Universidad Autónoma de Madrid

Stellar streams as targets for indirect dark matter searches

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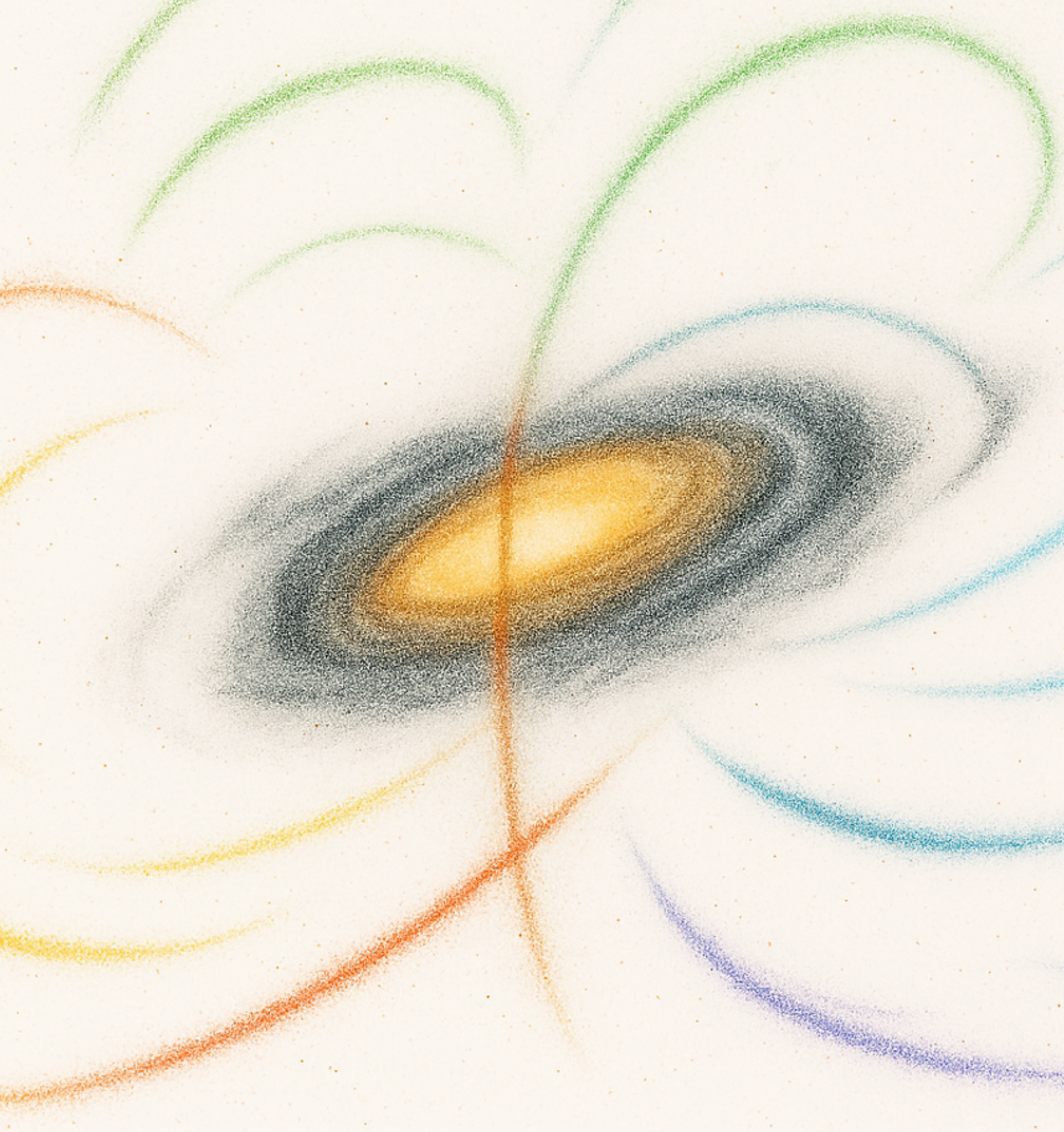
TeV Particle Astrophysics (TeVPA)
Valencia 2025



A New Target for indirect dark matter (DM) searches

arXiv: 2502.15656
JCAP 09 (2025) 003

A Search for Dark Matter Annihilation in Stellar Streams with the Fermi-LAT

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Goals: 1) To search for WIMP-induced gamma-ray signals from the direction of the core of a sample of 11 stellar streams whose progenitor is a dwarf galaxy (dG).
2) To demonstrate the potential of streams for indirect DM searches.

Sample Selection for DM searches

We build a sample of 11 streams most optimal for gamma-ray DM searches according to our criteria:

✱ **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 (°)	$\frac{M_*}{10^4}$ ($M_\odot$)
Golden sample				
Indus	(332.26, -49.19)	16.6	18.2	3.40
LMS-1	(43.27, 55.46)	18.1	179.2	10.00
Orphan-Chenab	(264.90, 43.60)	20.0	230.6	16.00
PS1-D	(230.95, 32.67)	22.9	44.9	0.75
Turranburra	(219.72, -40.79)	27.5	13.7	0.76
Cetus-Palca	(147.90, -67.80)	33.4	100.9	150.00
Styx	(35.40, 75.40)	46.5	60.4	1.80
Elqui	(293.88, -77.20)	50.1	10.9	1.04
Silver sample				
Monoceros	(180.0, 25.0)	10.6	46.9	600.00
AntiCenter	(140.0, 35.0)	11.7	57.7	0.93
Sagittarius	(6.01, -14.89)	25.0	280.0	13000.00

and separated in a *golden* and a *silver* samples, according to our level of confidence in them.

CFS & Sánchez-Conde
arXiv: 2502.15656

DM annihilation flux from stellar streams

- We assume that all the DM is in the form of WIMPs.
- WIMPs may be detectable in gamma rays since self-annihilation of WIMPs produce Standard Model particles, which can eventually yield photons, among other possible by-products.
- Expected flux due to WIMPs annihilation (Bergström+1998) is:

$$\mathcal{F}(E, \Delta\Omega, l.o.s) = f_{pp}(E) \times J(\Delta\Omega, l.o.s)$$

Astrophysical J-factor

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

DM density profile

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

DM annihilation flux from stellar streams

$$\mathcal{F}(E, \Delta\Omega, l.o.s) = f_{pp}(E) \times J(\Delta\Omega, l.o.s)$$

Astrophysical J-factor

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

DM density profile

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

- ★ We assume that the streams maintain the same density distribution as their progenitors within the core ($r \leq r_s$).
- ★ Rest of the DM outside r_s gets lost due to tidal stripping (e.g., Aguirre-Santaella+2023).

DM annihilation flux from stellar streams

Astrophysical J-factor

$$\mathcal{F}(E, \Delta\Omega, l.o.s) = f_{pp}(E) \times J(\Delta\Omega, l.o.s)$$

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

DM density profile

✱ We consider 3 different scenarios based on different mass-to-light (M/L) ratios to estimate the DM mass at accretion time:

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

Benchmark: $M/L = 5$

High: $M/L = 50$

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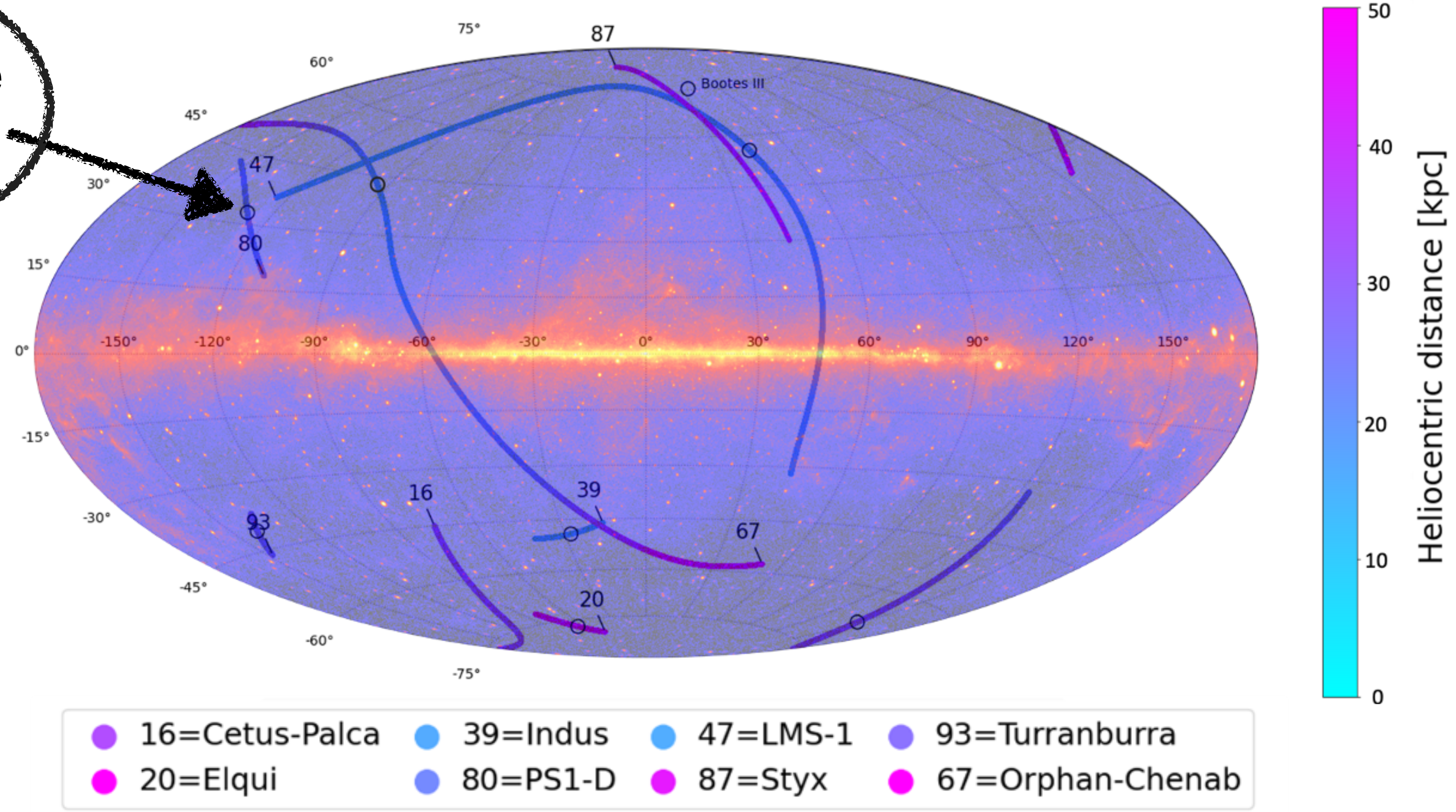
DM search in streams with the Fermi-LAT

✱ We search for any gamma-ray signal in 15 years of Fermi-LAT data from the direction of the assumed streams' cores.

We focus on the streams' core

'Golden' Sample



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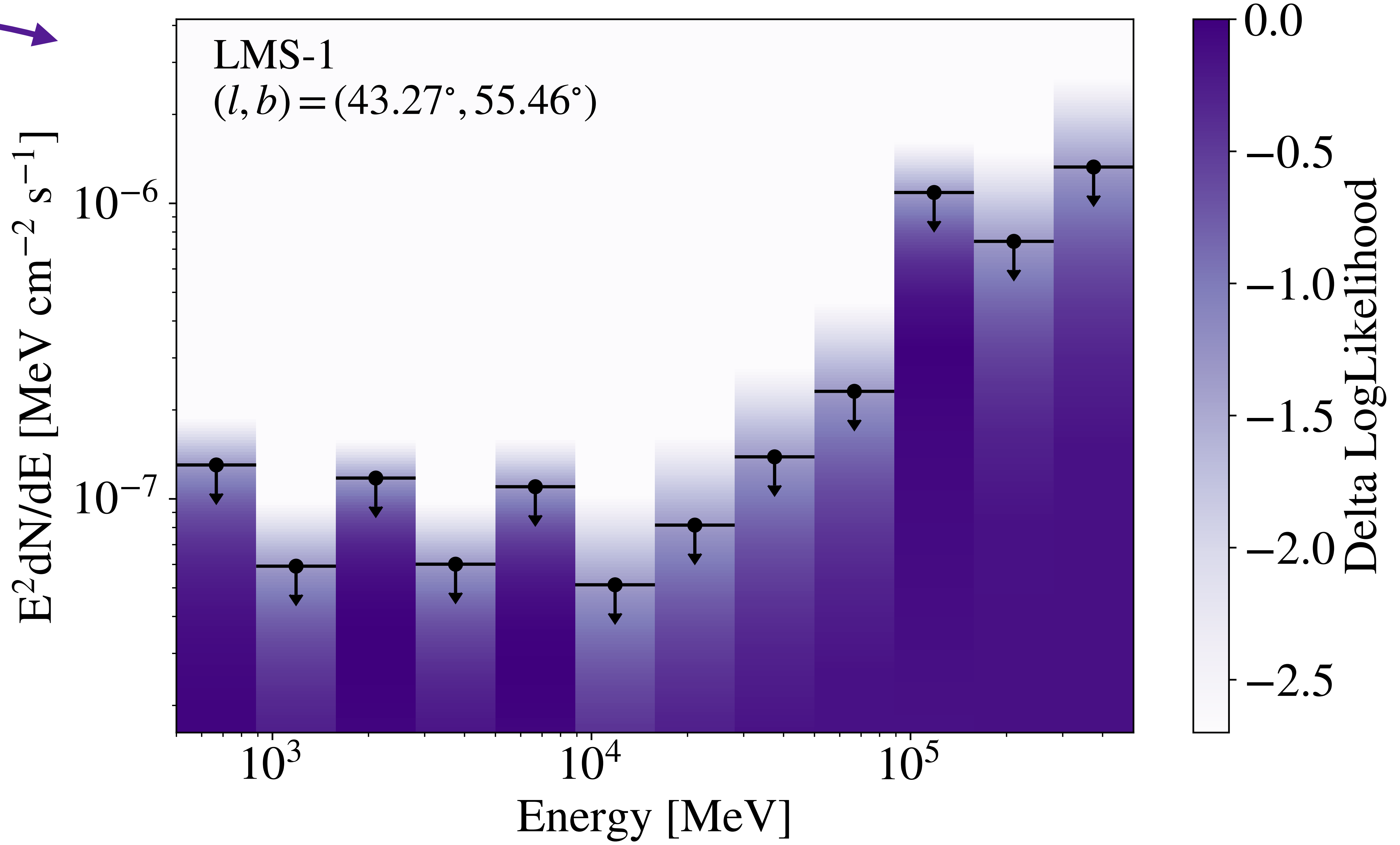
DM search in streams with the Fermi-LAT

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

We compute flux upper limits at 95% confidence level (C.L.) and place constraints on the DM particle properties.

Example for LMS-1 stream



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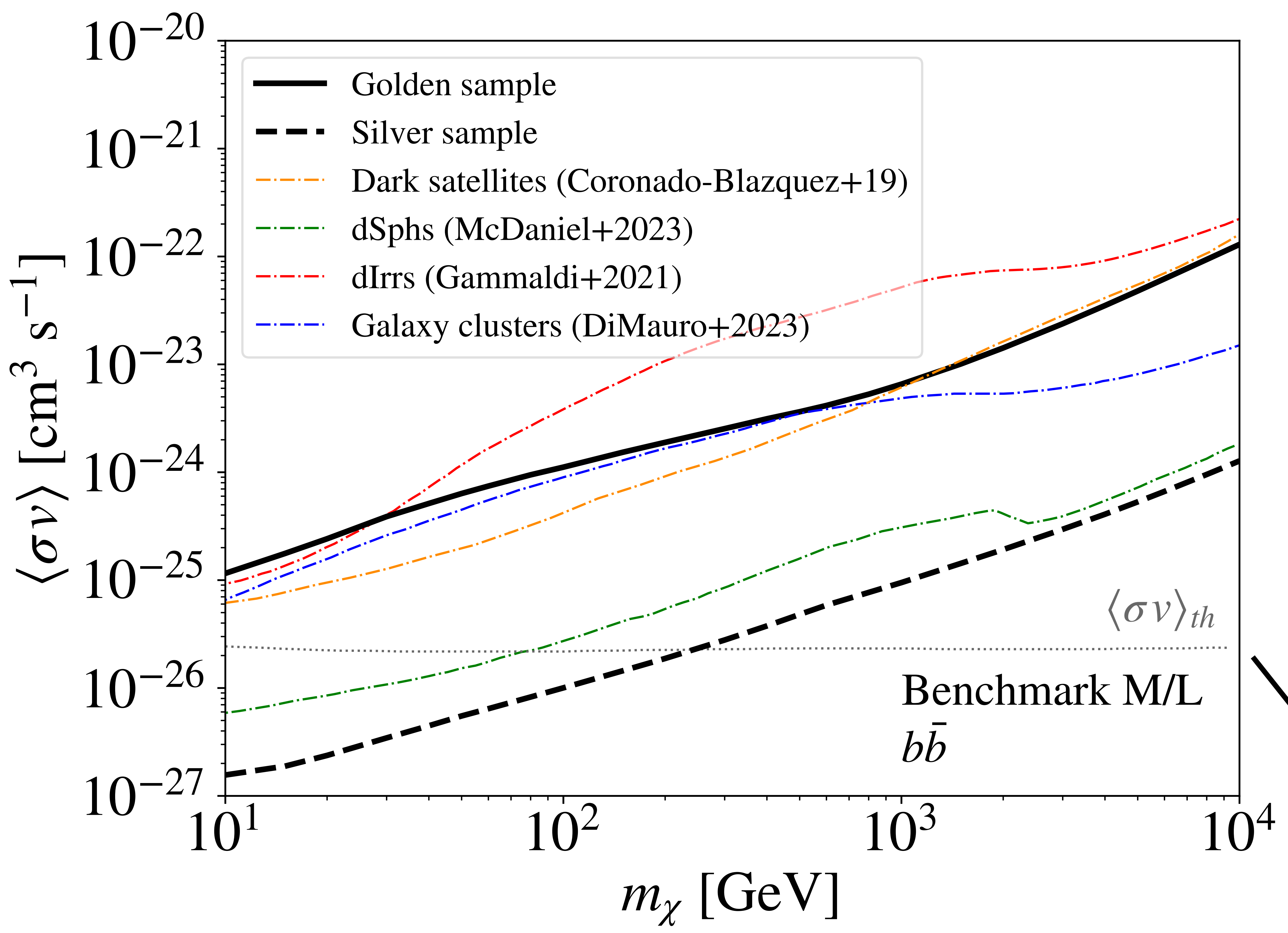
DM constraints: Comparison with other targets

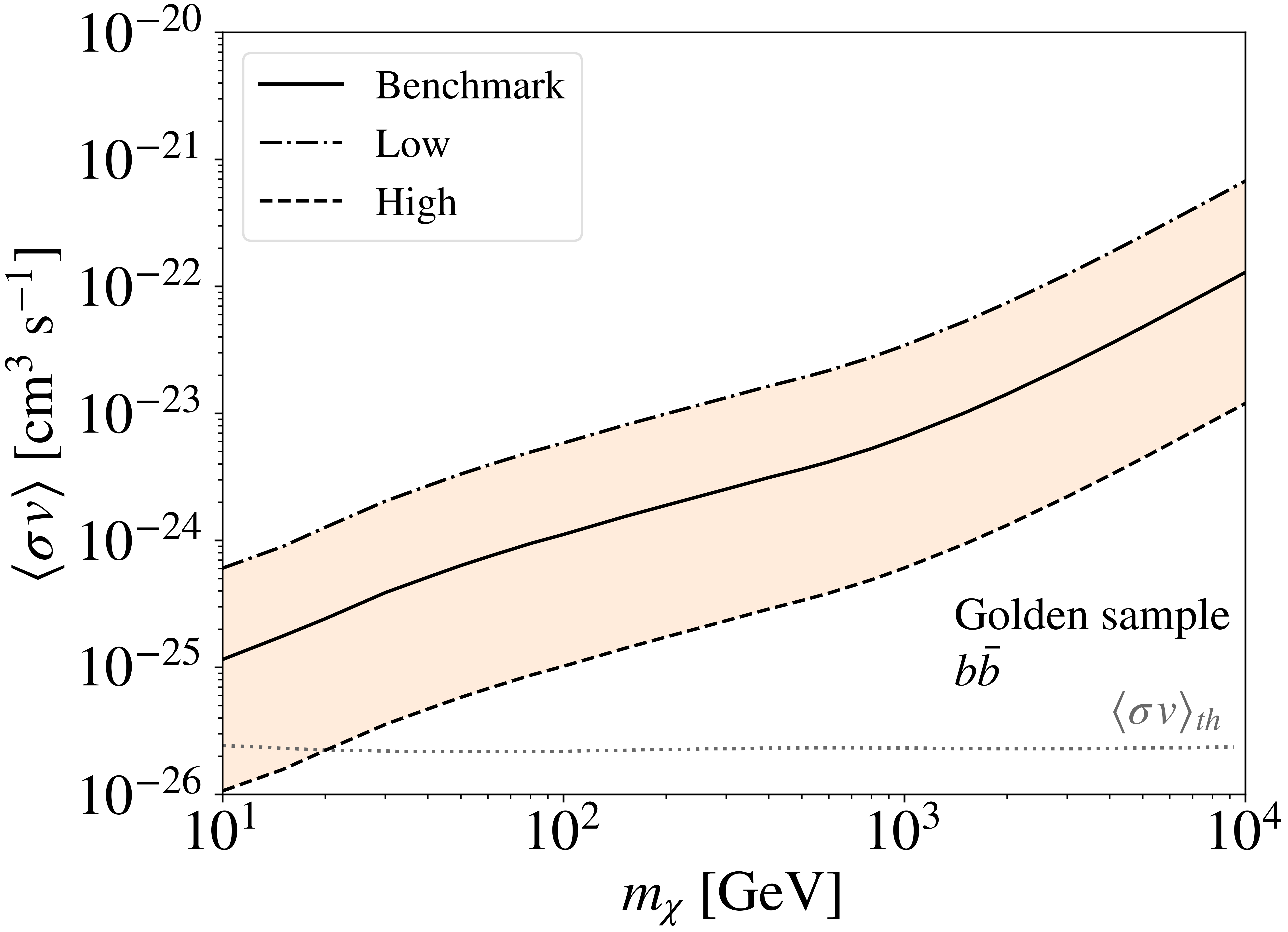


- Stellar streams can potentially provide very competitive limits.
- The ***golden*** sample of streams improve the limits achieved with dIrr galaxies, while they are similar to those for galaxy clusters and dark satellites.
- Results for the ***silver*** sample would be potentially comparable with those for dSphs.

Thermal relic cross-section: cross-section required to account for the amount of DM we observe today.

CFS & Sánchez-Conde, arXiv: 2502.15656

DM constraints: Golden Sample, M/L scenarios



- Overall uncertainty of $\mathcal{O}(100)$ in the DM limits.
- The combined constraints for the Benchmark scenario are $\mathcal{O}(10)$ above the thermal relic cross-section for the lowest considered WIMP masses.
- DM limits reach the thermal relic cross-section at lower masses when considering the High scenario.

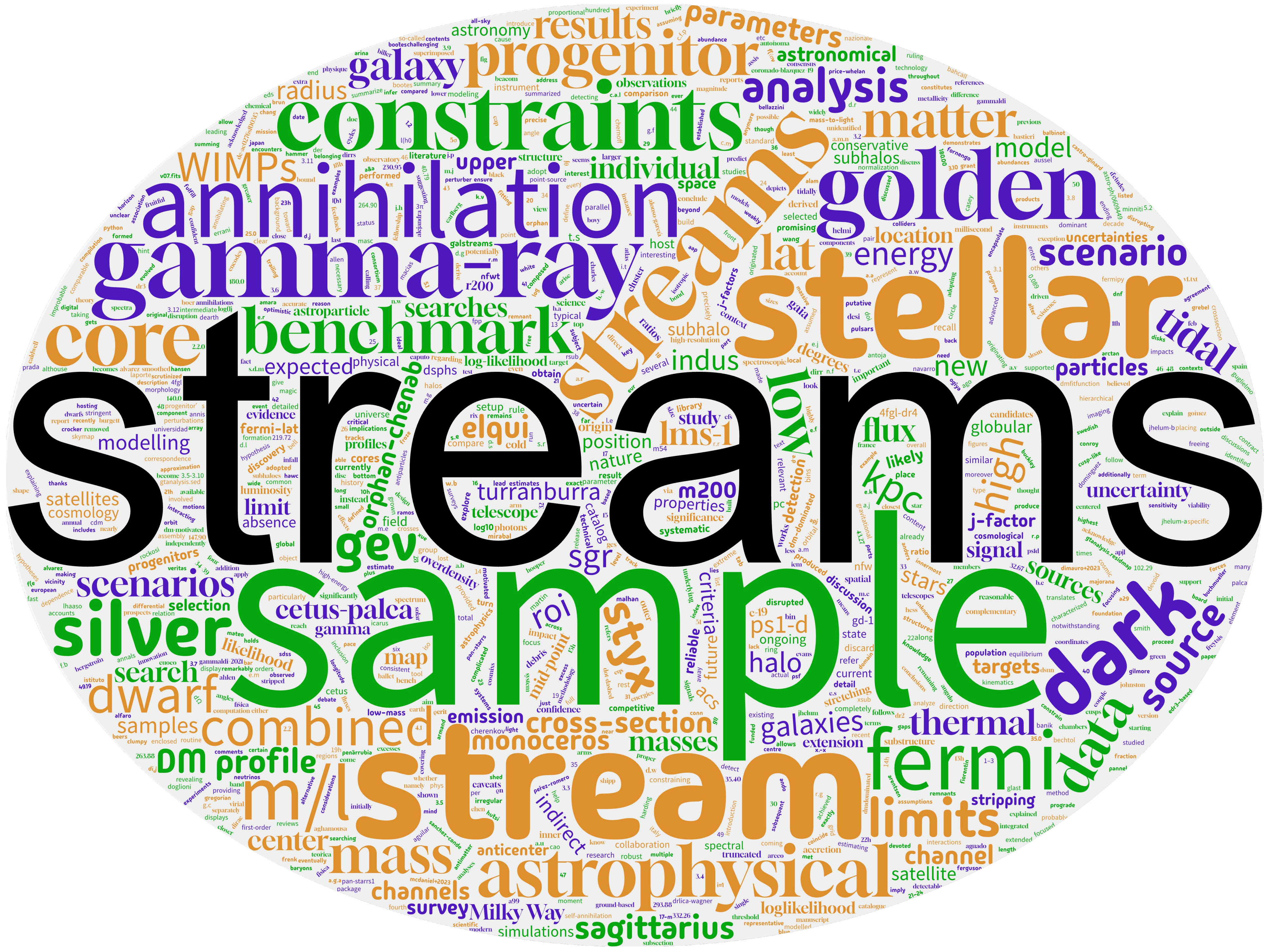
CFS & Sánchez-Conde, arXiv: 2502.15656

Main caveats

- *The mass of the streams is not well known*. Uncertainties are expected to be contained within our M/L uncertainty band.

- *The location of the streams' core is uncertain in most cases.* Already ongoing and future high-resolution spectroscopic observations (e.g. DESI) should help decreasing the uncertainty in the location of the cores of streams in our sample.

- *The underlying DM density profile of the streams is unclear.* Work is already ongoing in this direction, that uses the AURIGA hydrodynamical simulations.



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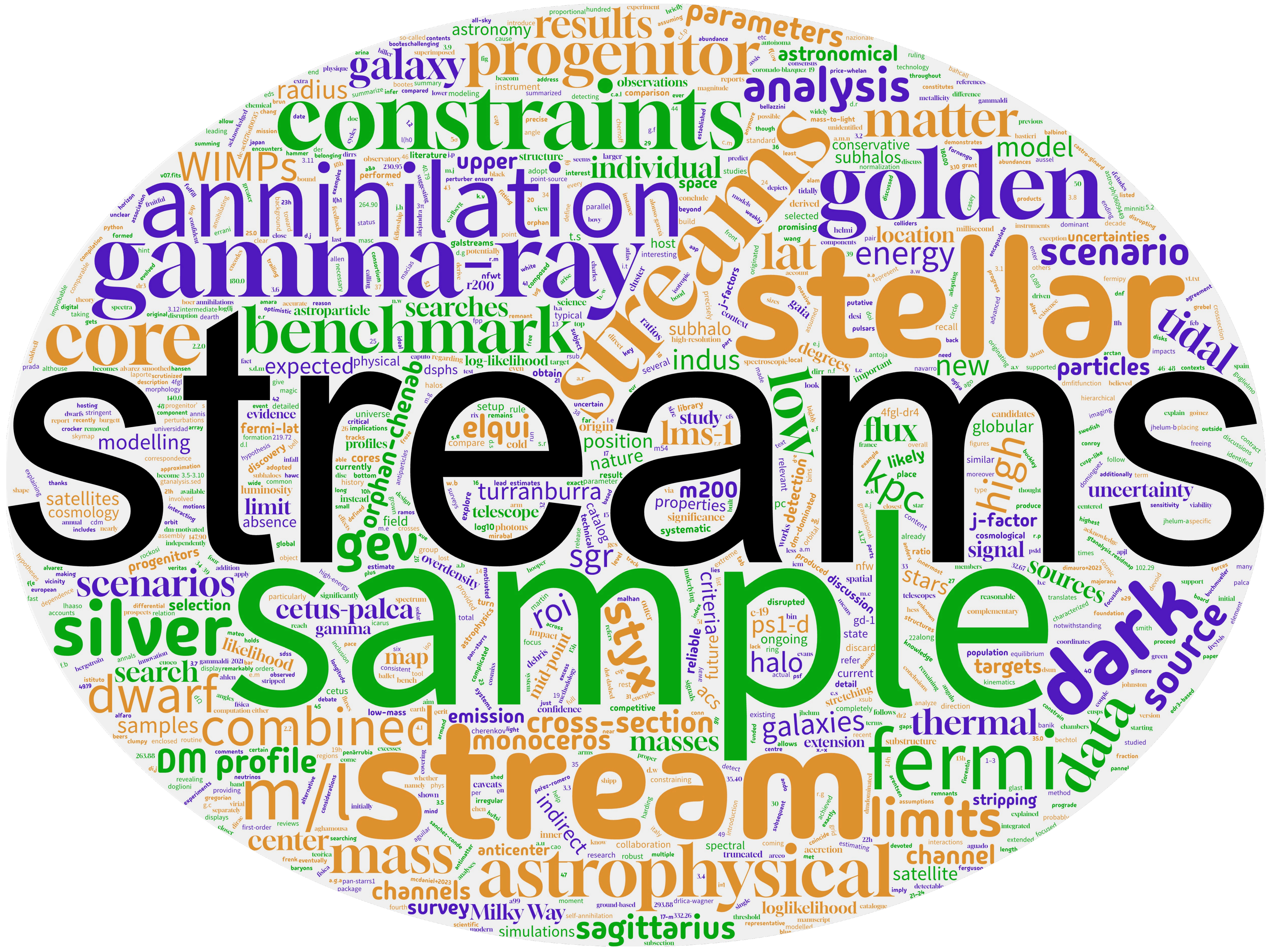
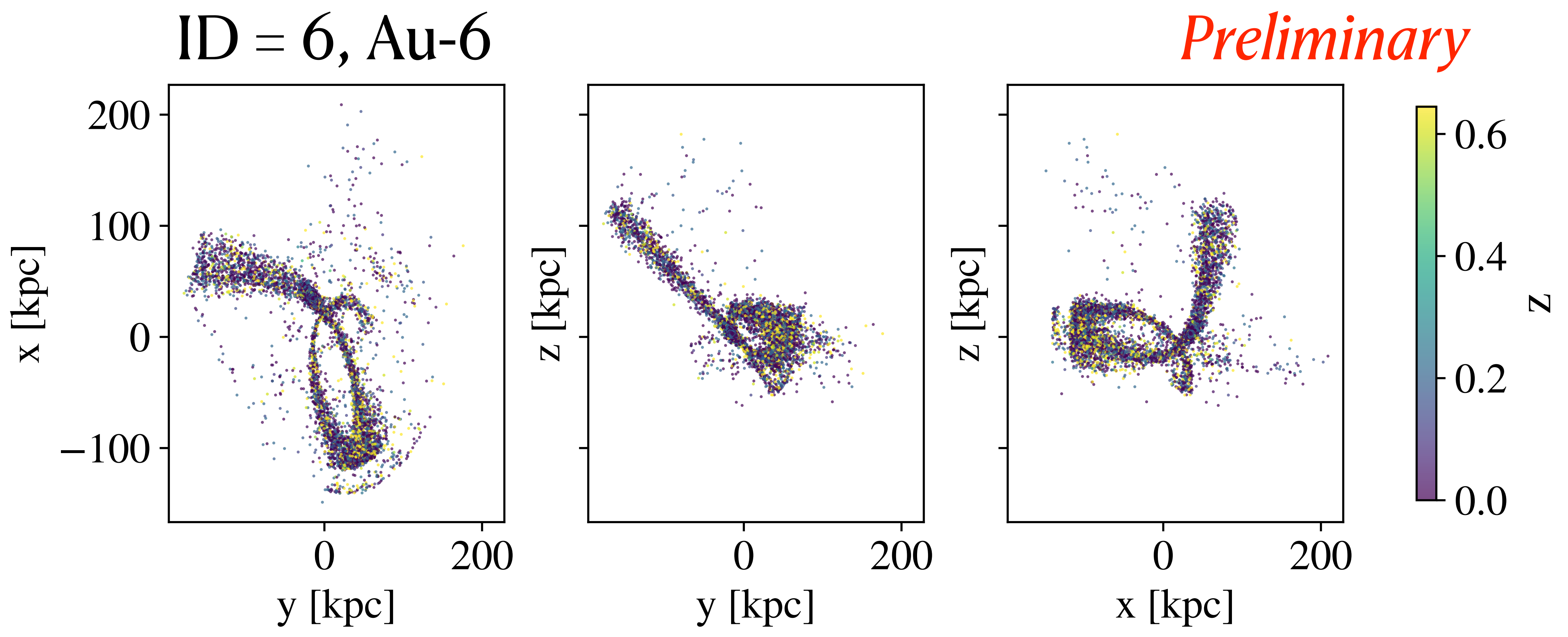


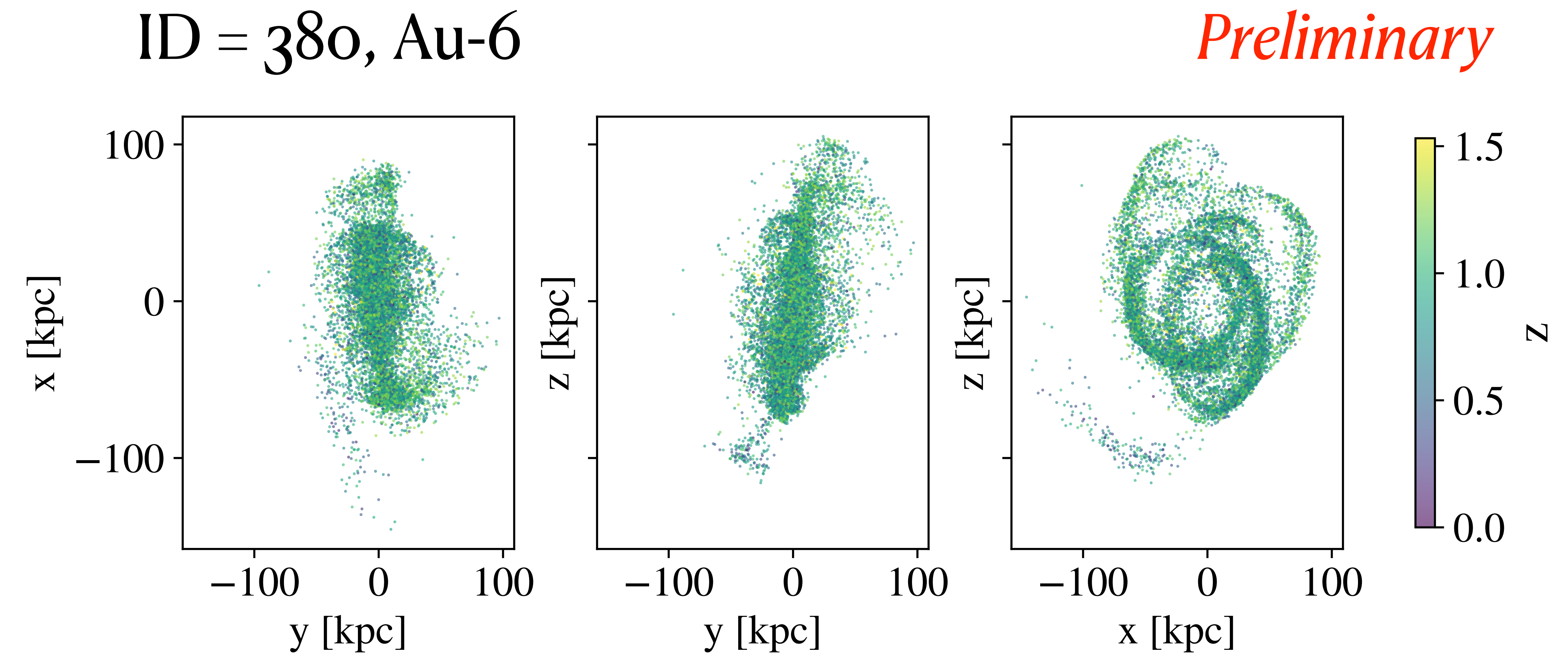
Auriga stellar streams

* We use the Auriga cosmological magneto-hydrodynamic simulations, with 6 Milky Way-mass halos at 'level 3' high resolution (Au-6, Au-16, Au-21, Au-23, Au-24, Au-27). (Grand+2017, Grand+2024)

Baryonic mass particle resolution: $\sim 6 \times 10^3 M_\odot$
DM particle mass resolution: $\sim 4 \times 10^4 M_\odot$
Softening length: 188 pc

* We adopt the catalogue presented in Riley+2024 to identify streams in Auriga. The final sample is composed by ~ 100 streams.





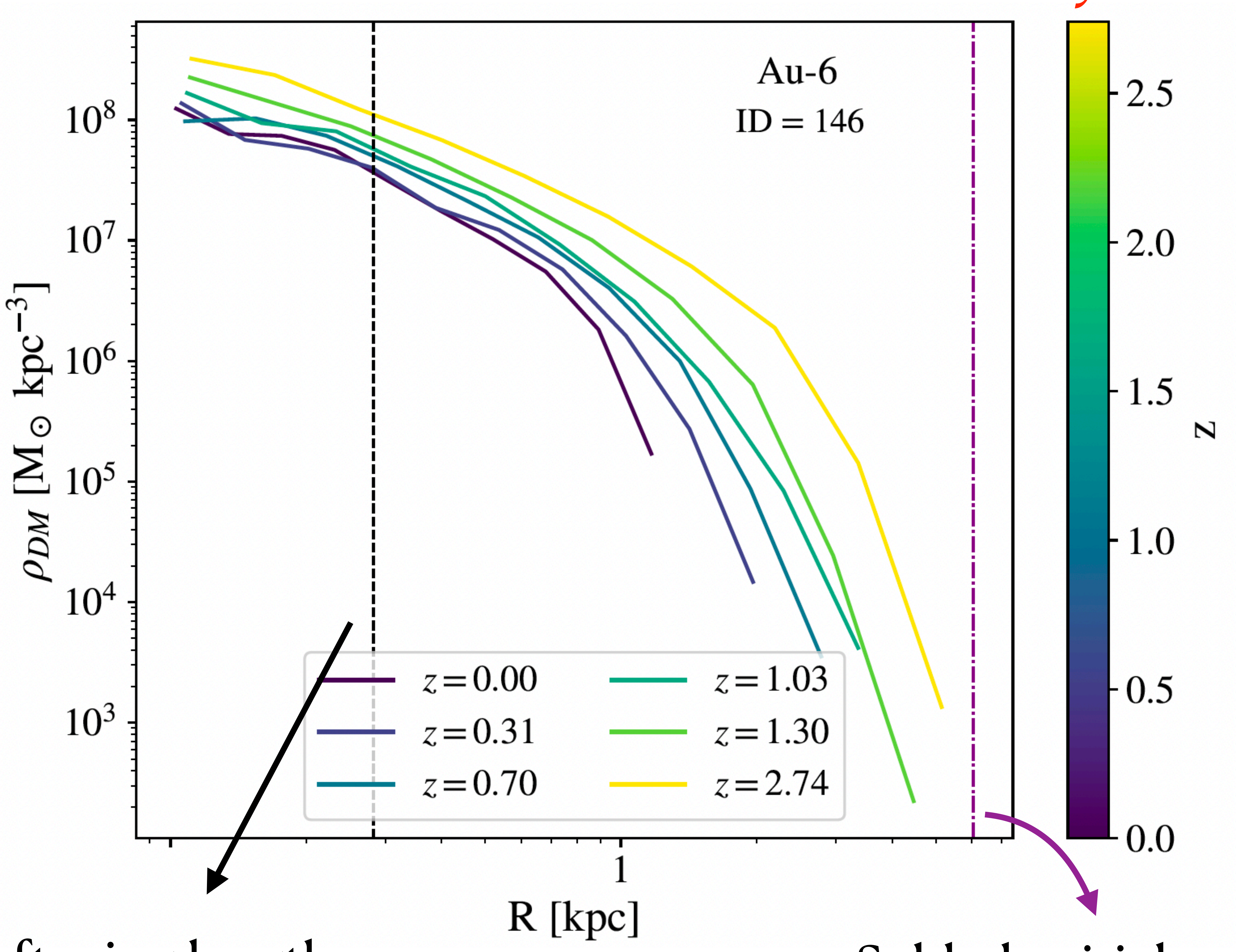
DM density profiles

- From raw particle data, we build the DM density profile of the Auriga streams and study their temporal evolution.

- We perform fits of each DM profile to different functional forms: NFW (Navarro+1996, Navarro+1997), gNFW (Hernquist+1990), NFW exp. cutoff, Einasto (Einasto 1965), Kazantzidis+2004, Errani & Navarro 2021.

- Best-fit provided by gNFW (according to the reduced χ^2 distributions).

Preliminary



1.5 × softening length, i.e. our resolution limit

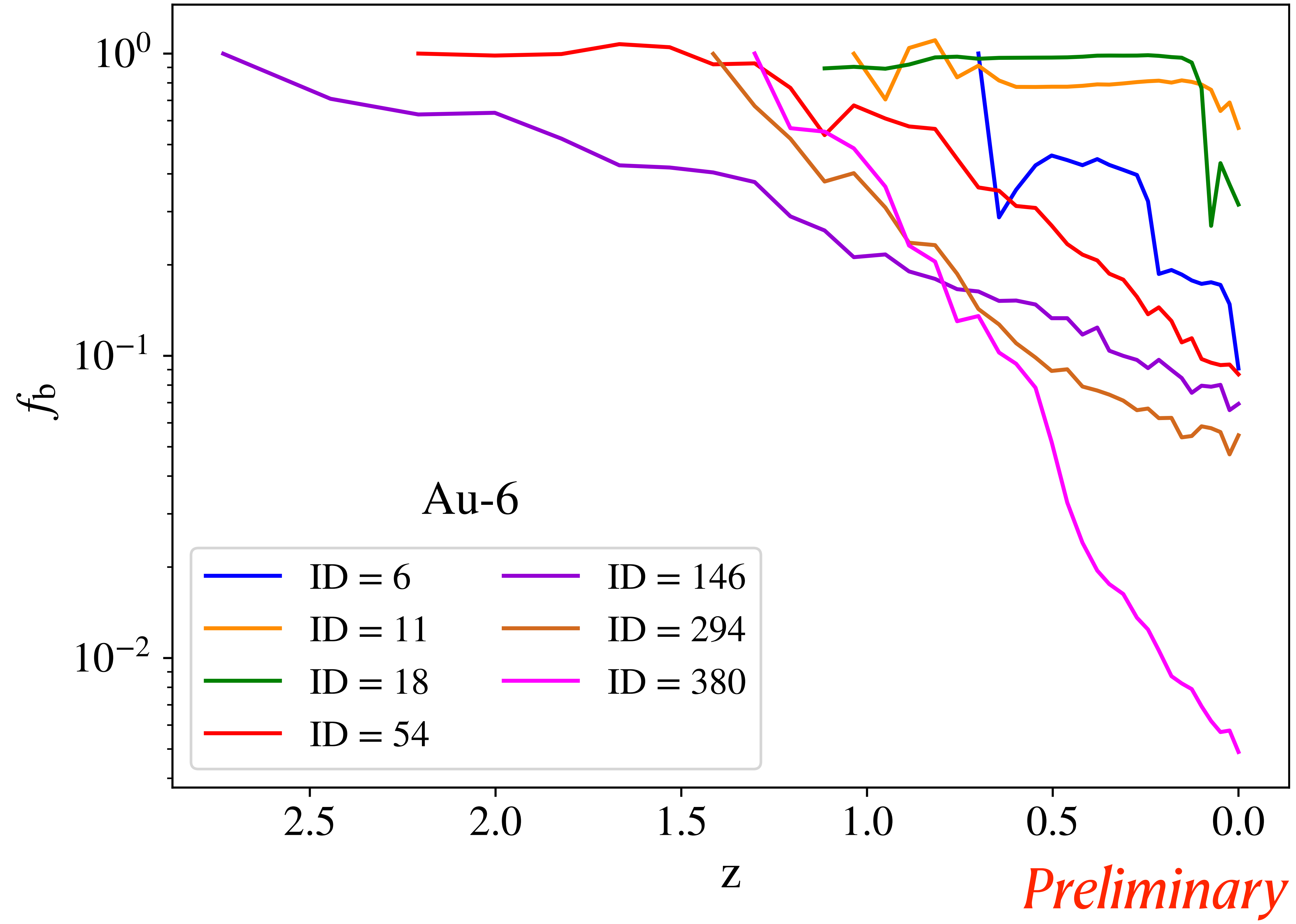
Subhalo virial radius at accretion time ($r_{200,sub}(z_{acc})$)

CFS, Sánchez-Conde & Aguirre-Santaella, *in prep.*

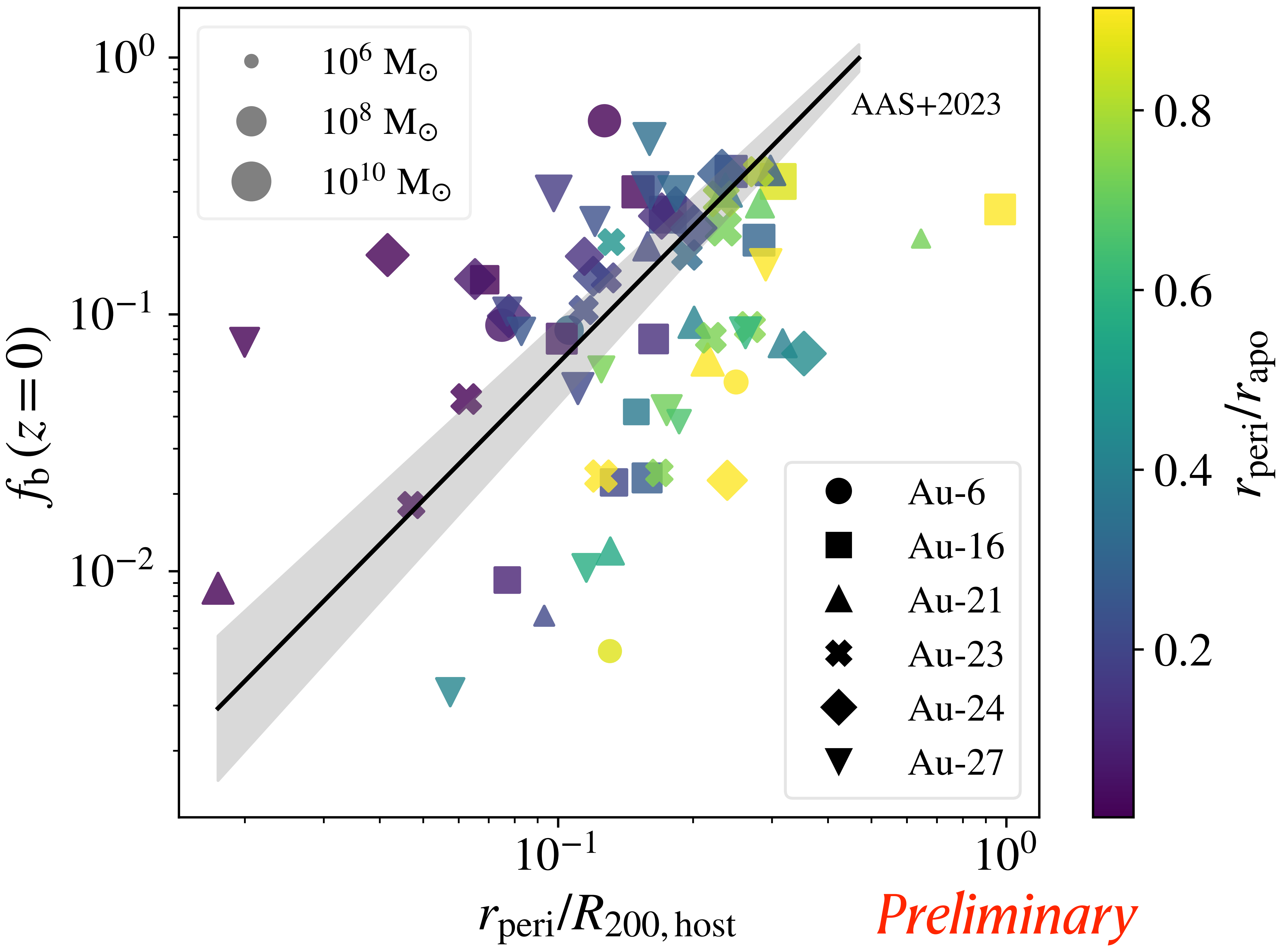
Bound mass fraction (f_b)

Fraction of mass that remains bound at a certain time t with respect to the initial subhalo mass (e.g., van den Bosch et al. 2018):

$$f_b = \frac{M(t)}{m_{200,sub}}$$



Sample of 76/104 streams after removing those not following ΛCDM expectations for their 'tidal tracks' (Aguirre-Santaella+2023, Stücker+2023)



✱ Lower f_b values for smaller pericenters.

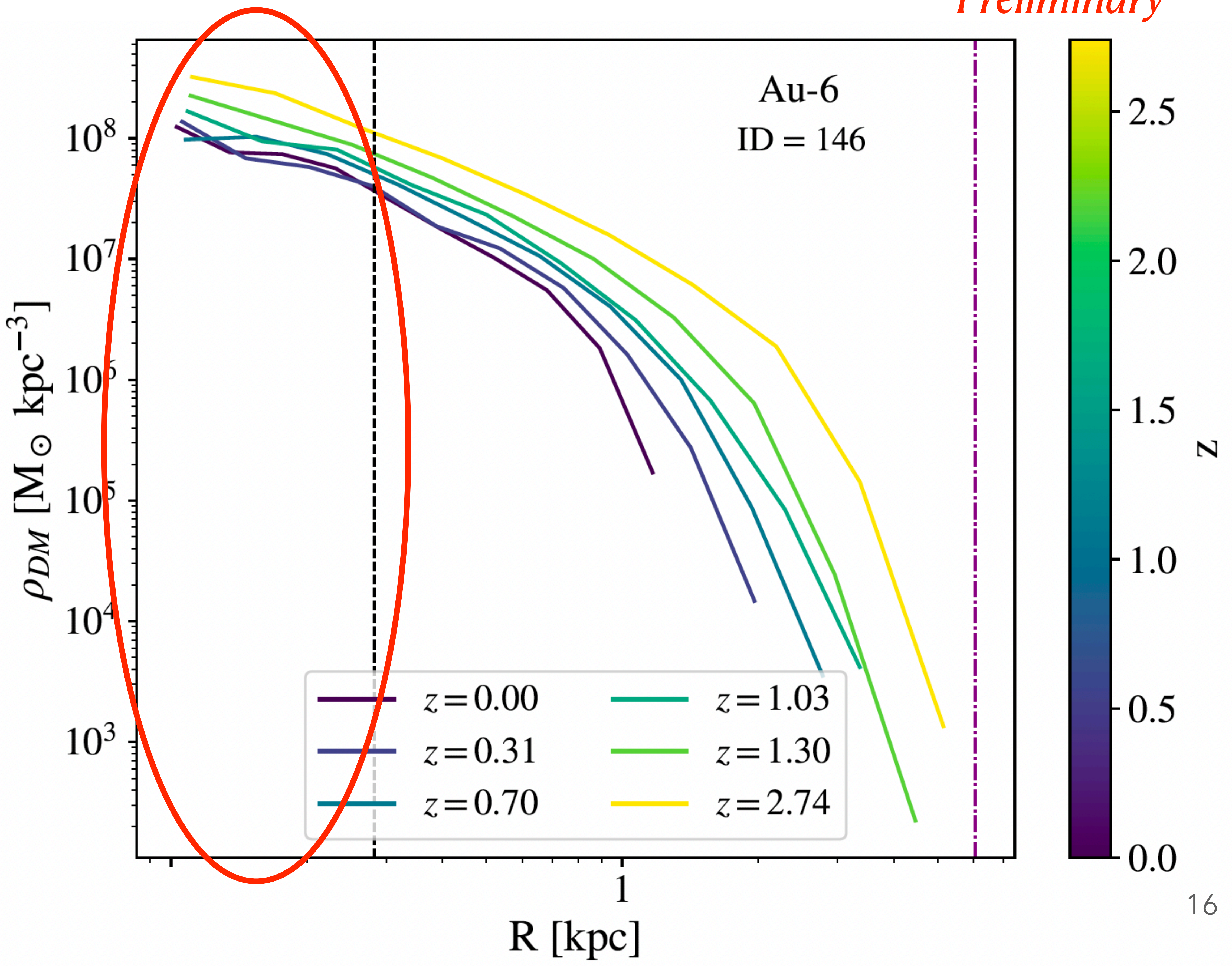
DM annihilation luminosity

- We aim to study the potential of the Auriga streams as targets for gamma-ray DM searches by computing the DM annihilation luminosity:

$$L_{ann} = \int_V \rho^2_{DM}(r)\, dV$$

- L_{ann} is very sensitive to the inner shape of the profile, where we face resolution issues.

Preliminary



CFS, Sánchez-Conde & Aguirre-Santaella, *in prep.*

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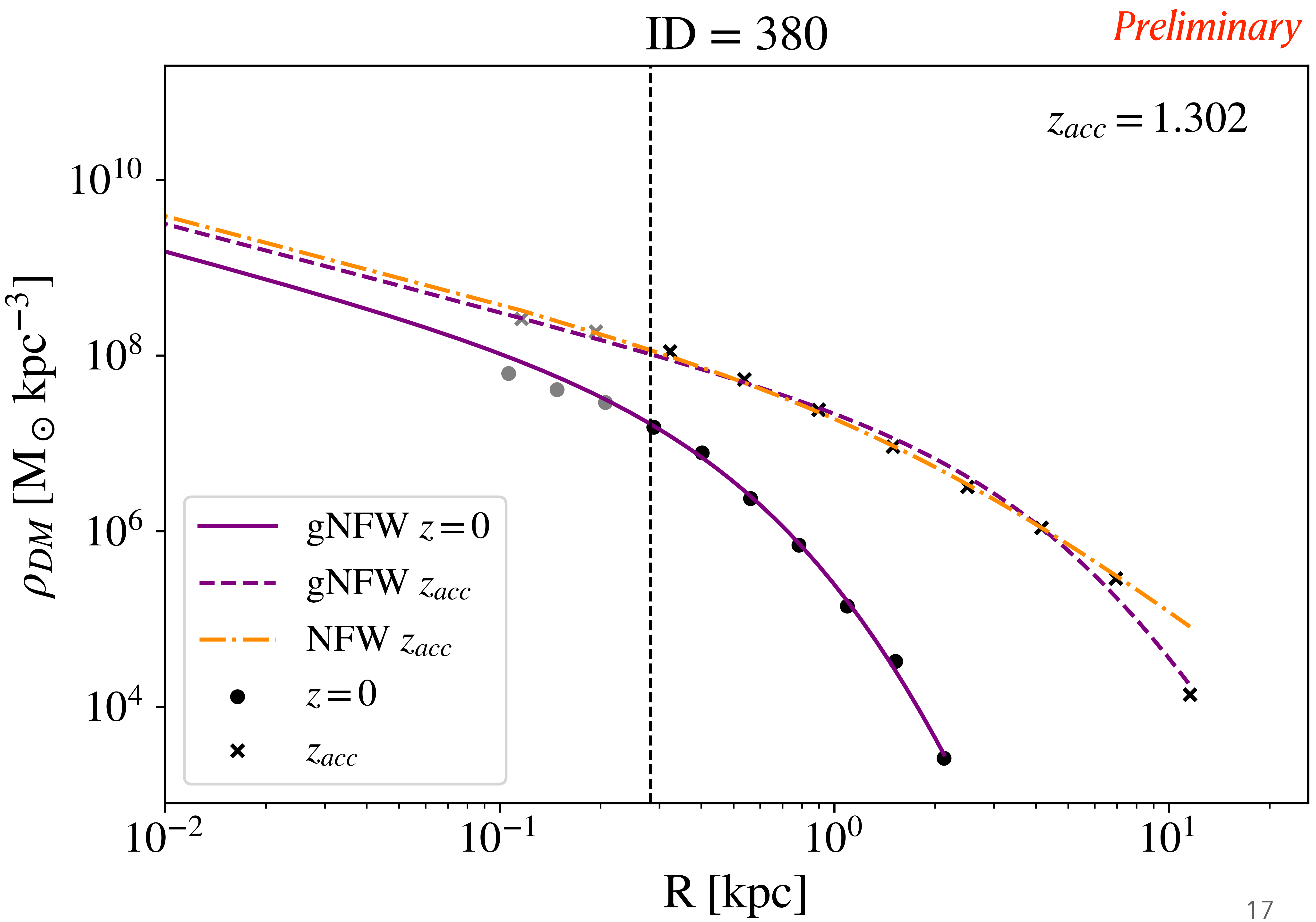
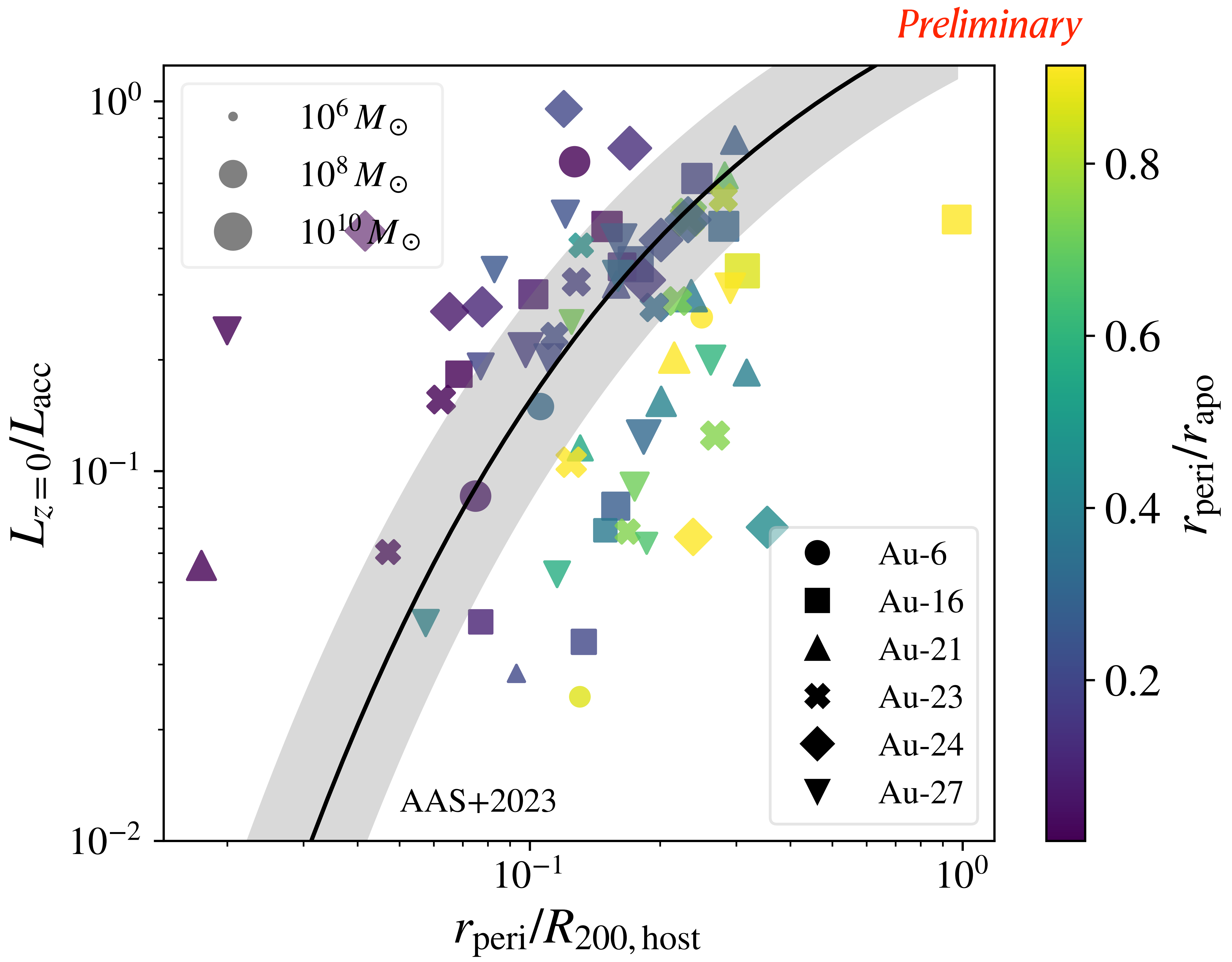
$$L_{ann} = \int_V \rho_{DM}^2(r)\, dV$$

- L_{ann} is very sensitive to the inner shape of the profile, where we face resolution issues.
- Reconstruction of this region: an *inner cusp* is expected at such low-mass subhalo scales, where baryons are not expected to play a significant role (Peñarrubia+2010, Aguirre-Santaella+2023, Stücker+2023).
- SIDM models could eventually lead to more *cored* profiles (e.g. Vogelsberger+2012, Zavala+2013, Adhikari+2022).



DM annihilation luminosity



Sample of 76/104 streams after removing those not following ΛCDM expectations for their 'tidal tracks' (Aguirre-Santaella+2023, Stücker+2023)

- In most cases there is a significant loss of luminosity (up to 90 %) due to the mass loss.
- In some cases, the present luminosity only decreases by a small percentage of its initial value.
- General tendency to have greater L_{ann} losses for small pericenter values, as expected (Aguirre-Santaella+2023).

Summary

CFS & Sánchez-Conde
arXiv: 2502.15656

✱ This work is the first one that uses stellar streams to set WIMP DM limits.

✱ We build a sample of 11 streams most optimal for gamma-ray DM searches.

✱ No signal is detected after the analysis of 15 years of Fermi-LAT data.

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

CFS, Sánchez-Conde & Aguirre-Santaella, *in prep.*

✱ Currently using the Auriga suite of high-resolution hydrodynamical simulations to shed light on the DM distribution within disrupted dG streams.

✱ Auriga streams (~ 100) better described with gNFW profile at $z = 0$.

✱ L_{ann} can decrease up to 90% of their initial values, still being competitive targets for indirect DM searches.

✱ Work in progress to provide the best fit gNFW parameters.

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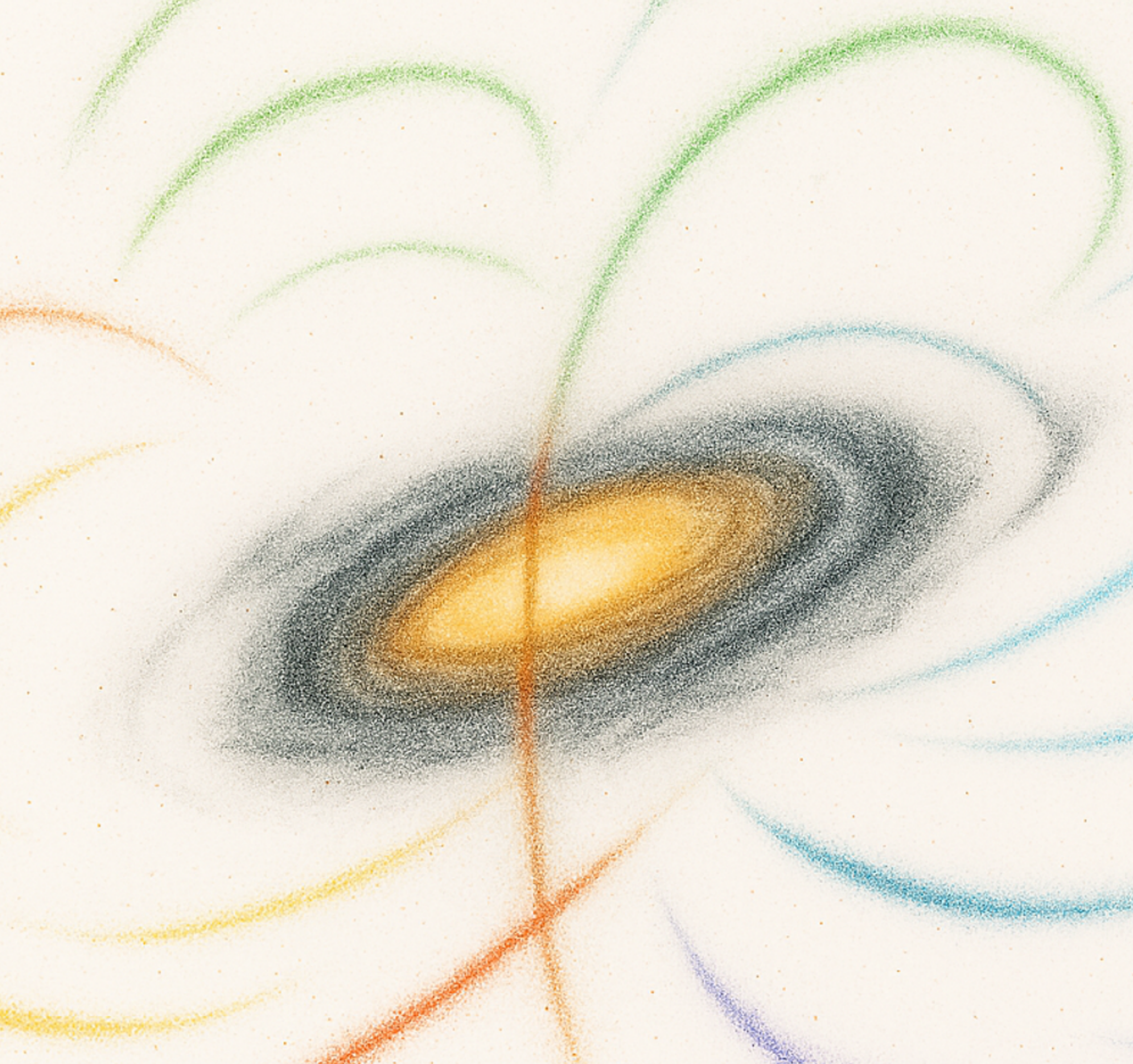
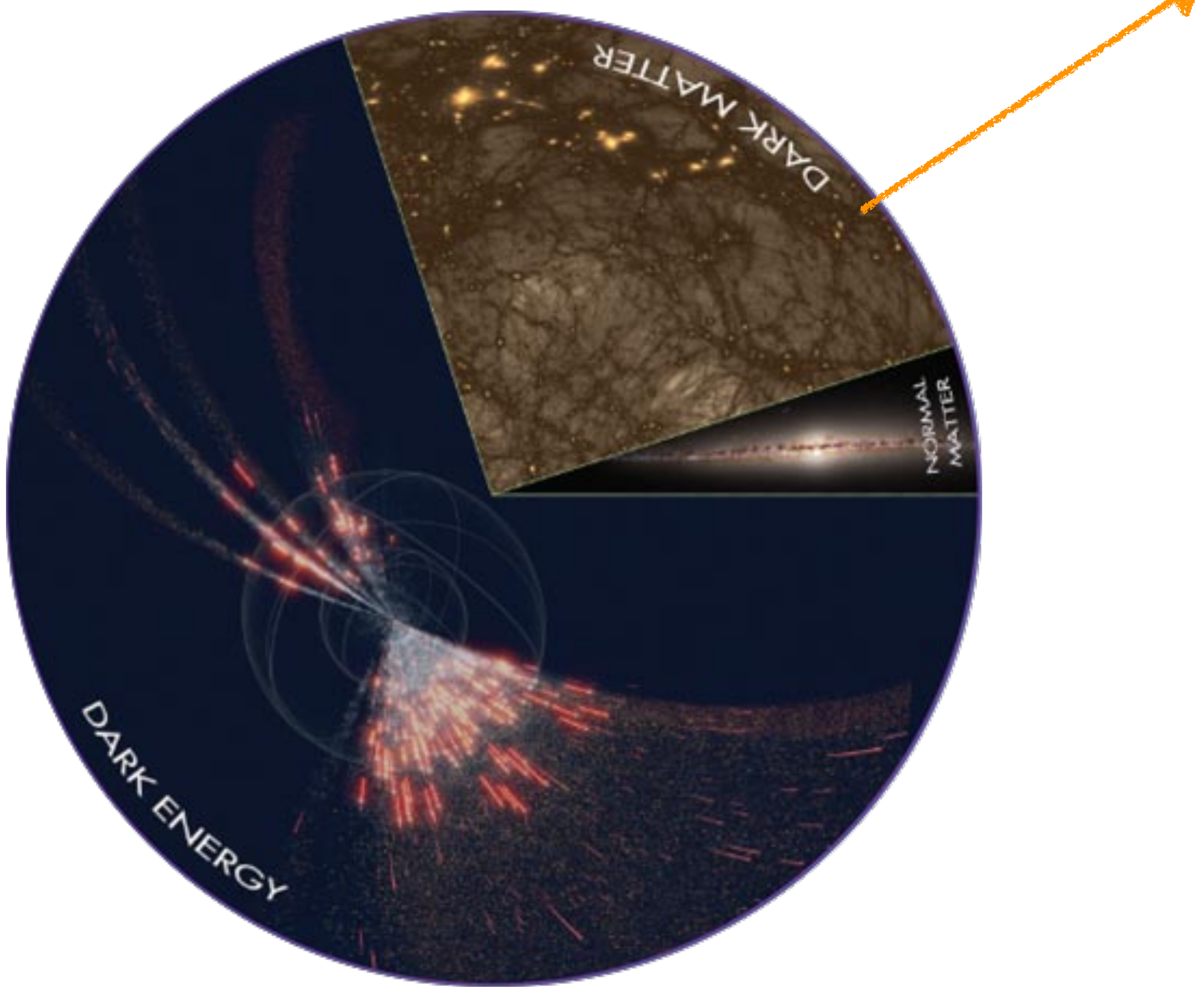


Thank you!

Backup Slides

Dark matter overview



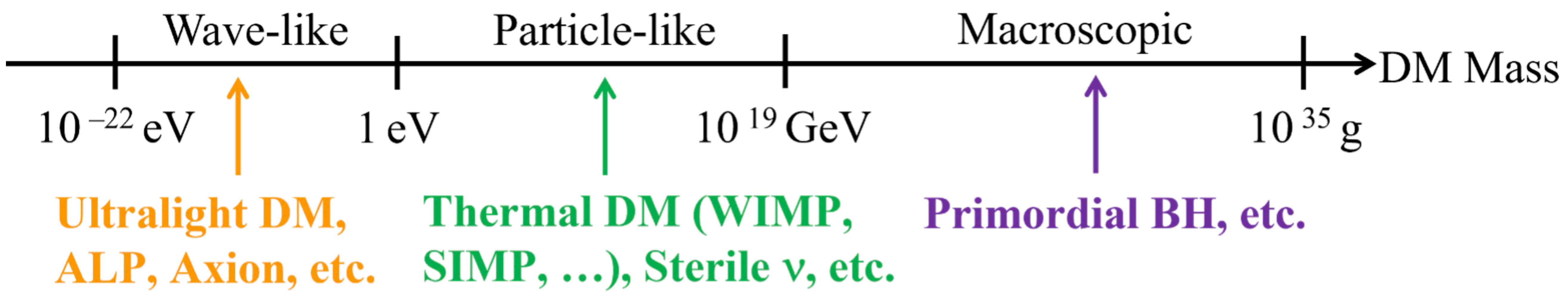
Credit: American Museum of Natural History

Dark matter (DM) ~ 27 %

✱ Multiple evidence from galactic to cosmological scales.

✱ Properties:

- Non-baryonic
- Neutral
- Non-relativistic (cold)
- Long lifetime (at least 13.8 Gyr)
- No viable candidate in the Standard Model (SM), we need candidates beyond the SM.



DM annihilation flux from stellar streams

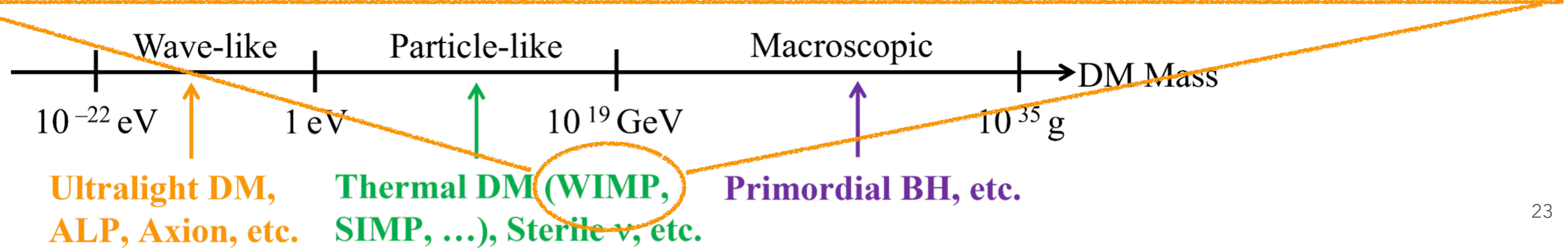
Weakly Interacting Massive Particles (WIMPs)

One of the most promising and well-motivated DM candidates (e.g. Bertone 2010): “*WIMP miracle*".

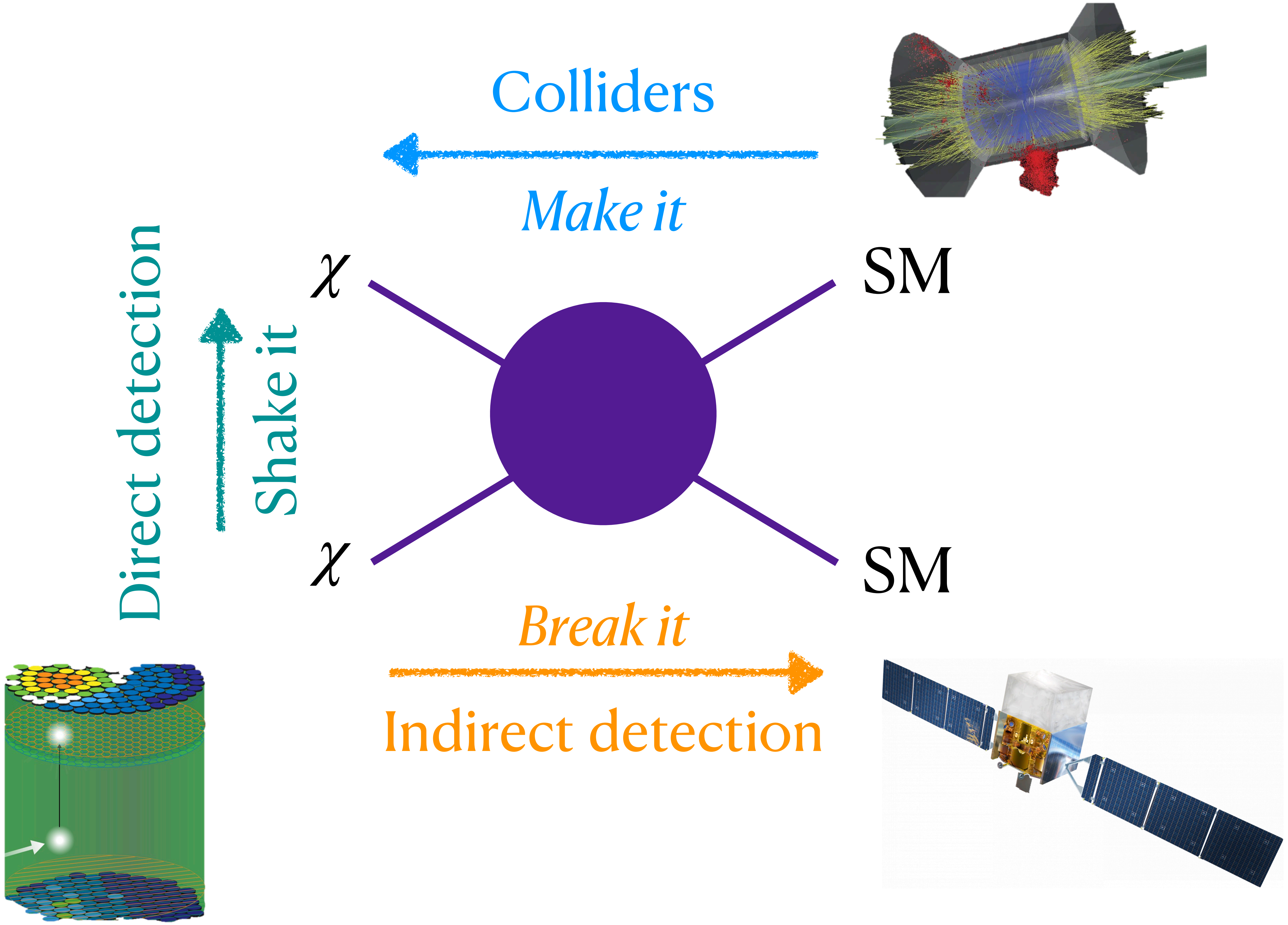
Expected to have GeV-TeV masses.

WIMPs arise in several theories beyond the Standard Model.

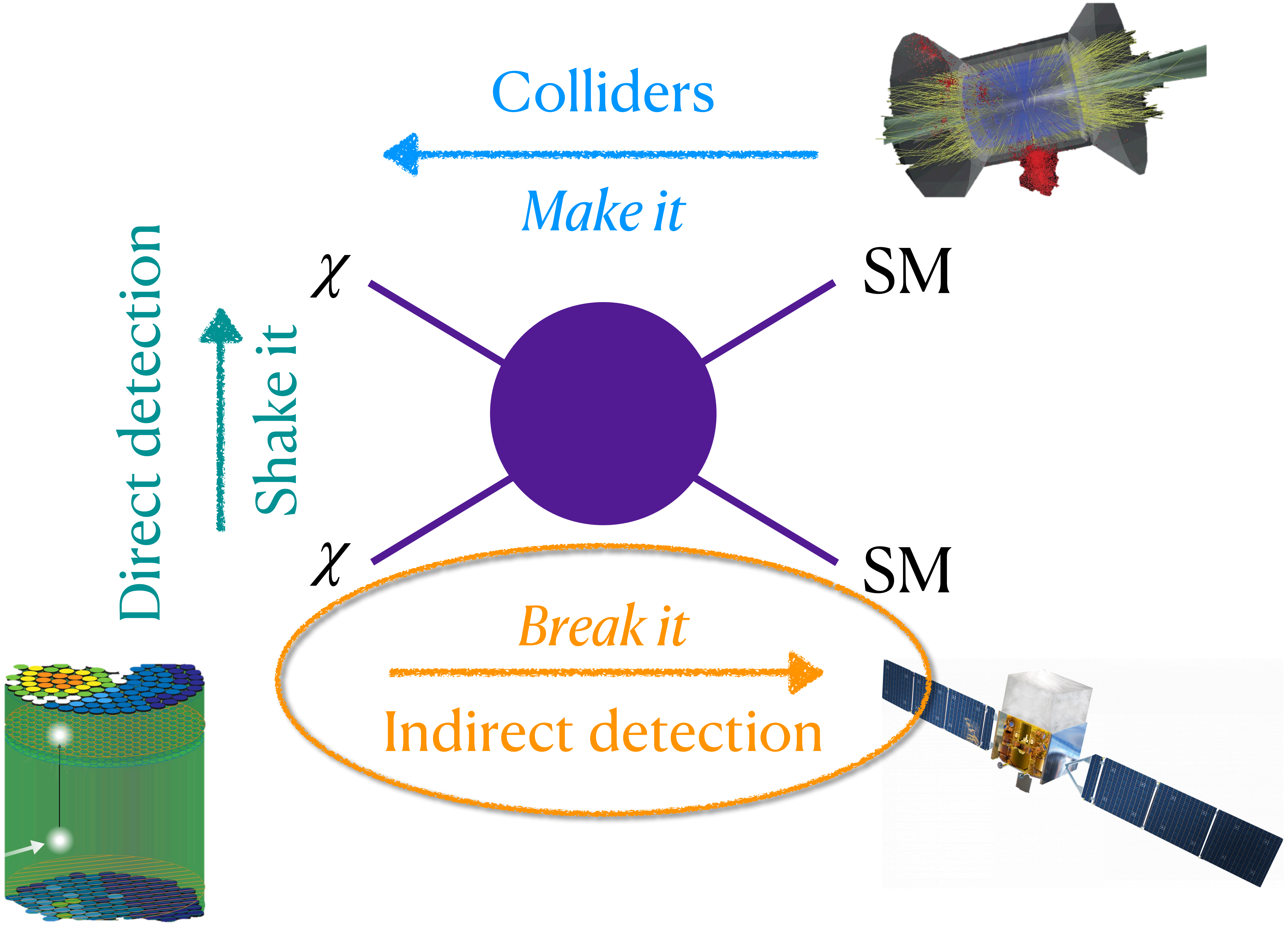
WIMPs may be detectable in gamma rays since self-annihilation of WIMPs produce Standard Model particles, which can eventually yield photons, among other possible by-products.



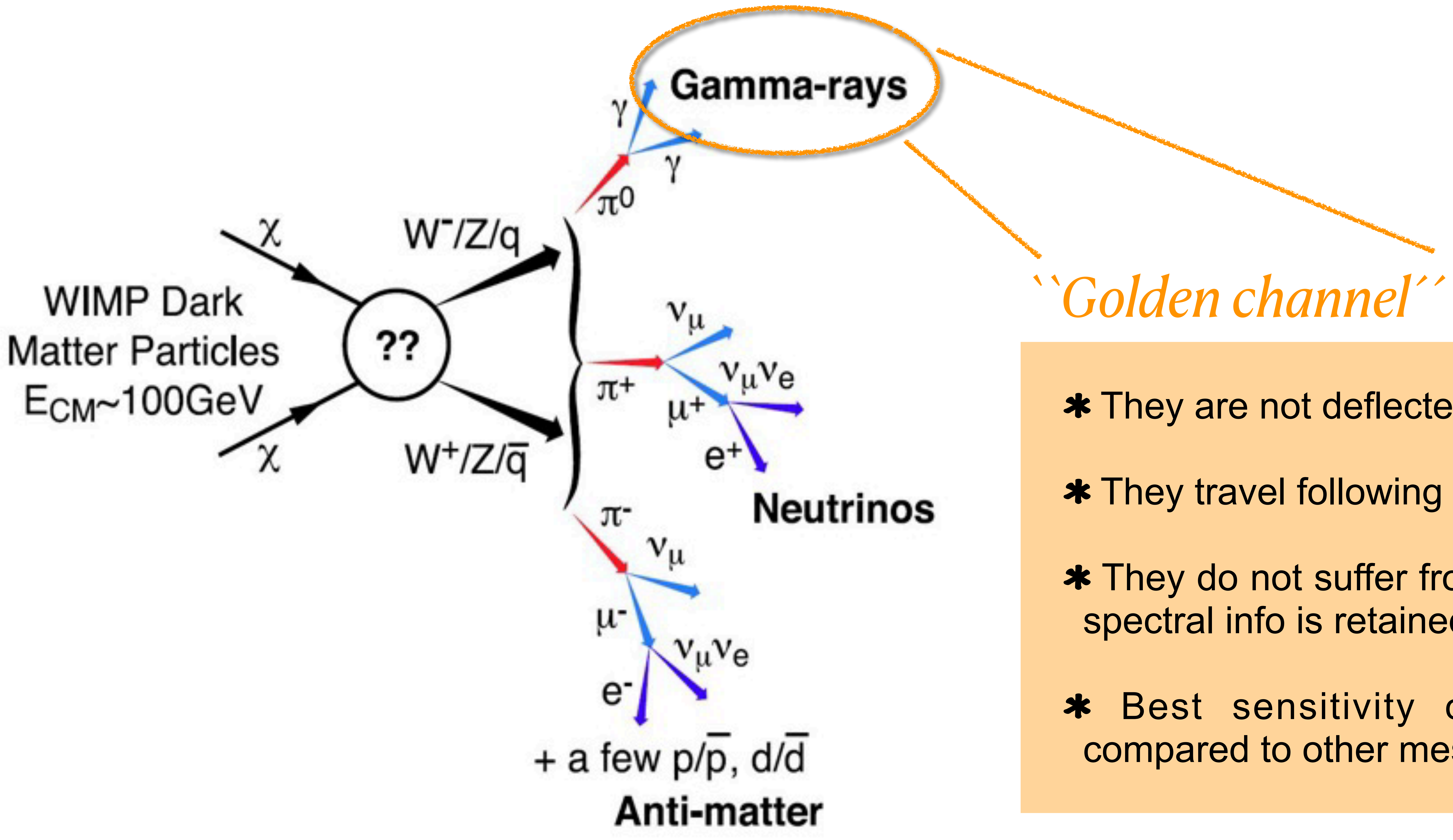
WIMPs' searches



WIMPs' searches



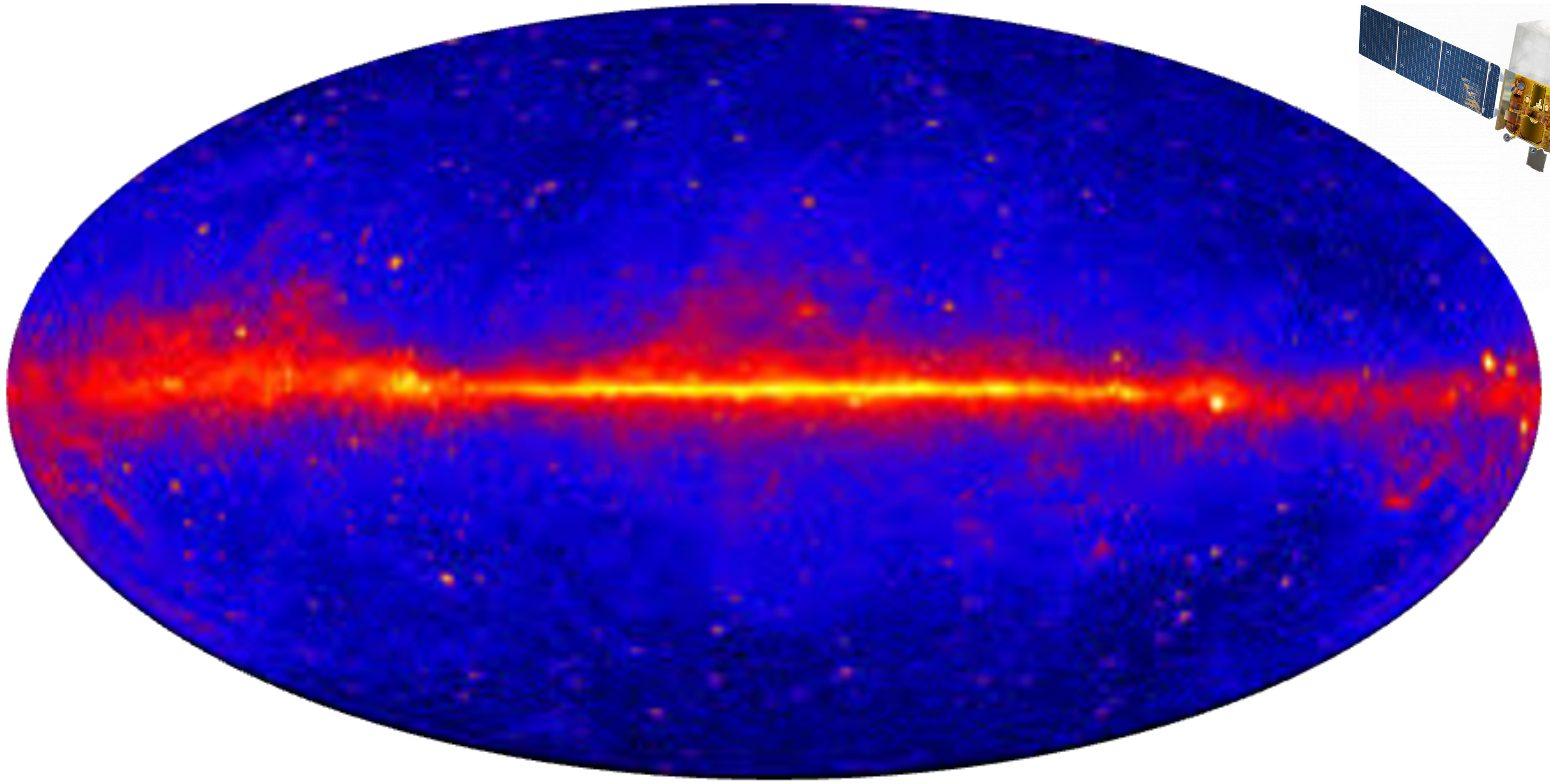
WIMPs' indirect detection

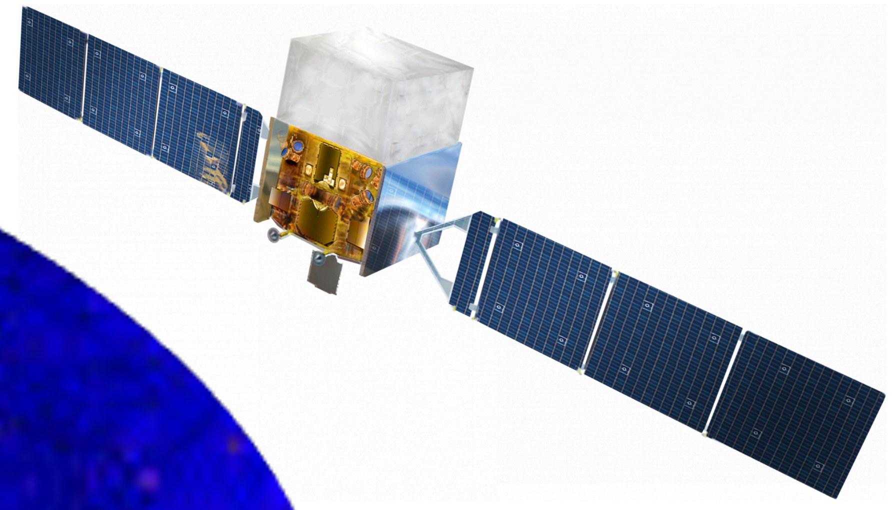


- ✱ They are not deflected by magnetic fields.
- ✱ They travel following almost straight lines.
- ✱ They do not suffer from energy losses, i.e. spectral info is retained.
- ✱ Best sensitivity of our instruments compared to other messengers.

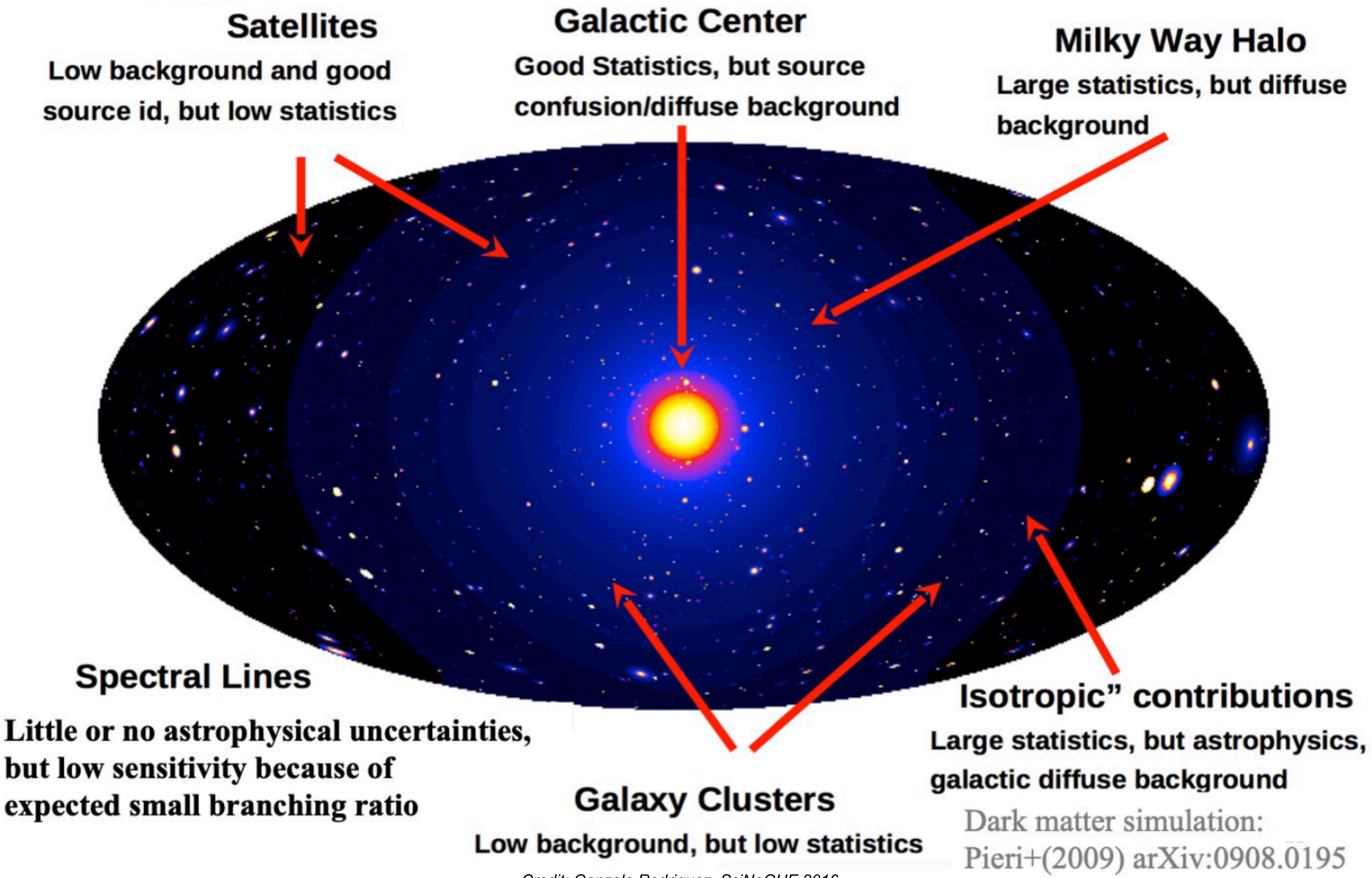
Fermi Large Area Telescope (*Fermi*-LAT)

- High-energy gamma-ray detector.
- Launched in 2008, surveys the whole sky every three hours.
- Mission led by NASA, with contributions from other countries. 
- Energy range: 20 MeV — 300 GeV : Ideal instrument for WIMP searches!



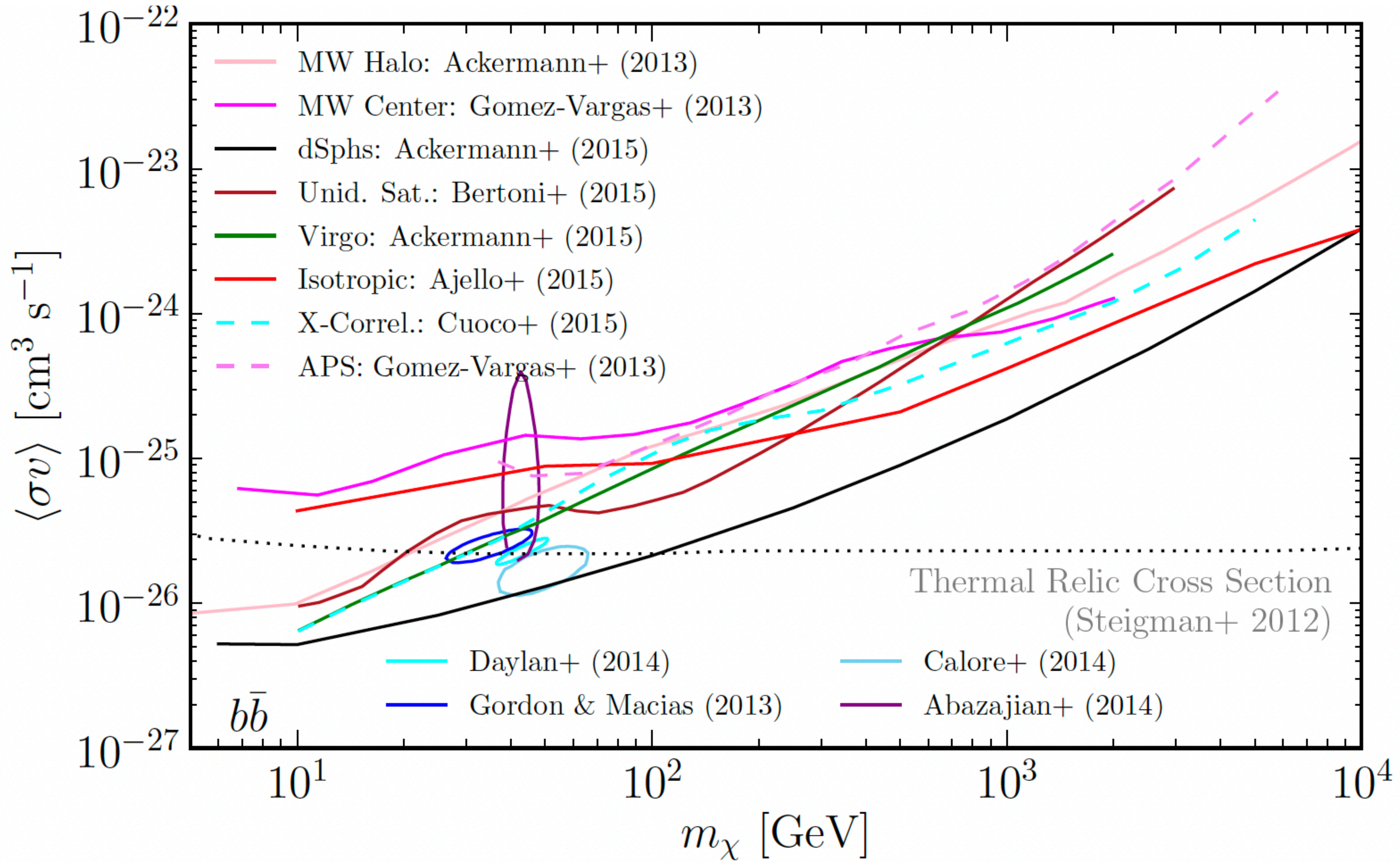


WIMP searches with gamma rays: *where should we look?*



Credit: *Gonzalo Rodriguez, SciNeGHE 2016 – 18 October 2016*

WIMP searches with gamma rays



Charles, Sánchez-Conde, et al. 2016

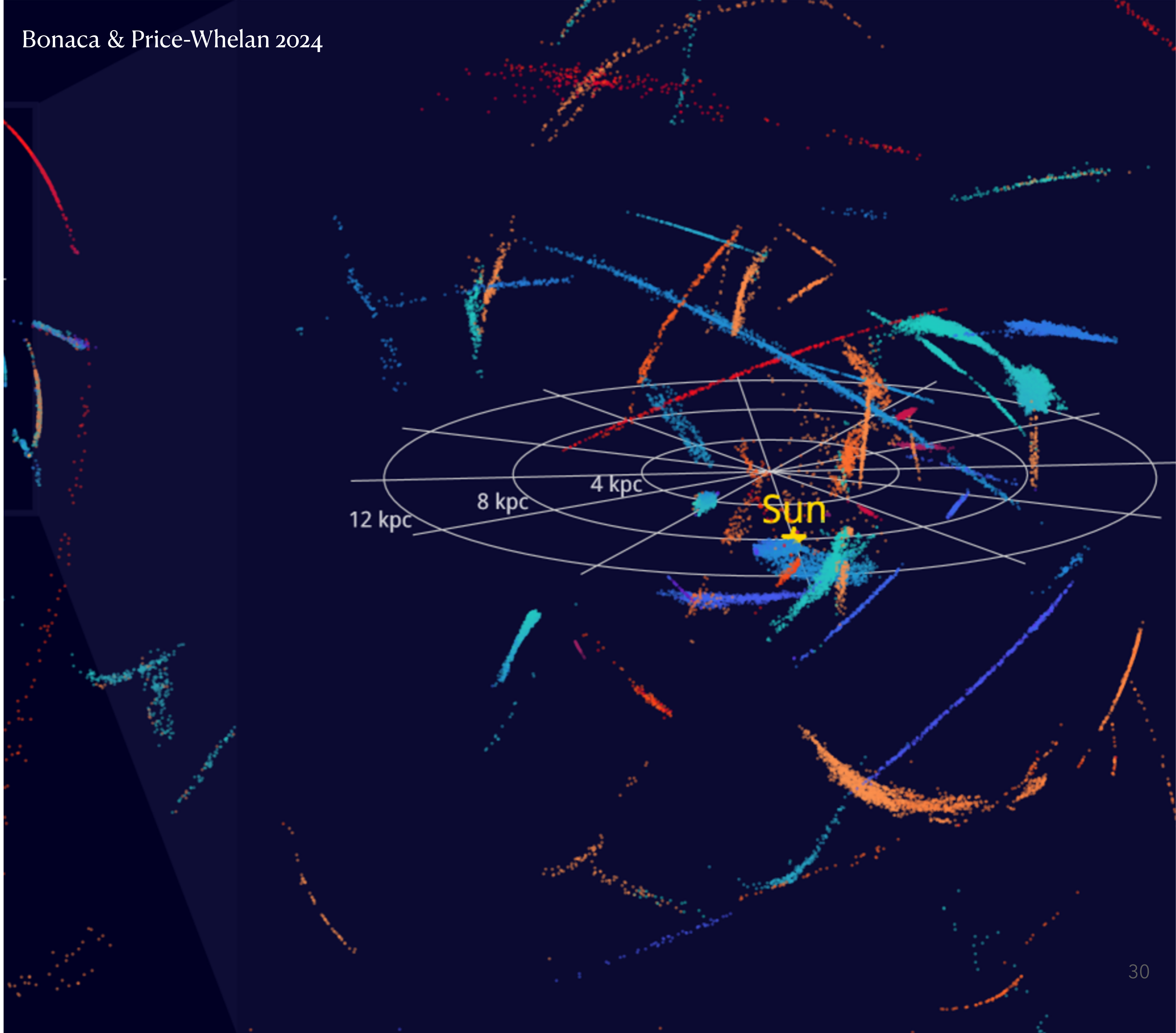
Stellar Streams in a nutshell

✱ 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.

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



Stellar Streams in a nutshell

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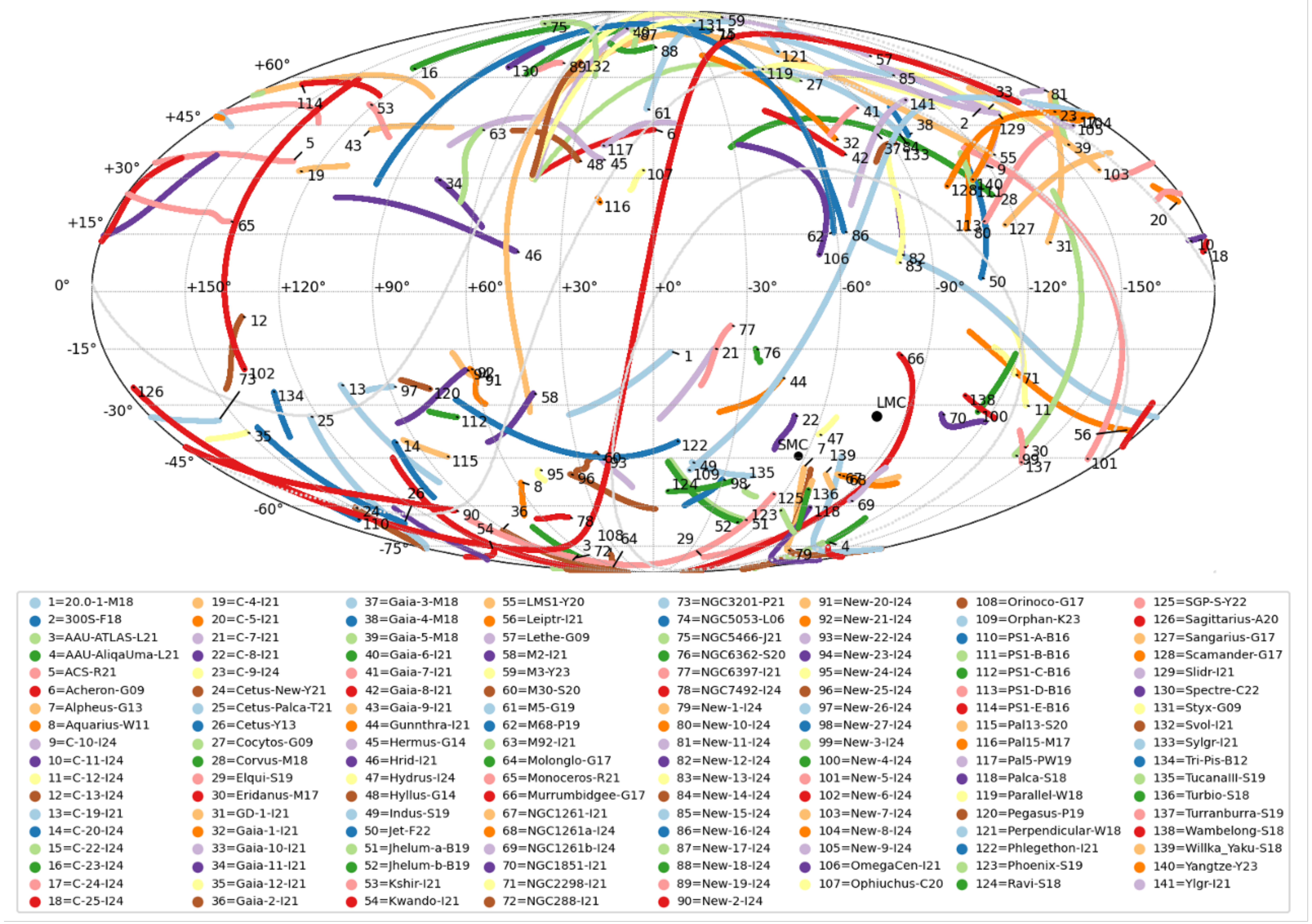
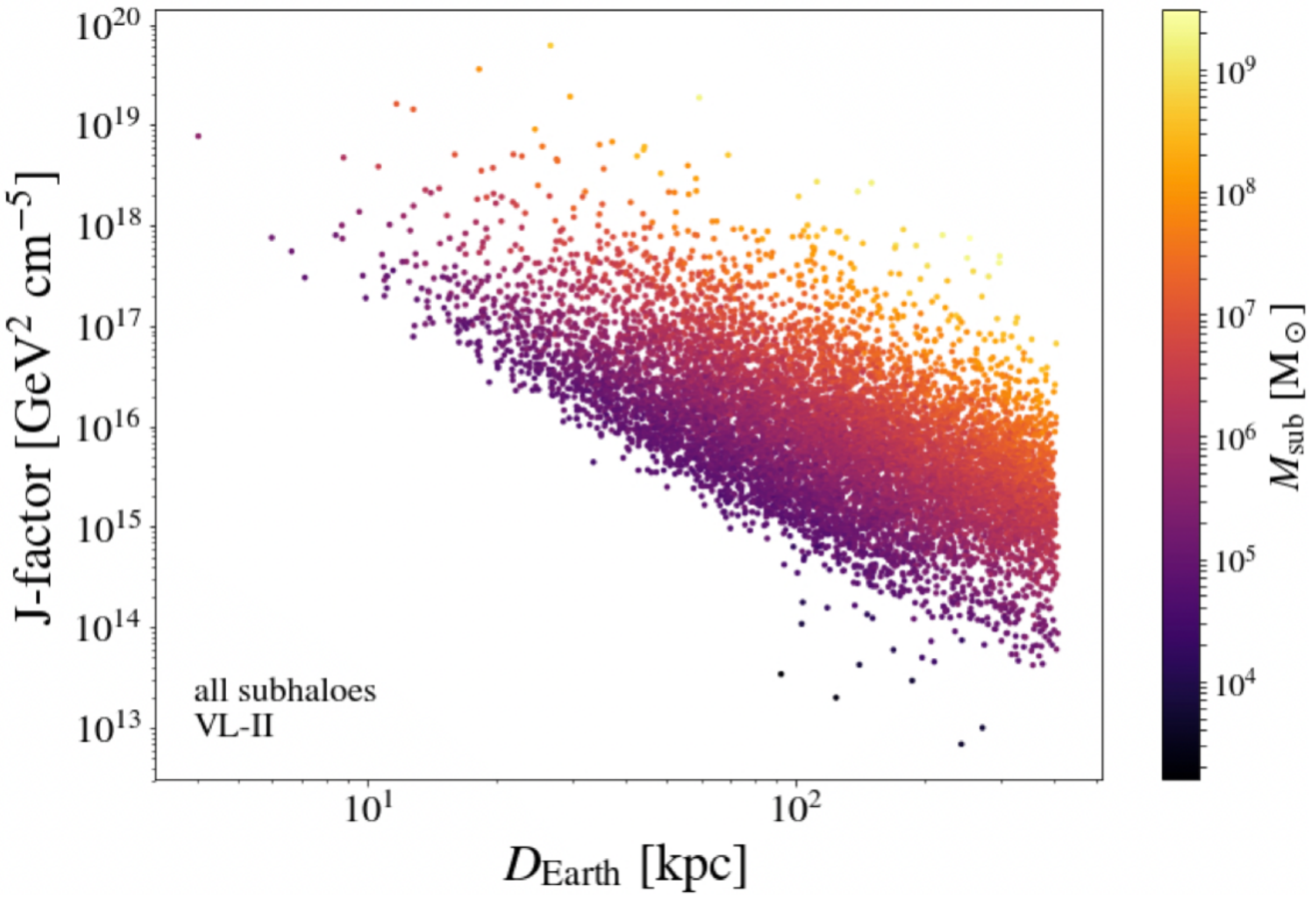
✱ More than 100 stellar streams have been observed around the Milky Way (MW).



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

Sample Selection: Distance



Aguirre-Santaella & Sánchez Conde, 2024

DM Modelling

✱ We assume that the streams maintain the same density distribution as their progenitors within the core ($r \leq r_s$).

✱ Rest of the DM outside r_s gets lost due to tidal stripping (e.g., Aguirre-Santaella et al. 2023).

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

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

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.

CFS & Sánchez-Conde
arXiv: 2502.15656

DM Modelling: M/L ratio scenarios

✱ 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}.

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

Benchmark: $M/L = 5$

High: $M/L = 50$

Typical M/L for dGs: 10 – 1000

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

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
Turranburra	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

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Stream	$\frac{M_{200}}{10^4}$ $(M_\odot)$		
	Low	*Bench.*	*High*
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★ LMS-1	10.00	50.00	500.00
★ Orphan-Chenab	16.00	80.00	800.00
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Low: $M/L = 2$
(same DM mass than baryonic mass)

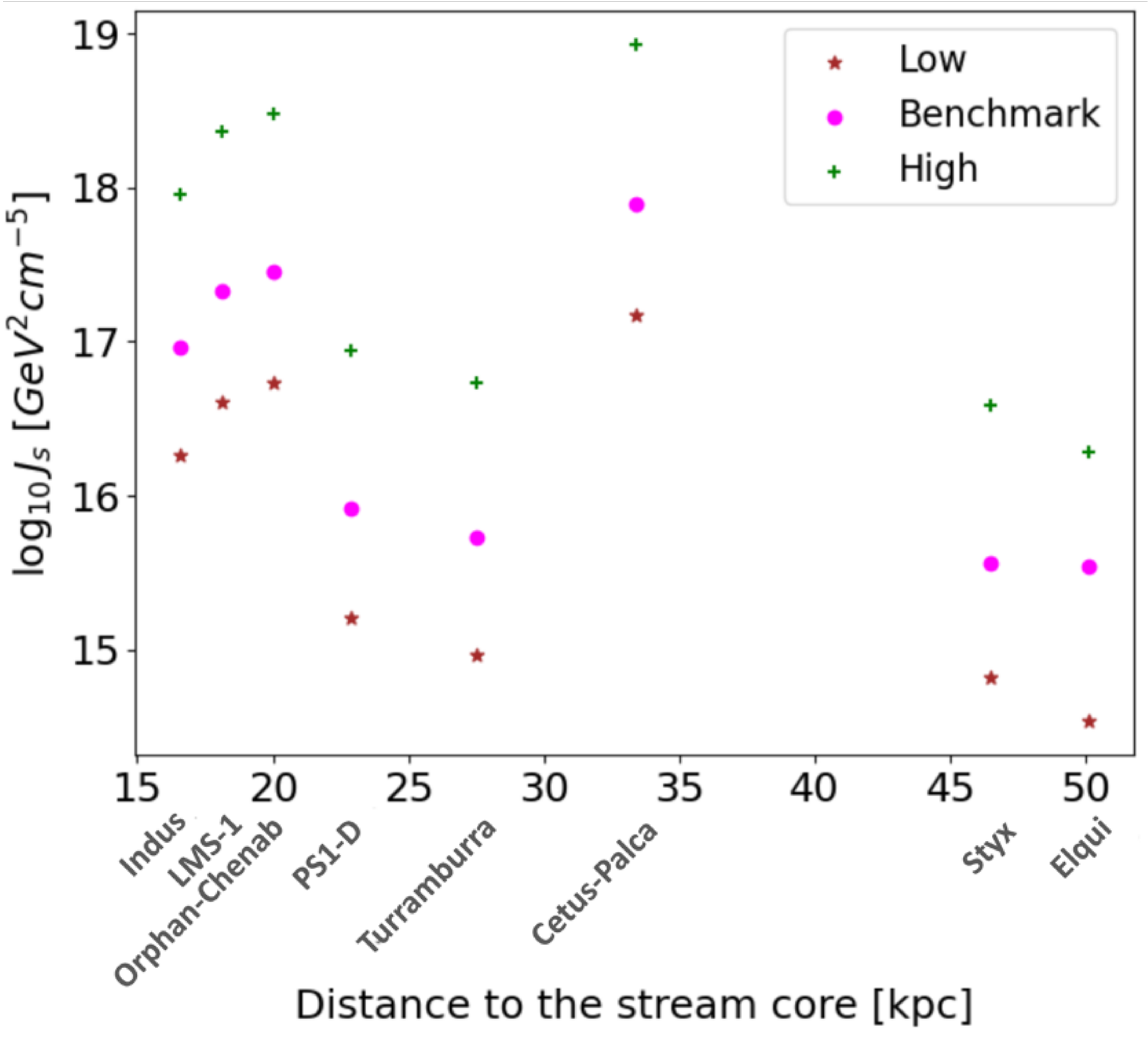
Benchmark: $M/L = 5$

High: $M/L = 50$

★ 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 almost the same.

DM Modelling: Streams' J-factors

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



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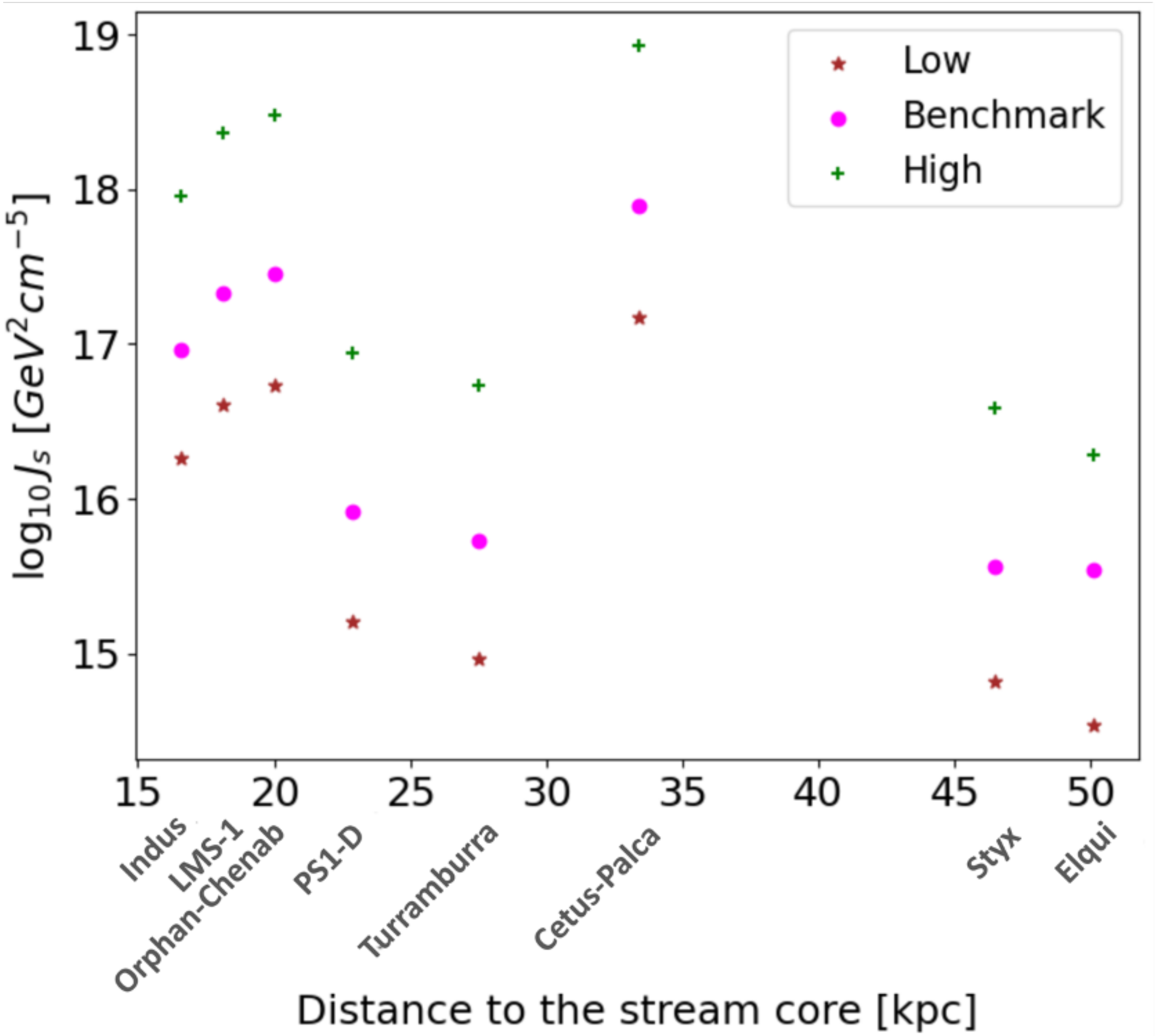
arXiv: 2502.15656

DM Modelling: Streams' J-factors



This work

CFS & Sánchez-Conde, arXiv: 2502.15656

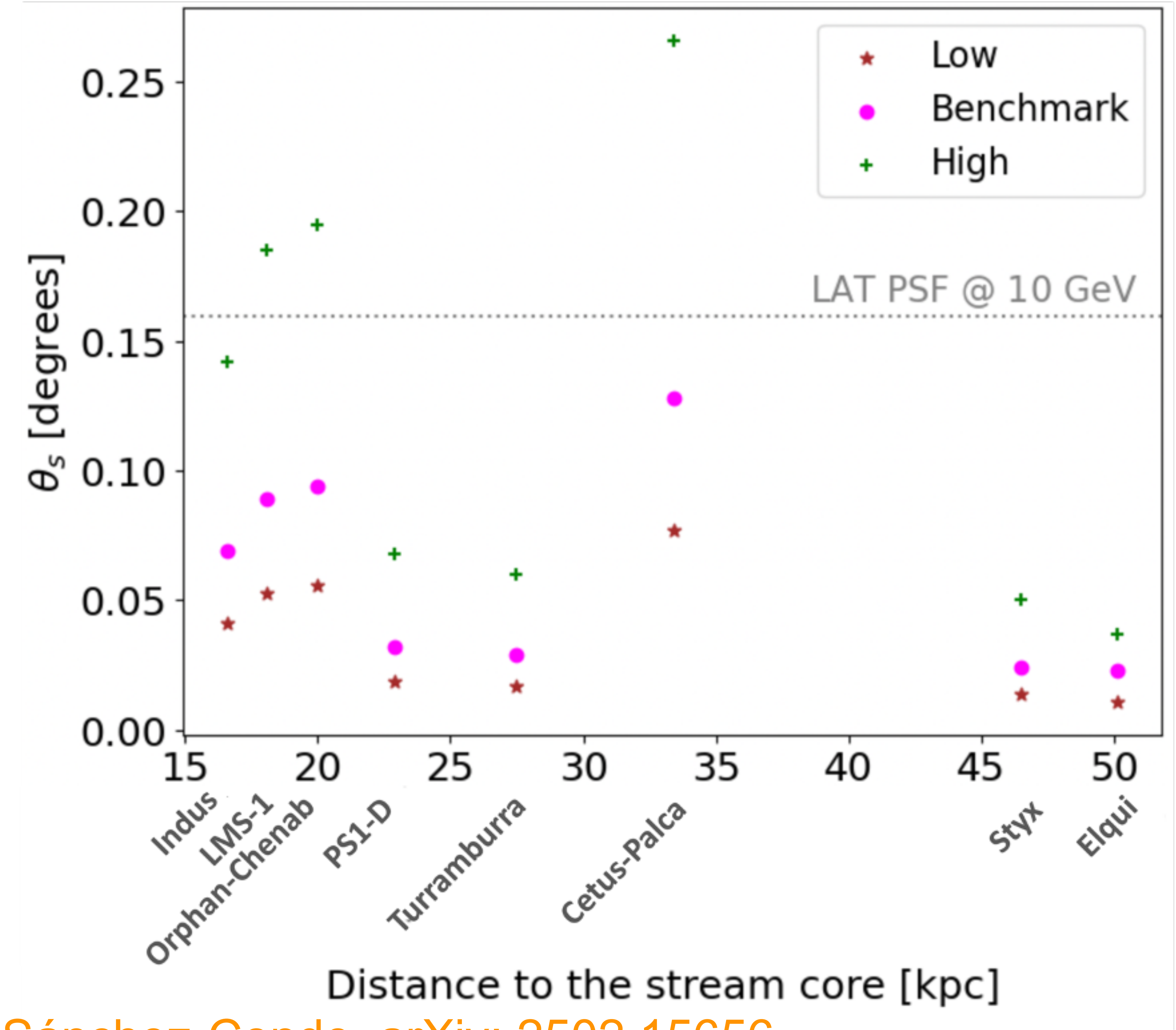
Target	Distance (kpc)	J factor ($\mathrm{GeV}^2\,\mathrm{cm}^{-5}$)
Galactic center / halo (§4.4)	8.5	3×10^{22} to 5×10^{23}
Known Milky Way satellites (§4.5)	25 to 300	3×10^{17} to 3×10^{19}
Dark satellites (§4.6)	up to 300	up to 3×10^{19}
Galaxy Clusters (§4.7)	$> 5\times10^{4}$	up to 1×10^{18}

Example of typical J-factor values for other targets

Charles, Sánchez-Conde+2016

DM Modelling: Streams' Angular sizes

- The extension in the sky of each stream's core will be given by the angle subtended by r_s: $\theta_s = \arctan\left(\frac{r_s}{d_{Sun}}\right)$



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

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

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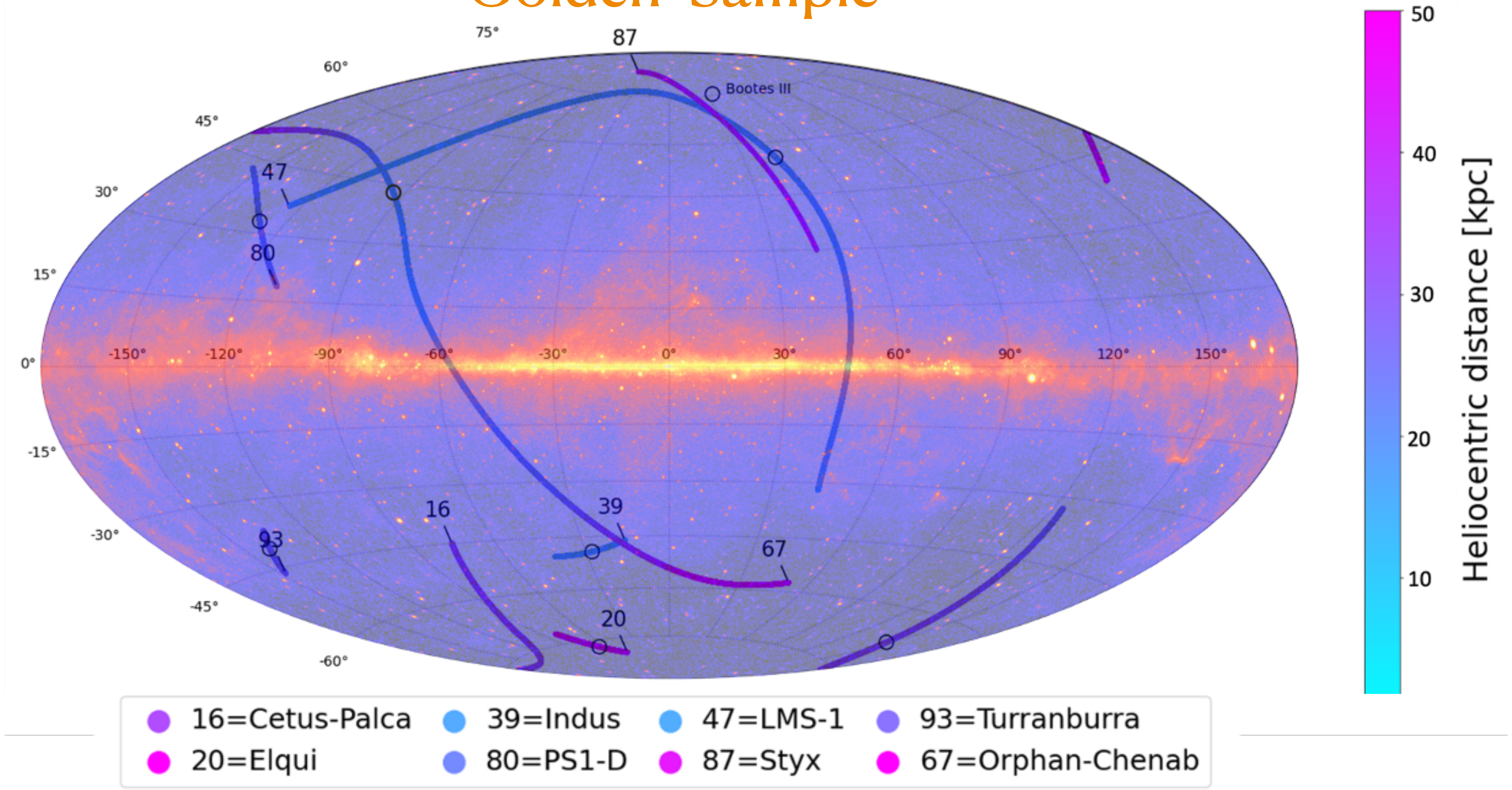
Fermi - LAT Data Analysis

✱ We search for any gamma-ray signal in 15 years of Fermi-LAT data from the direction of the assumed streams' cores.

'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

✱ 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: Flux upper limits

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

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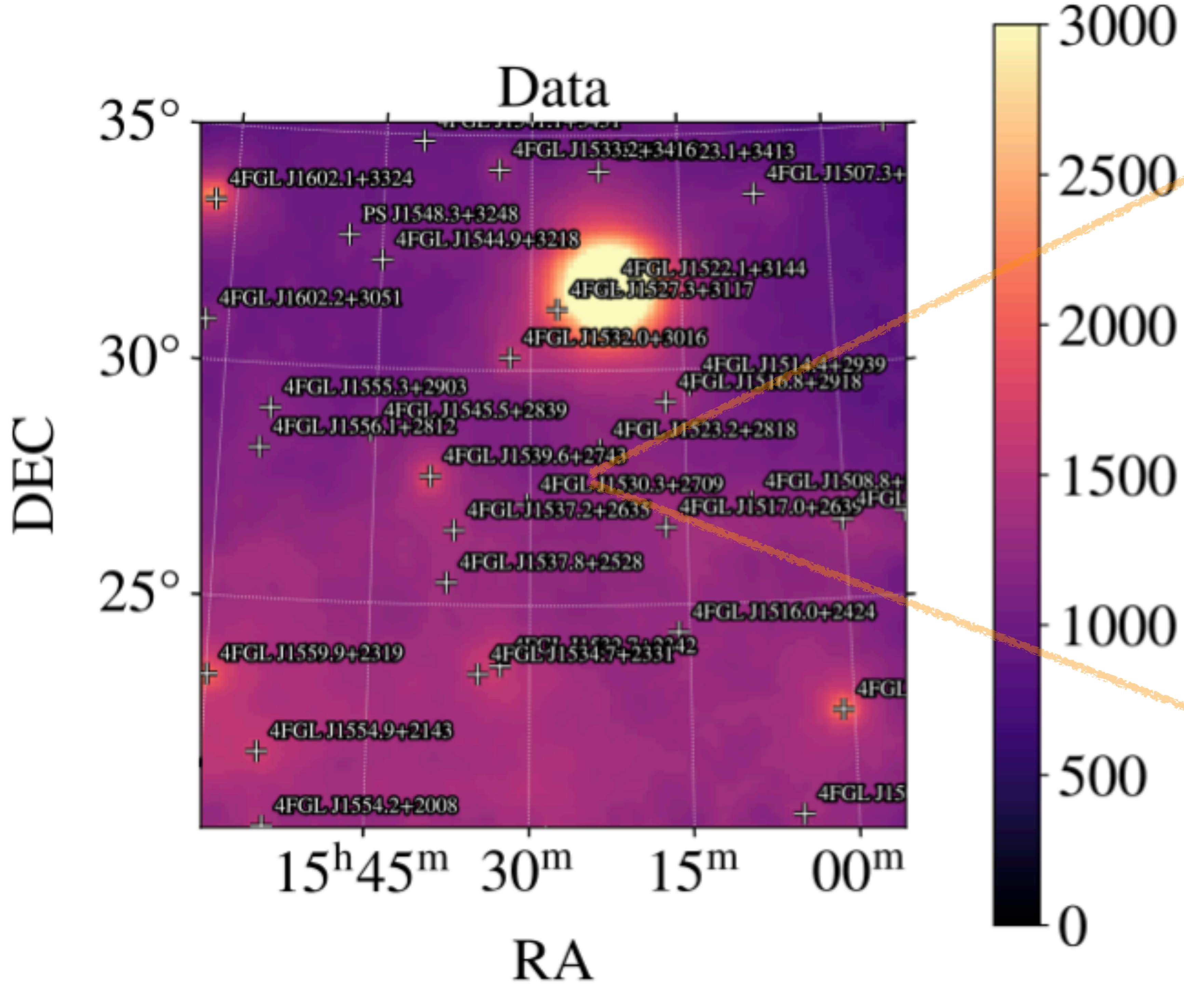
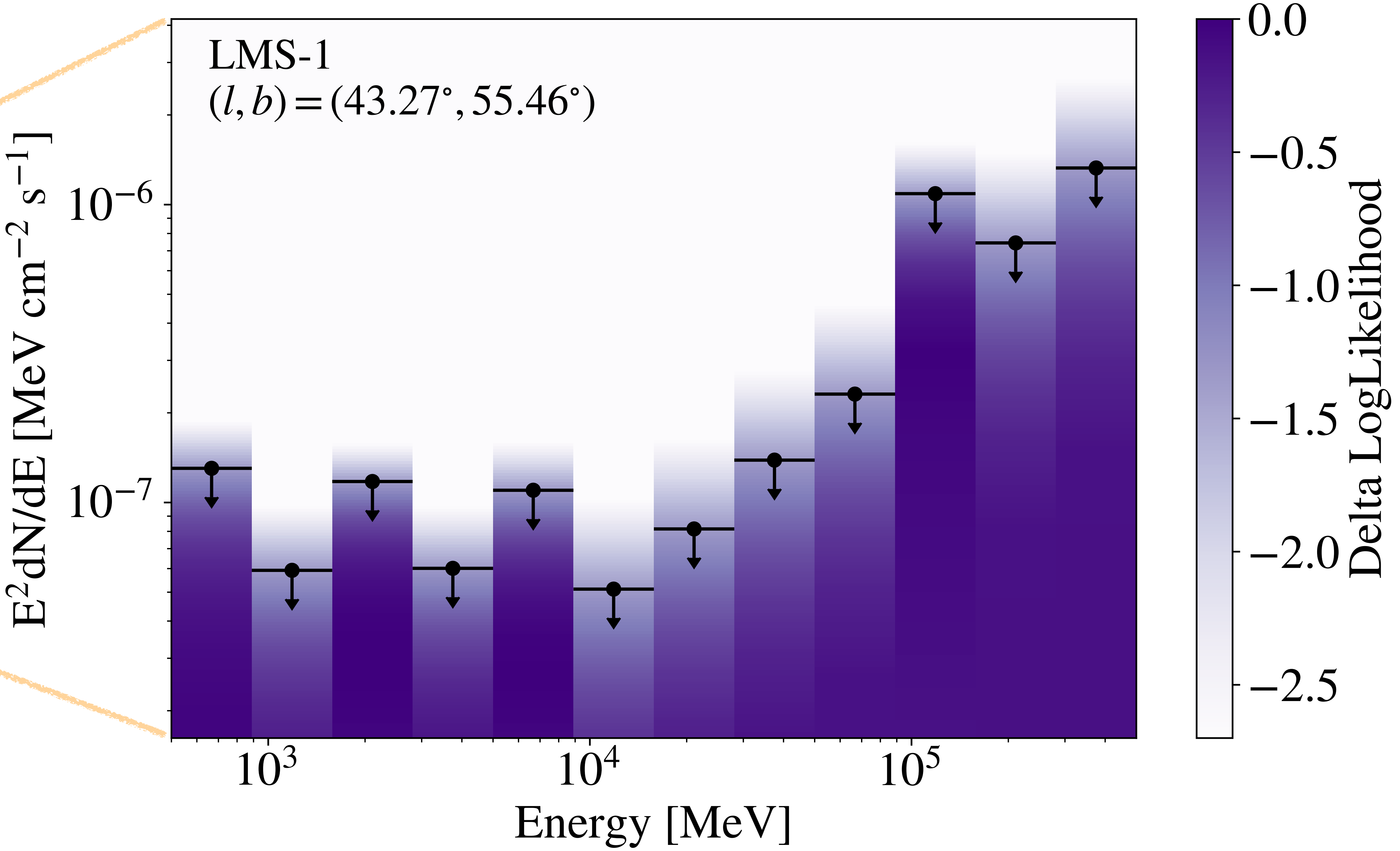
We introduce a putative DM source annihilating at the center of every ROI



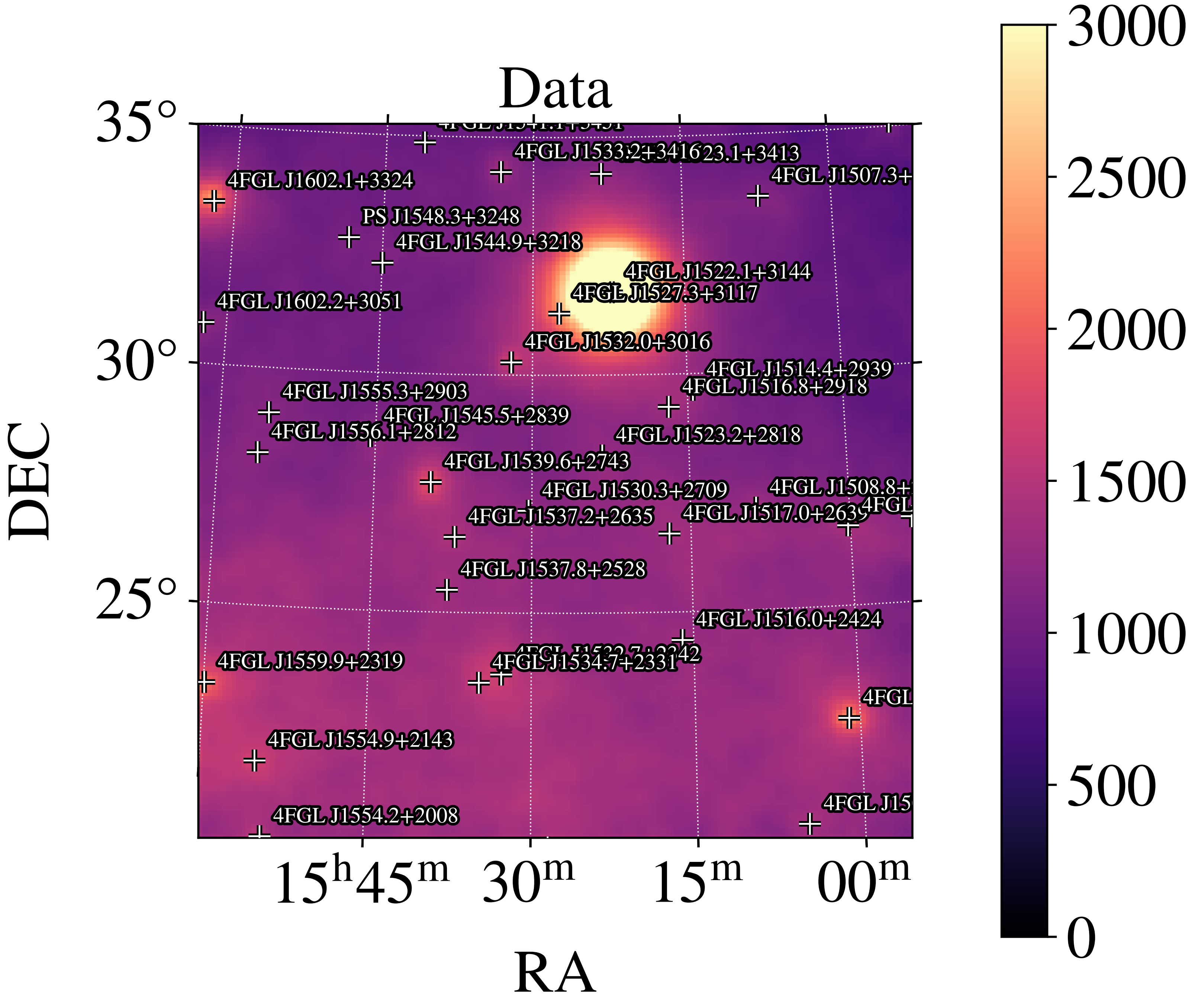
Example for LMS-1 stream

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

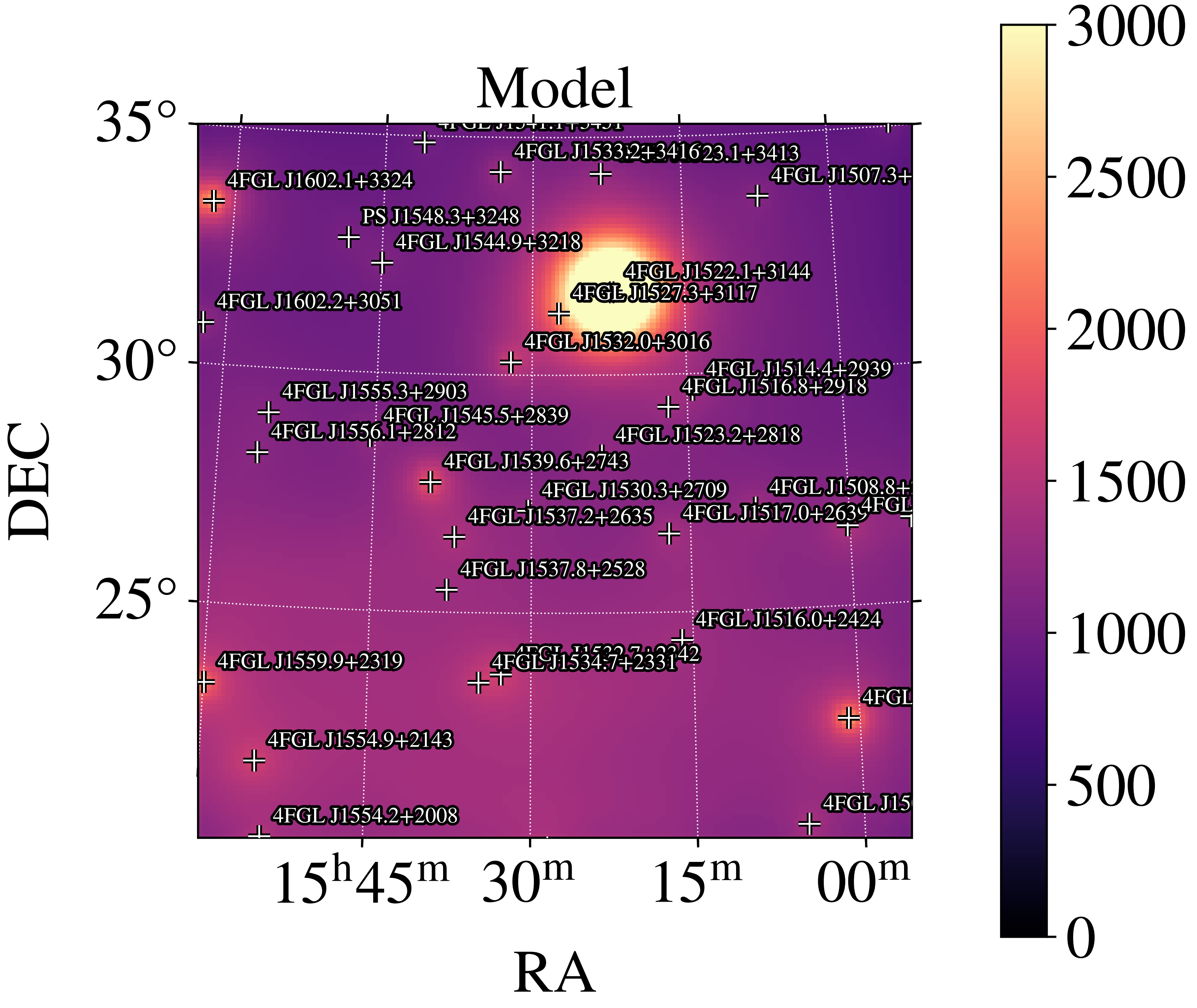


LAT Analysis Results: Example of skymaps

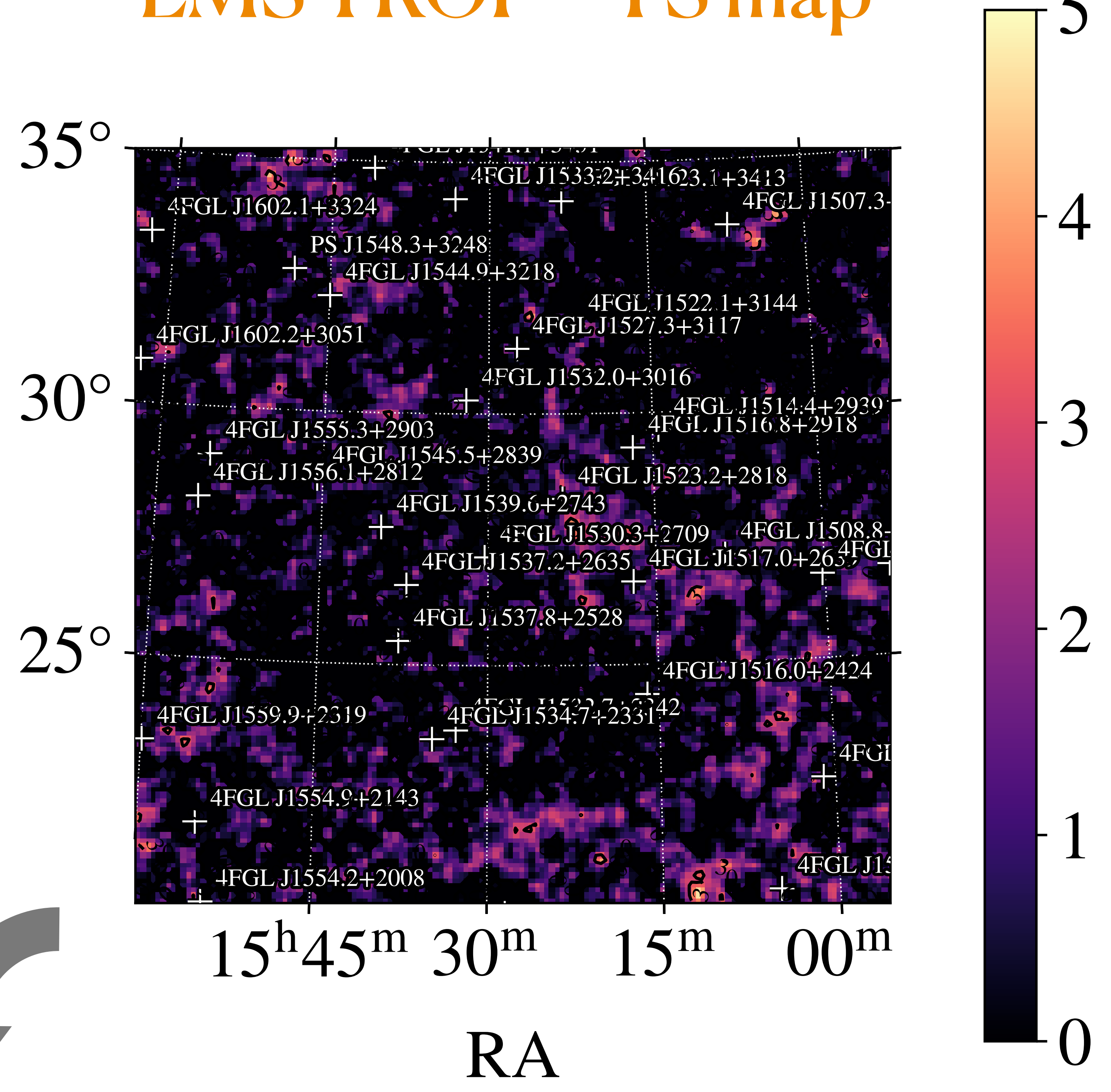
LMS-1 ROI — Data map



LMS-1 ROI — Model map



LMS-1 ROI — TS map



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

$$TS \sim \sigma^2$$

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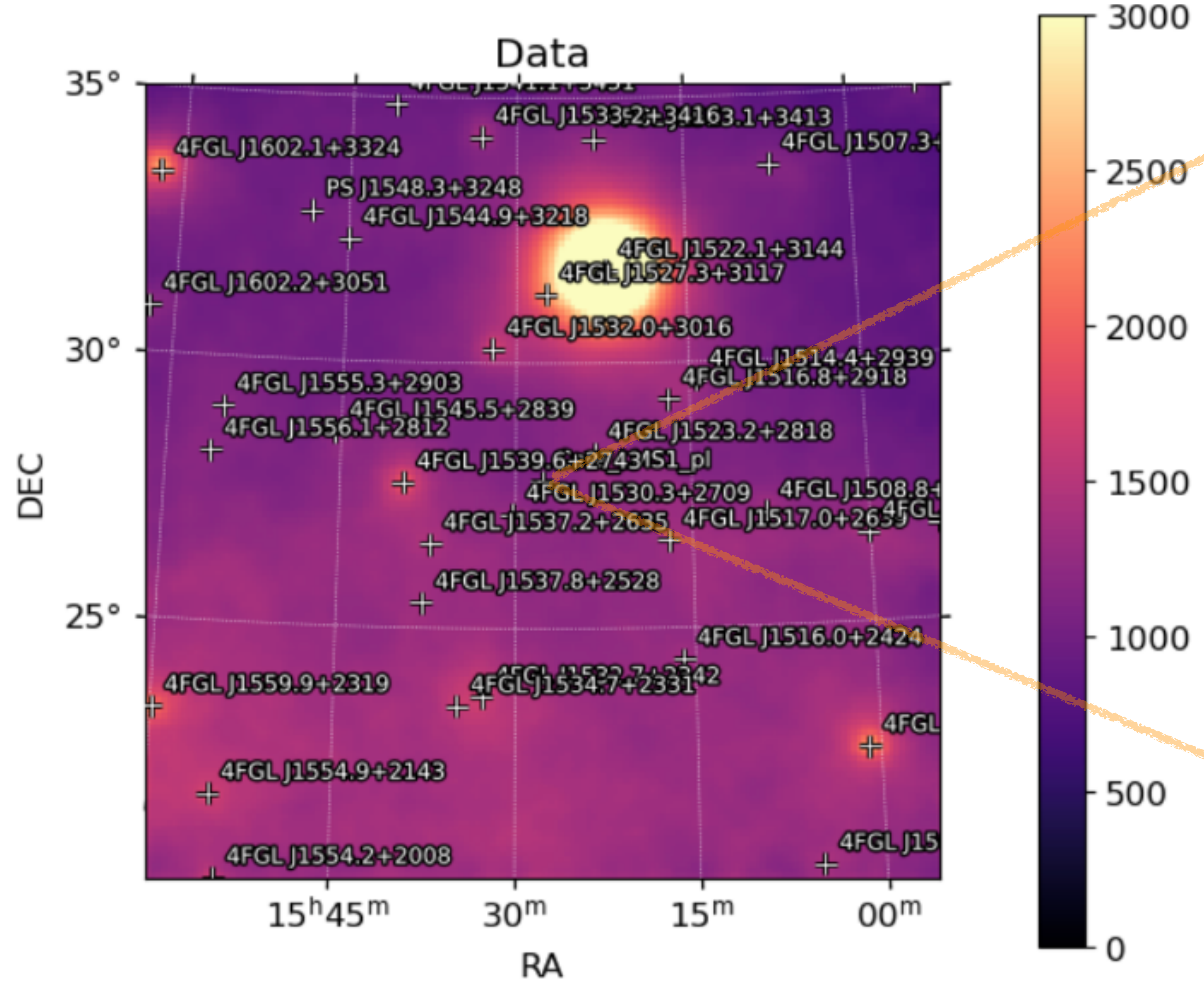
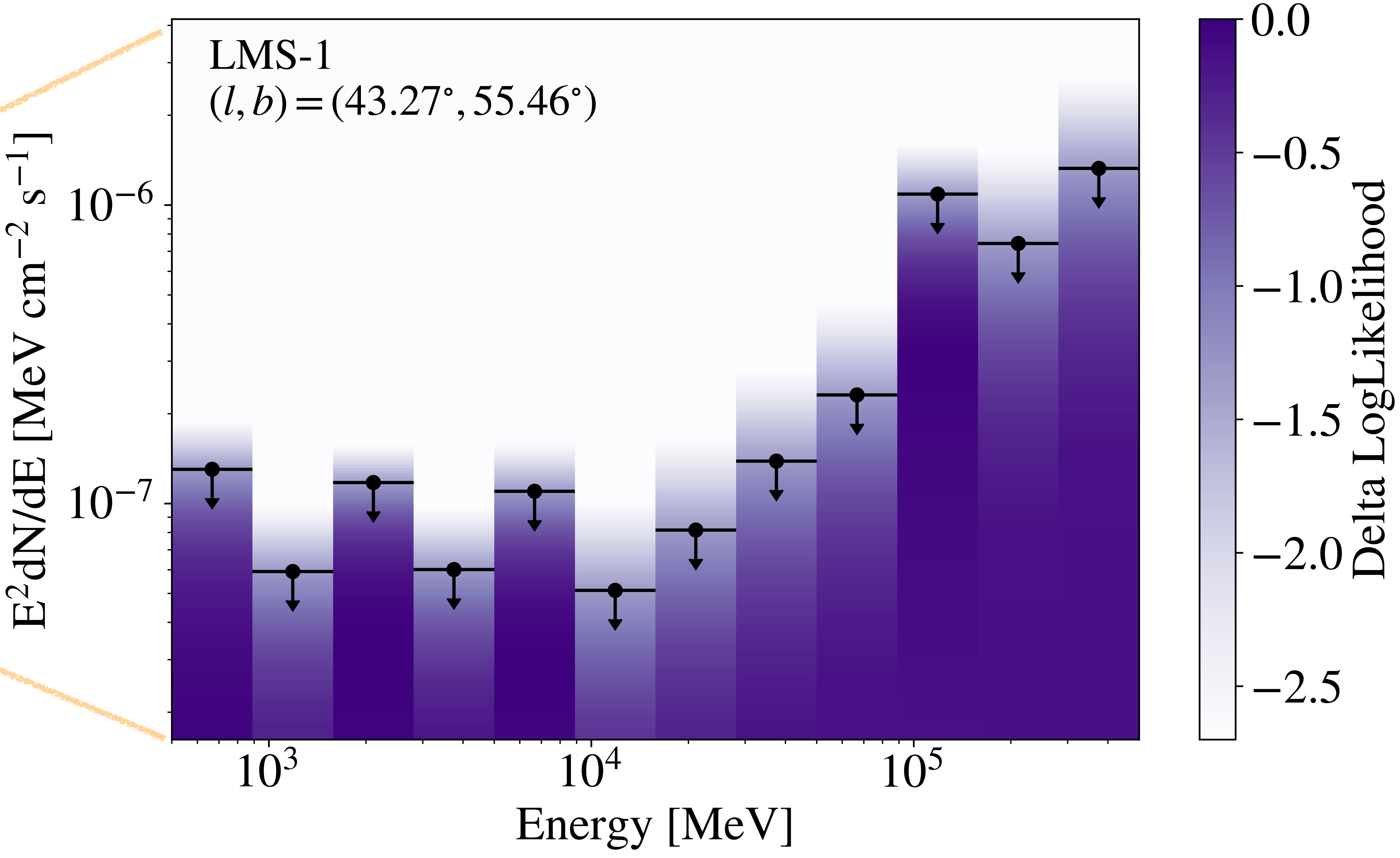
Analysis Results:
Flux upper limits with a *Power Law*

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

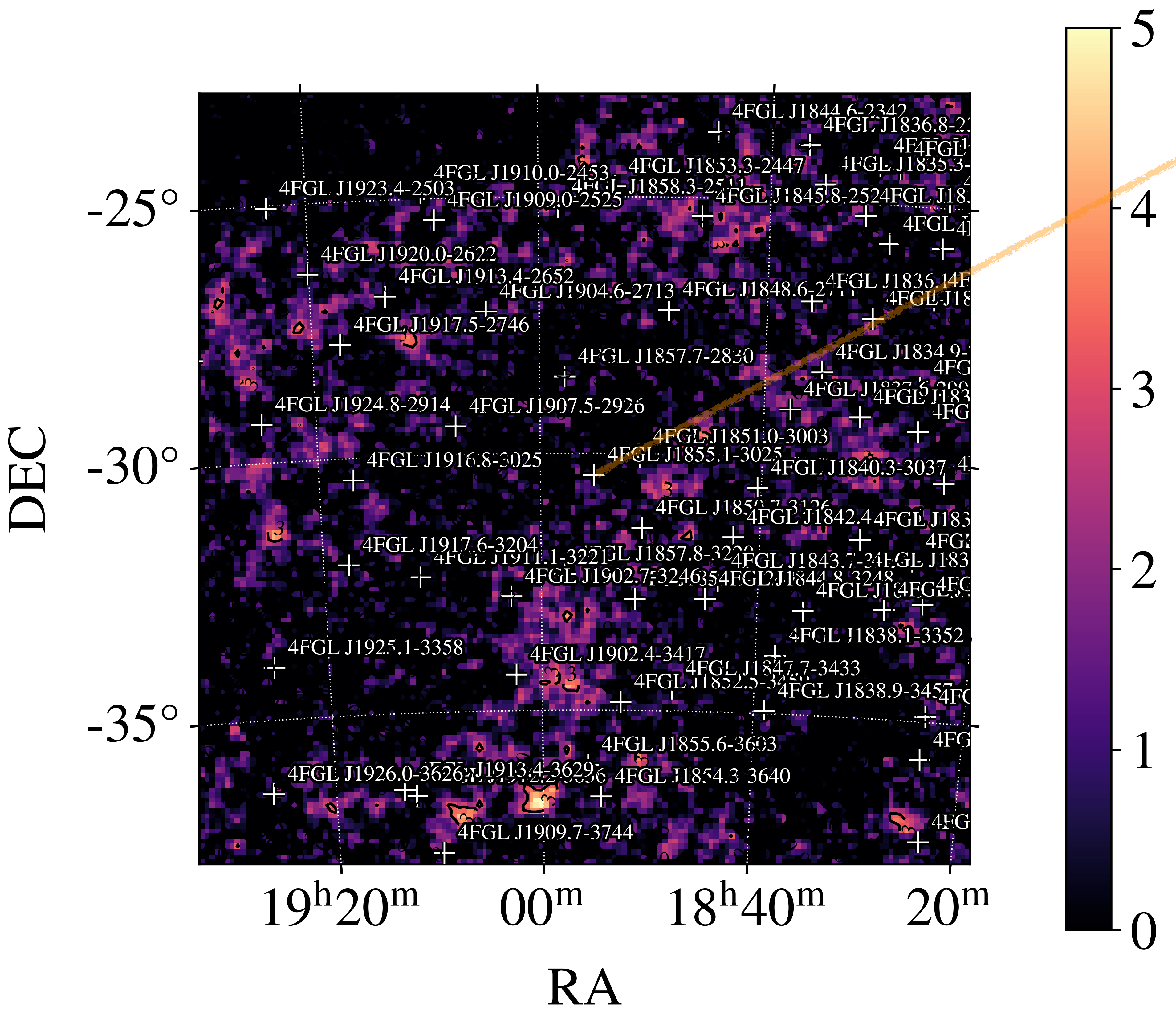


Example for LMS-1 stream

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



LAT Analysis Results: Sagittarius (Sgr) stream



TS map for Sgr

- The source 4FGL J1855.1-3025 is detected ~0.2 degrees from Sgr core. It is associated with the globular cluster M54 in the 4FGL-DR4 catalog.
- Current discussion about the origin of this emission (millisecond pulsars inside M54 or DM annihilation at the core of Sgr). We will investigate in the future whether this emission could be due to DM associated to Sgr in some way.
- By introducing a putative DM source at the exact location of Sgr core, we find no emission.

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DM Constraints

- In the absence of a gamma-ray signal from the direction of the streams' cores, we place constraints on the DM particle properties.

- We set constraints on the $\langle \sigma v \rangle$ for DM masses from 10 to 10^4 GeV in the $b\bar{b}$ and $\tau^+\tau^-$ annihilation channels.

DM particle mass

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

Velocity average 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 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 Constraints

- In the absence of a gamma-ray signal from the direction of the streams' cores, we place constraints on the DM particle properties.

- We set constraints on the $\langle \sigma v \rangle$ for DM masses from 10 to 10^4 GeV in the $b\bar{b}$ and $\tau^+\tau^-$ annihilation channels.

- Individual log-likelihood profile for each stream as a function of DM mass and $\langle \sigma v \rangle$:

Likelihood profile in flux-energy space

$$\mathscr{L} = (\mathscr{F}, E) \quad \longrightarrow \quad \mathscr{L}(\langle \sigma v \rangle, m_\chi) = \sum_{E_j} \mathscr{L}(\mathscr{F}(\langle \sigma v \rangle, m_\chi, E_j), E_j)$$

↑

Summing over all energy bins and introducing

$$\mathscr{F}(E, \Delta\Omega, l.o.s) = f_{pp}(E) \times J(\Delta\Omega, l.o.s)$$

DM Constraints: 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 ($\mathscr{D}$)

Same methodology used e.g. in previous LAT dwarf analysis (e. g. Albert et al. 2016, McDaniel et al. 2024).

Individual and combined log-likelihood profiles

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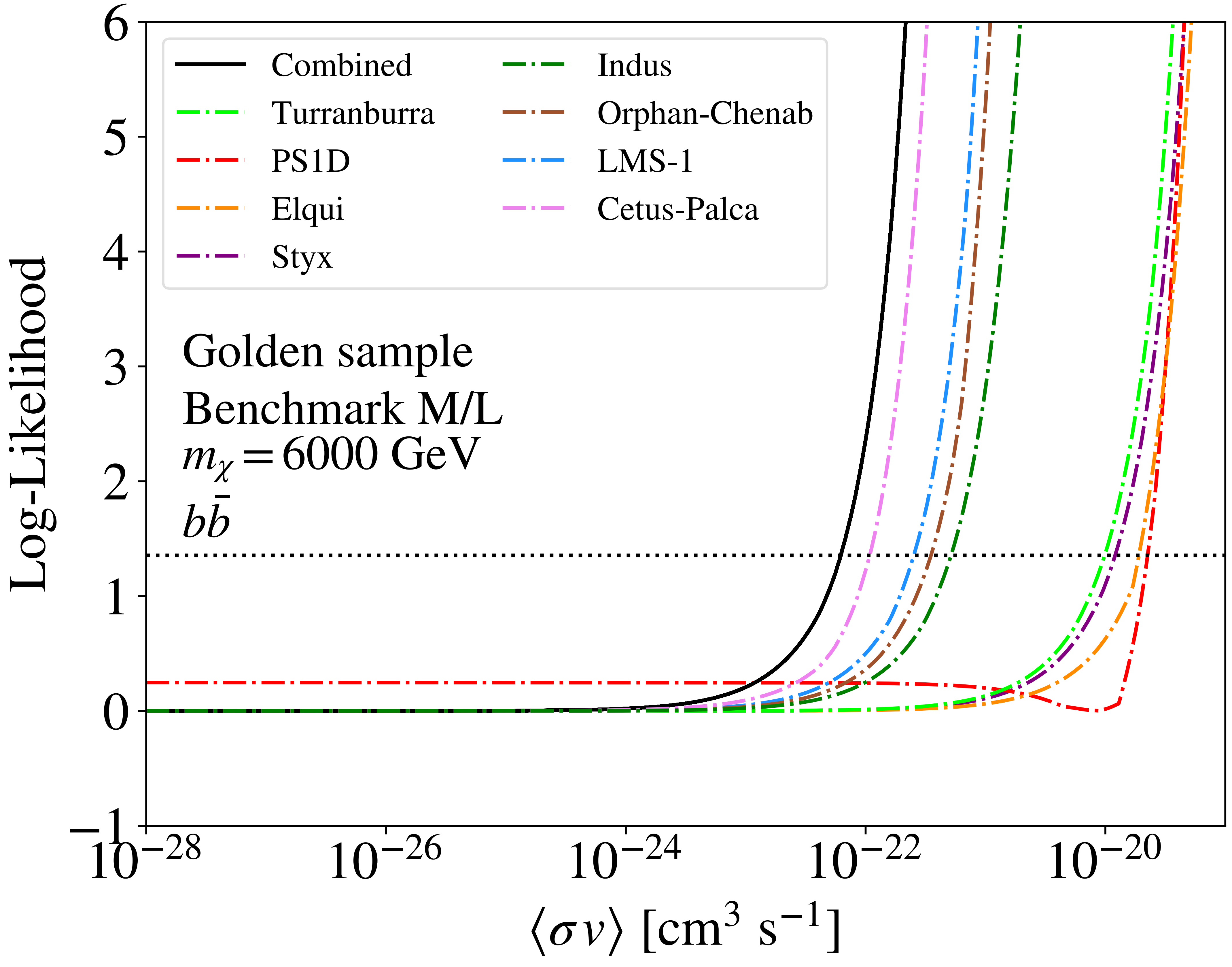

Example of the log-likelihood profiles for a particular DM mass and annihilation channel

The value of $\langle \sigma v \rangle$ for which $\Delta \mathscr{L} = 2.71/2$ is used to set the 95% C.L. upper limits on $\langle \sigma v \rangle$

DM constraints:
Golden Sample, Benchmark case

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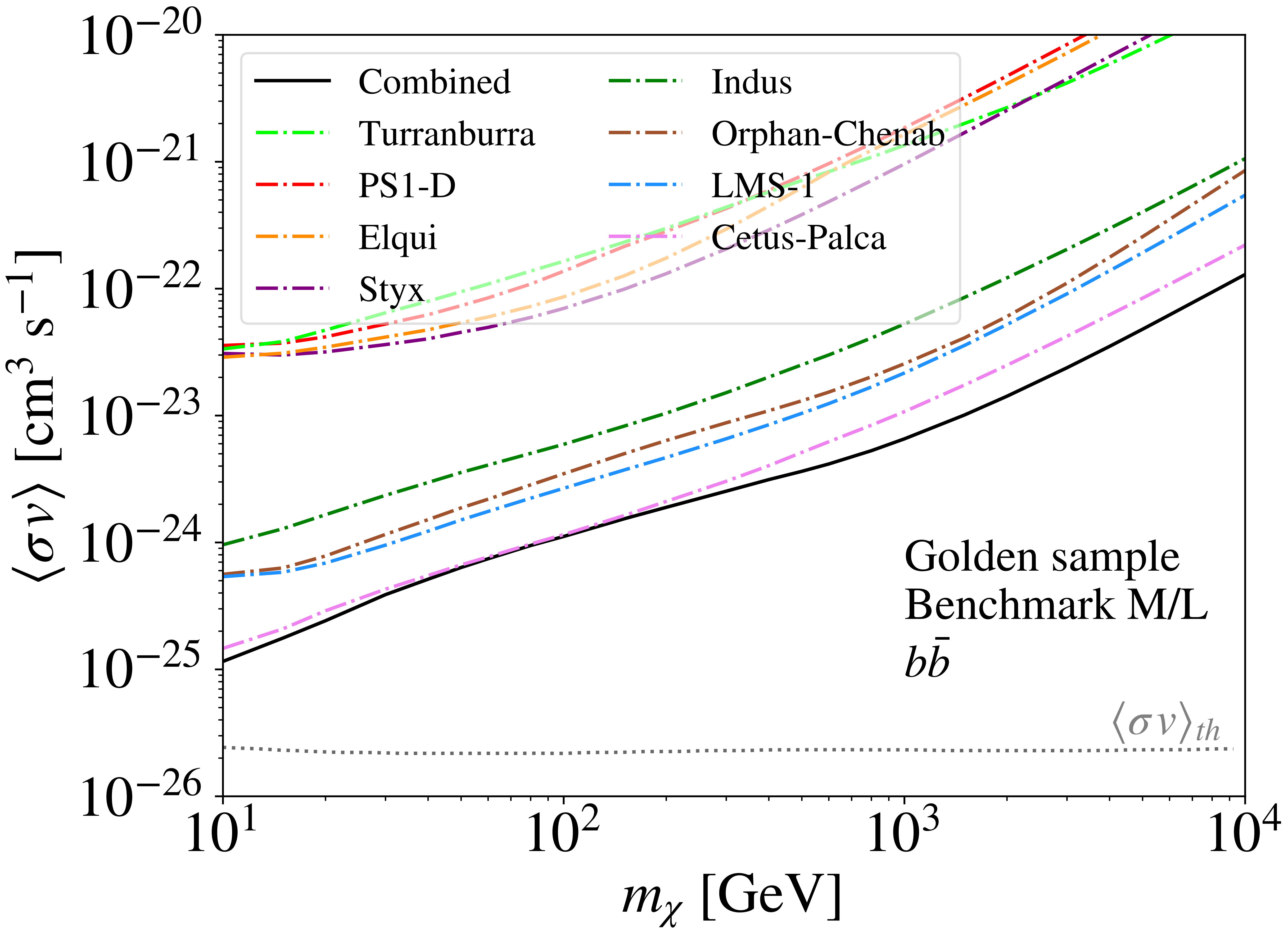
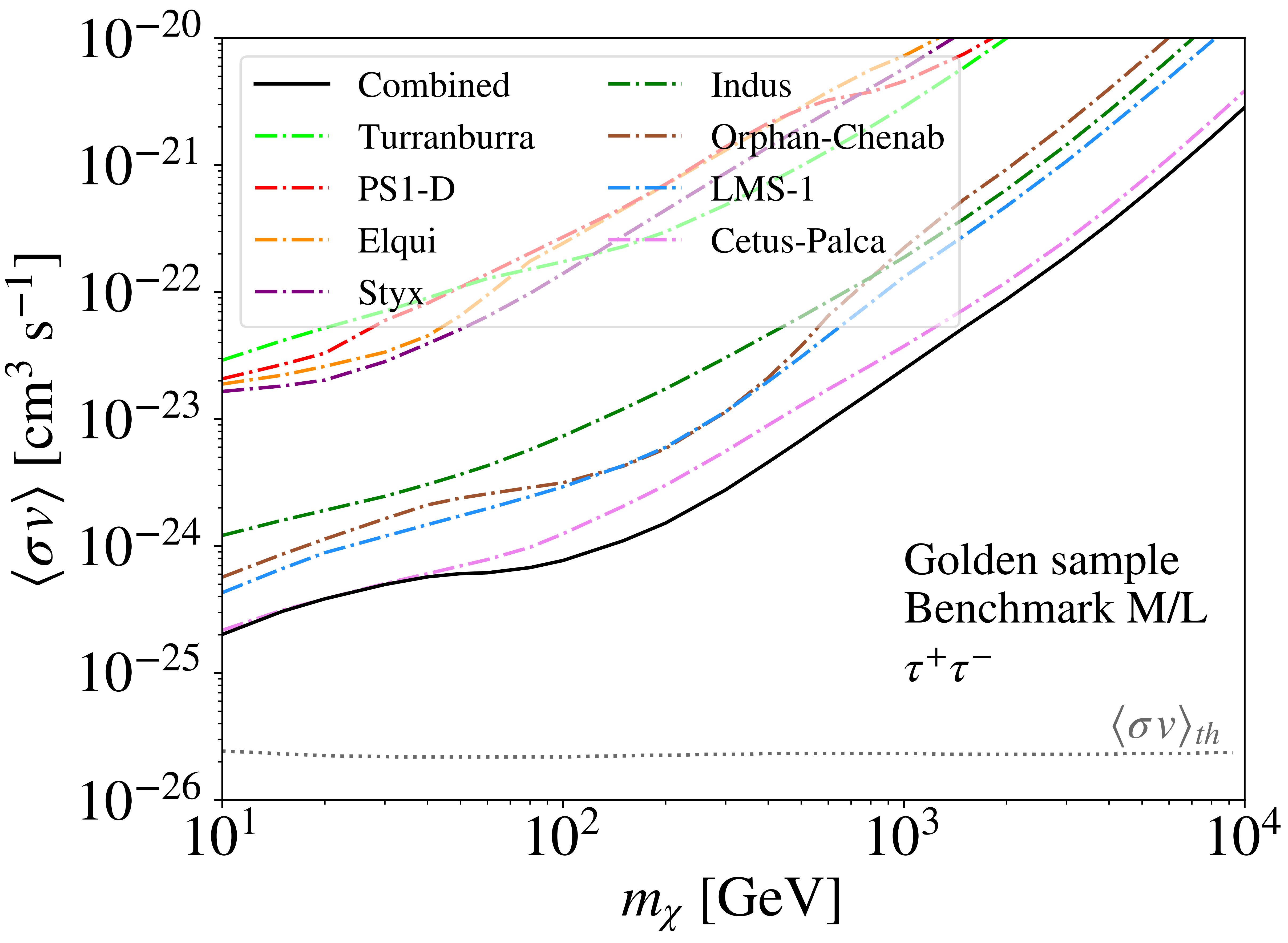
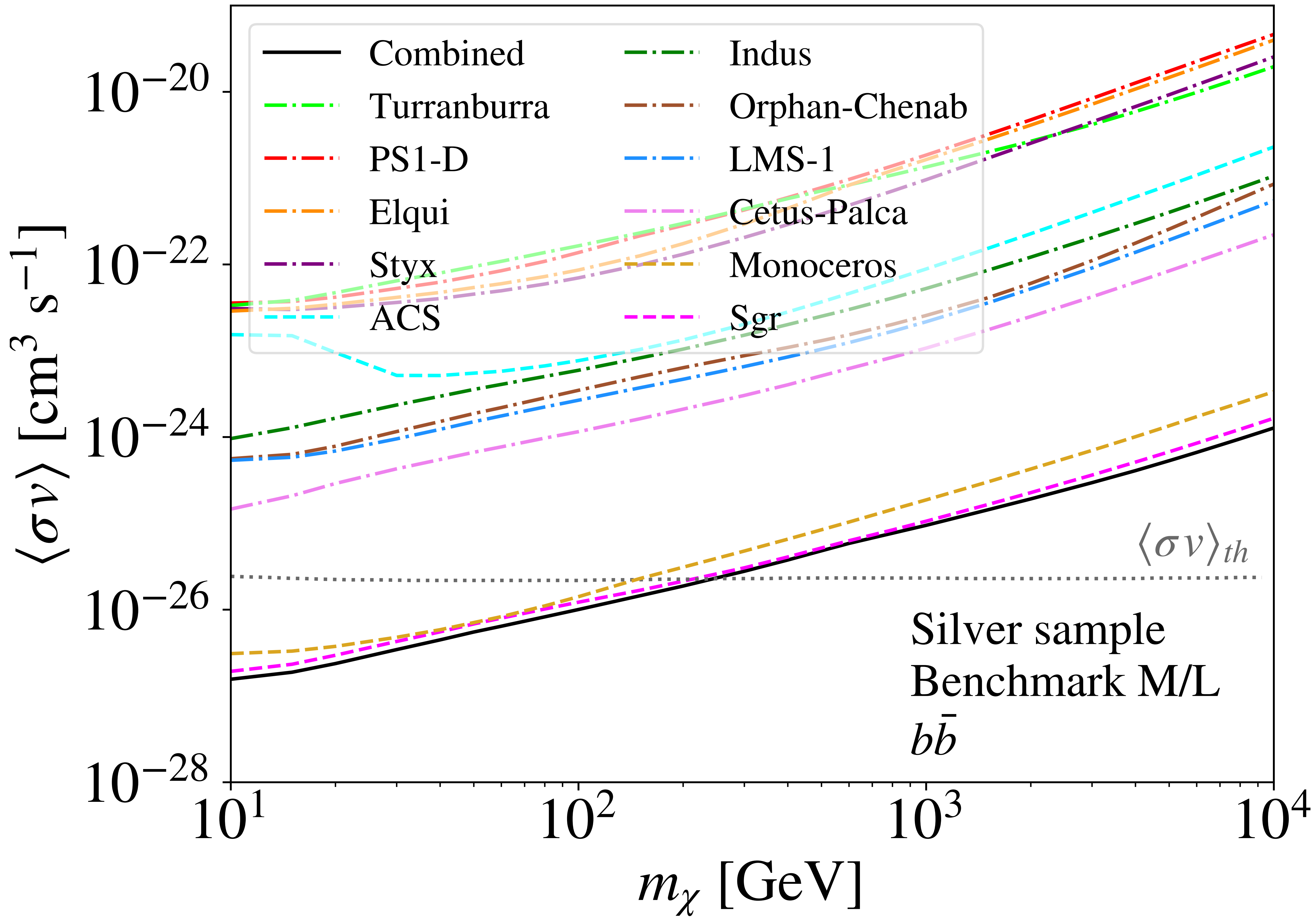


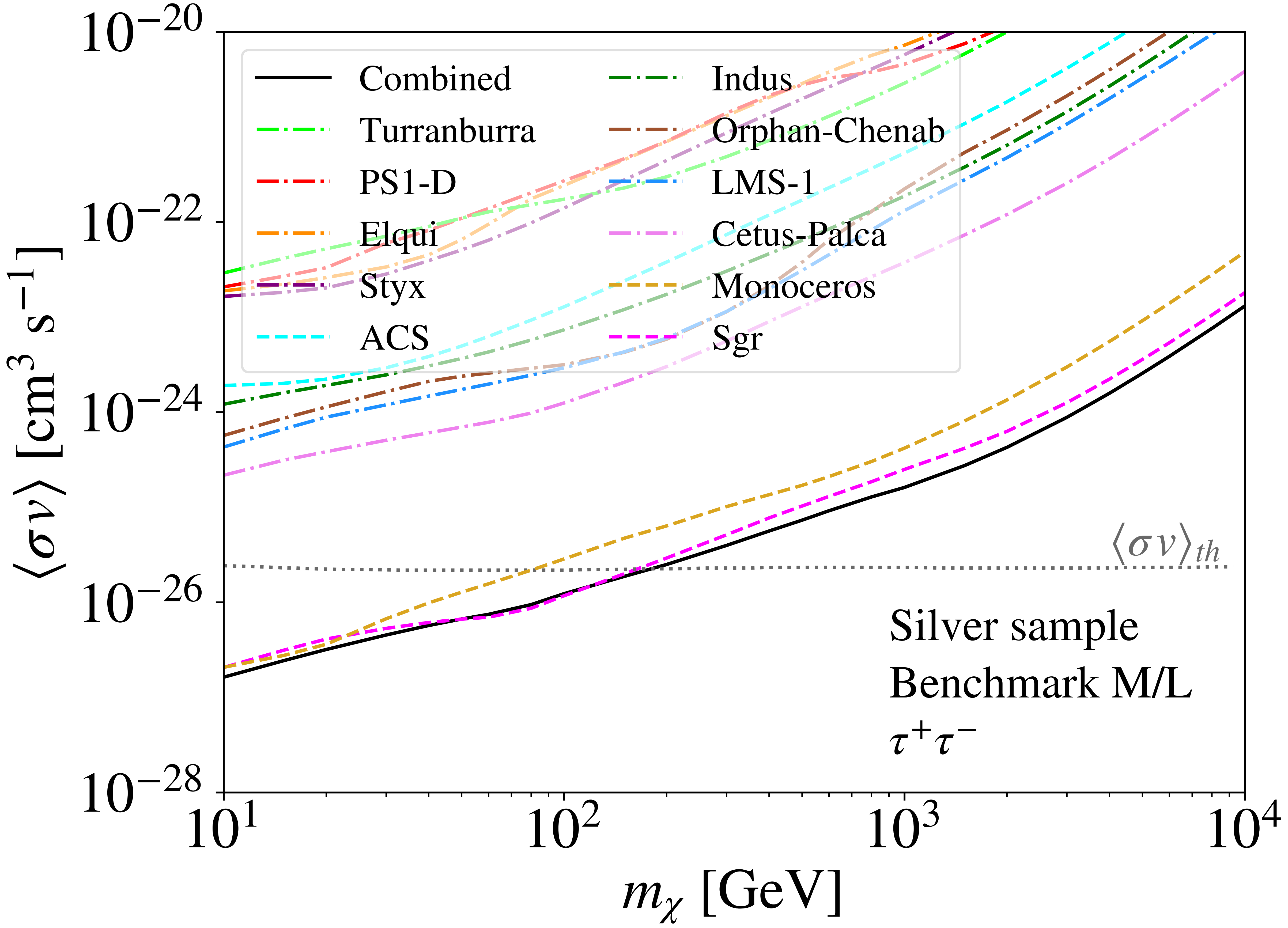


- The Cetus-Palca stream dominates the combined result.
- The combined constraints are $\mathcal{O}(10)$ above the thermal relic cross-section for the lowest considered WIMP masses and both channels.

DM constraints: Silver Sample, Benchmark case

CFS & Sánchez-Conde
arXiv: 2502.15656





- The Monoceros and Sagittarius streams dominate the combined DM limits.
- This sample allows to rule out WIMPs up to ~ 200 GeV for both channels.

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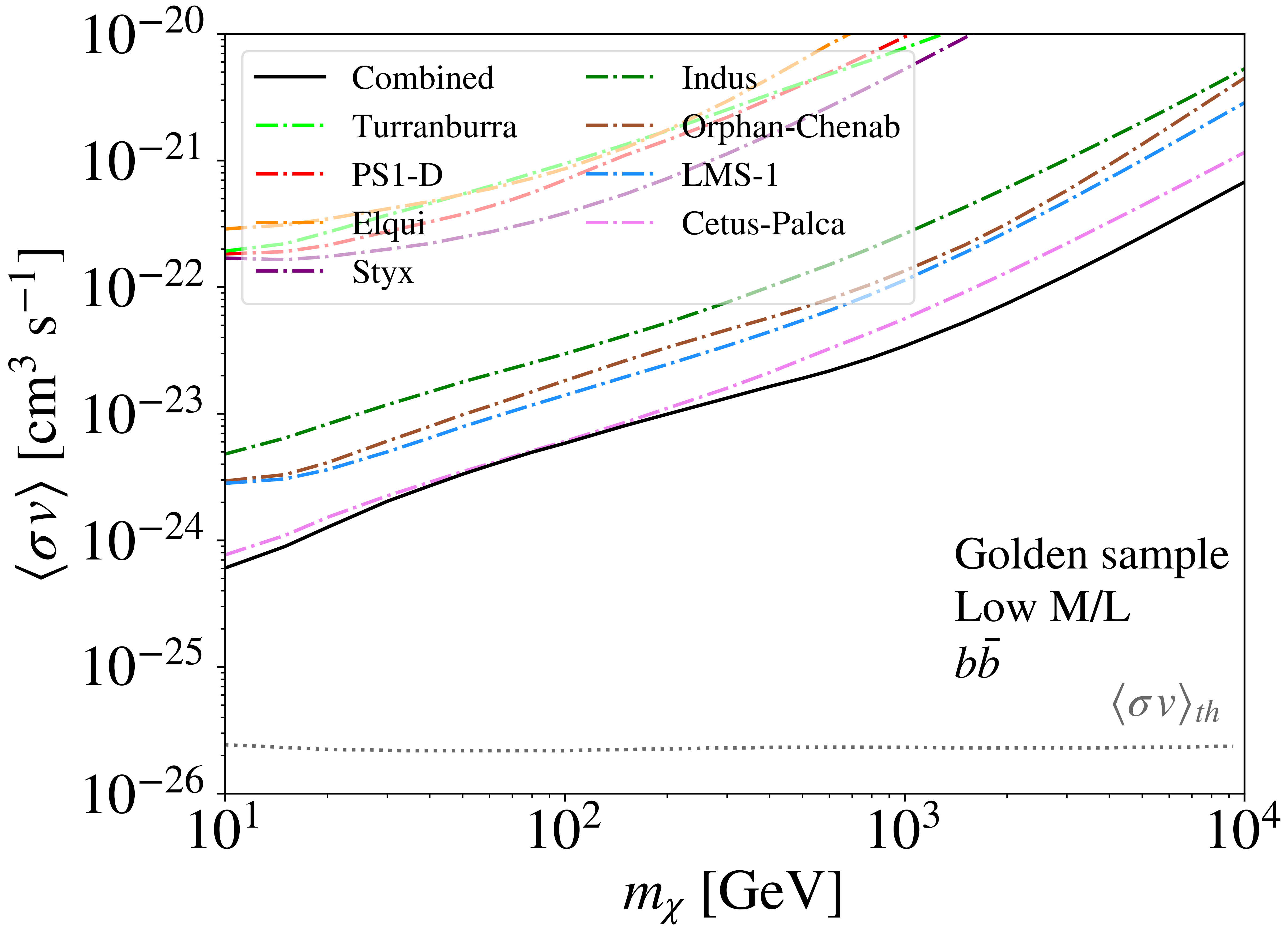
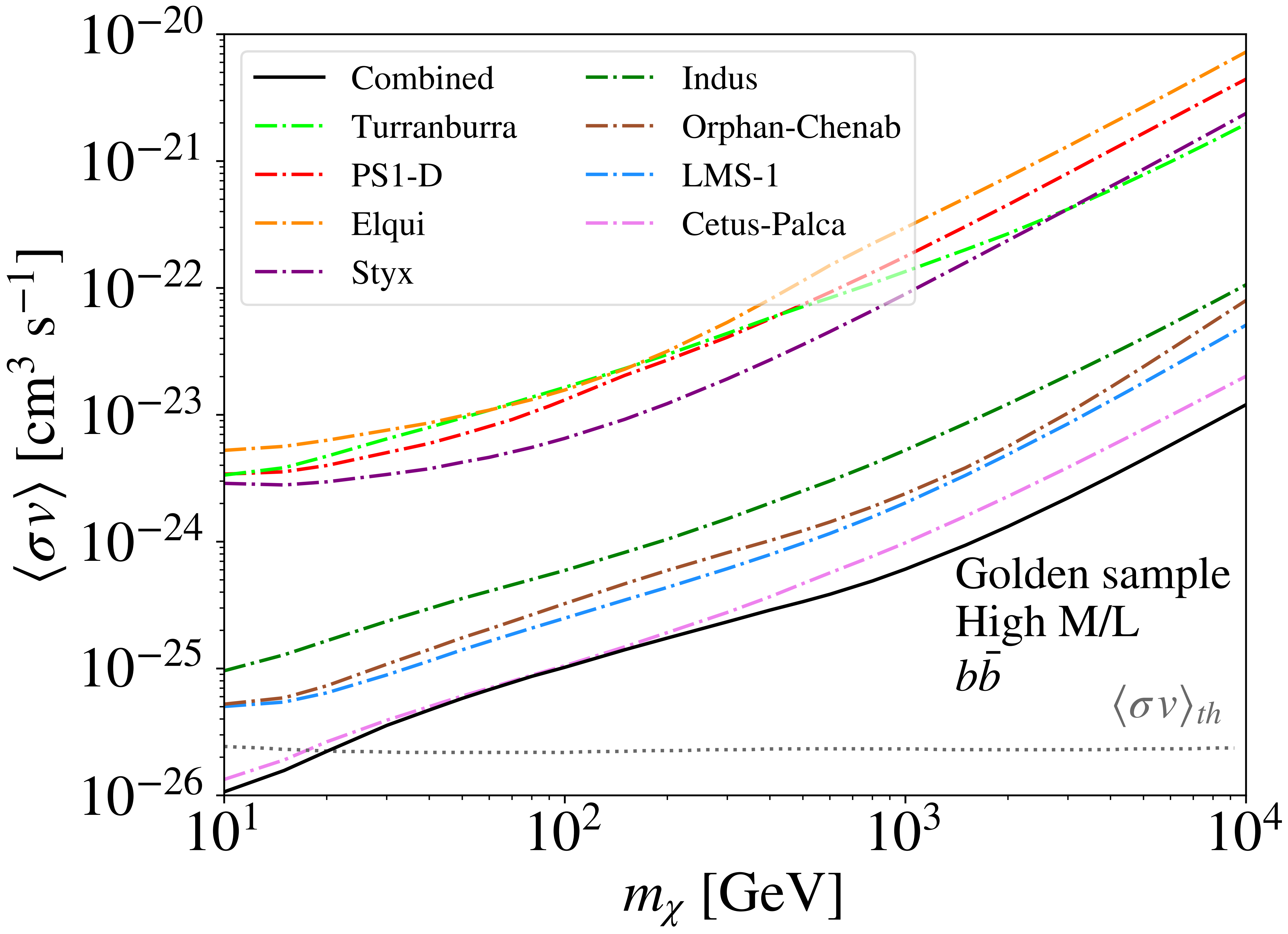
DM constraints: Golden Sample, Low and High cases





DM constraints: Golden Sample, Low and High cases

CFS & Sánchez-Conde
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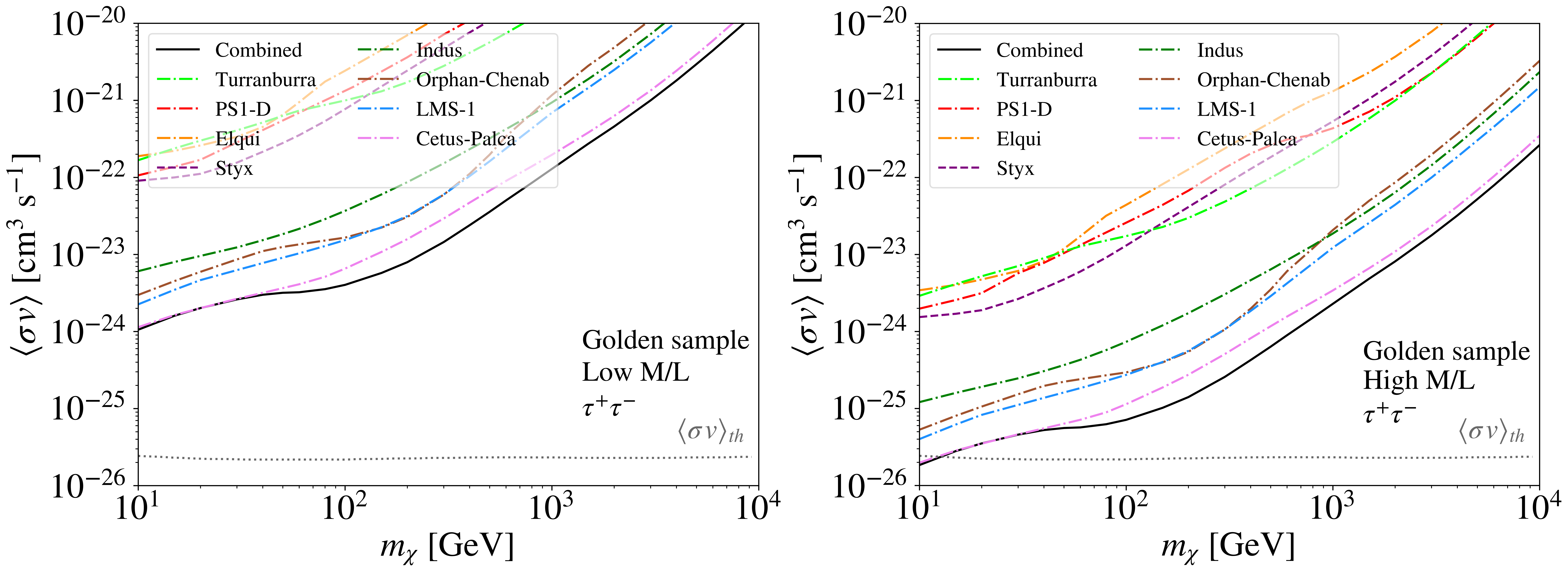
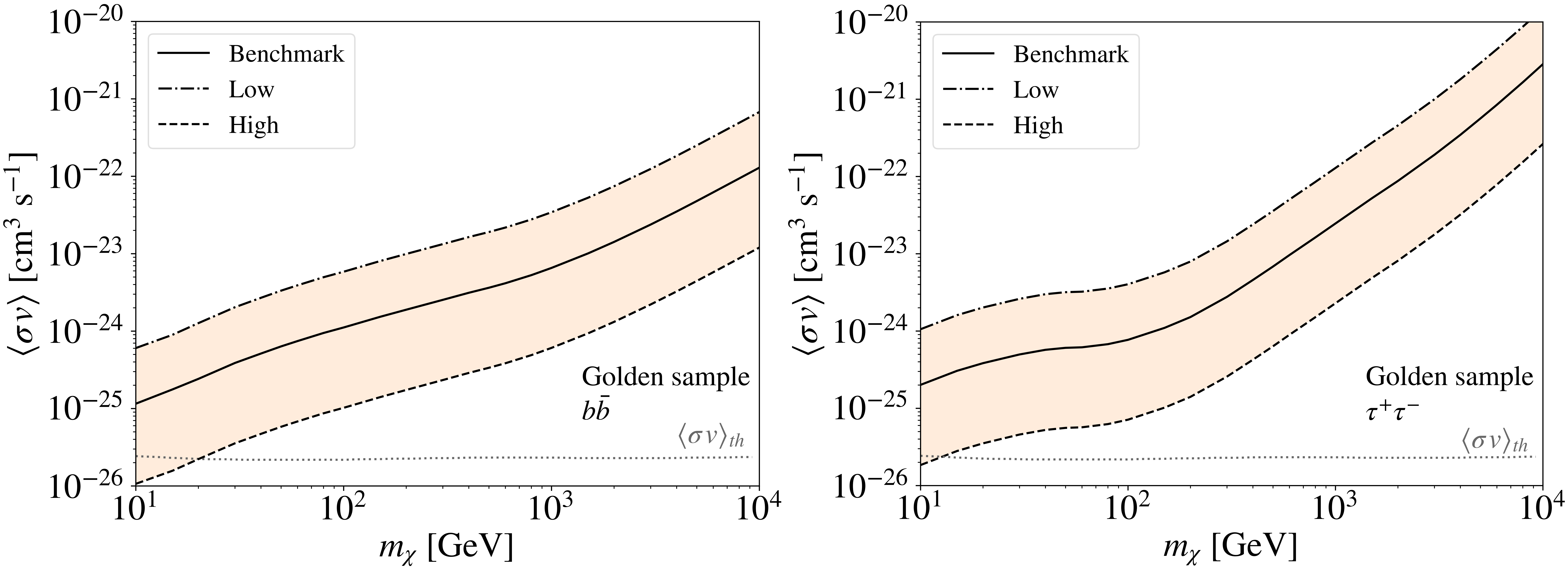


DM constraints: Golden Sample, M/L scenarios



- Overall uncertainty of $\mathcal{O}(100)$ in the DM limits.
- The combined constraints for the Benchmark scenario are $\mathcal{O}(10)$ above the thermal relic cross-section for the lowest considered WIMP masses and both channels.
- DM limits reach the thermal relic cross-section at lower masses when considering the High scenario.

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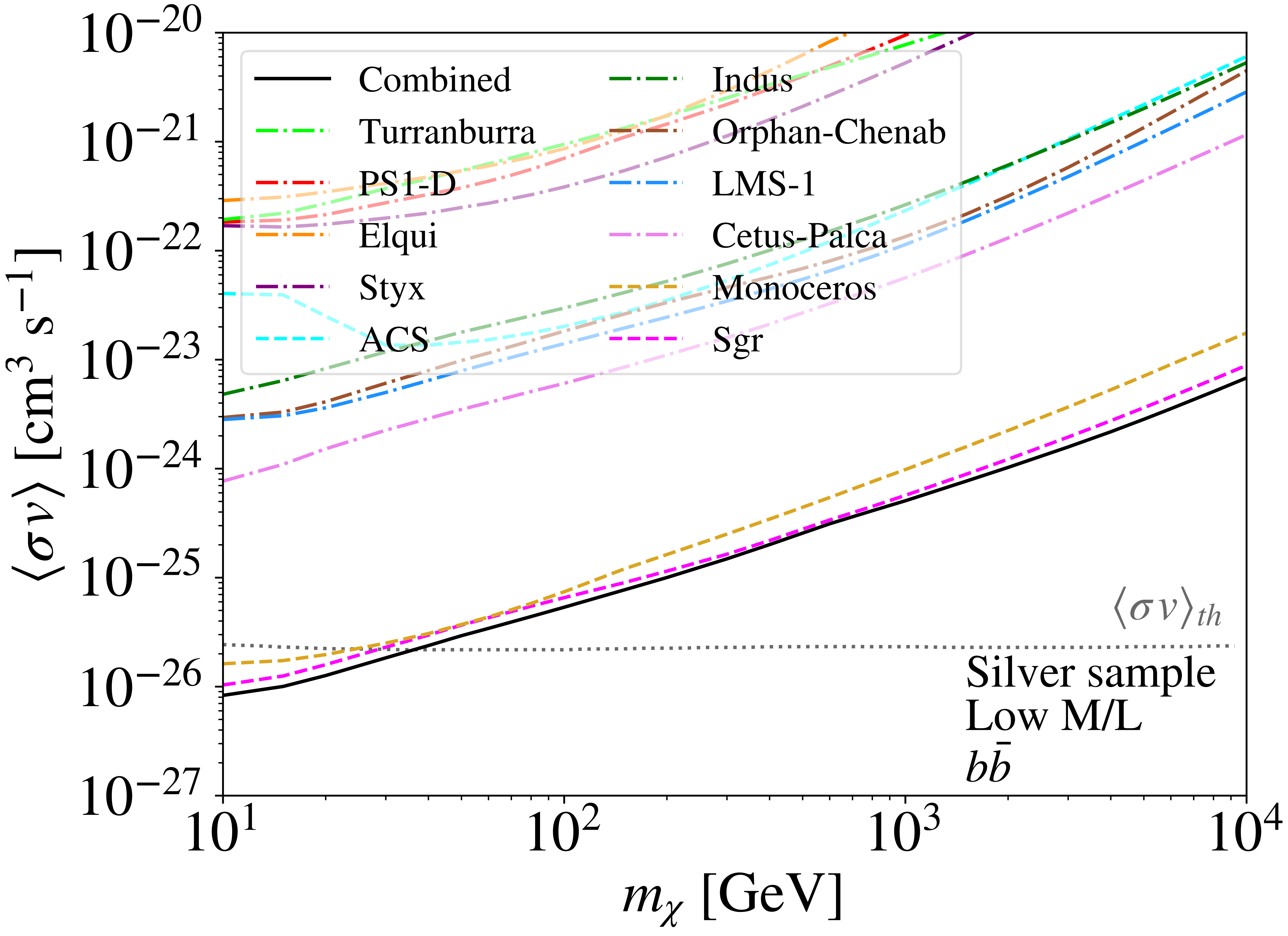
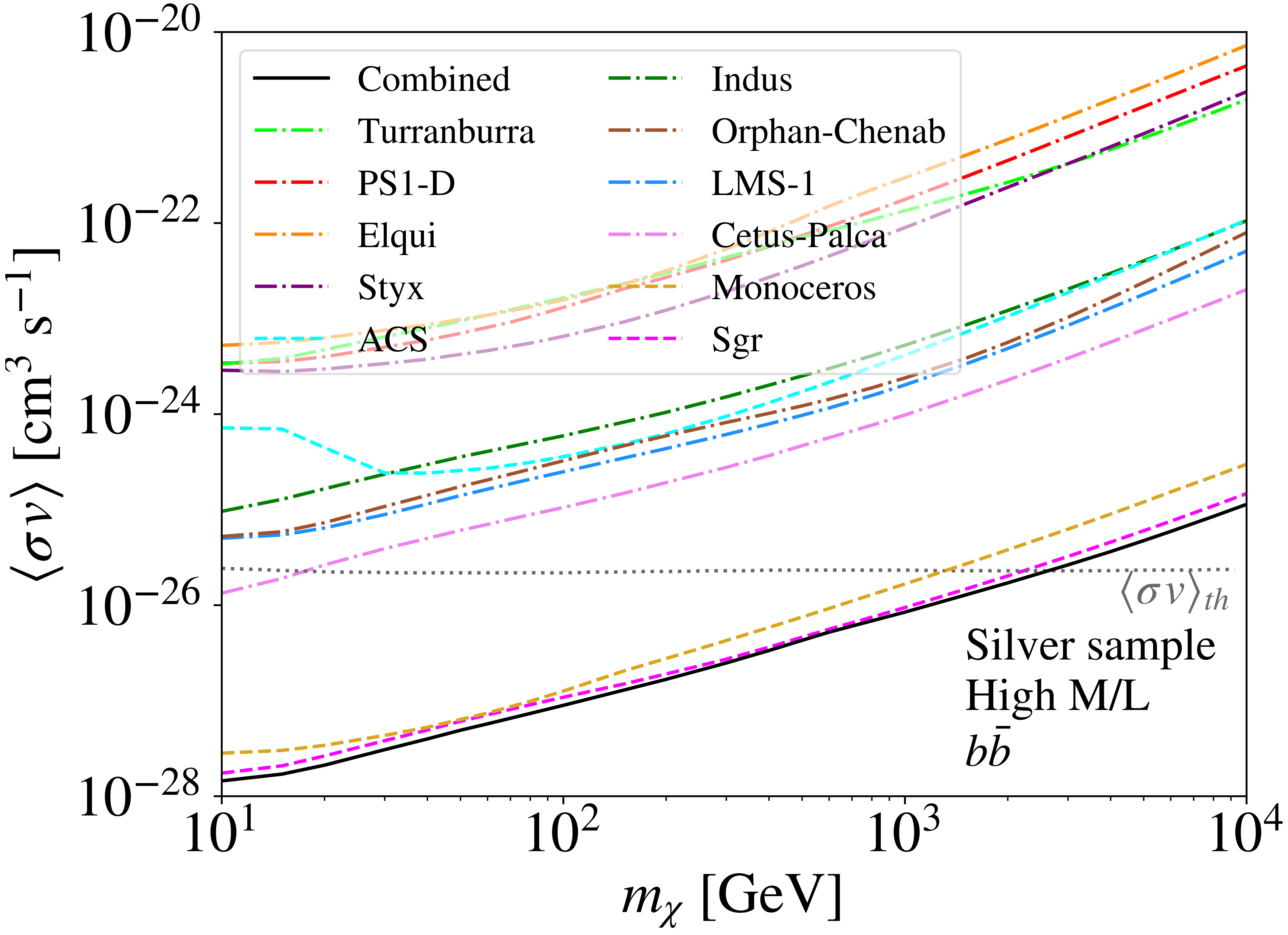
DM constraints: Silver Sample, Low and High cases





DM constraints: Silver Sample, Low and High cases

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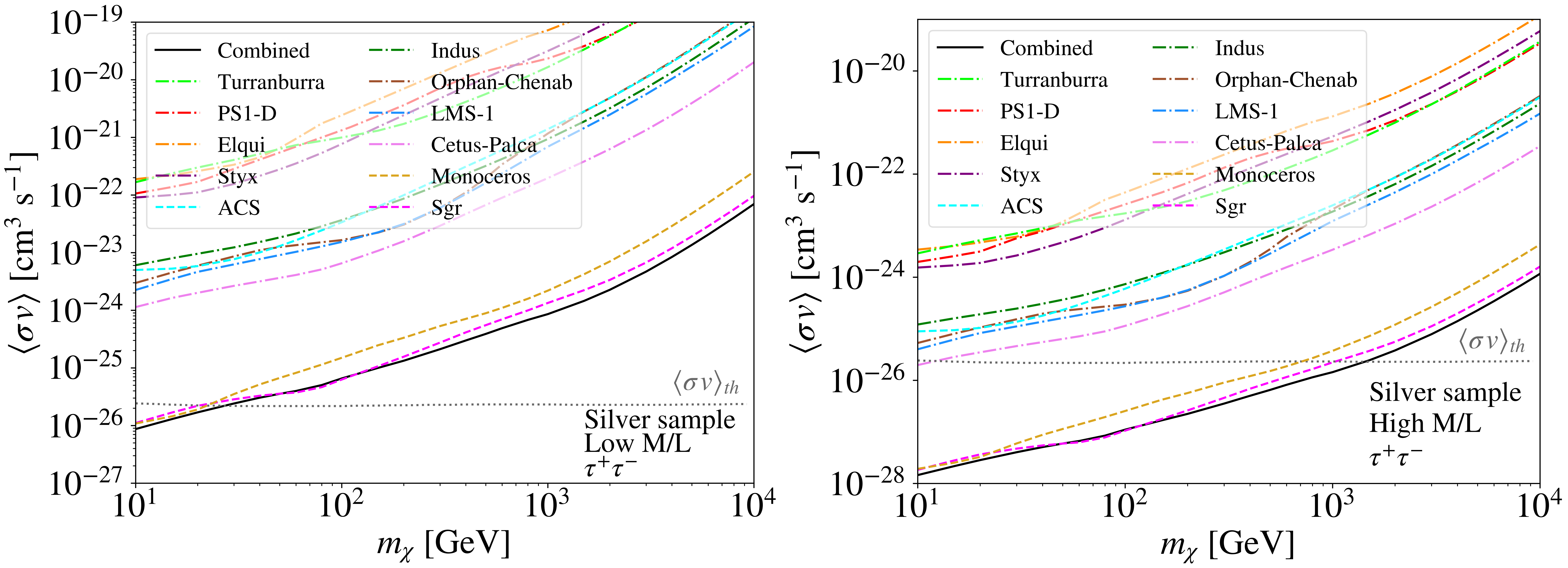
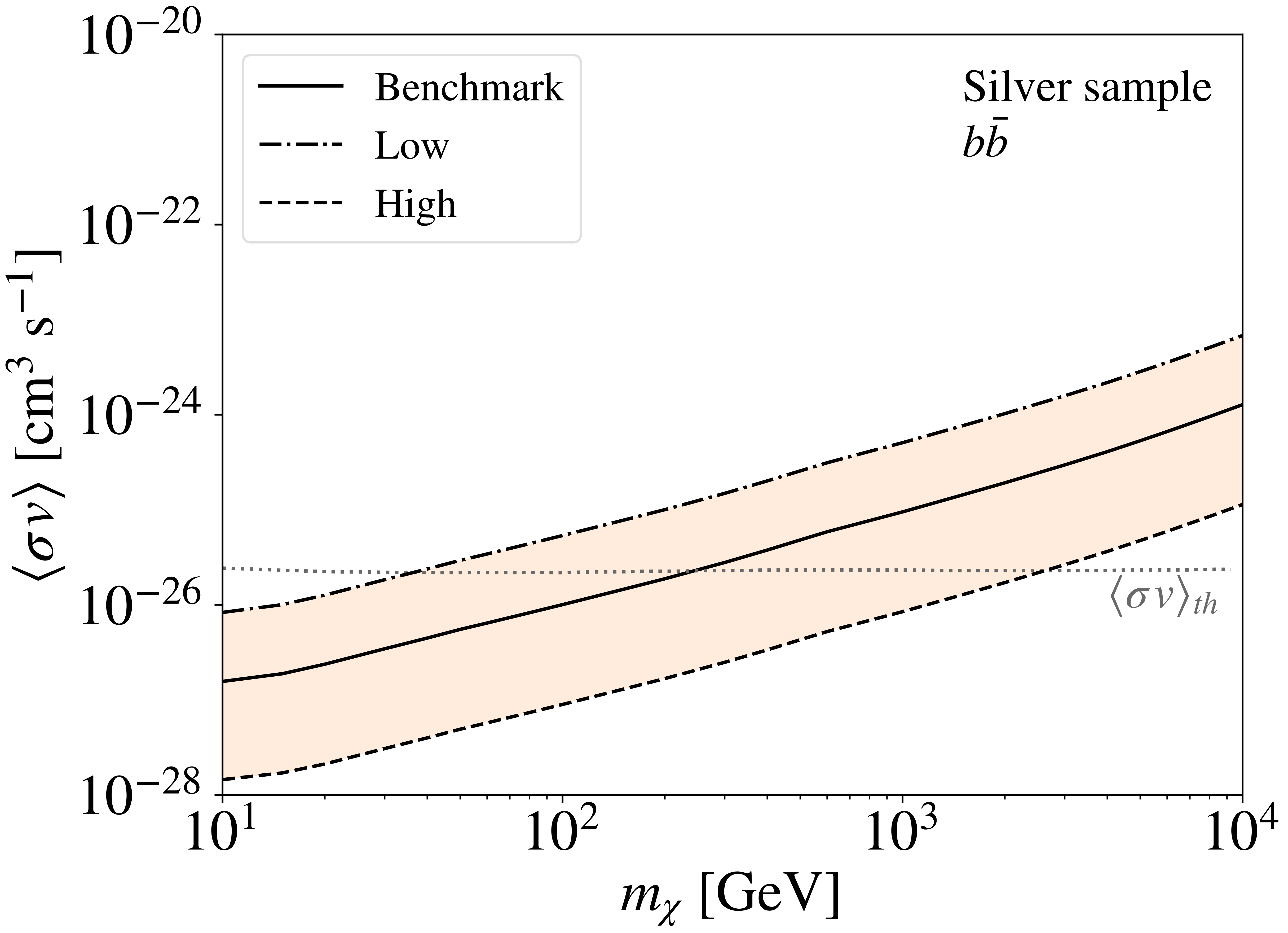
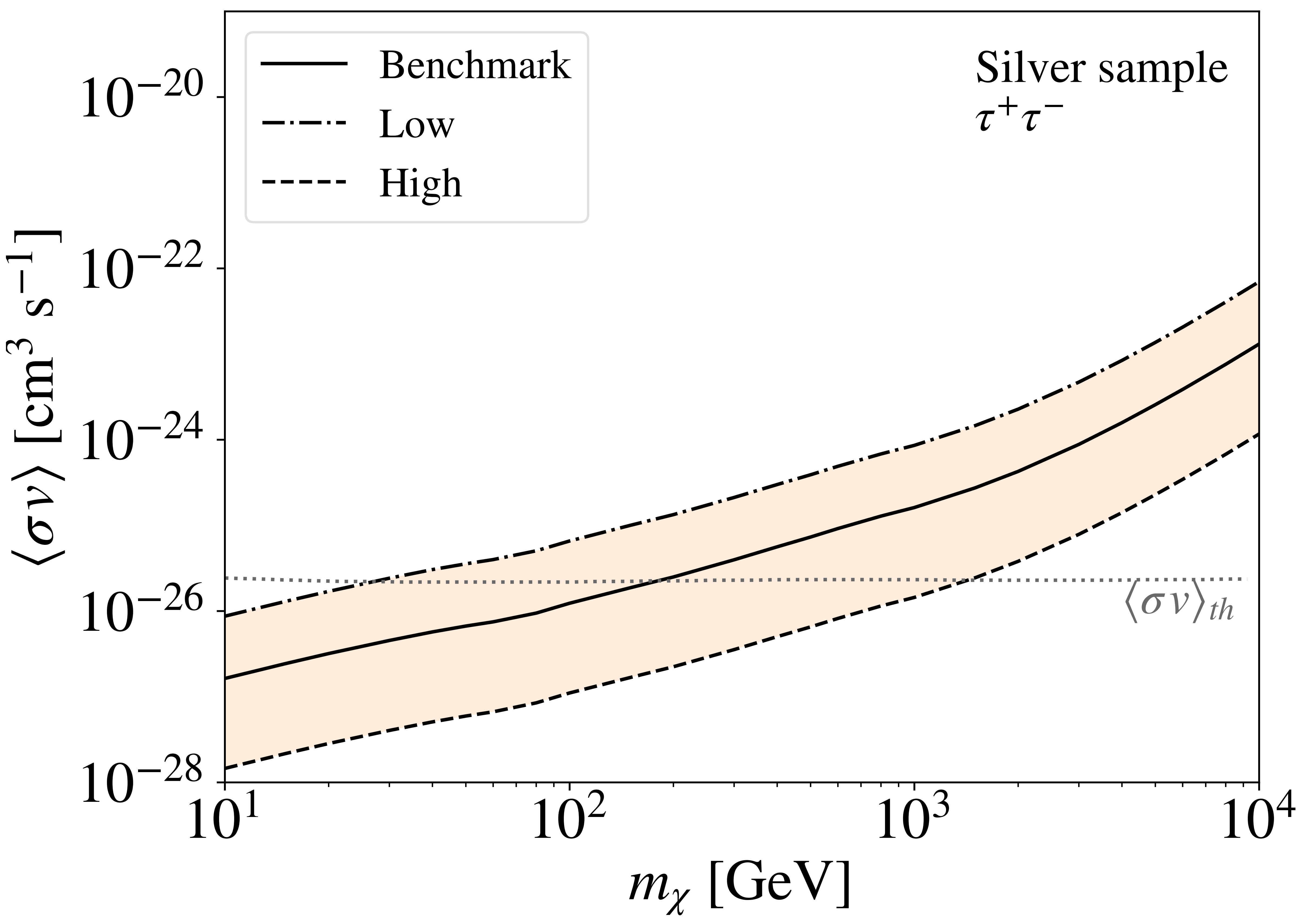


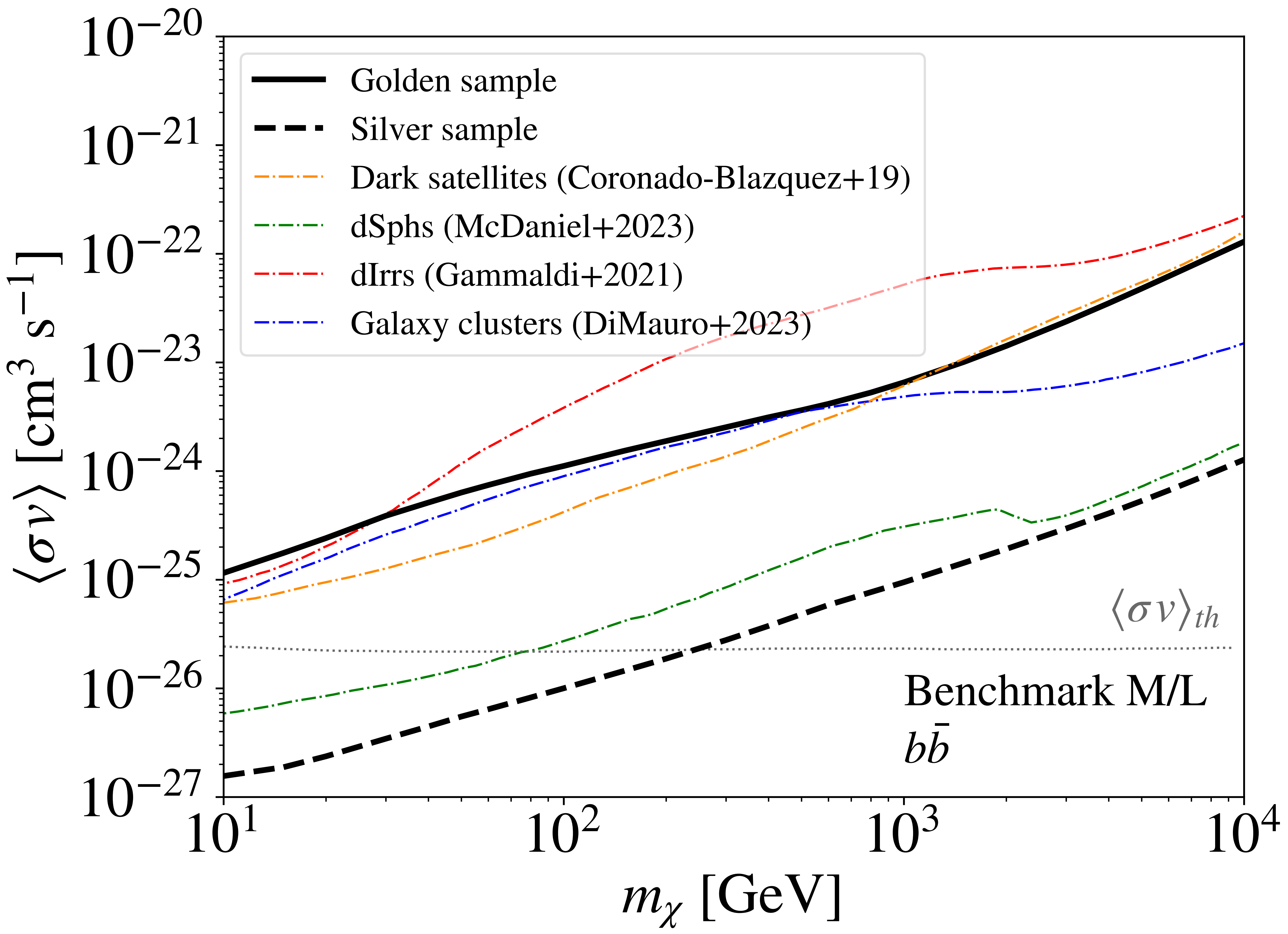
CFS & Sánchez-Conde
arXiv: 2502.15656

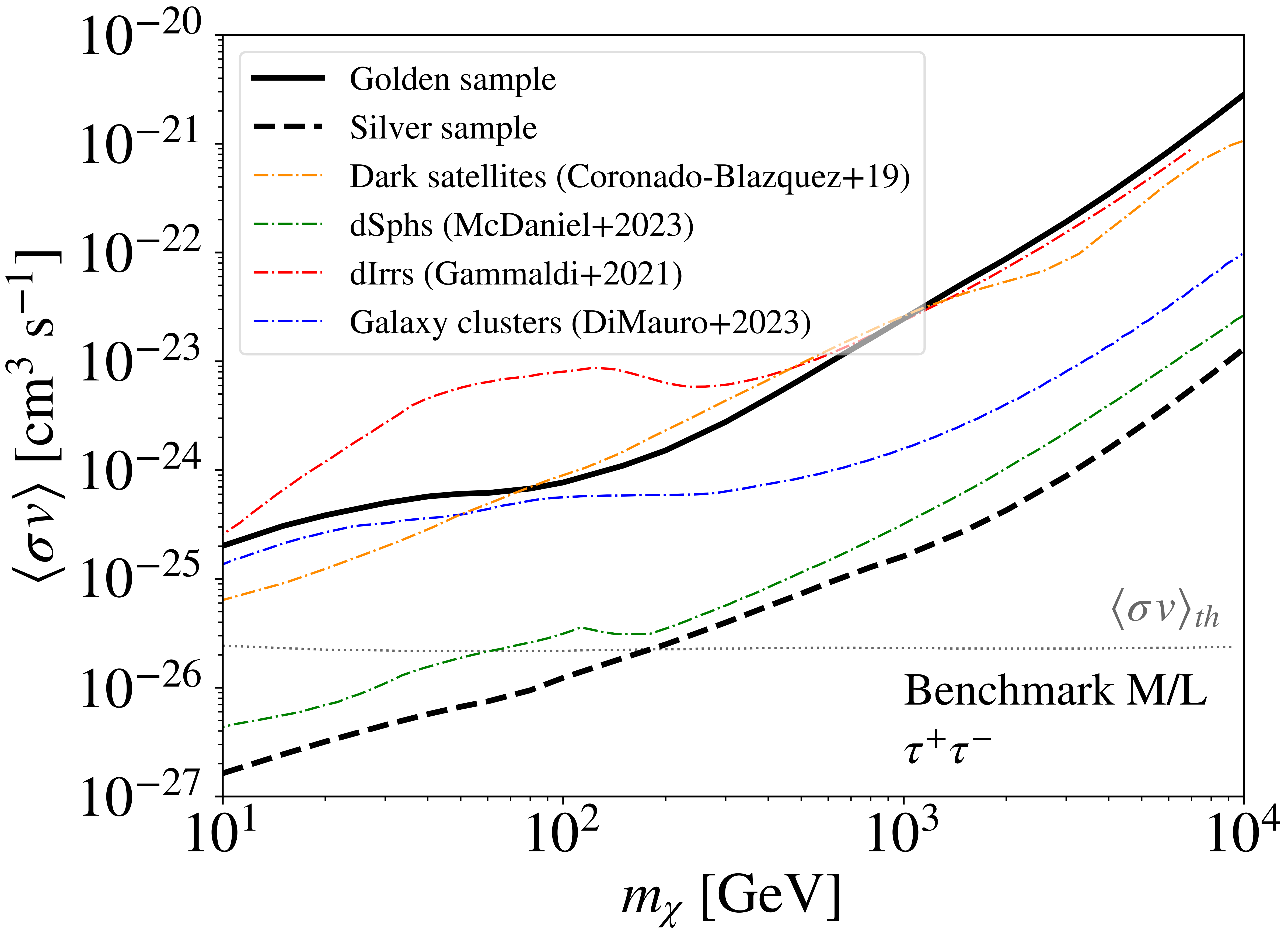
DM constraints: Silver Sample, M/L scenarios





DM constraints: Comparison with other targets





- The ***golden*** sample of streams improve the limits achieved with dIrr galaxies, while they are similar to those for galaxy clusters and dark satellites.
- Results for the ***silver*** sample would be potentially comparable with those for dSphs.

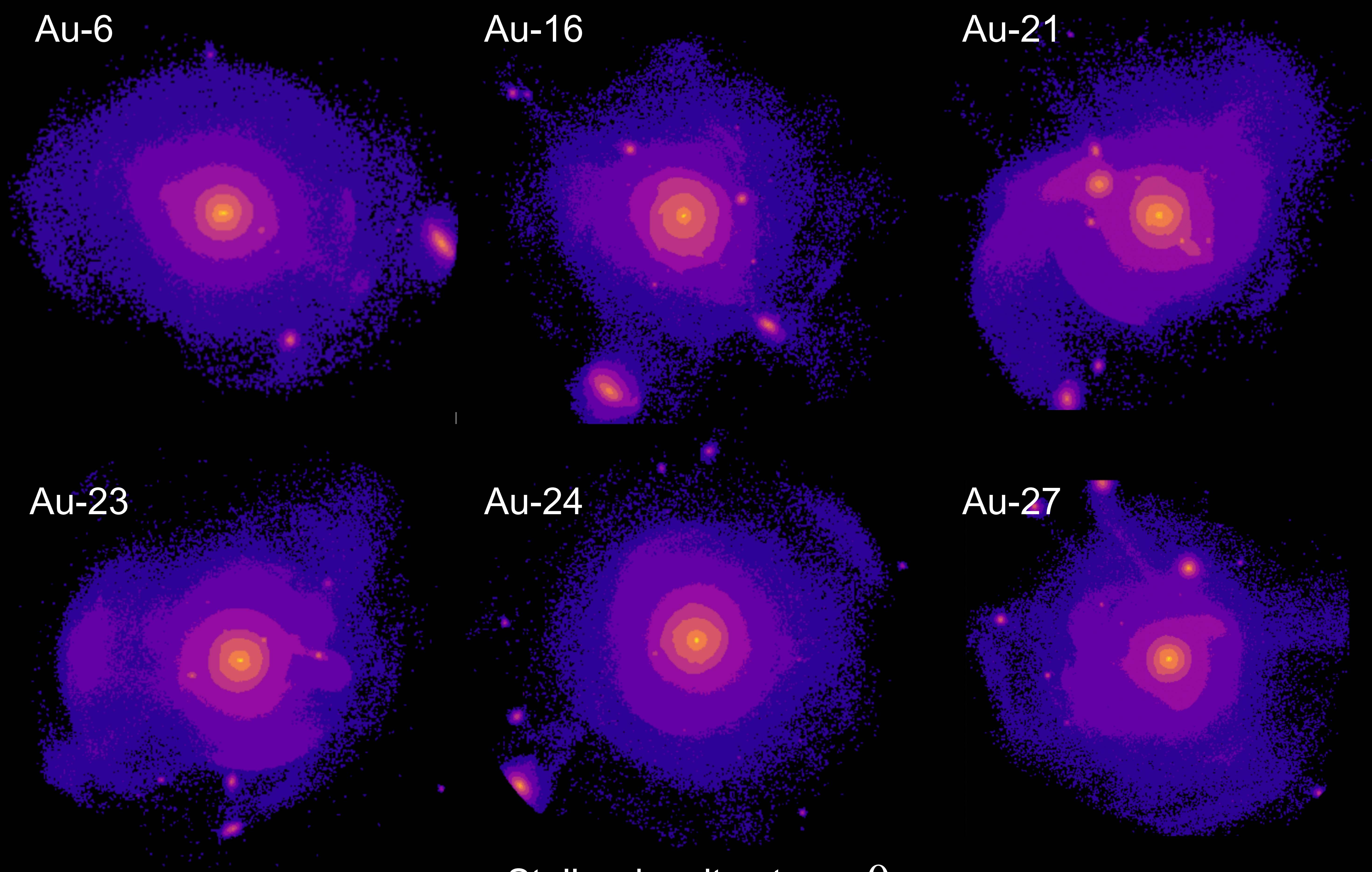
Auriga simulations

(Grand+2017. Grand+2024)

Auriga is a suite of cosmological magneto-hydrodynamic (MHD) zoom-in simulations of galaxy formation.

6 simulations of Milky Way-mass halos at ‘level 3’ high resolution (Au-6, Au-16, Au-21, Au-23, Au-24, Au-27).

(Baryonic mass particle resolution: $6.7 \times 10^3 M_\odot$, DM particle mass resolution: $3.6 \times 10^4 M_\odot$, Softening length: 188 pc)



Stellar density at $z = 0$

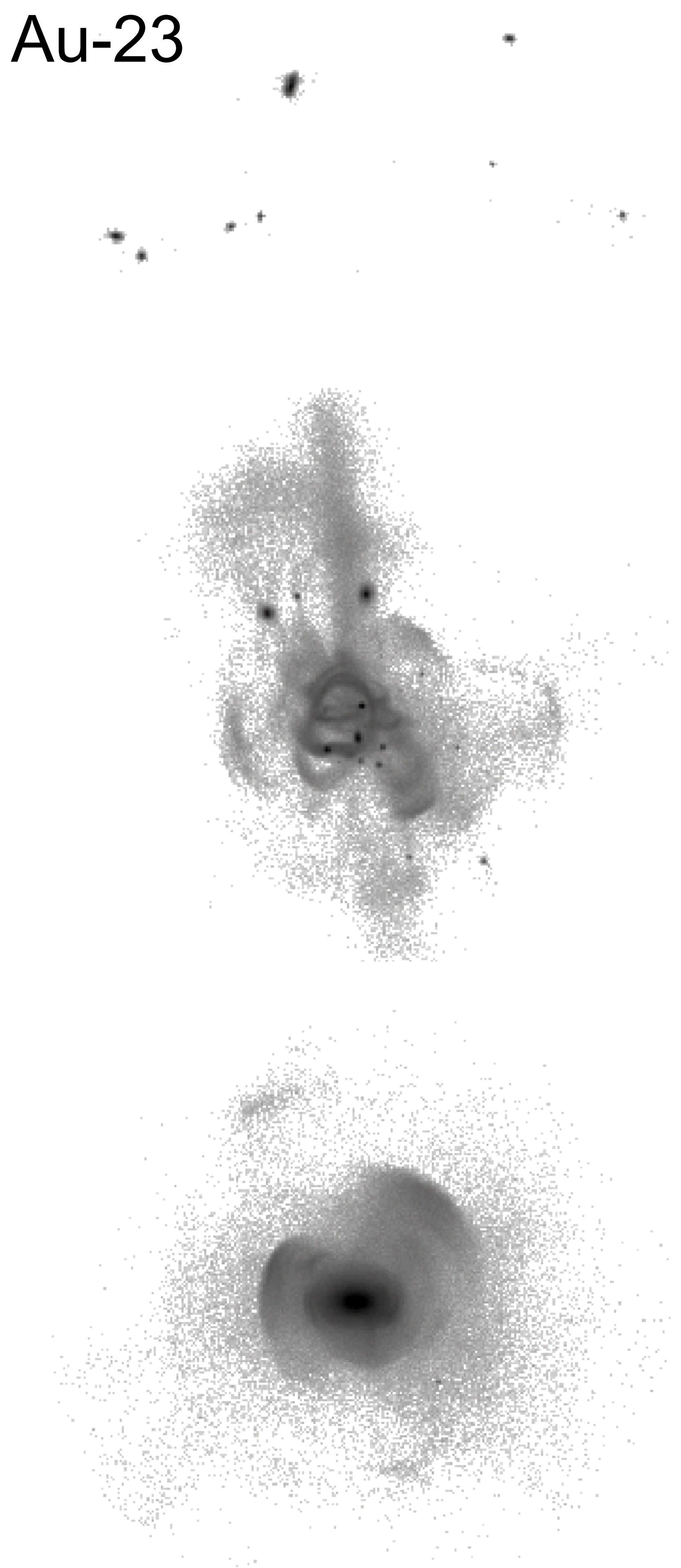
Identifying stellar streams in Auriga

✱ We adopt the catalogue presented in Riley et al. 2024 that classify accretion events as follows:

Intact: those subhalos that have experienced little or no disruption.

Stellar streams: they have experienced tidal disruption and produce coherent structures, having lost at least 3% of their stellar mass.

Phase-mixed: as disrupting satellites continue to evolve, they eventually become phase-mixed systems that are spatially smooth.

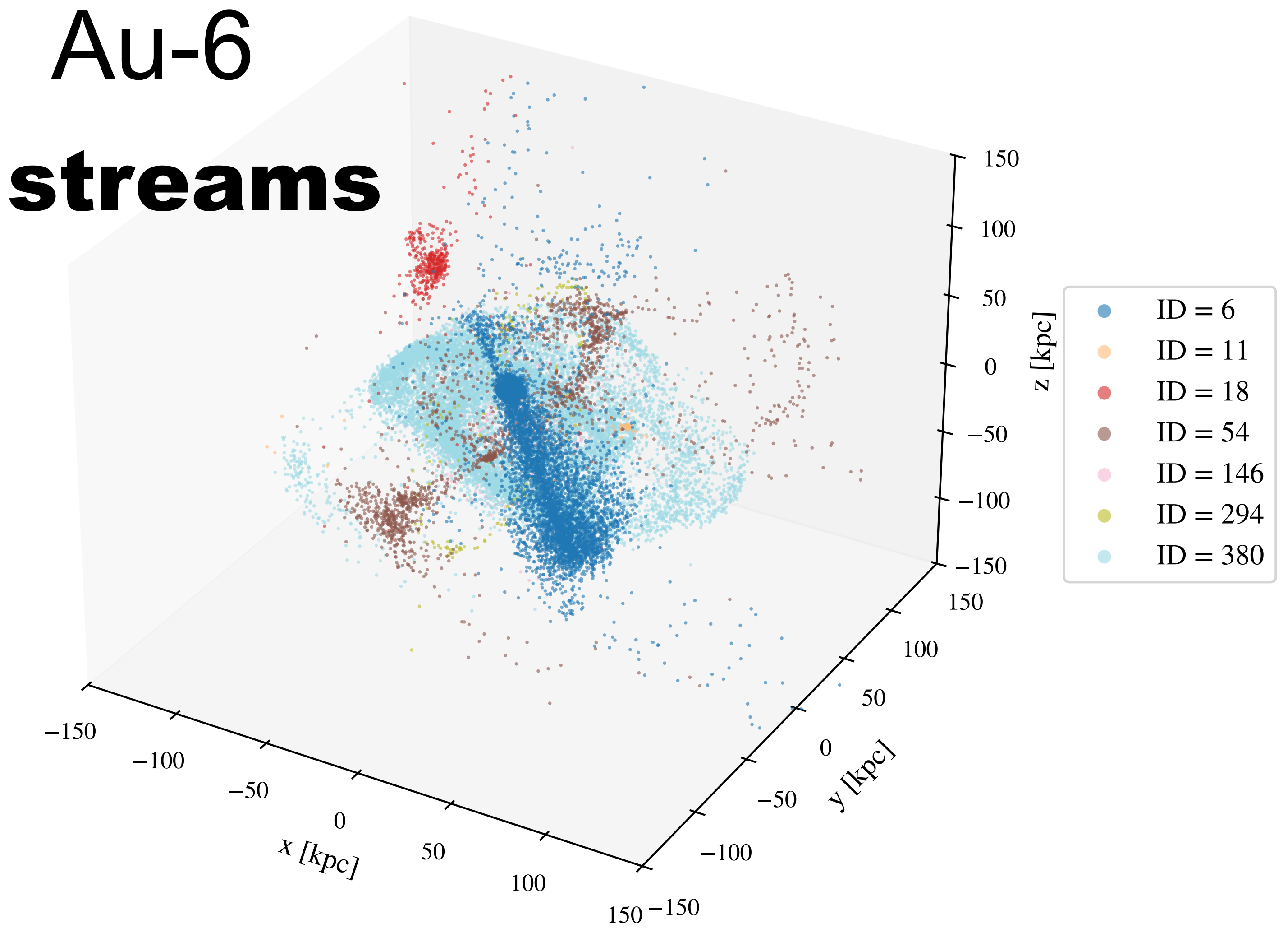


Riley et al. 2024

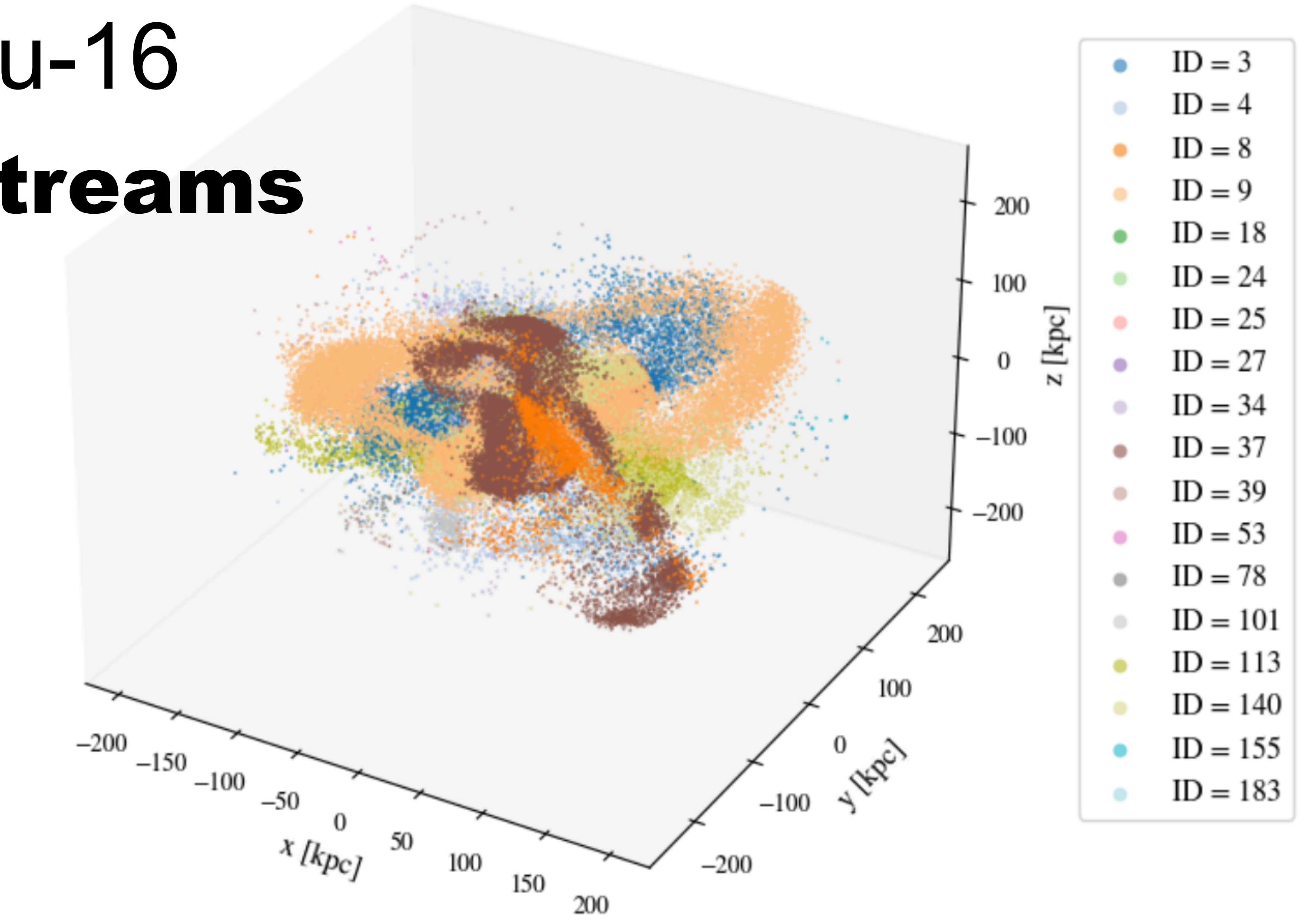
Auriga stellar streams

We adopt the catalogue presented in Riley+2024 to identify streams in Auriga

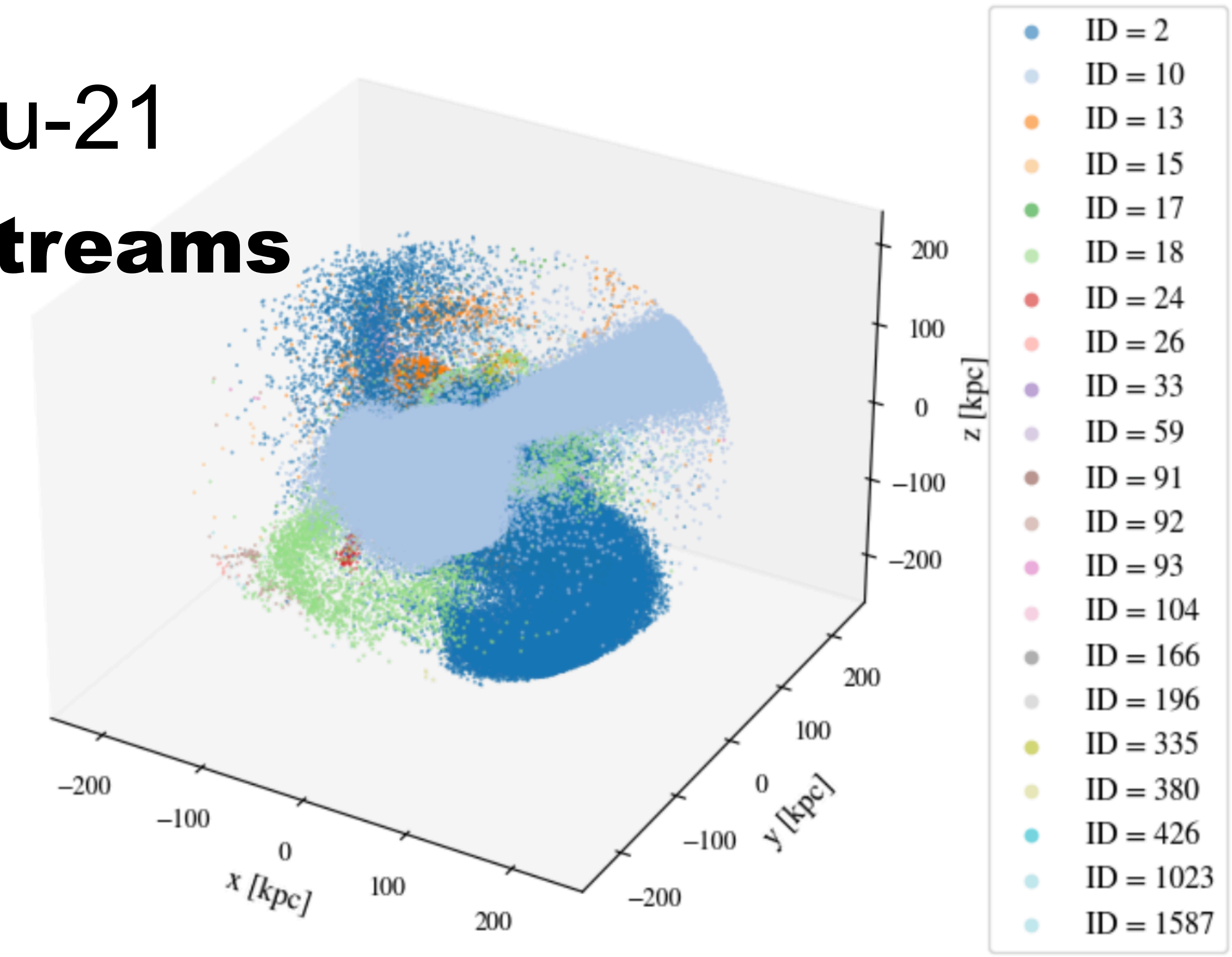
Au-6
7 streams



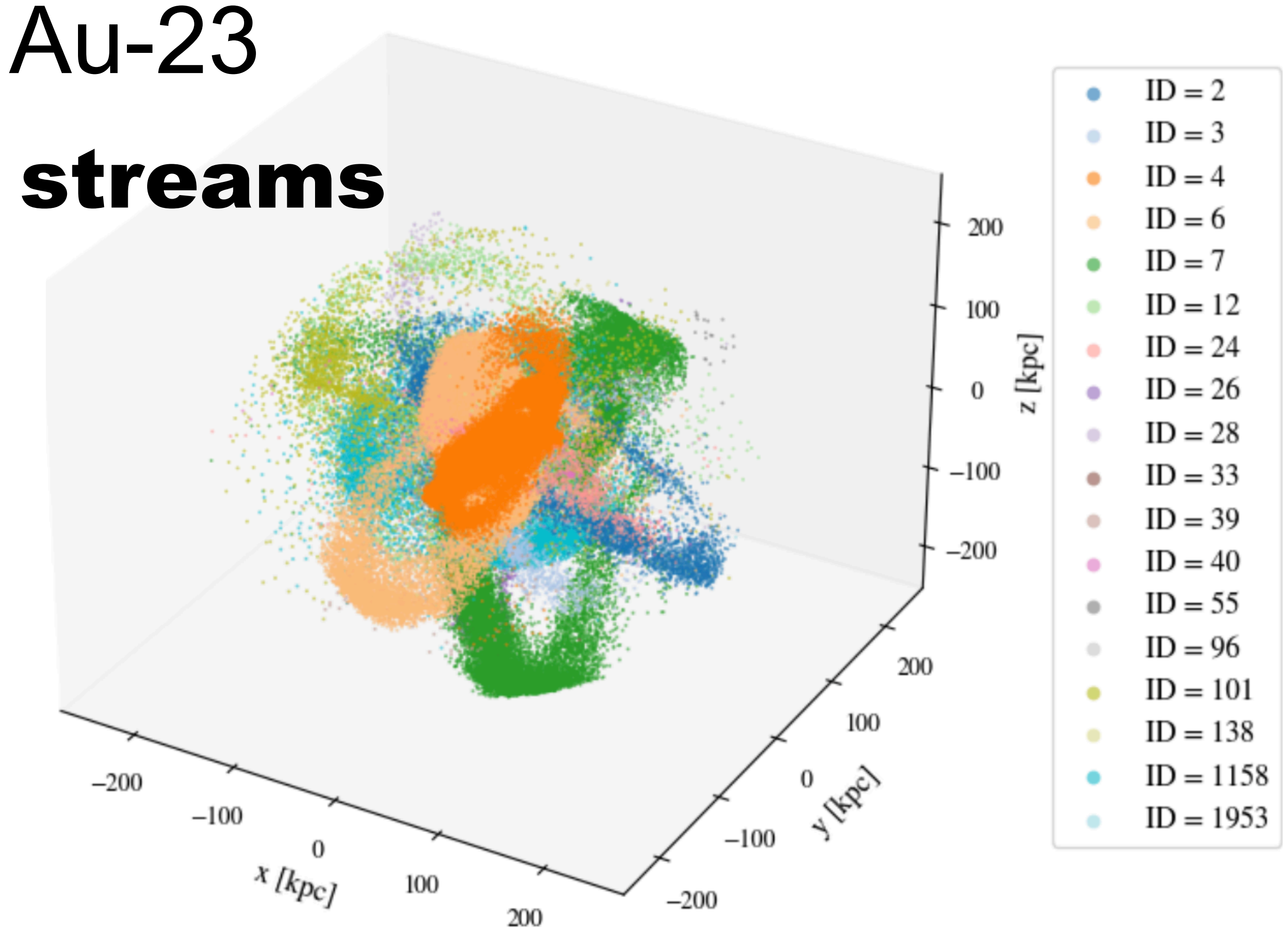
Au-16
18 streams



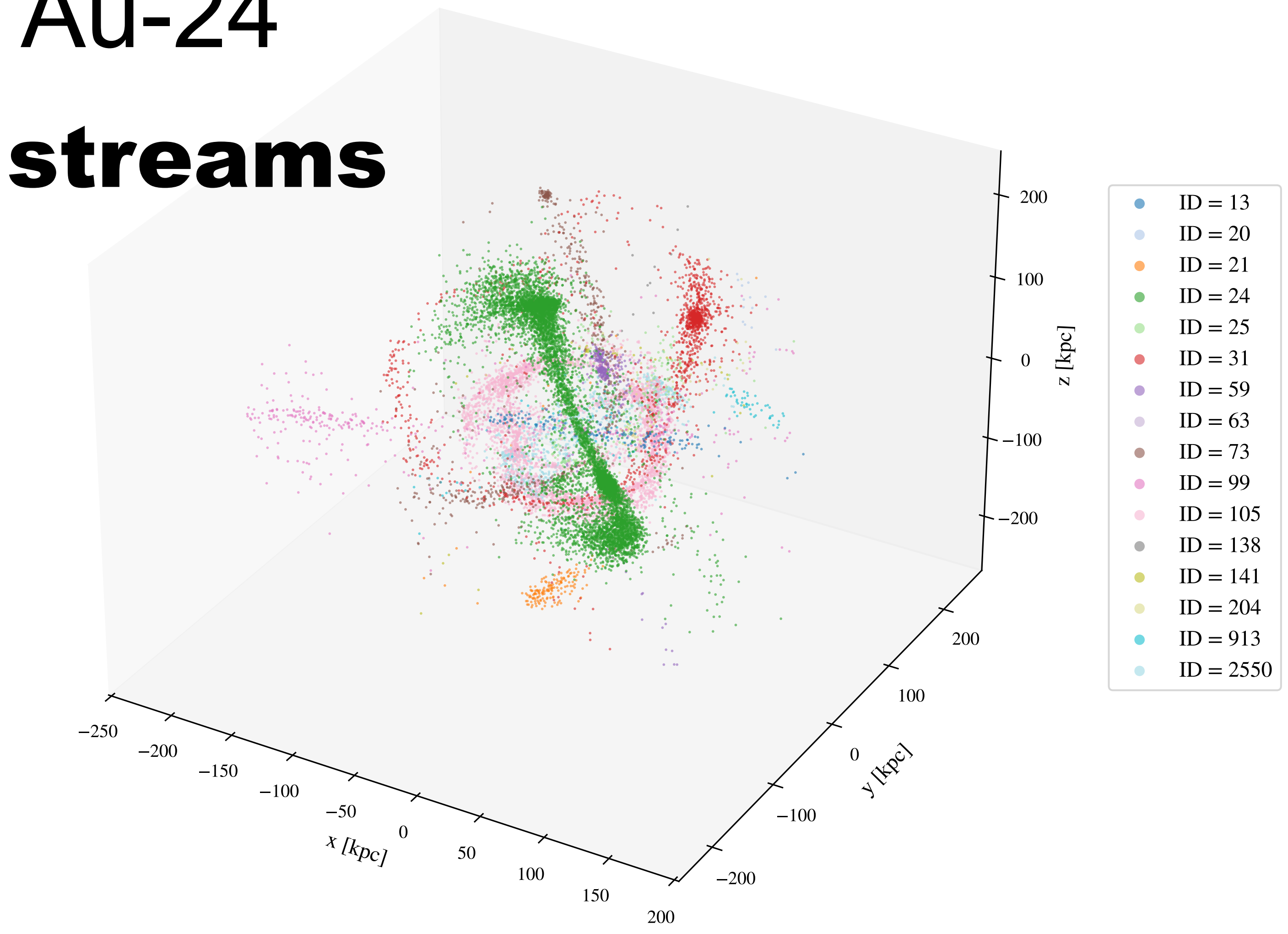
Au-21
21 streams



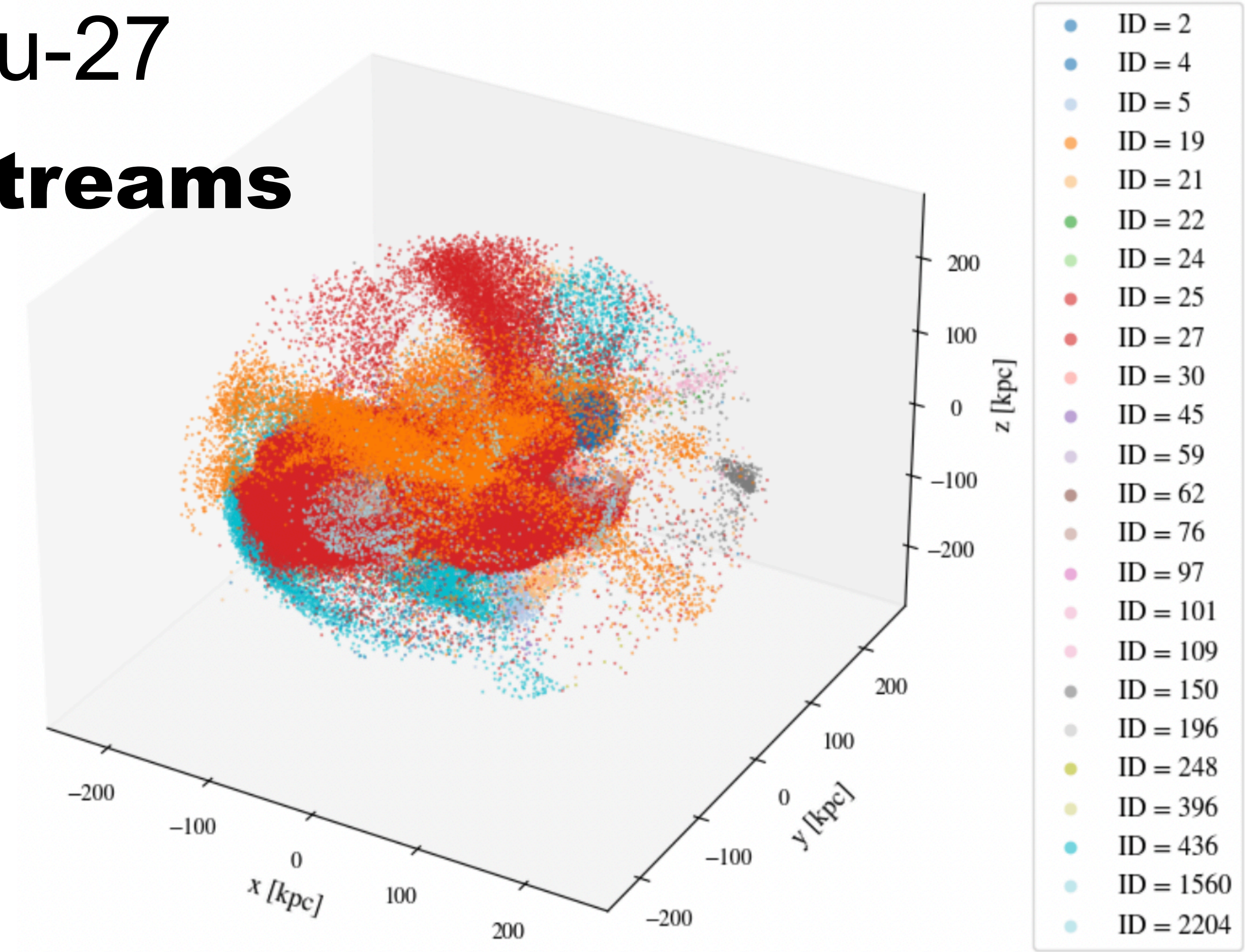
Au-23
18 streams



Au-24
16 streams



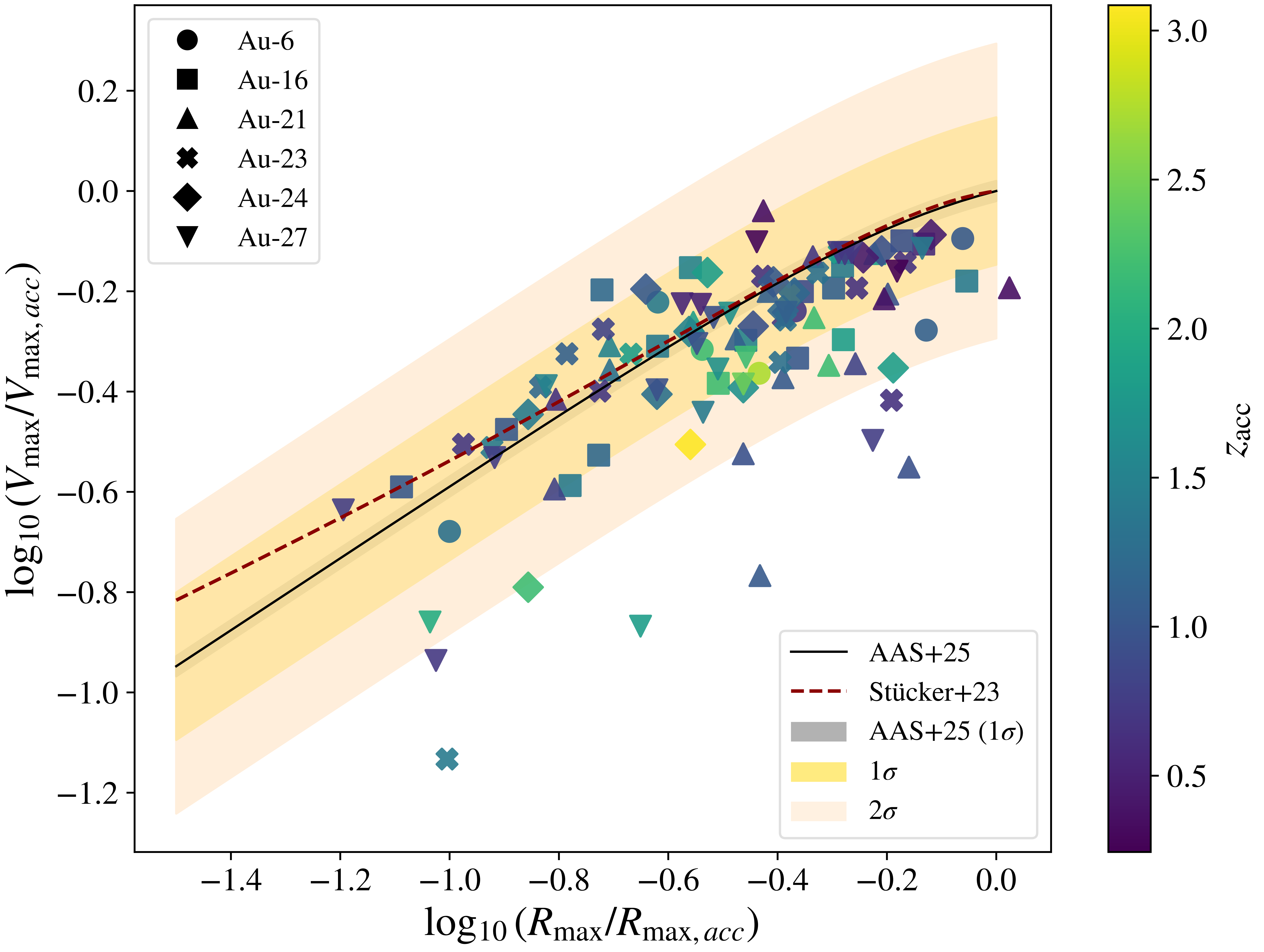
Au-27
24 streams



CFS, Sánchez-Conde & Aguirre-Santaella, *in prep.*

CFS, Sánchez-Conde & Aguirre-Santaella, *in prep.*

Tidal track



$V_{\rm max}$: maximum value of the spherically-averaged rotation curve. It describes the maximum rotation velocity within a subhalo, that is, the maximum circular velocity reached by DM within it.

$R_{\rm max}$: comoving radius at which the maximum rotation velocity is achieved.

Preliminary