The Sun at the TeV

gammas, neutrons, neutrinos, and a cosmic ray shadow

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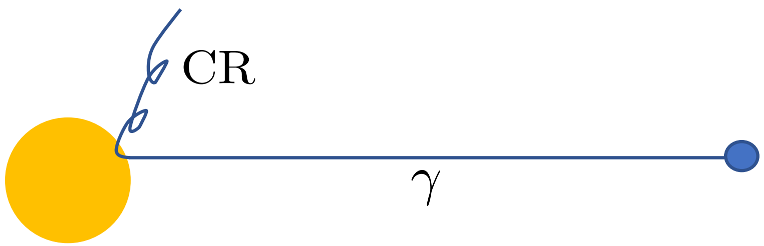
1. Gammas and the cosmic ray shadow of the Sun
2. Liouville's theorem
3. Gammas, neutrons and neutrinos
4. Detection strategy

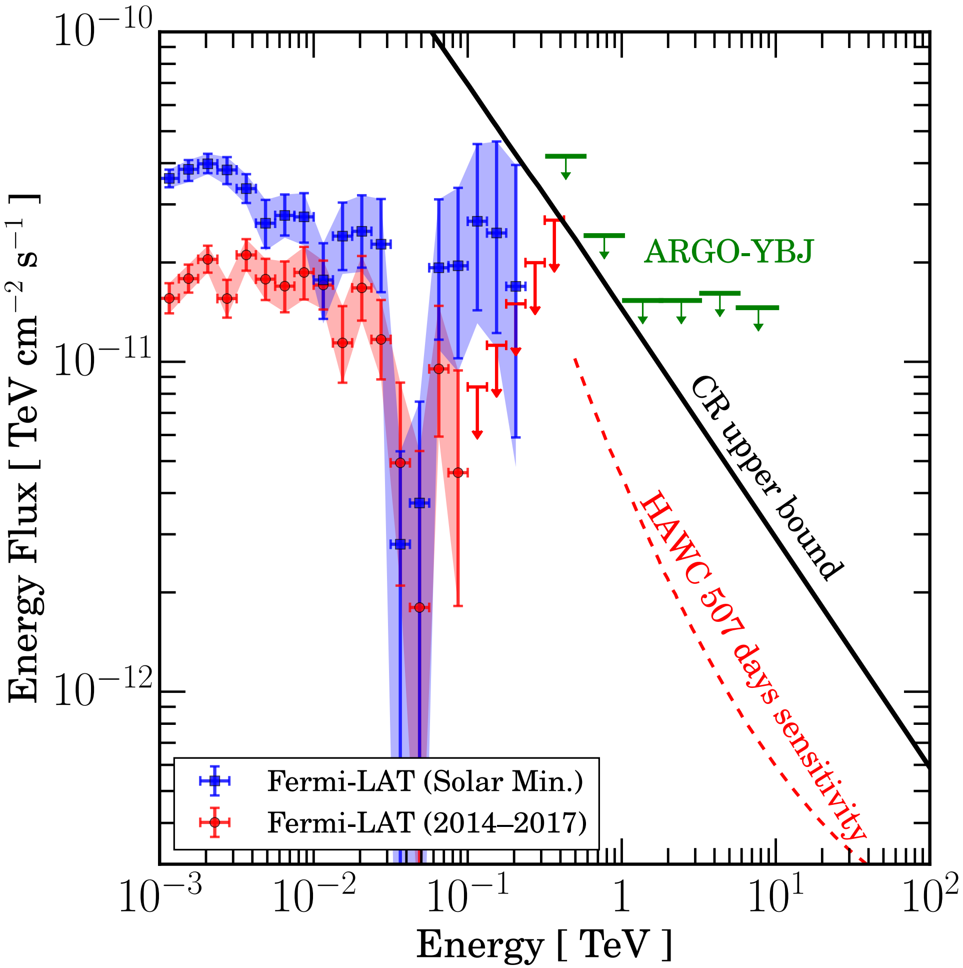
4th IBS-MultiDark-IPPP Daejeon 2019

• Is a sustained flux of TeV gammas or neutrinos coming from the Sun a *clear* sign of dark matter annihilation? The Sun *processes* CRs into high-energy particles...



γ ray flux

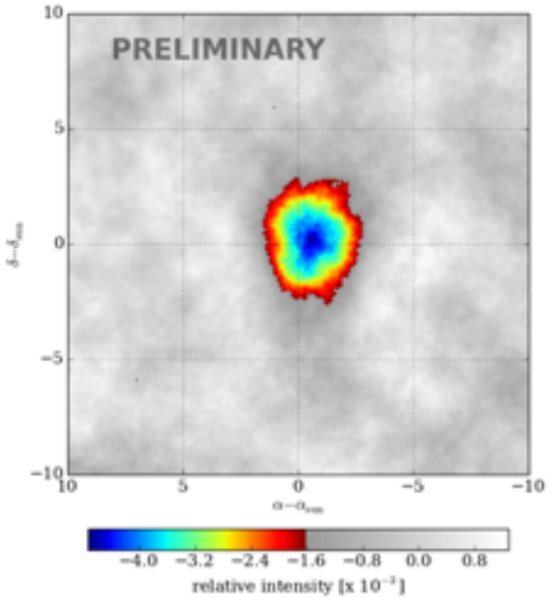
10 times larger than the diffuse background, 7 times larger than SSG91

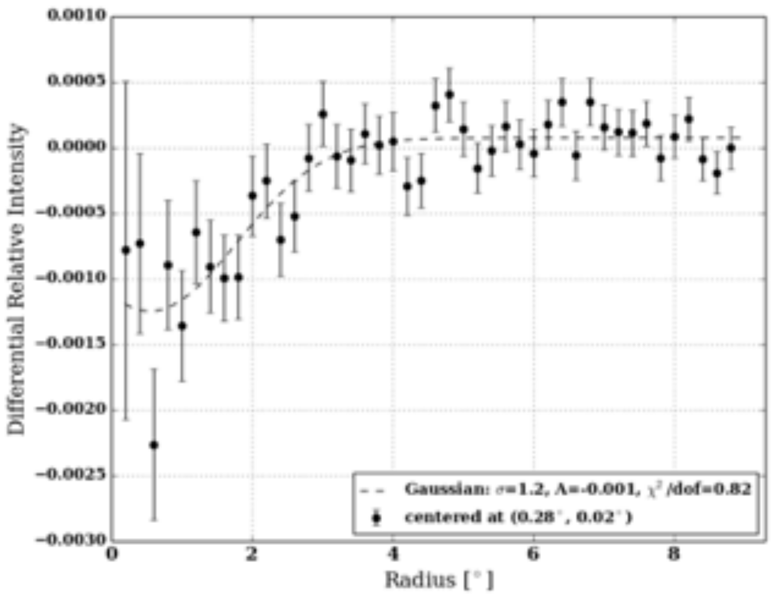


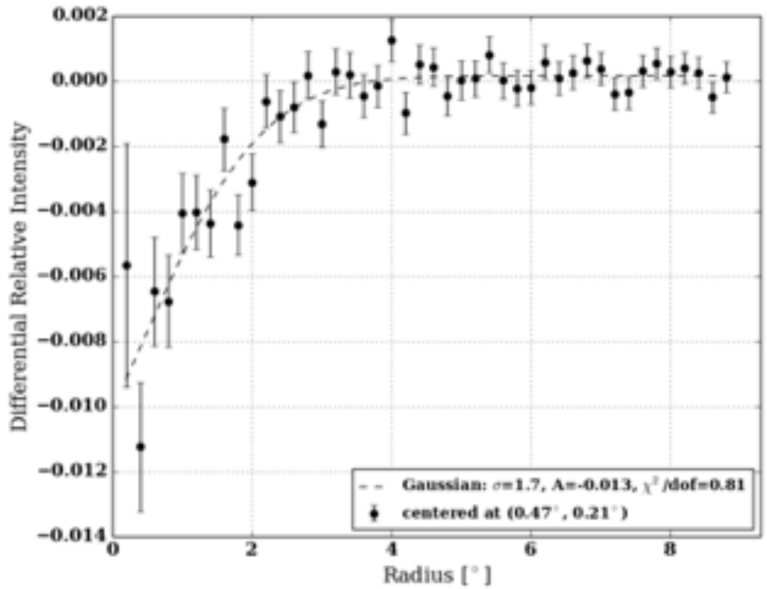
What should we expect (up to DM)? How do γ's correlate with ν's or n's?

• 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 (2013-2014 data, solar max):

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



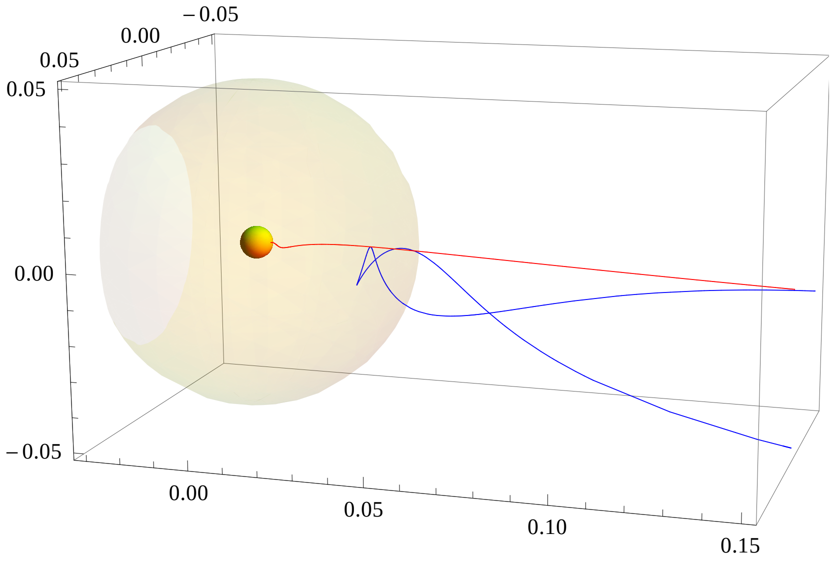


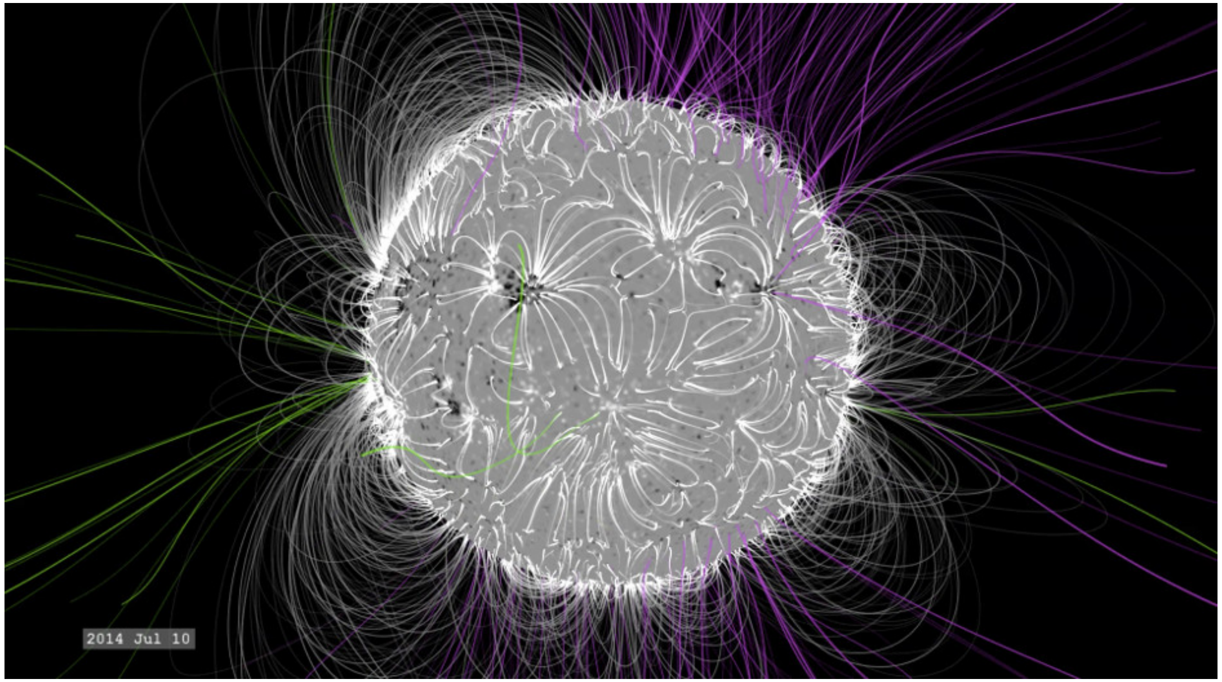


Total integrated deficit: 6% at 2 TeV 27% at 8 TeV 100% at 50 TeV

How does the CR shadow of the Sun correlate with the γ, ν, n fluxes?

• TeV CRs reach the Sun's surface *against* the solar magnetic field...

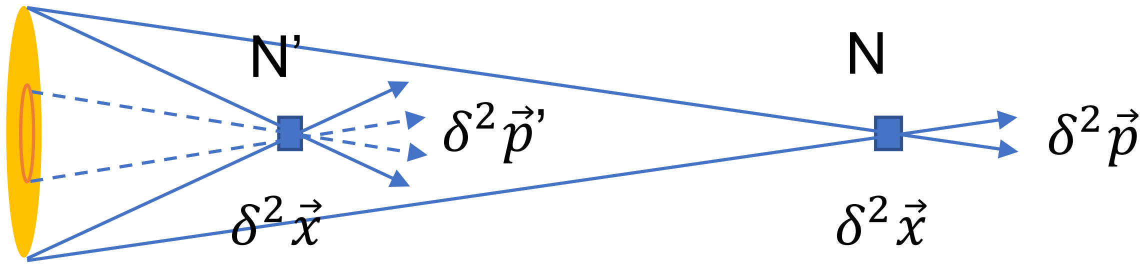




At $r > 10R_{\odot}$ interplanetary (Parker) field; strong radial component: magnetic mirror effect. At $r < R_{\odot}$ field lines tend to co-rotate ($T \approx 24$ days) with the Sun; open lines and loops that start and end on the surface. 11 year Solar cycle. CR transport affected by the solar wind (convection).

Liouville Theorem: density of trajectories in phase-space constant

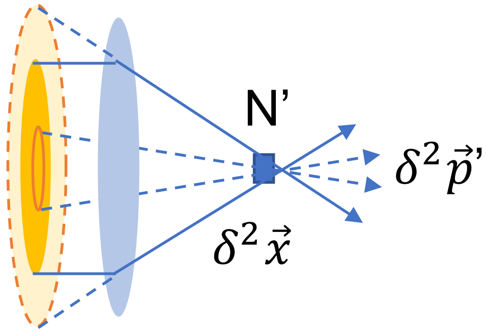
• Isotropic and homogeneous CR source, no magnetic force:



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

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

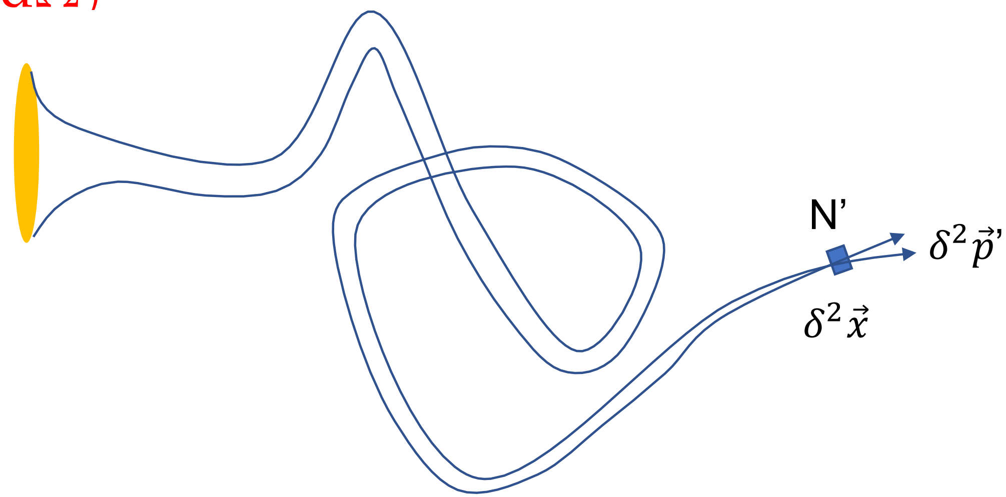
• Convergent (static) magnetic lens:



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

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

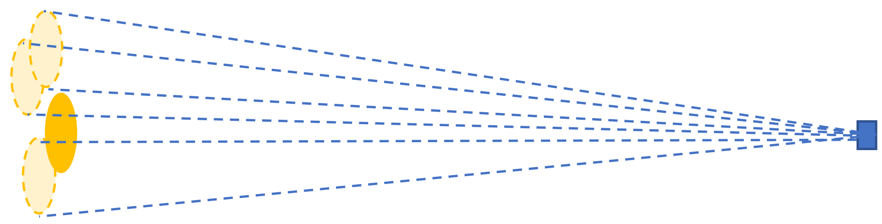
• Trajectories through an arbitrary (static) magnetic field:



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

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:



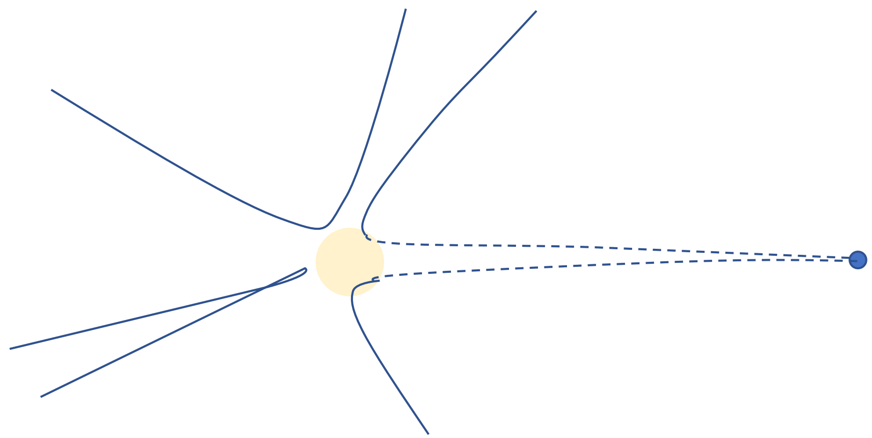
$$\Phi' = \frac{N'}{\delta^2\vec{x}\,\delta^2\vec{p}'} = \Phi$$

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!

• Liouville's theorem also implies that if the CR 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!



• As the Earth position and the magnetic field itself change the shadow is smeared (by the magnetic field and by the experimental error) into an angular region ten times larger than the Sun.

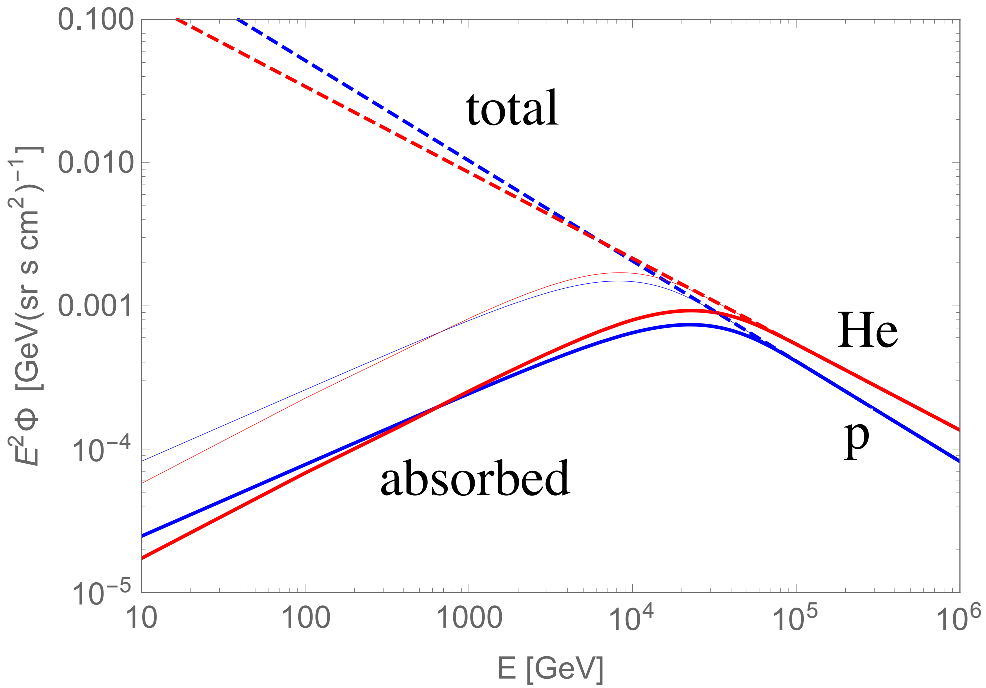
• The integrated deficit in the shadow at different energies reveals the fraction of CRs that have been absorbed by the Sun. If the (average) proton crosses a solar depth $\Delta X_H(E) \propto E^{1.2}$, then the probability to be absorbed is $(1 - e^{-\Delta X_H(E)/\lambda_{\rm int}^H})$. At lower energies (rigidities) the shadow tends to disappear: stronger magnetic mirror effect.

Helium finds it more difficult than protons to reach the Sun,

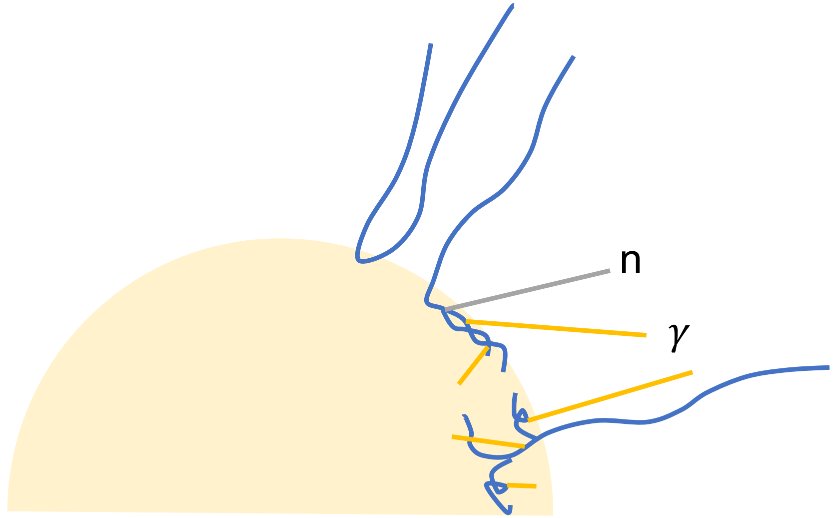
$$\Delta X_{\rm He}(E) = \Delta X_{\rm H}(E/2)$$

but it is easier to absorb

$$\lambda_{\rm int}^{\rm He} < \lambda_{\rm int}^{\rm H}$$

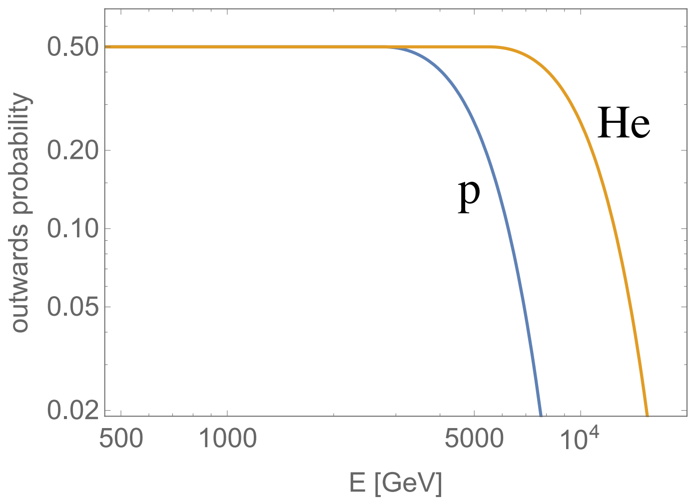


• The absorbed CR flux will be processed into secondary particles. Some of them will be absorbed by the Sun and others will escape and reach the Earth. Two main factors: how deep in the Sun they are produced, and in what direction (outwards or inwards) they propagate



• Protons and He nuclei reach the Sun following an open (radial) magnetic line.

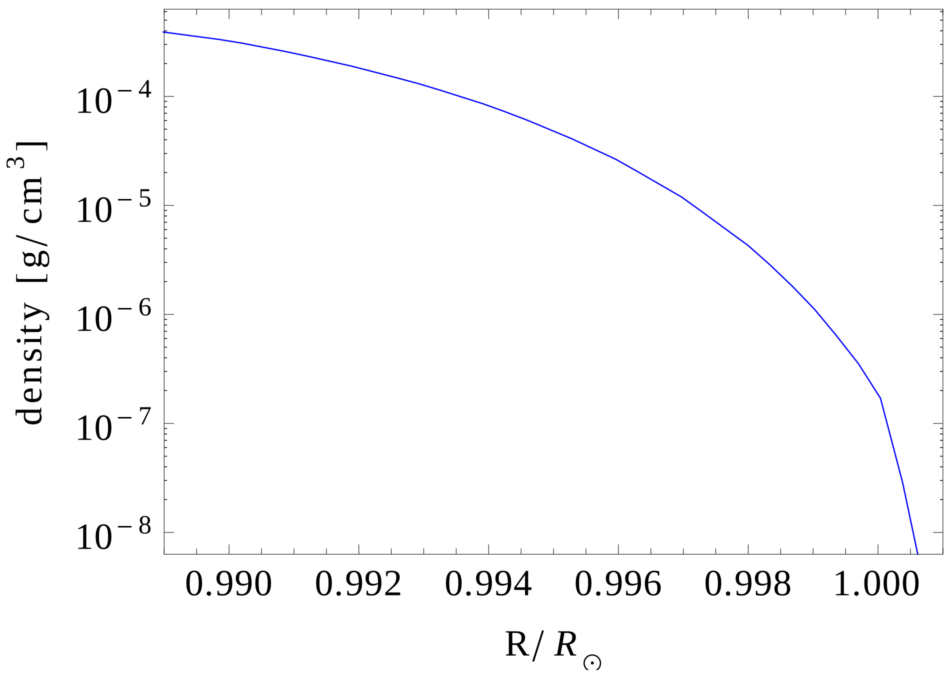
• Secondary particles of $E > E_{\rm crit} \approx 5$ TeV keep going inwards and shower.

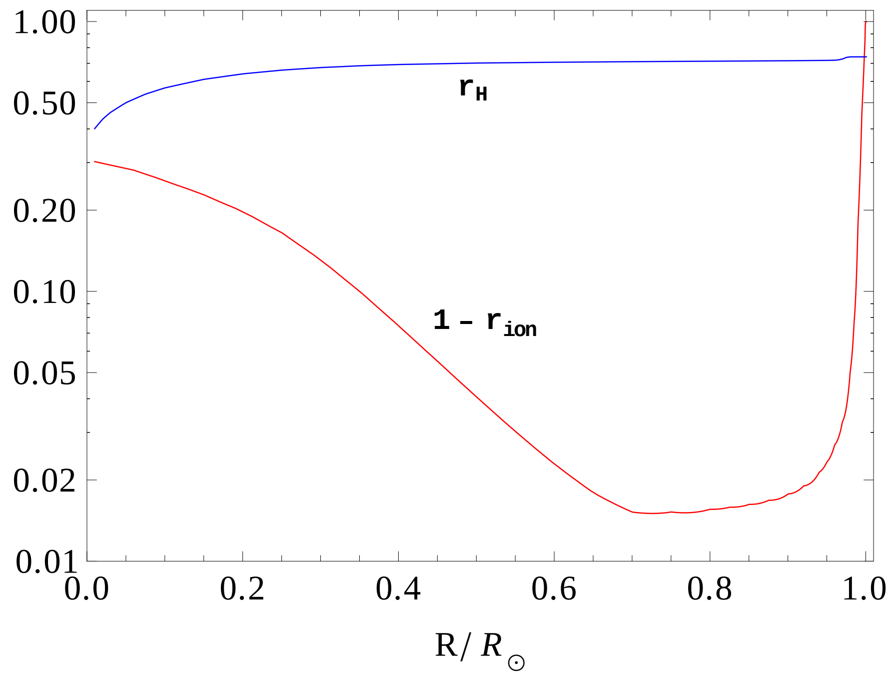


• Charged particles of $E < E_{\rm crit}$ are trapped by closed magnetic lines, shower at the solar depth where they have been created and produce γ's, ν's, n's that are emitted in a random (inwards or outwards) direction

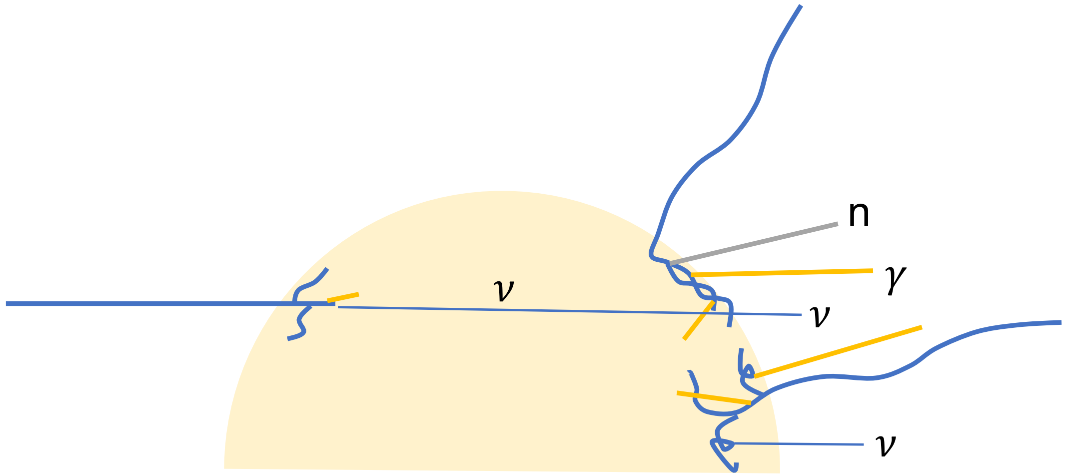
• The primary CRs enter the Sun and shower; low-energy charged particles are stalled at the depth where they are created; neutral particles are emitted inwards if the parent is very energetic and randomly if it is not; neutral particles emitted outwards have to propagate to the surface to emerge and scape the Sun

• The Sun's surface is very thin, it takes 1500 km to cross 100 g/cm^2. Secondary pions and kaons decay before they interact. TeV muons lose energy (radiative losses and ionization) at a lower rate than in the atmosphere, they also decay

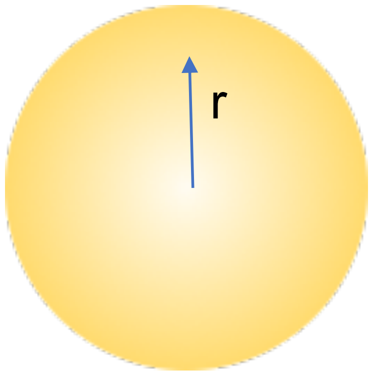




• The side of the Sun facing the Earth emits gammas, neutrons and neutrinos. The emission is near-isotropic. The hidden side of the Sun emits towards the Earth only neutrinos. Peripheric neutrinos from the hidden side are less absorbed by the Sun than the central ones.



• We assume spherical symmetry. An isotropic and homogeneous emission from the Sun's surface implies that gammas and neutrons are seen at the Earth with a distribution



$$\Phi_\gamma \approx \frac{1}{\sqrt{1 - \frac{r^2}{R_\odot^2}}}$$

• We obtain the fluxes solving transport equations (yields from EPOS-LHC)

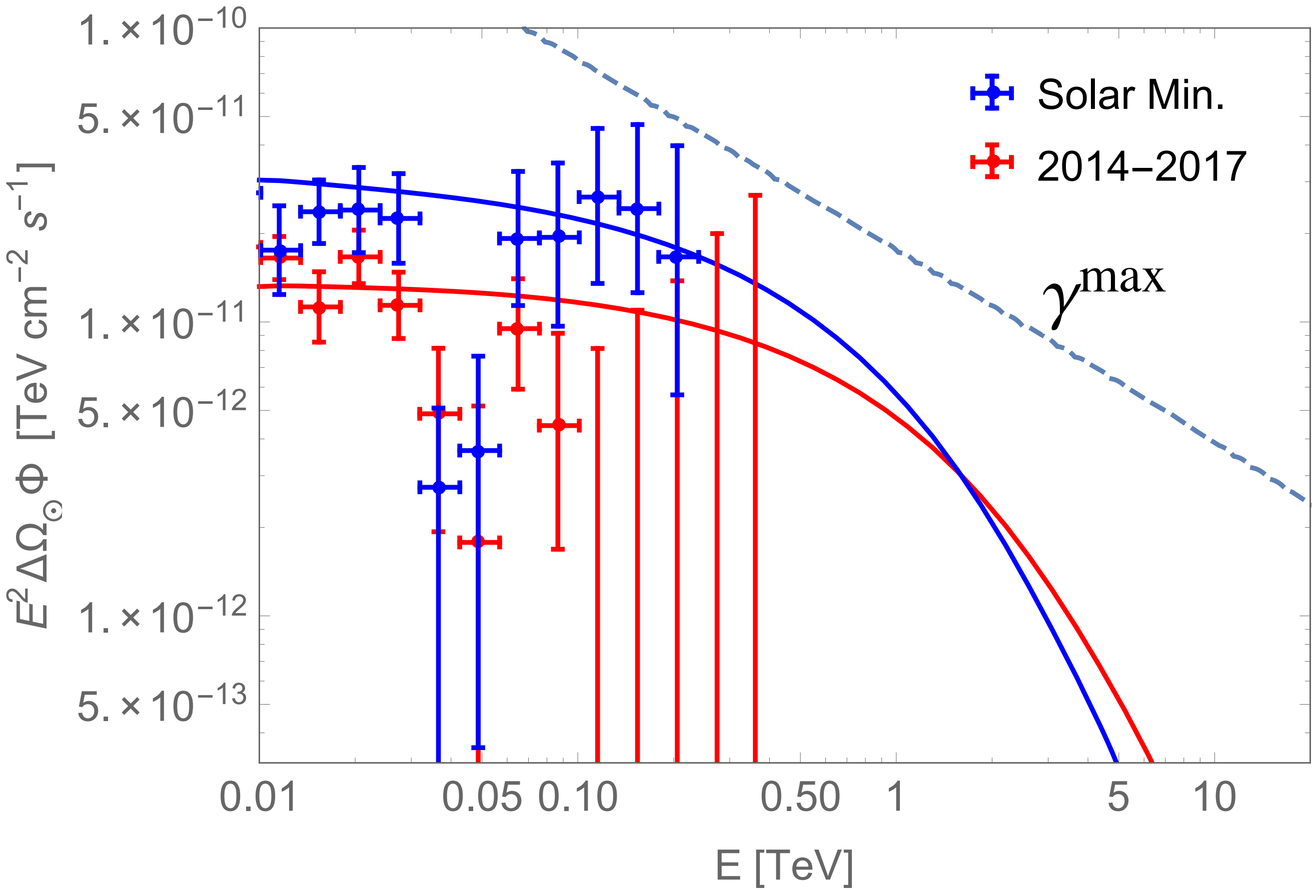
$$\frac{d\Phi_i(E,t)}{dt} = -\frac{\Phi_i(E,t)}{\lambda_i^{\text{int}}(E,t)} - \frac{\Phi_i(E,t)}{\lambda_i^{\text{dec}}(E,t)} + \sum_{j=h,e,\gamma} \int_0^1 dx\, \frac{f_{ji}(x,E/x)}{x} \frac{\Phi_j(E/x,t)}{\lambda_j^{\text{int}}(E/x,t)} +$$

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

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

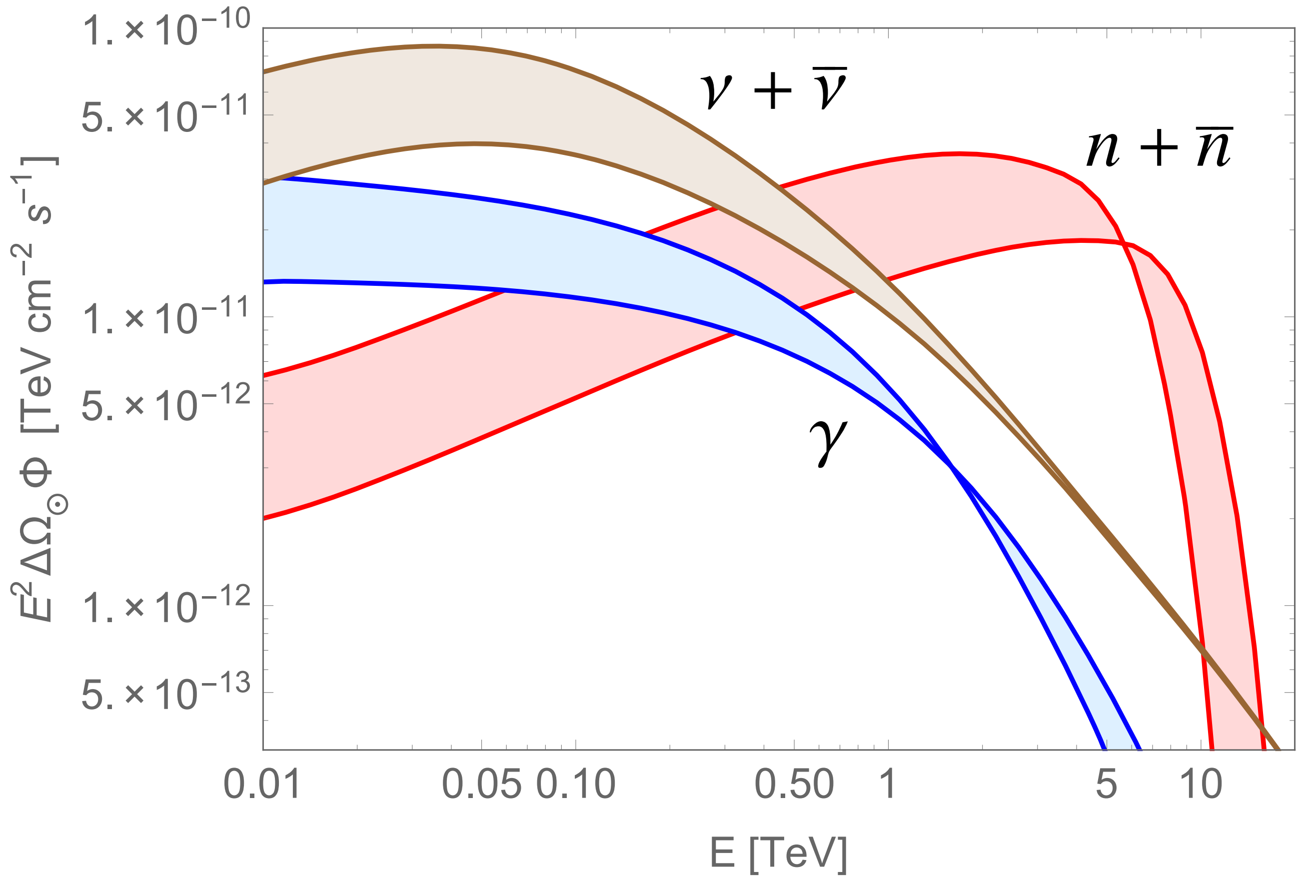
• The initial flux penetrates the Sun and showers; a fraction of the shower (charged particles) gets stalled at different depths, another fraction (neutral particles) propagates inwards (it is absorbed by the Sun) or outwards (it emerges and reaches the Earth). Neutrinos propagating inwards may cross the Sun and reach the Earth.

• Neutrinos will oscillate as they propagate between the Sun and the Earth; at $E < 10$ TeV we obtain equipartition of the 3 neutrino flavors (at $E > 1$ TeV antineutrinos are favored due to their longer absorption length)



• Consistent with Fermi-LAT gamma-ray (2014–2017) when we use HAWC cosmic-ray shadow (2013–2014)

• No dip at $E \approx 40$ GeV. During a solar minimum we expect a larger gamma flux (more CRs are absorbed by the Sun) but more suppressed at higher energies (a more inward shower). 0.5–5 TeV flux at the reach of HAWK



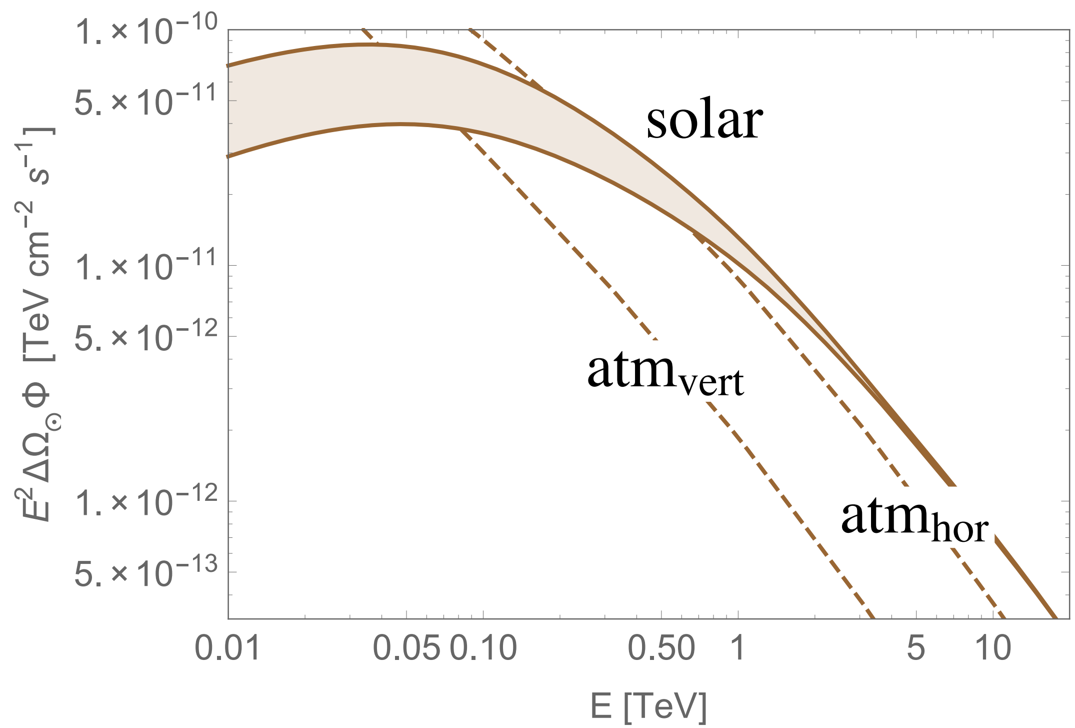
400–850 gammas   1000–2400 neutrinos   100–300 neutrons

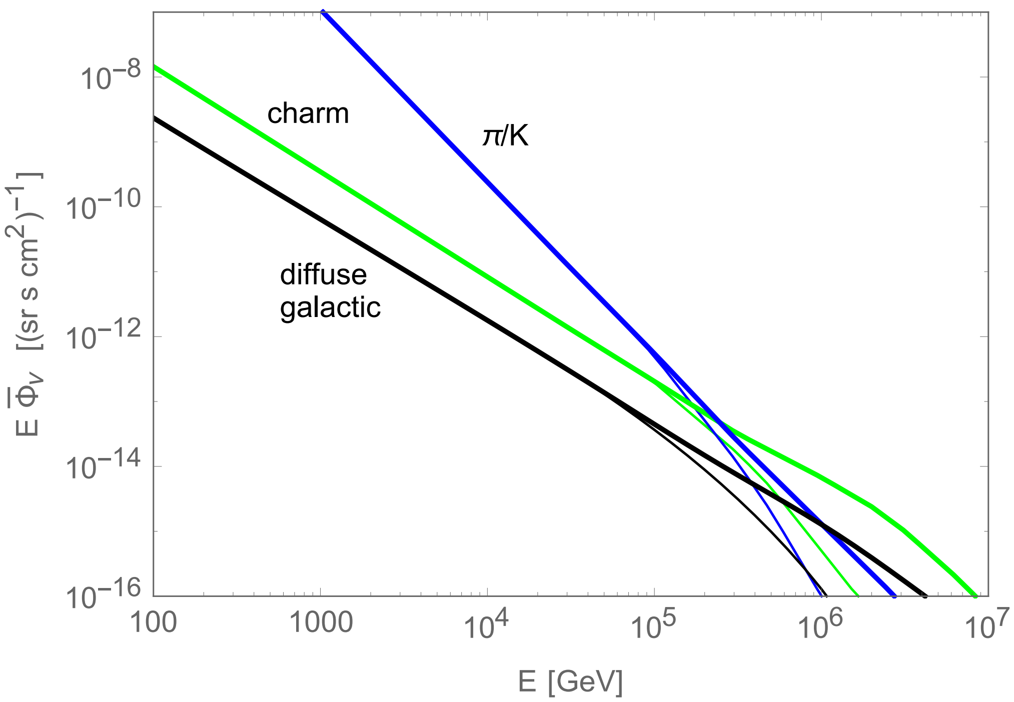
of $E \geq 10$ GeV per m^2 and year.

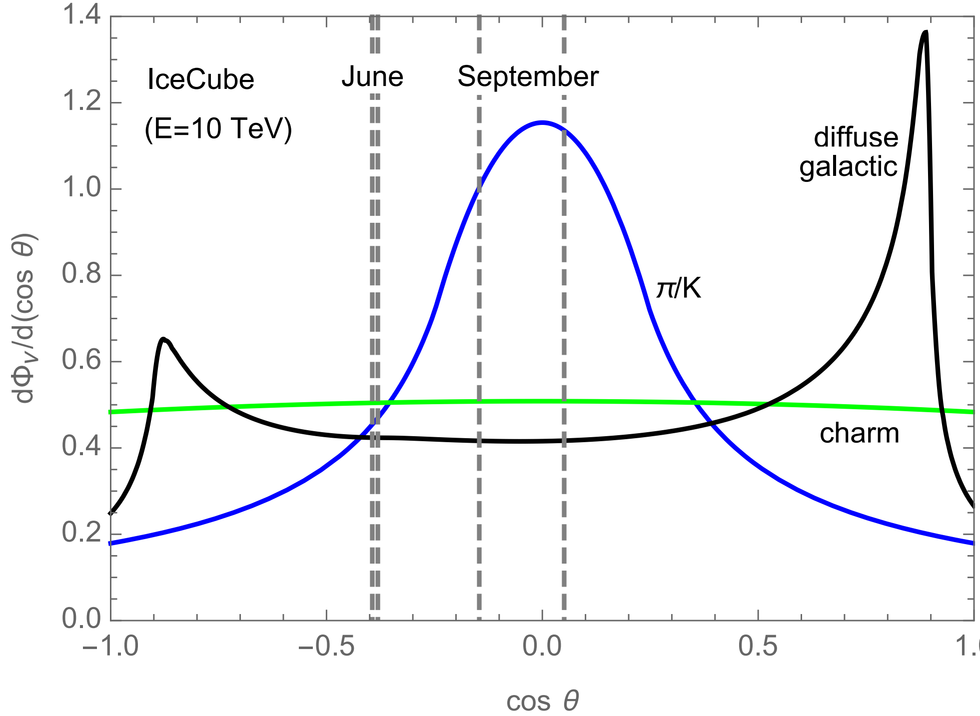
• At low energies, ν's double γ's (only outwards γ's reach the Earth). Most neutrons from He fragmentation. At $E > 10$ TeV, the Sun only emits ν's

• Gammas detected, but can neutrons and neutrinos be observed? Neutrons are unstable, they can reach from the Sun but not from outer space. At the detectors, non-ionizing but signal at the hadronic calorimeter (AMS, Fermi-LAT?). 200 neutrons per m^2 and year seem accessible at satellite experiments

• The solar ν flux implies 2–3 events ($E \geq 100$ GeV) per year at a km^3 telescope from a very small angular region (0.5° diameter). Above the atmospheric background at $E \geq 500$ GeV. Three flavors equally distributed







• In the search for the solar ν flux, 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.

• Notice that the same applies in the search for atmospheric charm through neutrinos

Summary

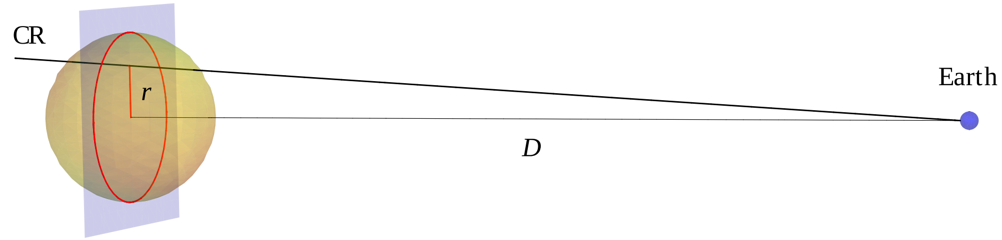
• The Sun is (probably) the brightest object in the sky also for TeV particles: neutrinos (strong atmospheric background!), gammas (difficult to look at!) and neutrons (...!).

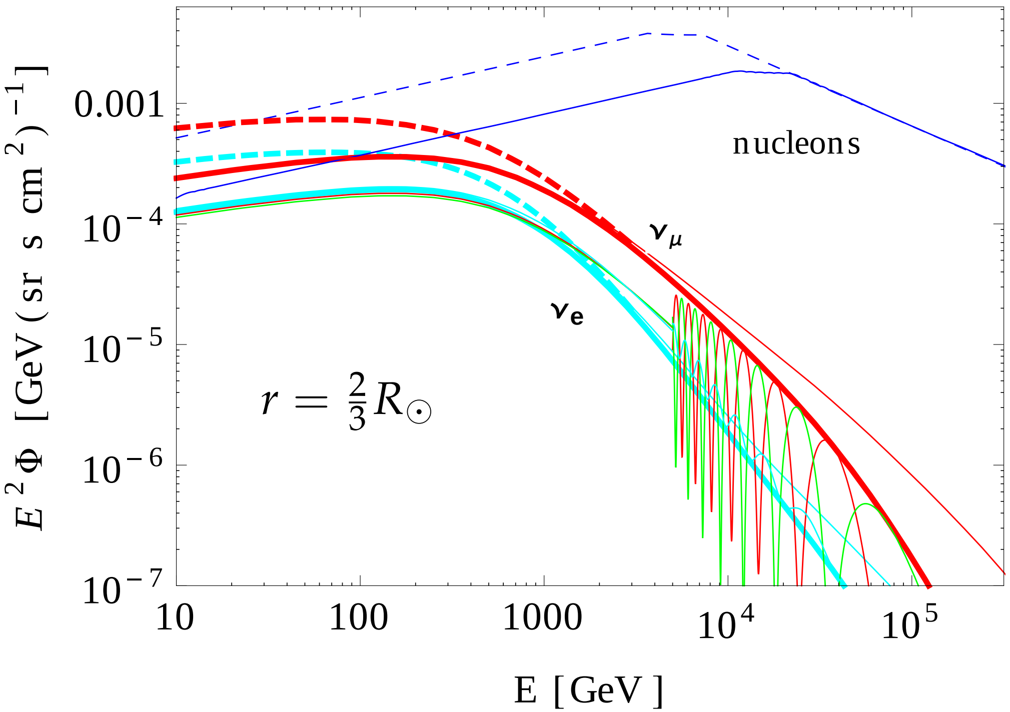
• Small angular size (100-1000 particles per m^2 and year): Ground based experiments (gammas and neutrinos) require good angular resolution, optimized analysis; Satellite based experiments (gammas and neutrons) could do it –Fermi-LAT did, AMS-like experiments may do it as well–

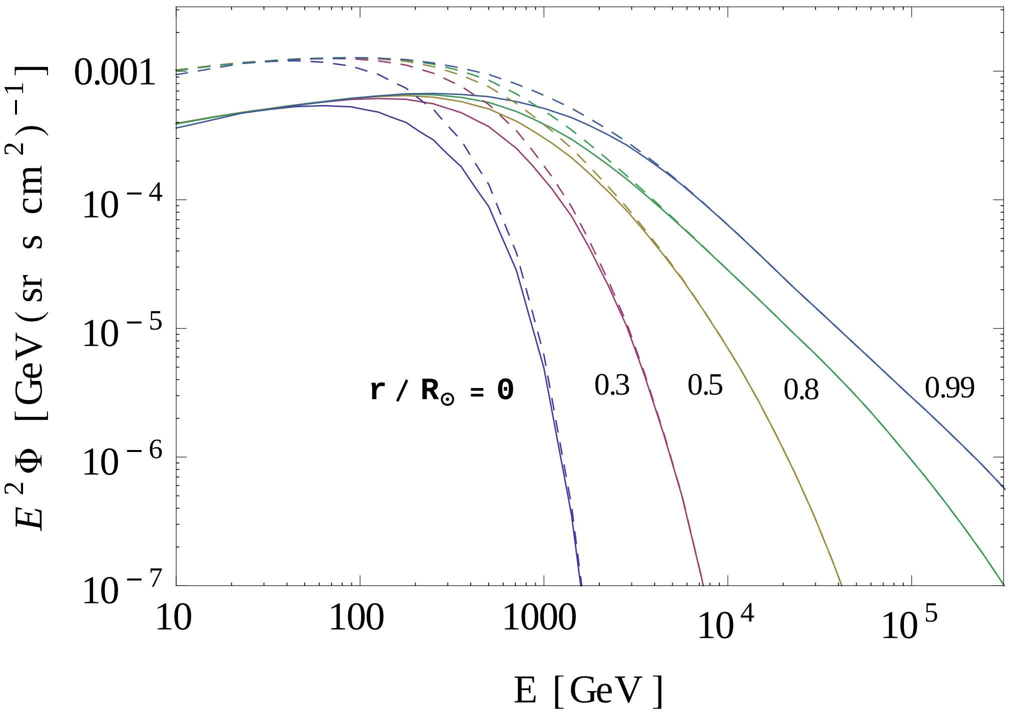
• Our main observation: This Solar flux of gammas, neutrons and neutrinos is correlated with the (time dependent) CR shadow of the Sun measured at HAWK

• The future detection of these fluxes could be used to calibrate neutrino telescopes and gamma ray observatories. This flux is itself an important background in DM searches

dark matter $\leftrightarrow$ cosmic rays $\leftrightarrow$ neutrinos $\leftrightarrow$ gammas $\leftrightarrow$ neutrons

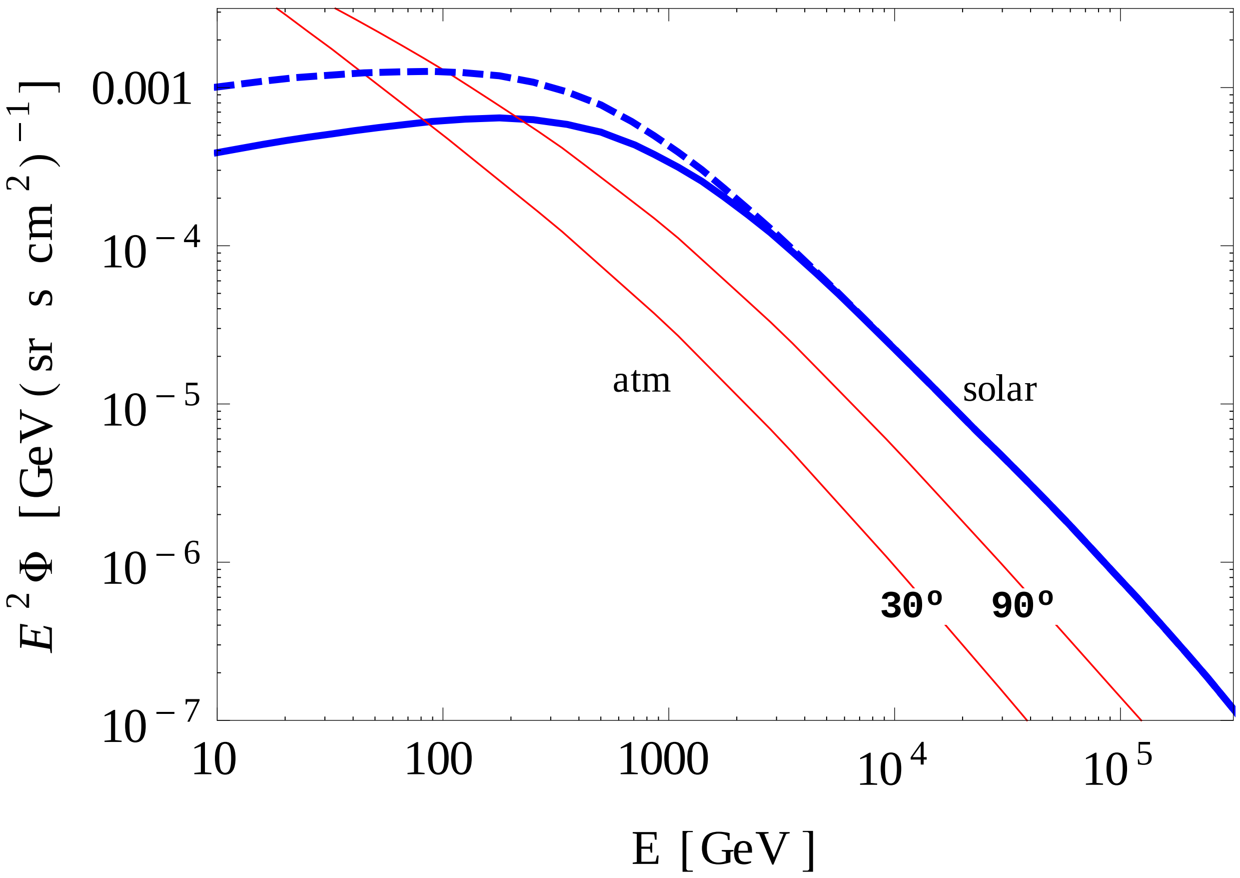






- Strong radial dependence of Φ_ν at $E_\nu > 1$ TeV: the flux is much weaker from the center ($r = 0$) than from peripheral regions

- 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

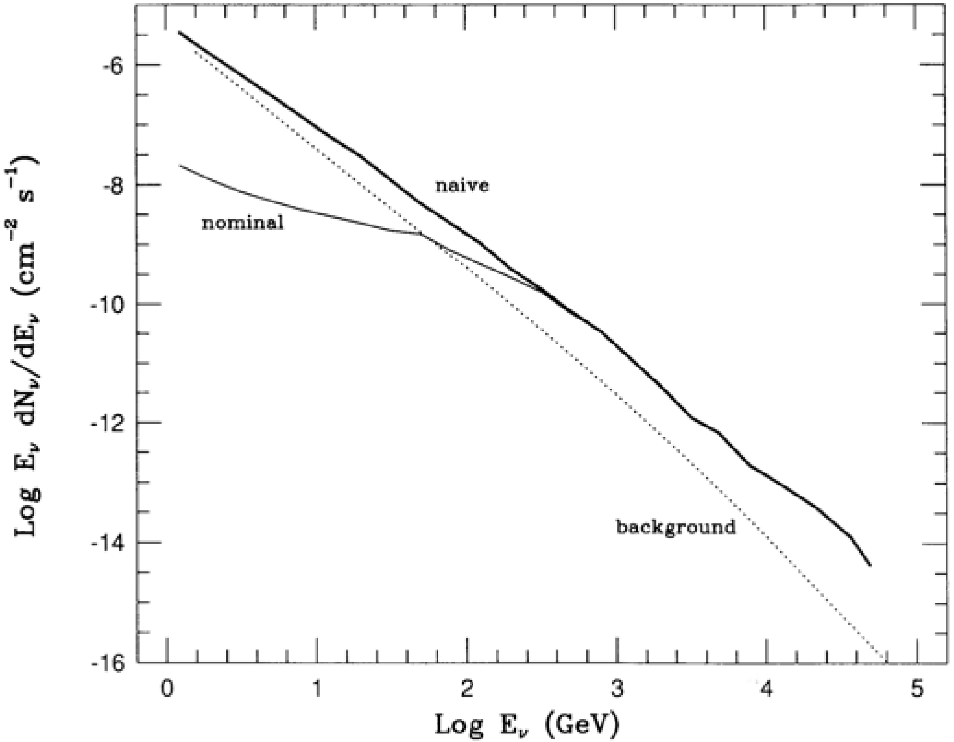
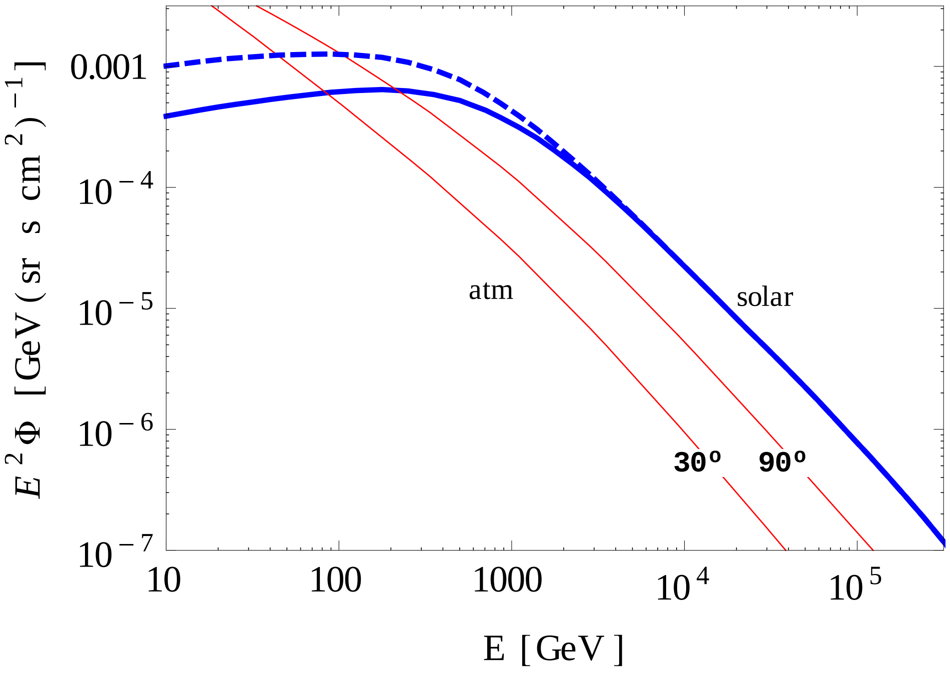


FIG. 4.—Neutrino flux at Earth for different assumptions about cosmic-ray transport. The bold curve shows an upper limit using the naive absorption rate shown as the bold curve in Fig. 3. The solid curve gives our nominal result. The background from terrestrial cosmic-ray cascades is shown for a solid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