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Solar & Atmospheric ν

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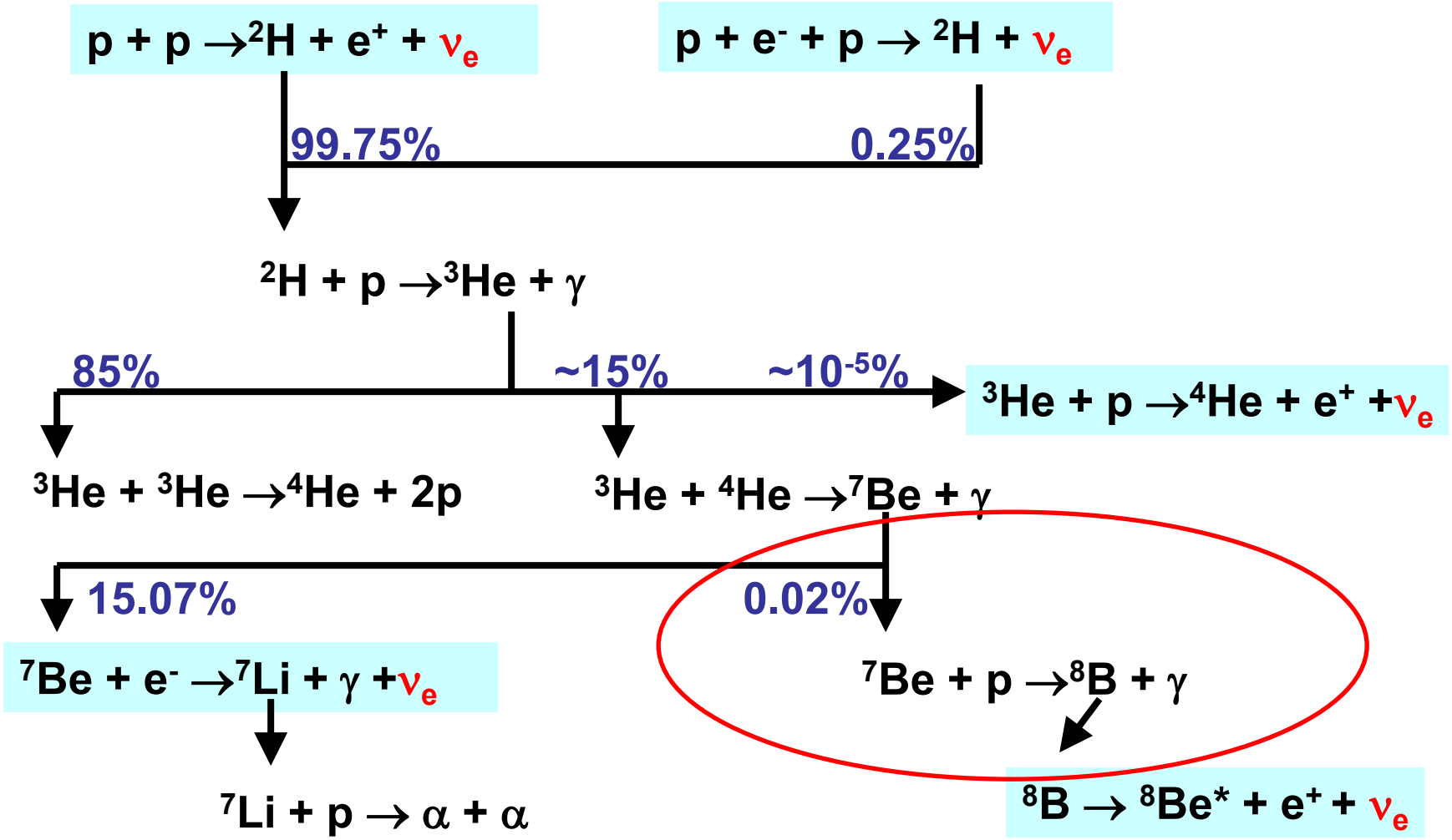
Outline

- Neutrinos from the Sun
  - The neutrinos
  - Past experiments
  - What we know and what we want to learn
- Atmospheric Neutrinos
  - The neutrinos
  - Past experiments
  - What we know and what we want to learn

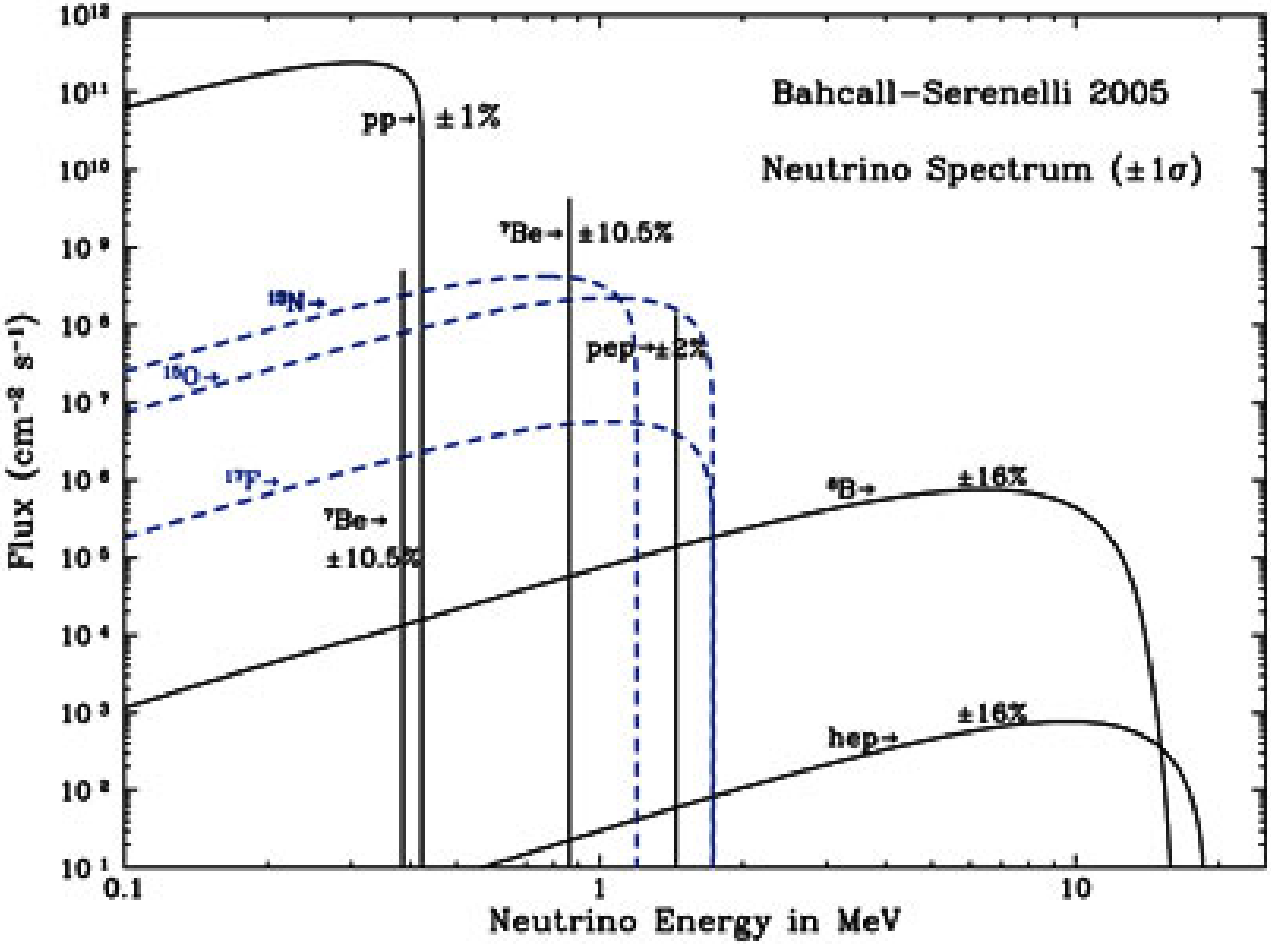
Solar Model Assumptions

- **Hydrostatic Equilibrium**
  - **radiative & particle pressures balance gravity**
- **Energy Transport**
  - **photon diffusion in deep interior**
- **Energy Generation**
  - **nuclear fusion**
- **Isotopic/Elemental Abundances**
  - **changes occur only by nuclear reactions**
  - **initially agrees with current surface observations**

The pp fusion reactions



The energy spectrum



MSW at high energies, vacuum at low.

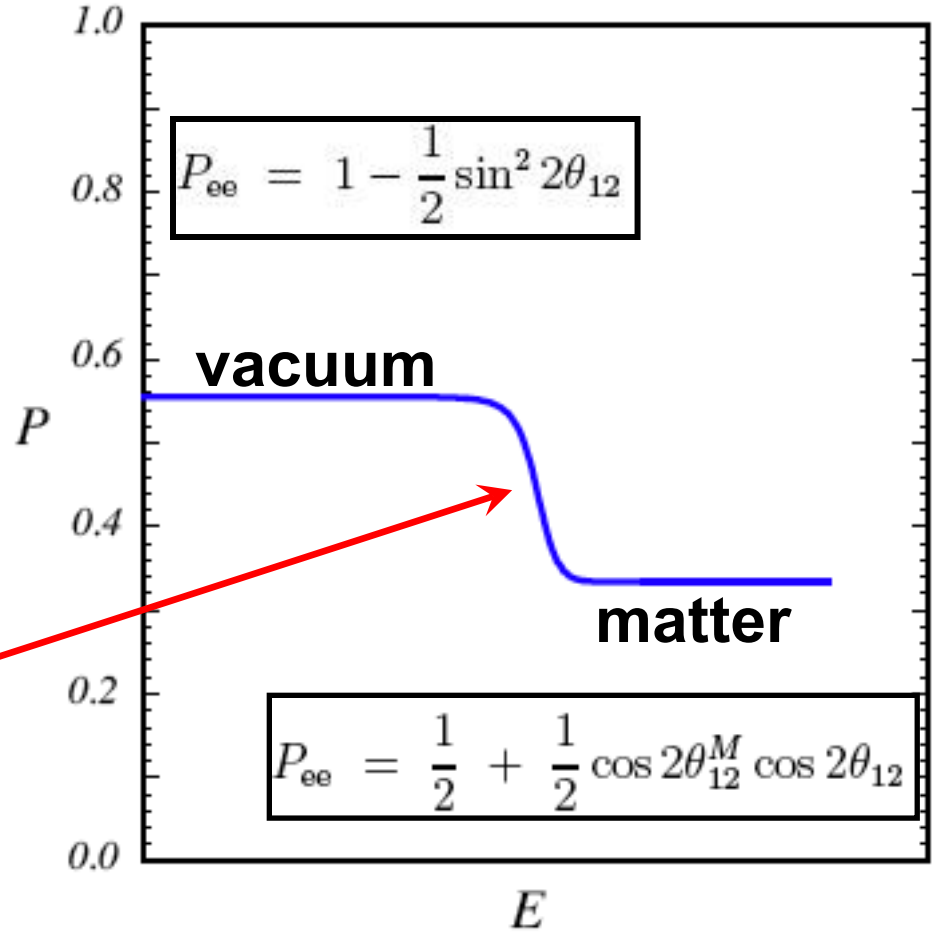
$$H = \begin{pmatrix} \frac{\Delta m^2 cos2\theta_{12}}{4E} - \frac{\sqrt{2}G_F n_e}{2} & \frac{\Delta m^2 sin2\theta_{12}}{2E} \\ \frac{\Delta m^2 sin2\theta_{12}}{2E} & -\frac{\Delta m^2 cos2\theta_{12}}{4E} + \frac{\sqrt{2}G_F n_e}{2} \end{pmatrix}$$

Ratio of oscillation length in matter to vacuum

Matter and Vacuum

If $\beta < \cos 2\theta_{12} \sim 0.4$ then the oscillation probability is given by the vacuum averaged result.

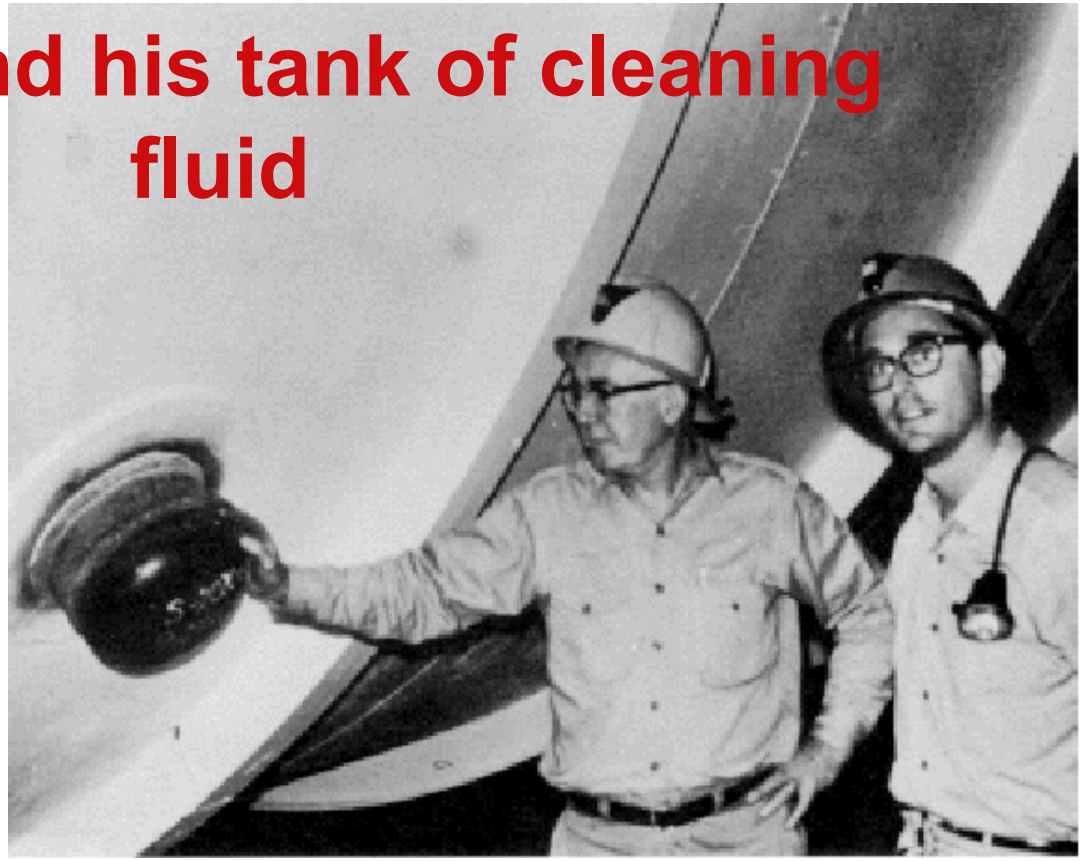
About 1 MeV
For the Sun



hep-ph/0305159

The Cl Experiment

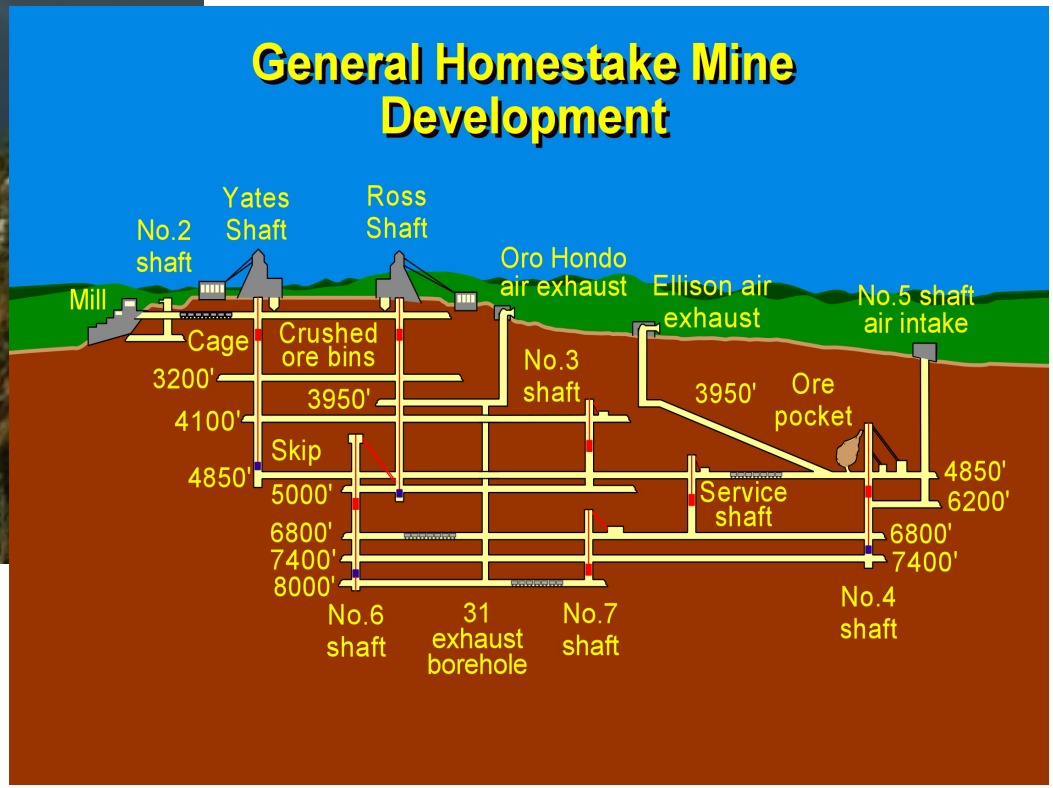
Ray Davis and his tank of cleaning fluid



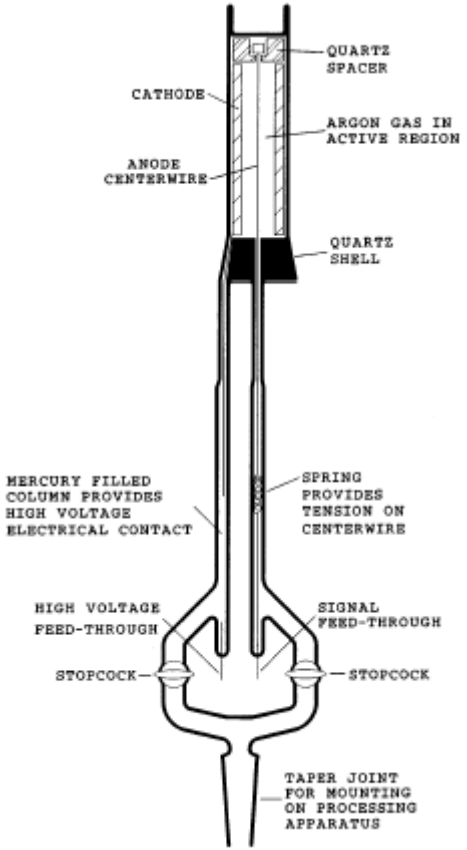
Cl Operations

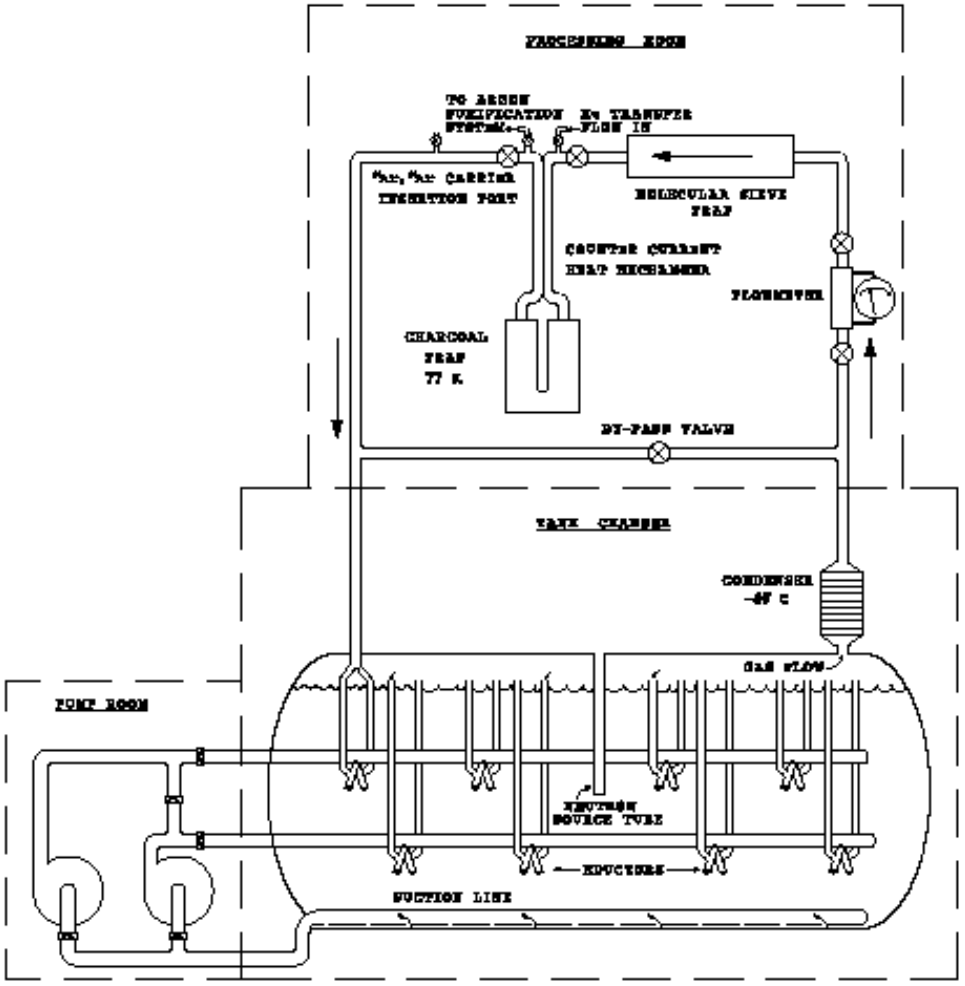
- **615 tons of C_2Cl_4 , 814-keV threshold**
- **Homestake Gold Mine**
- **Bubble He gas through to extract Ar**
- **Ar trapped in cold trap.**
- **PC filled with Ar gas (7% methane)**
- **^{37}Cl is 24% abundant.**

The Homestake Mine

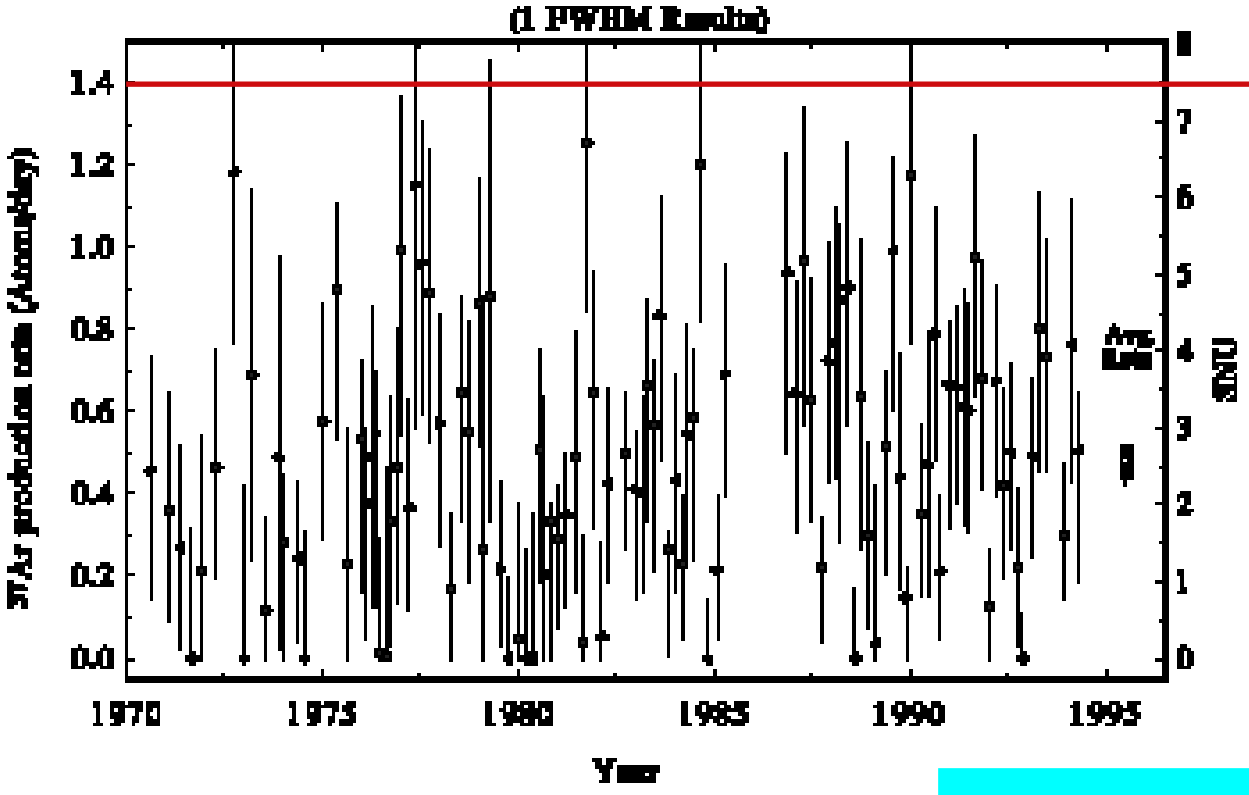


The Cl Apparatus





Cl Results



Expect 7.5 SNU

2.56 ± 0.16 ± 0.16 SNU

SAGE and Gallex (GNO)

- $^{71}Ga(\nu_e,e)^{71}Ge$
- ^{71}Ge has 11.4 day half life.
- Expose Ga to neutrinos
- Extract Ge and count via its decay.

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SAGE Operations

1. **Add carrier to Ga.**
2. **After about 3-4 weeks, extract Ge carrier and solar neutrino induced Ge.**
3. **Synthesize counter gas and fill proportional counter.**
4. **Count sample for about 6 months.**

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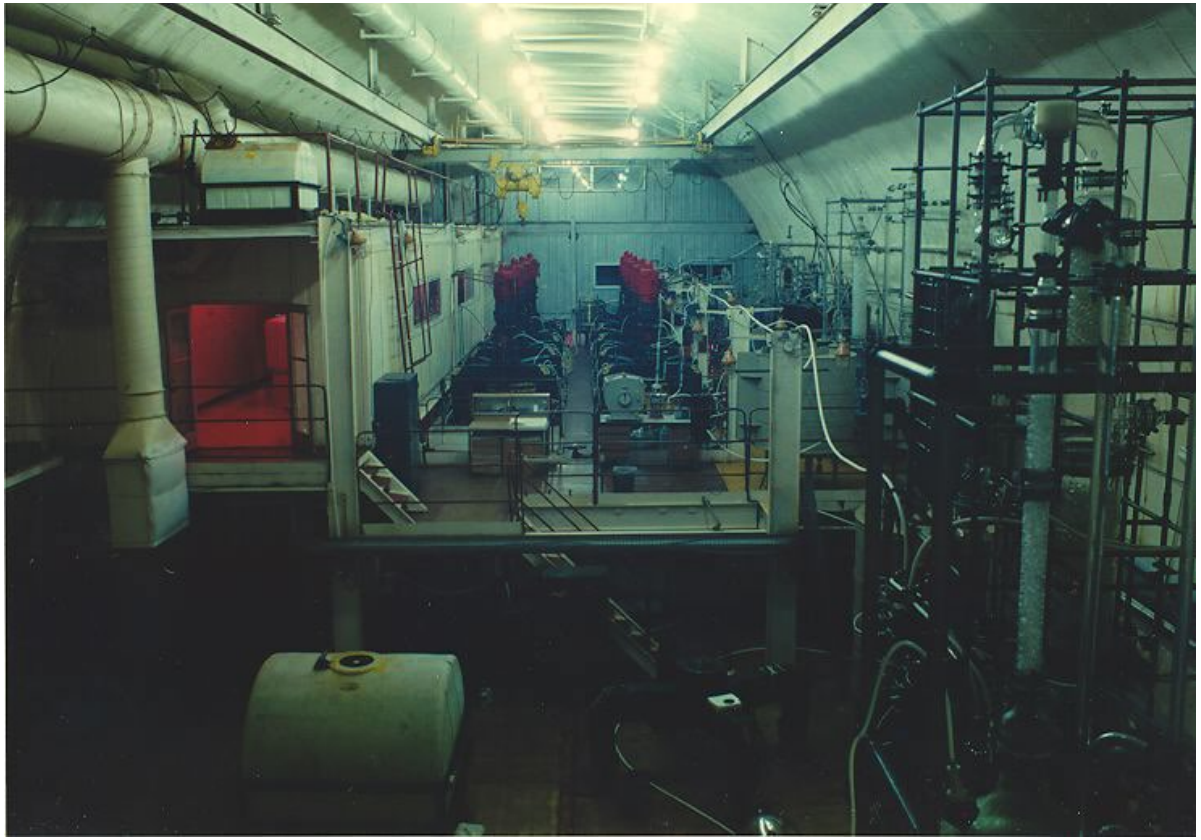
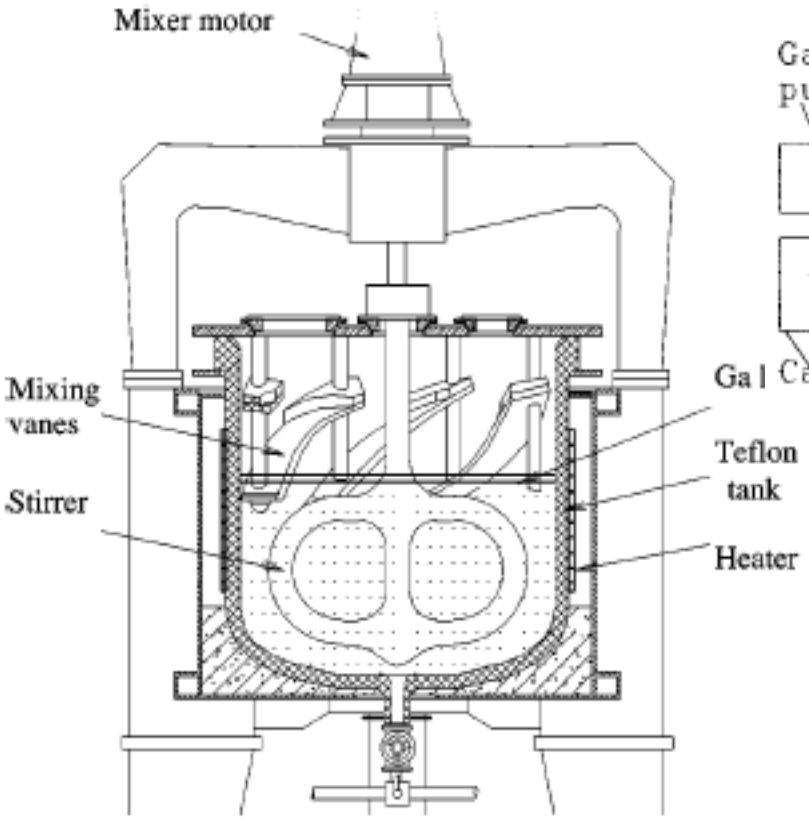
Mt. Andyrchi, Caucasus
Near Mt. Elbrus
Kabardino-Balkaria
Russia

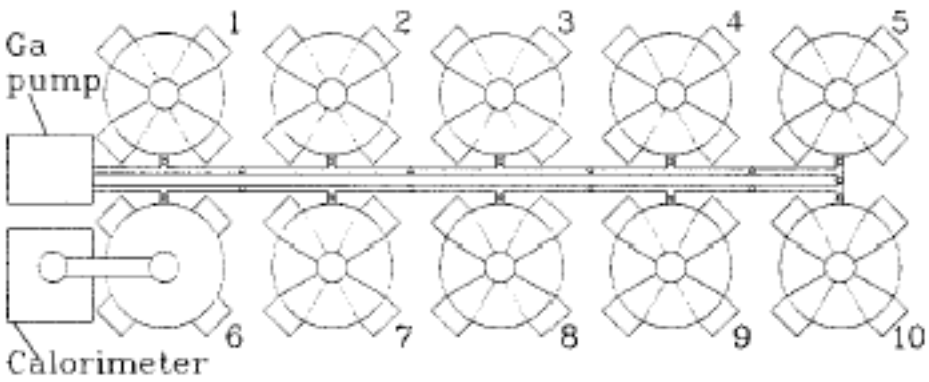
Map to SAGE

Baksan Valley, UG Laboratory



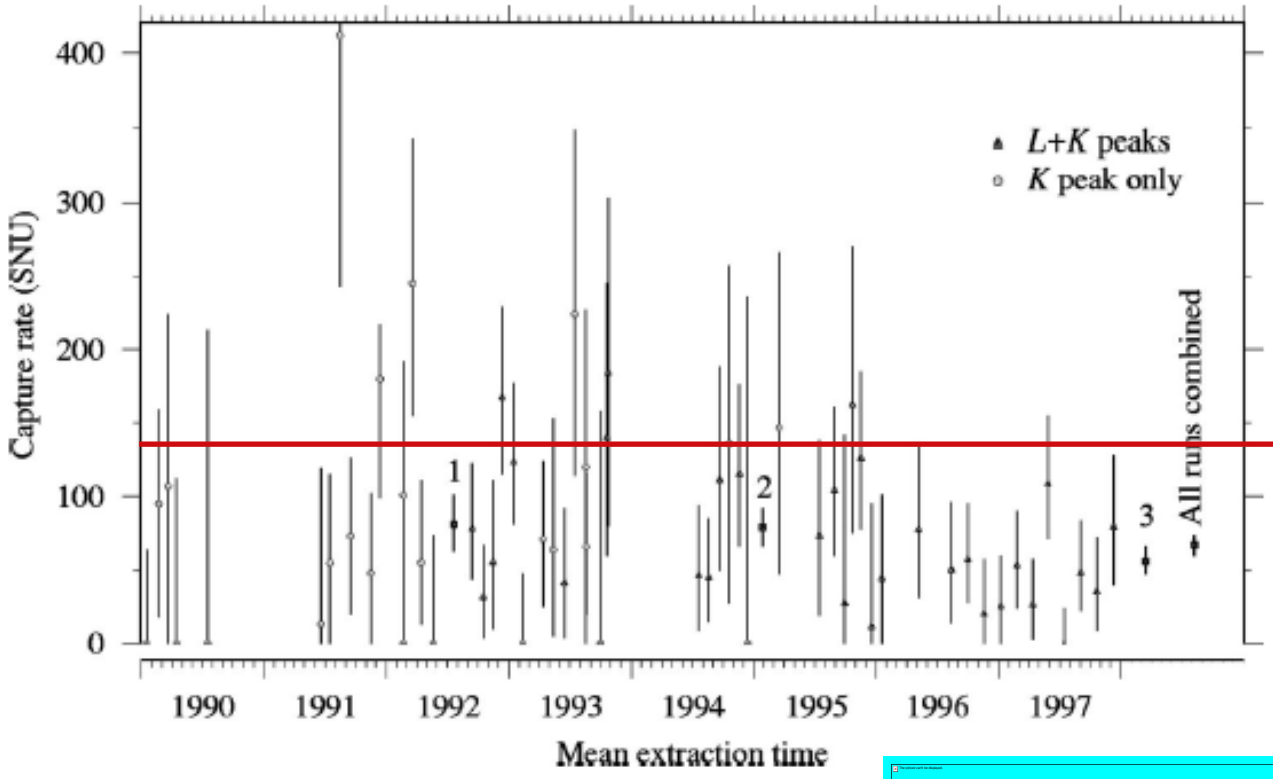
Reactor Layout





10 reactors
Each can hold 8 tons of Ga
Kept warm so Ga is liquid

Results - Solar Rate



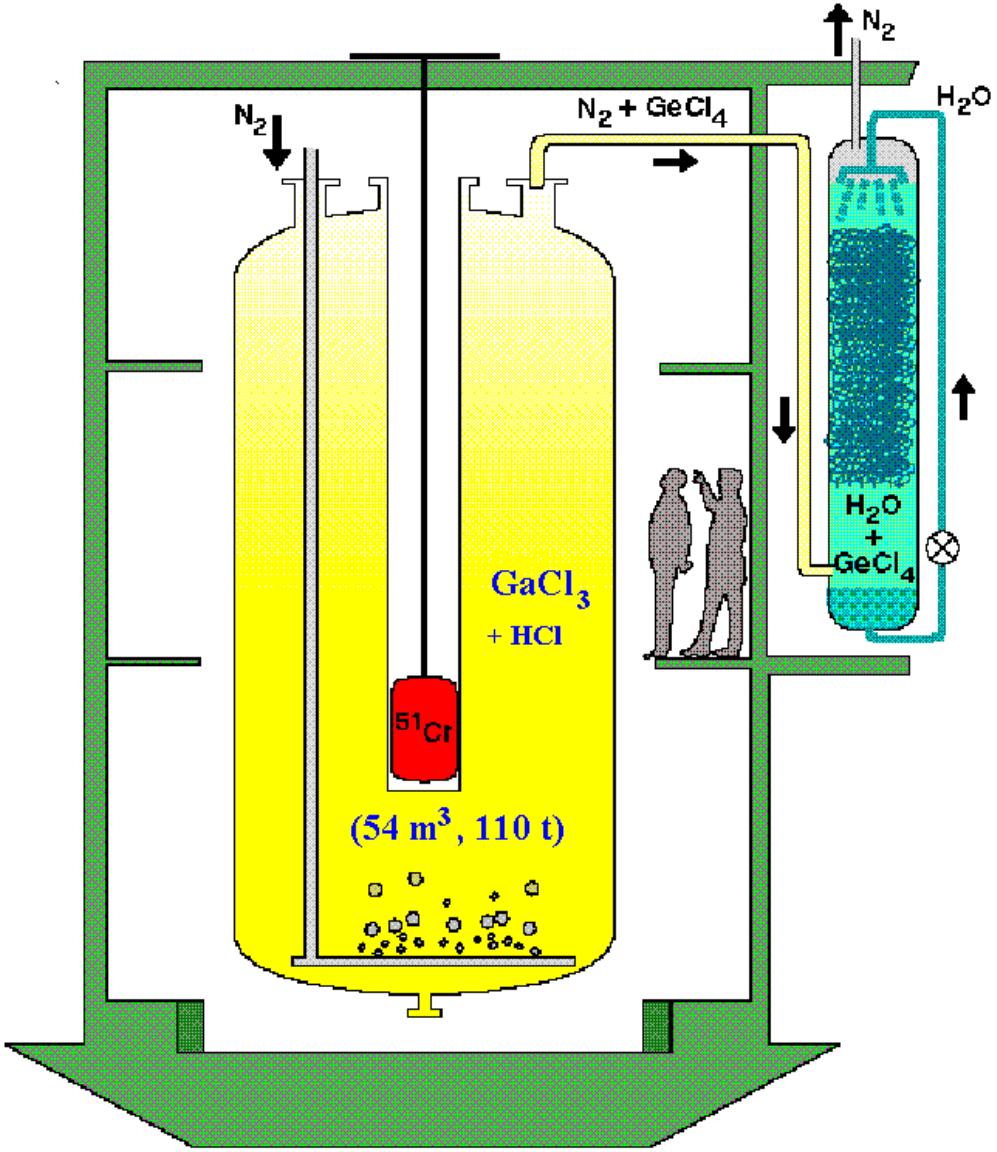
Each run saw about 6 signal Events.

Expect 128 SNU

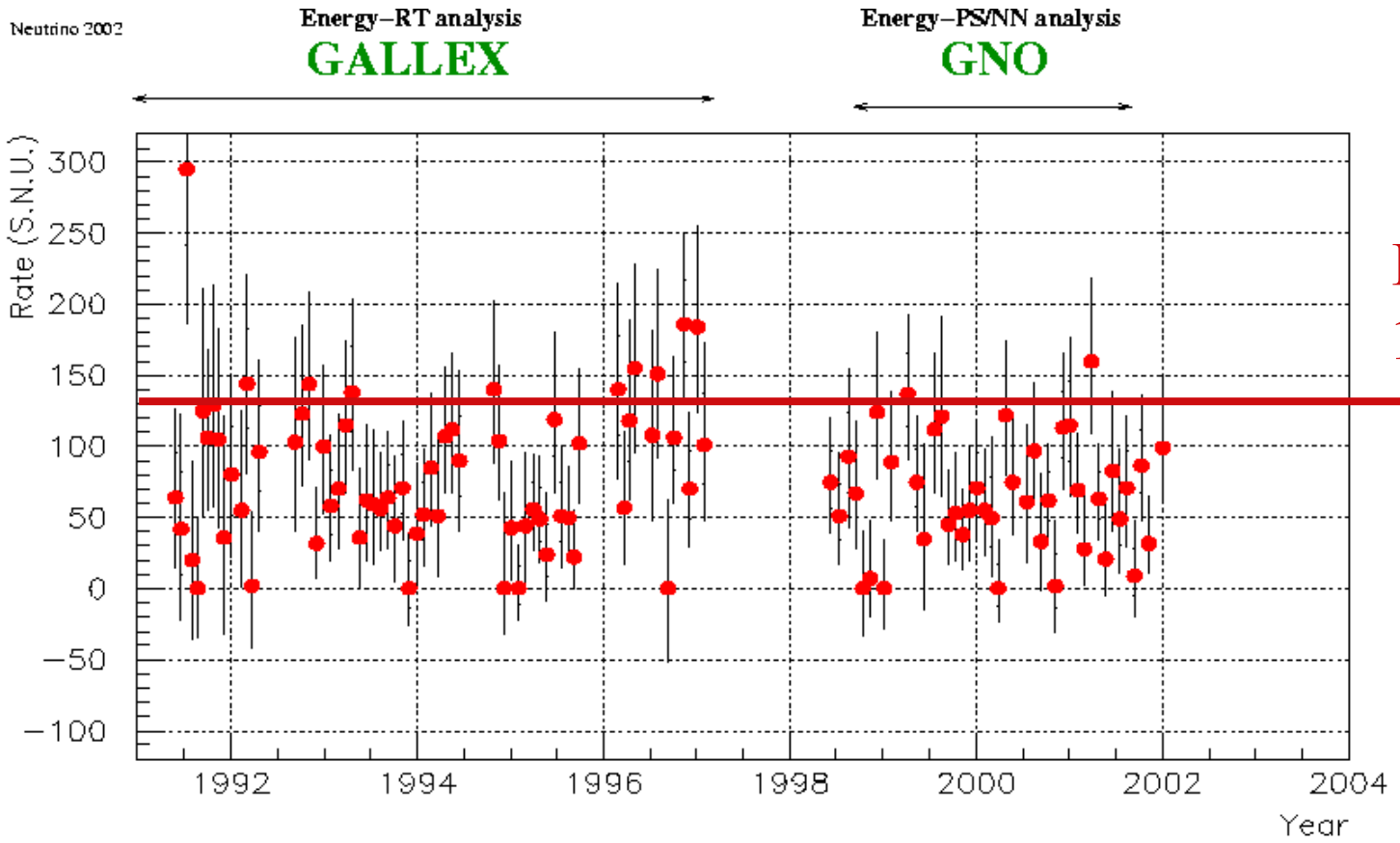
Gran Sasso

Italy:
Not too far
from Rome

GNO Layout



GALLEX Results

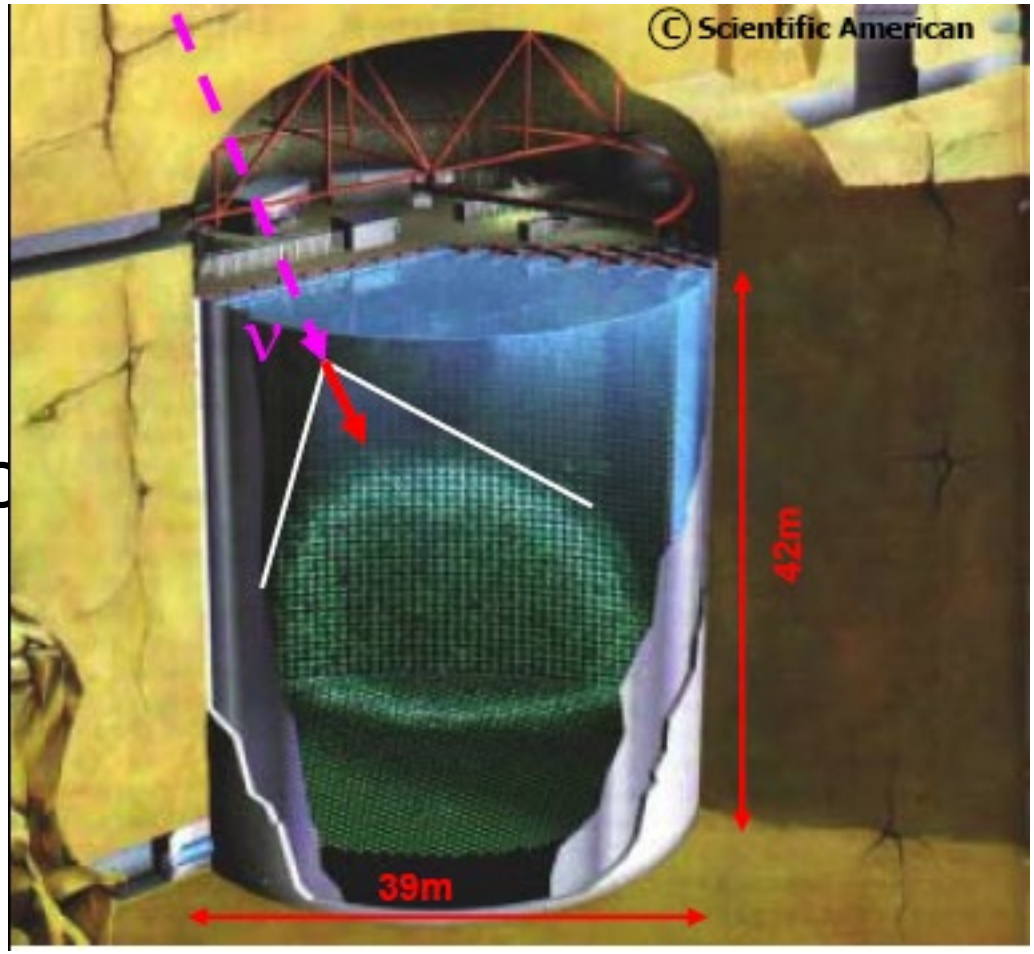


Expected 128 SNU

GALLEX	65 SR	77.5 +– 6.2 (stat) +– 4.5 (sys) SNU
GNO	43 SR	65.2 +– 6.4 (stat) +– 3.0 (sys) SNU
GNO+GALLEX	108 SR	70.8 +– 4.5 (stat) +– 3.8 (sys) SNU

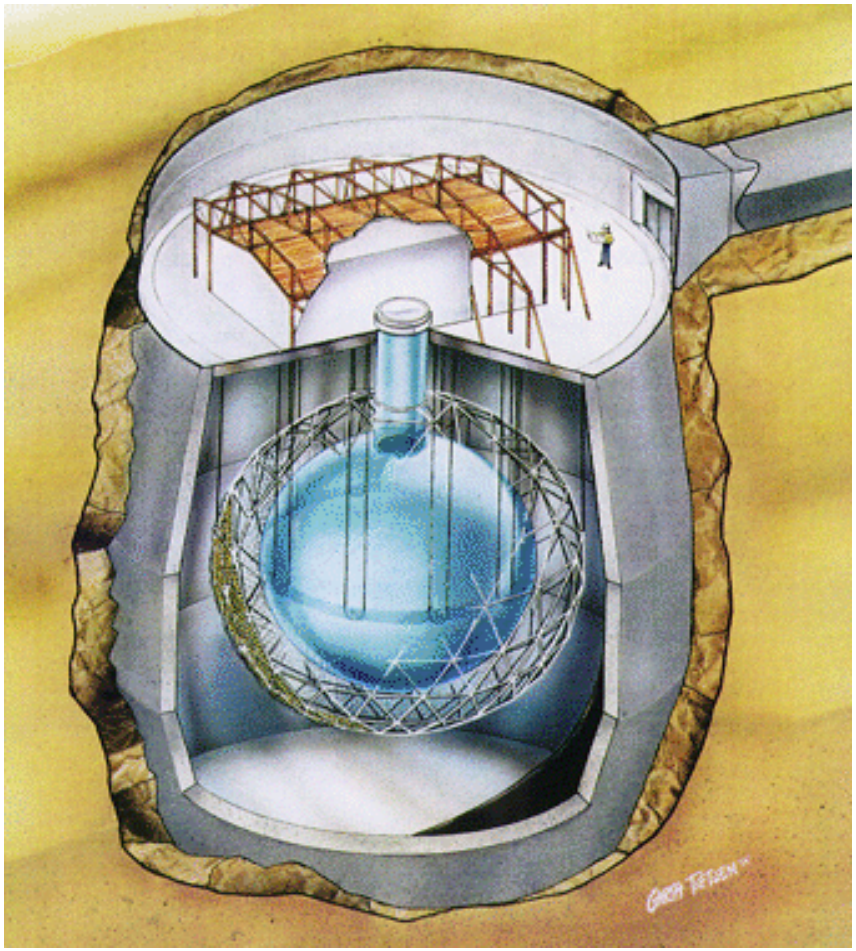
Kamiokande & SuperK

- Elastic scattering of e^- in a large water detector
- Mostly sensitive to ν_e because CC cross section is about 6x higher than NC

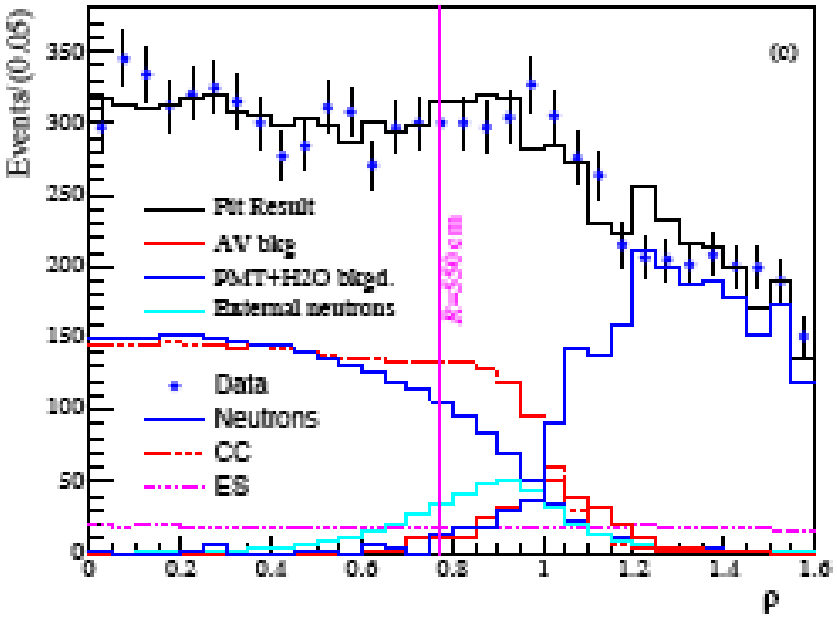


SNO

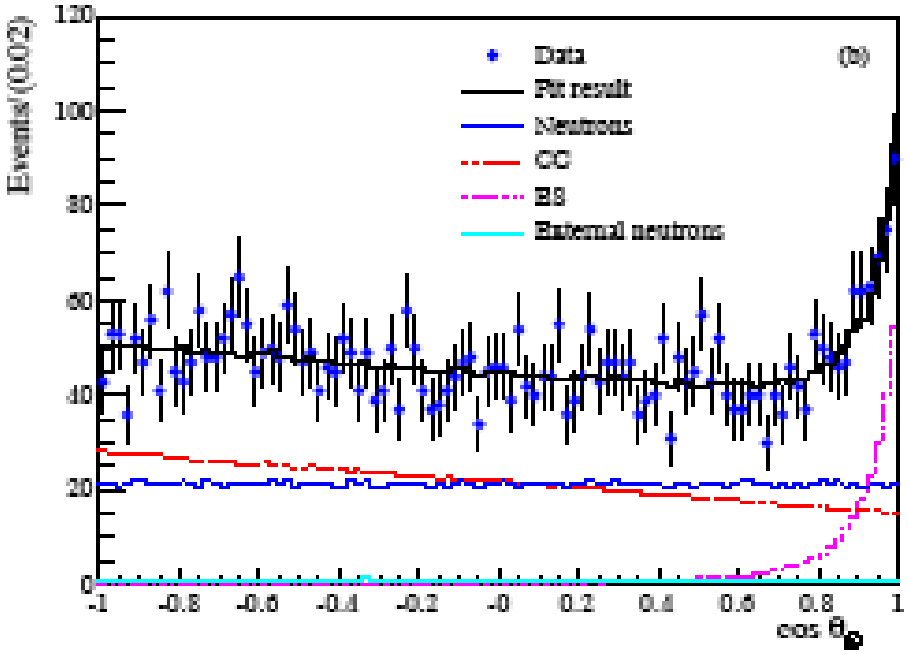
- **ES, CC, and NC**
- **CC: d(ν_e, pp)e^-**
  - **Sensitive only to ν_e**
- **NC: d(ν_x, np)ν_x**
  - **Sensitive to all ν_x**
- **NC/CC ratio**



SNO data

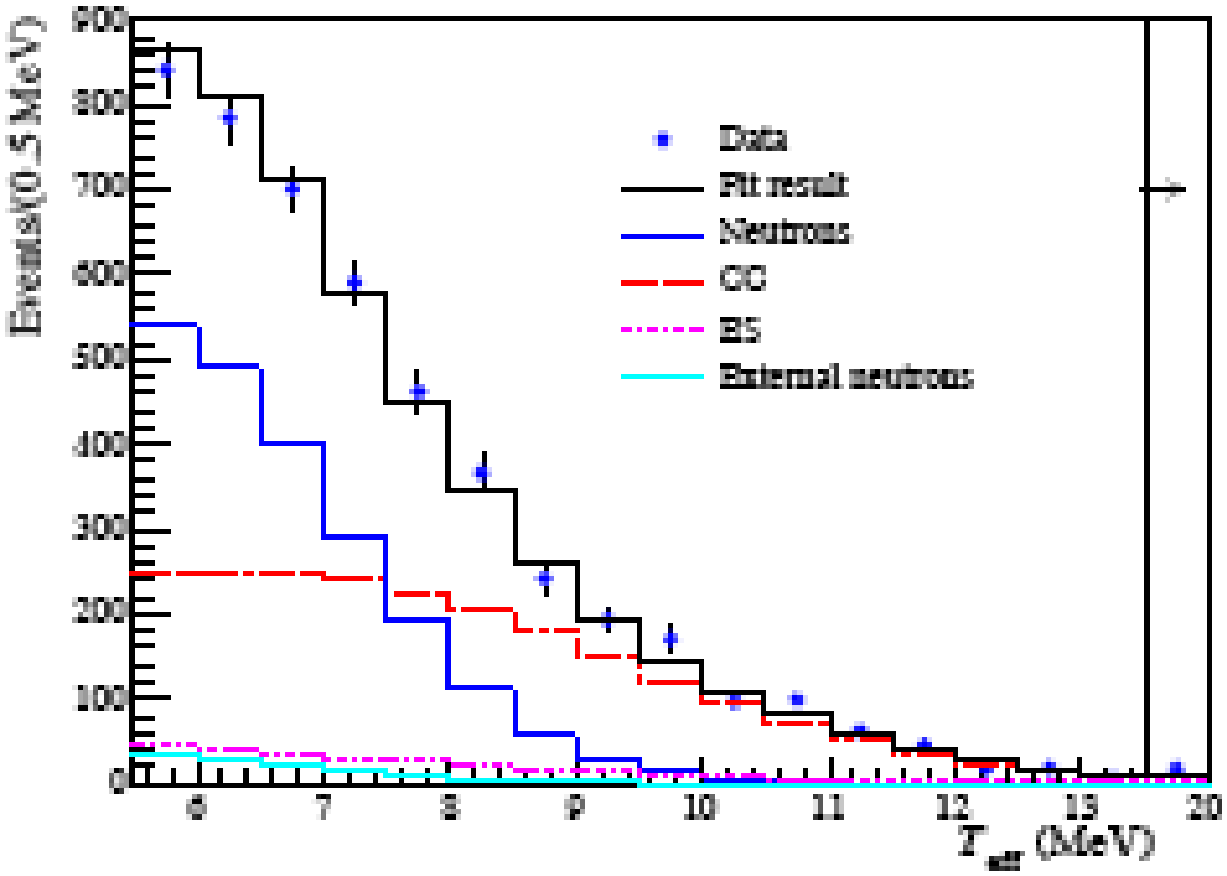


Radius of event vertex

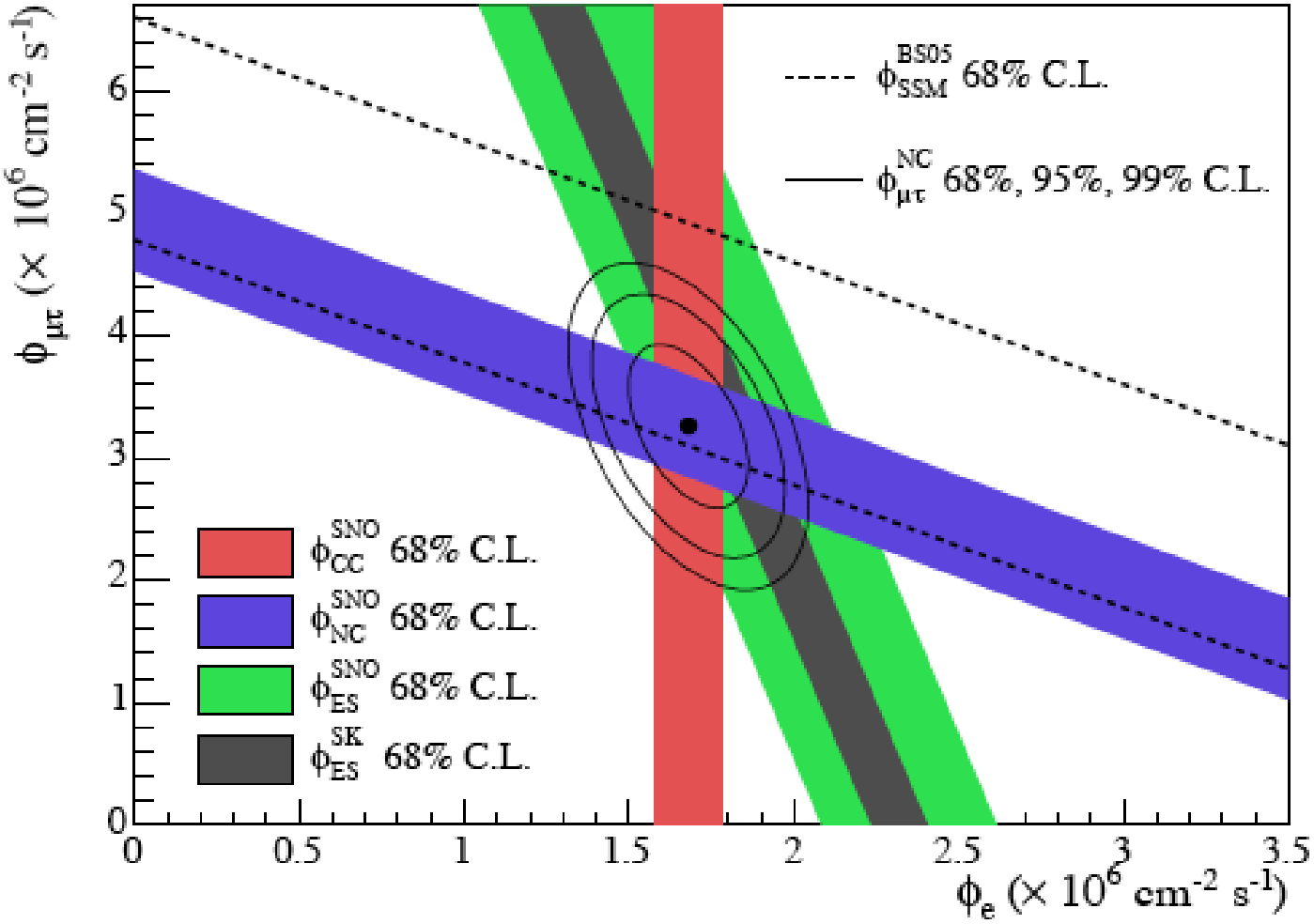


Angle with Sun

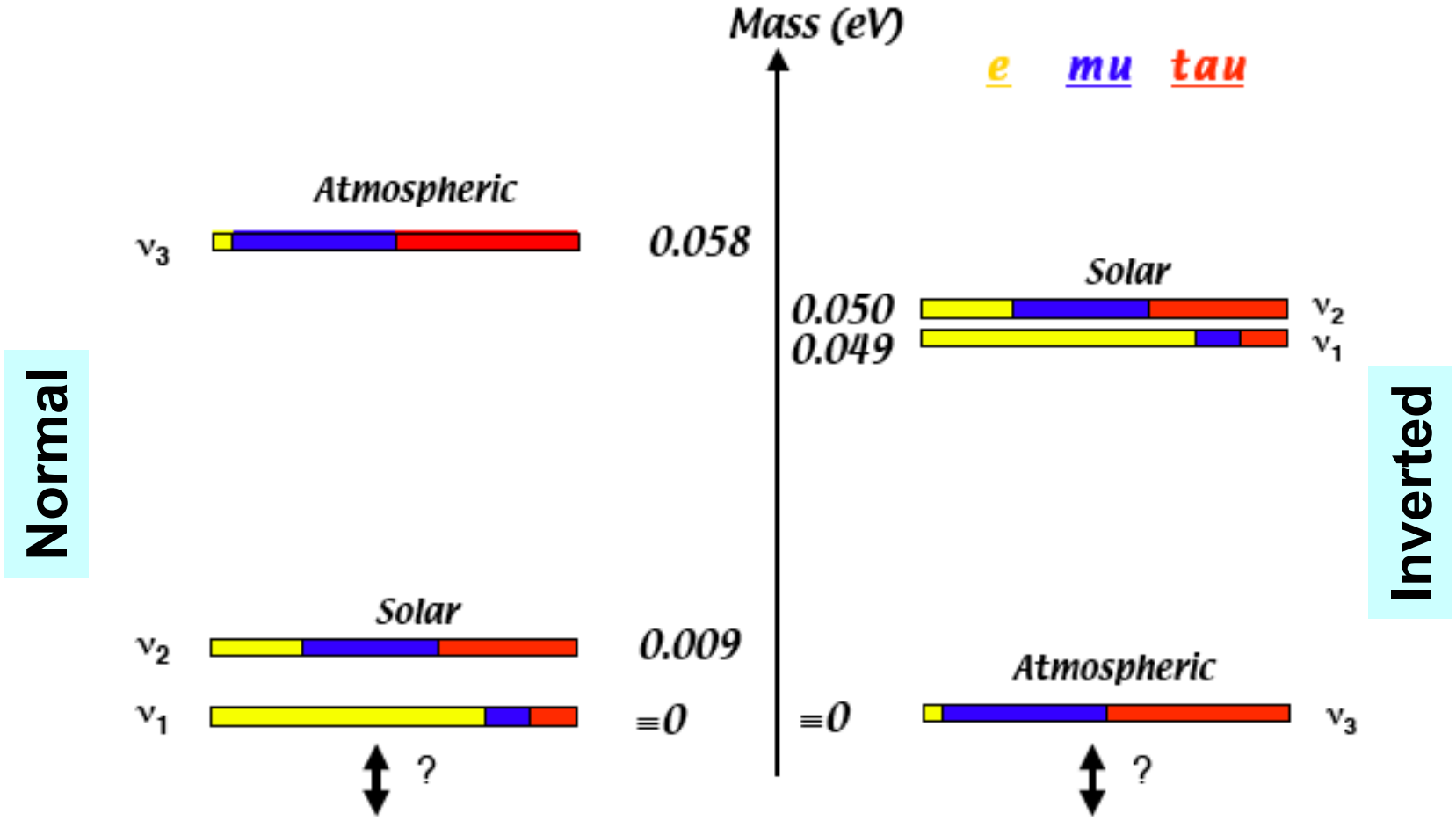
Event Energy



NC vs. CC response



The hierarchy question



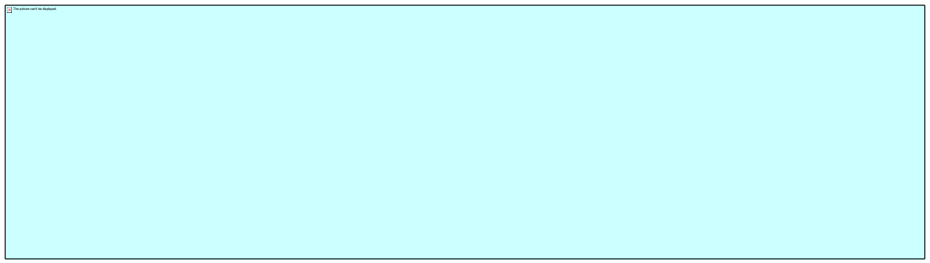
The “Dark Side” of solar neutrinos

Two “flavors” are involved in solar neutrino oscillations. ν_e and a linear combination of ν_μ and ν_τ.

The “Dark Side” of solar neutrinos II

For $\theta<\pi/4$, ν_1 is mostly ν_e. But for $\theta' = \pi/2 - \theta < \pi/4$, ν_1 is mostly $\nu_{\mu+\tau}$.

Thus, although oscillations in a vacuum cannot distinguish between θ and θ', matter oscillations can.

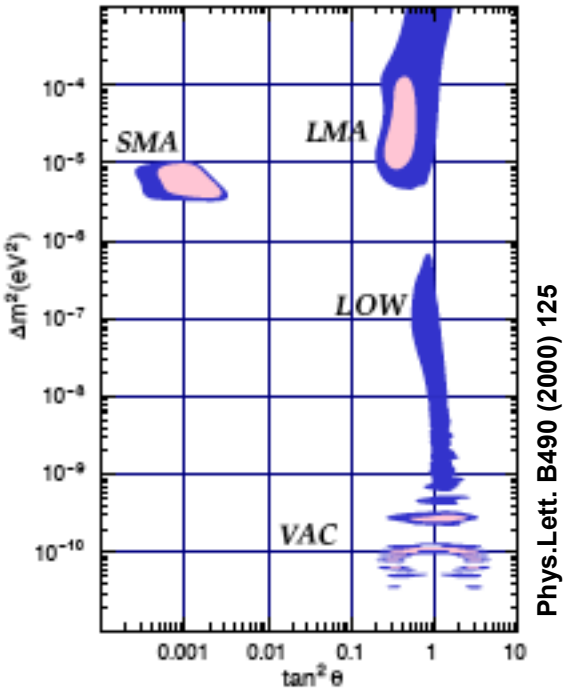


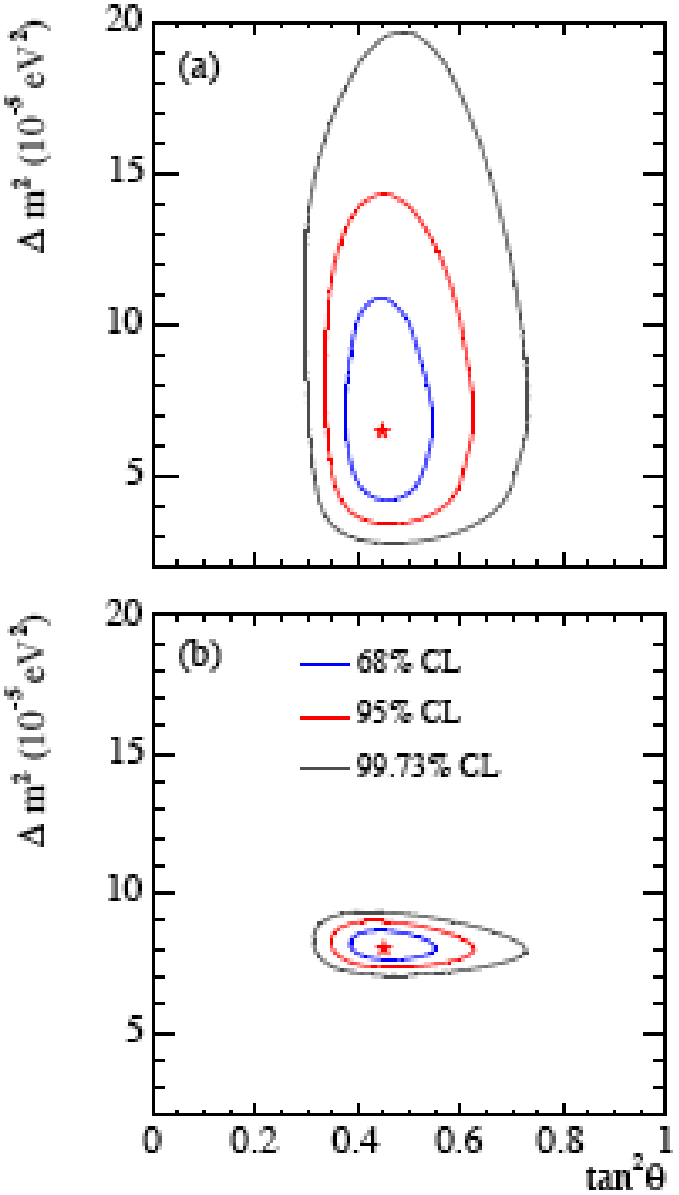
That is $\cos 2\theta$ changes sign.

Solar Neutrino Results

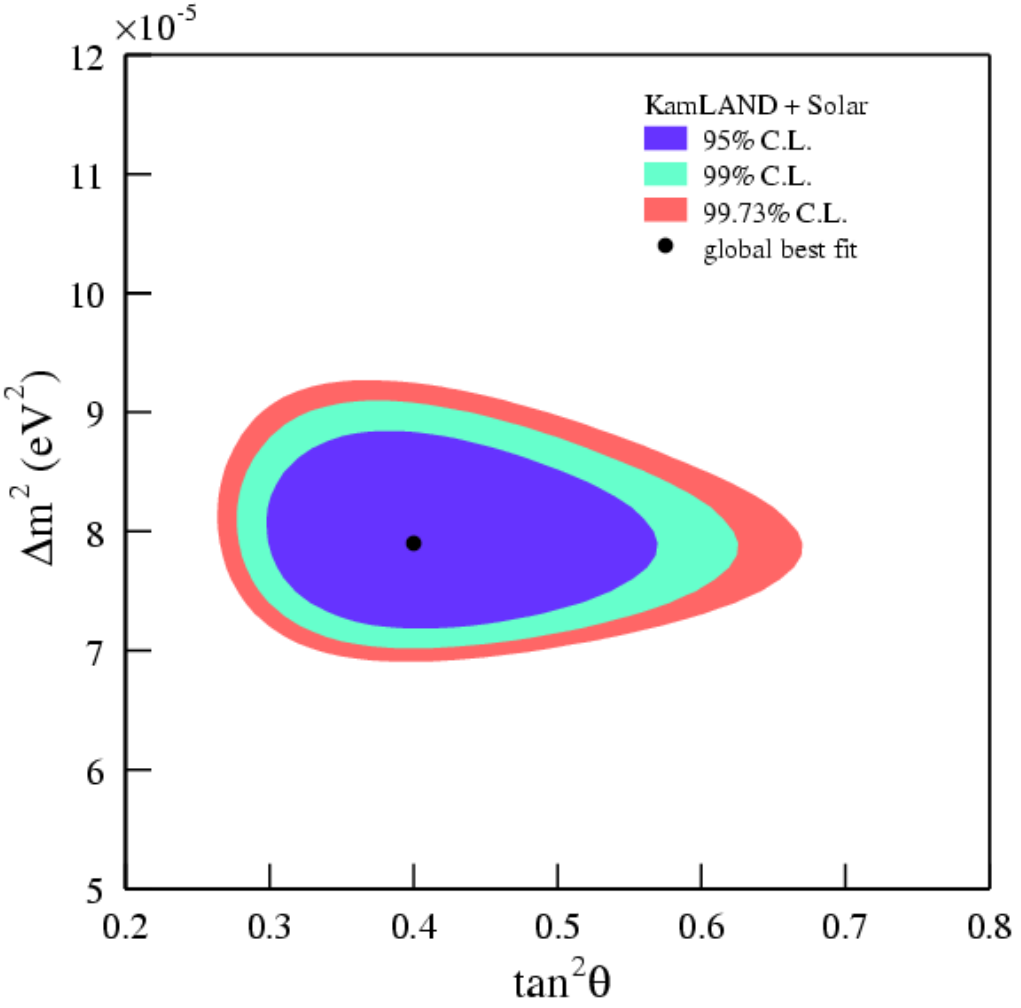
there is no dark side

Early fit to solar neutrino data. Note solution space for tanθ>1.





The addition of KamLAND



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What's left to do?

- Is our model of neutrino mixing and oscillation complete, or are there other mechanisms at work?
  - Without luminosity constraint, pp and ^{7}Be fluxes poorly known.
  - With constraint, ^{7}Be is still poorly known.
- Is nuclear fusion the only source of the Sun's energy and is it steady state?
- What is the correct hierarchial ordering of the neutrino masses?

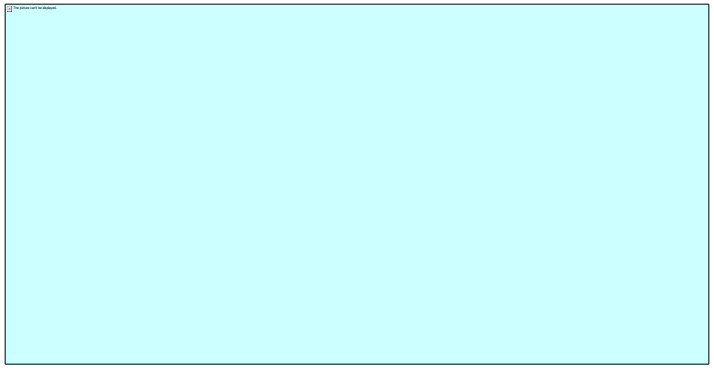
Non-Standard transformation possibilities

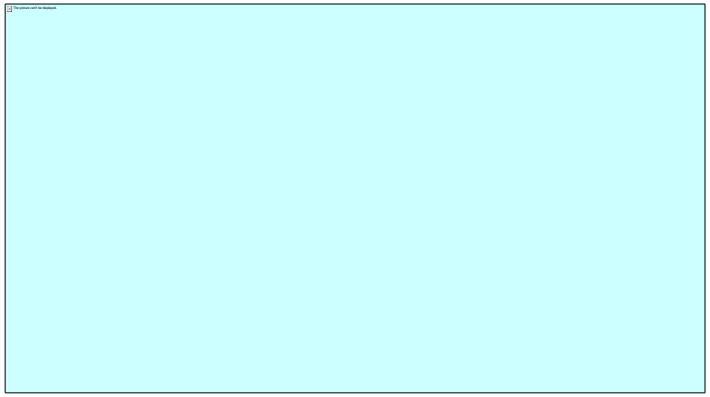
- Violation of equivalence principle
- Violation of Lorentz principle
- Non universal coupling
- Violation of Lorentz invariance due to CPT violating terms
- Non-standard neutrino interactions

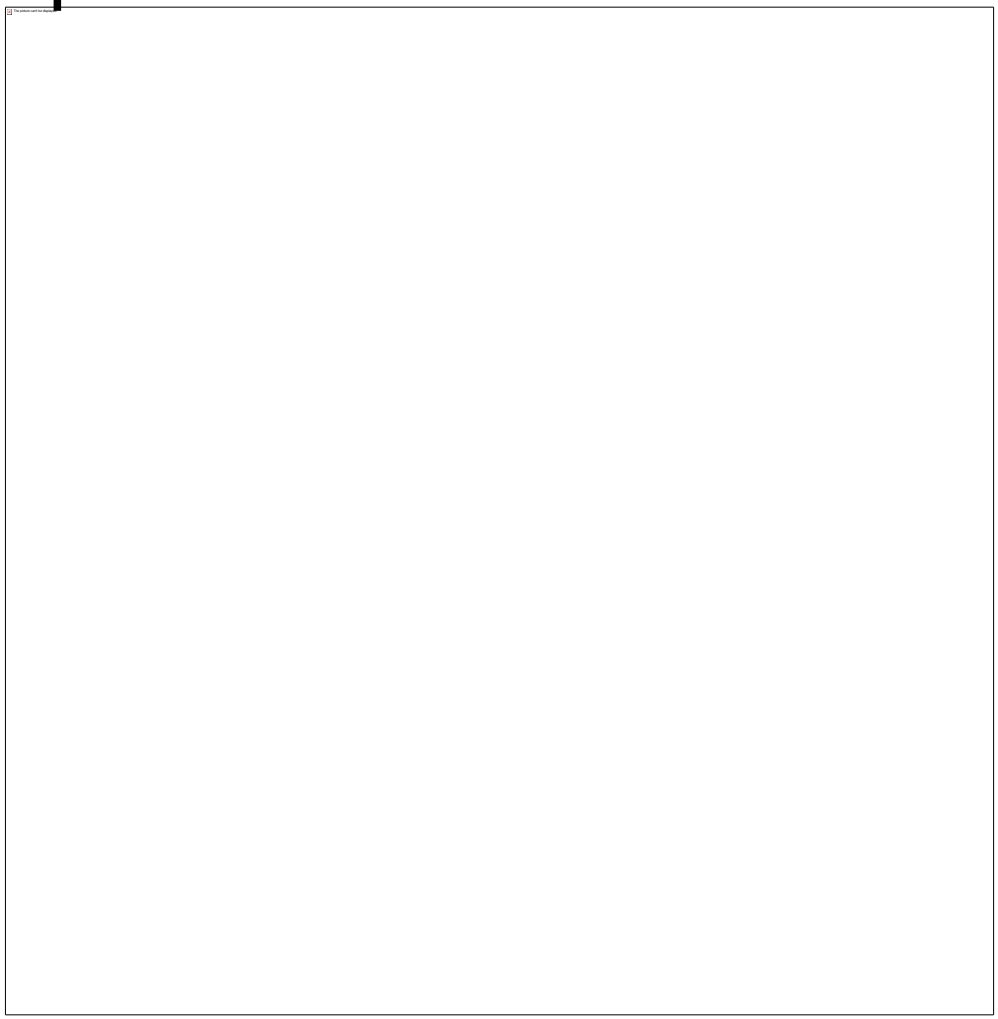
Future Solar Neutrino Experiments

Experiment	Target	Reaction	Threshold
Borexino	~300 t liq. Scint.	ES	~250 keV
KamLAND	~600 t liq scint.	ES	~250 keV
LENS	60 t In load in scint	CC	
HERON	68 m^3 LHe	ES	~45 keV
CLEAN	40 t liq. Ne	ES	~35 keV
MOON	Few t of ^{100}Mo	CC	168 keV

Atmospheric Neutrinos
Up vs. Down







IMB and Kamiokande

- **Previous large water Cherenkov detectors**
- **Built to look for proton decay, atmospheric neutrinos are a significant background: hence lots of study**
- **Kamiokande was able to lower threshold to see solar neutrinos**
- **Saw SN1987A, but not pdk**
- **Statistically weak indication of atmospheric neutrino oscillations**
- **Led to plan for Very Large SuperK**

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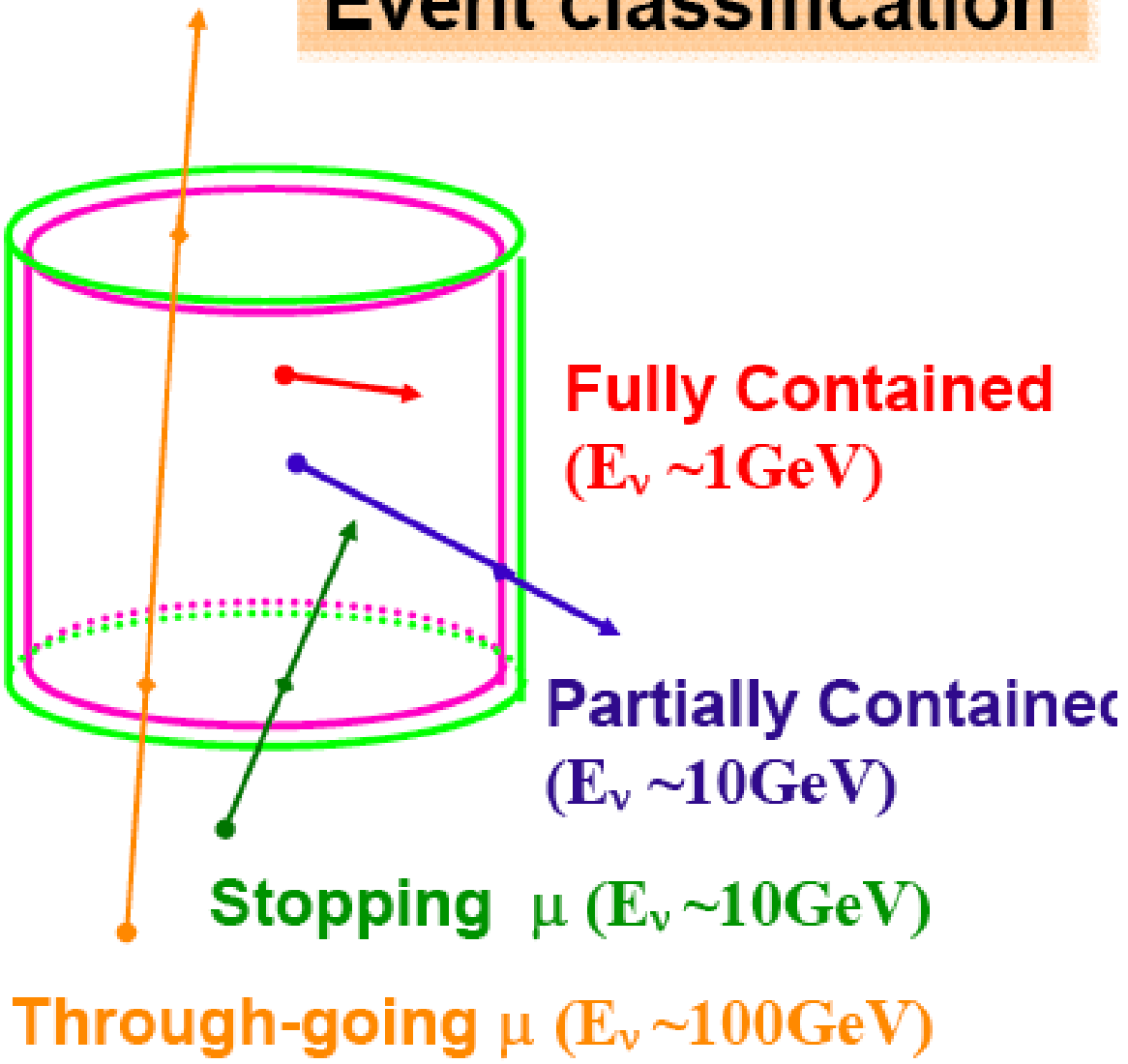
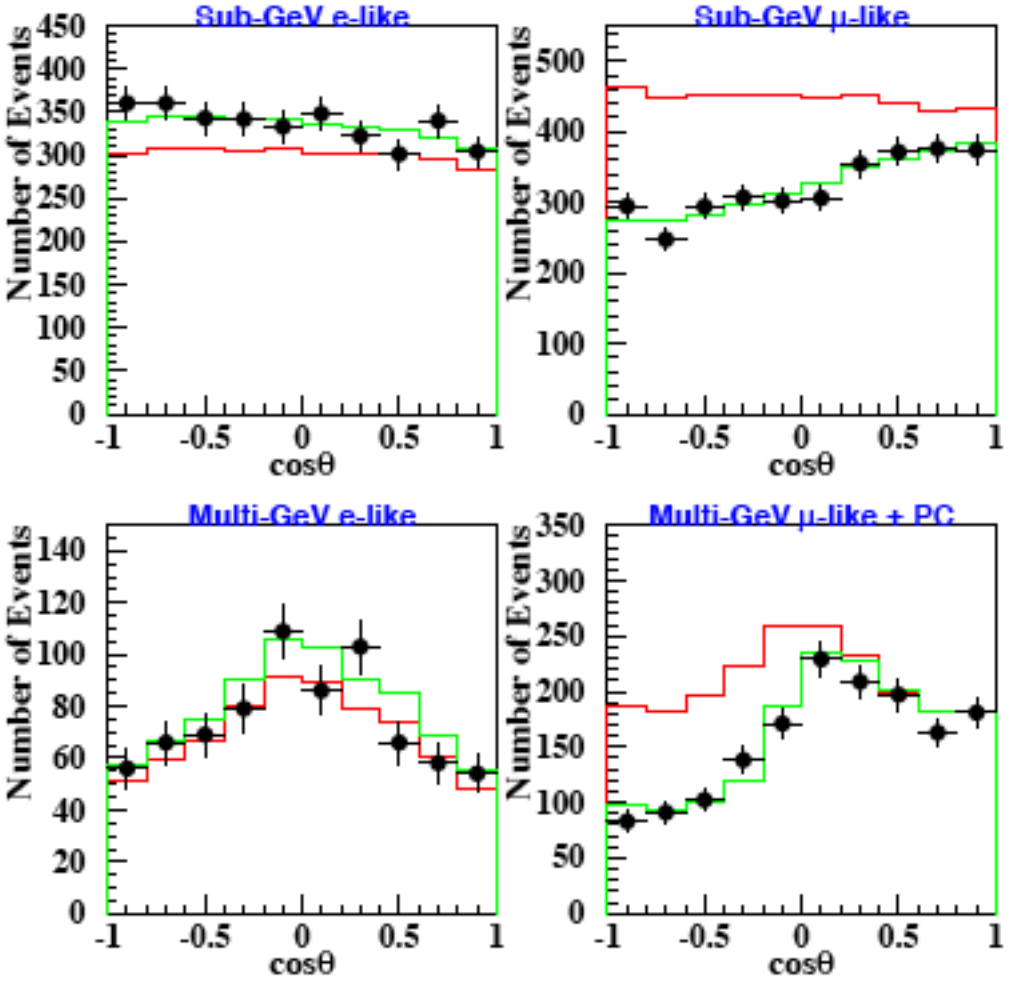
Event classification

SuperK

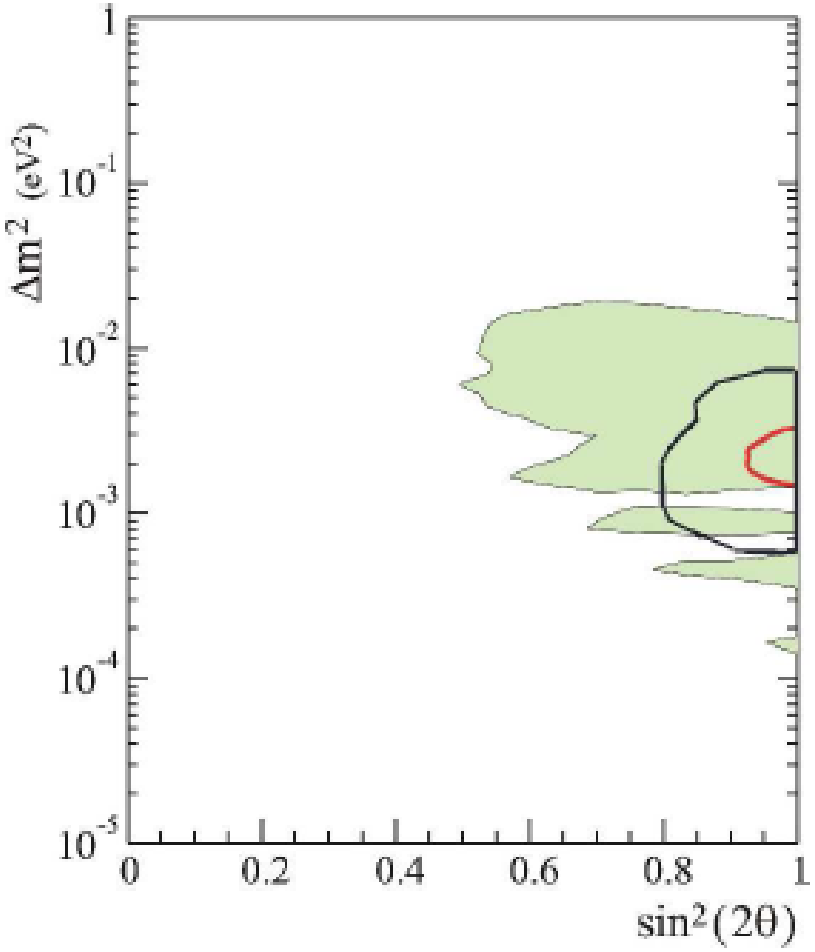
- 1000 m underground
- 50,000 tons of water
- 12,000 pmts



Results


Sub-GeV e-like
Sub-GeV μ-like
Multi-GeV e-like
Multi-GeV μ-like + PC
Number of Events
cosθ

Maximal mixing and the future

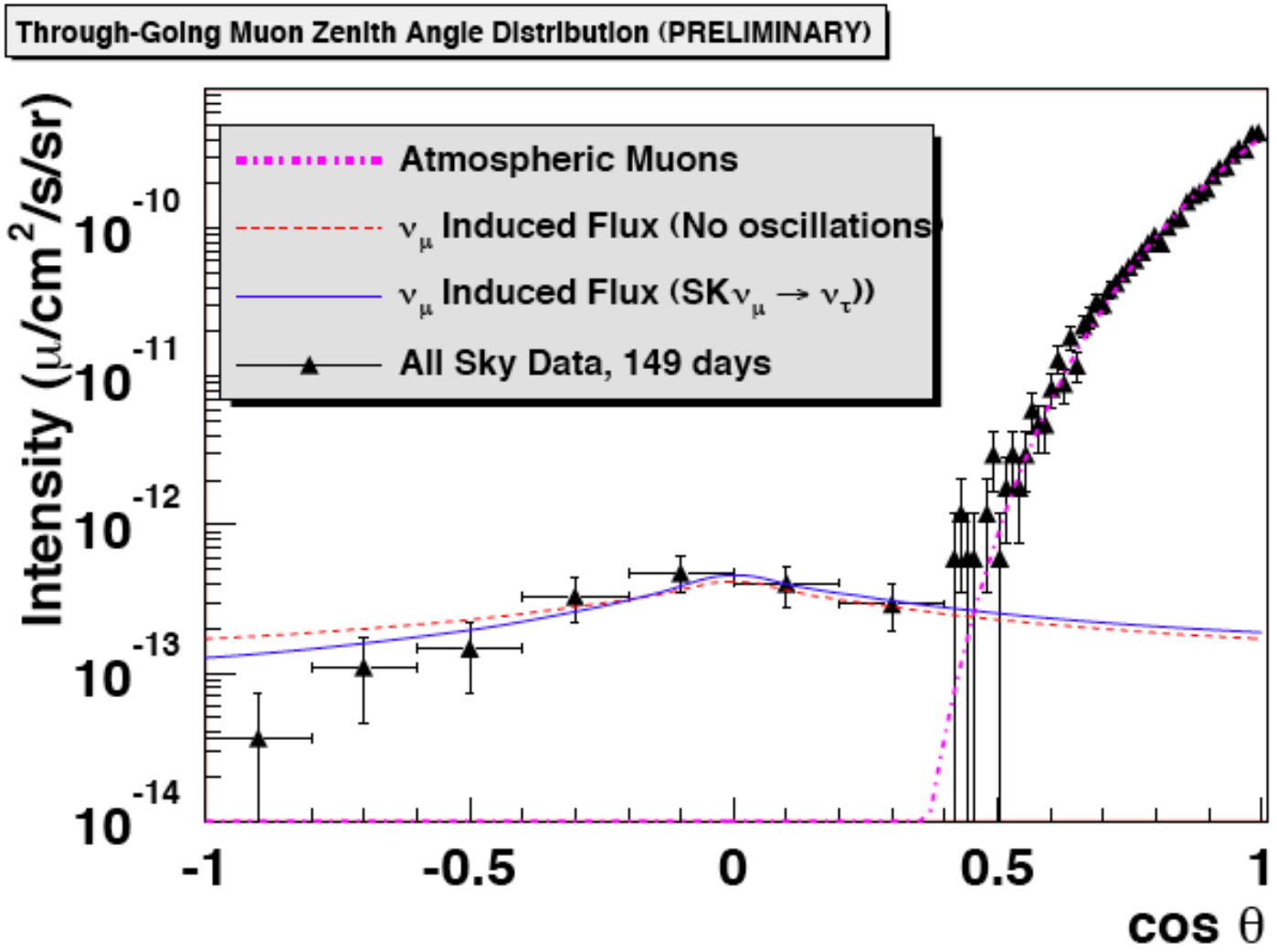


If $\sin^2\theta_{13}$ is different than 0, Earth matter effects can resonantly enhance the subdominate transitions depending on the sign of δm_{23}^2.

Future Experiments

Experiment	Target	Status
SuperK	50 kt water	Continue on
SNO	1 kt heavy water	Continue on
MINOS	Iron magnetized calorimeter	Operating, but small
INO	30-50kt magnetized tracking calorimeter	proposal
UNO/HyperK	Mt class water	proposal

SNO is “small” but deep



Resources

- Andrew Hime colloquium
- APS neutrino study on solar and atmospheric neutrinos