Reception of modulated neutrino day-night effect signal by neutrino detectors

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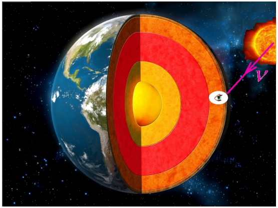
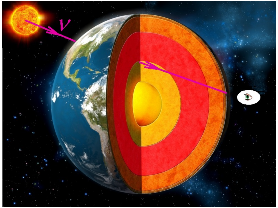
Why day-night effect? Why modulation?





- Day-night effect (day-night asymmetry, DNA): flavor composition of nighttime solar neutrinos $\neq$ that of daytime solar neutrinos $\leftarrow$ regeneration inside the Earth [Carlson, 1986; Baltz,Weneser, 1986]
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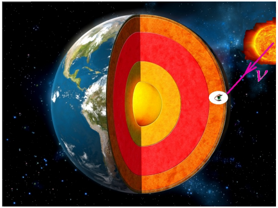

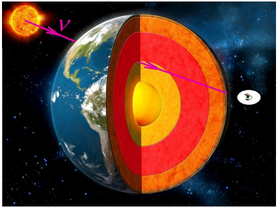

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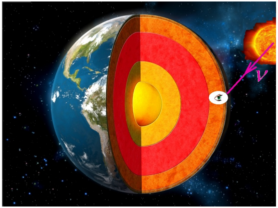

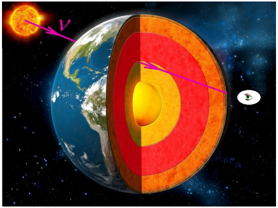

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▶ We probably lose the 'carrier' on $\int \mathrm{d}t$... Can we 'receive' it by 'smart demodulation'?

Oscillations in matter & Earth regeneration [1]

The theory of DNA is quite conventional: for each neutrino trajectory $r = r(x; \Theta_N(t))$,

$$\mathrm{i}\lambda\partial_x R(x, x_0) = H(x) R(x, x_0), \quad R(x_0, x_0) = \mathbb{1};$$

$$H(x) = \left(-\cos 2\theta_0 + \frac{2E\,V(x)}{\Delta m^2}\right)\sigma_1 + \sin 2\theta_0\ \sigma_3,$$

$R_{f,f'}(x, x_0) \equiv \langle \nu_f(x) \mid \nu_{f'}(x_0)\rangle$ is the flavor evolution matrix $(f, f' = e, x)$

$V(x) = \sqrt{2} G_F n_e(x)$ is the Wolfenstein potential
$\lambda = \Delta m^2/4E = \pi/\ell_{osc}$, $\ell_{osc} \sim 300$ km
$\sin^2 2\theta_0 \approx 0.86, \Delta m^2 \approx 7.6 \times 10^{-5}$ eV^2

$n_e(x)$ is the electron density
E is the ν energy
x goes along the ν ray

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In a number of papers [e.g., D'Olivo,1992; D'Olivo *et al.*, 2008; de Holanda, Wei Liao, Smirnov, 2004], this equation was solved leading to ν_e observation probabilities

$$P_e(\text{day}) = \frac{1}{2} + \frac{1}{2}\cos 2\theta_{\text{Sun}} \cos 2\theta_0,$$

$$P_e(\text{night}) = \frac{1}{2} + \frac{1}{2}\cos 2\theta_{\text{Sun}} \left\{ \cos 2\theta_n^- + 2\sin 2\theta_0 \sum_{j=1}^{n-1} \Delta\theta_j \cos 2\Delta\psi_{n,j} \right\}$$

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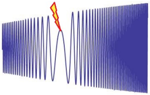
▶ $\int_a^b F(t) e^{\mathrm{i}\lambda S(t)} \mathrm{d}t = \sqrt{\frac{2\pi\mathrm{i}}{\lambda S''(t_0)}} F(t_0) e^{\mathrm{i}\lambda S(t_0)} + \left.\frac{F(t)e^{\mathrm{i}\lambda S(t)}}{\mathrm{i}\lambda S'(t)}\right|_a^b + O(\lambda^{-3/2}),\ \lambda \to +\infty$

The miracles of the stationary points [1]



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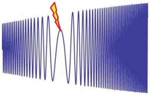

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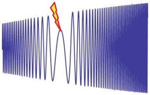

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- For the DN effect, $\int \mathrm{d}t \rightsquigarrow \int \mathrm{d}\varsigma \mathrm{d}\tau$ (ς = season, τ = time of day), and the stationary points occur at midnights for $\int \mathrm{d}\tau$ and on the two solstices for $\int \mathrm{d}\varsigma$

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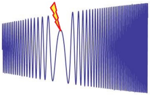

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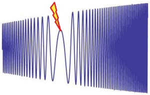

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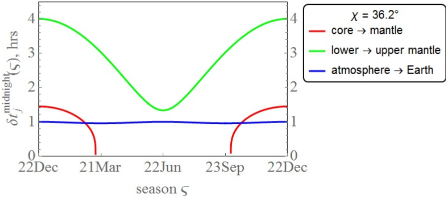
- The winter solstice contribution gets considerably augmented for a tropical detector ($\chi \sim 23.5^{\mathrm{o}}$) [Aleshin, O.K., Lobanov, PRD2013]
- Despite the Sun spends little time shining through the core, for the localized contribution, it may not be a problem

The miracles of the stationary points [1]: loc. scales

Latitude χ	Interfaces crossed	r_j, km	$\Delta t_j^{\rm season}$, month	$\delta t_{-1,j}^{\rm solstice}$ (winter solstice), month for $E = 10$ MeV ($E = 862$ keV)	$\delta t_{+1,j}^{\rm solstice}$ (summer solstice), month for $E = 10$ MeV ($E = 862$ keV)
26.0°	atmosphere→crust	6371	12.0	3.1 (0.9)	0.8 (0.2)
	upper mantle→lower mantle	5701	12.0	3.0 (0.9)	0.7 (0.2)
	lower mantle→outer core	3480	7.2	2.6 (0.8)	N/A
	outer core→inner core	1221	3.3	1.7 (0.5)	N/A
	inner core→outer core	1221	3.3	2.1 (0.6)	N/A
	outer core→lower mantle	3480	7.2	4.7 (1.4)	N/A
	lower mantle→upper mantle	5701	12.0	13 (3.7)	1.7 (0.5)
36.2°	atmosphere→crust	6371	12.0	1.4 (0.4)	0.7 (0.2)
	upper mantle→lower mantle	5701	12.0	1.3 (0.4)	0.6 (0.17)
	lower mantle→outer core	3480	5.5	1.1 (0.3)	N/A
	outer core→lower mantle	3480	5.5	2.0 (0.6)	N/A
	lower mantle→upper mantle	5701	12.0	5.6 (1.6)	0.9 (0.3)
42.5°	atmosphere→crust	6371	12.0	1.1 (0.3)	0.7 (0.20)
	upper mantle→lower mantle	5701	10.3	1.1 (0.3)	N/A
	lower mantle→outer core	3480	4.4	0.9 (0.3)	N/A
	outer core→lower mantle	3480	4.4	1.5 (0.4)	N/A
	lower mantle→upper mantle	5701	10.3	4.4 (1.3)	N/A



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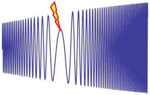

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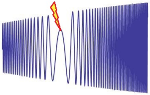

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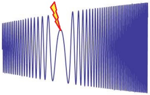

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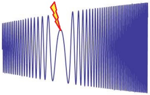

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$$N_{\text{night}}^{(w)} = \sum_{k=1}^{N_{\text{obs}}} \vartheta(\pi/2 - \Theta_{\mathrm{N}}(t_k))\, w(t_k)?$$

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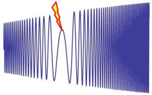

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N.B.: the noise of a half-year $N_{\mathrm{night}}^{(w)}$ is $\sqrt{2}$ times higher than that of the full-year one; the cumulative contribution to $\mathcal{A}_{\mathrm{dn}}$ is the same, while the localized one is multiplied by two! Thus, the SNR got even $\sqrt{2}$ times better for the localized DN effect!

Numerical simulation: definitions

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$$\hat{A}_{\rm dn}^{(w)}(E) = \frac{2\left[\langle P(\text{night}; E)\rangle_w - P(\text{day}; E)\right]}{\langle P(\text{night}; E)\rangle_w + P(\text{day}; E)},$$

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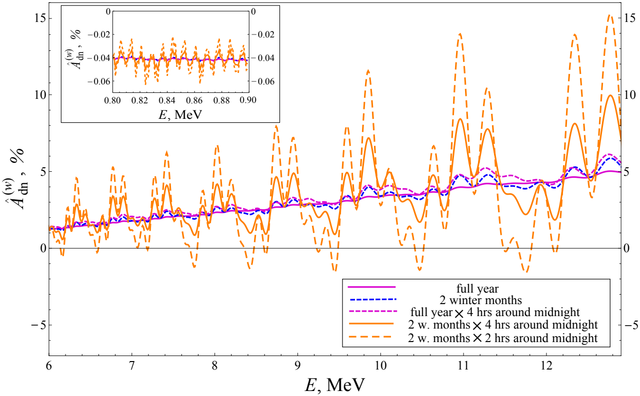
$$\langle P_{\nu_e}({\rm night};\, E)\rangle_w \equiv \frac{\int_0^{\pi/2} P_{\nu_e}(\Theta;E)\epsilon_w(\Theta)\mathrm{d}\Theta}{\int_0^{\pi/2}\epsilon_w(\Theta)\mathrm{d}\Theta}$$

- For a narrow electron recoil energy bin $[T, T+\Delta T]$, $\Delta T \to 0$,

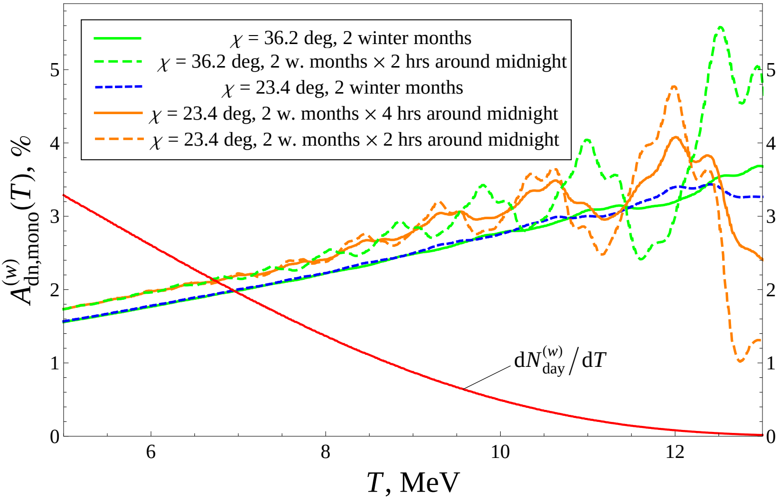
$$A_{\rm dn}^{(w)}(T) \approx \frac{\int \Phi(E)\mathrm{d}E\, \Delta\frac{\mathrm{d}\sigma(E,T)}{\mathrm{d}T} P_{\rm day}(E)\hat{A}_{\rm dn}^{(w)}(E)}{\int \Phi(E)\mathrm{d}E\left\{\Delta\frac{\mathrm{d}\sigma(E,T)}{\mathrm{d}T}P_{\rm day}(E) + \frac{\mathrm{d}\sigma_{\nu_x}(E,T)}{\mathrm{d}T}\right\}}$$

Numerical simulation: "probabilistic asymmetry factor"



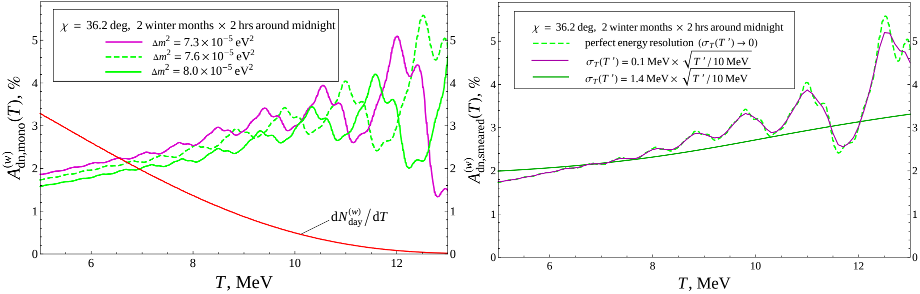
► The 'demodulation' of ^{7}Be neutrinos was studied by Ioannisian, Smirnov, and Wyler [PRD2015]

Numerical simulation: electron recoil signatures



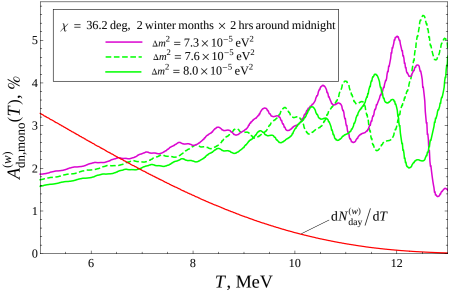
- The high-energy tail is affected; the signature depends strongly on the latitude

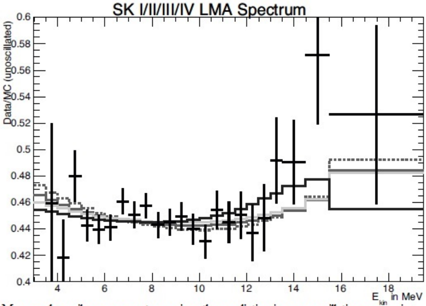
Numerical simulation: electron recoil signatures



- An 'interference' experiment for determining Δm^2?

Numerical simulation: a (possibly) rhetorical question





Measured recoil energy spectrum minus the prediction in a no-oscillations scenario [M.B. Smy for Super-Kamiokande Collaboration, *Terrestrial Matter Effects from Solar Neutrino Interactions in Super-Kamiokande*, Nucl. Part. Phys. Proceedings **265**, 135 (2015)]

- The same 'wiggly' signature? Could it be made more statistically significant by temporal weighting?

Some conclusions

- Although oscillatory contributions to the physical effects are usually assumed to average out, this may be not quite so if, e.g., the oscillations have stationary points

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Some conclusions

- Although oscillatory contributions to the physical effects are usually assumed to average out, this may be not quite so if, e.g., the oscillations have stationary points
- The day-night effect has these points around midnights/solstices, and one can use their localization to amplify their contributions
- Signatures of these points may be present in the high-energy tails of the recoil energy distributions and are quite sensitive to the oscillation parameters

Acknowledgments & publications

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References

[1] S. S. Aleshin, O. G. Kharlanov, and A. E. Lobanov, Analytical treatment of long-term observations of the day-night asymmetry for solar neutrinos, Phys. Rev. D **87**, 045025 (2013).
[2] O. G. Kharlanov, Peculiar seasonal effects in the neutrino day-night asymmetry, arXiv:1509.08073[hep-ph].

Thank you for your attention!