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]

Jordan Koechler

LPTHE, Sorbonne University, Paris

Théorie, Univers et Gravitation 2023

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Outline

- Introduction
- X-rays from Dark Matter (DM) annihilations/decays
- Analysis and results
- Summary and prospects

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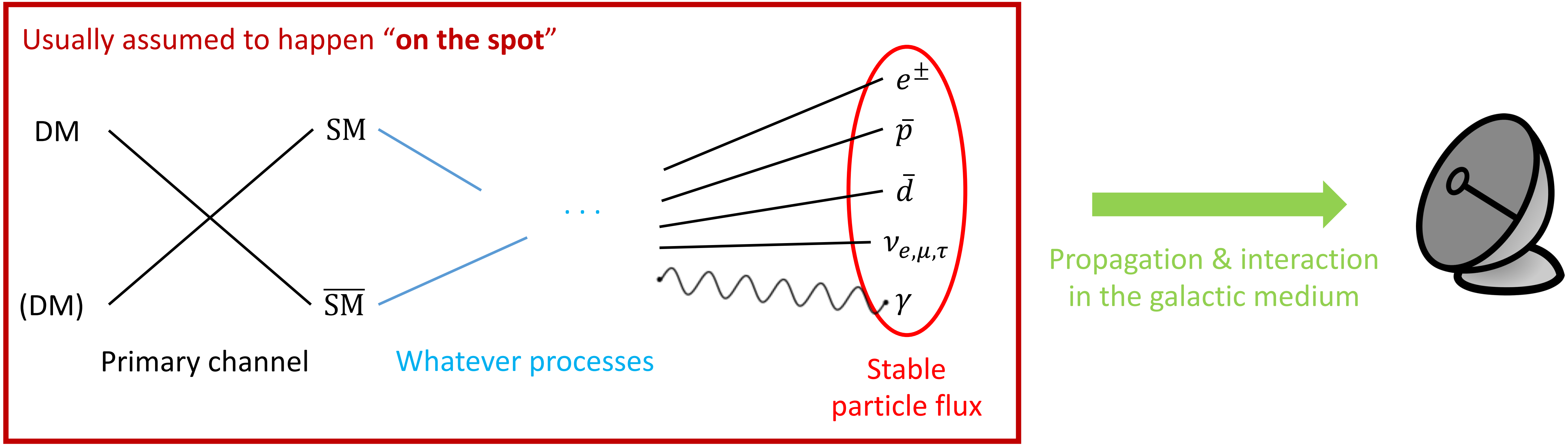

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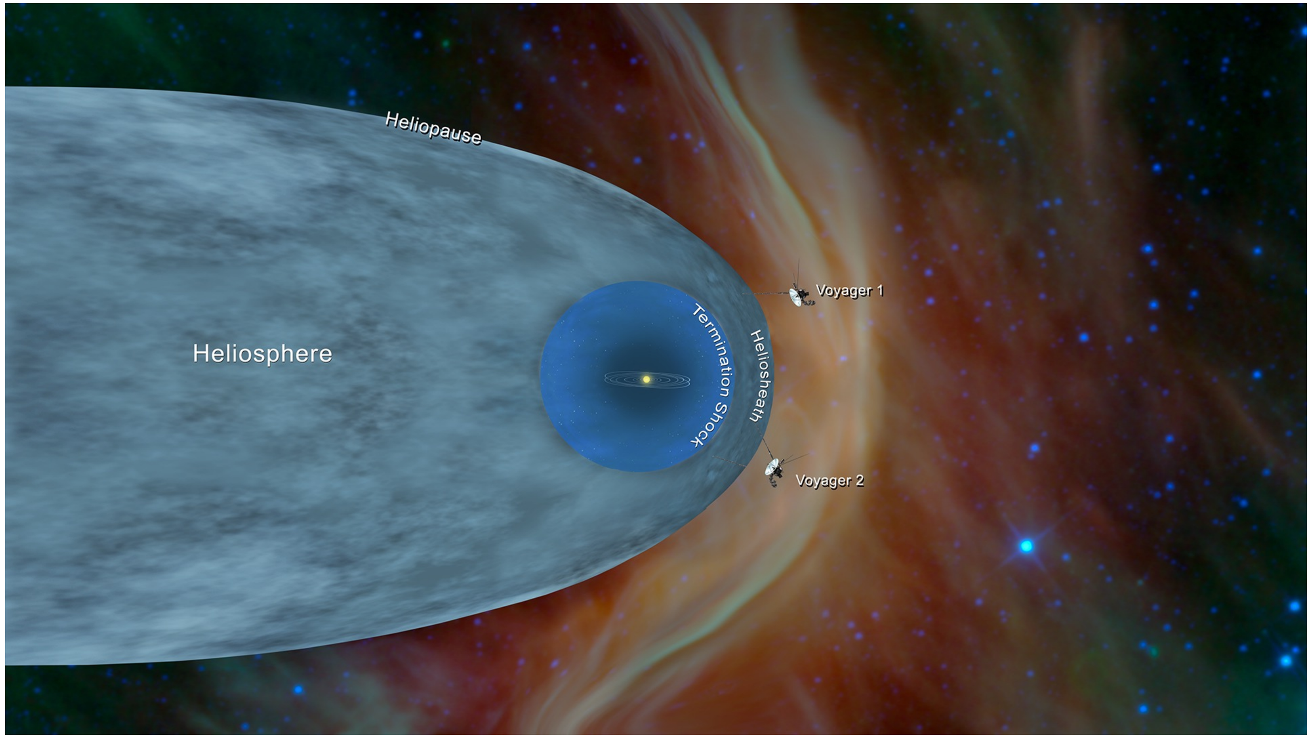

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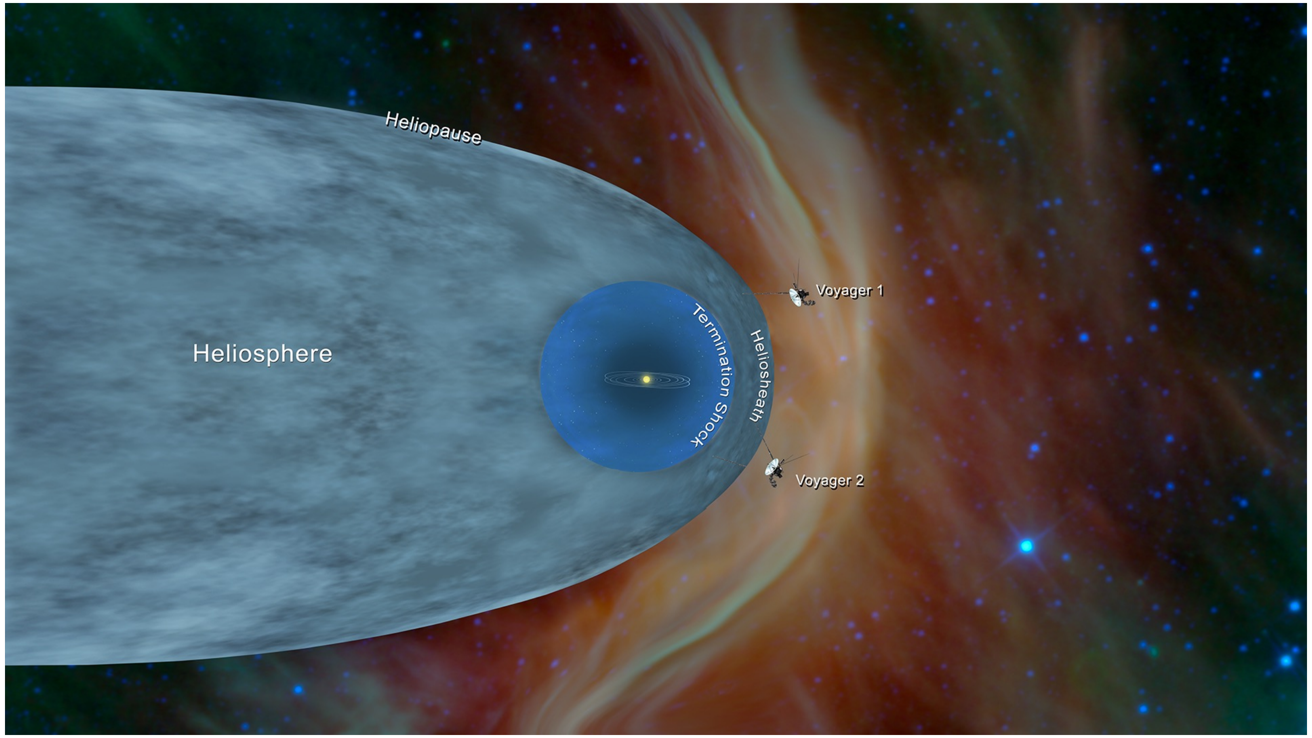

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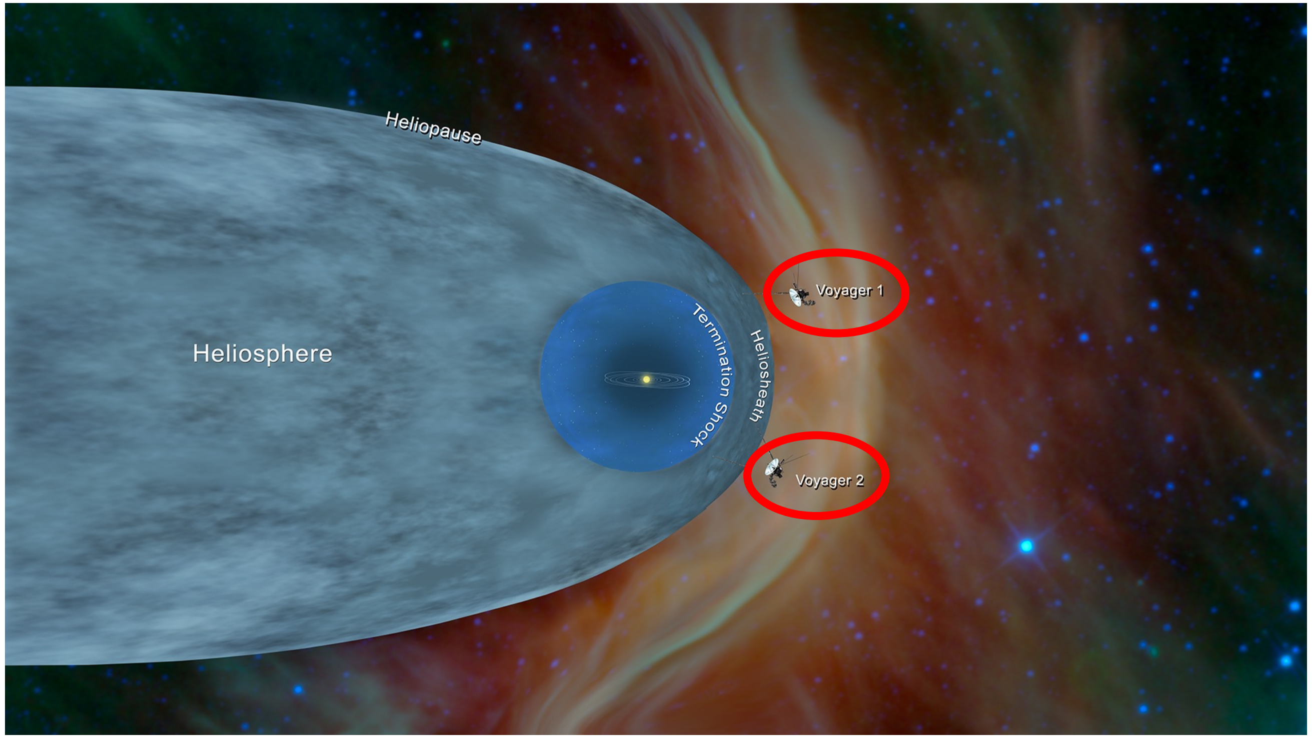

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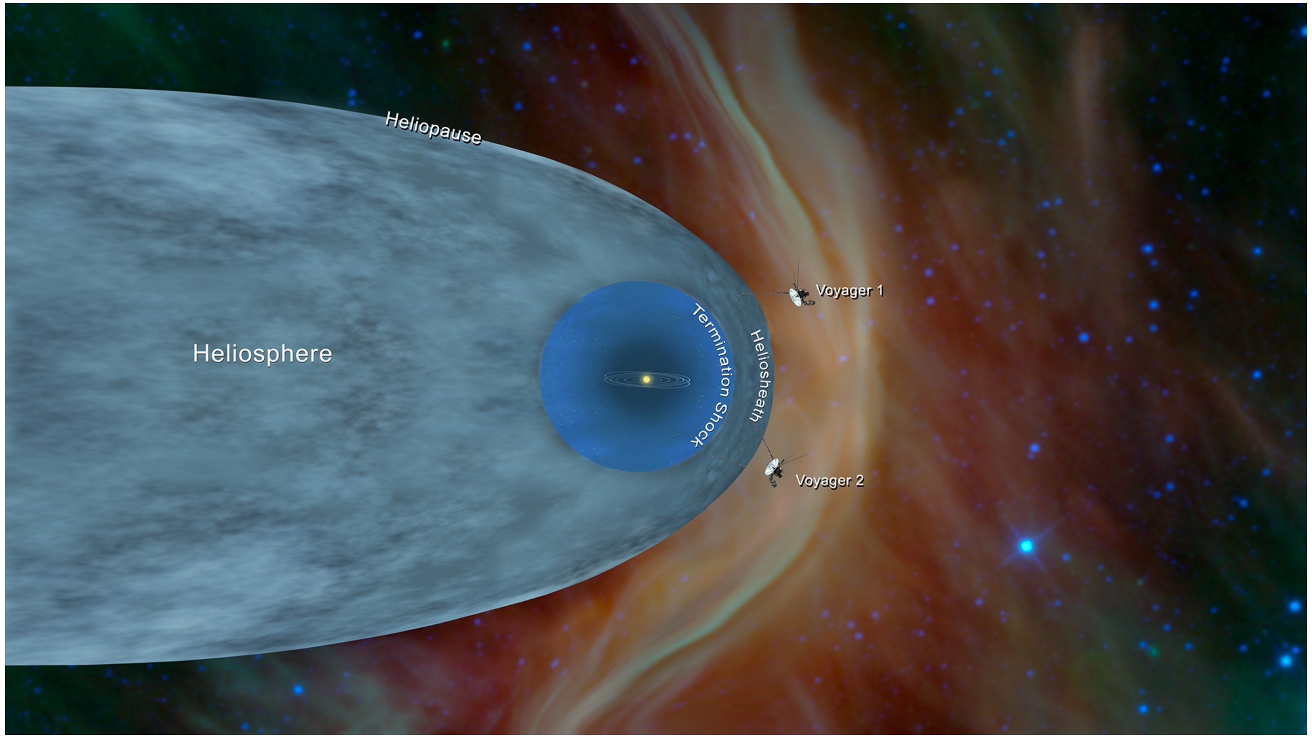
  - Look for γ-ray signals



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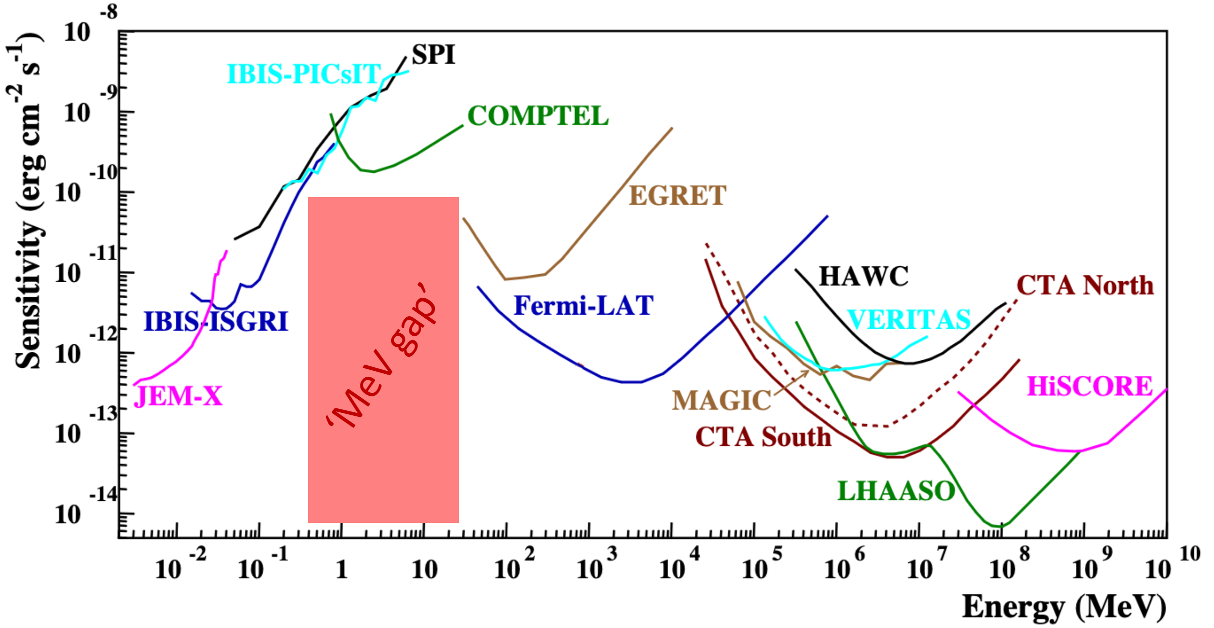

Adapted from De Angelis et al., eASTROGAM coll., 1611.02232

Introduction

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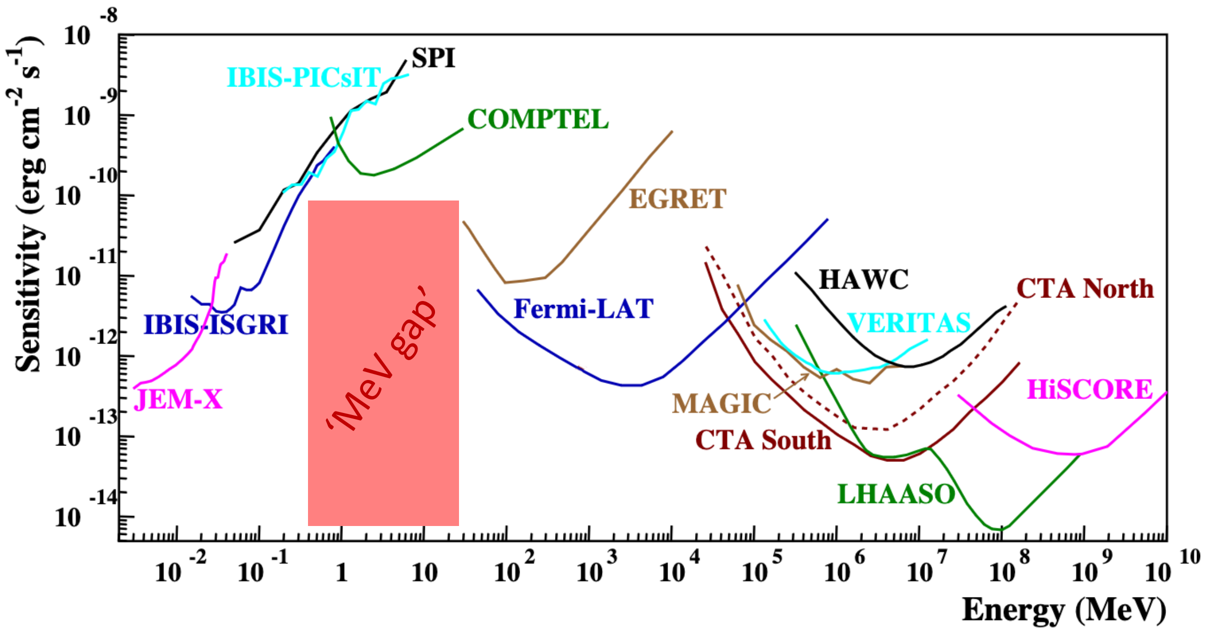
- Secondary emissions allow to circumvent the issue → study X-rays signals from light DM



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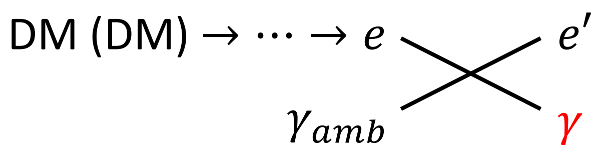
    - **Inverse-Compton scattering** (ICS): up-scattering of ambient photons thanks to DM-produced $e^\pm$



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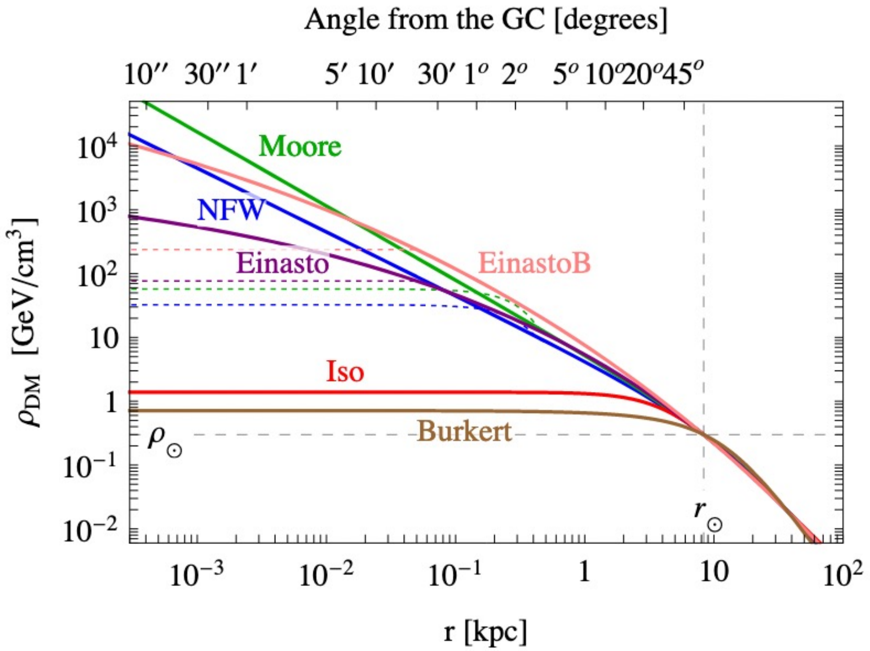

Cirelli et al., 1012.4515

X-rays from DM annihilations/decays

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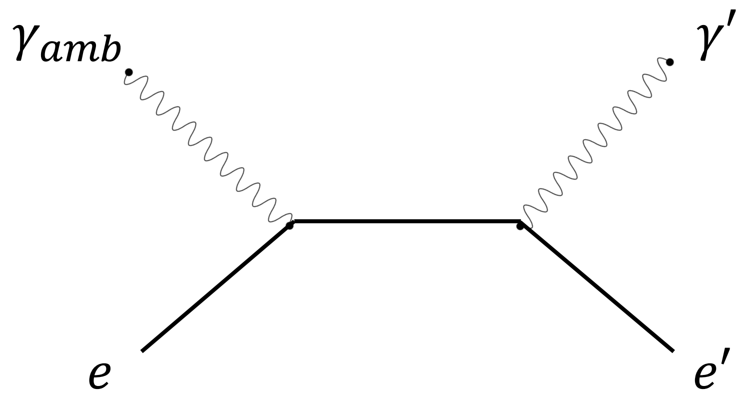

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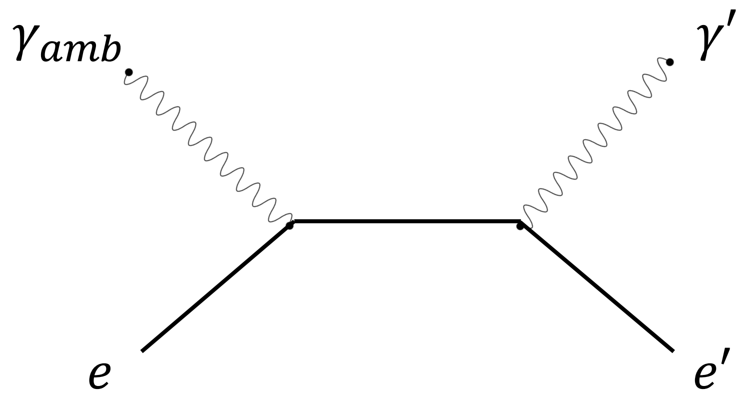

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- Energy range $\sim$ 0.1 meV to 10 eV

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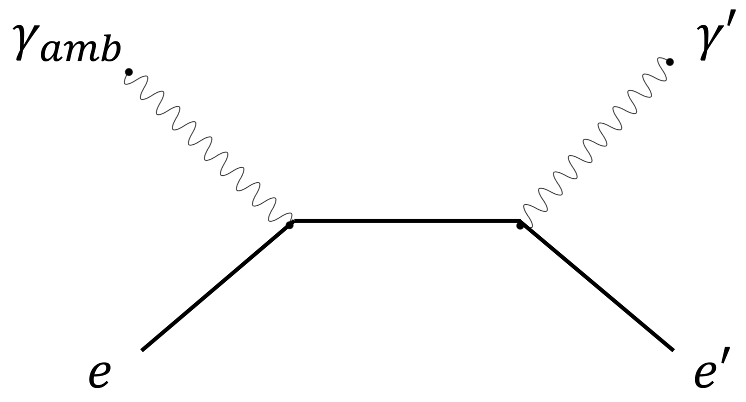

$$E_{\gamma'} \approx 4\gamma_e^2 E_{\gamma_{amb}} \qquad \gamma_e = \frac{E_e}{m_e}$$

For a CMB photon up-scattered by a 1 GeV $e^{\pm}$:

$$E_{\gamma_{amb}} \approx 0.2 \text{ meV } \rightarrow E_{\gamma'} \approx 3 \text{ keV}$$

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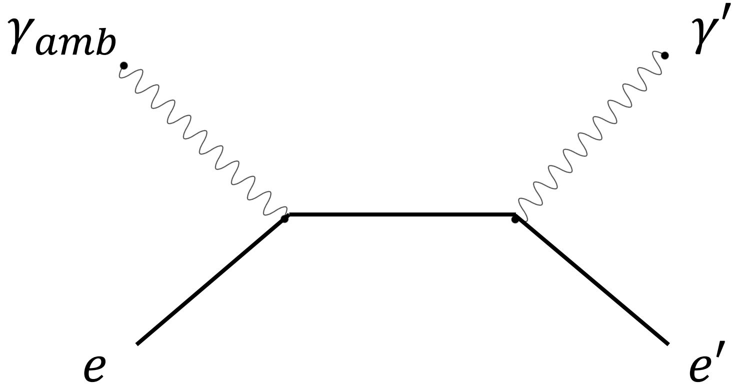
X-rays from DM annihilations/decays

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



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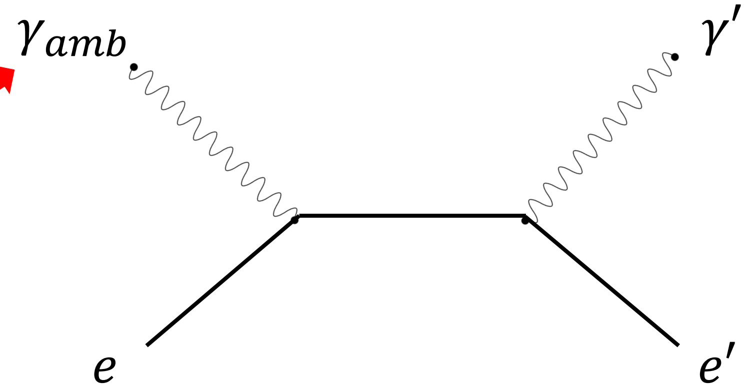
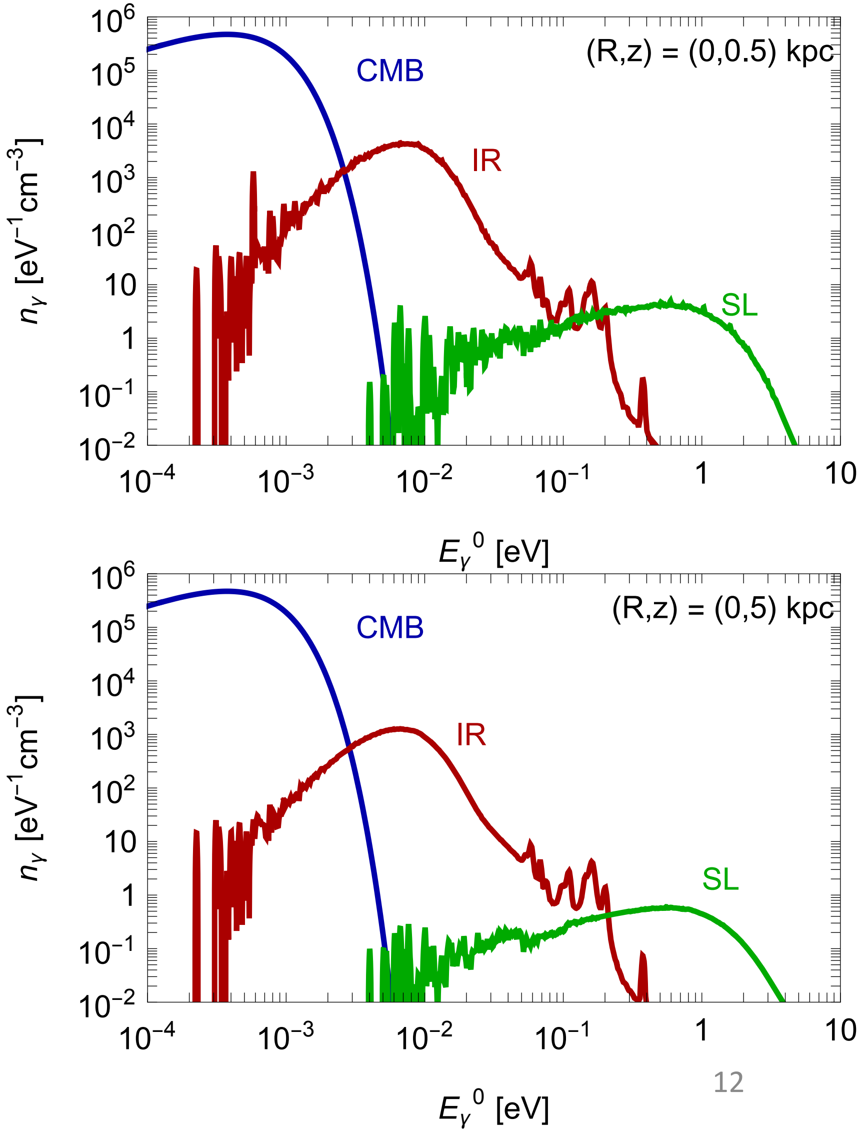
Local number density of ambient photons



X-rays from DM annihilations/decays

1) Local number density of ambient photons

- For CMB → black body spectrum
- For IR and SL → GalPROP intensity maps



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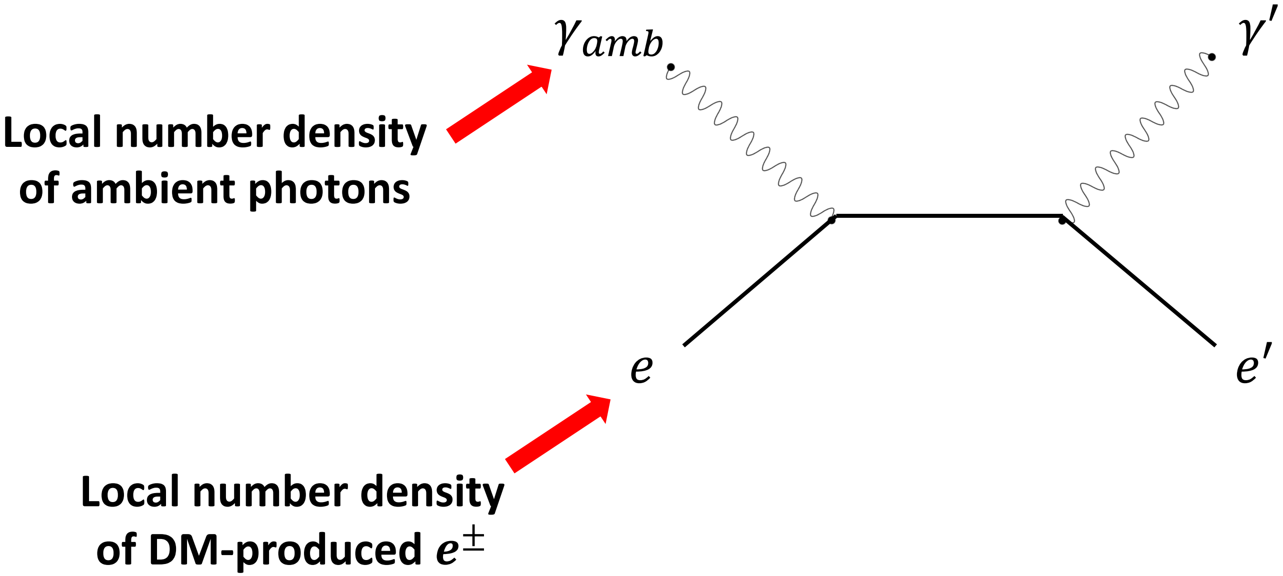

X-rays from DM annihilations/decays

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

$$\vec{\nabla}\left(K\,\vec{\nabla} f_{e^{\pm}} - \vec{v}_c f_{e^{\pm}}\right) + \frac{\partial}{\partial E_e}\left(b_{loss} f_{e^{\pm}} + \beta^2 K_{pp} \frac{\partial f_{e^{\pm}}}{\partial E_e}\right) + Q_{e^{\pm}}^{DM} = 0$$

spatial diffusion | convection | energy loss | momentum space diffusion | source

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The solution is now analytic!

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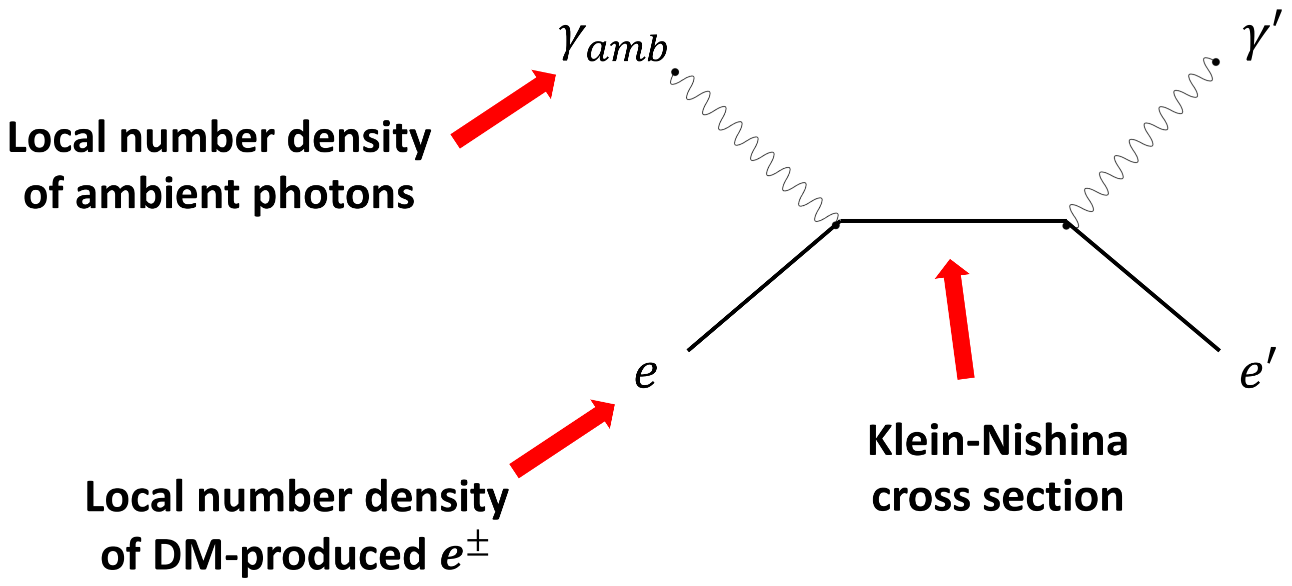

X-rays from DM annihilations/decays

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

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

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

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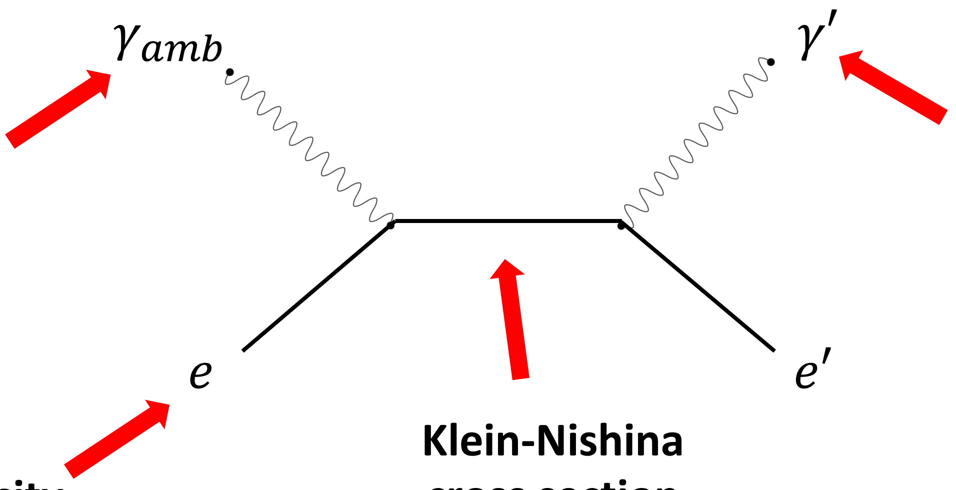

Local number density of ambient photons

Get the X-rays flux from ICS!

… after some integrations and convolutions

Klein-Nishina cross section

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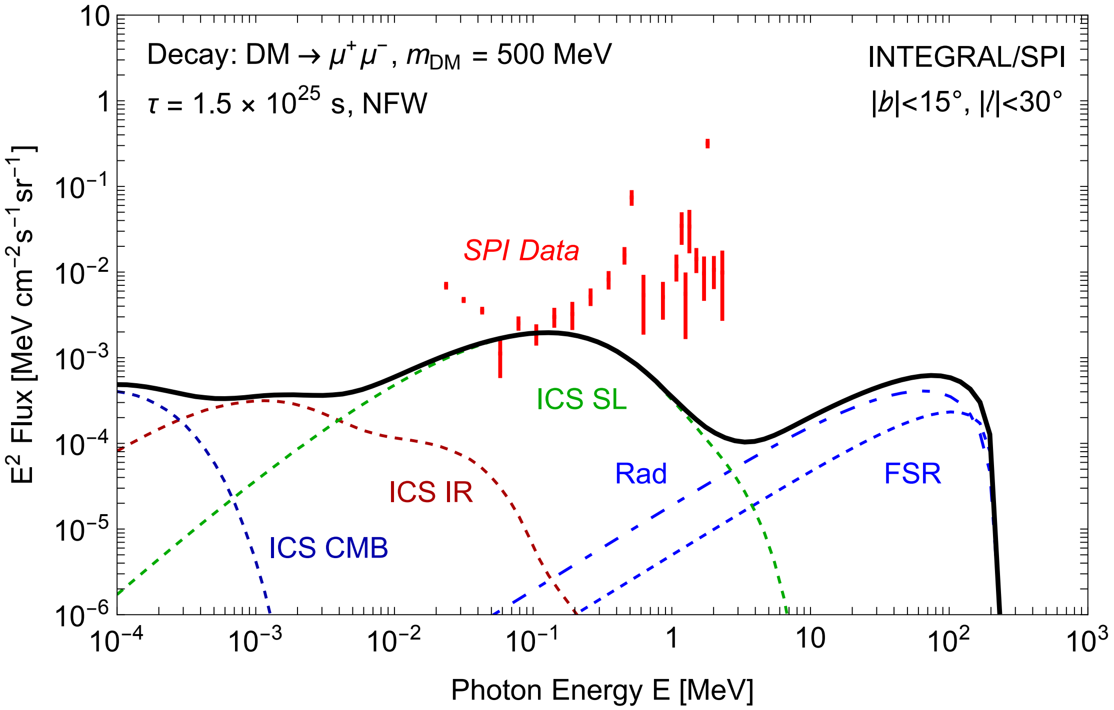
$$\chi^2_>(p, m_{DM}) = \sum_{i \in \text{bins}} \frac{\text{Max}\left(\Phi_{DM\gamma,i}(p, m_{DM}) - \Phi_i, 0\right)^2}{\sigma_i^2}$$

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

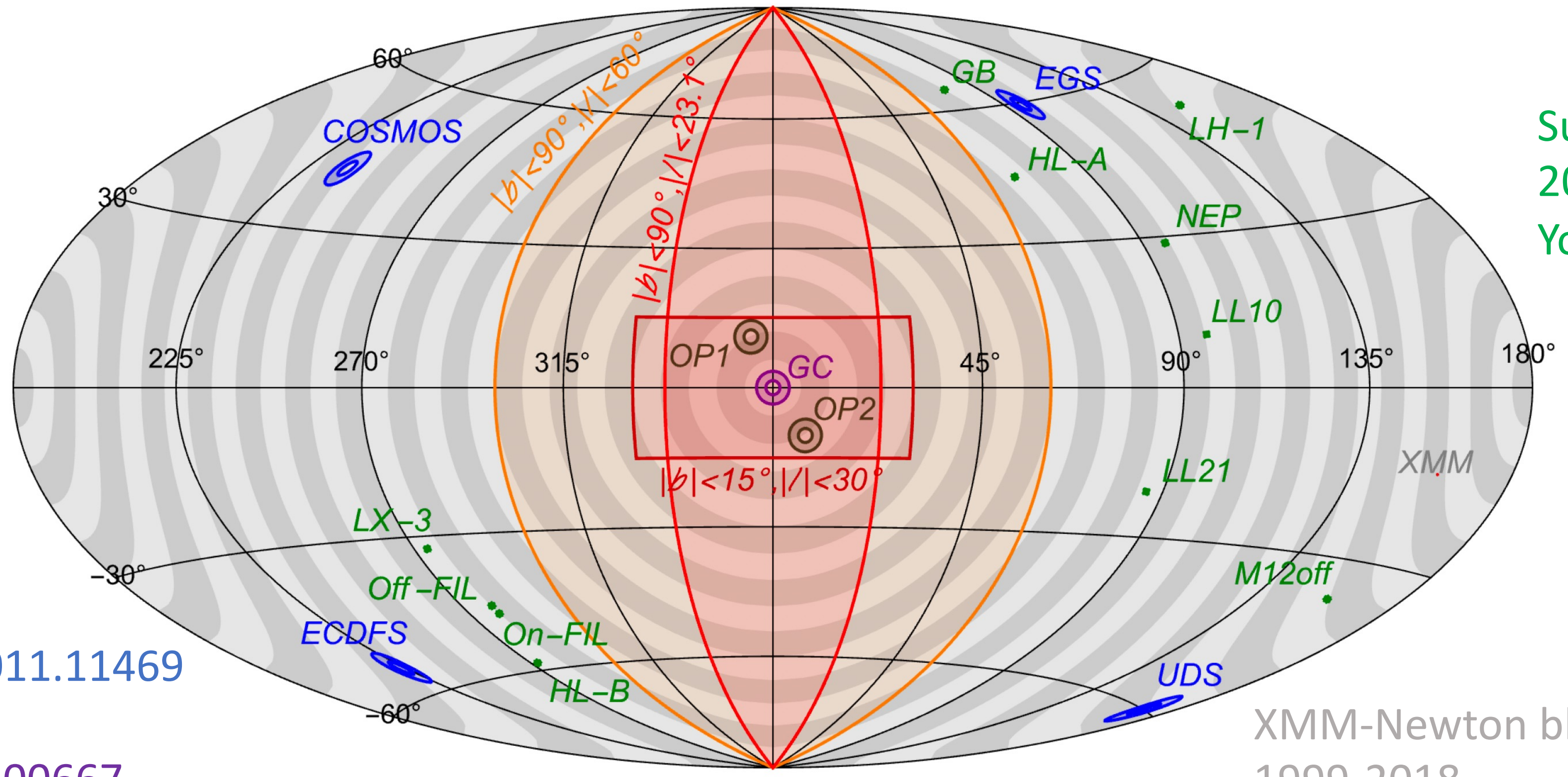
- Impose a (2σ) bound when $\chi^2_>(p, m_{DM}) \geq 4$



Analysis and results

INTEGRAL diffuse emission searches
2003-2009
Bouchet et al., INTEGRAL coll., 1107.0200

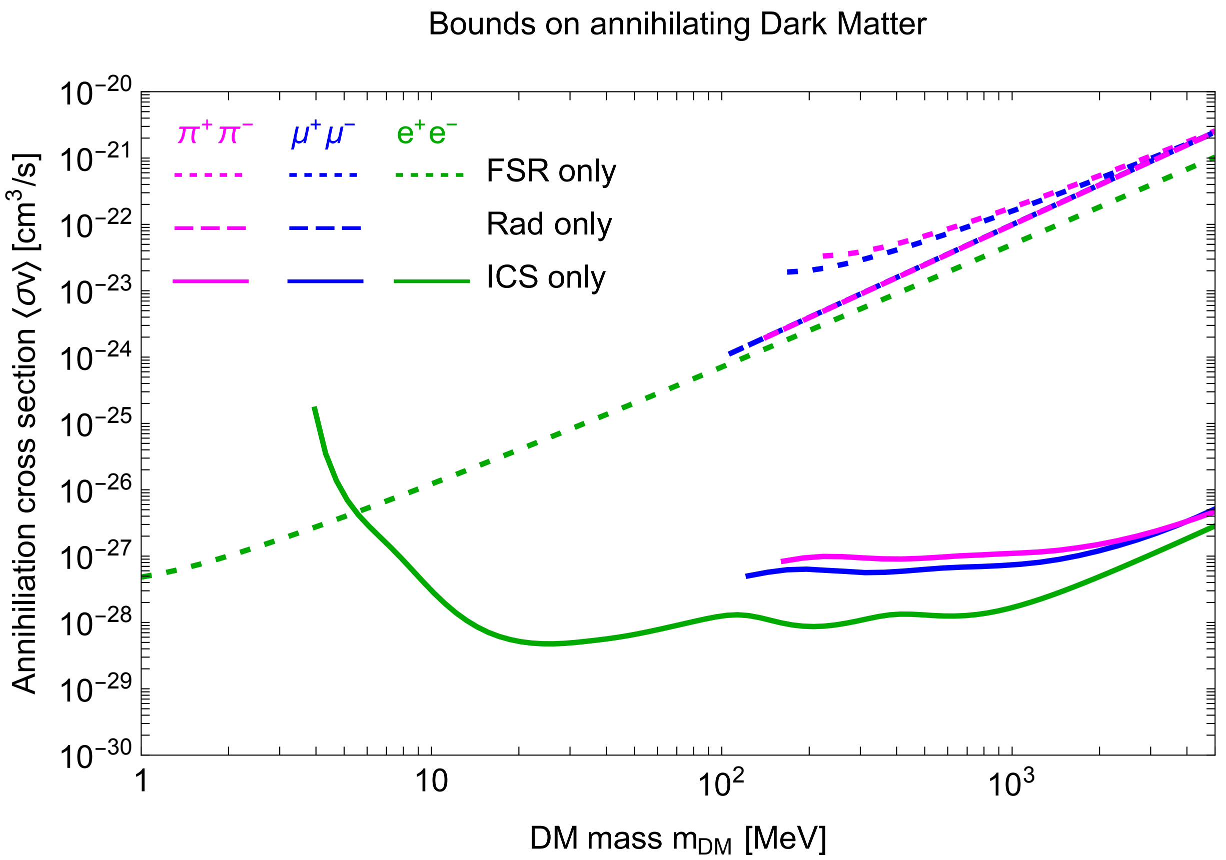
Suzaku high-latitude fields
2006-2008
Yoshino et al., 0903.2981

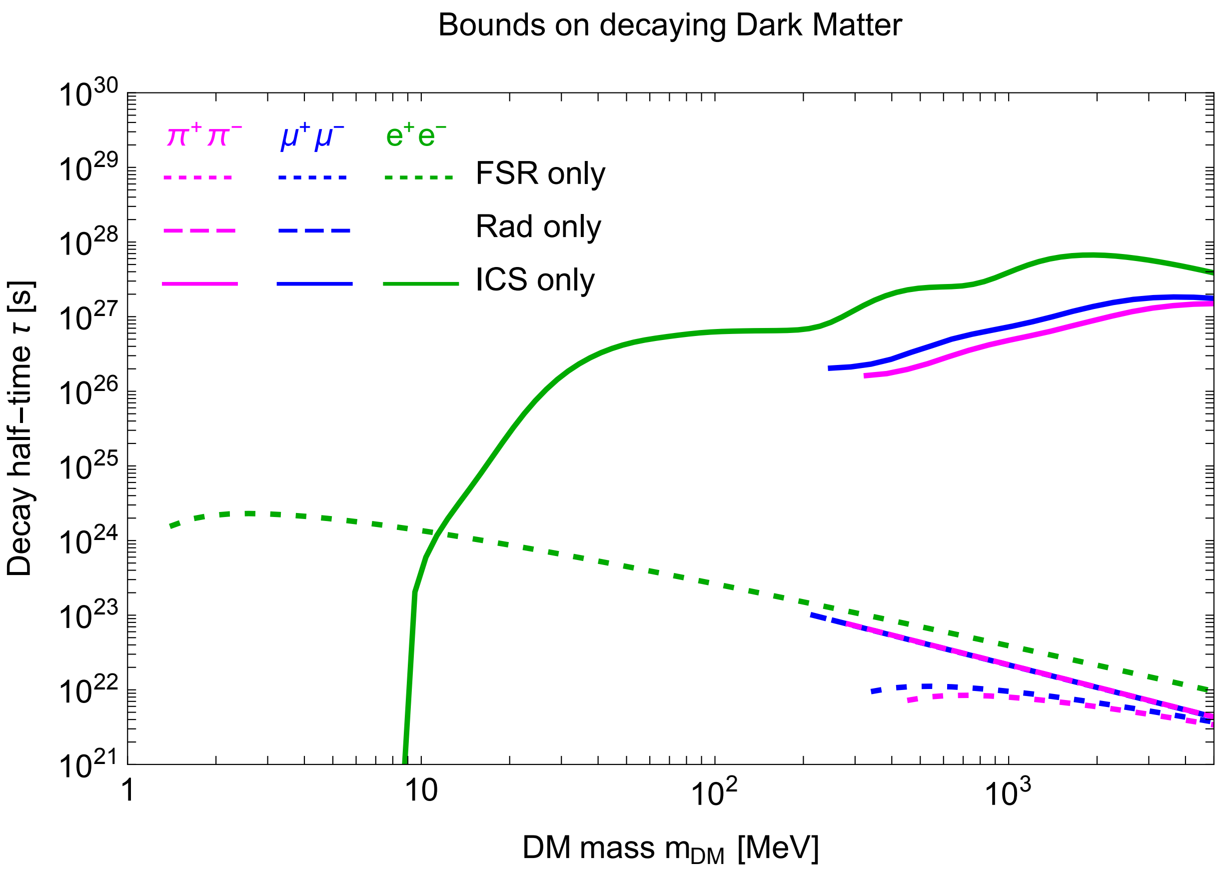


NuSTAR
2012-2018
Blank-sky fields
Krivonos et al., 2011.11469
GC observations
Perez et al., 1609.00667
Off-plane observations
Roach et al., 1908.09037

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

Analysis and results

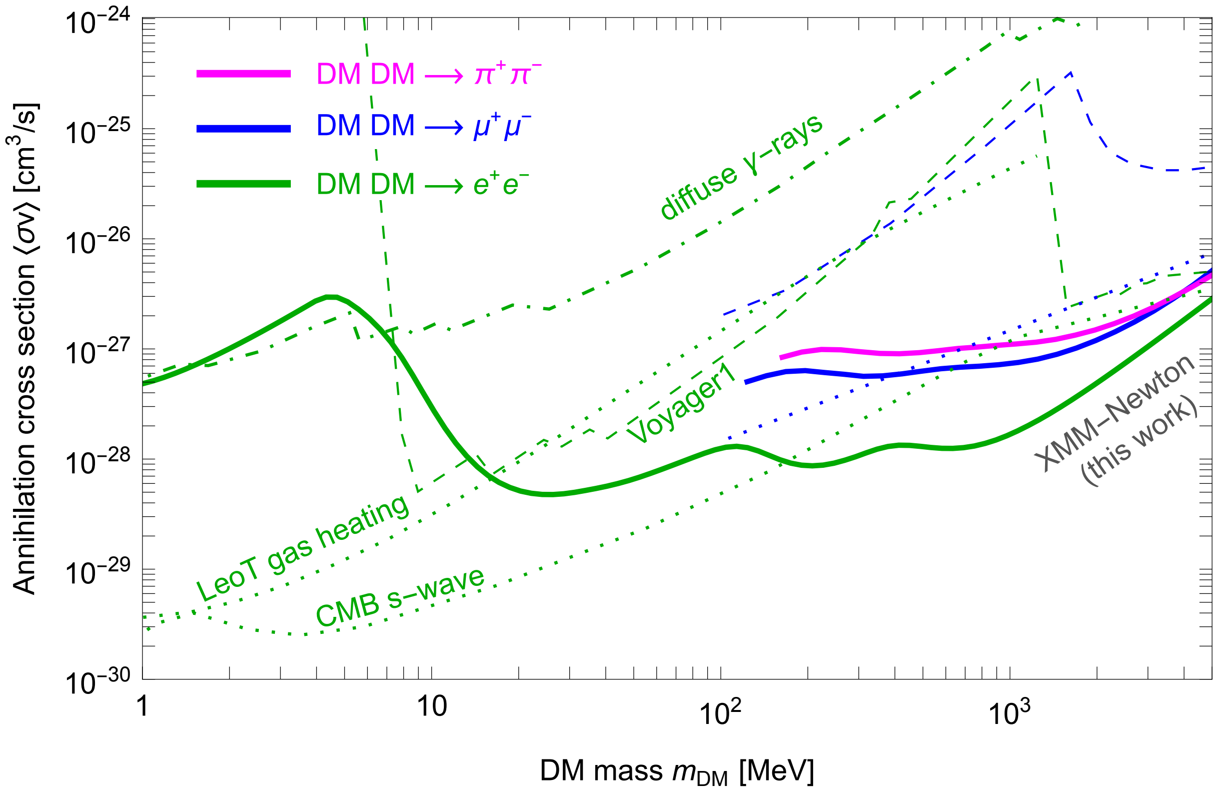




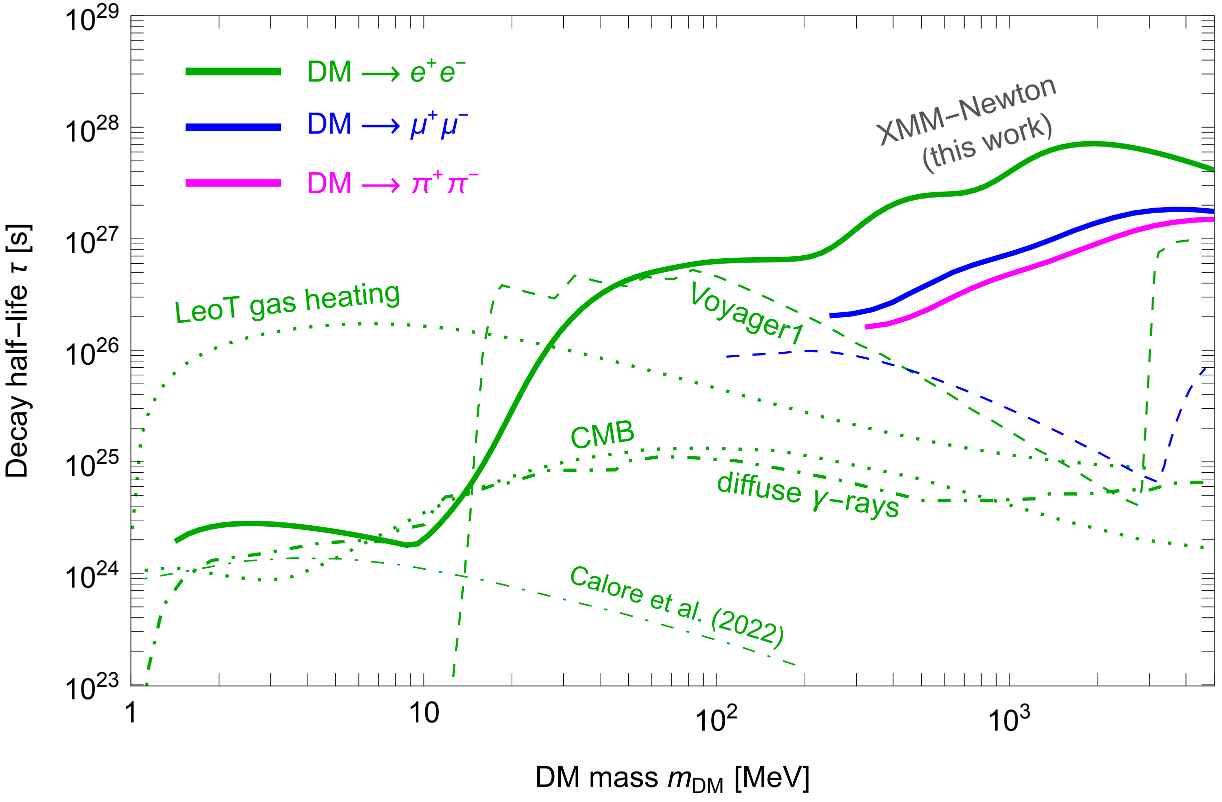
Analysis and results

<u>Diffuse γ-rays:</u> Essig et al., 1309.4091
<u>Voyager 1:</u> Boudaud et al., 1612.07698
<u>Leo T gas heating:</u> Wakedar and Wang, 2111.08025
<u>CMB:</u> Slatyer, 1506.03811,
Lopez-Honorez et al., 1303.5094,
Liu et al., 1604.02457
<u>INTEGRAL FSR:</u> Calore et al. 2209.06299

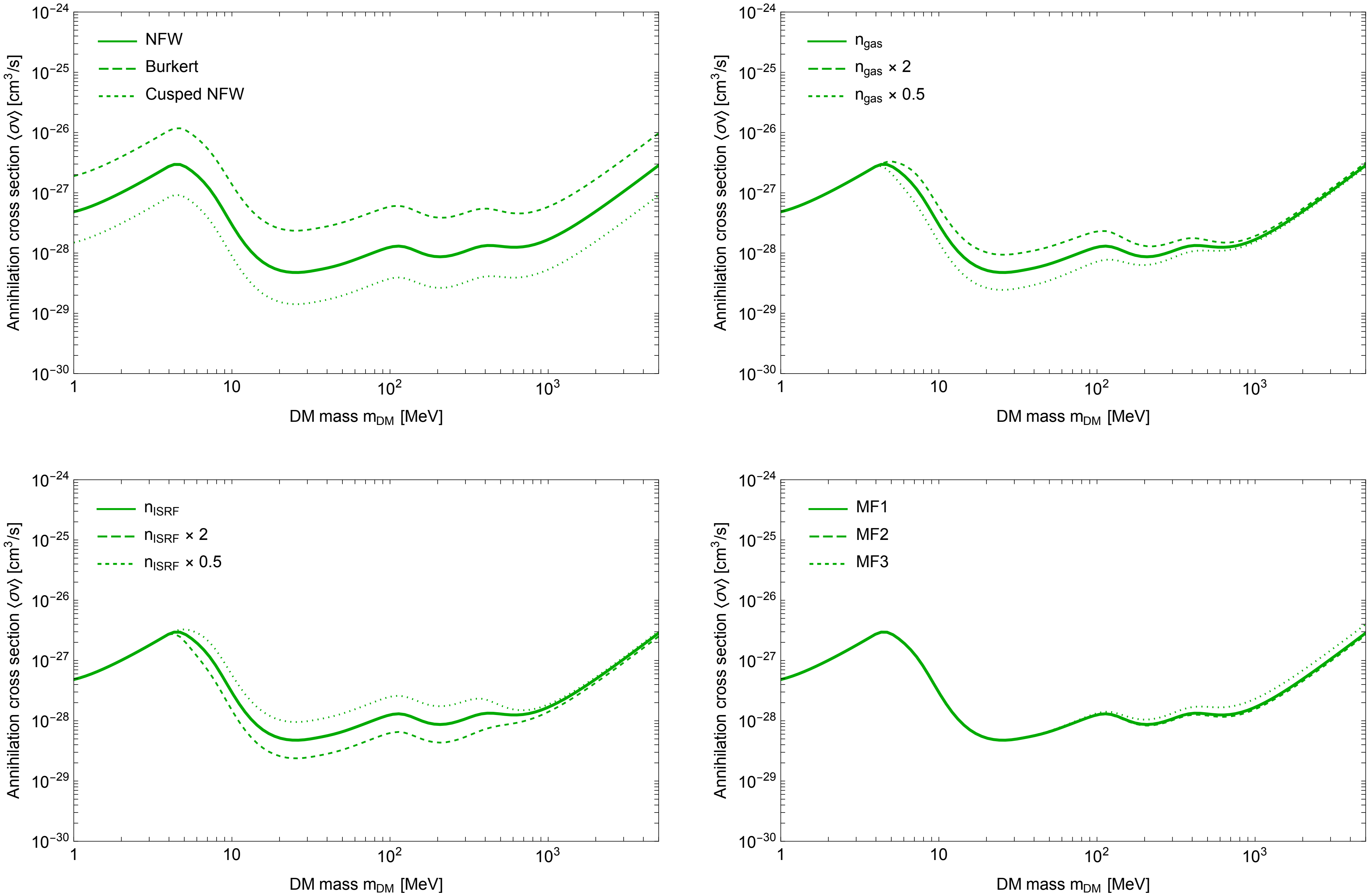
Bounds on annihilating Dark Matter



Bounds on decaying Dark Matter



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



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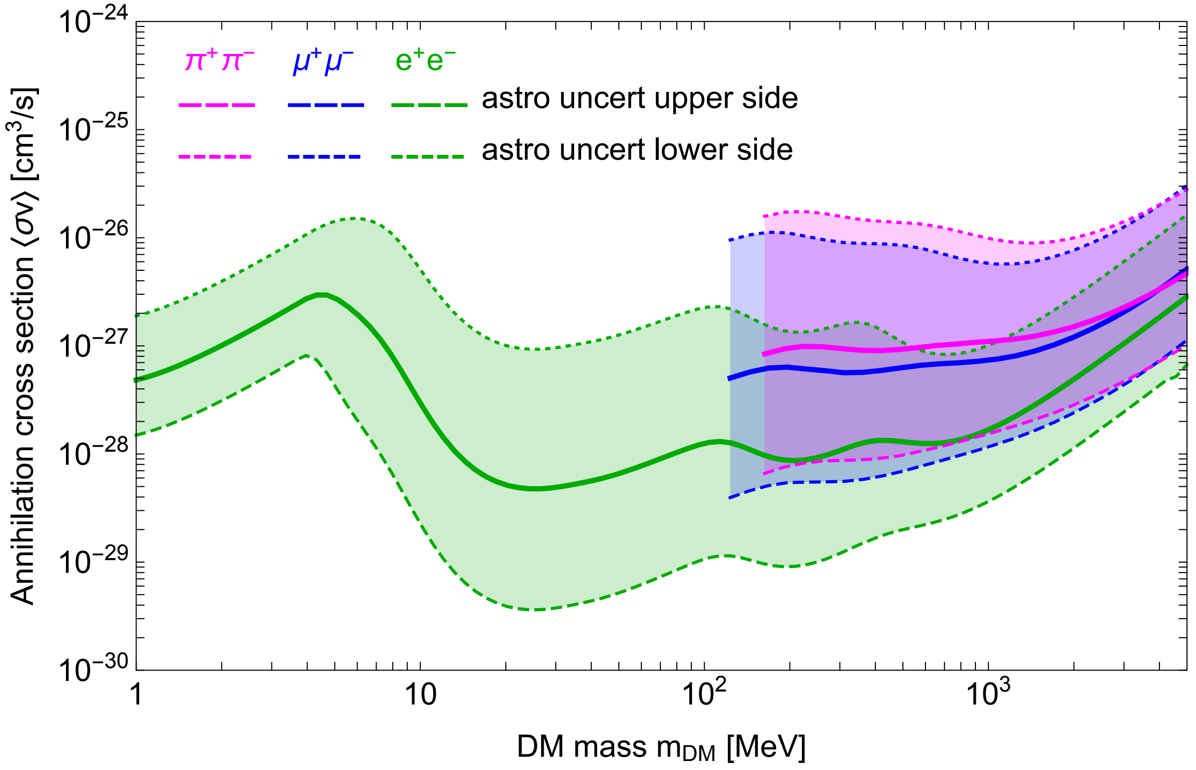

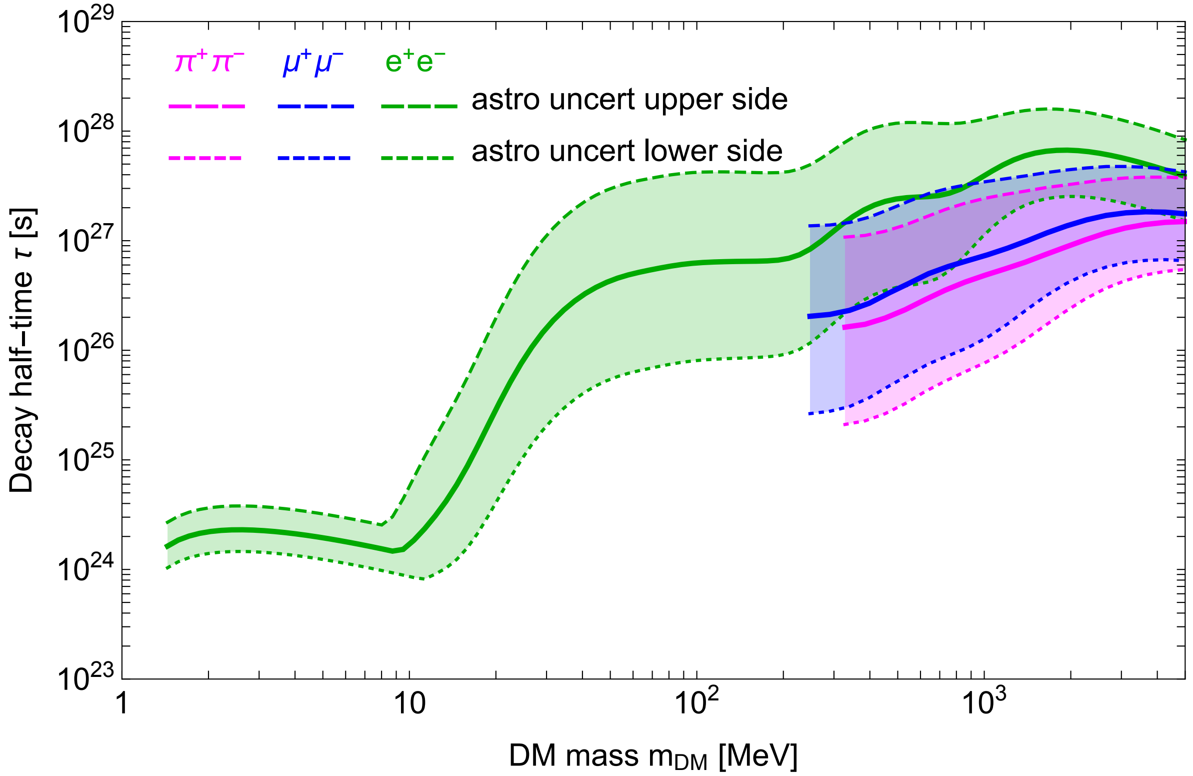

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- Proof of concept: secondary emissions allow to circumvent the MeV gap

- As a bonus they can set strong bounds on light DM, although their robustness is debatable

- Two possible improvements:
  1) Astrophysical background modeling
  2) Deviate from the minimal CR transport scheme (especially include K_{pp})

Balaji, De la Torre Luque, JK, to appear

Summary and prospects

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- Other prospects to explore:
  - Look at p-wave annihilation $\langle \sigma v \rangle = \langle \sigma v \rangle_s + \langle \sigma v \rangle_p v^2 + \mathcal{O}(v^4)$
  - Test BSM models that provide a light DM candidate:
    1) Injection spectra of $e^{\pm}$ from DM annihilations/decays channels
    2) Branching ratios
    3) Expression of $\langle \sigma v \rangle$ as a function of the couplings

Thank you for your attention!

Backup

Diffusion-loss equation ingredients

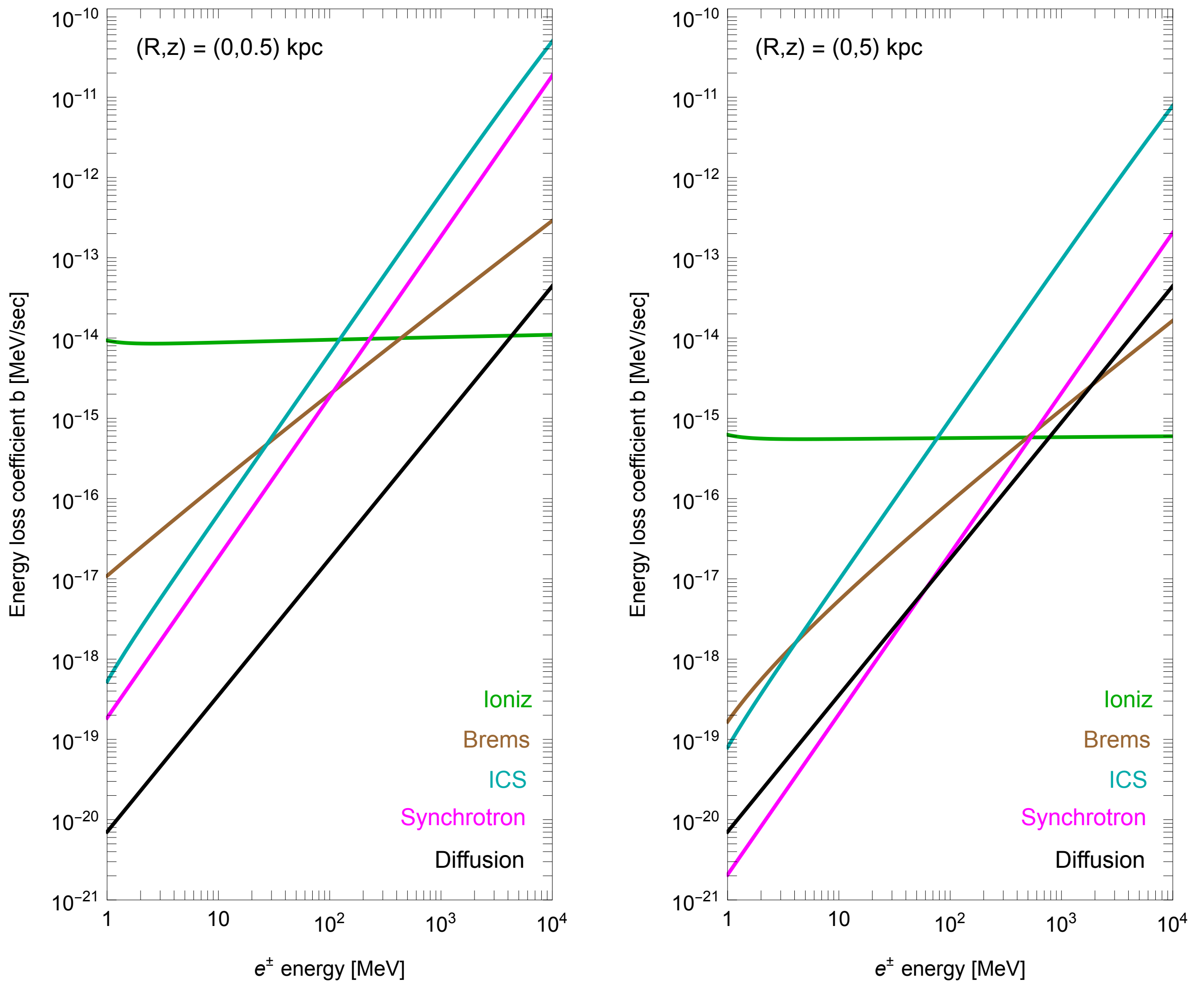
Depends on the local ISRF density

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

Depend on the local gas density

Depends on the galactic magnetic field configuration

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



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

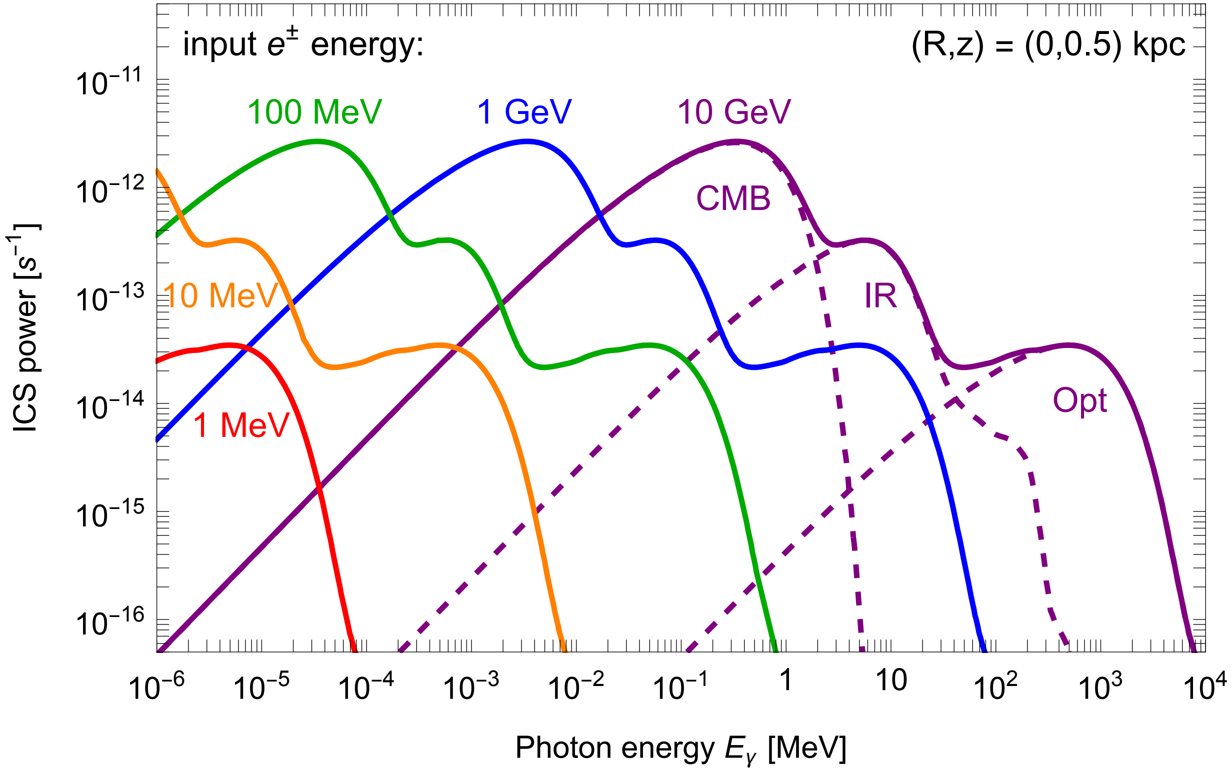
$$\xi = \frac{2E_e}{m_\mu}, \qquad \varrho = \frac{m_e}{m_\mu}$$

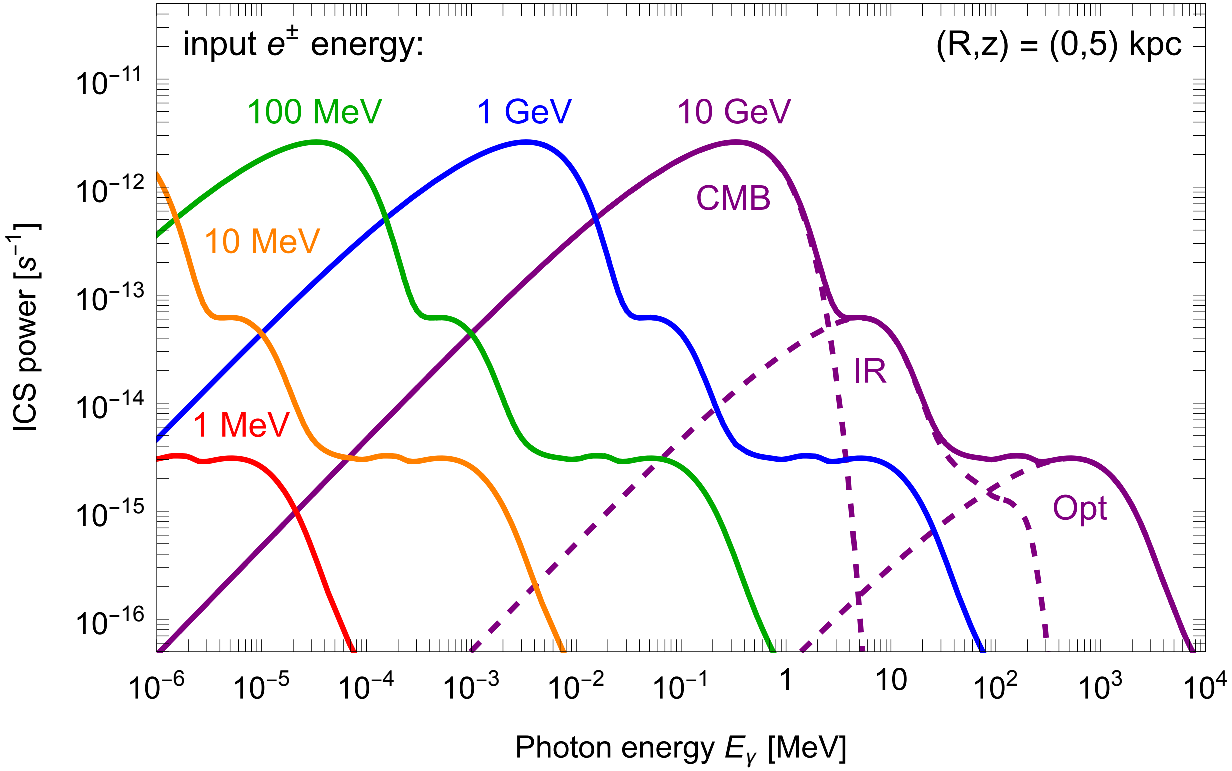
- Lorentz boost: $\frac{dN}{dE} = \frac{1}{2\beta\gamma}\int_{E'_{min}}^{E'_{max}} \frac{1}{p'}\frac{dN}{dE'}$

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

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

Inverse-Compton scattering power

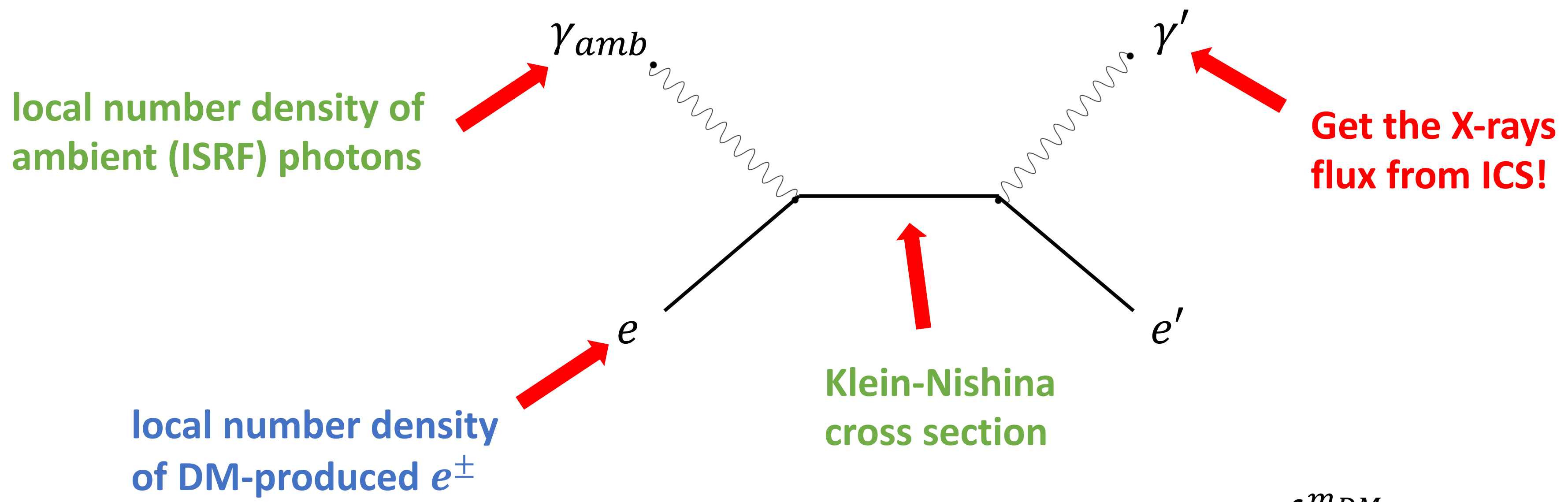




$$\mathcal{P}_{IC,i}(E_\gamma, E_e, \vec{x}) = E_\gamma \int dy\, n_i(y, \vec{x})\, \sigma_{IC}(E_e, y)$$

Inverse-Compton scattering

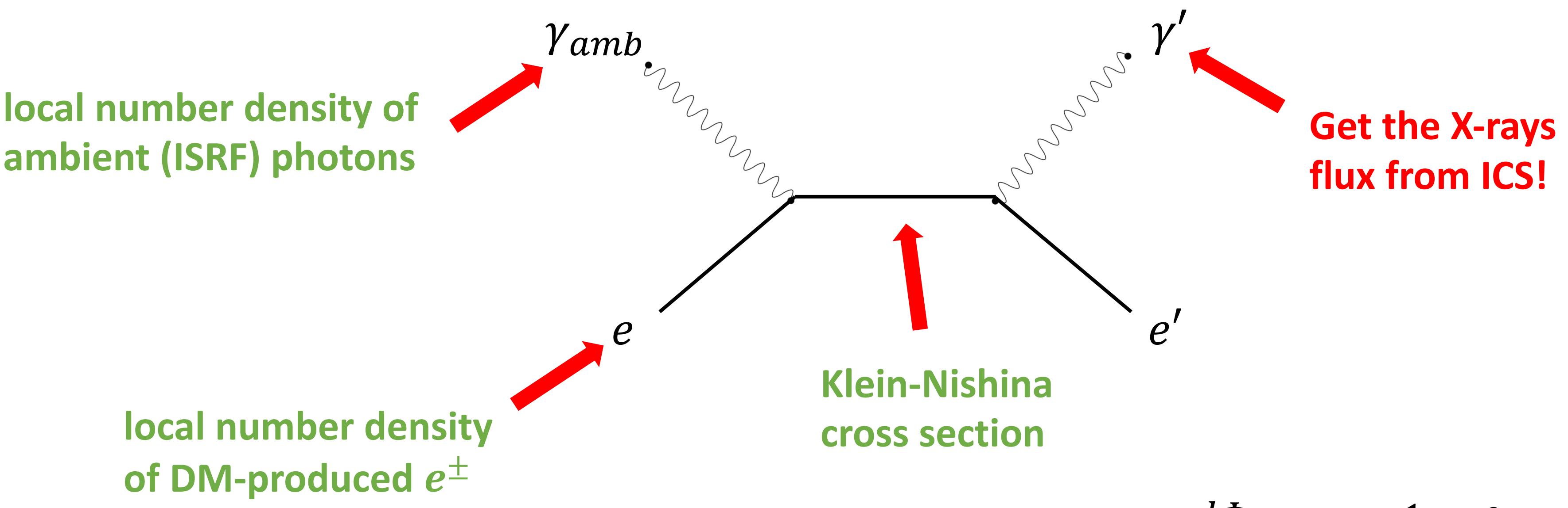
- To compute the IC-scattered photon flux, we need a few ingredients:



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

Inverse-Compton scattering

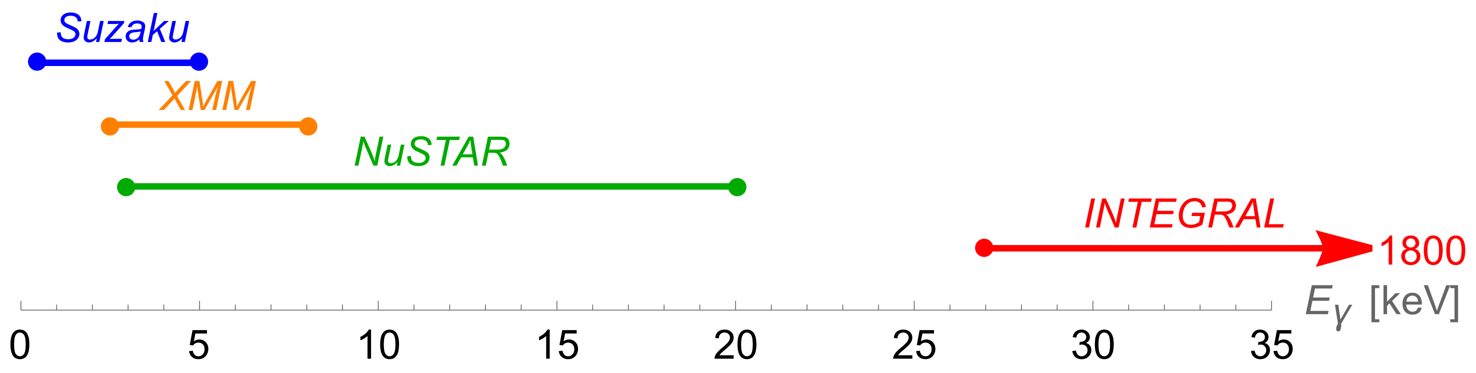
- To compute the IC-scattered photon flux, we need a few ingredients:



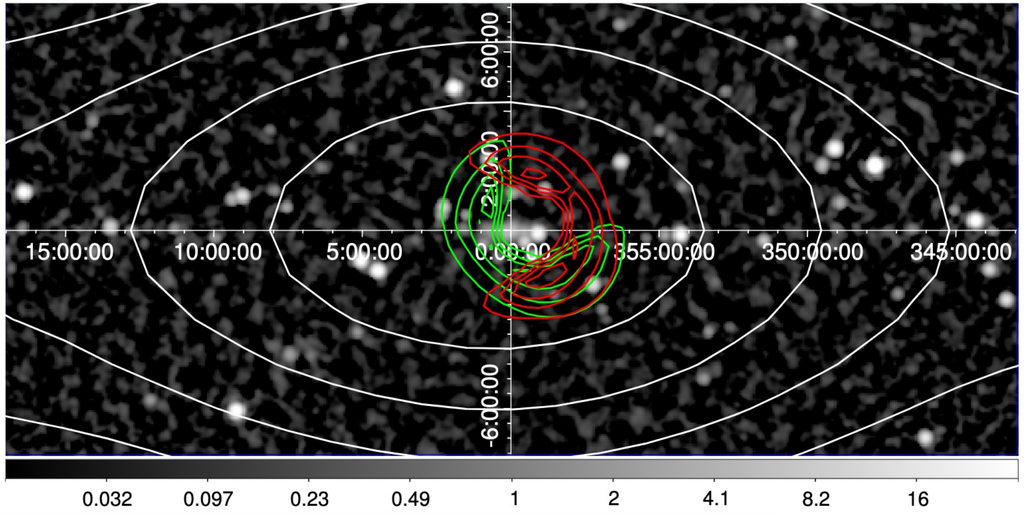
$$\frac{d\Phi_{IC\gamma}}{dE_\gamma d\Omega} = \frac{1}{4\pi E_\gamma}\int_{l.o.s.} ds\, j\big(E_\gamma, \vec{x}(s,b,l)\big)$$

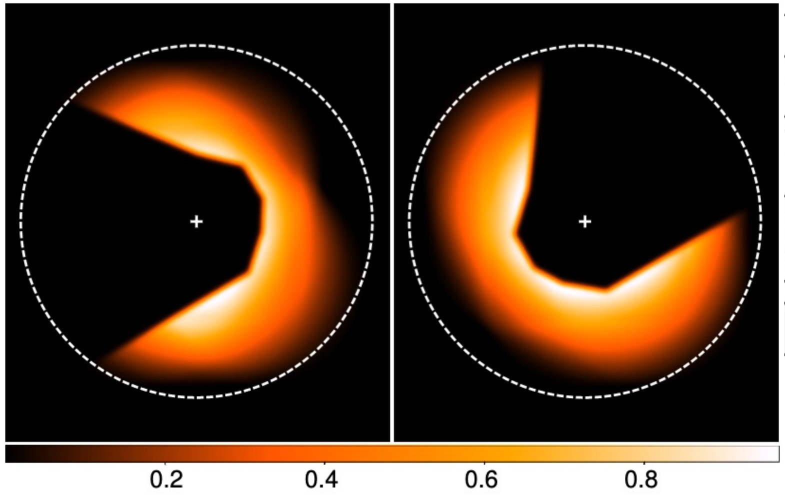
Dataset energy ranges

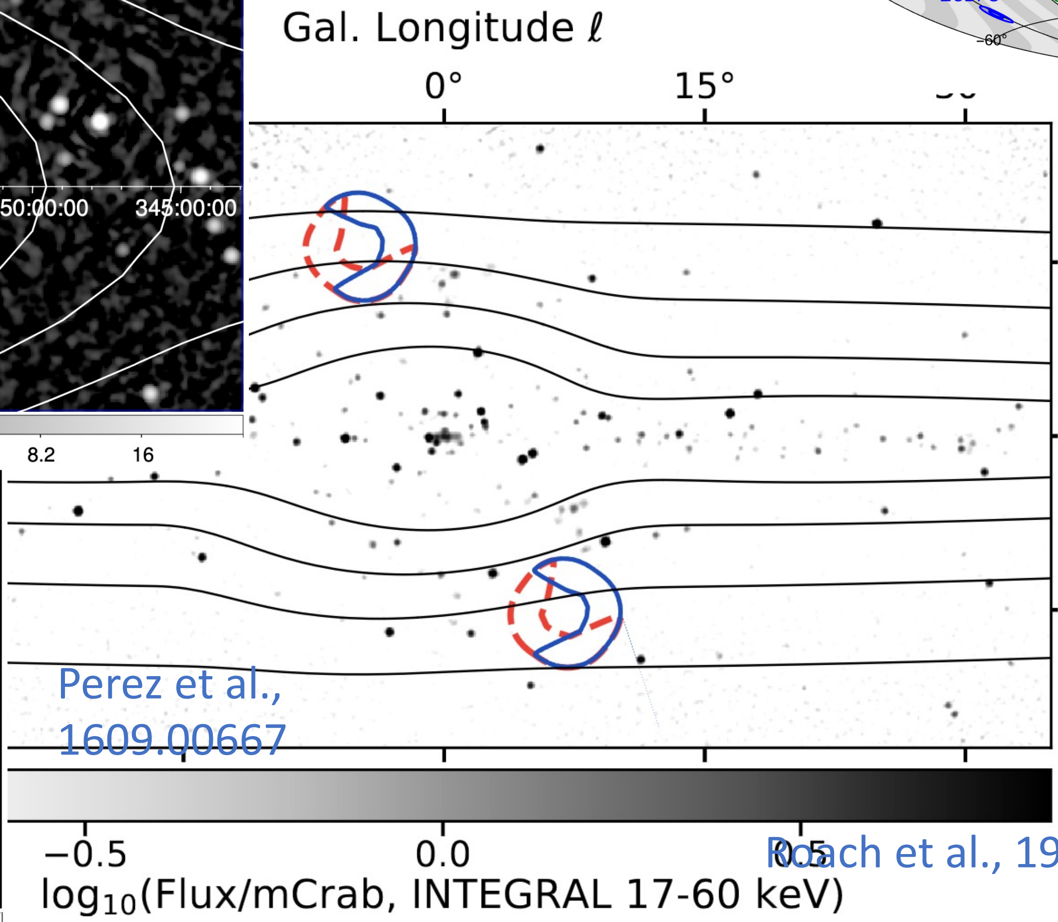
Suzaku: 0.4 – 5 keV
XMM-Newton: 2.5 – 8 keV
NuSTAR: 3 – 20 keV
INTEGRAL: 27 – 1800 keV



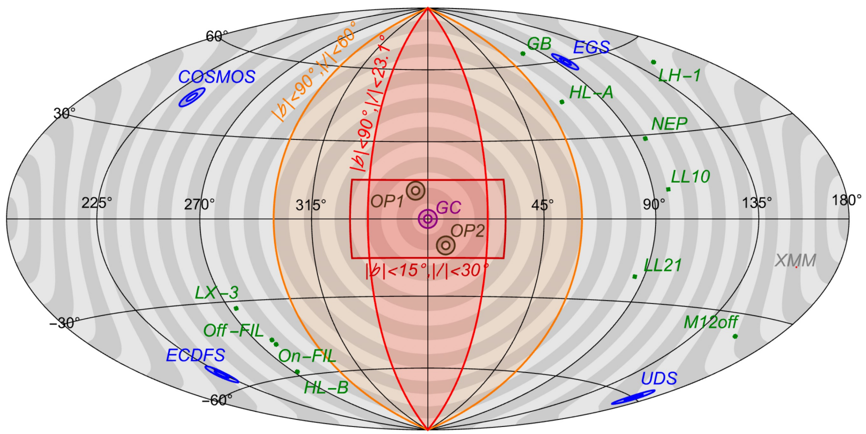
NuSTAR datasets







Perez et al., 1609.00667



Roach et al., 1908.09037

NuSTAR datasets

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

Observation ID	Pointing (J2000)[a] RA (deg)	DEC (deg)	Effective Exposure[b] FPMA / FPMB (ks)	Detector Area[c] FPMA / FPMB (cm^2)	Avg. Solid Angle[d] FPMA / FPMB (deg^2)
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 2. Data sets used in the analysis.

ID	Field	Begin	End	T_{exp}
1	COSMOS *EP1*	26-12-2012	20-01-2013	750 ks
2	COSMOS *EP2*	03-04-2013	21-05-2013	630 ks
3	COSMOS *EP3*	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 Galactic Bulge observations used in this analysis, with 0-bounce effective areas after data cleaning.

NuSTAR obsID	Pointing (J2000) RA, Dec (deg)	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)
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

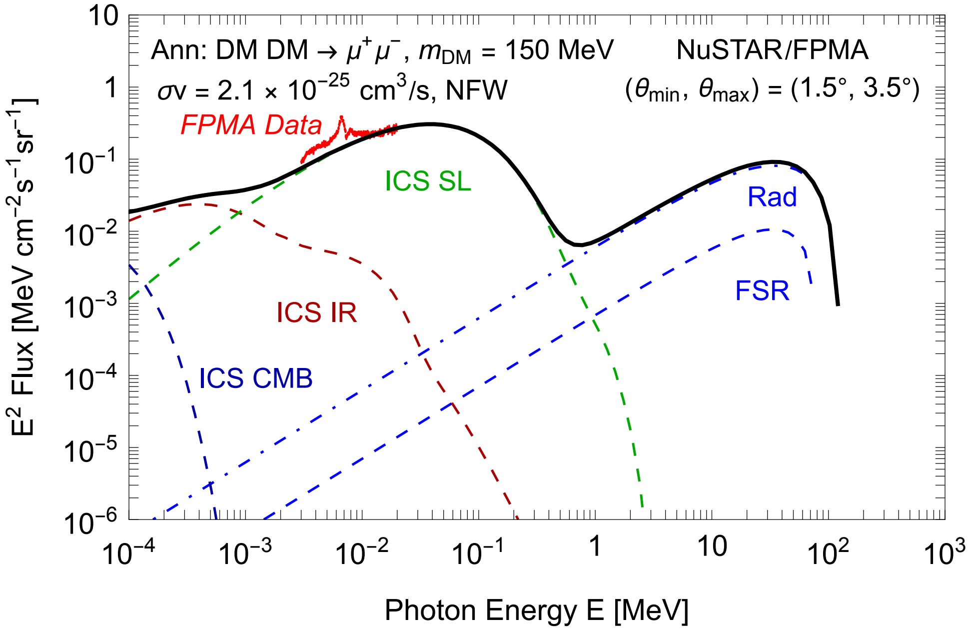
[a] After `OPTIMIZED` SAA filtering and manual data screening.
[b] After bad pixel removal (both obsIDs) and point-source masking (40410001002 only).
[c] Average solid angle of sky for detecting 0-bounce photons, after correcting for bad pixel removal and vignetting efficiency.

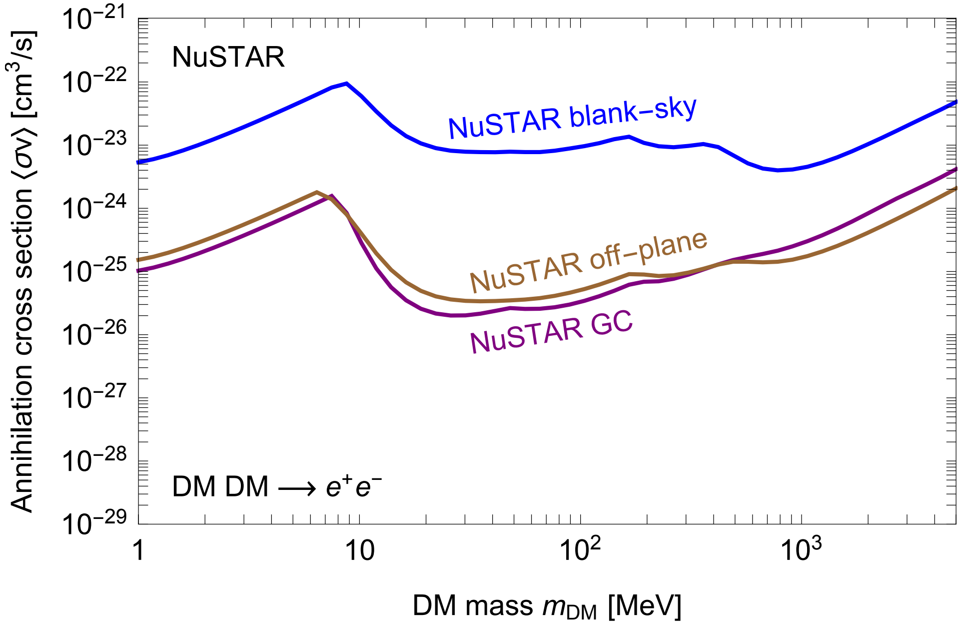
Roach et al., 1908.09037
Data taken between in 2018

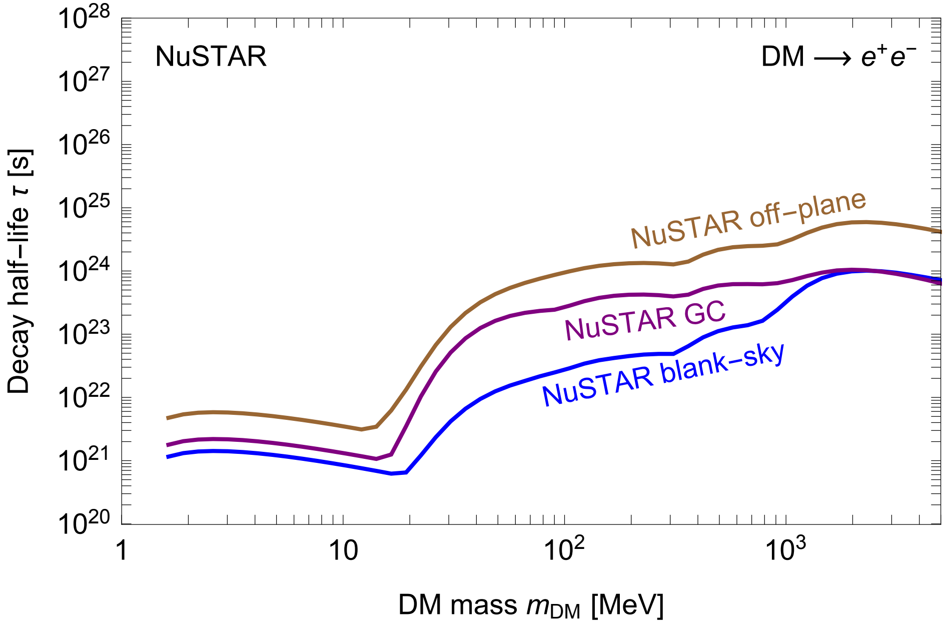
NuSTAR constraints

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

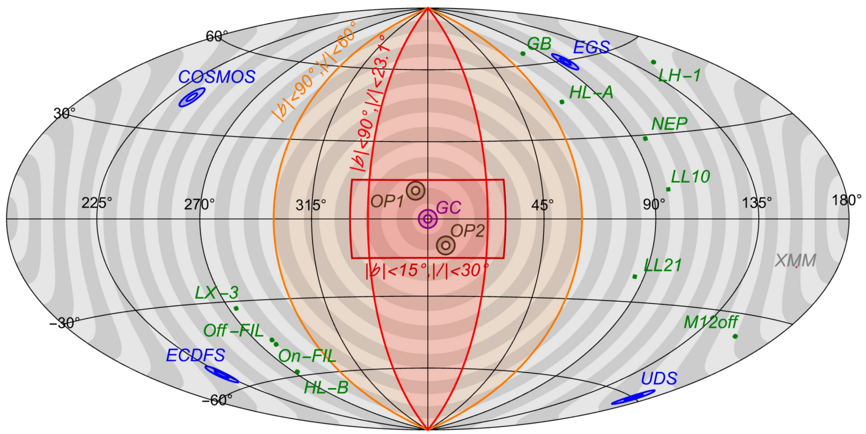
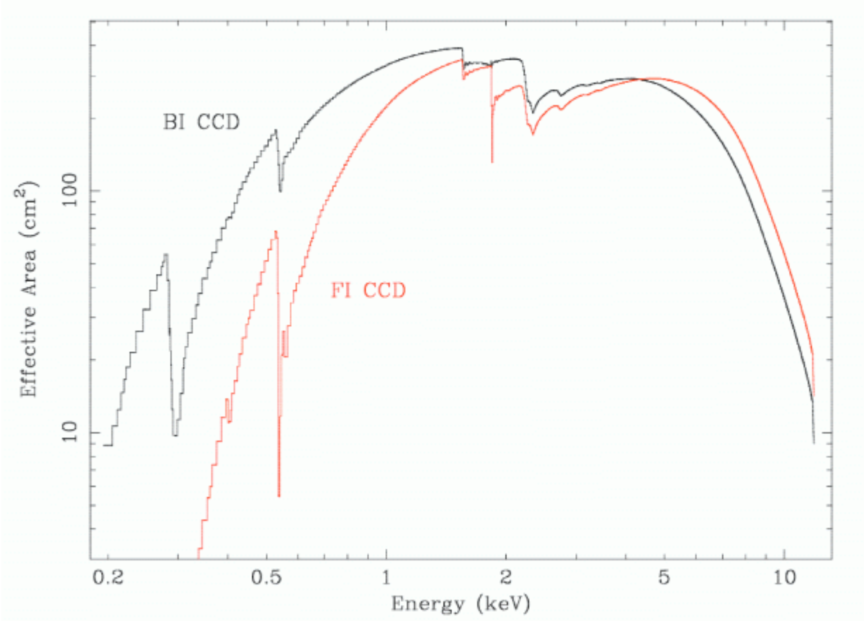


Table 1. Log of observations, ordered by $|b|$

Data set ID	Field Name (Short Name)	Obs ID	Date	Exposure (ks) Total	Cleaned	Aim point (ℓ, b)	$(E_{\rm Lon}, E_{\rm Lat})$*
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



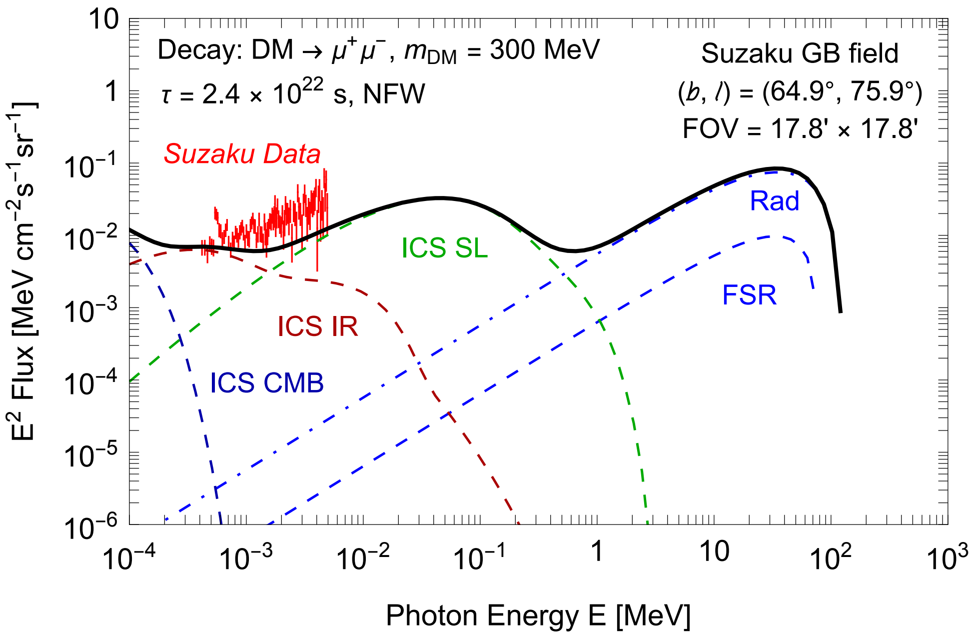
https://heasarc.gsfc.nasa.gov/docs/suzaku/gallery/performance/xis_area.html

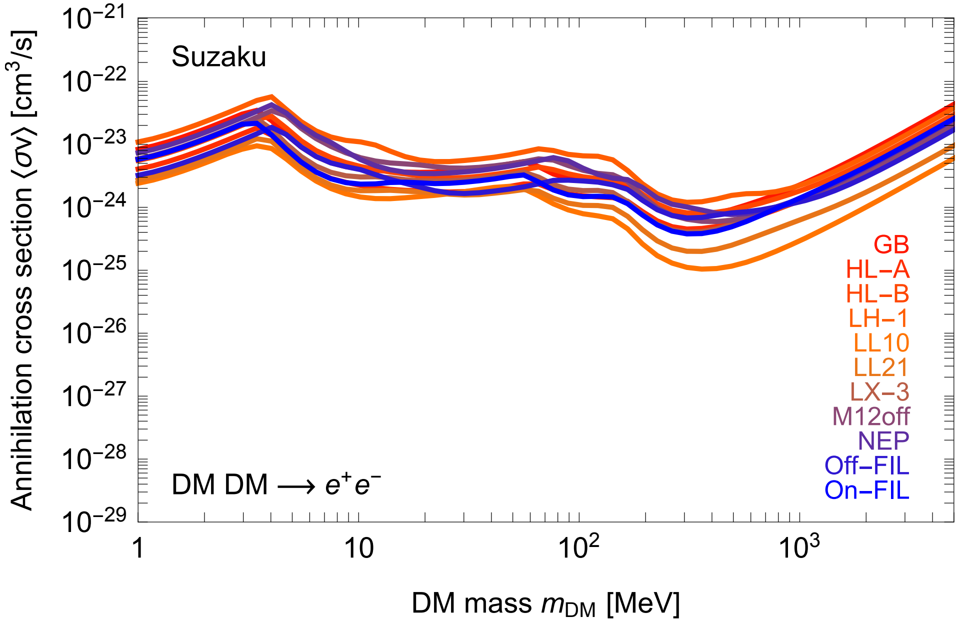
Suzaku constraints

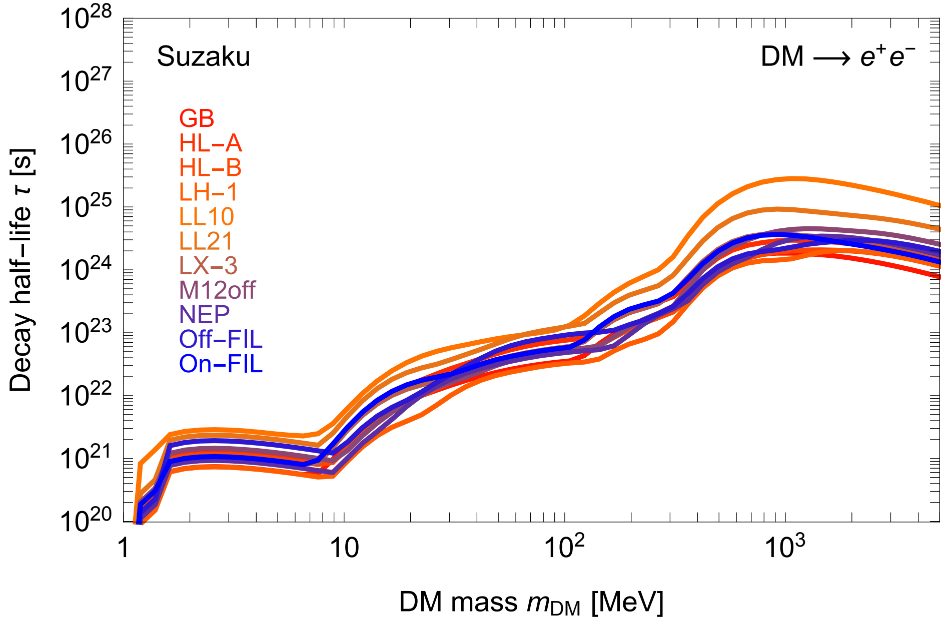
Suzaku high-latitude fields

2006-2008

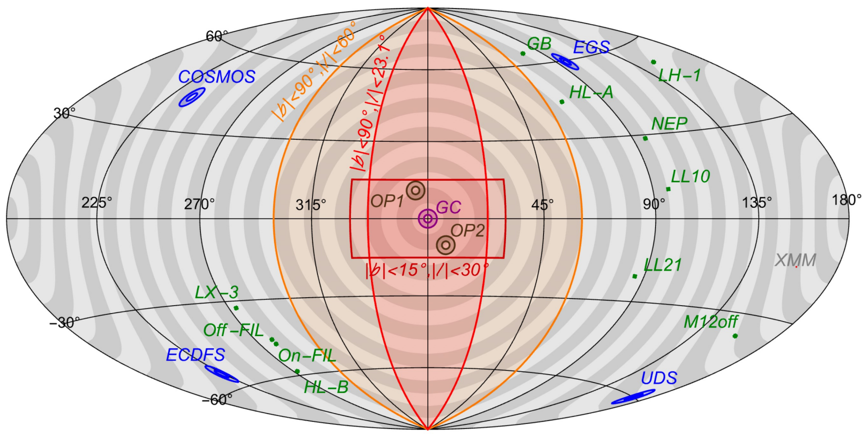
Yoshino et al., 0903.2981

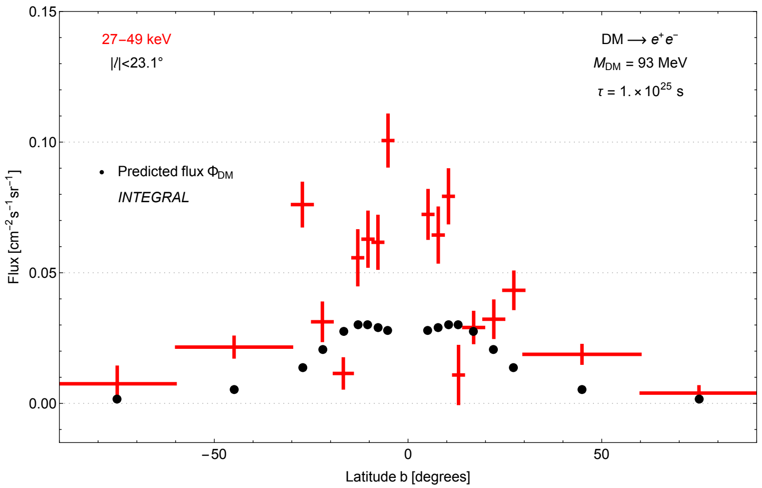


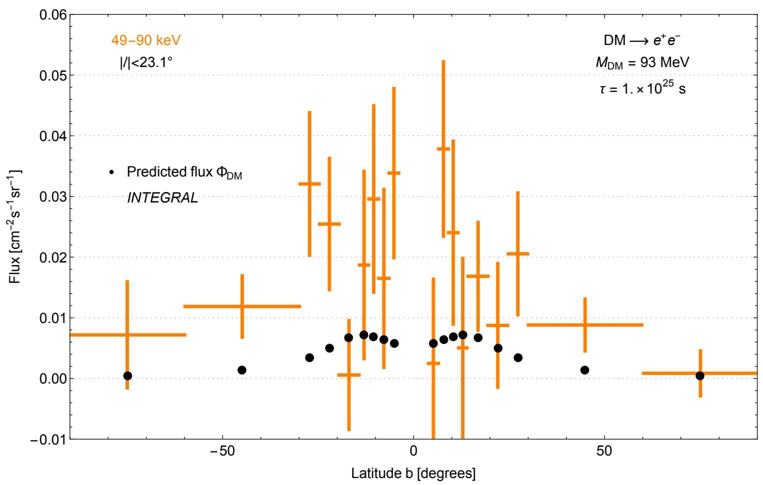




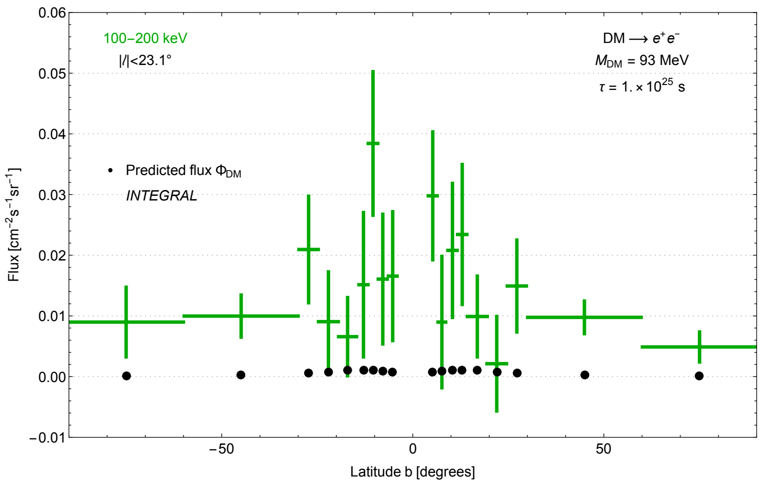
INTEGRAL datasets

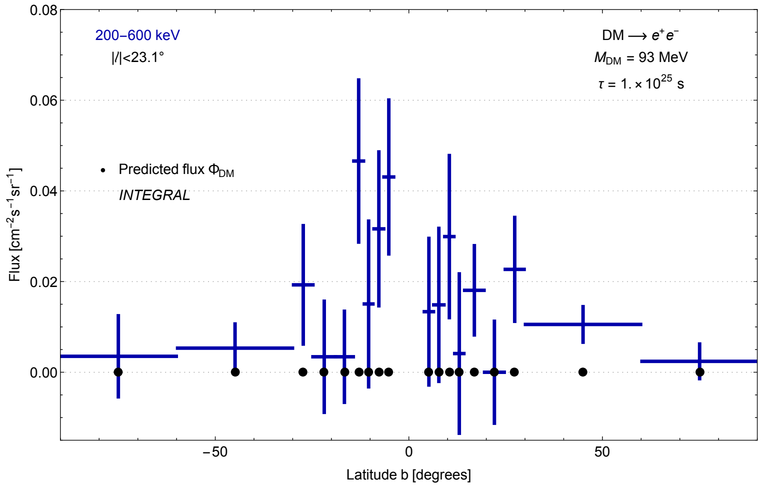


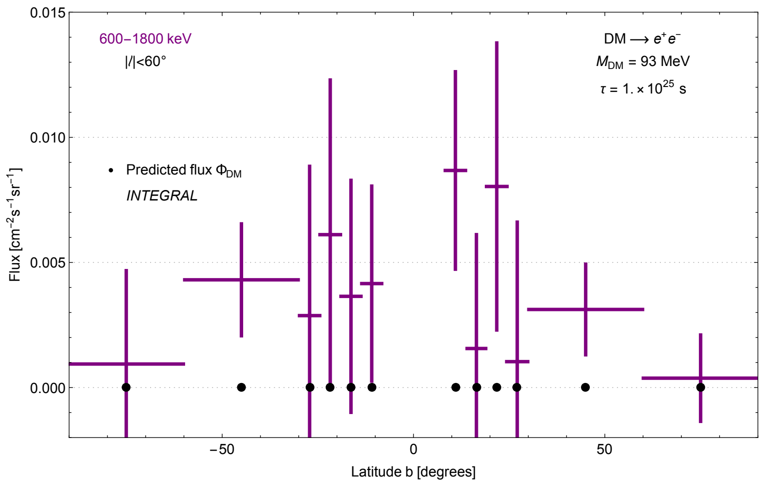




Bouchet et al., INTEGRAL coll., 1107.0200





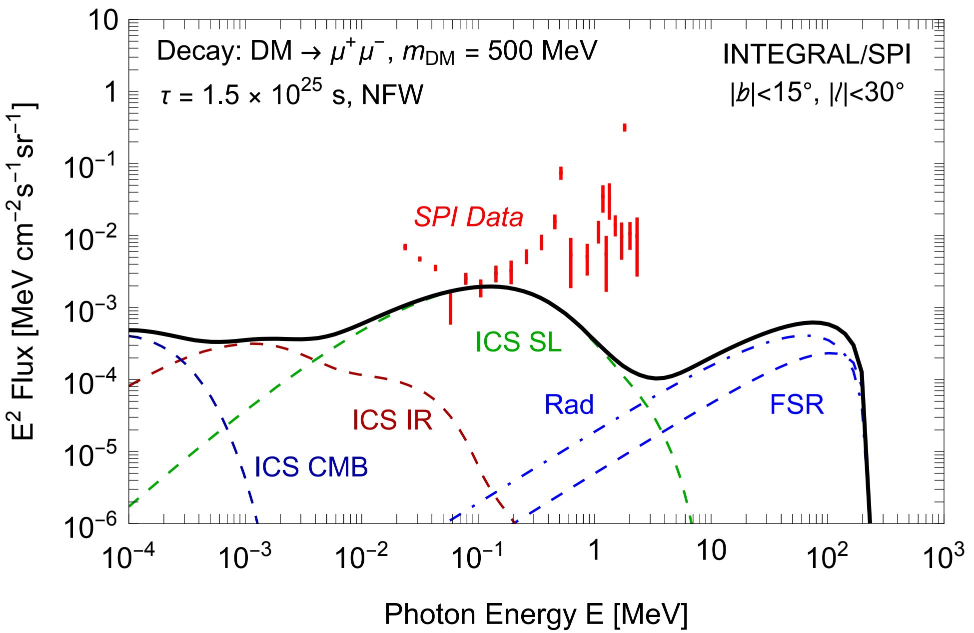


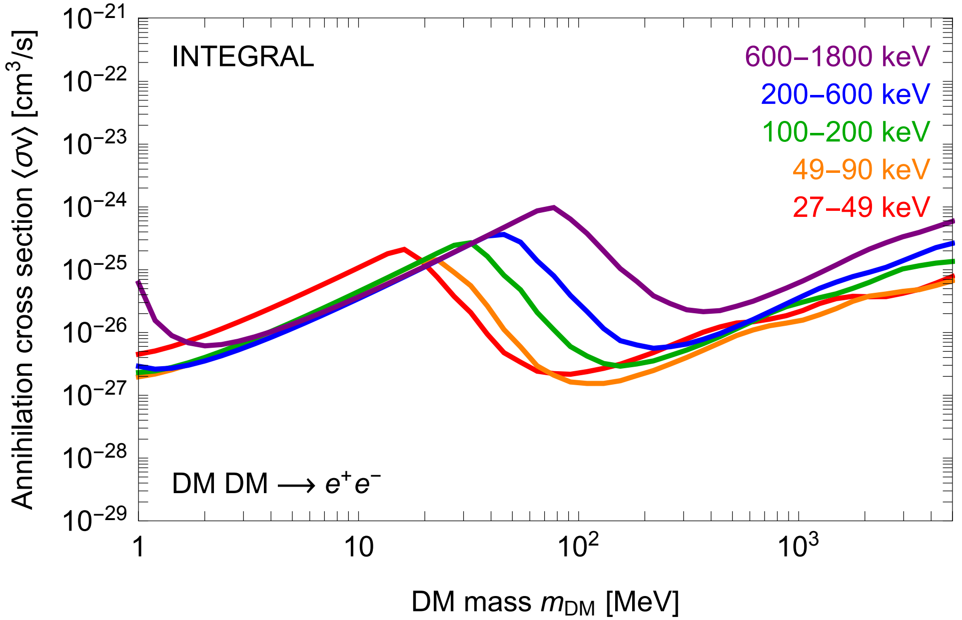
INTEGRAL constraints

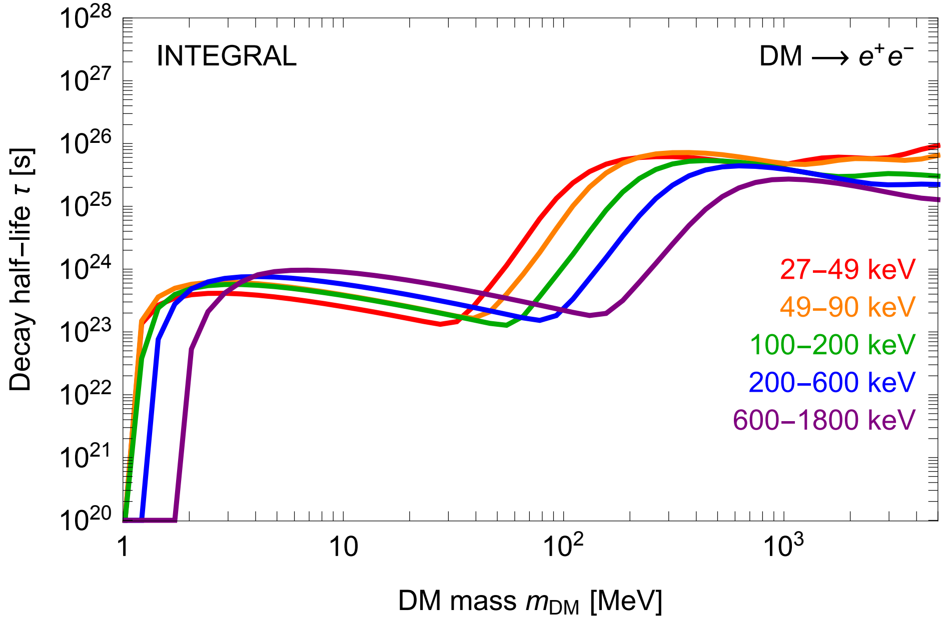
INTEGRAL diffuse emission searches

2003-2009

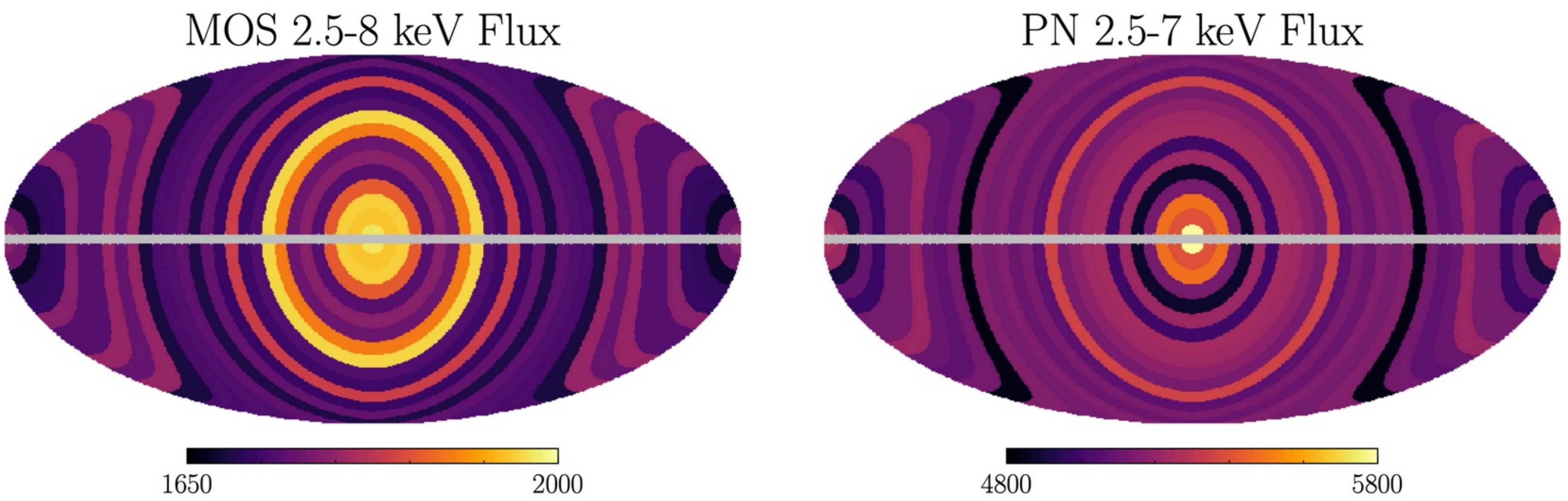
Bouchet et al., INTEGRAL coll., 1107.0200







XMM-Newton datasets



https://github.com/bsafdi/XMM_BSO_DATA

Datasets + Instrument response functions

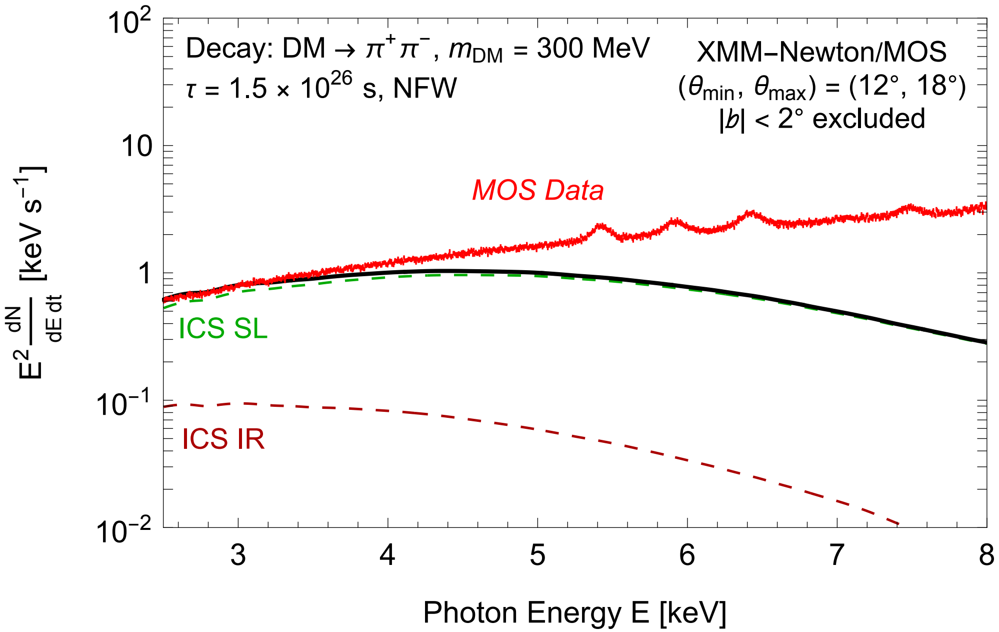
XMM-Newton constraints

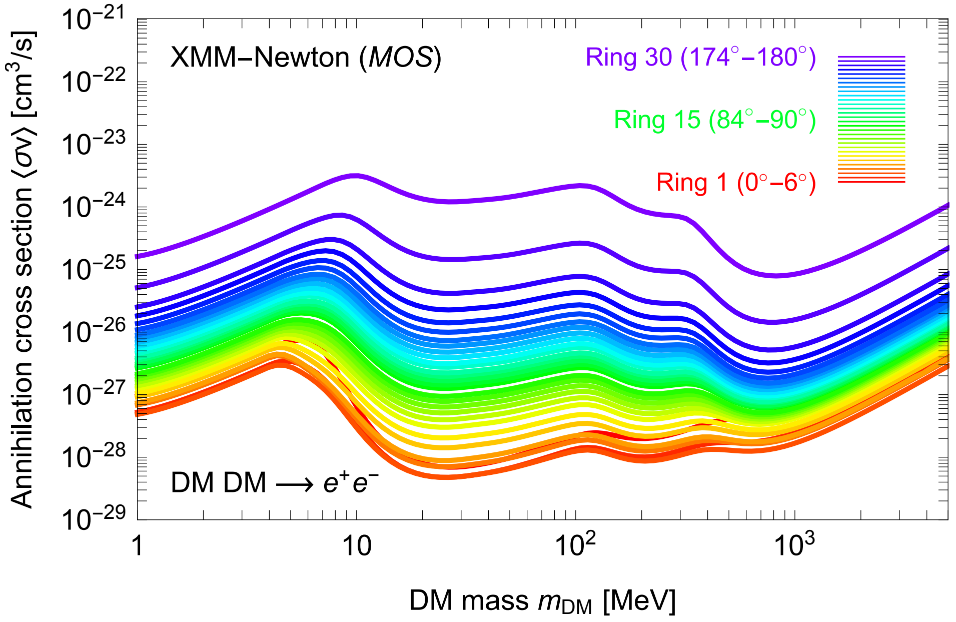
XMM-Newton whole-sky observations

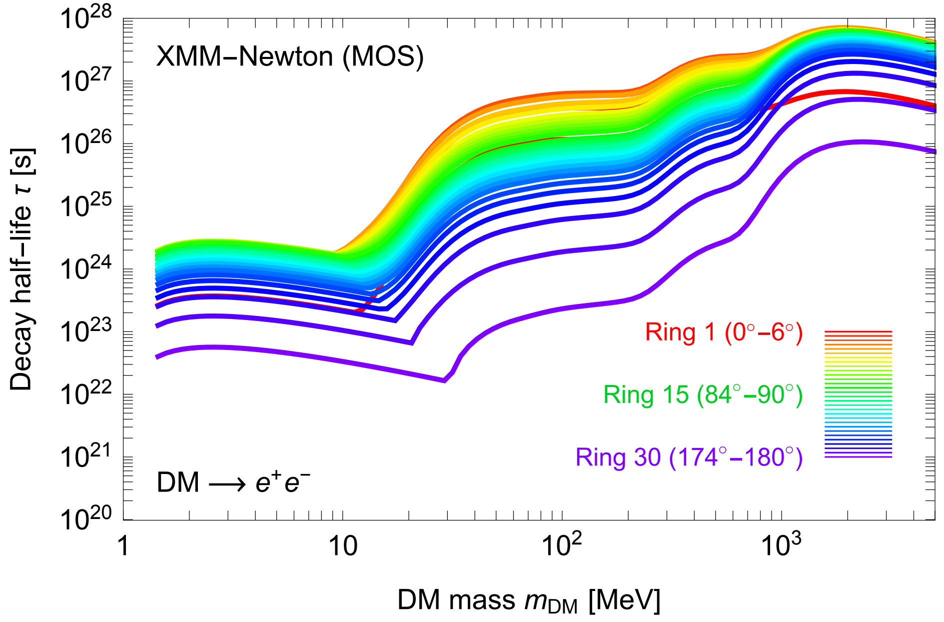
1999-2018

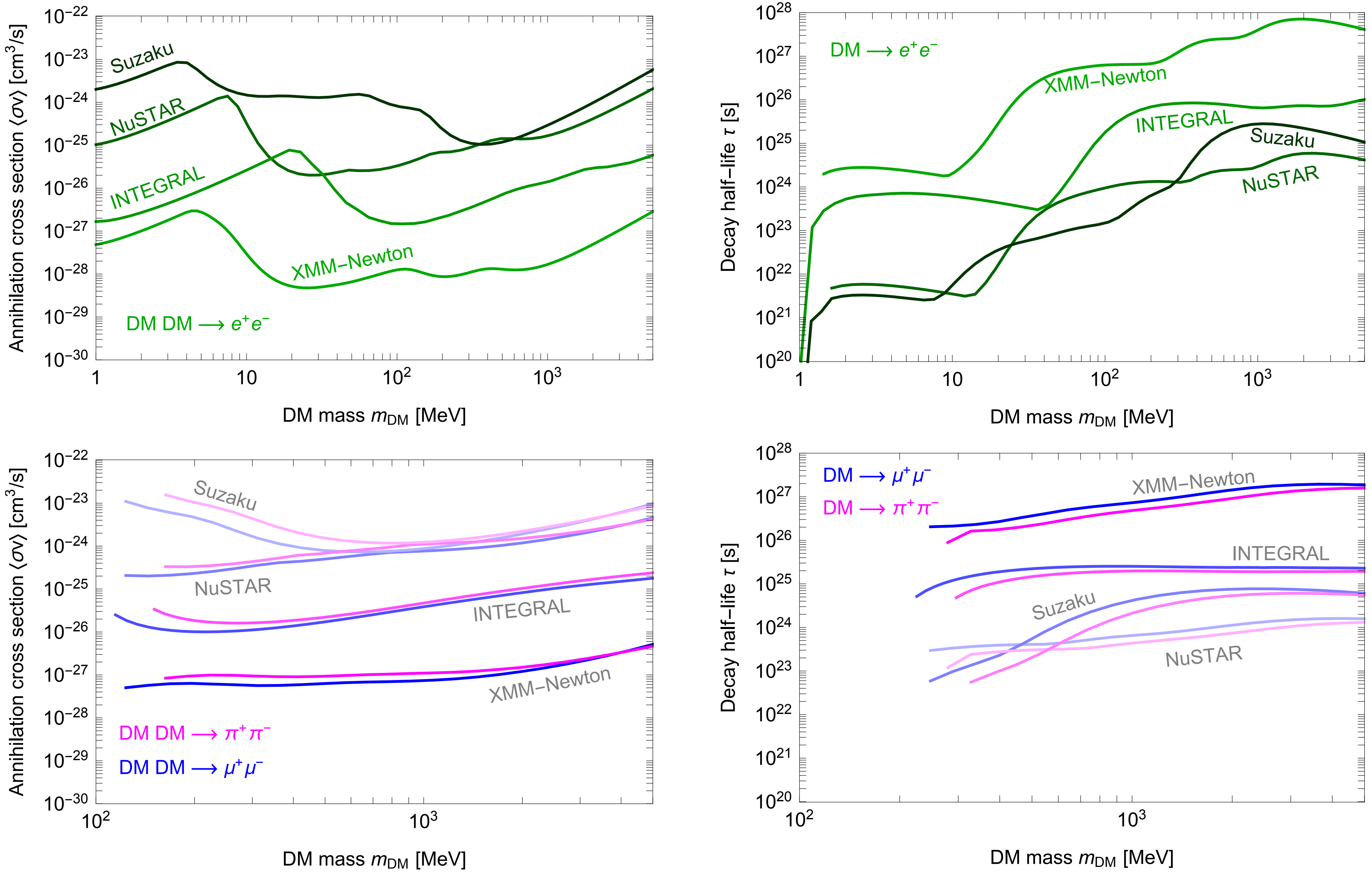
Foster et al., 2102.02207

https://github.com/bsafdi/XMM_BSO_DATA

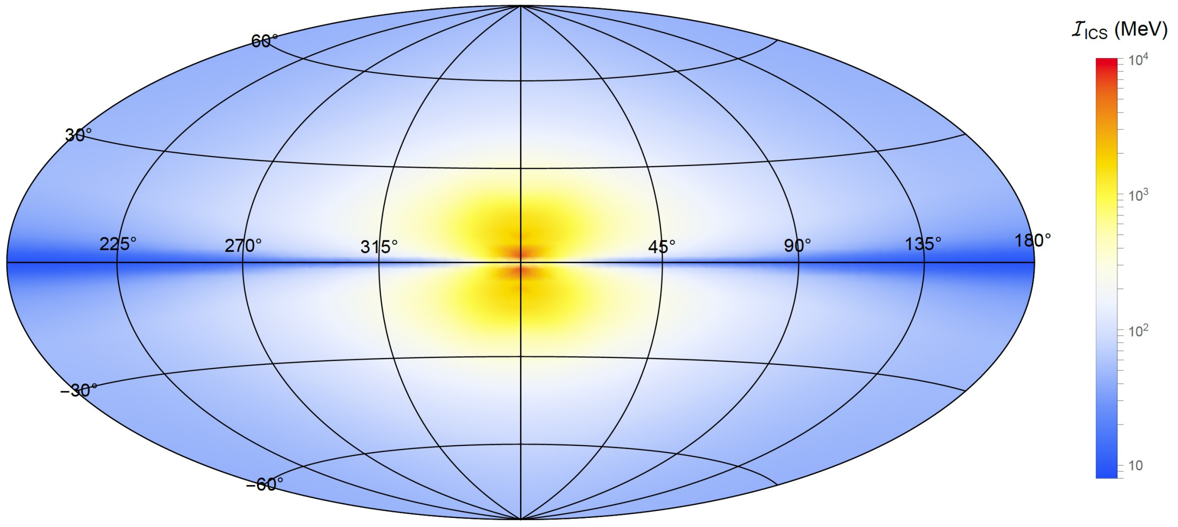




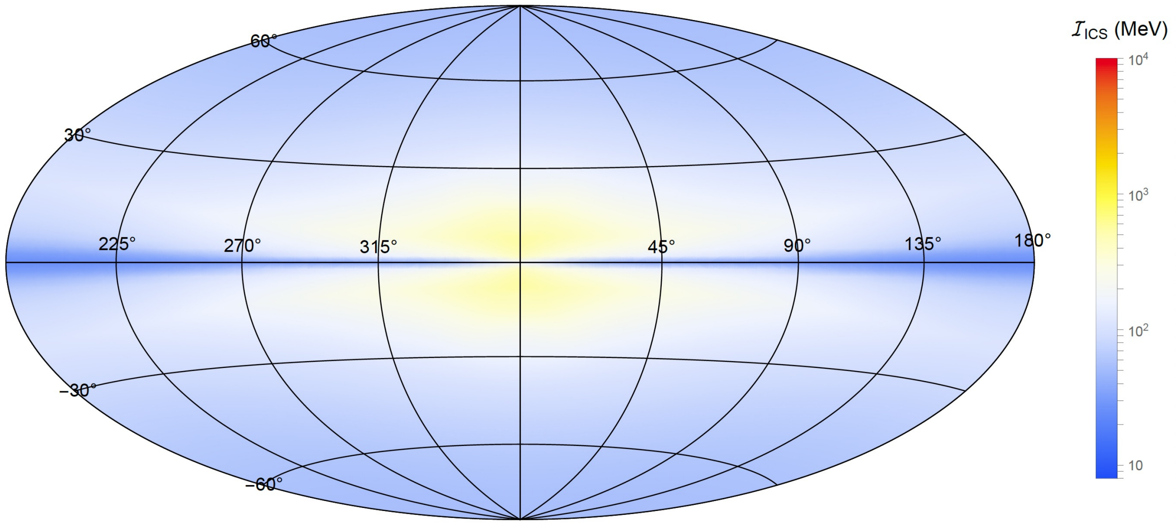



Annihilation cross section ⟨σv⟩ [cm³/s]
DM mass m_{DM} [MeV]
Suzaku
NuSTAR
INTEGRAL
XMM–Newton
DM DM ⟶ e^+e^-
Decay half-life τ [s]
DM ⟶ e^+e^-
XMM–Newton
INTEGRAL
Suzaku
NuSTAR
Annihilation cross section ⟨σv⟩ [cm³/s]
DM mass m_{DM} [MeV]
Suzaku
NuSTAR
INTEGRAL
XMM–Newton
DM DM ⟶ $\pi^+\pi^-$
DM DM ⟶ $\mu^+\mu^-$
Decay half-life τ [s]
DM mass m_{DM} [MeV]
DM ⟶ $\mu^+\mu^-$
DM ⟶ $\pi^+\pi^-$
XMM–Newton
INTEGRAL
Suzaku
NuSTAR

ICS halo function (spatial distribution)



Annihilation ($\eta = 2$)

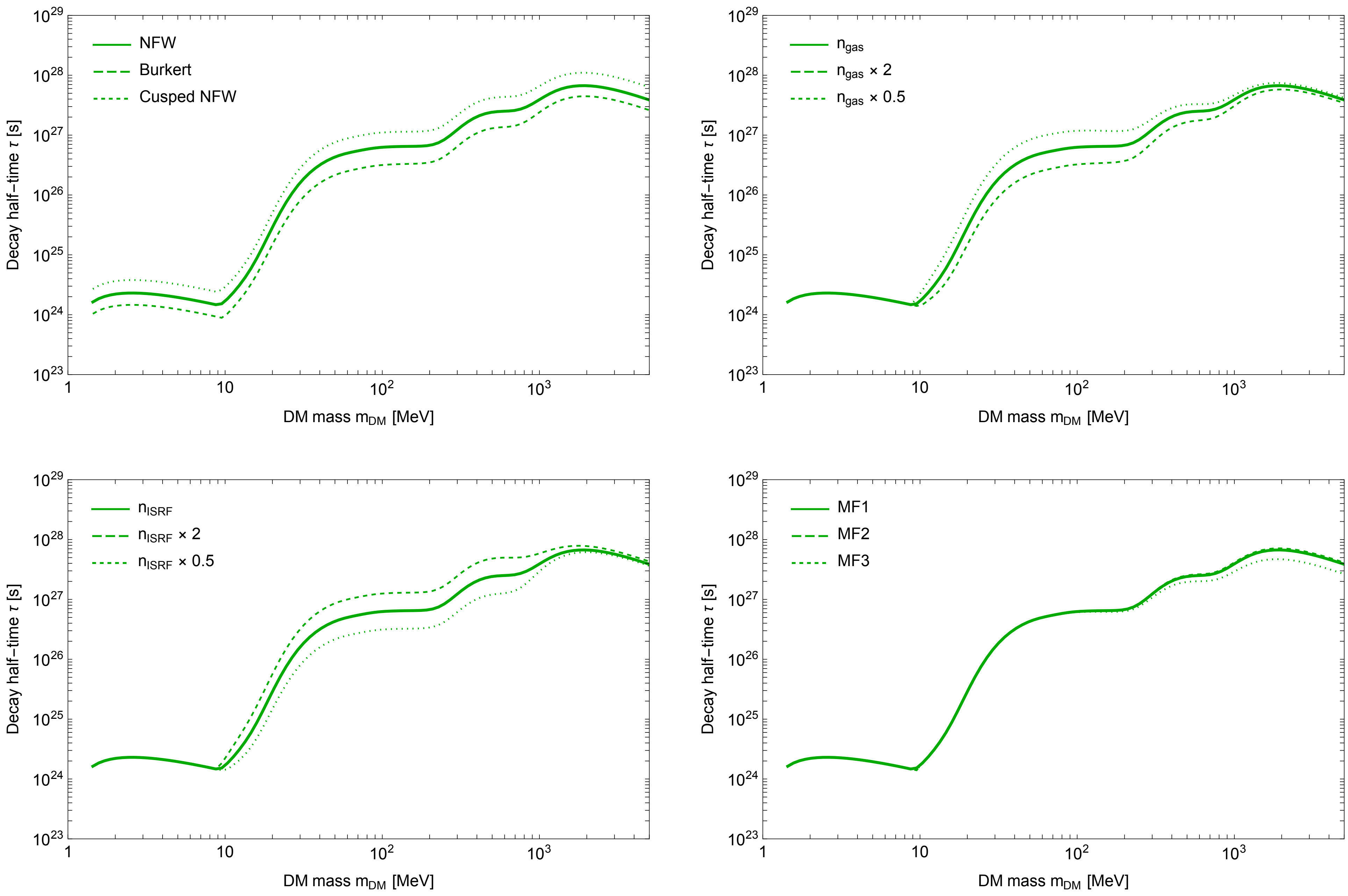


Decay ($\eta = 1$)

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

$E_\gamma = 5$ keV
$E_e = 1$ GeV

$DM \rightarrow e^+e^-$



Galactic magnetic field configurations

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

Models	$B_0\ (\mu G)$	$r_D\ (kpc)$	$z_D\ (kpc)$
MF1	4.78	10	2
MF2	5.1	8.5	1
MF3	9.1	30	4