

# Indirect dark matter searches with the MAGIC telescopes

David Paneque

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On behalf of the MAGIC Collaboration



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Max-Planck-Institut für Physik  
(Werner-Heisenberg-Institut)

TeVPA 2016



**MAGIC**  
Major Atmospheric  
Gamma Imaging  
Cerenkov Telescopes

## Outline

- 1 – The MAGIC telescopes
- 2 – The hunt for DM particles
- 3 – Conclusions

# **1 – The MAGIC telescopes (and collaboration)**

# The MAGIC Stereoscopic system

- MAGIC: Two Imaging Atmospheric Cherenkov Telescopes (IACTs) of 17 meter diameter mirror dish to perform Very High Energy (VHE) gamma-ray astronomy
  - Operational energy range ; from 50 (30) GeV to >50 TeV
  - Sensitivity: 0.7% the Crab Nebula flux (above 220 GeV) after 50 hours observation  
→ About 5% of the Crab Nebula flux in 1 hour of observation
- The strategy : operate until (at least) CTA is in scientific operation (> 2020)
  - 2004 : Beginning of scientific operation of MAGIC 1 (Single telescope)
  - 2006 : MAGIC upgraded with the MUX-DAQ system (More stable and Better pulse-information)
  - 2009 : MAGIC upgraded with a second telescope (stereo observations)
  - 2012 : Large Hardware of upgrade of the system (*improved sensitivity and reliability*)

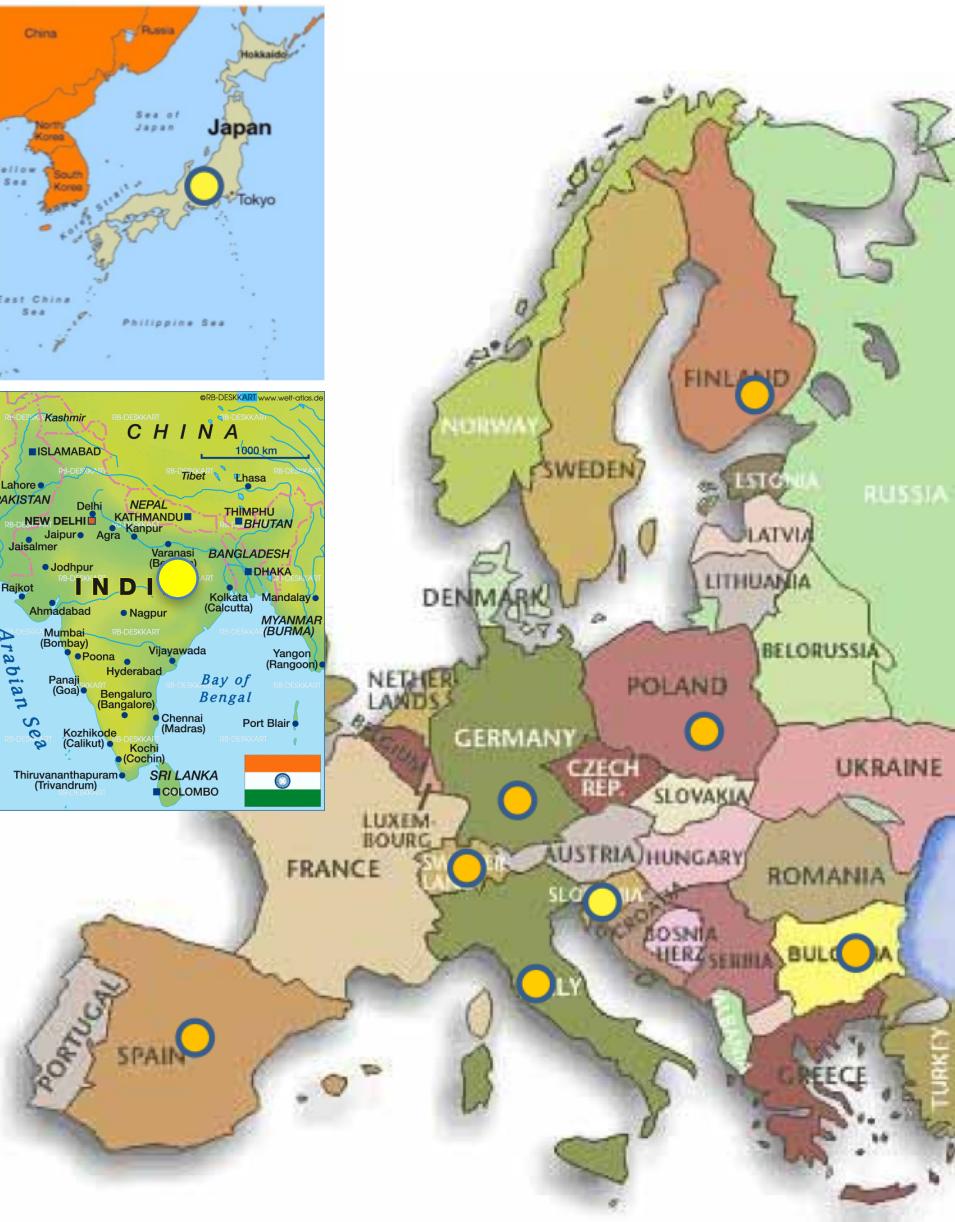
Observatorio Roque de los Muchachos (2200 meter a.s.l.)

La Palma, Canary islands (Spain)



# The MAGIC Collaboration

170 physicists from 10 countries



**Bulgaria** Sofia

**Croatia** Consortium (Zagreb, +...)

**Finland** Consortium (Tuorla, +...)

**Germany** DESY Zeuthen, U. Dortmund,  
MPI Munich, U. Würzburg

**Japan** Consortium (Kyoto, +...)

**Italy** INFN & U. Padova, INFN Pisa & U.  
Siena, INFN Como/Milano Bicocca,  
INFN Udine/Trieste & U. Udine,  
INAF (Consortium: Rome, +...)

**Poland** Lodz

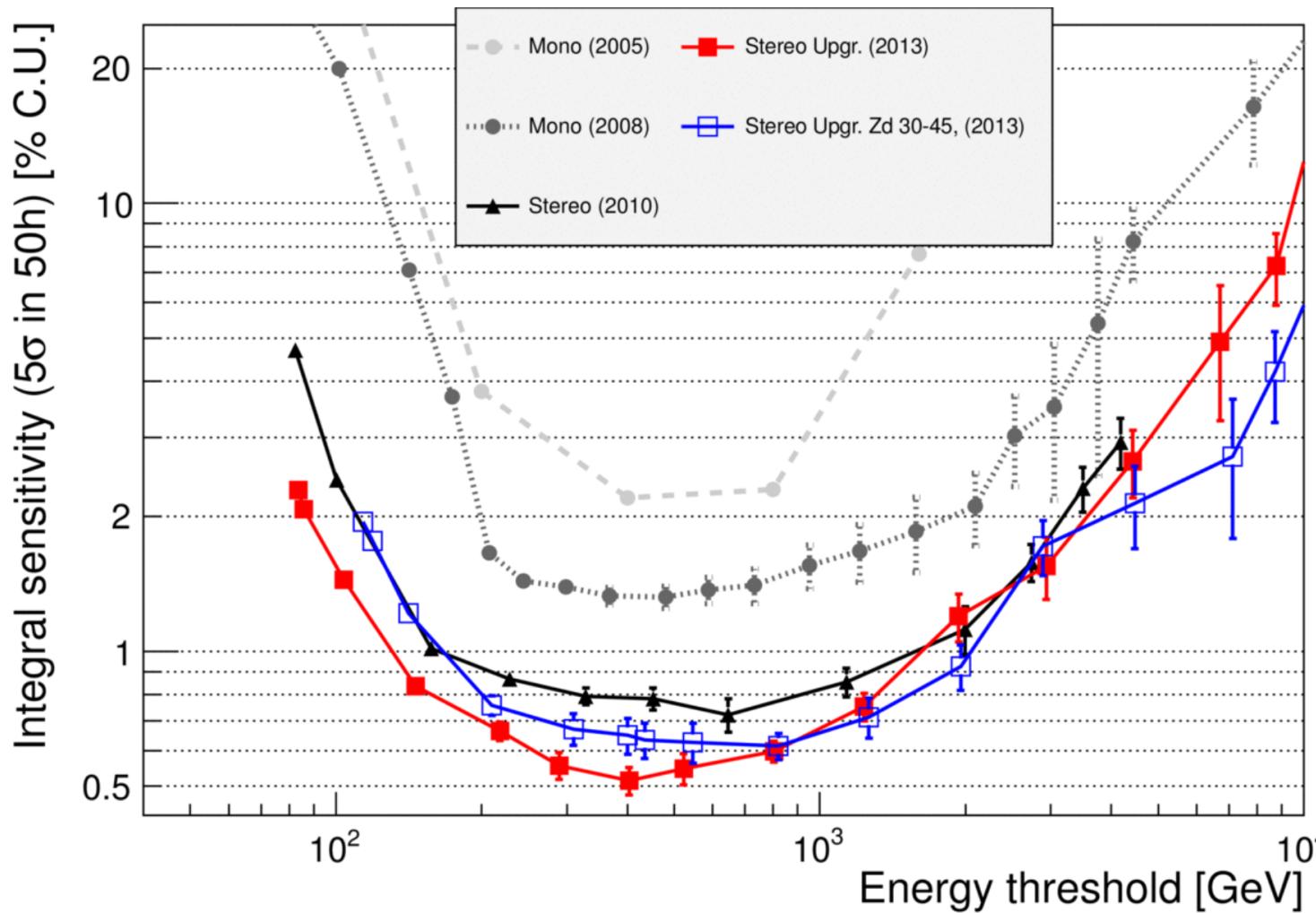
**Spain** U. Barcelona, UAB Barcelona,  
IEEC-CSIC Barcelona, IFAE  
Barcelona, IAC Tenerife, U.  
Complutense Madrid, CIEMAT  
Madrid

**Switzerland** ETH Zurich

**India:** Saha Institute of Nuclear Physics,  
Kolkata

# Overall evolution during the last decade

## 4-fold improvement in sensitivity over the last decade



Aleksic et al.,  
(MAGIC collab.)  
Astroparticle  
Physics 72, 76-92,  
2016

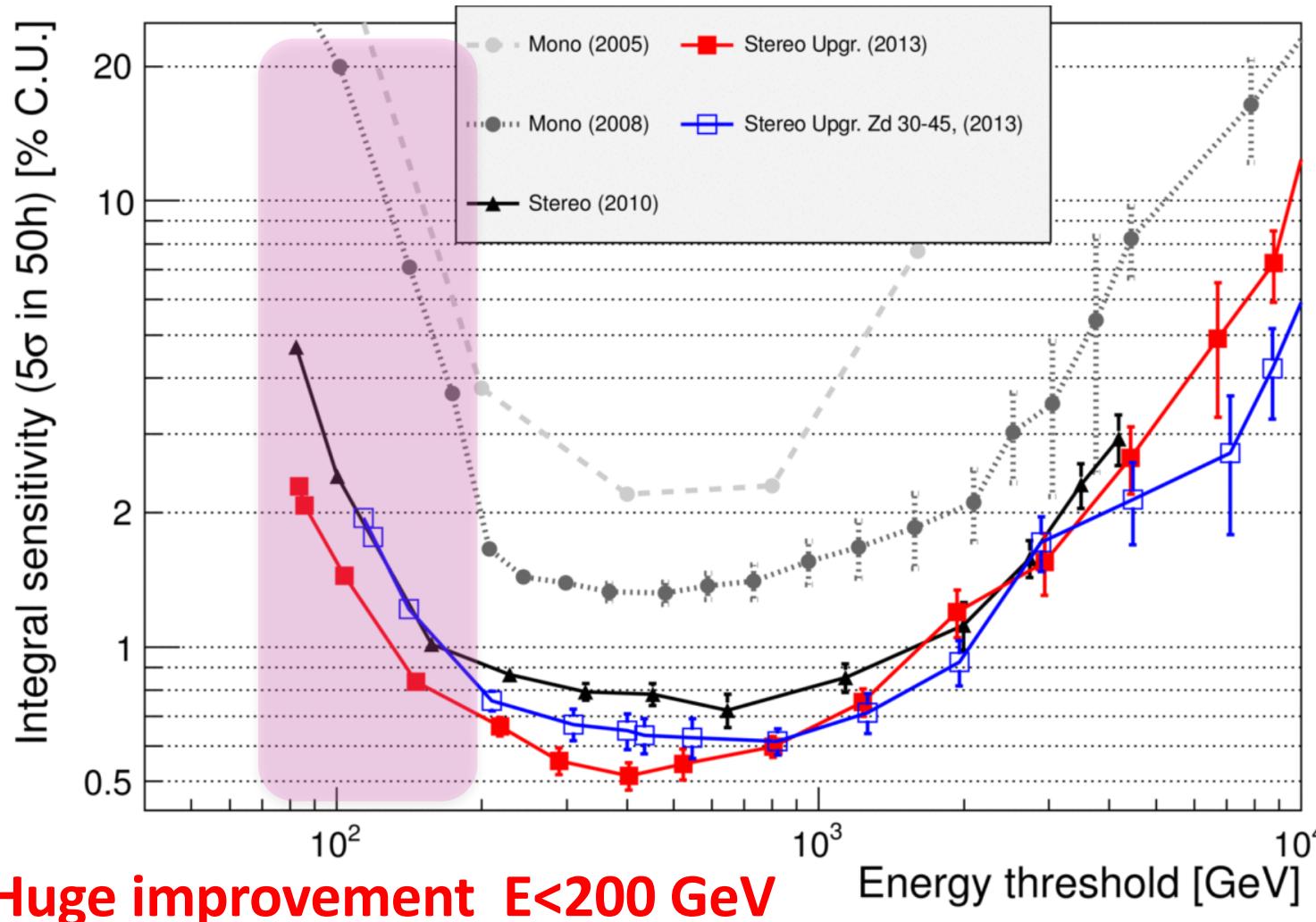
Better sensitivity + Lower energy threshold = More science !!

# Overall evolution during the last decade

4-fold improvement in sensitivity over the last decade

→ More than 10-fold improvement below 200 GeV

→ Obs. time for source detection reduced 100 below 200 GeV



Aleksic et al.,  
(MAGIC collab.)  
Astroparticle  
Physics 72, 76-92,  
2016

Better sensitivity + Lower energy threshold = More science !!

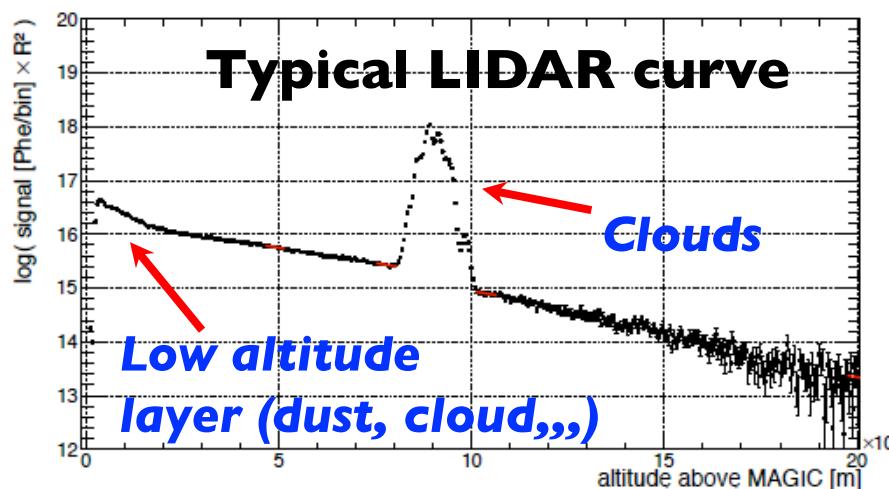
# Pioneering usage of LIDAR in IACT to mitigate effects of adverse atmospheric conditions

- 1) CORRECT data taken under non-perfect atmospheric conditions and
- 2) RECOVER data taken during adverse atmospheric conditions, which would be discarded otherwise



**More & Better Data**

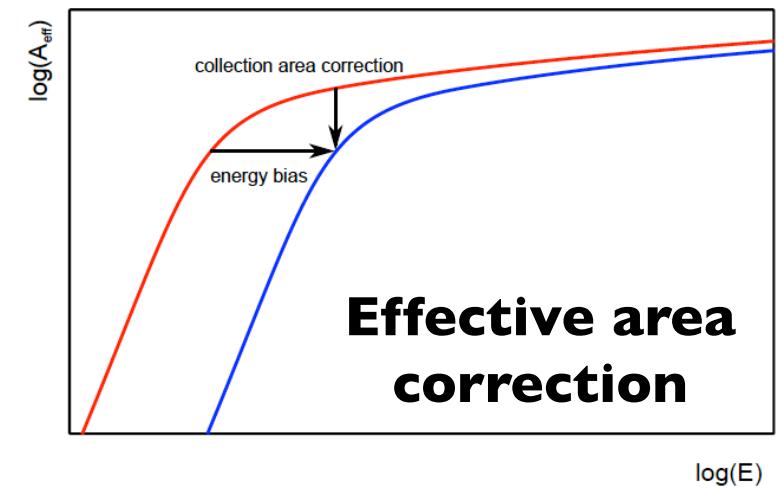
→ Important for long observations



Strategy presented in ICRC 2013 (*Fruck et al., #1054*)



**LIDAR, next to MAGIC**



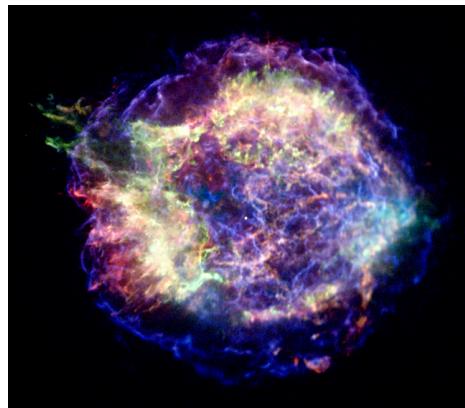
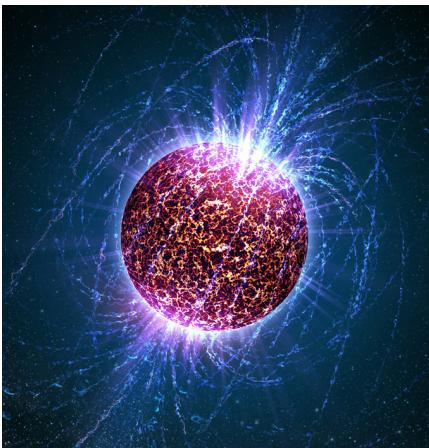
**First time that Cherenkov Telescope data are corrected with LIDAR**

- Procedures starting to be used routinely in MAGIC data
  - Recovered 10 hours of crucial data during flaring activity in Mrk501
- *arXiv:1508.05026 and ApJ 819 (2015) 156*

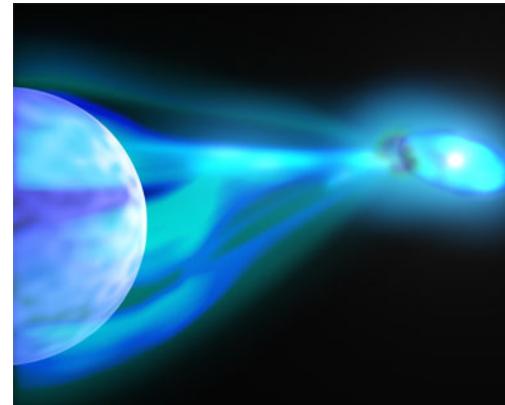
# MAGIC data address a wide range of scientific topics

## SNR+PWN

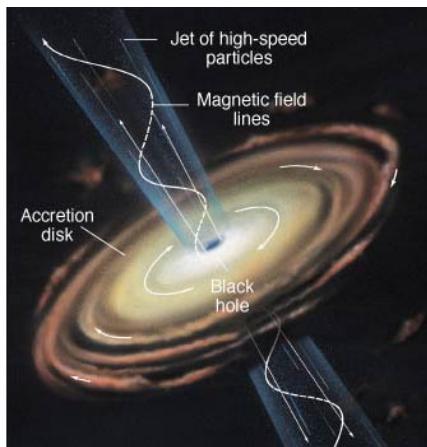
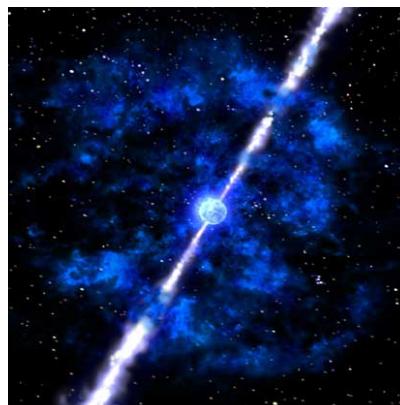
### Pulsars



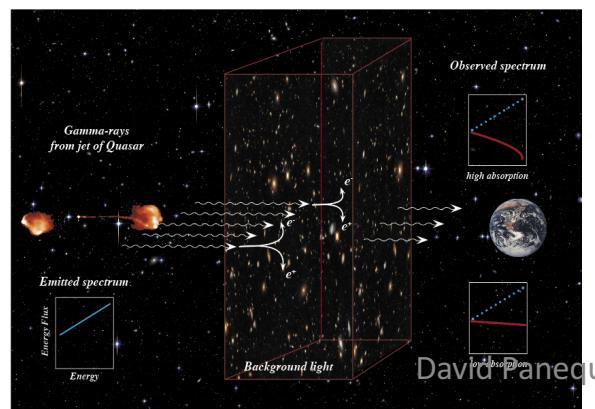
## Binary systems & Novae



## GRBs

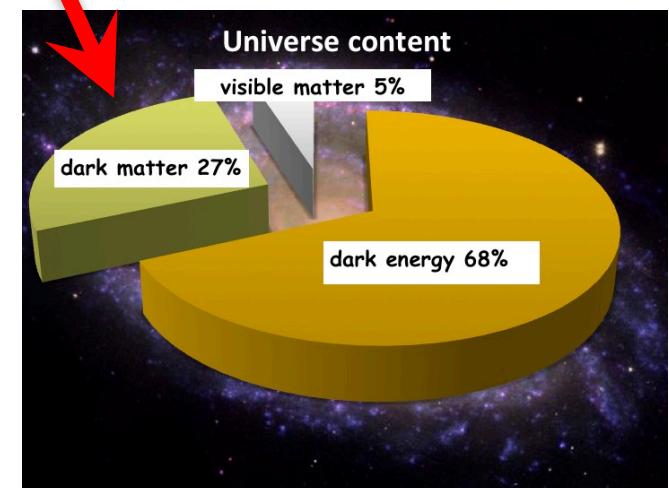


## AGNs



EBL  
IGMF  
ALPs  
LIV

This talk: hunting for  
DM with MAGIC

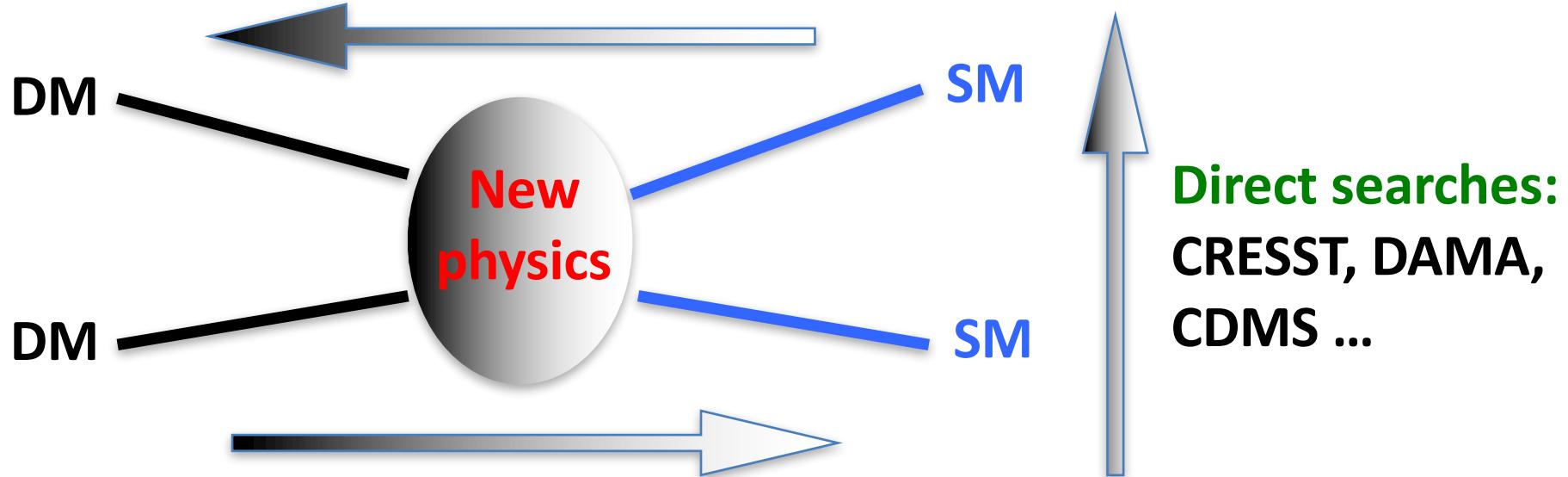


## **2 – The hunt for DM with MAGIC**

# Dark matter searches with MAGIC

Three different ways of looking for Dark Matter particles

Collider searches: ATLAS, CMS ...



Indirect searches: **MAGIC, HESS, VERITAS, Fermi, IceCube, AMS...**

Even if a signal was found in collider experiments or direct detection experiments, we would still need indirect detection searches in order to:

- 1) *confirm that whatever we find in the Lab is the same “dark matter” responsible for astrophysical and cosmological observations.*
- 2) *access particle information not otherwise available in the Lab (annihilation cross section or decay time, b.r.’s)*

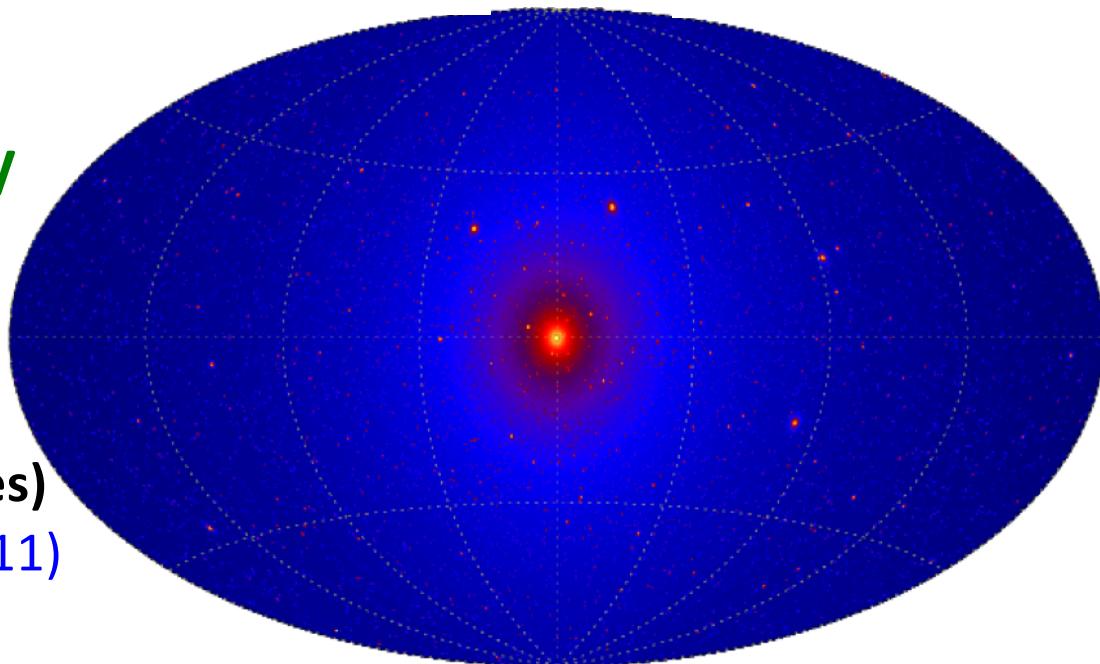
# Dark matter searches with MAGIC

**Simulated all-sky  
map of gamma-  
rays from DM  
annihilation  
(Galactic coordinates)**

PRD 83, 023518 (2011)

N-Body simulation

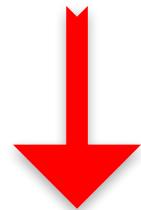
Via Lactea II



# Dark matter searches with MAGIC

## Dwarf Galaxies (dSph)

No BKG and close to us,  
small extension, but  
typically low DM signal



**Best target for  
DM annihilation  
searches with MAGIC  
( $J_{\text{ann}} \sim \int \text{DM\_density}^2$ )**

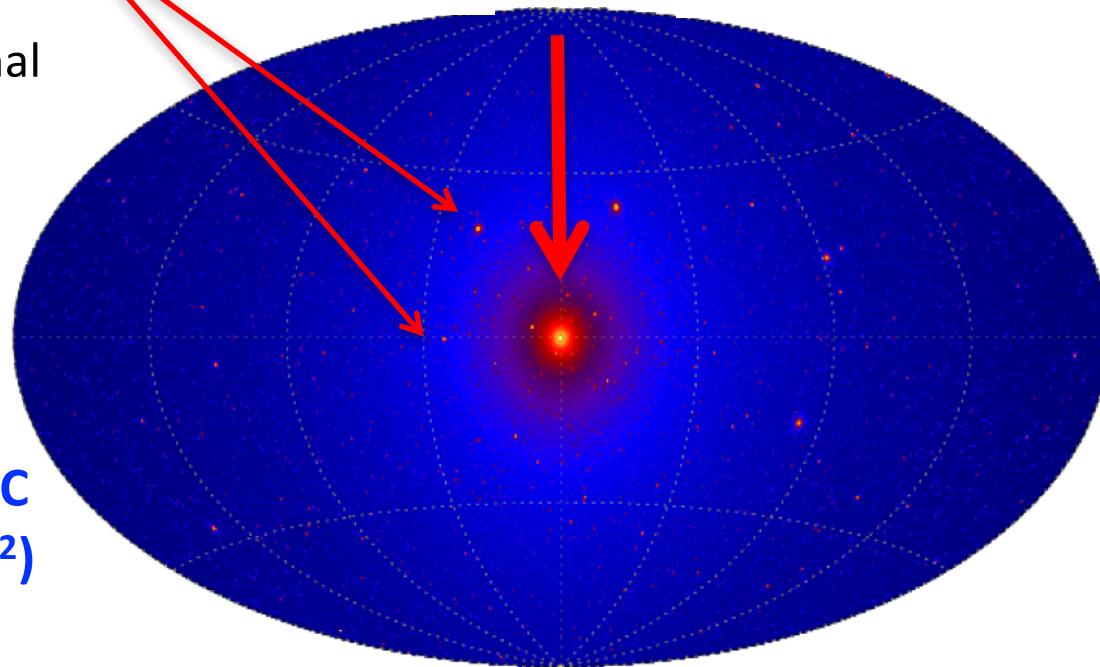
## Spectral lines

No astrophysical  
uncertainties, easy  
identification, but small  
branching ratio

*All potential DM sources  
can be used*

## Galactic Center and Halo

Good statistics, but extended,  
src confusion, diffuse BKG and  
large uncertainties in J-factor



## Galaxy Clusters

Large DM content, but  
extended, uncertainties in  
J-factor and far away from us



**Best target for  
DM decay  
searches with MAGIC  
( $J_{\text{dec}} \sim \int \text{DM\_density}$ )**

# Dark matter searches with MAGIC

## Dwarf Galaxies (dSph)

No BKG and close to us,  
small extension, but  
typically low DM signal

### Draco

ApJ 679 (2008) 428 , 8 hours of eff. MAGIC obs.

### Willman 1

ApJ 697 (2009) 1299, 16 hours of eff. MAGIC obs.

### Segue 1

JCAP 06 (2011) 035, 30 hours of eff. MAGIC obs.

JCAP 02 (2014) 008, 158 hours of eff. MAGIC obs.

JCAP 02 (2016) 039, MAGIC+Fermi

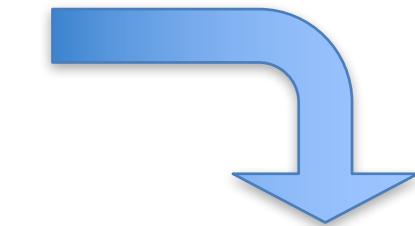
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ApJ Lett. 638 (2006) L101  
17 hours of observation  
(after quality cuts)

## Perseus cluster

ApJ 710 (2010) 634  
25 hours MAGIC obs.



## Galaxy Clusters

Large DM content, but  
extended, uncertainties in  
J-factor and far away from us

# Dark matter searches with MAGIC

## Dark matter searches in deep observations of Segue 1 with MAGIC

Aleksic *et al* *JCAP* **02** (2014) 008

**158 hours of effective time**

→ Deepest observation of  
any dSph by any IACT

**The dSph galaxy Segue 1 is an excellent target for DM searches  
with MAGIC**

- 1) Heavily dark matter dominated object
- 2) Least luminous galaxy
  - Mass to light ratio  $\sim 3400 M_\odot / L_\odot$
  - we do not expect “conventional” gamma-ray signals
- 3 ) Very close Close to Earth:  $23 \pm 2$  kpc
- 4) Northern hemisphere, culminates at 13 deg for MAGIC

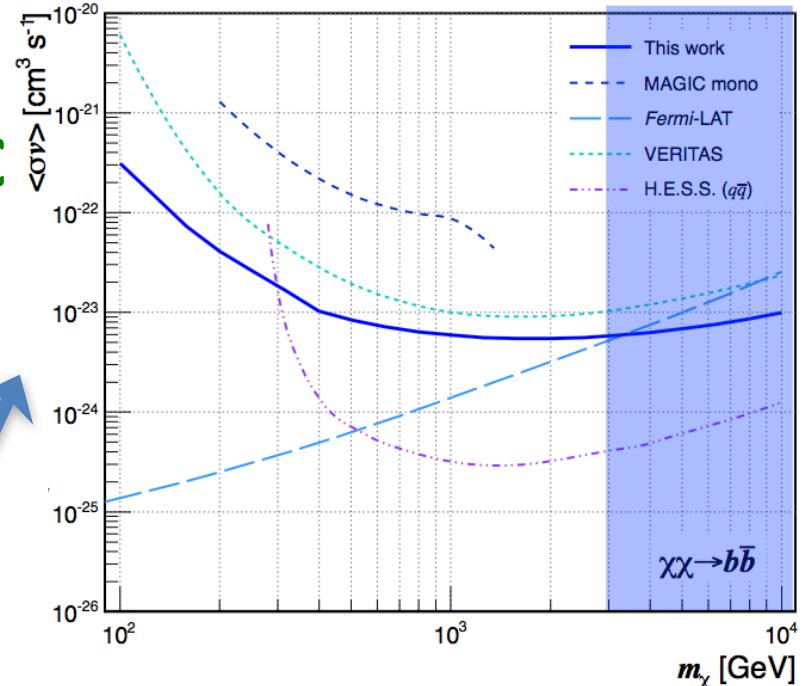
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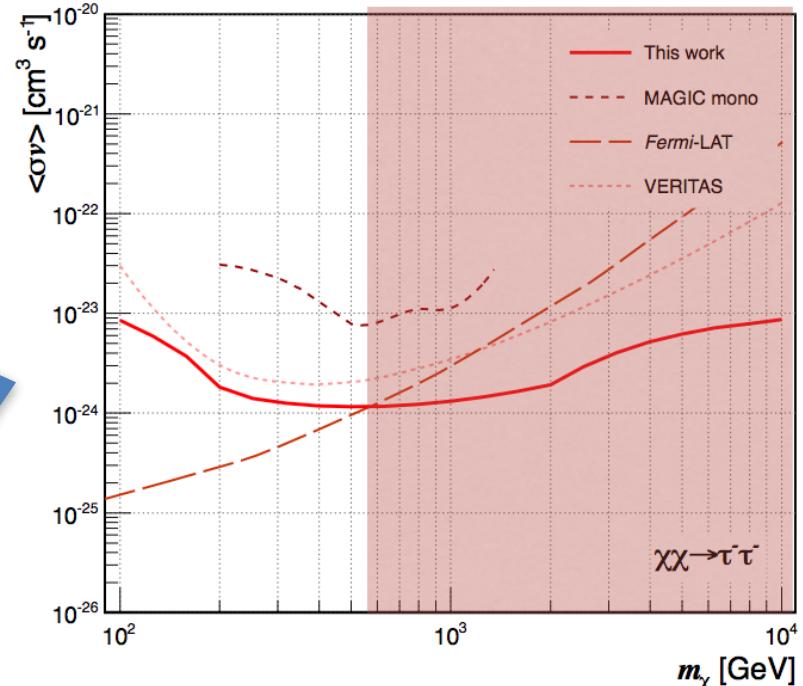
→ Deepest observation of any dSph by any IACT



Results made it into PDG

(K. A. Olive *et al.*, Review of Particle Physics, Chin. Phys. C, 38, (2014) 090001)

Best limits from dwarfs in high-mass range



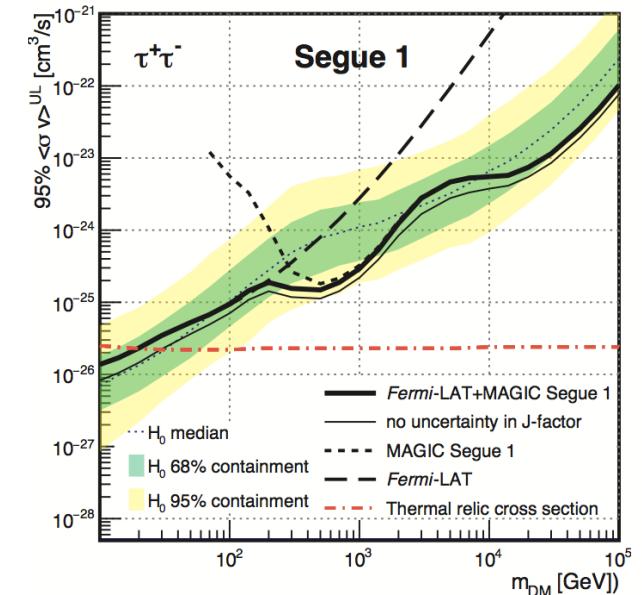
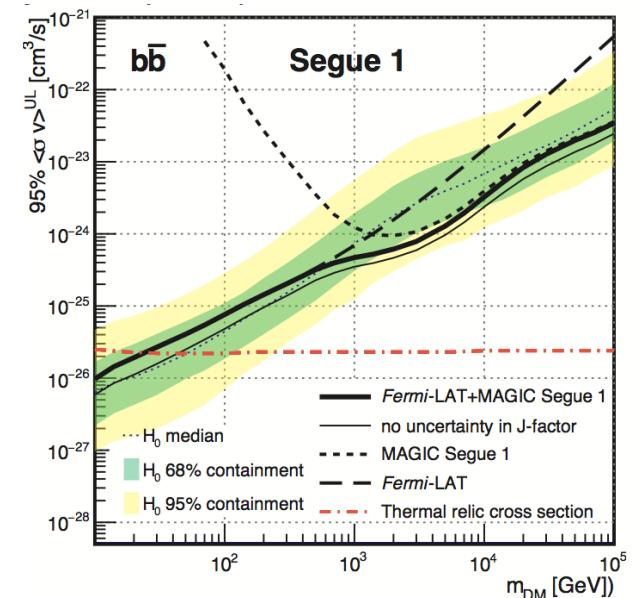
# Dark matter searches with MAGIC+Fermi

Upper limits improve  
when MAGIC Segue I  
data are combined with  
Fermi-LAT data (dwarfs)

Ahnen *et al*  
JCAP 02 (2016) 039

- Fermi-LAT+MAGIC Segue 1
- no J uncertainty
- - - MAGIC Segue 1
- Fermi-LAT
- - - Thermal relic cross section
  
- $H_0$  median
- $H_0$  68% containment
- $H_0$  95% containment

LAT+MAGIC (only Segue I)

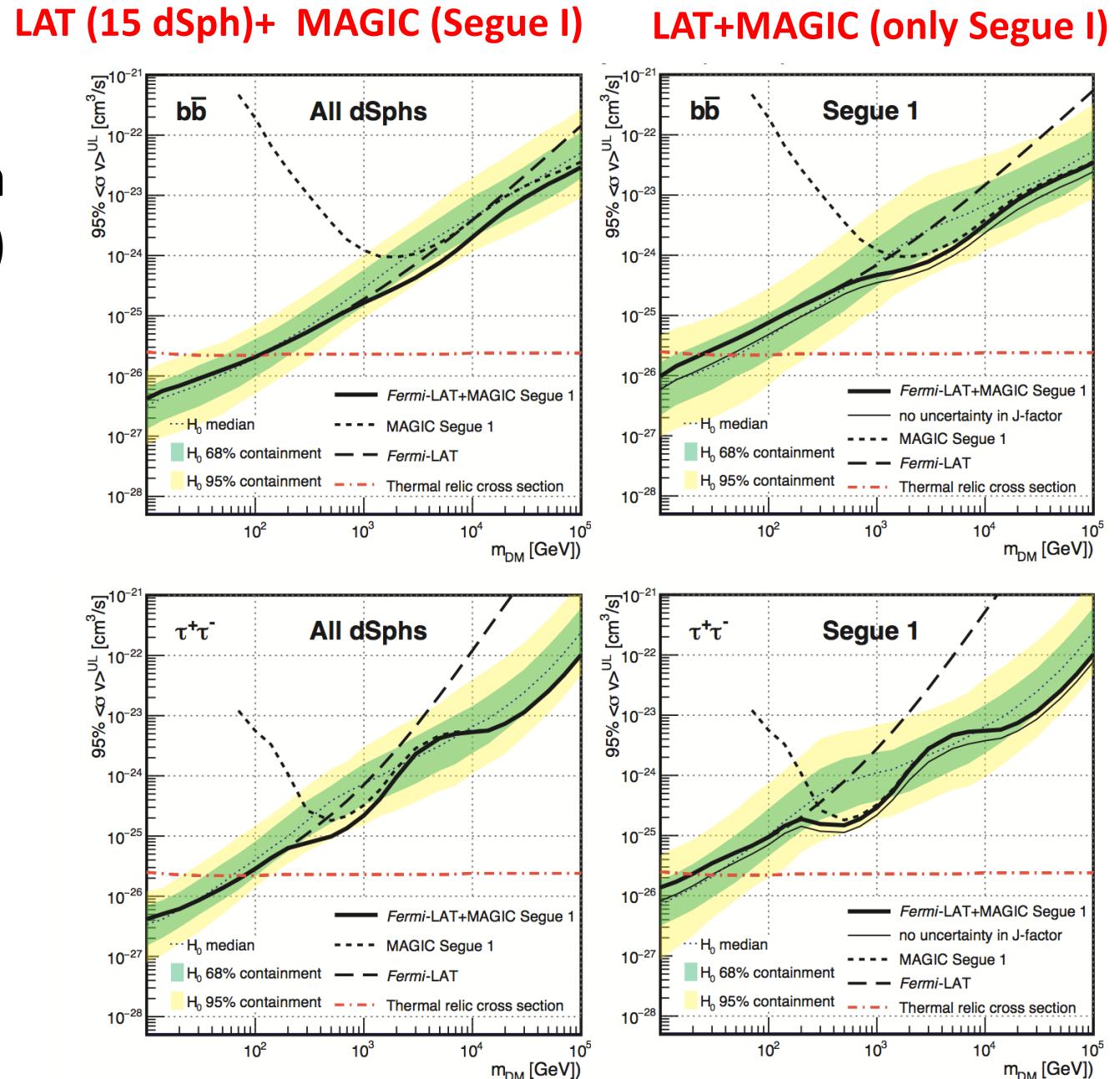


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Best limits using dSph to date

# Dark matter searches with MAGIC+Fermi

Ahnen et al

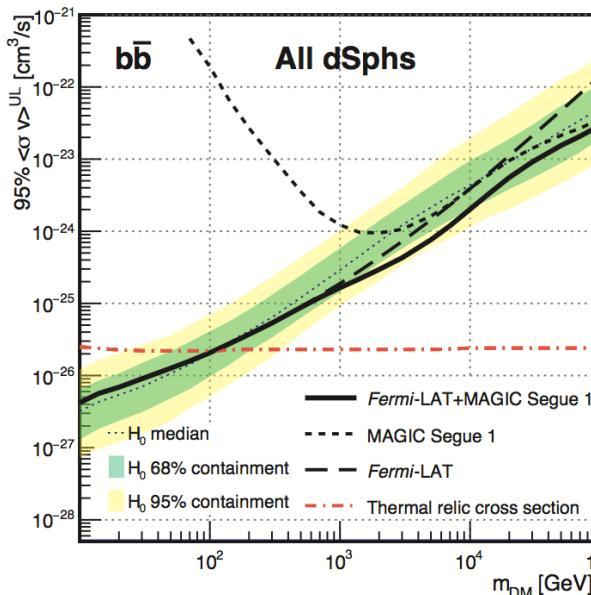
JCAP 02 (2016) 039

1) Coherent limits over 4 orders of magnitude

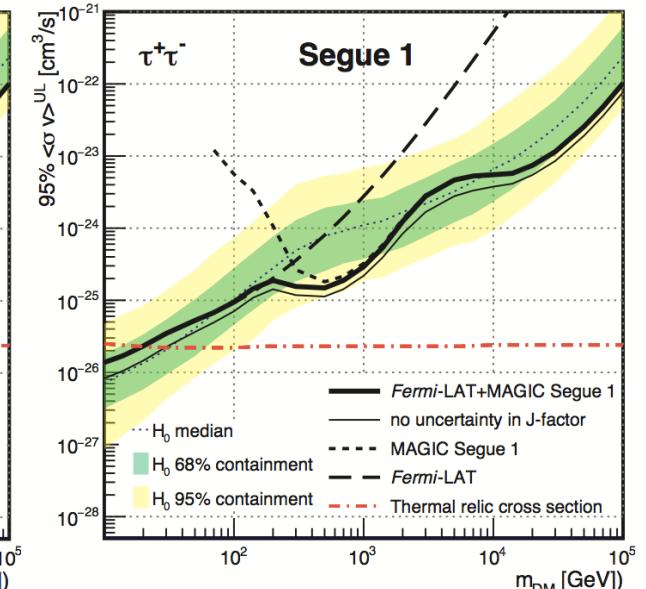
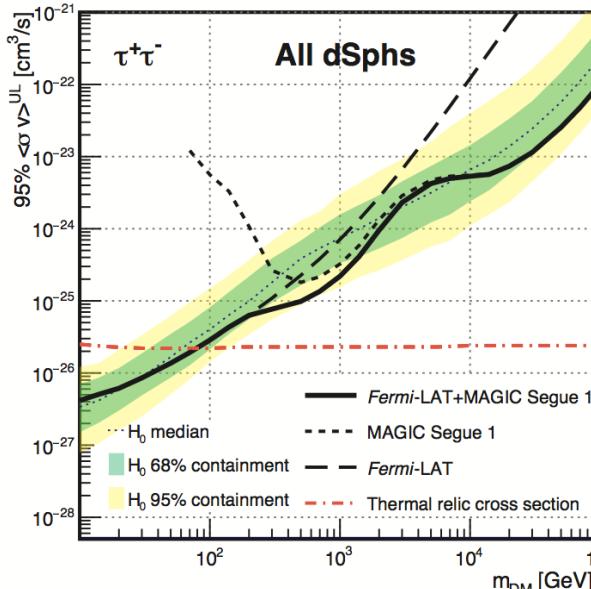
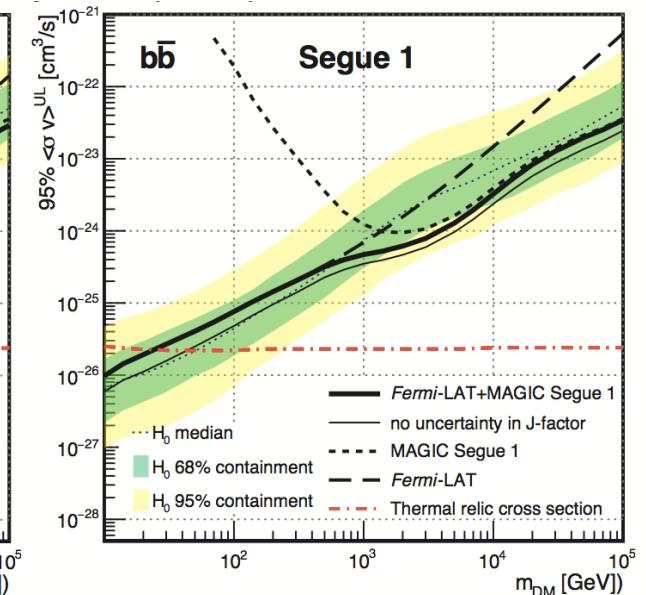
2) Fermi-LAT dominates limits below  $\sim 1$  TeV, MAGIC dominates above  $\sim 1$  TeV

3) Improvement by  $\sim 2$  in the intermediate mass range

LAT (15 dSph)+ MAGIC (Segue I)



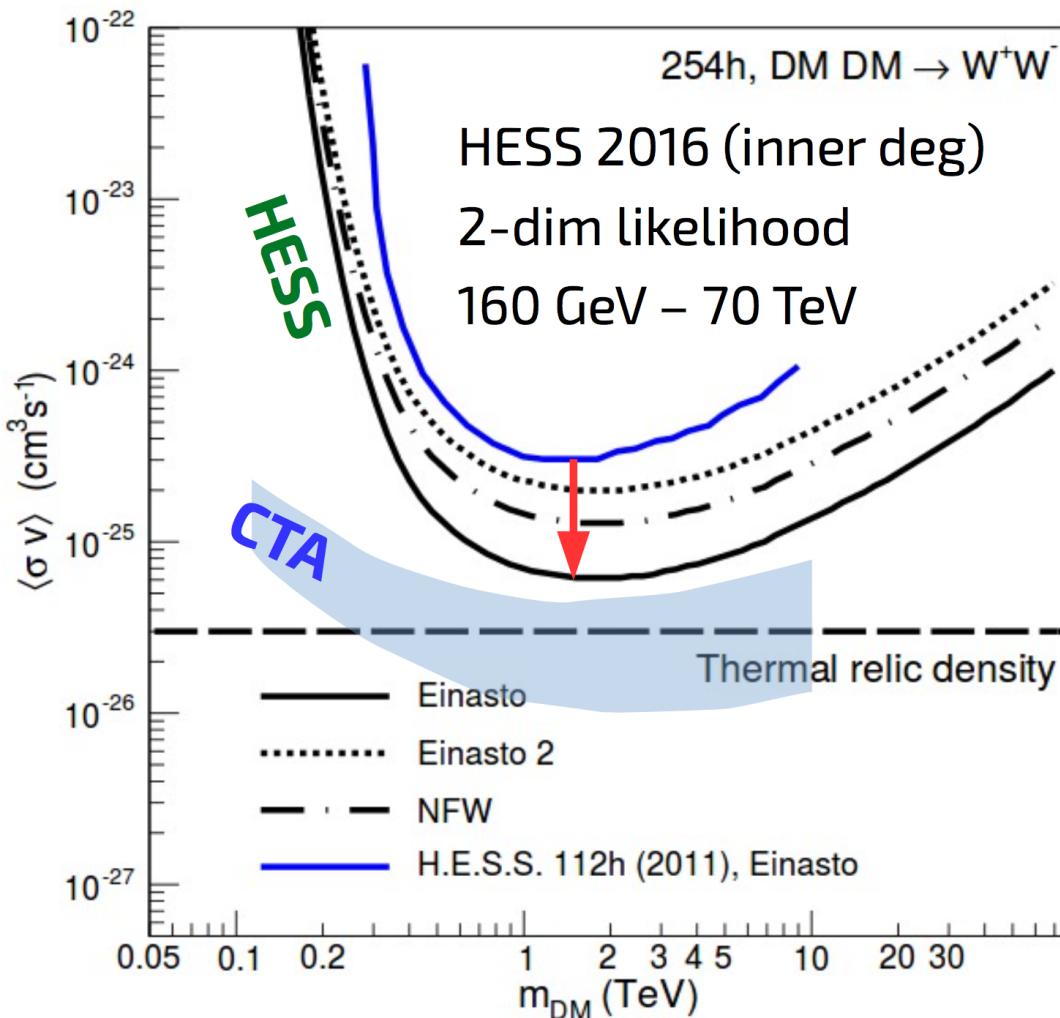
LAT+MAGIC (only Segue I)



Best limits using dSph to date

# Current most stringent upper limits at TeV energies from the Galactic Center (largest J-factor)

*Figure shown by C. Weniger  
(this conference, Wed. Sep14)*



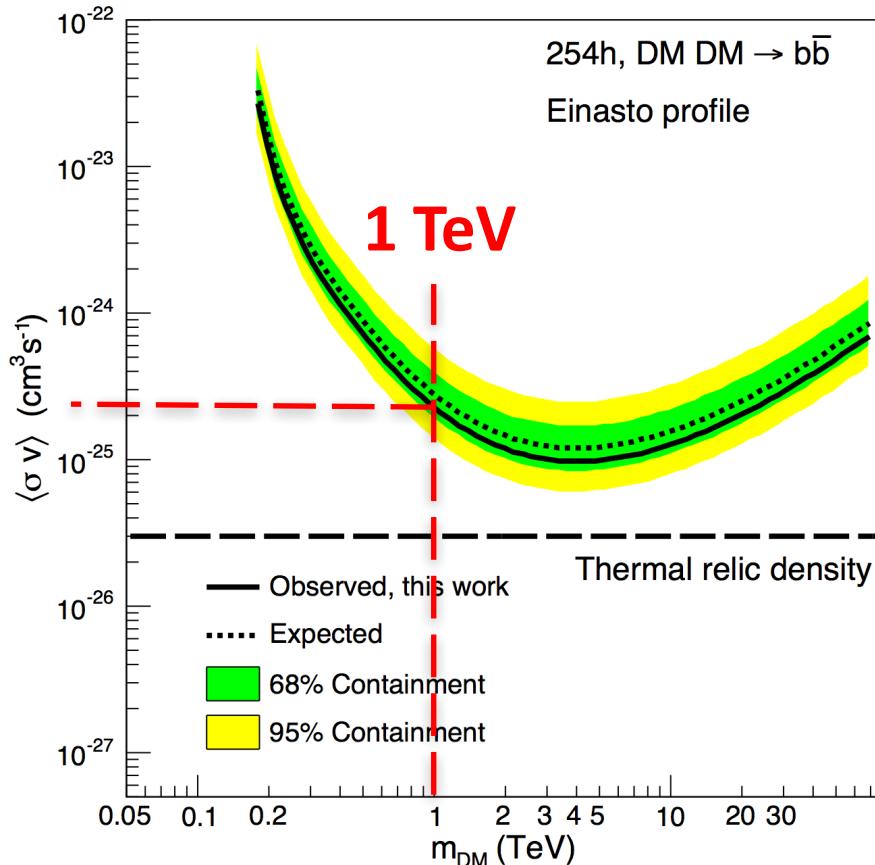
But keep in mind that, for the Galactic Center, there are important astrophysical gamma-ray backgrounds, and suffer from large uncertainties in J-factor, **and only possible to do with cusp DM profiles.**

**dSph galaxies provide the “less uncertain” upper limits on the velocity-averaged cross-sections**

# Current most stringent upper limits at TeV energies from the Galactic Center (largest J-factor)

**But not for all annihilation channels**

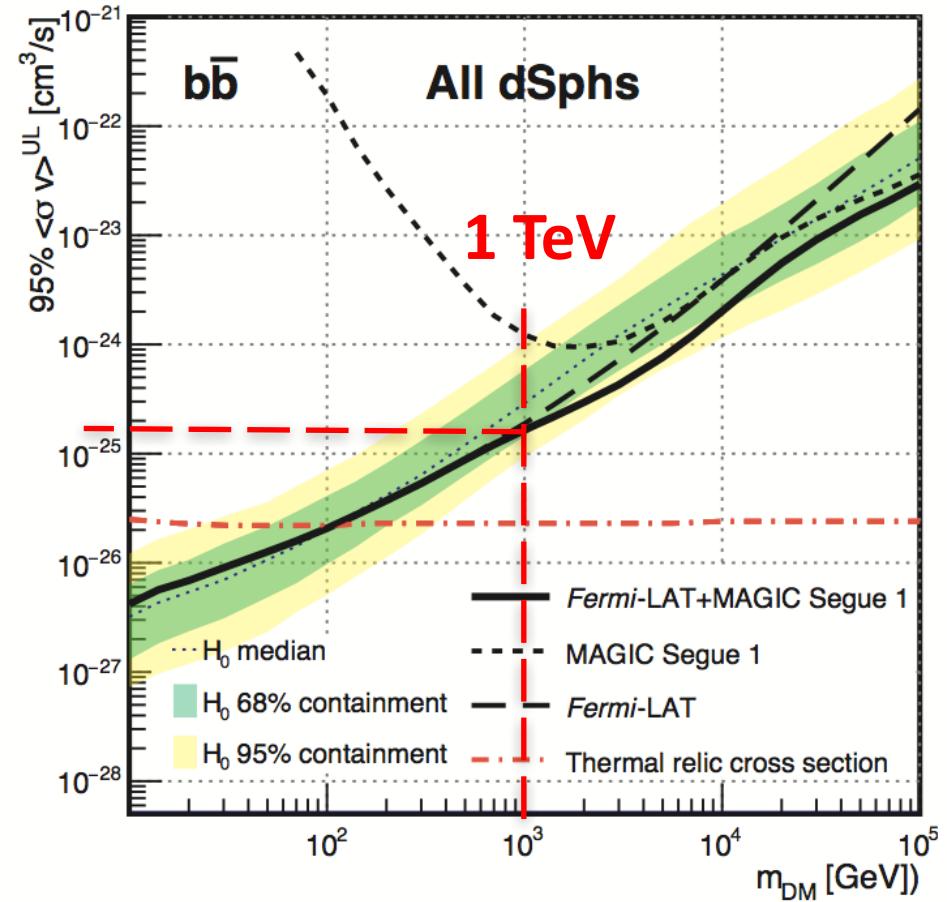
**HESS (GC, 254 h., Einasto)**



*Abdallah et al*

Phys. Rev. Lett. 117 (2016) 111301

**LAT+MAGIC (Segue1, 158 h., NFW)**

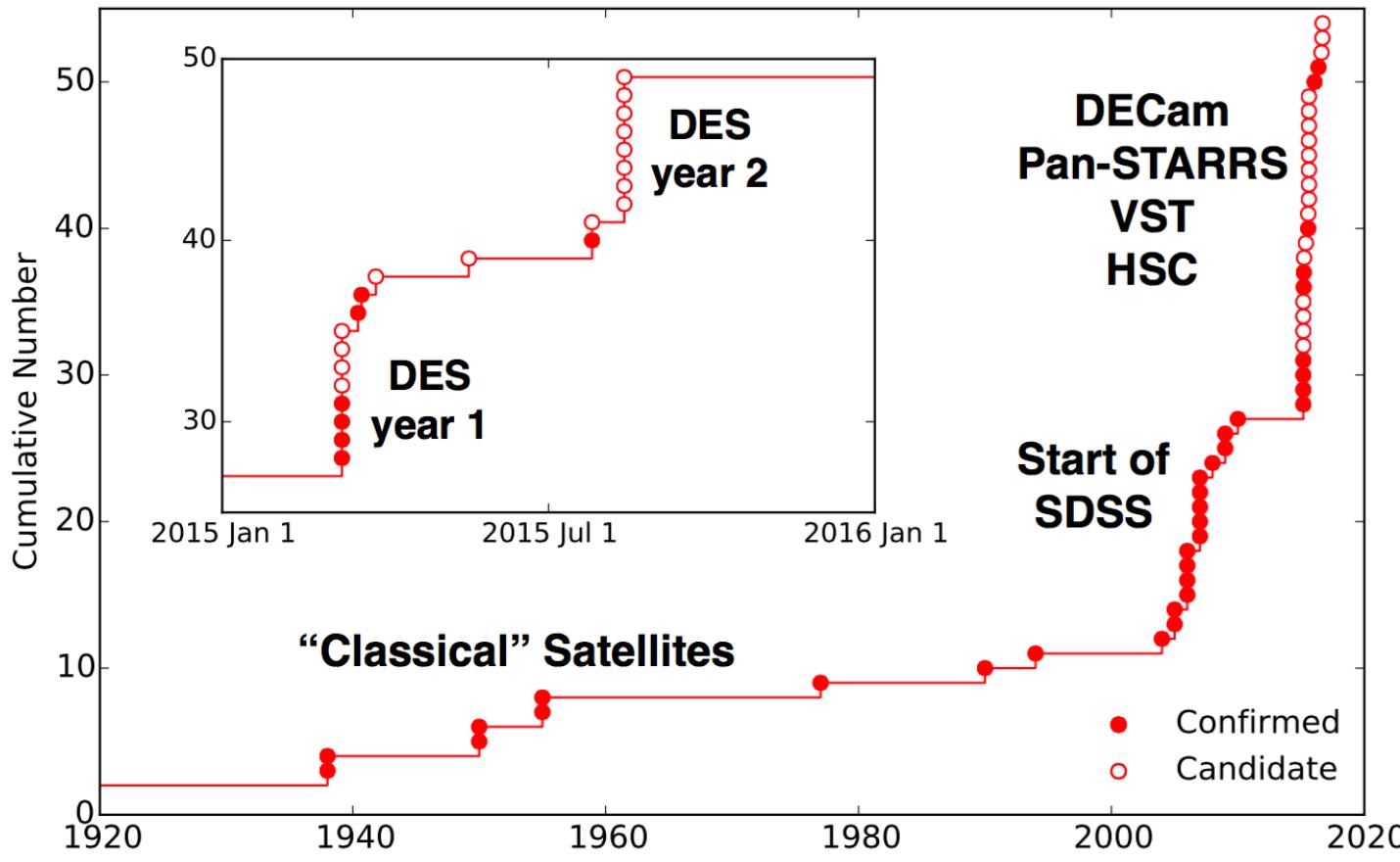


*Ahnen et al*

JCAP 02 (2016) 039

# Large optical surveys yielded a dramatic increase in the number of dSph galaxies: factor 2 in 1.5 years !!

*Plot from K. Bechtol (2016/09/15)*



- DES 2 Years**  
A. Drlica-Wagner et al.  
(DES collaboration)  
*ApJ 813 109 (2015)*
- DES 1 Year**  
K. Bechtol et al.  
(DES collaboration)  
*ApJ 807 50 (2015)*
- Koposov et al.  
(Using public DES data)  
*ApJ 830 130 (2015)*

Remember: Gamma-ray flux scales with  $1/\text{distance}^2$

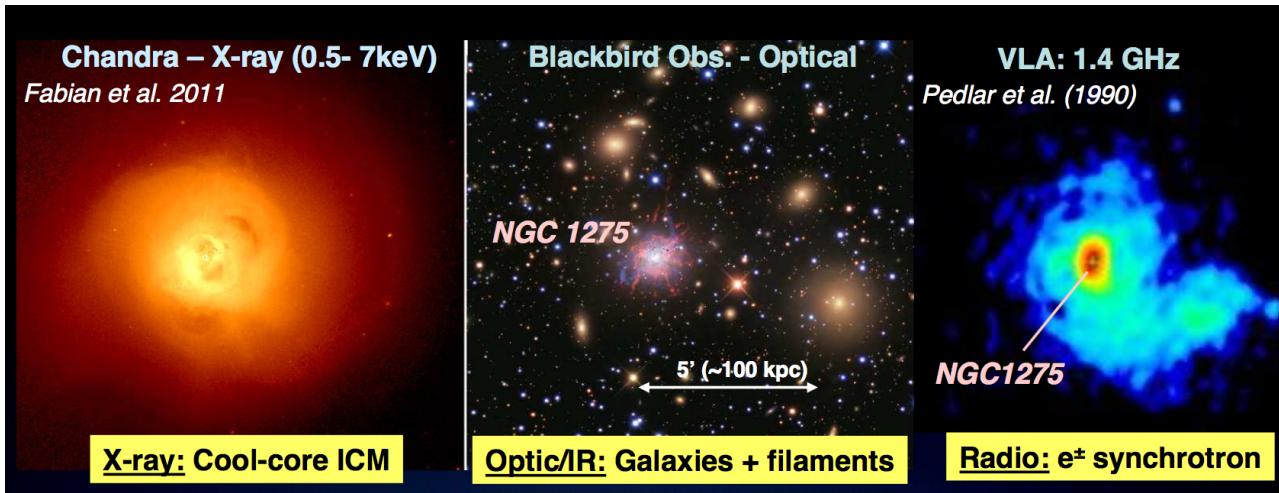
→ A new nearby+massive Dwarf galaxy may be a game changer  
→ Better upper limits OR Detection

# Dark matter searches with MAGIC

Clusters are the largest gravitationally bound systems in the Universe

- Mass:  $10^{14} - 10^{15}$  Solar masses ; Radius: few Mpc

**Mass composition:** - **Dark Matter: ~80%** - Intra-Cluster Matter: 15% - Galaxies: 5%



## Perseus cluster

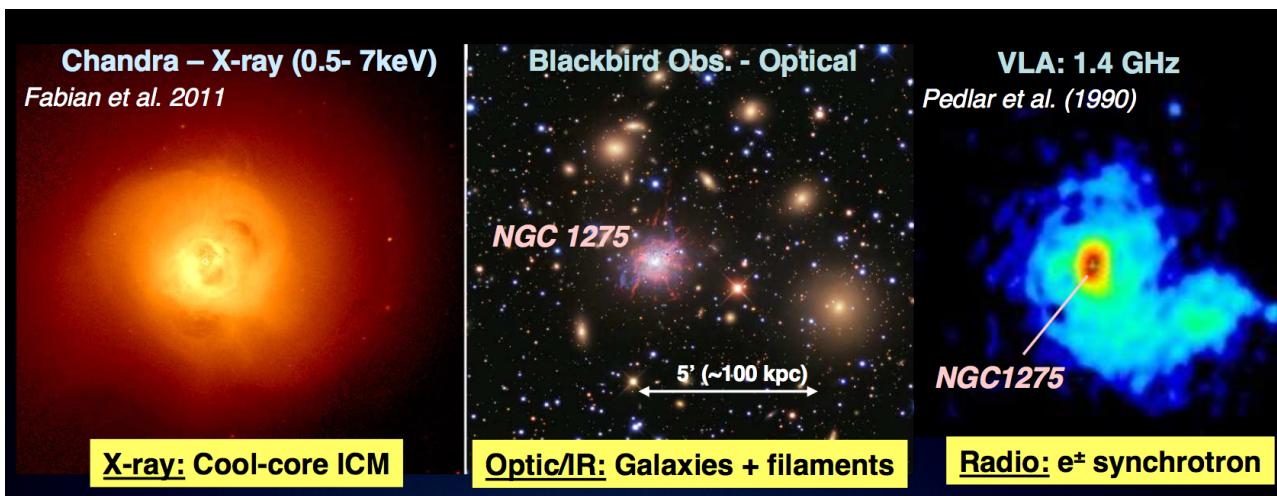
- Nearby ( $z=0.018$ )
- Brightest X-ray cluster
- Dominant central radio galaxy: NGC 1275
- Non-thermal emission: bright radio mini-halo

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## Perseus cluster

- Nearby ( $z=0.018$ )
- Brightest X-ray cluster
- Dominant central radio galaxy: NGC 1275
- Non-thermal emission: bright radio mini-halo

### 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

M.L. Ahnen et al., *Astron. Astrophys.* 589 (2016) A33

#### - NGC1275: first detected at VHE and modeled

J. Aleksić et al., *Astron. Astrophys.* 539 (2012) L2

J. Aleksić et al., *Astron. Astrophys.* 564 (2014) A5

#### - IC310: first detected at VHE, CR acceleration mechanism close to BH

J. Aleksić et al., *Astrophys. J.* 723 (2010) L207

J. Aleksić et al., *Astron. Astrophys.* 563 (2014) A91 + **J. Aleksić et al *Science*, 346 (2014) 1080**

## MAGIC observed Perseus for more than 250 hours

Lots of “somewhat conventional” science already done. Time to work on the Dark sector...

# Dark matter searches with MAGIC

## Results with Perseus Data

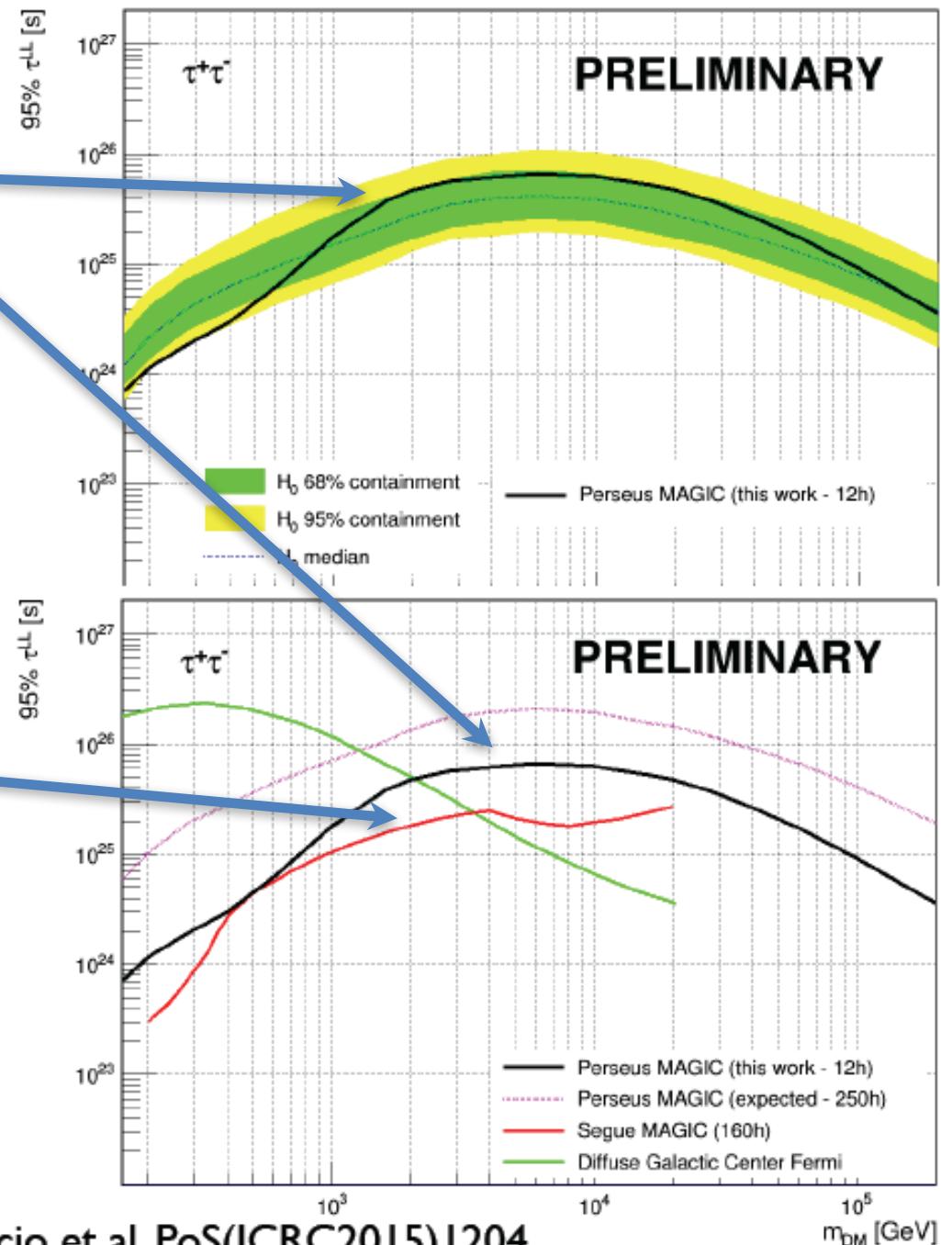
Analysis tested on 12 hours

→ Lower limit on decay time  
 $\sim 8 \times 10^{25}$  s (for a few TeV)

Better results than with  
158 h of Segue 1

Full data set ( $\sim 250$  h) will  
improve limits by  $\sim 4$

→ **Most constraining decay  
DM searches at TeV**



# Conclusions

## MAGIC telescopes currently operating better than ever

- Factor of 4 improvement in sensitivity over the last decade  
→ *More than one order of magnitude better sensitivity below 200 GeV*
- First Cherenkov Telescope that can correct data with LIDAR (since 2015)  
→ *Better & More data for scientific purposes*

## Rich program for indirect DM searches (+Fundamental Physics):

### Dwarf Galaxies:

deepest survey (Segue 1, 158 h) so far of any dSph with IACTs  
strongest limits above  $\sim 1$  TeV from dSph on various DM models

### Fermi-LAT/MAGIC dSphs combined results:

coherent limits in the wide energy window of 10 GeV – 100 TeV  
improvement of limits by a factor  $\sim 2$  in the intermediate mass range

### Perseus cluster:

deep survey ( $\sim 250$  h), expected very competitive DM decay-life limits

## MAGIC DM observation strategy: diversification of targets

reducing targets selection biases (due to *J-factor* uncertainties)

increasing chances for DM discovery

straightforward stacking of results (*full-likelihood* analysis)

→ **Rapid increase of dSph galaxies points to exciting times for DM searches**

# **Backup**

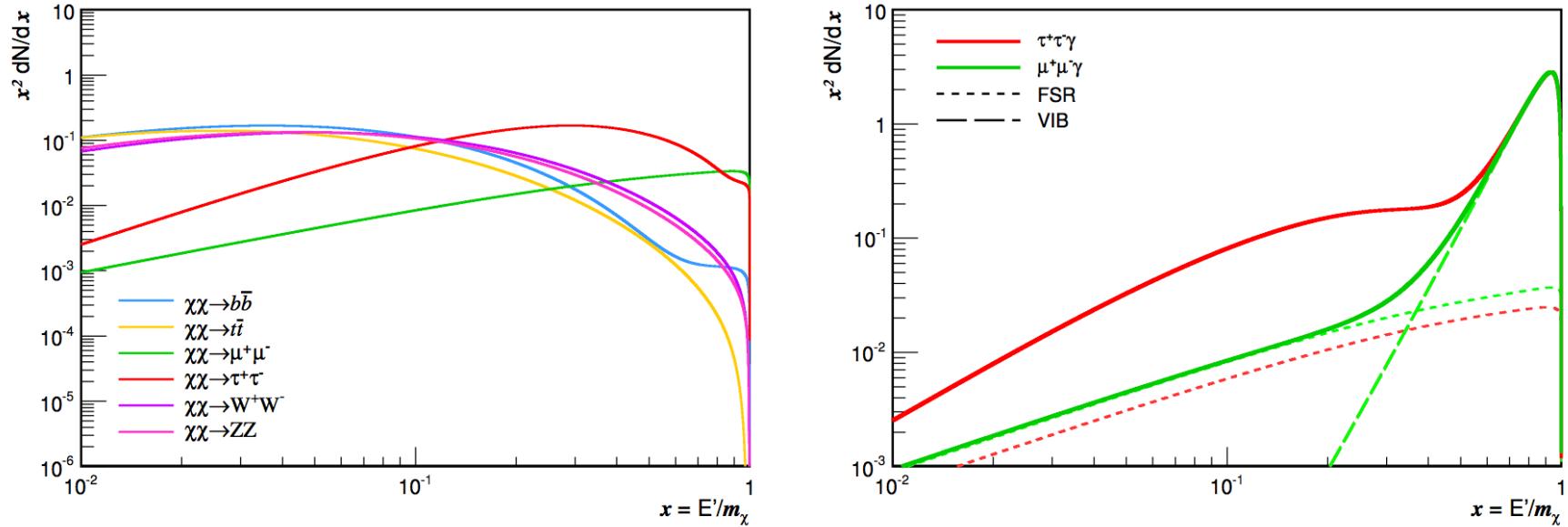
# The MAGIC Stereoscopic system

- MAGIC: Two Imaging Atmospheric Cherenkov Telescopes (IACTs) of 17 meter diameter mirror dish to perform Very High Energy (VHE) gamma-ray astronomy
  - Operational energy range ; 50 GeV – >50 TeV
  - Sensitivity: 0.7% the Crab Nebula flux (above 220 GeV) after 50 hours observation  
→ About 5% of the Crab Nebula flux in 1 hour of observation
  - Angular resolution: ~0.05-0.1 deg (energy dependent)
  - Energy resolution: ~15-20% (energy dependent)
  - Fast movement (points to any direction of the sky in less than 25 seconds)
  - Optical link system for transmission of analogue signals over long distances (160 m) with minimal deterioration (FWHM < 3ns)

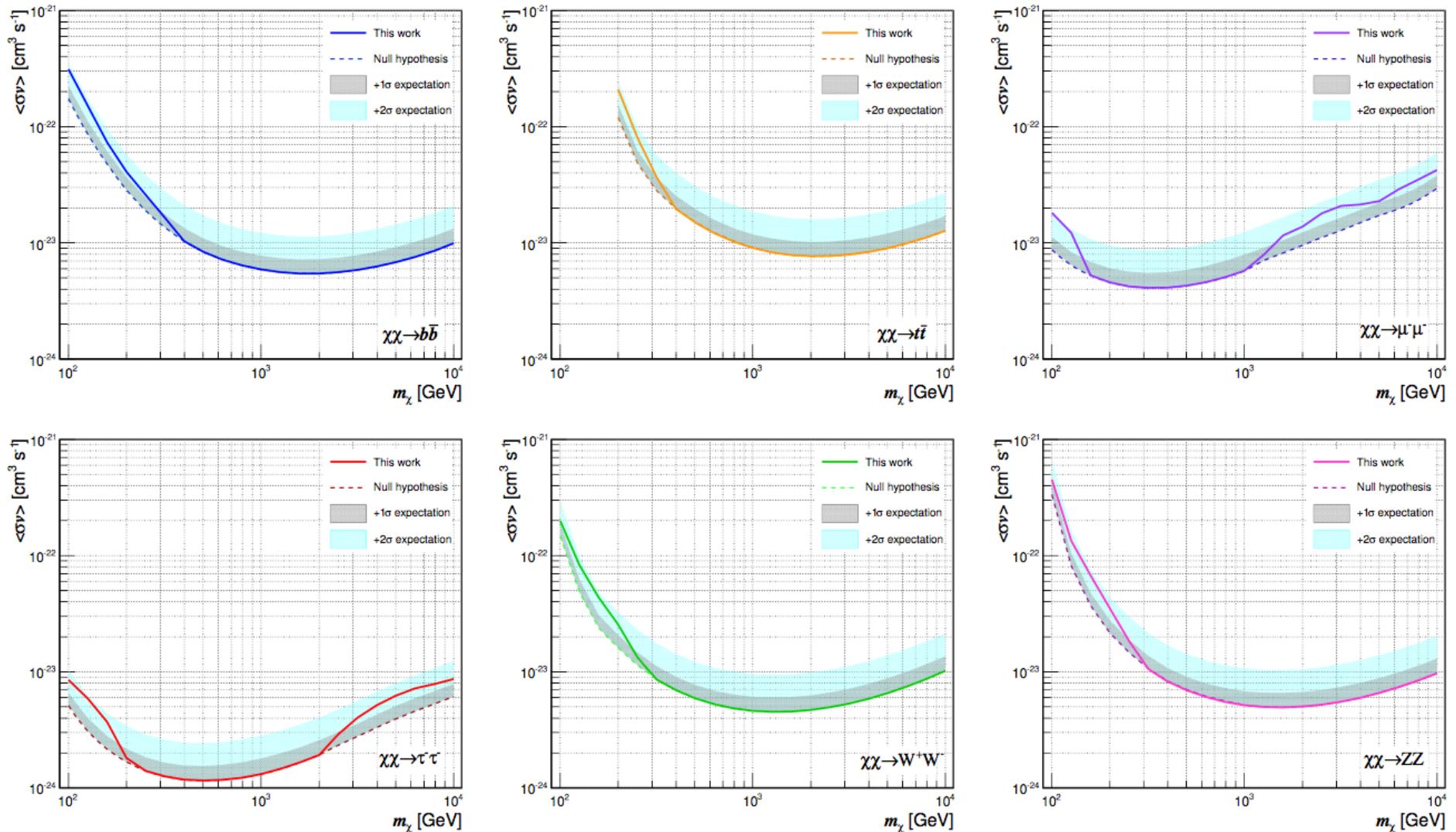
Observatorio Roque de los Muchachos (2200 meter a.s.l.)

La Palma, Canary islands (Spain)

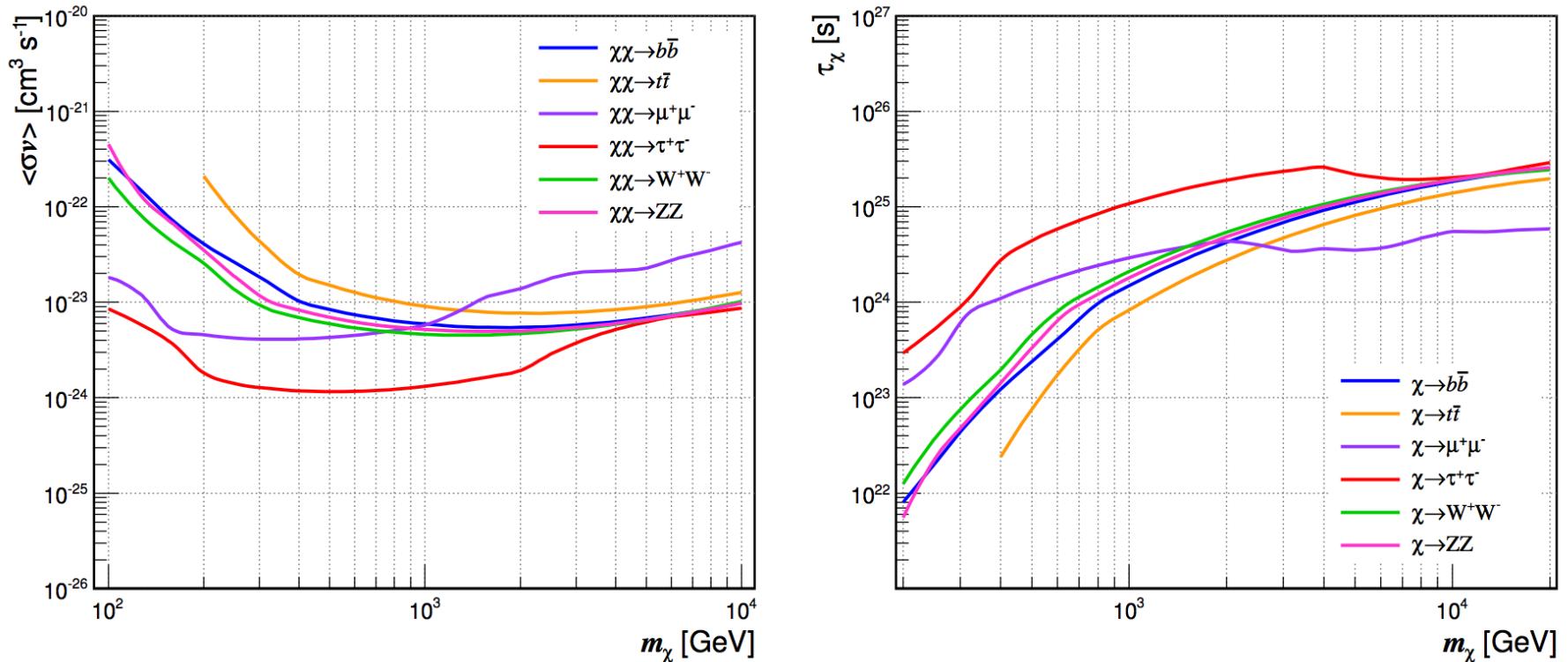




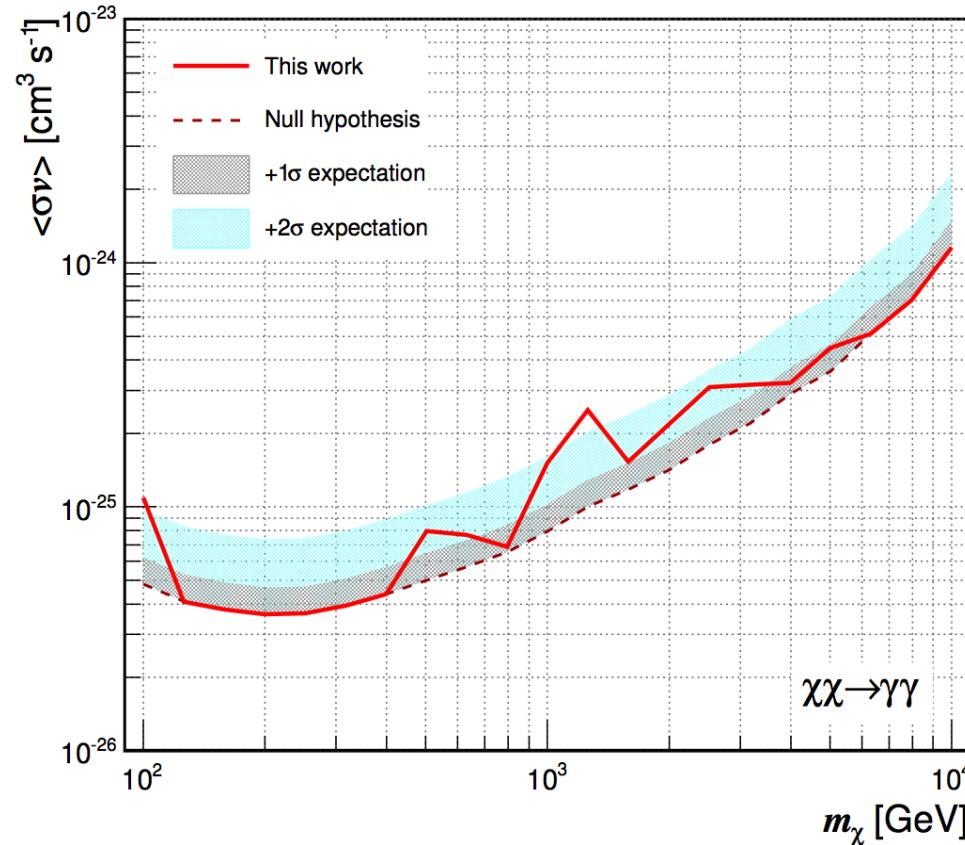
**Figure 3.** Gamma-ray spectrum for DM annihilation into different final states. **(Left)** Secondary photons (when applicable, the FSR is included in the spectrum). Modeling is done according to the fits provided in [39]. **(Right)** Spectral distribution from annihilation into leptonic three-body final states (solid lines), with the contributions from FSR and VIB photons (dashed and long-dashed lines, respectively). The assumed mass-splitting parameter value is  $\mu = 1.1$ .



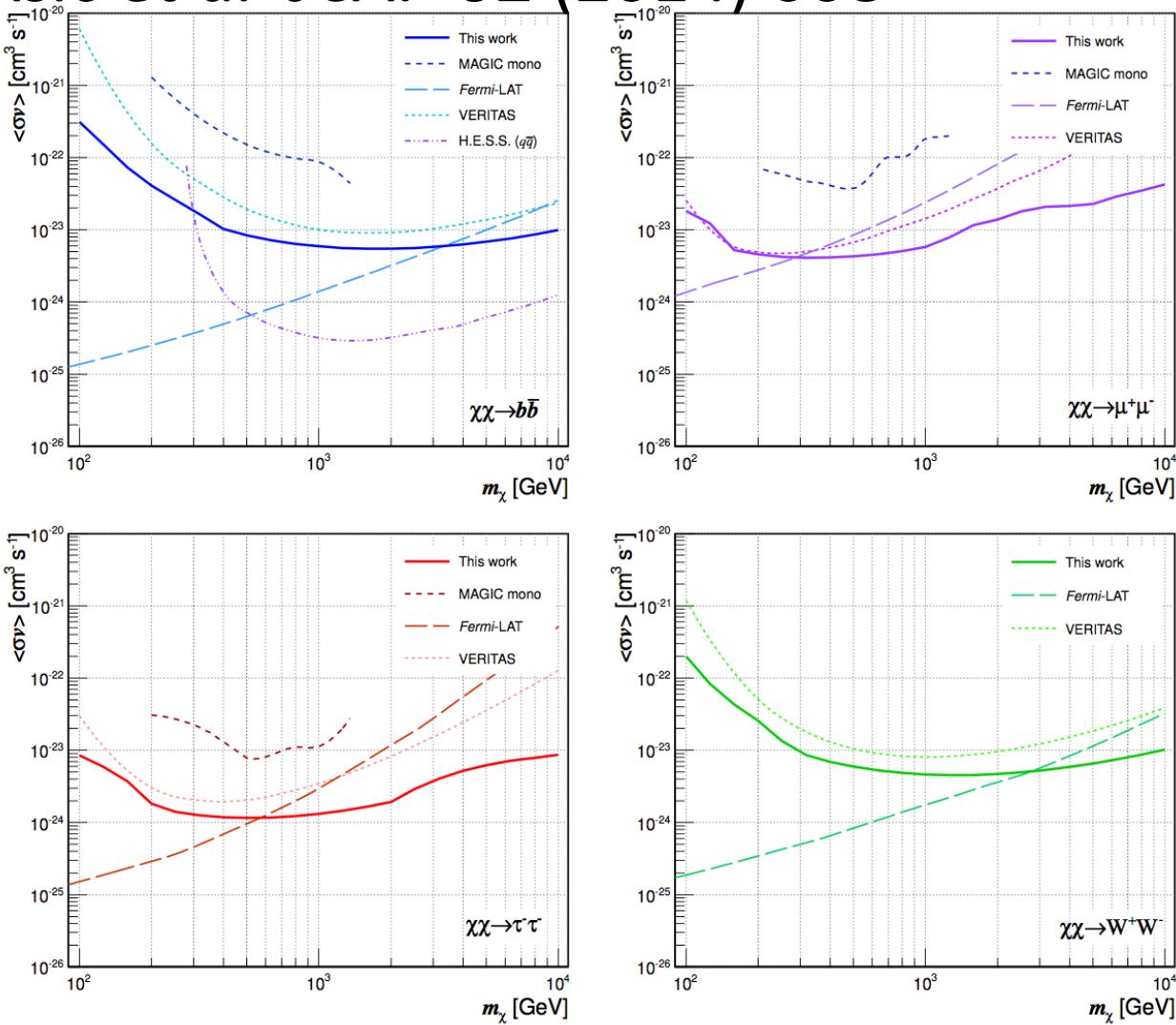
**Figure 5.** Upper limits on  $\langle\sigma_{\text{ann}}v\rangle$  for different final state channels (from top to bottom and left to right):  $b\bar{b}$ ,  $t\bar{t}$ ,  $\mu^+\mu^-$ ,  $\tau^+\tau^-$ ,  $W^+W^-$  and  $ZZ$ , from the Segue 1 observations with MAGIC. The calculated upper limit is shown as a solid line, together with the null-hypothesis expectations (dashed line), and expectations for  $1\sigma$  (shaded gray area) and  $2\sigma$  (shaded light blue area) significant signal.



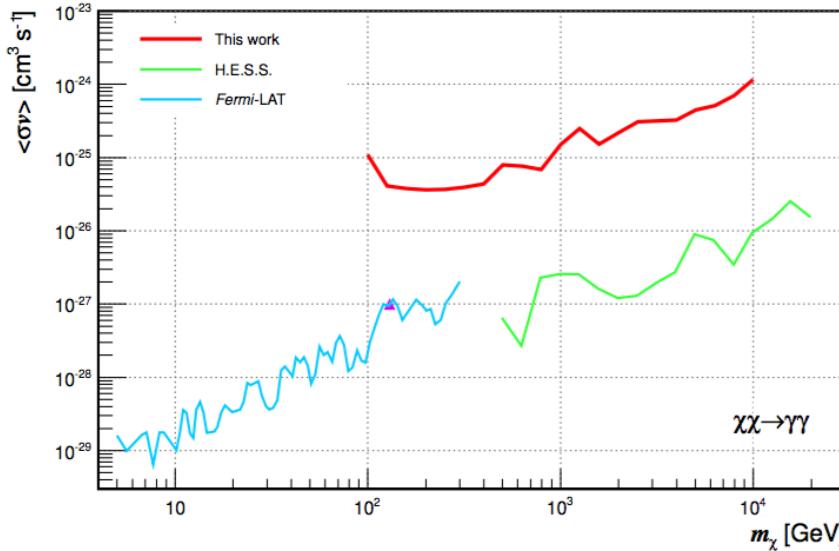
**Figure 6.** Upper limits on  $\langle \sigma_{\text{ann}} v \rangle$  (**left**) and lower limits on  $\tau_\chi$  (**right**), for secondary photons produced from different final state SM particles, from the Segue 1 observations with MAGIC.



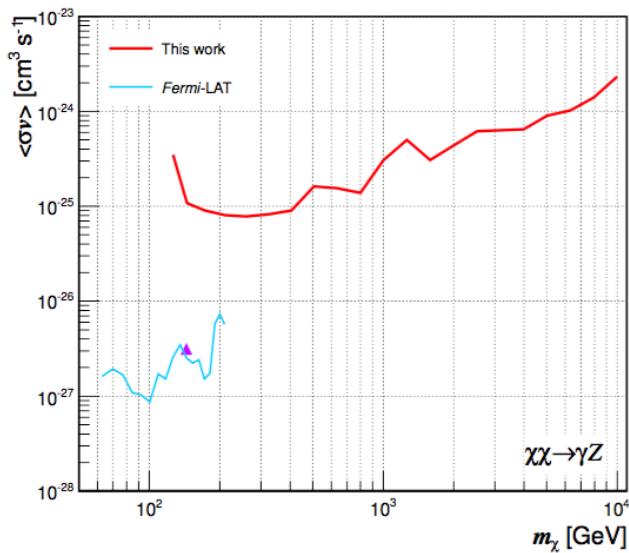
**Figure 7.** Upper limits on  $\langle\sigma_{\text{ann}}v\rangle$  for direct annihilation into two photons, as a function of  $m_\chi$ , from the Segue 1 observations with MAGIC (solid line) and as expected for the case of no signal (dashed line), as well as for a signal of  $1\sigma$  or  $2\sigma$  significance (gray and light blue shaded areas, respectively).



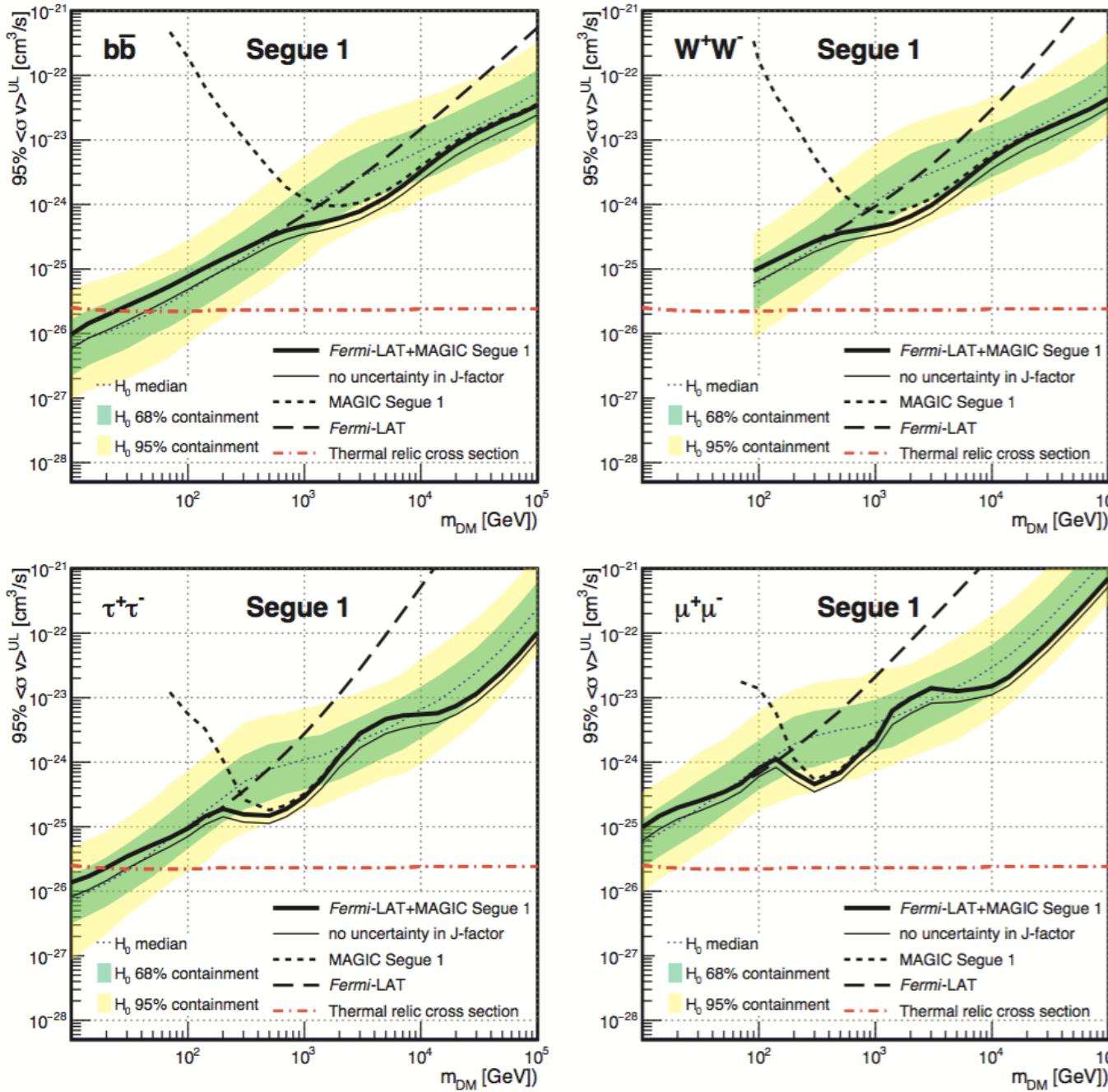
**Figure 13.** Upper limits on  $\langle\sigma_{\text{ann}}v\rangle$  for different final state channels (from top to bottom and left to right):  $b\bar{b}$ ,  $\mu^+\mu^-$ ,  $\tau^+\tau^-$  and  $W^+W^-$ , from the Segue 1 observations with MAGIC (solid lines), compared with the exclusion curves from *Fermi*-LAT (long-dashed lines, [25]), H.E.S.S. (dot-dashed line, [47]), VERITAS (dotted lines, [24]) and MAGIC-I (dashed lines, [19]).



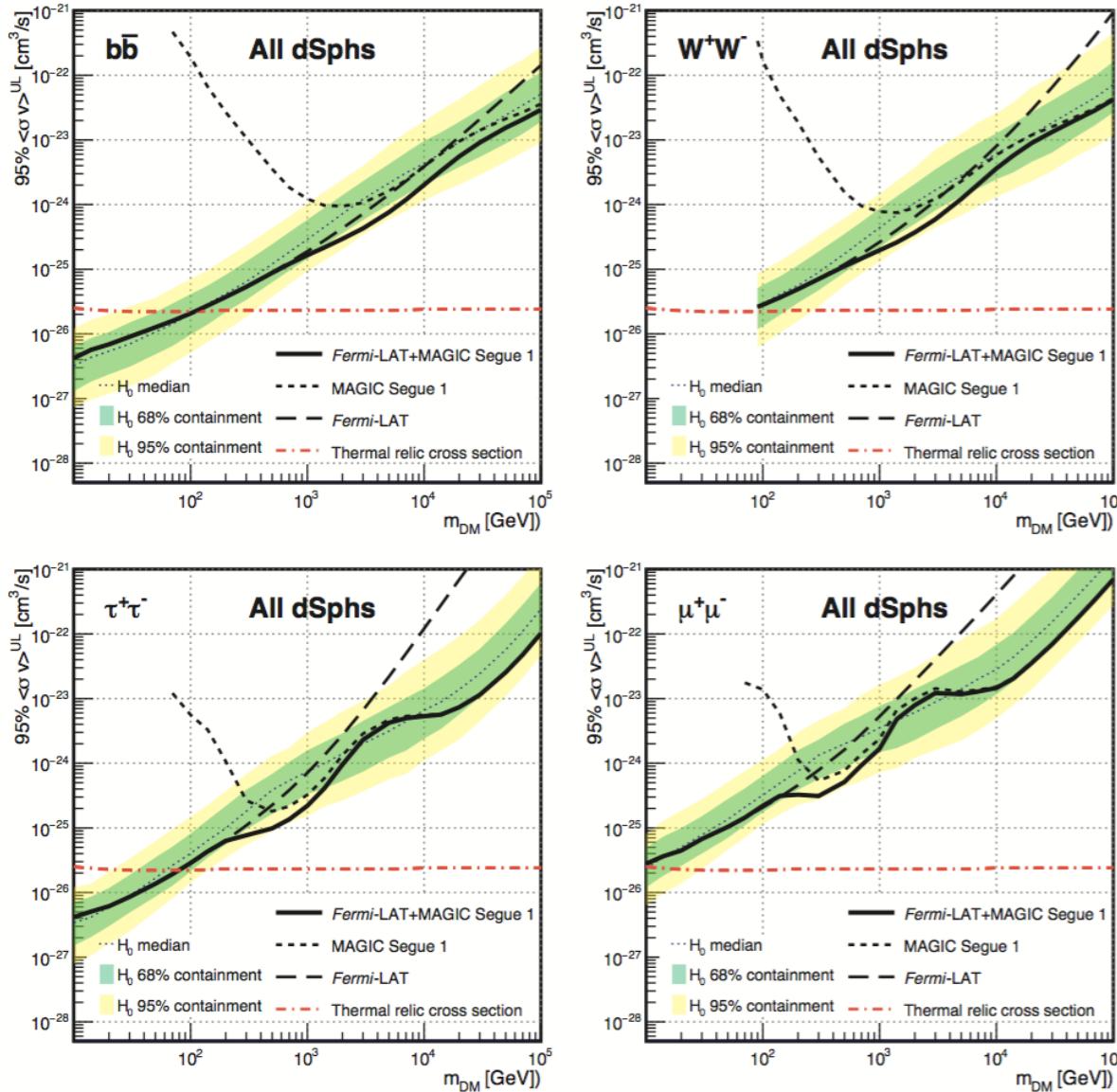
**Figure 15.** Upper limits on  $\langle\sigma_{\text{ann}}v\rangle$  for direct DM annihilation into two photons, from the Segue 1 observations with MAGIC (red line), compared with the exclusion curves from the GC region observations from *Fermi-LAT* (3.7 years, blue line, [62]) and H.E.S.S. (112 hours, green line, [63]). Also shown is the  $\langle\sigma_{\text{ann}}v\rangle$  value corresponding to the 130 GeV gamma-ray line (violet triangle, [64]).



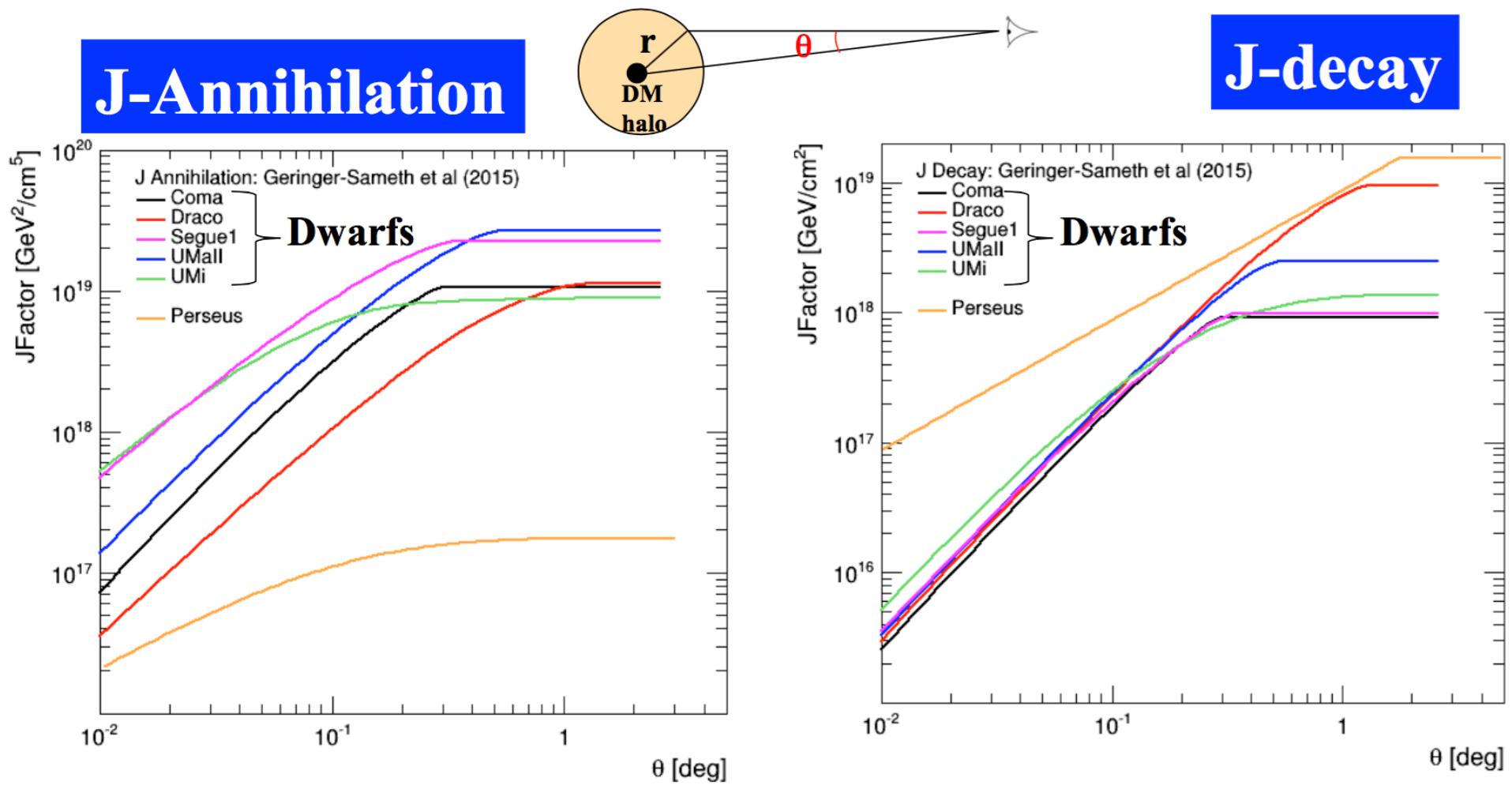
**Figure 16.** Upper limits on  $\langle\sigma_{\text{ann}}v\rangle$  for DM annihilation into a photon and a  $Z$  boson, from the Segue 1 observations with MAGIC (red line), compared with the exclusion curve from 2 years of the GC region observations with *Fermi-LAT* (blue line, [66]). Also show is the  $\langle\sigma_{\text{ann}}v\rangle$  value corresponding to the 130 GeV gamma-ray line (violet triangle, [64]).



**Figure 3.** Similar as figure 2 using Segue 1 observations only. The combined limits for the case when the J-factor is considered as a fixed (no statistical uncertainties) parameter are shown as a thin-solid line.



**Figure 2.** 95% CL upper limits on the thermally-averaged cross-section for DM particles annihilating into  $b\bar{b}$  (upper-left),  $W^+W^-$  (upper-right),  $\tau^+\tau^-$  (bottom-left) and  $\mu^+\mu^-$  (bottom-right) pairs. Thick solid lines show the limits obtained by combining *Fermi*-LAT observations of 15 dSphs with MAGIC observations of Segue 1. Dashed lines show the observed individual MAGIC (short dashes) and *Fermi*-LAT (long dashes) limits. J-factor statistical uncertainties (table 1) are considered as described in section 3.2. The thin-dotted line, green and yellow bands show, respectively, the median and the symmetrical, two-sided 68% and 95% containment bands for the distribution of limits under the null hypothesis (see main text for more details). The red-dashed-dotted line shows the thermal relic cross-section from ref. [54].



Segue I: one of the largest  $J_{\text{ann}}$

Perseus (galaxy cluster): larger  $J_{\text{decay}}$

**STRATEGY:** Given the large uncertainty in the J-factor, study different astrophysical sources to increase chance of a discovery!

# **DES 2 Years**

A. Drlica-Wagner et al.  
(DES collaboration)  
*ApJ 813 109 (2015)*

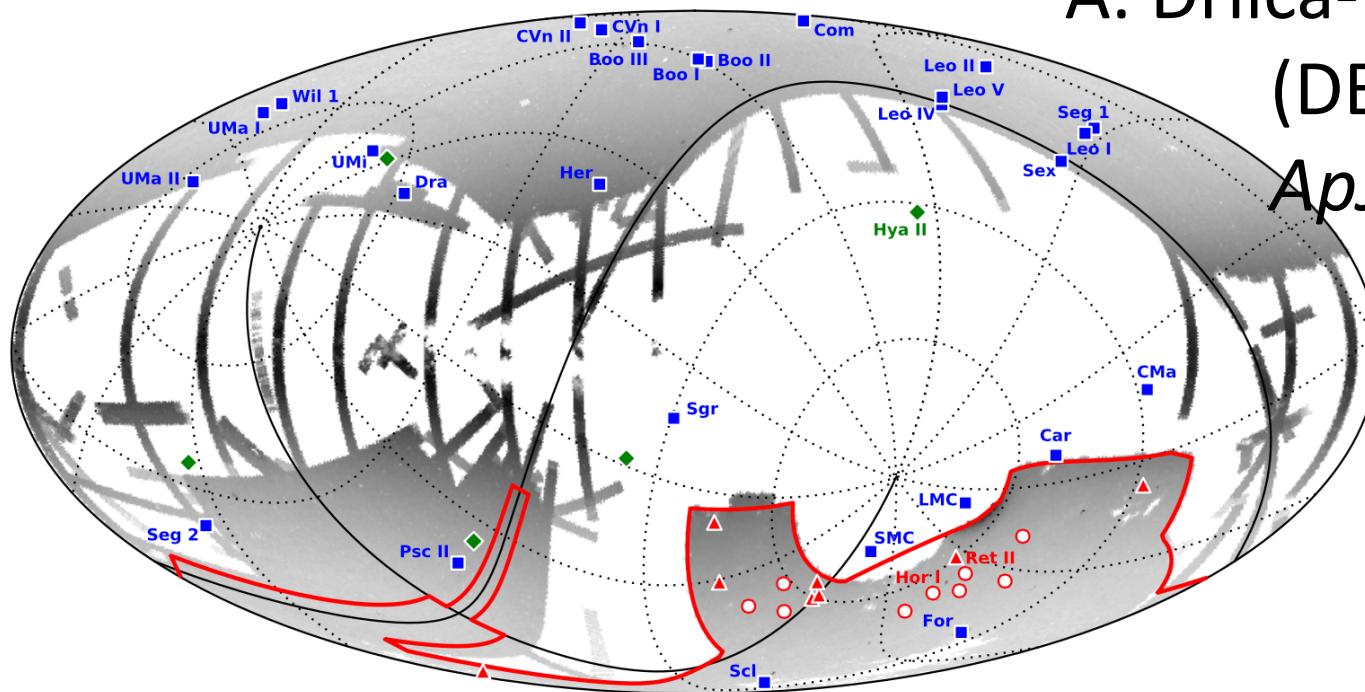
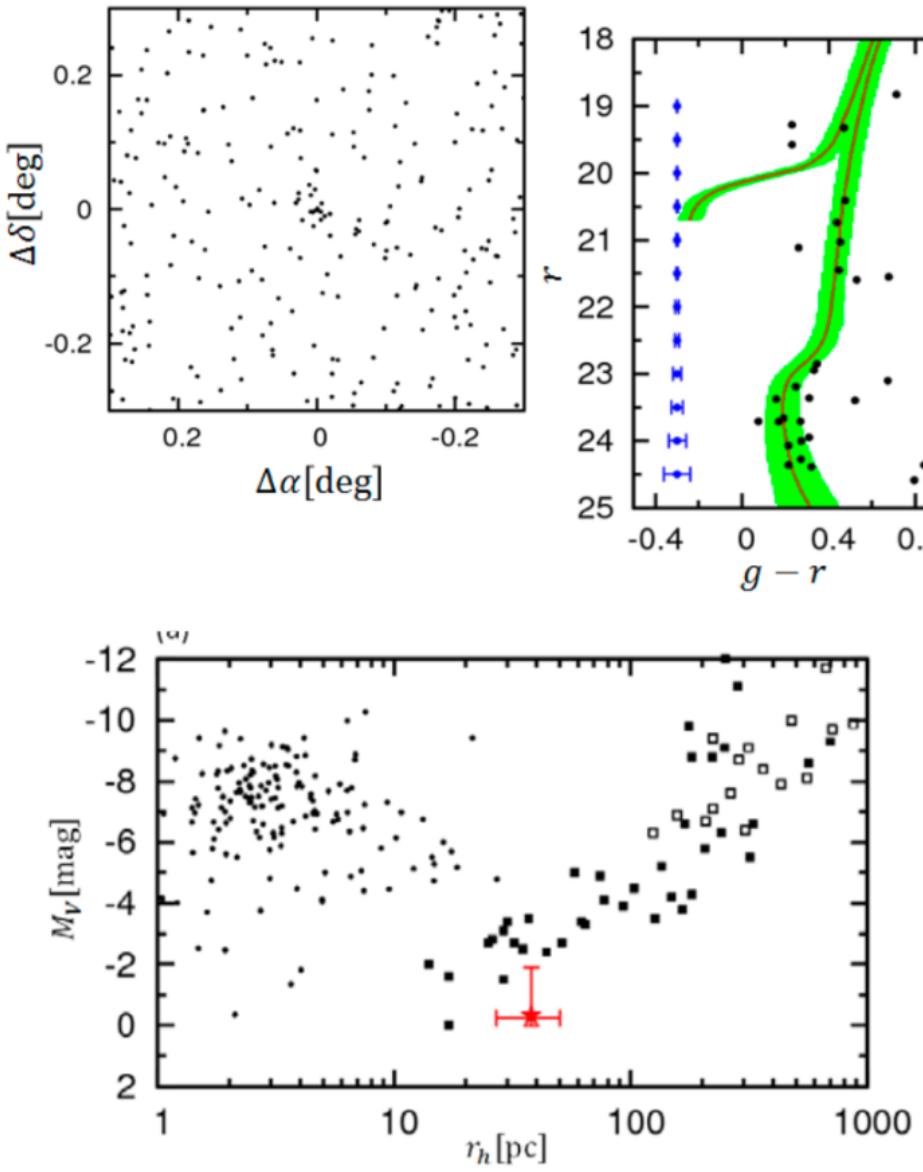


Fig. 1.— Locations of the eight new dwarf galaxy candidates reported here (red triangles) along with nine previously reported dwarf galaxy candidates in the DES footprint (red circles; Bechtol et al. 2015; Koposov et al. 2015a; Kim & Jerjen 2015b), five recently discovered dwarf galaxy candidates located outside the DES footprint (green diamonds; Laevens et al. 2015a; Martin et al. 2015; Kim et al. 2015a; Laevens et al. 2015b), and twenty-seven Milky Way satellite galaxies known prior to 2015 (blue squares; McConnachie 2012). Systems that have been confirmed as satellite galaxies are individually labeled. The figure is shown in Galactic coordinates (Mollweide projection) with the coordinate grid marking the equatorial coordinate system (solid lines for the equator and zero meridian). The gray scale indicates the logarithmic density of stars with  $r < 22$  from SDSS and DES. The two-year coverage of DES is  $\sim 5000 \text{ deg}^2$  and nearly fills the planned DES footprint (outlined in red). For comparison, the Pan-STARRS 1  $3\pi$  survey covers the region of sky with  $\delta_{2000} > -30^\circ$  (Laevens et al. 2015b).

David Panèque

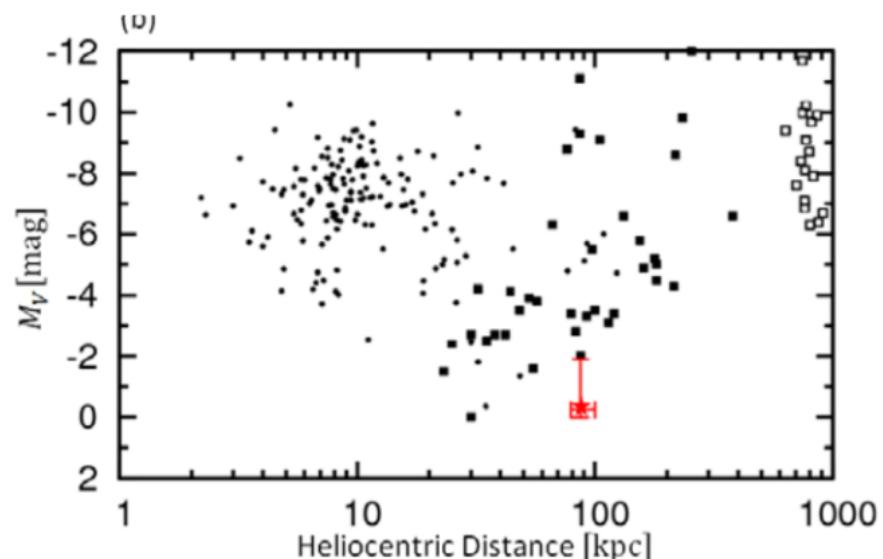
# Finding Ever Fainter and More Distant Dwarf Galaxies



A new ultra-faint galaxy candidate identified in **Hyper-Suprime Cam** data suggests that there are many more Milky Way companions to find with deeper surveys

Lower surface brightness than any previously known satellite, and found in only  $\sim 100 \text{ deg}^2$  of HSC data!

Homma et al. 2016  
arXiv:1609.04346



$i^{\text{th}}$ RoI	Inner radius	Outer radius	Angular size	$J$ -factor		
	[deg.]	[deg.]	[ $10^{-5}$ sr]	Einasto	NFW	Einasto [15]
1	0.3	0.4	4.9	4.3	2.5	1.3
2	0.4	0.5	6.8	5.6	3.0	1.7
3	0.5	0.6	8.7	6.6	3.3	2.0
4	0.6	0.7	10.6	7.4	3.5	2.3
5	0.7	0.8	12.5	7.9	3.6	2.5
6	0.8	0.9	14.4	8.3	3.7	2.6
7	0.9	1.0	16.3	8.7	3.8	2.8

TABLE I: J-factor values in units of  $\text{GeV}^2\text{cm}^{-5}$  in each of the 7 RoIs considered in this work. The first four columns give the inner radius, the outer radius, and the size in solid angle for each RoI. The fifth column provides the J-factor values for the Einasto profile considered in this work together with the values obtained for a NFW profile [10] and an alternative normalization of the Einasto profile [15].

***Abdallah et al***  
**Phys. Rev. Lett. 117 (2016) 111301**

		<b>Jann</b> [GeV <sup>2</sup> ·cm <sup>-5</sup> ]	<b>Jdec</b> [GeV·cm <sup>-2</sup> ]
dSph	<b>Segue 1</b>	1e19	2e17
Galaxy cluster	<b>Perseus</b>	1e17	2e18
Galaxy cluster	<b>Fornax</b>	1e18	1e19

