The Abdus Salam
International Centre for Theoretical Physics

United Nations
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2047-23

Workshop Towards Neutrino Technologies

13 - 17 July 2009

Neutrino mixing discriminates geo-reactor models

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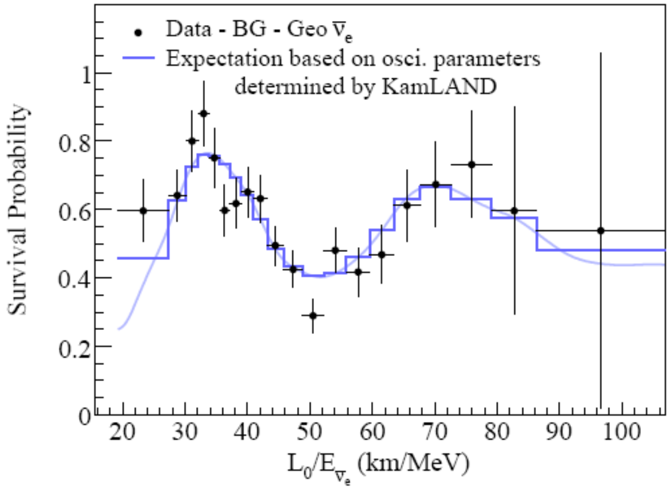
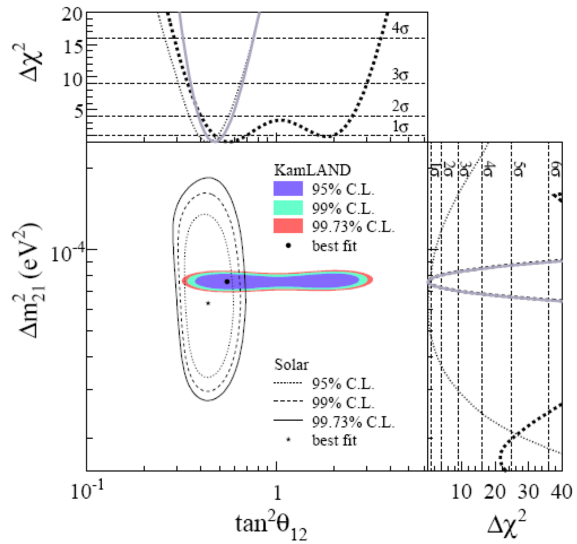
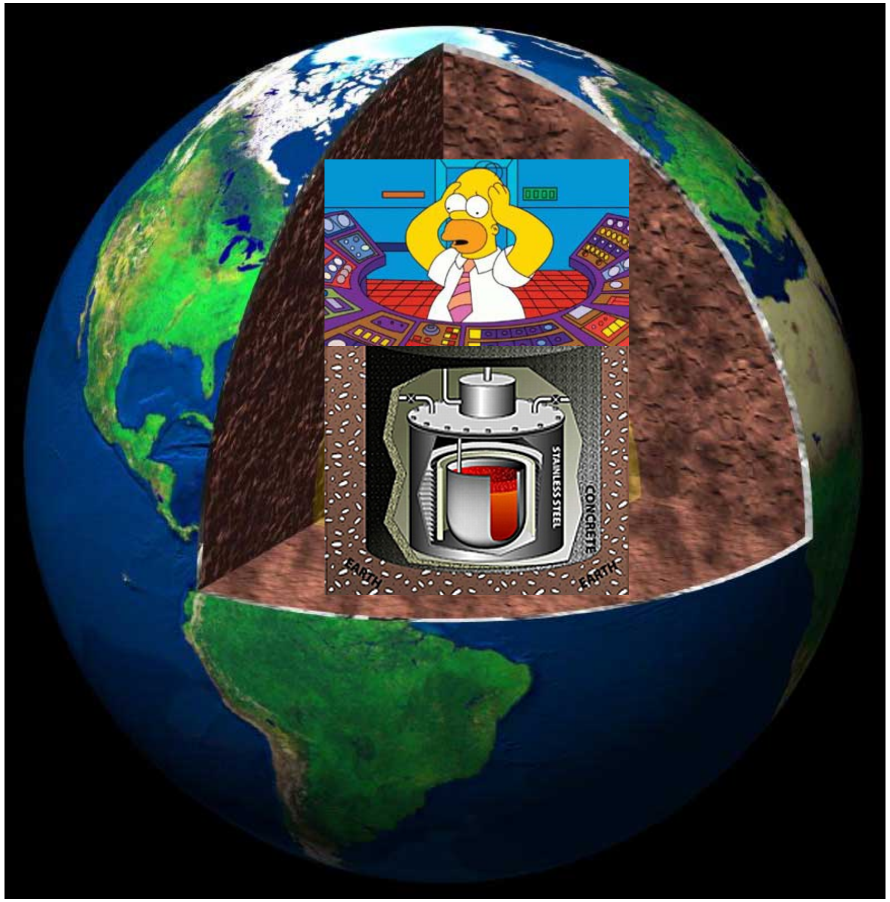
Neutrino Mixing Discriminates Geo-reactor Models







Steve Dye
Hawaii Pacific University
University of Hawaii

A Natural Fission Reactor

Predicted by P.K. Kuroda,
J. Chem. Phys. **25**, 781 (1956).

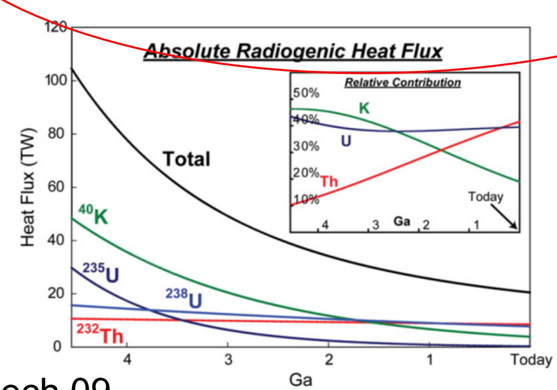
On the Nuclear Physical Stability of the Uranium Minerals

P. K. Kuroda
Department of Chemistry, University of Arkansas, Fayetteville, Arkansas
(Received July 26, 1956)

An attempt is made in this paper to apply the nuclear reactor theory in geochronology and to explain certain interrelations between the age and the nuclear physical stability of the uranium minerals, as well as the geological environments of the mineral formation.

It is worthy of note, however, that a slight increase of the water to uranium ratio could have easily caused a sharp upward change of p, without affecting f considerably, and the result of which could have been enough to make the system nuclear physically "unstable."

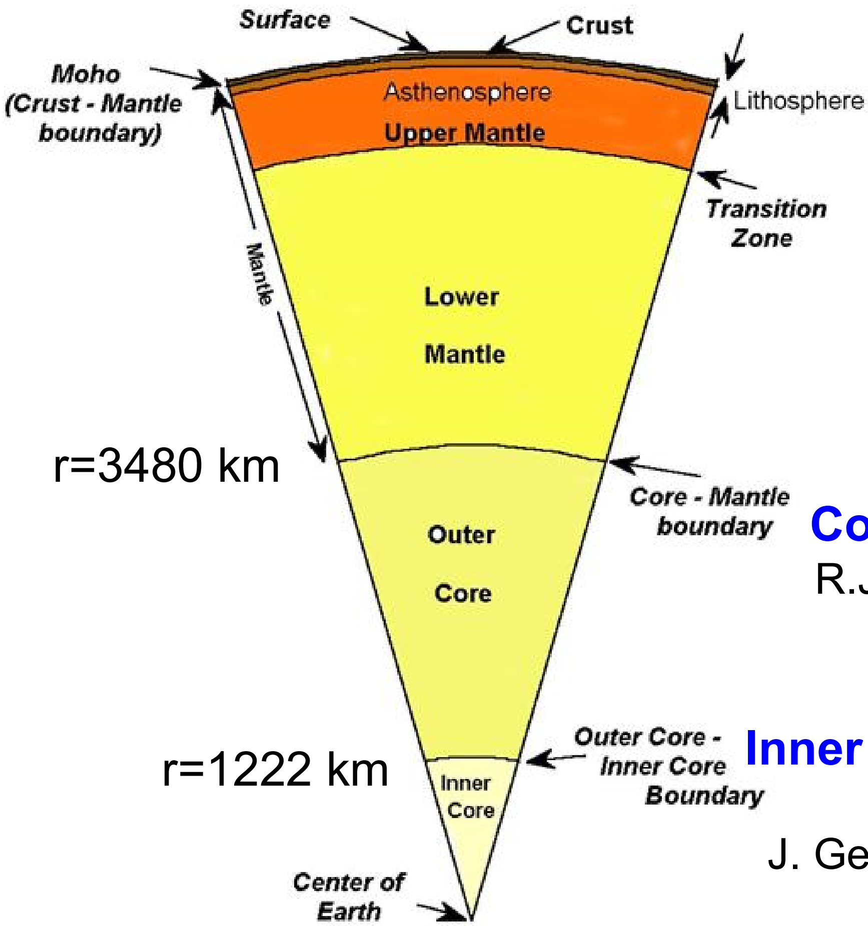
shows that the assemblages of the Johanngeorgenstadt pitchblende plus water were nuclear physically "unstable" 2100 million years ago, and the critical uranium chain reactions could have taken place, if the size of the assemblage was greater than, say, a thickness of a few feet. The effect of such an event could have been a



Discovered at Oklo in west Africa
G.A. Cowan, Sci. Am. **235**, 36 (1976).

- $^{235}U/^{238}U$ ~0.03 (~4 x present) 2 Gy ago
- Water concentrates deposit & moderates n
- Reactor released ~15 GW-yr of energy over few 10^5 yr

Deep-Earth Geo-reactor Models



r=3480 km

r=1222 km

Proposed at 3 depths w/ loosely defined power output sufficient to explain:
• surface heat flow > radiogenic heat
33-46 TW > ~20 TW
•^{3}He/^{4}He OIB>MORB
tritium fission product- $^3H \rightarrow {}^3He+\beta^- + \nu$

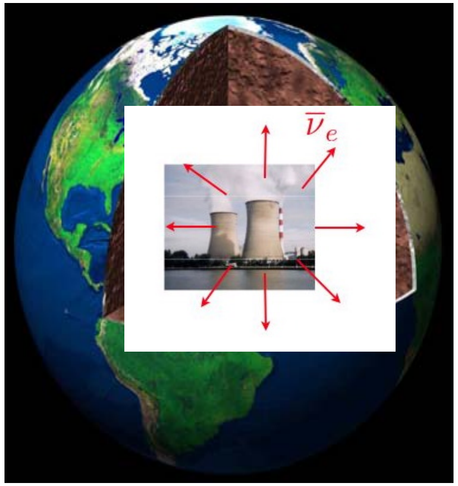
Core-Mantle Boundary *P*~5TW
R.J. de Meijer & W. van Westrenen
S. Afr. J. Sci. **104**, 111 (2008)

Inner Core Boundary *P*~20-30 TW
V.D. Rusov *et al.*,
J. Geophys. Res. **112**, B09203 (2007)

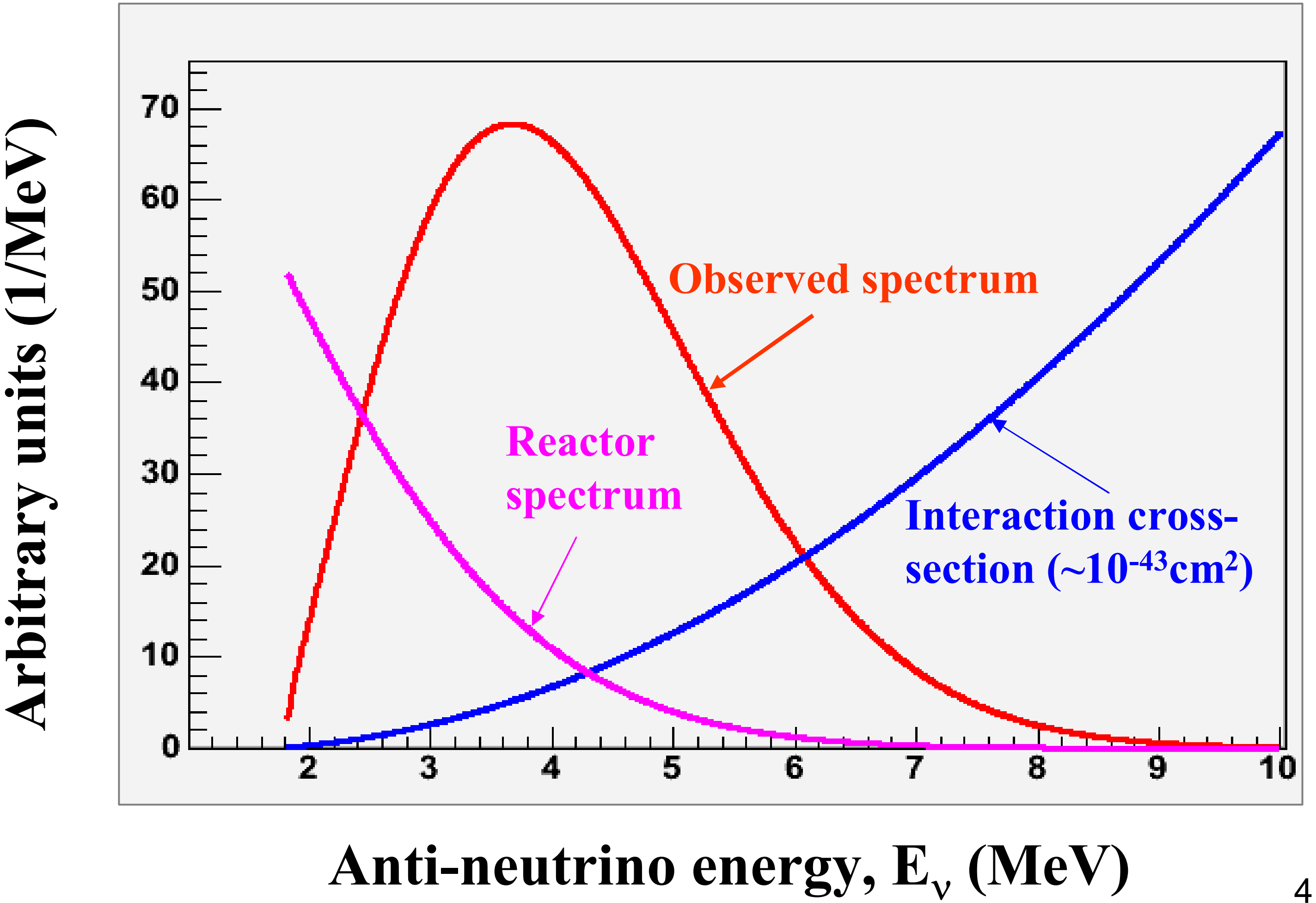
Earth Center *P*~3-10 TW
J.M. Herndon,
Proc. Nat. Acad. Sci. **93**, 646 (1996)

Deep-earth Geo-reactor:
Hypothetical and very speculative
Possible and not ruled out

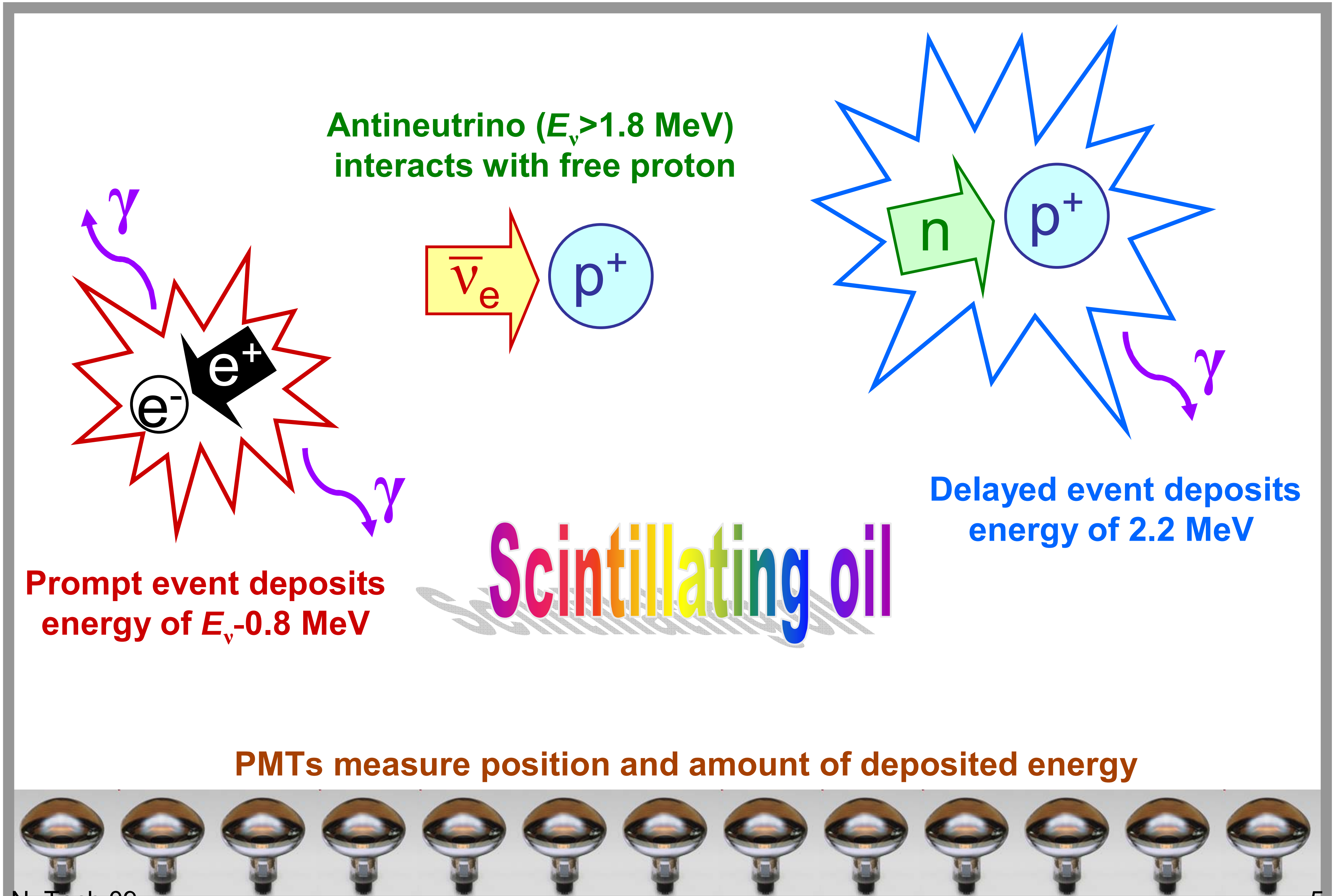
Observing a Deep-Earth Geo-reactor



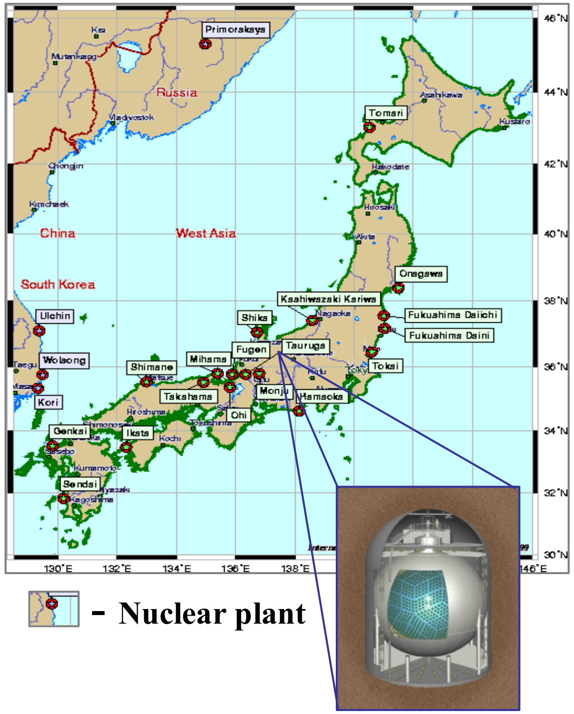
Model antineutrino flux & spectrum after commercial reactor
Observe using inverse beta reaction on free proton
Selection efficiency >0.9



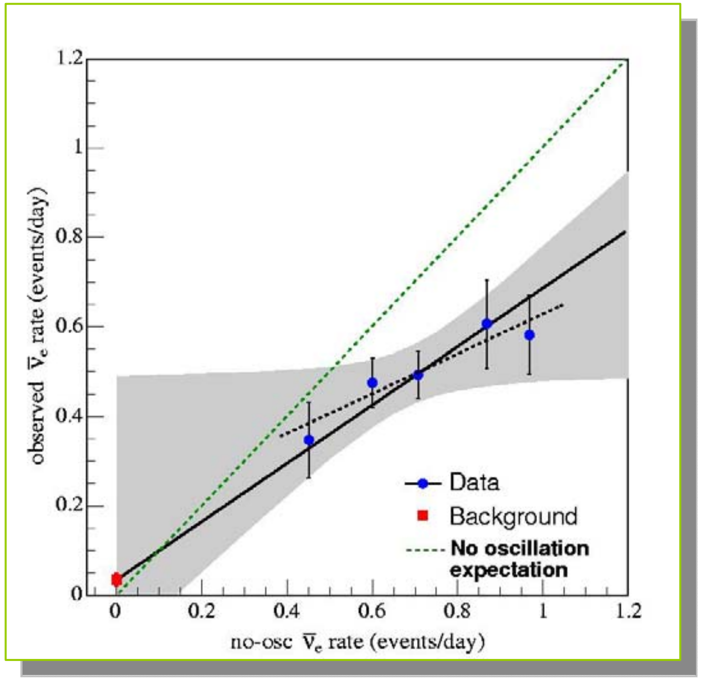
Antineutrino Detection

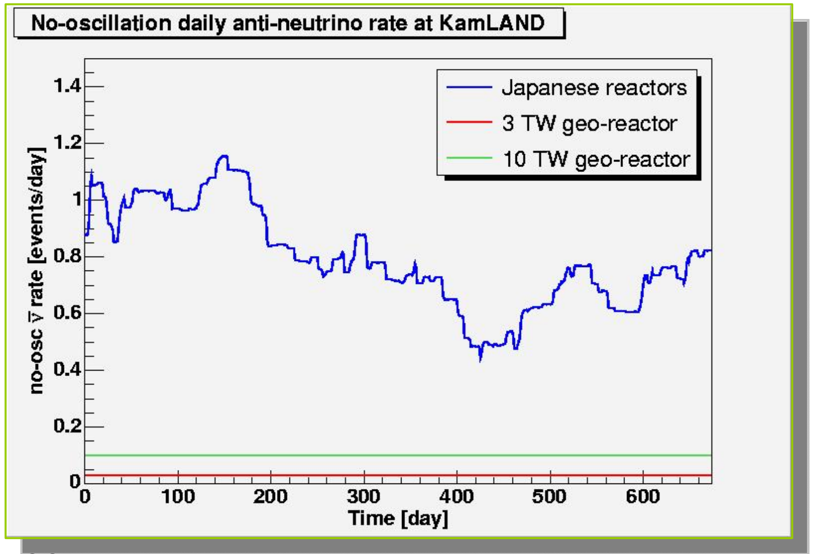


Experimental Constraint



55 Japanese nuclear power reactor units



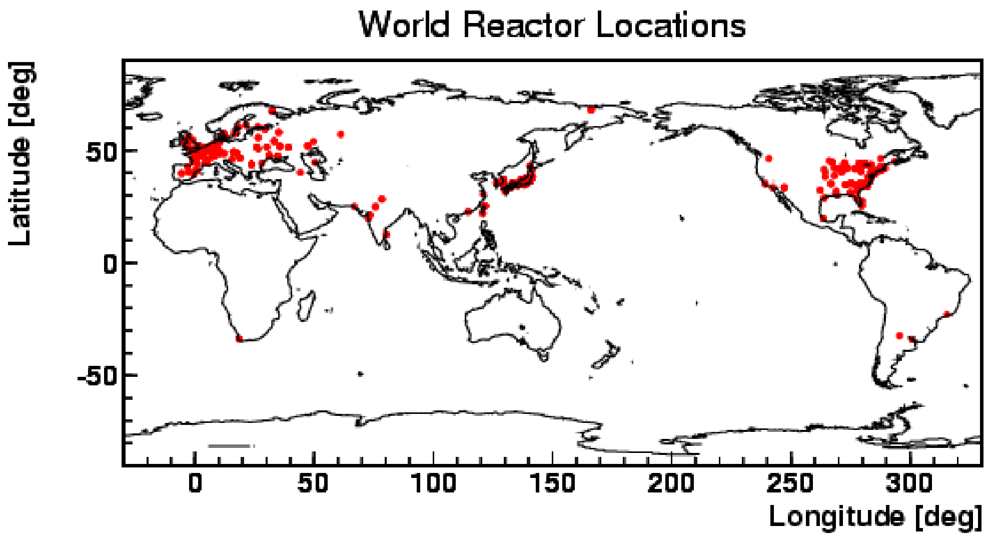


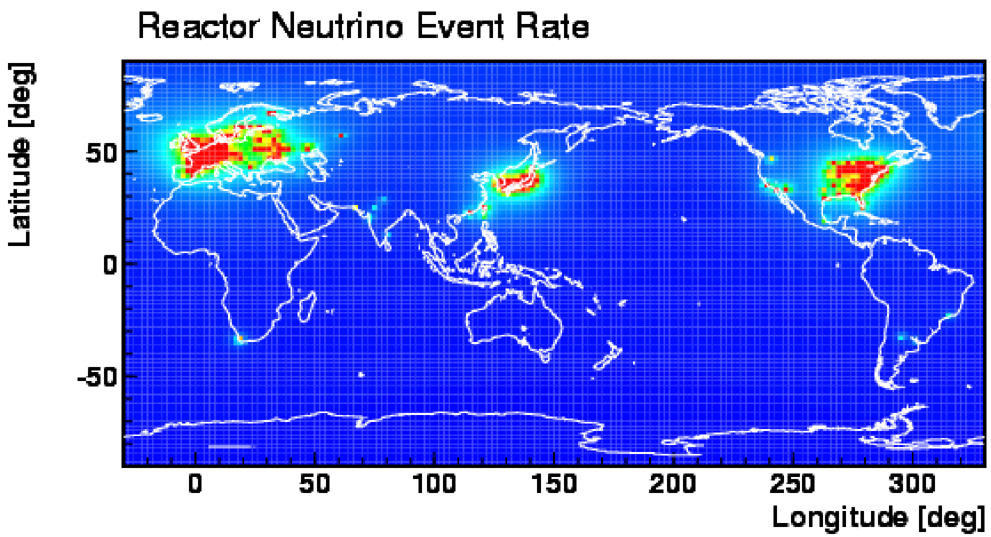
KamLAND exposure 2.44x10^{32}p^{+}-yr and solar neutrino data set upper limit to power of *earth-centered* geo-reactor

***P* < 6.2 TW (90% C.L.)**

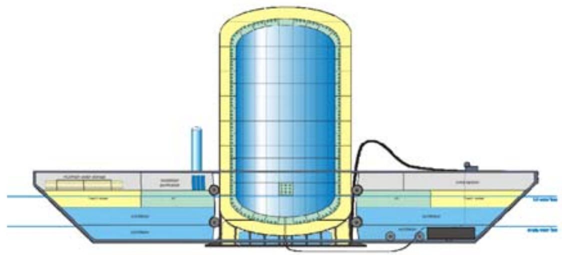
Abe et al., PRL **100**, 221803 (2008)

More Sensitive Search Possible





Oceanic antineutrino observatory operating far from reactors in deep ocean



Signal/Background ~0.8/TW

8.5×10^{32} p^{+}-yr exposure sets *P* < 0.5 TW at >95% C.L.

Or measure power to ~10% if *P*~ few TW at earth center

Dye et al., EMP **99**, 241 (2006)

Uncertainties- Power vs Location

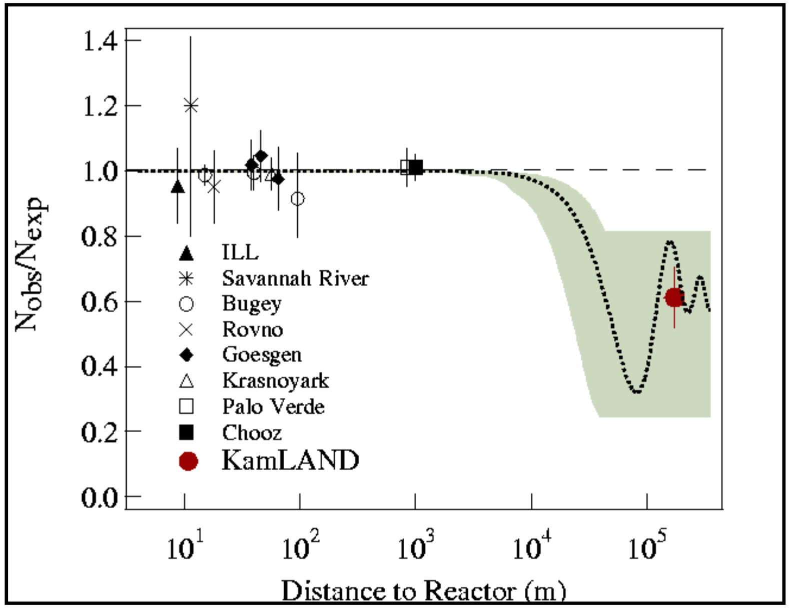
What if geo-reactor not earth-centered?
Models suggest 3 possible deep-earth locations:
Earth center
Inner core boundary
Core-mantle boundary

KamLAND power limit translates to 1.3 – 15 TW allowing geo-reactor position along diameter through core

Locating geo-reactor source position would lead to more precise power estimate and discriminate geo-reactor models

Could consider antineutrino direction measurement
Excellent recent progress at RCNS although technology not fully available

…or use neutrino oscillation pattern to make the map



Distortion of Energy Spectrum

Reactor spectrum approximated

$$N(E_{\bar{\nu}_e}) \propto$$

$$(E_{\bar{\nu}_e} - 1.4)^2 \exp - \left(\frac{E_{\bar{\nu}_e} + 0.8}{3.2} \right)^2$$

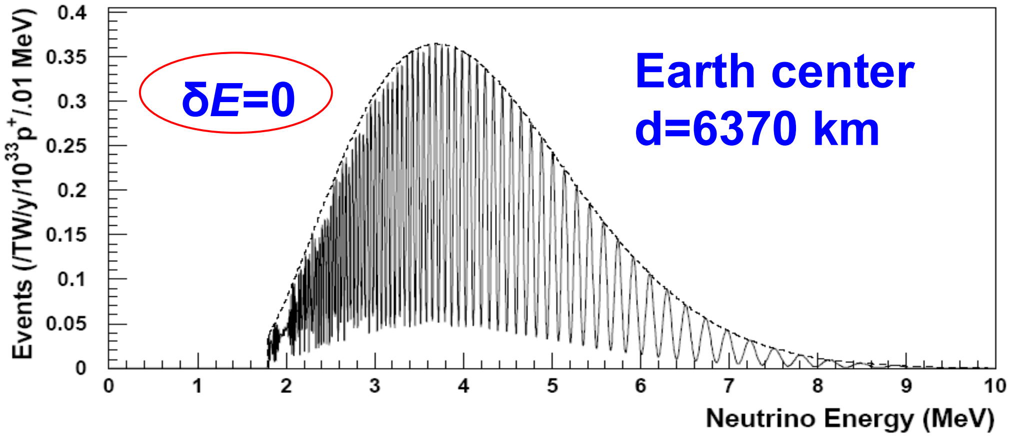
Mixing parameters from global solar + reactor fit

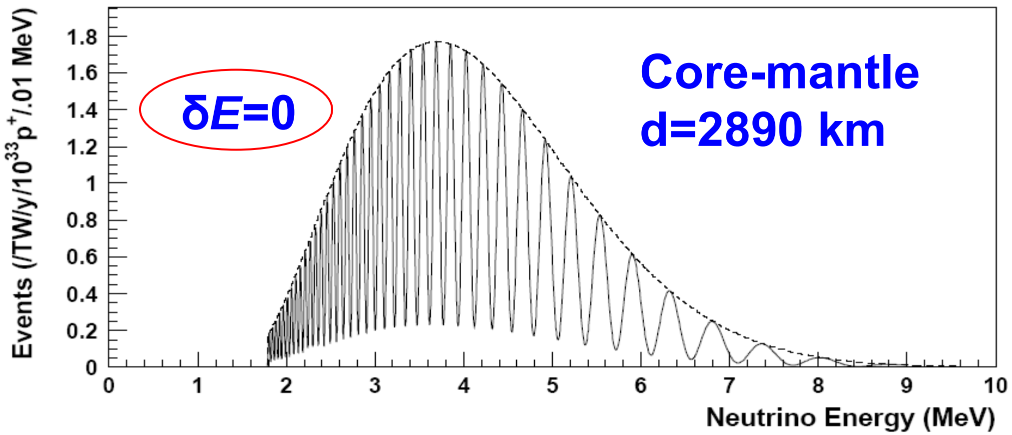
$$\tan^2 \theta_{12} = 0.47$$

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

Abe et al., PRL **100**, 221803 (2008)

Reactor antineutrino energy spectrum





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

Energy Resolution

Benchmark:
KamLAND visible energy resolution δ*E*/*E*=6.5%/√*E*

Visible energy related to antineutrino energy

$$E = E_{\overline{\nu}_e} - 0.8$$

Visible energy resolution determined by scintillation light collection:
- **Photocathode coverage**
- **Photocathode QE**
- **Scintillation light output**

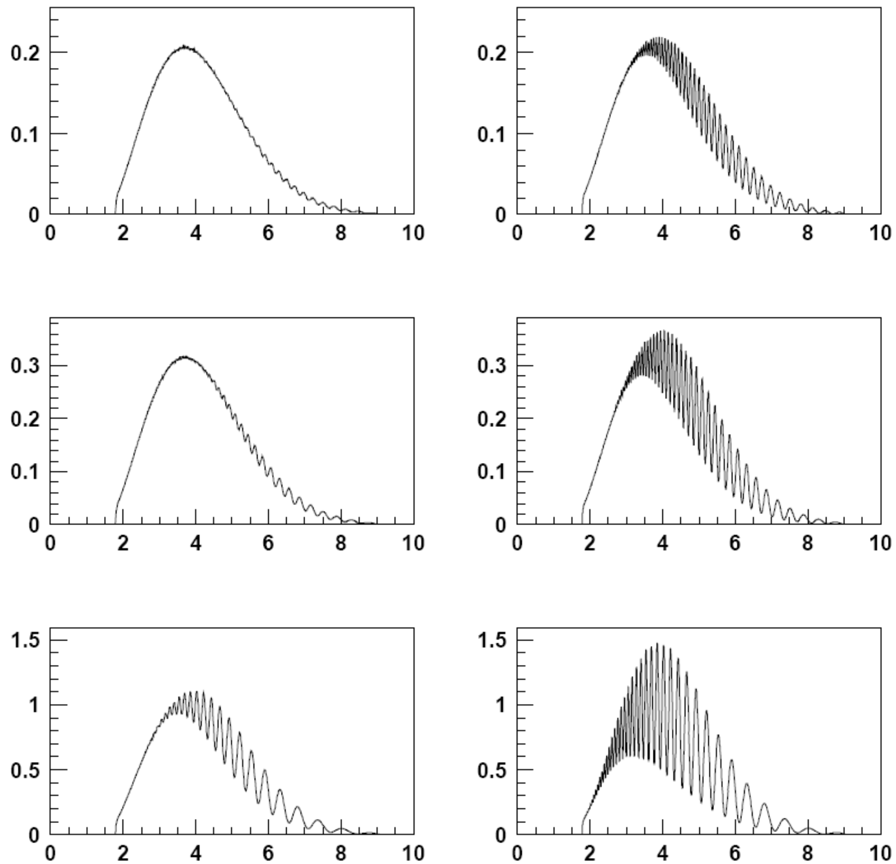
Idealized energy spectra: TW-10^33^p^+^-yr

δ*E*=6%√*E* | **δ*E*=3%√*E***

6370 km

5150 km

2890 km



Distortions well preserved with 3%√*E* energy resolution

Improving Energy Resolution

Benchmark- KamLAND at ~6%
Goal- Increase light collection x4 to achieve 3%

Increase photocathode coverage to SNO-like (55%)
x ~1.6
(B. Aharmin et al. 2007)

Brighter Scintillating Oil

Increase light output with LAB-based scintillating oil
x ~1.7
(M. Chen 2006)

Increase PC quantum efficiency
x ~1.6
(R. Mirzoyan et al. 2006)

3%$\sqrt{E}$ possible

Rayleigh Power Estimates Spectral Significance

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

amplitude **modulation**

For each event in the spectrum

$$\varphi_i = 1.27 \Delta m_{21}^2 L / E_i$$

Test significance of spectrum at distances *L*=500-8000 km

Use Rayleigh Power to estimate significance of spectral distortions

$$Z = \frac{\left(\sum_i^N \cos\varphi_i\right)^2 + \left(\sum_i^N \sin\varphi_i\right)^2}{N}$$

Introduced by Lord Rayleigh to study directions of pigeon flight

Used to test for periodicity of light curves in astronomy

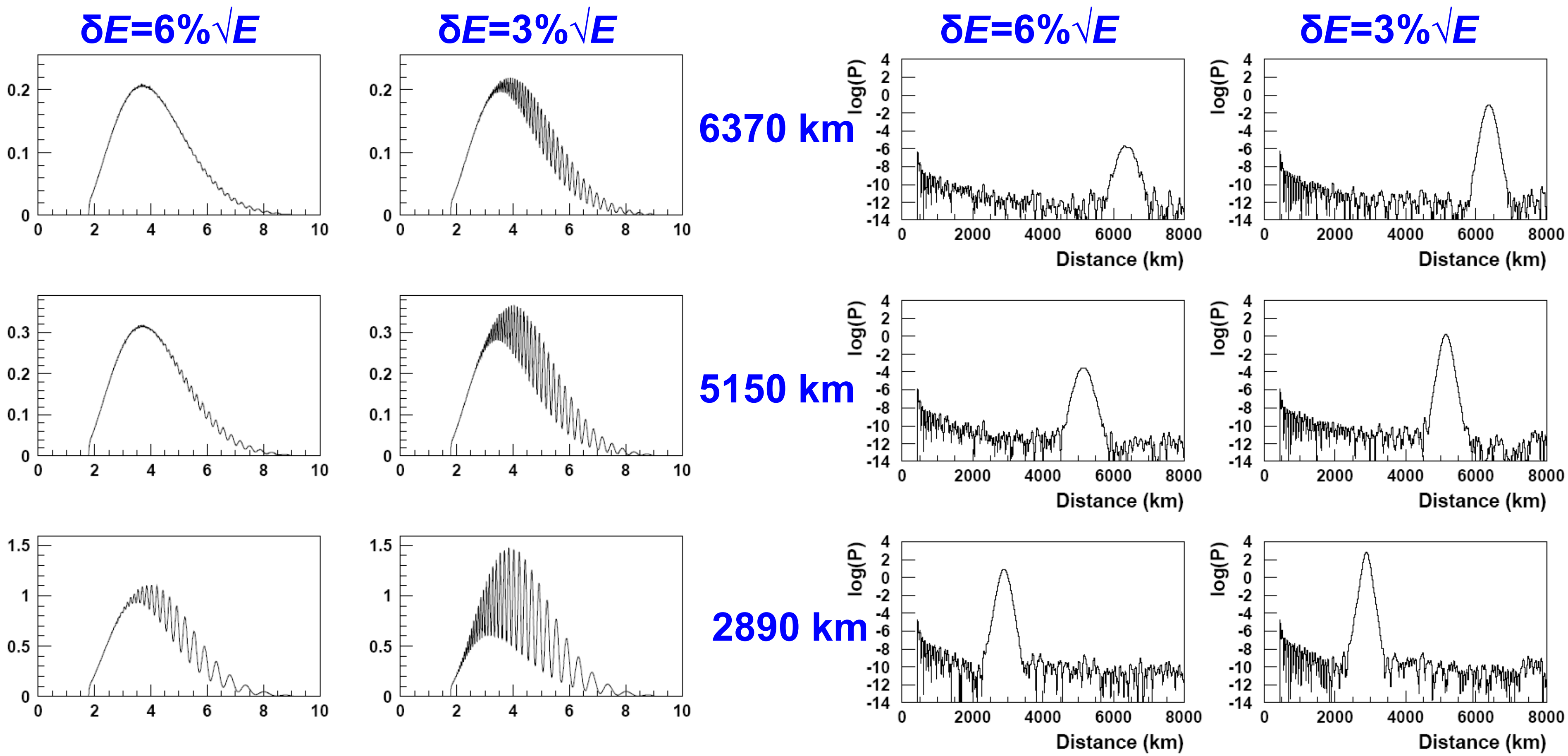
$$L_{ind} = \frac{2\pi}{1.27 \Delta m_{21}^2} \frac{E_{\max} E_{\min}}{E_{\max} - E_{\min}}$$

Independent Distance ~150 km

Distance limitations:
spectrum must modulate,
L_{ind} is minimum;
modulations must be resolved,
energy resolution sets maximum

Measuring Distance to Reactor

Idealized energy spectra: TW-10^{33}p^{+}-yr **Rayleigh Power Distributions**



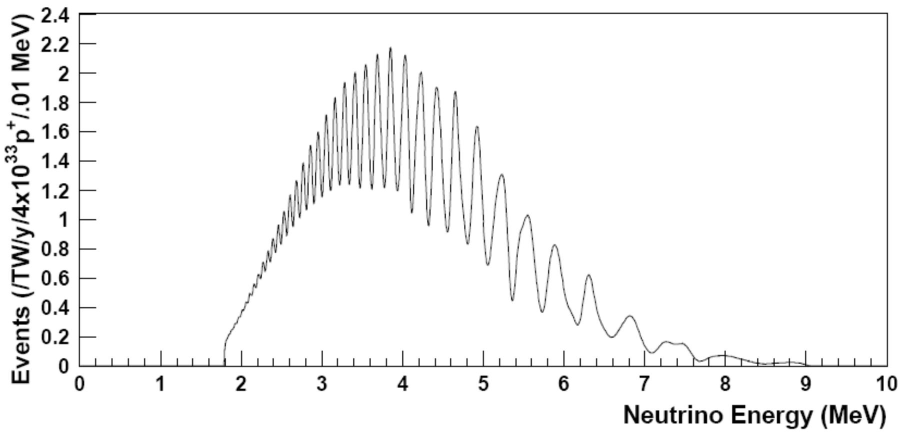
Oversampled x10

Power peaks at correct distance
FWHM ~1000 km

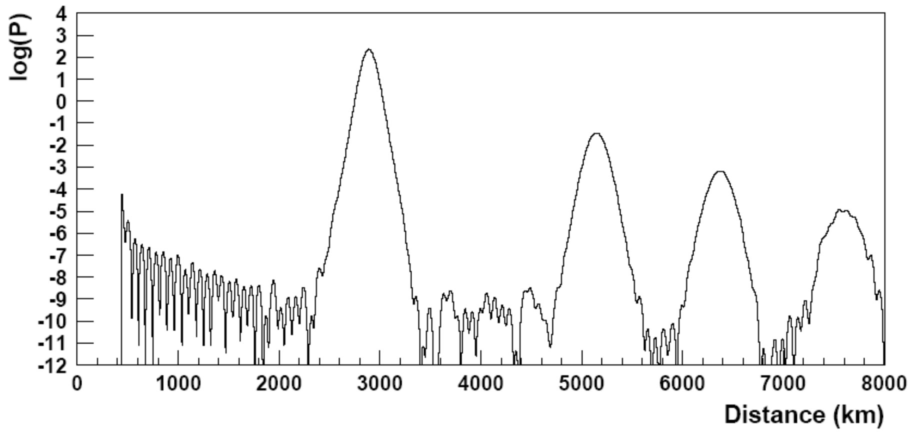
Resolving Distances to Multiple Sources

Idealized energy spectrum with $\delta E = 3\% \sqrt{E}$ from TW-$10^{33}p^{+}$-yr exposure to sources at:

- **CMB**
- **Inner core boundary- near**
- **Earth center**
- **Inner core boundary- far**



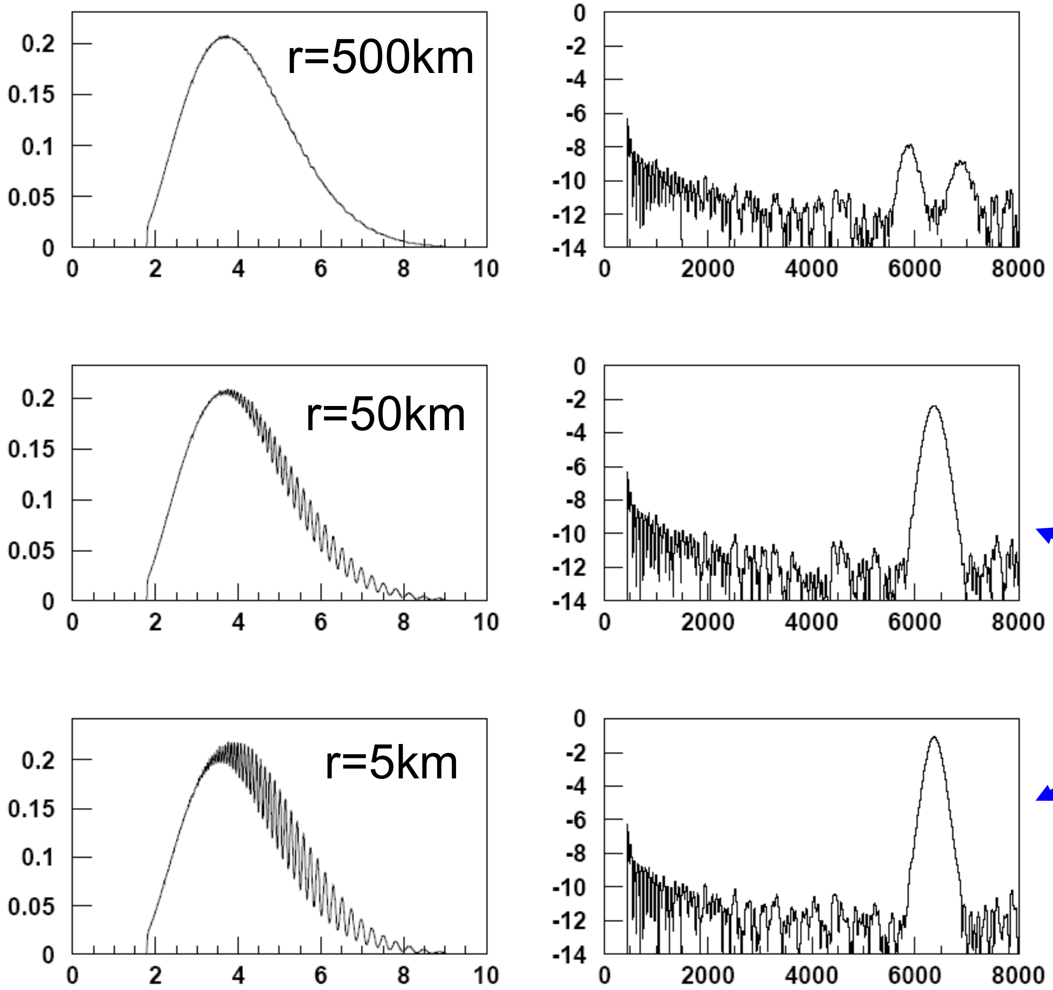
Rayleigh power distribution resolves discrete sources at different distances separated by > ~500 km



Method capable of finding discrete sources at different distances

Distributed Sources

Idealized energy spectra with $\delta E = 3\%\sqrt{E}$ from TW-10^{33}p^{+}-yr exposure to source distributed uniformly on a geo-centric, spherical shell: different radii



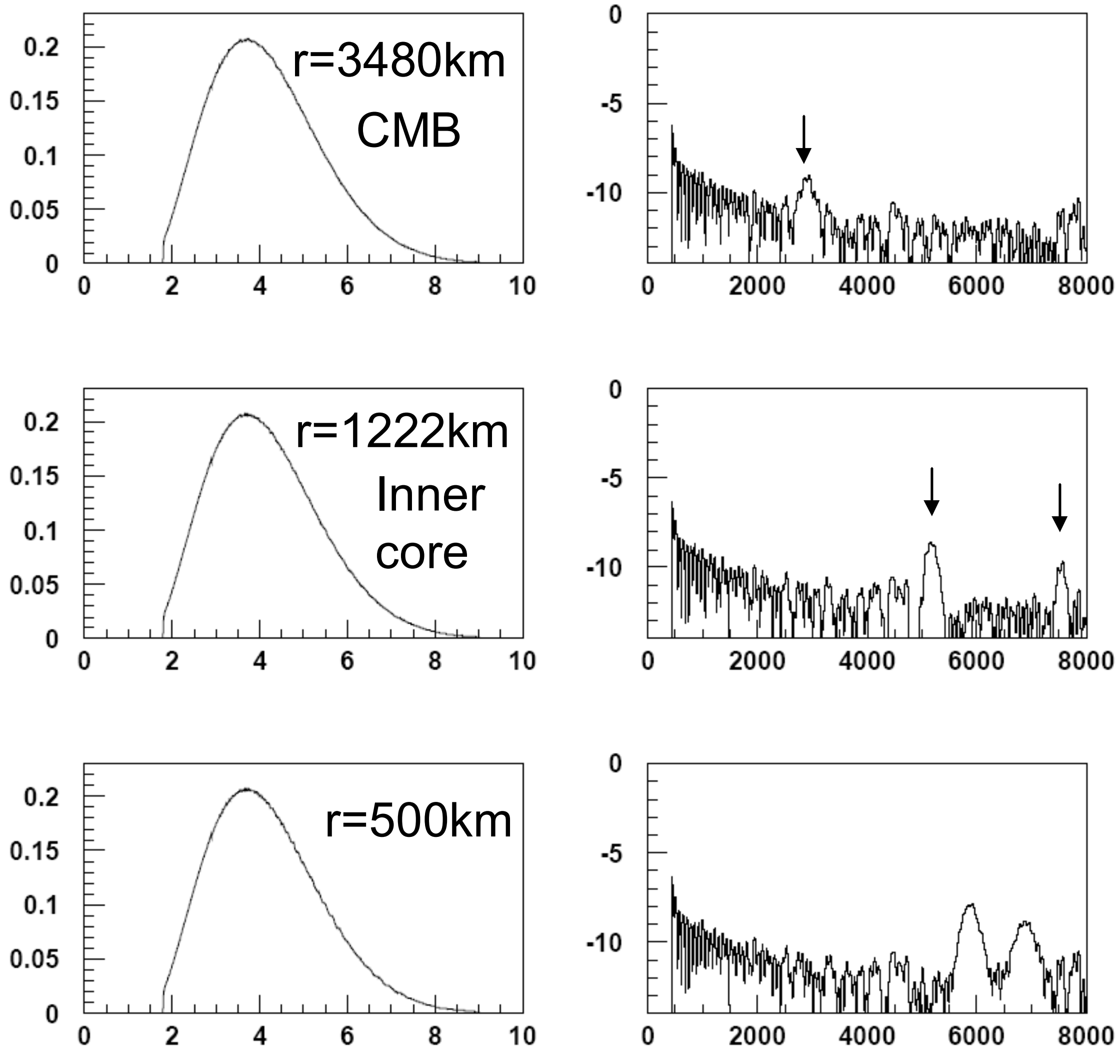
Near and far surfaces resolved!!!

Single source

Method has potential for finding distributed sources

Distributed Sources

Idealized energy spectra with $\delta E = 3\% \sqrt{E}$ from TW-10^{33} p^{+}-yr exposure
Geo-centric source uniformly distributed on spherical shell

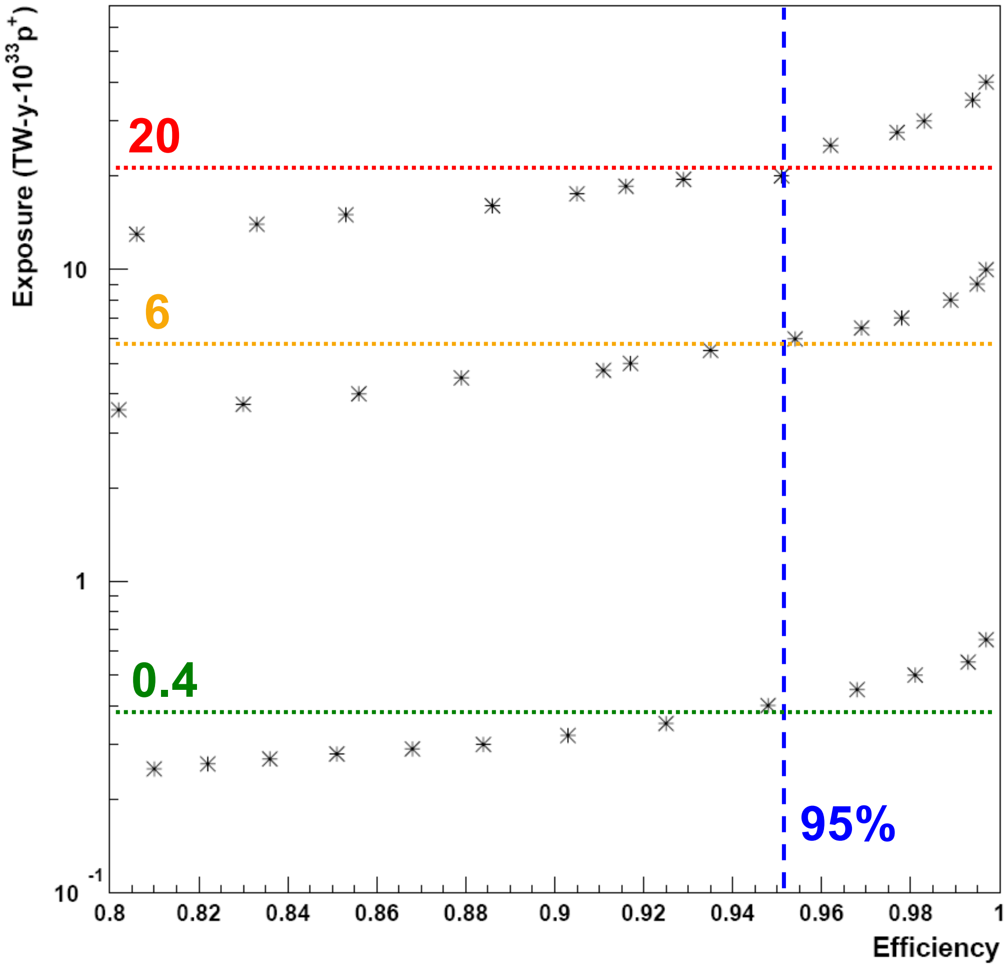


Peaks due to near and far surfaces just poking up above noise: potential for inner core boundary?

Assessing Exposure Requirements

- **Randomly sample idealized event spectra**
- **Number of sampled events determines exposure**
- **Generate Rayleigh power distribution**
- **Test if peak within ± L_{ind} (150 km) of “true” distance**
- **Repeat for 1000 spectra at each exposure**
- **Efficiency is fraction of “correct” distance measurements**

Efficiency Increases with Exposure



Earth-centered: r = 6370 km

Inner core boundary: r = 5150 km

Greater distance requires larger exposure

Core-mantle boundary: r = 2890 km

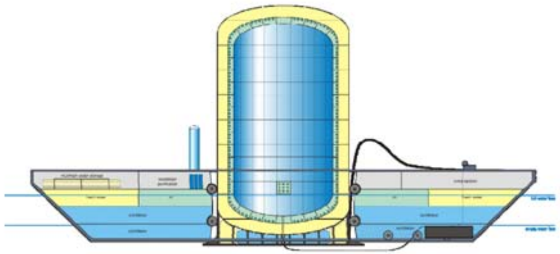
Exposures w/ efficiency ε=0.99

$\sigma_{distance} \approx L_{ind} \approx 150$ **km**

Limitations of Study

- **Background not included:**
  - **Reactor antineutrinos- far away from commercial plants**
  - **Cosmic rays- overburden > 3000 m.w.e.**
  - **Geo-neutrinos- far away from continents**

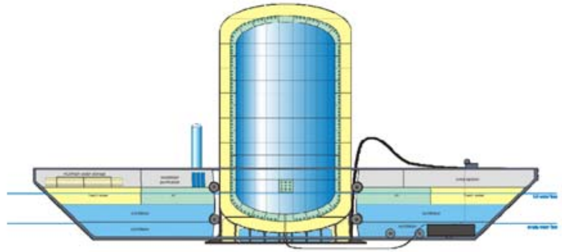
- **Solution: Observe from mid-Pacific location- Hanohano**



Conclusions

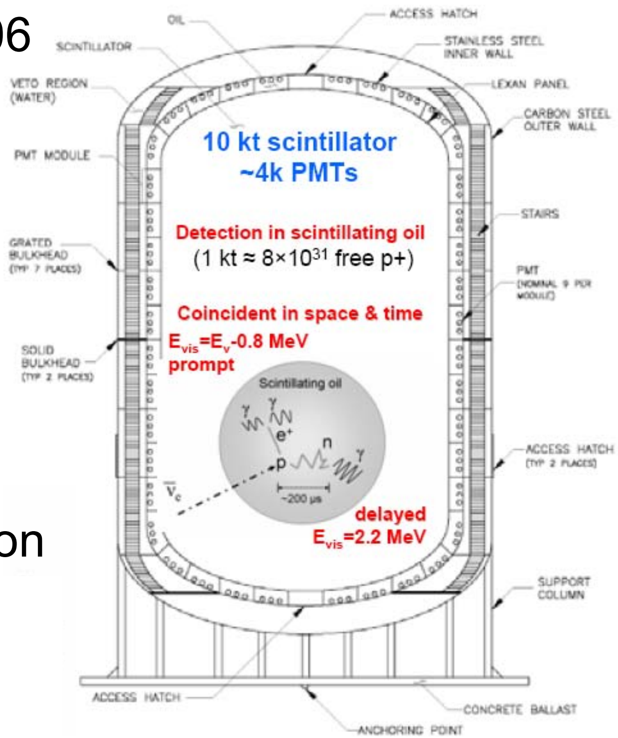
- **Neutrinos are marvelous tools**
- ***L/E* for reactor antineutrinos at deep-earth distances good match for solar mass-squared differences**
- **Energy spectrum distortions resolved with high light collection (~x4 KL)- aim for δE=3%$\sqrt{E}$**
- **Distances to deep-earth geo-reactors measured to ± few 100 km using Rayleigh power scan**
- **Suitable for discriminating geo-reactor models with detector like Hanohano**

Hanohano- Deep Ocean Anti-Neutrino Observatory



Project Overview
- portable 10 kt scintillator
- deploy and recover
- site determines science
- project cost >$100M, operate >10y
- international collaboration of ~100
- design study completed 2006

Detector Design
- 10-kt scintillating oil
- inverse-beta coincidence
- 2-m H_2O veto,1-m oil buffer
- PMTs in glass spheres
- carbon steel outer tank
- SS inner tank
- volume change compensation
- power <5 kW
- data rate few Gb/s



Custom Barge
- tow to any ocean
- 10m draft, fits harbors
- onboard
  - oil purification
  - RO water
  - detector support
- detector to 100 kt
- 9 kt max to fit Panama

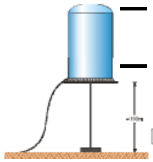
Deployment/Recovery
- tow to site, transfer fluids
- lower anchor, pass cable
- release anchor, fill hoses
- descent rate ~100 m/min
- take data for year or more
- max depth 6700 m
- release anchor to recover
- ascent rate ~100 m/min

Hanohano- Particle Physics & Geo/Astro Studies

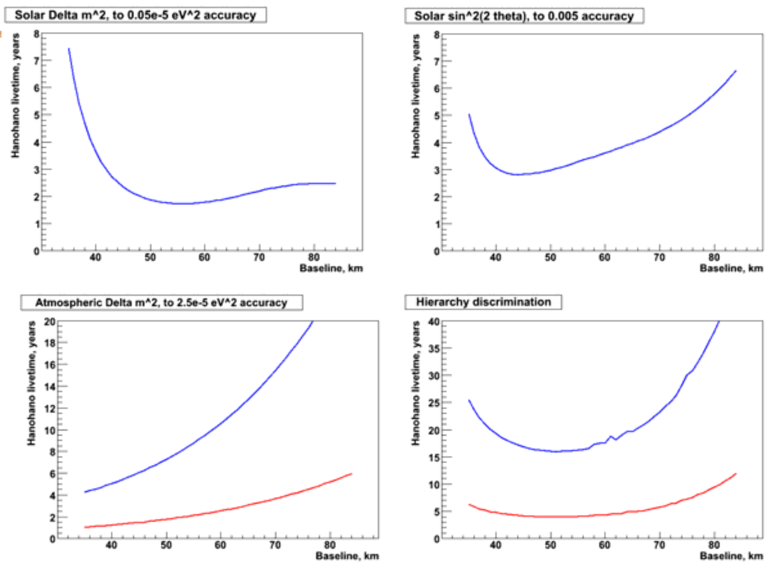
Reactor Site: Neutrino Parameters

Precision measurements in several years!

- optimum baseline ~50-60 km
- 5-6 GW sites available with 1-3 km depth
- need study of overburden requirement
- analysis w/ systematics- M. Batygov (UH)
- solar- Δm^2_{21}, $\sin^2(2\theta_{12})$ to ~1% in 2y, 4y
- if $\sin^2(2\theta_{13})>0.05$, then
  - Δm^2_{31} to ~1% in 2y
  - mass hierarchy in 5y



P=5 GW, $\delta E=2.5\%/\sqrt{E}$



Plots by M. Batygov, UH

Deep Ocean Site: Geo-nu & Solar-nu

Geo-neutrino measurements

- study origin, composition, distribution P_{earth}
- 3-4 km depth to filter cosmic ray muons
- resolution of mantle models
- synergy with continental observations
- sensitive test of geo-reactor hypothesis
- locate geo-reactor if existing

Solar-neutrino measurements

- *pep* and CNO solar neutrinos
  - >4 km depth for signal/noise>1
  - 55,000 events/y
  - probe vacuum/matter transition, NSI

All Sites: SN and proton decay search

Supernova neutrino measurements

- standard galactic core collapse SN
  - ~5000 CC & NC events in 10 s
  - measure SN & neutrino parameters
- observe relic SN neutrinos 1-4/y (DSNB)

SUSY proton decay search- GUT test

- $p \rightarrow \nu K^+$, $\tau/B>10^{34}$y w/ 10-y exposure