Geo-neutrinos
Discrepancy?

- The measured total heat flow is 46 TW.
- The estimated radiogenic heat produced is between 11 and 21 TW.
- Models of mantle convection suggest that the radiogenic heat production rate should be a large fraction of the measured heat flow.
- Problem with
  - Mantle convection model?
  - Total heat flow measured?
  - Estimated amount of radiogenic heat production rate?
- Geoneutrinos can serve as a cross-check of the radiogenic heat production.
Geoneutrino signal

Neutron inverse beta decay threshold

Diagram showing the number of anti-neutrinos per MeV per parent versus anti-neutrino energy. The graph includes different isotopes: $^{238}$U series, $^{232}$Th series, and $^{40}$K. The neutron inverse beta decay threshold is indicated by a vertical line at the energy where the anti-neutrino signal represents a notable change.
Current and future status

- KamLAND (1 kton) has measured the geoneutrino flux to ~37% (PRL 100, 221803), this could be expected to improve to ~20% with more time. Sensitivity limited by reactor neutrino background.
- Borexino (0.3 kton) has measured the geoneutrino flux to ~34% (arXiv:1003.0284), this could be expected to improve to ~25% with more time. Sensitivity limited by small fiducial volume.
- SNO+ (0.8 kton), currently under construction, could measure to ~15%.
- Proposed detectors:
  - LENA (50 kton), on continental crust
  - HanoHano (10 kton), on oceanic crust
Homestake detector

- Background from power plants
  - ~7% that in KamLAND
  - ~20% that at SNO+
- Sensitive to georeactor power down to ~1TW.
- Could measure total flux limited by systematics of ~5% in a very short time (detector dependent).
- Would allow us to test the U/Th ratio. Much of geophysics is based on ratios of elements, as this tells us about the formation processes. This would be the most accurate measurement of this ratio over a large volume.
Need for more detectors

- Ideally we would like to make a measurement in the ocean to probe the contribution from the mantle.
- However, with a precision measurement on the crust, and an accurate measurement of the local crustal contribution from heat flow measurements, could also obtain mantle contribution.
- Ideally we would like multiple measurements to probe local variations (despite our assumptions, the mantle is not uniform).
Reactor neutrinos
KamLAND used reactor neutrinos to measure neutrino oscillation parameters:

- $\Delta m^2_{12}$, measured to 2.7%, limited by energy scale and lack of multiple oscillation peaks
- $\theta_{12}$, measured to ~8%, limited by fiducial volume and reactor flux knowledge.
- $\theta_{13}$, limit placed by combining result with solar neutrino oscillation results. Limited by similar effects as $\theta_{12}$, but also requires accurate solar measurements.
Sensitivity of Reference Configurations
Detection requirements

- Need to be able to distinguish electron-antineutrinos from solar electron-neutrinos
- Need to be sensitive to neutrinos with energies
  - <3.4 MeV geo-neutrinos
  - <10 MeV reactor neutrinos
- Need to be sensitive to rates as low as
  - ~20 events/kton/year
Water Cherenkov

- Detect electron-antineutrinos from neutron inverse beta decay
  \( \bar{\nu}_e + p \rightarrow e^+ + n \)
- Not sensitive to geo-neutrinos because they are below the Cherenkov threshold
- Reactor neutrinos easily observable with Gd doped water, but poor energy resolution does not allow observation of oscillations
Liquid Argon

- Even more challenging than detecting relic SN neutrinos.
- Elastic scattering:
  - Low cross-section
  - Overwhelmed by solar neutrinos, therefore need good angular resolution
- CC, $\nu_e + ^{40}\text{Ar} \rightarrow e^+ + ^{40}\text{Cl}$:
  - Threshold too high (~8.5 MeV)

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Neutrino Absorption Cross Sections

Cross Section (x 10^{-12} cm^2) vs. $E_\nu$ (MeV)
Solar neutrinos
Solar $\nu$ Spectra

Bahcall–Serenelli 2005

Neutrino Spectrum ($\pm 1\sigma$)

Flux ($\text{cm}^{-2} \text{s}^{-1}$)

Neutrino Energy in MeV
Can we observe MSW signatures?

**Vacuum/Matter Transition**

\[
\beta = \frac{2^{3/2} G_F \cos^2 \theta_{13} n_e E \nu}{\Delta m^2_{21}}
\]

**Day-night asymmetry**

*Vacuum - Matter transition*
Vacuum-Matter transition
Day-night Asymmetry

Super-K

SNO

0.032±0.040
So far, it seems that Nature has picked out one of the few regions where we’d miss a direct MSW signature.
Strategy of Solar $\nu$ TPG

- Water Cherenkov detector can only see $^8$B and hep solar neutrinos, if that.
- LAr TPC could in principle also see lower energy solar neutrinos (pep, $^7$Be, pp, CNO) via elastic electron-neutrino signal, but probably only $^8$B and hep solar CC interactions are realistic.
- Therefore, concentrate discussion on water Cherenkov Day/Night asymmetry and hep neutrino detection.
LAr Possibilities

\[ \nu_e + {}^{40}\text{Ar} \rightarrow {}^{40}\text{K}^* + e^- \]

\[ \nu_\alpha + {}^{40}\text{Ar} \rightarrow {}^{40}\text{Ar}^* + \nu_\alpha \quad \rightarrow {}^{40}\text{Ar} + \gamma_1 + \ldots \gamma_n \]

\[ \nu_e + e^- \rightarrow \nu_e + e^- \]

\[ \bar{\nu}_e + e^- \rightarrow \bar{\nu}_e + e^- \]

\[ \nu_x + e^- \rightarrow \nu_x + e^- \]

C. Volpe* and J. Welzel†
DUSEL LBNE WC Requirements

- depth!
- high PMT density to achieve low energy threshold
- high PMT density to reject low energy radioactive background
- good radio-purity and control of Radon background (e.g. radon barrier around water volume!)
- low dark noise
- extremely precise calibration of up/down asymmetry of energy scale and other, zenith-angle dependent systematics
Day/Night Effect

ES cross section smears things out, energy resolution makes this worse, but...
DUSEL LBNE Detector

- with 300kt detector expect 470,000 events above 7 MeV in 10 years
  - reach about 0.3% accuracy of D/N (w/o zenith angle or energy fitting)
  - effect could be as large as $7\sigma$

- with 100kt detector expect 157,000 events above 7 MeV in 10 years
  - reach about 0.5% accuracy of D/N (w/o zenith angle fitting)
  - effect could be as large as $4\sigma$

- can study D/N effect in detail: zenith angle variation
only $^8$B neutrinos show any D/N effect, so neither BOREXINO, KamLAND, SNO+, CLEAN or LENS will make any progress on this

compétition is just SK which will reach $\sim 0.8\%$ in 2025 and $\sim 0.7\%$ in 2035
CPT Invariance?

- to test CPT invariance, the solar $\nu$ data constraint on $\Delta m^2$ must be greatly improved; only a good D/N measurement can do that, or an excellent measurement of the low energy $^8\text{B}$ spectrum
- Borexino, SNO+, KamLAND (solar) will take a very long time to measure low energy $^8\text{B}$ spectrum well enough
$\Delta m^2$ Constraint

“wiggle” are due to SK zenith angle data (D/N)
hep neutrinos

- perhaps chief background for SN relic neutrinos with a LAr TPC
- difficult to distinguish from $^8$B in a water Cherenkov detector (need excellent energy resolution)
- requires good control of energy resolution systematics (up to $3\sigma$ in the resolution tail or more!)
hep neutrinos

- Tough to do with ES and with poorer energy resolution,
- but lots of events---fit $^8$B shape?
- LAr might do very well especially with CC
D/N effect is an “ecological niche” of solar neutrino physics where large water Cherenkov detectors have essentially no competition.

LBNL DUSEL could find D/N effect with 4 to 7σ significance and study it in detail.

Have no man power to investigate several other physics topics requiring immense detector exposure:
- time variation of solar neutrino flux
- hep neutrinos
- MSW spectral distortion between ~7MeV and 15 MeV

Have no man power or expertise for a fair evaluation of LAr TPCs:
- CC/NC ratio of 8B neutrinos and CC spectrum
- energy threshold: elastic scattering of low energy solar ν’s?