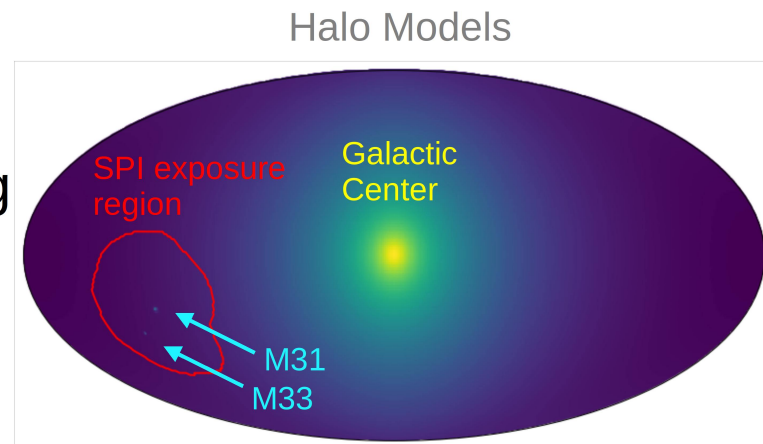


Observations of the Dark Matter Halo of the Andromeda Galaxy with INTEGRAL/SPI



Laura Eisenberger
T. Siegert, S. Mittal, D. Tsatsis
University of Würzburg

Dark Tools Workshop
Torino, June 2025

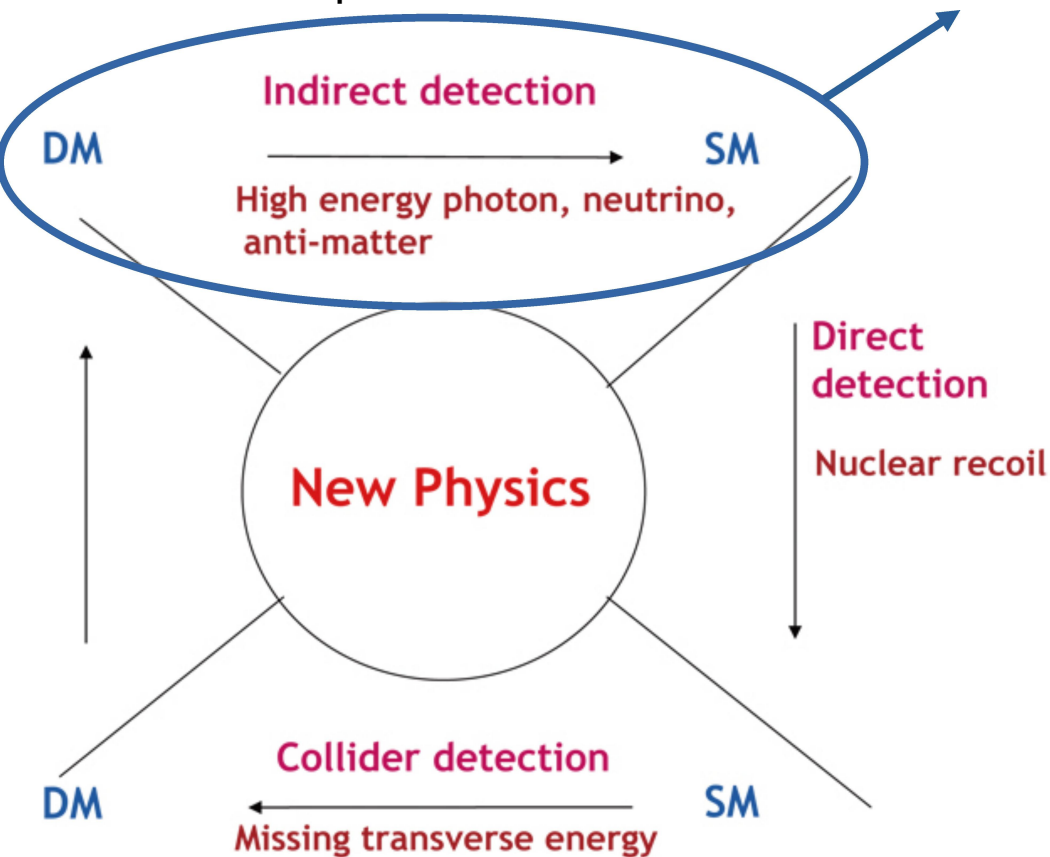


Indirect Search for DM

How could we observe a DM halo?

DM → a new particle?

DM annihilation signals



$$\frac{d\Phi_a}{dE} = \frac{1}{4\pi} \frac{\langle \sigma v \rangle}{2m_\chi^2} \frac{dN_a}{dE} \times J(\psi)$$

particle physics:

cross section, DM mass, annihilation spectrum

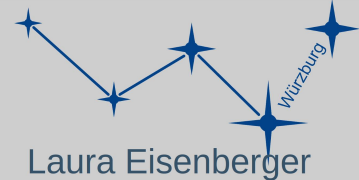
astrophysics:

J-Factor (annihilation)

$$J = \frac{1}{\Delta\Omega} \int_{\Delta\Omega} d\Omega \int_{\text{los}} \rho^2(\psi, l) dl$$

Andromeda Galaxy (M31)

Why should we look for DM in M31?



- **proximity:** $d_{\text{M31}} = 761 \text{ kpc}$ (Li et al. 2021)
- **68% DM** of total dynamical mass (Hammer et al. 2025)
- **entire halo** observable from the outside
- relatively high Galactic latitude
→ **less foreground** from MW plane
- excess **γ -ray signal** (Fermi/LAT)
towards M31's outer halo (Karwin et al. 2019)
→ Cosmic ray interaction or DM?

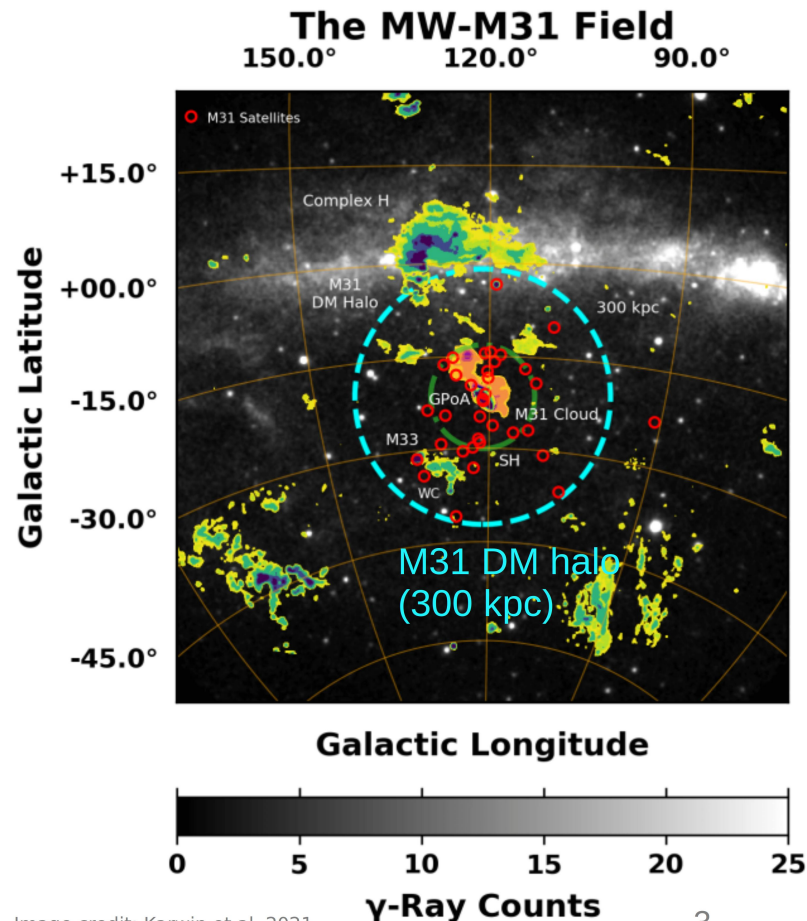
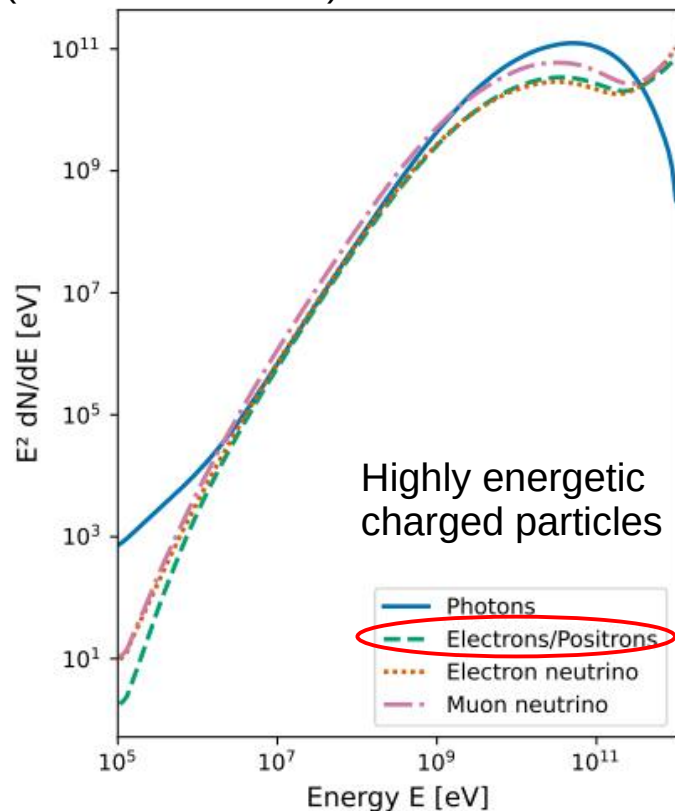


Image credit: Karwin et al. 2021

INTEGRAL/SPI Data

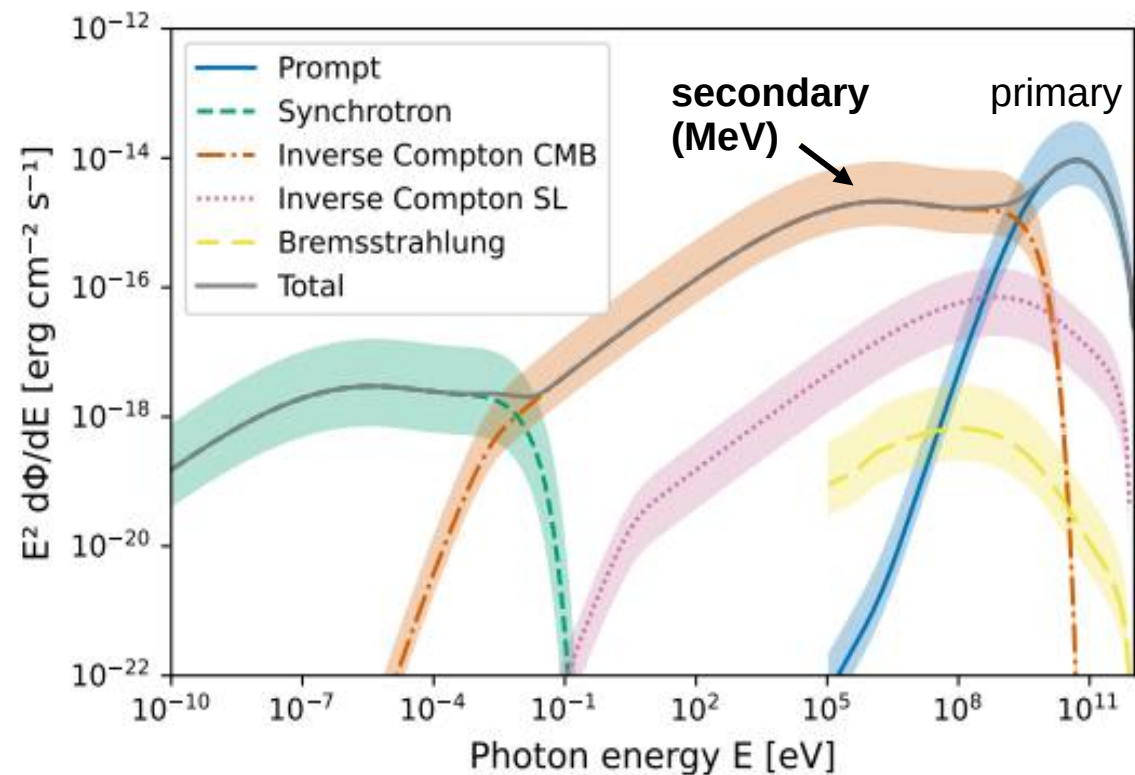
Why is the MeV range interesting also for WIMPs?

e.g. scotogenic WIMP ($m = 1$ TeV)
(Alvarez et al. 2023)



➡
Naima
Python
package

Example DM multiwavelength photon spectrum



MHz to TeV expectations from scotogenic WIMP dark matter
(Eisenberger et al. 2024), arXiv:2310.10421

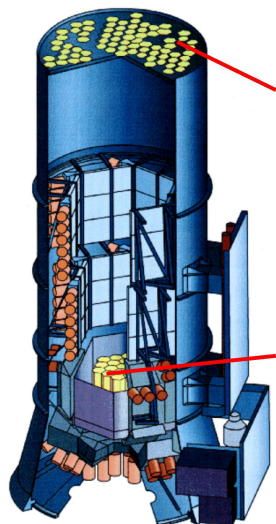
INTEGRAL/SPI Data

What MeV observations do we have of M31?



INTEGRAL operated from Oct 2002 to Feb 2025
→ **1.7 Ms** of SPI observations of M31 region

Spectrometer on INTEGRAL SPI:



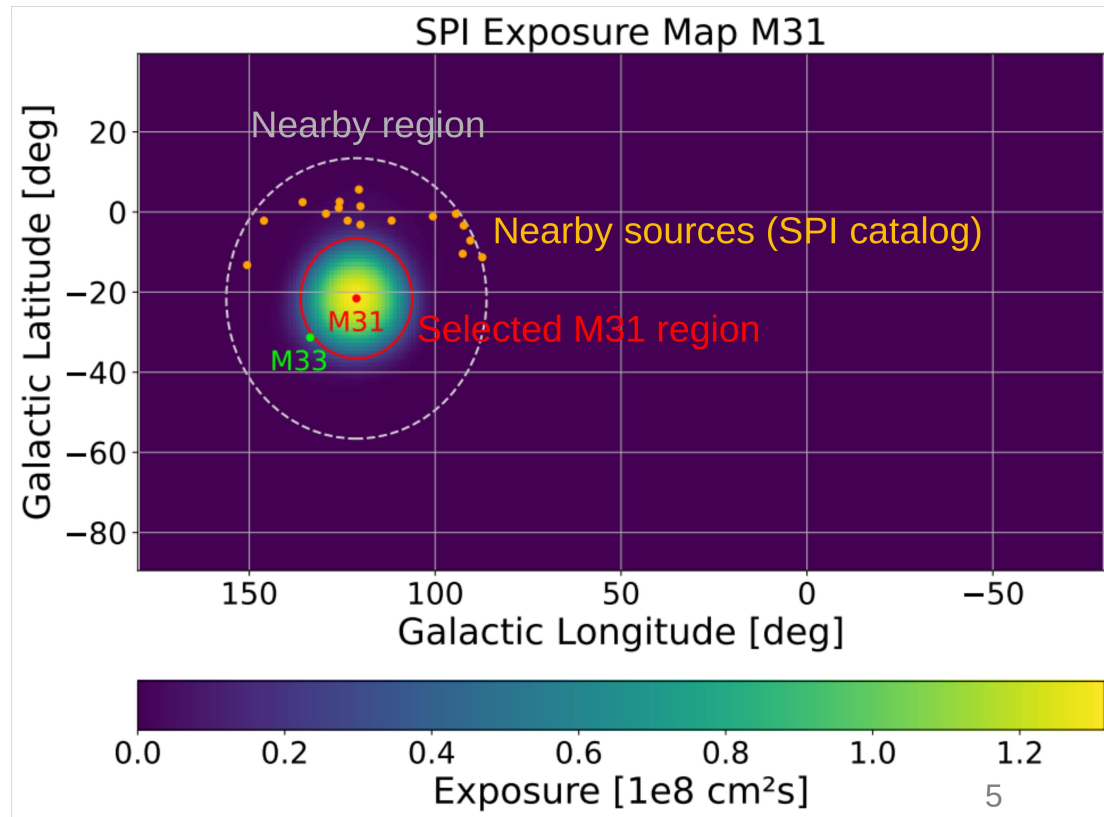
Coded mask

19 Germanium
detectors

energy:
18 keV –
8 MeV

resolution:
2.7 deg

FOV:
16°x16°



DM Halo Models

What is the DM distribution in M31?

e.g. NFW density profile (Navarro et al. 1997)
+ local substructure boost $B(r)$ (Kamionkowski et al. 2010)

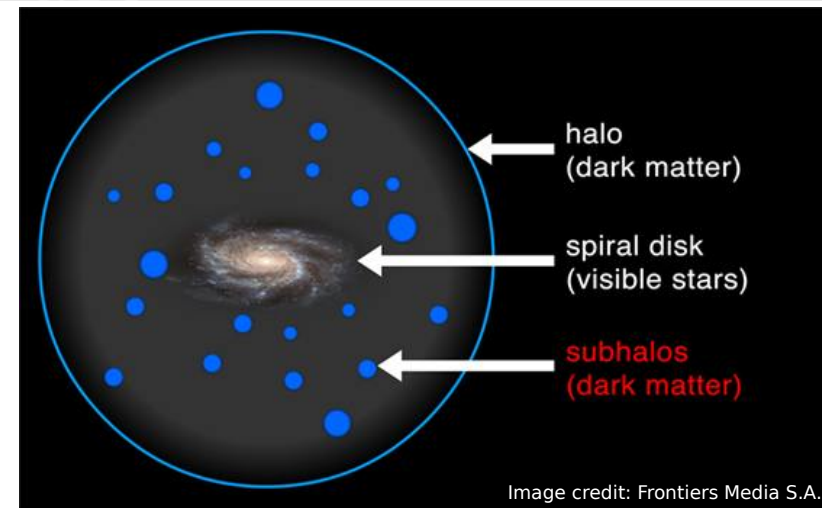
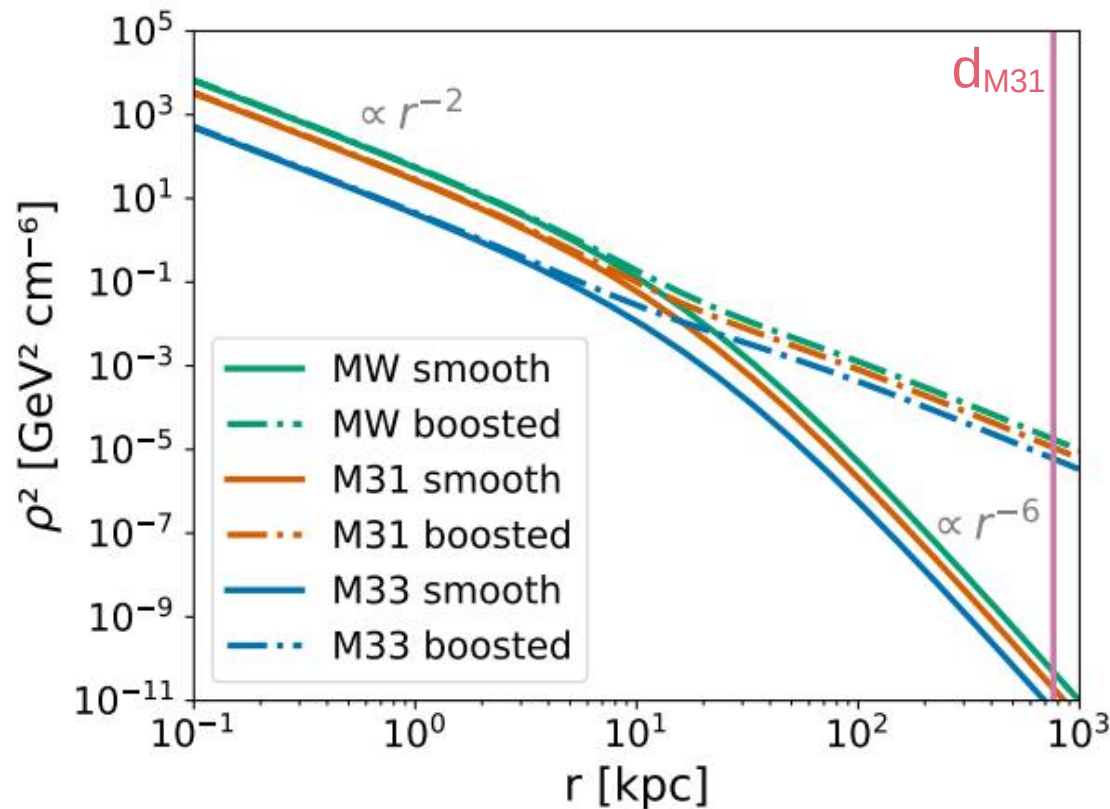


Image credit: Frontiers Media S.A.

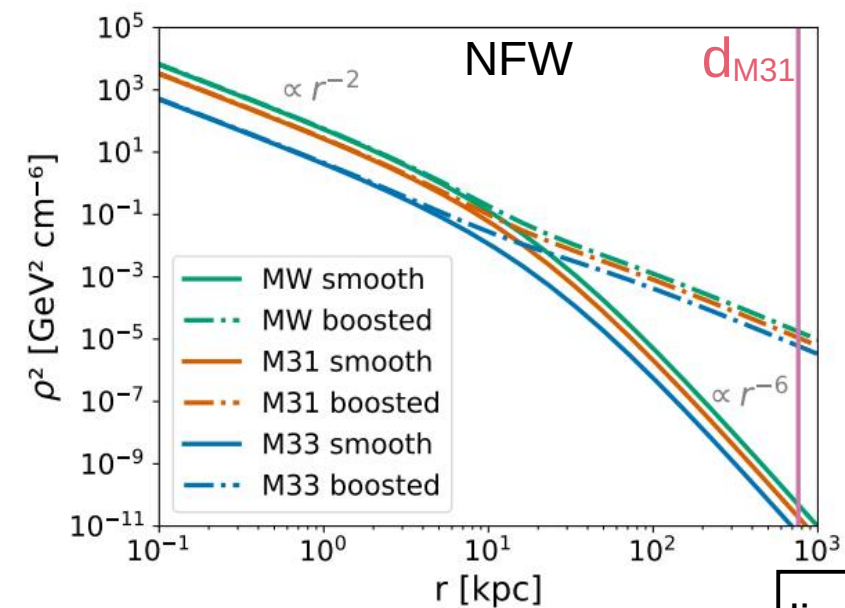
$$\rho_{\text{cusp}}(r) = \frac{\rho_s}{(r/r_s)^\gamma (1 + r/r_s)^{3-\gamma}}$$

NFW: $\gamma = 1$

scale density and radius according to
Karwin et al. 2020 and
Lopez Fune et al. 2017

DM Halo Models

Can we see M31 through the Milky Way halo?

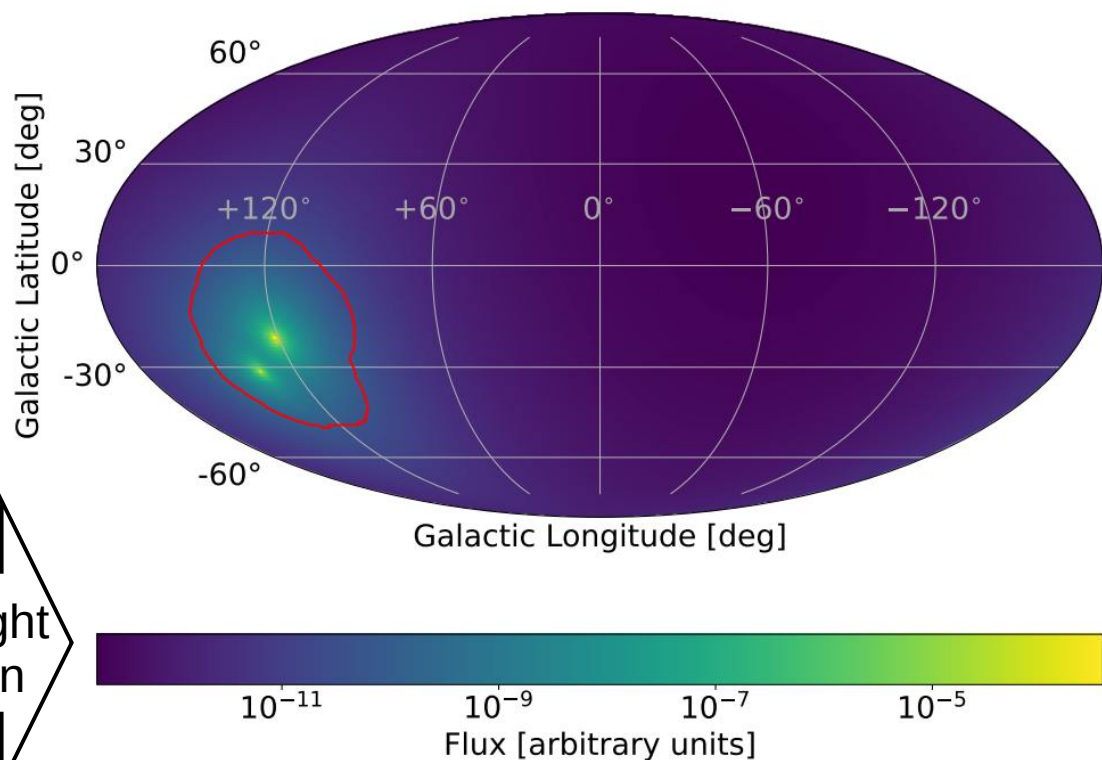


$$M_{MW} = 1.5 \times 10^{12} M_{\odot}$$

$$M_{M31} = 0.8 \times 10^{12} M_{\odot}$$

$$M_{M33} = 0.5 \times 10^{12} M_{\odot}$$

M31
M33
line-of-sight
integration

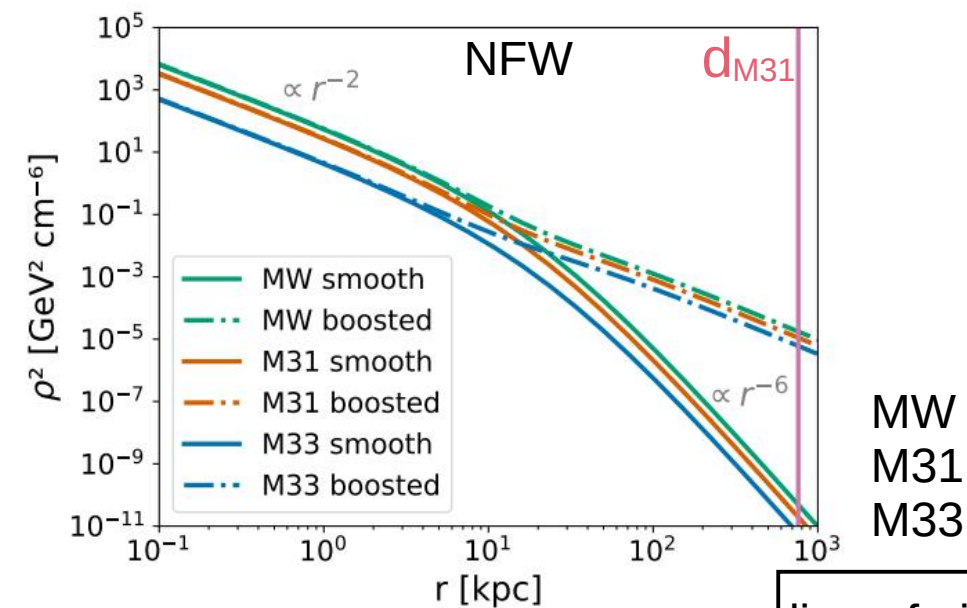


$$d_{M31} = 761 \text{ kpc}$$

$$d_{M33} = 850 \text{ kpc}$$

DM Halo Models

Can we see M31 through the Milky Way halo?



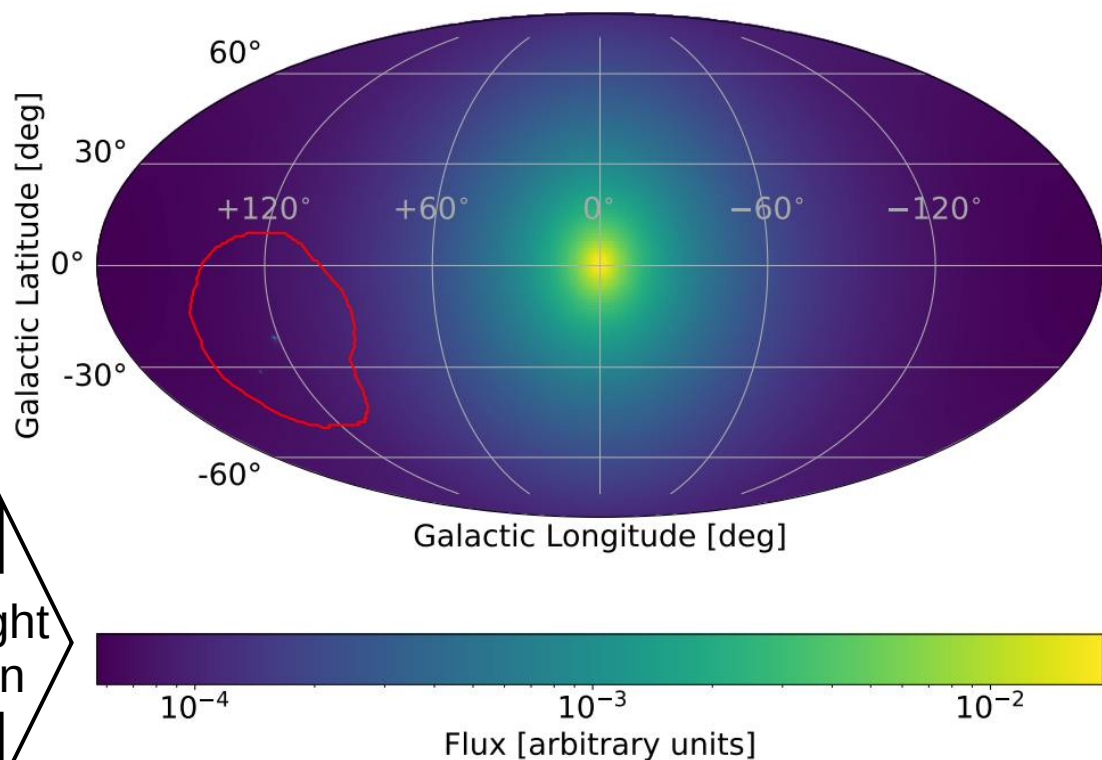
MW
M31
M33

line-of-sight
integration

$$M_{MW} = 1.5 \times 10^{12} M_{\odot}$$

$$M_{M31} = 0.8 \times 10^{12} M_{\odot}$$

$$M_{M33} = 0.5 \times 10^{12} M_{\odot}$$

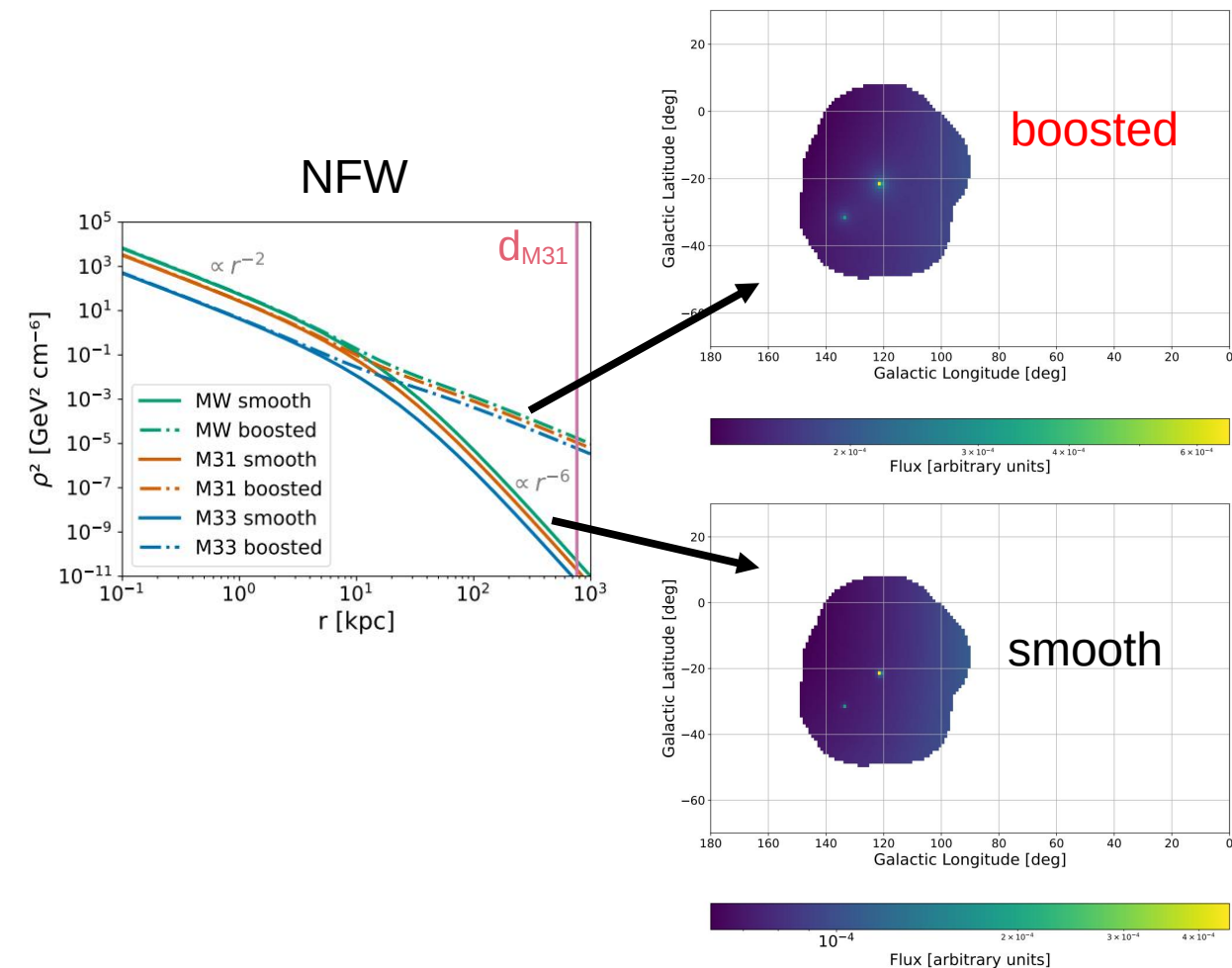


$$d_{M31} = 761 \text{ kpc}$$

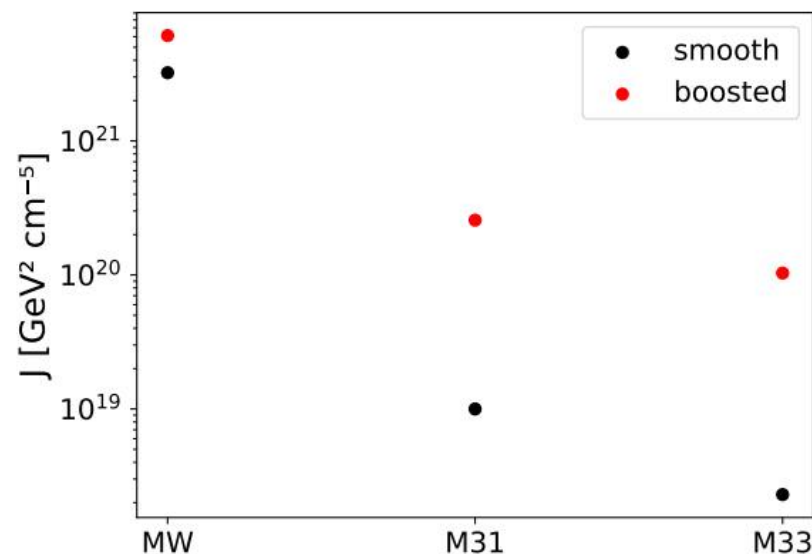
$$d_{M33} = 850 \text{ kpc}$$

DM Halo Models

Can we see M31 through the Milky Way halo?



J-Factor (line-of-sight integrated over the exposure region)

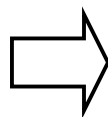


$$J = \frac{1}{\Delta\Omega} \int_{\Delta\Omega} d\Omega \int_{\text{los}} \rho^2(\psi, l) dl$$

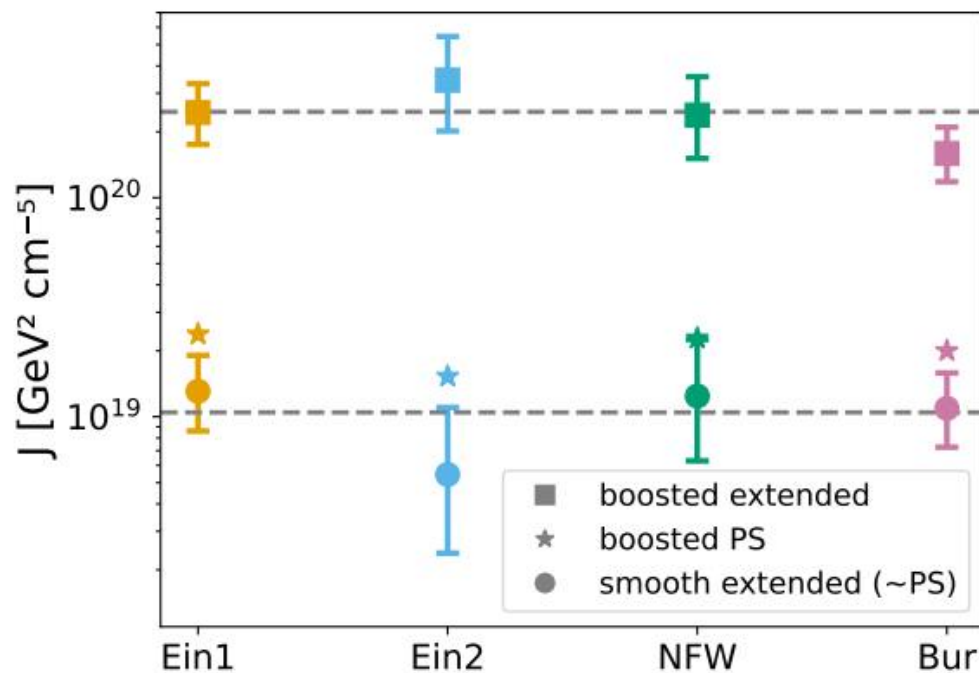
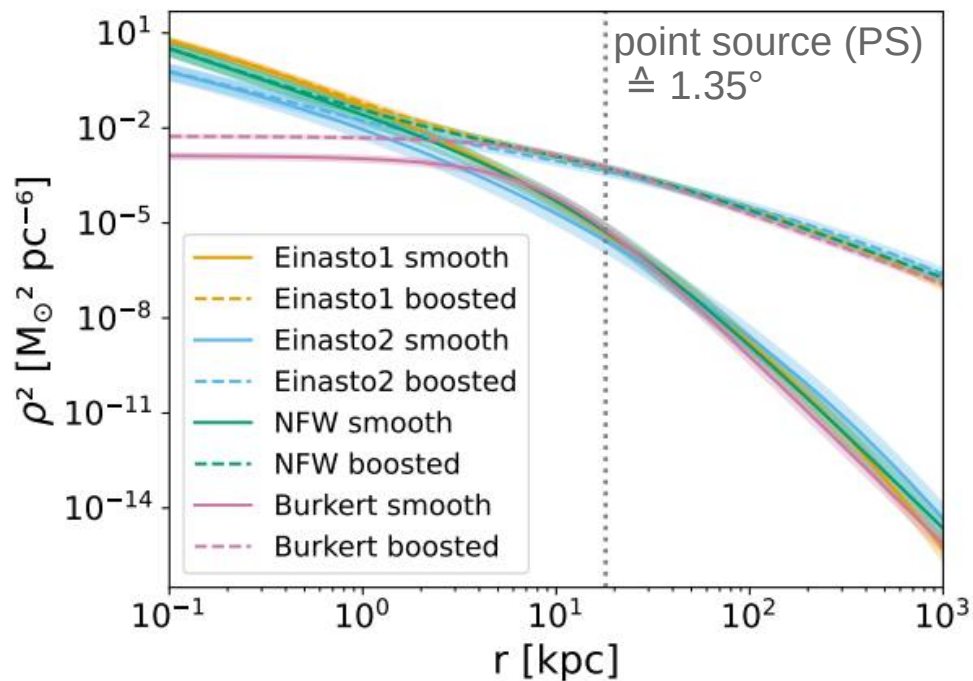
DM Halo Models

What are the uncertainties of the DM distribution?

different DM density profiles for M31
(Tamm et al. 2012) + uncertainties

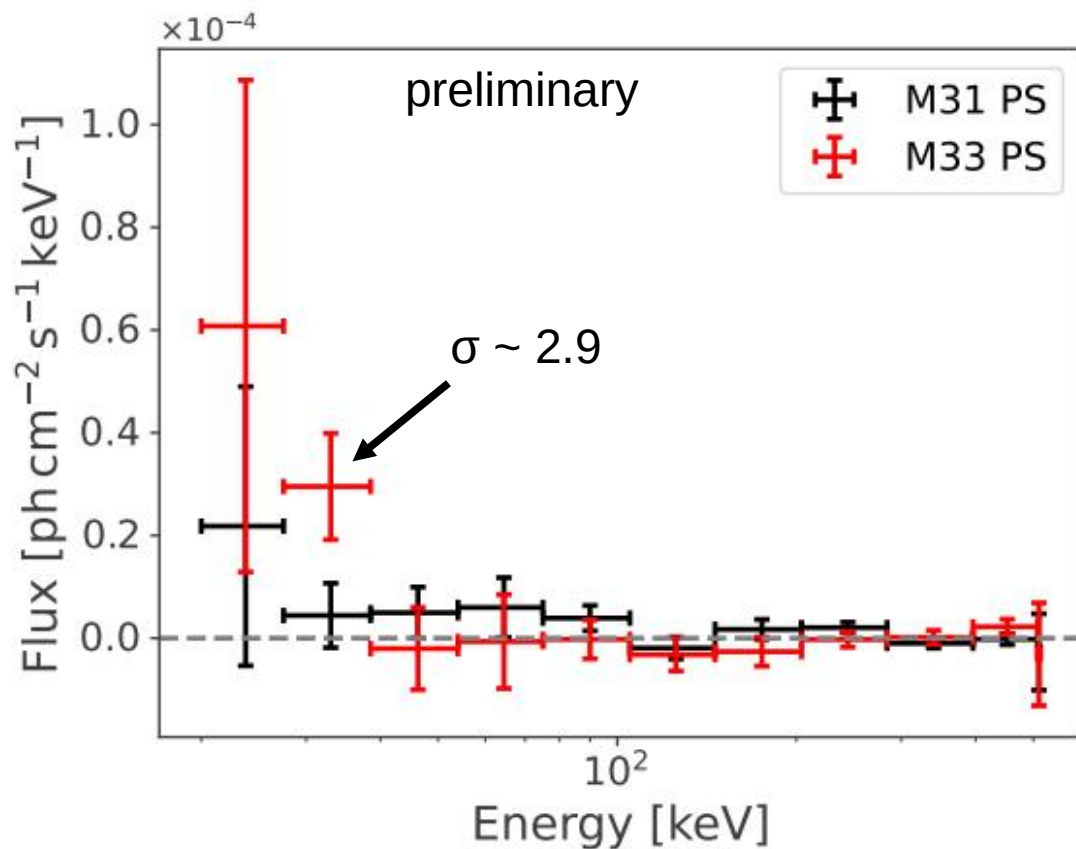


J-Factors (line-of-sight integrated
over the exposure region → extended
over circular region → PS with $r = 1.35^\circ$)



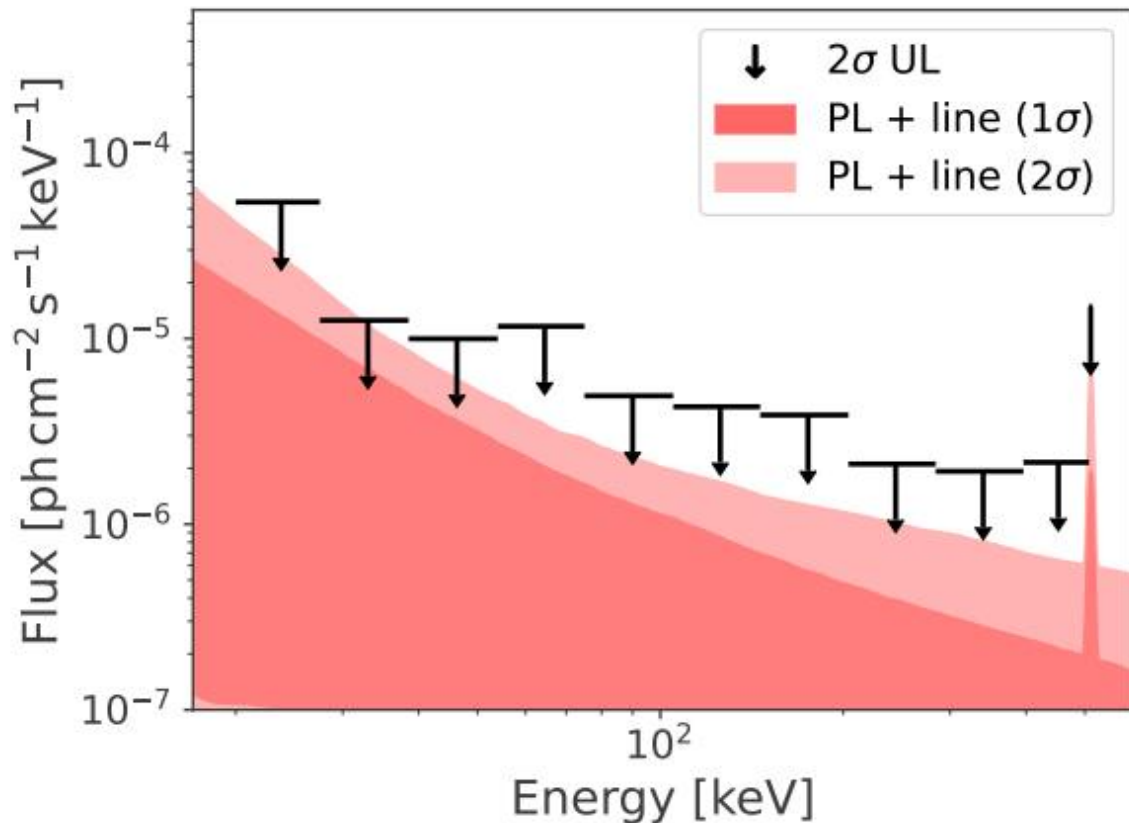
INTEGRAL/SPI Data

Has INTEGRAL/SPI detected M31?



- spectra mostly consistent with 0
→ 2σ upper limits (UL)
- hint of signal of M33 at ~ 30 keV
→ Comptonization component of ULX M33 X-8 above 10 keV (West et al. 2018)
- NuSTAR studies (Yang et al. 2022):
M33 dominated by HMXBs ↔
M31 dominated by LMXBs

M31 point source spectrum



fit power law continuum (empirical)
+
positron annihilation line (511 keV)

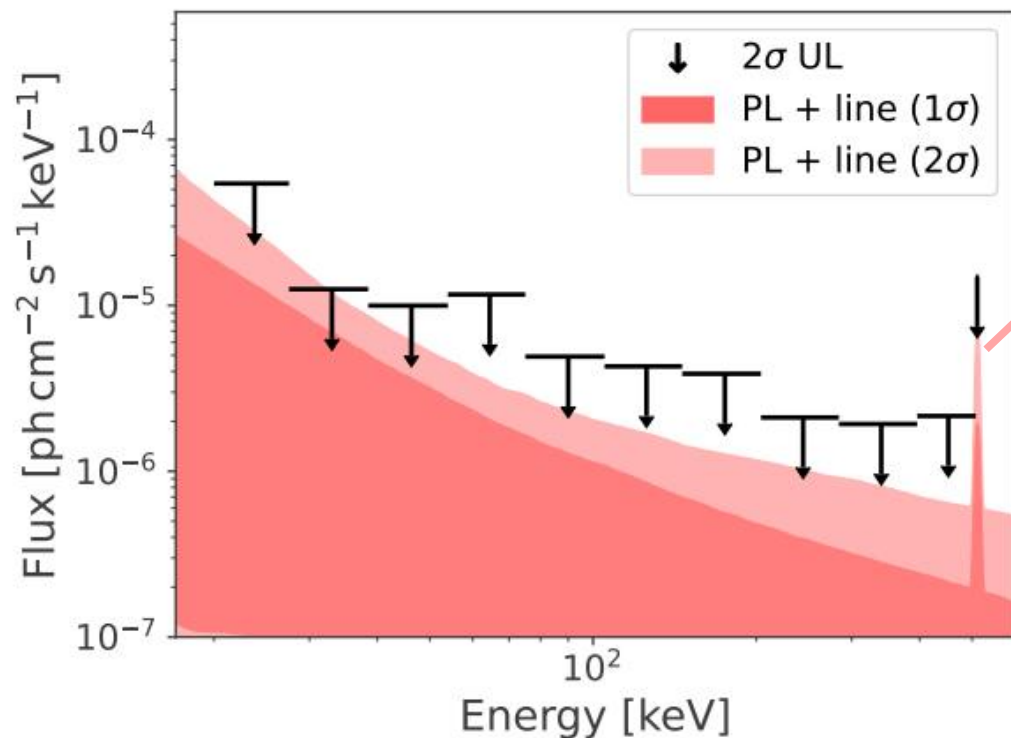
→ 2σ upper limit on line flux:
 $7 \times 10^{-5} \text{ ph cm}^{-2} \text{ s}^{-1}$

→ pair production rate limit:
 $2 \times 10^{45} \text{ s}^{-1}$

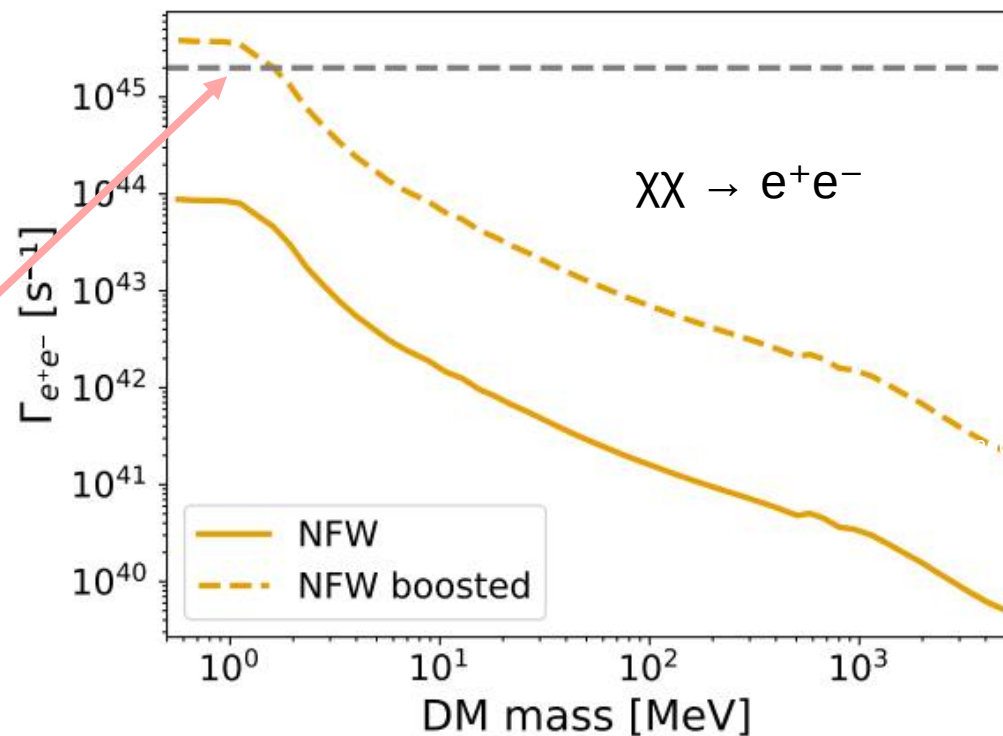
DM Limits

How can we use M31 data to constrain DM models?

M31 point source spectrum



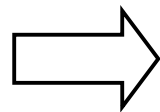
total pair production rate from thermal DM annihilation



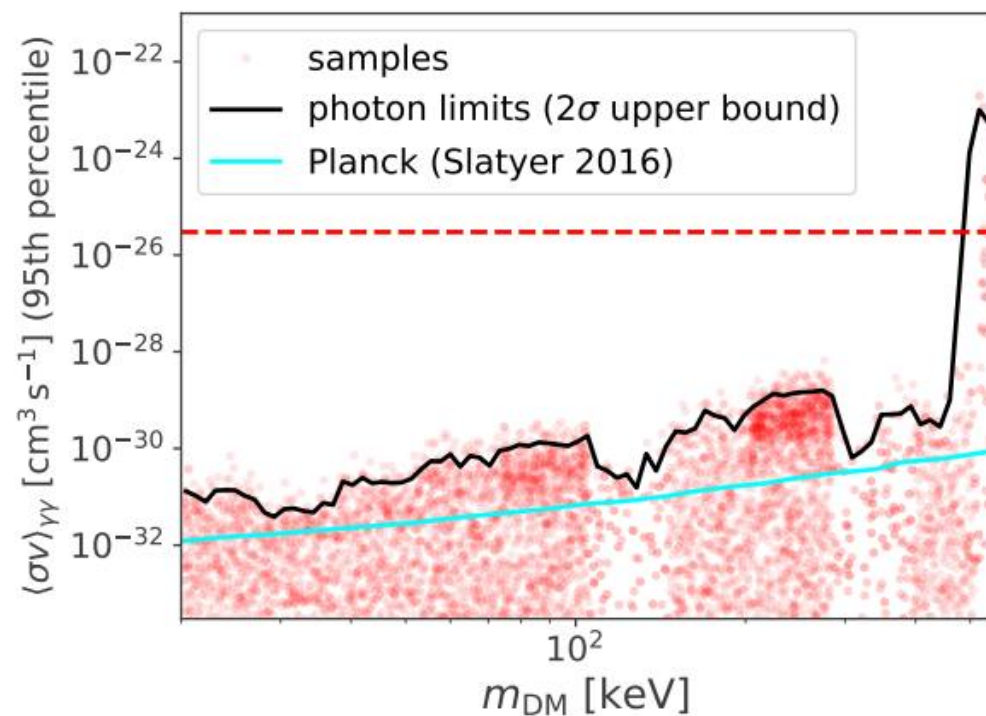
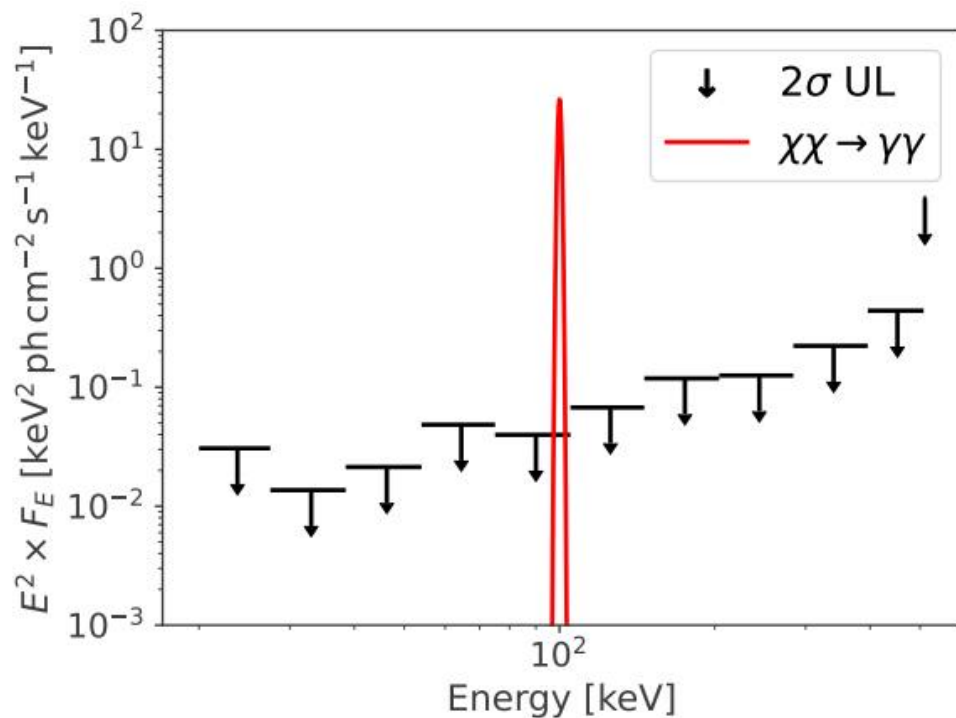
DM Limits

How can we use M31 data to constrain DM models?

DM annihilation into two photons

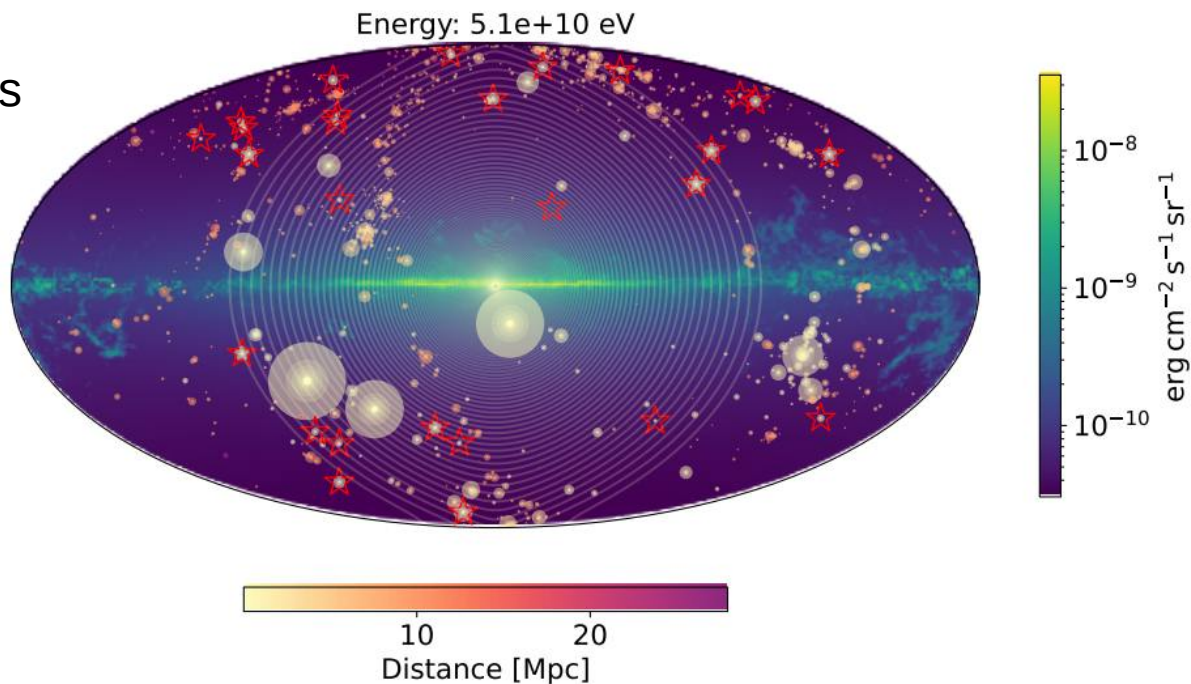


exclusion plot of the model parameter space



Summary and Outlook

- **model DM halo of M31, M33 and MW** within exposure outline of INTEGRAL/SPI dataset
 - exact DM profile less relevant compared to boost factor uncertainty
 - J-factor of M31 $\sim 10^{19} - 10^{20} \text{ GeV}^2 \text{ cm}^{-5}$
- **preliminary DM model constraints** from upper limits of M31 PS spectrum
 - e.g. lower limit on thermal DM mass
 - compare to extended emission
- test more DM models
 - secondary/tertiary WIMP emission
 - decaying DM
 - primordial black holes
- larger dataset with more galaxies
 - correlated analysis



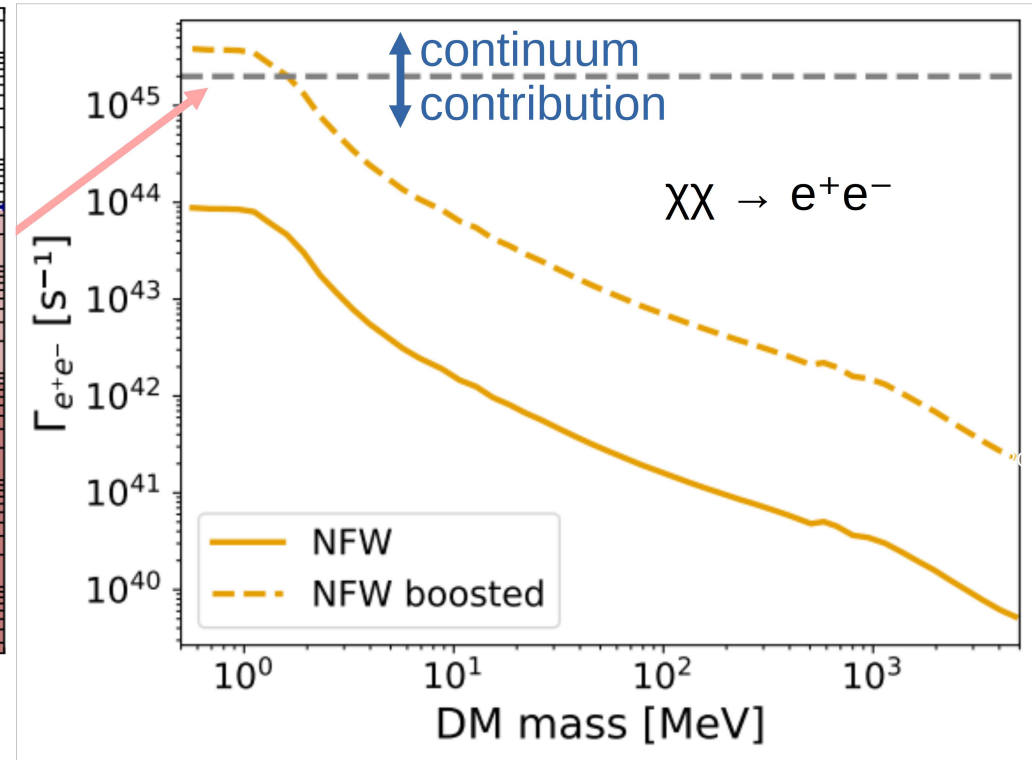
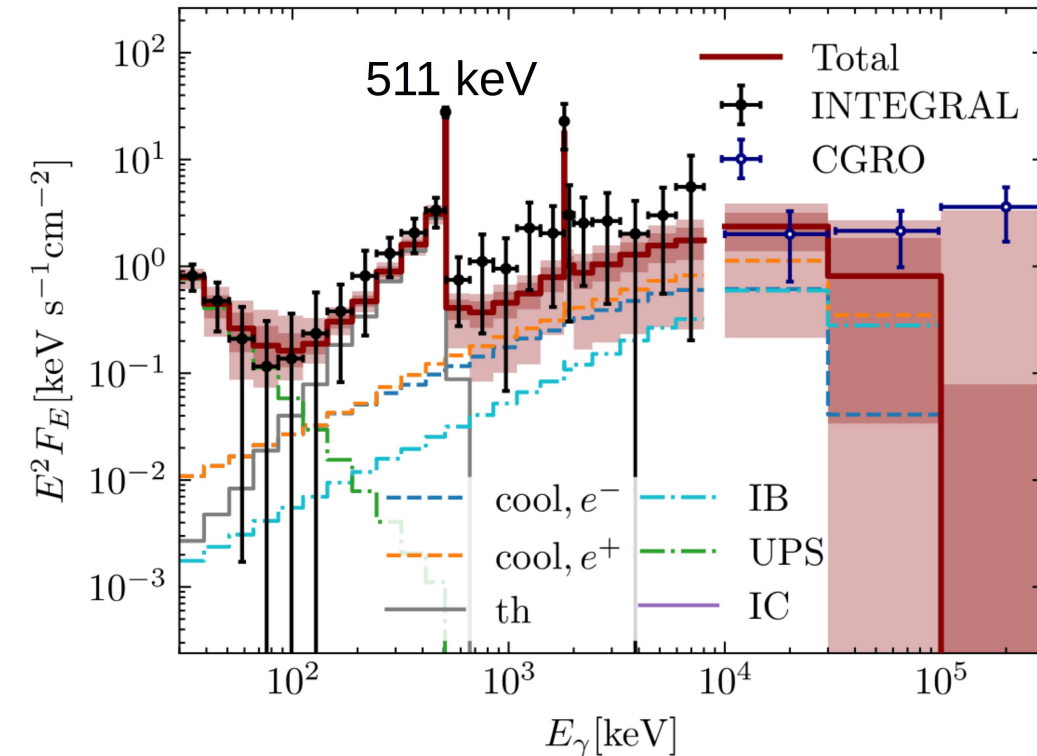


DM Limits

How can we use M31 data to constrain DM models?

MW annihilation signal + continuum

total pair production rate from thermal DM annihilation



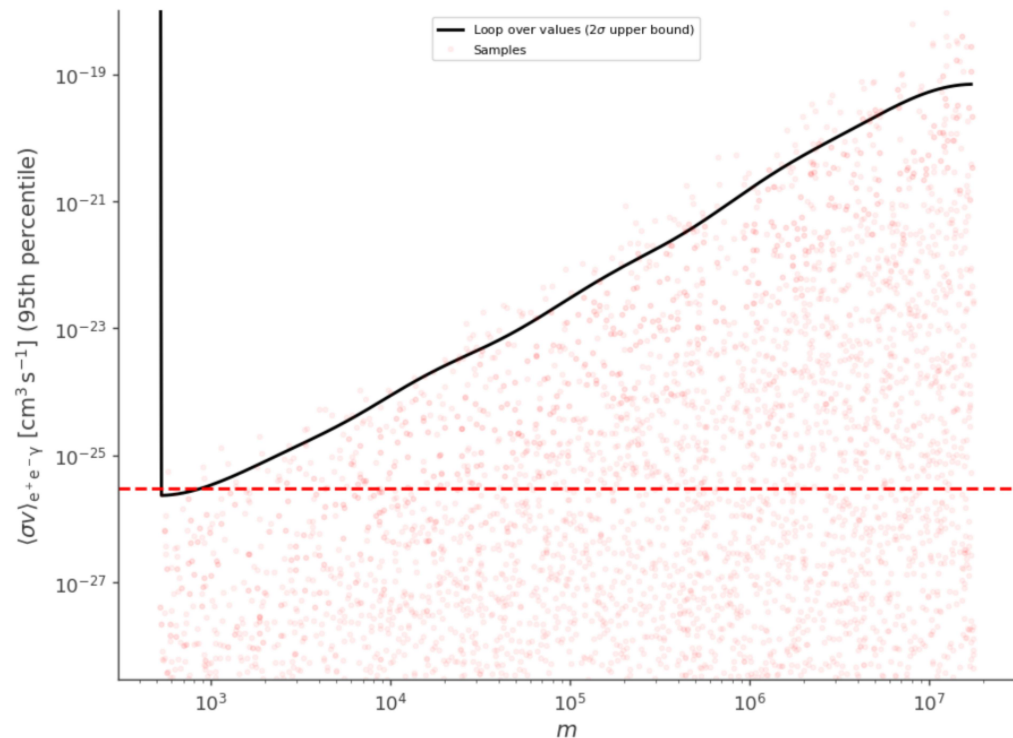
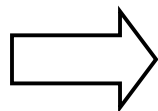
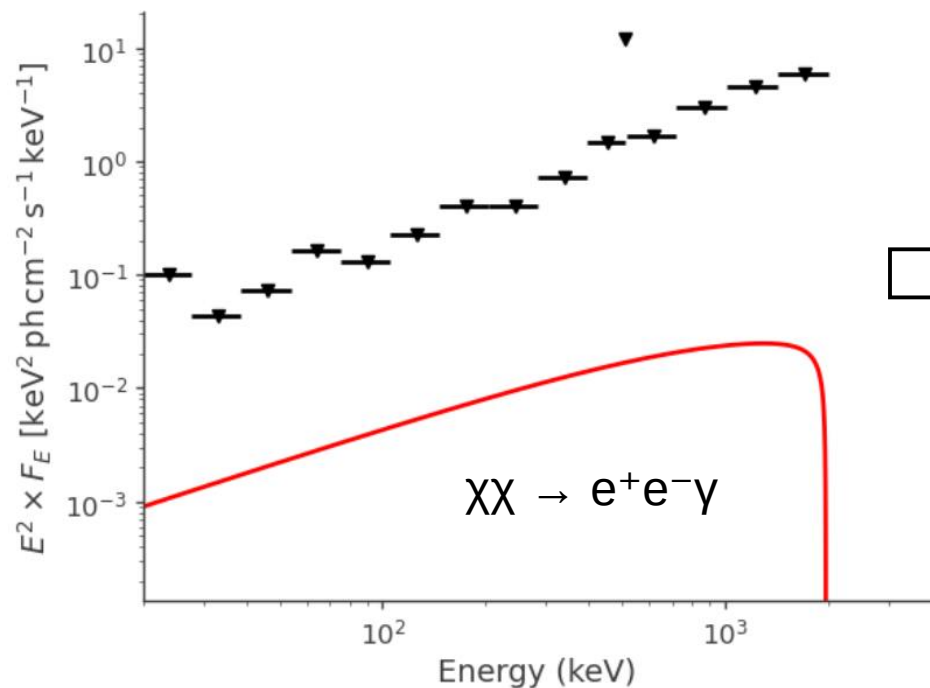
Das et al. in preparation

DM Limits

How can we use M31 data to constrain DM models?

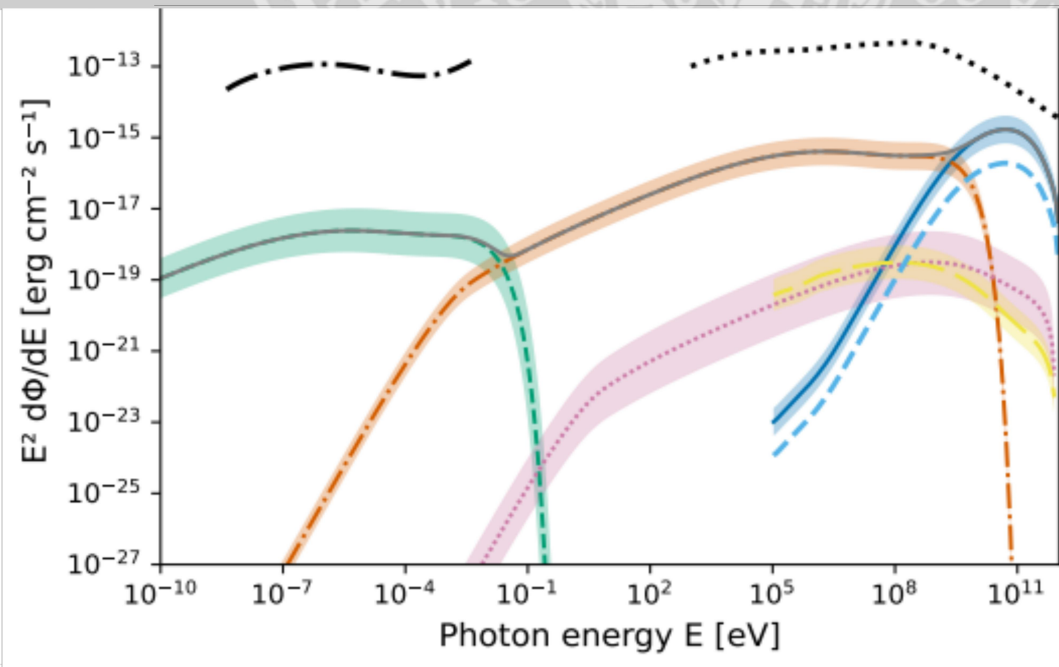
final state radiation of DM annihilation into e^+e^-

exclusion plot of the model parameter space



Signal-to-Background Ratio

Laura Eisenberger



DM spectrum for **Segue 1**:

Galaxy with largest ratio
 $\approx 10^{-4}$ (1 keV – 100 GeV)

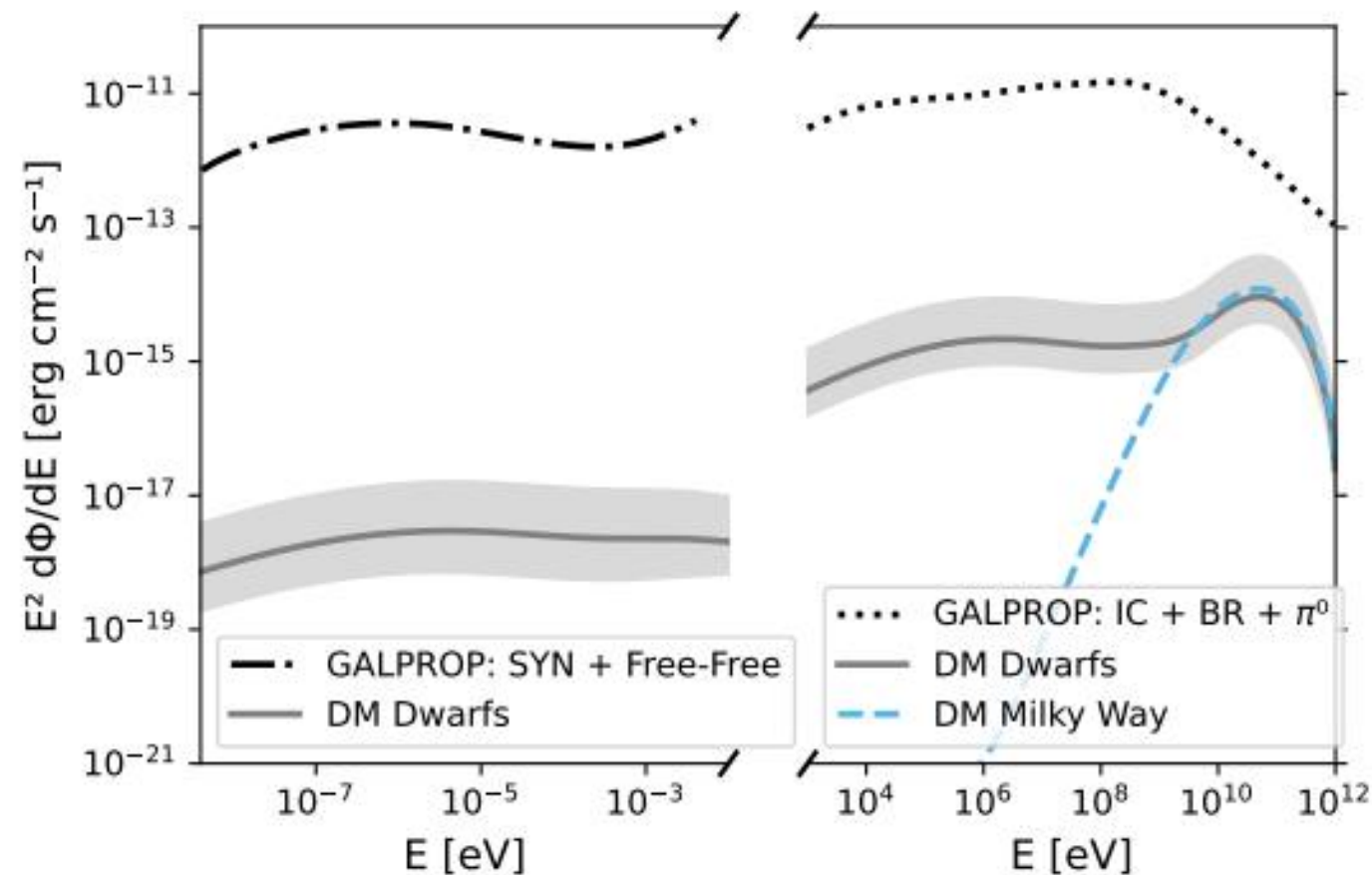


DM Signal (prompt + secondary)

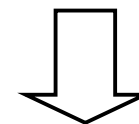
Background (Milky Way halo + diffuse)

Signal-to-Background Ratio

Laura Eisenberger



Cumulative signal of all 27 dSphs

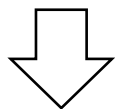


Max DM signal
 $\approx 10^{-14} \text{ erg cm}^{-2} \text{ s}^{-1}$ (50 GeV)

Background at 50 GeV
 $\approx 10^{-12} \text{ erg cm}^{-2} \text{ s}^{-1}$

- **WIMP**: Weakly Interacting Massive Particle
- **Scotogenic** models: additional Z_2 symmetry
(SM particles: even, new particles: odd)
- T1-2-A' model:

explains **neutrino masses**, the **muon anomalous magnetic moment** and potentially the **baryon asymmetry** of the Universe
consistent with limits for **cLFV decays** and **direct DM** detection and
DM **relic density** (Alvarez et al. 2023)



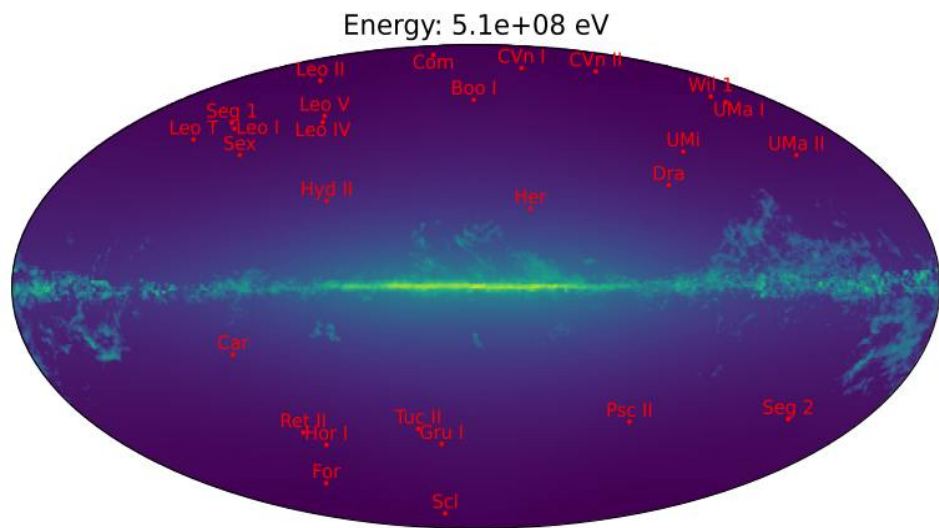
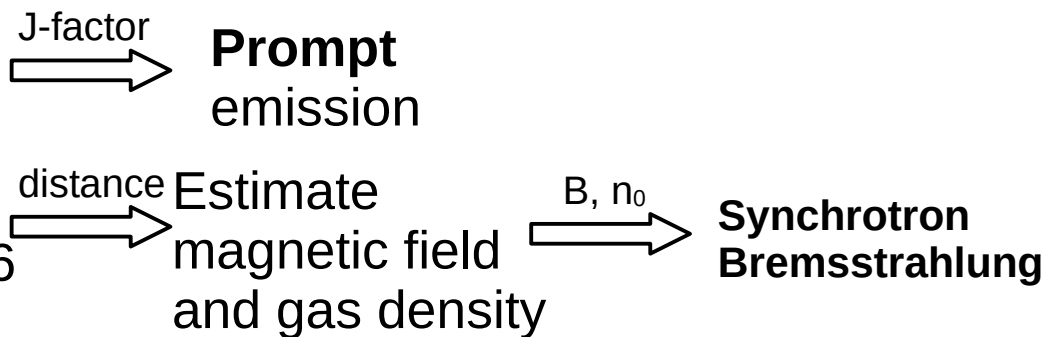
Promising scotogenic DM candidate:

fermionic, $m \approx 1.1 \text{ TeV}$, $\langle \sigma v \rangle \approx 9.5 \times 10^{-27} \text{ cm}^3 \text{ s}^{-1}$ (MicrOMEGAs)

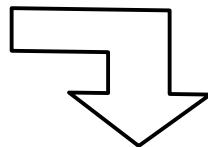
	fermionic				scalar	
	Ψ_1	Ψ_2	F_1	F_2	η	S
$SU(2)_L$	2	2	1	1	2	1
$U(1)_Y$	-1	1	0	0	1	0

New fields in the T1-2-A' model

- Large mass-to-light ratios
- Low intrinsic backgrounds
- J-factors calculated by Evans et al. 2016

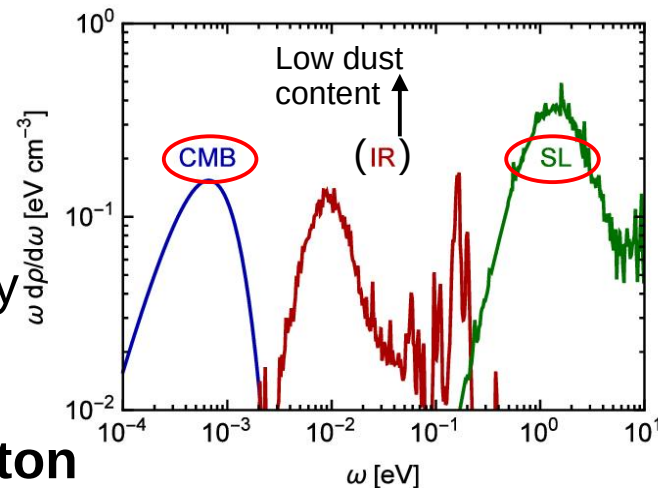


Visual magnitude
Half-light radius



Estimate starlight energy density

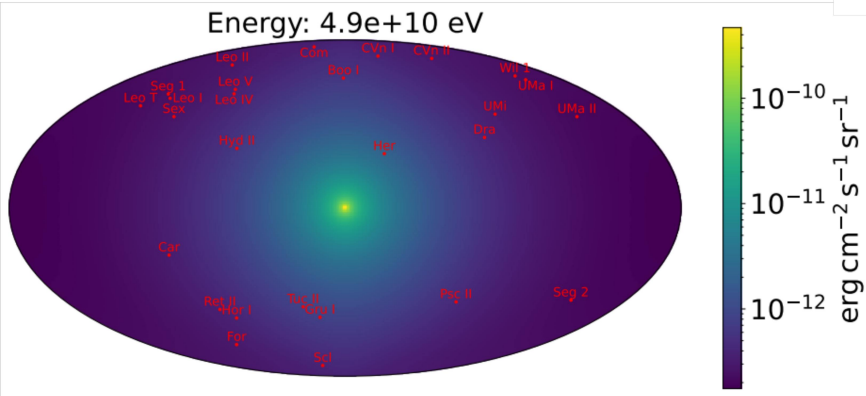
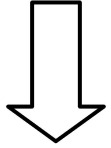
 + CMB 1
Inverse Compton



Astrophysical Fore- and Background

DM halo of the Milky Way

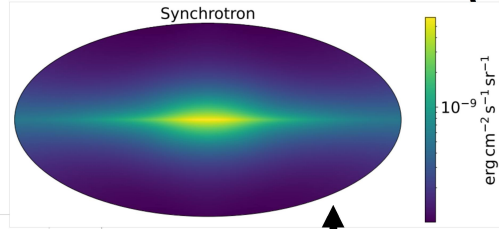
- Modeling of prompt emission



+

Diffuse Galactic emission

- GALPROP simulations



Total Sky

