CTA Swiss Day
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Dark matter search program

with CTA

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cta
cherenkov
telescope
array

FNSNF
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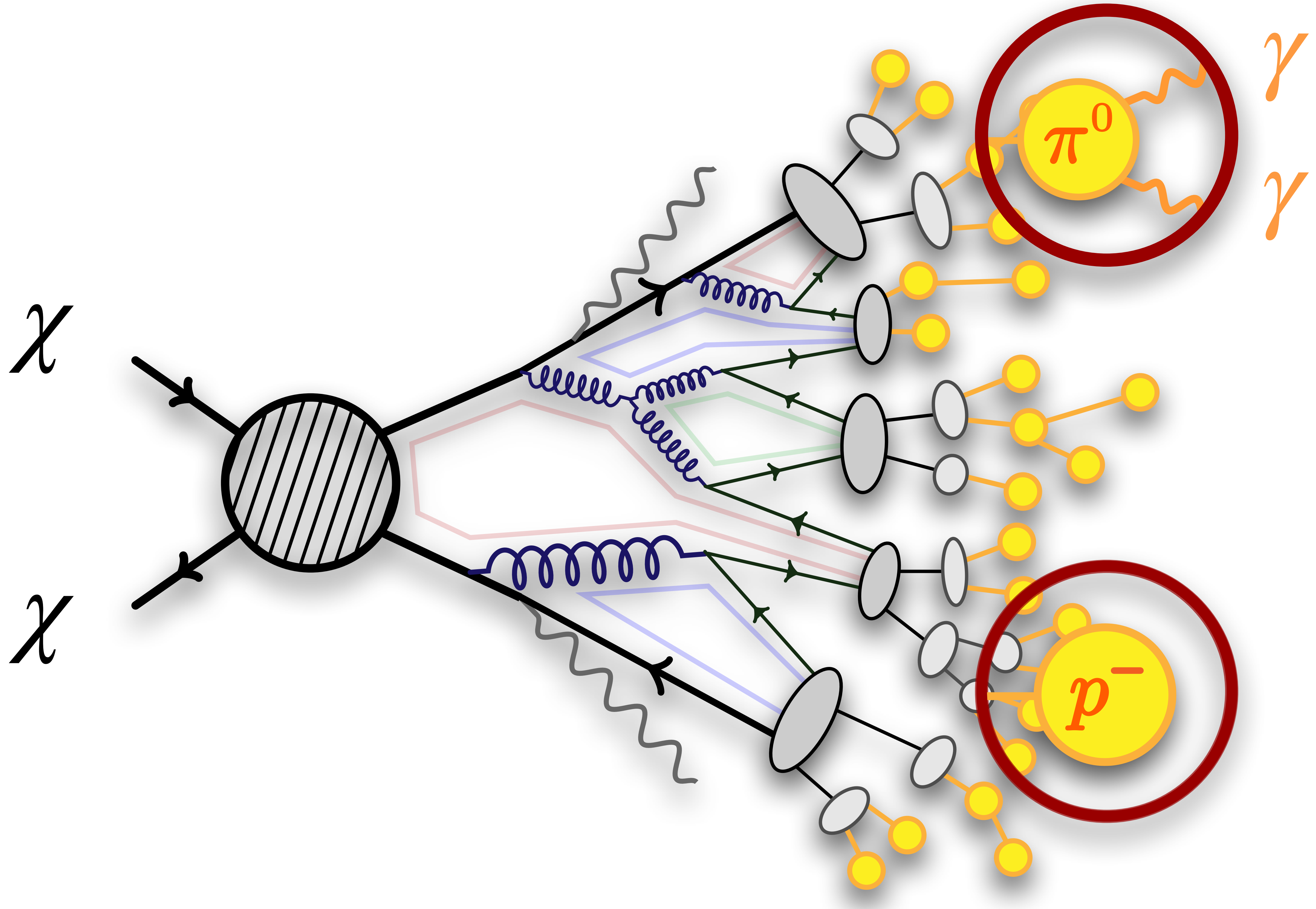
FONDO NAZIONALE SVIZZERO
SWISS NATIONAL SCIENCE FOUNDATION

OUTLINE

- **Introduction** to indirect detection
- **Most promising** targets
- **Current constraints** on dark matter
- **Prospects** with CTA in the framework of dark matter
- **Conclusions**

INDIRECT **SEARCHES**

INDIRECT SEARCHES



Dark Matter (DM) annihilation → Standard Model particles (bosons, quarks, leptons) → Final state products such as γ rays

INDIRECT **SEARCHES**

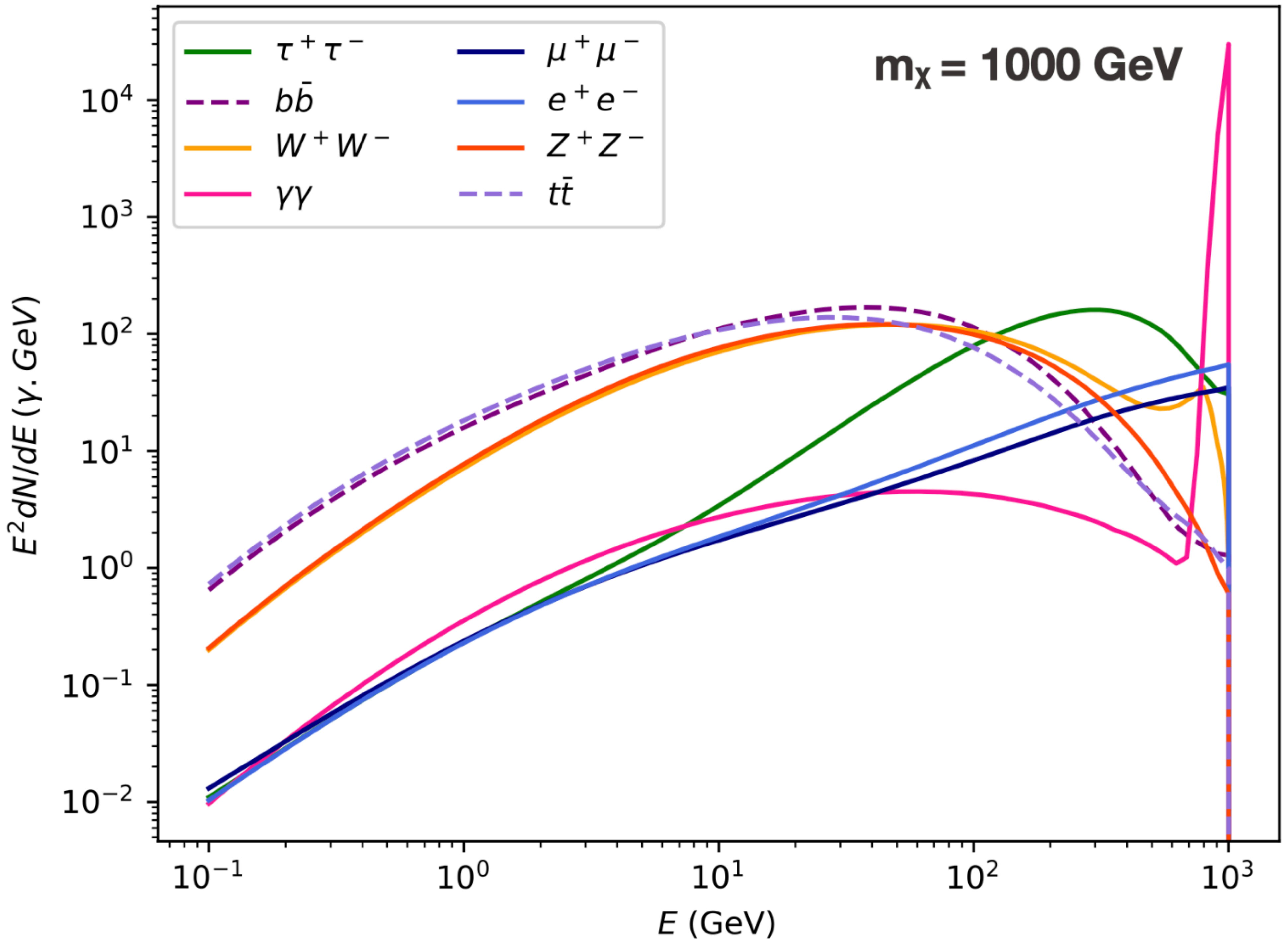
Dark matter Signatures

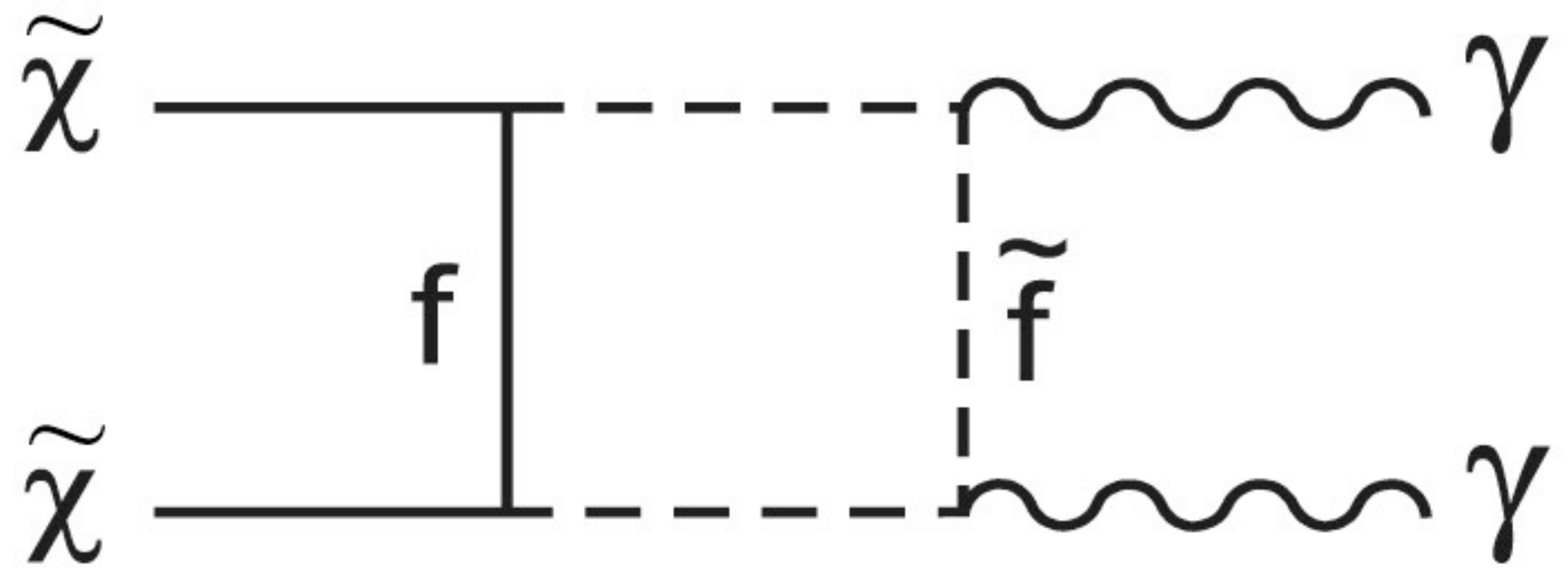
Continuum spectrum

- Up to the dark matter particle mass
- Non trivial to distinguish from other standard broadband astrophysical emissions

Spectral lines

- Prominent and narrow spectral line = “Smoking gun” signature
- Loop processes producing γX with X = γ, h, Z, or non Standard Model neutral particle
- No background as standard astrophysical processes do not produce monochromatic emission.





INDIRECT **SEARCHES**

Expected γ-ray flux from DM annihilation

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

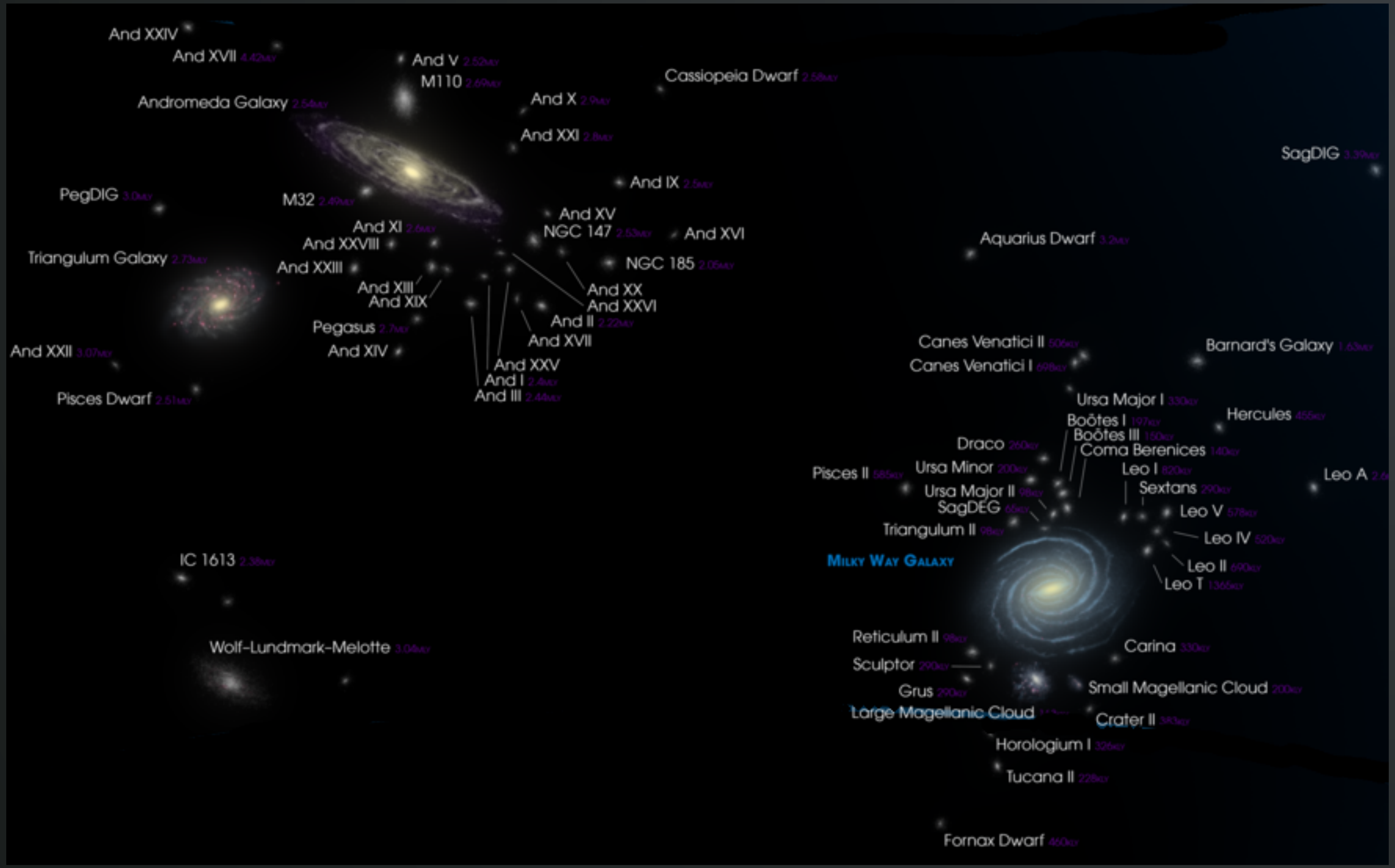
where

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

WHERE TO SEARCH?

Rich-DM environments

More annihilations



Galactic center (GC)

- Densest DM region
- Large astrophysical background
- Only visible in the South hemisphere

Satellite galaxies

- Medium statistics due to the distance
- Astrophysical background and foreground

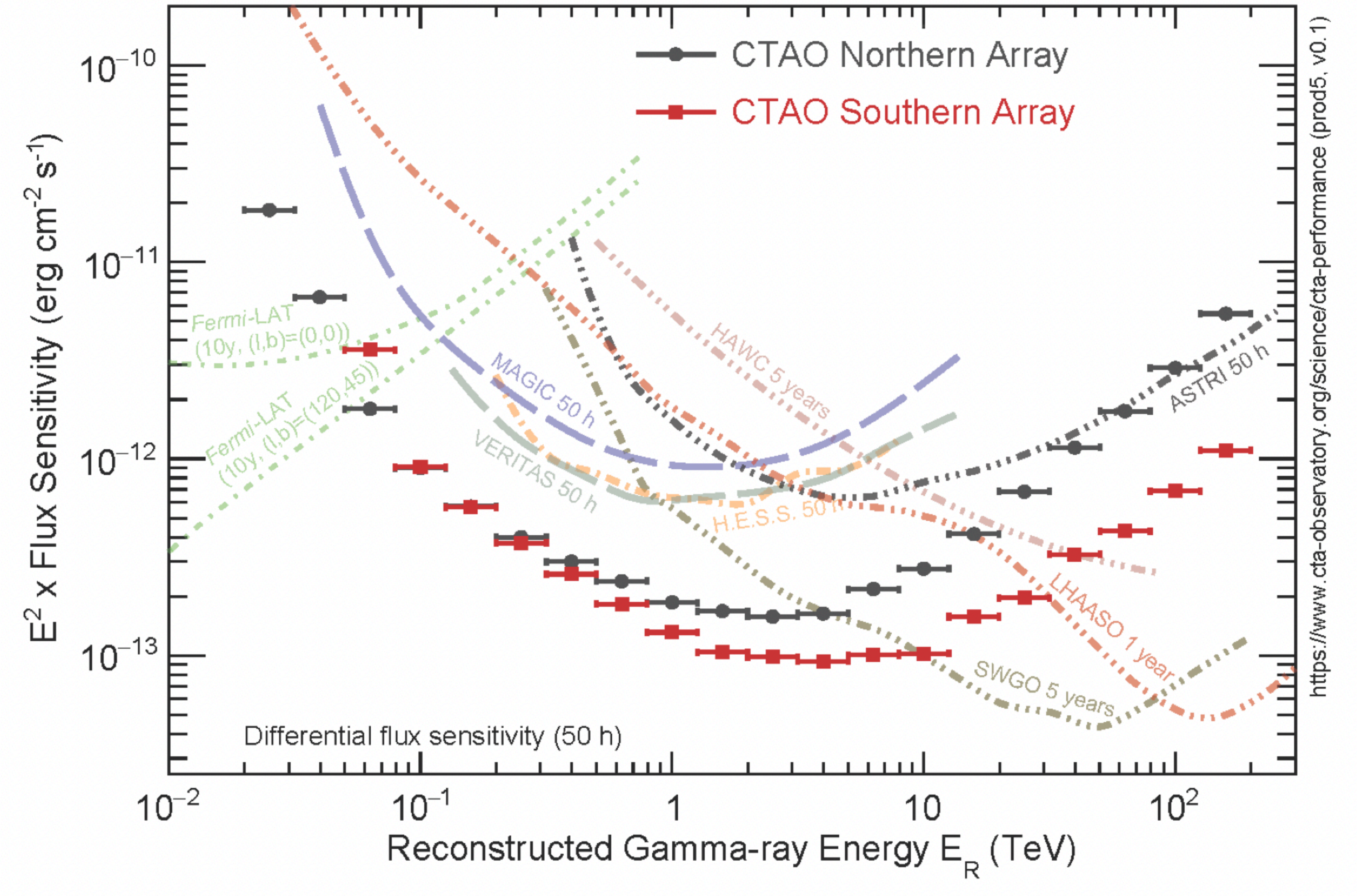
Dwarf galaxies

- Satellites orbiting the Milky Way
- Lower statistics due to the distance and lower content of DM (compared to GC)
- Absence of active astrophysical objets nearby

DIFFERENTIAL FLUX **SENSITIVITY**

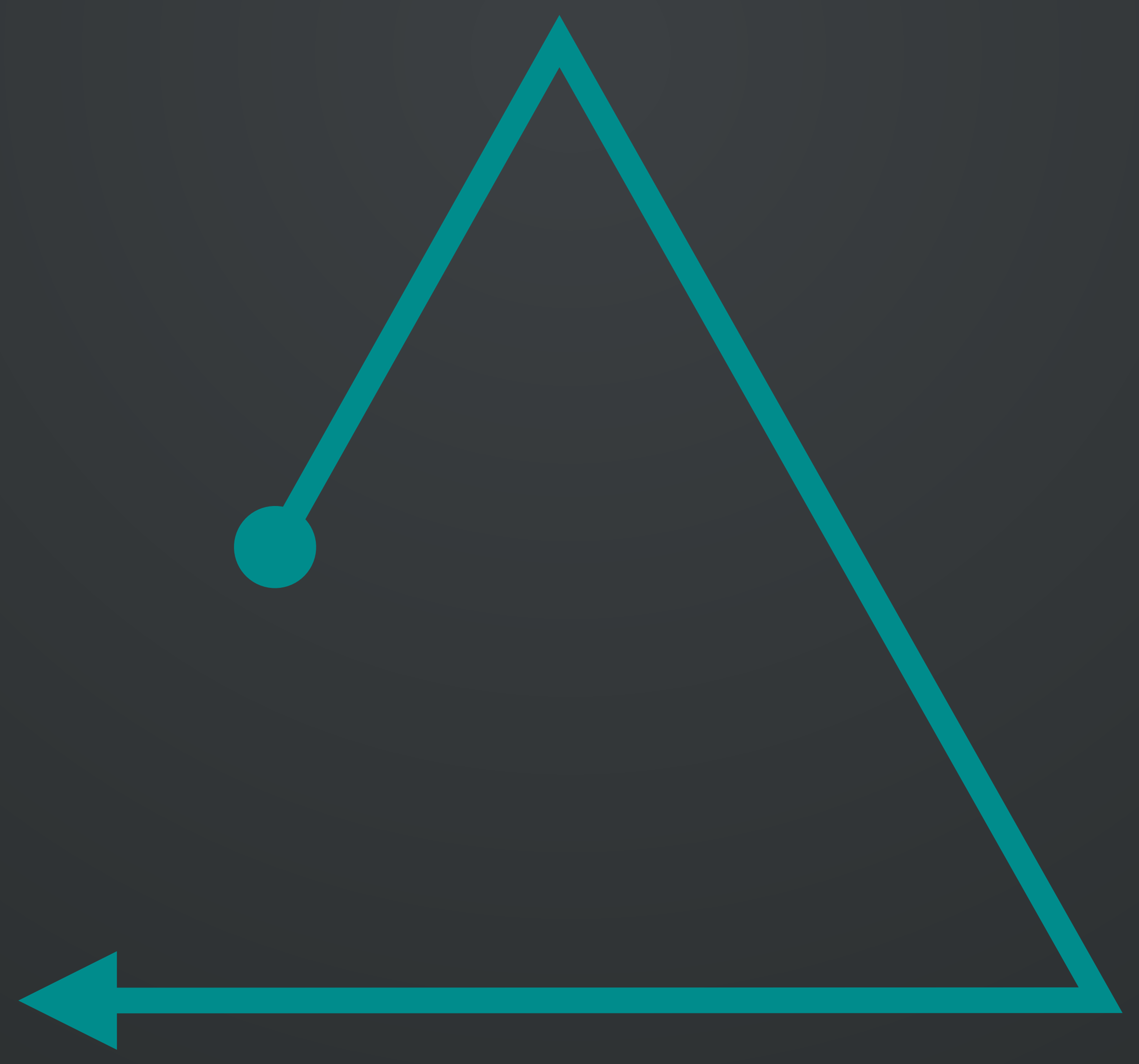
DIFFERENTIAL FLUX SENSITIVITY

Ref: https://pos.sissa.it/395/005/pdf



- **Better angular resolution** will help with the regions crowded by astrophysical sources (typically GC)
- **Better energy resolution** will help catch spectral feature (line search for instance)
- **Larger FoV** will help with the background estimation and large region investigation (Galactic center halo)

SO FAR …



No signal from DM annihilation

has been detected by any of the
current instruments

Statistical analysis

based on a log-likelihood technique

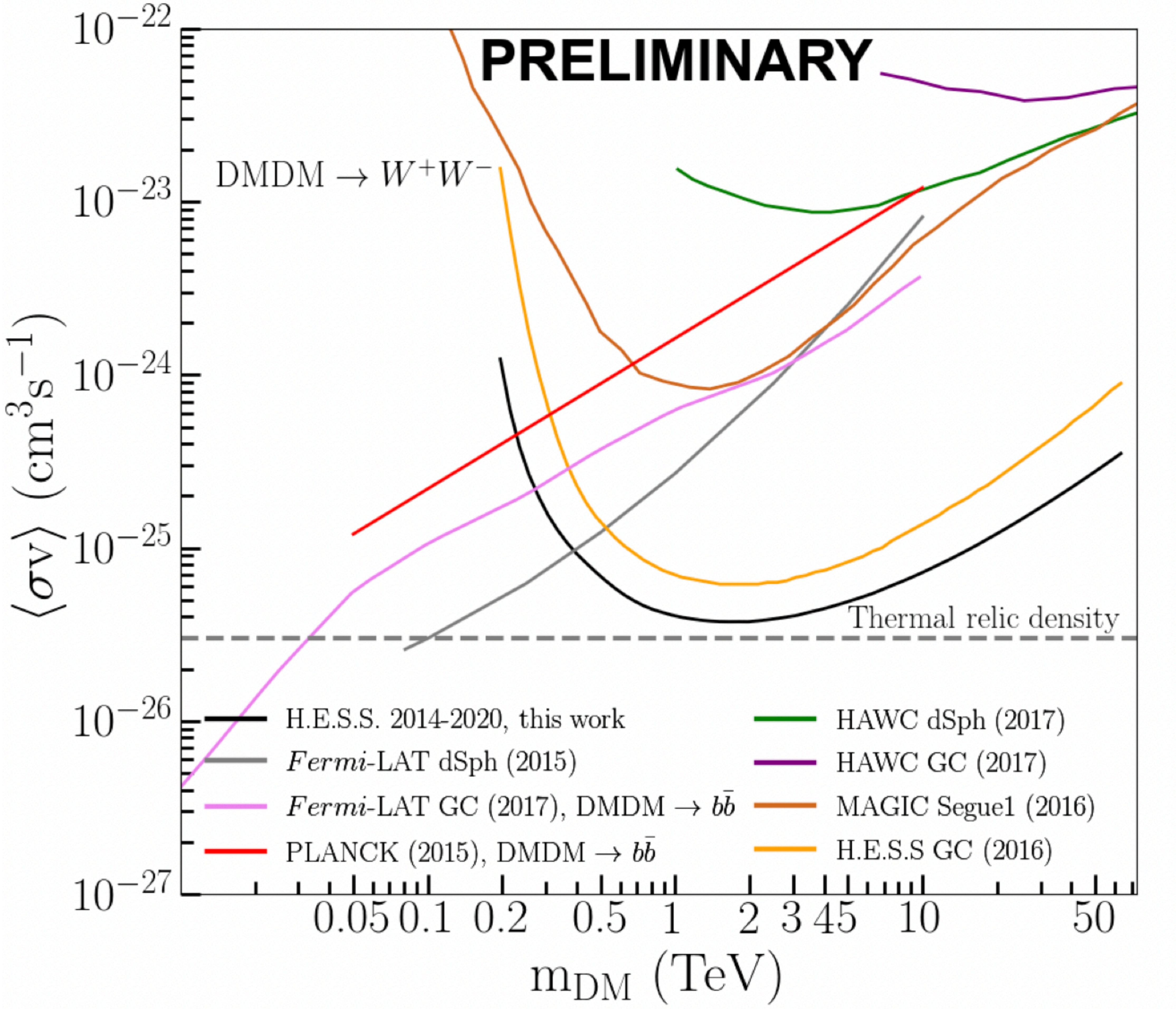
Derivation of upper limits

on the DM annihilation cross
section <σv> as a function of
the DM particle mass

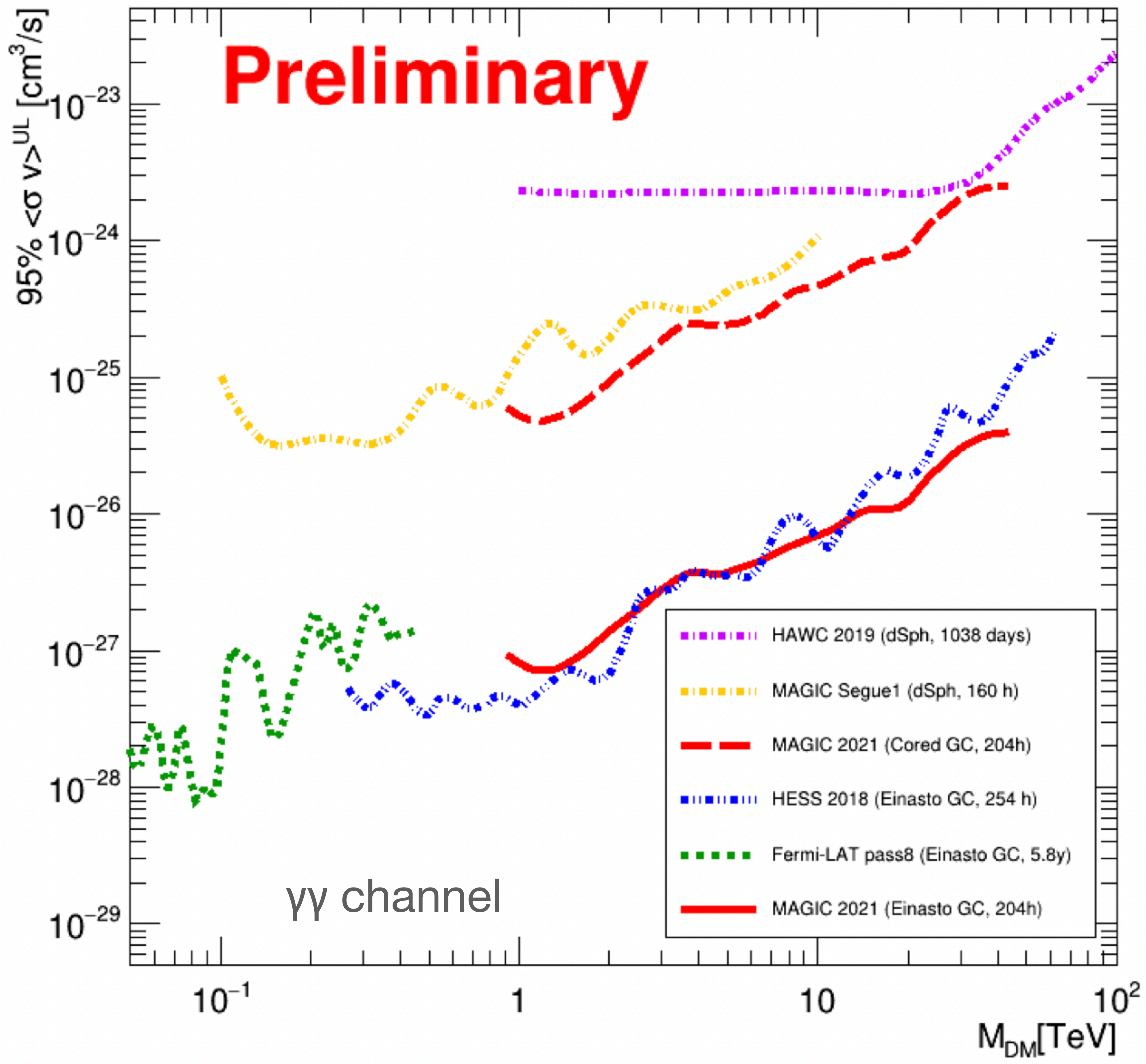
UPPER **LIMITS - OVERVIEW**

Current observatories

Ref: https://pos.sissa.it/395/511/pdf



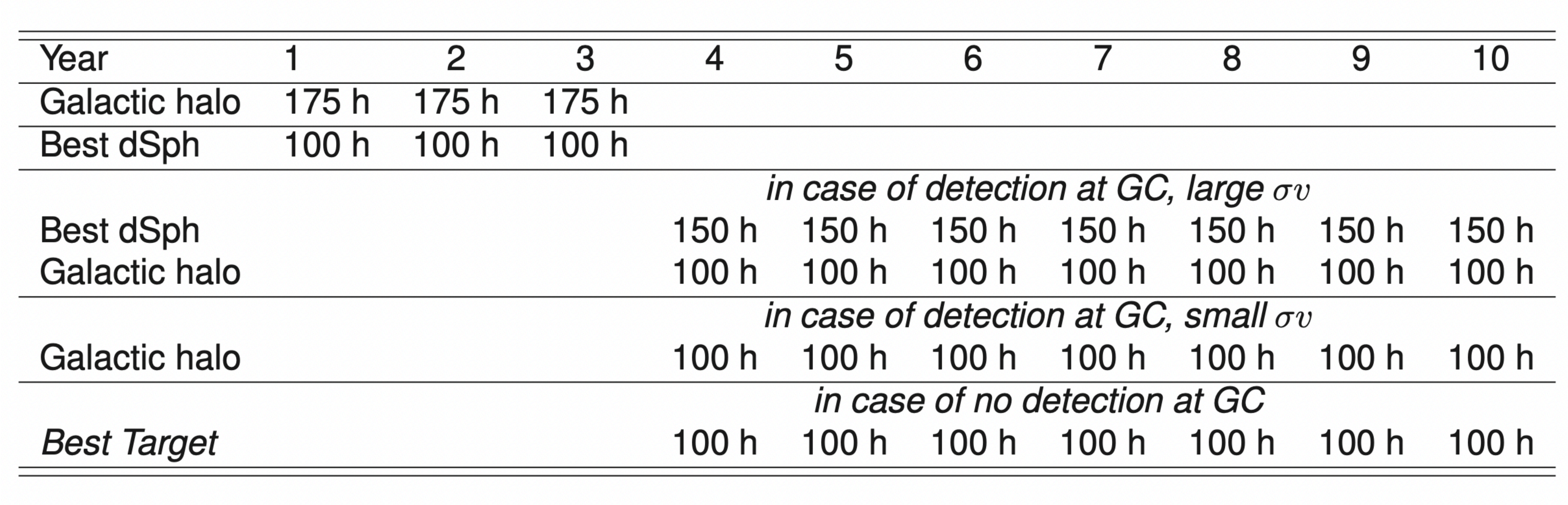
Ref: https://pos.sissa.it/395/520/pdf



CTA - DARK MATTER **PROGRAM**

CTA - DARK MATTER PROGRAM

Ref: https://arxiv.org/pdf/1709.07997.pdf



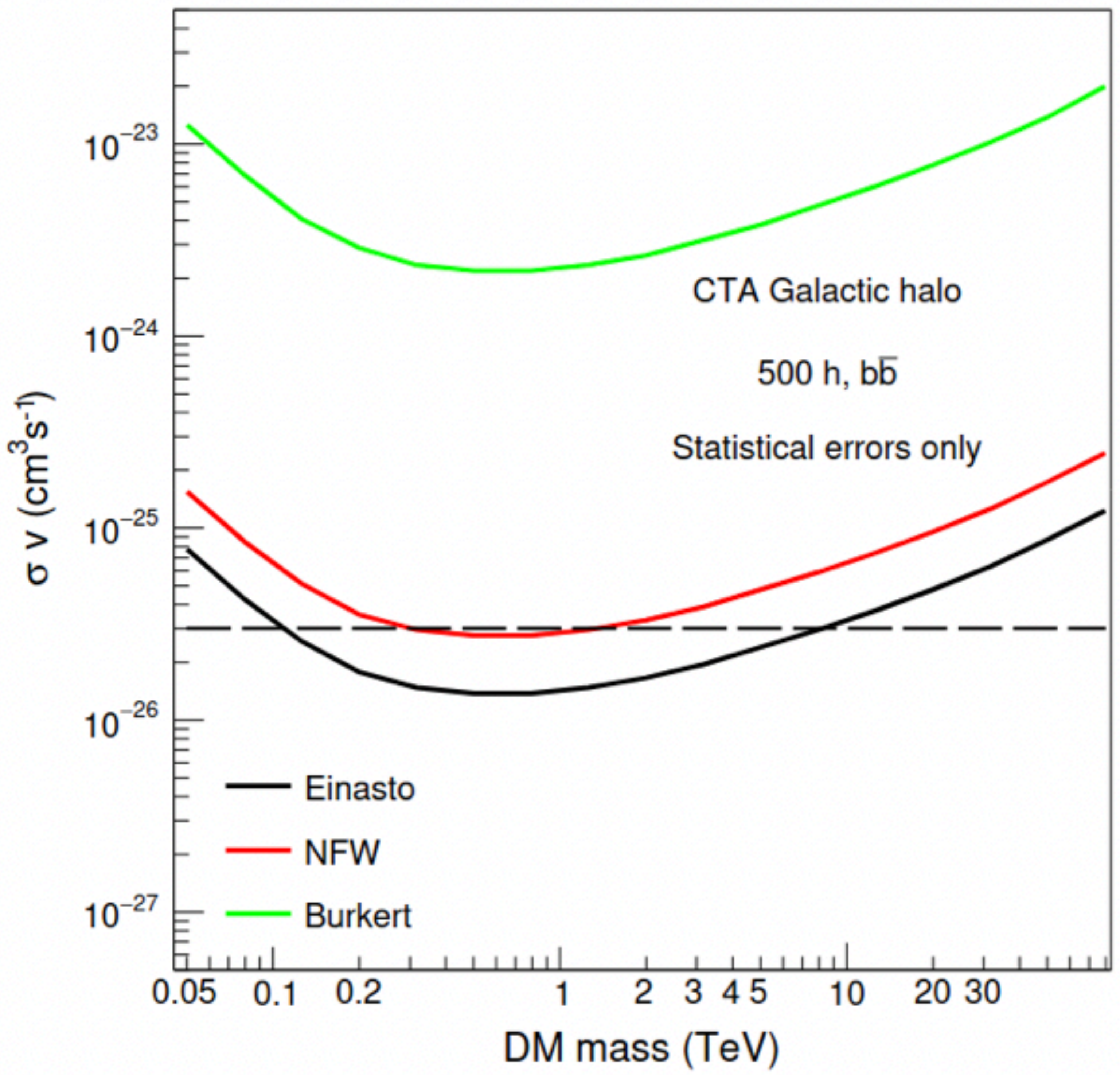
Year	1	2	3	4	5	6	7	8	9	10
Galactic halo	175 h	175 h	175 h							
Best dSph	100 h	100 h	100 h							
				in case of detection at GC, large σv						
Best dSph				150 h	150 h	150 h	150 h	150 h	150 h	150 h
Galactic halo				100 h	100 h	100 h	100 h	100 h	100 h	100 h
				in case of detection at GC, small σv						
Galactic halo				100 h	100 h	100 h	100 h	100 h	100 h	100 h
				in case of no detection at GC						
Best Target				100 h	100 h	100 h	100 h	100 h	100 h	100 h

*** LMC will be observed anyway for astrophysical reason**

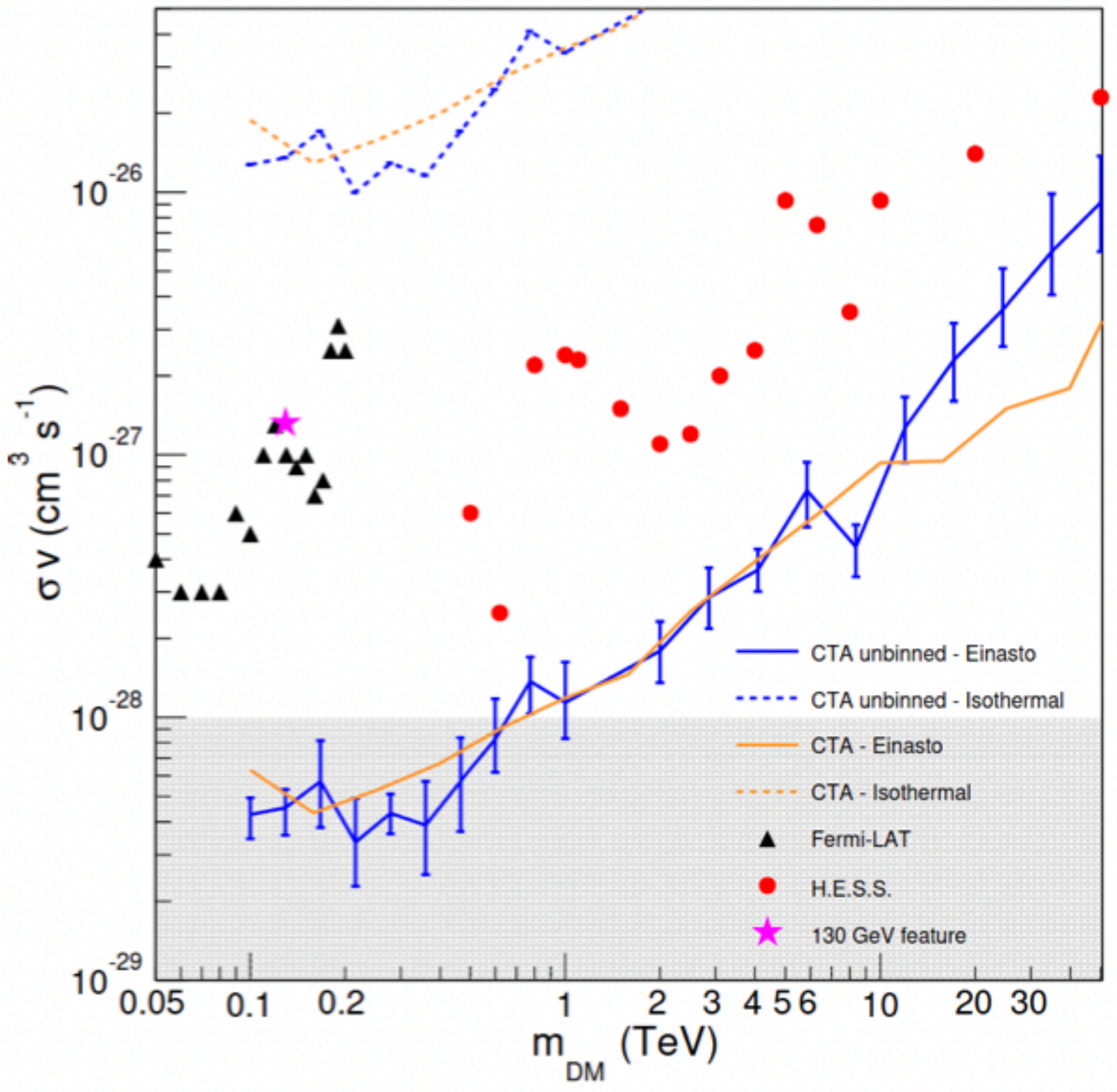
CTA - DARK MATTER **PROGRAM**

CTA - DARK MATTER PROGRAM

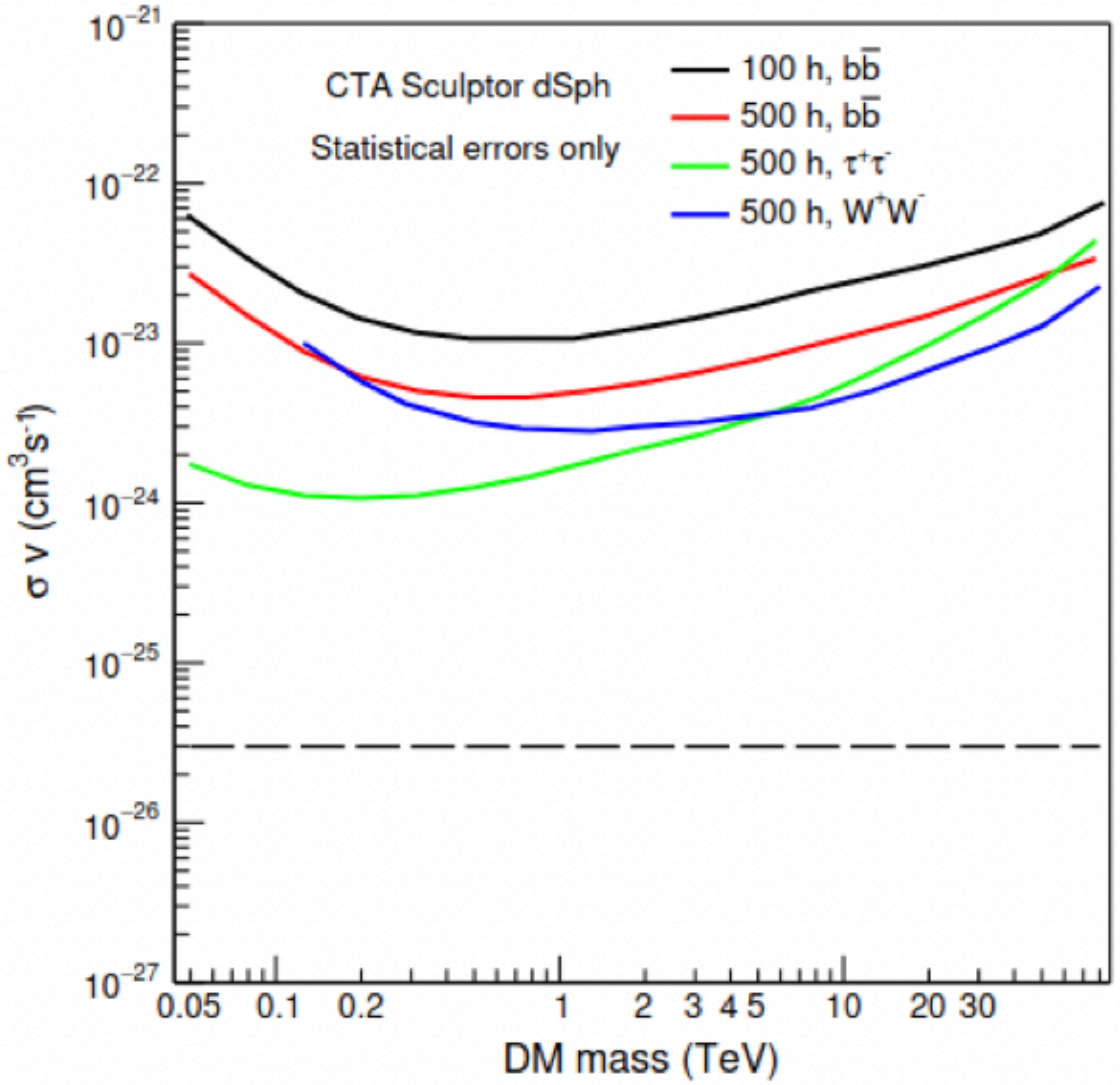
Continuum channel



Line search γγ channel



Continuum channels with dSph

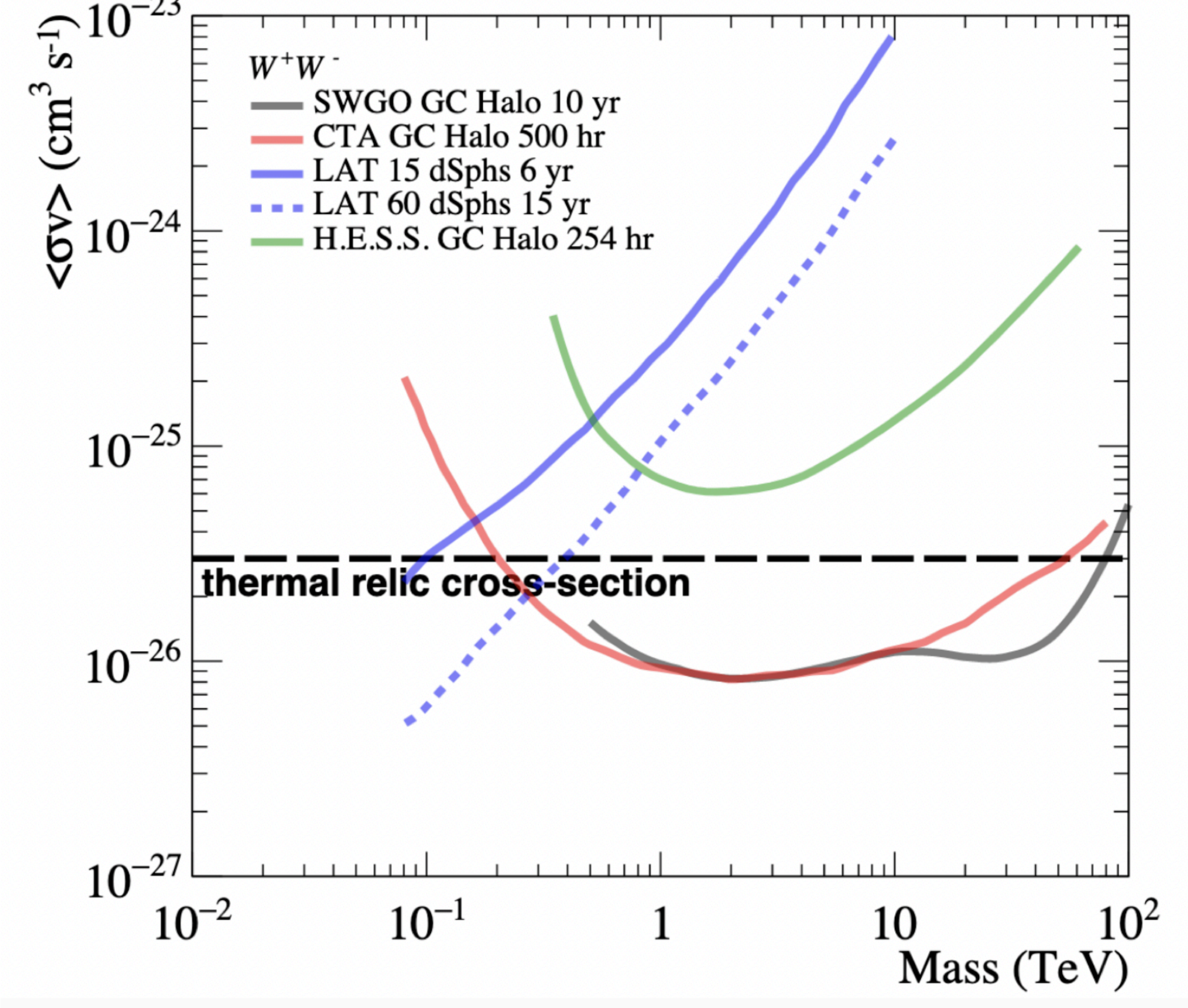


Ref: https://arxiv.org/pdf/1709.07997.pdf

- **Galactic halo =** best target for CTA but large uncertainty on the density profile
- **Best case scenario:** full exclusion of E < 100 TeV mass range (if no detection)

CTA - DARK MATTER **PROGRAM**

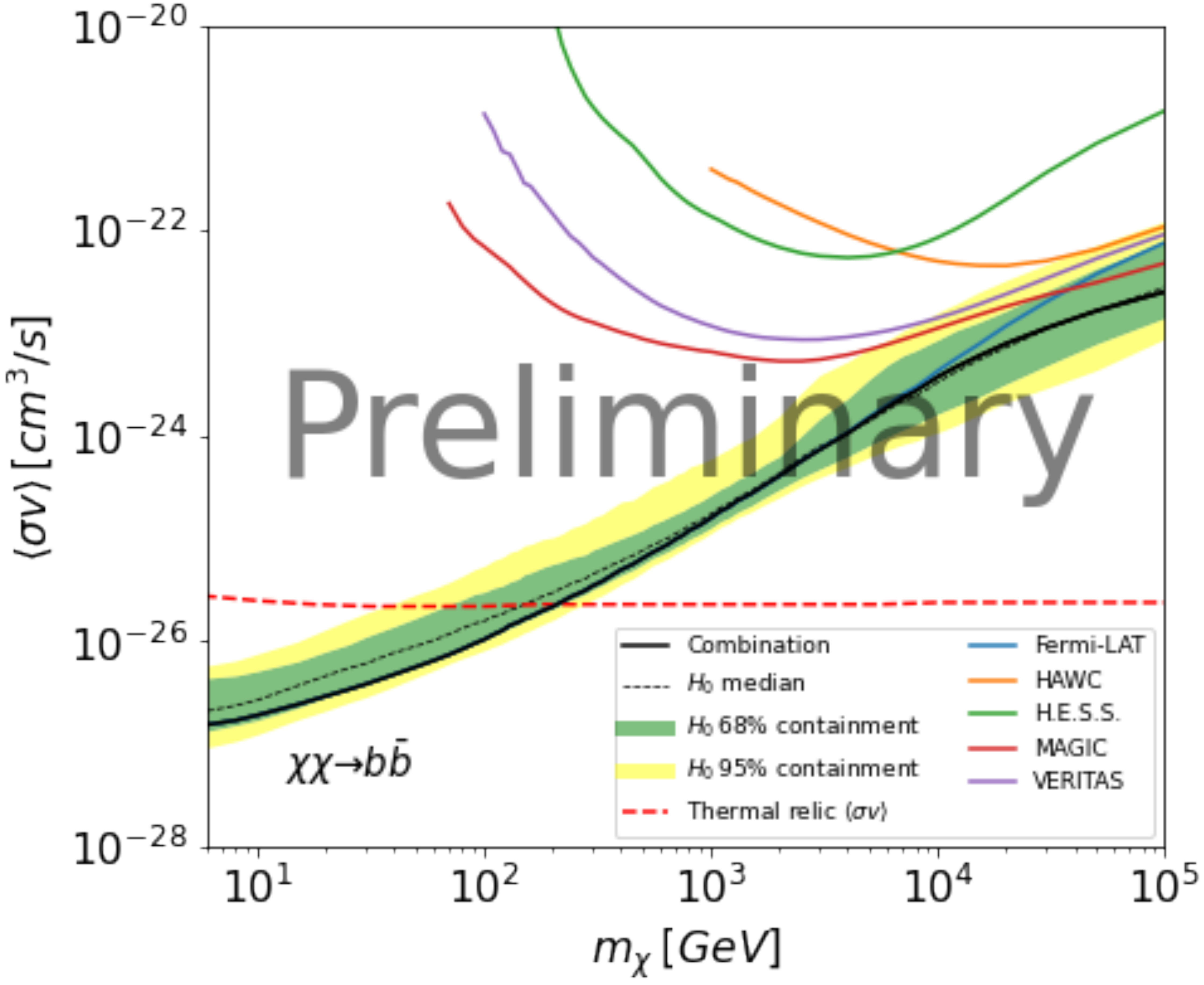
CTA - DARK MATTER PROGRAM



Ref: https://pos.sissa.it/395/047/pdf

- SWGO shows **very similar upper limits** as CTA
- **Combination of both** can be performed to increase the sensitivity

CONSTRAINTS ON **DARK MATTER**



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

- Combined upper limits between Fermi-LAT, HAWC, H.E.S.S., MAGIC, and VERITAS
- 2-3 times more constraining
- Pave the way for CTA (North and South)
- But also for future combination between observatories (Fermi-LAT, CTA, SWGO, LHAASO…)
- Starting point for combinations between different types of targets ?

  (So far dwarf spheroidal galaxies only)

CONCLUSIONS

- So far **no detection** of dark matter signals towards any of the observed targets

- Through **statistical analyses, constraints are derived** on the annihilation cross-section
- CTA gives a new chance of dark matter discovery thanks to its **better energy and angular resolution and the size of its FoV**

- **Possible combination** of the CTA results with those of the current and future observatories

  The **combined technique is currently being developed** on the dwarf spheroidal galaxies

- CTA can also set constraints on **Axion-like particles** (Gamma-ray propagation) and **Primordial Black hole** that can be linked to the dark matter topic


Fornax - credits: ESO/Digitized Sky Survey 2

THANKS FOR YOUR ATTENTION!

BACKUP

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**

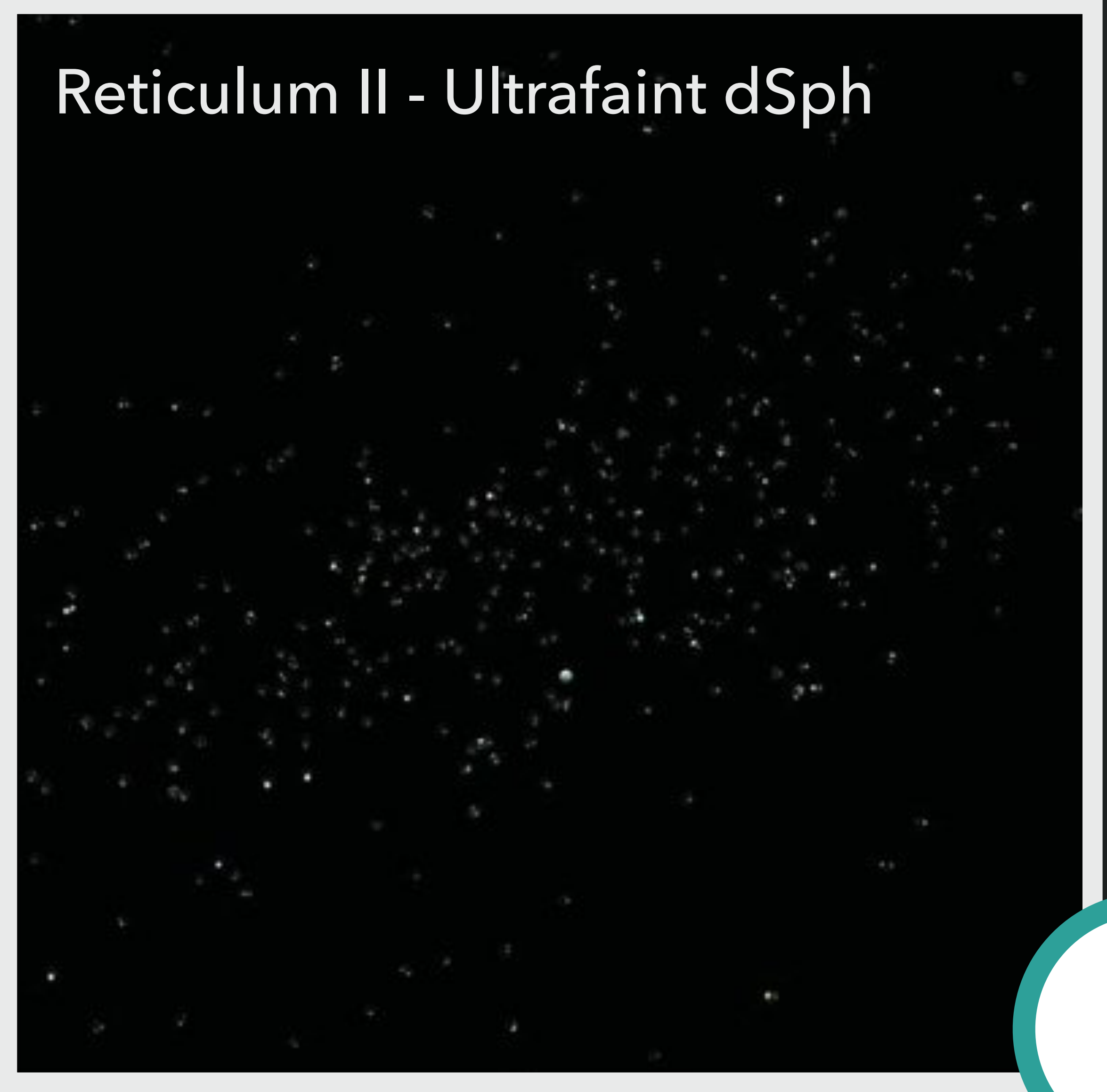
Classicals

~150 - 2500 bright stars
(tracers)

Ultrafaints

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


Sculptor - Classical dSph


Reticulum II - Ultrafaint dSph

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

STATISTICAL **ANALYSIS**

LIKELIHOOD FUNCTION

$$\mathscr{L}(\langle\sigma v; \nu \mid \mathscr{D}_{\text{dSphs}}) = \overset{\text{dSph}}{\prod_{k=1}} \overset{\text{Experiment}}{\prod_{l=1}} \underbrace{\mathscr{L}_{\text{dSph},l,k}\left(\langle\sigma v\rangle; J_{l,k}, \nu_{l,k} \mid \mathscr{D}_{\text{dSphs}}\right)}_{\text{Likelihood of individual instruments and individual dSphs}} \underbrace{\mathscr{J}_k(J_k \mid \bar{J}, \sigma_{\log_{10} J})}_{\text{J factor nuisance}}$$

Product of likelihoods of all energy bins

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

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

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

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

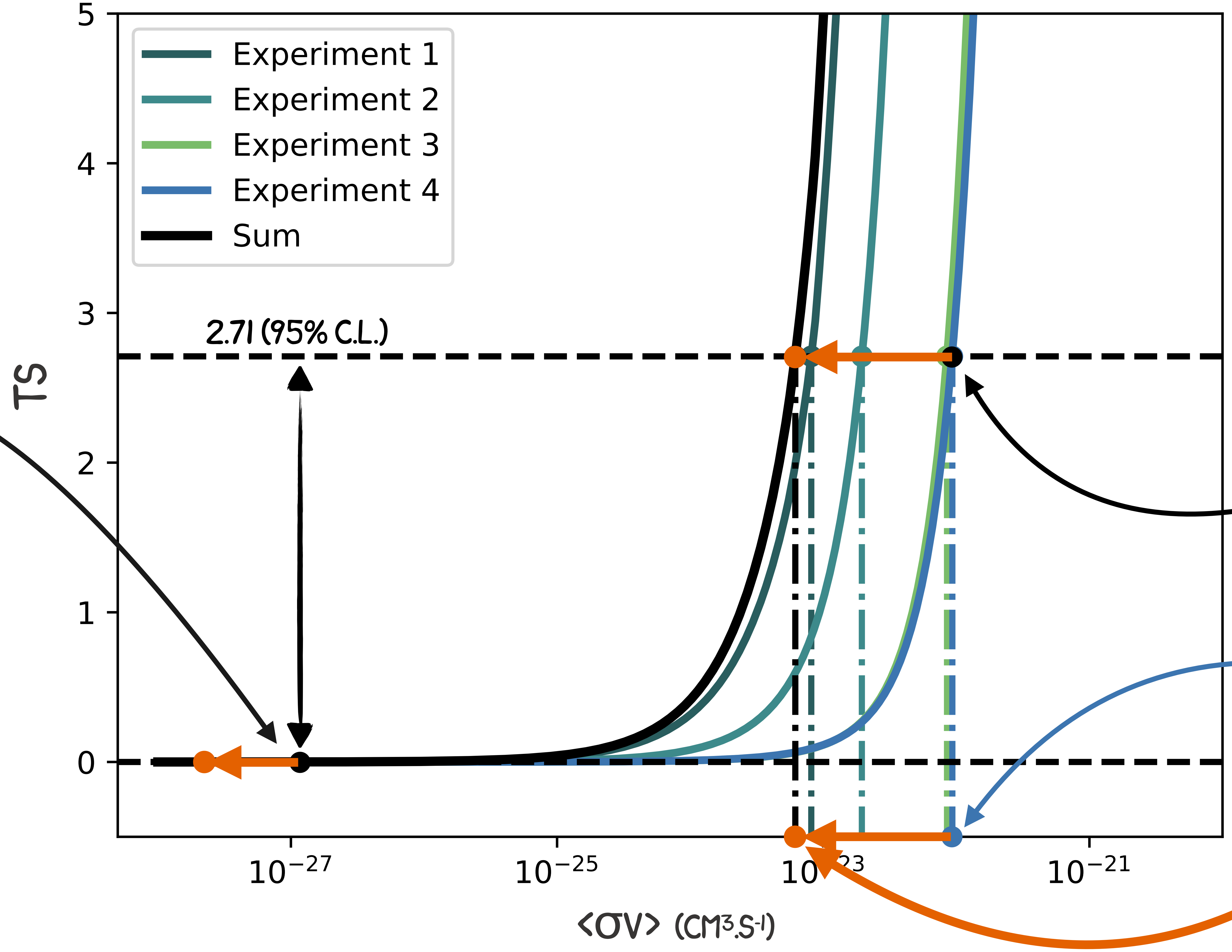
Ref: Cowan et al. (2011), European Physical Journal C, vol. 71 p1554

$\langle\sigma v\rangle$	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



GLOBAL MINIMUM

CONSTRAINED MINIMUM

UPPER LIMIT AT 95% C.L.
FOR A GIVEN CHANNEL / DM MASS / DWARF / EXPERIMENT

NEW UPPER LIMIT AT 95% C.L.
FOR A GIVEN CHANNEL / DM MASS / DWARF