Search for Dark Matter annihilation with a combined analysis of dwarf spheroidal galaxies from 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

Dark Matter indirect searches

- **Looking for DM particles self-annihilating into SM particles**

- **Gamma-rays are not deflected by magnetic fields and trace back to original source**

  → Critical to identify the (physical) origin of the signal and study DM spatial distribution

- **Classical targets for gamma-ray experiments include among others:**
  - The Galactic Center (high DM content with high uncertainties)
  - Dwarf spheroidal galaxies (lower DM content with smaller uncertainties)

- **Here we will focus on dwarf spheroidal galaxies (dSphs) for which:**
  - The expected astrophysical gamma-ray emission is negligible
  - Large data sets have been already collected

    → Combining data from existing experiments allows to maximize the sensitivity to potential DM signals by increasing the statistics without requesting more observation time

Involved experiments

- **Initiative by 5 gamma-ray experiments to combine their observations of dwarf galaxies:**
  - Fermi-LAT
  - HAWC
  - H.E.S.S.
  - MAGIC
  - VERITAS

Fermi-LAT

- **Satellite in operation since 2008**
- **Energy range:**
  20 MeV – above 300 GeV
- **Field of view ~20% of the sky**
- **Scan the whole sky every ~3 hours**

Fermi-LAT: in orbit at 550 km

HAWC

- **Array of water Cherenkov detectors in operation since 2013**
- **Energy range:**
  300 GeV – 100 TeV
- **Field of view ~15% of the sky**

HAWC: Puebla, Mexico, 4100 m

H.E.S.S.

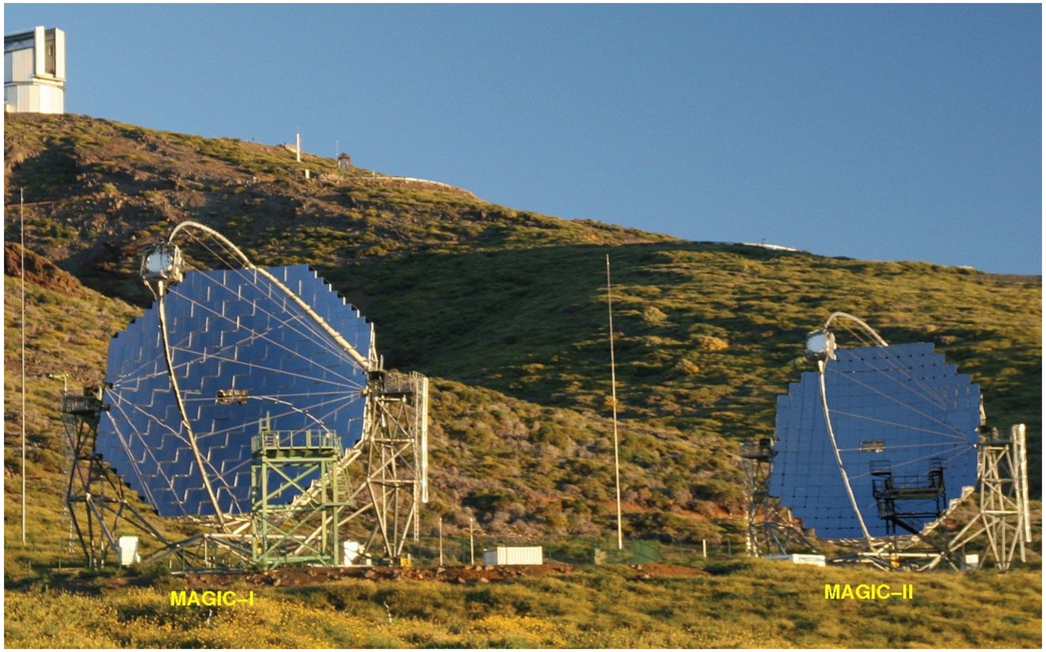
- **Array of five Cherenkov telescopes**
  - Phase I with 4 telescopes of 12 m diameter since 2003
  - Phase II with the addition of a telescope of 28 m diameter since 2012
- **Energy range:**

  30 GeV - 100 TeV
- **Field of view of 5°**

HESS: Khomas Highland, Namibia, 1800 m

MAGIC

- **MAGIC consists of two 17 m diameter Cherenkov telescopes**
  - First telescope since 2004
  - Second telescope since 2009
- **Energy range:**
  50 GeV - 50 TeV
- **Field of view of ~3.5°**



MAGIC: La Palma, Spain, 2200 m

VERITAS

- **Array of four 12 m diameter Cherenkov telescopes since 2007**
- **Energy range:**
  100 GeV - 30 TeV
- **Field of view of 3.5°**

VERITAS: Arizona, USA, 1300 m

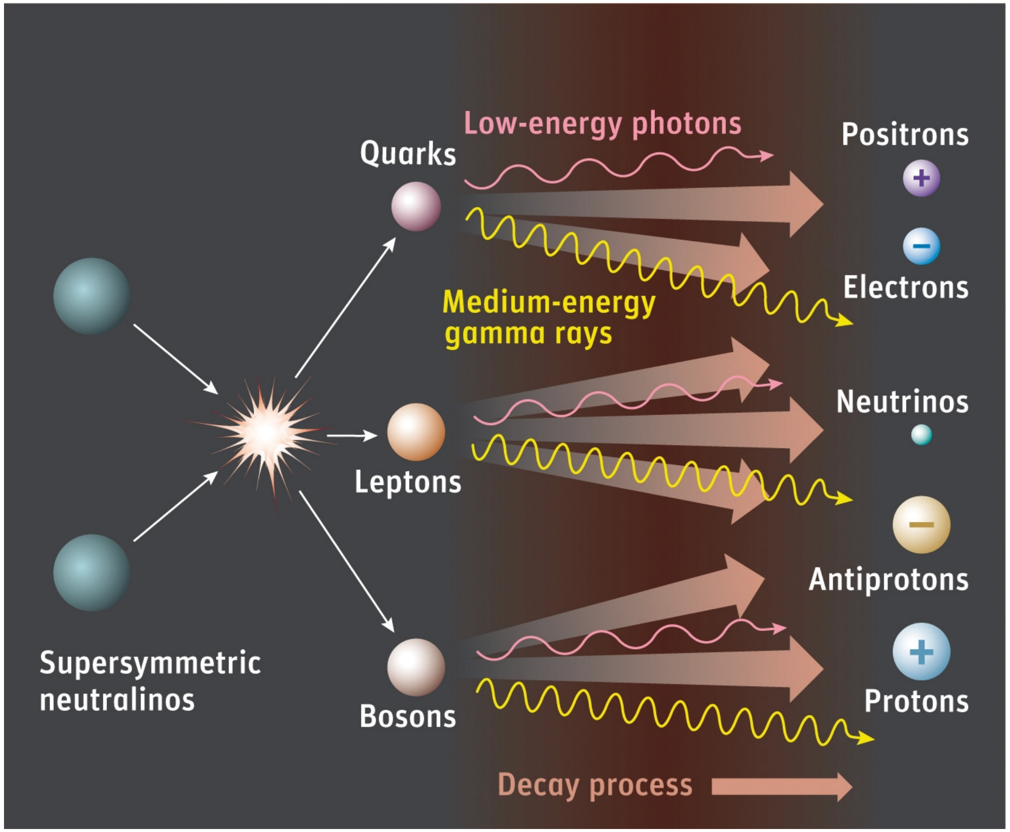
List of targets

- **In this project we use a list of 20 dwarf galaxies for which individual collaborations already published results**
- **In total, 45 different data sets used**

	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

Expected Dark Matter flux

$$\frac{d\Phi(\Delta\Omega)}{dE} = \frac{1}{4\pi}\frac{\langle\sigma_{\rm ann}v\rangle}{2m_{\rm DM}^2}\frac{dN}{dE} \times \int_{\Delta\Omega} d\Omega' \int_{\rm l.o.s.} dl\,\rho^2(l,\Omega')$$



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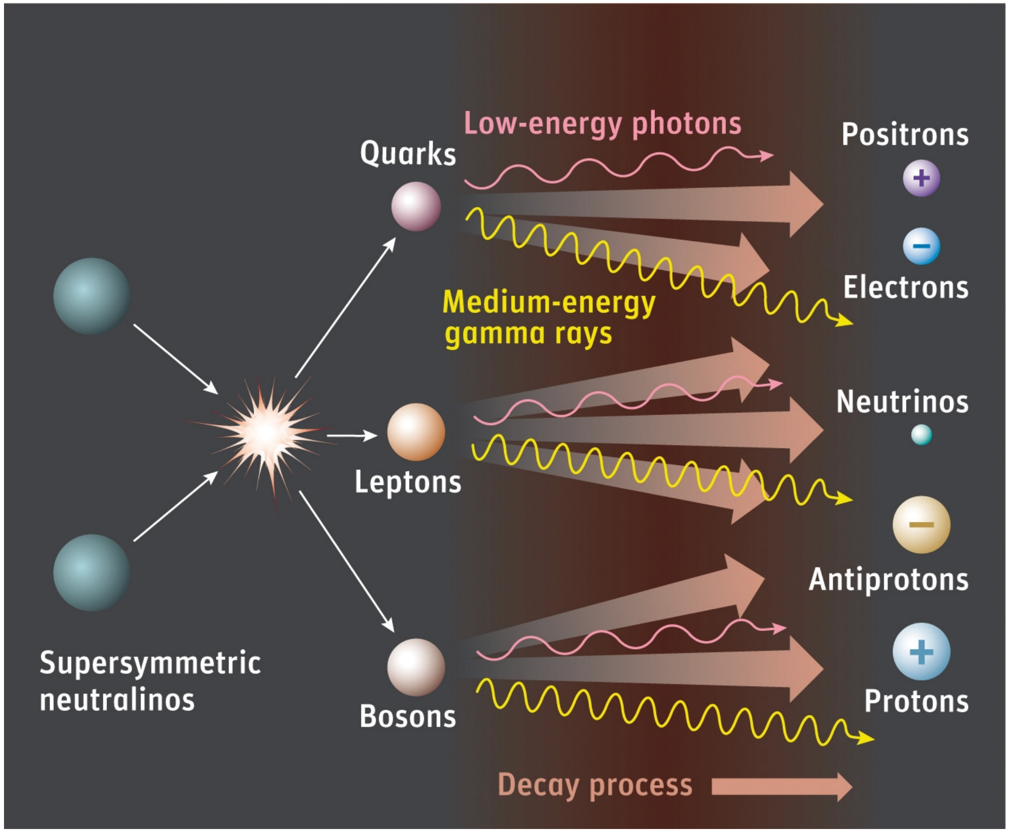

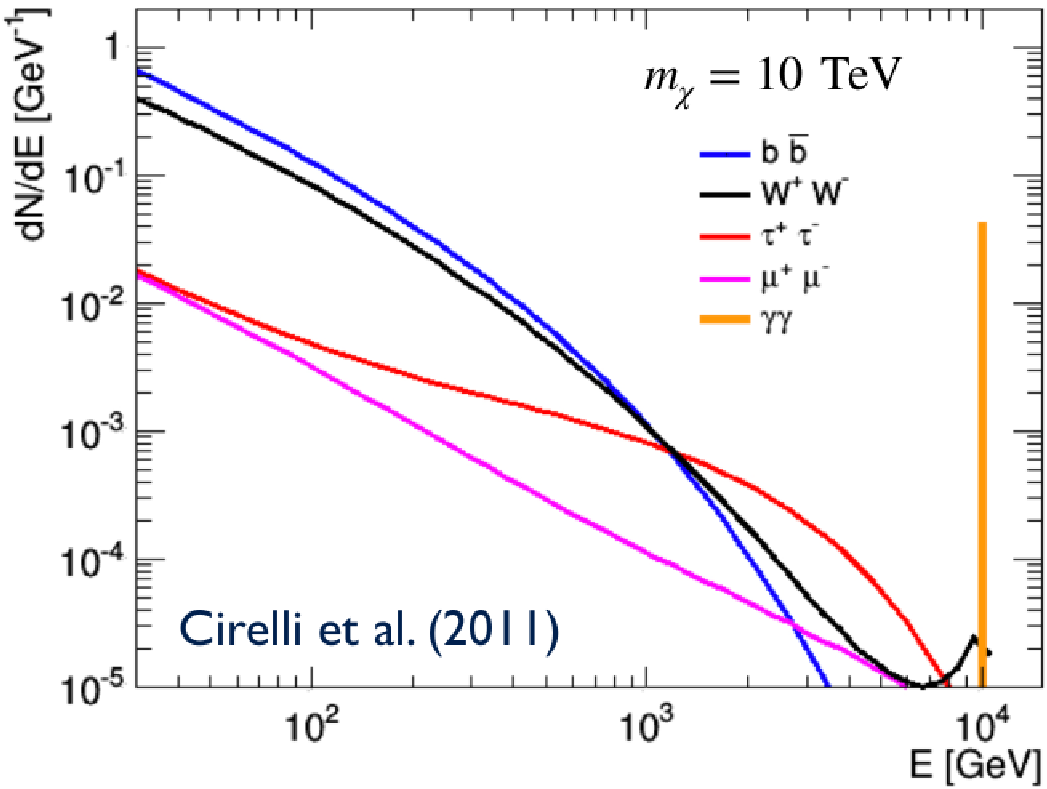

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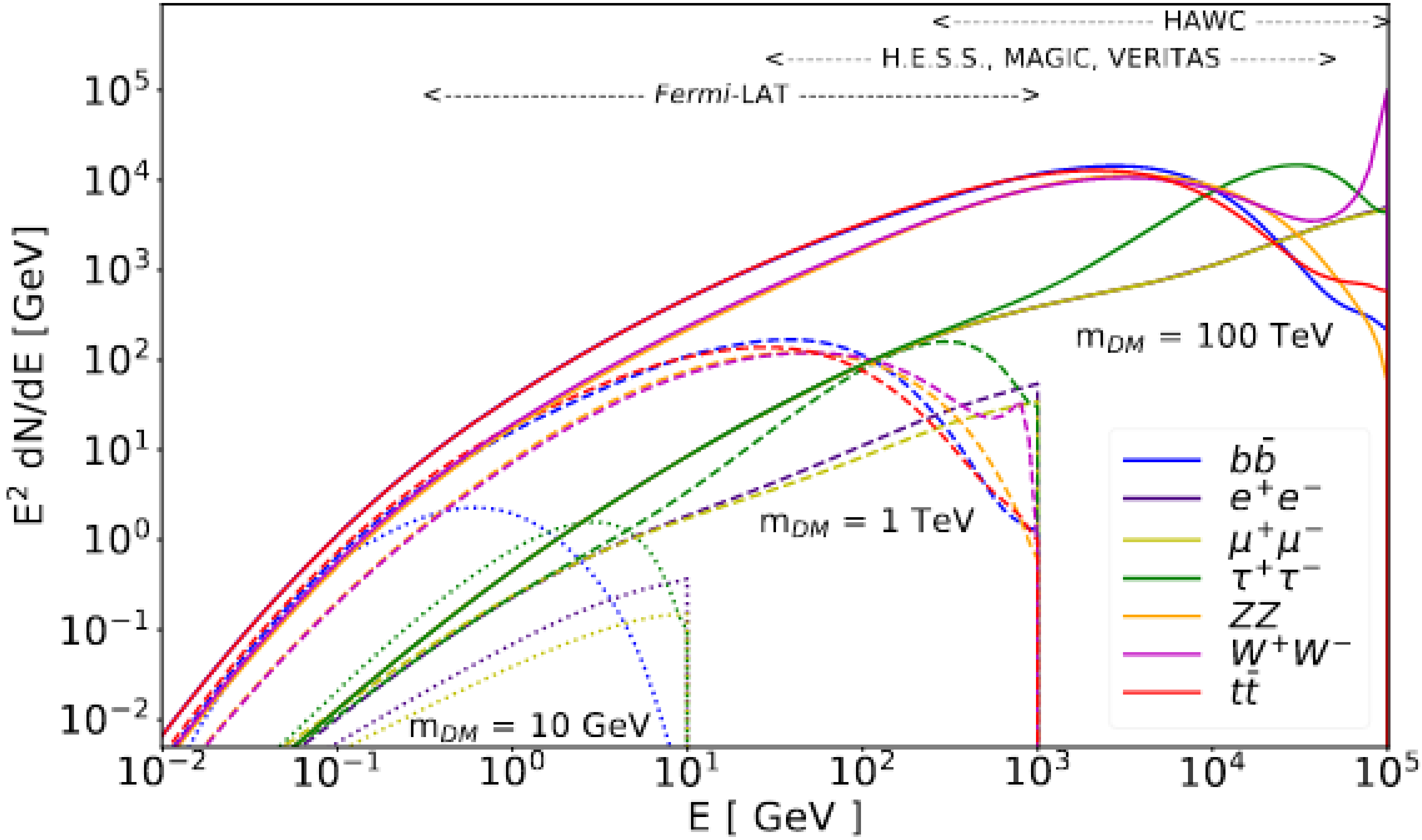

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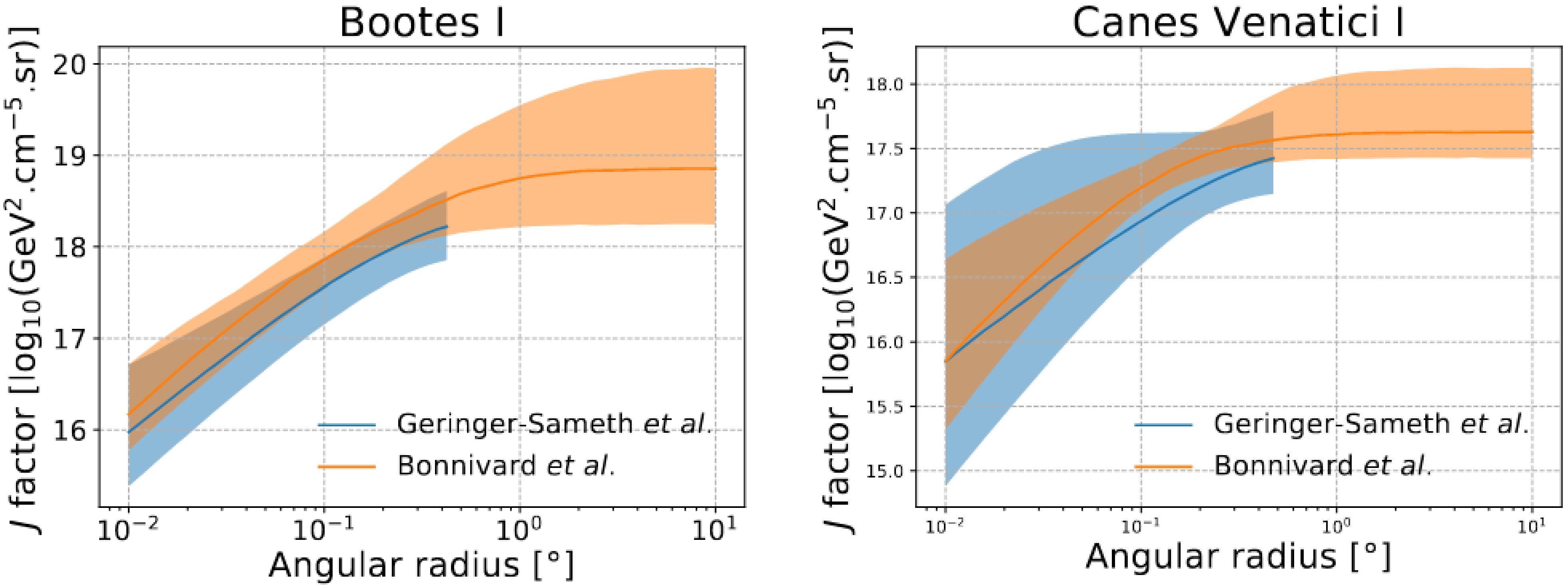


Examples of J-factors vs radius for two dSphs

Combined likelihood analysis

- **Expected gamma-ray flux from DM annihilation:**

$$\frac{d\Phi(\Delta\Omega)}{dE} = \frac{1}{4\pi}\frac{\langle\sigma_{\mathrm{ann}}v\rangle}{2m_{\mathrm{DM}}^2}\frac{dN}{dE} \times \int_{\Delta\Omega} d\Omega' \int_{\mathrm{l.o.s.}} dl\,\rho^2(l,\Omega')$$

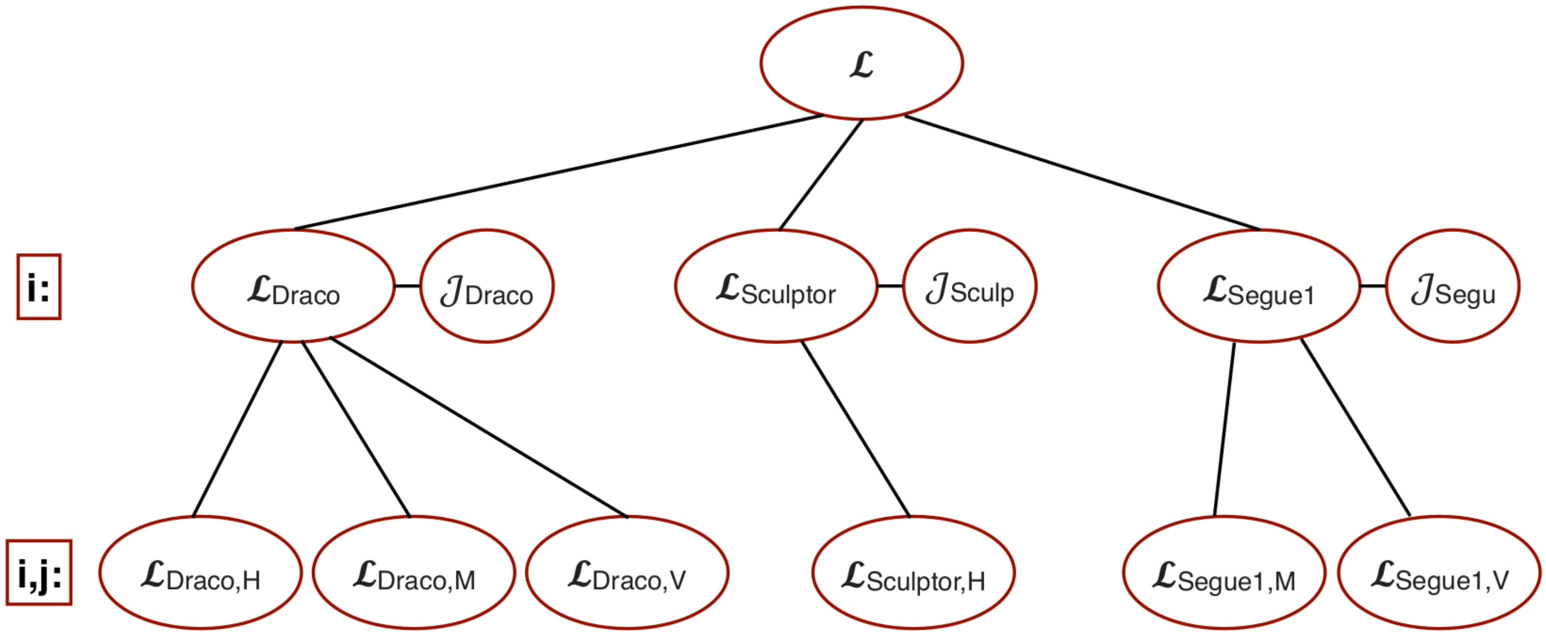
- **Using as many common ingredients as possible:**
  - Common range of channels and DM masses:
    - From 5 GeV to 100 TeV using the DM spectra from Cirelli et al. [JCAP 1103:051, 2011]
    - Studied 7 annihilation channels in total
  - Same J-factor values and statistical uncertainties

- **Individual experiments shared likelihood profile for each dSph/channel/mass combination for a fixed value of the J-factor**
  - statistical uncertainties on the J-factor are taken into account (the J-factor being a **nuisance parameter** in the combined likelihood)

Combined likelihood analysis

- **Combined likelihood:**

$$\mathcal{L}\left(\langle\sigma v\rangle;\boldsymbol{\nu}\mid\boldsymbol{\mathcal{D}}_{\mathrm{dSphs}}\right)=\prod_{l=1}^{N_{\mathrm{dSphs}}}\mathcal{L}_{\mathrm{dSph},l}\left(\langle\sigma v\rangle;J_l,\boldsymbol{\nu_l}\mid\boldsymbol{\mathcal{D}}_{\boldsymbol{l},\mathrm{measured}}\right)\times\mathcal{J}_l\left(J_l\mid J_{l,\mathrm{obs}},\sigma_{\log J_l}\right)$$

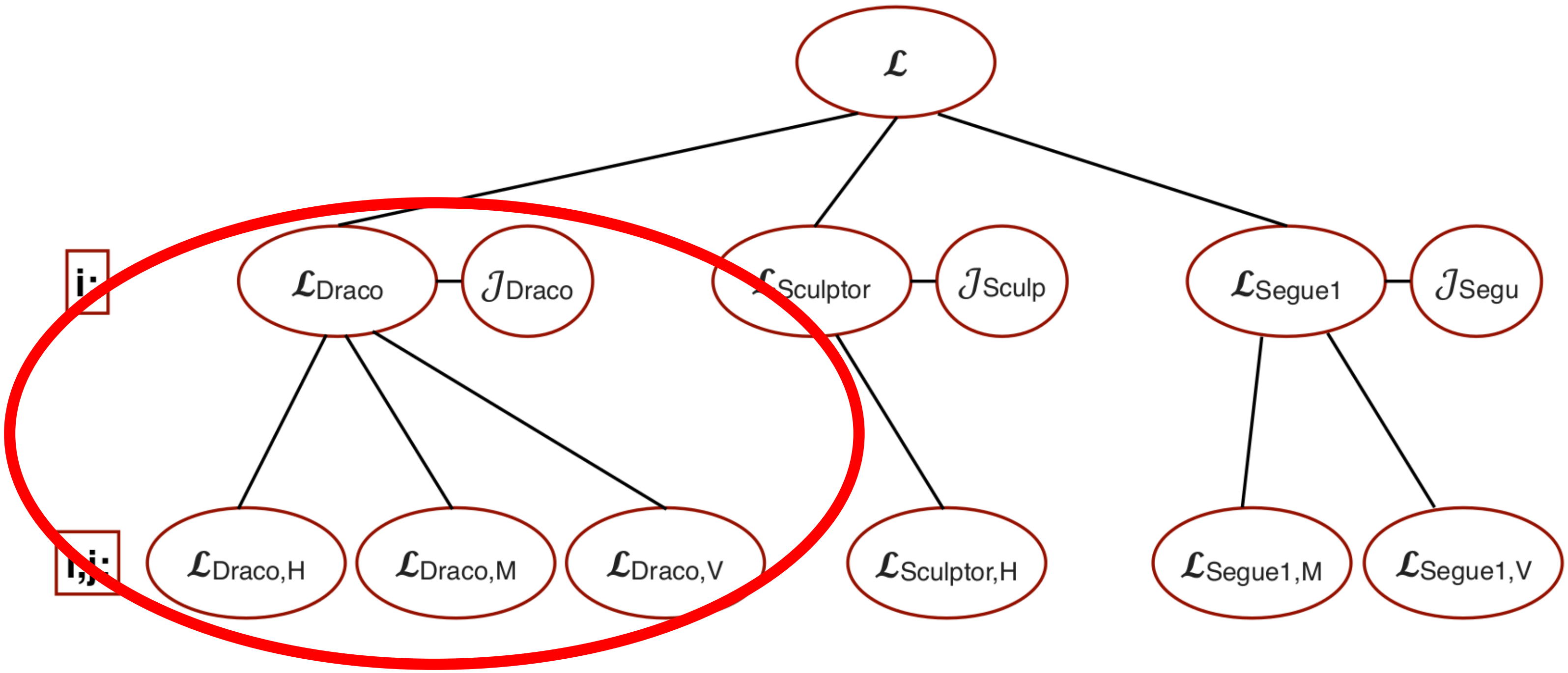


- **The combination was performed with two independent softwares:**
  - glike: https://doi.org/10.5281/zenodo.4028908
  - LklCombiner: https://doi.org/10.5281/zenodo.4450884

Combined likelihood analysis

- **Combined likelihood:**

$$\mathcal{L}\left(\langle\sigma v\rangle; \boldsymbol{\nu} \mid \boldsymbol{\mathcal{D}}_{\mathrm{dSphs}}\right) = \prod_{l=1}^{N_{\mathrm{dSphs}}} \mathcal{L}_{\mathrm{dSph},l}\left(\langle\sigma v\rangle; J_l, \boldsymbol{\nu_l} \mid \boldsymbol{\mathcal{D}}_{\boldsymbol{l},\mathrm{measured}}\right) \times \mathcal{J}_l\left(J_l \mid J_{l,\mathrm{obs}}, \sigma_{\log J_l}\right)$$



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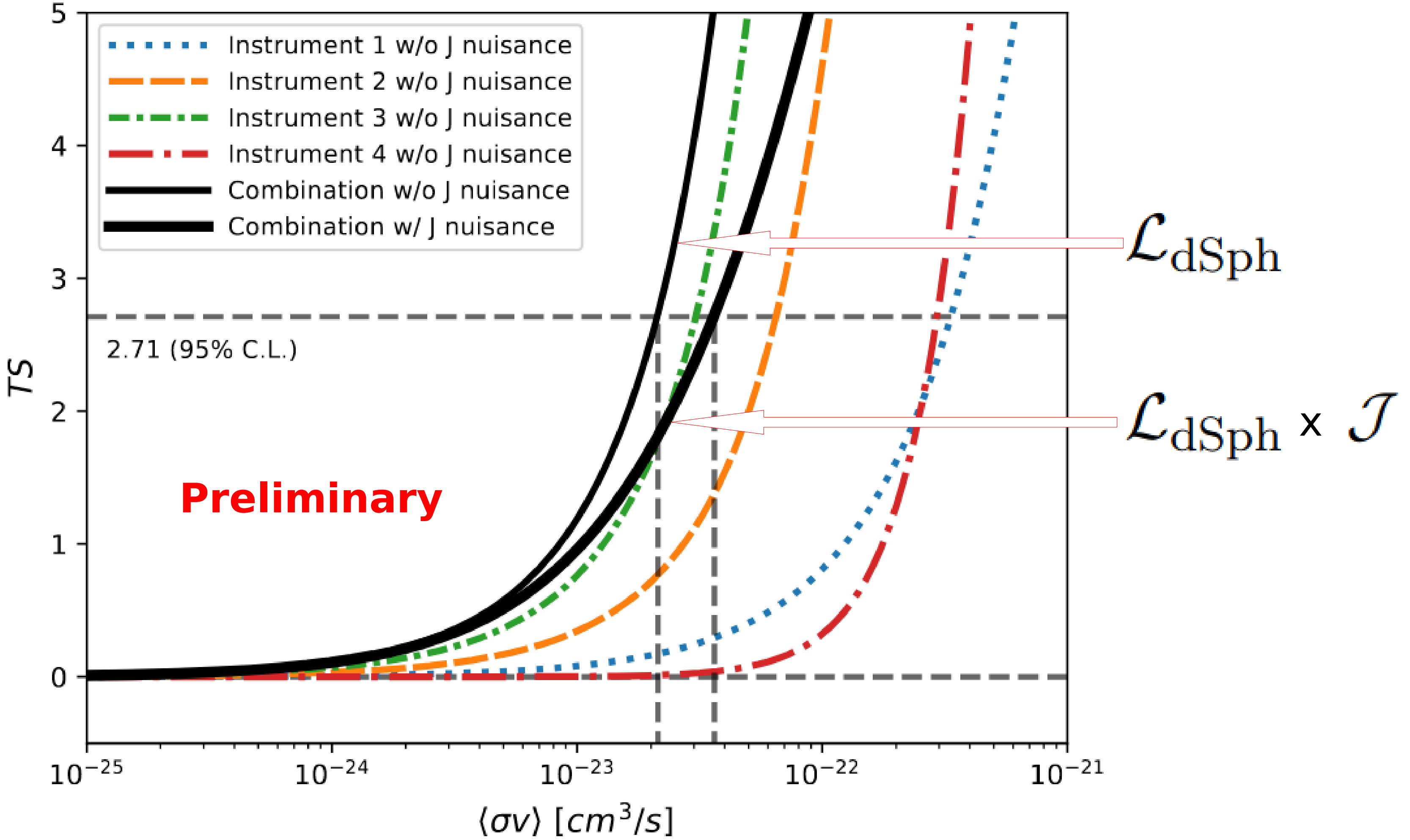
Combined likelihood analysis: an example for one dSph



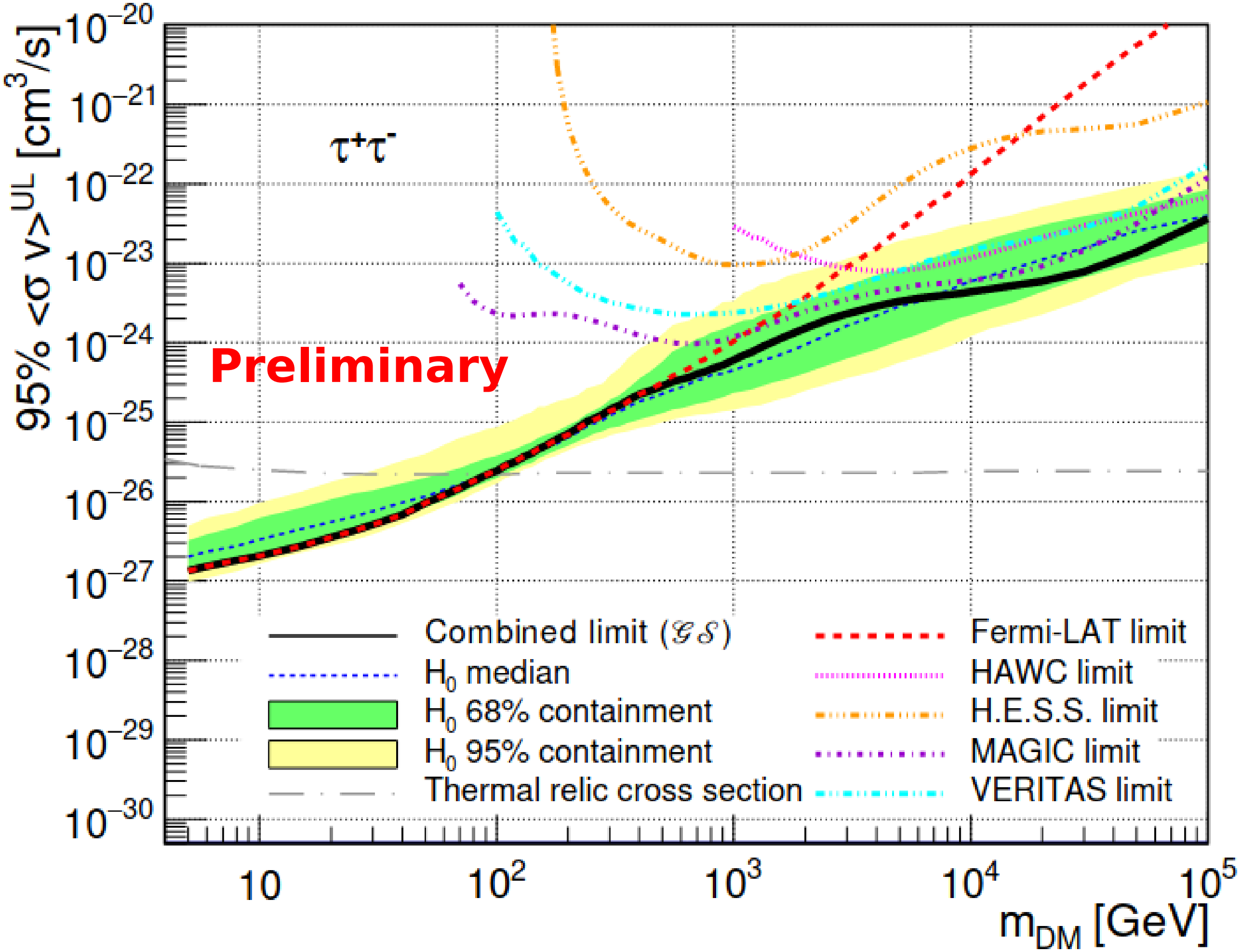
- **The total likelihood combines the likelihood of the 20 targets!**

Uncertainty on the DM content

- **The J-factor estimation is the largest source of uncertainty in this analysis**
- **We used 2 sets of J-factors to compare the effect on the final results**
    - From A. Geringer-Sameth et al. [APJ 801:74, 2015]
    - From V. Bonnivard et al. [MNRAS 446:3002, 2015 and MNRAS 453:849, 2015]
- **Some dSphs are marginally affected but some are very affected**

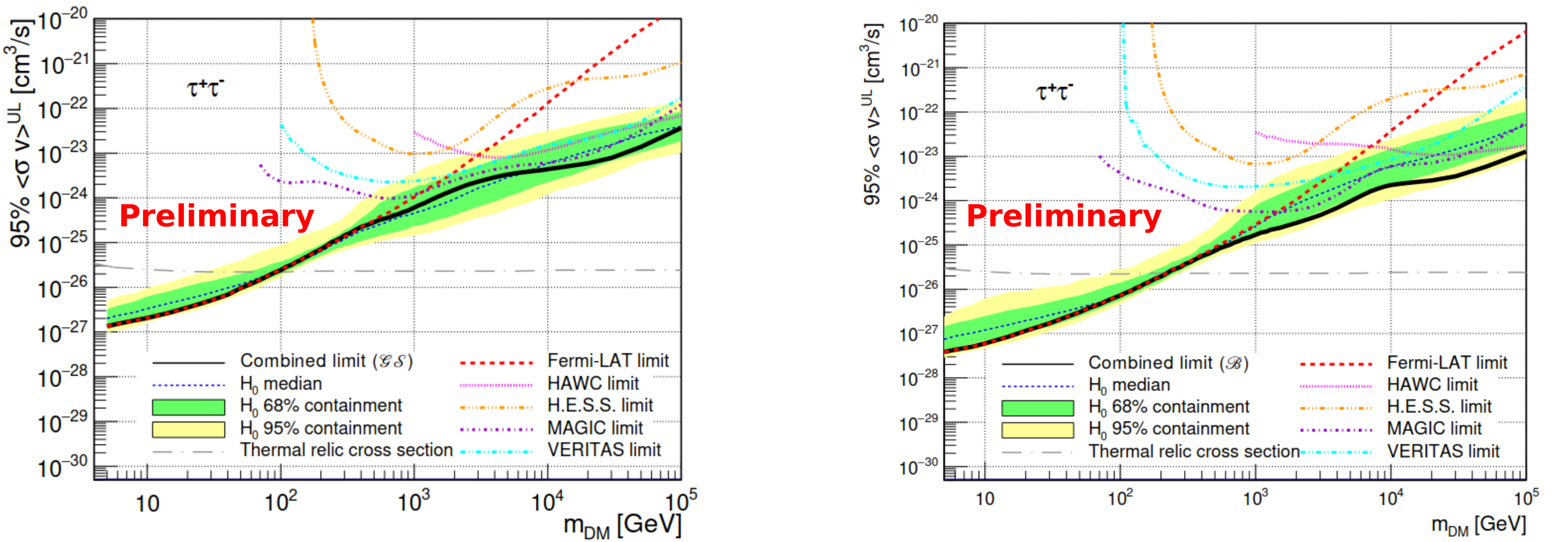
Name	$\log_{10} J$ ($\mathcal{GS}$ set) $\log_{10}(\mathrm{GeV^2cm^{-5}sr})$	$\log_{10} J$ ($\mathcal{B}$ set) $\log_{10}(\mathrm{GeV^2cm^{-5}sr})$
Boötes I	$18.24^{+0.40}_{-0.37}$	$18.85^{+1.10}_{-0.61}$
Canes Venatici I	$17.44^{+0.37}_{-0.28}$	$17.63^{+0.50}_{-0.20}$
Canes Venatici II	$17.65^{+0.45}_{-0.43}$	$18.67^{+1.54}_{-0.97}$
Carina	$17.92^{+0.19}_{-0.11}$	$18.02^{+0.36}_{-0.15}$
Coma Berenices	$19.02^{+0.37}_{-0.41}$	$20.13^{+1.56}_{-1.08}$
Draco	$19.05^{+0.22}_{-0.21}$	$19.42^{+0.92}_{-0.47}$
Fornax	$17.84^{+0.11}_{-0.06}$	$17.85^{+0.11}_{-0.08}$
Hercules	$16.86^{+0.74}_{-0.68}$	$17.70^{+1.08}_{-0.73}$
Leo I	$17.84^{+0.20}_{-0.16}$	$17.93^{+0.65}_{-0.25}$
Leo II	$17.97^{+0.20}_{-0.18}$	$18.11^{+0.71}_{-0.25}$
Leo IV	$16.32^{+1.06}_{-1.70}$	$16.36^{+1.44}_{-1.65}$
Leo V	$16.37^{+0.94}_{-0.87}$	$16.30^{+1.33}_{-1.16}$
Leo T	$17.11^{+0.44}_{-0.39}$	$17.67^{+1.01}_{-0.56}$
Sculptor	$18.57^{+0.07}_{-0.05}$	$18.63^{+0.14}_{-0.08}$
Segue I	$19.36^{+0.32}_{-0.35}$	$17.52^{+2.54}_{-2.65}$
Segue II	$16.21^{+1.06}_{-0.98}$	$19.50^{+1.82}_{-1.48}$
Sextans	$17.92^{+0.35}_{-0.29}$	$18.04^{+0.50}_{-0.28}$
Ursa Major I	$17.87^{+0.56}_{-0.33}$	$18.84^{+0.97}_{-0.43}$
Ursa Major II	$19.42^{+0.44}_{-0.42}$	$20.60^{+1.46}_{-0.95}$
Ursa Minor	$18.95^{+0.26}_{-0.18}$	$19.08^{+0.21}_{-0.13}$

Combined limits



- **Combined limits are up to a factor 2-3 more constraining**

Comparison of the limits using two different sets of J-factors



- **"Bonnivard" provides better limits than "Geringer-Sameth" by a factor 2-6**

Conclusion

- **This analysis framework allows us to perform multi-instrument and multi-target analysis**
- **No significant DM signal was observed**
- **Combined limits range from 5 GeV to 100 TeV and improve individual limits up to a factor 2 to 3**
- **Using 2 different sets of J-factors we were able to study the systematic impact on the results:**
  - **limits can vary by a factor of 2 to 6**
  - **combining many targets allows to minimize the importance of single dSphs, particularly relevant when their J-factor is (very) uncertain**
- **Combination including other messengers such as neutrinos is possible!**