Solar dark matter scattering constraints with the Fermi Large Area Telescope

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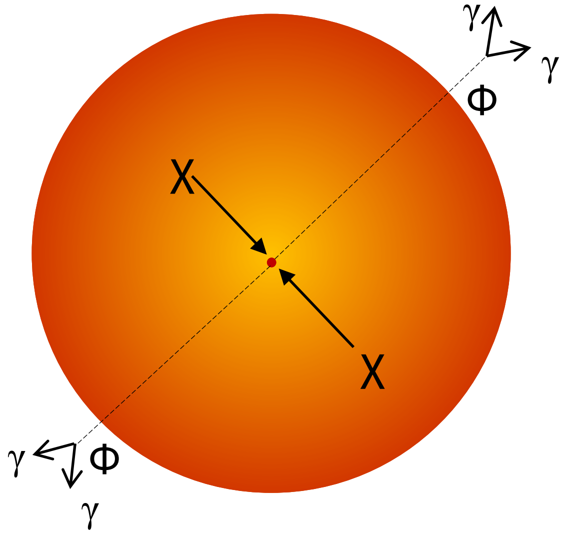
Dark matter Session

D.Serini,
F. Loparco,
M. N. Mazziotta

davide.serini@ba.infn.it

Dark matter scenarios (1/2)

- **DM particles χ interacting with the nuclei in the solar environment**
  - χ captured by the Sun through elastic scattering with the solar nuclei
- **Captured χ thermalize and sink in the core of the Sun, where they annihilate into intermediate state ϕ**
  - $\chi\chi\rightarrow\phi\phi$
  - The decay of the ϕ can yield gamma rays outside the Sun
- **In this work we have studied gamma rays produced from the ϕ decays into the $b\bar{b}$, $\tau^+\tau^-$, $\mu^+\mu^-$... channels**
  - These models predict a **broad continuous spectrum**
    - Its shape depends on the mediator decay channel and on the masses m_ϕ and m_χ



This work integrates our previous analysis (PRD102(2), 022003, 2020), where we studied the scenarios with solar gamma rays produced either in the WIMP annihilations or decays (e.g. $\chi\chi\rightarrow\gamma\gamma$) or in the mediator decays ($\chi\chi\rightarrow\phi\phi$, $\phi\rightarrow\gamma\gamma$)

Dark matter scenarios (2/2)

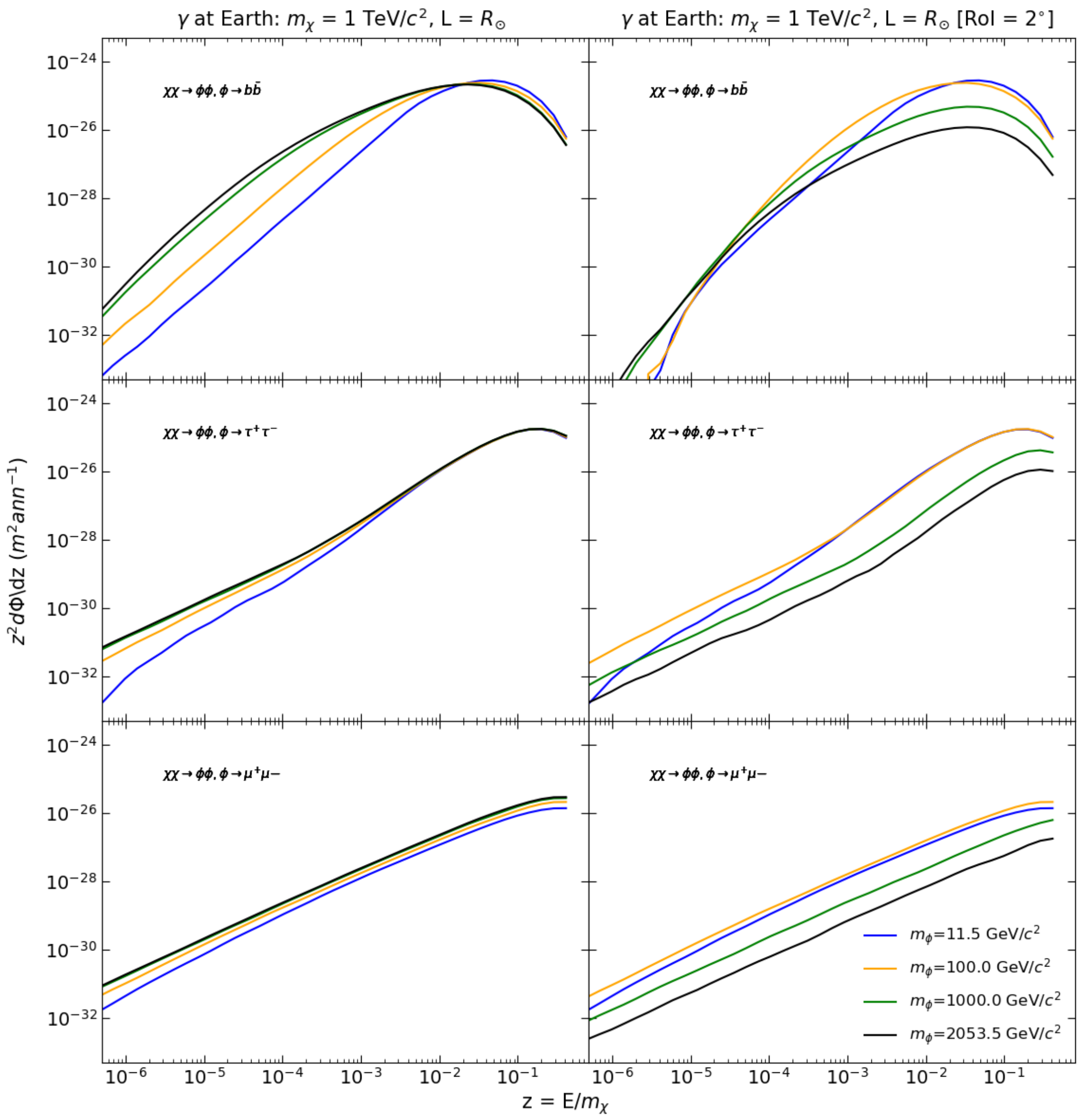
- **Expected DM γ-ray flux at Earth:**

$$\Phi_{DM}(E;\ m_\chi, m_\phi, \sigma, L, \dots) = \Gamma_{cap}\ (m_\chi, \sigma) \cdot \varphi(E, m_\chi, m_\phi, L)$$

  - L is the mediator decay length (in this work it is fixed at $L = R_\odot$)
  - Γ_{cap} is DM the capture rate in the Sun
    - It is calculated with DARKSUSY code for both spin-dependent and spin-independent cross sections assuming 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
      - σ_0= 10^{-40}cm^2
  - $\varphi(E, m_\chi, m_\phi, L) = \frac{1}{4\pi D^2} Y(E, m_\chi, m_\phi, L)$ is the γ-ray flux at Earth per DM annihilation:
    - $D = 1\ AU$ is the Sun-Earth distance
    - $Y(E, m_\chi, m_\phi, L)$ is the γ-ray yield which depends only on the kinematics of the mediator decay

DM γ -ray yield evaluation with `WIMPSim`

- We have used the **`WIMPSim`** tool **`med_dec`** to evaluate the DM γ-ray yields $Y(E, m_\chi, m_\phi, L=R_\odot)$
- For each pair of (m_χ, m_ϕ) a set of 10^5 events is simulated:
  - Different DM and mediator masses are explored in a range up to 1 TeV/c^2
  - We require that $m_\chi > m_\phi$ and $m_\phi > 2m_{X=b,\tau,\mu}$ …
    - m$_\phi$ > 11.5 GeV/c^2 for the bb decay channel
    - m$_\phi$ > 3.7 GeV/c^2 for the $\tau^+\tau^-$ decay channel
    - m$_\phi$ > 1.0 GeV/c^2 for the $\mu^+\mu^-$ decay channel
- Only gamma rays reaching the Earth without being absorbed in the Sun and with a direction lying within 2° from the Sun are selected



*plots taken from *D.Serini et al* arXiv:2208.13157 (2022)

Data analysis procedure (1/2)

We have implemented an analysis procedure to constrain the DM signal by the direct observation of the solar gamma-ray emission performed by the LAT

- **Dataset:** 13.5-years of Fermi-LAT observations

- We use an **ON/OFF technique**:
  - ON Region : RoI of 2° angular radius centered on the Sun
  - OFF Region: RoI of 2° angular radius centered on the 6 months time-offset Sun

- *We have developed two approaches for the analysis of the LAT data which do not require any template model for the standard solar emission*
  - **"Conservative" approach:**
    - the excess counts in the ON region wrt the OFF region are originated from a DM signal
      - The contribution of the steady solar emission is therefore neglected
      - The upper limits on the DM-nucleon cross section obtained with this approach will be overestimated
  - **"Optimistic" approach:**
    - the excess counts in the ON region wrt the OFF region are due to the steady solar emission
    - A possible DM signal should stay within the statistical fluctuations (saturated model)
      - The constraints on the DM-nucleon cross sections will be stronger

Data analysis procedure (2/2)

- Expected photon counts from DM annihilations in the ON region:

$$\mu_{DM}(E_o) = t_{on} \int dE\, \mathcal{R}_{on}(E_o|E)\Phi_{DM}(E, m_\chi, m_\phi, \sigma, L)$$

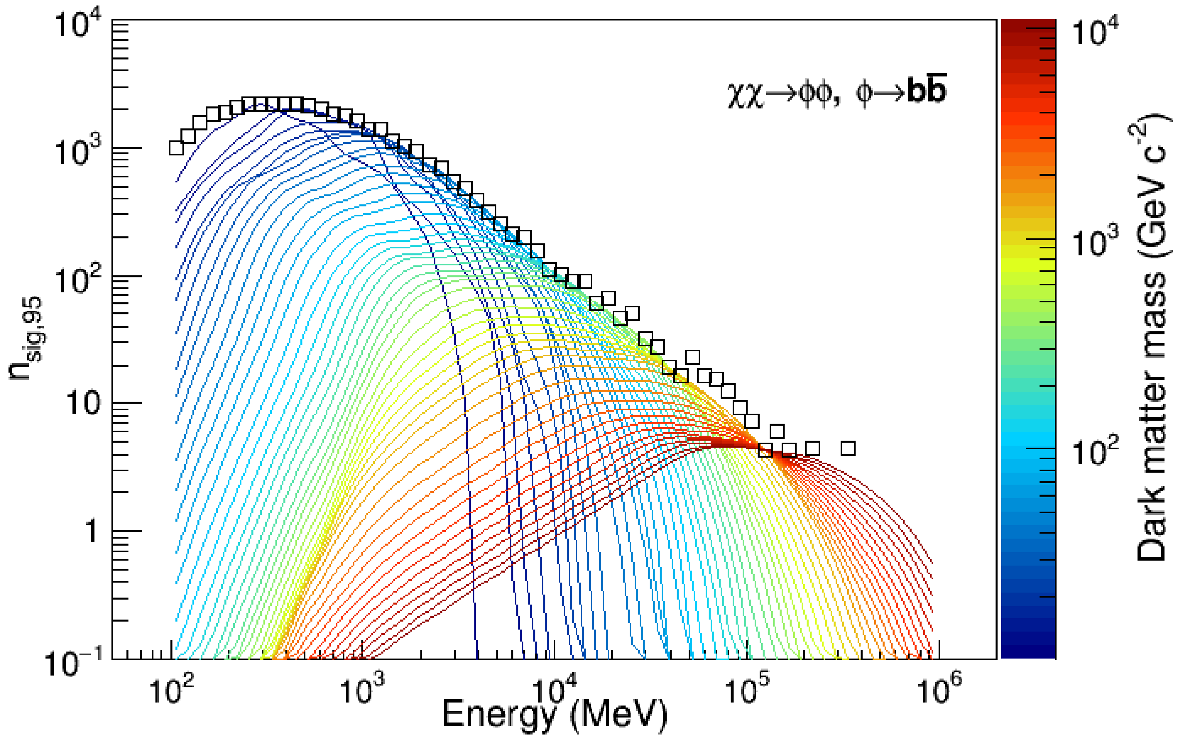
  - E_o is the observed photon energy
  - t_{on} *is the integrated live time in the ON region*
  - $\mathcal{R}_{on}(E_o|E)$ is the instrument response matrix incorporating the effective area, the angular resolution and the energy resolution of the LAT
  - $\Phi_{DM}(E, m_\chi, m_\phi, \sigma, L)$ is the expected DM γ -ray flux
- For each decay channel and pair of masses (m_χ,m_ϕ) we have modeled the expected DM γ -ray flux as:

$$\Phi_{DM}(E) = k_{DM} \cdot \Phi_{DM,0}(E, m_\chi, m_\phi, \sigma_0 = 10^{-40} cm^2, L = R_\odot)$$

  - $\Phi_{DM,0}$ is the reference flux with $\Gamma_{cap}\ (m_\chi, \sigma_0 = 10^{-40} cm^2)$
  - The normalization k_{DM} is left as a free parameter

Conservative approach

- In the **conservative approach** k_{DM} it is evaluated by imposing that the counts from DM annihilations $\mu_{DM}(E_o)$ do not exceed the upper limits at 95% confidence level (CL) on the signal counts $n_{sig,95}(E_o)$ in any observed energy bin
  - The values of $n_{sig,95}(E_o)$ have been calculated from the observed counts in the ON and OFF regions, $n_{on}(E_o)$ and $n_{off}(E_o)$, implementing a Bayesian method[1] that take the exposures of the two regions into account



[1] F. Loparco and M. Mazziotta. (2011). «***A Bayesian approach to evaluate confidence intervals in counting experiments with background***». *NIMA*, *646*, 167 (2011).

*plot taken from *D.Serini et al* arXiv:2208.13157 (2022)

Optimistic approach

- In the **optimistic approach** k_{DM} it is evaluated by implementing a hypothesis test based on the maximum likelihood formalism:
  - in the null hypothesis H_0 we assume that the observed counts $n_{on}(E_o)$ in each energy bin are originated from Poisson distributions with average values $n_{on}(E_o)$
  - in the alternative hypothesis H_1 we assume that the observed counts $n_{on}(E_o)$ are originated from Poisson distributions with average values $n_{on}(E_o) + k_{DM} \cdot \mu_{DM,0}(E_o)$
    - where $\mu_{DM,0}(E_o)$ are the expected DM counts when the cross section assumes its reference value $\sigma_0 = 10^{-40} cm^2$
  - We define the log-likelihood ratio as:

$$\lambda(k_{DM}) = \sum_{E_0} \left[-k_{DM} \cdot \mu_{DM,0}(E_o) - n_{on} \log \frac{n_{on}(E_o) + k_{DM} \cdot \mu_{DM,0}(E_o)}{n_{on}(E_o)} \right]$$

  - The best fit of k_{DM} is obtained by maximizing the log-likelihod ratio
  - The upper limit at 95%CL $k_{DM,95\%}$ is evaluated by solving the equation $\lambda = \lambda_{max} - \frac{2.71}{2}$
    - where λ_{max} is the maximum value of the log-likelihood ratio.

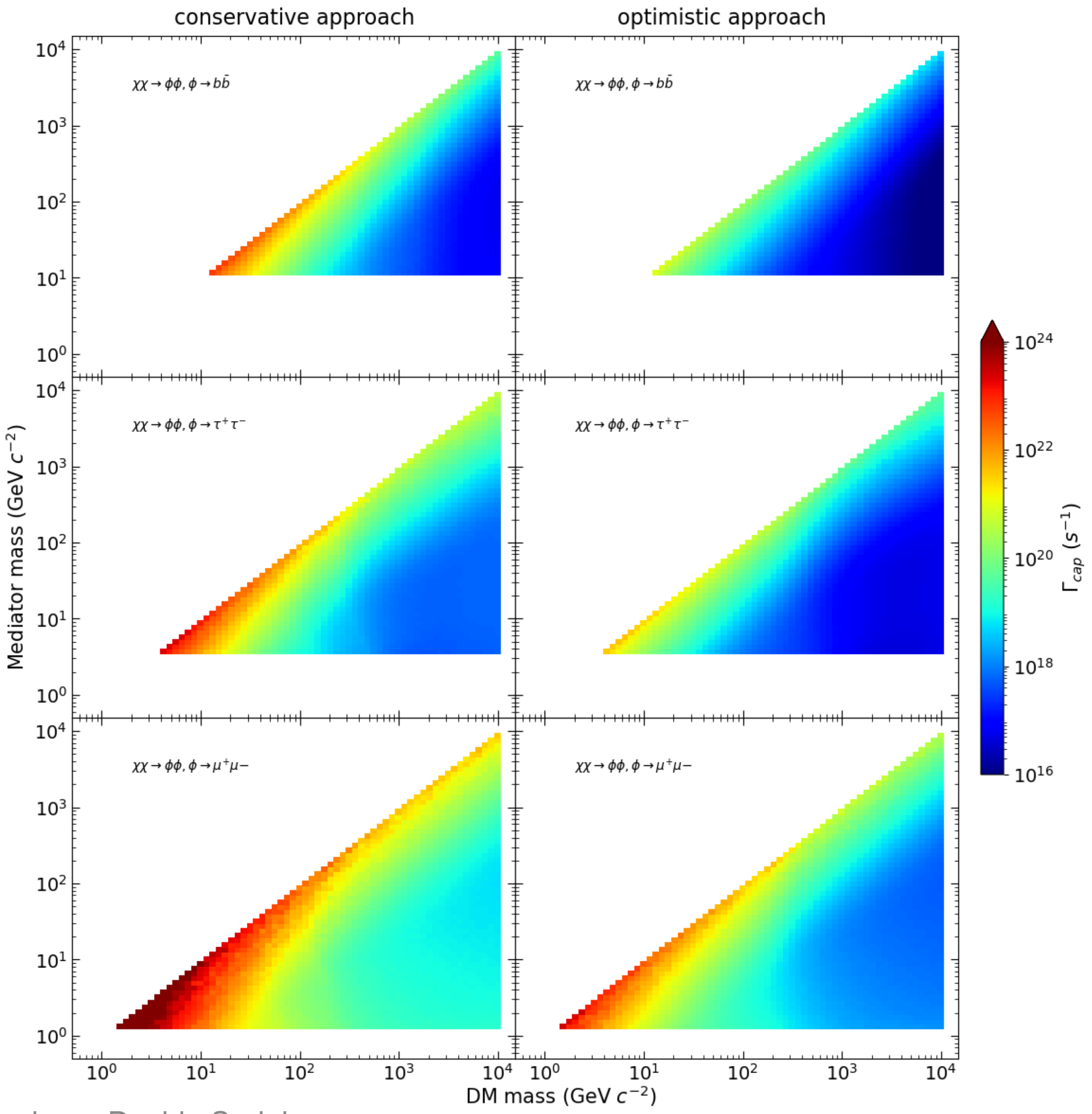
Solar capture rate constraints

- The limits on k_{DM} can be converted:
  - into constraints on the capture rate Γ_{cap}:

$$\Gamma_{cap,95\%} = k_{DM,95\%} \cdot 4\pi D^2$$

  - into constraints on the DM-nucleon spin-dependent and spin-independent scattering cross sections:

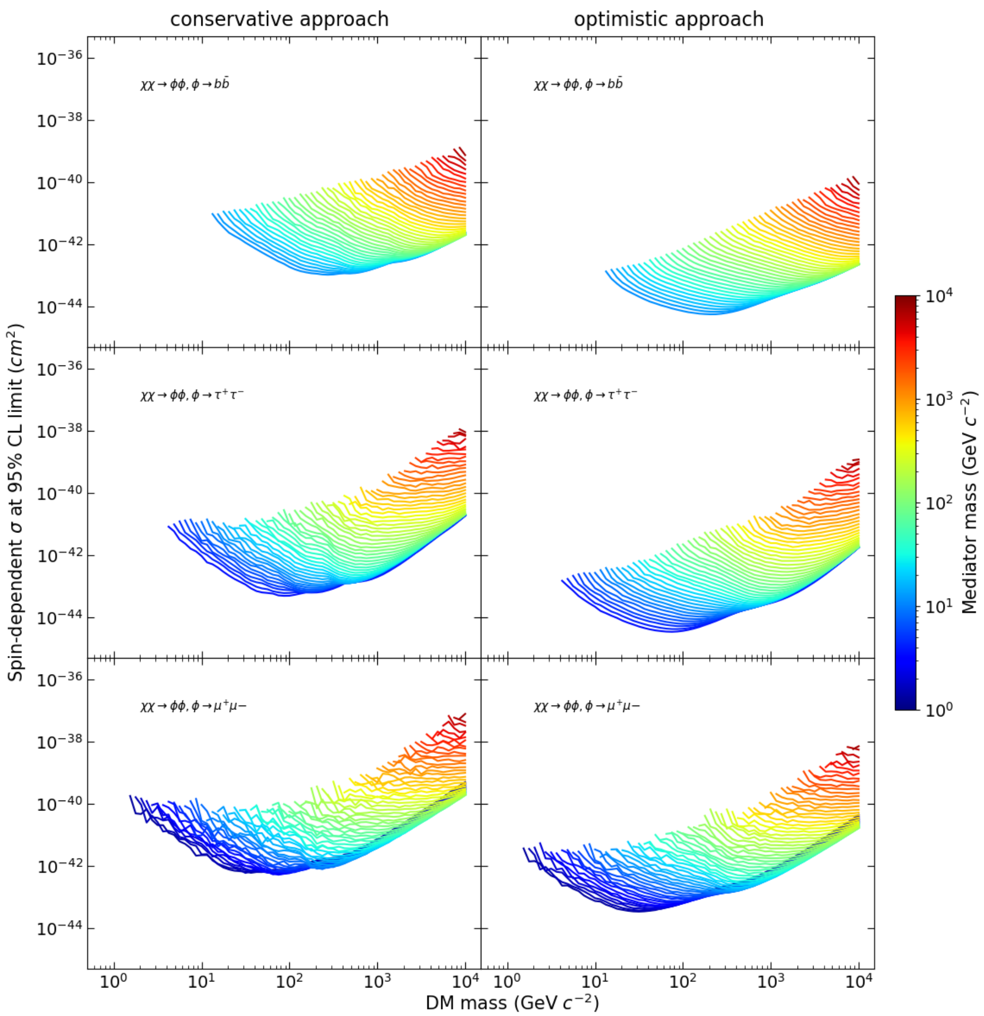
$$\sigma_{95\%} = \sigma_0 \cdot \frac{\Gamma_{cap,95\%}}{\Gamma_{cap,0}(m_\chi, \sigma_0)}$$

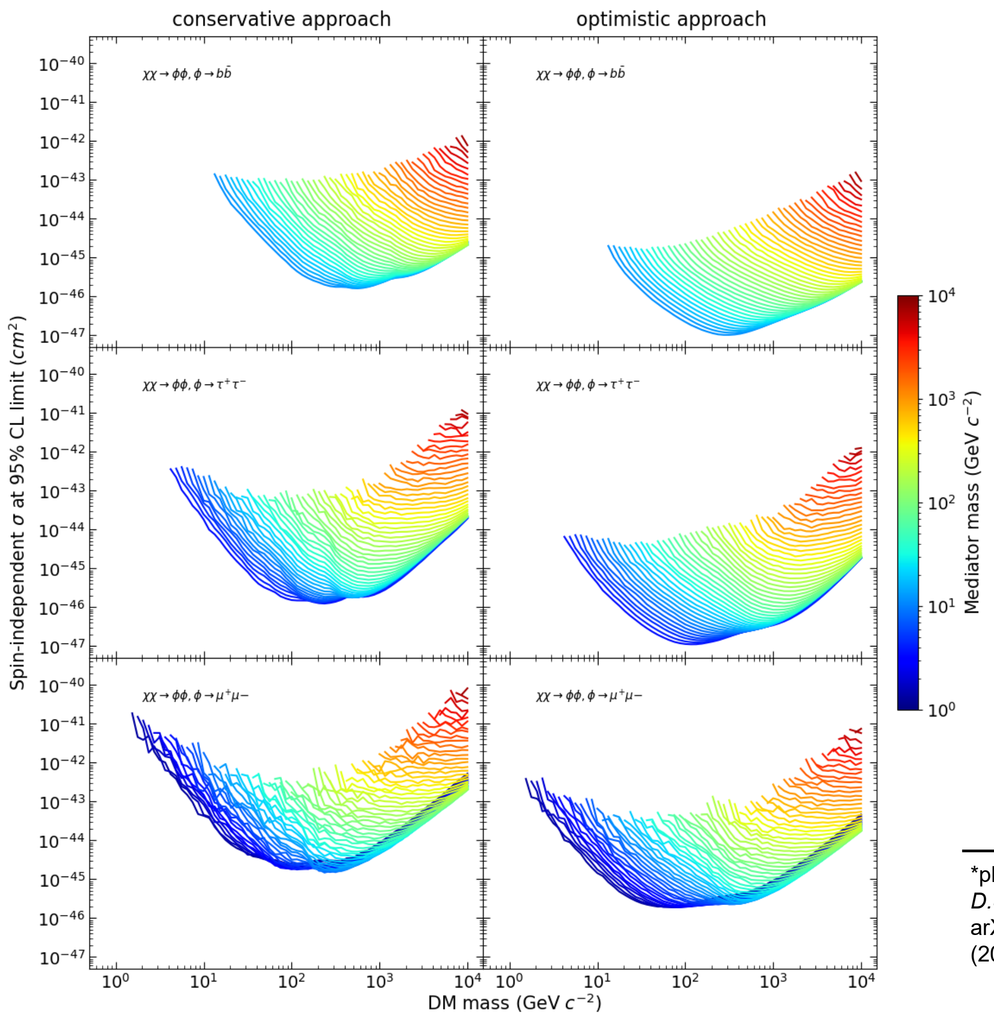


*plots taken from *D.Serini et al* arXiv:2208.13157 (2022)

DM-nucleon cross section constraints

- The DM-nucleon constraints obtained with the optimistic approach are stronger than those obtained with the conservative approach
  - For all the channels the limits lie in the range 10^{-45} - 10^{-39} cm^2 for σ_{SD} and 10^{-47} -10^{-42} cm^2 for σ_{SI}
  - The strongest constraints are obtained for the lowest allowed values of m_φ





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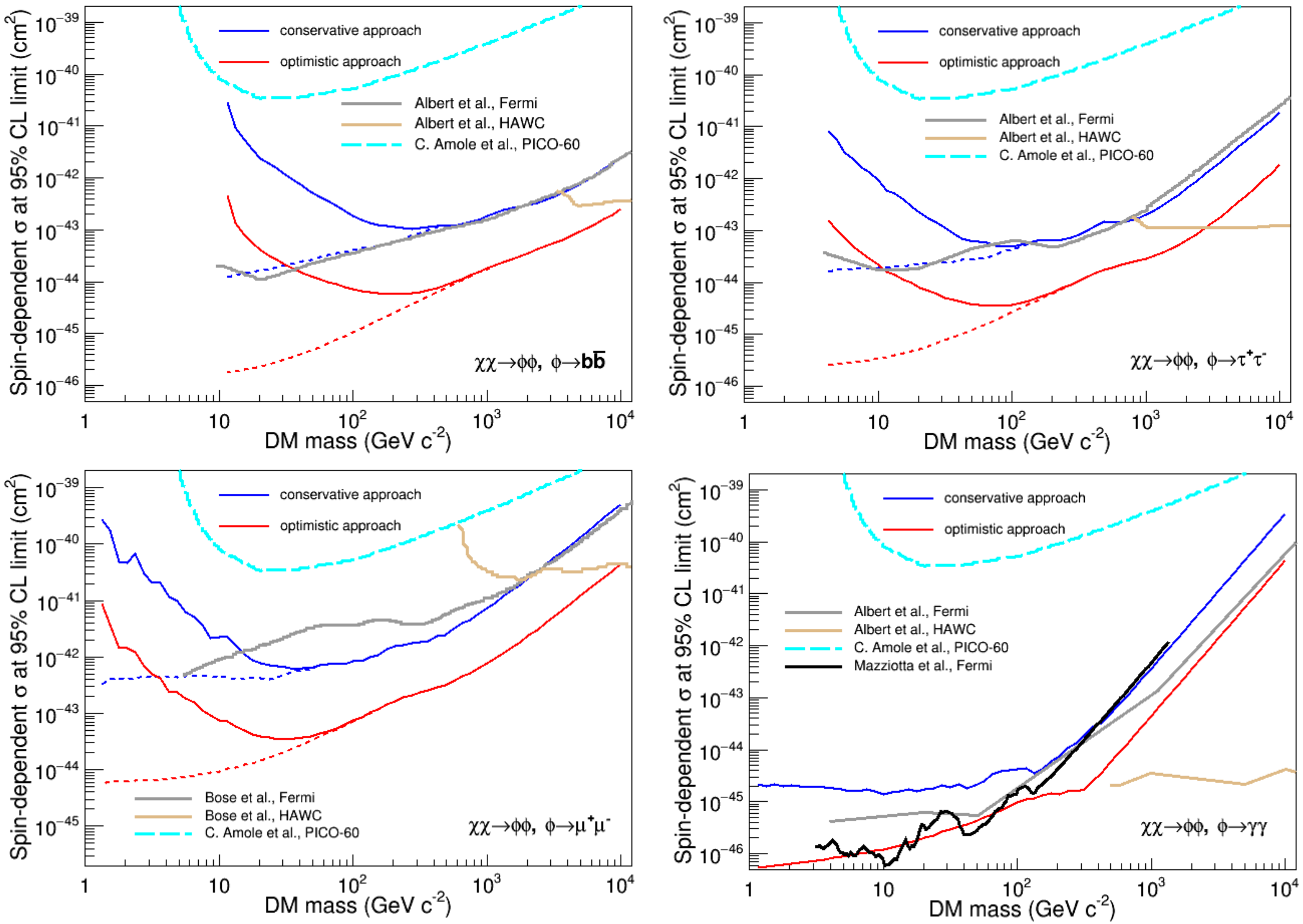
Current Limits on the spin-dependent cross section for L = R$_\odot$

- The results are compared with those obtained from previous analyses of the Fermi LAT and of the HAWC data within the same theoretical scenario[3-4]
- The 90% CL limits obtained from the PICO-60 direct measurements of the spin-dependent DM-nucleon cross sections are also shown[5]
- In the case of the $\gamma\gamma$ channel we also show the results of our previous analysis with 10 years of LAT data[2] (PRD102(2), 022003, 2020)
  - The limits obtained with the optimistic analysis approach are consistent with those of our previous work, although the analysis technique is different

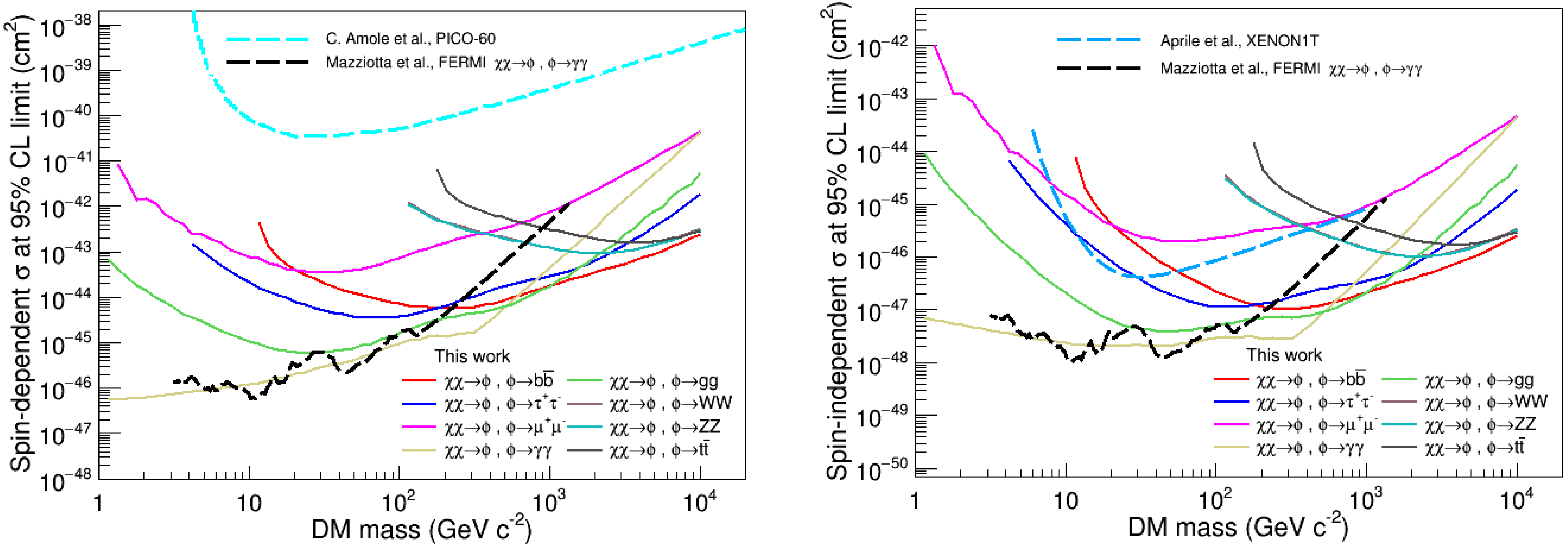


[2] Mazziotta, M. N et al Phys Rev D, *102*(2), 022003.
[3] A. Albert et al. (HAWC), Phys. Rev. D 98, 123012 (2018)
[4] D. Bose, T. N. Maity, and T. S. Ray, (2021), arXiv:2112.08286
[5] C. Amole et al. (PICO), Phys. Rev. D 100, 022001 (2019)

*plots taken from *D.Serini et al* arXiv:2208.13157 (2022)

Dark matter scattering constraints from long lived mediators

- We have performed a simulation campaign for all the possible decay channels provided by `med_dec`
  - The strongest limits are obtained with the optimistic approach and selecting the lowest kinematically allowed value of m_φ
  - Our results are compared with those obtained from the direct measurements performed by the PICO-60[5] (SD) and XENON1T (SI)[6] experiments
  - In the case of the $\gamma\gamma$ channel we also show the results of our previous analysis with 10 years of LAT data (PRD102(2), 022003, 2020)



[6] E. Aprile et al. (XENON), Phys. Rev. Lett. 121, 111302 557 (2018)

*plots taken from *D.Serini et al* arXiv:2208.13157 (2022)

Conclusions

- We have constrained a set of DM models predicting a gamma-ray signal from the Sun through the annihilation of solar WIMPs into long-lived mediators which can decay outside the Sun ($\chi\chi\rightarrow\phi\phi$, $\phi \rightarrow b\bar{b},\ \tau^{+}\tau^{-},\ \mu^{+}\mu^{-}...$)
  - These scenarios would yield a smooth γ-ray spectrum whose shape depends on m_{φ} and m_{χ} and on the mediator decay channel
  - The evaluation of the constraints on the DM-nucleon cross section is strongly model-dependent, since the mediator properties determine the final results
- The results obtained in this work show the potentiality of solar gamma rays as a probe for indirect DM detection, since the limits obtained with this analysis are comparable or even stronger than those currently quoted in the literature
- For more details see https://arxiv.org/abs/2208.13157

Conservative approach

- In the **conservative approach** k_{DM} it is evaluated by imposing that the counts from DM annihilations $\mu_{DM}(E_o)$ do not exceed the upper limits at 95% confidence level (CL) on the signal counts $n_{sig,95}(E_o)$ in any observed energy bin
  - The values of $n_{sig,95}(E_o)$ have been calculated from the observed counts in the ON and OFF regions, $n_{on}(E_o)$ and $n_{off}(E_o)$, implementing a Bayesian method[1] that take the exposures of the two regions into account
  - We assume that the counts in the off region are originated from background, while those in the on region are originated from both signal and background:
    - $n_{off}(E_o)$ is a Poisson random variable with average value $n_{bkg}(E_o)$
    - $n_{on}(E_o)$ is a Poisson random variable with average value $n_{sig}(E_o)+c \cdot n_{bkg}(E_o)$
      - *c is a constant which takes into account the exposures of the two regions*
  - The bayesian method allows the evaluation of the posterior PDF of the signal counts $n_{sig}(E_o)$ starting from the observed counts $n_{on}(E_o)$ and $n_{off}(E_o)$ and assuming uniform priors for both $n_{bkg}(E_o)$ and $n_{sig}(E_o)$
  - The upper limits at 95% C.L. on the signal counts in the ON region are calculated from the posterior PDF

[**1**] F. Loparco and M. Mazziotta. (2011). «***A Bayesian approach to evaluate confidence intervals in counting experiments with background***». *NIMA*, *646*, 167 (2011).