LATEST RESULTS ON SEARCHES FOR DARK MATTER SIGNATURE IN GALACTIC AND EXTRAGALACTIC SELECTED TARGETS BY THE MAGIC TELESCOPES

Topics in Astroparticle and Underground Physics
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OUTLINE

- Brief introduction:
  Dark Matter, WIMPs, indirect searches, possible targets

- *Florian Goebel* MAGIC telescopes

- DM searches with the MAGIC telescopes:
  Status of the study

- Results already reached and prospects for the near future

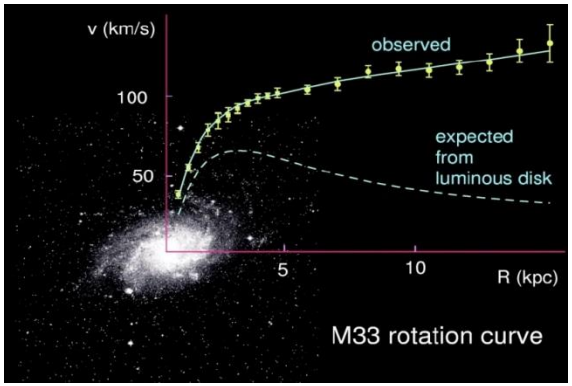
- Summary/Outlook

At the TAUP talks of:
A. Challinor
S.Bridle

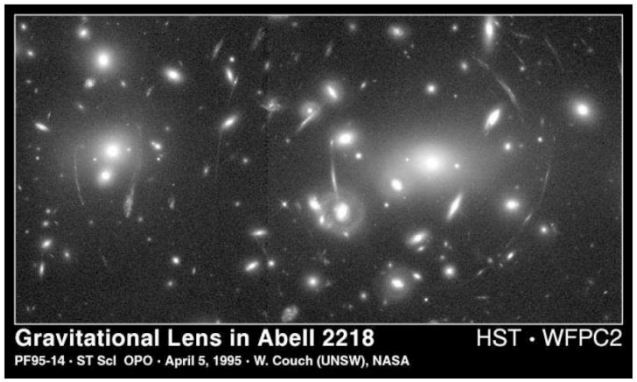
DARK MATTER

- Compelling evidences for a large (~85%) non-baryonic component of the matter density of the Universe at all astrophysical scales

Galaxy rotational curves

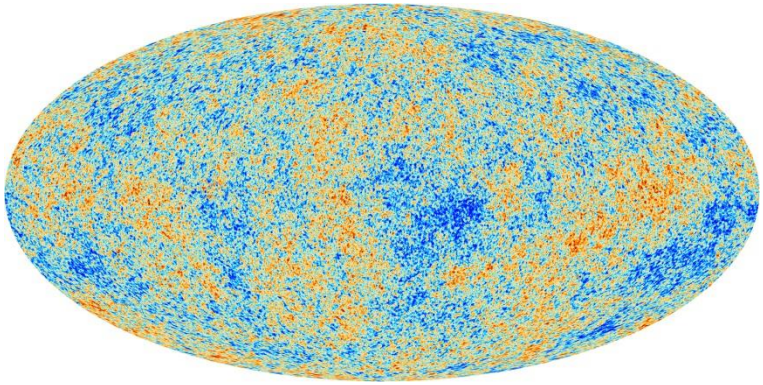


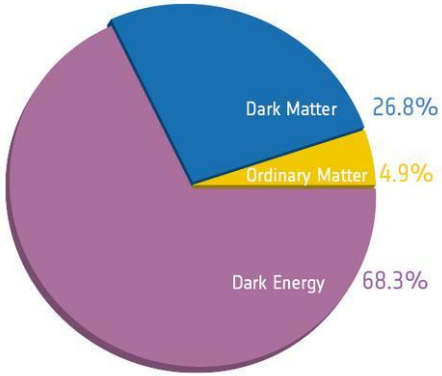
Gravitational lensing



Clusters of galaxies

CMB anisotropies





CDM model seems to fit all current cosmological data

Planck Coll. 2015, arXiv:1502.01589

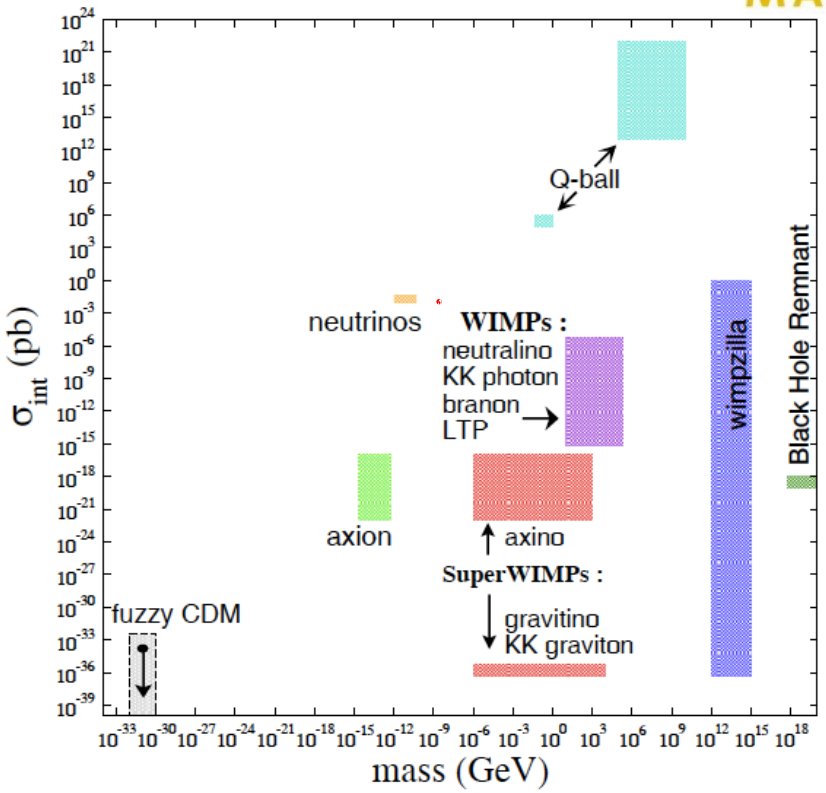
At the TAUP plenary session talks of: P.Gongolo

WIMPs

- Standard Cosmological scenario:
Λ-Cold-Dark-Matter (ΛCDM), Ω_{DM}~0.27

- Several SM extensions contain WIMP candidates: Supersymmetry (SUSY), minimal SM extensions, extra dimensions models, and others

- WIMPs are a class of particularly interesting CDM candidates:
  - Neutral electric
  - Interaction at weak scale
  - Stable on cosmological scales
  - Correct relic density
  - NON-BARYONIC



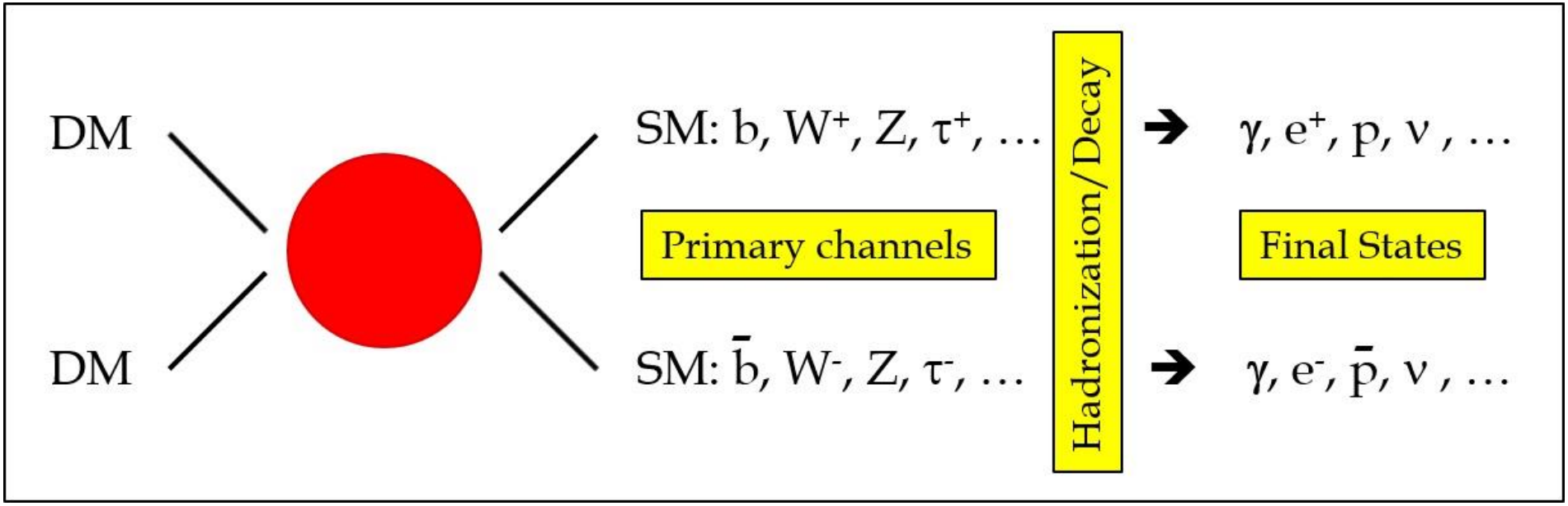
Present WIMPs mass range:
$m_{DM} \gtrsim 10$ GeV up to tens of TeV

$\langle\sigma v_{ann}\rangle \sim 3 \times 10^{-26}$ cm$^3\cdot$ s^{-1}

At the TAUP talks of: M.Cirelli

INDIRECT DARK MATTER SEARCHES

- Indirect searches for detection of SM products (**including gamma-rays**) from annihilation or decay of Dark Matter particles:



- We are looking for gamma-rays as final states because:
  - undeflected by magnetic field
  - trace back to abundance / distribution of DM
  - show peculiar spectral features (*smoking guns*)

INDIRECT DARK MATTER SEARCHES

- Expected gamma-ray fluxes:

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

	Particle Physics factor:	Astrophysical factor:
Annihilation:	$\frac{d\Phi^{\mathrm{PP}}}{dE'} = \frac{1}{4\pi}\frac{\langle\sigma_{\mathrm{ann}}v\rangle}{2m_\chi^2}\frac{dN}{dE'}$	$J_{\mathrm{ann}}(\Delta\Omega) = \int_{\Delta\Omega}\int_{los}\rho^2(l,\Omega)dl d\Omega.$
Decay:	$\frac{d\Phi^{\mathrm{PP}}}{dE'} = \frac{1}{4\pi\,\tau_\chi m_\chi}\frac{dN}{dE'}$	$J_{\mathrm{dec}}(\Delta\Omega) = \int_{\Delta\Omega}\int_{los}\rho(l,\Omega)dl d\Omega.$
	Large uncertainties from Fund. Phys. No target dependences (straightforward stacking analysis)	Large uncertainties from DM profiles (robust limits from less uncertain targets)

GALACTIC AND EXTRAGALACTIC TARGETS

- *Galactic center*
  + High *J-factor*
  − Very high astroph. bkg
  − Uncertainties on inner DM distribution
  − Southern Hemisphere

- *Galactic halo*
  + High *J-factor*
  − Not fully-free from astroph. bkg
  − Extended
  − Southern Hemisphere

- *DM Clumps*
  + Free from astroph. bkg
  + Nearby and numerous
  − To be found!
  − Bright enough?

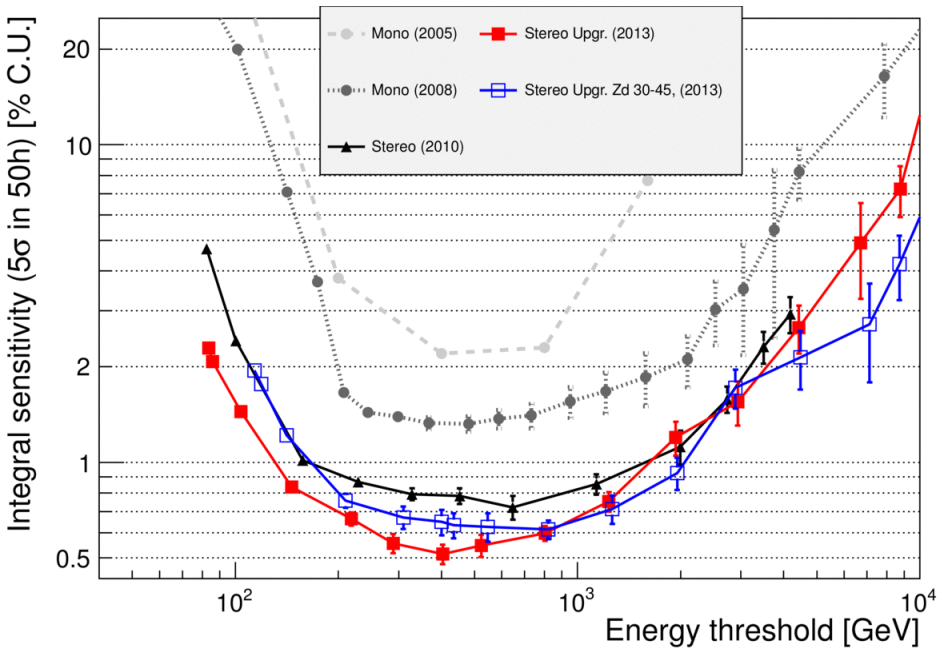
- *Galaxy Clusters*
  + Huge amount of DM
  − High astroph. bkg
  − Extended
  − High uncertainties on *J-factors*

- *Dwarf Spheroidal Galaxies(dSphs)*
  + DM dominated (high M/L ratios)
  + Free from astroph. bkg
  + Close (<~100 kpc)
  + Slightly extended at most
  + Less uncertainties on *J-factor*
  − *J-factors*~100 lower than for GC

At the TAUP plenary session talks of: D.Horns on gamma-ray astronomy from the ground

MAGIC TELESCOPES PERFORMANCE

Aleksić et al DOI:10.1016/j.astropartphys.2015.02.005, arXiv:1409.5594



Short history...

MONO

STEREO

UPGRADE

- MAGIC-1 (M1) located on the Canary Island of La Palma has started operation since 2004
- MAGIC-2 (M2) is operating togh. with M1 in stereo-mode since 2009
- Electronics and MAGIC-1 camera upgrade during 2011 – 2012

Now stereo system is in a period of steady observations

* Best sensitivity (low zenith angle): (0.66 ±0.03) % Crab in 50h above 220 GeV
* Energy range detection (~ 50 GeV,~ 50TeV)
* Angular resolution 0.07° at energy of few hundreds GeV
* Energy resolution 15% (low zenith angle in the range of a few hundred GeV)
* Point spread function (PSF) ~ 0.1°

MAGIC RESULTS ON dwarf spheroidal galaxy: SEGUE 1

(*Aleksić et al. JCAP 02 (2014) 008*)

SEGUE 1	
Coordinates	$10^h\ 07^m\ 04^s$, $+16°\ 04'\ 55''$
Distance	23±2 kpc
Number of resolved stars	71
Magnitude	$-1.5^{+0.6}_{-0.8}$
Apparent magnitude	13.8±0.5
Luminosity	340 $L_\odot$
Mass	$5.8^{+8.2}_{-3.1} \times 10^5\ M_\odot$
M/L	$\sim$3400 $M_\odot/L_\odot$
Half-light radius	29^{+8}_{-5} pc

- One of the most DM dominated object known
- The clostest dSphs of the Local Group (Northern hemisphere)
- No background in VHE gamma-rays of stellar origin
- Very close to be a point-like source for MAGIC
- Low zenith angle (13-35 deg) at the MAGIC site (-> low Energy threshold)

Einasto DM profile

- $J_{ann} = 1.1\ 10^{19}\ GeV^2\ cm^{-5}$
- $J_{dec} = 2.6\ 10^{17}\ GeV\ cm^{-2}$

Favorable target to evaluate expected DM annihilation signal. It has been observed by MAGIC in mono-mode and then in stereo (optimized analysis)

MAGIC RESULTS ON dwarf spheroidal galaxy: SEGUE 1

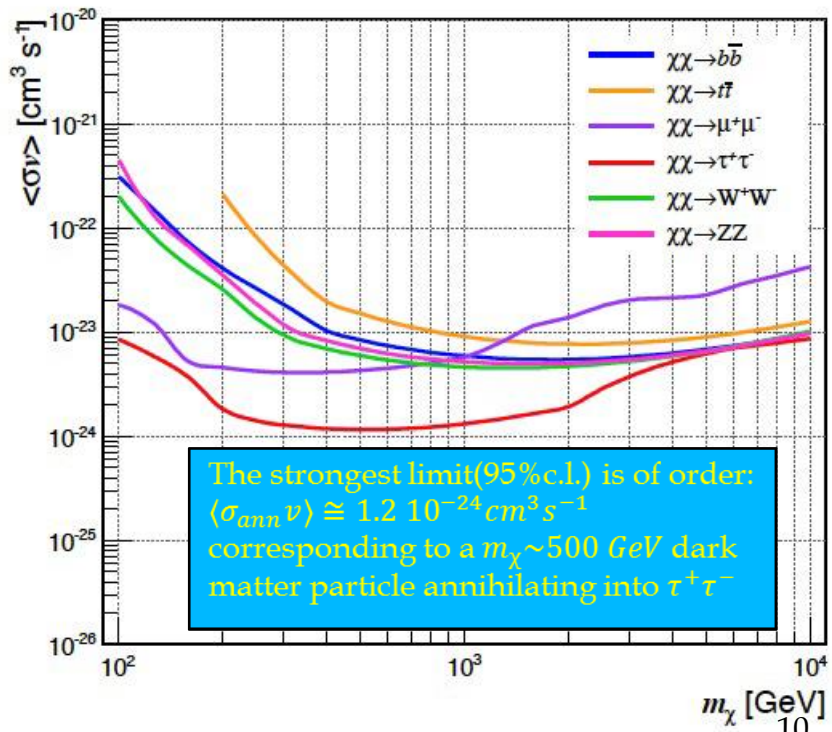
(*Aleksić et al. JCAP 02 (2014) 008*)

For the first time in the Cherenkov Astronomy the **Full-likelihood analysis** (*Aleksić et al.(JCAP 10 (2012) 032*) has been used:
It takes advantage from the expected spectral shape to improve constraints on <σv> (boost in sensitivity by a factor ~2)

Search for annihilation and decay into different final states using the parameterization from *Cembranos et al.* (*Phys. Rev. D83, 2011*)

158 hours of stereo observation(2011-13):

- **deepest survey of any dSph by any IACTs**
- **dedicated analysis optimized for spectra with features**
- **factor ~10 better sensitivity wrt mono observations**
- **strongest limits on various models from dSphs with IACTs**

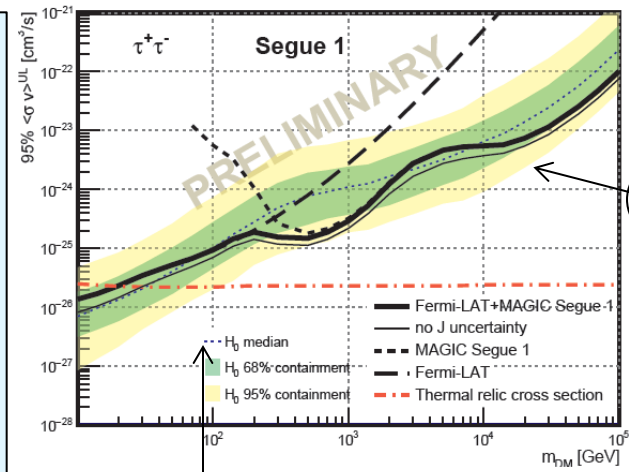


MERGING MAGIC RESULTS OF SEGUE 1 WITH FERMI-LAT RESULTS ON dSphs

J.Rico, M. Wood, et al arXiv:1508.05827v2

The universality of DM properties allows the combination of data from different experiment: <u>The first MAGIC/Fermi-LAT joint dark matter annihilation signal from dSphs</u>

- Combination of 158 hours of observations of Segue 1 by MAGIC with 6-years observations of 15 dwarf satellite galaxies by the Fermi-LAT processed with the latest (Pass8) data analysis
- limits on the annihilation cross-section for dark matter particle masses between 10 GeV and 100 TeV (the widest range so far explored)
- The combination provides a significant improvement in the range between 1 and 30 TeV (for bb_{bar}) or 0.2 and 2 TeV (for $\tau^+\tau^-$, here shown)
- maximum improvement of the combined limits with respect to the individual ones by a factor 2 at a mass of 500 GeV (for bb_{bar}) and 3 TeV (for $\tau^+\tau^-$, here shown)

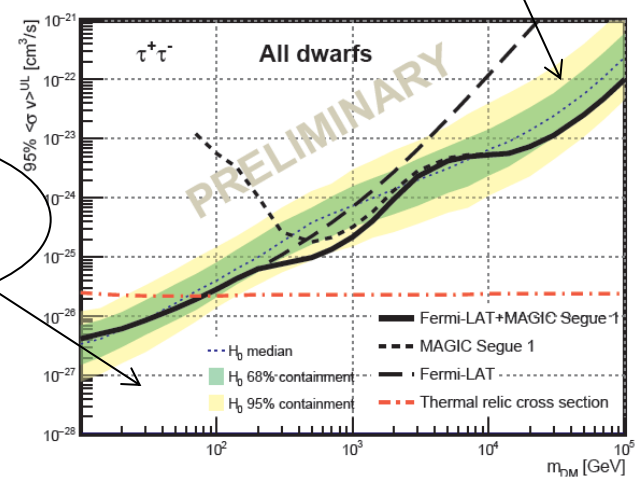


No DM-signal detected

First time

DM annih limits to particle mass above 10 TeV .(mass region fully dominated by MAGIC)

DM annih.limits below thermal relic (mass region fully dominated by Fermi-LAT)



MAGIC CAMPAIGN ON THE PERSEUS CLUSTER

Mass $10^{15}\ M_{\odot}$, 80% DM	
Distance	77.7 Mpc
DM density profile	NFW
Observational campaign (2009-2015)	300 hours

MAGIC results on Perseus:

- strongest limits in **CR acceleration**

J. Aleksić et al., Astrophys. J. 710 (2010) 634
J. Aleksić et al., Astron. Astrophys. 541 (2012) A99

- **NGC1275** discovered and modeled

J. Aleksić et al., Astron. Astroph 539 (2012) L2
J. Aleksić et al., Astron. Astrophys. 564 (2014) A5

- **IC310**: discovered, CR acceleration mechanism close to BH

J. Aleksić et al., Astrophys. J. 723 (2010) L207
J. Aleksić et al., Astron. Astrophys 563 (2014) A91

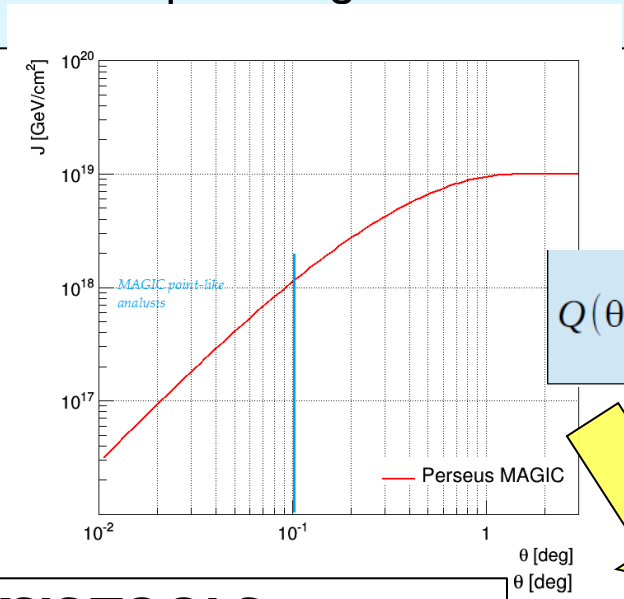
We focus on SIGNATURE OF DM DECAY, preliminary results considering :

- $\sim$ 12 hours of observation (zenith range 5-50 deg)
- $J_{dec} = 5.6\ 10^{18}\ GeV\ cm^{-2}$ optimized integration region (see next slide)
- Derived lower limits in decay lifetime for DM particle masses in the range (100GeV-20TeV)

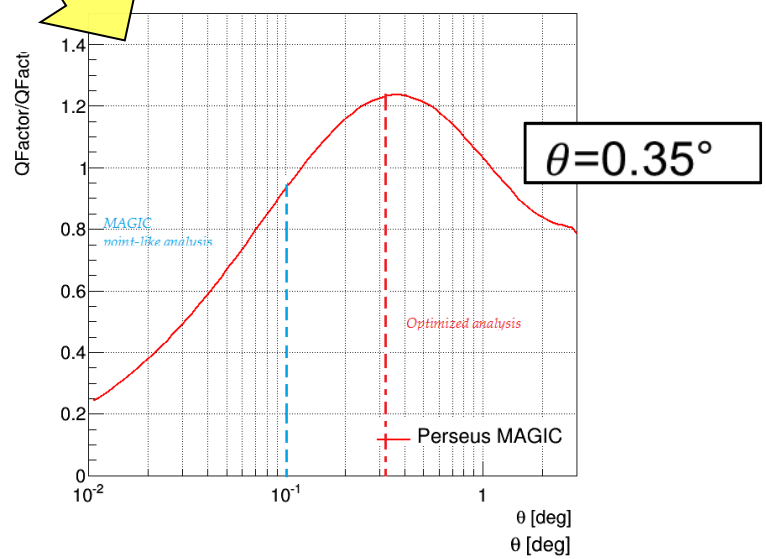
<u>Full likelihood analysis has been used : optimization for the spectral and morphological features expected in the dark matter decay signal</u>

DM DECAY IN PERSEUS CLUSTER

90% of the decaying DM signal is expected from a region defined as a circle of 1°around the sky source position, this study differs from the standard point-like source analysis. Specific tools have been required togheter with the *Full-likelihood* method used to analyze this kind of data.



$$Q(\theta_{cut}) = \frac{N_\gamma}{\sqrt{N_{bkg}}} \propto \frac{\int_{\Delta\Omega} d\Omega\, \epsilon_\gamma[r(\theta,\varphi)] \int_{los} \rho_{DM}(l,\Omega)\, dl}{\sqrt{\int_{\Delta\Omega} d\Omega\, \epsilon_{bkg}[r(\theta,\varphi)]}}$$



SPECIFIC ANALYSIS TOOLS

- optimization of analysis angular cut taking into account source shape and MAGIC camera response

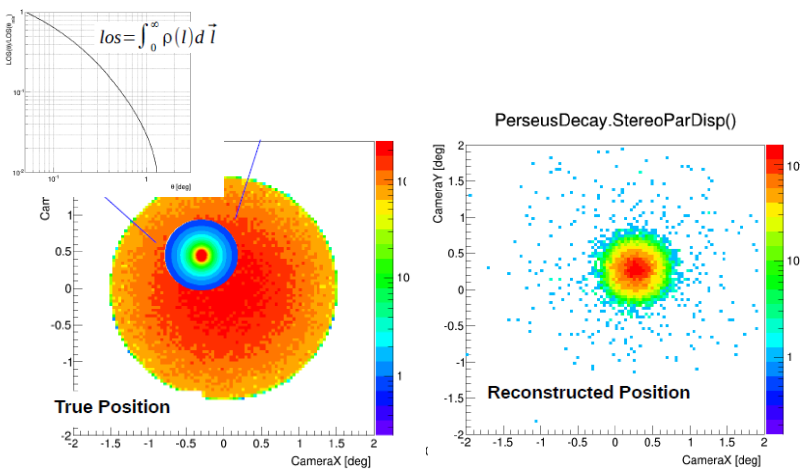
θ =0.35° More than 20% improvement in sensitivity with respect to the standard point-like analysis

DM DECAY IN PERSEUS CLUSTER

SPECIFIC ANALYSIS TOOLS

- dedicated DM MonteCarlo in order to build the correct instrument response functions (IRFs: mainly Aeff, energy migration tables) for a diffuse source

DM density parametrization on the source needed as external **INPUT** to obtain propers IRFs **OUTPUT**:

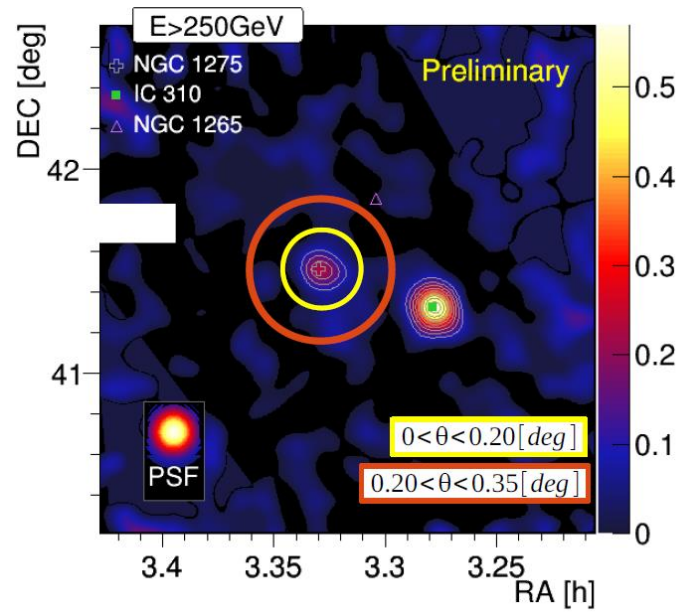


Diffuse MC

Events in the new MonteCarlo follow the expected distribution coming from Dark Matter

OBSERVATION STRATEGY

- Wobble mode (ON, OFF regions)
- Spatial binned signal region (red rings) > 95% NGC1275's emission is expected in the central ring



Signal (ON) and background (OFF) are obtained from circular regions of 0.35° size, 0.8° away each other and at the same distance with respect to the center of the camera.

DM DECAY IN PERSEUS CLUSTER: PRELIMINARY RESULTS AND PERSPECTIVES

Results on 12h of data

For τ τ

$$M_{DM} = 1[TeV] \rightarrow \tau \approx 3 \cdot 10^{25}[s]$$

$$M_{DM} = 10[TeV] \rightarrow \tau \approx 8 \cdot 10^{25}[s]$$

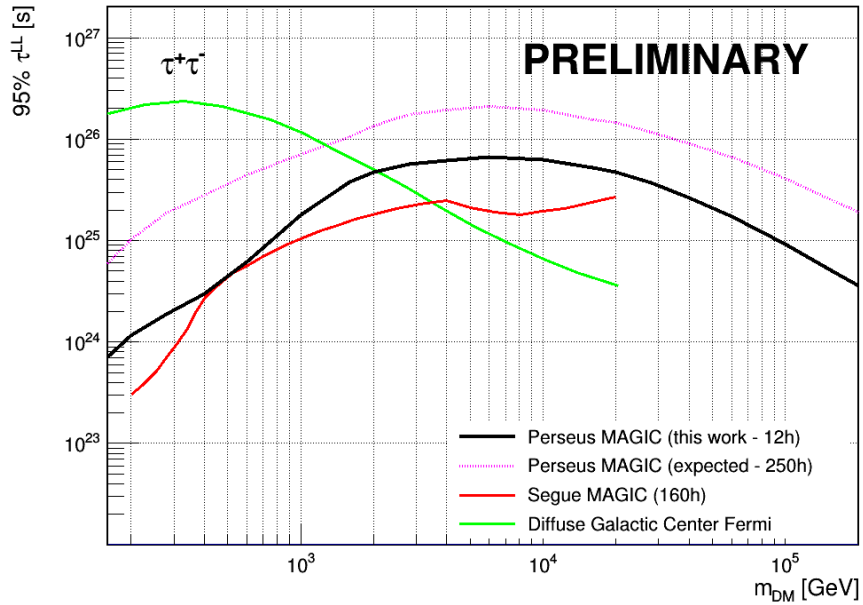
For bb

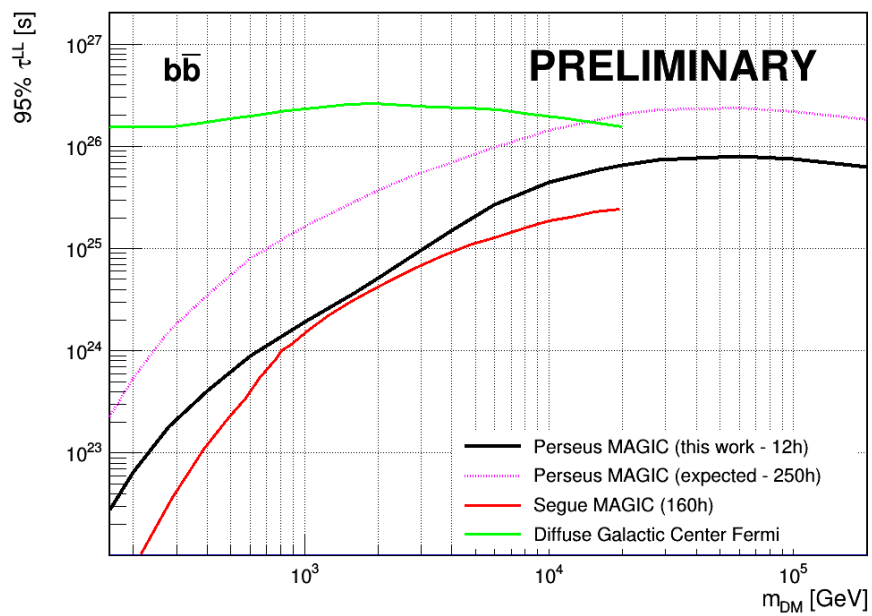
$$M_{DM} = 1[TeV] \rightarrow \tau \approx 4 \cdot 10^{24}[s]$$

$$M_{DM} = 10[TeV] \rightarrow \tau \approx 7 \cdot 10^{25}[s]$$

With 12h we obtain the best current limits on decay lifetimes for χ→τ τ for dark matter $\tau^+ \tau^-$ masses above 2 TeV

Full 300h analysis we expect sensitivities of ~2 · 10^26 s, obtaining the most constraining results on decay lifetimes of χ→$\tau^+\tau^-$ for dark matter masses above 1 TeV





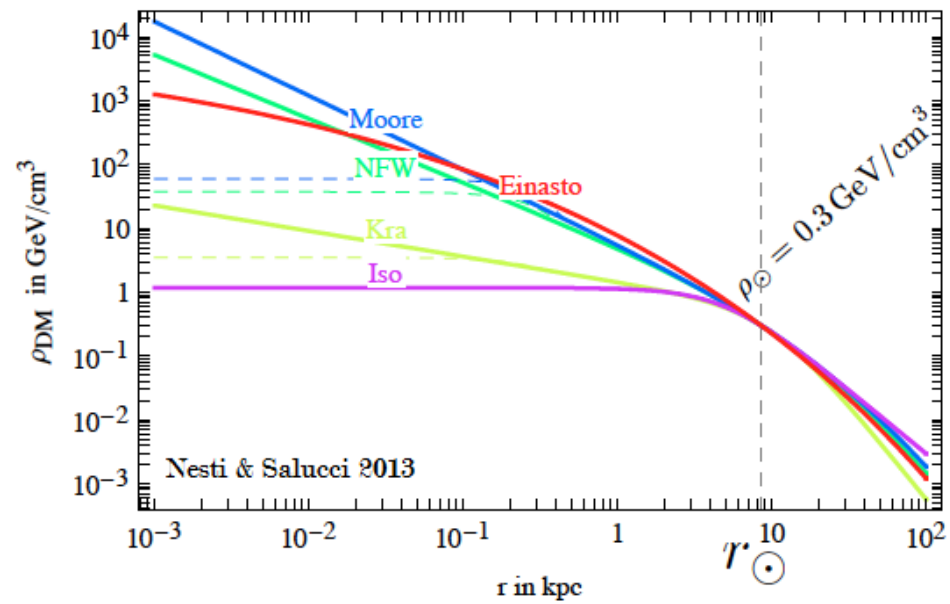
THE GALACTIC CENTER: MAGIC POINT OF VIEW

The good reason to survey the Galactic Center, to search for DM, is because it is not excluded that it could be the "brightest" DM source
The bad reason to survey the Galactic Center is because of the large astrophysical background! It is a very crowed region
OBSERVING THE GC IS A COMPELLING OPPORTUNITY

DM at the Galactic Center and surroundings

- ✓ The inner Galaxy is believed to host large concentrations of dark matter (DM) (Galaxies hosted by DM halo)
- ✓ GC is a prime target for DM searches with IACTs (best observability at the Southern hemisphere)

- ✓ DM modelling the GC is a very hard task: NFW , Einasto profile, core or cusp?
- ✓ Largest uncertainty at the very center
- ✓ In the RING region (0.3°-1° away to the center) the uncertainty and the astrophysical background decrease ⟹ BETTER TO OBSERVE NO EXACTLY CENTRAL REGION but the RING: the inner GALACTIC CENTER HALO



Strongest limits on thermally averaged cross section annihilation at the GC and Galactic Halo reached by H.E.S.S.

MAGIC DM SEARCH AT THE GALACTIC CENTER

GC (RA, Dec) = (17h45m36s,−28°56′) culmination at about 58° Zd at La Palma

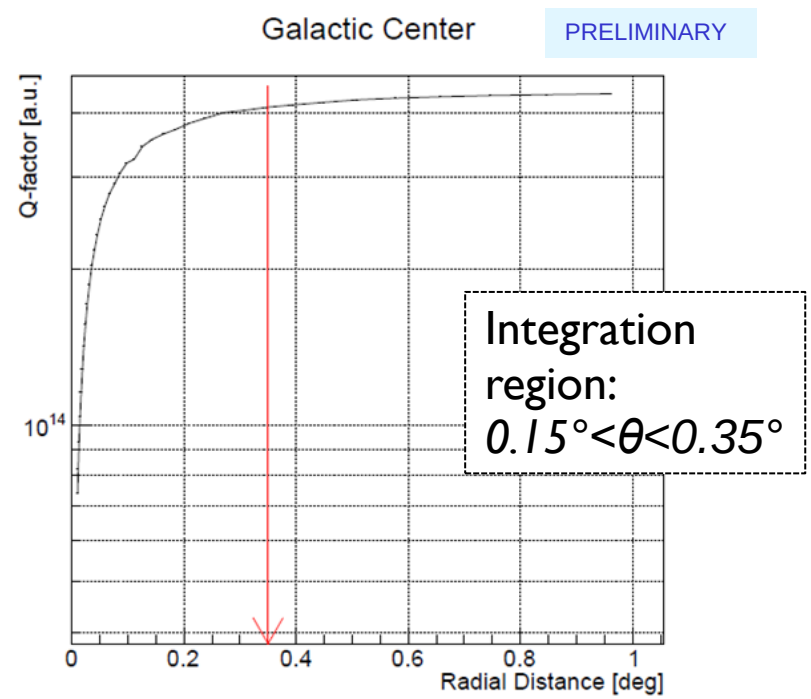
MAGIC devoted observational long monitoring time plan to the GC

GC is not the optimal observational target for the indirect DM search with MAGIC because of the low sensitivity due to high zenital observation (60°-70°) ⟹big collection area gives good sensitivity at the highest energies

For the scientific impact of the topic: a dedicated DM optimized analysis of data samples taken in GC campaign allows to do produce DM limit in this region

DETAILS OF ANALYSIS ONGOING

- 77 hours data taken
- Zd range: (58-70) deg ⟹ very hight energy threshold (several hundred GeV)
- Taylored MonteCarlo for analysis of diffuse source
- Definition of integration region
- DM density profile modeled by Einasto
- Evaluation of J-factor



SUMMARY/OUTLOOK

- MAGIC Telescopes are involved in DM searches campaign on several galactic and extragalactic targets, here we reported results achieved on Segue 1(dSphs), ongoing analysis on Perseus (galaxy cluster) and Galactic Center

- Development of tools for DM optimized analysis of available data allows to improve sensitivity, extending the study on all data sample of selected targets

- First MAGIC/Fermi-LAT merging results on dSphs: in the intermediate DM mass-range (few hundred GeV to few tens TeV) reached the sensitivity improvment by a ~ factor 2 with respect to the individual one (depending on the annih.channel) $\Longrightarrow$ development of a global analysis method of searching for DM signal

- Union is strength: looking forward to a global, sensitivity optimized dark matter search by combining data from present and future gamma-ray instruments (MAGIC, Fermi-LAT, VERITAS, H.E.S.S., CTA, HAWC) and neutrino detectors (IceCube, Antares)


THANK YOU
MAGIC
Florian Goebel
Telescopes
TAUP 2015, the 10th of September

BACKUP

What is full likelihood

- Using the a priori knowledge of expected spectral shape to increase sensitivity for gamma-ray searches
- Basically instead of using likelihood:

$$L(s,b;N_{\text{on}},N_{\text{off}}) = \frac{(s+b/\tau)^{N_{\text{on}}}}{N_{\text{on}}!}e^{-(g+b/\tau)} \times \frac{b^{N_{\text{off}}}}{N_{\text{off}}!}e^{-b}$$

we use

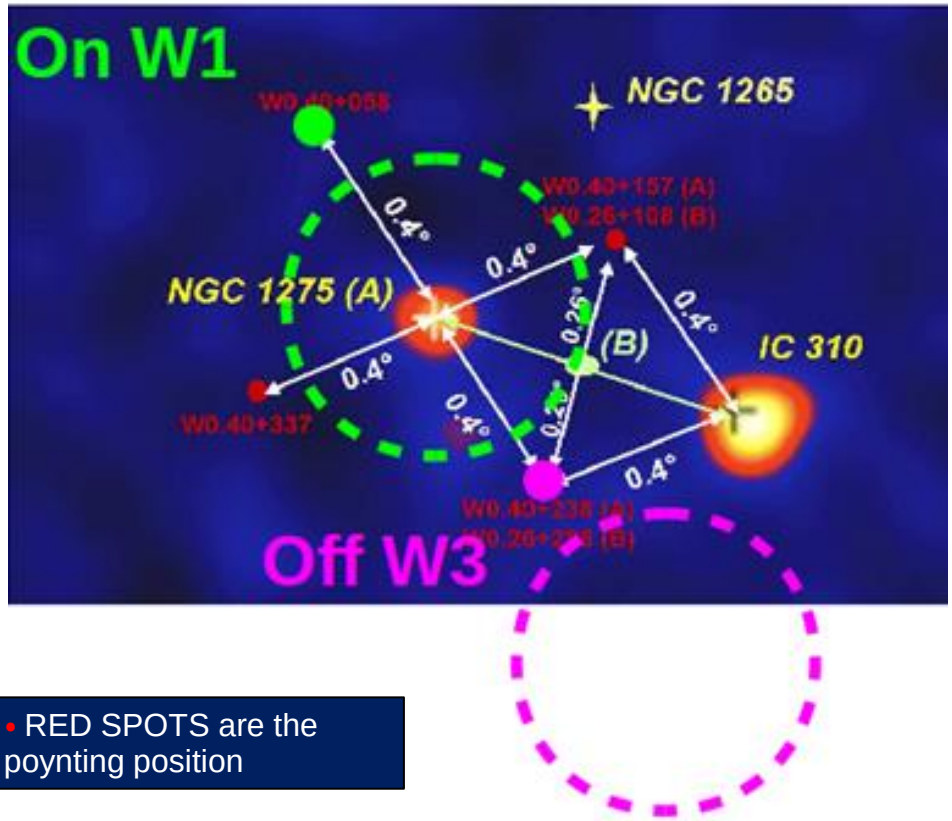
$$L(s,b \mid E_1,\ldots,E_{N_{\text{on}}},E_{N_{\text{on}}+1},\ldots,E_{N_{\text{on}}+N_{\text{off}}}) = \frac{(s+b/\tau)^{N_{\text{on}}}}{N_{\text{on}}!}e^{-(s+b/\tau)} \times \frac{b^{N_{\text{off}}}}{N_{\text{off}}!}e^{-b} \times \prod_{i=1}^{N_{\text{on}}} f(E_i \mid s,b) \times \prod_{i=1}^{N_{\text{off}}} g(E_i \mid b)$$

with *f* and *g* the PDFs for reconstructed energy of On and Off events, respectively

- Method characterized in Aleksić, Rico & Martínez JCAP 10 (2012) 32 and applied to MAGIC Stereo Segue analysis Aleksić et al. 02 (2014) 08 (with $\boldsymbol{\tau}$ as nuisance parameter)
- It provides an improvement in sensitivity of a factor of ~2 (depends on channel, mass, …)

- It is a tools for straightforward merging the results from heterogeneous data samples

PERSEUS sky map



- RED SPOTS are the poynting position

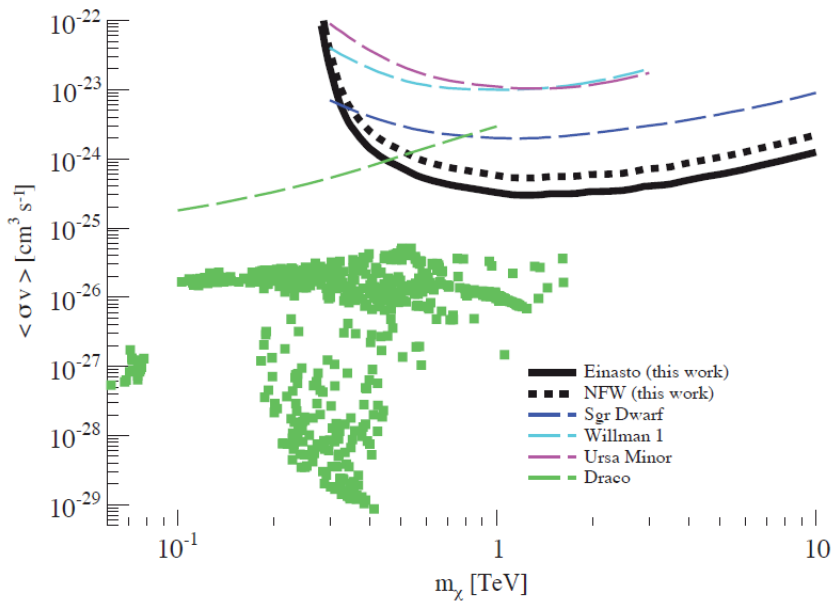
Upper Limits on the velocity averaged cross section annih.reached from HESS

- At the GC:

assuming central core DM density profile (with radius < 500kpc)
H.E.S.S. set (for IACTs) the currently strongest constraint of $< \sigma_{ann} v > \sim 3 \cdot 10^{-24}$ cm^3 /s for WIMPs masses between ~1-4 TeV,

- And in the inner Galactic Halo

Curves refer to generic annihilation in quark-antiquark particle



C. Van Eldik, arXiv:1505.0655