News From The Dark
Nov. 22-24th, 2021

Constraints on dark matter

from gamma-ray observations

Céline **Armand**

UNIVERSITÉ DE GENÈVE

OUTLINE

- **Presentation** of the sources and the experiments
- **Data** analysis
- **Statistical** analysis & **Combination**
- **Constraints** on dark matter
- **Conclusions** and perspectives

INDIRECT **SEARCHES**

Expected γ-ray flux from DM annihilation

Astrophysical
J factor

$$\frac{d\Phi\left(\langle\sigma v\rangle, J\right)}{dE} = \frac{1}{4\pi}\frac{\langle\sigma v\rangle}{2m_\chi^2}\sum_f \mathrm{BR}_f \frac{\mathrm{d}N_f}{\mathrm{d}E} \times \int_{\Delta\Omega}\int_{\mathrm{los}} \rho_{\mathrm{DM}}^2 ds d\Omega$$

Particle Physics
factor

where

- **<σv>** = annihilation cross-section
- **m_χ** = DM particle mass
- **BR_f** = branching ratio
- **dN_f/dE** = differential spectrum
- **ρ_{DM}** = DM density

DWARF SPHEROIDAL GALAXIES (dSphs)

A few properties ...

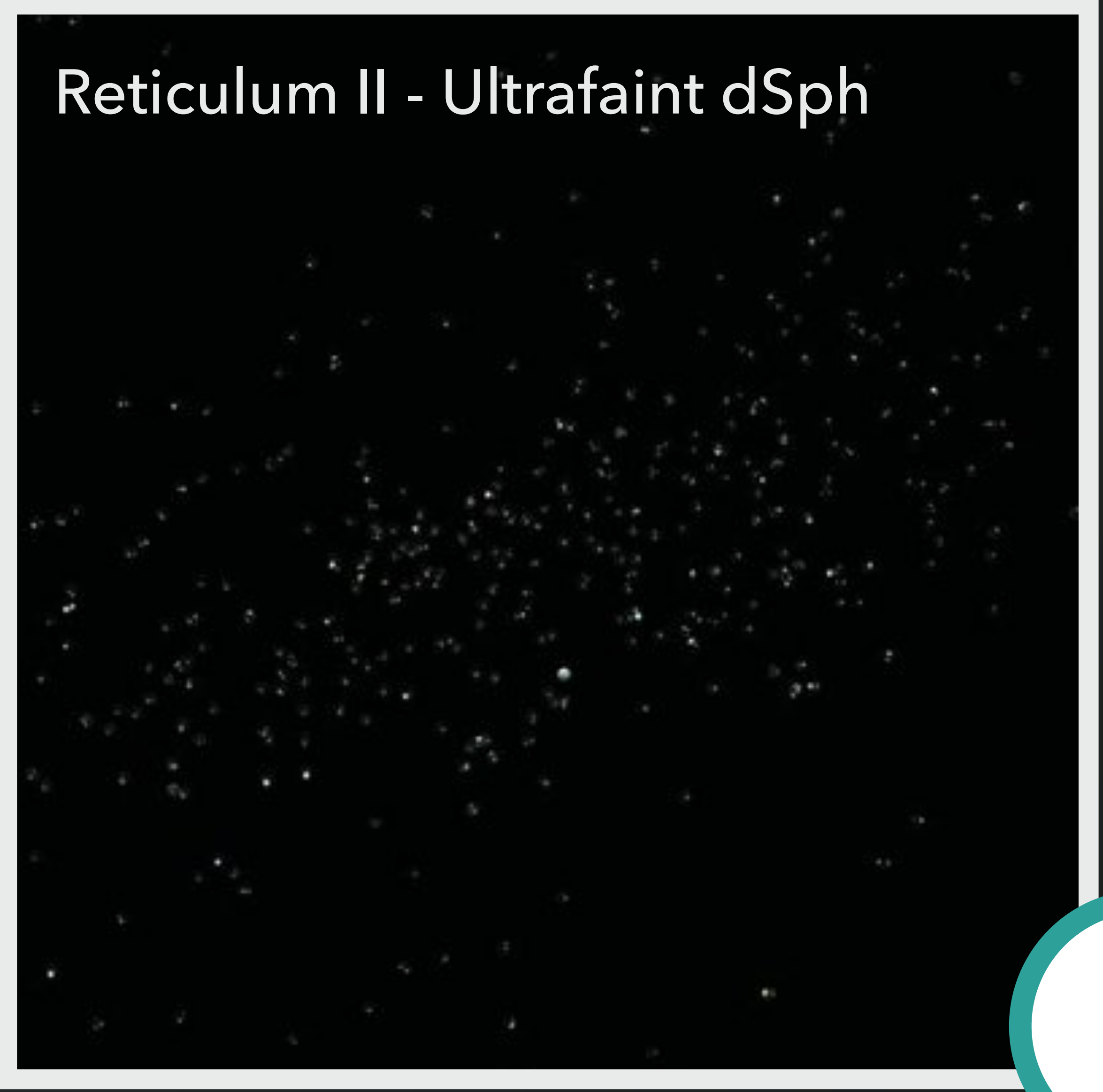
- Located between **~20 kpc and 200 kpc**
- **No rotation**
- **Little or no gas**
- **Old** stellar population
- Dark matter **dominated**

Classicals

~150 - 2500 bright stars
(tracers)

Ultrafaints

- **Higher** J factor
- **~ tens** of bright stars
- **Large uncertainties** on their dark matter distribution



FIVE **EXPERIMENTS**

All complementary

Cover a wide energy range

HAWC
300 water Cherenkov detectors
300 GeV to 100 TeV

VERITAS
4 imaging air Cherenkov telescopes (IACT)
85 GeV to 30 TeV

H.E.S.S.
5 imaging air Cherenkov telescopes (IACT)
30 GeV to 100 TeV

MAGIC
2 imaging air Cherenkov telescopes (IACT)
30 GeV to 100 TeV

Fermi-LAT
Space telescope
20 MeV to 1 TeV

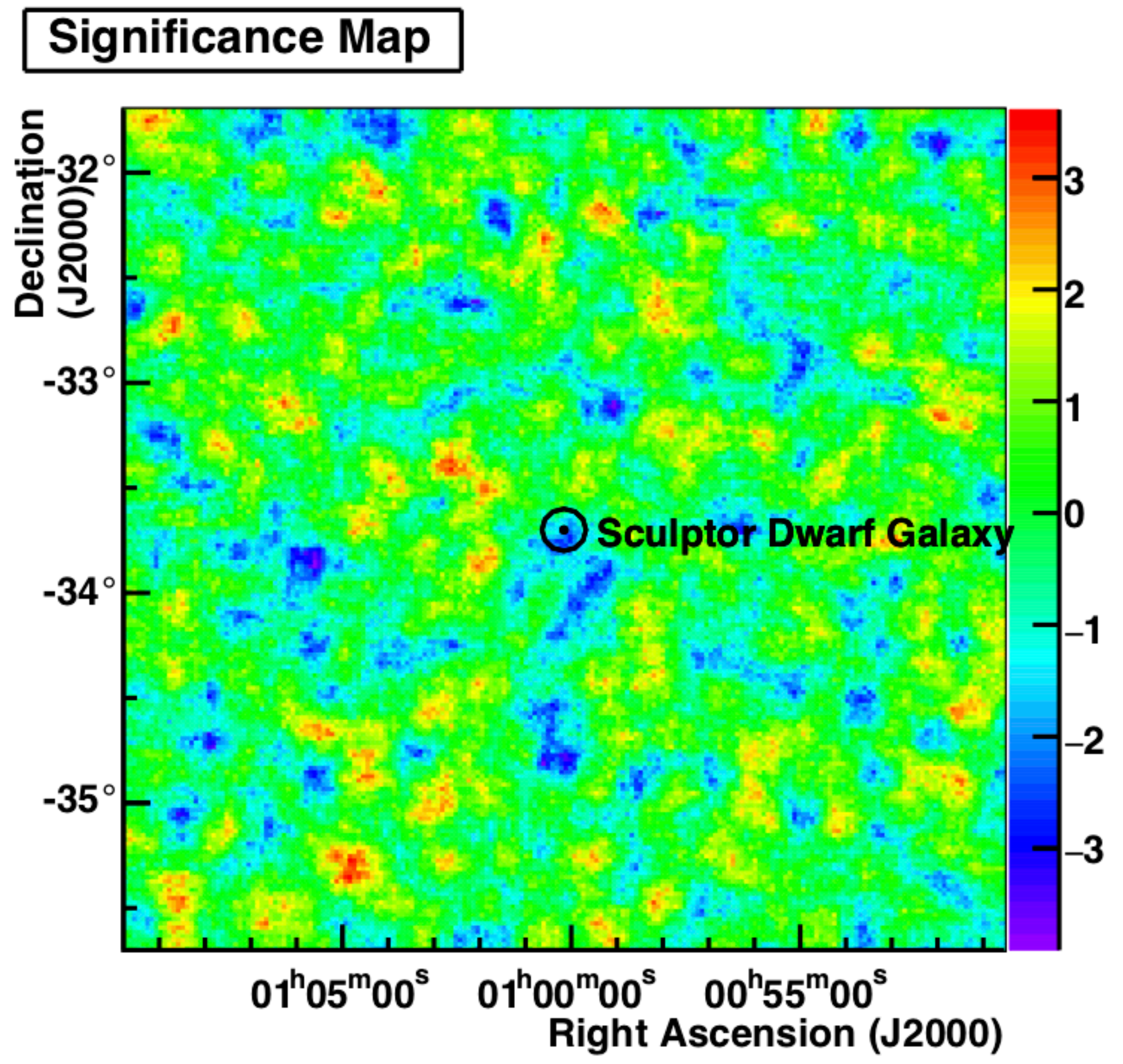
MeV → **GeV** → **TeV**

DATA ANALYSIS IN H.E.S.S.

Determination of the **event distributions in energy** of the signal and background regions

↓

Derivation of the **excess and its significance**



No significant excess observed

Data analysis **provides the event distributions and the parameters required** to perform the statistical analysis

STATISTICAL **ANALYSIS**

LIKELIHOOD FUNCTION

dSph → $\prod_{k=1}$; Experiment → $\prod_{l=1}$

$$\mathcal{L}(\langle\sigma v\rangle; \nu \,|\, \mathcal{D}_{\mathrm{dSphs}}) = \prod_{k=1} \prod_{l=1} \mathcal{L}_{\mathrm{dSph},l,k}\left(\langle\sigma v\rangle; J_{l,k}, \nu_{l,k} \,|\, \mathcal{D}_{\mathrm{dSphs}}\right) \mathcal{J}_k(J_k \,|\, \bar{J}, \sigma_{\log_{10} J})$$

Likelihood of individual instruments and individual dSphs

J factor nuisance

Product of likelihoods of all energy bins

$$\mathcal{L}_{\mathrm{dSph},l,k} = \prod_{e=1} \mathcal{L}_{P_e}(\langle\sigma v\rangle, J \,|\, \mathcal{D}_{\mathrm{data}_e})$$

Log-normal likelihood to model the uncertainties of the J factor

$$\mathcal{L}^J = \frac{1}{\ln(10)\sqrt{2\pi}\sigma_J J} \exp\left(-\frac{(\log_{10} J - \log_{10} \bar{J})^2}{2\sigma_J^2}\right)$$

STATISTICAL **ANALYSIS**

LOG-LIKELIHOOD RATIO TEST STATISTICS

Constrained minimization

$$TS = -2\ln \frac{\mathscr{L}\left(\langle \sigma v\rangle ; \hat{\hat{\nu}} \,|\, \mathscr{D}_{\mathrm{dSphs}}\right)}{\mathscr{L}\left(\widehat{\langle \sigma v\rangle} ; \hat{\nu} \,|\, \mathscr{D}_{\mathrm{dSphs}}\right)}$$

Global minimization

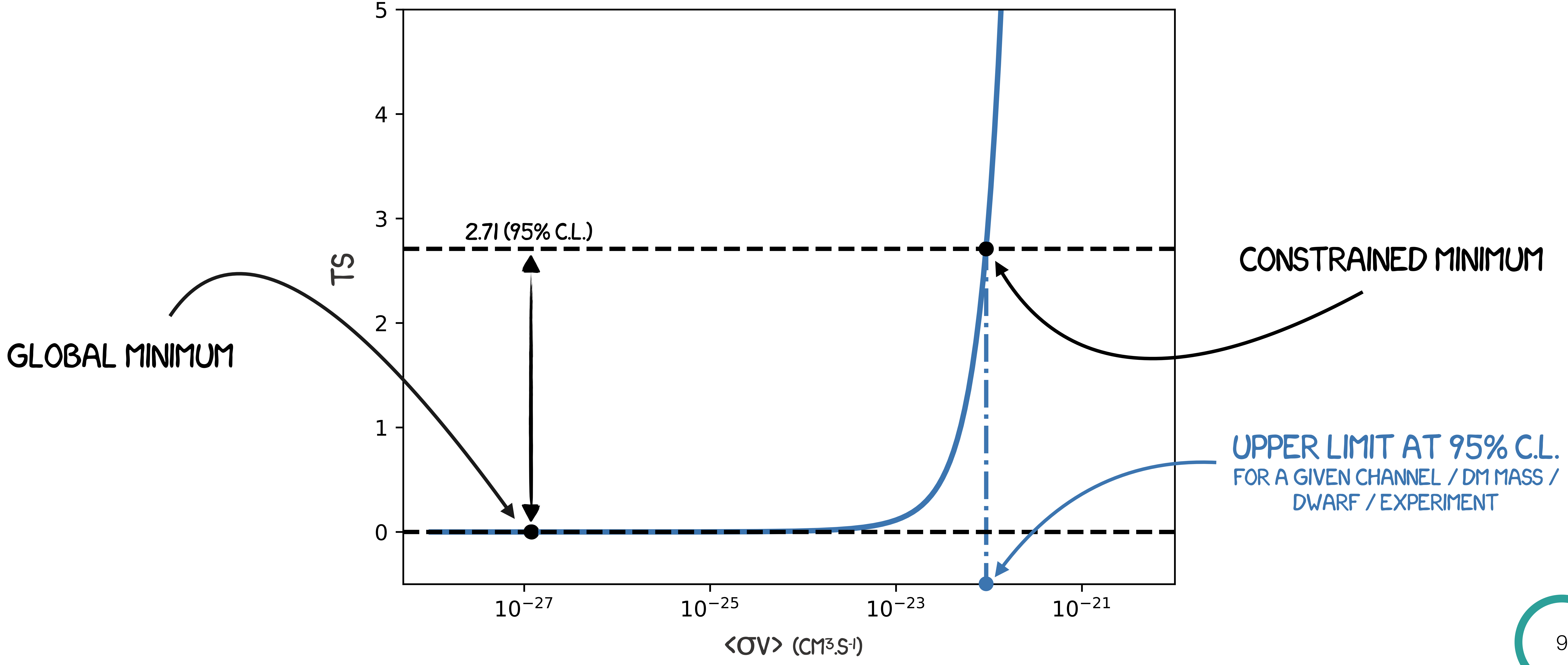
Ref: Cowan et al. (2011), European Physical Journal C, vol. 71 p1554

$\langle \sigma v \rangle$	Parameter of interest	$\mathscr{D}_{\mathrm{dSph}}$	Data of the dSphs
ν	Nuisance parameters	TS	2.71 for 1-sided 95% Confidence Level and 1 degree of freedom

STATISTICAL **ANALYSIS**

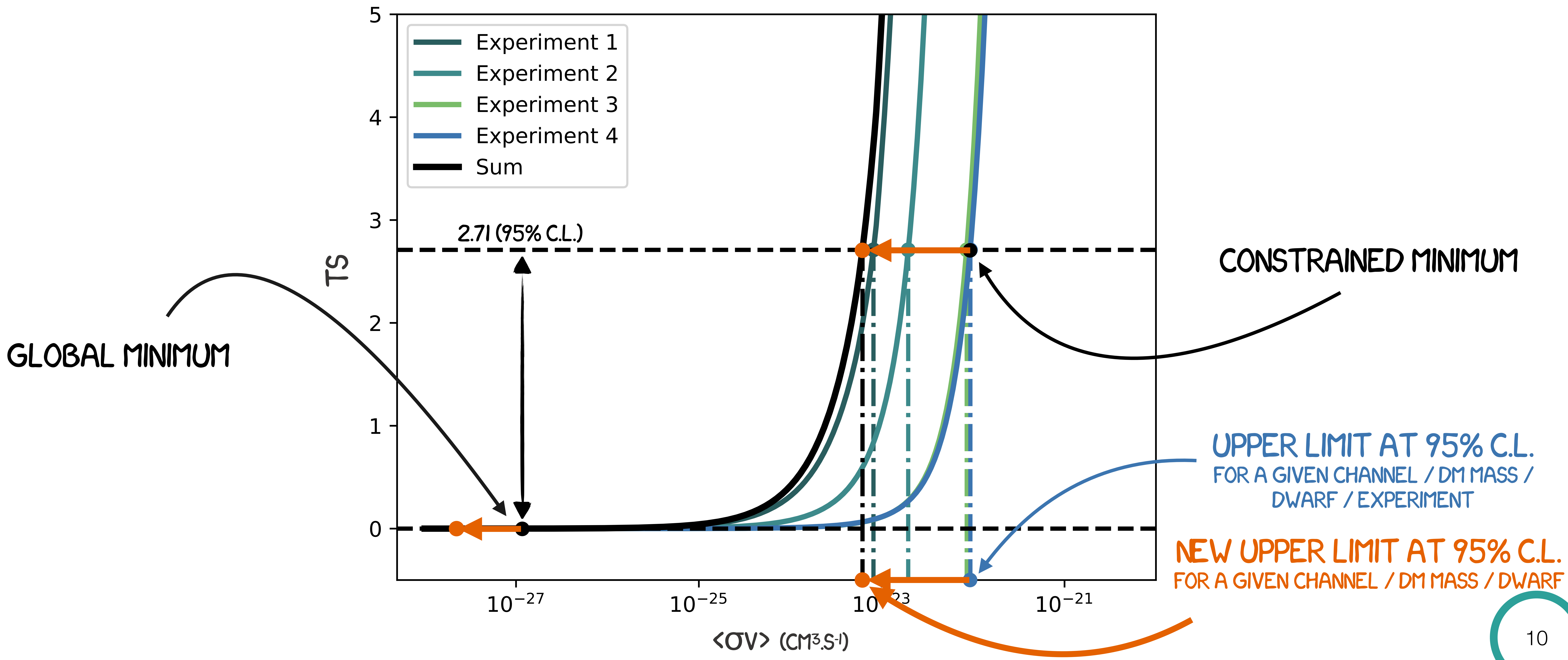
STATISTICAL ANALYSIS

LOG-LIKELIHOOD RATIO TEST STATISTICS



STATISTICAL **ANALYSIS**

LOG-LIKELIHOOD RATIO TEST STATISTICS



Combined DM search

	Fermi-LAT	HAWC	H.E.S.S, MAGIC, VERITAS		
Source name	Exposure (10^{11} s m^2)	$\|\Delta\theta\|$ (°)	IACT	Zenith (°)	Exposure (h)
Boötes I	2.6	4.5	VERITAS	15 – 30	14.0
Canes Venatici I	2.9	14.6	–	–	–
Canes Venatici II	2.9	15.3	–	–	–
Carina	3.1	–	H.E.S.S.	27 – 46	23.7
Coma Berenices	2.7	4.9	H.E.S.S.	47 – 49	11.4
			MAGIC	5 – 37	49.5
Draco	3.8	38.1	MAGIC	29 – 45	52.1
			VERITAS	25 – 40	49.8
Fornax	2.7	–	H.E.S.S.	11 – 25	6.8
Hercules	2.8	6.3	–	–	–
Leo I	2.4	6.7	–	–	–
Leo II	2.6	3.1	–	–	–
Leo IV	2.4	19.5	–	–	–
Leo V	2.4	–	–	–	–
Leo T	2.6	–	–	–	–
Sculptor	2.7	–	H.E.S.S.	10 – 46	11.8
Segue I	2.5	2.9	MAGIC	13 – 37	158.0
			VERITAS	15 – 35	92.0
Segue II	2.7	–	–	–	–
Sextans	2.4	20.6	–	–	–
Ursa Major I	3.4	32.9	–	–	–
Ursa Major II	4.0	44.1	MAGIC	35 – 45	94.8
Ursa Minor	4.1	–	VERITAS	35 – 45	60.4

20 dSphs

5 Experiments

16 People

- Observed by one or several experiments
- All previously published by individual collaborations

CONSTRAINTS ON **DARK MATTER**

CONSTRAINTS ON DARK MATTER

1. **Observed** limits - Collected data

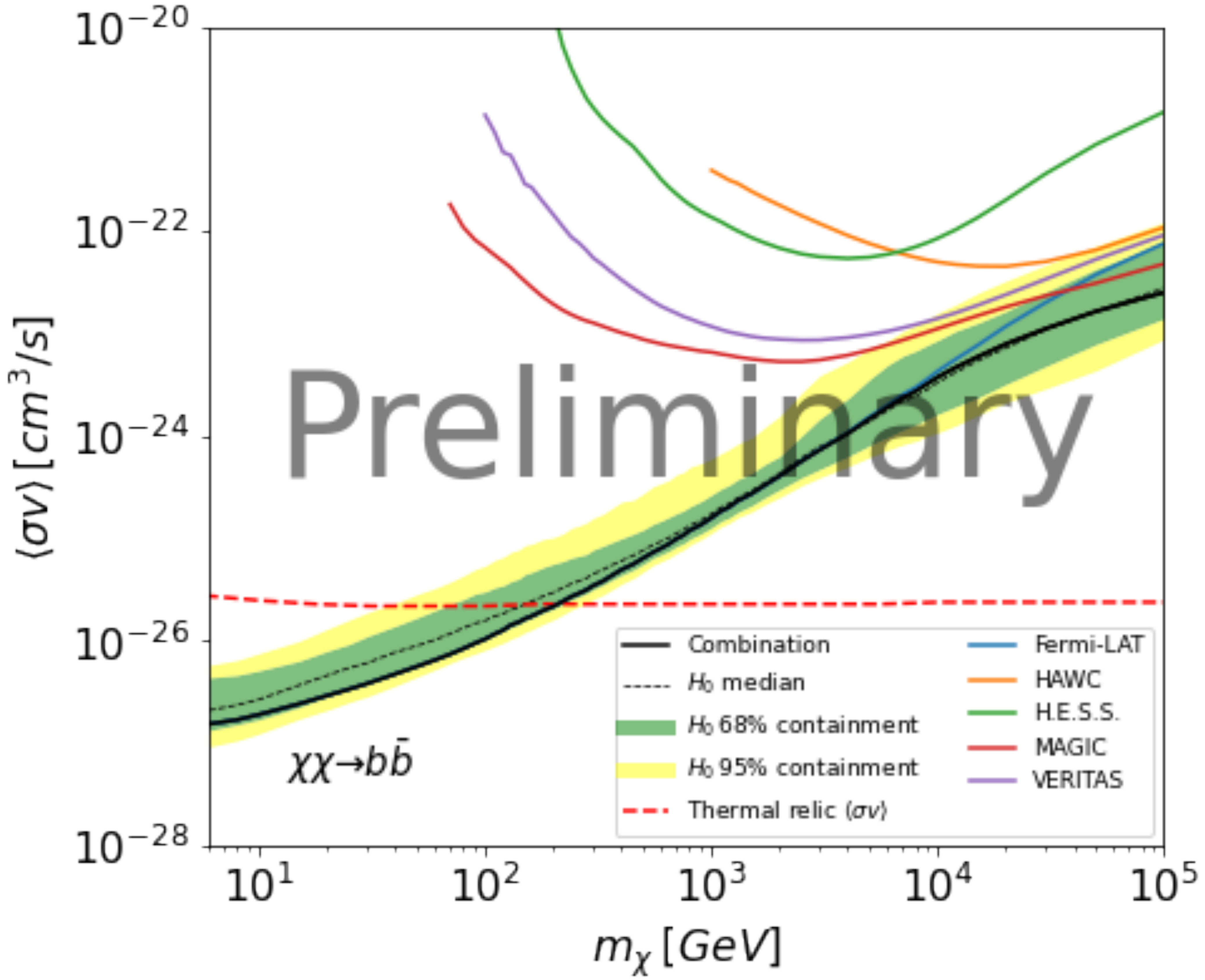
2. **Expected** limits - Sample of **300 Poisson realizations** of the background events produced by individual experiments

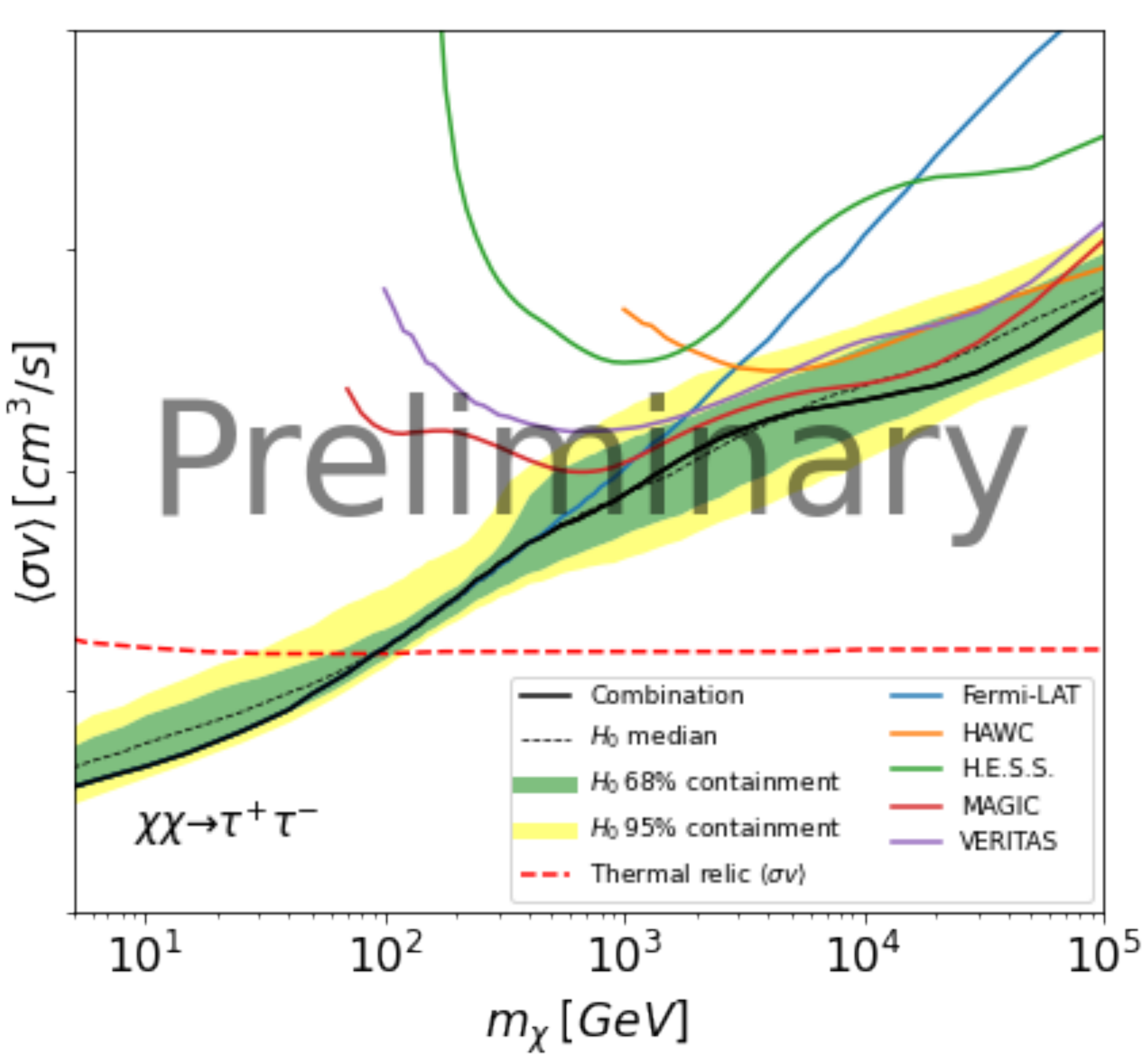
Mean expected limits
Mean of the derived <σv> distribution

Statistical uncertainty bands
Standard deviation at 1 and 2σ

CONSTRAINTS ON **DARK MATTER**

Ref: PoS ICRC2021 (2021) 528, arXiv: 2108.13646





Combined upper limits are **2-3 times more constraining**

CONSTRAINTS ON **DARK MATTER**

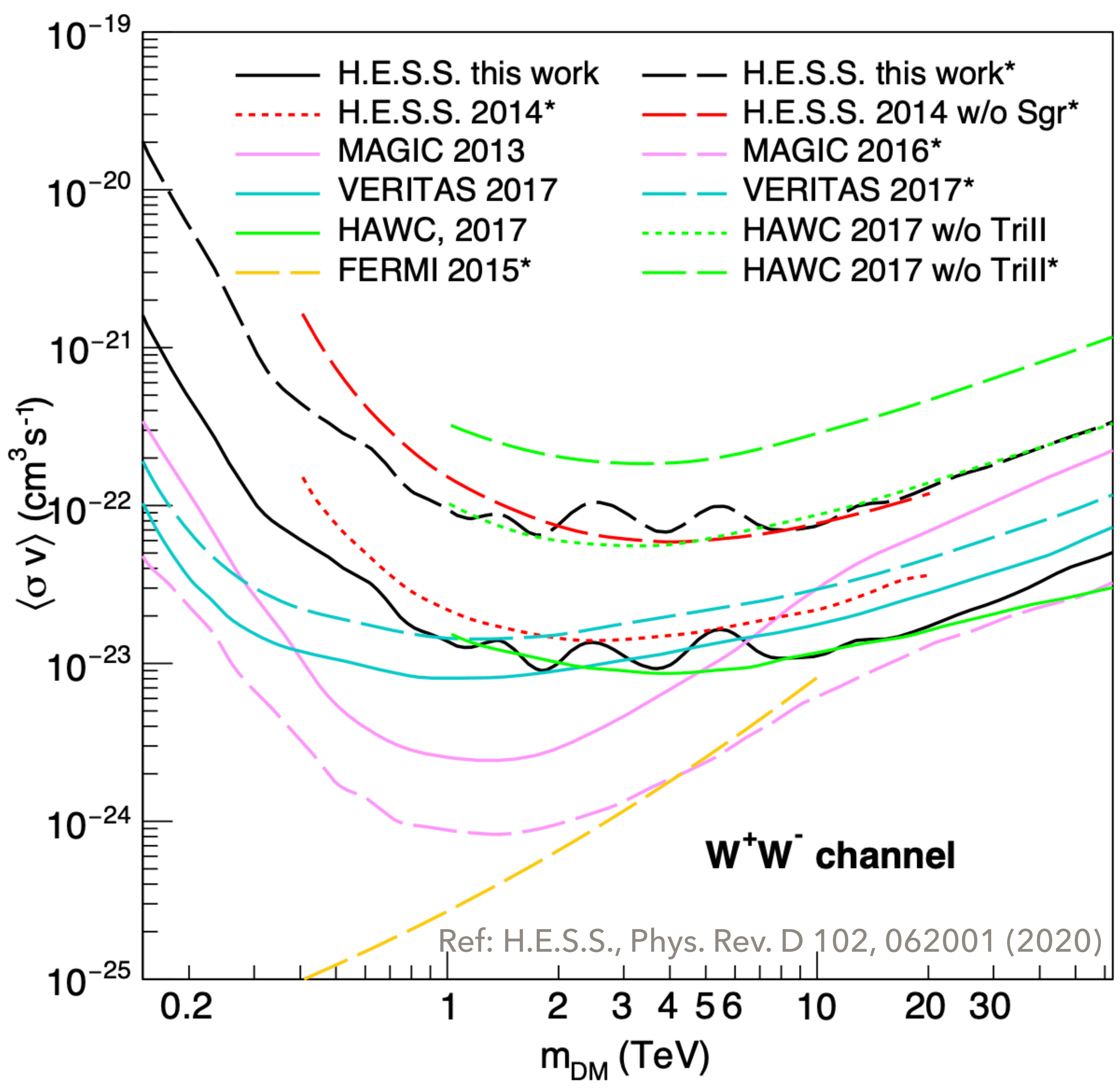
NOTE THAT

Upper limit profiles **depend on the choice** of the annihilation channel

Upper limits **driven by the objects with the highest J factors** that can be observed

Ultrafaint dSphs can be subject to **large systematic uncertainties** for the determination of their J-factors, e.g. Segue I

CONSTRAINTS ON **DARK MATTER**



Upper limits with the J nuisance **increase up to a factor of 10.**

- **H.E.S.S. - 5 ultrafaint dSphs**

  High uncertainties compared to those of the classical dSphs

  Degradation of the upper limits

$\log_{10} J(0.125°)$	
Ret II - 19.2 ± 0.6	Ref: Bonnivard et al, 2015 ApJ 801 74
Tuc II - 18.4 ± 0.7	Ref: Walker et al., 2016 Astrophys. J.819, 53
Tuc III - 18.8 ± 0.7	Estimations from empirical law Ref: Fermi-LAT, Astrophys. J.834,110 (2017)
Tuc IV - 18.1 ± 0.7	
Gru II - 18.1 ± 0.7	

Typical values for classical dSphs

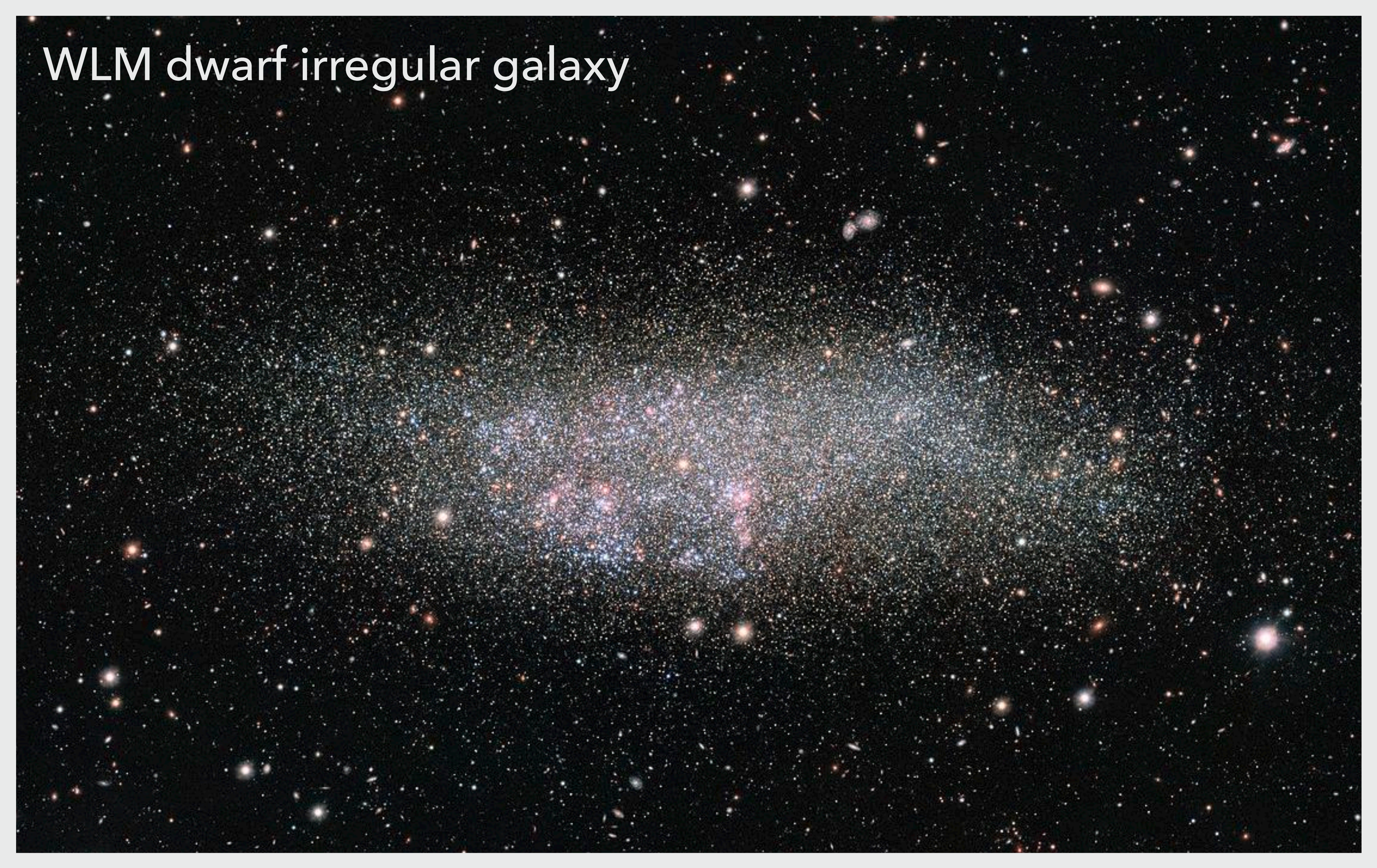
$\log_{10} J(0.125°) \sim 17\text{-}18$

$\log_{10} \Delta J(0.125°) \sim 0.1\text{-}0.3$

- Increase of the upper limits also in **HAWC (green) and VERITAS (blue)**

- The **increase of datasets** allows the derivation of **better upper limits** as in HESS (red) with/without sagittarius

Dwarf Irregular Galaxies

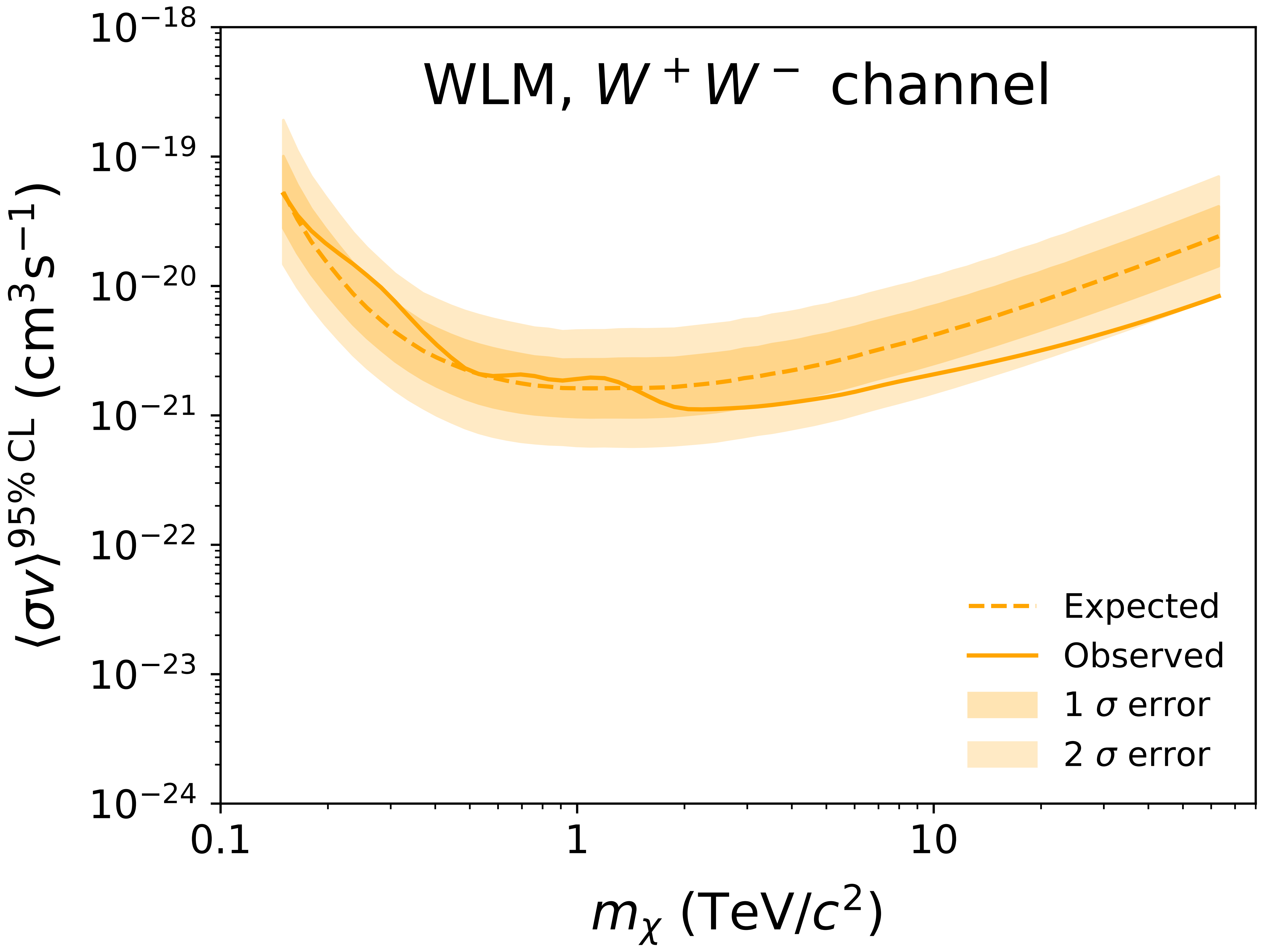


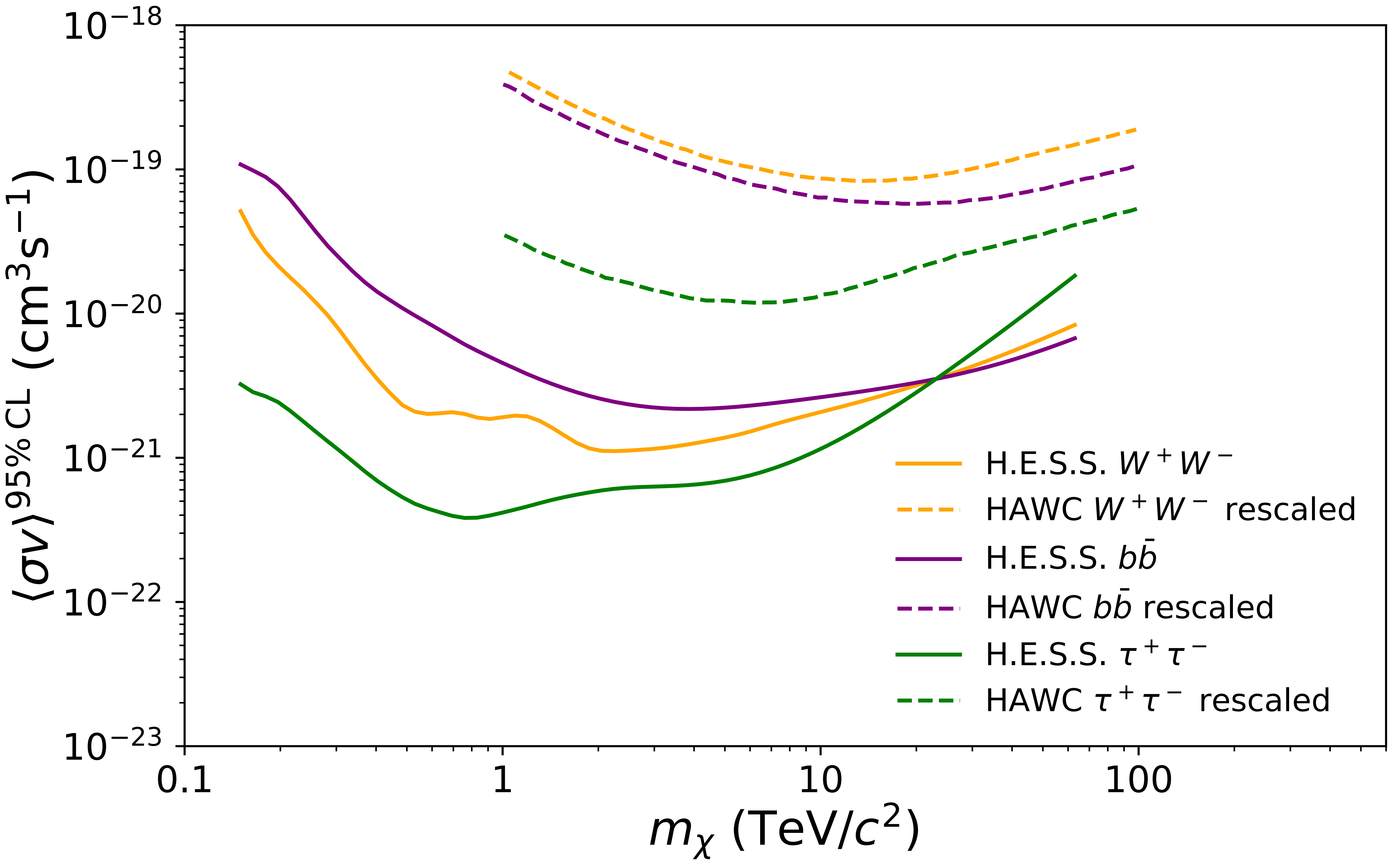
- Located between **~500 kpc and 1 Mpc**
- Dark matter **dominated**
- Contain **gas** (tracer)
- **Smooth** rotation curve
- **Smaller uncertainties** on their dark matter distribution and hence on the J factor

Case of WLM - $\log_{10} J(0.125°) = 16.68 \pm 0.05$

Derivation from a coreNFW density profile

CONSTRAINTS ON **DARK MATTER**





Small uncertainties on the J factor

No visible degradation of the upper limits on the plot

H.E.S.S. limits up to **200x better** than those published by HAWC

Ref: Gammaldi et al, Phys. Rev. D 98, 083008 (2018)

DECAYING **DARK MATTER**

$$\frac{d\Phi\left(\tau_\chi, D\right)}{dE} = \frac{1}{4\pi}\frac{1}{\tau_\chi m_\chi}\sum_f \mathrm{BR}_f \frac{\mathrm{d}N_f}{\mathrm{d}E} \times \int_{\Delta\Omega}\int_{\mathrm{los}} \rho_{\mathrm{DM}} ds d\Omega$$

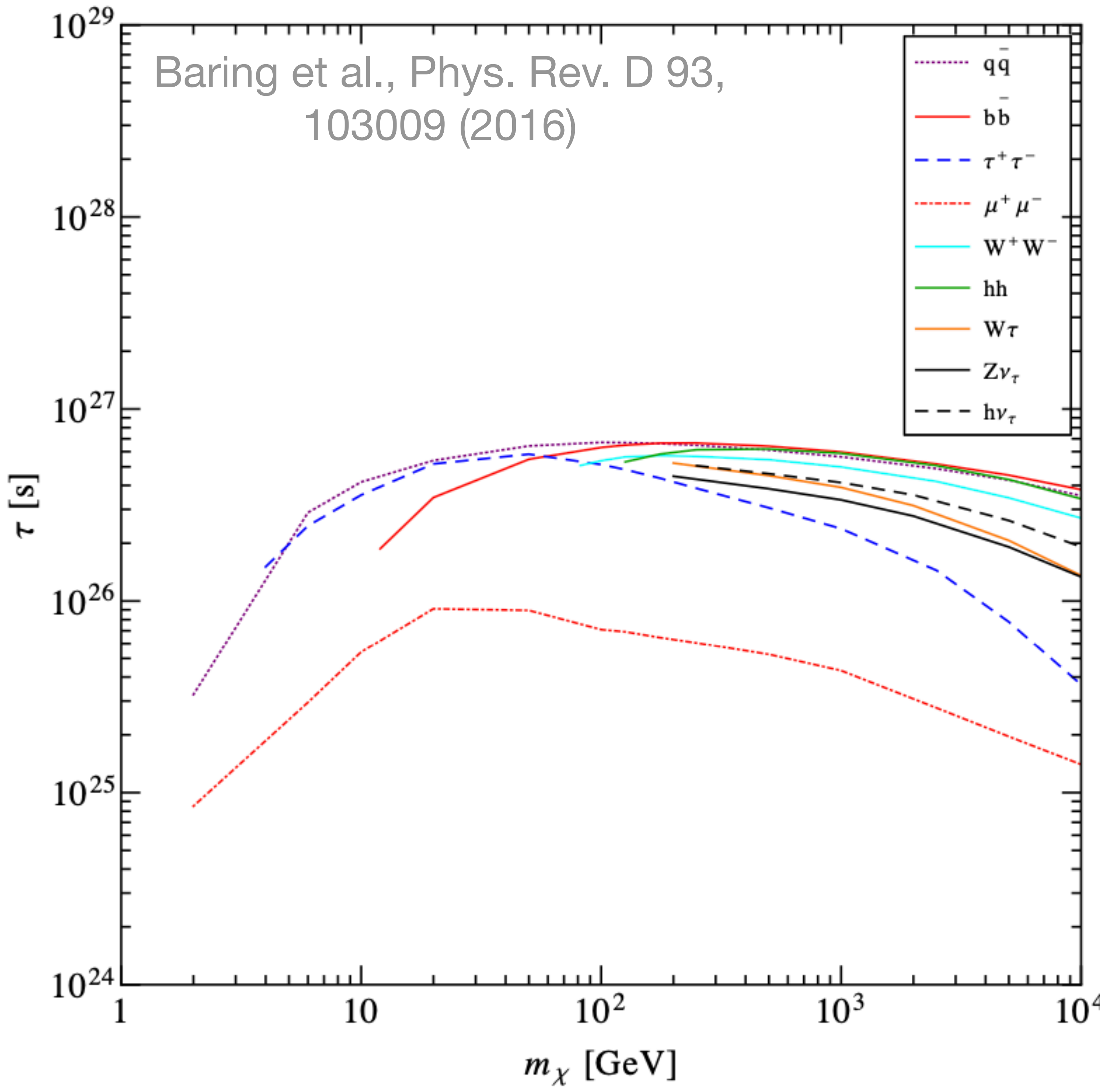
D factor

Particle Physics factor

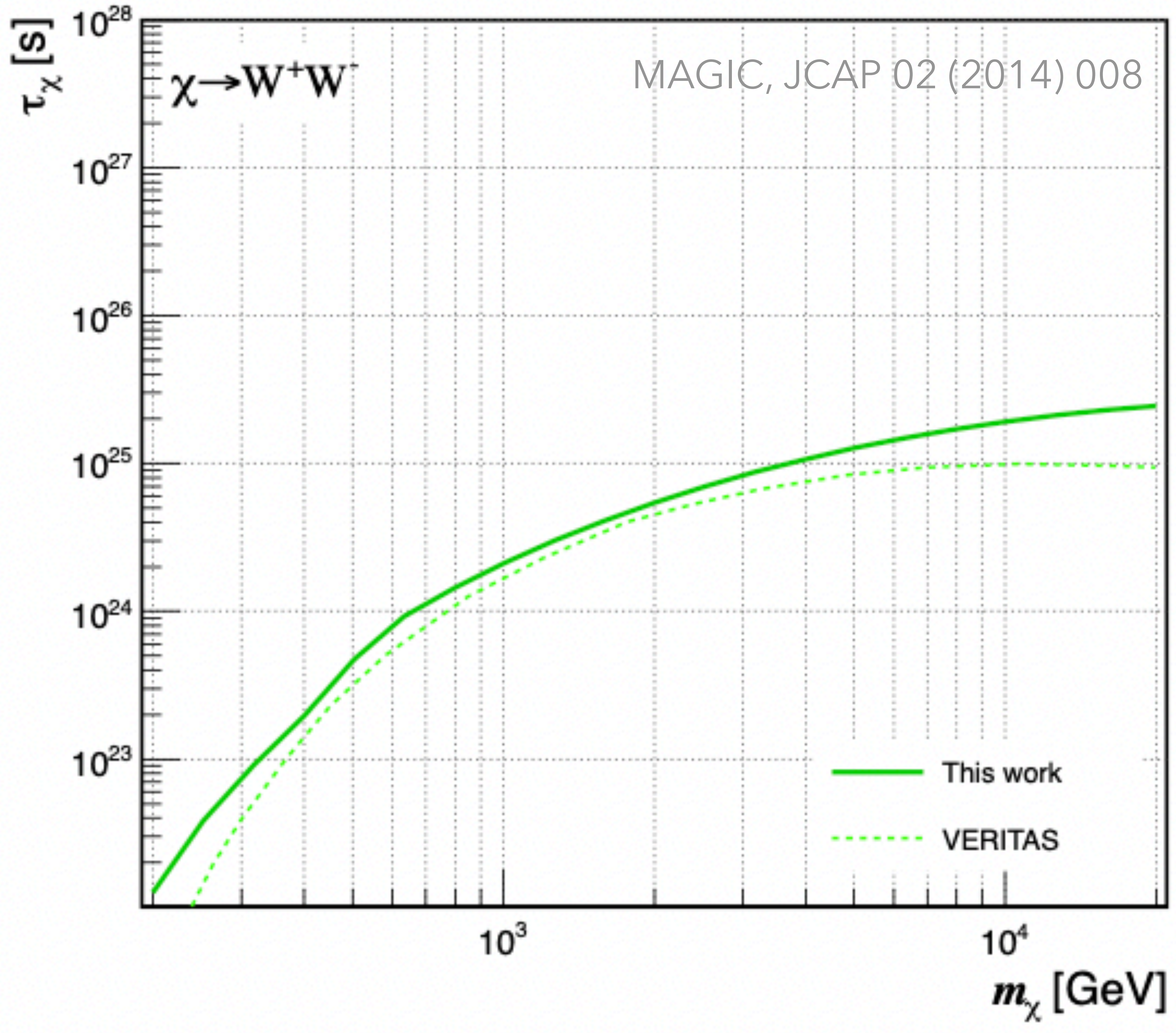
Same procedure **for limits derivation except that**

J factor	→	D factor
$\frac{\langle \sigma v \rangle}{2m_\chi^2}$	→	$\frac{1}{\tau_\chi m_\chi}$
Upper limits on the DM **annihilation cross section**	→	Lower limits on the DM **decaying lifetime**

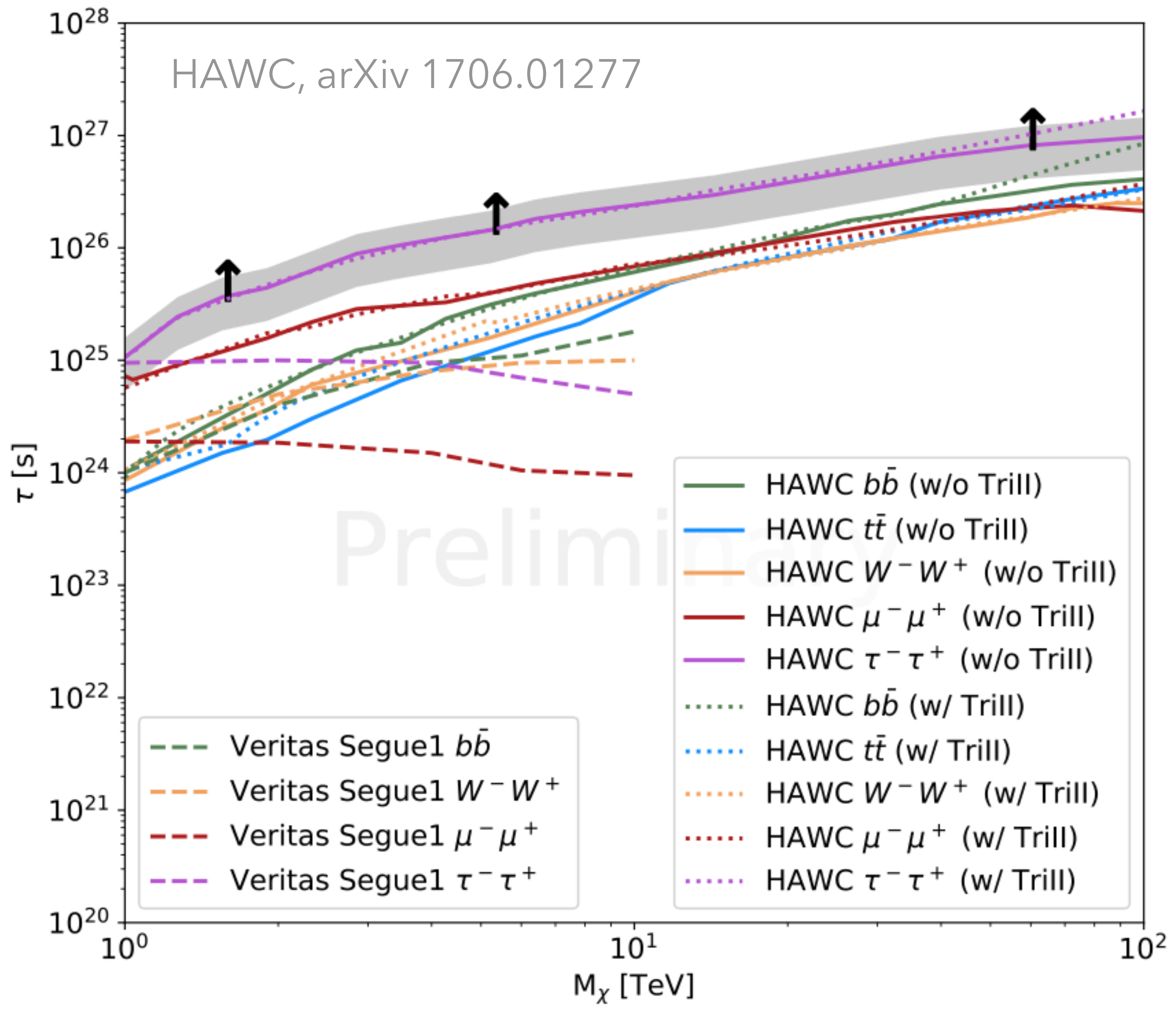
DECAYING **DARK MATTER**



Fermi LAT
Combined lower limits with 15 dSphs
6 years of data



MAGIC (160h) and **VERITAS** (48h)
Segue I only



HAWC
Combined lower limits with 15 and 14 dSphs

Better lower limits with the combination of dSphs

TAKE AWAYS

- **No significant DM signal** observed by any of the experiments
- Use of the **likelihood profiling** to derive limits on the DM cross section/decay lifetime
- Collaborative effort to **combine individual results** between experiments
- **More competitive** upper limits over the **widest mass range ever** for the DM WIMPs

- Possible combination including **other messengers such as neutrinos** (already some contacts with IceCube and ANTARES/KM3NeT)
- **Future observations** of Sculptor (South hemisphere) and Draco (North hemisphere) with **CTA**
- **LHAASO experiment (2019)** in China could also provide **further competitive results**

THANKS FOR YOUR ATTENTION!

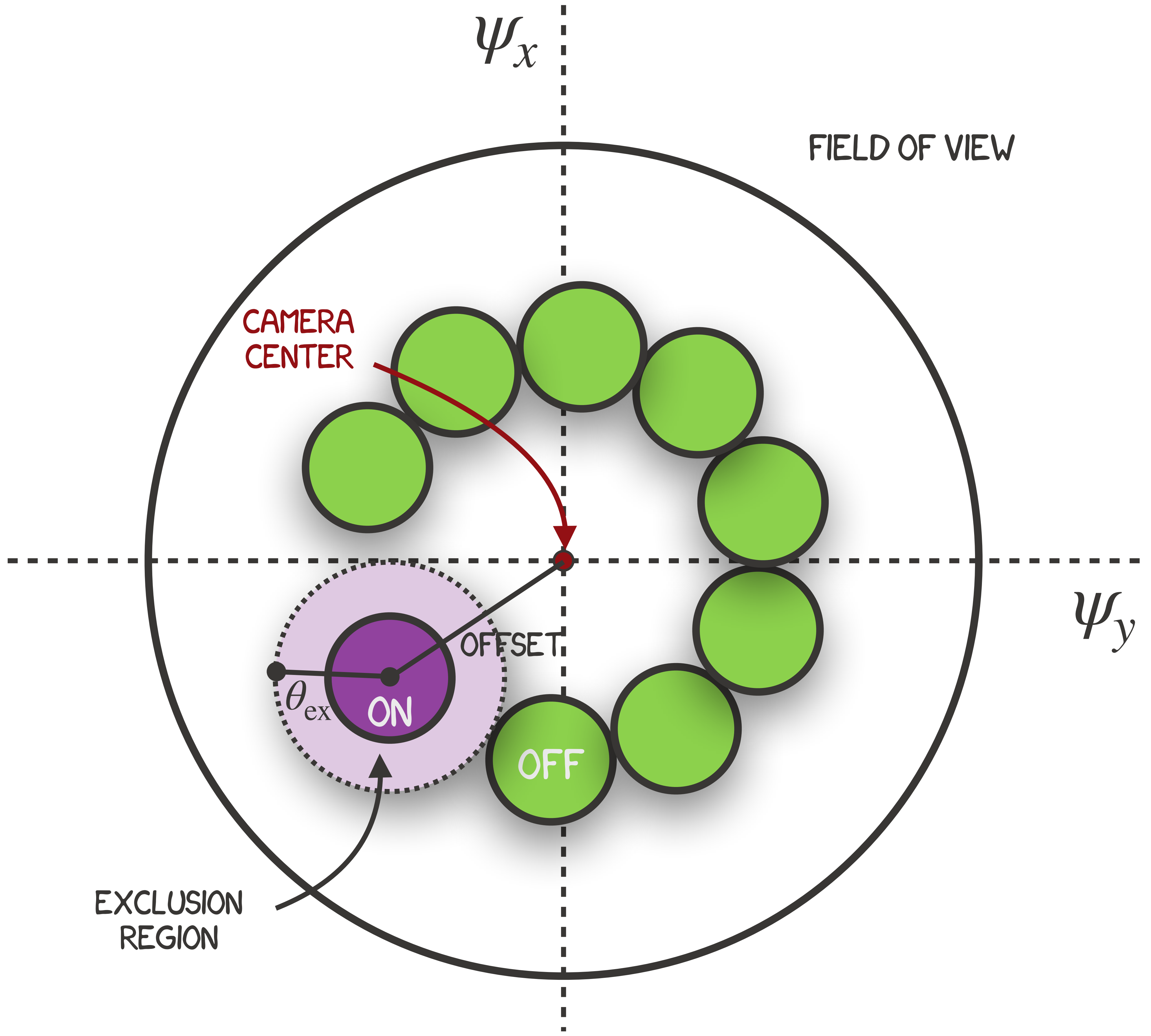
BACKUP

DATA ANALYSIS IN H.E.S.S.

DATA ANALYSIS IN H.E.S.S.

Multiple OFF technique

- **Pointing position slightly shifted** from the source position
- **Signal region -** ON region
- **Background region -** Many OFF regions distributed around the camera center



STATISTICAL ANALYSIS

STATISTICAL ANALYSIS

Total likelihood

$$\mathcal{L}(\langle\sigma v\rangle, N_B, J) = \prod_{i=1} \mathcal{L}_{P_i}(\langle\sigma v\rangle, N_{B_i}, J \,|\, N_{\mathrm{ON_i}}, N_{\mathrm{OFF_i}}, \alpha)\,\mathcal{L}^J(J \,|\, \bar{J}, \sigma_J)$$

Poisson likelihood

Log-normal likelihood

Poisson likelihood for each energy bin

$$\mathcal{L}_i^P = \frac{(N_{S_i} + N_{B_i})^{N_{\mathrm{ON}_i}}}{N_{\mathrm{ON}_i}!} e^{-(N_{S_i}+N_{B_i})} \cdot \frac{(\alpha N_{B_i})^{N_{\mathrm{OFF}_i}}}{N_{\mathrm{OFF}_i}!} e^{-\alpha N_{B_i}}$$

ON REGION

OFF REGION

Log-normal likelihood to model the uncertainties of the J factor

$$\mathcal{L}^J = \frac{1}{\ln(10)\sqrt{2\pi}\sigma_J J} \exp - \frac{(\log_{10} J - \log_{10} \bar{J})^2}{2\sigma_J^2}$$

STATISTICAL ANALYSIS

STATISTICAL ANALYSIS

$$N_{S_i} = \frac{1}{2}\frac{\langle \sigma v \rangle}{4\pi m_\chi^2} J \int_{\Delta E_i} \int_0^\infty \sum_f B_f \frac{dN_\gamma^f}{dE_\gamma} A_{\text{eff}}(E_\gamma) R(E_\gamma, E'_\gamma) T_{\text{obs}} dE_\gamma dE'_\gamma$$

SPECTRUM

ACCEPTANCE

ENERGY RESOLUTION

OBSERVATION TIME

CONVOLUTION

SPECTRA
interpolated from Cirelli *et al.*, *JCAP* 1103, page 051.

X

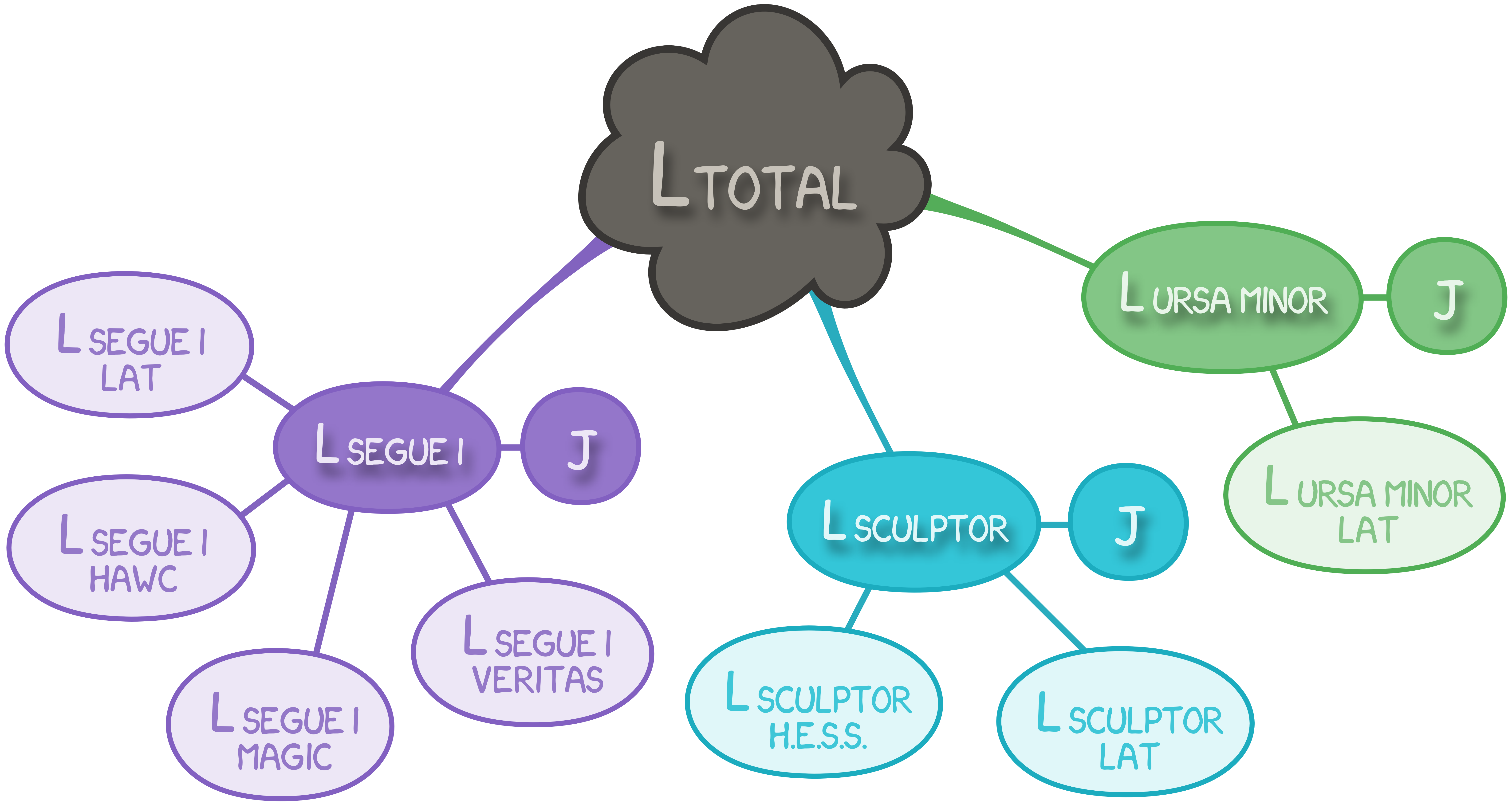
ACCEPTANCE
interpolated from the ParisAnalysis tables

X

ENERGY RESOLUTION
modeled by a Gaussian function

JOINT LIKELIHOOD **ANALYSIS**

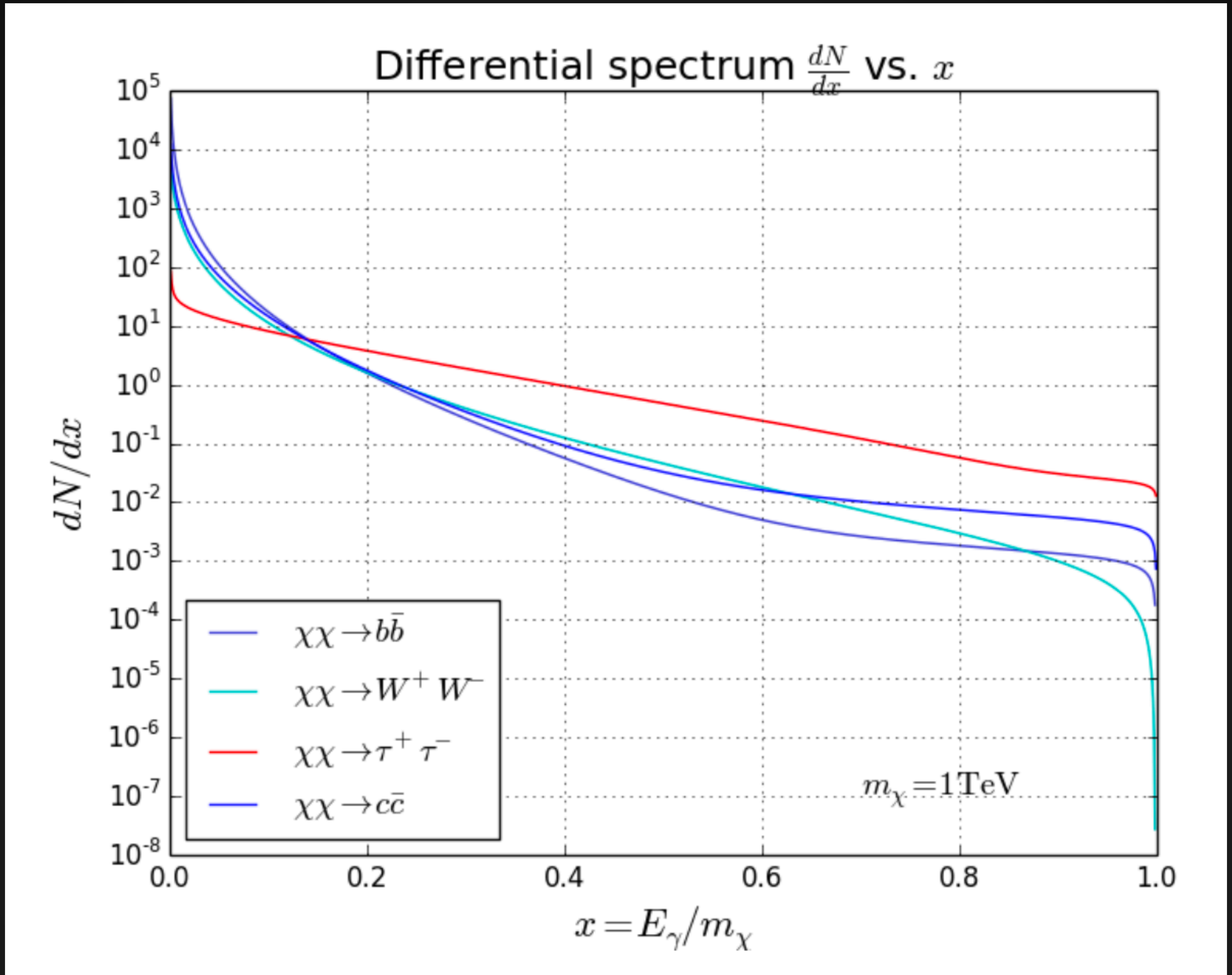
TOTAL LIKELIHOOD = PRODUCT OF INDIVIDUAL LIKELIHOODS



TARGETS

Name	Distance (kpc)	l, b (°)	$\log_{10} J$ ($\mathcal{GS}$ set) $\log_{10}(\mathrm{GeV^2 cm^{-5} sr})$	$\log_{10} J$ ($\mathcal{B}$ set) $\log_{10}(\mathrm{GeV^2 cm^{-5} sr})$
Boötes I	66	358.08, 69.62	$18.24^{+0.40}_{-0.37}$	$18.85^{+1.10}_{-0.61}$
Canes Venatici I	218	74.31, 79.82	$17.44^{+0.37}_{-0.28}$	$17.63^{+0.50}_{-0.20}$
Canes Venatici II	160	113.58, 82.70	$17.65^{+0.45}_{-0.43}$	$18.67^{+1.54}_{-0.97}$
Carina	105	260.11, −22.22	$17.92^{+0.19}_{-0.11}$	$18.02^{+0.36}_{-0.15}$
Coma Berenices	44	241.89, 83.61	$19.02^{+0.37}_{-0.41}$	$20.13^{+1.56}_{-1.08}$
Draco	76	86.37, 34.72	$19.05^{+0.22}_{-0.21}$	$19.42^{+0.92}_{-0.47}$
Fornax	147	237.10, −65.65	$17.84^{+0.11}_{-0.06}$	$17.85^{+0.11}_{-0.08}$
Hercules	132	28.73, 36.87	$16.86^{+0.74}_{-0.68}$	$17.70^{+1.08}_{-0.73}$
Leo I	254	225.99, 49.11	$17.84^{+0.20}_{-0.16}$	$17.93^{+0.65}_{-0.25}$
Leo II	233	220.17, 67.23	$17.97^{+0.20}_{-0.18}$	$18.11^{+0.71}_{-0.25}$
Leo IV	154	265.44, 56.51	$16.32^{+1.06}_{-1.70}$	$16.36^{+1.44}_{-1.65}$
Leo V	178	261.86, 58.54	$16.37^{+0.94}_{-0.87}$	$16.30^{+1.33}_{-1.16}$
Leo T	417	214.85, 43.66	$17.11^{+0.44}_{-0.39}$	$17.67^{+1.01}_{-0.56}$
Sculptor	86	287.53, −83.16	$18.57^{+0.07}_{-0.05}$	$18.63^{+0.14}_{-0.08}$
Segue I	23	220.48, 50.43	$19.36^{+0.32}_{-0.35}$	$17.52^{+2.54}_{-2.65}$
Segue II	35	149.43, −38.14	$16.21^{+1.06}_{-0.98}$	$19.50^{+1.82}_{-1.48}$
Sextans	86	243.50, 42.27	$17.92^{+0.35}_{-0.29}$	$18.04^{+0.50}_{-0.28}$
Ursa Major I	97	159.43, 54.41	$17.87^{+0.56}_{-0.33}$	$18.84^{+0.97}_{-0.43}$
Ursa Major II	32	152.46, 37.44	$19.42^{+0.44}_{-0.42}$	$20.60^{+1.46}_{-0.95}$
Ursa Minor	76	104.97, 44.80	$18.95^{+0.26}_{-0.18}$	$19.08^{+0.21}_{-0.13}$

Twenty Dwarf Spheroidal Galaxies



$\tau^\pm \to h^\pm + \geq 1$neutral $+ \nu_\tau$

Some of the neutral particles produced are pions π^0 which, in turn, decay as $\pi^0 \to \gamma\gamma$. These processes are highly energetic and so are the emitted γ photons. By contrast with the τ, the quarks produced by dark matter annihilation hadronize combining with quarks and antiquarks spontaneously created from the vacuum. The new particles created lead to decay chains emitting lower energy γ. Furthermore, all curves have a quick decrease for $x \to 1$ as the energy of the particles produced cannot be greater than the energy of the initial particle .