Dark Matter searches with H.E.S.S. towards dwarf spheroidals galaxies

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On behalf of the HESS collaboration

IRFU, CEA-Saclay

- H.E.S.S. telescope array
- Indirect Dark Matter search principle
- Dwarf spheroidal galaxies H.E.S.S. campaign
- Dark Matter flux enhancement effects
- Summary

The H.E.S.S. telescope array

Array of four Imaging Atmospheric Cherenkov Telescopes

located in Namibia (1800m a.s.l.)

- 12 m diameter telescopes : 107 m^2 each
- Observations on moonless nights, ~1000h/year
- Field of view of 5°

- Stereoscopic reconstruction
- Angular resolution < 0.1° /γ
- Energy threshold (zenith) ~ 100 GeV
- Energy resolution ~ 15%

5th telescope(28m) in contruction: HESS 2

Indirect dark matter searches through gamma-rays

DM self-annihilation rate :

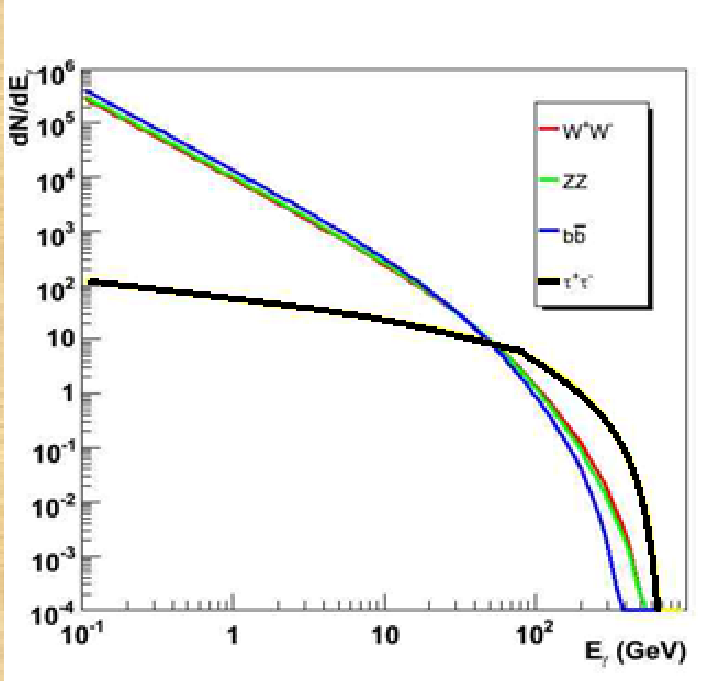
$$\Gamma_\chi \approx \sigma v \frac{\rho_\chi^2}{m_\chi^2}$$

Gamma-ray flux from annihilation of a WIMP:

$$\frac{d\Phi(\Delta\Omega, E_\gamma)}{dE_\gamma} = \frac{1}{8\pi} \underbrace{\frac{\langle\sigma v\rangle}{m_\chi^2} \frac{dN_\gamma}{dE_\gamma}}_{Particle\ Physics} \times \underbrace{\bar{J}(\Delta\Omega)\Delta\Omega}_{Astrophysics} \quad \mathrm{cm^{-2}s^{-1}GeV^{-1}}$$

where

Gamma spectrum: typically a continuum with an cut-off at the DM particle mass



and

$$\bar{J}(l,b) = \frac{1}{\Delta\Omega}\int_{\Delta\Omega} d\Omega \int_{los} \rho^2[r(s)]ds$$

HESS point-like obs.: $\Delta\Omega \approx 10^{-5} sr$

Dark matter halo modeling strong dependence; density profile model is needed

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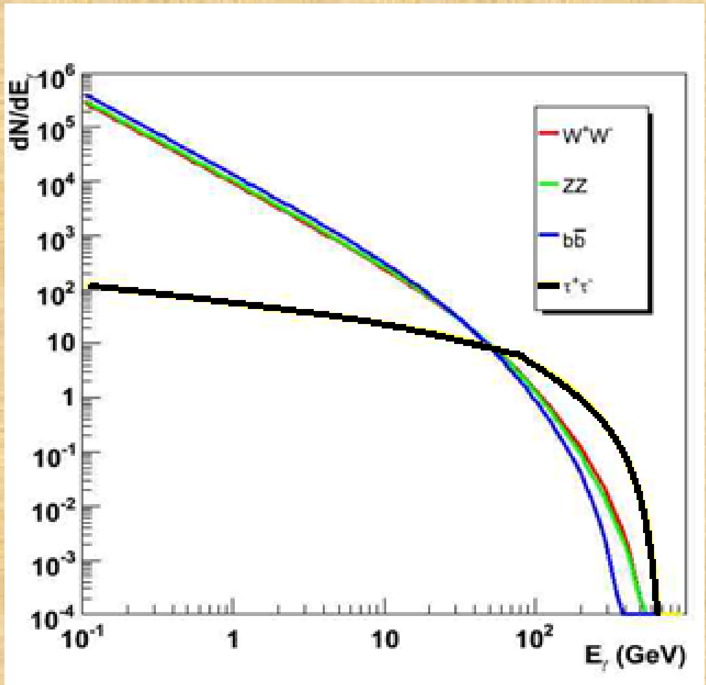

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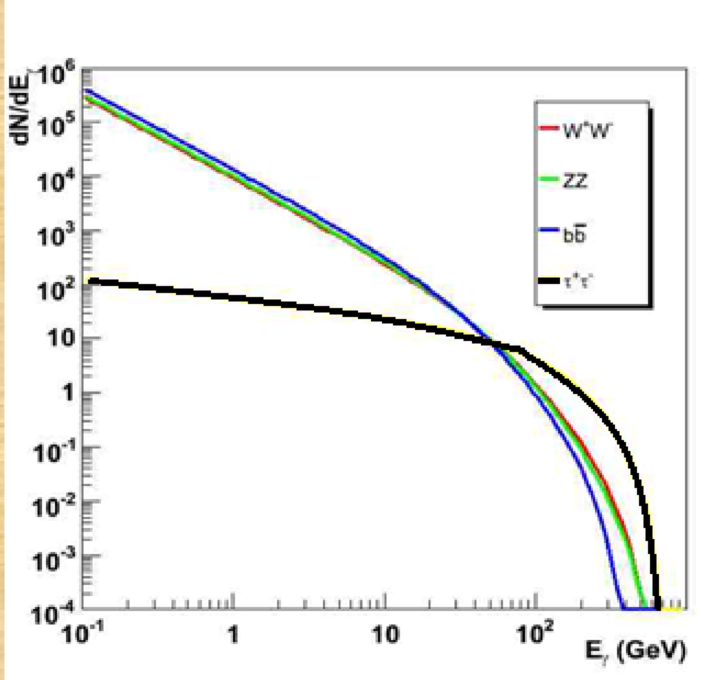

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Dark matter halo modeling strong dependence; density profile model is needed

Dark Matter halo modeling

$$\rho(r) \rightarrow ?$$

- N-body numerical simulations => Cusp profile
- Solution of the Jeans equation(hydrodynamics) => Cored profile

•Two differents types of
DM halo profiles are taken as examples:

-NFW profile: N-body simulations

-cored profile: analytic resolution of the Jeans equation

$$\rho_{NFW}(r) = \frac{A}{r(r+r_s)^2}$$

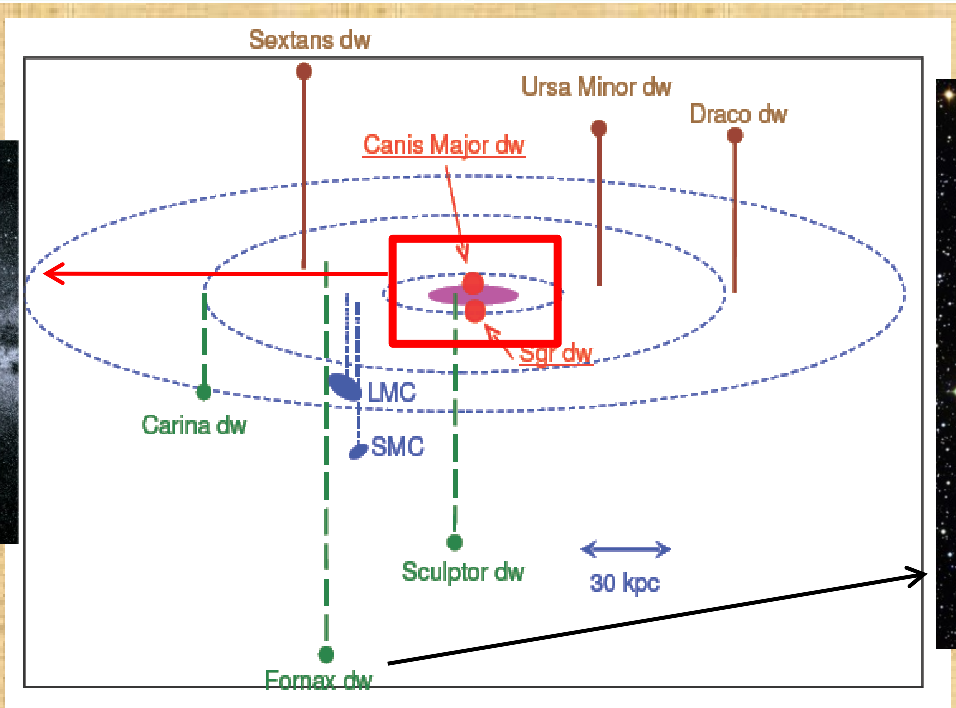
$$\rho_{core}(r) = \frac{v_a^2}{4\pi G} \frac{3r_c^2 + r^2}{(r_c^2 + r^2)^2}$$

The parameters are found after observation of the stars dynamics(luminous density, velocity dispersion, velocity anisotropy…) inside the galaxy

Observation campaigns of dSph galaxies, satellites of the Milky Way

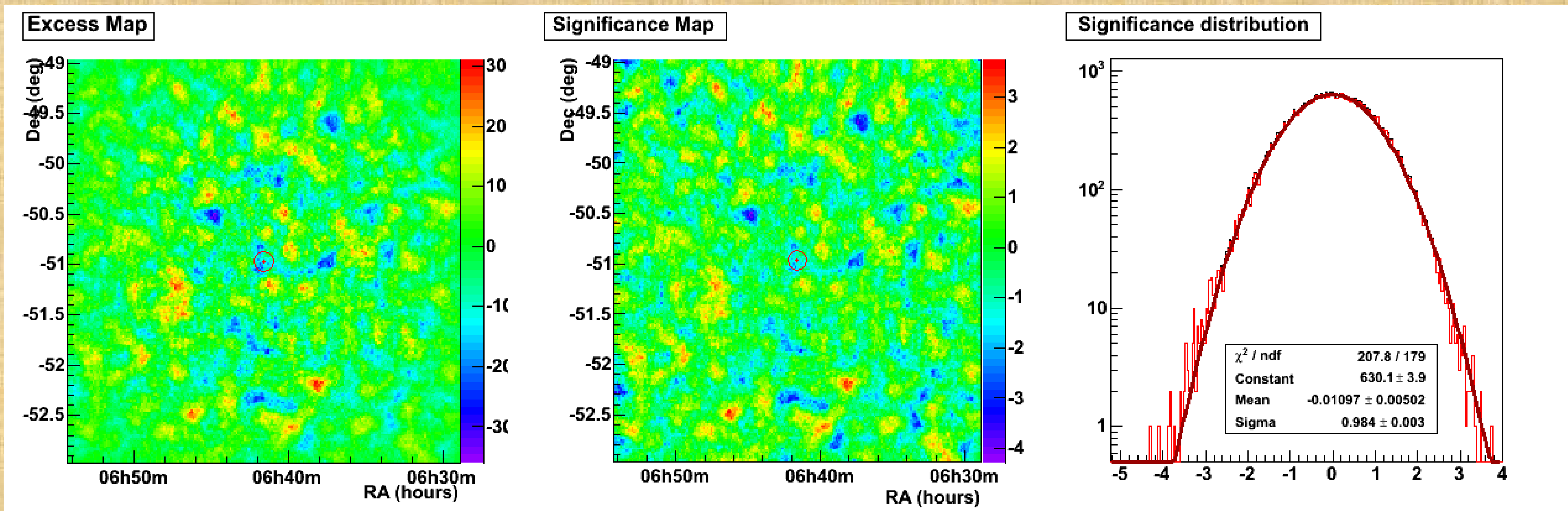
- **Four dSph galaxies (and candidates) studies published (or in process) by HESS**

	d(kpc)	**Virial mass (solar mass)**	**T_{obs} (h)**	**Observation Zenith angle**	**Tidal disruption**
Sagittarius	24	3.0×10^8	11 (> 40 h now)	19°	Yes
Canis Major	8	3.0×10^8 ??	10	10°	Yes
Sculptor	79	1.0×10^9	11.8	14°	**No**
Carina	101	2.0×10^8	14.8	34°	+/-

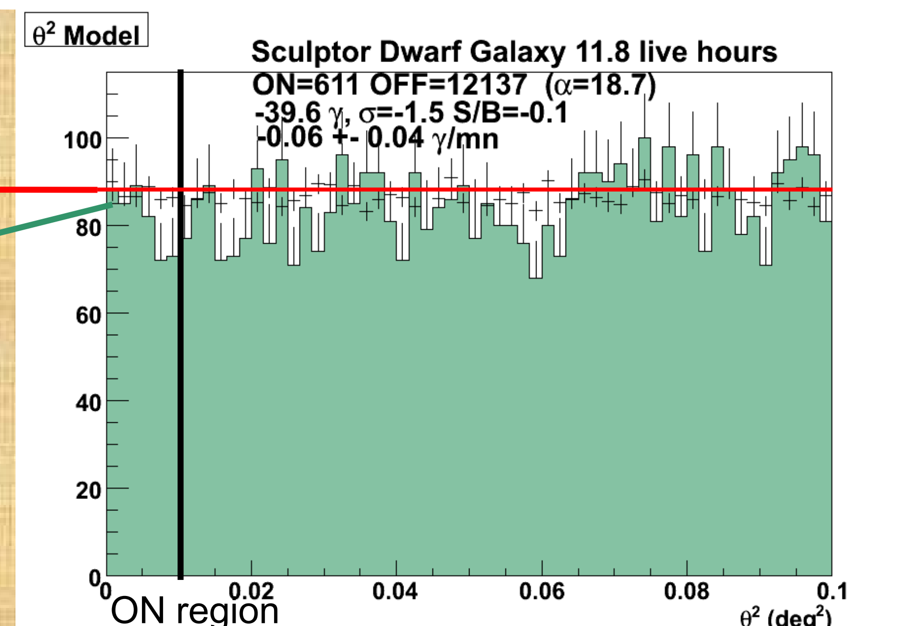


Sensitivity curves to DM annihilation

Observations: signal + background
Carina:



No significant gamma excess at target position



Estimated background

Observed gamma-ray candidates

« Measured »

$$N_\gamma^{95\%C.L.}$$

Upper limit on the number of « true » gamma-rays

Sensitivity curves to DM annihilation

Expected:

$$N_\gamma^{95\%}(\sigma v, m_{DM}) \propto \frac{d\Phi}{dE}(\sigma v, m_{DM}, \bar{J}) \times (active\ area) \times time$$

- Comparing the mesured N^{95} to the expected N^{95} => Upper limit on σv

$$\langle \sigma v \rangle_{DM}^{95\%C.L.}(m_{DM}, \bar{J})$$

➢ the velocity-weighted cross-section is then calculated as function of the DM particle mass

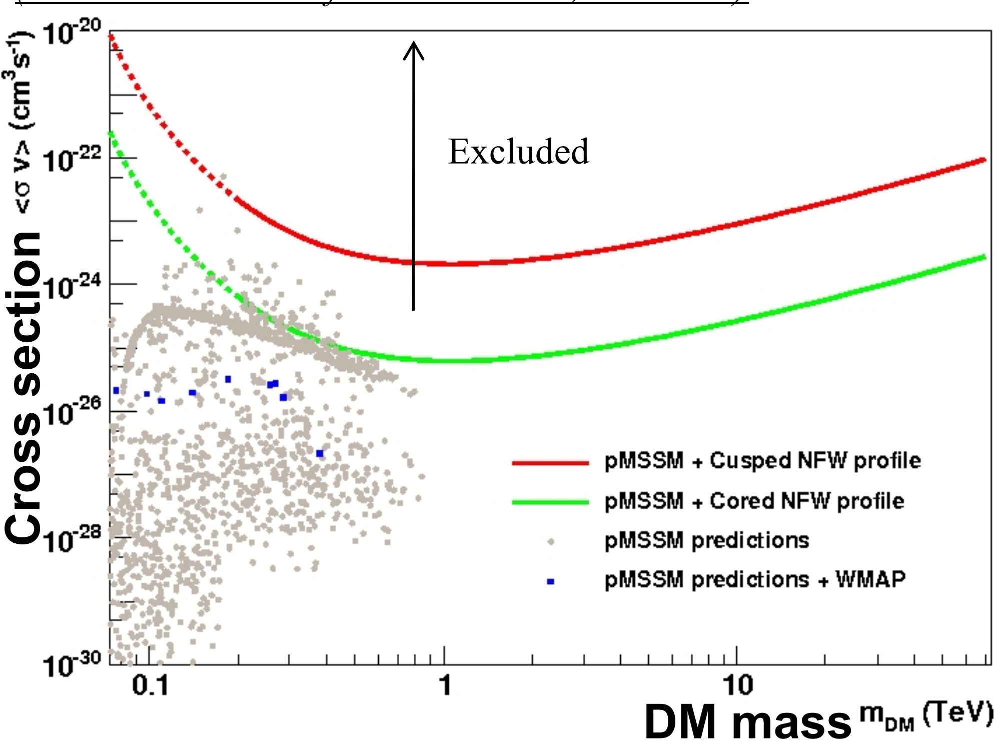
➢ two candidates of Dark Matter particle are usually studied: - neutralino (SUSY)
- Kaluza-Klein (UED) particles

Sensitivity curves for Sagittarius dSph and Canis Major overdensity

Constraints on dark matter sensitivity curve at 95% C.L.:

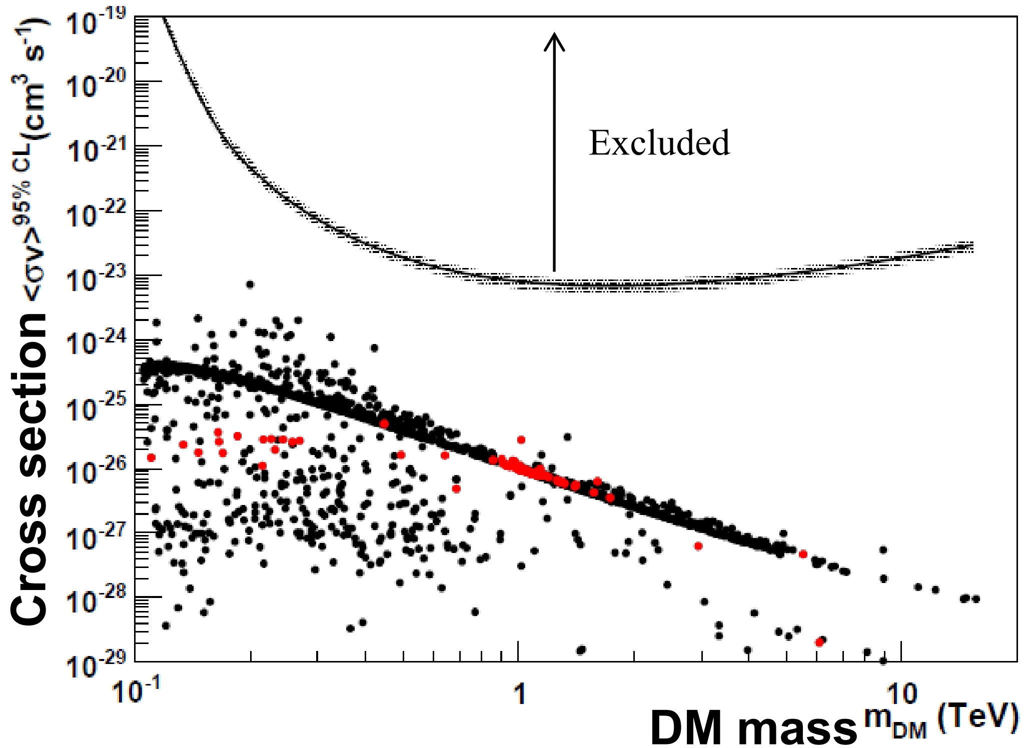
(HESS Collaboration (F. Aharonian et al.) Astropart.Phys 2007)

(See also C. Farnier for HESS colab., IDM2008)



Sagitarius dSph

(HESS Collaboration (: F. Aharonian et al.). ApJ 2008)



Canis Major

$$\bar{J} = 0.07 - 2.6\bar{J}_{NFW}^{GC}$$

Large uncertainty

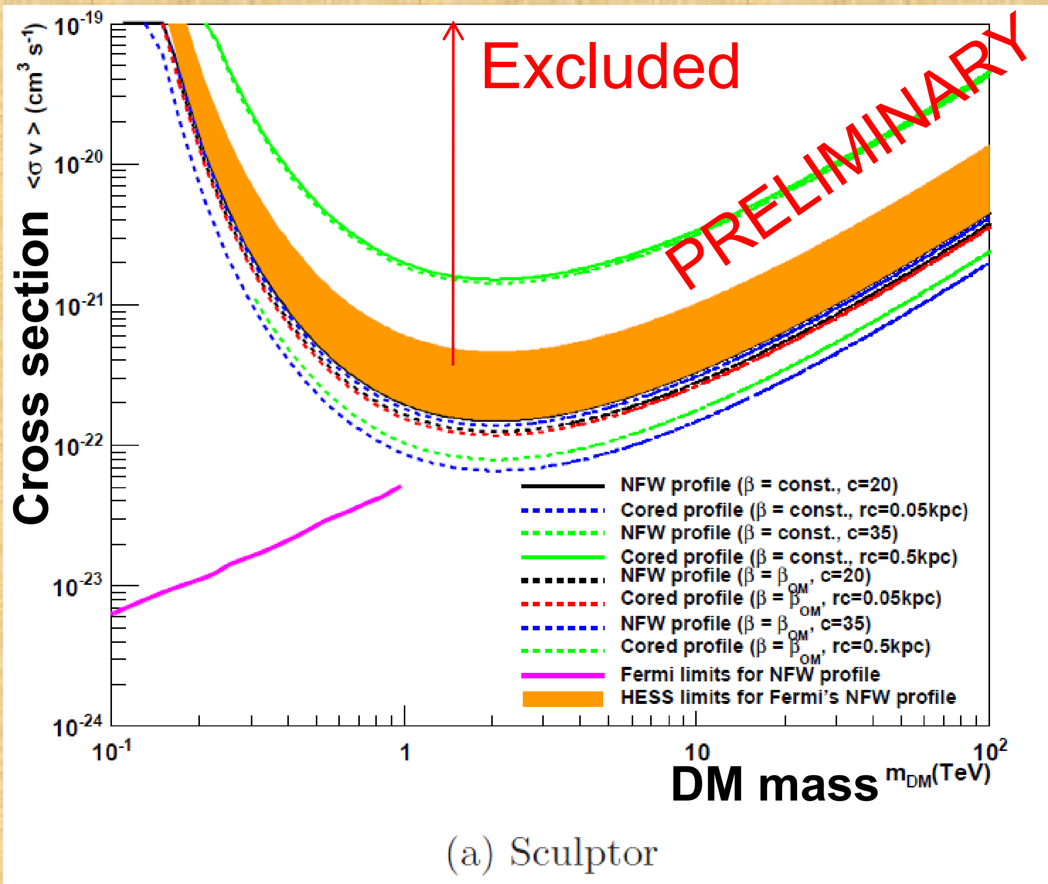
- Some pMSSM models with higgsino-like neutralino excluded
- **BUT** halo modeling of Sgr dSph too hard due to tidal stripping

$$\bar{J} = 0.2\bar{J}_{NFW}^{GC}$$

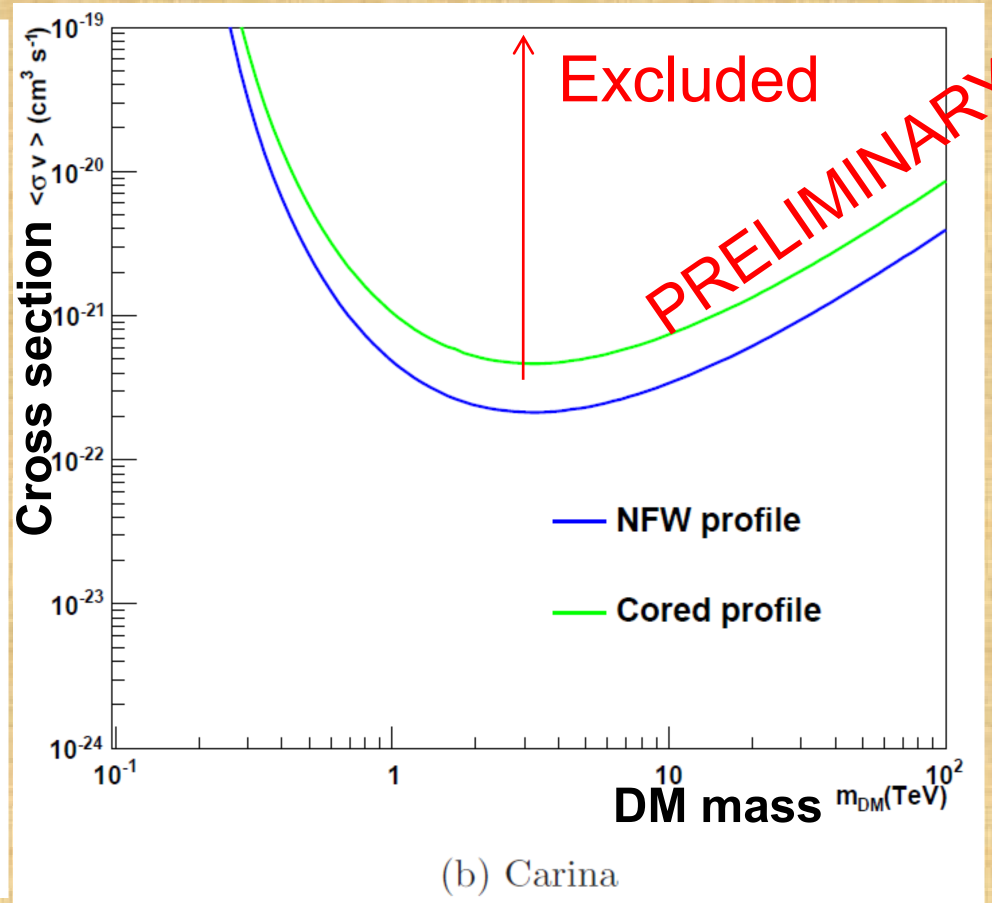
- Disrupted dwarf galaxy or simply a part of the warped Galactic disk?
- On the assumption of a dSph it has a very delicated halo modeling

Sensitivity curves for Sculptor and Carina dSph

Constraints on dark matter sensitivity curve at 95% C.L.:



(a) Sculptor



(b) Carina

$$\bar{J} = 0.2 - 2.2 \times 10^{-2} \bar{J}^{GC}_{NFW}$$

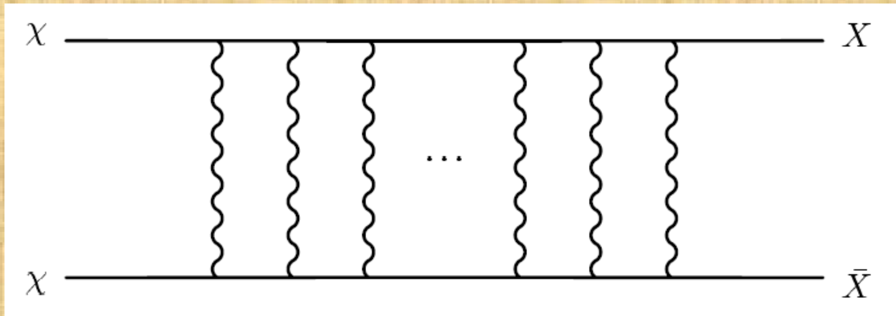
$$\bar{J} = 0.7 - 1.5 \times 10^{-3} \bar{J}^{GC}_{NFW}$$

- Similar analyses were made for both galaxies
- Various DM halo profile were studied in the case of Sculptor => helps to estimate the errors due to the halo modeling
- Complementary constrains from Fermi on Sculptor
- No Fermi result for Carina

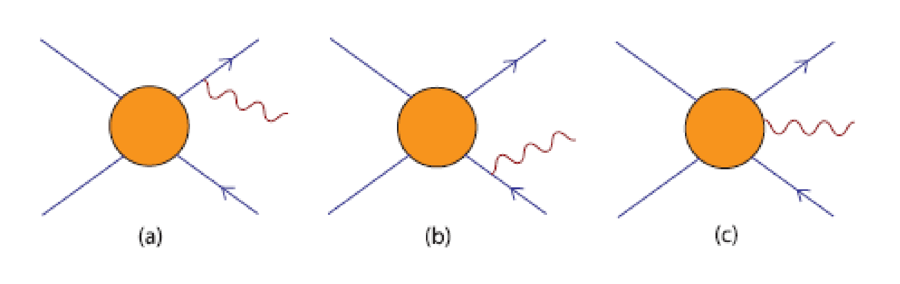
Gamma-ray signal enhancement effects

The gamma-ray flux can be enhanced by changes in the particle physics nature or the particle density distribution(astrophysics)

• From particle physics:

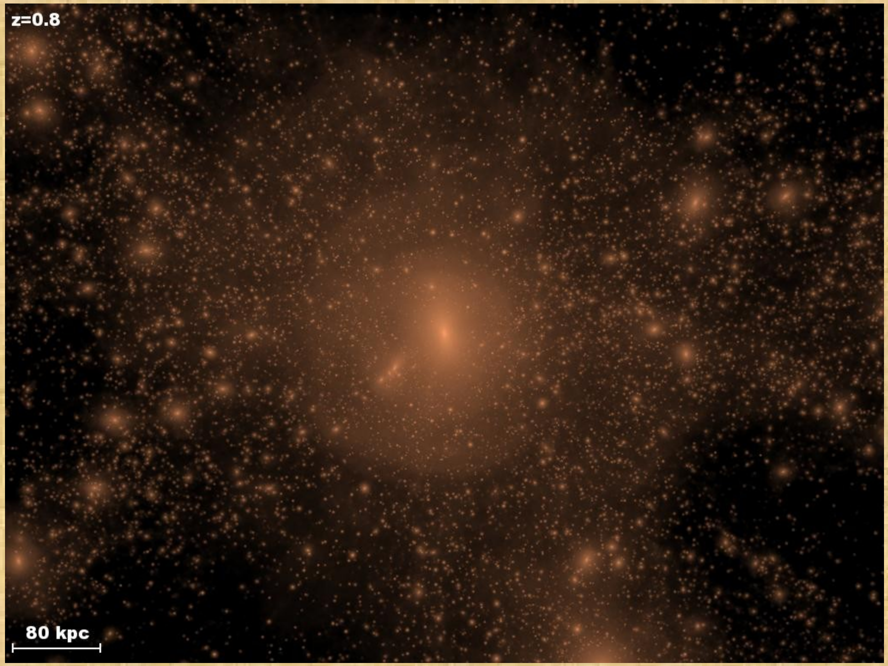


- *Boost in the annihilation cross-section;*
- *New contribution in the annihilation spectrum;*



• From astrophysics:

- *Contribution of the substructures(sub-halos) to the overall density <= $\langle\rho^2\rangle/\langle\rho\rangle^2$*

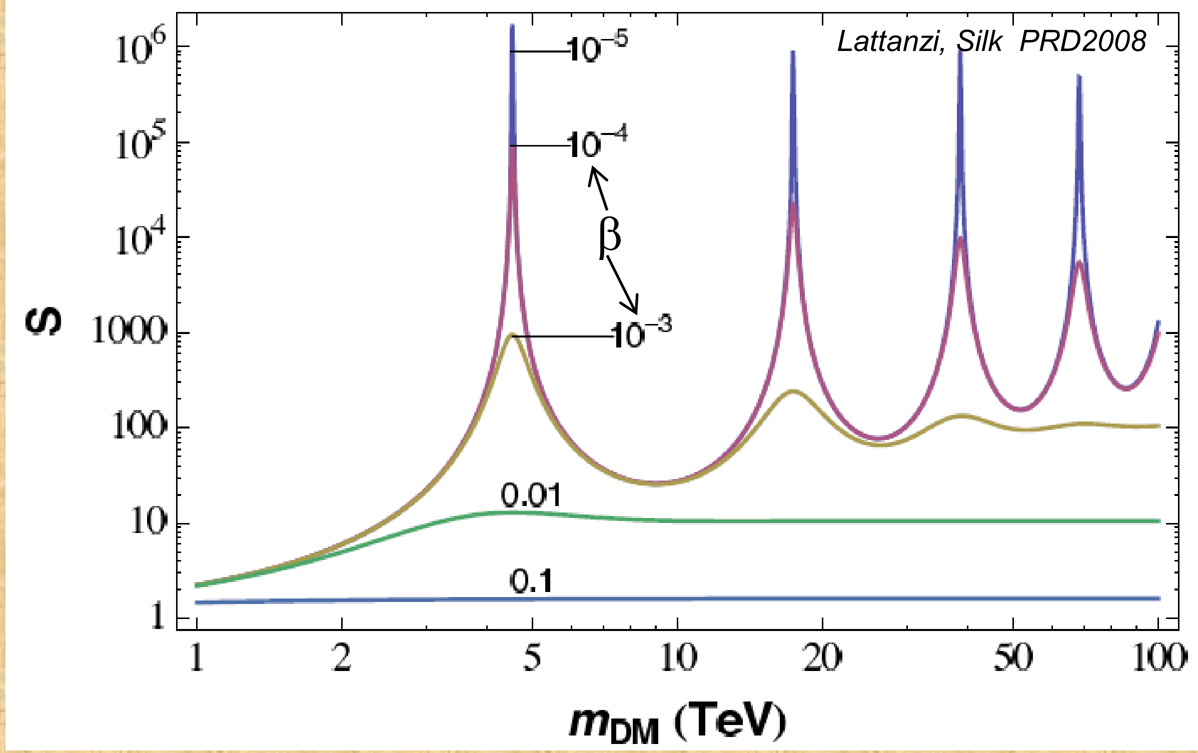


Gamma-ray signal enhancement effects

• **Particle physics enhancements: i) Sommerfeld effect**

Low velocity QFT(Schrodinger equation) effect due the interaction of the DM particles with a Yukawa potential(weak force) in its annihilation procces

$$\langle \sigma v \rangle = S \langle \sigma v \rangle_o$$



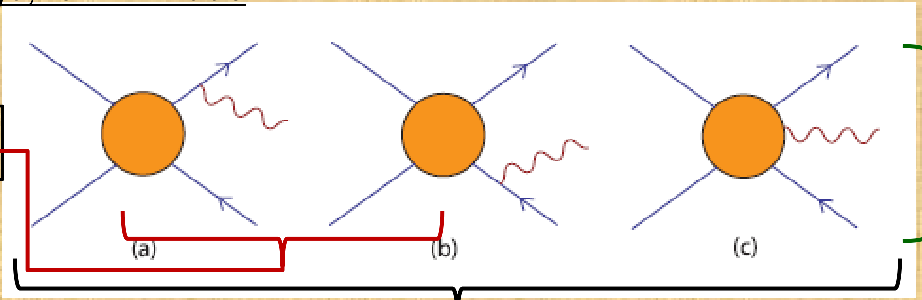
Very effective on the low-velocity regime!!

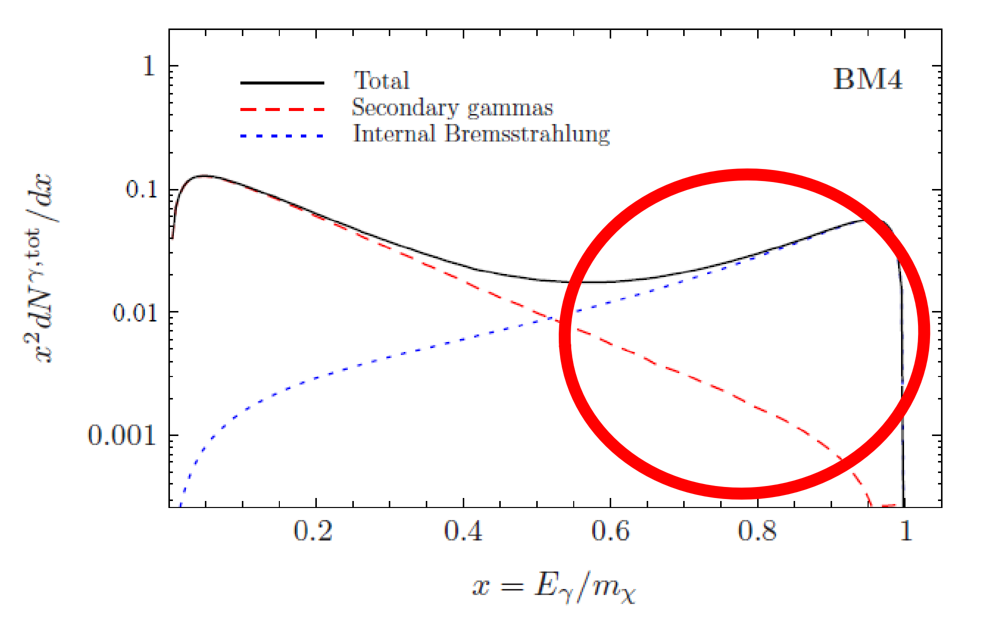
DM particles velocity dispersion:
~10.0 km/s for Sculptor
~7.5 km/s for Carina

Gamma-ray signal enhancement effects

• **Particle physics enhancements: ii) Light charged particles**

« Whenever WIMPs annihilate into pairs of charged particles, this process will with a finite probability automatically be accompanied by internal bremsstrahlung, i.e. the emission of an additional photon in the final state »
Bringmann, Bergstrom and Edsjo, JHEP 2008





$$\frac{dN_{W^+W^-}}{dx} \approx \frac{\alpha_{em}}{\pi} \frac{4(1-x+x^2)^2}{(1-x+\epsilon/2)x} \times \left[\log\left(2\frac{1-x+\epsilon/2}{\epsilon}\right) - 1/2 + x - x^3\right], \quad (8)$$

• **Contribution will depend on the HESS acceptance in the energy range**

• **In the wino case only significant for $E_\gamma > m_\chi/2$**

Gamma-ray signal enhancement effects

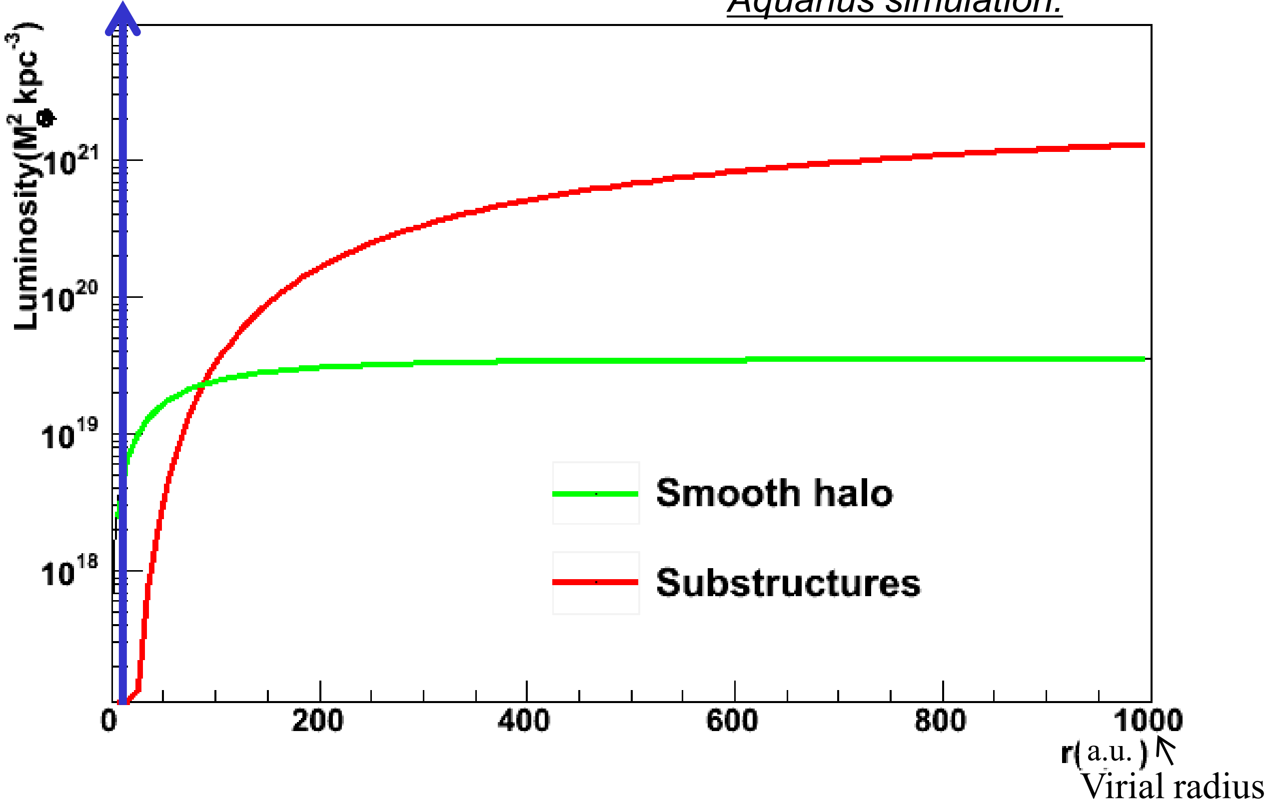
- **Astrophysics enhancements i.e. galactic substructures(« Clumps») :**

Motivations: simulations are scale invariant,
enhancement may be important inside dSph

Flux completely dominated by the smooth halo contribution

HESS ON region for point-like searches

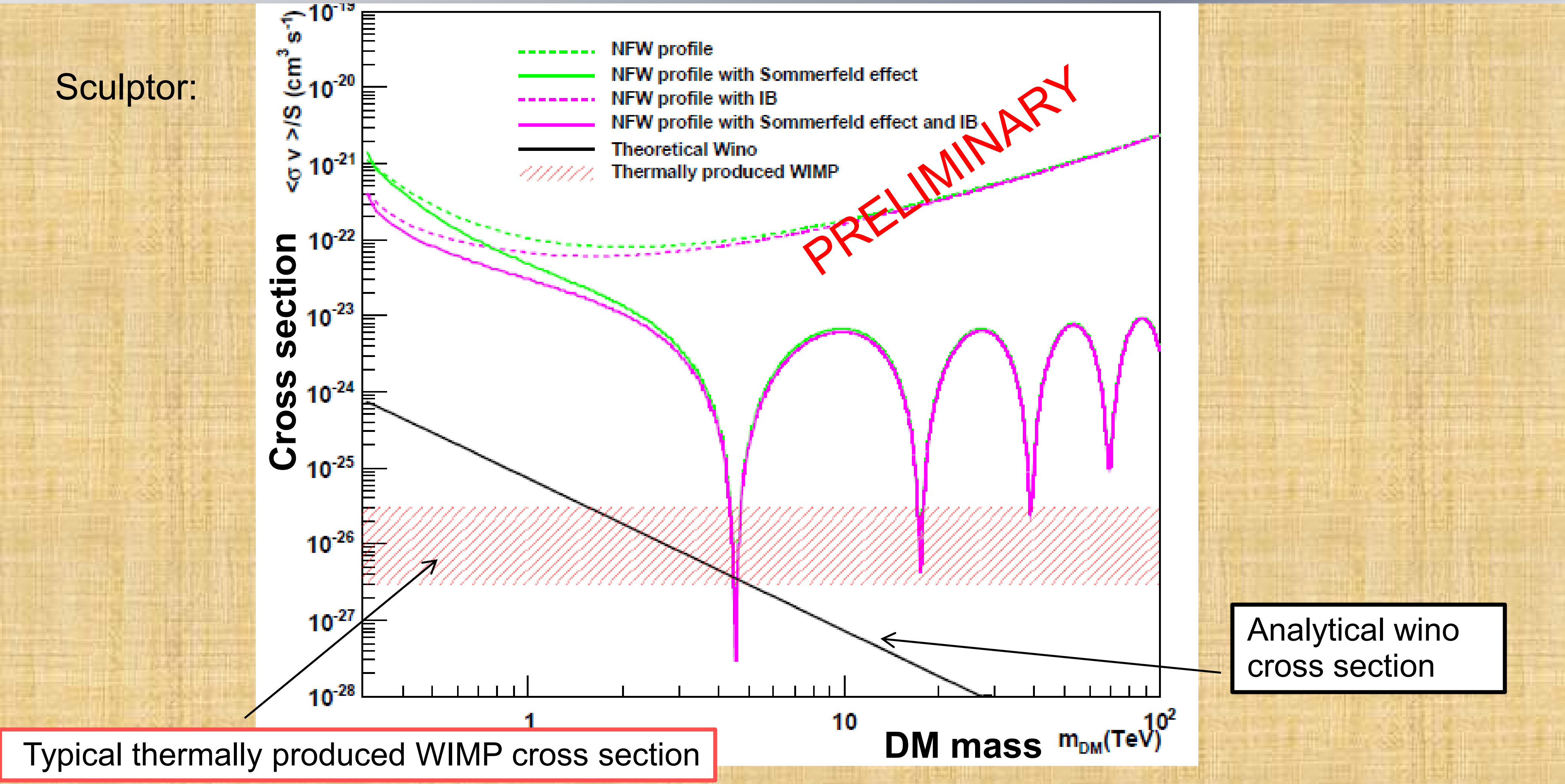
Pinzke, Pfrommer and Bergstrom, PRL 2009:
Aquarius simulation:



BUT No significant effect towards dSphs center in a point-like analysis

Gamma-ray signal enhancement effects

Sculptor:



- **Resonant exclusion limits with Sommerfeld effect**
- **Internal Bremstrahlung only significatif for low DM particle mass**

Summary

• **Several Dwarf Spheroidals galaxies studied by HESS collaboration**

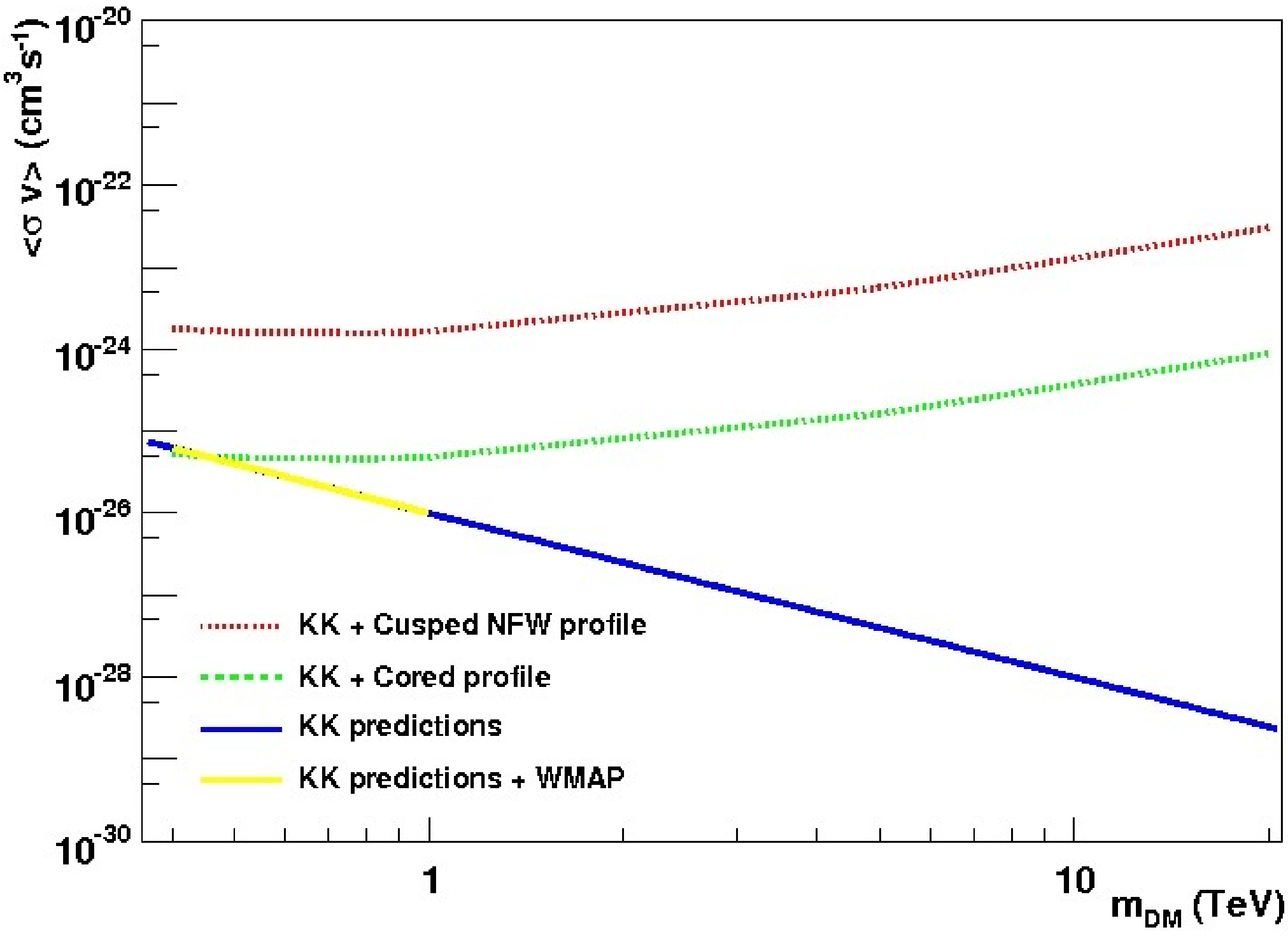
• **Observations of Sagittarius, Canis Major, Carina and Sculptor dSph didn't show any signal => constraints on Dark Matter self-annihilation cross-section**

• **despite no signal detection so far, dSph remains as one of the most promising enviroments for Dark Matter searches**

	Motivations	**Results**	**Issues**
Sagittarius	• small distance from us • DM-dominated environment	•Some pMSSM models with higgsino-like neutralino excluded	• halo modeling very uncertain • interaction with the MW disk must have disrupted it
Canis Major	• small distance from us • overdensity environment	• strong constraints	• astrophysical nature under dispute • very disrupted by tidal effects
Sculptor/ Carina	• far from the MW disk and center • no significant disruption(at least in Sculptor case…)	• large DM halo profile uncertainty coverage • strong constraints with Sommerfeld effect	• large distance from the sun ($1/D^2$)

Backup slides

Constraints on Kaluza_Klein dark matter
Sensitivity curve at 95% C.L.



Kaluza-Klein model predictions are analytic:

$$\langle \sigma v \rangle = \frac{95 g_1^4}{324 \pi m_{LKP}^2}$$

$$\simeq \frac{1.7 \times 10^{-26}\ \mathrm{cm}^3/\mathrm{s}}{(m_{LKP}/\mathrm{TeV})^2}.$$

Some KK models providing a relic density compatible with WMAP constraints are excluded in the case of the cored profile

Sculptor dSph

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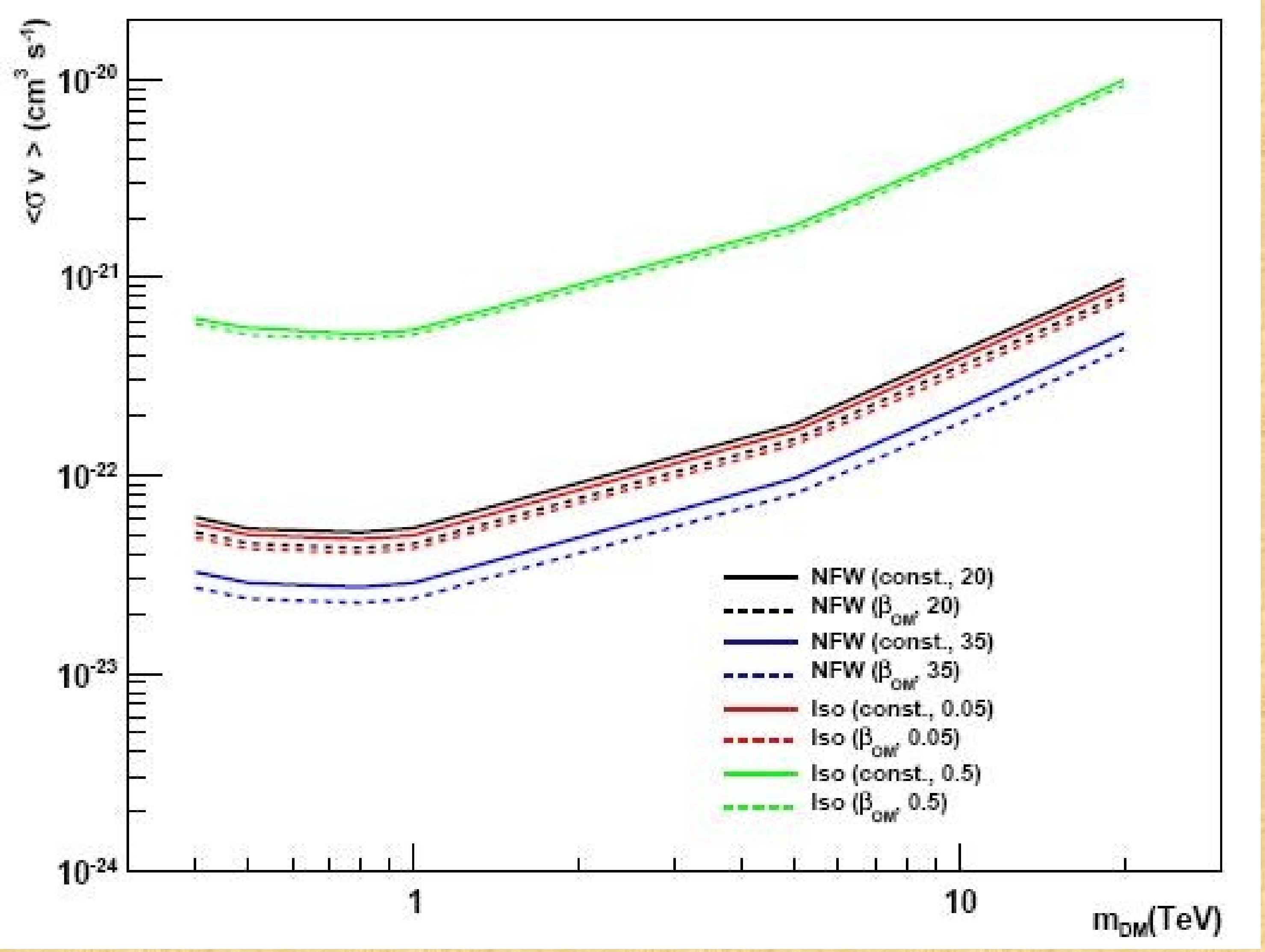

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Dark Matter halo modeling

•From Jeans Equation: $M(r) = r\langle v_r^2 \rangle \left(\frac{d\ln\rho}{d\ln r} + \frac{d\ln\langle v_r^2 \rangle}{d\ln r} - 2\beta \right)$

- $\langle v_r^2 \rangle$: radial velocity dispersion
- ρ: luminous density
- M: luminous + dark mass
- β: anisotropy

($\langle v_r^2 \rangle$ and ρ: observed; M and β: unknown)

•Assumed ⟶ $\beta(r)$
- solve for M(r) to get ρ_{dark}
OR
- fit DM halo parameters to $\langle v_r^2 \rangle$

•Two differents types of DM halo profiles are produced:

-NFW profile: fit of (A, r_s) parameters to $\langle v_r^2 \rangle$

-cored profile : $\langle v_r^2 \rangle$ assumed to be flat
- ⇒ analytic resolution of the Jeans equation

$$\rho_{NFW}(r) = \frac{A}{r(r + r_s)^2}$$

$$\rho_{core}(r) = \frac{v_a^2}{4\pi G} \frac{3r_c^2 + r^2}{(r_c^2 + r^2)^2}$$

Sensitivity curves to DM annihilation

$$N_\gamma = T_{\rm obs} \int_0^{m_{DM}} A_{\rm eff}(E_\gamma) \frac{d\Phi(\Delta\Omega, E_\gamma)}{dE_\gamma} dE_\gamma$$

- **The 95% C.L. limit on Nγ provides a 95% C.L. limit on the velocity-weighted cross section for a given DM profile:**

$$\langle \sigma v \rangle_{\rm min}^{95\%\, C.L.} = \frac{8\pi}{\overline{J}(\Delta\Omega)\Delta\Omega} \times \frac{m_\chi^2 \, N_{\gamma,tot}^{95\%\, C.L.}}{T_{\rm obs} \int_0^{m_\chi} A_{eff}(E_\gamma) \frac{{\rm d}N_\gamma}{{\rm d}E_\gamma}(E_\gamma)\, {\rm d}E_\gamma}$$

➢ **the velocity-weighted cross-section is then calculated as function of the DM particle mass**

➢ **two candidates of Dark Matter particle are usually studied:**
- neutralino (SUSY)
- Kaluza-Klein (UED) particles

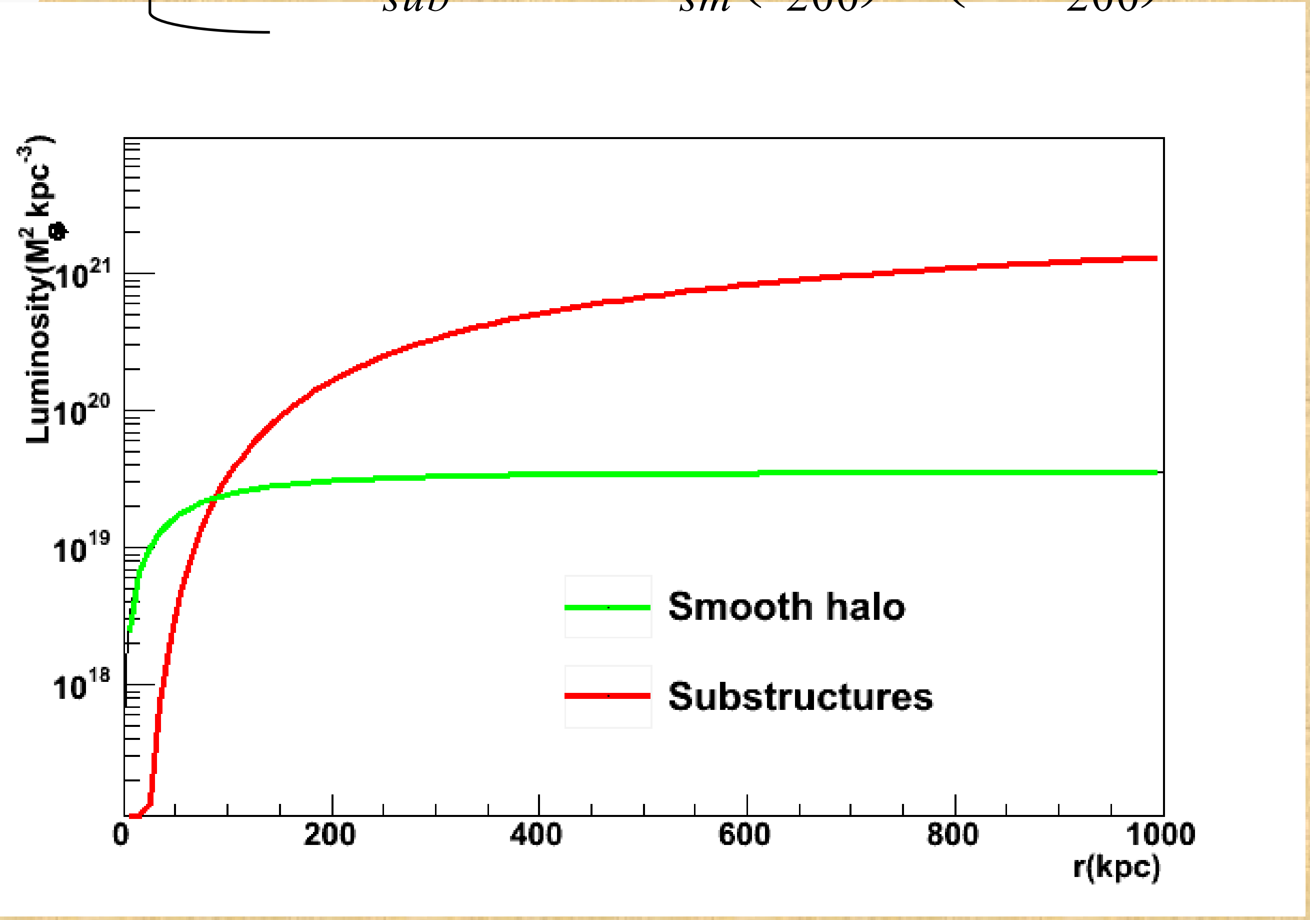
Gamma-ray signal enhancement effects for Fornax Cluster (1)

- **Astrophysics enhancements i.e. galactic substructures(« Clumps») :**

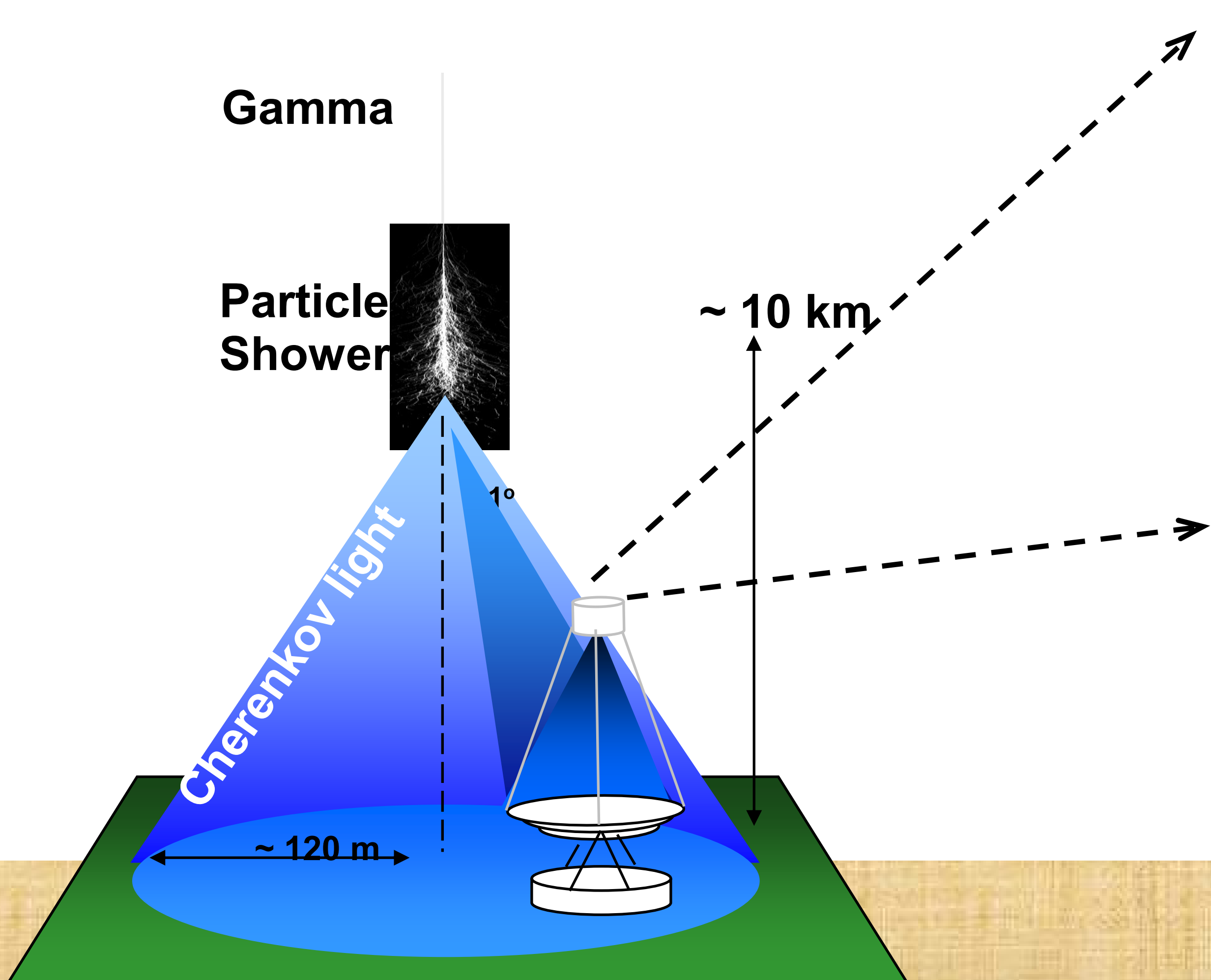
Luminosity

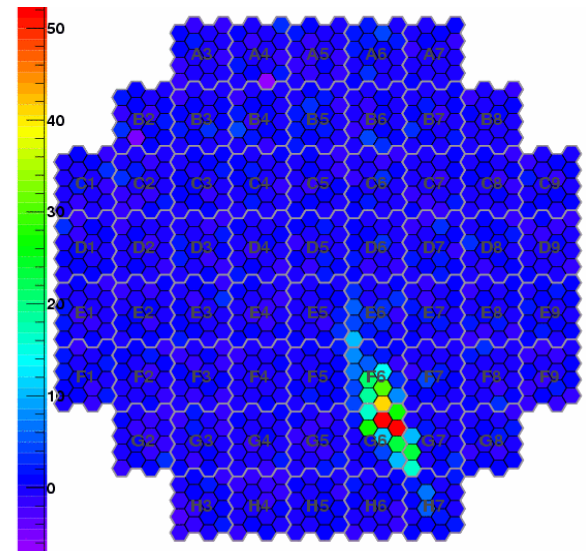
Halo → $$L_{smooth}(r) \approx 4\pi \int_0^r r' \rho^2(r')dr'$$

Substructures → $$L_{sub} = C * L_{sm}(r_{200}) * (r/r_{200})^{(0.8*(r/r_{200})^{(-0.315)})}$$



Imaging Atmospheric Cherenkov Telescopes technique





<u>Stereoscopy</u>:
- **Reconstruction of the primary gammas**
- **Improve the hadron rejection**
- **Capacity to construct gamma maps**