Search of DM annihilation in Stellar Streams with the Fermi LAT

Cristina Fernández-Suárez

In Collaboration with Miguel Á. Sánchez-Conde

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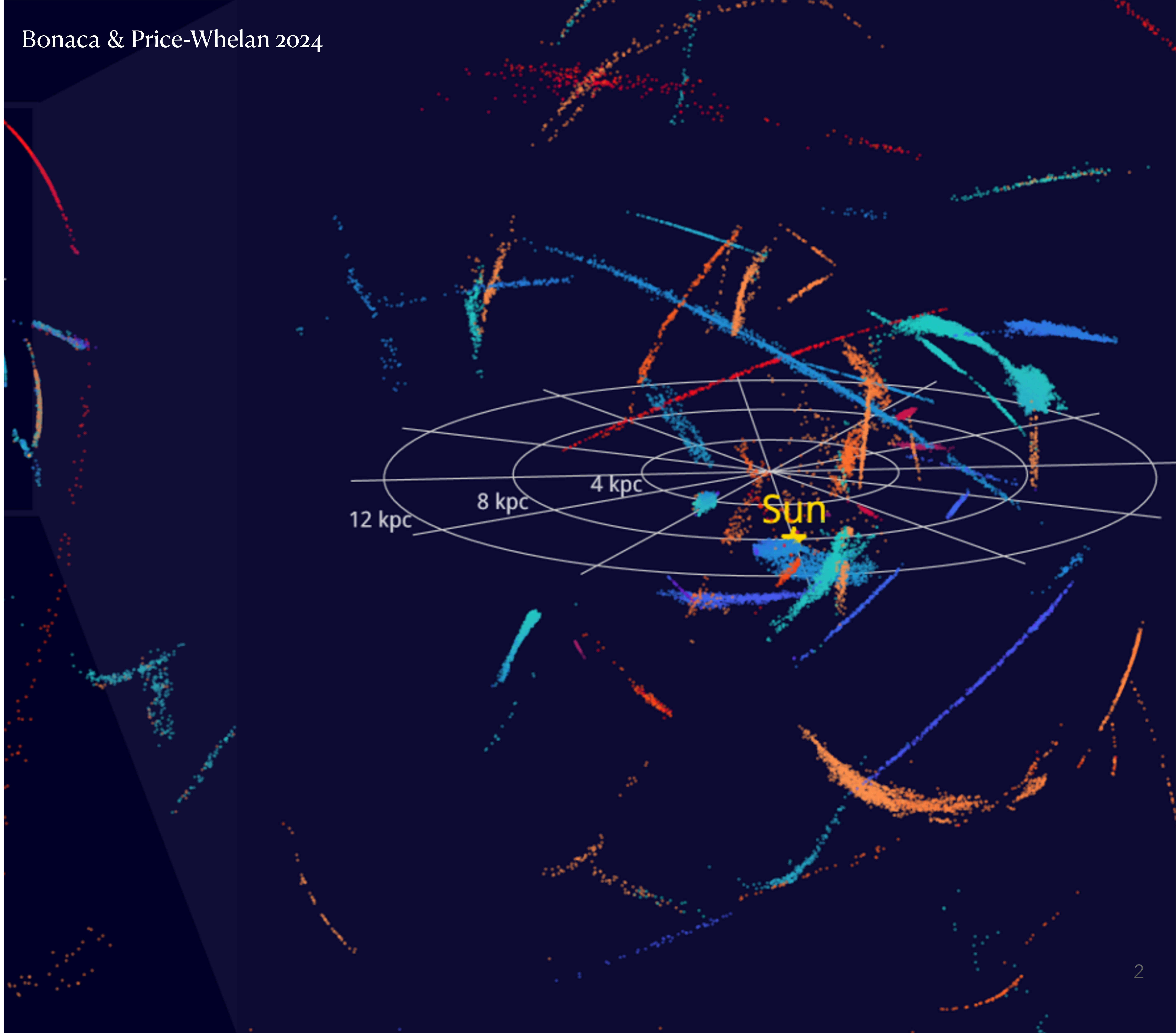
Stellar Streams in a nutshell

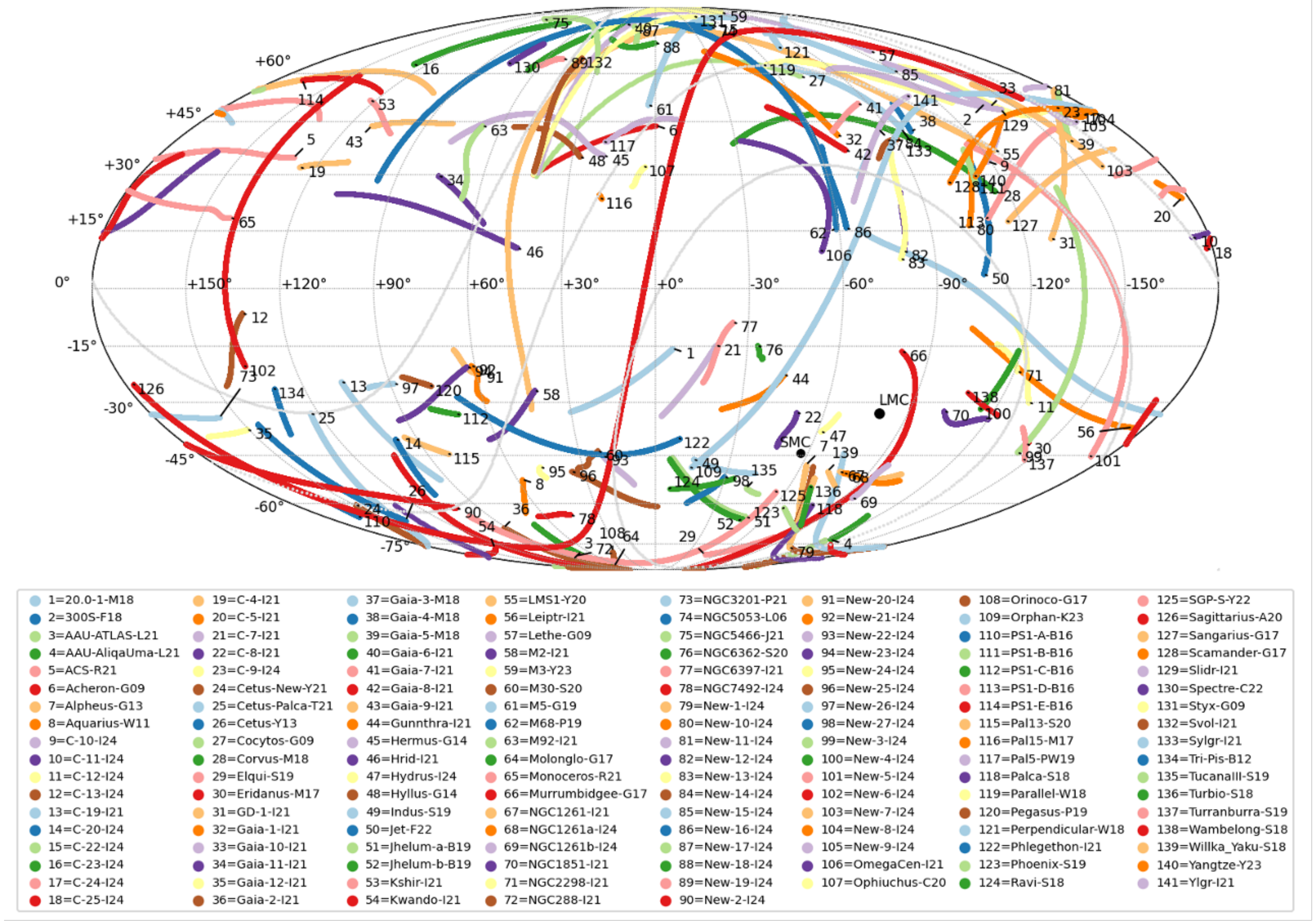
- Remnants of satellites, globular clusters (GCs) or dwarf galaxies (dGs), heavily stripped in the tidal field of the host galaxy.
- Extended structures, with lengths from 1 kpc to more than 100 kpc.
- Range in heliocentric distance from a few kpc to 100 kpc.



Stellar Streams in a nutshell

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

✱ Around 100 stellar streams have been observed around the Milky Way (MW).



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

Sample Selection for dark matter searches

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

- ✱ Progenitor:
  Streams whose progenitor is a dG.
- ✱ Distance:
  Streams closest to us (≲100 kpc).
- ✱ Mass:
  Streams whose stellar mass is known.

Stream	(l, b) (°)	d_{Sun} (kpc)	Length (°)
Golden sample			
Indus	(332.26, -49.19)	16.6	18.2
LMS-1	(43.27, 55.46)	18.1	179.2
Orphan-Chenab	(264.90, 43.60)	20.0	230.6
PS1-D	(230.95, 32.67)	22.9	44.9
Turranburra	(219.72, -40.79)	27.5	13.7
Cetus-Palca	(147.90, -67.80)	33.4	100.9
Styx	(35.40, 75.40)	46.5	60.4
Elqui	(293.88, -77.20)	50.1	10.9
Silver sample			
Monoceros	(180.0, 25.0)	10.6	46.9
AntiCenter	(140.0, 35.0)	11.7	57.7
Sagittarius	(6.01, -14.89)	25.0	280.0
Other streams whose progenitor is a dG			
Jhelum-a	-	13.0	30.0
Jhelum-b	-	13.0	30.0
Parallel	(263.88, 61.26)	14.3	37.7
C-19	(102.29, -38.54)	18.0	29.7

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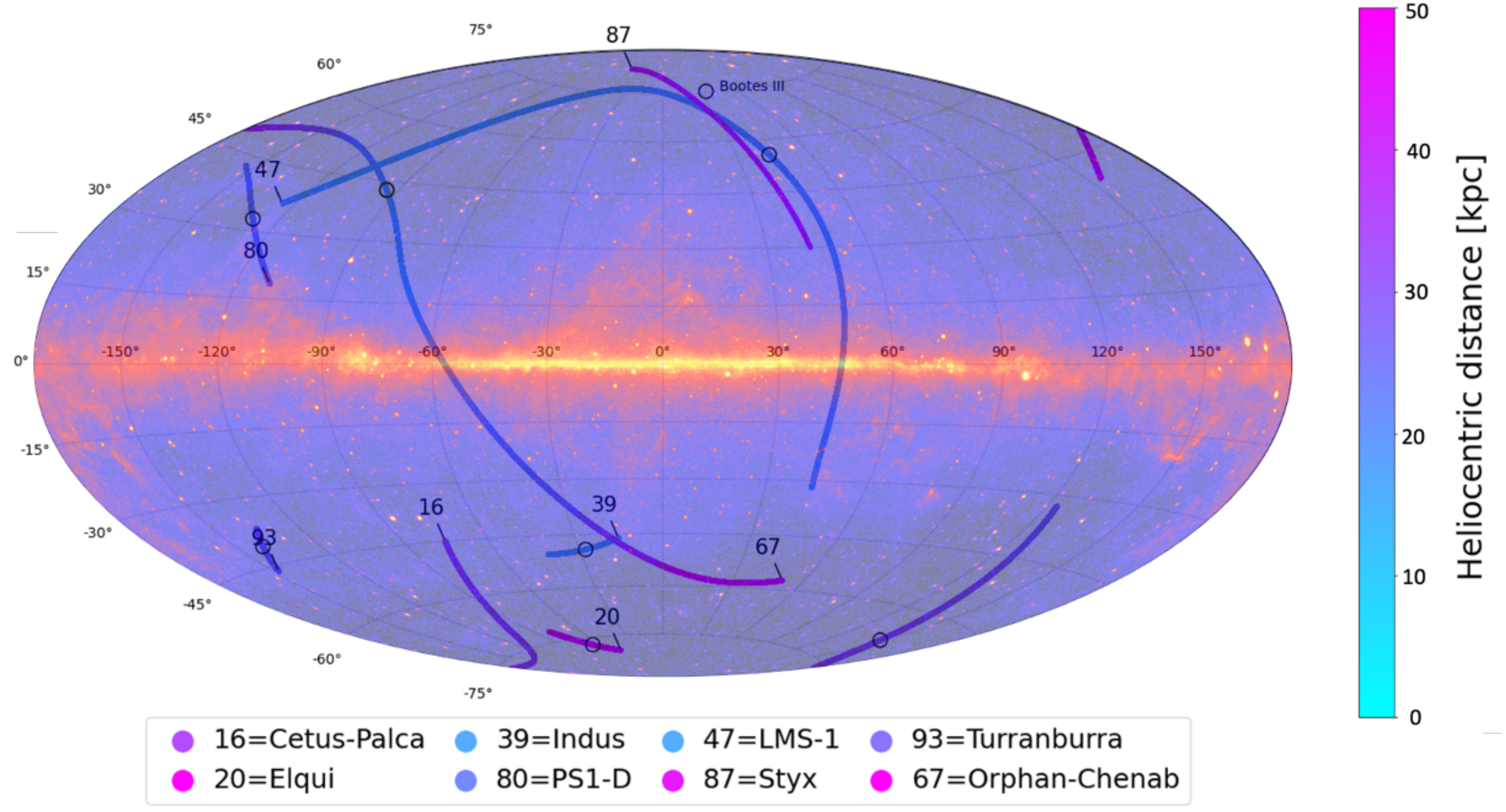
'Golden' Sample



Fermi - LAT Data Analysis

✱ We search for any gamma-ray signal in Fermi-LAT data from the direction of the streams' cores.

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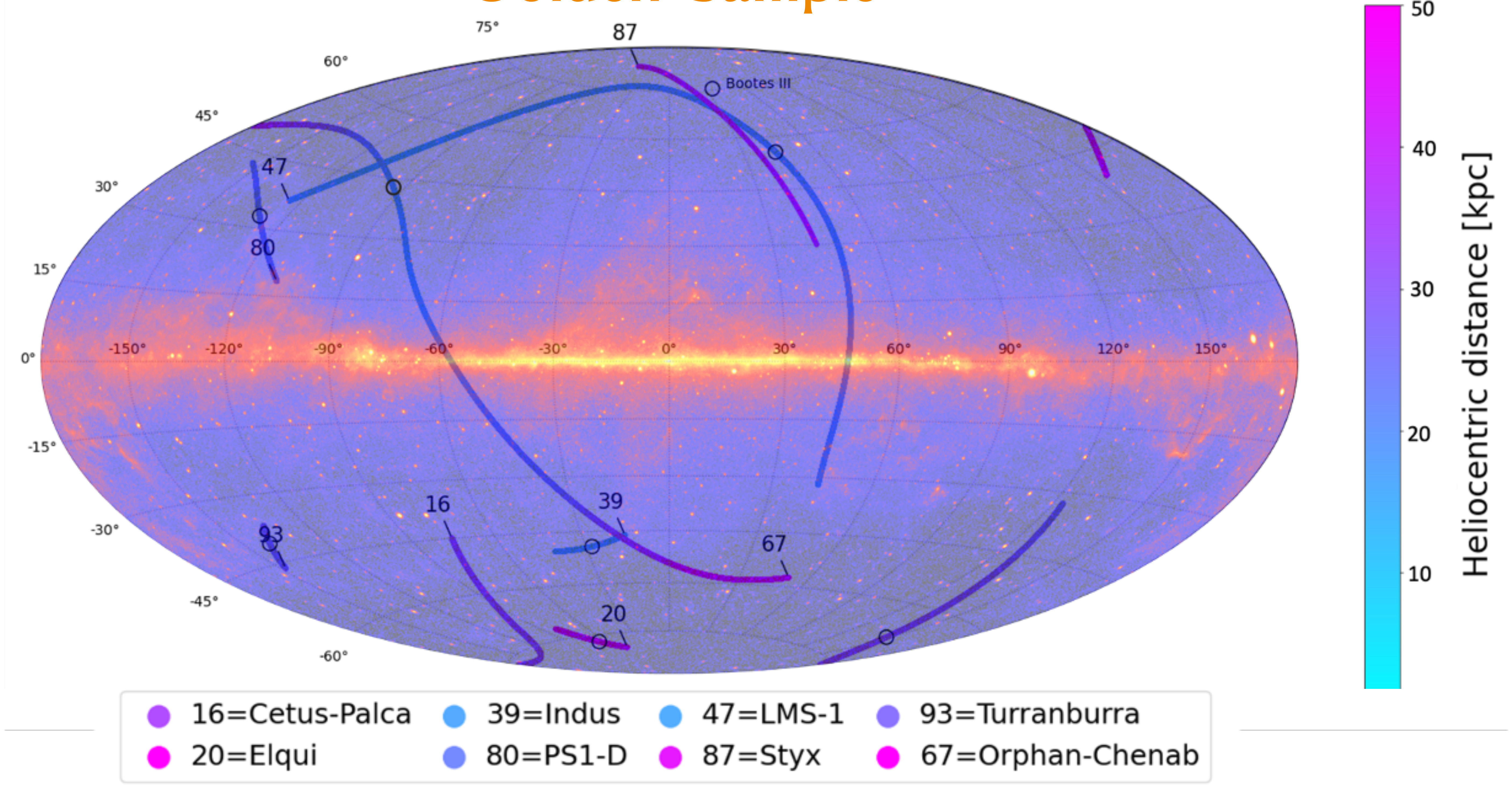


Spectral analysis technical setup

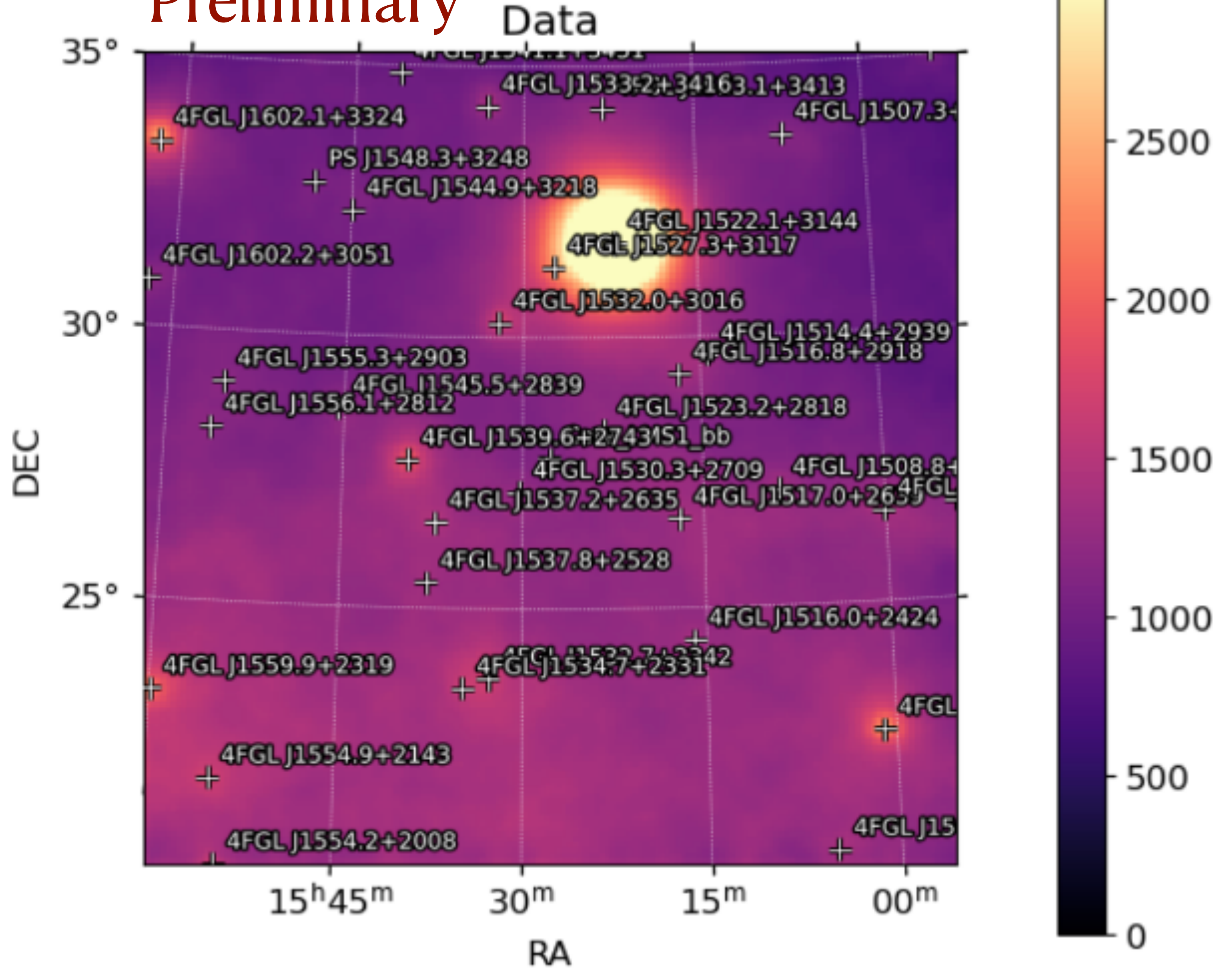
Time domain (Gregorian)	2008-08-04 to 2023-04-01
Time domain (MET)	239557417 to 702032312
Energy range	500 MeV - 500 GeV
IRF	P8R3_SOURCE_V3
Event type	FRONT + BACK
Point-source catalog	4FGL-DR4
ROI size	15° x 15°
Angular bin size	0.01°
Bins per energy decade	8
Galactic diffuse model	gll_iem_v07.fits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

✱ We perform the data analysis with the `Fermipy` python package.
✱ Sources within 3 degrees from stream's core: free normalization and spectral shape.
✱ Galactic diffuse component: free normalization and spectral index.
✱ Isotropic diffuse component: free normalization.

LAT Analysis Results: Example of skymaps

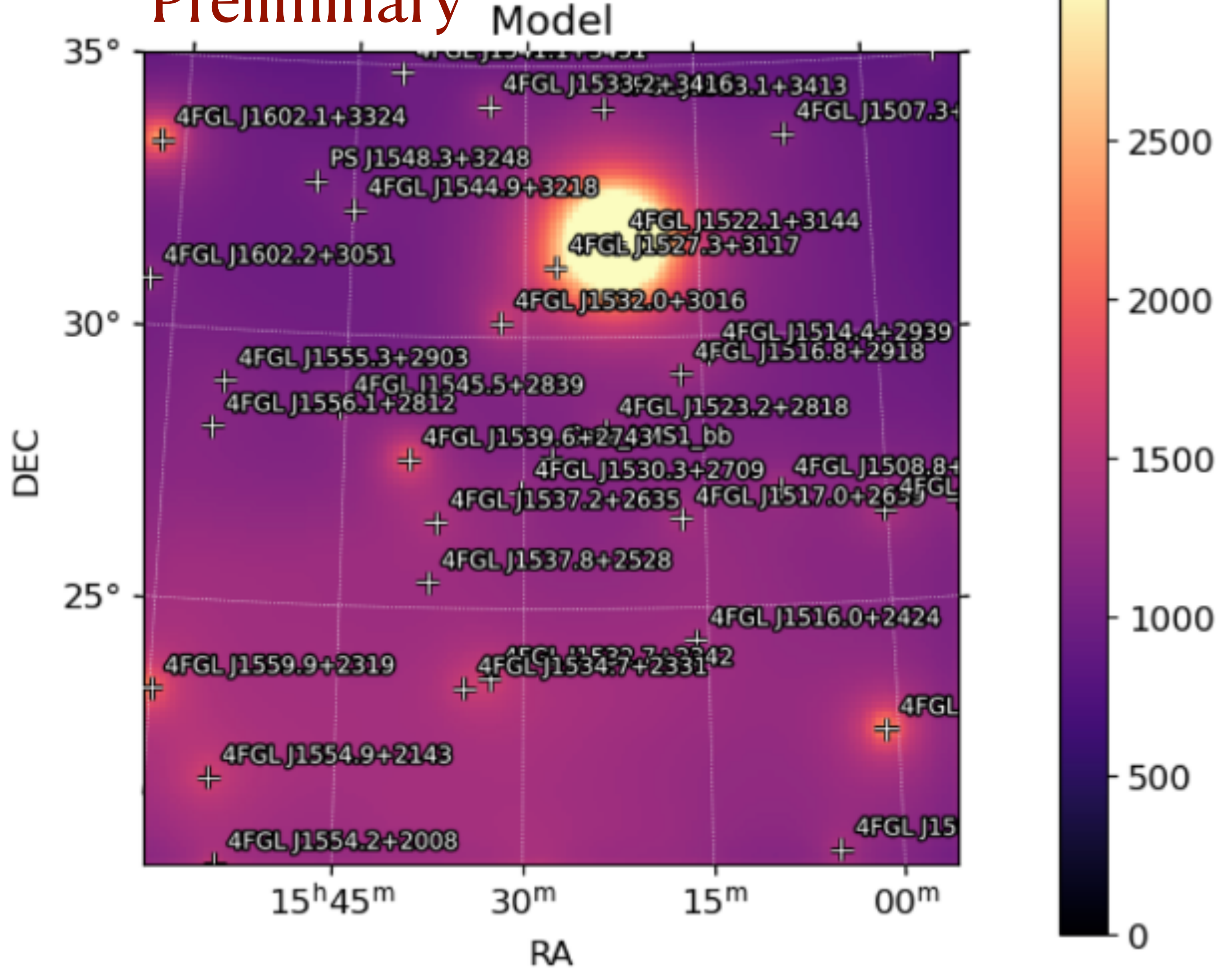
LMS-1 ROI — Data map

Preliminary



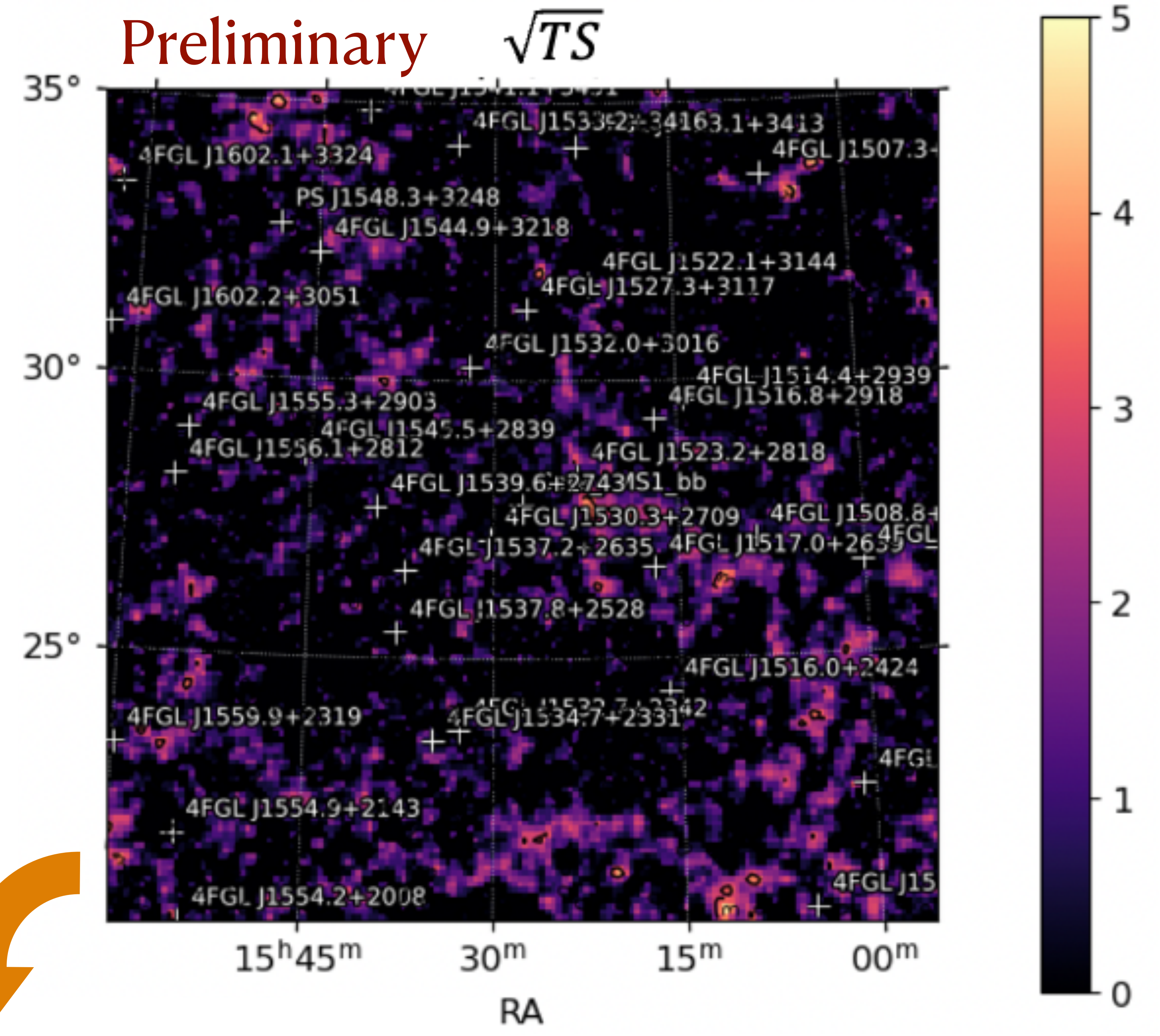
LMS-1 ROI — Model map

Preliminary



LMS-1 ROI — TS map

Preliminary



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

$$TS = -2 \log \left(\frac{\mathscr{L}(H_1)}{\mathscr{L}(H_0)} \right)$$

Likelihood of the alternative (existing DM source) hypothesis

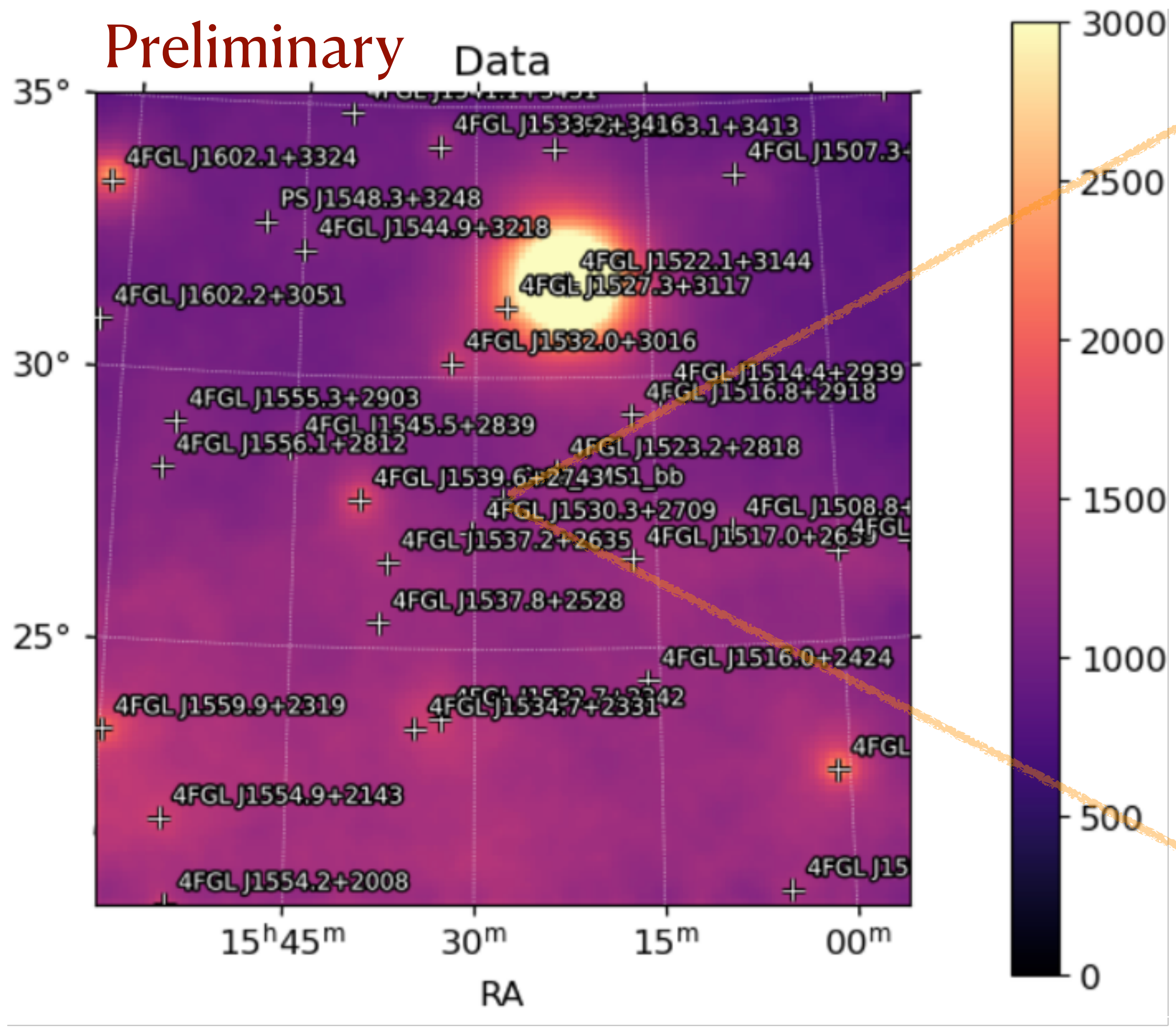
Likelihood under the null (no source) hypothesis

$$TS \sim \sigma^2$$

Analysis Results: Flux upper limits

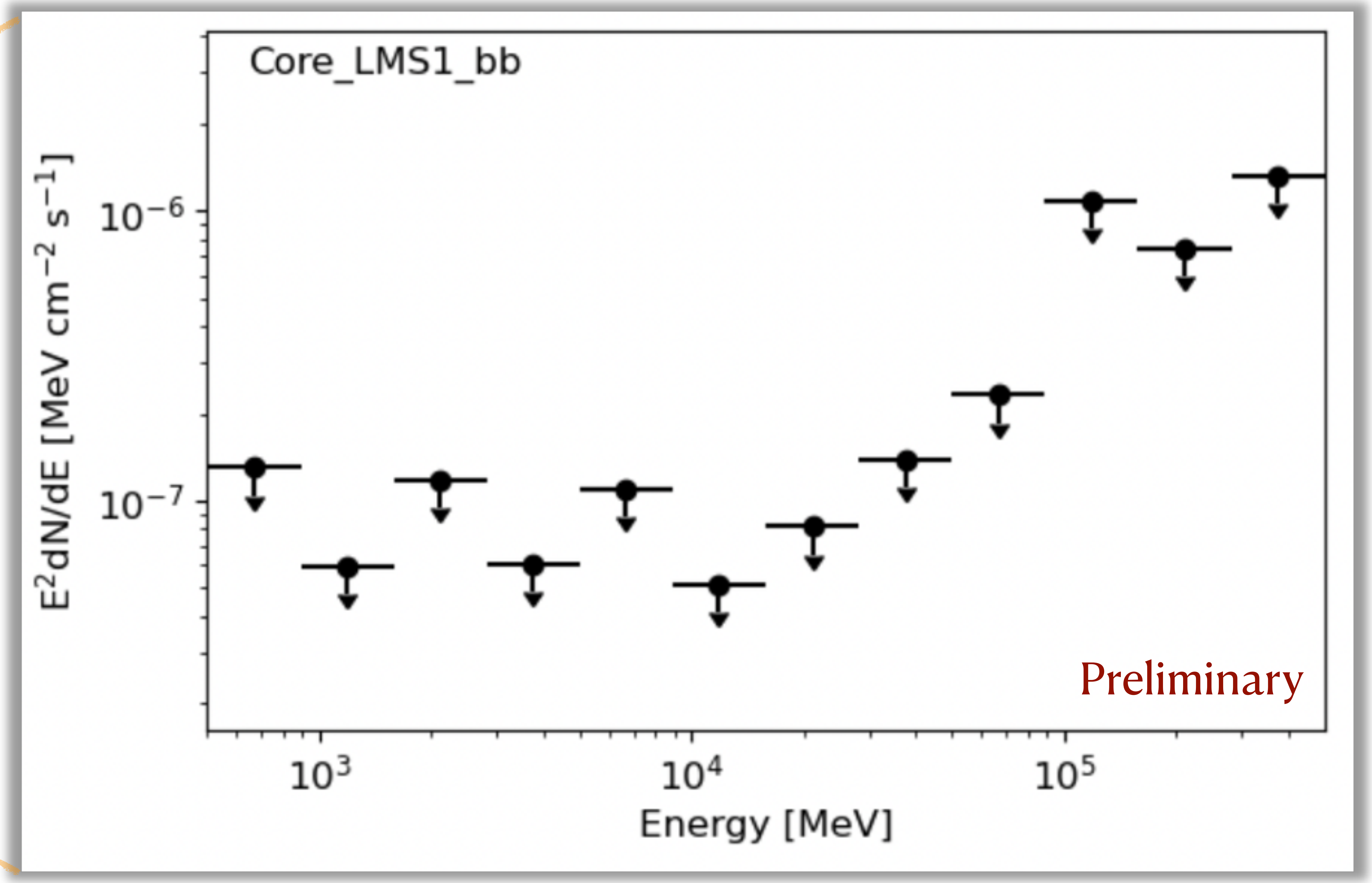
No significant emission is detected from any of the streams in our sample.

We introduce a putative DM source annihilating at the center of every ROI



Example for LMS-1 stream

Flux upper limits 95 % confidence level (C.L.)



DM Constraints

* In the absence of a signal, we put constraints on the DM particle properties.

* Assuming that all the DM is in the form of Weakly Interacting Massive Particles (WIMPs), the expected flux due to WIMPs annihilation (Bergström et al. 1998):

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

Particle physics term

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

Astrophysical J-factor

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

DM density profile

DM Constraints

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

Velocity average annihilation cross-section

DM particle mass

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

J-factor from our DM modelling

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

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J-factor from our DM modelling

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

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

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. 2024).

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

✱ We model the streams' core with a truncated Navarro-Frenk-White (NFWt) DM density profile.

If
$$r \leq r_s \longrightarrow \rho_{NFWt}(r) = \frac{\rho_0}{\left(\frac{r}{r_s}\right)\left(1 + \frac{r}{r_s}\right)^2}$$
$$r > r_s \longrightarrow \rho_{NFWt}(r) = 0$$

ρ_0 : characteristic DM density

r_s :scale radius

ρ_0 and r_s are obtained starting from the initial DM mass (M_{200}) and assuming the Moliné et al. 2017 subhalo concentration-mass relation.

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- The extension in the sky of each stream's core will be given by the angle subtended by r_s:

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

DM Modelling

* Starting from the known stellar mass, we adopt three different mass-to-light (M/L) ratios to estimate the 'original' DM mass of each stream at accretion time, M_{200}.

Stream	$\frac{M_{200}}{10^4}$ $(M_\odot)$		
	Low	*Bench.*	*High*
Indus	3.40	17.00	170.00
LMS-1	10.00	50.00	500.00
Orphan-Chenab	16.00	80.00	800.00
PS1-D	0.75	3.75	37.50
Turramburra	0.76	3.80	38.00
Cetus-Palca	150.00	750.00	7500.00
Styx	1.80	9.00	90.00
Elqui	1.04	5.20	52.00

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

Benchmark / Intermediate: M/L = 5

High: M/L = 50

Typical M/L for dGs: 10 – 1000

(e. g. M. Mateo 1998,
M. A. Sánchez-Conde et al. 2011,
Q. Guo et al. 2019).

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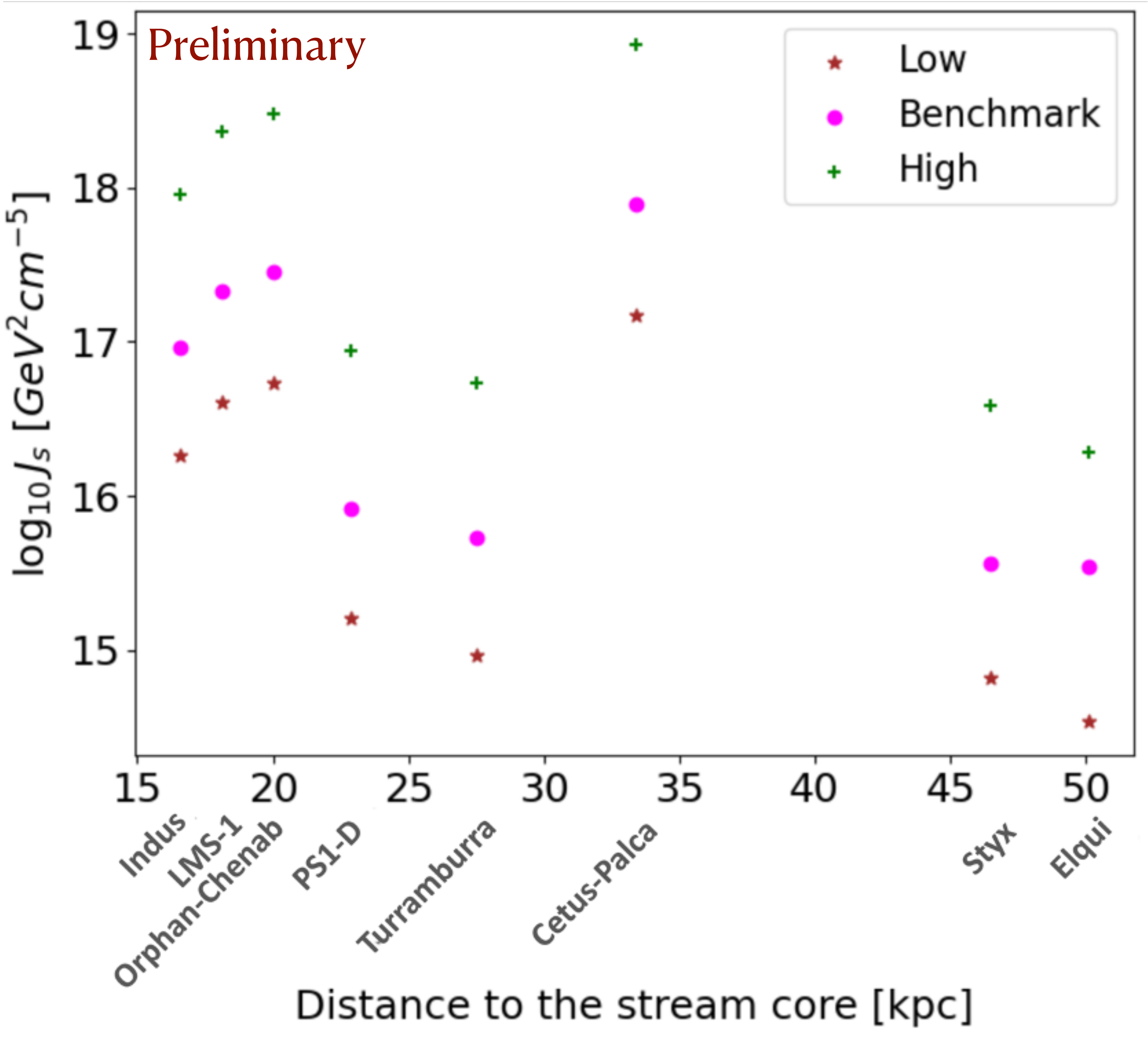
★ In cases where no estimates of the current streams' mass is available, we consider the stellar mass of the progenitor as the stellar mass of the stream: during the stretching process, the streams lose DM while we assume that the total baryon matter content remains the same.

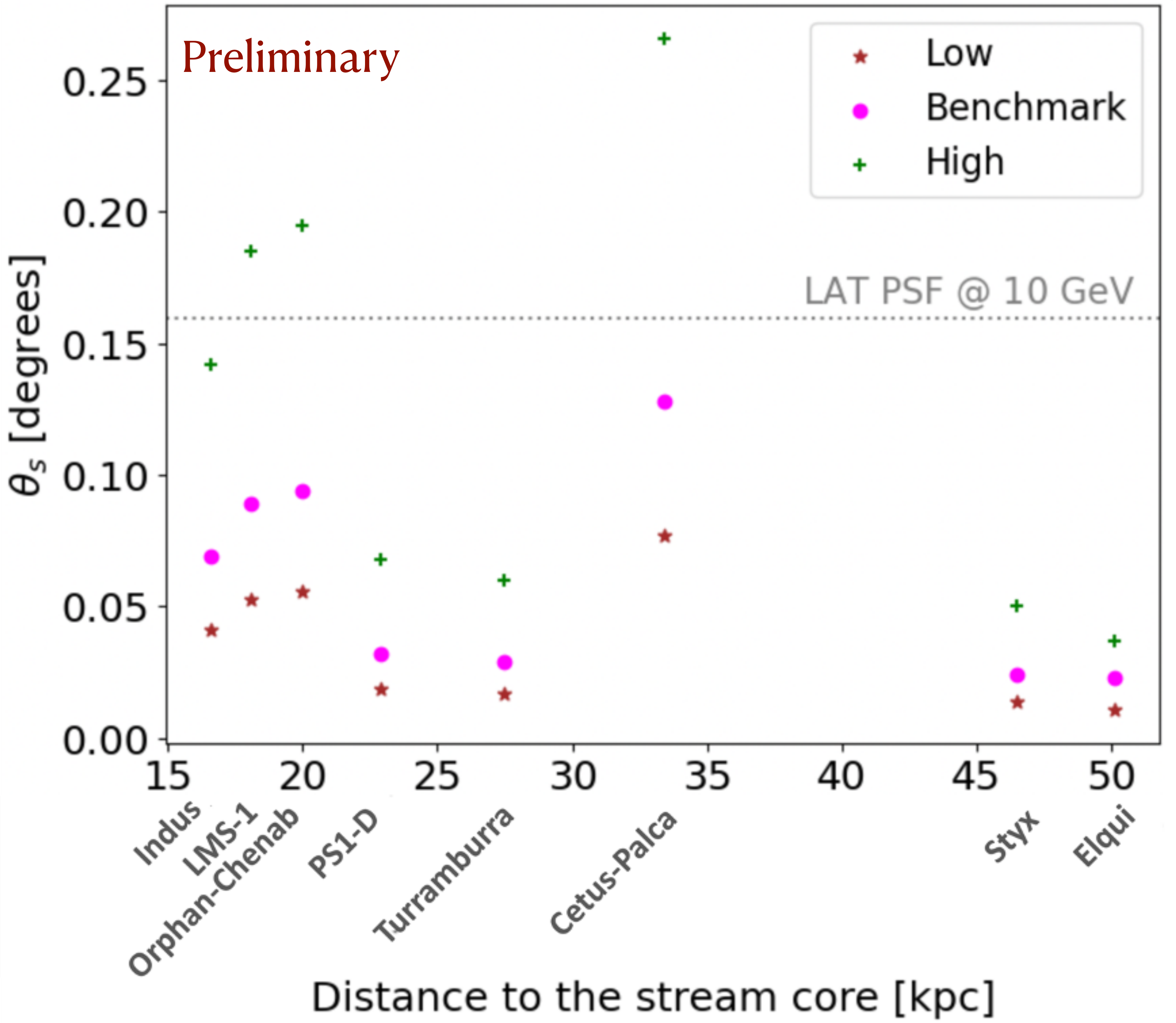
Streams' J-factors and Angular sizes

J_s : J-factor integrated up to the scale radius r_s



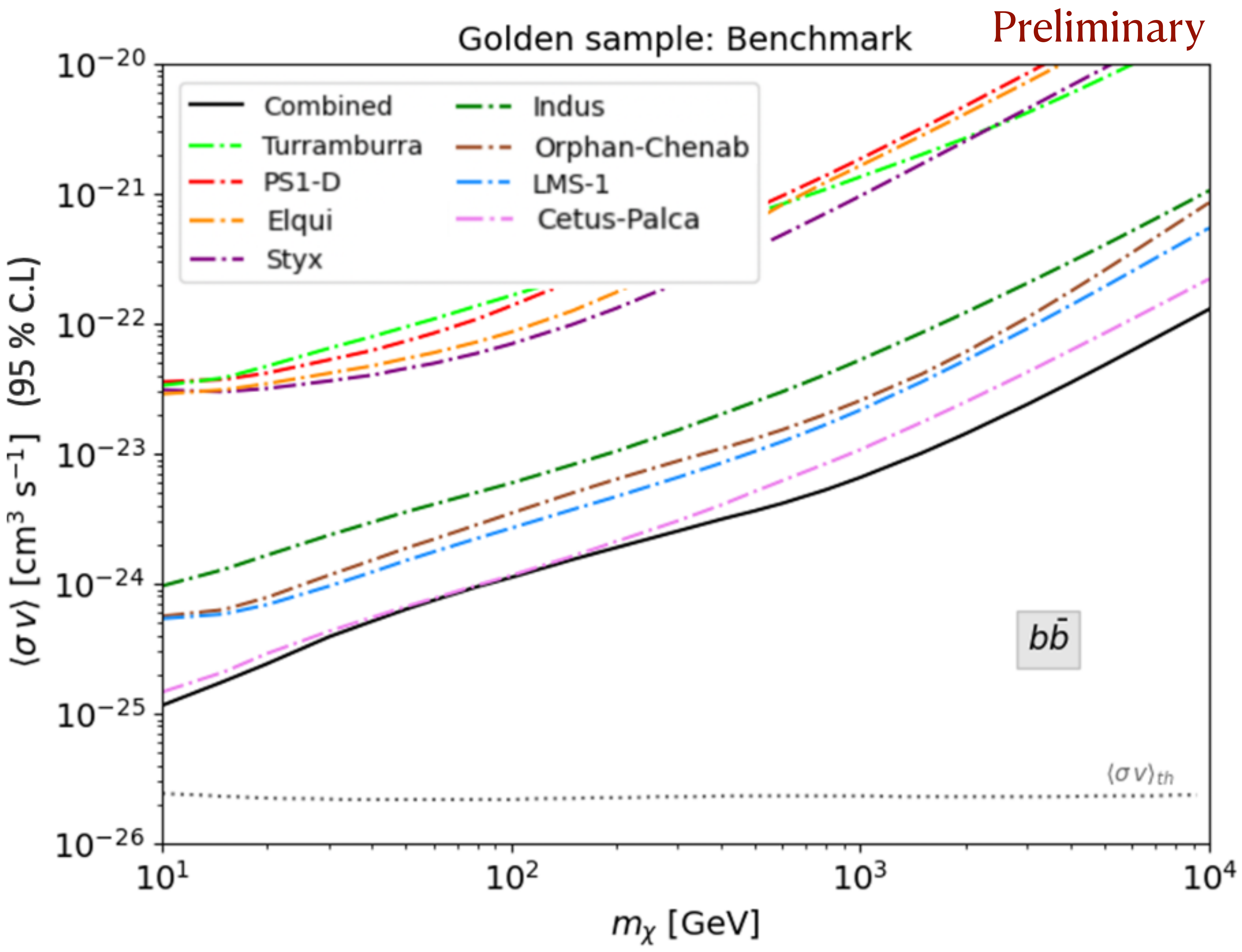
Streams' J-factors and Angular sizes

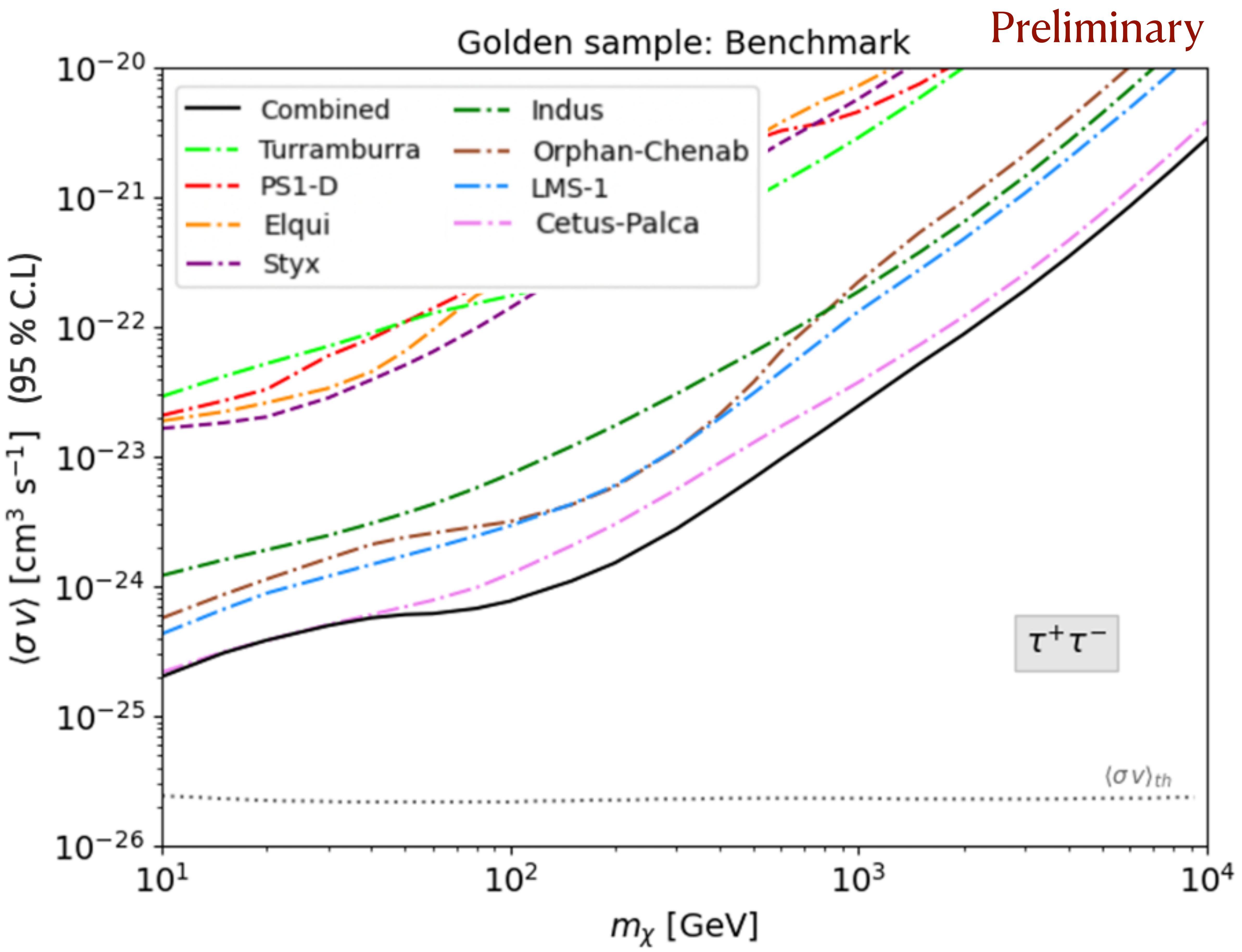
These objects are considered as point-like sources for the LAT



Angular resolution of the LAT at 10 GeV (1σ, 68% containment)

DM constraints:
Golden Sample, Benchmark case





Combined Likelihood Analysis

* Once the individual analysis of each stream is done, we combine the results obtained for each one by summing together the individual log-likelihood profiles independently for each energy bin, to obtain a global likelihood:

DM parameters
($\langle \sigma v \rangle$ and m_χ)

Parameters in the background model
(i.e., the nuisance parameters)

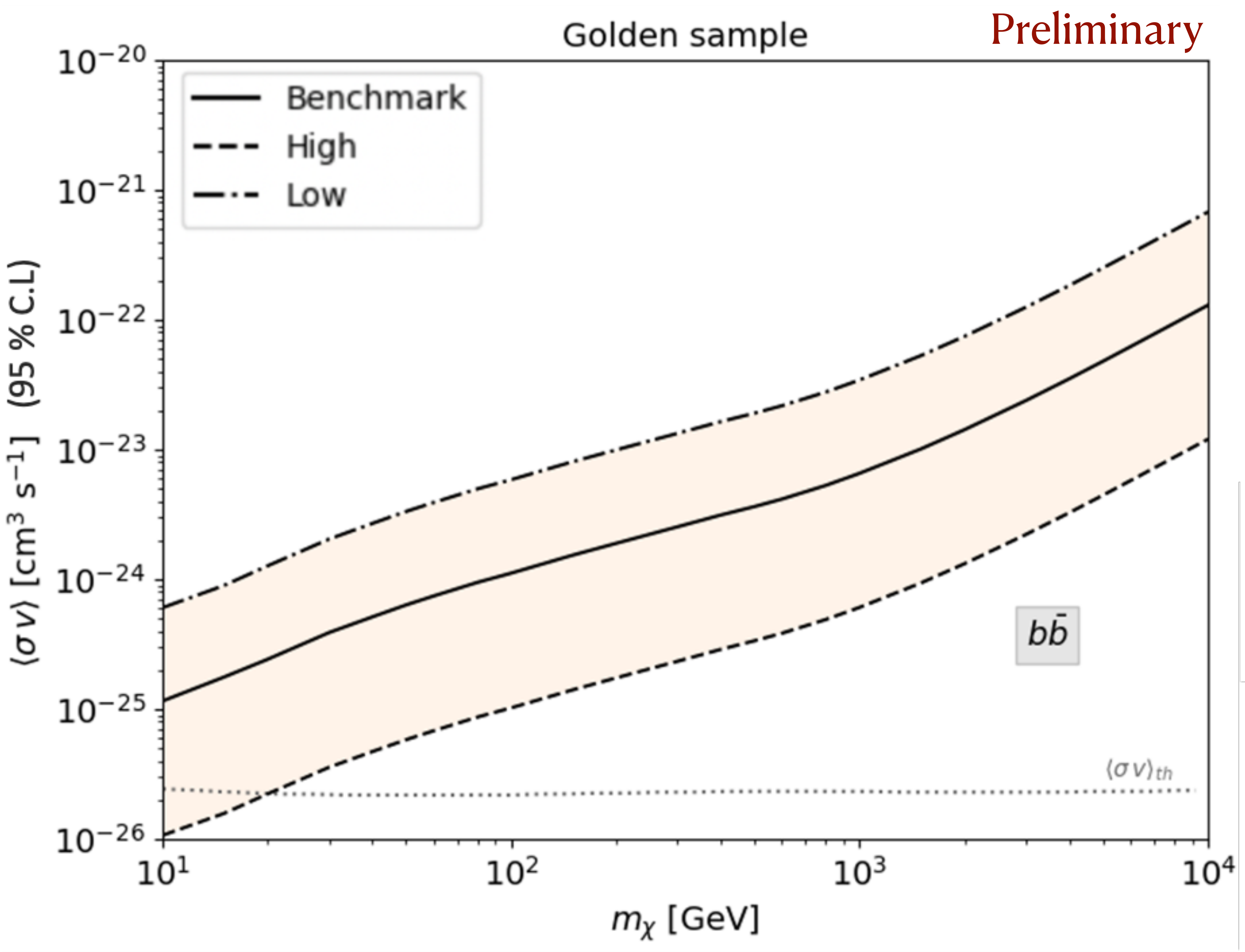
Combined likelihood for a particular DM annihilation channel as a function of the DM mass and $\langle \sigma v \rangle$ for all targets

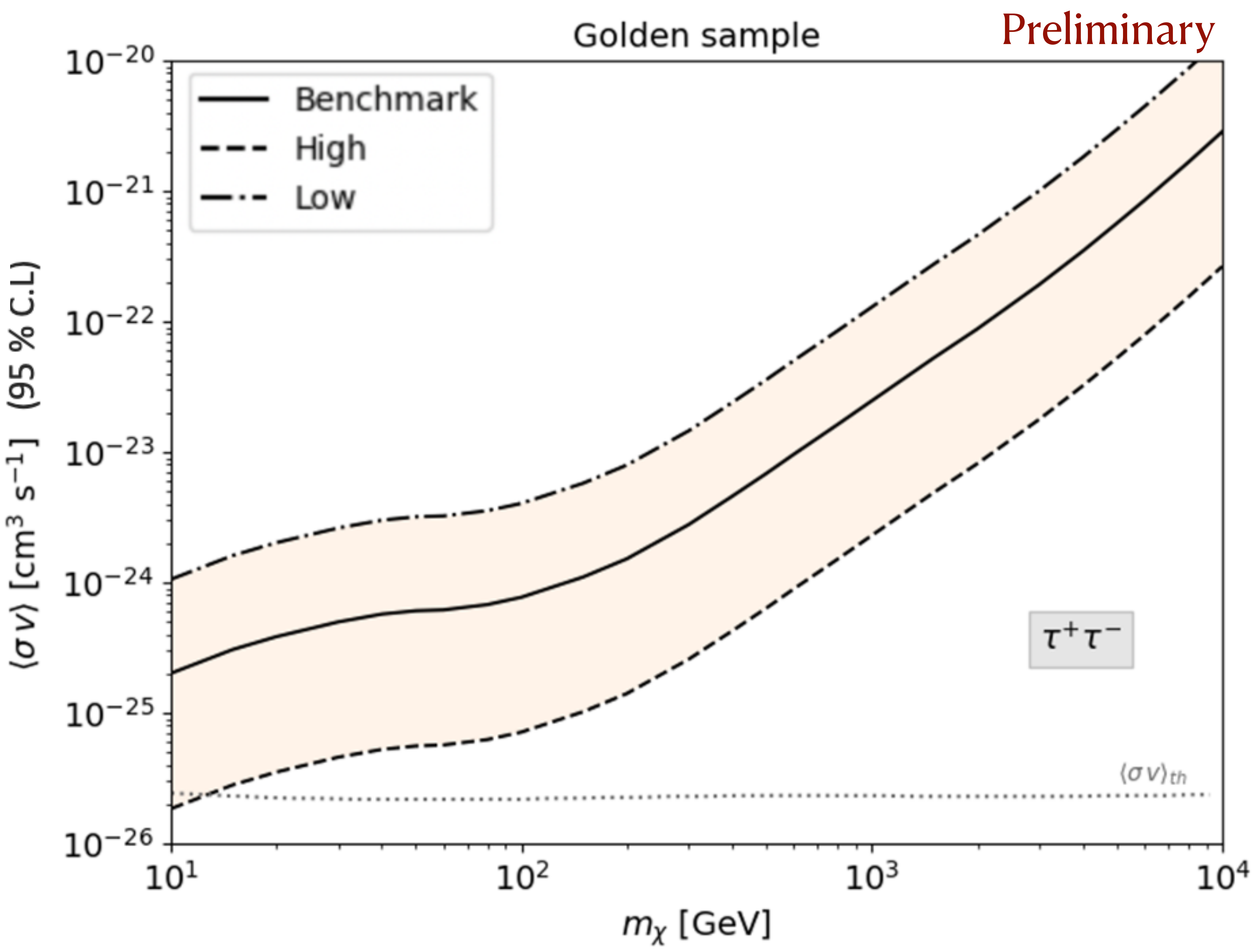
$$\log(\mathscr{L}_j(\mu, \theta_j | \mathscr{D}_j)) = \sum_i \log(\mathscr{L}_{i,j}(\mu, \theta_{i,j} | \mathscr{D}_{i,j}))$$

i: index of each target in the list

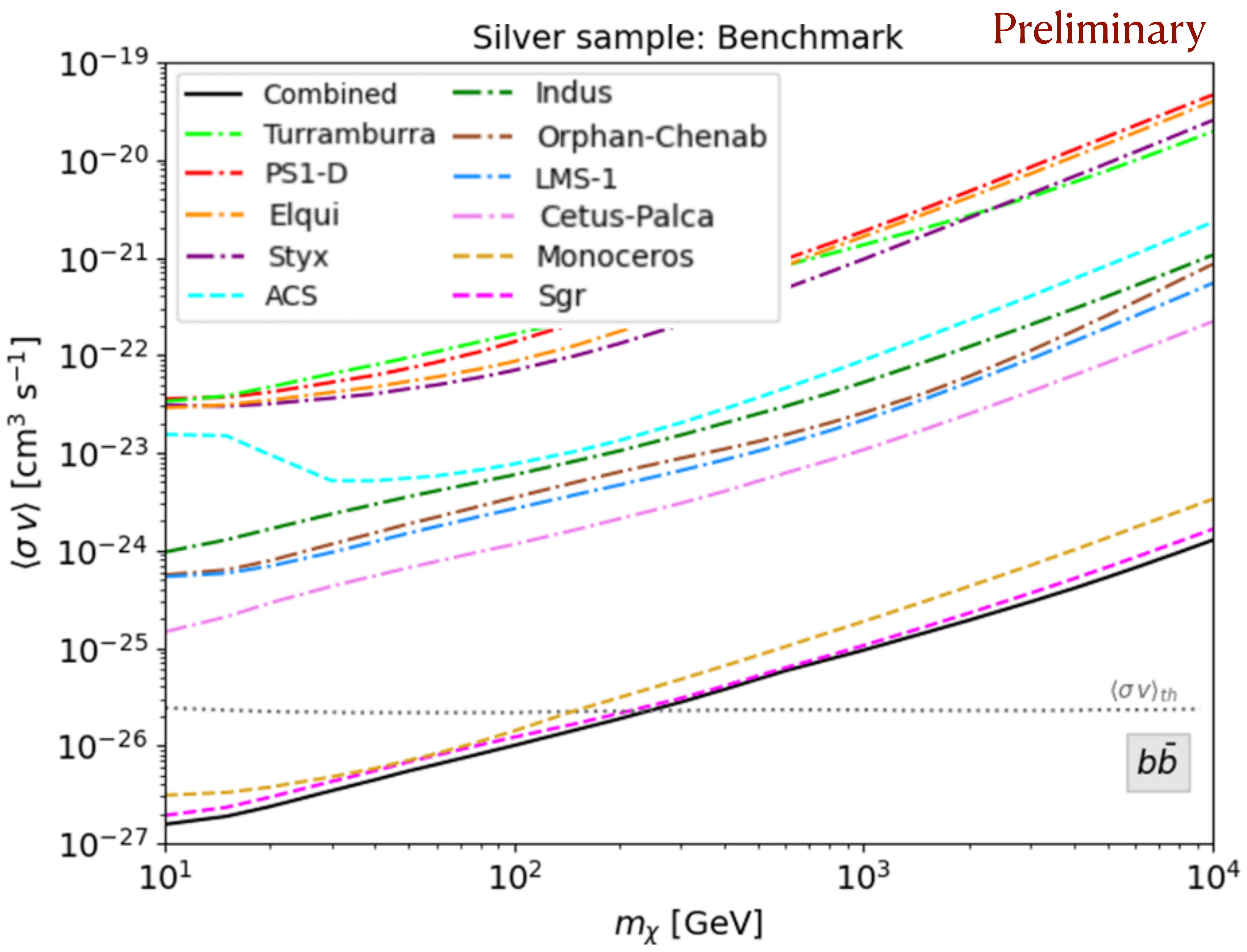
j: index of each energy bin of the LAT data ($\mathscr{D}$)

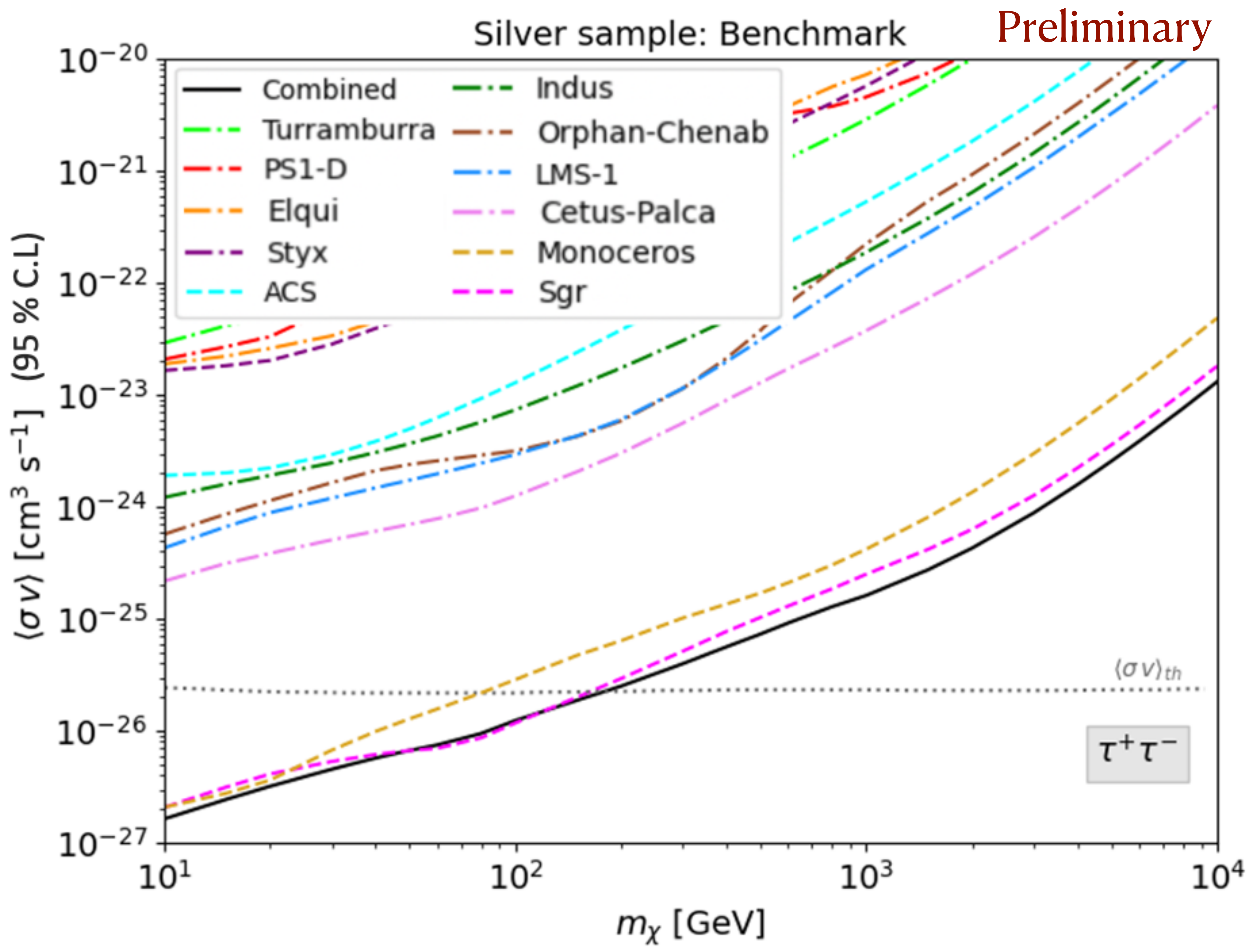
DM constraints: Golden Sample, M/L scenarios



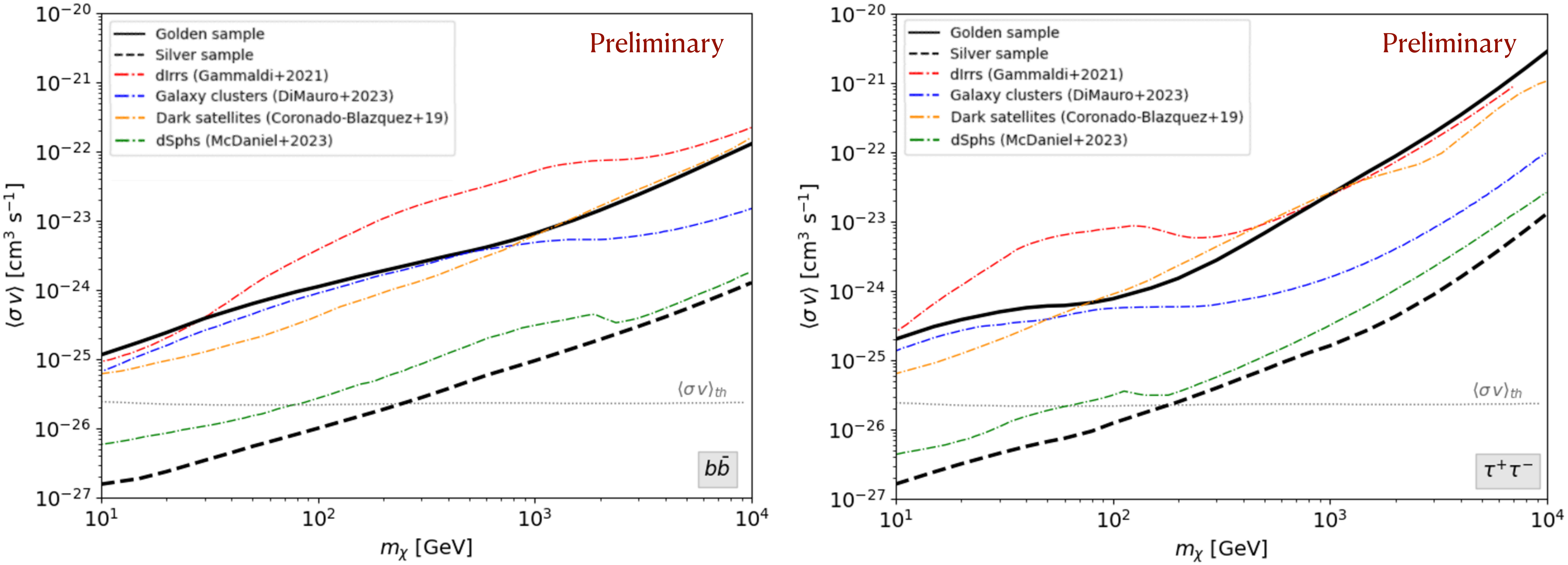


DM constraints: Silver Sample, Benchmark case





DM constraints: Comparison with other targets



- The results obtained for the golden sample of streams improve the limits achieved with dIrr galaxies, while they are similar to those for galaxy clusters and dark satellites.
- At present, dSphs provide the most stringent constraints. However, when considering the silver sample of streams, the DM limits would be potentially comparable with them.

General Remarks

* This work aims to provide a complementary target for indirect DM searches with gamma rays, potentially being as competitive as dSphs.

* No detection after looking at 11 stellar streams.

* The most reliable DM limits obtained (golden sample, benchmark scenario) are $\mathcal{O}(10)$ above the thermal relic cross-section for low WIMP masses for the $b\bar{b}$ and $\tau\bar{\tau}$ annihilation channels.

Caveats:

- The mass of the streams' core is currently uncertain. This could lead to overestimating or underestimating the J-factor, which would result into greater uncertainties of the DM limits. However, these uncertainties are expected to be contained within our M/L uncertainty band.

- High-resolution hydrodynamic simulations are needed to know the dynamic state of the core of each stream, as well as to accurately model their density profile accounting for tidal disruption. Work is already ongoing in this direction.

* The work is about to be submitted to the journal.

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Thank you!

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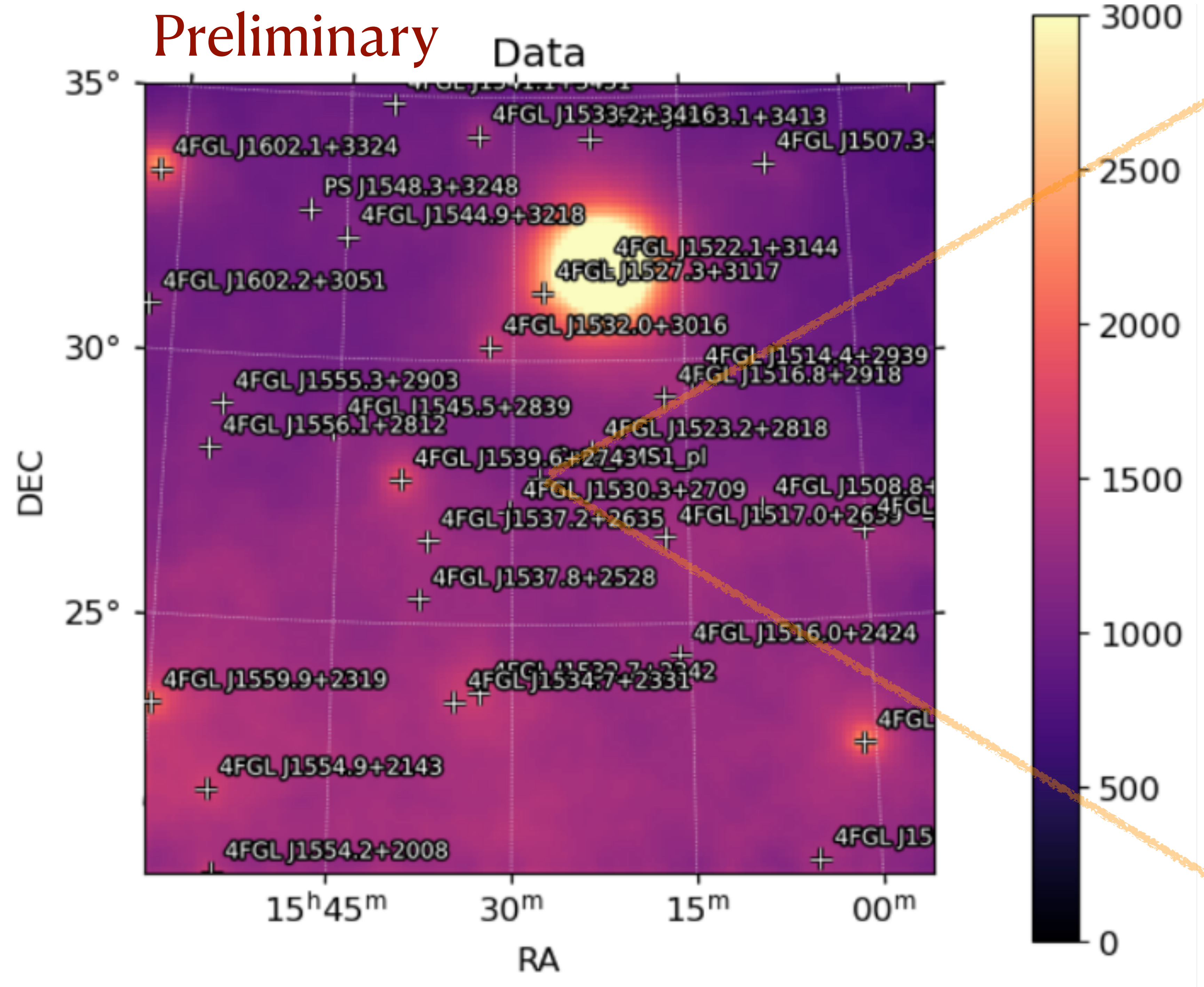
Backup Slides

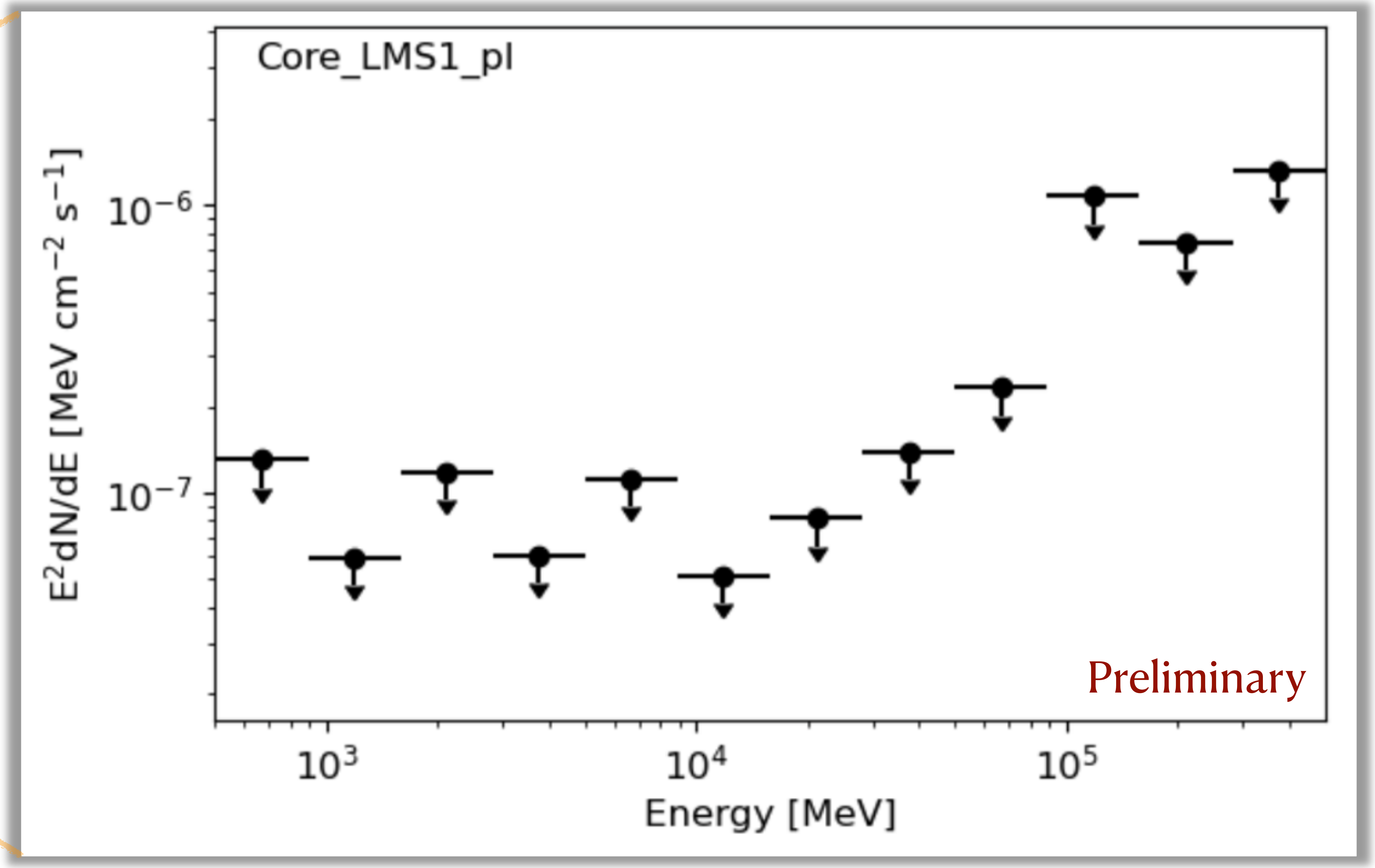
Analysis Results:
Flux upper limits with a *Power Law*

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

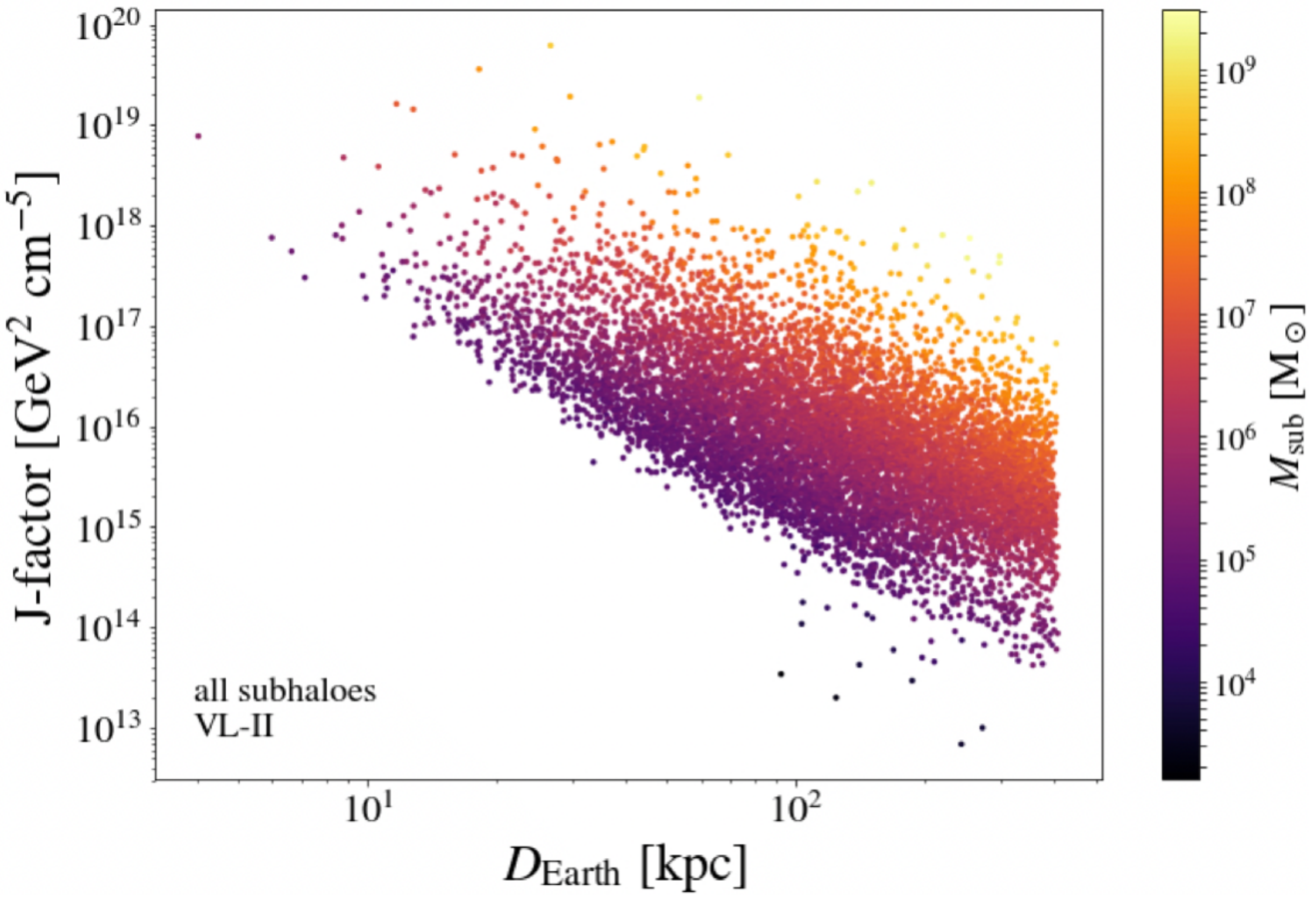


Example for LMS-1 stream

Flux upper limits 95 % confidence level (C.L.)

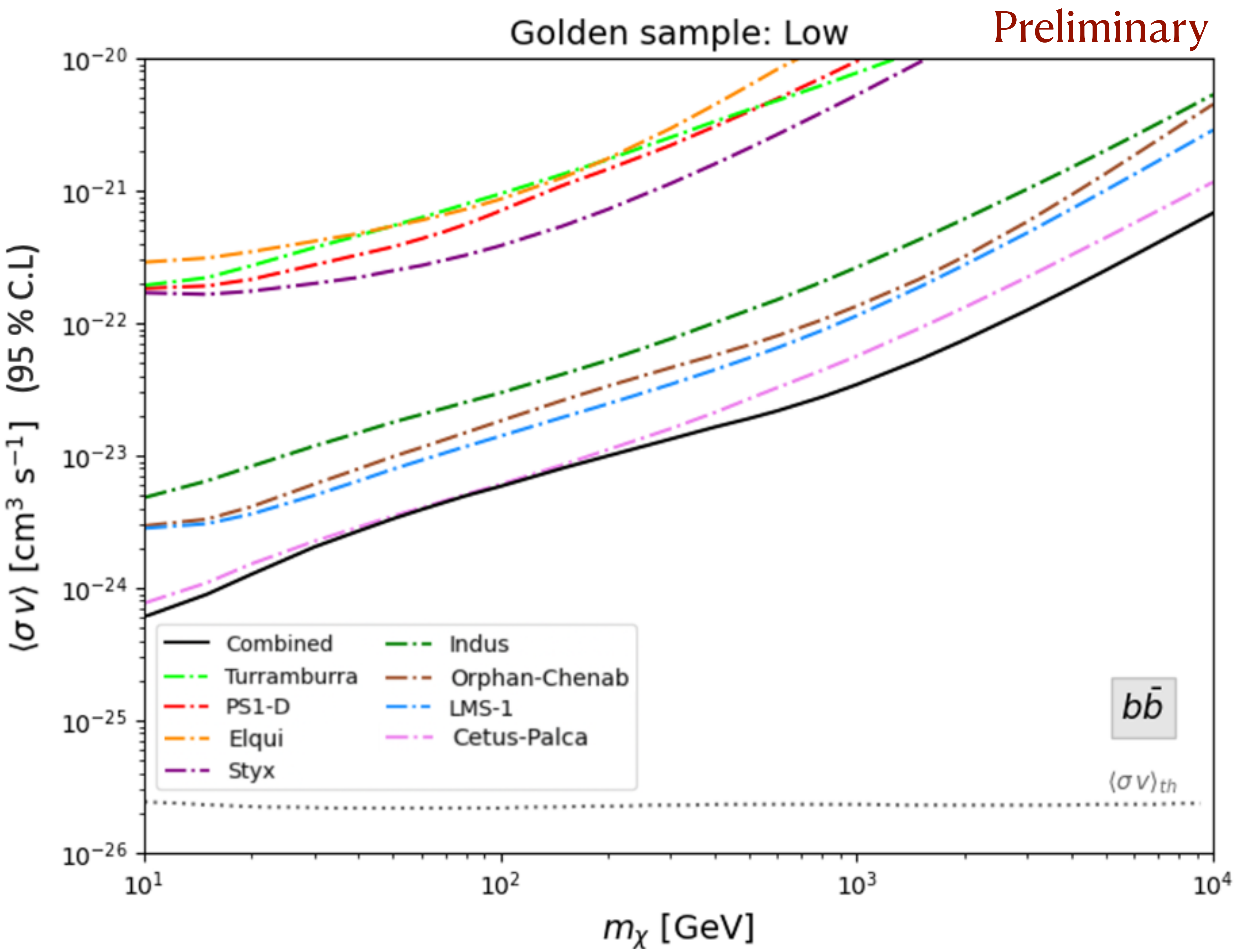


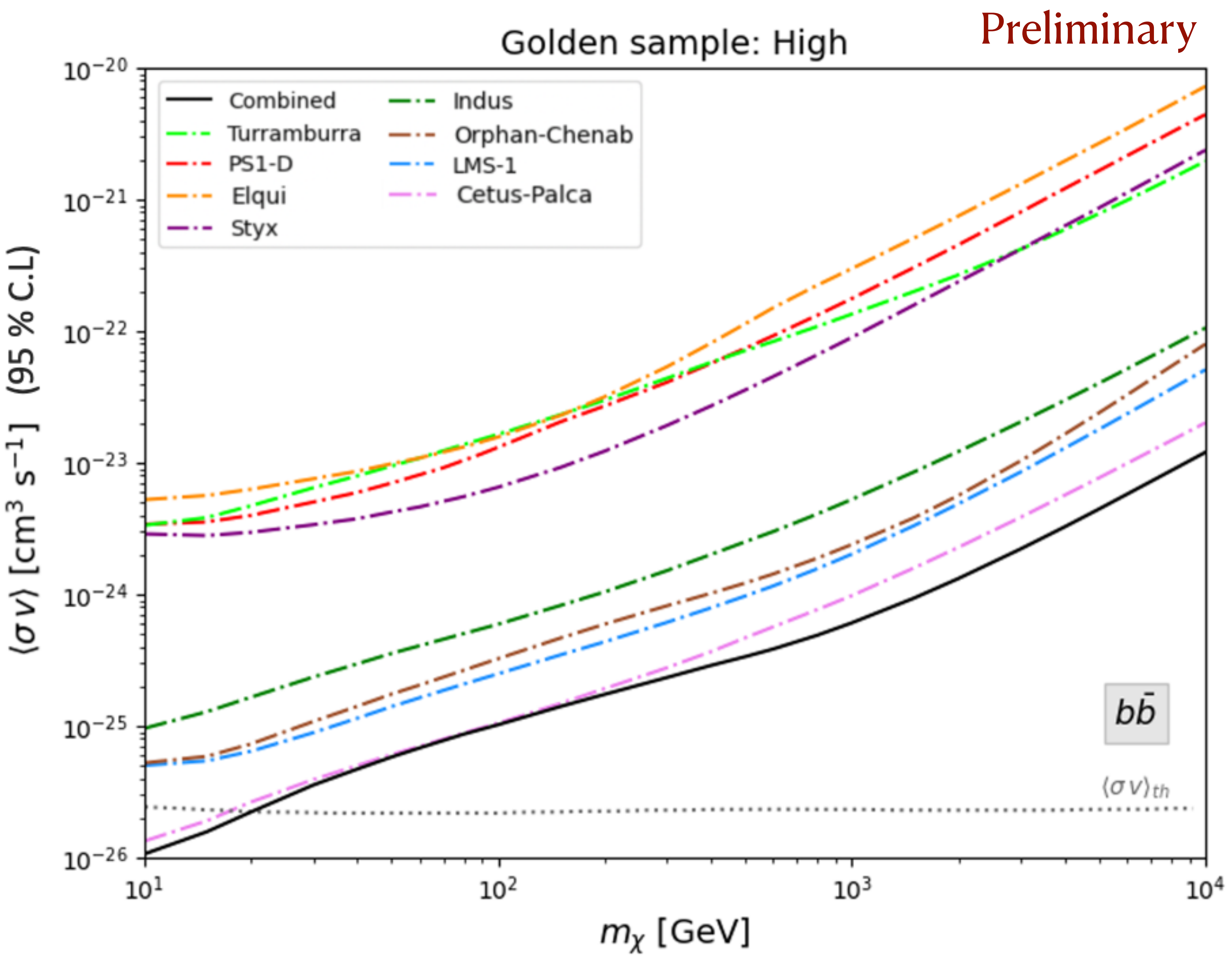
Sample Selection: Distance



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

DM constraints: Golden Sample, Low and High cases





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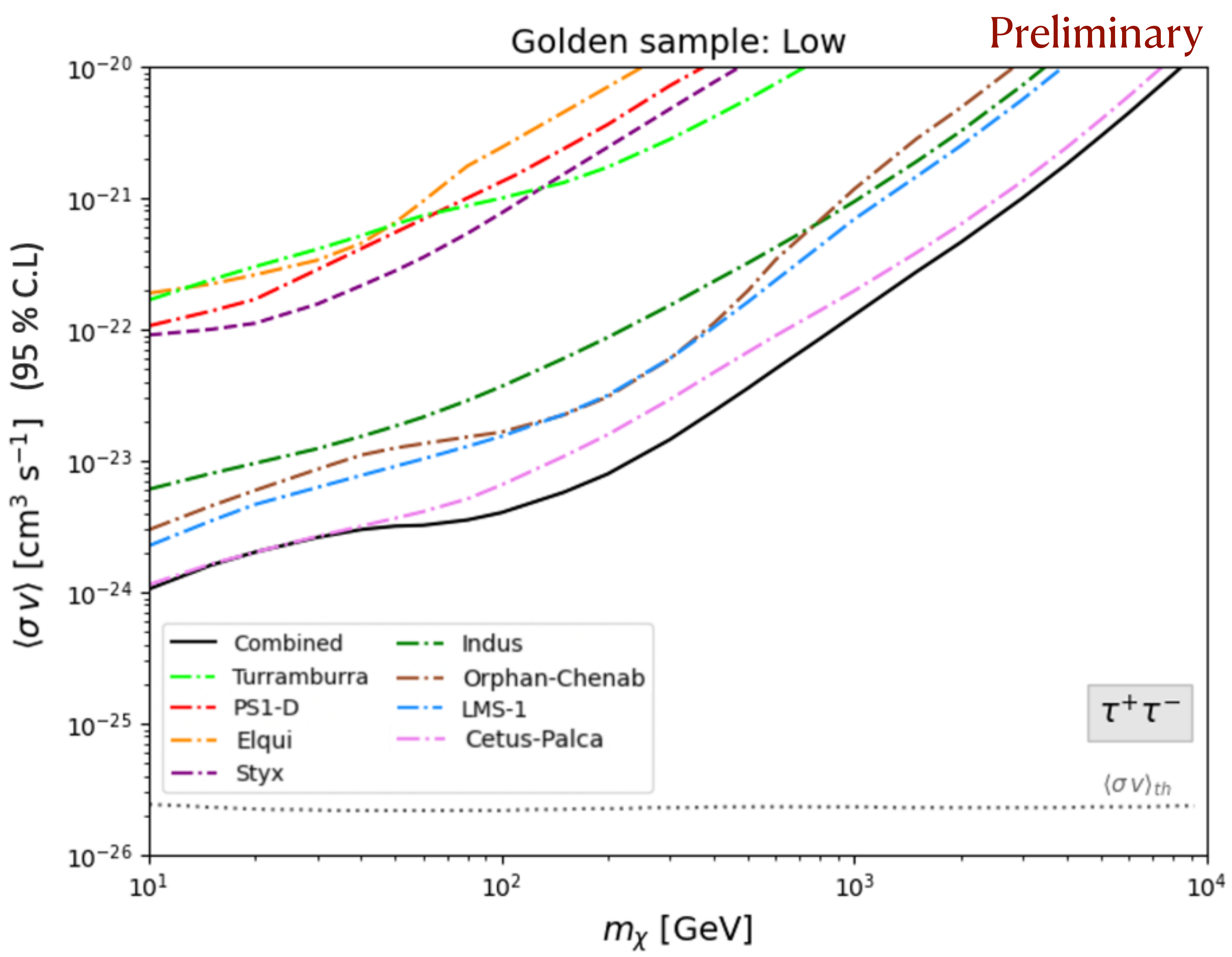

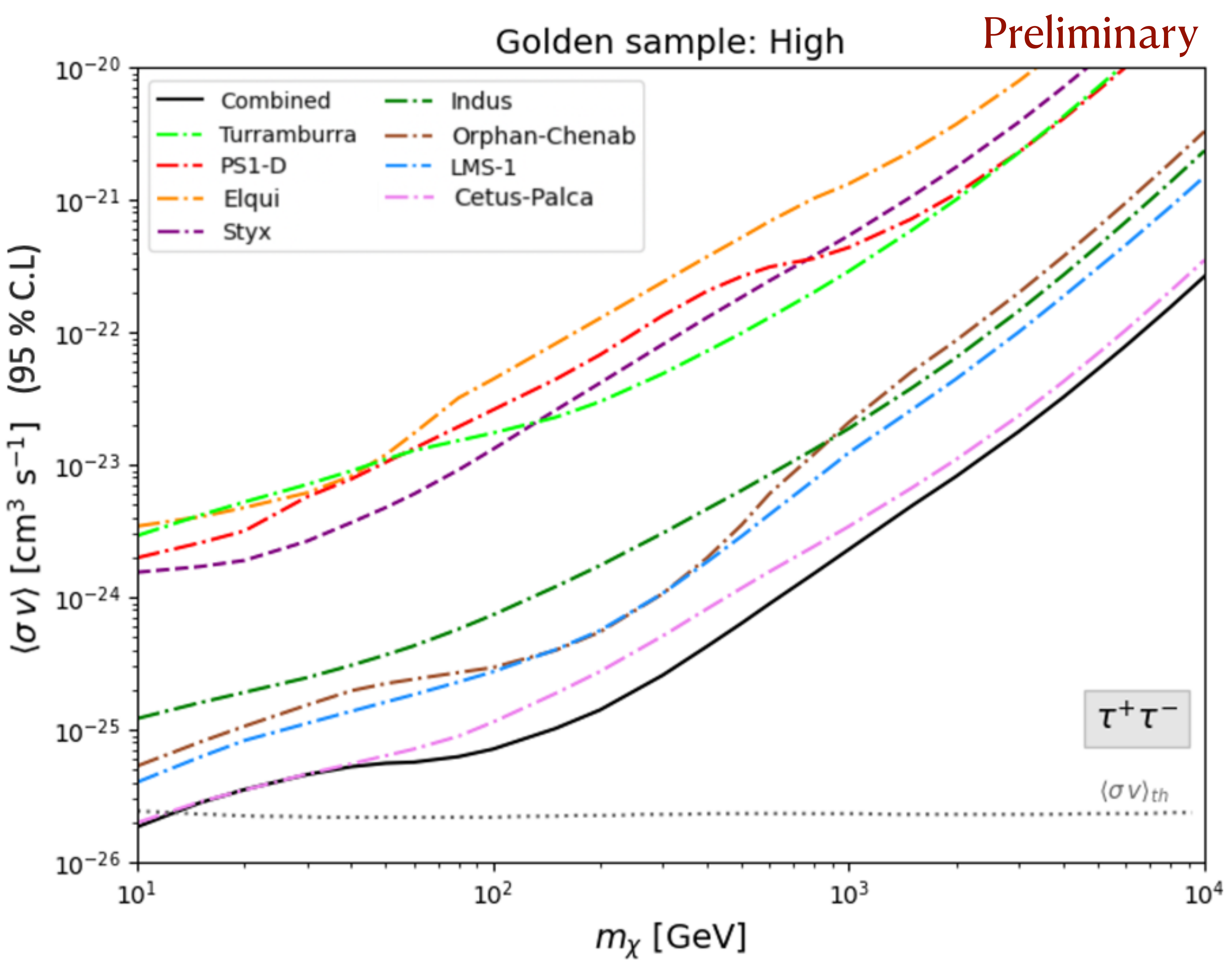

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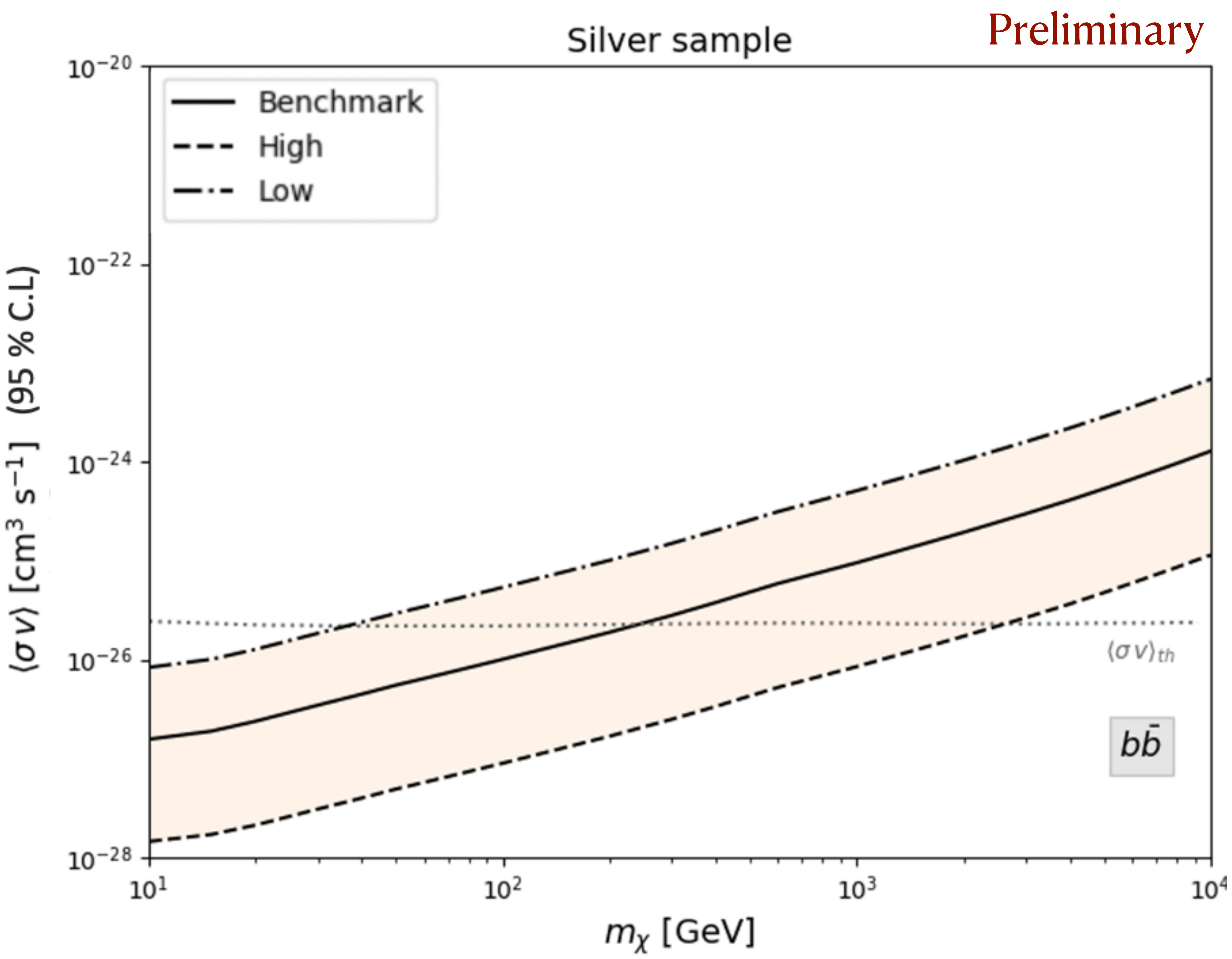

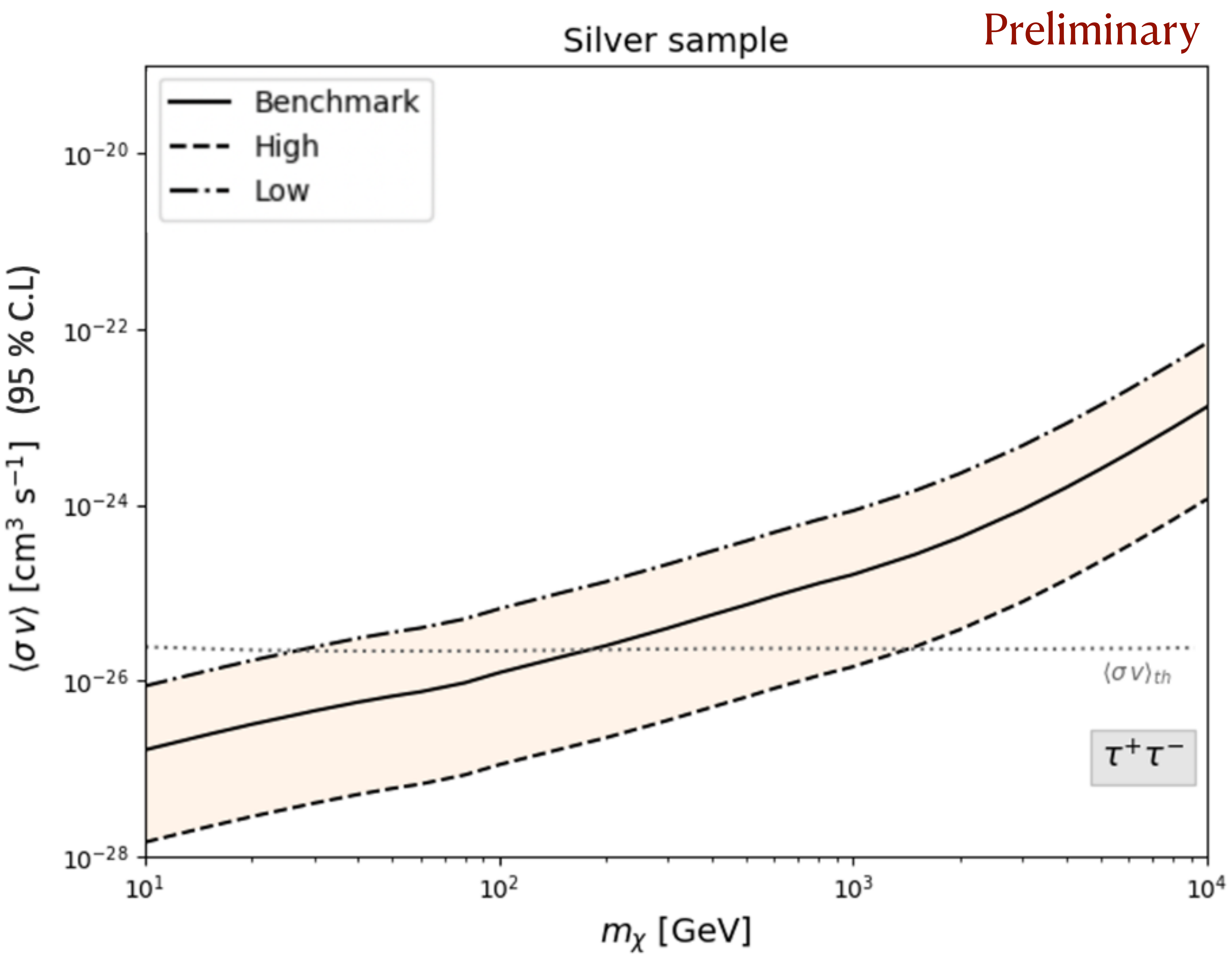

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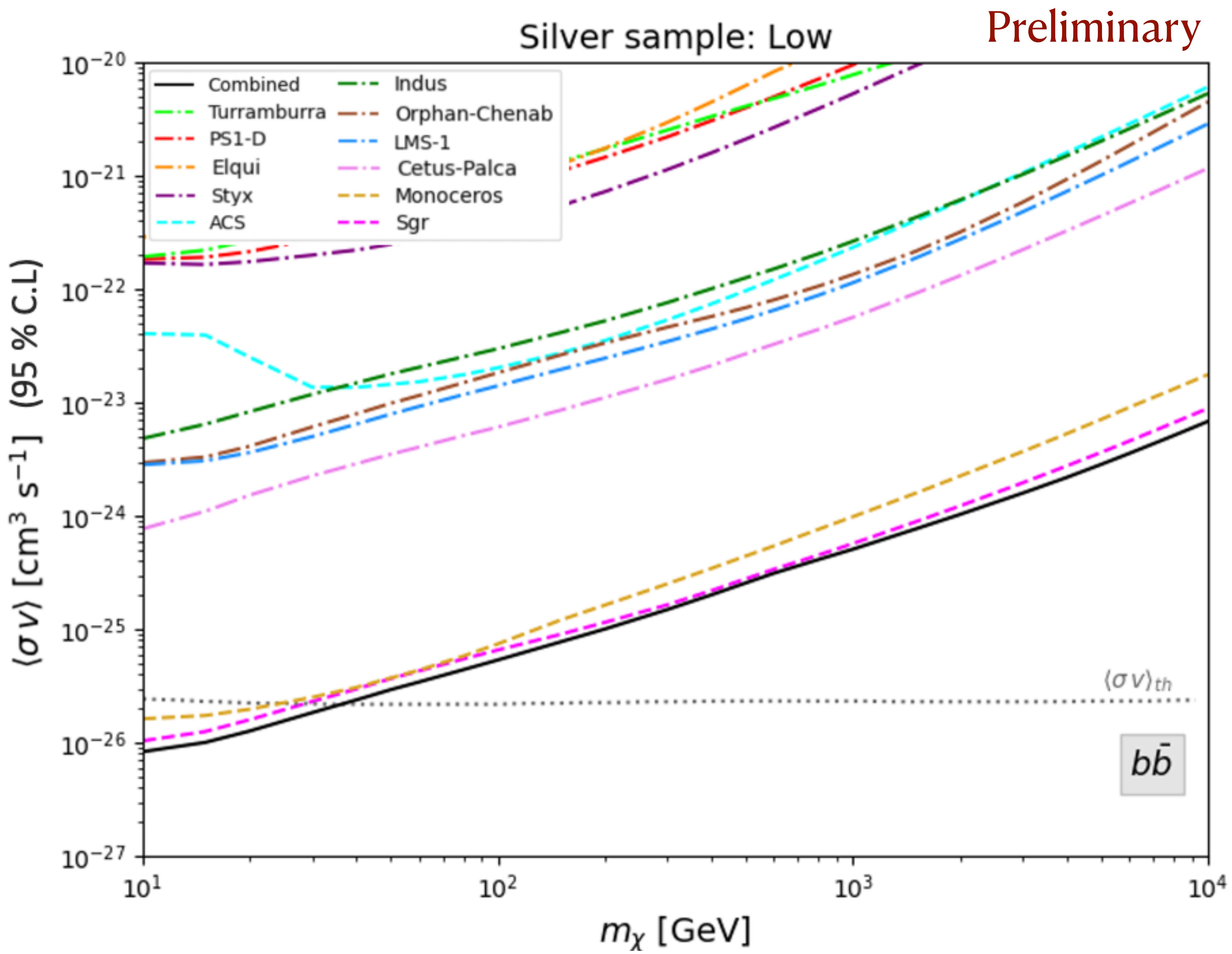

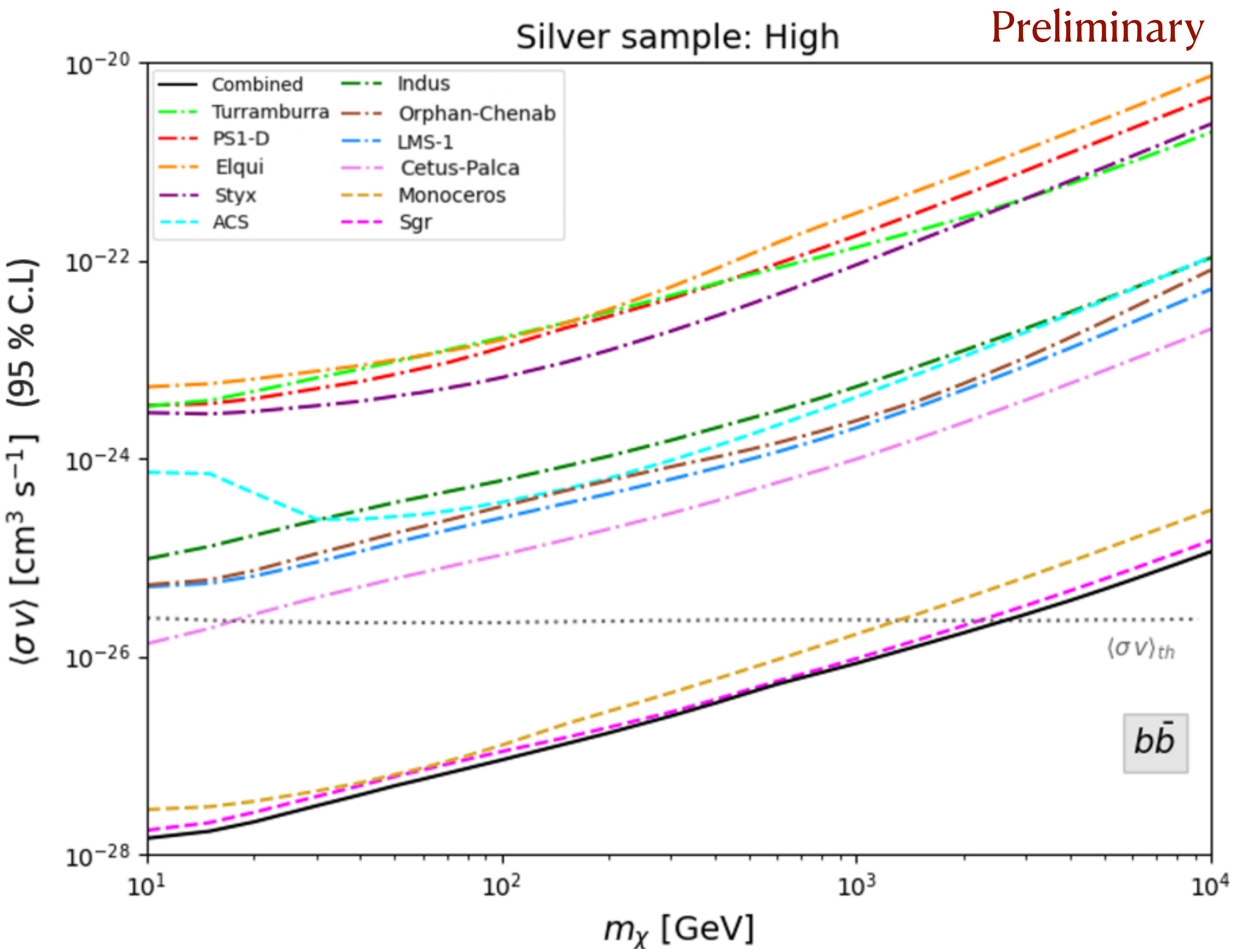

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