High energy neutrinos from the Sun

Manuel Masip

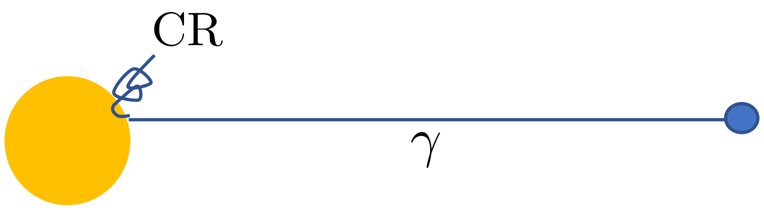
Universidad de Granada, Spain

1. Diffuse background
2. CRs through the solar magnetic field
3. Neutrinos from solar showers
4. Detection strategy

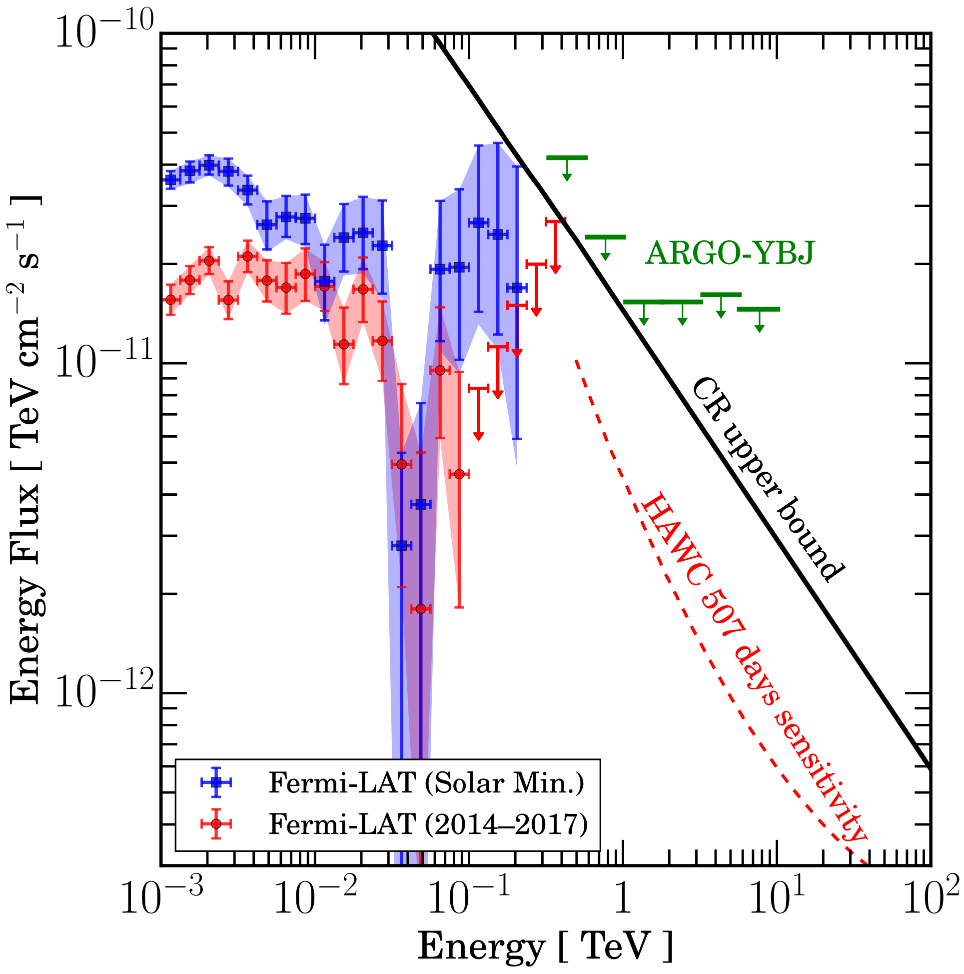
Dark Ghosts 2018

- The Sun emits light/ν's produced thermally and through nuclear reactions, but it also *processes* CRs into high-energy neutrinos and gamma rays (plus e^+, $\overline{p}$,...)

Gamma-ray flux at Fermi

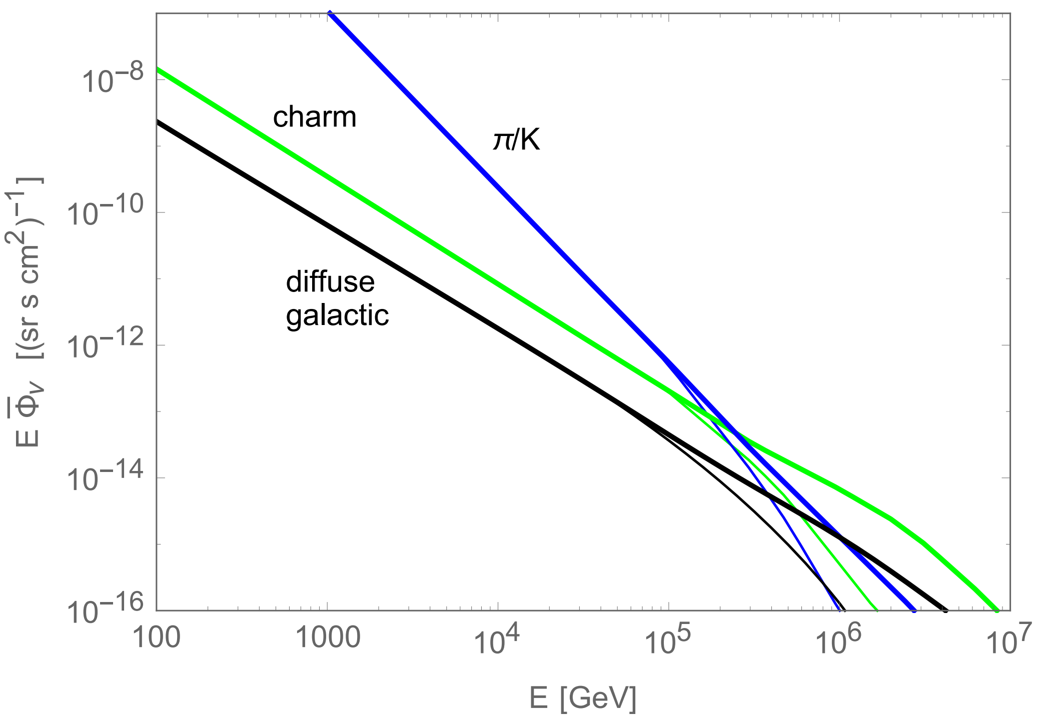


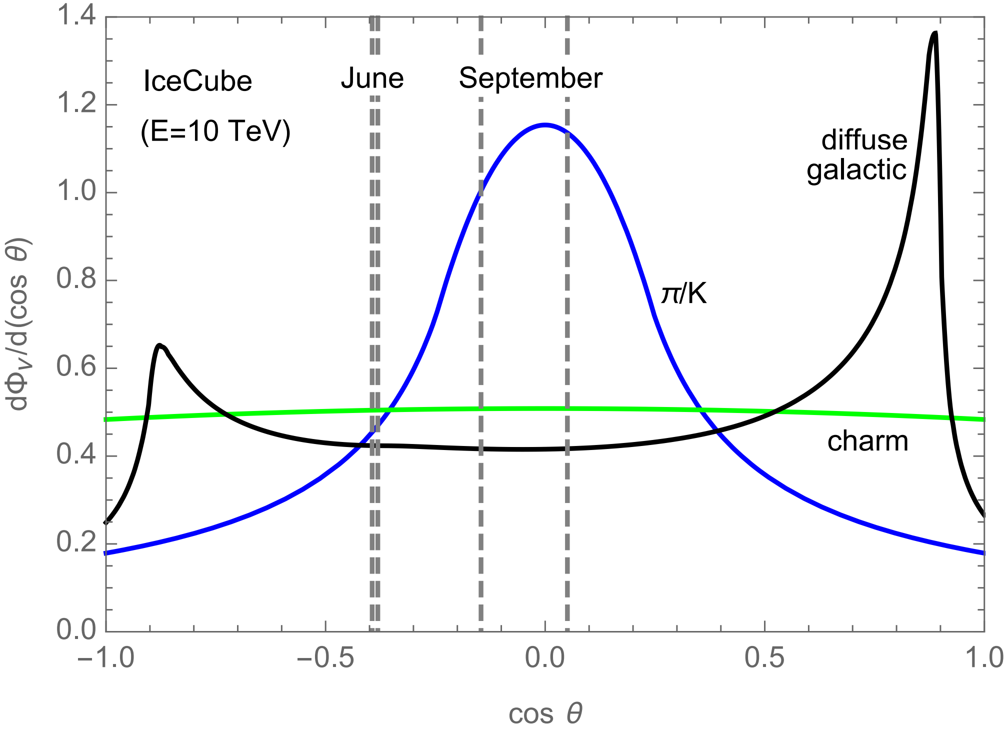
10 times larger than the diffuse background or the SSG91 prediction



What high-energy solar ν flux may we expect (up to DM)?

- Diffuse background with three components: conventional, charm and galactic ν's

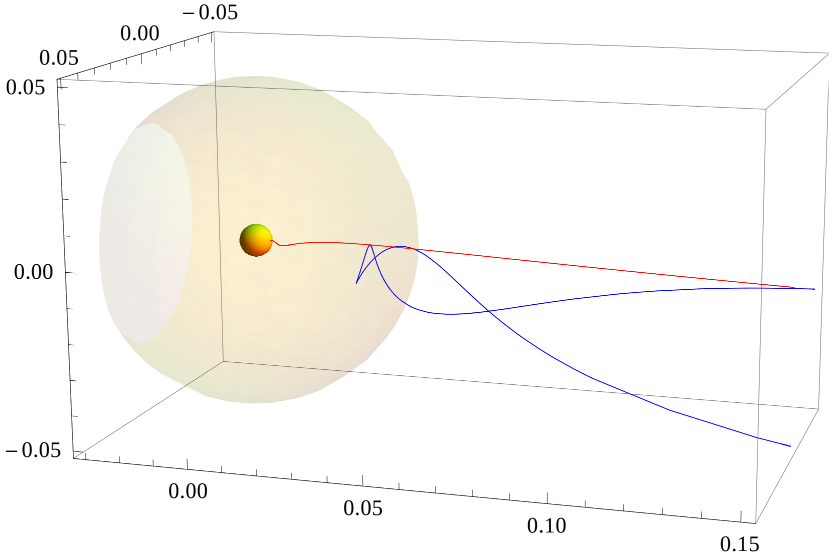


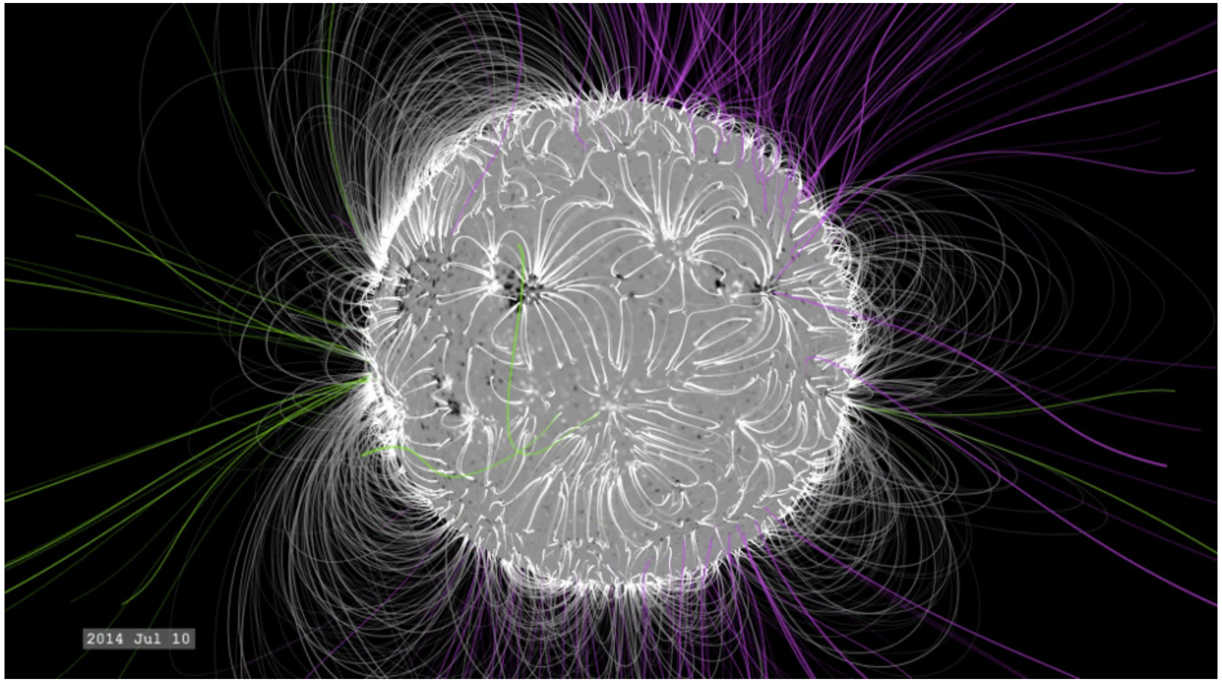


- At TeV energies only the conventional atmospheric ν is relevant (detectable). Mostly muon neutrinos, -3.7 spectral index, strong dependence with the zenith angle

- At $E_\nu = 10$ TeV the atmospheric background from the Sun position at IceCube is 3 times stronger in September than in June. At the KM3Net site, at sunrise today the background was 5 times larger than it will be at midnight

(i) Can TeV CRs reach the Sun's surface?

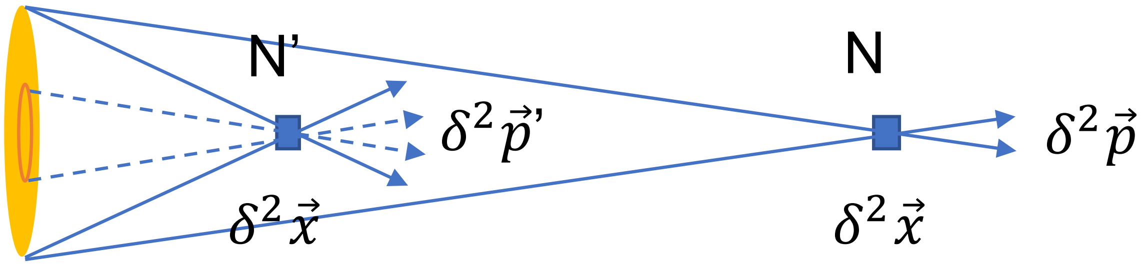




Magnetic field: At $r > 10R_\odot$ interplanetary (Parker) field. Strong radial component, magnetic mirror effect, ballistic CR trajectories. At $r < R_\odot$ field lines tend to co-rotate ($T \approx 24$ days) with the Sun, turbulence, diffusion, some lines start and end in the surface. 11 year Solar cycle.

Liouville Theorem: density of trajectories in phase-space constant

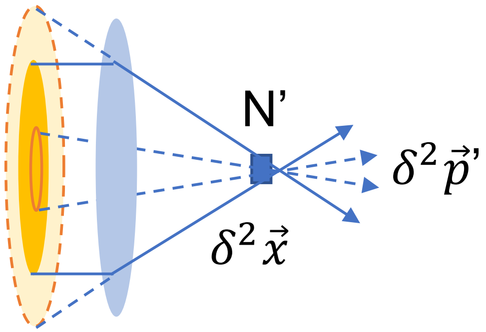
- Isotropic and homogeneous CR source, no magnetic force:



$$\Phi = \frac{N}{\delta^2\vec{x}\,\delta^2\vec{p}} \qquad \Phi' = \frac{N'}{\delta^2\vec{x}\,\delta^2\vec{p}'}$$

Liouville Th.: $\Phi' = \Phi$ ($N' > N$, but $\delta^2\vec{p}' > \delta^2\vec{p}$

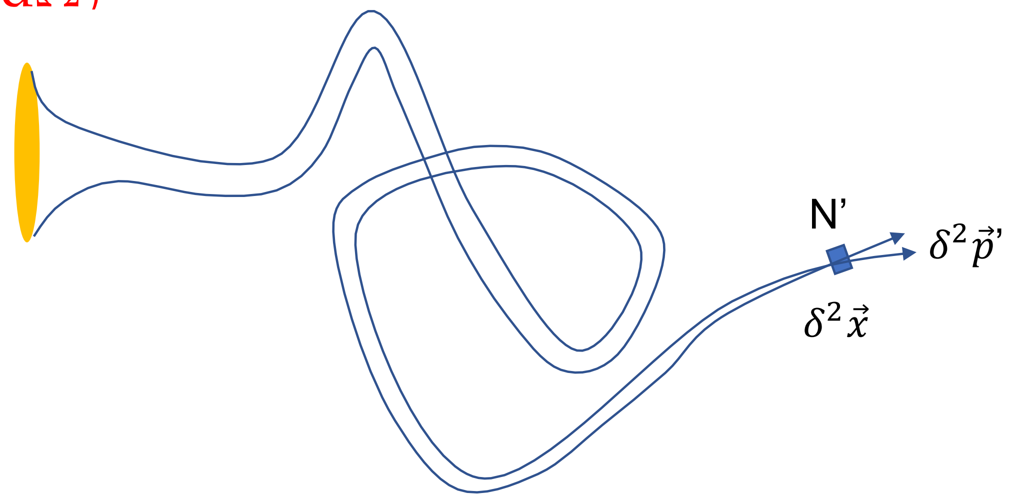
- Convergent (static) magnetic lens:



$$\Phi' = \frac{N'}{\delta^2\vec{x}\,\delta^2\vec{p}'} = \Phi$$

Larger source, but still same flux $\mathrm{d}N/(\mathrm{d}S\,\mathrm{d}\Omega)$

- Trajectories through an arbitrary (static) magnetic field:

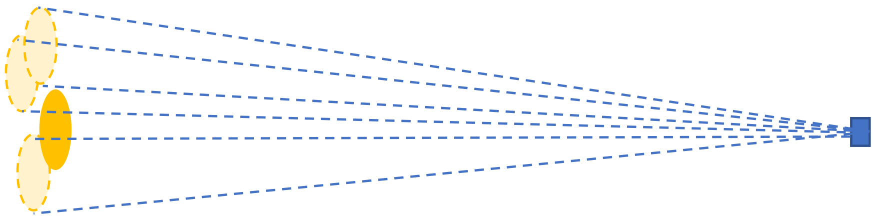


$$\Phi' = \frac{N'}{\delta^2\vec{x}\,\delta^2\vec{p}'} = \Phi$$

Smaller source at *different* position, but still same flux $\mathrm{d}N/(\mathrm{d}S\,\mathrm{d}\Omega)$

- If the position of the observer changes with time:

$$\Phi' = \frac{N'}{\delta^2\vec{x}\,\delta^2\vec{p}'} = \Phi$$

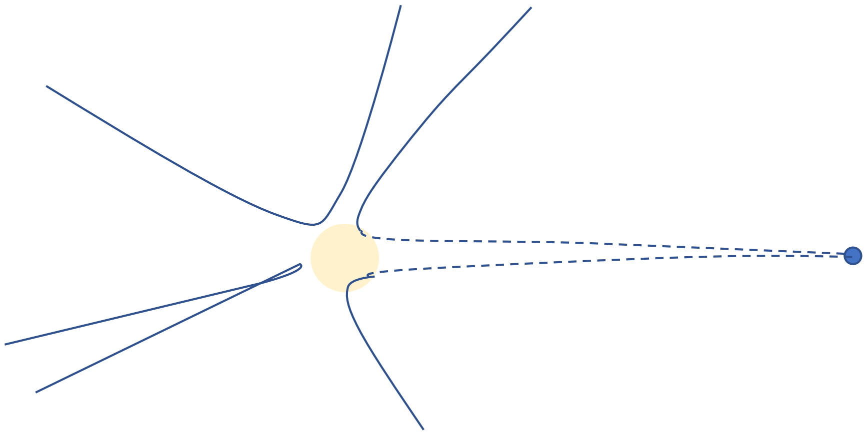


Position of the source may change with time, but still same flux per unit time.

- Diffusion through a turbulent magnetic field: at each time many (very long) trajectories can reach the observer. He sees a diffuse flux, with "many but very small" sources (i.e., no sources at all) but still same differential flux!

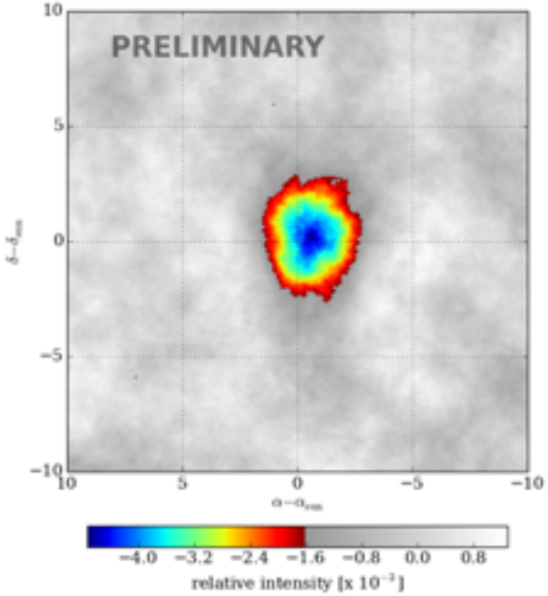
- The Liouville theorem also implies that if the flux entering the heliosphere is isotropic, then the solar magnetic field is unable to produce anisotropies:

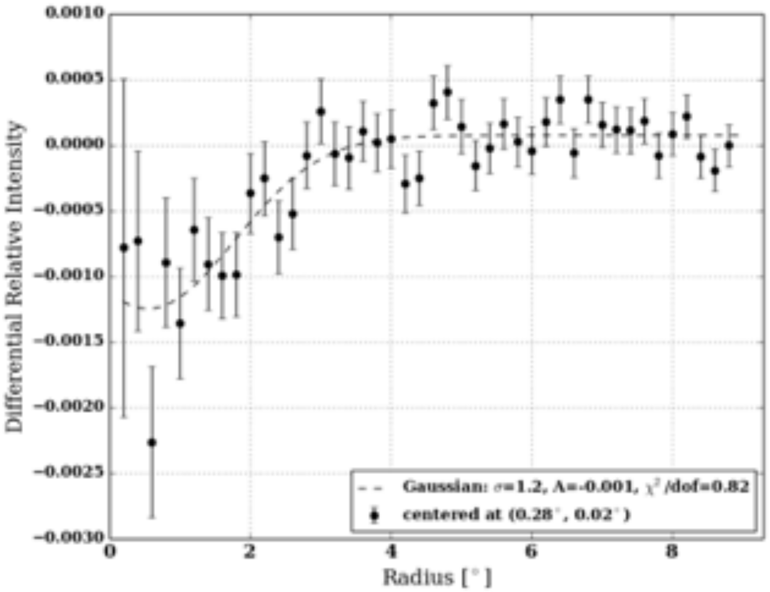
An isotropic flux through a magnetic lens (including a mirror) "stays" isotropic. But the Sun may interrupt trajectories that were aiming to the Earth, creating a CR shadow!

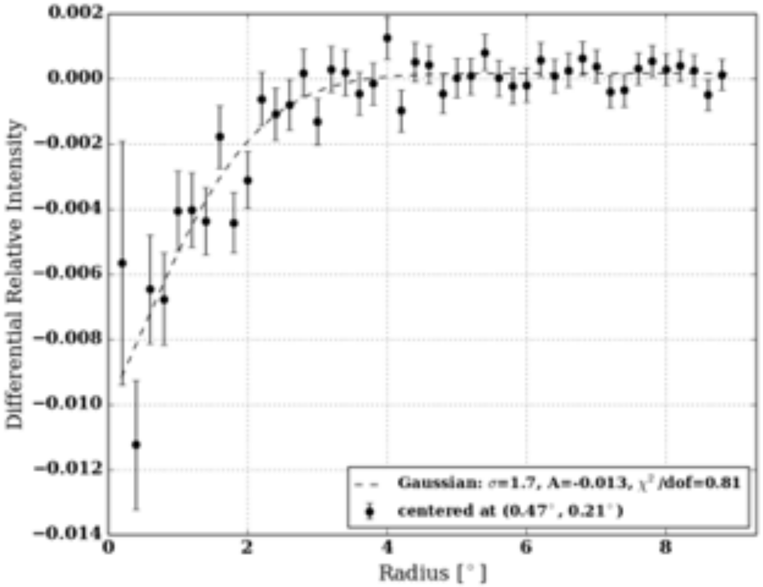


- TIBET and more recently HAWK have studied the CR shadow of the Sun: energy dependent, already present at $E \approx 2$ TeV, not a black disk (a 100% CR deficit) of 0.27° radius (the angular radius of the Sun) but a deficit that decreases radially along an angular region 10 times larger:

$$d(\theta) \approx -A \exp\left(-\frac{\theta^2}{2\sigma^2}\right)$$



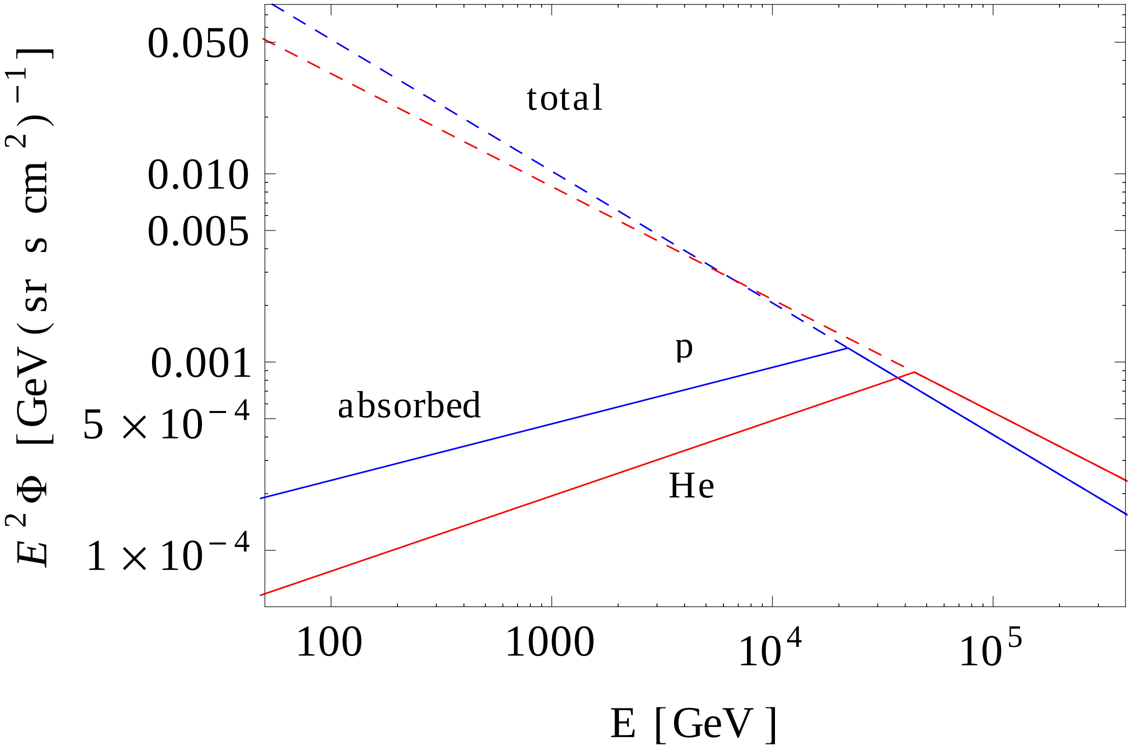




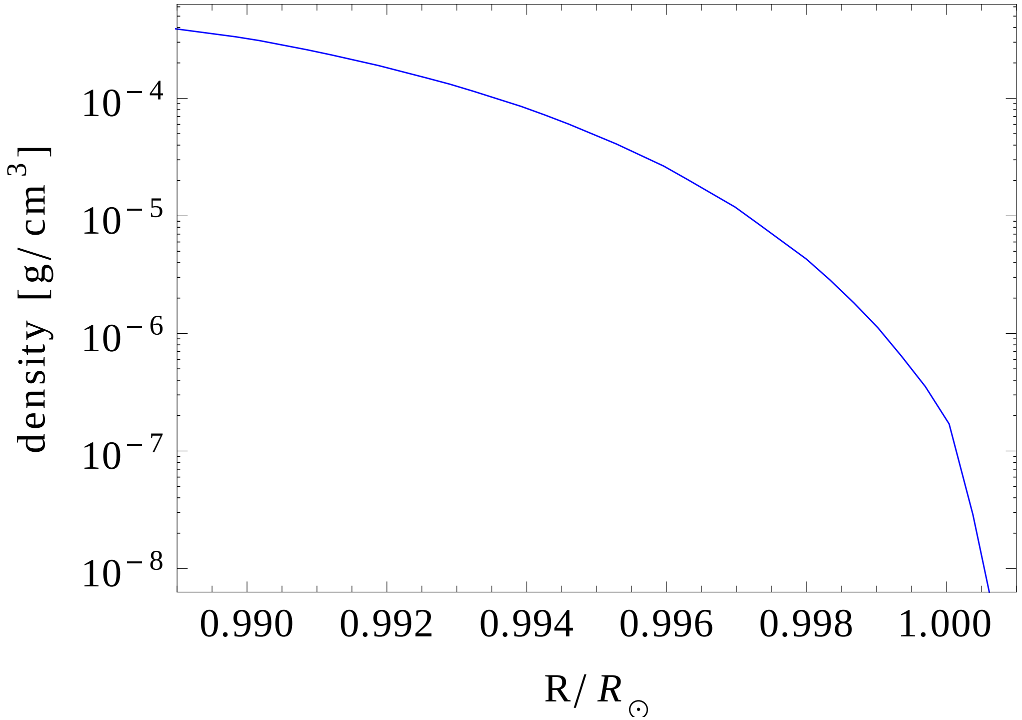
Total integrated deficit: 6% at 2 TeV 27% at 8 TeV 100% at 50 TeV

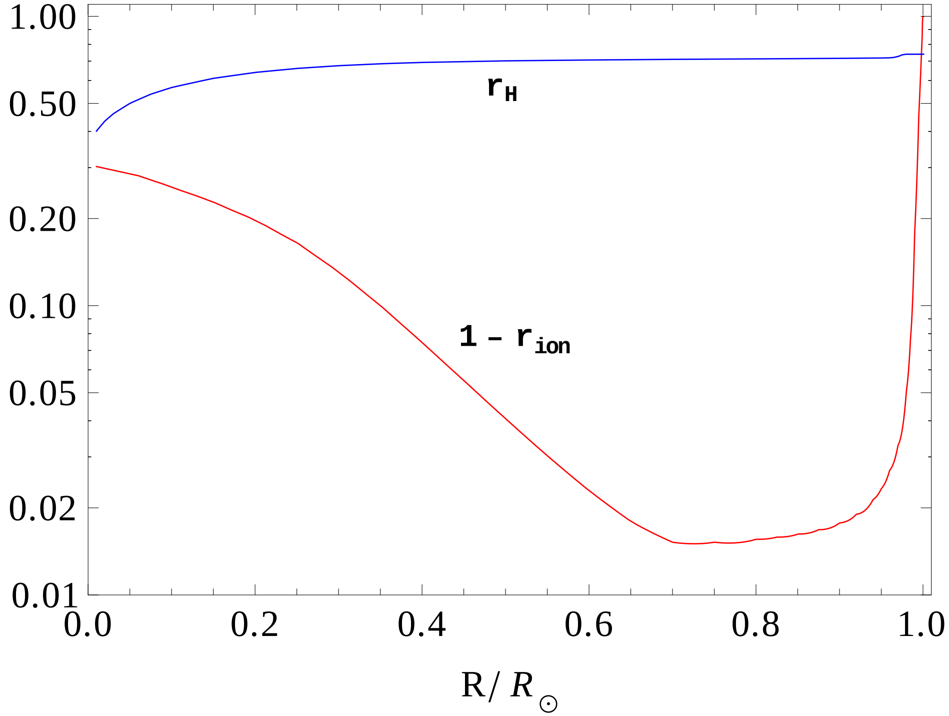
- As the Earth position and the magnetic field itself change, *(i)* the shadow may appear and disappear and *(ii)* it is smeared (by the magnetic field and by the experimental error) into an angular region ten times larger than the Sun

- The missing CR flux has been absorbed by the Sun. At lower energies (rigidities) the shadow tends to disappear: stronger magnetic mirror effect.



(ii) What do CR's find near the Sun's surface?

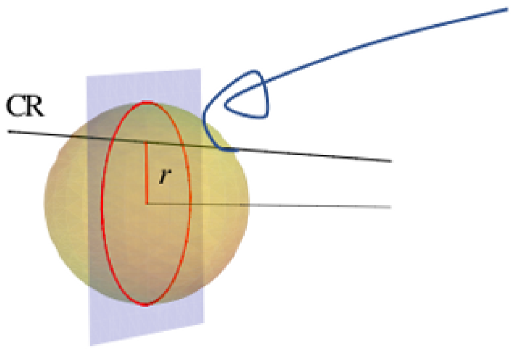




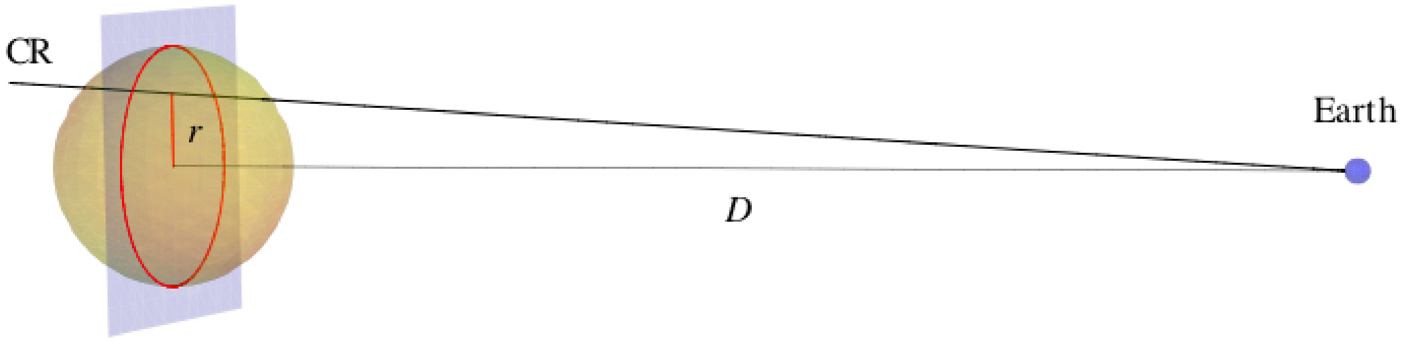
The photosphere extends up to 500 km above the Sun's optical surface and has a total depth of just 2.7 g/cm^2. Once on the surface, it takes 1500 km to cross 100 g/cm^2.

Secondary pions and kaons have plenty of time to decay before they interact. For muons, it takes 1.8×10^4 km to cross a total depth of 15 km w.e. Energy loss through radiative processes (lower Z nuclei) and ionization (partially ionized matter) is *slower* than in the atmosphere. In the Sun, most high-energy muons decay.

(iii) How to calculate the Solar neutrino flux?



- At low energy all trajectories provide a very similar neutrino yield.
- High energy trajectories are close to a straight line.

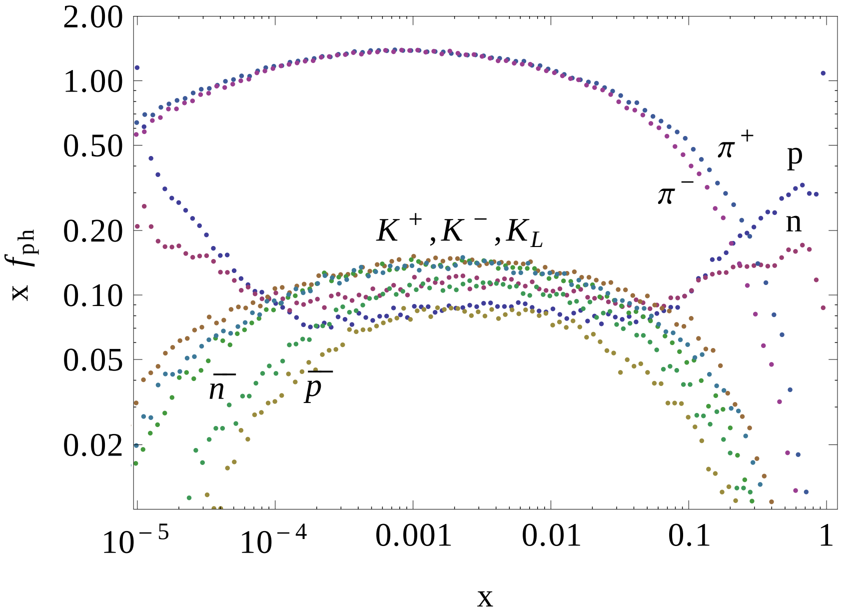


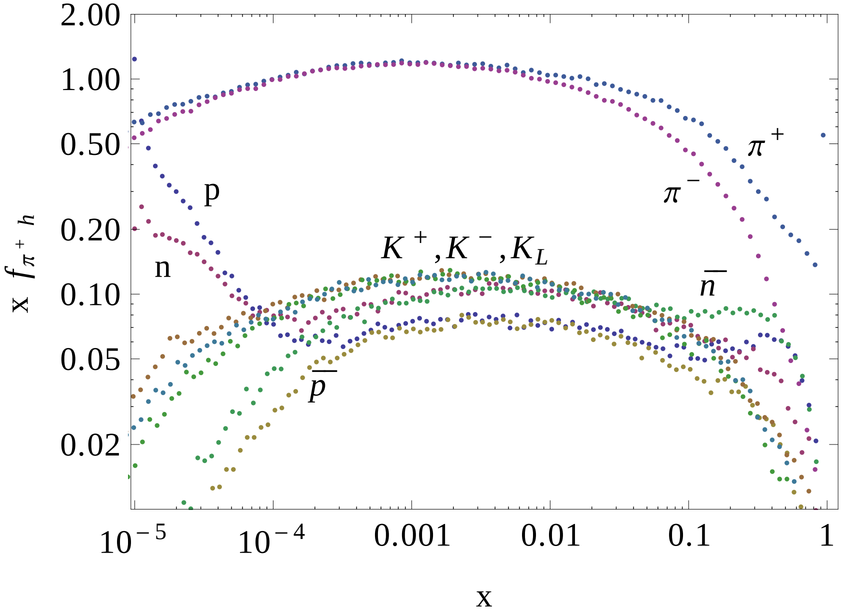
$$\frac{\mathrm{d}\Phi_i(E,t)}{\mathrm{d}t} = -\frac{\Phi_i(E,t)}{\lambda_i^{\mathrm{int}}(E,t)} - \frac{\Phi_i(E,t)}{\lambda_i^{\mathrm{dec}}(E,t)} + \sum_{j=h}\int_0^1 \mathrm{d}x\, \frac{f_{ji}(x,E/x)}{x}\,\frac{\Phi_j(E/x,t)}{\lambda_j^{\mathrm{int}}(E/x,t)} +$$

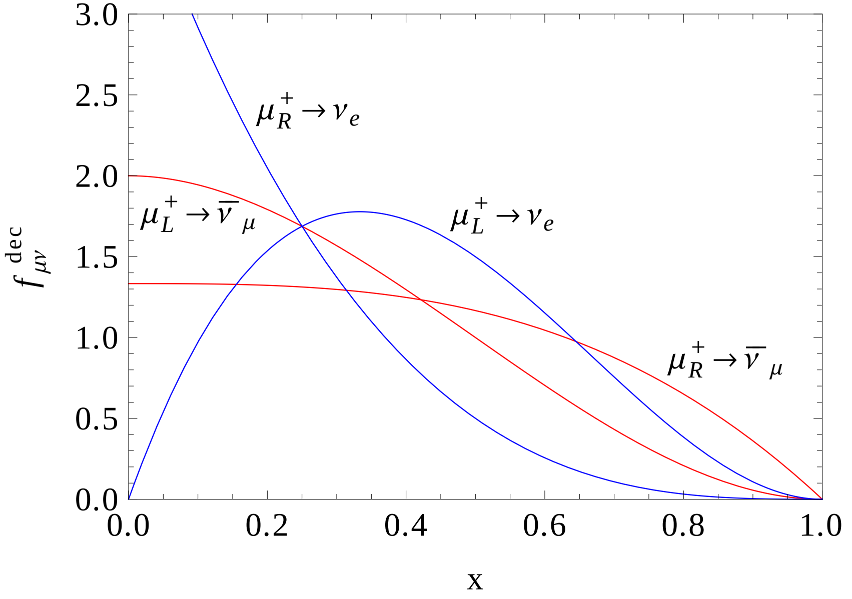
$$\sum_{k=h,\mu}\int_0^1 \mathrm{d}x\, \frac{f_{ki}^{\mathrm{dec}}(x,E/x)}{x}\,\frac{\Phi_k(E/x,t)}{\lambda_j^{\mathrm{dec}}(E/x,t)}$$

$i = h, \mu, \nu$ $\quad h = p, n, \bar{p}, \bar{n}, \pi^{\pm}, K^{\pm}, K_L$ $\quad \mu = \mu_L^{\pm}, \mu_R^{\pm}$ $\quad \nu = \nu_{e,\mu}, \bar{\nu}_{e,\mu}$

Yields at 10 TeV with EPOS-LHC







- The transport equation for muons includes energy loss:

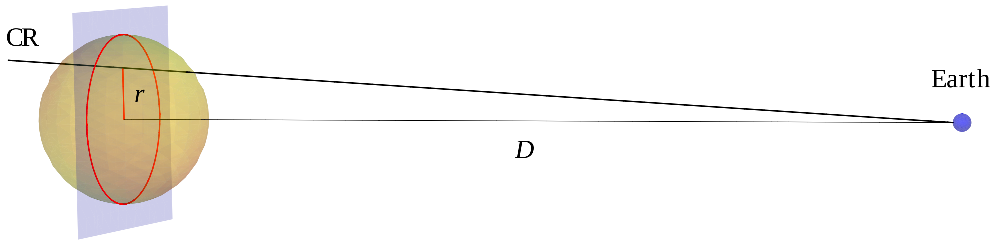
$$\frac{\mathrm{d}\Phi_\mu(E,t)}{\mathrm{d}t} \supset -\frac{\mathrm{d}\langle E_\mu\rangle}{\mathrm{d}t}\,\frac{\mathrm{d}\Phi_\mu(E,t)}{\mathrm{d}E} - \Phi_\mu(E,t)\,\frac{\mathrm{d}}{\mathrm{d}E_\mu}\left(\frac{\mathrm{d}\langle E_\mu\rangle}{\mathrm{d}t}\right)$$

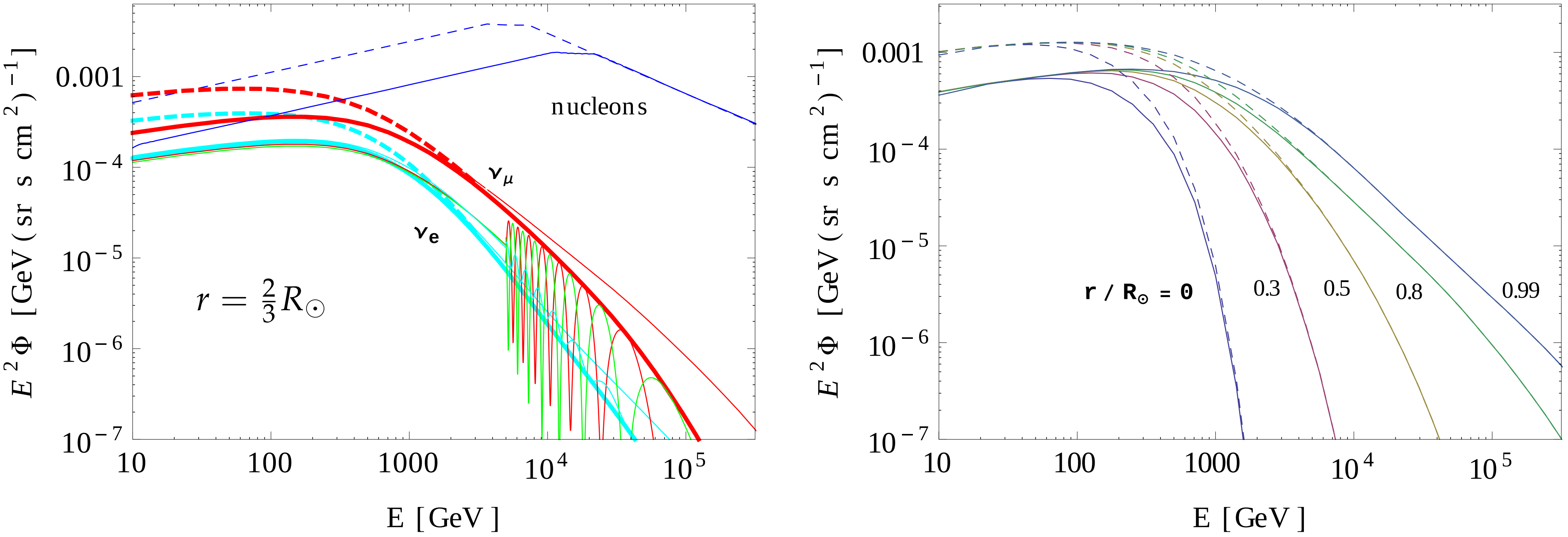
with $-\frac{\mathrm{d}\langle E_\mu\rangle}{\mathrm{d}t} = (1-r_{\mathrm{ion}})\left[r_{\mathrm{H}}\left(a^{\mathrm{H}}-a^{\mathrm{He}}\right)+a^{\mathrm{He}}\right]+\left[r_{\mathrm{H}}\left(b^{\mathrm{H}}-b^{\mathrm{He}}\right)+b^{\mathrm{He}}\right]E_\mu$

Muons lose energy at a smaller rate than in the atmosphere.

- Neutrino oscillations inside the Sun can be neglected, but vacuum oscillations between the Sun and the Earth must be included. Notice also that the absorption rate of neutrinos is higher than that of antineutrinos (factor of 1.5 at 10 TeV).

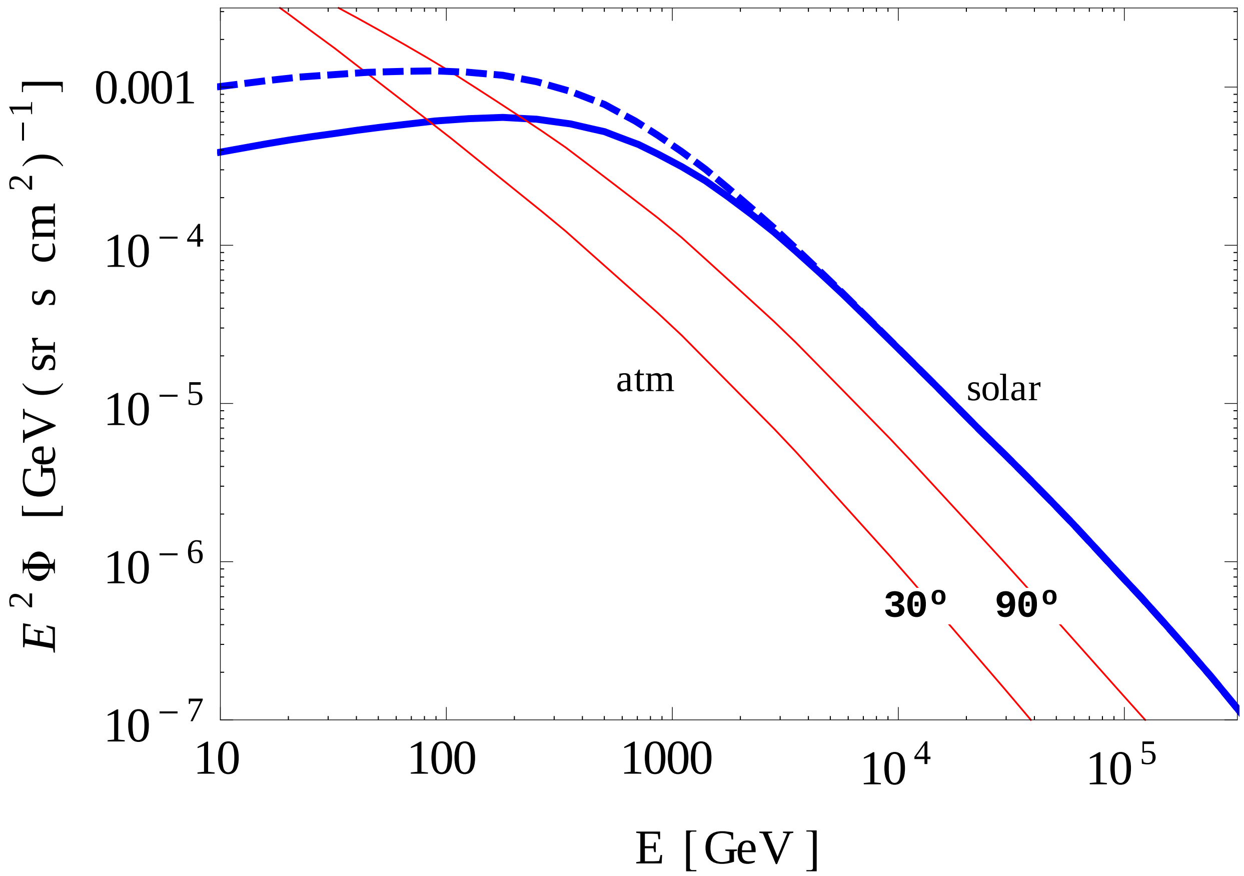
(**iv**) Results:





- Strong radial dependence of Φ_ν at $E_\nu > 1$ TeV: the flux is much weaker from the center ($r = 0$) than from peripheral regions

- Same frequency for the 3 flavors (antineutrinos favored, longer absorption length)



- Well above the atmospheric flux at $E \geq 1$ TeV, especially from vertical directions (low θ_z). At 5 TeV and $\theta = 30^\circ/150^\circ$, the ν_μ Solar flux is 7 times larger than the atmospheric one, and the total Solar ν flux is 20 times larger than the atm one.

- The TeV Solar flux is very steep at $E > 1$ TeV (high energy neutrinos are absorbed by the Sun) but almost flat at lower energies (low-energy CRs do not reach the Sun).

- Several estimates: Seckel, Stanev, Gaisser 1991

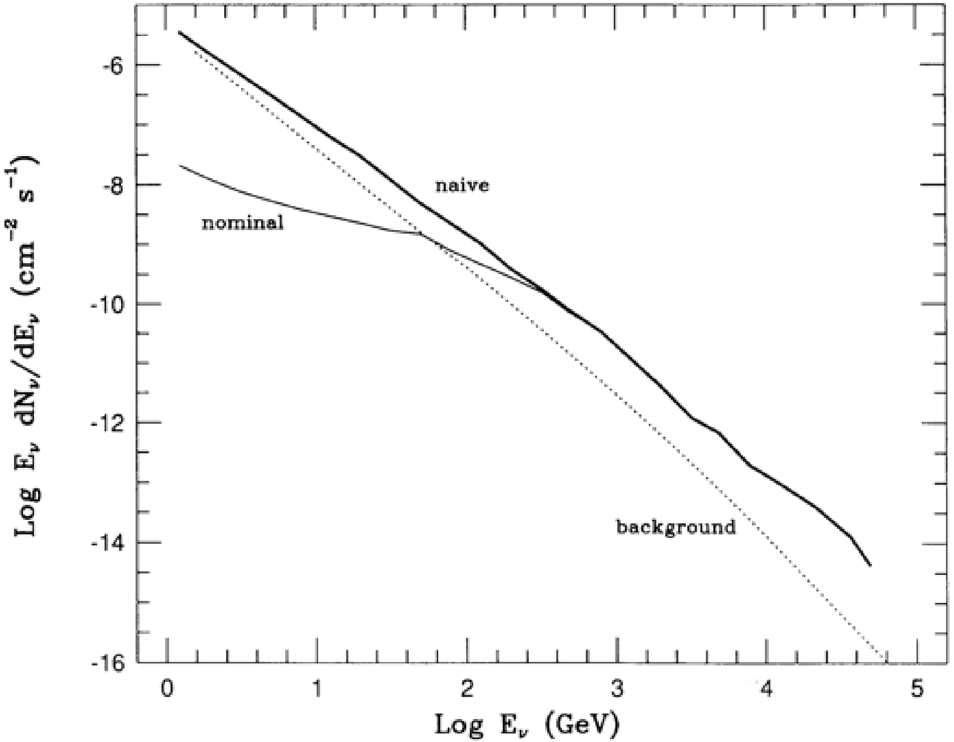
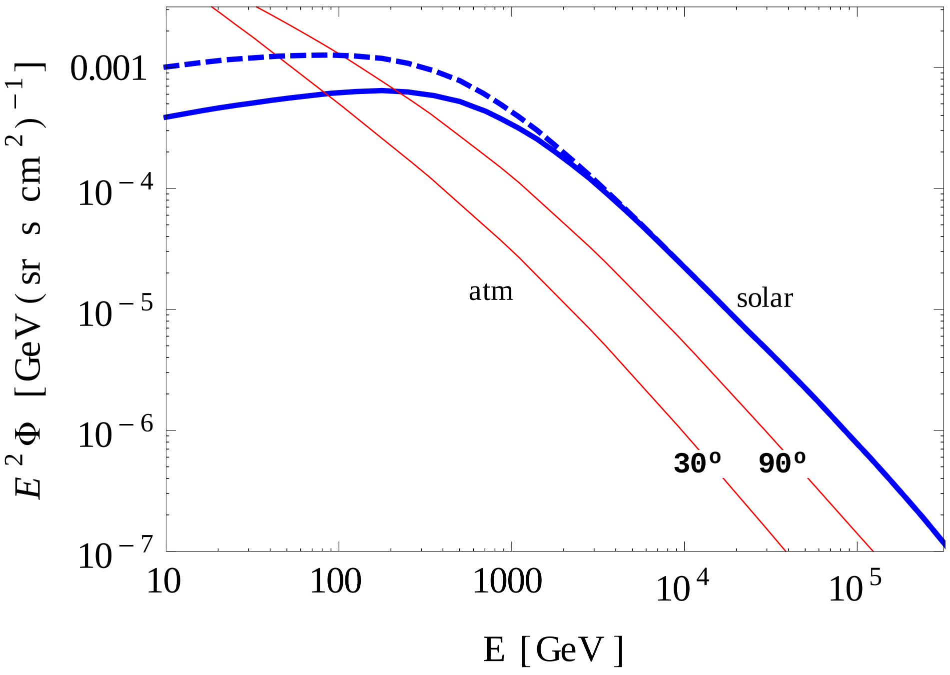


FIG. 4.—Neutrino flux at Earth for different assumptions about cosmic-ray transport. The bold curve shows an upper limit using the naive absorption rate shown as the bold curve in Fig. 3. The solid curve gives our nominal result. The background from terrestrial cosmic-ray cascades is shown for a solid angle equal to the size of the Sun's disk.



The neutrino flux at 1 TeV that we obtain (MM, Astropart. Phys. 97 (2018) 63) is

1.3 × Arguelles, Wasseige, Fedynitch, Jones 2017

1.5 × Ingelman, Thunman 1996

1.5 × Edsjo, Elevant, Enberg, Niblaeus 2017

Summary

• The Sun is (probably) the brightest object in the sky also for high energy neutrinos. It emits neutrinos equally distributed in flavor with a spectrum that is very steep ($E^{-3.5}$) at $E > 1$ TeV and flatter ($E^{-1.8}$) at 1–300 GeV. This high-energy Solar ν flux is correlated with the CR shadow of the Sun measured at HAWK.

• This ν flux is above the atmospheric background. The Sun angular radius is very small (0.27°), so it is essential to optimize the analysis: at $E_\nu = 10$ TeV the background is 5 times larger from the horizontal than from vertical directions (*only* 4 times larger at $E_\nu = 1$ TeV). The relative strength of the signal is time dependent: stronger signal in June than in September in IceCube and at midnight than at sunrise in KM3NeT.

• The detection of this flux seems not impossible. It could be used to calibrate neutrino telescopes (angular resolution, energy). At $E > 1$ TeV the Sun produces neutrinos but not gammas. This flux is itself an important background in DM searches.

Dark matter ↔ Cosmic rays ↔ neutrinos ↔ gammas