Peculiar seasoning in the neutrino day-night asymmetry: where and when to look for spices?

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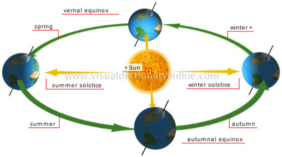
16th Lomonosov Conference on Elementary Particle Physics
26 August, 2013

What is seasoning?



1. Culinary seasoning
2. Solar ν seasonal effects & other time-regular effects
   - $\sim 7\%$ flux variations due to seasonal variation of Sun-to-Earth distance
   - solar cycles (including those assumed to exist due to acoustic waves in the core) $\longrightarrow$ neutrino flux variation
   - Solar ν oscillations inside the Earth $\longrightarrow$ Day-Night Asymmetry and its bizarre time variations (OUR TALK!)

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- Crucial for the entire framework of νOsc
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N.B. Extraction of DNA needs a long-term observation $\rightarrow$ we inevitably face seasonal effects!

Oscillations in matter & Earth regeneration [1]

The theory of DNA is quite conventional,

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

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

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

$V(x) = \sqrt{2}G_F N_e(x)$ is the Wolfenstein potential
$\lambda = \Delta m^2/4E = \pi/\ell_{osc}, \quad \ell_{osc} \sim 20\ldots300$ km
$\sin^2 2\theta_0 \approx 0.86, \Delta m^2 \approx 7.6\times10^{-5}$ eV^2[PDG2012]

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

Oscillations in matter & Earth regeneration [2]

$$i\lambda\partial_x R(x,x_0) = \left\{\left(-\cos 2\theta_0 + \frac{2EV(x)}{\Delta m^2}\right)\sigma_1 + \sin 2\theta_0\ \sigma_3\right\} R(x,x_0)$$

- There are various approximate approaches to this equation which are relevant to the Earth regeneration effect for solar neutrinos [D'Olivo,1992; Supanitsky,D'Olivo,Medina-Tanco,2008; Lisi,Montanino,1997; de Holanda,Wei Liao,Smirnov,2004; Ioannisian,Smirnov,2004; Blennow,Ohlsson,2004; Aleshin,Kharlanov,Lobanov,2013]
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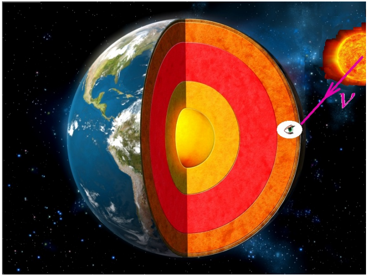
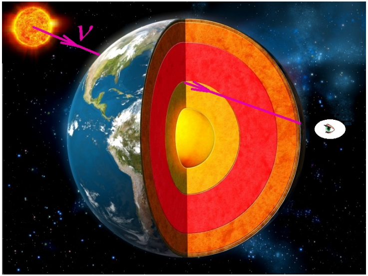
These approaches give virtually the same results for solar neutrinos in the Earth, considered as a spherically-symmetric layered structure (PREM)

Oscillations in matter & Earth regeneration [3]





Day/night probabilities of observing ν_e:

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

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

n is the number of crossed interfaces between the Earth's layers

$\Delta\psi_{n,j} \approx \pi L_{n,j}/\ell_{\text{osc}}$ is the osc. phase diff. (detector–jth crossing pt.)

$\Delta\theta_j$ are jumps of the effective mixing angle

θ_n^- is the effective mixing angle under the detector

As time goes by...

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

- The number of crossed interfaces n changes, depending on the zenith angle $\Theta_Z(t)$
- The distance from the jth crossing pt. to the detector $L_{n,j} = L_{n,j}(\Theta_Z(t))$

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In order to cope with such an object, we use the stationary phase approximation

$$\int_a^b F(\tau)e^{i\lambda S(\tau)}d\tau = \sqrt{\frac{2\pi i}{\lambda S''(\tau_0)}}F(\tau_0)e^{i\lambda S(\tau_0)} + \left.\frac{F(\tau)e^{i\lambda S(\tau)}}{i\lambda S'(\tau)}\right|_a^b + O(\lambda^{-3/2}), \quad \lambda \to +\infty,$$

where $F(\tau)$ and $S(\tau)$ are smooth on $[a, b]$ and $S'(\tau) = 0$ only at $\tau = \tau_0 \in (a, b)$.

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- Stationary points $\Theta_Z'(t) = 0$: midnights when integrating over the night and solstices when integrating over the seasons;
- Edge terms vanish
- We take the dependence $\Theta_Z(t)$ from spherical astronomy
- The small parameter here is $\ell_{\text{osc}}/L_{n,j}$

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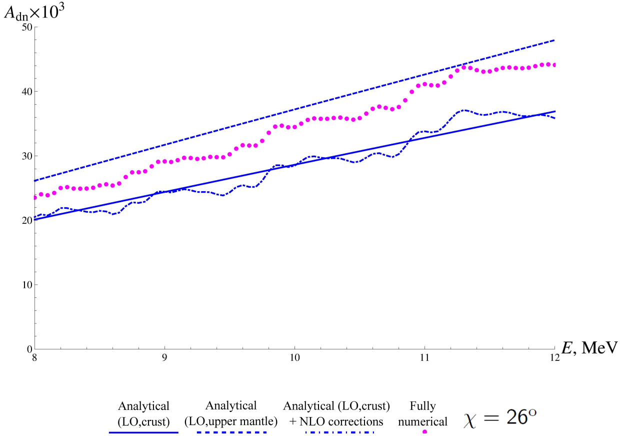
$$\langle P_e(\text{night}) - P_e(\text{day})\rangle_{\text{year}} \approx \frac{1}{2}\cos 2\theta_{\text{Sun}}(\cos 2\theta_n^- - \cos 2\theta_0)$$

$$+\cos 2\theta_{\text{Sun}} \sin 2\theta_0 \sum_{j=1}^{n-1} \Delta\theta_j \sum_{s=\pm 1} \frac{\vartheta(r_j - r_n \sin(\chi + s\varepsilon))}{2\pi\sqrt{\sin\varepsilon \cos\chi \sin(\chi + s\varepsilon)}} \frac{\sqrt{r_j^2/r_n^2 - \sin^2(\chi + s\varepsilon)}}{\lambda L_{n,j}^{\text{solstice}}}$$

$$\times \cos\{2\Delta\psi_{n,j}^{\text{solstice}} + s'(s-1)\pi/4\},$$

$s' \equiv \text{sgn}\{L_{n,j}^{\text{solstice}} - r_n \cos(\chi + s\varepsilon)\}$, $\Theta_Z = \pi - \chi - s\varepsilon$ (solstice $s = \pm 1$); χ is the detector latitude, $\varepsilon = 23.5^{\circ}$; r_j are the radii of the Earth's shells.

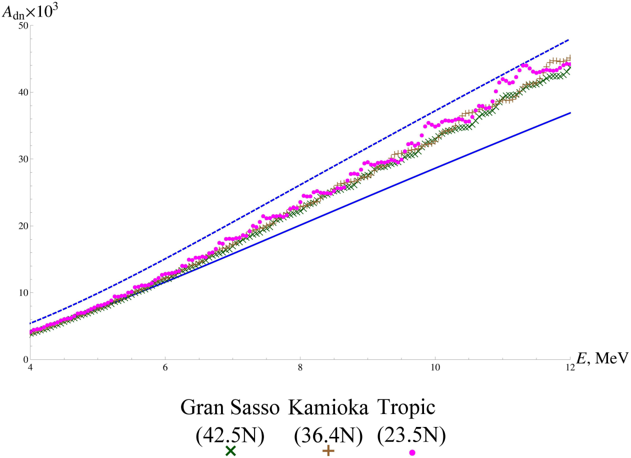
A test drive: analytics vs. numerics $A_{\rm dn} = \frac{2(P_e(\text{night}) - P_e(\text{day}))}{P_e(\text{night}) + P_e(\text{day})}$



The constant vertical shift is due to the unaccounted fine structure of the crust under the detector. It is smooth enough and is season-independent, so we do not bother about it.

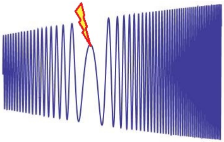
A test drive: different latitudes

$$A_{\text{dn}} = \frac{2(P_e(\text{night}) - P_e(\text{day}))}{P_e(\text{night}) + P_e(\text{day})}$$



Indeed, the closer to the Tropic, the more vivid are the oscillatory contributions of the stationary points!

The Miracles of the Stationary points



- The peak structure of $A_{\mathrm{dn}}(E)$ is up to 10% in amplitude and comes from the vicinities of the two solstices
- For off-tropic latitudes, it is strongly suppressed

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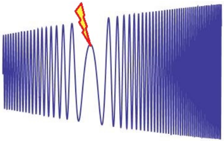

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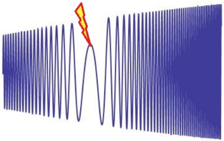

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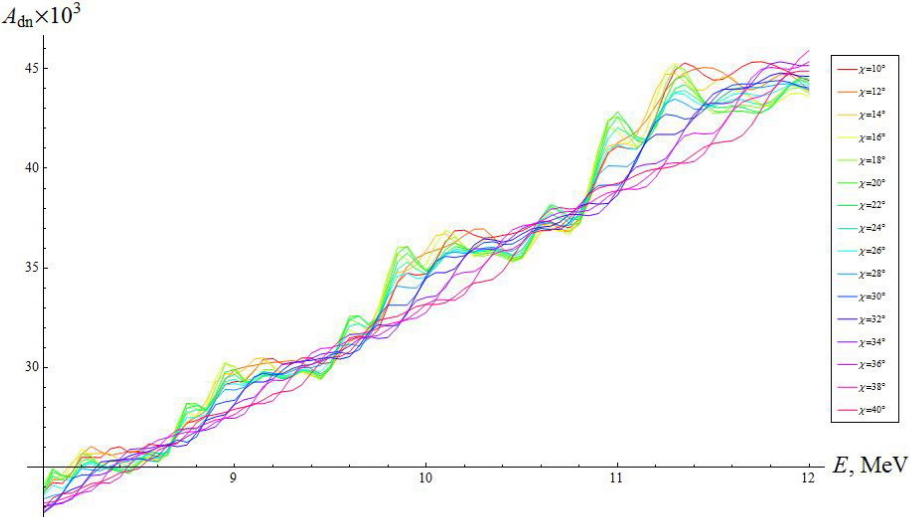
- Moreover, it is wrong to say that *the Earth's core does not contribute to DNA since the Sun rarely descends low enough to shine through it.* Rareness is not a measure for this localized contribution!

The tropical Sun

$$A_{dn} = \frac{2(P_e(\text{night}) - P_e(\text{day}))}{P_e(\text{night}) + P_e(\text{day})}$$



The curves around $\chi = 23.5^{\circ}$ exhibit the clean and vivid oscillations; the positions of the peaks are very sensitive to Δm^2 and $\{r_j\}$

Interference experiment in ν oscillations?

When and where to look for spices? (a conclusion)

- When? Near the solstices
- Where? Near the Tropics, the closer the better (Sao Paolo, $23^{o}33'S$)

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- Really? In order to distinguish these effects, one needs within one order more detection events at the currently achieved energy resolution $\delta E \sim 0.5$ MeV, if one employ the adaptive recognition of wave-like patterns on the $A_{dn}(E)$ profile [to be published]

Acknowledgments & publications

The numerical simulations were made using the Supercomputing cluster "Lomonosov" (MSU)

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, and A. E. Lobanov, Peculiar seasonal effects in the neutrino day-night asymmetry, submitted to Phys. Rev. D.

Thank you for your attention!