The Abdus Salam
International Centre for Theoretical Physics

United Nations
Educational, Scientific and
Cultural Organization

IAEA
International Atomic Energy Agency

2047-9

Workshop Towards Neutrino Technologies

13 - 17 July 2009

Prospects for large liquid scintillation detectors in particle physics, astrophysics, geophysics and reactor-monitoring

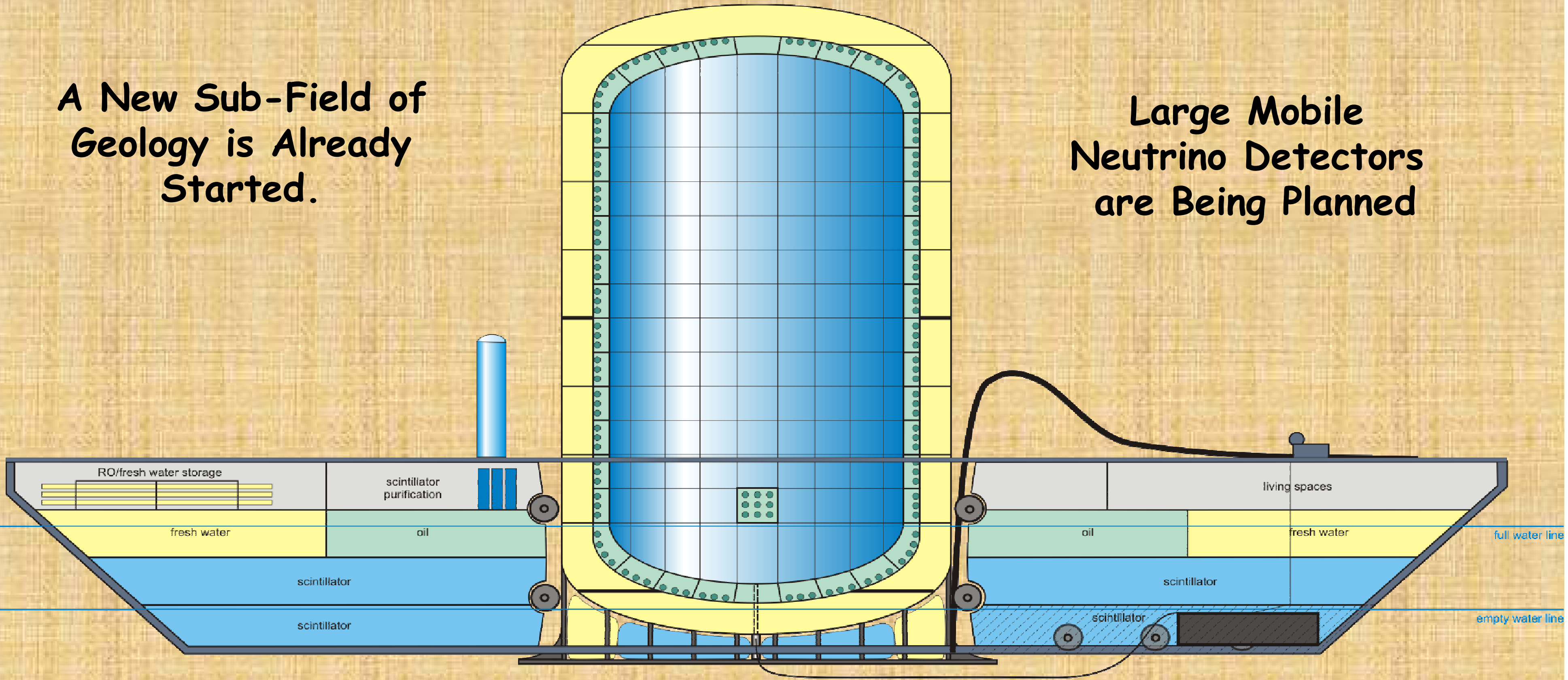
John G. LEARNED

University of Hawaii
Department of Physics & Astronomy
2505 Correa Road
Honolulu, HI 96822, U.S.A.

Large Liquid Scintillation Detectors for Physics, Geology, Anti-Proliferation, and Much More

A New Sub-Field of Geology is Already Started.

Large Mobile Neutrino Detectors are Being Planned



John Learned, *University of Hawaii at Manoa*

(& other colleagues at UH and elsewhere)

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

Outline

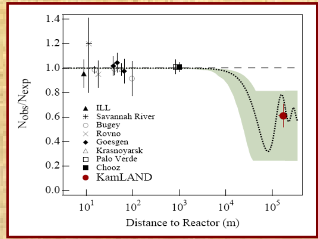
- **Hanohano**
  - deep ocean, portable
  - 10-100 kiloton liquid scintillator
  - known reliable technology
  - challenges: directionality,better reolution, K detection
  - (Watanabe talk, this afternoon)
- Overlapping goals with LENA... Oberauer talk, next

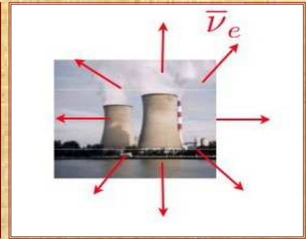
- **Neutrino Geophysics**
  - U & Th mantle flux from ocean
  - Th/U ratio
  - Georeactor search
  - (Talks of McDonough,Fiorentini, Mitsui, Ianni, Dye)

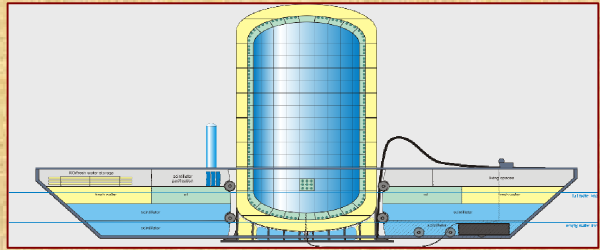
- **Reactor Monitoring**
  - CTBT renews activity, near and far
  - (Talks of Vogel, Cribier, Reyna, Battagieri)

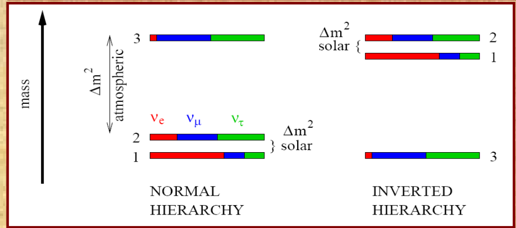
- **NEW GeV Neutrinos: Fermat Surface**
  - new recognition, '09
  - competitor for long baseline expts

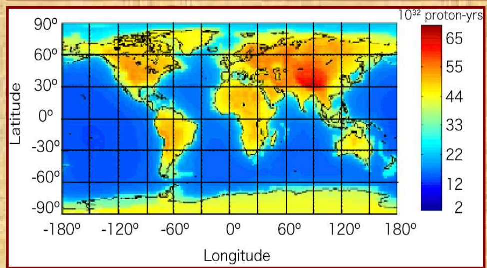
- **Other Physics**
  - oscillations, mass hierarchy
  - astrophysics
  - nucleon decay
- **Challenges**
  - directionality

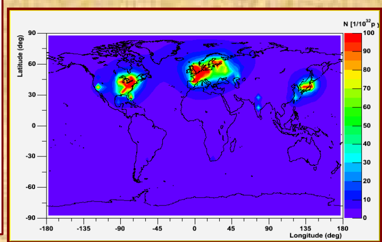












Hanohano
a mobile deep ocean detector

Measure electron antinus for:

Particle physics (hierarchy, mixing parameters)

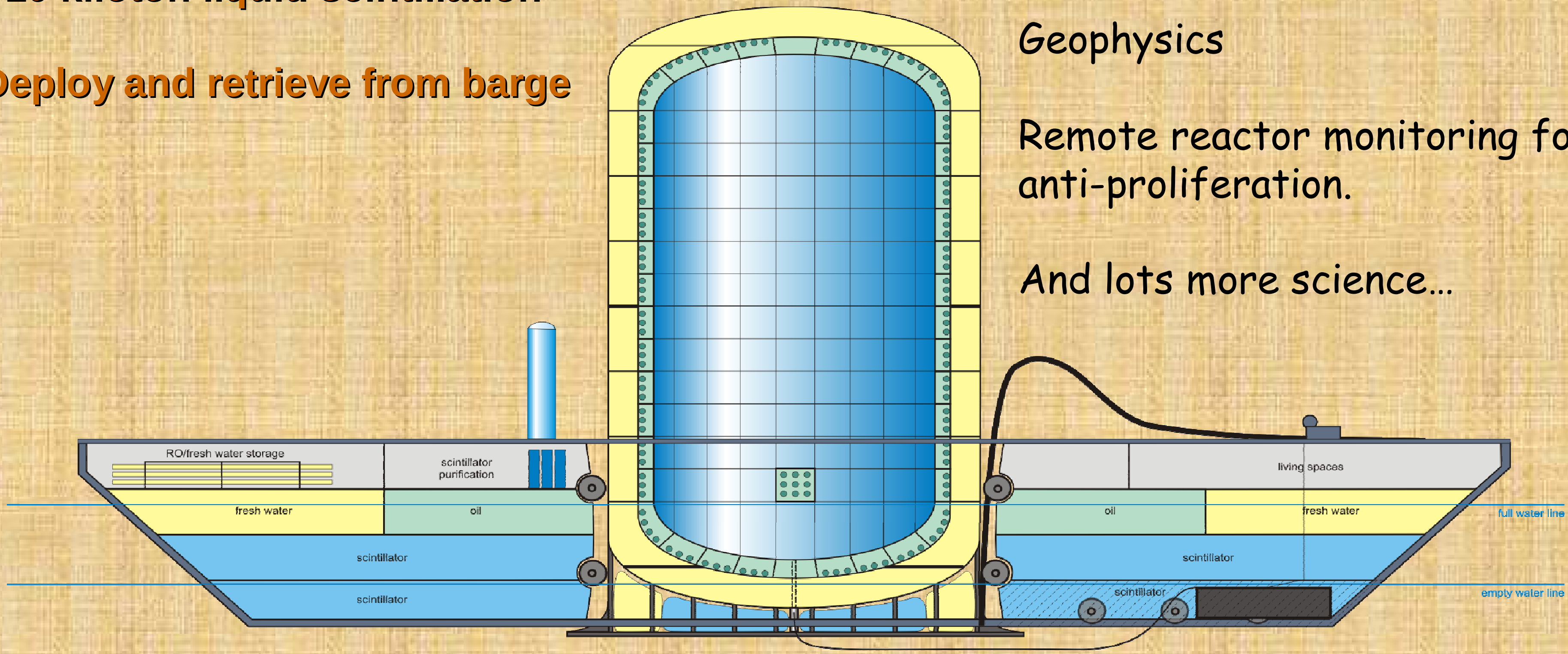
Geophysics

Remote reactor monitoring for anti-proliferation.

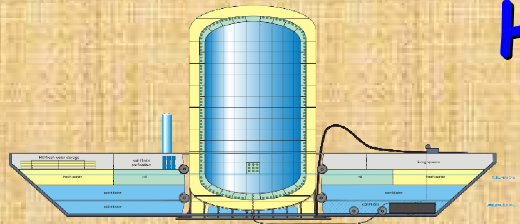
And lots more science…

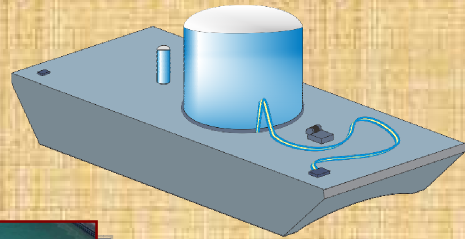
>10 kiloton liquid scintillation

Deploy and retrieve from barge



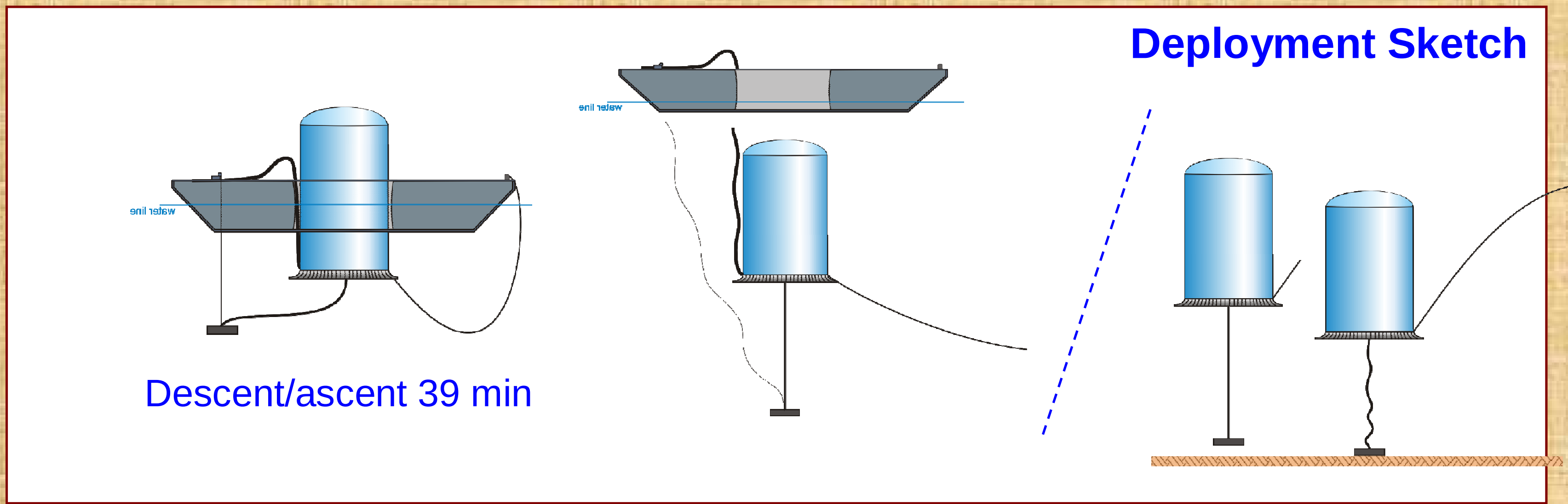
Hanohano Engineering Studies
Makai Ocean Engineering





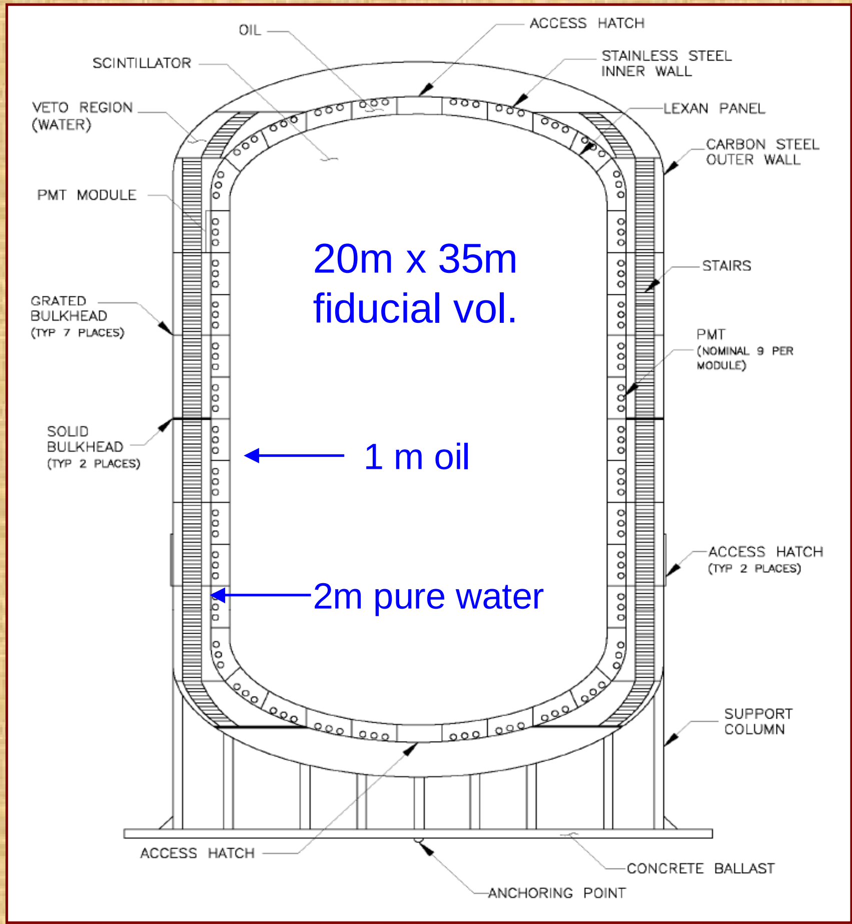
- Studied vessel design up to 100 kilotons, based upon cost, stability, and construction ease.
  - Construct in shipyard
  - All connections under oil
  - Fill/test in port
  - Tow to site, can traverse Panama Canal
  - Deploy ~4-5 km depth, less
  - Recover, repair or relocate, and redeploy

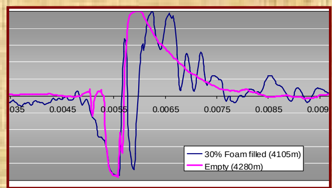
Barge 112 m long x 23.3 wide



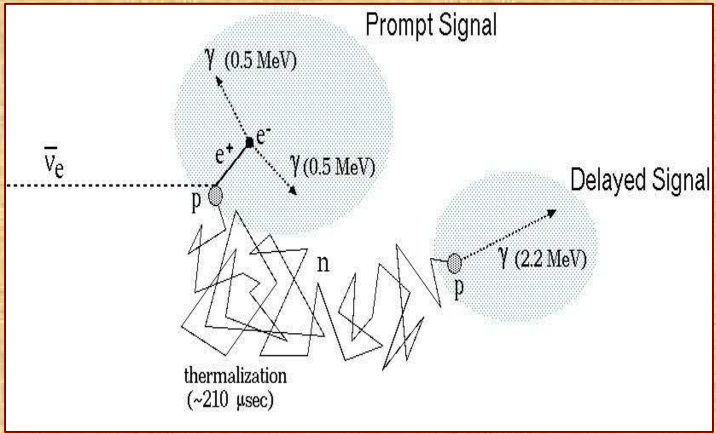
Addressing Technology Issues

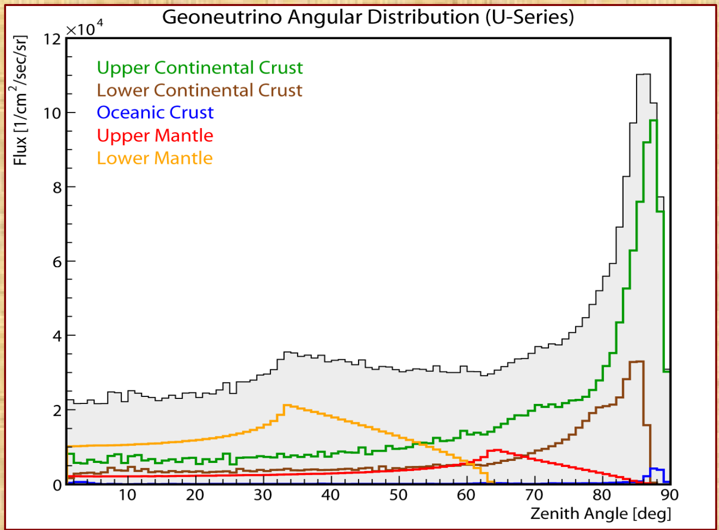
- Scintillating oil studies in lab
  - P=450 atm, T=0°C
  - Tested PC, PXE, LAB and dodecane
  - No problems, LAB chosen… optimization needed
  - second round studies in motion
- Implosion studies
  - Design with energy absorption
  - Computer modeling & at sea
  - No stoppers
- Power and comm, no problems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





Future Dreams: Directional Sensitivity w/Scintillators





Directional information provides:

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

Directional (statistical) Resolution:

- Recoil neutron remembers direction
- Thermalization blurs the info
- Gamma diffusion spoils the info
- Present resolution is too poor
- Doable (Chooz.. need better though)

Goals:

- large neutron capture cross-section
- (heavy) charged particle emission
- excellent energy resolution (3%/√(E)?)
- high spatial resolution detector (~1cm)

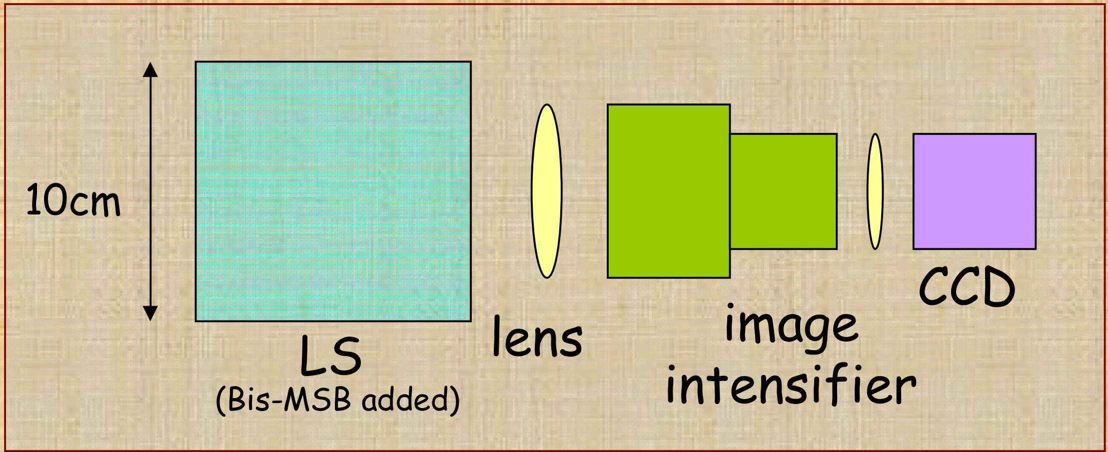
see Oberauer, Watanabe, Dye talks

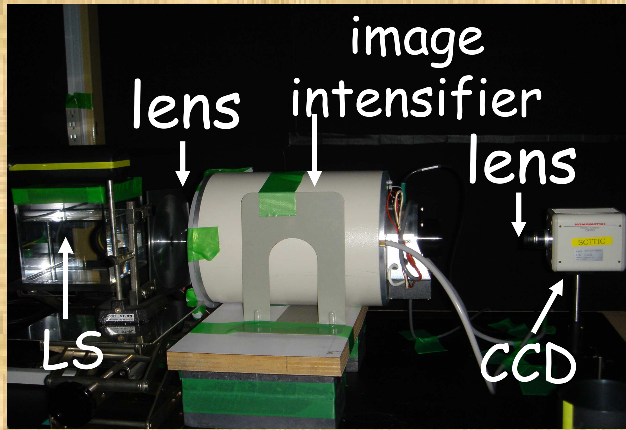
Direct Track Imagine in Scintillator

~1M pixel imaging can achieve 1 cm resolution

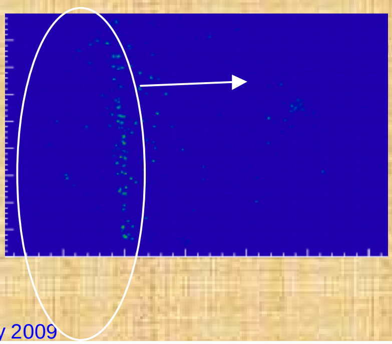
- Proper optics need to be implemented
- Sensitivity to 1 p.e. and high-speed readout required

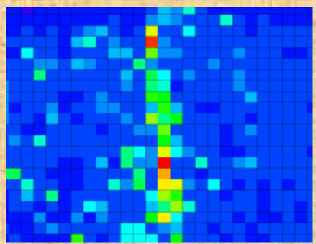
First step for LS imaging, just started…



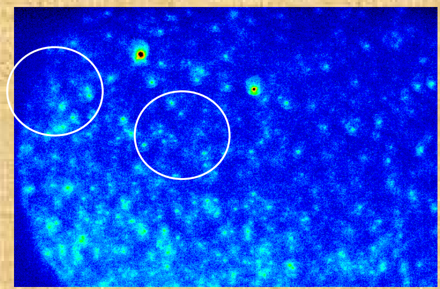


Muon Event ???





Isotope Decay Event ???



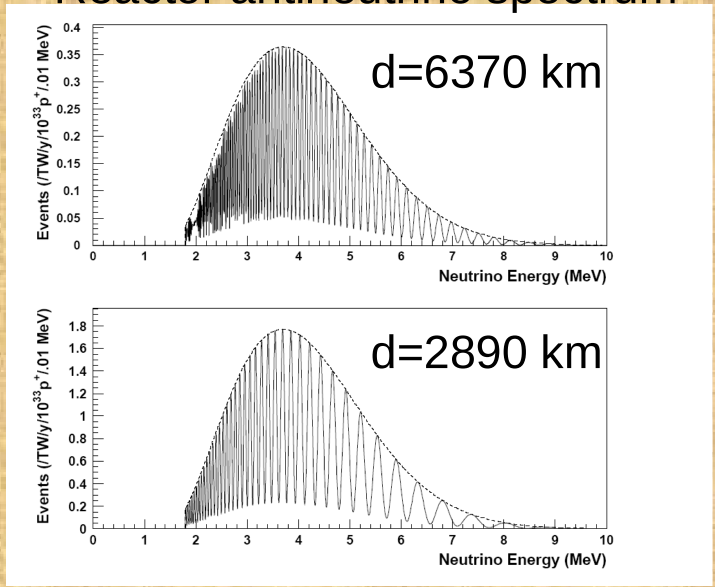
Fresnel lens

See Watanabe talk

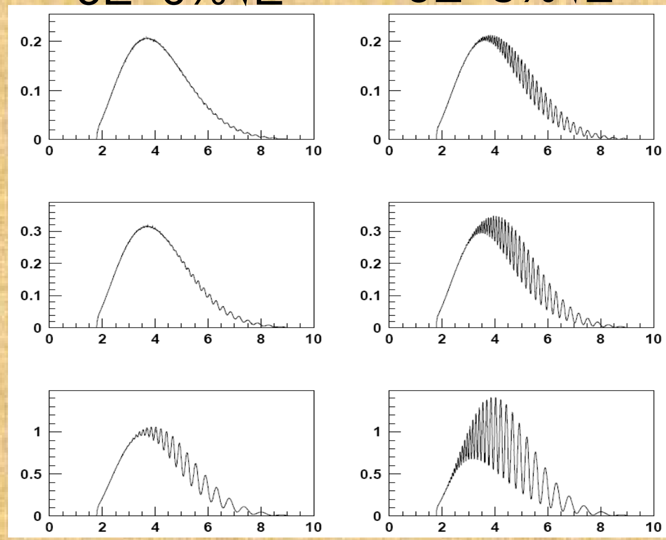
Source Ranging via Distortion of Energy Spectrum by Mixing of Neutrino Mass States

$$P_{\bar{\nu}_e \to \bar{\nu}_e} \cong 1 - \sin^2(2\theta_{12})\sin^2(1.27\Delta m^2_{21} L / E_{\bar{\nu}_e})$$

Reactor antineutrino spectrum



δE=6%√E δE=3%√E



d=6370 km

d=5150 km

d=2890 km

$$\tan^2\theta_{12} = 0.47^{+0.06}_{-0.05}$$

$$\Delta m^2_{21} = (7.59 \pm 0.21) \times 10^{-5} \text{ eV}^2$$

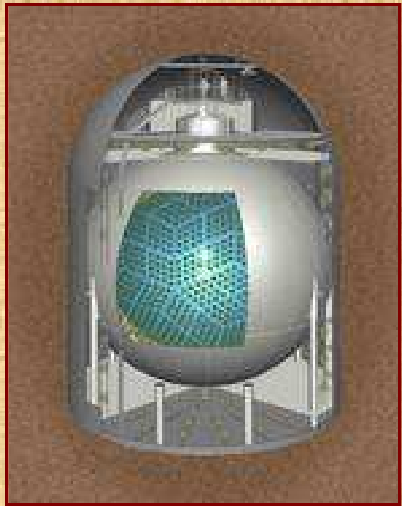
Abe et al. (2008)

Detector energy resolution critical for d~R_E

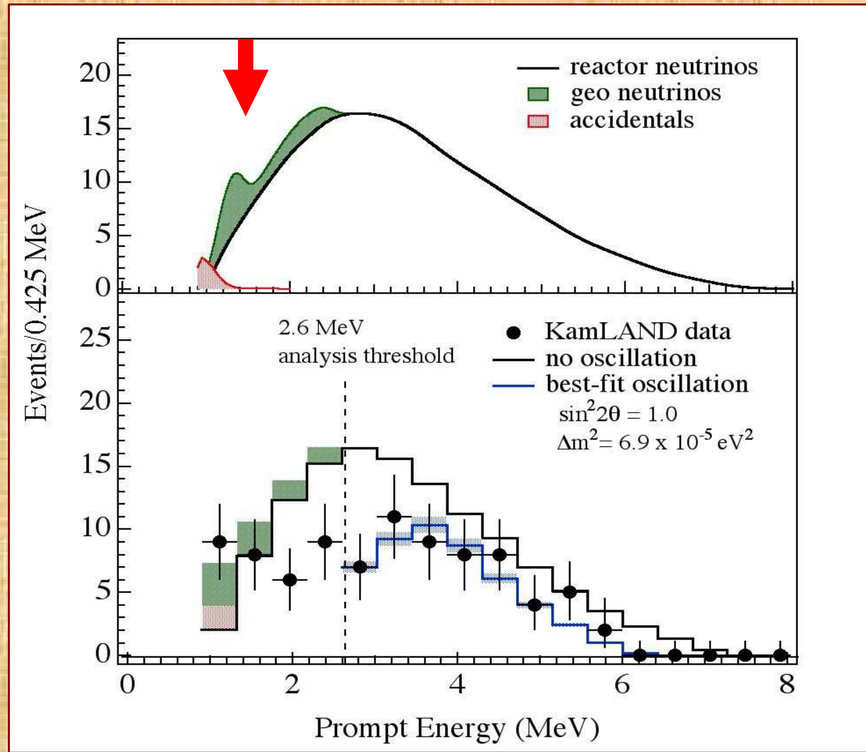
Distortions retained with 3% energy resolution

see S.T. Dye talk and arXiv:0905:0523

KamLAND:
1000 ton
liquid scintillator
detector
in a mine in Japan



GeoNeutrinos
starting a new science

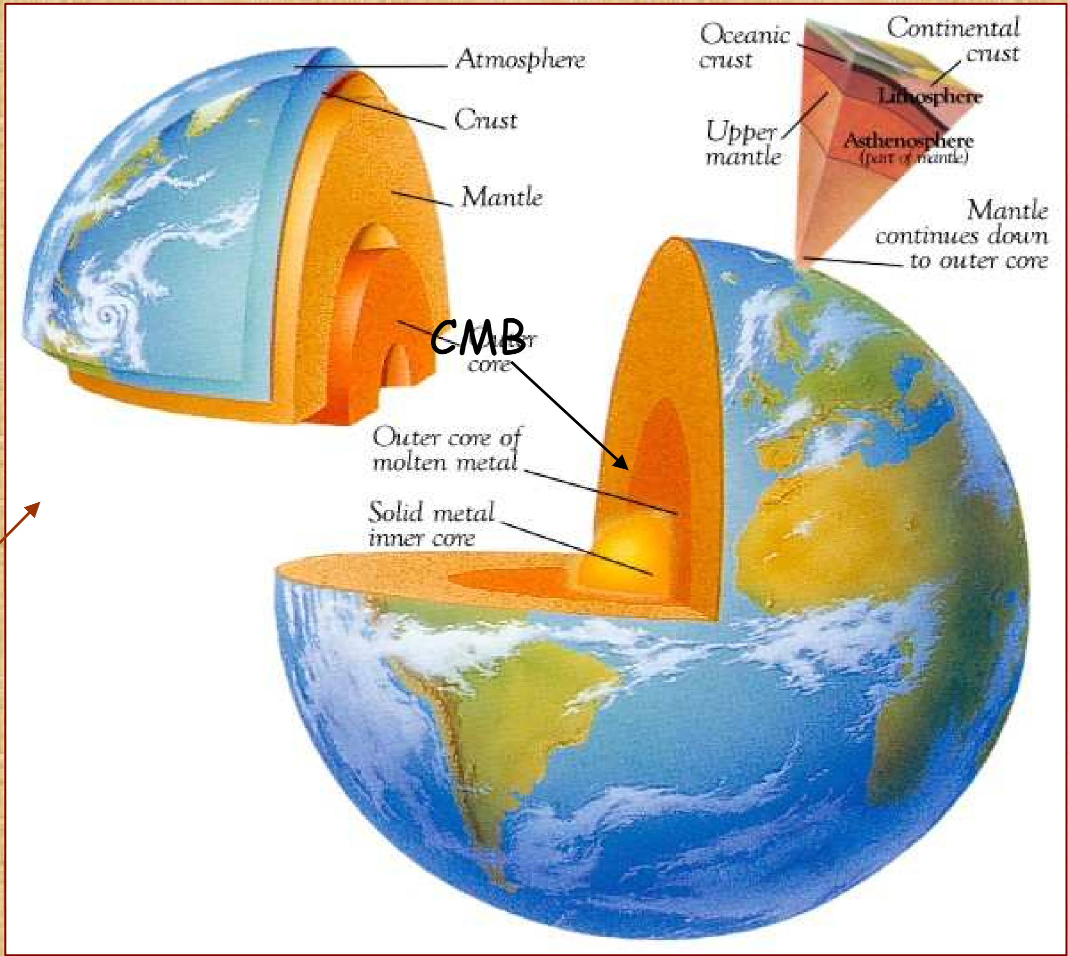


KamLAND cover article in Nature in 2006: first observation

See Mitsui talk

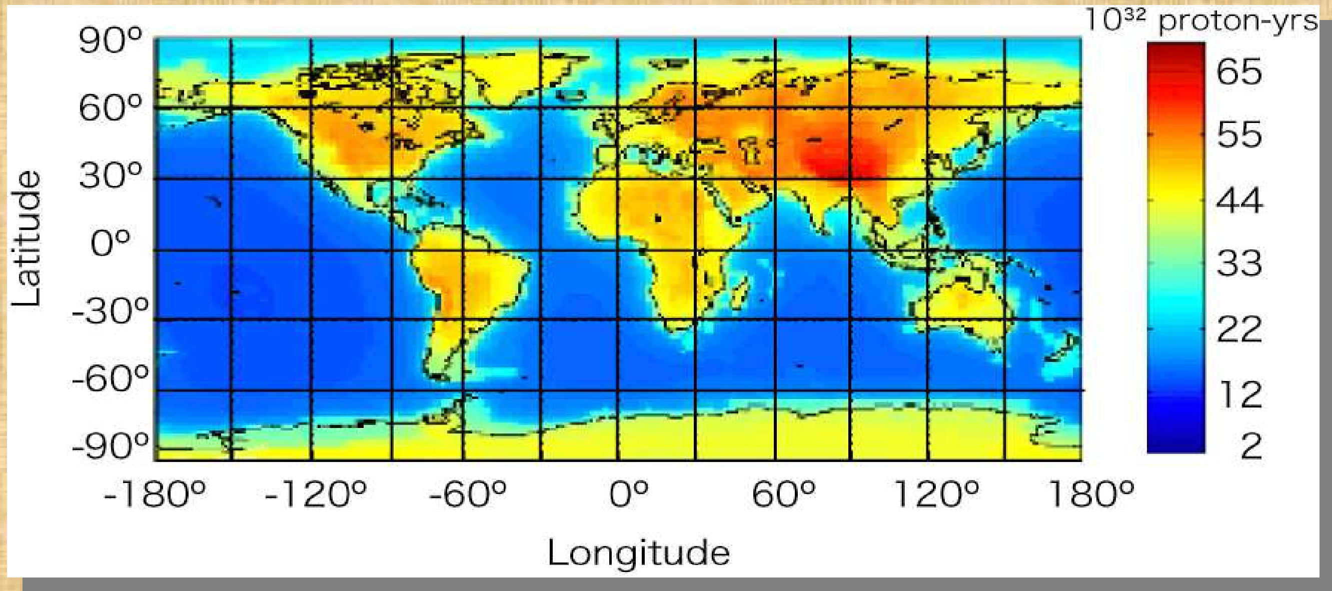
Structure of the Earth

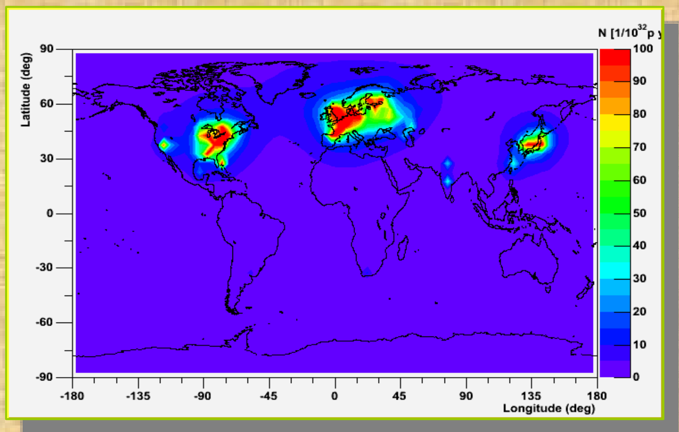
U&Th heating drives almost all of geodynamics
- seafloor spreading
- hot spots (Hawaii)
- earthquakes
- geomagnetic field



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

Predicted Geoneutrino Flux
Mostly from Not so Interesting Crust





Reactor Flux -
irreducible background

Geoneutrino flux determinations

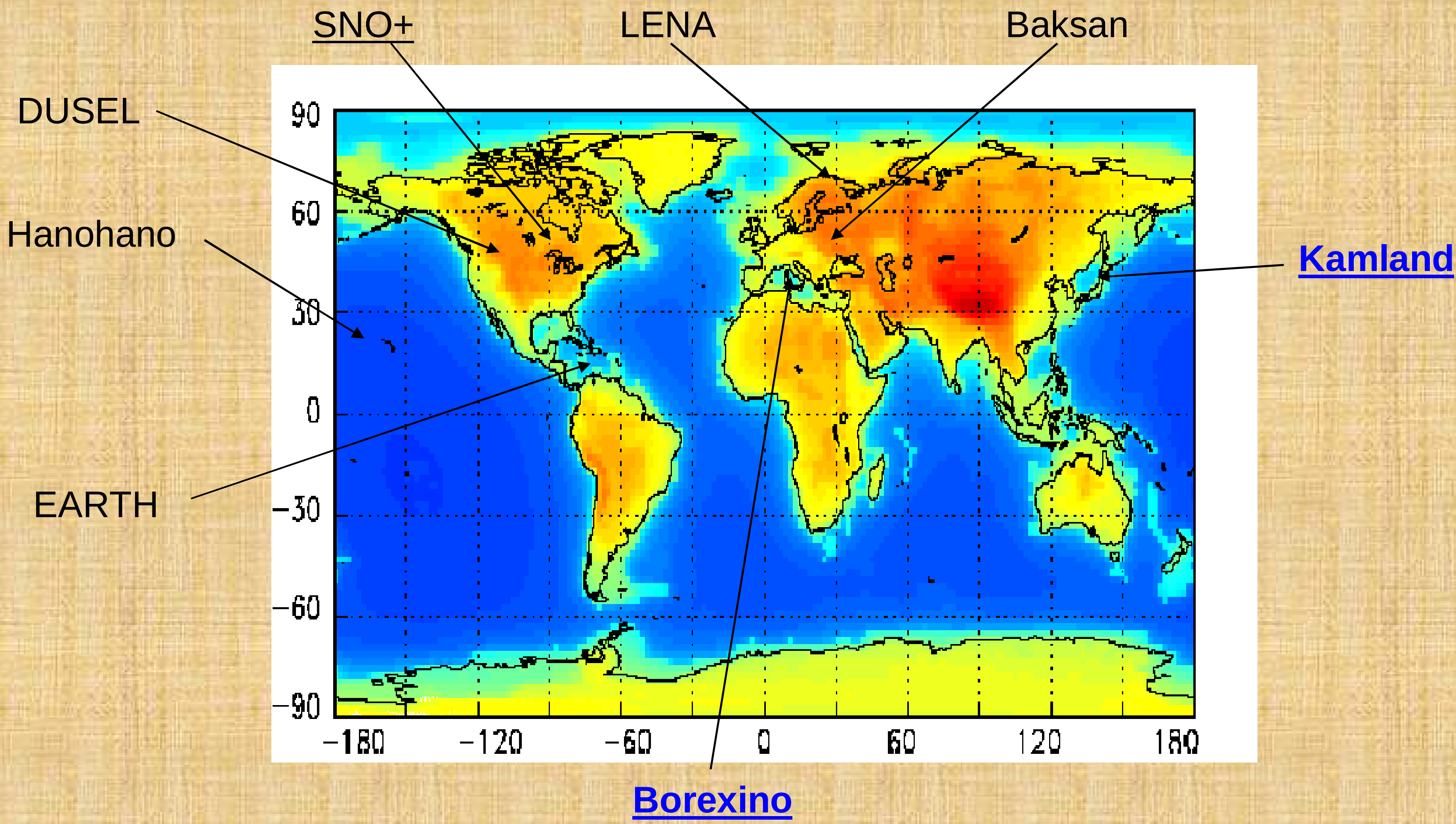
-continental (Dusel, SNO+, LENA?)

-oceanic (Hanohano)

synergistic

See Fiorentini talk

Locations for Present & Possible Geonu Experiments



Color indicates U/Th neutrino flux, mostly from crust

Deep EarthNatural Reactors?

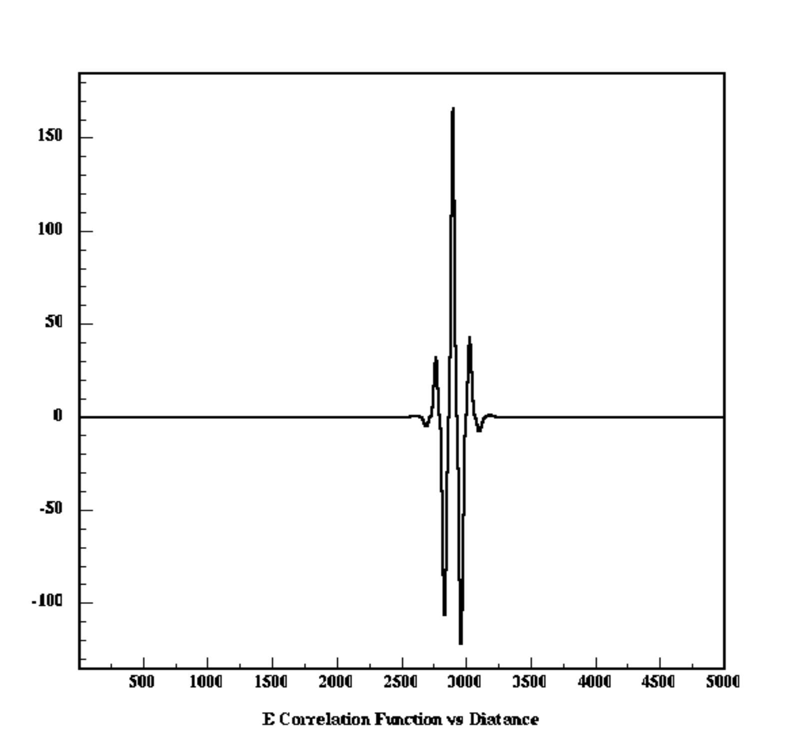
- Suggested for core (Herndon) or near Core-Mantle Boundary (Rusov and deMeijer)
- Where is the heating for the outer core?
- 5-10 TW could help explain heating, convection, He3 anomaly, and some isotope curiosities.
- Both models disfavored <u>strongly</u> by geochemists
- Due to high neutrino energies,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

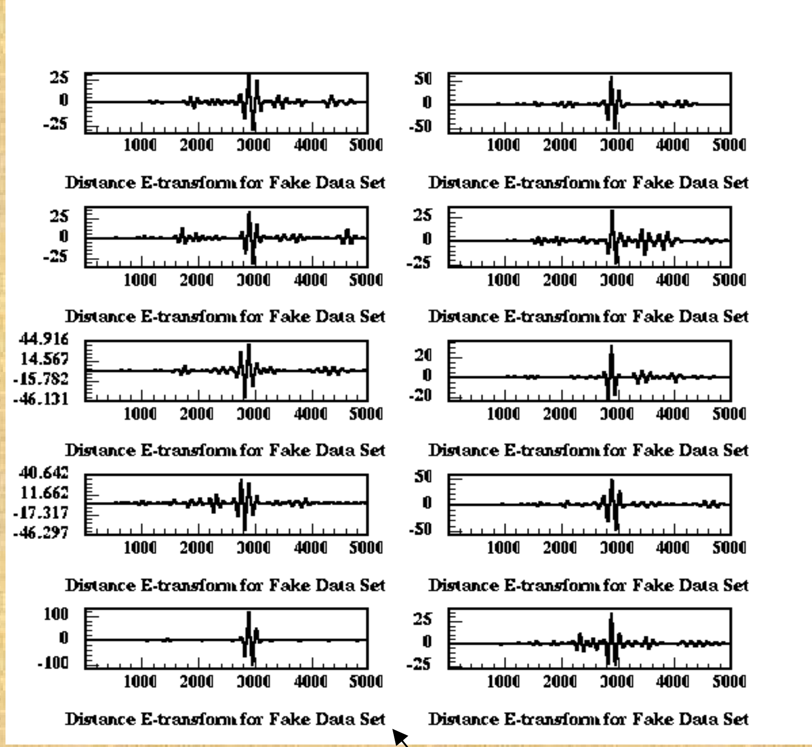
  (see Mitsui talk)
- So seem to be unlikely…. Yet there is something amiss with the overall earth heat picture.

Single Reactor Source at CMB

resolution to few km

10 sample simulated 1 yr runs





1 GW source observed by 100 kT detector

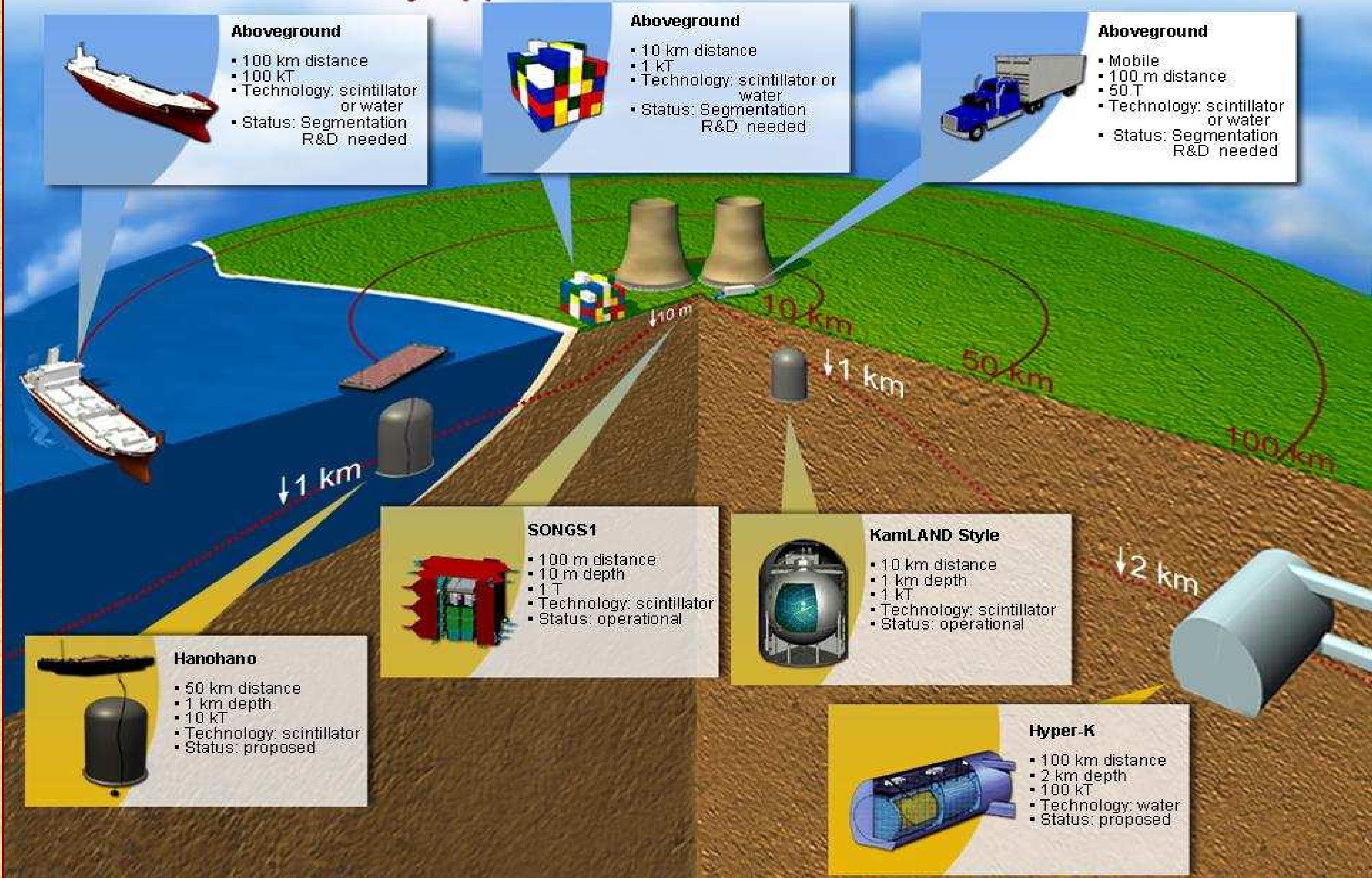
can be cleaned up

see Steve Dye talk

Agenda 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….

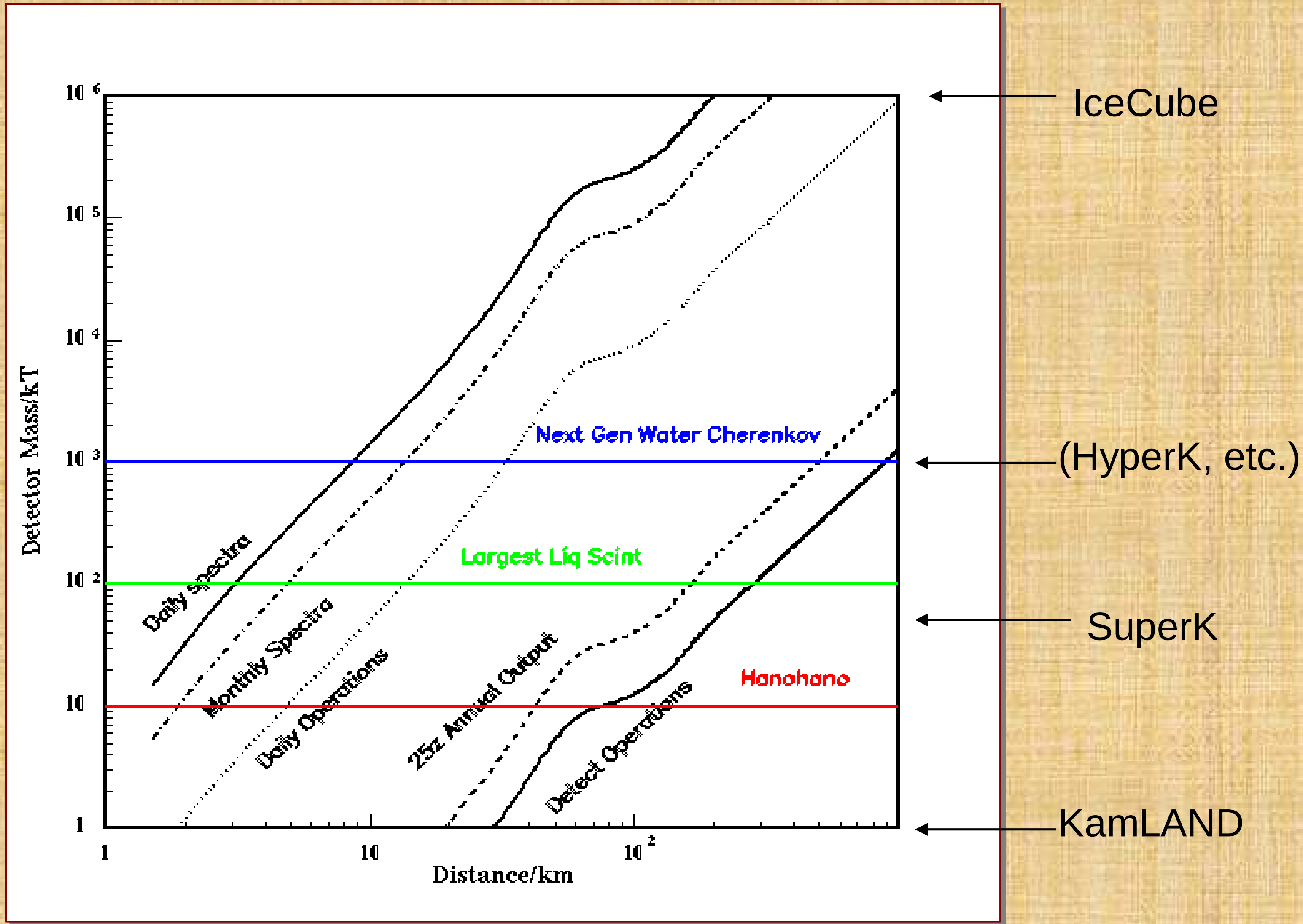
Security Applications for Antineutrino Detectors



Close-In Reactor Monitoring

- Much activity on ton scale, 10's of m range detectors: See talks of Vogel, Cribier, Reyna and Battagieri (and yesterday's talks by Scholberg, Collar, Giomataris and Li)
- So far, only shielded (~10mwe) detectors demonstrated.
- Big challenge to make surface mounted, segmanted detector (see Reyna and Battagieri)
- IAEA probably will mandate these.

Required Detector Size versus Reactor Range



Summary of Present Long Range Reactor Monitoring Abilities

- Scaled for a **10 MWt Reactor** (~smallest to make bad things)
- A typical power reactor (few GW) much much easier.

Goal	Rate	#/Yr	Detector Size		
			10 KT	1MT	100 MT
Detect Operation ~1yr	~5 Events/yr	~5	70 km	800 km	>>1000 km
Total annual energy output with 25% accuracy	16 events/yr	16	35 km	400 km	>>1000 km
Daily operations, catch rod changes	> 10 events/day	3600	6 km	60 km	600 km
Monthly spectra, and hence fuel mix	> 3000 events/ month	36K	2 km	20 km	350 km
Daily spectra, fuel evolution	> 3000 events/day	100K	1 km	12 km	120 km

3-ν Mixing: Reactor Neutrinos

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

mixing angles mass diffs

- Survival probability: 3 oscillating terms each cycling in L/E space (~t) with own "periodicity" (Δm^2~ω)
  - 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
- In energy space it is like a **chirped signal**… very good for correlations.
- **Hanohano can do well on θ_{13} and mass hierarchy.**

- **Three ~ AAP meetings in Hawaii (2004, 2005, 2007), and one at LLNL (2006) http://www.phys.hawaii.edu/~sdye/hanohano.html**

- Paris 12/07: 65 participants, much international interest in neutrino reactor monitoring, including IAEA people. http://www.apc.univ-paris7.fr/AAP2007/

- **AAP Brazil end of March '09 (http://indico.cern.ch/conferenceDisplay.py?confId=50498).**

- **NUTECH 2009 in Trieste 13-17 July '09.**

- **ANT09 in Hawaii, late August (exclusive technology focus).**

- **Next AAP meeting in Japan, Spring 2010**

Reactor Monitoring Workshops
Maryland, 3-5 January 2008
Hawaii, 16-17 March 2009

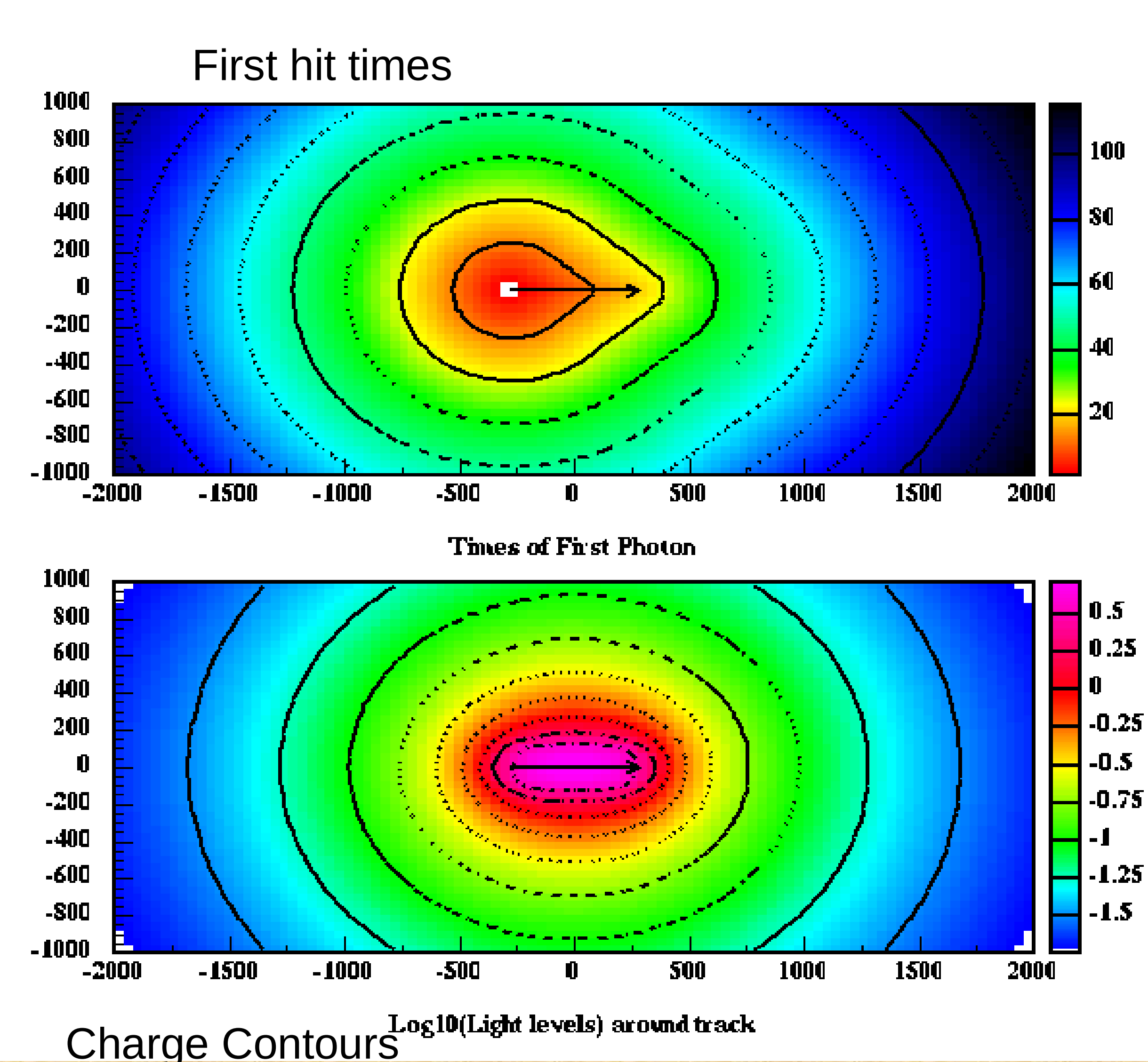
- Representatives from academe, nuclear monitoring community and intelligence community.
- Potential for nuclear reactor and bomb monitoring via neutrinos, near and far.
- White paper produced making case for large scale, interdisciplinary National Antineutrino Science Center, as well as specific projects.
- **Hanohano endorsed as flagship project, not to wait for NASC.**

NEW: The Fermat Surface

- Central idea:
  - Scintillation radiation is isotropic
  - Large (many kiloton) scintillation detector PMTs would have > 100 PE/PMT @ 1 GeV
  - First hit is very close to Fermat Surface (Cherenkov and spheres)
  - Huge statistics determining surface.
  - Large difference between equi-charge and equi-time surfaces reflect topology of interaction (i.e. muon or electron).
  - There is much more information… how complex a topology can we extract?
- **High Energy ~1 GeV neutrino interactions may thus be studied (& Nucleon Decay)**
- Potential for long baseline experiments, and many others
- Does not interfere with lower energy (MeV) physics (e.g. reactors, geonus, supernovae, etc.)

Much useful work done by muon fitting using Fermat Principle by KL folks: Mitsui, Tajima, Enomoto and others. Thanks to UH colleagues (Jason, Misha, Shige, Steve, Stephanie, Sandip) for discussions that launched this investigation.

Fermat and Equi-Charge Surfaces



Strong separation between mu's and e's

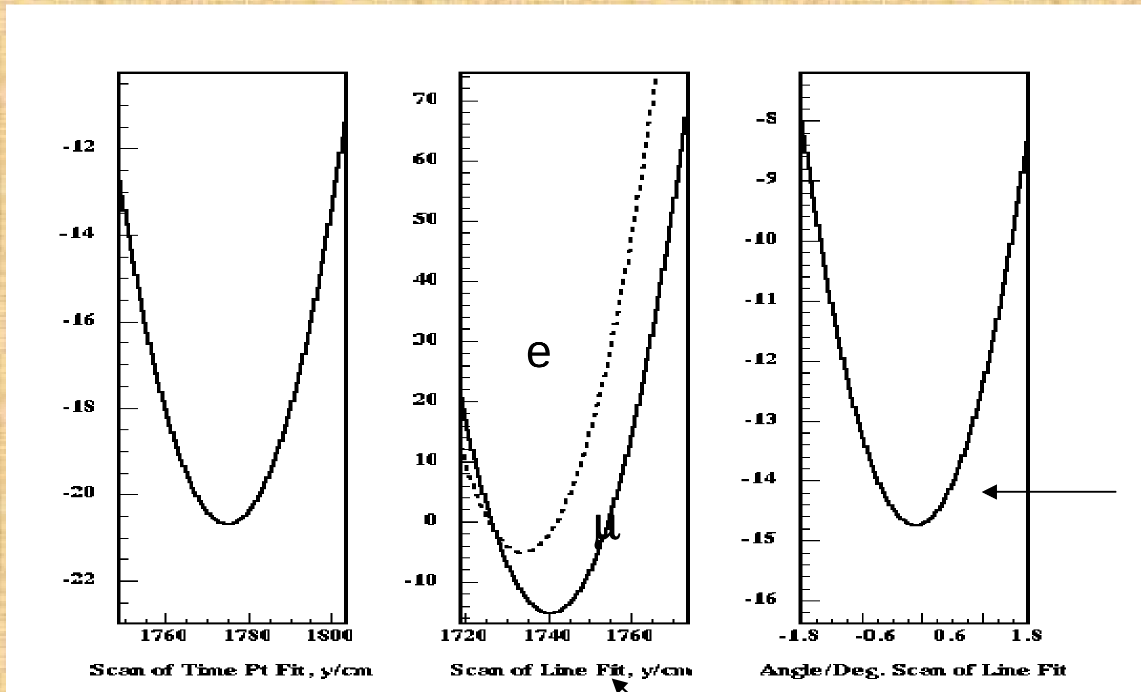
Angles to <1 degree

Untangle more complicated topology

Simple Point Fits (Q and T) Give Center of Track and point Near Origin

Chisquare/DOF

Equivalent



Muon angular resolution to <1 Degree

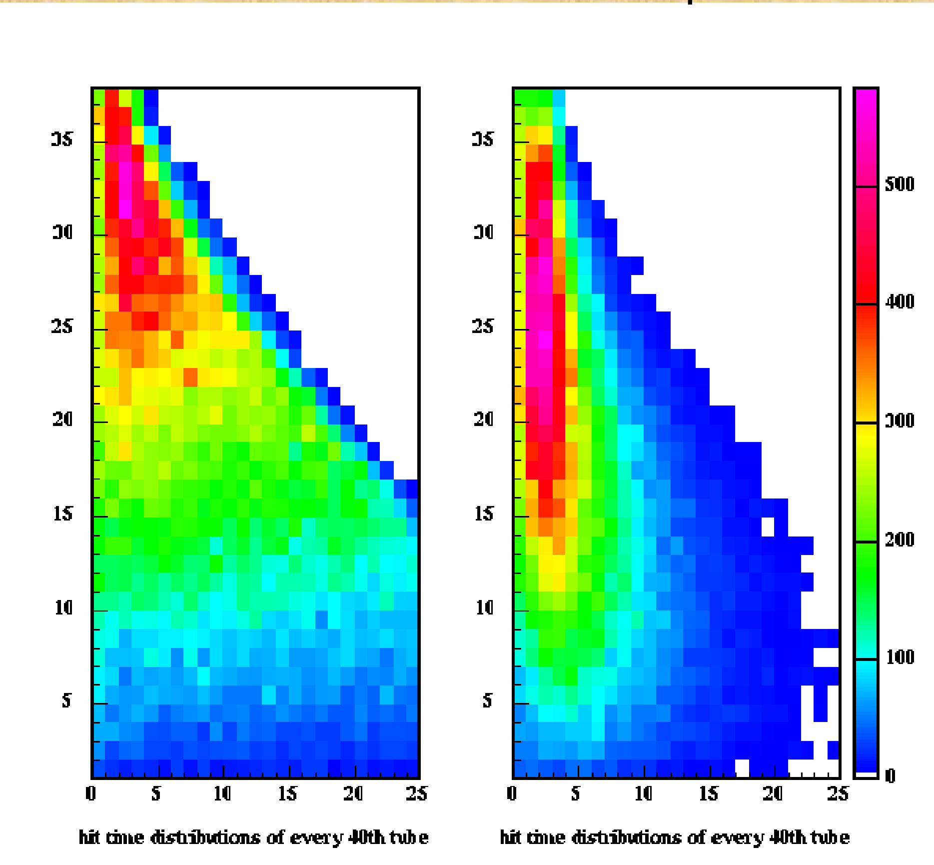
Vertex location to few cm with first point fit.

10 sigma better fit to line than shower profiles

Further: Much Information in Time Distribution of Hits (PMT Waveform)

Sample PMT hit time distributions from top of detector

1 GeV Muon



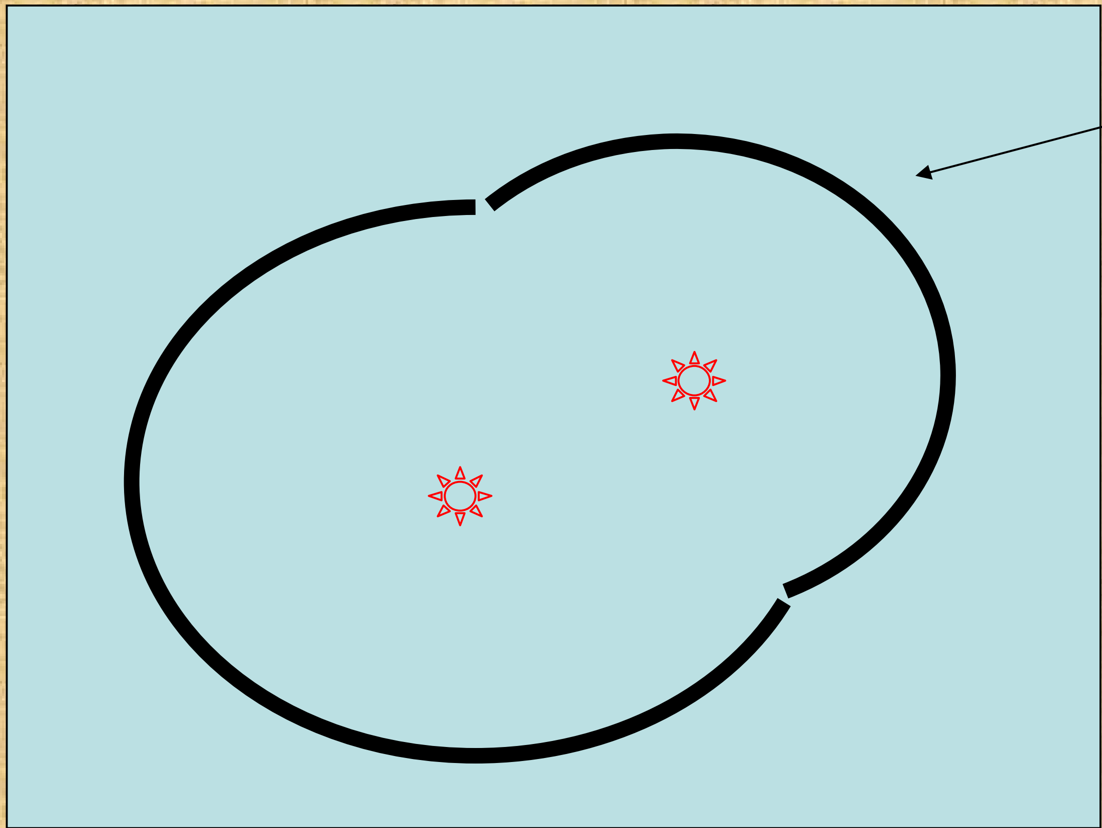
1 GeV e Shower

Given real world problems (PMTs, scint lifetime, scattering….), how much of this can we utilize? Needs detailed modeling.

There is much more information in the Fermat Surface: Multiple particles resolvable?

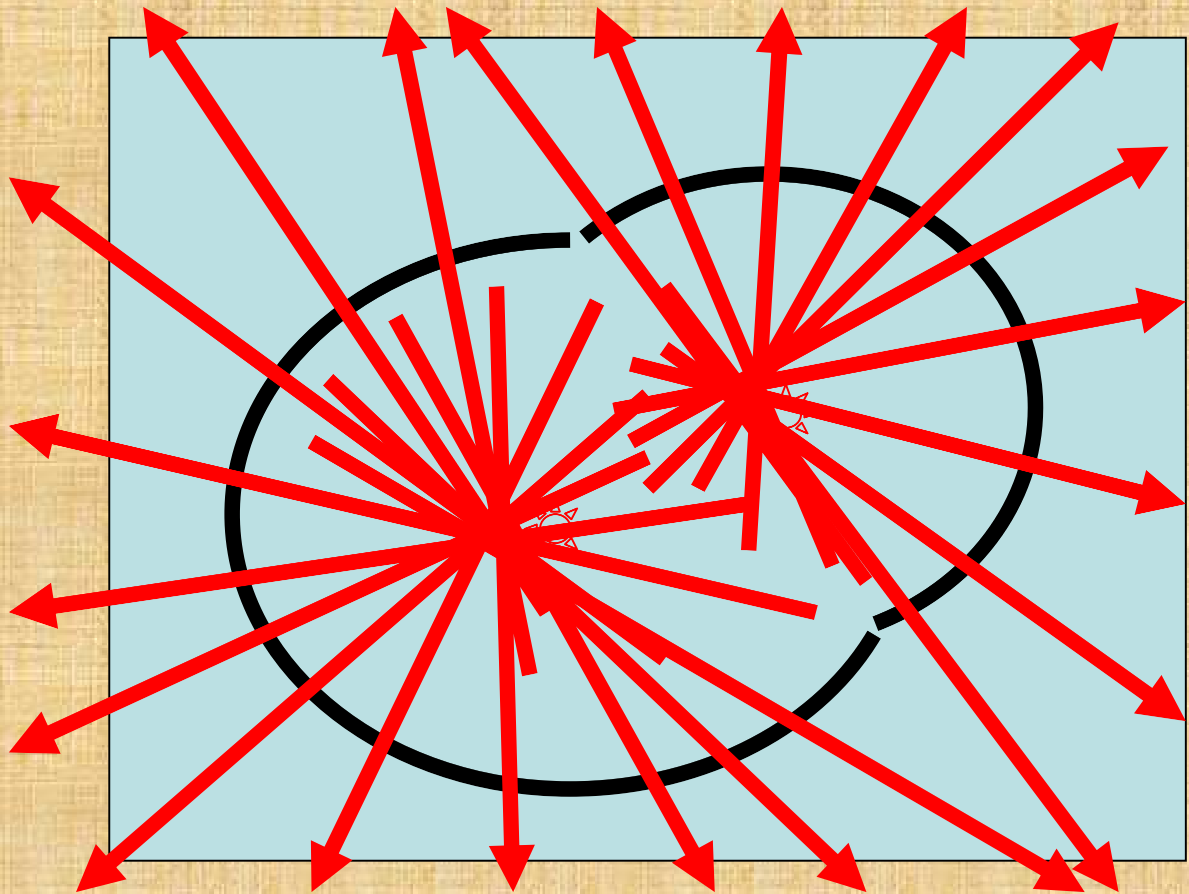
- Huge statistics on shape of surface.
- Local vectors determine shape (Q and T)
- Surface in some regions has texture.
- Key question for LB experiments: How well at resolving asymmetric pi-zeroes realtive to Water Cherenkov. Needs detailed Monte Carlo study.
- Need good model of light propagation in LS, including Cherenkov.

Fermat Surface Crossection for Two Tracks



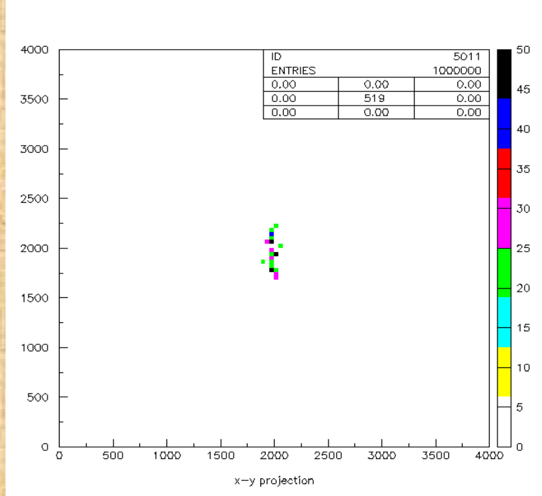
- Equi-time contours.
- How well can we resolve multi-track events via Fermat Surface fitting?

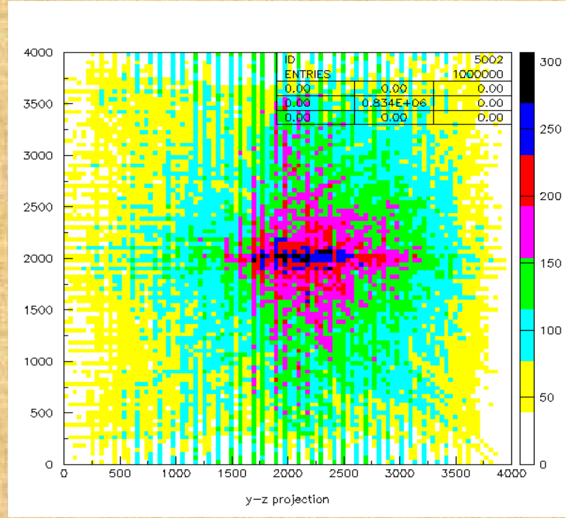
Pictorial Fermat Surface Crossection for Two Tracks



- Project back from PMT clusters by first-PE-time gradient.
- Do it in 3D, and include time (back projections crossing at same time).
- A form of tomography
- Demands high time resolution and dealing with prepulses.

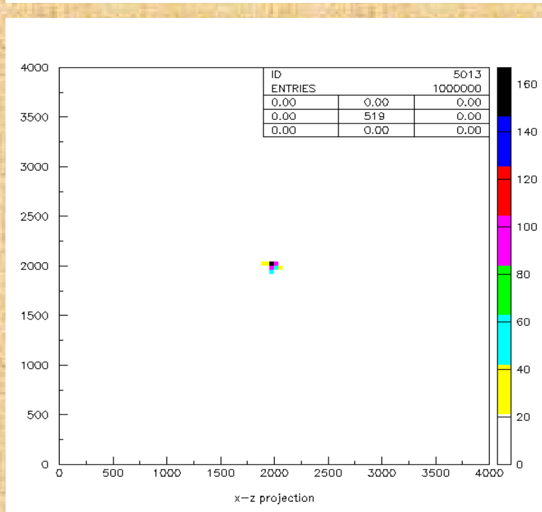
First Results on Tomographic Reconstruction from Fermat Surface

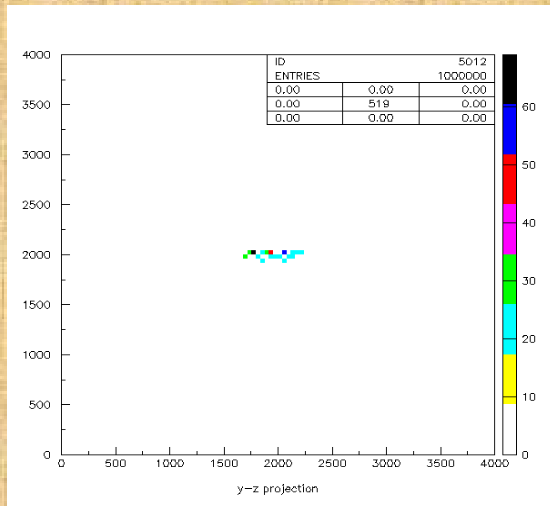




Should be able to reconstruct bubble chamber like images from multiple tracks

before contrast cuts





Example: Single 1 GeV Muon track

jgl 10 July '09

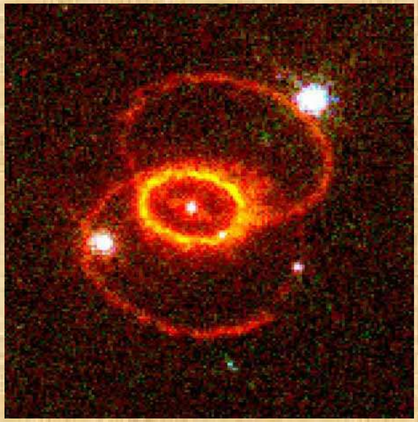
Applications

- Long Baseline with accelerators ~ 1 GeV
  - **Hanohano with Tokai Beam? (Demonstration)**
  - LENA with CERN beam?
  - New DUSEL Experiment with Fermilab Beam?
- Nucleon Decay (high free proton content)
  - See details of decays such as Kaon modes
- Particle Astrophysics (low mass WIMPS,…)
- All the Low Energy Physics (geonus, reactor studies, monitoring, solar neutrinos…..) unimpeded!

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.

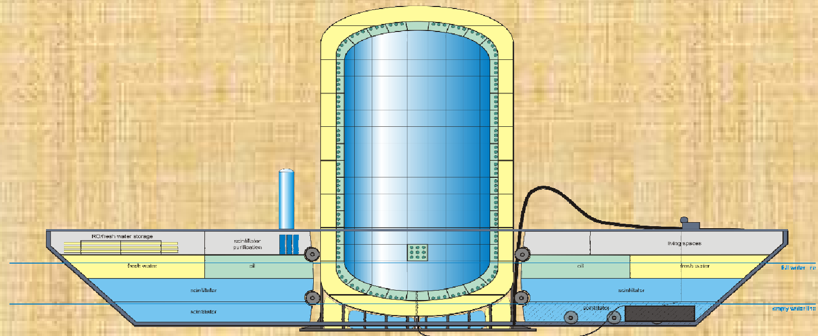
Summary of Expected Results
Hanohano- 10 kt-1 yr Exposure

- **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 θ_{13}≠0 w/multi-cycle & no near detector; insensitive to background, systematic errors; complementary to Minos, Nova
  - **Lots to measure even if θ_{13}=0**

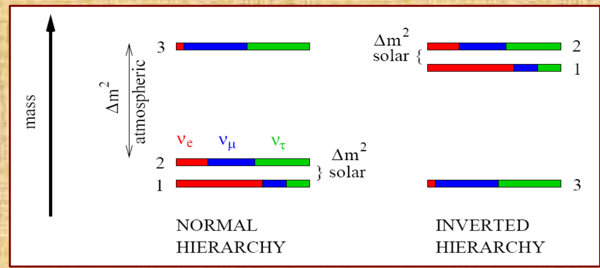
- **Much other astrophysics and nucleon decay too….**

Summary



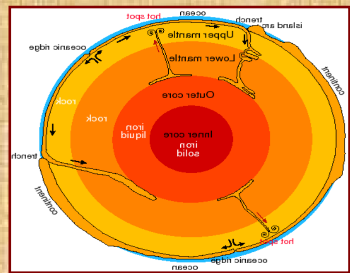
- **Proposal** for portable, deep-ocean, 10 kiloton, liquid scintillation electron anti-neutrino detector.

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



- First long distance portable reactor monitor.

- 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.