A Deep Ocean Anti-Neutrino Observatory

An Introduction to the Science Potential of Hanohano

Presented by
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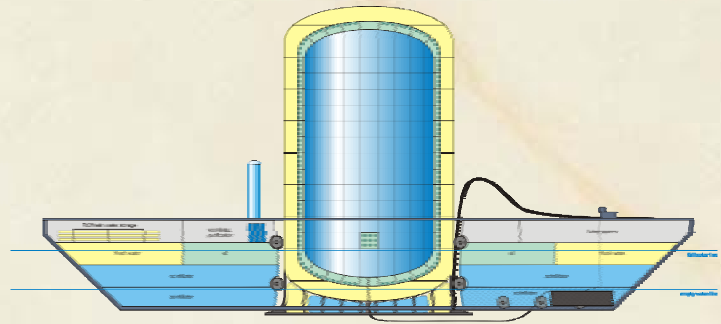
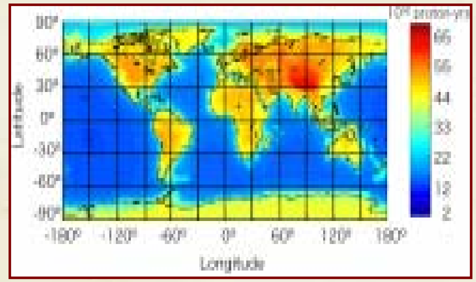
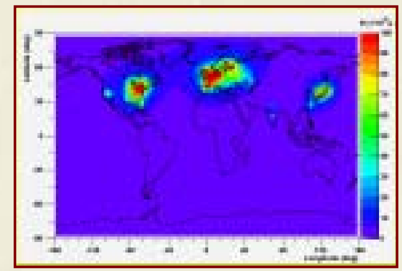
University of Hawaii at Manoa

Outline

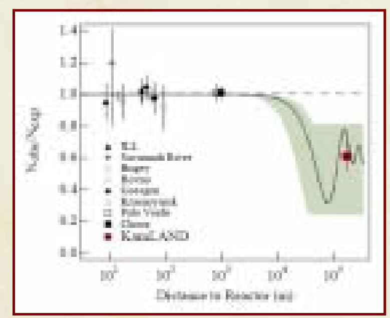


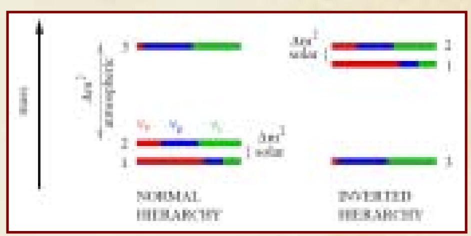
- Detector Development
- Neutrino Geophysics
  - U/Th mantle flux
  - Th/U ratio
  - Georeactor search





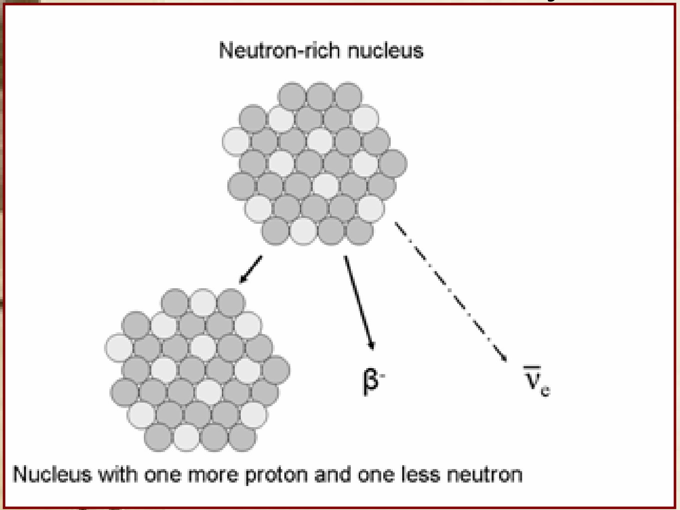
- Neutrino Oscillation Physics
  - Mixing angles θ_{12} and θ_{13}
  - Mass squared difference $\Delta m^2{}_{31}$
  - Mass hierarchy



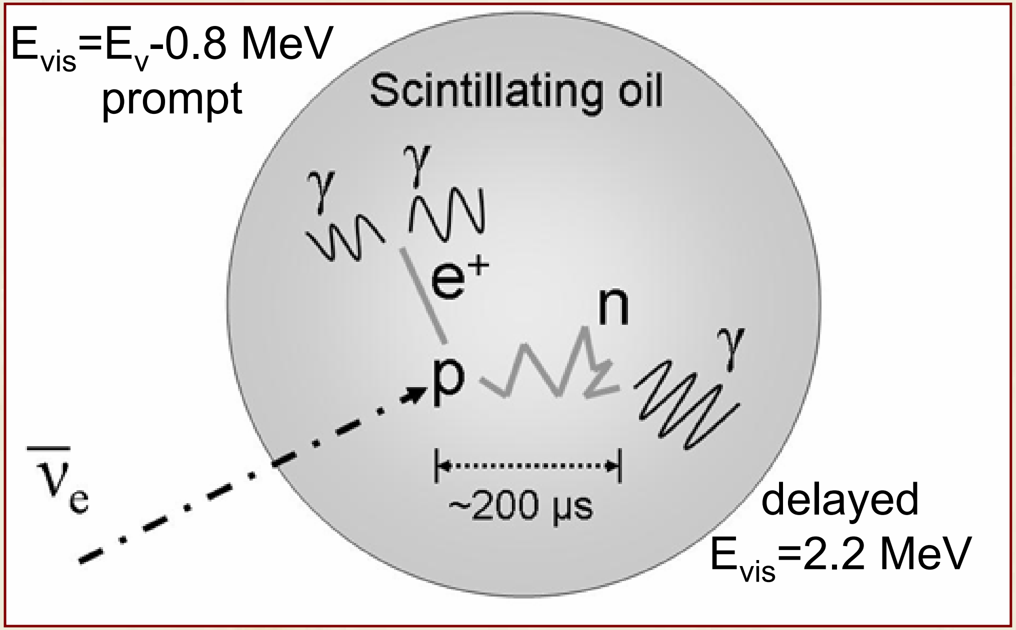


MeV-Scale Electron Anti-Neutrino Detection

Production in reactors and natural decays



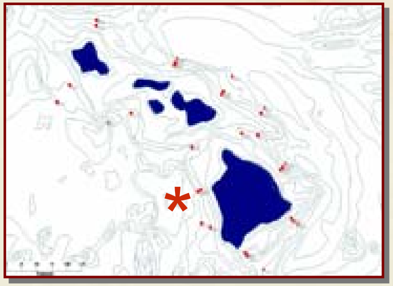
Detection

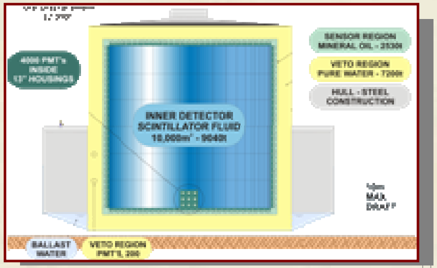


- Standard inverse β-decay coincidence
- E_{ν} > 1.8 MeV
- Rate and spectrum - no direction

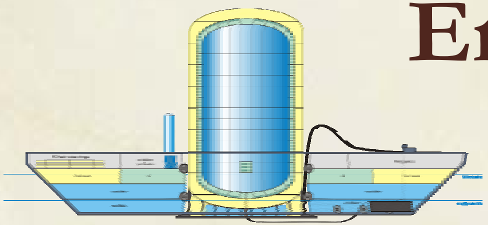
Deep Ocean Anti-Neutrino Detection

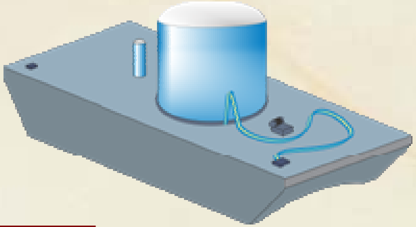
- Overburden ‘free’
  - Invest excavation time and cost in detector
  - Much investment in ocean oil field technolgy
- Location flexibility, aim at 1 year cycles
  - Far from continental crust and reactors for neutrino geophysics- Hawaii, So. Pacific
  - Offshore of reactor for neutrino oscillation physics- California, Taiwan examples
- Engineering / technology challenges
  - Deployment / recovery/ repair
  - Remote operation via fiber optics
  - High pressure / low temperature
- Hawaii Anti-Neutrino Observatory
  - Hanohano (distinguished in Hawaiian)
  - One year science and engineering design study completed.



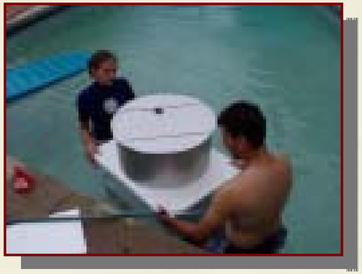


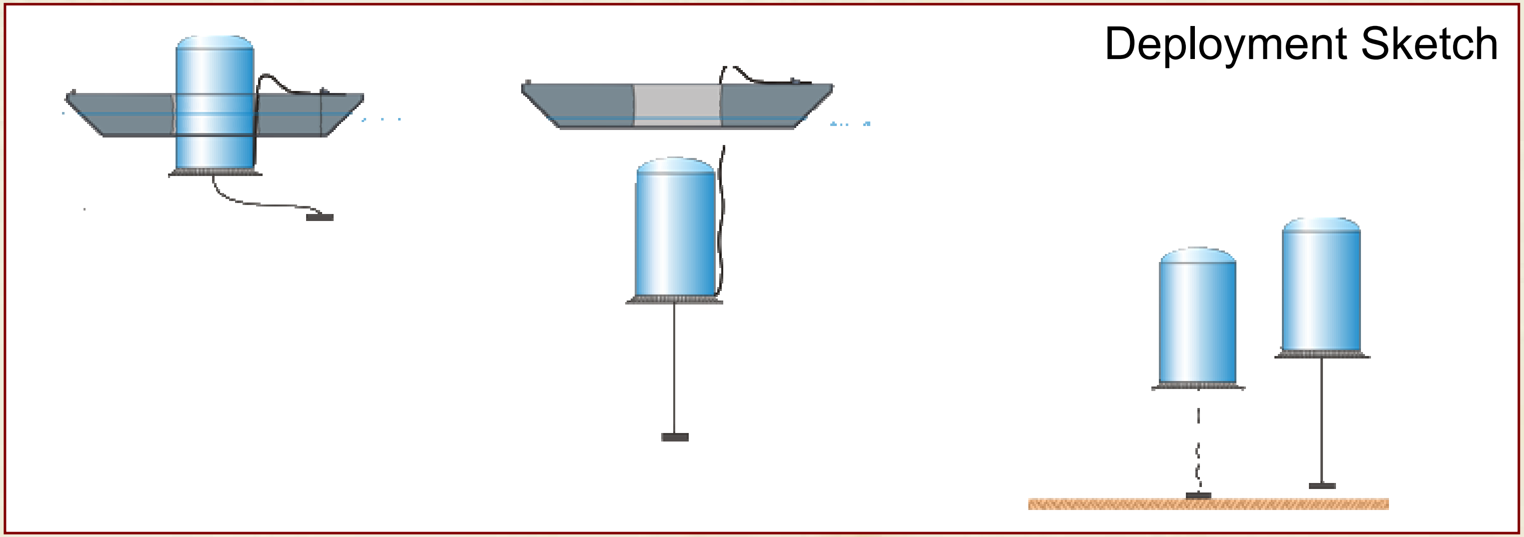
Engineering Studies





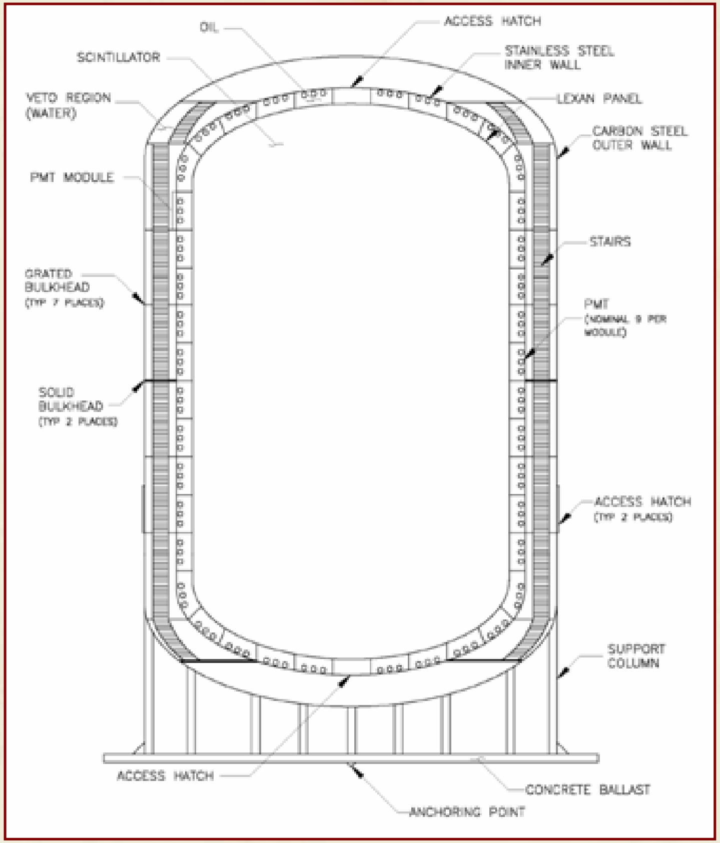
- Studied vessel design up to 100 kilotons, based upon cost, stability, and construction ease.
- Construct in shipyard
- Fill/test in port
- Tow to site
- Deploy ~4-5 km
- Recover/ repair or relocate and redeploy
- Can traverse Panama Canal

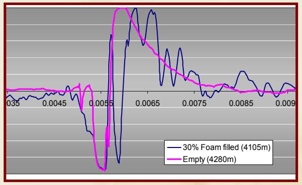




Addressing Technological Issues

- Scintillating oil studies in lab
  - P=450 atm, T=0° C
  - Testing PC, PXE, LAB and dodecane
  - No problems so far, LAB favorite
- Implosion studies
  - Design with energy absorption
  - Computer modeling
  - At sea
  - No stoppers

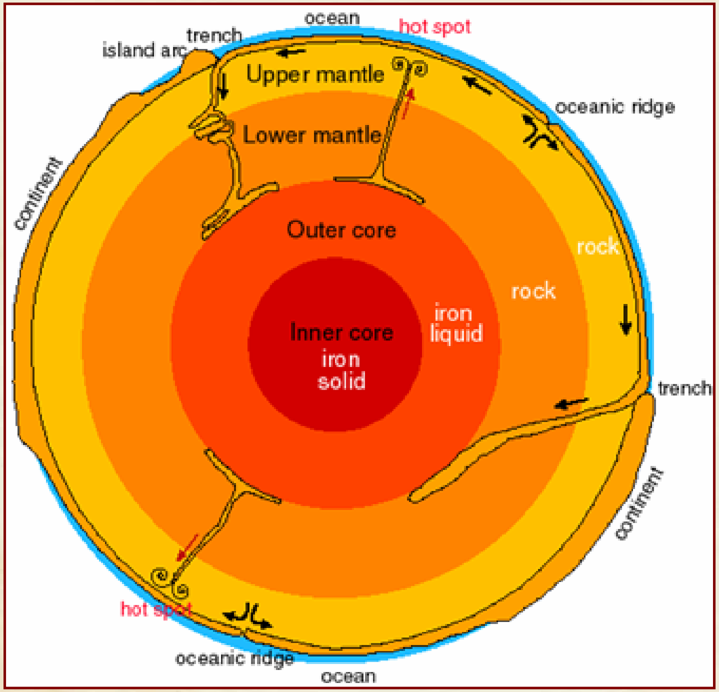




Neutrino Geophysics

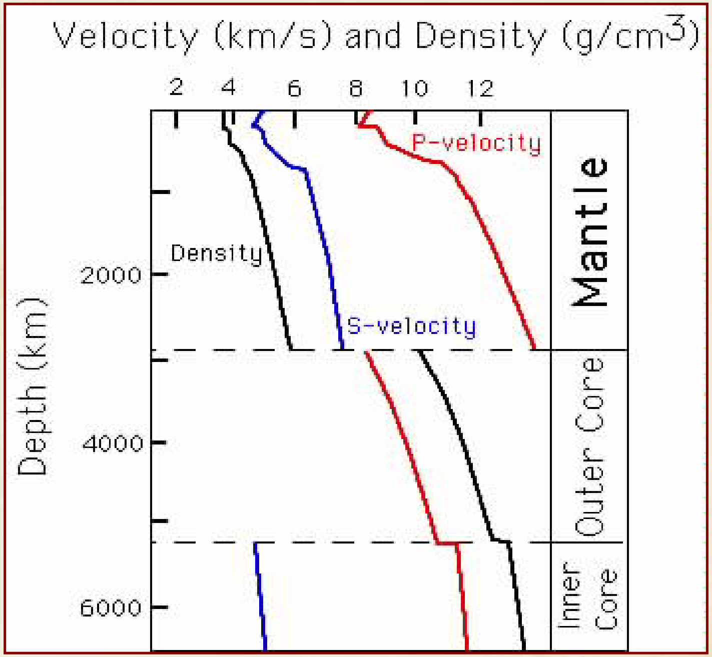
Primary question: from where comes the heat that drives crustal motion and ghe geomagnetic field?

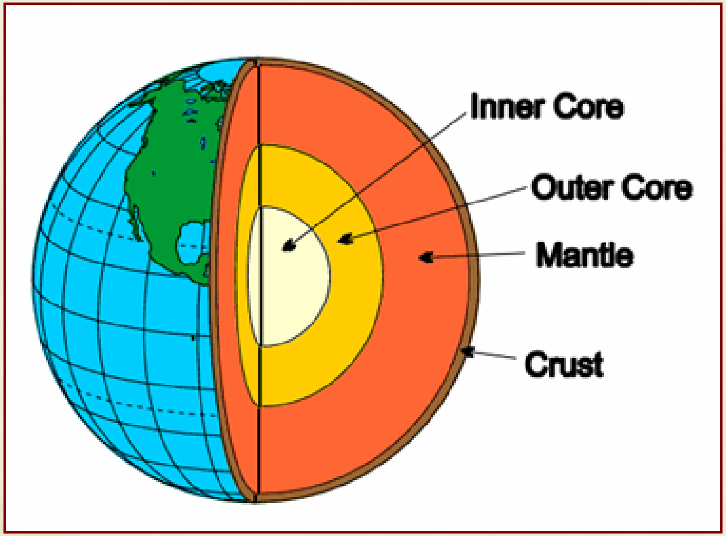
- Overview of some relevant geology
  - Geophysics
  - Geochemistry
  - Terrestrial heat flow
- Geoneutrinos
  - Flux measurement from mantle
  - Th/U ratio measurement
- Georeactor search



Geophysics:
Preliminary Reference Earth model

Knowledge of earth interior from seismology:
measure velocity, guess composition, infer density

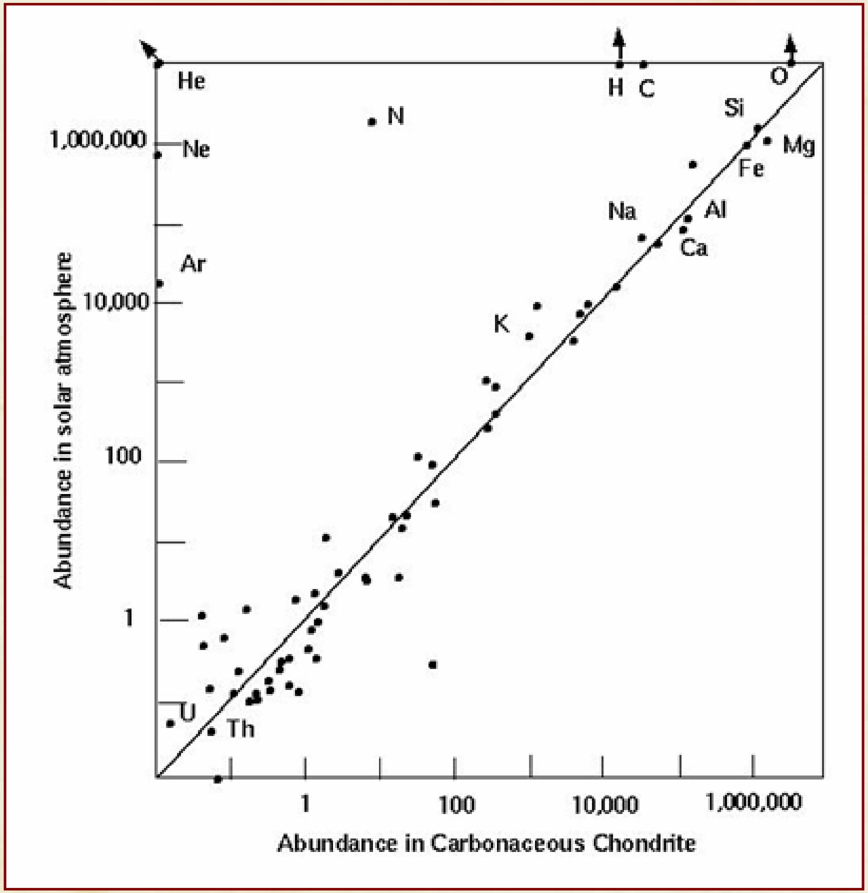




Dziewonski and Anderson, *Physics of the Earth and Planetary Interiors* **25** (1981) 297-356.

Geochemistry: Bulk Silicate Earth Model

Knowledge of Earth composition largely model dependent. "Standard Model" based on 3 meteorite samples.

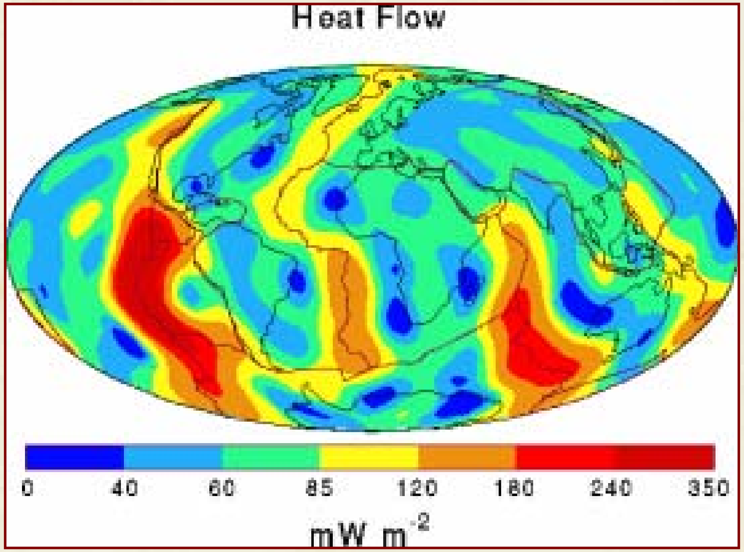


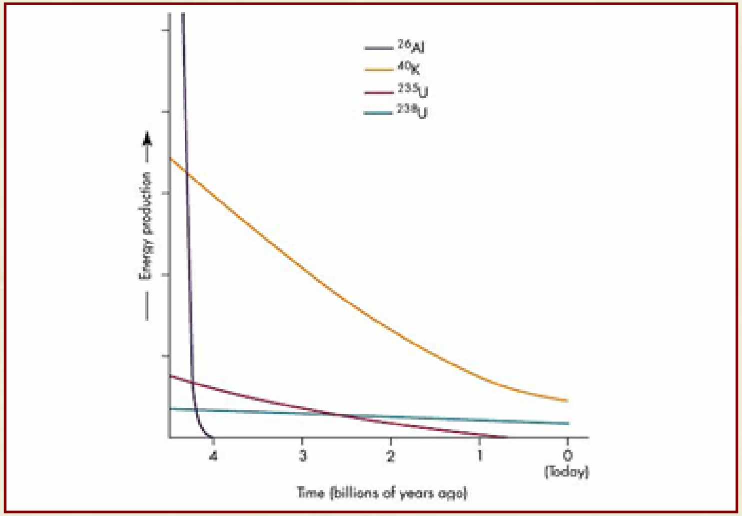
Abundance of uranium uncertain to 20%, maybe more.

McDonough and Sun, *Chemical Geology* **120** (1995) 223-253.

Terrestrial Heat Flow: 31-44 TW

Present controversy over hydrothermal flow



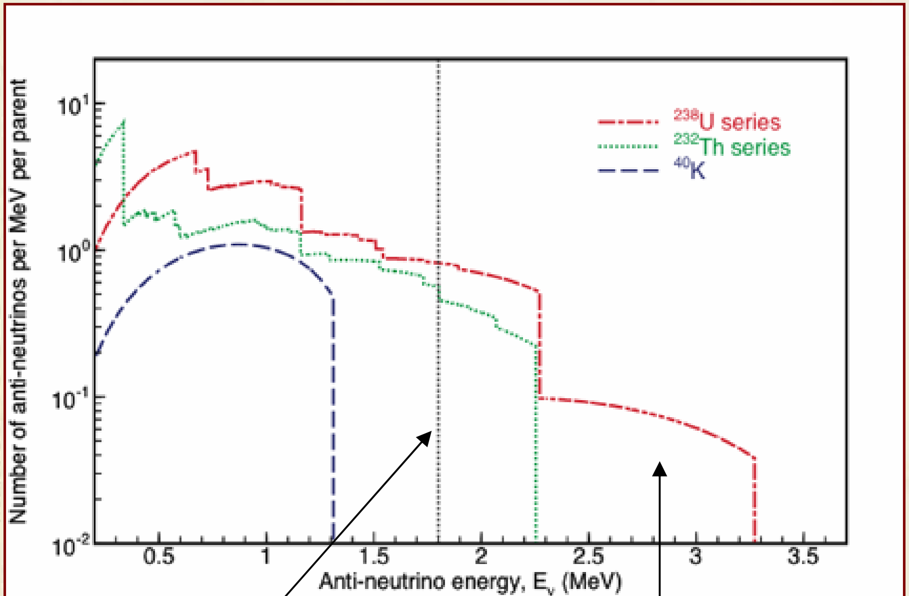


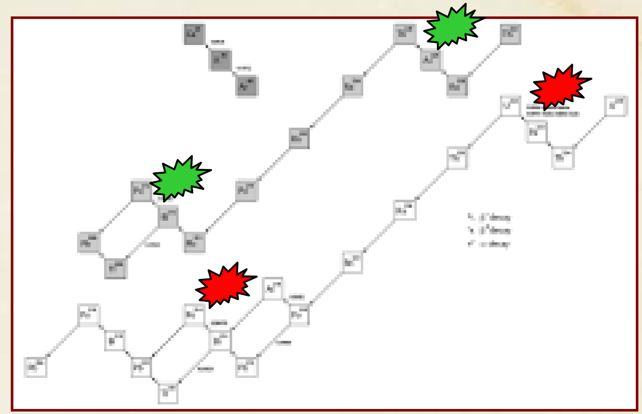
Geologists believe Uranium and Thorium are dominant heat source,
But much controversy about how much U/Th and where it resides.

Pollack, Hurter, and Johnson, *Reviews of Geophysics* **31**(3) (1993) 267-280.

Hofmeister and Criss, *Tectonophysics* **395** (2005) 159-177.

Geoneutrino - Parent Spectrum





Threshold for inverse β-decay

Only U: allows Th/U ratio measurement

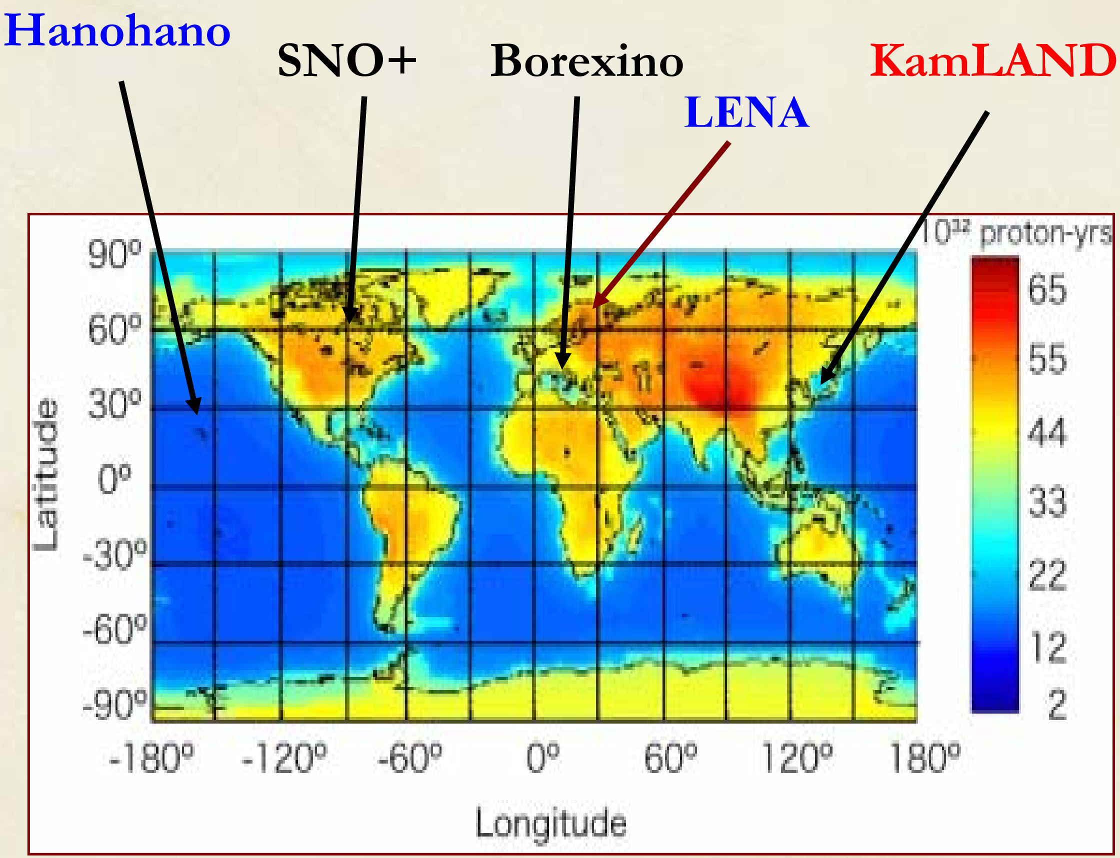
thorium chain

uranium chain

Potassium

- Spectrum below threshold
- Possible energy source and light element in core
- New detection technique needed

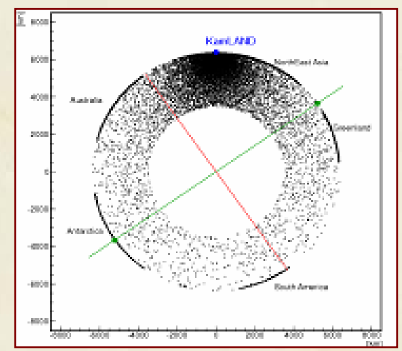
Predicted Geoneutrino Event Rate



F. Mantovani *et al.*, Phys. Rev. D **69** (2004) 013001.

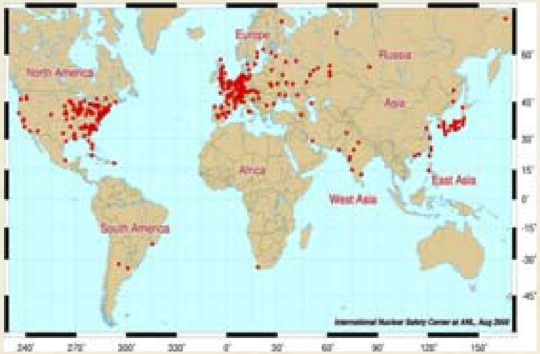
Crust signal dominates on continents

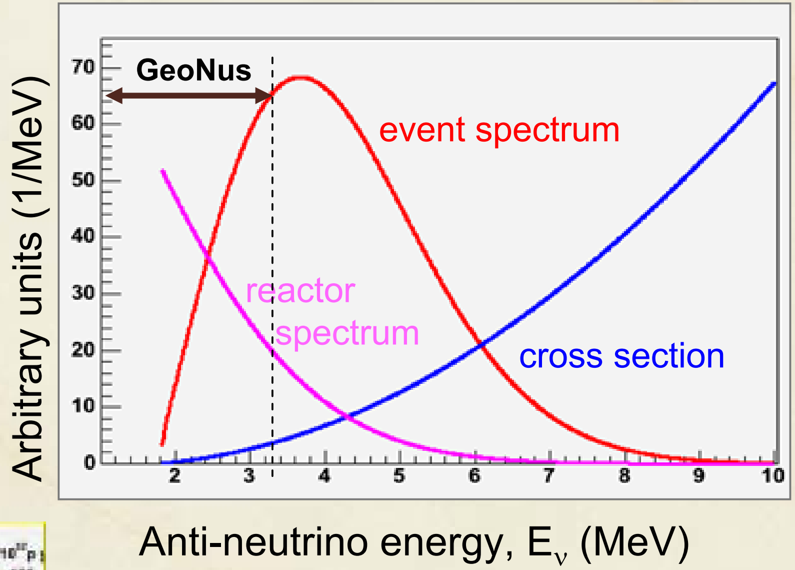
Mantle signal dominates in ocean

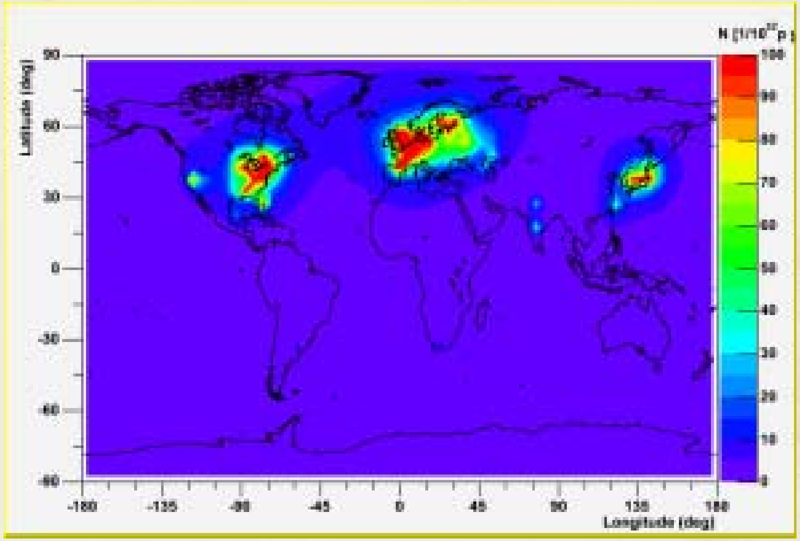


Simulated event source distribution
Signal mostly from <1000 km

Geonu Major Background – Reactor AntiNeutrinos





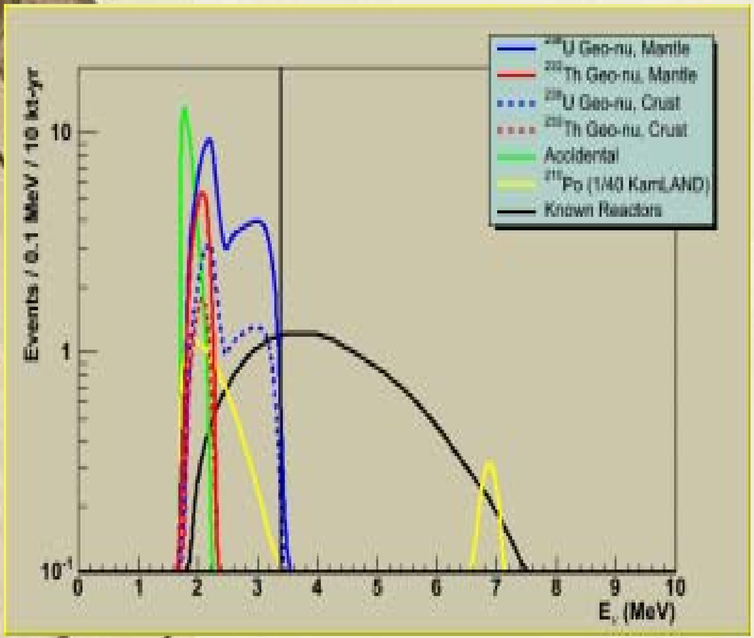


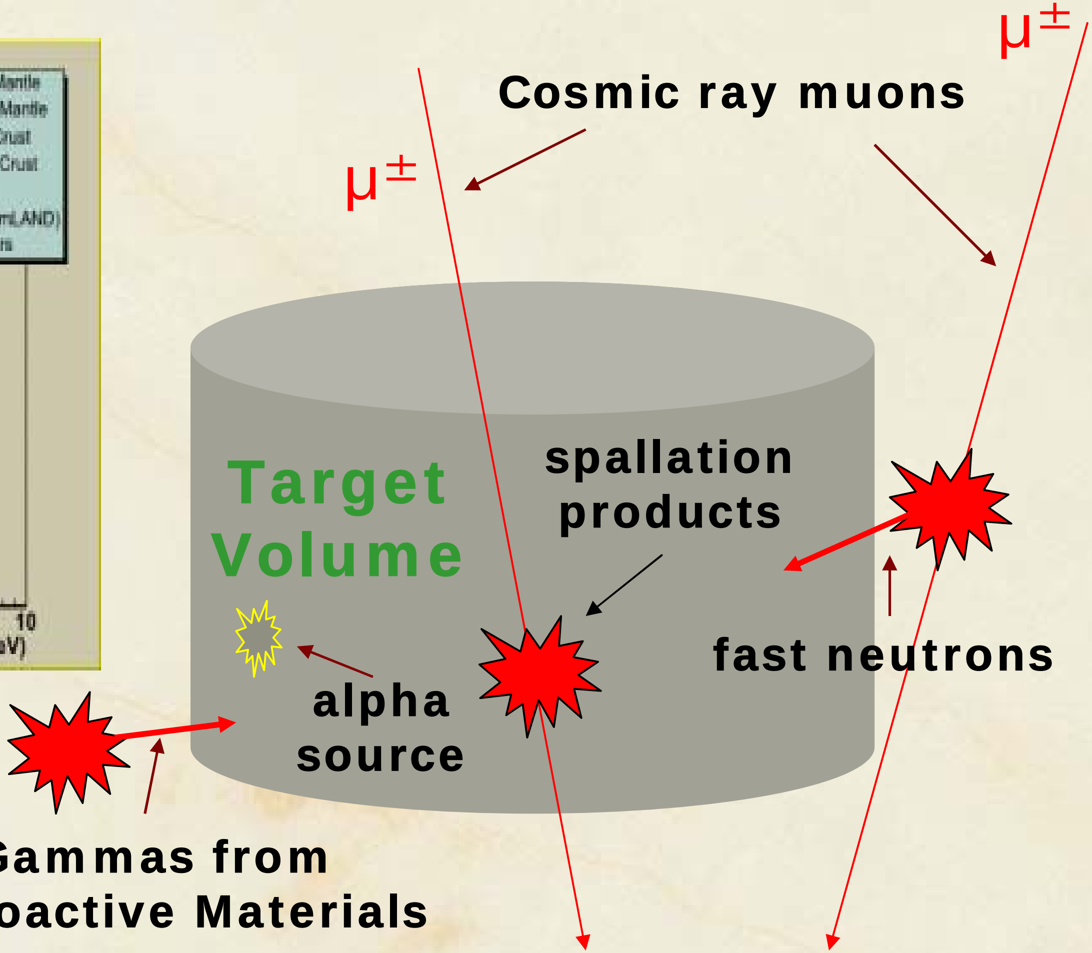
Reactors present a major source of background near many heavily populated areas

Geo-ν + Background Spectra

Background manageable

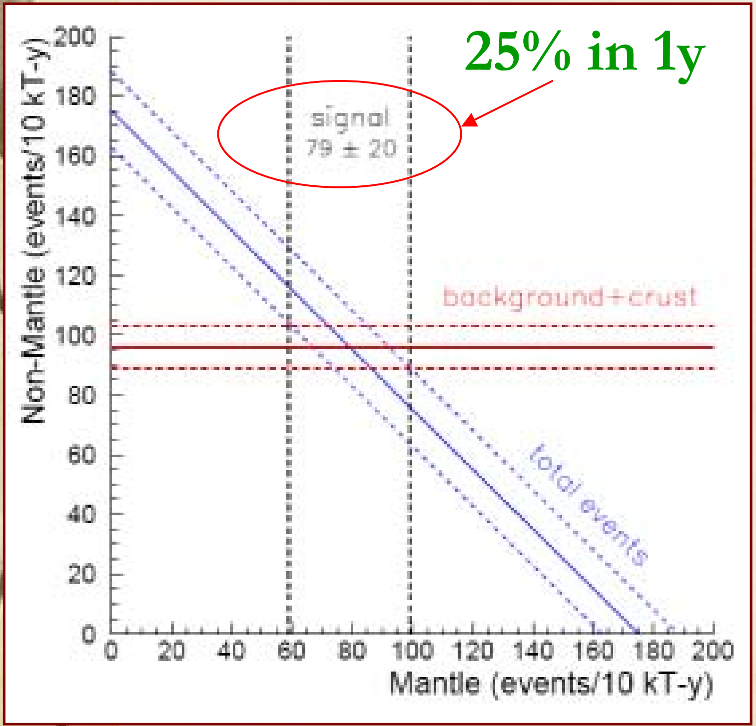
Depths >3KM preferred for geonus





Hanohano: Mantle Measurement

Major background from crustal geonus

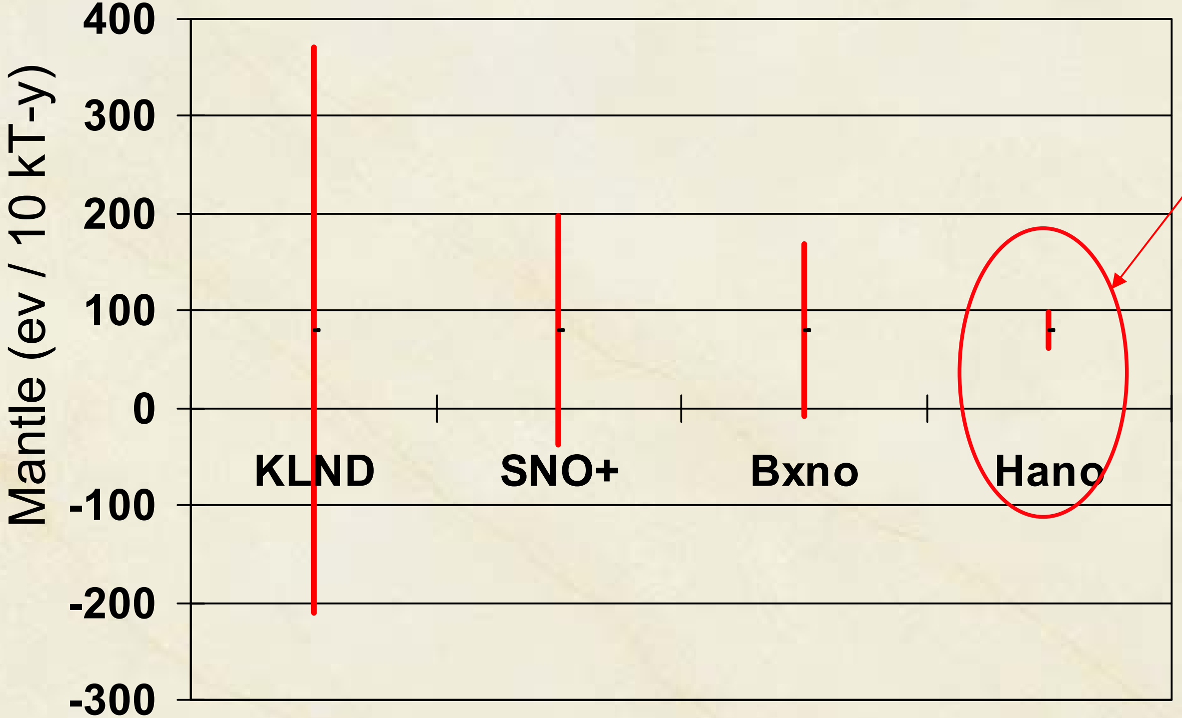


	Events (10 kT-y)$^{-1}$		
	SNO+	**Borexino**	**Hanohano**
^{9}Li	0 ± 0	3 ± 1	3 ± 1
^{210}Po	8 ± 2	8 ± 2	8 ± 2
Accidental	42 ± 1	42 ± 1	42 ± 1
Reactor	528 ± 21	295 ± 12	12 ± 1
Crust Geo-νs	368 ± 74	279 ± 56	31 ± 6
Background	946 ± 77	627 ± 57	96 ± 7
Mantle	79	79	79
Total ($N \pm \sqrt{N}$)	1025 ± 32	706 ± 27	175 ± 13
Expected Signal	79 ± 109	79 ± 84	79 ± 20
	15 y	48 y	

S.T. Dye *et al.*, hep-ex/0609041

LENA will have similar background
to SNO if in Finland, but at larger scale.

Hanohano: Mantle Measurement



25% in 1 y

Uncertainty in ν oscillation parameters introduces further error of +15% to -6%

Limit: 20% systematic uncertainty in U/Th content of crust

Hanohano ultimate sensitivity of <10%

Continental detectors ultimate sensitivity >50%

LENA backgrounds similar to SNO+ if in Finland

Earth Th/U Ratio Measurement

Project *crust type*	δR/R (1 yr exposure)	Th/U (1 yr exposure)	Years to 10% measurement
KamLAND *island arc*	2.0	4 ± 8	390
Borexino *continental*	1.1	4 ± 4	120
SNO+ *continental*	0.62	3.9 ± 2.4	39
Hanohano *oceanic*	0.20	3.9 ± 0.8	3.9

Statistical uncertainties only; includes reactors

LENA, similar to Hanohano, depending upon location and size

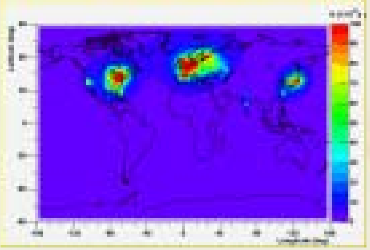
Antineutrinos From the Core?

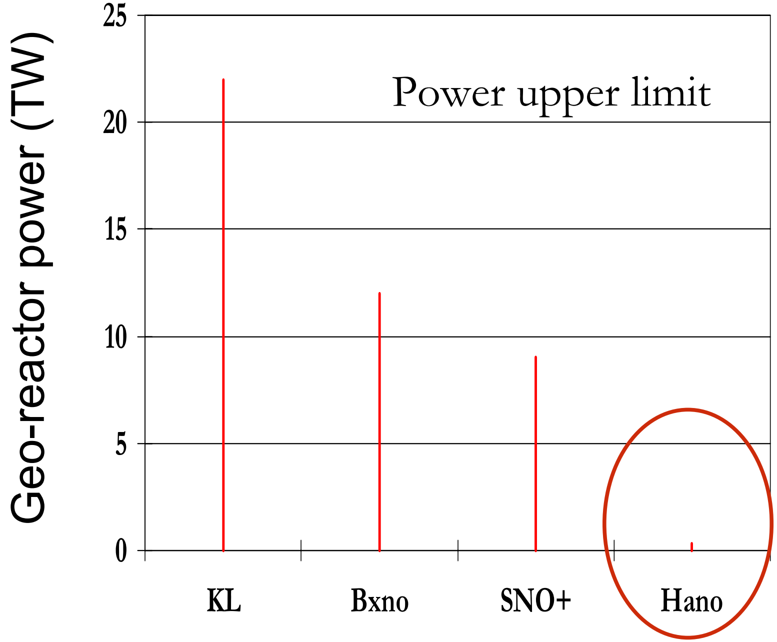
Herndon hypothesis- natural fission reactor in core of Earth
P=1-10 TW
Controversial but not ruled out

Georeactor hypothesis

Herndon, *Proc. Nat. Acad. Sci.* **93** (1996) 646.
Hollenbach and Herndon, *Proc. Nat. Acad. Sci.* **98** (2001) 11085.

Georeactor Search





Project *crust type*	Power limit 99% CL (TW)	5σ discovery power (TW)
KamLAND *island arc*	22	51
Borexino *continental*	12	43
SNO+ *continental*	9	22
Hanohano *oceanic*	0.3	1.0

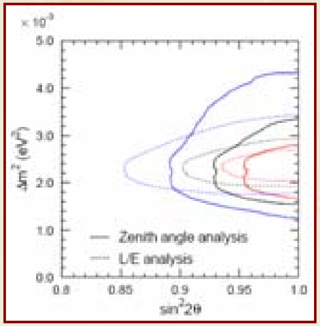
~few TW needed to drive geomagnetic field

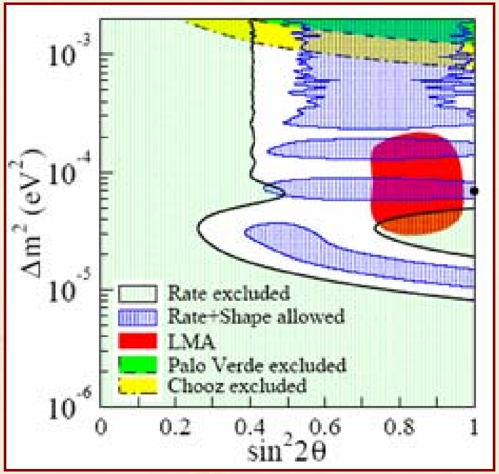
1 year run time- statistical uncertainties only

LENA similar to SNO+, depending upon scale and location.

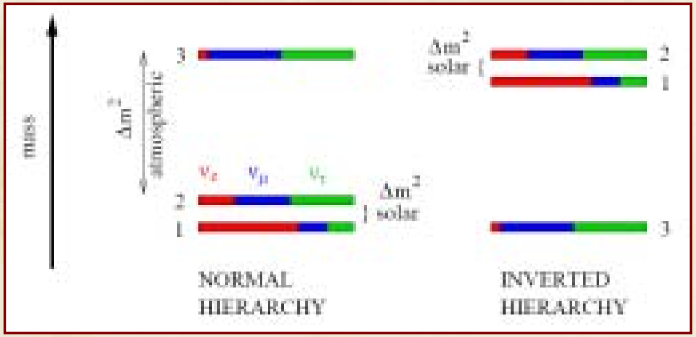
Neutrino Oscillation Physics

- Precision measurement of mixing parameters





- Determination of mass hierarchy **(newly proposed method)**



3-ν Mixing: Reactor Neutrinos

$$
\left.\begin{aligned}
P_{ee}=1-\{ &\cos^4(\theta_{13}) \sin^2(2\theta_{12}) [1-\cos(\Delta m^2_{21}L/2E)] \\
&+ \cos^2(\theta_{12}) \sin^2(2\theta_{13}) [1-\cos(\Delta m^2_{31}L/2E)] \\
&+ \sin^2(\theta_{12}) \sin^2(2\theta_{13}) [1-\cos(\Delta m^2_{32}L/2E)]\}/2
\end{aligned}\right.
$$

} wavelength close, 3%

→ Each of 3 amplitudes cycles (in L/E ~ "t") with own periodicity (Δm^2 ~ "ω")

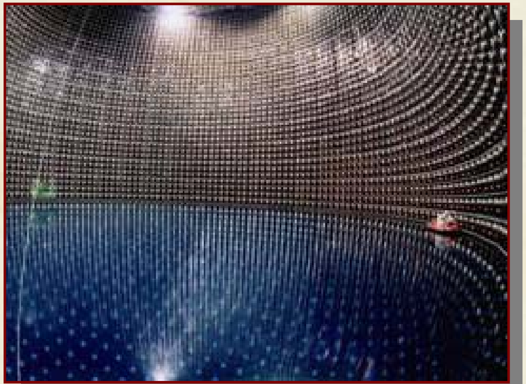
- amplitudes *13.5 : 2.5 : 1.0* above
- wavelengths ~110 km and ~4 km at reactor peak ~3.5 MeV

- ½-cycle measurements can yield
  - Mixing angles, mass-squared differences
- Multi-cycle measurements can yield
  - Mixing angles, precise mass-squared differences
  - Potential for mass hierarchy
  - **Less sensitivity to systematics**

ν_e Mixing Parameters: Present Knowledge

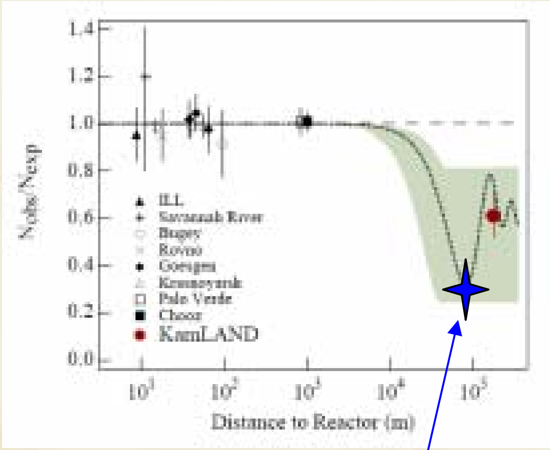
- KamLAND combined analysis:
  $\tan^2(\theta_{12})=0.40(+0.10/-0.07)$
  $\Delta m^2_{21}=(7.9\pm0.7)\times10^{-5}\ \mathrm{eV}^2$
  Araki et al., *Phys. Rev. Lett.* **94** (2005) 081801.

- CHOOZ limit: $\sin^2(2\theta_{13}) \leq 0.20$
  Apollonio et al., *Eur. Phys. J.* **C27** (2003) 331-374.
- SuperK and K2K:
  $\Delta m^2_{31}=(2.5\pm0.5)\times10^{-3}\ \mathrm{eV}^2$
  Ashie et al., *Phys. Rev.* **D64** (2005) 112005
  Aliu et al., *Phys. Rev. Lett.* **94** (2005) 081802



Suggested ½-cycle θ_{12} measurement
with Hanohano

- Reactor experiment- $\bar{\nu}_e$ point source
- $P(\nu_e \rightarrow \nu_e) \approx 1 - \sin^2(2\theta_{12})\sin^2(\Delta m^2_{21} L/4E)$
- 60 GW ·kT ·y exposure at 50-70 km
  - ~4% systematic error from near detector
  - $\sin^2(\theta_{12})$ measured with ~2% uncertainty



Bandyopadhyay et al., *Phys. Rev.* D**67** (2003) 113011.
Minakata et al., hep-ph/0407326
Bandyopadhyay et al., hep-ph/0410283

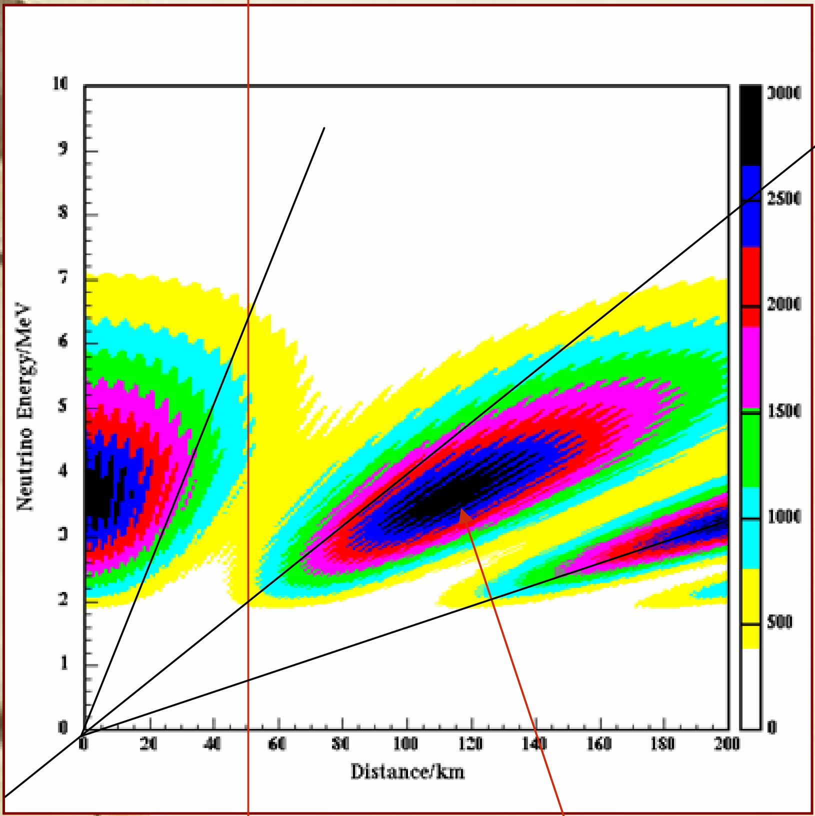
oscillation maximum
at ~ 60 km

Energy Spectra, Distance and Oscillations

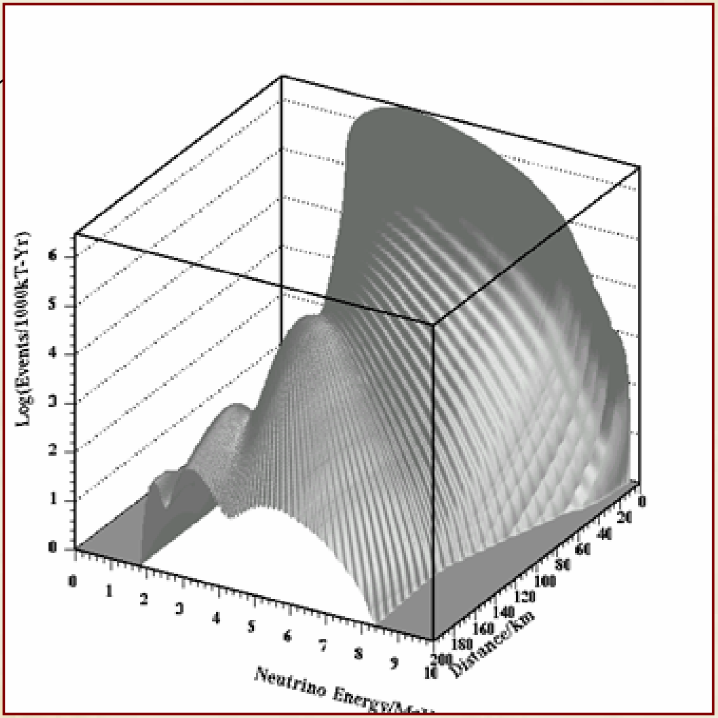
Constant L/E

50 km study

E



L

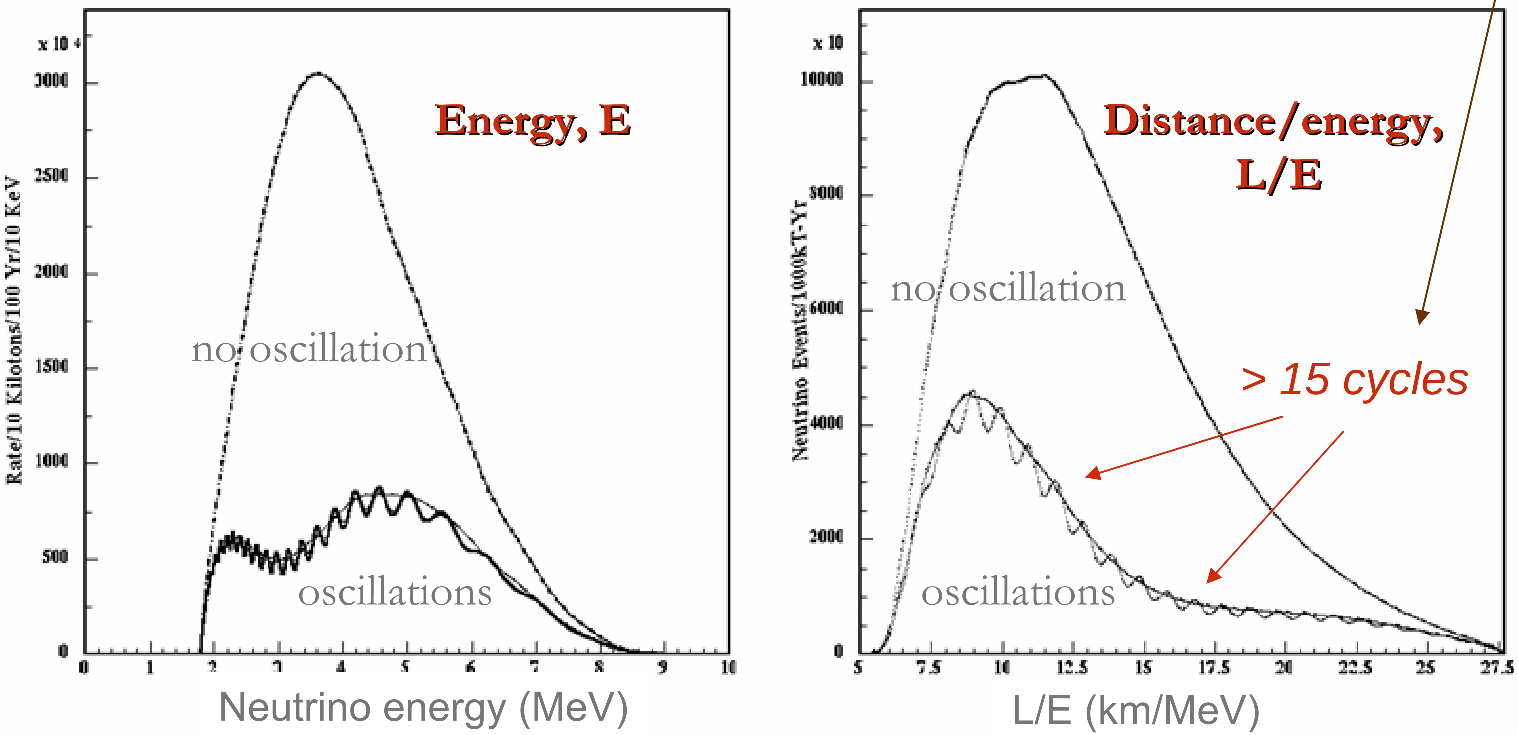


Log(Rate) vs Energy and DIstance

First return of
“solar” oscillation

Reactor Anti-Neutrino Spectra at 50 km

suggests using Fourier Transforms



1,2 oscillations with $\sin^2(2\theta_{12})=0.82$ and $\Delta m^2_{21}=7.9\text{x}10^{-5}\ eV^2$

1,3 oscillations with $\sin^2(2\theta_{13})=0.10$ and $\Delta m^2_{31}=2.5\text{x}10^{-3}\ eV^2$

Proposed ½-cycle θ_{13} Measurements

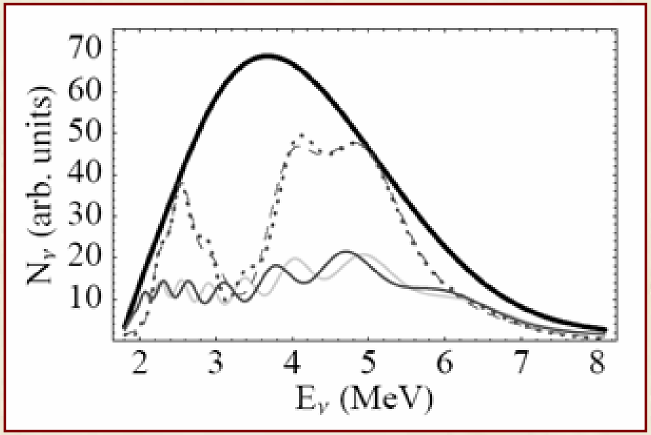
other than Hanohano

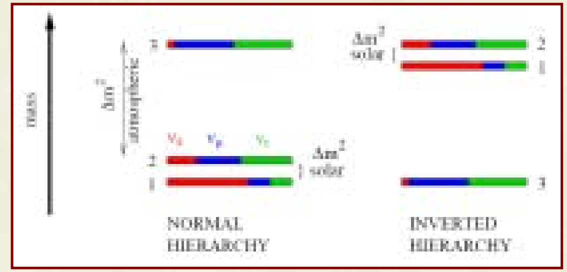
- Reactor experiment- ν_e point source
- $P(\nu_e \rightarrow \nu_e) \approx 1 - \sin^2(2\theta_{13}) \sin^2(\Delta m^2_{31} L/4E)$
- Double Chooz, Daya Bay, RENO- measure θ_{13} with "identical" near/far detector pair
  - $\sin^2(2\theta_{13}) \leq 0.03$-$0.01$ in few years
  - Solar and matter insensitive
  - Challenging systematic errors

Anderson et al., hep-ex/0402041
Mikaelyan and Sinev, *Phys. Atom. Nucl.* **62** (1999) 2008-2012.

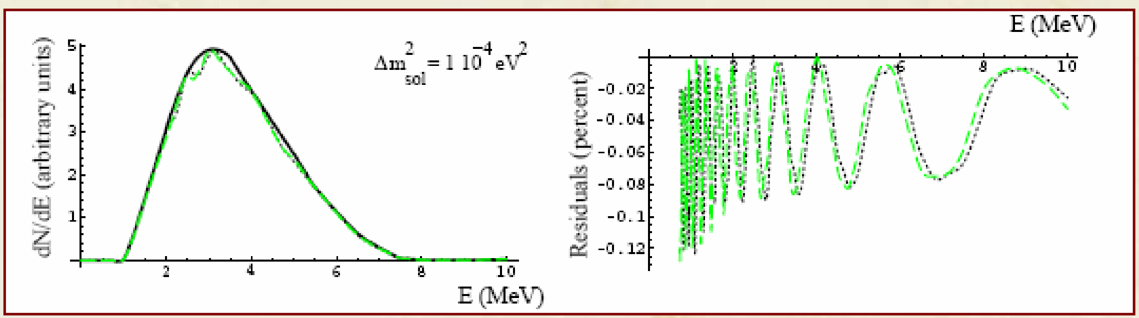
Suggested Mass Hierarchy Determination-via Reactor Neutrino Spectral Distortion

Earlier suggestions



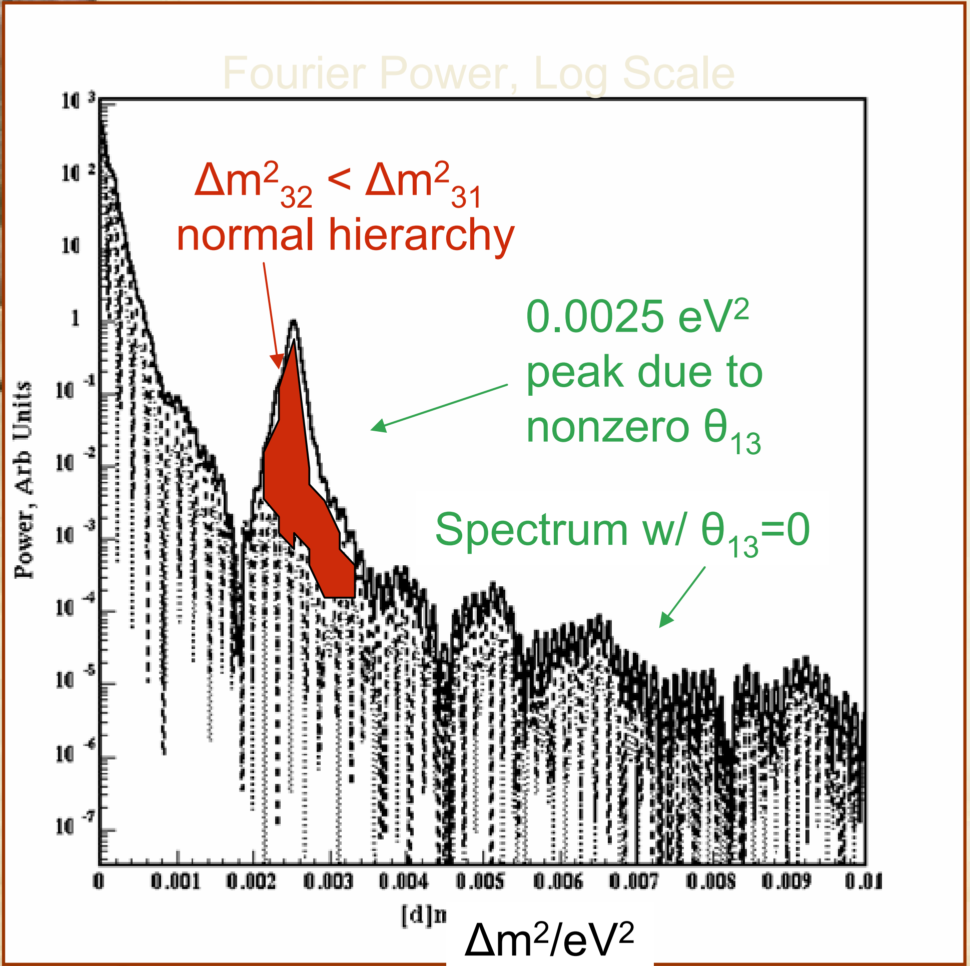


Petcov and Piai, *Phys. Lett.* B533 (2002) 94-106.

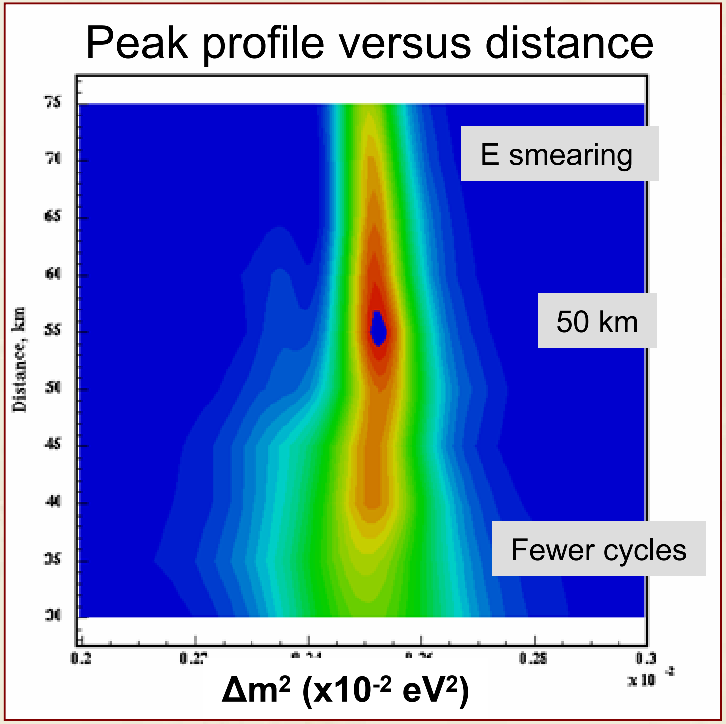


Schoenert, Lasserre, and Oberaurer, *Astropart.Phys.* 18 (2003) 565-579.

Fourier Transform on L/E to Δm^2



Includes energy smearing



Preliminary-

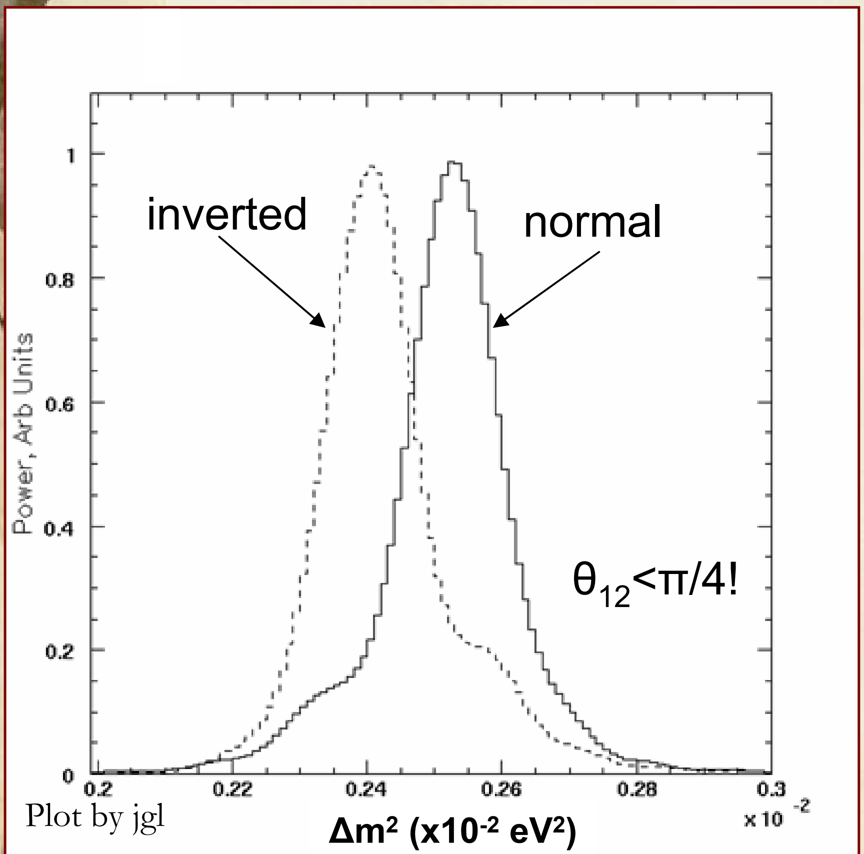
50 kt-y exposure at 50 km range

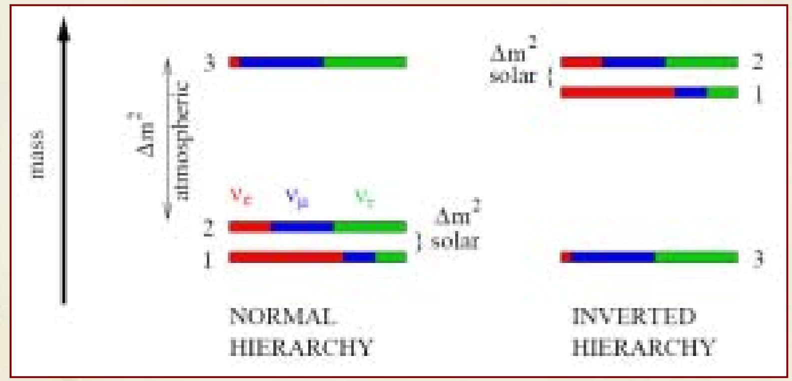
$\sin^2(2\theta_{13}) \geq 0.02$

Δm^2_{31}=0.0025 eV² to 1% level

Learned, Dye,Pakvasa, Svoboda *hep-ex/0612022*

Measure Δm^2_{31} by Fourier Transform
Determine ν Mass Hierarchy





$\Delta m^2_{31} > \Delta m^2_{32}$ $|\Delta m^2_{31}| < |\Delta m^2_{32}|$

Determination possible at 50 km range

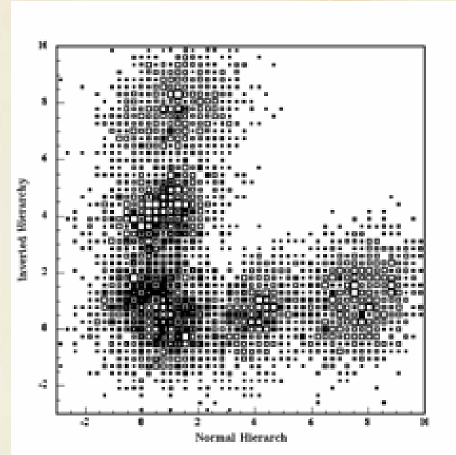
$\sin^2(2\theta_{13}) \geq 0.05$ and 10 kt-y

$\sin^2(2\theta_{13}) \geq 0.02$ and 100 kt-y

Learned, Dye, Pakvasa, and Svoboda, *hep-ex/0612022*

Hierarchy Determination

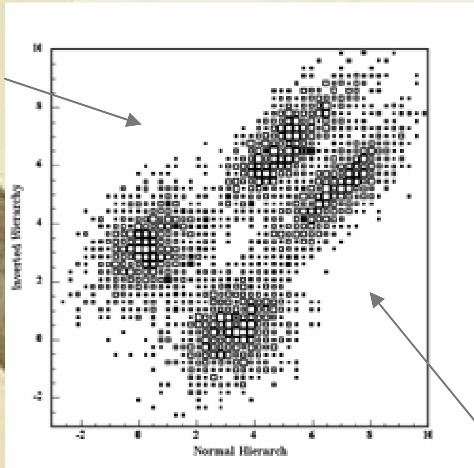
Sin22θ13 Variation: 0.02 – 0.2



Ideal Case with 10 kiloton Detector off San Onofre

Distance variation: 30, 40, 50, 60 km

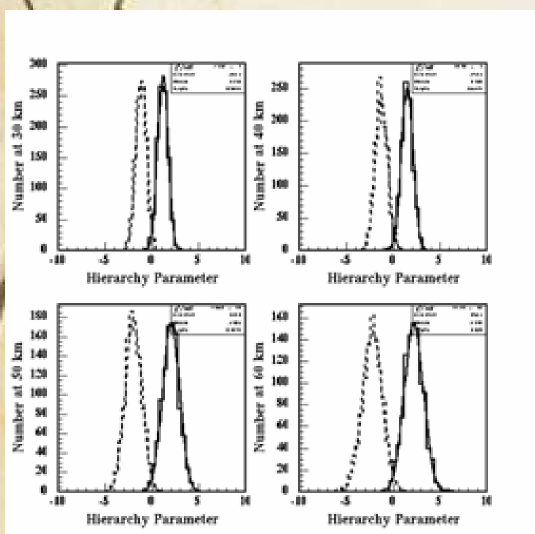
Inverted hierarchy



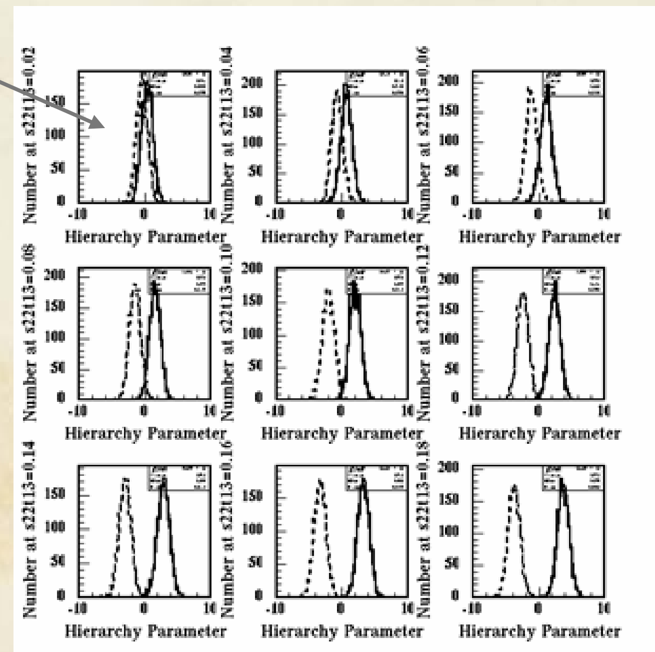
Hierarchy tests employing Matched filter technique, for Both normal and inverted hierarchy on each of 1000 simulated one year experiments using 10 kiloton detector.

But ten years separates even at 0.02

Normal Hierarchy, 1000 experiments, several distances



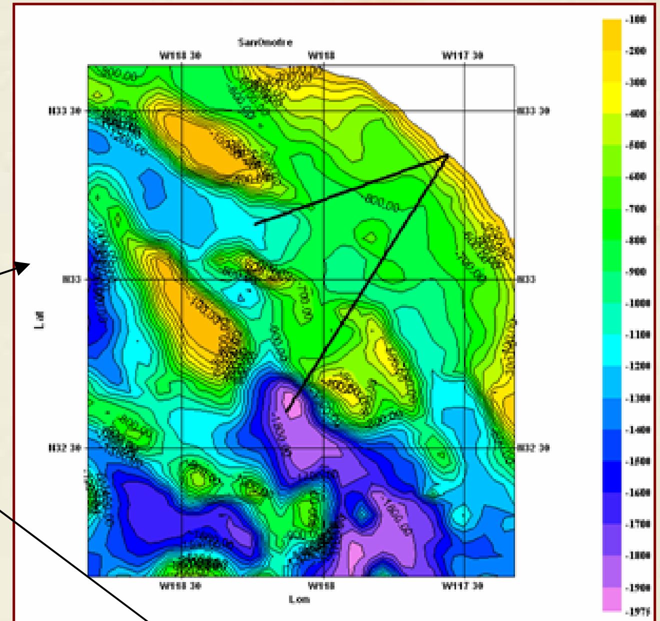
Sensitive to energy resolution: probably need 3%/sqrt(E)

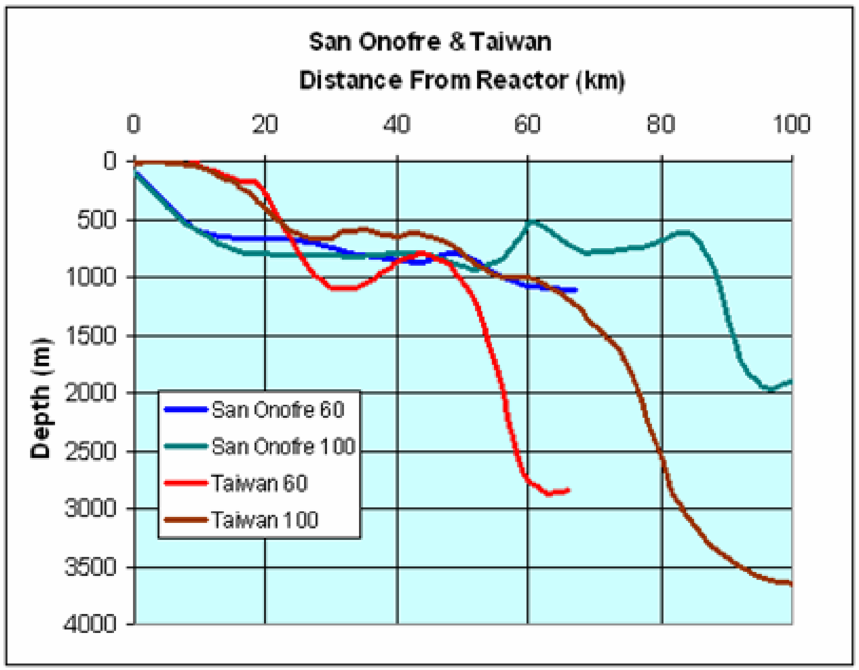


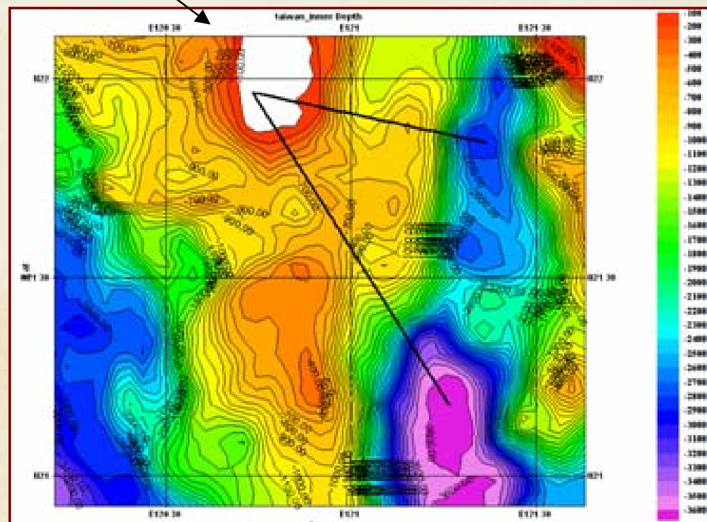
Hanohano-
Candidate Reactor Sites

San Onofre- ~6 GW_{th}

Maanshan- ~5 GW_{th}







Hanohano- 10 kT-y Exposure

- Neutrino Geophysics- near Hawaii
  - Mantle flux U/Th geo-neutrinos to ~25%
  - Measure Th/U ratio to ~20%
  - Rule out geo-reactor of P>0.3 TW
- Neutrino Oscillation Physics- ~55 km from reactor
  - Measure $\sin^2(\theta_{12})$ to few % w/ standard ½-cycle
  - Measure $\sin^2(2\theta_{13})$ down to ~0.05 w/ multi-cycle
  - Δm^2_{31} to less than 1% w/ multi-cycle
  - Mass hierarchy if $\theta_{13} \neq 0$ w/multi-cycle & no near detector; insensitive to background, systematic errors; complimentary to Minos, Nova
  - **Lots to measure even if θ_{13}=0**
- **Much other astrophysics and PDK too….**

Hanohano Summary

- Proposal for new portable, deep-ocean, 10 kiloton, liquid scintillation electron anti-neutrino detector.
- Unique geophysics, particle physics and astrophysics, all at nuclear energies.
- Program under active engineering, Monte Carlo simulations, and studies in laboratory and at sea.
- Collaboration within a year, aimed at decade or more multi-disciplinary program between physics and geology.
- Meeting in Hawaii, 23-25 March 2007, http://www.phys.hawaii.edu/~sdye/hano.html

Appendix

ν_e flux measurement uncertainty

- Flux from distant, extended source like Earth or Sun is fully mixed
- $P(\nu_e \rightarrow \nu_e)$

  $=1-0.5\{\cos^4(\theta_{13})\sin^2(2\theta_{12})+\sin^2(2\theta_{13})\}$

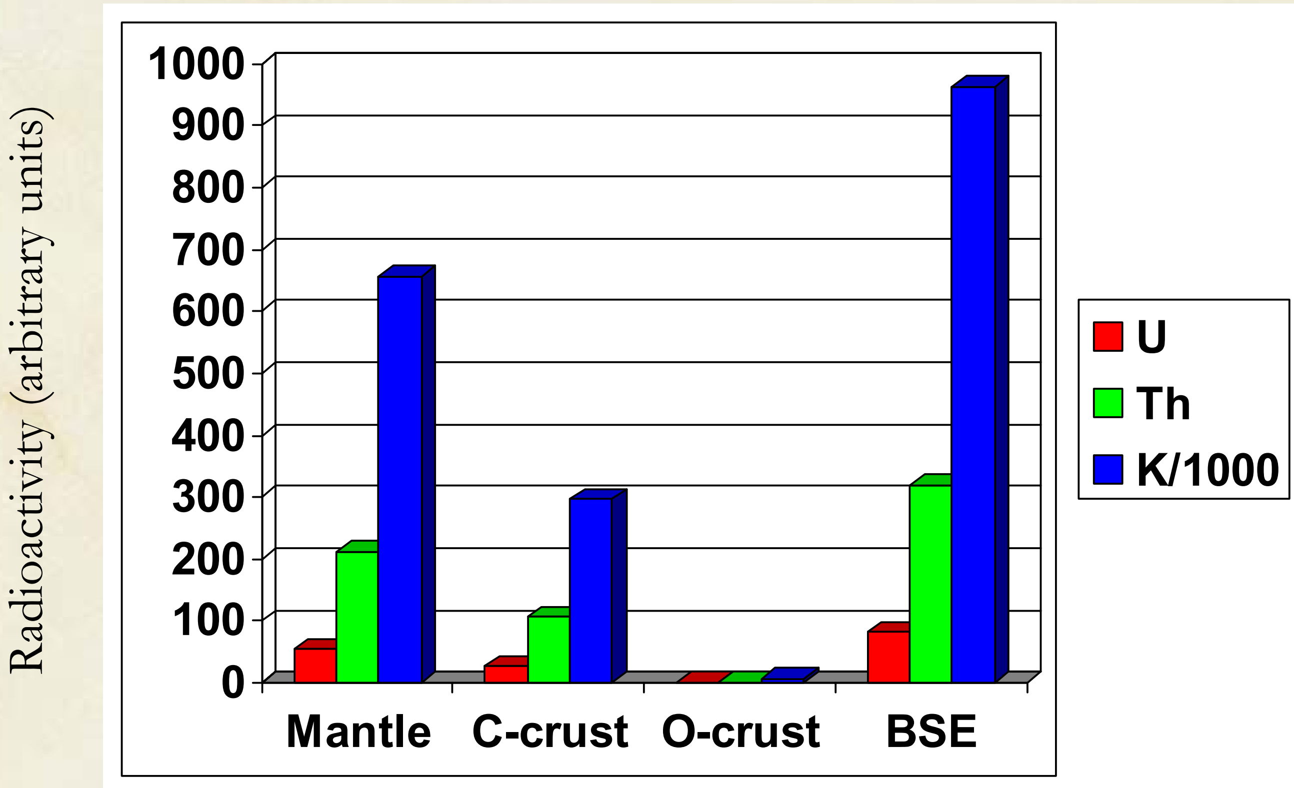
  $=0.592\ (+0.035/-0.091)$

  Lower value for maximum angles

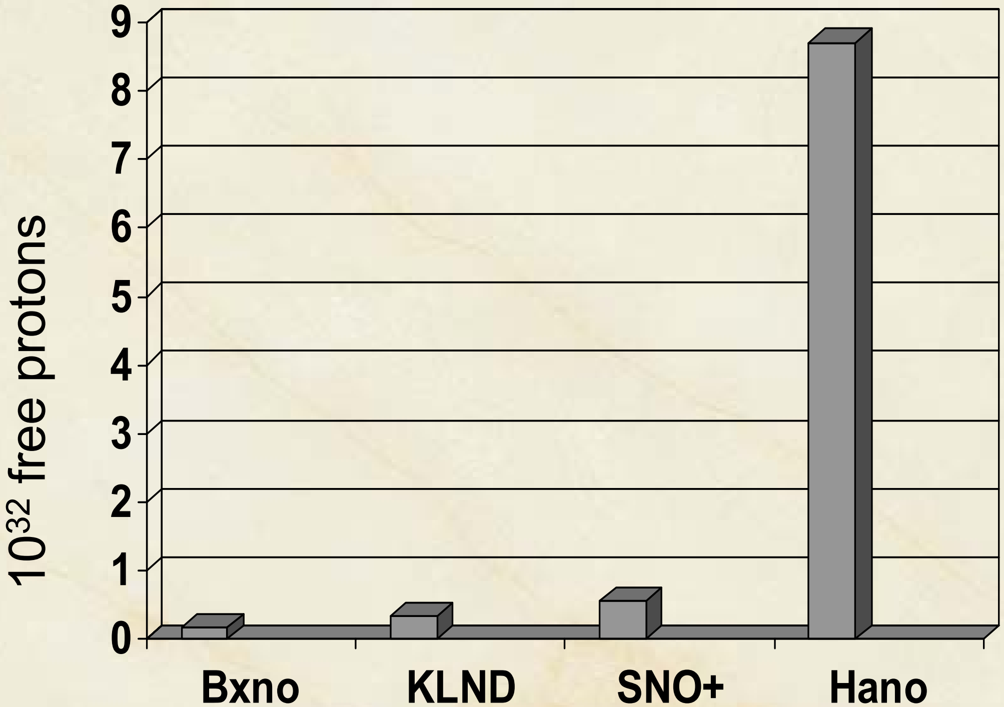
  Upper value for minimum angles
- $\Phi_{source} = \Phi_{detector}/P(\nu_e \rightarrow \nu_e)$

  Uncertainty is +15%/-6%

Standard model: mantle has most U/Th and core has none.

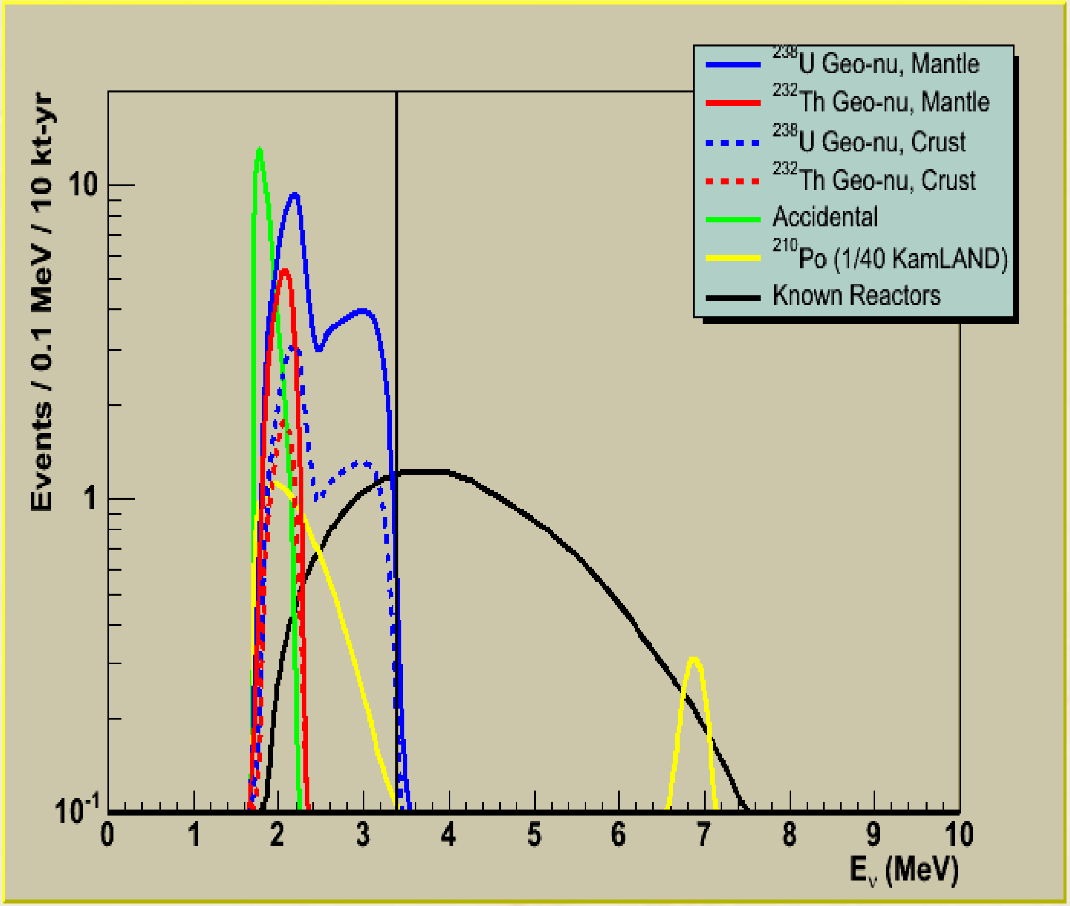


Geo-neutrino projects: targets

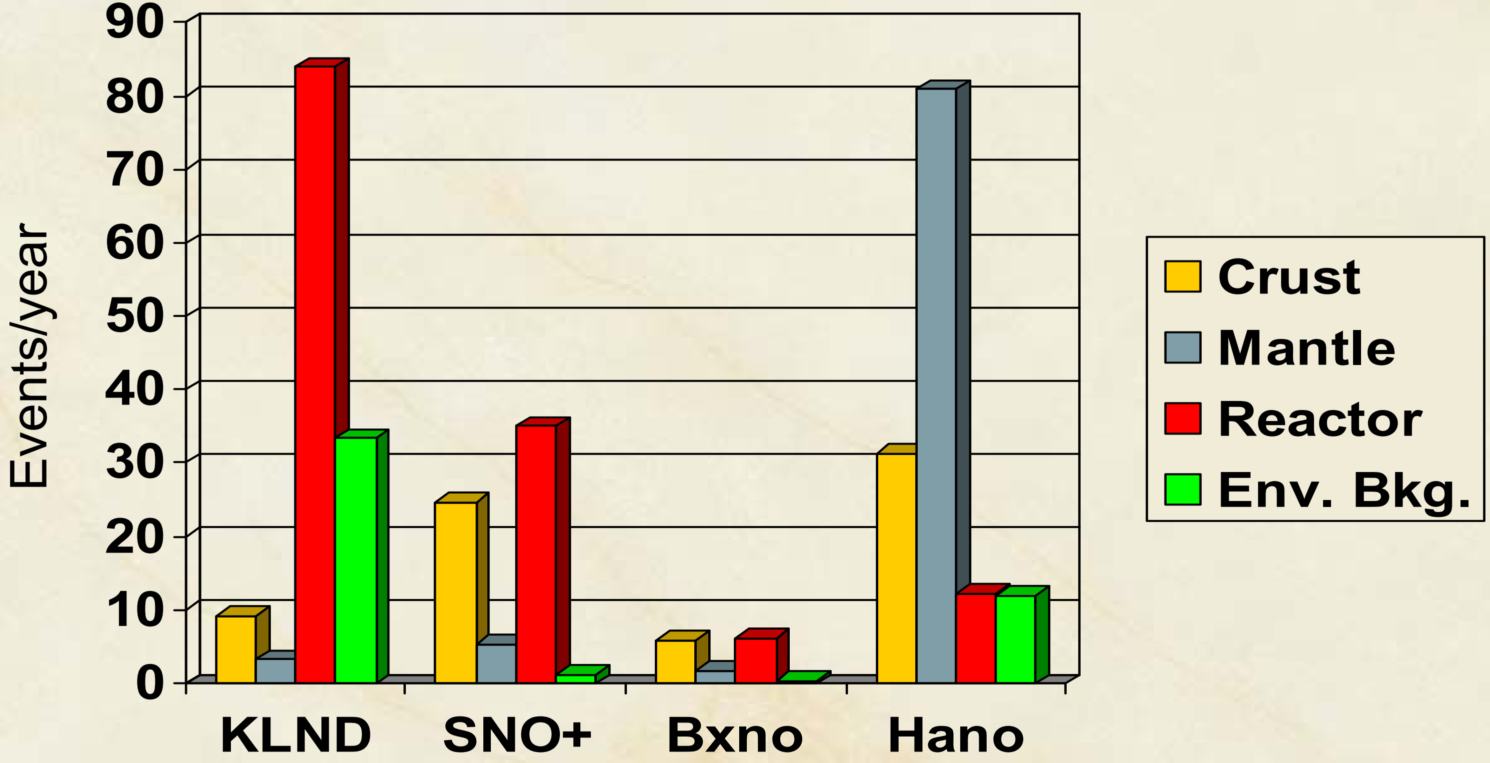


Proposed LENA may have 50 kilotons, 5x Hanohano, but will be probably on continental location.

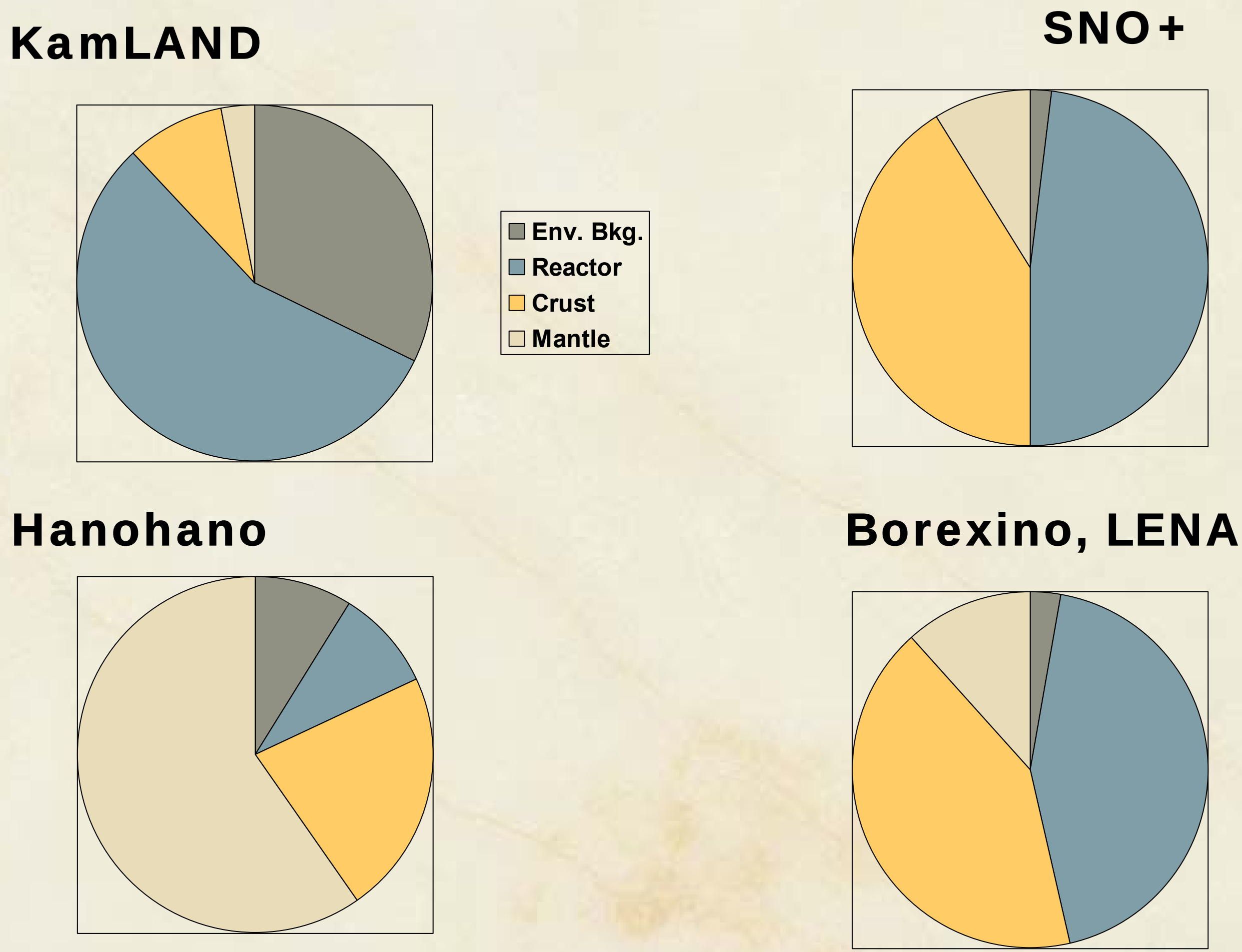
Geo-neutrinos + backgrounds



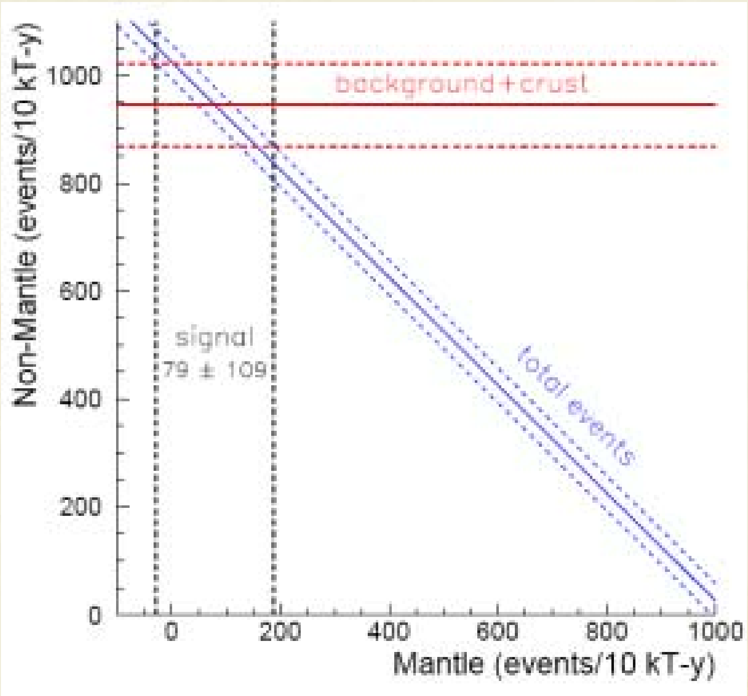
Geo-neutrino projects: rates



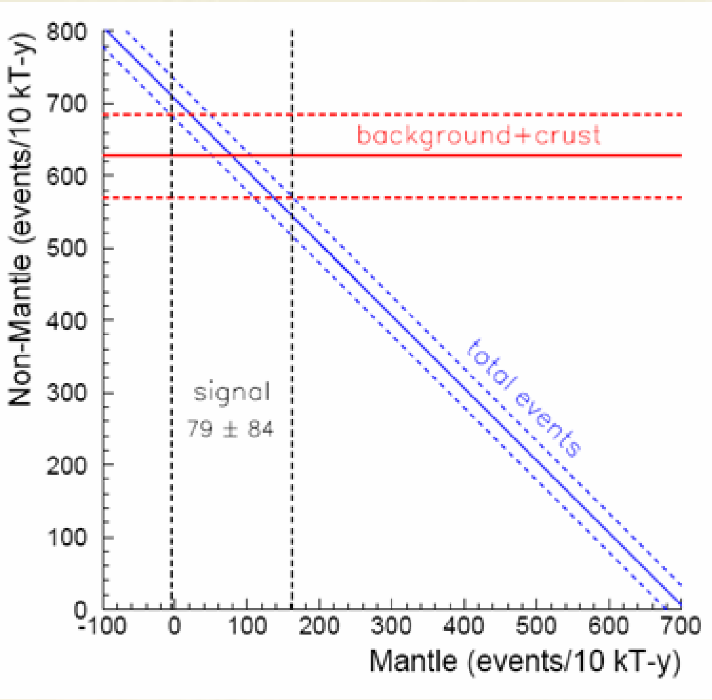
Event fractions



Mantle and Other Rates at SNO+ and Borexino



SNO+



Borexino

Beauty of Employing Fourier
(new realization, by us anyway)

- Normal statistical sqrt(n) Poisson errors apply to peak **amplitude** (mixing angle),
- but **NOT** to peak **location**… allows possibility for very precise measurement of Δm^2 (<1%?)
- Beats χ^2 and normal Max£, I think. (?)
- Employ signal processing tricks to maximize information extraction (ie. matched filter).