Search of DM annihilation in Stellar Streams with the Fermi LAT

Cristina Fernández-Suárez

In collaboration with Miguel A. Sánchez-Conde

20th MultiDark Workshop

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Fermi Gamma-ray Space Telescope

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UAM Universidad Autónoma de Madrid

Motivation

* Different strategies for dark matter (DM) searches.

* Gamma rays as the *golden channel* for DM indirect searches, with many astrophysical targets already scrutinized (galactic center, dwarf spheroidal galaxies, galaxy clusters, …).

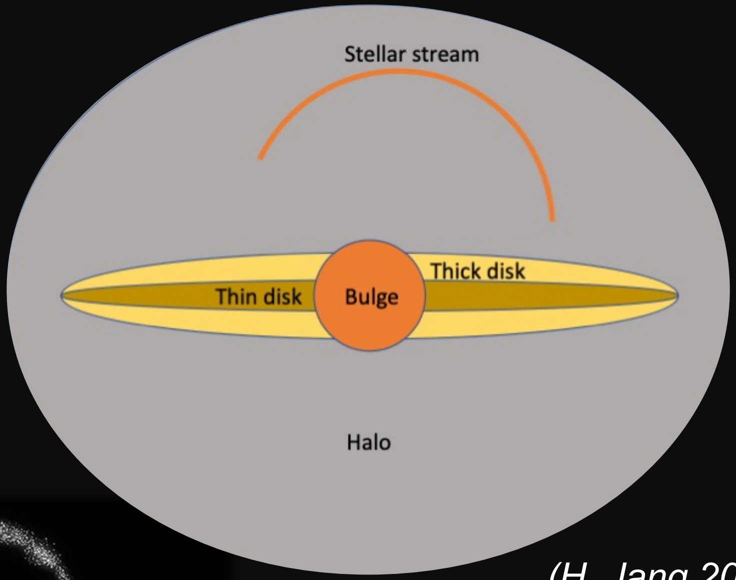
Goal: Explore the potential of considering stellar streams as a new target for DM indirect searches with gamma rays.

What are stellar streams?

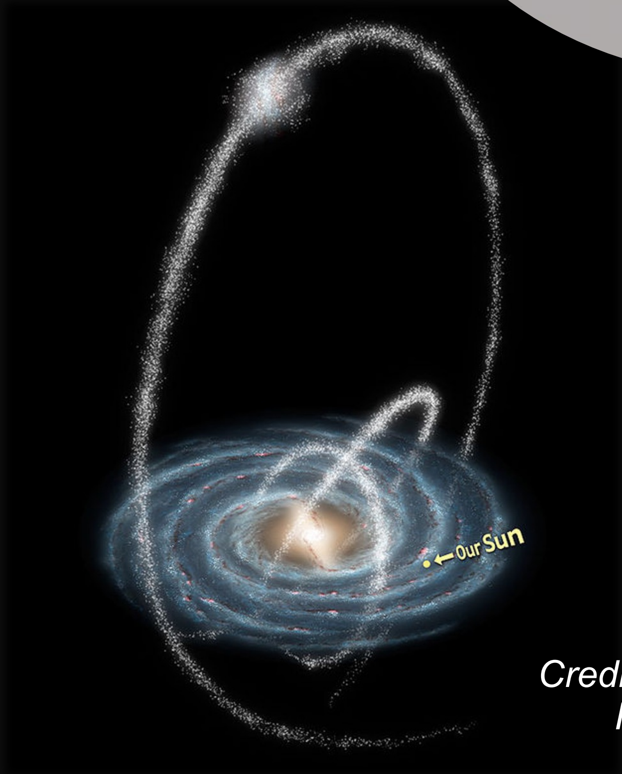
* Narrow tubular galactic structures made of stars, orbiting a galaxy, remnants of ancient globular clusters or dwarf galaxies heavily stripped in the tidal field of the galaxy.

* Extended structures, with lengths from 1 kpc to more than 100 kpc.

* Range in heliocentric distance from a few kpc to 100 kpc.

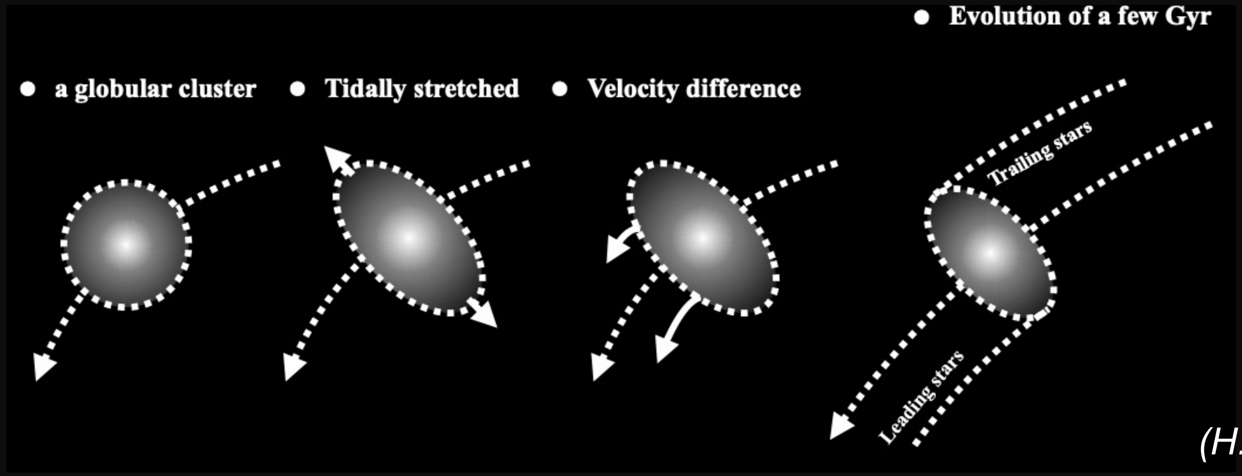


(H. Jang 2021)



Credit: NASA/JPL-Caltech/R. Hurt (SSC/Caltech)

How do stellar streams originated?

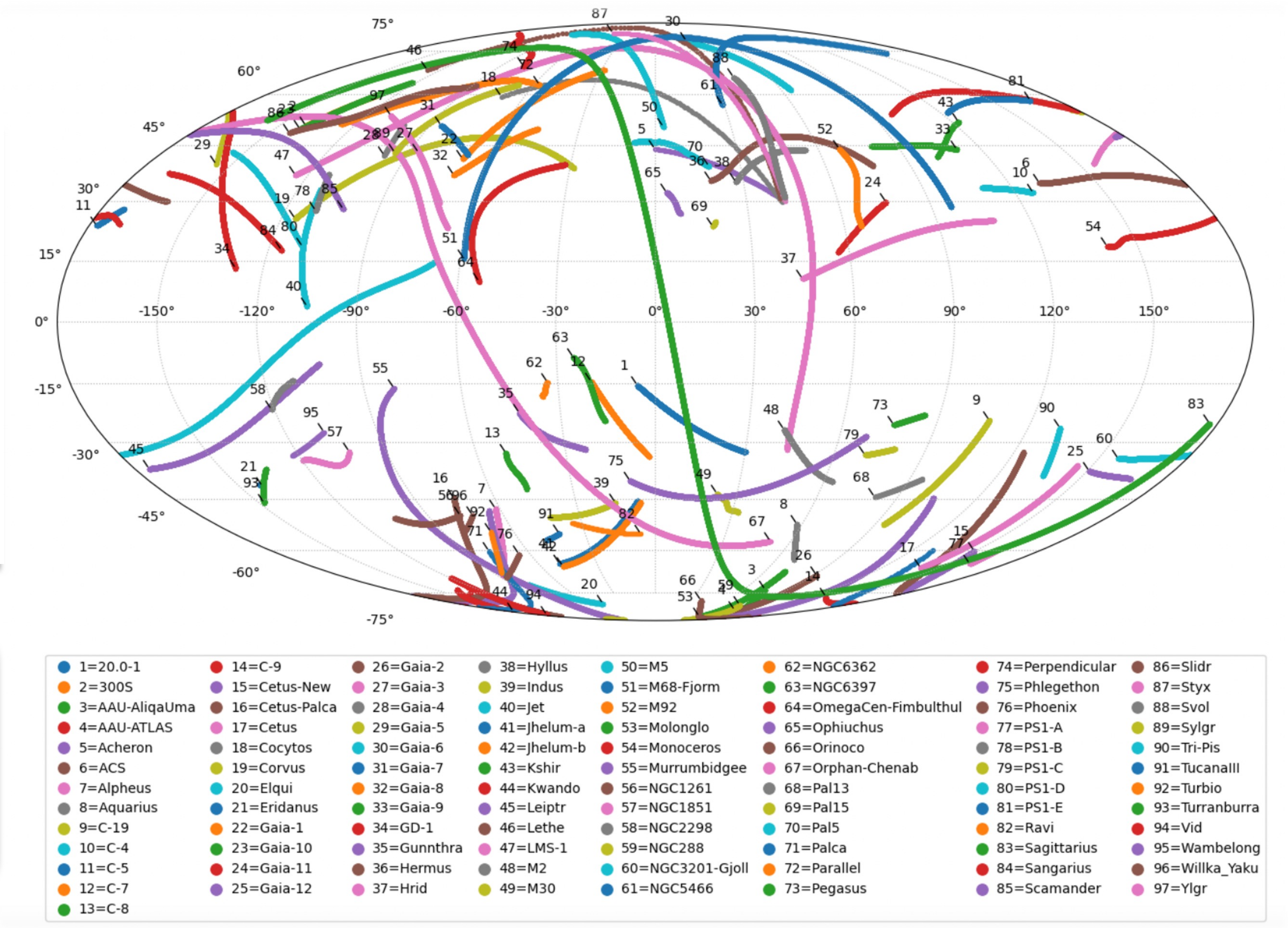


(H. Jang 2021)

- ⁎ Streams form as a result of the gravitational tidal force applied by the host Galaxy on the stream's progenitor, which is a globular cluster (GC) or a dwarf galaxy (dG).
- ⁎ A GC or a dG orbiting around the galaxy gets tidally stretched by the galactic potential, with the gravitational pull being harder on the closer stars to the galactic centre.
- ⁎ The inner stars become a leading arm of the stellar stream while the outer stars form a trailing arm.

Known stellar streams (~ 100)

Observed by wide and deep sky surveys, such as SDSS, Pan-STARRS, Gaia and DESI.



Plot made with the Galstreams library (Mateu et al. 2018, Mateu 2023)

Sample selection

Criteria to build the best **sample of stellar streams** for gamma-ray DM searches, according to the most relevant properties:

Stream	l (°)	b (°)	d_{Sun} (kpc)	Length (°)
Golden sample				
Indus	(344.8, 318.1)	(-46.1, -50.2)	16.6	18.2
LMS-1	(235.6, 43.8)	(36.8, -31.8)	18.1	179.2
Orphan-Chenab	(50.8, 155.4)	(-57.4, 39.8)	20.0	230.6
PS1-D	(250.3, 205.5)	(18.5, 43.0)	22.9	44.9
Turranburra	(212.0, 225.4)	(-46.3, -36.9)	27.5	13.7
Cetus-Palca	(284.8, 123.1)	(-44.9, -32.5)	33.4	100.9
Styx	(314.5, 42.7)	(82.7, 30.0)	46.5	60.4
Elqui	(312.2, 279.6)	(-79.8, -71.9)	50.1	10.9
Silver sample				
Monoceros	(140, 189.5)	(18, 24.1)	10.6	46.9
AntiCenter	(199.5, 130.5)	(29.9, 34.8)	11.7	57.7
Other streams proceeding from dGs				
Jhelum-a	(310.9, 353.5)	(-64.6, -45.5)	13.0	30.0
Jhelum-b	(311.6, 354.7)	(-65.4, -46.1)	13.0	30.0
Parallel	(302.8, 234.0)	(62.9, 50.8)	14.3	37.7
C-19	(106.4, 93.5)	(-24.4, -52.4)	18.0	29.7
Sagittarius	(177.3, 201.7)	(-25.1, 52.0)	25.0	280.0

- ✻ Streams whose progenitor is a dwarf Galaxy (dG).
- ✻ Streams closest to us ($\lesssim 100$ kpc).
- ✻ Streams whose stellar mass is known.

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+ Sagittarius ?

- Globular Cluster M54 in the same position as Sagittarius core.
- Hard to distinguish if the gamma emission comes from DM annihilation or from millisecond pulsars inside M54.

A. J. Evans et al. 2022
arXiv:2212.08194

Sample selection for DM searches

Stream	l (°)	b (°)	d_{Sun} (kpc)
Golden sample			
Indus	(344.8, 318.1)	(-46.1, -50.2)	16.6
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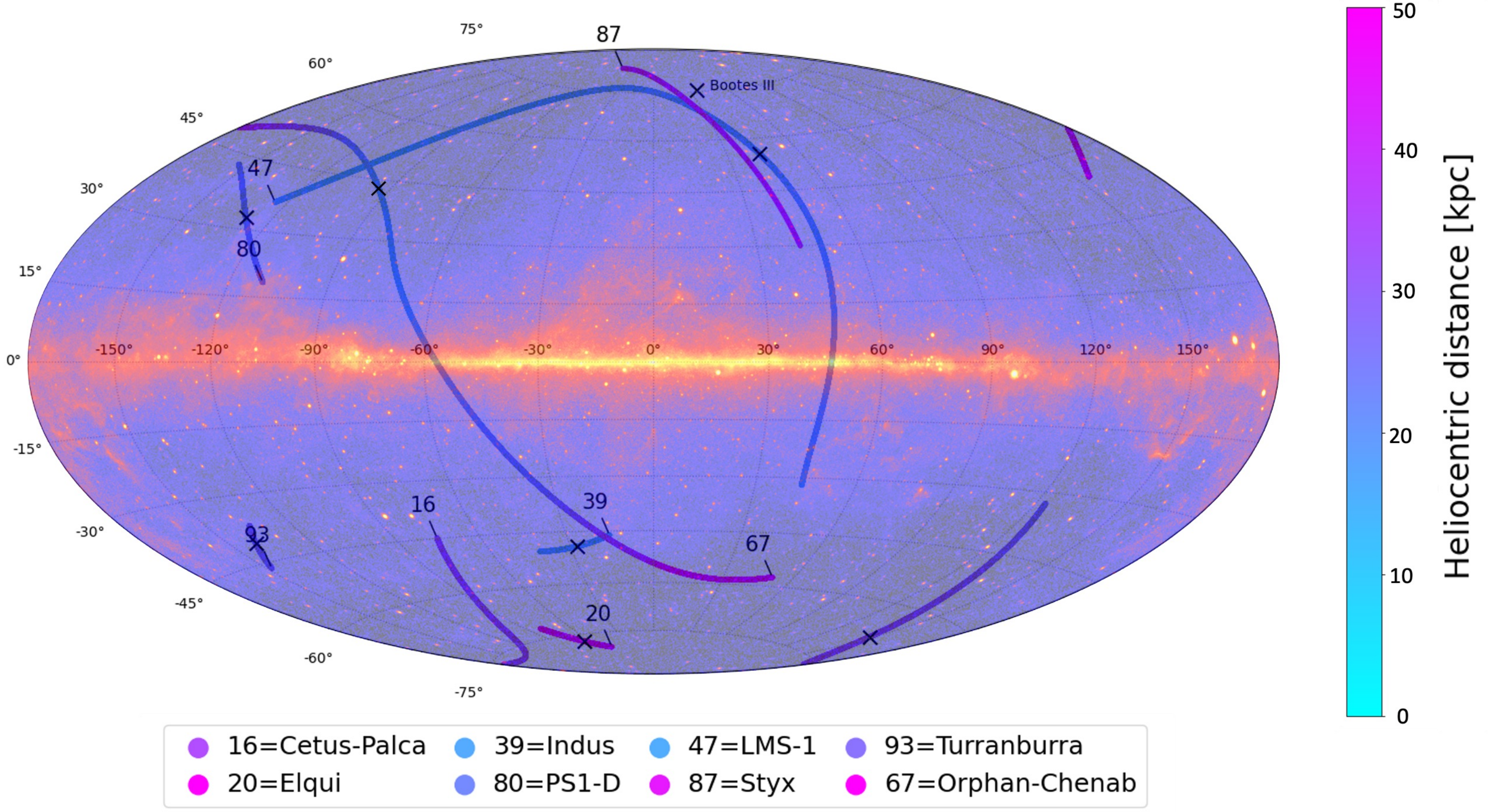
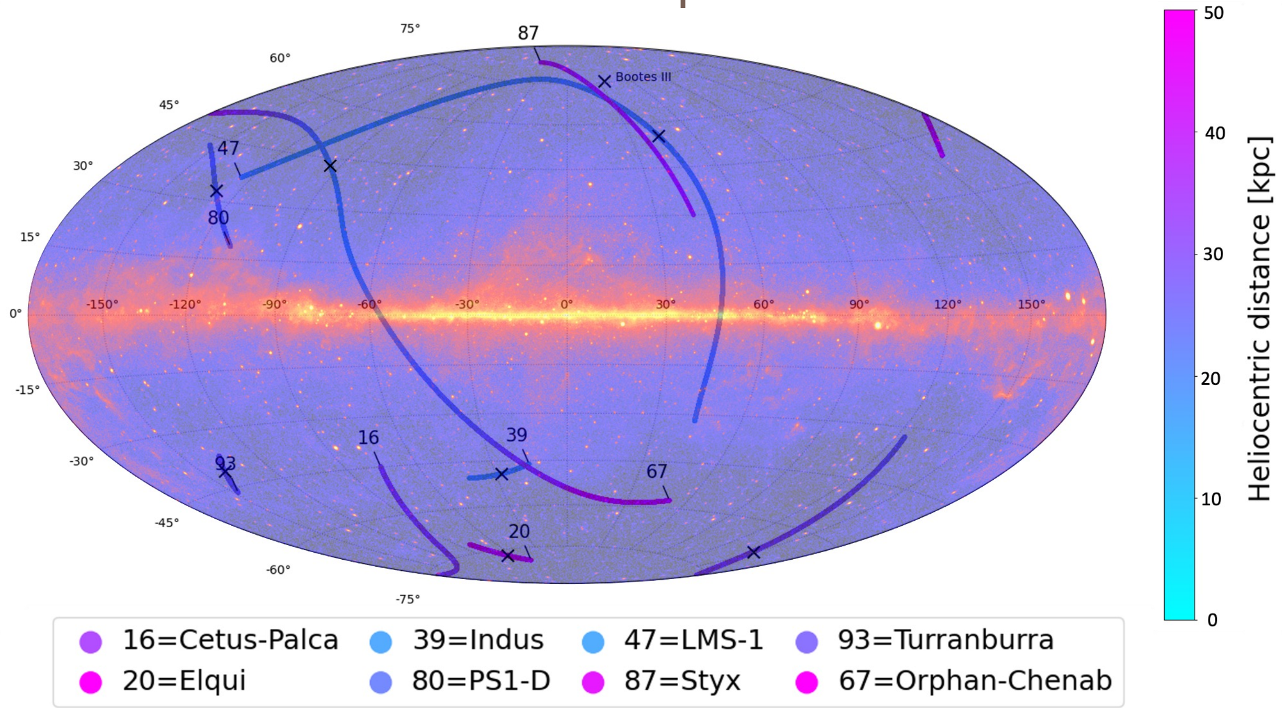
'Golden' Sample



Data Analysis – Fermipy

‘Golden’ Sample

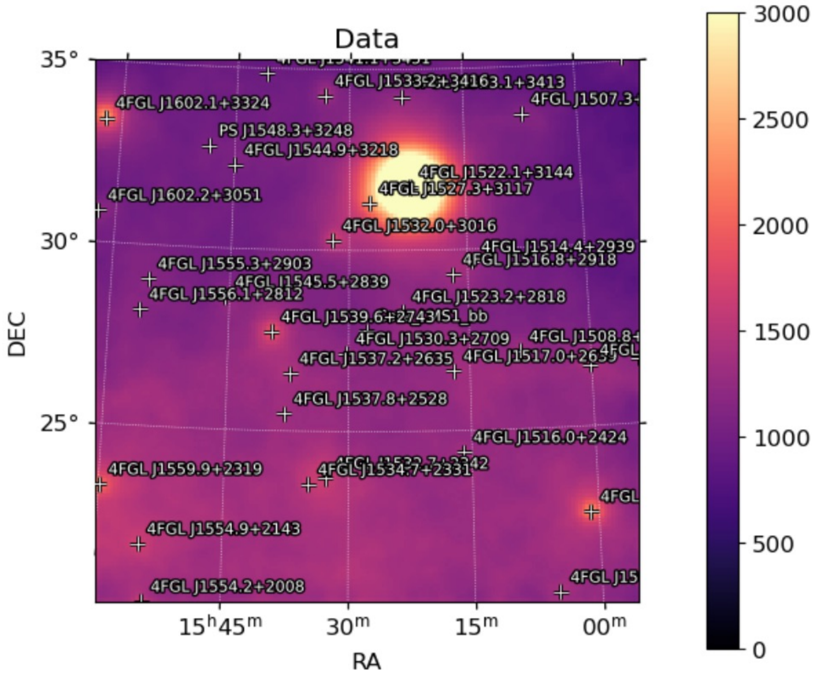


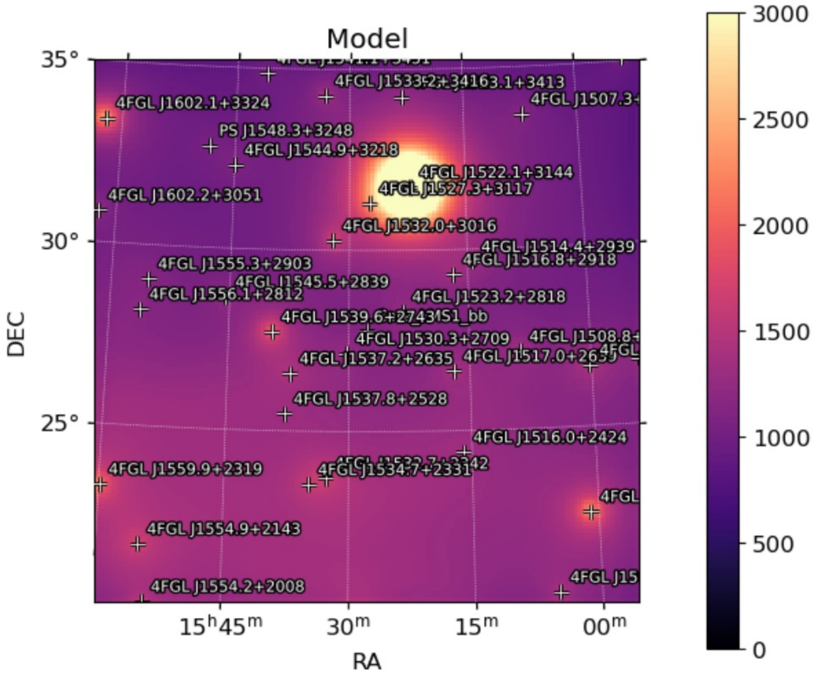
Spectral analysis technical setup

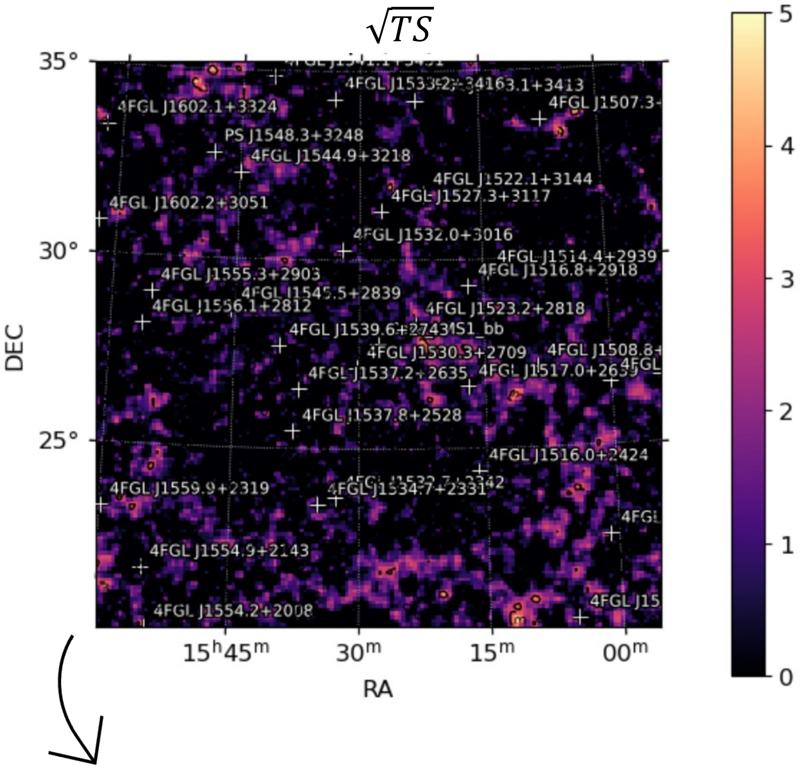
Time domain (Gregorian)	2008-08-04 to 2023-04-01
Time domain (MET)	239557417 to 702032312
Energy range	500 MeV - 500 GeV
IRF	P8R3_SOURCE_V3
Event type	FRONT + BACK
Point-source catalog	4FGL-DR4
ROI size	15° x 15°
Angular bin size	0.01°
Bins per energy decade	8
Galactic diffuse model	gll_iem_v07.fits
Isotropic diffuse model	iso_P8R3_SOURCE_V3_v1.txt

- ⁎ Sources within 3 degrees from the ROI center: free normalization and spectral shape.
- ⁎ Galactic diffuse component: free normalization and spectral index.
- ⁎ Isotropic diffuse component: free normalization.

Analysis Results: Example of skymaps





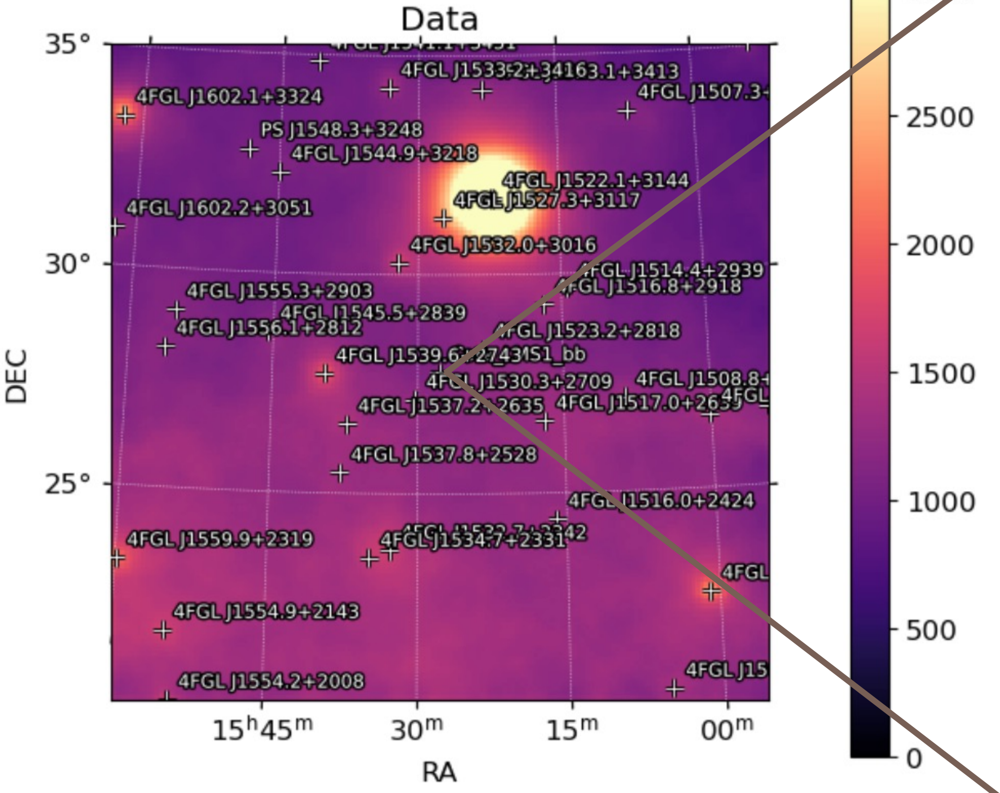


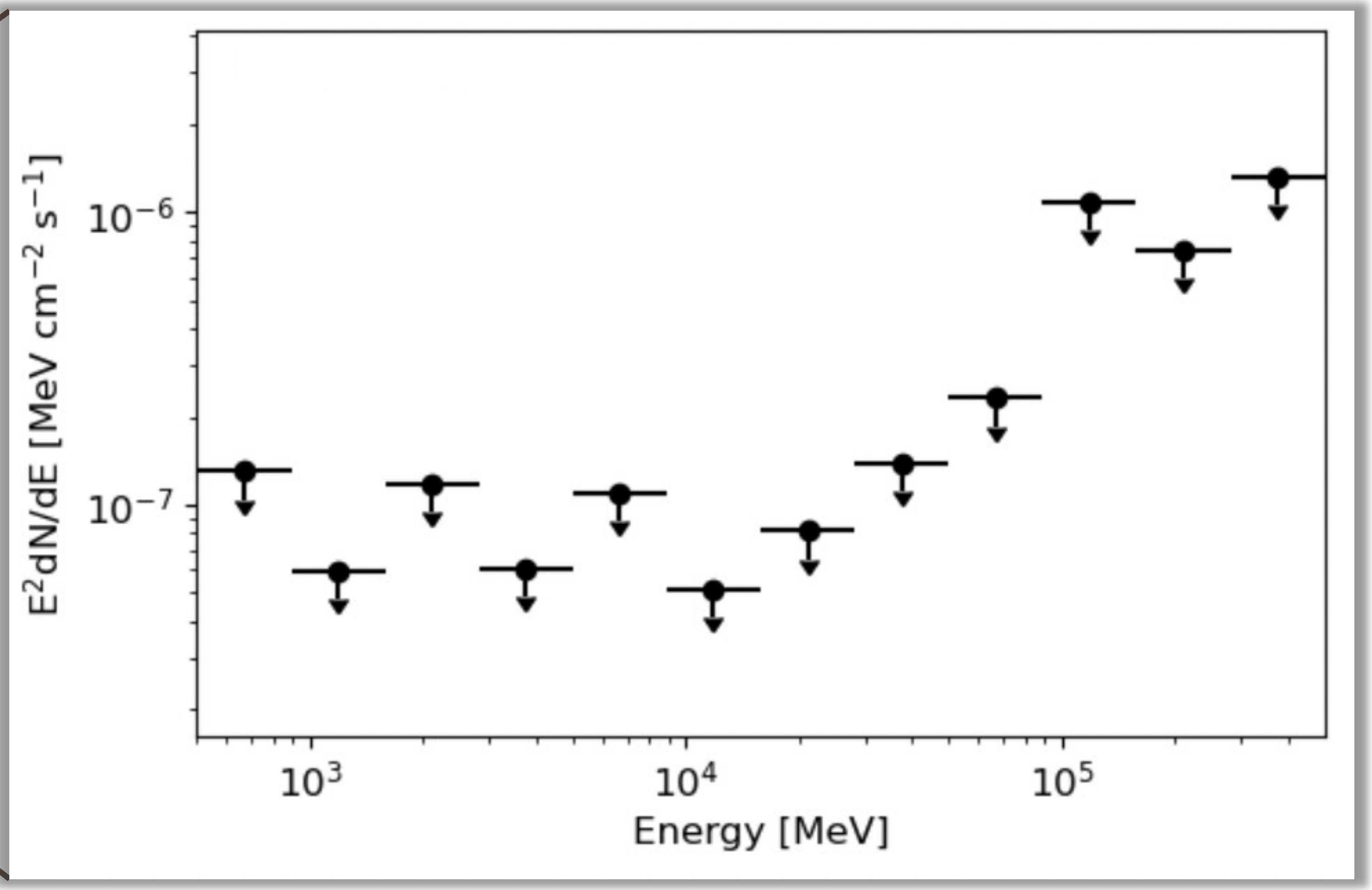
Test statistic (TS): positive deviations with respect to the model

Work under Fermi LAT embargo: only showing generic examples.

Analysis Results: Flux upper limits

We introduce a putative DM source annihilating via the $b\bar{b}$ channel at the center of the ROI





DM constraints

- In the absence of a signal, we put constraints on the DM particle properties.
- We assume that all the DM is in the form of *Weakly Interacting Massive Particles* (WIMPs).
- Expected flux due to WIMPs annihilation:

$$\frac{d\Phi_\gamma}{dE}(E,\Delta\Omega,l.o.s) = \frac{d\phi_\gamma}{dE}(E) \times J(\Delta\Omega,l.o.s)$$

Astrophysical J-factor

$$J(\Delta\Omega, l.o.s) \propto \iint \boldsymbol{\rho_{DM}}^2 \, dl \, d\Omega$$

DM density profile

Particle physics term
(DM particle mass, annihilation cross section $\langle\sigma v\rangle$, and DM spectrum)

DM constraints

DM particle mass

Minimum detection flux, i.e. flux upper limits from our DAT analysis

Velocity-averaged annihilation cross-section

$$\langle \sigma v \rangle = \frac{8\pi \cdot m_\chi^2 \cdot F_{min}}{J \cdot N_\gamma}$$

J-factor from our DM modeling

DM spectrum for a particular annihilation channel integrated within an energy range (Cirelli+11)

DM modelling

* We assume that the streams maintain the same density distribution as their progenitors within the core ($r \leq r_s$) (*e.g., Aguirre-Santaella et al. 2023*).

* Rest of the DM outside r_s gets lost due to tidal stripping.

* Following results from DM-only cosmological simulations, we model the streams' core with a truncated **Navarro-Frenk-White** (NFW) DM density profile:

If $r \leq r_s$ → $\rho_{NFW}(r) = \dfrac{\rho_0}{\left(\frac{r}{r_s}\right)\left(1+\frac{r}{r_s}\right)^2}$

If $r > r_s$ → $\rho_{NFW}(r) = 0$

ρ_0: characteristic DM density at r_s

r_s: scale radius

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* The extension in the sky of the DM subhalo hosted by each stream will be given by the angle subtended by r_s:

$$\theta_s = \arctan\left(\frac{r_s}{d_{Sun}}\right)$$

DM modelling

⁎ We take the stellar mass of the stream from the literature and adopt three different mass-to-light (M/L) ratios to estimate the DM mass of each stream.

Stream	M_{200} ($M_\odot$)		
	Lower	*Intermediate*	*Upper*
Indus	3.4×10^4	1.7×10^5	1.7×10^6
LMS-1	1.0×10^5	5.0×10^5	5.0×10^6
Orphan-Chenab	1.6×10^5	8.0×10^5	8.0×10^6
PS1-D	7.5×10^3	3.75×10^4	3.75×10^5
Turranburra	7.6×10^3	3.8×10^4	3.8×10^5
Cetus-Palca	1.5×10^6	7.5×10^6	7.5×10^7
Styx	1.8×10^4	9.0×10^4	9.0×10^5
Elqui	1.04×10^4	5.2×10^4	5.2×10^5

Lower: M/L = 2
(same DM mass than baryonic mass)

Intermediate: M/L = 5

Upper: M/L = 50

Typical M/L for dGs: 10 – 1000 (Q. Guo et al. 2019, arXiv:1908.00046v2*).*

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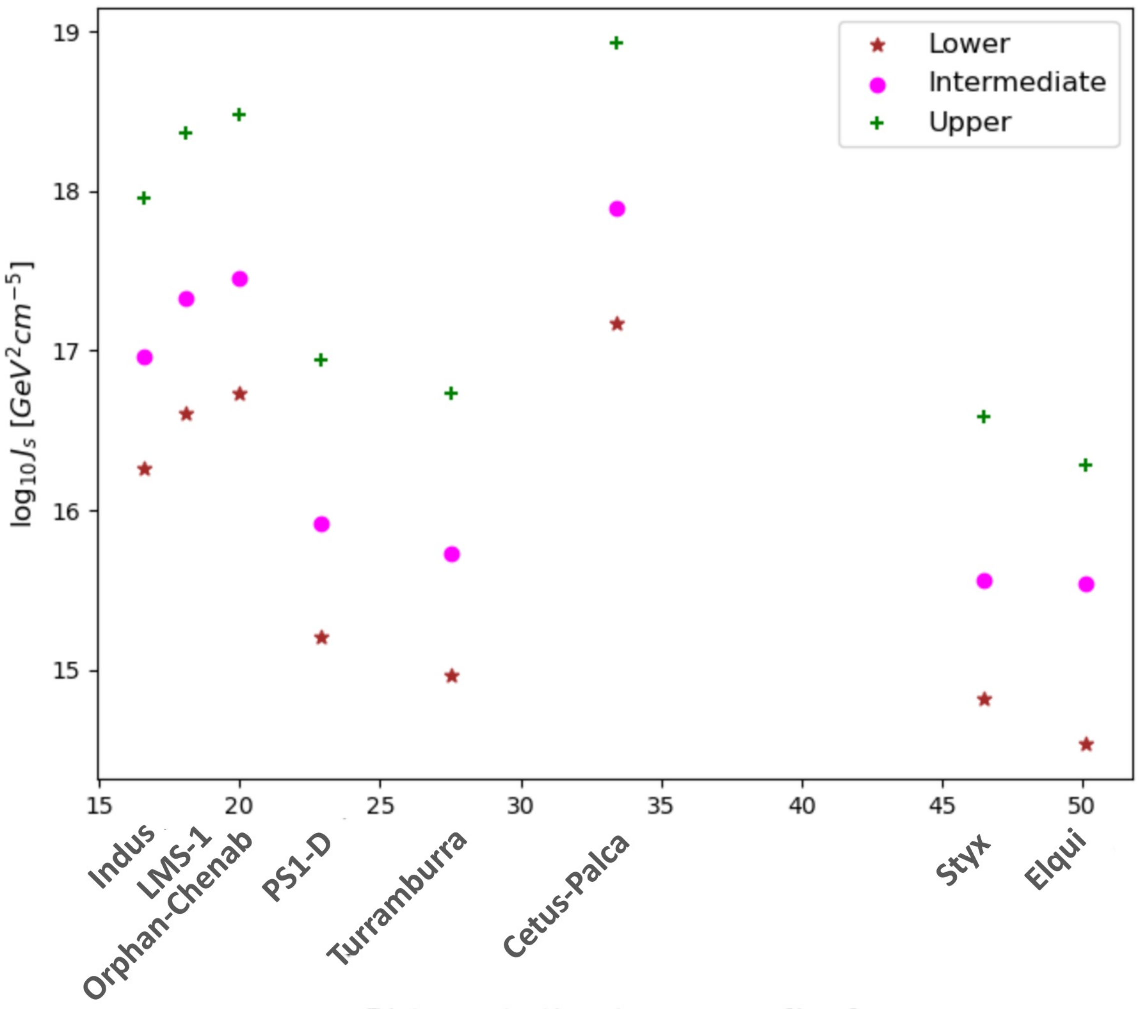
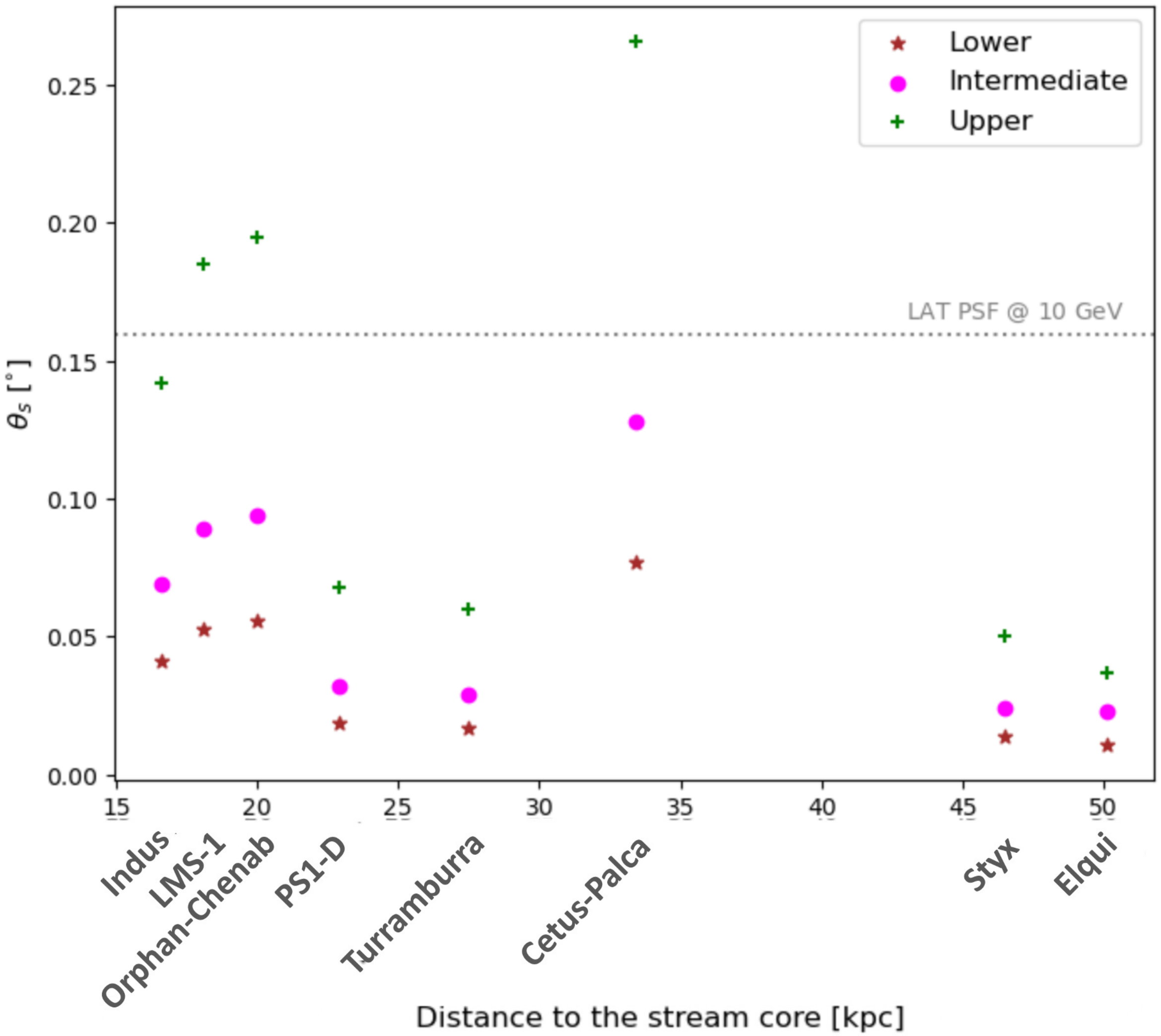
★ In cases where no estimates of the current streams' mass is available, we consider the stellar mass of the progenitor as the stellar mass of the stream: during the stretching process, the streams lose DM while the total baryon matter content remains the same.

Streams' J-factors and Angular sizes





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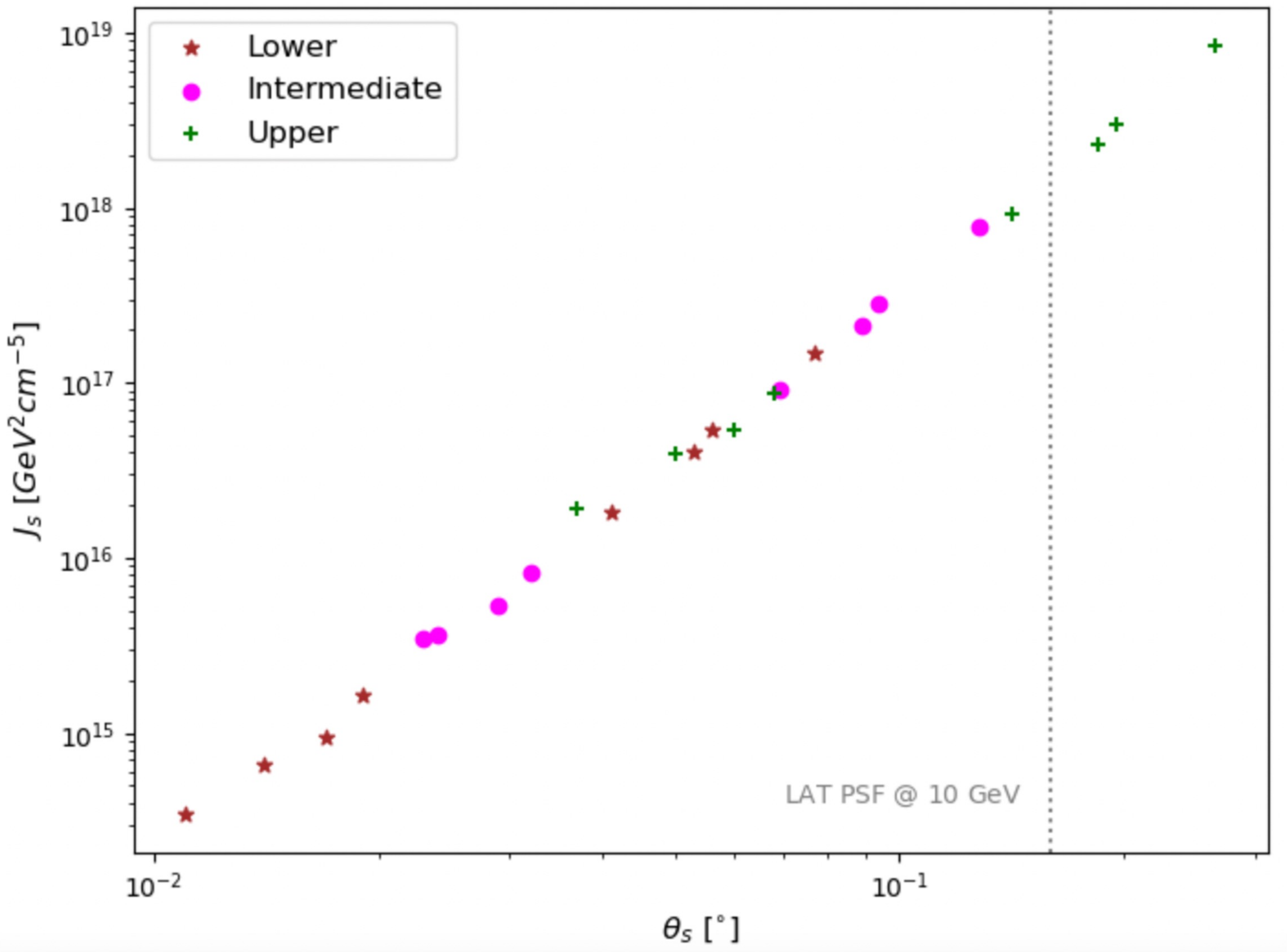
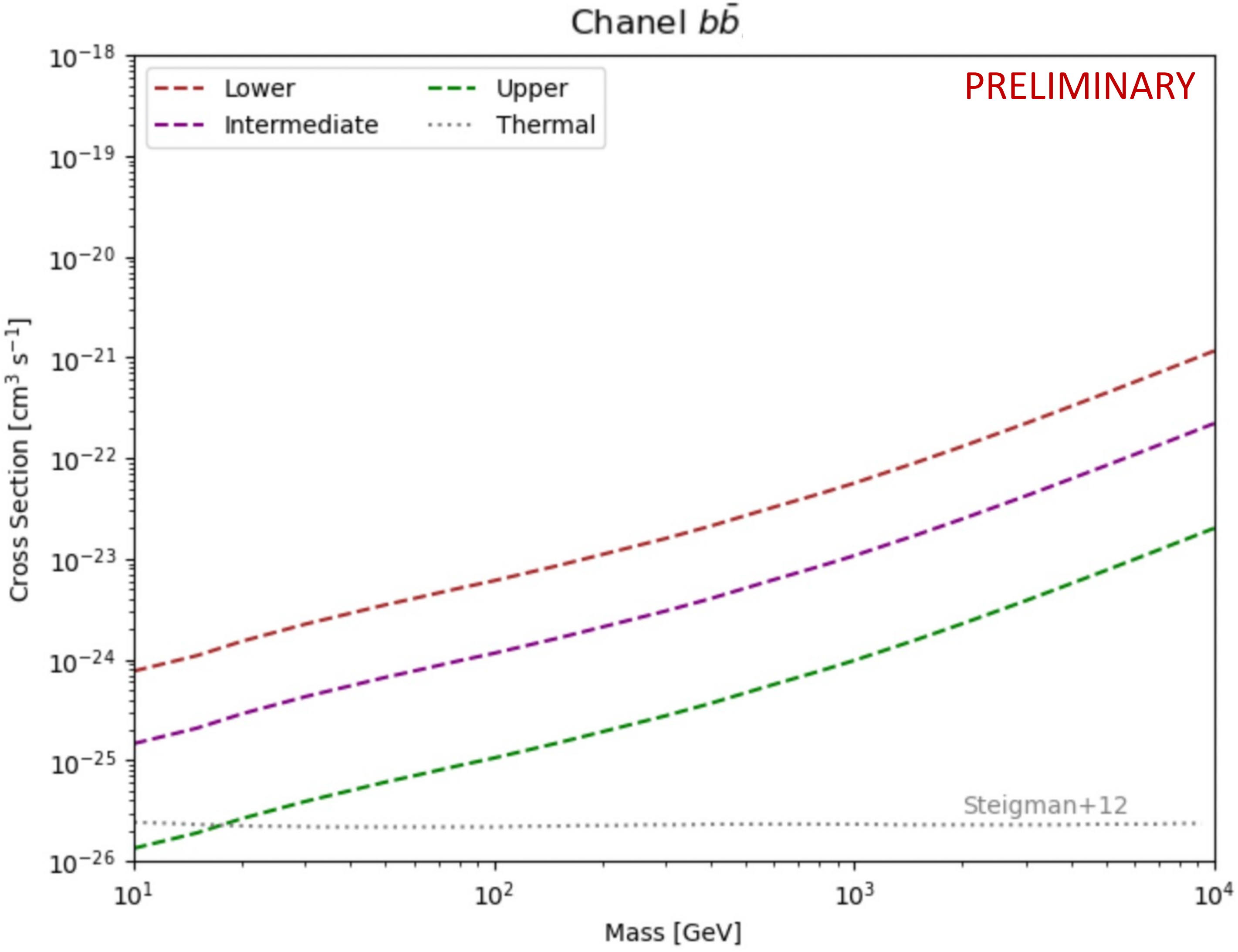


These objects can be treated as point-lilke sources in the analysis, this way simplifying it.

DM constraints: Example of individual limits



Work under Fermi LAT embargo: only showing generic examples.

General Remarks

- ✳ Our main objective is to use stellar streams as a new tool to shed light on the properties of the DM particle.

Ongoing taks

- ✳ Combining the results for the individual streams to improve the DM constraints (combined likelihood analysis).
- ✳ Considering the inclusion of Sagittarius stream in our golden sample.
- ✳ Working on the paper's draft.

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Thank you!

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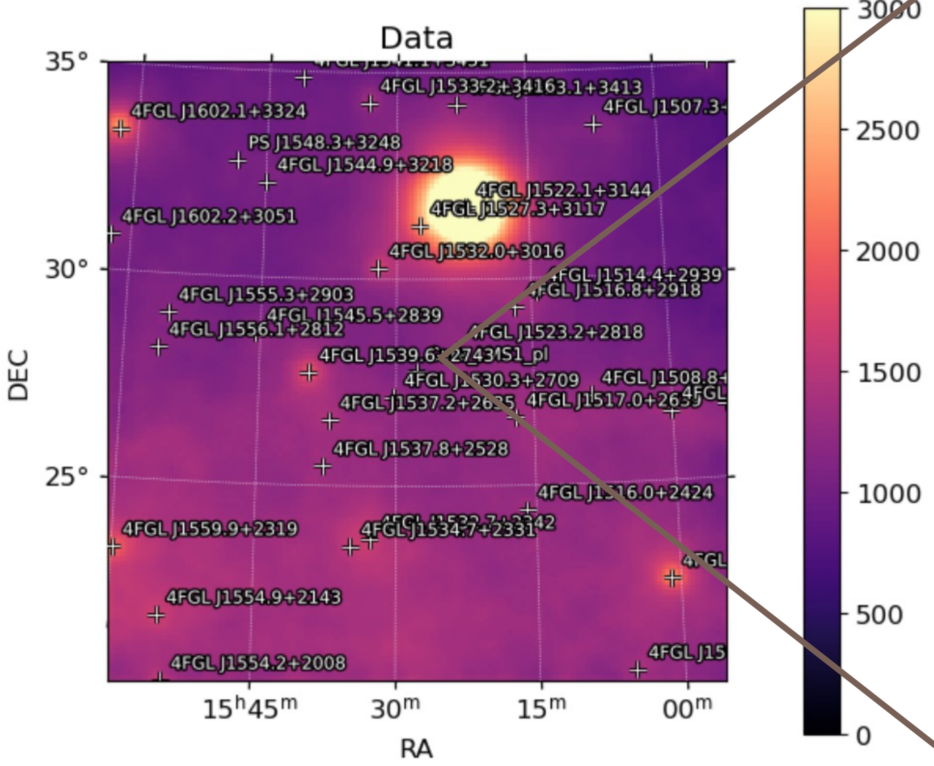
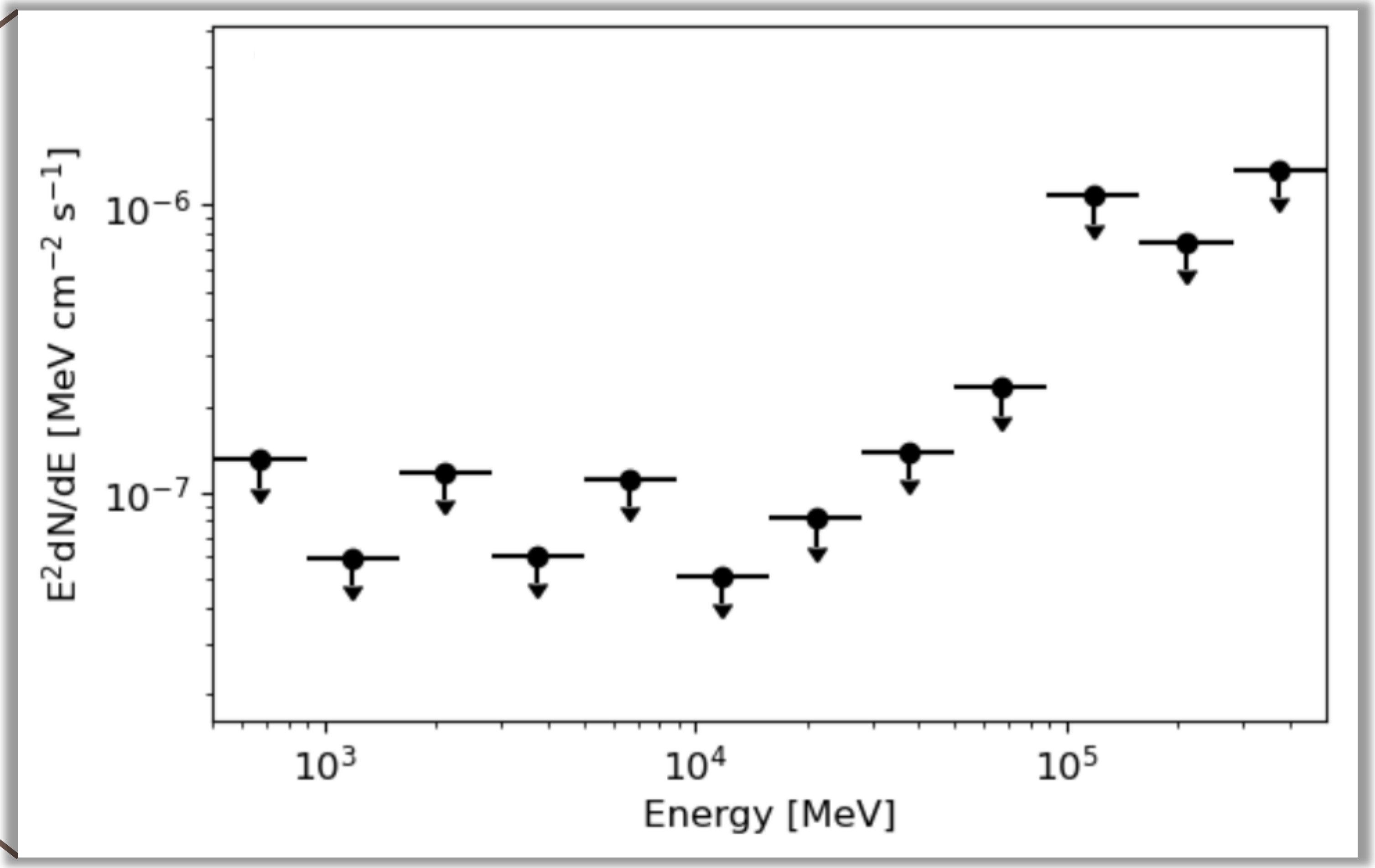
Backup Slides

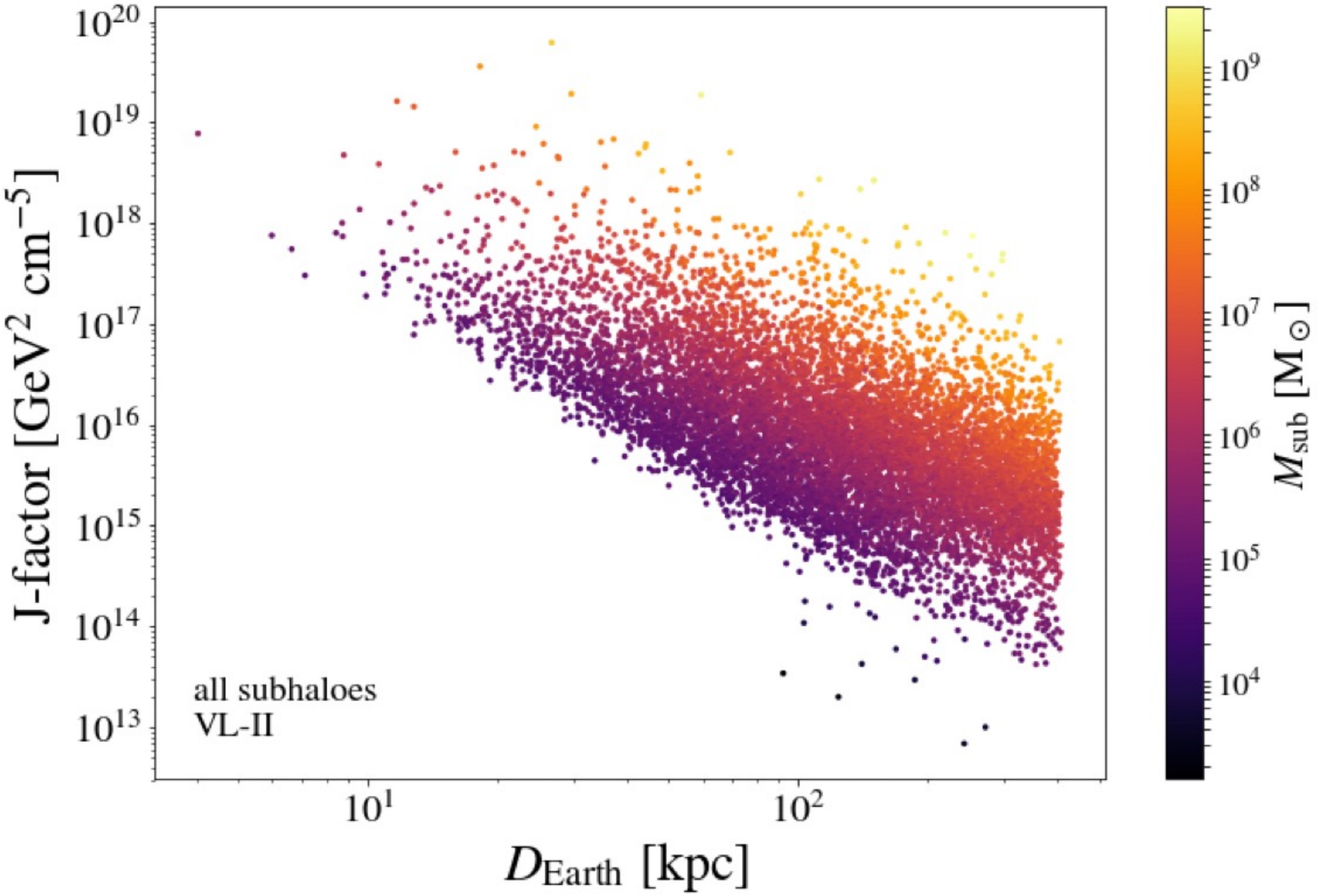
Analysis Results: Flux upper limits with a Power Law

We introduce a power law source at the center of the ROI





Sample selection: Distance



A. Aguirre-Santaella and M.A. Sánchez Conde, 2023.
arXiv:2309.02330v1