Observation of γ-rays from the Galactic Center with the MAGIC telescope

Indirect searches of supersymmetric dark matter

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on behalf of the MAGIC Collaboration

[Dark Matter and exotics PWG]

Introduction: The Dark Matter Paradigm

~95% of the Universe content is still unknown

Considered to be a major unresolved question in astrophysics, cosmology and particle physics nowadays.

Well-known luminous matter (baryons, i.e. stars, planets, ourselves...) only account for 5% ... Embarrassing?

~70% = Dark Energy ⟷ ~25% = Dark Matter

Determination of dark matter nature is one of the biggest challenges by far in present-day fundamental science.

Introduction: Neutralino – Indirect searches

Extensive WIMP searches
Direct & Indirect ways

→ **Direct production at laboratory:** ***Tevatron*** **and** ***LHC*****. Bounds imposed by** ***LEP2*****.**

→ **Scattering with WIMP [χ] to nuclei ($\propto$WIMP local density)**

→ **χ annihilations in high dark matter density ($\propto$(WIMP density)^2)**

neutralino $\chi + \chi$

$\nu, \bar{\nu}$

γ continuum

γ lines

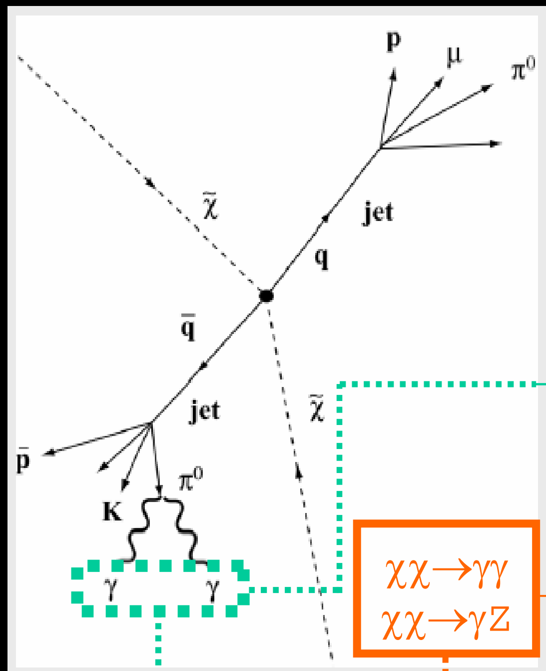
Point back to source

$\bar{p}$

e^+

$\bar{d}$

Search for excess components in cosmic rays (DIFUSION)



$\chi\chi \rightarrow \gamma\gamma$
$\chi\chi \rightarrow \gamma Z$

Continuum γ-ray spectra
From π^0s decays.
Spectra extends up to m_χ.

mono-energetic γ-lines
Loop suppresed annihilations.
Not considered, normally...

MAGIC: Major Atmospheric Gamma-Ray Imaging Cherenkov Telescope

Largest Imaging Air Cherenkov Telescope for **γ-ray astronomy**

(17 m mirror dish)

Design optimized for:

low energy threshold

E_γ = 50 GeV

fast repositioning

t_R<30 sec

Canary Island **La Palma**

2200 m asl

Collaboration: ~150 physicists & technicians, 16 institutes, 9 countries:

Barcelona IFAE, Barcelona UAB, HU Berlin, U.C. Davis, U. Dortmund, U. Lodz, UCM Madrid, MPI München, INFN/ U. Padova, INFN/ U. Siena, Inst. for Nuclear Research Sofia, Tuorla Observatory, Yerevan Phys. Institute, INFN/ U. Udine, U. Würzburg, ETH Zürich.

The analysis procedure

DATA SELECTION
- Trigger rates
- Atmospheric conditions, ...

↓

DATA PROCESSING
- Signal extraction & calibration
- Image cleaning
- Image parameterization (HILLAS)
- Data Quality checks + corrections

↓

EVENTS SELECTION → γ/h separation: RANDOM FOREST classification method; HADRONNESS cut + Quality Cuts

↓

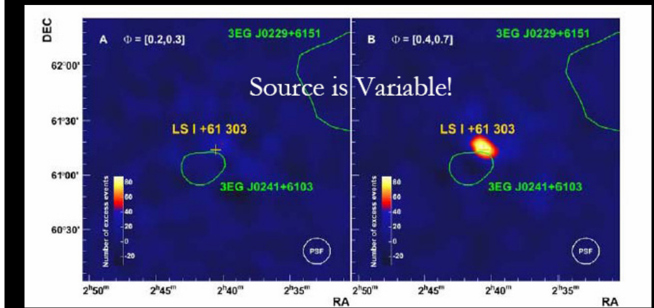
RECONSTRUCTION PRIMARY PARAMETERS → Arrival direction (DISP), Energy estimation

↓

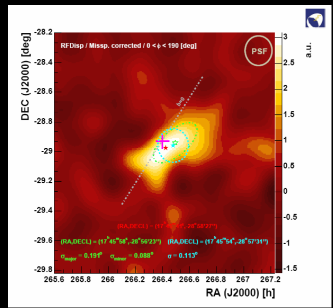
SIGNAL EVALUATION → ON/OFF Alpha Plots, θ^2 Plots → Differential Energy Spectrum; Light-Curve: Flux stability; Location of the emission: extension?; Sky-maps

MC: Effective Areas, Cut efficiency, Energy estimation, DISP Optimization ↔ Differential Energy Spectrum; Light-Curve: Flux stability; Location of the emission: extension?; Sky-maps

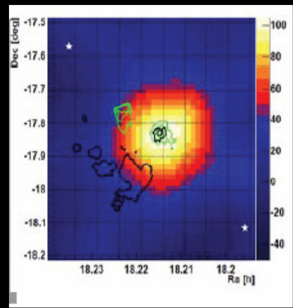
MAGIC highlights – after 1.5 observation years



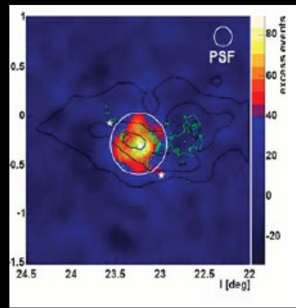
LS I +61 303



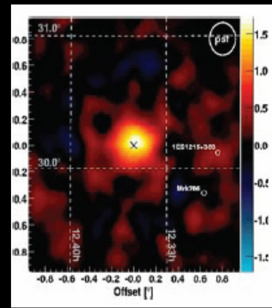
Galactic Center



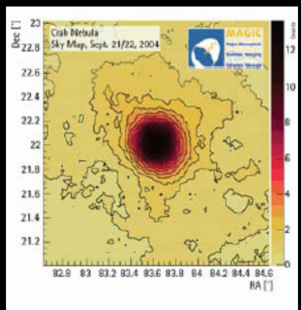
HESS J1813-178



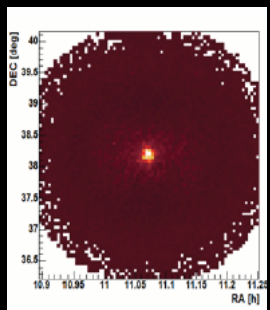
HESS J1834-087



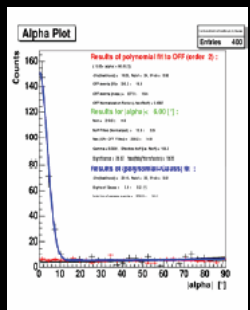
1ES 1218+30.4



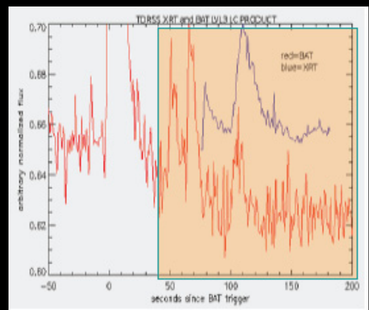
Crab Nebula



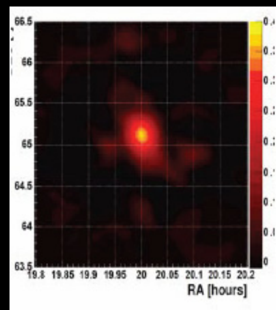
Mrk 421



Mrk 501



GRB 050713a



1ES1959+650

...

+ many more to come!

PART I:

Supersymmetric dark matter

&

Indirect search strategy

with MAGIC

Evaluating the γ-ray fluxes from χ annihilations I:

– γ-rays from annihilations arrive to earth and can be detected by a γ-ray Telescope ($E>E_0$), while pointing to a dark matter populated region:

$$\int d\Omega \int \frac{dN_\gamma}{dS\,dt\,d\Omega} dE \equiv \Phi_\gamma(\Psi, E > E_0) = f_{SUSY} \cdot J(\Psi, \theta)$$ ph cm^{-2} s^{-1}

$$f_{SUSY} = \frac{1}{4\pi} \frac{\sum_i N_\gamma^i \cdot BR_i \langle \sigma v \rangle_{ann}}{2 m_\chi^2}$$

$$J(\Psi, \theta) = \int_{\Delta\Omega} B(\Omega) d\Omega \int_{los} \rho_\chi^2 [r(s)] ds$$

FLUX COMPUTATION FACTORIZES

Particle Physics:

- $\langle\sigma v\rangle_{ann}$ = thermally averaged annihilation cross-section.

- γs from several ann. channels.
[labeled *i*, with branching ratios BR_i]

- m_χ = neutralino mass.

Astrophysics:

- ρ_χ = dark matter density profile.

- l.o.s integral over the instrument solid angle.

- $B(\Omega)$ = accounts the angular resolution response of the Telescope (Gaussian, etc...).

Evaluating the γ-ray fluxes from χ annihilations II:

SUSY

CHOOSE a SUSY scenario
MSSM, mSUGRA …

Evaluate $\langle\sigma v\rangle$, m_χ, γ-yield…
f_{SUSY}

Relic density constrains
$\Omega h^2 < WMAP_{MAX}$
Evaluation of the relic density

Apply accelerator bounds
SUSY particles and Higgs searches
decay $b \rightarrow s\gamma$, …

FLUX COMPUTATION FACTORIZES

DM HALO MODELIZATION

CHOOSE a TARGET
Galactic Center, dSph, Nearby galaxies

Model the Dark Matter density
Profiles from N-Body simulations or suggested by Obs. Constrains
Use observational DATA, if possible.

Evaluate the l.o.s Integral $J(\Psi)$
Within the detector angular acceptance

SUSY dark matter: MSSM & mSUGRA

- In general MSSM:

  many new parameters ⇒ MSSM 124

- Universal mass parameters:

assuming mass universality at GUT scale (~10^{15} GeV):

⇒ $m_{0,I} = m_0$ common scalar mass

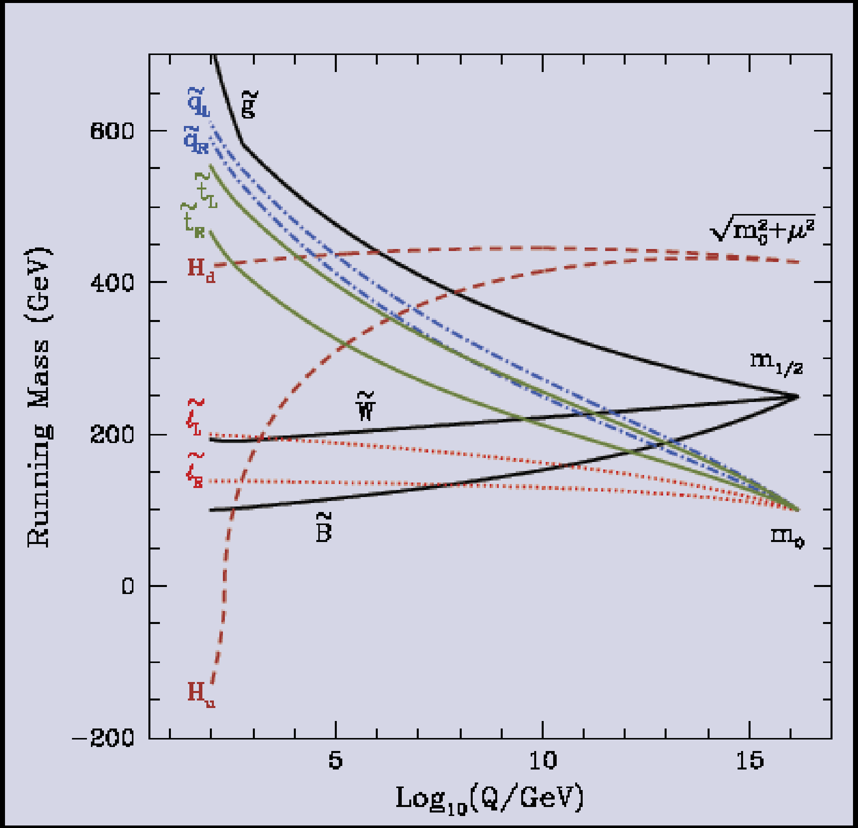
⇒ $m_{1/2,a} = m_{1/2}$ common gaugino masses

⇒ $A_{0,i} = A_0$ common trilinear couplings

only 5 remaining parameters

(in addition to SM parameters)

MSUGRA (Minimal SUper GRAvity)



m_0 , $m_{1/2}$, A_0 , $\tan\beta$, sign(μ) → Iterative application of renormalization group equations [SUSPECT, ISAJET, SOFTSUSY] → Couplings and mass spectra at the EW scale

SUSY dark matter: f_{SUSY} in mSUGRA I

DarkSUSY+ISAJET

~10^6 input Models

$$\begin{aligned} 0 < m_{1/2} < 5\ TeV \\ 0 < m_0 < 10\ TeV \\ 3 < \tan\beta < 52 \\ -10 < A_0 < 10\ TeV \\ \mu > 0 \end{aligned}$$

1.8% with $\Omega h^2 < 0.13$

[Viable]

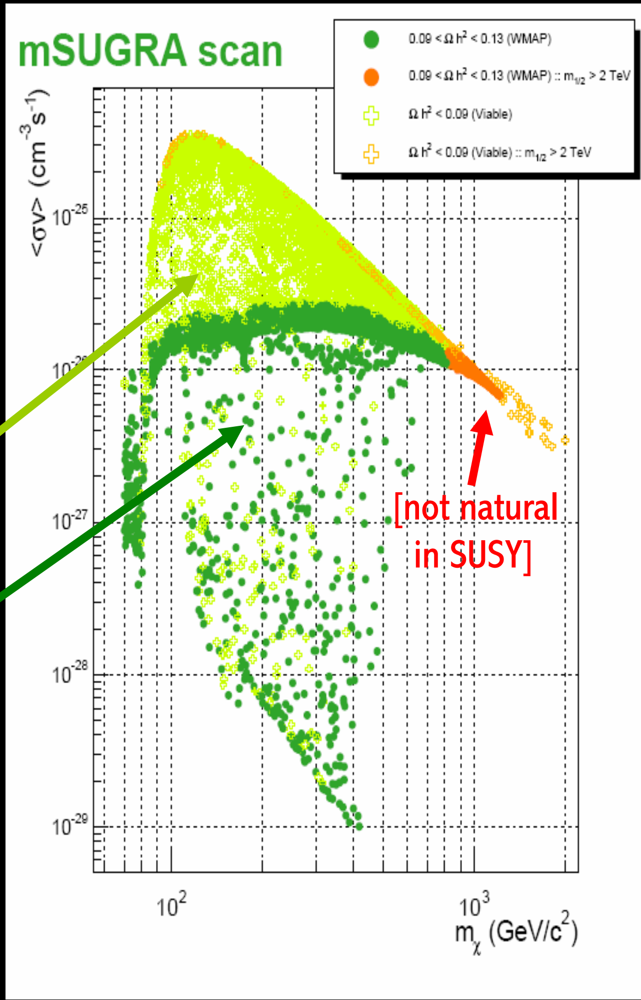
$\Omega h^2 <$ WMAP$_{min}$ sub-dominant DM component

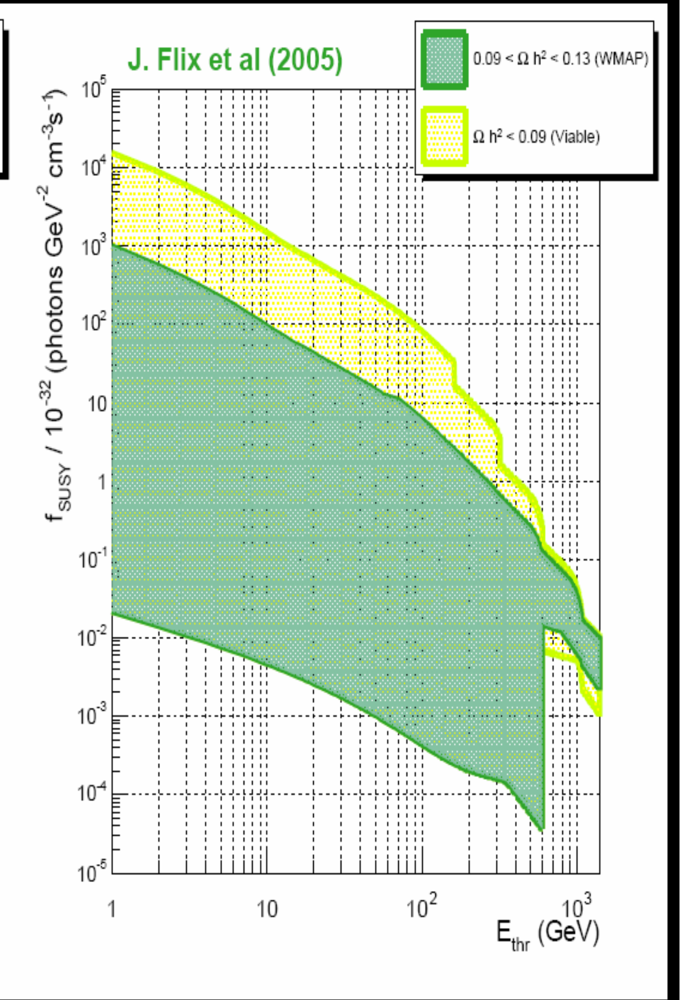
0.25% with Ωh^2 in WMAP range

[WMAP]

$$f_{SUSY} = \frac{1}{4\pi} \frac{\sum_i N_\gamma^i \cdot BR_i \langle \sigma v \rangle_{ann}}{2 m_\chi^2}$$

f_{SUSY} differs by 4 to 6 orders of magnitude





SUSY dark matter: f_{SUSY} in more general MSSM

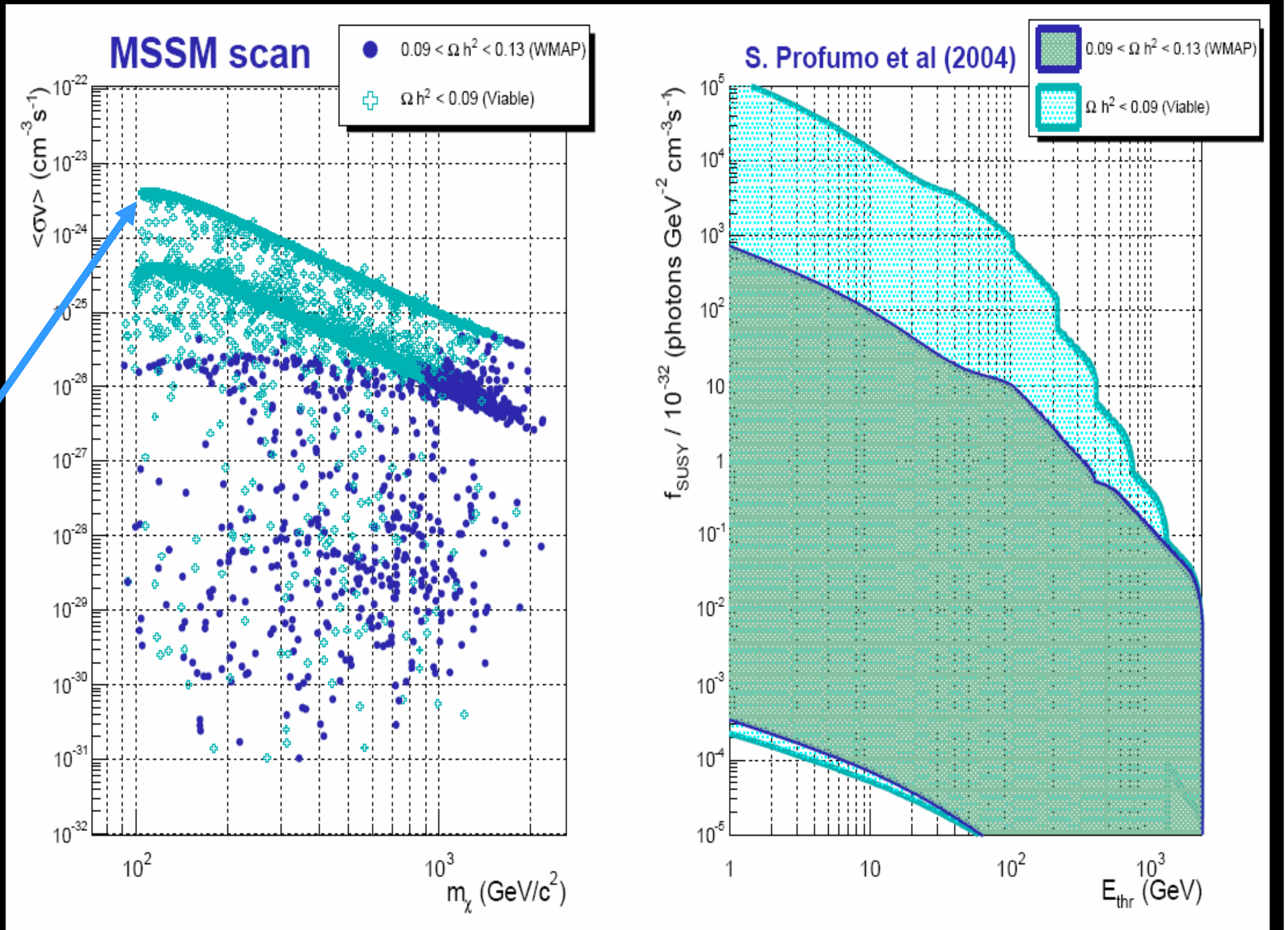
Statistical study: random scan at the EW scale

20 parameters:

$3 < \tan\beta < 50$
50 GeV < all masses < 5 TeV
@ EWS

New neutralino phenomenology (Wino-like neutralinos, not allowed in mSUGRA)

f_{SUSY} differs by 6 to 8 orders of magnitude



Halo Modelling: Best candidates for indirect searches I

From ΛCDM cosmological simulations

An universal profile for Dark Matter halos is predicted

Generally: $\rho(r) \sim r^{-\alpha}$

→ Example: Navarro-Frenk-White profile.

$$\rho_{NFW}(r) = \rho_o \frac{r_s}{r}\left(1+\frac{r}{r_s}\right)^{-2}$$

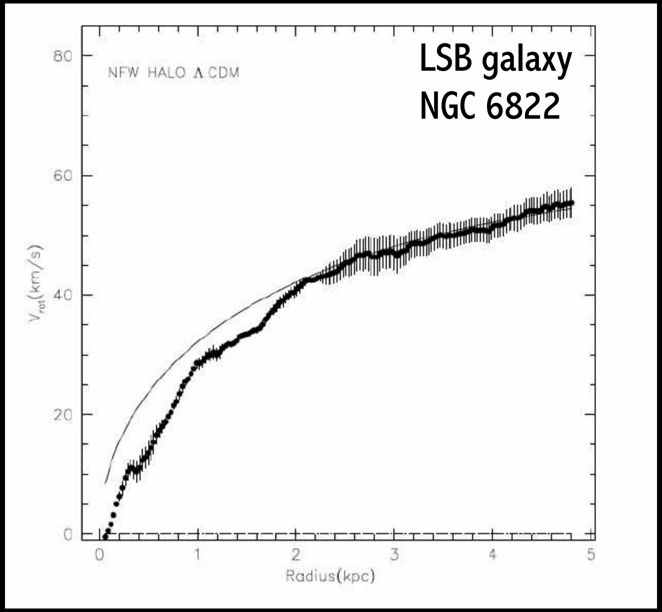
Spherical

Expected γ ray emission maximizes at the center of Dark Matter halos.

+ Moore et al (α=1.5) → Diemand et al (α=1.16), cored (α=0), etc… CUSPED or CORED

Halo Modelling: Best candidates for indirect searches II

Expected γ ray emission maximizes at the center of Dark Matter halos.



- In some cases, there is a clear disagreement of what it is the expected α-value from N-body simulations and the obtained from real observations...

Non-unique values of α are provided

Dark matter luminosity $\propto (\rho)^2 \propto r^{-\alpha}$ → Differences in α → huge differences in luminosity

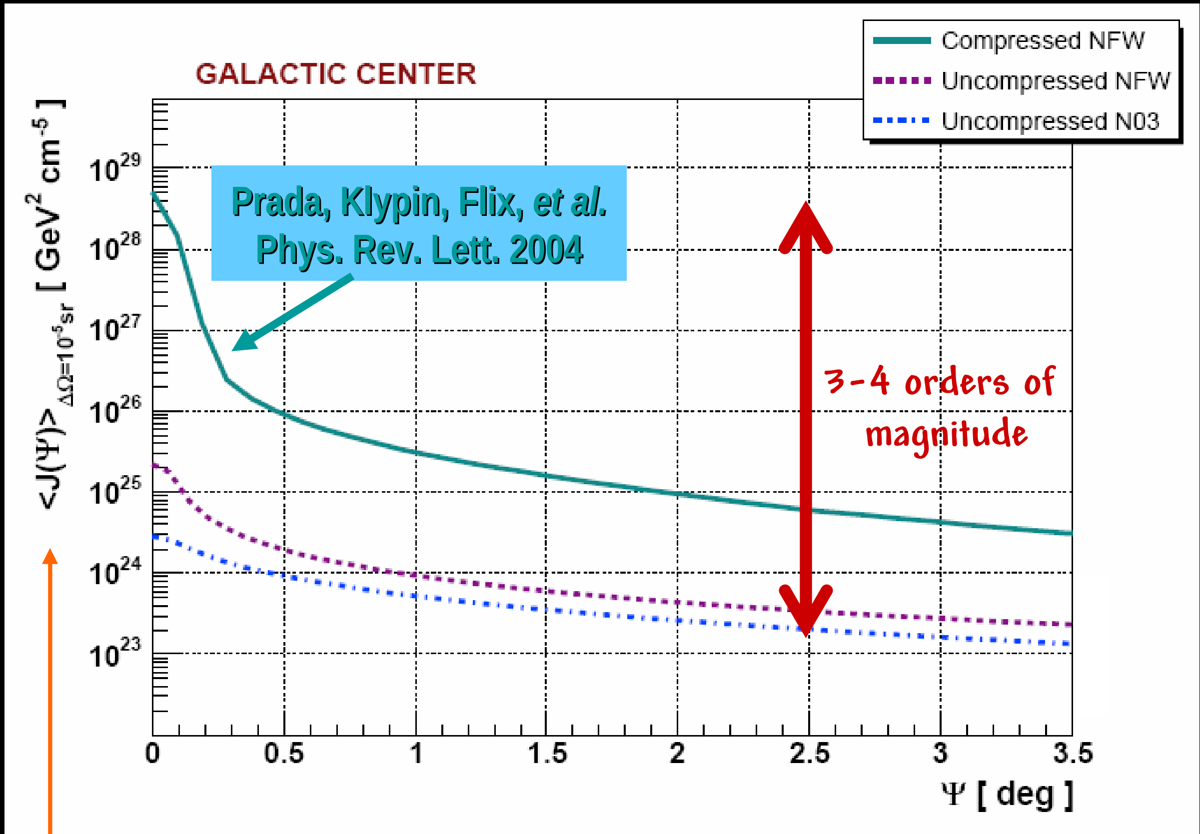
→ Several α-values are considered for selected targets

Halo Modelling: Best candidates for indirect searches III

- Galactic Center.
- Dwarf spheroidals: DRACO (huge M/L)
- Nearby galaxies, such as M31, ...
- Milky Way dark matter subhaloes (clumps).
- Cosmological neutralino annihilations.

Halo Modelling: The Galactic Center – Considered Dark Matter Profiles

- Evaluation of averaged l.o.s Integral $J(\Psi)$:



$$\langle J\rangle_{\Delta\Omega} \equiv \langle J(\Psi,\theta)\rangle_{\Delta\Omega} = \frac{1}{\Delta\Omega} J(\Psi,\theta)$$

- Profiles considered span different α-values:

1.45 (adiabatic compressed NFW)
1.0 (uncompressed NFW)
0.0 (cored – N03)

-Assumed an IACT with angular resolution of ~0.1° [MAGIC]

- Luminosity changes 4-orders of magnitude, depending on α.

- Expected luminosity is point-like or extended (need special analysis)

Halo Modelling: Predictions for Selected Candidates I

Object	ZA [deg]	E_{thr} [GeV]	$\langle J(\Psi)\rangle_{\Delta\Omega}$ [GeV^2 cm^{-5}]	Ψ_{10} [deg]	Comments
GC (NFW ad.cont.)	~60	~650	$5.2 \cdot 10^{28}$	~0.1	point,VHE
GC (NFW)	~60	~650	$2.2 \cdot 10^{25}$	~0.6	ext.,VHE
GC (N03)	~60	~650	$2.8 \cdot 10^{24}$	>2.	ext.,VHE
DRACO (NFW)	~29	~150	$7.6 \cdot 10^{23}$	~0.3	ext.,no VHE
DRACO (NFW α=0.5)	~29	~150	$6.0 \cdot 10^{23}$	~0.3	ext.,no VHE
DRACO (NFW +cut-off)	~29	~150	$2.3 \cdot 10^{23}$	~0.25	ext.,no VHE
DRACO (Cored)	~29	~150	$2.3 \cdot 10^{23}$	~0.3	ext.,no VHE
M31 (M04)	~13	~110	$3.7 \cdot 10^{23}$	~0.35	ext.,VHE
M31 (NFW2)	~13	~110	$3.5 \cdot 10^{23}$	~0.25	ext.,VHE
M31 (NFW1)	~13	~110	$3.2 \cdot 10^{23}$	~0.3	ext.,VHE

Objects and dark matter density profiles considered

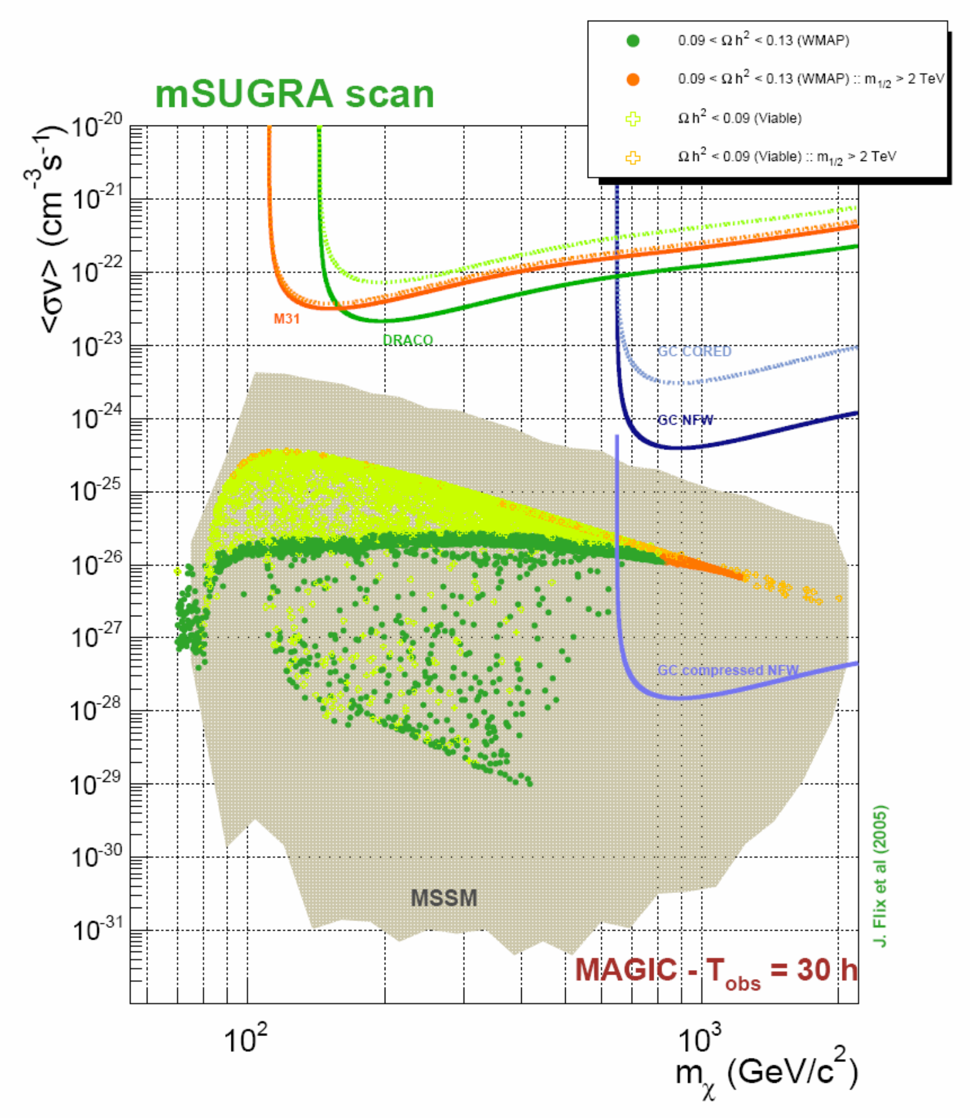
If ZA is large, more C-light is absorbed in the atmosphere and the E_{thr} of the IACT Telescope is affected.

Assumed Ethr (ZA = 0º) = 100 GeV

Ψ_{10} = pointing angle from halo center in which luminosity is decreased a factor 10.

VHE = known VHE emitters within angular resolution?

Halo Modelling: Predictions for Selected Candidates II



- 5σ exclusion limits for MAGIC observations on the selected targets (30 h).

- Assumed MAGIC sensitivity at low ZA, and scaled with ZA.

- Galactic Center expected to be the most luminous object from dark matter annihilations.

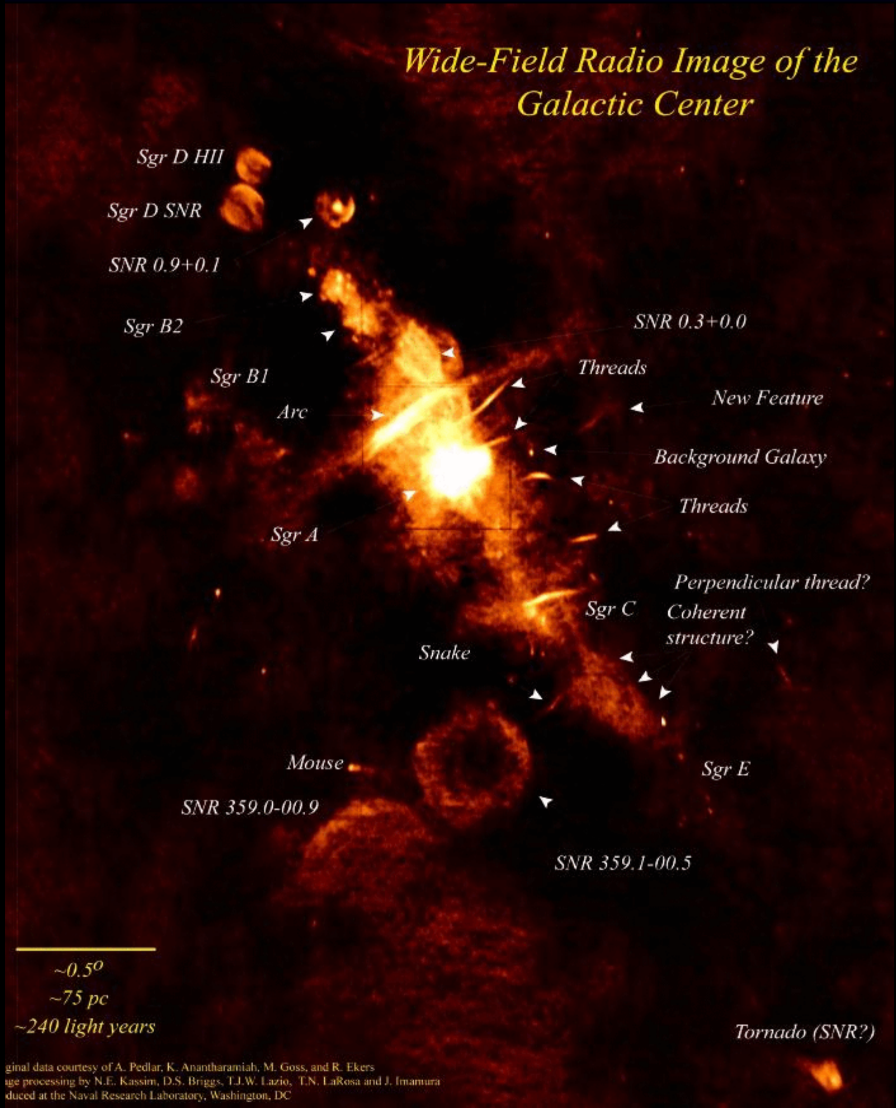
-Draco and M31faint sources: 10^{-13}-10^{-14} ph cm^{-2} s^{-1}

- Enhancement factors: DM-substructures, etc... **not applied**.
[conservative (?) scenario]

PART II:

MAGIC observations
in the Galactic Center direction

The Galactic Center region I



Extreme environment

Totally obscured in the Optical
Only visible from Radio to IR and high energies

Proximity (~8 kpc)

Unique lab. for modern astrophysics

Last 2 years: valuable results

X-rays to γ-rays

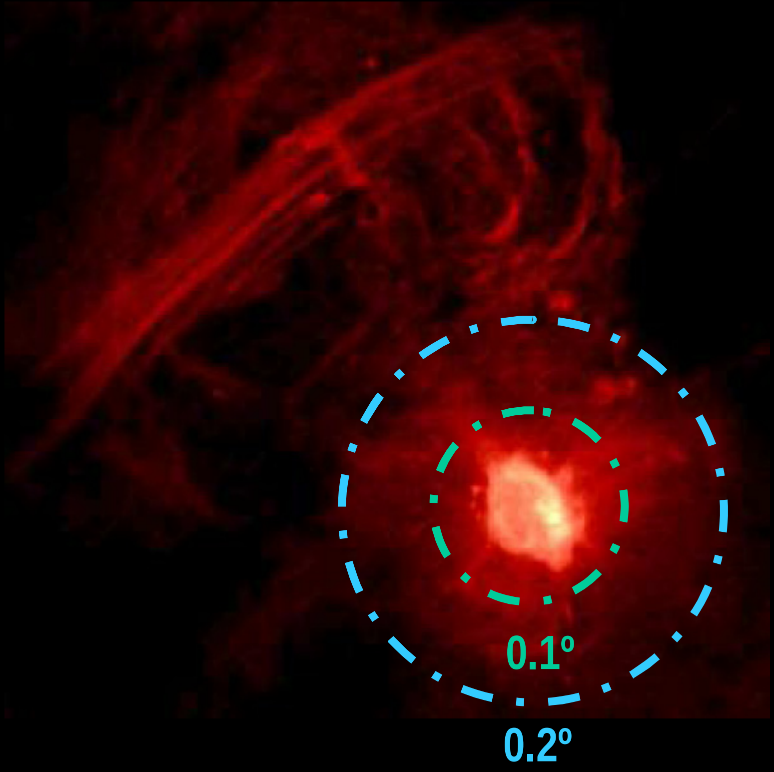
CHANDRA, XMM-Newton, INTEGRAL, H.E.S.S.

GC contains:

10 % of galactic interstellar medium [giant molecular clouds]
Host the nearest [hypothetical] super-massive BH
Variety of VHE emitters: SNRs, MC, non-thermal arcs...

The Galactic Center region II

Central 30 pc (~13', ~2°)
SgrA complex



A few MCs [M-0.02-0.07, M-0.13-0.06]

An expanding SNR [Sgr A East].

Non-thermal radio-source.

Extended diffuse emission, 50'' from SgrA* (2 pc).

Shell appears in expansion, compressing the MC-0.02-0.07, prob. creating structures around the shell.

Thermal diffuse nebula [SgrA West, IRS16].

Ionized by a cluster of young and massive stars. Stellar winds interact with medium. Probably feed the SMBH.

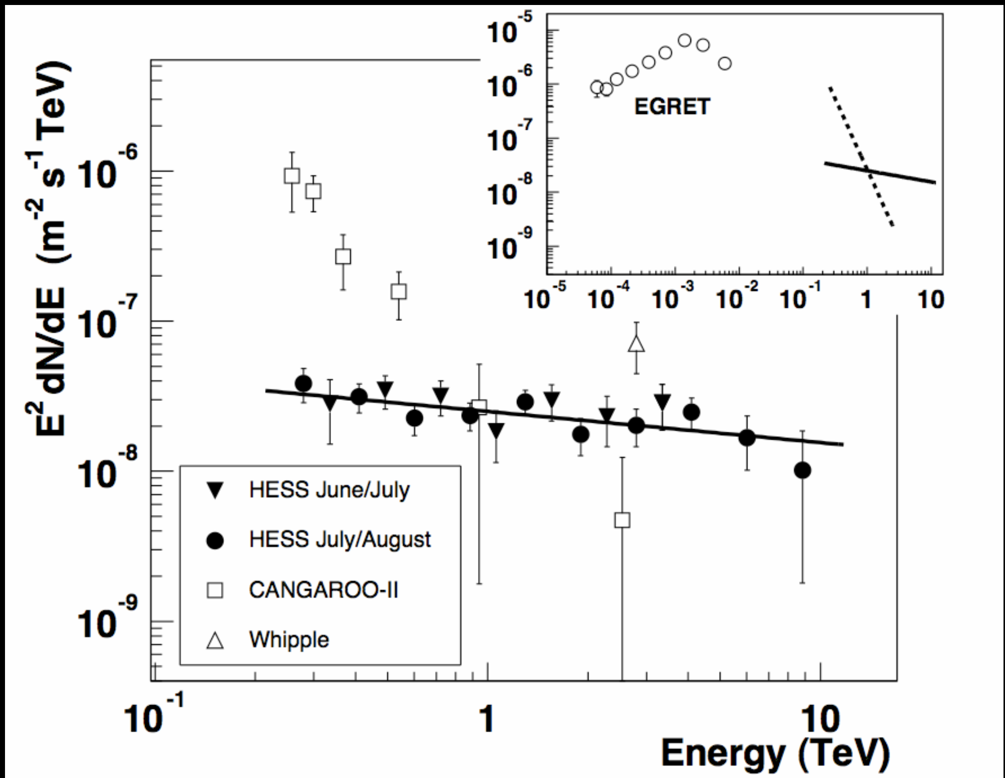
Centered 2'' from SgrA*.

Central HII region surrounding the bright compact radio source Sgr A*.

Radio manifestation of the central SMBH.
Matter dynamics $\rightarrow$ BH 3-4 10^6 $M_\odot$ - R_s ~ 0.06 AU.

The Galactic Center region III

- GC region is very active in infrared/radio and soft X-rays.
- Hour-scale flares in IR/X-rays: flux variations up to a factor of 200 (200s).
- VHE γ-ray observations: by Whipple, CANGAROO, and the H.E.S.S. telescopes.



EGRET measurement is almost excluded to be the counterpart of X-ray (INTEGRAL) and VHE emission.
(recent re-analysis shows GeV emission 0.2º from GC)

Discrepancy in the VHE measurements

- Is there variability?
- Inter-calibration problems?
- Other reasons?

Picture before MAGIC observations

The Galactic Center: Motivations for MAGIC observations

Measure the γ-ray **differential energy spectra** (large ZA → higher E_{th} compared to H.E.S.S telescopes). Benefit of higher energies up to about 20 TeV to be accessible.

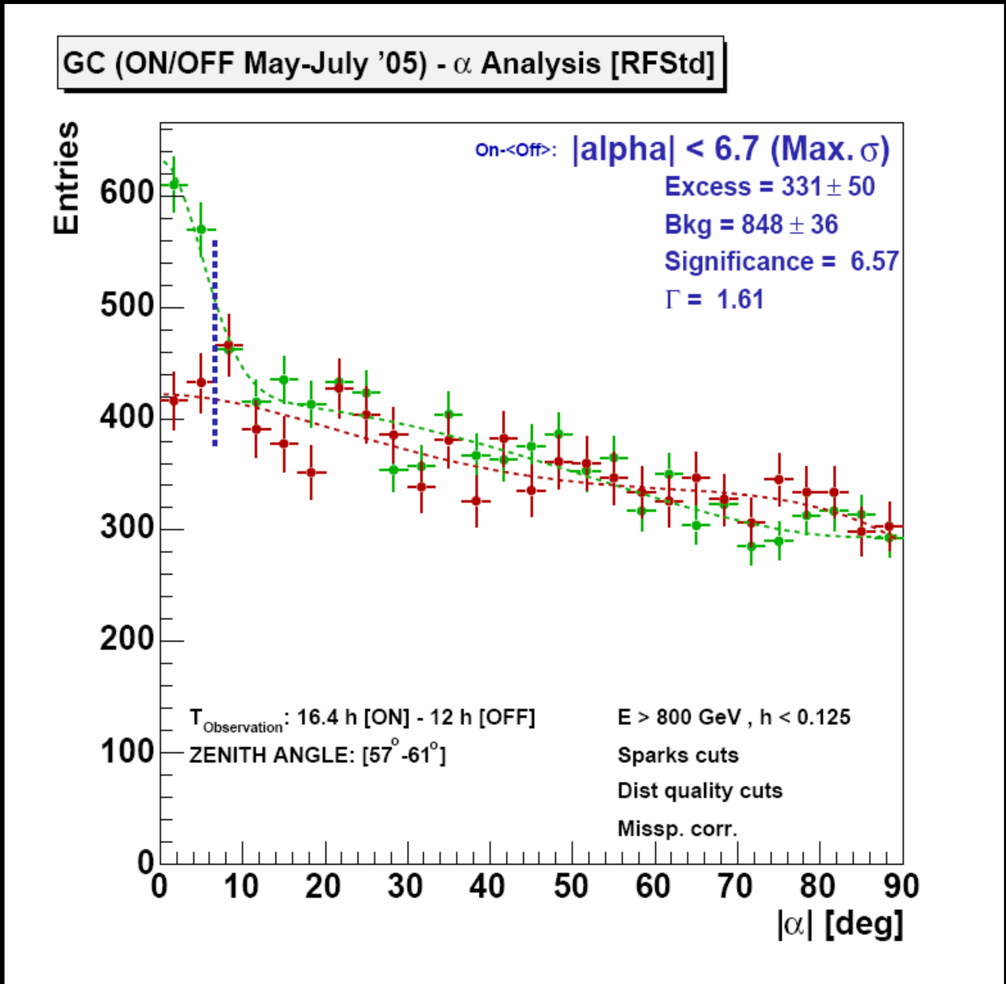
Help **resolving the main differential energy spectra discrepancies** between VERITAS, H.E.S.S and CANGAROO.

Study if the **emission is extended or compatible to a point-like source**.

Check for **variability** of the γ-ray emission.

Gain information about the nature and production mechanism of γ-rays in the direction of the GC. Particularly, set **constrains on models for dark-matter-particle annihilation**.

The Galactic Center: detected signal



ALPHA distribution for ON and irreducible OFF data, after cuts:

16.4h ON lifetime.

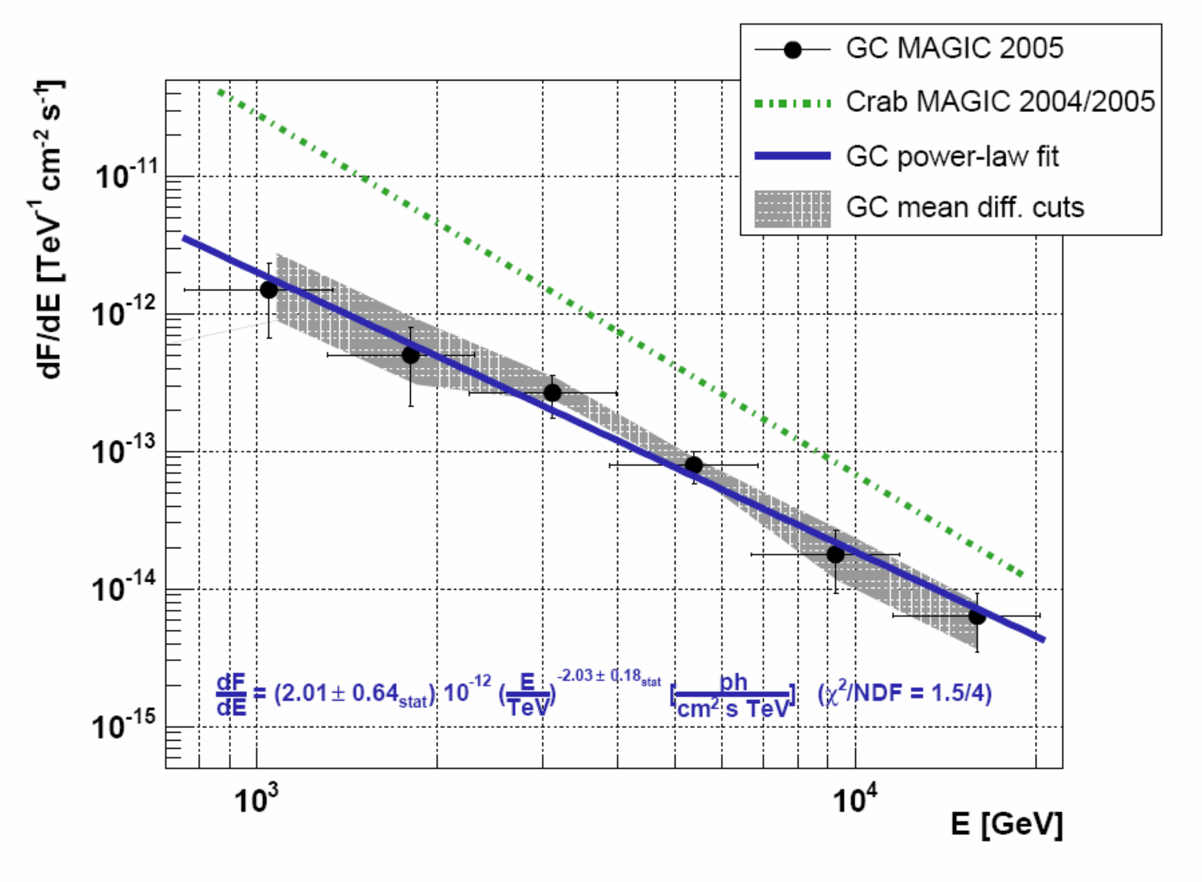
Observed excess: ~ 6.6 σ

330 Excess events

γ ray energies > 800 GeV

The Galactic Center: the differential energy spectra

Flux about 10% (E > 1 TeV) of the Crab nebula



Differential energy spectra compatible to a power-law.

Cut efficiencies ($\varepsilon_\gamma \sim 50\%$).

errors (1σ) are statistical.

systematics

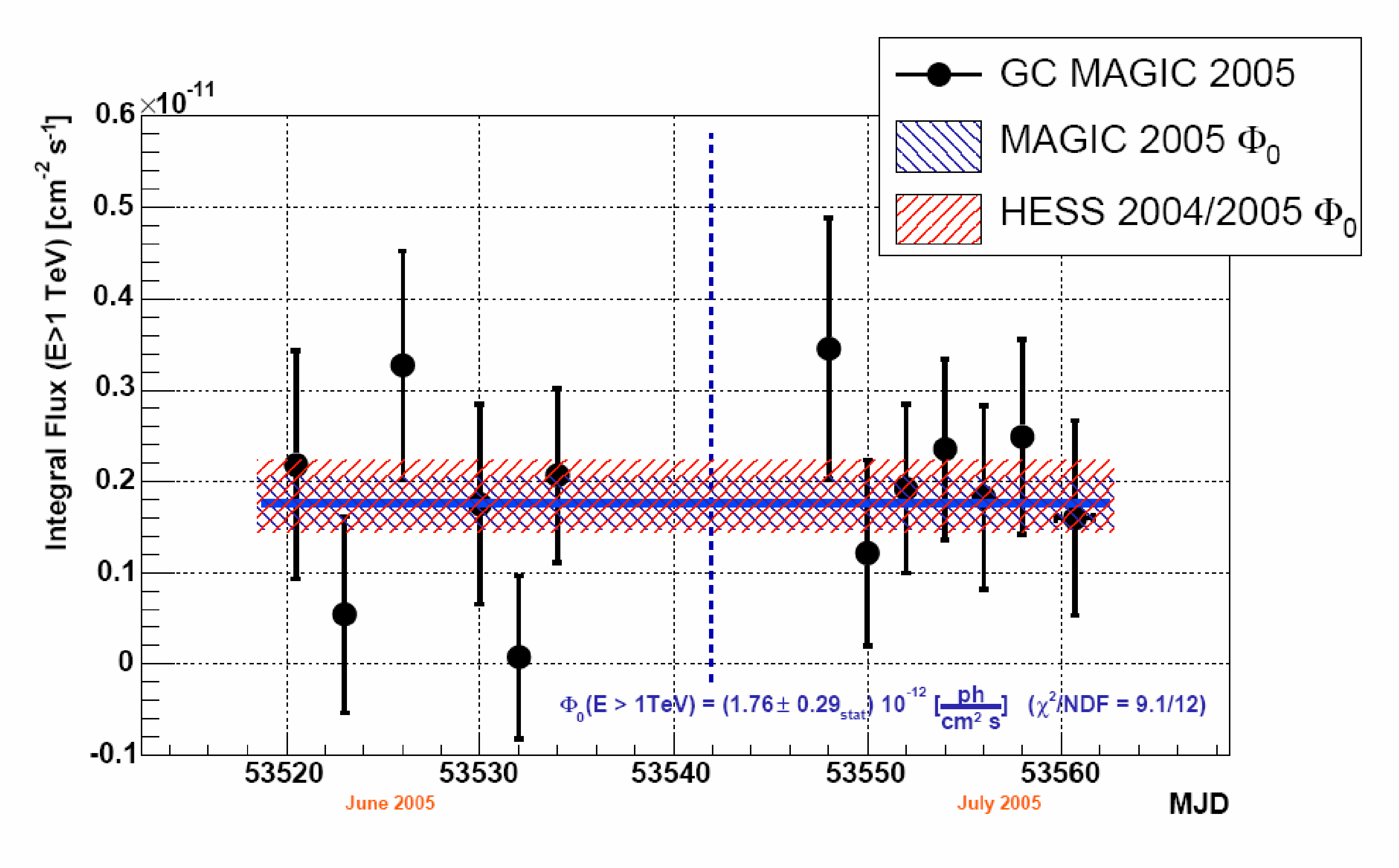
$\pm 35\%$ syst. error in the flux level

± 0.2 in the spectral index.

Flux level consistent within errors with the H.E.S.S. measurements

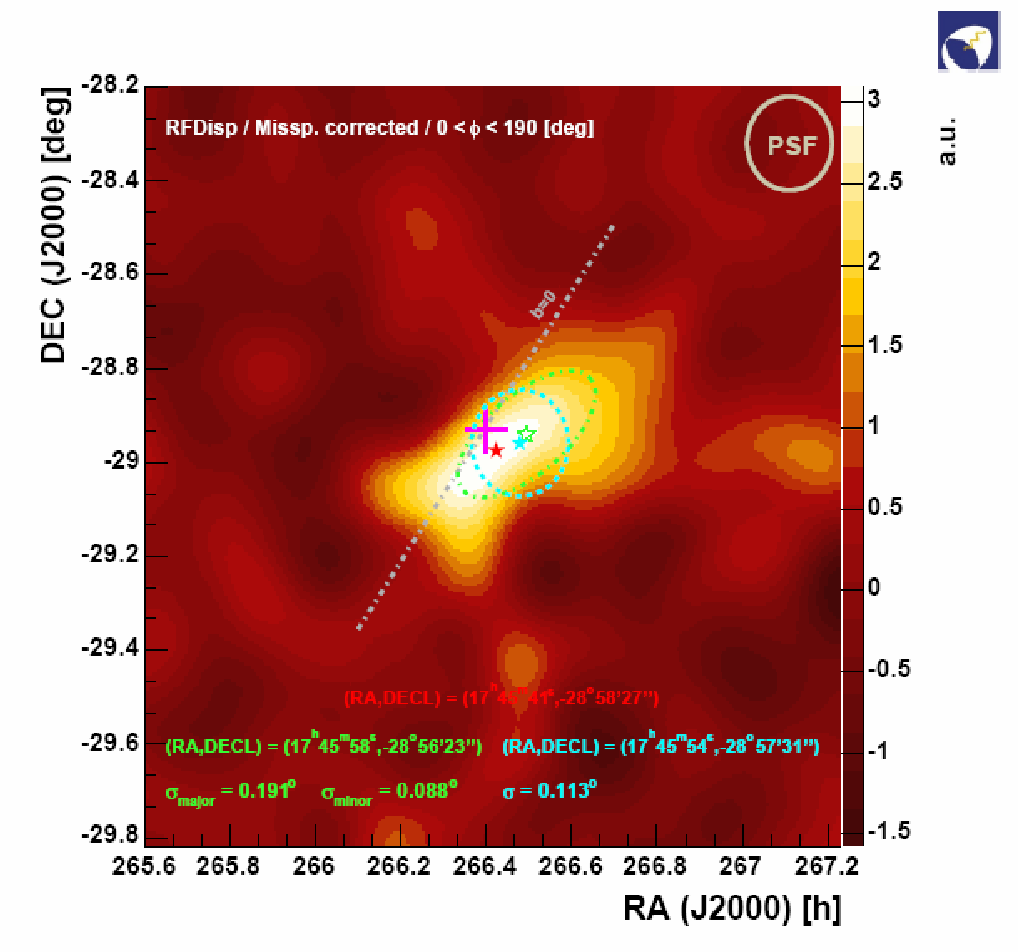
The Galactic Center: flux stability

Flux level and variability consistent within errors with the H.E.S.S. measurements



Integral VHE flux > 1 TeV.
Flux is steady within errors [2 months] - errors (1σ) are statistical.

The Galactic Center: source location and extension?



Sky-coordinates distribution of γ-ray excess for ~ 1.6° field-of-view.
E > 1 TeV

Arrival direction estimated using the DISP analysis method.

VHE γ-ray emission spatially consistent with emission from BH candidate Sgr A* and SNR Sgr A East.

Compatible to point-source, but extended fainter elongation along the Galactic Plane...

PART III:

Discussion of the results

Discussion: the Galactic Center at VHE

MAGIC results confirms previous H.E.S.S measurements

Flux level :: consistent with H.E.S.S.

MAGIC goal was to achieve highest energies on the measured spectra (recent H.E.S.S. result - 160 GeV to 30 TeV)
MAGIC results up to 15 TeV – over-estimated capabilities at large ZA (worst sensitivity than expected)

Source is steady

Emission seems stable in VHE in time-scales of years (MAGIC – H.E.S.S.)
Recent result: H.E.S.S., 3σ in 20'… 1863 excess evts – 37.9σ – flare searches down to 10'…

Location is compatible either with SgrA* or Sgr A East

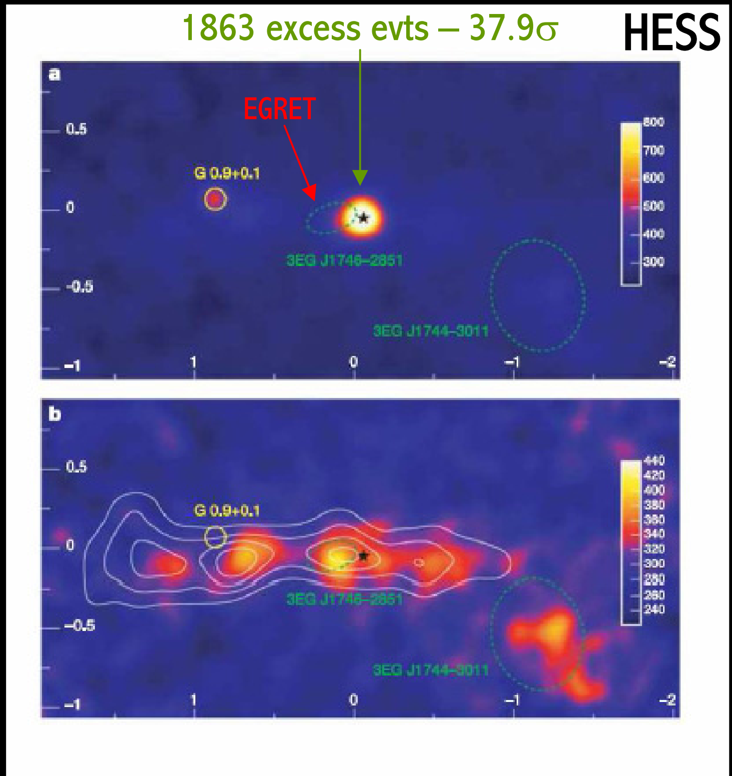
Emission compatible with point-source + extended emission

Recent result: H.E.S.S. sees a point source + extended emission, with shape elongated along the Galactic Plane.
Partially supported by MAGIC observations.

Discussion: Interpretation of γ-ray emission in a dark matter scenario I

Source Morphology – Energy Spectra

MAGIC & HESS



HESS latest results [Nature – 2006]

Very sensitive exposure on the GC

Subtraction of point sources

& search for faint extended emission

inner DM density profile follows $\rho(r) = r^{-\alpha}$

α imposes constrains on the extension of the emission from the GC.

NFW $\alpha=1 \rightarrow$ extended emission

Cusped profiles $\alpha>1 \rightarrow$ point-like emission

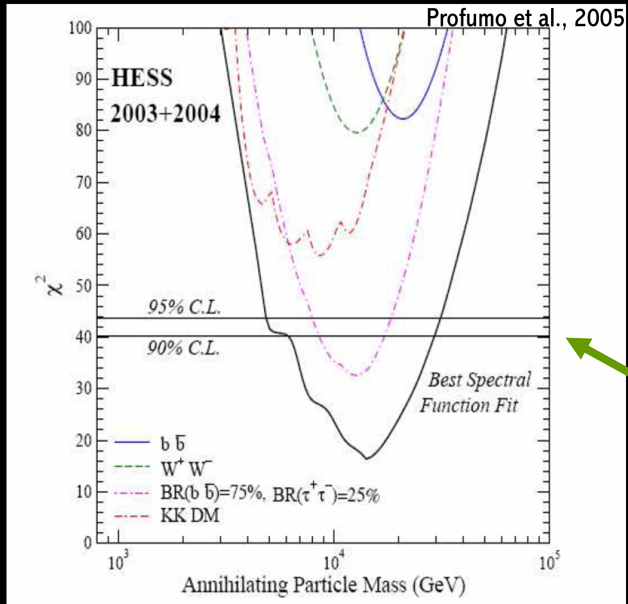
From HESS results → $\alpha>1.2$ (95% CL)

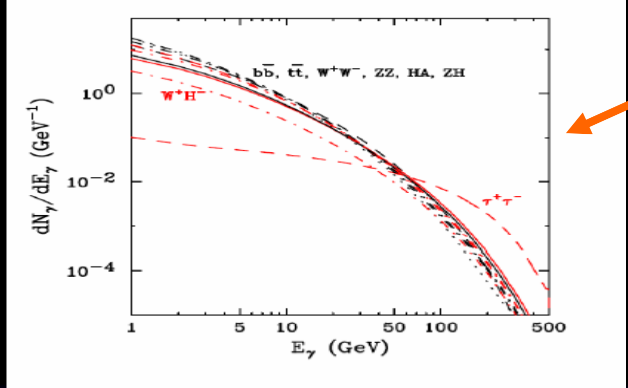
CUSPED PROFILES ARE PREFERRED

Ad. Contracted NFW $\alpha=1.45$

Discussion: Interpretation of γ-ray emission in a dark matter scenario II

Source Morphology – Energy Spectra





Extension of the spectrum up to 30 TeV

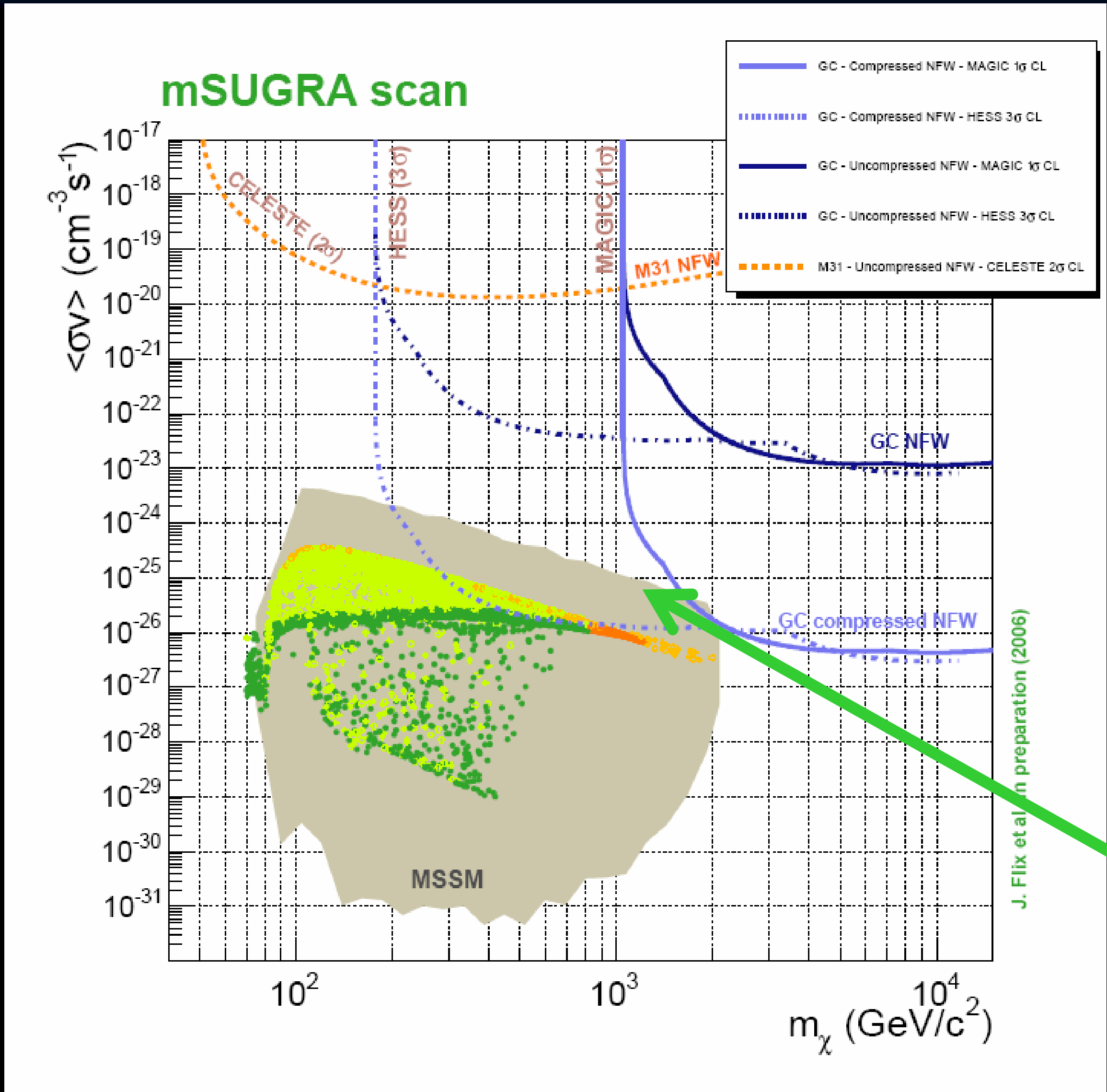
uncomfortably large for 'conservative' MSSM models
requires $m_\chi \sim 30$ TeV

Moreover, the data has been fitted with neutralino annihilations spectra by some authors…

… the pure power-law spectra from 160 GeV to 30 TeV is difficult to be ajusted by neutralino annihilations.
(that exhibits a curved spectrum, even multiple channels)

The emission interpreted as a whole has some difficulties to be interpreted within a 'conservative' SUSY dm scenario

Discussion: Interpretation of γ-ray emission in a dark matter scenario III



Exclusion limits

$m_\chi > 160$ GeV

non-SUSY-DM origin

MAGIC 1σ CL exclusion limits

H.E.S.S. 3σ CL exclusion limits

+ CELESTE 2σ CL limits from M31 observations

Exclusion of a portion of the MSSM parameter space, for a given DM halo model (NFW ad. contracted)

Enhancement factors: DM-substructures, etc... not applied.

Discussion: Other γ-ray emission mechanisms (most (?) probable)

Particle interactions in the vicinity of the SMBH

- *proton-proton* interactions.
- Electronic models: synchroton radiation & inverse compton.
- runaway protons interacting with surrounding interstellar gas (diffuse component).

Non-thermal VHE emission from stellar wind shocks

- GC region stars with high mass loss rate → shocks with hot plasma, accelerates *protons* and *electrons* → γ-radiation.

Capture of stars by the central SMBH

- Stars tidally disrupted and feed into BH → powerful particle acceleration.

Stochastic particle acceleration

- Small accretion torus around SMBH → powerful particle acceleration.

SNR Sgr A East

- Expanding shell interacting with very dense medium → natural source of accelerated hadrons.
- Galactic Center VHE spectrum similar to other SNR observed at VHE.

PART V:

Conclusions

Concluding remarks I

MAGIC intended to contribute to the understanding of indirect searches of SUSY dark matter with IACTs.

1) Theoretical and phenomenological approach

Identify suitable places for indirect searches of SUSY dark matter with the MAGIC Telescope:

- Predictions of expected γ-yield from χ annihilations in SUSY models.
- Dark Matter modeling of selected candidate regions.
- Studying the effects of adiabatic dark matter compression at the center of the Milky Way.
- Selection of the brightest candidate (Galactic Center) & its observation with MAGIC.

MAGIC intended to contribute to the understanding of indirect searches of SUSY dark matter with IACTs.

2) Experimental: observational approach

- Analysis of the significant GC detection: estimation of energy spectrum, flux stability, and source location and possible extension.

- Interpretation of the signal in a SUSY dark matter scenario, which seems to be rather unlikely.

-Conservative exclusion limits derived on the $<\sigma v>$ vs. m_χ SUSY plane.

Nature of the GC VHE γ-ray source is not yet identified!

(*) The **CACTUS** collaboration has recently reported γ-ray emission from Draco in the 50 to 150 GeV energy window... This reported flux is detectable with MAGIC within minutes! ;)

MAGIC has taken 20h of data in the direction of Draco (this happened last weeks)... The results will be reported and published soon.