Neutrinos from cosmic-ray interactions from the sun

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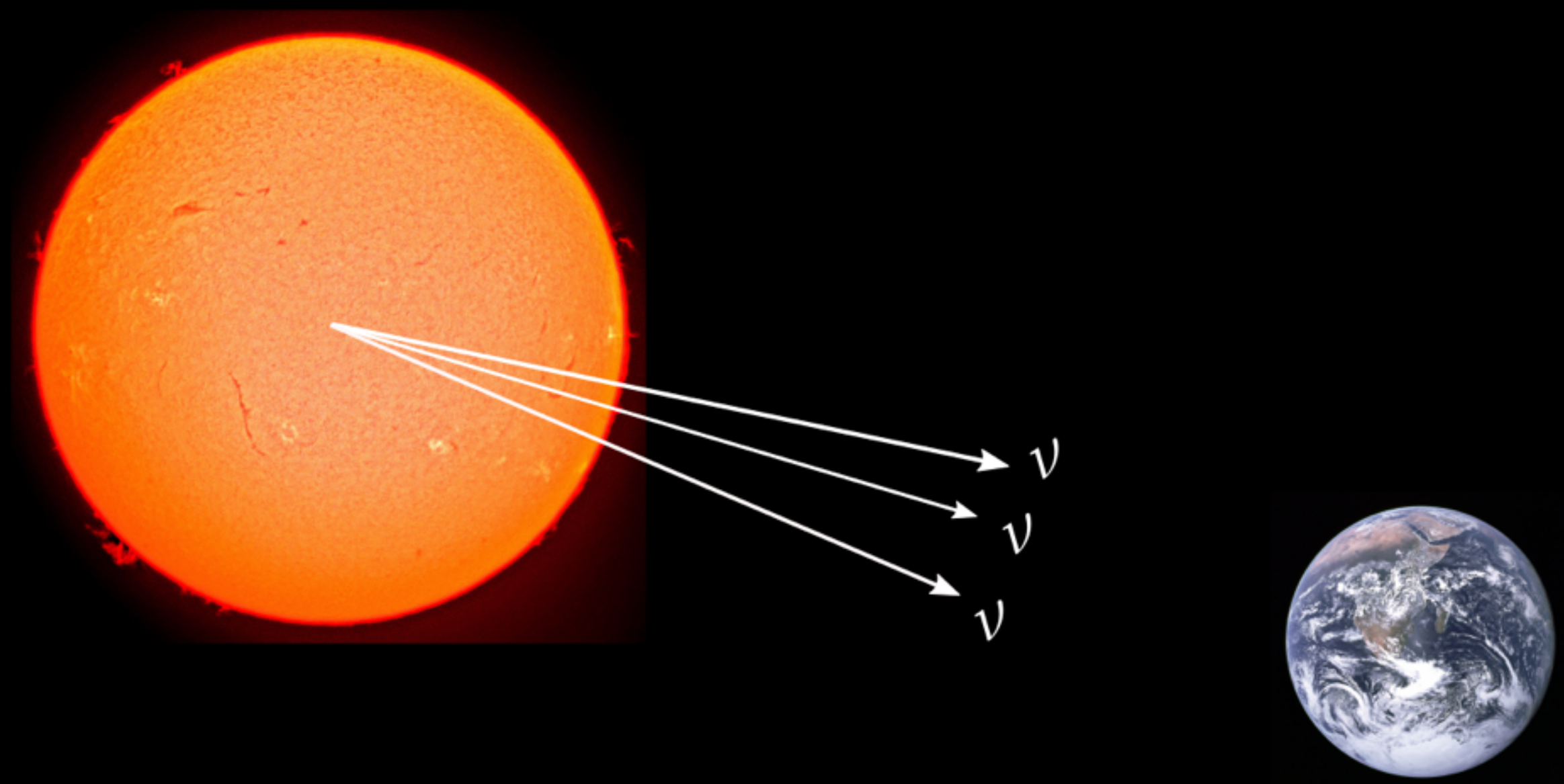
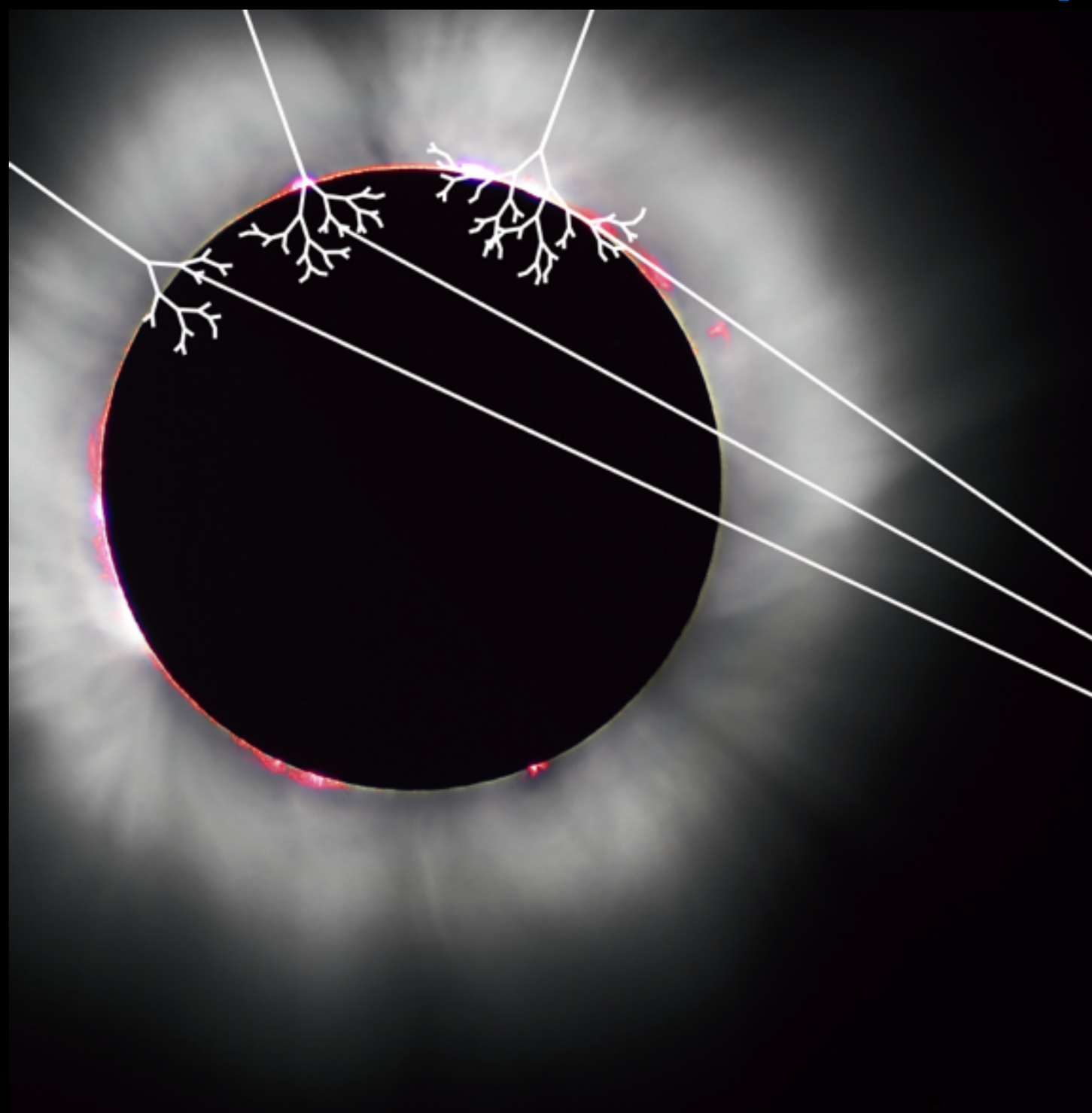
Solar neutrinos emitted from core…



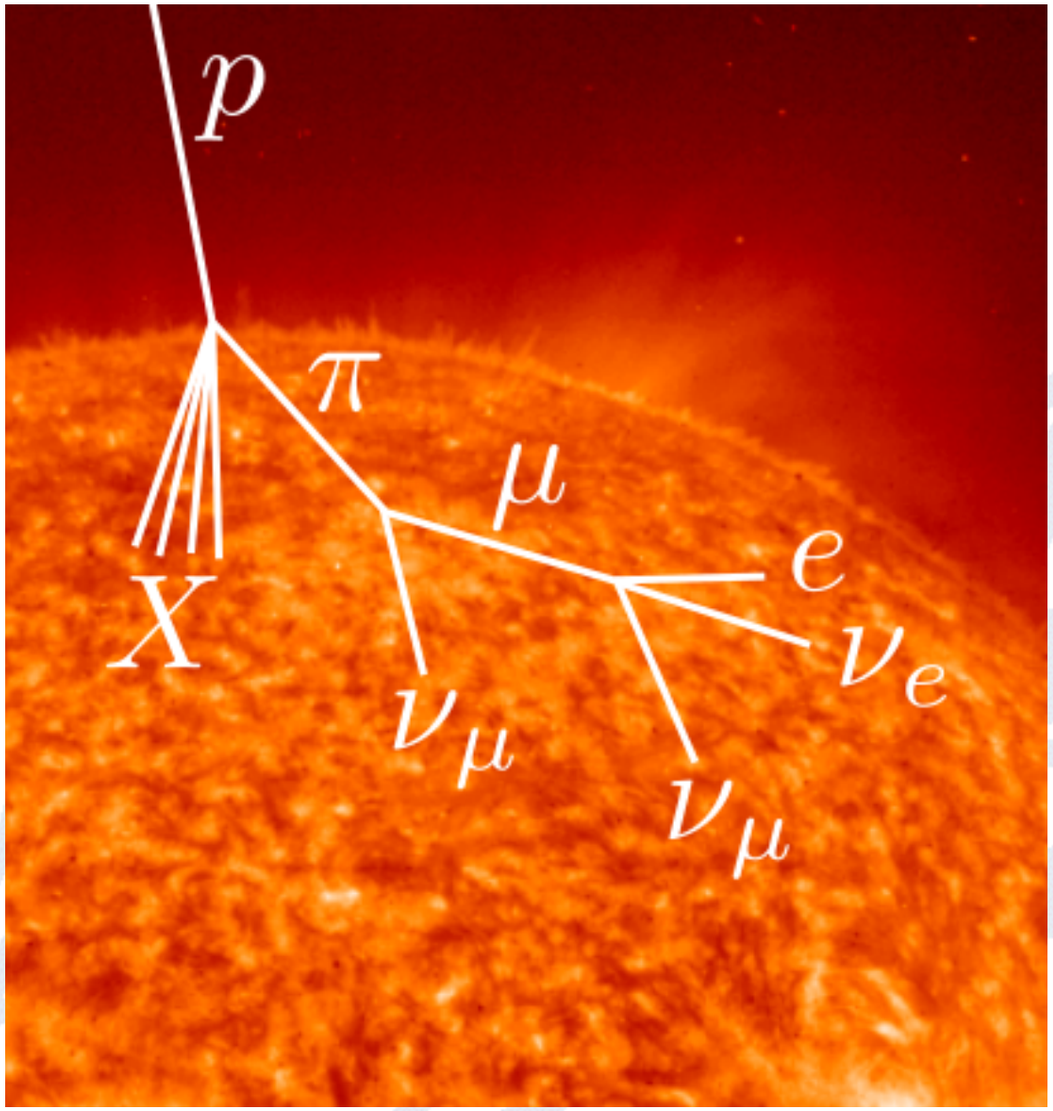
…but also from cosmic rays hitting the solar atmosphere!

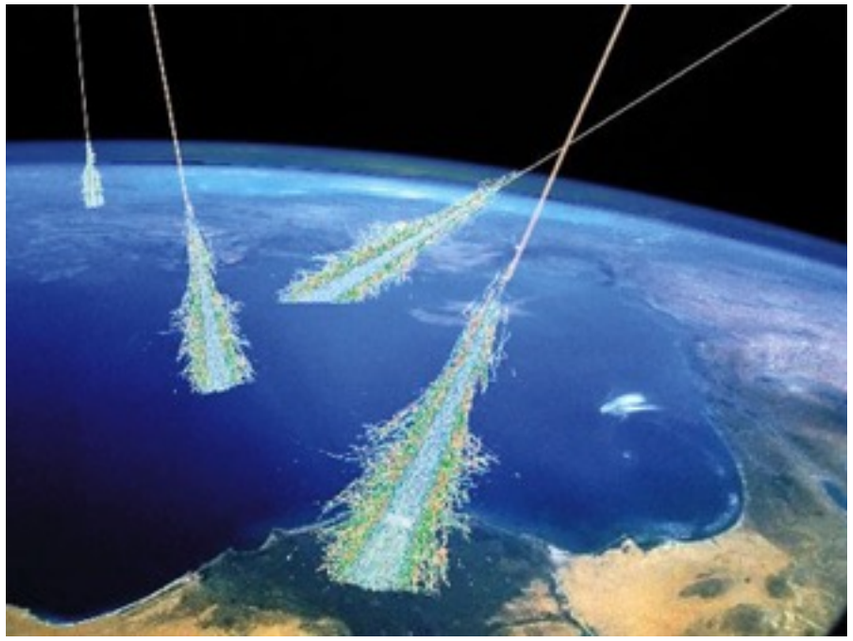


Main question:
What is the neutrino flux at the earth originating from CR interactions in the sun?

Introduction

Neutrinos are produced in cascades in solar atmosphere





- Neutrinos come from meson decays in solar atm. (SAν)
- Similar to CR showers in earth's atmosphere

These neutrinos are a background for solar WIMP searches

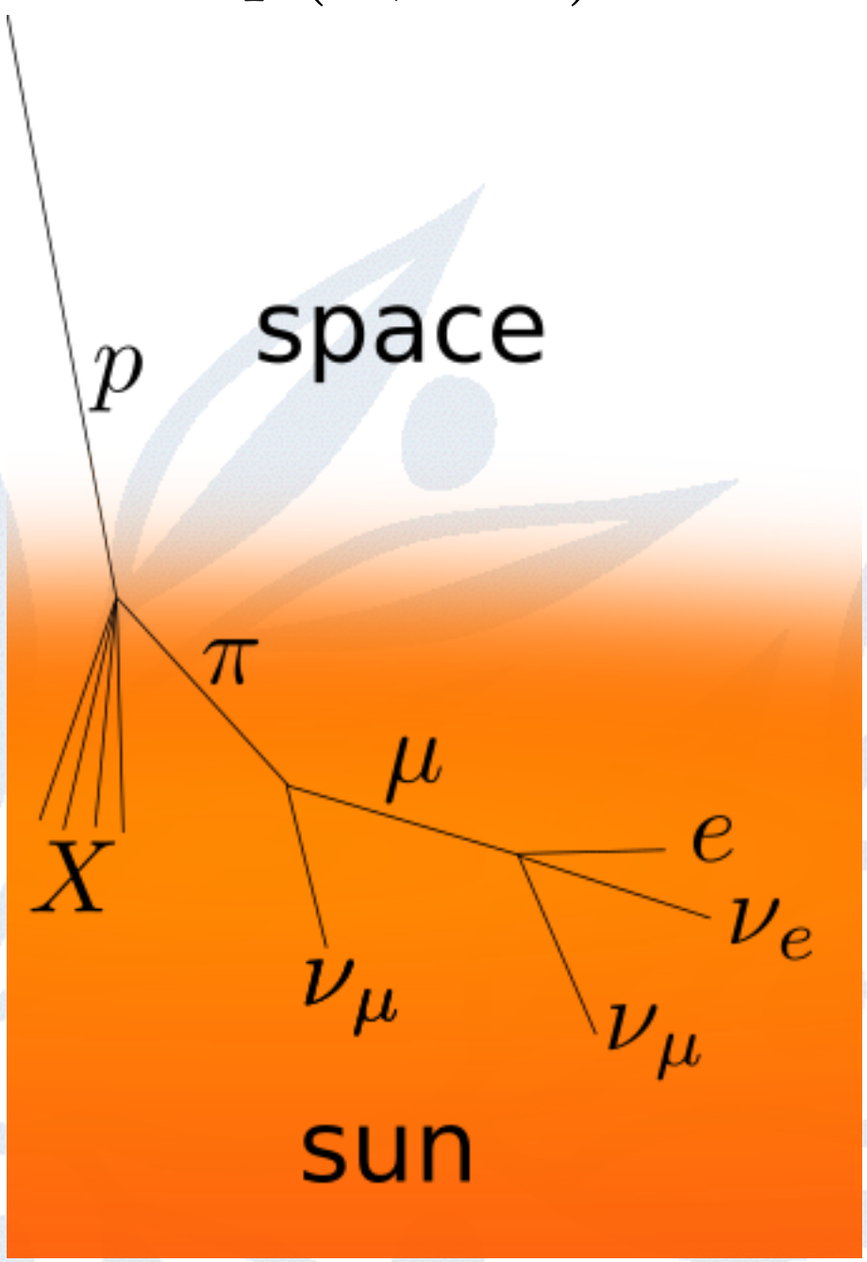
- WIMP annihilations typically give ν signal at energies $O(m_X)$
- Main backgrounds for WIMP signal:
  - Atmospheric muons (shield with earth)
  - Earth atm. ν (on-off regions)
  - Solar atm. ν (earth can **not** shield)

Important to characterize SAν signal if WIMP signal detected

- Detection? —> need to disentangle WIMP signal from background
- Important to estimate size but also characterize **energy dependence**
- SAν can also give information on structure of solar atmosphere, magnetic fields on surface etc.

Most neutrinos come from meson decays

$$p(\alpha, \text{etc.}) + N \to \pi^{\pm}(K^{\pm}) + X$$
$$\hookrightarrow \mu^{\pm} + \nu_{\mu}/\overline{\nu}_{\mu}$$
$$\hookrightarrow e^{\pm} + \nu_{e}/\overline{\nu}_{e} + \overline{\nu}_{\mu}/\nu_{\mu}$$



- Flux has flavor ratio ~1:2:0
- Defines *conventional flux*
- *Prompt flux* from charm meson decays important at high energies (E~10^7 GeV)

Expect more neutrinos from sun compared to earth

- Cascade mesons (π, K,…) will interact or decay
- Solar atmosphere less dense than earth's
  - Larger fraction of mesons **decay before interacting** than on earth
- Expect therefore **more neutrinos** in solid angle of sun (with some caveats…)

Earlier studies

Seckel et al. (1991): early calculation of neutrino flux

- Calculated the neutrino (and n, γ, $\overline{p}$) flux induced by CR interactions on solar surface
- Estimated magnetic field effects
- Up to E_ν ~100 TeV (no prompt)
- No oscillations

D. Seckel, T. Stanev and T.K. Gaisser, Astrophys. J. 382 (1991) 652

Ingelman et al. (1996): further refinements, ν oscillations

- Use PYTHIA to obtain full neutrino fluxes at sun, for three *b*-values
- Include **weak interactions (attenuation)**
- Look at oscillation effects (2-flavor)
- **The most recent calculation of CR-induced neutrino flux at the sun**

G. Ingelman and M. Thunman, Phys. Rev. D 54, 4385 (1996) [hep-ph/9604288]

Later studies focus on oscillations

- Hettlage et al. [astro-ph/9910208] and Fogli et al. [hep-ph/0608321] include full 3-flavor oscillations
- Both use Ingelman et al. neutrino fluxes (at the sun)
- Oscillation effects seem to average out

C. Hettlage, K. Mannheim, and J. G. Learned, Astropart. Phys. 13, 45 (2000)
G. L. Fogli, E. Lisi, A. Mirizzi, D. Montanino, and P. D. Serpico, Phys. Rev. D74, 093004 (2006)

Method

Calculation is split in two parts

MCEq + WimpSim

Cascade development, CR interactions

Neutrino propagation from sun to earth incl. weak interactions, oscillations

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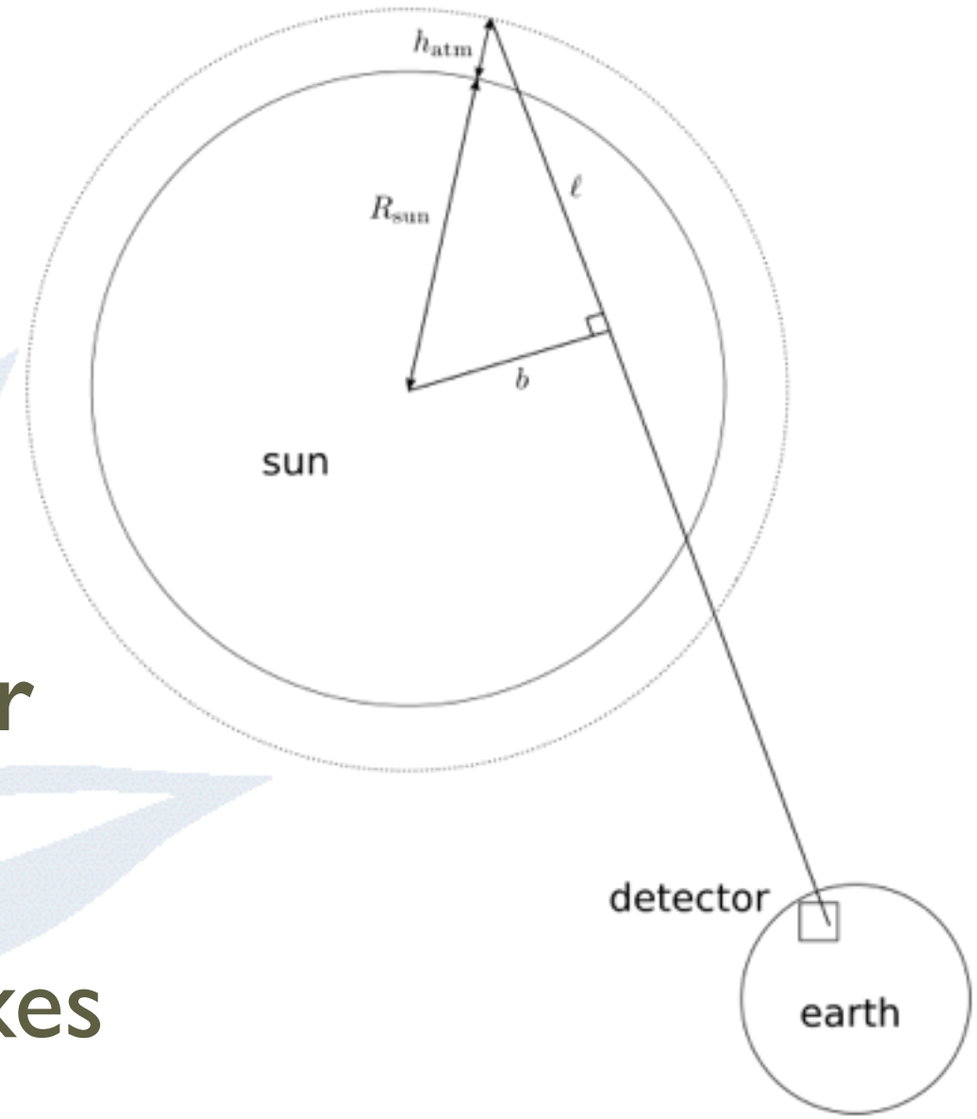
MCEq evolves cascades and calculates fluxes

- We use code **MCEq** (A. Fedynitch, et al. [hep-ph/1503.00544]) to find the **neutrino fluxes induced by CR showers**
- Solves cascade equations in matrix fashion
- Options for hadronic interaction models, CR fluxes, charm production, (earth) atmosphere etc.
- Code not yet officially released but publicly available

A. Fedynitch, R. Engel, T. K. Gaisser, F. Riehn, T. Stanev, arXiv:1503.00544, http://mceq.readthedocs.io/en/latest/index.html

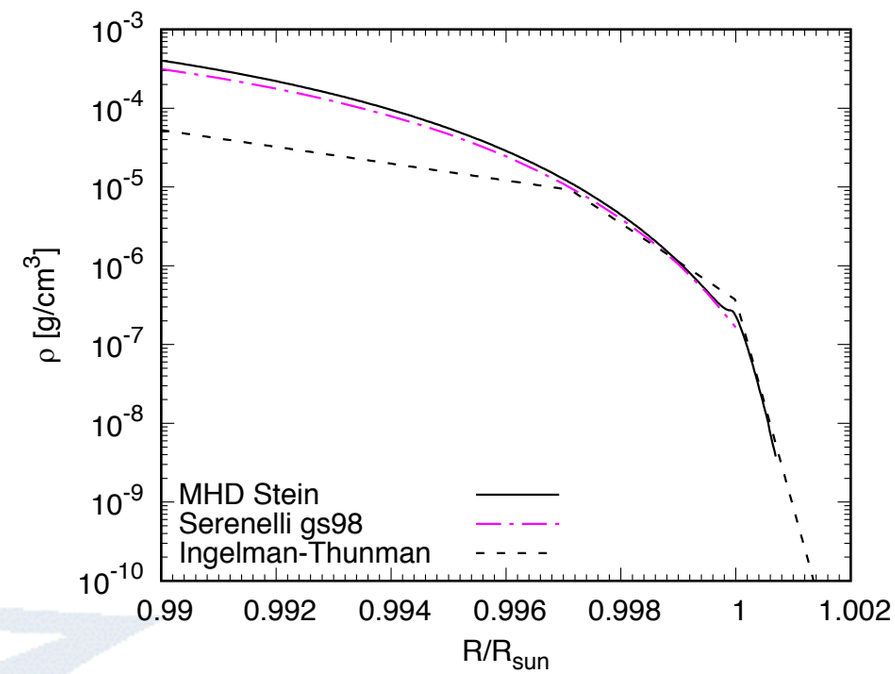
Adapting MCEq to the sun

- MCEq intended for simulation in earth's atmosphere
- Put in model of **solar atmosphere** and **solar geometry**
  - Can then obtain fluxes in solar atmosphere



Adapting MCEq cont.

- Standard Solar Models (SSM:s) intended for interior of sun, need others at surface
- We use exponential fit from Ingelman et al., MHD simulation by Stein, SSM by Serenelli
- Include also muon energy loss to ensure decay

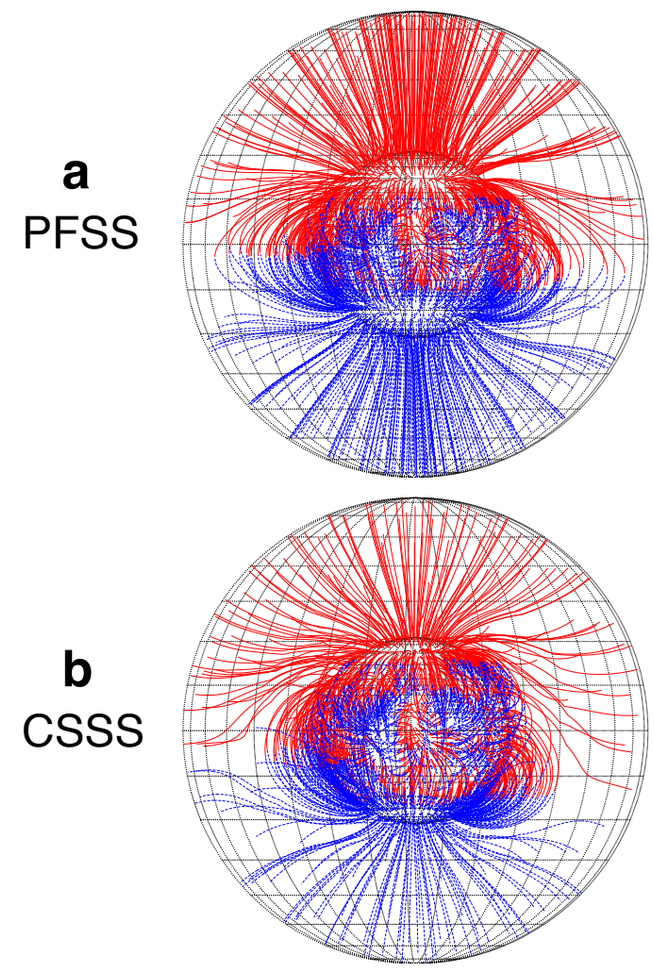


$$\frac{\mathrm{d}E}{\mathrm{d}\ell} = -\rho(\alpha + \beta E)$$

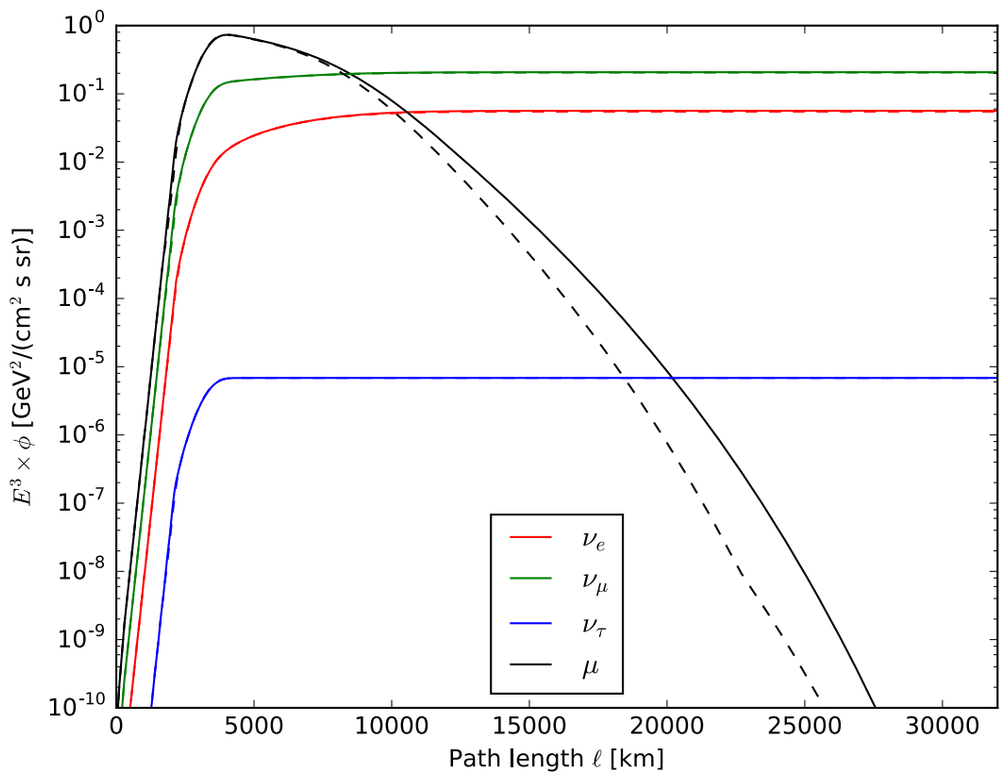
with α, β appropriate for mixture *He+H*

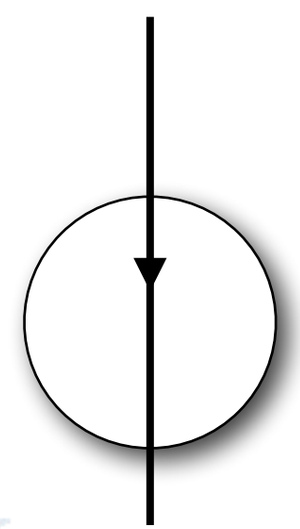
Sun has a complicated magnetic field structure

- Time-varying with solar cycle
- Unclear how to model impact on CR flux
  - Use γ-ray observations?
  - HelioProp?
- Could affect CR flux up to $E \sim 10^2 - 10^3$ GeV
  [Seckel et al. (1991)]



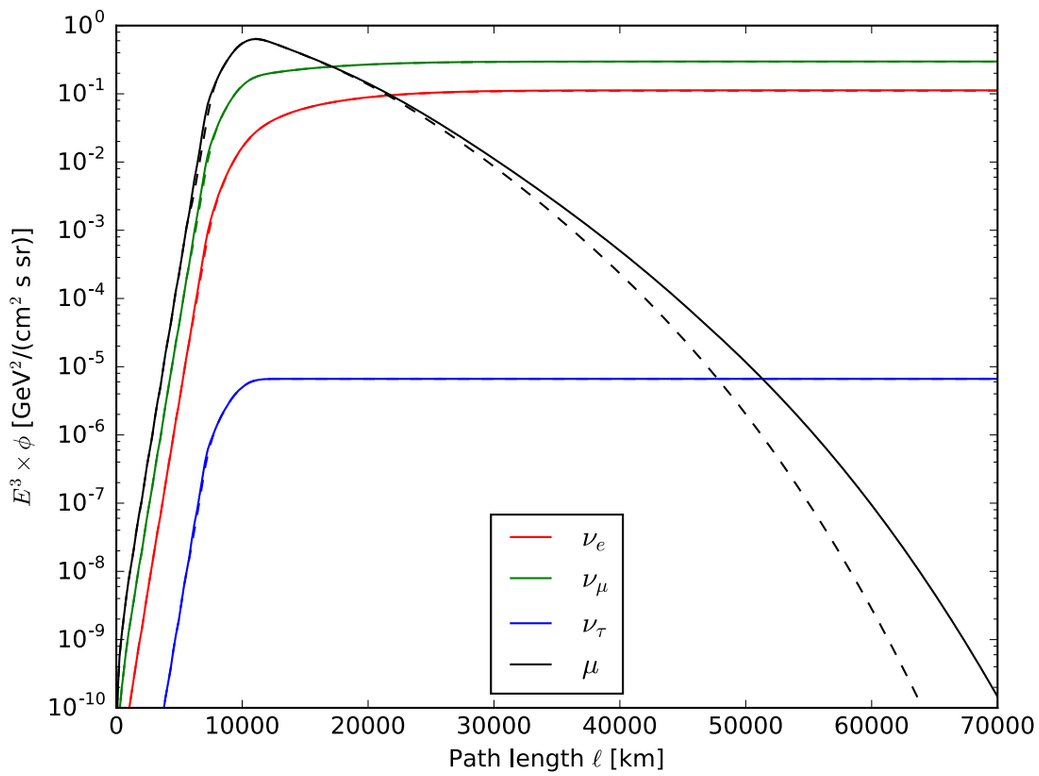
Fluxes as function of length travelled, *b=0*





Solid: Serenelli_agss09_gs98 + Ingelman et al.
Dashed: Serenelli_agss09 + Stein + Ingelman et al.

Fluxes as function of length travelled, *b=0.957*



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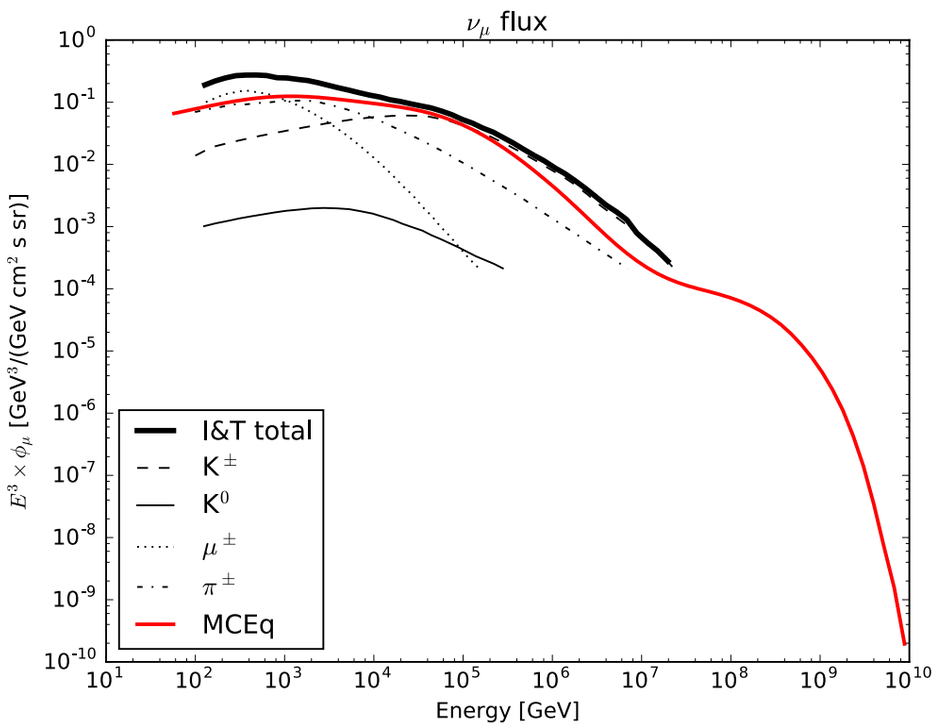
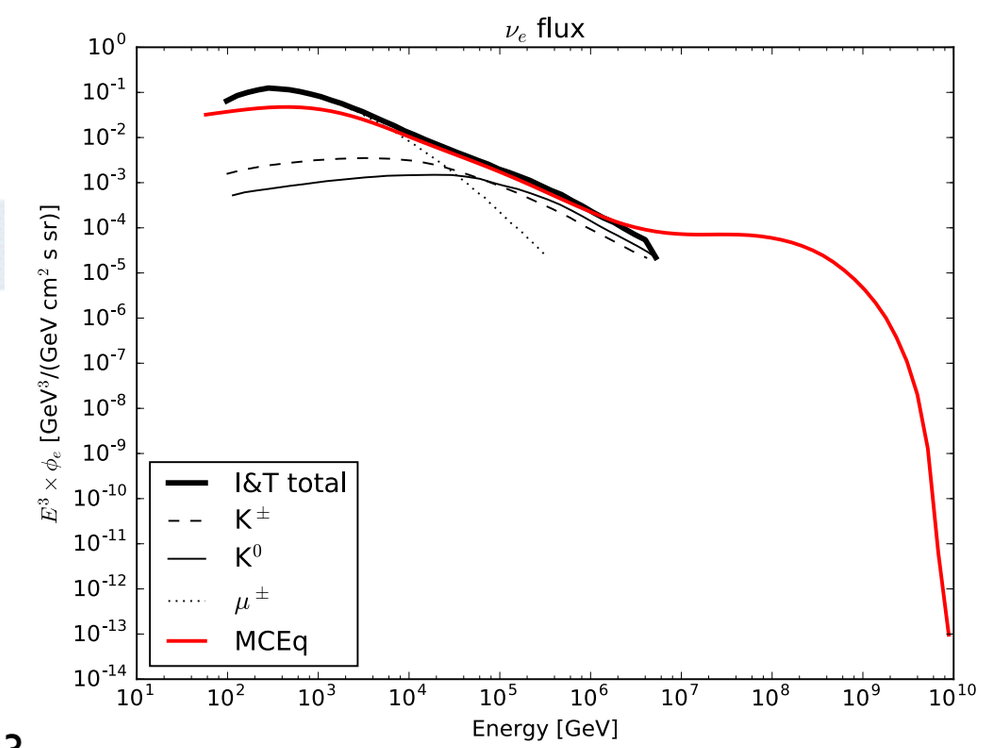
Final neutrino fluxes in sun after cascade evolution



MCEq (ours) in red
Ingelman et al. in black

ν_μ ν_e



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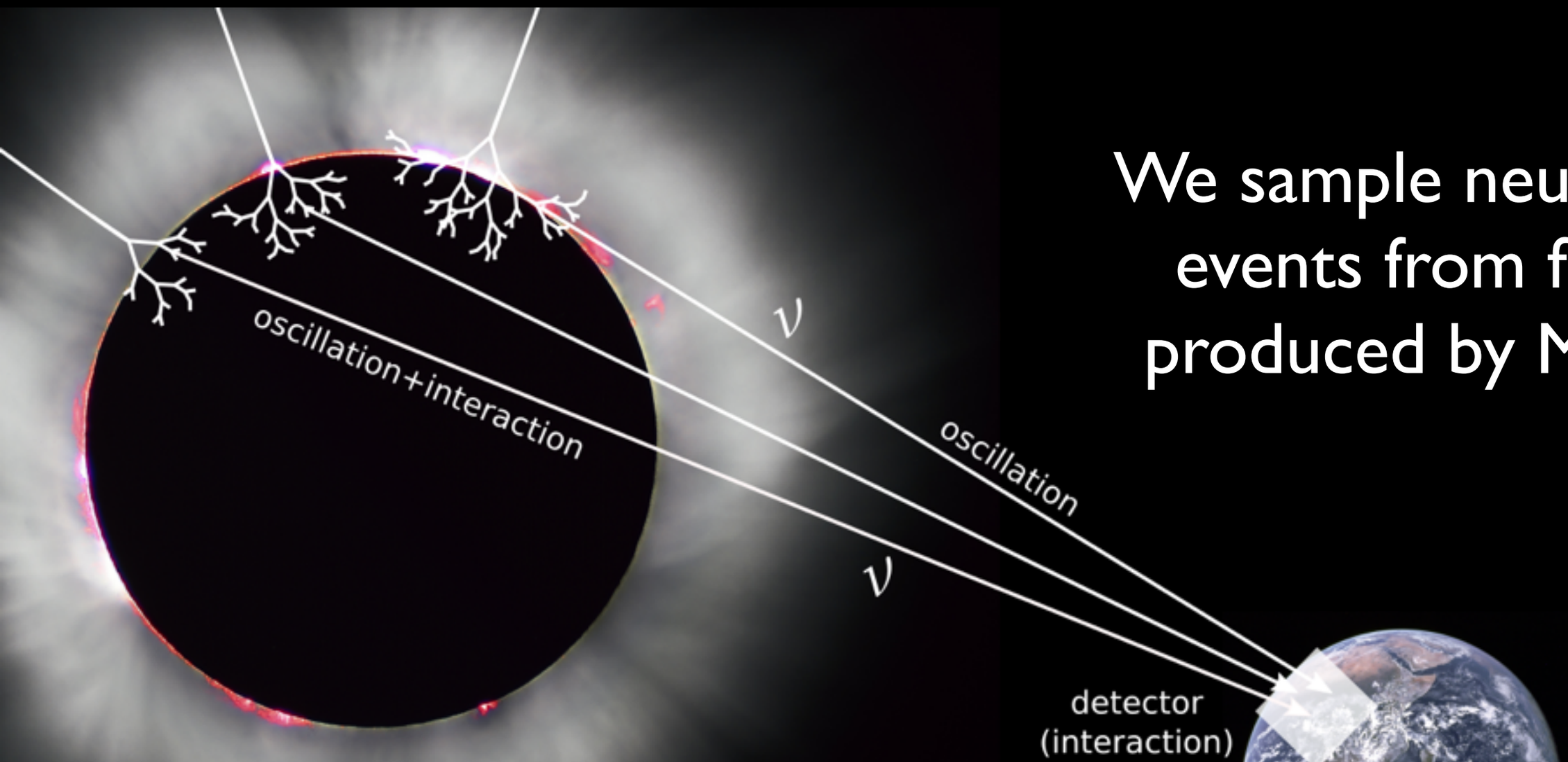
WimpSim handles neutrino weak interactions and oscillations

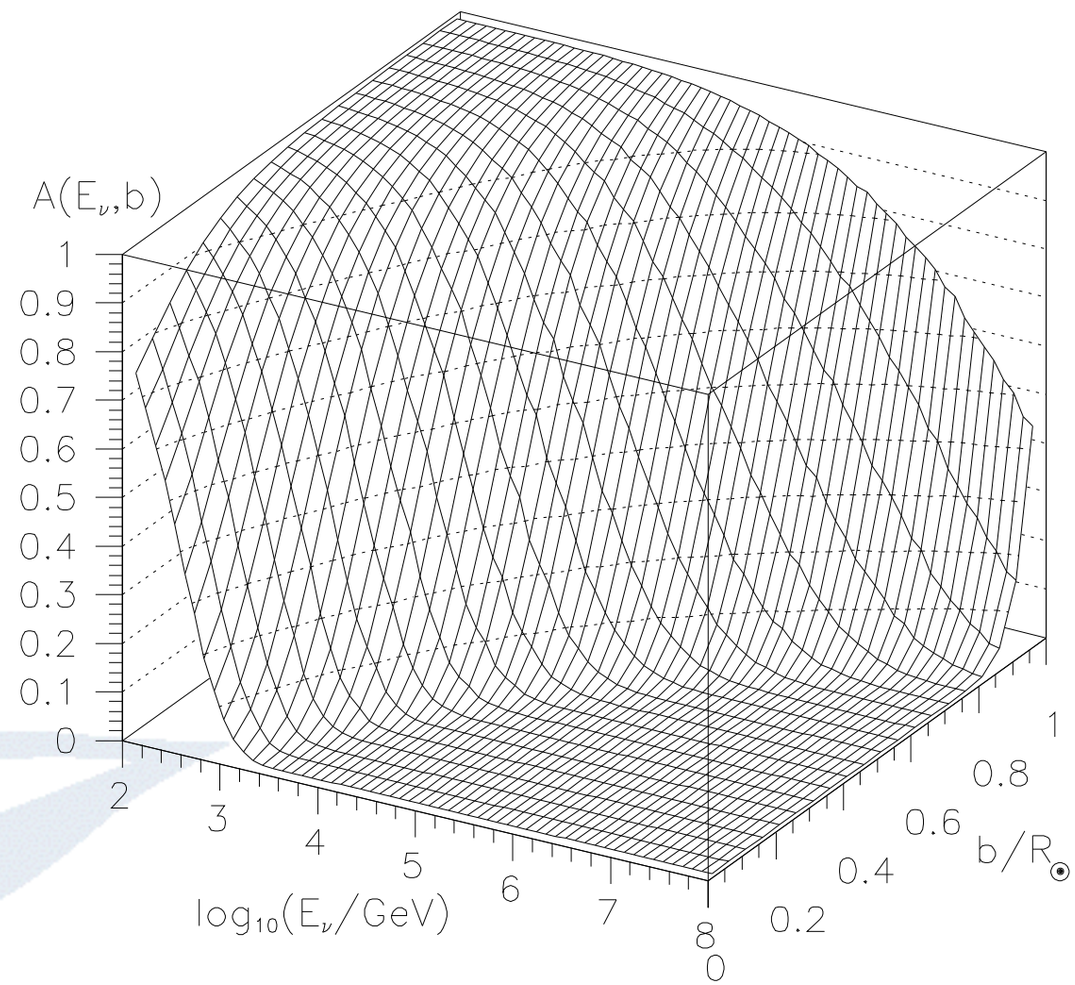


We sample neutrino events from fluxes produced by MCEq

WimpSim (Edsjö) then handles weak interactions and oscillations and produces event file

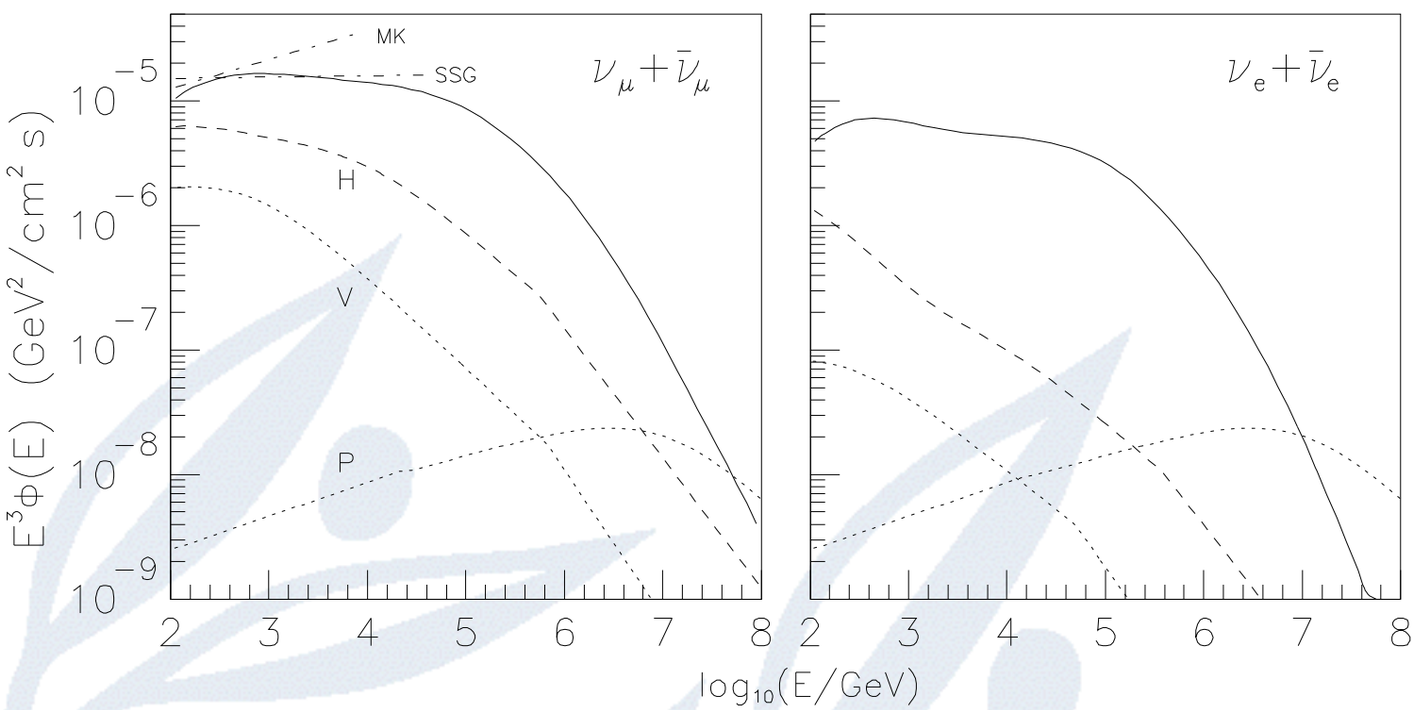
WimpSim include neutrino weak interactions that give absorption

- Depends on energy and impact parameter *b* (path through sun)
- For $b=0$, $E>10^4$ GeV: $A\approx 0$ (full shielding)
- But most flux comes from paths nearer the surface



Plot from Ingelman et al. [hep-ph/9604288]

O(few) events per year possible in km^3-sized detector



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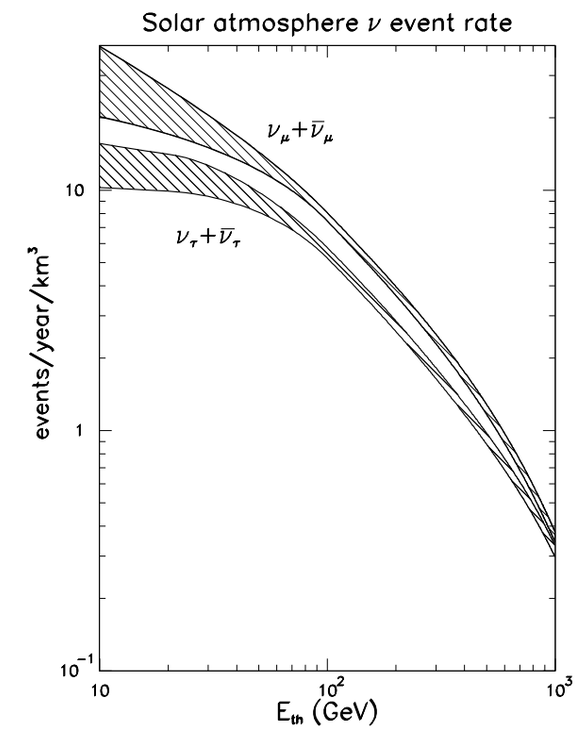

Plot from Fogli et al. [hep-ph/0608321]

- Above: all flux integrated over a sharp E_{th} (in reality more complicated)
- We will make MC-based event files in a form hopefully of interest to current ν experiments

Summary

- CR interactions in solar atmosphere result in ν flux at earth
- Our improvements include
  - ν fluxes at sun (last calculation from 96)
  - more complete geometrical treatment
  - output event files in style of ν expt's
- Flux (magnitude and energy dep.) needs to be known in case of WIMP ν signal