Searches for Dark Matter using H.E.S.S.

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SA-GAMMA
THE SOUTH AFRICAN GAMMA-RAY ASTRONOMY PROGRAMME

H.E.S.S.

NRF National Research Foundation
science & innovation
Department: Science and Innovation
REPUBLIC OF SOUTH AFRICA

NWU
NORTH-WEST UNIVERSITY
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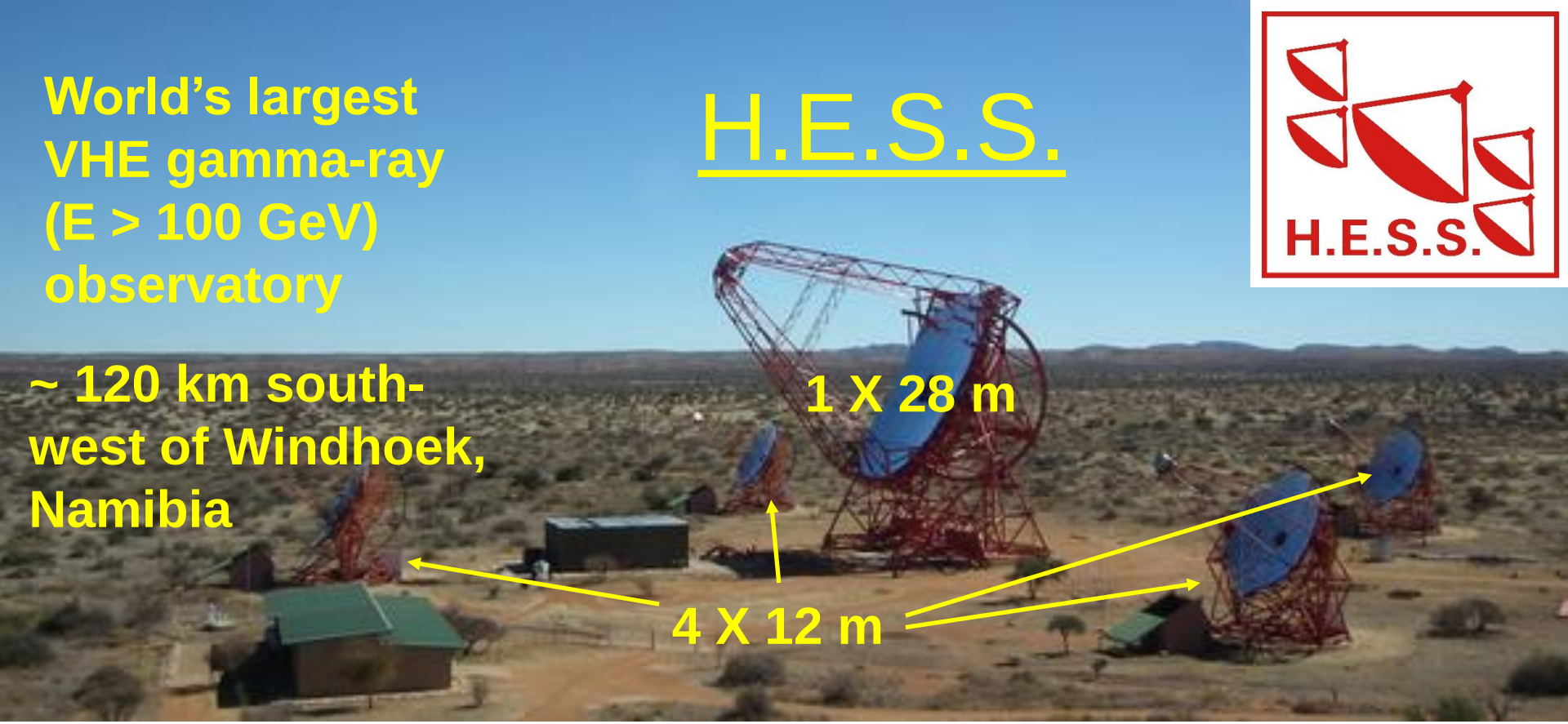
YUNIBESITI YA BOKONE-BOPHIRIMA

H.E.S.S.

World's largest VHE gamma-ray (E > 100 GeV) observatory

~ 120 km south-west of Windhoek, Namibia



Operated by a collaboration of ~ 250 scientists from

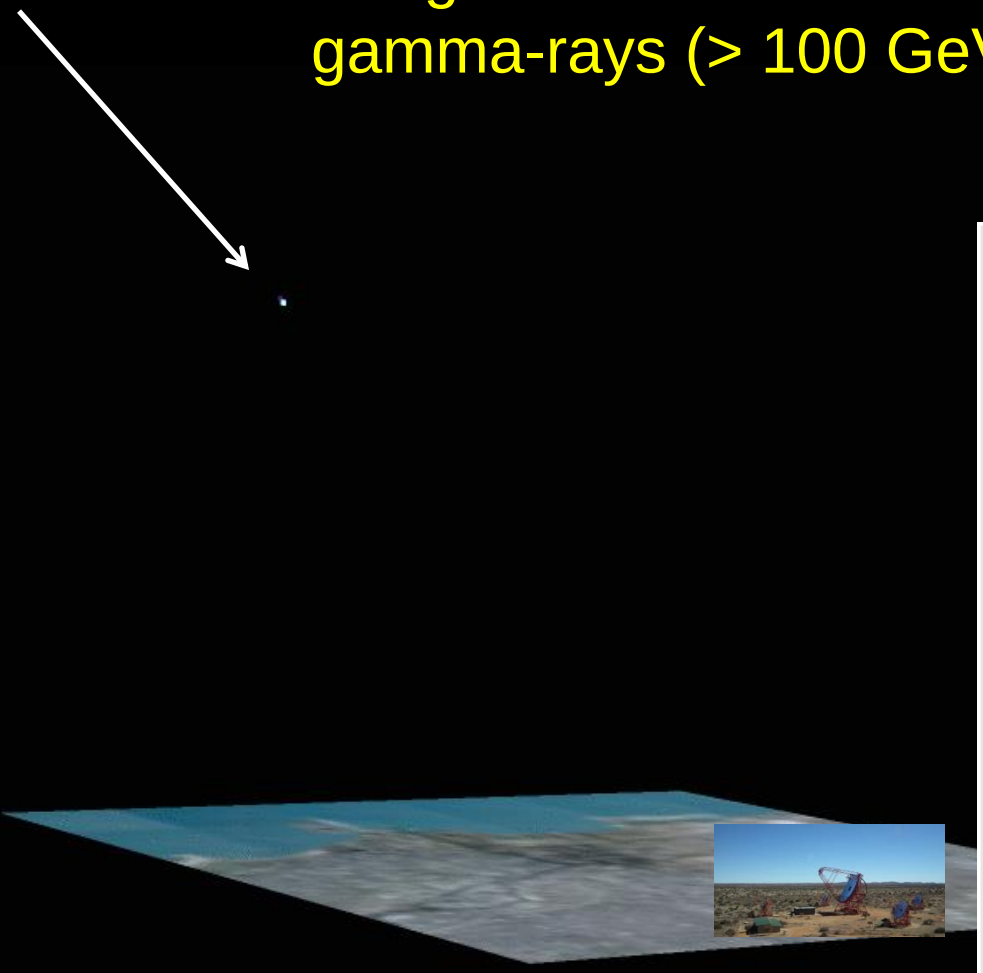
- Germany
- France
- United Kingdom
- **Namibia**
- **South Africa**
- Ireland
- Japan
- Armenia
- Poland
- Australia
- Austria
- Netherlands
- Sweden

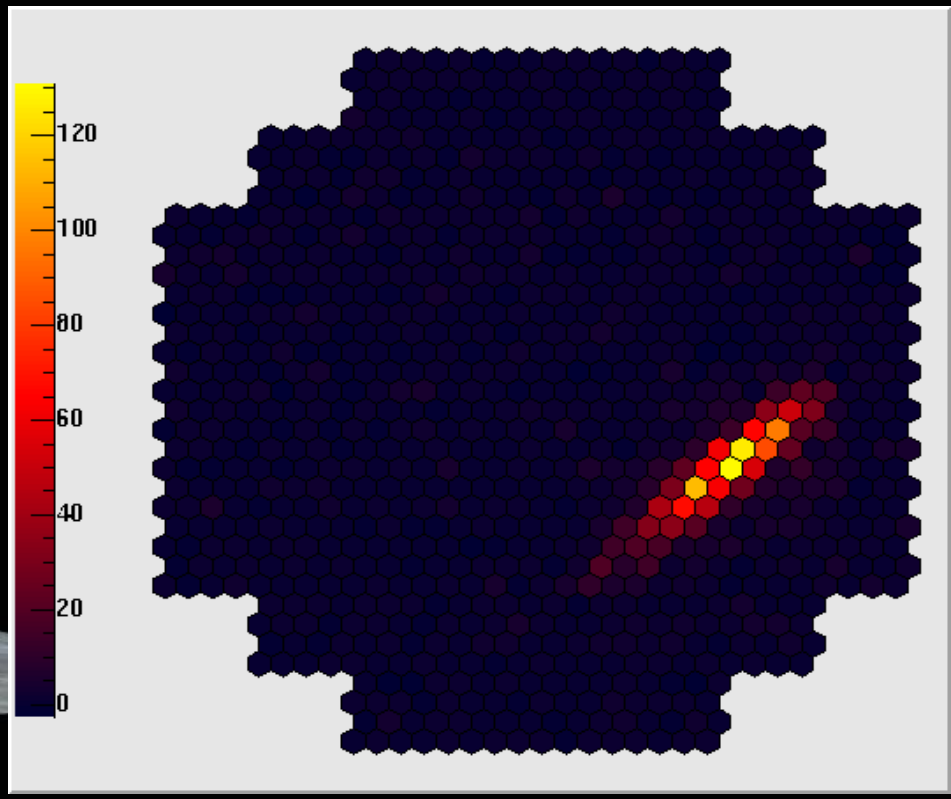
SA/Nam Members:

- NWU
- Wits
- UFS
- UNAM

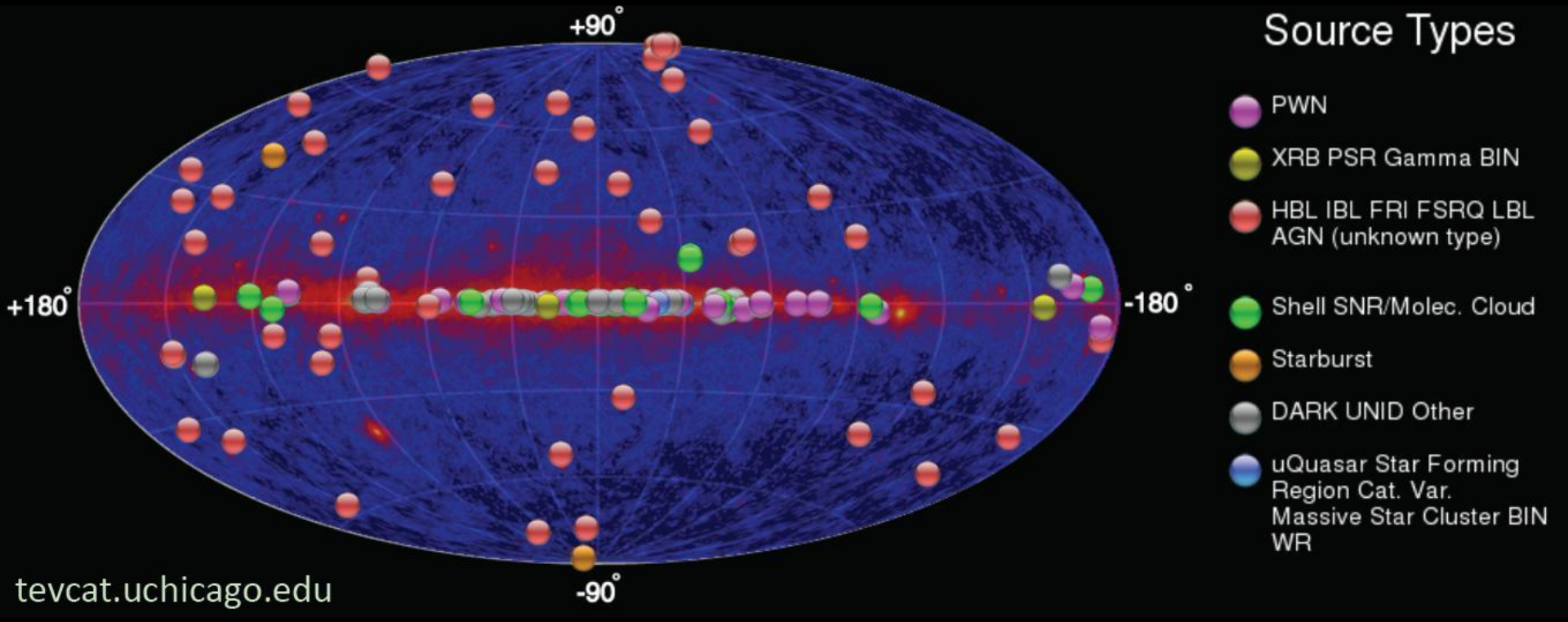
Detecting Gamma-Rays with Cherenkov Telescopes

Cherenkov light from air showers initiated by very-high-energy gamma-rays (> 100 GeV) in the atmosphere.





The Very-High-Energy Gamma-Ray Sky



Astrophysical Dark Matter

- Underlying assumption: DM = weakly interacting massive particles (WIMPs, beyond standard model [SM]) that may self-annihilate → SM particles (incl. γ-rays)
- Most commonly considered annihilation channels: W^+W^-, $\tau^+\tau^-$, (ZZ, $t\bar{t}$, $b\bar{b}$, e^+e^-, $\mu^+\mu^-$)
- Expected γ-ray flux from DM annihilation:

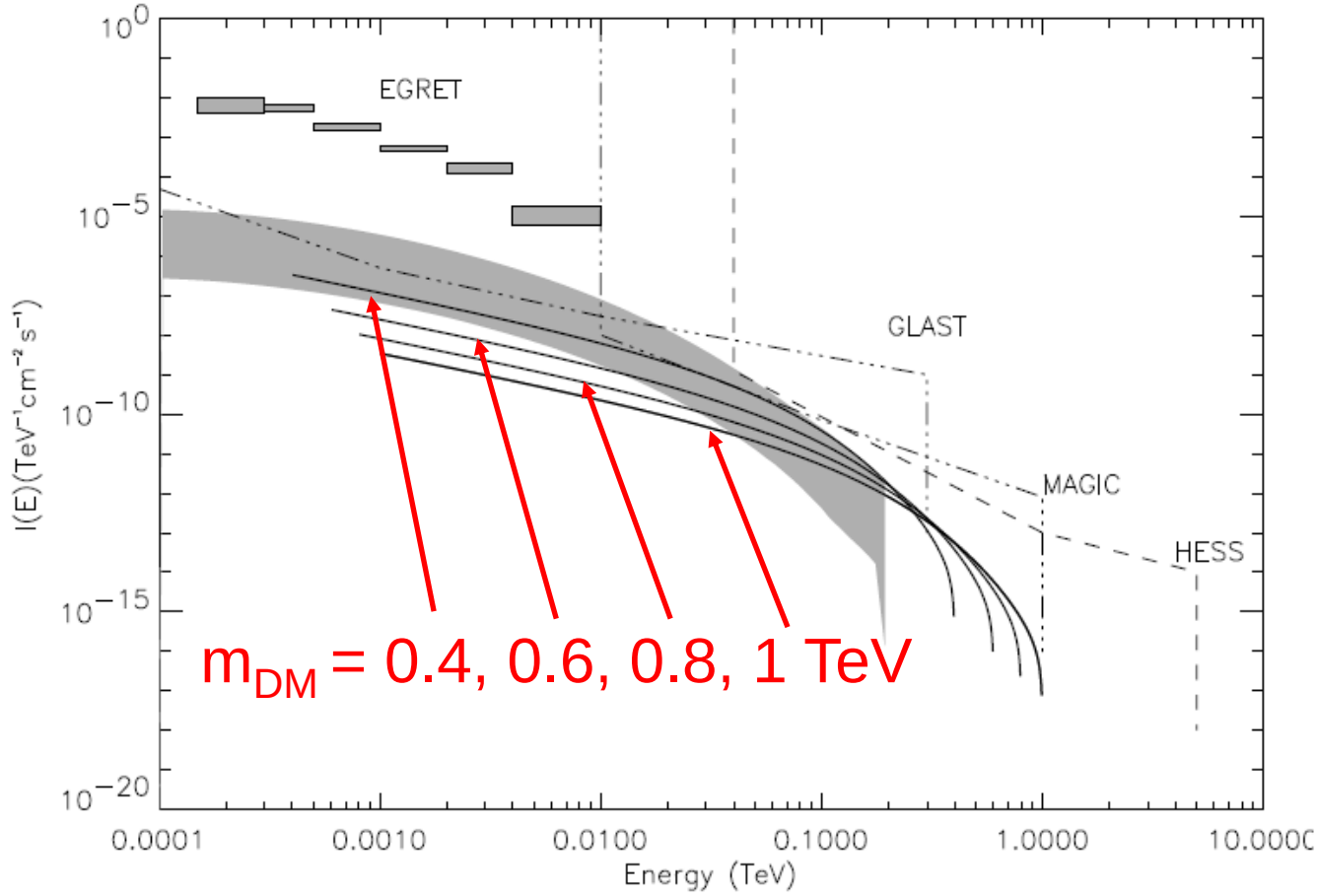
$$\frac{d\Phi_\gamma}{dE_\gamma}(E_\gamma, \Delta\Omega) = \frac{\langle\sigma v\rangle}{8\pi m_{DM}^2}\sum_f BR_f \frac{dN^f}{dE_\gamma} J(\Delta\Omega)$$

Particle physics factors: velocity-averaged ann. cross section; DM mass; Branching ratios; γ-ray spectrum from annihil. Event

- For thermal relic WIMPS: Expect $\langle\sigma v\rangle \sim 3\cdot10^{-26}$ cm^3 s^{-1}

Astrophysical Dark Matter

Expected DM annihilation spectrum (Galactic Center):



(Bertone et al. 2004)

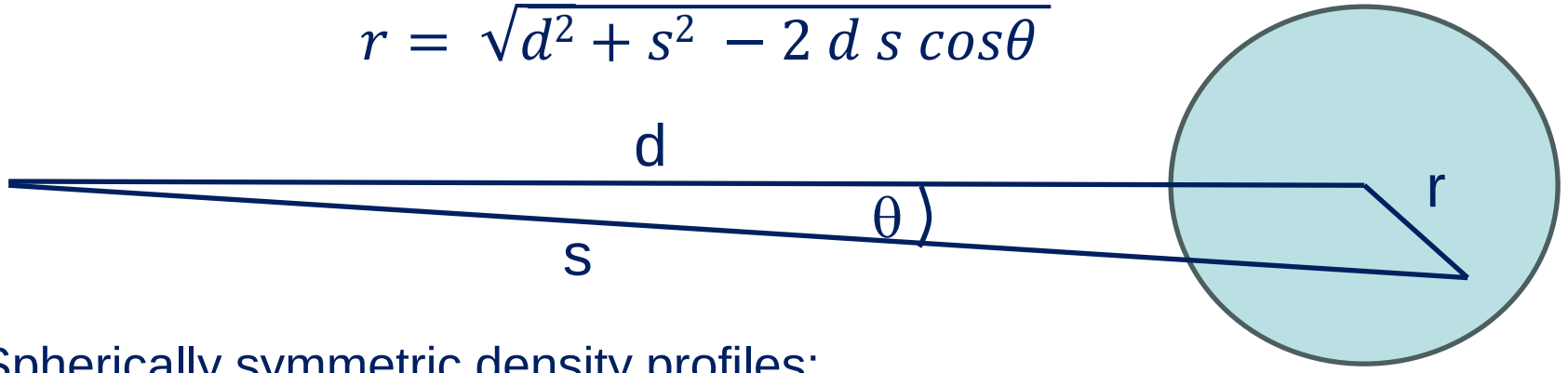
Astrophysical Dark Matter

- Astrophysical factor ("J factor"):

$$J(\Delta\Omega) = \int_{\Delta\Omega} d\Omega \int_{l.o.s.} ds\, \varrho^2(r[s,\theta])$$

(Units of GeV^2 cm^{-5})

$$r = \sqrt{d^2 + s^2 - 2\, d\, s\, cos\theta}$$



Spherically symmetric density profiles:

- Einasto: $\varrho_E(r) = \varrho_s \exp\left(-\frac{2}{\alpha_s}\left[\left(\frac{r}{r_s}\right)^{a_S} - 1\right]\right)$
- Navarro-Frenk-White (NFW): $\varrho_{NFW}(r) = \varrho_s \left(\frac{r}{r_s}\left[1 + \frac{r}{r_s}\right]^2\right)^{-1}$

Astrophysical Dark Matter

Candidate sources

Require:

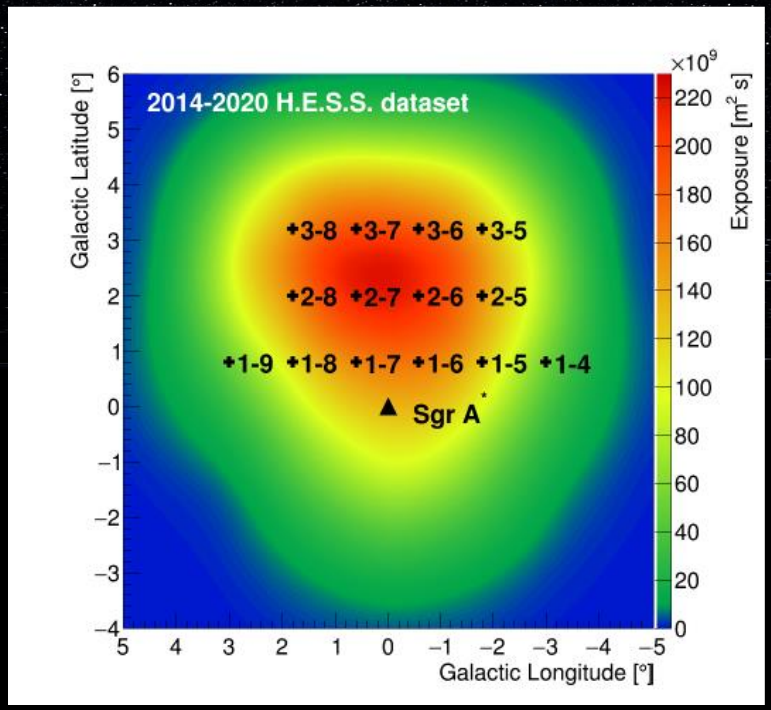
- High DM concentration (large J factor)
- Nearby
- Devoid of foreground γ-ray sources (e.g., AGN activity, supernova remnants, pulsar-wind nebulae, …)

Most commonly studied sources:

- Galactic center
- Dwarf spheroidal galaxies (Milky-Way satellites)
- DM sub-halos of the Milky Way

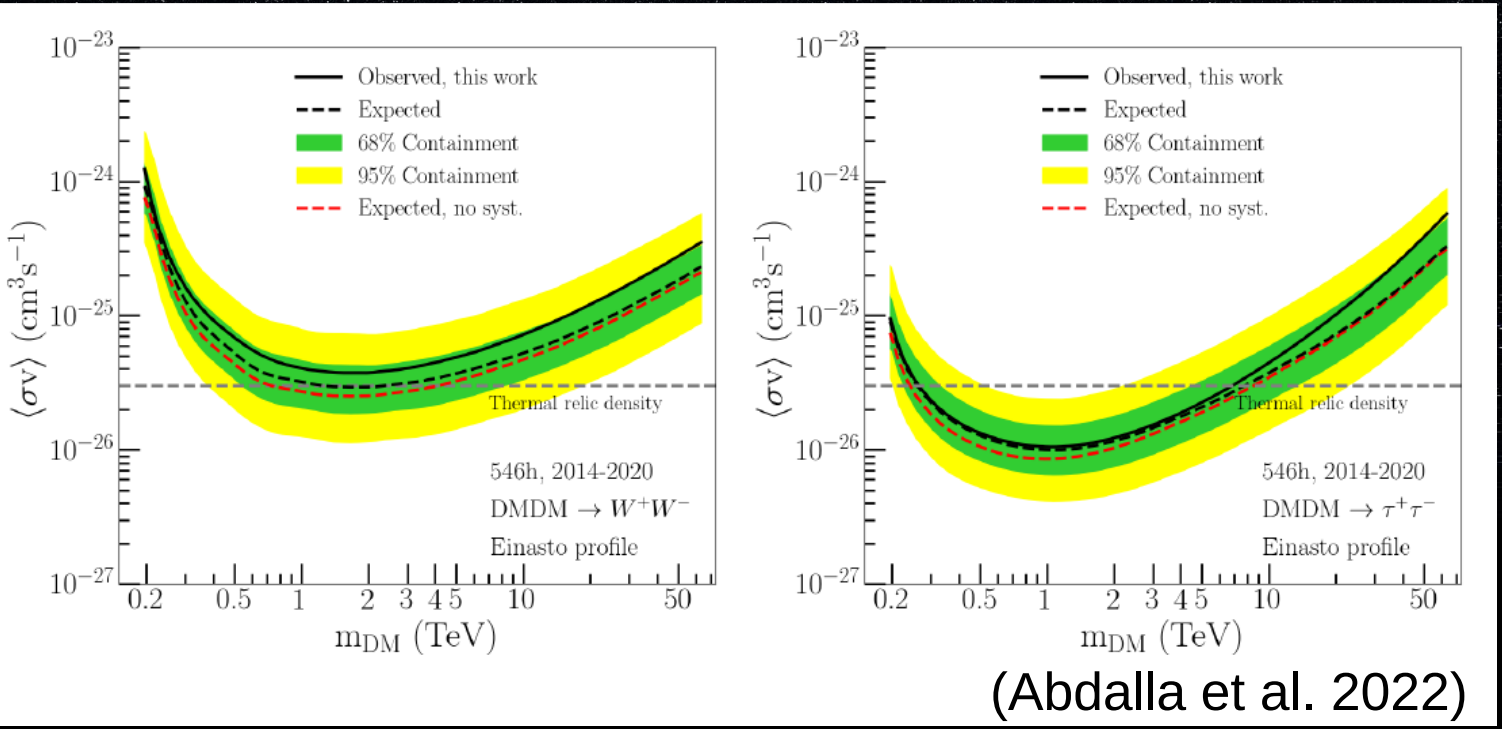
The Galactic Center

- High concentration of DM (J ~ 10^{21} GeV^2 cm^{-5})
- Foreground VHE γ-ray sources well characterized
- Nearby (8 kpc)
- Well studied by H.E.S.S. through the Inner Galaxy Survey (Abdalla et al. 2022).



The Galactic Center

No excess VHE γ-ray emission found
→ Derive upper limits on $\langle\sigma v\rangle$



(Abdalla et al. 2022)

$\langle\sigma v\rangle < 3.7 \cdot 10^{-26}$ cm^3 s^{-1} (W^+W^-)

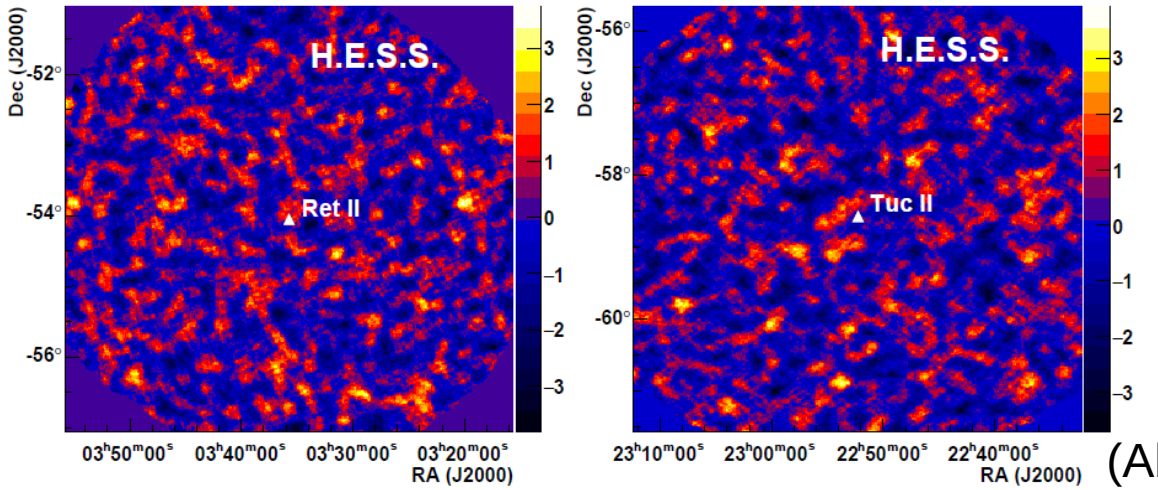
$\langle\sigma v\rangle < 1.2 \cdot 10^{-26}$ cm^3 s^{-1} ($\tau^+\tau^-$) for $m_{DM} \sim 1$ TeV

Dwarf Spheroidal Galaxies

- Very faint satellites of the Milky Way → Nearby.
- Most DM-dominated objects in the Universe.
- No sign of non-thermal processes (γ-ray emitters).
- Old stellar populations.
- Almost devoid of gas (no targets for cosmic-ray interactions).

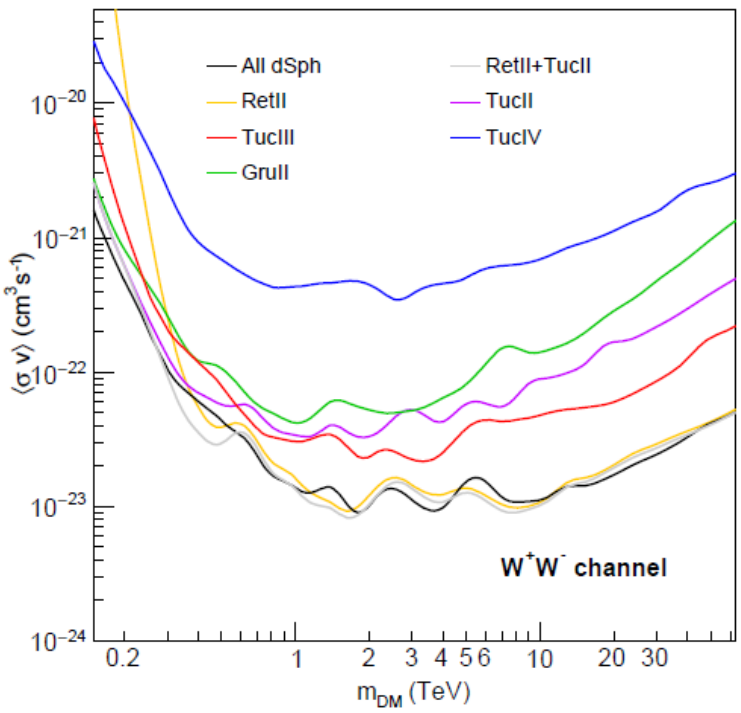
Dwarf Spheroidal Galaxies

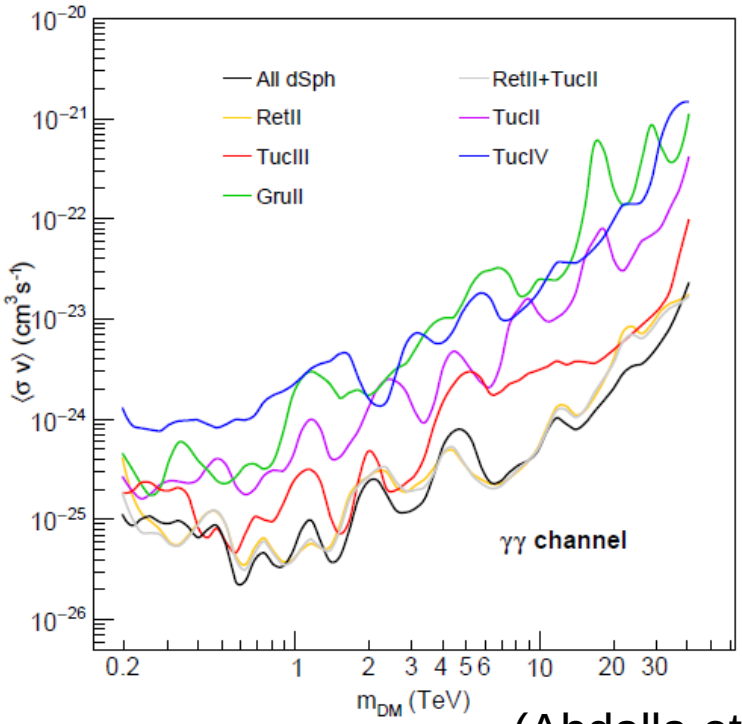
- Several efforts by H.E.S.S. and other γ-ray observatories to detect DM-annihilation signatures from dSphs (e.g., Abdalla et al. 2020, 2021).
- Example: H.E.S.S. observations of 5 nearby (25 kpc < d < 58 kpc) DES-detected dSphs with J ~ 10^{19} GeV^2 cm^{-5} (Abdalla et al. 2020).
- Exposures of 11.3 – 23.6 hours per target.
- No significant γ-ray excess found. → Upper limits on $\langle\sigma v\rangle$



(Abdalla et al. 2020)

Dwarf Spheroidal Galaxies



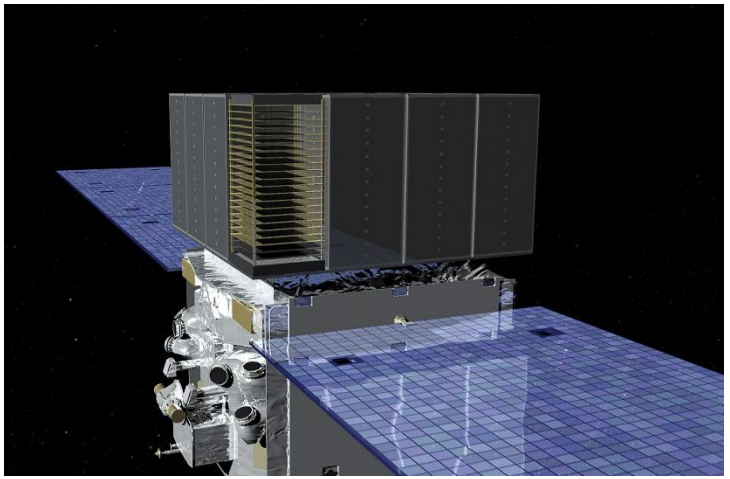


(Abdalla et al. 2020)

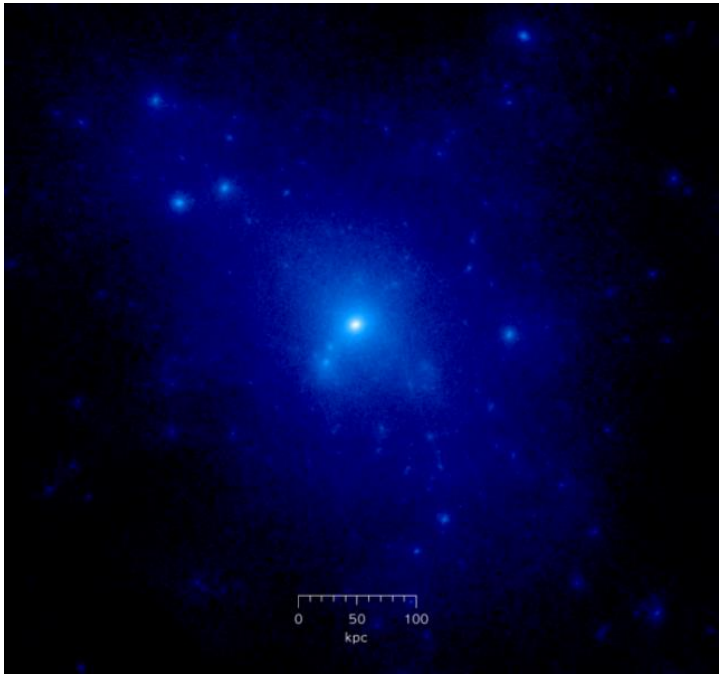
- $\langle\sigma v\rangle < 4 \cdot 10^{-26}$ cm^3 s^{-1} for direct $\gamma\gamma$ channel and $m_{DM} \sim 1.5$ TeV
- Limits for other channels much larger than from Galactic center measurements.

Unidentified Fermi-LAT Objects (UFOs)

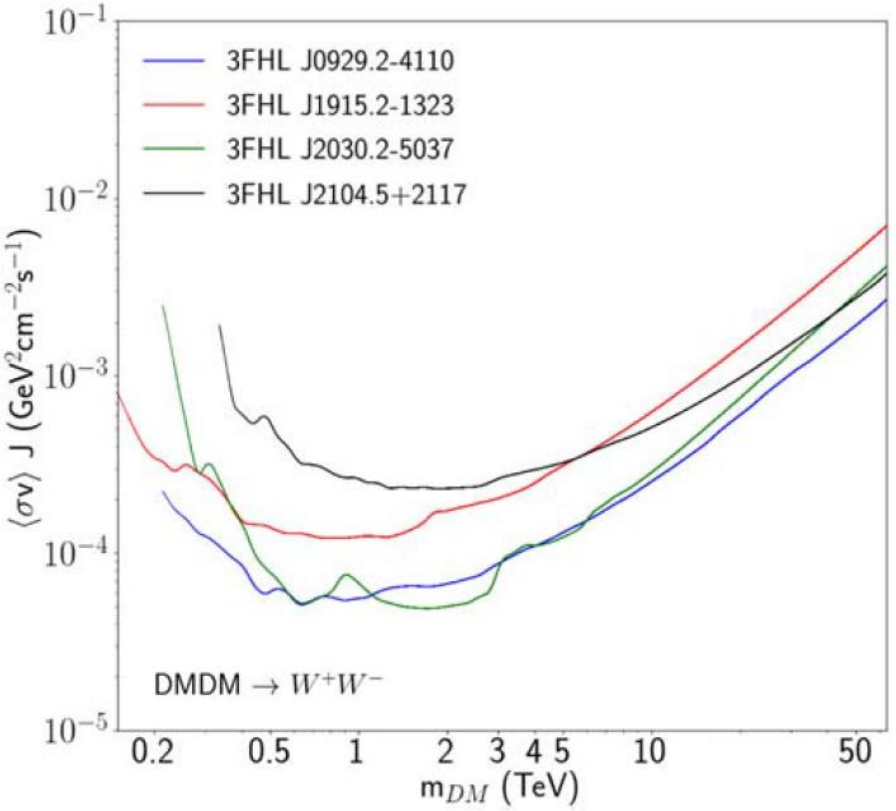
- Hypothesis: Unidentified Fermi-LAT sources = DM sub-halos of the Milky-Way DM halo, ~ 10^8 – 10^{10} $M_\odot$
- Not associated with any stellar activity. → No known γ-ray sources.
- J-factors unknown.
- Selected 4 steady, hard-spectrum UFOs with no known multi-wavelength counterpart.
- No VHE γ-ray emission found.
- Limits on $\langle\sigma v\rangle J$

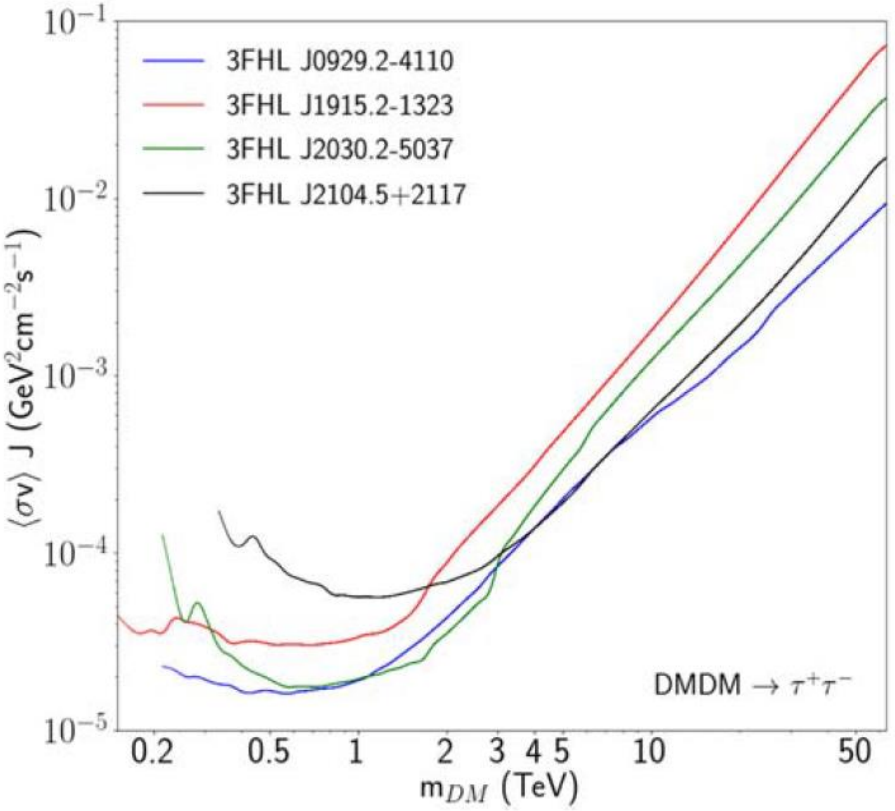


Fermi Gamma-ray Space Telescope



Unidentified Fermi-LAT Objects (UFOs)





(Abdalla et al. 2021)

For thermal relic WIMPS ($\langle\sigma v\rangle \sim 3\cdot10^{-26}$ cm^3 s^{-1}) → limits on J-factors:

$2.4\cdot10^{20}$ GeV^2 cm^{-5} < J < $1.3\cdot10^{21}$ GeV^2 cm^{-5} for W^+W^- channel;
$1.5\cdot10^{20}$ GeV^2 cm^{-5} < J < $5.9\cdot10^{20}$ GeV^2 cm^{-5} for $\tau^+\tau^-$ channel.

Summary

- TeV-scale WIMP CDM may self-annihilate into SM particles, incl. γ-rays, potentially detectable by ground- and satellite-based γ-ray observatories.
- Prime targets for searches for DM annihilation signatures are the Galactic center, dwarf spheroidal Milky-Way satellites, and Galactic DM sub-halos.
- No γ-ray signatures from DM annihilation have been found yet.
- Limits on $<\sigma v>$ become comparable to relic WIMP expectation for some annihilation channels and DM particle masses.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