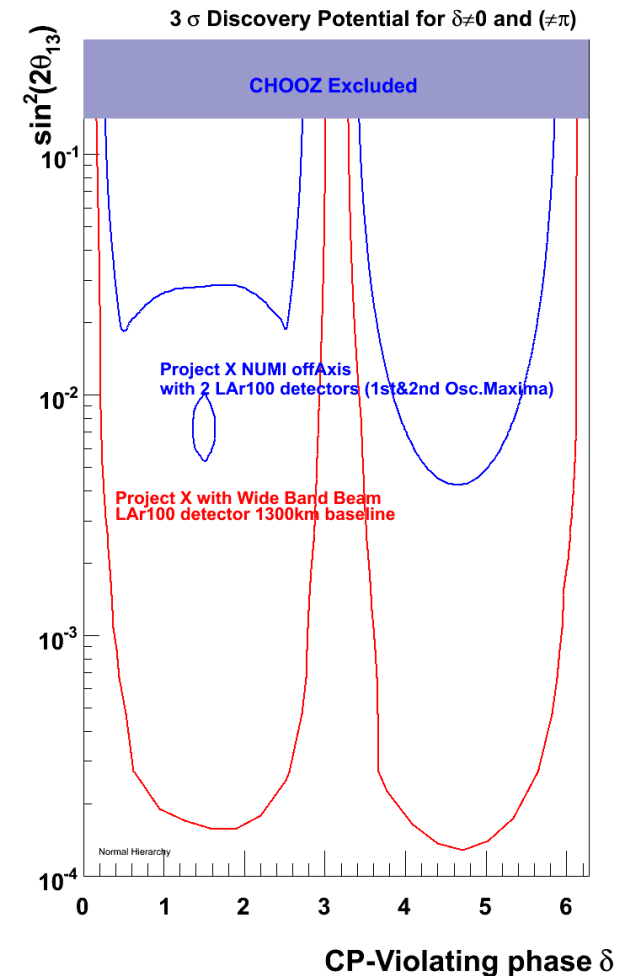
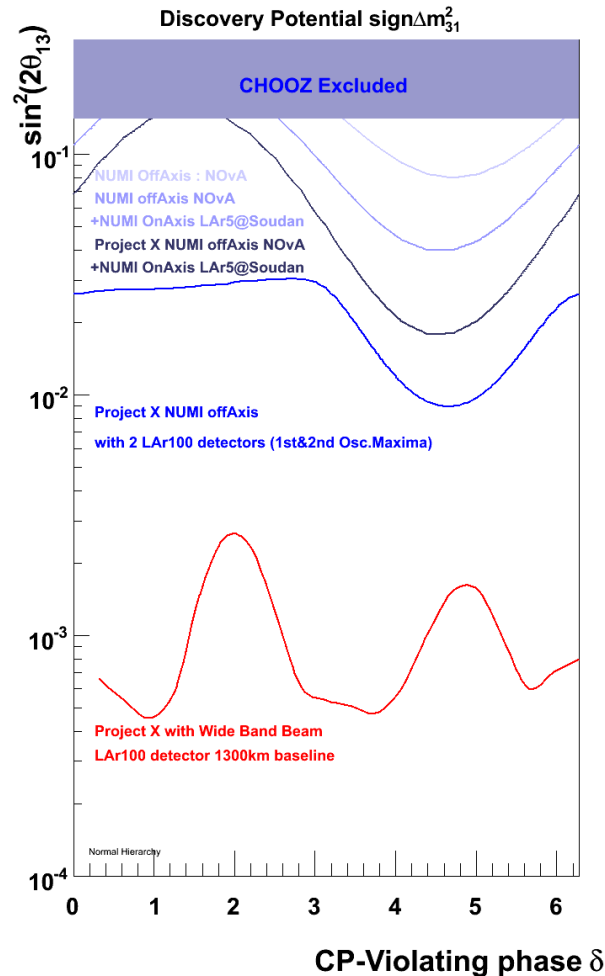
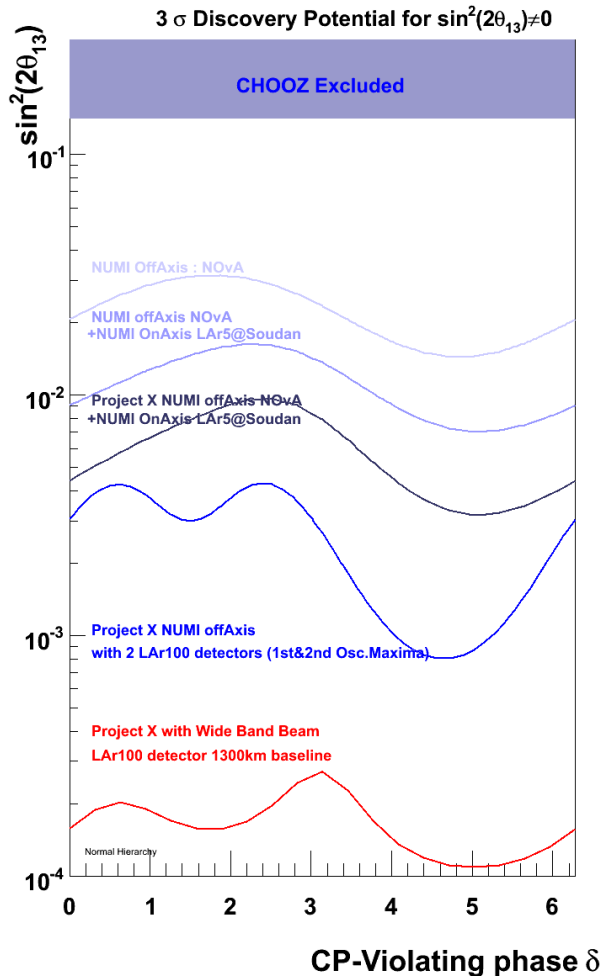
Atmospheric
Cross-Mixing
Solar

**CP Violation  
Parameter**



# How do we get there?

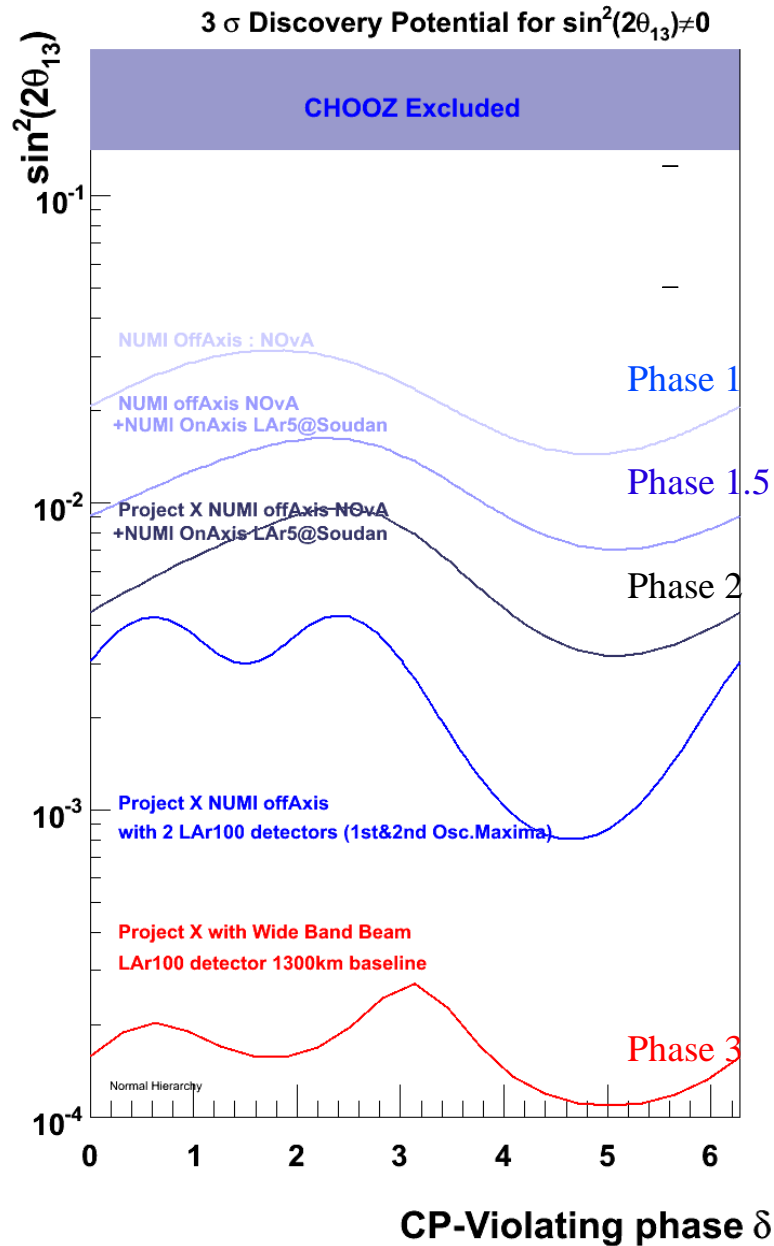
## Staged approach in measuring $\sin^2 2\theta_{13}$ , mass hierarchy, CP Violation



Discovery potential at each stage with ability to upgrade to extend reach

# How do we get there?

Staged approach in measuring  $\sin^2 2\theta_{13}$ , mass hierarchy, CP Violation



*LAr5 = 5kton  
LArTPC on-axis  
at Soudan  
more later.....*

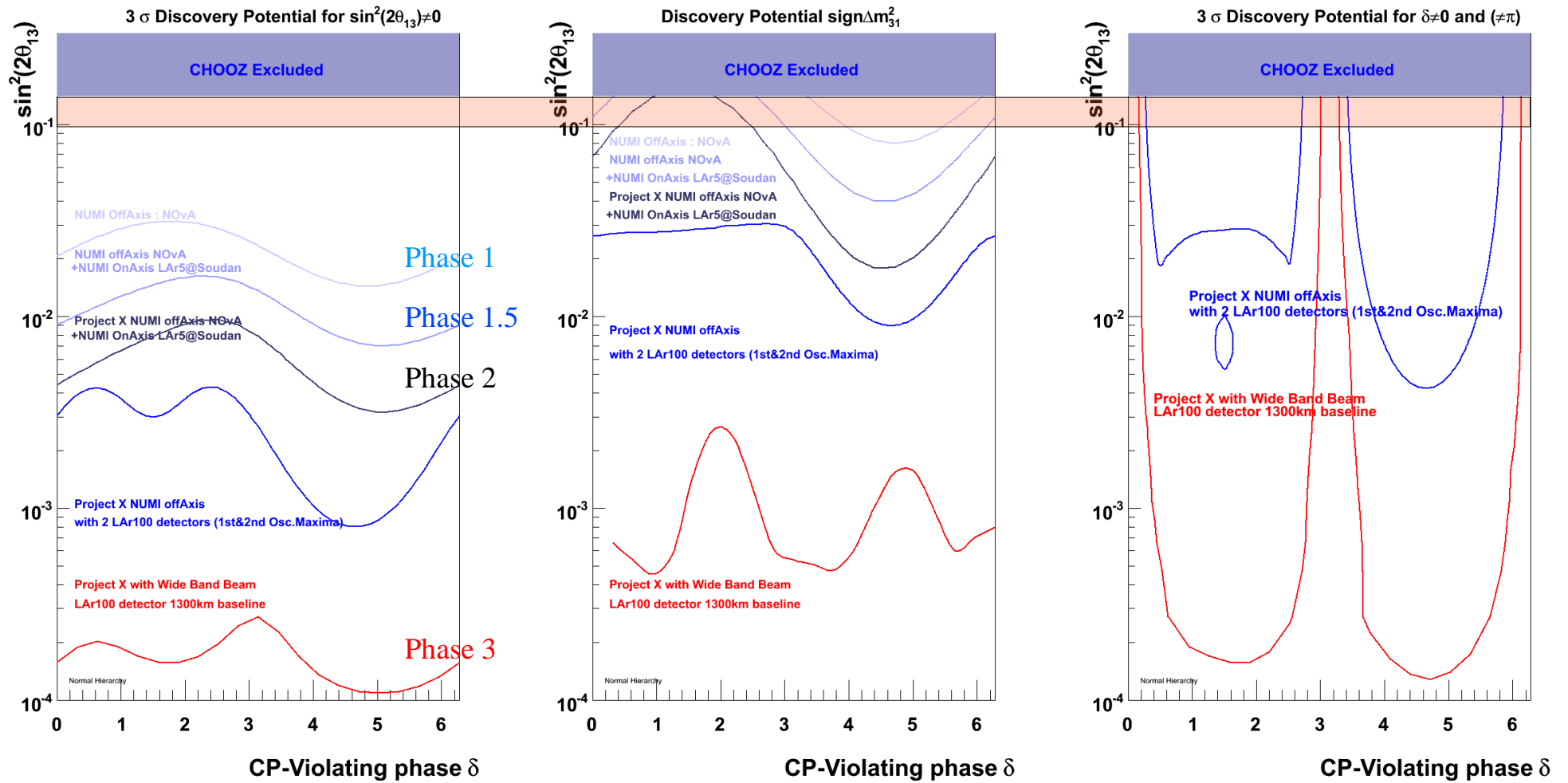
NuMI Off-axis: NOvA

NOvA + LAr5

Project X NOvA + LAr5

Project X NOvA + 2x LAr100  
(1<sup>st</sup> and 2<sup>nd</sup> oscillation max)

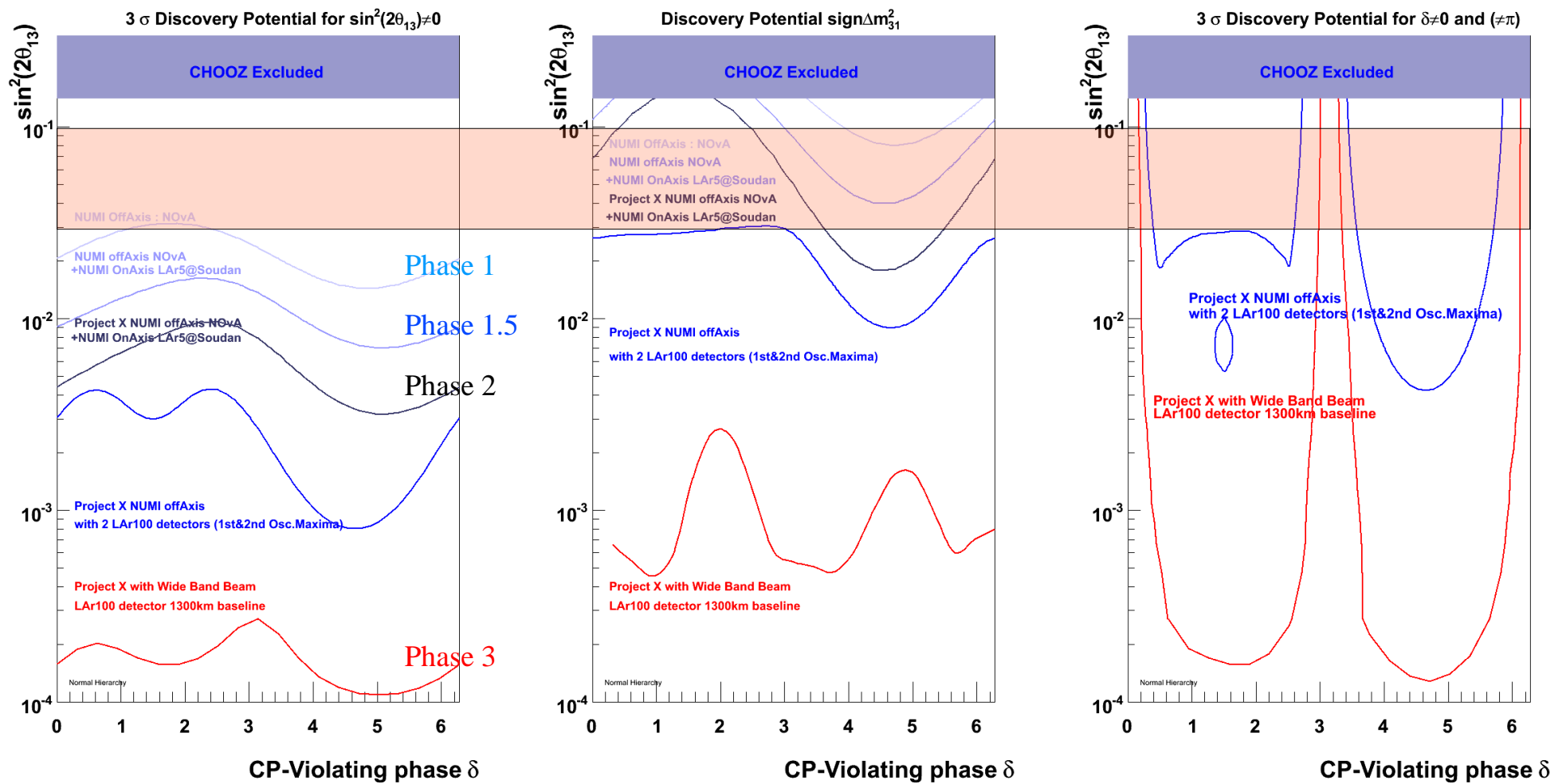
Project X with wide band  
beam to DUSEL



Large  $\sin^2 2\theta_{13}$  (from NuSAG:  $> 0.1$ )

- Will observe  $\theta_{13}$  by 2012 with MINOS, D CHOOZ, T2K

*Need NovA for any mass hierarchy reach*  
*Need high intensity proton source*  
*to see CP violation*

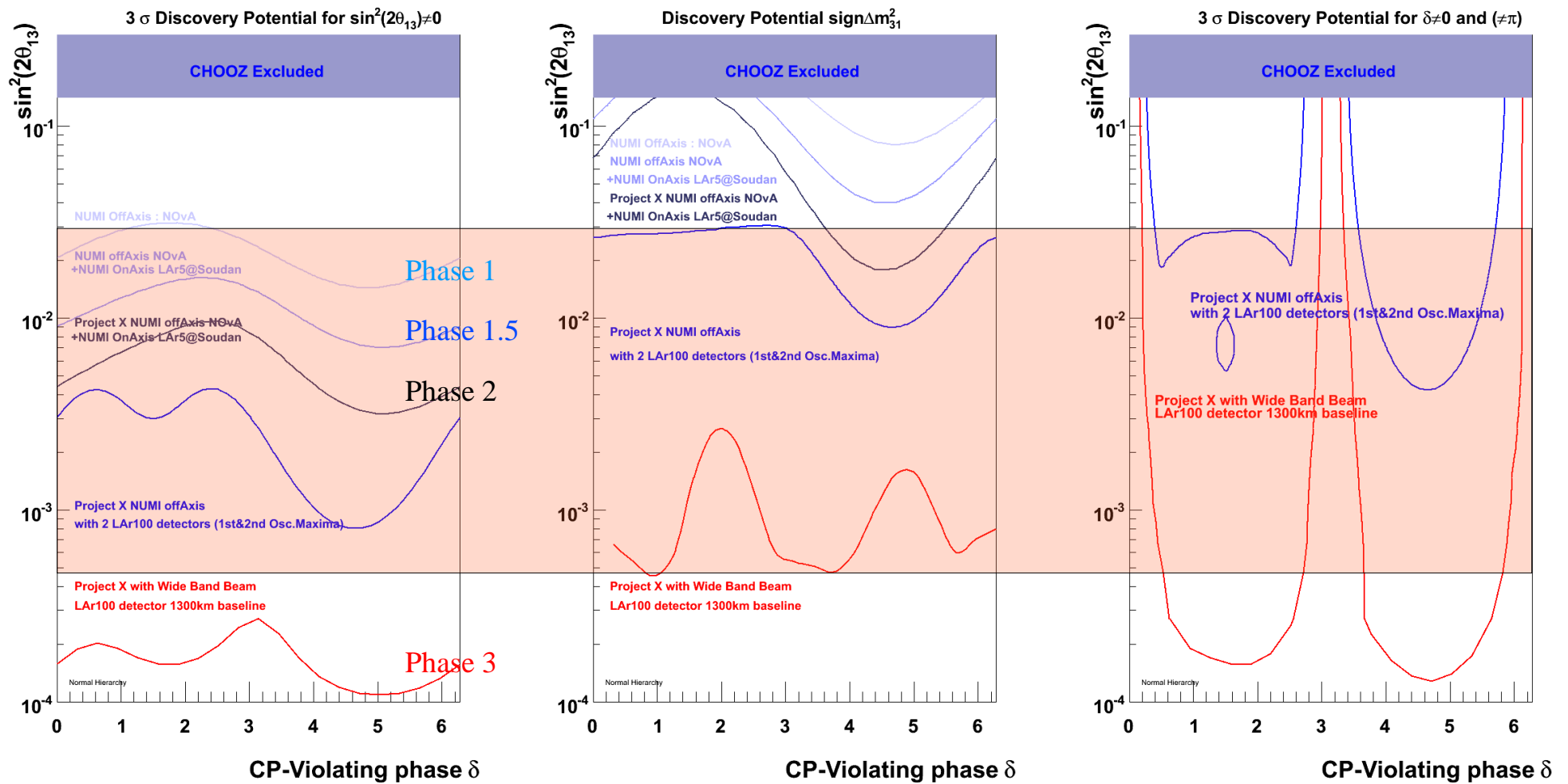


Medium  $\sin^2 2\theta_{13}$  (from NuSAG:  $0.03 < \sin^2 2\theta_{13} < 0.1$ )

- Will observe  $\theta_{13}$  by 2015 with NOvA, T2K, D. CHOOZ, Daya Bay
- Possibility of mass hierarchy with NOvA, improvement with NOvA + LAr5
- To see CP violation and increased potential of mass hierarchy....

*Need high intensity proton source  
and wide band beam to DUSEL*

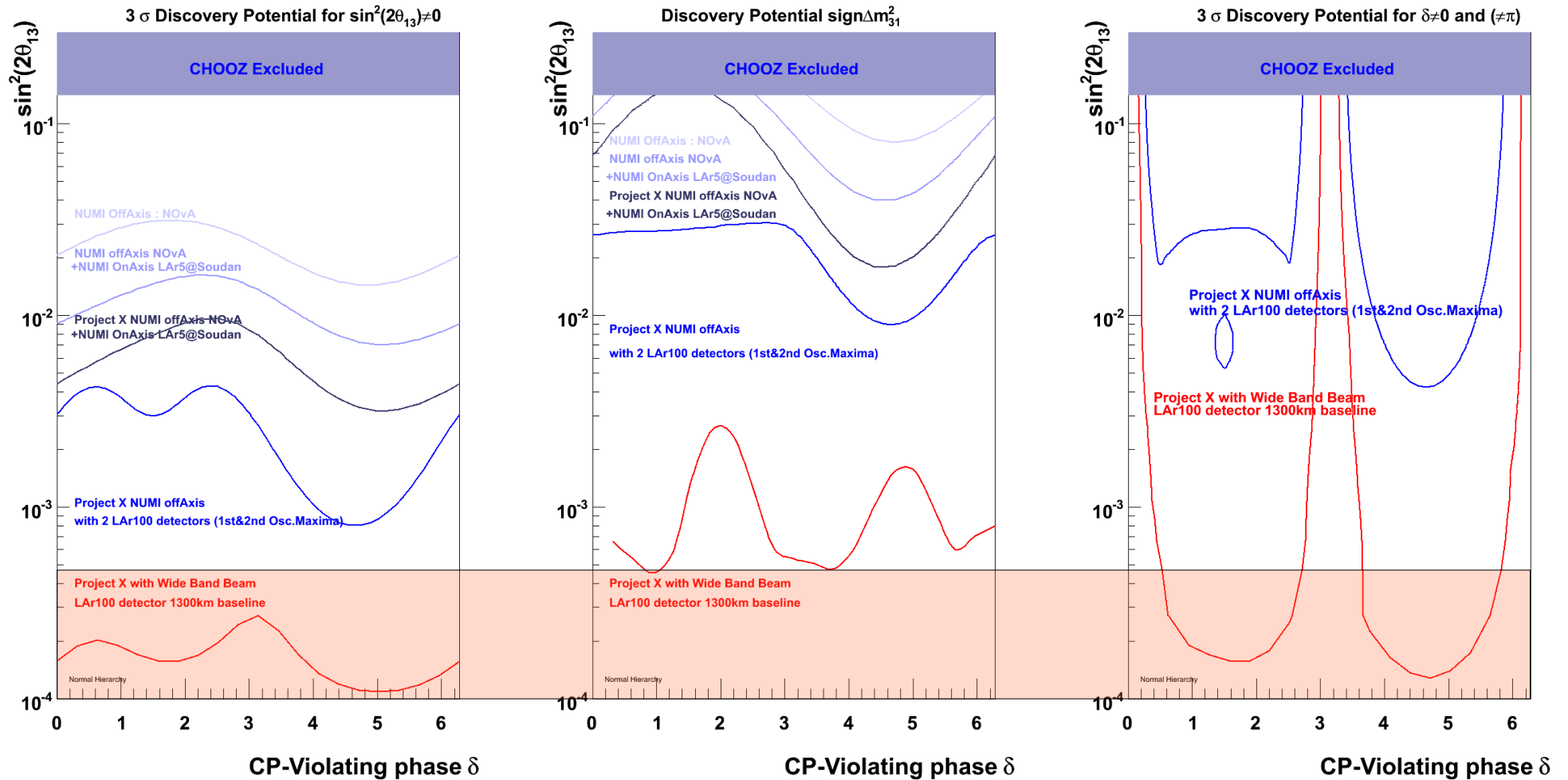




Small  $\sin^2 2\theta_{13}$  (from NuSAG:  $\sin^2 2\theta_{13} < 0.03$   
 with this work, down to  $\sin^2 2\theta_{13} < 0.0008$ )

- Sensitivity to some values of  $\theta_{13}$  and mass hierarchy with Phase 1&2
- To extend reach in these and see CP Violation

*Need high intensity proton source  
 and wide band beam to DUSEL*



Tiny  $\sin^2 2\theta_{13}$ :  $< 0.0008$

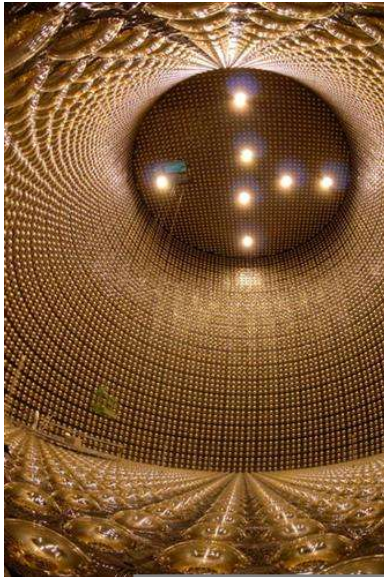
May see  $\theta_{13}$  and hint of CP with long baseline program.  
 For a definitive study of all the parameters...

*Need neutrino factory and perhaps beyond*

# Massive detectors for long baseline program

## Water Cerenkov

- known technology

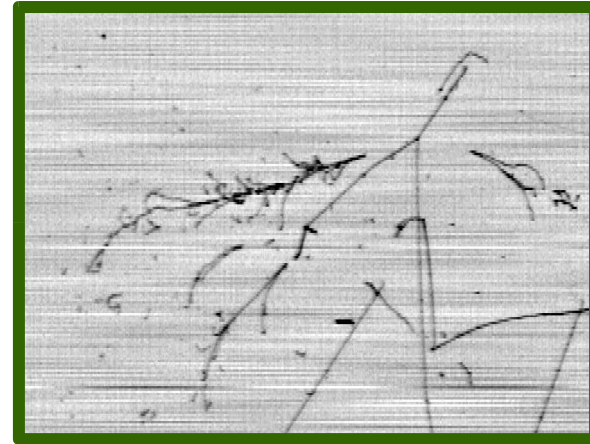


### R&D:

- PMT production delivery and cost
- Single or modular design
- Must be sited underground

## Liquid Argon TPCs

- Great promise in physics reach (3-4 times more sensitive than WC)



### R&D:

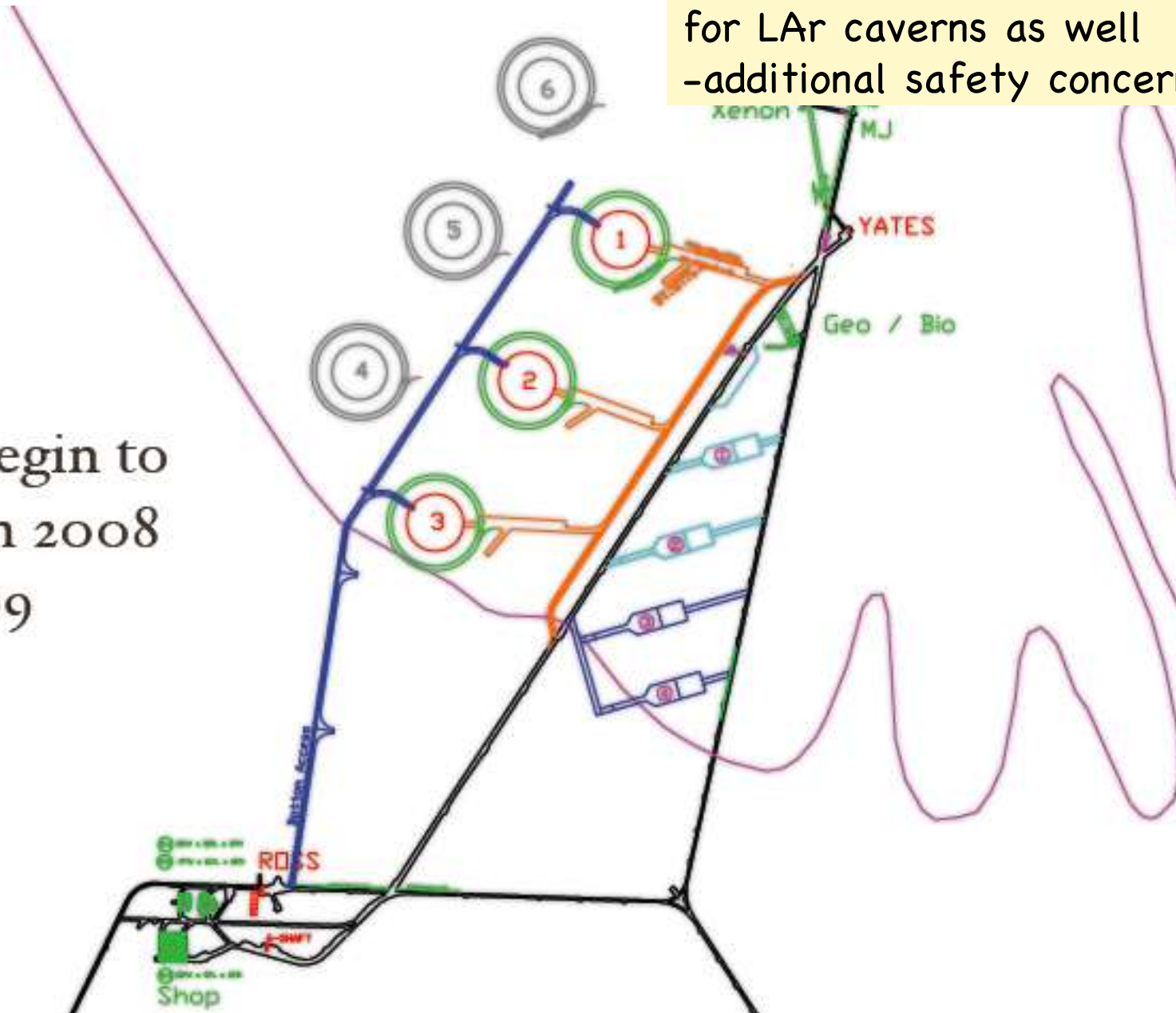
- Argon purity
- Low noise electronics
- Data analysis techniques
- Can be sited on surface but physics reach is compromised

### Options under consideration:

100 kt Lar, 300 kton WC, or some combination of the two technologies

# DUSEL

Possible sites for WC modular caverns at 4850 ft site. Options for LAr caverns as well  
-additional safety concerns for LAr



Can begin to  
core in 2008  
& 2009

# Evolution of a Liquid Argon Detector Program

Need a staged program for LarTPC detectors

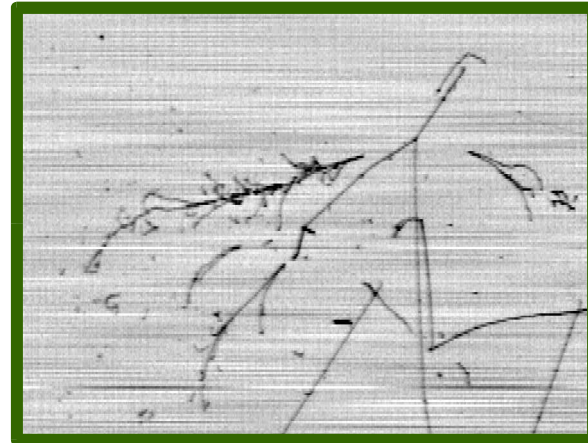
- address R&D questions at the relevant scale
- Move from R&D to physics goals
- Appropriate steps in size and cost

*Recommendation from NuSAG:*

*“A phased program with milestones and using technology suitable for a 50-100kton detector is recommended for the liquid argon detector option.”*

Liquid Argon TPCs

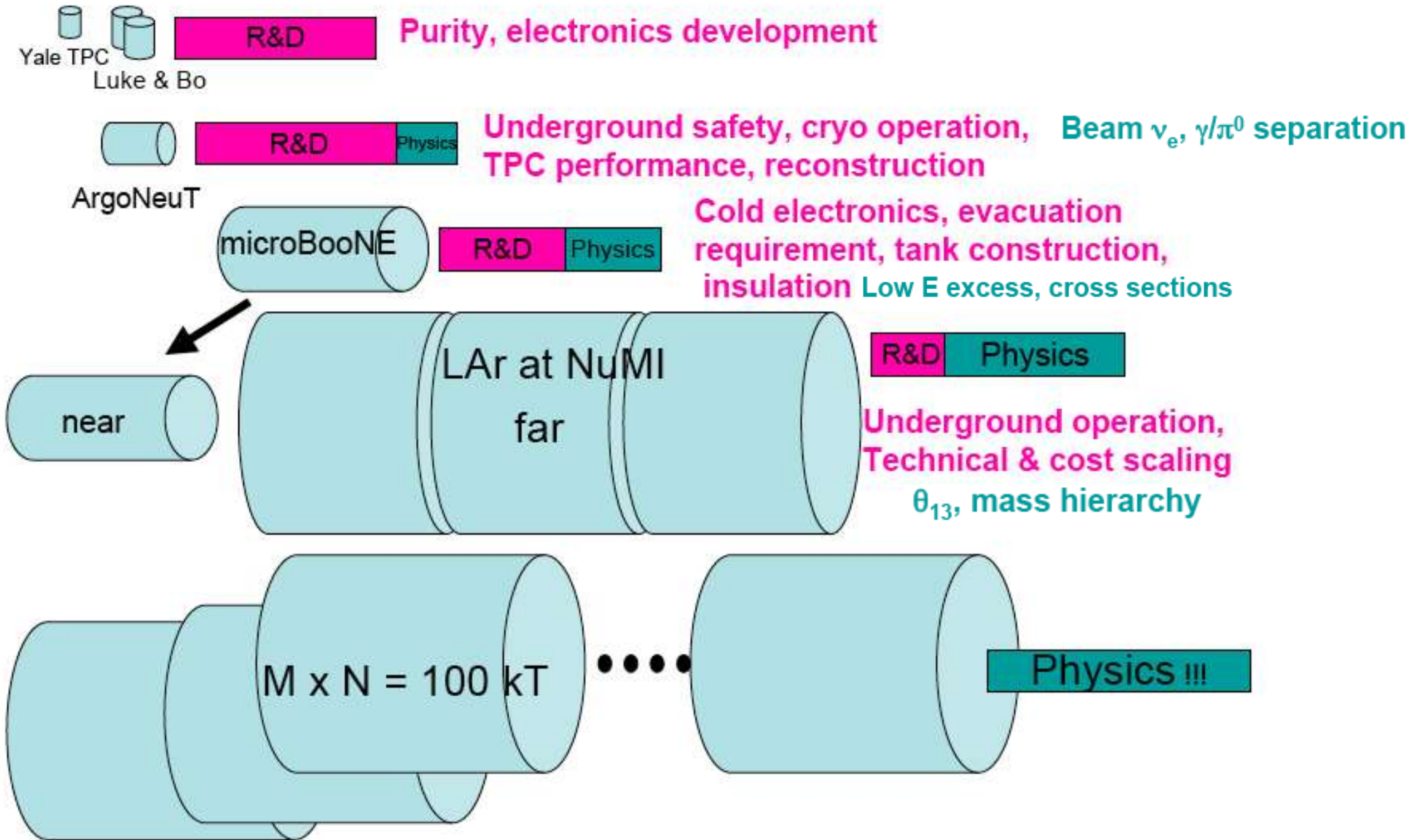
- Great promise in physics reach (3-4 times more sensitive than WC)



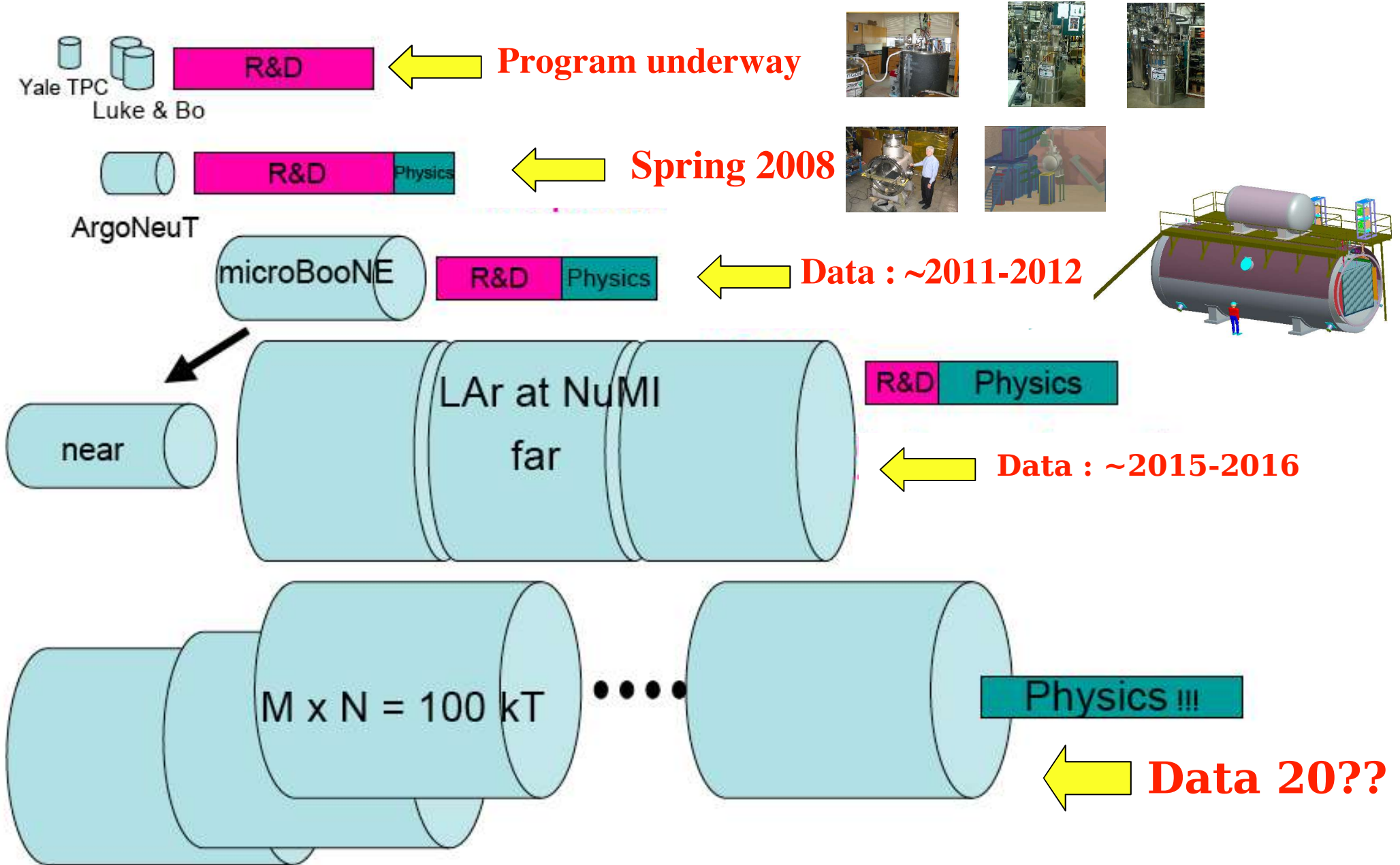
R&D:

- Argon purity
- Low noise electronics
- Data analysis techniques
- Can be sited on surface but physics reach is compromised

# Evolution of the Liquid Argon Physics Program



# Evolution of the Liquid Argon Physics Program



# Phase 1.5: Interim step: use NuMI beamline with on- and off-axis beams

## On-axis beams

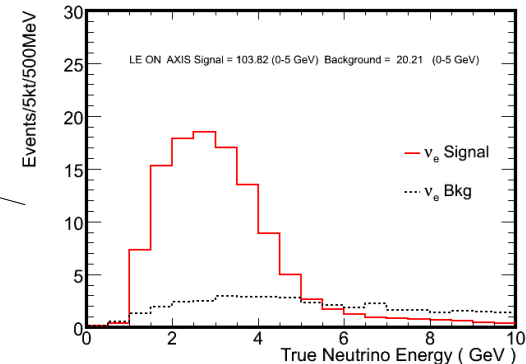
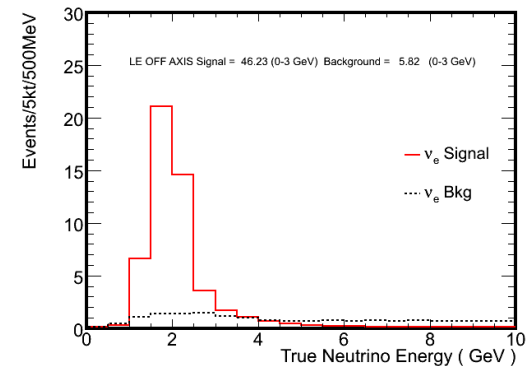
- Good event rates
  - high  $NC\pi^0$  backgrounds (mitigated by a LarTPC)
- LAr5 at Soudan



- Phase in program in:
- beamline configuration
  - discovery potential
  - detector mass

## Off-axis beams

- Maximize Signal/backgrounds
  - lower event rates
- NOvA experiment

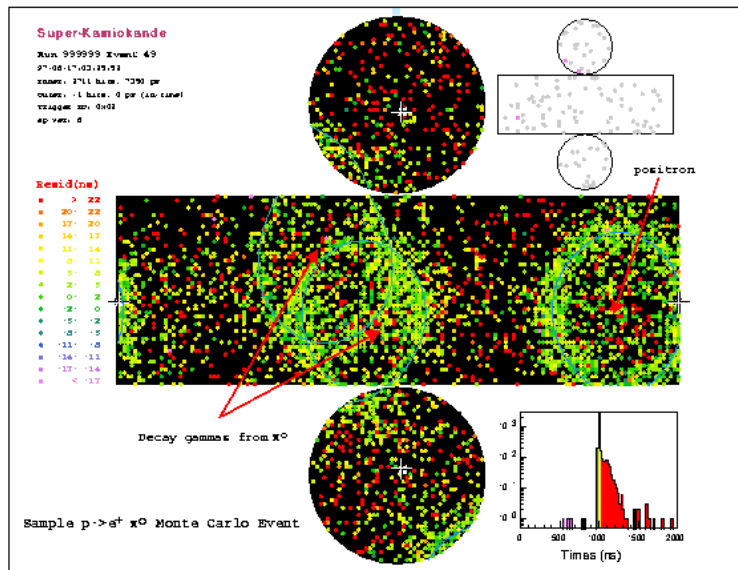




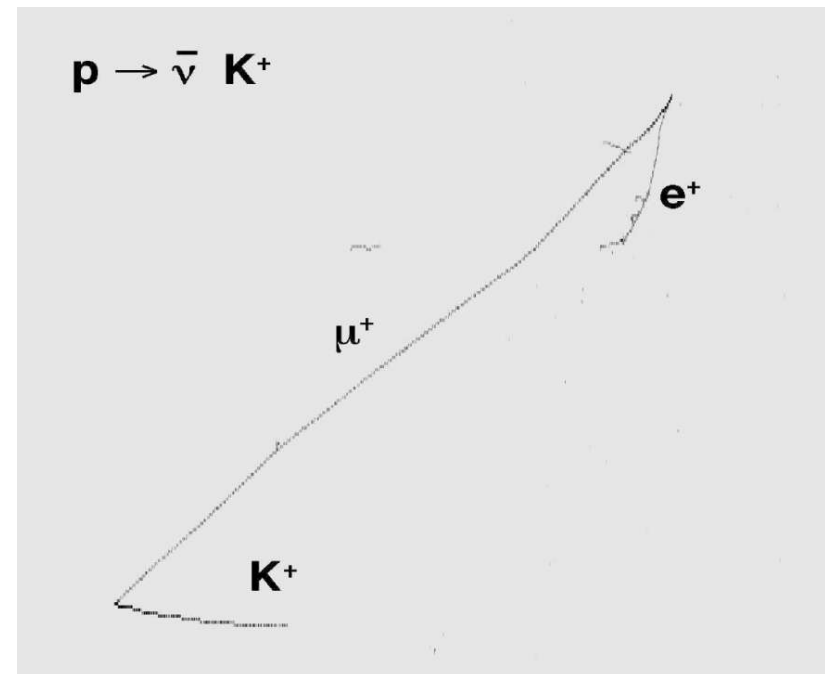
# Massive underground detectors are rich in physics reach beyond oscillations

Opportunities to

- Extend reach in proton decay sensitivity
  - Water Cerenkov detectors most sensitive to  $p \rightarrow e\pi^0$
  - Lar detectors most sensitive to  $p \rightarrow \nu k$



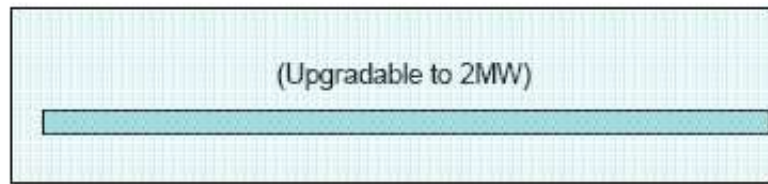
SuperK simulation of  $e\pi^0$



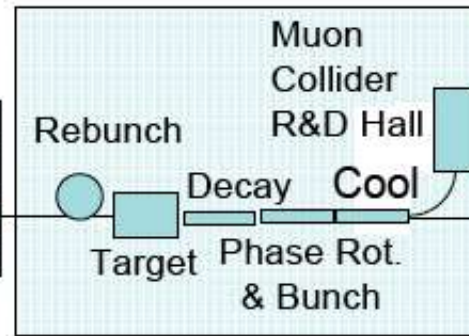
Candidate  $K^+$  event in LAr

- Supernova live
- Measure extraterrestrial neutrinos: solar, atmospheric, ...

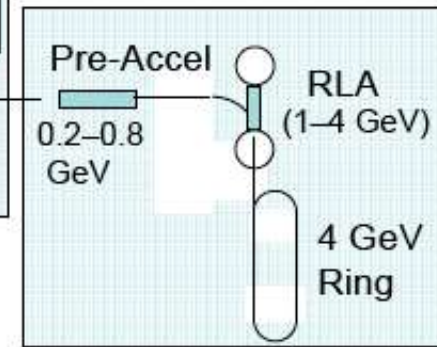
# Beyond Project X: Neutrino Factory



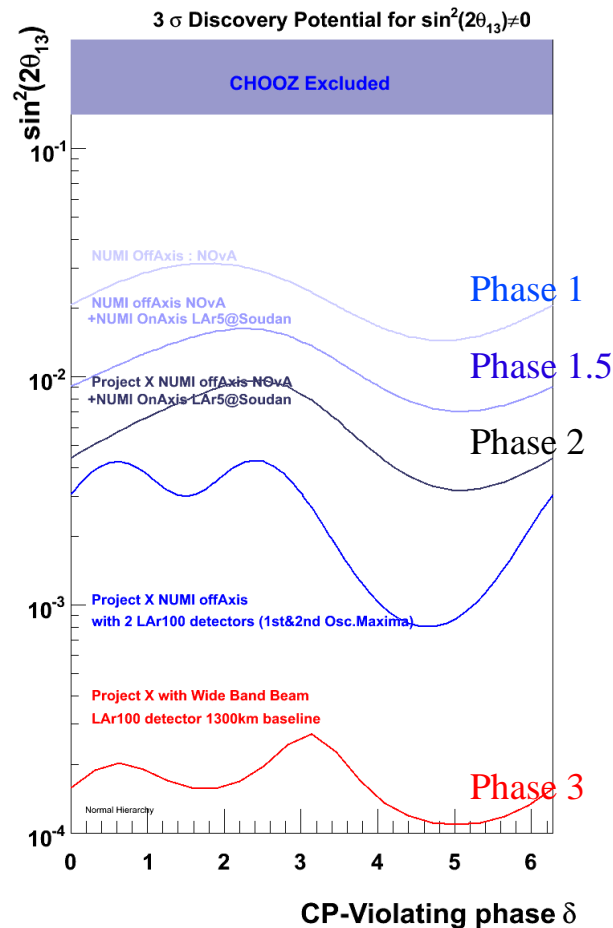
PROJECT X



MUON COLLIDER TEST FACILITY



NEUTRINO FACTORY PROJECT



If nature is very un-kind  
Tiny  $\sin^2 2\theta_{13}$

*Need a neutrino factory for definitive measurements*

Project X, upgradeable to 2MW at 8 GeV, is the front end for

- Neutrino factory
- Muon collider test facility

One of the most fundamental questions in particle physics today is understanding our matter dominated universe

The search for CP violation in the neutrino sector will provide a vital clue to this question

The US has an opportunity to develop a visionary, world-class, neutrino program to address this!

Discovery potential at every stage with path towards the future.