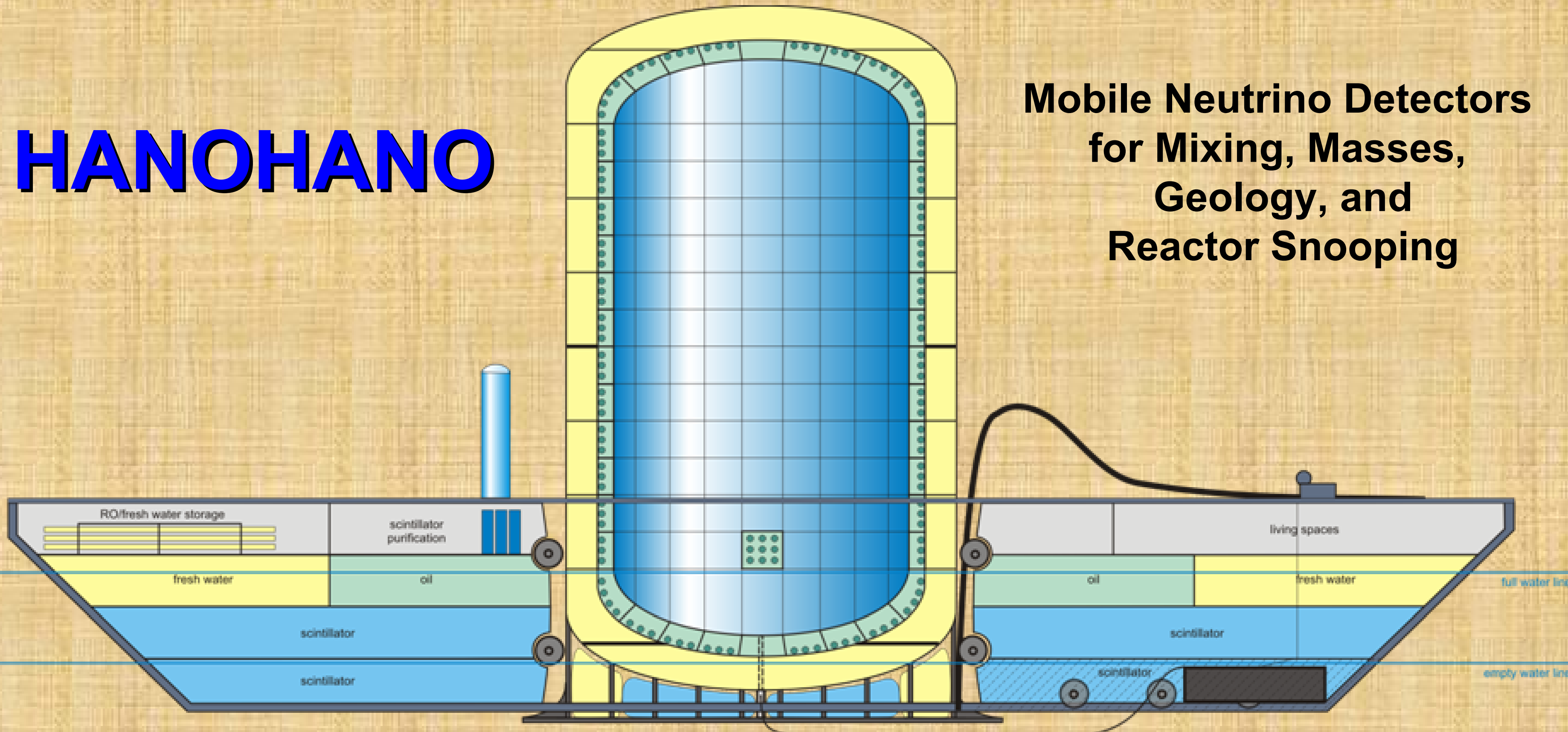
HANOHANO



Mobile Neutrino Detectors for Mixing, Masses, Geology, and Reactor Snooping

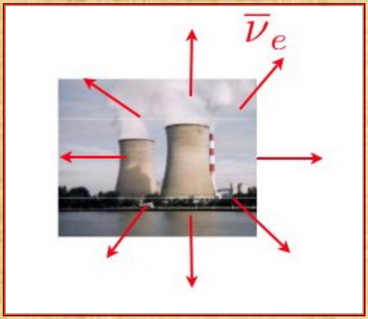
John Learned, *University of Hawaii at Manoa*

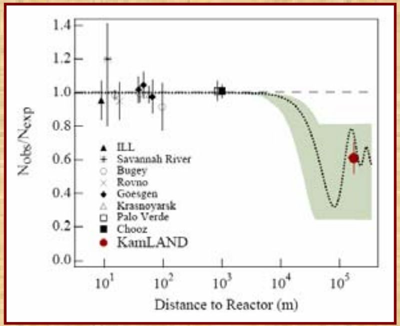
(& other colleagues at UH and elsewhere)

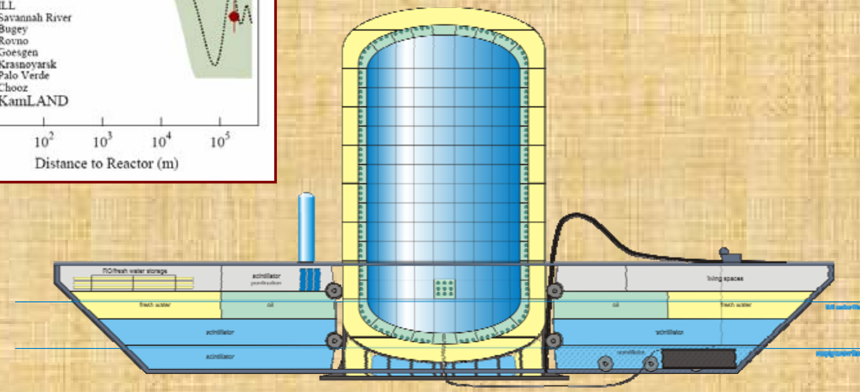
(HANOHANO consists of about 20 institutions, collaboration not yet official, including U. Tohoku, U. Maryland, U. Alabama, Stanford, Caltech, UC Davis, U. Munich, and more)

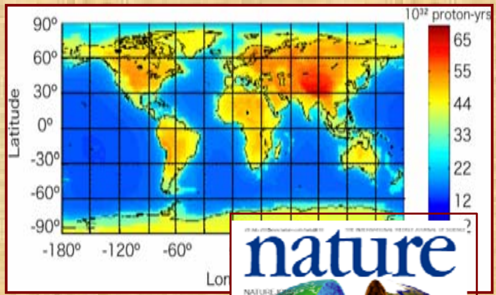
Outline

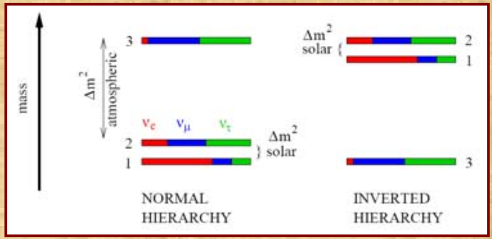
- **Neutrino Oscillation Physics**
  - Review KamLAND results
  - Mixing angles θ_{12} and θ_{13}
  - Mass squared difference Δm^2_{31}
  - Mass hierarchy
- **Hanohano:**
  - **Deep ocean**: measure mantle neutrinos
  - **Mobile**: position off shore reactor at ideal distance(s)
  - Detector Studies
- **Neutrino Geophysics**
  - U & Th mantle flux
  - Th/U ratio
  - Georeactor search
- Other studies, **future**

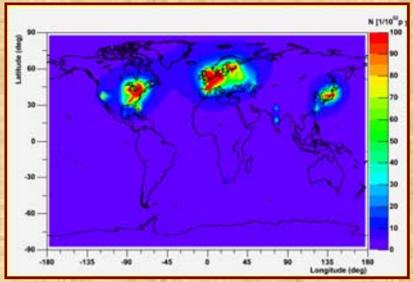








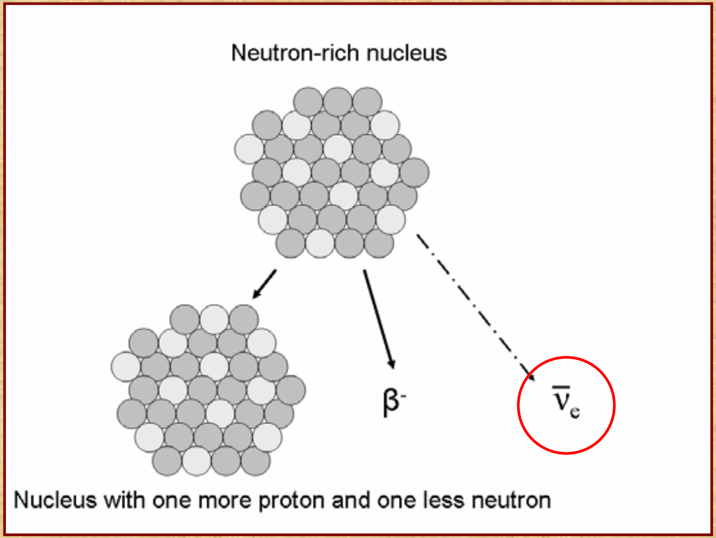




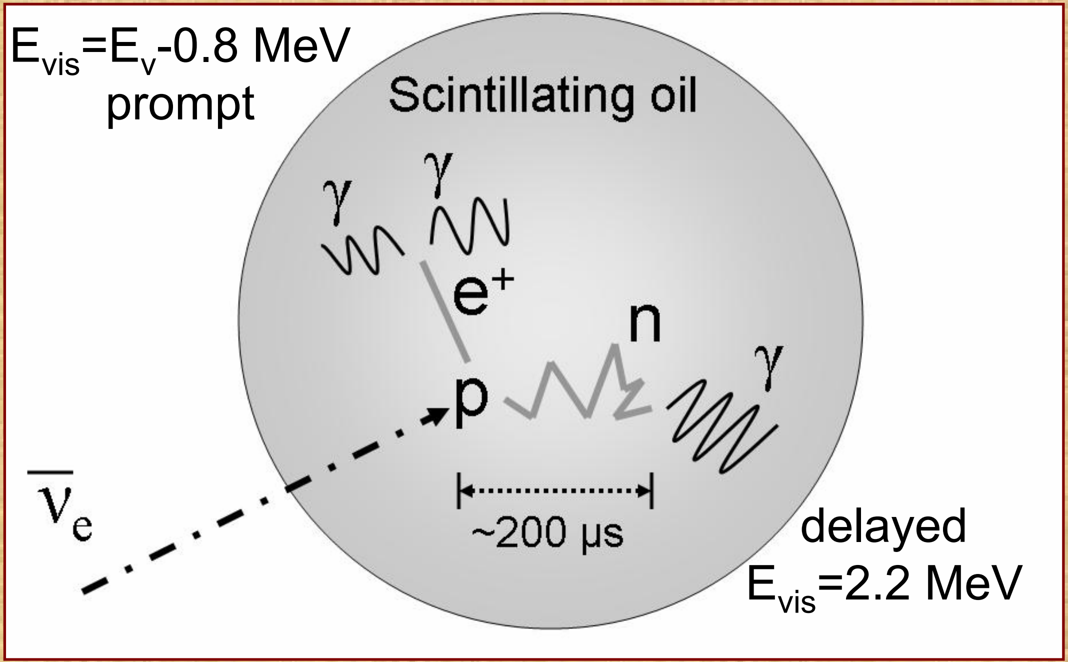
MeV-Scale Electron Anti-Neutrino Detection

Key: 2 flashes, close in space and time, 2nd of known energy, eliminate background

Production in reactors and natural decays



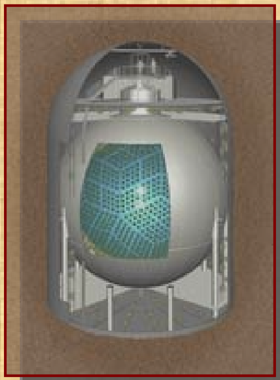
Detection



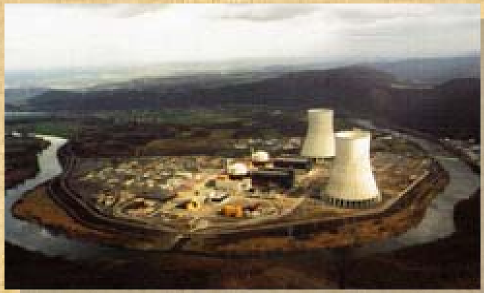
Reines & Cowan

- Standard inverse β-decay coincidence
- $E_\nu > 1.8$ MeV
- Rate and spectrum - no direction

$\bar{\nu}_e$ Mixing Parameters: Present Knowledge

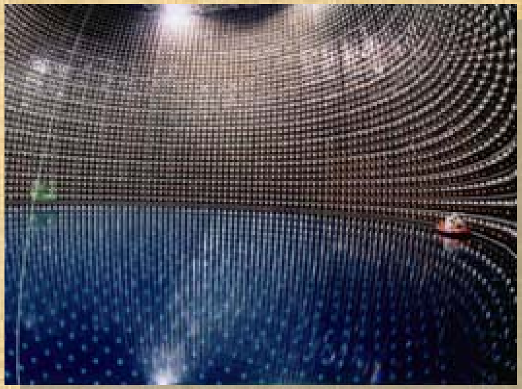


- KamLAND combined analysis:
  $\tan^2(\theta_{12})=0.40(+0.10/-0.07)$
  $\Delta m^2_{21}=(7.9\pm0.7)\times10^{-5}$ eV^2
  Araki et al., *Phys. Rev. Lett.* 94 (2005) 081801.
  (update on next slide)



- CHOOZ limit: $\sin^2(2\theta_{13}) \leq 0.20$
  Apollonio et al., *Eur. Phys. J.* C27 (2003) 331-374.

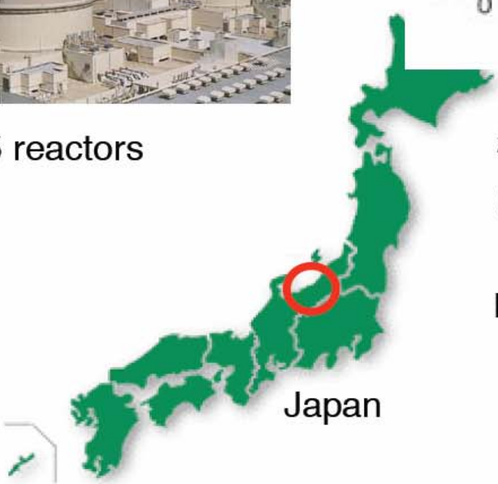
- SuperK and K2K:
  $\Delta m^2_{31}=(2.5\pm0.5)\times10^{-3}$ eV^2
  Ashie et al., *Phys. Rev.* D64 (2005) 112005
  Aliu et al., *Phys. Rev. Lett.* 94 (2005) 081802



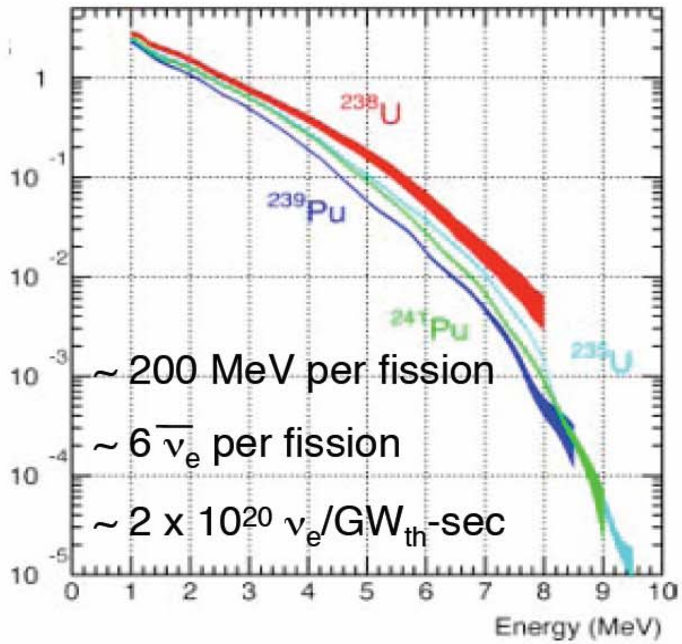
Measurement of Reactor Antineutrinos in KamLAND

Japanese Reactors

55 reactors



Reactor Isotopes



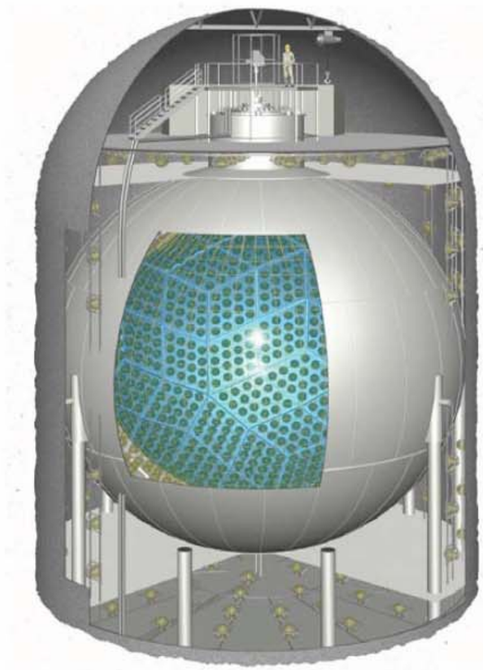
$^{235}U:^{238}U:^{239}Pu:^{241}Pu$ =
0.570: 0.078:0.0295:0.057

reactor $\bar{\nu}$ flux ~ 6 x $10^6/cm^2/sec$

Antineutrino Detection in KamLAND

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

through inverse β-decay



TAUP2007, Sendai, Japan, September 13, 2007

Systematic Uncertainty

<u>"full volume" calibration lowered the fiducial volume error</u>

(4.7% in previous analysis)

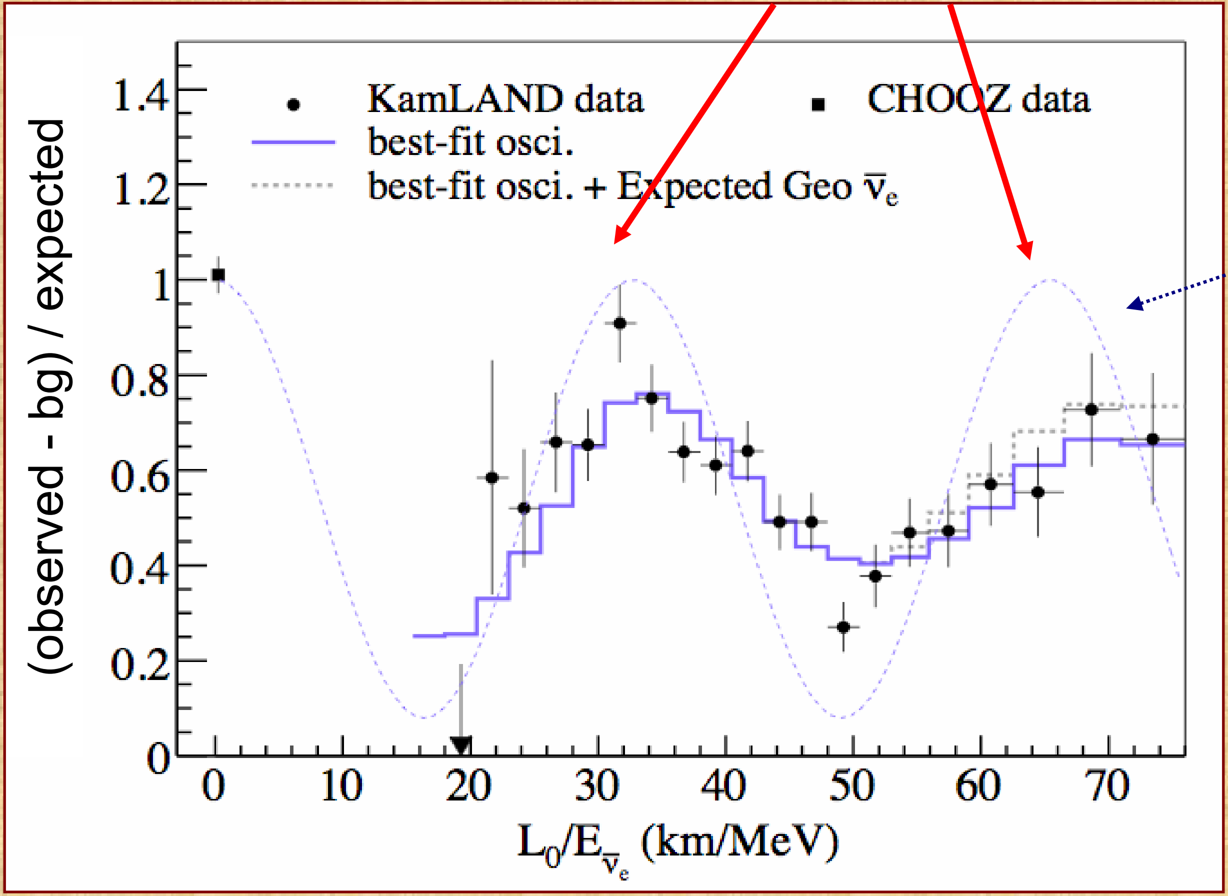
Detector related		Reactor related	
Fiducial volume	1.8%	$\overline{\nu}_e$ spectra	2.4%
Energy scale	1.5%	Reactor power	2.1%
L-selection eff.	0.6%	Fuel composition	1.0%
OD veto	0.2%	Long-lived nuclei	0.3%
Cross section	0.2%	Time lag	0.01%
	2.4%		3.4%

Total systematic uncertainty : 4.1%

TAUP Sept. 2007

Survival Probablity: L/E Variation

Oscillations: 1st and 2nd reappearance!

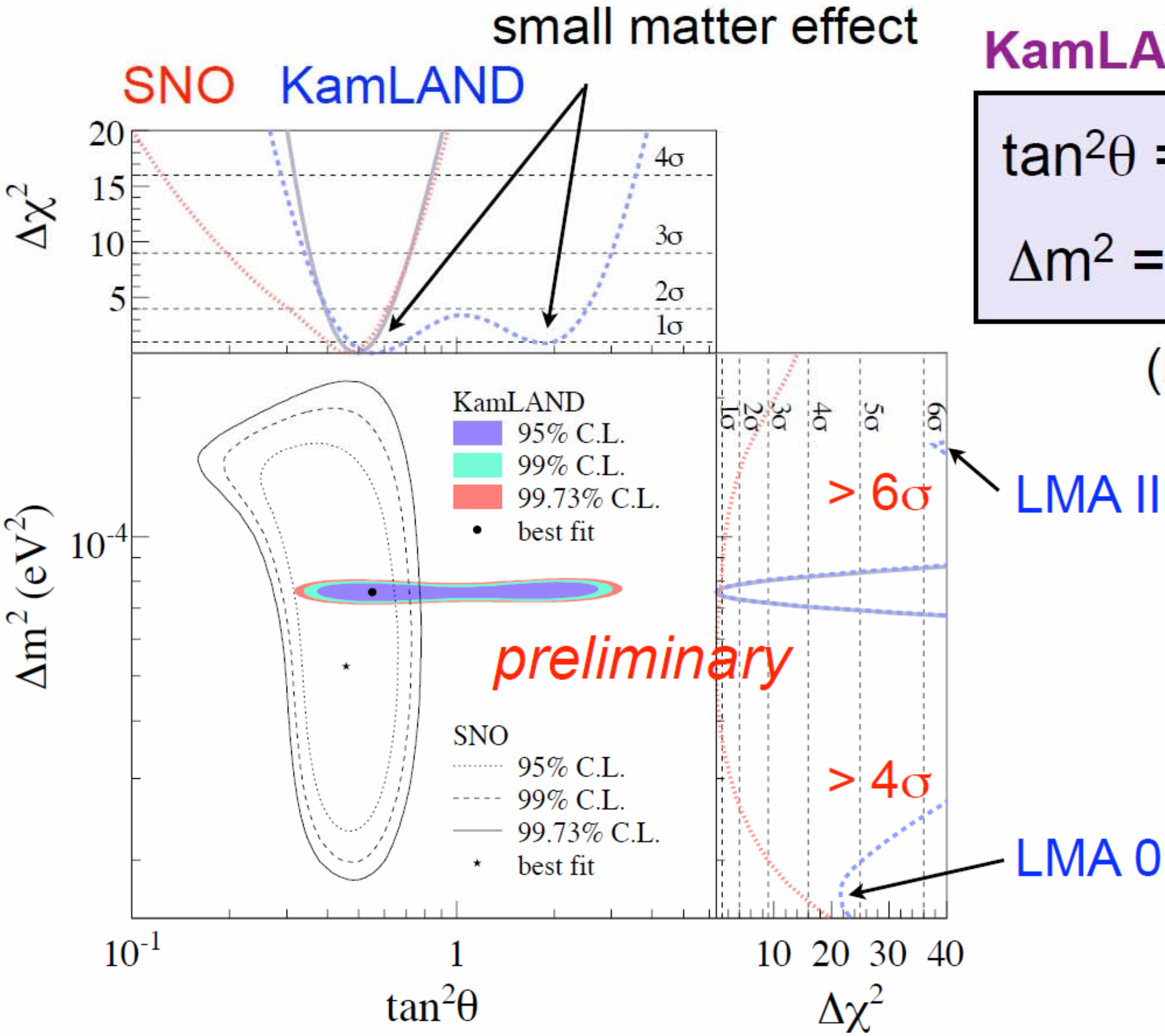


Expected survival probablity for point source at 180km baseline

L_0 = 180km flux-weighted average reactor distance

Definitely oscillations… alternatives not viable any more.

Oscillation Parameters



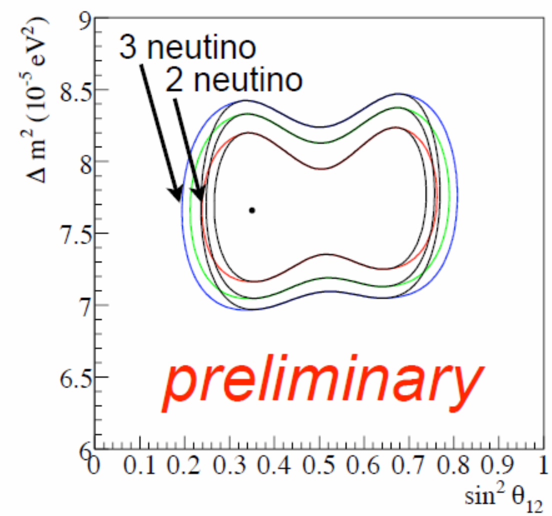
KamLAND only

$$\tan^2\theta = 0.56^{+0.14}_{-0.09}$$

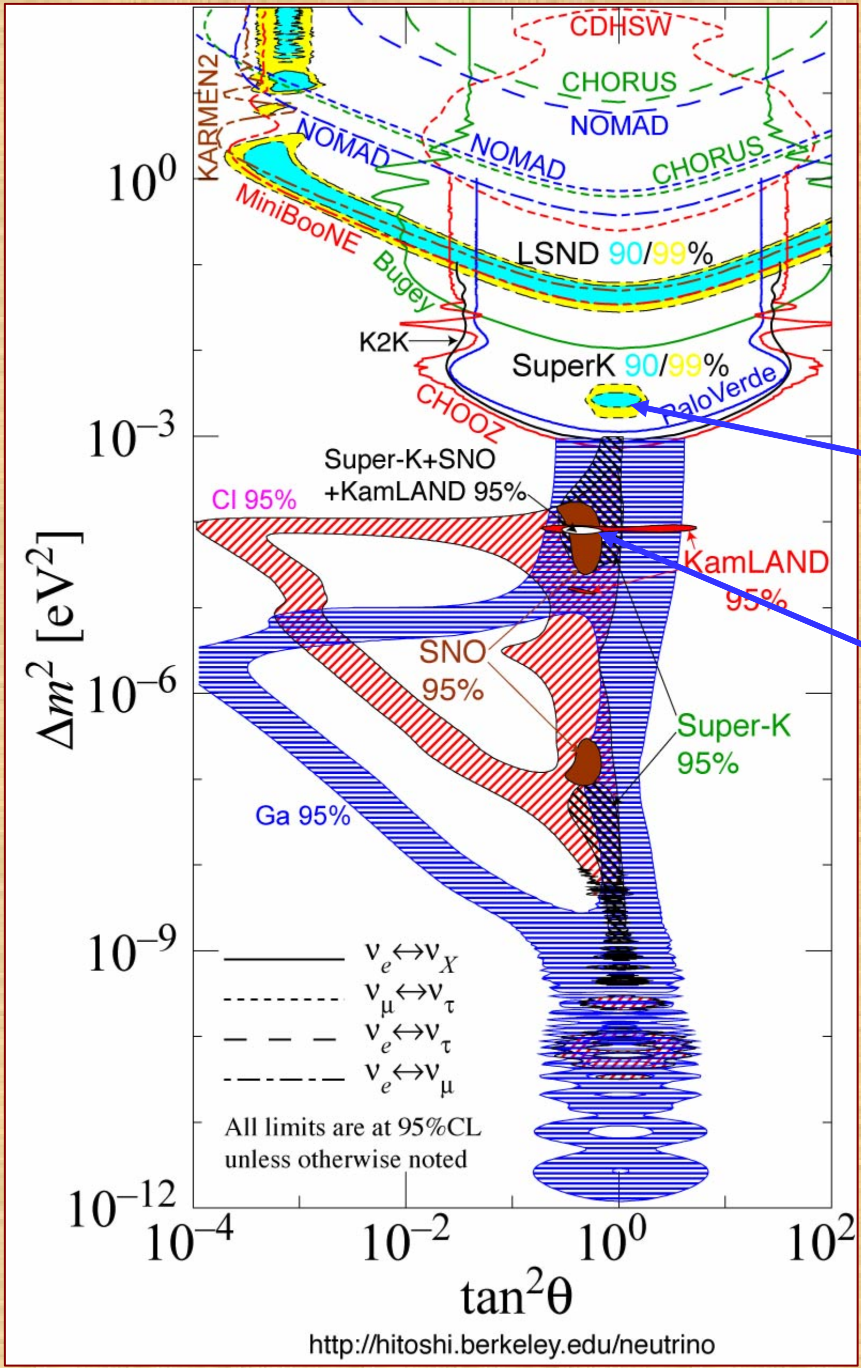
$$\Delta m^2 = 7.58^{+0.21}_{-0.20} \times 10^{-5}\ \mathrm{eV}^2$$

(marginalized error)

3 neutrino effect



same result for Δm^2



Neutrino Oscillations Parameters Summary

Atmospheric Neutrinos

Solar & Reactor Neutrinos

(And forget the rest!)

Dirty laundry or smudged glasses? The LSND-MiniBOONE Problem

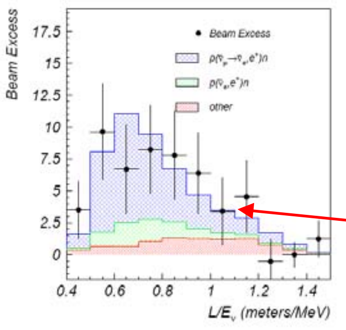


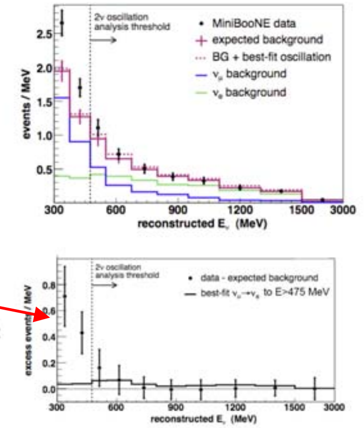
FIG. 24: The L_ν/E_ν distribution for events with $R_\gamma > 10$ and $20 < E_e < 60$ MeV, where L_ν is the distance travelled by the neutrino in meters and E_ν is the neutrino energy in MeV. The data agree well with the expectation from neutrino background and neutrino oscillations at low Δm^2.

As planned before opening the box....
Report the full range: $300<E_\nu^{QE}<3000$ MeV

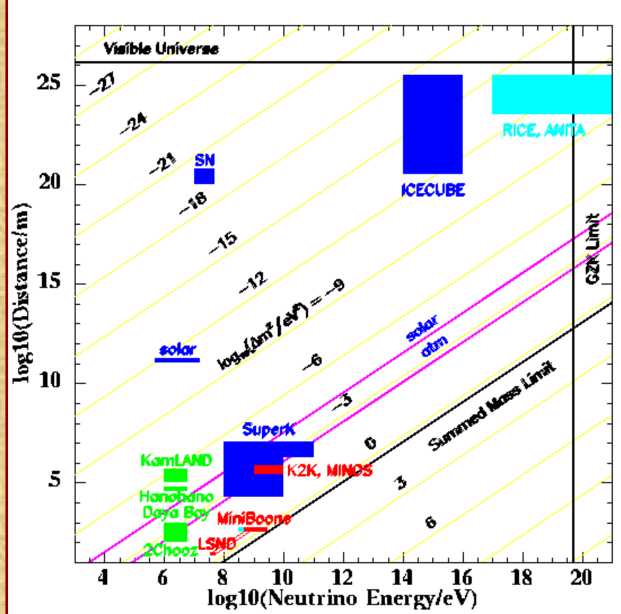
$96 \pm 17 \pm 20$ events above background, for $300<E_\nu^{QE}<475$MeV

Deviation: 3.7σ

Background-subtracted:



Excess



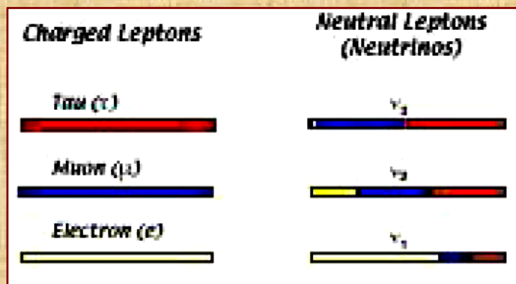
Conclusion: Each experiment has an "anomaly" with spectrum like the background; together are incompatible with any oscillations interpretation.

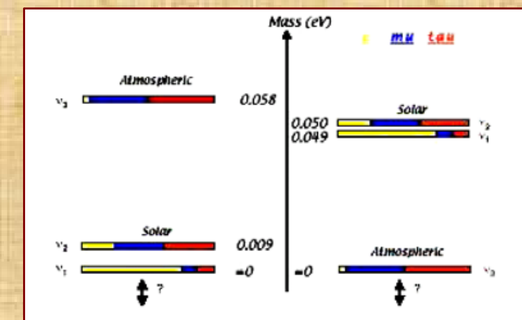
What they want: More beamtime.

Best bet (JGL): Waste of time.
But maybe not…

The State of the Neutrino Mixing Matrix (MNSP)

Normal hierarchy --- Inverted Hierarchy





≠0?
CPV?

$$U_{MNS} = \begin{pmatrix} U_{e1} & U_{e2} & U_{e3} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} \end{pmatrix}$$

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

Neutrinos

$$U_{MNSP} \sim \begin{pmatrix} 0.8 & 0.5 & ? \\ 0.4 & 0.6 & 0.7 \\ 0.4 & 0.6 & 0.7 \end{pmatrix}$$

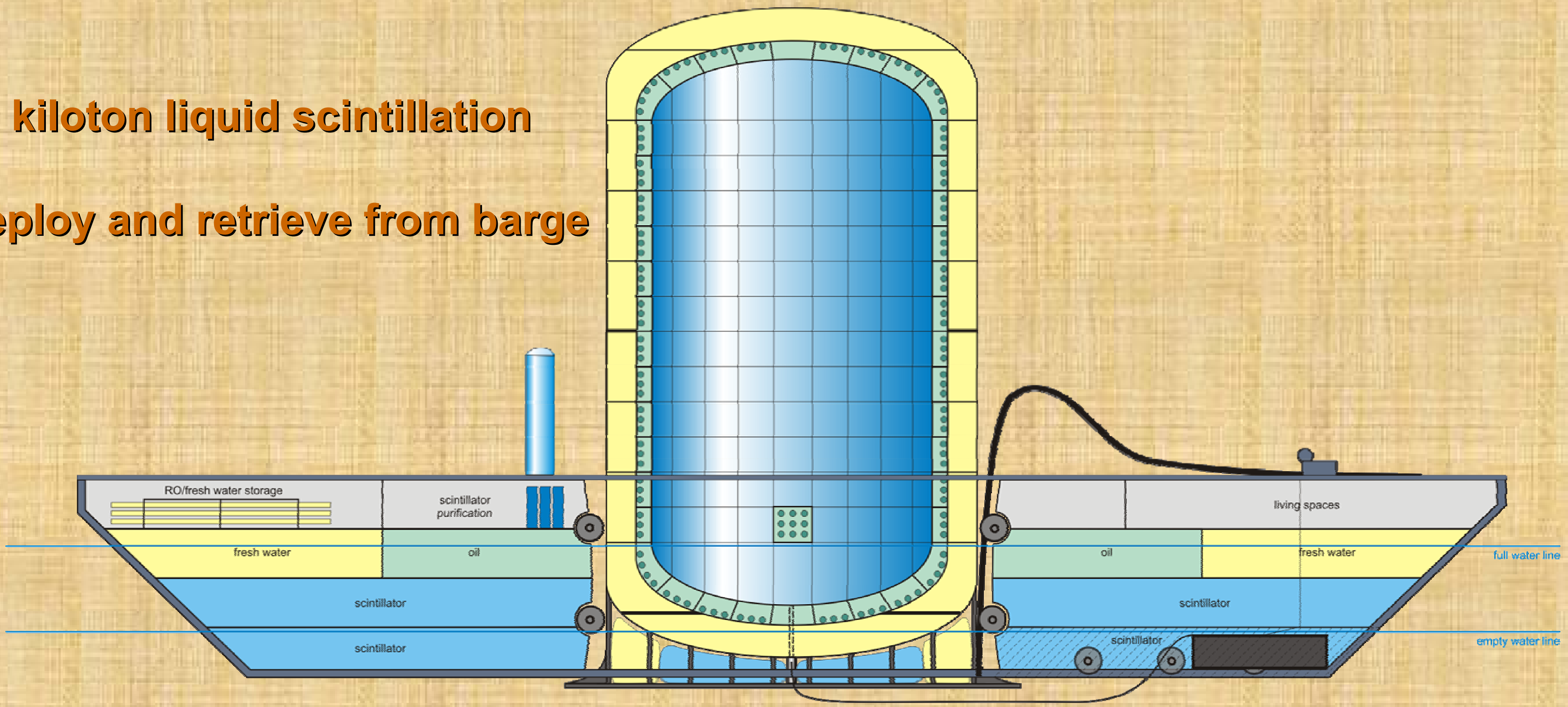
Quarks

$$V_{CKM} \sim \begin{pmatrix} 1 & 0.2 & 0.005 \\ 0.2 & 1 & 0.04 \\ 0.005 & 0.04 & 1 \end{pmatrix}$$

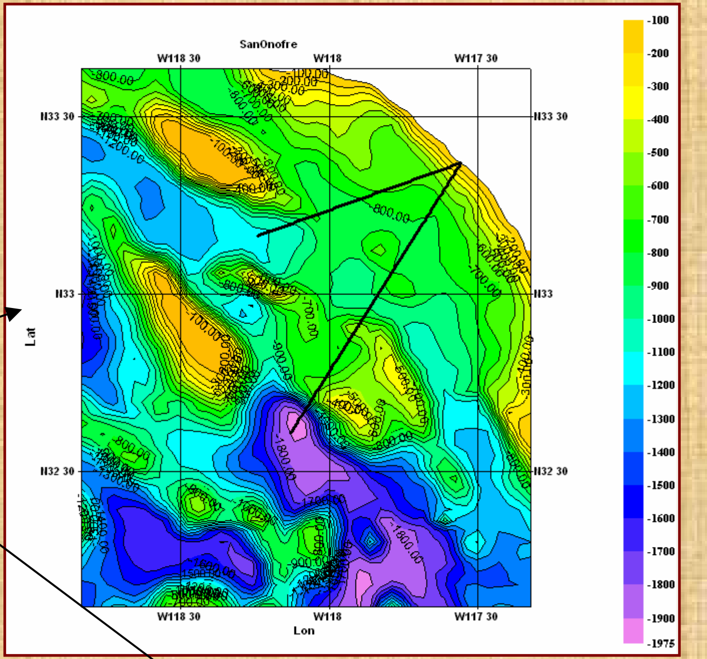
Hanohano
a mobile deep ocean detector

10 kiloton liquid scintillation

Deploy and retrieve from barge

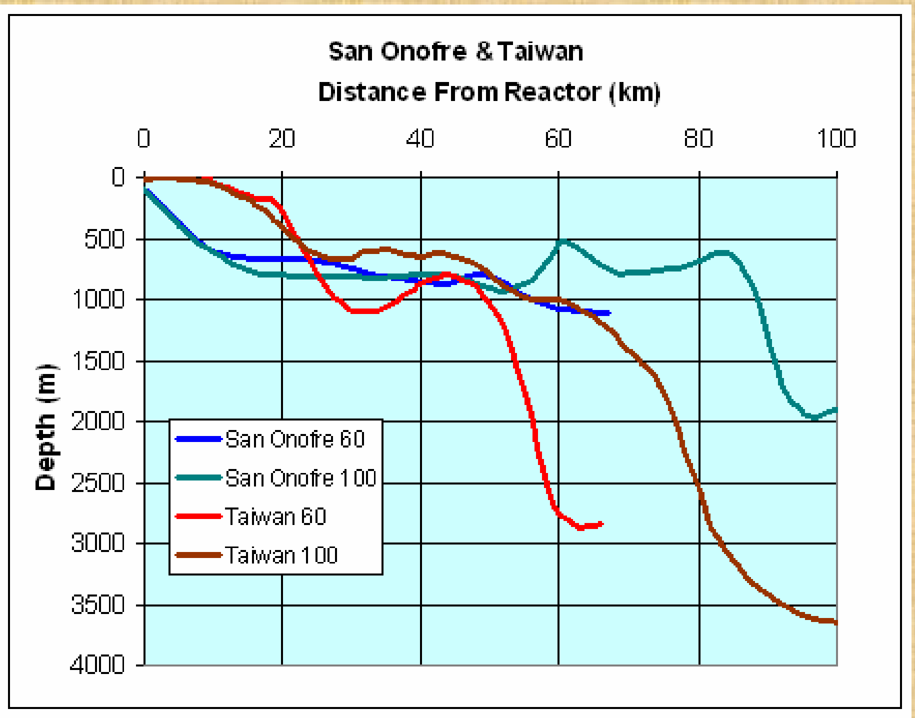


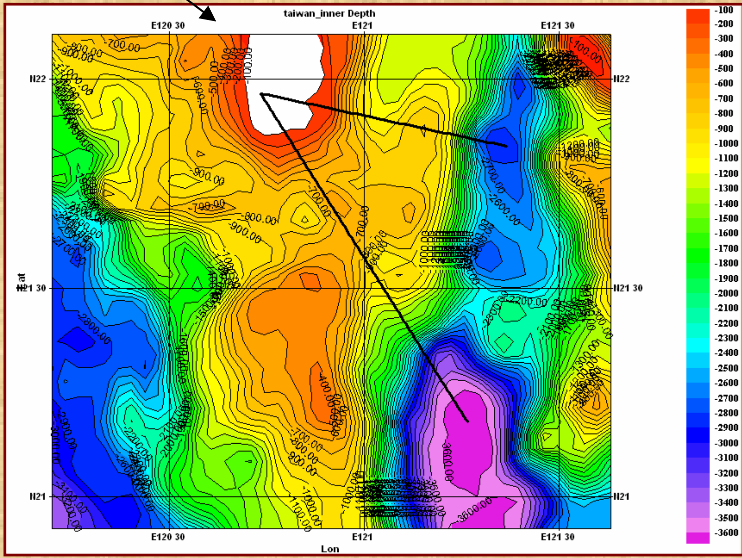
2 Candidate Off-shore Sites for Physics



San Onofre, California- ~6 GW_{th}

Maanshan, Taiwan- ~5 GW_{th}





Need study of backgrounds versus depth

Neutrino Oscillation Physics with Hanohano

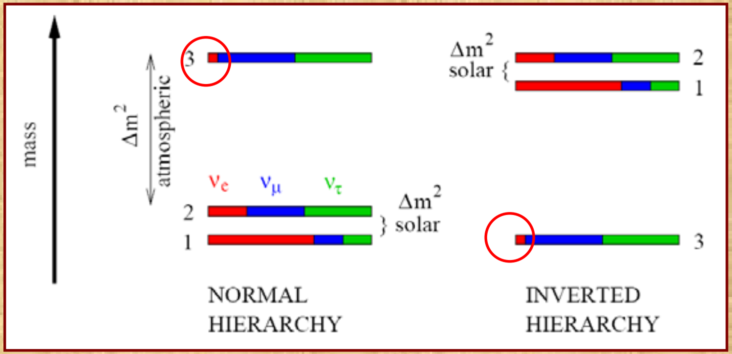
- **Precision measurement of <u>mixing parameters</u> needed**
  (4 of 5 in Hanohano)

- **World effort to determine θ_{13} (= θ_{31})**
  (Hanohano, unique method)

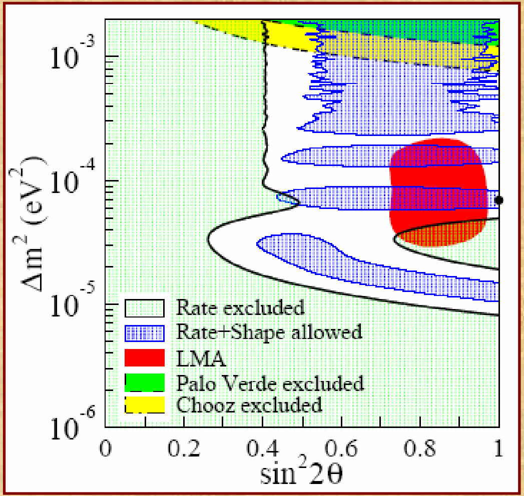
- **Determination of <u>mass hierarchy</u>**
  (Hanohano novel method)

- **Neutrino properties relate to origin of matter, formation of heavy elements, and may be key to unified theory (*pace* Landscape folks).**

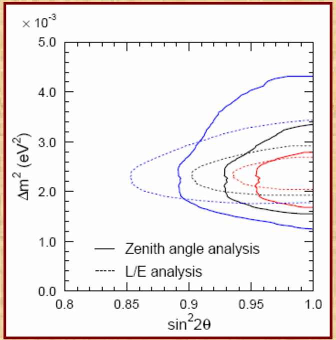
MNSP Mixing Matrix



2 mass diffs, 3 angles, 1 CP phase



Solar, KamLAND



Atmospheric, SuperK

3-ν Mixing: Reactor Neutrinos

$$P_{ee}=1-\{\cos^4(\theta_{13})\sin^2(2\theta_{12})[1-\cos(\Delta m^2_{12}L/2E)]$$
$$+\cos^2(\theta_{12})\sin^2(2\theta_{13})[1-\cos(\Delta m^2_{13}L/2E)]$$
$$+\sin^2(\theta_{12})\sin^2(2\theta_{13})[1-\cos(\Delta m^2_{23}L/2E)]\}/2$$

} wavelength close, 3%

mixing angles

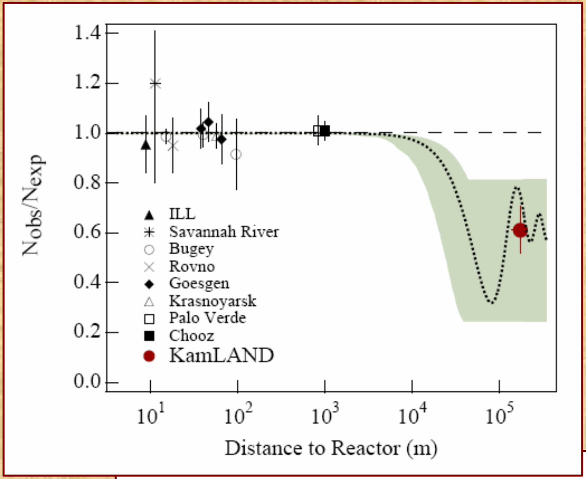
mass diffs

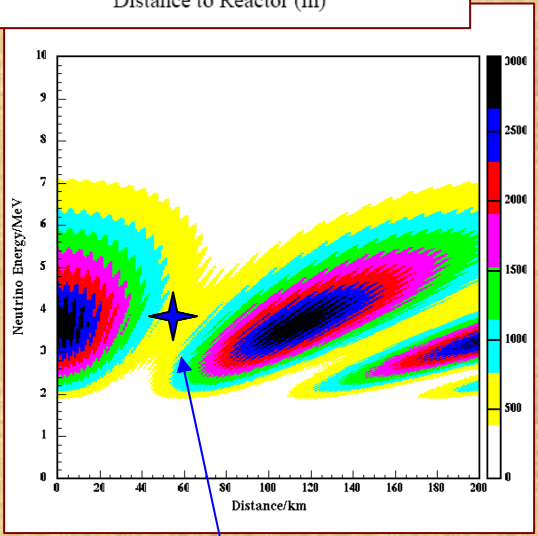
- Survival probability: 3 oscillating terms each cycling in L/E space (~t) with own "periodicity" ($\Delta m^2 \sim \omega$)
  - Amplitude ratios ~13.5 : 2.5 : 1.0
  - Oscillation lengths ~**110 km** (Δm^2_{12}) and ~**4 km** ($\Delta m^2_{13} \sim \Delta m^2_{23}$) at reactor peak ~3.5 MeV
- ½-cycle measurements can yield
  - Mixing angles, mass-squared differences
- Multi-cycle measurements can yield
  - Mixing angles, precise mass-squared differences
  - Mass hierarchy
  - **Less sensitivity to systematic errors**

Hanohano: Guaranteed Precise measurement for ½-cycle θ_{12} (=θ_{21})

- 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.* **D67** (2003) 113011.
Minakata et al., hep-ph/0407326
Bandyopadhyay et al., hep-ph/0410283





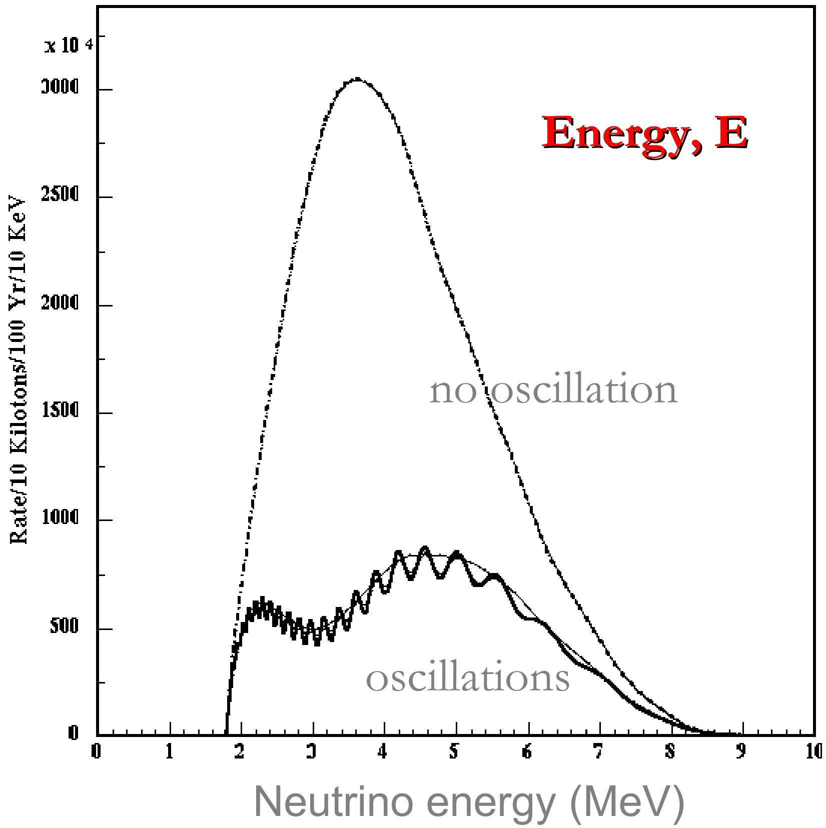
oscillation maximum at ~ 50-60 km

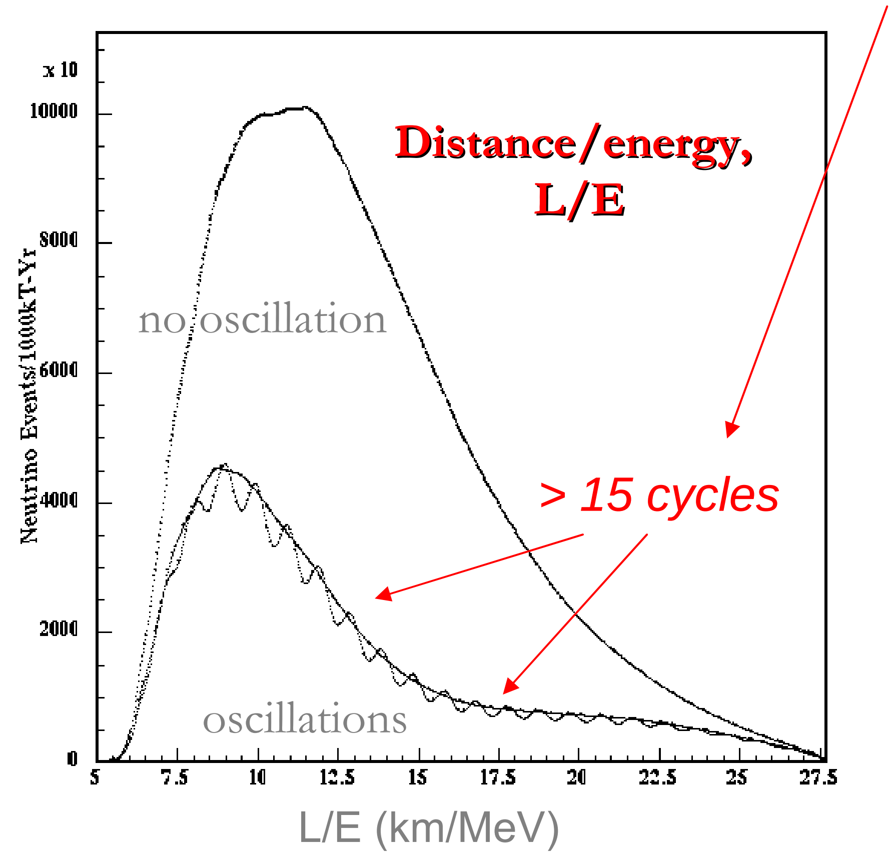
Reactor ν_e Spectra at 50 km

~4400 events per year from San Onofre

Fitting will give improved θ_{12}

invites use of Fourier Transforms

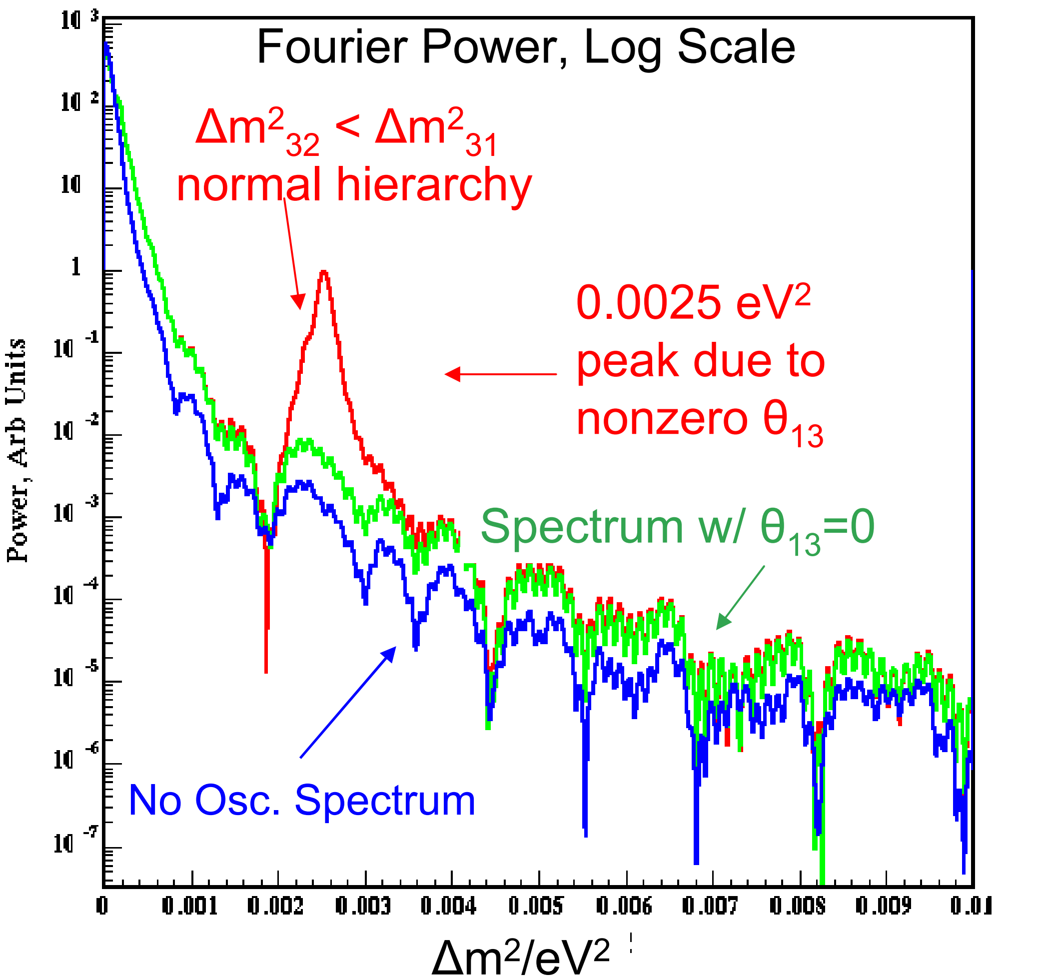




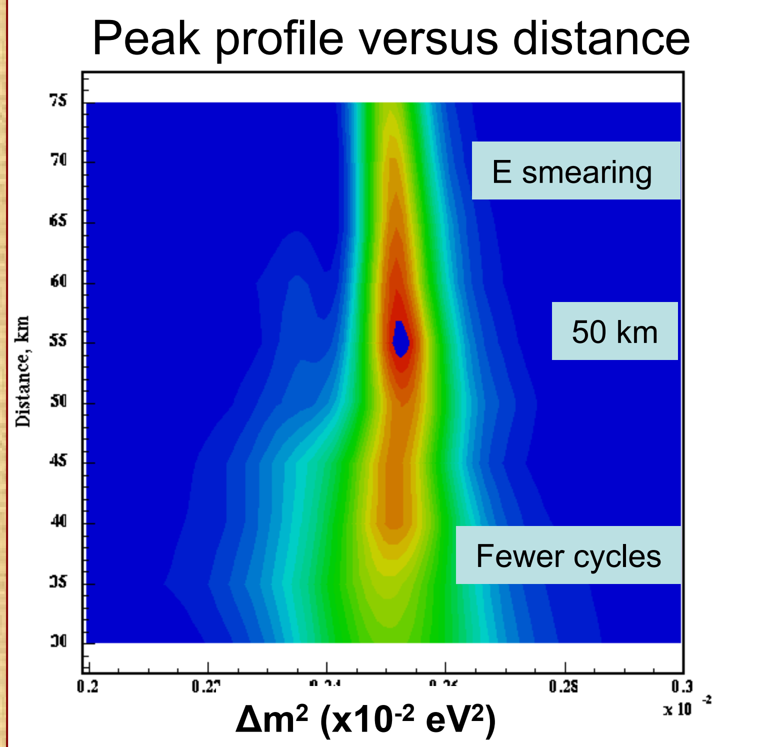
1,2 oscillations with $\sin^2(2\theta_{12})=0.82$ and $\Delta m^2_{21}=7.9\text{x}10^{-5}$ eV^2

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

Fourier Transform on L/E to Δm^2



Includes energy smearing



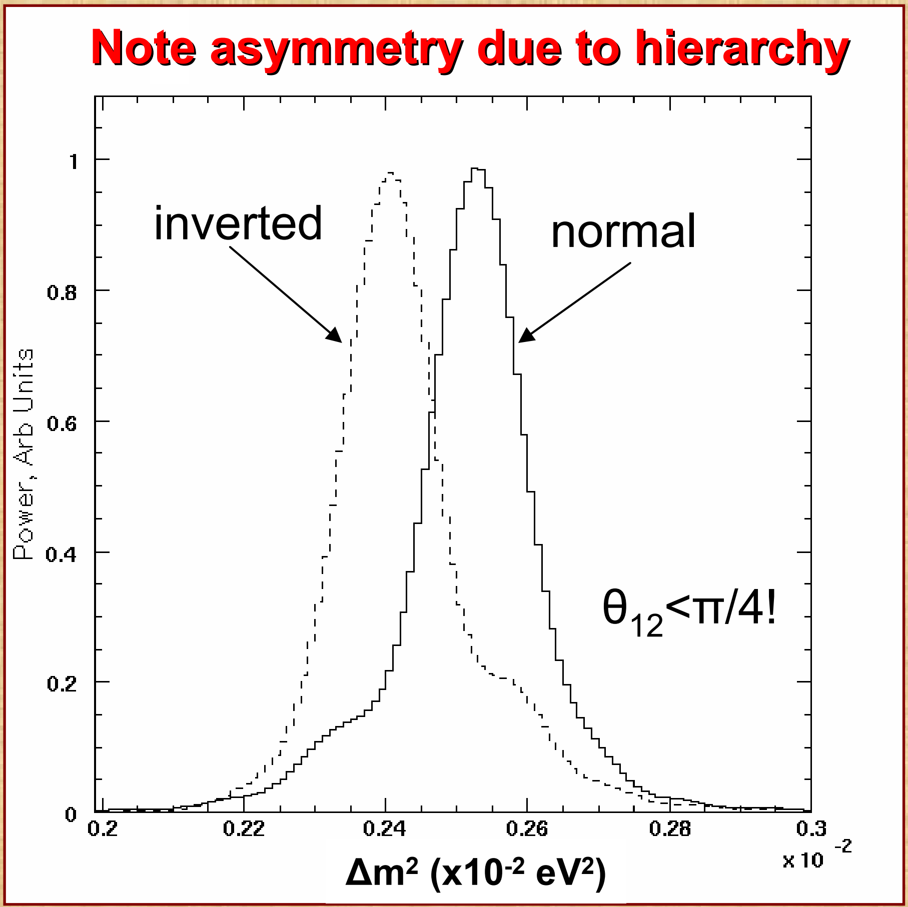
50 kt-y exposure at 50 km range

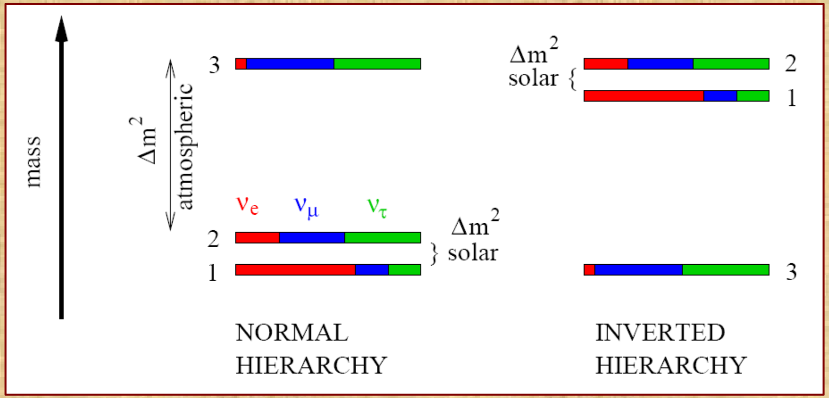
$\sin^2(2\theta_{13}) \geq 0.02$

$\Delta m^2_{31} = 0.0025$ 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 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

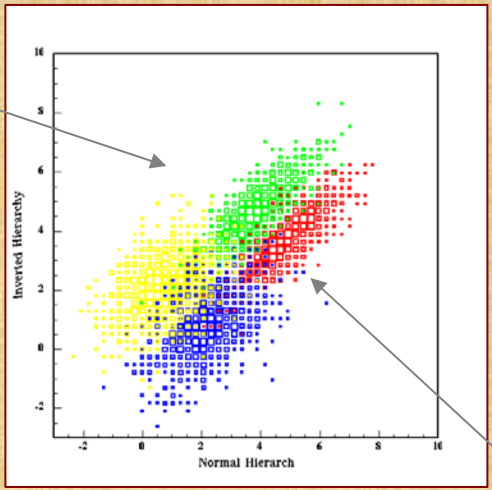
Learned, Dye, Pakvasa, and Svoboda, *hep-ex/0612022*

Hierarchy Determination

Ideal Case with 10 kiloton Detector, 1 year off San Onofre

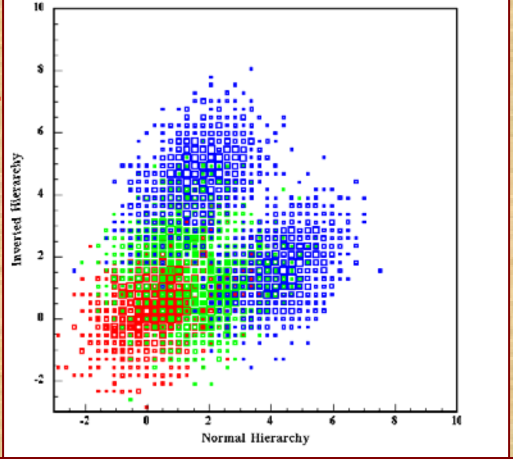
Distance variation: 30, 40, 50, 60 km

Inverted hierarchy



Sin$^2 2\theta_{13}$ Variation: 0.02 – 0.2

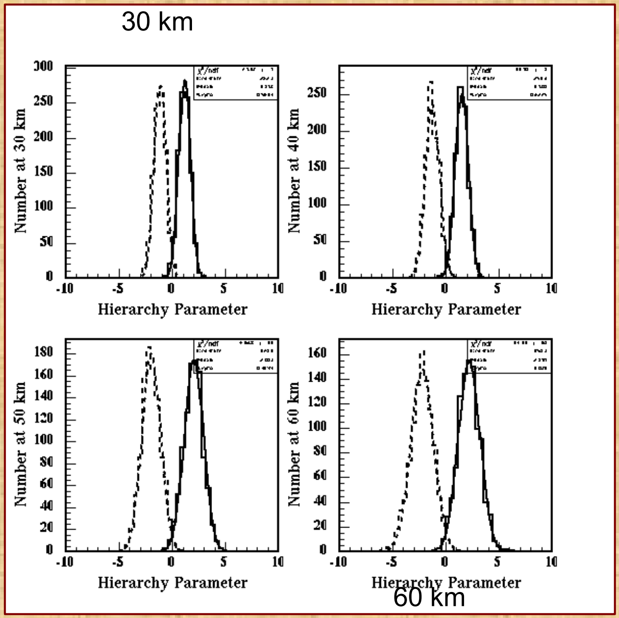
Inv.



Norm.

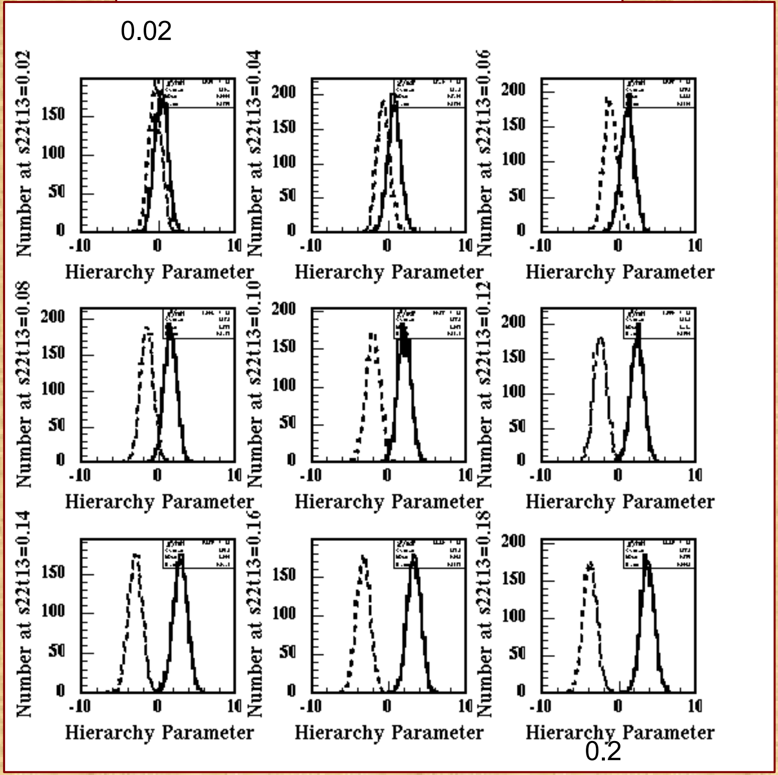
Hierarchy tests employing Matched filter technique, for Both normal and inverted hierarchy on each of 1000 simulated one year experiments using 10 kiloton detector.

Normal Hierarchy



100 kt-yrs separates even at 0.02

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



Misha's New Simulation:

- Calculations of the expected Hanohano live-times to reach various physics goals were done under the assumptions of:

  -- 10 kt detector (fiducial)

  -- 5 GWt single power plant

  -- Same # of protons per mass as KamLAND

- Main points:

  -- Systematics considered:

  a) "general efficiency": fiducial volume, number of protons, eff. of cuts, etc.

  b) error in detector resolution estimation.

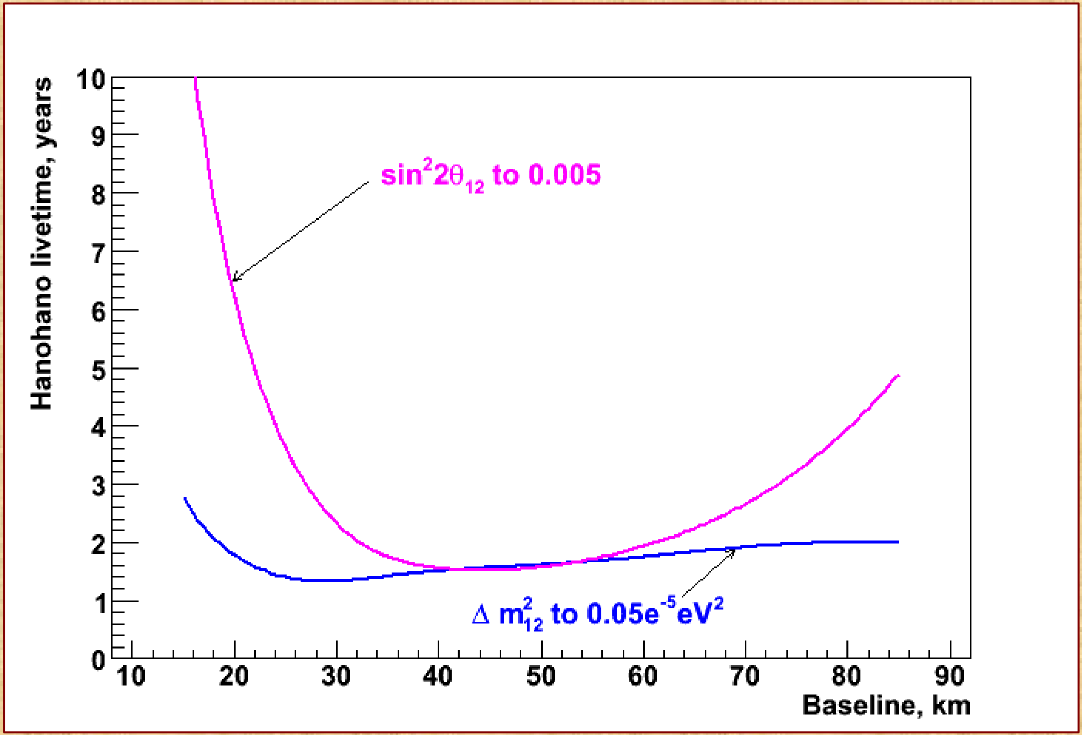
  -- Systematics ignored at this point:

  a) overall energy scale error

  b) background uncertainties

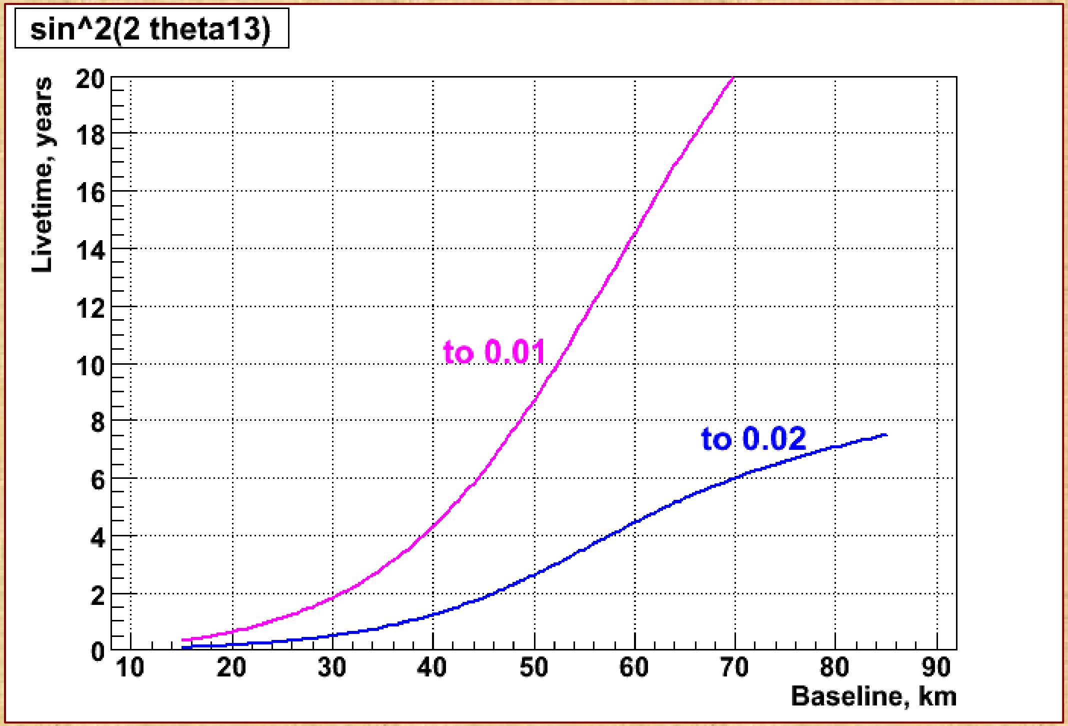
Precision Measurement of Θ_{12}

- -- Solar Parameters: ~2 years at ~40 km baseline
  - $\sin2(2\Theta_{12})$ down to 0.005
  - Δm^2_{12} to 0.05E-5 eV^2
- 4x the current SNO/KL best value
- mixing angle
  - more sensitive to the optimum choice of the baseline
  - some dependence on the small "efficiency" systematics
- Δm^2_{12}
  - less sensitive to baseline
  - doesn't depend on the systematics
  - May depend on the ignored energy scale error.
  - Neither depends much on energy resolution.



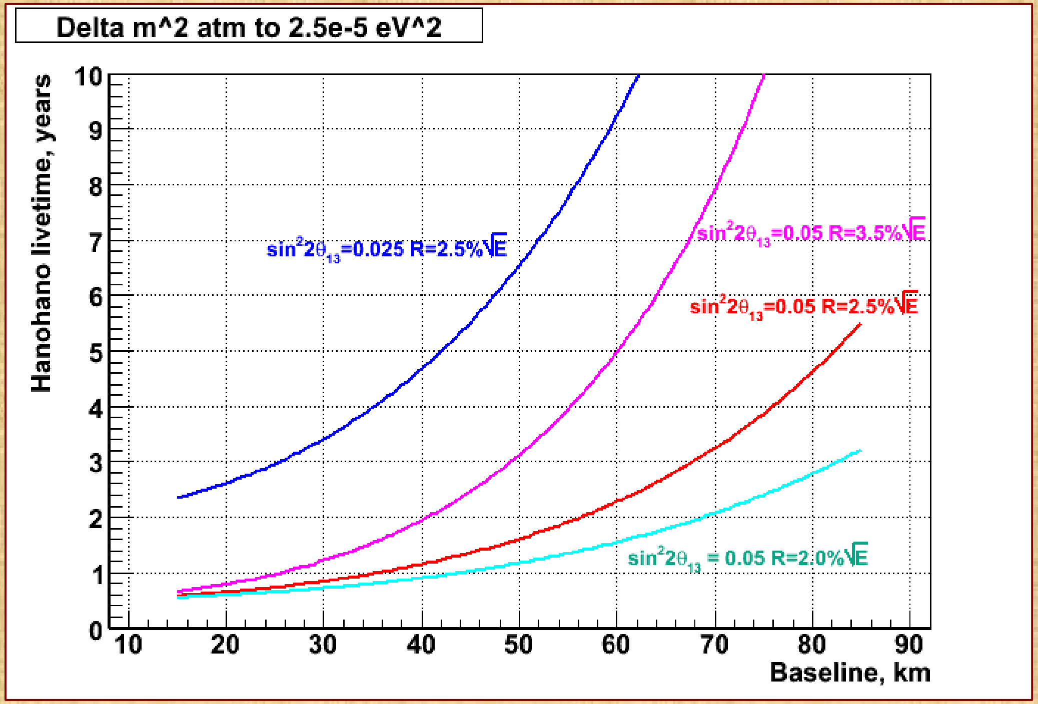
Measuring Θ_{13}

- $\sin^2(2\,\Theta_{13})$:
  - can be measured to 0.02 in 2-3 years
  - baselines above 20 km are not optimal (# events dominate)
  - doesn't depend strongly on the energy resolution of the detector
  - depends on the systematic uncertainty of energy resolution (esp. for longer baselines)
  - depends on the efficiency error (esp. shorter baselines)
  - doesn't depend on the actual value of $\sin^2(2\Theta_{13})$: 0.05 vs 0.06 is as difficult as 0 vs 0.01



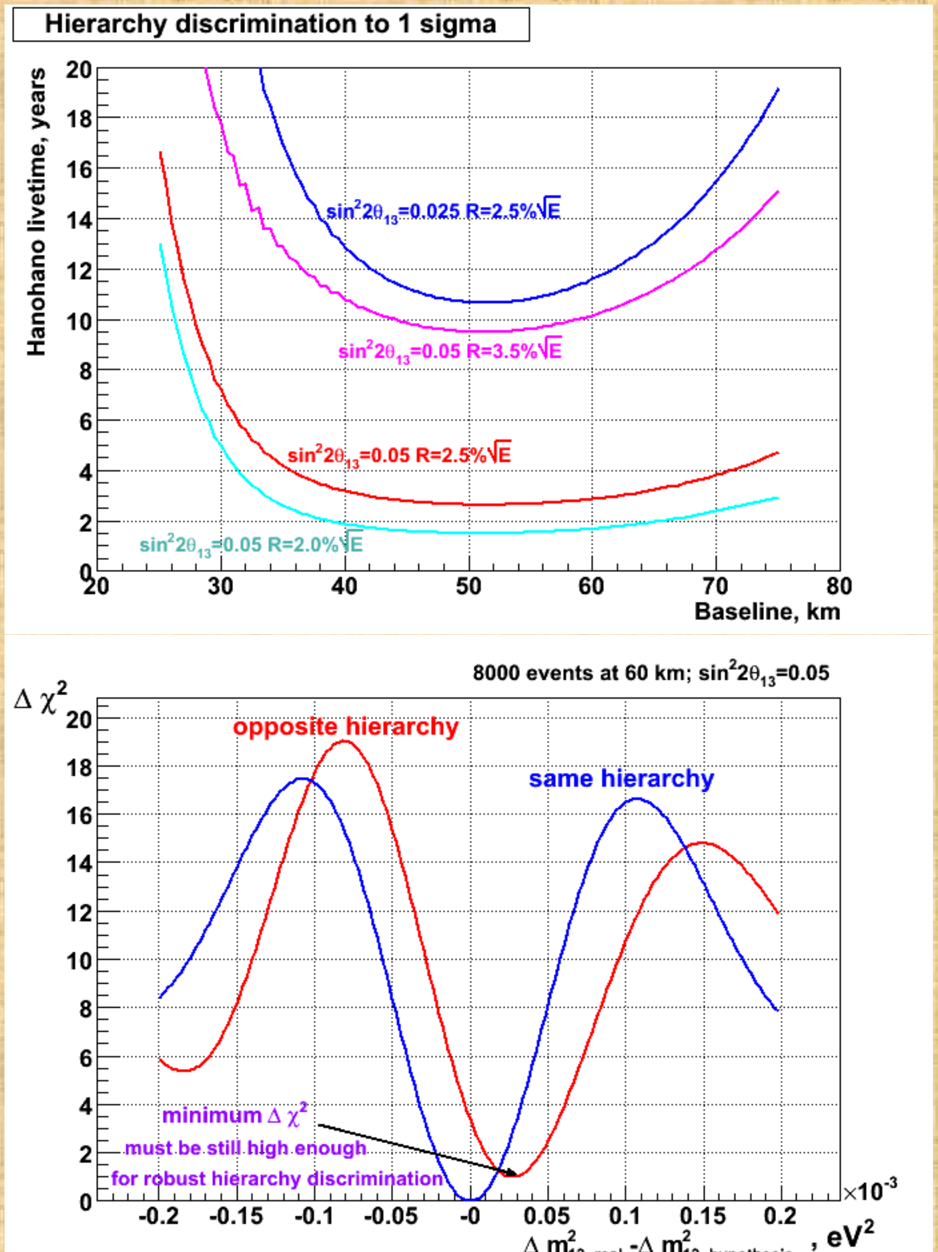
Atmospheric Δm^2

- shorter baselines better, but not as much as for Θ_{13}
- relies on non-zero $\sin^2(2\Theta_{13})$
- accuracy degrades in case of small Θ_{13}
- depends significantly but not critically on the detector resolution
- for $\sin^2(2\Theta_{13})=0.05$ and $\Delta E/E=0.025 \times \sqrt{(Evis/MeV)}$
- can be measured to 2.5E-5 eV^2 (~1% of value)
  - < 2 years;
  - not much systematics-limited;
  - If hierarchy not known, splits into two possible solutions.

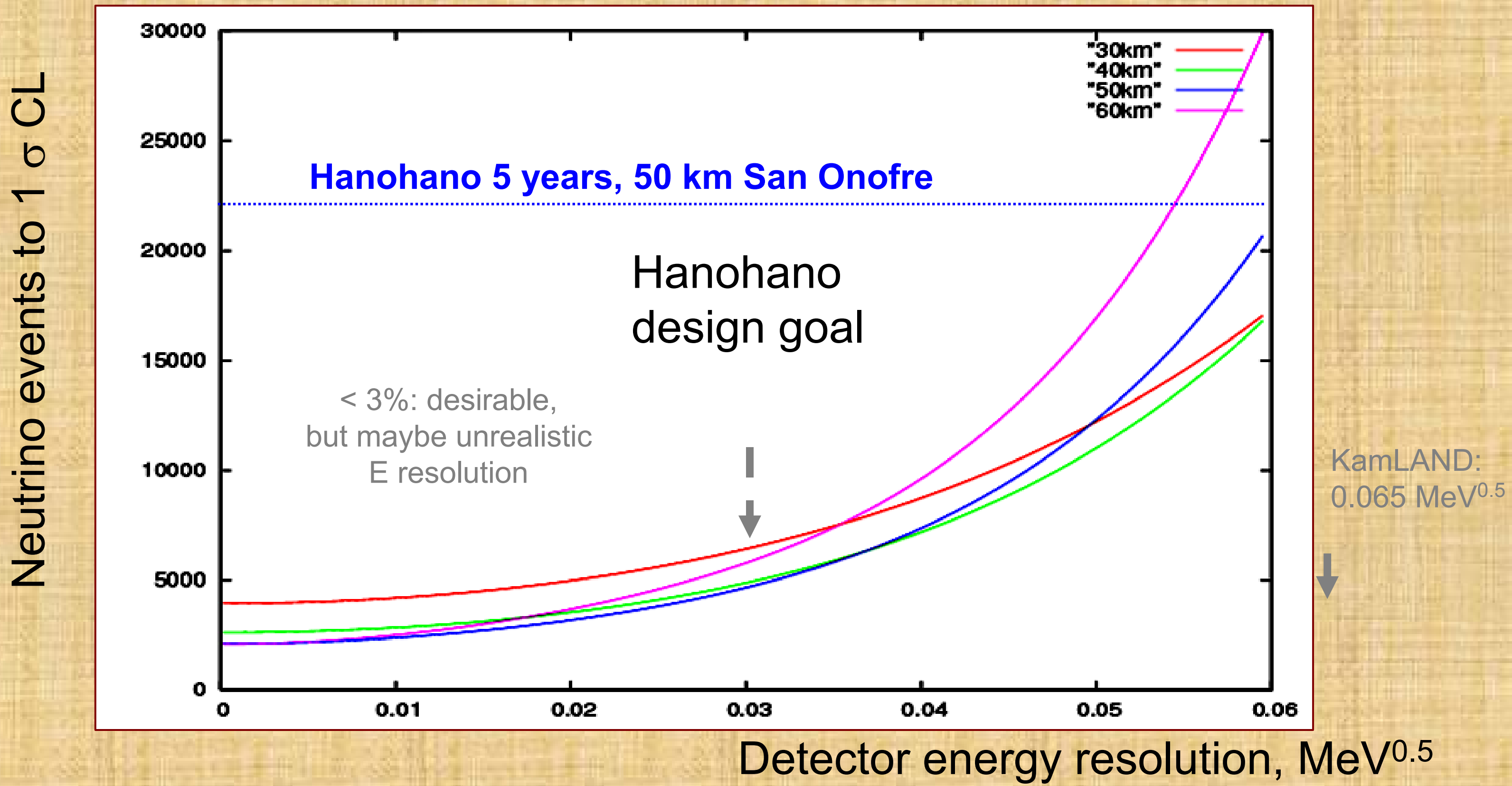


Mass Hierarchy Determination

- optimal baseline ~50 km
- strong dependence on the baseline
- relies on non-zero $\sin^2(2\Theta_{13})$
  - accuracy degrades in case of small Θ_{13}
  - depends critically on the detector resolution
  - resolution of 2%x√(Evis) gives almost 2X statistical advantage over the 2.5% but not very realistic;
  - 3.5% vs 2.5% resolution is a 4x hit in statistics
  - for 2.5%X√(Evis) and $\sin^2(2\Theta_{13})$=0.05 there it is possible to separate hierarchies to 1σ CL in 2.5 years;
  - weak systematics-limitation.



Estimation of the statistical significance for Hierarchy Determination



- Thousands of events necessary for reliable discrimination – big detector needed
- Longer baselines more sensitive to energy resolution; may be beneficial to adjust for actual detector performance

Thanks Misha Batygov

GeoNeutrinos

you've probably heard lots about this from Nikolai and Kazumi....

Big picture questions in Earth Sci

What drives **plate tectonics**?

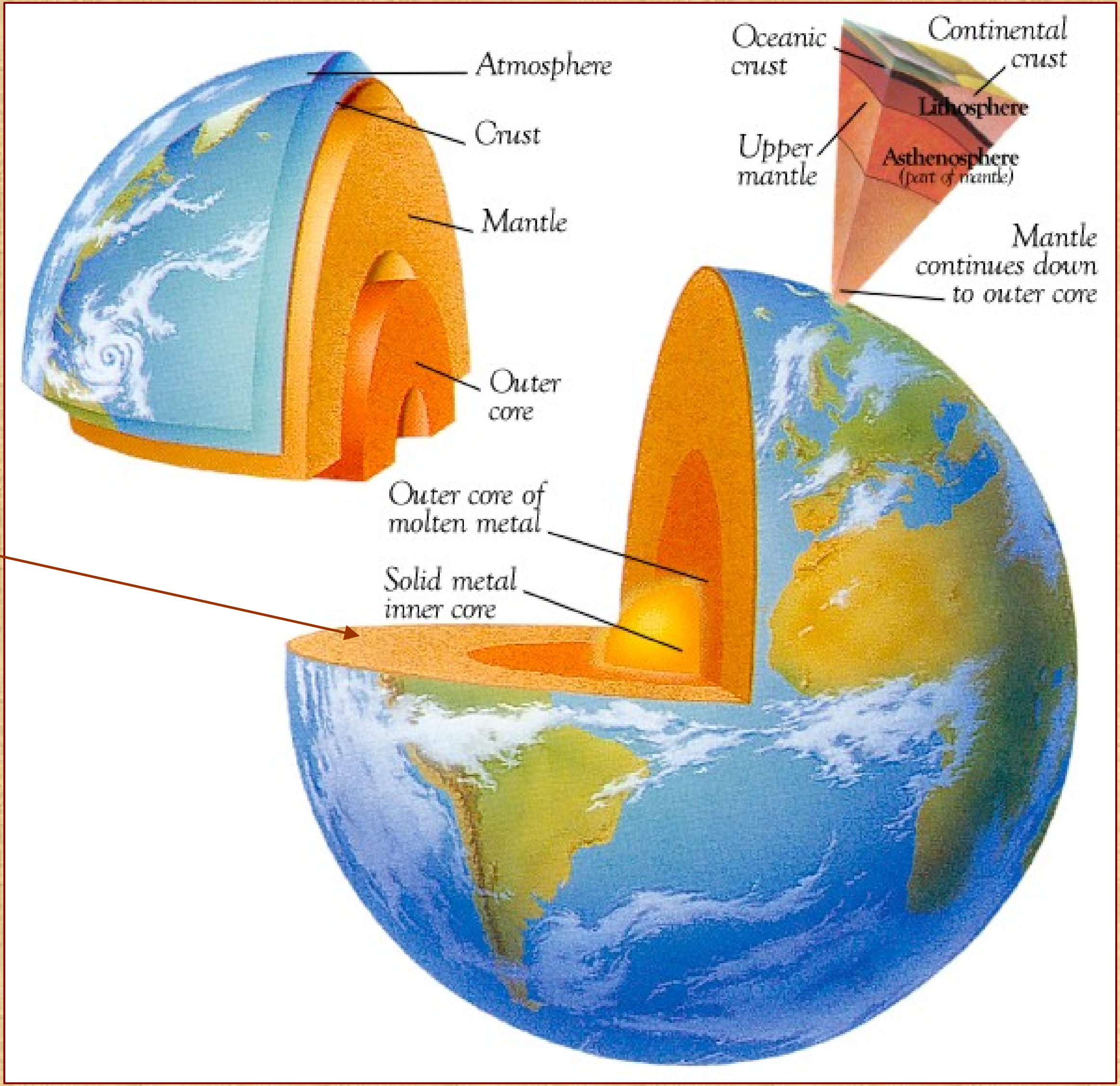
What is the Earth's **energy budget**?

What is the **Th & U conc**. of the Earth?

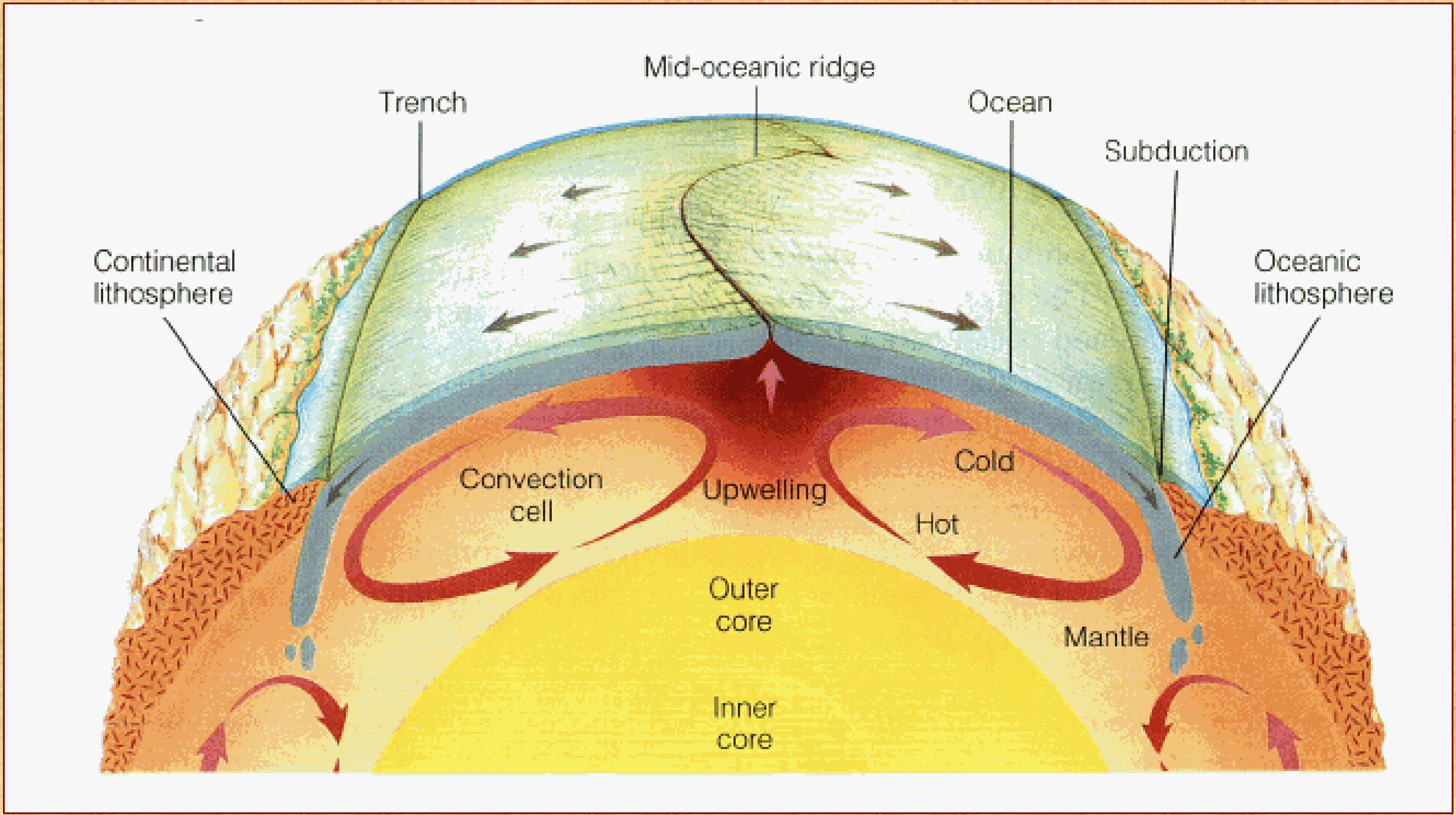
Energy source driving the **Geodynamo**?

Structure of the Earth

We do not know How much U & Th is in the mantle



Convection in the Earth



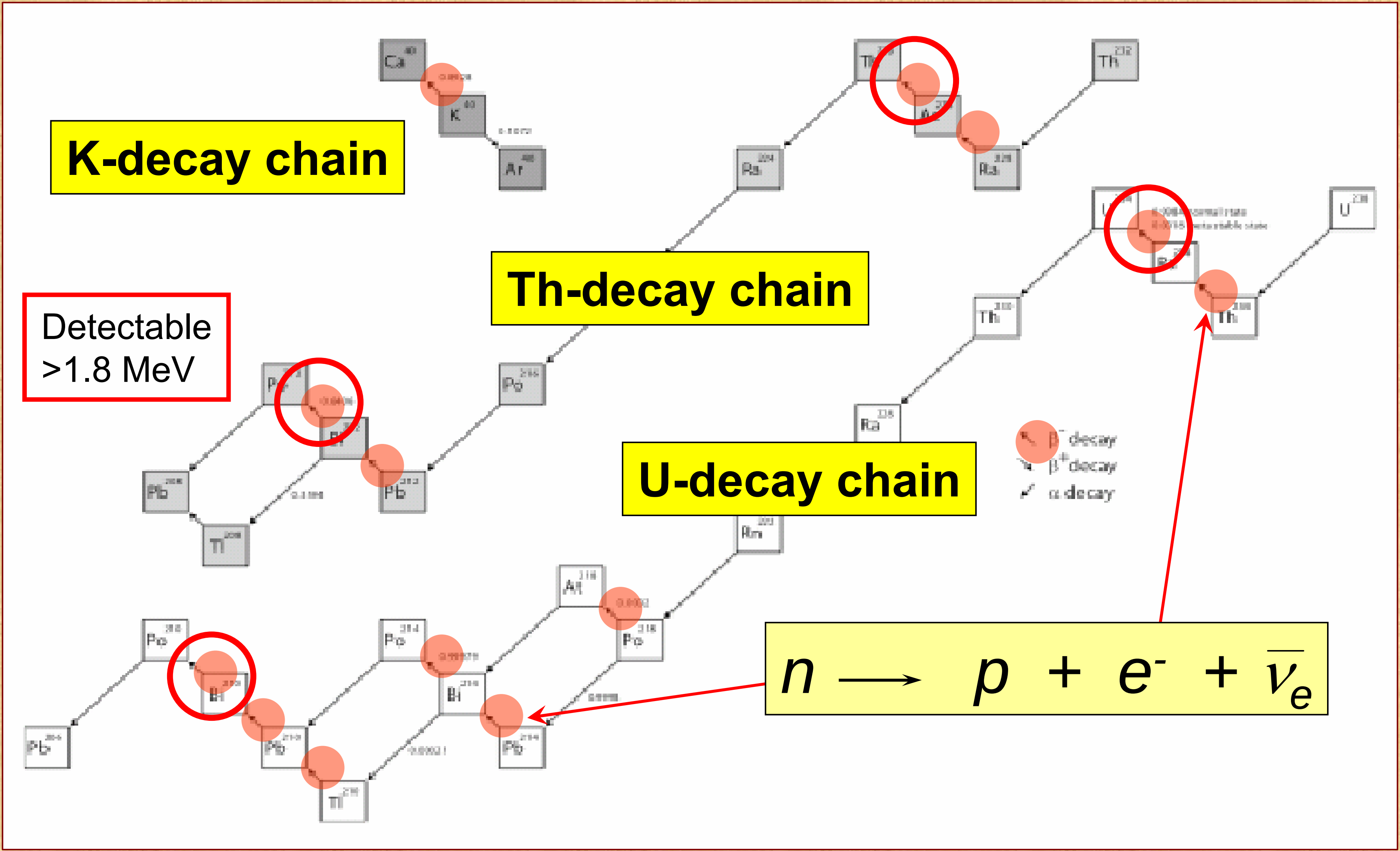
- The mantle convects.
- Plate tectonics operates via the production of oceanic crust at mid-ocean ridges and it is recycled at deep sea trenches.

How much Th, U and K is there in the Earth?

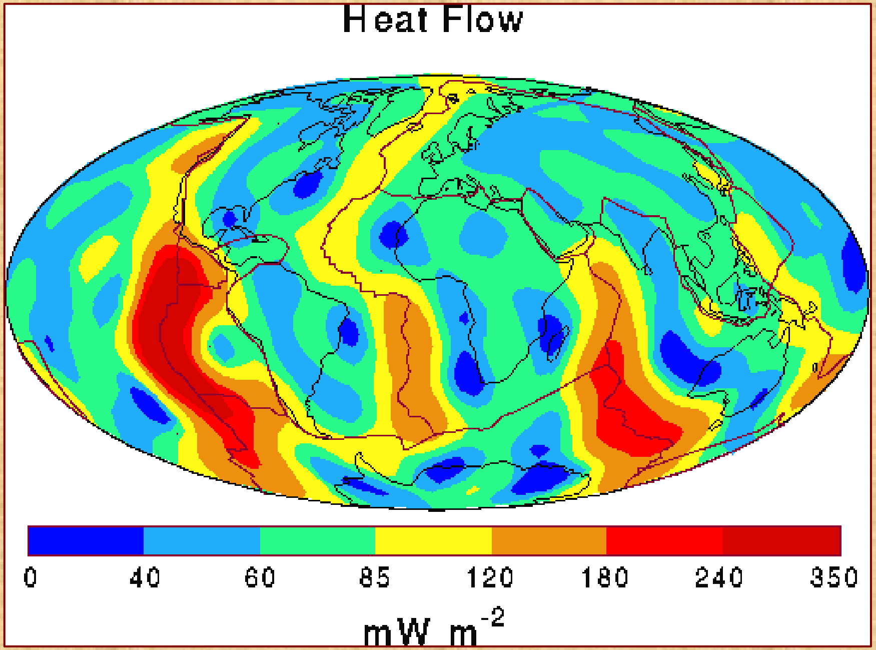
Inconsistent results {
- Heat flow measurements
- Geochemical modeling

- Neutrino Geophysics

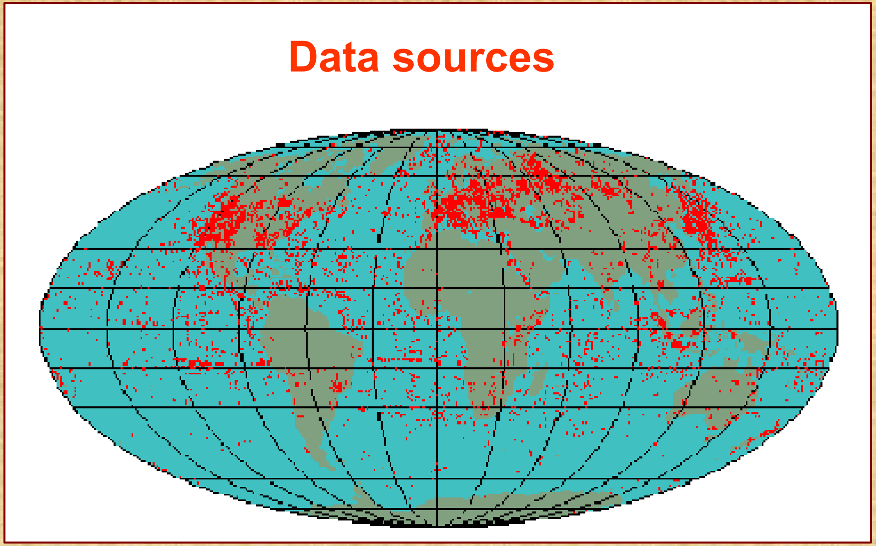
Radiogenic heat & "geoneutrinos"



Earth's Total Heat Flow



- Conductive heat flow measured from bore-hole temperature gradient and conductivity



Total heat flow

<u>Conventional view</u>

44±1 TW

<u>Challenged recently</u>

31±1 TW

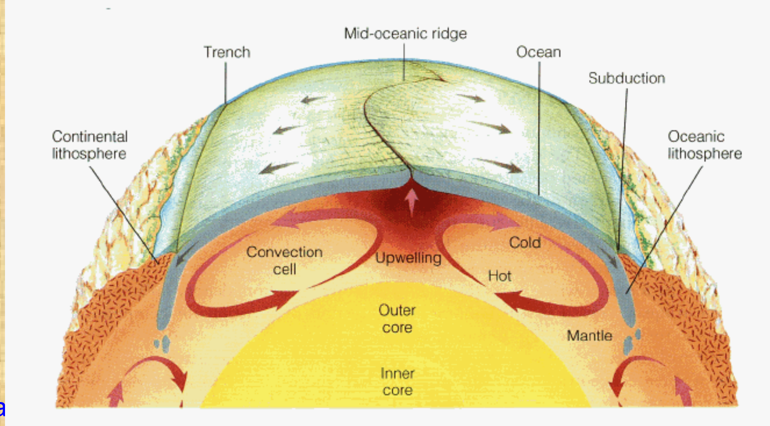
strongly model dependent

Urey Ratio and Mantle Convection Models

$$\text{Urey ratio} = \frac{\textbf{radioactive heat production}}{\textbf{heat loss}}$$

- Mantle convection models typically assume:
  mantle Urey ratio: 0.4 to 1.0, generally ~0.7
- Geochemical models predict:
  Urey ratio 0.4 to 0.5.

generally geologists believe these inconsistent



Discrepancy?

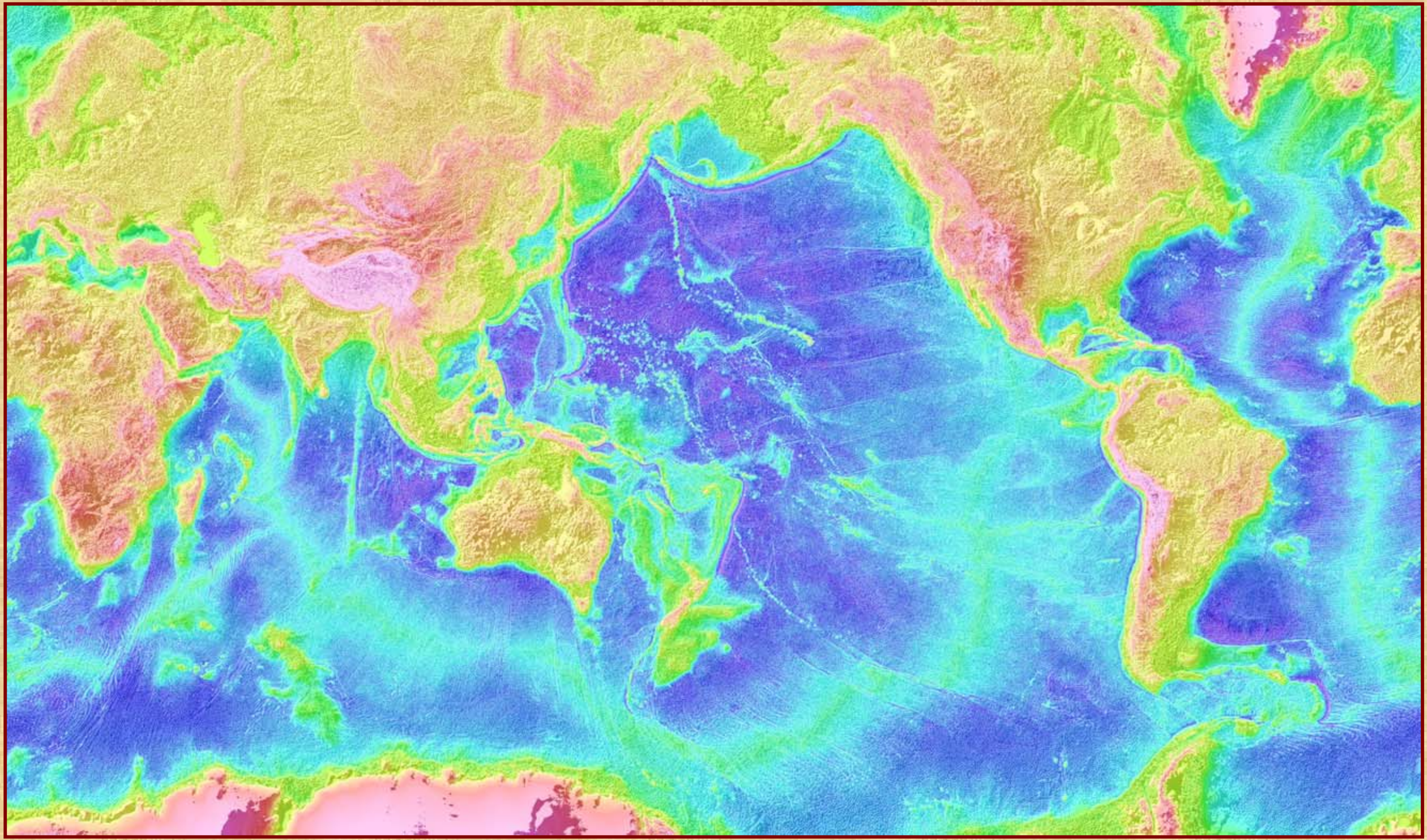
- Est. total heat flow, **44 or 31TW**
  est. radiogenic heat production **19TW or 31TW**
  give Urey ratio ~0.4 to ~1
- Where are the problems?
  - Mantle convection models?
  - Total heat flow estimates?
  - Estimates of radiogenic heat production rate?
- Mantle geoneutrino measurements can constrain the planetary radiogenic heat production.

Chondritic Meteorites

- Estimated abundances of U and Th in the Earth are based on measurements of chondritic meteorites.
- Solar photosphere and chondrites possess similar ratios of non-volatile elements.
- Chondritic Th/U ratio is 3.9±0.3.
- Earth's Th/U ratio is known better than the absolute concentrations.

Allende chondrite

Two types of crust: Oceanic & Continental



Oceanic crust: single stage melting of the mantle
Continental crust: multi-stage melting processes → Compositionally distinct

U and Th Distribution in the Earth

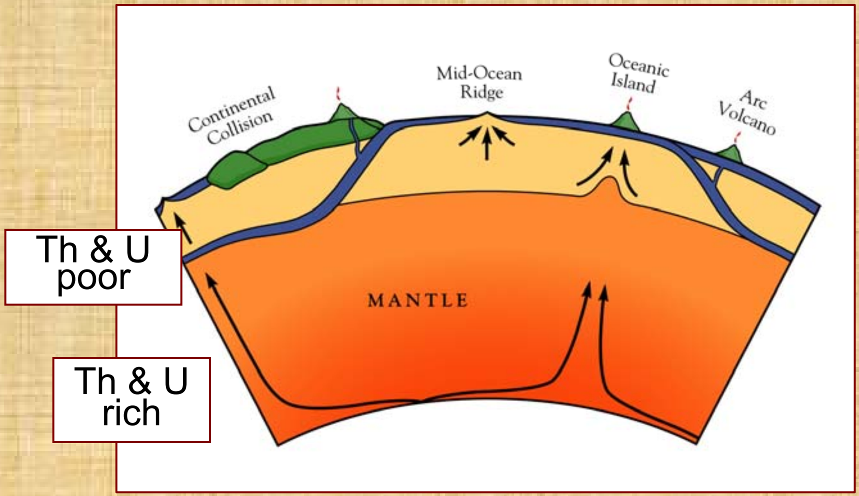
- U and Th are thought to be absent from the core and present in the mantle and crust.
  - Core: Fe-Ni metal alloy
  - Crust and mantle: silicates

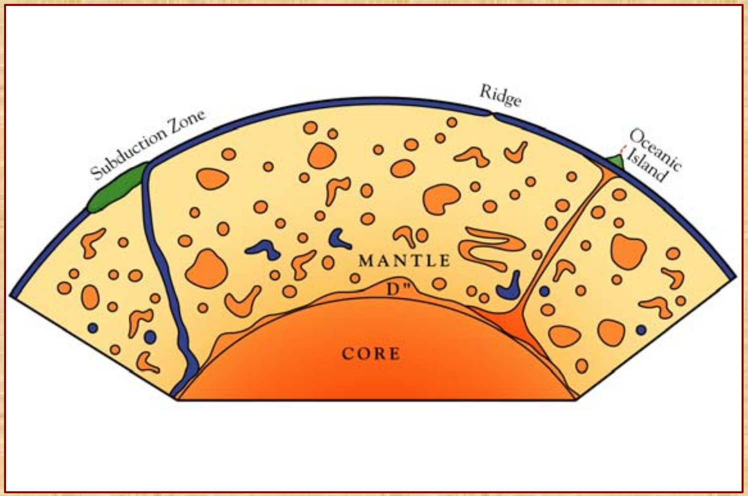
- U and Th concentrations are the highest in the continental crust.
  - Continents formed by melting of the mantle.
  - U and Th prefer to enter the melt phase

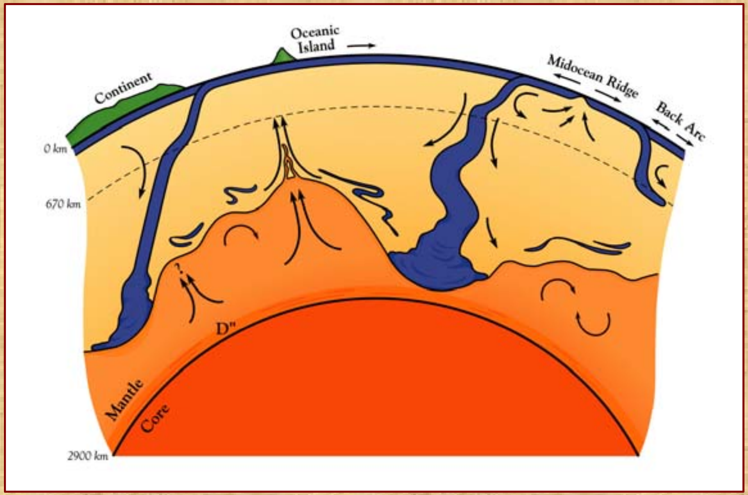
- Continental crust: insignificant in terms of mass but major reservoir for U, Th, K.

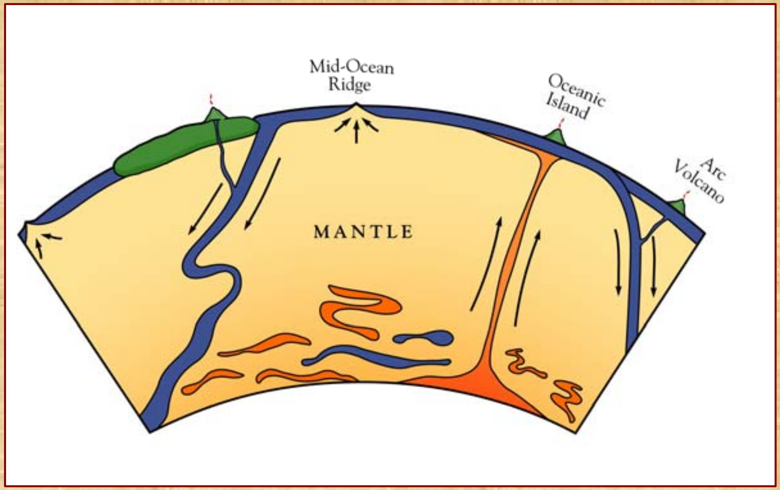
Mantle is depleted in some elements (e.g., Th & U) that are enriched in the continents.

-- models of mantle convection and element distribution









Natural Reactors?

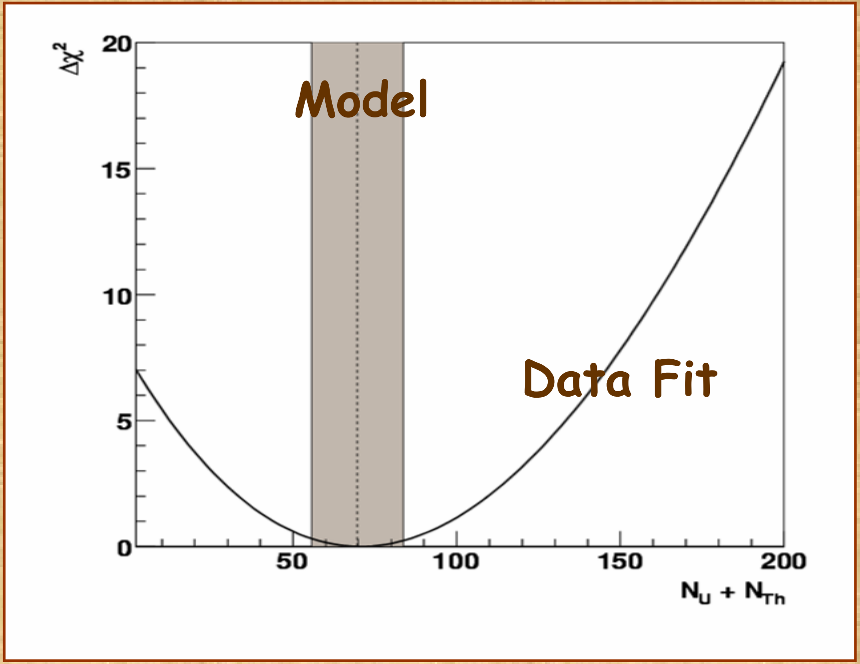
- Suggested for core (Herndon) or near Core-Mantle Boundary (Rusov and deMeijer)
- 5-10 TW could help explain heating, convection, He3 anomaly, and some isotope curiosities.
- Both models disfavored strongly by geochemists (comments from dynamo people here today?)
- Due to high neutrino energies, easily tested.
- KamLAND limit on all unknown reactors is 6.2 TW (90% C.L.) at earth center equivalent range.

What Next for Geonus?

- Measure gross fluxes from crust and mantle
- Discover or set limits on georeactors.
- Explore lateral homogeneity
- Better earth models
- Use directionality for earth neutrino tomography
- Follow the science….

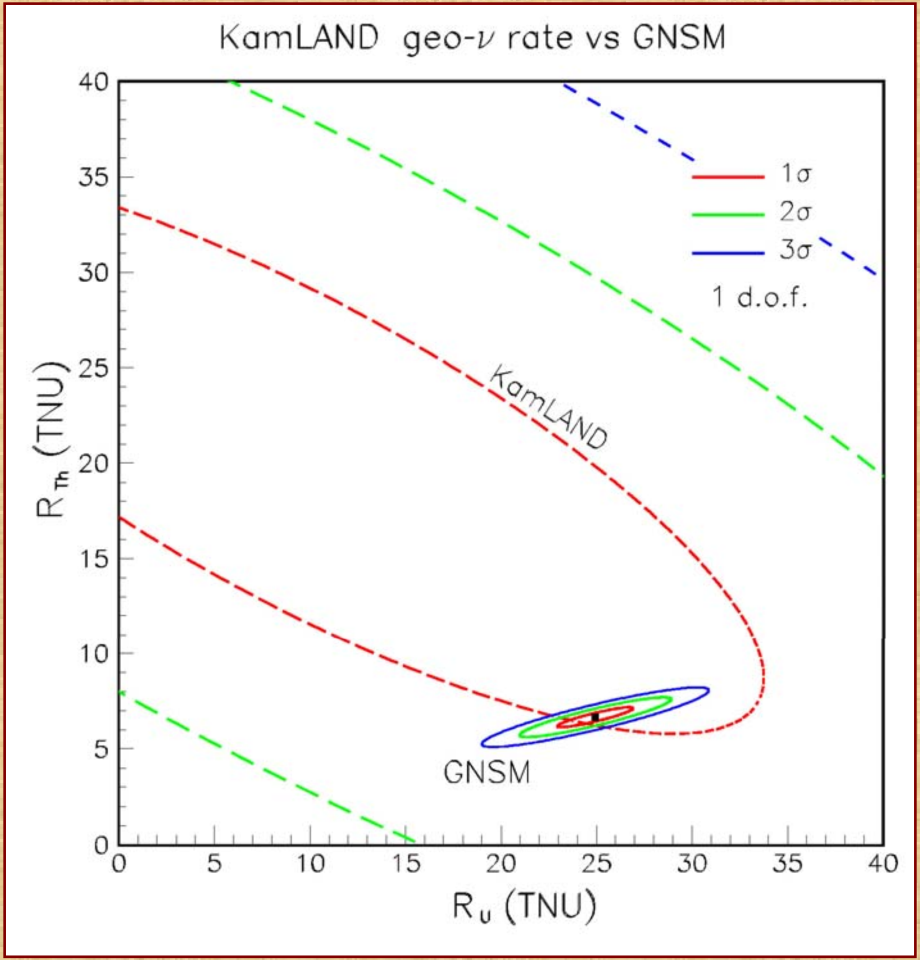
New KamLAND Results

- Fiducial Radius: 6.0 m *(but uses L-selection cut to suppress accidental backgrounds)*
- Livetime: 1491 days
- Exposure: 2.44 × 10^{32} proton-year (corresponding to 2881 ton-year)
- Energy resolution: 6.5%/ √E(MeV)
- Analysis threshold: 0.9 MeV
- Geonu flux from Enomoto *et al.* model: 16TW U+Th total
- U&Th strongly anti-correlated
- Mauve band from Enomoto geo model, shows 20% uncertainty (maybe too too small)



	Events	TNU	Flux $x10^6/cm^2s$
Model **U/Th**	**56.6** **13.1**	**29.2** **7.7**	**2.24** **1.90**
Best fit **U/Th**	**25** **36**	**12.6** **21.0**	
Fit with3.9 ratio fixed	**73±27**	**39±14**	**4.4±1.6**

Geonu Measurements: Intepretation from KamLAND data



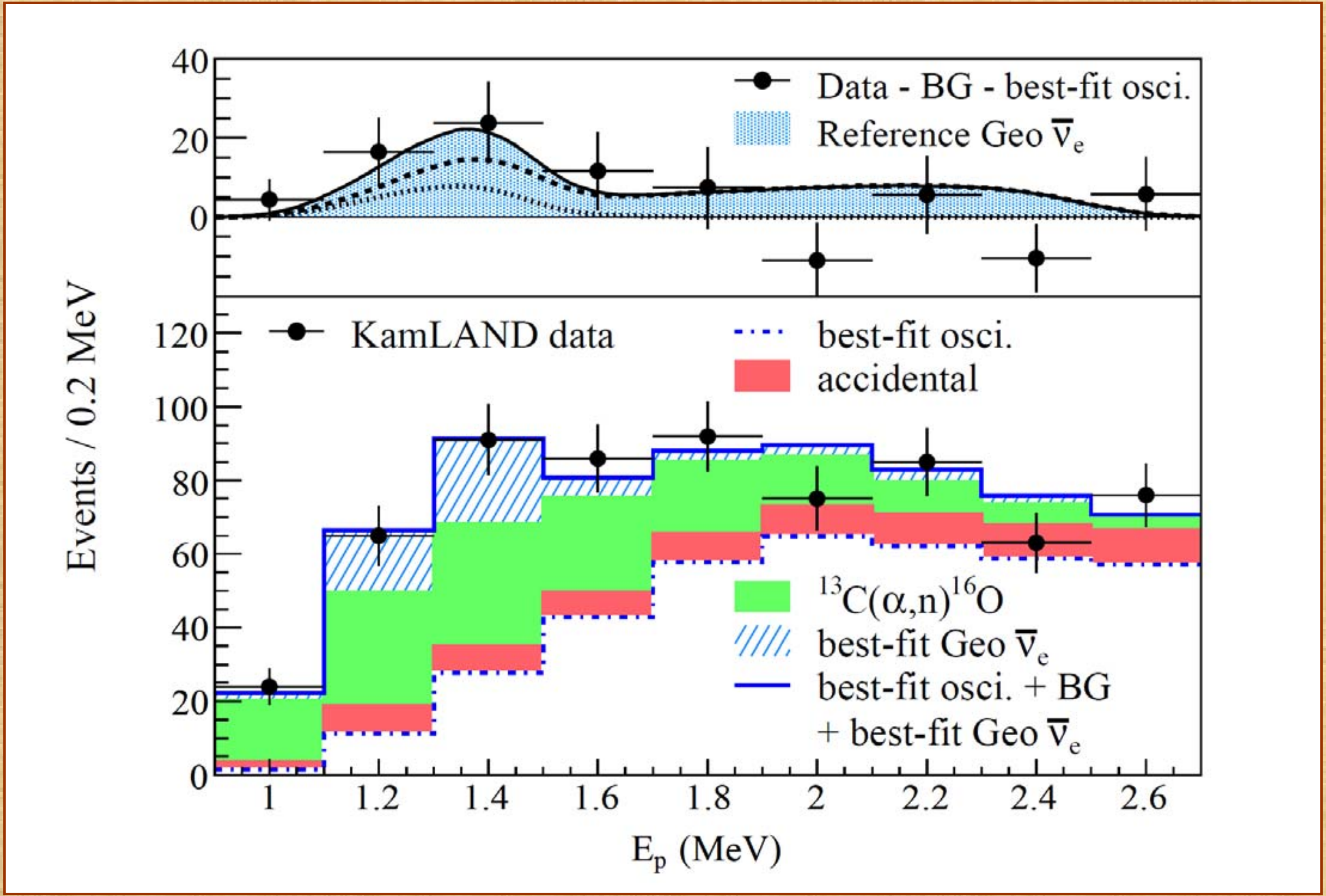
Conclusions at this time:
Data compatible with models, but does not constrain much yet, and virtually no constraints on mantle component.

G.L.Fogli, E. Lisi, A. Palazzo, and A.M. Rotunno, preprint in preparation

Thanks Eligio Lisi

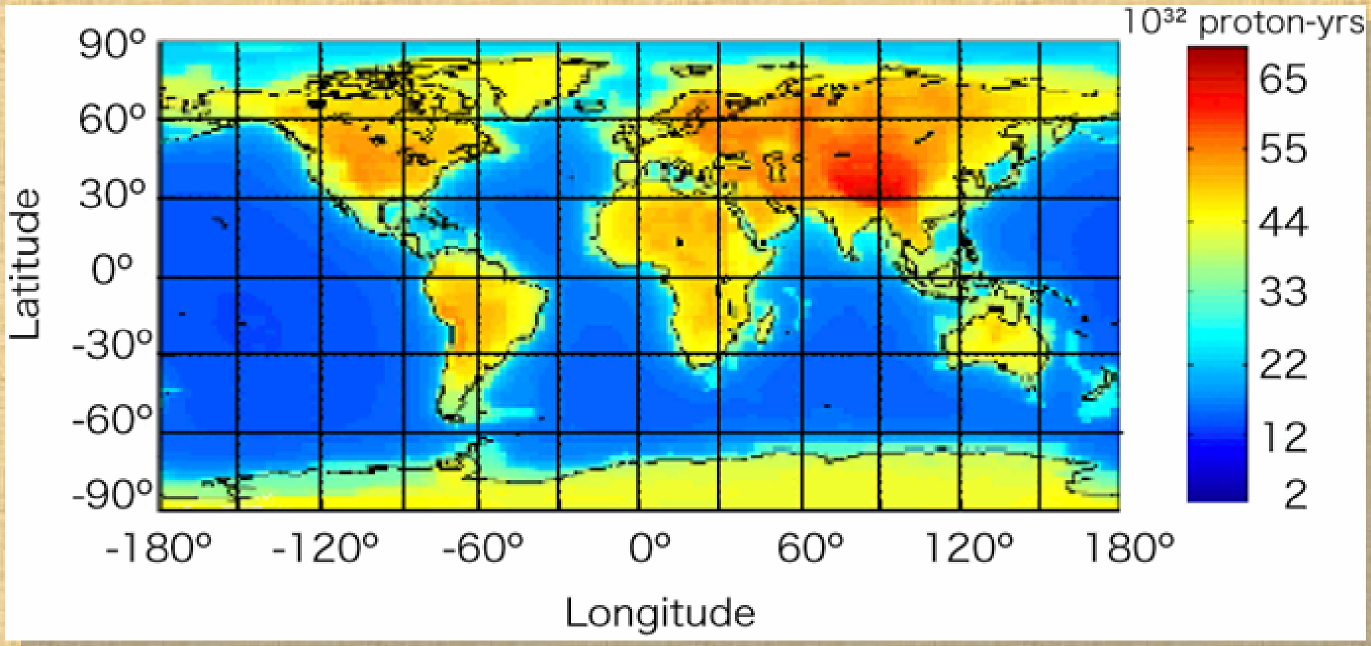
KamLAND New Results – Geonu Spectrum

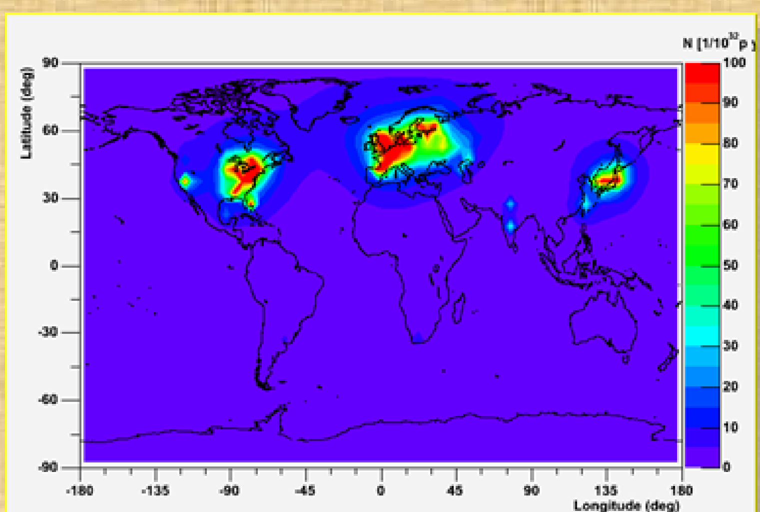
1491 day data set



Thanks Patrick Decowski

Predicted Geoneutrino Flux





Reactor Flux -
irreducible background

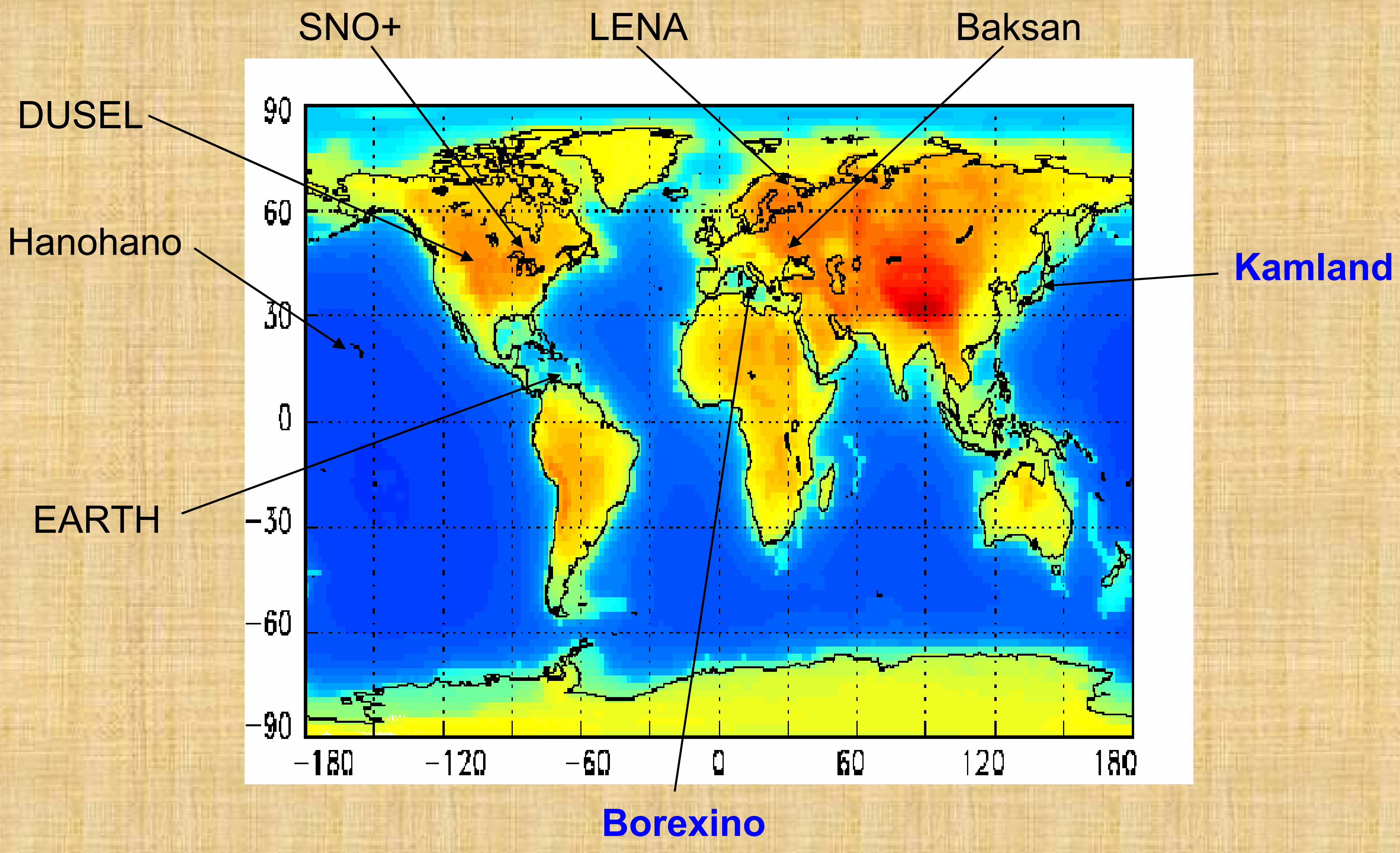
Geoneutrino flux determinations

-continental (Dusel, SNO+, LENA?)

-oceanic (Hanohano)

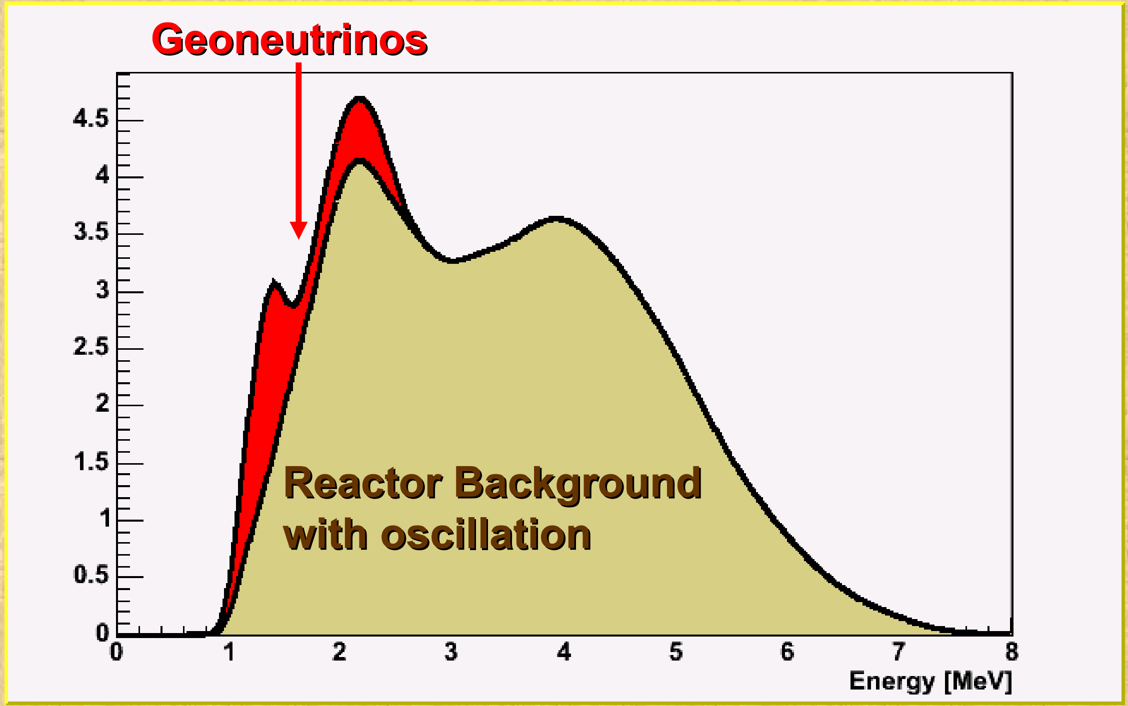
synergistic

Locations for Possible Geonu Experiments



Color indicates U/Th neutrino flux, mostly from crust

Reactor “Background”

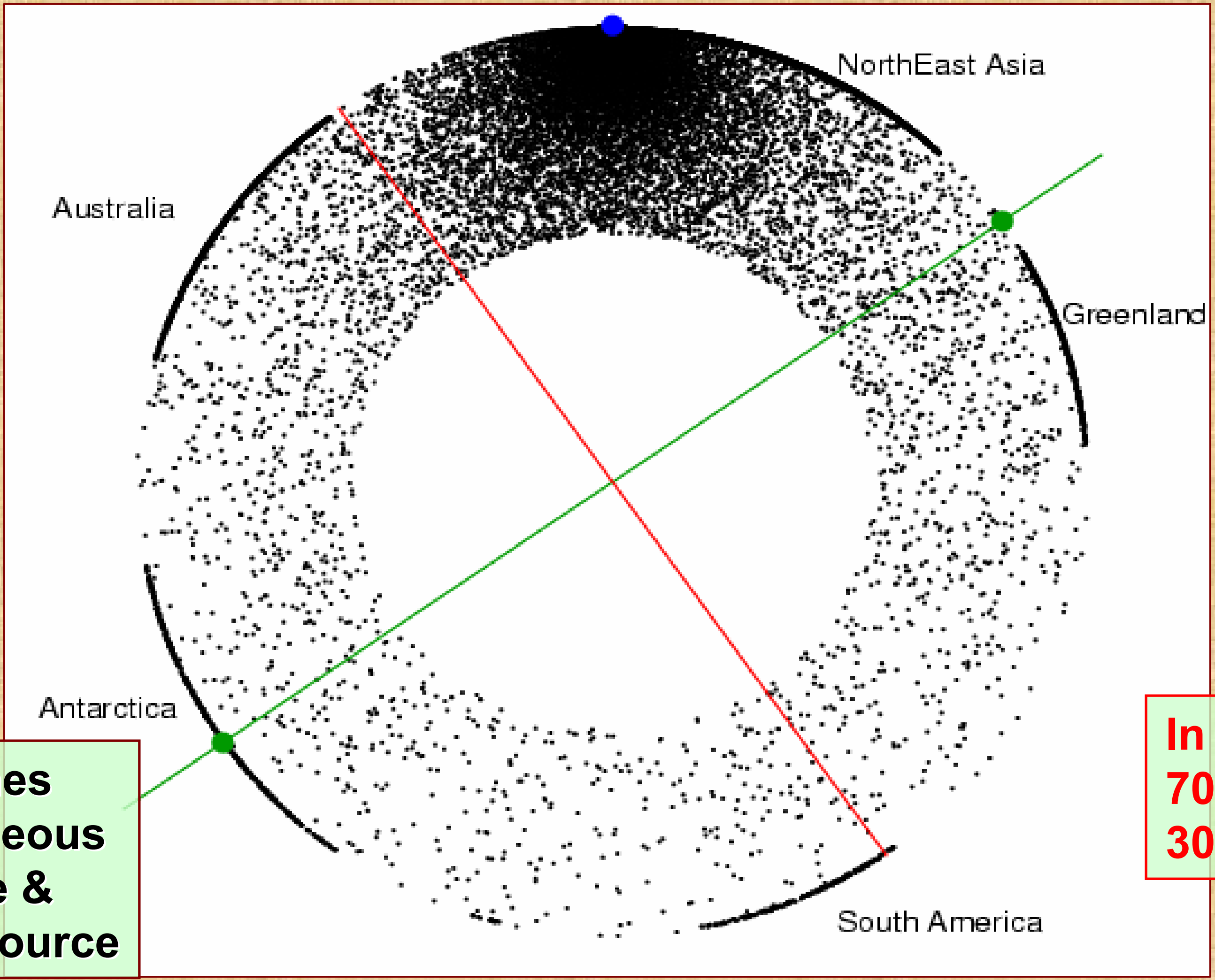


- KamLAND was designed to measure reactor antineutrinos.
- Reactor antineutrinos are the most significant background.

Simulated Geoneutrino Origination Points

KamLAND

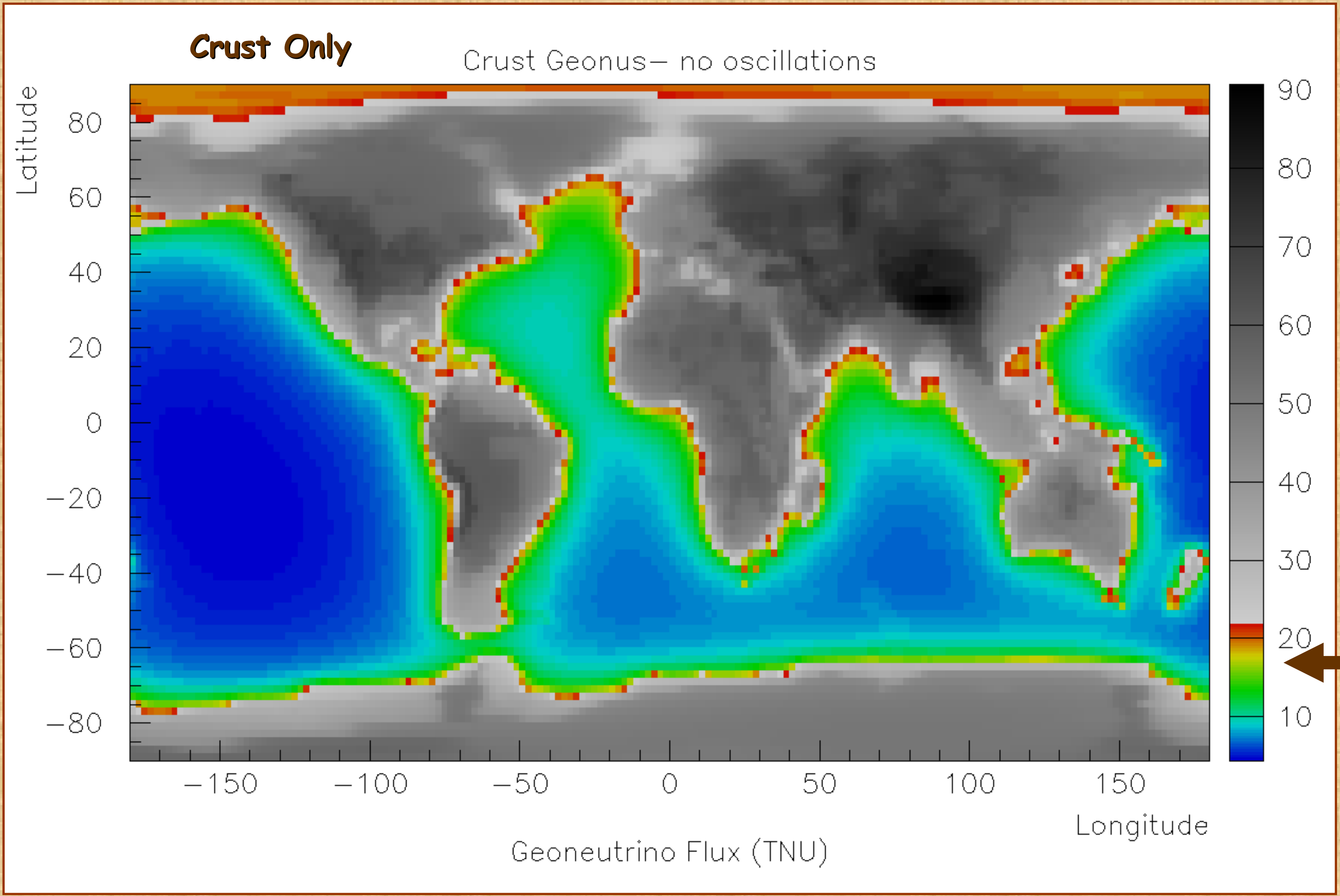
50% within 500km
25% from Mantle



Assumes homogeneous mantle & no core source

In Mid-Ocean
70% Mantle
30% Other

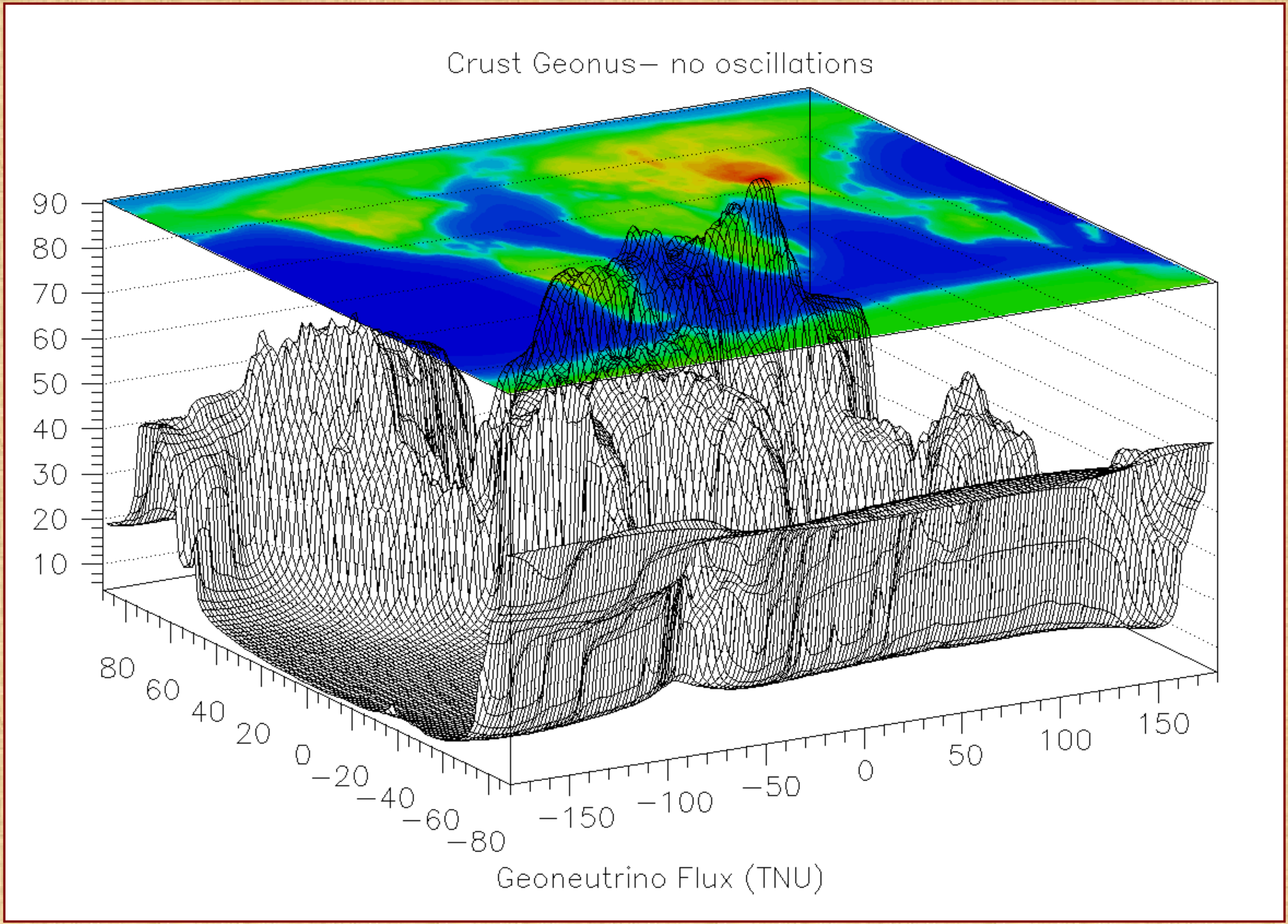
Why we need Geonu measuements in the deep ocean to measure the Mantle Contribution



Mantle Models
16-18 typical
12-39 extreme

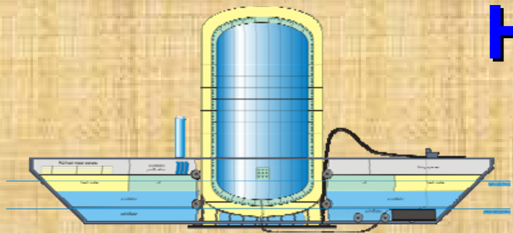
mantle

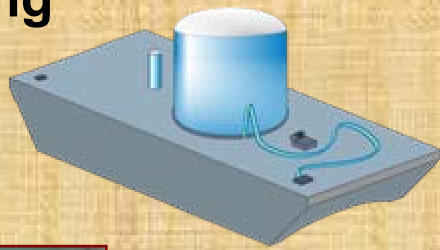
More dramatically… Why one wants to go to the ocean to measure the mantle neutrinos



Hanohano Engineering Studies

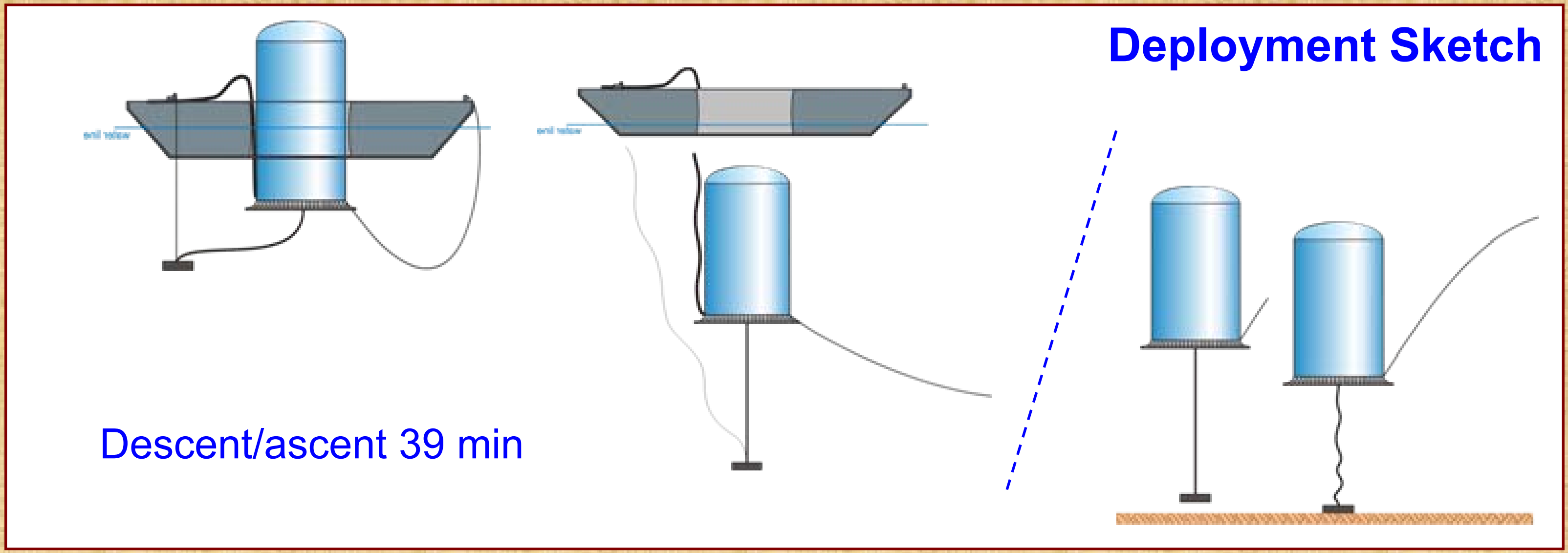
Makai Ocean Engineering





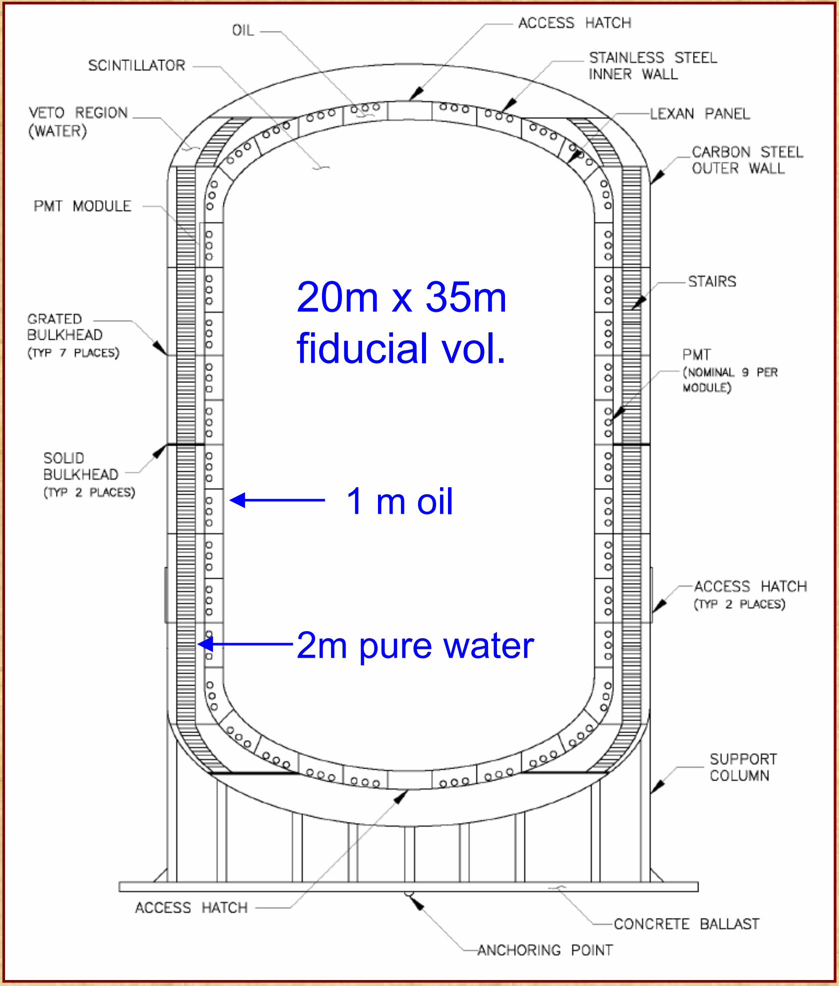
- Studied vessel design up to 100 kilotons, based upon cost, stability, and construction ease.
  - Construct in shipyard
  - Fill/test in port
  - Tow to site, can traverse Panama Canal
  - Deploy ~4-5 km depth
  - Recover, repair or relocate, and redeploy

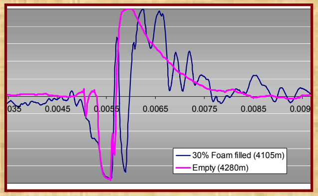
Barge 112 m long x 23.3 wide



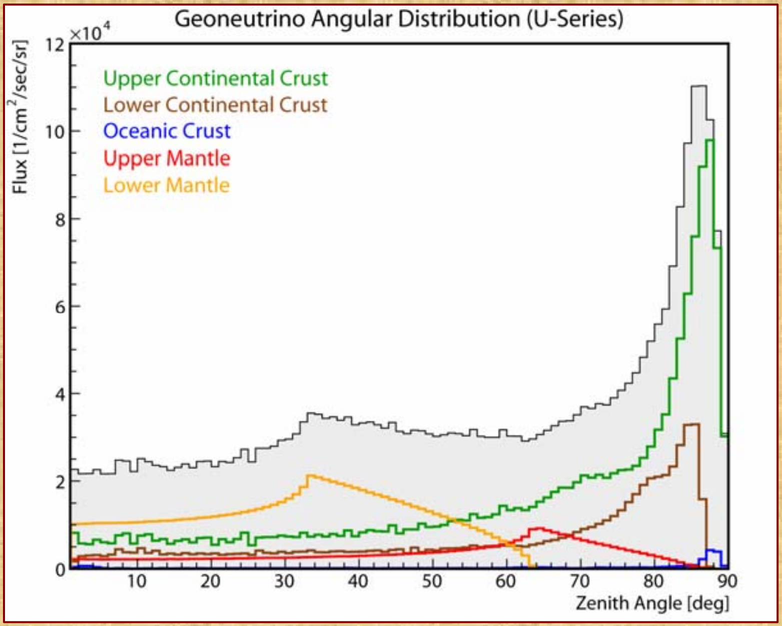
Addressing Technology Issues

- Scintillating oil studies in lab
  - P=450 atm, T=0°C
  - Testing PC, PXE, LAB and dodecane
  - No problems so far, LAB favorite… optimization needed
- Implosion studies
  - Design with energy absorption
  - Computer modeling & at sea
  - No stoppers
- Power and comm, no problems
- Optical detector, prototypes OK
- Need second round design





Future Dreams: Directional Sensitivity



Directional information provides:

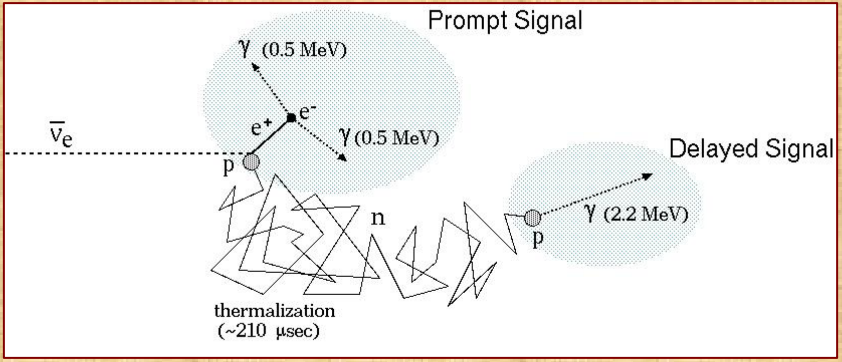
- Rejection of backgrounds
- Separation of crust and mantle
- Earth tomography by multiple detectors

Good News:

- Recoiled neutron remembers direction

Bad News:

- Thermalization blurs the info
- Gamma diffusion spoils the info
- Reconstruction resolution is too poor



Wish List:

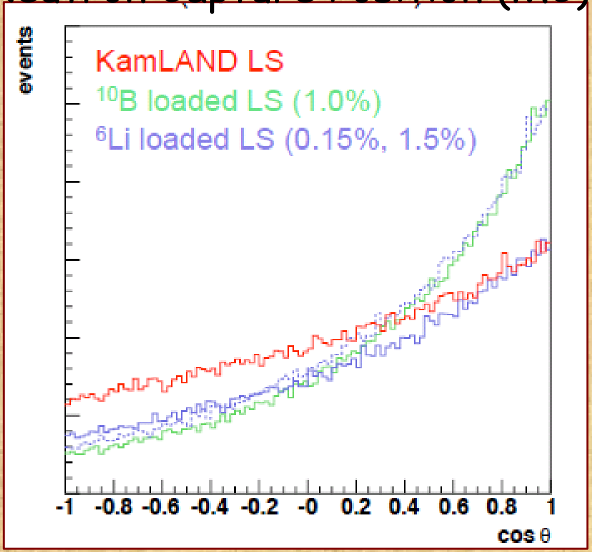
- large neutron capture cross-section
- (heavy) charged particle emission &
- good resolution detector (~1cm)

Towards Directional Sensitivity 1

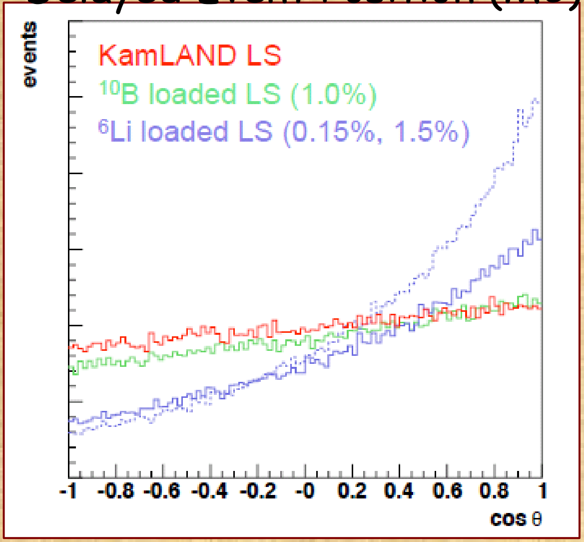
^{6}Li loading helps preserving directional information

- ^{6}Li + n → α + T : no gamma-ray emission
- Natural abundance 7.59%
- Large neutron capture cross-section: 940 barn

Neutron Capture Position (MC)



Delayed Event Position (MC)



Various chemical forms for Li loading are being tested…

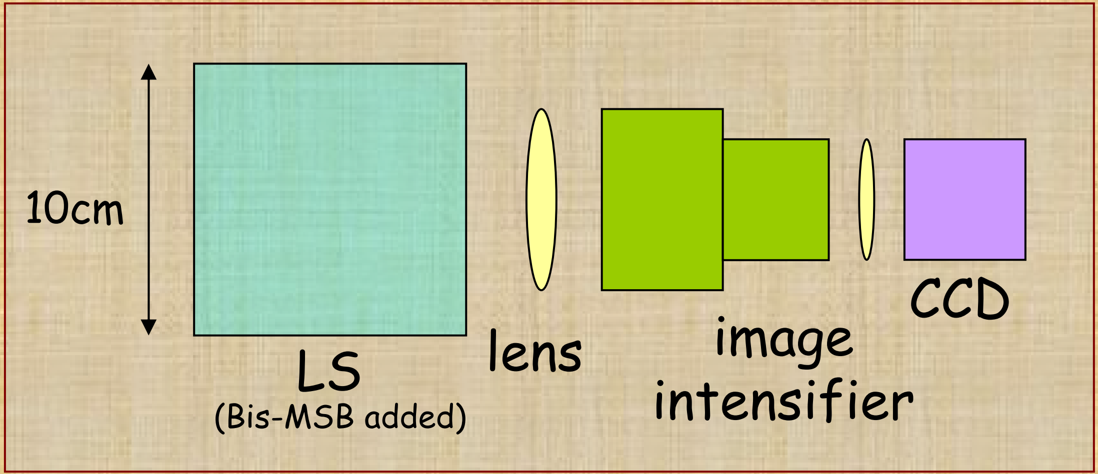
Tohoku

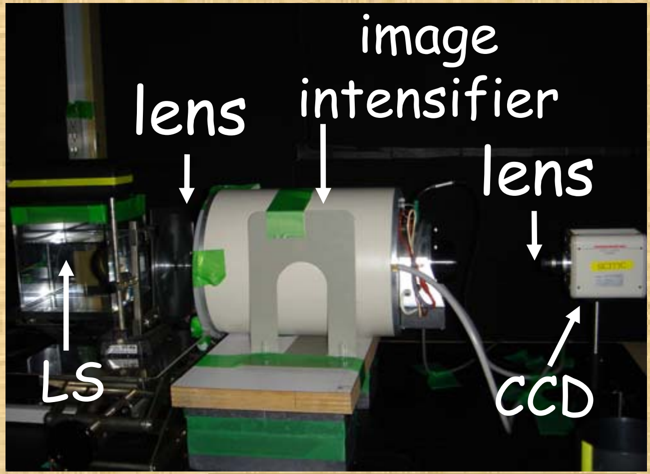
Towards Directional Sensitivity 2

~1M pixel imaging can achieve 1 cm resolution

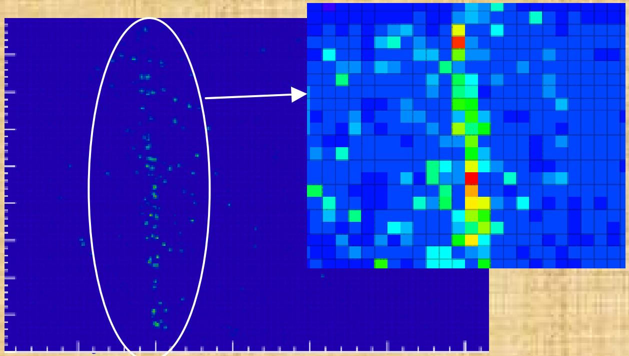
- Proper optics need to be implemented
- Sensitivity to 1 p.e. and high-speed readout required

First step for LS imaging, just started…

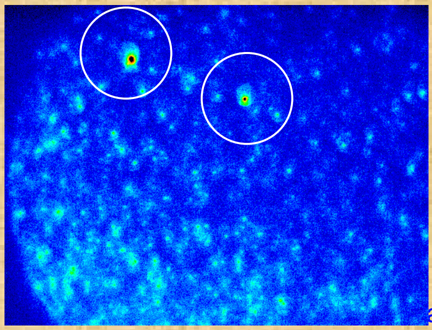




Muon Event ???

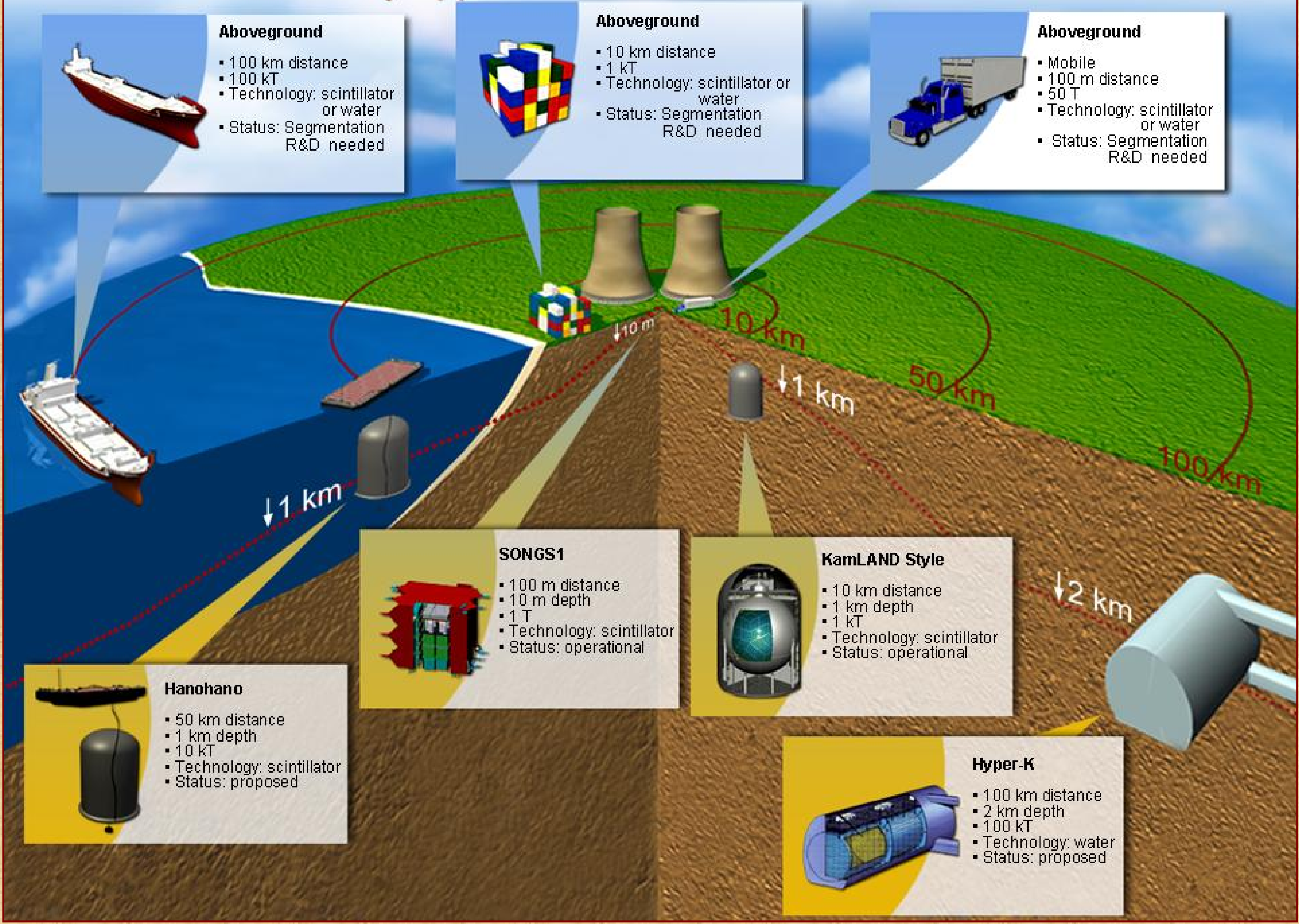


Isotope Decay Event ???



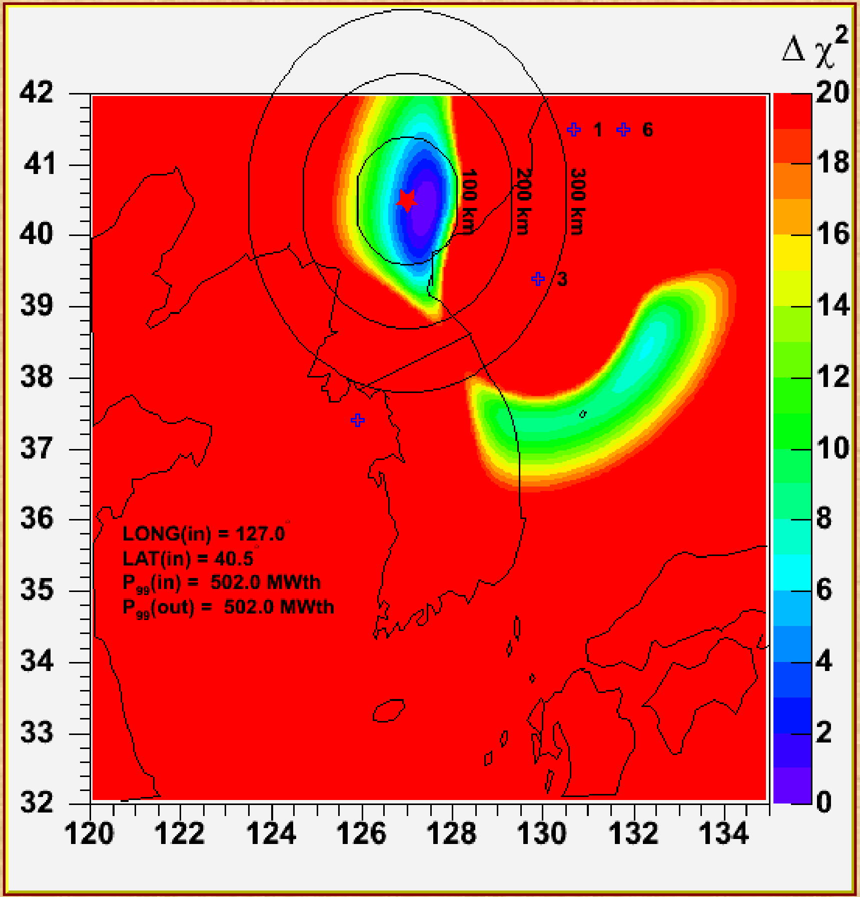
Tohoku

Security Applications for Antineutrino Detectors

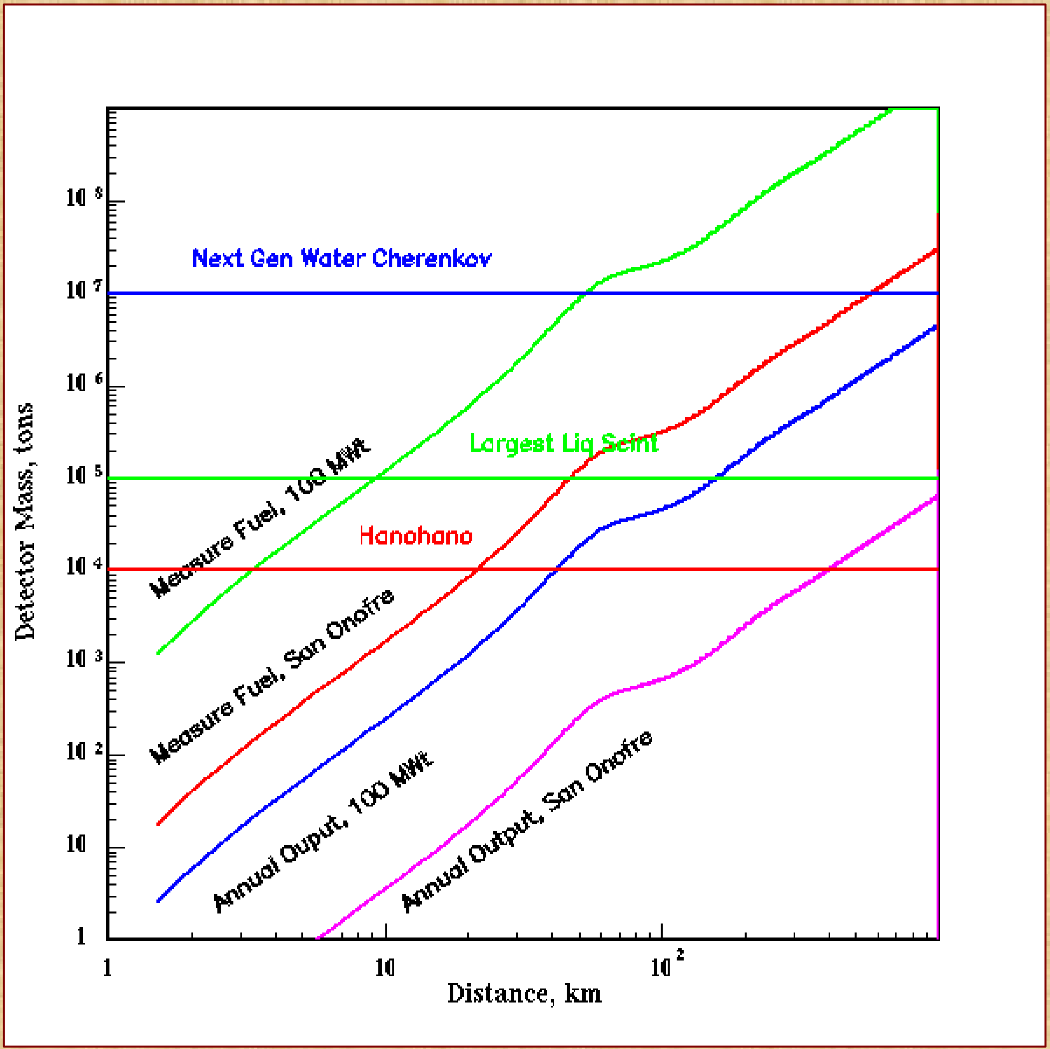


Practical Application

- Remote monitoring of nuclear reactors
- Proliferation of reactors in near future
- Need to keep track of “special materials”
- Giant neutrino detector network will help.
- Network can detect bomb tests too.

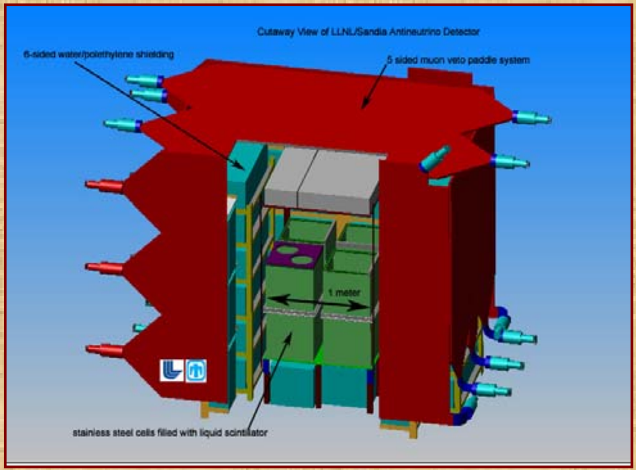


Reactor Monitoring with Anti-Neutrinos



small 100 MWt reactor
observed with 10MTdetector
- daily ops out to ~60 km
- annual output to 1000 km

D~10 m unintrusive detector
of ~ 1 ton, for IAEA?



APC Paris, France
December 13-14 2007

AAP 2007

Applied Antineutrino Physics

Applied Antineutrino Physics Workshop AAPW, Paris December 2007

- http://www.apc.univ-paris7.fr/AAP2007/
- 65 participants, much interest in neutrino reactor monitoring, including IAEA people.
- Very good meeting… much enthusiasm for neutrino monitoring of reactors, close to far.

Neutrino Monitoring Workshop, U. Maryland, 3-5 January 2008

- Brought together representatives from academe, nuclear monitoring community and intelligence community.
- Discussed future potential of nuclear reactor and bomb monitoring near and far.
- White paper produced making case for large scale, interdisciplinary National Antineutrino Science Center, as well as specific projects.
- Hanohano endorsed as flagship project, not to wait for NASC.

Summary of Expected Results

Hanohano- 10 kt-1 yr Exposure

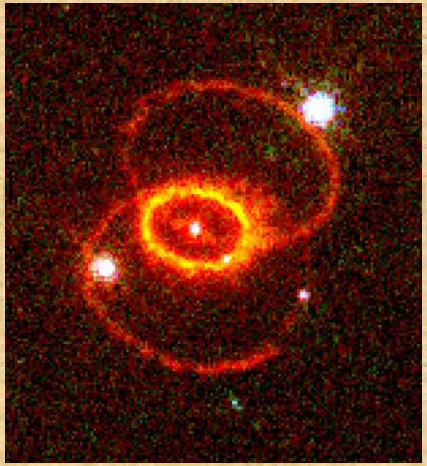
- **Neutrino Geophysics- near Hawaii**
  - Mantle flux U geoneutrinos to ~10%
  - Heat flux ~15%
  - Measure Th/U ratio to ~20%
  - Rule out geo-reactor if P>0.3 TW
- **Neutrino Oscillation Physics- ~55 km from reactor**
  - Measure $\sin^2(\theta_{12})$ to few % w/ standard ½-cycle
  - Measure $\sin^2(2\theta_{13})$ 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; complementary to Minos, Nova
  - **Lots to measure even if $\theta_{13}=0$**

- **Much other astrophysics and nucleon decay too….**

Additional Physics/Astrophysics

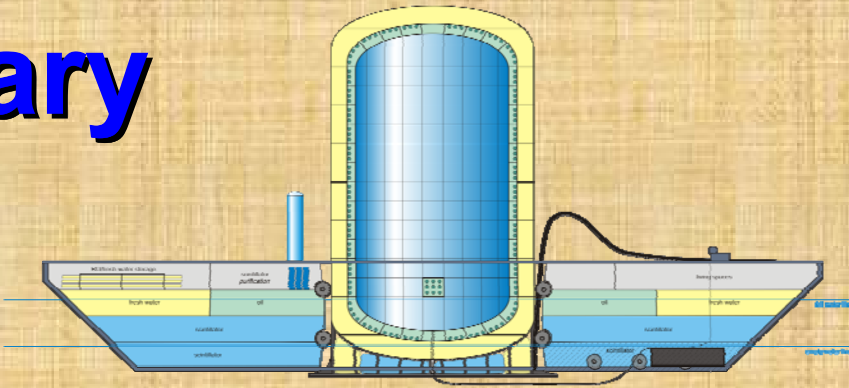
Hanohano will be biggest low energy neutrino detector (except for maybe LENA)

- **Nucleon Decay: SUSY-favored kaon modes**
- **Supernova Detection: special ν_e ability**
- **Relic SN Neutrinos**
- **GRBs and other rare impulsive sources**
- **Exotic objects (monopoles, quark nuggets, etc.)**
- **Long list of ancillary, non-interfering science, with strong discovery potential**

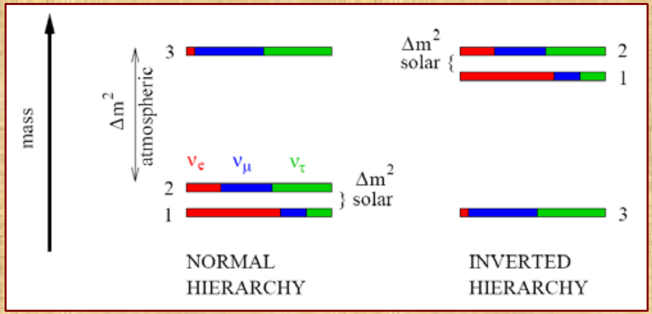


Broad gauge science and technology, a program not just a single experiment.

Hanohano Summary

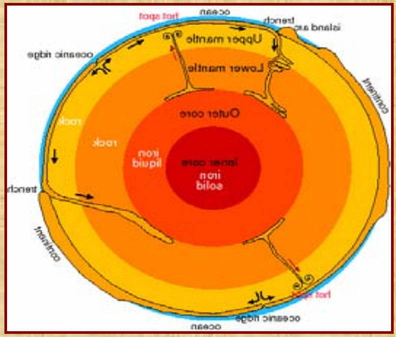


- **Proposal for portable, deep-ocean, 10 kiloton, liquid scintillation electron anti-neutrino detector.**



- **Transformational geophysics, geochemistry, particle physics and astrophysics: answers to key, big questions in multiple disciplines. Enormous discovery potential.**

- **Program under active engineering, Monte Carlo simulations, and studies in laboratory and at sea.**



- **Collaboration formed, aimed at decade or more multi-disciplinary program between physics and geology. Open to more collaborators.**

- **Future, much science and many applications for low energy neutrino detection with huge instruments.**