

X-rays constraints on sub-GeV Dark Matter

Based on work with M. Cirelli, N. Fornengo, E. Pinetti & B. M. Roach

JCAP 07 (2023) 026 [[arXiv:2303.08854](https://arxiv.org/abs/2303.08854)]

Jordan Koechler

LPTHE, Sorbonne University, Paris

DESY Theory Workshop 2023



Introduction

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- Null results on WIMPs in colliders, direct and indirect detection

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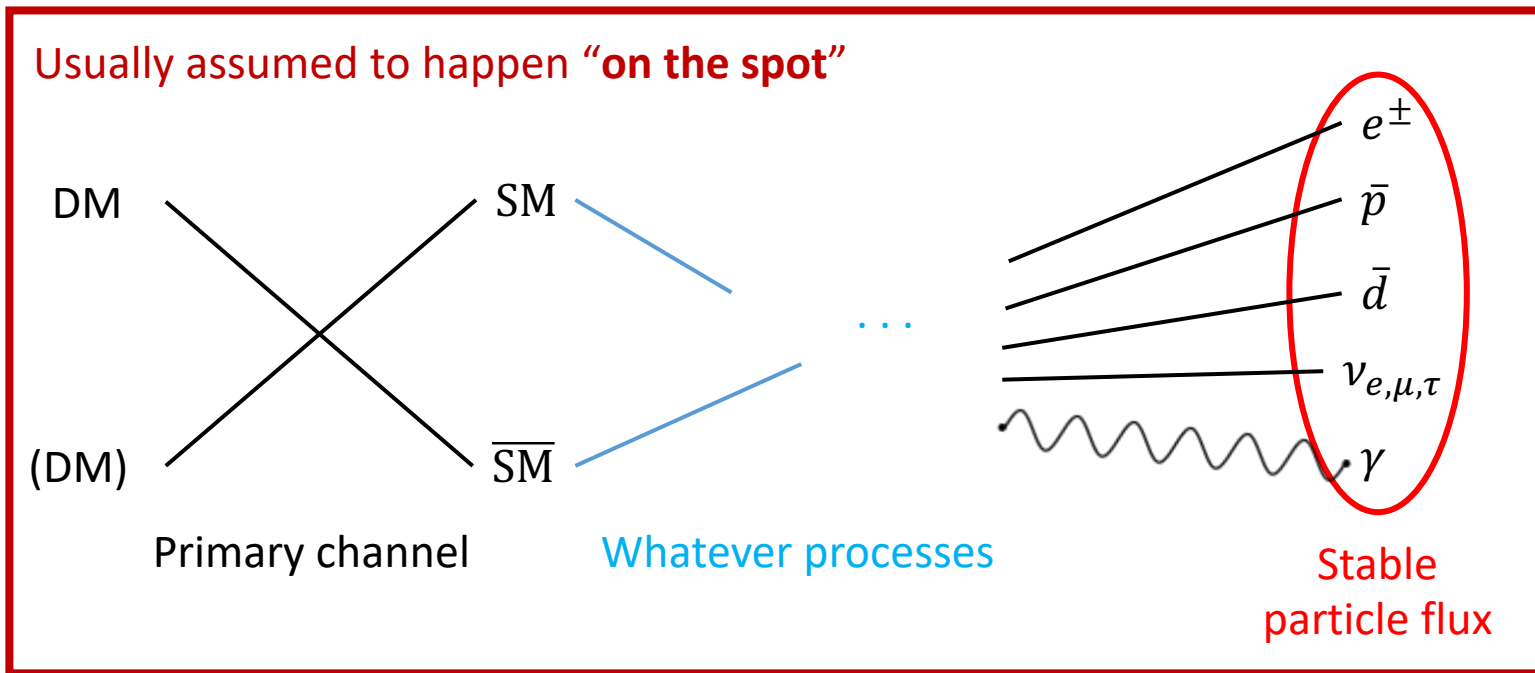
- Null results on WIMPs in colliders, direct and indirect detection
- A lot of ‘light’ DM models are well-motivated:
 - Hidden sector/secluded DM
 - SIMP DM
 - Asymmetric DM
 - ...

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- Null results on WIMPs in colliders, direct and indirect detection
- A lot of ‘light’ DM models are well-motivated:
 - Hidden sector/secluded DM
 - SIMP DM
 - Asymmetric DM
 - ...
- Light DM detection is challenging

Introduction

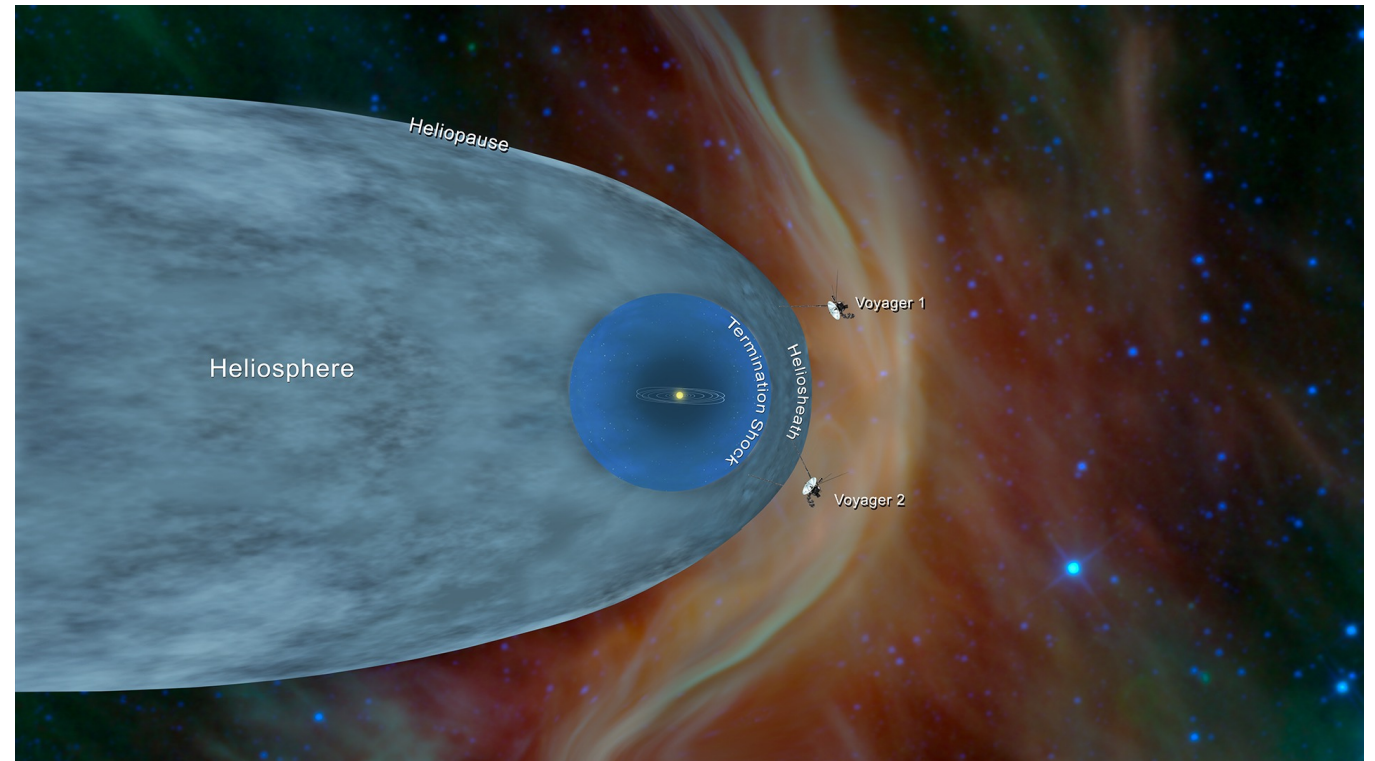
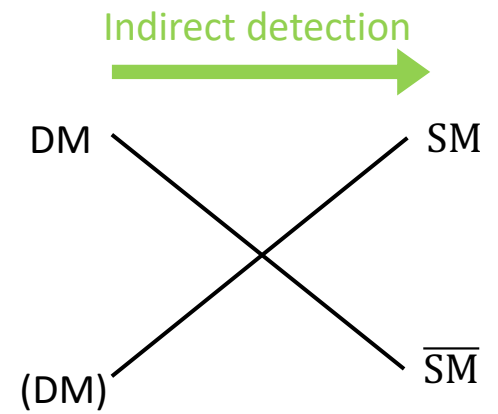
- Principle behind DM indirect detection:



Introduction

Light DM detection is challenging in indirect detection

Solar winds are a barrier to low-energy charged particles



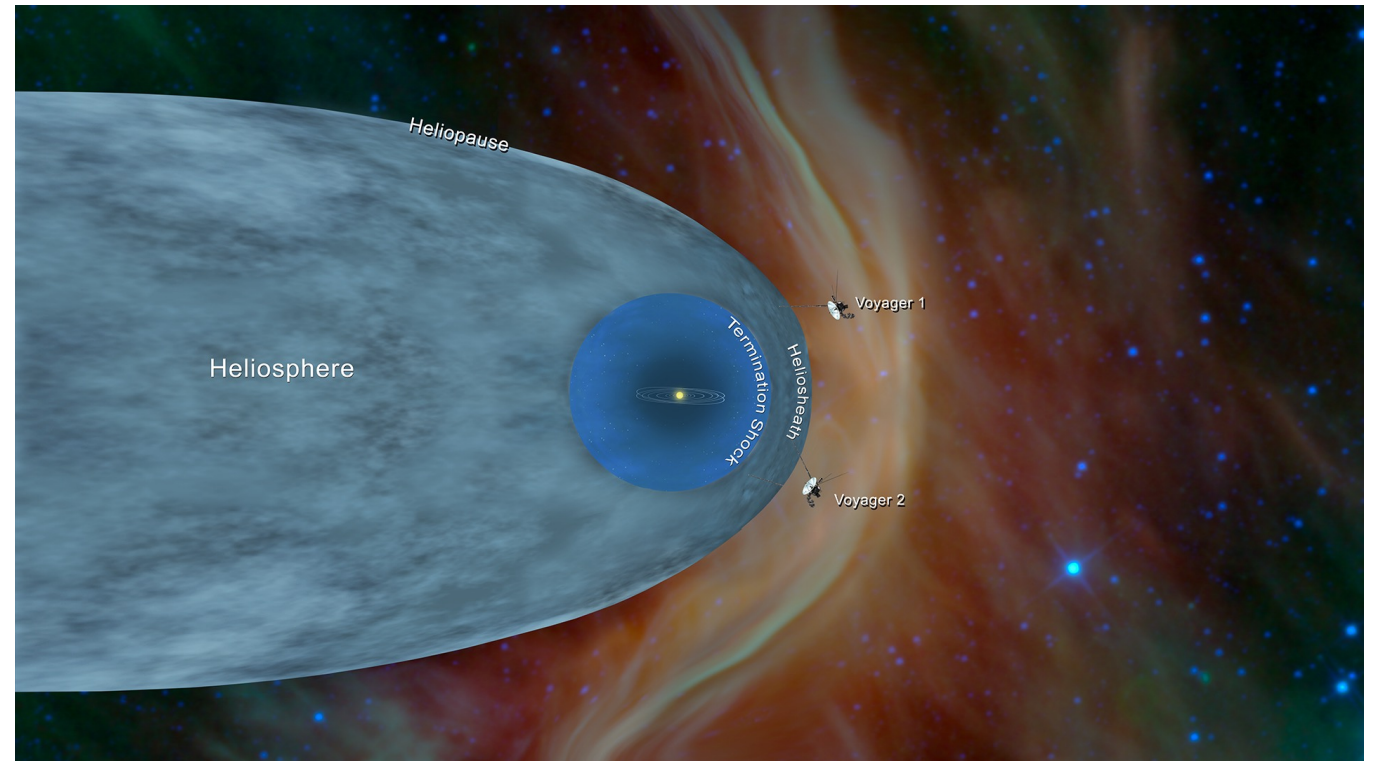
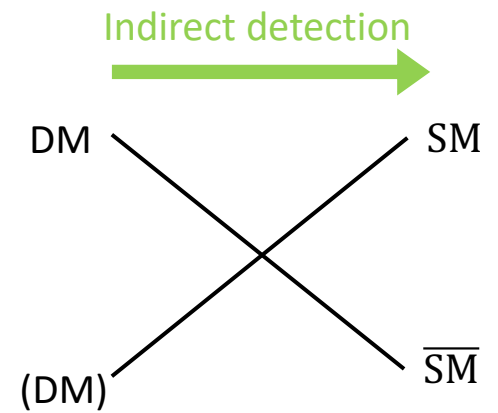
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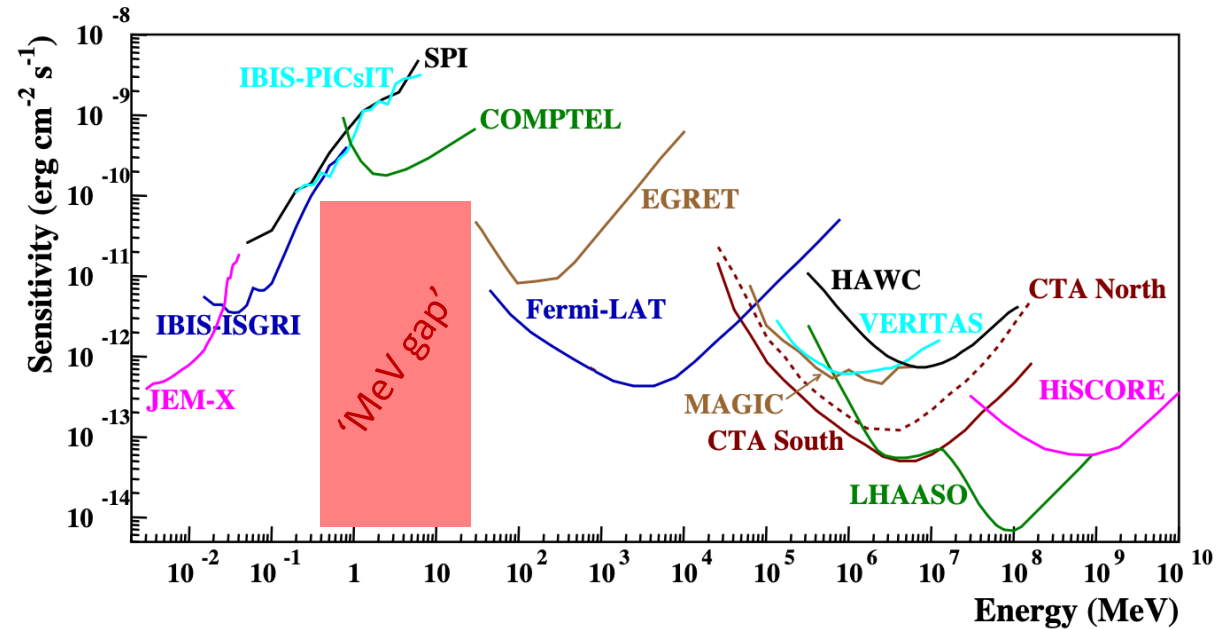
Solutions:

- Look at Voyager1 & 2 data!
- What about photons?



Introduction

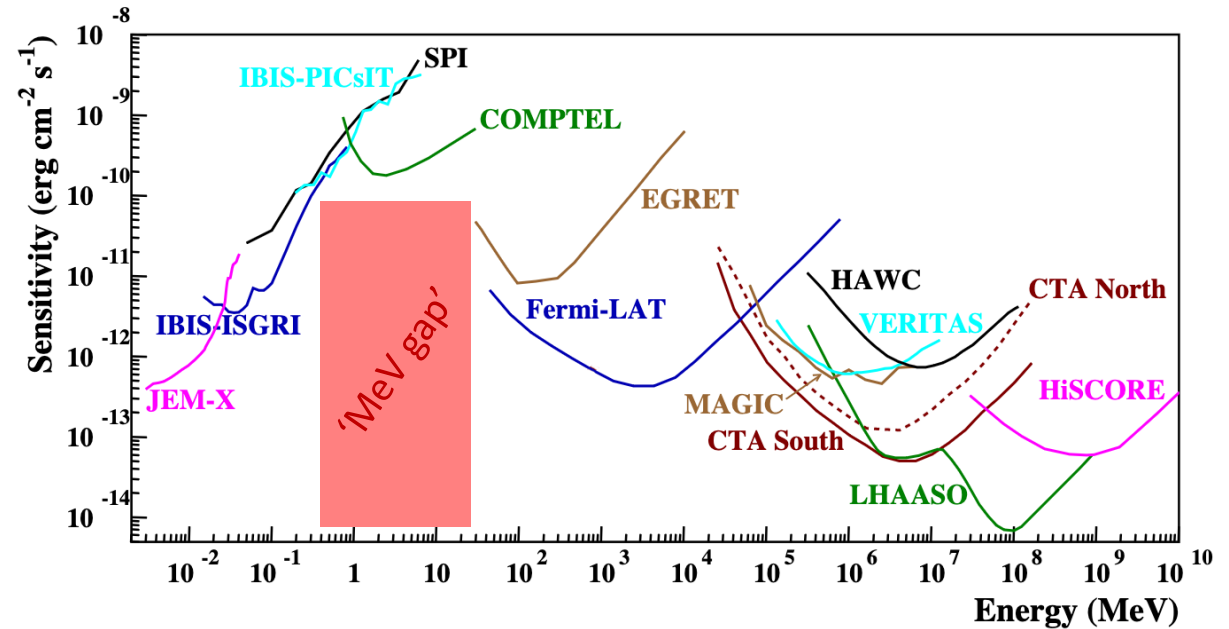
- No data of quality for γ -rays between ~ 100 keV – 100 MeV



Adapted from [De Angelis et al., eASTROGAM coll., 1611.02232](#)

Introduction

- No data of quality for γ -rays between ~ 100 keV – 100 MeV
- We focus on secondary emissions to circumvent this problem, and study light DM signals in the Milky Way using X-rays



Adapted from [De Angelis et al., eASTROGAM coll., 1611.02232](#)

X-rays from DM
annihilation/decay

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 - Secondary emissions:
 - **Inverse-Compton scattering** (ICS): up-scattering of ambient photons thanks to DM-produced $e^\pm$

$$\text{DM (DM)} \rightarrow \dots \rightarrow e \begin{array}{c} \diagup \quad \diagdown \\ \gamma_{amb} \quad \gamma \end{array} e'$$

X-rays from DM annihilation/decay

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$$1 \text{ MeV} < m_{DM} < 5 \text{ GeV}$$

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X-rays from DM annihilation/decay

- Differential flux of photons from prompt emissions:

X-rays from DM annihilation/decay

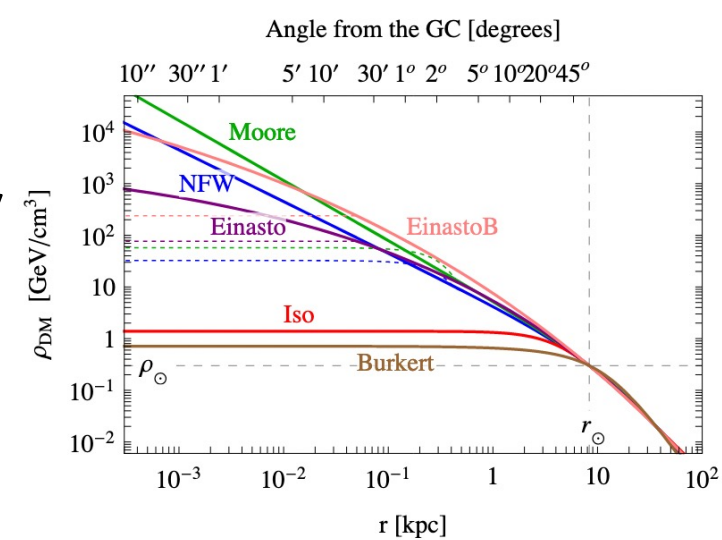
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$$f = \text{FSR, Rad} \quad \frac{d\Phi_{f,\gamma}}{dE_\gamma d\Omega} = \frac{1}{4\pi} \frac{dN_\gamma^f}{dE_\gamma} \times \begin{cases} \frac{1}{2} \frac{\langle\sigma v\rangle}{m_{DM}^2} \int_{l.o.s.} \rho_{DM}^2 ds & \text{(annihilation)} \\ \frac{\Gamma}{m_{DM}} \int_{l.o.s.} \rho_{DM} ds & \text{(decay)} \end{cases}$$

X-rays from DM annihilation/decay

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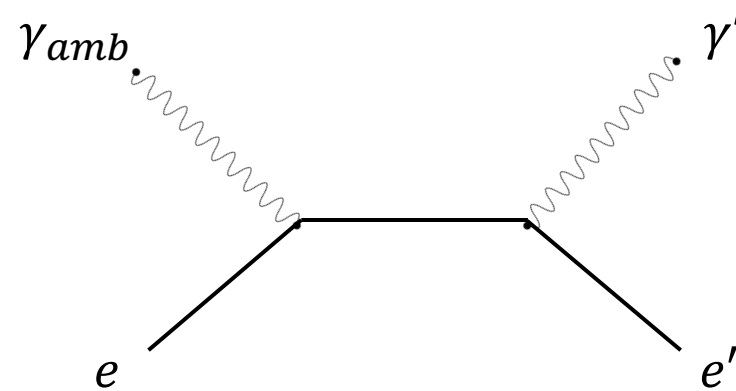
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Cirelli et al., 1012.4515

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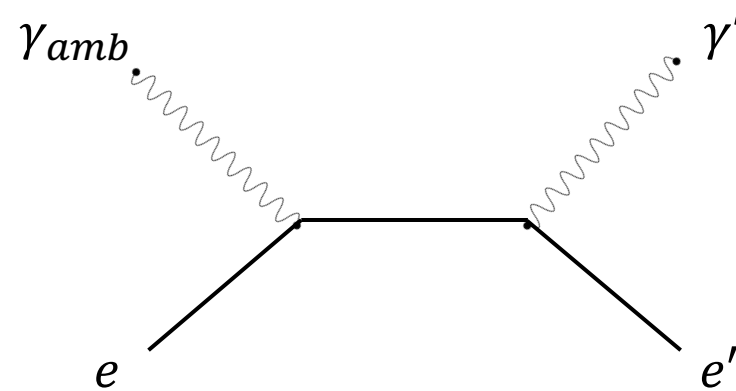
- DM-produced $e^\pm$ can up-scatter ambient photons up to X-ray energies



$$E_{\gamma'} \approx 4\gamma_e^2 E_{\gamma_{amb}} \quad \gamma_e = \frac{E_e}{m_e}$$

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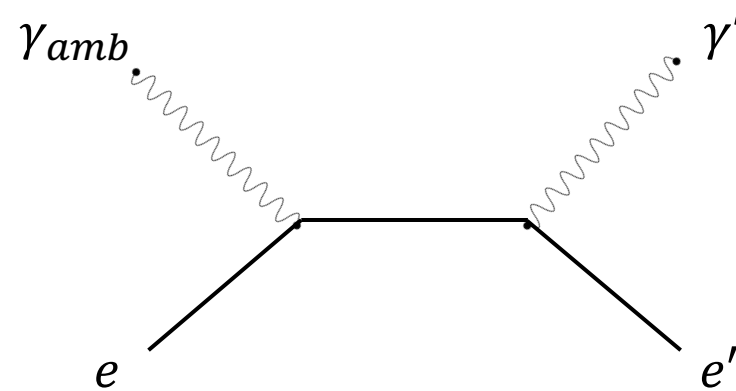


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- Energy range ~ 0.1 meV to 10 eV

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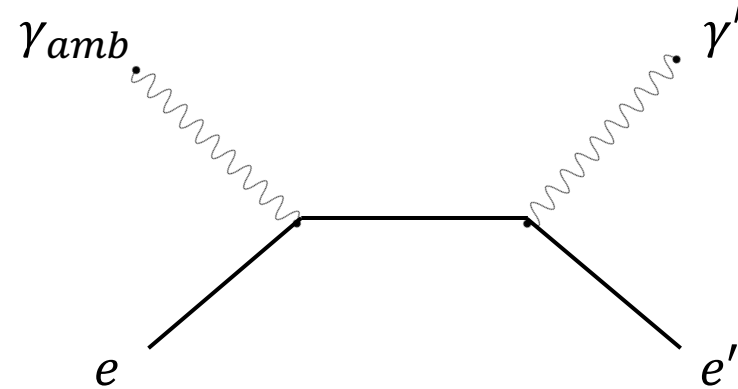
$$E_{\gamma'} \approx 4\gamma_e^2 E_{\gamma_{amb}} \quad \gamma_e = \frac{E_e}{m_e}$$

For a CMB photon up-scattered by a 1 GeV $e^\pm$:
 $E_{\gamma_{amb}} \approx 0.2 \text{ meV} \rightarrow E_{\gamma'} \approx 3 \text{ keV}$

- Ambient photons are: **CMB, dust-rescattered IR and optical starlight (SL)**
- Energy range $\sim 0.1 \text{ meV}$ to 10 eV

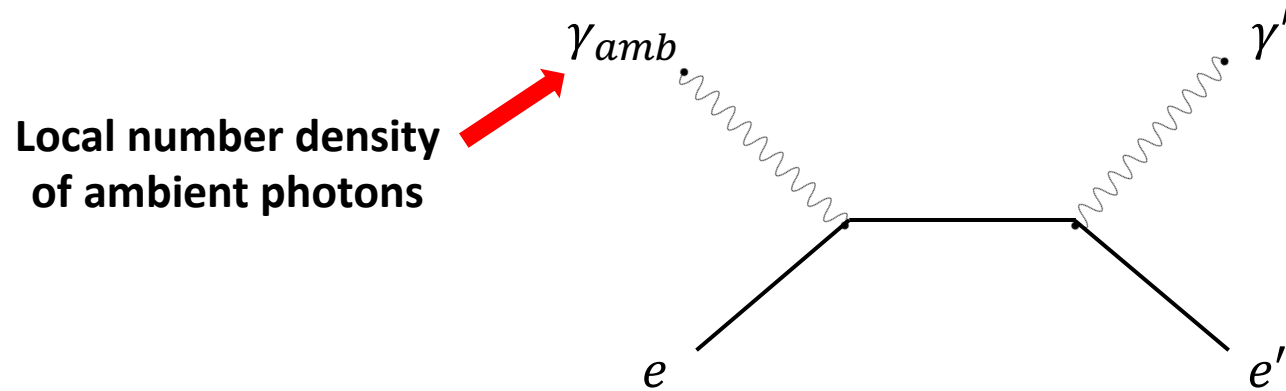
X-rays from DM annihilation/decay

- To compute the IC-scattered photon flux, we need a few ingredients:



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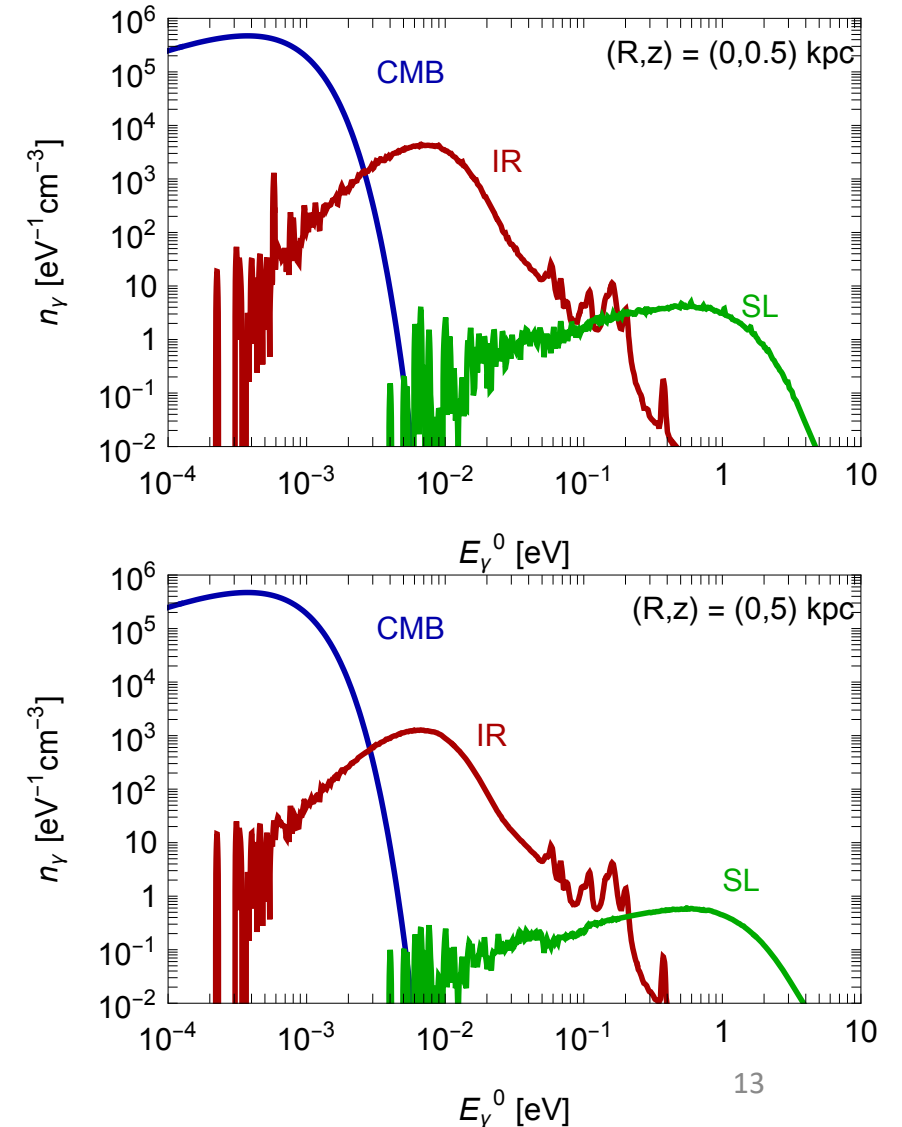
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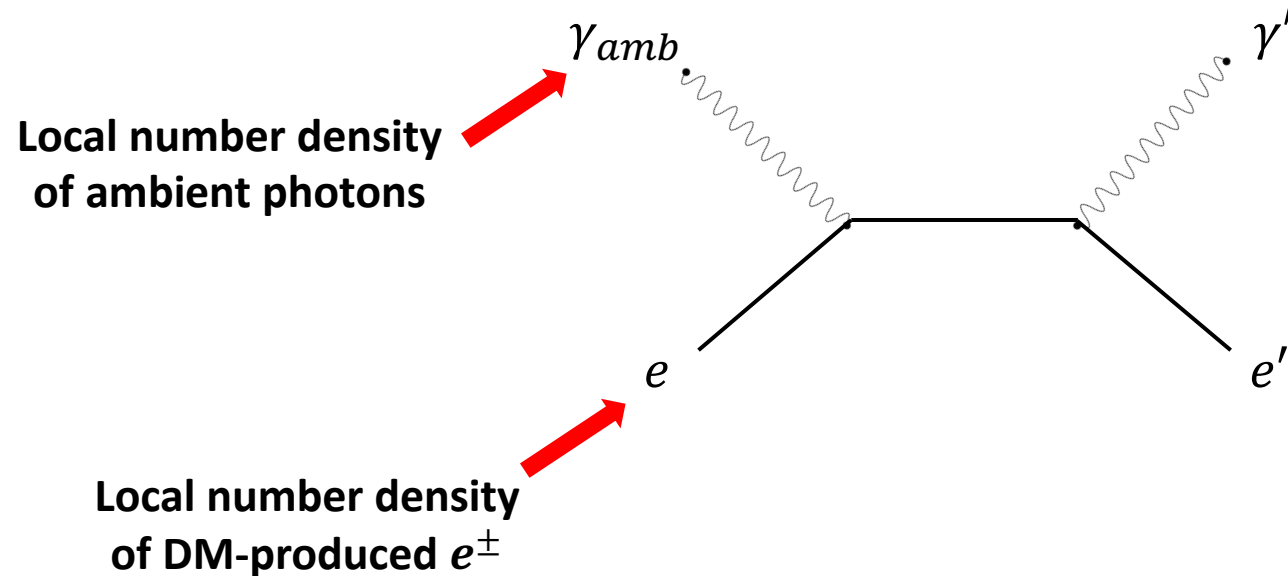
1) Local number density of ambient photons:

- For CMB, we use the black body spectrum
- For IR and SL, we use GalPROP intensity maps, in turn based on actual observations from COBE/DIRBE



X-rays from DM annihilation/decay

- To compute the IC-scattered photon flux, we need a few ingredients:



X-rays from DM annihilation/decay

2) Local number density of DM-produced $e^\pm$:

$$\frac{\partial f}{\partial t} = \underbrace{\nabla(\mathcal{K}(E_e, \vec{x})\nabla f)}_{\text{diffusion term}} + \underbrace{\frac{\partial}{\partial E_e}(b(E_e, \vec{x})f)}_{\text{energy loss term}} + \underbrace{Q(E_e, \vec{x})}_{\text{source term}}$$

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diffusion term

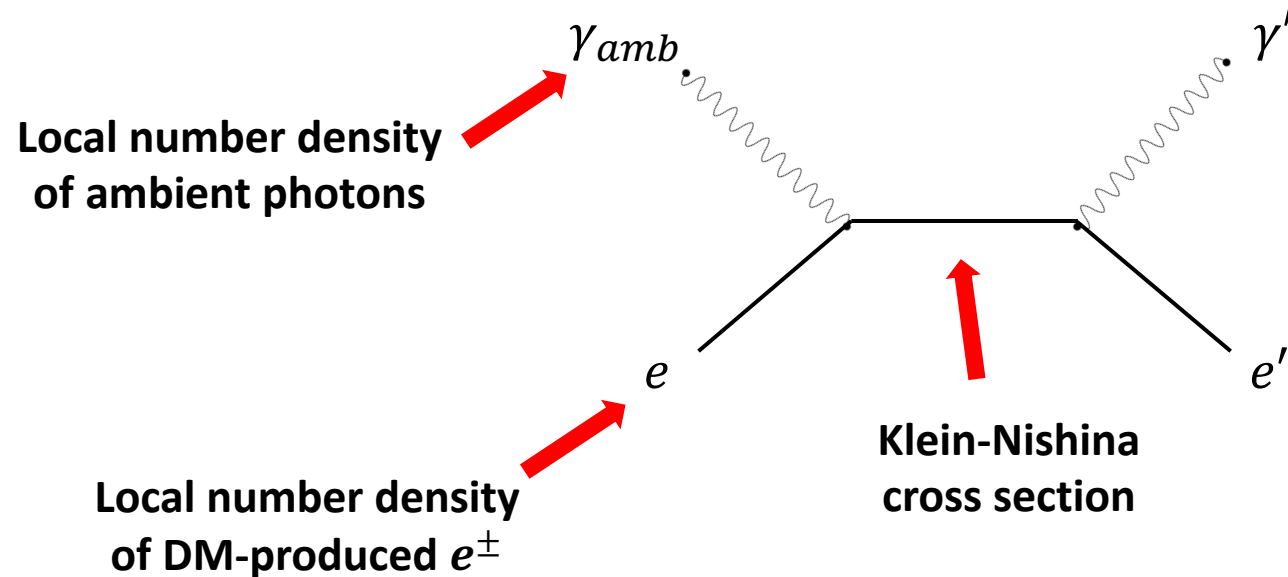
energy loss term

source term

- We study the steady-state regime
- For high-energy $e^\pm$ in the Milky Way, energy loss dominates over diffusion

X-rays from DM annihilation/decay

- To compute the IC-scattered photon flux, we need a few ingredients:



X-rays from DM annihilation/decay

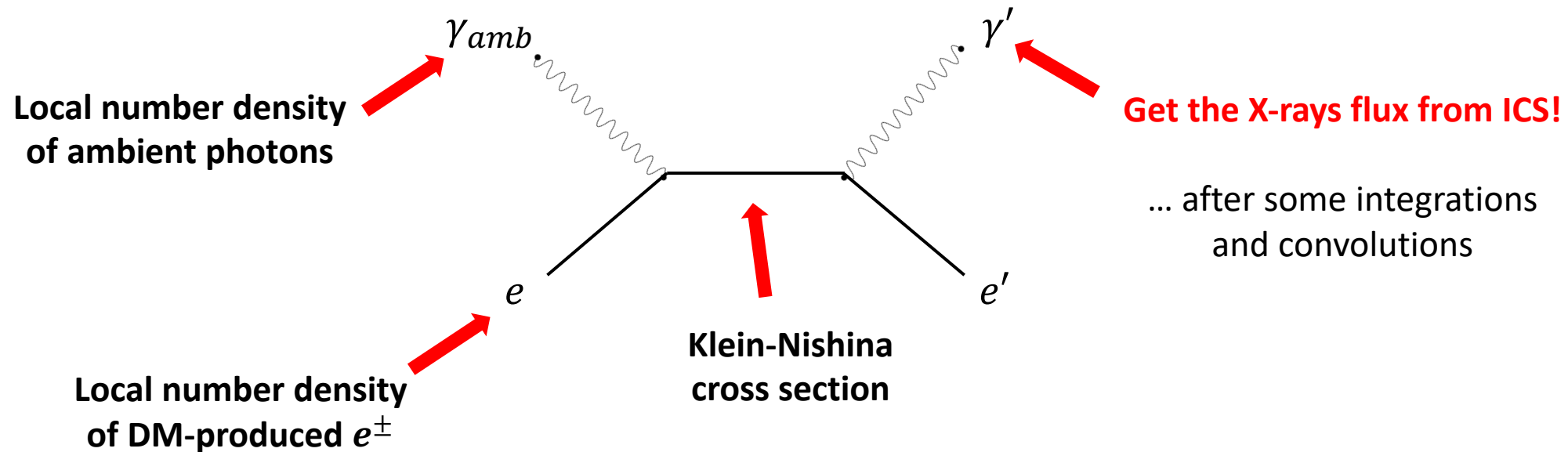
3) Klein-Nishina cross section in the Thomson limit ($E_\gamma \ll E_e$)

$$\sigma_{IC}(y, E_e) = \frac{3\sigma_T}{4\gamma_e^2} \frac{2y \ln y + y + 1 - 2y^2}{y}$$

$$y = \frac{E_\gamma}{4\gamma_e^2 E_\gamma^0}, \quad \gamma_e = \frac{E_e}{m_e}$$

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Analysis and results

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- In this study we keep a **conservative** approach:

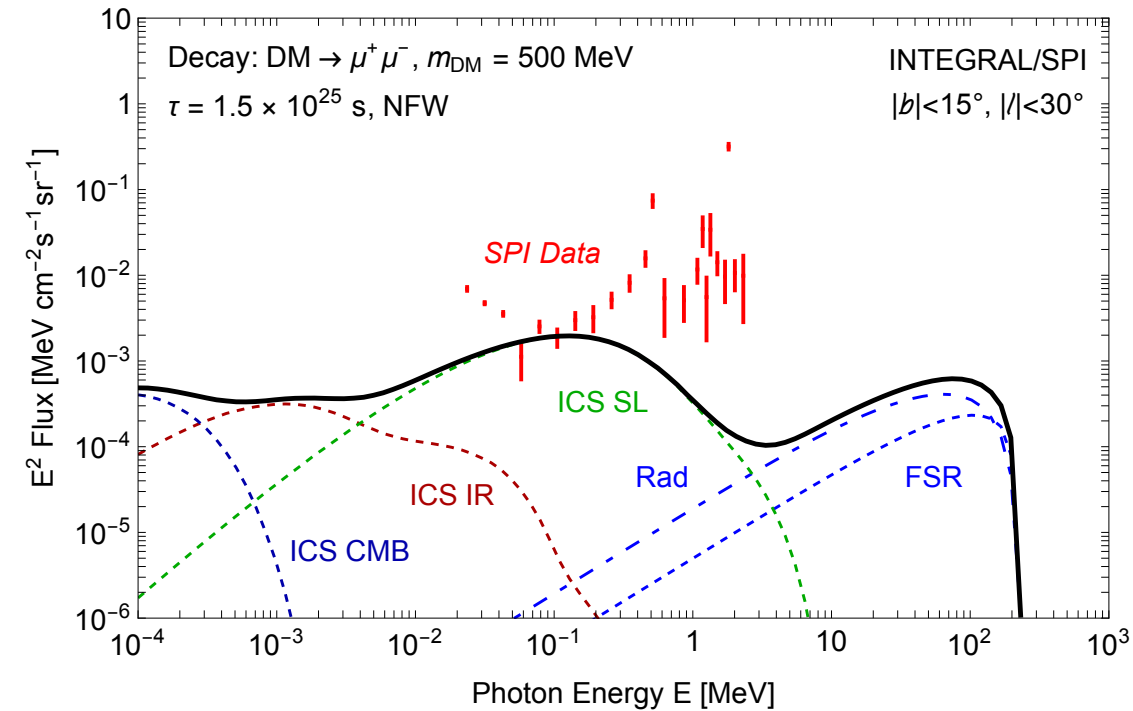
Analysis and results

- In this study we keep a **conservative** approach:

$$\chi^2_{>}(p, m_{DM}) = \sum_{i \in \text{bins}} \frac{\text{Max}(\Phi_{DM\gamma,i}(p, m_{DM}) - \Phi_i, 0)^2}{\sigma_i^2}$$

$$p = \langle \sigma v \rangle, \Gamma$$

- Impose a (2σ) bound when $\chi^2_{>}(p, m_{DM}) \geq 4$

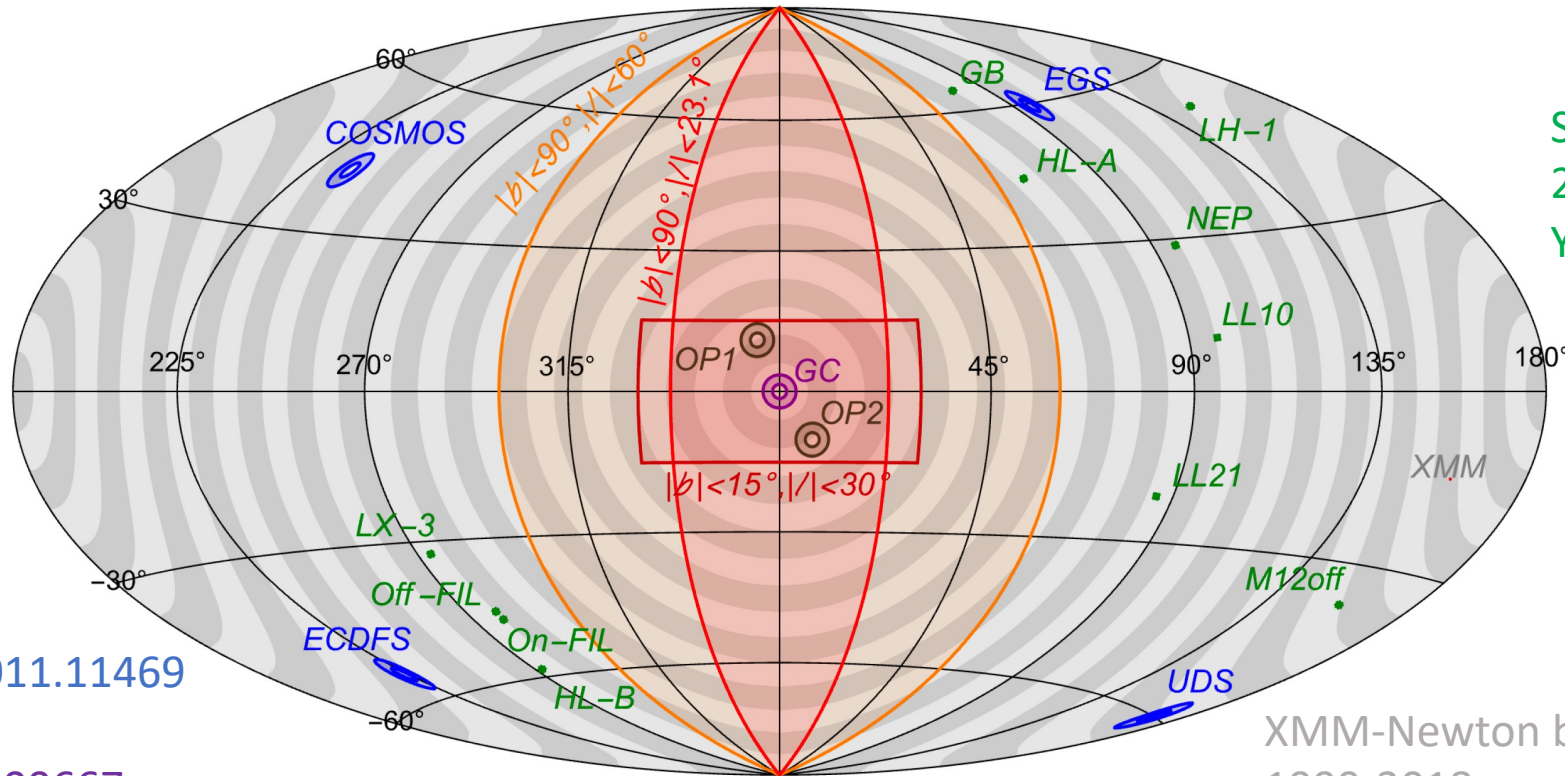


Analysis and results

INTEGRAL diffuse emission searches
2003-2009

Bouchet et al., INTEGRAL coll., 1107.0200

Suzaku high-latitude fields
2006-2008
Yoshino et al., 0903.2981

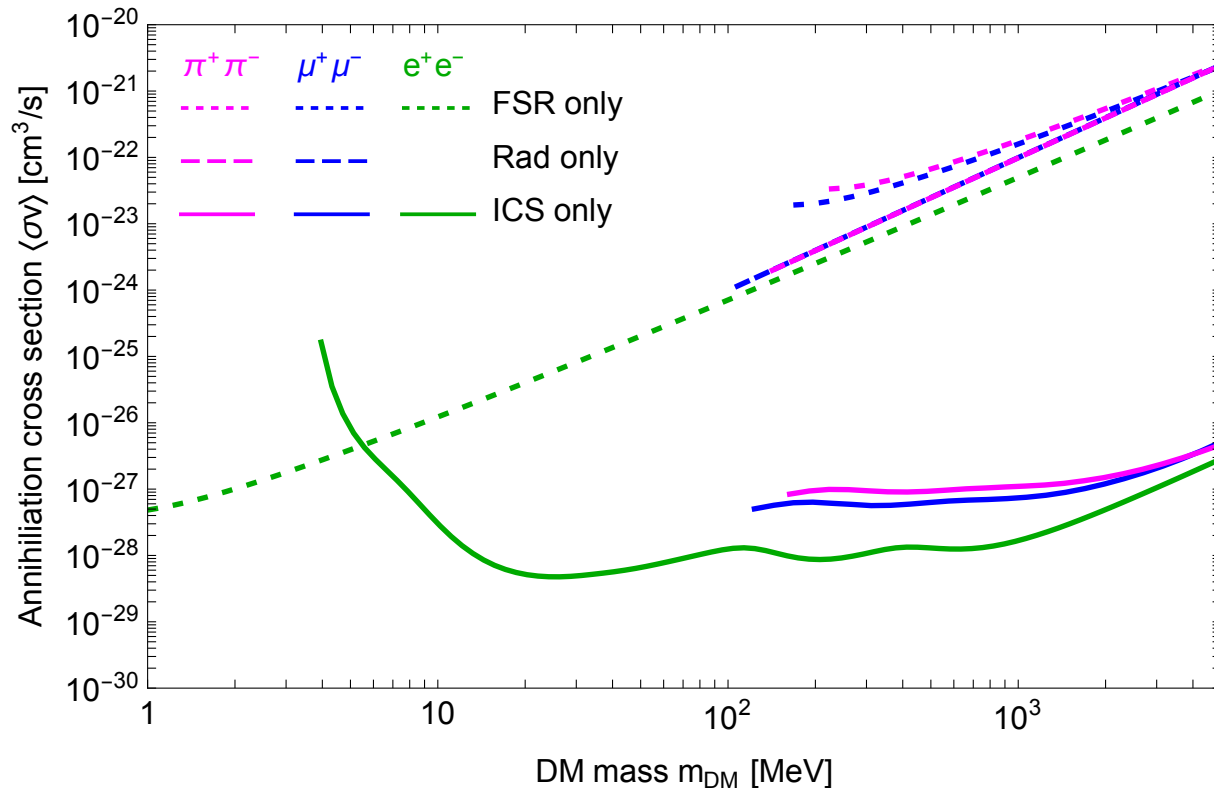


NuSTAR
2012-2018
Blank-sky fields
Krivonos et al., 2011.11469
GC observations
Perez et al., 1609.00667
Off-plane observations
Roach et al., 1908.09037

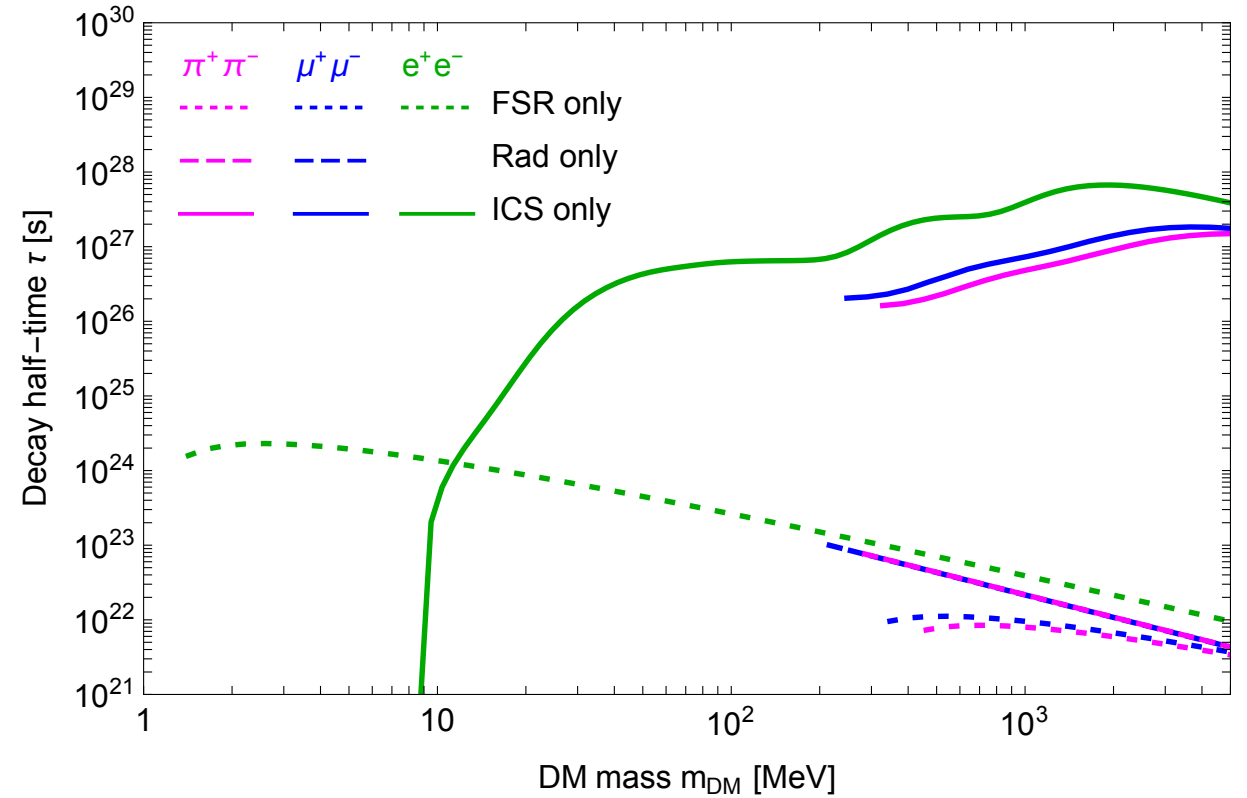
XMM-Newton blank-sky data
1999-2018
Foster et al., 2102.02207
https://github.com/bsafdi/XMM_BSO_DATA

Analysis and results

Bounds on annihilating Dark Matter



Bounds on decaying Dark Matter



Analysis and results

Diffuse γ -rays: [Essig et al., 1309.4091](#)

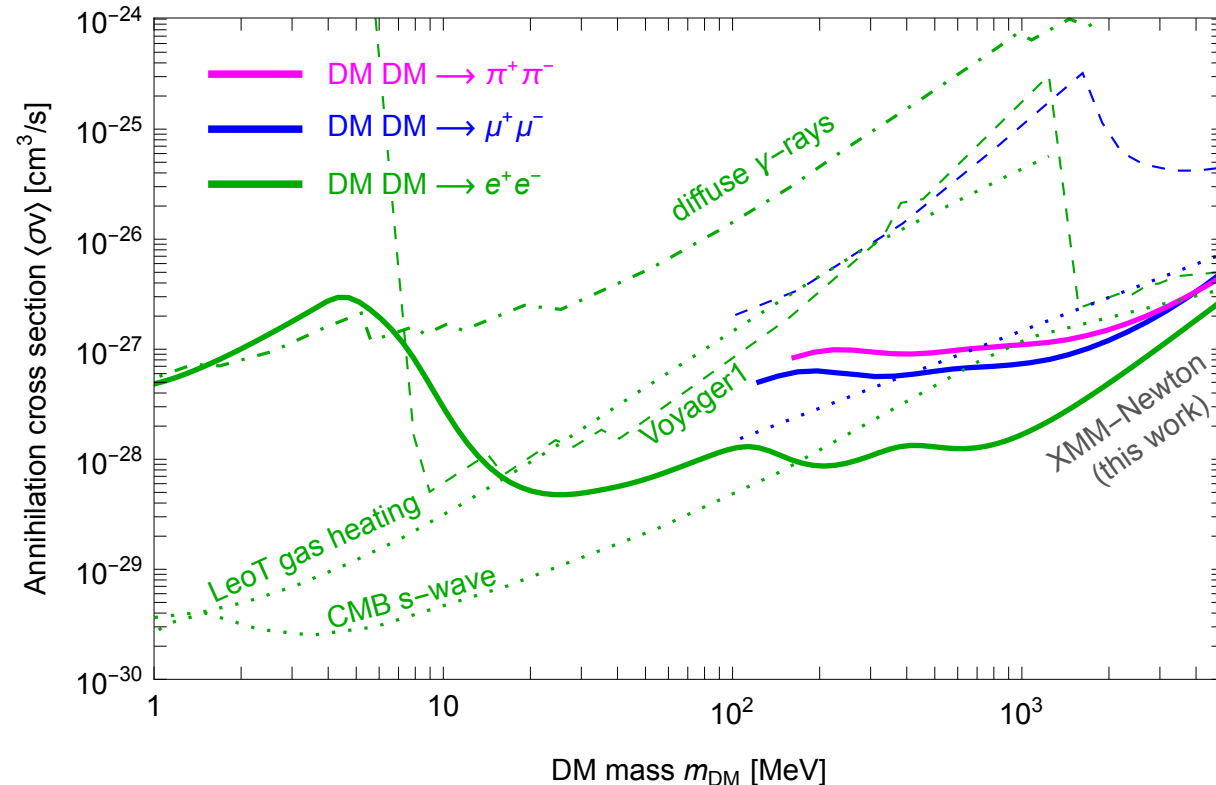
Voyager1: [Boudaud et al., 1612.07698](#)

Leo T gas heating: [Wakedar and Wang, 2111.08025](#)

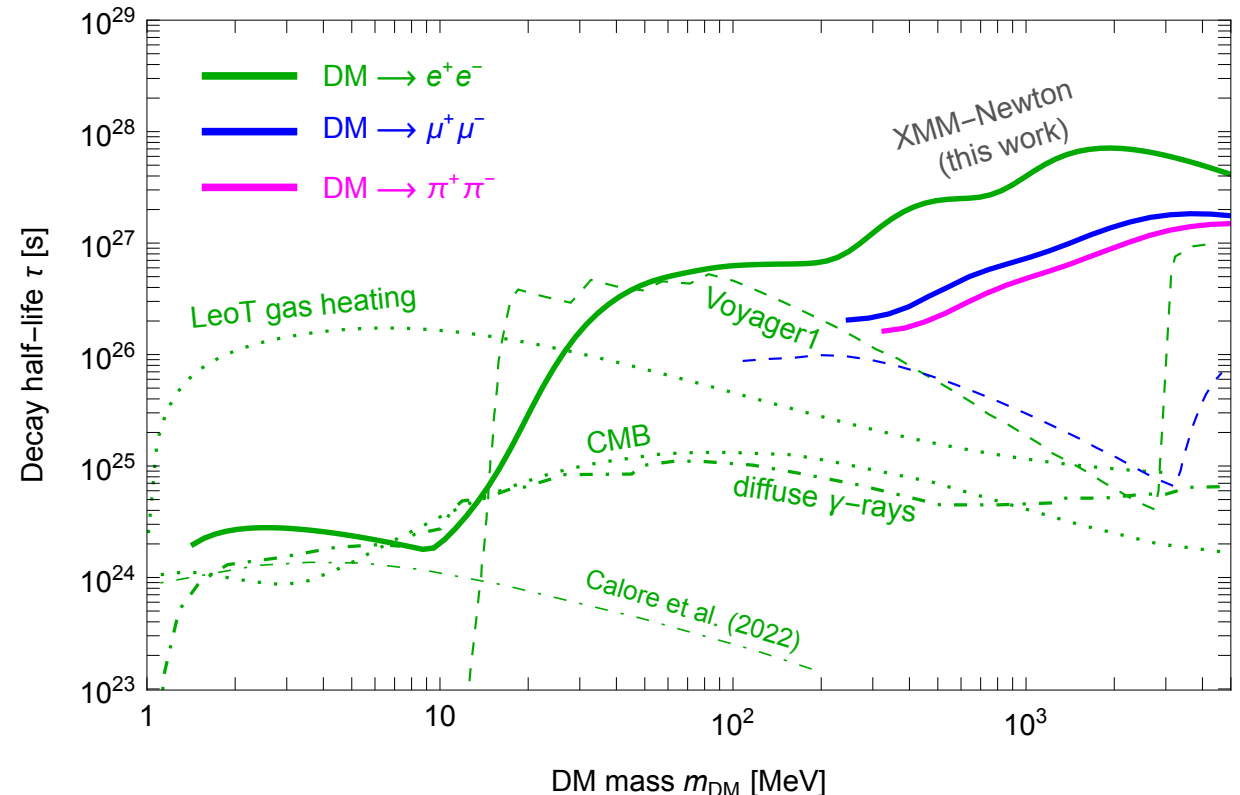
CMB (s-wave): [Slatyer, 1506.03811](#),
[Lopez-Honorez et al., 1303.5094](#),
[Liu et al., 1604.02457](#)

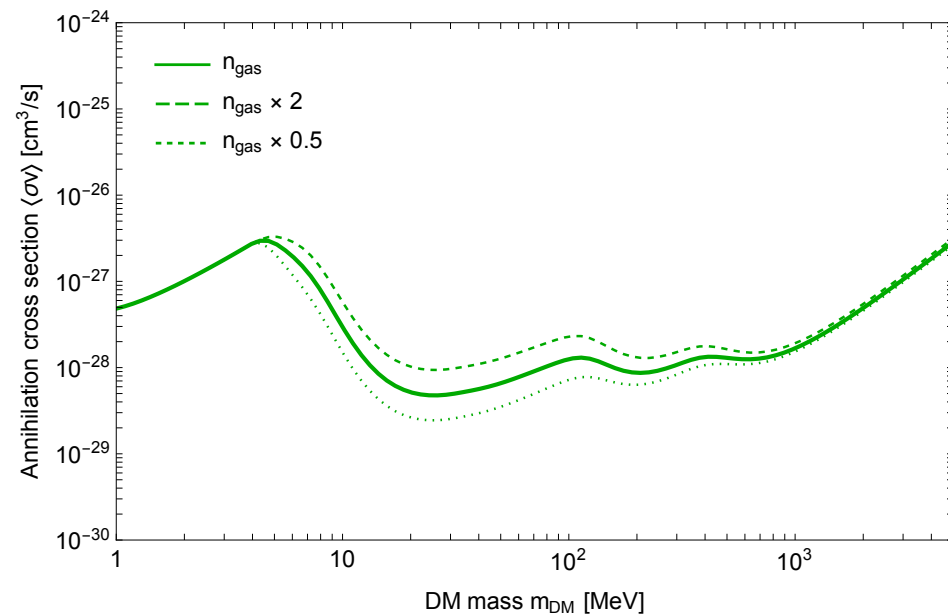
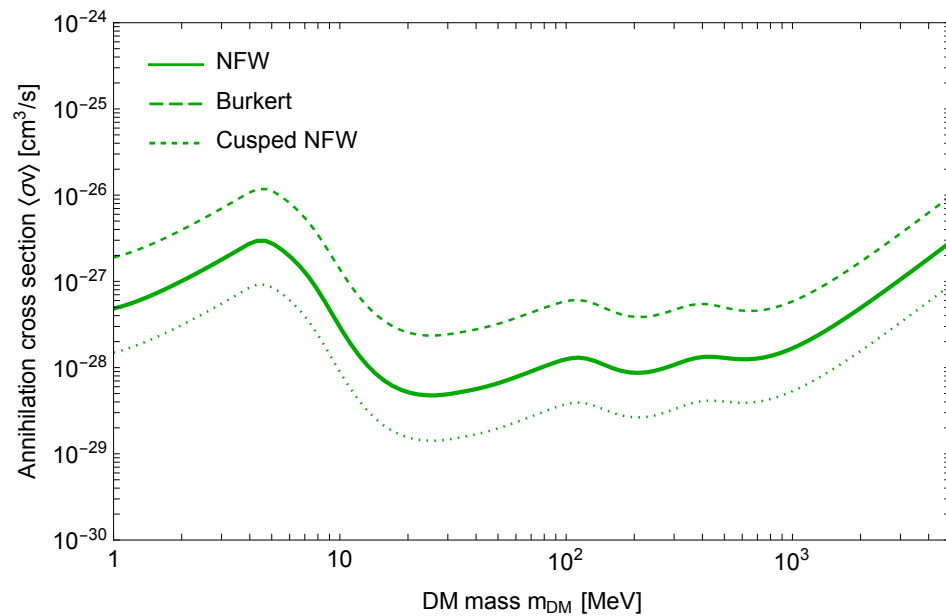
INTEGRAL FSR: [Calore et al. 2209.06299](#)

Bounds on annihilating Dark Matter

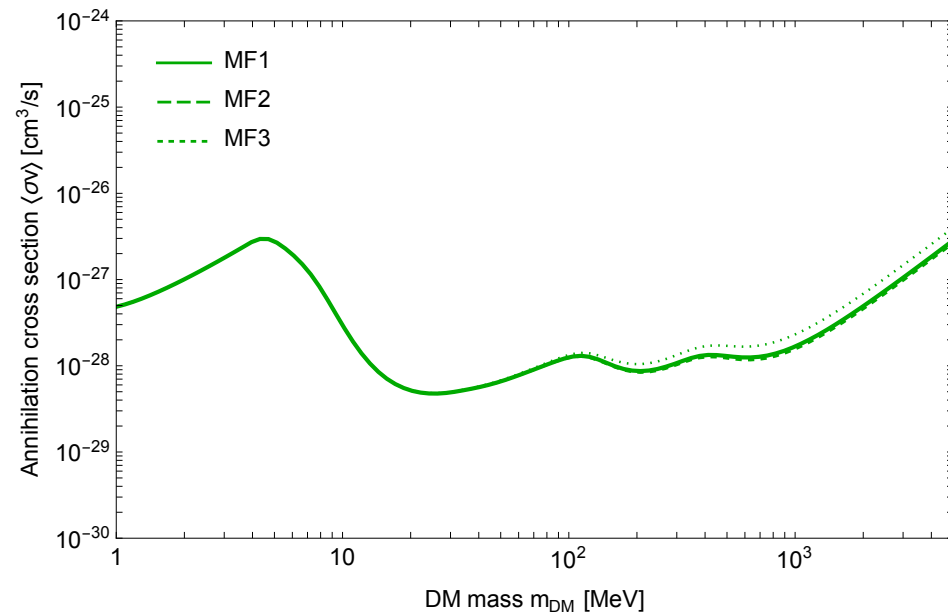
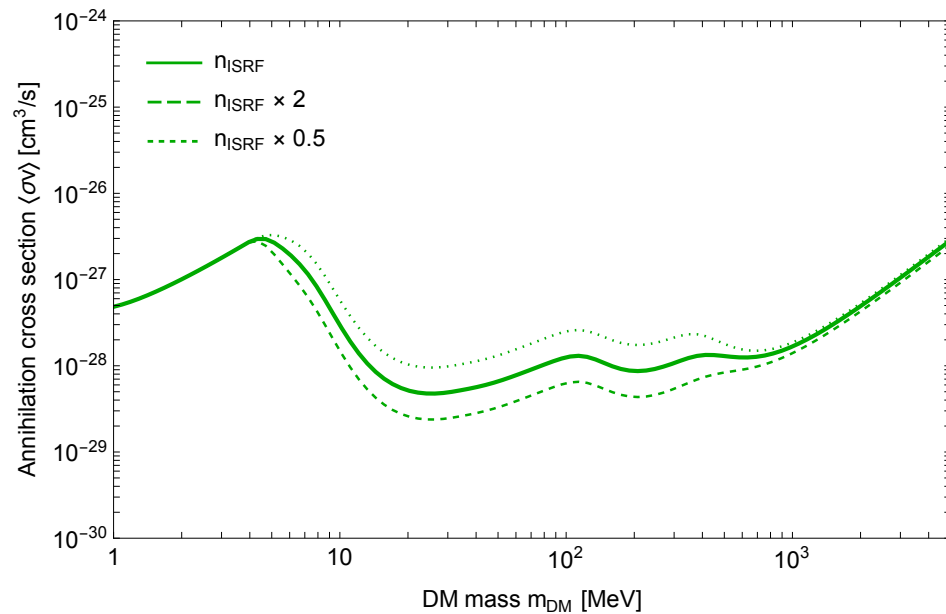


Bounds on decaying Dark Matter

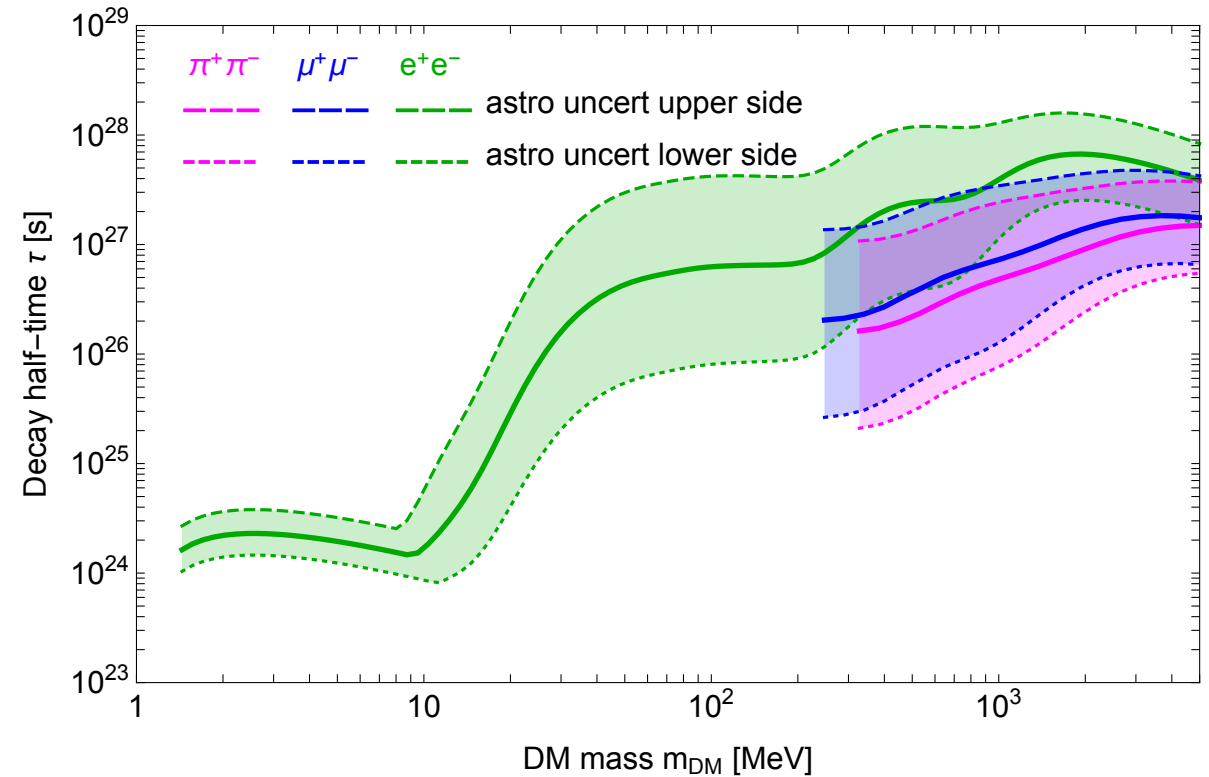
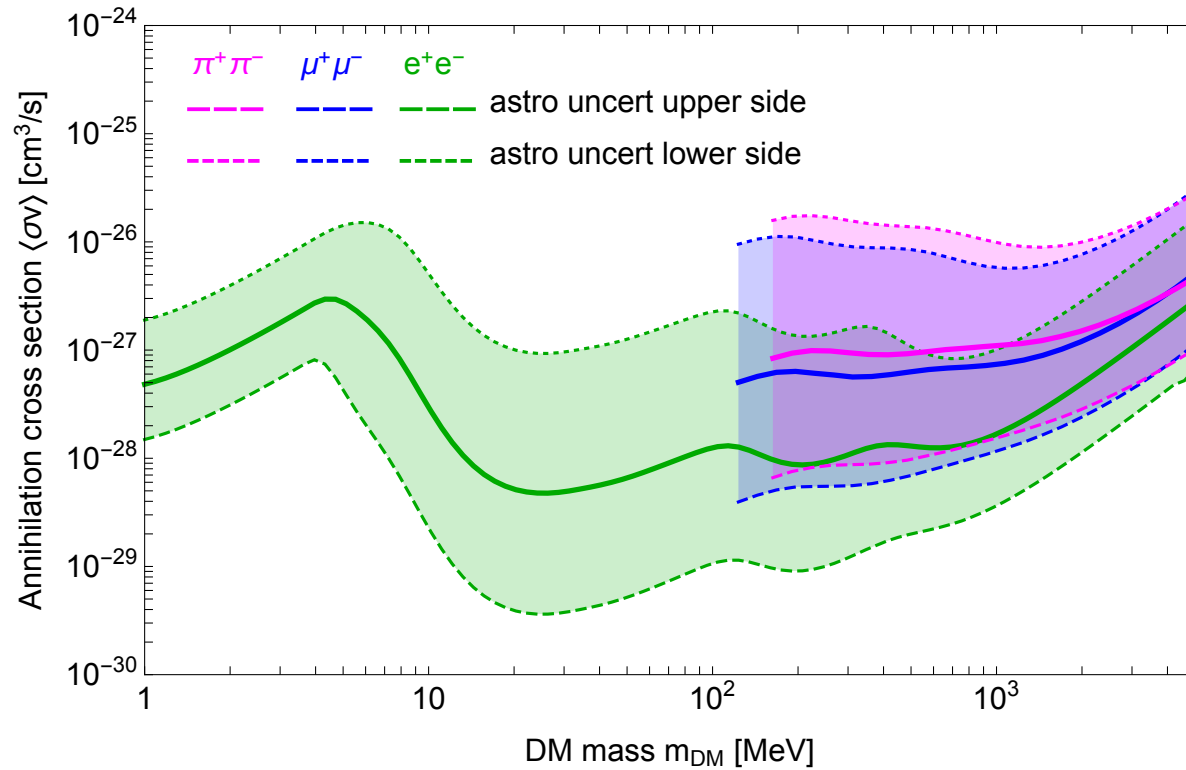




DM DM $\rightarrow e^+e^-$



Analysis and results



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- Background modeling can improve our constraints
- Uncertainties are large, using more up-to-date ingredients may help
- Other possible directions: p-wave annihilation, testing BSM models, ...

Thank you for your attention!

Backup

Diffusion-loss equation ingredients

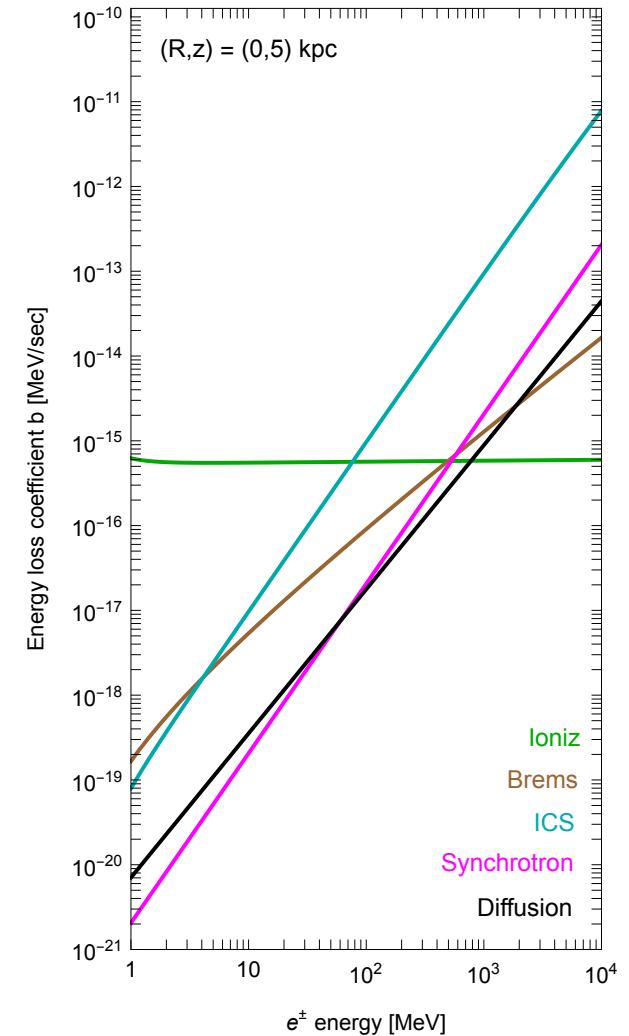
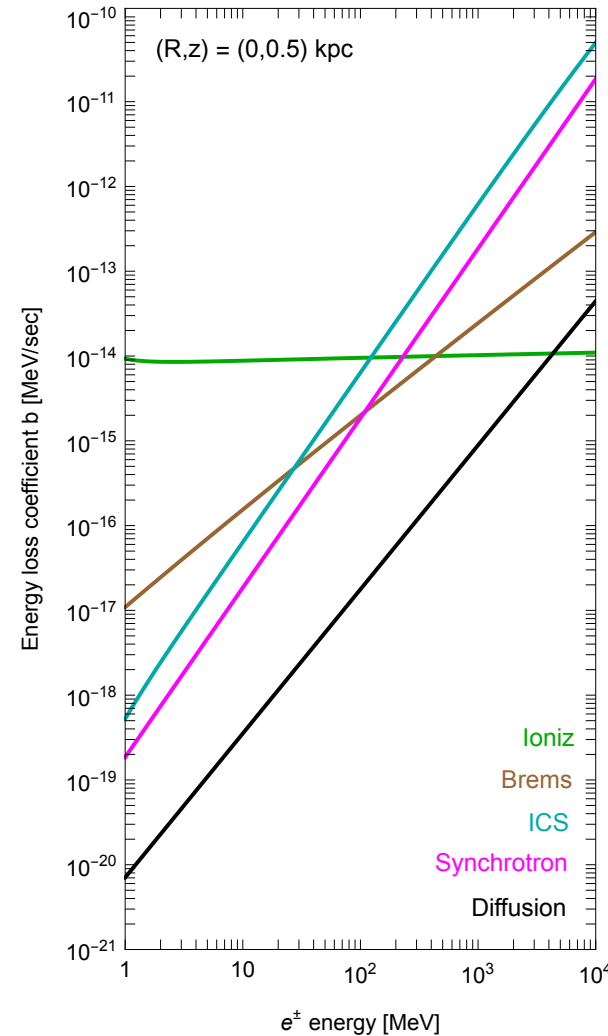
$$b(E_e, \vec{x}) = b_{\text{Coul}+\text{ioniz}} + b_{\text{brems}} + b_{\text{ICS}} + b_{\text{syn}}$$

Depends on the local ISRF density

Depend on the local gas density

Depends on the galactic magnetic field configuration

- $b(E_e, \vec{x})$ taken from [PPPC4DMID](#)
- Diffusion curve: $b_{\text{diff}}(E_e) \sim E_e / \tau_{\text{diff}}(E_e)$



Diffusion-loss equation ingredients

- Source term: $Q(E_e, \vec{x}) = \begin{cases} \frac{\langle \sigma v \rangle}{2} \left(\frac{\rho_{DM}(\vec{x})}{m_{DM}} \right)^2 \frac{dN_{e^\pm}}{dE_e} \\ \Gamma \left(\frac{\rho_{DM}(\vec{x})}{m_{DM}} \right) \frac{dN_{e^\pm}}{dE_e} \end{cases}$
- Where $\frac{dN_{e^\pm}}{dE_e}$ is the $e^\pm$ injection spectrum:
 - For the e^+e^- channel: monochromatic ($DM \rightarrow e^\pm$)
 - For the $\mu^+\mu^-$ channel: boosted Michel spectrum ($DM \rightarrow \mu^\pm \rightarrow e^\pm$)
 - For the $\pi^+\pi^-$ channel: double boosted Michel spectrum ($DM \rightarrow \pi^\pm \rightarrow \mu^\pm \rightarrow e^\pm$)

Michel spectrum and boosts

- Michel spectrum:
$$\frac{dN_e^{\mu \rightarrow e \nu \bar{\nu}}}{dE_e} = \frac{4\sqrt{\xi^2 - 4\varrho^2}}{m_\mu} [\xi(3 - 2\xi) + \varrho^2(3\xi - 4)]$$

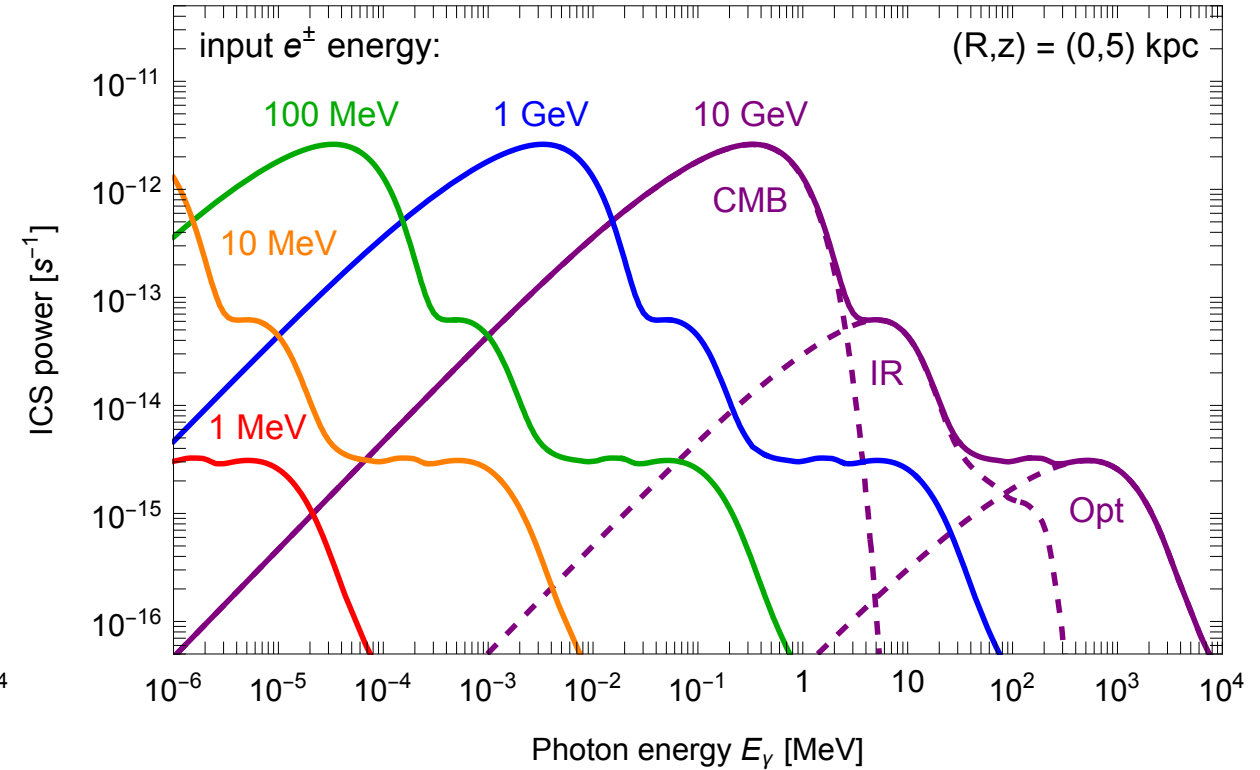
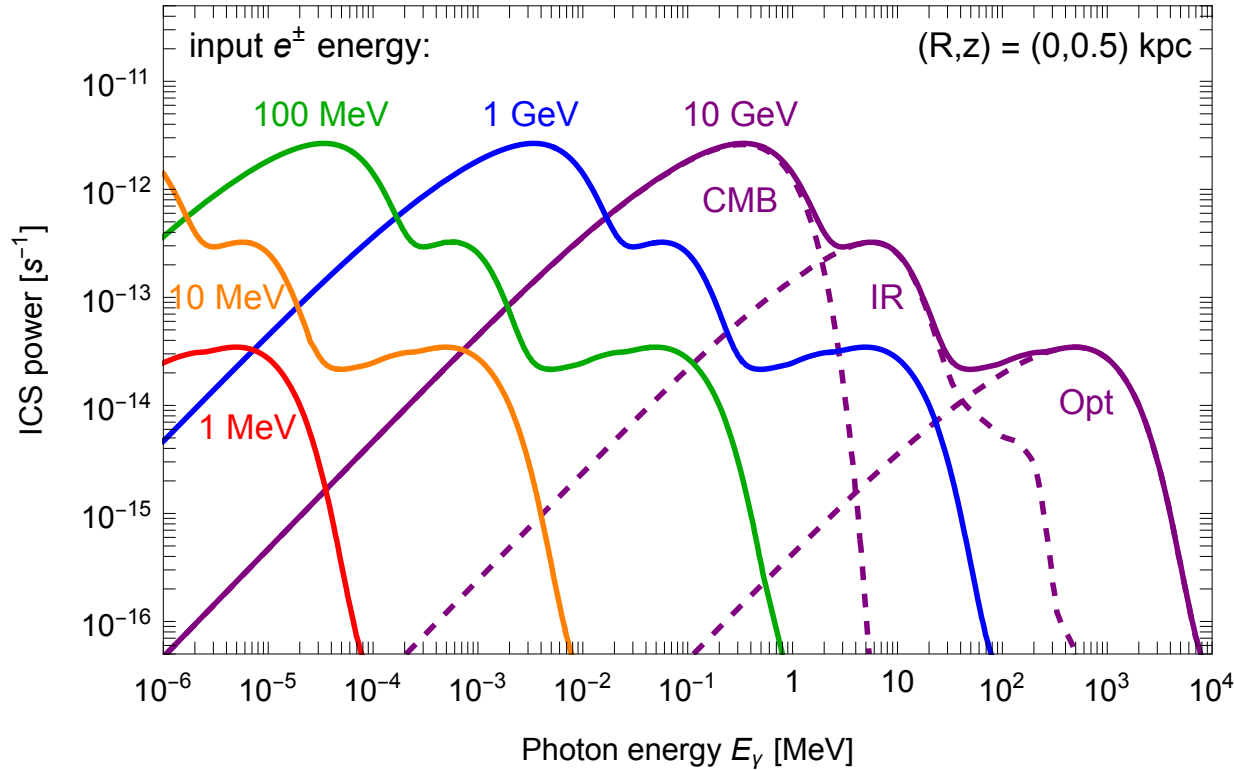
$$\xi = \frac{2E_e}{m_\mu}, \quad \varrho = \frac{m_e}{m_\mu}$$

- Lorentz boost:
$$\frac{dN}{dE} = \frac{1}{2\beta\gamma} \int_{E'_{min}}^{E'_{max}} \frac{1}{p'} \frac{dN}{dE'}$$

$$E'_{max|min} = \gamma(E \pm \beta p)$$

$$\gamma = \frac{E_A}{m_A} \quad (A = \text{parent particle})$$

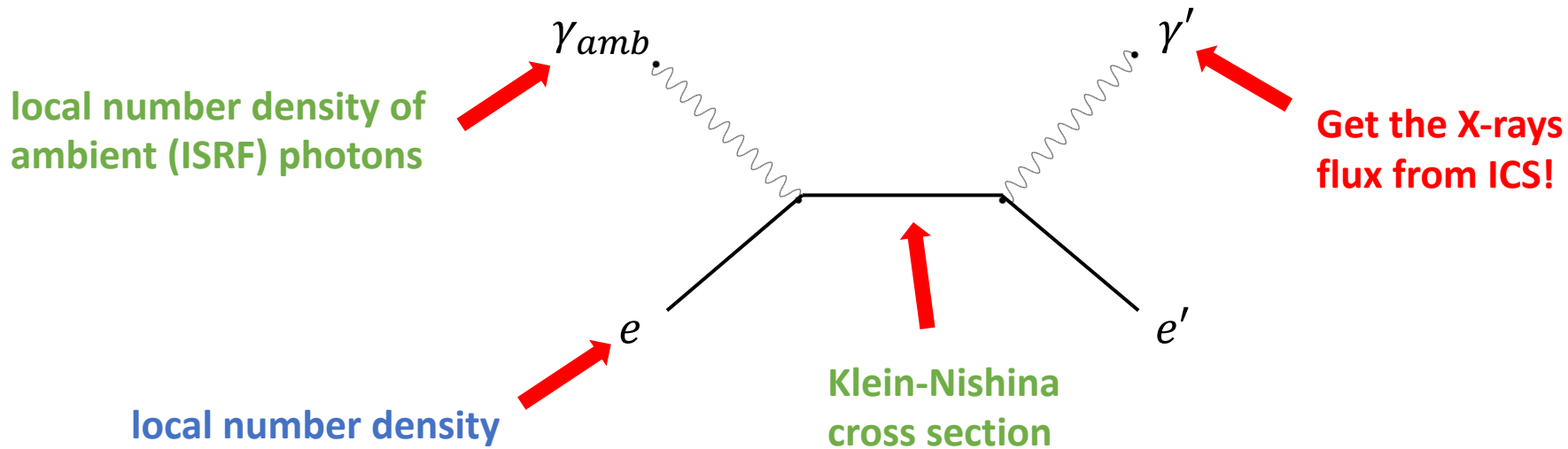
Inverse-Compton scattering power



$$\mathcal{P}_{IC,i}(E_\gamma, E_e, \vec{x}) = E_\gamma \int dy n_i(y, \vec{x}) \sigma_{IC}(E_e, y)$$

Inverse-Compton scattering

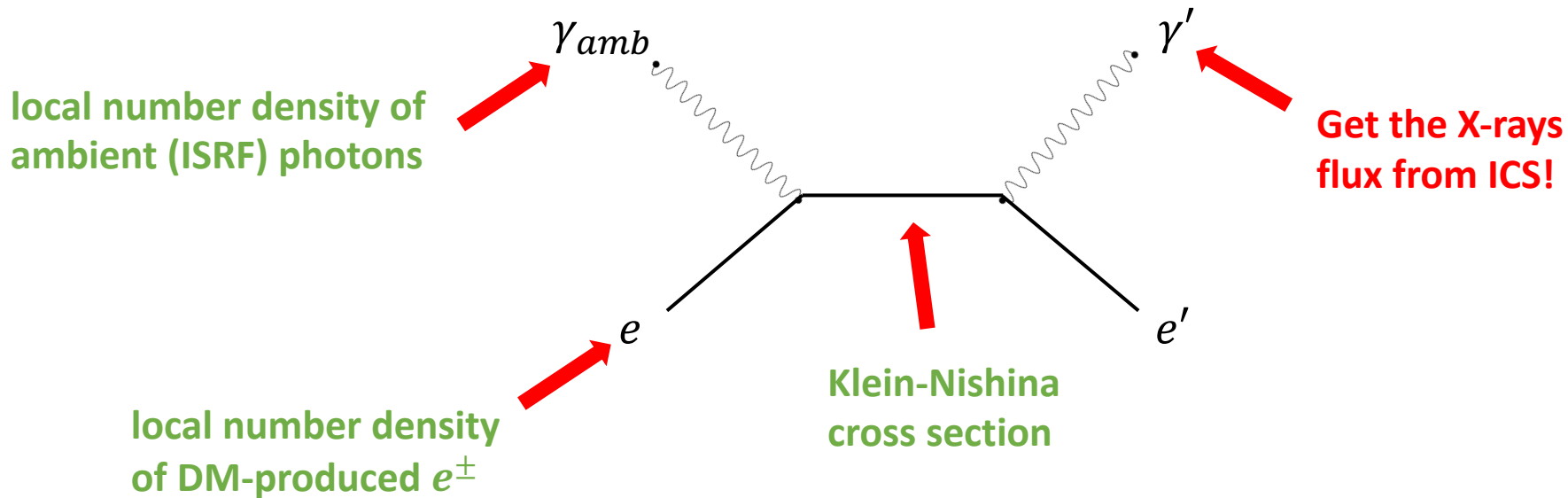
- To compute the IC-scattered photon flux, we need a few ingredients:



$$j(E_\gamma, \vec{x}) = 2 \int_{m_e}^{m_{DM}} dE_e \mathcal{P}_{IC,tot}(E_\gamma, E_e, \vec{x}) f(E_e, \vec{x})$$

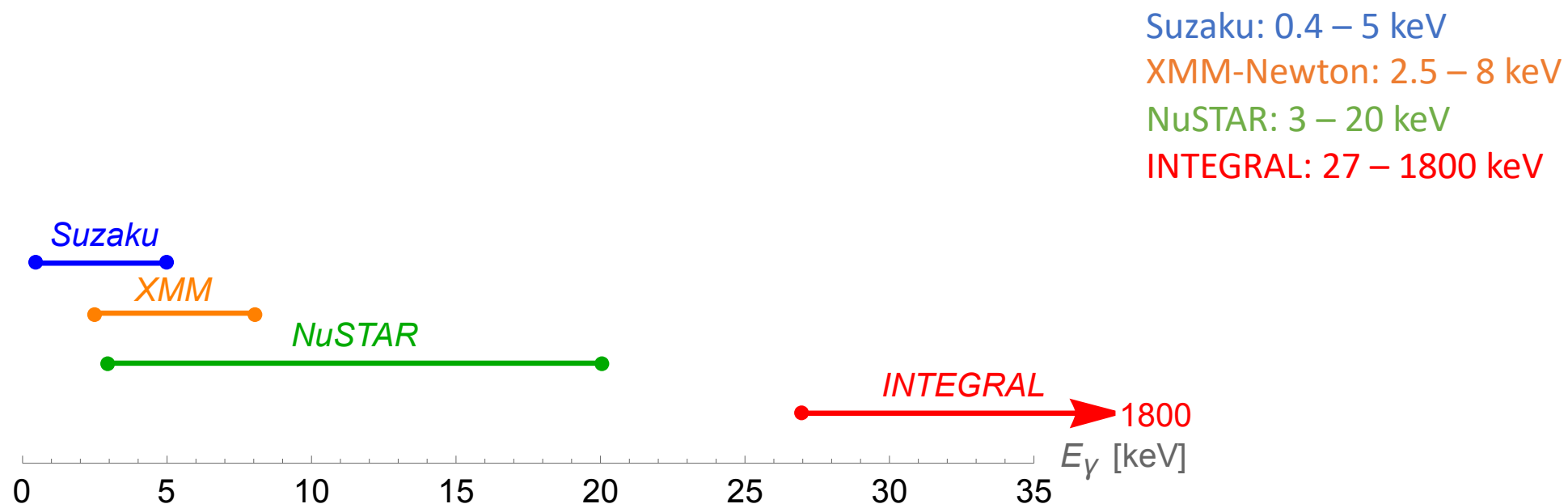
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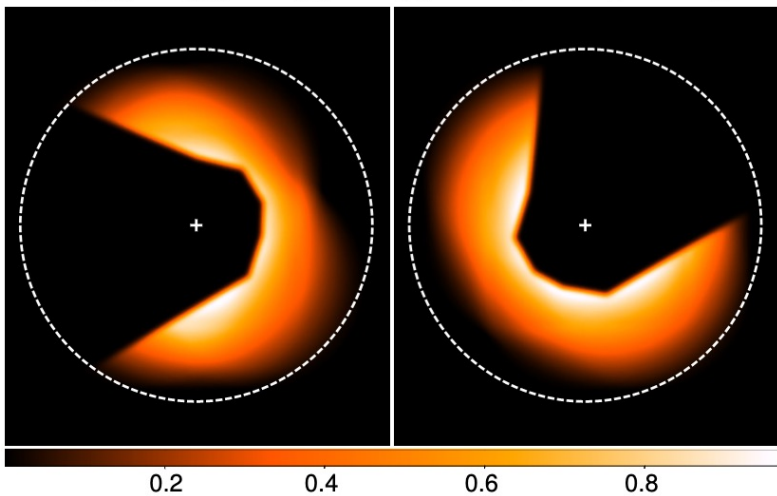
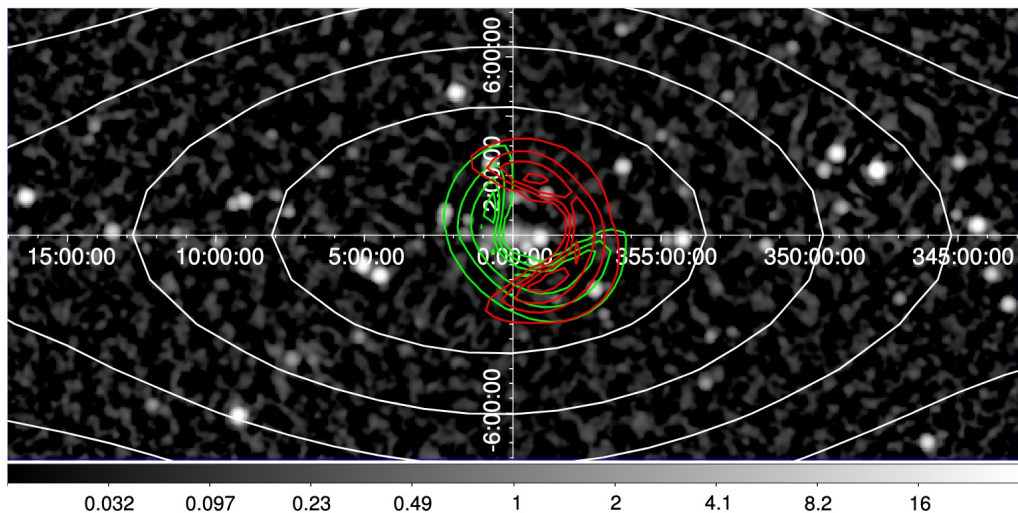


$$\frac{d\Phi_{IC\gamma}}{dE_\gamma d\Omega} = \frac{1}{4\pi E_\gamma} \int_{l.o.s.} ds j(E_\gamma, \vec{x}(s, b, l))$$

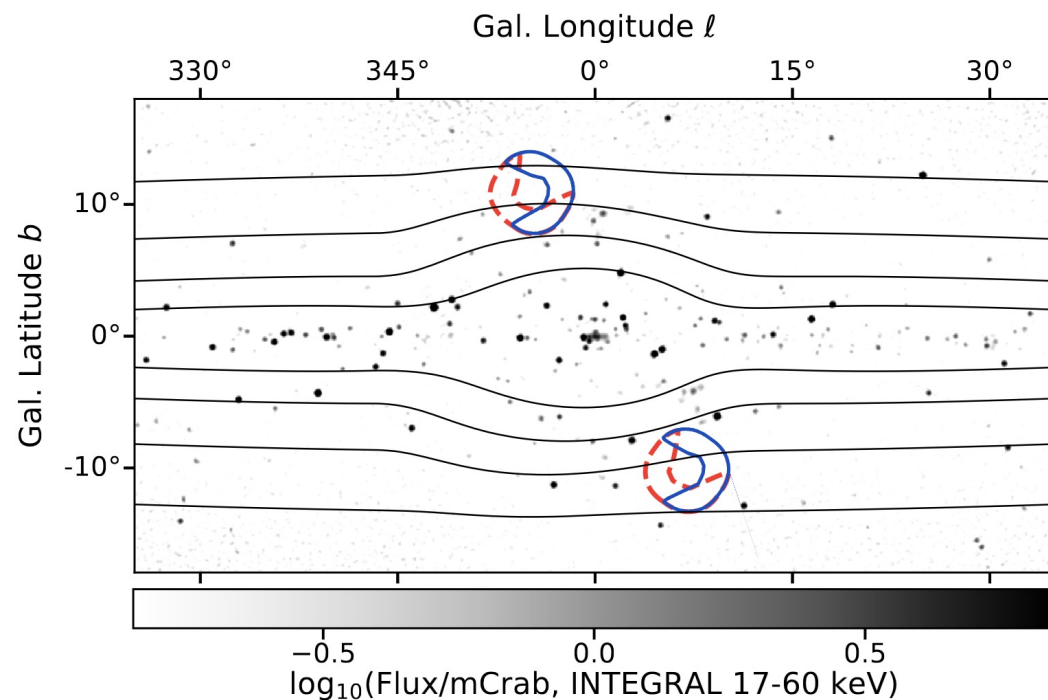
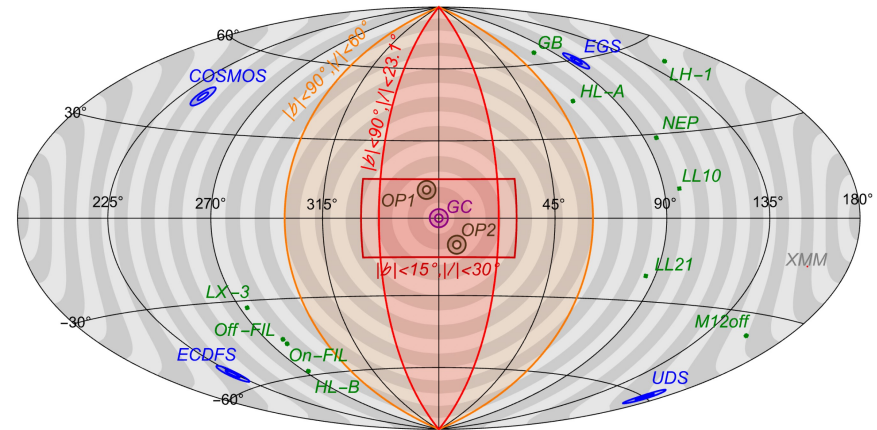
Dataset energy ranges



NuSTAR datasets



Perez et al.,
1609.00667



Roach et al., 1908.09037

NuSTAR datasets

Table 2. Data sets used in the analysis.

ID	Field	Begin	End	T_{exp}
1	COSMOS <i>EP1</i>	26-12-2012	20-01-2013	750 ks
2	COSMOS <i>EP2</i>	03-04-2013	21-05-2013	630 ks
3	COSMOS <i>EP3</i>	03-12-2013	25-02-2014	1020 ks
4	EGS	15-11-2013	27-11-2014	1.5 Ms
5	ECDFS	28-09-2012	01-04-2013	1.4 Ms
6	UDS	24-01-2016	18-11-2016	1.7 Ms

Krivonos et al., 2011.11469

Data taken between 2012 and 2016

TABLE I. *NuSTAR* observations used for this analysis.

Observation ID	Pointing (J2000) ^a		Effective Exposure ^b FPMA / FPMB (ks)	Detector Area ^c FPMA / FPMB (cm ²)	Avg. Solid Angle ^d FPMA / FPMB (deg ²)
	RA (deg)	DEC (deg)			
40032001002	265.8947	−29.5664	39.7 / 39.6	9.89 / 11.10	3.73 / 4.09
40032002001	265.7969	−29.5139	39.8 / 39.6	7.14 / 8.05	4.06 / 4.12
40032003001	265.6991	−29.4613	39.8 / 39.6	8.18 / 8.92	3.47 / 4.01
40032004002	265.9550	−29.4812	22.6 / 22.7	4.19 / 6.54	2.34 / 3.13
40032005002	265.8572	−29.4288	25.6 / 25.8	9.78 / 7.85	3.80 / 3.85
40032006001	265.7595	−29.3762	28.6 / 28.6	9.98 / 6.18	3.76 / 3.74

^a Roll angle was 332° for all.

^b After all data cleaning.

^c After stray light, ghost ray, and bad pixel removal.

^d Average solid angle of sky from which 0-bounce photons can be detected, after correcting for removal of stray light, ghost rays, and bad pixels, as well as efficiency due to vignetting effects.

Perez et al., 1609.00667

Data taken between 2012 and 2014

TABLE I. *NuSTAR* Galactic Bulge observations used in this analysis, with 0-bounce effective areas after data cleaning.

NuSTAR obsID	Pointing (J2000)	Effective Exposure ^a FPMA / B (ks)	Detector Area A_{0b} ^b FPMA / B (cm ²)	Solid Angle $\Delta\Omega_{0b}$ ^c FPMA / B (deg ²)
	RA, Dec (deg)			
40410001002	253.2508, −26.6472	50.0 / 49.8	11.97 / 11.88	4.36 / 4.62
40410002002	280.3521, −27.6344	44.7 / 44.6	12.71 / 12.60	4.53 / 4.56

^a After OPTIMIZED SAA filtering and manual data screening.

^b After bad pixel removal (both obsIDs) and point-source masking (40410001002 only).

^c Average solid angle of sky for detecting 0-bounce photons, after correcting for bad pixel removal and vignetting efficiency.

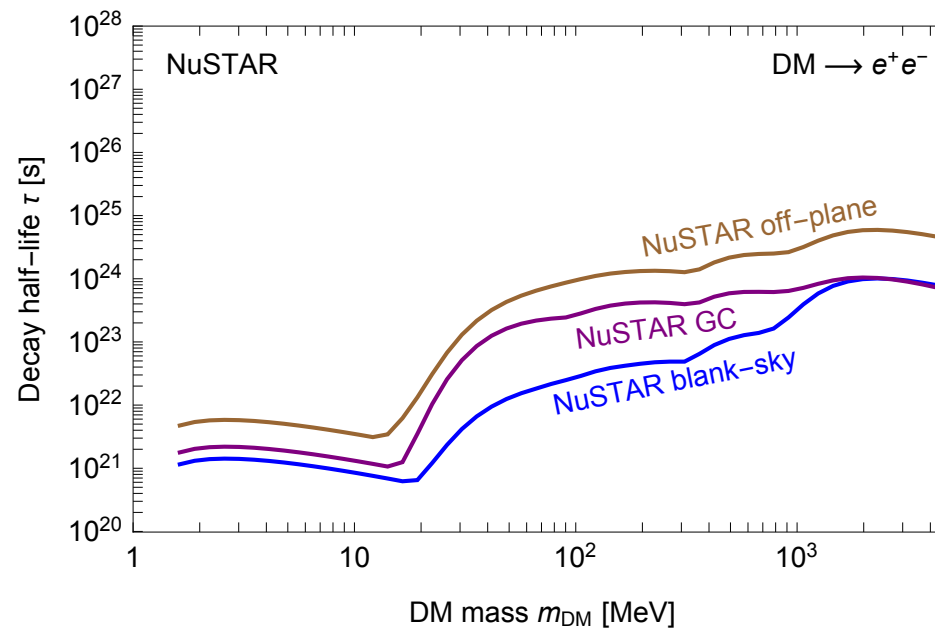
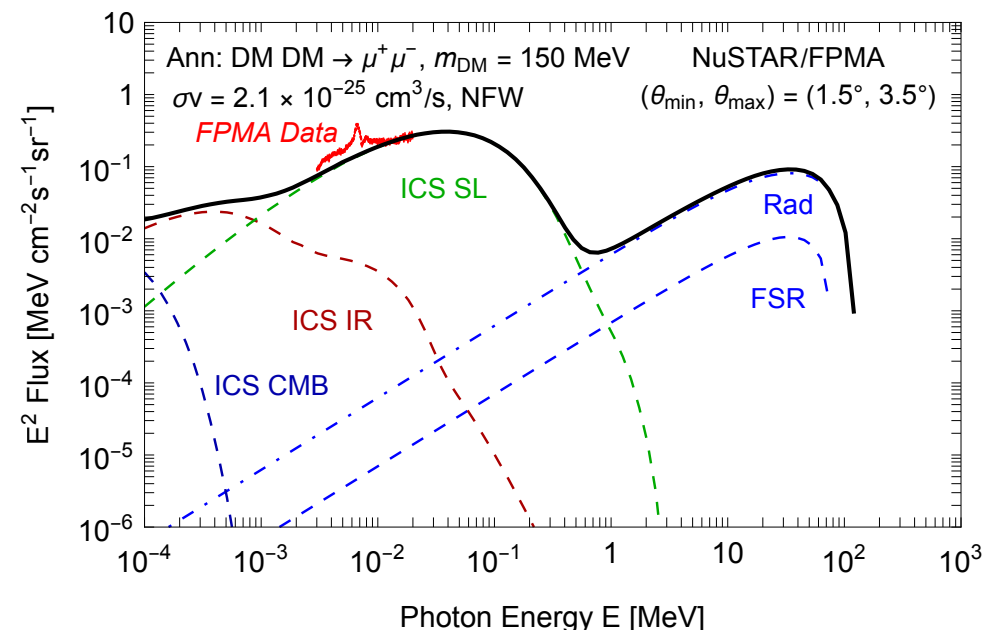
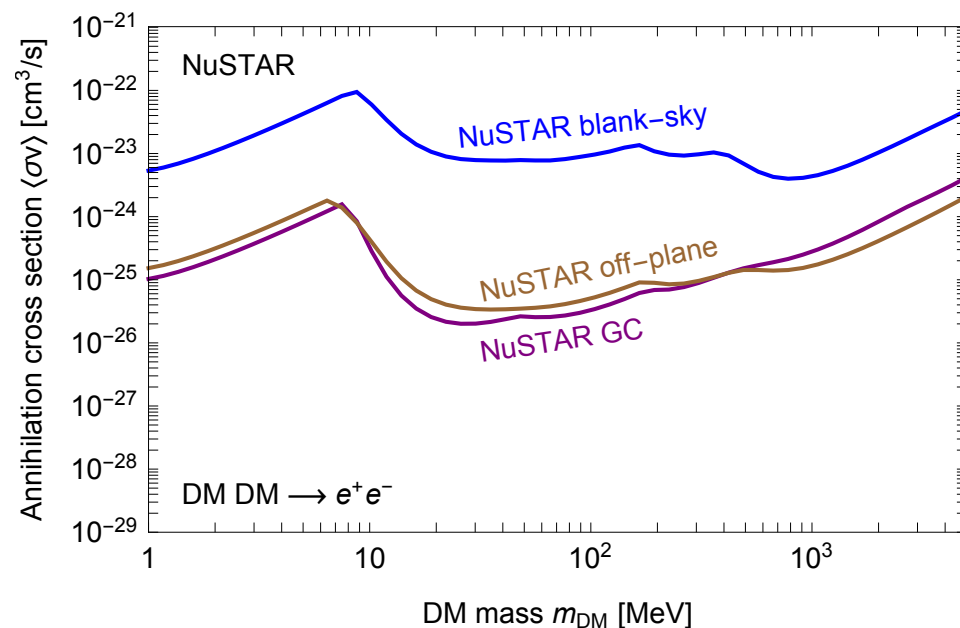
Roach et al., 1908.09037

Data taken between in 2018

NuSTAR constraints

NuSTAR (2012-2018 data):

- blank-sky fields [Krivonos et al., 2011.11469](#)
- GC obs. [Perez et al., 1609.00667](#)
- off-plane obs. [Roach et al., 1908.09037](#)



Suzaku datasets

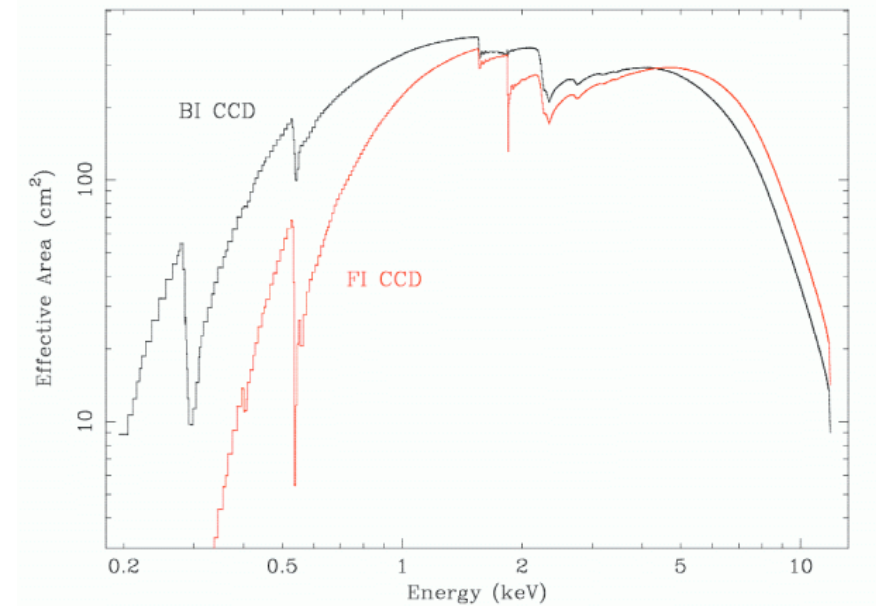
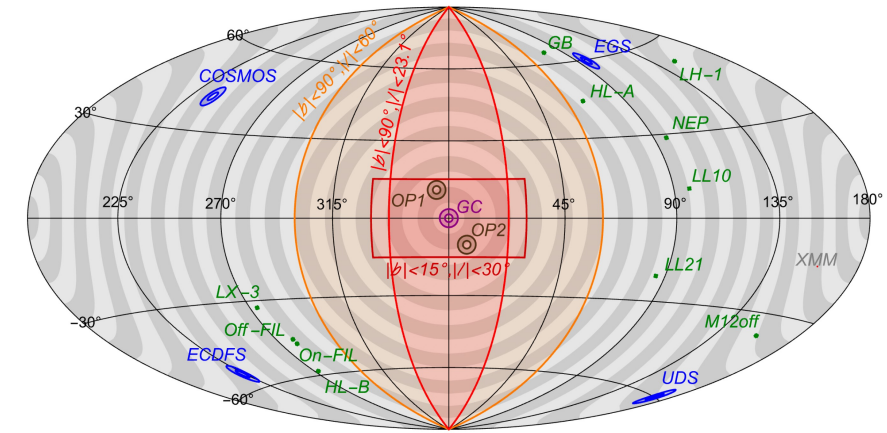
Table 1. Log of observations, ordered by $|b|$

Data set		Obs ID	Date	Exposure (ks)		Aim point	
ID	Field Name (Short Name)			Total	Cleaned	(ℓ, b)	$(E_{\text{Lon}}, E_{\text{Lat}})^*$
1	GB1428+4217 (GB)	701092010	Jun 12-13, 2006	48.7	34.9	(75.9, 64.9)	(194.2, 52.7)
2	High latitude B (HL-B)	500027020	Feb 17-20, 2006	103.6	29.7	(272.4, -58.3)	(4.4, -61.4)
3	Lockman hole 2 (LH-2)	101002010	May 17-19, 2006	80.4	40.0	(149.7, 53.2)	(137.1, 45.1)
4	Lockman hole 1 (LH-1)	100046010	Nov 14-15, 2005	77.0	61.7	(149.0, 53.2)	(137.2, 45.5)
5	Off Filament ^a (Off-FIL)	501001010	Mar 1-2, 2006	80.1	59.6	(278.7, -47.1)	(354.8, -72.6)
6	On Filament ^a (On-FIL)	501002010	Mar 3-6, 2006	101.4	59.2	(278.7, -45.3)	(354.1, -74.4)
7	High latitude A (HL-A)	500027010	Feb 14-15, 2006	73.6	53.2	(68.4, 44.4)	(228.8, 63.5)
8	MBM12 off cloud ^b (M12off)	501104010	Feb 6-8, 2006	75.3	51.0	(157.3, -36.8)	(44.5, 2.3)
9	LMC X-3 Vicinity ^c (LX-3)	500031010	Mar 17-18, 2006	82.0	56.1	(273.4, -32.6)	(41.2, -86.2)
10	North Ecliptic Pole 1 ^d (NEP1)	100018010	Sep 2-4, 2005	106.2	58.7	(95.8, 28.7)	(334.8, 88.7)
11	North Ecliptic Pole 2 (NEP2)	500026010	Feb 10-12, 2006	75.6	16.5	(95.8, 28.7)	(334.8, 88.7)
12	Low latitude 86-21 (LL21)	502047010	May 9-10, 2007	81.5	57.0	(86.0, -20.8)	(347.6, 38.4)
13	Low latitude 97+10 (LL10)	503075010	Apr 15-16, 2008	79.8	40.8	(96.6, 10.4)	(0.7, 70.6)
R1	MBM12 on cloud ^{b,e} (M12on)	500015010	Feb 3-6, 2006	102.9	68.0	(159.2, -34.5)	(47.2, 2.6)
R2	Midplane 235 ^e (MP235)	502021010	Apr 22-25, 2007	189.5	53.0	(235.0, 0.0)	(119.5, -40.6)

Results previously published by ^a Henley et al. (2007), ^b Smith et al. (2007), ^c Yao et al. (2009), ^d Fujimoto et al. (2007), ^e Masui et al. (2009).

* Ecliptic coordinate

Yoshino et al., 0903.2981



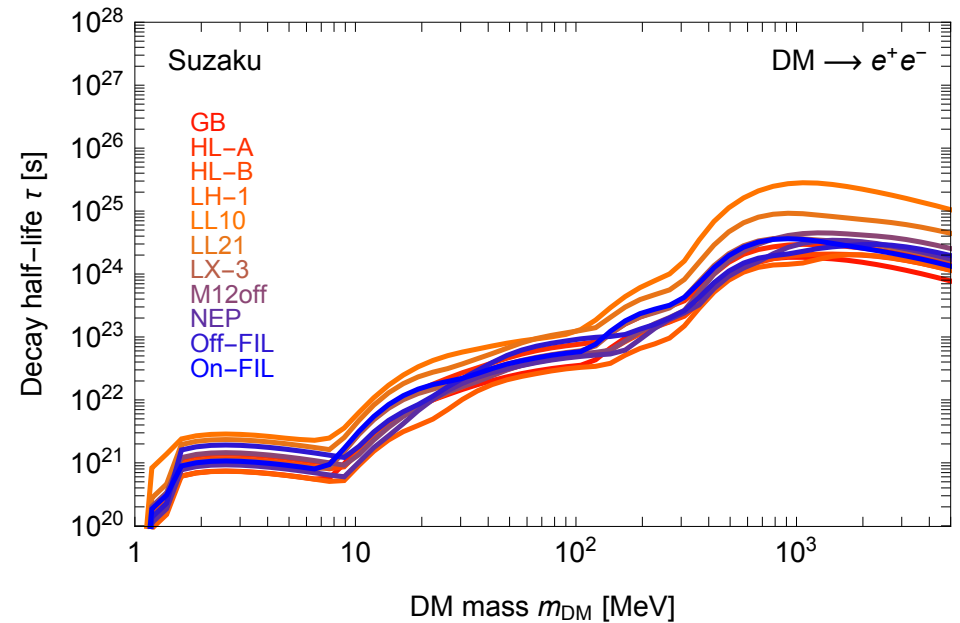
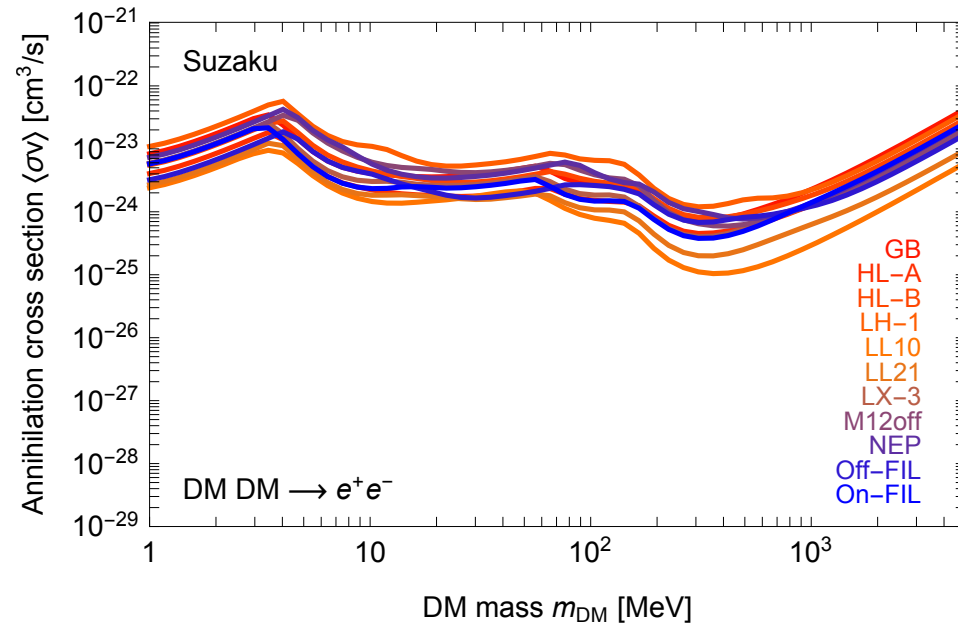
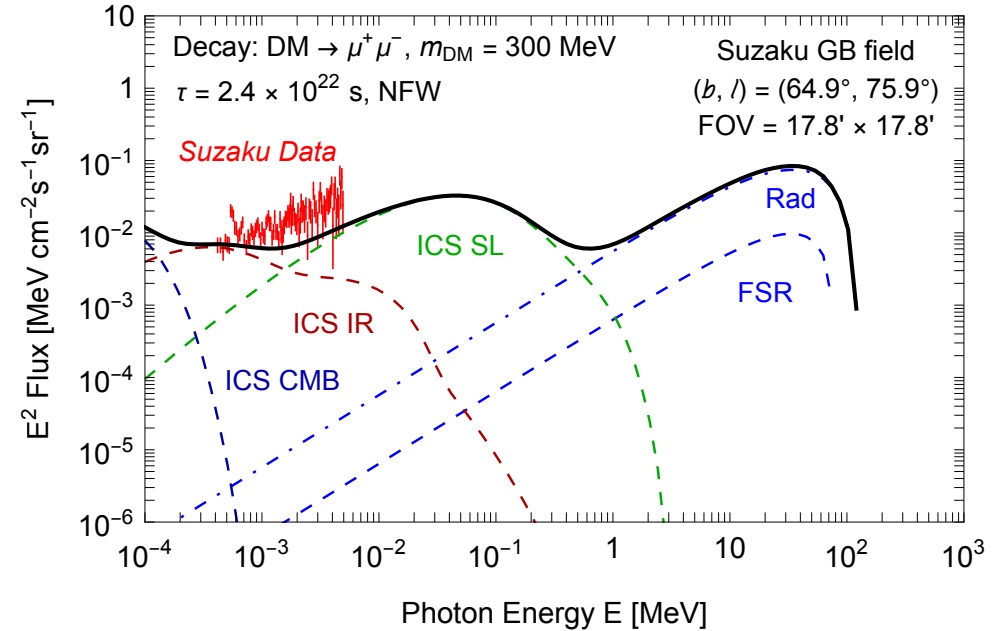
https://heasarc.gsfc.nasa.gov/docs/suzaku/gallery/performance/xis_area.html

Suzaku constraints

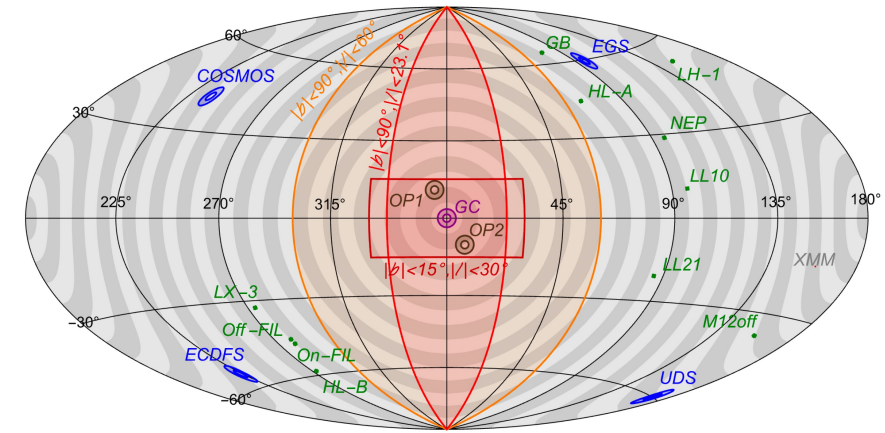
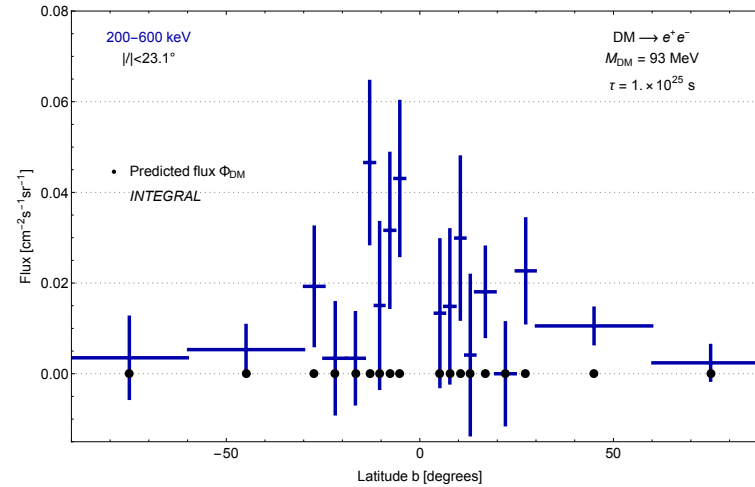
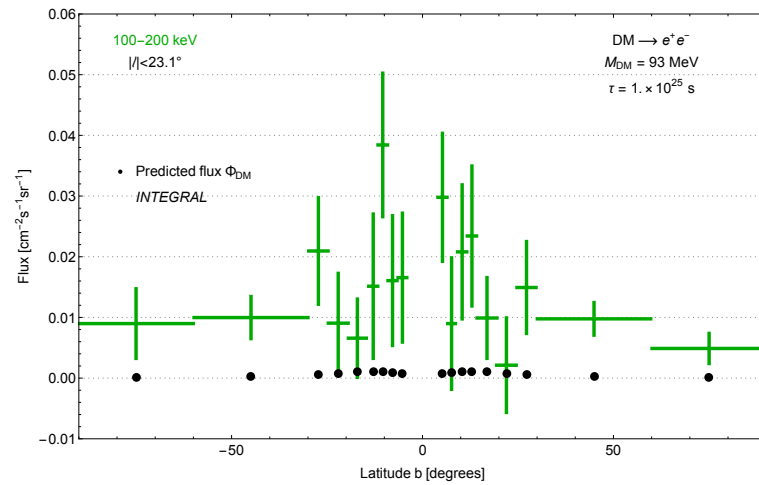
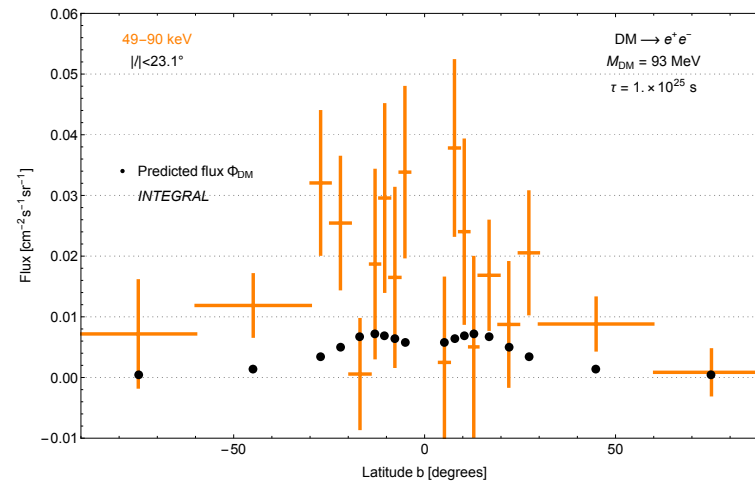
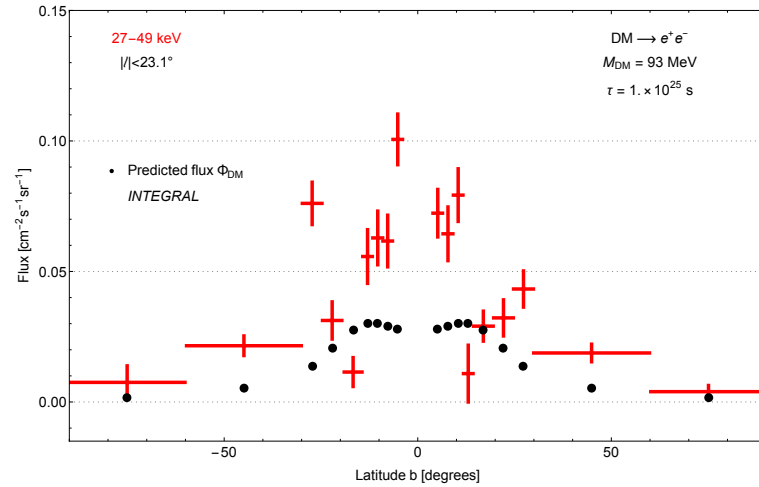
Suzaku high-latitude fields

2006-2008

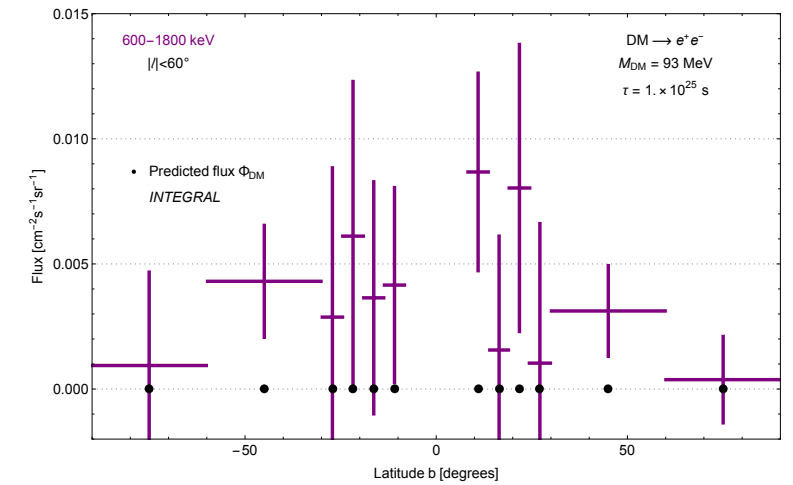
Yoshino et al., 0903.2981



INTEGRAL datasets



Bouchet et al., INTEGRAL coll.,
 1107.0200

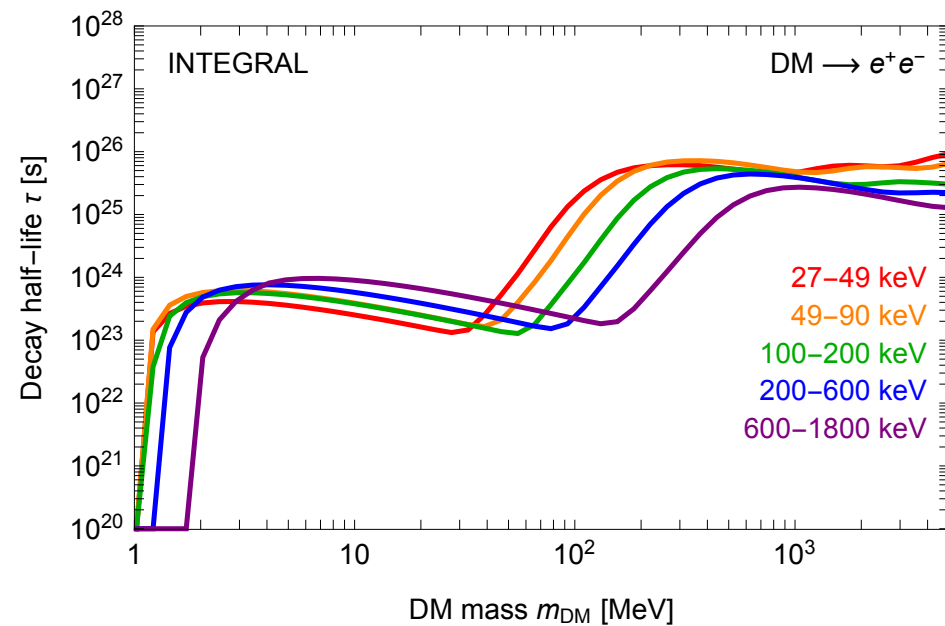
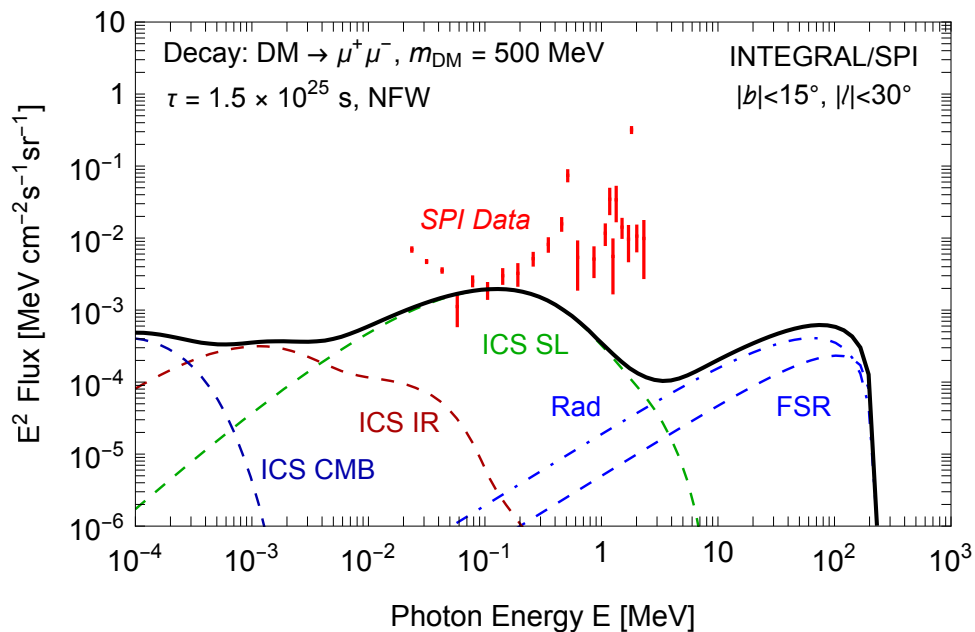
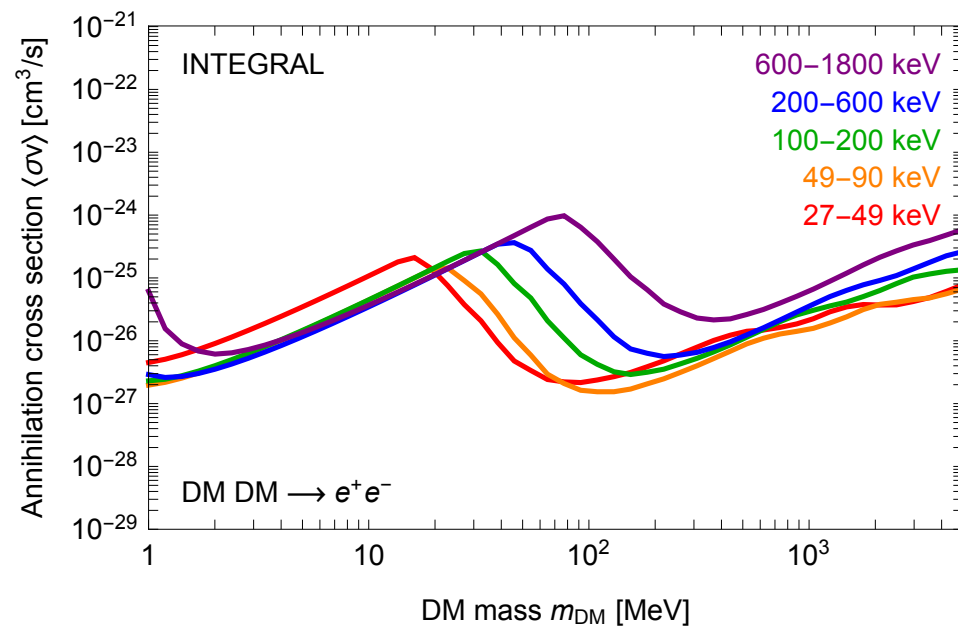


INTEGRAL constraints

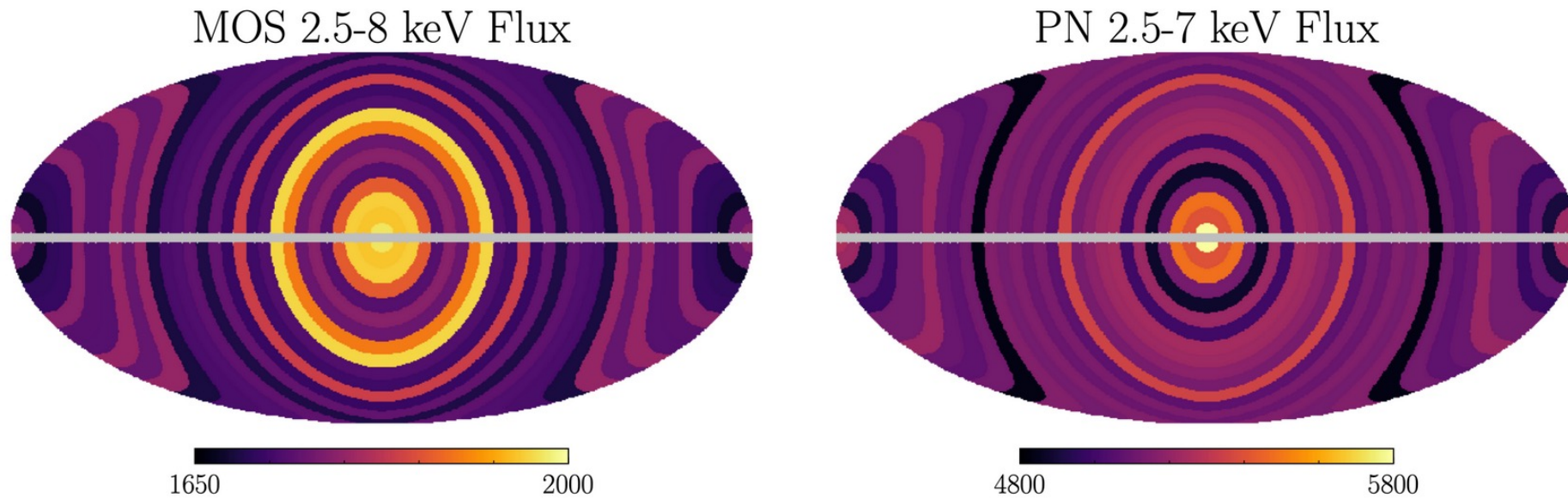
INTEGRAL diffuse emission searches

2003-2009

Bouchet et al., INTEGRAL coll., 1107.0200



XMM-Newton datasets



https://github.com/bsafdi/XMM_BSO_DATA

Datasets + Instrument response functions

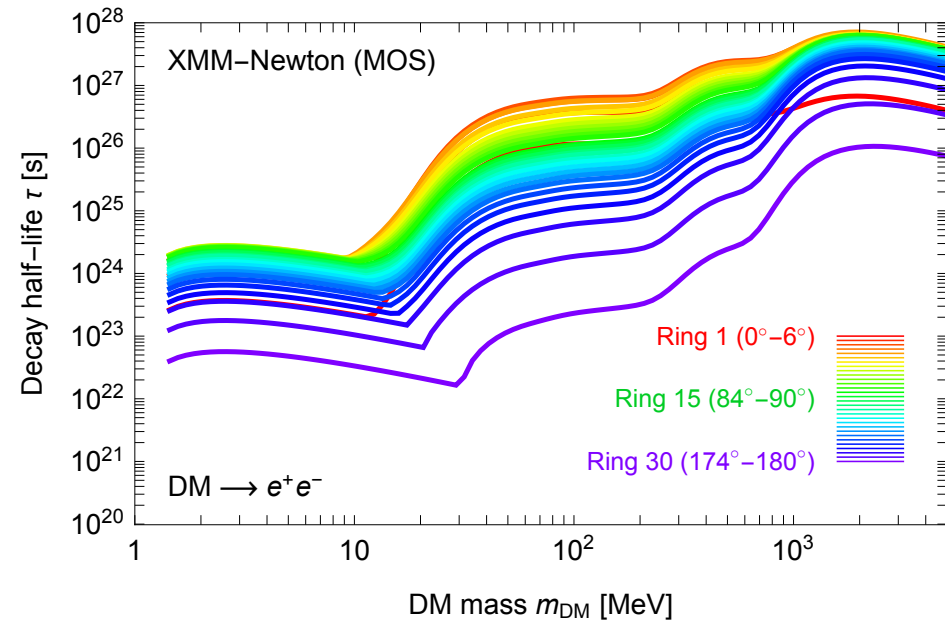
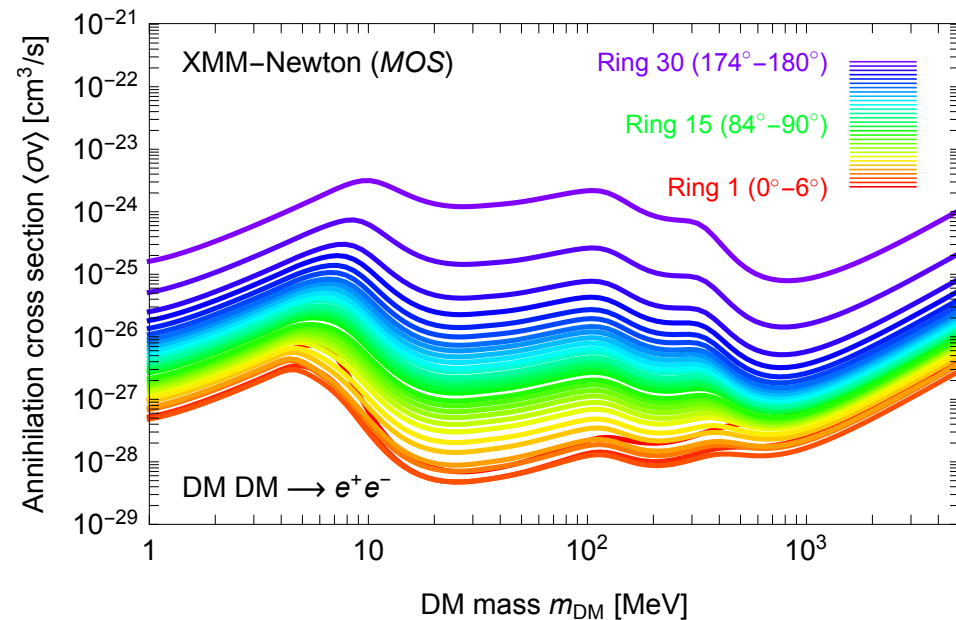
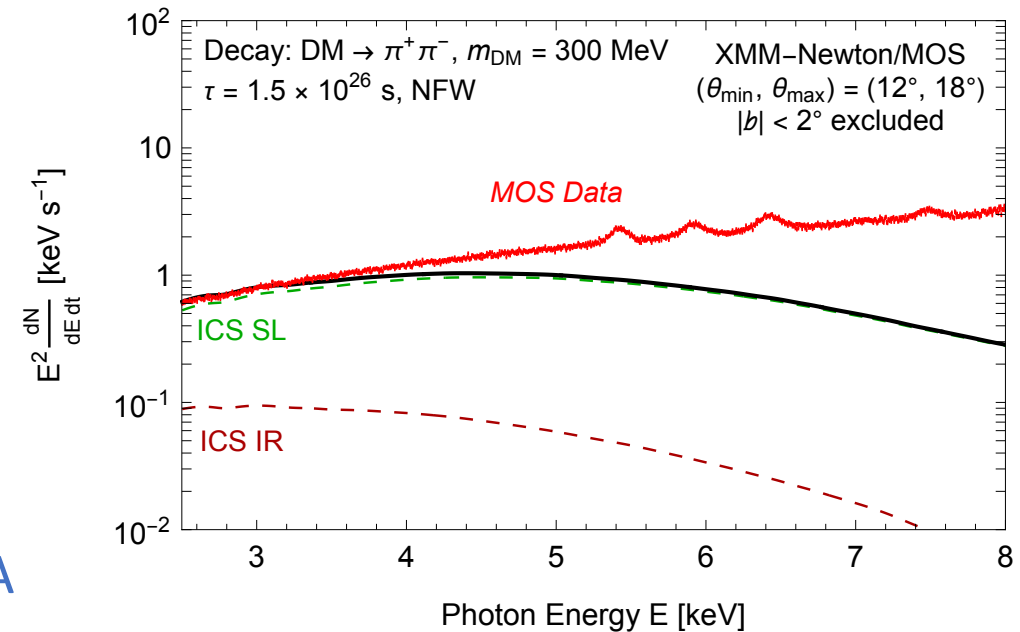
XMM-Newton constraints

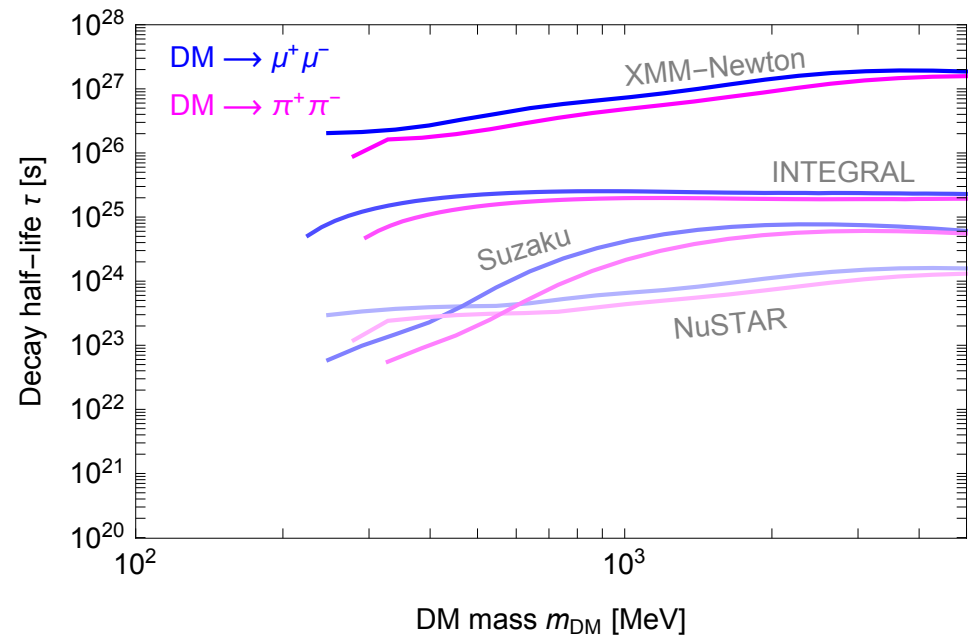
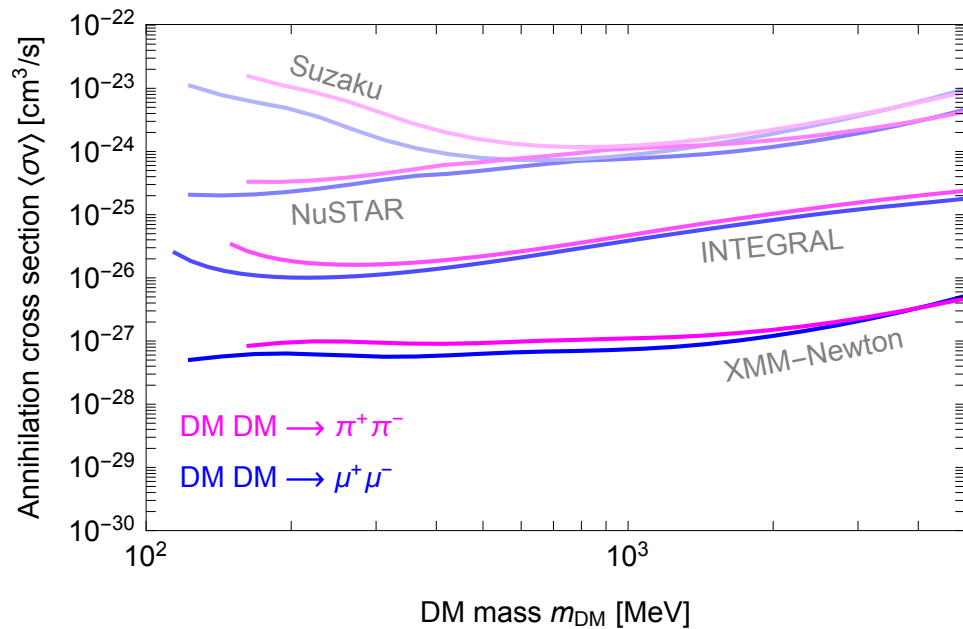
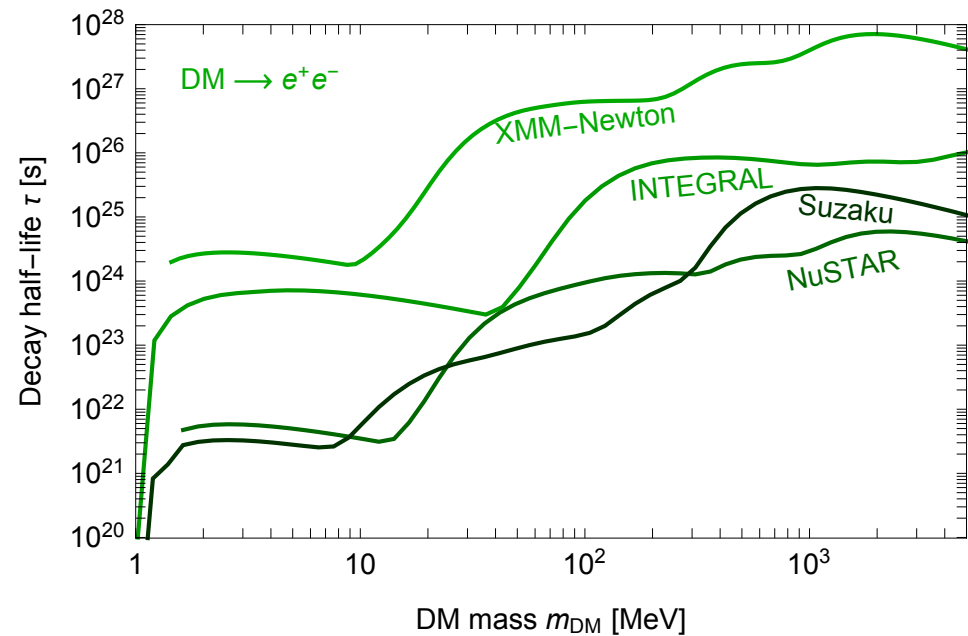
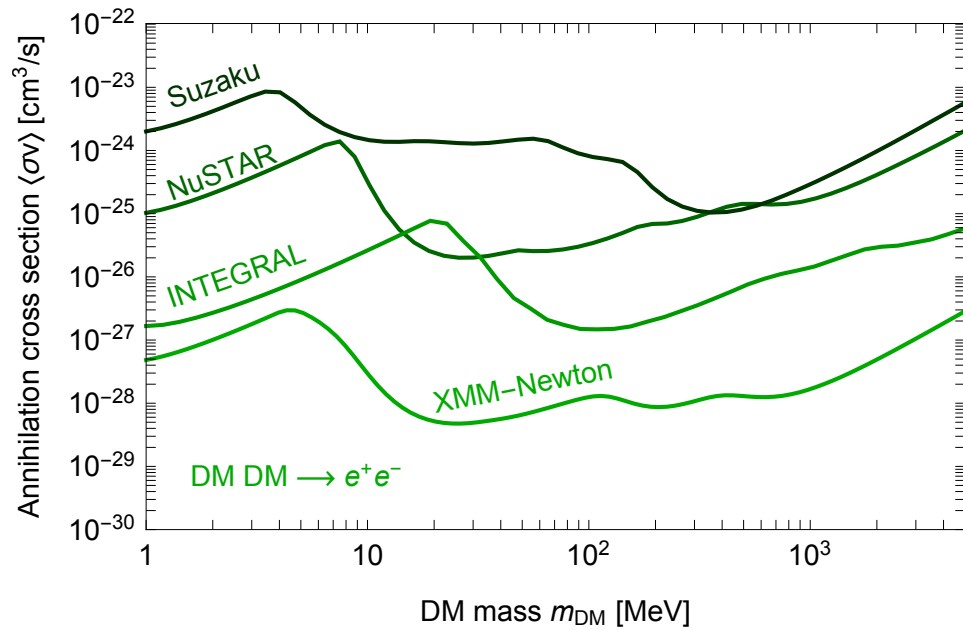
XMM-Newton whole-sky observations

1999-2018

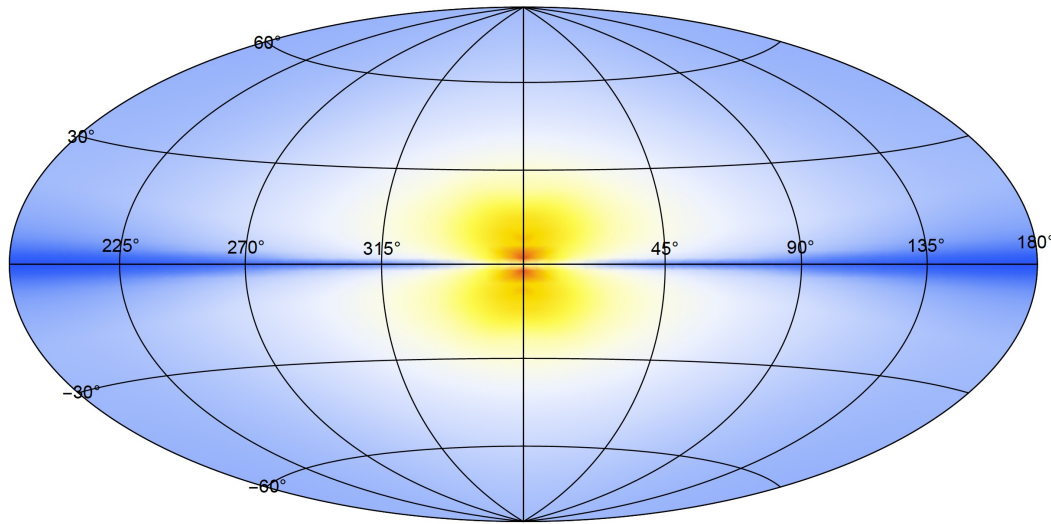
Foster et al., 2102.02207

https://github.com/bsafdi/XMM_BSO_DATA

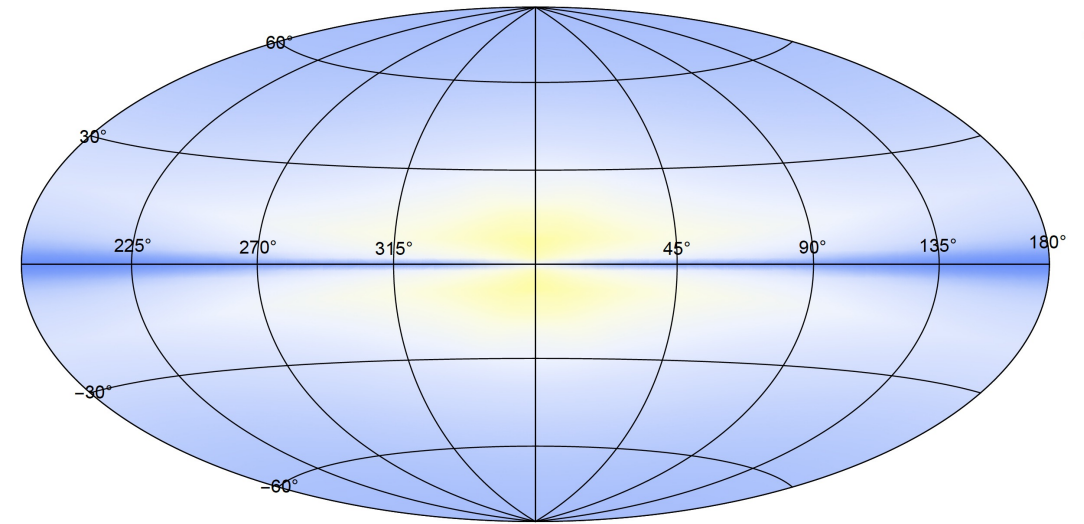
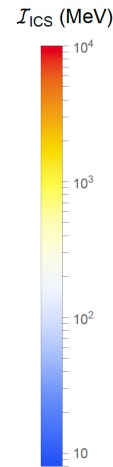




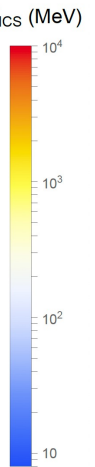
ICS halo function (spatial distribution)



Annihilation ($\eta = 2$)

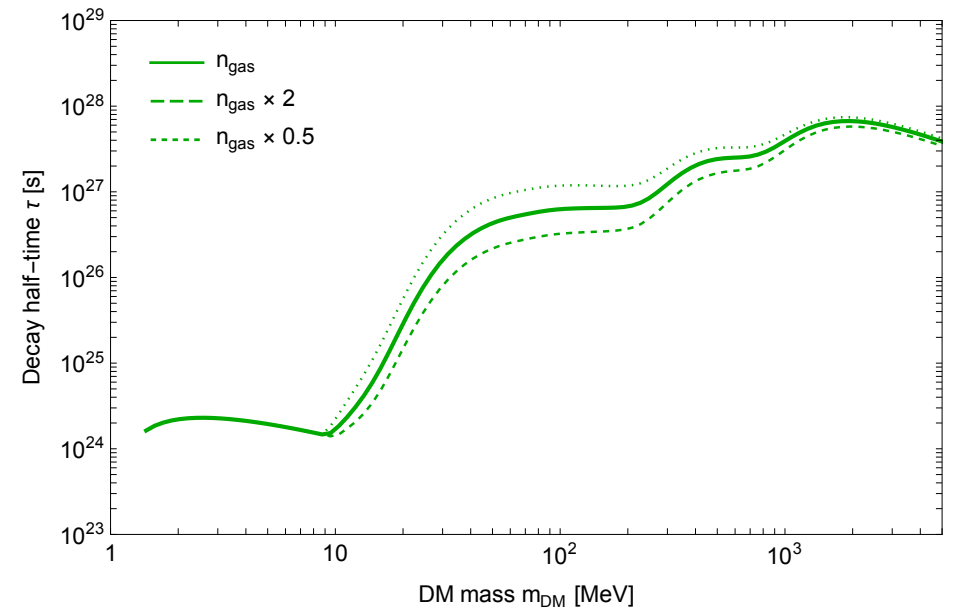
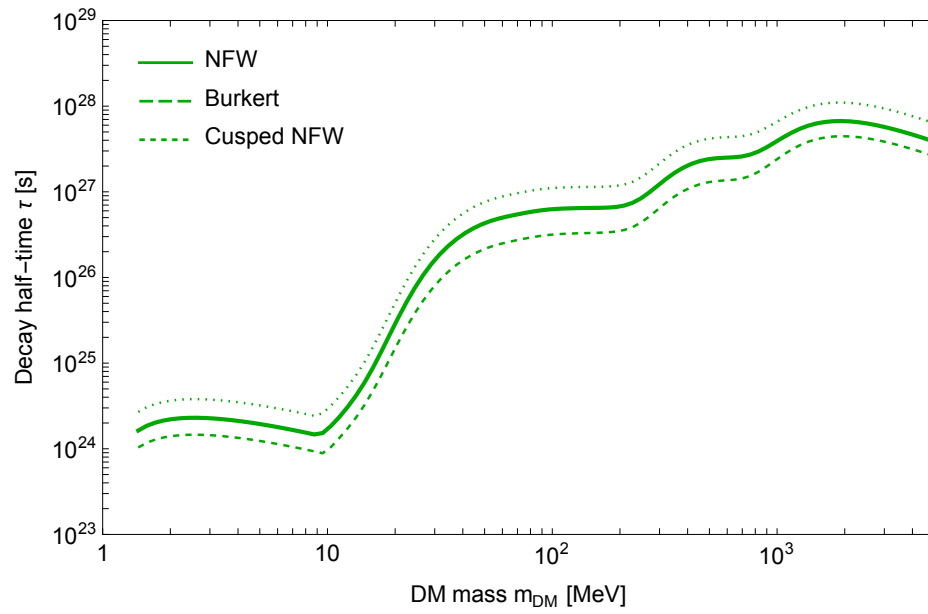


Decay ($\eta = 1$)

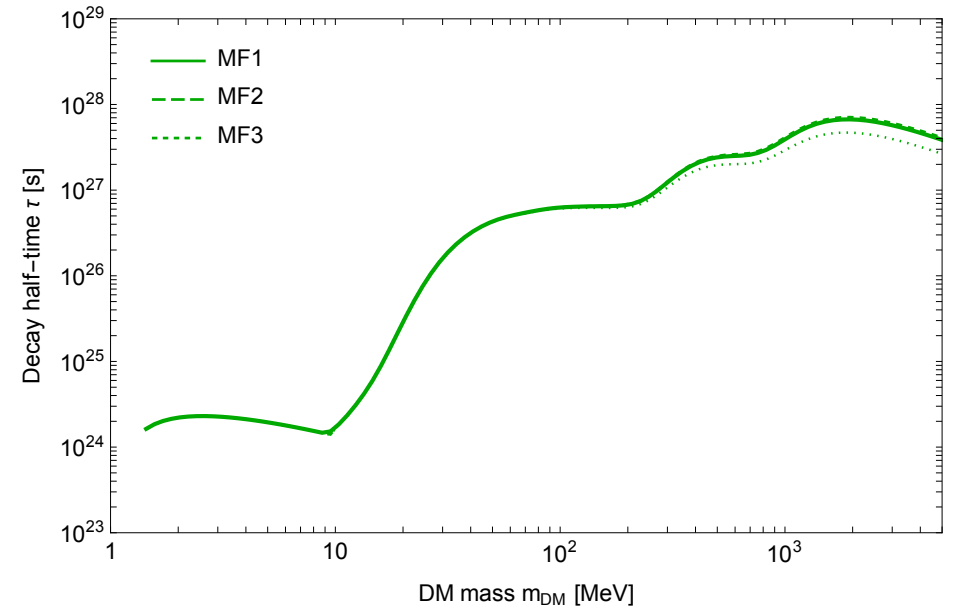
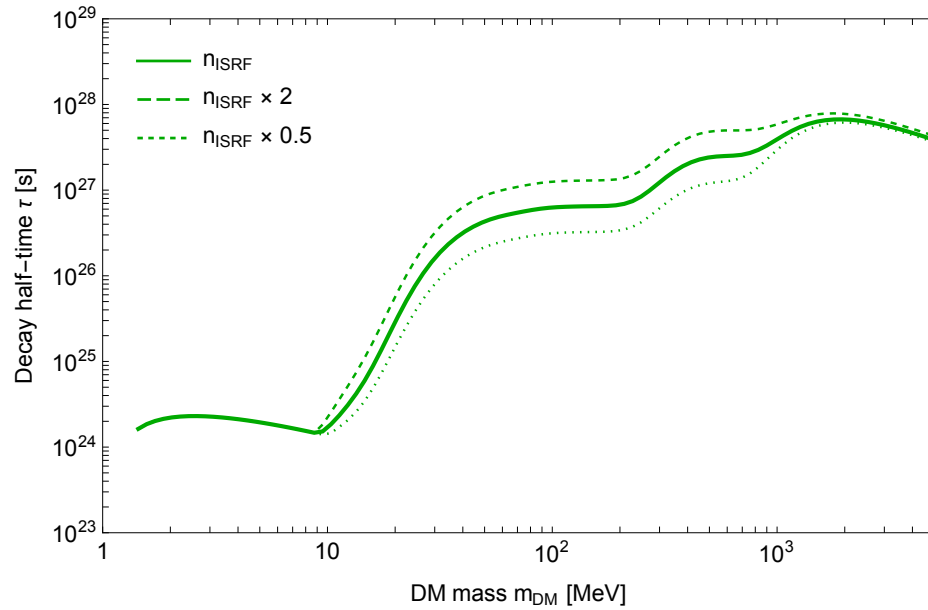


$$I_{ICS}(E_\gamma, E_e, b, l) = 2 E_\gamma \int_{l.o.s.} \frac{ds}{r_\odot} \left(\frac{\rho(s, b, l)}{\rho_\odot} \right)^\eta \int_{m_e}^{E_e} dE \frac{\mathcal{P}_{IC}(E_\gamma, E, s, b, l)}{b(E, s, b, l)}$$

$$\begin{aligned} E_\gamma &= 5 \text{ keV} \\ E_e &= 1 \text{ GeV} \end{aligned}$$



$\text{DM} \rightarrow e^+e^-$



Galactic magnetic field configurations

$$B(r, z) = B_0 \exp \left(-\frac{r - r_\odot}{R_D} - \frac{|z|}{z_D} \right)$$

Models	B_0 (μG)	r_D (kpc)	z_D (kpc)
MF1	4.78	10	2
MF2	5.1	8.5	1
MF3	9.1	30	4