Searching for Dark Matter annihilation with a combined analysis of dwarf spheroidal galaxies data from Fermi-LAT, HAWC, H.E.S.S., MAGIC and VERITAS

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Dark Matter indirect searches

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

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

  → critical to study the spatial distribution of DM

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

  → if detected, a DM signal should be seen in both targets!

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

Improving our sensitivity to DM

- **Already existing large data sets**

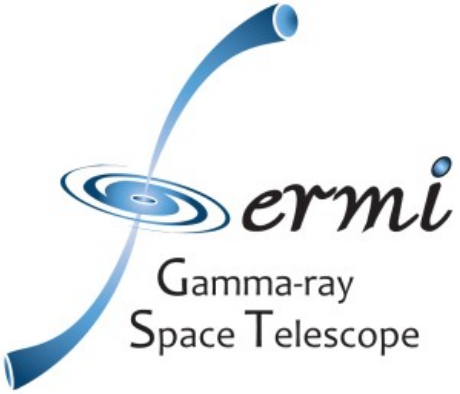
- **How to improve current results?**
  - Accumulating more data
    - With current experiments
    - With next generation experiments
  - Combining data from existing experiments

    → this technique allows to maximize the sensitivity to potential DM signal by increasing the statistics without requesting more observation time

    → **Strategy followed in this work!**

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°**

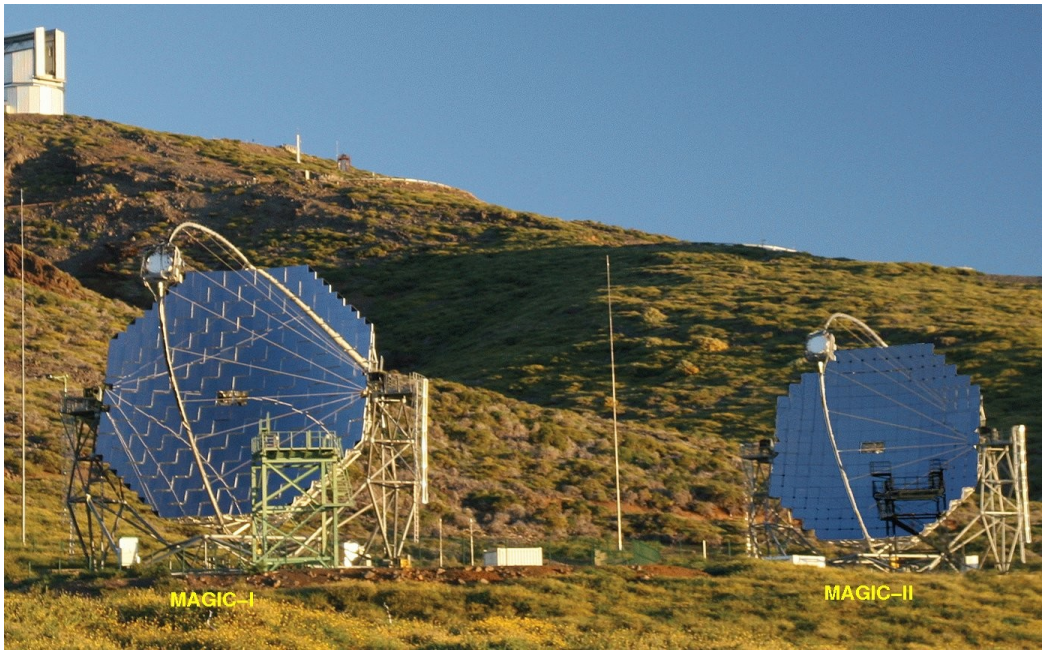
HESS: Khomas Highland, Namibia, 1800 m

MAGIC

- **MAGIC consists of two 17 m diameter Cherenkov telescopes**
  - First telescope since 2004
  - Second telescope since 2009

- **Energy range:**
  30 GeV - 30 TeV

- **Field of view of ~3.5°**



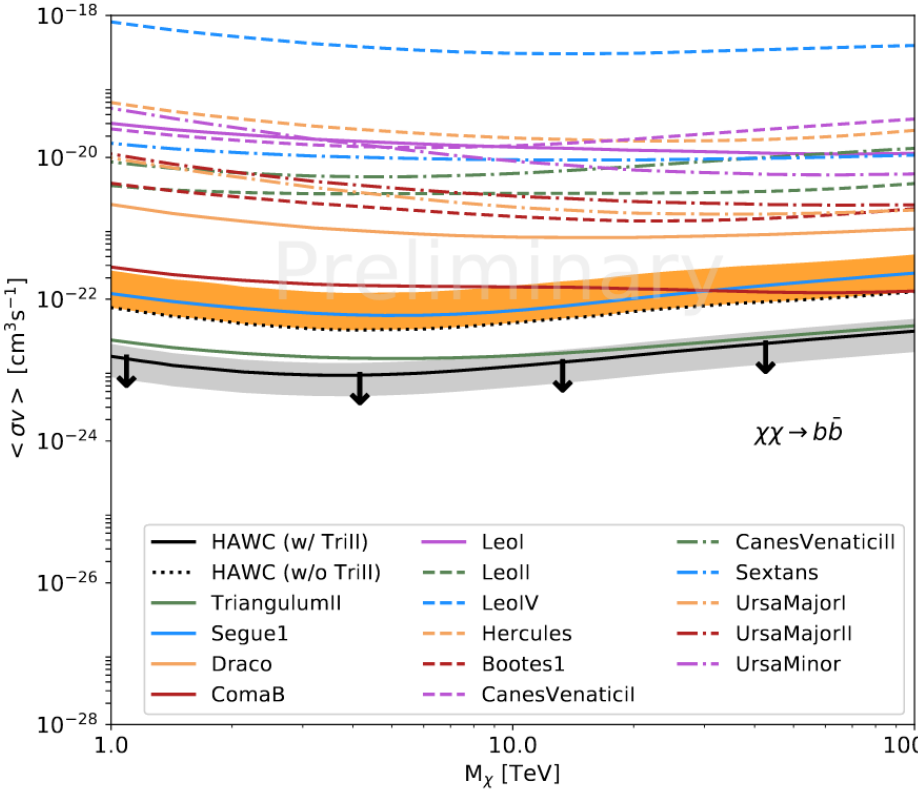
MAGIC: La Palma, Spain, 2200 m

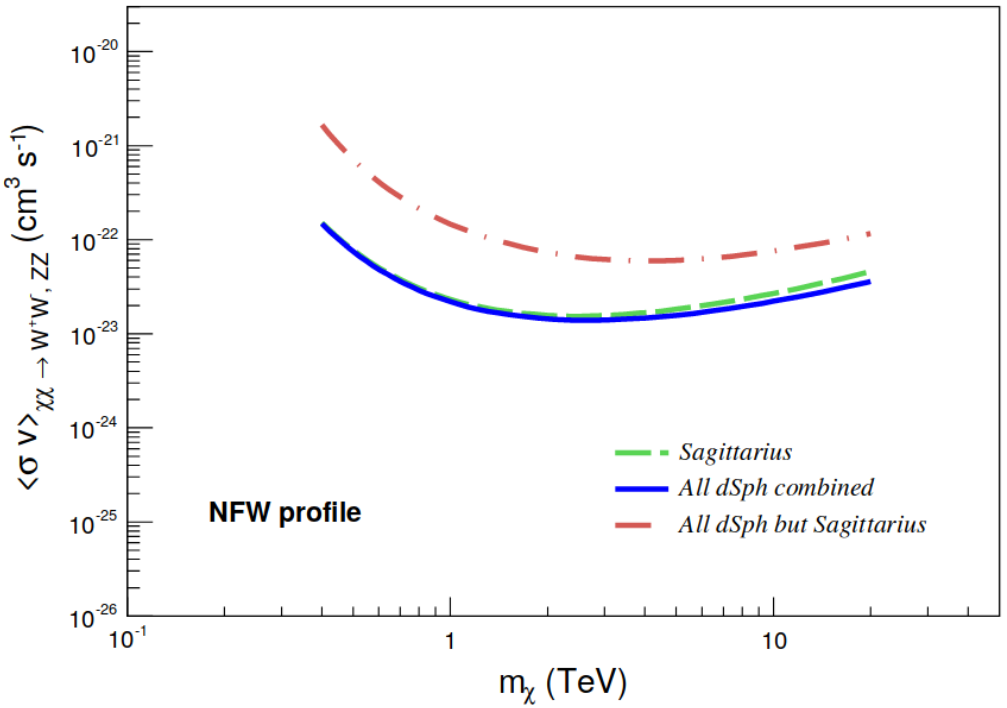
VERITAS

- **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

Previous combination

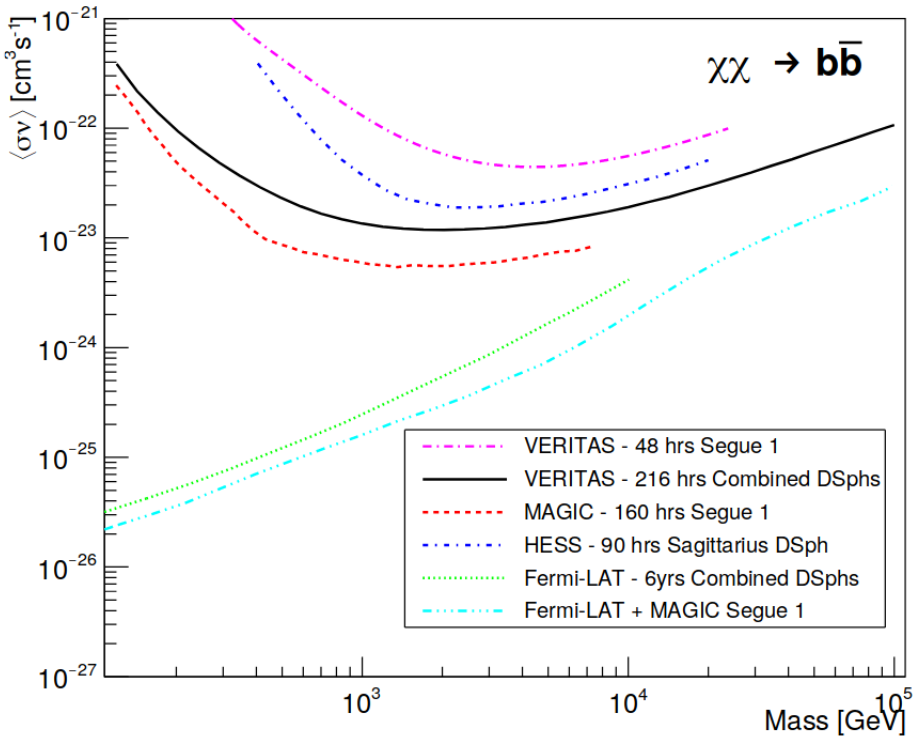


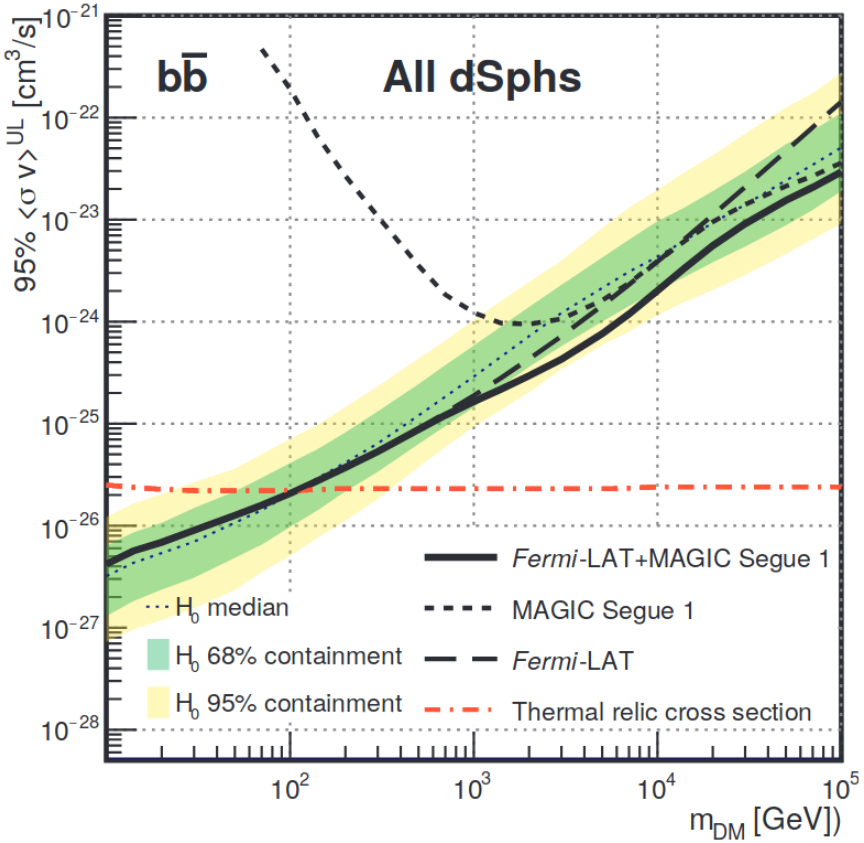


HAWC (left): arxiv:1706.01277

H.E.S.S. (right): arxiv:1410.2589

Previous combination





VERITAS (left): arxiv:1703.04937

Fermi-LAT+MAGIC (right): arxiv:1601.06590

List of targets for combination

- **In this project we use a list of 20 dwarf galaxies for which individual collaborations already published results**
- **In total, 40 different data sets**
- **Final combination may contain more data sets**

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

Combining likelihoods

- **Strategy for the combination:**
  - Each experiment computes the likelihood for each dwarf that it observed
  - These likelihoods follow this general formula:

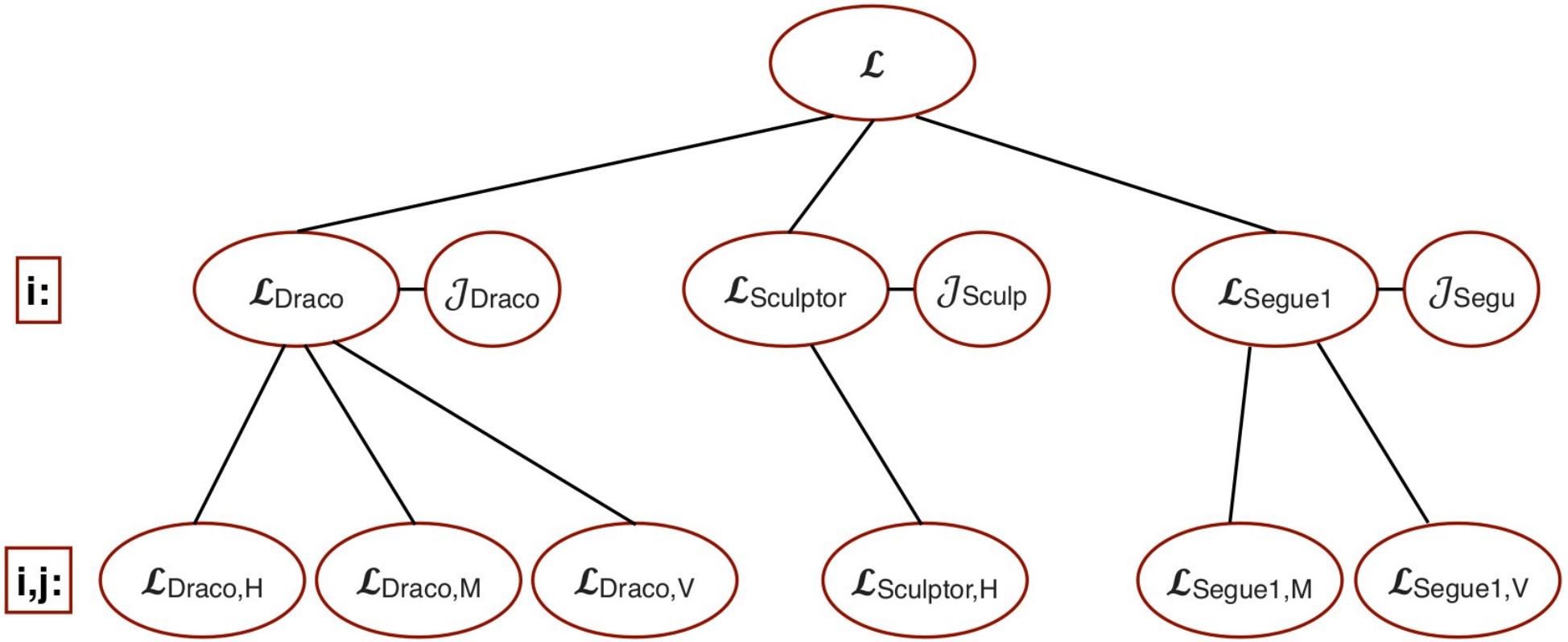
$$\mathscr{L}_{\gamma}(\langle\sigma v\rangle \bar{J}_l; \mu | D_{\gamma}) = \prod_{k=1}^{N_{meas}} \mathscr{L}_{\gamma,k}(\langle\sigma v\rangle \bar{J}_l; \mu_k | D_{\gamma,k})$$

  - They are computed for a fixed J-factor. J-factor uncertainties are taken into account when combining the different observations of the same dwarf

Combining likelihoods

Total likelihood formula:

$$\mathcal{L}(\alpha;\boldsymbol{\nu}|\boldsymbol{\mathcal{D}}) = \prod_{l=1}^{N_{\mathrm{dSph}}} \mathcal{L}_\gamma(\alpha\bar{J}_l;\boldsymbol{\mu}_l|\boldsymbol{\mathcal{D}}_{\gamma_l}) \cdot \mathcal{L}_J(\bar{J}_l|\boldsymbol{\mathcal{D}}_{J_l})$$



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- **These likelihoods are then shared for the combination**

  → a common approach to compute them is required

Recipe for a good combination

As many common ingredients as possible:

- Same J-factor values and statistical uncertainties

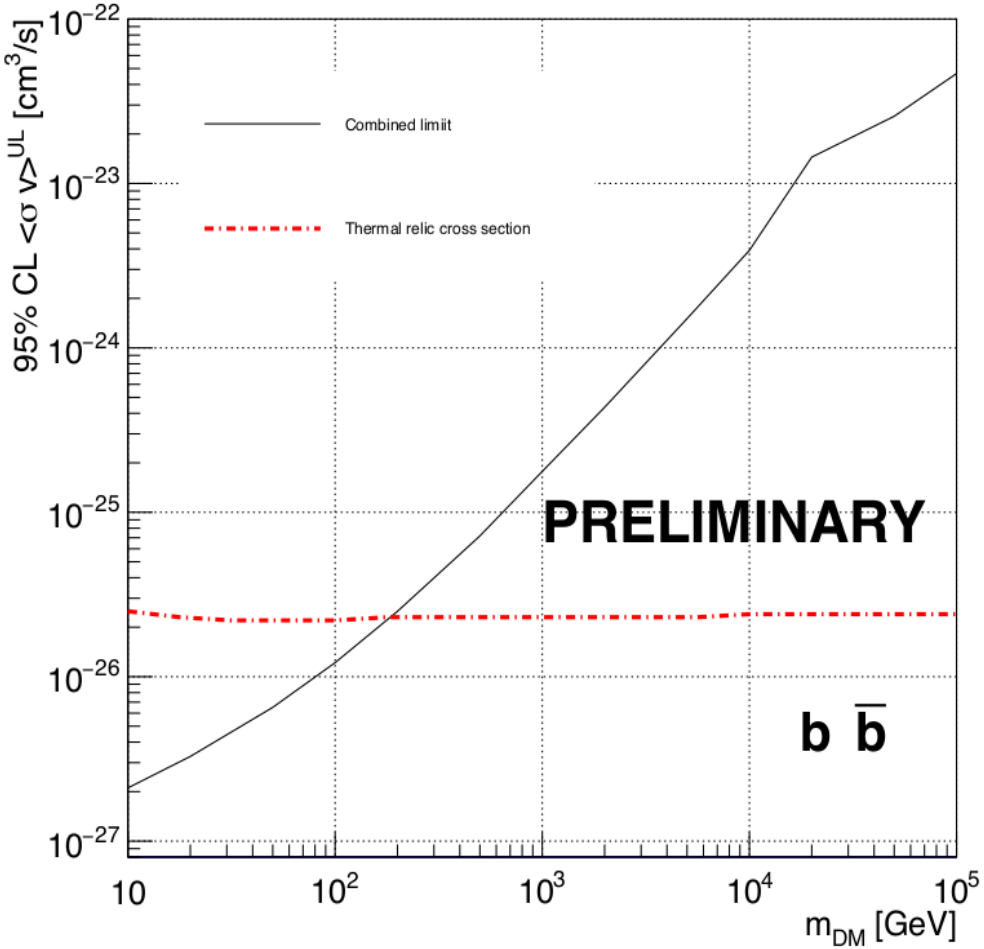
  (taken from A. Geringer-Sameth et al, Astrophys.J. 801, no.2, 74, 2015)

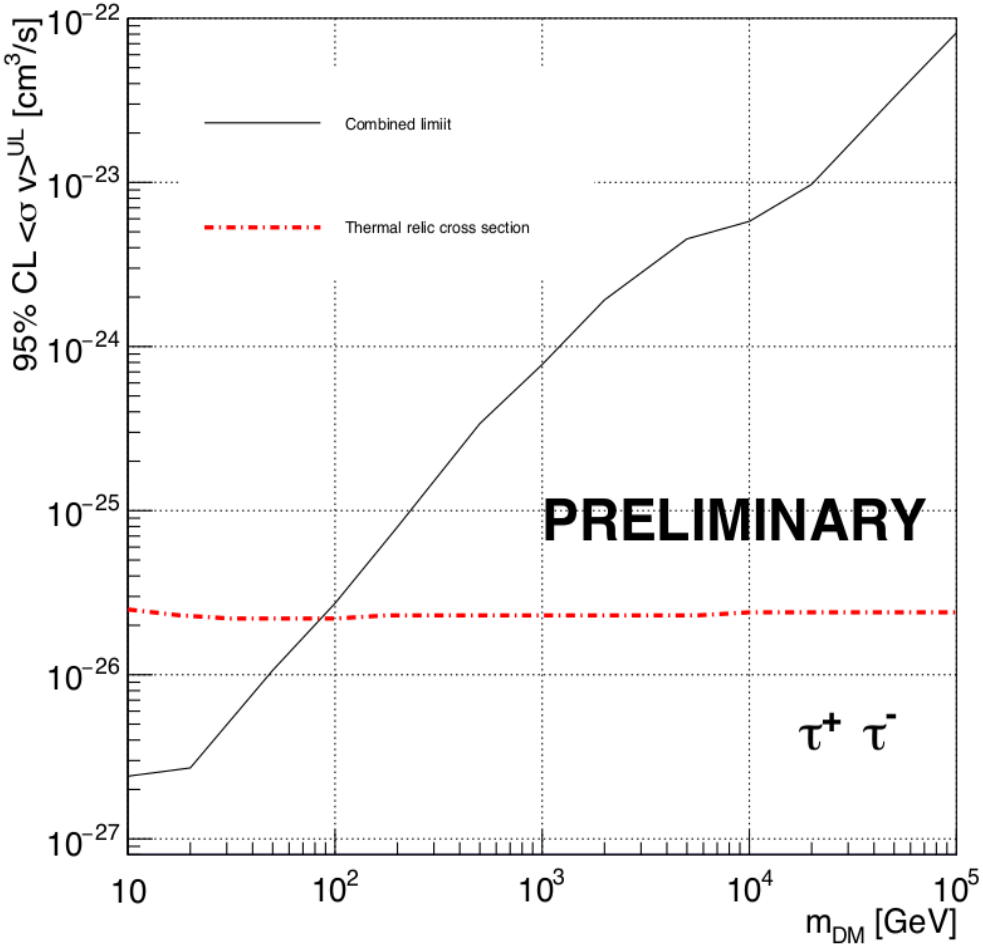
- Probe a common range of DM masses: 10 GeV to 100 TeV
- Use the same DM spectra

  (taken from M. Cirelli et al, JCAP 1103:051, 2011)

- Define a common treatment for all relevant statistical and systematical uncertainties, in particular for Cherenkov telescopes
- Use finest analysis technique:
  - Binned likelihood
  - Extension of the dwarf if relevant
  - Use $\langle \sigma v \rangle > 0$ prescription
  - J-factor statistical error taken into account as nuisance parameter in the likelihood

Preliminary results





Next steps

- **Take into account the systematic uncertainties on the J-factor by using different sets of J-factor values**
- **Compute the 68% and 95% confidence intervals of the limits using MC simulations**
- **Combination for many more channels:**
  - **tt**
  - **ee**
  - **μμ**
  - **WW**
  - **ZZ**
  - **γγ**

Future prospects

- **This approach could be extended for other targets such as galaxy clusters and other scenarios such as decaying DM**

- **New dwarf galaxies might be discovered by ongoing or future surveys and allow to extend the considered data sets**

- **CTA will gradually supersede the current IACTs (H.E.S.S., MAGIC and VERITAS) and will improve the current results by at least a factor 10 in their energy range**

  → Combination of results from CTA, Fermi-LAT and HAWC?

- **Combination including other messengers such as neutrinos are possible**

  → extension of the combination to IceCube and KM3NeT?

Conclusion

- **This analysis framework allows us to perform multi-instruments and multi-targets analysis**

- **Preliminary combined results for the bb and ττ channels from 10 GeV to 100 TeV by Fermi-LAT, HAWC, H.E.S.S., MAGIC, and VERITAS allows us to probe the thermal relic cross-section up to a few hundreds GeV**

- **Publication under preparation will include more channels (such as tt, ee, μμ, WW, ZZ and γγ) and potentially more targets**

→ will produce legacy results from the current generation of gamma-ray instruments for the search for annihilating DM in dwarf galaxies

Thank you for your attention!