Dark matter line searches towards the Galactic Center halo with H.E.S.S.

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H.E.S.S.

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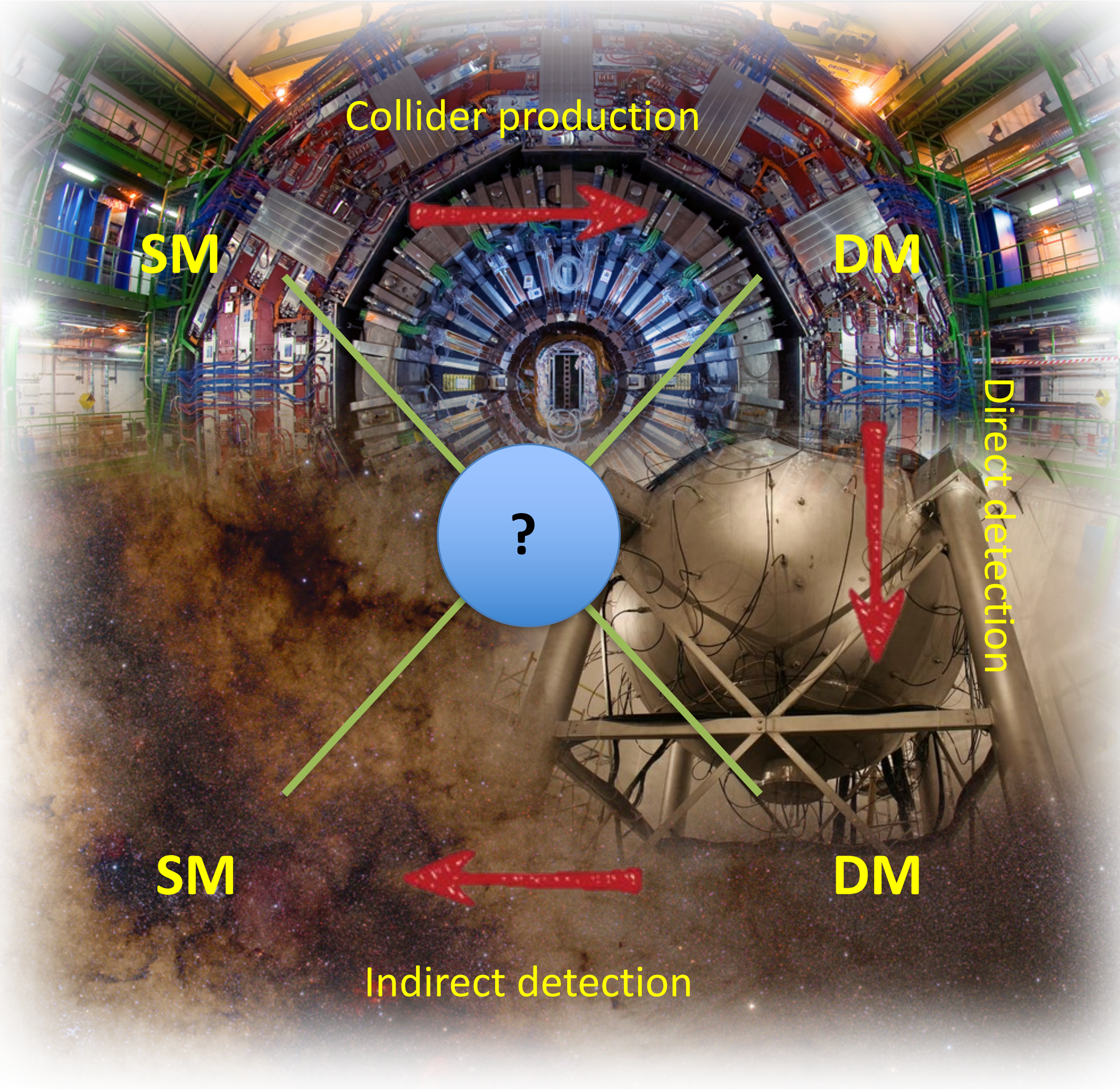
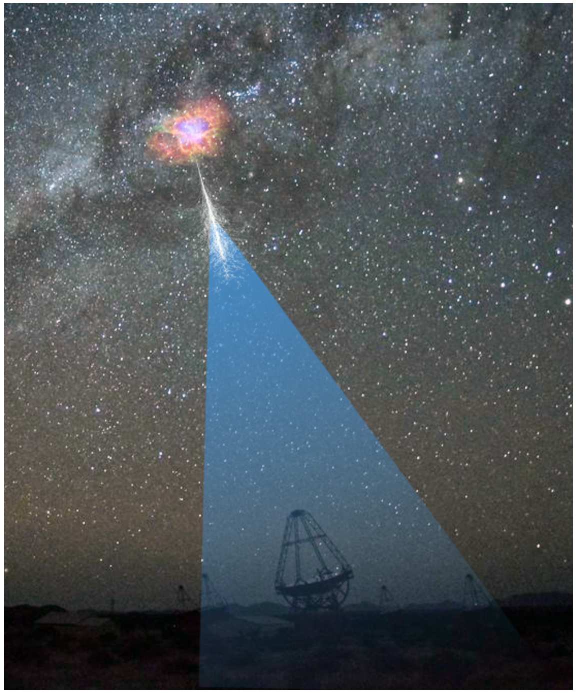
Dark matter detection



Why gamma-rays ?

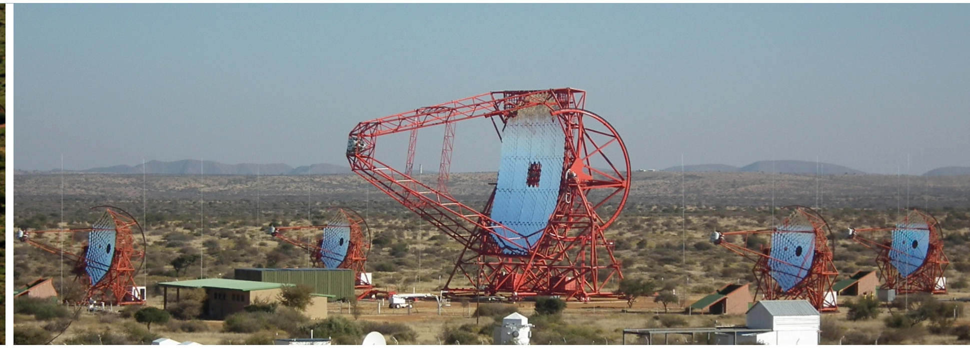
- Exploit the annihilation of the dark matter (DM) into Standard Model (SM) particles, which are detectable
- DM properties can be inferred from DM annihilation products
- Gamma-rays are not bent in magnetic fields, so they point back to the source
- Through gamma-rays detection from DM annihilation, in principle, the DM distribution in the universe can be mapped



- The environment with highest expected DM content can be pointed with the telescopes
- The most promising candidates for DM particles (WIMPs) most likely lie in the mass range GeV-TeV, probed by very-high-energy (VHE) gamma-rays detectors

The H.E.S.S. experiment

An array of 5 Imaging Atmospheric Cherenkov Telescopes in Namibia



- **H.E.S.S. phase I (since 2003)**
  - four 12 m Ø telescopes
  - FoV 5 deg
  - energy range 100 GeV-100 TeV
  - angular resolution < 0.1 deg
  - about 1000 observation h/yr
  - stereoscopic reconstruction
- **H.E.S.S. phase II (since 2012)**
  - same four 12 m Ø telescopes
  - one additional 28 m Ø telescope (FoV 3.5 deg)
  - energy threshold lowered
  - angular resolution from 0.4 deg to less than 0.1 deg

H.E.S.S. phase I → H.E.S.S. phase II

Dark matter annihilation signal

$$\frac{d\Phi(\Delta\Omega)}{dE} = \frac{d\Phi^{pp}}{dE} \times J(\Delta\Omega)$$

$$\frac{d\Phi^{pp}}{dE} = \frac{1}{4\pi}\frac{\langle\sigma v\rangle}{2{m_{DM}}^2}\sum_{i=1}^{n} Br_i \frac{dN_i}{dE'}$$

Particle physics term:

- thermally-averaged velocity-weighted annihilation cross section $\langle\boldsymbol{\sigma}\mathbf{v}\rangle$
- dark matter mass $\mathbf{m_{DM}}$
- Flux: sum of the channels weighted on their branching ratio
- annihilation spectrum $\mathbf{dN/dE'}$

Astrophysics term:
J-factor

$$\mathbf{J(\Delta\Omega)} = \int_{\Omega}\int_{los}\boldsymbol{\rho}^2(\mathbf{s},\boldsymbol{\Omega})\mathbf{ds\,d\Omega}$$

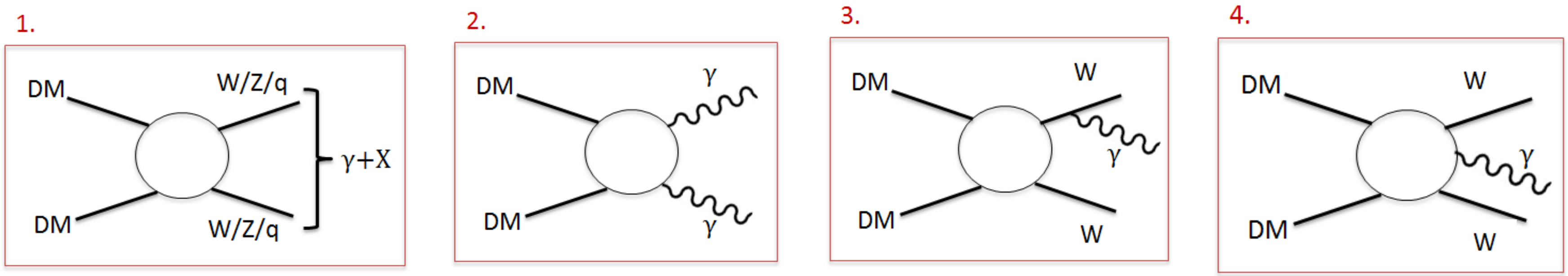
with:

$\mathbf{s}$ position along the line of sight,
$\boldsymbol{\Omega}$ solid angle,
$\boldsymbol{\rho}$ DM density profile

Dark matter annihilation signals in gamma-rays

1. Continuum: hadronization and/or decay of W/Z, quarks, leptons…
2. Line from prompt annihilation in two photons

   not at tree level: suppressed ⟶ but clear signature at DM mass !
3. Final state radiation
4. Virtual internal bremsstrahlung



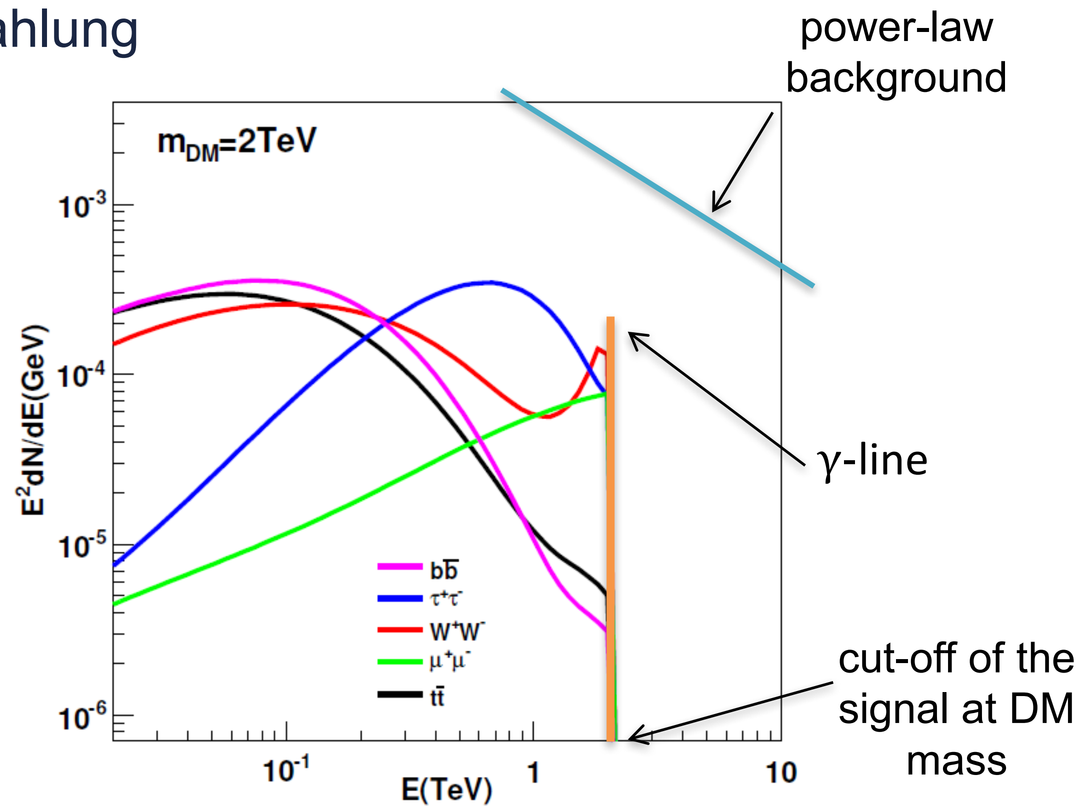
Thermal relic cross section for WIMPs:

- For the continuum signal : $\langle\sigma v\rangle \sim 3{\times}10^{-26}\mathrm{cm^3 s^{-1}}$
- For the prompt line signal : $\langle\sigma v\rangle \sim 10^{-29}\mathrm{cm^3 s^{-1}}$

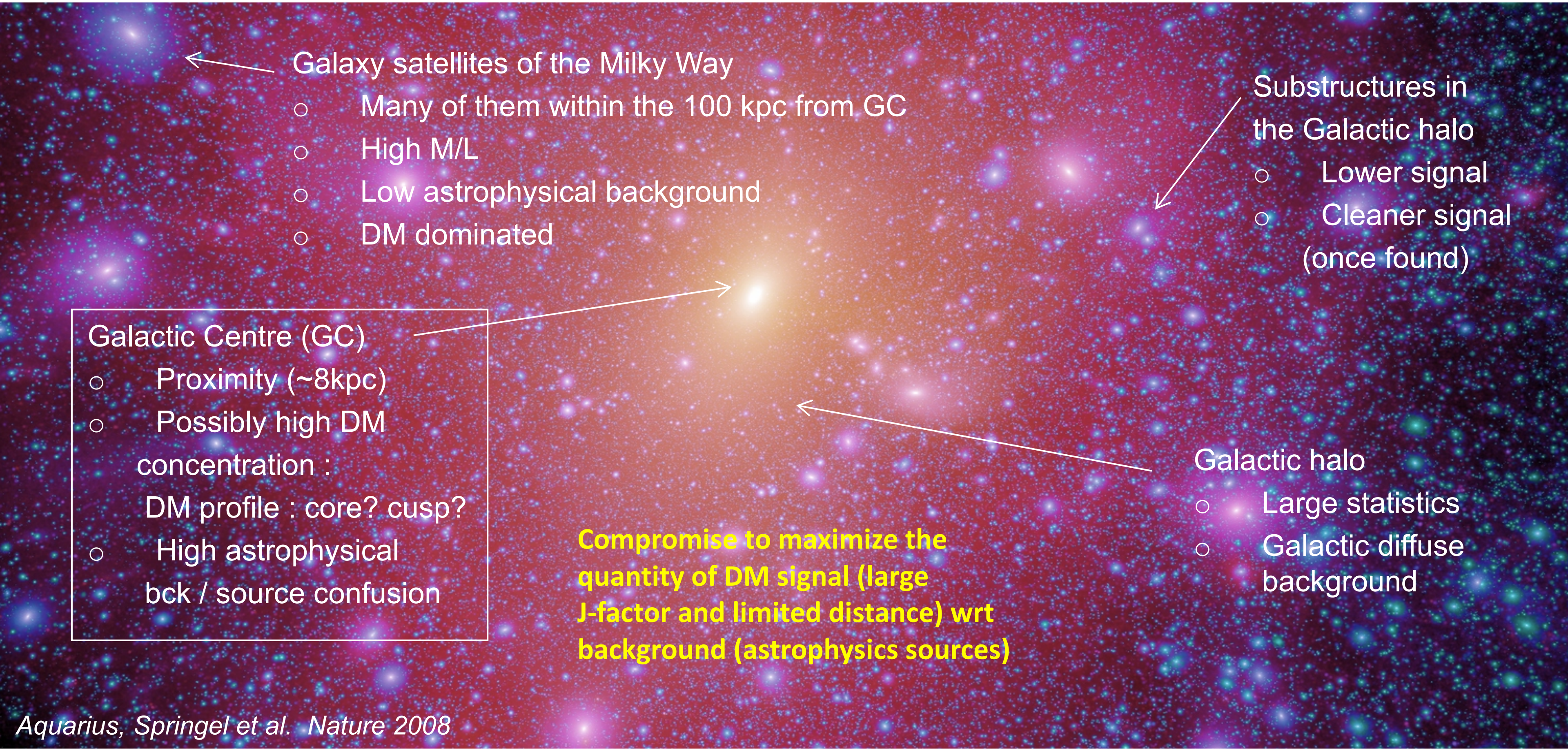
Dark matter annihialiton signals

1. Continuum: hadronization and/or decay of W/Z, quarks, leptons…
2. Line from prompt annihilation in two photons
3. Final state radiation
4. Virtual internal bremsstrahlung

The spectral information can be exploited for a better signal vs background discrimination (energy binning in the likelihood)



Dark matter targerts VHE gamma-ray searches



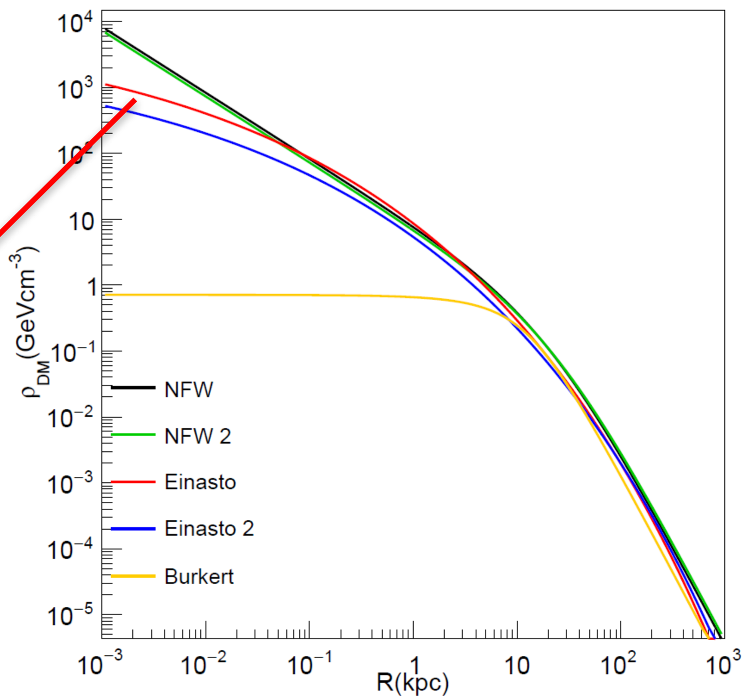
Aquarius, Springel et al. Nature 2008

- DM density profile matters
- Astrophysical background matters as well

H.E.S.S.

Dark matter distribution in the Galactic Centre region

We assume cusped DM density profiles, e.g. the Einasto, NFW, …



$$\rho_{Ein1}(r) = \rho_s \exp\left[\frac{-2}{\alpha}\left(\left(\frac{r}{r_s}\right)^{\alpha} - 1\right)\right]$$

parametrized with

$\alpha = 0.17$

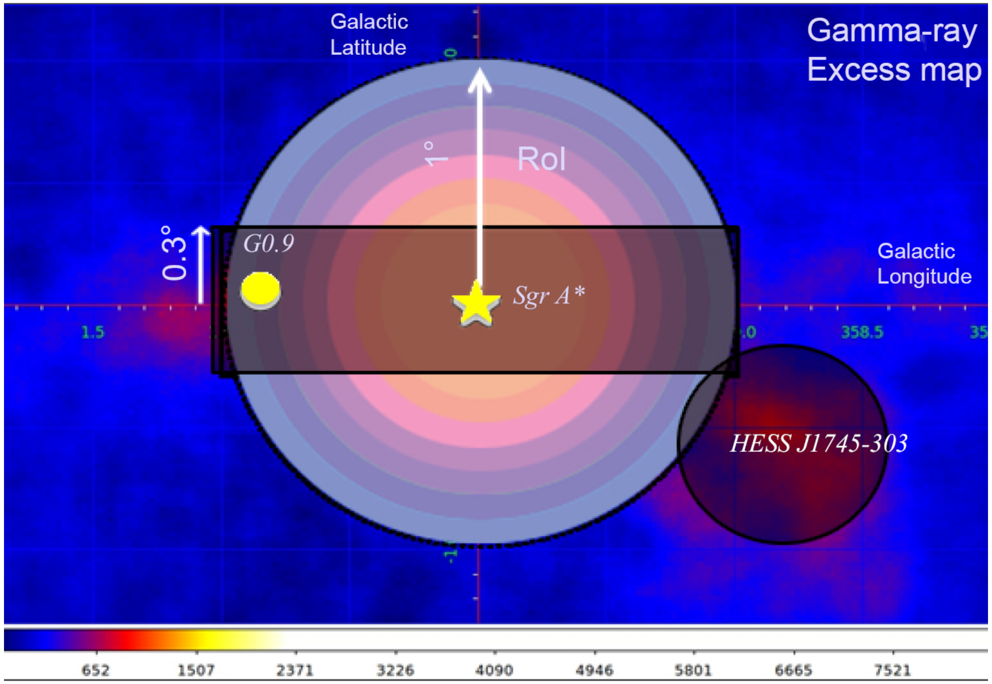
$r_s = 21\ kpc$

$\rho_s = 0.07\ GeV cm^{-3}$

as used in HESS GC 2011, 2013 papers

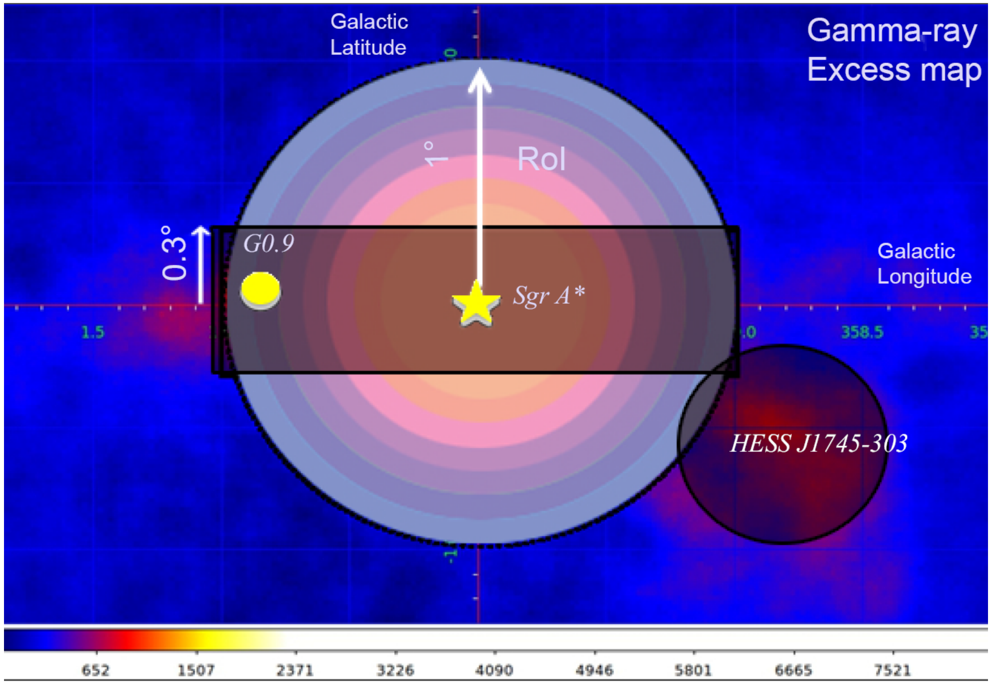
- **Spatial information can be used to discriminate from the isotropic residual background via spatial binning in the likelihood**

Data set



- 10-year observations with H.E.S.S. 1 toward the GC
  - same dataset as used in the 2016 DM continuum paper at GC halo
  - zenith angle on average 19 deg
- Gamma-ray statistics : 254 h compared to 112 h (2011/2013 papers)
- GC region is a crowded environment at VHE

Region of interest (RoI) definition

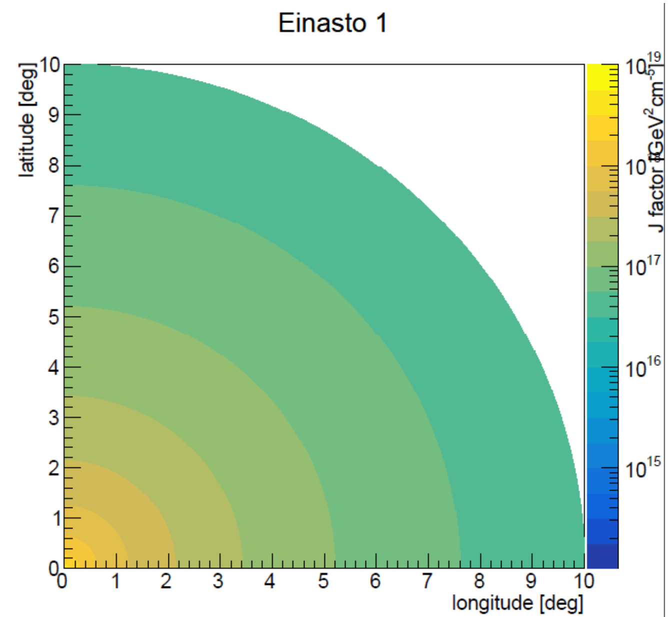


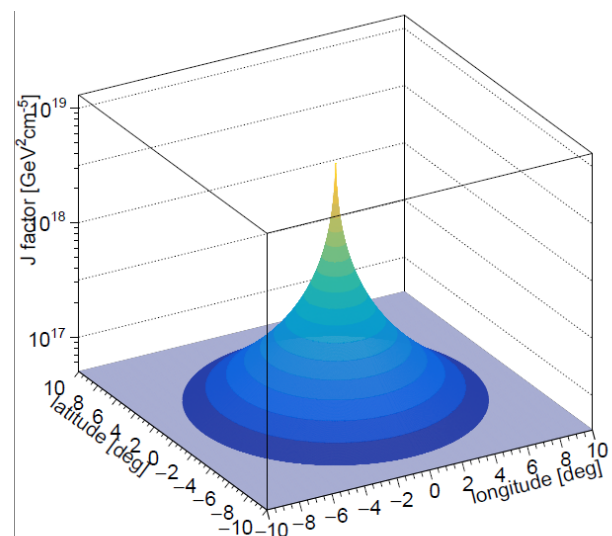
- Excluded region ±0.3° : dominated by astrophysical sources and diffuse emission
- Whole region of Interest (RoI) : 1° in radius (like in 2013 paper)
- RoI divided in 7 sub-regions of 0.1°: spatial binning

Dark Matter signals and J-factors

We assume cusped DM density profiles, e.g. the Einasto, NFW, …

i^{th} RoI	J-factor (10^{20} GeV^2 cm^{-5})		
	Einasto	NFW	Einasto modified
1	4.3	2.5	1.3
2	5.6	3.0	1.7
3	6.6	3.3	2.0
4	7.4	3.5	2.3
5	7.9	3.6	2.5
6	8.3	3.7	2.6
7	8.7	3.8	2.8

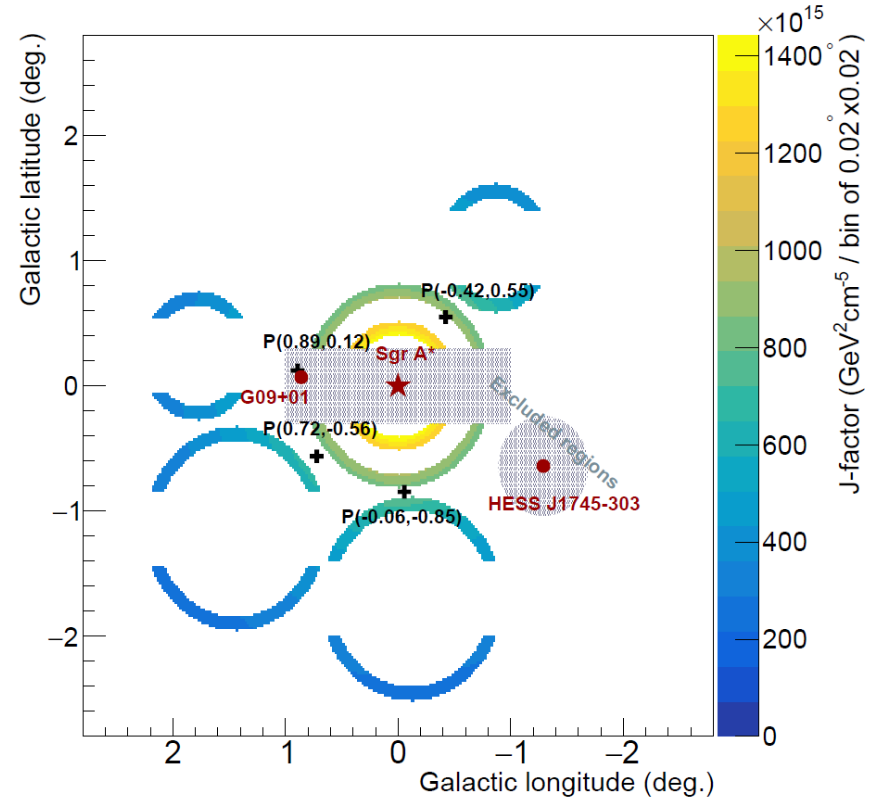




RoI definition and background measurement

- OFF regions are chosen symmetrically to ON regions with respect to the pointing position
- Overlapping areas are discarded to maintain the dark matter gradient

e.g. in one run for a given RoI and pointing position:



⇒ same acceptance in ON and OFF region (due to azimuthal symmetry)

+

⇒ strong dark matter gradient that improves the limits

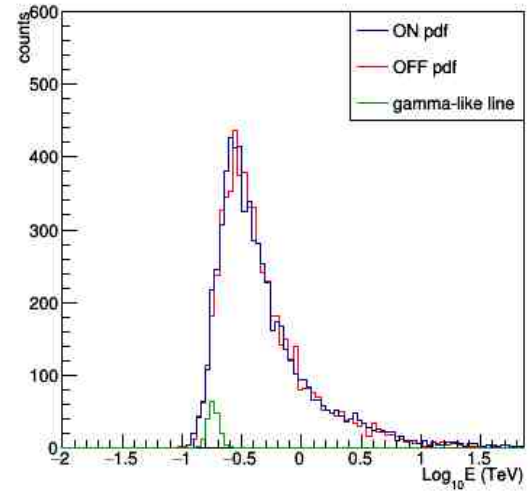
ON and OFF measurements

RoI	Measured OFF	Measured ON
1	5500	5794
2	11091	11616
3	16289	16916
4	21216	21581
5	22817	23175
6	23645	24255
7	25079	25868

- No significant excess in the ON pdfs w.r.t. OFF pdfs
- => limits can be derived on the DM annihilation cross section

Gamma line rate

$$N_{ij}^{\gamma} = \frac{1}{4\pi}\frac{\langle\sigma v\rangle}{2m_{DM}^2}\int\frac{dN}{dE'}R(E,E')T_{obs}A_{eff}(E)dE' \text{ x } J(\Delta\Omega)$$



- Spectrum : Dirac delta function at m_{DM}

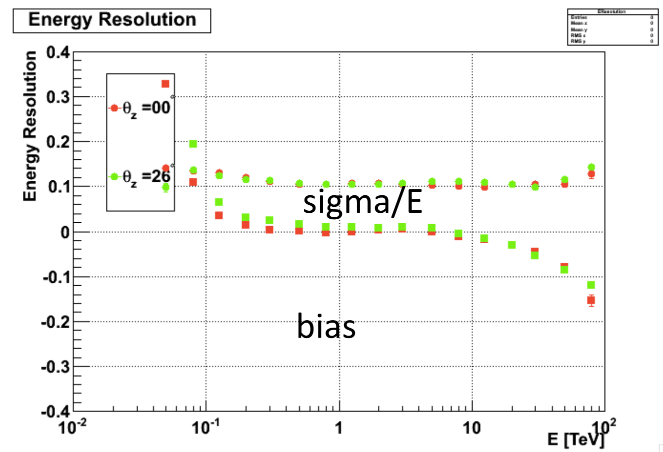
$$\frac{dN}{dE'} = 2\delta(E' - m_{DM})$$

- Energy resolution
- Effective area
- Gaussian resolution

$$R(E,E') = \frac{1}{\sqrt{2\pi}\sigma}e^{-\frac{(E-E')^2}{2\sigma^2}}$$

with $\sigma = 10\%$ E

- almost independent of the offset and the azimuthal angle



2D-binned likelihood analysis

- Likelihood function binned in energy (bin j) and space (RoI, bin i)

$$\mathcal{L}_{ij}(N_{ON}, N_{OFF}\,|N_S, N_B) = \frac{(N_S + N_B)^{N_{ON}}}{N_{ON}!} e^{-(N_S+N_B)} \frac{\left(N_S{'} \; + N_B\right)^{N_{OFF}}}{N_{OFF}!} e^{-(N_B+N_S{'}\;)}$$

where expected N_B obtained from dL/dNB = 0

$$\mathcal{L} = \prod_{i,j} \mathcal{L}_{ij}$$

N_{ON}	Observed signal (ON region)
N_{OFF}	Observed background (OFF region)
N_S	Line signal (expected in ON)
N'_S	Line signal (expected in OFF)
N_B	Expected background

- Test statistics: likelihood-ratio test

$$TS = -2\log\frac{\mathcal{L}_W}{\mathcal{L}_{WO}} = -2\log\frac{\mathcal{L}\left(N_{ON}, N_{OFF}\middle|N_S, N_S{'}\;, N_B\right)}{\mathcal{L}(N_{ON}, N_{OFF}|N_B)}$$

TS = 2.71
for a 95% CL limit

Sensitivity: expected limit

- Expected limit computed from blank-field observations at high Galactic latitudes:
  - Gamma-ray background taken from all the extragalactic runs (|b|>10°) after quality checks
- Expected GC background estimated in the same observation conditions on a run by run basis from the GC run list

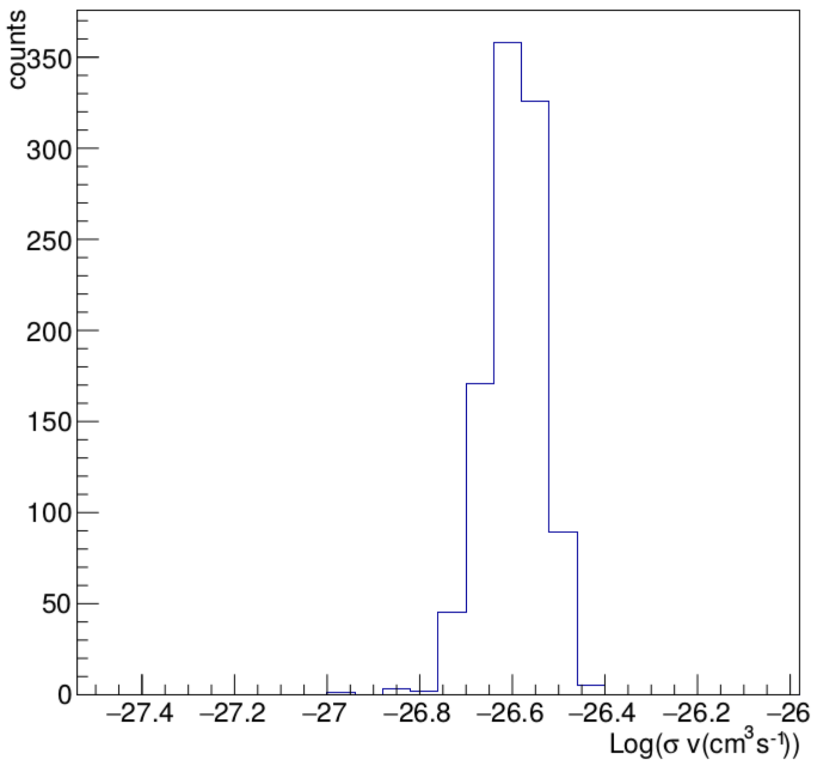
RoI	Measured OFF	Expected OFF
1	5500	6060
2	11091	11823
3	16289	16254
4	21216	20726
5	22817	22893
6	23645	24658
7	25079	27091

Sensitivity: expected limit

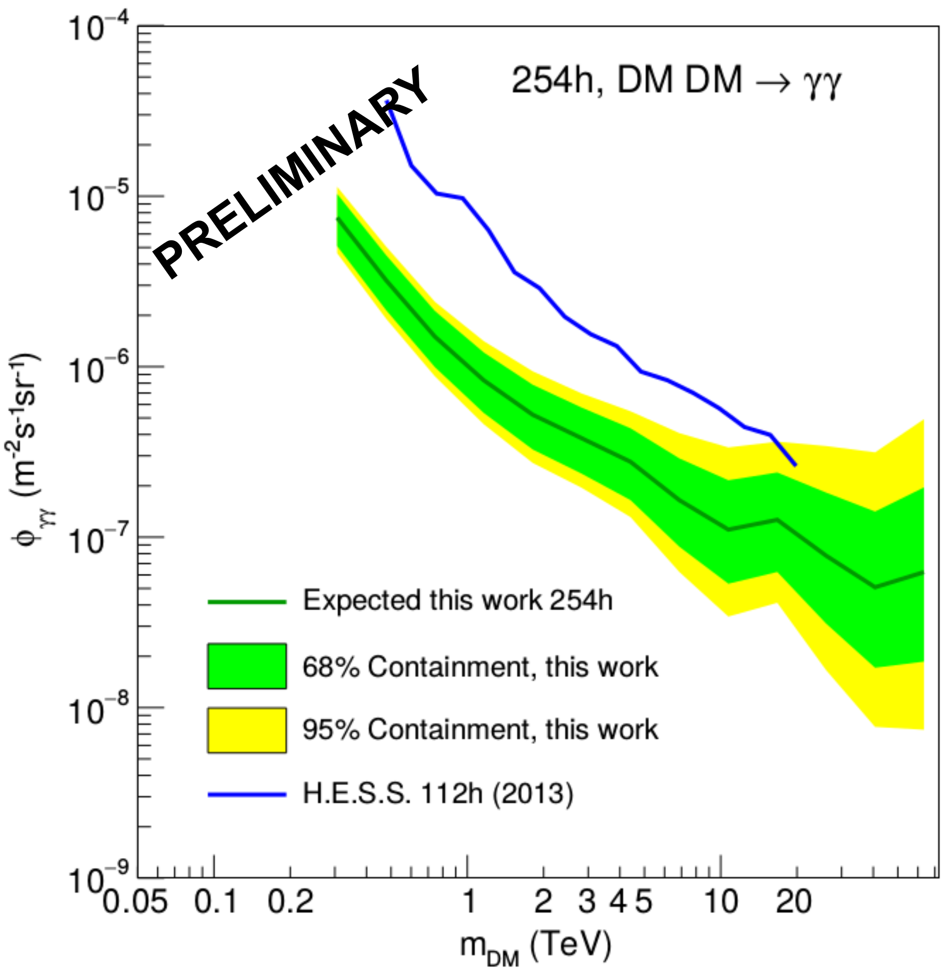
- 1000 Poisson realizations are made on this background
- The likelihood analysis is applied on each realisation
- From the distribution of the annihilation cross section values obtained in each realisation for each mass

- the mean expected limit is extracted as the mean of the distribution
- the 68% and 95% containment band are computed from the standard deviation of the distribution

Example at mass 10 TeV:

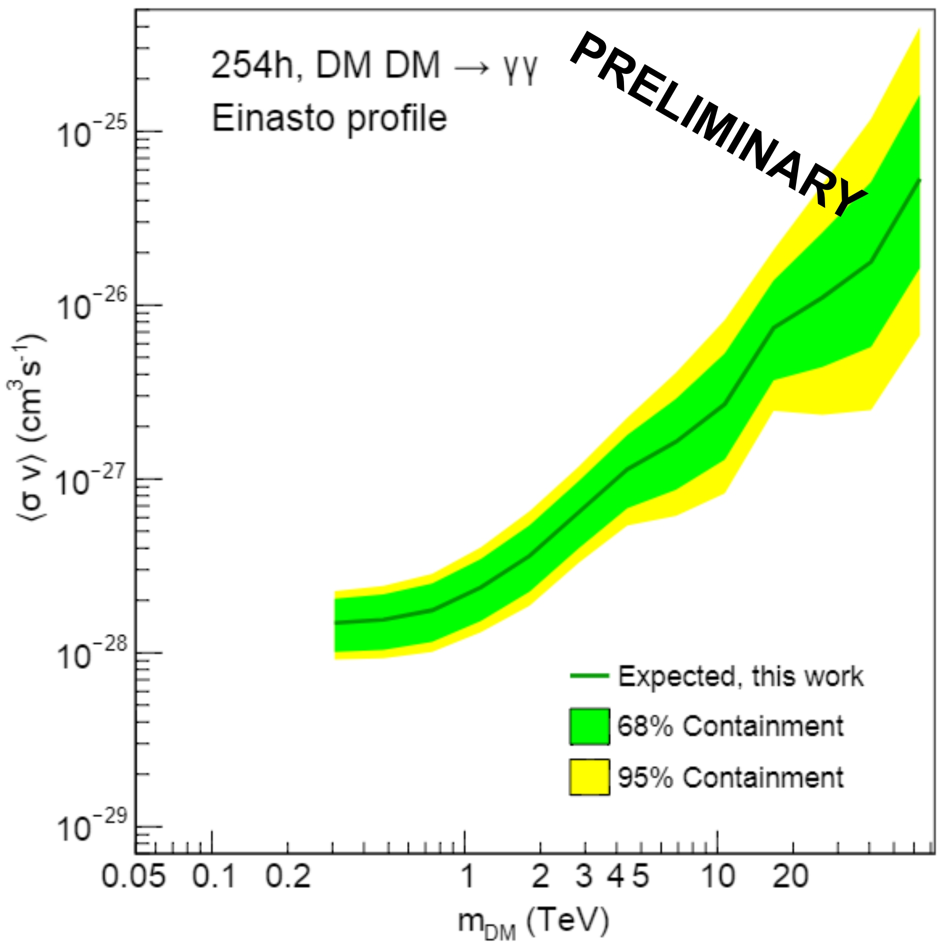


Comparison of the mean expected sensitivity on the flux with previous H.E.S.S. results



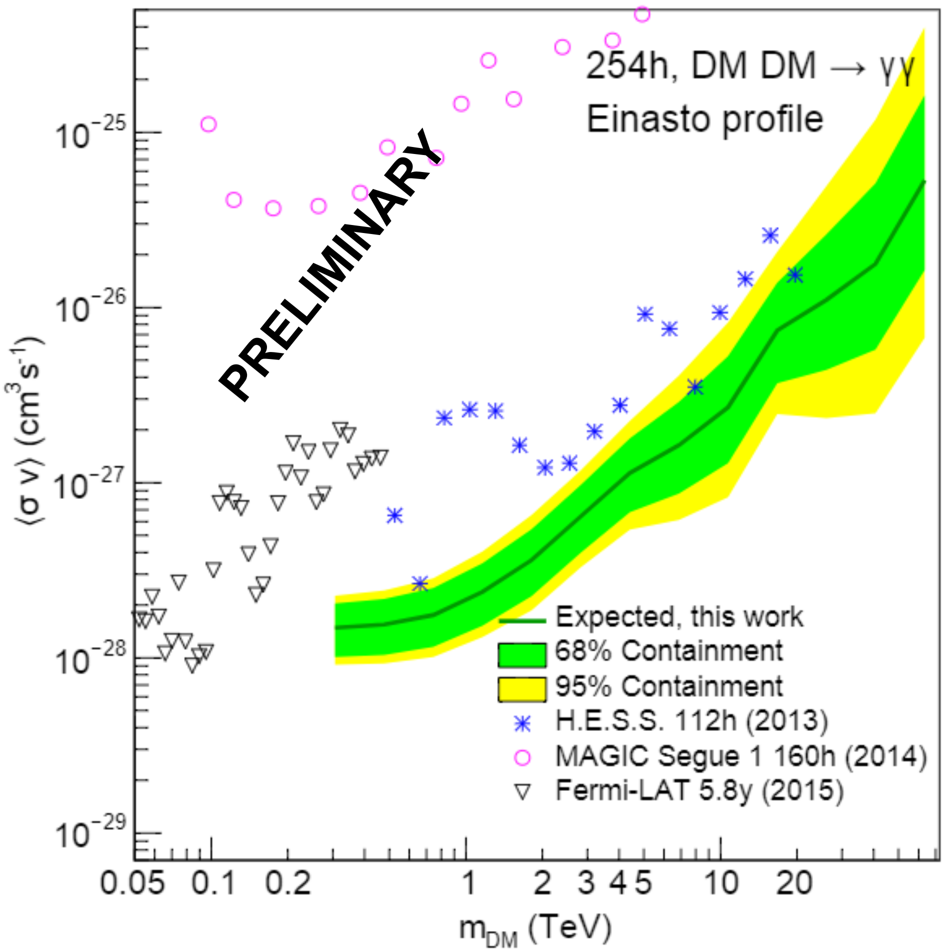
- Improvement of a factor about 8 observed @ 1 TeV on the mean expected limits
- Improvement from the analysis: exclusion regions, 2D approach, implementation of the background, and higher statistics ($stats \propto \sqrt{T_{obs}}$)
- Remaining improvement from new raw data analysis

Expected mean sensitivity on σv with previous H.E.S.S. results



- best limit $2 \times 10^{-28} cm^3 s^{-1}$ @1TeV
- mass range extended down to 300 GeV and up to 70 TeV
- lower energy threshold thanks to the improved raw data analysis: best limit shifted down to lower masses

Comparison of the expected mean sensitivity on σv with previous results by other experiments



- best limit $2\text{x}10^{-28}\text{cm}^3\text{s}^{-1}$ @1TeV
- lower energy threshold thanks to the improved raw data analysis: best limit shifted down to lower masses
- Fermi-LAT limits surpassed of a factor about 6 @300 GeV

Summary

- Full H.E.S.S.-I GC dataset analysis for dark matter line searches in the inner GC halo in the DM mass range 300 GeV – 70 TeV
- Improvement at 1 TeV with respect to 2013 results is about 8 on the mean expected sensitivity
  - higher photon statistics
  - higher sensitivity of the new raw data analysis
  - 2D likelihood approach
- Next step :

- Follow-up study with H.E.S.S.-II data: more statistics and extended pointings from IGS
- Tests of different DM models (wino, 3-plet, 5-plet) can be performed
- Methodology is useful for other target fileds