Indirect DM search with MAGIC

Konstancja Satalecka (UCM) for the MAGIC Collaboration

Patras Workshop, Zaragoza, 23rd June 2015

Outline

- Imaging Atmospheric Cherenkov Telescopes
- MAGIC
- Indirect DM search with IACTs
- MAGIC DM search:
  - ★ Perseus Cluster
  - ★ Dwarf Galaxies
  - ★ Unassociated Fermi Objects
- Summary

IACTs

★ energy range: 50 GeV – 50 TeV

★ γ-ray interacts in the atmosphere
and produces an electromagnetic cascade

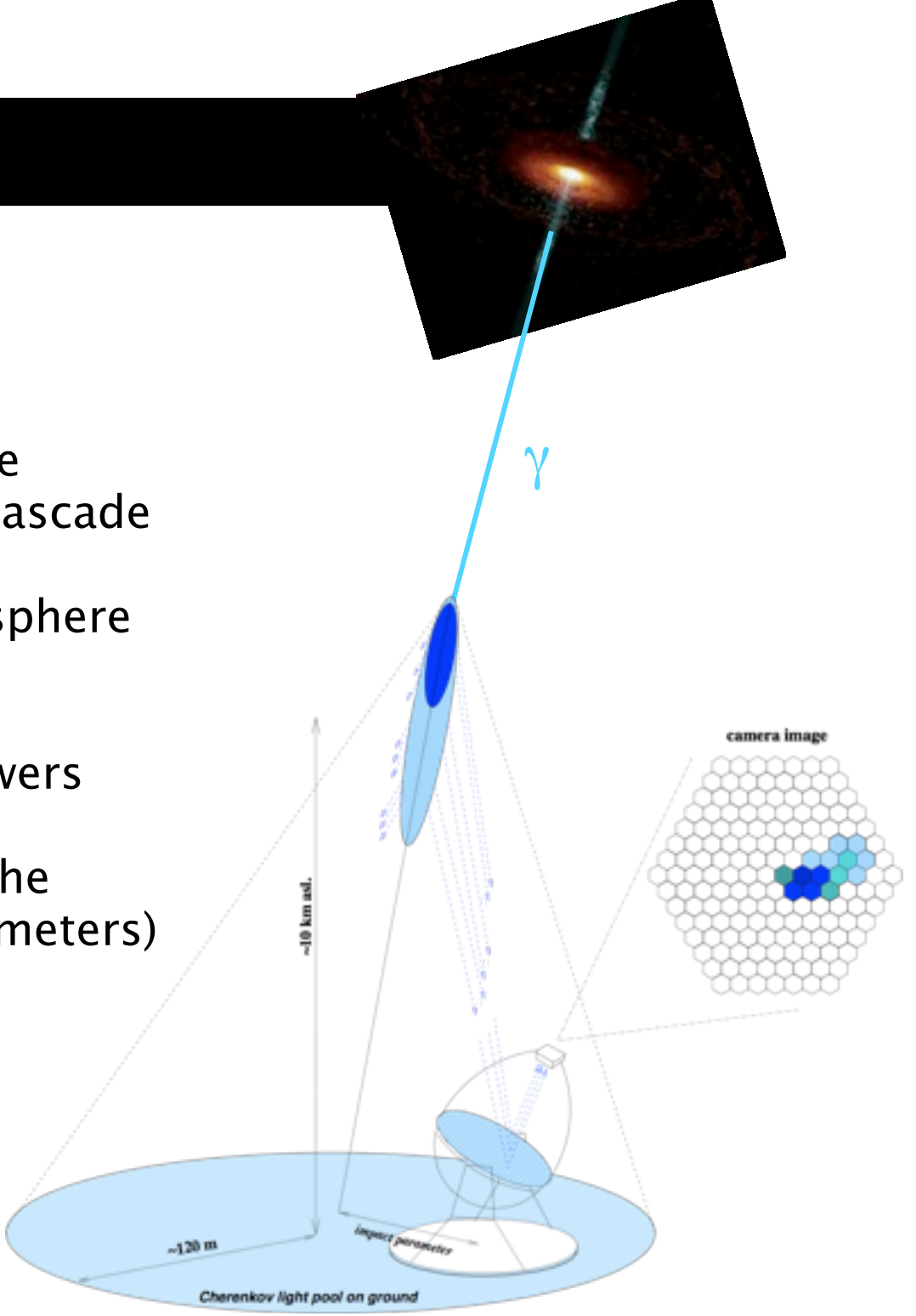
★ cascade propagates in the atmosphere
radiating Cherenkov γ

★ main background: hadronic showers

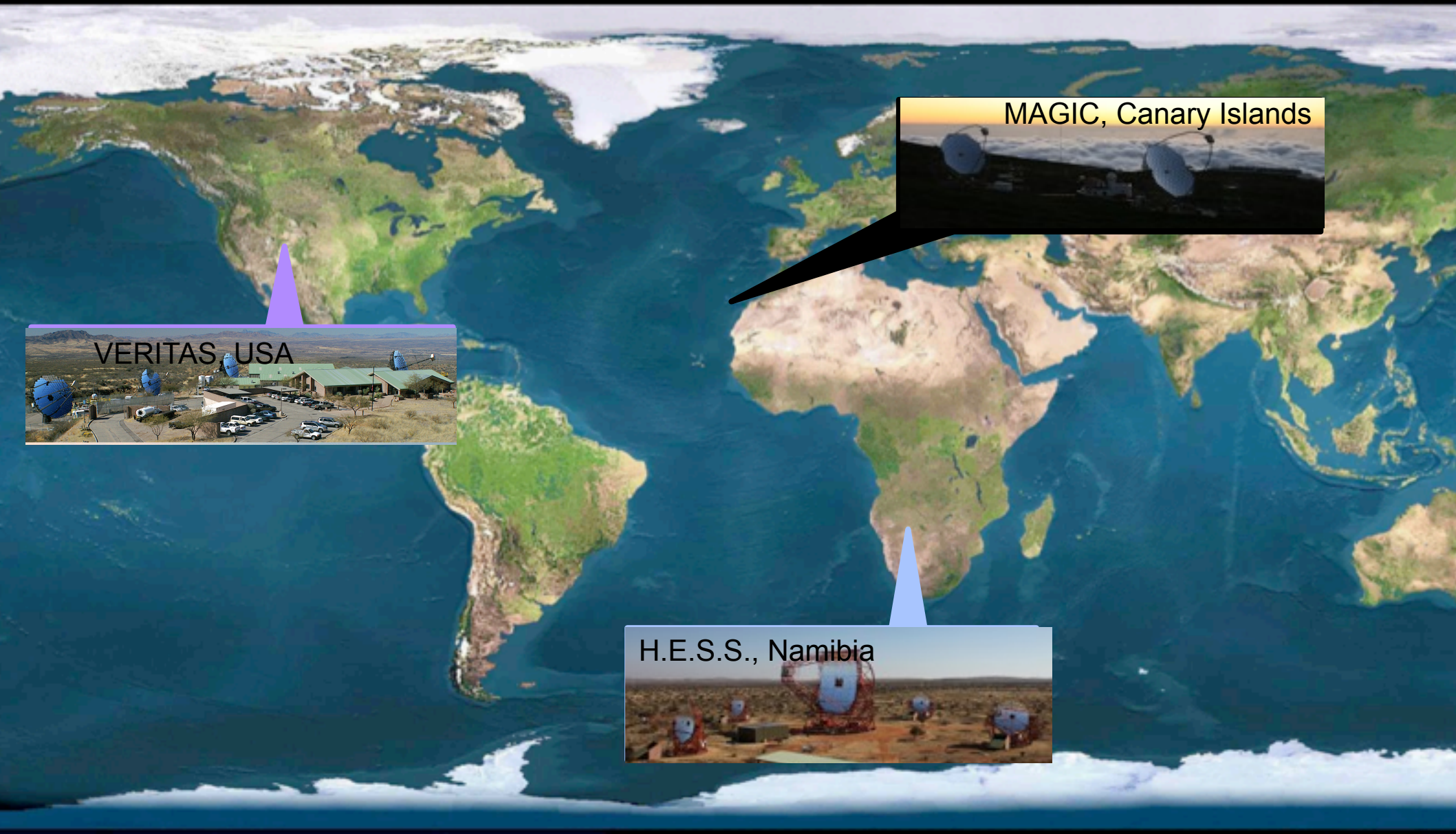
★ background rejection based on the
geometry of the image (Hillas parameters)

★ stereoscopy helps a lot!

★ >100 sources discovered so far



IACTs



MAGIC

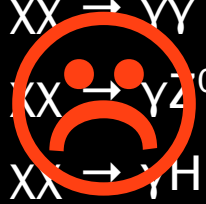
- Location: Roque de los Muchachos on La Palma (Canary Islands, Spain)
- Collaboration of >150 scientists, 25 institutes, 8 countries
- MAGIC-I in operation since 2004, MAGIC-II (stereo mode) since 2009
- Camera Field of View: 3.5 deg
- Low energy threshold: ~50 GeV (25 GeV with Sum Trigger)
- Energy resolution: ~15% @ 1 TeV
- Angular resolution: ~0.05 deg @ 1 TeV
- Integral sensitivity: ~0.7% C.U [3.2×10^{-13} cm $^{-2}$s $^{-1}$] > 1TeV

IACTs favorite DM candidates: WIMPs

★ WIMP (neutralino χ) mass lower limits – in IACT energy range

★ WIMP self-annihilation → VHE γ-rays

★ γ-ray lines



Loop suppressed!

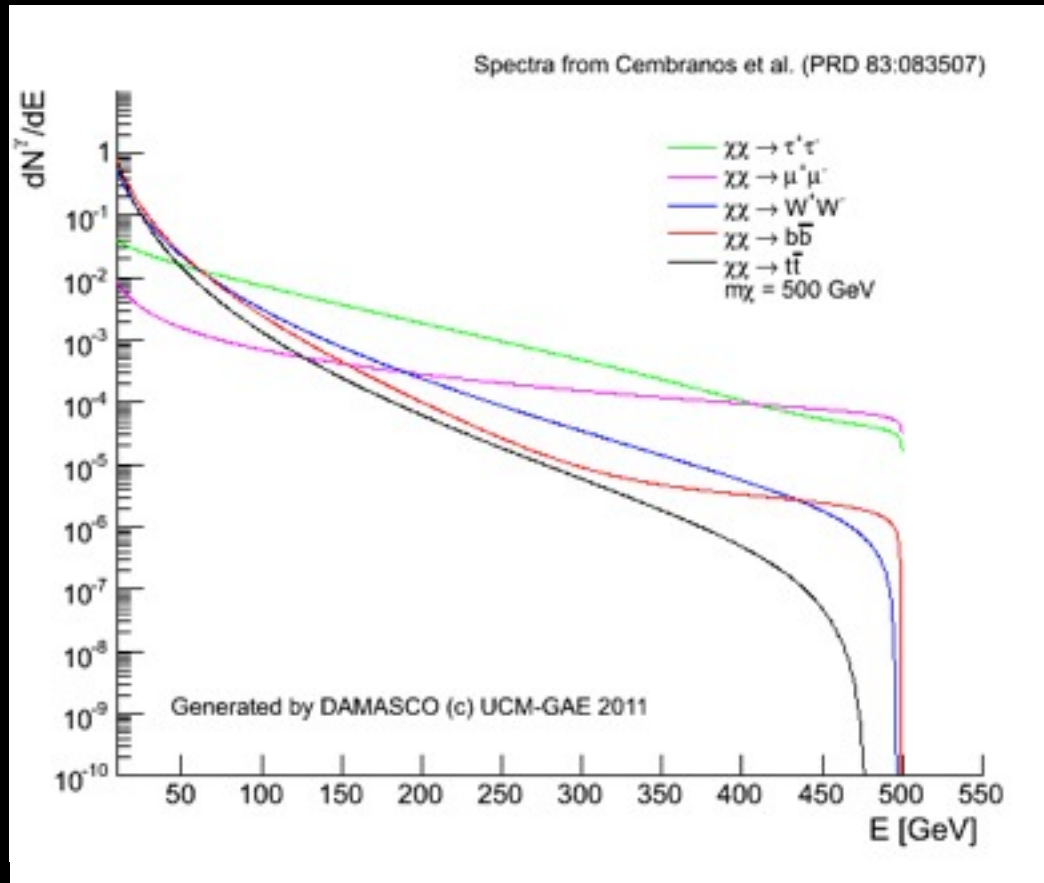
★ continuous spectrum:

$\chi\chi \rightarrow qq, \tau\tau, WW, \rightarrow \pi^0 + \ldots \rightarrow \gamma\gamma$

★ Characteristical features in IACTs energy range:

- cut off @ mχ
- Internal Bremsstrahlung peaks

★ Challenge: background from astrophysical sources



Indirect DM searches: γ-ray flux

γ ray flux from χ annihilation: $\Phi(> E_0, \Delta\Omega) = \Phi_\epsilon^{PP}(> E_0)\, J(\Delta\Omega)$

Particle Physics factor

$$\Phi_\epsilon^{PP}(> E_0) = \frac{1}{4\pi} \frac{\langle \sigma_{\rm ann} v \rangle}{2m_\chi^2} \int_{E_0}^{m_\chi} \sum_{i=1}^{n} B^i \frac{dN_\gamma^i}{dE}\, dE$$

Astrophysical factor

$$J(\Delta\Omega) = \int_{\Delta\Omega} \int_{los} \rho^2(r(s,\Omega))\, ds\, d\Omega$$

Huge uncertainties

Branching ratio & cross section:

$\Delta\Phi/\Phi$ up to $O(10^6)$

Halo radial profile model:

$\Delta J/J$ up to $O(10^2)$

Indirect DM searches: targets

Key selection criteria: M/L, ρ_{DM}, distance, background

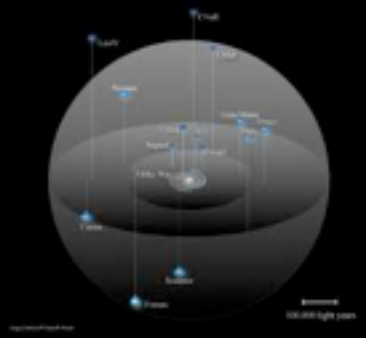
★ Galaxy Center
★ High flux
★ Huge background

ApJ Lett. 638 (2006) L10 (17 h)

★ Galaxy Clusters
★ Huge DM content
★ Large distance
★ Huge background

Perseus:
ApJ 710 (2010) 634 (25 h)

★ Dwarf Galaxies
★ Large M/L
★ No background
★ Low flux



Draco: ApJ 679 (2008) 428 (8 h)
Willman 1: ApJ 697 (2009) 1299 (16 h)
Segue 1:
JCAP 06 (2011) 035 (30 h)
JCAP 02 (2014) 008 (158 h)

★ DM subhalos:
★ Where are they?
★ J_astro?
★ Unassociated Fermi Objects?

Galaxy Clusters: Perseus

★ ~80% of cluster's mass = DM

★ 10^3 farther than GC,
but ~10^6 more DM than dSph

★ caveats:
- bright galaxy NCG 1275 in FoV
- extended source

★ MAGIC observations:
2008 Nov and Dec, 25.5 h (mono)

Photo credit: R. Jay GaBany, Cosmotography.com

★ no signal detected, F_{UL} (> 100 GeV) ~ 4.6 x10^{-12} cm^{-2} s^{-1} (for Γ=1.5)

★ assumptions:

- NFW profile: J_{ASTRO} ~1.4x10^{16} Gev^2 cm^{-5}
- f_{SUSY} (>100 GeV) = 10^{-32} GeV^{-2} cm^{-2} s^{-1}
  (Sanchez-Conde et al., 2007)

} F_{DM} (>100 GeV) ~ 1.4x10^{-16} cm^{-2} s^{-1}

★ minimal boost factor: ~10^4

MAGIC Coll., ApJ 710 (2010) 634 (25 h)

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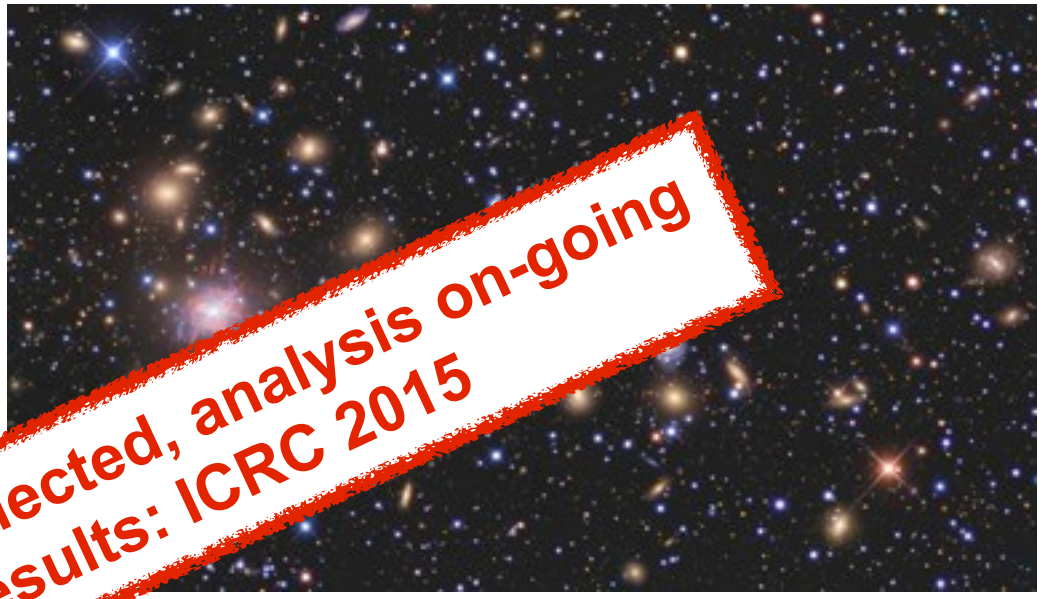

300 h of stereo data collected, analysis on-going
Preliminary results: ICRC 2015

★ no signal dete… …V) ~ 4.6 x10^{-12} cm^{-2} s^{-1} (for Γ=1.5)

★ assum…

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MAGIC Coll., ApJ 710 (2010) 634 (25 h)

Dwarf Galaxies: Segue 1

Segue 1:

★ discovered in 2007

★ 23 kpc away

★ M/L ~ 3400 $M_\odot/L_\odot$

★ Einasto profile ➡ J_{ASTRO} ~10^{19} Gev^2 cm^{-5}

MAGIC observations:

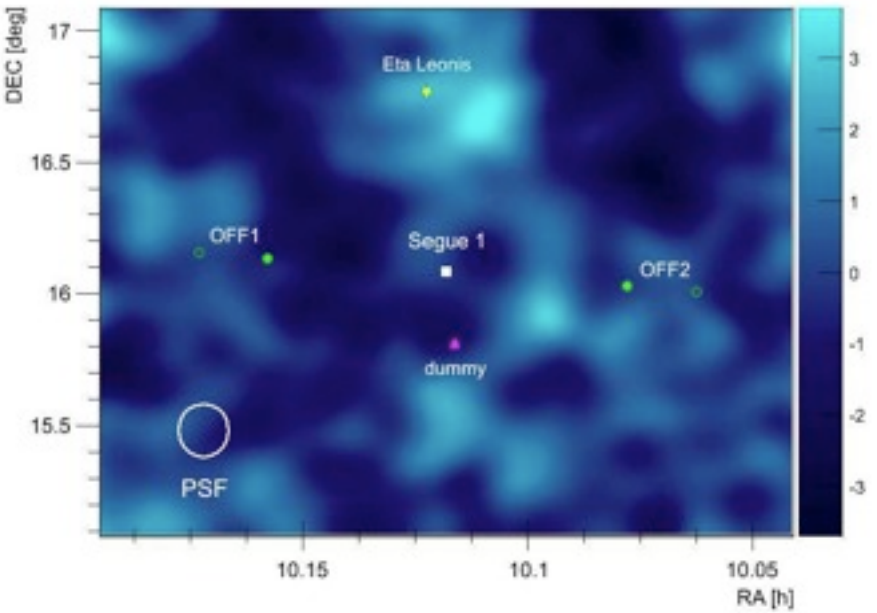
★ Jan 2011 – Feb 2013
(158 h after quality selection)

★ no signal detected

★ new analysis method:
full likelihood analysis (JCAP, 10 (2012) 032)

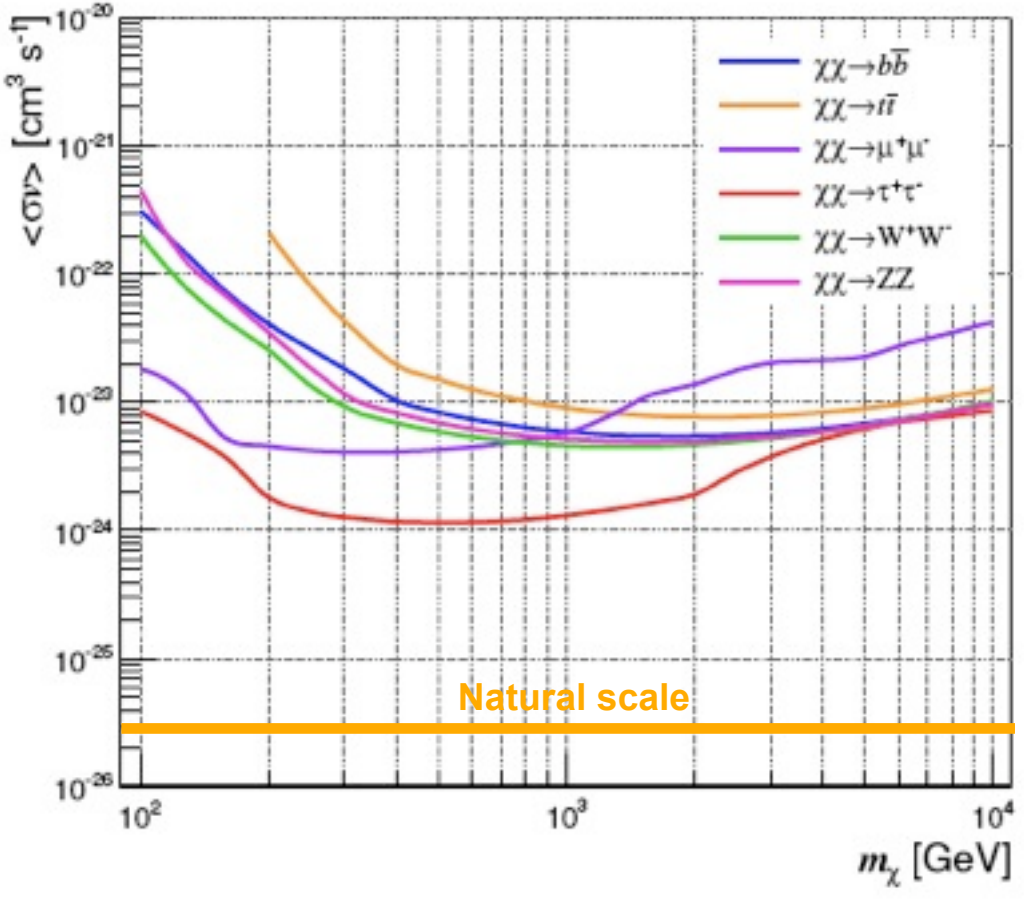
★ UL calculated for several DM annihilation/decay models: continuous spectrum, lines, VIB...

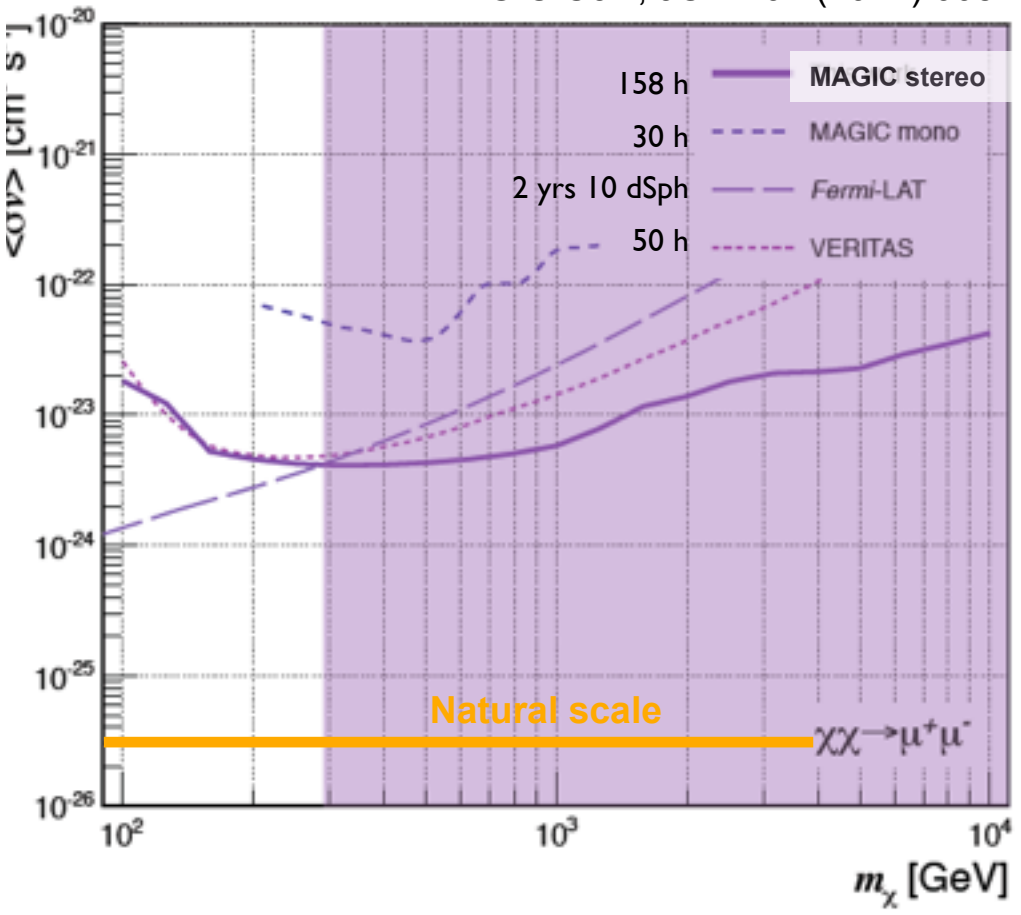
Significance map for events above 150 GeV in the Segue 1 sky region.
MAGIC Coll., JCAP 02 (2014) 008



Segue 1: annihilation

MAGIC Coll., JCAP 02 (2014) 008

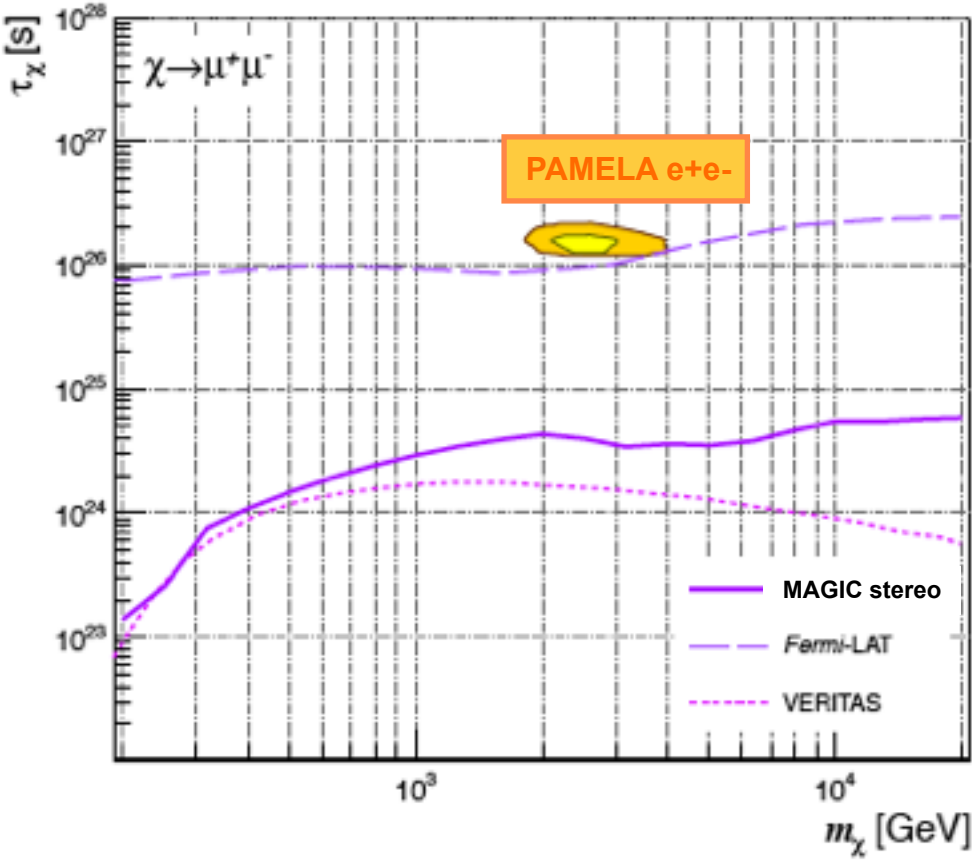


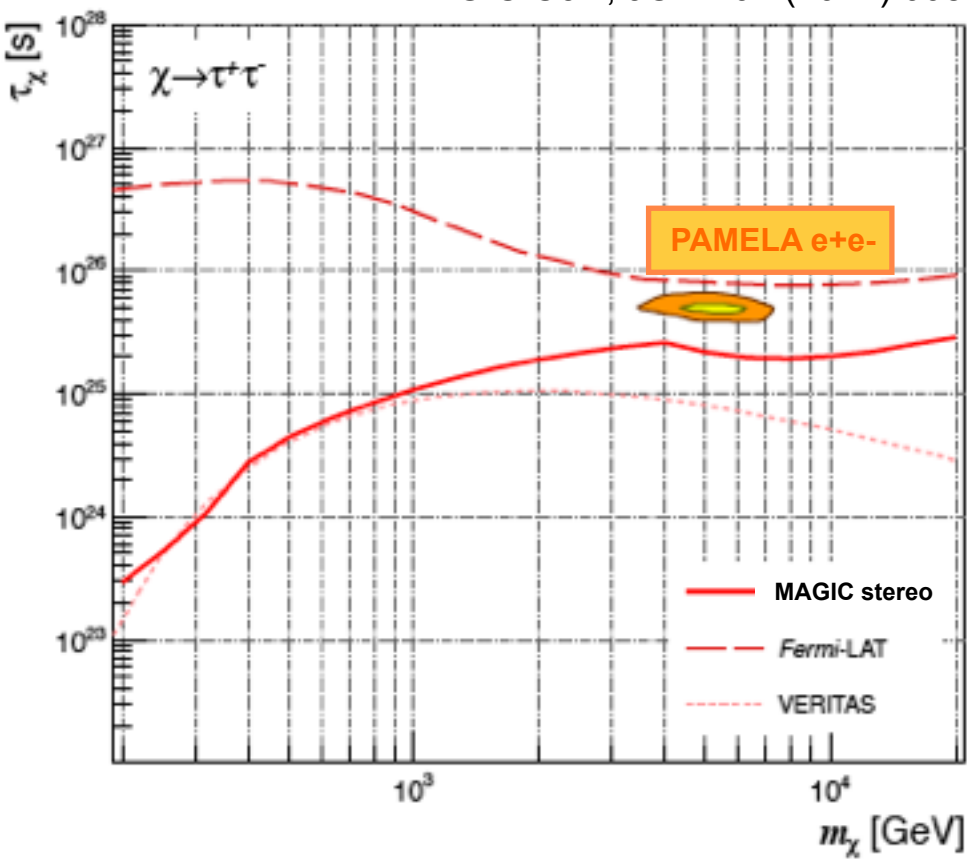


Most constraining limits for annihilating DM from dSph > few 100 GeV!!!

Segue 1: decay

MAGIC Coll., JCAP 02 (2014) 008

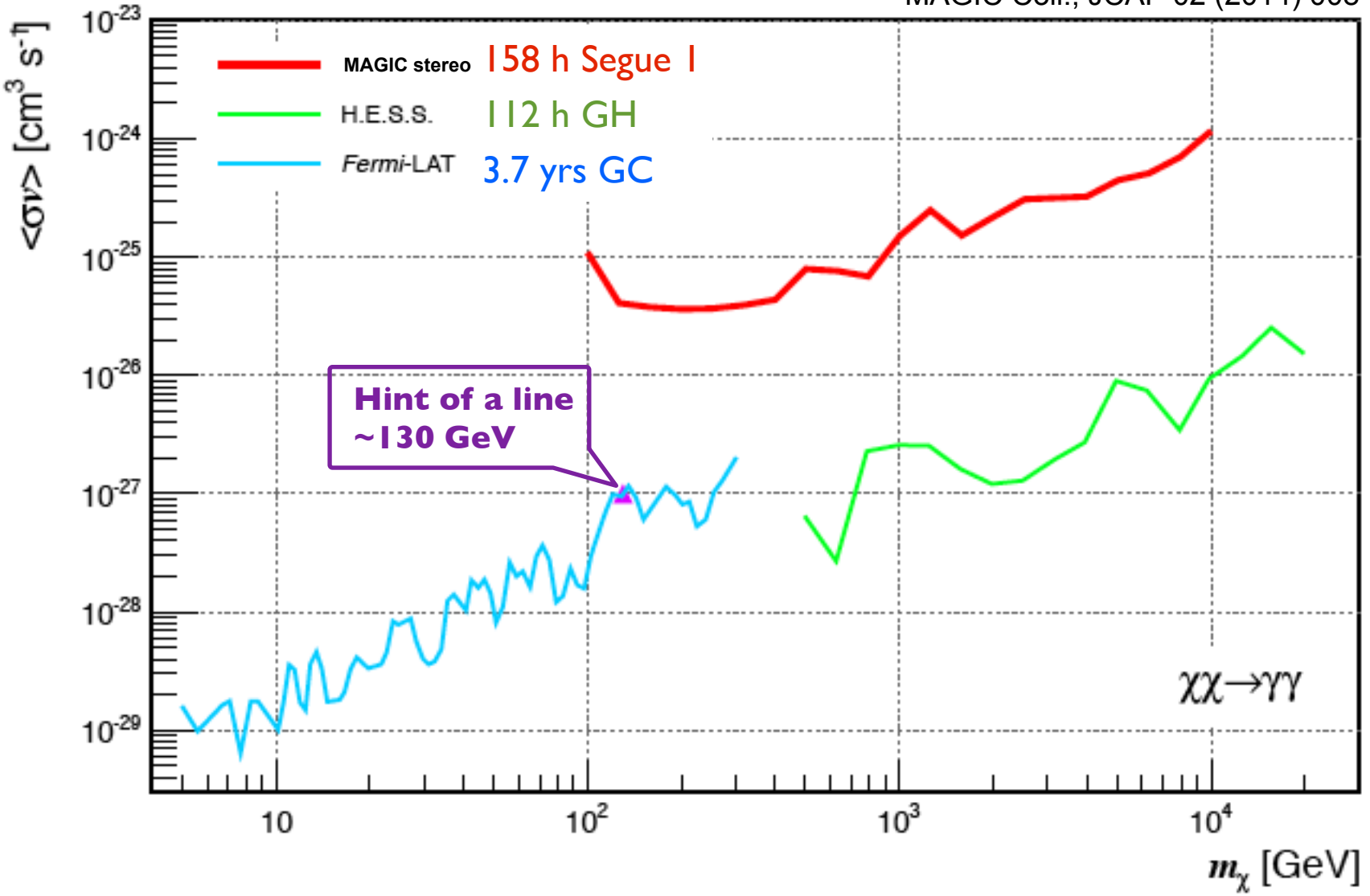




Most constraining limits from IACTs for decaying DM !

Segue 1: lines

MAGIC Coll., JCAP 02 (2014) 008



Unassociated Fermi Objects

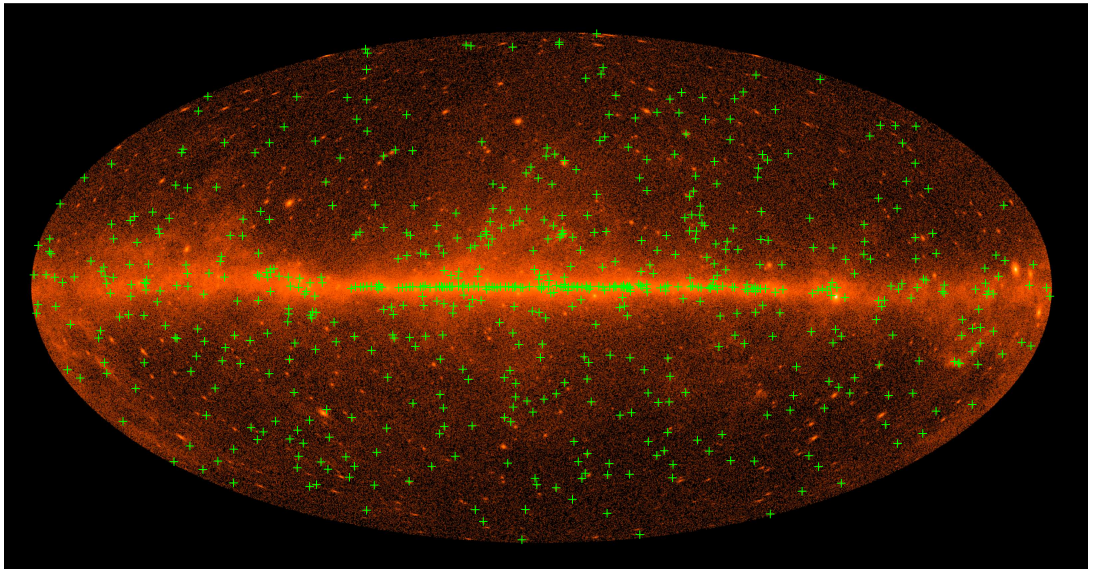
Assumptions:

★ Cosmological N-body simulations:
DM halos host numerous sub-halos

★ Sub-halos too small to attract
baryonic matter ➡ signal only from DM

★ will show up in all sky surveys ➡ Fermi

★ DM mass > 50 GeV ➡ spectral cut-off
in IACT range



Selection criteria for 1FGL and 2FGL:

★ Source out of Galactic plane, non-variable

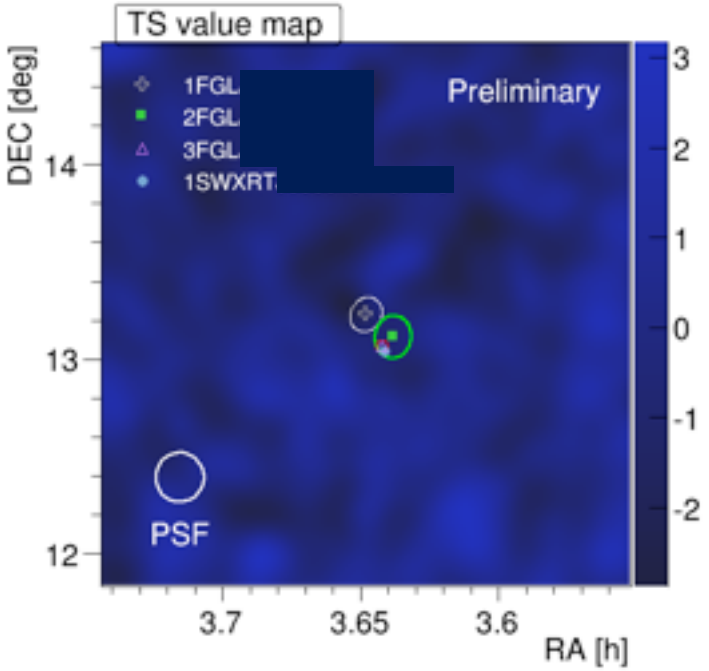
★ Hard spectrum w/o cut-off in Fermi energy range

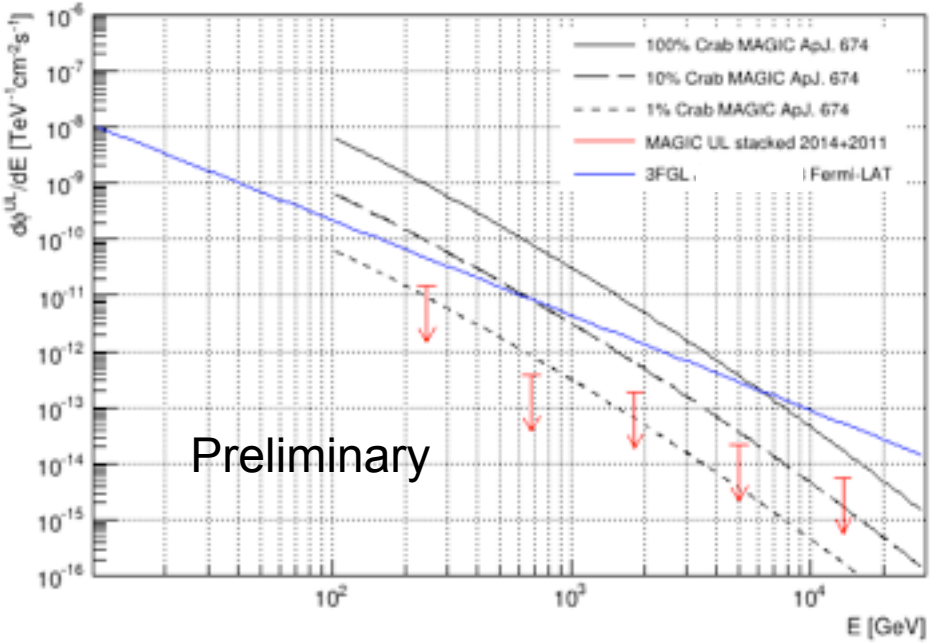
★ Dedicated search for possible counterparts (ASDC data base, Swift sky maps, ...)

★ High energy (> 10 GeV) Fermi photons study

★ Estimation of MAGIC detection prospects

Unassociated Fermi Objects

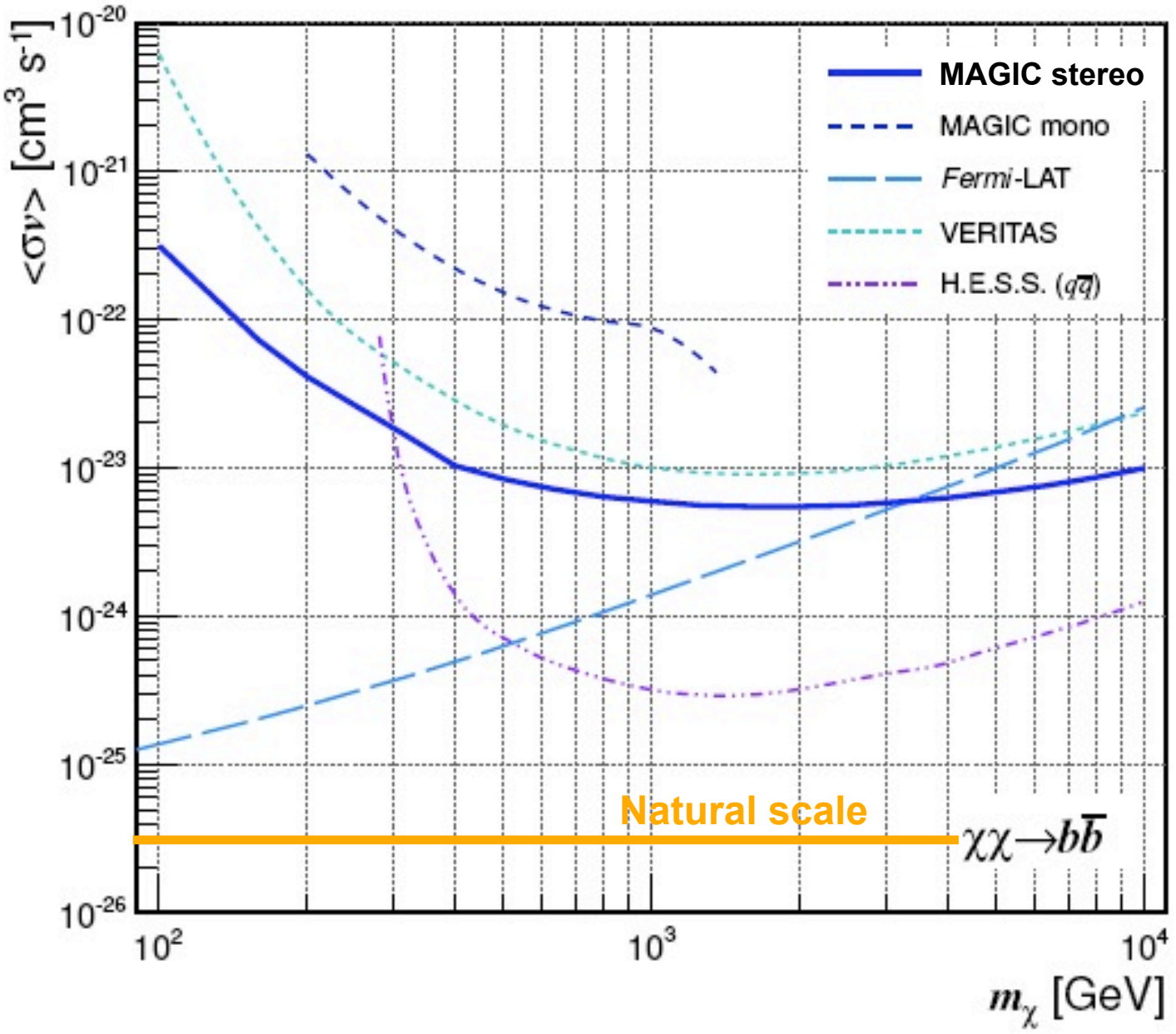




- 7 UFOs selected as good DM clump candidates from 1FGL and 2FGL
- 4 observed - no detection
- MAGIC and recent MWL data suggest rather AGN origin of emission

Results: ICRC 2015 + paper coming soon...!

IACTs and WIMPs: current status



158 h Segue 1

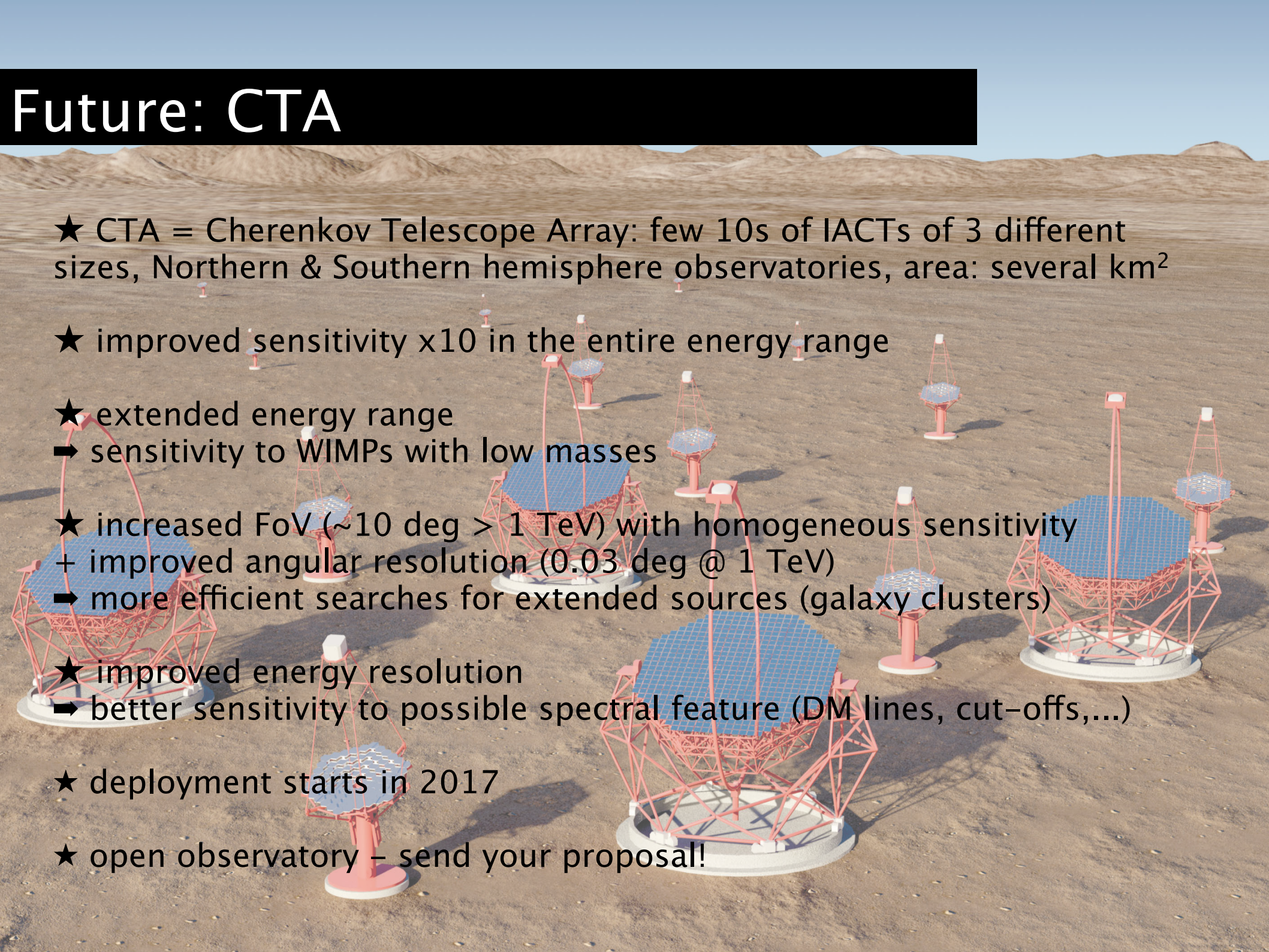
30 h Segue 1

4yrs 15 dSph

50 h Segue 1

112 h GH

Future: CTA



★ CTA = Cherenkov Telescope Array: few 10s of IACTs of 3 different sizes, Northern & Southern hemisphere observatories, area: several km^2

★ improved sensitivity x10 in the entire energy range

★ extended energy range
➡ sensitivity to WIMPs with low masses

★ increased FoV (~10 deg > 1 TeV) with homogeneous sensitivity
+ improved angular resolution (0.03 deg @ 1 TeV)
➡ more efficient searches for extended sources (galaxy clusters)

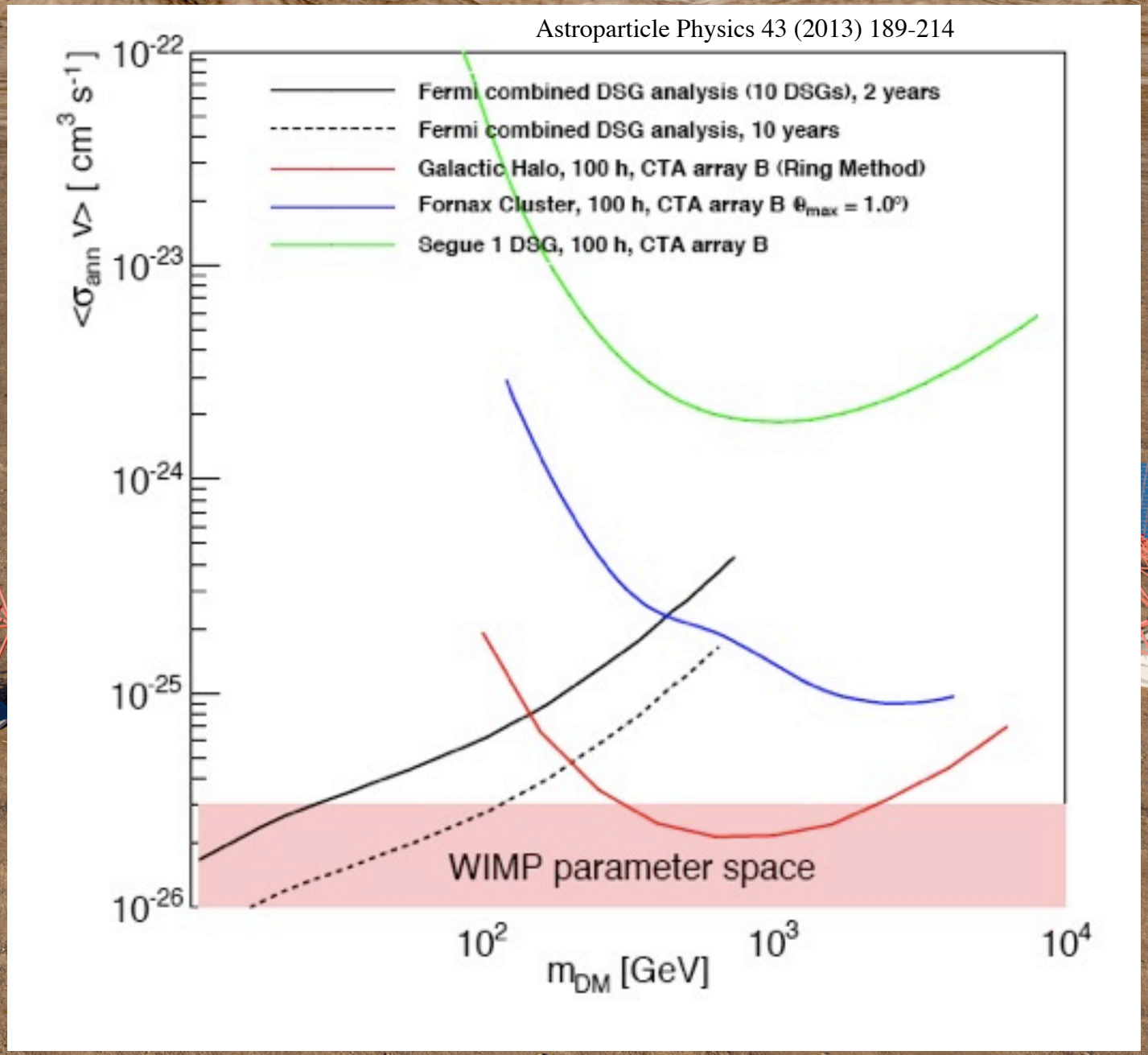
★ improved energy resolution
➡ better sensitivity to possible spectral feature (DM lines, cut-offs,...)

★ deployment starts in 2017

★ open observatory – send your proposal!

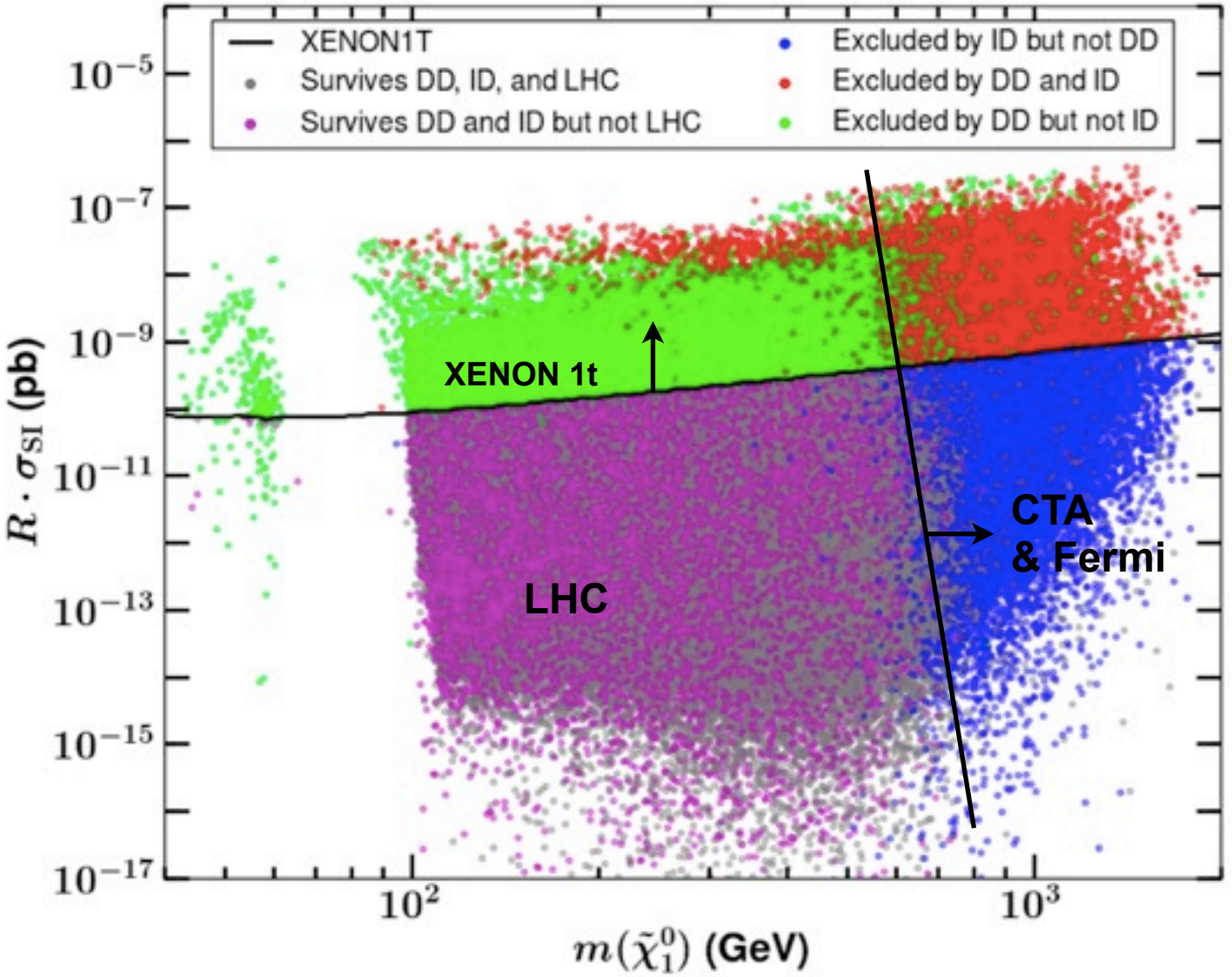
Future: CTA

Astroparticle Physics 43 (2013) 189-214



Future: CTA, DD and LHC

M. Cahill-Rowley et al., arXiv:1305.6921



Summary & Outlook

☆ MAGIC: low energy threshold + high sensitivity ➡ perfect for DM search in the very high energy range

☆ Indirect DM search with MAGIC

★ Galaxy Clusters:

➡ no signal detected from Perseus (25 h)

➡ thermal DM models still far away

➡ NEWS: 300 h of stereo data collected, analysis is ongoing...

★ Dwarf Galaxies:

➡ Segue 1 stereo observations 150 h + likelihood analysis method

➡ most constraining limits for annihilating DM from dSph > few 100 GeV

➡ best IACT limits for decaying DM

★ UFOs:

➡ selection from 1FGL and 2FGL – 4 sources observed – no signal found

➡ MAGIC & recent MWL data seem to suggest AGN origin of emission

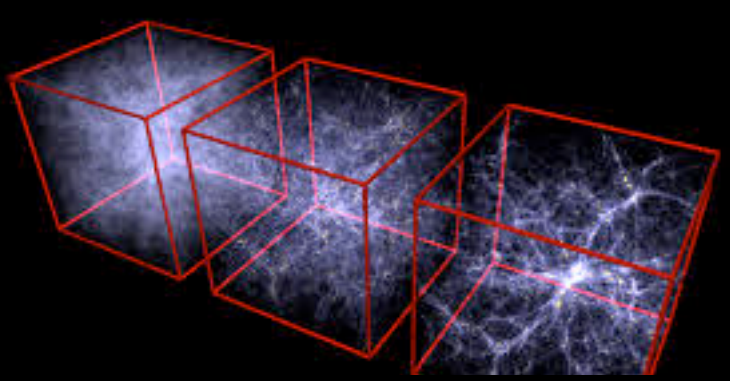
➡ NEWS: paper coming soon!

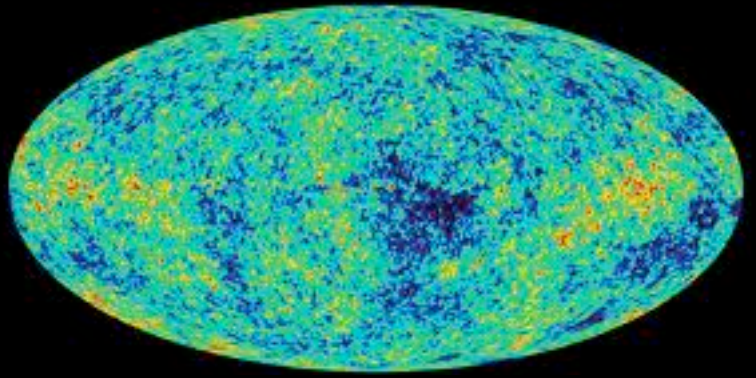
☆ Future:

★ MAGIC DM program continues

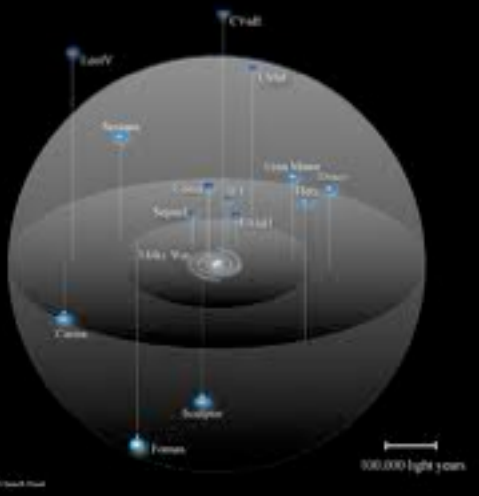
★ likelihood analysis: combined ULs from different experiments

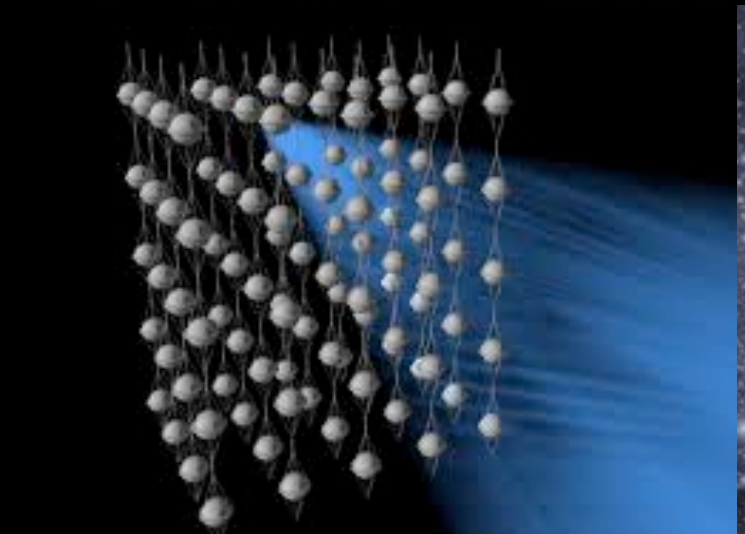
★ start of CTA deployment planned for 2017

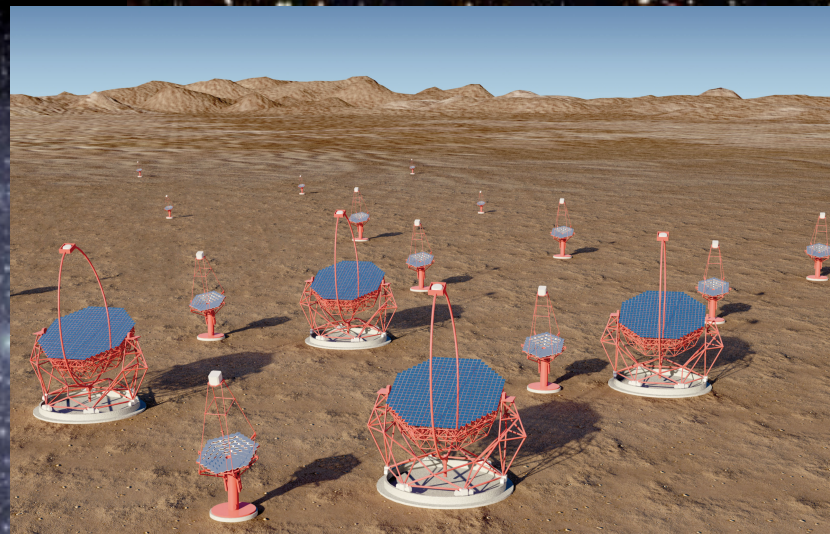




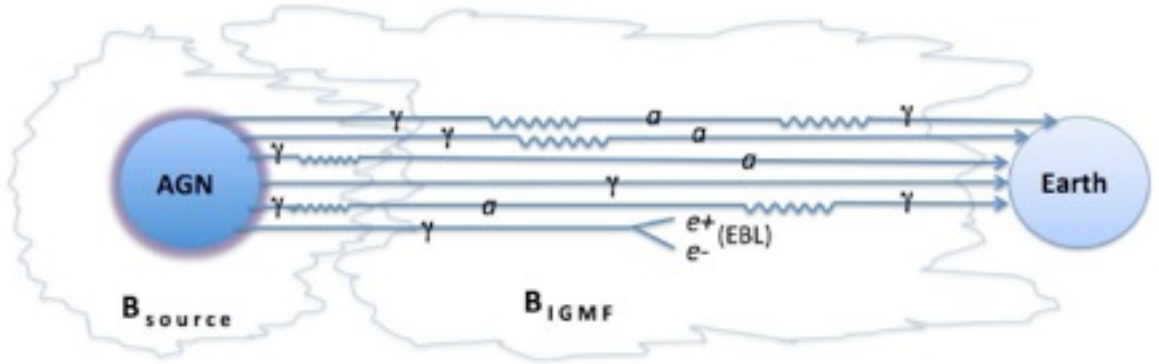
Back- up

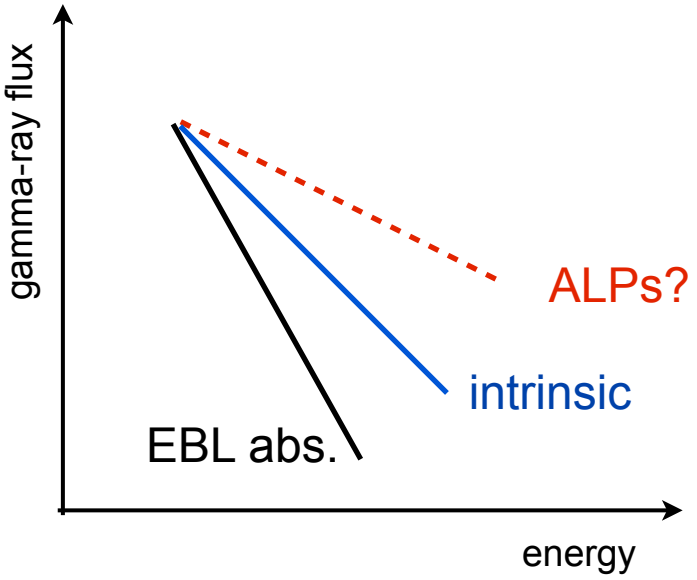






MAGIC and DM: ALPs





★ ALPs oscillate into photons in the source and IGMF

★ gamma-rays absorbed on EBL (energy and distance dependent)

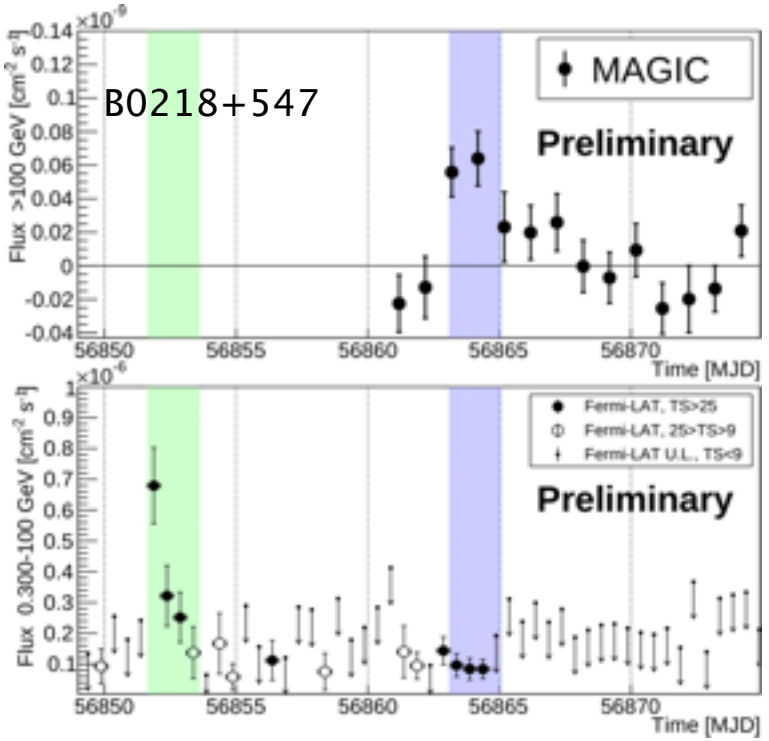
★ depending on B, source distance (z) and ALP mass (~1neV):
gamma-ray flux can be significantly enhanced (against the EBL absorption)

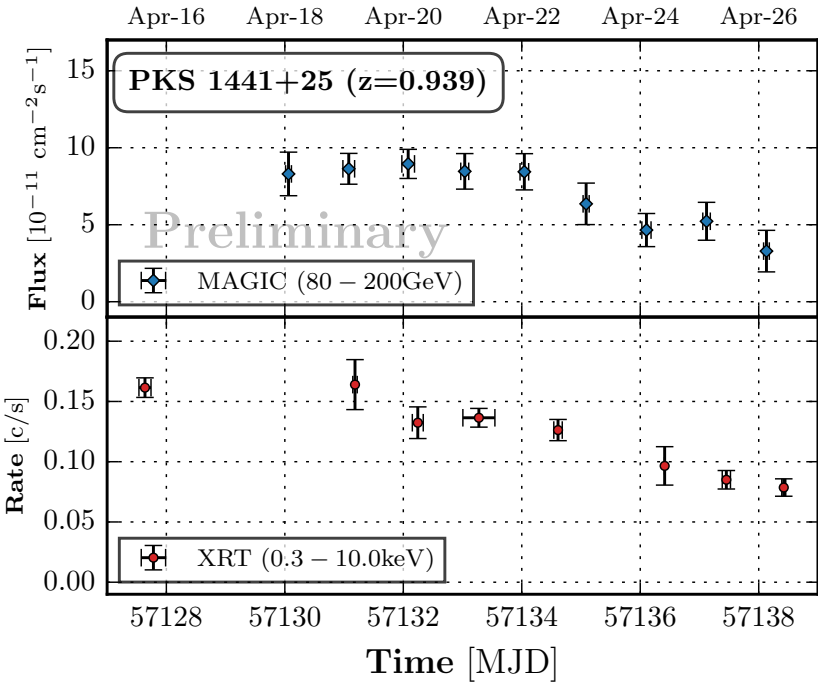
MAGIC and DM: Axions

★ Recent MAGIC discoveries: B0218+547 and PKS1441+25 **z>0.9** !!!

★ Difficult analysis: soft spectra, need a careful treatment of systematics!

★ More: ICRC 2015

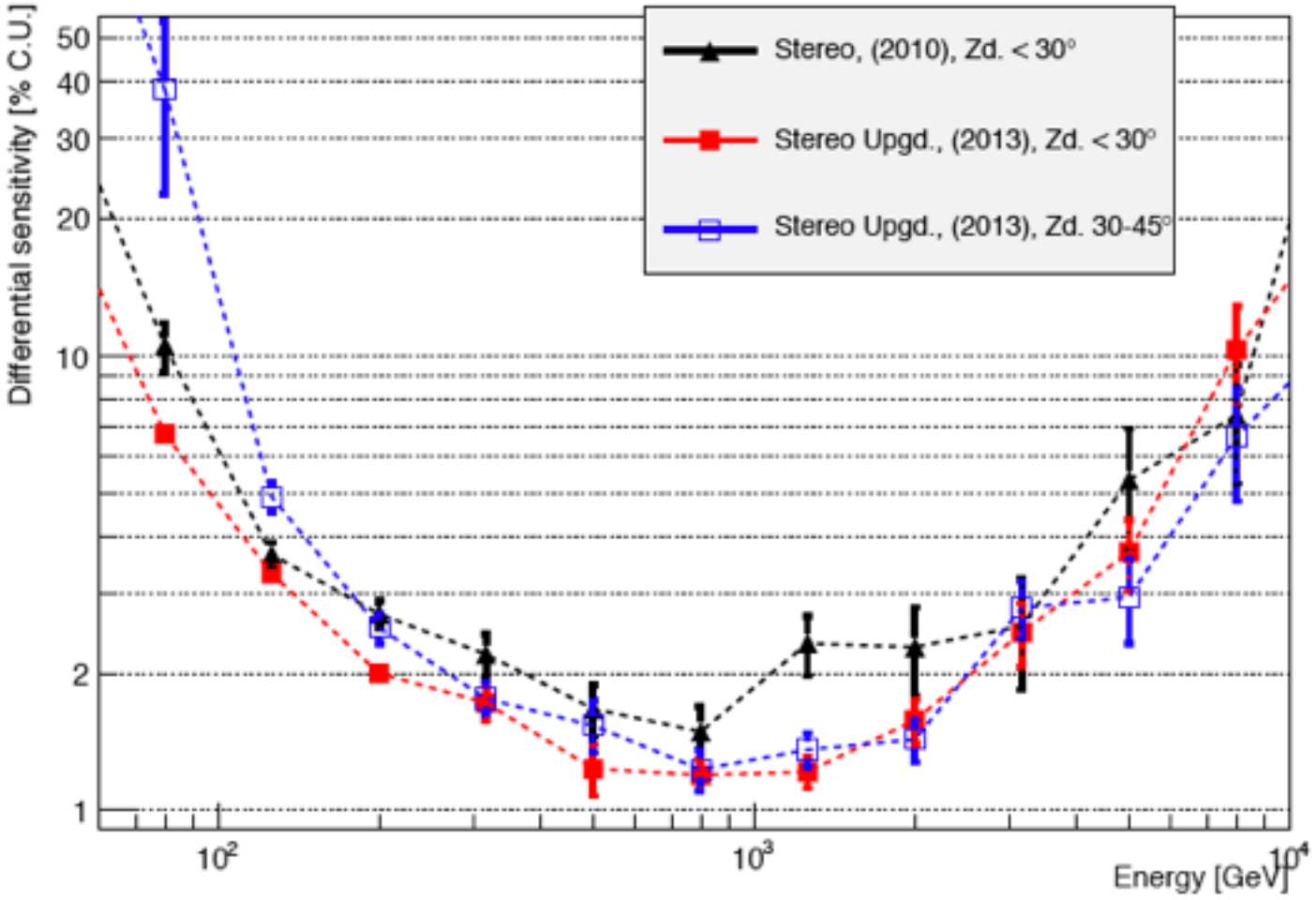




Stay tuned!!!

MAGIC SENSITIVITY

Performance paper: Alecsic` et al., accepted for publication in Astroparticle Physics 2015



Integral sensitivity: the flux of the source above a given energy for which $N_{excess}/\sqrt{N_{bgd}} = 5$ after 50h of observations

★ Low energy threshold: ~50 GeV
★ Very high sensitivity for E< 200 GeV

Full likelihood analysis

NUM OF EVENTS SPECTRAL SHAPE

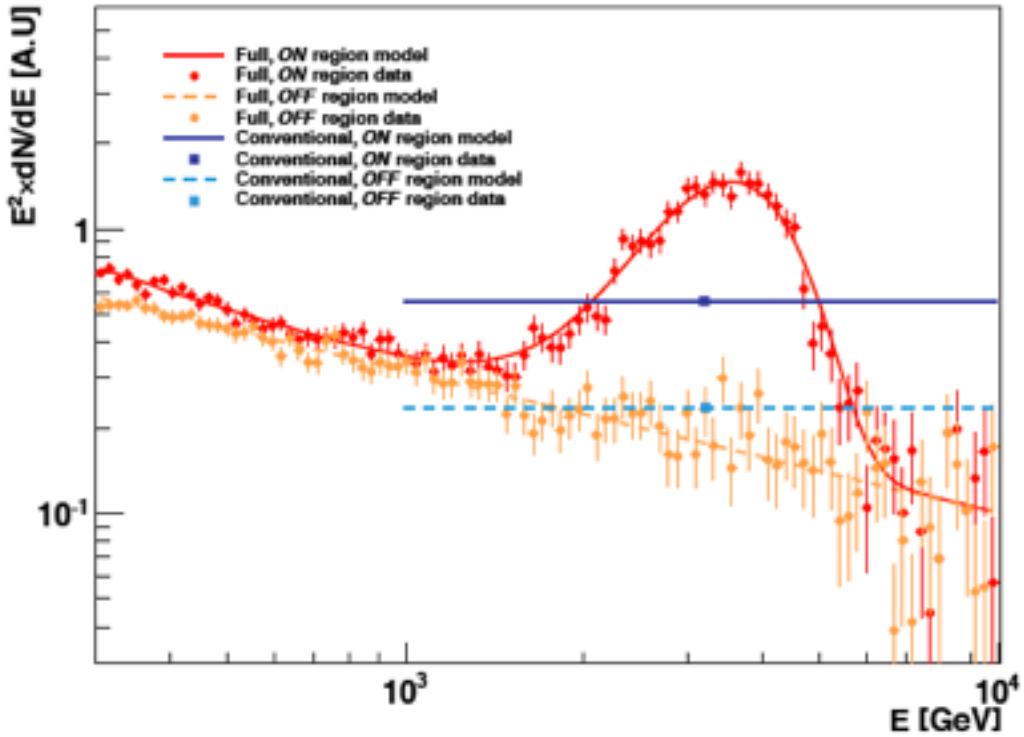
$$\mathcal{L}(N_{\rm EST}, M(\theta) \mid N_{\rm OBS}, E_1, .., E_{N_{\rm OBS}}) = \frac{N_{\rm EST}^{\ N_{\rm OBS}}}{N_{\rm OBS}!} e^{-N_{\rm EST}} \times \prod_{i=1}^{N_{\rm OBS}} \mathcal{P}(E_i; M(\theta))$$

Aleksić, Rico & Martinez, JCAP 10 (2012) 032

N_{OBS}, N_{EST} – measured and estimated total number of events

E, E' – measured and true energy

$M(\theta)$ – DM model with parameters θ



★A priori assumption on the expected spectral shape
→ maximum advantage of potential features
★ Unbiased, stable and robust
★ Significant improvement wrt the Conventional analysis
★ Straightforward combination of results from different instruments / sources →

$$\mathcal{L}_{\rm Global}(M(\theta)) = \prod_{i=1}^{N_{\rm inst}} \mathcal{L}_i(M(\theta))$$

Dwarf Galaxies: Draco

★ Distance 82 kpc

★ M/L > 200 M_O/L_O

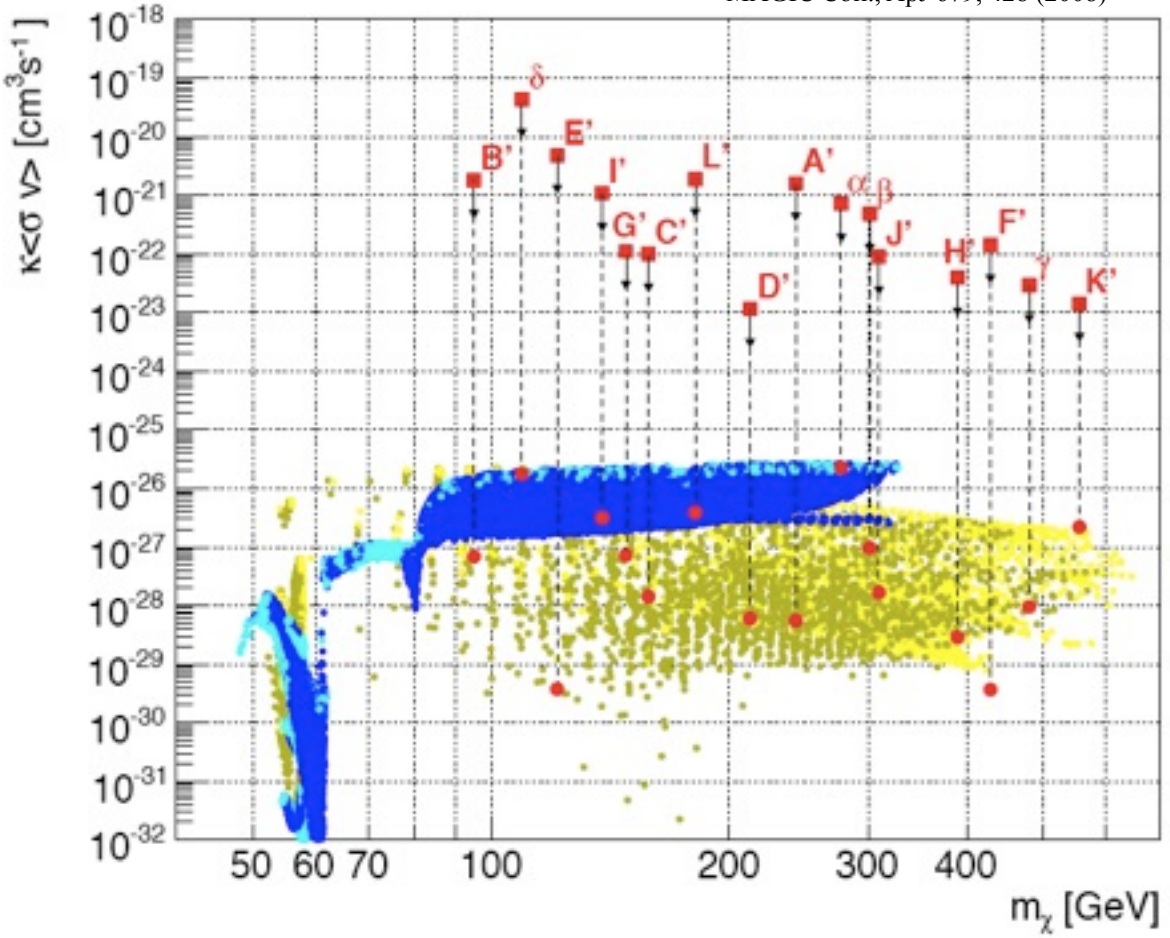
★ MAGIC-I Observations:
May 2007 (7.8 h)

★ γ-ray flux UL @ 2σ C.L.:
1.1×10^{-11} ph cm^{-2} s^{-1}
for E>140 GeV

★ Test on a set of
mSUGRA models
(Battaglia et al. 2004)

★ Internal Bremsstralung NOT
taken into account

MAGIC Coll., ApJ 679, 428 (2008)



★ ULs 10^3 – 10^9 above models predictions

Dwarf Galaxies: Willman 1

★ Distance 38 kpc

★ M/L = 500 – 700 M_O/L_O

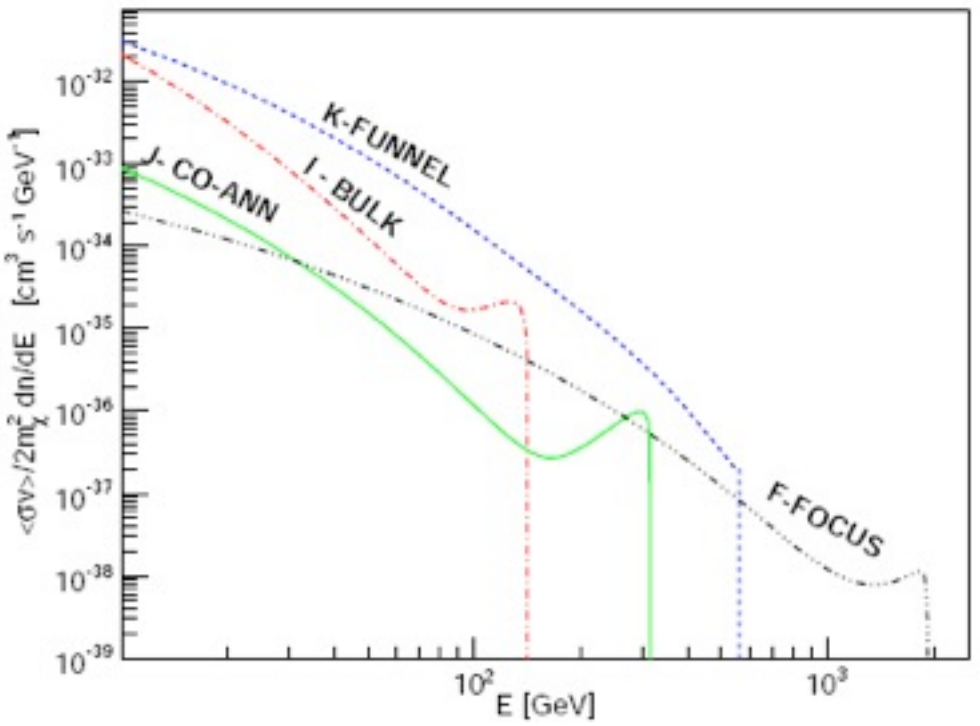
★ MAGIC-I Observations:
March – May 2008 (15.5 h)

★ Differential g-ray flux ULs

★ Test on 4 mSUGRA models
(Bringmann et al. (2008b))

★ Internal Bremsstralung is
taken into account

E. Aliu, Astrophys. J. 697 (2009) 1299



★ ULs 10^3 – 10^5 above models predictions

BM	$\Phi^{model}(>100$ GeV)	$\Phi^{u.l.}(>100$ GeV)	$B^{u.l.}$
I'	2.64×10^{-16}	9.87×10^{-12}	3.7×10^{4}
J'	4.29×10^{-17}	5.69×10^{-12}	1.3×10^{5}
K'	2.32×10^{-15}	6.83×10^{-12}	2.9×10^{3}
F^*	2.09×10^{-16}	7.13×10^{-12}	3.4×10^{4}

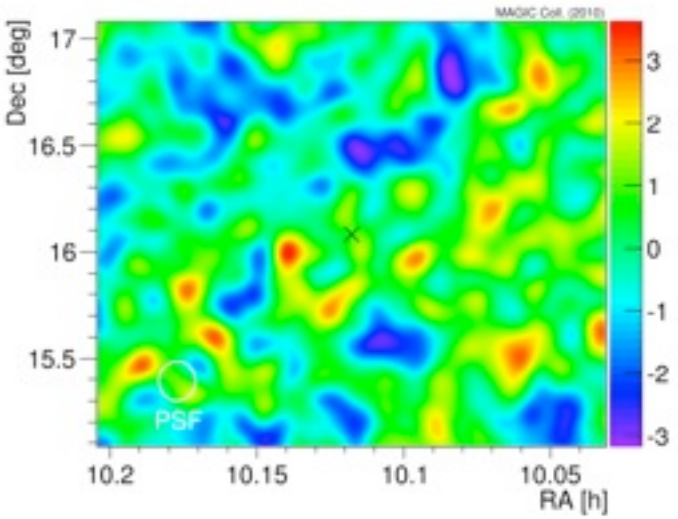
Dwarf Galaxies: Segue 1

Segue 1, currently the best DM clump candidate:

★ discovered in 2007
★ 23 kpc away
★ 71 member stars
★ 3.8 km/s velocity dispersion
★ $r^{1/2}$ = 30 pc
Mass ~ 3.8×10^5 M_O(within $r^{1/2}$)
★ $M^{1/2}$ /$L^{1/2}$ ~ 3400 M_O/L_O
★ Astrophysical factor: log10 [J(0.1°)/GeV^{2}cm^{-5}] = 19.0+/−0.60

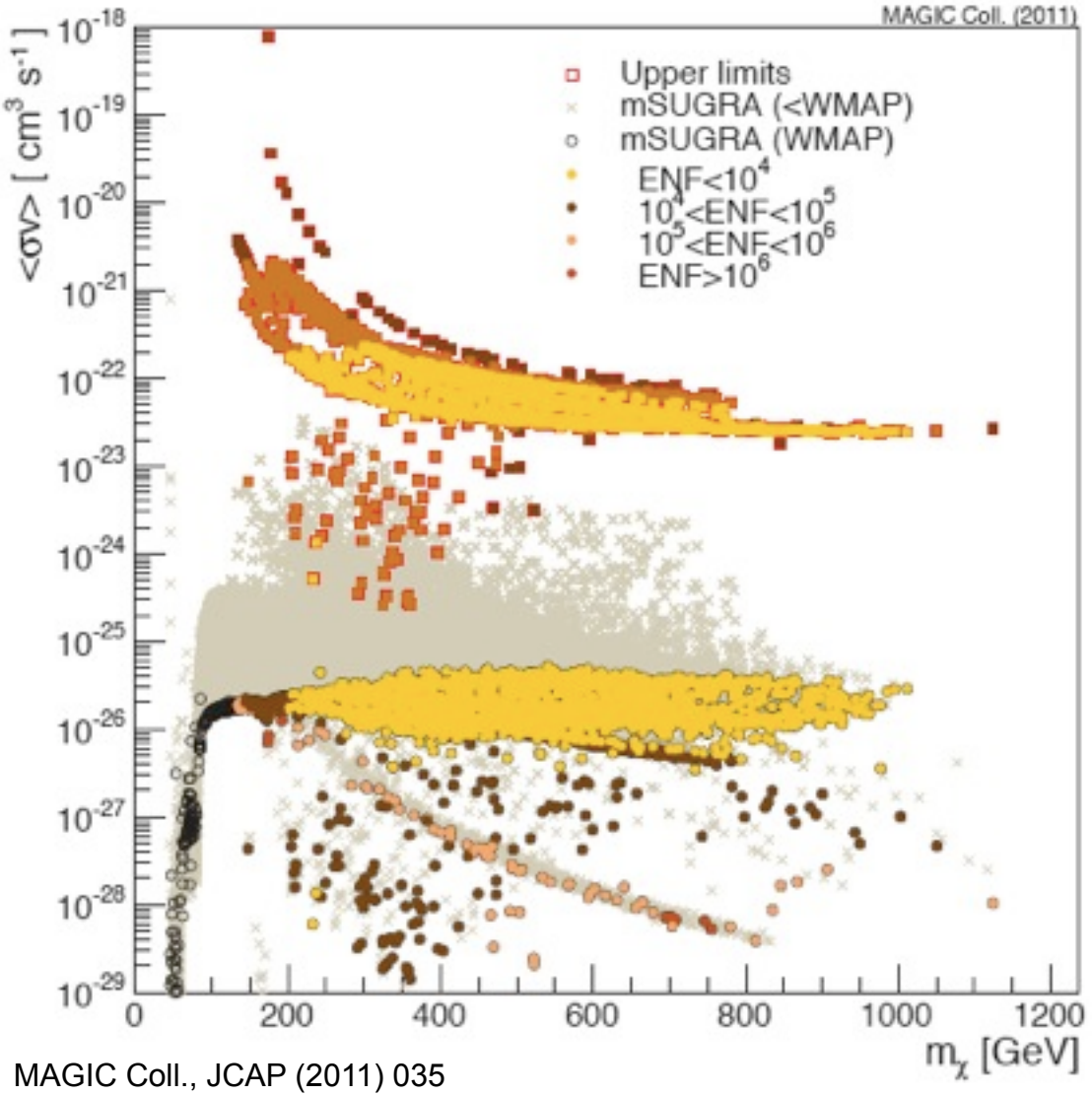
MAGIC-I observations:

★ November 2008 – March 2009
(29.4 h after quality selection)
★ no signal detected
★ ULs for differential energy spectrum



Significance map for events above 200 GeV in the Segue 1 sky region.
MAGIC Coll., JCAP (2011) 035

Dwarf Galaxies: Segue 1



MAGIC Coll., JCAP (2011) 035

x annihilation cross section values which pass the SM constraints and with a relic density < WMAP bound.

○ models within $3\sigma_{WMAP}$ from WMAP.

□ annihilation cross section ULs computed for individual points in mSUGRA parameter space scan.

Circles and squares are color coded by the enhancement factor (ENF) defined as the ratio between the UL on the averaged cross section and the value predicted by mSUGRA.

Segue 1: Constraining PAMELA's excess

★ DM particle should be heavy and annihilate into many leptons

★ Channels:

μ+μ−

τ+τ−

φφ → 2e+e− (mφ = 1GeV)

★ ENF in case of PAMELA is much smaller than in the case of mSUGRA

★ Probing τ+τ− region, but can not exclude (due to the uncertainties in the astrophysical factor)

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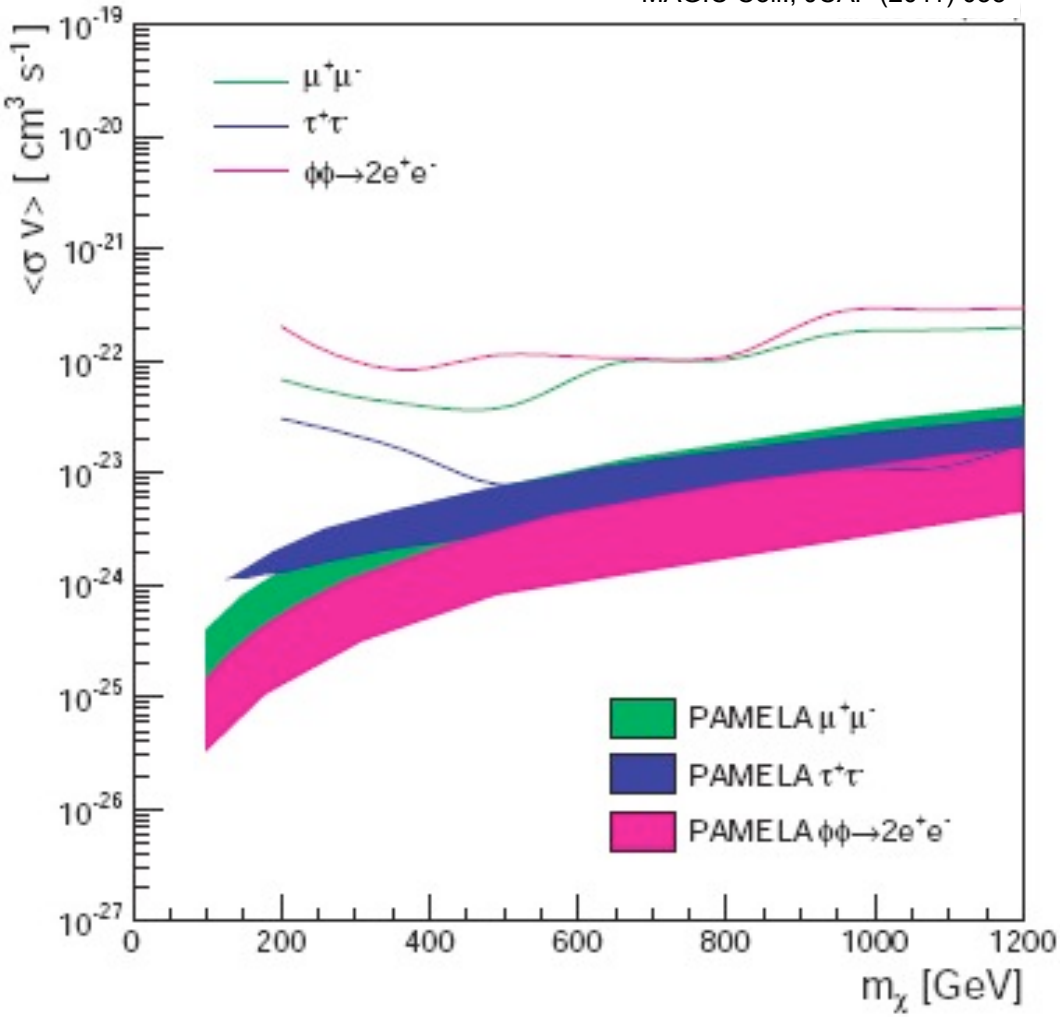


Electron + positron spectrum

★ selected extragalactic sky areas (no gamma-ray emission)

★ 14 h of stereo data

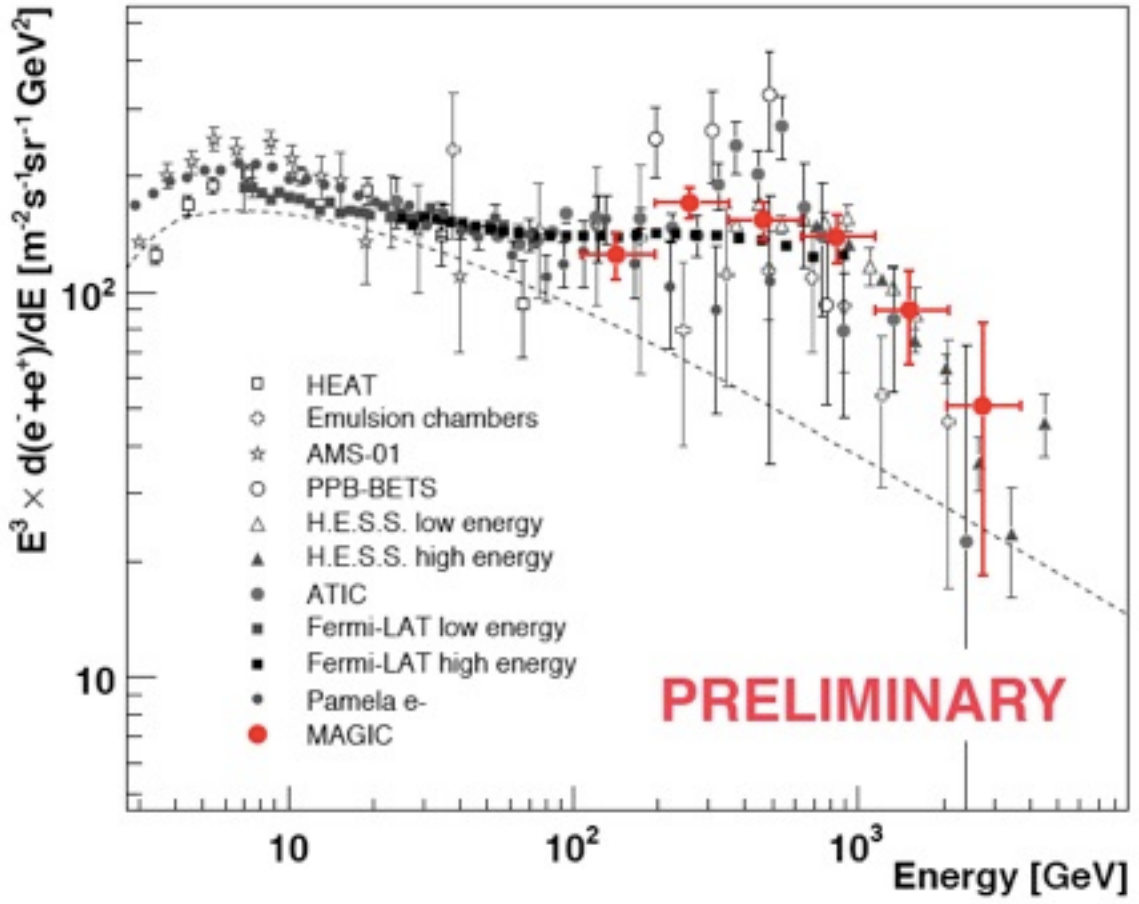
★ low zenith angle 14-27 deg

★ special analysis to discriminate $e^{\pm}$ from hadrons

★ special $e^{\pm}$ MC production

★ signal: 4668 $e^{\pm}$ excess events
significance of 11.75 σ
in the energy range 150 GeV - 2 TeV

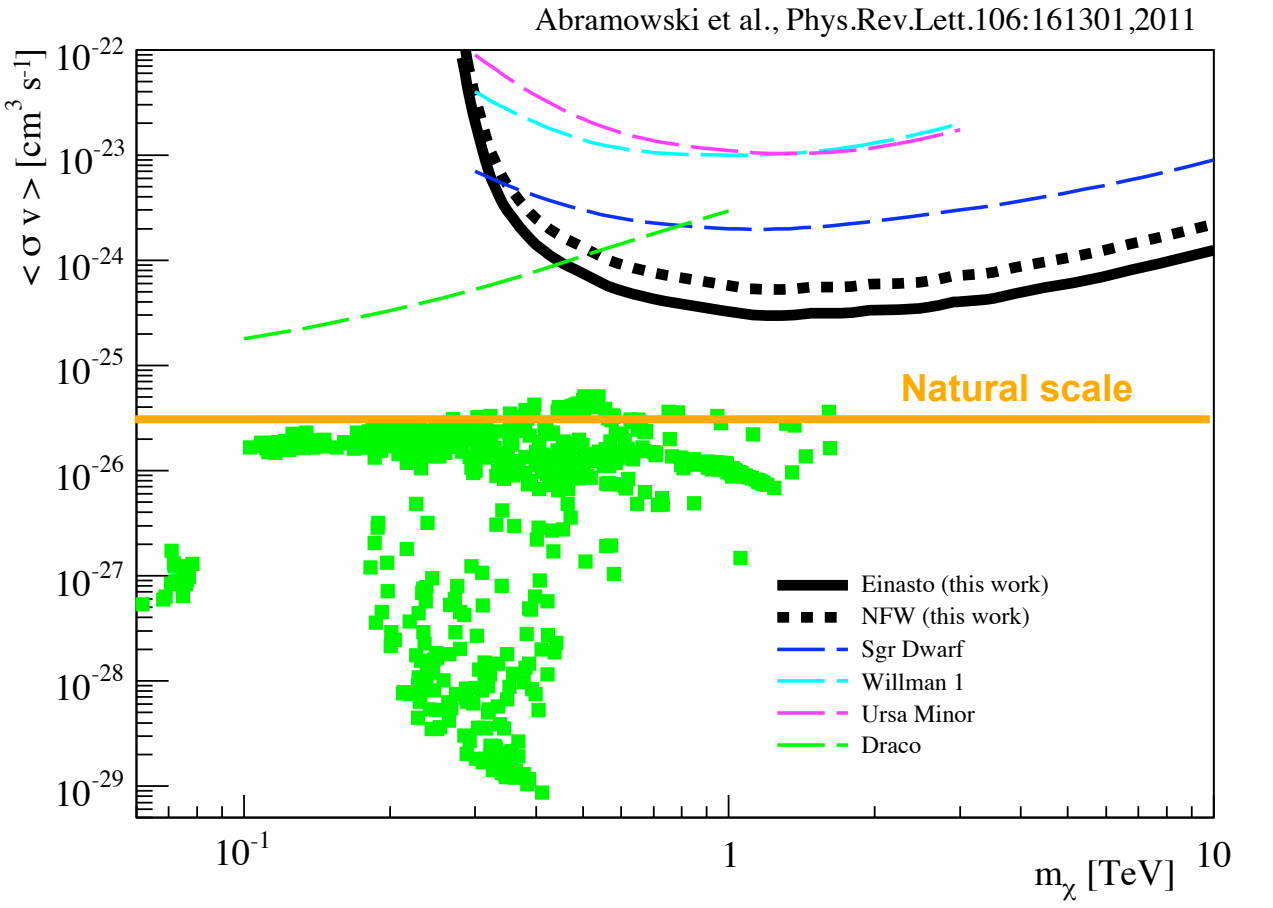
★ fitted with a power-law:
$\alpha = -3.16 \pm 0.06(\text{stat}) \pm 0.15(\text{sys})$

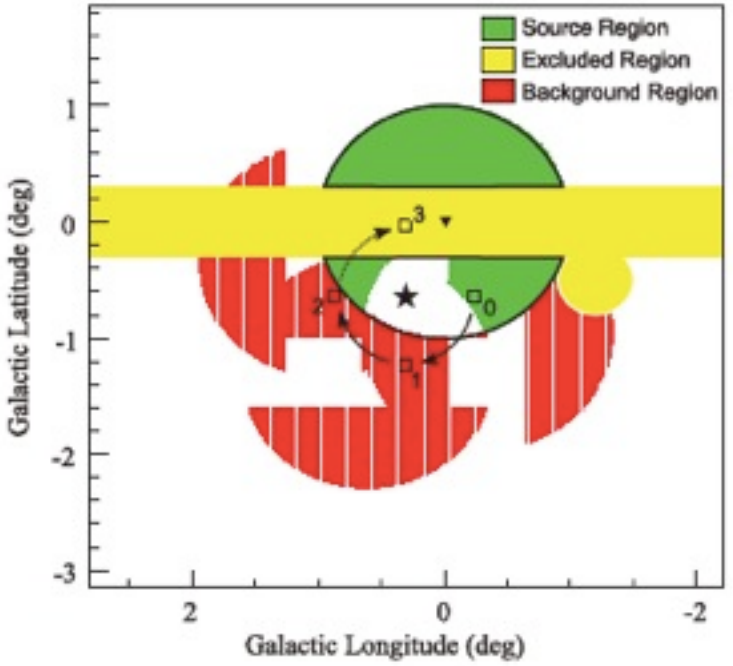


★ good agreement with ATIC, Fermi and H.E.S.S., but cannot rule out/confirm the excess...

★ NEWS: 40 h of data more, larger MC sample, analysis is ongoing - stay tuned!

Galaxy Center H.E.S.S.





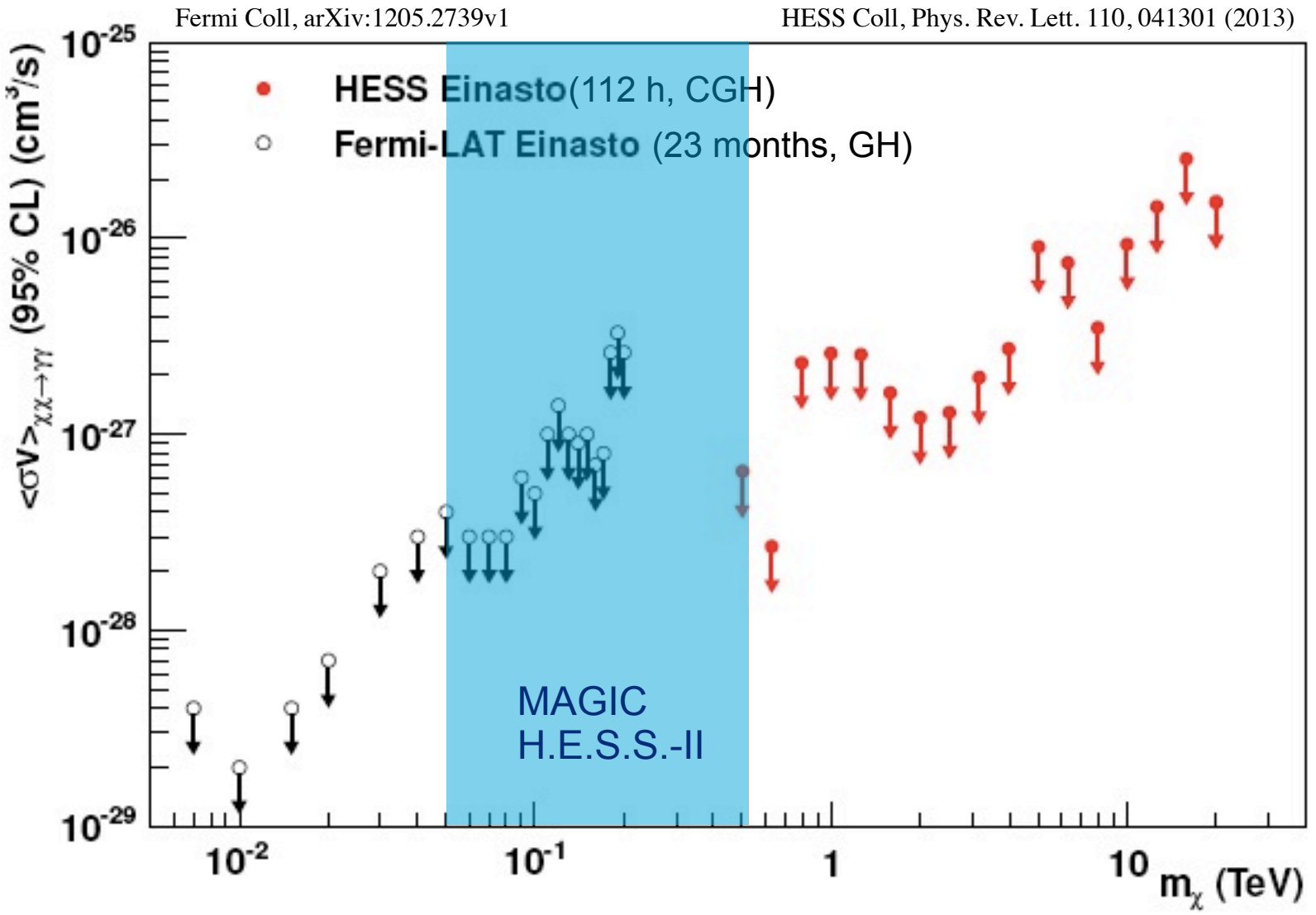
Challenge: exclude emission from standard baryonic sources!

★ distance: 8.5 kpc, J_{ASTRO} ~7.4×10^{24} Gev^2 cm^{-5}

★ H.E.S.S. observations of Galactic Center 2005-2008 (112 h)

★ best UL at $m_\chi \sim 1$ TeV: $\langle \sigma v \rangle > 3 \times 10^{-25}$ cm^3 s^{-1} are excluded @ 95% C.L.

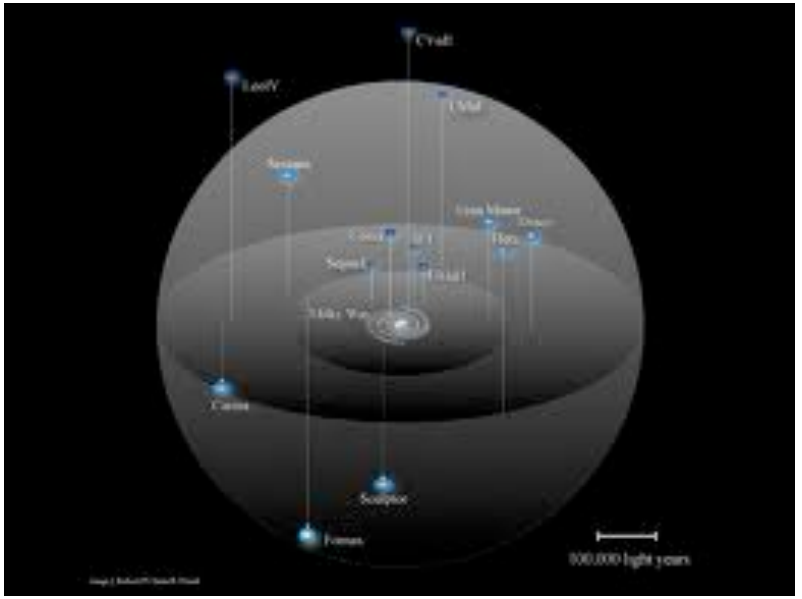
DM lines...?


Fermi Coll, arXiv:1205.2739v1
HESS Coll, Phys. Rev. Lett. 110, 041301 (2013)
HESS Einasto(112 h, CGH)
Fermi-LAT Einasto (23 months, GH)
MAGIC
H.E.S.S.-II
<σv>χχ→γγ (95% CL) (cm³/s)
10⁻²⁵
10⁻²⁶
10⁻²⁷
10⁻²⁸
10⁻²⁹
10⁻²
10⁻¹
1
10
mχ (TeV)

CTA and DM: dSpher

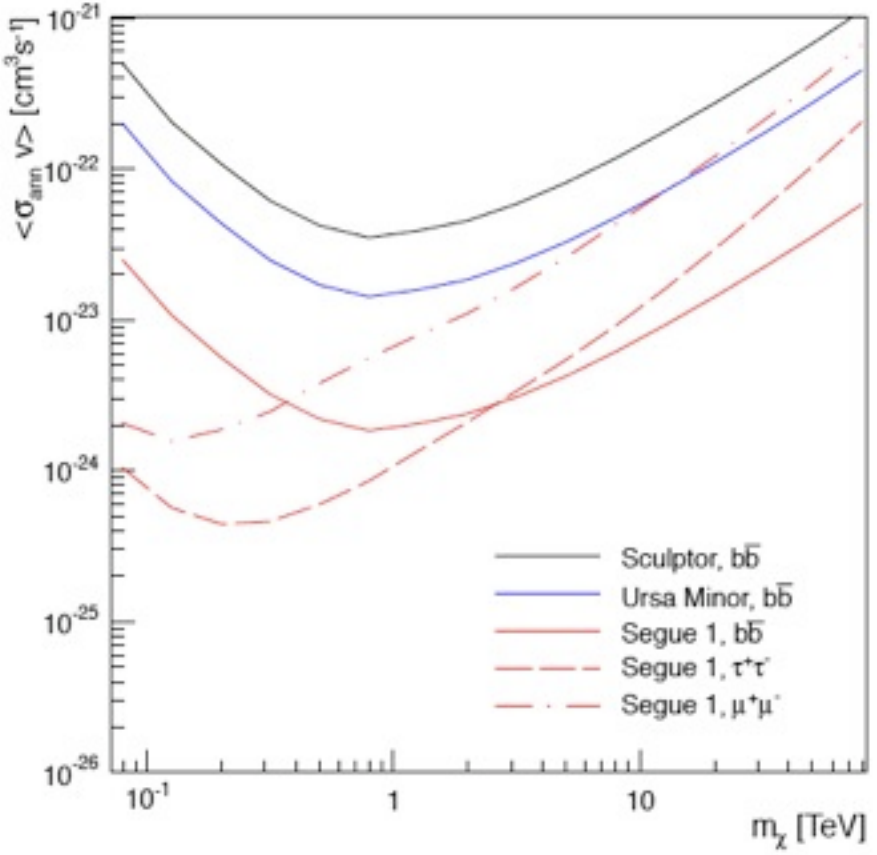
★ Dwarf Galaxies
- ★ Large M/L
- ★ No background
- ★ Short distance < 100 kpc
- ★ Low flux

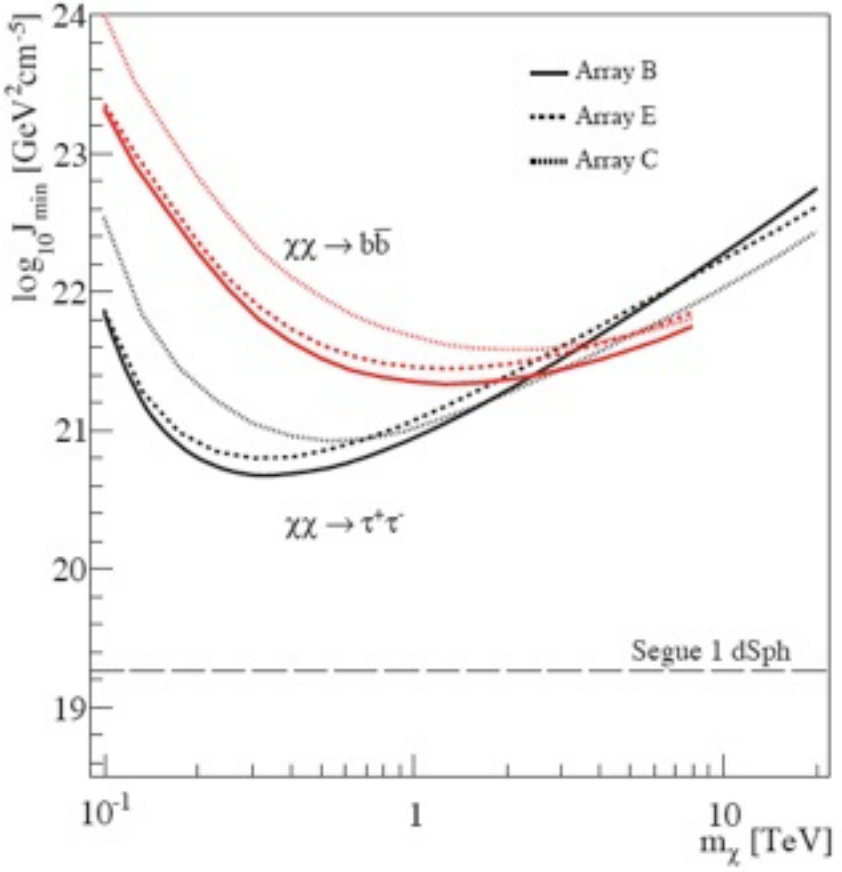
★ Parameter comparison:
- ★ J-factors: NWF, Einasto, ISO
- ★ North vs. South objects
- ★ Decaying channels
- ★ Array layouts: B, C, E



dSph	Dec. [deg]	D [kpc]	$\bar{J}$ [GeV^2 cm^{-5}]	Profile
Ursa Minor	+44.8	66	2.2×10^{18}	NFW
Draco	+34.7	87	7.1×10^{17}	NFW
Sculptor	−83.2	79	8.9×10^{17}	NFW
			2.7×10^{17}	ISO
Carina	−22, 2	101	2.8×10^{17}	NFW
Segue 1	+16.1	23	1.7×10^{19}	Einasto
Willman 1	+51.1	38	8.4×10^{18}	NFW
Coma Berenices	+23.6	44	3.9×10^{18}	NFW

CTA and DM: dSpher



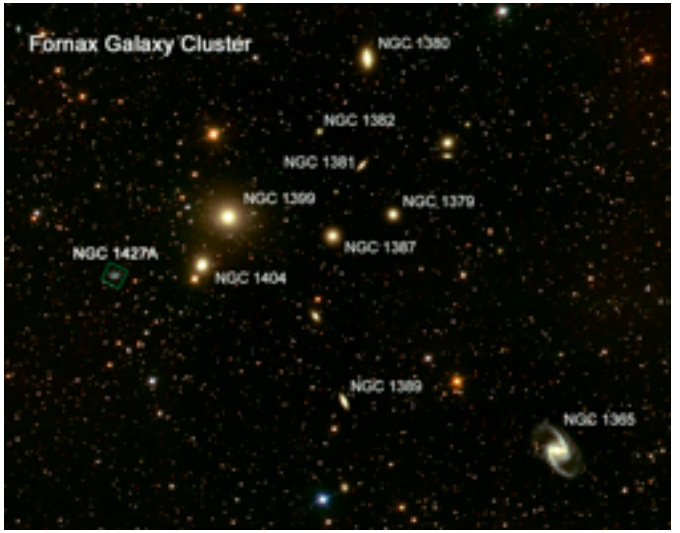


★ Best candidate: Segue 1
★ IACTs most sensitive for leptophilic DM
★ Array B (optimized for low E) best
★ Minimal boost factor required for a detection: 25
★ ToDo: stacking + likelihood analysis

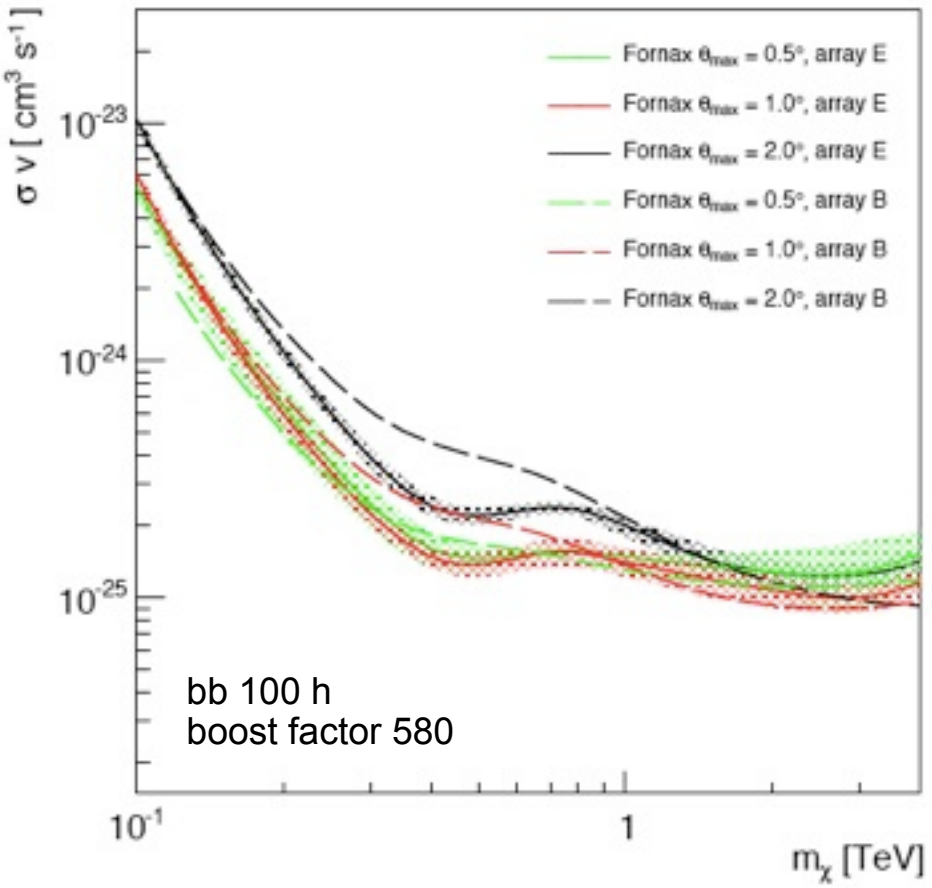
CTA and DM: Galaxy Clusters

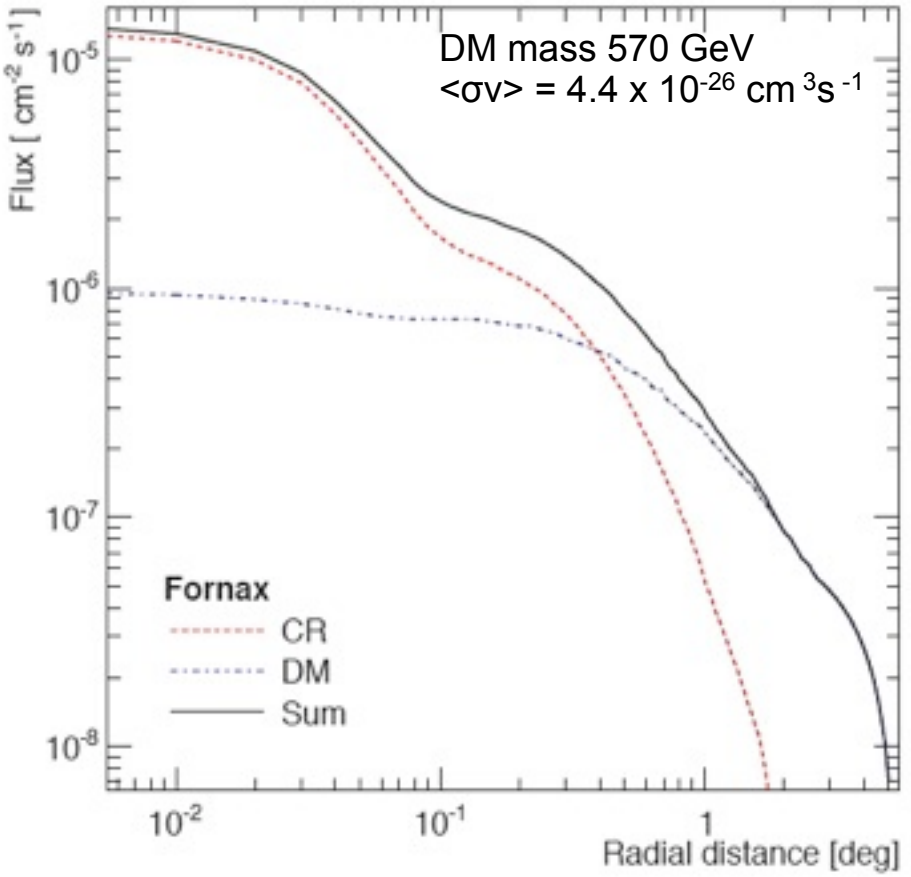
★ Galaxy Clusters:
- ★ Huge DM content (80% of total mass)
- ★ Presence of subhalos – signal boost
- ★ Large distance
- ★ Huge background from AGN and CR

★ Parameter comparison:
- ★ Perseus (North) vs. Fornax (South)
- ★ ROI extensions up to 2 deg
- ★ Array layout: B, E



CTA and DM: Galaxy Clusters

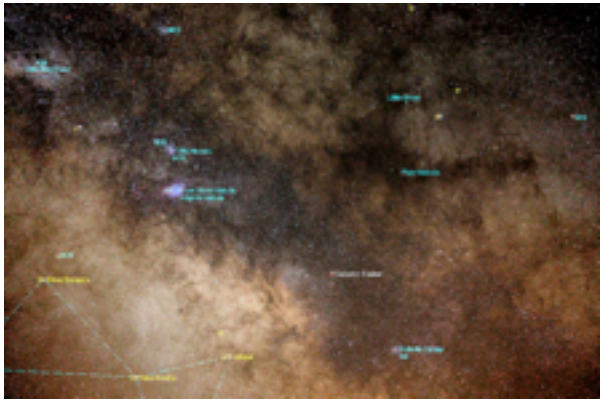


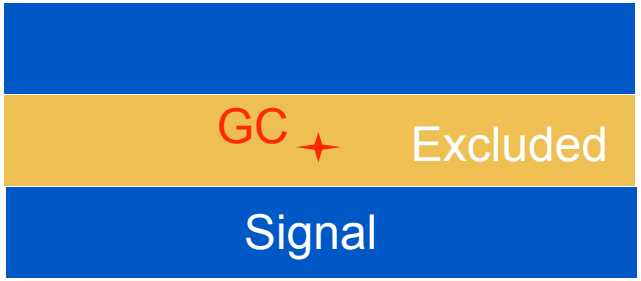


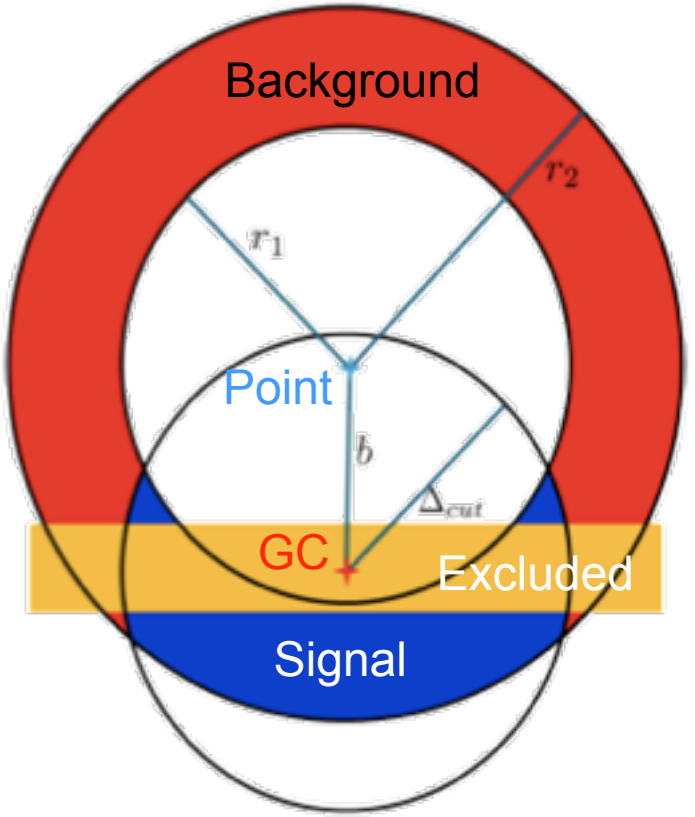
★ Best candidate for DM: Fornax (assuming DM-only emission)
★ Boost factor might vary: 10-10^4 (~600 assumed)
★ Large FoV (> 5º) helps disentangle DM from CR

CTA and DM: Galaxy Halo

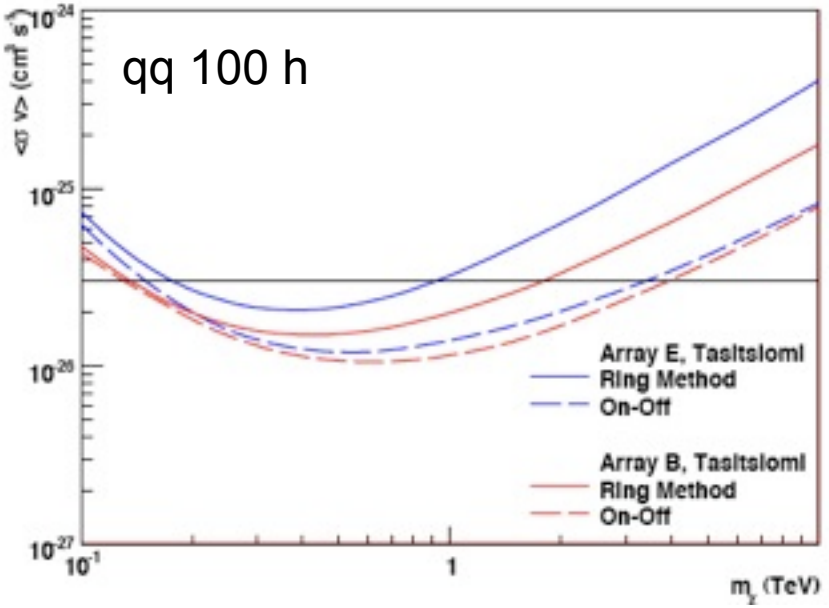
- ★ Galaxy Center
  - ★ High flux
  - ★ Short distance
  - ★ Huge background: astrophysical sources and diffuse emission from Galactic Plane
- ★ Galaxy Halo:
  - ★ Still high flux
  - ★ Less background
- ★ Parameter comparison:
  - ★ J-factors: NFW~Einasto > 10 pc from GC
  - ★ Array layout: B, E
  - ★ Observation modes: On-Off vs. Ring

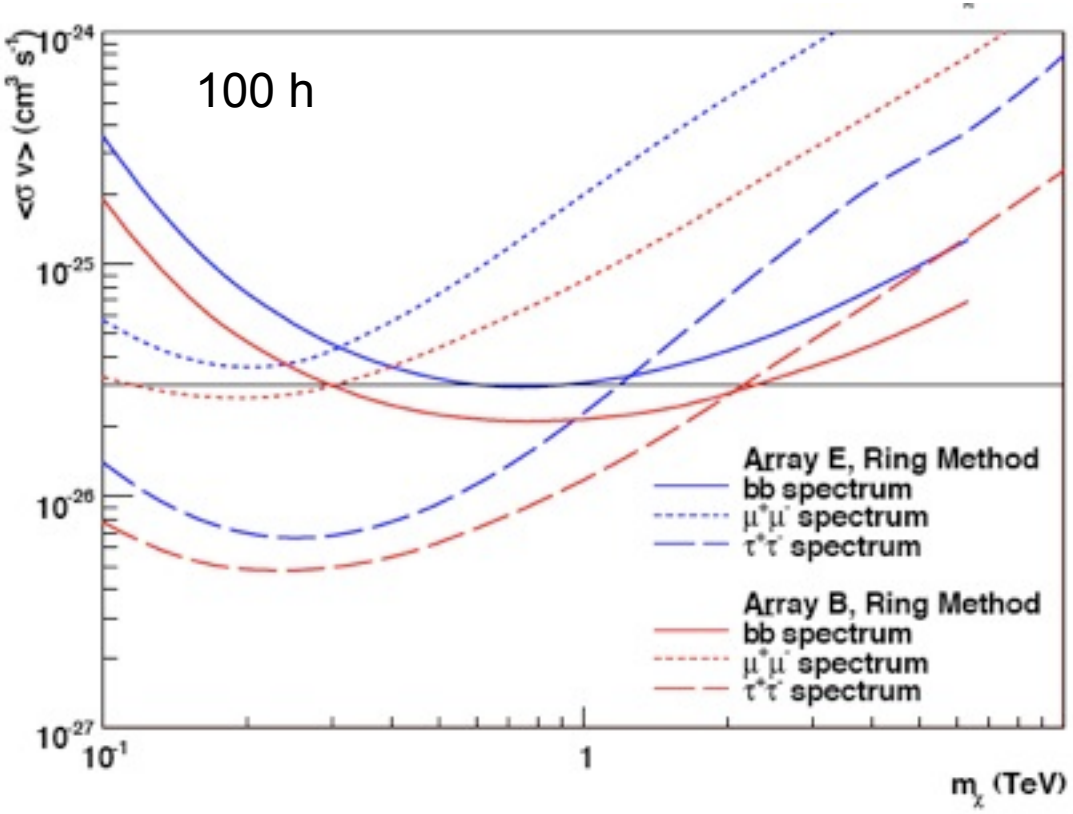






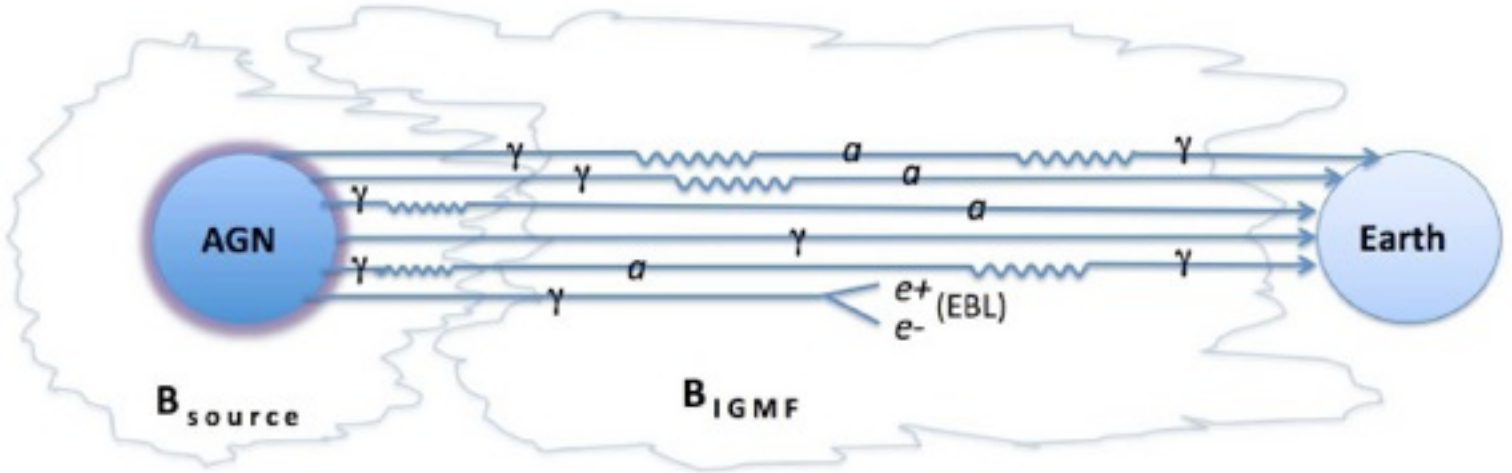
CTA and DM: Galaxy Center

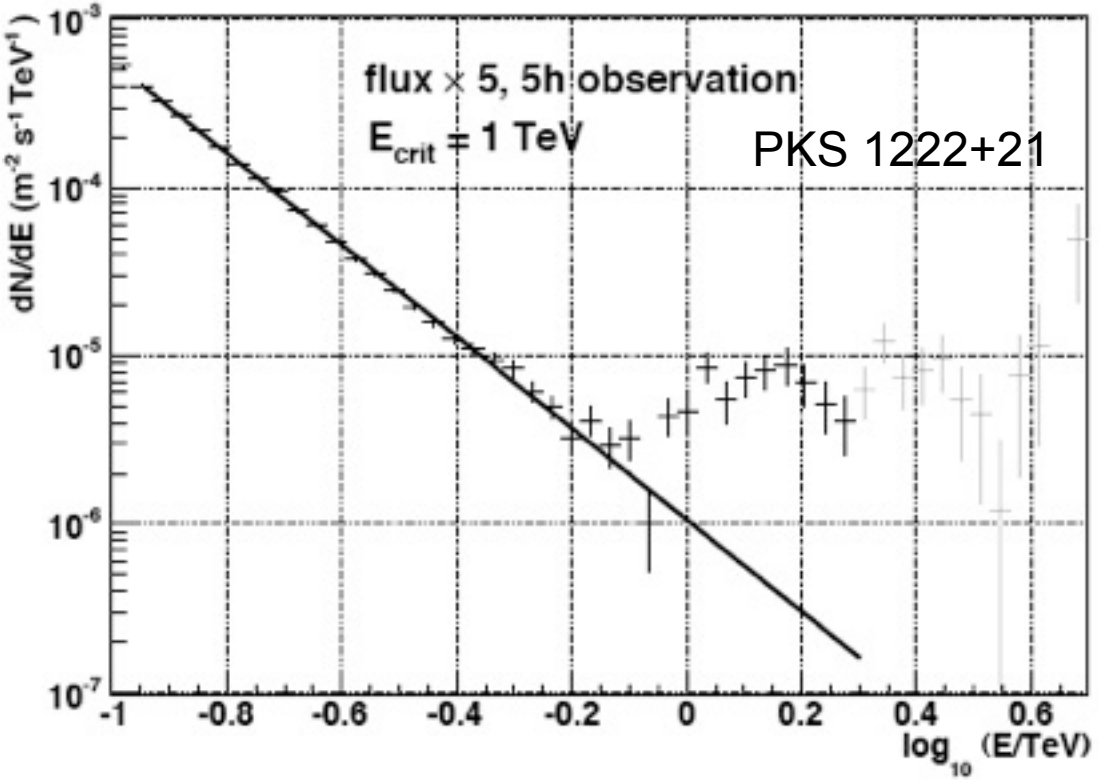




★ On-Off more sensitive, but...
  ⋆ 50% of time lost for Off only
  ⋆ more dependent on observational conditions
★ Array B more sensitive (5 vs 4 LSTs)
★ In 100 h limit below WIMP classical $\langle\sigma v\rangle$!!!

CTA and DM: Axions





$$P_0 = \frac{1}{1 + (E_{crit}/E_\gamma)^2} \sin^2\left[\frac{B\,s}{2\,M}\sqrt{1 + \left(\frac{E_{crit}}{E_\gamma}\right)^2}\right]$$

$$E_{crit}(GeV) \equiv \frac{m^2_{\mu eV}\, M_{11}}{0.4\, B_G}$$

MAGIC & WIMPs: Future

★ Perseus cluster:
  ★ 300 h of stereo data – analysis is ongoing
  ★ Focus on DM decay: J_{ASTRO} ~$7x10^{18}$ Gev cm^{-2}
  ★ Full likelihood method
  ★ Refined morphological information (Sanchez-Conde et al. JCAP 12 (2011)) to calculate exact response functions of the instrument

★ dSph program continues...

★ Looking for new targets: globular clusters...?

★ Stacking results from different experiments using full likelihood

Stay tuned!!!