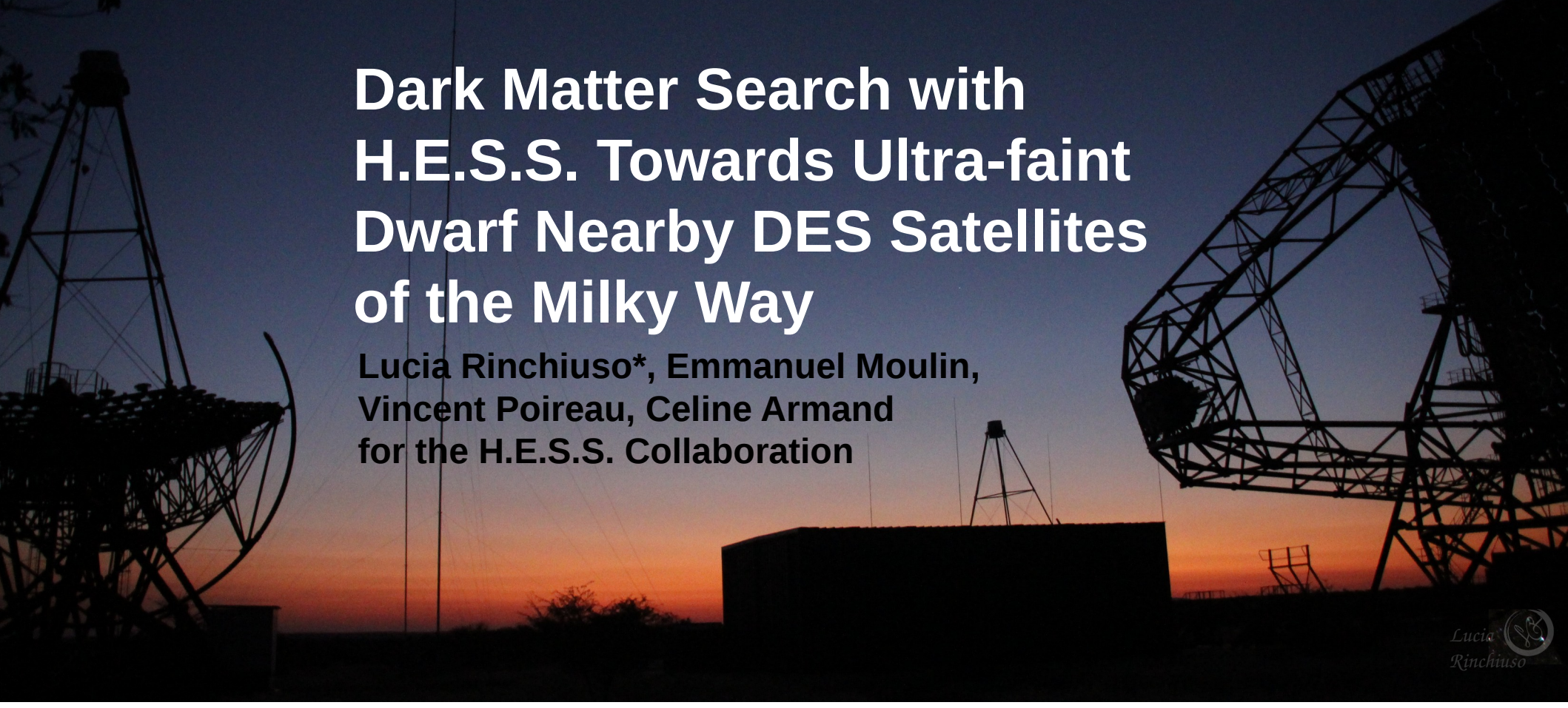


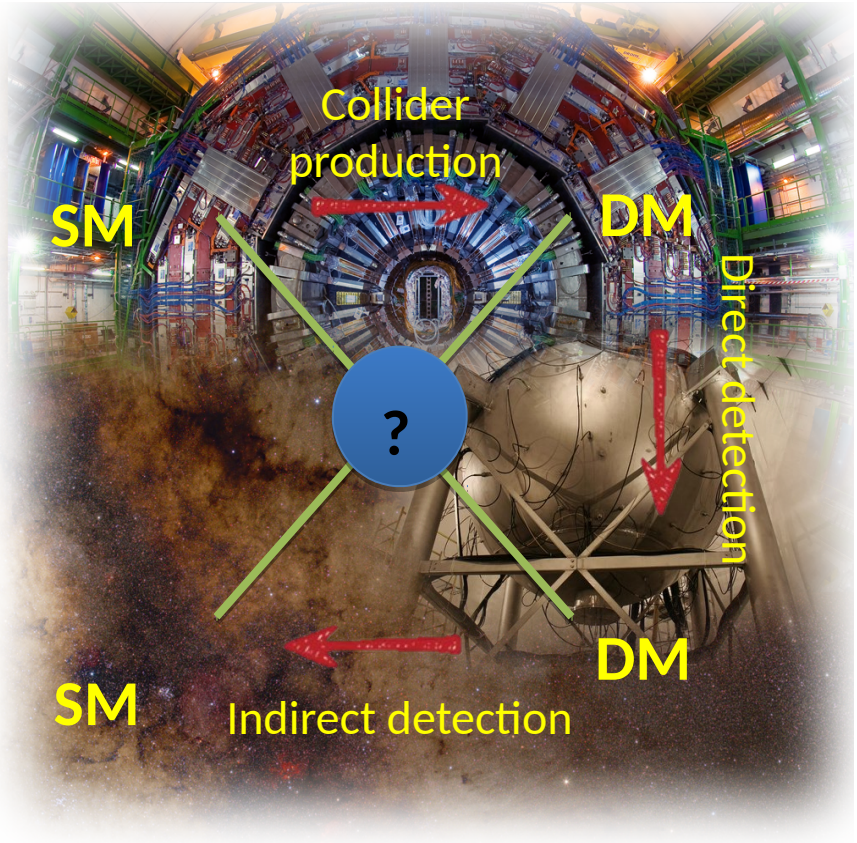
Dark Matter Search with H.E.S.S. Towards Ultra-faint Dwarf Nearby DES Satellites of the Milky Way

Lucia Rinchiuso*, Emmanuel Moulin, Vincent Poireau, Celine Armand for the H.E.S.S. Collaboration

36th International Cosmic Ray Conference
Madison, Wisconsin, US
30th July 2019

Irfu - CEA Saclay
Institut de recherche sur les lois fondamentales de l'Univers

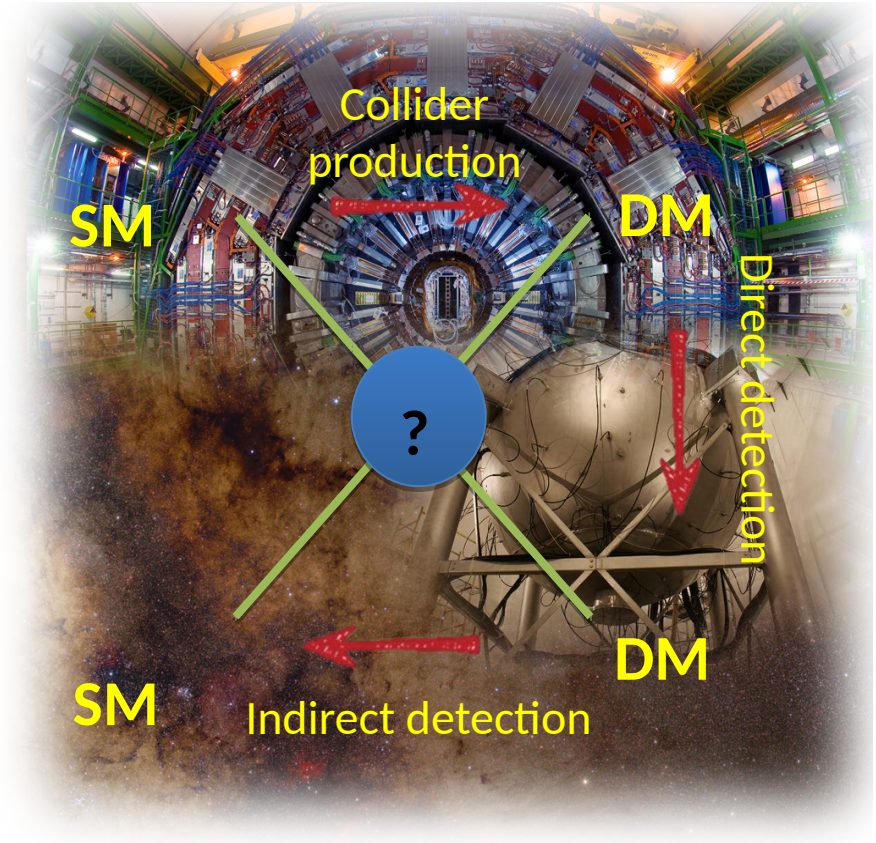
Dark matter search techniques



Complementary techniques for dark matter (DM) searches

- Make it: production at colliders
- Shake it: nuclear recoil in direct detection
- Break it: standard particles from annihilation or decay

Dark matter search techniques



Complementary techniques for dark matter (DM) searches

- Make it: production at colliders
- Shake it: nuclear recoil in direct detection
- Break it: standard particles from annihilation or decay
  → **indirect detection with gamma-ray telescopes**

Dark matter signal in gamma rays

Gamma-ray flux from DM annihilation

$$\frac{\mathrm{d}\phi_\gamma}{\mathrm{d}E}(E,\Delta\Omega) = \underbrace{\frac{1}{4\pi}\frac{\langle\sigma v\rangle}{m_{\mathrm{DM}}^2}\sum_{\mathrm{i}} Br_{\mathrm{i}}\frac{\mathrm{d}N_{\mathrm{i}}}{\mathrm{d}E}(E)}_{particle\,physics} \times \underbrace{J(\Delta\Omega)}_{astrophysics} .$$

Dark matter signal in gamma rays

Gamma-ray flux from DM annihilation

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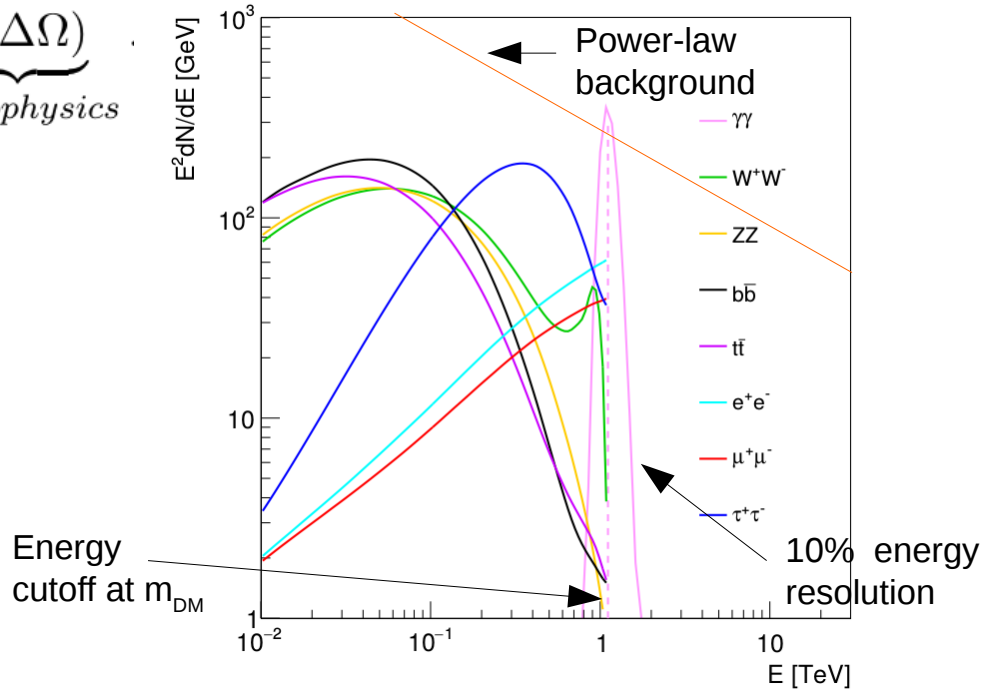
- **Spectral information**
  - Spectral shape
  - Branching ratios
- DM mass m_{DM}
- Annihilation cross section $<\sigma v>$



Dark matter signal in gamma rays

Gamma-ray flux from DM annihilation

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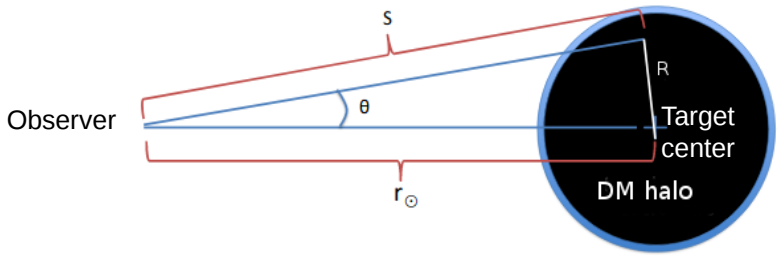
- **Spatial information**
  - It depends on the DM density distribution
  - J-factor

$$J(\Delta\Omega) = \int_{\Delta\Omega}\int_{\mathrm{los}} \rho^2(r(s,\theta))\mathrm{d}s\mathrm{d}\Omega.$$



Dark matter signal in gamma rays

Gamma-ray flux from DM annihilation

$$\frac{\mathrm{d}\phi_\gamma}{\mathrm{d}E}(E,\Delta\Omega) = \underbrace{\frac{1}{4\pi}\frac{\langle\sigma v\rangle}{m_{\mathrm{DM}}^2}\sum_{\mathrm{i}} Br_{\mathrm{i}}\frac{\mathrm{d}N_{\mathrm{i}}}{\mathrm{d}E}(E)}_{particle\,physics} \times \underbrace{J(\Delta\Omega)}_{astrophysics}$$

Choose a target and region of interest
+ choose an annihilation channel and m_{DM}
+ convolve for the IRFs and the observation live time
→ expected gamma-ray count from DM annihilation N_S

Likelihood technique for DM search

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

$$\mathcal{L}_{\mathrm{i,j}}(\boldsymbol{N_S}, \boldsymbol{N_B} | \boldsymbol{N_{ON}}, \boldsymbol{N_{OFF}}, \boldsymbol{\alpha}) = \frac{(N_{\mathrm{S,i,j}} + N_{\mathrm{B,i,j}})^{N_{\mathrm{ON,i,j}}}}{N_{\mathrm{ON,i,j}}!} e^{-(N_{\mathrm{S,i,j}} + N_{\mathrm{B,i,j}})} \frac{(\alpha_{\mathrm{j}} N_{\mathrm{B,i,j}})^{N_{\mathrm{OFF,i,j}}}}{N_{\mathrm{OFF,i,j}}!} e^{-(\alpha_{\mathrm{j}} N_{\mathrm{B,i,j}})}$$

Likelihood technique for DM search

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

Expected DM signal in the ON region (signal region)

Expected background in the ON region

$$\mathcal{L}_{i,j}(\boldsymbol{N_S}, \boldsymbol{N_B} | \boldsymbol{N_{ON}}, \boldsymbol{N_{OFF}}, \boldsymbol{\alpha}) = \frac{(N_{S,i,j} + N_{B,i,j})^{N_{ON,i,j}}}{N_{ON,i,j}!} e^{-(N_{S,i,j}+N_{B,i,j})} \frac{(\alpha_j N_{B,i,j})^{N_{OFF,i,j}}}{N_{OFF,i,j}!} e^{-(\alpha_j N_{B,i,j})}$$

Measured counts in the ON region

Ratio between the size of the OFF and ON regions

Measured counts in the OFF region (control region)

Likelihood technique for DM search

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

$$\mathcal{L}_{\mathrm{i,j}}(\boldsymbol{N_S}, \boldsymbol{N_B} | \boldsymbol{N_{ON}}, \boldsymbol{N_{OFF}}, \boldsymbol{\alpha}) = \frac{(N_{\mathrm{S,i,j}} + N_{\mathrm{B,i,j}})^{N_{\mathrm{ON,i,j}}}}{N_{\mathrm{ON,i,j}}!} e^{-(N_{\mathrm{S,i,j}}+N_{\mathrm{B,i,j}})} \frac{(\alpha_{\mathrm{j}} N_{\mathrm{B,i,j}})^{N_{\mathrm{OFF,i,j}}}}{N_{\mathrm{OFF,i,j}}!} e^{-(\alpha_{\mathrm{j}} N_{\mathrm{B,i,j}})}$$

- **Total likelihood** over the bins:

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

- Can be combined over many targets or data sets

$$\mathcal{L}_{\mathrm{tot}} = \prod_{k=1}^{n_{\mathrm{targets}}} \mathcal{L}_{\mathrm{k}}.$$

Likelihood technique for DM search

- **2D-Poisson likelihood** exploits spatial and spectral DM features: bins in energy (i) and space (j)
- **Total likelihood** over the bins
- Can be combined over many targets or data sets
- In absence of any significant excess in the ON region:
  - 95% C.L. upper limits on the free parameter $\langle\sigma v\rangle$ are set using a **log-likelihood ratio test statistics**
- Computation of **expected limits and containment bands**
  - Poisson realizations of the measurements → mean and std dev of the distribution of the obtained $\log_{10}\langle\sigma v\rangle$ values

Targets for dark matter search in VHE γ-rays

Best targets: large DM signal + low VHE background

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Targets for dark matter search in VHE γ-rays

Best targets: large DM signal + low VHE background

Galactic Center (GC)

- Nearby (~8.5 kpc)
- Largest DM content
  → $\log_{10}J_{tot}$~21-22
- VHE astrophysical background

Dwarf galaxies of the Local Group

- DM dominated
- Further (20-100 kpc)
  → $\log_{10}J_{tot}$~18-19
- No VHE background

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Targets for dark matter search in VHE γ-rays

Best targets: large DM signal + low VHE background

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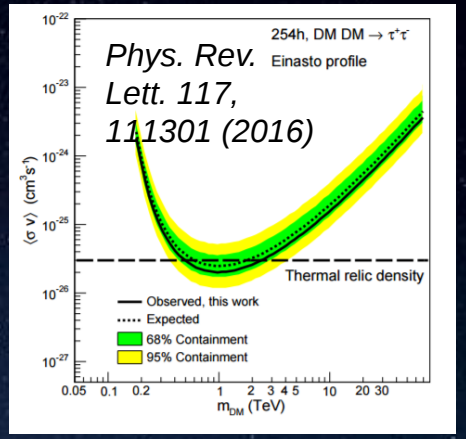

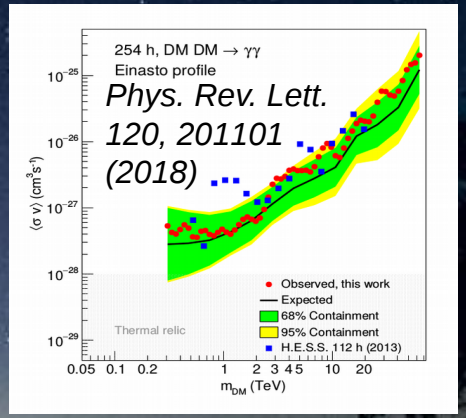

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Targets for dark matter search in VHE γ-rays

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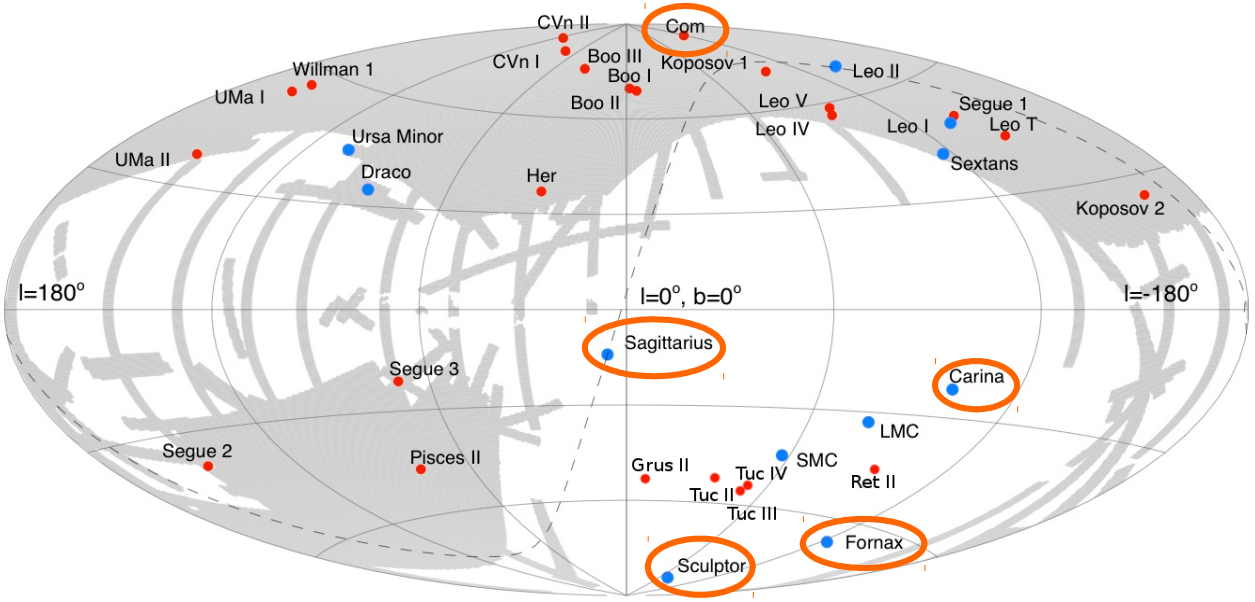
Dwarf galaxy observations with H.E.S.S.

Long-term observation program on nearby dwarf galaxies:
Combination (including Coma Berenices): Phys. Rev. D 90, 112012 (2014)



Previous H.E.S.S. observations on
- 4 classical dSphs
- The ultra-faint dSph Coma Berenices

H.E.S.S.

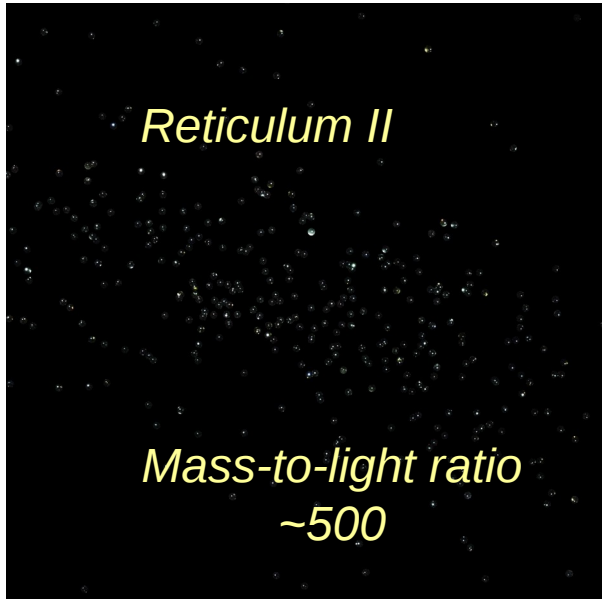
DES dwarf galaxies of the Local Group

Recently discovered by the Dark Energy Survey (DES)

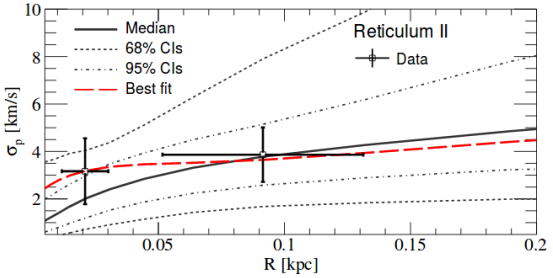
Ultra-faint

Best observed from the Southern hemisphere

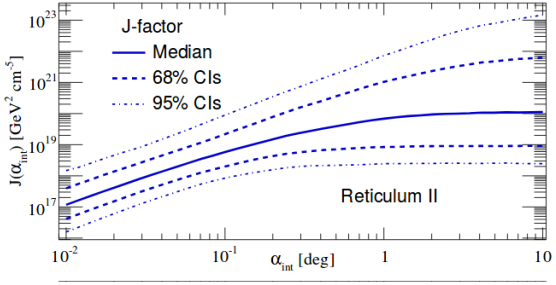
From: DES Collab., Astrophys. J. 813 (2015) no.2, 109



From velocity dispersion



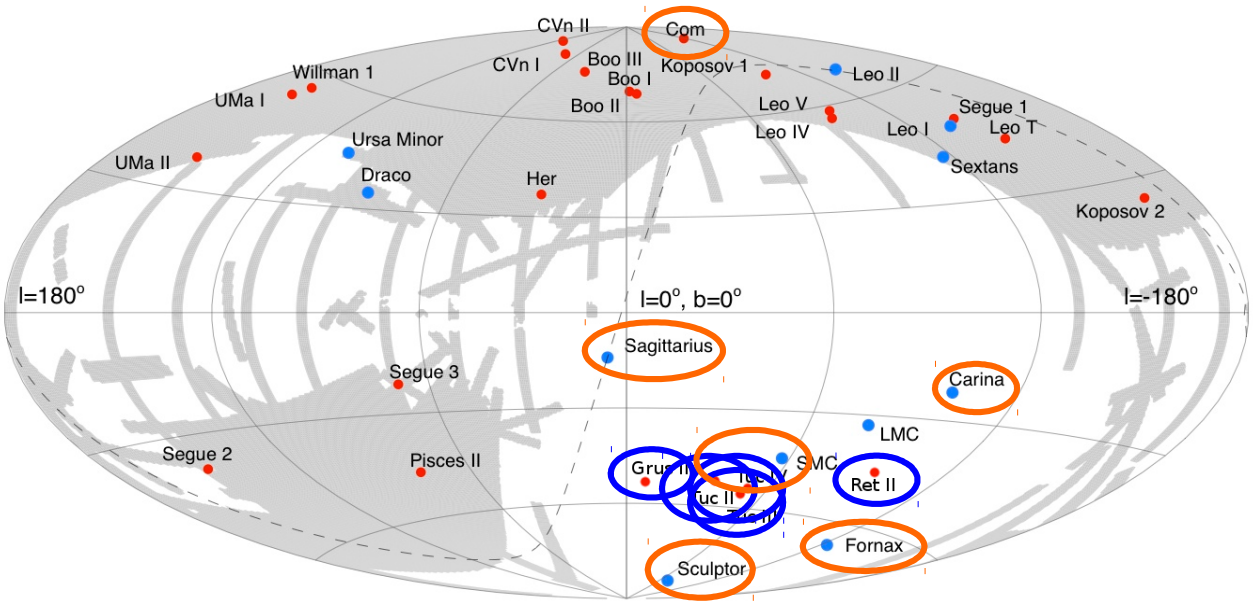
➔ Expected large J



Promising targets for DM unambiguous detection

DES dwarf galaxies observations with H.E.S.S.

H.E.S.S. selection of recently-detected Milky Way ultra-faint satellites by DES



New

- Coordination of the 2017-2018 observation proposals
- Most promising targets: $\log_{10}J(0.5^{o})\sim19$
- ~80 hours of observation in total

H.E.S.S.

DES dwarf galaxies observations with H.E.S.S.

H.E.S.S. selection of recently-detected Milky Way ultra-faint satellites by DES: observations with H.E.S.S. II

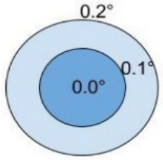
Galaxy	**Distance** (kpc)	**$Log_{10}J(0.5)$** $\log_{10}(GeV^2cm^{-5})$	**T_{obs}** (h)
Reticulum II	32	19.6	17
Tucana II	58	18.7	17
Tucana III	25	19.4	25
Tucana IV	48	18.7	12
Grus II	53	18.7	13

- Coordination of the 2017-2018 observation proposals
- Most promising targets: $\log_{10}J(0.5°)$~19
- ~80 hours of observation in total

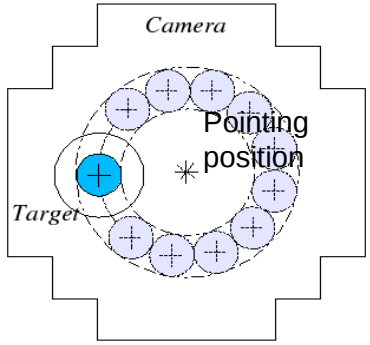
DM search towards DES dwarf galaxies

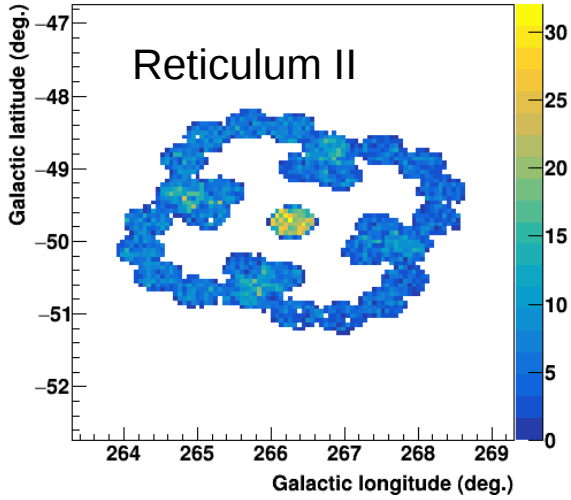
- Definition of **signal and control regions** for dark matter search

Signal region:
Multi-ROI



Background regions:
Multiple OFF

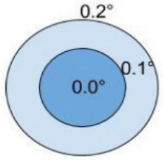




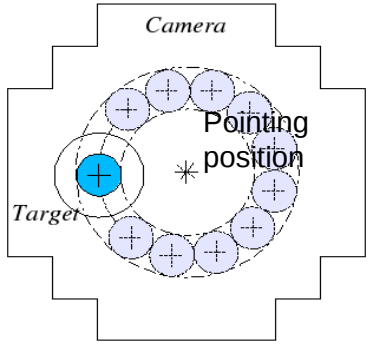
DM search towards DES dwarf galaxies

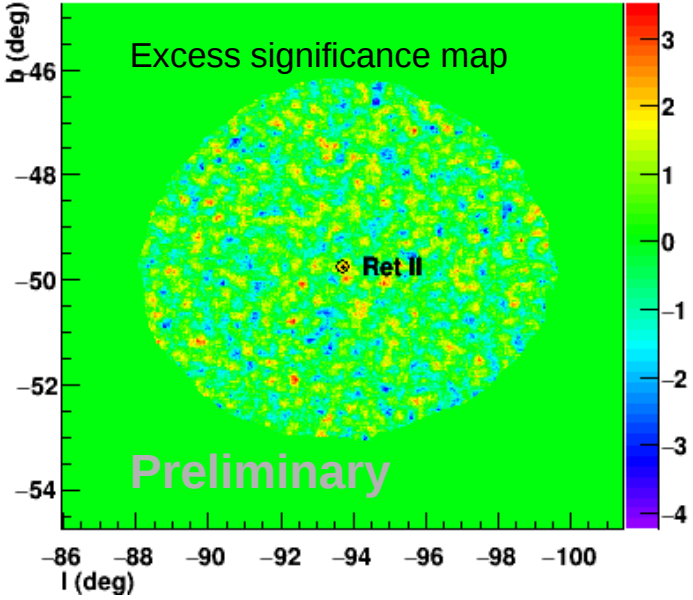
- Definition of **signal and control regions** for dark matter search
- **No significant excess** in any dSphs →95% C.L. **upper limits on <σv>** as function of m_{DM}

Signal region:
Multi-ROI



Background regions:
Multiple OFF



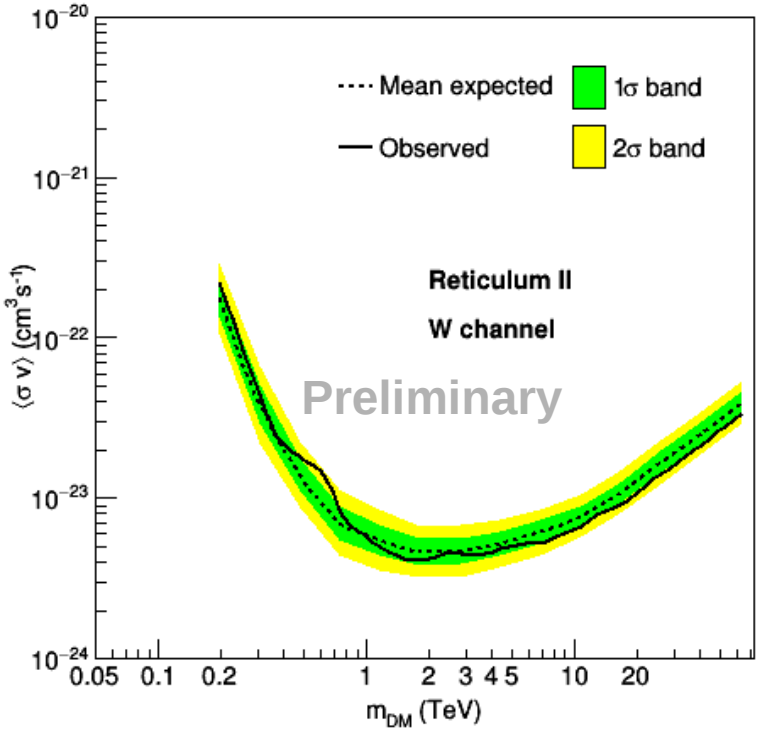


DM search towards DES galaxies: Reticulum II

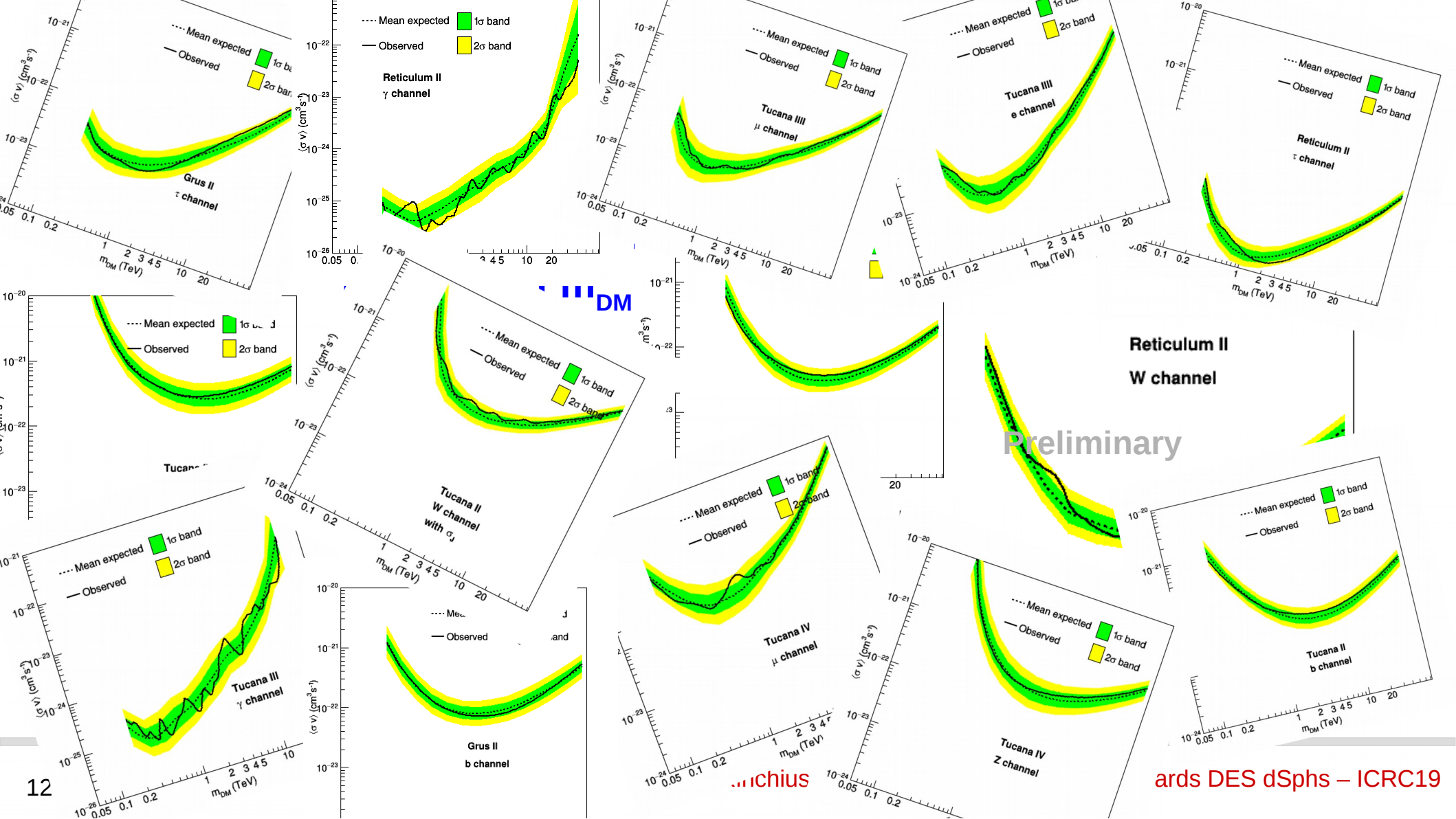
- **No significant excess** in any dSphs → 95% C.L. **upper limits on <σv> as function of m_{DM}**

- 5 targets and 8 annihilation channels considered
  - **RetII: ~5x10^{-24} cm^{3}s^{-1} in W$^+$W$^-$ channel at 1 TeV**

H.E.S.S. Collaboration, Search for dark matter signals towards the recently detected DES dwarf galaxy satellites of the Milky Way with H.E.S.S., in preparation

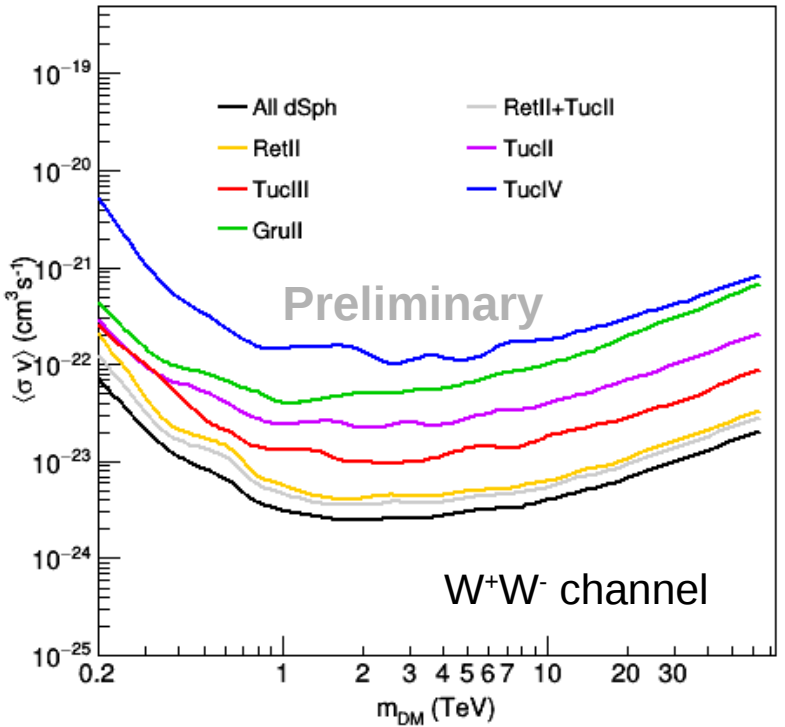


H.E.S.S.


Mean expected
Observed
1σ band
2σ band
Grus II
τ channel
Reticulum II
γ channel
Tucana IIII
μ channel
Tucana IIII
e channel
Reticulum II
τ channel
DM
Reticulum II
W channel
Preliminary
Tucana II
W channel
with σ_J
Tucana III
γ channel
Grus II
b channel
Tucana IV
μ channel
Tucana IV
Z channel
Tucana II
b channel
m_DM (TeV)
⟨σ v⟩ (cm³s⁻¹)

Combined DM search towards DES galaxies

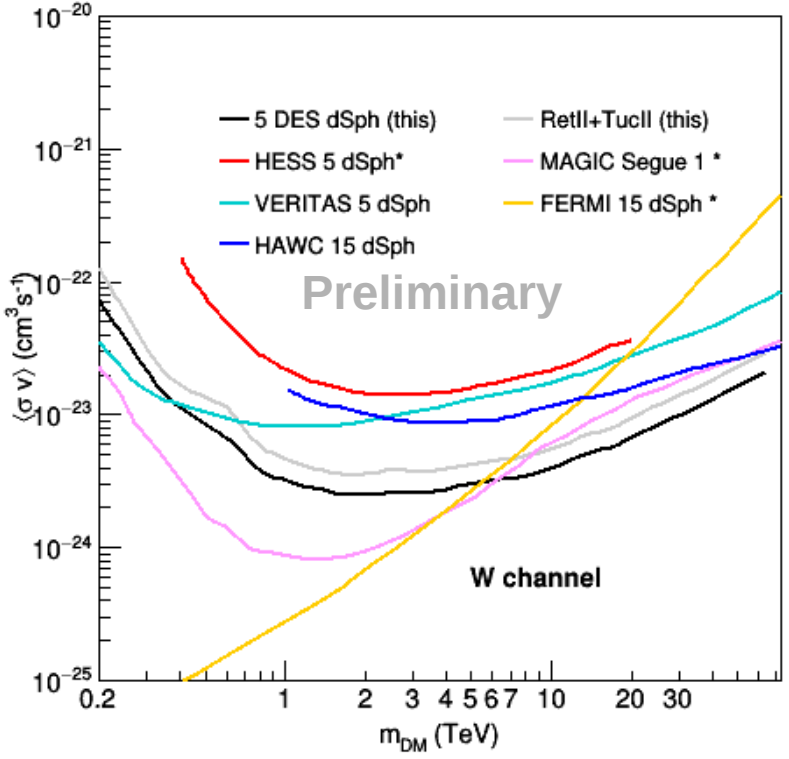
- Most stringent limits for RetII, followed by TucIII
- **Combination of the targets** at the likelihood level $\mathcal{L}_{\rm tot} = \prod_{k=1}^{n_{\rm targets}} \mathcal{L}_{\rm k}.$
- ➔ **At 1 TeV: 3x10^{-24} cm^{3}s^{-1} in W$^+$W$^-$ channel**



H.E.S.S. Collaboration, Search for dark matter signals towards the recently detected DES dwarf galaxy satellites of the Milky Way with H.E.S.S., in preparation

Combined DM search towards DES galaxies

- Most stringent limits for RetII, followed by TucIII
- **Combination of the targets** at the likelihood level $\mathcal{L}_{\rm tot} = \prod_{k=1}^{n_{\rm targets}} \mathcal{L}_{\rm k}.$
- ➔ **Most stringent constraints above 6 TeV in W^+W^-**



H.E.S.S. Collaboration, Search for dark matter signals towards the recently detected DES dwarf galaxy satellites of the Milky Way with H.E.S.S., in preparation

Summary

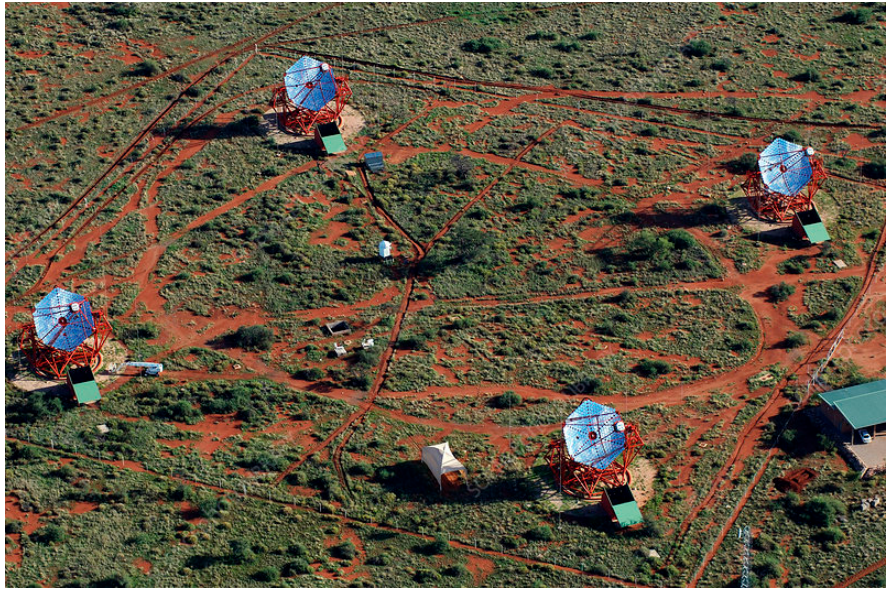
- Observation of a selection of **5 DES dwarf spheroidal galaxies** of the Local Group
- **No significant** gamma-ray **excess**
- 95% C.L. upper limits derived with a **2D-likelihood ratio test statistics**
  - Most promising target Reticulum II
  - Constraints down to ~5×10^{-24} cm^3s^{-1} in W^+W^- channel at 1 TeV
- **Combination of targets datasets at the likelihood level**
  - ➔ Combined limits down to ~3×10^{-24} cm^3s^{-1} in the W^+W^- annihilation channel at 1 TeV
  - ➔ **Constraints complementary to other experiments**
  - ➔ Most stringent limits so far above several TeV

Thanks

The H.E.S.S. experiment

Array of 5 Imaging Atmospheric Cherenkov Telescopes located in Namibia (at 1800 m a.s.l)

- **H.E.S.S. I** (since 2003)
  - 4 telescopes (Ø 12 m)
  - Energy range 100 GeV-100 TeV
  - Energy resolution ~10%
  - Angular resolution < 0.1 deg
  - FoV 5 deg



The H.E.S.S. experiment

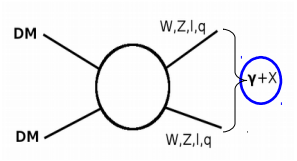
Array of 5 Imaging Atmospheric Cherenkov Telescopes located in Namibia (at 1800 m a.s.l)

- **H.E.S.S. II** (since 2012)
  - Additional 5th larger telescope (Ø 28m)
    - ➔ Lower energy threshold
  - FoV of CT5: 3.5 deg
  - CT1-4 cameras upgraded

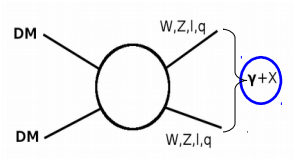
H.E.S.S. in numbers:

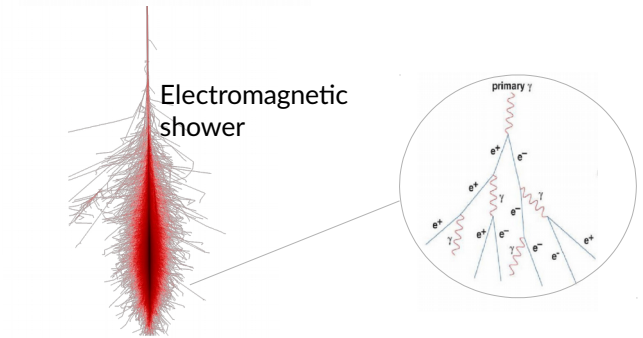
13 countries, 39 Institutions, ~230 people, 15 years of operation

Indirect DM search: signal



Indirect DM search: signal





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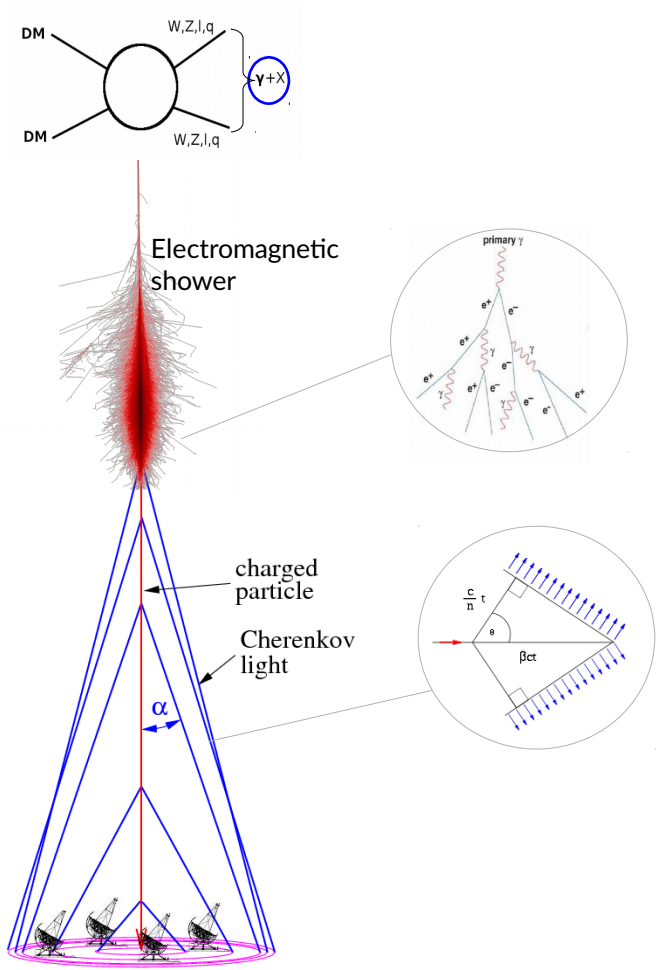
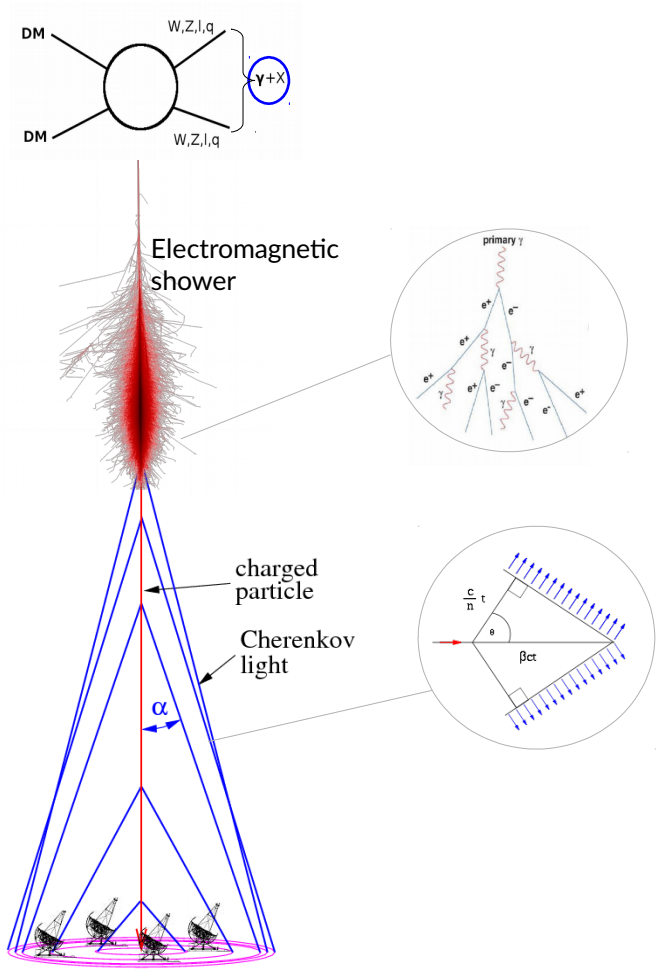
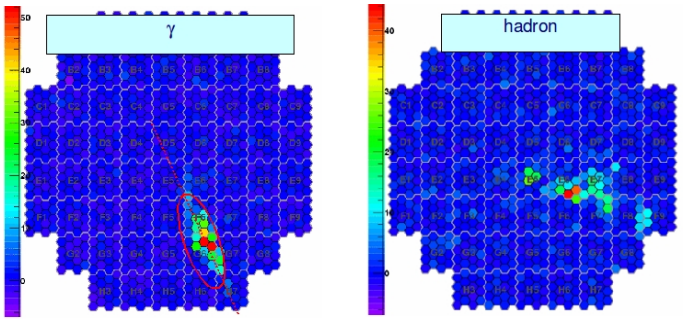
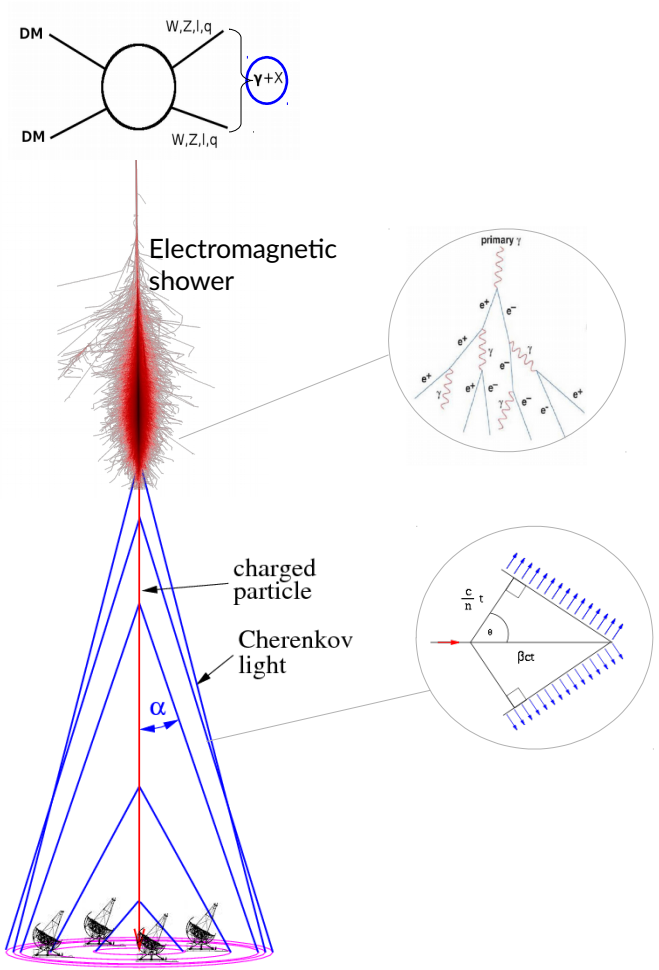


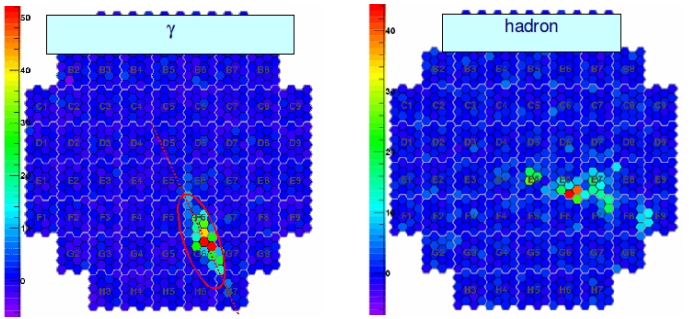
Indirect DM search: signal and background

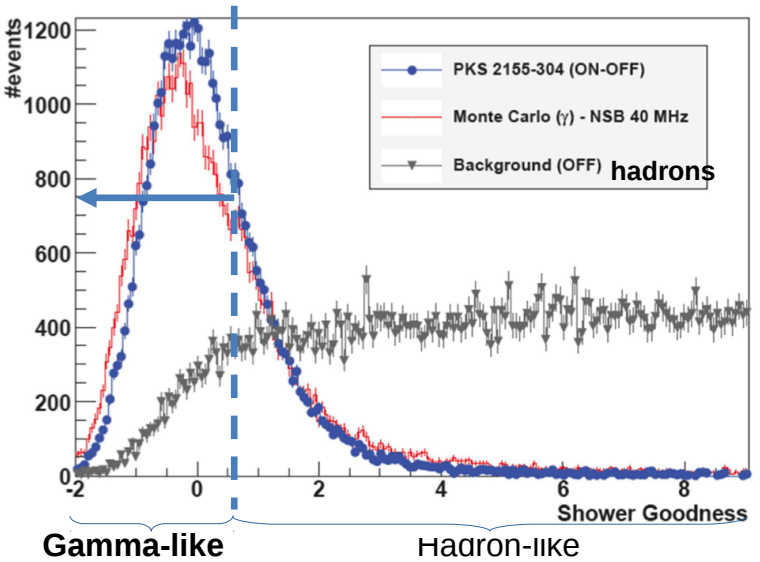




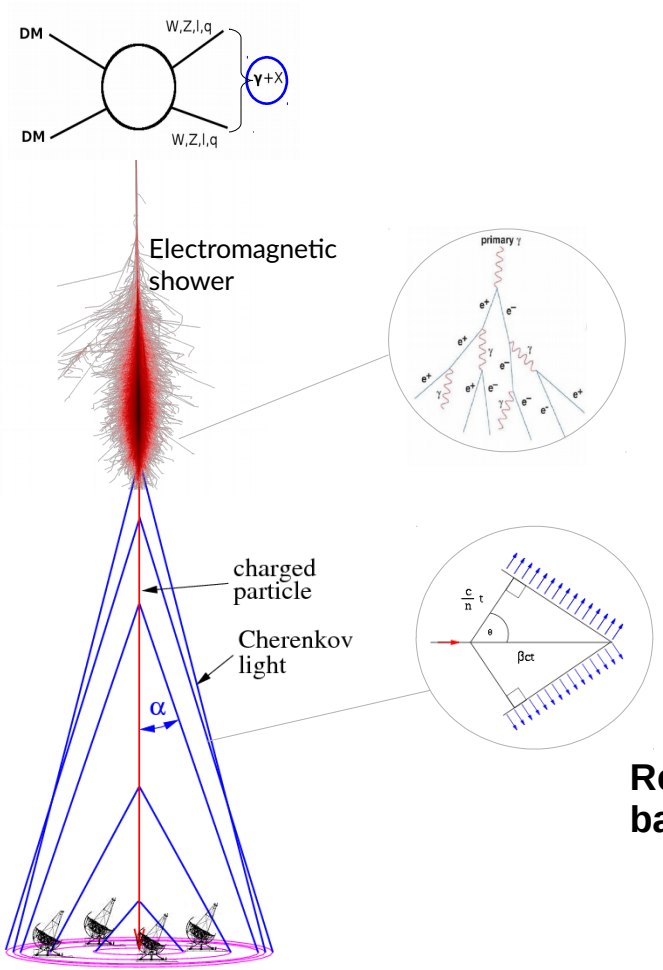
Indirect DM search: signal and background

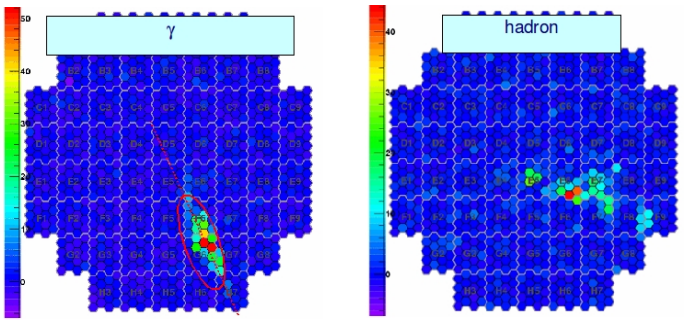


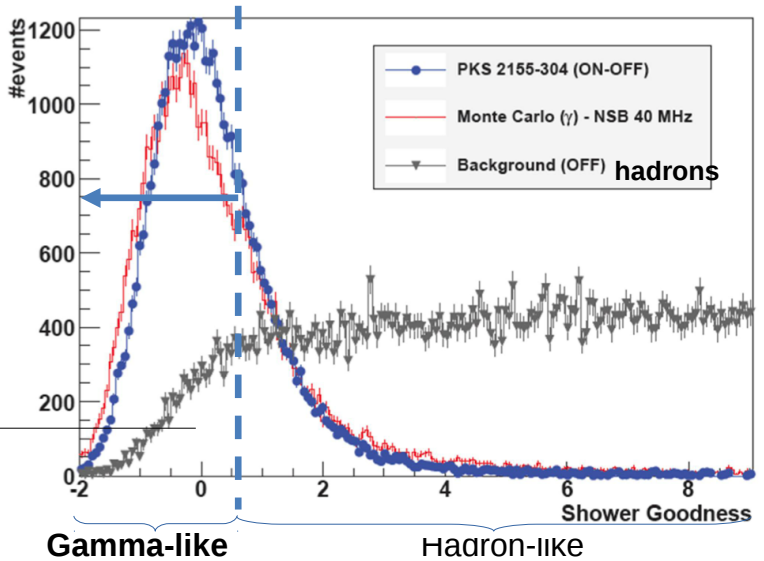




Indirect DM search: signal and background







DES dSphs DM density profile

Stars as tracers of DM → spectroscopy + Jean's eq → J-factor measure

$$\frac{1}{\nu}\frac{\mathrm{d}}{\mathrm{d}r}(\nu\bar{v}_r^2) + 2\frac{\beta(r)\bar{v}_r^2}{r} = -\frac{GM(r)}{r^2}$$

Spectroscopy measurement AVAILABLE

Tucana II and Reticulum II

Distribution of J-factor vs θ are available

→ Consider more RoIs

NO spectroscopy measurement

Tucana III, Tucana IV and Grus II

Use upper value for the predicted J-factor: approximated formula

→ Consider point-like sources

DES dSphs DM density profile

Stars as tracers of DM → spectroscopy + Jean's eq → J-factor measure

$$\frac{1}{\nu}\frac{\mathrm{d}}{\mathrm{d}r}(\nu\bar{v}_r^2) + 2\frac{\beta(r)\bar{v}_r^2}{r} = -\frac{GM(r)}{r^2}$$

Spectroscopy measurement AVAILABLE

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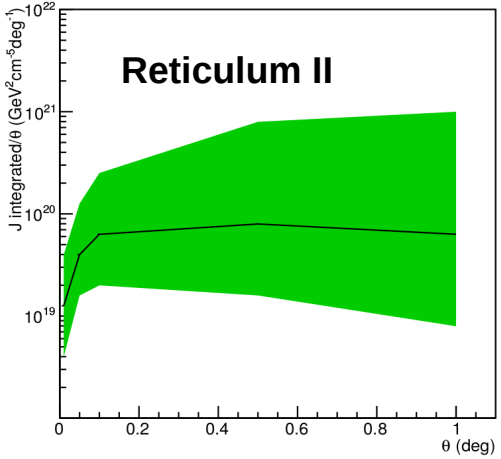
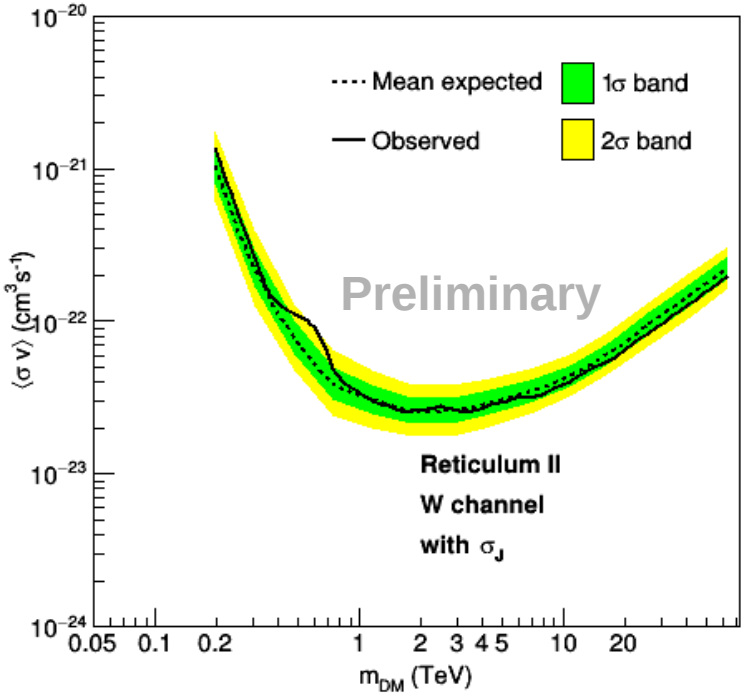


Derived from: Bonnivard et al., Astrophys.J. 808 (2015) no.2, L36

DM search towards DES galaxies: Reticulum II

- **Uncertainty on the J-factor** introduced as a nuisance parameter in the likelihood function
  - **Degradation of the limits** due to J-factor statistical uncertainty
  - Factor 6 for Reticulum II

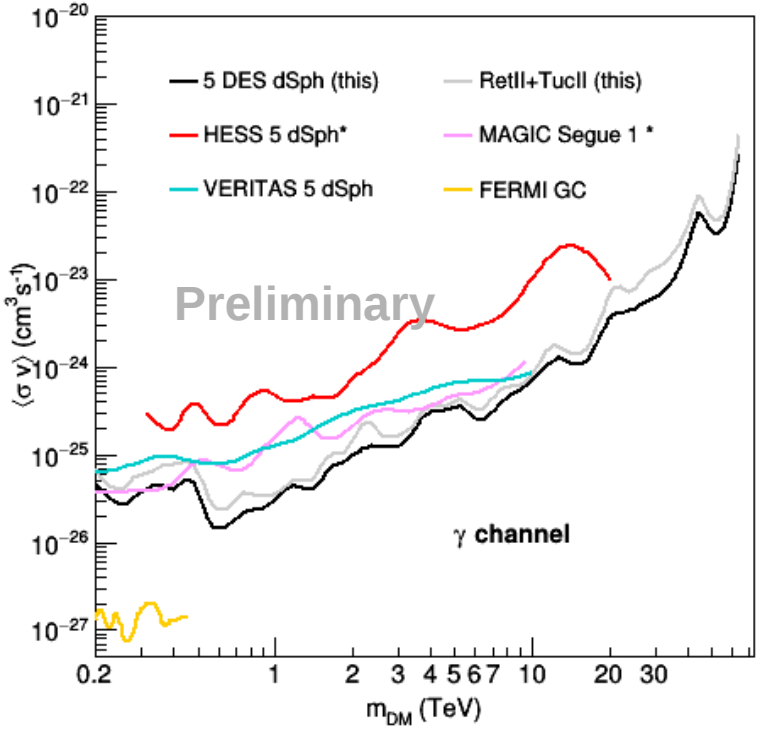


H.E.S.S. Collaboration, Search for dark matter signals towards the recently detected DES dwarf galaxy satellites of the Milky Way with H.E.S.S., in preparation

Combined DM search towards DES galaxies

- Most stringent limits for RetII, followed by TucIII
- **Combination of the targets** at the likelihood level

➔ **Most stringent constraints above 500 GeV in ϒ**



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