Search for dark matter annihilating into long-lived mediators from dwarf spheroidal galaxies

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Introduction

- Dwarf spheroidal galaxies (dSphs) are prime candidates for the indirect detection of dark matter, as they *possess minimal astrophysical γ-ray background fluxes and have extremely high mass-to-light ratios.*
- We explore a scenario where where DM first annihilate into long-lived mediator ϕ which later decay (outside the dSph) into $\gamma-$photons. $\chi\chi \to \phi\phi$; with $m_\phi \ll m_\chi$, $\phi \to \gamma\gamma \implies$ 4 photons per annihilation $\implies$ enhanced $\gamma-$ ray flux.
- The two step process gives box-shaped spectrum and we also include Sommerfeld Enhancement.

Theoretical Framework

When DM particles traverse through the dSphs, if colliding one or multiple times, they lose sufficient energy and eventually get captured. The total capture rate is

$$C_{\rm tot}(r) = \sum_{N=1}^{\infty} C_{\rm N}(r)\,, \qquad (1)$$

The capture rate associated with N scatterings [1]

$$C_N(r) = \pi R_{1/2}^2 \mathcal{P}_N(\tau) \int_0^\infty du_\chi n_\chi \frac{f(u_\chi)}{u_\chi} w^2 g_N(w),$$

$w^2 = u_\chi^2 + v_e^2(r)$ and prob. $\mathcal{P}_N(\tau)$ with optical depth τ

$$\tau = \frac{3\sigma_{\chi n} N_T}{2\pi R_{1/2}^2}. \qquad (2)$$

Captured DM particles may undergo self-annihilation. The time evolution equation is:

$$\frac{dN(t)}{dt} = C_{\rm tot} - C_{\rm ann} N^2(t), \qquad (3)$$

where $C_{\rm ann} = \langle\sigma_{\rm ann} v\rangle / V_{\rm ann}$. If capture rate and annihilation rate of DM particles are in equilibrium,

$$\Gamma_{\rm ann} = \frac{C_{\rm ann} N^2}{2} \to \frac{C_{\rm tot}}{2} \qquad (4)$$

Differential flux of gamma rays at Fermi-LAT detector from DM annihilation via long-lived mediators

$$E^2 \frac{d\Phi_\gamma}{dE} = \frac{\Gamma_{\rm ann}}{4\pi\, d^2} \times E^2 \frac{dN_\gamma}{dE} \qquad (5)$$

The gamma-ray spectrum from the decay of LLM is then given by a *box-shaped spectrum* [2]

$$\frac{dN_\gamma}{dE} = \frac{4}{\Delta E} \Theta\left(E - E_-\right) \Theta\left(E_+ - E\right) \qquad (6)$$

Source Details and Properties

Source	RA [deg]	DEC [deg]	Distance (kpc)	$M_{1/2}$(GeV)	$R_{1/2}$ (pc)	$\sigma_{\rm l.o.s}$ (km/s)
Draco II	238.17	64.58	22.0	1.28×10^{62}	17	3.4
Segue I	151.75	16.08	23.0	1.25×10^{62}	20	3.1
Sagittarius	283.83	-30.55	26.7	1.3×10^{65}	1565	11.4
Hydrus I	37.39	-79.31	28.0	2.5×10^{62}	53	2.7
Reticulum II	53.92	-54.05	30.0	2.32×10^{62}	31	3.4
Ursa Major II	132.87	63.13	32.0	2.86×10^{63}	85	7.2
Carina II	114.11	-58.0	36.0	5.77×10^{62}	77	3.4
Bootes II	209.51	12.86	42.0	2.13×10^{62}	39.0	2.9
Willman I	162.34	51.05	38.0	2.63×10^{62}	20	4.5
Coma Berenices	186.75	23.91	44.0	8.17×10^{62}	57	4.7

- As the flux $\propto 1/d^2 \implies$ only dSphs whose distance is less than 50 kpc
- Mass of dSph; $M_{1/2} = \frac{2.5}{G}\sigma_{\rm l.o.s}^2 R_{1/2}$, DM density profile; $\rho_\chi^{\rm NFW}(r) = \rho_s \frac{r_s}{r}\left(1+\frac{r}{r_s}\right)^{-2}$; $r_s = 5R_{1/2}$; $\rho_s = \frac{M_{1/2}}{4\pi r_s^3}\left[\log\left(1+\frac{R_{1/2}}{r_s}\right) - \frac{R_{1/2}}{r_s+R_{1/2}}\right]^{-1}$

$\gamma-$ ray flux upper limits in FERMI-LAT data

- We analyze nearly 16 years of Fermi-LAT data with $E \in$[0.5,500] GeV.
- No significant excess emission is detected at any dSph location, compute the 95% C.L. upper limits on the gamma-ray flux for each dSph.

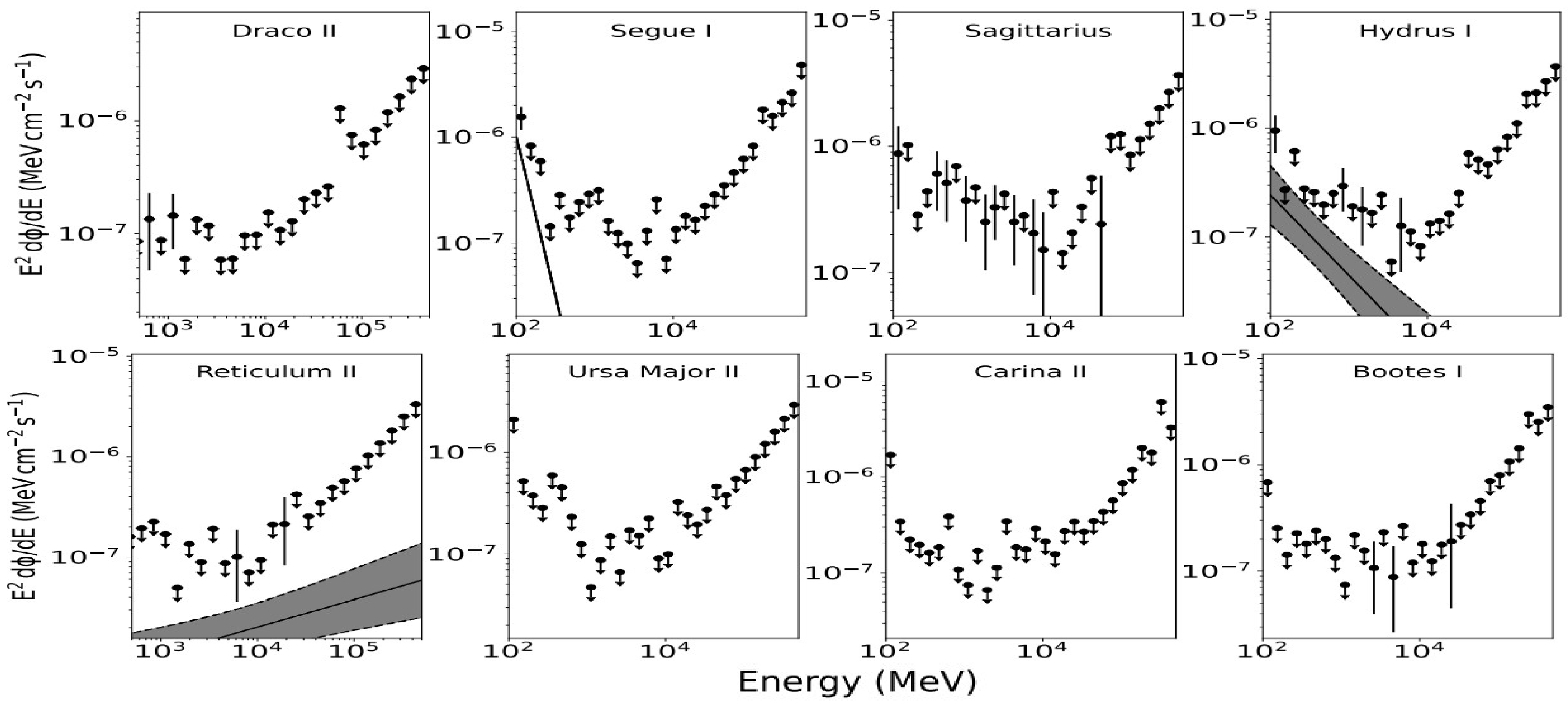
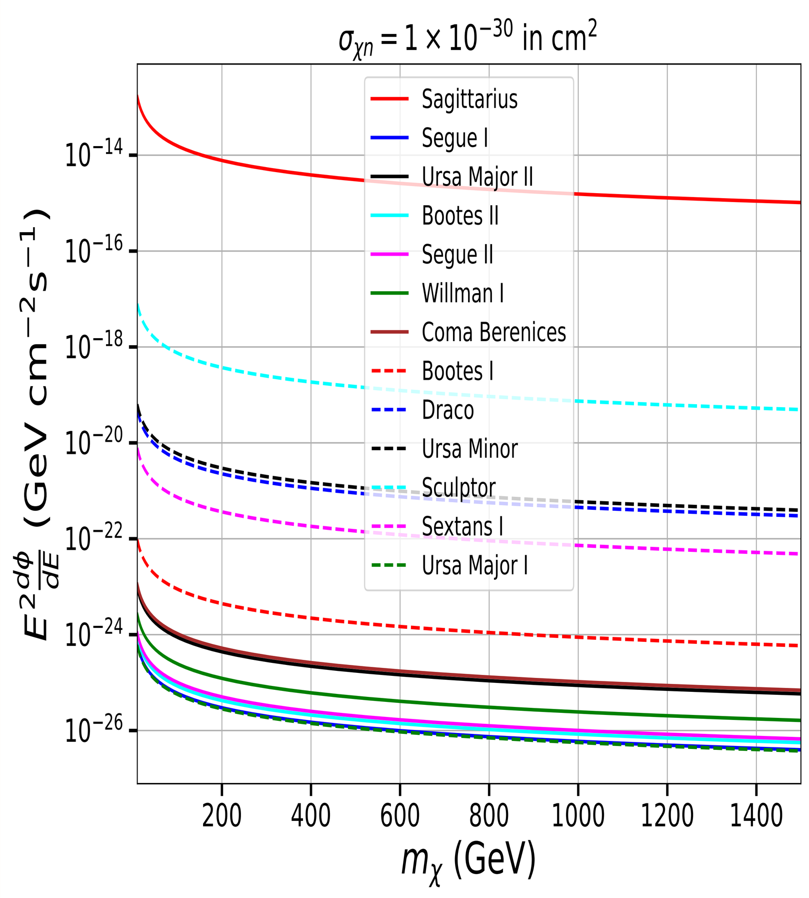
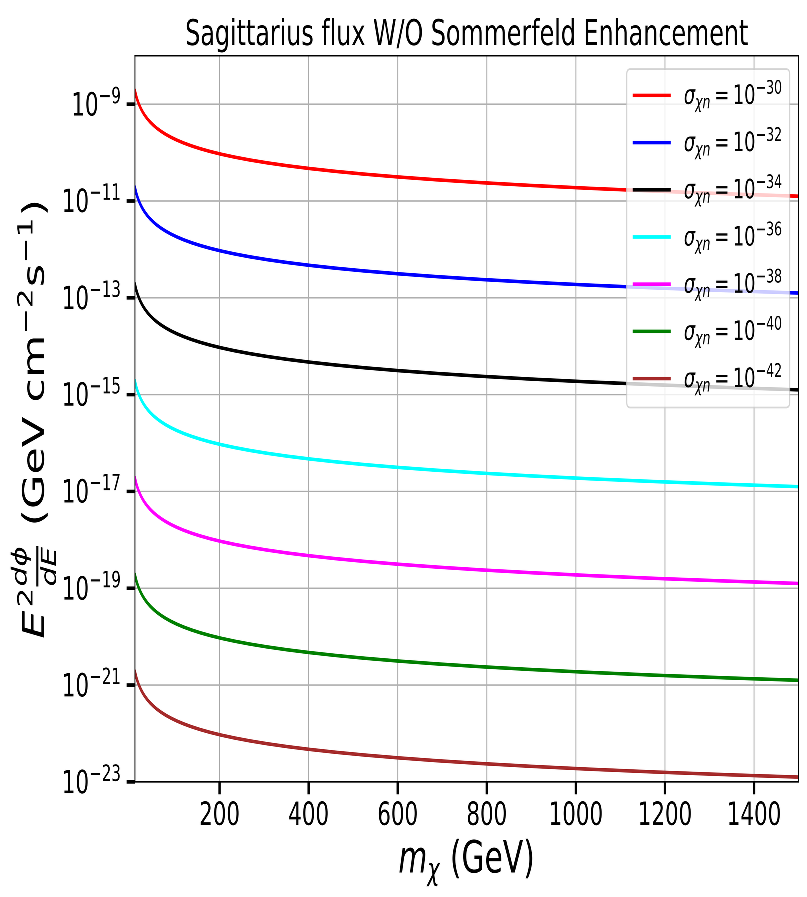


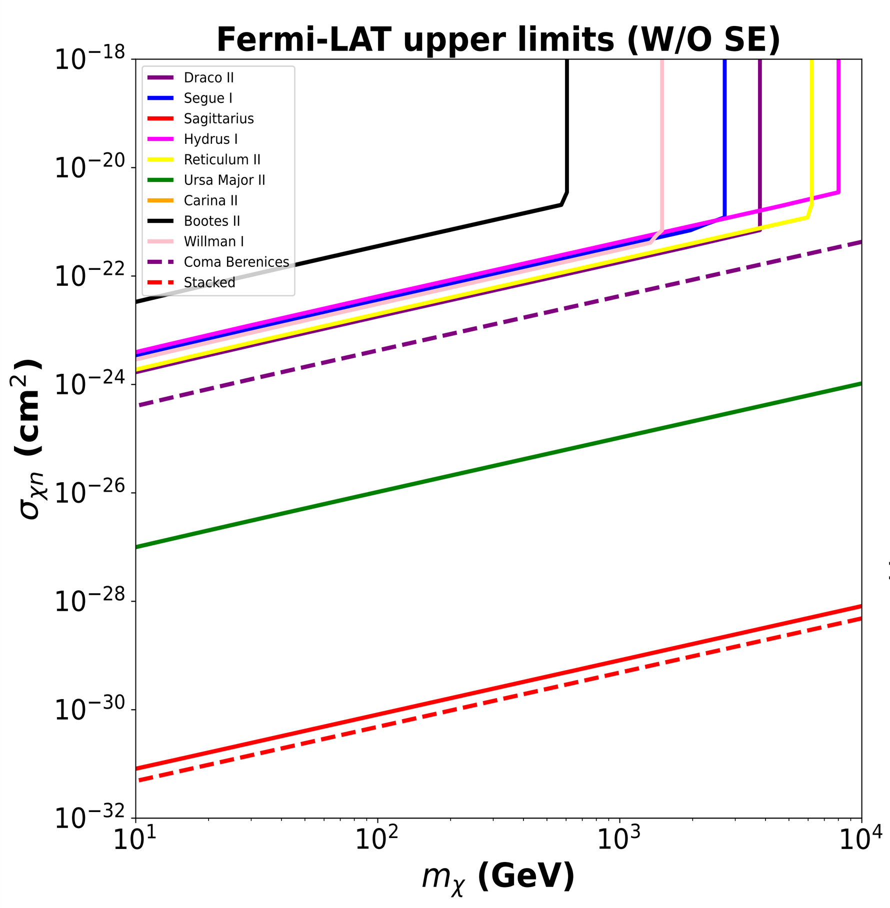
Fig.: Bin-by-bin $E^2 d\Phi/dE$ upper limits at 95% C.L. chosen dSphs.

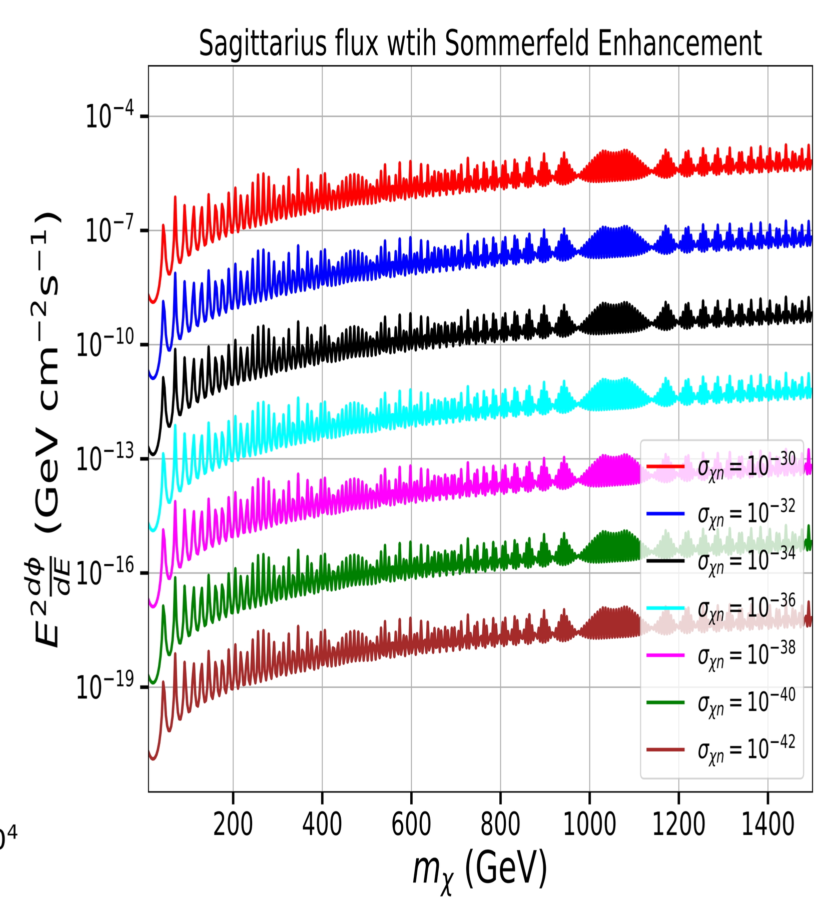
We translate the Fermi-LAT gamma-ray flux upper limits into constraints on the DM particle parameter space $\to$ set bounds on the DM-nucleon scattering cross section.

Results: Flux and Sensitivity

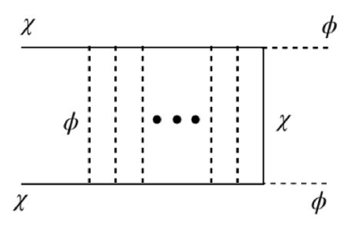








Sommerfeld Effect



$\langle\sigma_{\rm ann} v\rangle$ enhances due to long-range attractive potential

- Sommerfeld factor $\propto 1/v$ and the relative velocities of DM particles in dSphs tend to be much lower than galaxy clusters or Milky Way [3].
- ***MODEL: Light LLM ϕ is responsible for both SE and box-shaped spectrum***
- This is possible if we consider scalar DM interacting with scalar mediator
- $\langle\sigma_{\rm ann} v\rangle_S = \langle\sigma_{\rm ann} v\rangle_{\rm Born}\langle S_{\rm s}\rangle$ and

$$S_{\rm s} = \frac{\pi}{\beta}\frac{\sinh 2\pi\beta\zeta}{\cosh 2\pi\beta\zeta - \cos(2\pi\sqrt{\zeta - \beta^2\zeta^2})},$$

where $\beta = v/(2\alpha_\chi)$ and $\zeta = 6\alpha_\chi m_\chi/(\pi^2 m_\phi)$.

- For $m_\phi \ll m_\chi$

$$\langle\sigma_{\rm ann} v\rangle_{\rm Born} = \frac{g_\chi^2}{64\pi m_\chi^3}\left(1 + \frac{g_\chi v_\phi^2}{m_\chi^2}\right)^2$$

- $\alpha_\chi \approx 9.62 \times 10^{-8}(m_\chi^2/{\rm GeV}^2)$

Key Takeaways

- In this ongoing work, *for the first time*, we are investigating the framework where both **box-shaped spectrum and Sommerfeld Enhancement** are considered together.
- We use dSphs as a target to probe DM parameter space and using the flux upper limits from FERMI-LAT data constraints on the DM-nucleon scattering cross section have been derived for the selected dSphs.
- We find that, *the bound given by Sagittarius dSph is the most stringent compared to other dSphs.*
- *For the scalar DM and scalar mediator case, when both box-shaped spetcrum and SE are present, the flux seems to increase with m_χ!*

References

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