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Non-Accelerator Neutrino Physics

Steve Elliott

Los Alamos National Laboratory

Outline

- **What we know about ?’s**
  - **The role of non-accelerator experiments**
- **What we want to know**
  - **A prioritized list**
- **The proposed experiments**
  - **The role of non-accelerator experiments**
- **The need for a US underground lab**

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The Mixing Matrix

and the origin of our current understanding

$$U = \begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix} \begin{pmatrix} c_{13} & 0 & s_{13}e^{-i\delta} \\ 0 & 1 & 0 \\ -s_{13}e^{i\delta} & 0 & c_{13} \end{pmatrix} \begin{pmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix} \begin{pmatrix} e^{i\alpha_1} & 0 & 0 \\ 0 & e^{i\alpha_2} & 0 \\ 0 & 0 & 1 \end{pmatrix}$$

Atmospheric	Reactor	Solar
? studies	? studies	? studies

?, $?_1$ and $?_2$ are the CP violating phases

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Neutrino Masses and Flavor Content

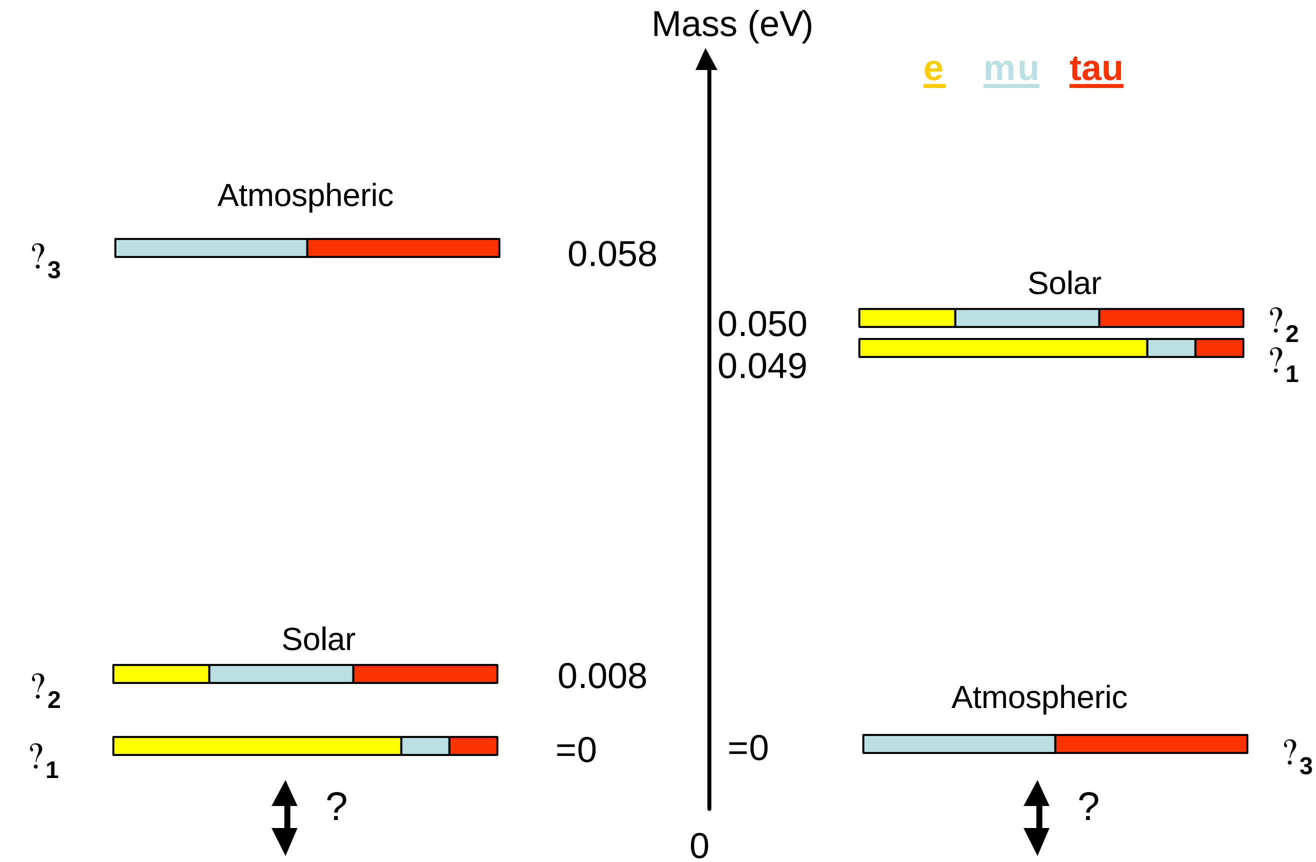

Figure: Courtesy H. Robertson

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How do know wh know?

? 12	~33º	S
? 23	~45º	
? 13	<9º	
absolute mass scale	For at least one ? 0.05 eV < *m* < 2.2 e	
$?m^2_{21}$	~7x10^{-5} eV^2	
$?m^2_{31}$	~2x10^{-5} eV^2	Atm s.
Phases		No data yet
Sterile ?	Maybe Yes / Maybe No	Some indication from LSND

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A Prioritized List

My priorities anyway.

1. **Absolute mass scale**	?? ??,?, cosmology
2. **Dirac vs. Majorana**	?? ??
~~3. $?_{13}$~~ **You've heard enough already**	~~ong baseline~~
4. **Precision measurements, Parameters are uncertain** $?_{12}$, $?_{23}$, $?m^2$	4. **Solar, Atmospheric, Reactor, long baseline**
5. **CP violation**	5. **Very long baseline**
6. **Steriles and CPT violation**	6. **Short baseline, solar vs. reactor, other cross checks**

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Absolute Mass Scale

A List of Upcoming Techniques

- **Supernovas - relatively poor sensitivity**
- **Cosmology - reach below 100 meV, but model dependent**
- **Nuclear/Particle Physics**
- ? **decay - relatively poor sensitivity**
- ? **decay - relatively poor sensitivity**
- ? **decay - hope to reach below 500 meV**
- ?? **decay - hope to reach below 50 meV**
- **oscillations - sensitivity to mass differences**

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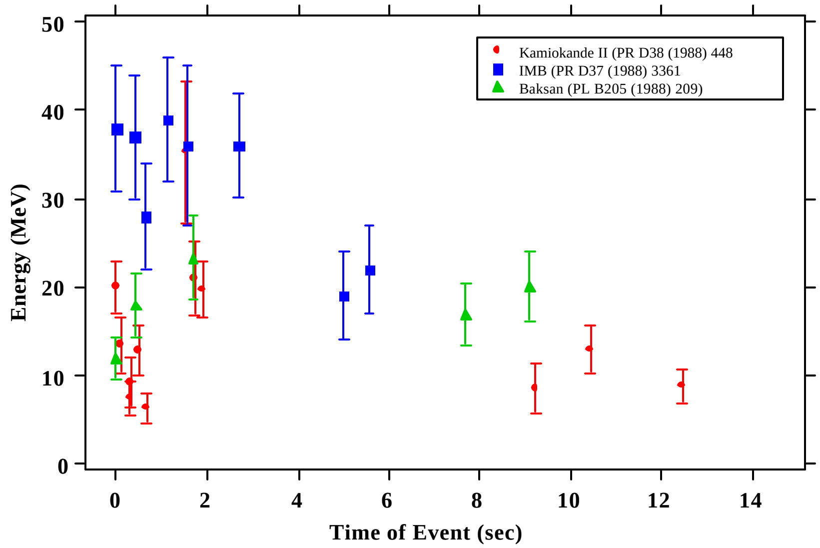
Supernova Tests

- **Spread of neutrino arrival times can give indication of mass.**
- **SN1987a: about 20 eV limit but conclusions varied.**
- **Frequency of SN a concern.**
- **SN dynamics makes for model dependencies.**
- **Future sensitivity might be a few eV.**



But Earth effects might be exploited for ?$_{13}$ and sgn(?m^2) measurments

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Supernova ? Experiments

Detector	Type	Mass (kton)	Location	# events at 10 kpc	status
Super-K	H_2O Cerenkov	32	Japan	7000	Running
SNO	Heavy Water (salt)	1.4 H_2O / 1 D_2O	Canada	350, 450	Running
LVD	Scintillator	1	Italy	200	Running
KamLAND	Scintillator	1	Japan	300	Running
Borexino	Scintillator	0.3	Italy	100	Soon?
Baksan	Scintillator	0.33	Russia	50	Running
MINIBooNE	Scintillator	0.7	USA	200	Running
AMANDA	Ice	M_{eff} ~ 0.4/PMT	South Pole	N/A	Running
Icarus	Liquid Ar	2.4	Italy	250	Soon
OMNIS	Pb, Fe	4, 1	USA	2000	Proposed
LANNDD	Liquid Ar	70	USA	6000	Proposed
UNO	H_2O Cerenkov	600	USA	>100,000	Proposed
Hyper-K	H_2O Cerenkov	1000	Japan	>100,000	Proposed
LENA	Scintillator	30	Europe	15,000	Proposed

Table aby Schollberg (NESS)

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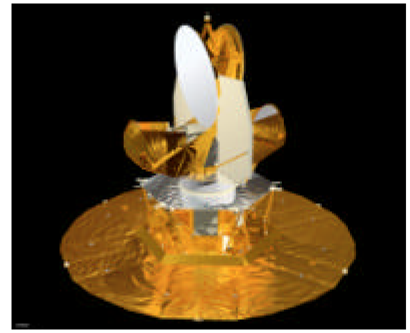
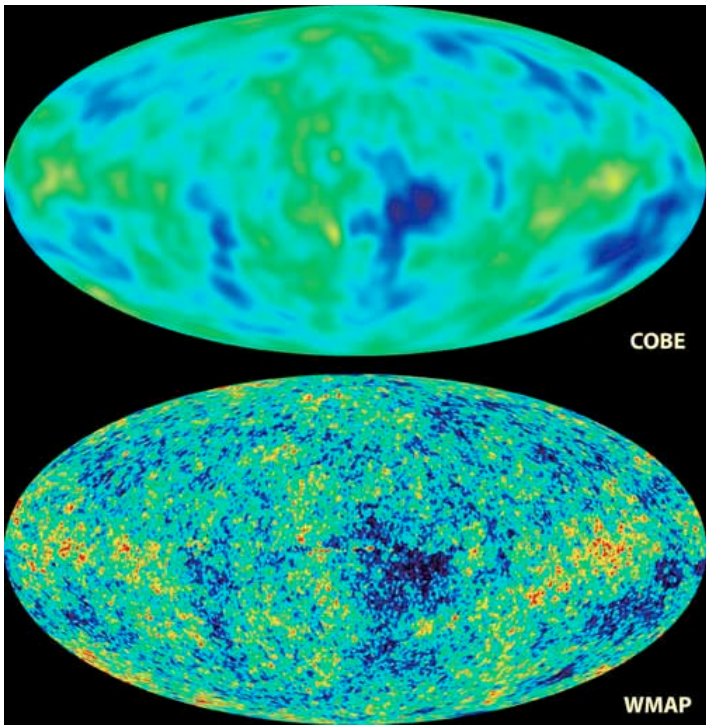
Cosmology
Measure ? $_{?}h^2$





- WMAP measured cosmological parameters very precisely. This allowed precise estimates of ? $_{?}h^2$ from LSS measurements.
- WMAP results indicate ? m_i < about 1 eV. A very competitive result. (one interpretation claims ? m_i = 0.64 eV!)
- But, correlations between parameters result in assumption dependent conclusions.
- Want laboratory experiments.

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Cosmology - Future Measurements

- **MAP/PLANCK CMB measurements with high precision galaxy surveys (Sloan Digital Sky Survey): ? m_i < ~300 meV**
- **If weak lensing by LSS is also considered: ? m_i < ~40 meV**
- **Even with the correlations, cosmology will play an important role in the interpretation of neutrino mass.**

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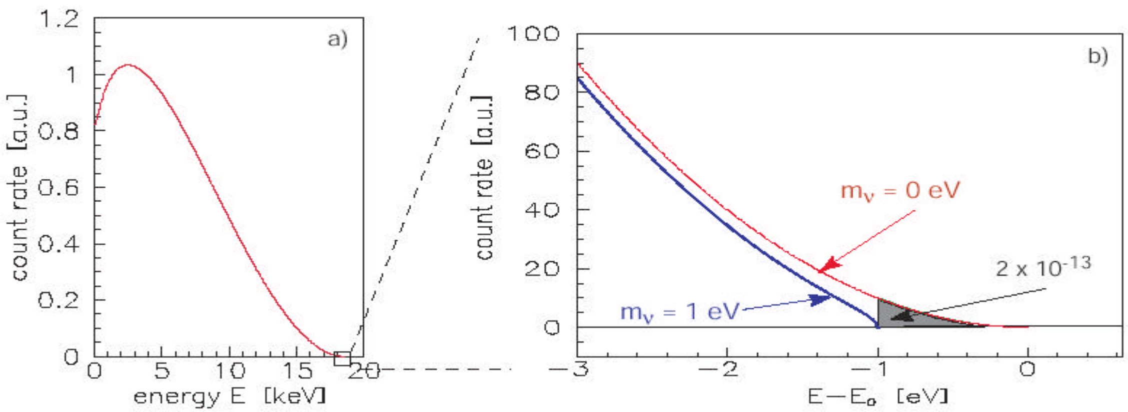
The Neutrino Mass from ? decay

The shape of the ? energy spectrum near the endpoint depends on $m_?$.



KATRIN LOI

$$\langle m_? \rangle ? \sqrt{\overset{3}{\underset{i?1}{?}} |U_{ei}|^2 m_i^2} ? 2.2 \text{ eV}$$

NP B (Proc. Suppl.) 91 (2001), 273

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? decay Experiments

1. KATRIN

Very big spectrometer using gaseous and thin sources. A big step forward.

2. Univ. of Texas-Austin

t_2 source in magnetic free environment.

3. Re ?-decay experiments don’t yet have competitive sensitivity.

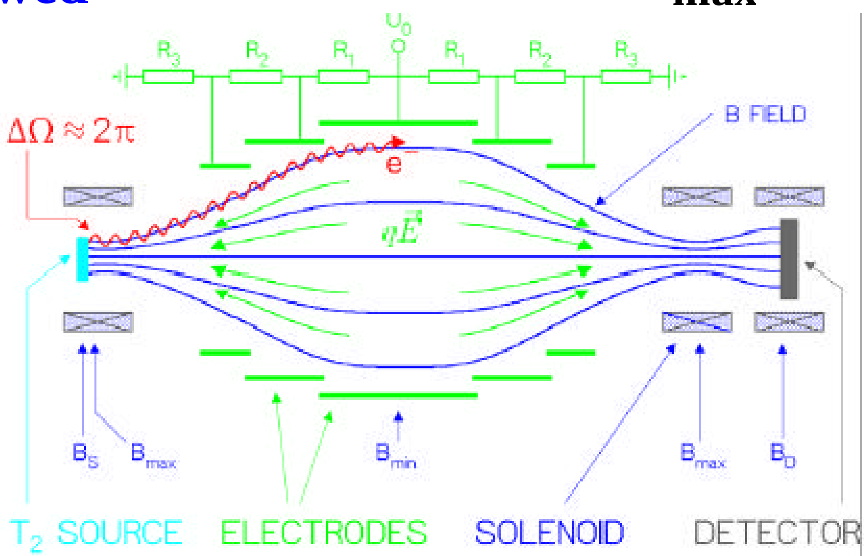
The MAC-E Filter

$$\frac{?E}{E} ? \frac{B_{\min}}{B_{\max}}$$

- **Magnetic Adiabatic Collimation followed by an Electrostat Filter**

- **High luminosity**
- **Low background**
- **Good energy resolutior**

- **Integrating high-pass filter**



KATRIN LOI

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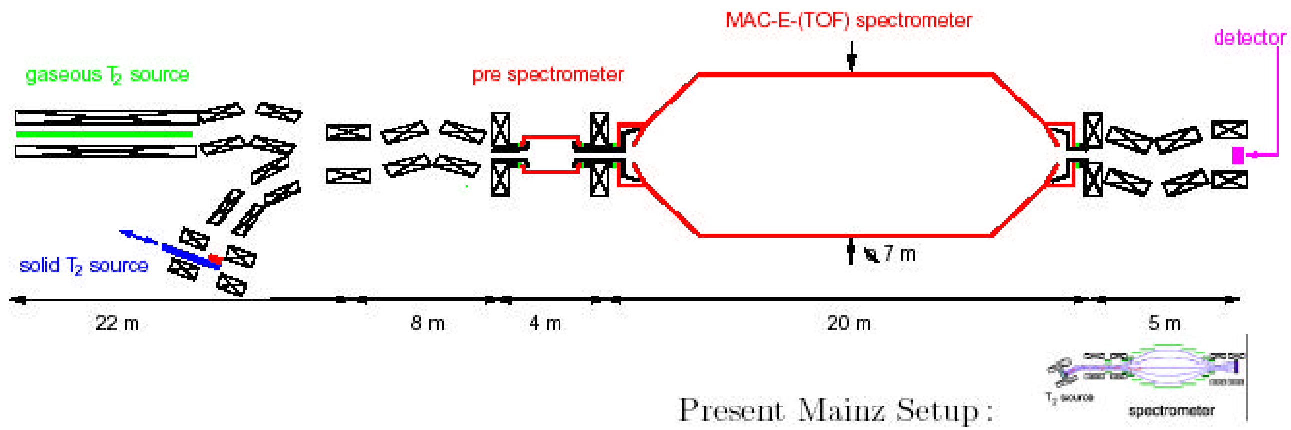
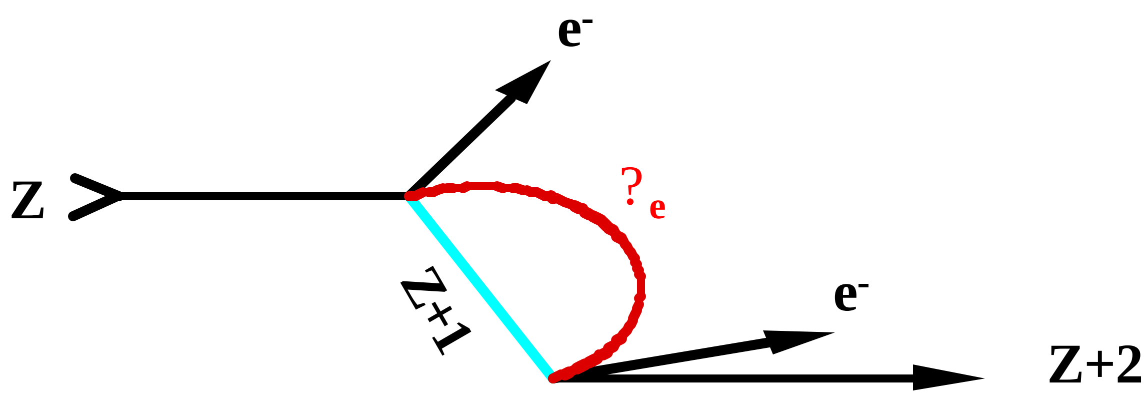
KATRIN (LOI version)



KATRIN will be sensitive to about 350 meV. Thus if the m_i follow a degenerate pattern and m_1 is within the sensitivity, the experiment may see $<m_?> = m_1$.

Dirac vs. Majorana

? ? (0?): requires massive Majorana ?



$$n ? \quad p ? e^{?} ? \bar{?}_e$$

(RH $\bar{?}_e$) (LH $?_e$)

$$?_e ? n ? \quad p ? e^{?}$$

?? Decay Rates

$$?_{2?} \; ? \; G_{2?} \left| M_{2?} \right|^2$$

$$?_{0?} \; ? \; G_{0?} \left| M_{0?} \right|^2 \left\langle m_{??} \right\rangle^2$$

G are calculable phase space factors.

$G_{0?} \sim Q^5$

|M| are nuclear physics matrix elements.

Hard to calculate.

$m_?$ is where the interesting physics lies.

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Min. <m$_{??}$> as a vector sum

$$\langle m_{??} \rangle \; ? \; \left| |U_{e1}|^2 m_1 \; ? \; e^{i?} |U_{e2}|^2 m_2 \; ? \; e^{i?} |U_{e3}|^2 m_3 \right|$$

<m$_{??}$> is the modulus of the resultant vector in the complex plane. (In this example, <m$_{??}$> has a min. It cannot be 0.)

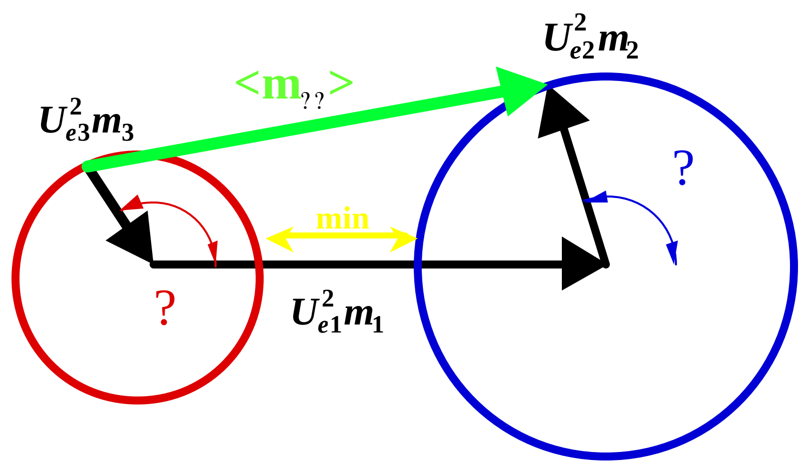

Figure from: PR D63, 073005

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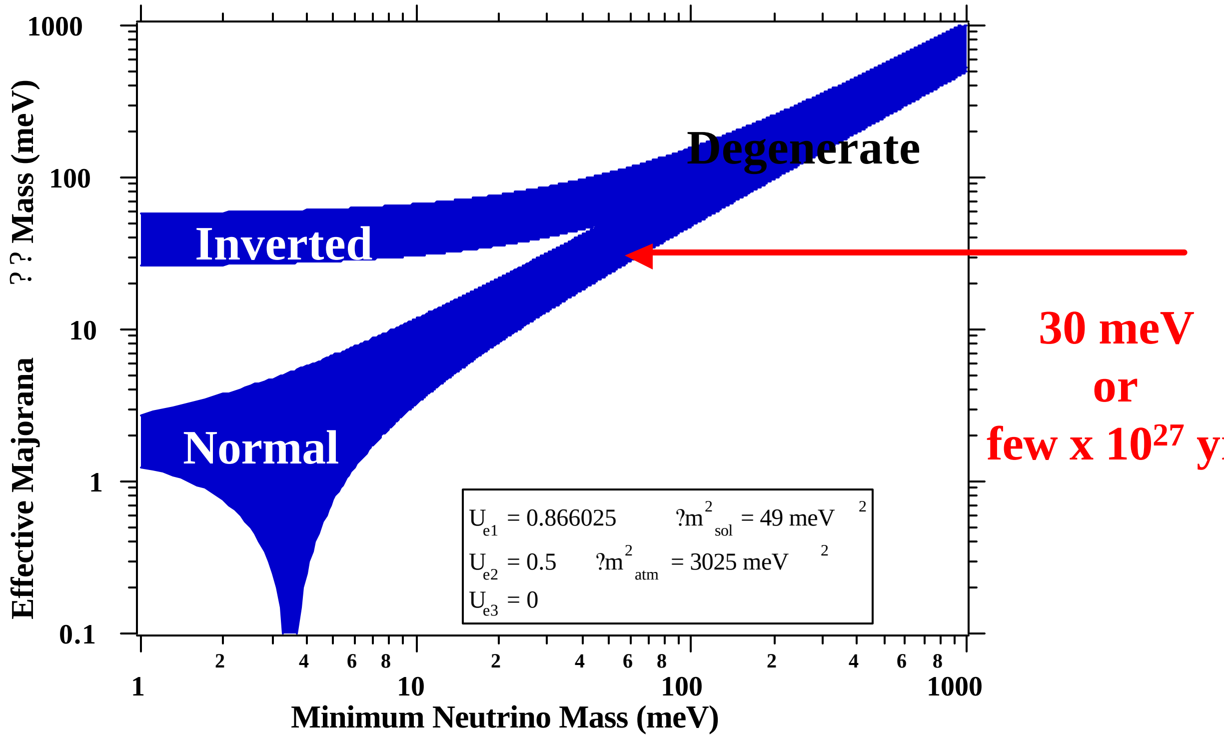
Effective Majorana ?? Mass



30 meV
or
few x 10^{27} yr

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Summary of Physics Reach

Even null results will have implications!

Normal Hierarchy	Inverted Hierarchy	Degenerate
m_1 ~ 0 meV	~55 meV	= M > about 100 meV
m_2 ~ 7 meV	~55 meV	M
m_3 ~ 55 meV	~0 meV	M
$<m_{??}>$ ~ 5 meV		

Solar + KamLAND + Atmospheric (U_{e3}~ 0)

$$\langle m_{??} \rangle ? ?0.5?^2 m_1 ? ?_{21} ?0.866?^2 \sqrt{m_1^2 ? ?m_{21}^2}$$

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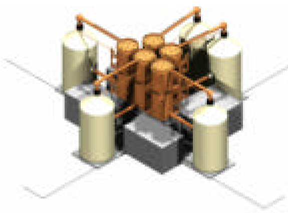
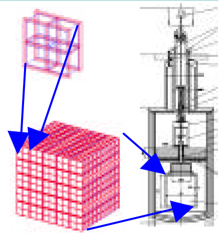
Next generation 0 ??? ?-decay experiments



Majorana

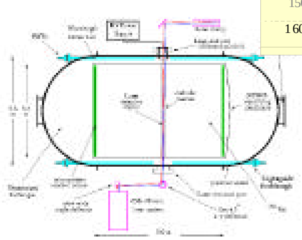


CUORE

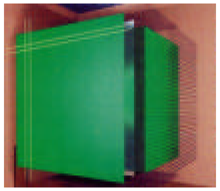
Next Generation Double Beta Decay Experiments

Isotope	Experiment	Technique	Isotope Mass (t)	Enriched	$Q_{??}$ (MeV)	Expected Sensitivity $T_{1/2}^{0?}$
^{48}Ca	***CANDLES***	CaF_2 crystals in liq. scint.	~1-3	No	4.27	1 x 10^{26}
^{76}Ge	***GEM***	Ge diodes in LN	1	Yes	2.04	7 x 10^{27}
^{76}Ge	***GENIUS***	Ge diodes in LN	1	86%	2.04	1 x 10^{28}
^{76}Ge	***MAJORANA***	**Segmented Ge crystals**	**.5**	**86%**	**2.04**	**3 x 10^{27}**
^{82}Se, ^{100}Mo, ^{116}Cd, ^{150}Nd	***NEMO3***	drift chamber-scintillator	.001, .007, .001, .001	Yes	3.0,3.0, 2.8,3.4	4 x 10^{24}
^{100}Mo	***MOON***	**Scint+Foils (or Bolometer)**	**34**	**No**	**3.03**	**1 x 10^{27}**
^{116}Cd	***CAMEO***	$CdWO_4$ - Borexino CTF	~1	Yes	2.8	> 10^{27}
^{116}Cd	***CWO***	$CdWO_4$	~1	Yes	2.8	1 x 10^{26}
^{130}Te	***COBRA***	CdZnTe or TeO_2 semi conductors	.01	No	2.6	1 x 10^{24}
^{130}Te	***CUORICINO***	Cryogenic TeO_2 crystals	.04	No	2.6	1 x 10^{24}
^{130}Te	***CUORE***	**Cryogenic TeO_2 crystals**	**.75**	**No**	**2.6**	**2 x 10^{26}**
^{136}Xe	***EXO***	**Liquid Xe**	**1-10**	**Yes**	**2.47**	**8 x 10^{26}**
^{136}Xe	***Xe***	Xe in liquid scintillator	1.6	Yes	2.47	5 x 10^{26}
^{136}Xe	***XMASS***	liquid Xe (solar ?)	10	No	2.47	3 x 10^{26}
^{150}Nd	***DCBA-II(2)***	foils and tracking chambers	.02	Yes	3.37	2 x 10^{25}
^{160} Gd	***GSO***	Gd_2SiO_5 :Ce crystal scint. in liq. scint.	2	No	1.73	2 x 10^{26}

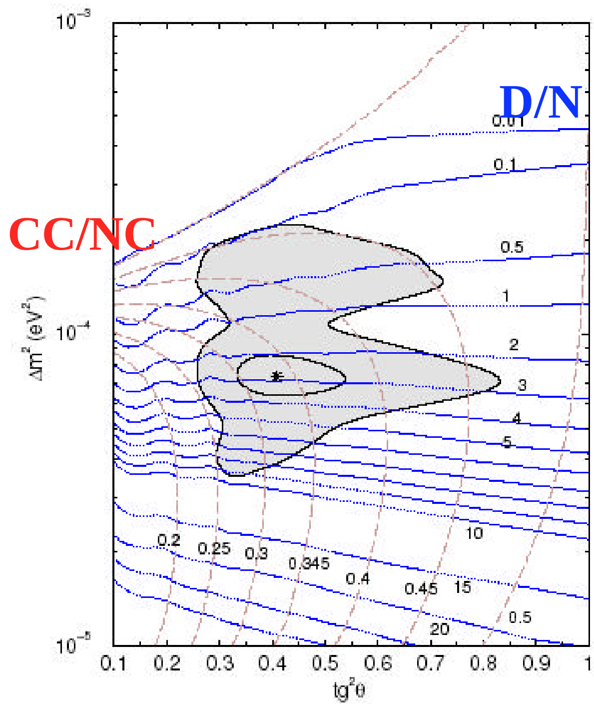
EXO



MOON



Precision Measurements: ? $_{12}$



Smirnov hep-ph/0306075

- **Copious supply of well characterized ? .**
  - **The pp flux is theoretically well known (~1%)**
  - **The spectral shapes of the other ? s are well known.**
- **Low energy**
- **Very far away**

This is a great source for the study of ? characteristics.

Cross Checks from Solar ?s for LMA

- **Day-Night asymmetry: A_{SNO} ~4%, A_{SK} ~2%**
- **Spectrum distortion:5-10% upturn expected between 5 and 8 MeV**
- **Suppression of intermediate energies (i.e. ^{7}Be)**
- **Seasonal variation is very small**
- **Suppression of low energies (i.e. pp)**
  - **Next generation of pp experiments**

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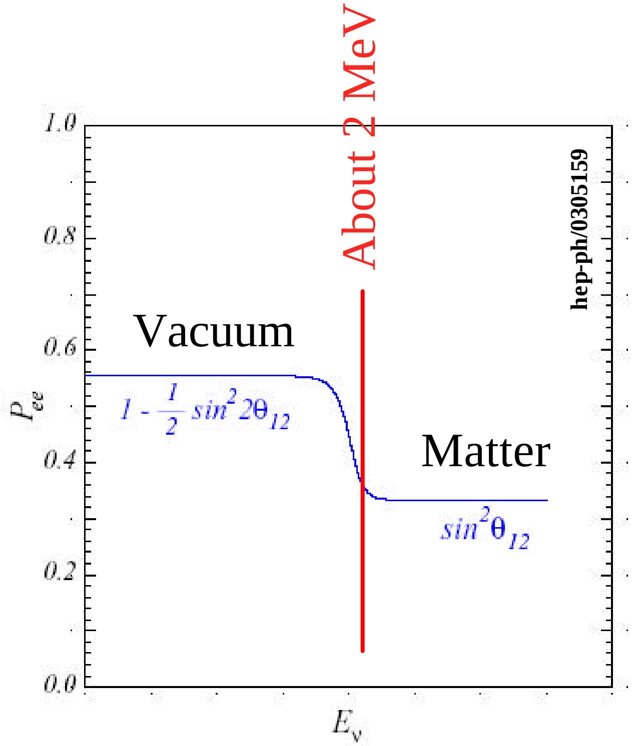
Why do a pp measurement?



1. **Precise measurement of vacuum mixing angle, and improved value for sterile** ? **component**
2. **Potential new phenomena at low energies.**
3. **Flux measurements compared to solar models will be strong tests of astrophysics.**

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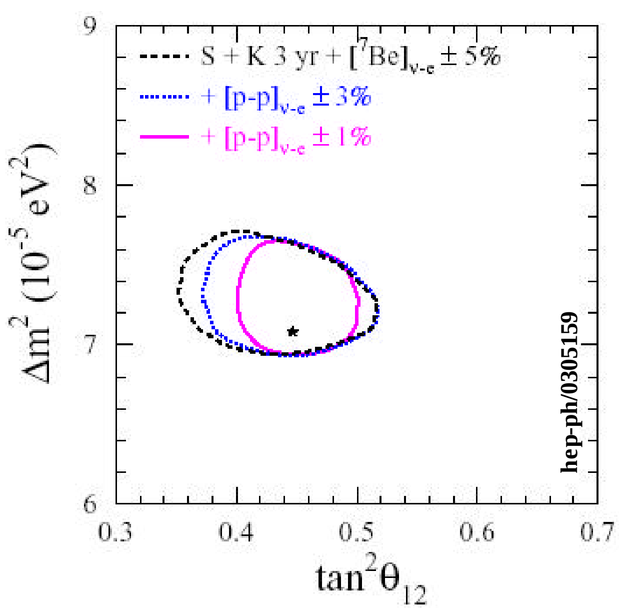
What about a future pp measurement?

From Bahcall and Pena-Garay



- **Assuming that the ^{7}Be is measured to 5%**
- **Assuming 3 years of KamLAND running**

- **A pp flux measurement to better than 3% will make a significant improvement on ?$_{12}$.**
- **A 1% pp measurement would only make a modest improvement on the ?$_{13}$ bound.**

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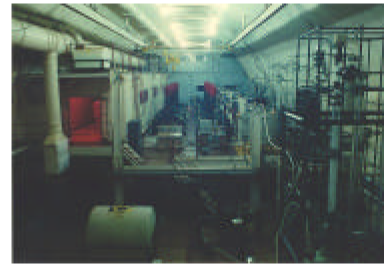

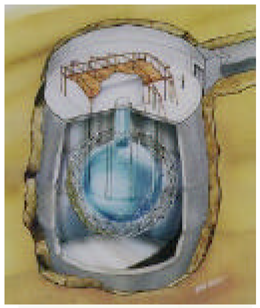

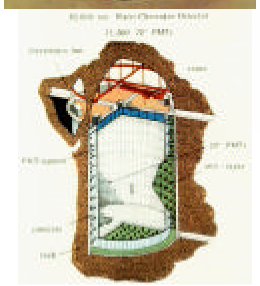

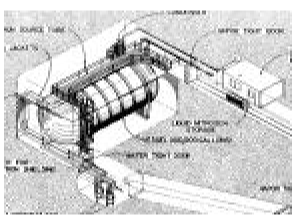

Solar Neutrino Experiments

Solar Neutrino Experiments

		Fiducial Mass		Threshold, keV			BP00 Rates per year					
Expt.	Type	Tons	of	ES	CC	NC	pp +pep	^{7}Be	^{8}B	CNO	Event Eff. %	Start
Cl-Ar	Radioch.	135	^{37}Cl		814		14	72	363	26	16	1968
Kamioka	Cerenkov	680	water	7000					120		100	1985
SAGE	Radioch.	23	^{71}Ga		233		181	86	31	22	25	1990
Gallex	Radioch.	12	^{71}Ga		233		94	45	16	11		1991
SuperK	Cerenkov	22000	water	5500					10200		100	1996
GNO	Radioch.	12	^{71}Ga		233		94	45	16	11		1998
SNO	Cerenkov	2000	water	5000					1100		100	1999
		200	^{2}H		6400				10000		100	1999
		200	^{2}H			2223			5000		50	1999
Borexino	Scintillator	100	scintillator	250				20000				2001
KamLAND	Scintillator	1000	scintillator									2001
HERON	L He rotons, Scintillator	5	He	100			3025	1500	2	125	80	
TPC	Gas TPC	7	He	180			4000					
LENS	Scintillator	5	^{176}Yb		301,445		570	400	32	136		
MOON	Scint+Foils	3.3	^{100}Mo		168		409	129	14	34	20	
CLEAN	Scintillator	12.5	Ne	100			9000					
Cl	Hybrid	2200	^{37}Cl		814		230	1200	5900	420	16	
GaAs	Ionization		^{71}Ga									
LiF	Bolometer	0.9	^{7}Li		862	487	27	29			100	

Hamish Robertson, University of Washington   Snowmass, July 17, 2001

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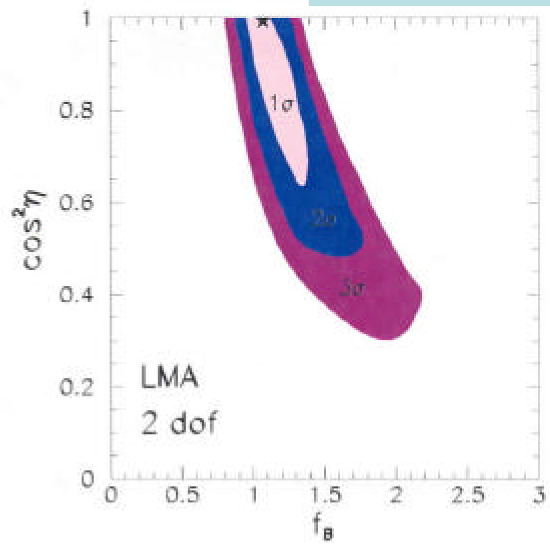
Precision Measurements of $?_{23}$ and $?m^2_{23}$

- **Atmospheric ? experiments have provided $?_{23}$ and $?m^2_{23}$.**
- **Future precision measurements of these parameters will most likely come from long baseline studies. K2K, MINOS, CGS, etc.**

Sterile Neutrinos?



Bahcall, Gonzalez-Garcia, Pena-Garay, hep-ph/0204194

By comparing solar experiments with reactor experiments, one can constrain the sterile flux of neutrinos from the Sun.

sin^2? is fraction of sterile admixture. A 1% measurement of the pp flux would improve the bound on this parameter.

SNO (Total Flux Unknown): ?$_e$ ✍ ?$_x$ **Disappearance**
?$_e$ ✍ ?$_{??}$ **Appearance**

KamLAND (Total Flux Known): $\overline{?}_e$ ✍ $\overline{?}_x$ **Disappearance**

Sterile Neutrinos and the *upturn*.

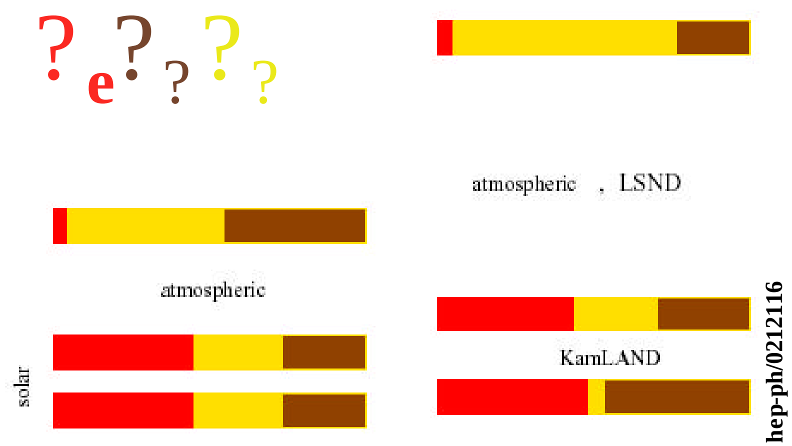
- The LMA solution predicts a 5-10% upturn at 5-8 MeV. SNO and SK don't see this (could be statistics).
- And… the Cl experiment sees a modest suppression (~2?) from the LMA expectation.
- Both results could be explained by a weak mixing between $?_1$ and $?_s$

A further suppression between 0.8 and 5 MeV would also arise due to this mixing. Future experiments sensitive to ^{7}Be ? could test this.

hep-ph/0306075

Tests of CPT

hep-ph/0306226 claims this scheme doesn't fit the data.



Solar expts., KamLAND, MINIBooNE, short baseline expts, MINOS(as atm. ? detector), SuperK atmos, K2K LBL all play roles in the required 3? +3 anti-? analysis.

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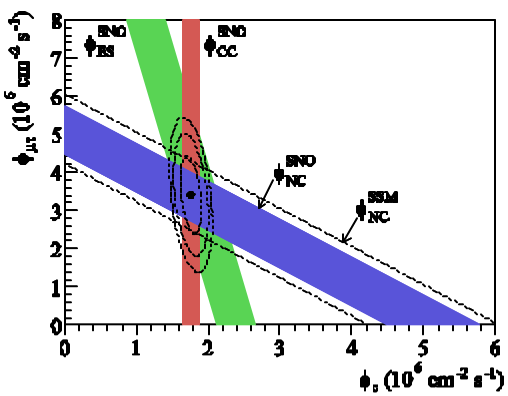
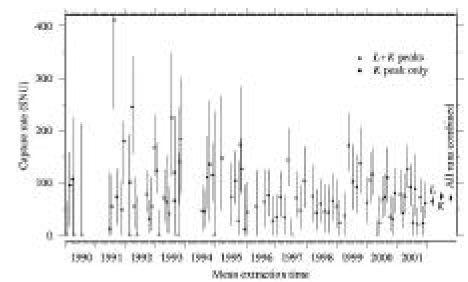
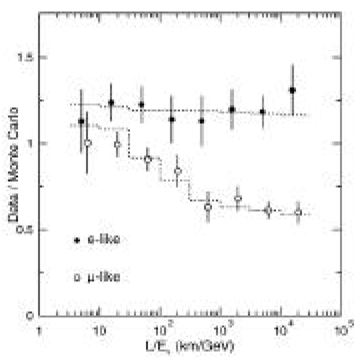
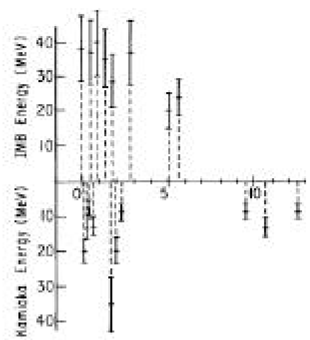
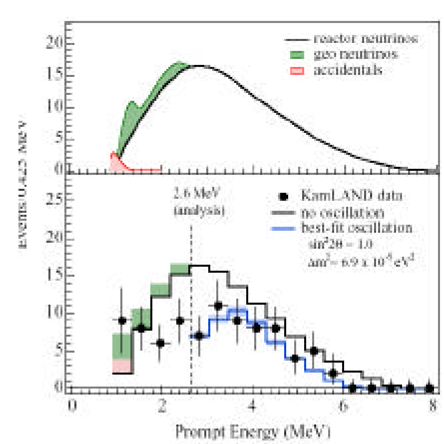
Underground Research has Produced Numerous Dramatic Results.











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What future underground science lies ahead?

- **Atmospheric ?s**
- **Dark Matter**
- **Double ? Decay**
- **Nucleon Decay**
- **Solar Neutrinos**
- **Supernova ?s**
- **Very Long Baseline ? Oscillation Expts.**

Many of the experiments proposed for these fields have strong synergies.

In many cases, a detector designed to observe ? from an accelerator source also performs a "non-accelerator" style measurement.

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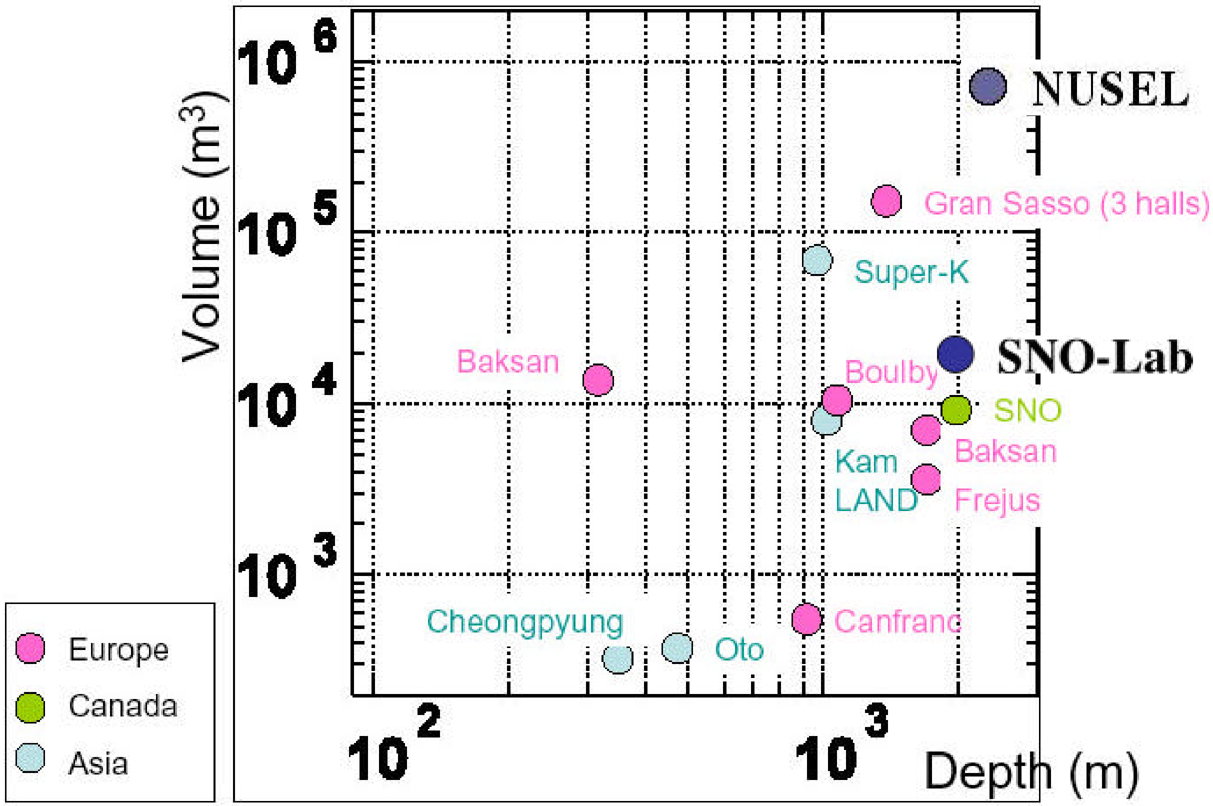
Why a New Lab and Why in North America?

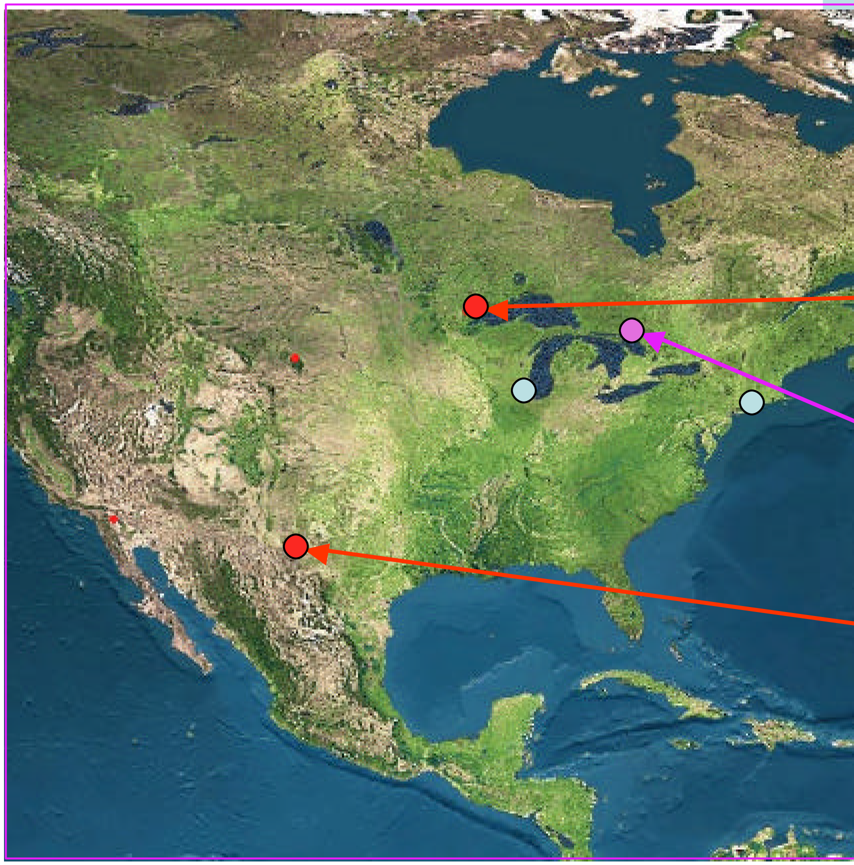
- *The science is compelling.*
- *There is a lack of deep sites for next generation expts.*

  Background requirements have typically increased by a factor of 100-1000 since Gran Sasso and Kamioka were built 20 years ago.
  - **dark matter: ~4500 mwe**
  - **double beta decay: 2400 - 6000 mwe**
  - **solar neutrinos: ~6000 mwe**
- *There is a lack of space in existing laboratories*
- *The lack of a US laboratory has inhibited the development of underground science within the US.*
- *NUSEL will encourage synergies that will advance science.*

The World's Underground Labs



Existing North American UG Labs



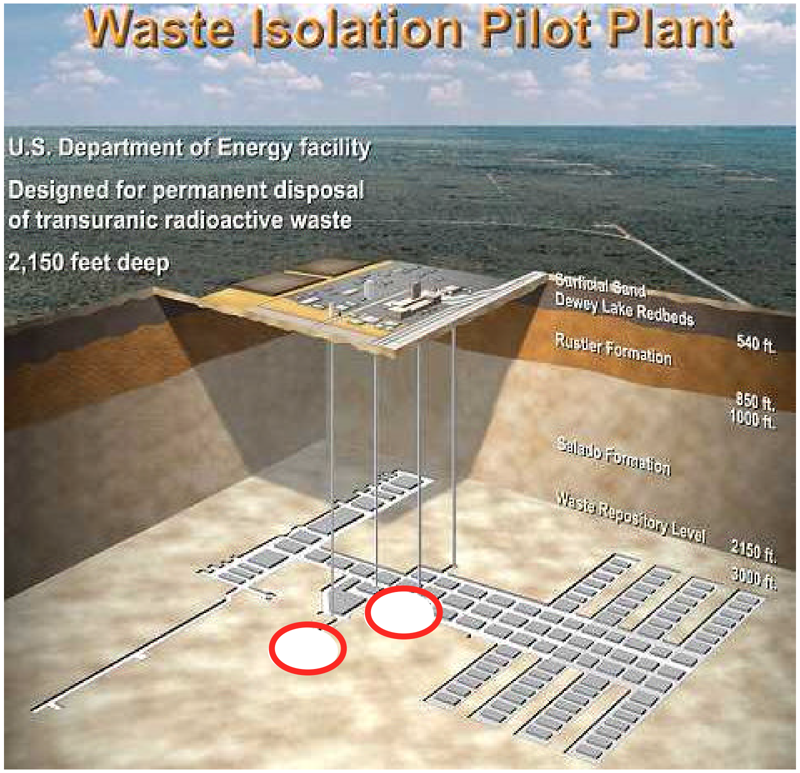
Soudan (2100 mwe)

Sudbury (6010 mwe)

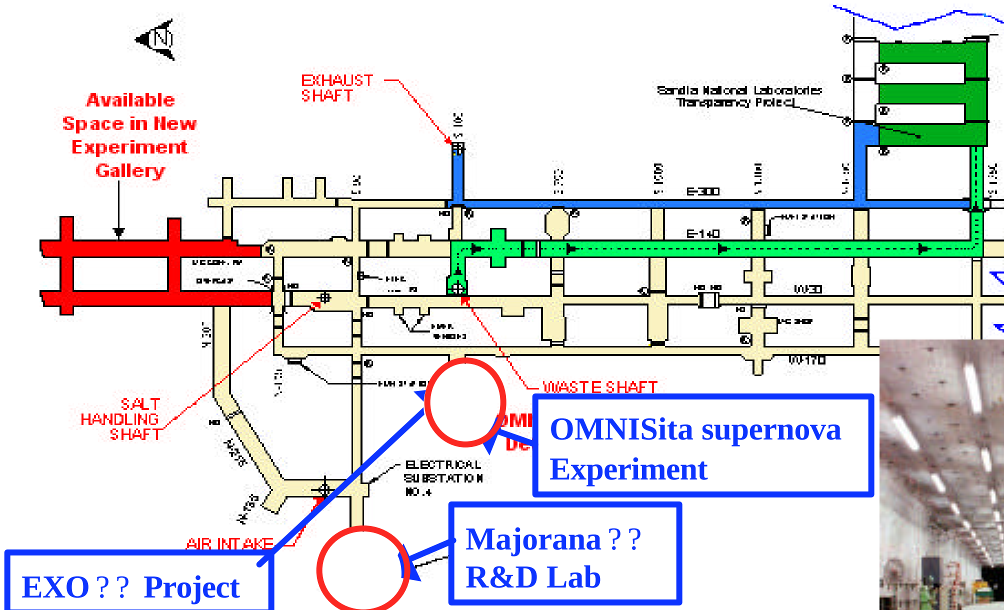
WIPP (1700 mwe)

WIPP

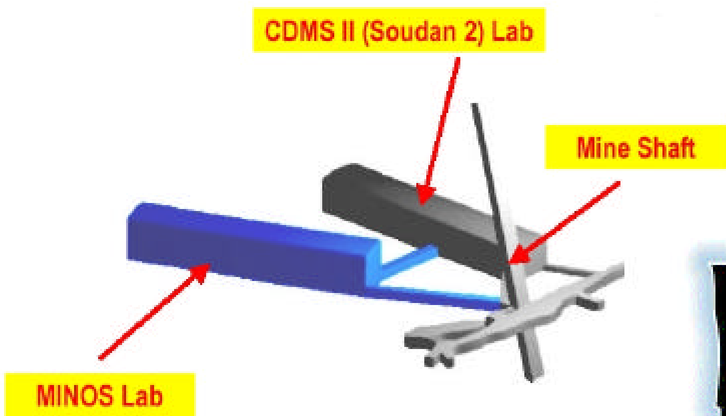
- DOE Facility
- Impressive infrastructure
- Modest depth (1600 mwe)
- Science as add-on to primary mission
- Low background counting lab being developed LANL-PNNL



Experimental Operations



Soudan

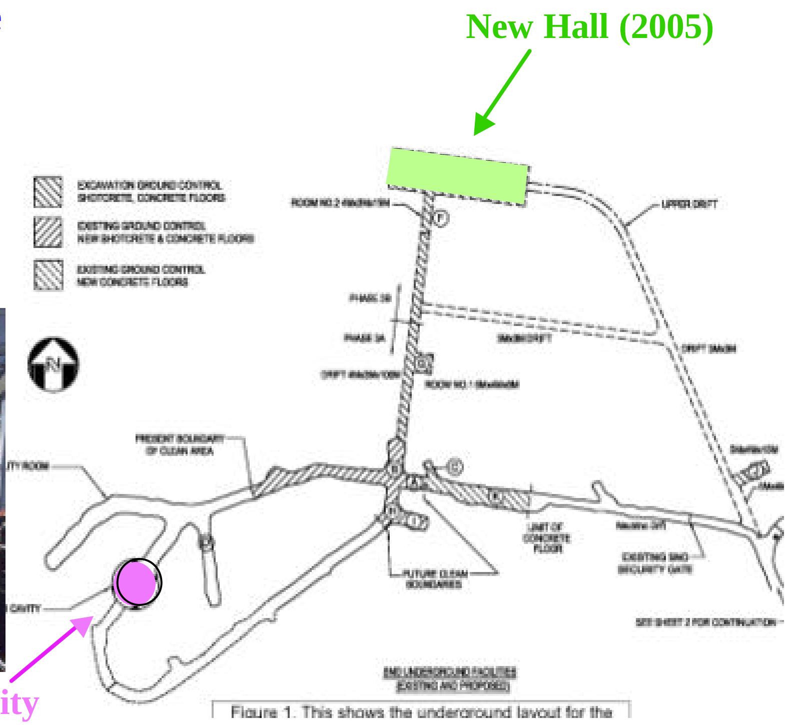

CDMS II (Soudan 2) Lab
Mine Shaft
MINOS Lab


Soudan
Duluth
MN
WI
Madison
MI
IA
Fermilab
IL
IN
MO

Nuclear Physics
Los Alamos

Sudbury Neutrino Observatory

- **INCO (commercial) Ni mine**
- **Restricted shaft size**
- **Deep (6010 mwe)**
- **Planned expansion can incorporate 2 modest-sized experiments**



Conclusions

- **Much of what we know about neutrinos comes from non-accelerator physics. In particular, underground experiments have been crucial.**
- **Our next goals for learning about neutrino characteristics will also see a large role for non-accelerator experiments. And again UG science will play a large role.**
- **A National UG Laboratory would not only provide infrastructure for such experiments, but also a focal point to define a program in UG science.**