Experimental Neutrino Physics

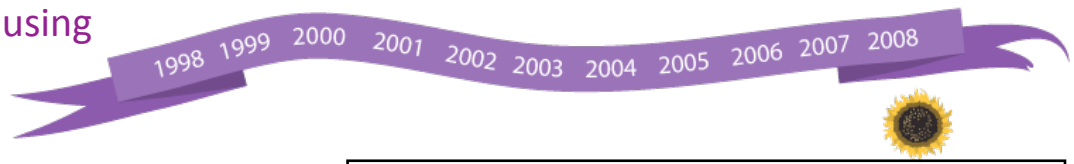
CHRIS WALTER, DUKE UNIVERSITY

Fermi National Accelerator Laboratory Colloquium

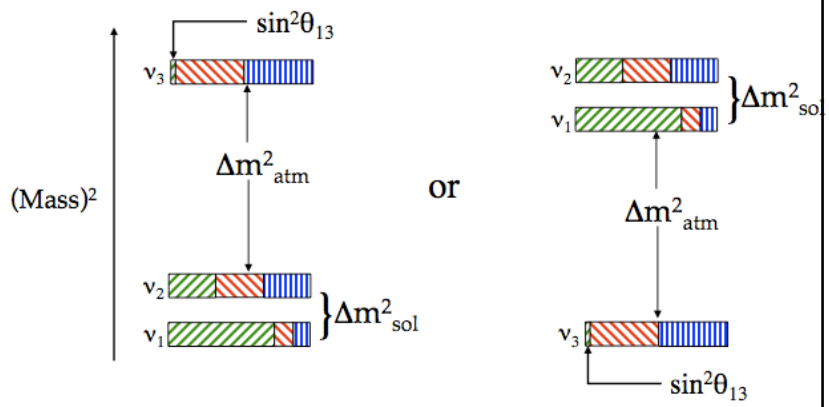
Wednesday August 13th 2008

Introduction

10 years since the discovery of neutrino mass using atmospheric neutrinos.



- Solution to the solar neutrino problem.
- Confirmation of solar and atmospheric neutrinos parameters with man-made sources on earth.
- First real time measurement of low energy solar neutrinos



"Normal" "Inverted"

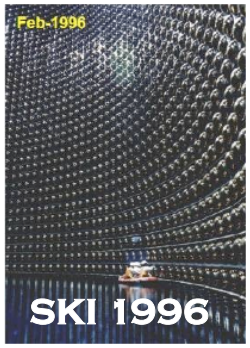
- What is the absolute mass?
- What is the pattern of neutrino masses?
- Are neutrinos their own anti-particles?
- Is there CP violation in the neutrino sector? Is it big enough to drive lepto-genesis and is it related to the quark sector?
- What is the value of the final unmeasured mixing angle, and is the atmospheric angle maximal?

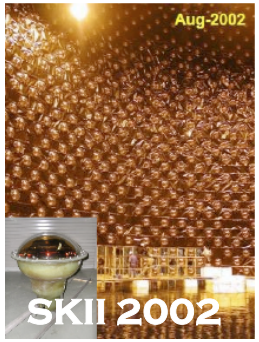
Atmos Oscillations — unknown — Solar Oscillations

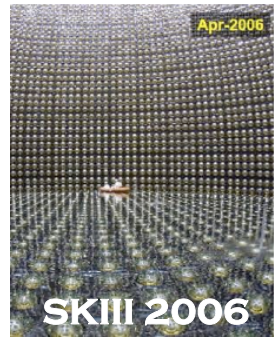
$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = \mathrm{U} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix} \quad \mathrm{U} = \begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix} \begin{pmatrix} c_{13} & 0 & \boxed{s_{13}e^{i\delta}} \\ 0 & 1 & 0 \\ -s_{13}e^{i\delta} & 0 & c_{13} \end{pmatrix} \begin{pmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix}$$

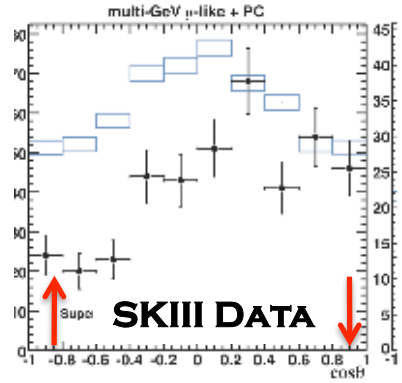
$$c_{23} = \cos\theta_{23}$$

Atmospheric ν oscillations: Super-K







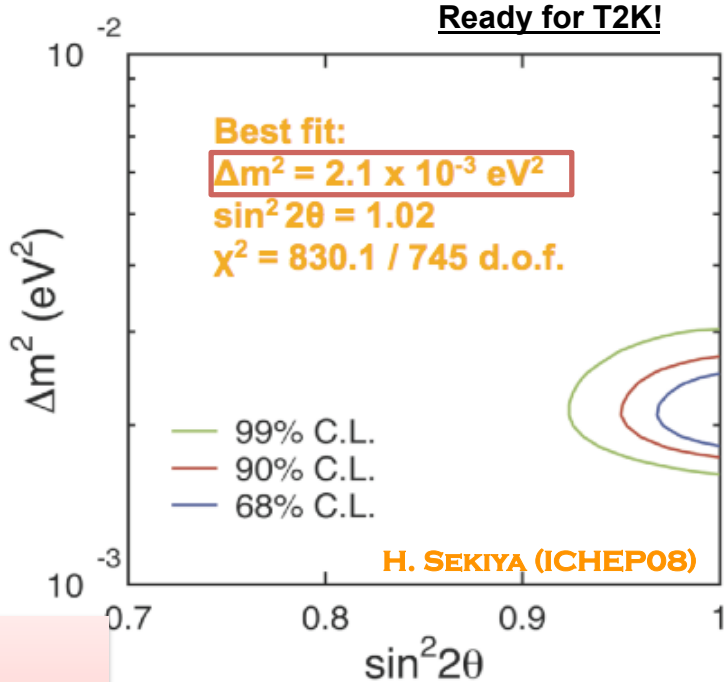


Ready for T2K!

Updated Analysis

- New Flux (~5% increase)
- Reconstruction Improvements
- Monte Carlo Update (100 -> 500yr)
- Re-evaluation of systematic errors
- Detector Simulation Updates

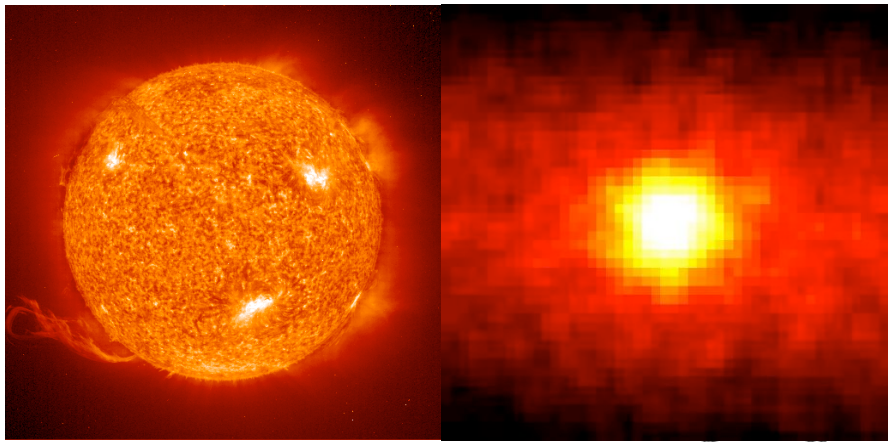
SKI + SKII 141 kton-yr



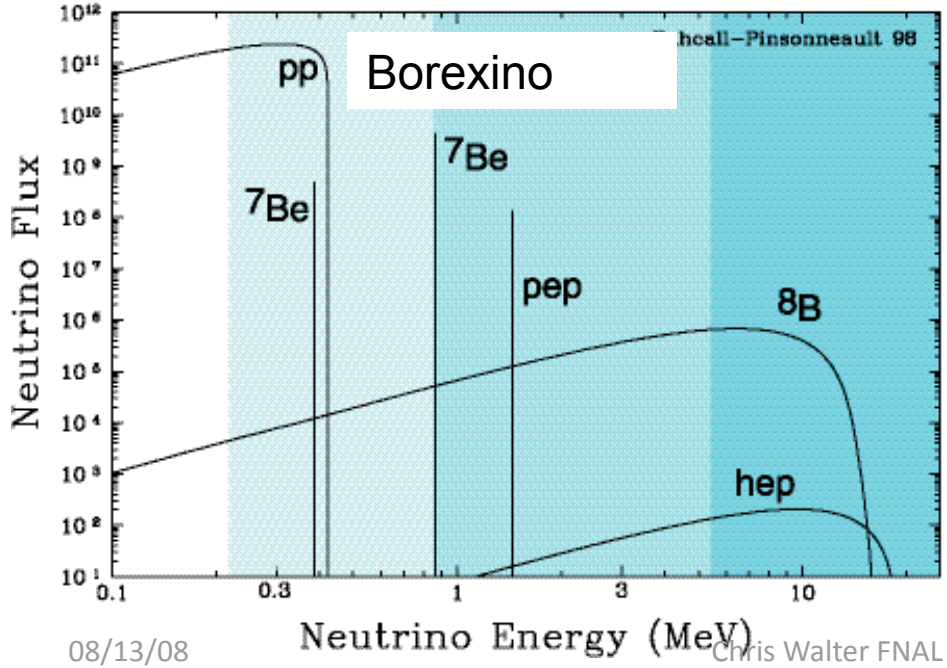
$$P_{\mu\tau} = \sin^2 2\theta \sin^2 \frac{1.27 \Delta m^2 L}{E}$$

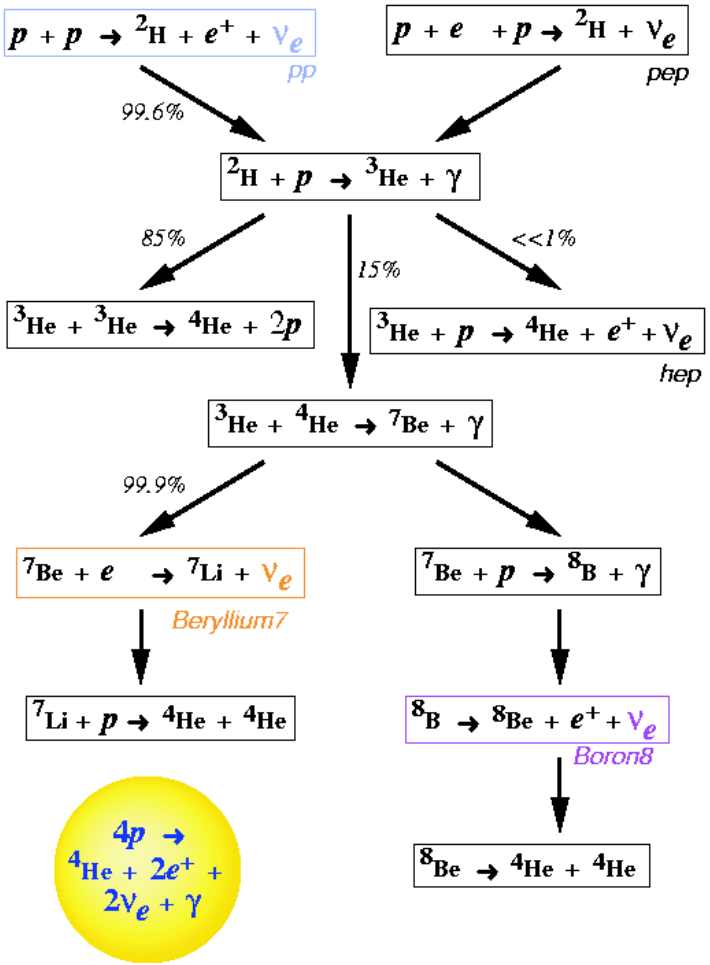
Decay and Decoherence excluded at 4.1 and 5.0 σ
θ_{23} measured to ~45 ± 4° (10% accuracy)
A 23% admixture of sterile neutrinos are allowed.
Soon will have new results on θ_{13} (current limit $\sin^2\theta_{13} < .14$)

Solar Neutrinos



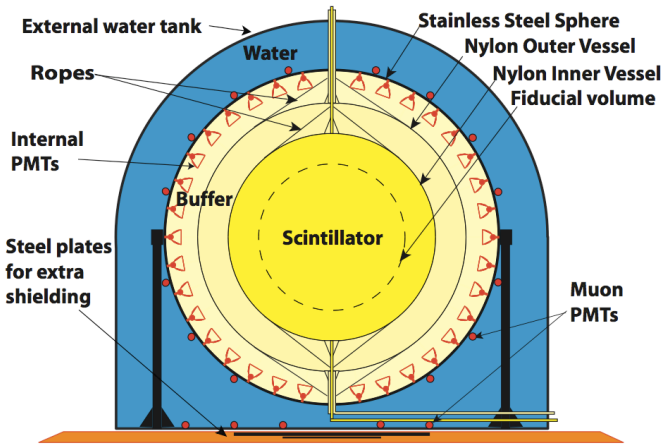
Gallium Chlorine SK/SNO



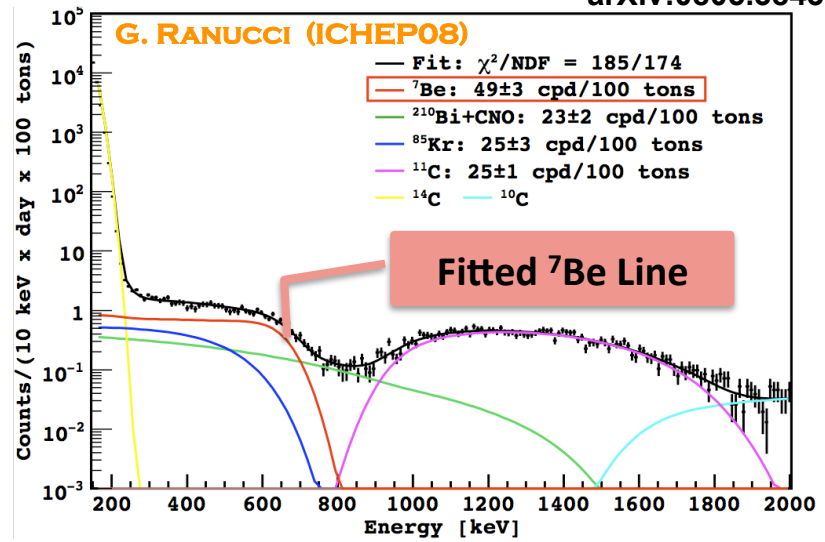


Borexino Results

Also: Galbiati@neutrino2008
arXiv:0805.3843



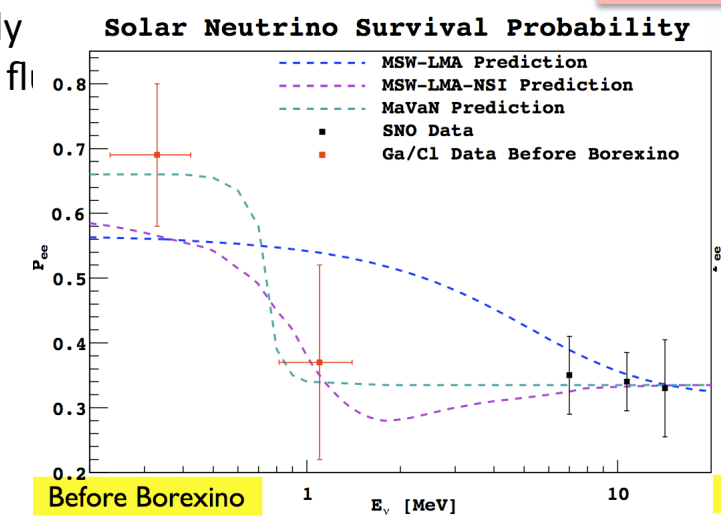
Uses ~300 tons of liquid scinitillator to measure low energy Solar neutrinos.



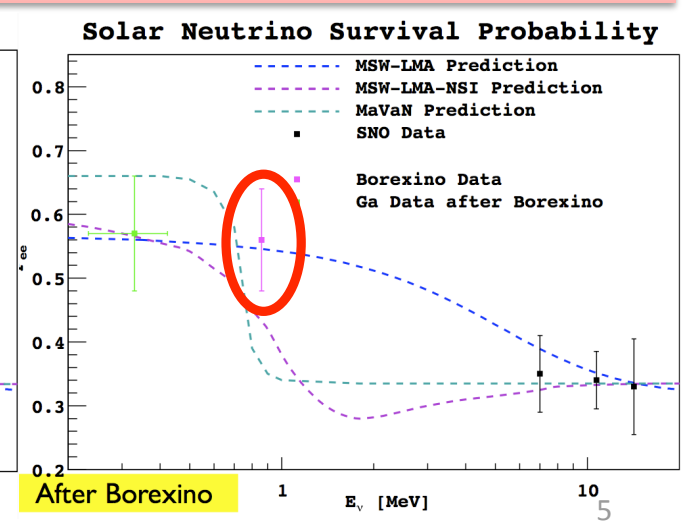
Data: 49 ± 3 (stat) ± 4 (sys)
No Oscillation: 75 ± 4
MSW LMA: 48 ± 4 counts/day/100 ton

New Results

- Use **neutrino electron scattering** to accurately measure the ^{7}Be solar flu
- 192 Days of Data
- **Low energy data consistent with LMA solution!**

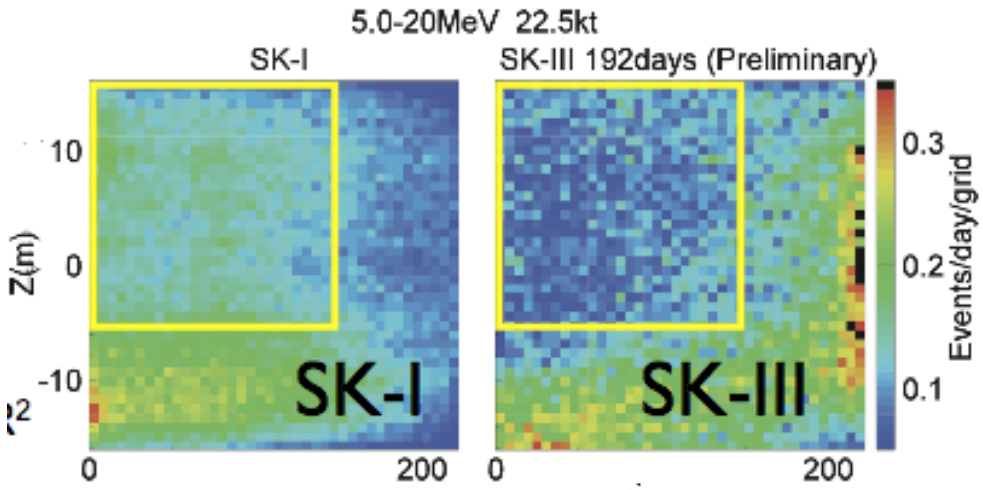


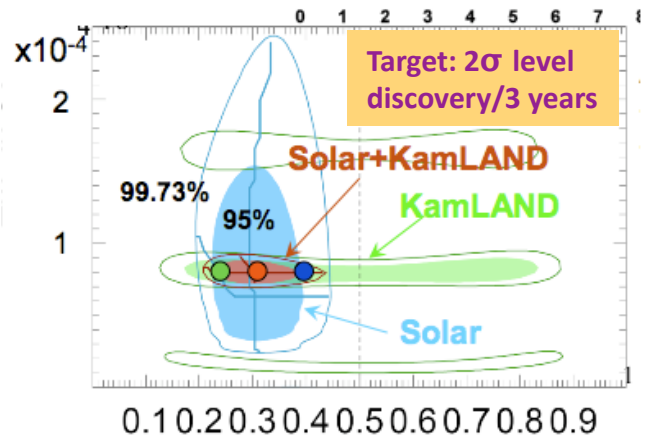
Before Borexino

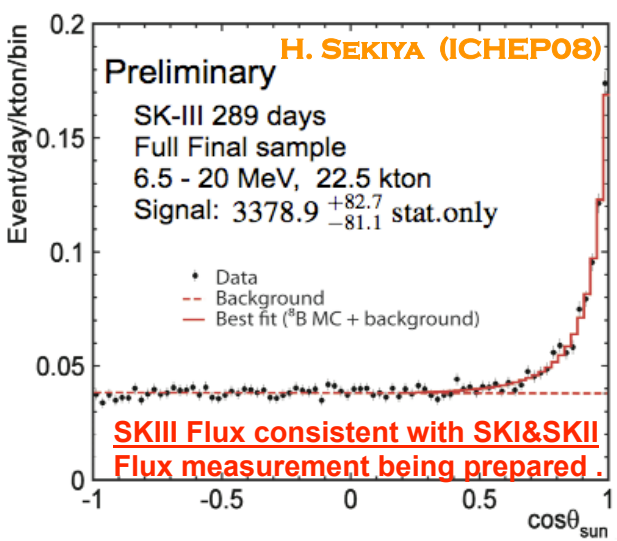


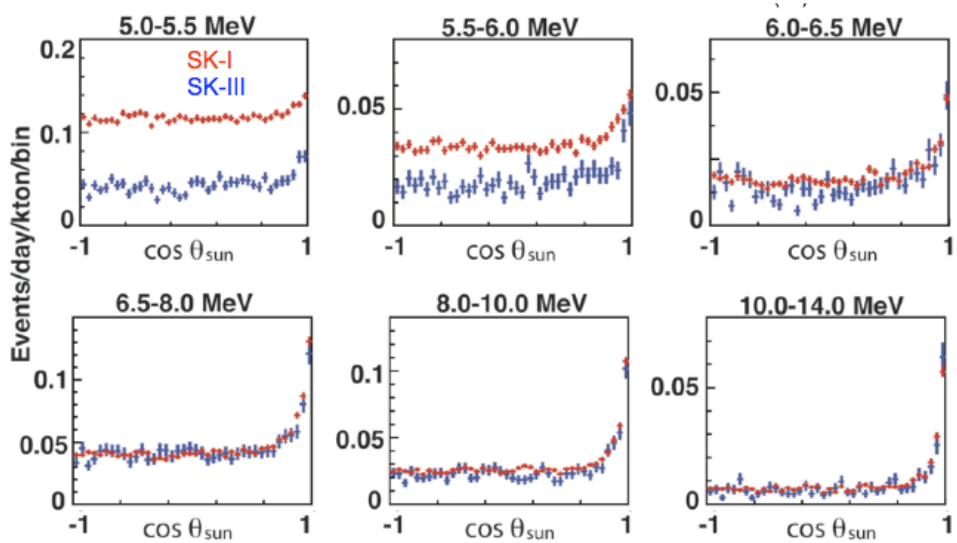
After Borexino

SUPER-K III Solar results and plans





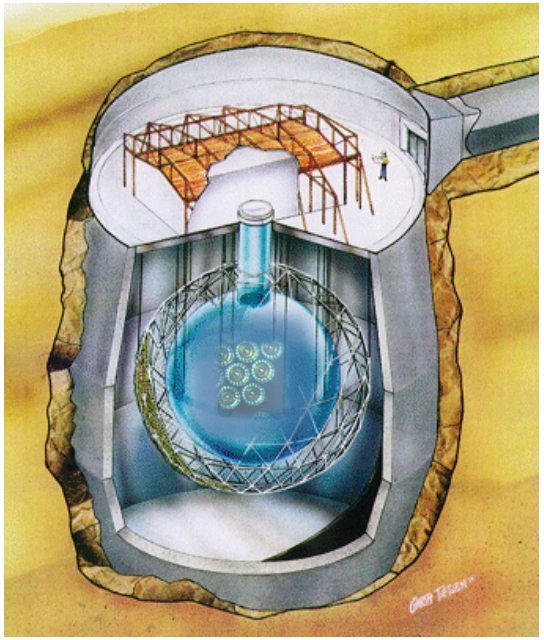




Goal: **See the upturn in probability predicted by LMA** (~10% effect in SK).

-> lower statistical error, lower energy correlated systematic error (to ½ SKI),

-> lower radon background to SK-III levels, reduce threshold (to 4.0 MeV).



SNO Phase III

Three ways to see Solar neutrinos:

$$\nu_x + e^- \rightarrow \nu_x + e^-$$ (Elastic scattering)

$$\nu_e + d \rightarrow p + p + e^-$$ (Charged Current)

$$\nu_x + d \rightarrow p + \boxed{n} + \nu_x$$ (Neutral Current)

Three ways to see neutron:

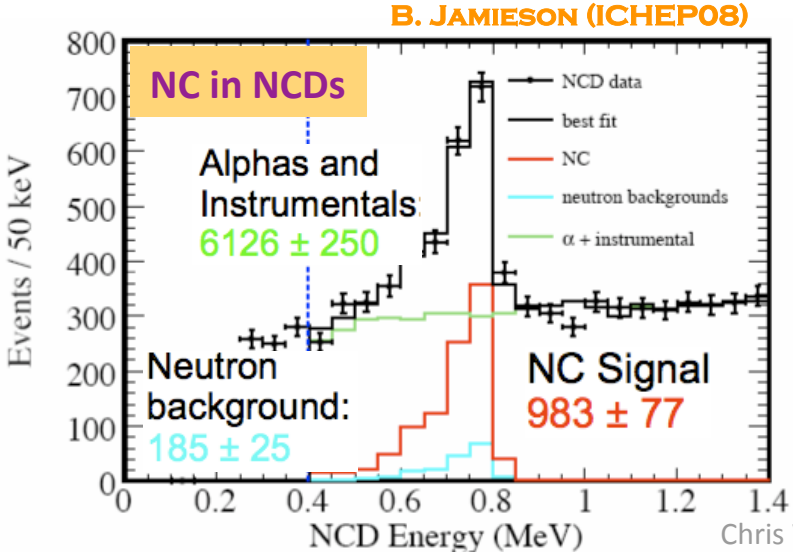
$$n + d \rightarrow t + \gamma + 6.25 \text{ MeV}$$ (Pure D_2O)

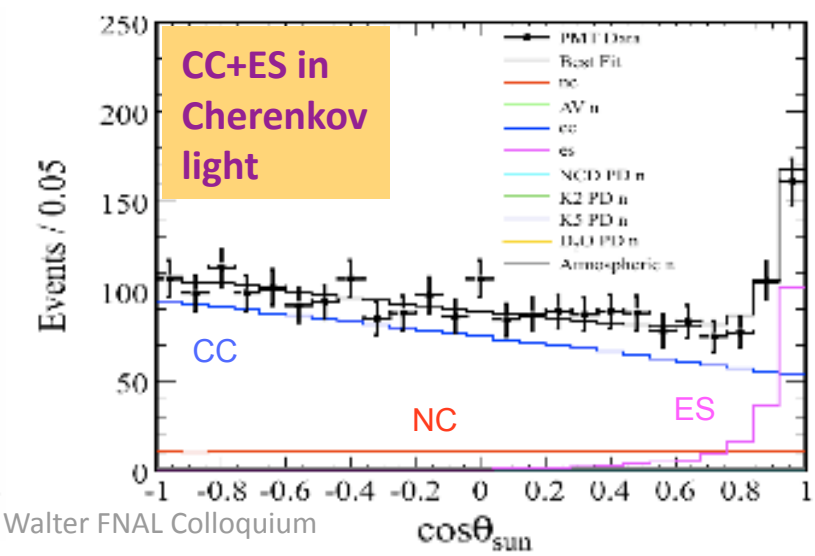
$$n + {}^{35}Cl \rightarrow {}^{36}Cl + \gamma + 8.6 \text{ MeV}$$ (Salt)

$$\boxed{n + {}^{3}He \rightarrow p + t + 0.76 \text{ MeV}}$$ (^{3}He Counter)

NCDs break the correlation between CC and NC
Have different systematic errors

B. Jamieson (ICHEP08)

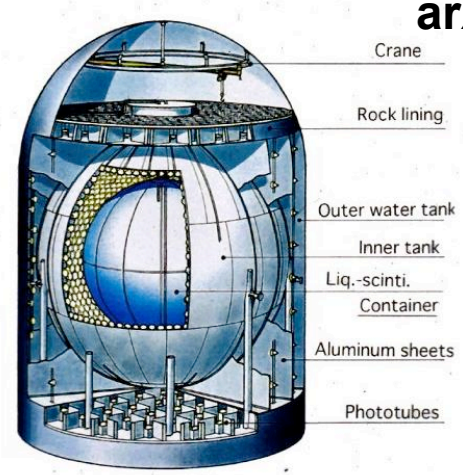




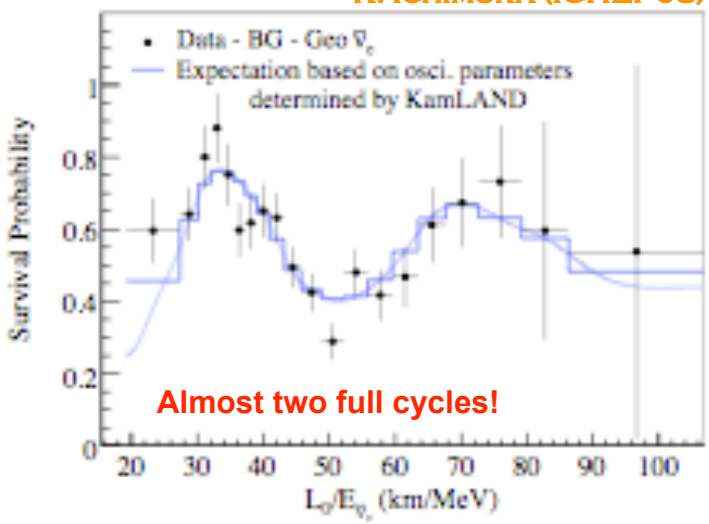
Can now fit separately

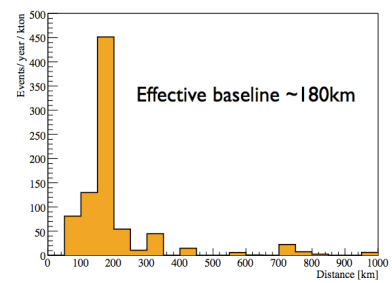
Kamland 2008 Results

arXiv:0806.2237 [hep-ex]



K. Ichimura (ICHEP08)





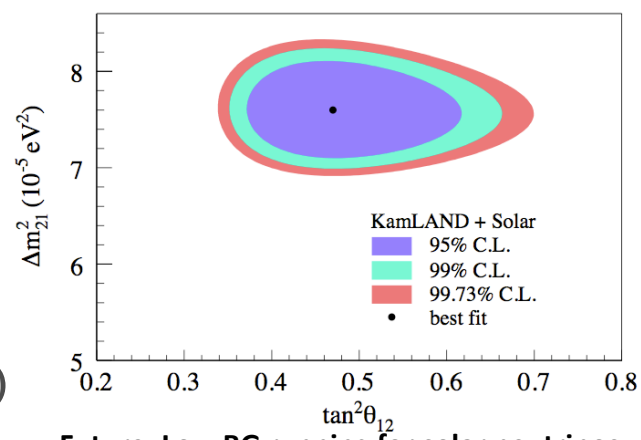
Primary Energy threshold lowered to 1.0 MeV

Event characteristic cut allows data at lower energies closer to the wall.

	Max R (m)	Livetime (days)	Exposure (ton-yr)	increase
KL 2002	5	145	162	X 1
KL 2004	5.5	515	766	X 4.7
2008	**6**	**1491**	**2881**	**X 17.8**

$$\Delta m^2 = 7.59^{+0.21}_{-0.21} \times 10^{-5}\,\mathrm{eV}^2 \quad (2.7\%\ \text{Accuracy})$$

$$\tan^2\theta = 0.47^{+0.06}_{-0.05}$$



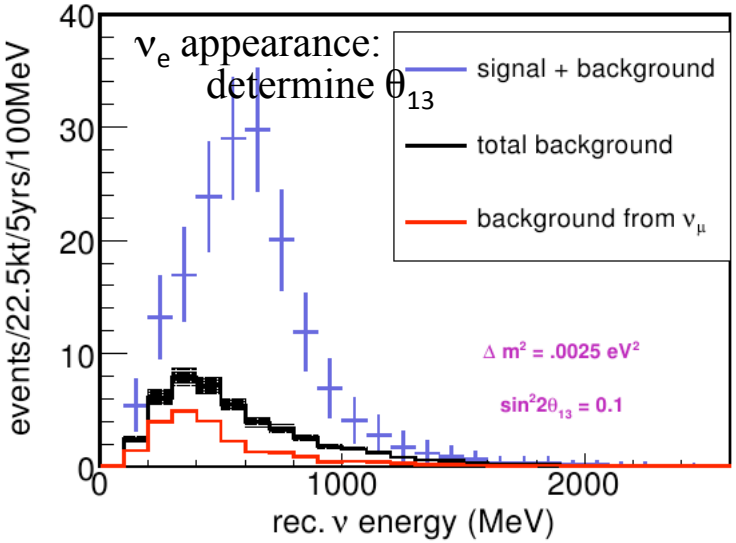
Future: Low BG running for solar neutrinos.

Continue to run with reactor neutrinos

Oscillation searches at accelerators

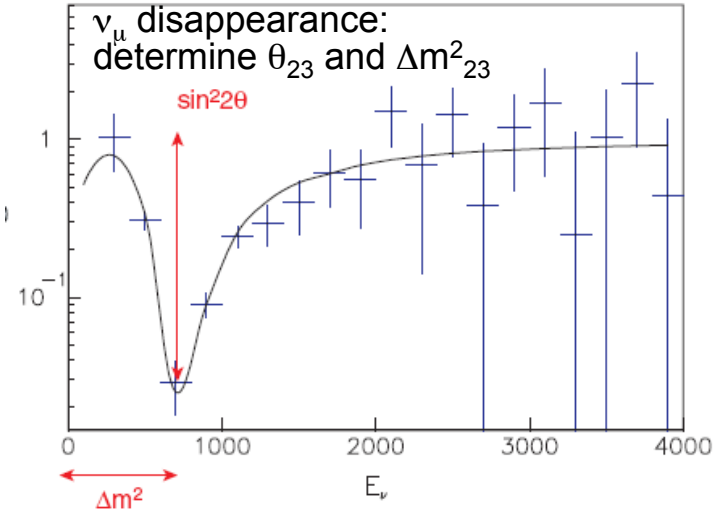
There are two types of searches:
Appearance and Disappearance

- Appearance: MiniBoone, T2K, Nova, OPERA



Enough energy to produce lepton in CC reaction.

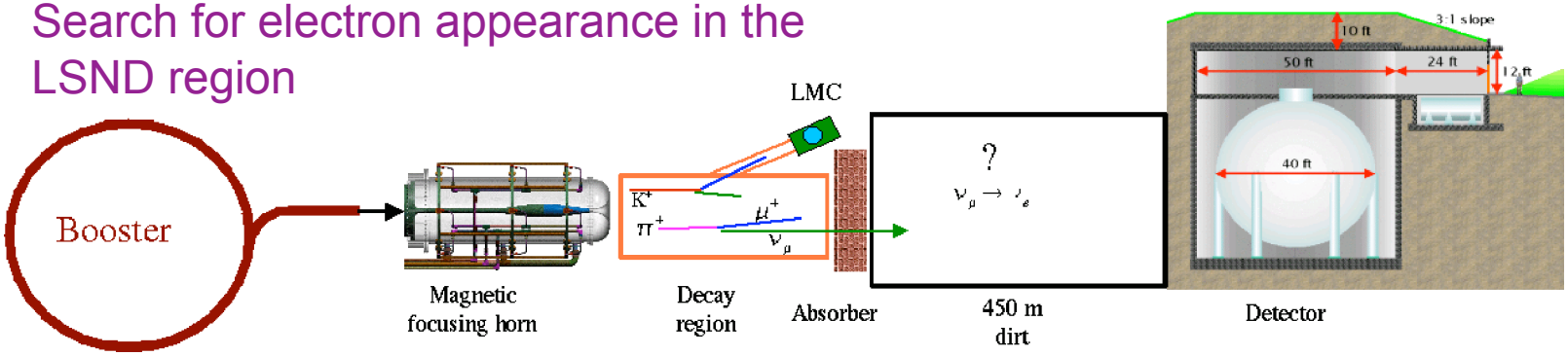
- Disapearance: MINOS, K2K, SK



NOT enough energy to produce lepton in CC reaction.

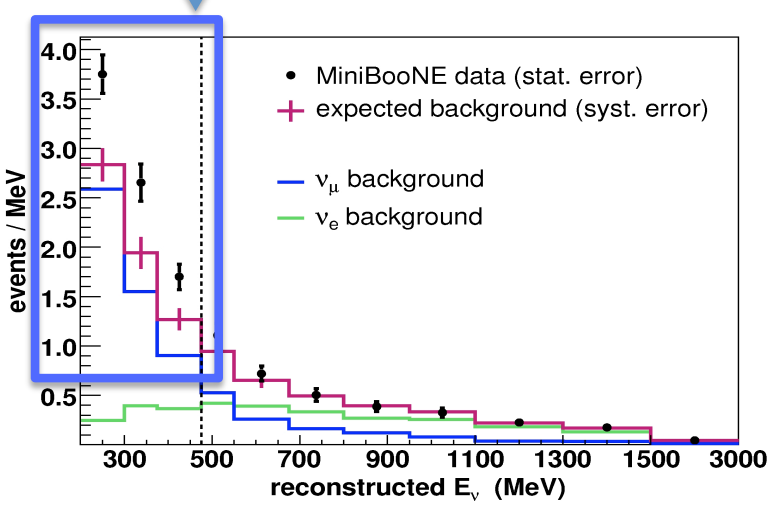
MiniBooNE RESULTS

Search for electron appearance in the LSND region



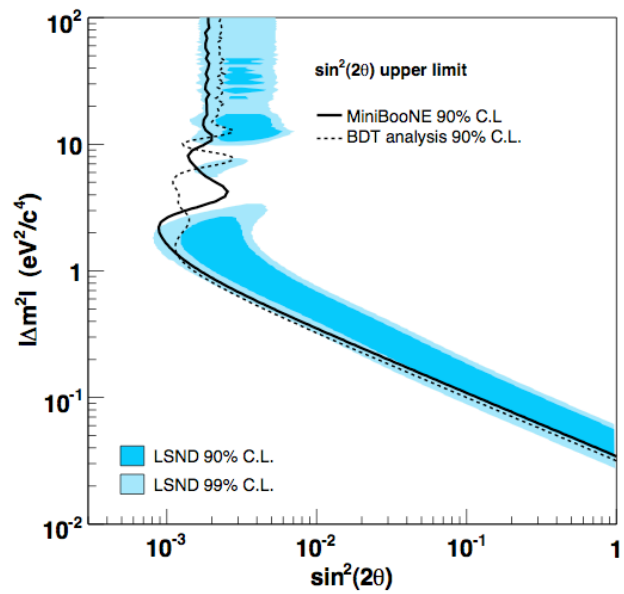
What's going on here?

$475 < E_\nu < 1250$ MeV
380 events Exp: 358±19±35 events
0.55 σ Difference



Phys. Rev. Lett. 98, 231801 (2007), **arXiv:0704.1500 [hep-ex]**

2 neutrino oscillation in the LSND region
Excluded at 98%

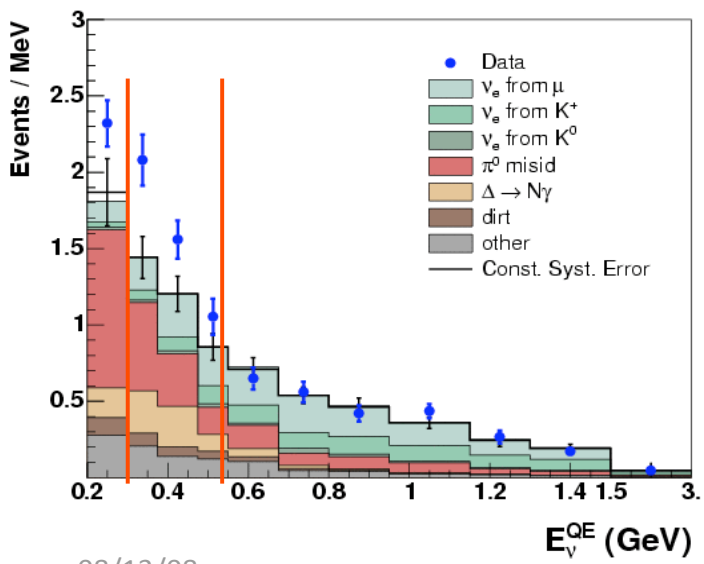


Studying the low energy excess

- Improved coherent π^0 model
- Rechecked backrounds ($\Delta \rightarrow N\gamma$,etc.)
- Included Photo-nuclear interactions.
- Better modeling and rejection of entering background
- Analysis threshold lowered to 200 MeV.
- Systematic errors on flux improved
- Added Data: 5.58×10^{20} pot -> 6.46×10^{20} pot.

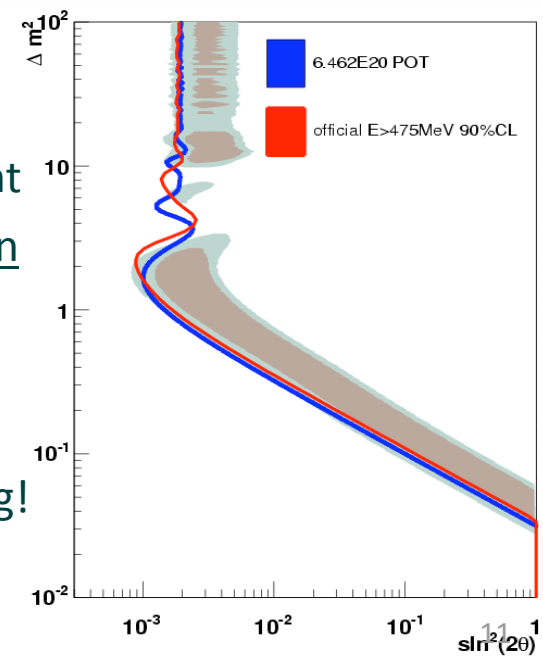
E_ν [MeV]	200-300	300-475	475-1250
total background	186.8±26	228.3±24.5	385.9±35.7
ν_e intrinsic	18.8	61.7	248.9
ν_μ induced	168	166.6	137
NC π^0	103.5	77.8	71.2
NC $\Delta \rightarrow N\gamma$	19.5	47.5	19.4
Dirt	11.5	12.3	11.5
other	33.5	29	34.9
Data	232	312	408
Data-MC	45.2±26	83.7±24.5	22.1±35.7
Significance	1.7σ	3.4σ	0.6σ

Z. Djurcic (ICHEP08)

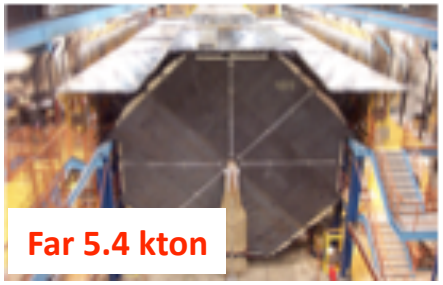


Conclusions:

- Excess remains significant
- Oscillation results remain unchanged
- Now studying NuMI νs with a different L
- Anti-ν results are coming!



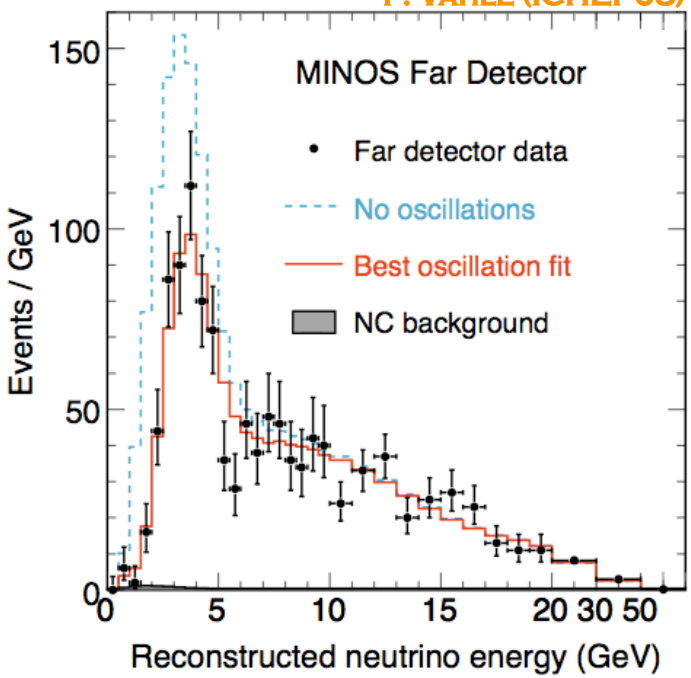
MINOS Results

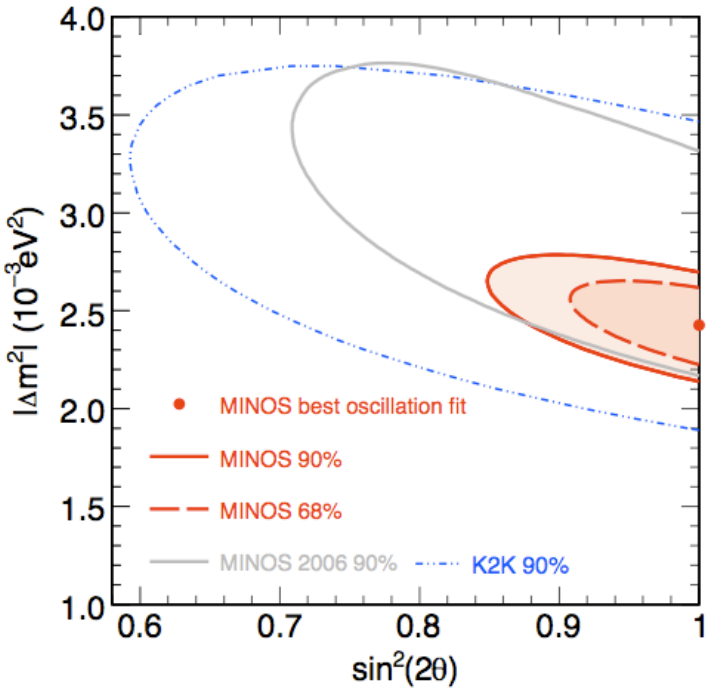


Updated results:
1.3 x 10^{20} pot -> 3.4 x10^{20} pot
arXiv:0806.2237 [hep-ex]
arXiv:0807.2424 [hep-ex]

$|\Delta m^2_{32}|=2.43\pm0.13 \times 10^{-3}$ eV^2 (68% C.L.)
$\sin^2(2\theta_{23})>0.90$ (90% C.L.)

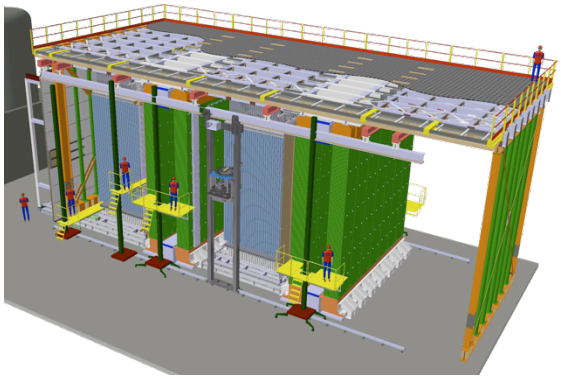
P. Vahle (ICHEP08)





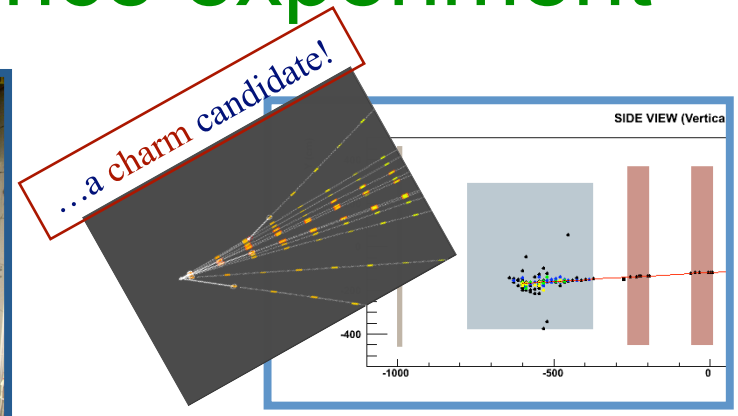
Decay and Decoherence excluded at 4-6 σ
Δm^2_{23} measured to 2.4 ± .13 (5% accuracy)
A 68% admixture of sterile neutrinos are allowed.
Soon will have results on θ_{13} w/sensitivity < CHOOZ

OPERA tau appearance experiment

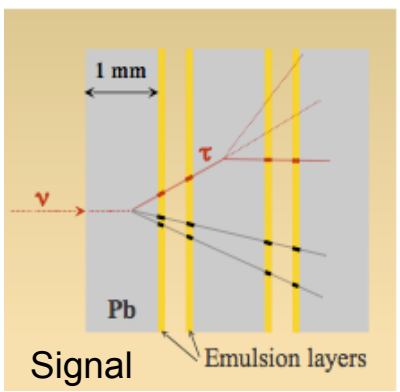


Uses ECC (Emulsion Cloud Chamber)
With automatic scanning
+ Magnetic spectrometer.

After 1.5 years
Block installation done.



Electronic trackers point
Back to bricks.

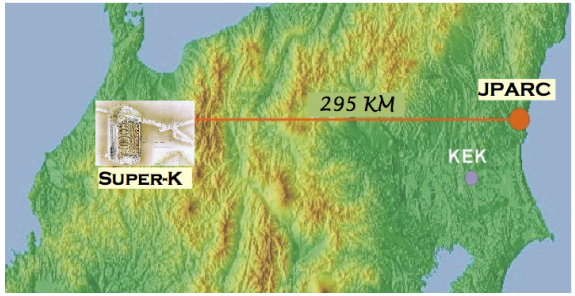


Full beam in 2008

D. Duchesneau (ICHEP08)

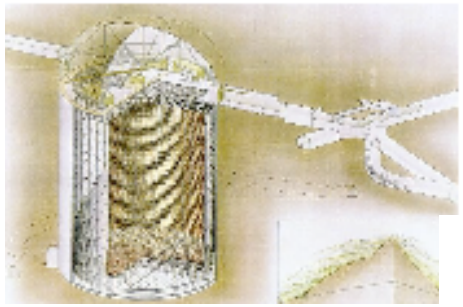
τ decay channel	signal ($\Delta m^2 = 2.5\times10^{-3}$ eV^2)	signal ($\Delta m^2 = 3.0\times10^{-3}$ eV^2)	Bg
τ→ μ	2.9	4.2	0.17
τ→e	3.5	5.0	0.17
τ→h	3.1	4.4	0.24
τ→3h	0.9	1.3	0.17
Total	10.4	14.9	0.75

Full mixing, 5 year run
4.5×10^{19} pot/year, 1.35 kton fiducial mass



T2K

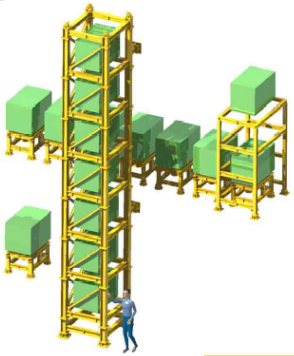
- Neutrino beam starts April 2009
- 280m on-axis + SK ready for beam start
- 280m off-axis installed by fall 2009
- Full running in winter of 2009

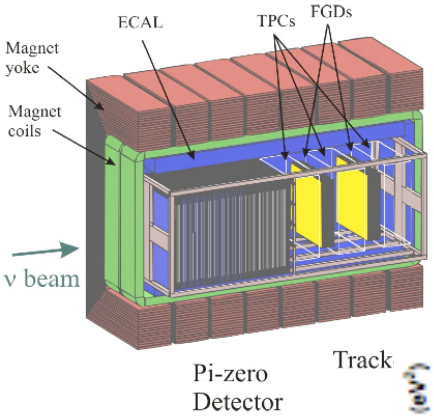


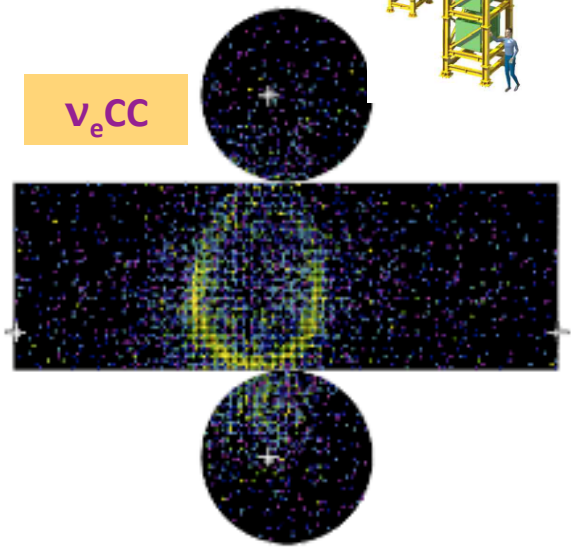
N. McCauley (ICHEP08)

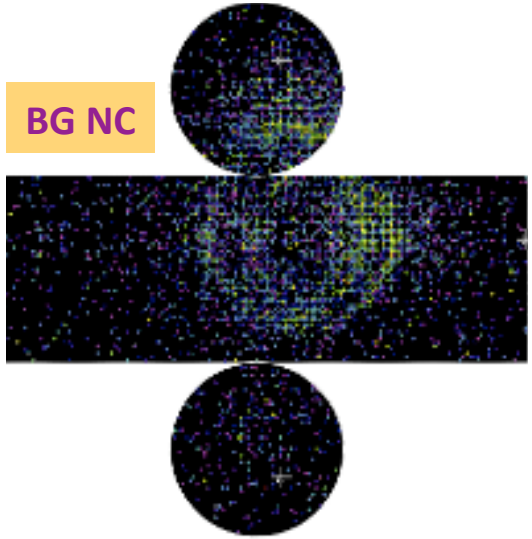
Far detector: Super-K

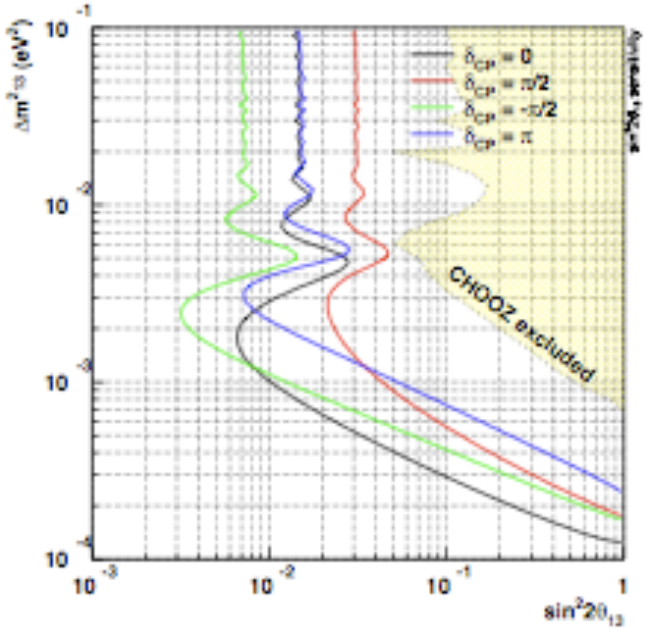
On and off-axis hybrid near detectors





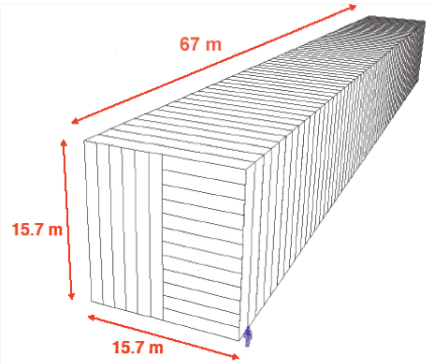






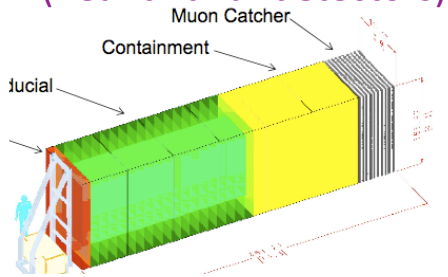
Nova

- 15 kton "totally active" liquid scintillator detector
- 700kw NuMi beam
- A long baseline giving it **sensitivity to matter effects**



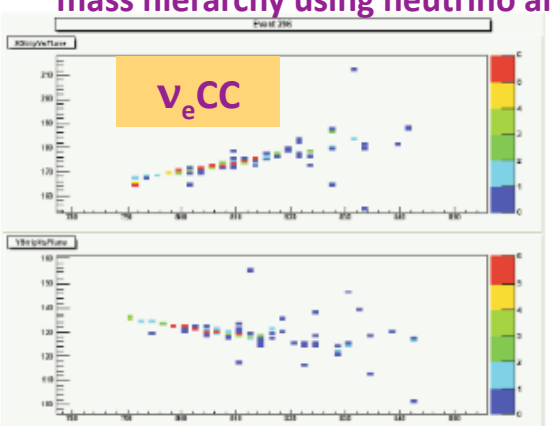
Low Z calorimeter

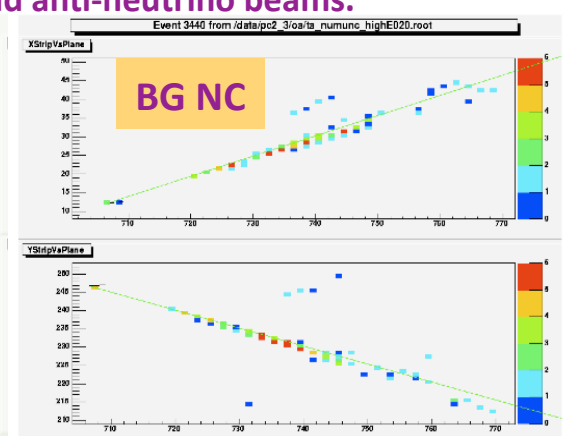
(near and far detectors)

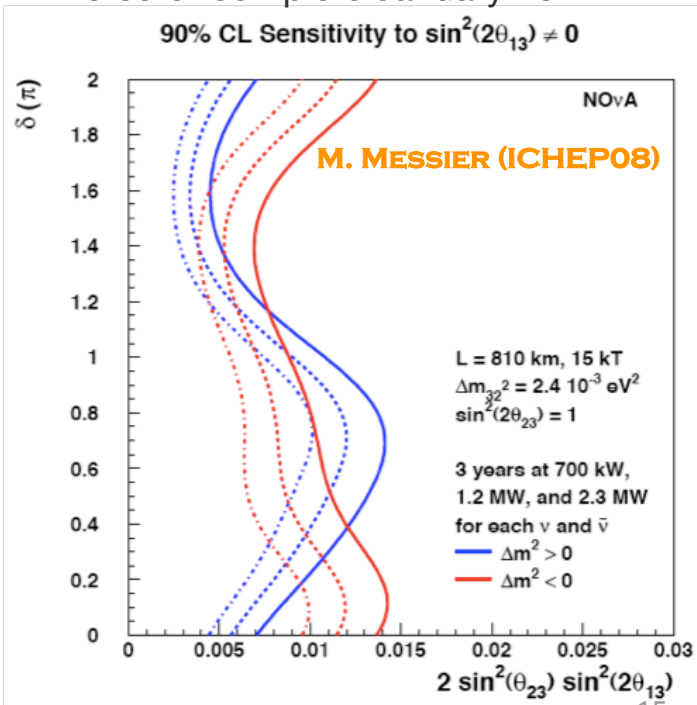


- Start of construction April 2009
- First 2.5 kt taking data August 2012
- Detector complete January 2014

Nova is unique in current generation of experiments for addressing mass hierarchy using neutrino and anti-neutrino beams.







θ_{13} at reactors

Use inverse beta decay and look for energy dependence *disappearance*.

- Double Chooz [*France / 8.7 GW*]
- Daya Bay [*China / 11.6 GW*]
- Reno [*Korea / 17.3 GW*]
- Angara [*Brazil – also safeguard applications*]

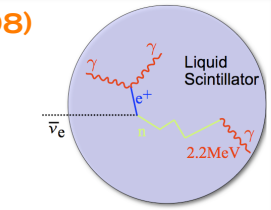
Dekowski (NU2008)

Inverse beta decay

$$\bar{\nu}_e + p \rightarrow e^+ + n$$

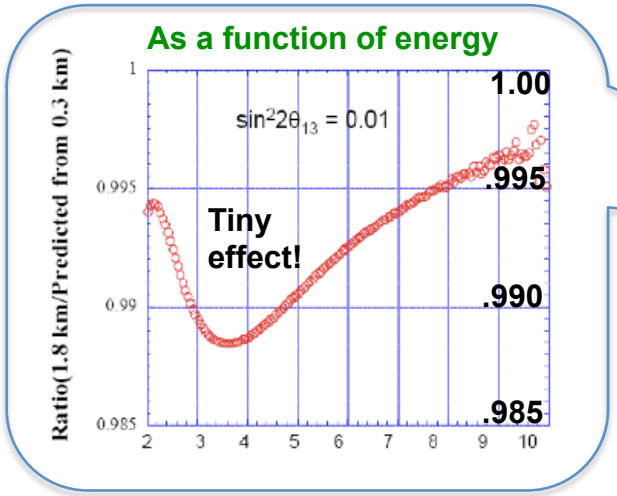
$\downarrow$ 207 μs

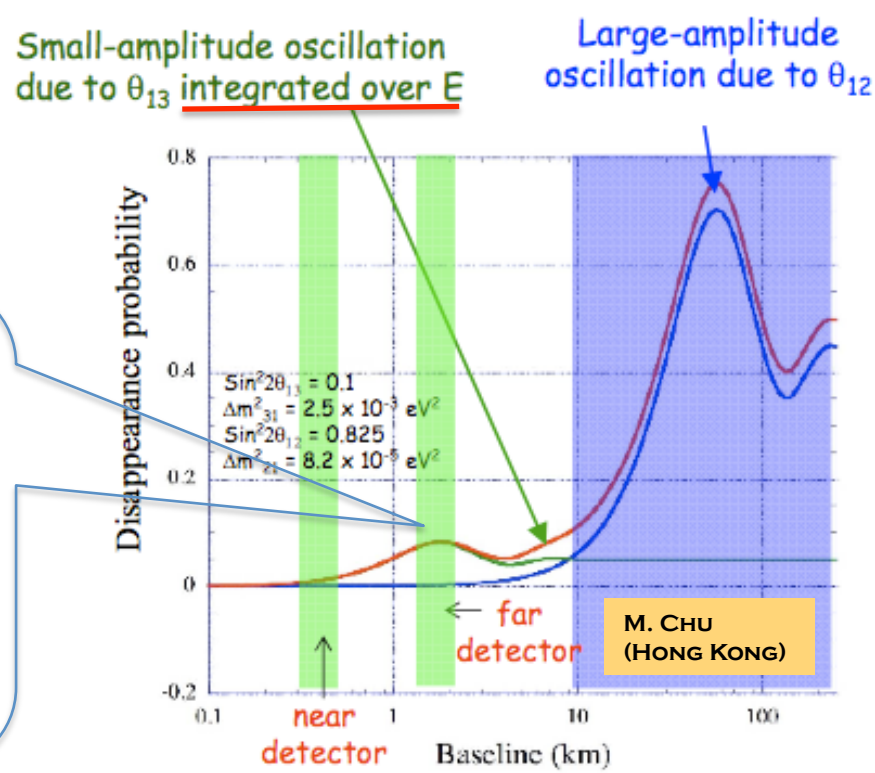
$$n + p \rightarrow d + \gamma$$



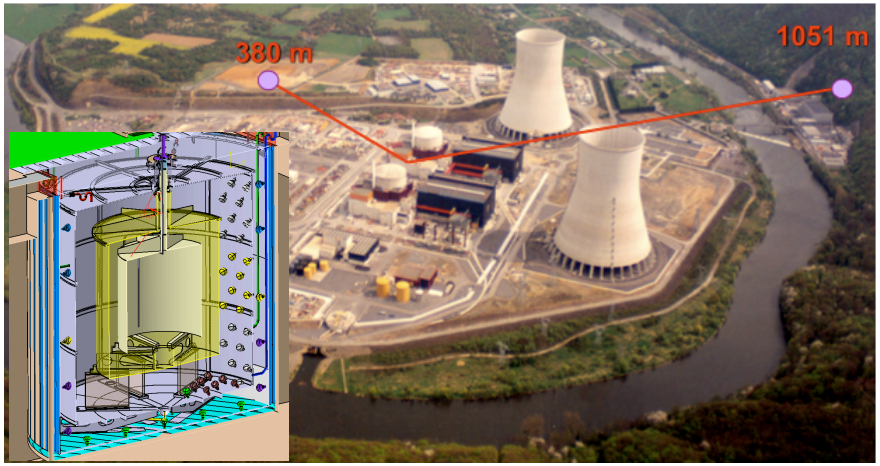
Scintillator is both target and detector

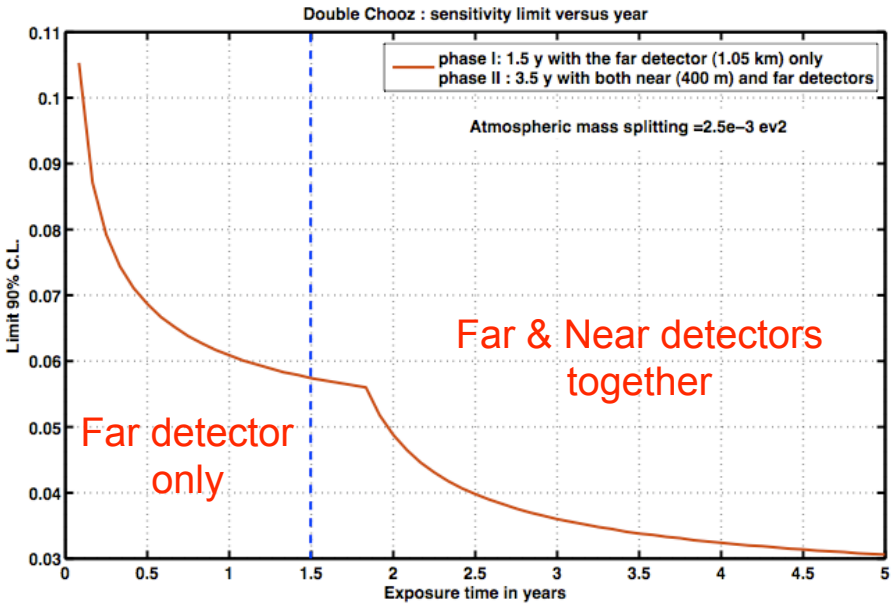
$$P(\bar{\nu}_e \rightarrow x) \approx \sin^2 2\theta_{13} \sin^2\left(\frac{\Delta m^2_{31} L}{4E}\right) - \cos^4\theta_{13} \sin^2 2\theta_{12} \sin^2\left(\frac{\Delta m^2_{21} L}{4E}\right)$$





C. Lane (ICHEP08)



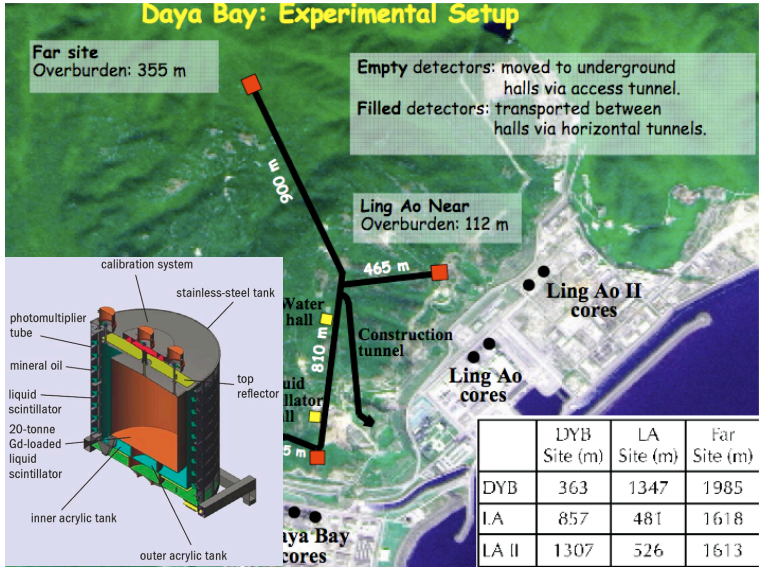


Use two detectors, rely on relative measurements. Lower thresholds, add calibration systems and vetos lower backgrounds.

	Chooz	Double-Chooz
Reactor cross section	1.9 %	—
Number of protons	0.8 %	0.2 %
Detector efficiency	1.5 %	0.5 %
Reactor power	0.7 %	—
Energy per fission	0.6 %	—
Statistical error	2.7%	0.5%

- Far Lab: shielding installed, late June 2008
- Far Detector running early 2009
- Near Lab begin digging Late 2008
- Near Lab finish digging Mid 2009
- Near Lab start assembly after digging
- Near Lab finish assembly late 2009

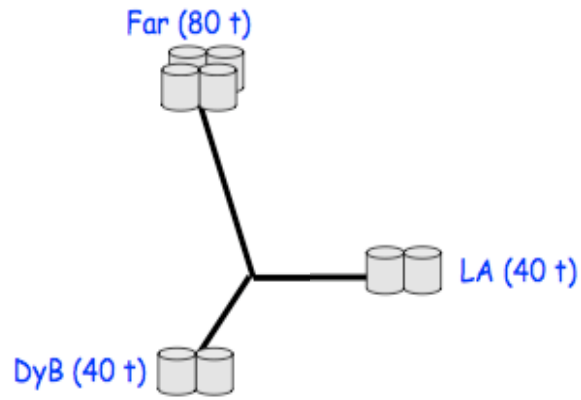
Goal: measure $\sin^2\Theta_{13} < .01$



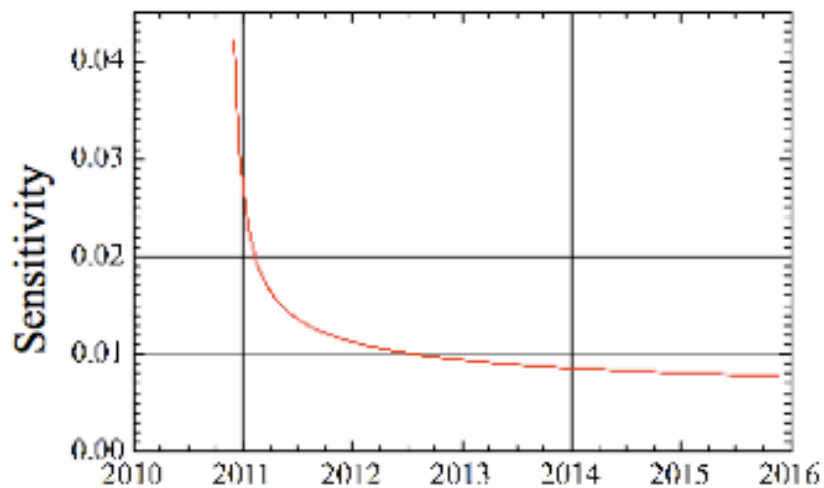
	DYB Site (m)	LA Site (m)	Far Site (m)
DYB	363	1347	1985
LA	857	481	1618
LA II	1307	526	1613

Use large mass/ high reactor power with multiple near and far detectors. Optimize the distance, and try to reduce cosmogenic background by going deep. Make a comprehensive veto. Possibly "Swap" detectors.

Source	Uncertainty
Reactor power	0.13%
Detector (per module)	0.38% (baseline) 0.18% (goal)
Signal statistics	0.2%

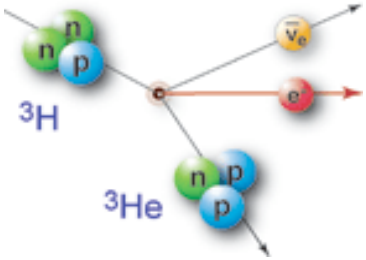


M.. CHU (ICHEP08)

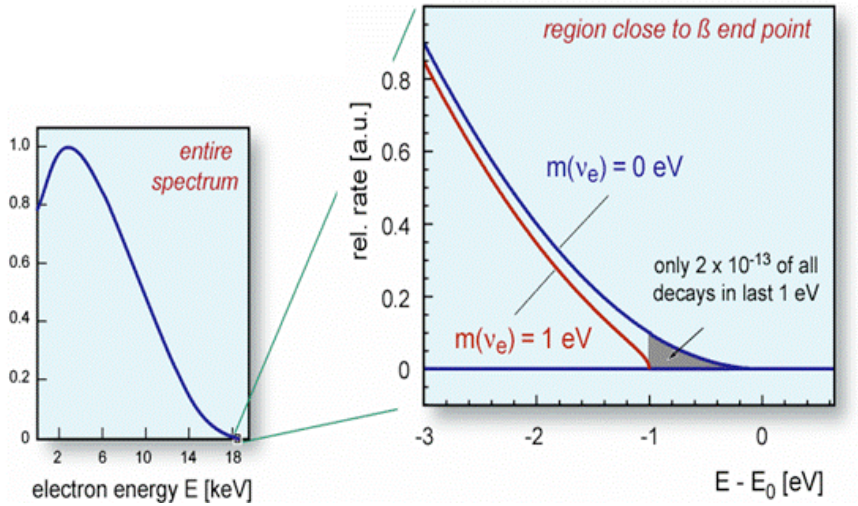


- Surface Assembly Building - Summer 2008
- DB Near Hall - installation activities begin early in 2009
- Assembly of first AD pair - Spring 2009
- Commission Daya Bay Hall by November 2009
- LA Near and Far Hall - installation activities begin late in 2009
- Data taking with all eight detectors in three halls by Dec. 2010

Direct mass measurements with KATRIN

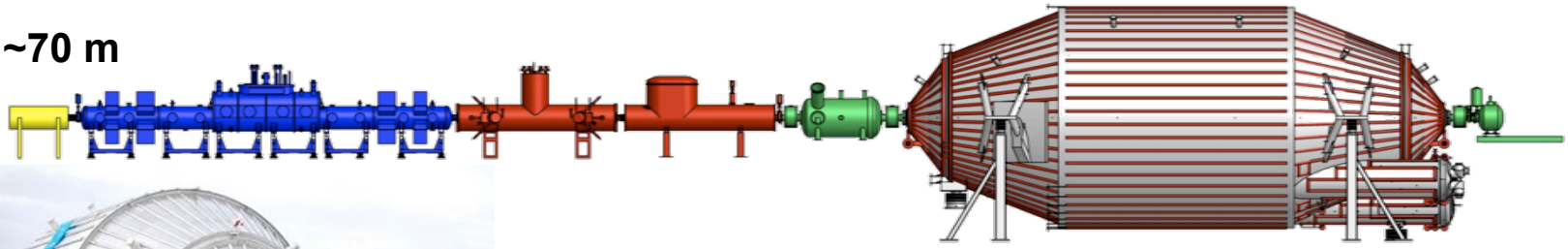


$$m_{\nu_e} = \sqrt{\sum_{i=1}^{3} |U_{ei}|^2 m_i^2}$$



rear	source (WGTS)	diff. pumping	pre-spectrometer	main spectrometer	detector

~70 m



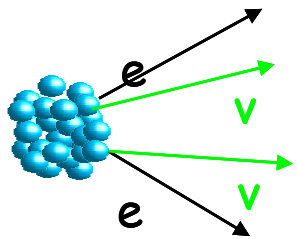
J. Wolf (ICHEP08)

Test spectrometer: 2009

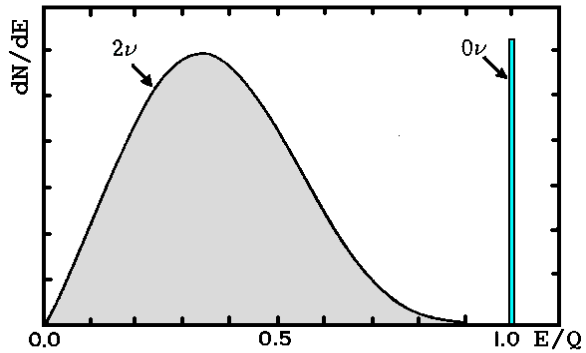
Start measurements: 2010

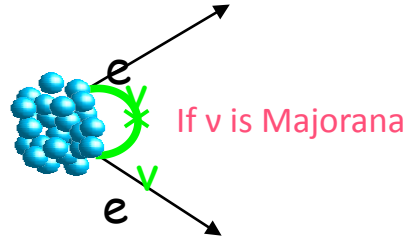
5 years run sensitivity (0.2 eV/c²)

Direct mass another way.



double β decay





ν-less double β decay

Observation tells us:
- **Mass of neutrino**
- **Majorana nature**
- **Mass pattern**

Phase Space

$$T^{0\nu}_{1/2} = 1 / [\, \Gamma(Q_{\beta\beta}{}^5)\, |M_{nucl}|^2 \langle m_{\beta\beta}\rangle^2 \,]$$

$$\langle m_{\beta\beta}\rangle = |\, \Sigma_i\ U_{ei}^2 m_i \,|$$

Effective Majorana mass

Couples mostly to first two mass states. <u>The pattern is important</u>!

<u>Many Techniques:</u>

Nemo3 [Foils]

Cuore [Bolometer]

SNO+ [Liq Scin]

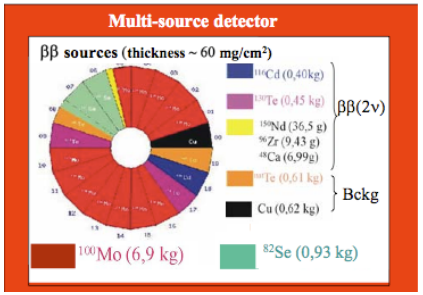
Majorana/**Gerda** [Ge]

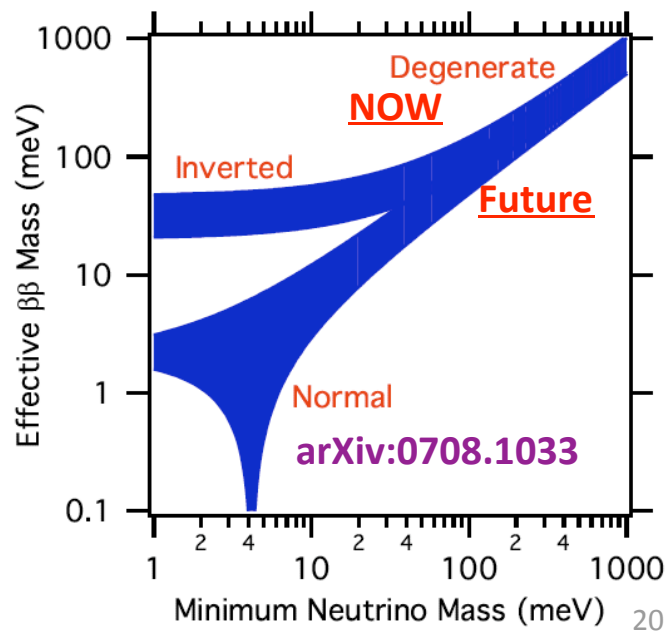
EXO/XMASS [Liquid Xe]

.....

<u>2νββ decay important!:</u>

Can use for calculations of nuclear matrix element. NEMO-3 has led the way on this. See backup slide.





Gerda / Majorana

- common MC T. Knoepfle (ICHEP08)
- material screening/exchange of materials
- characterization of Ge detectors
- participation in the collaboration meetings

These experiments use enriched Ge-76 diodes. The energy resolution is excellent.

Gerda's goal is to reduce the background amount by 10-100 relative to the HM experiment. [Check a claimed positive signal]

They do this by deploying strings of naked Ge detectors on Lar. Majorana uses a similar technique in a Cu Cryostat.

Under construction completed by spring 2009

Phase I: Existing Ge-76 Diodes
Phase II: Add new enriched diodes
Phase III: Possible WW large experiment.

EXO

L. Yang (ICHEP08)

- Use Liquid Xe. Already a gas, so easily repurified and recycled.
- ^{136}Xe is the heaviest candidate
- No long lived isotopes
- BKG reduction by Ba daughter tagging.

Detect both scintillation light and charge in TPC.

200 KG prototype installed At WIPP. Cool down in Early 2009.

SNO+

M. Chen (ICHEP08)

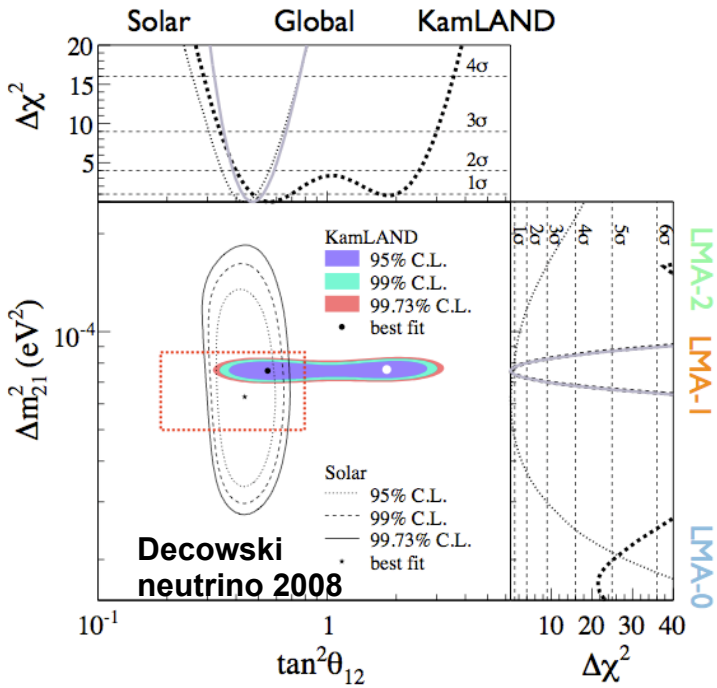
- Fill SNO with liquid scintillator
- Dope scintillator w/Nd

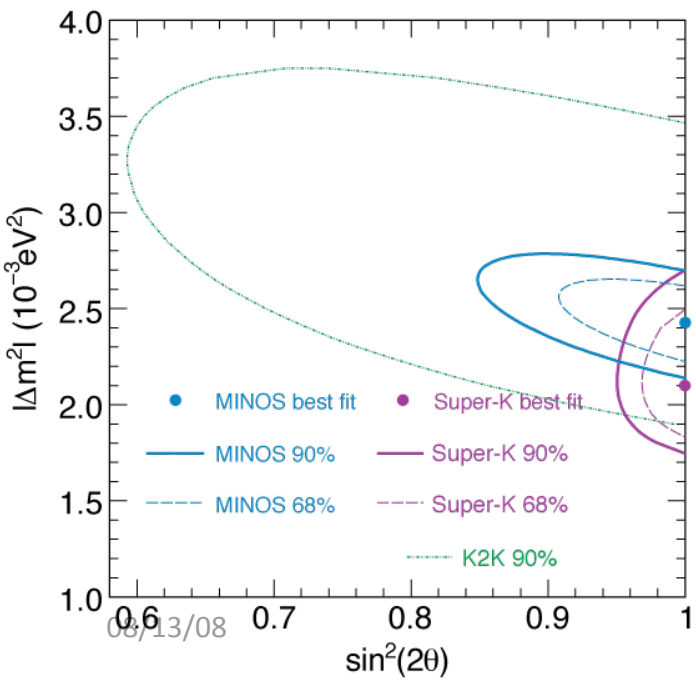
Double Beta decay
Solar/geo/reactor/SN neutrinos

Scintillator for ββ: High endpoint **(^{150}Nd)**
[xmass/candles..] Use shape signal fitting

Large self shielded mass!

Putting it all together…



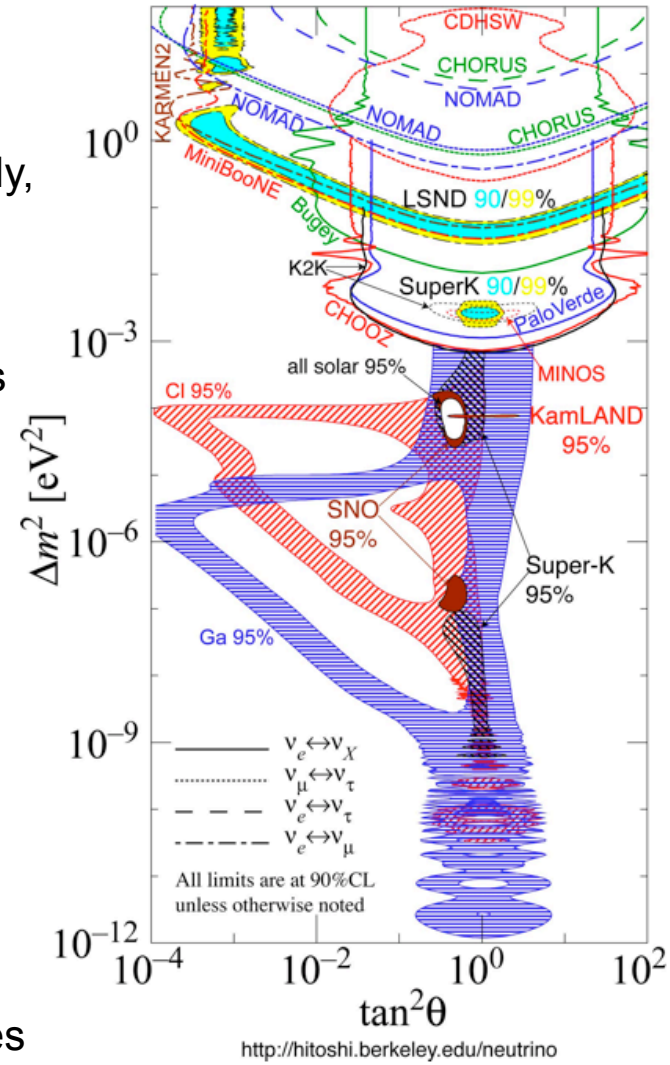


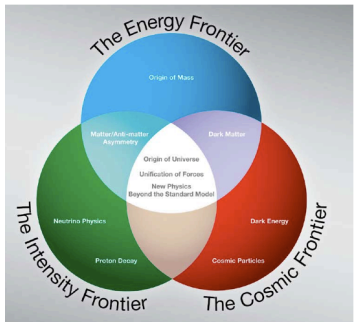
We now have a consistent set of experiments. Currently, the precision is at the 2-10% level.

The next experiments will hopefully get us close to the 1% precision level.

We also hope to add info on directly measured absolute mass to this picture along with the unknown mixing angles.

All of these techniques must work **together**.





Future Facilities: "What's δ" ?

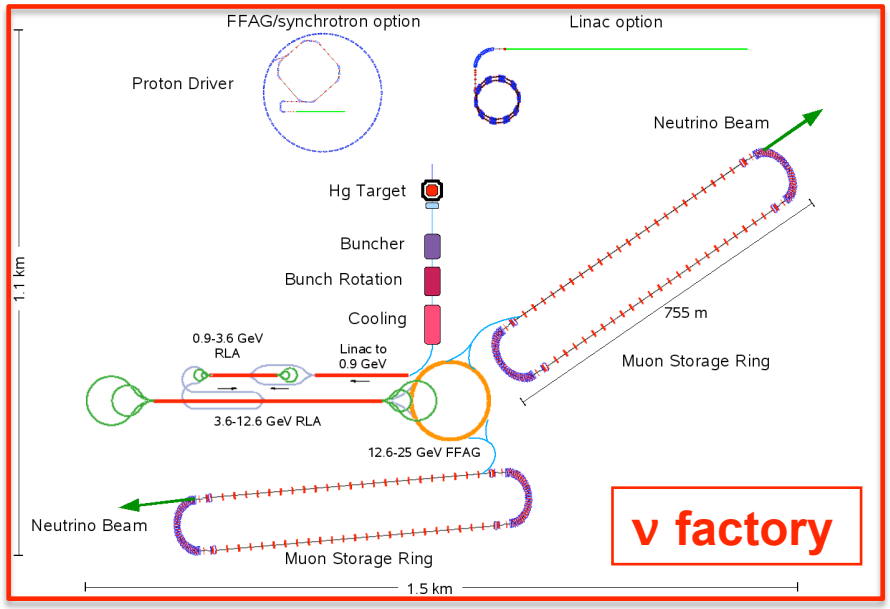
(ISS, EUROSOL, FNAL Steering Group)

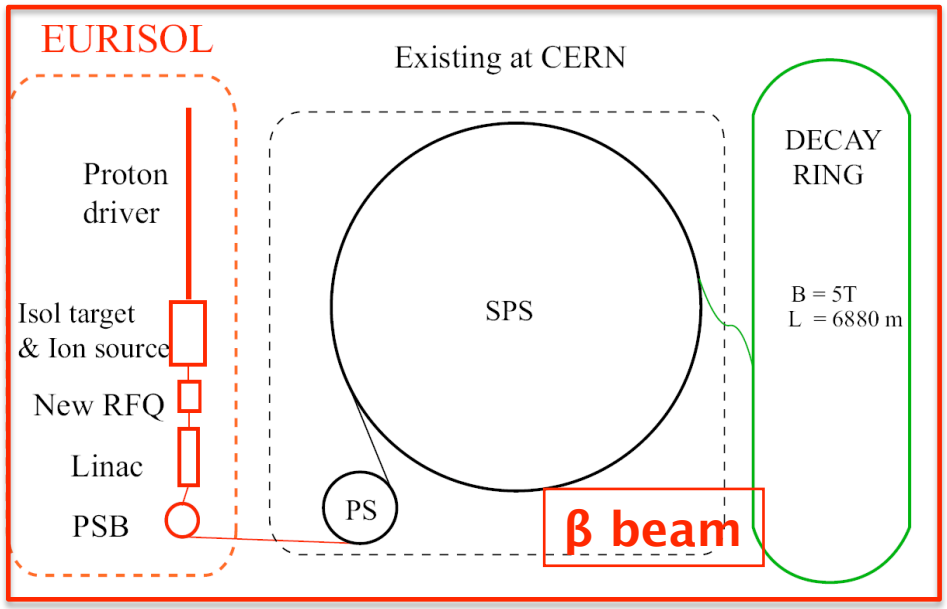
Super-beams in US/EU/Japan (2-4 MW)

This is an evolutionary approach. Use conventional beams from pion decay but upgrade the power, targeting etc.

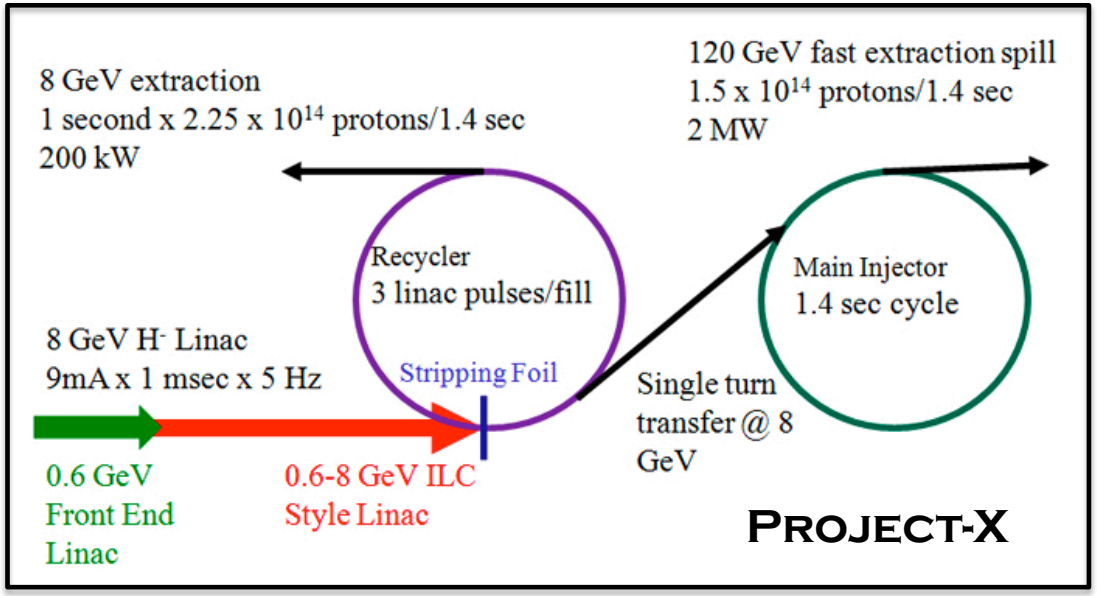
Examples:

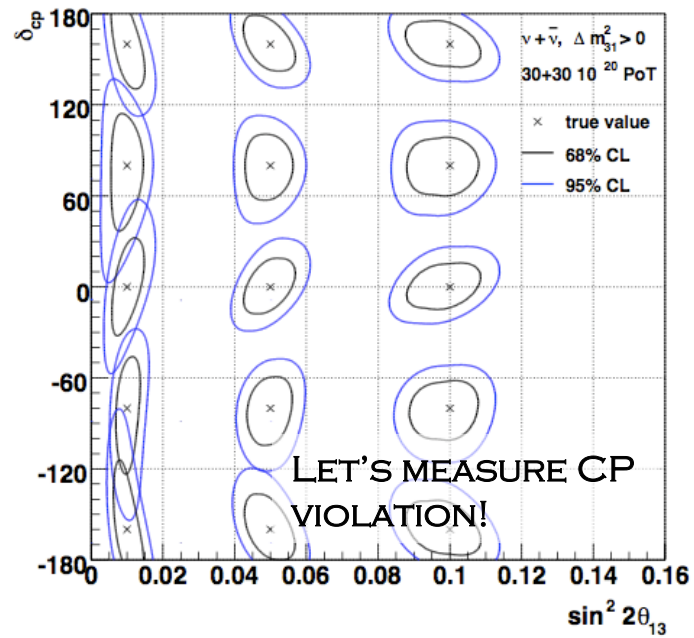
JPARC –> Hyper-K
Project-X –> DUSEL



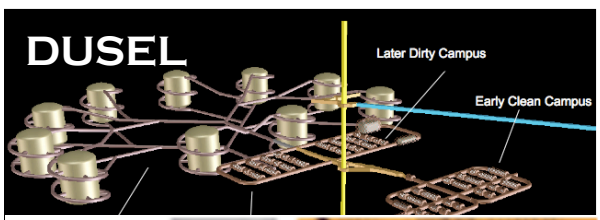


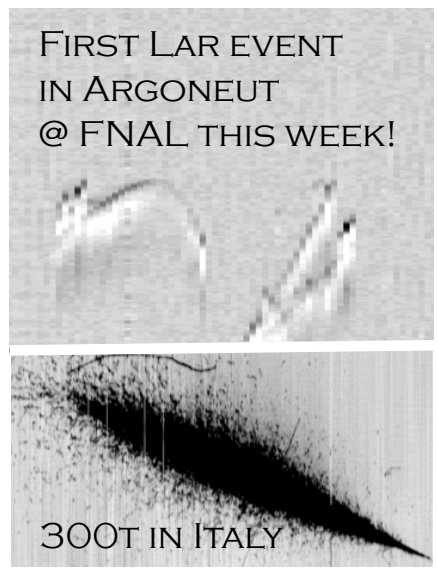
Superbeams & big detectors

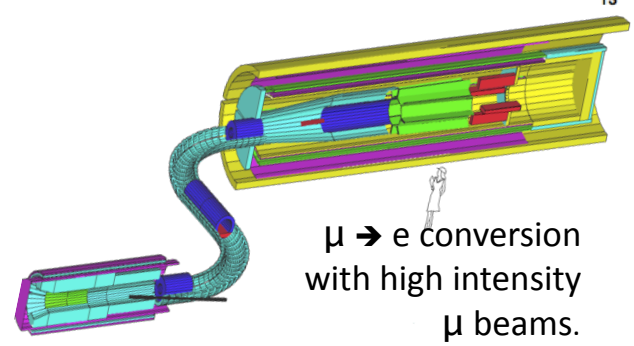




Worldwide R&D program on large WC and LAr detectors.







If possible make neutrinos part of the larger vision and program.

Some things I had to skip:

- INO/ Future Atmospheric experiments
- Hadron Production experiments
- Neutrino interaction experiments
- Low Energy neutrino electron reactor scattering
- NEMO-III Details

See my backup slides in this talk.

- Astrophysics / Dark Matter
- Neutrino mass in/from cosmology
- DUSEL/SNOLAB/Project-X/Hyper-K/T2KK/Titand
- High energy neutrino scattering
- Osc-SNS (Spallation neutron source)
- Proton Decay
- Geo-neutrinos
- Supernova
- Future Solar experiments (xmass, Deep, lens)
- Icarus & Liquid Argon R&D
- Coherent neutrino scattering search(nuSNS: CLEAR)
- …..

Conclusion

- The last 10 years have seen the discovery of neutrino mass, the solution to the solar neutrino problem and the start of precision neutrino measurements. So far everything fits together well.
- If we are lucky, in the next decade we will measure the remaining mixing angle, learn the nature and absolute mass of the neutrino along with the mass pattern.
- This information, coupled with new knowledge gained at the LHC will let us plan our next steps.

It's a vibrant field!

We must pity the student in his deep dark hole
Whose thesis depends on that one monopole,
Or on solar neutrinos that wriggle about
Unless they are saying our sun has gone out.

- S. Glashow

...
These words come from Glashow; we know they are true;
For he's been to Stockholm, unlike me and you.
Who is this legion, so dirty and weary?
Sad underground scientists, unfit to do theory.

• • •

So **gladly** we march to mines, tunnels or seas:
New physics or not, we get PhD's --
Condensed to a preprint we'll mail to our mothers
Of one page of physics (two pages of authors).

- B. Nolty & K. Scholberg