Dark ghosts from the solar disk

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1. Absorption of cosmic rays
2. Gamma rays
3. Neutrons, CR shadow and muon shadow
4. Neutrinos

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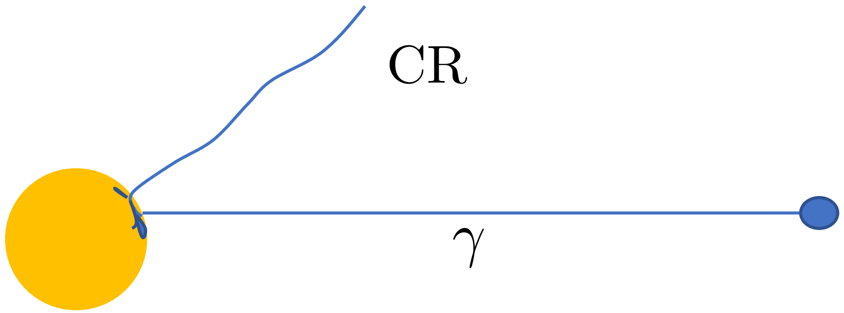
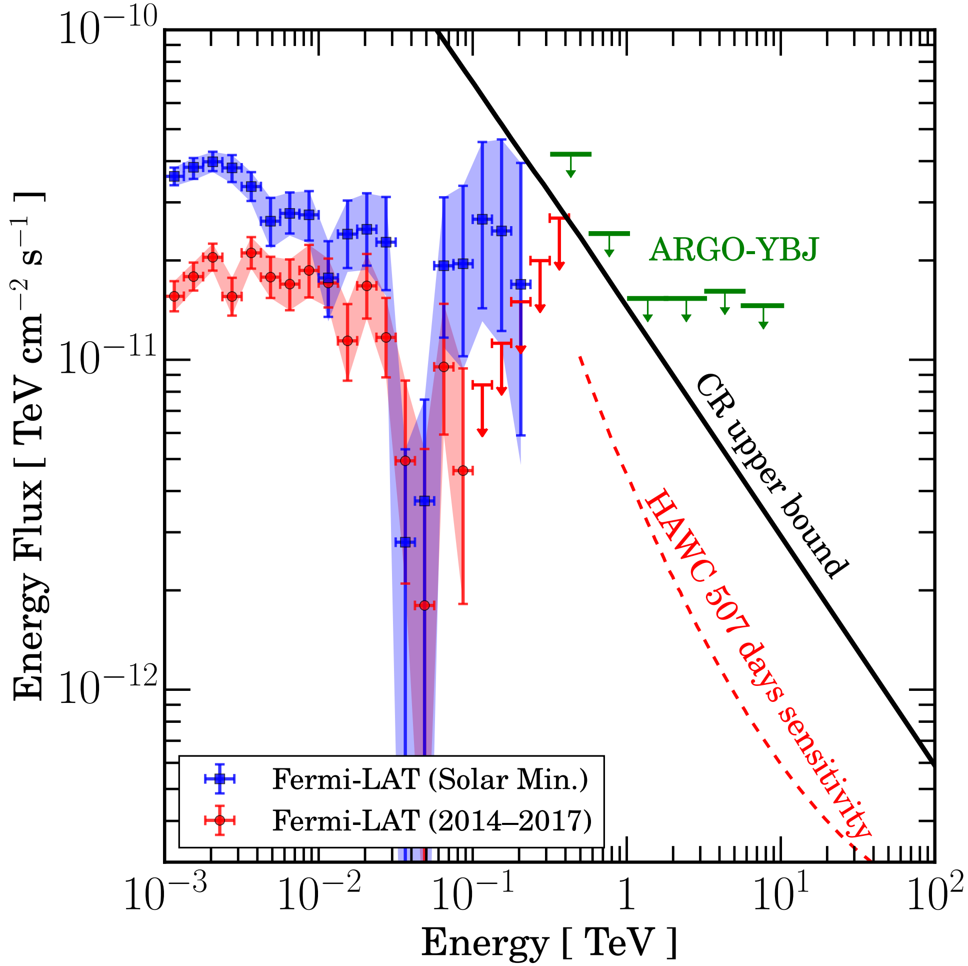
• The Sun is burning Hydrogen at 1 keV, it produces neutrinos of up to 10 MeV, solar flares accelerate nuclei and electrons up to 1 GeV. It also *processes* CRs into high-energy particles...



γ ray flux

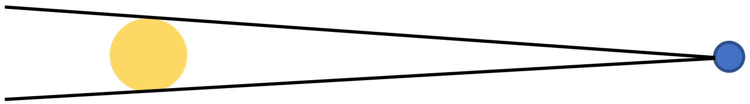
10 times larger than the diffuse background, 7 times larger than SSG91



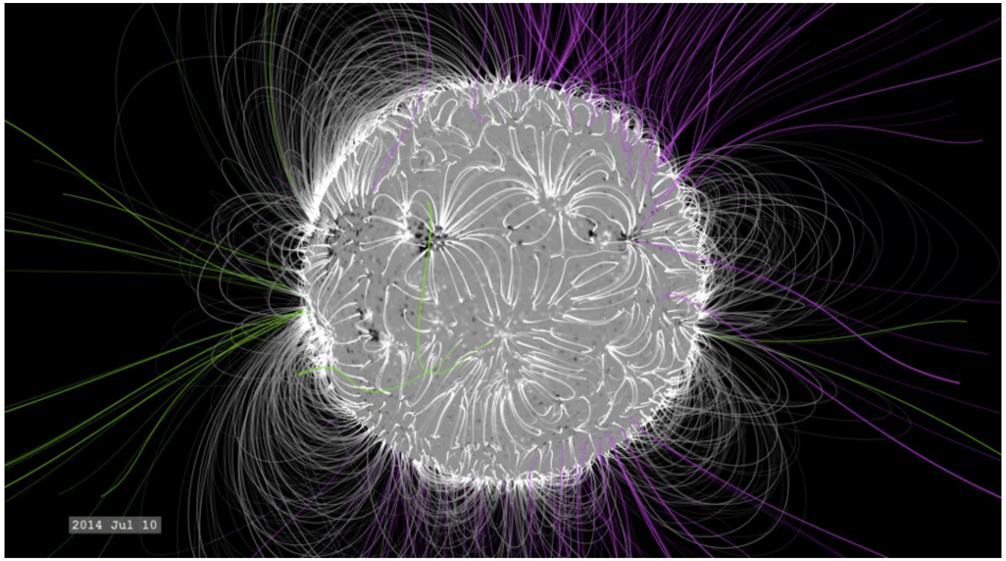
What do we expect to see when we look at the Sun?

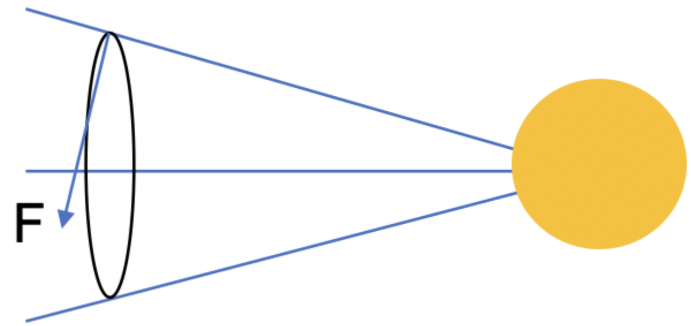
Absorption of cosmic rays

- If there were no magnetic fields, we would see a CR shadow of 0.26° angular radius.



However, there is (i) a solar magnetic field with a strong radial component (mirror effect); (ii) a solar wind that carries the solar magnetic field (convection); (iii) strong turbulence and magnetic loops that start and end on the solar surface

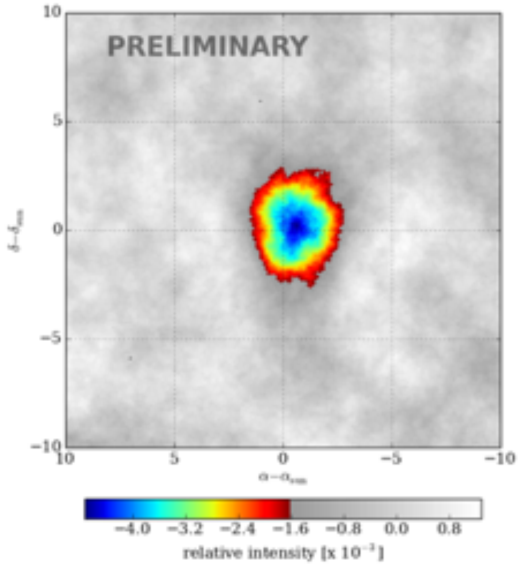


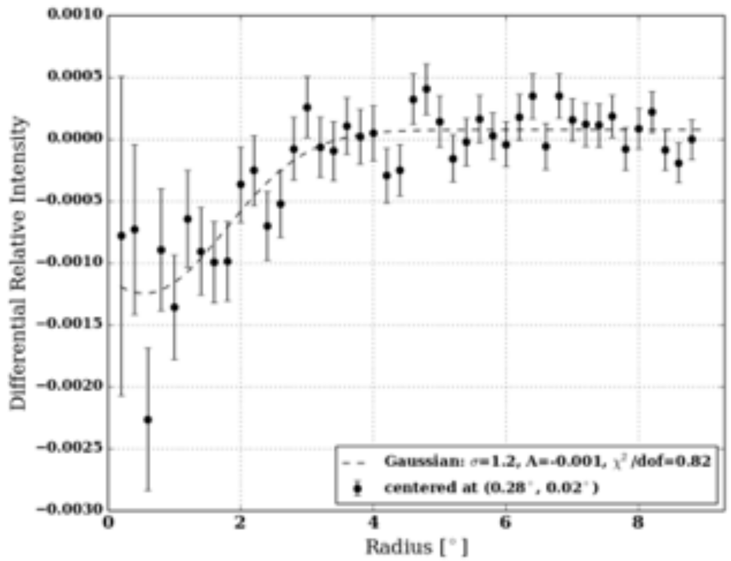


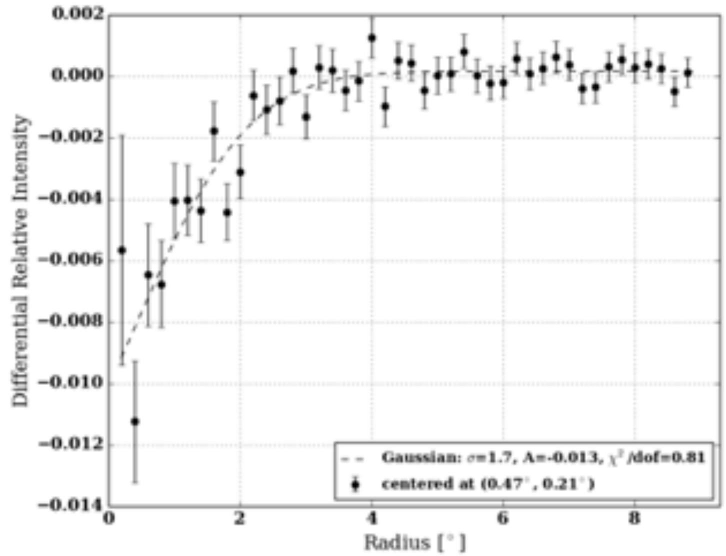
Liouville's Theorem + data on the CR shadow $\Longrightarrow$ fraction of the CR flux absorbed by the Sun

• TIBET and more recently HAWC 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 0.26° radius but a deficit that decreases radially.

2013-2014 data, solar max:

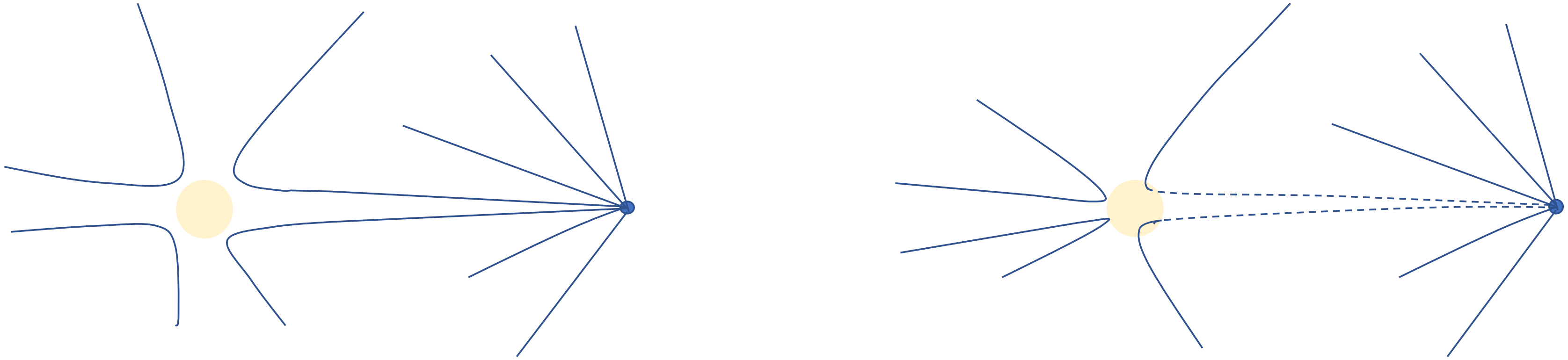






Total integrated deficit: 6% at 2 TeV 27% at 8 TeV 100% at 50 TeV

• Liouville's Theorem: an isotropic flux through a magnetic lens (including a mirror) stays isotropic. The only possible effect of the Sun on the CR flux is to interrupt (absorb) some of the trajectories that were aiming to the Earth and create a shadow.



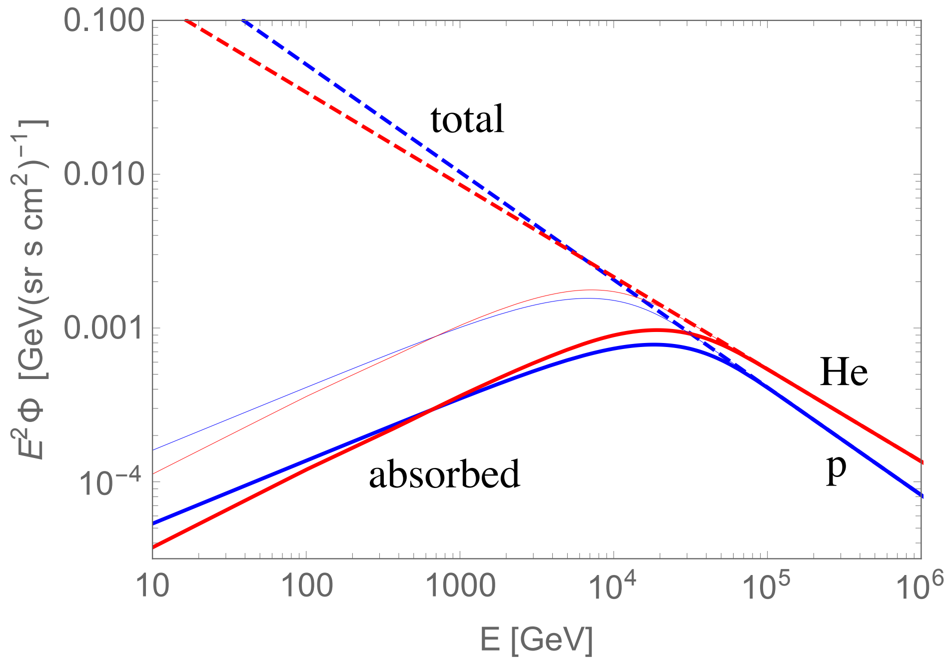
• If the (average) proton crosses a solar depth $\Delta X_H(E) \propto E^{1.12}$, then the probability to be absorbed is $1 - e^{-\Delta X_H(E)/\lambda_{\rm int}^H}$. At lower energies (rigidities) the shadow disappears

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

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

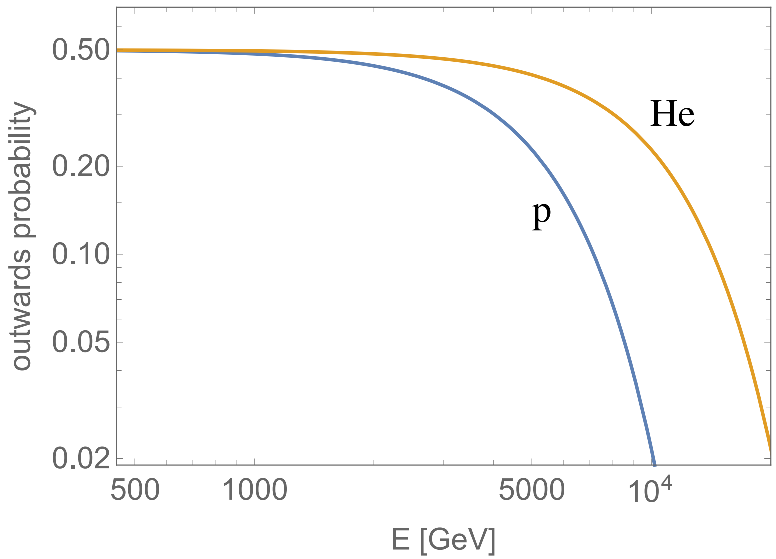
but it is absorbed more easily,

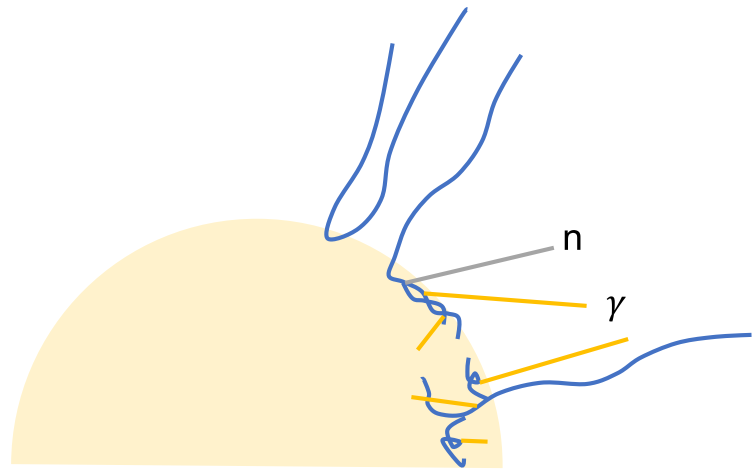
$$\lambda_{\rm int}^{\rm He} < \lambda_{\rm int}^{\rm H}$$



• Protons and He nuclei reach the Sun following an open (radial) magnetic line. Once there they are processed into secondary particles; some of them are absorbed by the Sun and others escape and reach the Earth. Two main factors: how deep in the Sun and in what direction (outwards or inwards) they are produced

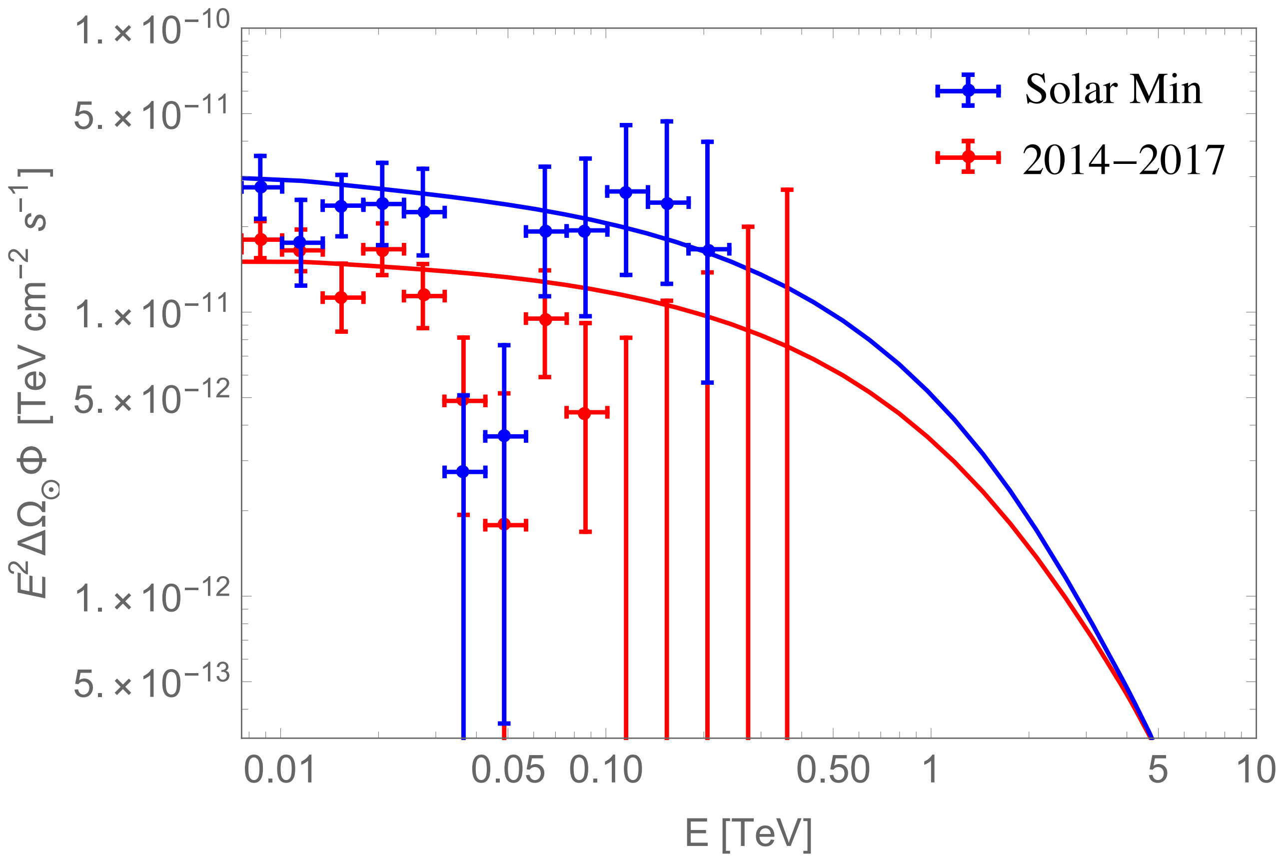
• If the parent particle is very energetic the secondary particles are emitted inwards. Secondaries of $E > E_{\rm crit} \approx 5$ TeV keep going inwards and shower. Charged particles of $E < E_{\rm crit}$ are trapped by closed magnetic lines, shower at the solar depth where they produced and give γ's, ν's, n's emitted in a random (inwards or outwards) direction.





• We solve the cascade equations in the Sun surface for hadrons, photons and leptons

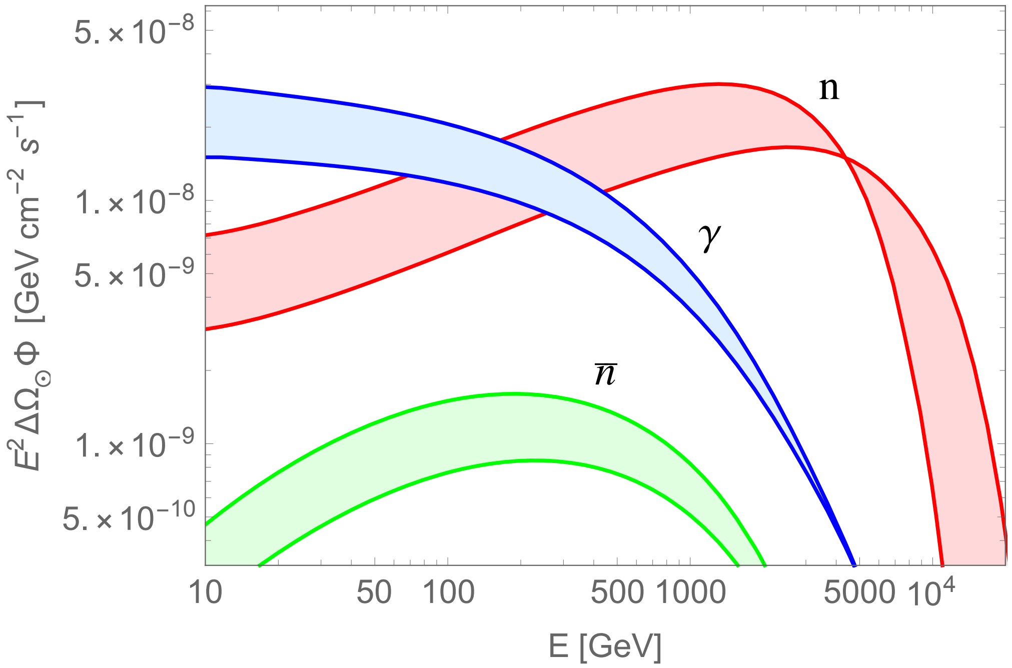
Gamma rays from the Sun

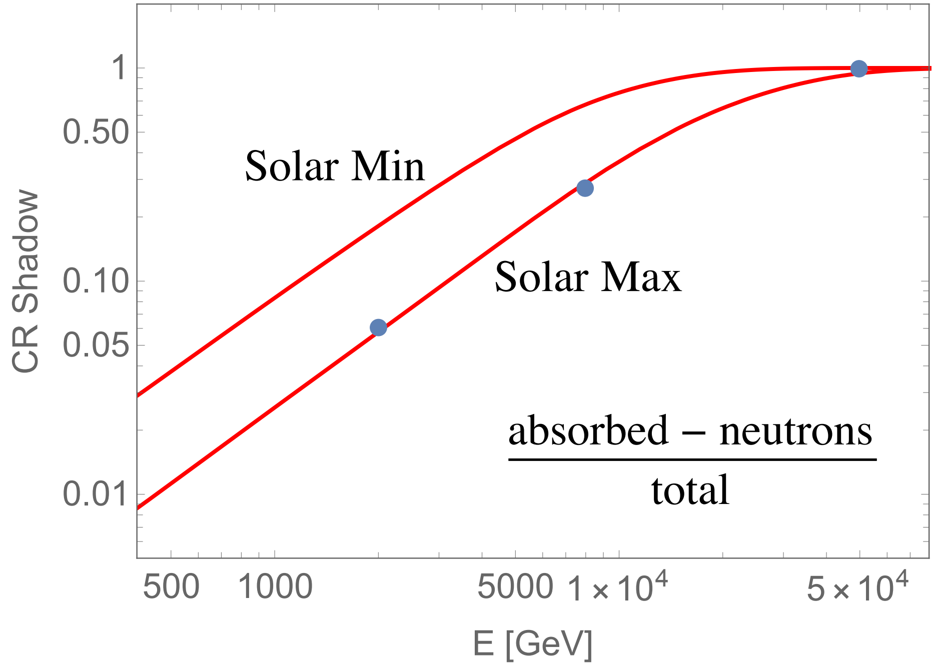


• Consistent with Fermi-LAT observations. At low energies CRs do not reach the Sun, at high energies gammas are emitted inwards. No dip at $E \approx 40$ GeV.

400–800 gammas of $E \geq 10$ GeV per m^2 and year.

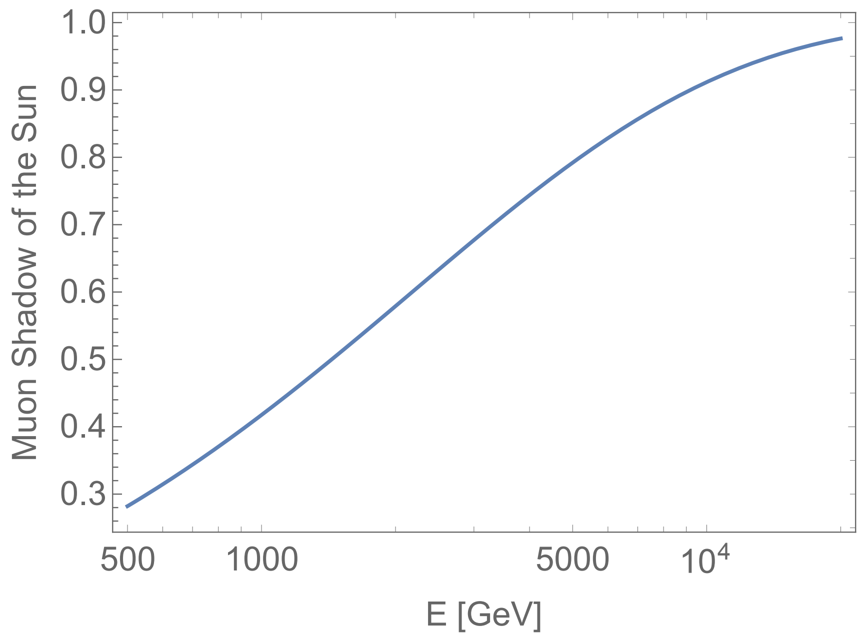
Neutrons, CR shadow and muon shadow

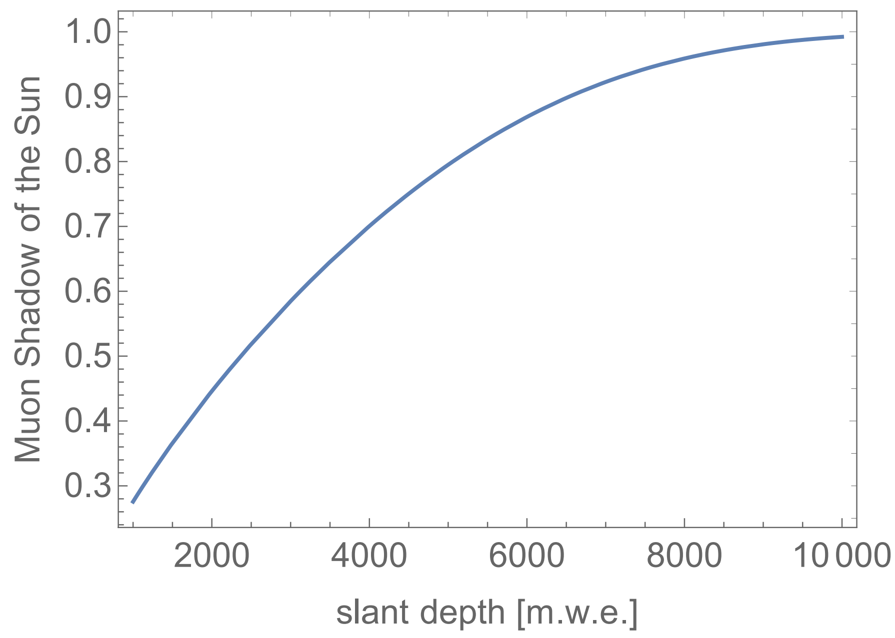




150–300 neutrons of $E \geq 10$ GeV per m^2 and year.

- Most neutrons from He fragmentation.
- At HAWC (2013–2014, near a solar max.) neutrons "reduce" the CR shadow
- At a neutrinos telescope the CR shadow induces a muon shadow of the Sun:





Shadow at a given slant depth X: number of down-going muons of energy above the minimum one to reach that depth

$$\text{muon shadow} = 1 - \frac{N_\mu^{\odot}}{N_\mu^{\text{atm}}}$$

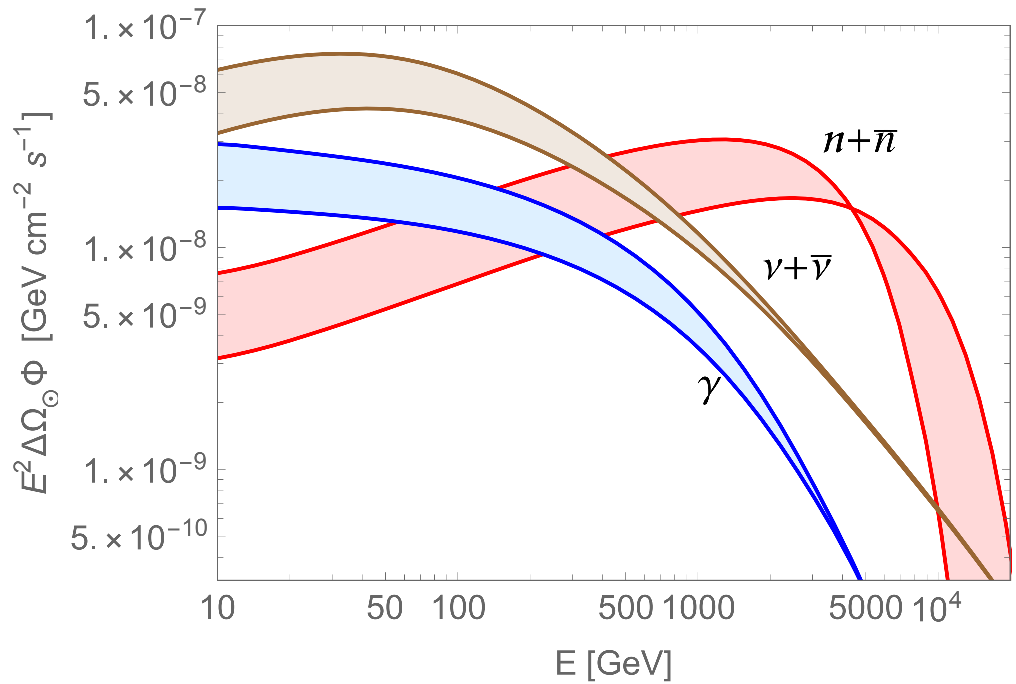
Neutrinos

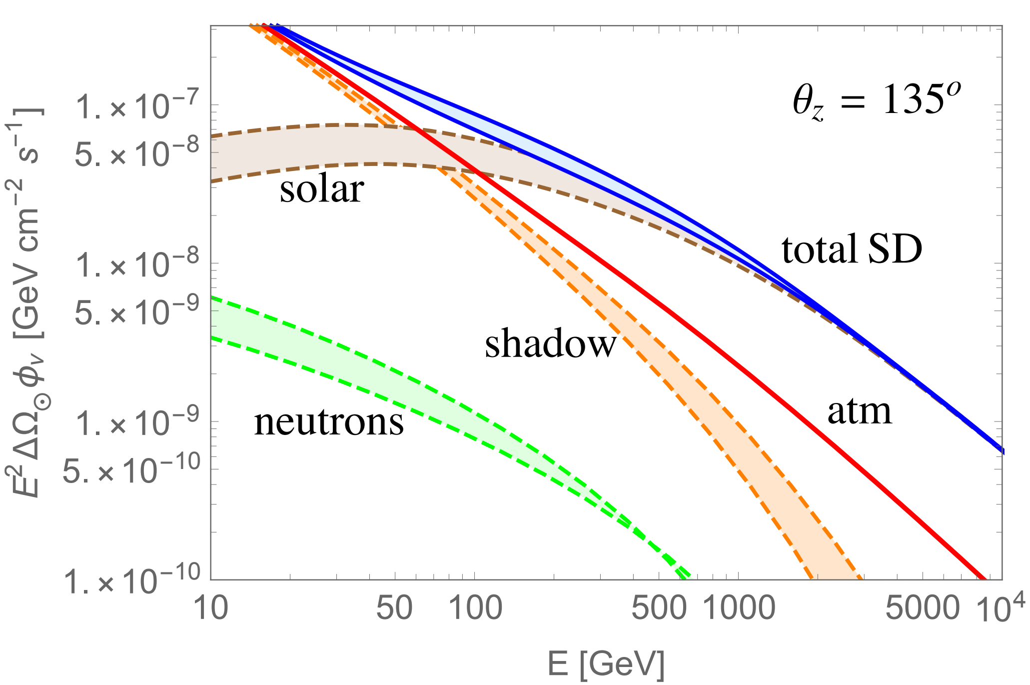
• When we look at the solar disk with a neutrino telescopes we observe 3 components:

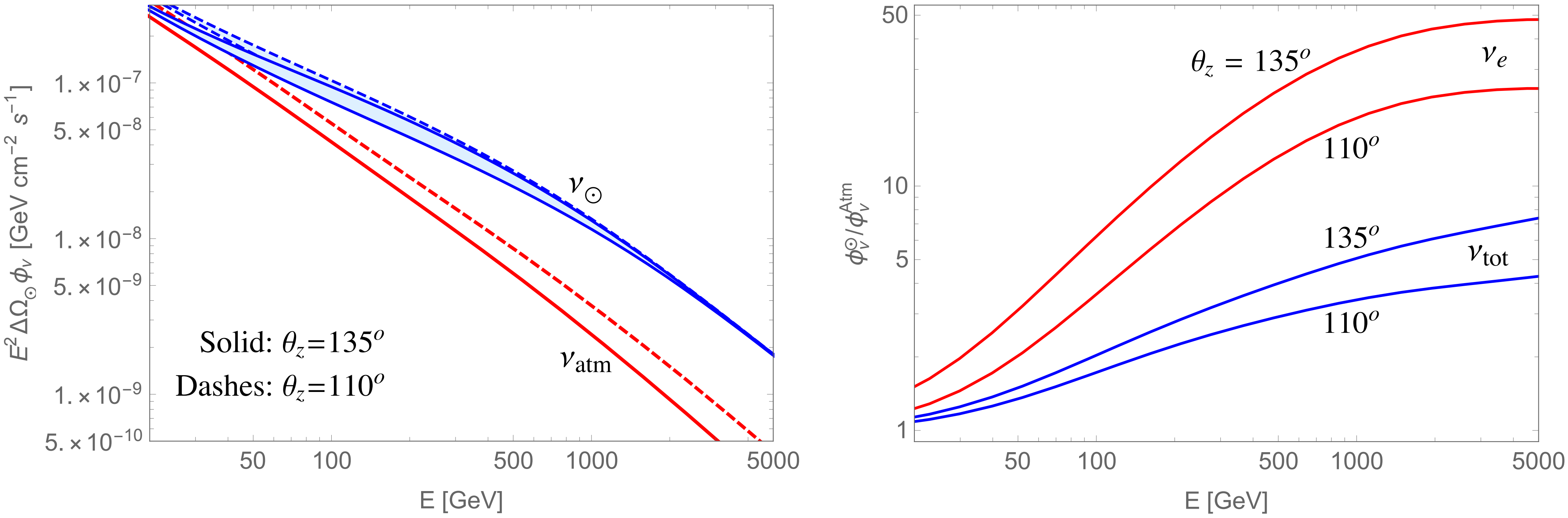
(i) A fraction of the atmospheric ν flux: the CR shadow of the Sun is not complete at $E < 50$ TeV.

(ii) The solar ν flux from CRs showering in (both sides of) the Sun's surface

(iii) Atmospheric ν's from high-energy solar neutrons







• The change in the total ν flux from the solar disk observed at a telescope during the solar cycle is below 25% (versus the 70% increase in the solar ν flux during a solar min; notice that the CR shadow of the Sun is stronger during the min)

• The solar neutrino flux includes the 3 flavors in the same proportion. From vertical directions, at 1 TeV the flux of ν_e from the solar disk is 40 times larger than the atm one. CC ν_τ interactions give a cascade event (with no muon) 82% of the times

Summary

• If we look at the Sun at high energies we see (i) a cosmic ray shadow (HAWC), (ii) a muon shadow (IceCube, KM3NeT), (iii) a gamma ray flux (Fermi-LAT), (iv) a neutron flux (there are no hadronic calorimeters in space...) and (v) a solar neutrino flux

• These fluxes are correlated. At a ν telescope they "mix": the partial CR shadow and the solar neutron flux produce neutrinos in the atmosphere that add to the ones coming from the Sun

• The Sun has a 0.26° angular radius. A solar disk 5 times brighter (for ν_μ) than the atmospheric background becomes just a 30% excess diluted in a 1° radius; a disk 50 times brighter (for ν_e) becomes a 14% excess diluted in a disk of 5° radius

• An precise estimate of the solar flux at a ν telescope requires the effective area for ν_i $i = e, \mu, \tau$ to give track and shower events, $A_{\text{eff}}^{i-\text{tr}}(E_\nu, \theta_z)$ and $A_{\text{eff}}^{i-\text{sh}}(E_\nu, \theta_z)$

cosmic rays $\leftrightarrow$ neutrinos $\leftrightarrow$ muons $\leftrightarrow$ gammas $\leftrightarrow$ neutrons