Constraints on Dark Matter WIMPs models with H.E.S.S. observations of the Canis Major overdensity

Emmanuel Moulin for Matthieu Vivier, on behalf the H.E.S.S. collaboration

Paper reference: « A search for a dark matter annihilation signal towards the Canis Major overdensity with H.E.S.S. », to be published in ApJ (2009), arXiv:0809.3894.

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  → γ*-ray lines*

  → γ*-ray continuum* with a cut-off at the DM particle mass

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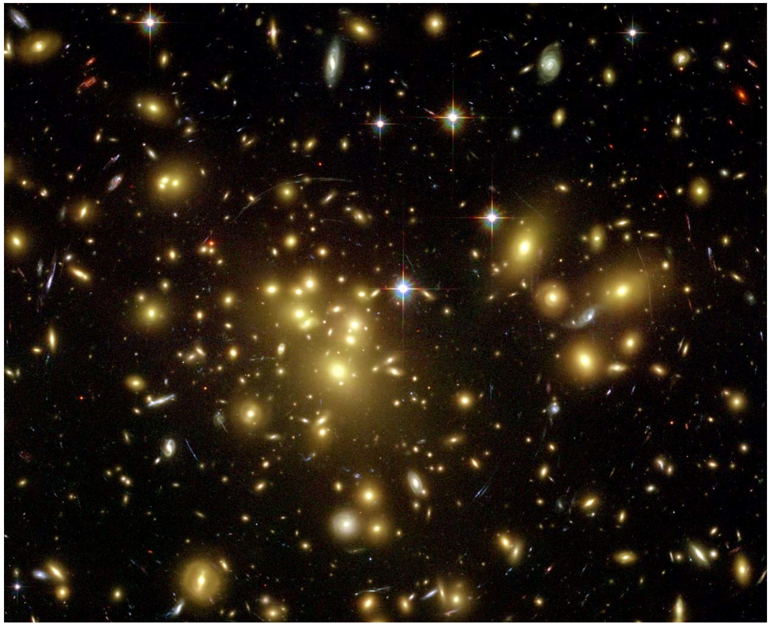
- Potential targets are region of high concentration of DM:

    -Clusters of galaxies



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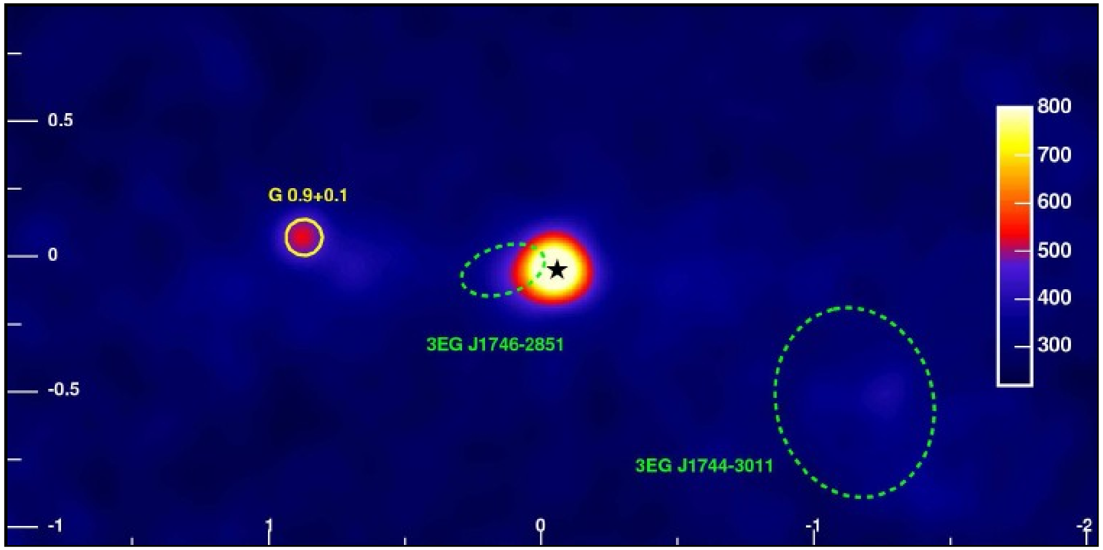
- Potential targets are region of high concentration of DM:

  -The Galactic Center (Aharonian et al., 2006)



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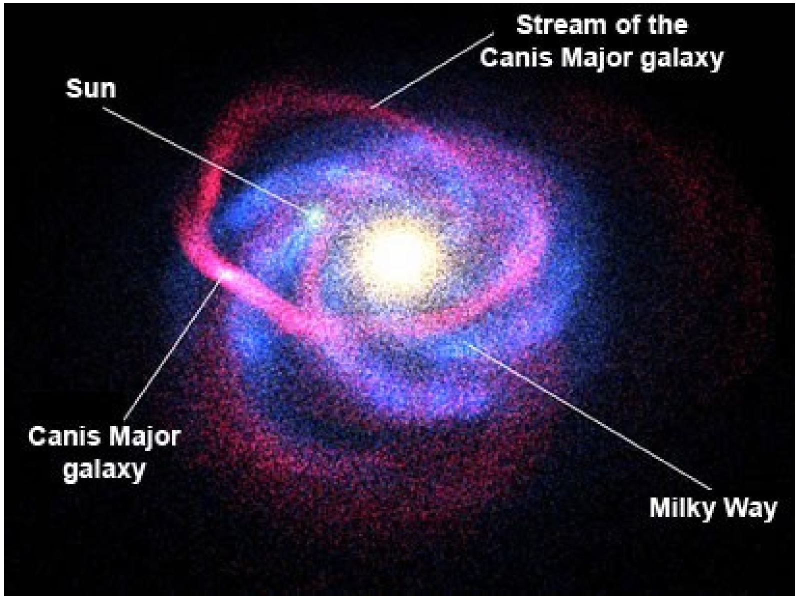
  -Dwarf spheroidal galaxies (dSph): Sagittarius(Aharonian et al., 2006), Draco, Canis Major (Aharonian et al., 2009)



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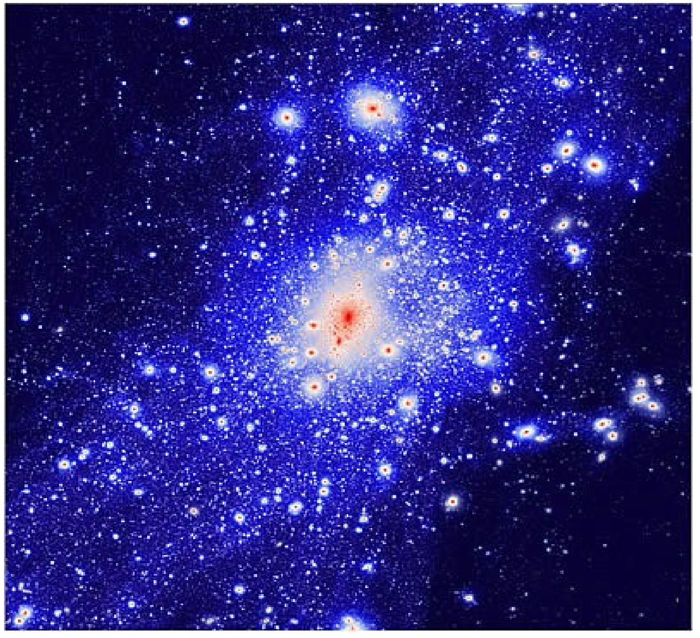
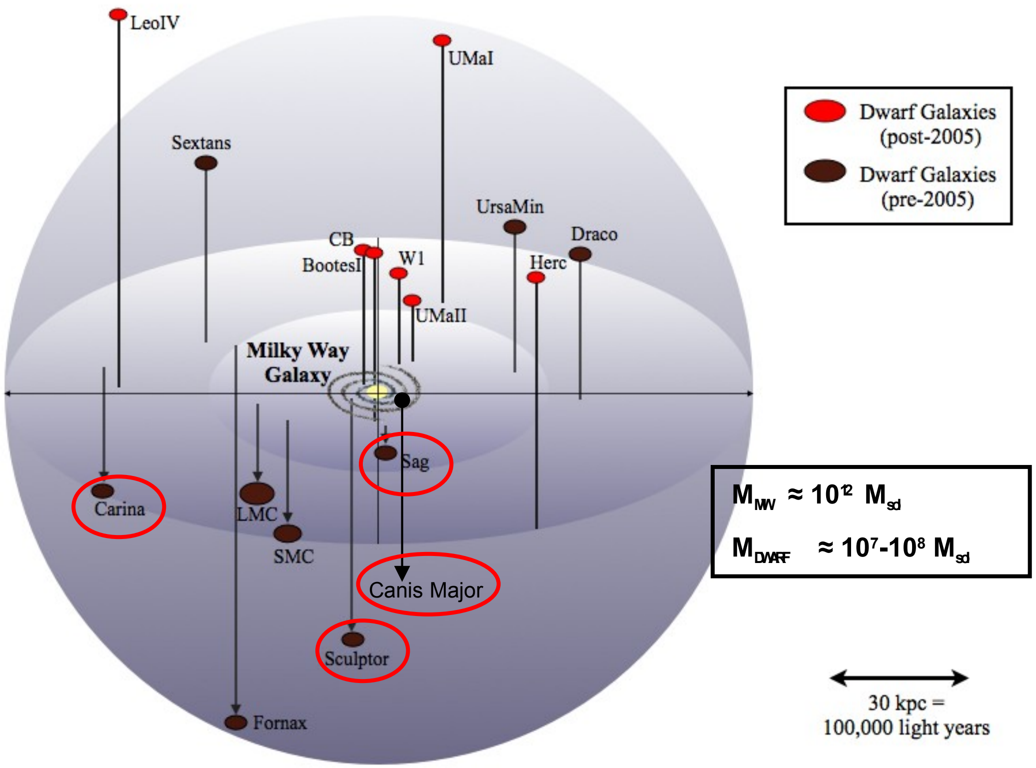
  -Dark Matter substructures: clumps, Intermediate Mass Black Holes (see Emmanuel Moulin’s talk)…



The dwarf spheroidal galaxies



- Small galaxies that orbits around the Milky Way.
- Predicted by simulations of structure formation.
- Very faint objetcs, difficult to detect.
- Highly dominated by DM, very good candidate for the detection of DM.
- Observed by H.E.S.S. in the southern hemisphere: Sagittarius, Canis Major, Carina, Sculptor.

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- An overdensity of stars located towards the Galactic anti-center direction, under the Galactic plane.

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  - →A part of the warped Galactic disk (Momany et al, 2006)
  - →The remnant of a dSph that would have been absorbed by the Milky Way (Martinez-Delgado et al, 2004)

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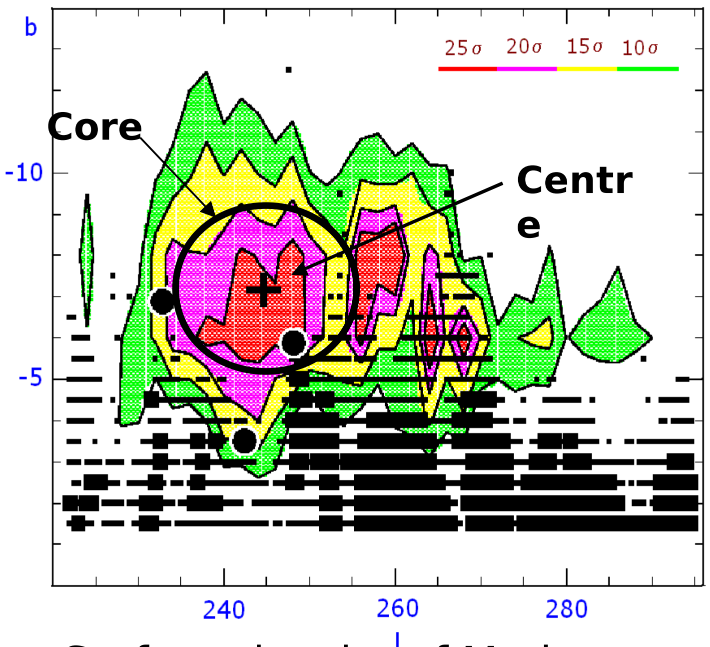


Surface density of M-giant stars (Bellazinni et al, 2005)

- Distance: 7± 1 kpc (three times closer than Sagittarius)
- Very extended: Δl=12°, Δb=10°
- Mass ≈ 10^8 M_{solar} (Evans et al., 2004), similar to Sagittarius
- 9.6 hours of good quality data taken with H.E.S.S.

H.E.S.S.

A square array of four *Imaging Atmospheric Cherenkov Telescopes*, dedicated for the detection of very high energy γ-rays

→13m diameter telescope: mirror area of ≈ 100 m² + a camera covering a 5° total field of view

→Stereoscopic reconstruction

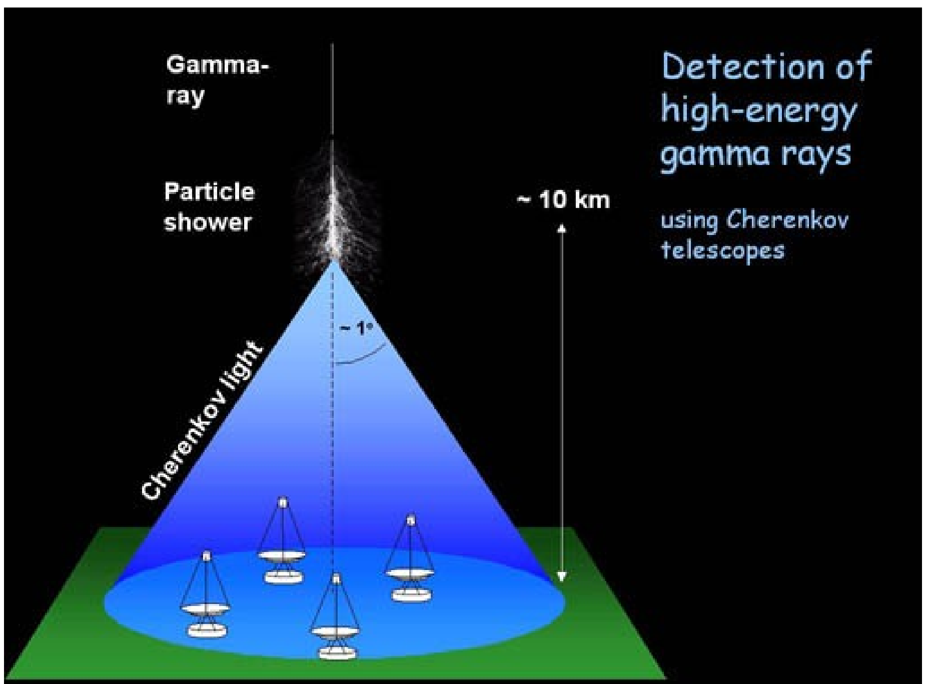
→Angular resolution < 0.1°/γ

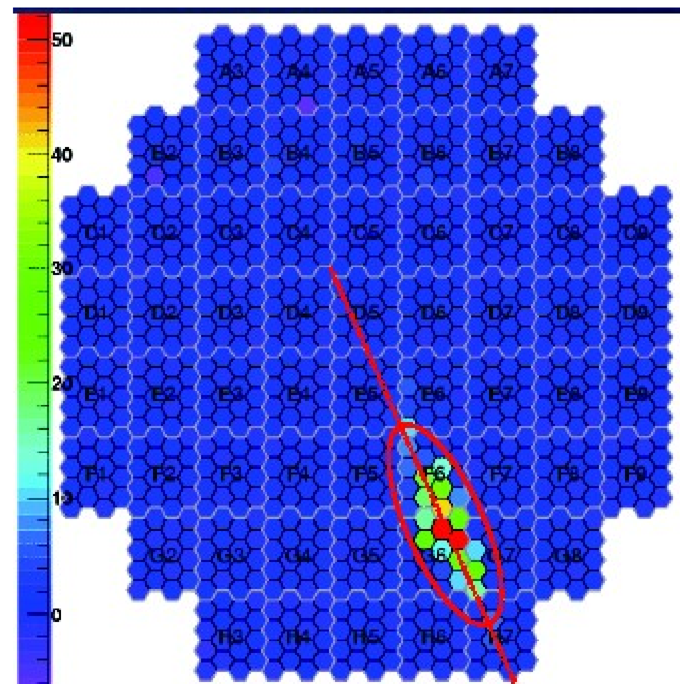
→Energy threshold ≈ 100 GeV at zenith

→Sensitivity: 1% of the Crab flux in 25 hours (5σ)

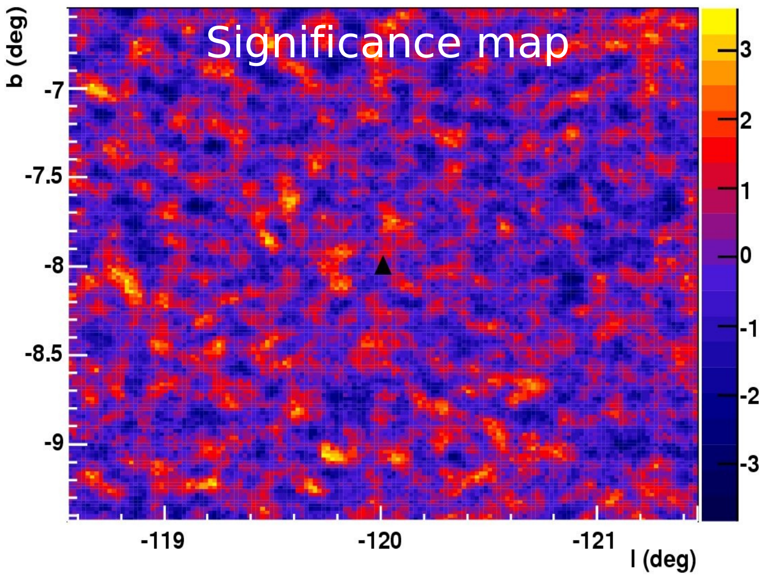
Data analysis

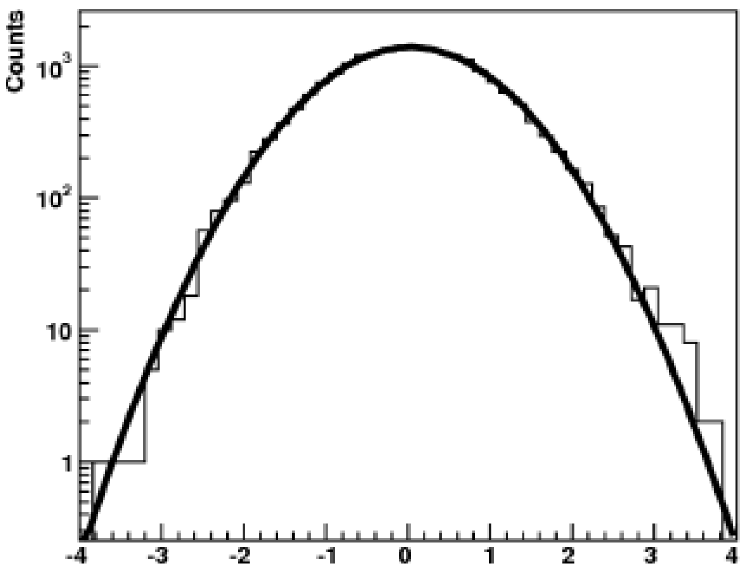
- Combines a semi-analytical model of air showers (which predicts the expected intensity of Cherenkov light in each pixels of the camera) & the Hillas moments method.
- γ selection cuts computed with simulations.
- Energy and direction of the γ-ray are fitted to match the camera images.





Canis Major data analysis results





- No significant excess at the target position (black triangle)
- Distribution of significance: gaussian of mean 0 and variance 1
- Constraints on WIMP models given the absence of signal in the entire field of view

Expected γ-ray flux from DM annihilation

$$\phi_\gamma = \frac{d\Phi^{PP}}{dE_\gamma} \times f^{AP}$$

Particle Physics model

$$\frac{d\Phi^{PP}}{dE} = \frac{\langle \sigma v \rangle}{4\pi m_{DM}^2} \int_0^{m_{DM}} \overline{A_{eff}}(E_\gamma) \left(\frac{dN}{dE} \right)_{DM} dE_\gamma$$

- $\langle\sigma v\rangle$: velocity-weighted annihilation cross-section of WIMPs
- m_{DM} : WIMP mass
- A_{eff} (E): H.E.S.S. effective area ≈ efficiency in collecting a γ of energy E_γ
- $(dN/dE)_{DM}$: γ-ray annihilation spectrum (particle physics model)
  1) SUSY
  2) Kaluza-Klein

Expected γ-ray flux from DM annihilation

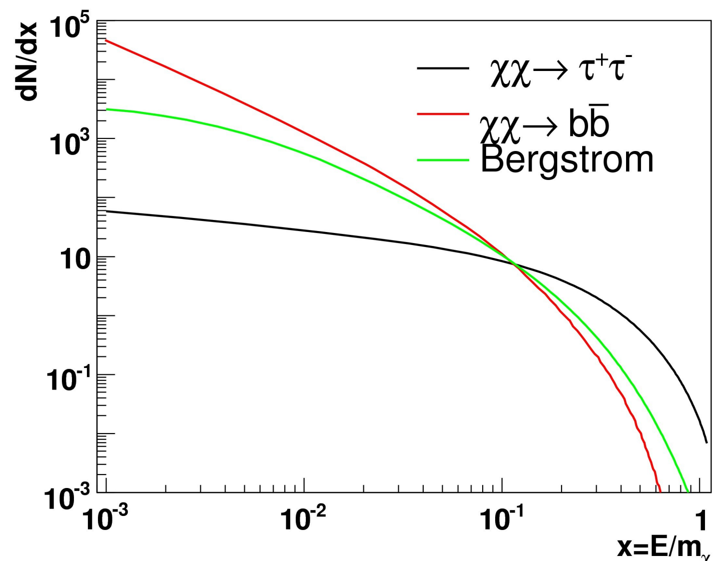
$$\phi_\gamma = \frac{d\Phi^{PP}}{dE_\gamma} \times f^{AP}$$

Particle Physics model

1)Neutralino annihilation *(*phenomenological Minimal SUSY extension of the Standard Model of particle physics*)*

→Parametrization of the γ-ray spectrum taken from *Bergström et al, 1998*.

$$\frac{dN}{dE} = \frac{p_1}{m_c} \;\square\; \frac{e^{-p_2 E/m_c}}{(E/m_c)^{p_3} + p_4}$$



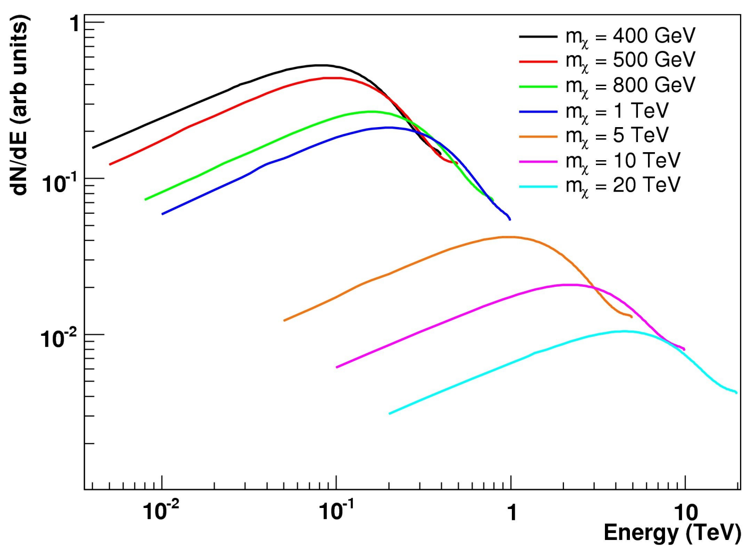
Expected γ-ray flux from DM annihilation

$$\phi_\gamma = \frac{d\Phi^{PP}}{dE_\gamma} \times f^{AP}$$

Particle Physics model

2)Kaluza-Klein particle annihilation (Universal Extra Dimensions models)

→Spectrum simulated with the PYTHIA package taking the branching ratic



Expected γ-ray flux from DM annihilation

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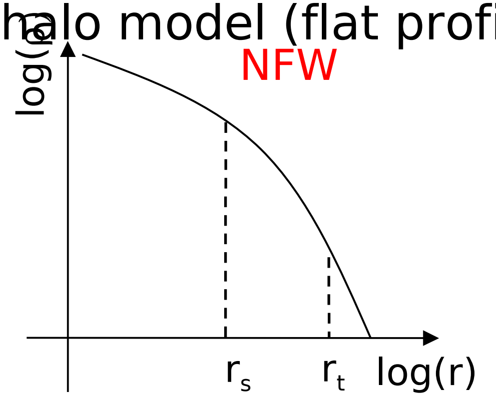
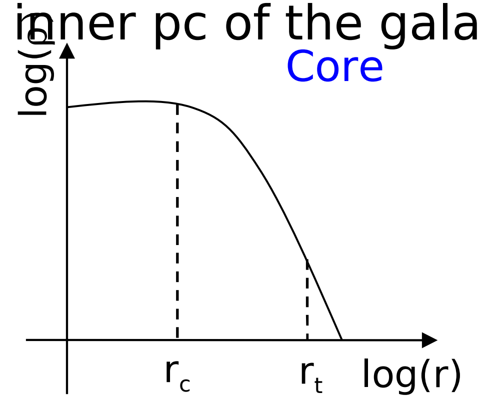
DM mass distribution modelling

- Usually constrained with observational data (velocity dispersion of stars and luminosity profiles of the galaxies).
- Two main parametrizations of the DM profile are used in the literature:

  →cusped NFW model (predicted by N-body simulations)

  →core halo model (flat profile in the inner pc of the galaxy)





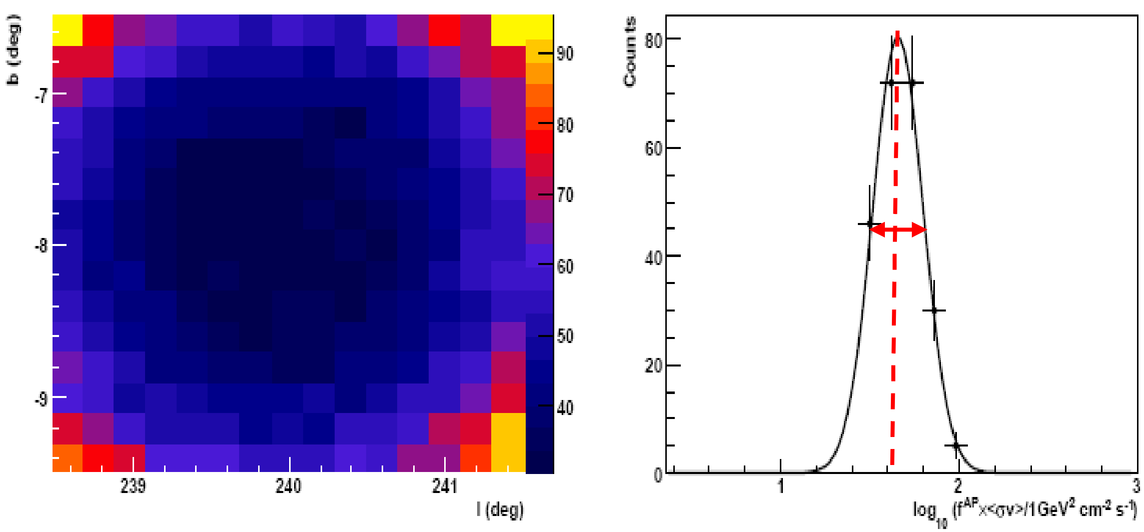
Halo independent constraints: limits on $<\sigma v>\times f^{AP}$

- Method:

  1) Given the absence of signal in the entire field of view: computation of the uppers limit on the number of γs in each direction of the field of view

     →Upper limit γ map

  1) Upper limit map on the value of $f^{AP}\times<\sigma v>$, *given a specific WIMP mass* + the corresponding 1D-distribution (well-fitted by a gaussian)

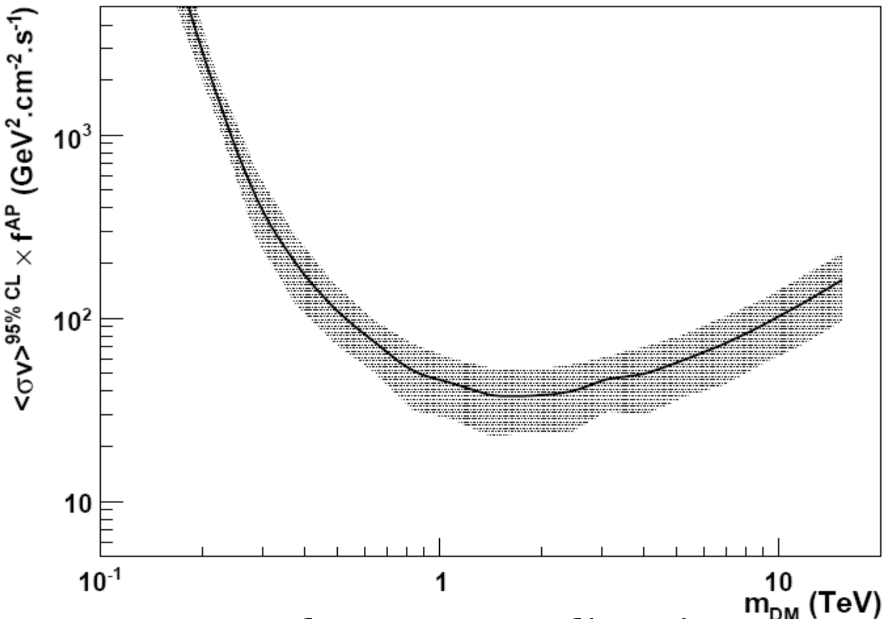


$f^{AP}*<\sigma v>$ upper limit map + the corresponding 1D-distribution for a 1TeV neutralino

Halo independent constraints: limits on $<\sigma v> \times f^{AP}$

- Method:

3) Repeat the procedure with varying the neutralino mass

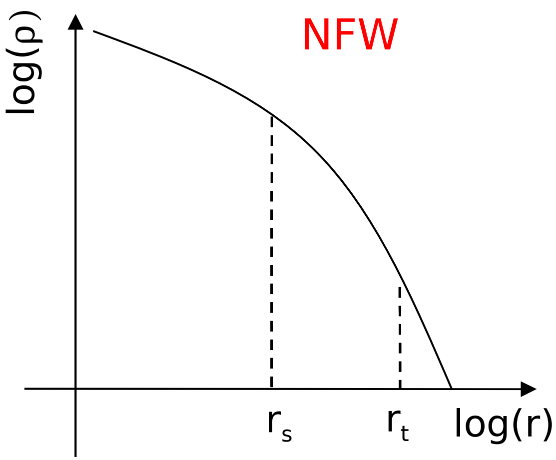


$f^{AP} \times <\sigma v> = f(m_{DM})$

- Grey shaded area = 1σ variation of gaussian fits
- Limits on f^{AP} x <σv> ➔ limits on CMa mass and <σv> with respectively assumptions on <σv> and the total CMa mass.

Canis Major DM halo modelling

- No observationnal data to constrain the DM halo profile of Canis Major
- Hypothesis of a standard cusped NFW profile
- Computation of the parameters with the help of the lastest results from the simulations of structure formation.



$$\rho_{cusped}(r) = \frac{\rho_0}{\frac{r}{r_s}(1+\frac{r}{r_s})^2}$$

Halo parameters

- ρ_0: mass density normalisation
- r_s: scale radius
- r_t: tidal radius
- M_{tot} : mass of Canis Major (volume integral of the DM mass distribution between 0 and r_t).

Canis Major DM halo modelling

- Computation of the halo parameters ρ_0 & r_s by solving a system of three equations:

  →uses the definition of the virial mass M_{vir} of the CMa halo (eq. 2)

  →uses the relation between the concentration parameter C_{vir} and M_{vir} (eq. 3). Taken from Dolag et al., 2004.

(1) $$M_{vir} = \int_0^{R_{vir}} \rho_{cusped}(r) \times d^3\vec{r}$$

(2) $$M_{vir} = \frac{4\pi}{3}\rho_{200} \times R_{vir}^3$$

(3) $$C_{vir}(M_{vir}, z) = \frac{c_0}{1+z} \times \left(\frac{M_{vir}}{10^{14}h^{-1}M_{sun}}\right)^{\alpha}$$

- ρ_{200} = 200 × (ρ_u= 83 M_{solar} /kpc^3)
- $C_{vir} = R_{vir} / r_s$.
- α = -0.1; c_0 = 9.6 in a ΛCDM cosmology (Dolag et al., 2004)

- But... $M_{vir} \neq M_{tot}$ ➔ Iterative tidal stripping procedure to relate M_{vir} & M_{tot} .

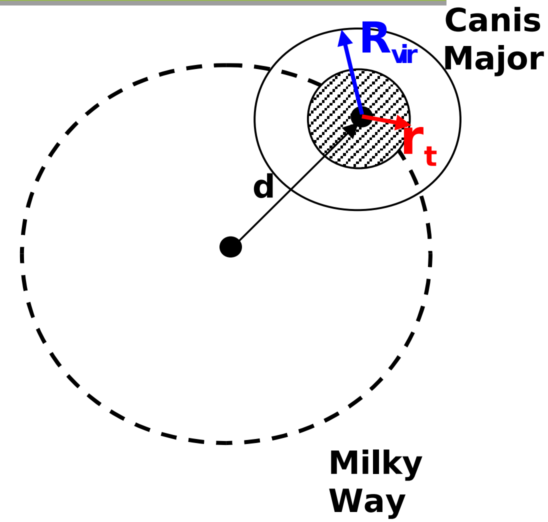
Canis Major DM halo modelling

$M_{vir} \rightarrow$

r_t

$$r_t = d \left(\frac{M_{CMa}}{3 M_G(r \le d)} \right)^{1/3} \qquad M = \int_0^{r_t} \rho(r)\, d^3 \vec{r}$$

M



- $M_{vir} \neq M_{tot}$
- Assumes that: $M_{tot} = M(r \leq r_t)$, r_t tidal radius
- r_t computed with an iterative tidal stripping procedure
- $M_{tot} \approx 0.1\ M_{vir}$ at the end of the procedure

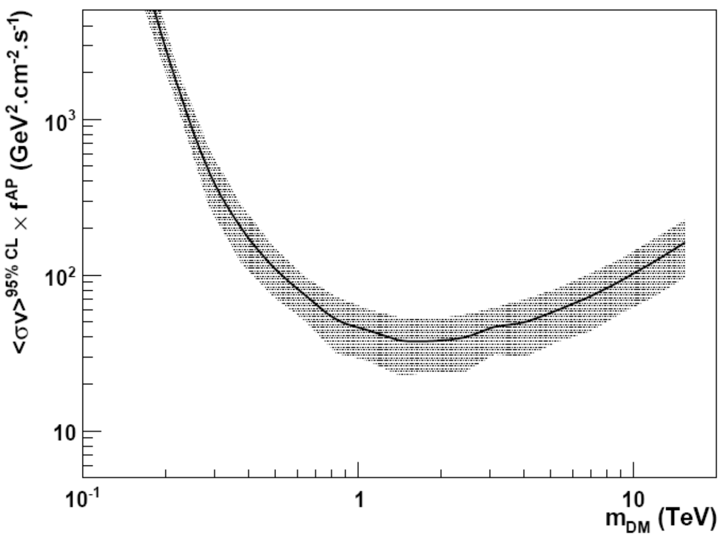
→then we have $M_{tot} = f(\rho_0, r_s)$ and computation of the astrophysical factor $f^{AP} = f(M_{tot})$

M_{vir} ($M_\odot$)	ρ_0 ($10^8 M_\odot$ kpc^{-3})	r_s (kpc)	r_t (kpc)	$M(r \leq r_t)$ ($M_\odot$)	f^{AP} (10^{24}GeV^2 cm^{-5})
10^6	4.7	0.04	0.28	$3.9\ 10^5$	0.24
10^8	1.3	0.28	1.17	$3.1\ 10^7$	2.2
10^{10}	0.39	2.08	4.15	$1.9\ 10^9$	12

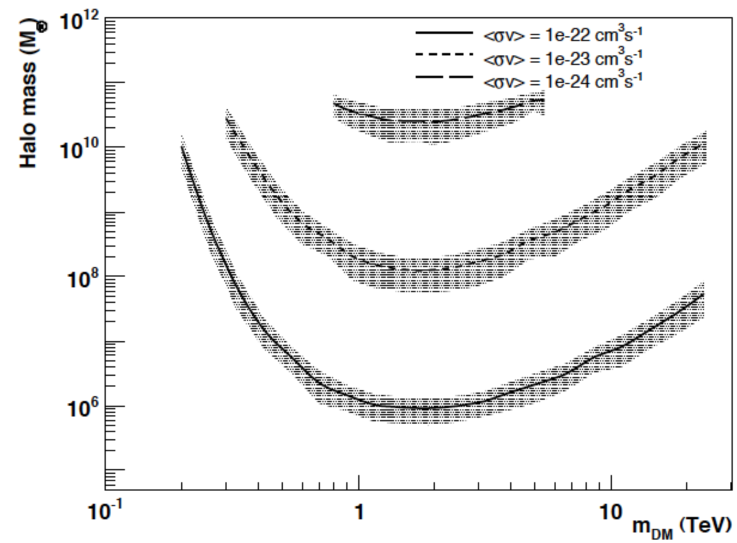
Limits on the Canis Major halo mass

- Assumes a fixed value for <σv>

$f^{AP} \times \langle\sigma v\rangle = f(m_{DM})$



$M_{tot} = f(m_{DM})$



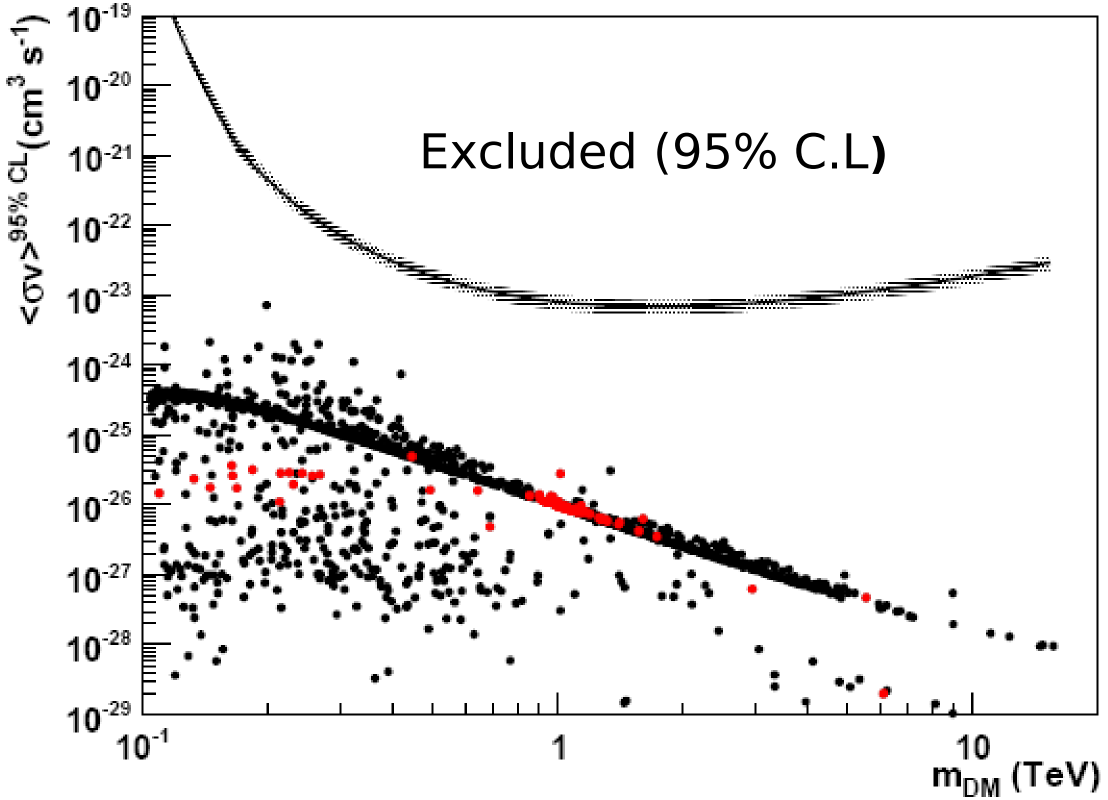
<σv> fixed + $f^{AP} = f(M_{tot})$

- Relatively high value for <σv> (> 3×10^{-26} cm^3 s^{-1}) to constrain the mass

Limits on <σv>

- Assumes $M_{tot} = 3 \times 10^8 M_{solar}$ (Evans et al., 2004)

1) SUSY models: pMSSM



Red = pMSSM predictions compatible with the value of Ω_{CDM} as measured by WMAP.

$<\sigma v>^{95\% CL} \approx 5.10^{-24}$ $cm^3 s^{-1}$

Limits on <σv>

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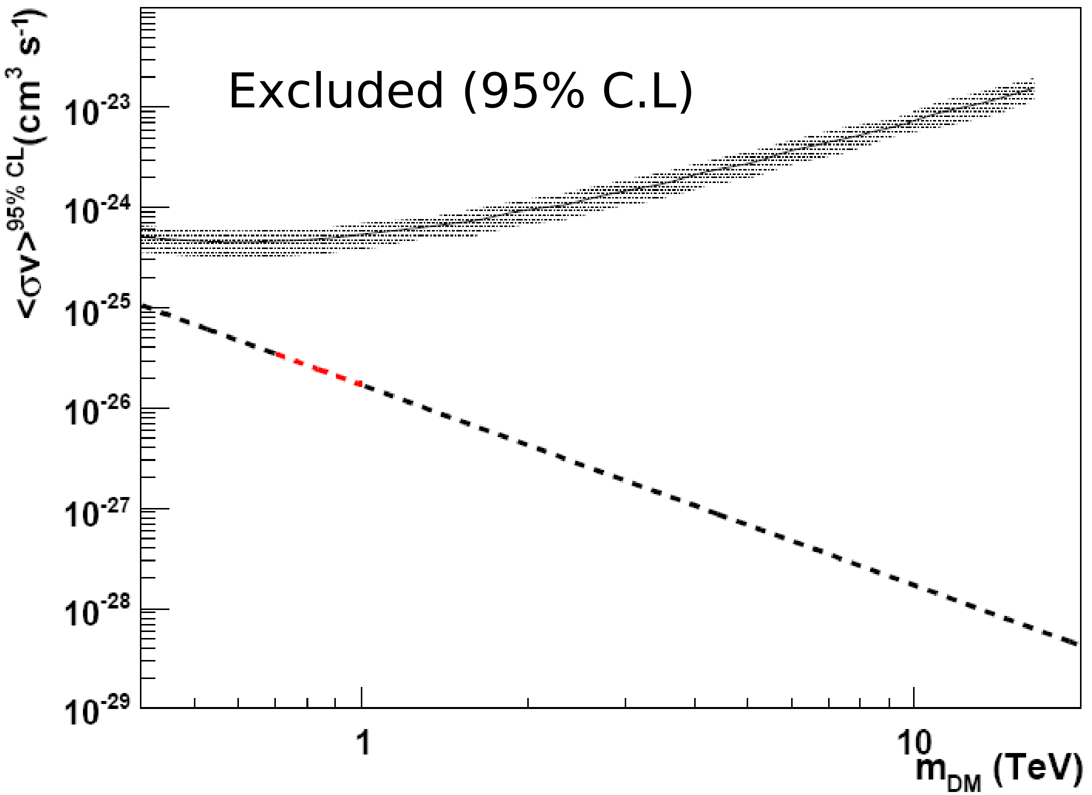
2) Kaluza-klein models



Red = KK models compatible with the value of Ω_{CDM} as measured by WMAP.

$<\sigma v>^{95\% CL} \approx 5.10^{-25}$ cm^3 s^{-1}

H.E.S.S. limits comparison

- Competitive limits for Canis Major

Targets | WIMPs model	pMSSM	Kaluza-Klein
Galactic Center (NFW)	$\langle\sigma v\rangle^{95\%CL} \sim 10^{-23}$ cm^3 s^{-1}	$\langle\sigma v\rangle^{95\%CL} \sim 10^{-24}$ cm^3 s^{-1}
Sgr Dwarf (NFW)	$\langle\sigma v\rangle^{95\%CL} \sim 10^{-23}$ cm^3 s^{-1}	$\langle\sigma v\rangle^{95\%CL} \sim 10^{-24}$ cm^3 s^{-1}
Sgr Dwarf (Core)	$\langle\sigma v\rangle^{95\%CL} \sim 2.10^{-25}$ cm^3 s^{-1}	$\langle\sigma v\rangle^{95\%CL} \sim 5.10^{-26}$ cm^3 s^{-1}
CMa Dwarf (NFW)	$\langle\sigma v\rangle^{95\%CL} \sim 5.10^{-24}$ cm^3 s^{-1}	$\langle\sigma v\rangle^{95\%CL} \sim 5.10^{-25}$ cm^3 s^{-1}

Conclusions

- No signal detected.
- Halo modelling: no observational data. Assumed NFW + tidal stripping.
- Close to exclude pMSSM predictions with higgsino-like neutralinos.
- No KK scenarios excluded.
- Good limits in comparison with the other targets observed by H.E.S.S.