A. Montanari (presenter),
E. Moulin and D. Malyshev
on behalf of the H.E.S.S.
Collaboration

TeVPA – October 2021

Search for dark matter in the Galactic Centre region with the H.E.S.S. Inner Galaxy Survey

UNIVERSITÉ PARIS SUD

université PARIS-SACLAY

Irfu

H.E.S.S.

OUTLINE

- Introduction: indirect Dark Matter search in gamma rays
- Inner Galaxy Survey performed by H.E.S.S.
- H.E.S.S. data analysis
- Computation of the upper limits on <σv>
- Conclusions

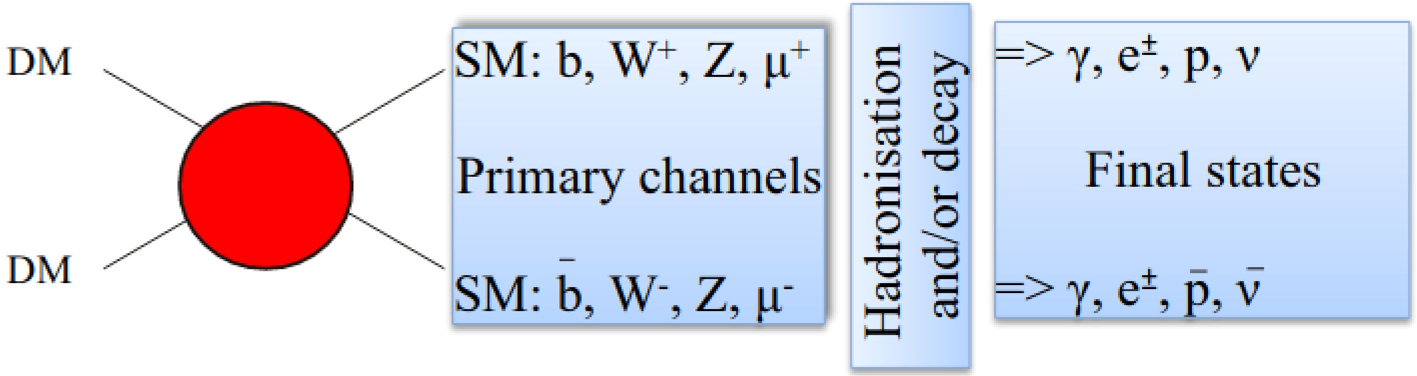
Indirect Dark Matter search

- Growing astrophysical and cosmological evidence about the existence of Dark Matter (DM).

- WIMPs → one of the most compelling DM particle candidates.

- WIMPs created thermally in the Early Universe:
  - Annihilation cross section expected for thermal WIMPs ($<\sigma v>_{th}=3x10^{-26}$ cm^3 s^{-1}).

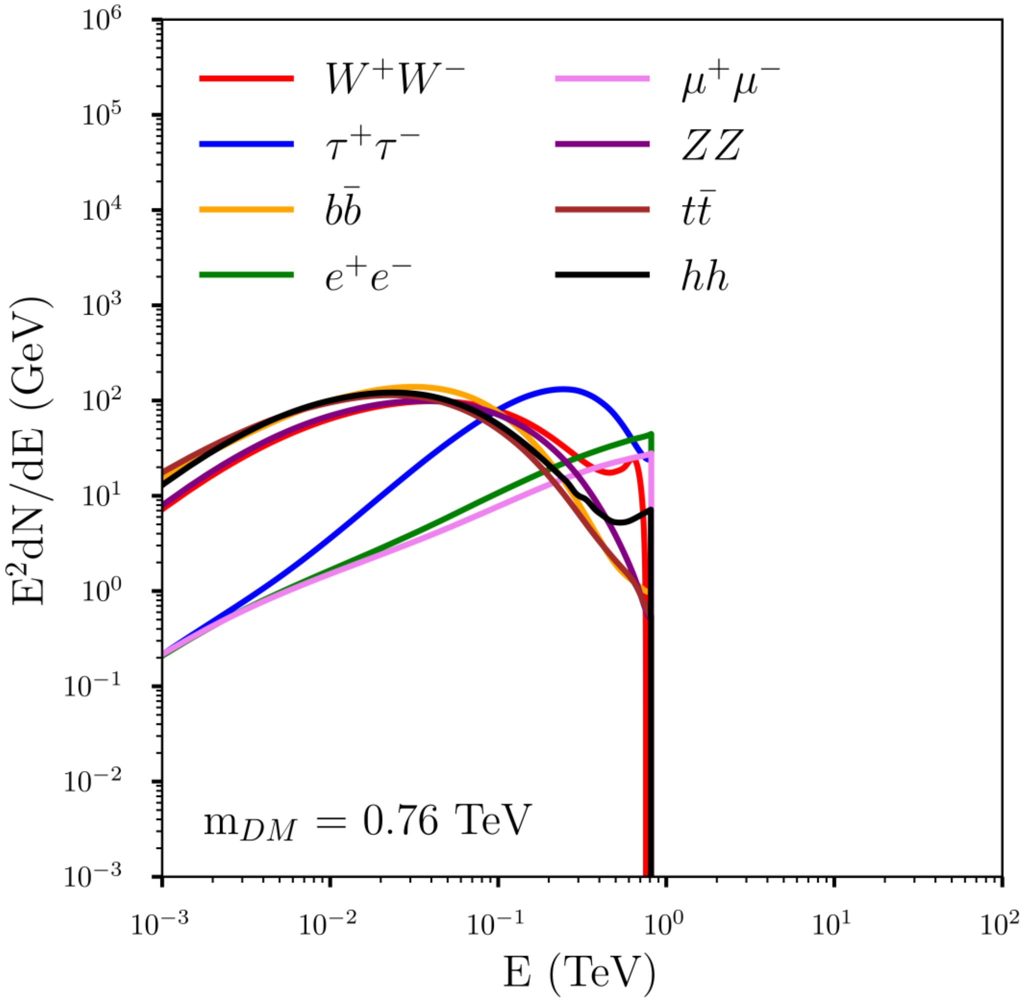
- Self-annihilating WIMPs can produce Standard Model particles in the final states → detectable by satellite (*Fermi*-LAT) and ground-based experiments (H.E.S.S., MAGIC, VERITAS).



Indirect Dark Matter search in gamma rays

- WIMPs can self-annihilate and produce gamma-rays eventually detectable by H.E.S.S.
- Assuming annihilation process almost at rest:
  - A smoking-gun signature for DM is a very distinct energy cut-off, close to the DM particle mass.
- Gamma-ray flux expected from DM annihilations:

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

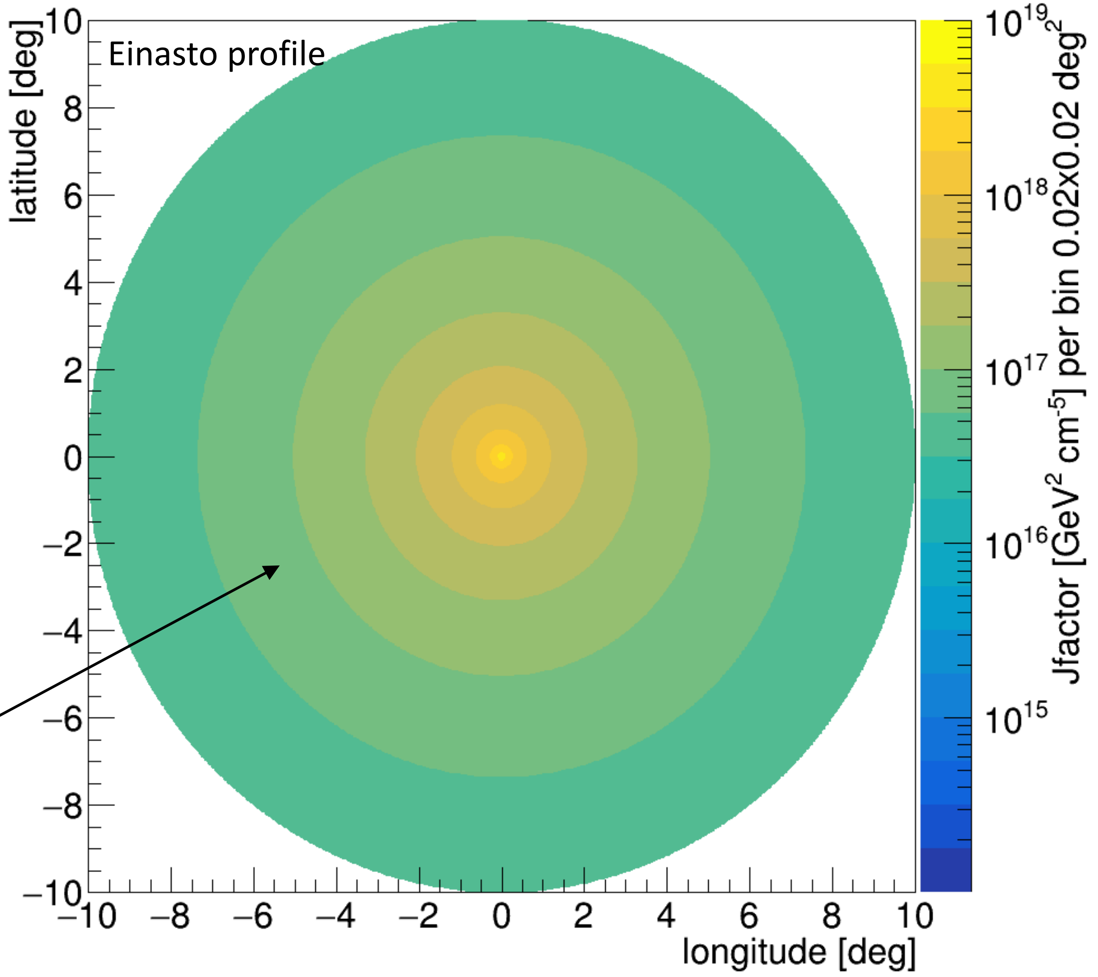


Indirect Dark Matter search in gamma rays

- WIMPs can self-annihilate and produce gamma-rays eventually detectable by H.E.S.S.
- Assuming annihilation process almost at rest;
  - A smoking-gun signature for DM is a very distinct energy cut-off, close to the DM particle mass.
- Gamma-ray flux expected from DM annihilations:

$$\frac{d\phi_\gamma}{dE}(E_\gamma, \Delta\Omega) = \frac{\langle\sigma v\rangle J(\Delta\Omega)}{8\pi m_{\mathrm{DM}}^2} \sum_f Br_f \frac{dN_f}{dE_\gamma}$$

- **Astrophysical term** $\boldsymbol{J(\Delta\Omega) = \int \rho^2 \, (r(s,\theta)) ds d\Omega}$**:**
  - Model needed for the density profile;
  - Dependence on dark matter halo modeling.



Indirect Dark Matter search in gamma rays: targets

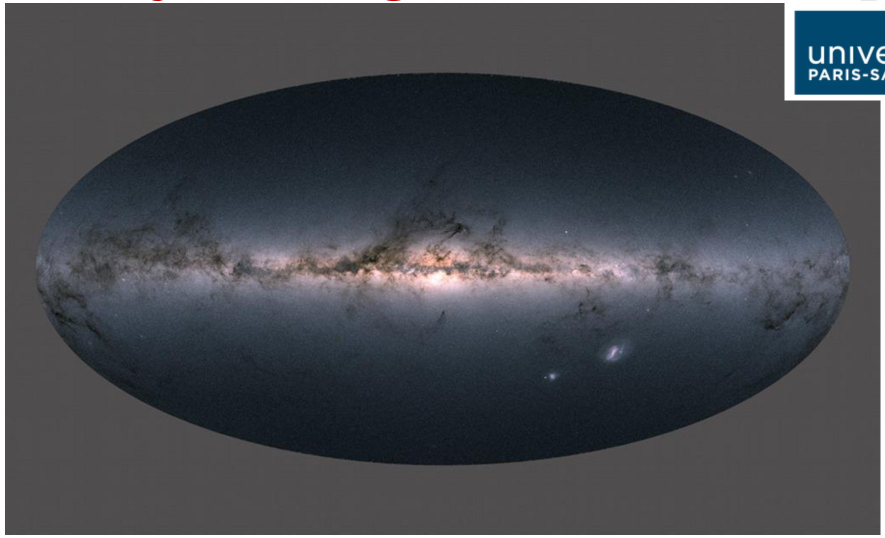
- Astrophysical term $J(\Delta\Omega) = \int \rho^2 \left(r(s,\theta)\right) ds d\Omega$:
  - Model needed for the density profile;
  - Dependence on dark matter halo modeling.

- **Most promising candidates** for DM detection:
  - **Galactic Center region** and nearby dwarf galaxies.

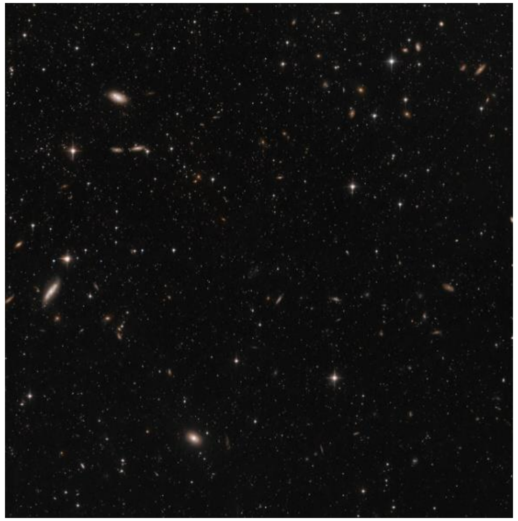
    Refs. Abdalla et al. [H.E.S.S. collaboration], Phys. Rev. Lett. 2016
    Abdalla et al. [H.E.S.S. collaboration], Phys. Rev. Lett. 2018
    Abdalla et al. [H.E.S.S. collaboration], JCAP 2018
    Abdalla et al. [H.E.S.S. collaboration], Phys. Rev. D. 2020

- Other compelling and complementary DM targets are:
  - Dark Matter subhalos populating the Galactic Halo.

    Ref. Abdalla et al. [H.E.S.S. collaboration], Astrophys. J., 918, 17 (2021)



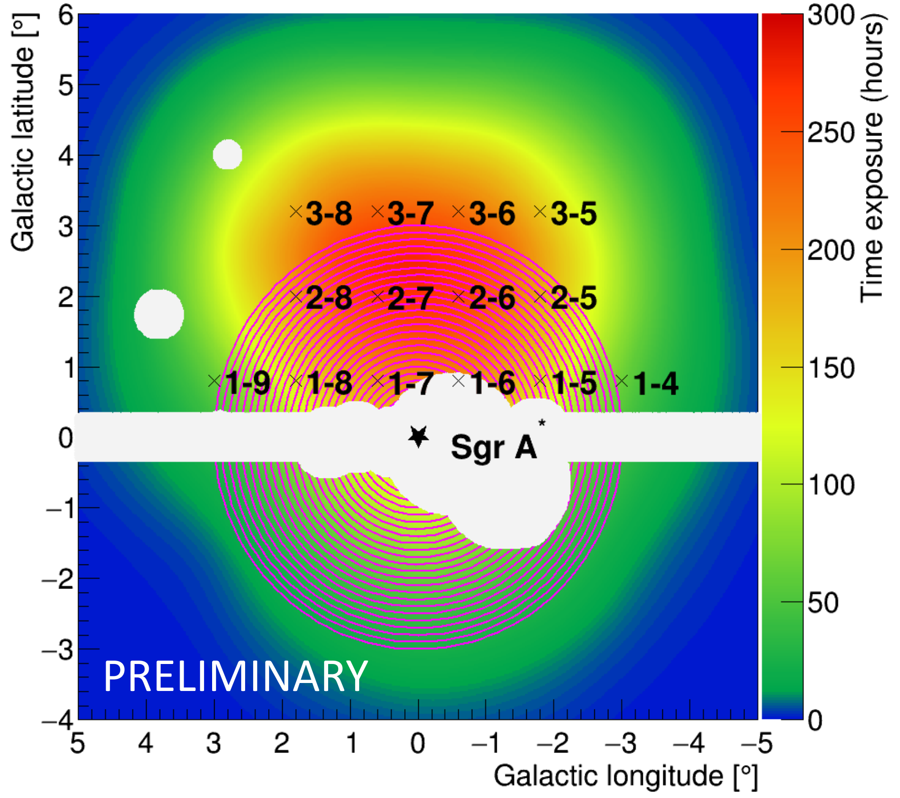
Grand all sky of our Milky Way and nearby galaxies. Credit: Gaia's satellite second data release



A small portion of the Sculptor dwarf galaxy, a satellite galaxy of the Milky Way, as observed by the NASA/ESA Hubble Space Telescope. This image shows one of two different pointings of the telescope.

Inner Galaxy Survey (IGS) performed by H.E.S.S.

- The first ever conducted VHE gamma-ray survey of the Galactic Center (GC) region.
- Aim: to provide **unprecedented sensitivity** to DM signals in the GC region.
- Dataset: 2014-2020 observations of the GC region.
- 2014-2020 exposure map with IGS pointing positions:
  - Exposure up to b ≈ 6°;



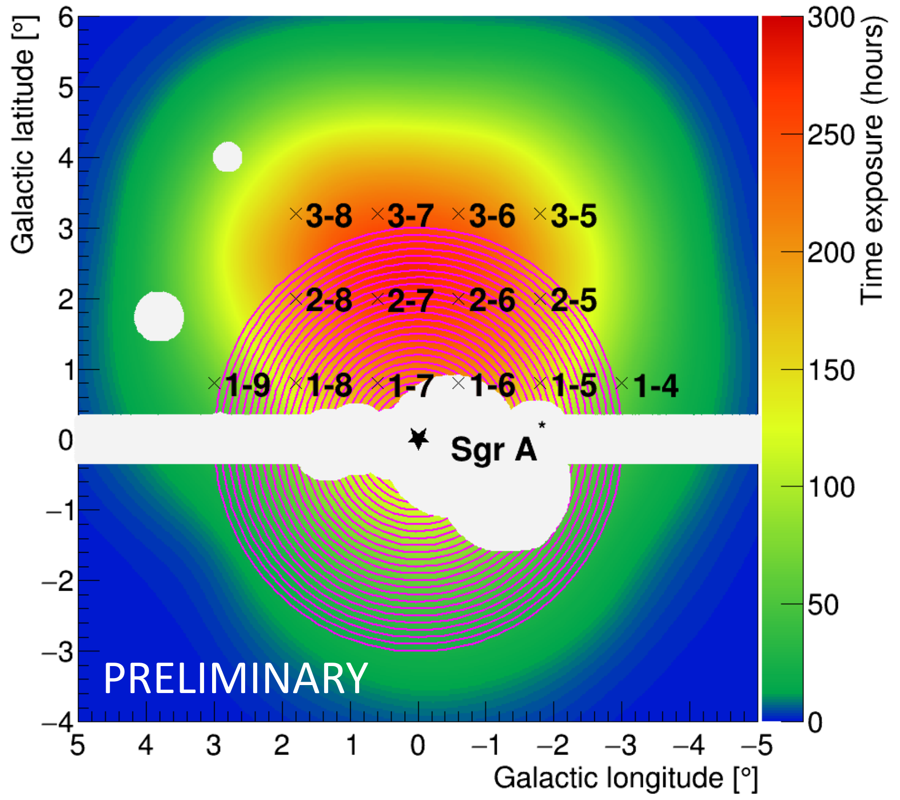
Inner Galaxy Survey (IGS) performed by H.E.S.S.

- **The first ever conducted VHE gamma-ray survey of the Galactic Center (GC) region.**

- Aim: to provide **unprecedented sensitivity** to DM signals in the GC region.

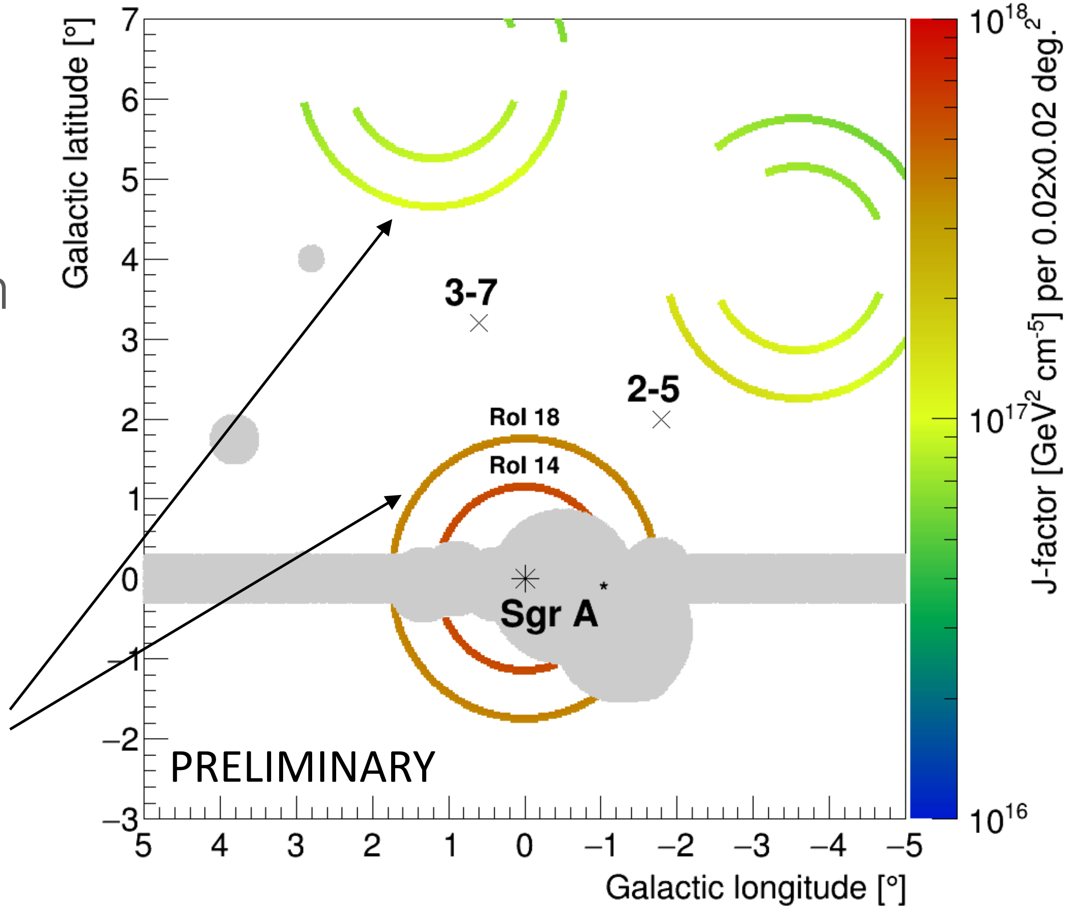
- Dataset: 2014-2020 observations of the GC region.

- 2014-2020 exposure map with IGS pointing positions:
  - Exposure up to b ≈ 6°;
  - 25 regions of interest (ROI) defined to search for DM: 0.1°-width open rings;
  - Set of exclusion regions to avoid gamma-ray contamination in the ROIs.



H.E.S.S. data analysis: background measurement, ON/OFF construction

- Definition of the ON region: 25 ROI.
- **Reflected background method:**
  - OFF region:
    - Symmetric to the ON region wrt the pointing position
      - Same FoV and acceptance;
    - The excluded regions are cut symmetrically
      - Same solid angle size;
    - Cut overlapping areas and areas where OFF is closer to GC than the ON:
      - The DM signal in the ON region is always higher than in the OFF region.



- Repeated for all the 25 ROI and over the ~1300 runs.

H.E.S.S. data analysis: Likelihood analysis and Test Statistics

- 2D binned Poisson likelihood function exploits spatial and spectral DM features: bins in energy (i) and space (j):

$$\mathcal{L}_{i,j}(N_{S,ij}, N_{B,ij}, \beta_{ij} | N_{ON,ij}, N_{OFF,ij}, \alpha_j) = \frac{[\beta_{ij}(N_{S,ij} + N_{B,ij})]^{N_{ON,ij}}}{N_{ON,ij}!} e^{-\beta_{ij}(N_{S,ij}+N_{B,ij})} \frac{[\beta_{ij}(N'_{S,ij} + \alpha_j N_{B,ij})]^{N_{OFF,ij}}}{N_{OFF,ij}!} e^{-\beta_{ij}(N'_{S,ij}+\alpha_j N_{B,ij})} e^{\frac{(1-\beta_{ij})^2}{\sigma_\beta}}$$

- Total likelihood function: $\mathcal{L} = \prod_{i,j} \mathcal{L}_{i,j}$

- $N_{ON,ij}$ and $N_{OFF,ij}$ $\rightarrow$ number of measured events in spatial ON and OFF regions;
- $N_{S,ij} + N_{B,ij}$ $\rightarrow$ expected total number of events in the spatial ON region;
- $N'_{S,ij} + \alpha_j N_{B,ij}$ $\rightarrow$ expected total number of events in the spatial OFF region;
- $\alpha_j = {}^{\Delta\Omega_{ON}}/_{\Delta\Omega_{OFF}}$ $\rightarrow$ ratio between angular size of ON and OFF regions.

H.E.S.S. data analysis: Likelihood analysis and Test Statistics

- 2D binned Poisson likelihood function exploits spatial and spectral DM features: bins in energy (i) and space (j):

$$\mathcal{L}_{i,j}(N_{S,ij}, N_{B,ij}, \beta_{ij} | N_{ON,ij}, N_{OFF,ij}, \alpha_j) = \frac{[\beta_{ij}(N_{S,ij} + N_{B,ij})]^{N_{ON,ij}}}{N_{ON,ij}!} e^{-\beta_{ij}(N_{S,ij}+N_{B,ij})} \frac{[\beta_{ij}(N'_{S,ij} + \alpha_j N_{B,ij})]^{N_{OFF,ij}}}{N_{OFF,ij}!} e^{-\beta_{ij}(N'_{S,ij}+\alpha_j N_{B,ij})} e^{\frac{(1-\beta_{ij})^2}{\sigma_\beta}}$$

- Total likelihood function: $\mathcal{L} = \prod \mathcal{L}_{i,j}$

- **The systematic uncertainties can be included via a nuisance parameter;**

Refs: Silverwood, et al, JCAP03, 055 (2015); Lefranc, et al. Phys. Rev. D91, 122003 (2015); CTA DM Programme (2019)

  - A value of 1% is used for the determination of the limits: σ_β=0.01
  - The value of β is determined via conditional maximization
    - β is computed for each energy and spatial bins, i.e., $\beta_{i,j}$.

H.E.S.S. data analysis: Likelihood analysis and Test Statistics

- 2D binned Poisson likelihood function exploits spatial and spectral DM features: bins in energy (i) and space (j):

$$\mathcal{L}_{i,j}(N_{S,ij}, N_{B,ij}, \beta_{ij} | N_{ON,ij}, N_{OFF,ij}, \alpha_j) = \frac{[\beta_{ij}(N_{S,ij} + N_{B,ij})]^{N_{ON,ij}}}{N_{ON,ij}!} e^{-\beta_{ij}(N_{S,ij}+N_{B,ij})} \frac{[\beta_{ij}(N'_{S,ij} + \alpha_j N_{B,ij})]^{N_{OFF,ij}}}{N_{OFF,ij}!} e^{-\beta_{ij}(N'_{S,ij}+\alpha_j N_{B,ij})} e^{\frac{(1-\beta_{ij})^2}{\sigma_\beta}}$$

- Total likelihood function: $\mathcal{L} = \prod \mathcal{L}_{i,j}$

- In absence of any significant excess in the FoV:
  → 95% C.L. upper limits on the free parameter <σv> from a log-likelihood ratio test statistics (TS).
  Ref. Cowan, G., Cranmer, K., Gross, E. *et al. Eur. Phys. J. C* 71, 1554 (2011)

- **Computation of expected limits and containment bands**:
  - Independent Poisson realizations for the ON and OFF measurements;
    → mean and std deviation derived from the distribution of the obtained <σv> values.

H.E.S.S. expected and observed upper limits

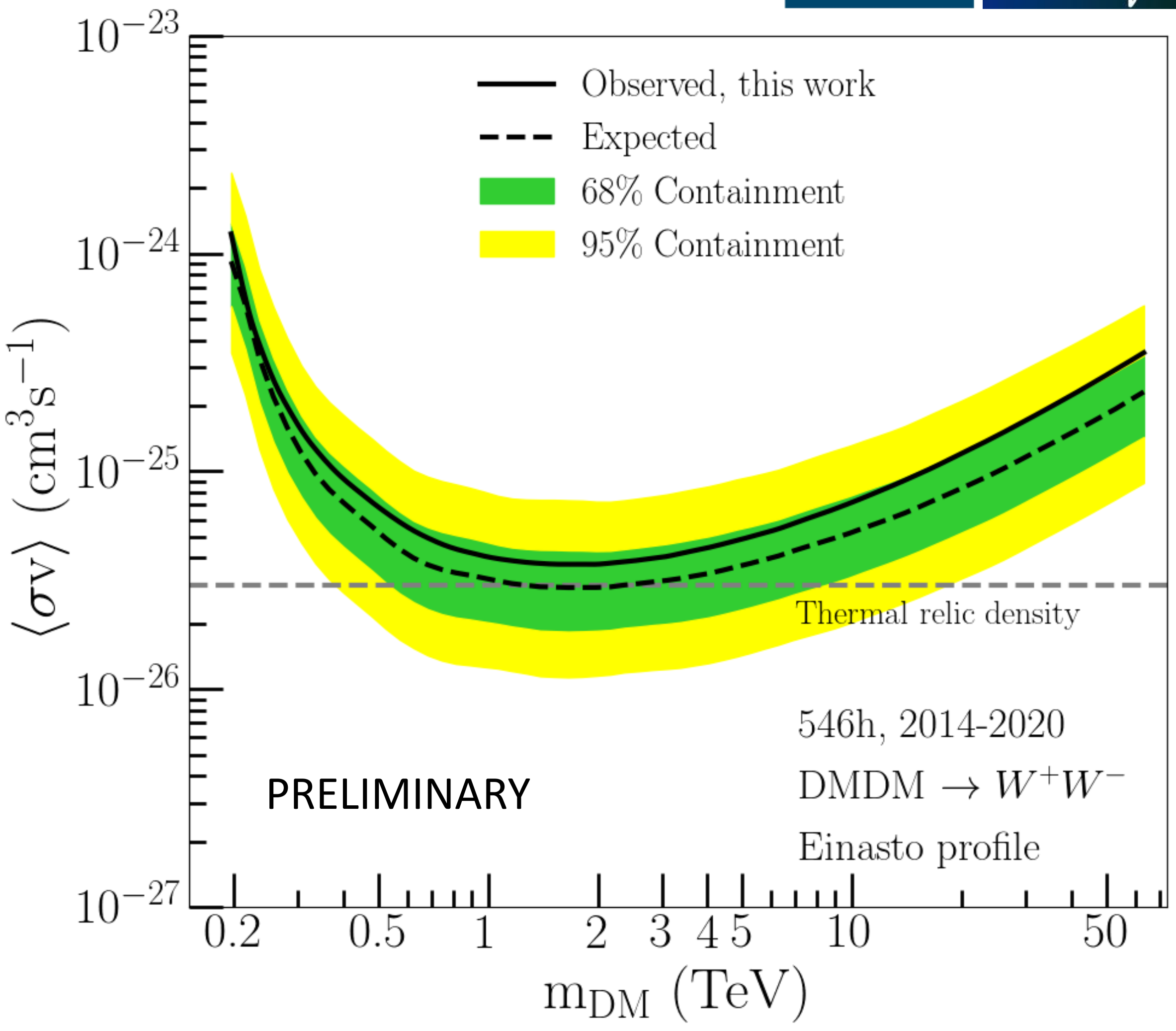
- No significant excess in the FoV:
  → 95% C.L. upper limits on <σv> from the TS;

- H.E.S.S. upper limits;

- Independent Poisson realizations for N_{ON} and N_{OFF} in the computation of the expected limits;

- Containment bands plotted at 1σ and 2σ level;

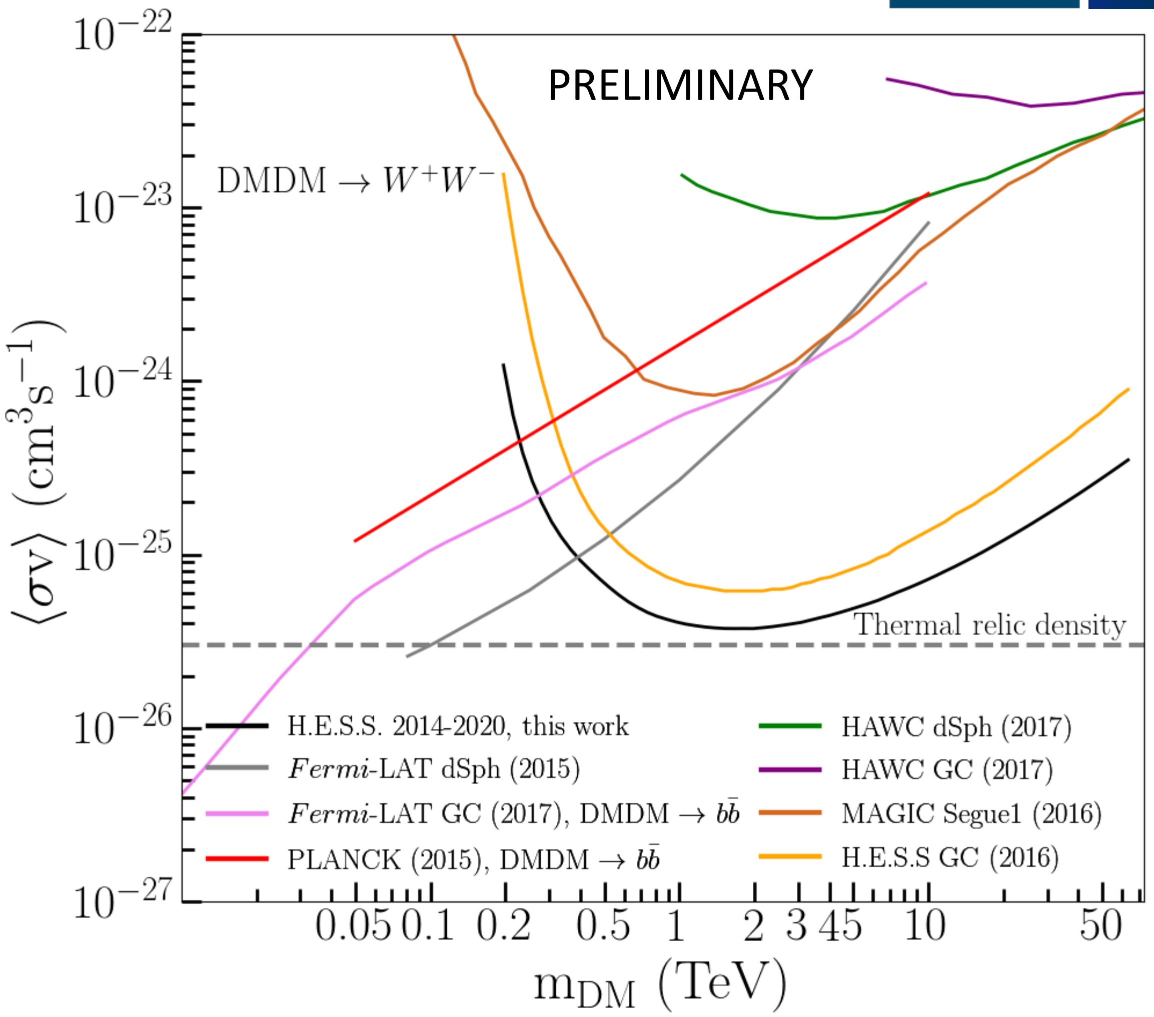
- Systematic uncertainty included in the limits via a nuisance parameter in the likelihood function.



Current observed upper limits

- H.E.S.S. upper limits.
- *Fermi*-LAT dSph and GC, HAWC dSph and GC, MAGIC Segue 1, PLANCK CMB, H.E.S.S. GC (2016) and this work.

→ Most constraining limits in the TeV-energy range.



Conclusions

- IGS campaign with pointing positions up to 3.2° is very fruitful:
  - Around 546 hours of high-quality data from 2014 to 2020.
- Computation of 95% C.L. expected and observed upper limits including systematic uncertainty.
- VHE observations of the GC region are unique for the study of the WIMP paradigm.
- With the unprecedented IGS dataset:
  → strongest constraints obtained in the TeV mass range.
- Limits are computed in other channels → can challenge the thermal relic scale.
- The IGS is one of the legacy of the H.E.S.S. collaboration and it paves the way for CTA.