

Scanning the Earth with solar neutrinos and DUNE

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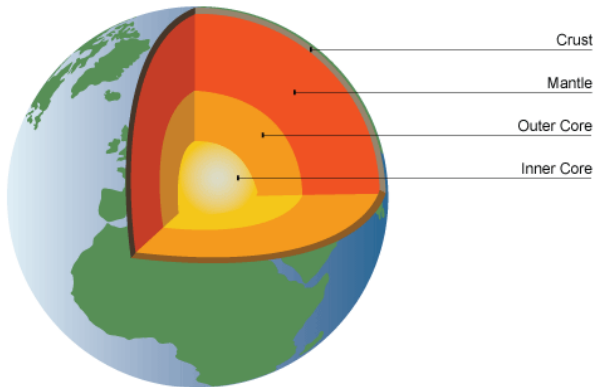
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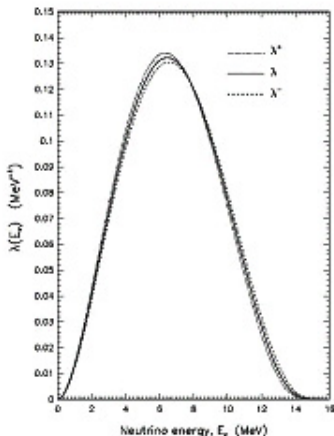
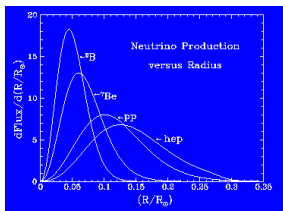
11-15 September, 2017



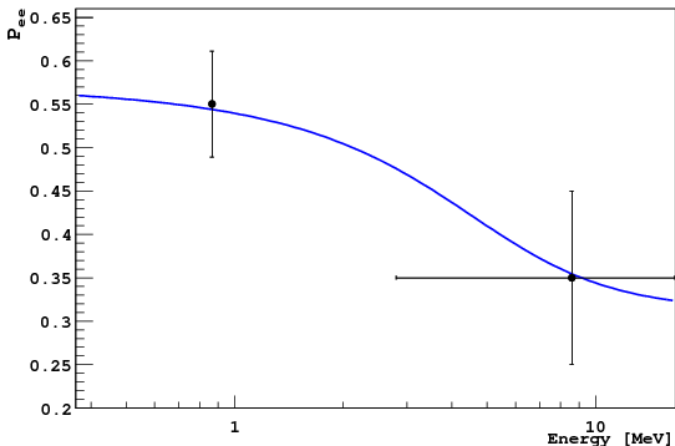
Geophysics, Scan the Earth via solar boron neutrinos at DUNE

Ara Ioannisian, Alexei Smirnov and Daniel Wyler



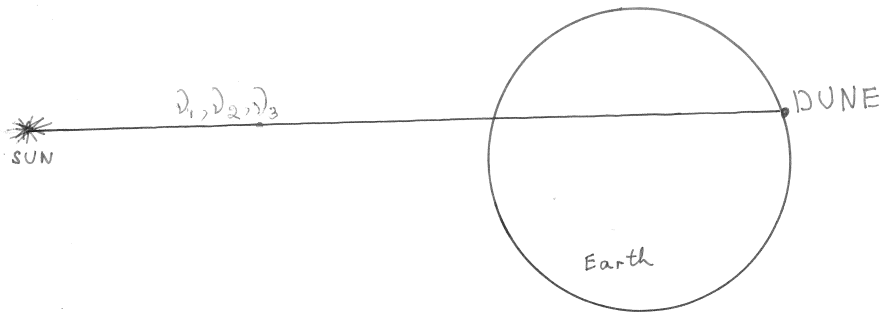


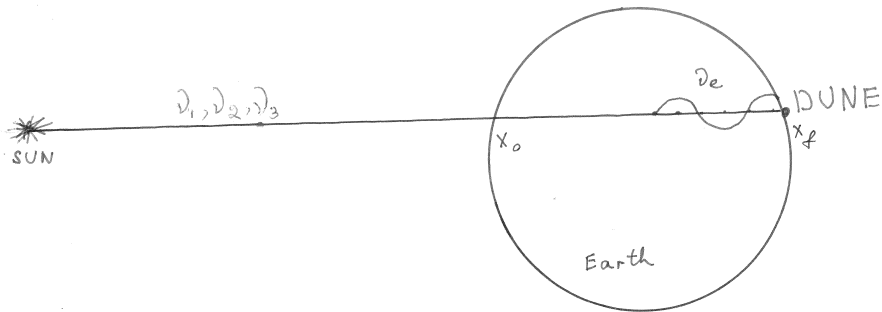
From the Earth 8B neutrino production region in the Sun is seen as a very small disk with angular size $\approx 10^{-4}$



$$P_D \equiv P_{ee} = \frac{c_{13}^4}{2} (1 + \cos 2\bar{\theta}_{12}^{\odot} \cos 2\theta_{12}) + s_{13}^4 \simeq$$

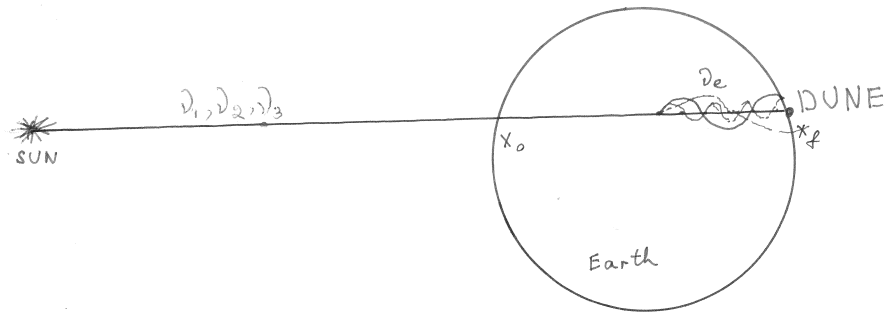
$$c_{13}^2 s_{12}^2 + s_{14}^4 + \frac{1}{4} \cos 2\theta_{12} \sin^2 2\theta_{12} \left(\frac{\Delta m_{12}^2}{2EV_e^0} \right)^2 \simeq 0.32$$





$$\Delta P_{\nu_2 \rightarrow \nu_e} = C \sqrt{2} G_F \int_{x_0}^{x_f} dx N_e(x) \sin \frac{\Delta m_{21}^2}{2E} (x_f - x)$$

$$\Delta P_{ee} = -\frac{c_{13}^2}{2} (2P_{ee} - c_{13}^4 - 2s_{13}^4) \frac{\sin^2 2\theta_{12}}{\cos 2\theta_{12}} \sqrt{2} G_F \int_{x_0}^{x_f} dx N_e(x) \sin \frac{\Delta m_{21}^2}{2E} (x_f - x)$$



$$g(E, E') = \frac{1}{\sigma\sqrt{2\pi}} e^{-\frac{(E-E')^2}{2\sigma^2}}$$

$$\overline{\Delta P_{ee}} = -\frac{c_{13}^2}{2} (2P_{ee} - c_{13}^4 - 2s_{13}^4) \frac{\sin^2 2\theta_{12}}{\cos 2\theta_{12}} \sqrt{2} G_F \int_{x_0}^{x_f} dx F(x_f - x) N_e(x) \sin \frac{\Delta m_{21}^2}{2E} (x_f - x)$$

$$F(x_f - x) \simeq e^{-2\left(\frac{\pi\sigma(x_f-x)}{E l_\nu}\right)^2}$$

There are several matter density jumps in the Earth.
 Within those jumps matter density changes weakly \rightarrow adiabatic conditions of neutrino oscillation is held within layers between density jumps.

$$\Delta P_{ee} = -\frac{2P_{ee} - c_{13}^4 - 2s_{13}^4}{\cos 2\theta_{12}} \left\{ -\sin^2 \theta_{12} - \sin 2\theta_{12}^s \sin(-2\theta_{12}^s + 2\theta_{12}) \sin^2 \frac{\Phi}{2} - 2 \sin(-4\theta_{12}^s + 2\theta_{12}) \sin \frac{\Phi}{2} \sum \Delta\theta_{12}^i \sin \phi_i \right\}$$

θ_{12}^s mixing angle at surface,

Φ full phase in the Earth,

$\Delta\theta_{12}^i$ jump of the mixing angle at the interface of different layers of the Earth,

ϕ_i phase from the density jump to the detector

	$A_{\text{DN}} \pm (\text{stat}) \pm (\text{syst})$	$A_{\text{DN}}^{\text{fit}} \pm (\text{stat}) \pm (\text{syst})$
SK-I	$(-2.1 \pm 2.0 \pm 1.3)\%$	$(-2.0 \pm 1.7 \pm 1.0)\%$
SK-II	$(-5.5 \pm 4.2 \pm 3.7)\%$	$(-4.3 \pm 3.8 \pm 1.0)\%$
SK-III	$(-5.9 \pm 3.2 \pm 1.3)\%$	$(-4.3 \pm 2.7 \pm 0.7)\%$
SK-IV	$(-5.3 \pm 2.0 \pm 1.4)\%$	$(-3.4 \pm 1.8 \pm 0.6)\%$
Combined	$(-4.2 \pm 1.2 \pm 0.8)\%$	$(-3.2 \pm 1.1 \pm 0.5)\%$

for fit they use $\Delta m^2 = 4.8_{-0.9}^{+1.8} 10^{-5} \text{eV}^2$, $\theta_{12} = 35.8^0 \pm$, $\theta_{13} = 9.1^0$
 KamLAND $\Delta m^2 = 7.5 10^{-5} \text{eV}^2$ one expects at SK $A_{\text{DN}} = -2.1\%$

Thus SK sees 2 (fitted 1.5) times larger effect \rightarrow 2 (1.5) times larger electron density

mater density is known \rightarrow chemical composition

Therefore there is more (much more) hydrogen must be in the Earth in order to explain SK DN result

Liquid Argon detectors.

$$A_e(E) = \frac{\int dE' g(E, E') \sigma_{\nu Ar}(E') f_{B8}(E') \Delta P_{ee}(E')}{\int dE' g(E, E') \sigma_{\nu Ar}(E') f_{B8}(E') P_{ee}(E')}$$

$$\Delta P_{ee} = -\frac{c_{13}^2}{2} (2P_D - c_{13}^4 - 2s_{13}^4) \frac{\sin^2 2\theta_{12}}{\cos 2\theta_{12}} \sqrt{2} G_F \int_0^L dx N_e(x) \sin \frac{\Delta m_{21}^2}{2E} (L-x)$$

$$f_{B8}(E_\nu) = C E_\nu^2 (E_\nu^{max} - E_\nu + m_e) \sqrt{(E_\nu^{max} - E_\nu + m_e)^2 - m_e^2}$$

$$E_\nu^{max} \simeq 14.1 \text{ MeV.}$$

$$C = 260 \frac{\text{Flux}_{B8}}{5.7 \cdot 10^6 \text{ cm}^{-2} \text{ sec}^{-1}} \frac{1}{\text{MeV}^5} \frac{1}{\text{cm}^2 \text{ sec}}$$

About 9.7% of B⁸ neutrinos have energy $E_\nu > 11$ MeV and 0.96 % have energy above $E_\nu > 13$ MeV.

$$g(E, E') = \frac{1}{\sigma_E \sqrt{2\pi}} e^{-\frac{(E-E')^2}{2\sigma_E^2}}$$

^{40}Ar has 0 spin and ^{40}K has 4 spin. Therefore it is highly suppressed direct transition via weak current W exchange. That transition becomes allowed via intermediate states, excitation states of ^{40}K , and farther emission of photons. These transition probabilities are not measured yet. In our numerical study we'll approximate to

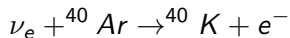
$$\sigma_{\nu_e \text{Ar}} \simeq 2 \cdot 10^{-43} \text{cm}^2 \frac{p_e E_e}{\text{MeV}}$$

where $E_e = E_\nu - 5.8\text{MeV}$.

In our computations we used the spherically symmetric Earth PREM model (density jumps at 15, 25, 210, 400, 670, 2830 and 5150 km from the surface of the Earth.

Trajectories with $\eta < 0.58$ cross the core of the Earth.

Annually we expect about 27000 registered electron neutrinos ($E_\nu > 11$ MeV) at 40kt liquid argon detector due to the reaction



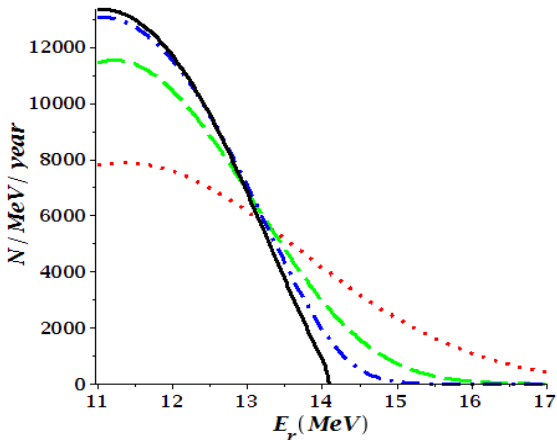
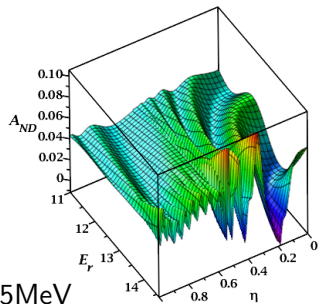
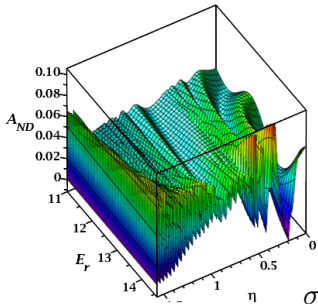
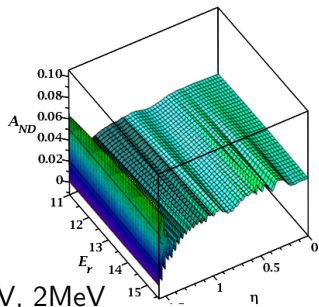
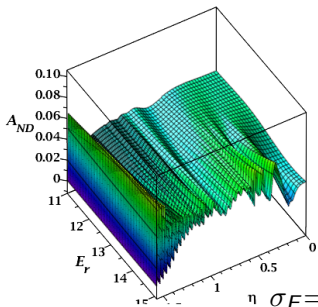


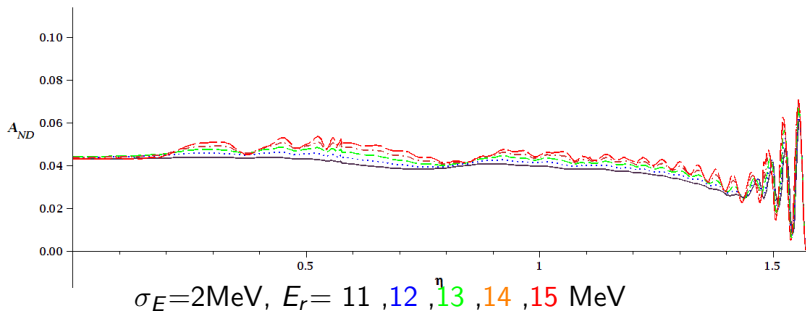
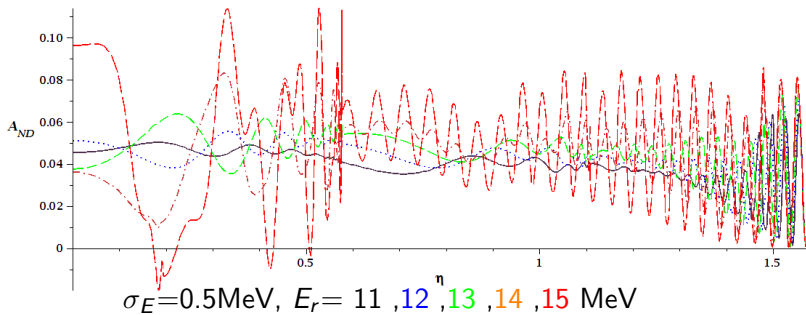
Figure: (Annually expected) registered neutrino spectrum on reconstructed neutrino energy (E_r). The number of expected total registered neutrinos with energy $E_r > 11$ MeV is about 27000 and it almost does not depend on energy resolution of the detector. solid line (black) -exact neutrino spectrum, dot line (blue) - 0.5 MeV resolution, dash line (green) - 1 MeV resolution, dash-dot line (red) -2 MeV resolution.



$\sigma_E = 0.5 \text{ MeV}$



$\sigma_E = 1 \text{ MeV}, 2 \text{ MeV}$



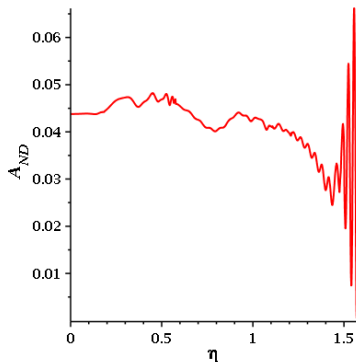
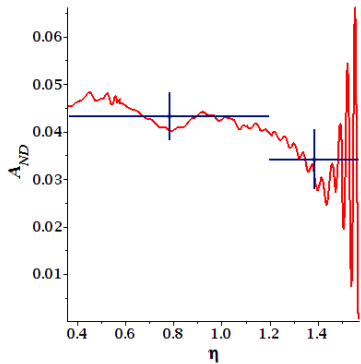
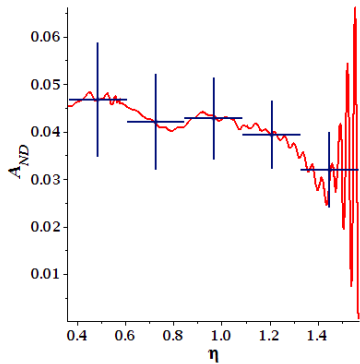
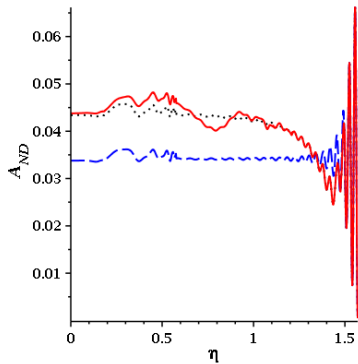
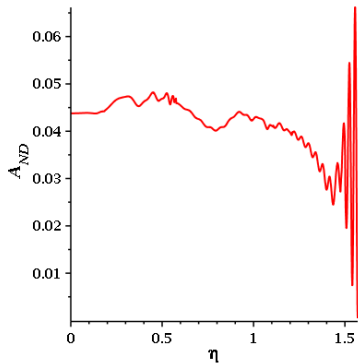


Figure: The relative variation of the boron solar neutrino flux with energy $E_r > 11$ MeV as function of the nadir angle of the neutrino trajectory.





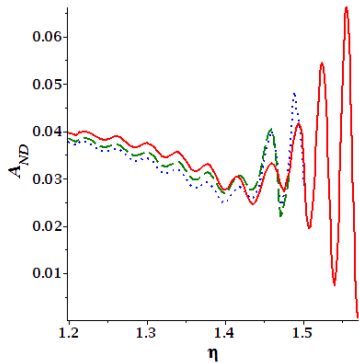


Figure: The relative excess of night events integrated over $E_r > 11$ MeV as function of the nadir angle of the neutrino trajectory for changed parameters of density jumps. Red line is the old one with jumps at 15 km and 25 km; blue-dotted line is for jumps at $h_1 = 20.5$ km and $h_2 = 30$ km; green-dashed line is for jumps at $h_1 = 15$, $h_2 = 30$. Parametric enhancement of oscillations is seen in the 3rd and 4th periods.

CONCLUSIONS

- ▶ Water Cherenkov or scintillator detectors are "shortsighted".
- ▶ **DUNE is an unique instrument to scan the Earth**
- ▶ At night time the regeneration of ν_e ($11\text{MeV} < E_\nu < 14\text{ MeV}$) is **4 %**, with modulation up to 10 %. One year of taking data from one 10 kt module of DUNE far detector will determine the Earth matter effect at 2.6σ c.l. (SuperKamiokande reached that result after 20 years of taking data). After 10 years of taking data from all 4 DUNE modules the Earth matter effect will be determined in more than **16 σ c.l.**
- ▶ Good energy resolution ($\sigma < 7\%E_\nu$) will make it possible to measure electron density at deep layers of the Earth and with the known density profile of the Earth learn about the chemical composition of the Earth's interior.

THANK YOU

Preliminary Reference Earth Model (PREM) (Dziewonski & Anderson, 1981)									
Region	Radius (km)	α (m/s)	β (m/s)	ρ (kg/m ³)	K_s (Gpa)	μ (Gpa)	ν	P (Gpa)	g (m/s ²)
Inner Core	0	11266.2	3667.8	13088.48	1425.3	176.1	0.4407	363.85	0
	200	11255.93	3663.42	13079.77	1423.1	175.5	0.4408	362.9	0.7311
	400	11237.12	3650.27	13053.64	1416.4	173.9	0.441	360.03	1.4604
	600	11205.76	3628.35	13010.09	1405.3	171.3	0.4414	355.28	2.1862
	800	11161.86	3597.67	12949.12	1389.8	167.6	0.442	348.77	2.9068
	1000	11105.42	3558.23	12870.73	1370.1	163	0.4428	340.24	3.6203
	1200	11036.43	3510.02	12774.93	1346.2	157.4	0.4437	330.05	4.3251
	1221.5	11028.27	3504.32	12763.6	1343.4	156.7	0.4438	328.85	4.4002
	1221.5	10355.68	0	12166.34	1304.7	0	0.5	328.85	4.4002
	1400	10249.59	0	12069.24	1267.9	0	0.5	318.75	4.9413
	1600	10122.91	0	11946.82	1224.2	0	0.5	306.15	5.5548
	1800	9985.54	0	11809	1177.5	0	0.5	292.22	6.1689
	2000	9834.96	0	11654.78	1127.3	0	0.5	277.04	6.7715
	2200	9668.65	0	11483.11	1073.5	0	0.5	260.68	7.3645
	2400	9484.09	0	11292.98	1015.8	0	0.5	243.25	7.9425
	2600	9278.76	0	11083.35	954.2	0	0.5	224.85	8.5023
2800	9050.15	0	10853.21	888.9	0	0.5	205.6	9.0414	
3000	8795.73	0	10601.52	820.2	0	0.5	185.64	9.557	
3200	8512.98	0	10327.26	748.4	0	0.5	165.12	10.0464	
3400	8199.39	0	10029.4	674.3	0	0.5	144.19	10.5065	
3480	8064.82	0	9903.49	644.1	0	0.5	135.75	10.6823	
3480	13716.6	7264.66	5566.45	655.6	293.8	0.3051	135.75	10.6823	
3600	13687.53	7265.75	5506.42	644	290.7	0.3038	128.71	10.5204	
3630	13680.41	7265.97	5491.45	641.2	289.9	0.3035	126.97	10.4844	
3630	13680.41	7265.97	5491.45	641.2	289.9	0.3035	126.97	10.4844	
3800	13447.42	7188.92	5406.81	609.5	279.4	0.3012	117.35	10.3095	
4000	13245.32	7099.74	5307.24	574.4	267.5	0.2984	106.39	10.158	
4200	13015.79	7010.53	5207.13	540.9	255.9	0.2957	95.76	10.0535	
4400	12783.89	6919.57	5105.9	508.5	244.5	0.2928	85.43	9.9859	
4600	12544.66	6825.12	5002.99	476.6	233.1	0.2898	75.36	9.9474	
4800	12293.16	6725.48	4897.83	444.8	221.5	0.2864	65.52	9.9314	
5000	12024.45	6618.91	4789.83	412.8	209.8	0.2826	55.9	9.9326	
5200	11733.57	6563.7	4678.44	380.3	197.9	0.2783	46.49	9.9467	
5400	11415.6	6378.13	4563.07	347.1	185.6	0.2731	37.29	9.9698	
5600	11043.57	6240.46	4443.17	313.3	173	0.2668	28.29	9.9985	
5600	11065.57	6240.46	4443.17	313.3	173	0.2668	28.29	9.9985	
5701	10751.31	5945.08	4380.71	299.9	154.8	0.2798	23.83	10.0143	
5701	10266.22	5570.2	3992.14	255.6	123.9	0.2914	23.83	10.0143	
5771	10157.82	5516.01	3975.84	248.9	121	0.2909	21.04	10.0038	
5871	9645.88	5224.28	3849.8	218.1	105.1	0.2924	17.13	9.9883	
5971	9133.97	4932.59	3723.78	189.9	90.6	0.2942	13.35	9.9686	
5971	8905.22	4769.89	3543.25	173.5	80.6	0.2988	13.35	9.9686	
6061	8732.09	4706.9	3489.51	163	77.3	0.2952	10.2	9.9361	
6151	8558.96	4643.91	3435.78	152.9	74.1	0.2914	7.11	9.9048	
6151	7989.7	4418.85	3356.5	127	65.6	0.2797	6.11	9.9048	
6221	8033.7	4443.61	3367.1	128.7	66.5	0.2796	4.78	9.8783	
6291	8076.88	4469.53	3374.71	130.3	67.4	0.2793	2.45	9.8553	
6291	8076.88	4469.53	3374.71	130.3	67.4	0.2793	2.45	9.8553	
Lid	6346.6	8110.61	4490.94	3380.78	131.5	68.2	0.2789	0.604	9.8394
6346.6	6800	3900	2900	75.3	44.1	0.2549	0.604	9.8394	
6356	6800	3900	2900	75.3	44.1	0.2549	0.337	9.8332	
6356	5800	3200	2600	52	26.6	0.2812	0.337	9.8332	
Crust	6368	5800	3200	2600	52	26.6	0.2812	0.3	9.8222
6368	1450	0	1020	2.1	0	0.5	0.3	9.8222	
Ocean	6371	1450	0	1020	2.1	0	0.5	0	9.8166

Averaging over neutrino energy

$$A_e = \int dE' g(E', E) \frac{P_N - P_D}{P_D} .$$

$$A_e = -f(\Delta m_{21}^2, \theta_{12}) \frac{1}{2} \int_0^L dx V(x) F(L-x) \sin \phi_{x \rightarrow L}^m,$$

The decrease of F means that contributions from the large distances to the integral are suppressed.

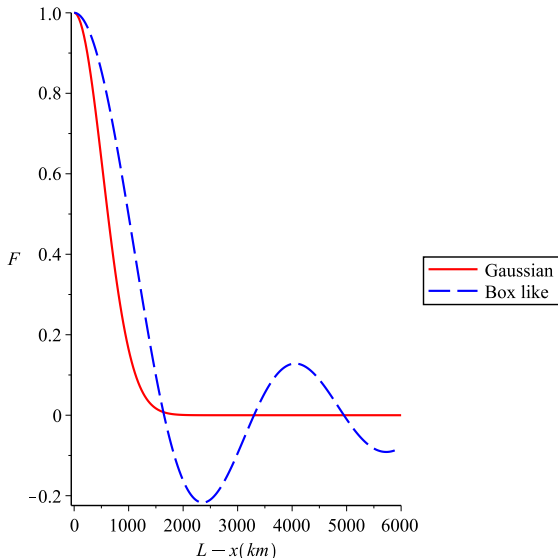
Gaussian energy resolution function

$$g(E, E') = \frac{1}{\sigma\sqrt{2\pi}} e^{-\frac{(E-E')^2}{2\sigma^2}}, \quad F(L-x) \simeq e^{-2\left(\frac{\pi\sigma(L-x)}{E l_\nu}\right)^2}$$

Box like energy resolution function

$$A_e = \frac{1}{2\sigma} \int_{E-\sigma}^{E+\sigma} dE' \frac{P_N - P_D}{P_D}$$

$$F(L-x) \simeq \frac{1}{Q(L-x)} \sin Q(L-x), \quad Q(L-x) \equiv \frac{2\pi\sigma(L-x)}{E l_\nu},$$



The attenuation factor F as function of $(L-x)$ (distance from detector). $E = 10$ MeV, $\sigma = 1$ MeV, and $\Delta m_{21}^2 = 7.5 \cdot 10^{-5} \text{ eV}^2$

WC

$$A_e(T, \eta) = \frac{\int dT' g(T, T') \int_{T+\frac{m_e}{2}} dE \Delta P_{ee}(E) j_B(E) \left(\frac{d\sigma_{\nu ee}}{dT'} - \frac{d\sigma_{\nu \alpha e}}{dT'} \right)}{\int dT' g(T, T') \int_{T+\frac{m_e}{2}} dE j_B(E) \left(P_{ee} \frac{d\sigma_{\nu ee}}{dT'} + (1 - P_{ee}) \frac{d\sigma_{\nu \alpha e}}{dT'} \right)}$$

$$\Delta P_{ee} = P_N - P_D = -\frac{c_{13}^2}{2} (2P_{ee} - c_{13}^4 - 2s_{13}^4) \frac{\sin^2 2\theta_{12}}{\cos 2\theta_{12}} \int_0^L dx V(x) \sin \phi_{x \rightarrow L}^m$$

$$\frac{d\sigma_{\nu ee}}{dT'} / \frac{d\sigma_{\nu \alpha e}}{dT'} \simeq 6$$

$$A_e \simeq 1.7\%$$

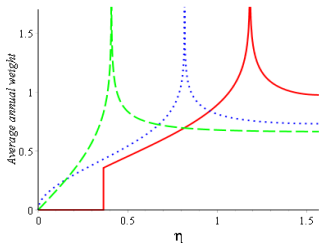


Figure: Dependence of average annual weight function on the nadir angle of neutrino trajectory (η is in radians). Outer core ($\eta < 0.58$) is "visible" at Homestake (SD) site about 9% of night time

$$P_{1e/c_{13}^2} = \cos^2 \theta_{12} - \frac{1}{2} \sin^2 2\theta_{12} c_{13}^2 \int_0^L dx V_e(x) \sin \phi_{x \rightarrow L}^m,$$

where

$$\phi_{x \rightarrow L}^m(E) \equiv \int_x^L dx \Delta_m(x),$$

$$\Delta_m(x) \equiv \frac{\Delta m_{21}^2}{2E} \sqrt{[\cos 2\theta_{12} - c_{13}^2 \epsilon(x)]^2 + \sin^2 2\theta_{12}}$$

$$\epsilon(x) \equiv \frac{2V_e(x)E}{\Delta m_{21}^2}$$

$$\approx 0.03 \left(\frac{\rho(x)}{3 \frac{\text{g}}{\text{cm}^3}} \right) \left(\frac{7.5 \cdot 10^{-5} \text{eV}^2}{\Delta m_{21}^2} \right) \left(\frac{E}{10 \text{ MeV}} \right) \left(\frac{Y_e(x)}{0.5} \right)$$

The oscillation length can be written as

$$l_m = \frac{2\pi}{\Delta_m(x)} = l_\nu [1 + \cos 2\theta_{12} c_{13}^2 \epsilon + O(\epsilon^2)].$$

$$l_\nu \approx 330 \left(\frac{7.5 \times 10^{-5} \text{eV}^2}{\Delta m_{21}^2} \right) \left(\frac{E}{10 \text{ MeV}} \right) \text{km}$$