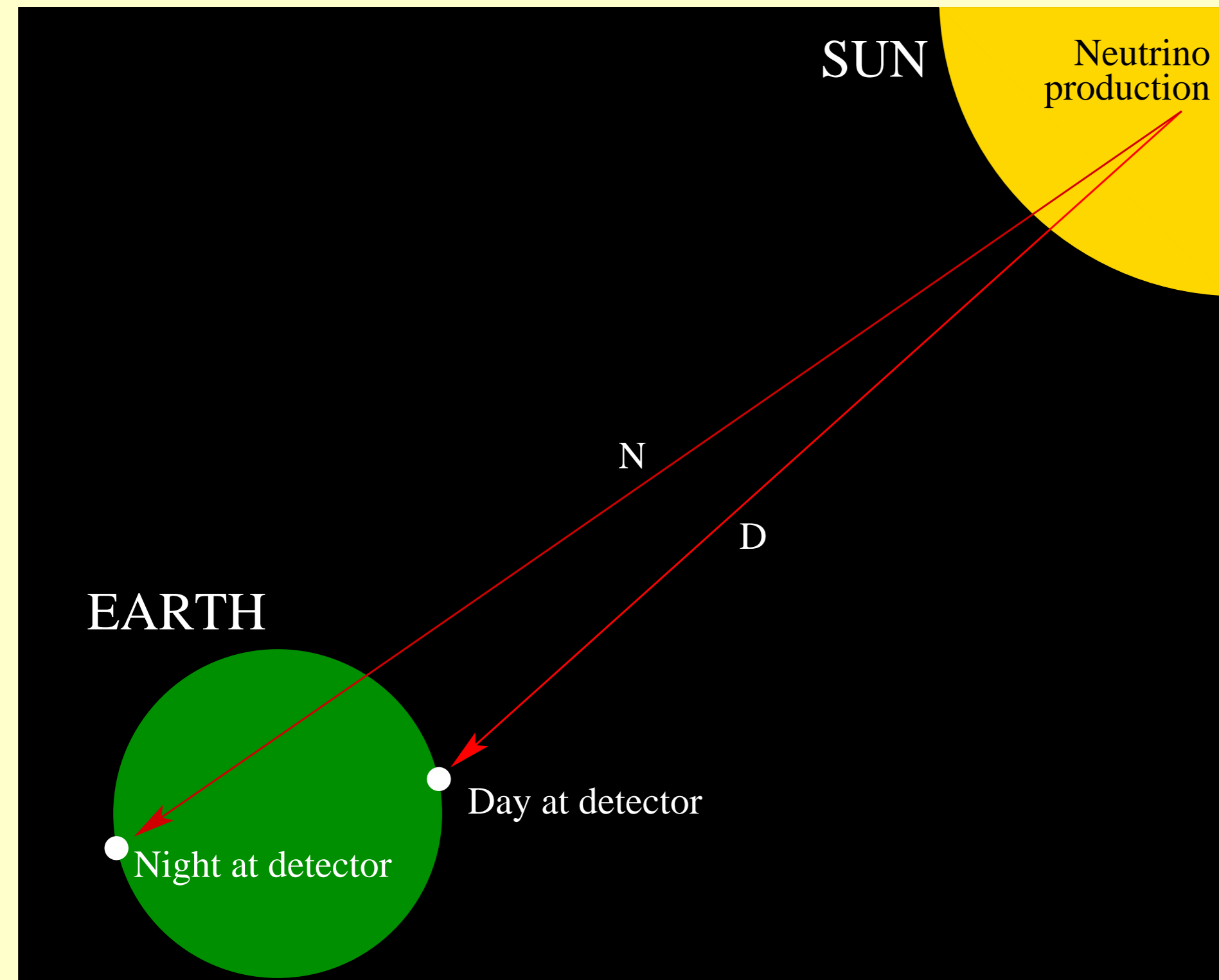


We summarize the results of Ref. [1] in which we determine the effects of three flavor mixing on the day-night asymmetry in the flux of solar neutrinos. Analytic methods are used to determine the difference in the day and night solar electron neutrino survival probabilities and numerical methods are used to determine the effect of three flavor mixing at detectors.

Day-Night Effect



Different event rates at a detector during day D and night N due to matter effects in the Earth.

The day-night asymmetry is defined as

$$A_{n-d} = 2 \frac{N - D}{N + D}.$$

Our general approach is that neutrinos arrive at the Earth in an incoherent superposition of neutrino mass eigenstates [2]. The daytime solar electron neutrino survival probability is then given by

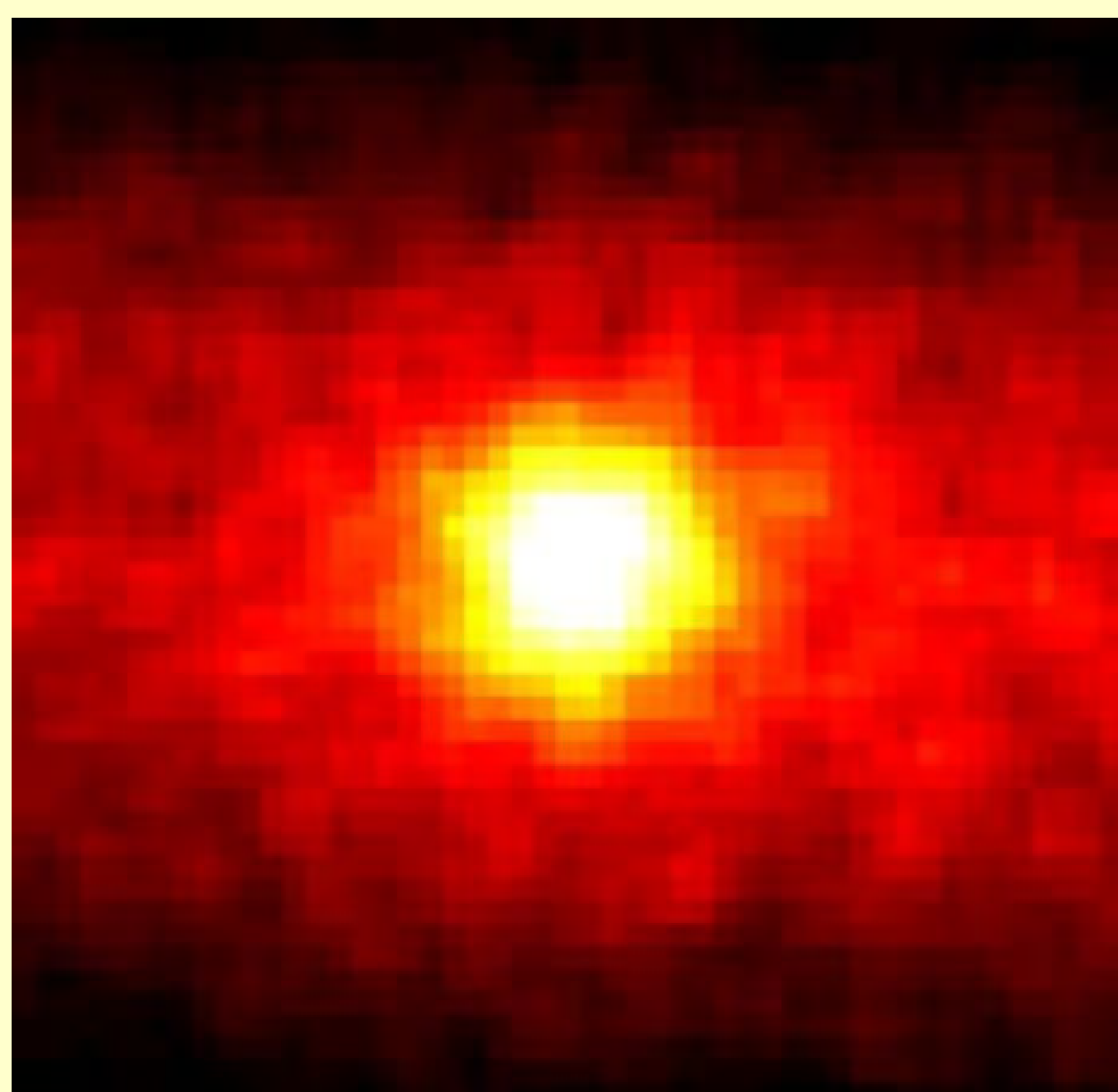
$$P_S = \sum_{i=1}^n k_i |\langle \nu_e | \nu_i \rangle|^2,$$

where k_i is the fraction of the mass eigenstate ν_i in the solar neutrino flux and n is the number of neutrino flavors.

The nighttime solar electron neutrino survival probability is given by

$$P_{SE} = \sum_{i=1}^n k_i P_{ie},$$

where P_{ie} is the probability of the mass eigenstate ν_i being detected as the flavor state ν_e after traversing the Earth.



The Sun seen in elastic scattering detection of neutrinos. Is it brighter at night than at day?

Two Flavor Case

In two flavor oscillations, we have the mixing angle θ and the mass squared difference Δm^2 as fundamental parameters. The probabilities also depend on the neutrino energy E . Using an approximation of constant electron number density in the Earth, the difference between the night and day survival probabilities for solar electron neutrinos becomes

$$P_{n-d} = P_{SE} - P_S = -D_{2\nu} \frac{KV_E}{4a^2} \sin^2(2\theta) \sin^2(aL),$$

where

$$D_{2\nu} = \int_0^{R_\odot} dr f(r) \cos(2\hat{\theta}(r)),$$

$$a = \frac{1}{2} \sqrt{V_E^2 - 2KV_E \cos(2\theta) + K^2},$$

$K = \Delta m^2 / (2E)$, $\hat{\theta}$ is the mixing angle in matter, $f(r)$ the normalized spatial distribution function of neutrino production in the Sun, L the length the neutrinos travel in the Earth, and V_E the effective Earth potential.

The matter effects of the Sun are included in the parameter $D_{2\nu}$ and the matter effects of the Earth in the effective Earth potential V_E . The expression for P_{n-d} has many nice limits, in particular, $P_{n-d} = 0$ when $D_{2\nu}$, L , or V_E vanish.

In the LMA region, P_{n-d} is well approximated by

$$P_{n-d} \simeq -D_{2\nu} \frac{V_E}{K} \sin^2(2\theta) \sin^2\left(\frac{K}{2}L\right).$$

Three Flavor Case

In the three flavor case, we can make some well-motivated approximations:

- The third mass eigenstate is not affected by the effective matter potential in the Sun.
- The third mass eigenstate is not affected by the effective matter potential in the Earth.
- The two remaining mass eigenstates evolve according to an approximate two flavor case.

As a result of these approximations, the difference between the night and day survival probabilities in the three flavor case becomes

$$P_{n-d} = -c_{13}^6 D_{3\nu} \frac{KV_E}{4a^2} \sin^2(2\theta_{12}) \sin^2(aL),$$

where

$$D_{3\nu} = \int_0^{R_\odot} dr f(r) \cos(2\hat{\theta}_{12}(r)),$$

$$a = \frac{1}{2} \sqrt{c_{13}^4 V_E^2 - 2K c_{13}^2 V_E \cos(2\theta) + K^2},$$

and $\hat{\theta}_{12}$ is calculated as $\hat{\theta}$ in the two flavor case using the effective potential $V_{\text{eff}} = c_{13}^2 \sqrt{2} G_F N_e$.

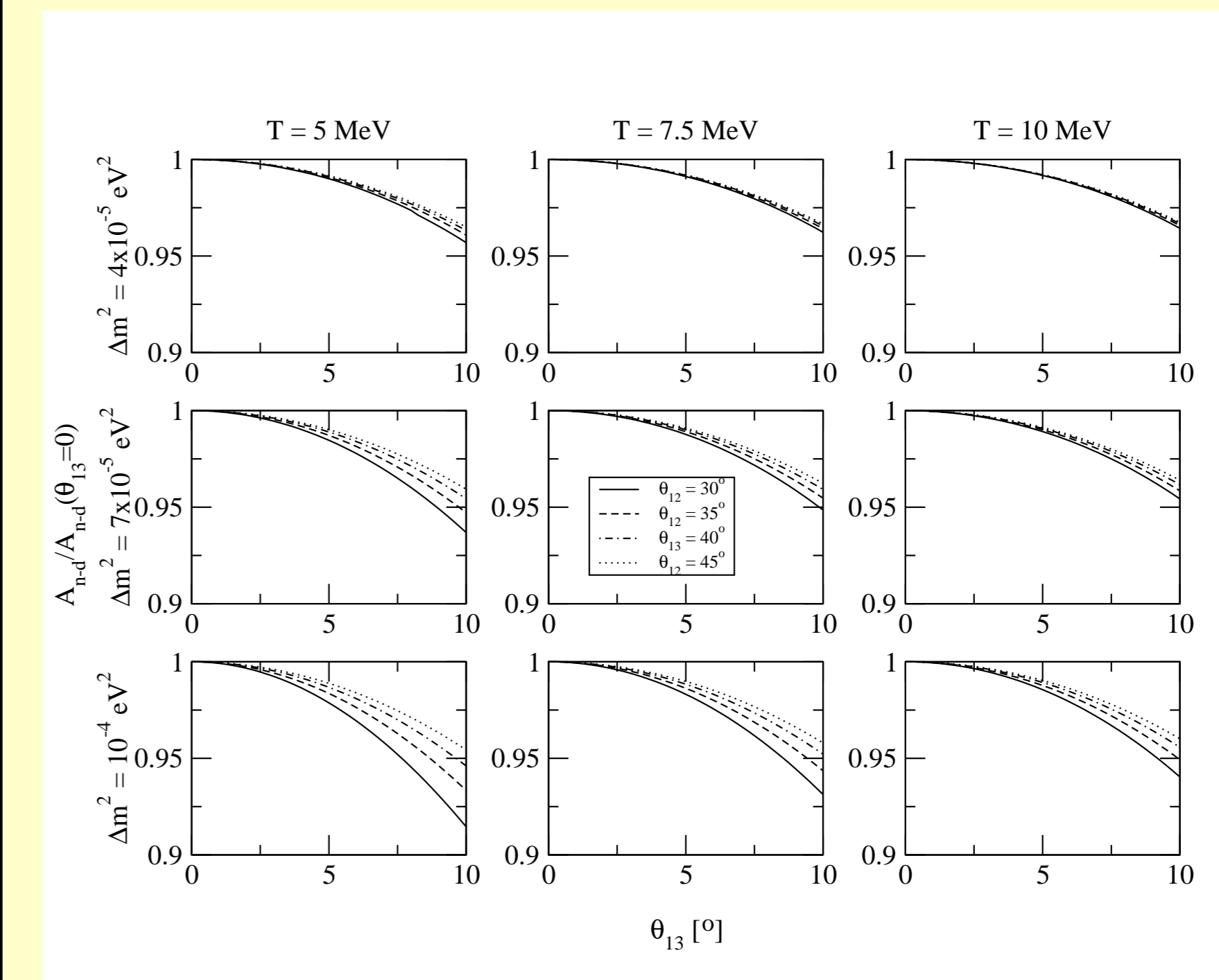
In the LMA region, the three flavor expression for P_{n-d} is well approximated by

$$P_{n-d} \simeq -c_{13}^6 D_{3\nu} \frac{V_E}{K} \sin^2(2\theta_{23}) \sin^2\left(\frac{K}{2}L\right).$$

Effect at Detectors

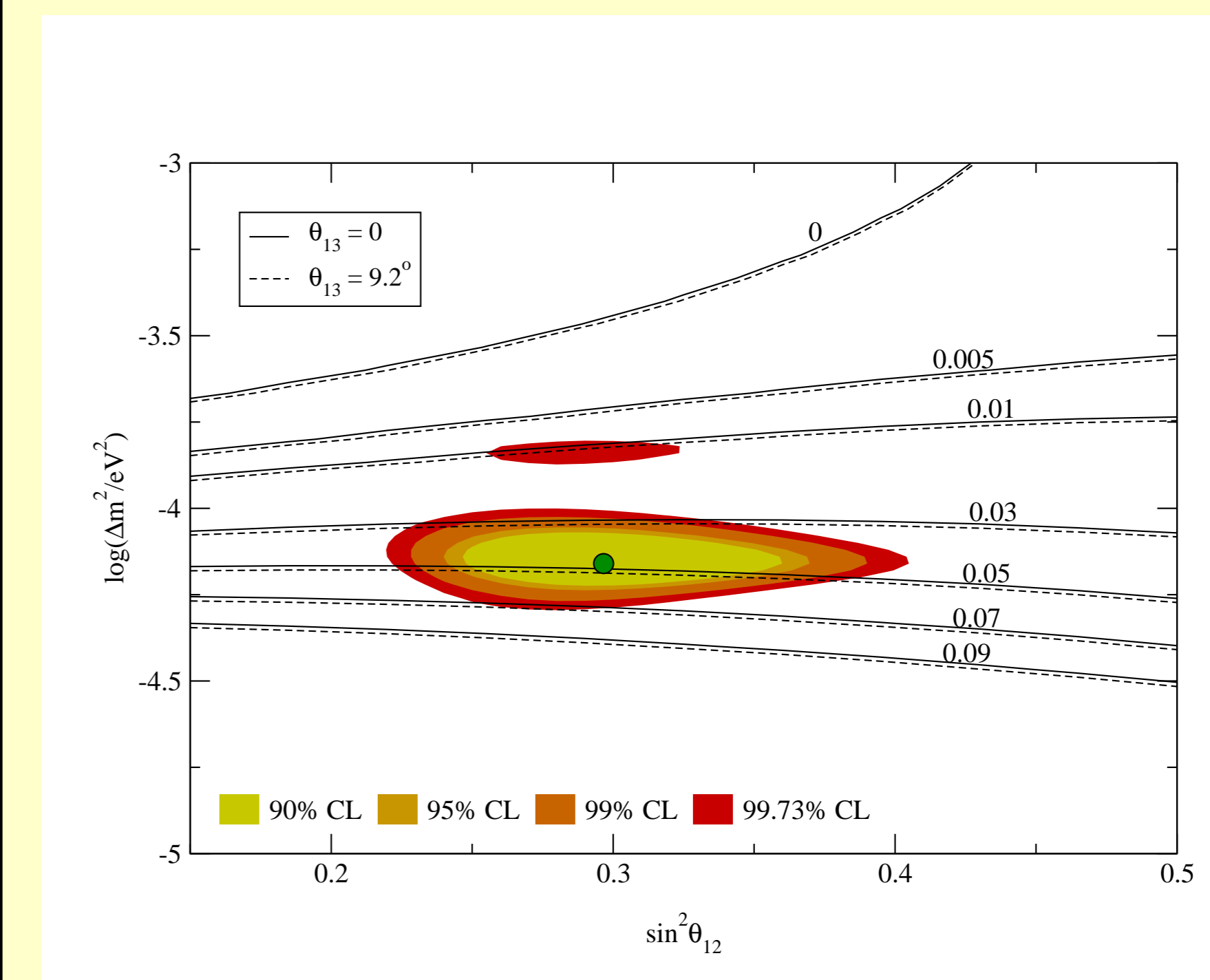
We study the effect of a non-zero θ_{13} on the day-night asymmetry at detectors [3, 4], both for the total day-night asymmetry and the day-night asymmetry at specific energies. Here we give the results for the charged-current (CC) detection at the Sudbury Neutrino Observatory (SNO). The results for the elastic scattering (ES) detection at Super-Kamiokande are similar.

Results at specific energies



The relative effects of a non-zero θ_{13} . The effects become larger for decreasing θ_{12} , decreasing energy, and increasing Δm^2 .

Results for total asymmetry



Isocontours in the θ_{12} - Δm^2 parameter space for the CC day-night asymmetry for two different values of θ_{13} . The values of A_{n-d} for the different isocontours are shown in the figure. The colored regions correspond to the allowed regions of the parameter space for different confidence levels and the circle corresponds to the best-fit point according to Ref. [5].

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References

- [1] M. Blennow, T. Ohlsson and H. Snellman, [hep-ph/0311098](https://arxiv.org/abs/hep-ph/0311098).
- [2] A.H. Guth, L. Randall and M. Serna, JHEP 08 (1999) 018, [hep-ph/9903464](https://arxiv.org/abs/hep-ph/9903464).
- [3] Super-Kamiokande Collaboration, M.B. Smy et al., [hep-ex/0309011](https://arxiv.org/abs/hep-ex/0309011).
- [4] SNO Collaboration, Q.R. Ahmad et al., Phys. Rev. Lett. 89 (2002) 011302, [nucl-ex/0204009](https://arxiv.org/abs/nucl-ex/0204009).
- [5] M. Maltoni et al., [hep-ph/0309130](https://arxiv.org/abs/hep-ph/0309130).