July 8th - 12th, 2022

TeVPA 2022, Kingston, Canada
Aug 9th, 2022

Combined Dark Matter Search

With Fermi-LAT, HAWC, H.E.S.S., MAGIC, and VERITAS





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FOR THE FERMI-LAT, HAWC, H.E.S.S., MAGIC, AND VERITAS COLLABORATIONS

INTRODUCTION

INTRODUCTION

DARK MATTER

85% of the total matter of our Universe

Its identification would reveal new Physics

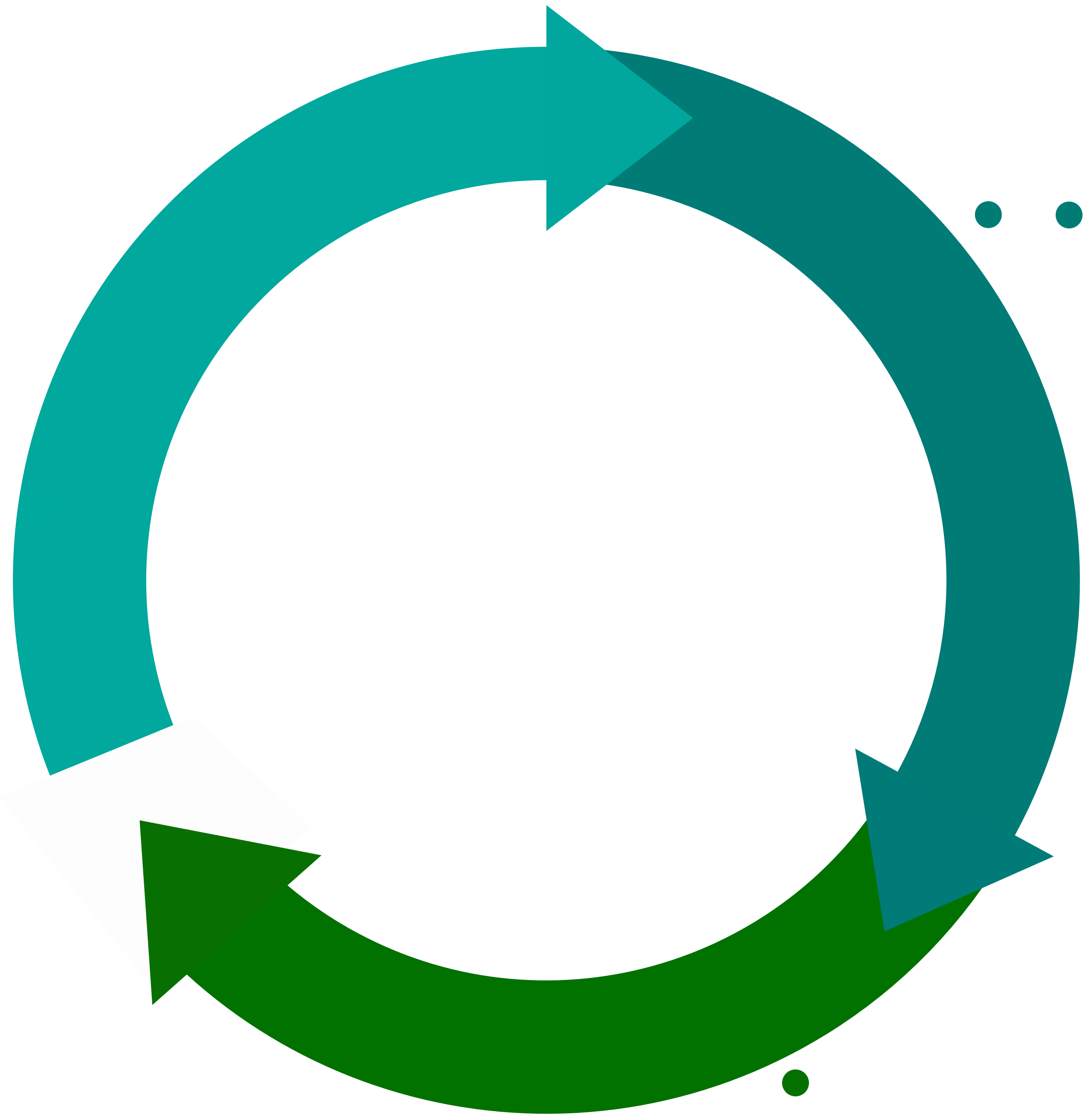
Proving its existence and nature would improve our understanding of the Universe

FIVE EXPERIMENTS

Combination of the observation results towards dwarf spheroidal galaxies (dSphs)

GOAL

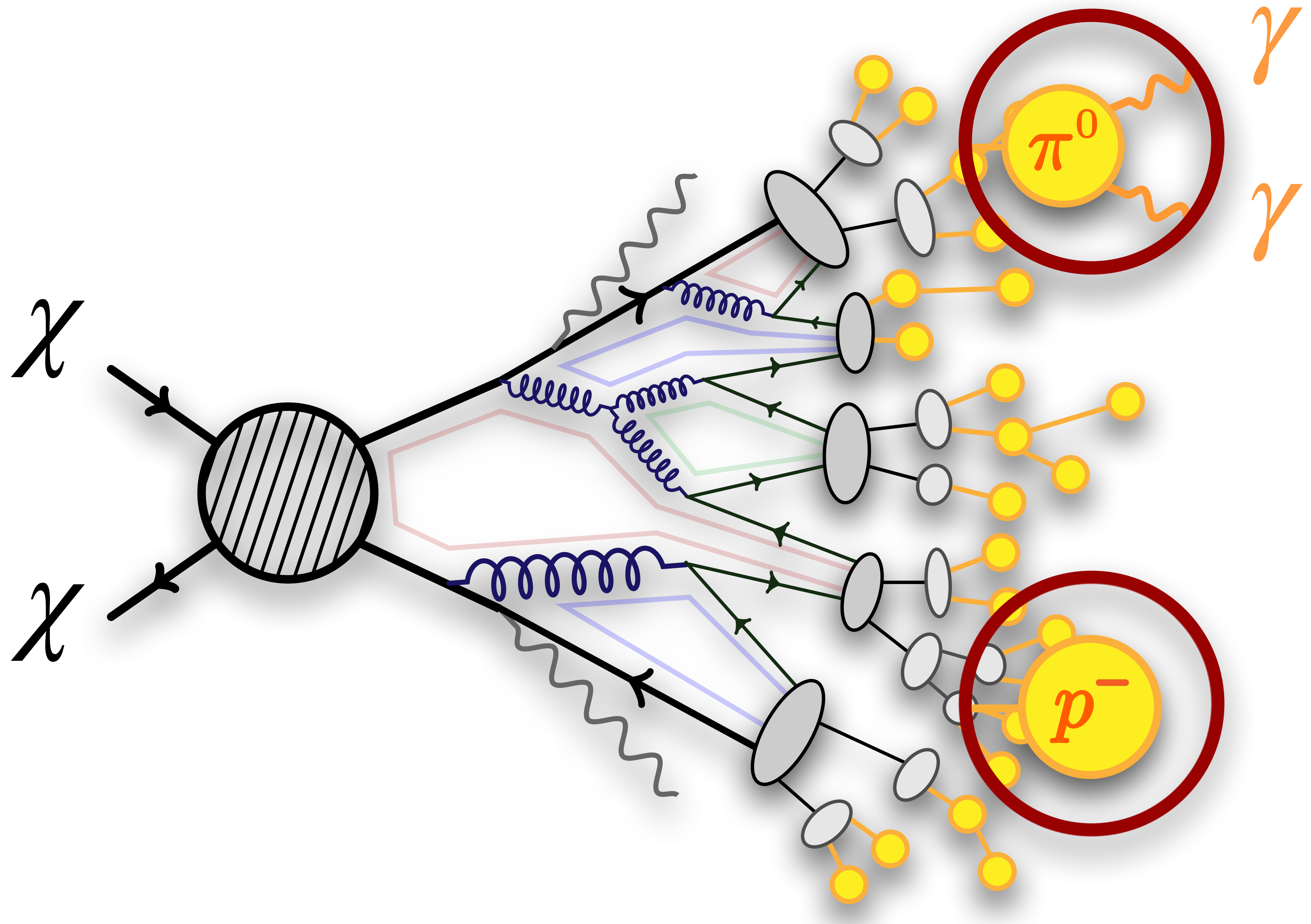
Combination of the individual results published by each collaboration



Significant increase of the statistics

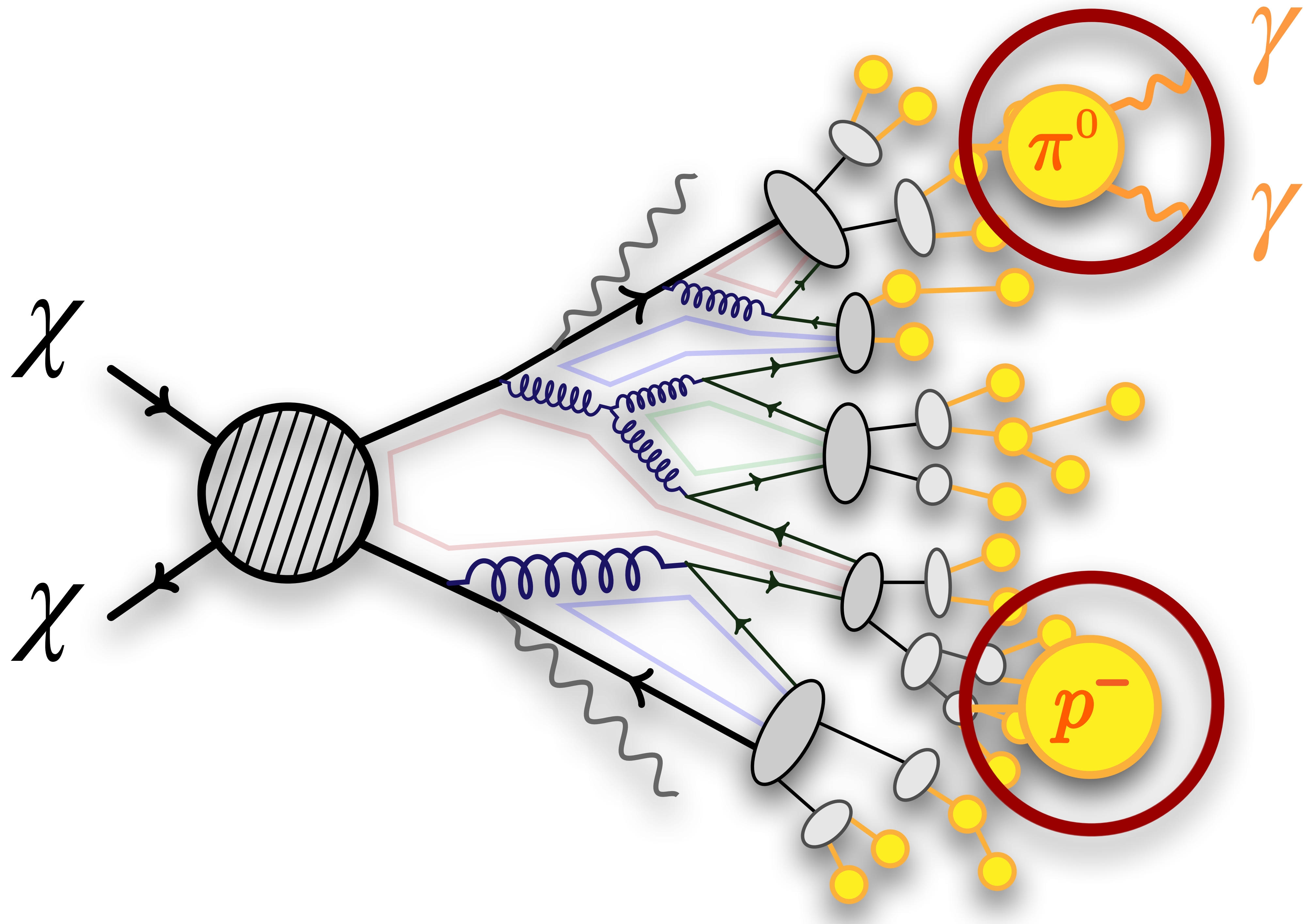
Increase the sensitivity to potential dark matter signals

INDIRECT **SEARCHES**



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

INDIRECT **SEARCHES**



Astrophysical
J factor

$$\frac{d^2\Phi\left(\langle\sigma v\rangle, J\right)}{dE d\Omega} = \frac{1}{4\pi}\frac{\langle\sigma v\rangle}{2m_\chi^2}\sum_f BR_f \frac{dN_f}{dE} \times \frac{dJ}{d\Omega}$$

Particle Physics
factor

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

WHAT ARE DWARF SPHEROIDAL GALAXIES?

- Few bright stars - Classicals up to 2,500 and Ultrafaints up to a few tens
- Low/no gas, dust, or recent star formation
- DM dominated objects
- No expected astrophysical γ-ray background
- **Ideal laboratories for DM indirect searches**

TARGETS

Source name	Experiments
Bootes I	*Fermi*-LAT, HAWC, VERITAS
Canes Venatici I	*Fermi*-LAT
Canes Venatici II	*Fermi*-LAT, HAWC
Carina	*Fermi*-LAT, H.E.S.S.
Coma Berenices	*Fermi*-LAT, HAWC, H.E.S.S., MAGIC
Draco	*Fermi*-LAT, HAWC, MAGIC, VERITAS
Fornax	*Fermi*-LAT, H.E.S.S.
Hercules	*Fermi*-LAT, HAWC
Leo I	*Fermi*-LAT, HAWC
Leo II	*Fermi*-LAT, HAWC
Leo IV	*Fermi*-LAT, HAWC
Leo T	*Fermi*-LAT
Leo V	*Fermi*-LAT
Sculptor	*Fermi*-LAT, H.E.S.S.
Segue I	*Fermi*-LAT, HAWC, MAGIC, VERITAS
Segue II	*Fermi*-LAT
Sextans	*Fermi*-LAT, HAWC
Ursa Major I	*Fermi*-LAT, HAWC
Ursa Major II	*Fermi*-LAT, HAWC, MAGIC
Ursa Minor	*Fermi*-LAT, VERITAS

Twenty Dwarf Spheroidal Galaxies

All previously published by individual collaborations

FIVE **EXPERIMENTS**

Cover the widest energy range ever investigated

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**

COMMON **INGREDIENTS**

COMMON INGREDIENTS

1. **STATISTICAL APPROACH**

   Many exchanges to homogenize the statistical approach and derive the observed, the mean expected limits, and the uncertainty bands

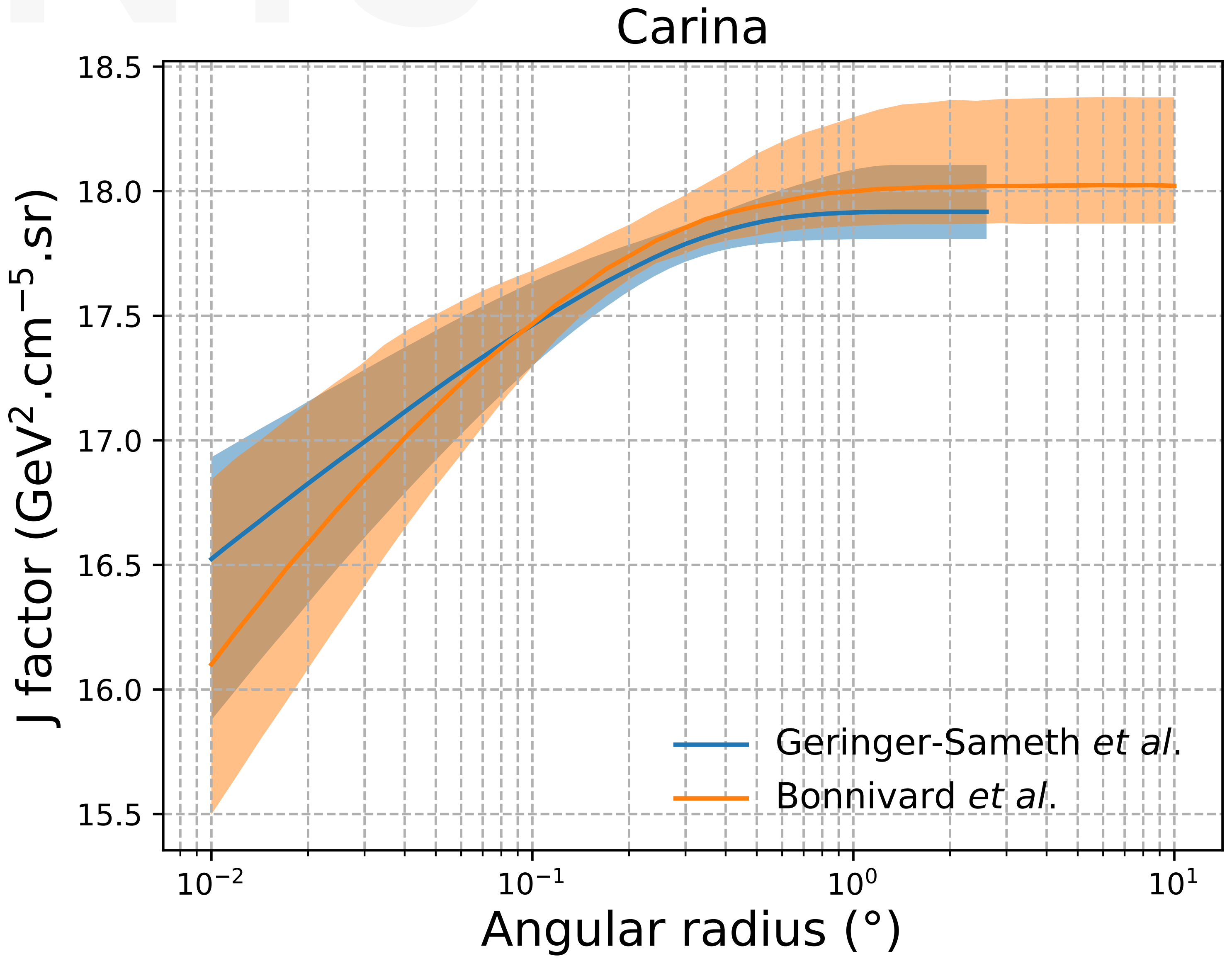
2. **DATA SHARING** - Use of a common format (TS vs <σv>)

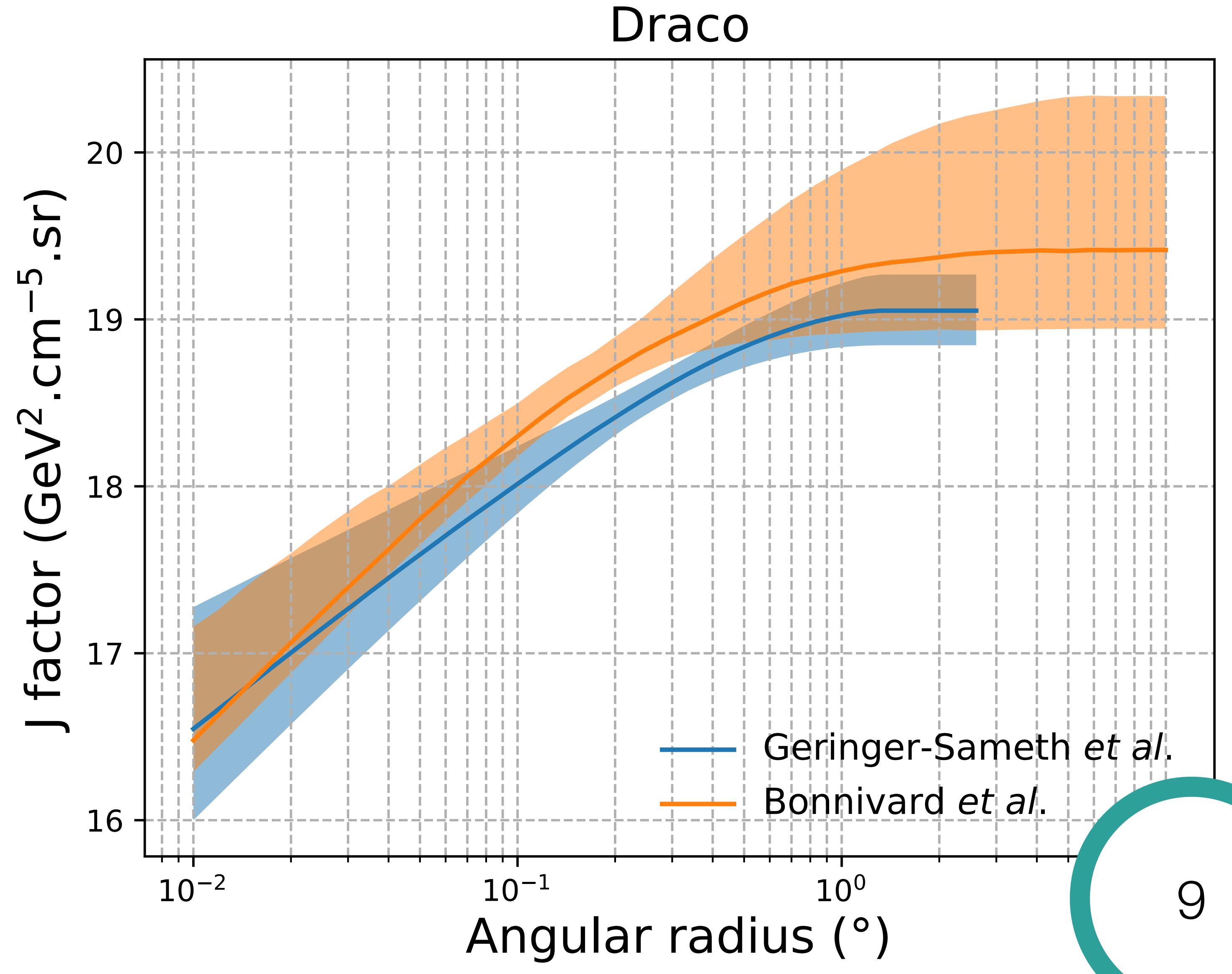
3. **CHANNELS** - $\tau^+\tau^-$, W^+W^- and bb (presented), and Z^+Z^-, $\mu^+\mu^-$, e^+e^-, tt, γγ

4. **SPECTRUM** - Cirelli et al. (Ref: JCAP 1103:051, 2011)

5. **J FACTOR** - 1st set: Taken from Geringer Sameth et al. (Ref: APJ 801:74 (18pp), 2015)
   - 2nd set: Taken from Bonnivard et al. (Ref: ApJ 808 L3, 2015)

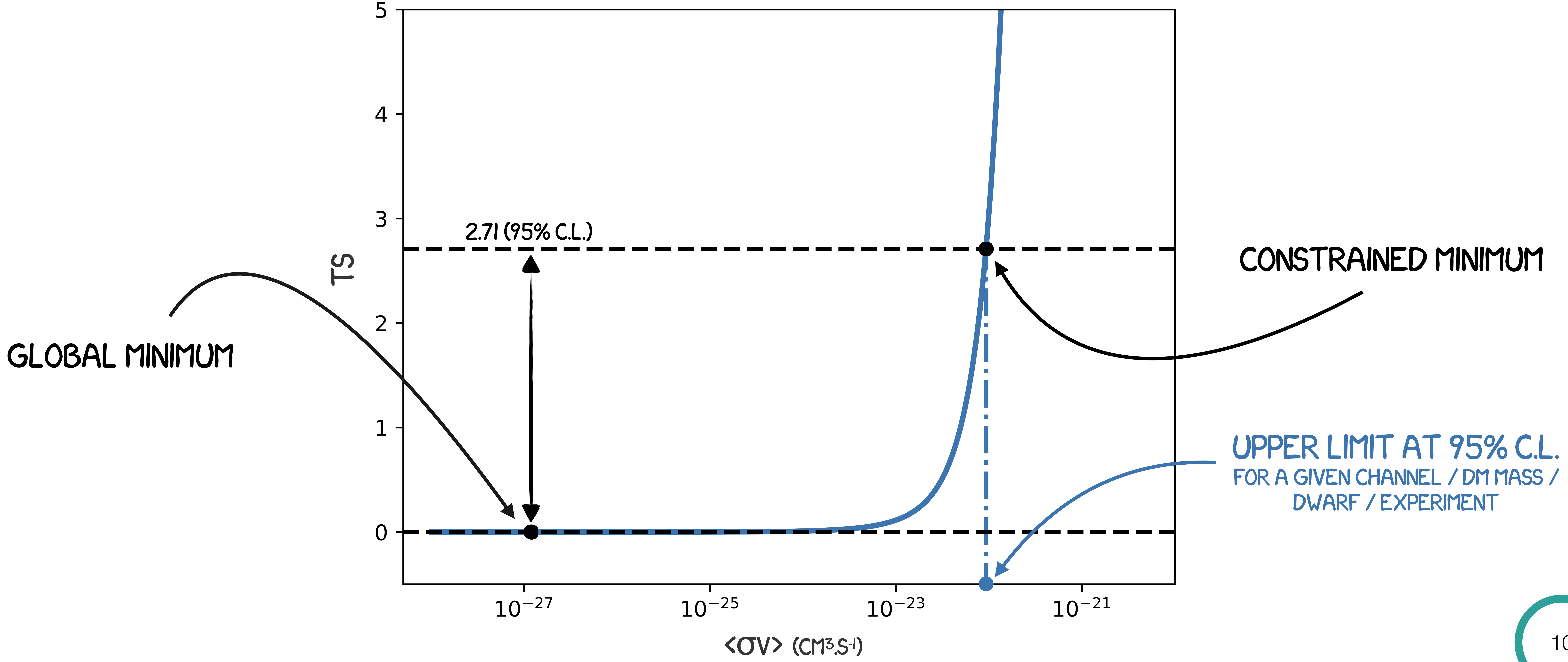
6. **DM PROFILE** - 1st set: Zhao-Hernquist, generalized DM profile
   - 2nd set: Einasto DM profile





STATISTICAL **ANALYSIS**

LOG-LIKELIHOOD RATIO TEST STATISTICS



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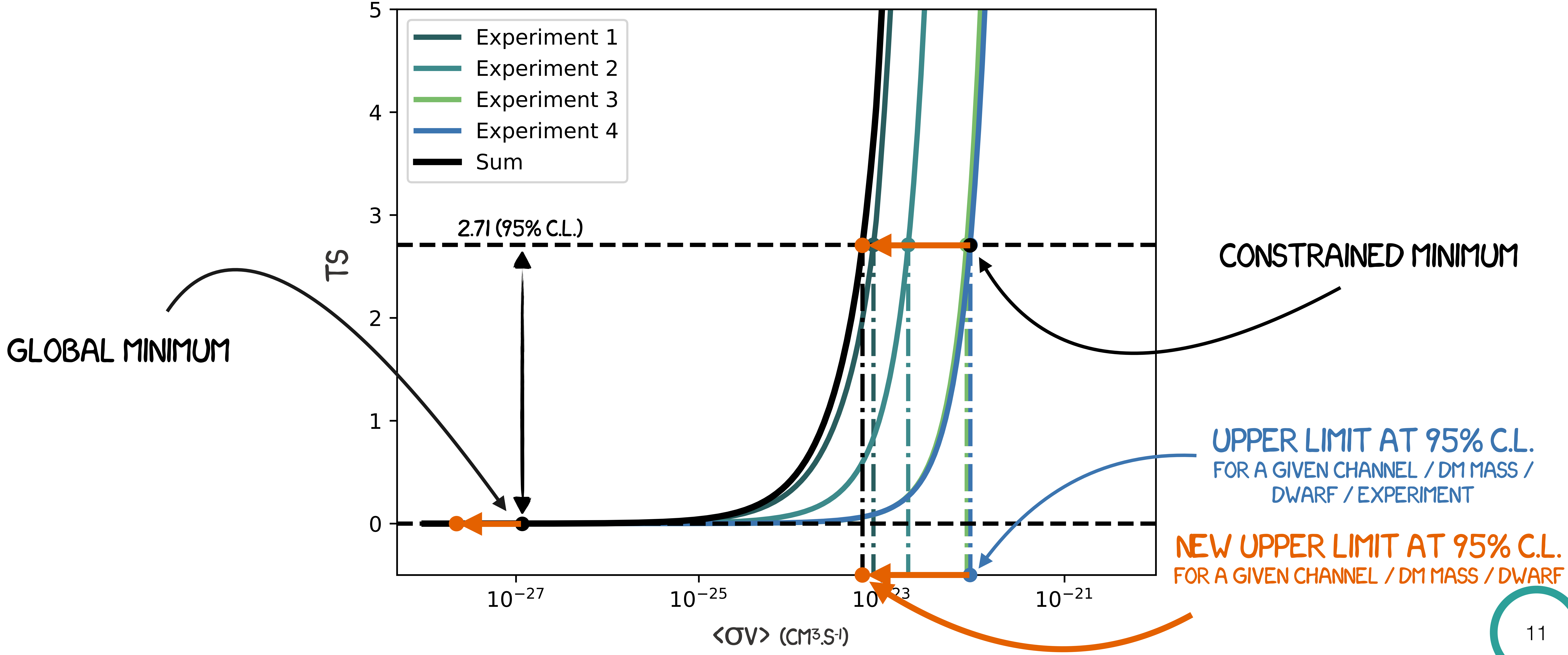


COMBINED **RESULTS**

NO significant excess

found in the data

Upper limits

on the DM annihilation cross section

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 $\langle\sigma v\rangle$ distribution

Statistical uncertainty bands

Standard deviation at 1 and 2σ

COMBINED **RESULTS**

Three channels bb, W+W-, τ+τ-, using the 1st set of J factor (Geringer Sameth et al.)

Combined upper limits are up to 3 times more constraining

Depending on the annihilation channel and the mass

COMBINED **RESULTS**

Three channels bb, W^+W^-, $\tau^+\tau^-$, using the 1st set of J factor (Geringer Sameth et al.)

1 **Below ~2 - 30 TeV -** DM limits largely dominated by Fermi-LAT

COMBINED **RESULTS**

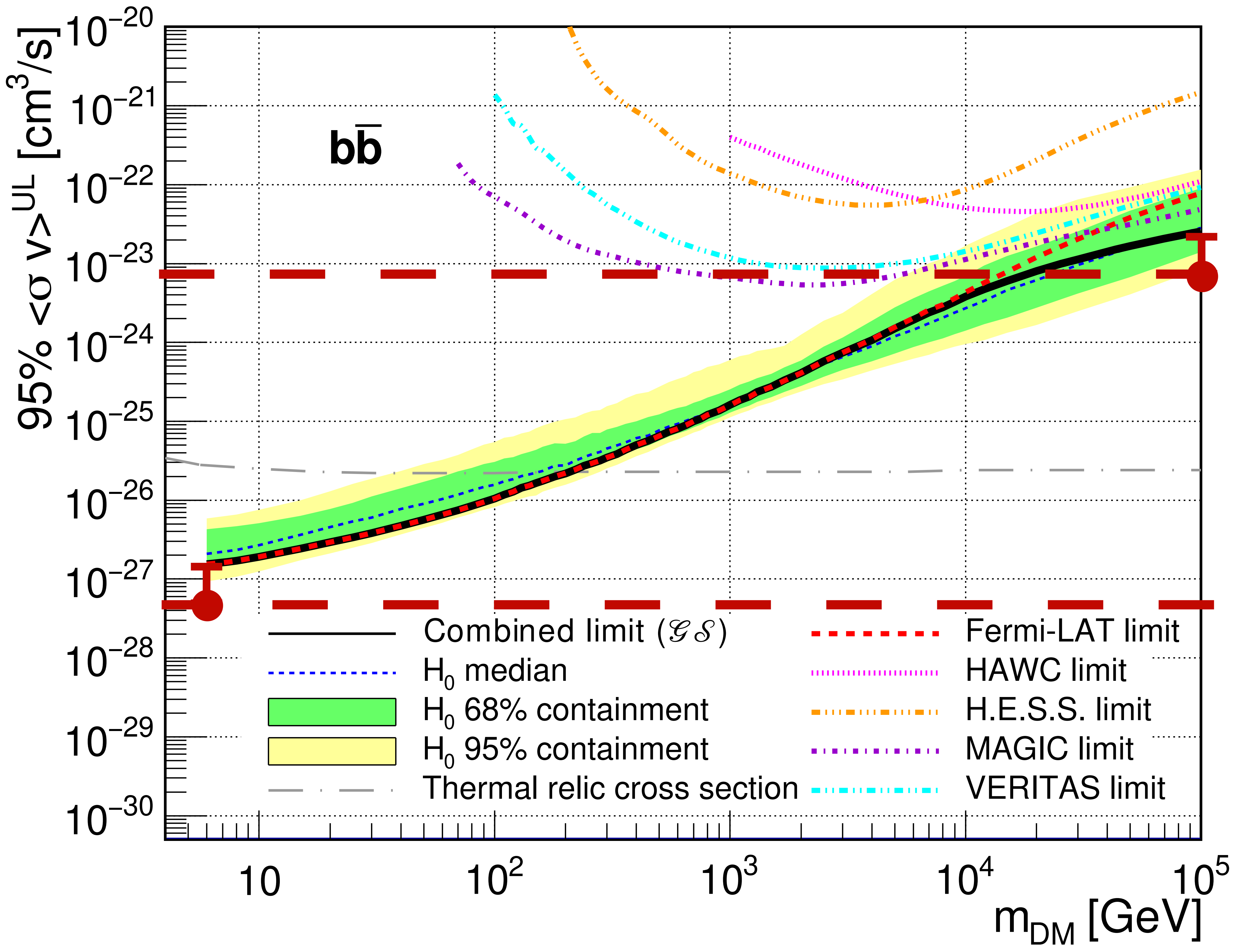
Three channels bb, W^+W^-, $\tau^+\tau^-$, using the 1st set of J factor (Geringer Sameth et al.)

1 **Below ~2 - 30 TeV -** DM limits largely dominated by Fermi-LAT

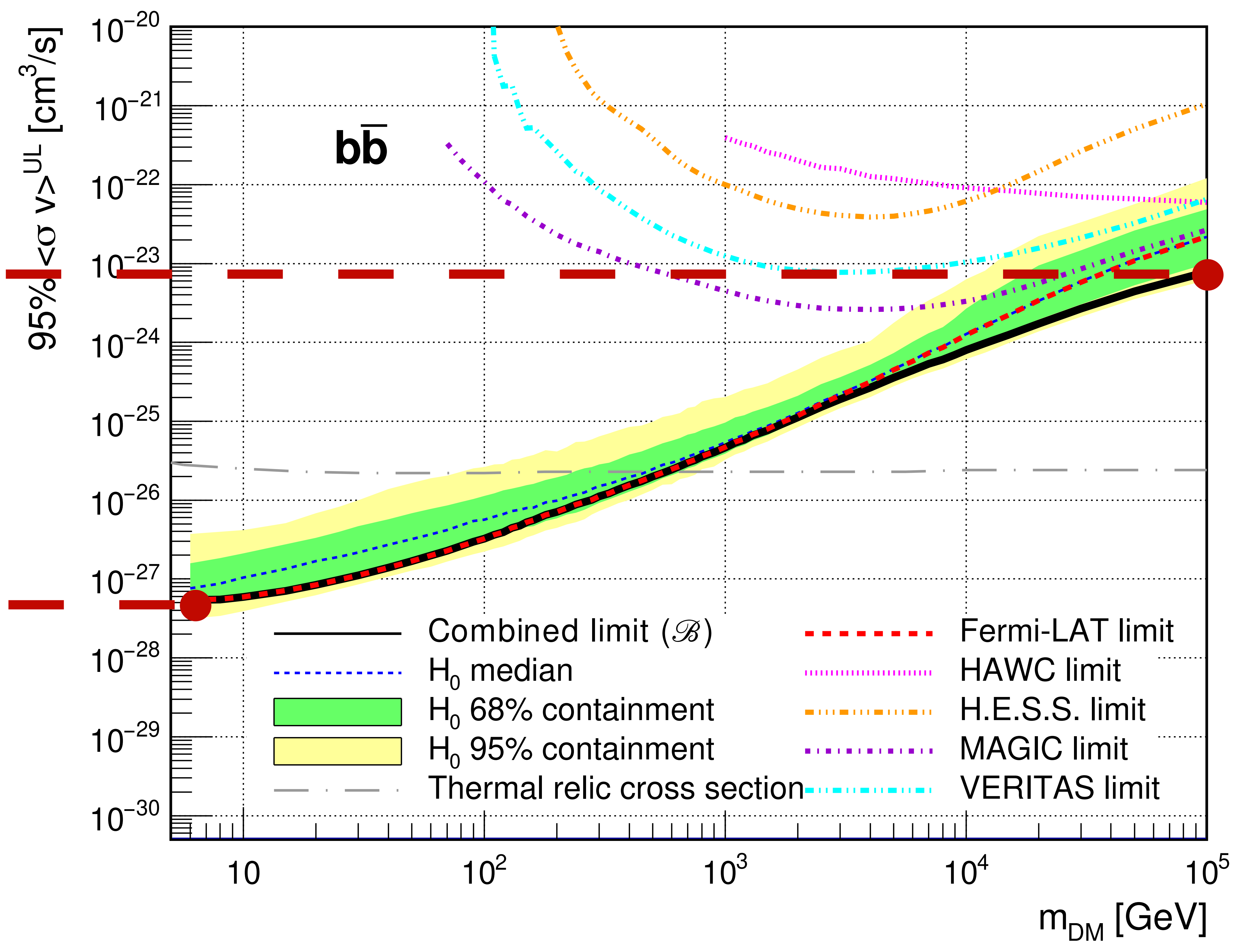
2 **Above ~2 - 30 TeV -** IACTs and HAWC take over

COMBINED **RESULTS**

Limits with J factors of Geringer Sameth et al.



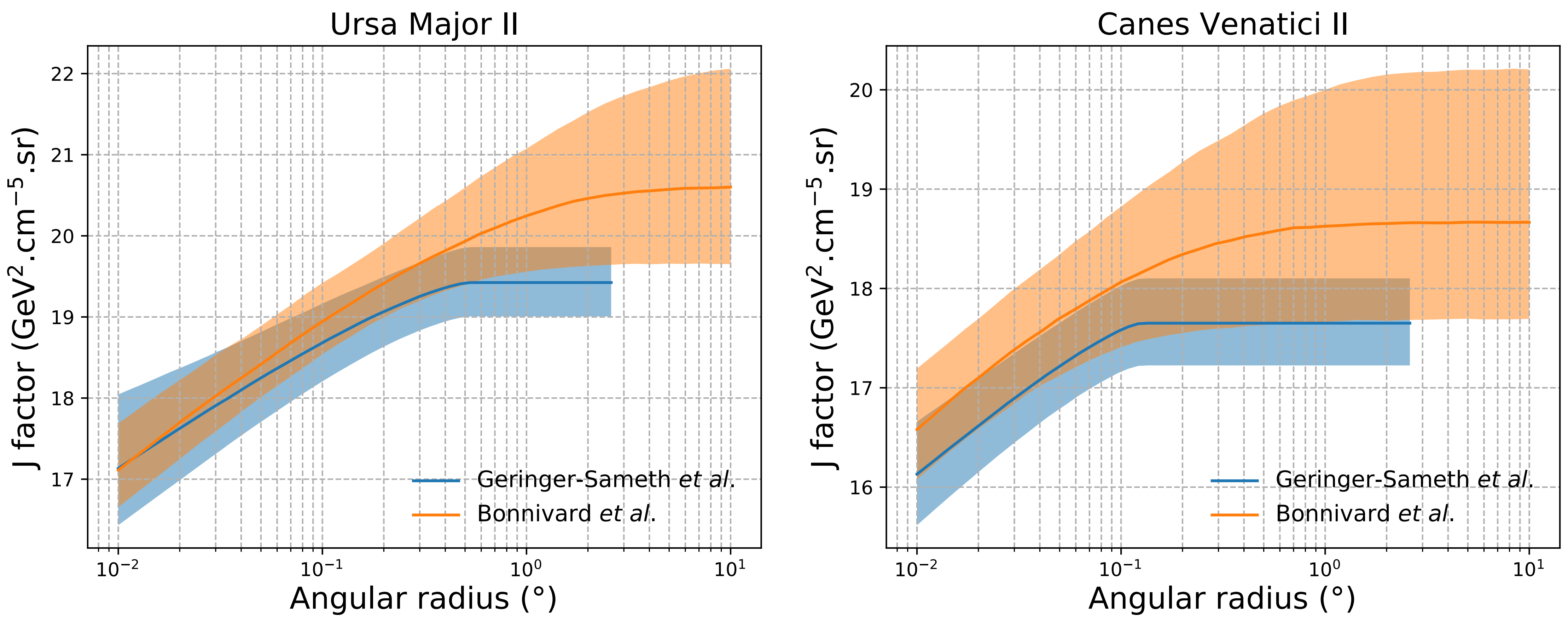
Limits with J factors of Bonnivard et al.

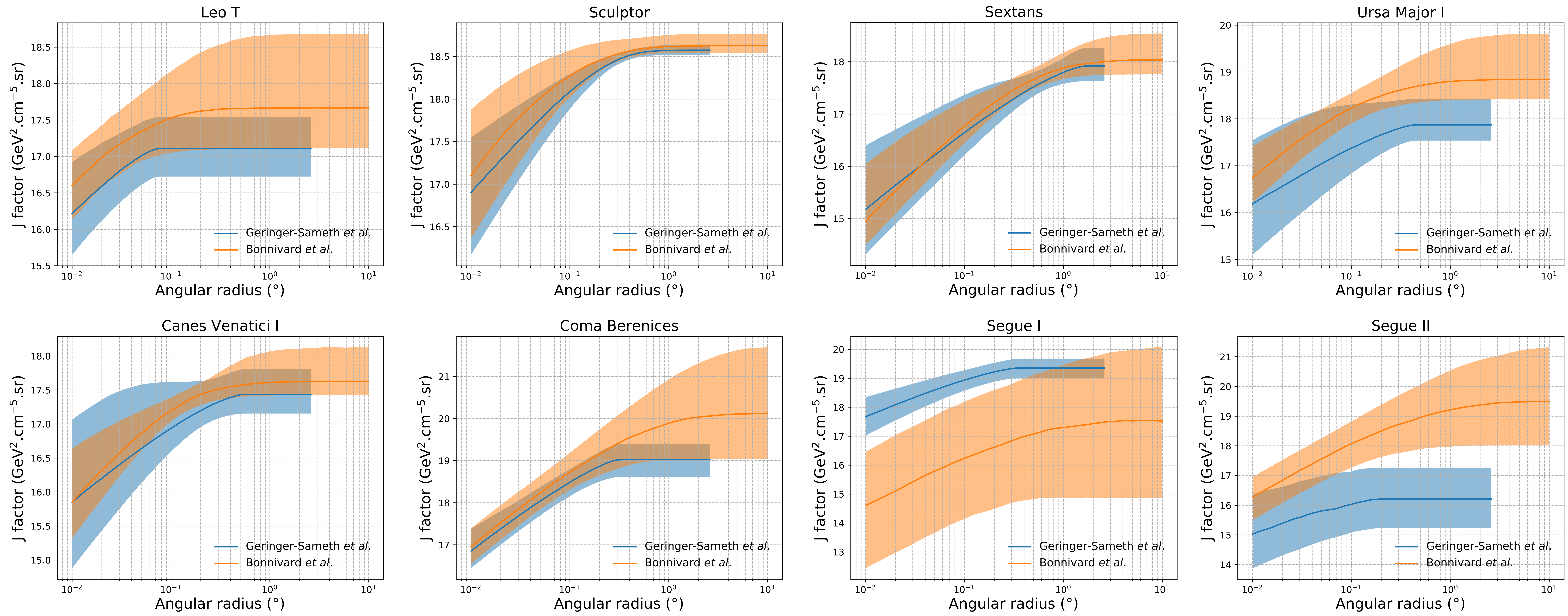


- Limits **3-5x more constraining** using the J factors of Bonnivard et al. depending on the energy
- With the **largest ratio around 10 TeV**
- Bonnivard et al. provide **higher J factors** for the majority of the studied dwarf galaxies

J FACTORS

J FACTORS





CONCLUSIONS

- **No significant DM signal** observed by any of the experiments, nor in the combination
- Use of the **likelihood profiling and common ingredients** to derive upper limits
- Derivation of upper limits over the **widest mass range ever** for the DM WIMPs
- Combined upper limits **improved by 2-3 times** compared to the individual limits
- Possible combination including **other messengers such as neutrinos** (already some contacts with IceCube and ANTARES/KM3NeT)
- In the paper currently in internal review: **5 additional** channels: ZZ, μμ, ee, tt, γγ


Fornax - credits: ESO/Digitized Sky Survey 2

THANKS FOR YOUR ATTENTION!

Fermi Gamma-ray Space Telescope

HAWC High Altitude Water Cherenkov Gamma-Ray Observatory

H.E.S.S.

MAGIC

VERITAS

TARGETS

	Fermi-LAT	HAWC	H.E.S.S, MAGIC, VERITAS		
Source name	Exposure (10^{11} s m^2)	$\lvert\Delta\theta\rvert$ (°)	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

All previously published by individual collaborations

Twenty Dwarf Spheroidal Galaxies

STATISTICAL **ANALYSIS**

TOTAL LIKELIHOOD = PRODUCT OF INDIVIDUAL LIKELIHOODS

dSph (index k) — Experiment (index l)

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

Likelihood of individual instruments and individual dSphs — **J factor nuisance**

Combination performed using two independent public analysis softwares

gLike
https://doi.org/10.5281/zenodo.4028908 (2020)

LklCombiner
https://doi.org/10.5281/zenodo.4450884 (2021)

JOINT LIKELIHOOD **ANALYSIS**

LOG-LIKELIHOOD RATIO TEST STATISTICS

Constrained minimization

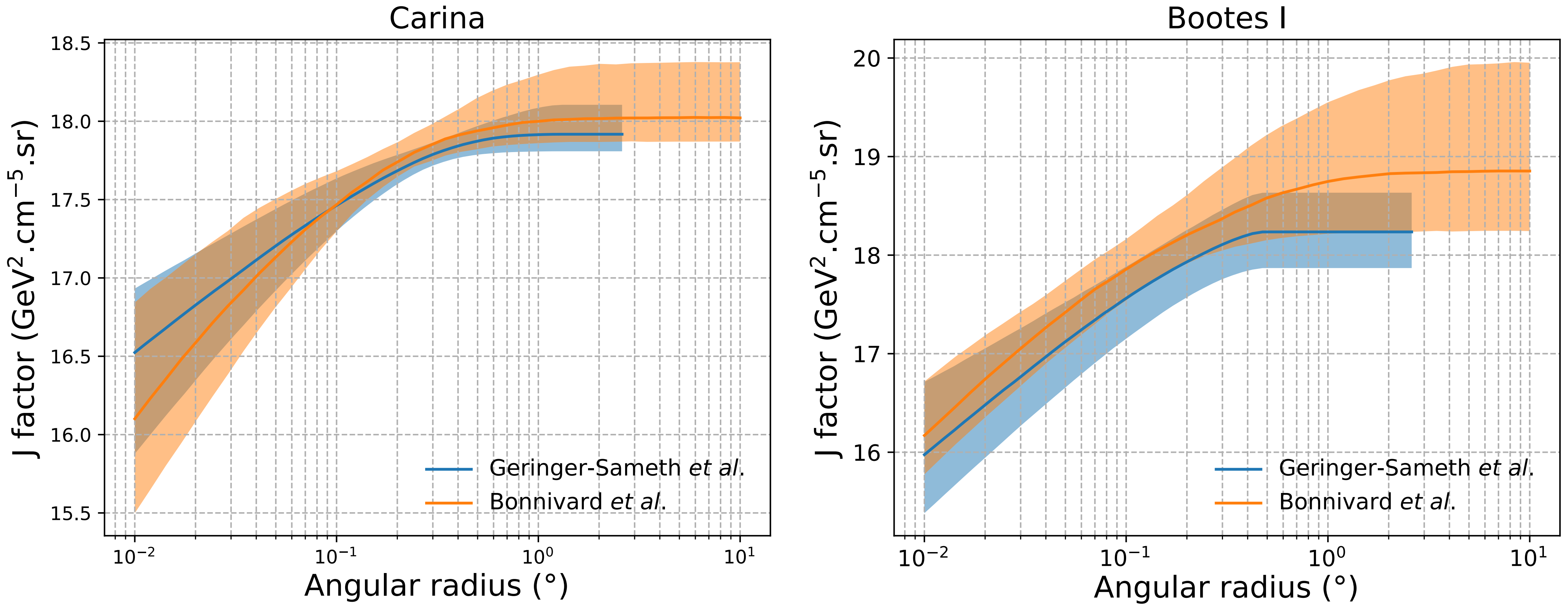
$$TS = -2\ln\lambda = -2\ln\frac{\mathscr{L}\left(\langle\sigma v\rangle;\hat{\hat{\nu}}\,|\,\mathscr{D}_{\mathrm{dSphs}}\right)}{\mathscr{L}\left(\widehat{\langle\sigma v\rangle};\hat{\nu}\,|\,\mathscr{D}_{\mathrm{dSphs}}\right)}$$

Global minimization

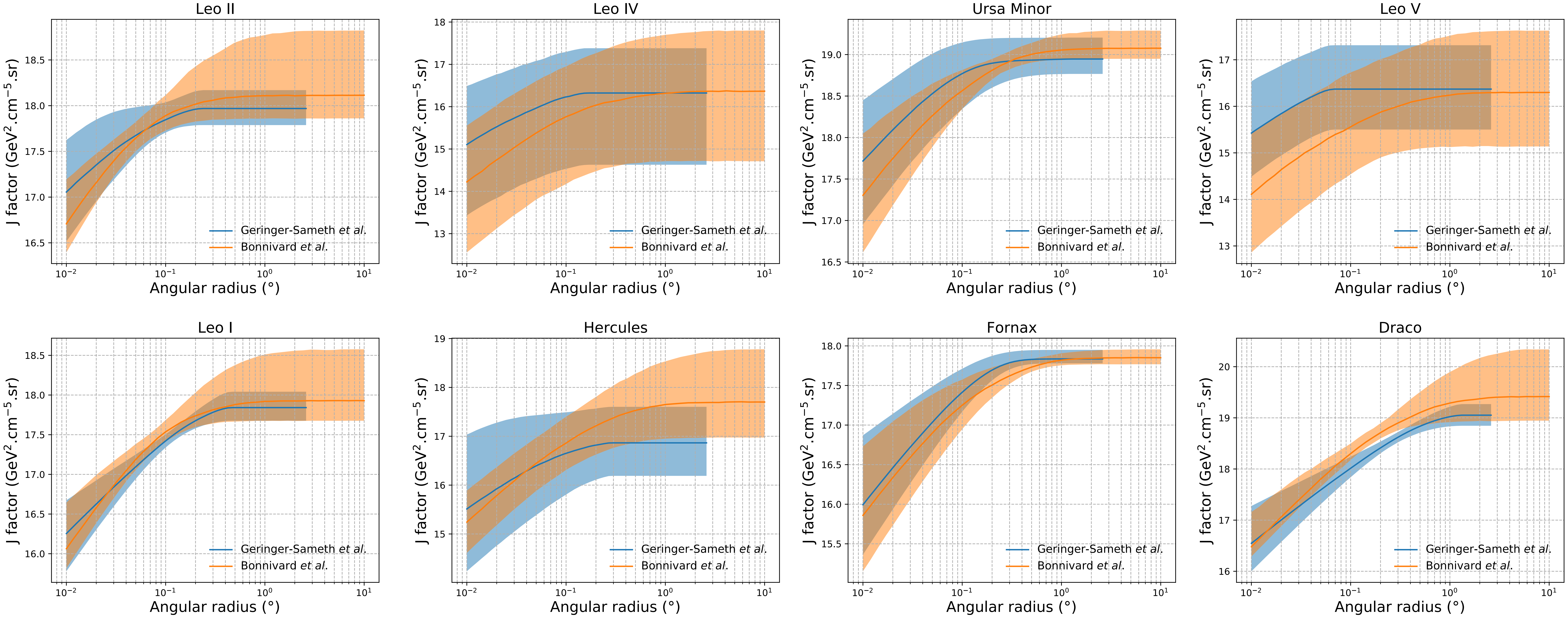
Ref: Cowan et al. (2011), European Physical Journal C, vol. 71 p1554

$\langle\sigma v\rangle$	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

J FACTORS



Carina
Bootes I
J factor (GeV^2.cm^{-5}.sr)
Angular radius (°)
Geringer-Sameth *et al.*
Bonnivard *et al.*



Leo II
Leo IV
Ursa Minor
Leo V
Leo I
Hercules
Fornax
Draco
J factor (GeV^2.cm^{-5}.sr)
Angular radius (°)
Geringer-Sameth *et al.*
Bonnivard *et al.*