Solar γ-rays as a complementary probe of Dark Matter

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Complementarity in Dark Matter searches is a priceless asset: can solar γ-rays be a competitive probe of DM?

The Sun can serve as a «reservoir» of DM: scatter off solar matter results in DM energy loss, leading to gravitational capture and DM accumulation in the center of the Sun, where it can annihilate

Steigman, Sarazin, Quintana, Faulkner (1978); Press and Spergel (1985); Gould (1987)

Solar γ-rays features

- **Low background** at energies above GeV
- **Smaller DM density uncertainties** with respect to Galactic Center
- **Proximity to Earth**: lower flux suppression than Dwarf Galaxies and GC
- γ-rays trace the **production point**

Simplified model with mediator-quark Yukawa-like couplings

Quark q_j — Mediator — Dark Matter

$$\mathcal{L} \;=\; g_q\, y_{q_j} \bar{q}_j \left[\cos\alpha + i \sin\alpha\, \gamma_5\right] q_j\, Y + g_X\, \bar{X} \left[\cos\alpha + i\sin\alpha\,\gamma_5\right] X\, Y$$

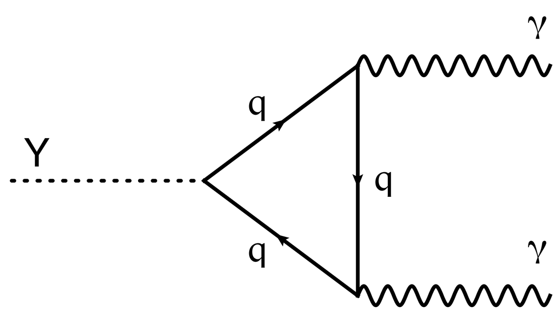
Mediator escapes from the Sun if

$$\frac{1}{\Gamma_Y}\frac{m_X}{m_Y} \gtrsim R_\odot \;\Longrightarrow\; \left(\frac{\Gamma_Y}{\text{GeV}}\right)\left(\frac{m_Y}{m_X}\right) \lesssim 2.84\times 10^{-25}$$

Long lived mediator — Hierarchy of masses

DM capture requires $g_q \neq 0$

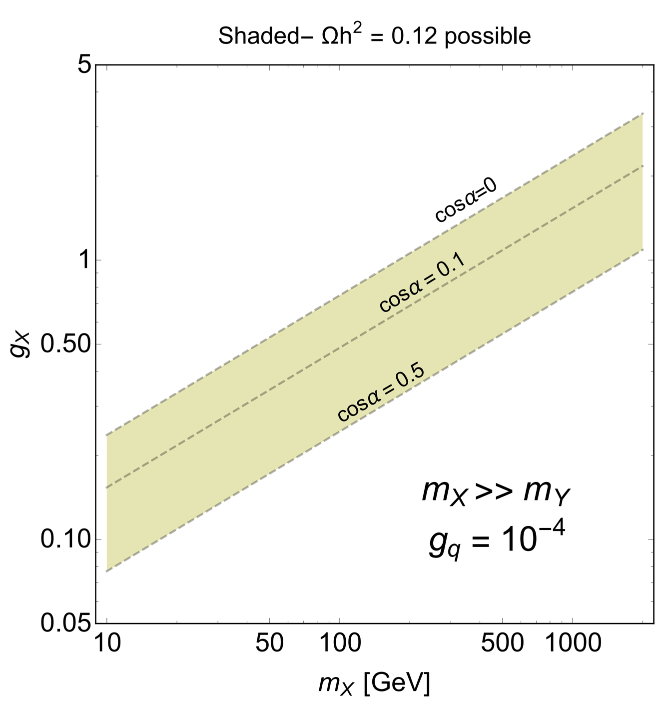
Perturbative $Y\gamma\gamma$ coupling



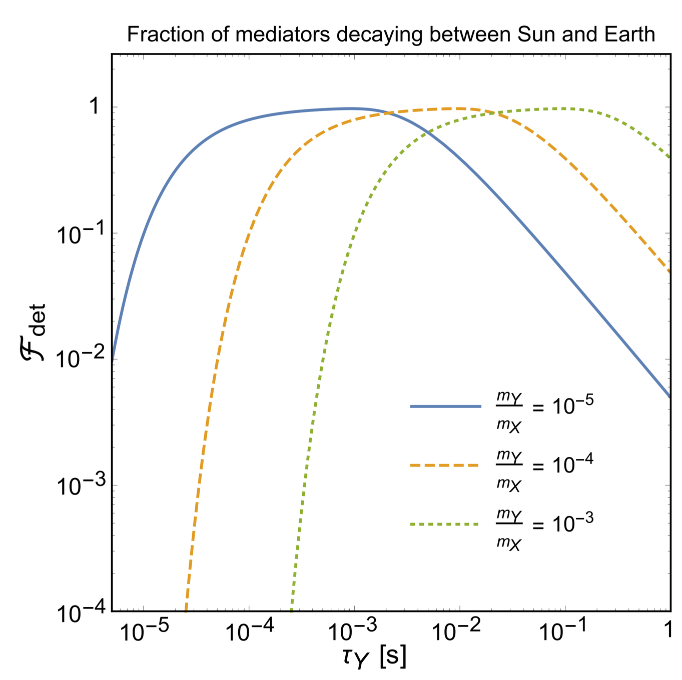
For $m_Y < m_\pi$ the Branching Ratio is 100% in photons

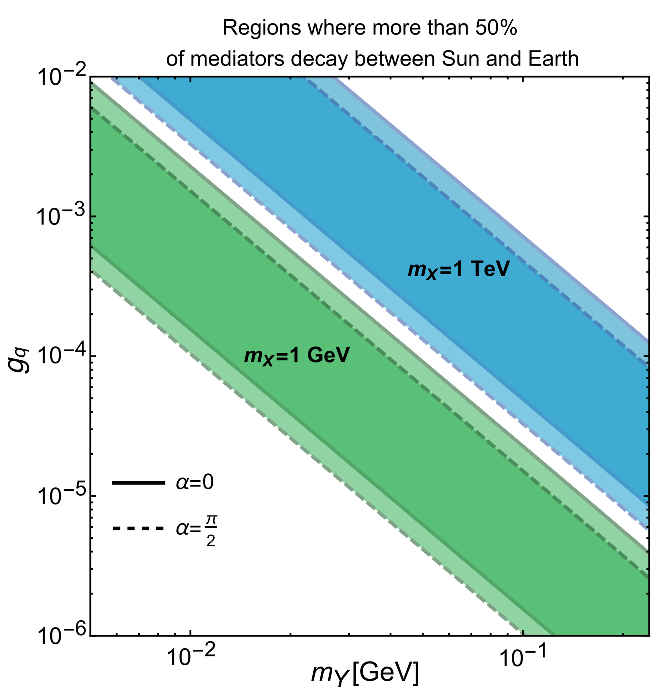
$$\Gamma_Y = \frac{9}{8}\frac{g_q^2\alpha_e^2 m_Y}{\pi^3}\left[\cos^2\alpha\left|\sum_q Q_q^2\frac{m_q}{v_h}F_S\left(\frac{m_Y^2}{4m_q^2}\right)\right|^2 + \sin^2\alpha\left|\sum_q Q_q^2\frac{m_q}{v_h}F_P\left(\frac{m_Y^2}{4m_q^2}\right)\right|^2\right]$$

PARAMETER SPACE:



$g_X \sim 1$ is required





The **region** where a **sizeable fraction** of mediators decays between Sun and Earth spans **different orders of magnitude**

Benchmark model points

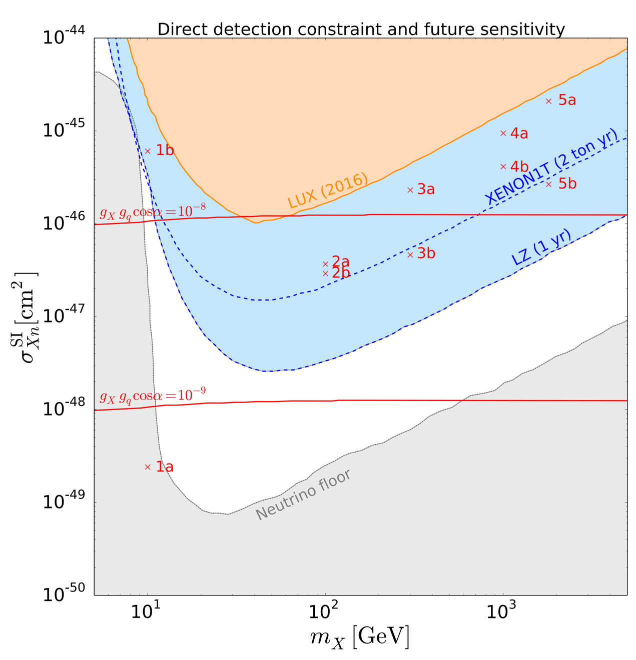
Benchmark	m_X[GeV]	m_Y[GeV]	g_X	g_q	$\cos\alpha$	m_Y/m_X	τ [s]	$\mathcal{F}_{\rm det}$	$\mathcal{F}_{2\gamma}$
1a	10	0.1	0.24	2×10^{-5}	0.01	0.01	0.19	0.88	4.3×10^{-20}
1b	10	0.01	0.24	0.001	0.001	0.001	0.076	0.97	3.3×10^{-11}
2a	100	0.1	0.76	5×10^{-5}	0.012	0.001	0.031	0.93	4.7×10^{-15}
2b	100	0.05	0.76	0.0001	0.004	0.0005	0.061	0.96	4.8×10^{-10}
3a	300	0.1	1.4	0.0001	0.01	0.00033	0.0076	0.9	8.3×10^{-17}
3b	300	0.05	1.4	7×10^{-5}	0.004	0.00017	0.12	0.48	1.4×10^{-8}
4a	1000	0.1	2.5	9×10^{-5}	0.011	0.0001	0.0094	0.97	9.1×10^{-7}
4b	1000	0.05	2.5	0.0002	0.003	5×10^{-5}	0.015	0.8	2.7×10^{-5}
5a	1800	0.1	3.4	0.0001	0.011	5.6×10^{-5}	0.0076	0.96	6×10^{-6}
5b	1800	0.05	3.4	0.00012	0.003	2.8×10^{-5}	0.042	0.28	0.0001

The fraction of events $\mathcal{F}_{2\gamma}$ giving rise to **correlated 2-photons signal** is **negligible**

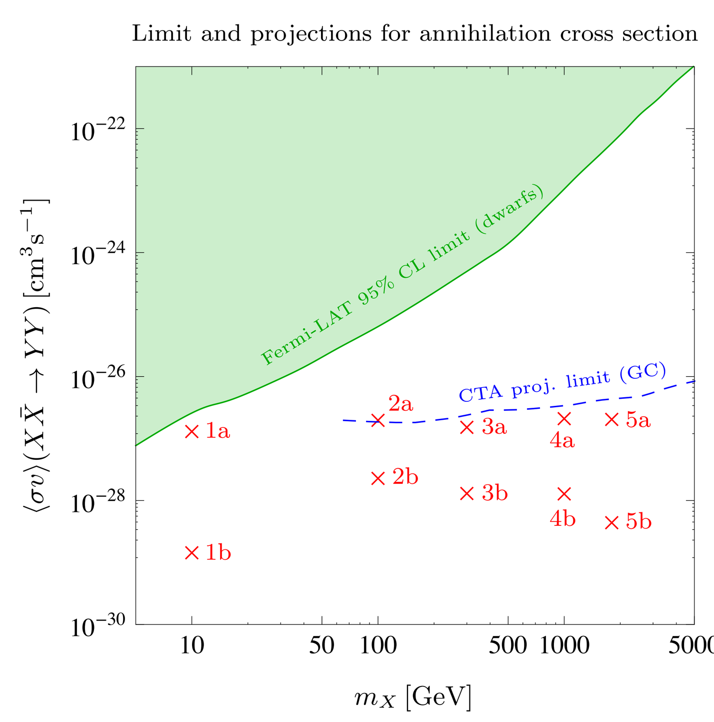
Dominant annihilation channels

$$\frac{1}{2}\langle\sigma v\rangle(X\bar{X}\to YY) = \frac{g_X^4\sin^2 2\alpha}{64 m_X^2\pi} + \frac{g_X^4\,(3+8\cos 2\alpha+7\cos 4\alpha)\,\langle v\rangle^2}{1536 m_X^2\pi};\quad \frac{1}{2}\langle\sigma v\rangle(X\bar{X}\to t\bar{t}) = \frac{3g_q^2 g_X^2 y_t^2}{64 m_X^2\pi}\left[\sin^2\alpha + \frac{1}{4}\cos 2\alpha\langle v\rangle^2\right]$$

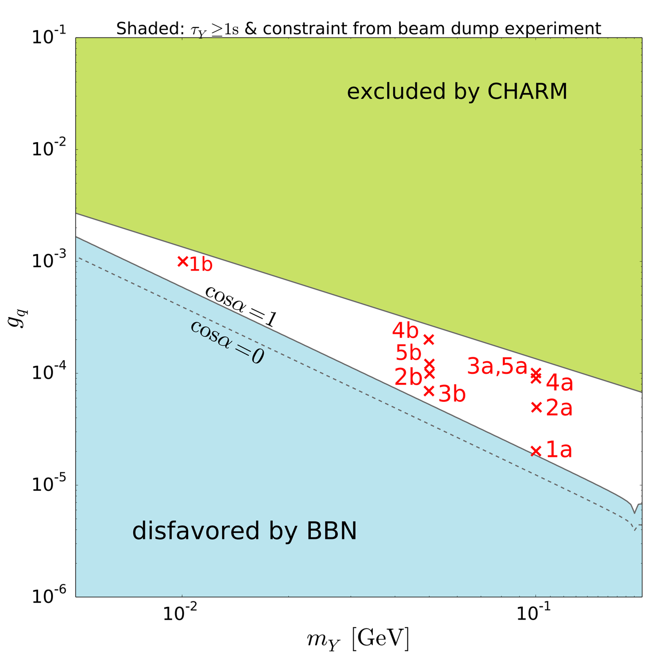
CONSTRAINTS:



Solar γ-rays are **complementary** to direct detection searches



The **parameter space** is only **marginally probed** by **dwarfs** and **GC** γ-rays



Cosmological and **laboratory** constraints: right region for **sizeable signals**

DM-nucleon scattering cross section

$$\sigma^{\rm SI}_{Xn} = \frac{\mu_n^2}{\pi}\frac{g_X^2 g_q^2\cos^4\alpha\, m_n^2}{m_Y^4}\left(\sum_{q=u,d,s}\frac{y_q}{m_q}f_q^n + \sum_{q=c,b,t}\frac{2}{27}\frac{y_q}{m_q}f_G^n\right)^2$$

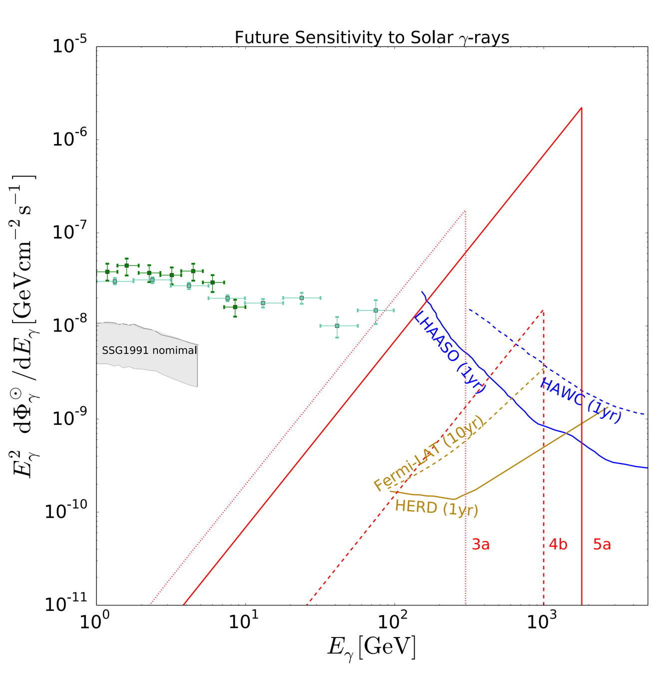
Number of DM particles in the Sun

$$\frac{{\rm d}N}{{\rm d}t} = C_{\rm cap} - C_{\rm ann}N^2 \;\longrightarrow\; N = \sqrt{\frac{C_{\rm cap}}{C_{\rm ann}}}\tanh\left(\sqrt{C_{\rm cap}C_{\rm ann}}\,t_\odot\right)$$

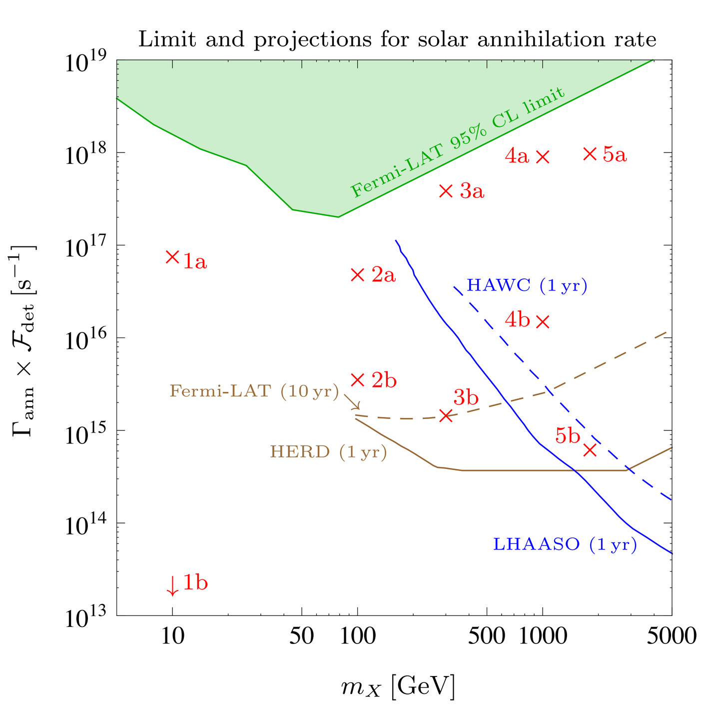
$$\Gamma_{\rm ann} = \frac{N^2}{4V_{\rm eff}}\left[\langle\sigma v\rangle(X\bar{X}\to YY) + \langle\sigma v\rangle(X\bar{X}\to t\bar{t})\right];\quad C_{\rm ann} = \frac{2\Gamma_{\rm ann}}{N^2}$$

$$C_{\rm cap} = 4.8\times10^{24}{\rm s}^{-1}\left(\frac{\rho_\odot}{0.3\ {\rm GeV cm^{-3}}}\right)\left(\frac{\rm GeV}{m_X}\right)\left(\frac{270\ {\rm km s^{-1}}}{\bar{v}}\right)\times \sum_i F_i(m_X)\left(\frac{\sigma_{XN_i}}{10^{-40}{\rm cm}^2}\right)\times f_i\times\phi_i\times S\left(\frac{m_X}{m_{N_i}}\right)\left(\frac{\rm GeV}{m_{N_i}}\right)$$

RESULTS:



At energies **above 100 GeV** low background is expected: **clear signal. Below 100 GeV good angular resolution is necessary** in order to disentangle between signal and background



Benchmark	$\Phi_\gamma^\odot$[cm^{-2} s^{-1}]	$N_\gamma^\odot$(1 yr)	$\sqrt{C_{\rm cap}C_{\rm ann}}t_\odot$
1a	1.6×10^{-15}	0.00018	0.0039
1b	1.1×10^{-10}	12	0.02
2a	7×10^{-11}	8.0	0.15
2b	5.2×10^{-12}	0.59	0.044
3a	5.7×10^{-10}	64	0.36
3b	2.1×10^{-12}	0.24	0.065
4a	1.3×10^{-9}	8.3×10^{15}	0.79
4b	2.2×10^{-11}	1.4×10^{14}	0.14
5a	1.4×10^{-9}	1.6×10^{16}	1.1
5b	9×10^{-13}	1×10^{14}	0.1

Number of **expected events N_γ** estimated in **satellite** (Fermi-LAT, HERD) and **Earth based** (HAWC, LHAASO) experiments, for values of ***m_X*** **below** and **above 500 GeV**, respectively

CONCLUSIONS

The **Sun** is a potential nearby **reservoir** of **DM** and a **poor source** of **high-energy γ-rays**

Solar γ-rays can probe DM models with **comparable** or **superior sensitivity** with respect to **dwarfs** and **Galactic Center** signals

DM capture and **annihilation** proceed typically **out of equilibrium**: possible to extract **information on $\Gamma_{\rm ann}$** if direct detection is observed

Solar γ-rays signals would point towards the **existence** of a **long-lived mediator**

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