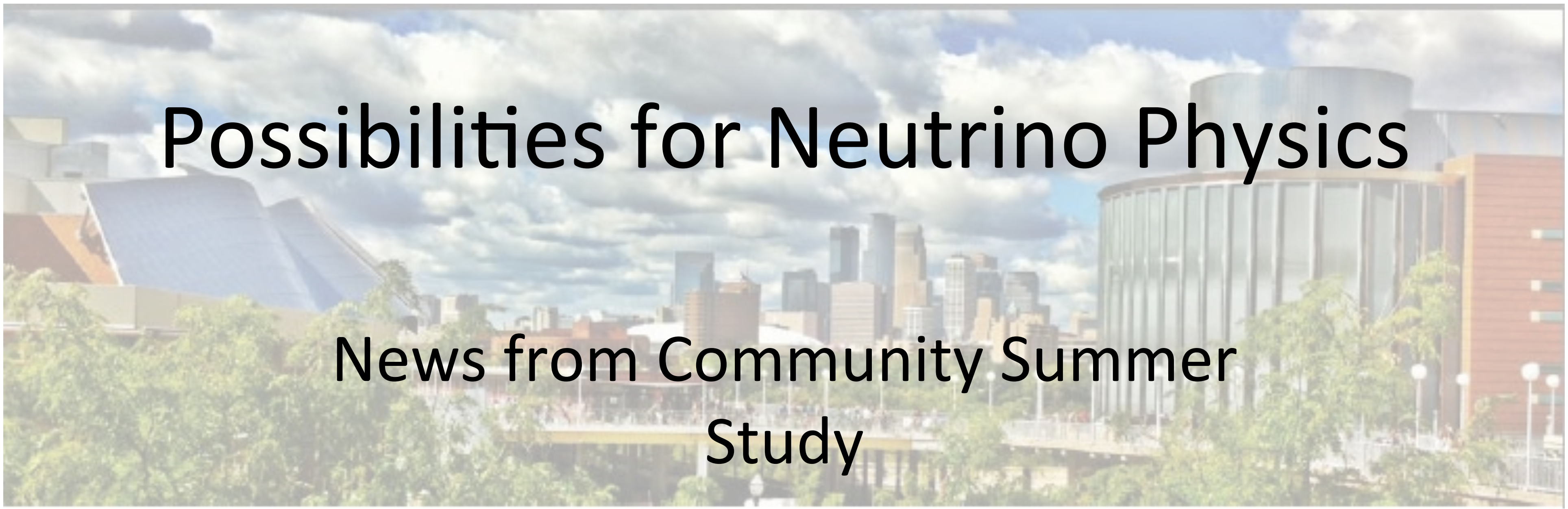
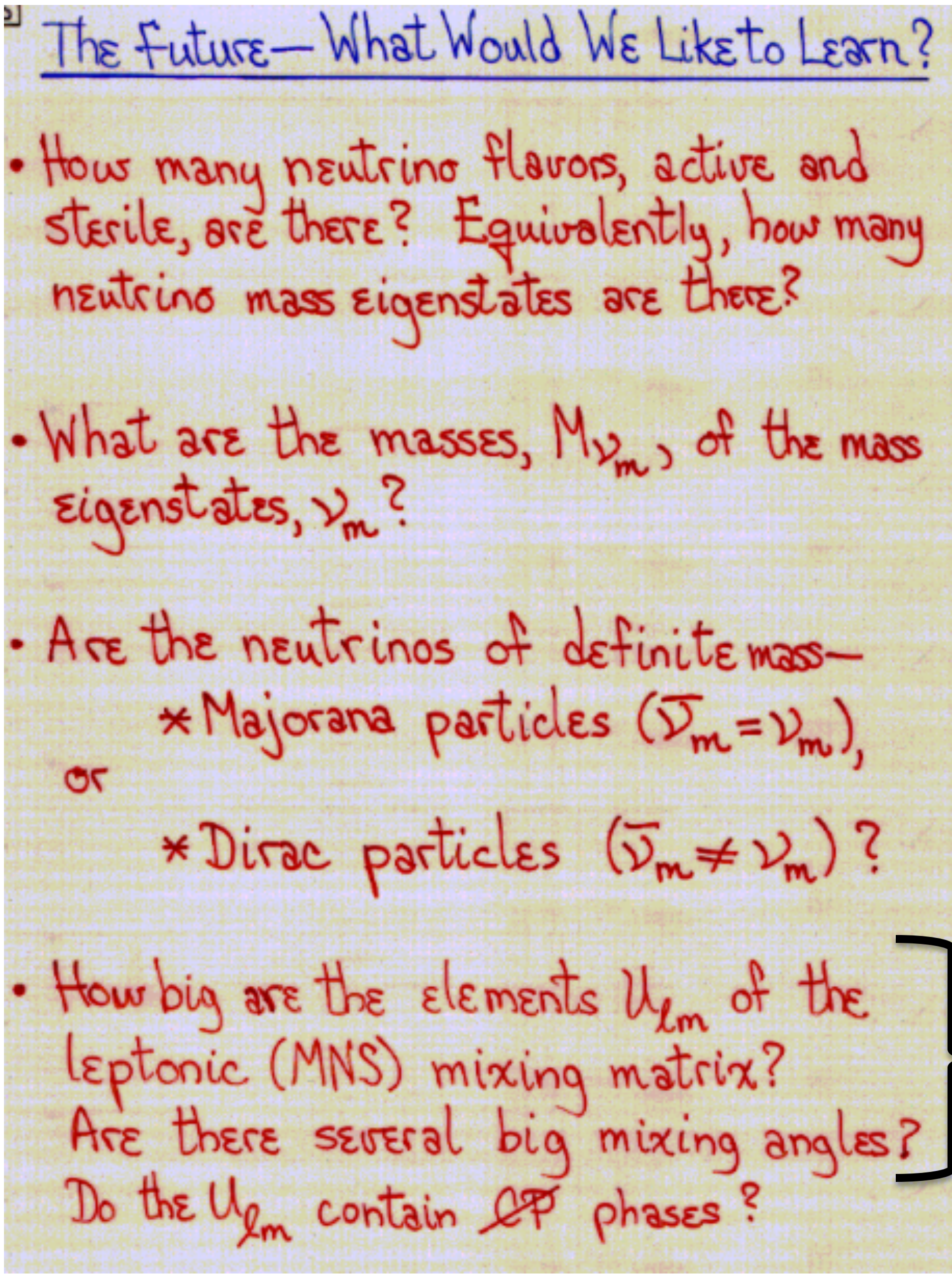
B. Fleming
August 13, 2013
DPF 2013

Possibilities for Neutrino Physics

News from Community Summer Study



Snowmass 2001



The Future — What Would We Like to Learn?

- How many neutrino flavors, active and sterile, are there? Equivalently, how many neutrino mass eigenstates are there?
- What are the masses, M_{ν_m}, of the mass eigenstates, ν_m?
- Are the neutrinos of definite mass —
  - $*$ Majorana particles ($\bar{\nu}_m = \nu_m$),

  or

  - $*$ Dirac particles ($\bar{\nu}_m \neq \nu_m$)?
- How big are the elements $U_{\ell m}$ of the leptonic (MNS) mixing matrix? Are there several big mixing angles? Do the $U_{\ell m}$ contain ~~CP~~ phases?

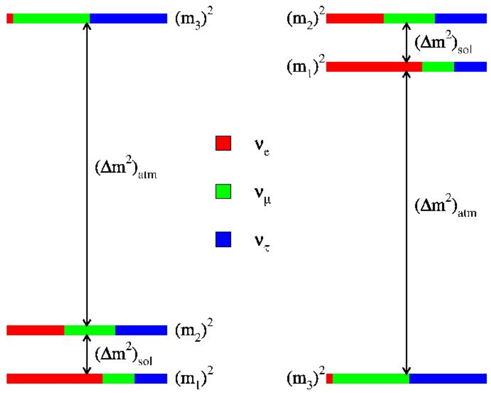
- neutrino summary from Snowmass 2001 (Boris Kayser)

- circa Snowmass 2013

parameter	best fit	1σ range	2σ range	3σ range
Δm^2_{21} [10^{-5}eV^2]	7.62	7.43–7.81	7.27–8.01	7.12–8.20
$\lvert\Delta m^2_{31}\rvert$ [10^{-3}eV^2]	2.55 2.43	$2.46-2.61$ $2.37-2.50$	$2.38-2.68$ $2.29-2.58$	$2.31-2.74$ $2.21-2.64$
$\sin^2\theta_{12}$	0.320	0.303–0.336	0.29–0.35	0.27–0.37
$\sin^2\theta_{23}$	0.613 (0.427)[a] 0.600	0.400-0.461 & 0.573–0.635 0.569–0.626	0.38–0.66 0.39–0.65	0.36–0.68 0.37–0.67
$\sin^2\theta_{13}$	0.0246 0.0250	0.0218–0.0275 0.0223–0.0276	0.019–0.030 0.020–0.030	0.017–0.033
δ	0.80π -0.03π	$0-2\pi$	$0-2\pi$	$0-2\pi$

(for example: arXiv:1205.4018)

The big questions…..



- *what is the absolute neutrino* ***mass scale***
- *are neutrinos* ***Majorana or Dirac****?*
- *what is the neutrino mass ordering?*
- *is* ***CP*** *violated in the neutrino sector?*
- *to what extent does the 3ν paradigm* ***describe nature****?*
- *are there already hints of* ***new physics*** *in existing data?*
- *what new knowledge will neutrinos from* ***astrophysical sources*** *bring?*

•we know this information for every other particle!

Neutrino smmary from Snowmass 2013
Hewitt/Weerts

Many talks at this DPF!

Neutrino Working Group

conveners: André de Gouvêa, Kevin Pitts, Kate Scholberg, Sam Zeller

subgroups and subgroup conveners:

(Nu1) **Neutrino Oscillations and the Three-Flavor Paradigm**
subgroup conveners: Mary Bishai (BNL), Karsten Heeger (Wisconsin), Patrick Huber (Virginia Tech)

(Nu2) **The Nature of the Neutrino: Majorana vs. Dirac**
subgroup conveners: Steve Elliott (LANL), Lisa Kaufman (Indiana)

(Nu3) **Absolute Neutrino Mass Scale**
subgroup conveners: Hamish Robertson (Washington), Ben Monreal (UCSB)

(Nu4) **Neutrino Interactions**
subgroup conveners: Jorge Morfin (FNAL), Rex Tayloe (Indiana)

(Nu5) **Anomalies and New Physics**
subgroup conveners: Boris Kayser (FNAL), Jon Link (Virginia Tech)

(Nu6) **Astrophysical and Cosmological Neutrinos**
subgroup conveners: Kara Hoffman (Maryland), Cecilia Lunardini (Arizona State), Nikolai Tolich (Washington)

(Nu7) **Neutrinos and Society**
subgroup conveners: Adam Bernstein (LLNL), Jose Alonso (LBNL)

Input From the Community

- the response from the ν community has been overwhelming

- three very successful neutrino working group meetings:
  - *Oct 24, 2011 at Fermilab, 120 participants*
  - *Nov 30-Dec 2, 2011, Rockville, 145 ν WG participants*
  - *March 6-7, 2013, SLAC, 97 participants*

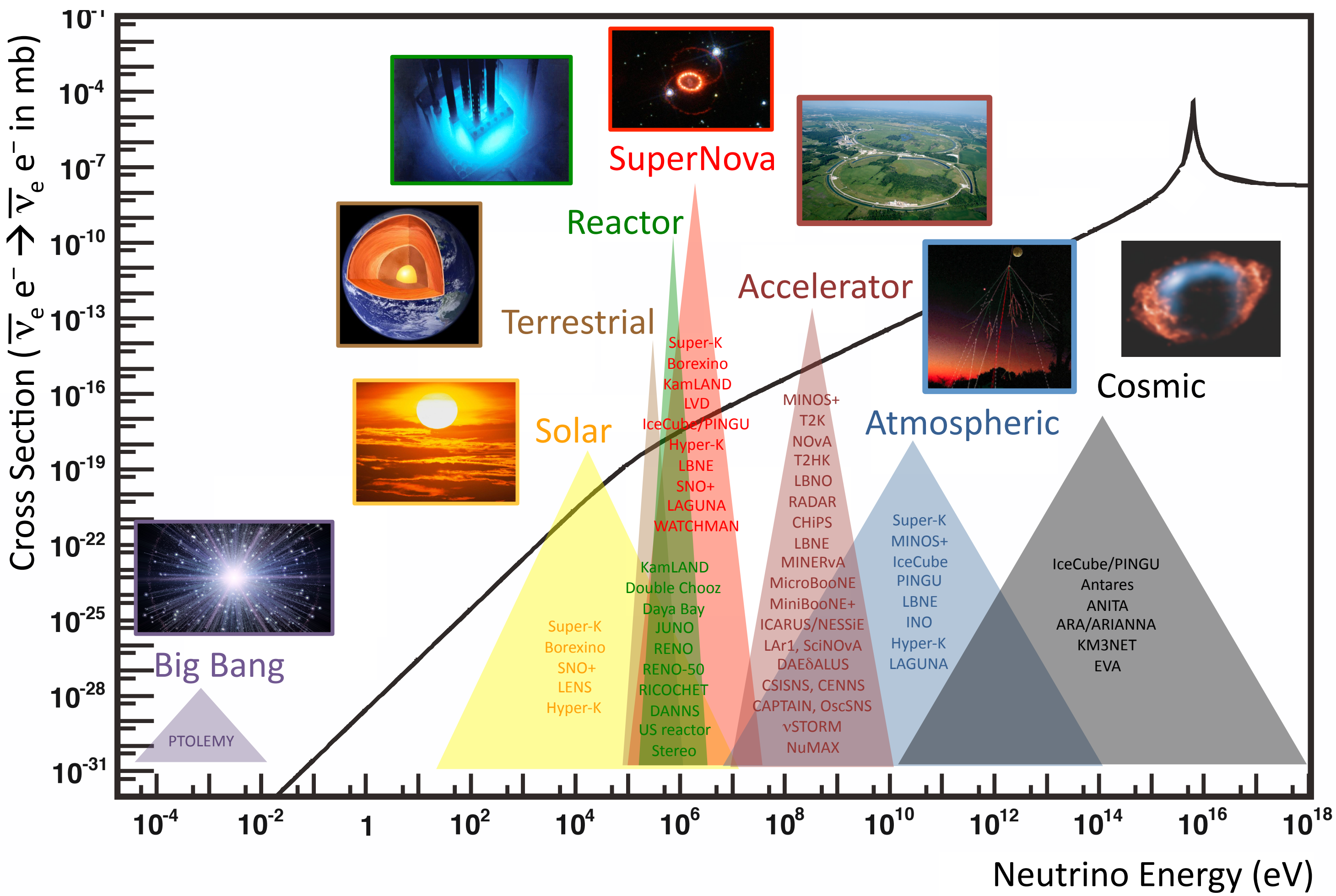
- 85 whitepapers received

- draft of neutrino report is available on the Snowmass wiki (http://if-neutrino.fnal.gov/snowmass/neutrinos-v2.0.pdf)

a lot of input!

Neutrino Sources

• many sources ➔ many experimental opportunities



Too much to cover in one talk – my apologies for omissions!

Breadth in program

- Breadth:
  - Physics of neutrinos addressing some of the most compelling questions in particle physics
    - About neutrinos
    - About the Standard Model and the Universe
    - Across traditional subfields
  - Many different ways to address questions: source, size, technology
  - Questions span understanding observed phenomena to looking for the unexpected

- Big experiments, small experiments, different technologies, near term, longer term…
  - Lots of opportunities to train young scientistists

The big questions…..

- what is the absolute neutrino ***mass scale***
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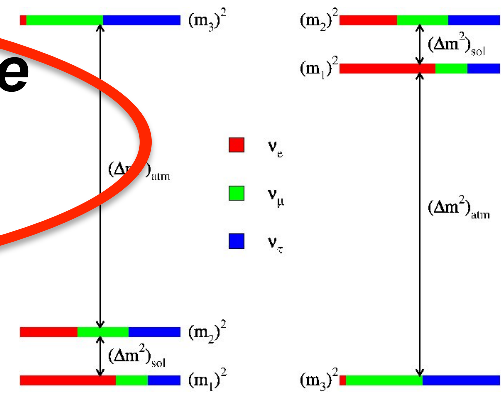
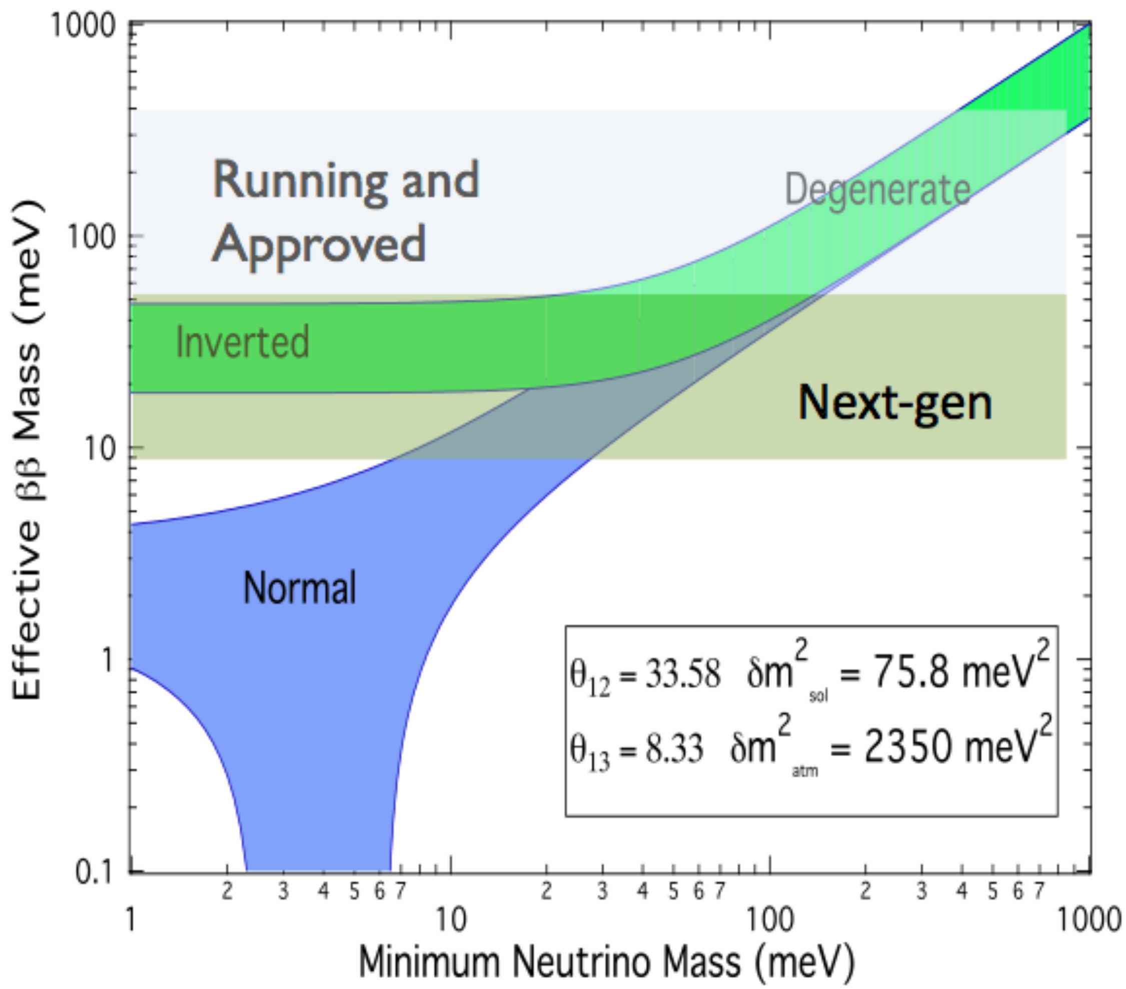


•we know this information for every other particle!

The Nature of the Neutrino
Goals for Next Generation $0\nu\beta\beta$



(Lisa Kaufman)

- next generation $0\nu\beta\beta$ experiments must cover the entire allowed region of the inverted hierarchy
- also allows us to pick a technology for the future
- ideas for probing the normal hierarchy exist

$0\nu\beta\beta$ Experiments and Proposals

Experiment	Isotope	Mass	Technique	Status	Location
AMoRE[125, 126]	^{100}Mo	50 kg	$CaMoO_4$ scint. bolometer crystals	Devel.	Yangyang
CANDLES[127]	^{48}Ca	0.35 kg	CaF_2 scint. crystals	Prototype	Kamioka
CARVEL[128]	^{48}Ca	1 ton	CaF_2 scint. crystals	Devel.	Solotvina
COBRA[129]	^{116}Cd	183 kg	^{enr}Cd CZT semicond. det.	Prototype	Gran Sasso
CUORE-0[114]	^{130}Te	11 kg	TeO_2 bolometers	Constr. (2013)	Gran Sasso
CUORE[114]	^{130}Te	203 kg	TeO_2 bolometers	Constr. (2014)	Gran Sasso
DCBA[130]	^{150}Ne	20 kg	^{enr}Nd foils and tracking	Devel.	Kamioka
EXO-200[115, 116]	^{136}Xe	200 kg	Liq. ^{enr}Xe TPC/scint.	Op. (2011)	WIPP
nEXO[117]	^{136}Xe	5 t	Liq. ^{enr}Xe TPC/scint.	Proposal	SNOLAB
GERDA[131]	^{76}Ge	≈35 kg	^{enr}Ge semicond. det.	Op. (2011)	Gran Sasso
GSO[132]	^{160}Gd	2 t	Gd_2SiO_5:Ce crys. scint. in liq. scint.	Devel.	
KamLAND-Zen[118, 120]	^{136}Xe	400 kg	^{enr}Xe dissolved in liq. scint.	Op. (2011)	Kamioka
LUCIFER[133, 134]	^{82}Se	18 kg	ZnSe scint. bolometer crystals	Devel.	Gran Sasso
MAJORANA [111, 112, 113]	^{76}Ge	30 kg	^{enr}Ge semicond. det.	Constr. (2013)	SURF
MOON [135]	^{100}Mo	1 t	^{enr}Mo foils/scint.	Devel.	
SuperNEMO-Dem[123]	^{82}Se	7 kg	^{enr}Se foils/tracking	Constr. (2014)	Fréjus
SuperNEMO[123]	^{82}Se	100 kg	^{enr}Se foils/tracking	Proposal (2019)	Fréjus
NEXT [121, 122]	^{136}Xe	100 kg	gas TPC	Devel. (2014)	Canfranc
SNO+[136, 137, 35]	^{130}Te	800 kg	Te-loaded liq. scint.	Constr. (2013)	SNOLAB

Table 1-4. *A summary list of neutrinoless double-beta decay proposals and experiments.*

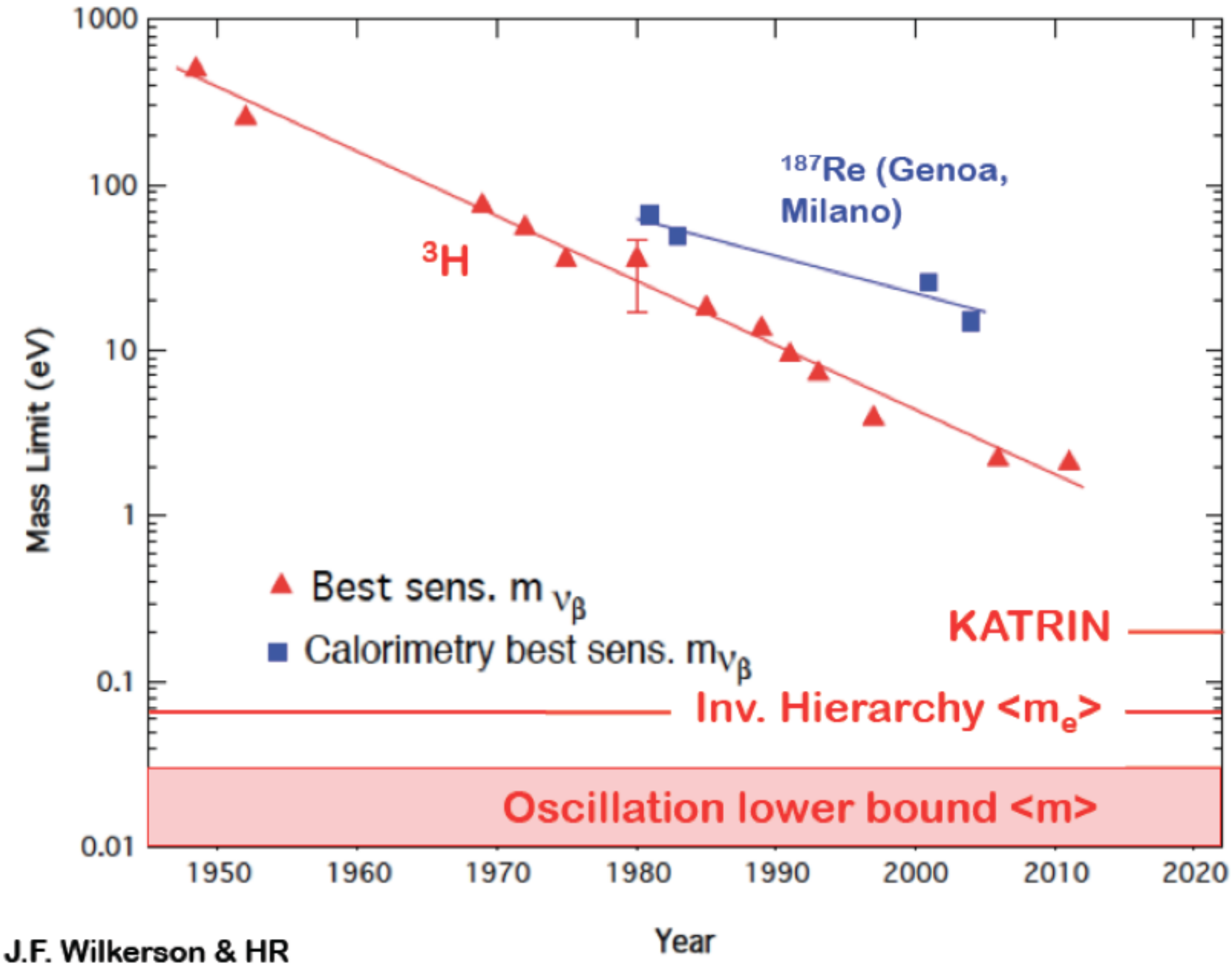
- multiple isotopes and several complementary experiments are needed for confirmation of a signal
- significant overlap in technologies/facilities with DM community

Neutrino Mass

- understanding of absolute neutrino mass is vital for a complete picture of fundamental particle masses, and is crucial information for cosmology and theories of flavor.

- the next generation of tritium-beta-decay experiments will directly probe neutrino masses a factor of 10 smaller the best current bounds; innovative new ideas may help to go beyond this level of sensitivity

Direct Neutrino Mass Measurements

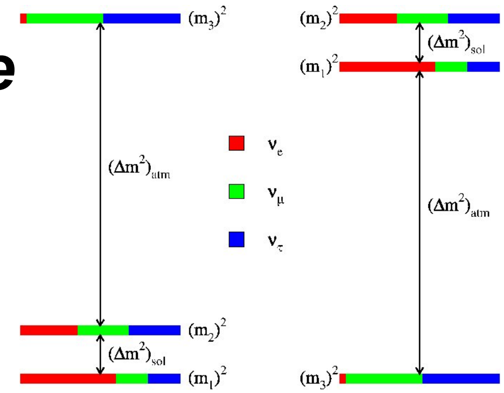


- have been doing this since the 1950's

where we are headed

(Hamish Robertson)

The big questions…..



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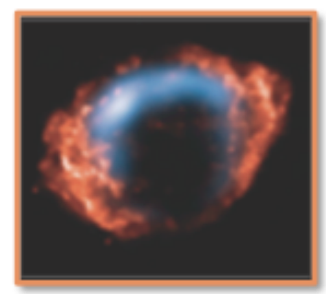
Astrophysical Neutrinos

Neutrinos come from natural sources as close as the Earth and Sun, to as far away as distant galaxies, and even as remnants from the Big Bang. They range in kinetic energy from less than one meV to greater than one PeV, and can be used to study properties of the astrophysical sources they come from, the nature of neutrinos themselves, and cosmology.

supernova neutrinos

solar neutrinos

atmospheric neutrinos



cosmic neutrinos

low energy ⟵⟶ high energy

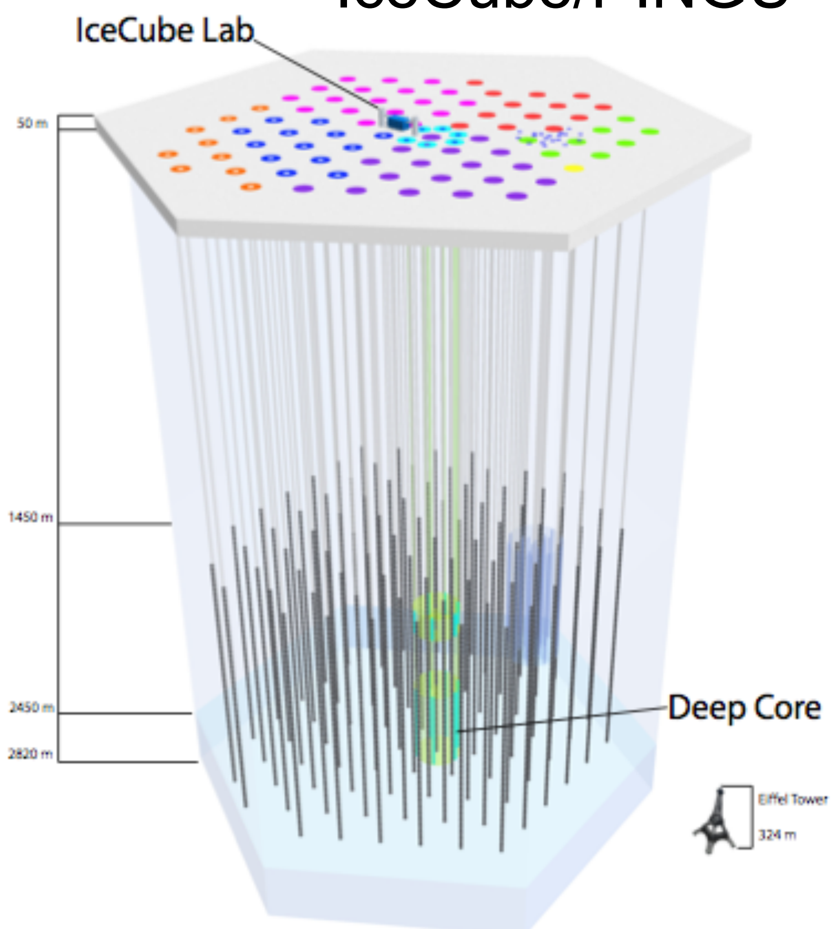
Low Energy Astrophysical Neutrino Detectors

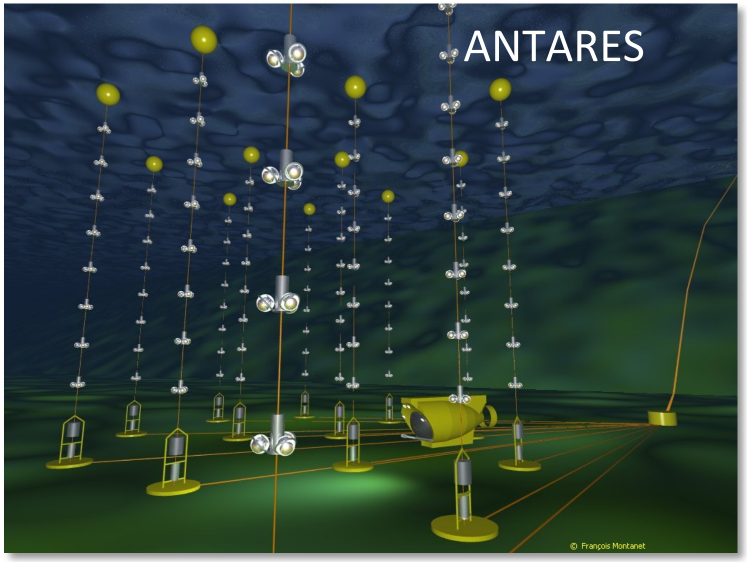
Table 1-6. *Summary of low-energy astrophysics detectors. **indicates significant potential, and * indicates some potential but may depend on configuration.*

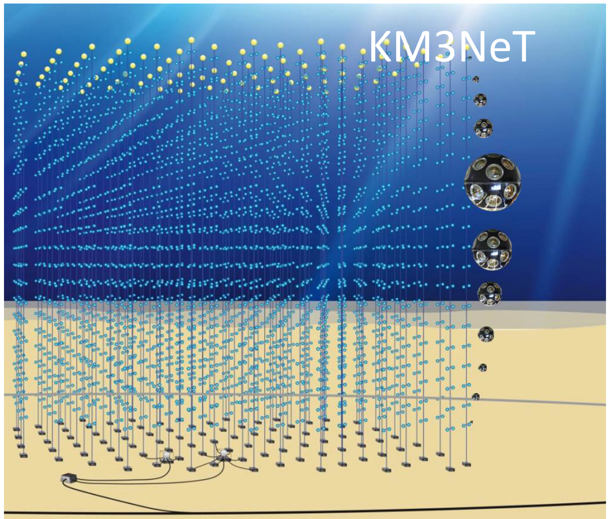
Detector Type	Experiment	Location	Size (kton)	Status	Solar	Geo	Supernova
Liquid scintillator	Borexino	Italy	0.3	Operating	**	**	*
Liquid scintillator	KamLAND	Japan	1.0	Operating	**	**	*
Liquid scintillator	SNO+	Canada	1.0	Construction	**	**	*
Liquid scintillator	RENO-50	South Korea	10	Design/R&D	*	*	**
Liquid scintillator	JUNO (DB II)	China	20	Design/R&D	*	*	**
Liquid scintillator	Hanohano	TBD (USA)	20	Design/R&D	*	**	**
Liquid scintillator	LENA	TBD (Europe)	50	Design/R&D	*	**	**
Liquid scintillator	LENS	USA	0.12	Design/R&D	**		*
Water Cherenkov	Super-K	Japan	50	Operating	**		**
Water Cherenkov	IceCube	South Pole	2000	Operating			**
Water Cherenkov	Hyper-K	Japan	990	Design/R&D	**		**
Liquid argon	LBNE	USA	35	Design/R&D	*		**

High Energy Astrophysical Neutrino Detectors

IceCube/PINGU

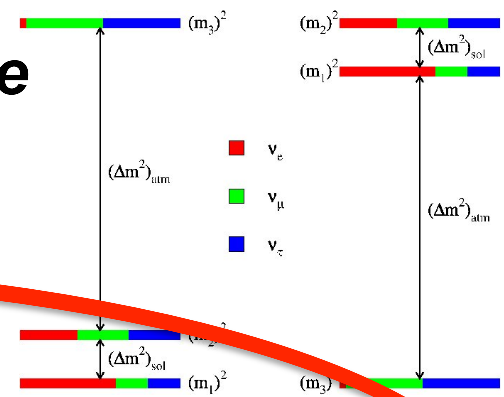






See talks 8/16: Whitehorn/Williams

The big questions….



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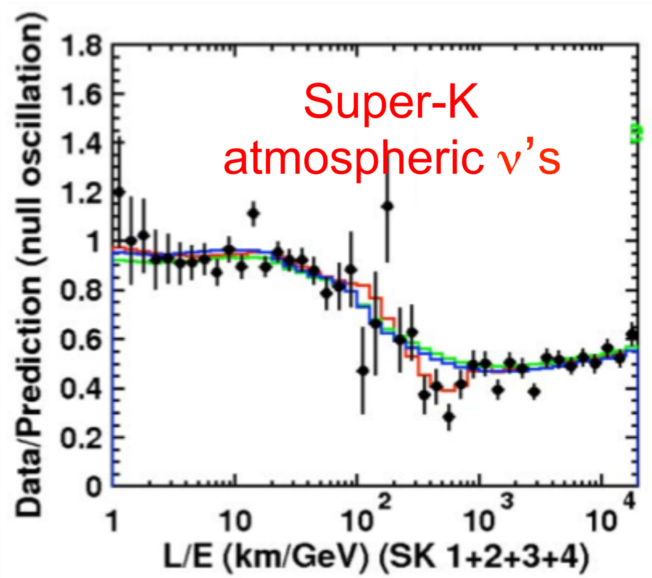
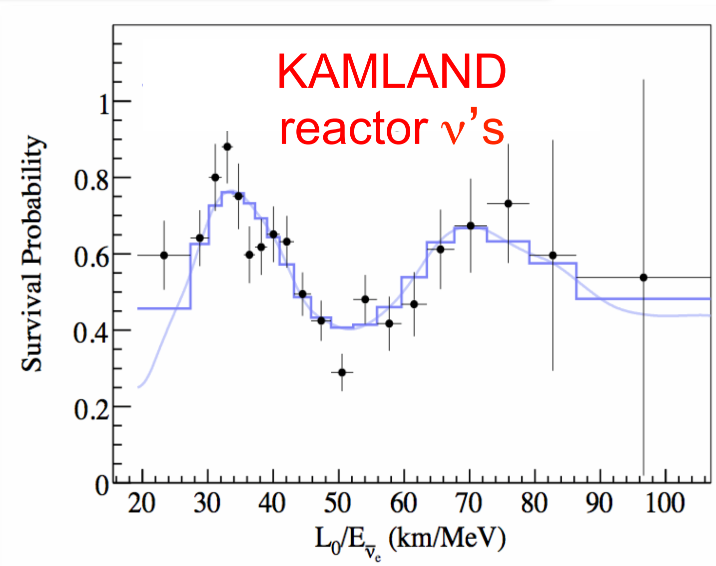
Neutrino Oscillations

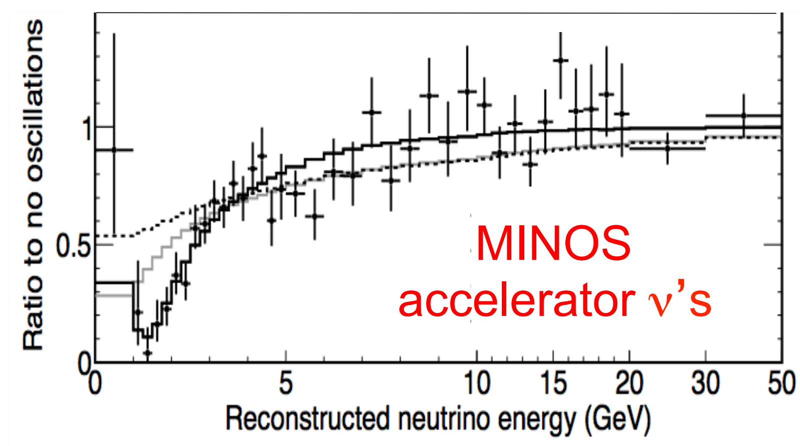
- we have made a lot of progress …



- experiments with solar, atmospheric, accelerator, and reactor ν's have clearly demonstrated that ν's oscillate

- we see the characteristic L/E pattern with multiple sources & experiments





3-Flavor Mixing Picture

- probability of $\nu_\mu \rightarrow \nu_e$ (and $\overline{\nu}_\mu \rightarrow \overline{\nu}_e$) over long distances:

$$
\begin{aligned}
P(\nu_\mu \to \nu_e) \sim\ & \sin^2 2\theta_{13} && \times \sin^2 \theta_{23} \frac{\sin^2[(1-x)\Delta]}{(1-x)^2} \\
& -\alpha \sin 2\theta_{13} && \times \sin\delta \sin 2\theta_{12} \sin 2\theta_{23} \sin\Delta \frac{\sin(x\Delta)}{x} \frac{\sin[(1-x)\Delta]}{(1-x)} \\
& +\alpha \sin 2\theta_{13} && \times \cos\delta \sin 2\theta_{12} \sin 2\theta_{23} \cos\Delta \frac{\sin(x\Delta)}{x} \frac{\sin[(1-x)\Delta]}{(1-x)} \\
& +\alpha^2 && \times \cos^2 \theta_{23} \sin^2 2\theta_{12} \frac{\sin^2(x\Delta)}{x^2}
\end{aligned}
$$

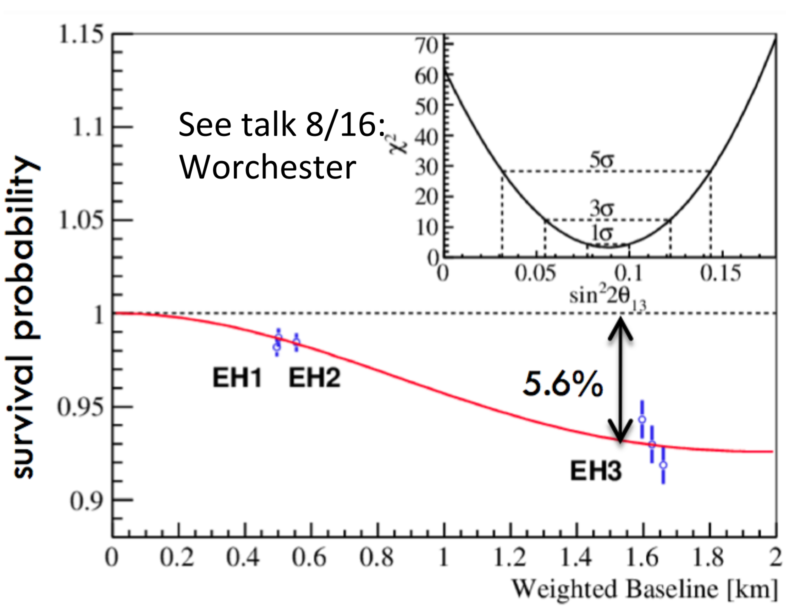
$$
\alpha \equiv \frac{\Delta m^2_{21}}{\Delta m^2_{31}} \sim \frac{1}{30} \qquad \Delta \equiv \frac{\Delta m^2_{31} L}{4E} \qquad x \equiv \frac{2\sqrt{2} G_F N_e E}{\Delta m^2_{31}}
$$

- gives a measure of several very important things:
  - δ_{CP} and CP violation
    (appears in combination with $\sin 2\theta_{13}$, $\sin 2\theta_{12}$, $\sin 2\theta_{23}$)
  - neutrino mass hierarchy (through matter effects)
  - θ_{23} octant (which tells us about the nature of ν_3)

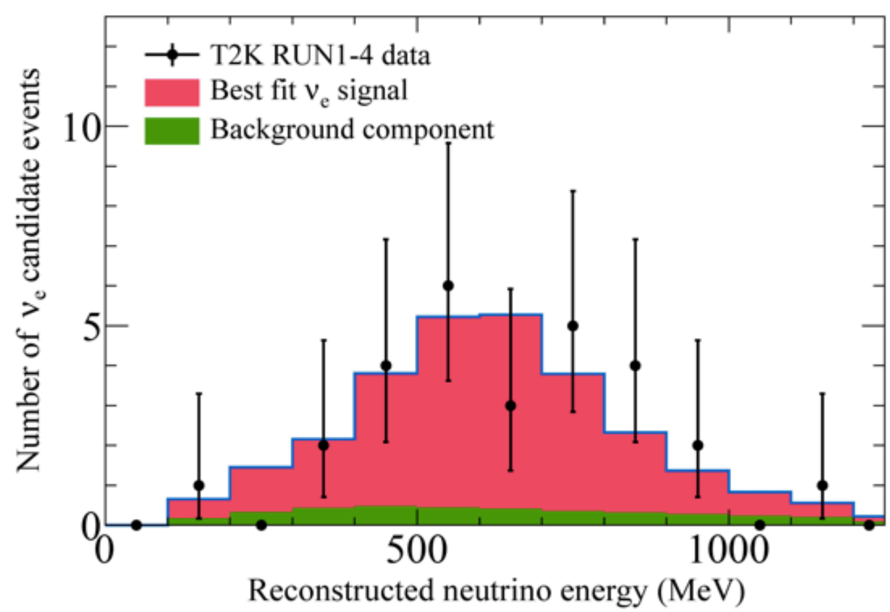
effects are all entangled

Precision Era

- we are entering an era of precision neutrino physics
- the very successful measurement of the smallest mixing angle (θ_{13}) has also recently provided some important clarity
- we know where we want to go



Daya Bay: $\overline{\nu}_e$ disappearance



T2K: ν_e appearance

Many experiments measuring neutrino oscillations – running, in planning, in proposal stage

Category	Experiment	Status	Osc params
accelerator	T2K	data-taking	MH/CP/octant
accelerator	NOνA	commissioning	MH/CP/octant
accelerator	RADAR	R&D	MH/CP/octant
accelerator	CHIPS	R&D	MH/CP/octant
accelerator	T2HK	design/ R&D	MH/CP/octant
accelerator	LBNE	design/ R&D	MH/CP/octant
accelerator	DAEδALUS	design/ R&D	CP
reactor	JUNO	design/R&D	MH
reactor	RENO-50	design/R&D	MH
atmospheric	Super-K	data-taking	MH/CP/octant
atmospheric	Hyper-K	design/R&D	MH/CP/octant
atmospheric	LBNE	design/R&D	MH/CP/octant
atmospheric	INO	design/R&D	MH/octant
atmospheric	PINGU	design/R&D	MH
atmospheric	ORCA	design/R&D	MH
supernova	existing	N/A	MH

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accelerator	T2K	data-taking	MH/CP/octant
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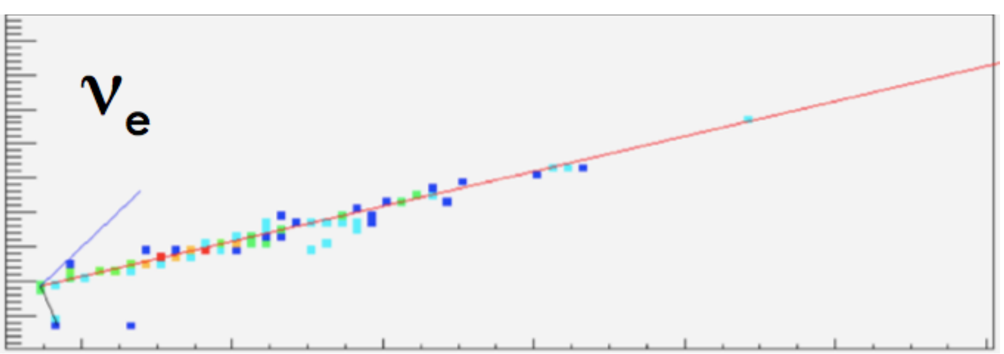
accelerator	RADAR	R&D	MH/CP/octant
accelerator	CHIPS	R&D	MH/CP/octant
accelerator	T2HK	design/ R&D	MH/CP/octant
accelerator	LBNE	design/ R&D	MH/CP/octant
accelerator	DAEδALUS	design/ R&D	CP
reactor	JUNO	design/R&D	MH
reactor	RENO-50	design/R&D	MH
atmospheric	Super-K	data-taking	MH/CP/octant
atmospheric	Hyper-K	design/R&D	MH/CP/octant
atmospheric	LBNE	design/R&D	MH/CP/octant
atmospheric	INO	design/R&D	MH/octant
atmospheric	PINGU	design/R&D	MH
atmospheric	ORCA	design/R&D	MH
supernova	existing	N/A	MH

Experiments I'll focus on -> US based LBL program

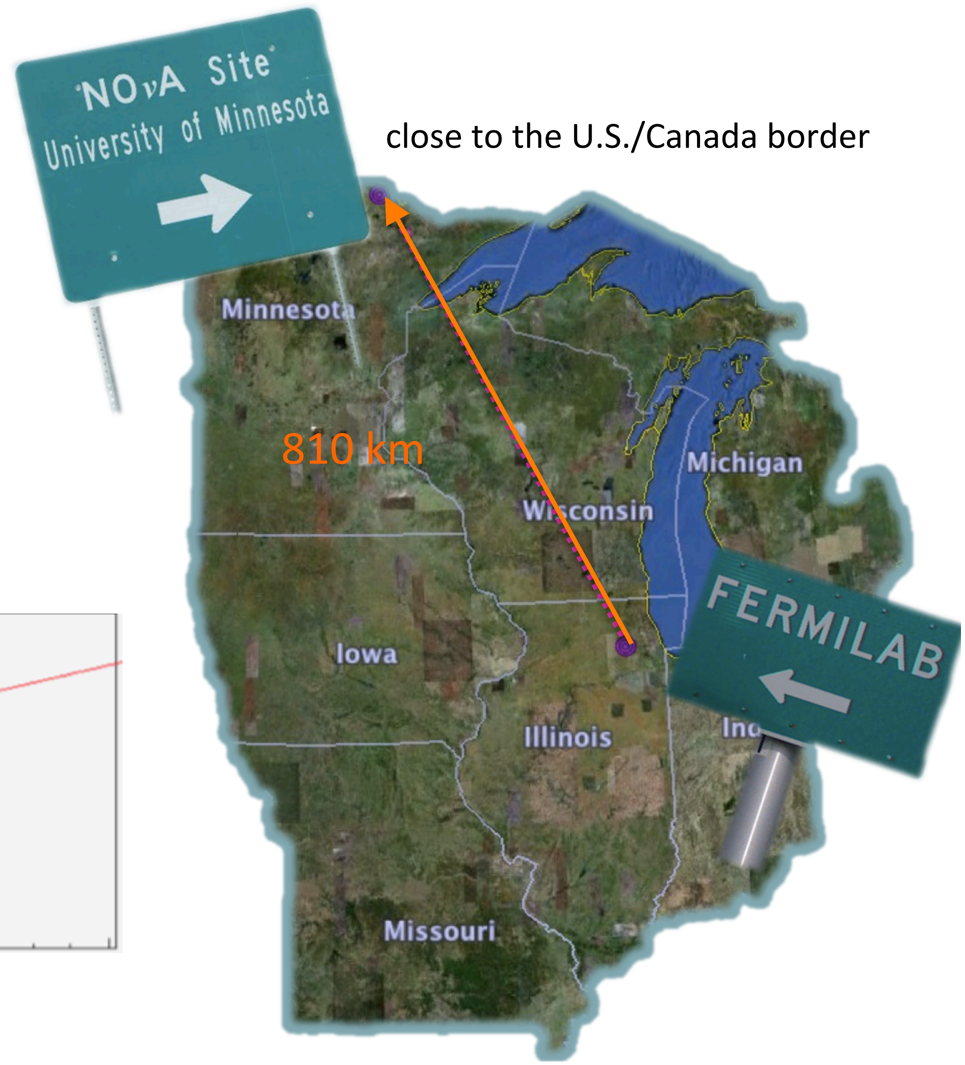
NOvA

See talks 8/16:
Bian
Sachedev
Baird

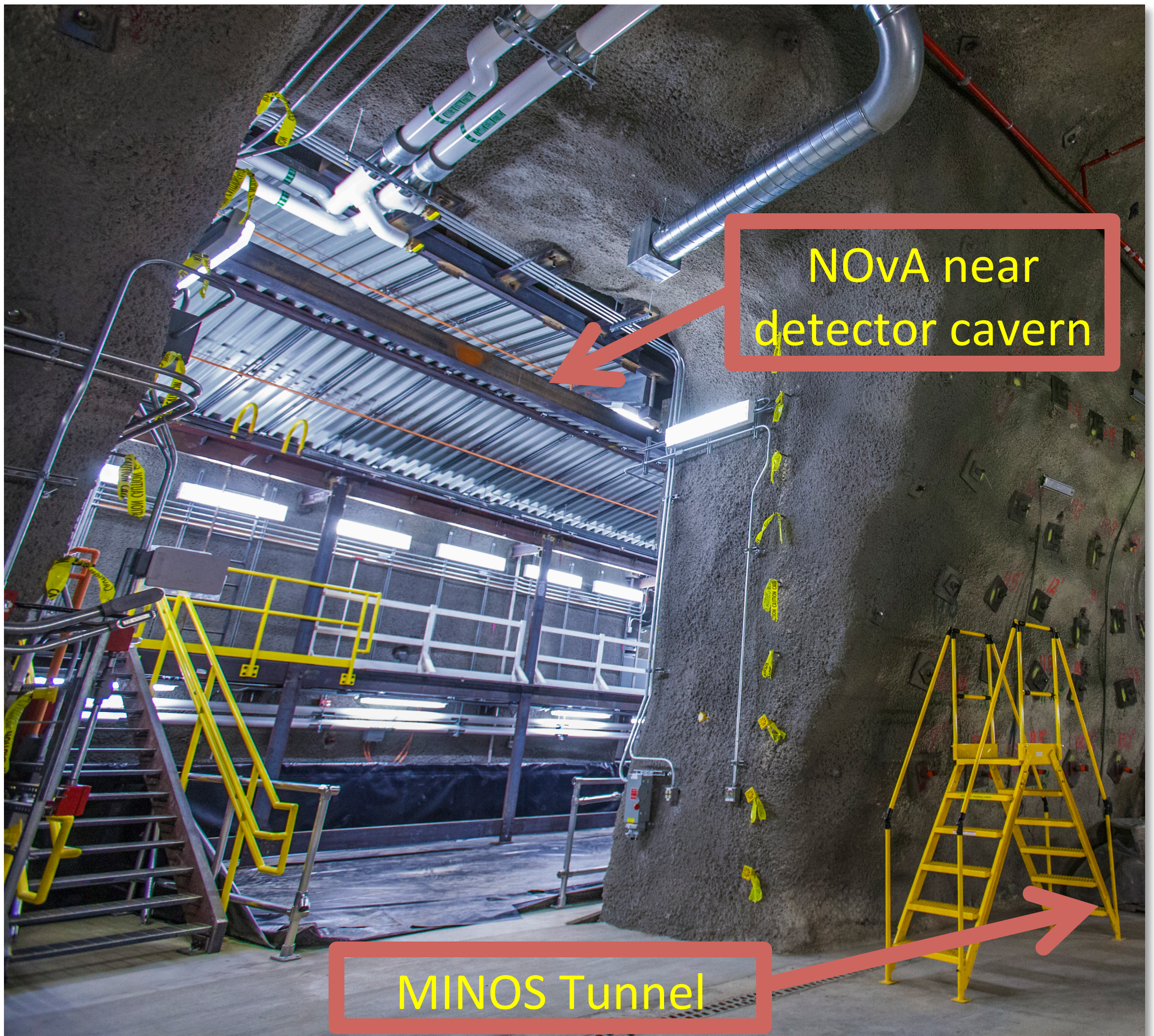
- 2nd generation long-baseline ν oscillation experiment coming online soon
  - will study $\nu_\mu \rightarrow \nu_e$ add $\overline{\nu}_\mu \rightarrow \overline{\nu}_e$ transitions over a distance of 810 km using an off-axis, narrow beam
  - world's most intense accelerator based ν beam (700 kW)



close to the U.S./Canada border



Near Detector



- NOvA near detector cavern completed
- near detector assembly starts this month
- goal: ½ of near detector complete by end of year

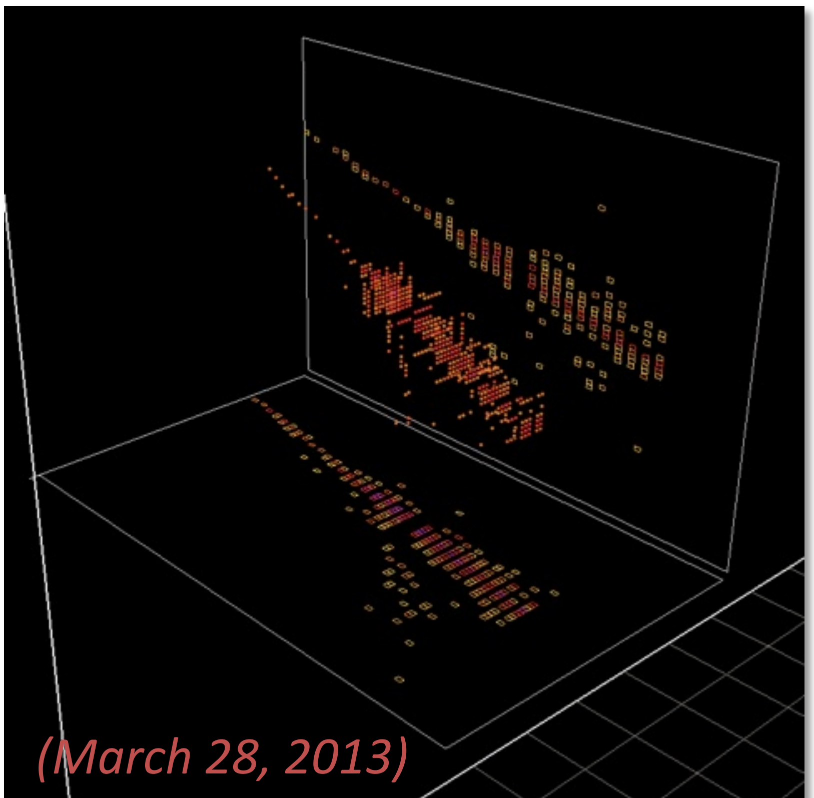
Far Detector

- site at Ash River was completed last year
- NOvA is in steady production mode getting this detector built
  - *54% of the blocks have been installed*
  - *33% of the detector has been filled*
  - *1.4 kton instrumented*

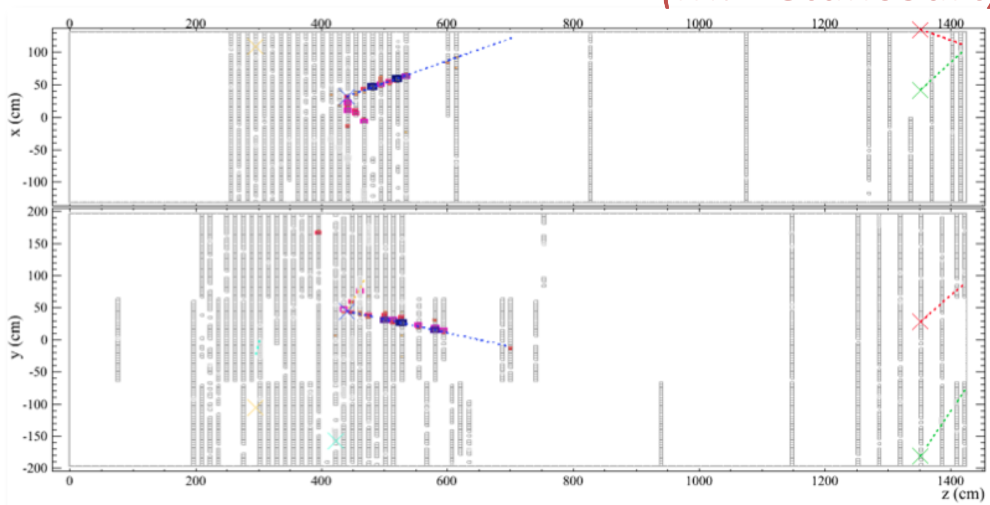
(status as of June 24, 2013)

Ready for Neutrino Beam!

- 3D image of a cosmic ray in instrumented portion of the NOvA far detector



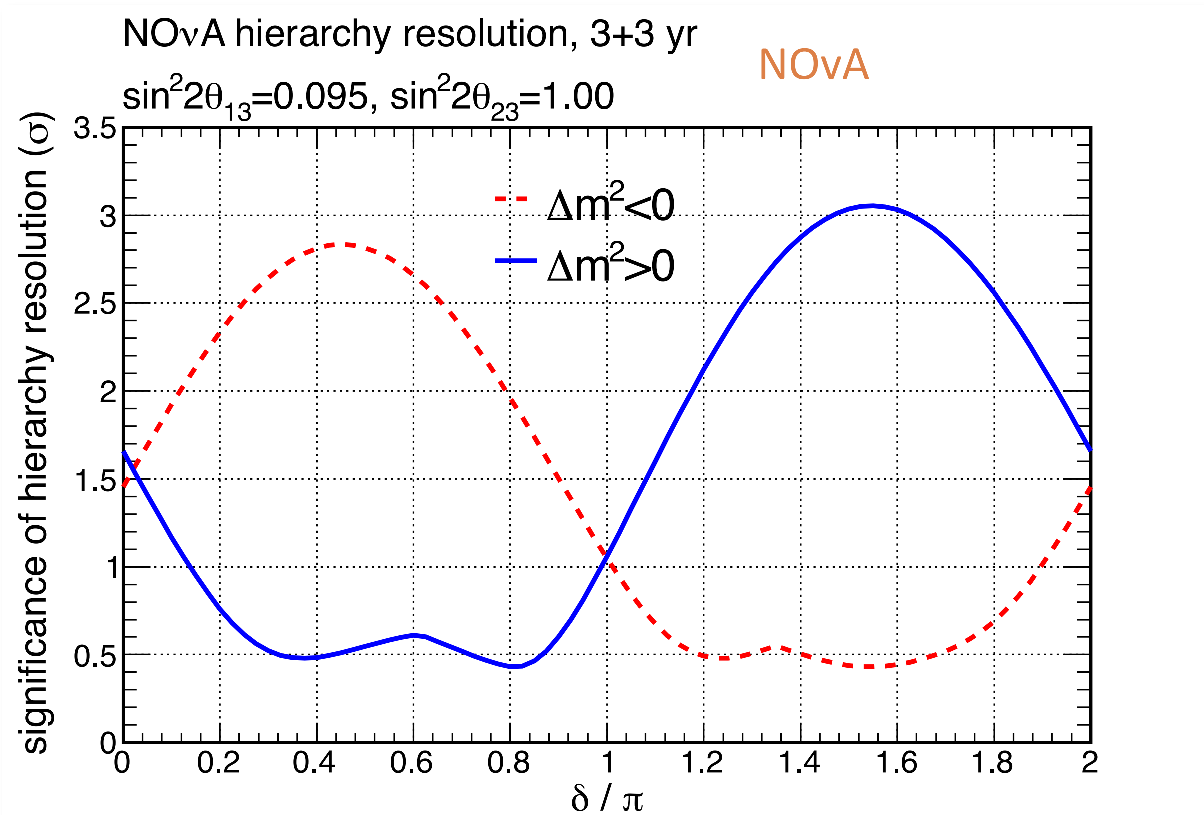
(M. Betancourt)



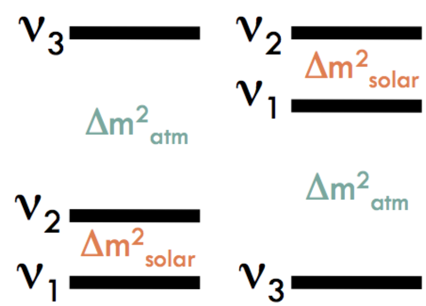
- also, extracting 1st physics from the Near Detector On Surface (NDOS)

NOvA ν_e Appearance

- resolving the neutrino mass hierarchy



- will get the world's best look at this in a hurry



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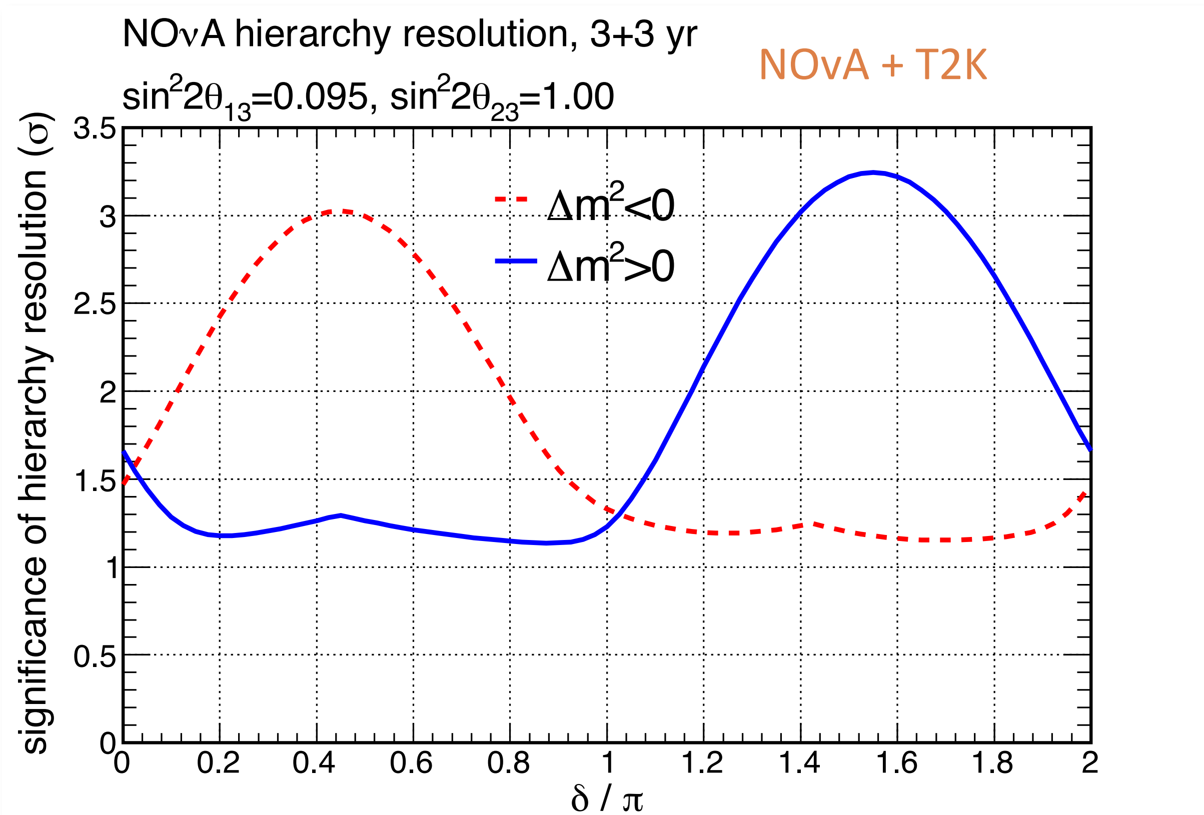

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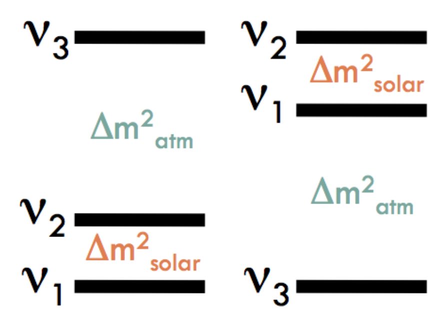
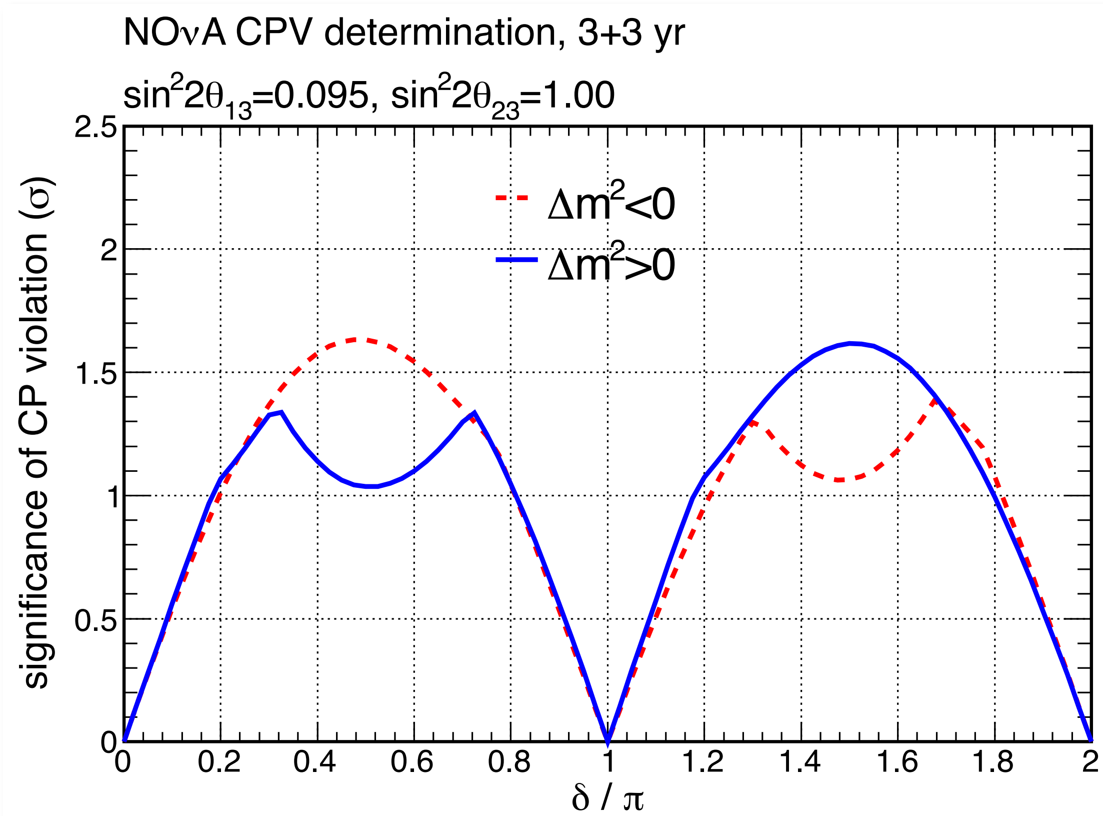


• T2K data is very important in combination!

• also, some new ideas for measuring this with atmospheric & reactor ν's

NOvA ν_e Appearance

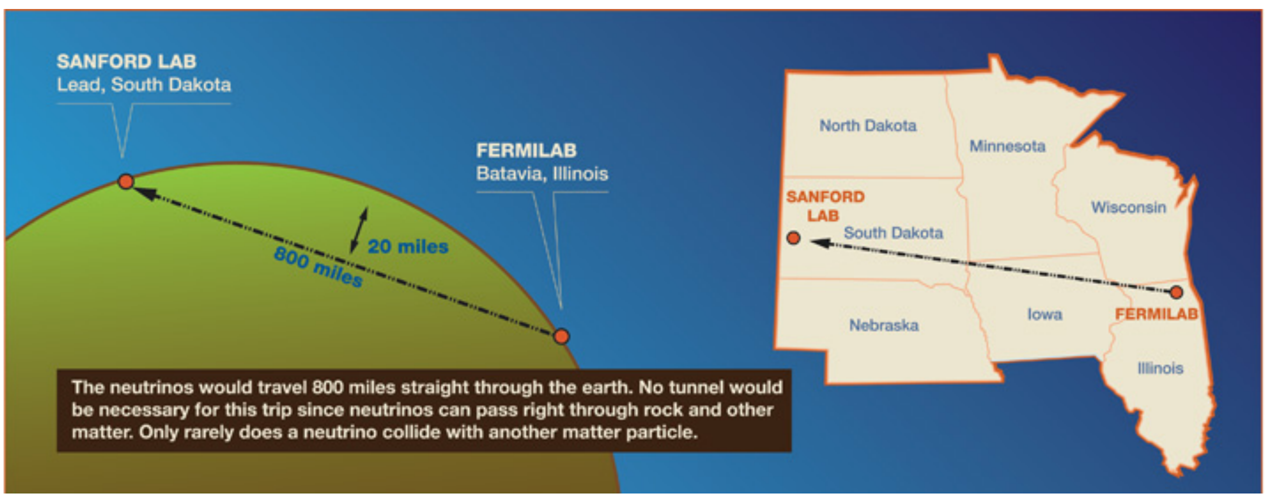


- may even get a first glimpse at C̸P if we're lucky

- while new data from both NOvA and T2K are highly anticipated, we know it will be difficult discover C̸P with current generation experiments

LBNE: Long Baseline Neutrino Experiment

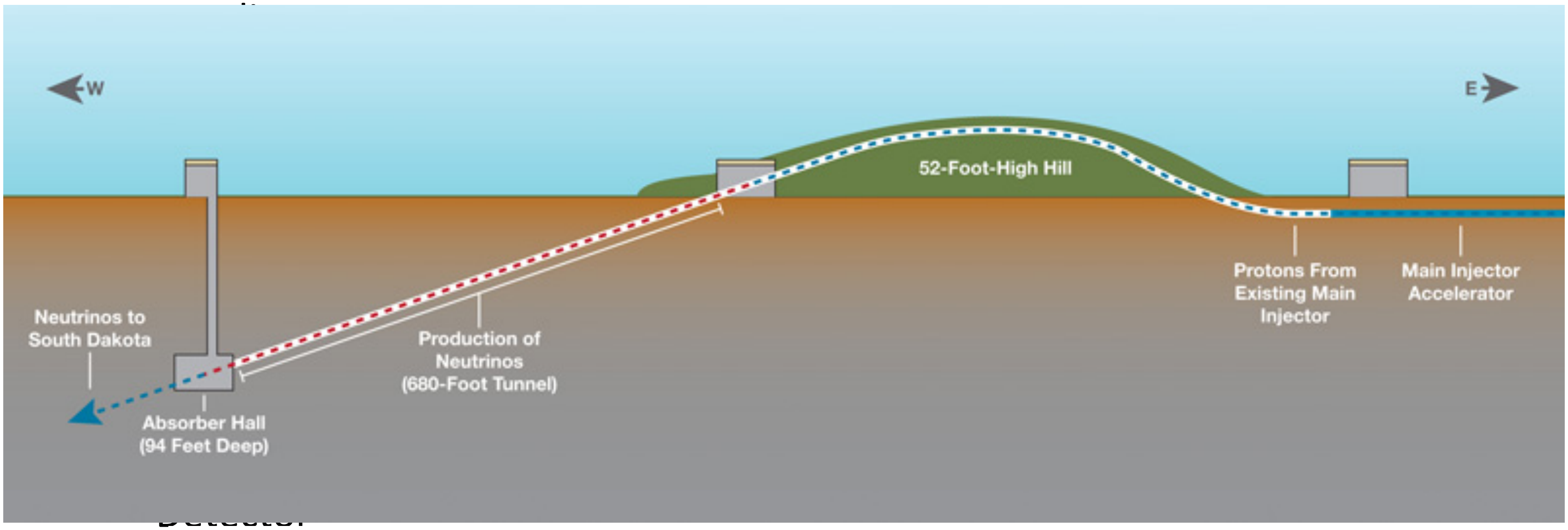
- New neutrino beam at FNAL
  - 700 kW, 60-120 GeV proton beam
  - 2.3 MW capable
- Near detector for neutrinos
- 34 kton far detector at 1300 km baseline (at Sanford Underground Research Facility, SURF)
  - Ultimately positioned underground with 4850' overburden



See talks 8/15: Guardincerri Bass

Ingredients For Success

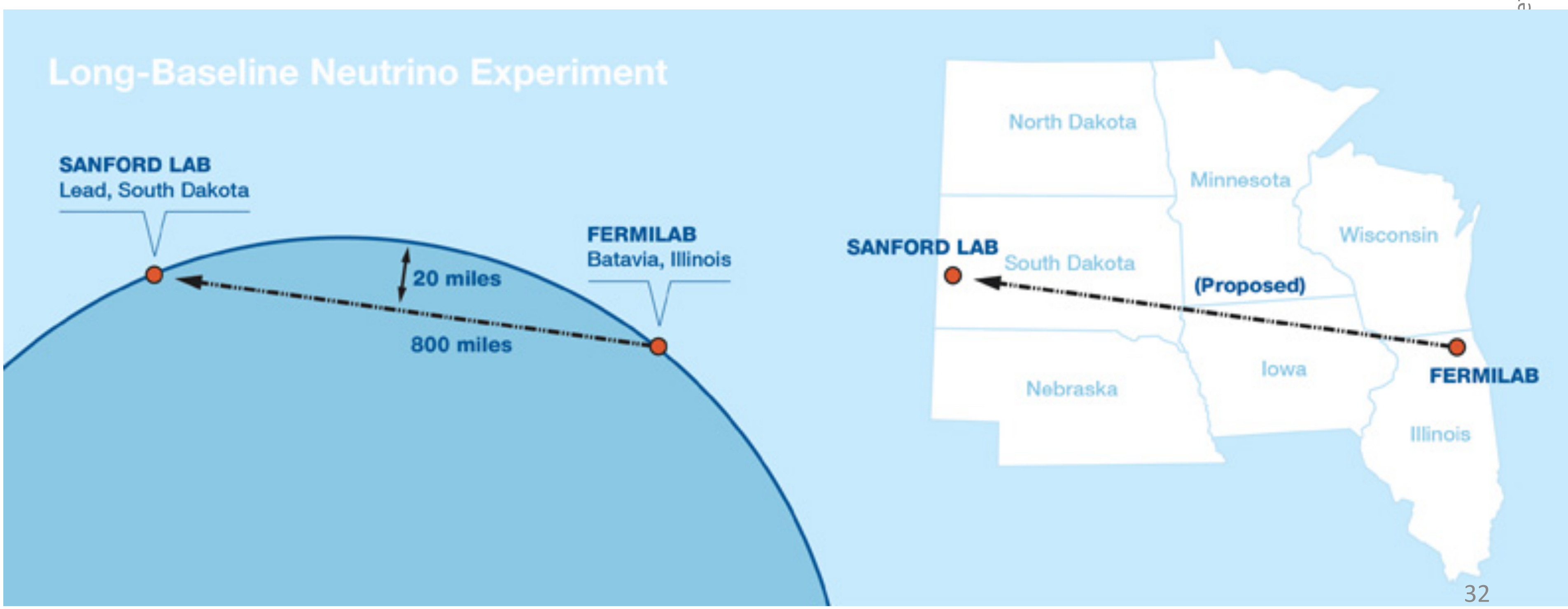
- **Wide Band Beam**
  - We know how to build this, based on past experience
  - Beamline also capable of handling higher power (2.3 MW)



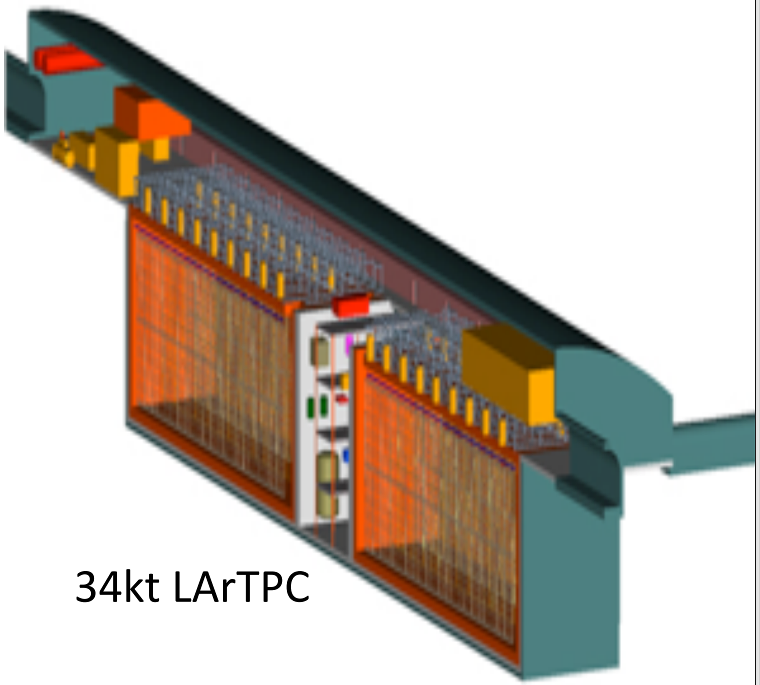
Above ground target area with beam pointing towards SD

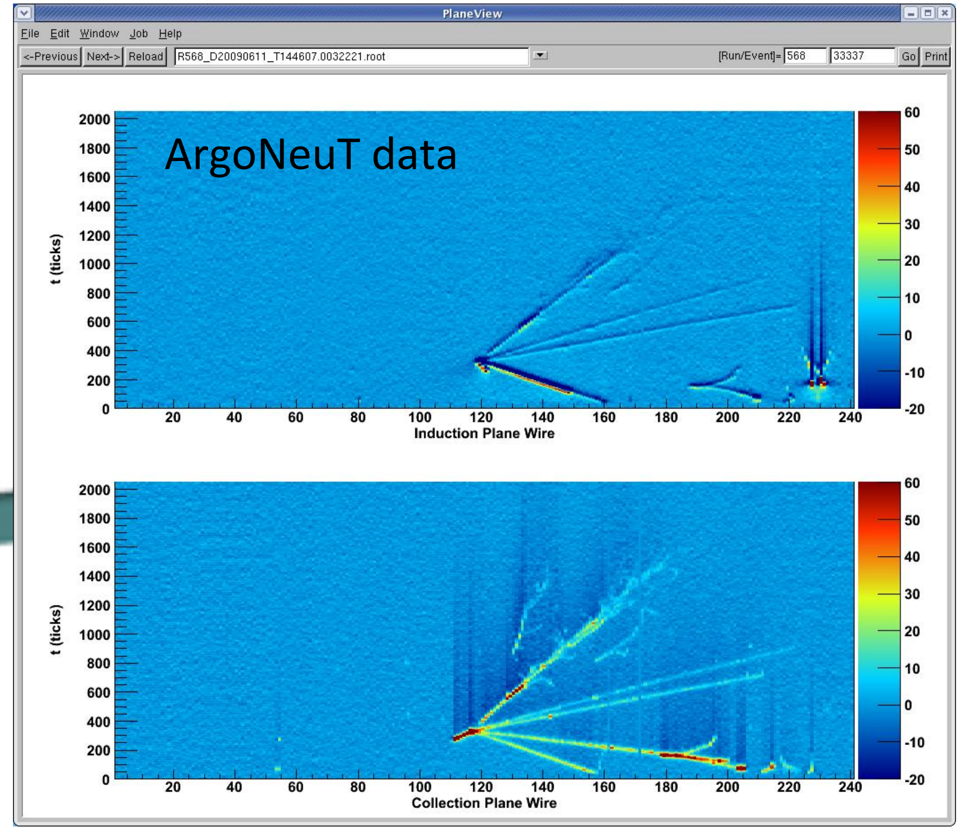
Ingredients For Success

- **Beam**
  - We know how to build this, based on past experience
  - Beamline also capable of handling higher power (2.3 MW)
- **Baseline**
  - We know how to send neutrinos long distances (e.g., MINOS, NOvA)
  - Many detailed studies show that 1300 km (~800 miles) is optimal for this physics

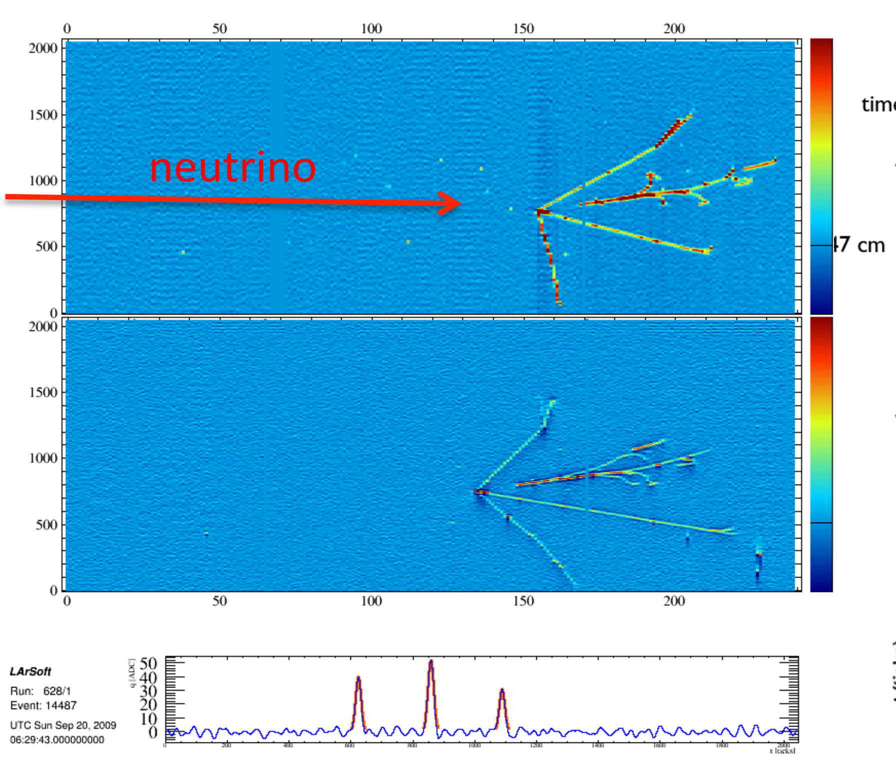


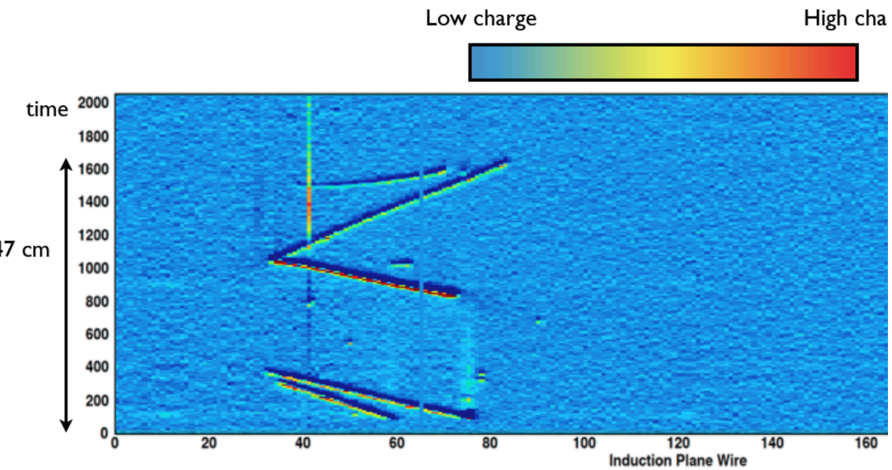
Ingredients For Success

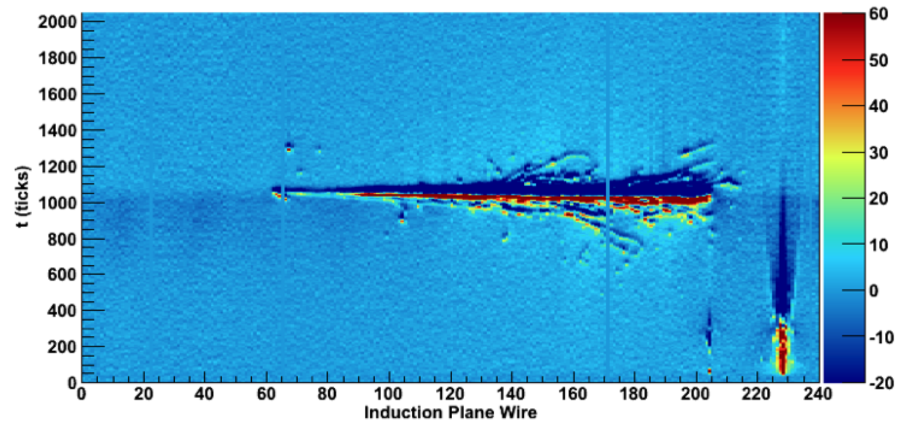




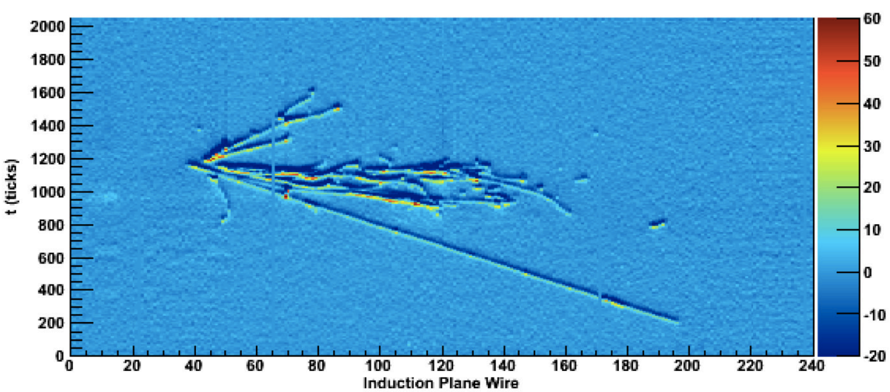
- **Detector**
  - Liquid Argon time projection chamber (LArTPC)
    - High signal efficiency, low backgrounds, excellent resolution
  - Successfully built and operated on small scales
  - Now working to demonstrate that it can be done at the massive scale needed for LBNE

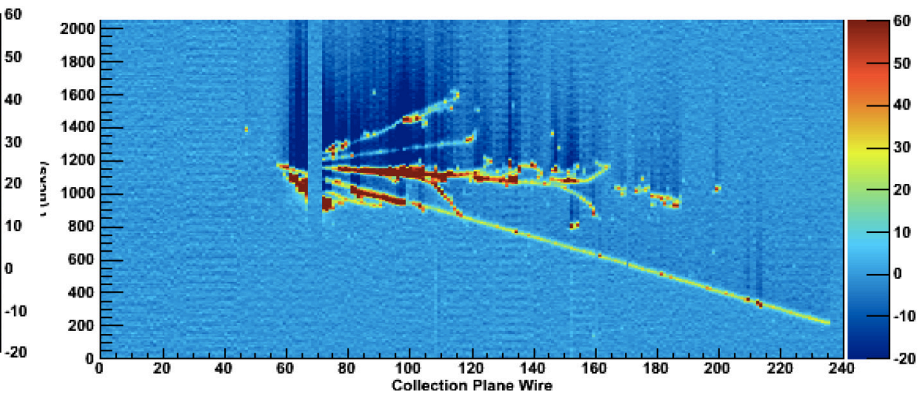






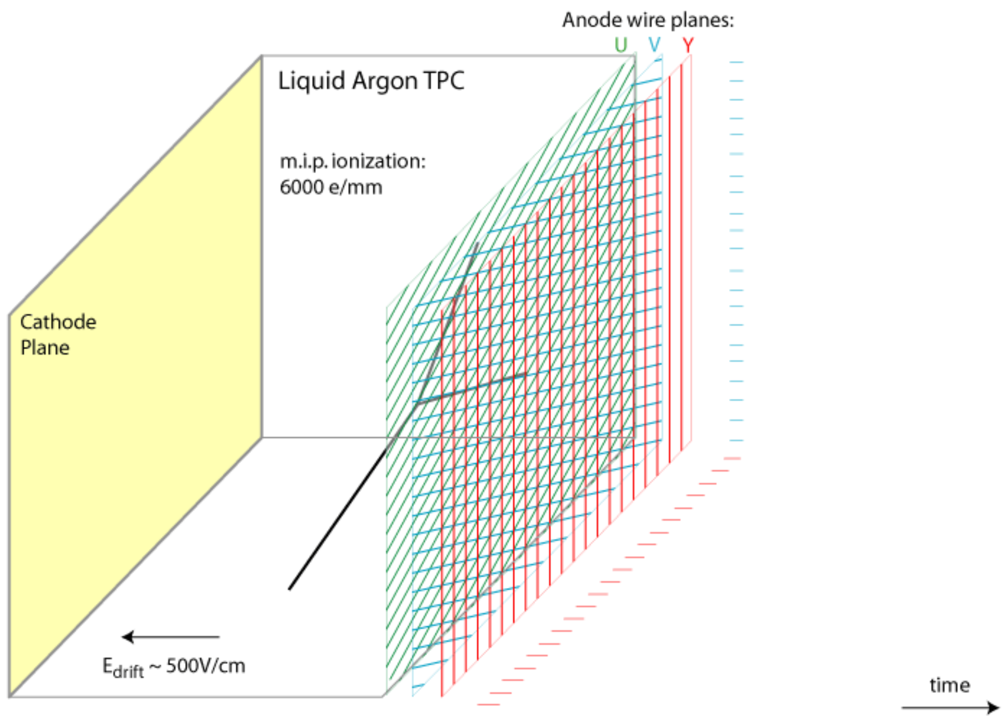
Neutrino interactions in LArTPCs (in ArgoNeuT)





Liquid Argon Time Projection Chambers

- Passing charged particles ionize Argon
- Electric fields drift electrons meters to wire chamber planes <- 500 V/cm
- Induction/Collection planes image charge, record dE/dx

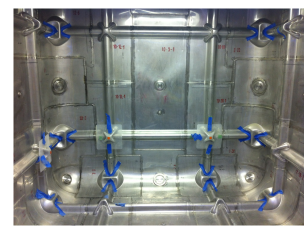


Need very pure argon, and low noise electronics, also want to collect The scintillation light produced – cryogenic PMTs

Development Program towards LArTPC detectors

See talks:
Szelc, Carls
Grant, Lockwitz

35 ton



Develop systems for next generation LArTPC detectors:

- Cold electronics
- Cryostat and cryogenics
- High voltage
- TPC geometry and readout
- Light collection
- "Physics R&D"

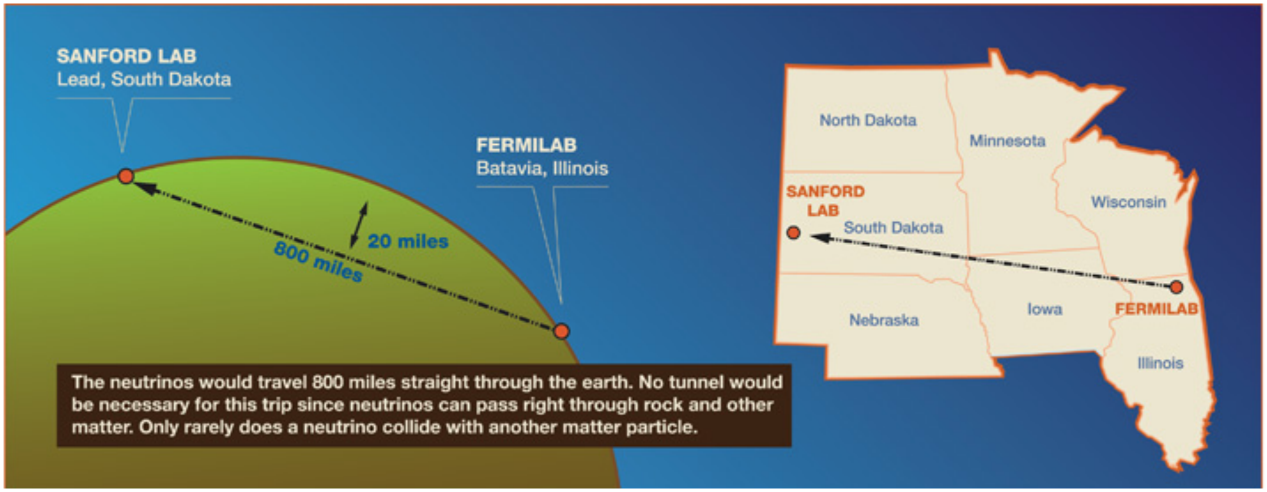
LBNE

DOE requests a staged program.

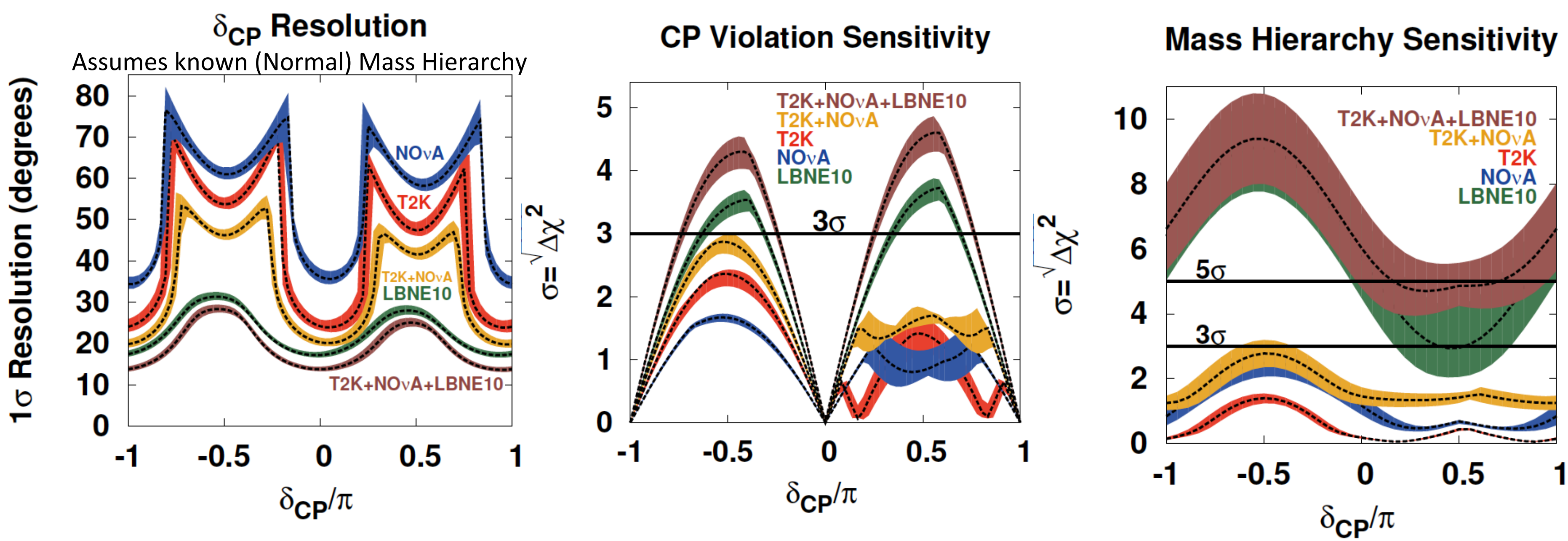
Initial approval for a 10 kton on the surface, can be changed before finalized.

Seeking partners to accomplish full LBNE

- New neutrino beam at FNAL
  - 700 kW, 60-120 GeV proton beam
  - 2.3 MW capable
- Near detector for neutrinos
- 34 kton far detector at 1300 km baseline (at Sanford Underground Research Facility, SURF)
  - Ultimately positioned underground with 4850' overburden



LBNE 10kt Would be a Major Advance



Bands: 1σ variations of θ_{13}, θ_{23}, Δm_{31}^2 (Fogli et al. arXiv:1205.5254v3)

T2K 750 kW x 5 yr (7.8×10^{21}pot) ν

NOνA 700 kW x (3 yr ν + 3 yr $\bar{\nu}$) (3.8×10^{21}pot)

LBNE10 (80 GeV*) 700 kW x (5 yr ν + 5 yr $\bar{\nu}$)

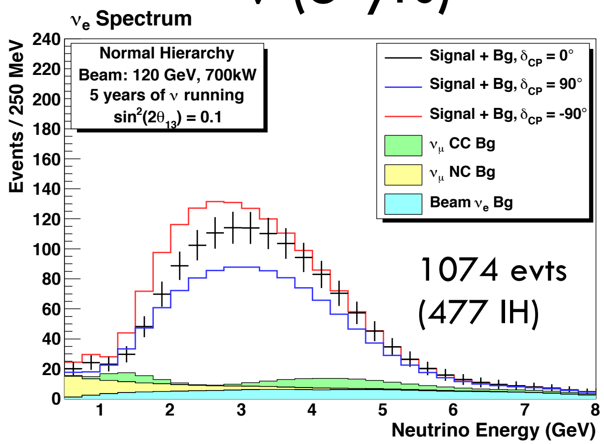
*Improved over CDR 2012 120 GeV MI proton beam

LBNE Spectra (34 kton LAr)

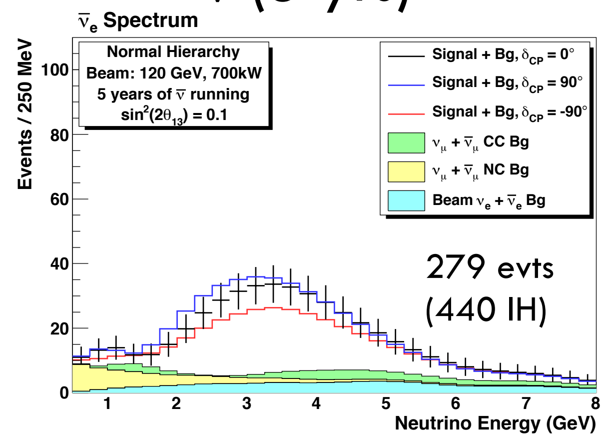
Appearance

$\nu_\mu \rightarrow \nu_e$

ν (5 yrs)

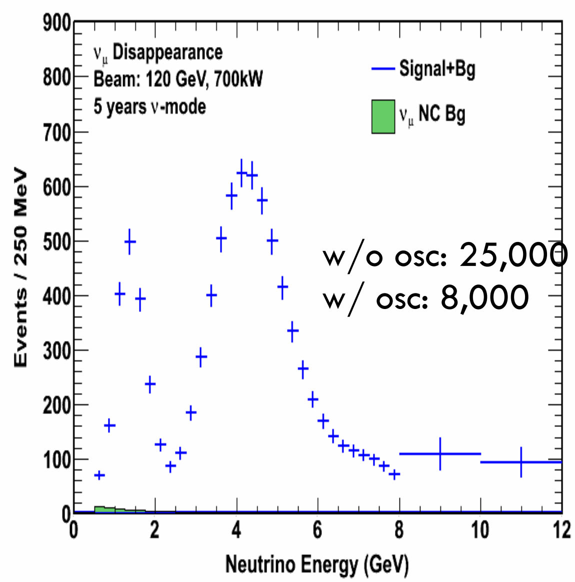


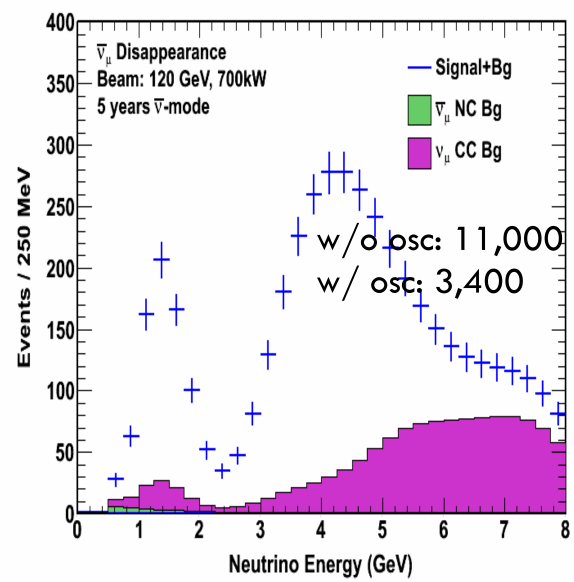
$\bar{\nu}$ (5 yrs)



Disappearance

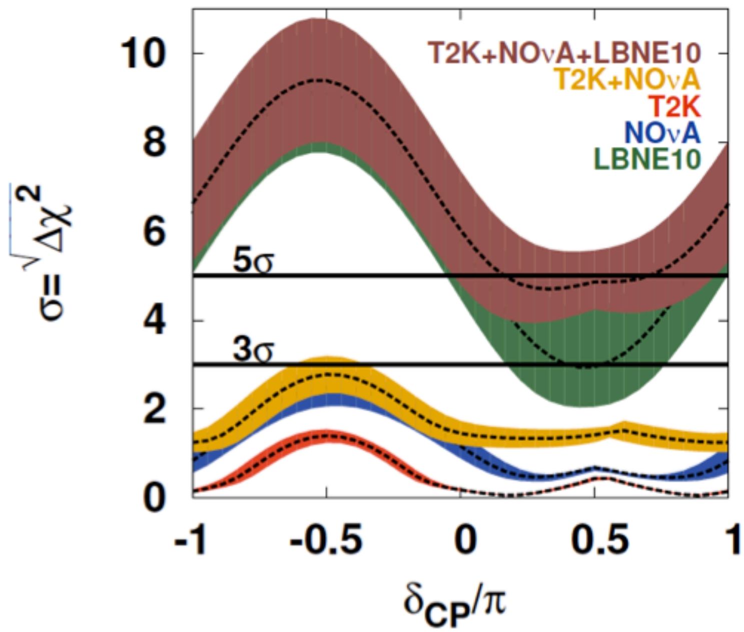
$\nu_\mu \rightarrow \nu_\mu$

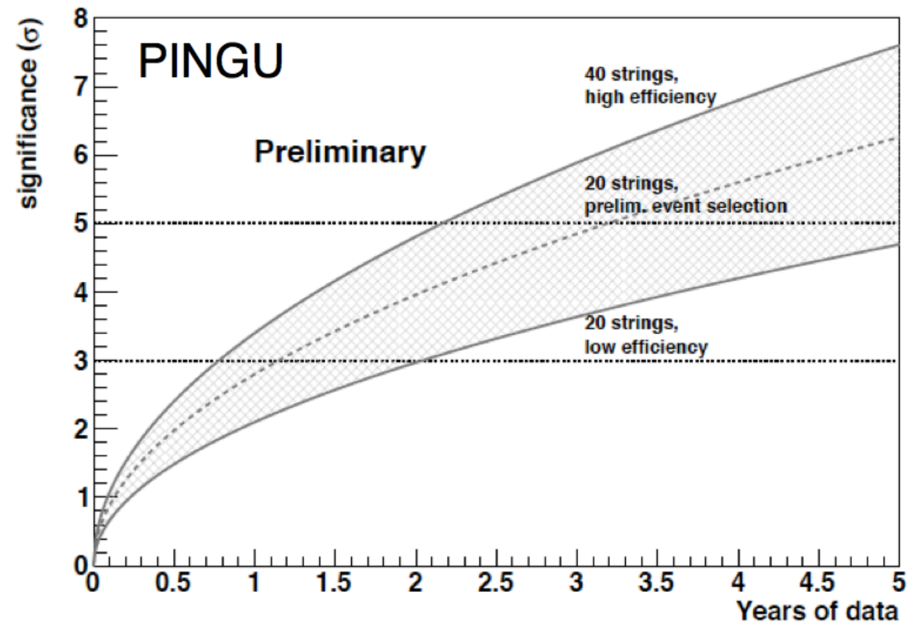




spectra from LBNE PWG Report (2011) - “2010 beam”

Mass Hierarchy

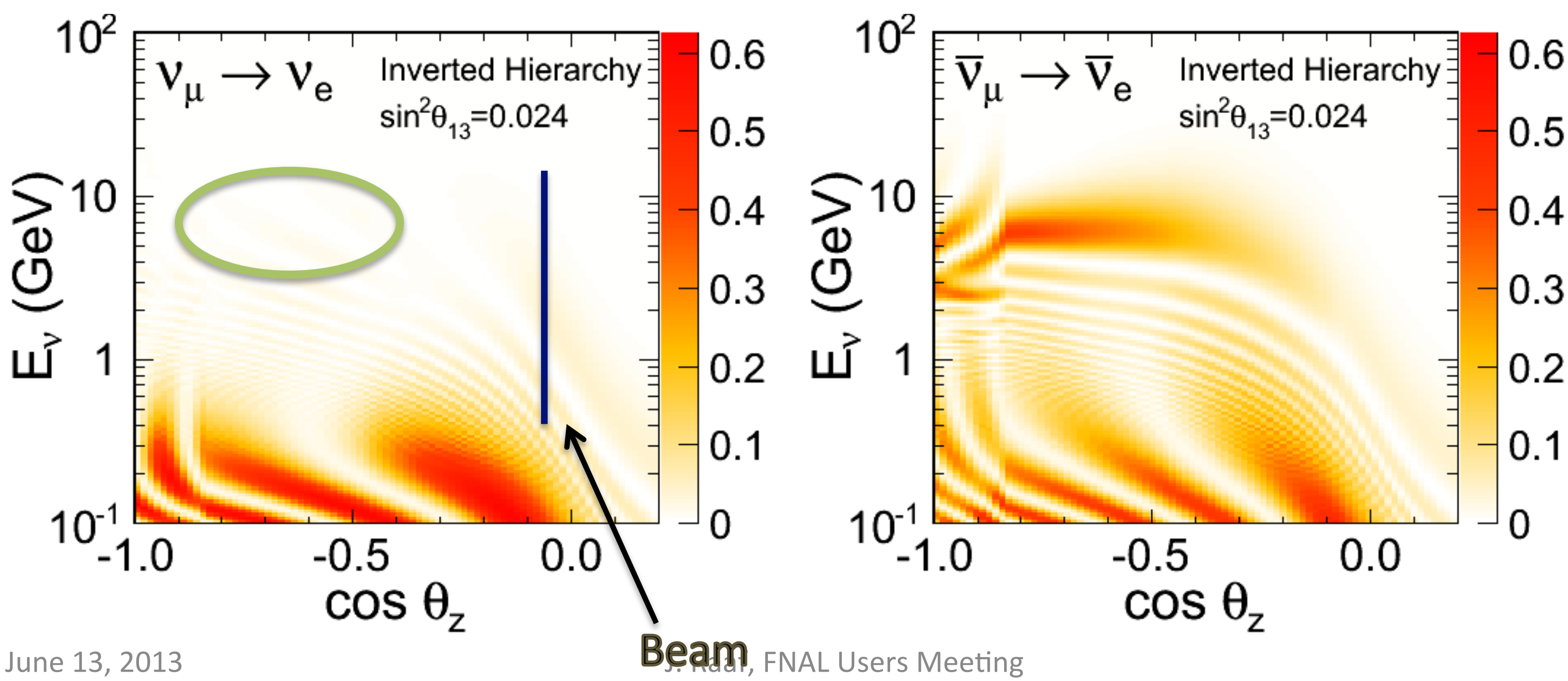




- MH determination by long-baseline neutrino experiments "guaranteed" with sufficient distance/exposure
- other techniques are promising; systematics challenging
  - *- PINGU IceCube infill: atmospheric neutrinos*
  - *- JUNO, RENO-50 reactor experiments*
- there could also be information from cosmology

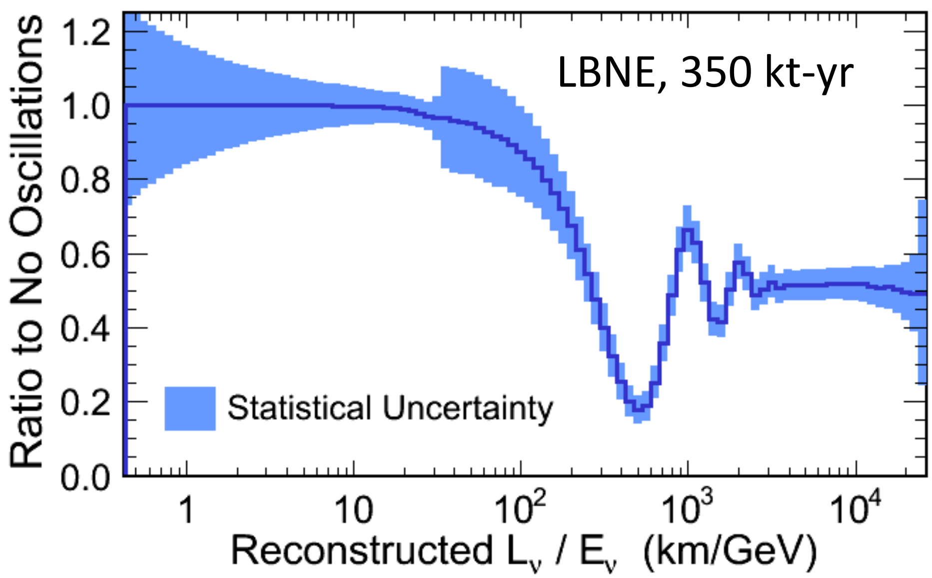
Atmospheric Neutrinos

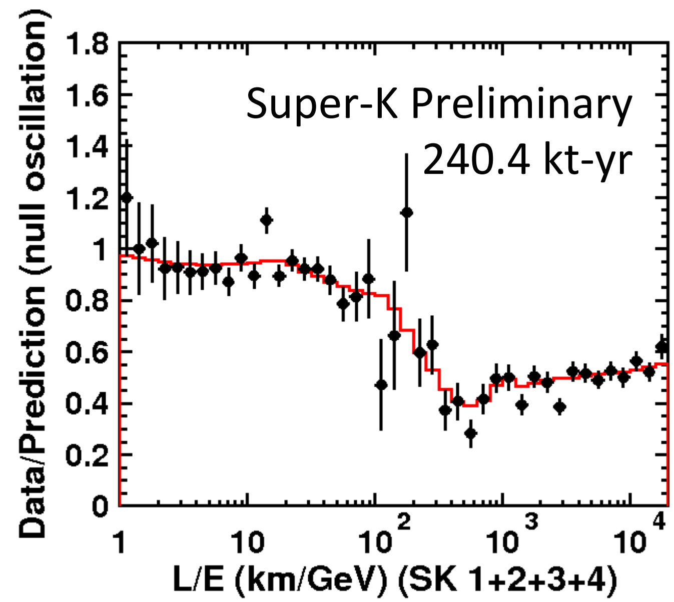
- Excellent source of data for detailed exploration of ν oscillations
  - Free! Huge range of energies and baselines
  - Complementary dataset; help break degeneracies in beam-only analyses
- Mass hierarchy
  - Enhancement in 2-10 GeV upward-going ν for normal hierarchy (anti-ν for inverted hierarchy)



L/E Oscillation Pattern

A. Blake et al., hep-ex/1208.2899



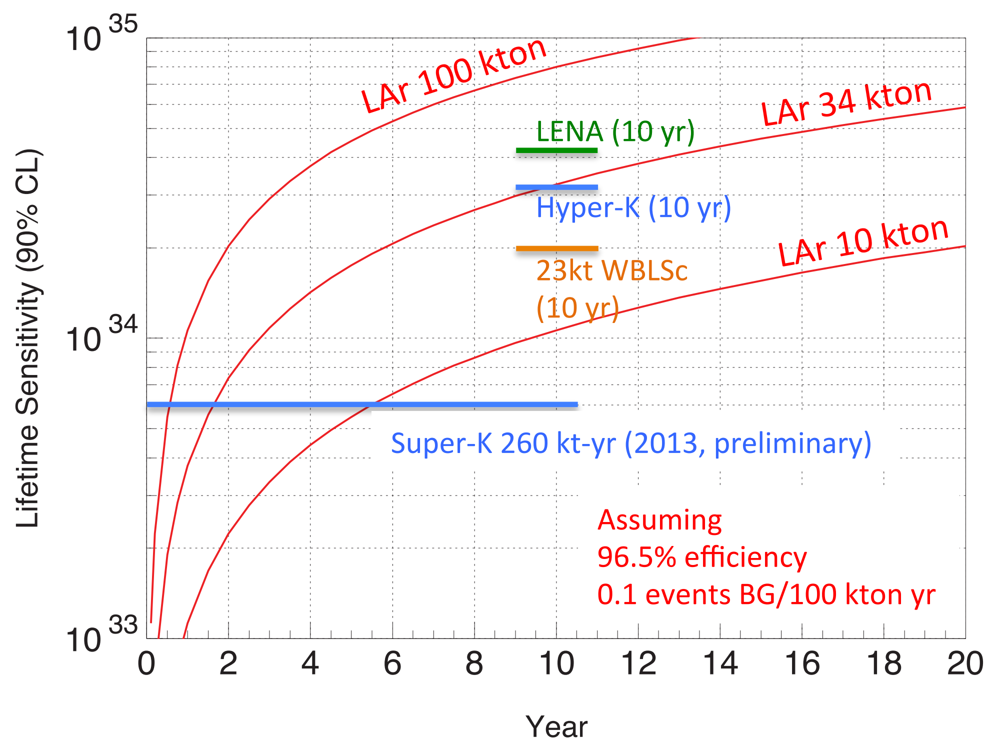


- Select atmospheric events with good energy and angle resolution
  - Compare observed data to expectation for no oscillation
- Spectacular signature in Super-K water Cherenkov detector, even more distinct in LAr (multiple oscillation dips visible!)

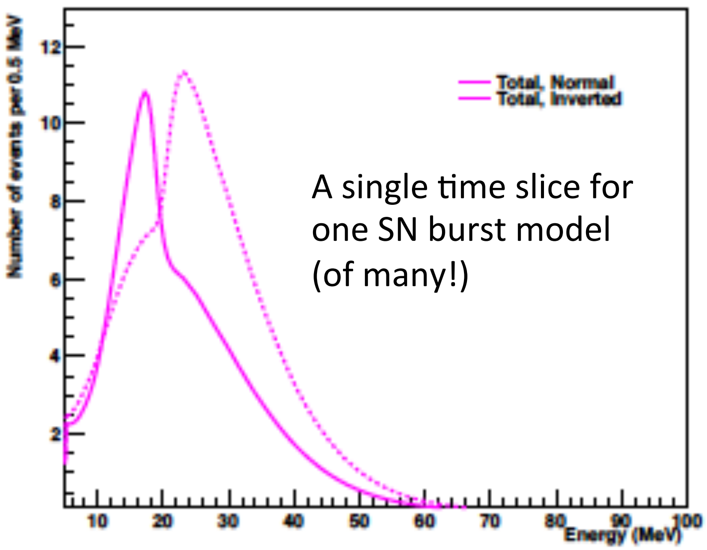
Proton Decay

- In a large mass underground detector, look for signatures of proton decay in the data sample of fully-contained ν's
  - Atmospheric ν's = background to proton decay searches

- LAr has high efficiency for detecting SUSY-favored decay modes
  - Best for $p \rightarrow \bar{\nu}K^+$ but also good for many other modes
  - Even if no signal is seen, limits place strong constraints on theory



Supernova ν's



Channel	Events, "Livermore" model	Events, "GKVM" model
$\nu_e + ^{40}\text{Ar} \rightarrow e^- + ^{40}\text{K}^*$	2308	2848
$\bar{\nu}_e + ^{40}\text{Ar} \rightarrow e^+ + ^{40}\text{Cl}^*$	194	134
$\nu_x + e^- \rightarrow \nu_x + e^-$	296	178
Total	2794	3160

- Supernova at the galactic center (10 kpc) would produce thousands of neutrino interactions in 34 kt LAr detector in a very short time (10's of seconds)
- LAr detectors sensitive to ν_e's, water detectors sensitive to anti-ν_e's
  - Complementary measurements in LAr & WC elucidate SN burst physics
- A supernova will eventually happen (1~few per century per galaxy)

LBNE Scientific Motivations

- **Explore 3x3 model of ν mixing**
  - Broad band beam and high resolution detector
- **Atmospheric neutrinos**
  - Independent ν source, can determine mass hierarchy, and others
- **New ν physics**
  - Non-standard interactions, sterile ν, others
- **Proton Decay**
  - Test fundamental but unexplained conservation of baryon number
  - Grand Unified Theories predict specific decay modes, lifetimes, branching ratios
- **Astrophysics**
  - Supernova burst ν

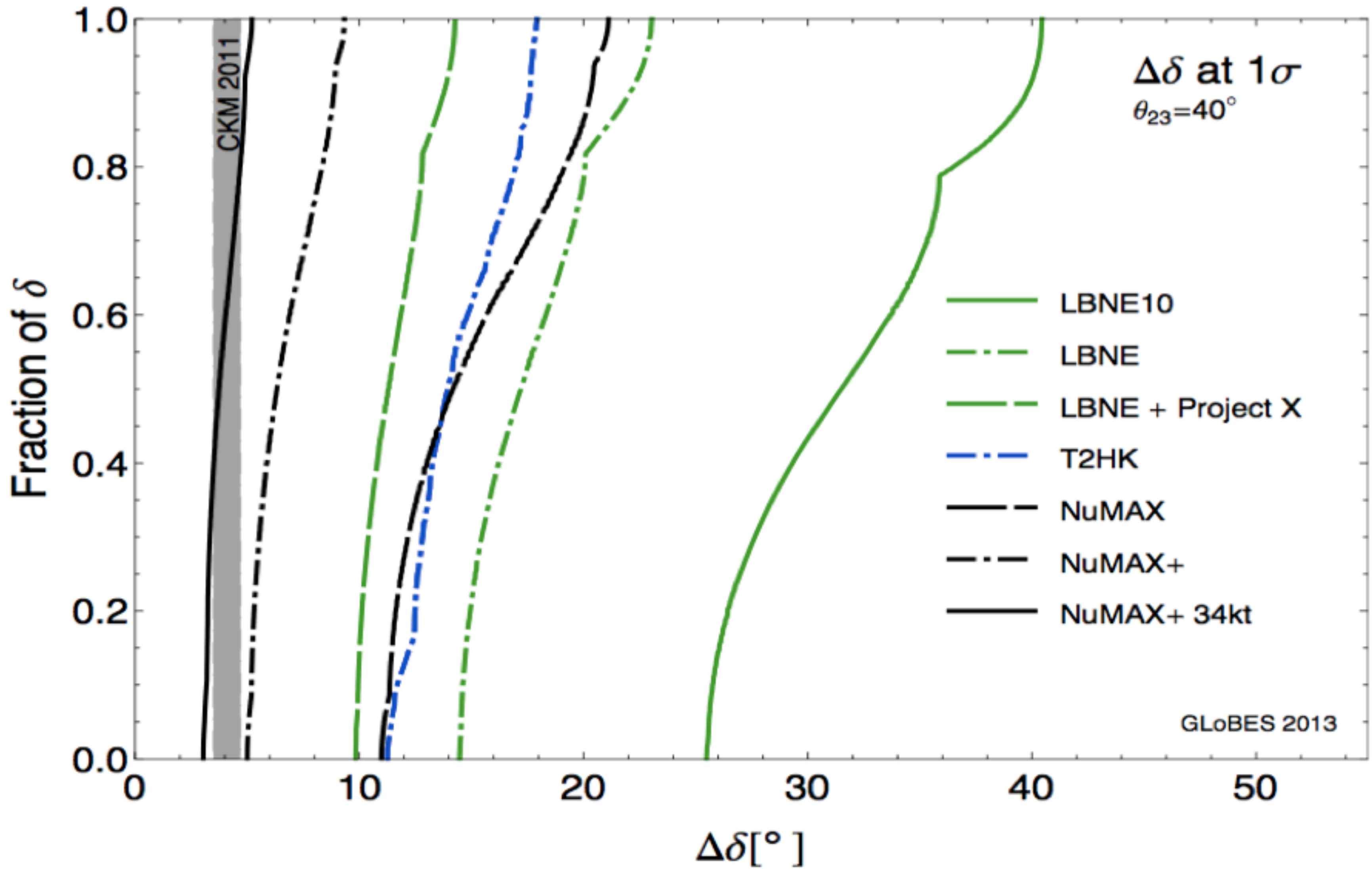
Breadth and Diversity of program

Beyond LBNE

Next-next generation experiments will require better neutrino beam. Options include increased intensity, neutrinos from muon storage rings (NuMAX) and very intense sources of pion decay at rest (DAEδALUS).

See talk 8/16: Shaevitz

Far Future Precision



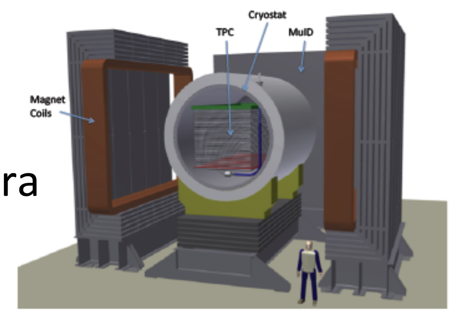
(Patrick Huber *et al.*)

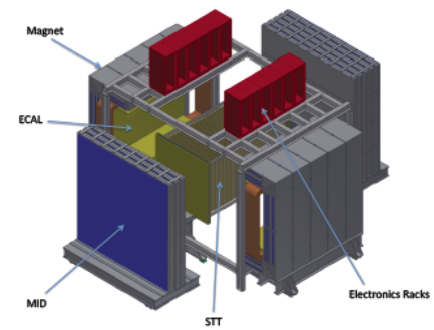
Neutrino Interactions and Cross Sections

• Experiments running and in planning will measure neutrino cross sections for neutrino oscillations and for what we learn about the neutrino

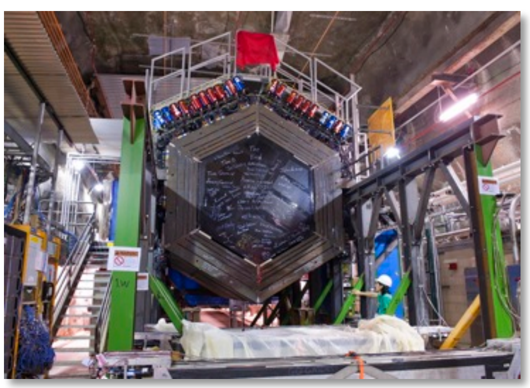
•These are stand alone experiments, development experiments, or function as near detectors for oscillation programs….

See talks 8/15
Rakotondravohitra
Hansen
Adam

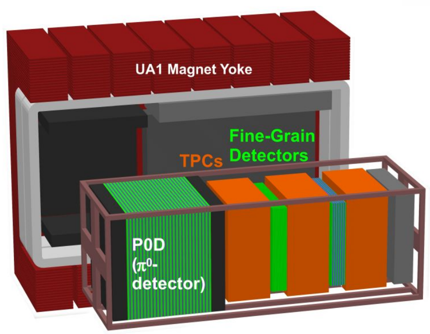




LBNE ND concepts

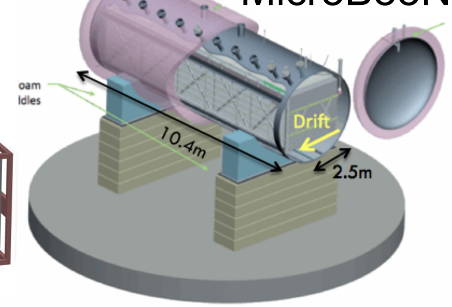


MINERvA



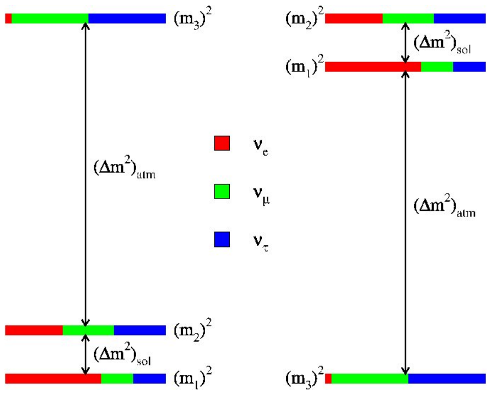
T2K ND280

MicroBooNE



NOvA ND

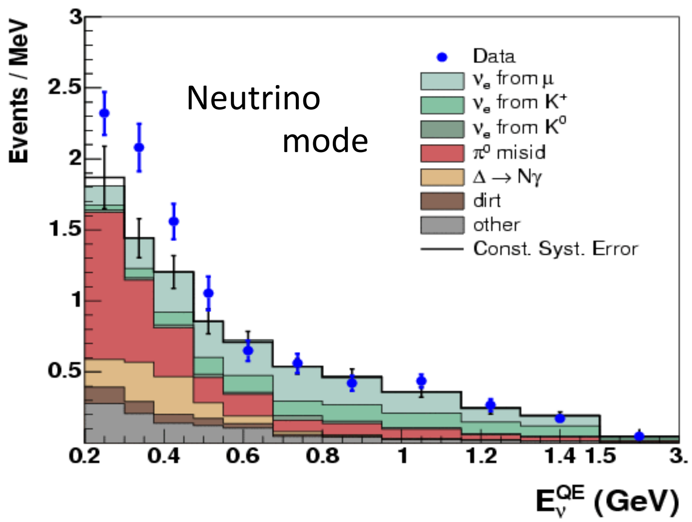
The big questions….

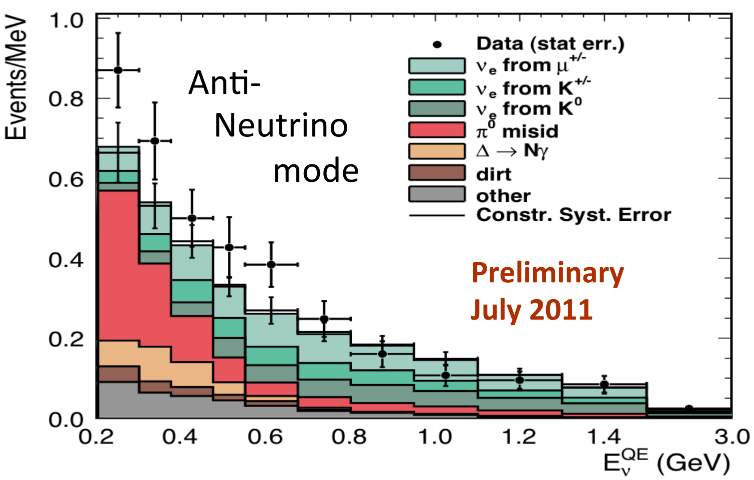


- *what is the absolute neutrino* ***mass scale***
- *are neutrinos* ***Majorana or Dirac****?*
- *what is the neutrino mass ordering?*
- *is* ***CP*** *violated in the neutrino sector?*
- *to what extent does the 3ν paradigm* ***describe nature****?*
- *are there already hints of* ***new physics*** *in existing data?*
- *what new knowledge will neutrinos from* ***astrophysical sources*** *bring?*

•we know this information for every other particle!

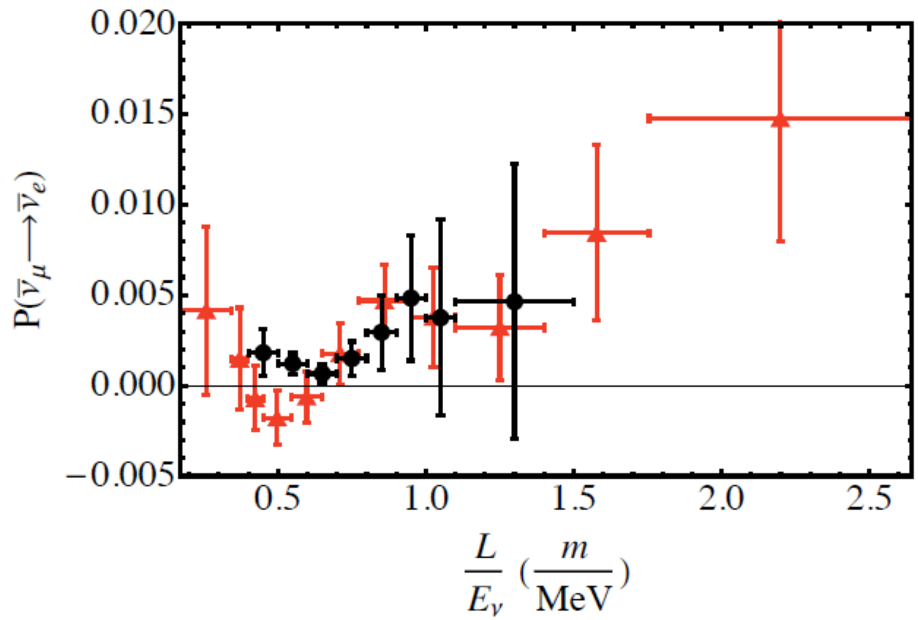
Short Baseline Accelerator Anomalies: LSND and MiniBooNE





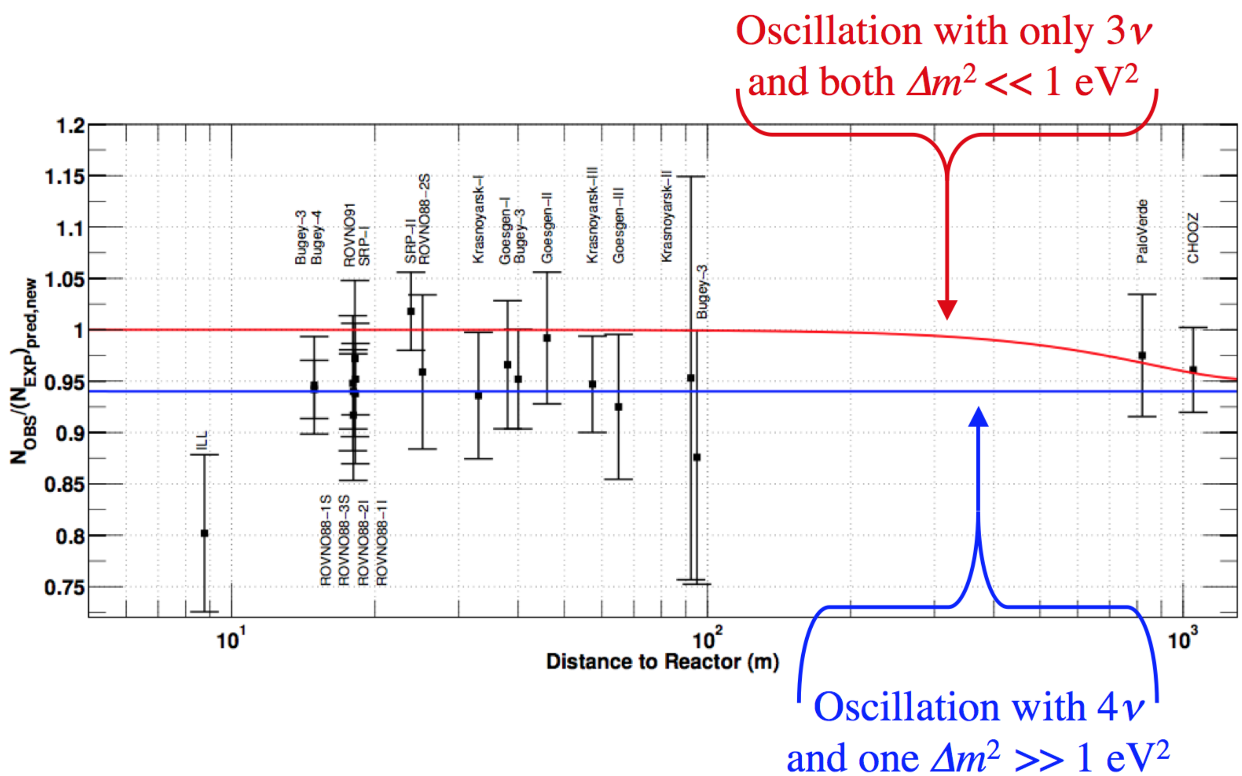
MiniBooNE “low energy excess” – electron-like events in Cherenkov imaging detector, in neutrino and anti-neutrino mode, consistent with LSND anti-electron neutrino appearance.

L/E Comparison
of LSND & MiniBooNE Antineutrino mode



Reactor $\overline{\nu}_e$ Anomaly

In 2011, updated analysis of reactor anti-neutrino spectrum increased expected flux by 3% (Mueller et al., Huber), + increase in calculated cross-section (new neutron lifetime) changed expected detected rate by ~6%



Lhuillier, EPS HEP 2013

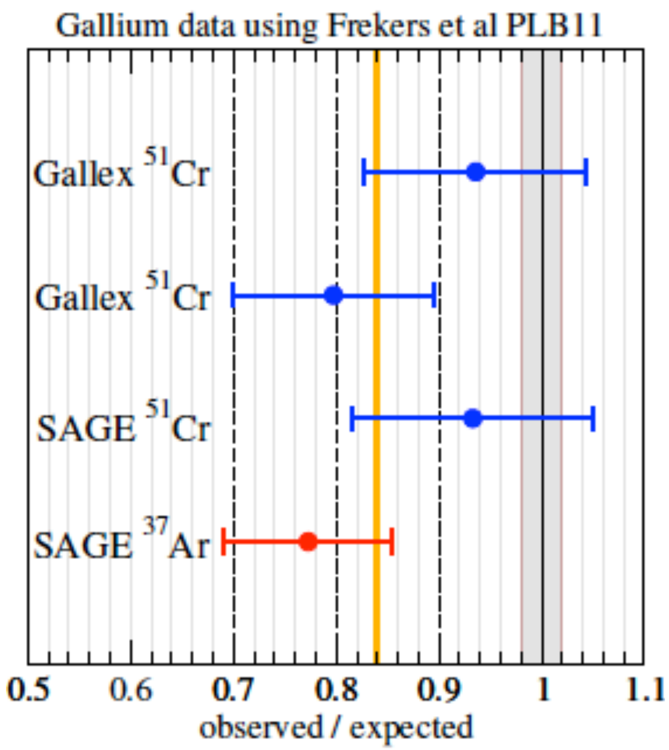
Av. measured/ expected = 0.935 ± 0.024 (2.7σ)

L/E ~ 1–50 m/MeV

Zhang et al (arXiv:1303:0900) say that including LBL reactor data reduces significance: 0.956 ± 0.028 (1.4σ). However, others say otherwise (Kopp et al.)

Radioactive Source Anomaly

Gallex: ^{51}Cr source (750 keV)
Sage: ^{51}Cr & ^{37}Ar (810 keV)



The solar radiochemical detectors GALLEX and SAGE used intense ^{51}Cr and ^{37}Ar electron-capture neutrino sources to "calibrate" the ν_eGa cross-section.

The average measurement / theory:

$$R = 0.84^{+0.054}_{-0.051} \qquad (2.9\sigma)$$

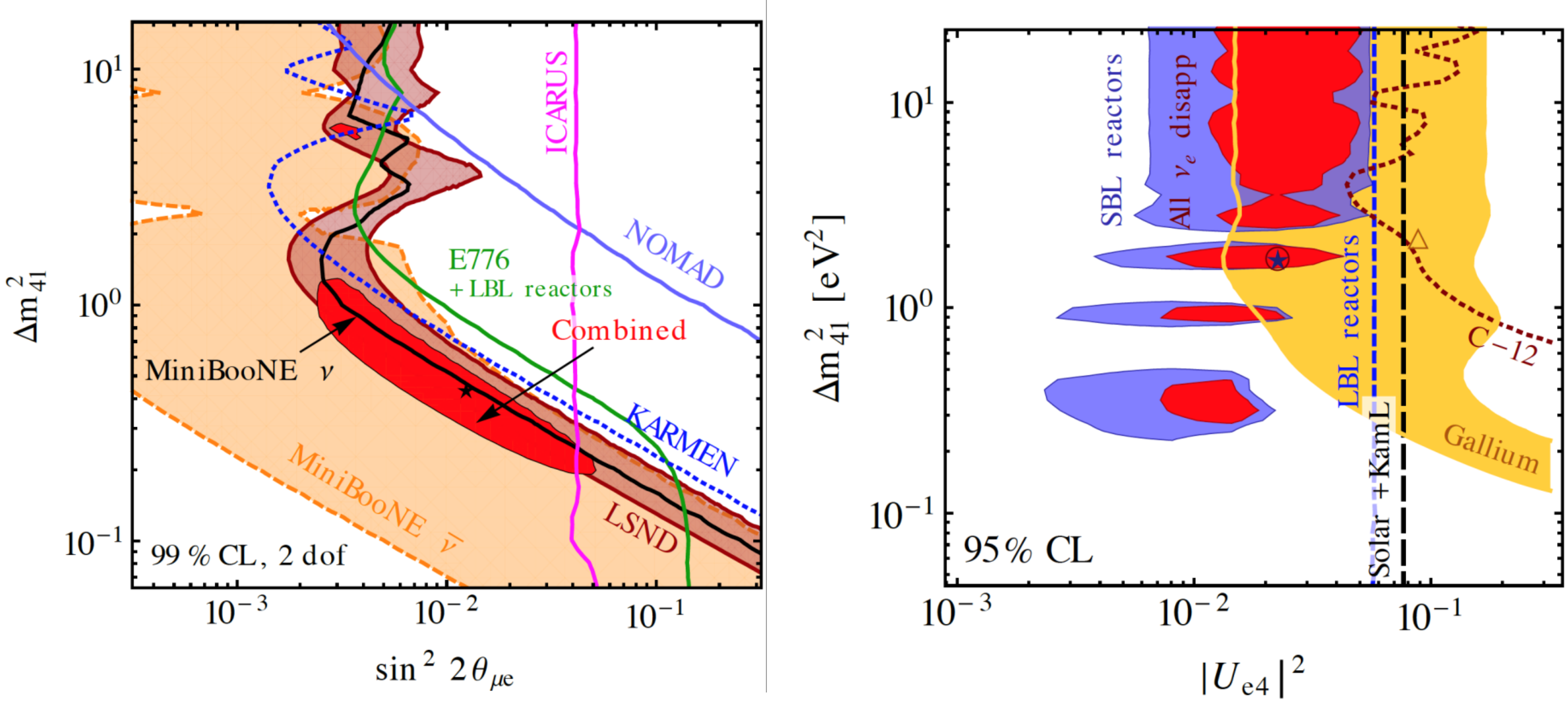
L = O(1) m, E ~ 800 KeV, hence L/E = O(1) m / MeV

INTERPRETATION AS NEW PHYSICS

- Although there are several possibilities (new interactions, violation of fundamental symmetries, sterile neutrinos, …)
- The best motivated new-physics interpretation is as evidence for one or more sterile ν states with masses below a few eV: 3+n models have n new sterile ν states.
- 3+1 models provide good fits for sub-sets of the data (e.g. all the disappearance data, or all the appearance data) but not all of the data. Adding additional sterile neutrinos (3+2, 1+3+1, 3+3, …) does not appear to resolve all of the tensions.

Appearance vs Disappearance

Allowed regions of 3+1 parameter space, 95%CL



Kopp, Machado, Maltoni, Schwetz arXiv: 1303.3011

Subsets of appearance and disappearance data are found to be consistent, and it is only when they are combined and when, in addition, exclusion limits on ν_μ disappearance are included, that tension appears.

Neutrino Anomalies

- clarifying the nature of the existing short-baseline neutrino anomalies is important → we need definitive reactor, source, and accelerator-based experiments

- given the experiments that are already being prepared, we can anticipate significant progress before the next "Snowmass"

  - next 3-5 years: MicroBooNE, MINOS+, radioactive source experiments, new reactor measurements

- if it turns out that any of the anomalies are due to new physics associated with L/E ~ O(1m/MeV) it will be an exciting and revolutionary discovery, and will almost certainly motivate an extensive experimental program

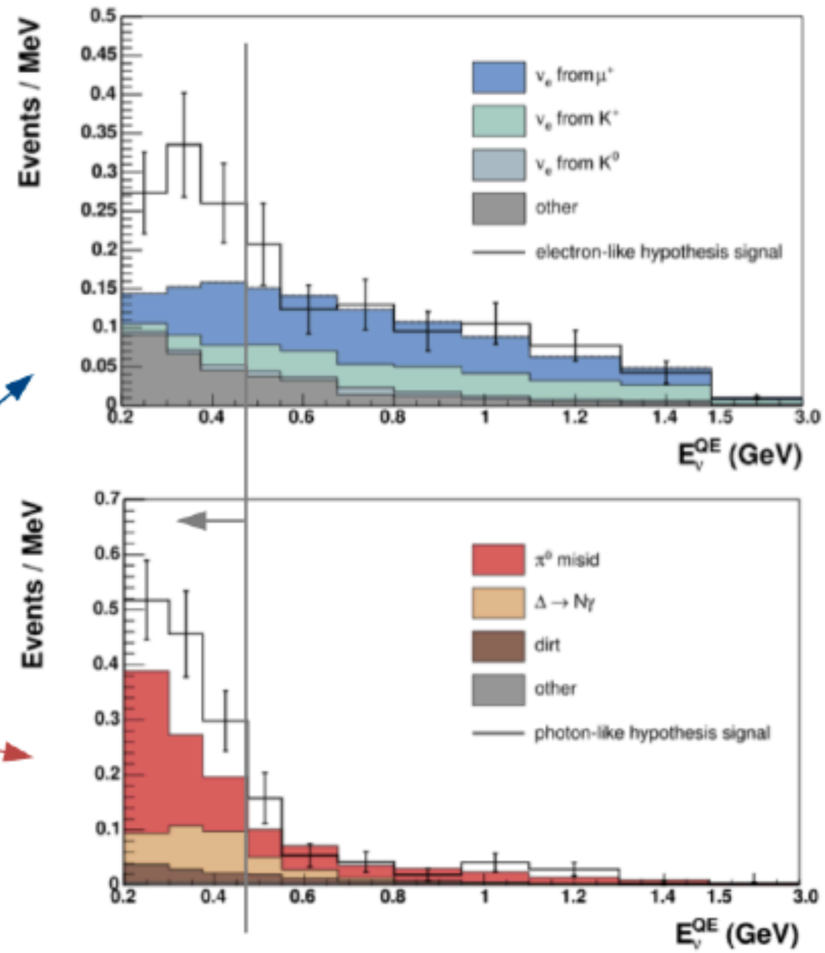
MicroBooNE at Fermilab
170 ton LArTPC at MiniBooNE baseline
Look for MiniBooNE excess with precision detection technique

MicroBooNE sensitivity to low energy excess:

(neutrino running,
- 70 ton fiducial volume,
- x2 higher PID efficiency than MiniBooNE,
- 3% mis-ID,
- 6.0e20 POT)

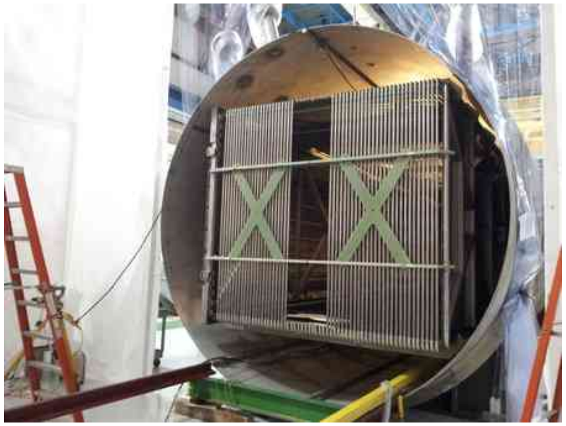
Electron-like hypothesis:
36.8 excess events
41.6 background events
5.7σ stat. significance

Photon-like hypothesis:
36.8 excess events
78.9 background events
4.1σ stat. significance



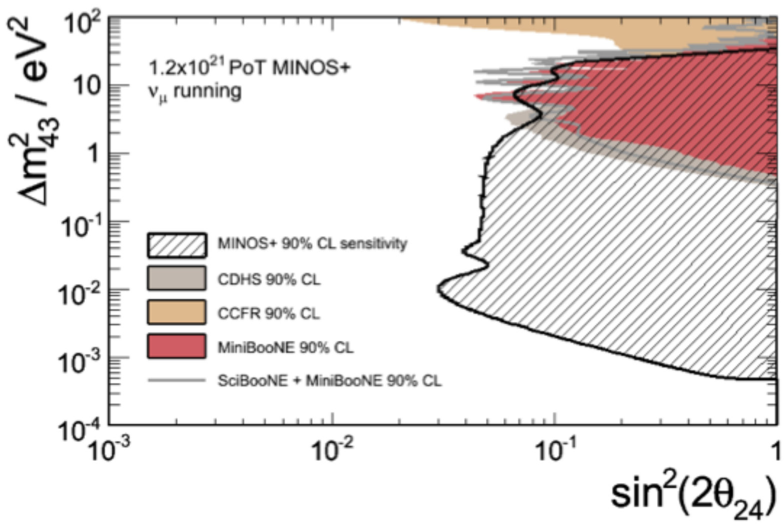
The first to address MiniBooNE low energy excess with data taking in early 2014 uBooNE under construction

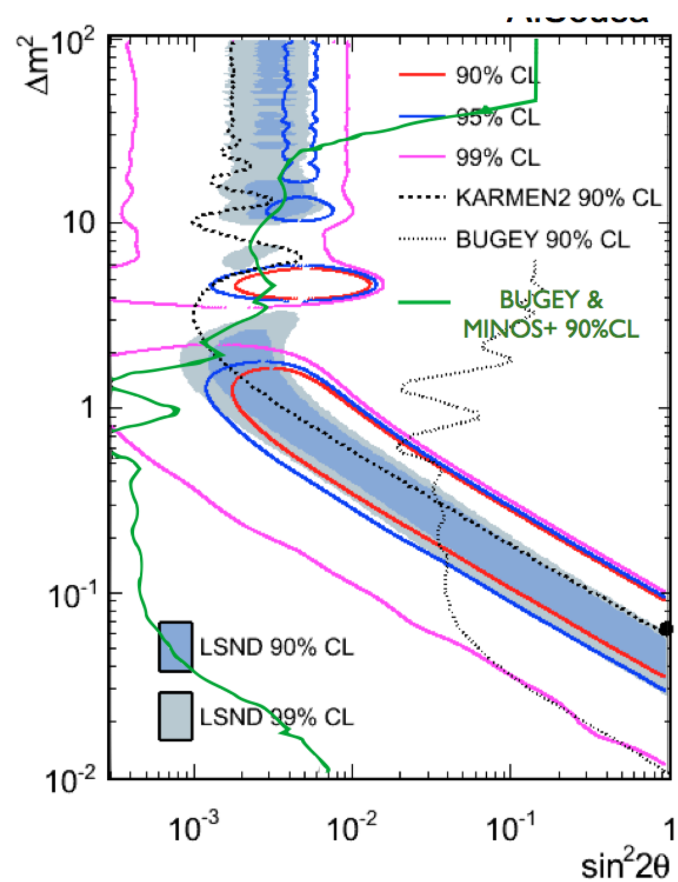
See talk 8/15: Collin



MINOS+ at Fermilab

Search for ν_μ and anti-ν_μ disappearance starts this year





$\sin^2(2\theta_{\mu e}) = 4|U_{e4}|^2 * |U_{\mu 4}|^2$

Within the 3+1 frame-work, can combine ν_μ disappearance and anti-ν_e disappearance results to say some-thing about ν_μ ν_e transitions.

See talk 8/16: Aurisano

New Initiatives

- Many ideas worldwide – *US based examples*

Experiment	ν Source	ν Type	Channel	Host	Cost Category[1]
Ce-LAND [194]	^{144}Ce-^{144}Pr	$\bar{\nu}_e$	disapp.	Kamioka, Japan	small[2]
Daya Bay Source [195]	^{144}Ce-^{144}Pr	$\bar{\nu}_e$	disapp.	China	small
SOX [196]	^{51}Cr	ν_e	disapp.	LNGS, Italy	small[2]
	^{144}Ce-^{144}Pr	$\bar{\nu}_e$	disapp.		
US Reactor [197]	Reactor	$\bar{\nu}_e$	disapp.	US[3]	small
Stereo	Reactor	$\bar{\nu}_e$	disapp.	ILL, France	NA[4]
DANSS [198]	Reactor	$\bar{\nu}_e$	disapp.	Russia	NA[4]
OscSNS [199]	π-DAR	$\bar{\nu}_\mu$	$\bar{\nu}_e$ app.	ORNL, US	medium
LAr1 [200]	π-DIF	$\overset{(-)}{\nu}_\mu$	$\overset{(-)}{\nu}_e$ app.	Fermilab	medium
MiniBooNE+ [201]	π-DIF	$\overset{(-)}{\nu}_\mu$	$\overset{(-)}{\nu}_e$ app.	Fermilab	small
MiniBooNE II [202]	π-DIF	$\overset{(-)}{\nu}_\mu$	$\overset{(-)}{\nu}_e$ app.	Fermilab	medium
ICARUS/NESSiE [203]	π-DIF	$\overset{(-)}{\nu}_\mu$	$\overset{(-)}{\nu}_e$ app.	CERN	NA[4]
IsoDAR [96]	^{8}Li-DAR	$\bar{\nu}_e$	disapp.	Kamioka, Japan	medium
νSTORM [147]	μ Storage Ring	$\overset{(-)}{\nu}_e$	$\overset{(-)}{\nu}_\mu$ app.	Fermilab/CERN	large

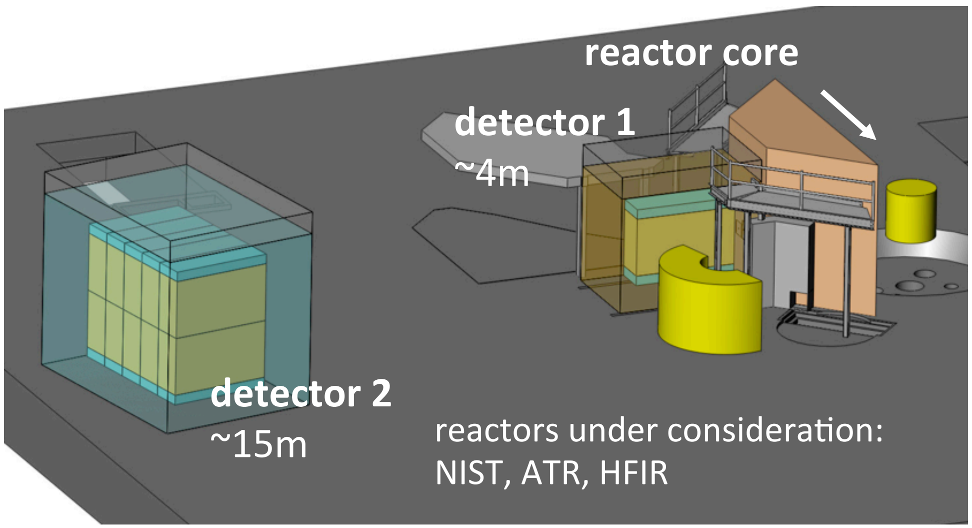
as listed in neutrino working group paper

US Short-Baseline Reactor Experiment

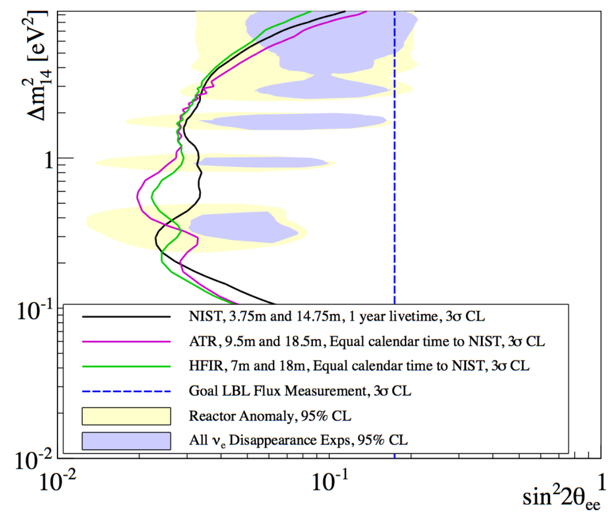
Objectives

- short-baseline neutrino oscillation search with high sensitivity, probe of new physics
- test of the oscillation region suggested by reactor anomaly and $\bar{\nu}_e$ disappearance channel
- precision measurement of reactor $\bar{\nu}_e$ spectrum for physics and safeguards
- develop antineutrino-based reactor monitoring technology for safeguards

2-Detector Oscillation Experiment



Discovery Potential



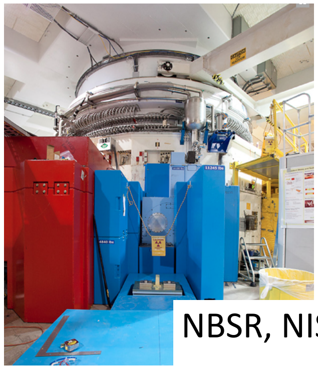
Technically Limited Schedule

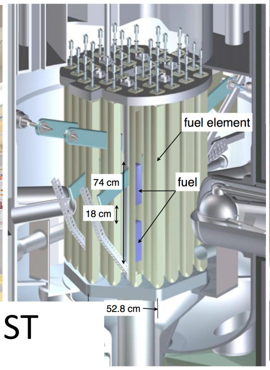
FY13-14 - R&D
FY14-15 - design&construction
FY 2016 - first data?

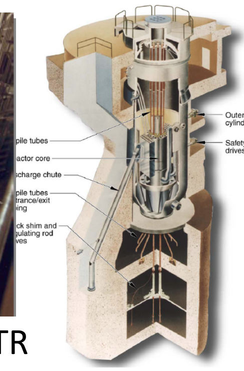
Scientific Reach:

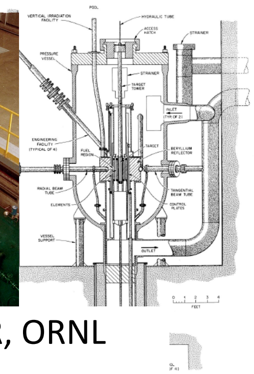
3σ in 1 year, 5σ in 3 years

US Research Reactors



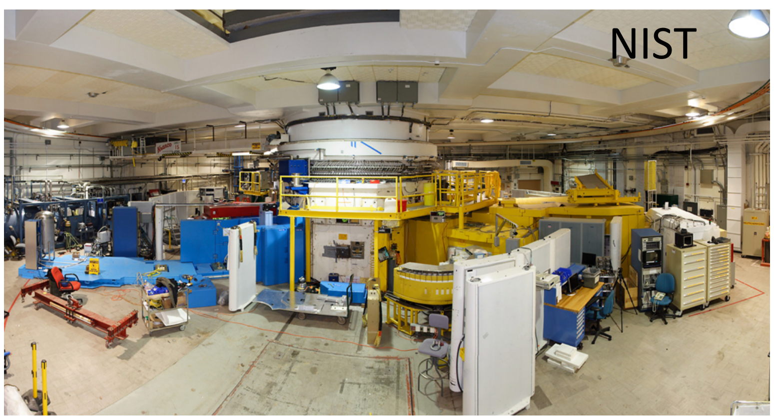


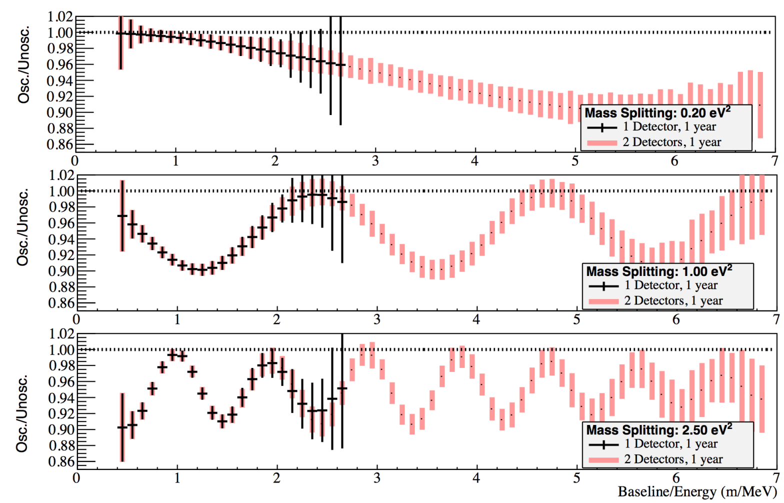




Site	Power	Duty Cycle	Near Detector Baseline	Average $\bar{\nu}$ Flux (Near)	Far Detector Baseline	Average $\bar{\nu}$ Flux (Far)
NIST	20 MW_{th}	68%	3.9m	1	15.5	1
HFIR	85 MW_{th}	41%	6.7m	0.96	18	1.93
ATR	120 MW_{th}	68%	9.5m	1.31	18.5	4.30

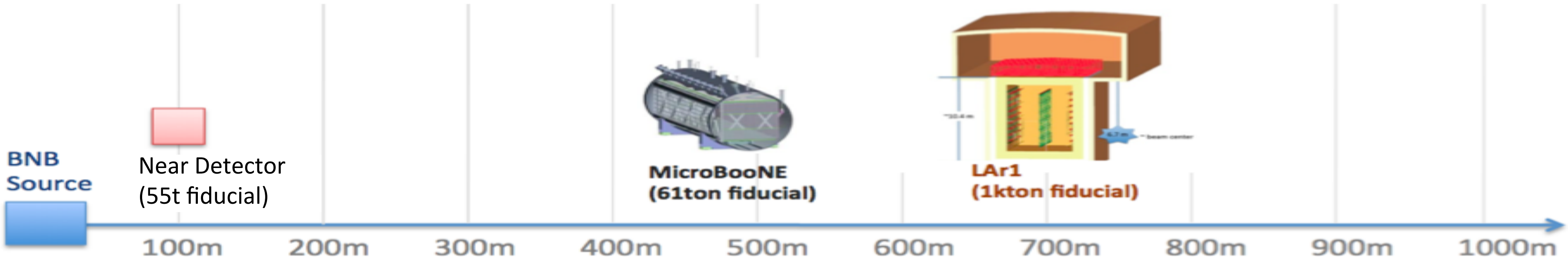
arXiv:1307.2859 (2013)
Mumm, Littlejohn, KMH





LAr1: MicroBooNE follow-on for near-far comparisons for nu and nubar searches

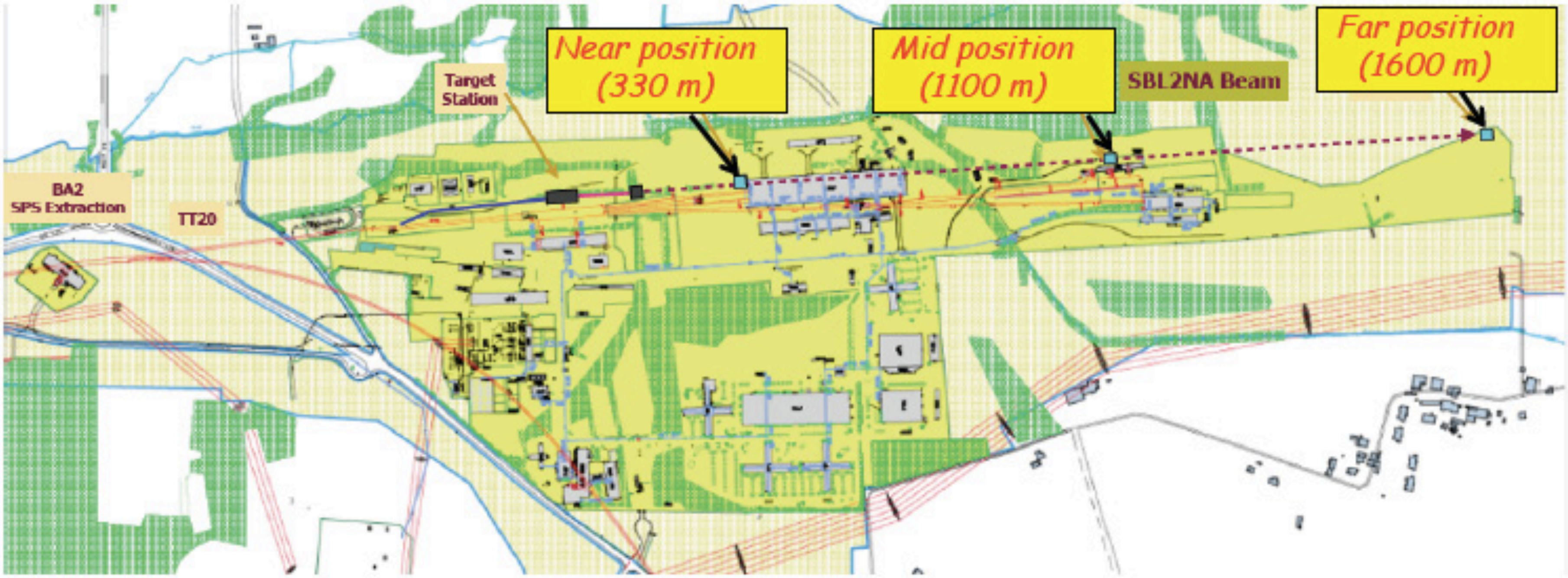
$(40t, 100\ m)$ $(61t, 470\ m)$ $(1000t, 700\ m)$



Phase 1: Near detector at 100m from target to measure un-oscillated flux: neutrino mode with uboone. Interpret uboone result! Due to oscillations?

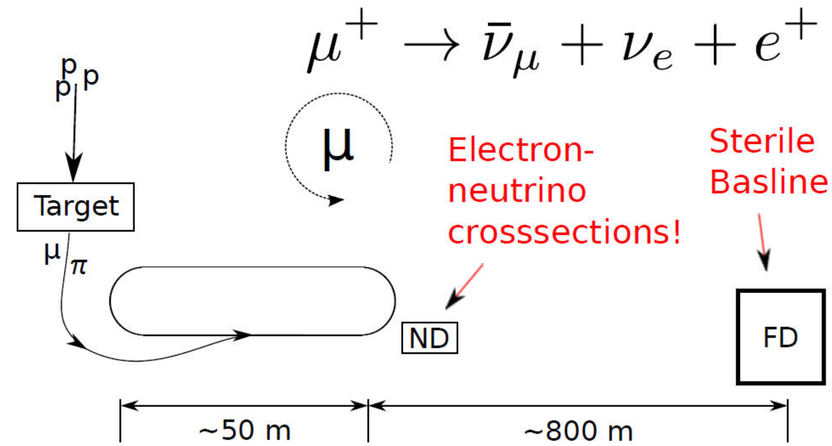
Phase 2: Second far detector (1kton fiducial) for anti-neutrino mode

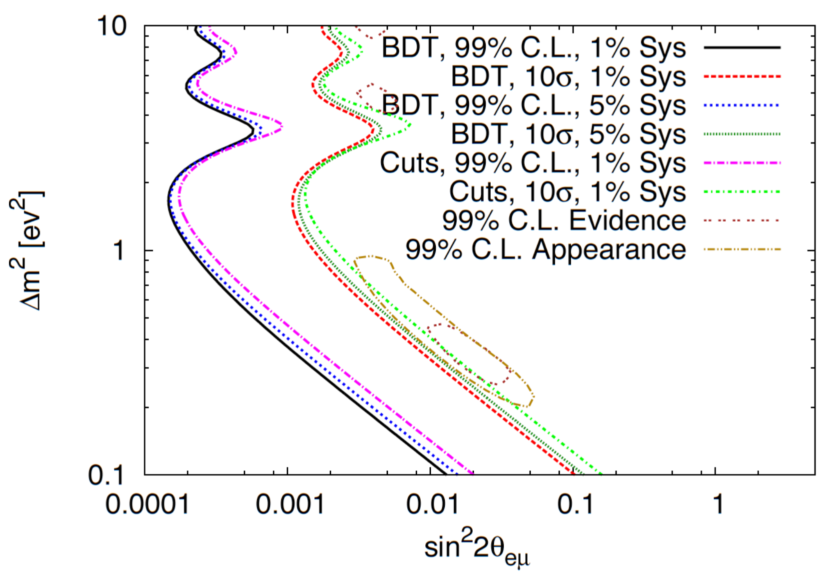
New Neutrino Facility in the CERN North Area

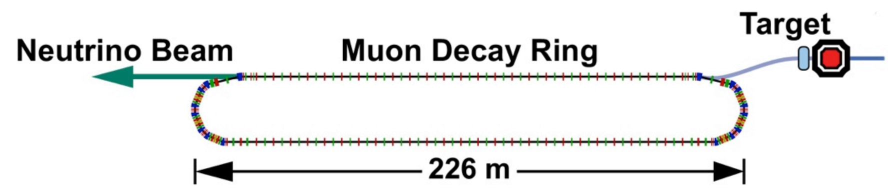


100 GeV primary beam fast extracted from SPS; target station next to TCC2; decay pipe l =100m, ø = 3m; beam dump: 15m of Fe with graphite core, followed by μ stations.
Neutrino beam angle: pointing upwards; at -3m in the far detector ~5mrad slope.

νSTORM







Muon storage ring neutrino source proposed at FNAL (stage 1 approval) & CERN.

At FNAL use 120 GeV MI protons, carbon target, horn focusing, decay channel, storage ring, 2 magnetized detectors … i.e. existing technologies.

Offers advantages of Neutrino Factory without the intensity … OK for SBL experiment & offers a path towards a NF in the longer term.

Impressive sensitivity.

Worldclass, diverse program of neutrino physics

- Physics of neutrinos addressing some of the **most compelling questions** in particle physics
  - About **neutrinos**
  - About the **Standard Model** and the **Universe**
  - Across traditional subfields
- Many different ways to address questions: source, size, technology
- Questions span understanding observed phenomena to looking for the **unexpected**