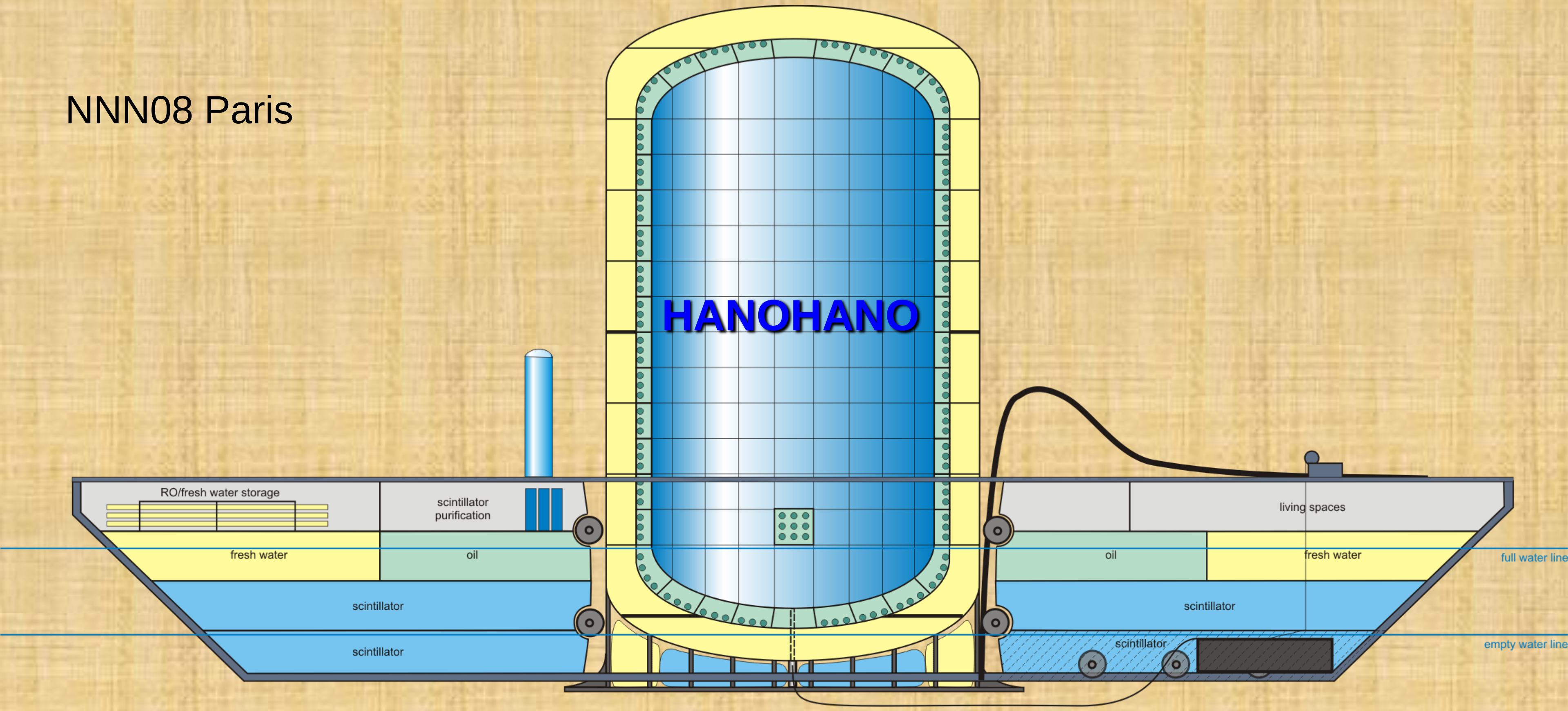
New Directions in Neutrino Research: Mobile Detectors for Geology, Neutrino Mixing and Mass Measurements, and Nonproliferation

NNN08 Paris



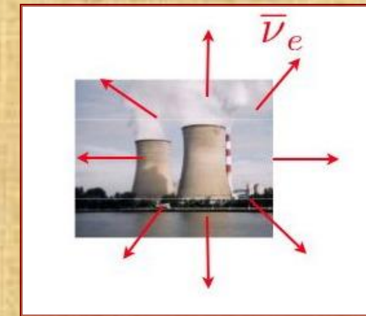
Robert C. Svoboda, *University of California at Davis*

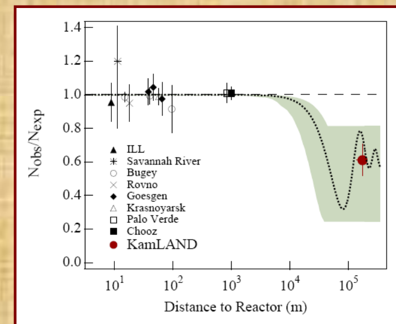
(for John Learned plus colleagues at UH and elsewhere)

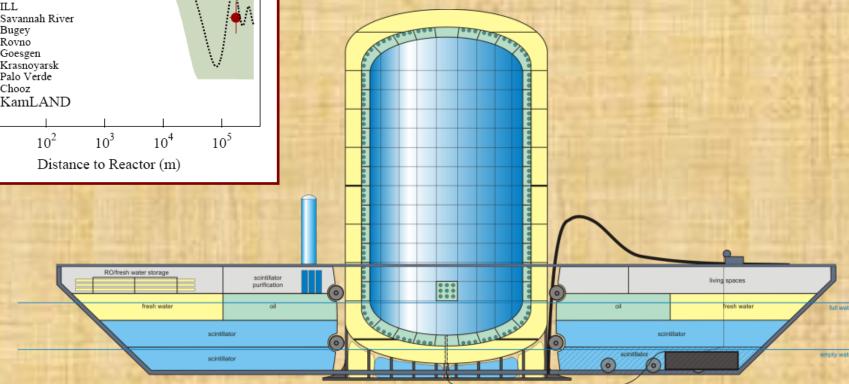
(HANOHANO consists of about 20 institutions, collaboration not yet official, including U. Tohoku, U. Maryland, U. Alabama, Stanford, Caltech, UC Davis, U. Munich, and more)

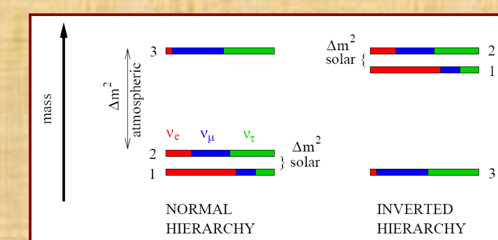
Outline

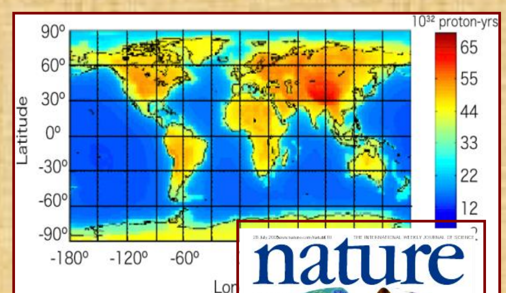
- **Neutrino Oscillation Physics**
  - Review KamLAND results
  - Mixing angles θ_{12} and θ_{13}
  - Mass squared difference Δm^2_{31}
  - Mass hierarchy
- **Neutrino Geophysics**
  - U & Th mantle flux
  - Th/U ratio
  - Georeactor search
- **Hanohano:**
  - Deep ocean: measure mantle neutrinos
  -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

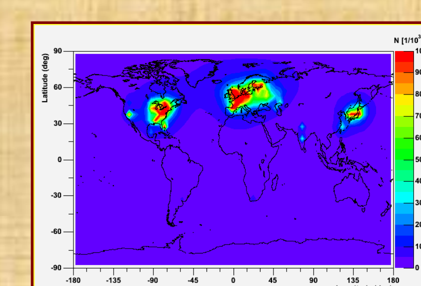








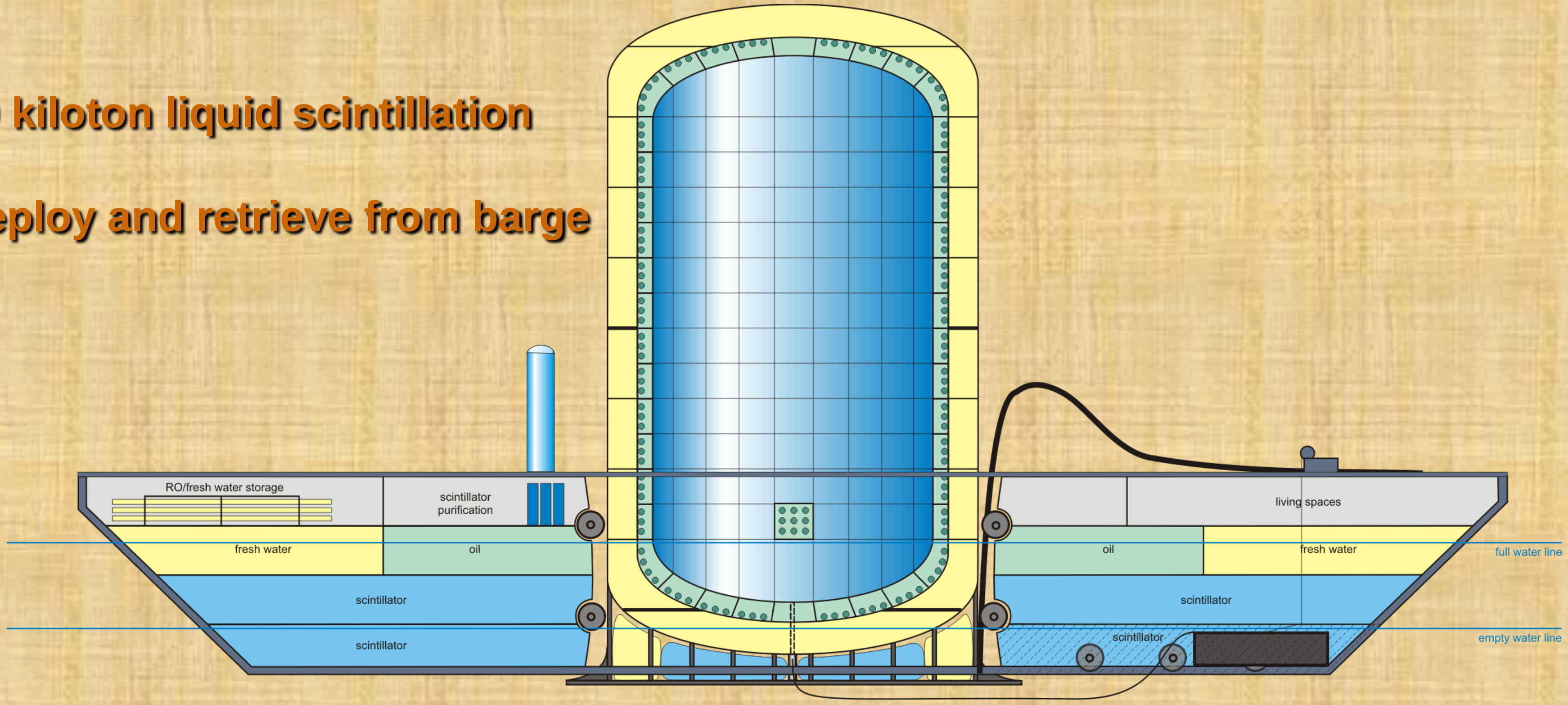


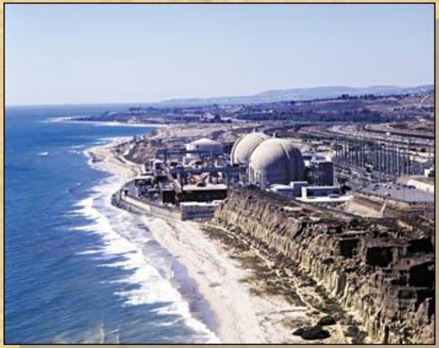


Hanohano
a mobile deep ocean detector

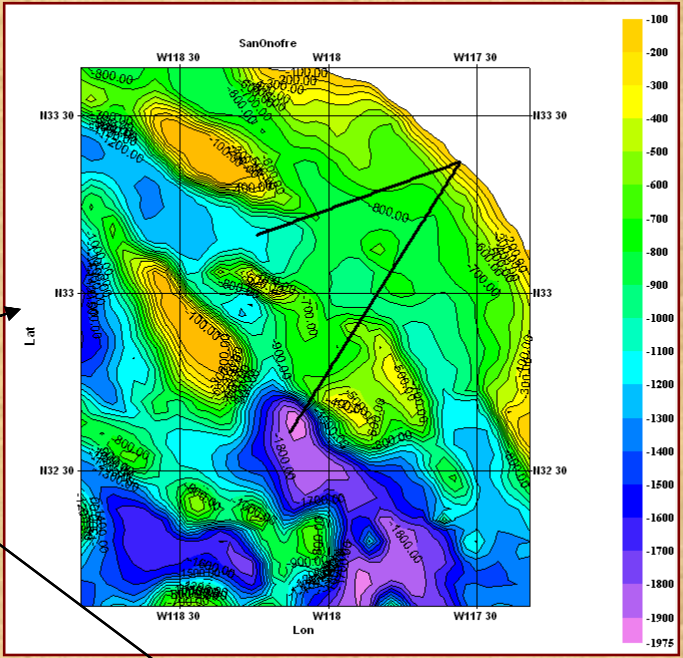
10 kiloton liquid scintillation

Deploy and retrieve from barge

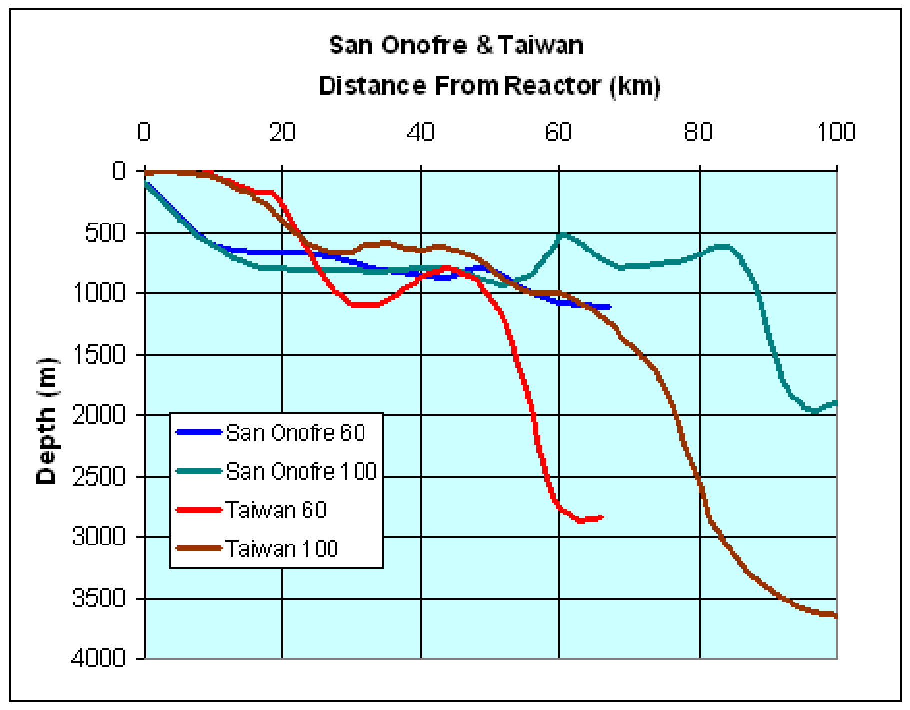


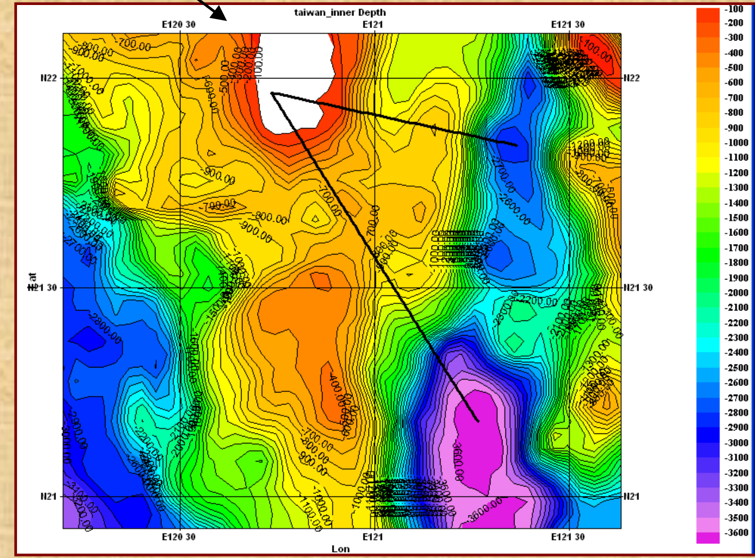


2 Candidate Off-shore Sites for Physics



San Onofre, California- ~6 GW_{th}
Maanshan, Taiwan- ~5 GW_{th}





Need study of backgrounds versus depth

Neutrino Oscillation Physics with Hanohano

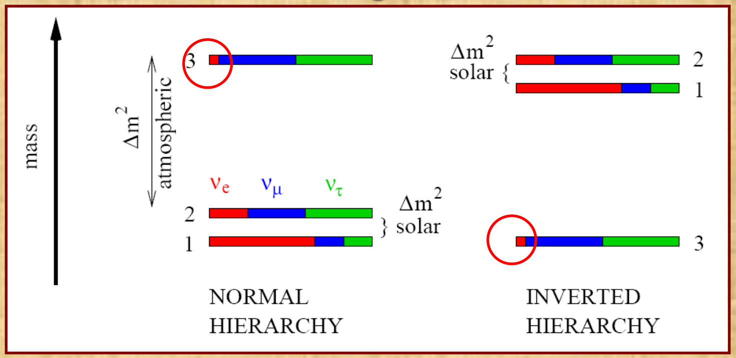
- **Precision measurement of mixing parameters needed**
  (4 of 5 in Hanohano)

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

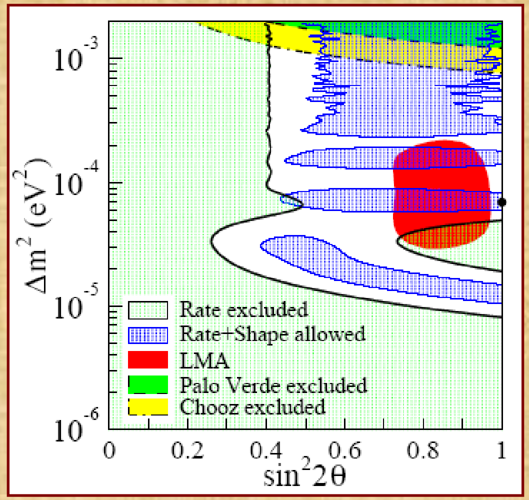
- **Determination of mass hierarchy**
  (Hanohano novel method)

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

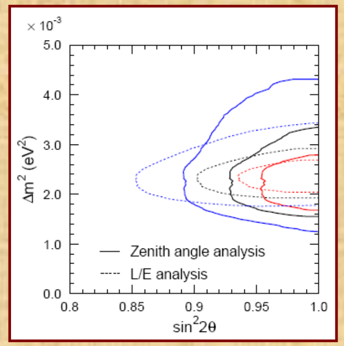
MNSP Mixing Matrix



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

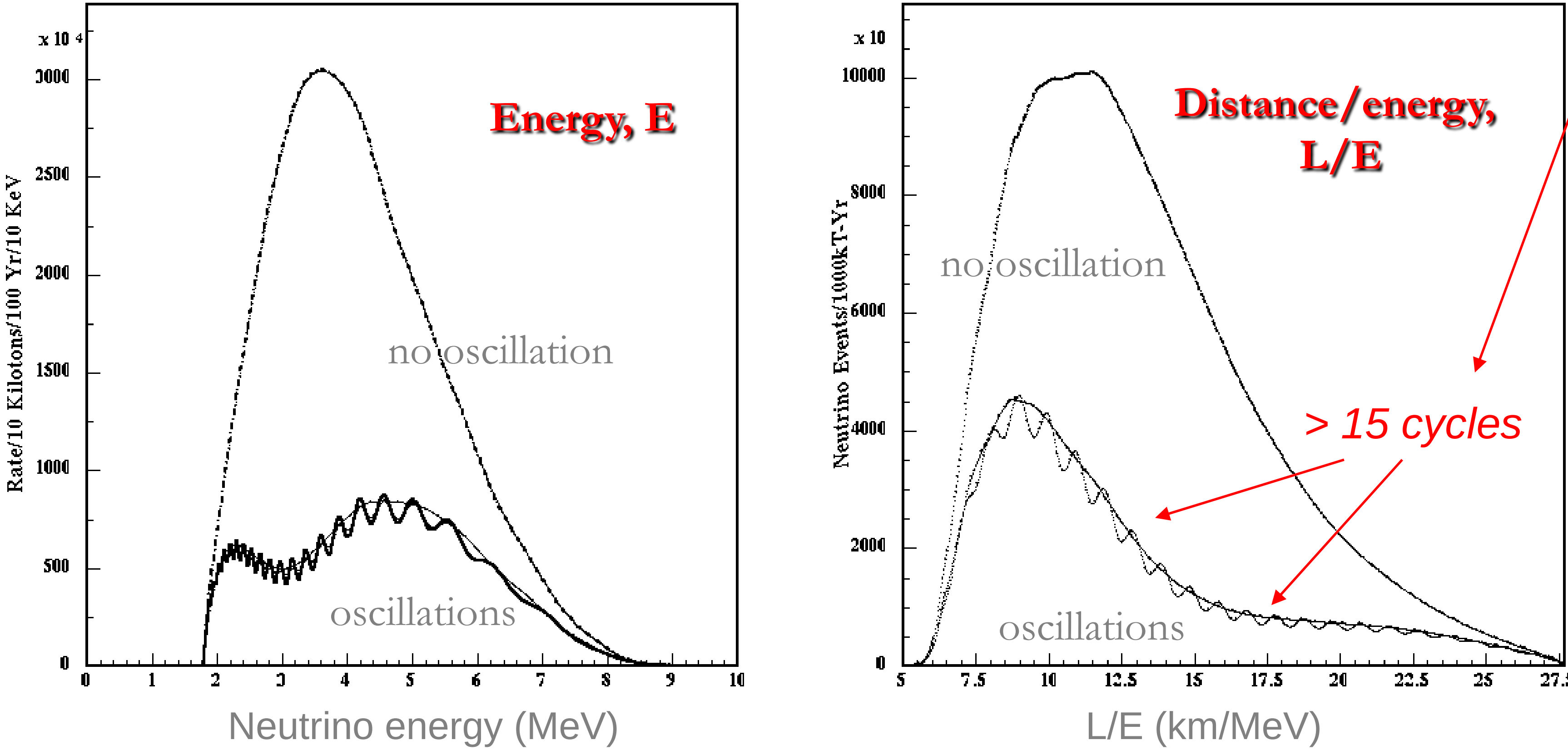
- Multi-cycle measurements can yield
  - Mixing angles, precise mass-squared differences
  - Mass hierarchy
  - **Less sensitivity to systematic errors**

Reactor ν_e Spectra at 50 km

~4400 events per year from San Onofre

Fitting will give improved θ_{12}

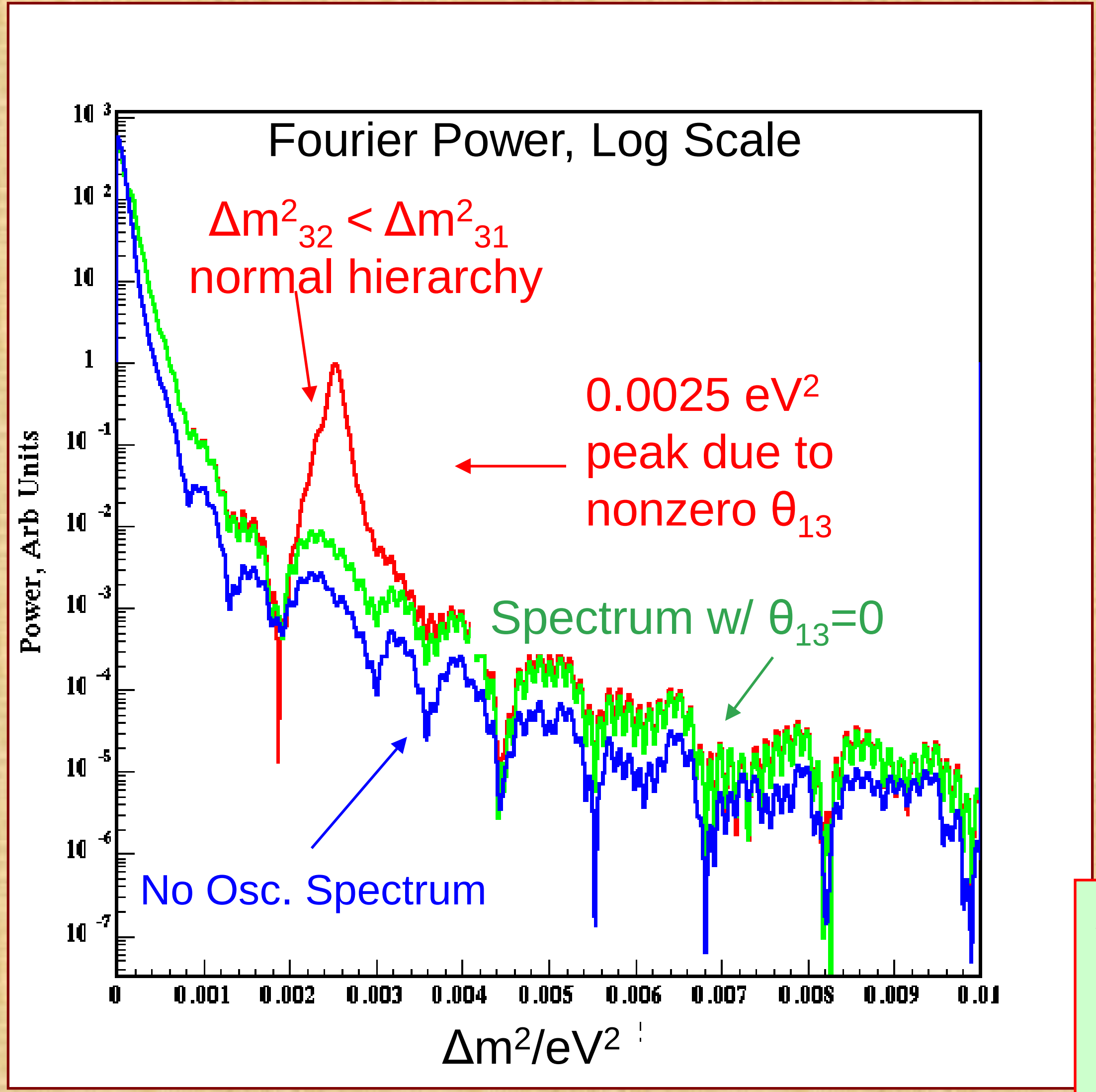
invites use of Fourier Transforms



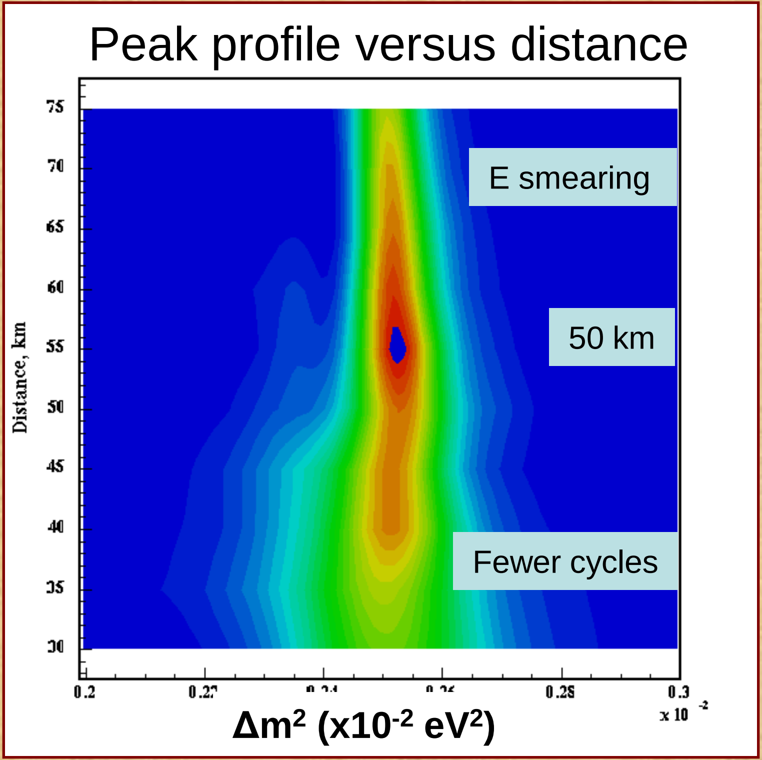
1,2 oscillations with $\sin^2(2\theta_{12})=0.82$ and $\Delta m^2_{21}=7.9\text{x}10^{-5}\ \text{eV}^2$

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

Fourier Transform on L/E to Δm^2



Includes energy smearing



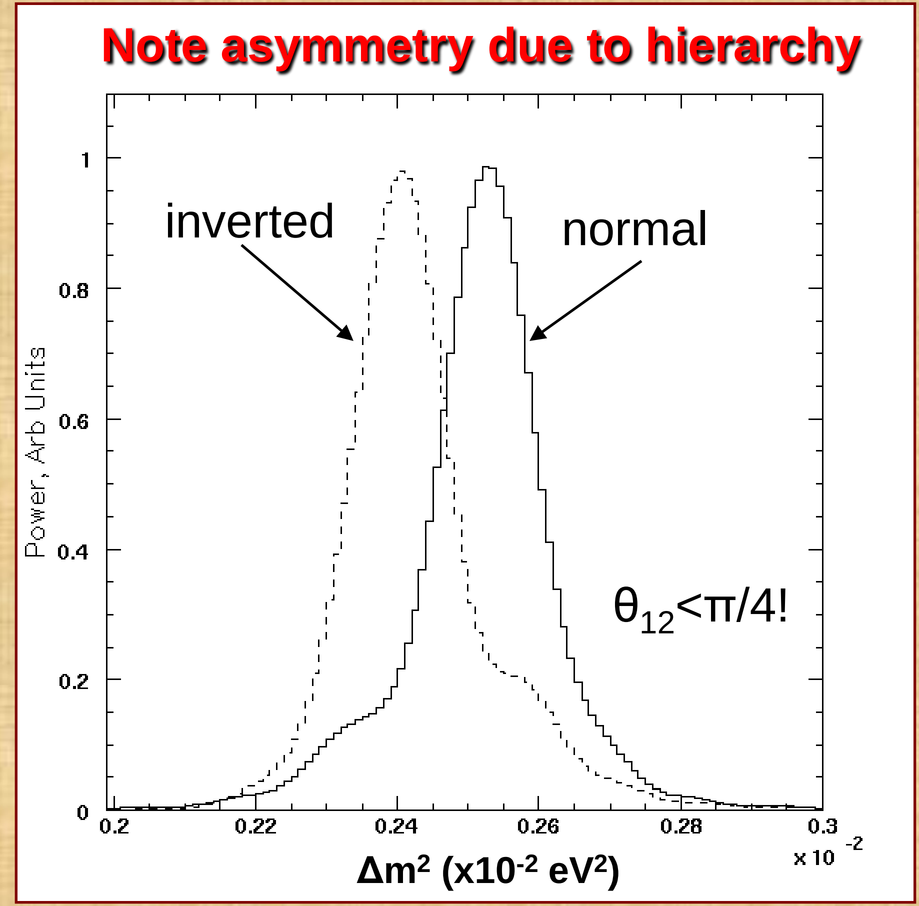
50 kt-y exposure at 50 km range

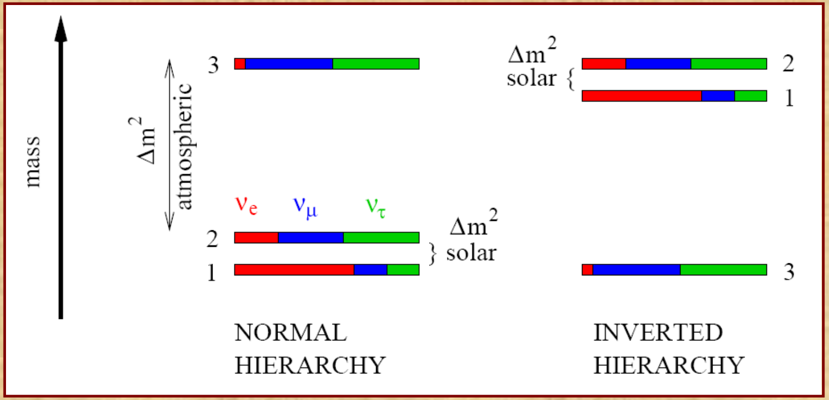
$\sin^2(2\theta_{13}) \geq 0.02$

Δm^2_{31}=0.0025 eV^2 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

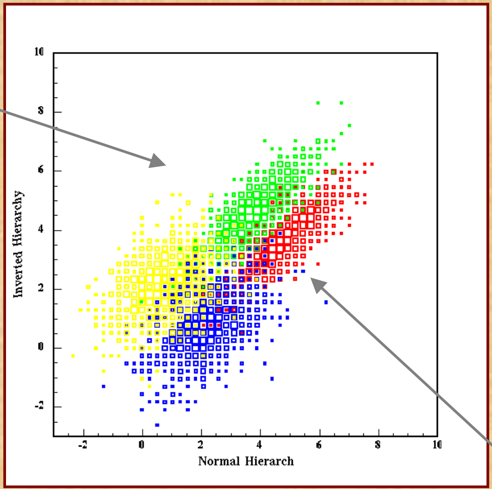
Learned, Dye, Pakvasa, and Svoboda, *hep-ex/0612022*

Hierarchy Determination

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

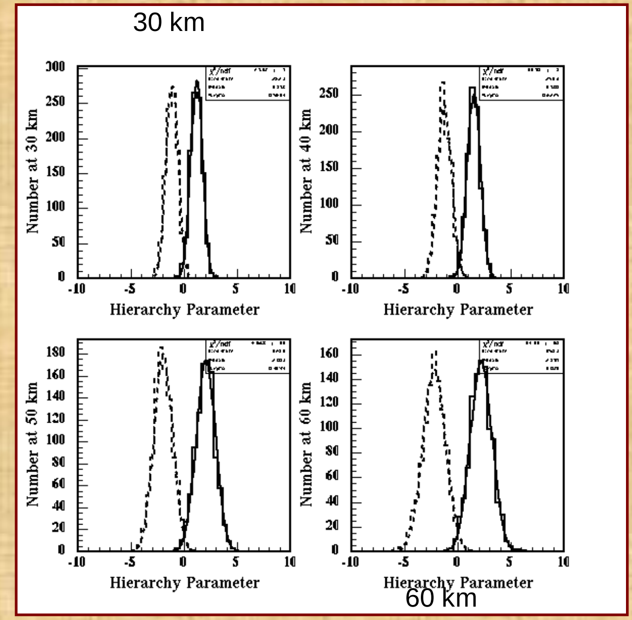
Distance variation: 30, 40, 50, 60 km

Inverted hierarchy



Normal Hierarchy

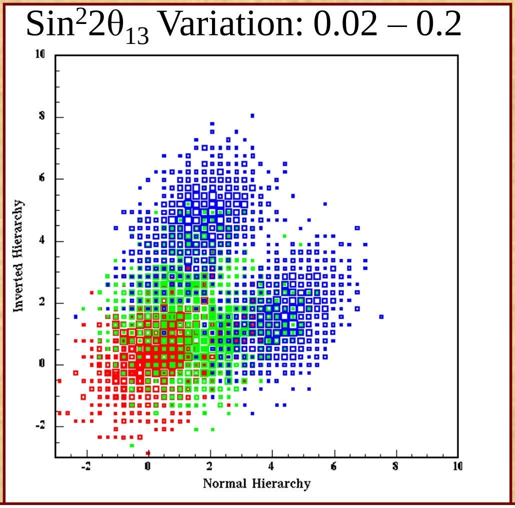
Hierarchy tests employing Matched filter technique, for Both normal and inverted hierarchy on each of 1000 simulated one year experiments using 10 kiloton detector.



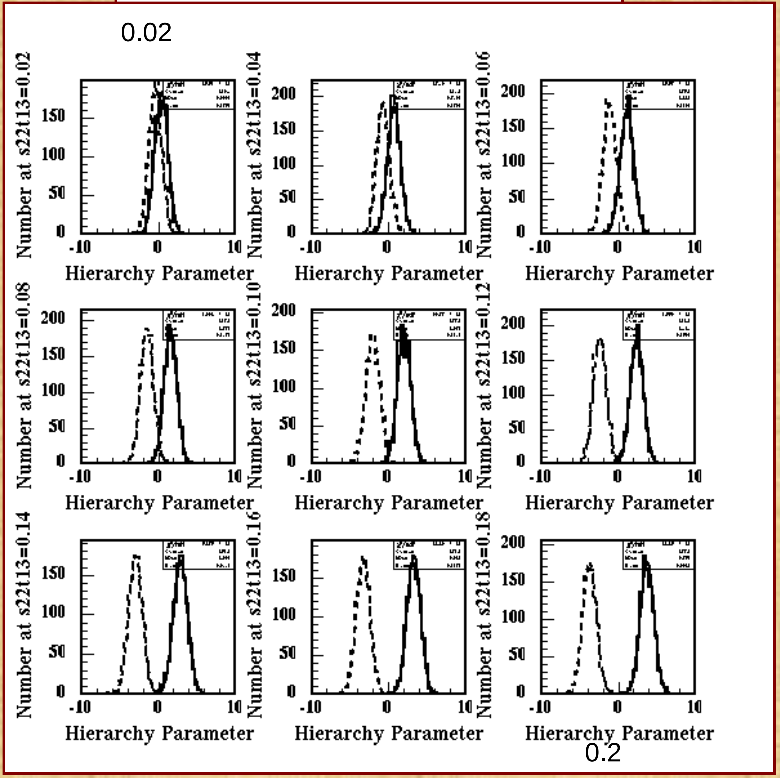
1000 kt-yrs separates even at 0.02

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

Inv.



Norm.

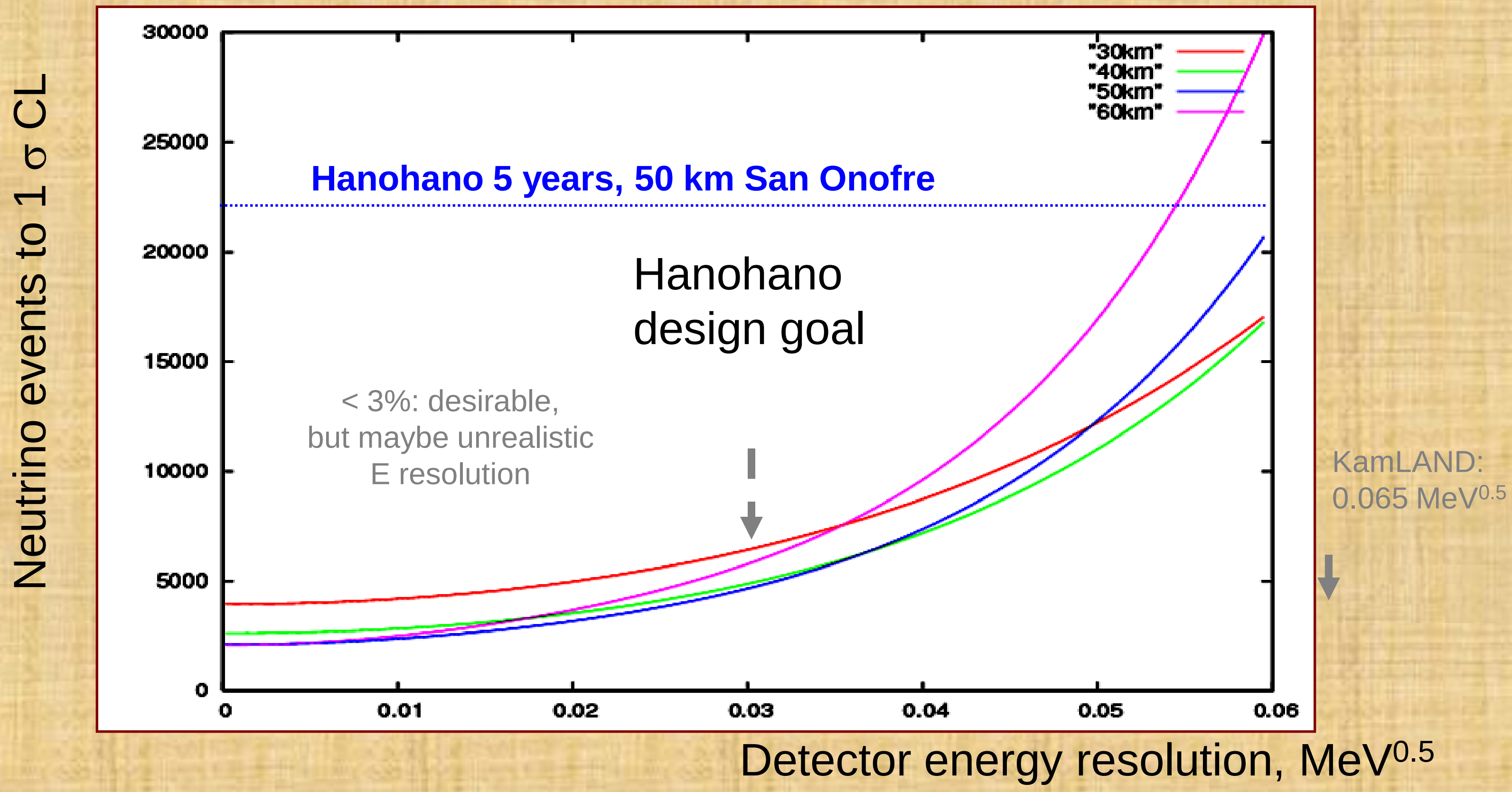


New Hanohano Physics Simulation

- Main points of full maximum Liklihood treatment
  - 10 kt detector, 5MWt power plant, same scint. as KamLAND
  - Systematics considered:
    - "general efficiency": fiducial volume, number of protons, eff. of cuts, etc.
    - error in detector resolution estimation.
  - Systematics ignored at this point:
    - overall energy scale error
    - background uncertainties
- Conclusions: different optimal baselines for different measures, but confirm earlier calculations with Fourier methods.

Calculations my Misha Batygov at UH, paper out soon.

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

Big picture questions in Earth Sci

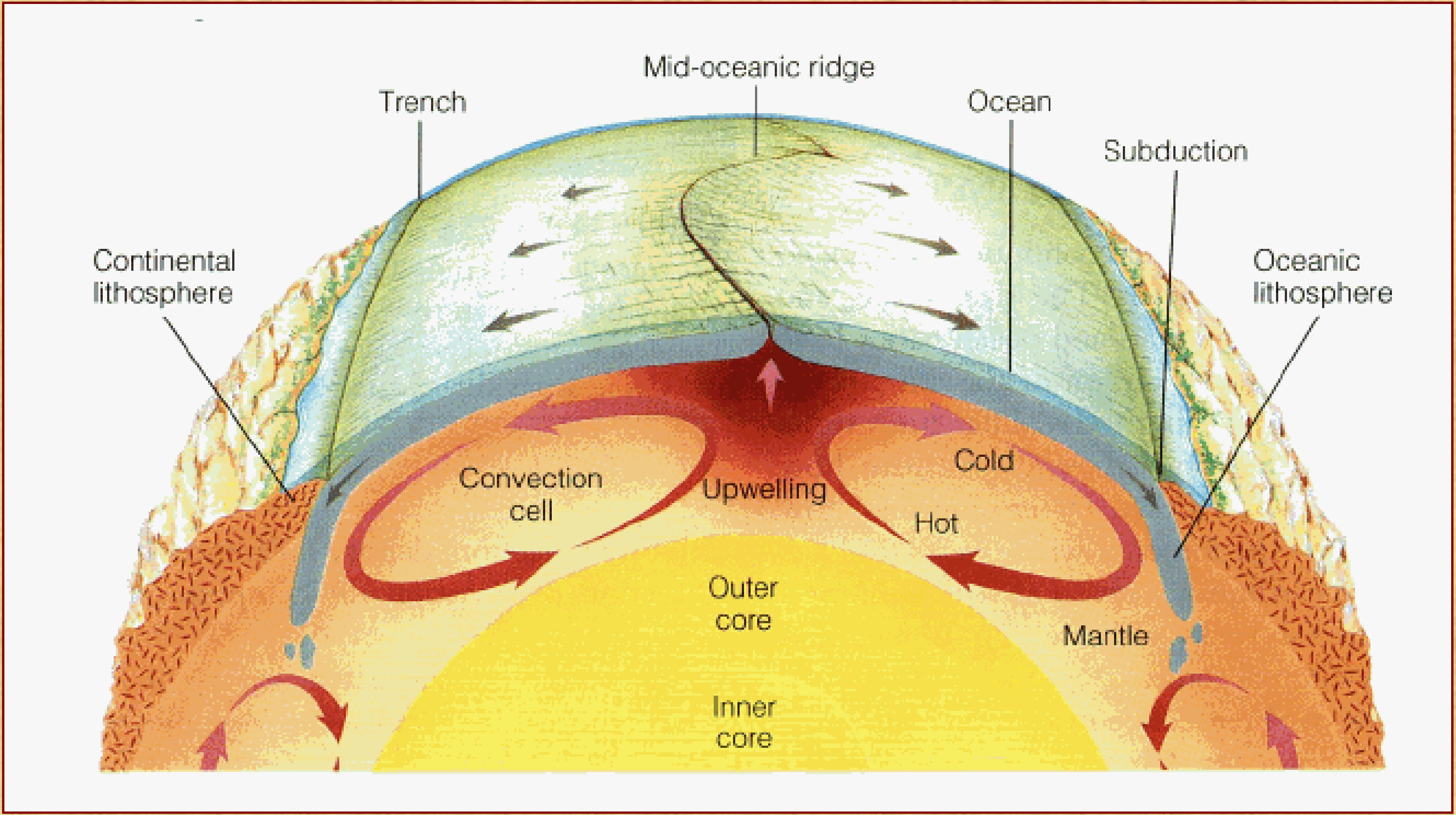
What drives **plate tectonics**?

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

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

Energy source driving the **Geodynamo**?

Convection in the Earth

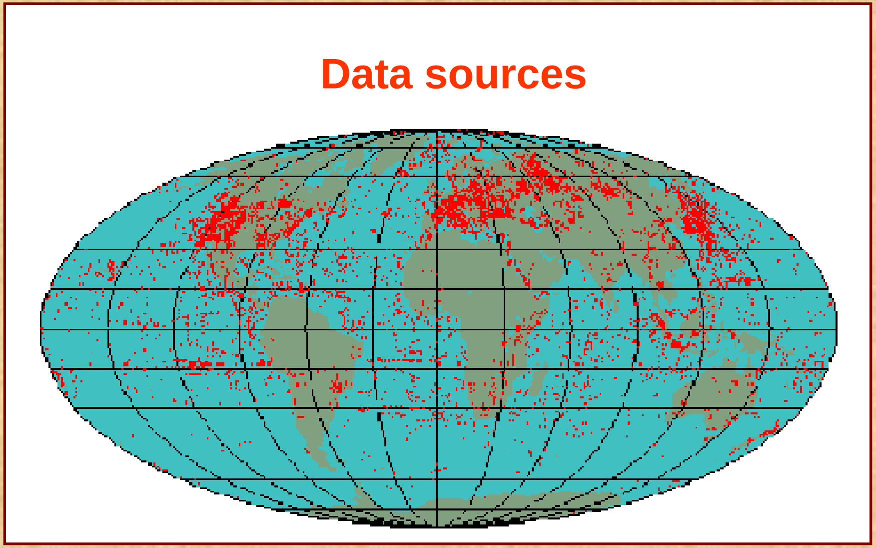


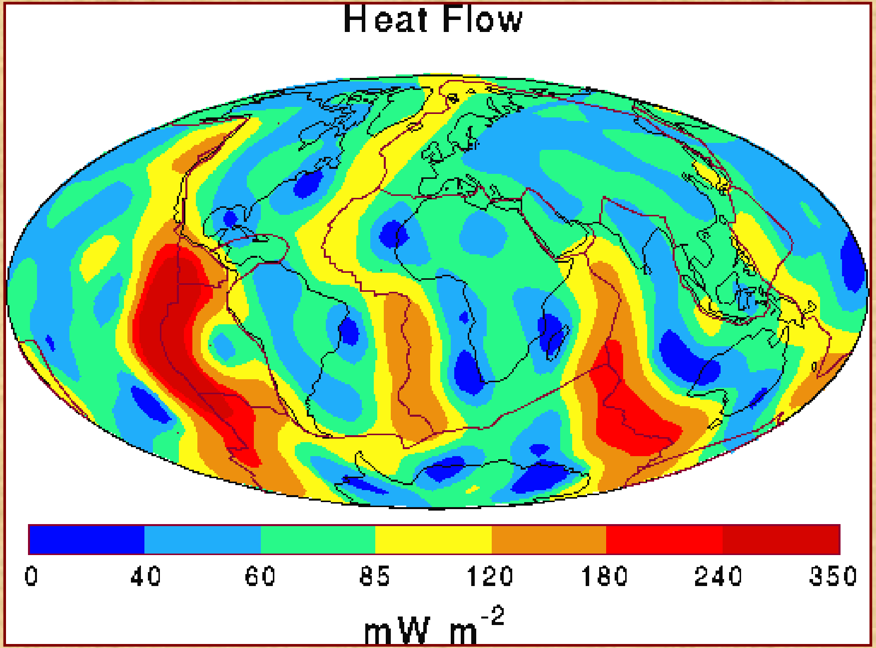
- **The mantle convects.**
- **Plate tectonics operates via the production of oceanic crust at mid-ocean ridges and it is recycled at deep sea trenches.**

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

Inconsistent results {
- Heat flow measurements
- Geochemical modeling

- Neutrino Geophysics





Earth's Total Heat Flow

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

Total heat flow

Conventional view

44±1 TW

Challenged recently

31±1 TW

strongly **model** dependent

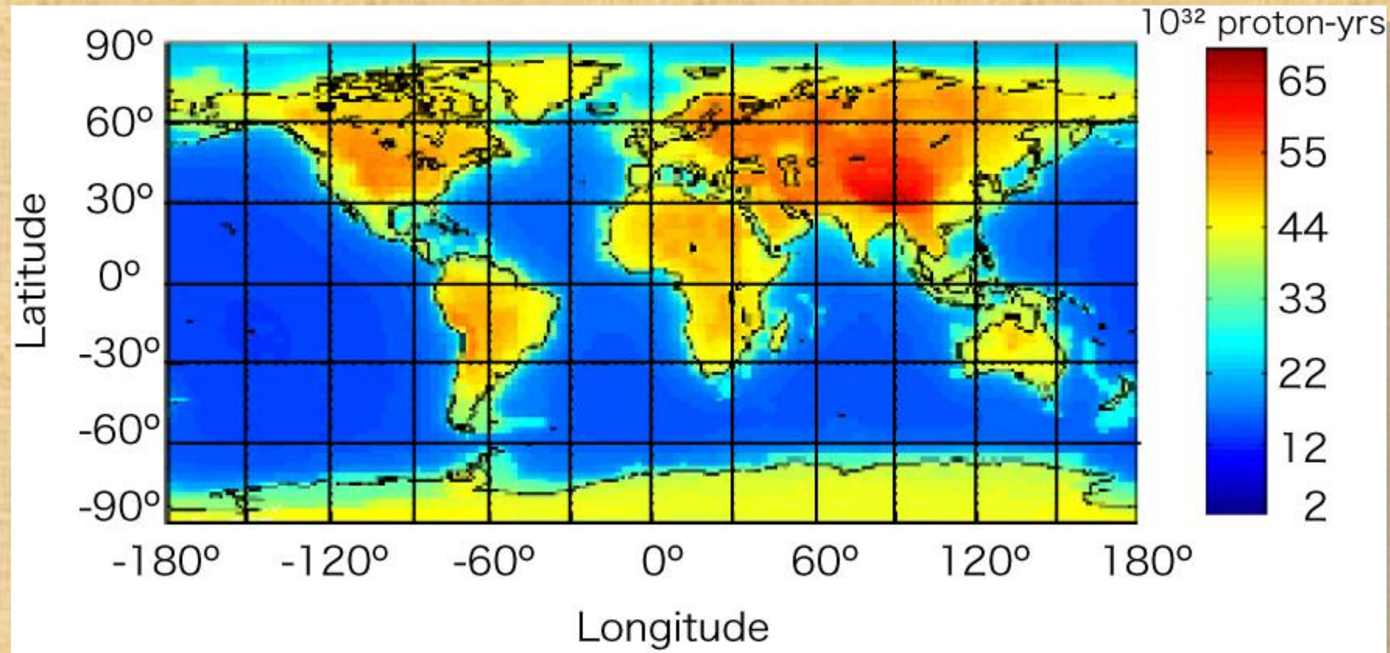
Discrepancy?

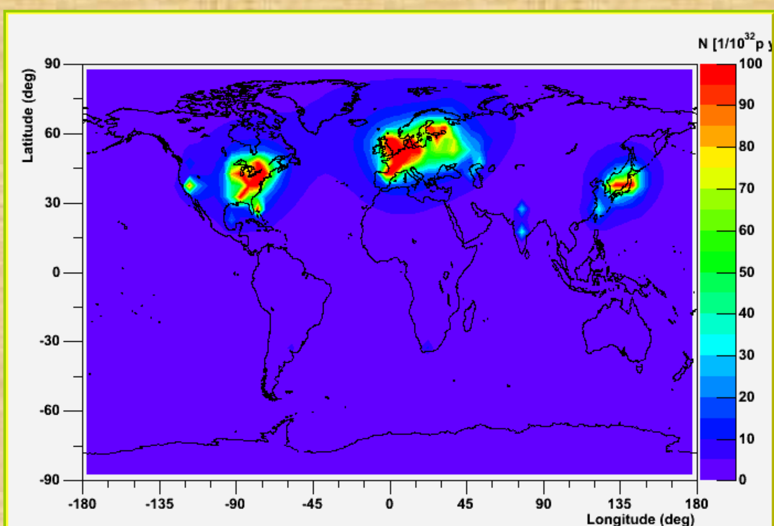
- Est. total heat flow, **44 or 31TW**
  est. radiogenic heat production **19TW or 31TW**
  give Urey ratio ~0.4 to ~1
- Where are the problems?
  - Mantle convection models?
  - Total heat flow estimates?
  - Estimates of radiogenic heat production rate?
- Mantle geoneutrino measurements can constrain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

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….

Predicted Geoneutrino Flux



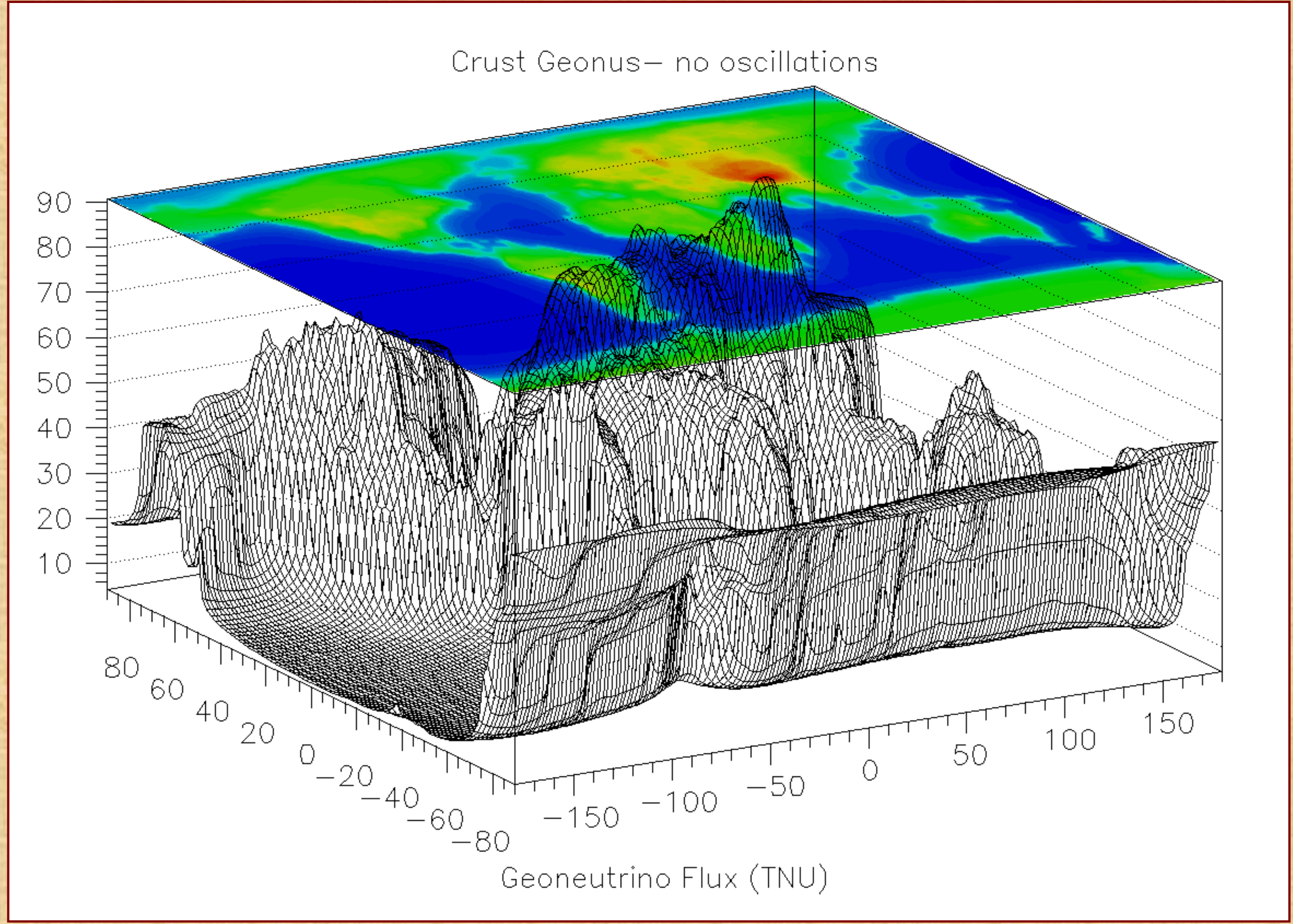


Reactor Flux -
irreducible background

Geoneutrino flux determinations
-continental (Dusel, SNO+, LENA?)
-oceanic (Hanohano)

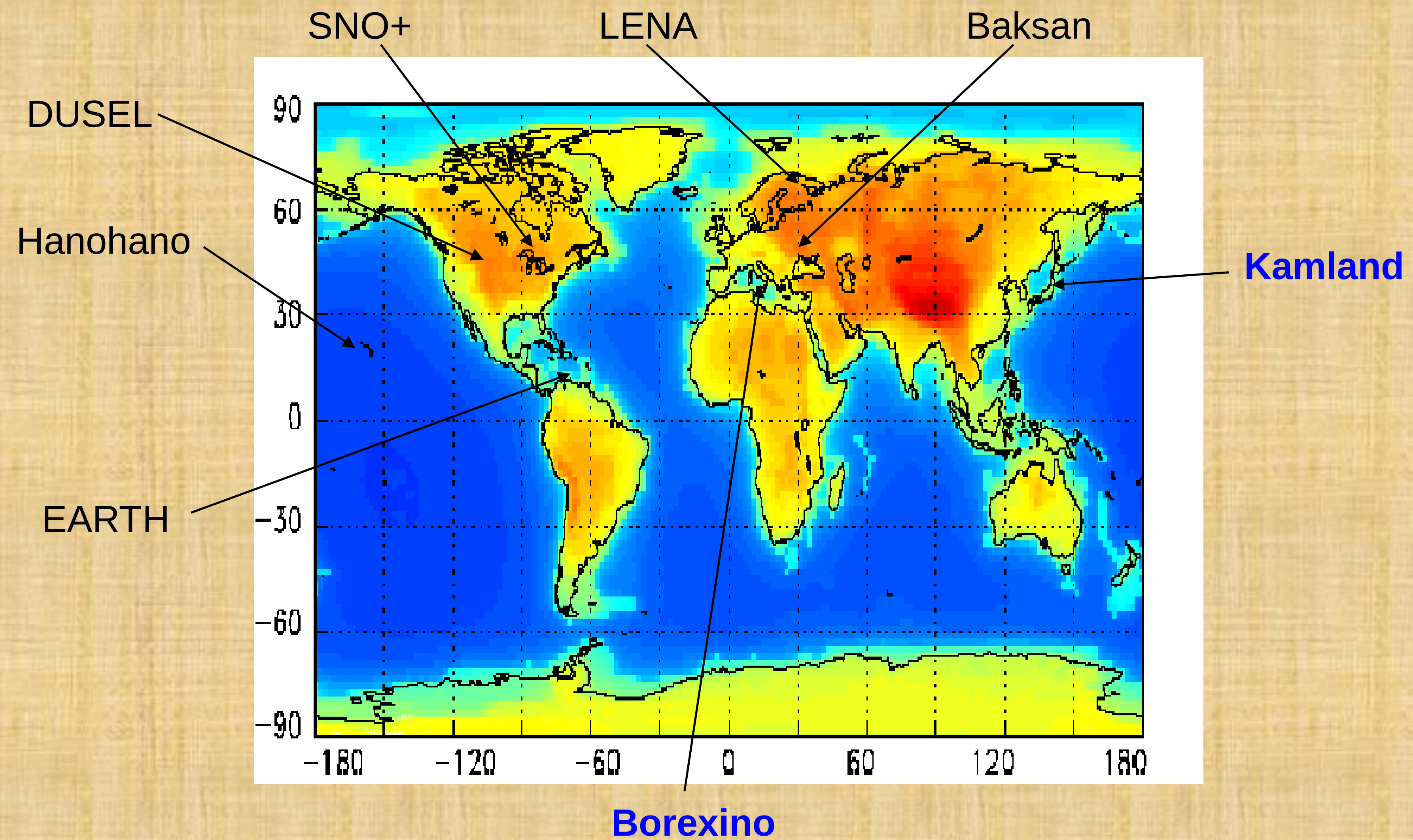
synergistic

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



Thanks Steve Dye

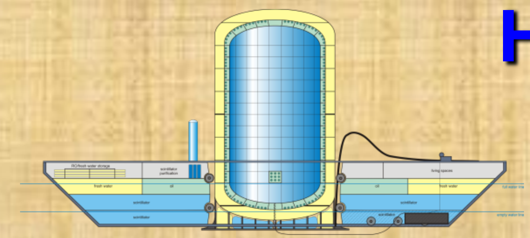
Locations for Possible Geonu Experiments

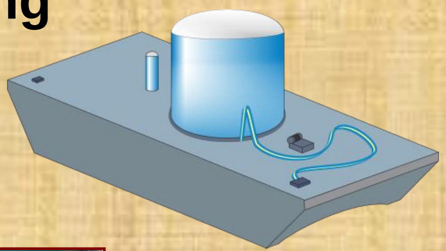


Color indicates U/Th neutrino flux, mostly from crust

Hanohano Engineering Studies

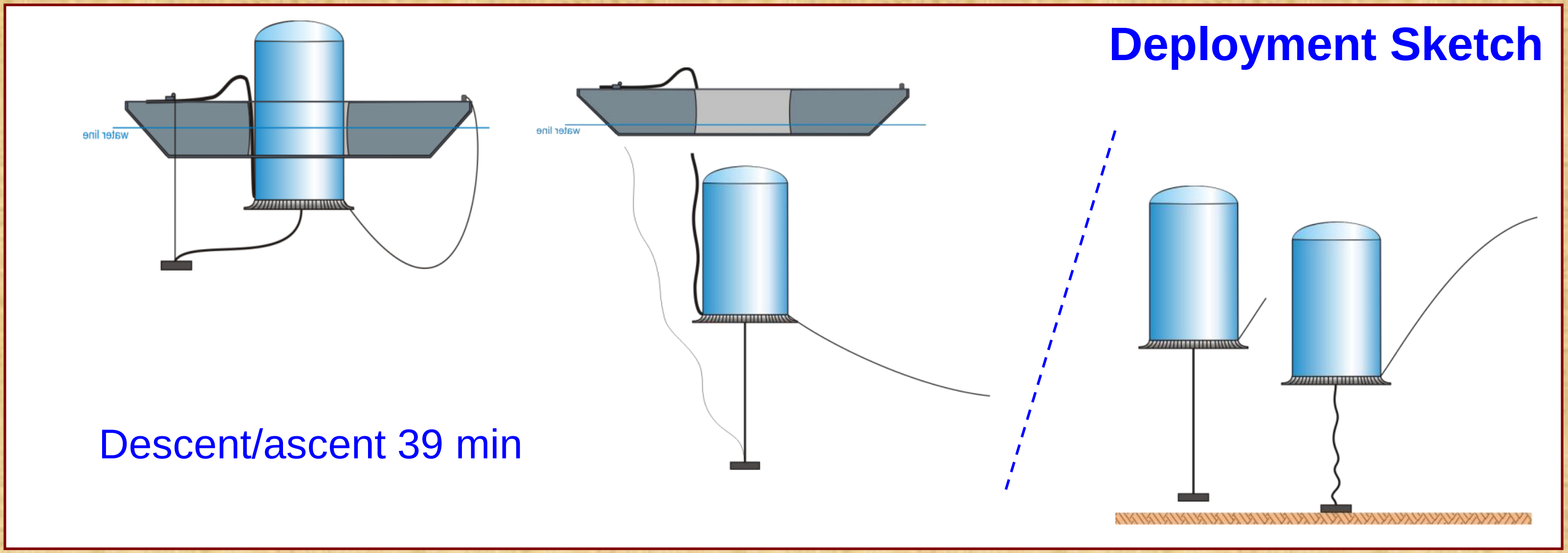
Makai Ocean Engineering





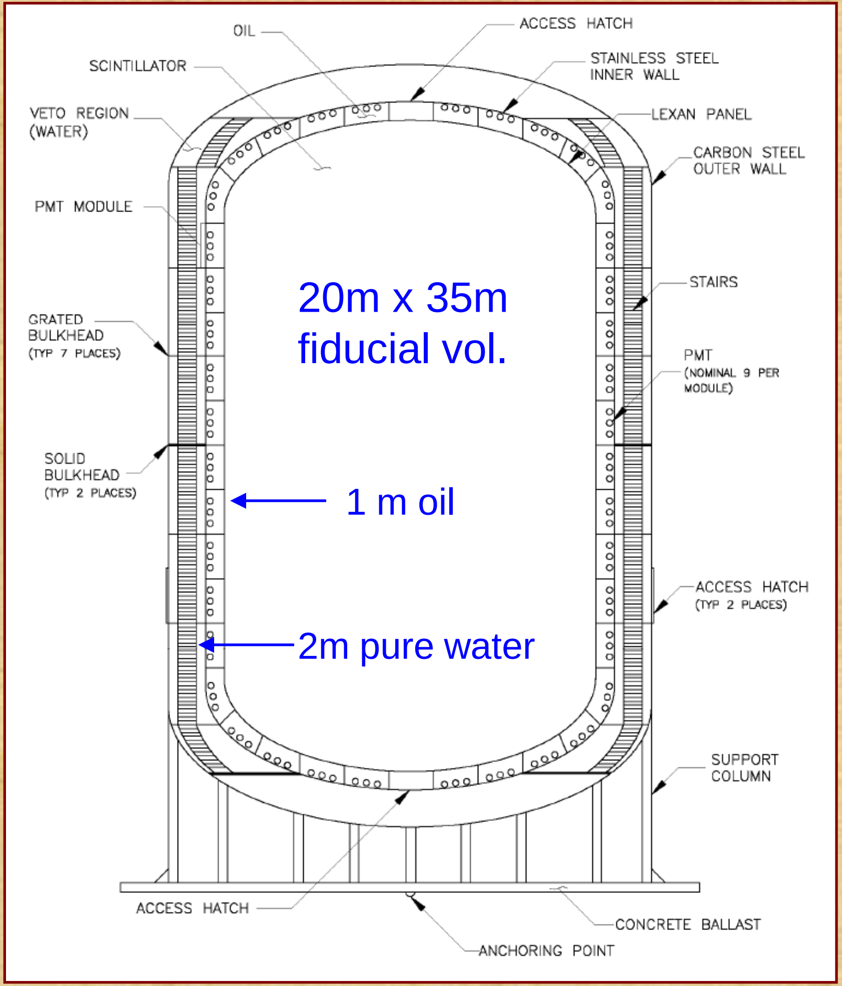
- **Studied vessel design up to 100 kilotons, based upon cost, stability, and construction ease.**
  - **Construct in shipyard**
  - **Fill/test in port**
  - **Tow to site, can traverse Panama Canal**
  - **Deploy ~4-5 km depth**
  - **Recover, repair or relocate, and redeploy**

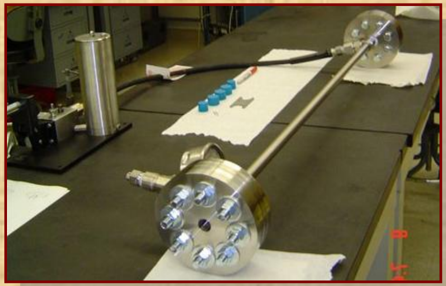
Barge 112 m long x 23.3 wide

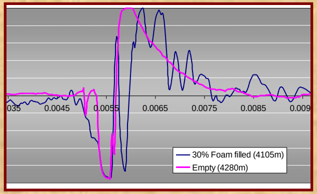


Addressing Technology Issues

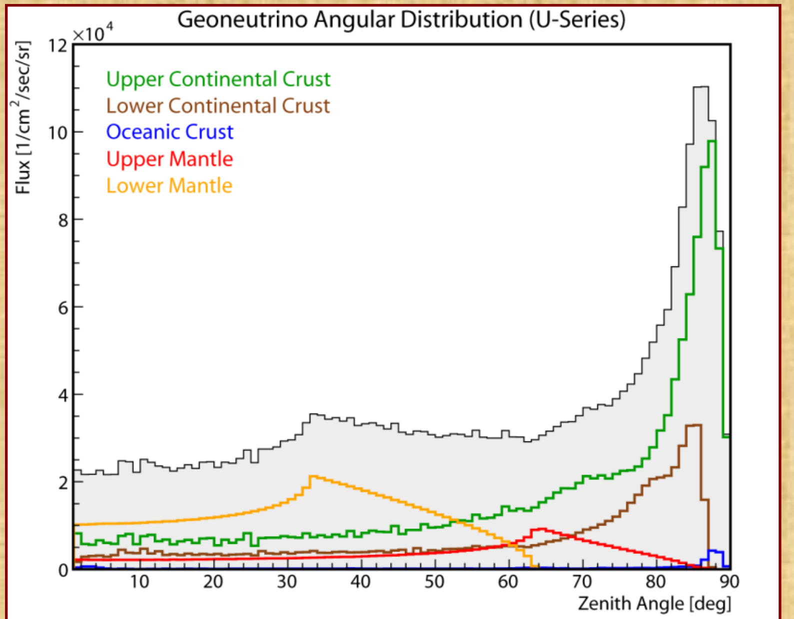
- Scintillating oil studies in lab
  - P=450 atm, T=0°C
  - Testing PC, PXE, LAB and dodecane
  - No problems so far, LAB favorite… optimization needed
- Implosion studies
  - Design with energy absorption
  - Computer modeling & at sea
  - No stoppers
- Power and comm, no problems
- Optical detector,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







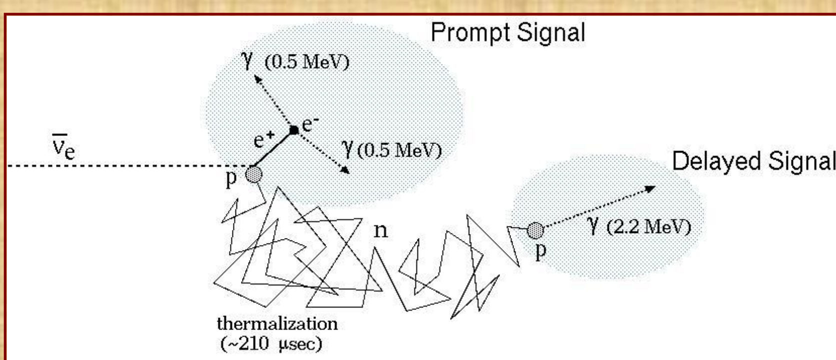
Future Dreams: Directional Sensitivity



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



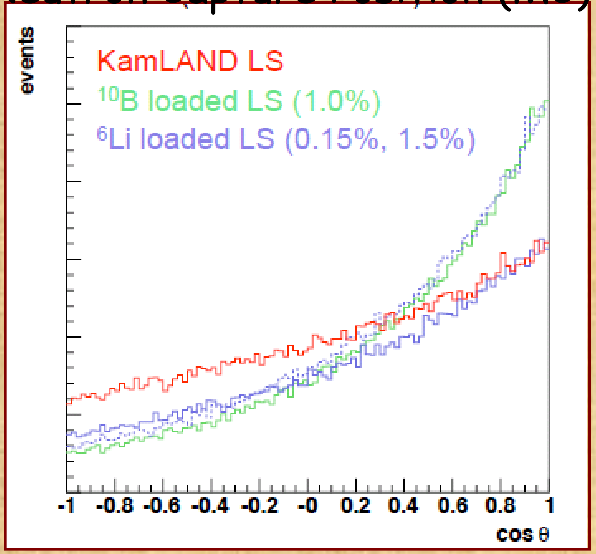
Wish List:
- large neutron capture cross-section
- (heavy) charged particle emission &
- good resolution detector (~1cm)

Towards Directional Sensitivity 1

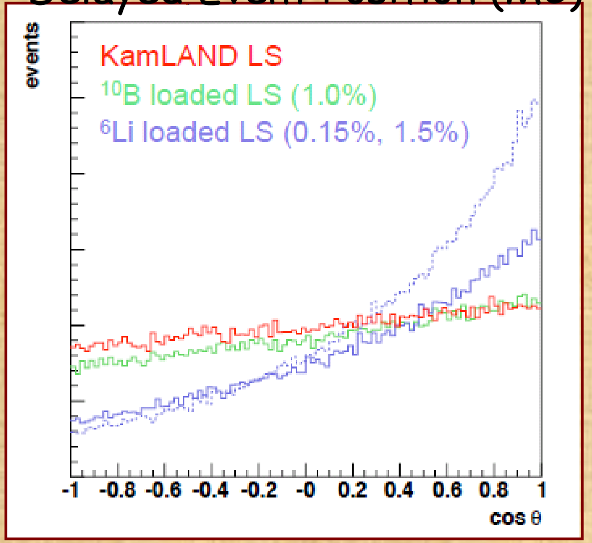
^6Li loading helps preserving directional information

- $^6Li + n \rightarrow \alpha + T$: 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…

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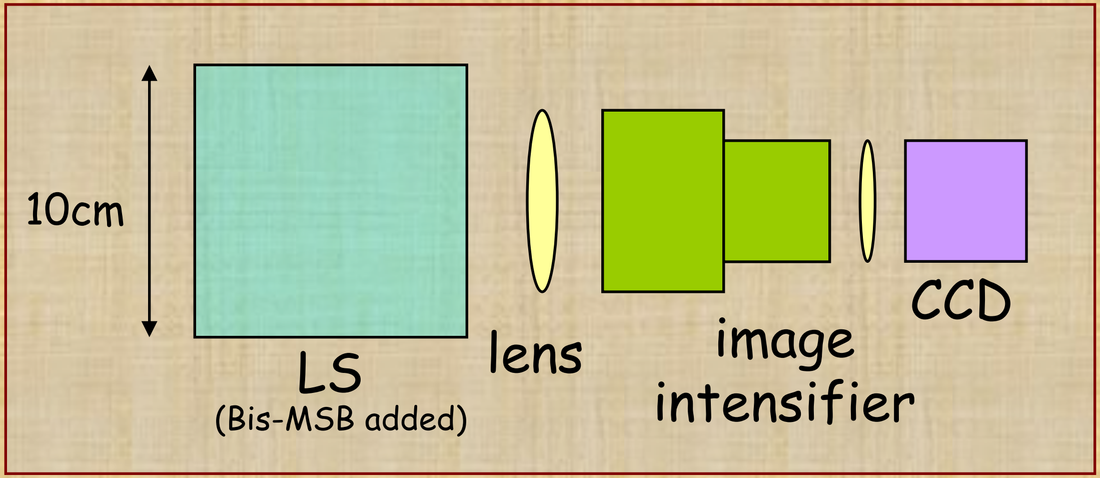
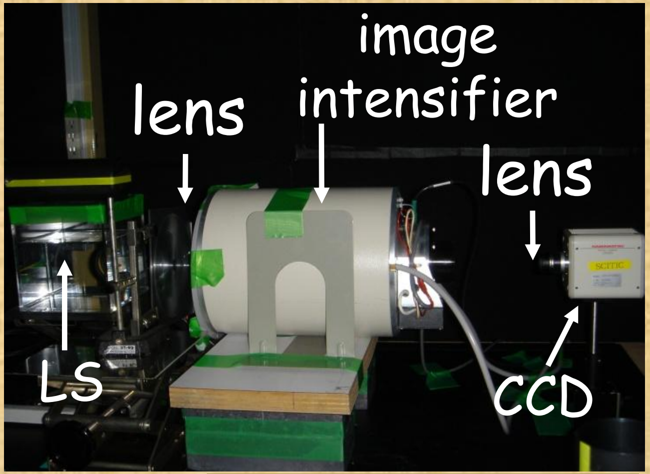
Towards Directional Sensitivity 2

~1M pixel imaging can achieve 1 cm resolution

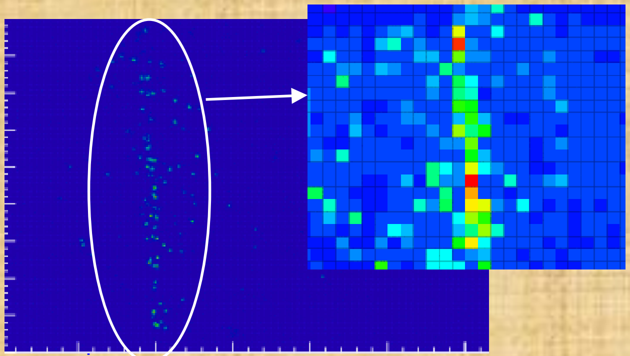
- Proper optics need to be implemented
- Sensitivity to 1 p.e. and high-speed readout required

First step for LS imaging, just started…

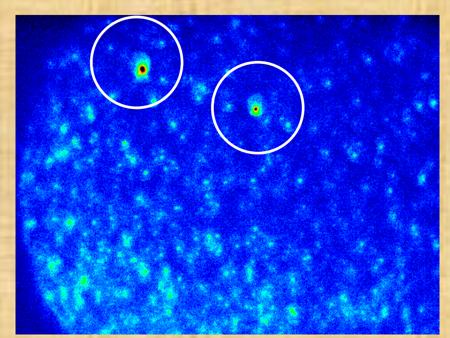




Muon Event ???



Isotope Decay Event ???



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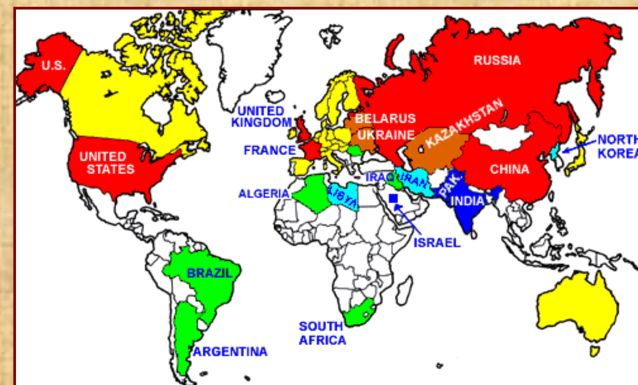
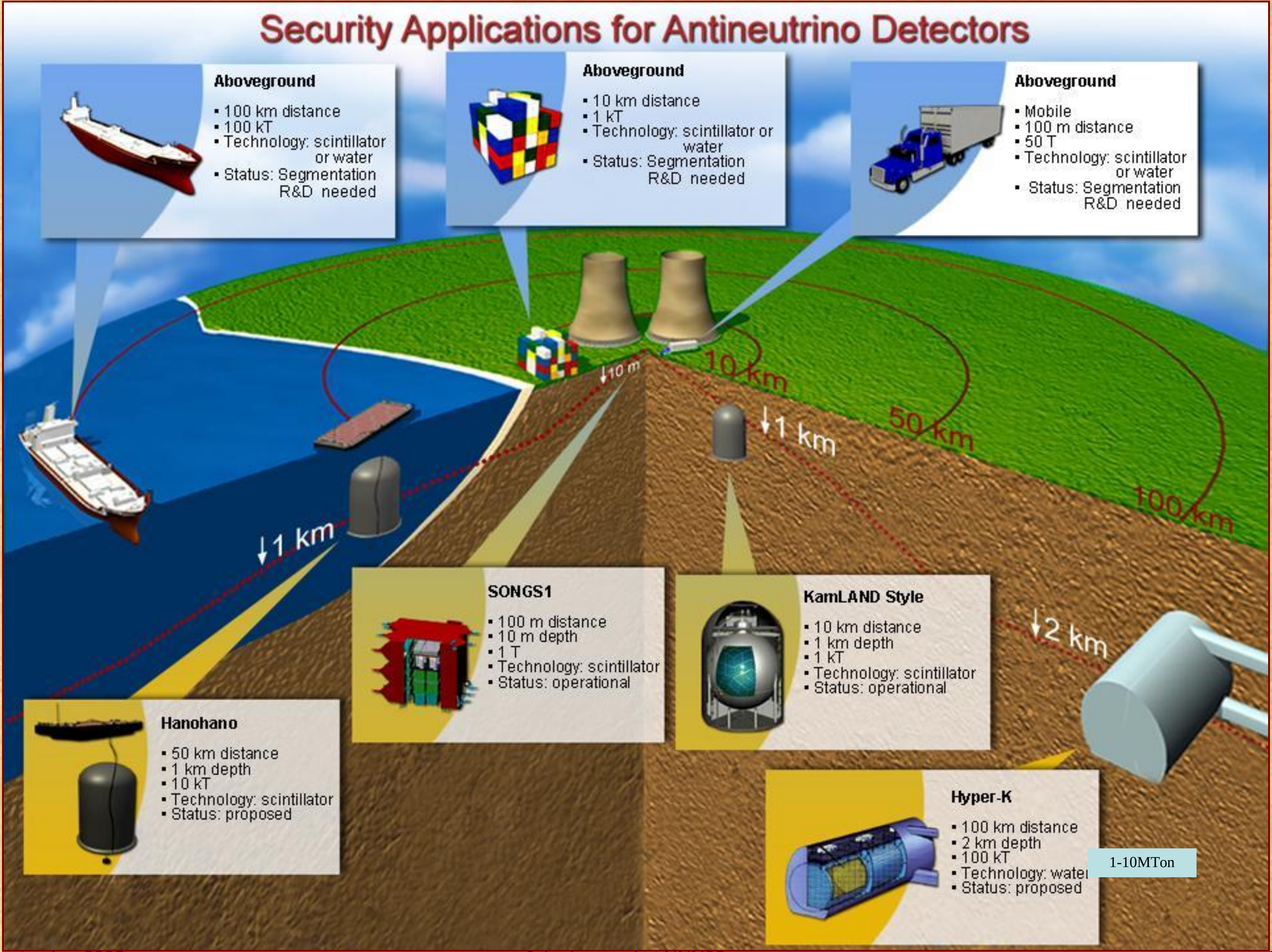
Nuclear Proliferation is a Great Danger to Mankind: **Can ν Physics Help?**

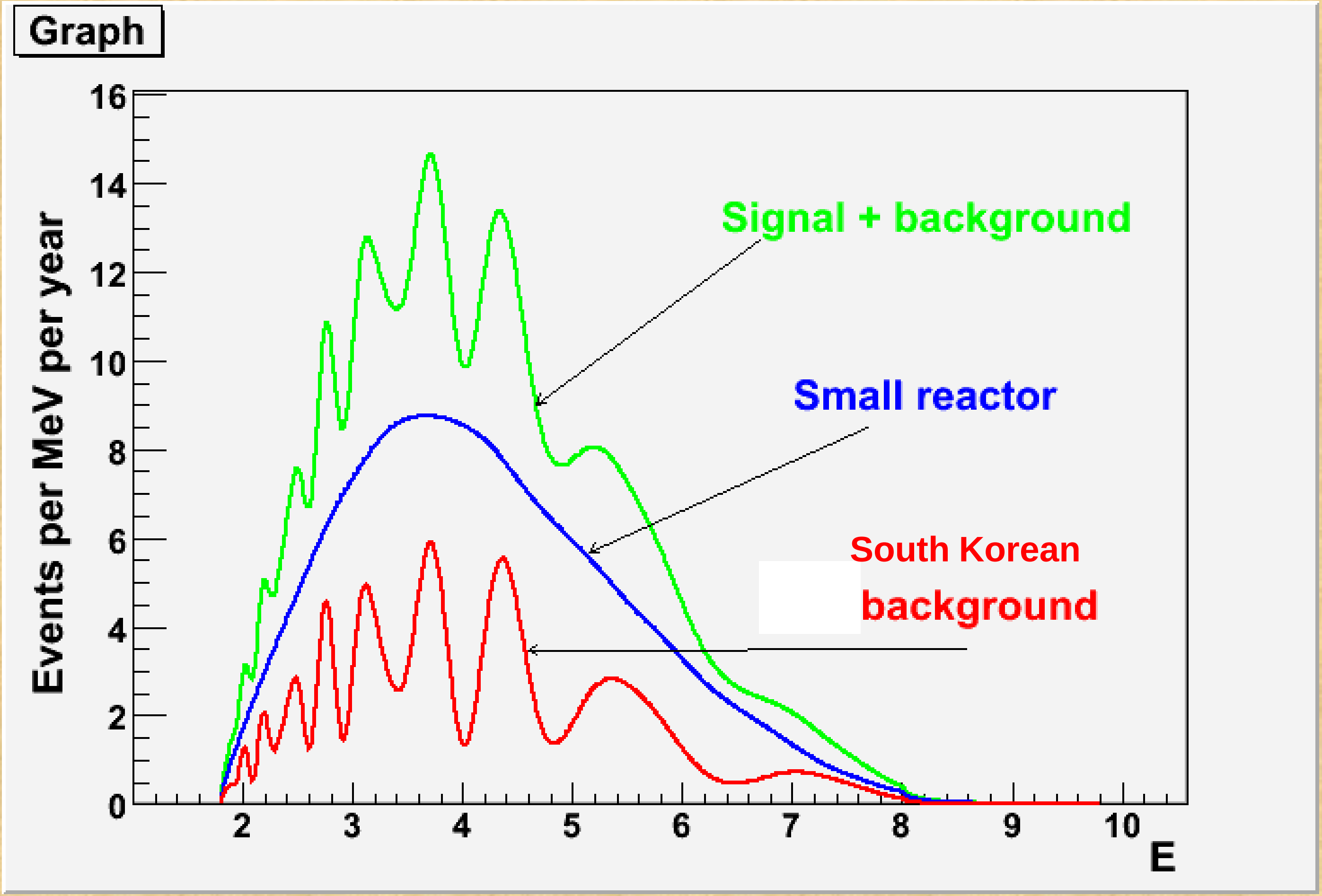


- Monitor cooperating reactors for compliance with stated operations (no making bomb material)? **Yes, close-in.**
- Detect clandestine reactors at modest ranges? **Yes.**
- Track multiple reactor operations in a region? **Yes, with multi-detectors.**
- But are these affordable? **Yes, but large arrays need development.**
- What about bomb detection? **Comes for free with very large array.**



Security Applications for Antineutrino Detectors
Aboveground
• 100 km distance
• 100 kT
• Technology: scintillator or water
• Status: Segmentation R&D needed
Aboveground
• 10 km distance
• 1 kT
• Technology: scintillator or water
• Status: Segmentation R&D needed
Aboveground
• Mobile
• 100 m distance
• 50 T
• Technology: scintillator or water
• Status: Segmentation R&D needed
10 m
10 km
1 km
50 km
100 km
1 km
2 km
SONGS1
• 100 m distance
• 10 m depth
• 1 T
• Technology: scintillator
• Status: operational
KamLAND Style
• 10 km distance
• 1 km depth
• 1 kT
• Technology: scintillator
• Status: operational
Hanohano
• 50 km distance
• 1 km depth
• 10 kT
• Technology: scintillator
• Status: proposed
Hyper-K
• 100 km distance
• 2 km depth
• 100 kT
• Technology: water
• Status: proposed
1-10MTon

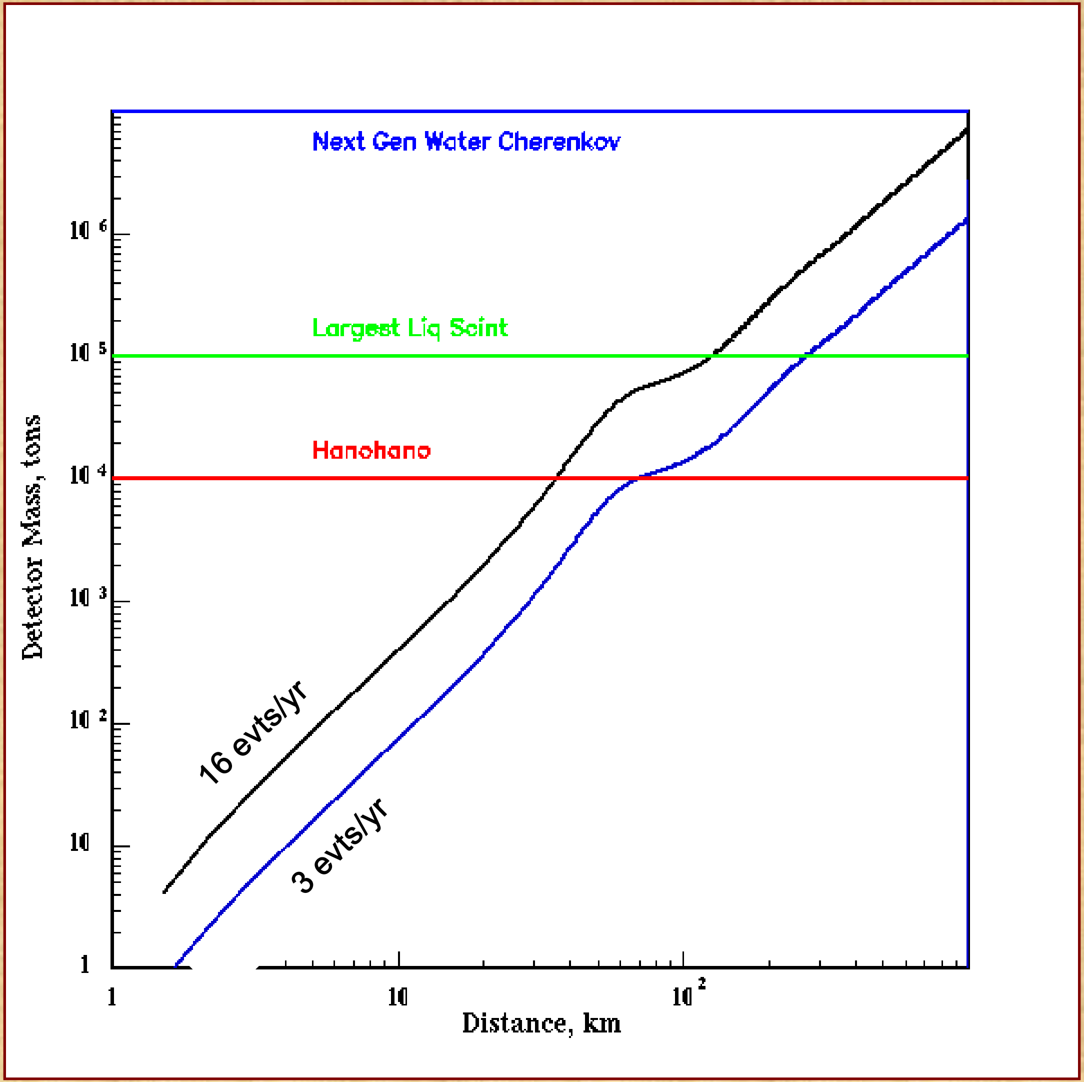
Spectrum can help separate near and far reactors



10 MWt reactor
in N. Korea
10 km distance
1 kiloton detector

Misha Batygov

Reactor Monitoring with Anti-Neutrinos



small 10 MWt reactor observed with 10MT detector
no background

- daily ops out to ~60 km

- annual output to >1000 km

Summary of Expected Results

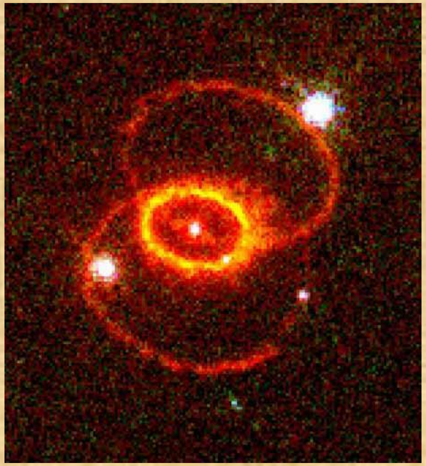
Hanohano- 10 kt-1 yr Exposure

- **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)

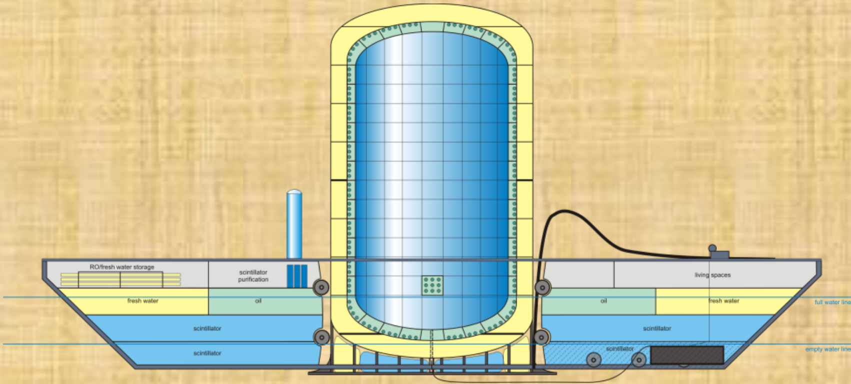
- Nucleon Decay: SUSY-favored kaon modes
- Supernova Detection: special ν_e ability
- Relic SN Neutrinos
- GRBs and other rare impulsive sources
- Exotic objects (monopoles, quark nuggets, etc.)
- Long list of ancillary, non-interfering science, with strong discovery potential

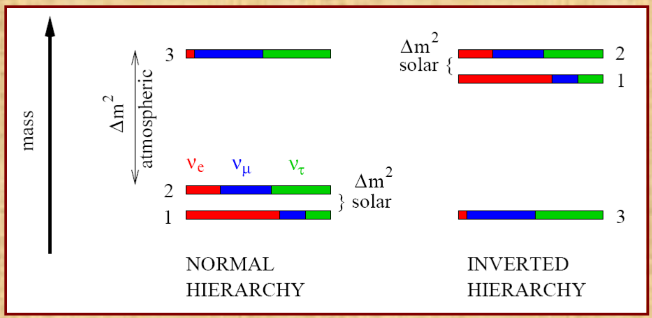


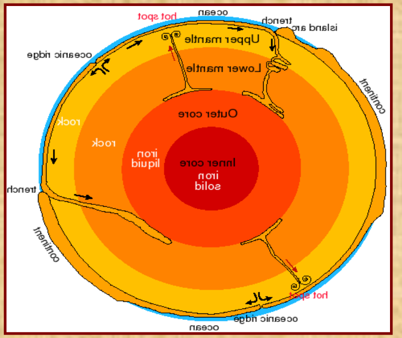
Broad gauge science and technology, a program not just a single experiment.

Summary

- Close-in reactor monitoring ready to go.
- Need development of segmented detectors for surface applications.
- Hanohano proposal for portable, deep-ocean, 10 kiloton, liquid scintillation electron anti-neutrino detector ready to move ahead.
- 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, and particularly remote monitoring of reactors.







Urey Ratio and Mantle Convection Models

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

- 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