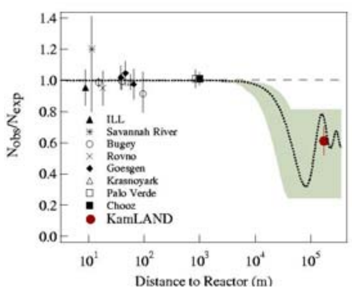
Reactor Monitoring (near and far) with Neutrinos

Neutrino Applications are on the horizon



John G. Learned

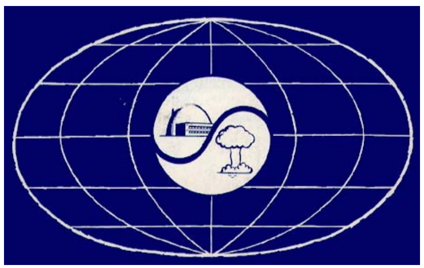
Physics and Astronomy, University of Hawaii

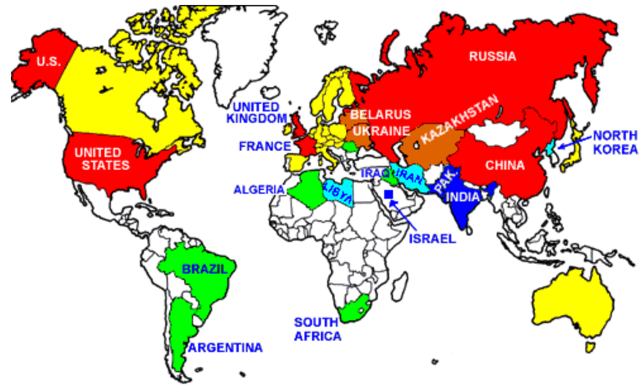
$\overline{\nu_e}$

relevant JGL background

- Particle physics and astrophysics, initiator and participant in many neutrino experiments (IMB, DUMAND, SuperK, KamLAND, K2K,+…).
- Pioneered much muon neutrino oscillations analysis in SuperK.
- Group were first to find SN1987A events in IMB
- Worked at SLAC: beam polarization, psi photoproduction, etc.
- Early work in liquid Ar drifting. co-proposed LANDD.
- Long worked towards establishment of neutrino astronomy.
- Long engagement in nucleon decay searches.
- Former life as engineer, worked in communications and cryptography.
- Also write neutrino phenomenolgy and speculative future science papers.

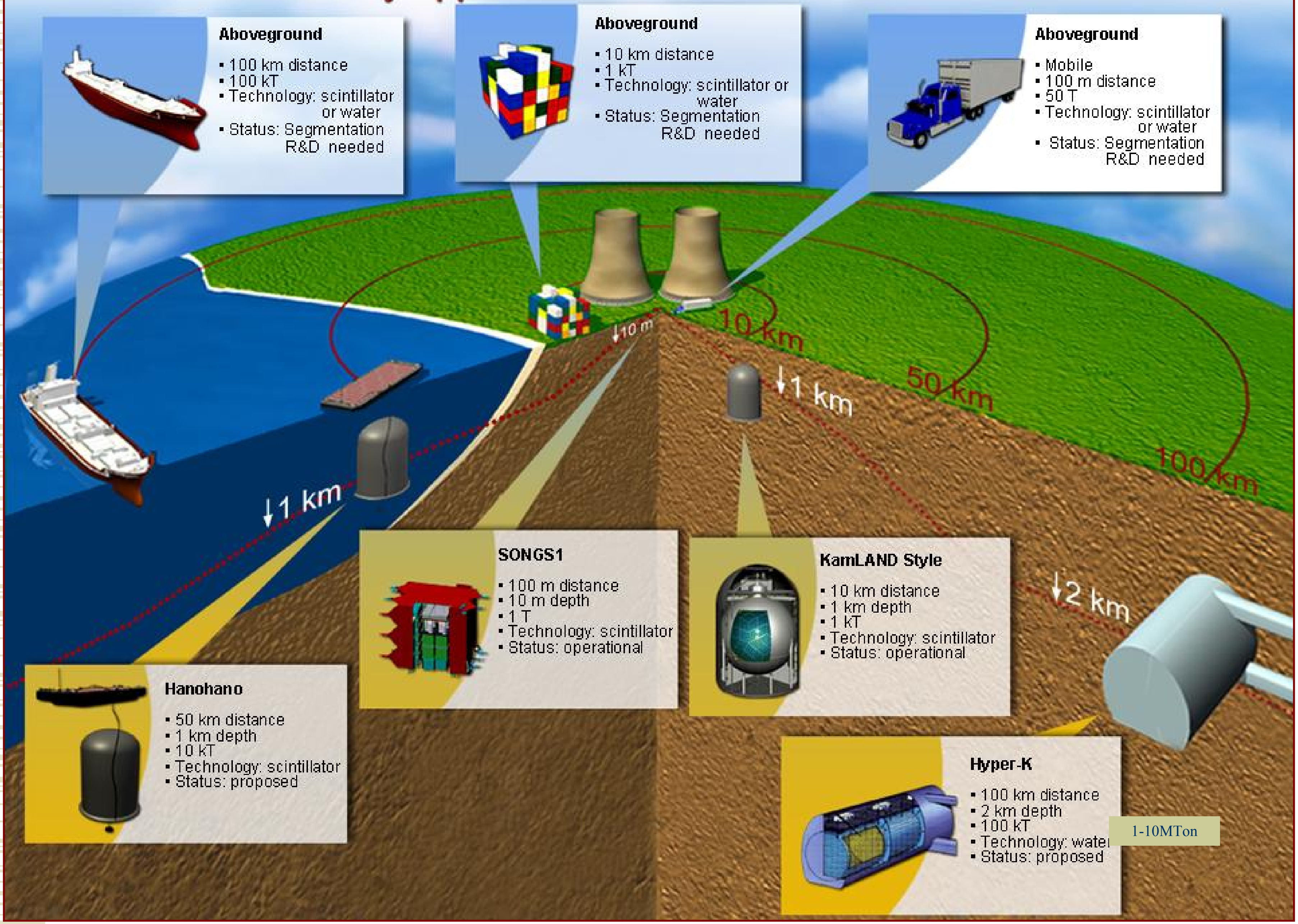
$\bar{\nu}_e$ Nuclear Proliferation is a Great Danger to Mankind: **Can ν Physics Help?**





- Monitor cooperating reactors for compliance with stated operations (no making bomb material)? Yes, close-in. (Bernstein talk)
- 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



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Outline

- Review anti-neutrino detection and state of the art of measuring properties, mainly oscillations.
- Long range reactor measurements, potential and some examples.
- Hanohano: geophysics, particle physics and remote reactor monitoring demonstration
- Summary of needs to make long range progress.

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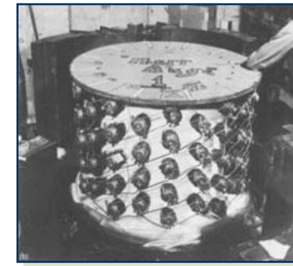
Reines' Old Method: Detect Inverse Beta Decay

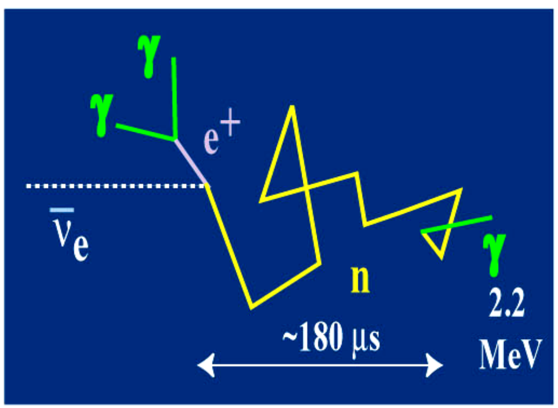


Need ~1 MeV sensitivity

reaction process : inverse- β decay $(\bar{\nu}_e + p \longrightarrow e^+ + n)$

$n + p \longrightarrow d + \gamma$

distinctive two-step signature



$$E_{th} = \frac{(M_n + m_e)^2 - M_p^2}{2M_p} = 1.806\ MeV$$

- **prompt part :** e^+

$\bar{\nu}_e$ energy measurement

$$E_\nu \sim (E_e + \Delta)[1 + \frac{E_e}{M_p}] + \frac{\Delta^2 - m_e^2}{M_p}$$

$$\Delta = M_n - M_p$$

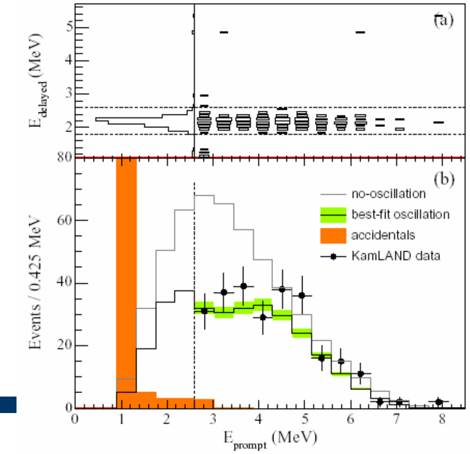
- **delayed part :** γ **(2.2 MeV)**

(shorter time & ~8 MeV in Gd or Cl)

- **tagging : correlation of time, position and energy between prompt and delayed signal**

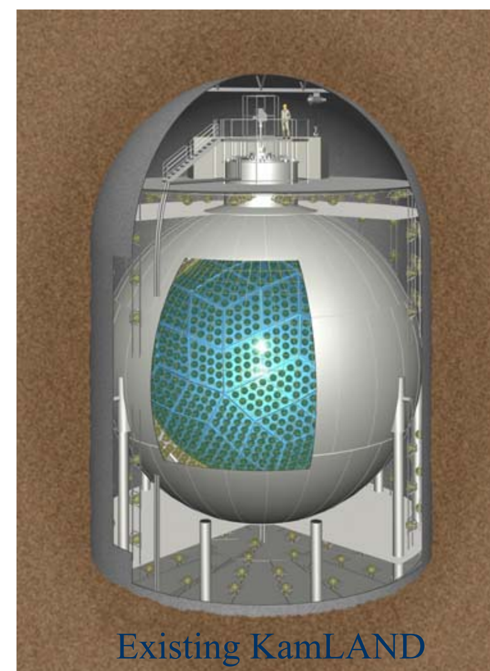
$\bar{\nu}_e$

Long Distance Reactor Rates



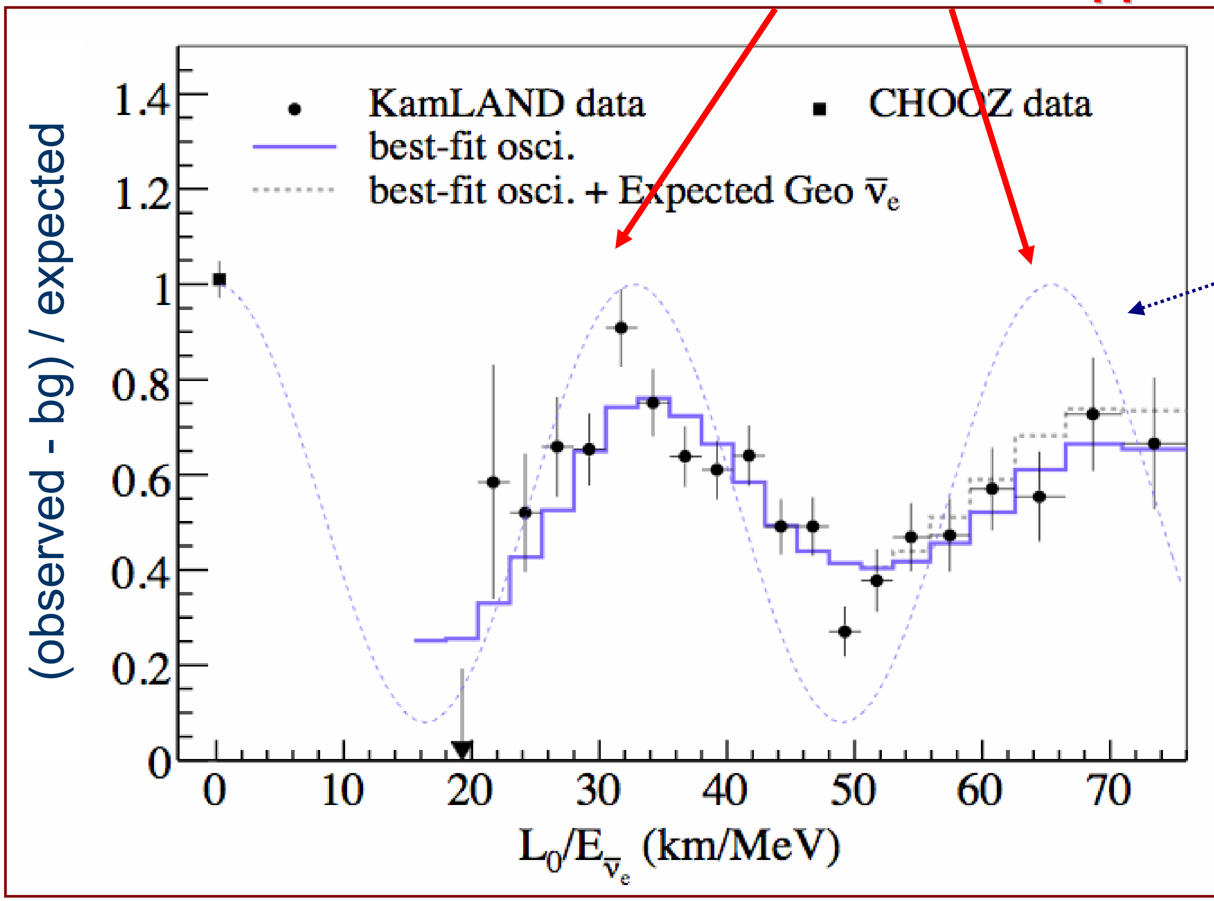
$$R_{\bar{\nu}_e} \cong \frac{500}{day}\left(\frac{P}{1GW}\right)\left(\frac{1000\ km}{L}\right)^2\left(\frac{V}{1km^3}\right)$$

- **Scale rates from KamLAND measurements ~0.5/d from 180km, including oscillations.**
- **Negligible background if deep (> 3km water equiv). Less depth manageable, but needs study.**


Existing KamLAND

Survival Probablity: L/E Variation

Oscillations: 1st and 2nd reappearance!

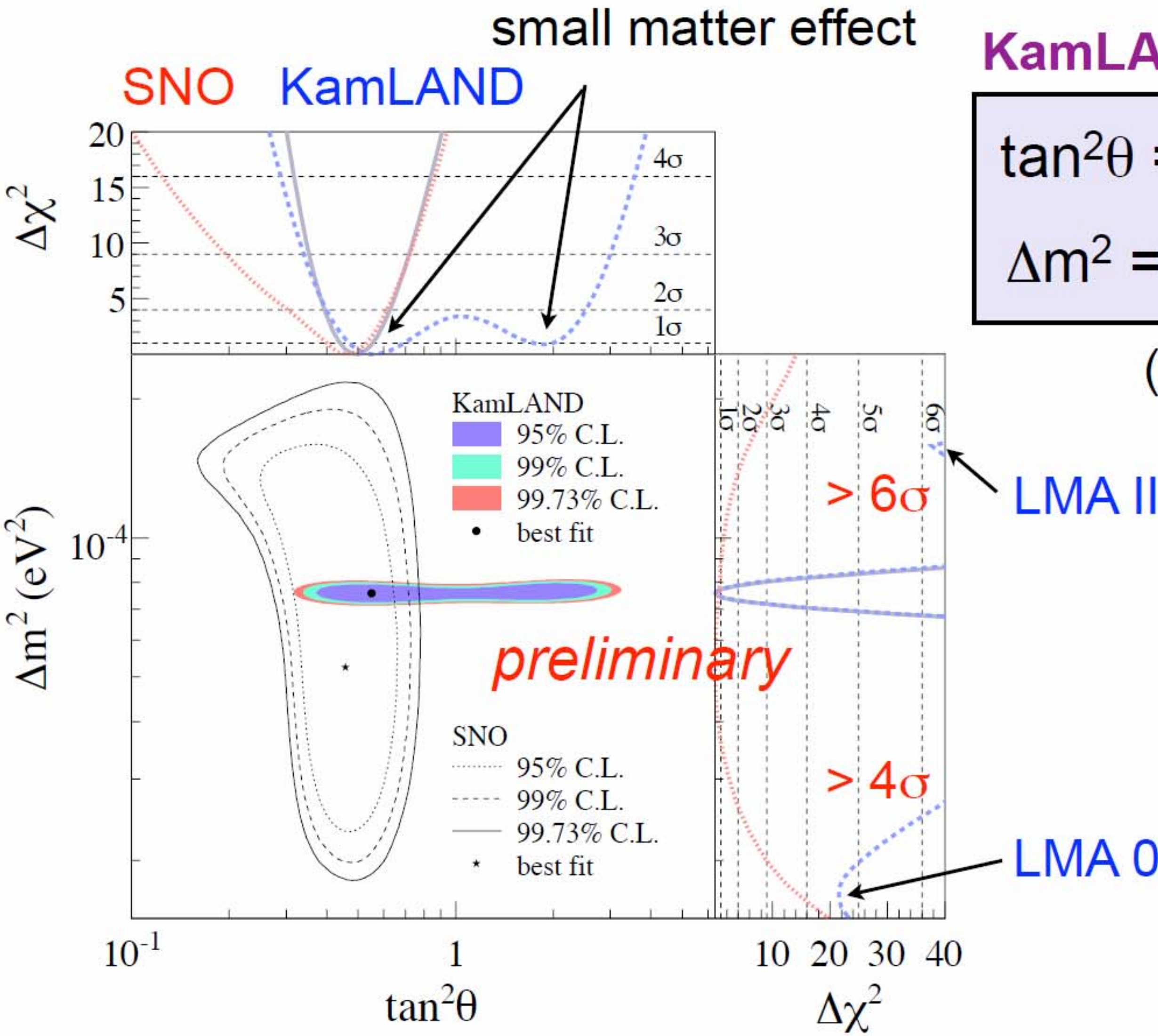


Expected survival probablity for point source at 180km baseline

L_0 = 180km flux-weighted average reactor distance

Definitely oscillations… alternatives not viable any more.

Oscillation Parameters



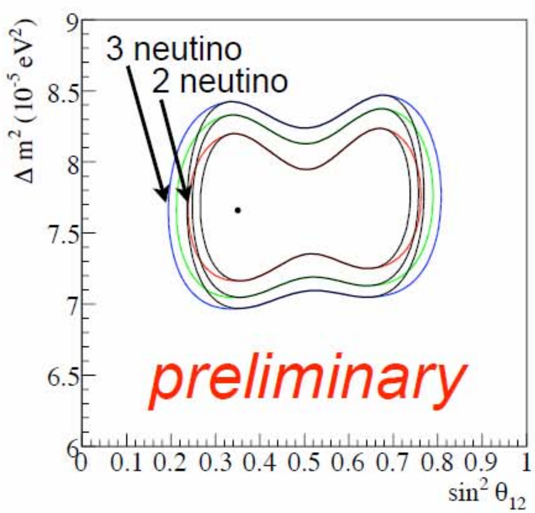
KamLAND only

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

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

(marginalized error)

3 neutrino effect

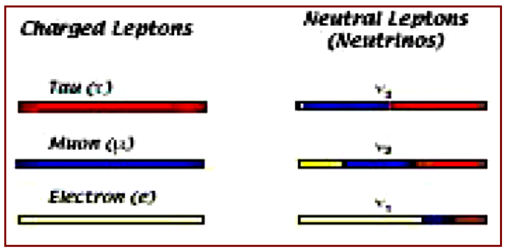


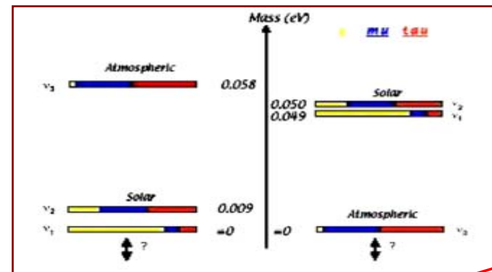
same result for Δm^2

thanks Patrick Decowski

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

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

Incredible progress in the last decade!

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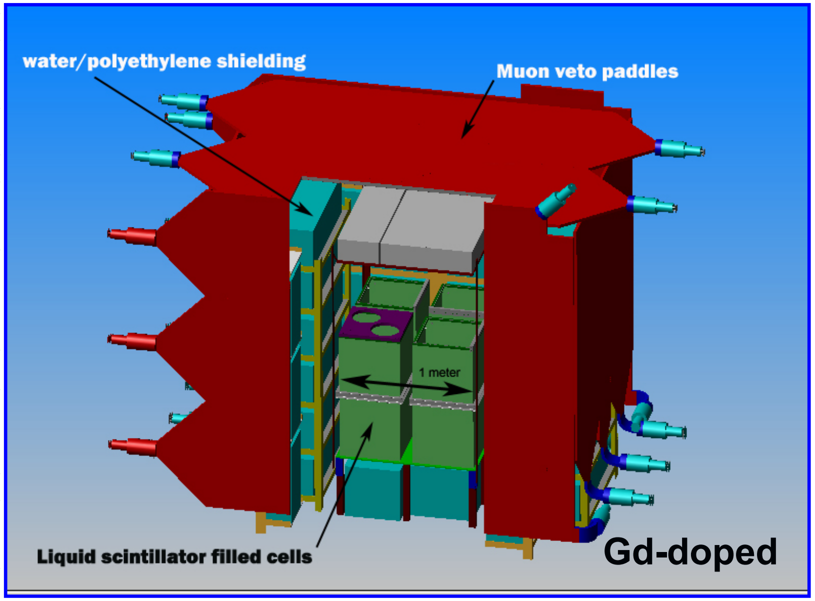
Close-in Monitoring: Seems to be ready to develop for wide deployment

See notes from JASON briefing Thur 7/10/08 by Adam Bernstein of LLNL



LLNL/Sandia Antineutrino Detector at San Onofre

Currently operational at SONGS:

· 3 Test Detectors (LLNL/Sandia)

· Prototype coherent detector (Collar)

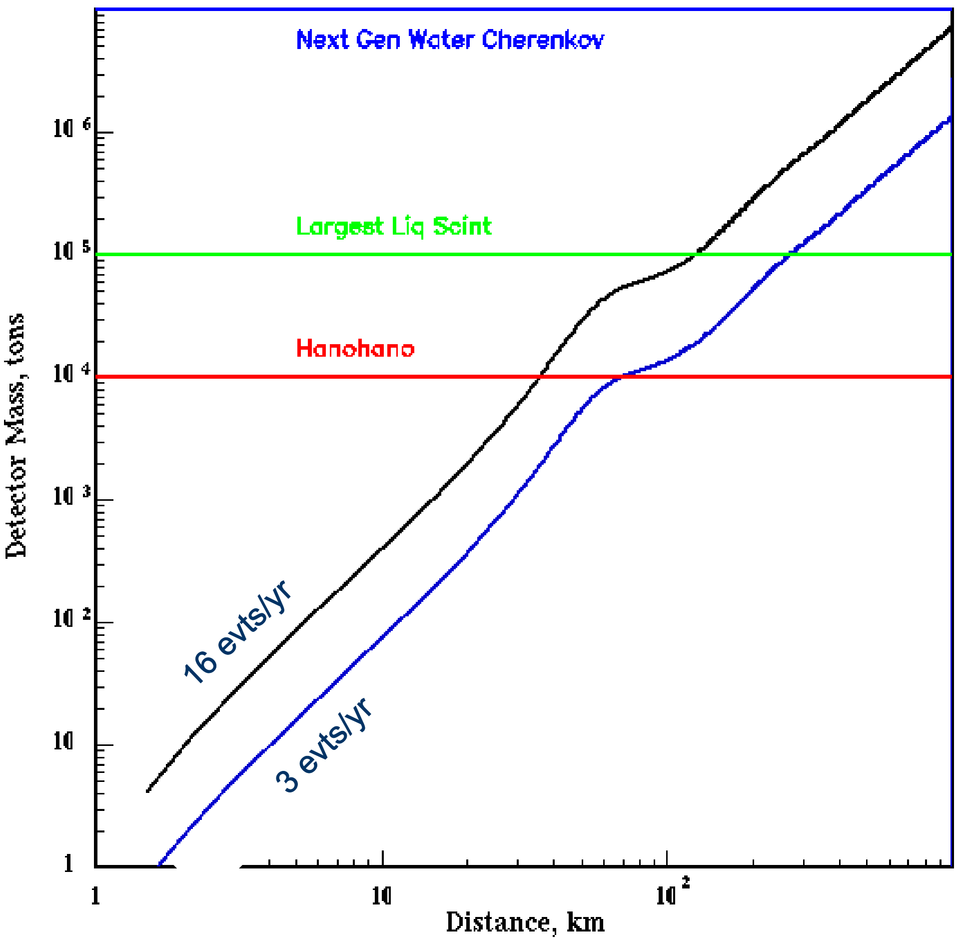
· Few meters of concrete shielding

· Unintrusively monitor daily operations (present IAEA protocol requires tap into plumbing!)

· Possible economic benefit to power companies.

Need development of surface detector for use in portable container outside. Must use segmentation to beat backgrounds.

$\bar{\nu}_e$ Reactor Monitoring with Anti-Neutrinos



small 10 MWt reactor observed with 10MT detector <u>no background</u>

- daily ops out to ~60 km

- annual output to >1000 km

$\bar{\nu}_e$

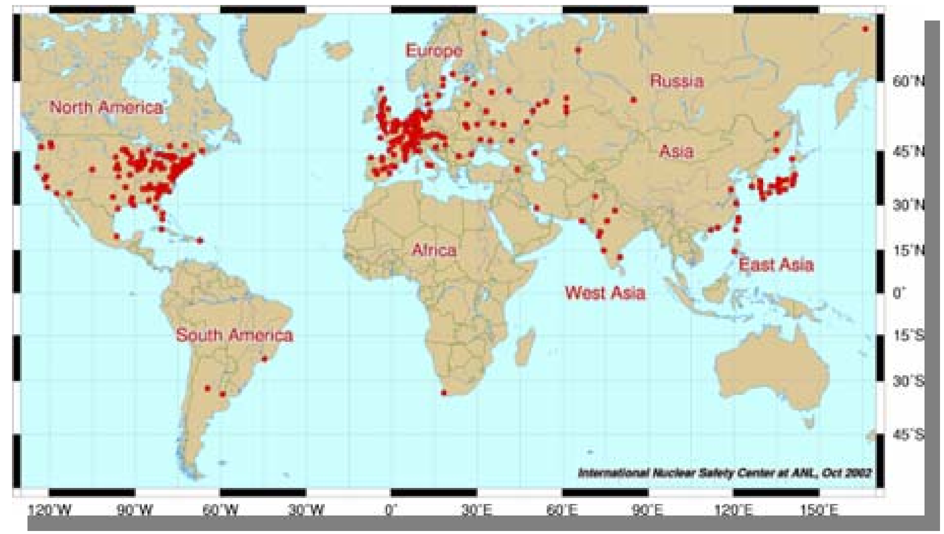
Sum of All Reactor Power

- 440 power reactors, 2GWt/reactor
- Rate in 1 gigaton about 17,000 nuebar/day
- Typical pwr reactor 1000 km away,

  1543 cts/day,

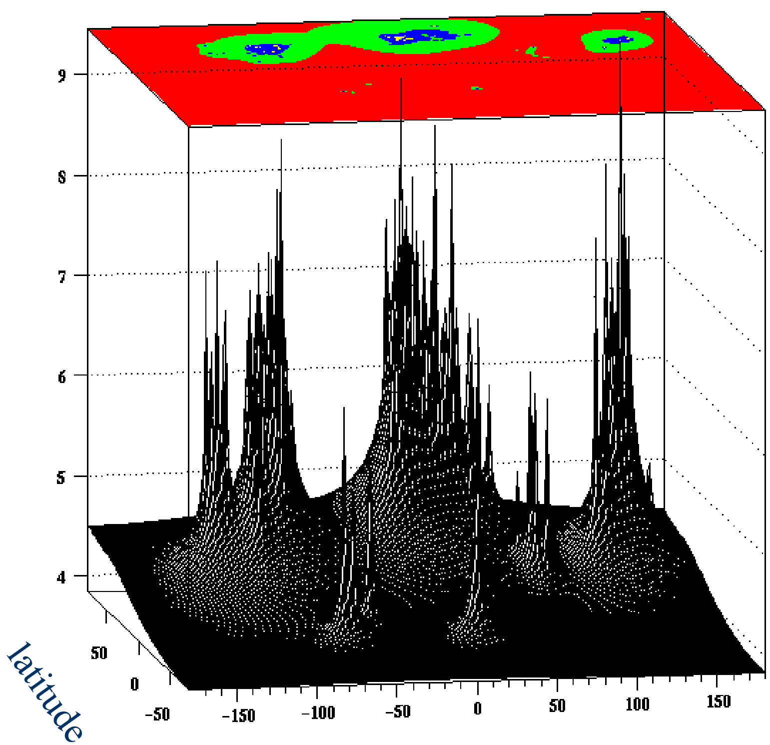
  ~12 σ measurement

  each day!

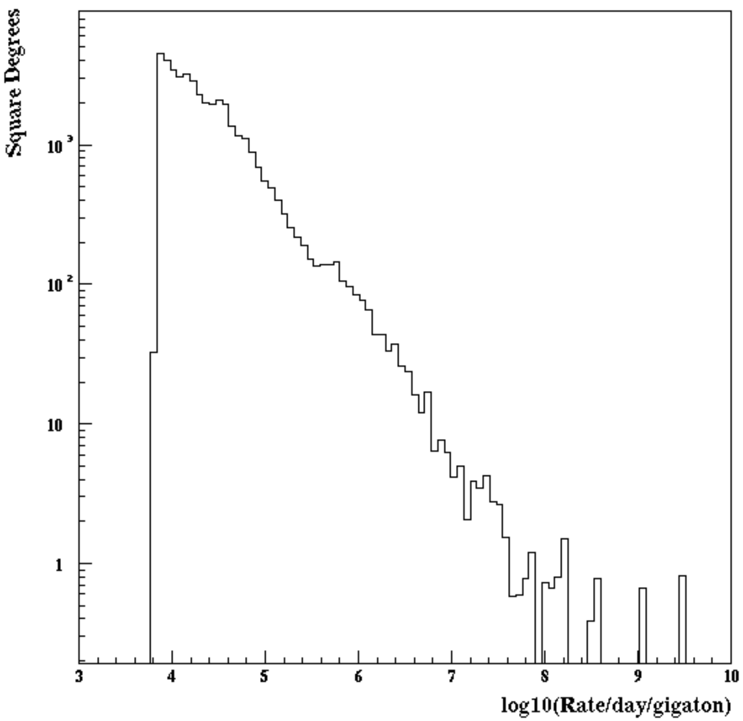


25 MWt
N. Korea
reactor

World $\overline{\nu}_e$ Rates



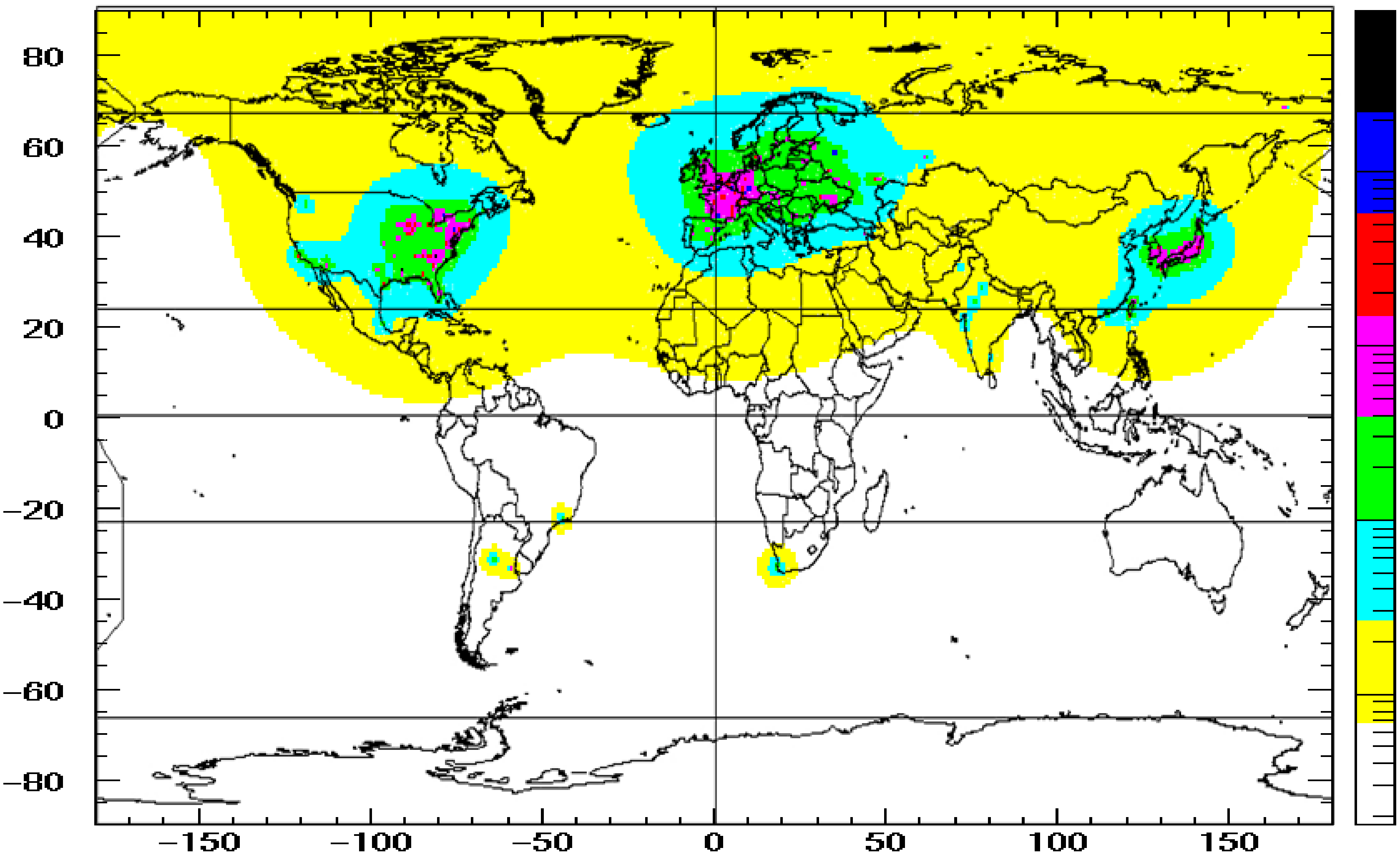
most probable ~10^4 counts per day



gigaton detector $\log_{10}$(rate)

Reactor $\overline{\nu}_e$ Rates with Oscillations

nuebar events/kt-yr



Thanks Andreas Piepke

$\bar{\nu}_e$

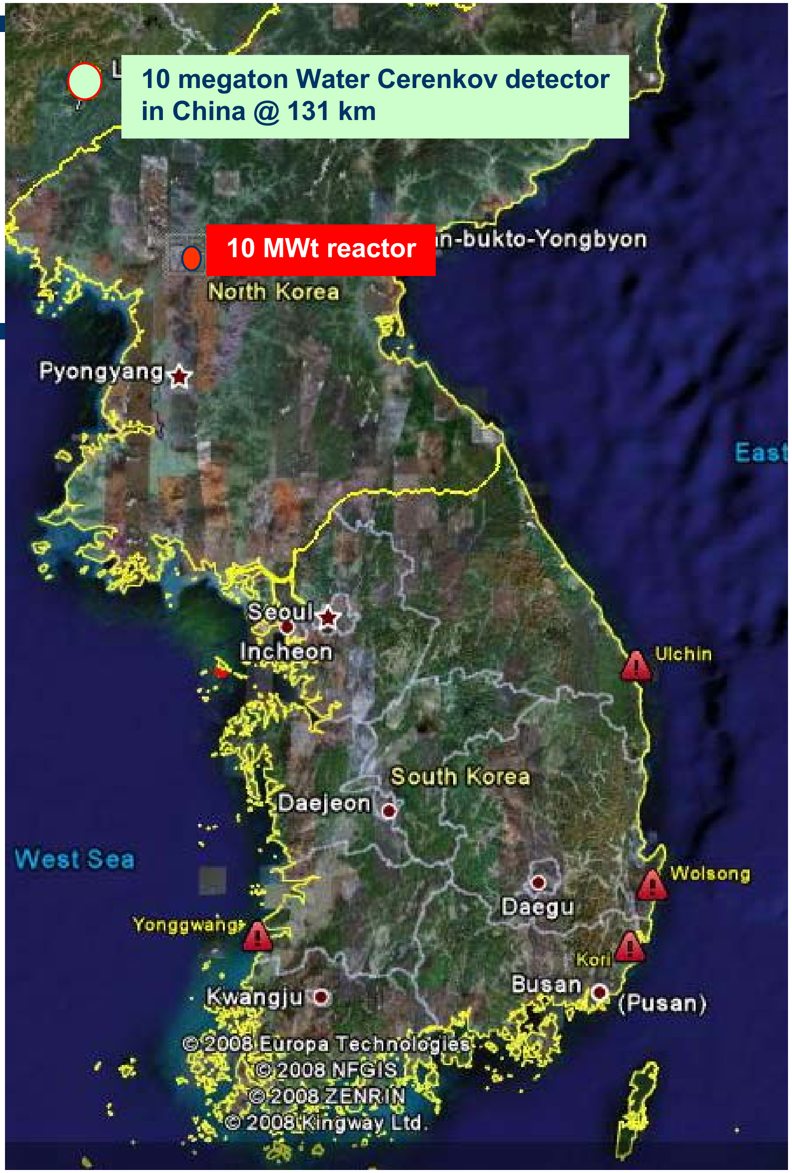
Bernstein's Example 3:
10 MWt reactor in YongByon @130 km

But assume: 10 megaton water Cherenkov detector

Reactor	Standoff	Evts/yr	S/sqrt(B)
All SK reactors (~40GWt)	400-600 km	288k	
Unknown 10 MWt	130 km	1100	~2 σ

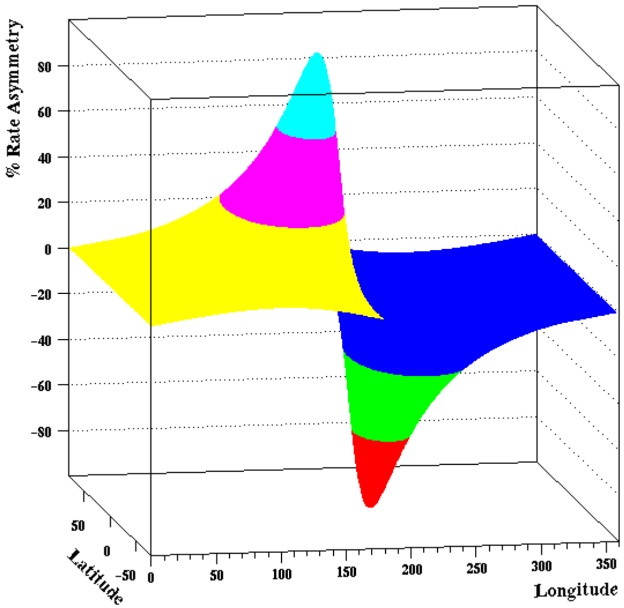
What can improve this?
- Precise monitoring of SK reactors (predict Bkgd)
- Multiple detectors (several 1 MT detectors)
- Time variations in other reactor signals
- Directionality (not ready yet)

A 10 MT detector could be built now, in a mine, BUT COSTLY.

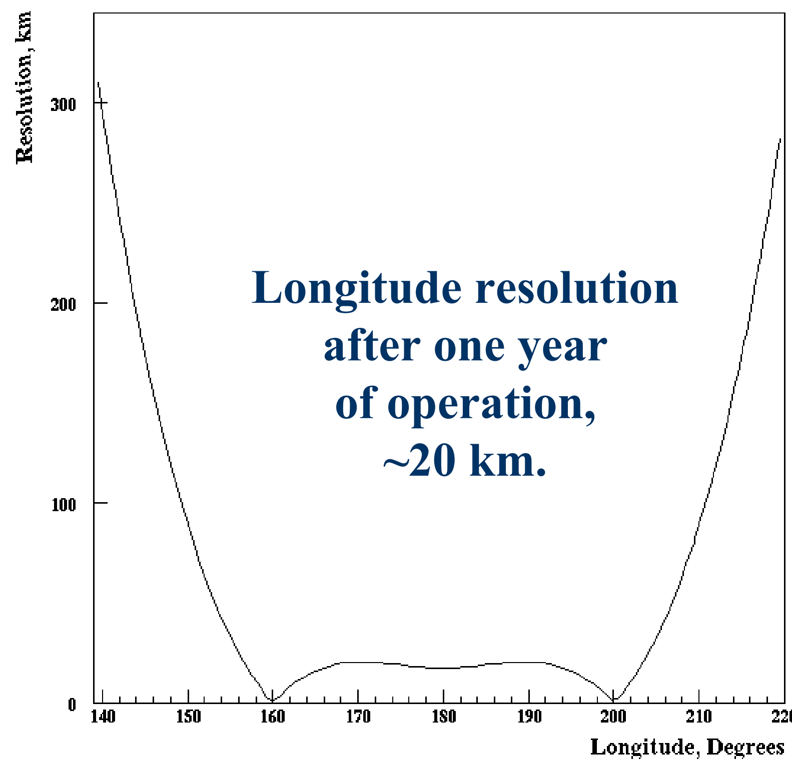


10 MWt reactor in NK could be monitored from 130km as of now, but is it worth it?

Toy Model of Unknown Reactor Position Resolution in One Year



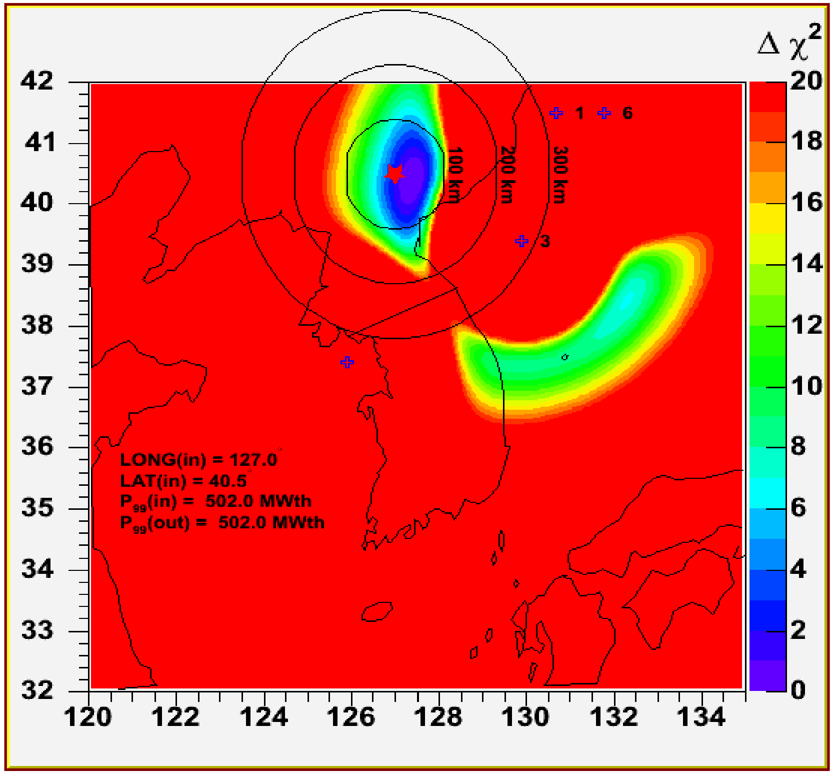
Counting rate asymmetry, $(n_1-n_2)/(n_1+n_2)$, between 2 detectors spaced **4500 km** apart along the equator.



- 2 detectors gets longitude and power of unknown reactor.
- 3 detectors gets 2D location and power.

Practical Application

- Example: finding unknown PRK reactor with 3 10MT detectors.
- Answer depends upon question: location known? Power known? Neighbor reactors monitored?
- Network can detect bomb tests too.



Far future: Gigaton Scale Multi-component Detector

- 10 Megaton modules?
- Place in deep ocean for low rates and mobility. Mine based detectors not affordable.
- Must use water, nothing else affordable.
- Not ocean water, for acceptable backgrounds.
- Possibly load with low ^{40}K salt: not expensive, helps neutron detection and 3% buoyancy of seawater.

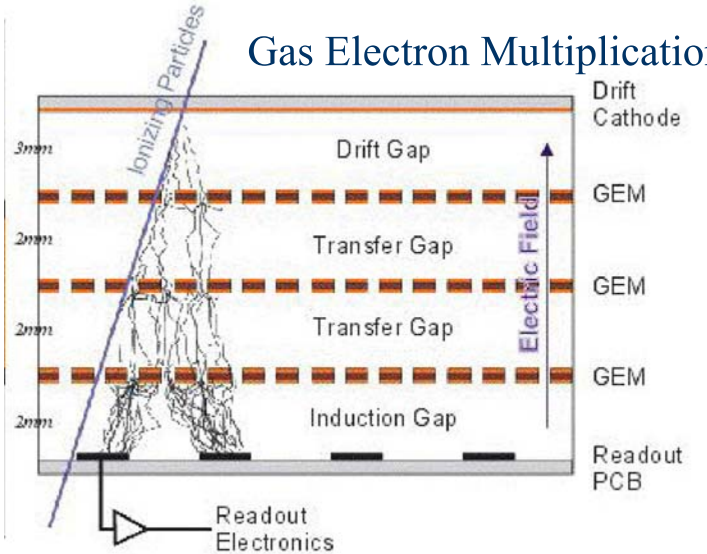
$\overline{\nu}_e$

Need New Photodetectors

- Need research and industrial effort on new technology.
- Develop new photodetection with cost reduction of 10x, aim for 100x.
- PMTs cost $1/cm^2 , aim for $100/m^2
- Encouraging new technology with sheets, such as micromegas technique.
- Explore organic sensors.
- Possibility for photodetector "wallpaper".
- Significant investment needed in R&D.

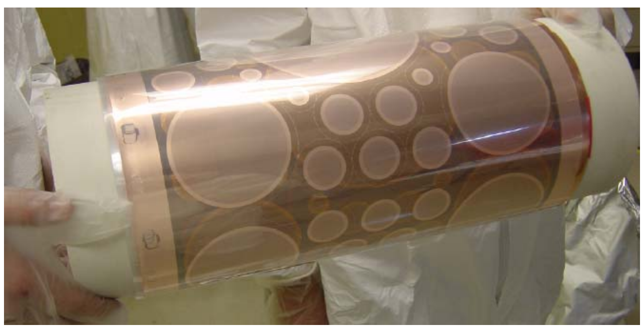
PMTs outmoded?

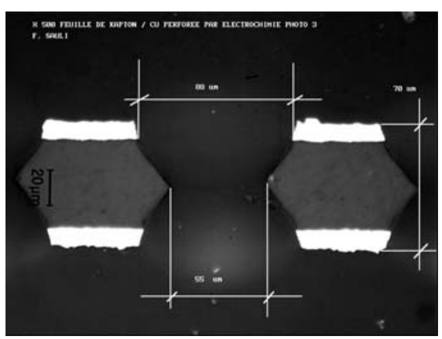
Gas Electron Multiplication

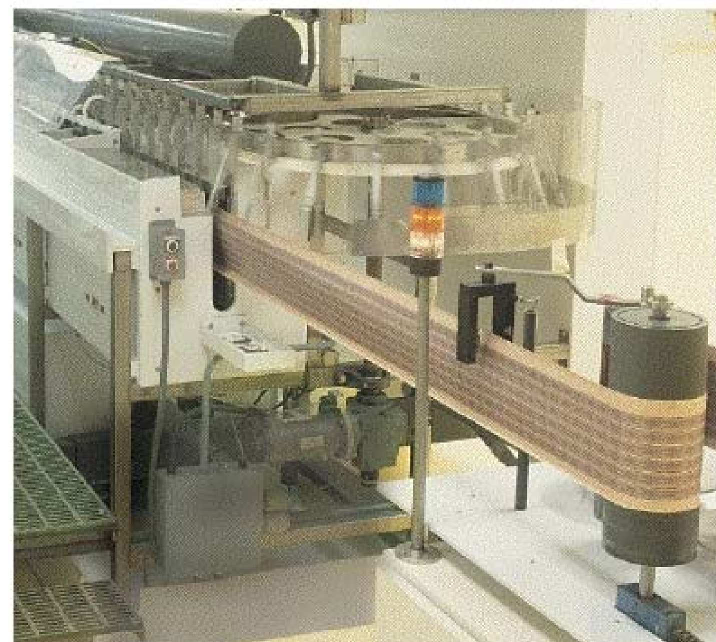


“Wallpaper” photodetectors?

Original motivation for first mass-production of MPGDs: Low-background applications (in particular coherent neutrino-nucleus scattering… J. Collar)



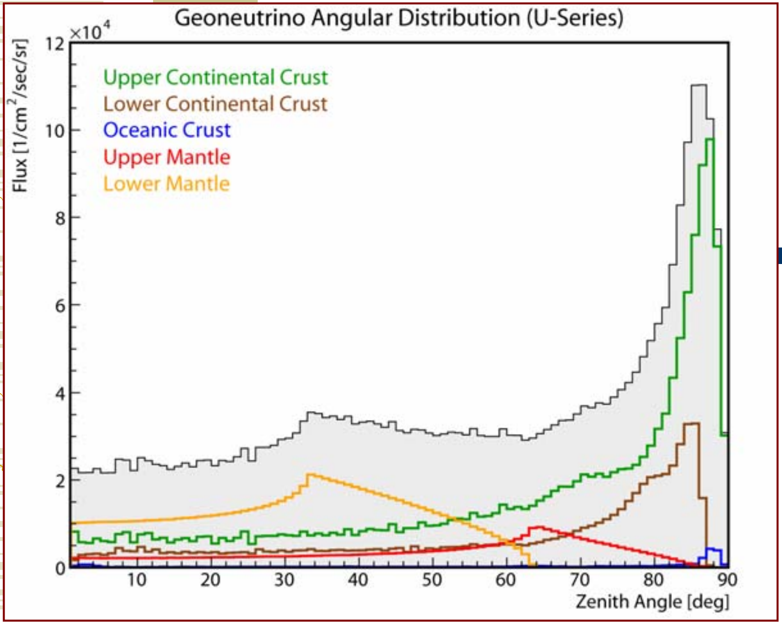




but many other applications can profit from “industrialization”: TPC readout, large-area tracking devices, X-ray astronomy, neutron physics, medical & industrial imaging, photonics... **very large ν detectors?**

P. Barbeau

Future Dreams: Directional Sensitivity



Directional information provides:

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

Good News:

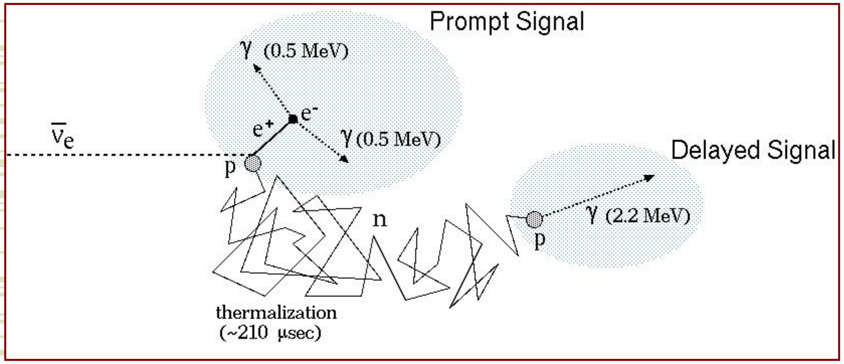
- Recoiled neutron remembers direction

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)

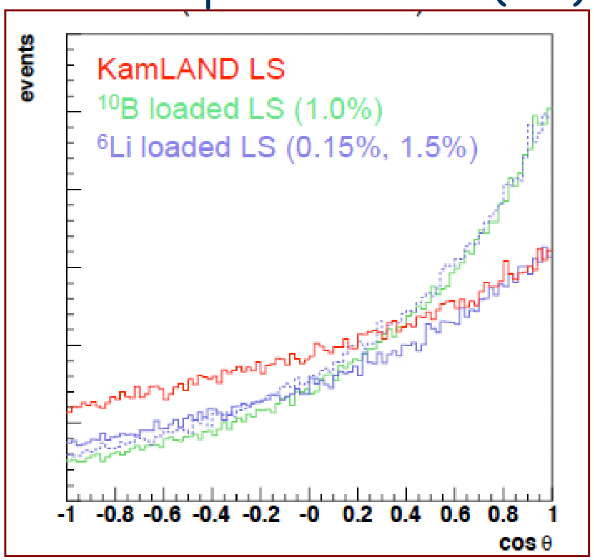


Towards Directional Sensitivity 1

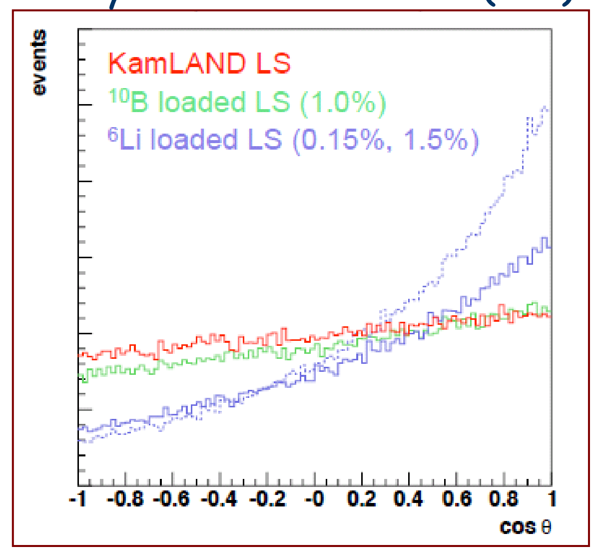
^{6}Li loading helps preserving directional information

- ^{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

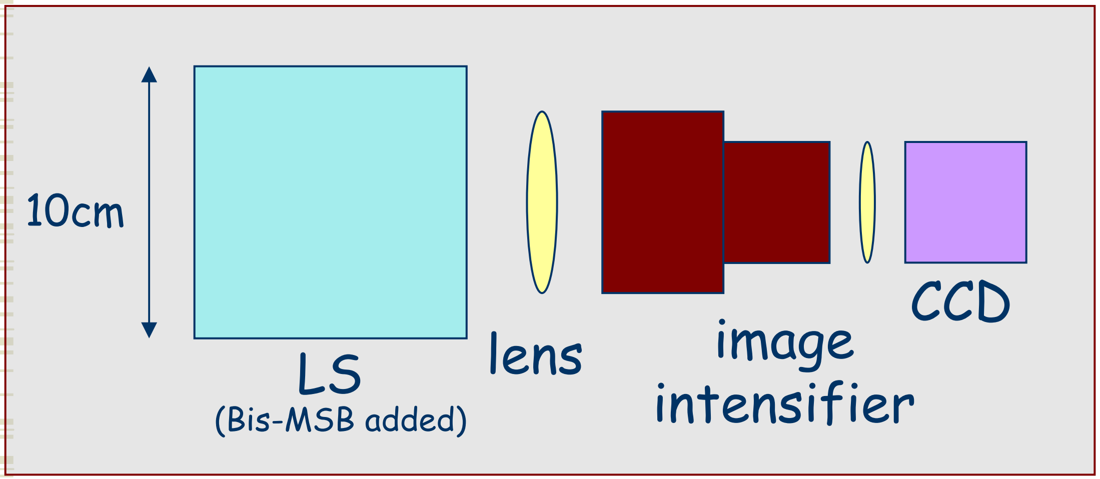
Towards Directional Sensitivity 2

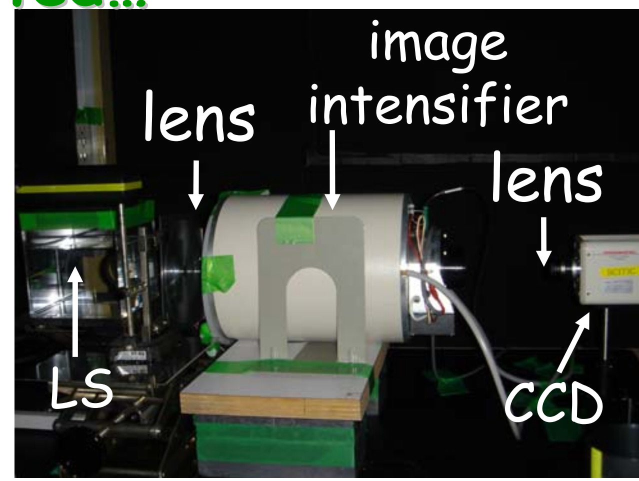
$\bar{\nu}_e$

~1M pixel imaging can achieve 1 cm resolution

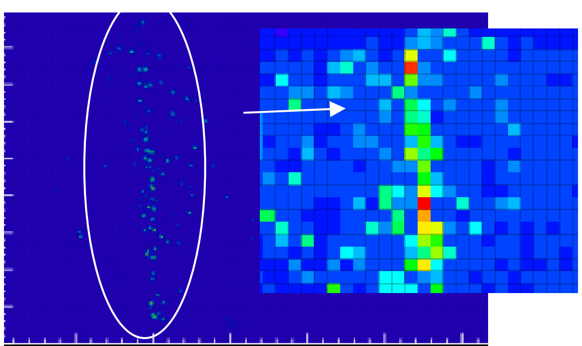
- Proper optics need to be implemented
- Sensitivity to 1 p.e. and high-speed readout required

First step for LS imaging, just started…

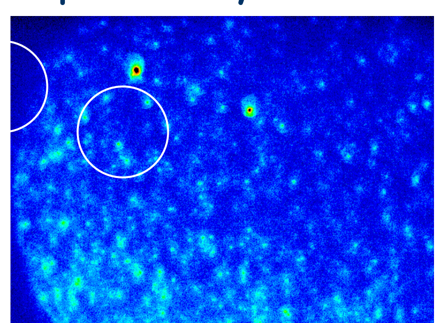




Muon Event ???



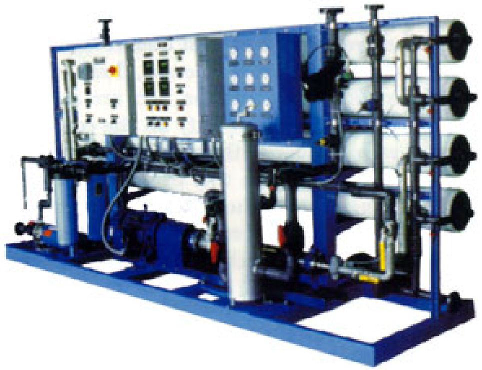
Isotope Decay Event ???

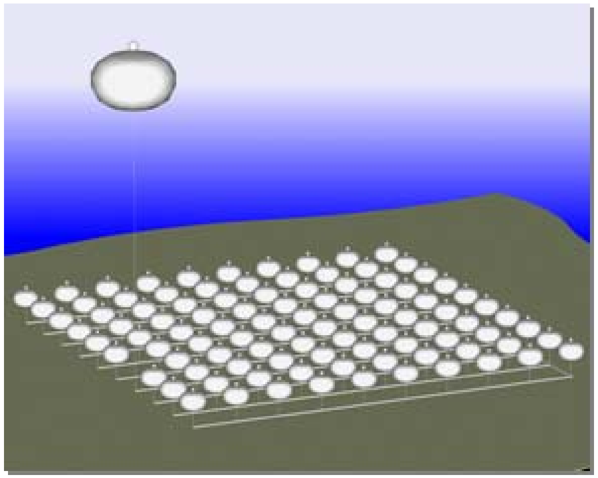


Tohoku

10 Megaton Modules

- Assume 100 modules at 10^7 ton each.
- Reverse osmosis is affordable.
- Size equivalent to balloons with radius 134 m.
- Flexible bag with photodetector and electronics on inner wall, pressure tolerant.
- Anchoring forces <30 tons, OK.
- Slightly buoyant, haul up for service.
- Large quantity cost on $100 M scale.



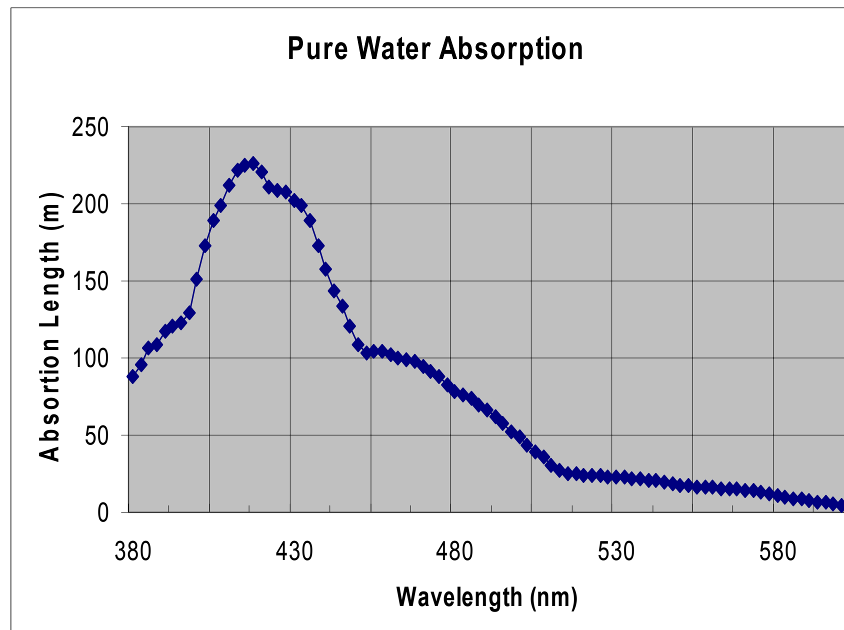


$\bar{\nu}_e$

Sensitivity

- **Assume 100% wall coverage with photodetectors.**
- **Pure water, >100 m attenuation length.**
- **Sensitivity to Cherenkov ~same as SuperK: 10 PE/MeV (larger size, larger coverage).**
- **Add some dopant to multiply sensitivity, but keep directionality.**
- **Achieve ~3x sens, min signal ~66 PE at 2.2 MeV appears viable.**

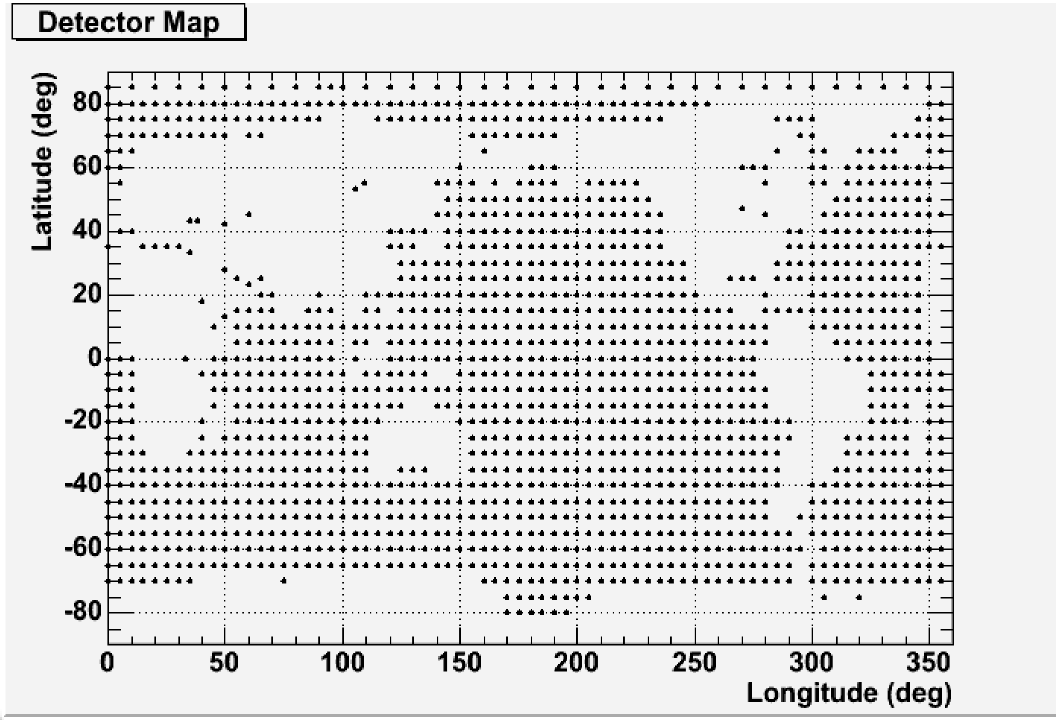
optical absorption length reaches
225 m in pure water



Pope & Fry 1997

Far Future: Exploring Distribution of Detectors Around the World

- Easy model: place them on a 5 deg x 5 deg grid, except near poles, in all oceans
- Add in some lakes (Baikal, Victoria, Great Lakes)
- Get 1596 detectors…. clearly too many.
- Use for study, but can eliminate most.



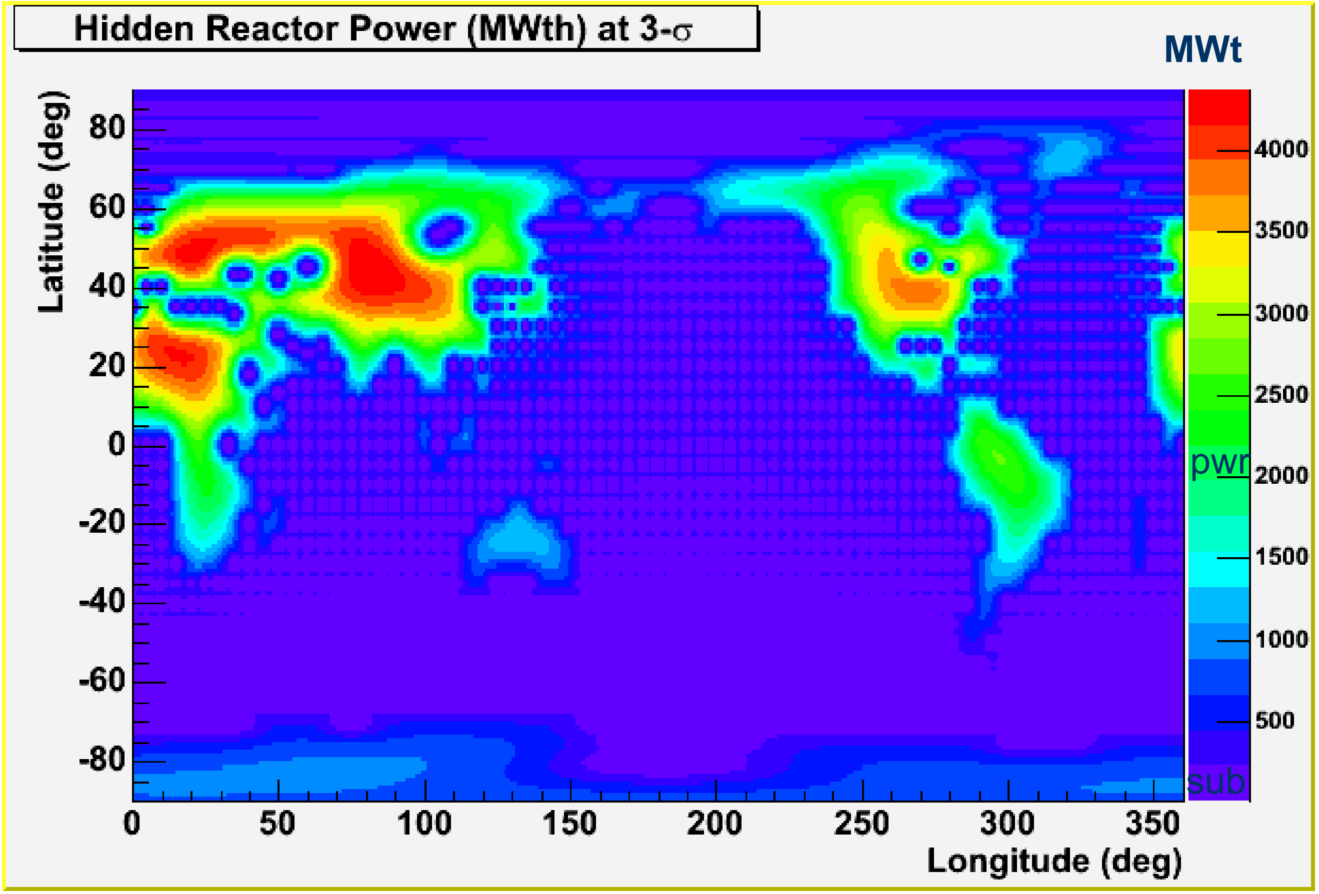
Finding Hidden Reactors **Day-by-day**

One day 3 sigma detection hidden reactor power

1596 10 megaton detectors

(roughly every 5 deg in oceans and some big lakes)

Can eliminate many detectors in southern oceans.



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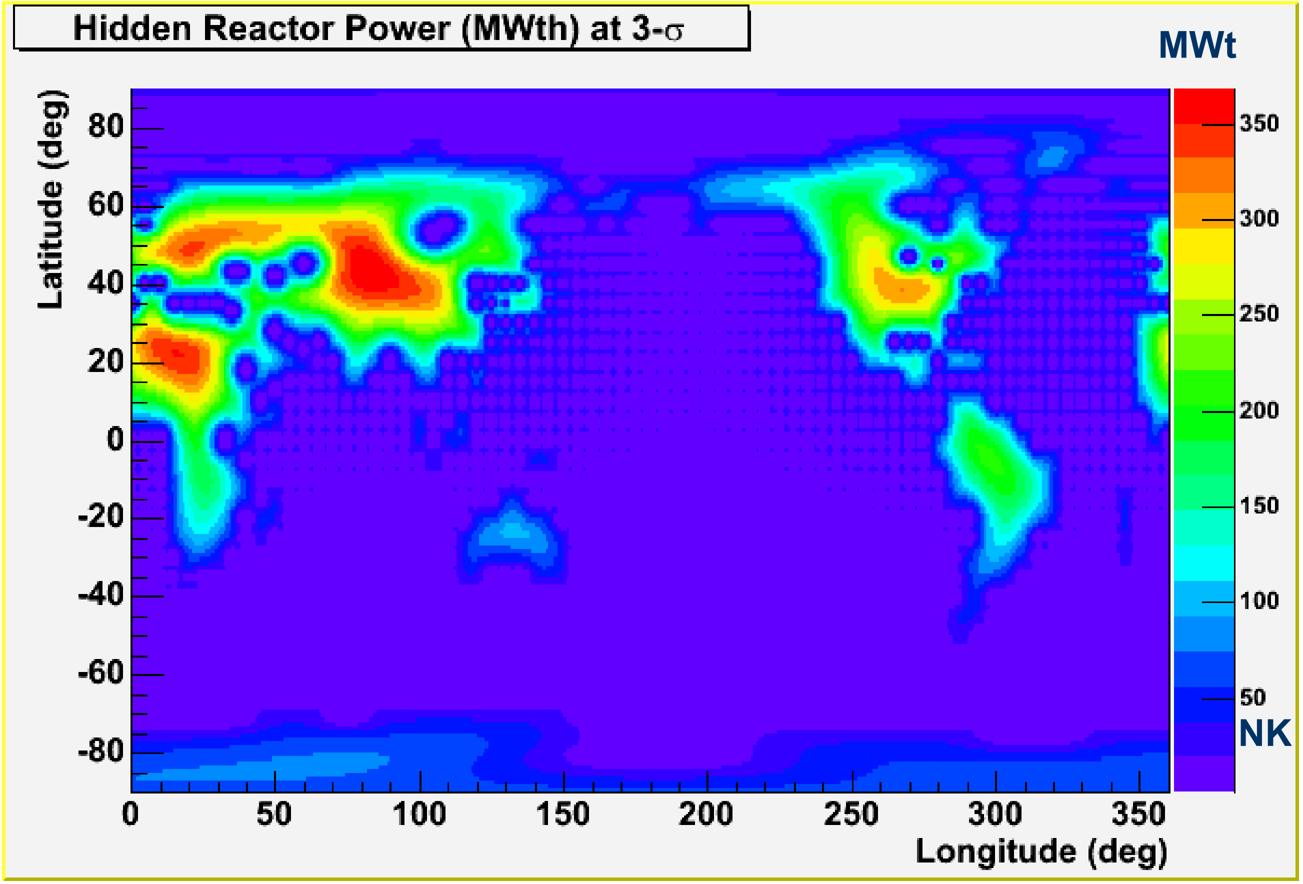
Can Detect Bomb Material Production Reactors Anywhere in the World

- Integrating over **one year** operation.
- At this level can detect bomb material production at level of North Korean activity, anywhere.

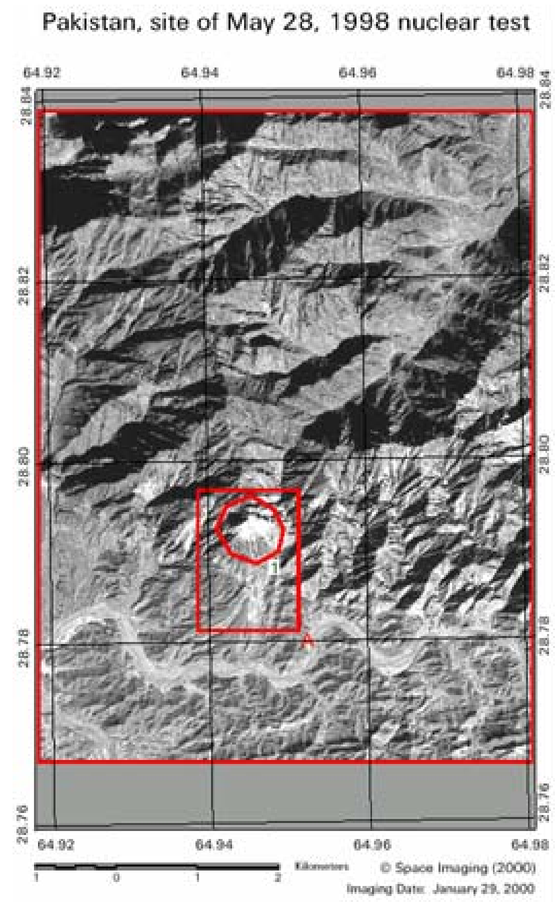


$\overline{\nu}_e$

Detection of Nuclear Explosions? Yes!

US tpotmoth 1955 2Kt

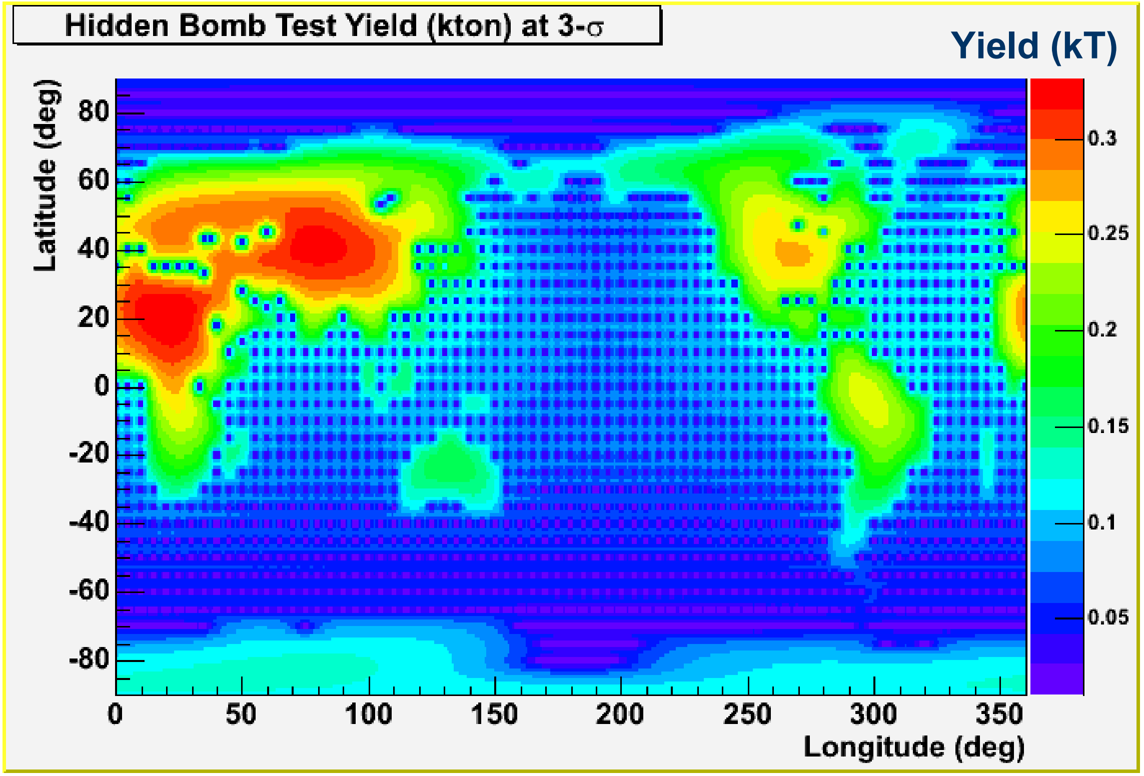
- **Beauty of this method is that neutrinos cannot be faked, jammed or shielded.**
- **Detection measures weapon yield.**
- **Detect 100 kT device out to 1000 km → 2000 counts in gigaton equiv. detector.**
- **Distributed arrays do much better (*next slide*).**



10-12 kT

Detect Bomb Tests >0.3 kT Anywhere on Earth !

- **Integrate over 10 seconds in world array**



3 sigma detection threshold, Kilotons TNT equiv.

ν_e Gigaton Array has Huge Program of Unprecedented Other Physics Studies

- **Proton decay** search to **>10^{36} yr**, tests all SUSY models.
- **Solar neutrino** temporal variation to 0.13%/sqrt(days).
- >1 Type II **Supernova**/ 20 days (~100 counts/few sec, E~10-50 MeV), clear signal from all of **Virgo Cluster**.
- **Neutrino** point source **astronomy**…. MeV to PeV.
- **Far detector** for neutrino-factory physics.
- Search for **dark matter** annihilations in earth, sun, galaxy
- **Geophysics** in study of earth density to core.
- Large enough program to engage **many scientists** and engineers for **many years**.

Example: Neutrinos from Distant Past Supernovae

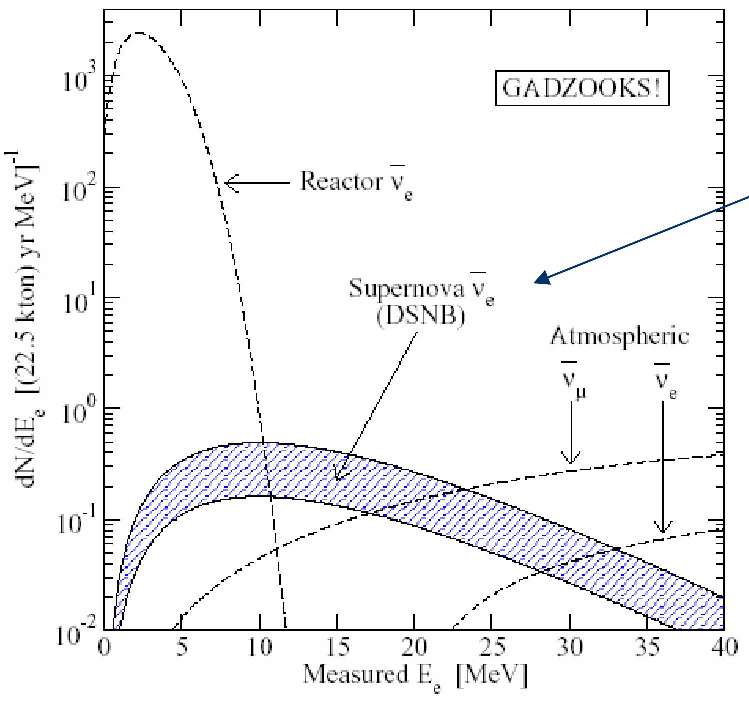
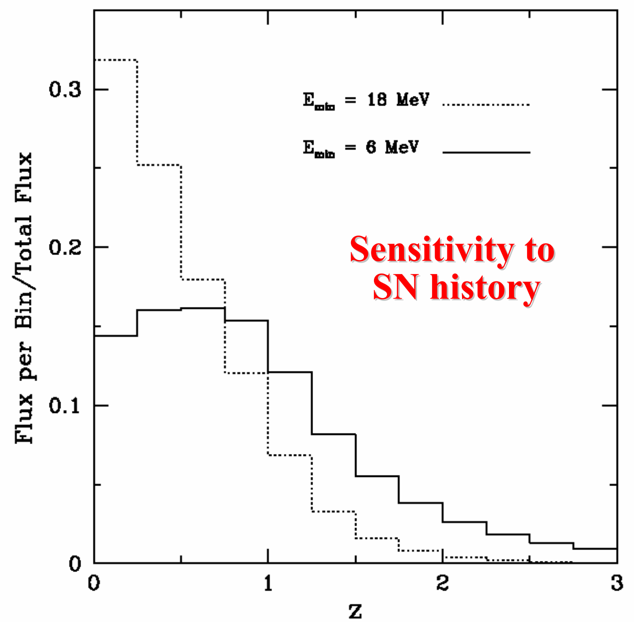


FIG. 1: Spectra of low-energy $\bar{\nu}_e + p \to e^+ + n$ coincidence events and the sub-Čerenkov muon background. We assume full efficiencies, and include energy resolution and neutrino oscillations. Singles rates (not shown) are efficiently suppressed.

Beacom and Vagins hep-ph/030930

1-3 x 10^5 events per year in gigaton detector



Sensitivity to SN history

Strigari, *et al*, astro-ph/0312346

$\bar{\nu}_e$

Type II Supernova Early Warning

Silicon burning during last ~2 days prior to collapse detectable from whole galaxy!

Sudden increase in single neutron appearance

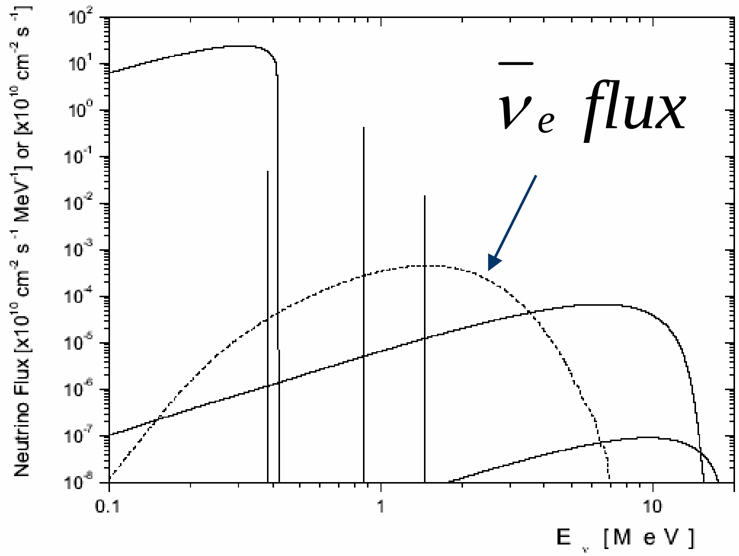


Fig. 2. The standard solar neutrino spectrum (BP2000, [5]) for pp fusion reactions in the Sun (solid lines) and the spectrum of pair-annihilation neutrinos emitted by a 20 $M_\odot$ star during silicon burning stage (dashed line). Star is located at a distance of 1 kpc.

Burning Phase	T_c [MeV]	ρ_c [g/cc]	μ_e [MeV]	L_ν [erg/s]	Duration τ	Total energy emitted [erg]
C	0.07	$2.7 \cdot 10^5$	0.0	$7.4 \cdot 10^{39}$	300 yrs	$7 \cdot 10^{49}$
Ne	0.146	$4.0 \cdot 10^6$	0.20	$1.2 \cdot 10^{43}$	140 days	$1.4 \cdot 10^{50}$
O	0.181	$6.0 \cdot 10^6$	0.24	$7.4 \cdot 10^{43}$	180 days	$1.2 \cdot 10^{51}$
Si	0.319	$4.9 \cdot 10^7$	0.84	$3.1 \cdot 10^{45}$	2 days	$5.4 \cdot 10^{50}$

Table 2
Properties of a 20 $M_\odot$ star according to Ref. [6]. We have calculated the total energy radiated in neutrinos as a product τL_ν. Actually, the neutrino emission is expected to be a function of time.

Odrzywolek, et al., astro-ph/0311012

$\overline{\nu}_e$

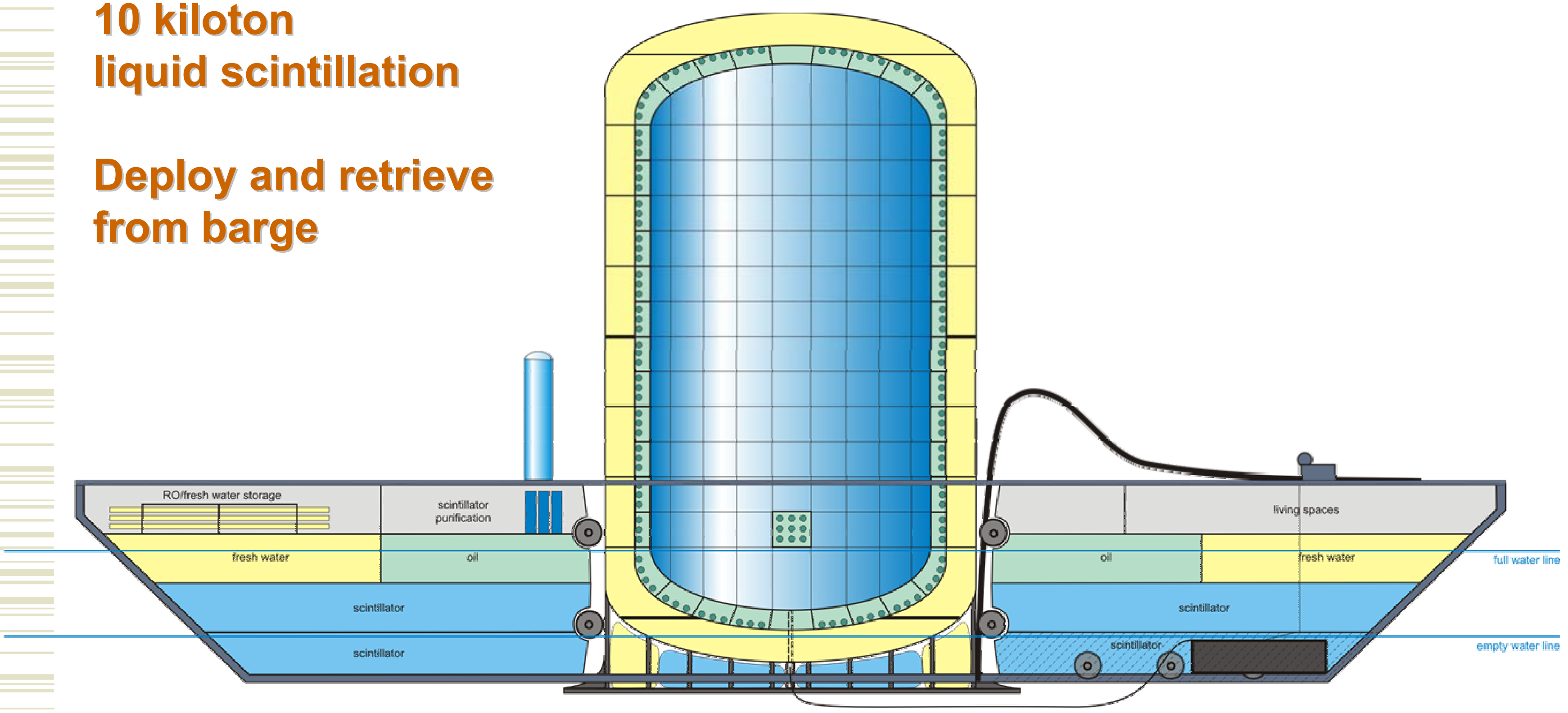
Neutrino Monitoring Workshop, U. Maryland, 3-5 January 2008

- 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.**

Hanohano
a mobile deep ocean detector

10 kiloton
liquid scintillation

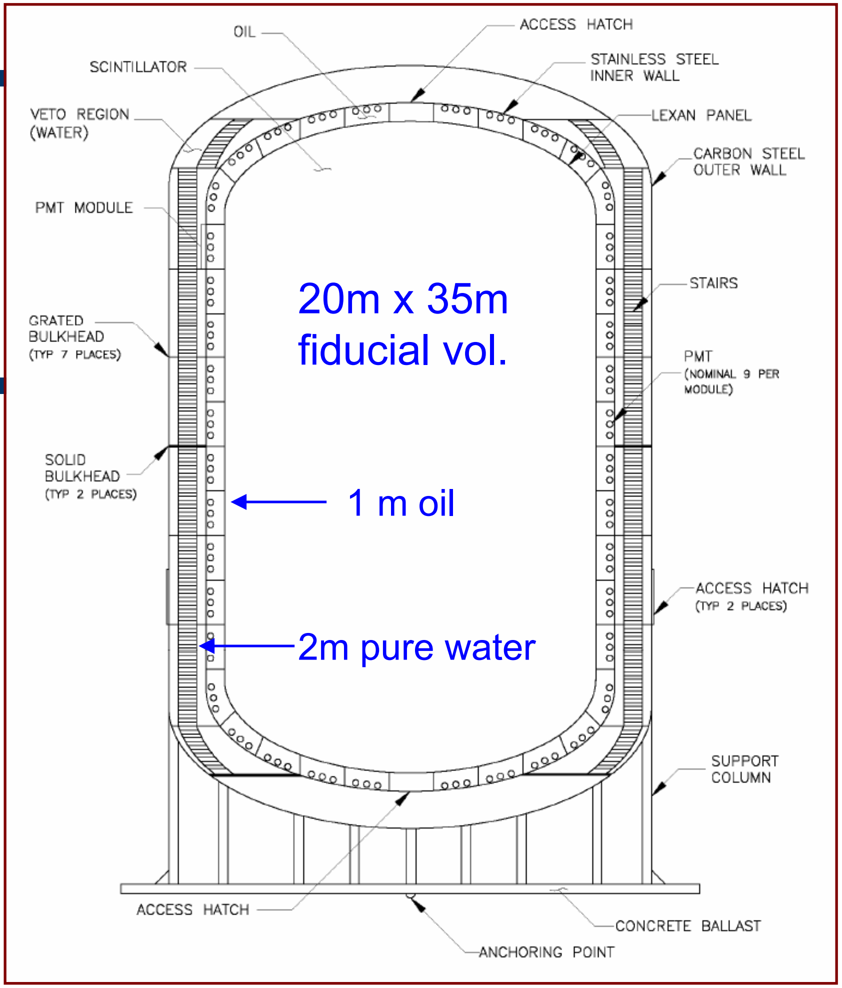
Deploy and retrieve
from barge

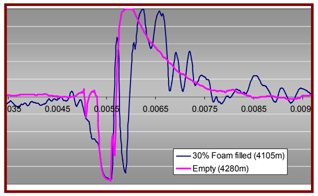


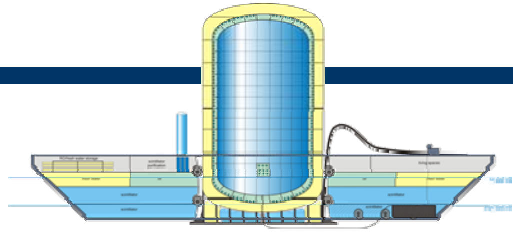
ν_e

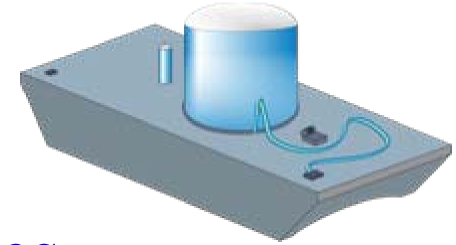
Addressing Technology Issues

- 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







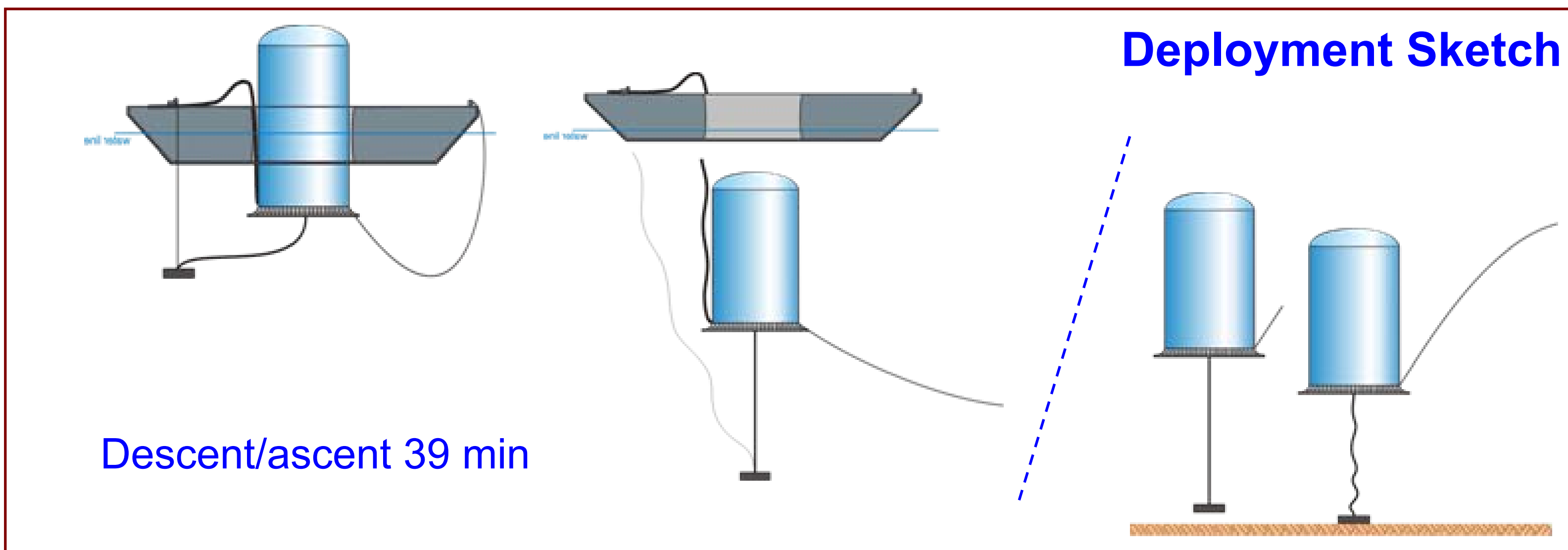


Hanohano Engineering Studies

Makai Ocean Engineering

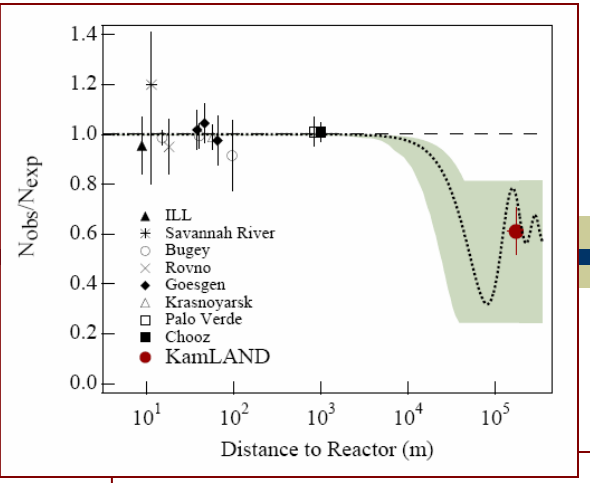
- **Studied vessel design up to 100 kilotons, based upon cost, stability, and construction ease.**
  - **Construct in shipyard**
  - **Fill/test in port**
  - **Tow to site, can traverse Panama Canal**
  - **Deploy ~4-5 km depth**
  - **Recover, repair or relocate, and redeploy**

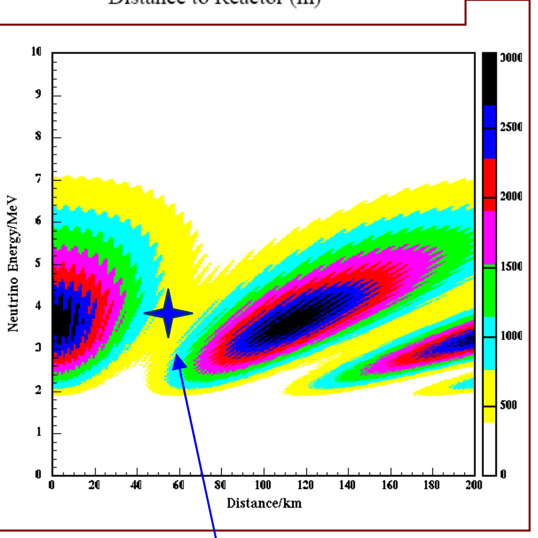
Barge 112 m long x 23.3 wide



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

- **Reactor experiment- ν_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**





oscillation maximum at ~ 50-60 km

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

$\overline{\nu}_e$

3-ν Mixing: Reactor Neutrinos

mixing angles → mass diffs

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

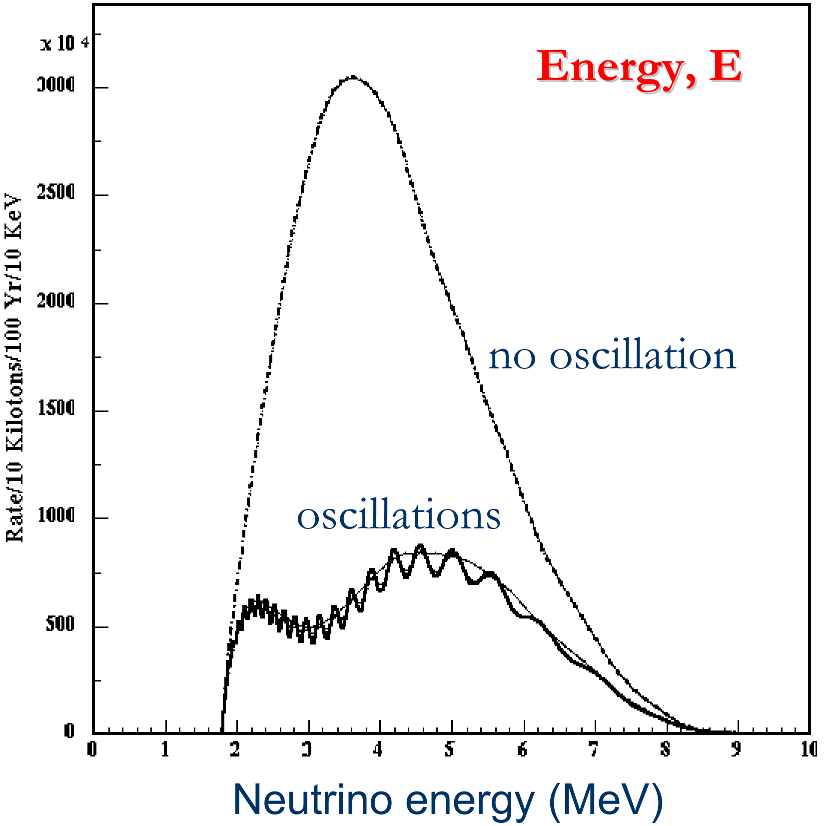
} wavelength close, 3%

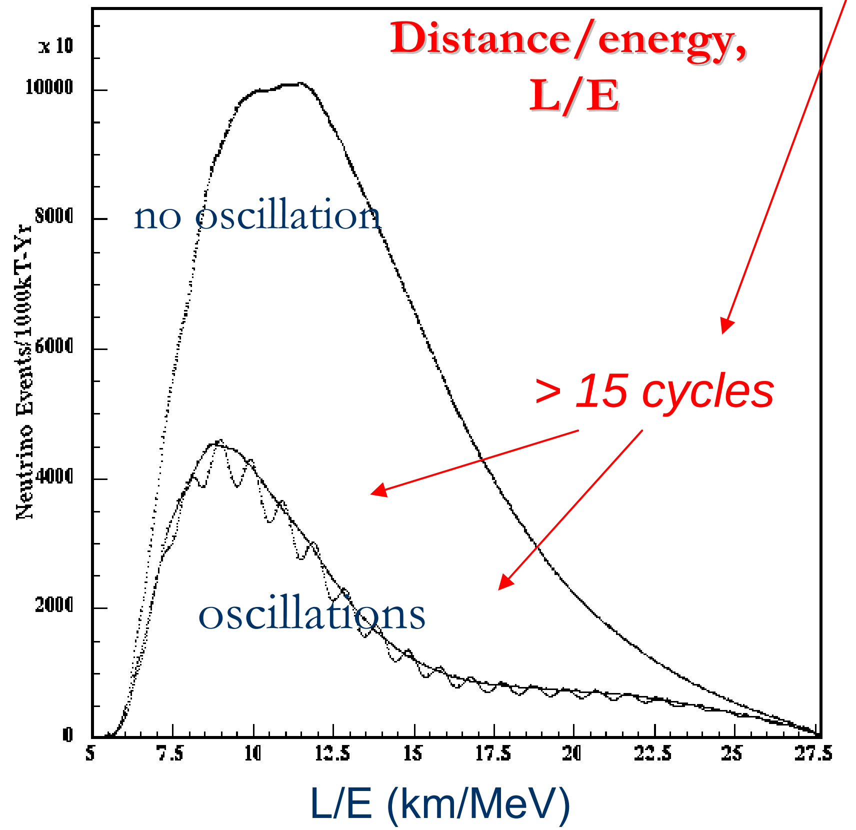
- Survival probability: 3 oscillating terms each cycling in L/E space (~t) with own "periodicity" ($\Delta m^2 \sim \omega$)
  - Amplitude ratios ~13.5 : 2.5 : 1.0
  - Oscillation lengths ~**110 km** (Δm^2_{12}) and ~**4 km** ($\Delta m^2_{13} \sim \Delta m^2_{23}$) at reactor peak ~3.5 MeV
- ½-cycle 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}

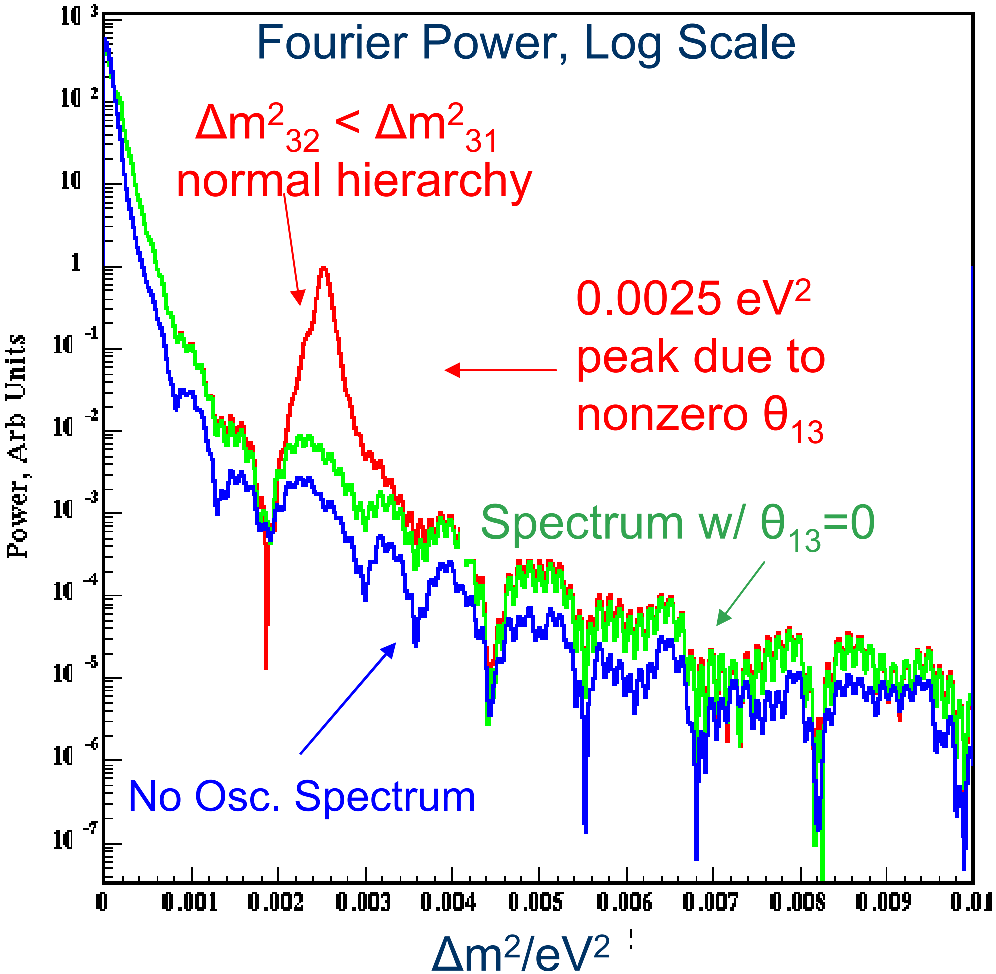
invites use of Fourier Transforms



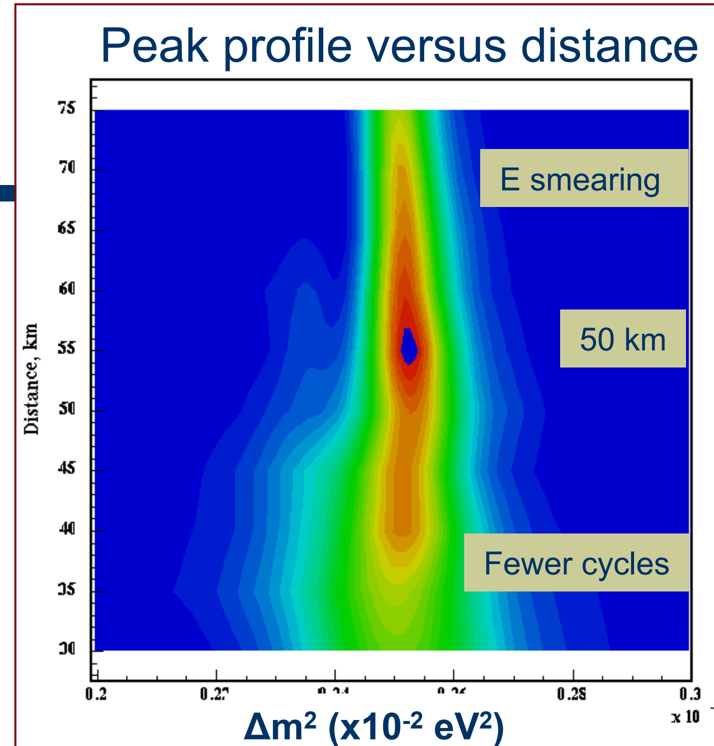


1,2 oscillations with $\sin^2(2\theta_{12})=0.82$ and $\Delta m^2_{21}=7.9\times10^{-5}$ eV^2
1,3 oscillations with $\sin^2(2\theta_{13})=0.10$ and $\Delta m^2_{31}=2.5\times10^{-3}$ eV^2

Fourier Transform on L/E to Δm^2



Includes energy smearing



50 kt-y exposure at 50 km range

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

Δm^2_{31}=0.0025 eV² to 1% level

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

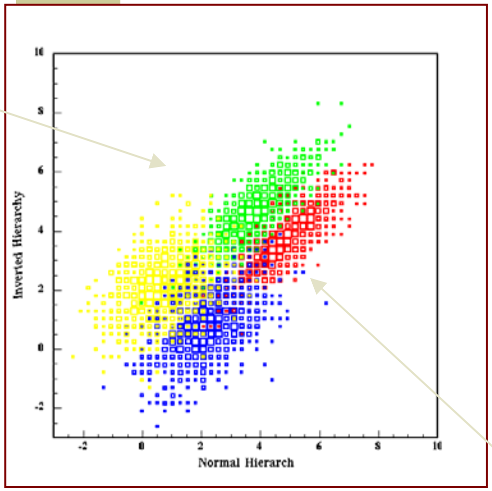
Hierarchy Determination

Ideal Case with 10 kiloton Detector,

1 year off San Onofre

Distance variation: 30, 40, 50, 60 km

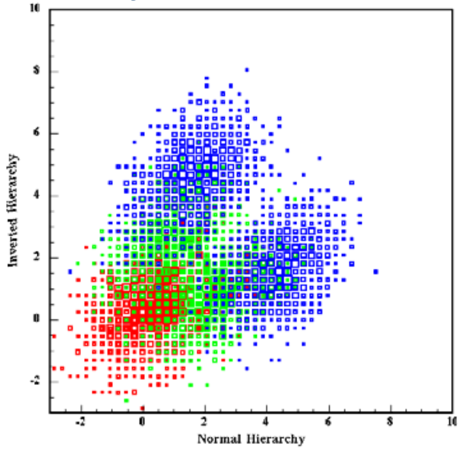
Inverted hierarchy



Normal Hierarchy

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

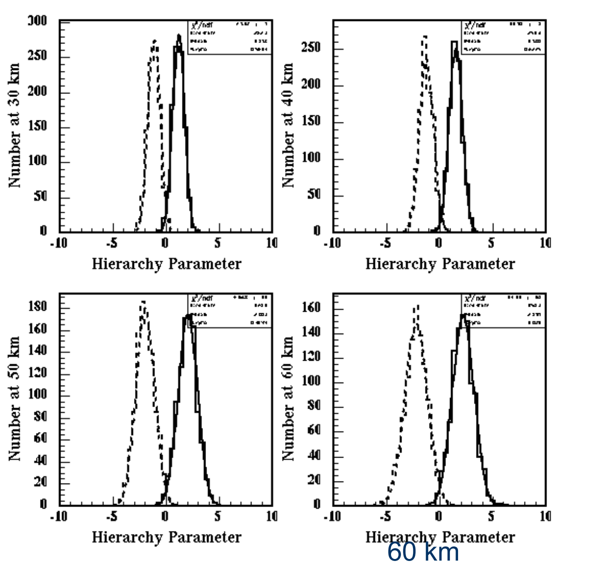
Inv.



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.

30 km

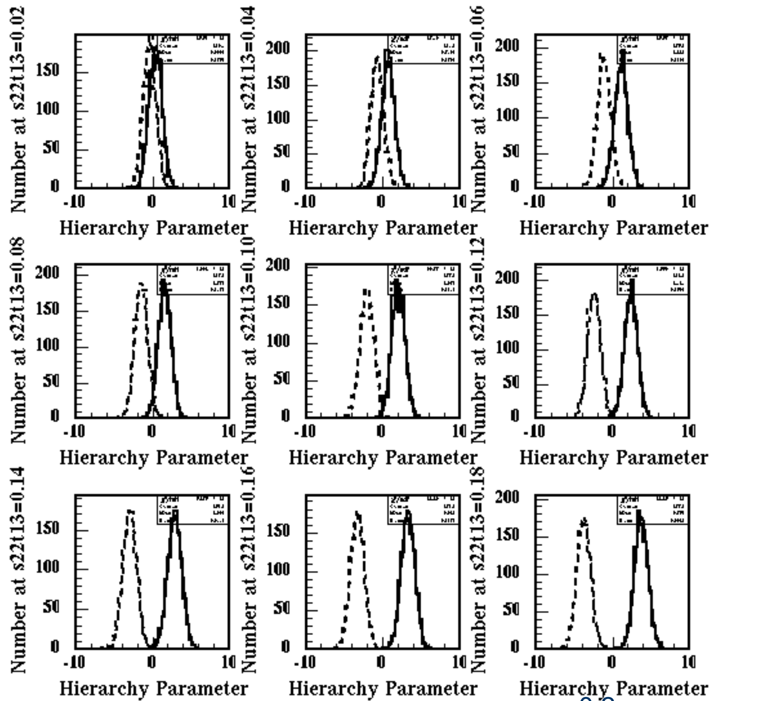


60 km

100 kt-yrs separates even at 0.02

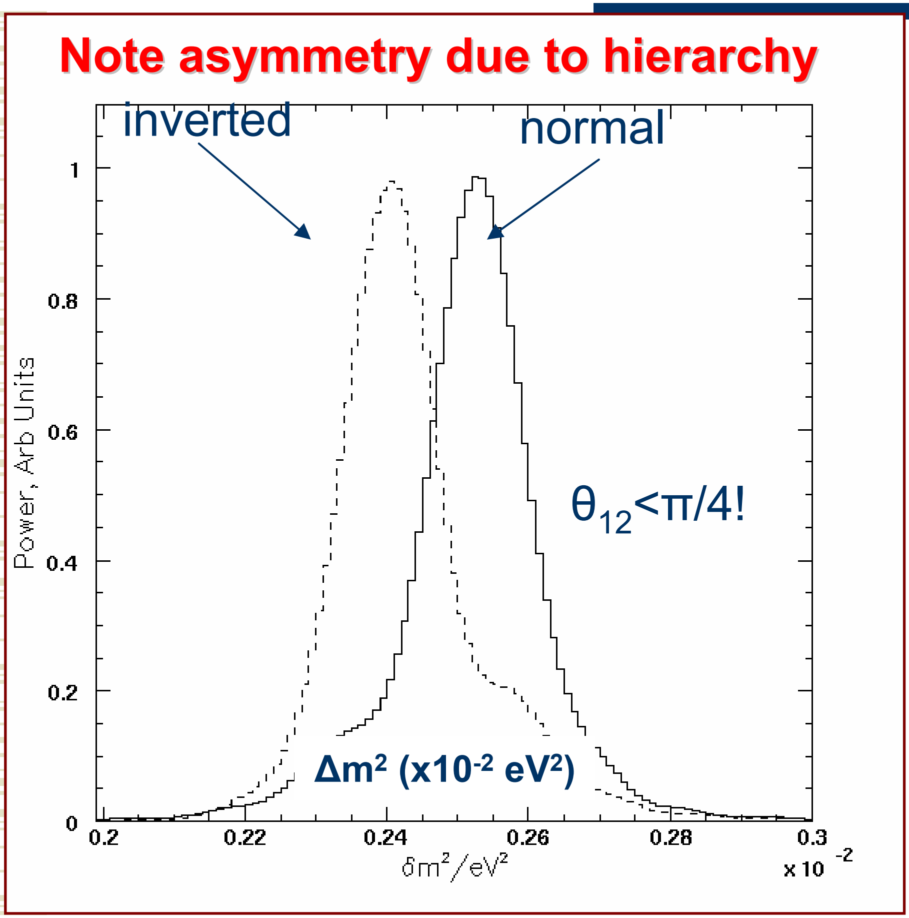
Sensitive to energy resolution: probably need 3%/sqrt(E)

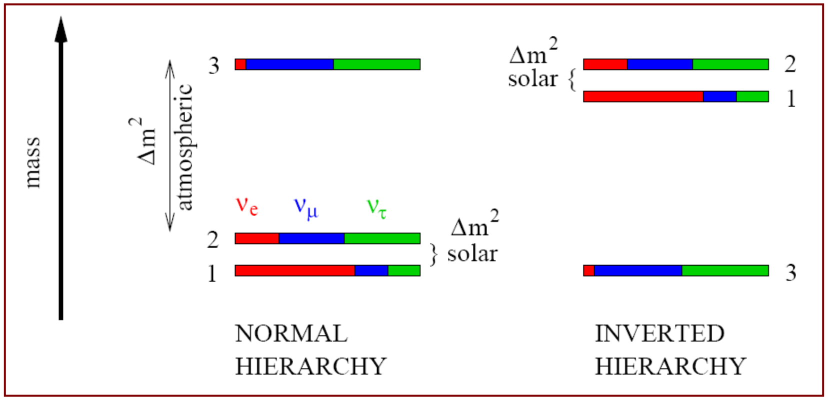
0.02



0.2

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*

$\overline{\nu}_e$

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….**

$\overline{\nu}_e$

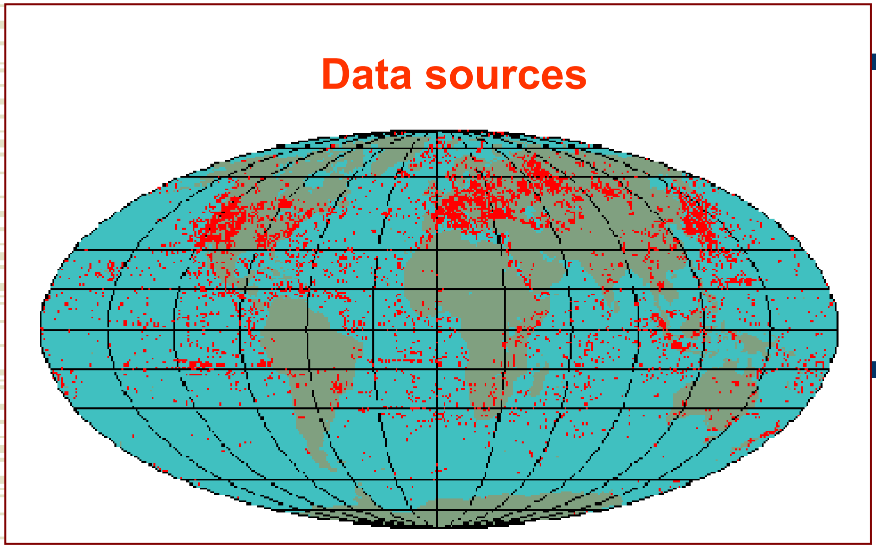
Big picture questions in Earth Sci

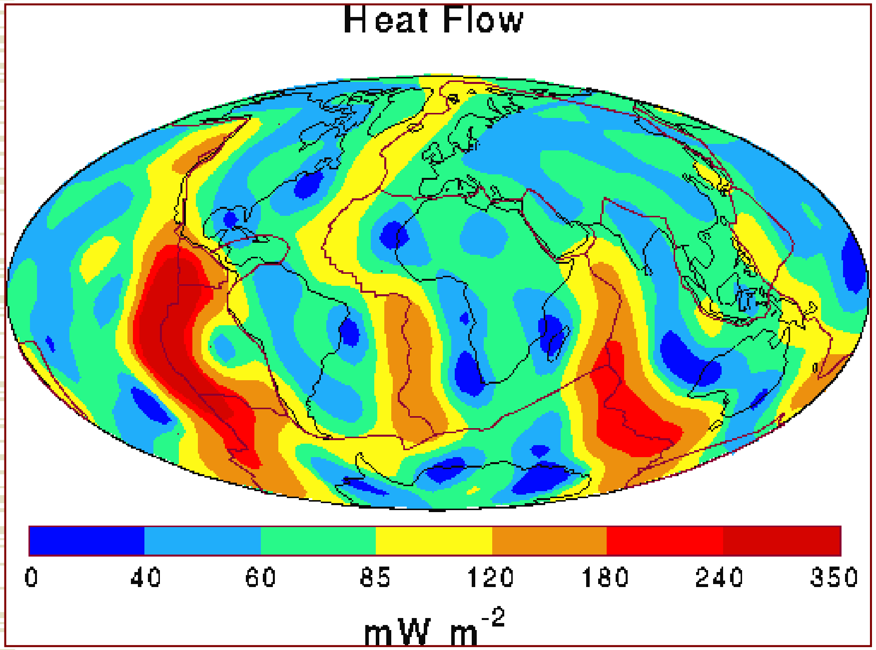
What drives **plate tectonics**?

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

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

Energy source driving the **Geodynamo**?





Earth's Total Heat Flow

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

Total heat flow

Conventional view

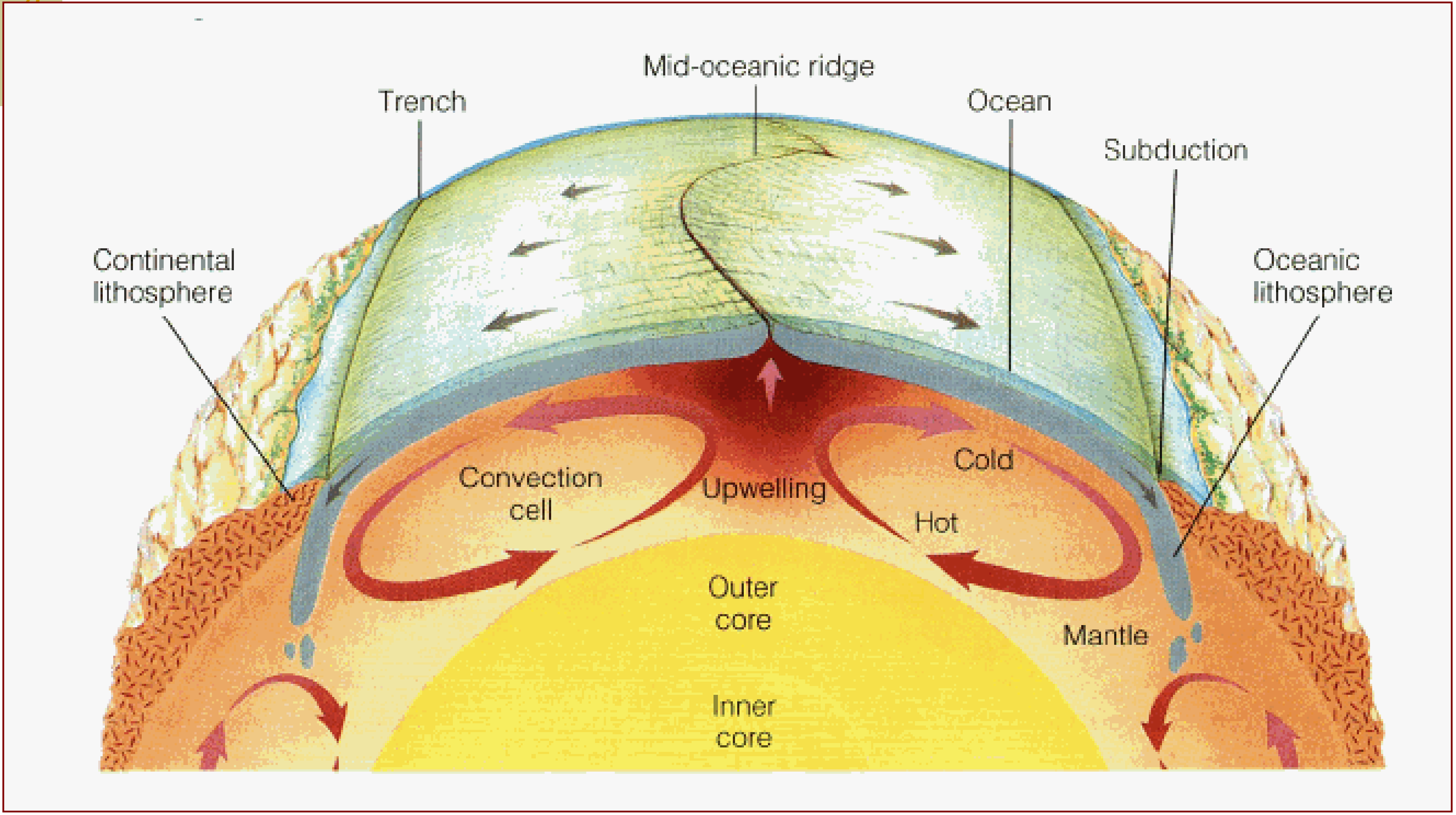
44±1 TW

Challenged recently

31±1 TW

strongly **model** dependent

Convection in the Earth

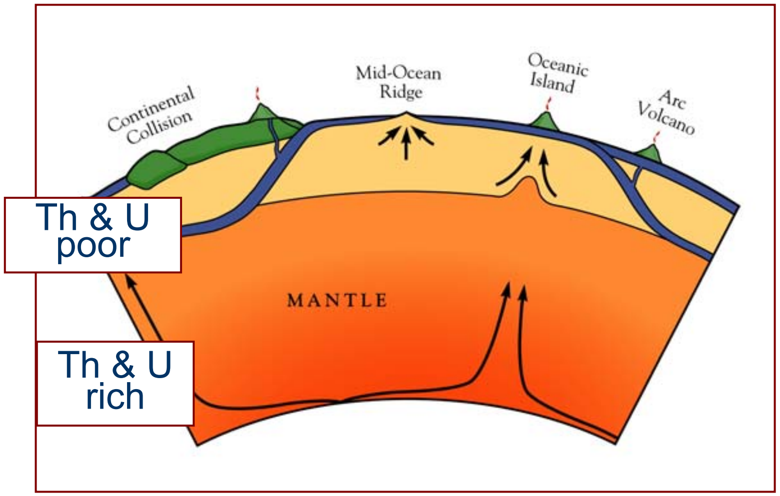


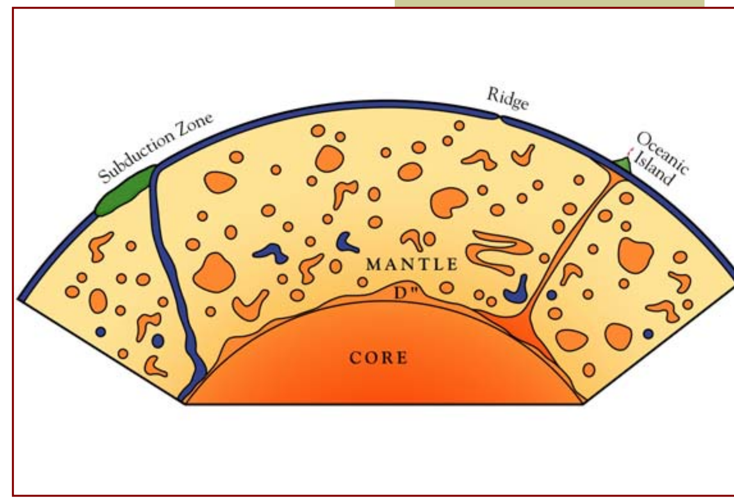
- **The mantle convects.**
- **Plate tectonics operates via the production of oceanic crust at mid-ocean ridges and it is recycled at deep sea trenches.**

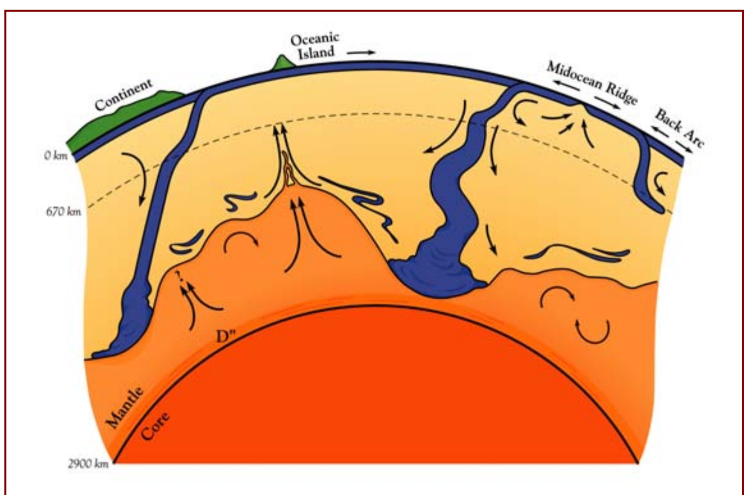
$\bar{\nu}_e$

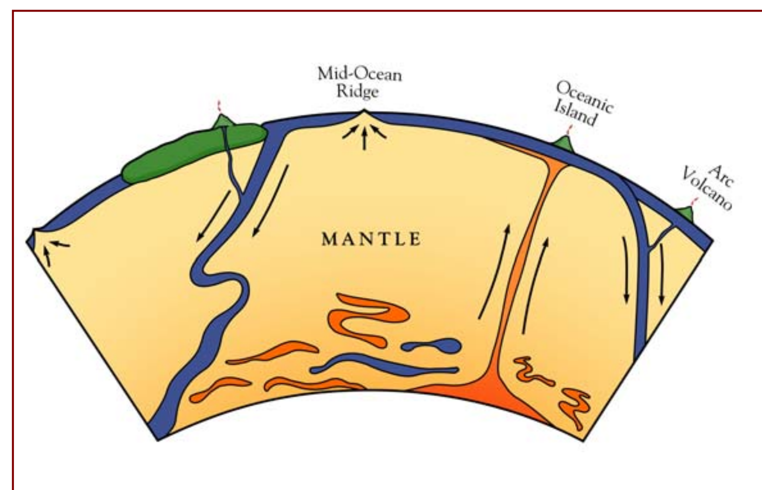
Mantle is depleted in some elements (e.g., Th & U) that are enriched in the continents.

models of mantle convection and element distribution



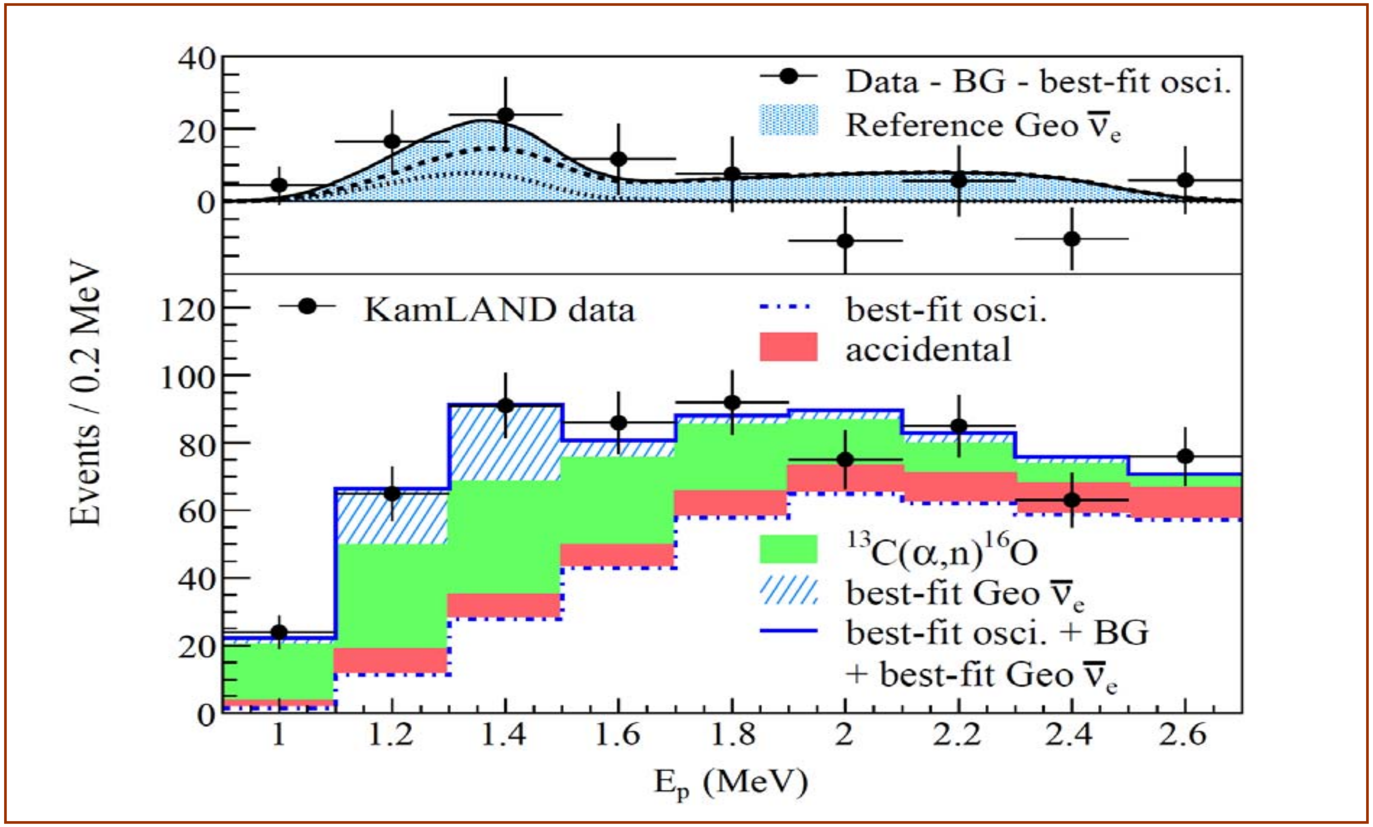






KamLAND New Results – Geonu Spectrum

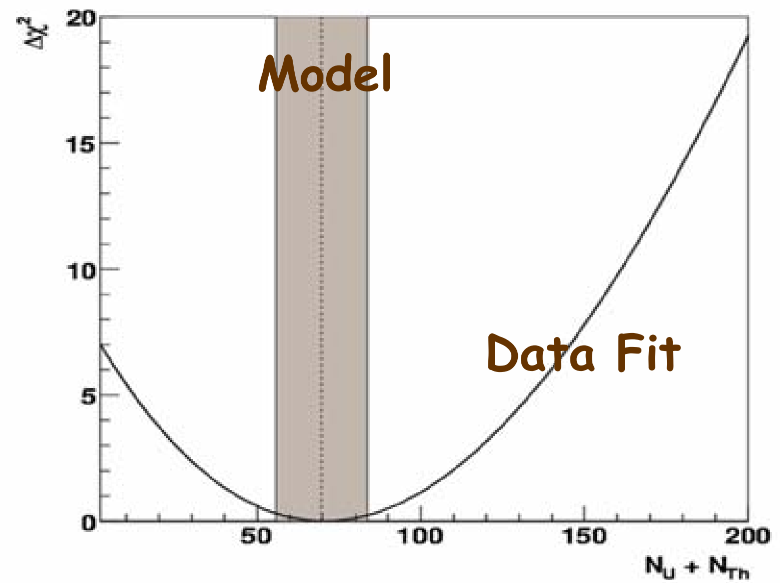
1491 day data set



Thanks Patrick Decowski

$\bar{\nu}_e$

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 $\times 10^6/cm^2s$
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**

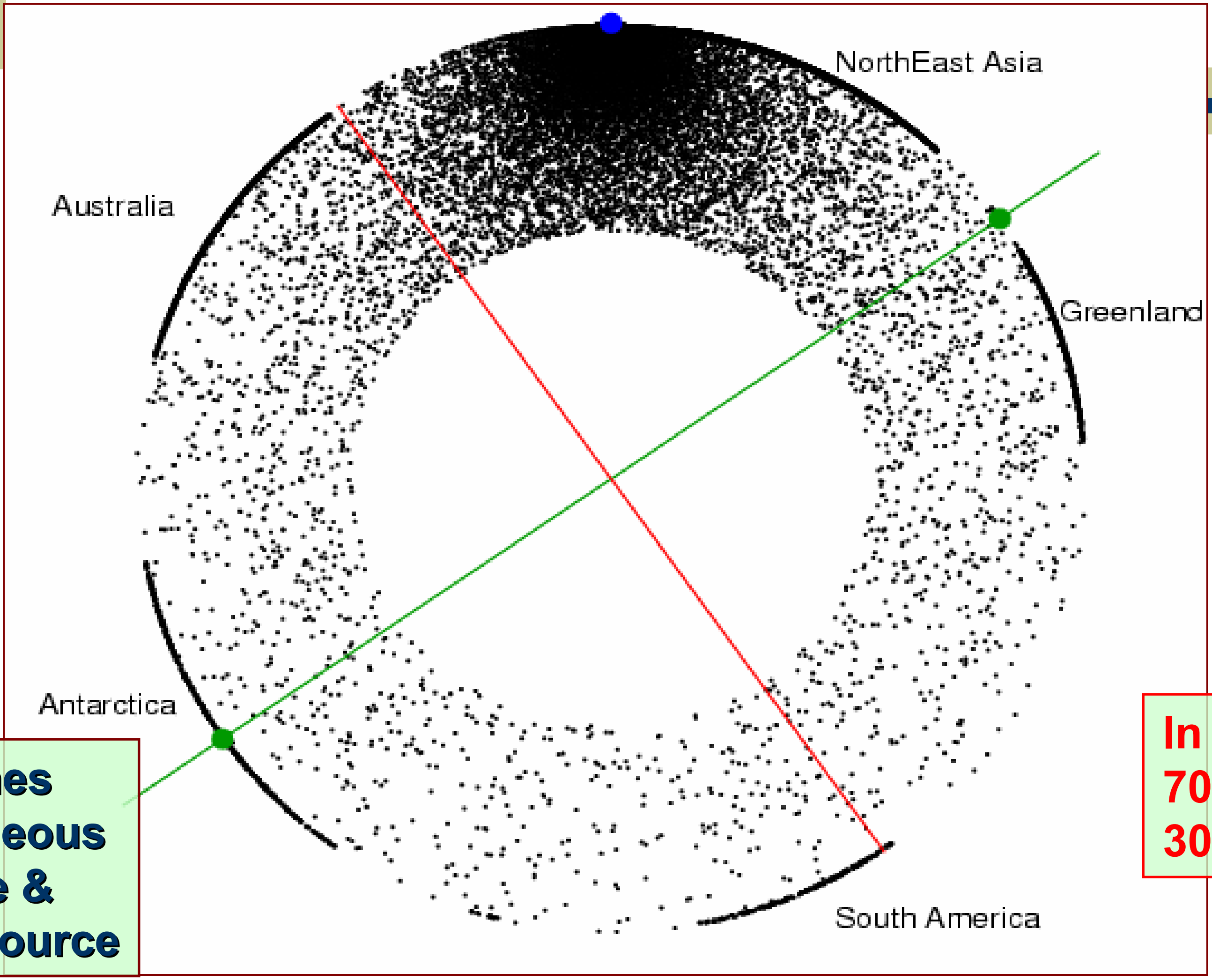
Thanks Patrick Decowski

Simulated Geoneutrino Origination Points

$\bar{\nu}_e$

KamLAND

50% within 500km
25% from Mantle



Assumes homogeneous mantle & no core source

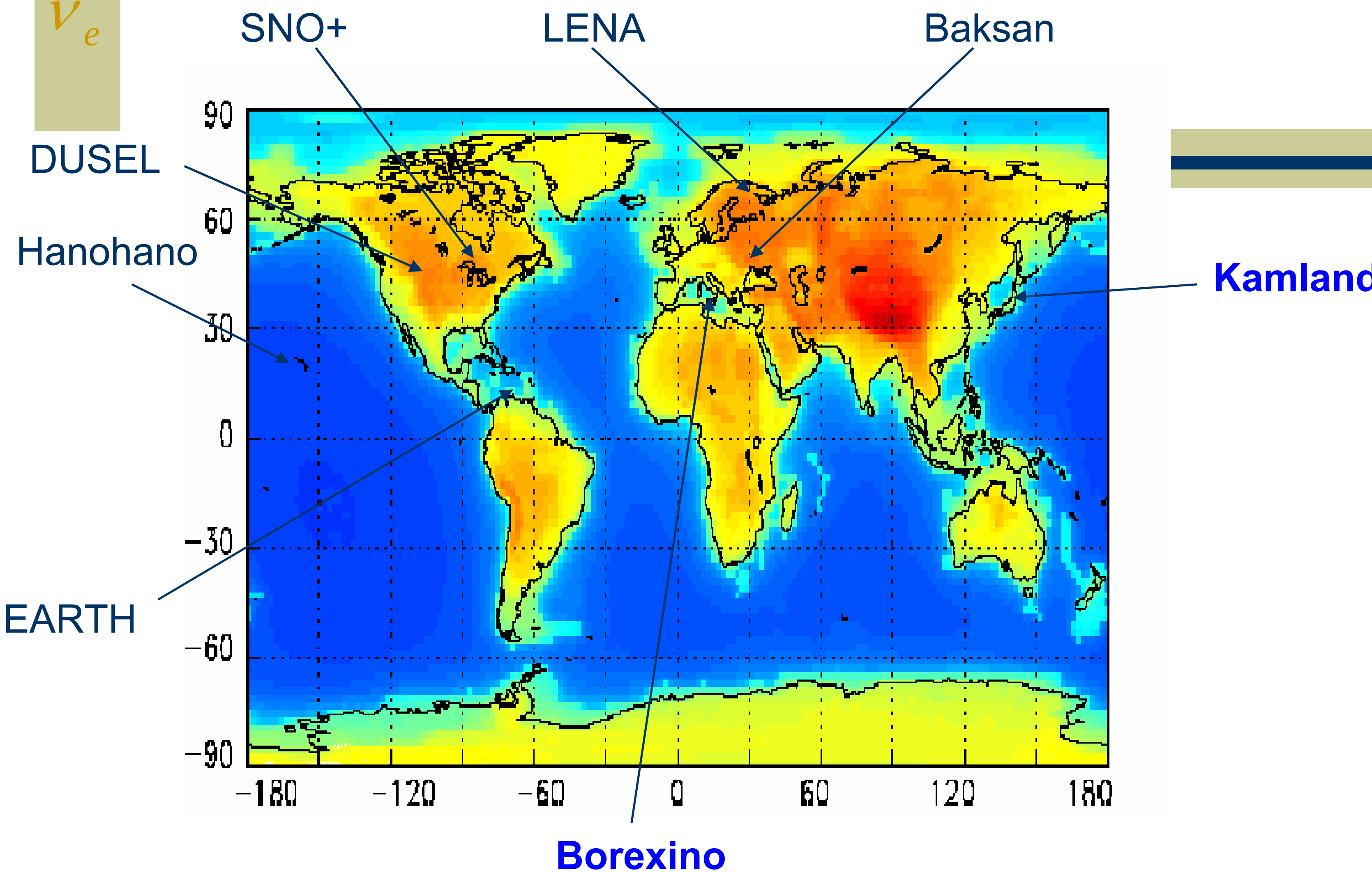
In Mid-Ocean
70% Mantle
30% Other

$\overline{\nu_e}$

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.

Locations for Possible Geonu Experiments



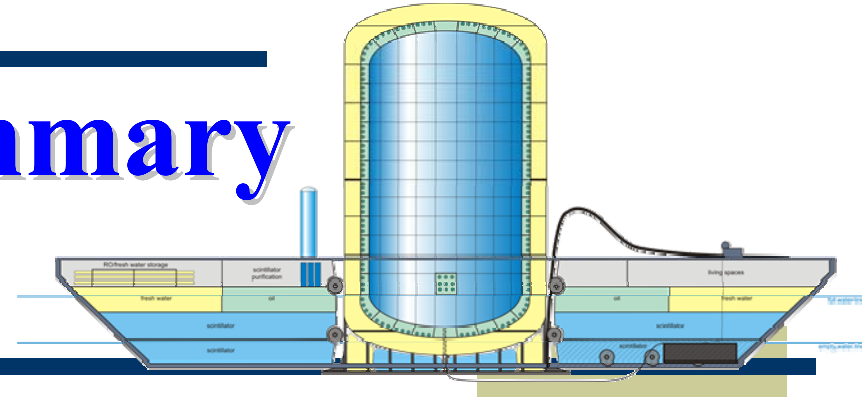
Color indicates U/Th neutrino flux, mostly from crust

What Next for Geonus?

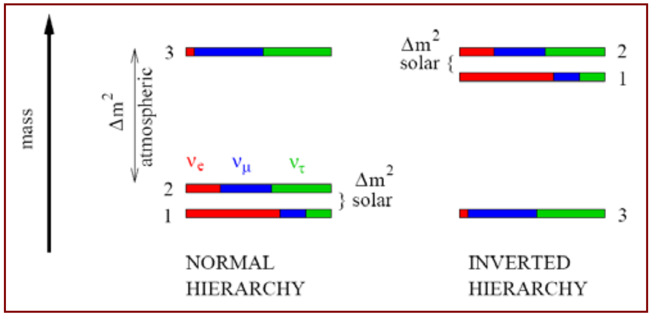
- Mantle can only be measured from ocean location.
- Measure gross fluxes from crust and mantle
- Discover or set limits on georeactors.
- Explore lateral homogeneity
- Better earth models
- Use directionality for earth neutrino tomography
- Follow the science….

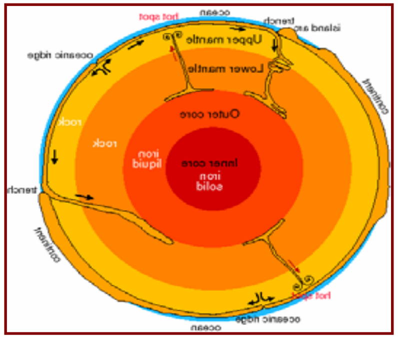
$\bar{\nu}_e$

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.
- First **demonstration** of portable long range reactor monitoring
- 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.





Summary: $\bar{\nu}_e$ Options for Reactor Monitoring

- **Close-in reactor monitors of cooperating reactors, has been demonstrated… maybe worthwhile just for reactor logging.**
- **Intermediate range options possible, depending upon mission.**
- **Far future, distributed array of multi-km^3 - 2 MeV anti-neutrino detectors in deep ocean is certainly possible, question is economics and scaling… first cut indicates it may be on few x \$10B scale.**
- **Significant optical detector development needed, plus other studies.**
- **Would allow detection and location of new reactors to few tens of km.**
- **Huge pure-scientific program and community involvement: high spin-off in science and technology.**