Indirect search of Dark Matter signatures in the gamma-ray flux towards the Sun with the Fermi LAT

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9th International Fermi Symposium
Johannesburg, 12th April 2021

Session: Indirect Dark Matter Searches

The Sun as a «target» for DM searches with γ rays

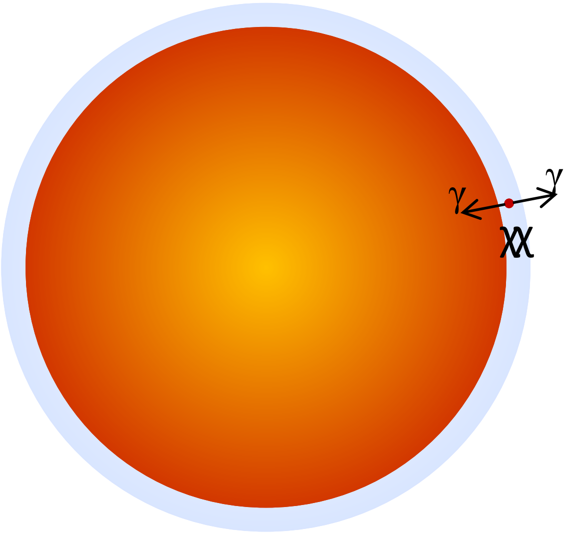
- DM particles from the galactic halo can be gravitationally trapped by the Sun through scattering interactions with the nuclei in the solar environment
  - DM particles can be captured by the Sun in external orbits (thus forming a halo around the Sun) and then annihilate outside the Sun producing gamma rays, electrons, or other SM particles:

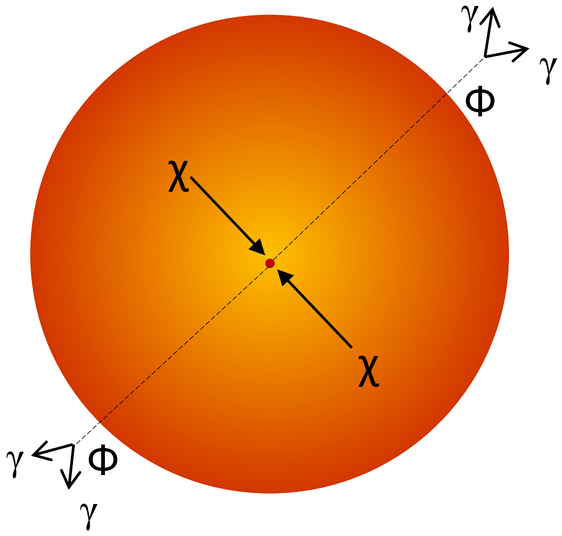
$$\chi\chi \rightarrow \gamma\gamma, \ldots$$

  - DM particles can continue to lose energy through subsequent scatterings, reaching the thermal equilibrium at the Sun core
    - The over density of DM in the core can result in annihilations into SM particles
    - SM particles produced in the Sun (except low-energy neutrinos) are absorbed in the Sun interior
    - DM particles can annihilate into pairs of long-lived mediators that can escape and decay outside the Sun into gamma rays, electrons, or other SM particles:

$$\chi\chi \rightarrow \phi\phi \qquad \phi \rightarrow \gamma\gamma \ldots$$

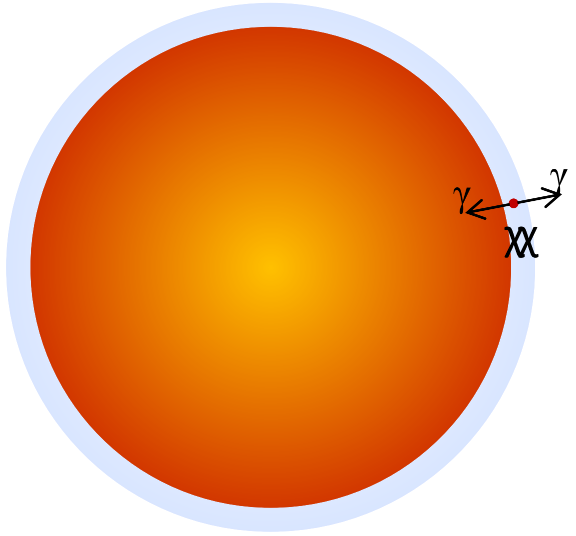
$$\rightarrow \ldots \rightarrow \gamma\gamma, \ldots$$



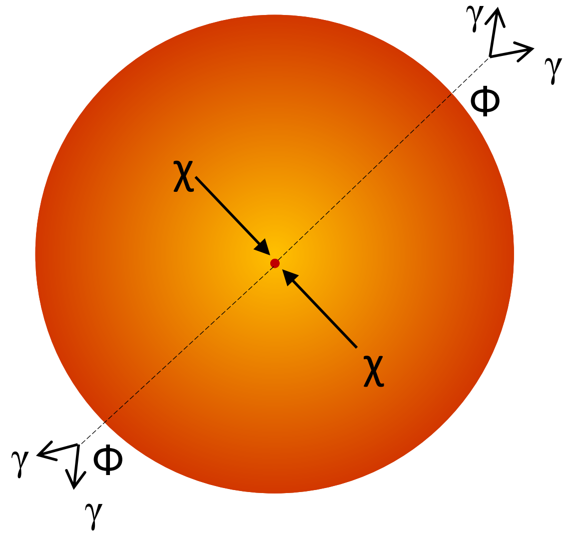


γ-ray signals from DM annihilation

- Both scenarios predict an enhancement of the DM photon flux close to Sun



- DM signals would appear as an excess on the top of the standard emission:
  - WIMPs annihilating directly into γ pairs ($\chi\chi \rightarrow \gamma\gamma$) → local ***line-like*** feature
    - The energy of the line corresponds to m_χ
  - WIMPs annihilating into light mediators ($\chi\chi \rightarrow \phi\phi$):
    - Mediators decaying directly into gamma-ray pairs ($\phi \rightarrow \gamma\gamma$) → ***box-shaped feature***
      - The center and the width of the box depend on m_ϕ and m_χ
      - If $m_\phi \ll m_\chi$ (i.e. light mediator) the box extends up to m_χ



Solar DM capture

- Balance equation for solar DM:

$$\frac{dN_\chi}{dt} = \Gamma_{cap} - C_{ann} N_\chi^2$$

  - Γ_{cap} is the capture rate
  - C_{ann} is the annihilation factor, which depends on the DM annihilation cross section

- Equilibrium assumption:

$$\frac{dN_\chi}{dt} = 0 \Rightarrow \Gamma_{ann} = \frac{1}{2} C_{ann} N_\chi^2 = \frac{1}{2}\Gamma_{cap}$$

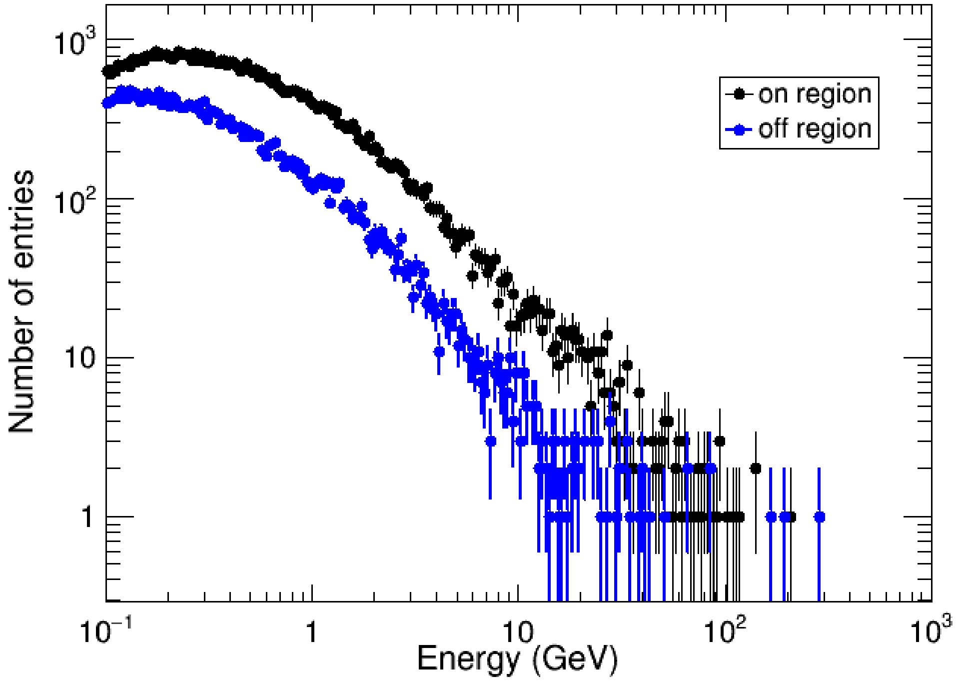
- Expected γ ray flux in the mediator scenario:

$$\Phi_{DM}(E;\ m_\chi, \sigma_{DM-N}, L, \dots) = \Gamma_{cap} \frac{1}{4\pi D^2}\left(e^{-\frac{R_\odot}{L}} - e^{-\frac{D}{L}}\right) N_\gamma(E)$$

  - L is the mediator decay length
  - N_γ (E) is the DM γ-ray yield:
    - In case of light mediators and direct gamma-ray pair production $N_\gamma(E) = 2\frac{H(m_\chi - E)}{m_\chi}$

Data Selection

- Dataset: 10-years of Fermi-LAT observation
  - Energy range 100 MeV – 150 GeV
- ON/OFF technique analysis:
  - The Sun is a moving source
    - ON Region : RoI of 2° angular radius centered on the Sun current position
    - OFF Region: RoI of 2° angular radius centered on the 6 months time-offset position
    - The OFF region follows the same path in the sky of the Sun
      - *It is used as control region to constrain the background*
- Good Time Intervals:
  - ϑ + ROI < 65° (maximum allowed off-axis angle)
  - Zenith + ROI < 80°
  - Bright 3FGL-Sun (time-offset Sun) angular separation > 5°
    - Bright 3FGL sources are those with $\Phi(E>100\text{ MeV}) > 4 \times 10^{-7}\text{ cm}^{-2}\text{ s}^{-1}$
  - Sun (time-offset Sun) + ROI at least 5°away from the galactic plane
  - Angular separation between the Moon and the Sun > 2×ROI
  - Time intervals with solar flares removed



- A Poisson maximum likelihood approach is used combining the counts in the ON and OFF regions
  - Analysis performed in sliding energy windows (half-width $w_E = 0.6E_w$)

Search for line-like and box-like features

➢Flux models:

- $\Phi^{ON}(E) = \Phi_{smooth,bkg}(E) + \Phi_{feat}^{extra}(E) + \Phi_{smooth,sig}(E) + \Phi_{feat}^{ON}(E)$
- $\Phi^{OFF}(E) = \Phi_{smooth,bkg}(E) + \Phi_{feat}^{extra}(E)$

➢Flux contributions:

- $\Phi_{smooth,bkg}(E)$: power-law model
- $\Phi_{smooth,sig}(E)$: standard solar emission with power-law model (narrow energy window)
- $\Phi_{feat}^{ON}(E)$:
  - line like feature $\Phi_{feat}(E) = s\,\delta(E_w - E)$
  - box-like feature $\Phi_{feat}(E) = s\,H(E_w - E)$
- $\Phi_{feat}^{extra}(E)$: possible instrumental systematic effect constrained in the control region

➢Expected counts in a bin of observed energy E_j:

- $\mu^{ON/OFF}(E_j) = \int \mathcal{E}^{ON/OFF}(E_j|E)\,\Phi^{ON/OFF}(E)dE$

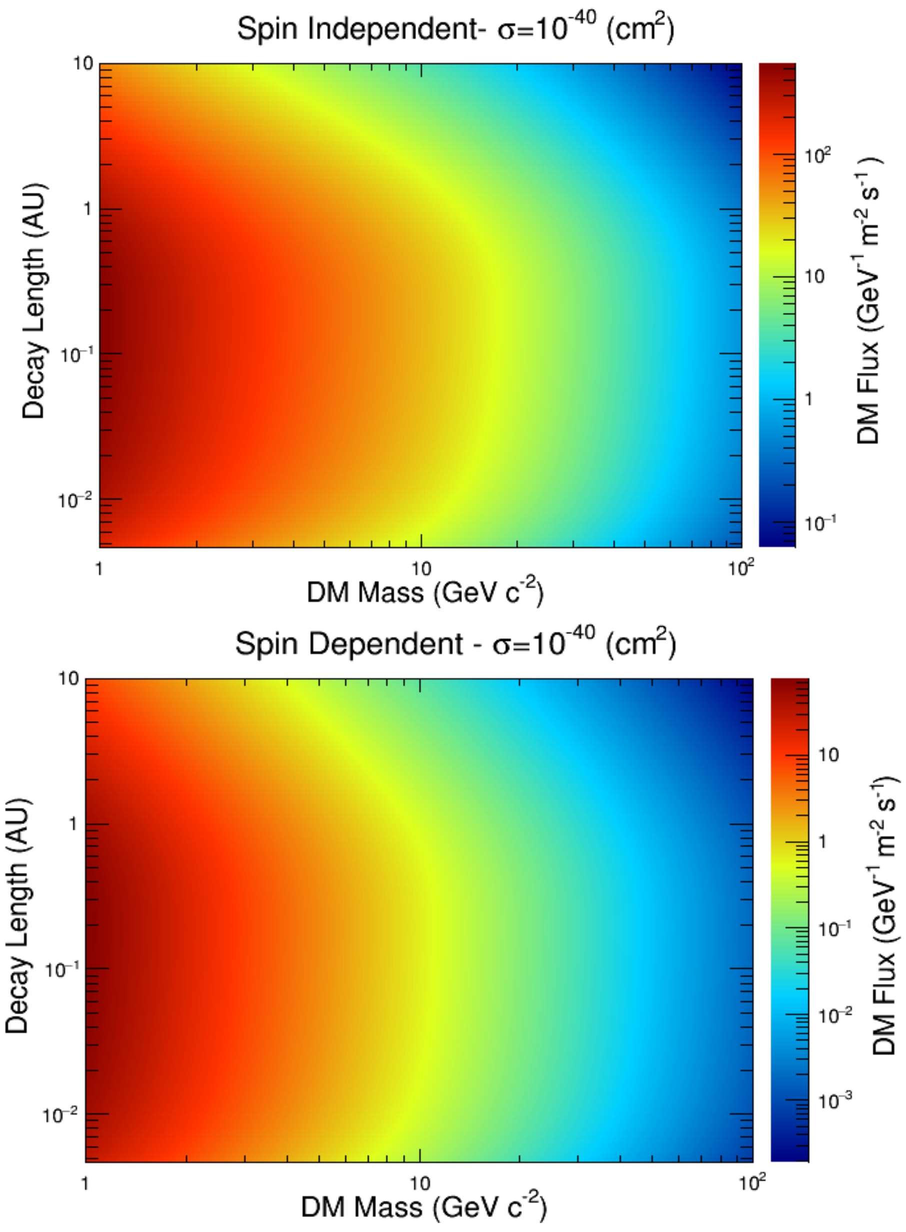
DM signal significance

- The parameters of the models are calculated with MINUIT maximizing the likelihood
  - MINOS is used to evaluate the 95%CL intervals of the parameters
- Null Hypothesis H_0: $\Phi_{feat}^{ON}(E) = 0$
- Alternative Hypothesis H_1: $\Phi_{feat}^{ON}(E) > 0$
- Local Test Statistic: $TS_{local} = -2\,(\log \mathcal{L}_{0,max} - \log \mathcal{L}_{1,max})$
- Expectation sensitivity bands without DM signal evaluated with the pseudo-experiment technique
  - global significance also evaluated
- No significant feature detected:
  - *The most significant features corresponds to a global significance ~1σ*
- Limits on the signal strength at 95%CL have been evaluated for all the DM masses explored

DM - Nucleon cross section limits (1)

- The limits on the box feature intensities can be converted into limits on the DM-nucleon cross section by means of the capture rate evaluated at a reference σ and assuming a linear scaling ($\Gamma_{cap} \propto \sigma$)
  - The capture rate has been calculated with the DARKSUSY code in case of spin-dependent and spin-independent cross sections assuming the default settings:
    - local DM density $\rho_{\odot} = 0.3$ GeV/cm^3
    - Maxwellian velocity distribution with <v> = 220 km/s and v_{rms} = 270 km/s
    - $\sigma_0 = 10^{-40}$cm^2
- Using the evaluation of Γ_{cap} it is possible to evaluate the expected DM gamma-ray flux at Earth Φ_{DM}

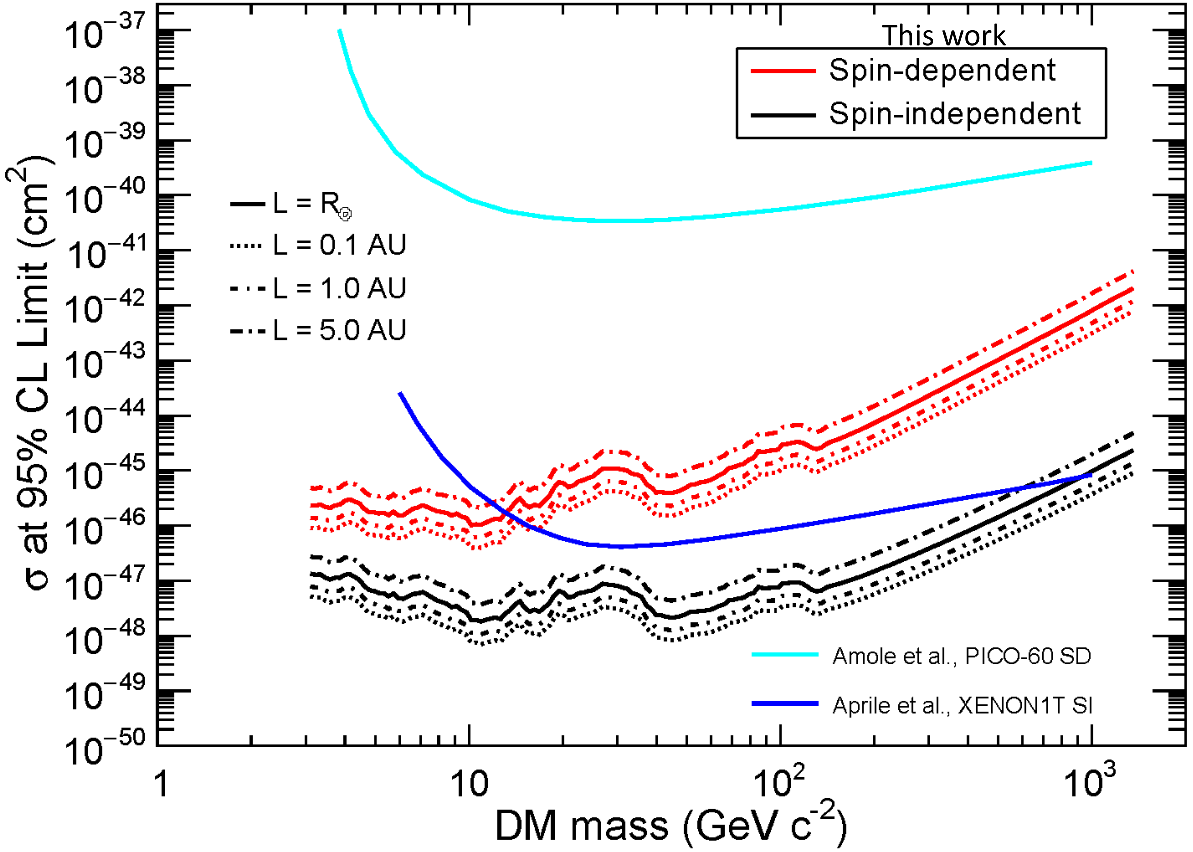
$$\sigma_{UL} = \frac{\Phi_{UL}(E = m_\chi)}{\Phi_{DM}(E = m_\chi)} \times 10^{-40} cm^2$$



DM - Nucleon cross section limits (2)

➢ Limits on the cross-sections evaluated are in the range of 10^{-46}-10^{-45} cm^2 for the spin-dependent scattering and 10^{-48}-10^{-47} cm^2 for the spin-independent scattering

- The limits depend on the decay length of the mediator



*For the line-like feature the ULs on the line intensities have not been converted in DM-nucleon cross section constraints since no models for the calculation of the capture rate are available in the energy range explored in our analysis

Non-equilibrium case

- The limits obtained on DM-nucleon cross section might be inconsistent with the equilibrium hypothesis
- The general solution of the balance equation is

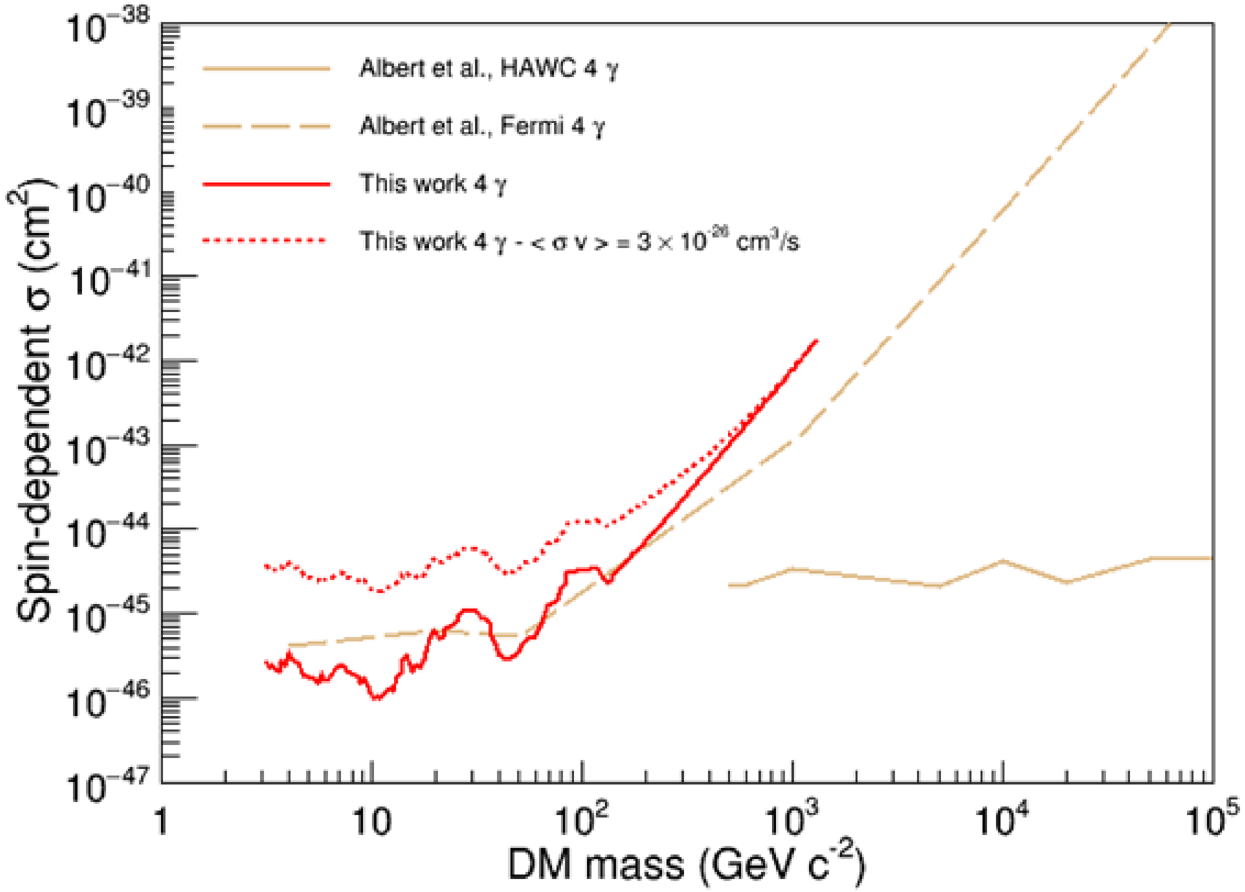
$$N_\chi(t) = \sqrt{\frac{\Gamma_{cap}}{C_{ann}}} \tanh\left(\frac{t}{\tau}\right) \quad where \;\; \tau = \left(\Gamma_{cap} C_{ann}\right)^{-1/2} \Rightarrow \Gamma_{ann} = \frac{1}{2}\Gamma_{cap}\left(\tanh\frac{t}{\tau}\right)^2$$

- The equilibrium is reached if $t_\odot \gg \tau$
  - $t_\odot$ = 4.5 Gyr Sun lifetime
  - τ depends on $\langle\sigma_{ann} v\rangle$ and σ_{DM-n} and corresponds to the time-scale of the process
- Assuming $\langle\sigma_{ann} v\rangle$ = $3 \times 10^{-26}\, cm^3/s$ and $\sigma_{DM-n} \sim \mathcal{O}(10^{-46} cm^2) \Rightarrow t_\odot \sim \tau$

The equilibrium hypothesis might be not verified.

Current Limits on the spin-dependent cross section for L = R$_\odot$

- The limits are corrected taken into account the non equilibrium scenario setting $\langle \sigma_{ann} v \rangle = 3 \times 10^{-26}\, cm^3/_s$
  - For DM masses below 100 GeV the non equilibrium constraints are a factor 10 weaker than those in the equilibrium scenario, while for DM masses in the TeV range the two scenarios yield similar limits



- The results obtained are compared with those obtained by the HAWC collaboration combining with the Fermi-LAT and HAWC data (A. Albert et al. arXiv:1808.05624)
  - They compute the spin dependent cross-section limits for dark matter masses between 4 and 10^6 GeV combining FERMI and HAWC 3-years data of observation of the Sun
  - 3 years in the high solar activity with a different approach

Conclusions

- We have searched for possible excesses in the solar gamma-ray spectrum as DM signature
  - DM particles annihilating directly into γ-ray pairs $\chi\chi \rightarrow \gamma\gamma$ (line-like feature)
  - DM particles annihilating into light intermediate states $\chi\chi \rightarrow \phi\phi$, mediator escaping from the Sun and decaying into γ-ray pairs $\phi \rightarrow \gamma\gamma$ (box-shaped feature)
- No statistically significant excess in the energy spectra found:
  - Limits on the strength of the DM signals converted into constraints on the DM-nucleon scattering cross section
- Constraints comparable with those from other experiments and other channels:
  - See also F.Loparco talk for results on Cosmic-Ray electrons and positrons (section Diffuse Gamma Rays & Cosmic Rays – Parallel4 13 April, 16.00)
- For further details see:
  - Mazziotta, M. N., Loparco F., Serini D. et al. (2020) "*Search for dark matter signatures in the gamma-ray emission towards the Sun with the Fermi Large Area Telescope*" Physical Review D, 102(2), 022003