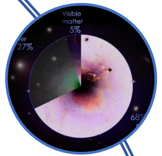
A. Montanari (presenter),
E. Moulin and D. Malyshev
on behalf of the H.E.S.S.
Collaboration

IRN Terascale @ Bonn
– 29th March 2022

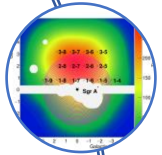
Dark Matter annihilation signals' search in the H.E.S.S. Inner Galaxy Survey

REF. A. Montanari et al. on behalf of the H.E.S.S. Collaboration, POS(ICRC2021)511

OUTLINE

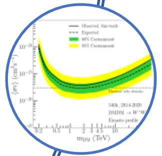


Introduction: WIMPs & Indirect Dark Matter search in gamma rays



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

H.E.S.S. data analysis



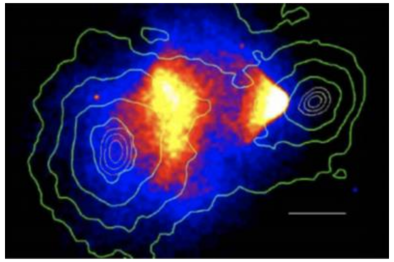
Computation of upper limits on <σv>

Conclusions

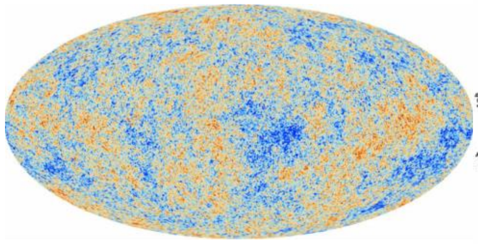
OUTLINE

Introduction: WIMPs & Indirect Dark Matter search in gamma rays

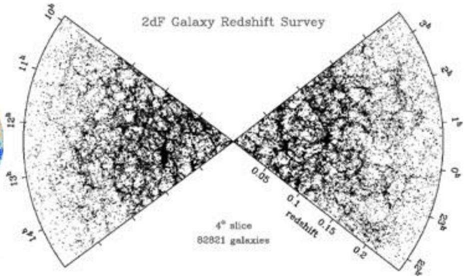
Evidence



Bullet cluster

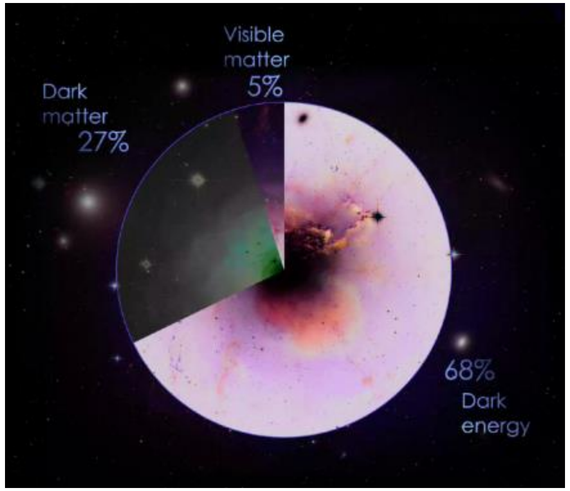


CMB



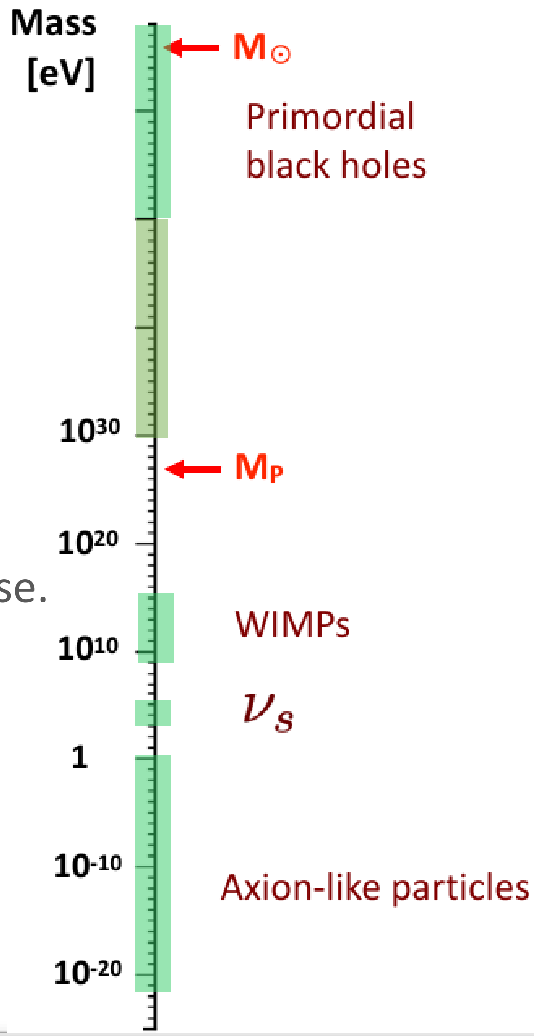
LSS

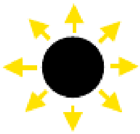
....

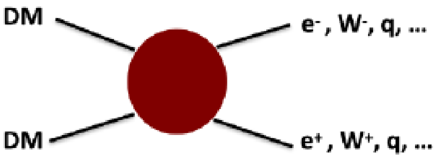


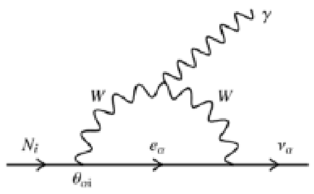
- Doesn't scatter/emit/absorb light.
- Does have mass (and hence gravity).
- Is about 84% of the matter in the universe.
- Forms the primordial "scaffolding" for the visible universe.
- Forms "halos" around galaxies.
- Interacts with other particles weakly or not at all (except by gravity).

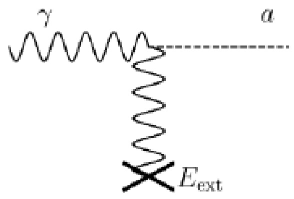
Candidates...





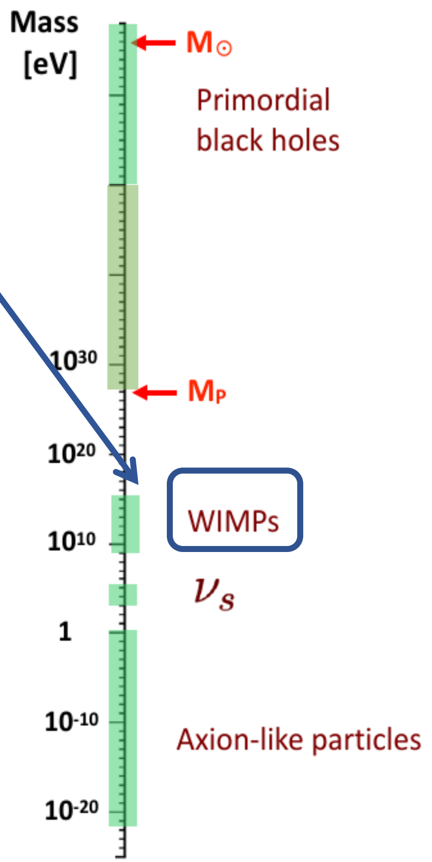






- Cold Dark Matter paradigm
- Focusing on Weakly Interactive Massive Particles (WIMPs)
- WIMPs created thermally in the Early Universe
  - Annihilation cross section expected for thermal WIMPs ($\langle\sigma v\rangle_{th} = 3x10^{-26}\ \mathrm{cm}^3\ \mathrm{s}^{-1}$).

Candidates …



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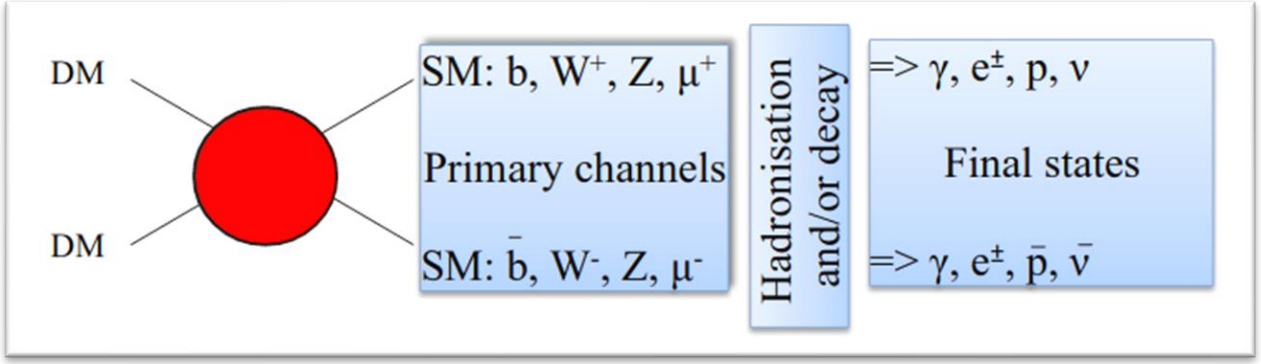
- WIMPs can self-annihilate and produce Standard Model particles in the final states



Introduction: WIMPs & Indirect Dark Matter search in gamma rays

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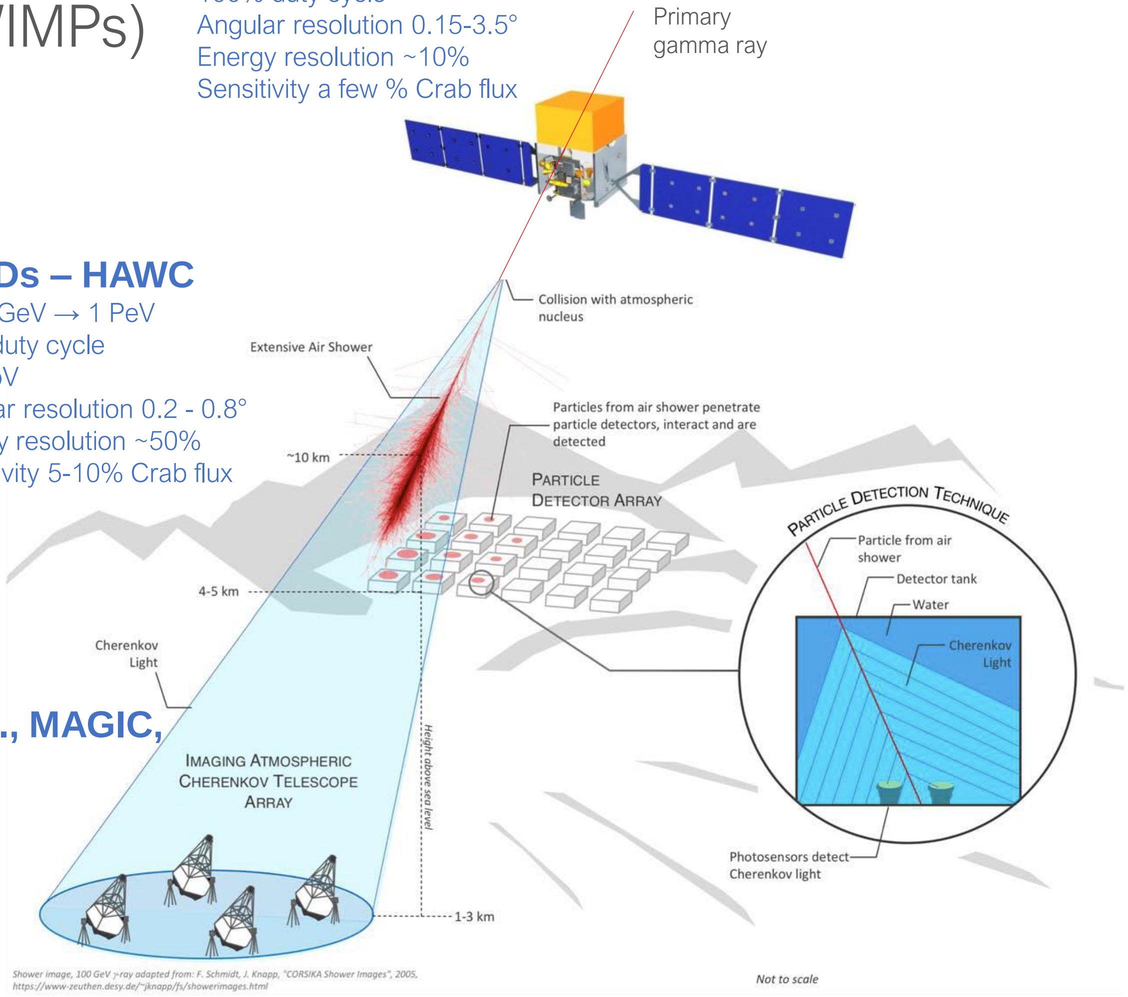
- WIMPs can self-annihilate and produce Standard Model particles in the final states eventually **detectable by satellite (*Fermi*-LAT) and ground-based experiments (HAWC, H.E.S.S., MAGIC, VERITAS).**

Satellites – AGILE, Fermi-LAT
~20 MeV → 300 GeV
>2 sr FoV
100% duty cycle
Angular resolution 0.15-3.5°
Energy resolution ~10%
Sensitivity a few % Crab flux

WCDs – HAWC
~100 GeV → 1 PeV
90% duty cycle
~sr FoV
angular resolution 0.2 - 0.8°
energy resolution ~50%
sensitivity 5-10% Crab flux

IACTs – H.E.S.S., MAGIC, VERITAS
~30 GeV → ~100 TeV
Small FoV : ~ 5°
Duty-cycle: 10-15%
Angular resolution <0.1°
Energy resolution ~10%
sensitivity 1% Crab flux



Introduction: WIMPs & Indirect Dark Matter search in gamma rays

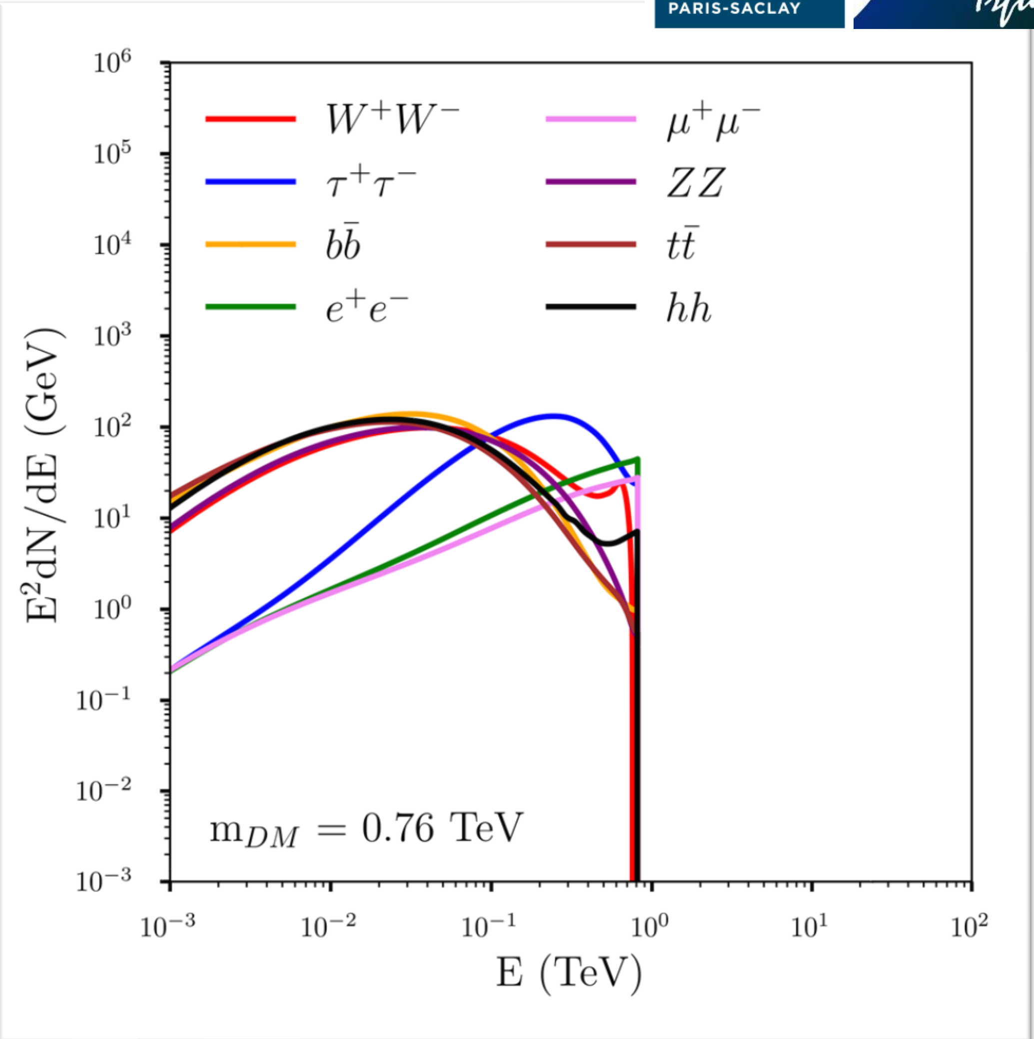
- WIMPs can self-annihilate and produce
  → gamma-rays eventually detectable by H.E.S.S.

- 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:

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

Particle physics factor



Spectra computed from *Ref. Cirelli et al., JCAP 1103, page 051*

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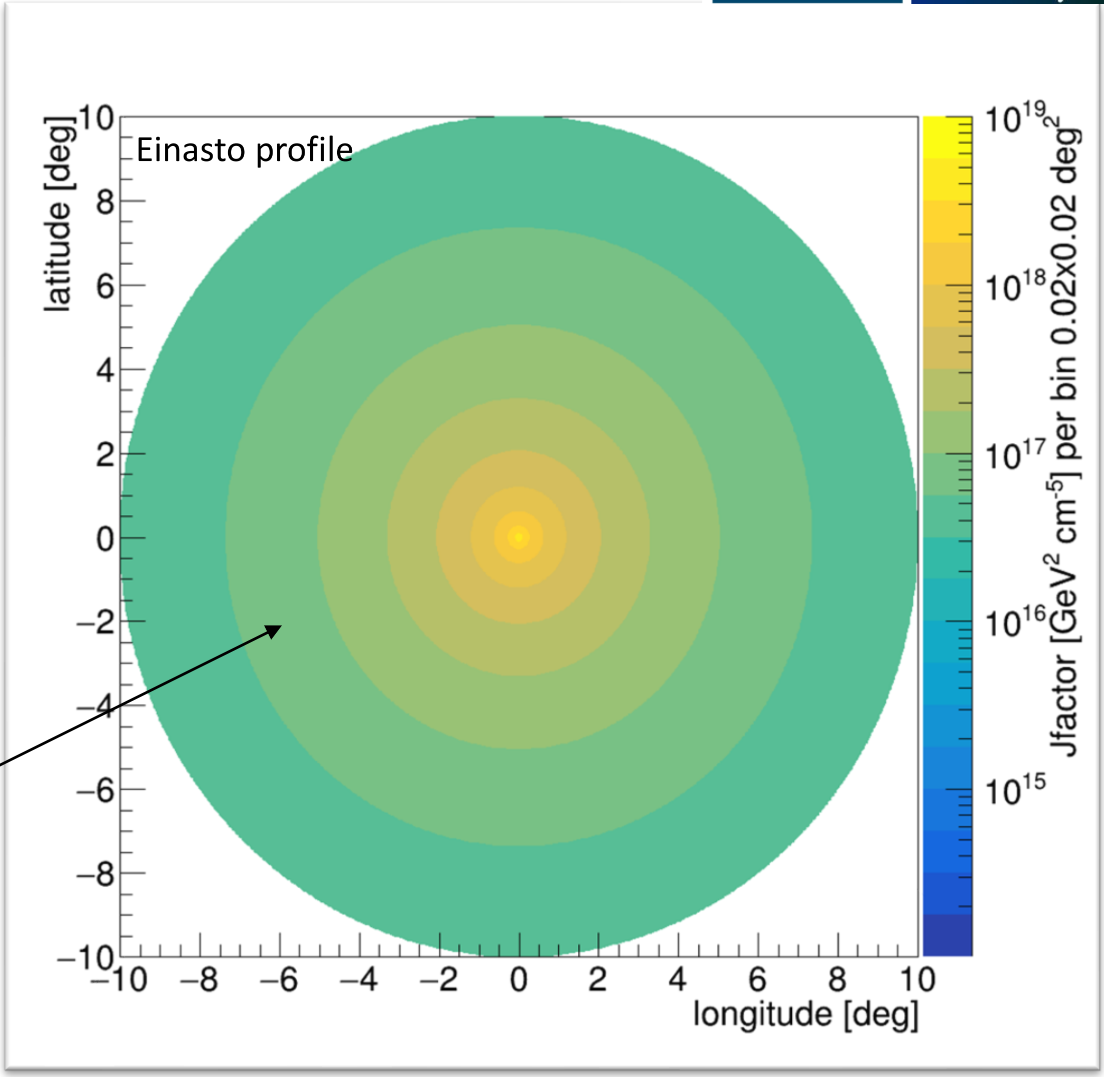
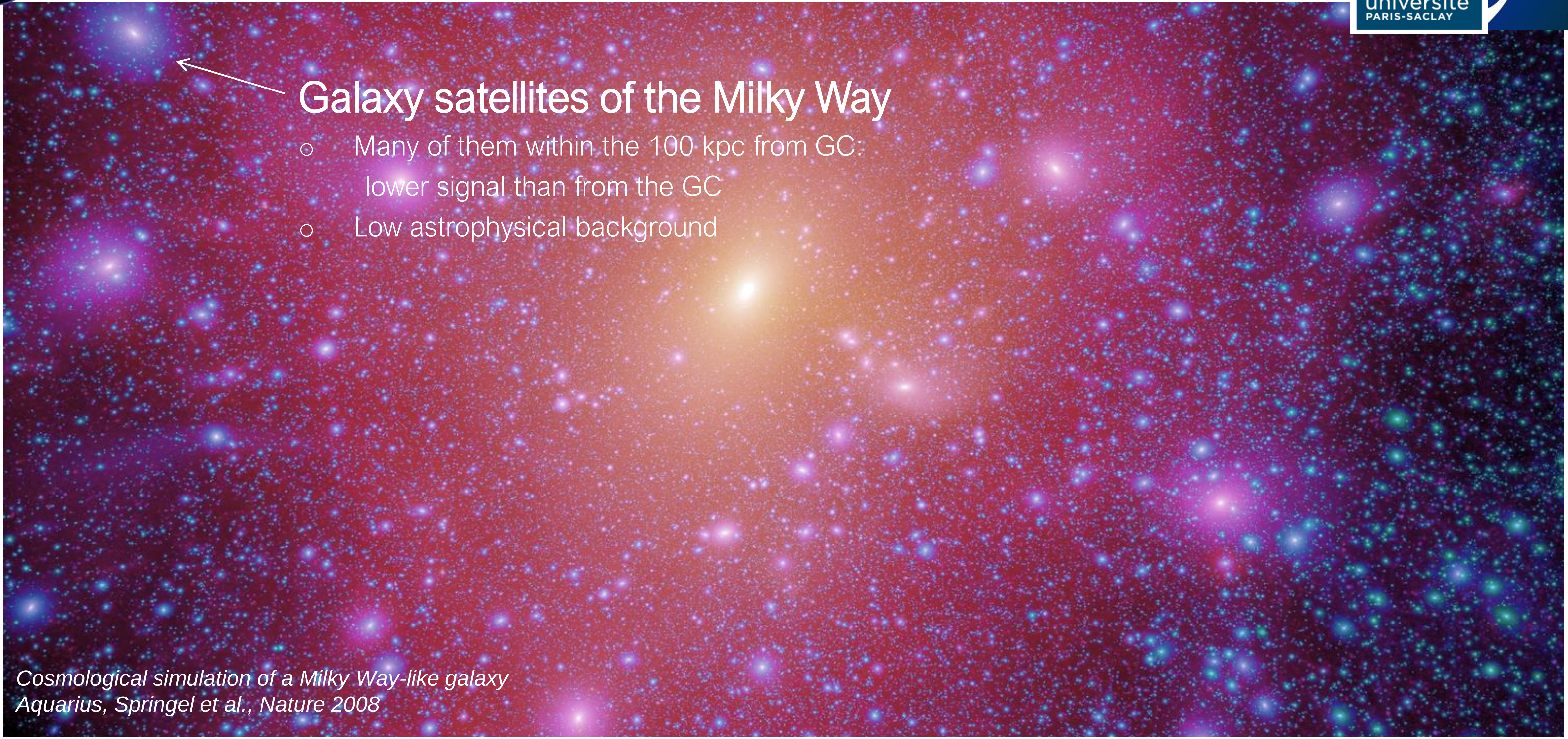
Astrophysical factor $\boldsymbol{J(\Delta\Omega) = \int \rho^2 (r(s,\theta)) ds d\Omega}$:

- Model needed for the density profile;
- Dependence on dark matter halo modeling.



Galaxy satellites of the Milky Way

- Many of them within the 100 kpc from GC: lower signal than from the GC
- Low astrophysical background



Cosmological simulation of a Milky Way-like galaxy
Aquarius, Springel et al., Nature 2008

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Dark Matter subhalos in the Milky Way halo

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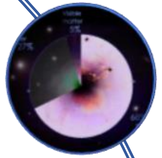
Galactic Centre (GC)

- Proximity (~8kpc)
- Possibly brightest source of DM annihilation signals: DM profile: core? cusp?
- High astrophysical bck / source confusion

Inner Galactic halo

- Large statistics
- Galactic diffuse background

Cosmological simulation of a Milky Way-like galaxy
Aquarius, Springel et al., Nature 2008



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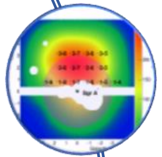
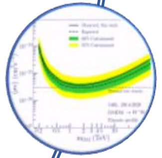


H.E.S.S. Inner Galaxy Survey (IGS)

H.E.S.S. data analysis



Computation of upper limits on $<\sigma v>$

Conclusions

- **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.

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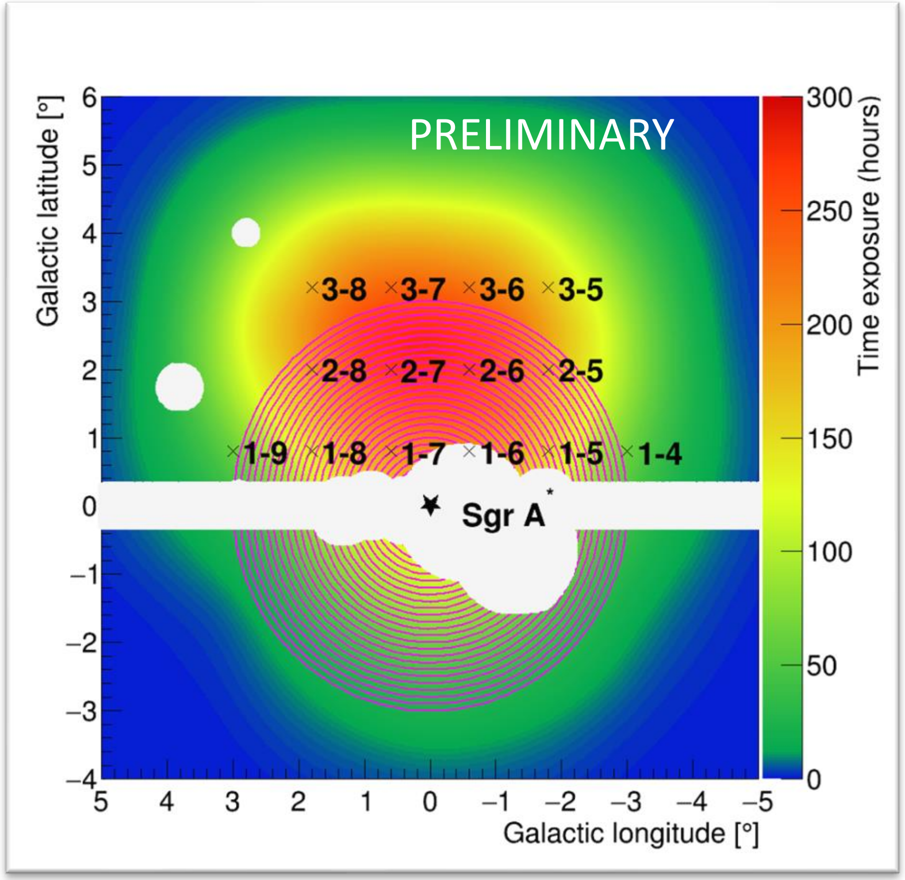
- Dataset: 2014-2020 observations of the GC region with **the full five-telescopes H.E.S.S. array**.

- **2014-2020 exposure map with IGS pointing positions:**
  - Exposure up to b ≈ 6°;
  - Total 546 hours of high-quality data;



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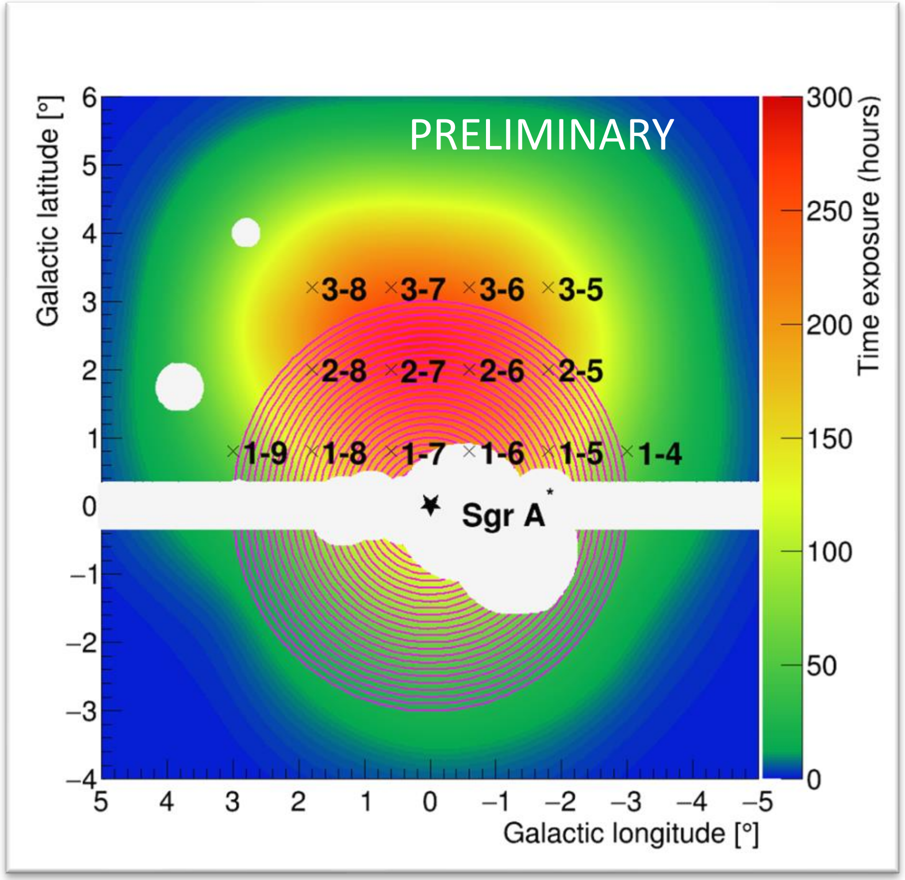
- **2014-2020 exposure map with IGS pointing positions:**
  - Exposure up to b ≈ 6°;
  - Total 546 hours of high-quality data;
  - 25 regions of interest (ROI) defined to search for DM: 0.1°-width open rings;
  - Set of exclusion regions to avoid gamma-ray contamination in the ROIs.



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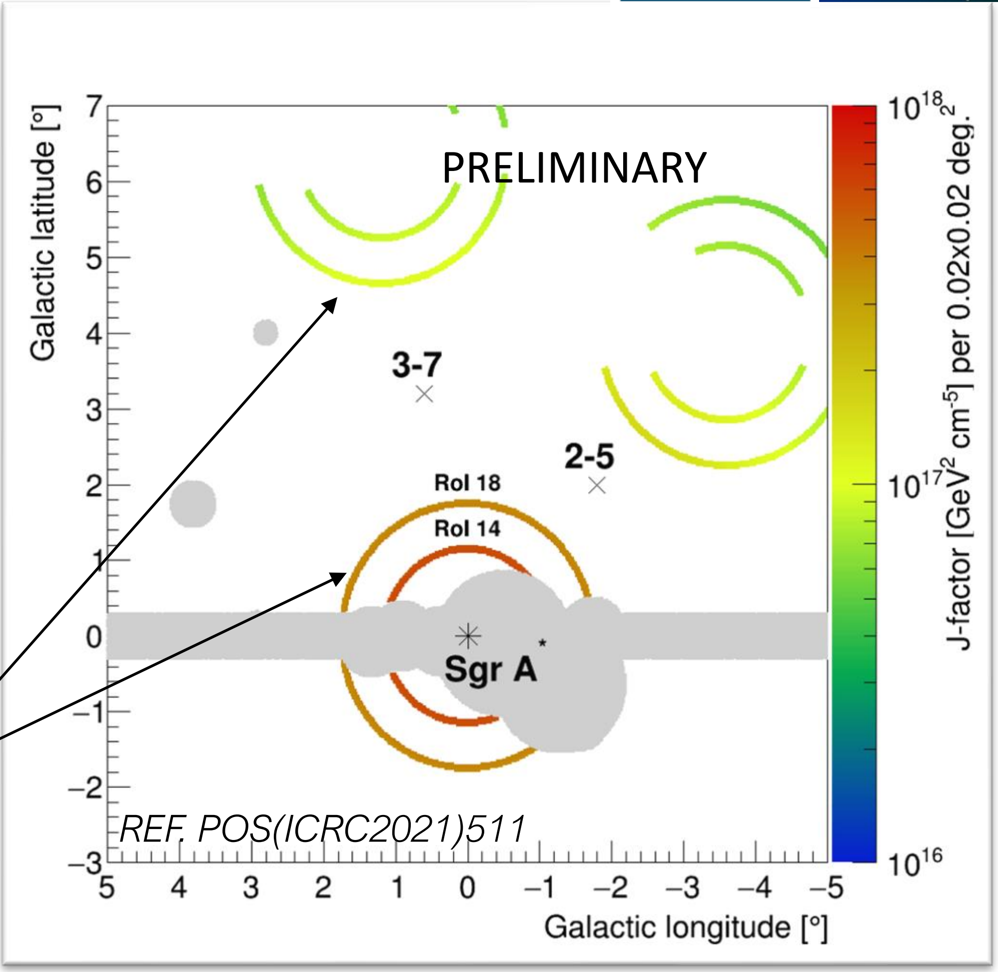
- Definition of the ON region: 25 ROI.
- **Reflected background method:**
  - OFF region:
    - Symmetric to the ON region wrt the pointing position
      - Same FoV and acceptance;
    - The excluded regions are cut symmetrically
      - Same solid angle size;
    - Cut overlapping areas and areas where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

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

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

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

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

- **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 Dark Matter 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., $\beta_{i,j}$.

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

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

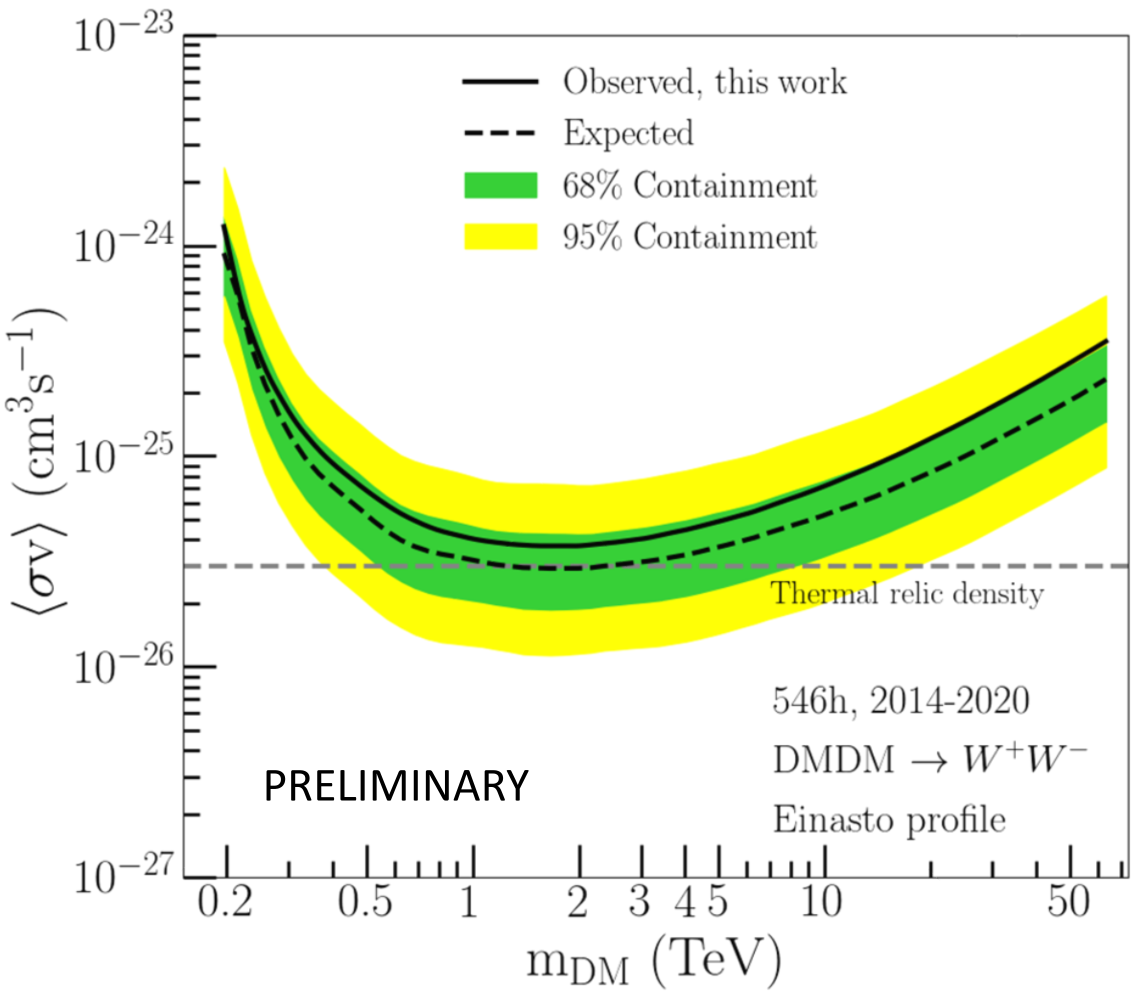
- Total likelihood function: $\mathcal{L} = \prod_{i,j} \mathcal{L}_{i,j}$

- 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.

Computation of upper limits on <σv>

- 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.



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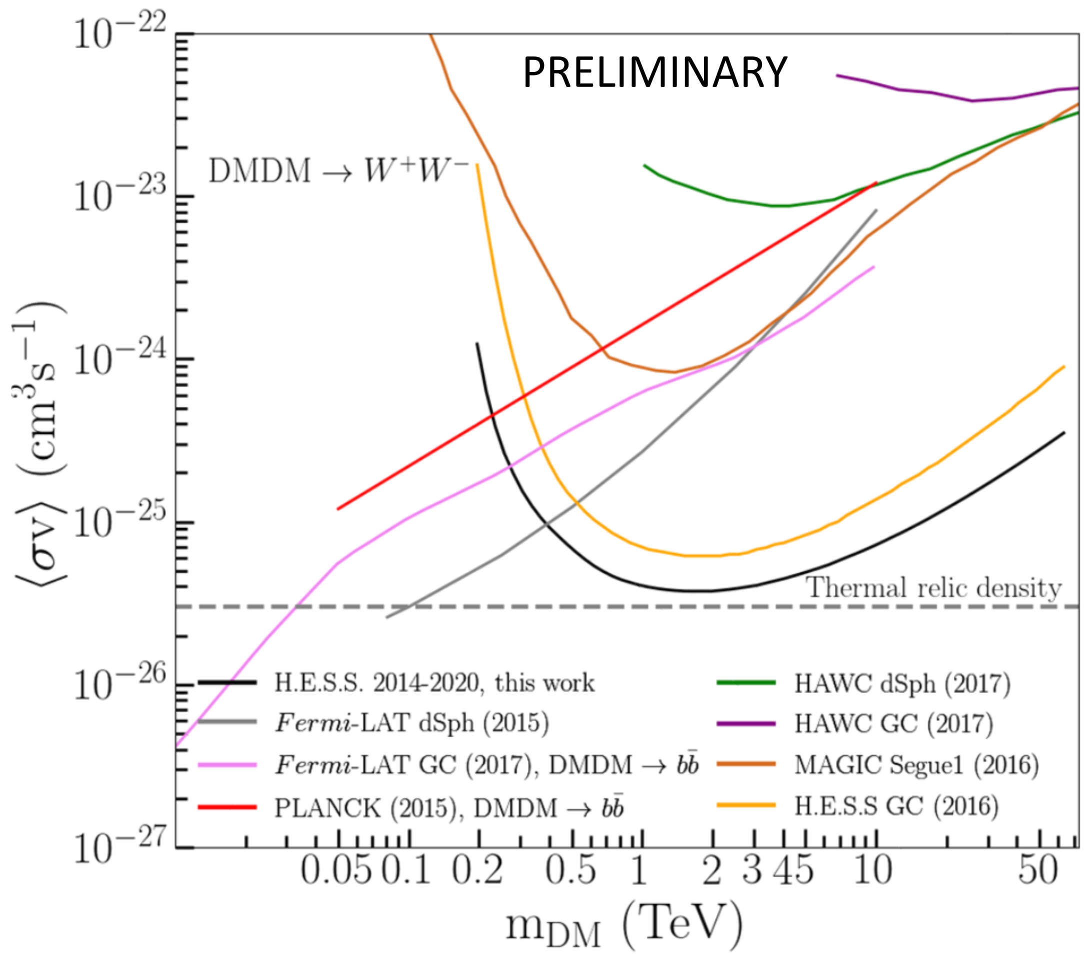
Computation of upper limits on <σv>

- 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.**



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Introduction: WIMPs & Indirect Dark Matter search in gamma rays

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- 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 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 probe 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.**

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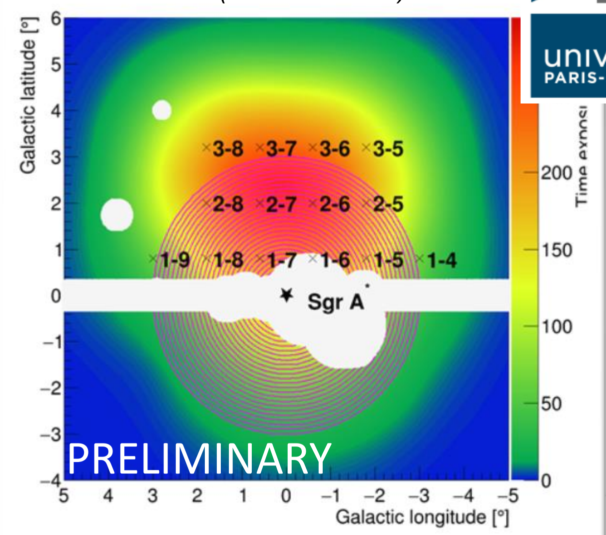

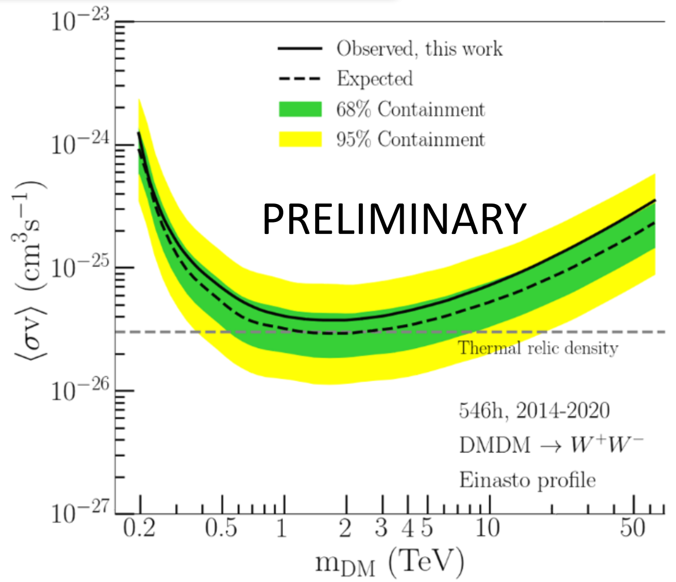

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- H.E.S.S. data analysis
- Computation of upper limits on <σv>
- Conclusions