Combined Limits from Dwarf Spheroidal Galaxies

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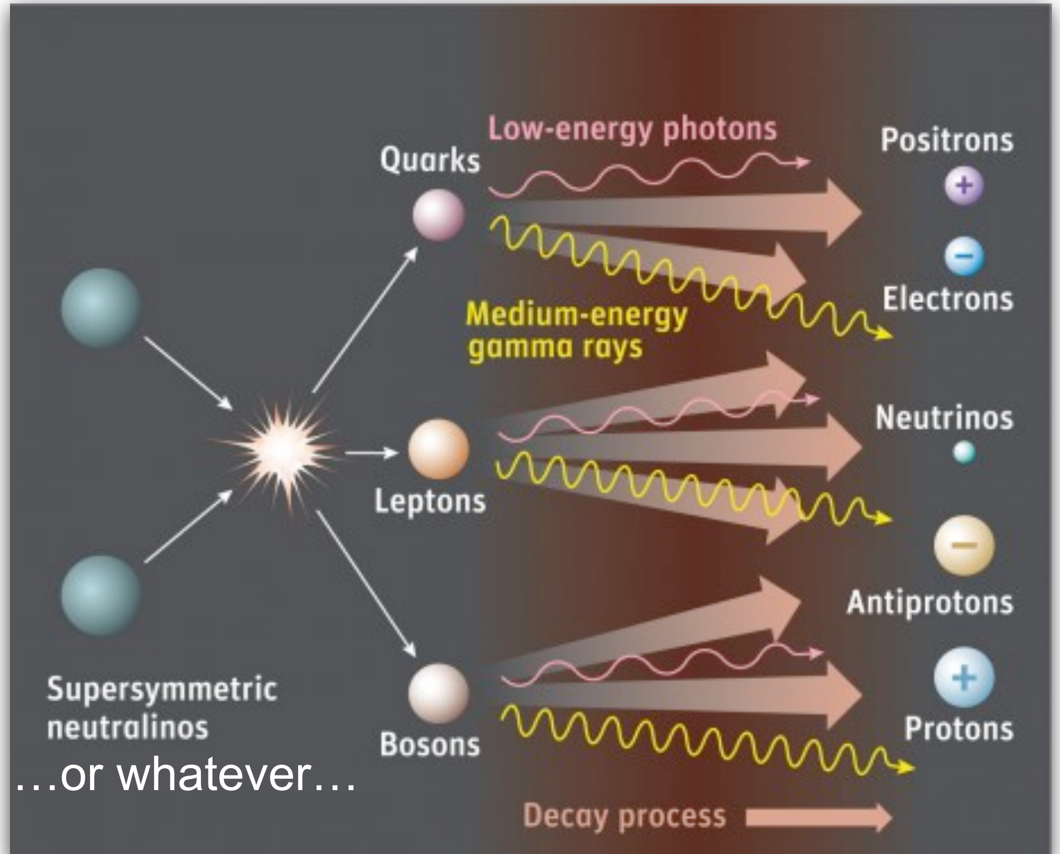
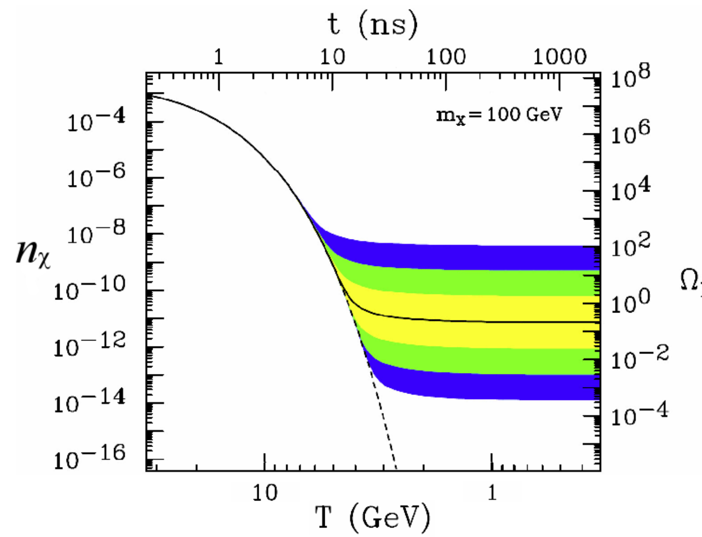
HELMHOLTZ RESEARCH FOR GRAND CHALLENGES
HELMHOLTZ Young Investigators
DESY.

Indirect Searches for Dark Matter Annihilation



Appealing to consider **GeV-TeV mass, weakly-interacting** particle



"WIMP Miracle"

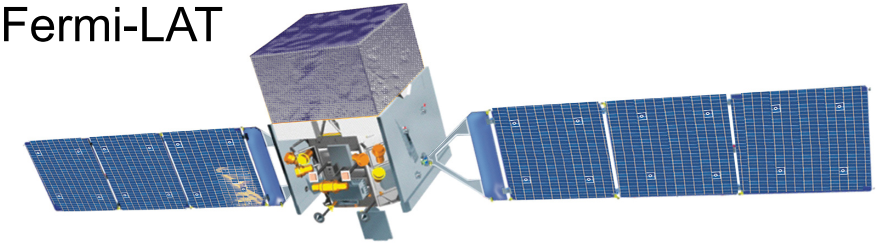
$\langle \sigma v \rangle \sim 3 \times 10^{-26}$ cm^{3}s^{-1}

Astrophysical signal from **annihilation** or **decay** to standard model particles

We are focused on final-state **gamma rays**

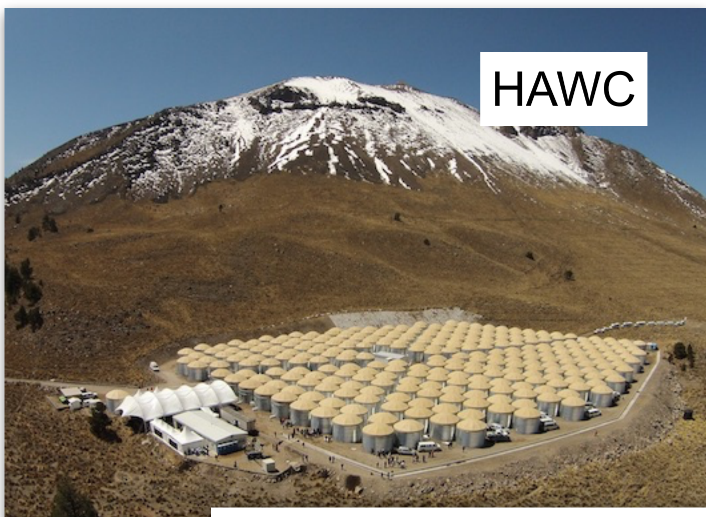
The Gamma-ray Searchers

Fermi-LAT



Energy range: 100 MeV to ~1 TeV
Large field of view

Imaging atmospheric Cherenkov telescope arrays (IACTs)
Energy range: ~30 GeV to ~100 TeV
Field of view: several degrees



Energy range: ~1 TeV - 100 TeV
Large field of view

Predicted Gamma-ray Signal

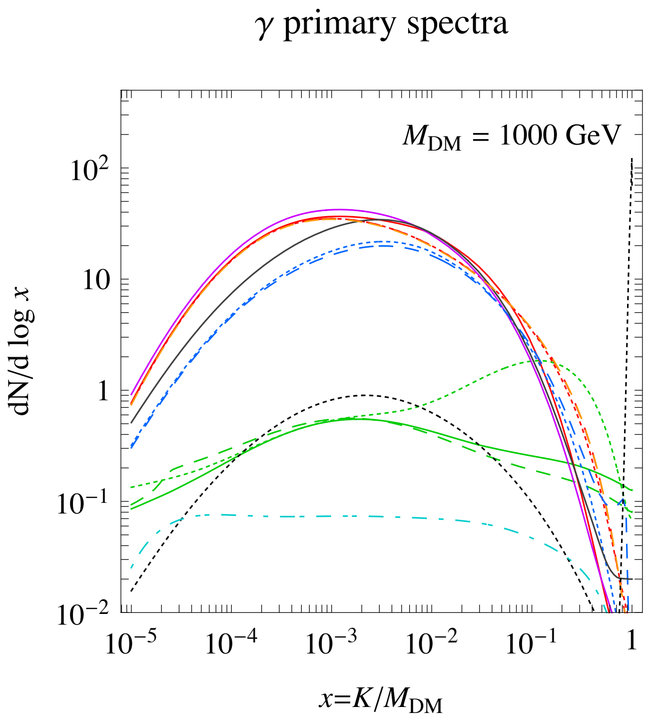
$$\frac{d^2\Phi\left(\langle\sigma v\rangle, J\right)}{dE d\Omega} = \frac{1}{4\pi} \frac{\langle\sigma v\rangle}{2m_{\rm DM}^2} \sum_f {\rm BR}_f \frac{dN_f}{dE} \int_{\rm l.o.s.} \rho_{\rm DM}^2(r(s,\theta))\, ds$$

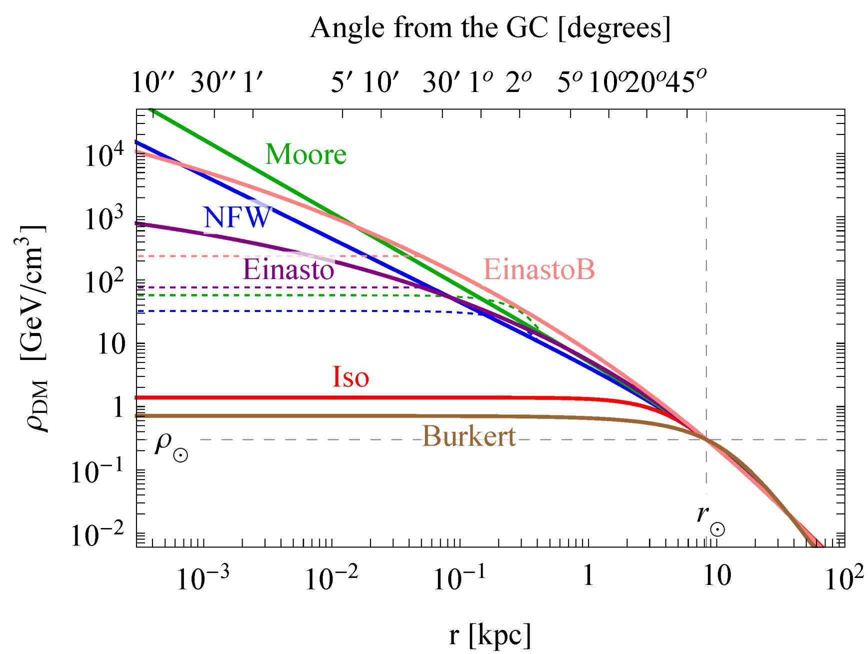
Particle physics

Spectral information: lines or cut-offs

Astrophysics

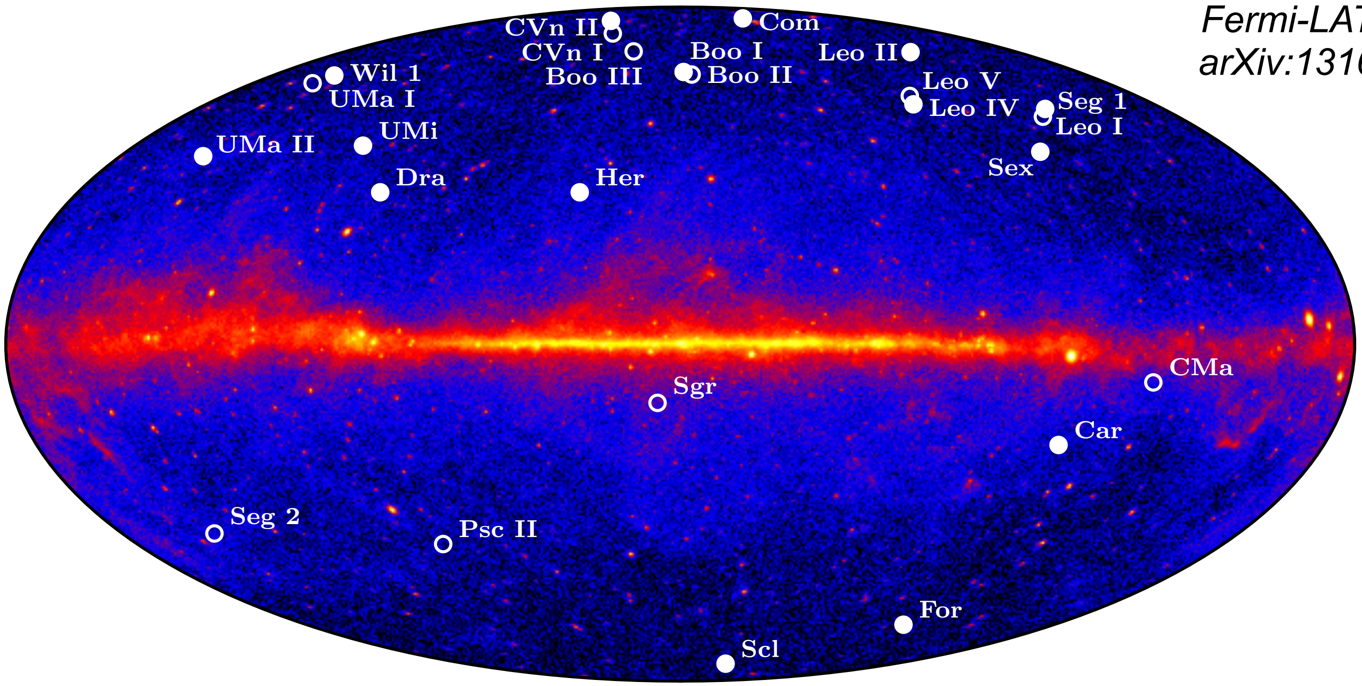
"J factor": DM distribution, distance to source, instrument response





Cirelli et al. 2011 arXiv:1012.4515

Why Dwarf Spheroidal Galaxies?

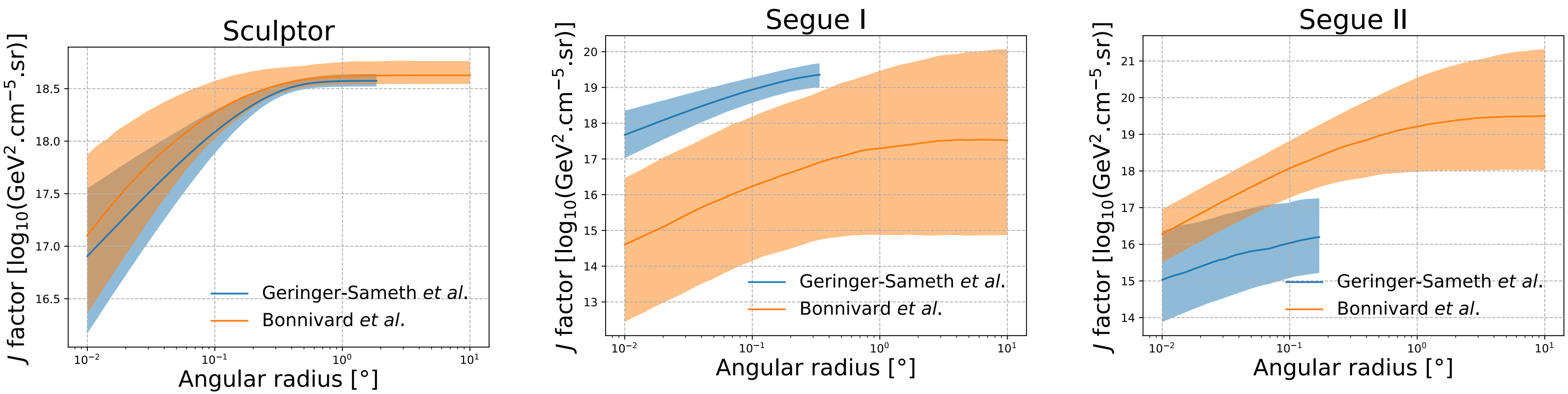


Fermi-LAT 2014
arXiv:1310.0828

- Milky Way satellites: nearby (~20-200 kpc)
- Classic (thousands of bright stars) and Ultrafaint (tens of bright stars)
  - Multiple objects = less sensitivity to mis-modeling of single object
- Large mass to light ratios: ~O(1000) $M_\odot/L_\odot$
- Low astrophysical background (no known gamma-ray emitters)
- Ideal target for IACTs due to modest angular extension

Dwarf Spheroidal Galaxies: Still Challenging

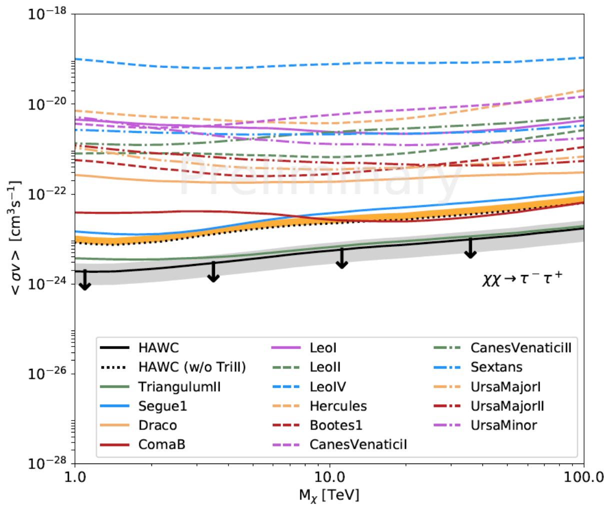
- J-factor estimation major source of uncertainty
- Differences of approach in literature
- Quantify uncertainty considering two independent calculations
  - Geringer-Sameth et al. 2015 (*arXiv:1408.0002*)
  - Bonnivard et al. 2015 (*arXiv:1407.7822*, *arXiv:1504.02048*)
  - Different choices for DM density profile, velocity anisotropy, light profile, consideration of systematics



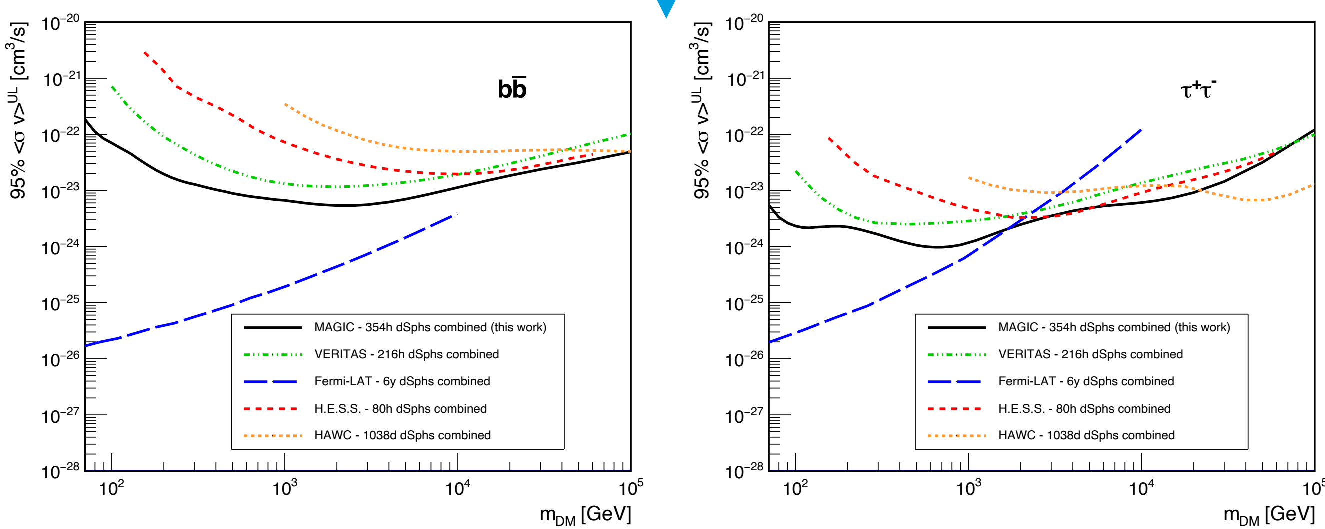
Good agreement for some objects, significant differences for others

Former State of the Art

Each instrument stacks observations to produce combined limits…



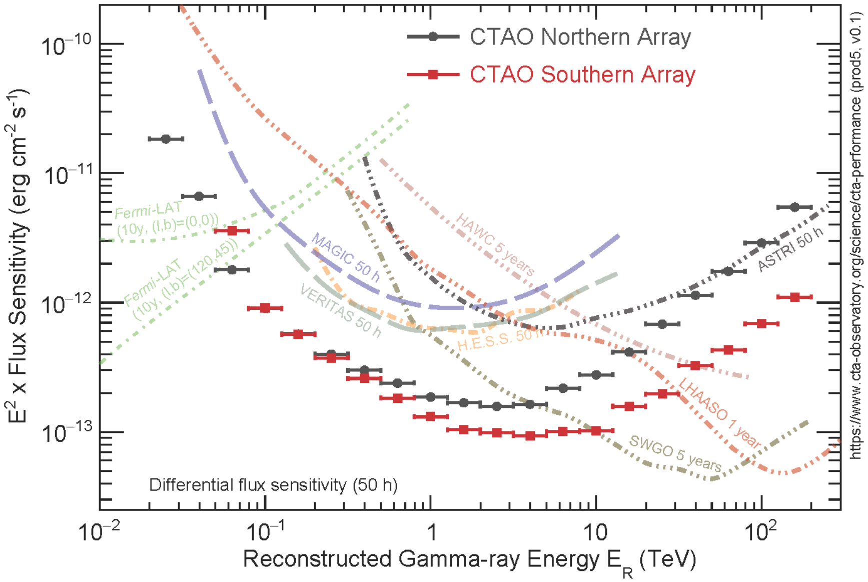
HAWC 2017
arXiv:1706.01277



MAGIC 2021
arXiv:2111.15009

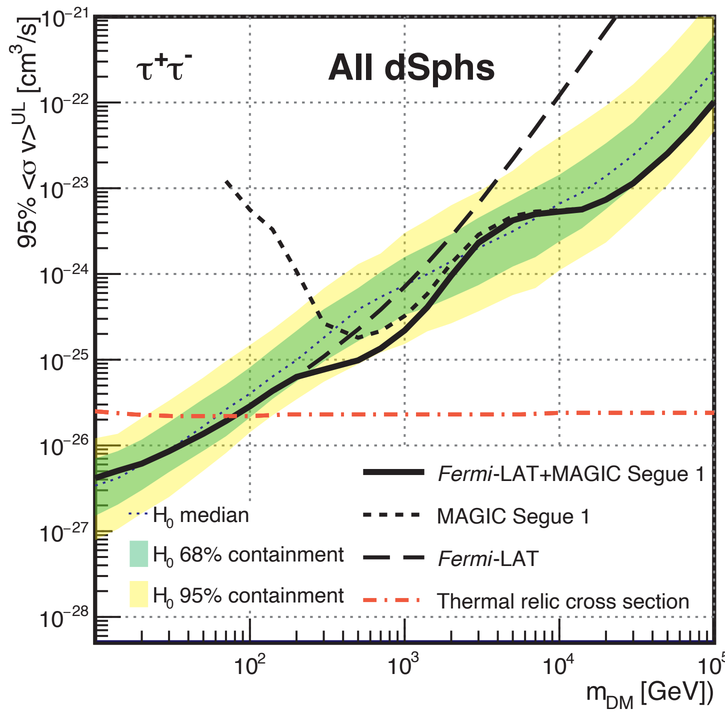
…but then we have five upper limit curves from the gamma-ray community…

How to Improve Without Building a New Instrument



- Cherenkov Telescope Array will supersede current measurements
- x10 improvement in sensitivity
- Still some years from full array

- Combine gamma-ray results
  - Improve statistical power
  - Present consistent picture
- Groundwork: MAGIC + Fermi-LAT combined likelihood analysis (*arXiv:1601.06590*)



Observation Summary

Source name	Fermi-LAT Exposure (10^{11} s m^2)	HAWC $|\Delta\phi|$ (°)	IACT	Zenith (°)	Time 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	2.5	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 dwarf spheroidal galaxies observed, including classical and ultrafaint objects
- ~625 hours IACT, 10 years Fermi-LAT, ~1000 days HAWC observations
- Inexact mapping to previous publications: some reanalysis, modified target selection

(More) Common Approach

- **Each instrument** performs likelihood analysis with **internal software**
  - VERITAS: unbinned maximum likelihood
  - Other instruments: binned maximum likelihood
  - Analysis choices vary between instruments (e.g. treatment of point spread function, size of signal region…)
- Common **statistical format**
  - Share high-level data: test statistic versus DM annihilation cross section, calculated at common set of masses
- Common **expected signal** inputs
  - Expected photon spectrum from Cirelli et al. 2011 (*arXiv:1012.4515*)
    - DM annihilation to $W^+W^-, Z^+Z^-, t\bar{t}, b\bar{b}, \tau^+\tau^-, \mu^+\mu^-, e^+e^-$
  - Marginalize over two sets of J-factors
    - Geringer-Sameth et al. 2015
    - Bonnivard et al. 2015

Joint Likelihood Analysis

Test statistic shared per instrument, per dwarf and per annihilation channel

v = nuisance parameters

$\mathscr{D}$ = gamma-ray observations

$$\lambda\left(\langle\sigma v\rangle \mid \boldsymbol{\mathcal{D}}_{\text{dSphs}}\right)=\frac{\mathcal{L}\left(\langle\sigma v\rangle ; \hat{\hat{\boldsymbol{\nu}}} \mid \boldsymbol{\mathcal{D}}_{\text{dSphs}}\right)}{\mathcal{L}\left(\widehat{\langle\sigma v\rangle} ; \hat{\boldsymbol{\nu}} \mid \boldsymbol{\mathcal{D}}_{\text{dSphs}}\right)}$$

constrained minimum scan in <σv> (numerator)

global minimum (denominator)

Partial joint likelihood - product of all dwarves per instrument

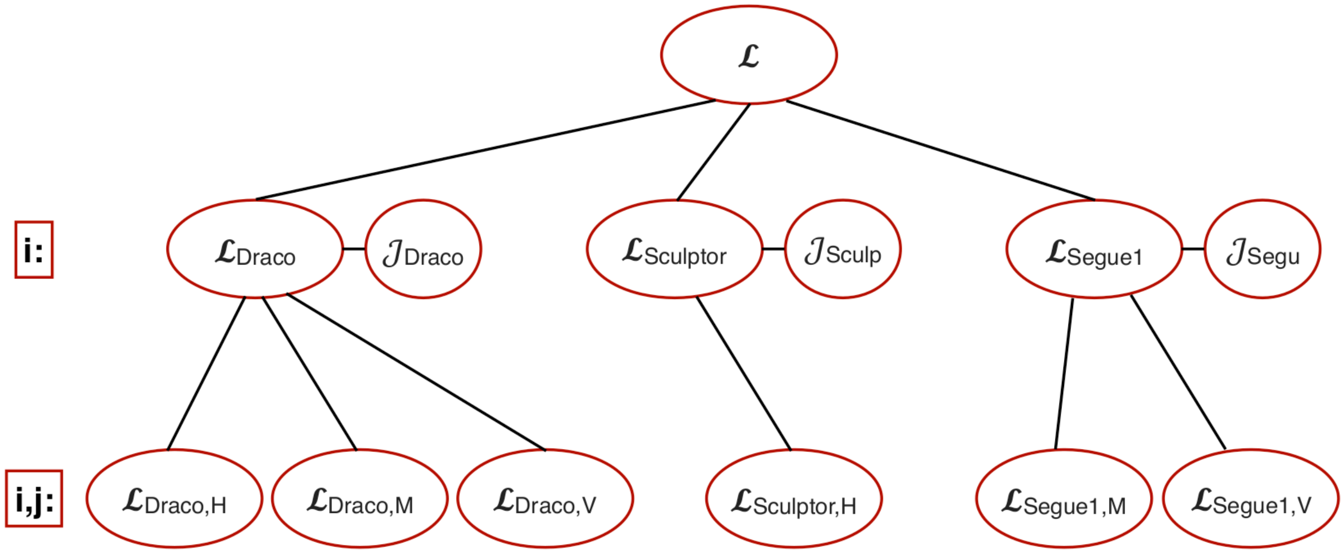
$$\mathcal{L}\left(\langle\sigma v\rangle ; \boldsymbol{\nu} \mid \boldsymbol{\mathcal{D}}_{\text{dSphs}}\right)=\prod_{l=1}^{N_{\text{dSphs}}} \mathcal{L}_{\text{dSph}, l}\left(\langle\sigma v\rangle ; J_l, \boldsymbol{\nu}_{\boldsymbol{l}} \mid \boldsymbol{\mathcal{D}}_{\boldsymbol{l}}\right) \times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

Separate term in likelihood constraining J-factor

$$\mathcal{J}_l\left(J_l \mid J_{l, \text{obs}}, \sigma_{\log J_l}\right)=\frac{1}{\ln (10) J_{l, \text{obs}} \sqrt{2 \pi} \sigma_{\log J_l}} \exp \left(-\frac{\left(\log_{10} J_l-\log_{10} J_{l, \text{obs}}\right)^2}{2 \sigma_{\log J_l}^2}\right)$$

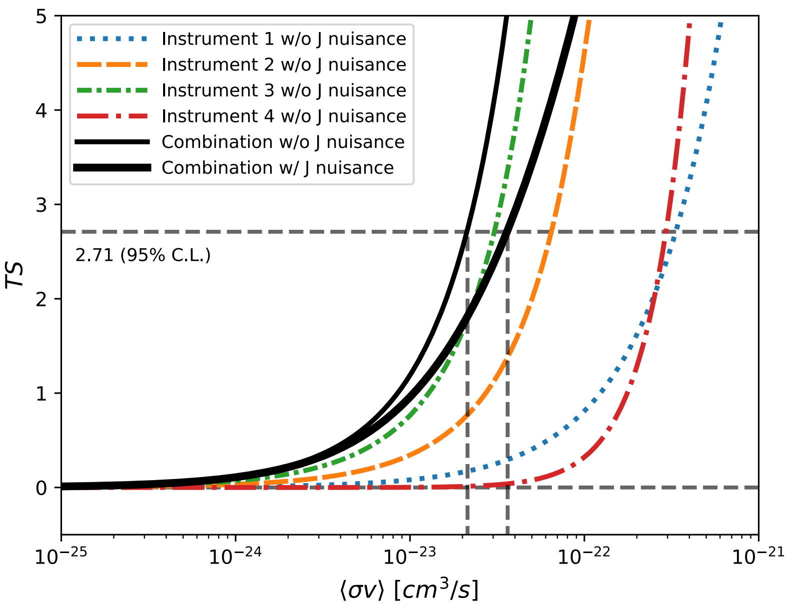
Total joint likelihood - product of partial joint likelihoods from all instruments

Joint Likelihood Analysis



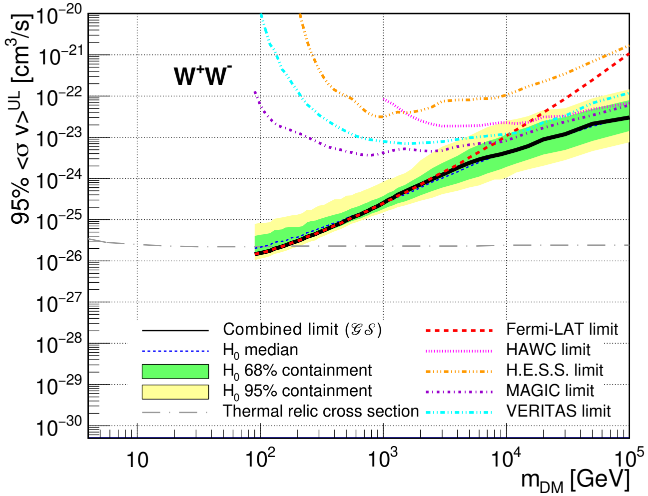
- Two independent combination codes developed
  - gLike: https://doi.org/10.5281/zenodo.4028908
  - LklCombiner: https://doi.org/10.5281/zenodo.4450884

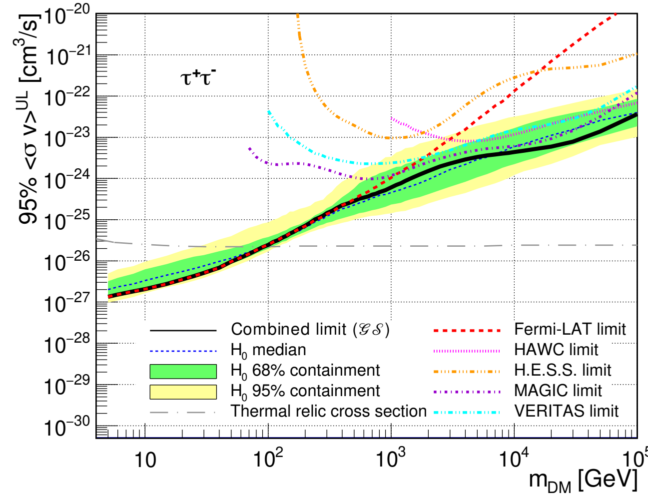
- No signal observed; extract 95% confidence level limits on DM annihilation cross section

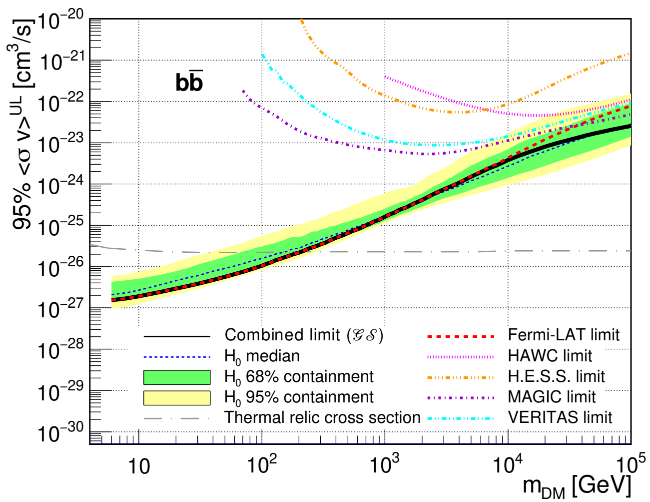


Results

Example bosonic, hadronic and leptonic channels (from 7 channels total)





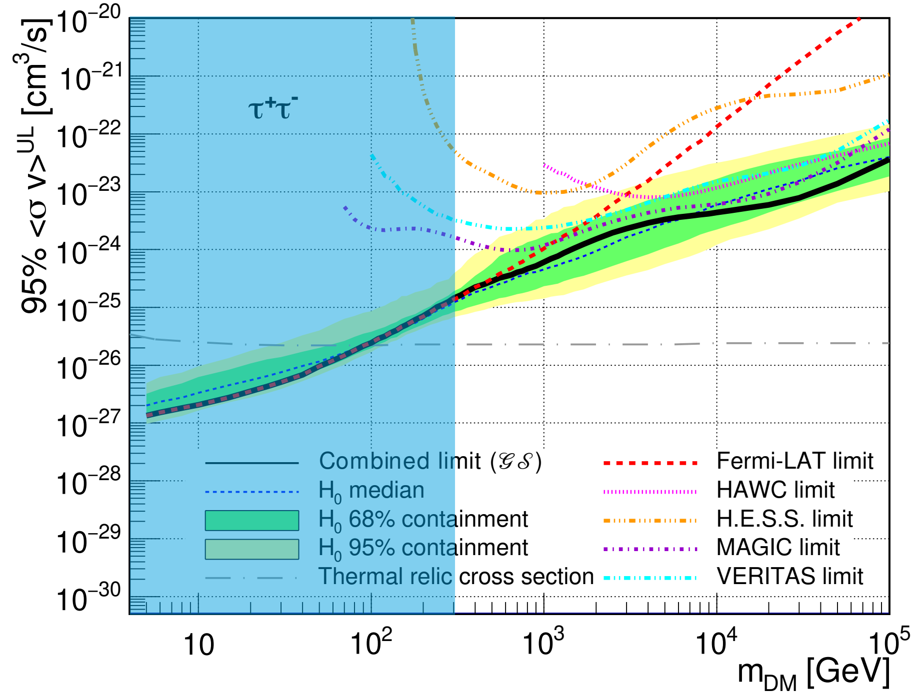


Factor 2-3 improvement in limits

Consistency between observed and expected limits

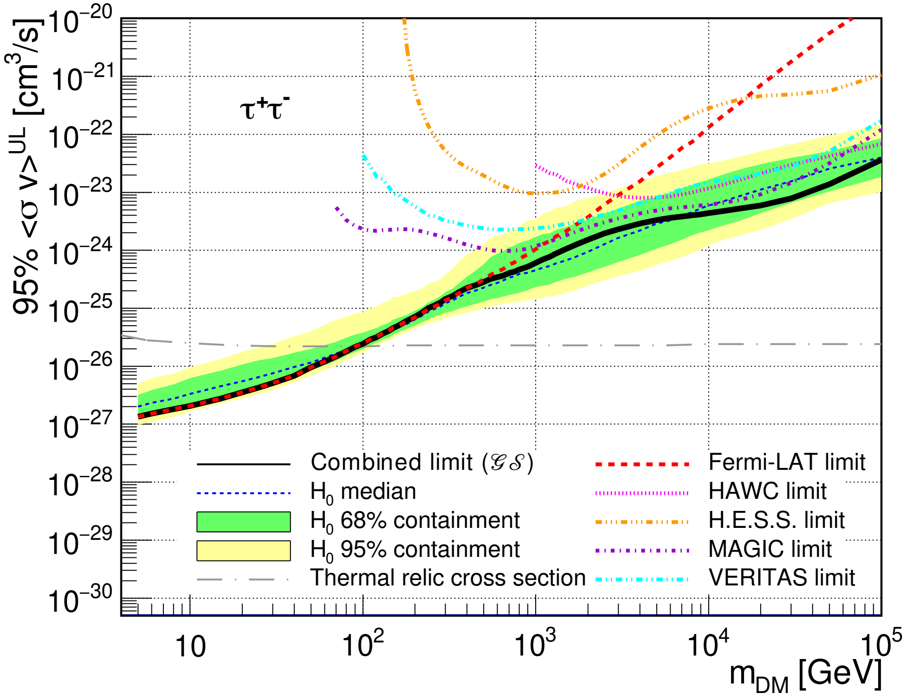
Interpretation of Results

- Fermi-LAT dominates below 300 GeV
- Above 300 GeV balance of contributions depends on channel and DM particle mass
- IACTs take an increasing role in leptonic channels with increasing DM particle mass
    - Contribute to hadronic channels above ~2 TeV
- HAWC contributes to leptonic channels above ~10 TeV

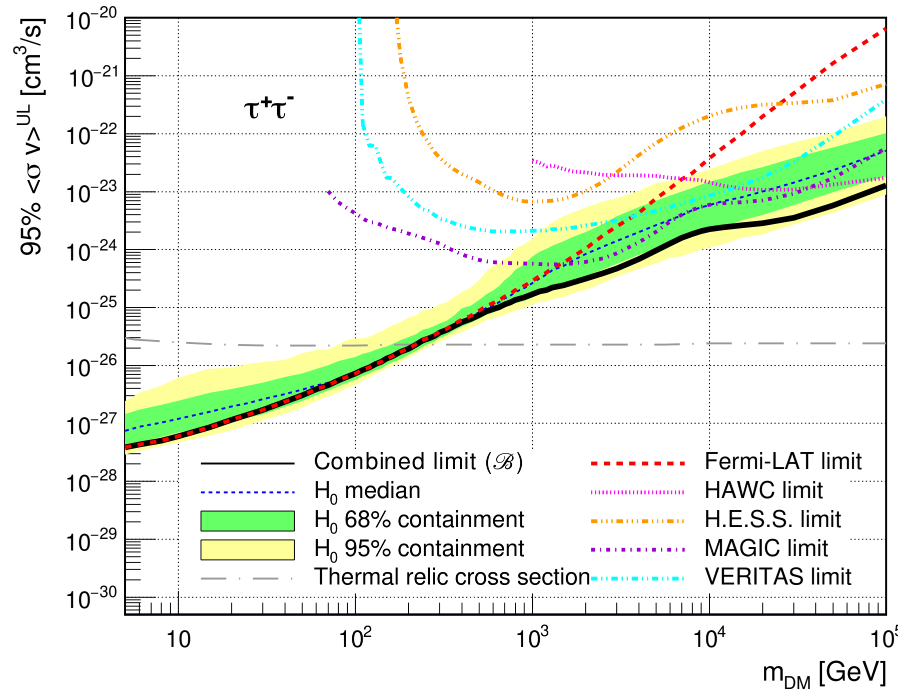


Impact of J-factor Uncertainty

Limits with Geringer-Sameth et al. J-factors



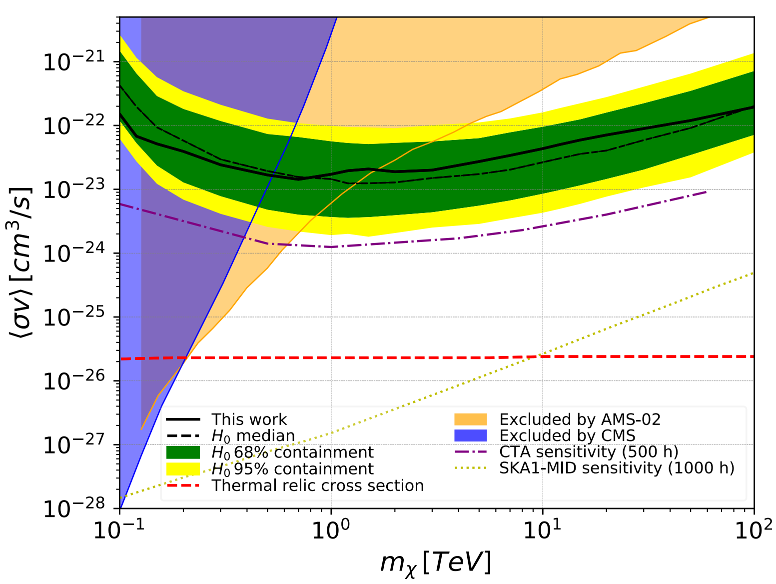
Limits with Bonnivard et al. J-factors



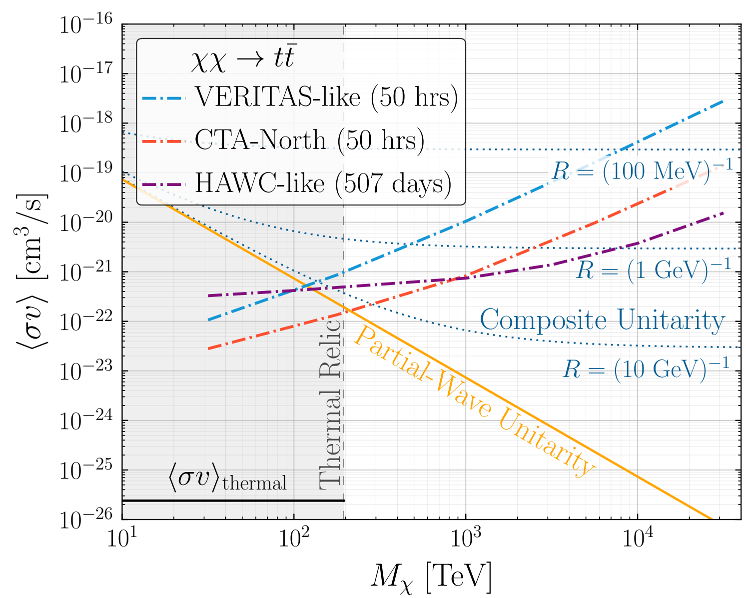
- Bonnivard et al. J-factors consistently produce more constraining limits
  - Larger J-factors for majority of objects
  - Factor 3-5 difference for bosonic and hadronic channels
  - Factor 2-6 difference for leptonic channels
  - Peak differences for ~TeV DM masses

Where to Next?

- New **data**
  - Instruments have taken/analyzed more data beyond datasets here
- New **channels**
  - Annihilation to gamma rays or neutrinos
    - Latter case - combine with IceCube, ANTARES
  - Decaying dark matter
- New **instruments**
  - Combination with LHAASO (higher energy gamma rays), CTA, SWGO…
- New **interpretations**!



Miener et al. 2022 arXiv:2201.03344

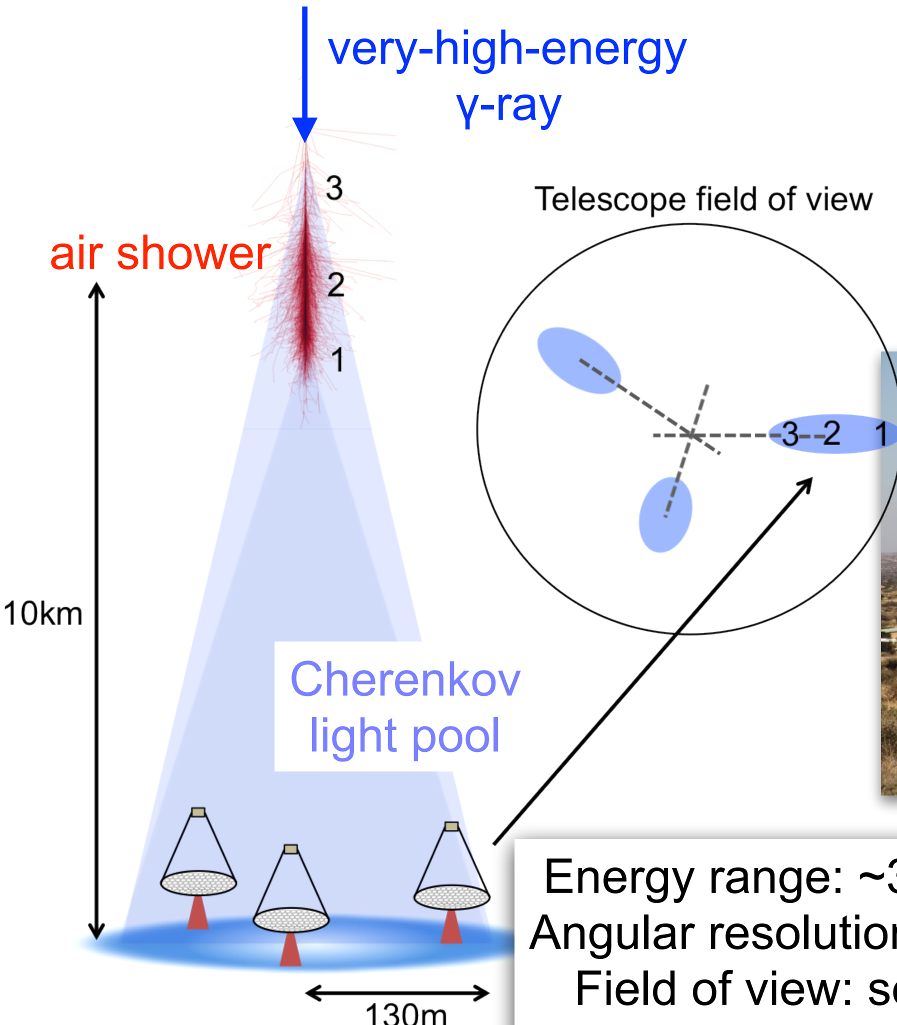


Tak et al. 2022 arXiv:2208.11740

Thanks!

Backup

Imagining Atmospheric Cherenkov Telescopes



Credit: J. Holder

Energy range: ~30 GeV - 50 TeV
Angular resolution: <0.1° @ 1 TeV
Field of view: several degrees
Limited duty cycle
>10 years of observations

J-Factor Comparison

Name	Distance (kpc)	l, b ($^\circ$)	$\log_{10} J$ ($\mathcal{GS}$ set) $\log_{10}(\mathrm{GeV}^2\mathrm{cm}^{-5}\mathrm{sr})$	$\log_{10} J$ ($\mathcal{B}$ set) $\log_{10}(\mathrm{GeV}^2\mathrm{cm}^{-5}\mathrm{sr})$
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	$104.97,\ 44.80$	$18.95^{+0.26}_{-0.18}$	$19.08^{+0.21}_{-0.13}$