Past, present and future of the MAGIC Dark Matter hunt program

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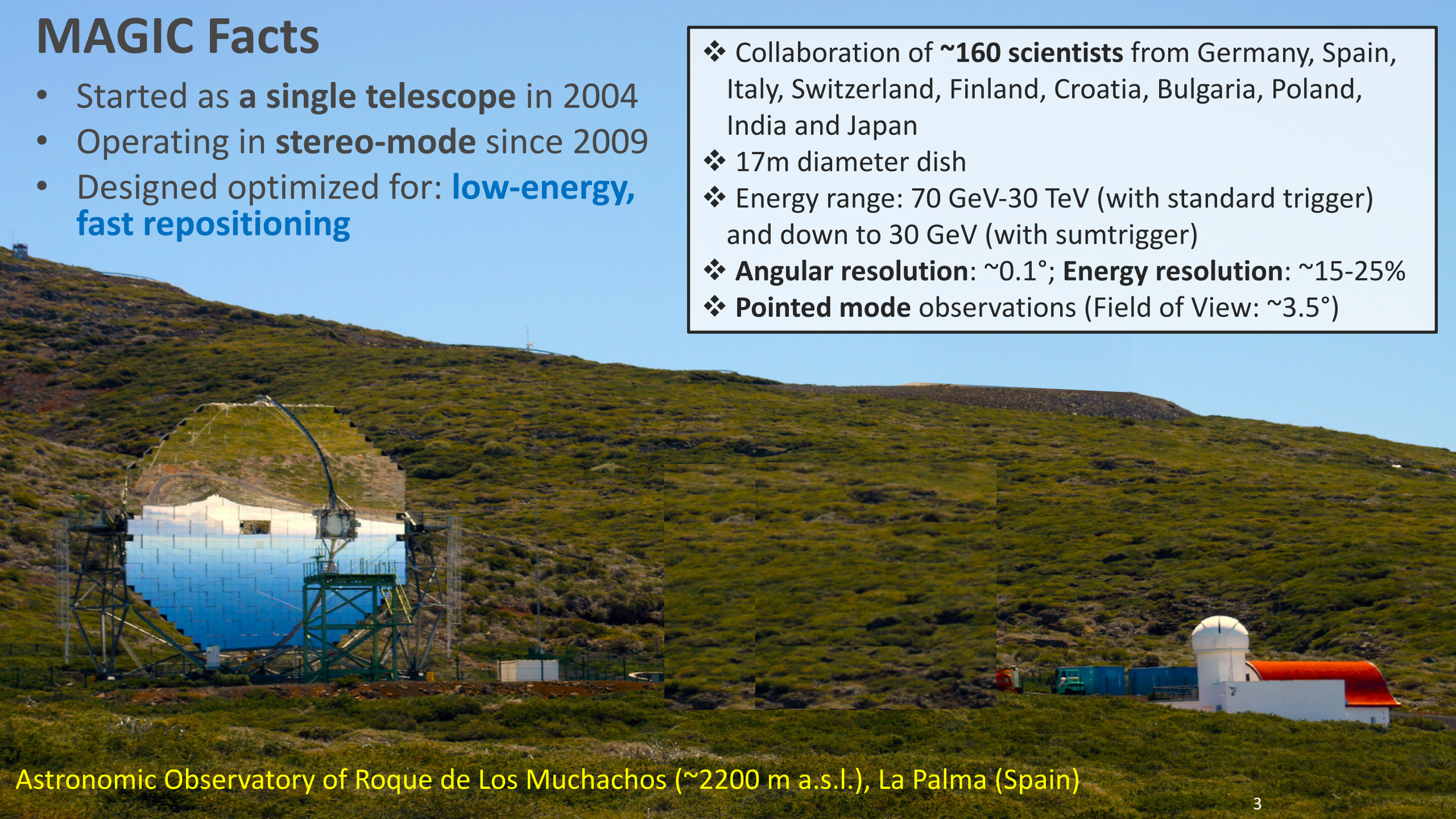
Outline

- Hunting dark matter
- Review of MAGIC results
- A look at the future
- Conclusions

MAGIC Facts

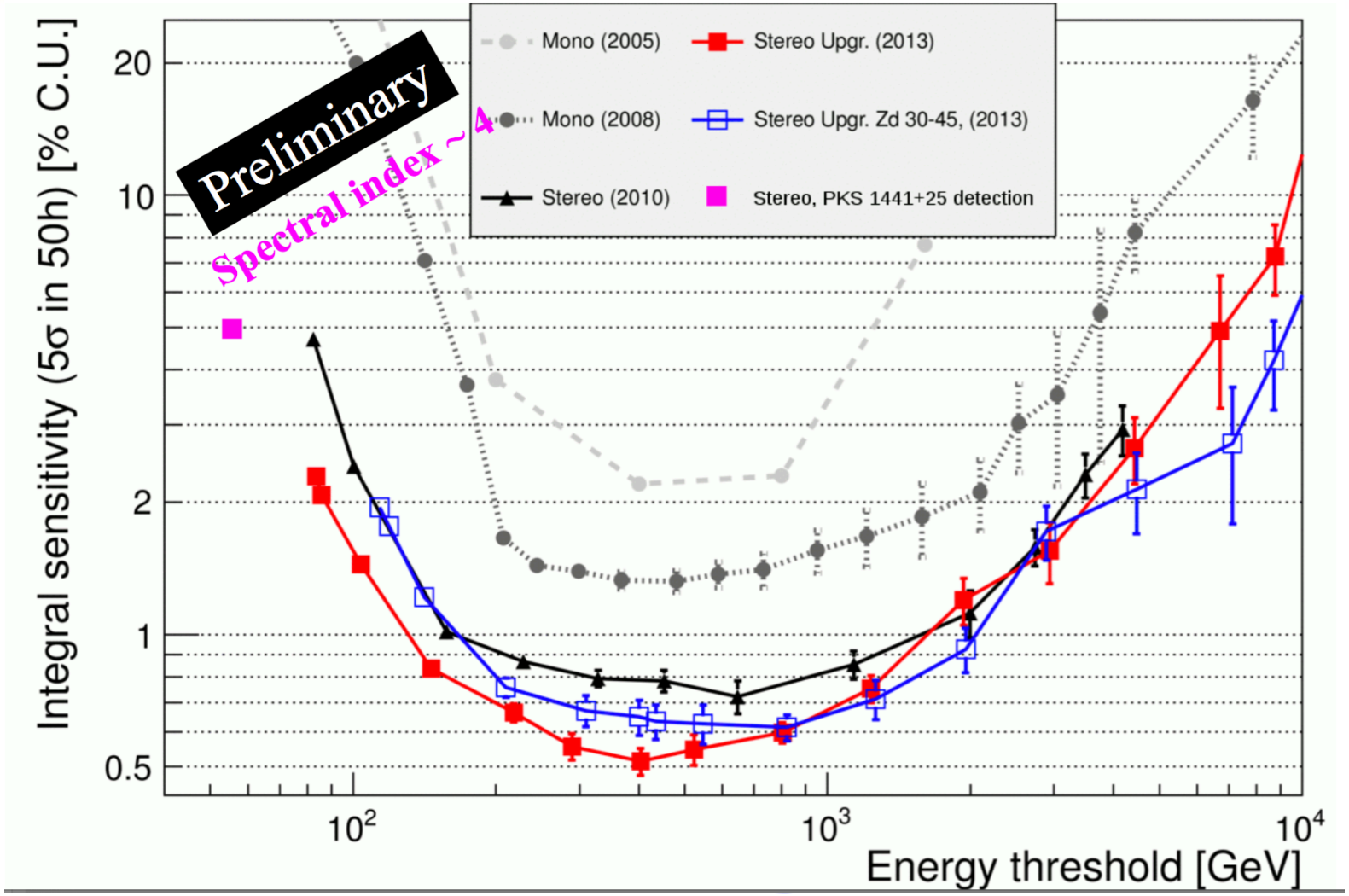
- Started as **a single telescope** in 2004
- Operating in **stereo-mode** since 2009
- Designed optimized for: **low-energy, fast repositioning**

- ❖ Collaboration of **~160 scientists** from Germany, Spain, Italy, Switzerland, Finland, Croatia, Bulgaria, Poland, India and Japan
- ❖ 17m diameter dish
- ❖ Energy range: 70 GeV-30 TeV (with standard trigger) and down to 30 GeV (with sumtrigger)
- ❖ **Angular resolution**: ~0.1°; **Energy resolution**: ~15-25%
- ❖ **Pointed mode** observations (Field of View: ~3.5°)



Astronomic Observatory of Roque de Los Muchachos (~2200 m a.s.l.), La Palma (Spain)

A continuous effort



- **Mono**:
  - Light Gray circles: first installation (2005)
  - Dark gray: different readout system (2008)
- **Stereo**-phase:
  - **Black** triangles: stereo phase 1 (2010)
  - Squares: stereo after camera upgrade:
    - zenith angle below 30◦ (red, filled),
    - 30 – 45◦ (blue, empty)
- **Sum-trigger** allowed <50 GeV

4-fold improvement in sensitivity over the last decade

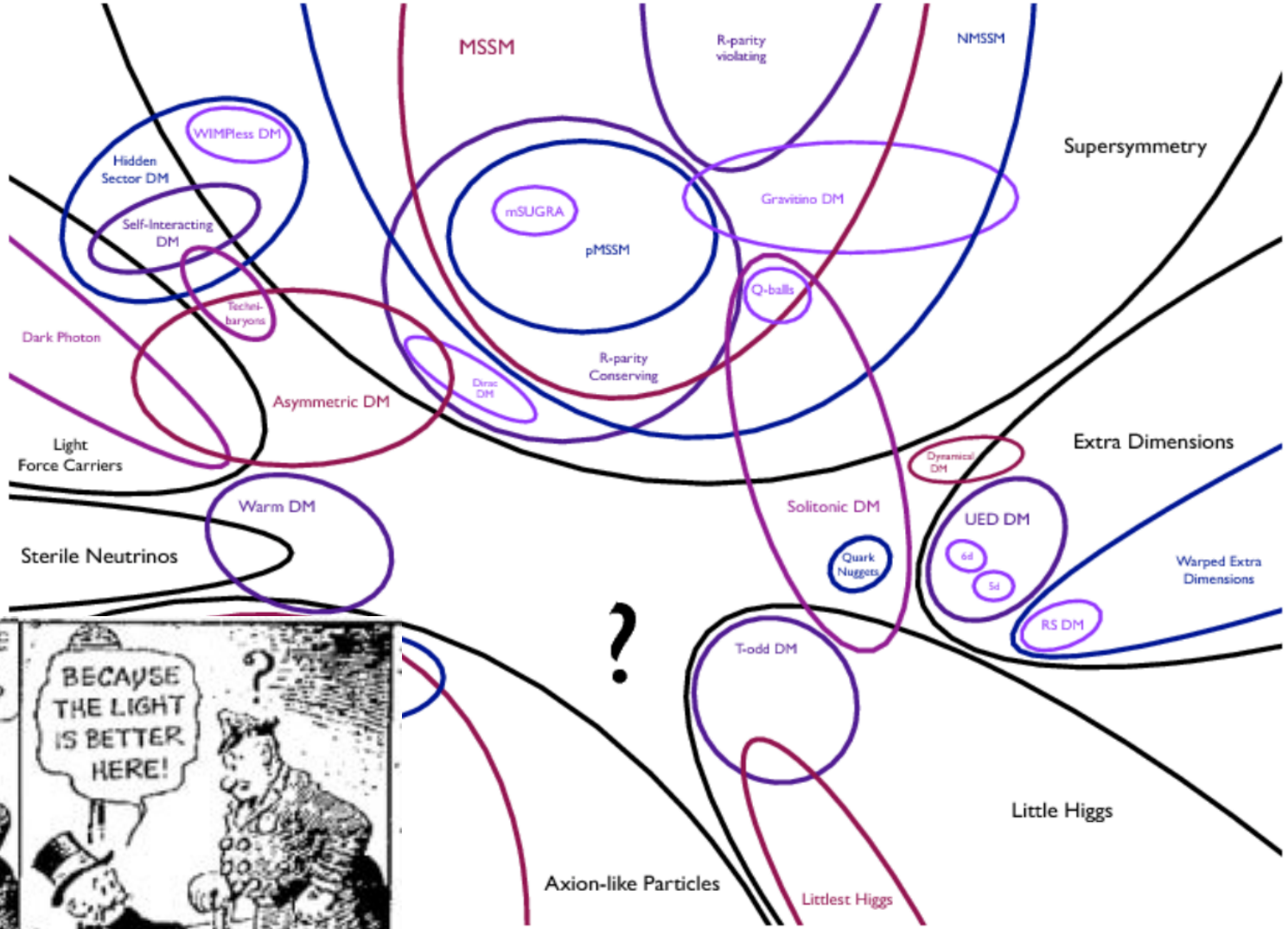
→ ~10-fold improvement at the lowest energies !!

← 16 times less needed observation time!

Hunting many dark mysteries (beside astronomy)

What is DM??

- See introductory talk by Jan too
- Where to look?

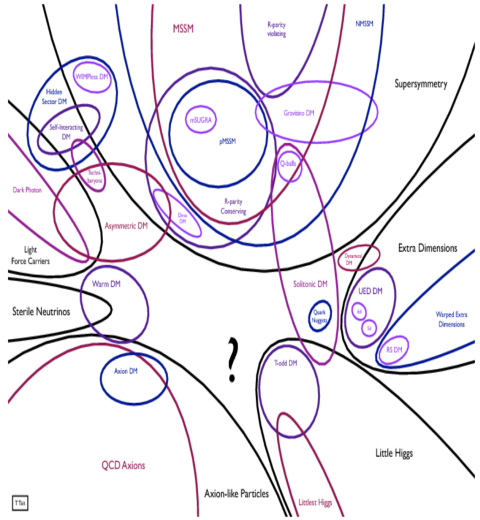


What influences the flux on Earth

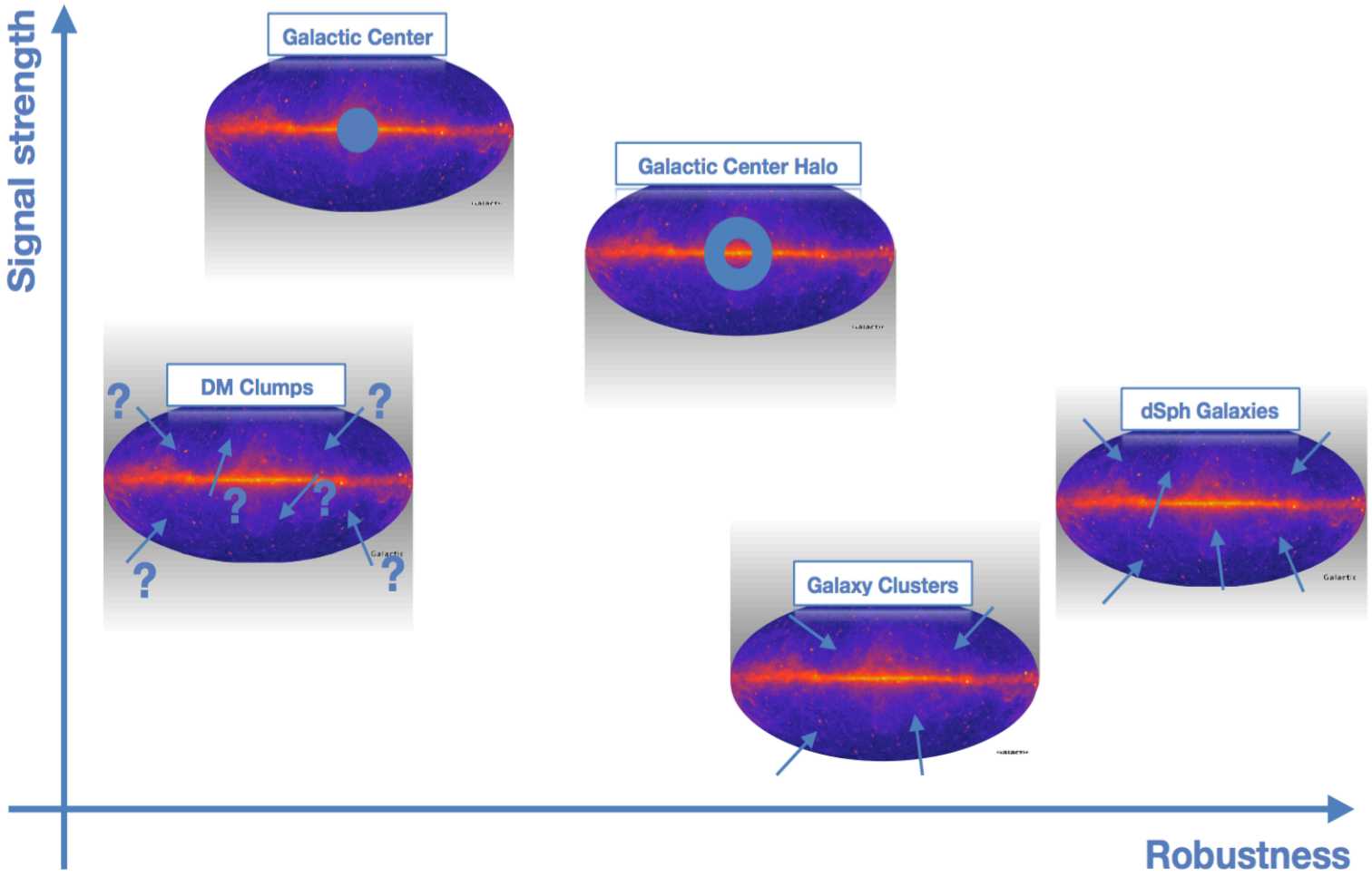
$$\frac{d\Phi(\Delta\Omega)}{dE'} = \frac{d\Phi^{\mathrm{PP}}}{dE'} \times J(\Delta\Omega)$$

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

- Hunting the **highest J-factor**
- Left with huge **uncertainties in the particle physics**



Dark Matter Program



❖ ***DM anisotropies***

+ In principle possible with IACTs although challenging

❖ ***Galactic halo and the halo around***

+ Highest *J-factor*
- Strong Astrophysical contamination
- Huge uncertaintiy in core\cusp
– "wrong" hemisphere for MAGIC)

❖ ***Galaxy Clusters***

+ Huge amount of DM but far distance → moderate/low J-factor
– High astropysocal contamination
- Large uncertainties in baryon feedback and substructure contributions
– Extended

❖ ***Dwarf Galaxies***

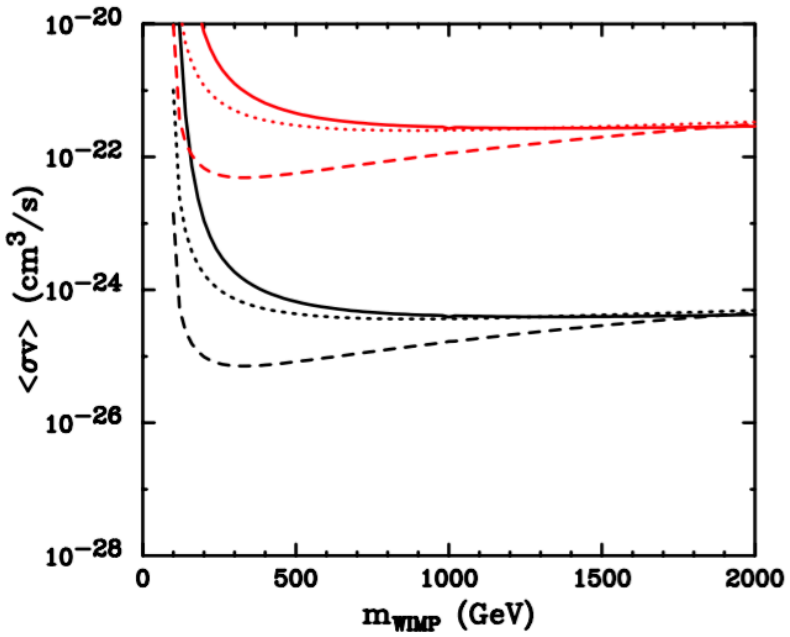
+ DM dominated (high M/L ratios) and Free from astroph. bkg
+ Less uncertainties on *J-factors*
- Low J-factor

❖ ***Dark Clumps?***

+ Free from astroph. bkg
+ Nearby and numerous
– How to know where they are?
– Bright enough?

10 years ago

Bergstrom, Hooper PRD73 2006



- In 2006, hints of detection of the Draco dsph by CACTUS, GLAST was to be launched, and there were good expectations that short-exposure might have been sufficient

All instruments launched in the search!...but investing few hours

Dwarf Satellite Galaxies		Obs. Time [h]		
Draco	2003	7.4	Whipple	[5]
	2007	7.8	MAGIC	[7]
	2007	18.4	VERITAS	[8]
Ursa Minor	2003	7.9	Vhipple	[5]
	2007	18.9	VERITAS	[8]
Sagittarius	2006	11	H.E.S.S.	[9]
Canis Major	2006	9.6	H.E.S.S.	[10]
Willman 1	2007–2008	13.7	VERITAS	[8]
	2008	15.5	MAGIC	[11]
Sculptor	2008	11.8	H.E.S.S.	[12]
Carina	2008–2009	14.8	H.E.S.S.	[12]
Segue 1	2008–2009	29.4	MAGIC	[13]
	2010–2011	48	VERITAS	[14]
Boötes	2009	14.3	VERITAS	[8]

MD, NIM A 742 (2014)

Search expanded at all targets

Target	Year	Time	Experiment	Ref.
Globular Clusters				
M15	2002	0.2	Whipple	[5]
	2006–2007	15.2	H.E.S.S.	[6]
M33	2002–2004	7.9	Whipple	[5]
M32	2004	6.9	Whipple	[5]
NGC 6388	2008–2009	27.2	H.E.S.S.	[6]
Dwarf Satellite Galaxies				
Draco	2003	7.4	Whipple	[5]
	2007	7.8	MAGIC	[7]
	2007	18.4	VERITAS	[8]
Ursa Minor	2003	7.9	Vhipple	[5]
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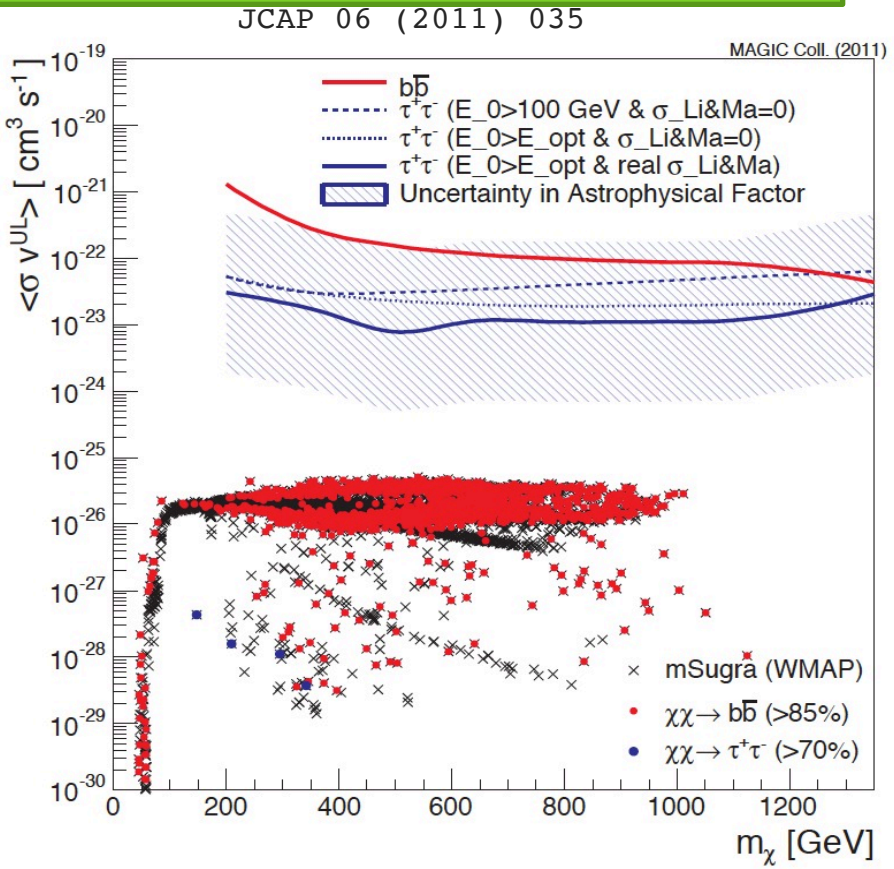
Carina	2008–2009	14.8	H.E.S.S.	[12]
Segue 1	2008–2009	29.4	MAGIC	[13]
	2010–2011	48	VERITAS	[14]
	2010–2013	158	MAGIC	[15]
Boötes	2009	14.3	VERITAS	[8]
Galaxy Clusters				
Abell 2029	2003–2004	6	Whipple	[16]
Perseus	2004–2005	13.5	Whipple	[16]
	2008	24.4	MAGIC	[17]
Fornax	2005	14.5	H.E.S.S.	[18]
Coma	2008	18.6	VERITAS	[19]
The Milky Way central region				
MW Center	2004	48.7	H.E.S.S.	[20]
MW Center Halo	2004–2008	112	H.E.S.S.	[21]
Other searches				
IMBH	2004–2007	400	H.E.S.S.	[22]
	2006–2007	25	MAGIC	[23]
Lines	2004–2008	112	H.E.S.S.	[24]
	2010–2013	158	MAGIC	[15]
UFOs	–	–	MAGIC	[25]
	–	–	VERITAS	[26]
All-electron	2004–2007	239	H.E.S.S.	[27,28]
	2009–2010	14	MAGIC	[29]
Moon-shadow	–	–	MAGIC	[30]

Single-telescope (MAGIC-I alone) results

- Galactic Center
  - **(17 h)** ApJ Lett. 638 (2006) L101
- Galaxy clusters
  - **Perseus (25 h)** ApJ 710 (2010) 634
- Dwarf Galaxies:
  - **Draco (8 h):** ApJ 679 (2008) 428
  - **Willman 1 (16 h):** ApJ 697 (2009) 1299
  - **Segue 1 (30 h):** JCAP 06 (2011) 035

← *MD, NIM A 742 (2014)*



Constraints from Segue 1:

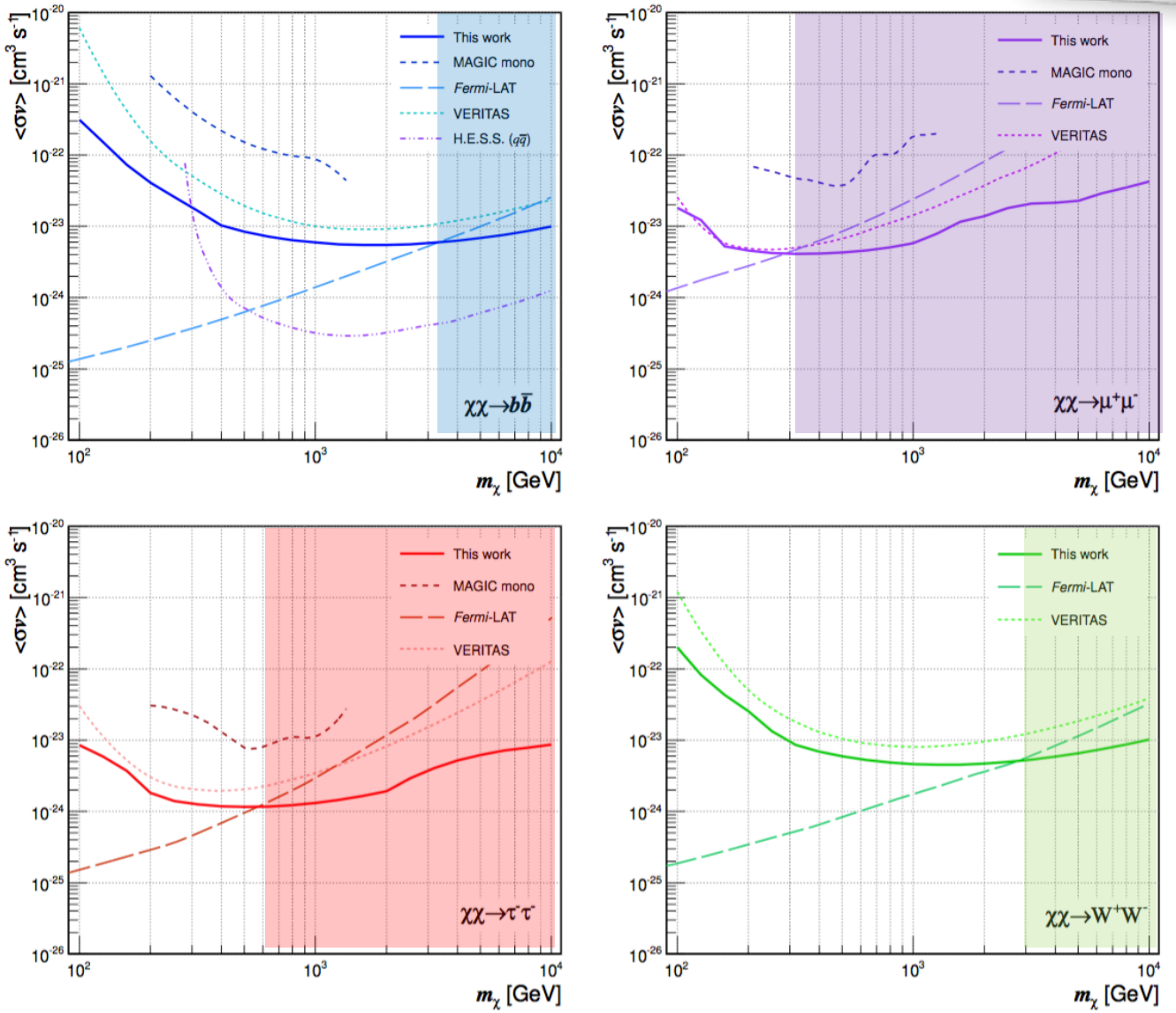
- $<\sigma_{ann}v>^{ul} \sim 10^{-22}$ cm^3 s^{-1} (for $m_{DM} \approx 1$ TeV to bb-bar)
- Required boost factors ~ 10^3 - 10^5

#1 Segue 1 Deep Scan with MAGIC stereo

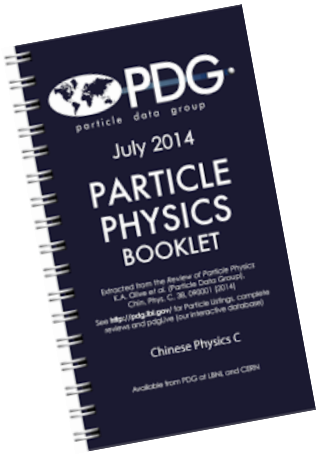
Best limits from dwarfs in high-mass range

- MAGIC decided to perform the **longest exposure on a single dSph**: Segue 1
- **160 hours** of good-quality data between 2011 and 2013.
- Optimized statistical treatment allowed performance boost

See Aleksic+ **JCAP 1210 (2012) 032**



- Strongest constraints above few hundreds GeV according to channel
- Results made into the PDG



Segue stereo stat treatment

- In all DM searches, we try to measure the **same universal parameter,** e.g. $\langle\sigma v\rangle$ through gamma-ray flux:

$$\frac{d\Phi(\Delta\Omega, E_\gamma)}{dE_\gamma} = B_F \cdot \underbrace{\frac{1}{4\pi}\frac{(\sigma_{ann} v)}{2m_\chi^2}\sum_i BR_i \frac{dN_\gamma^i}{dE_\gamma}}_{\text{Particle physics}} \cdot \underbrace{\tilde{J}(\Delta\Omega)}_{\text{Astrophysics}},$$

- Different observations of different targets differ in the astrophysical or J-factor

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

- **Aim: combine measurements** of $\langle\sigma v\rangle$ from different targets and instruments

The likelihood was prepared so that results from different experiments could be combined

$$\mathcal{L}_{iM}(\langle\sigma v\rangle; J_i, \mu_{iM} | \mathcal{D}_{iM}) = \prod_{k=1}^{N} \mathcal{L}_{iMk}(\langle\sigma v\rangle; J_i, \mu_{iMk} | \mathcal{D}_{iMk})$$

MAGIC

$$\mathcal{L}_{iF}(\langle\sigma v\rangle; J_i, \mu_{iF} | \mathcal{D}_{iF}) = \prod_{k=1}^{N_{E\text{-bins}}} \mathcal{L}_{iFk}(\overline{E\Phi}_k \langle\sigma v\rangle; J_i)$$

Fermi Gamma-ray Space Telescope

Generic Instrument j and particular target i

$$\mathcal{L}_i(\langle\sigma v\rangle; J_i, \mu_i | \mathcal{D}_i) = \prod_{j=1}^{N\ instrument} \mathcal{L}_{ij}(\langle\sigma v\rangle; J_i, \mu_{ij} | \mathcal{D}_{ij})$$

nuisance parameters

input data set

The instrument response functions do not need to be combined, but can be used on individual factor of the likelihood→GREAT ADVANTAGE

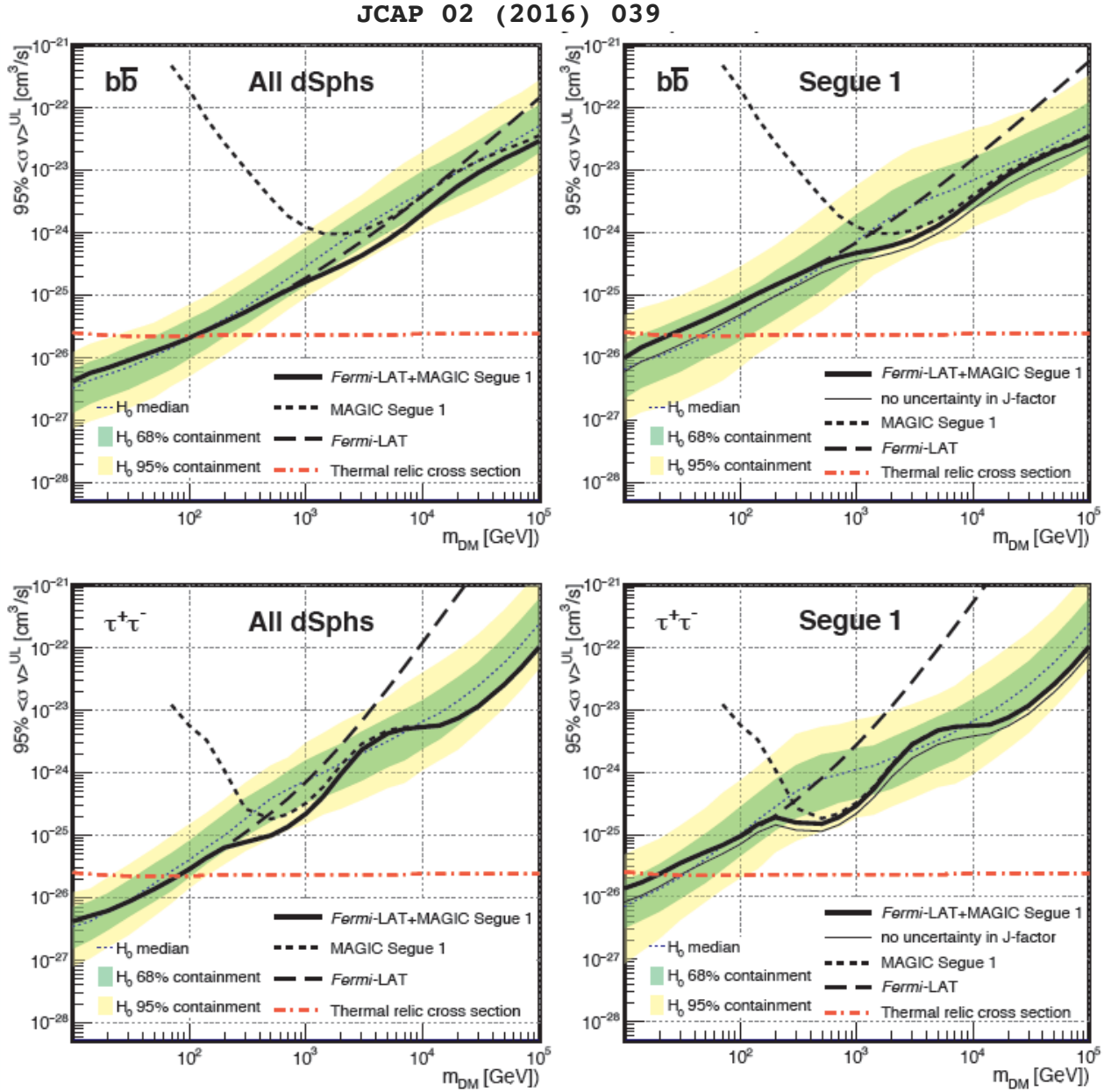
RESULTS FROM DIFFERENT INSTRUMENTS AND DIFFERENT TARGETS CAN BE NOW COMBINED TO IMPROVE SENSITIVITY

MAGIC + Fermi combined

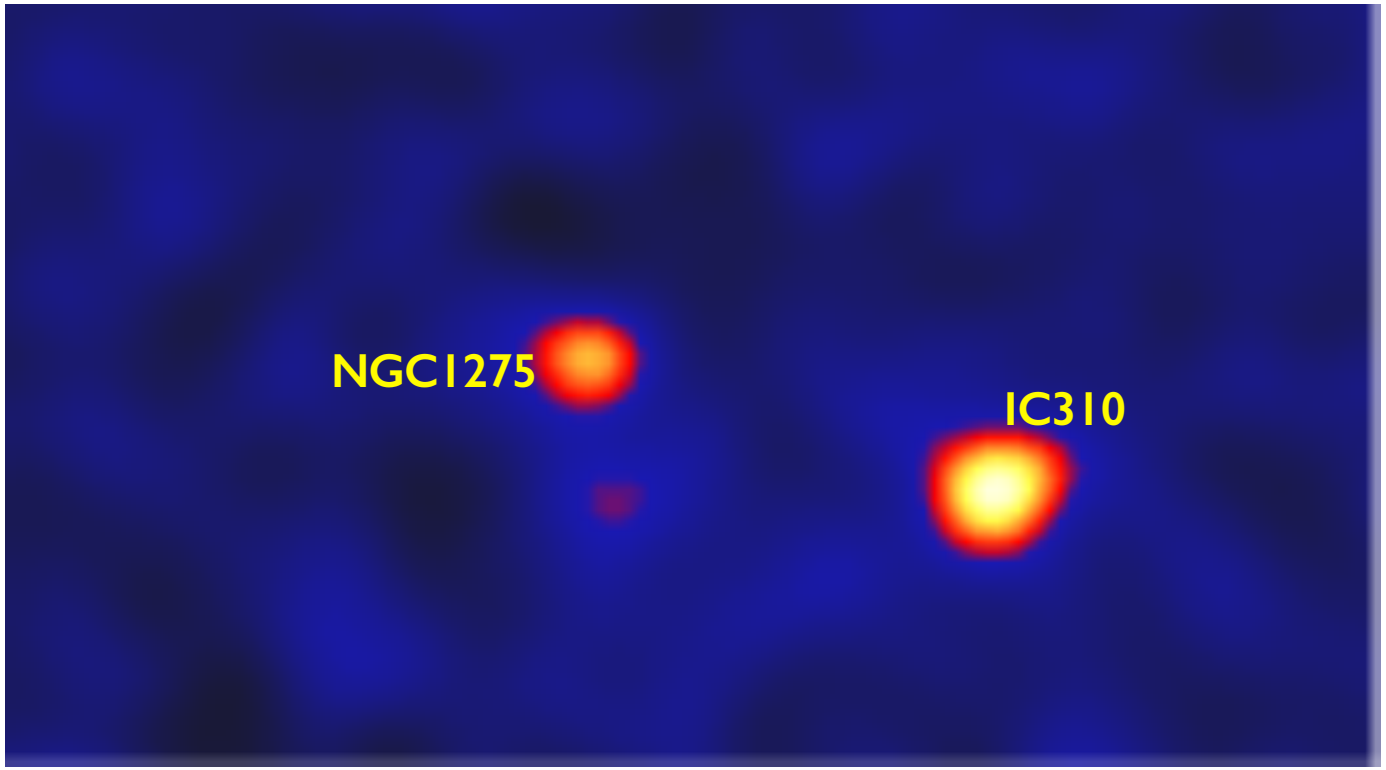
- MAGIC: Segue 1 (158 h) and Fermi-LAT: 15 dwarfs (6 years, Pass8)

- **Coherent limits** between 10 GeV and 100 TeV (widest range so far explored)
  - Annihilation limits for DM particle masses below O(1) TeV dominated by Fermi-LAT, above O(1) TeV by MAGIC (and IACTs, in general)
- **Effective combination (2x stronger constraints) in the range 300-500 GeV**

- *Possible to add additional indirect detection instruments (a call was raised by MAGIC)*

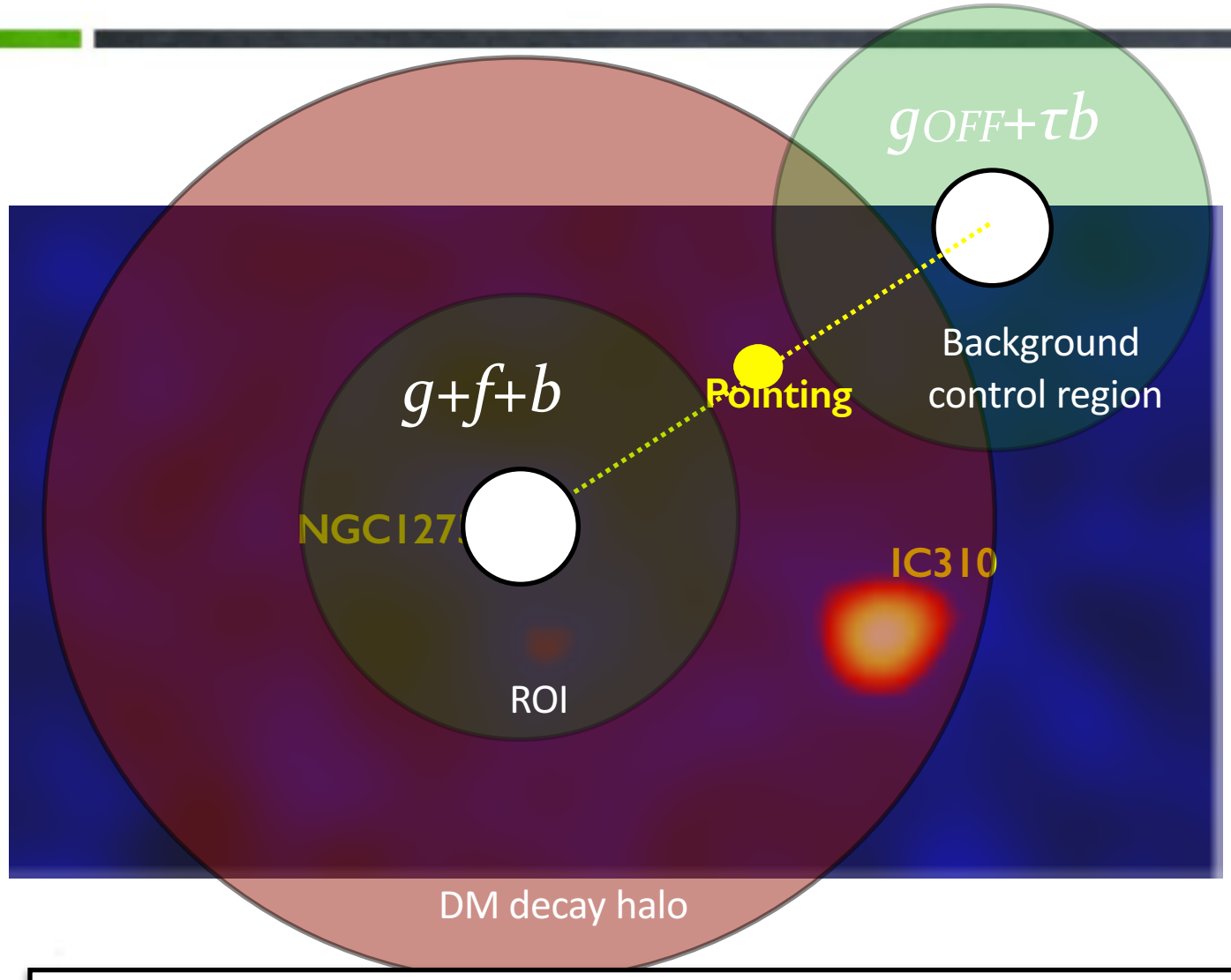


#2 Search for decaying DM in the Perseus Galaxy Cluster



- The Perseus galaxy cluster is a cool-core cluster expected to be emitting gamma-rays from accelerated hadrons
- MAGIC performed a deep scan during 2012-2016: 300 h
- Clusters are hardly predictable for the DM annihilating case
  - Uncertain baryon feedback
  - Possible large contributions of substructures
- MAGIC is investigating **its DM decaying** content

Non trivial reconstruction



- The DM decay halo is extended
- A Region of Interest is selected
- The central emission from NGC1275 is excluded
- A background control region is defined
- The likelihood function is built

$$\mathcal{L}(g(\tau_{DM}); f, b, g_{OFF}, \nu | N_{ON}, N_{OFF}) \sim \frac{(g(\tau_{DM}) + f + b)^{N_{ON}}}{N_{ON}!} e^{-(g(\tau_{DM})+f+b)} \times \frac{(\tau b + g_{OFF})^{N_{OFF}}}{N_{OFF}!} e^{-(\tau b + g_{OFF})}$$

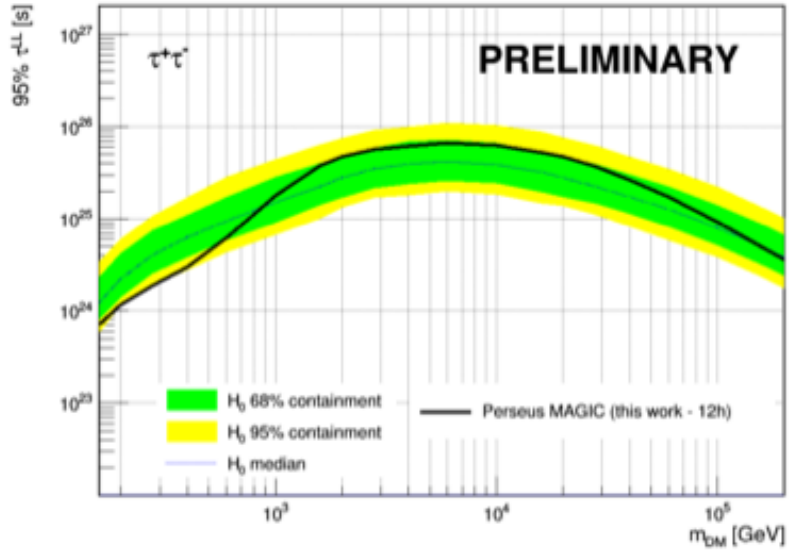
→ For each E bin → binned likelihood

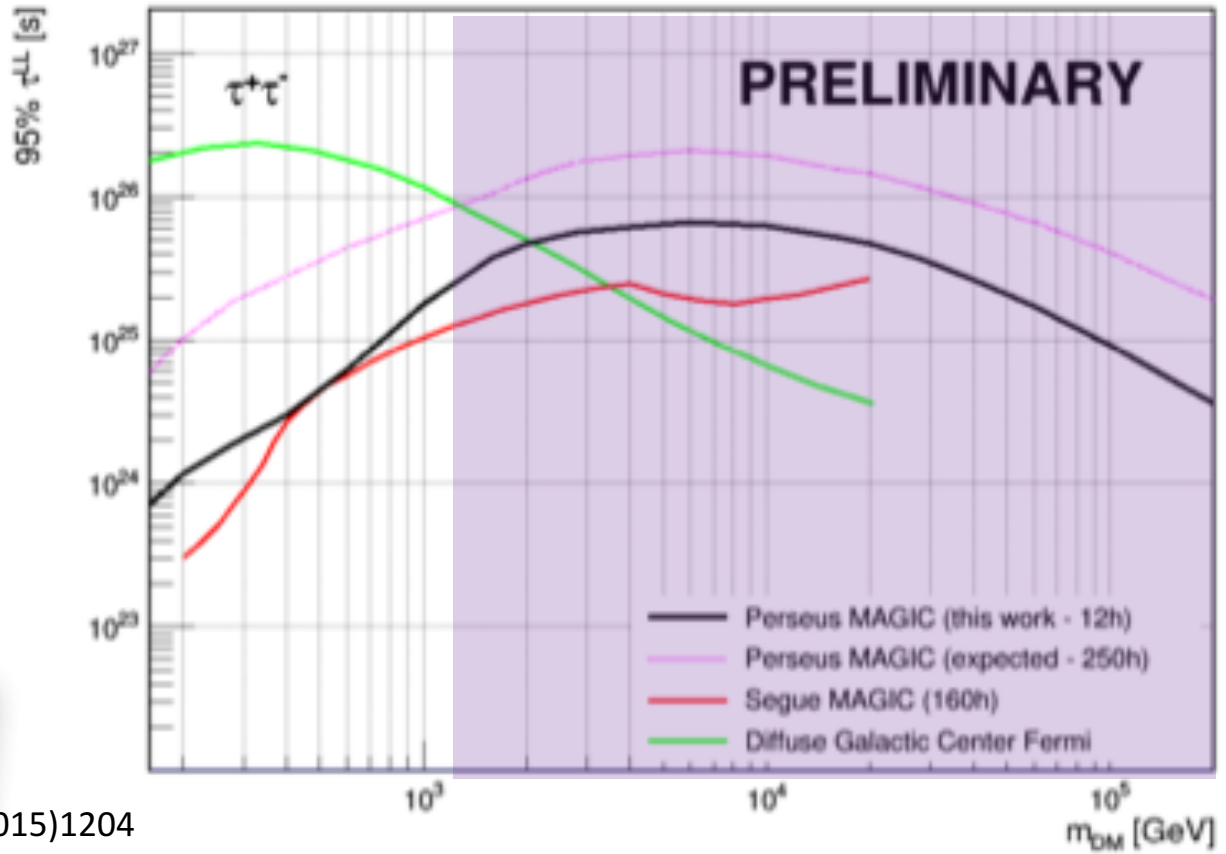
Decaying DM preliminary results

- Methodology checked on 12h of data in Palacio et al. PoS (ICRC2015)1204
- Sensitivity up to ~8×10^{25} s: Better results than for 160h with Segue 1
- With whole data sample (~200 h), sensitivity will improve by a factor ~4

- **Most constraining decaying DM searches at the TeV**

Best limits from dwarfs in high-mass range

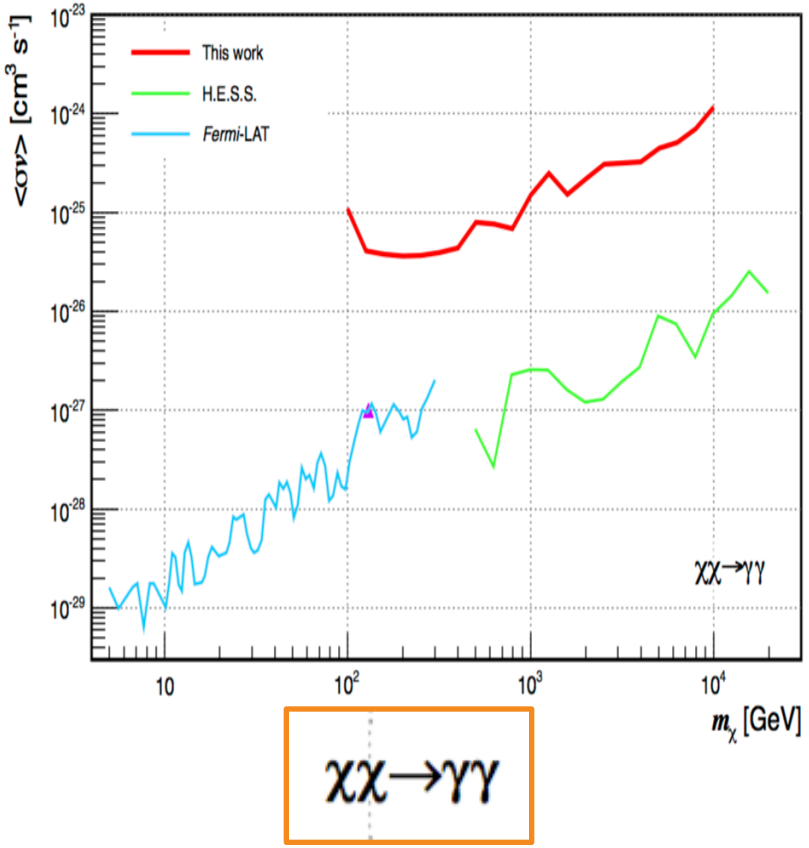




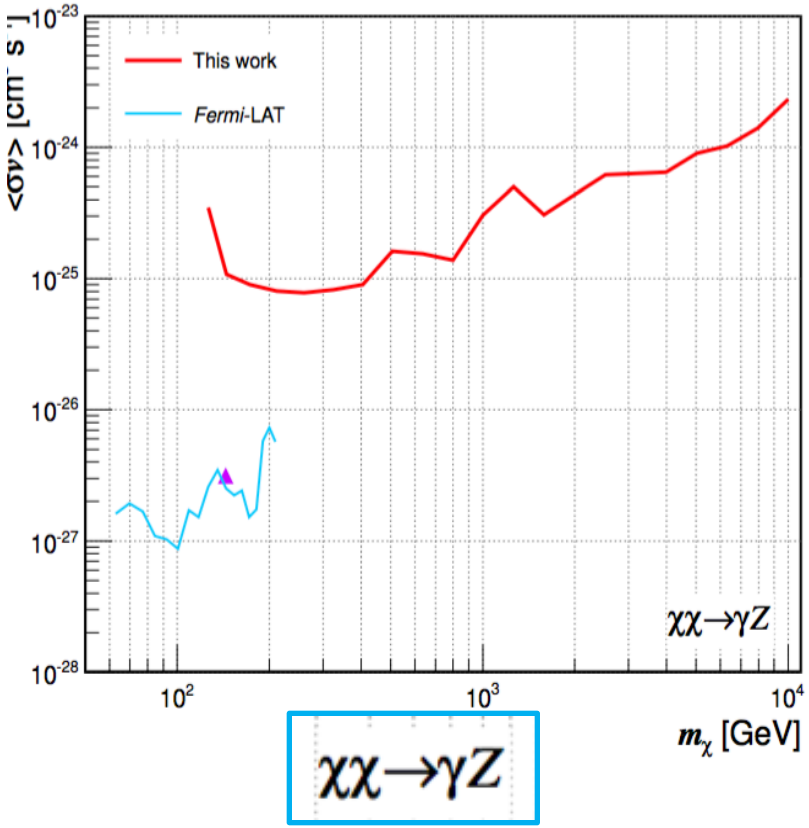
Palacio et al. PoS(ICRC2015)1204

#3 Lines

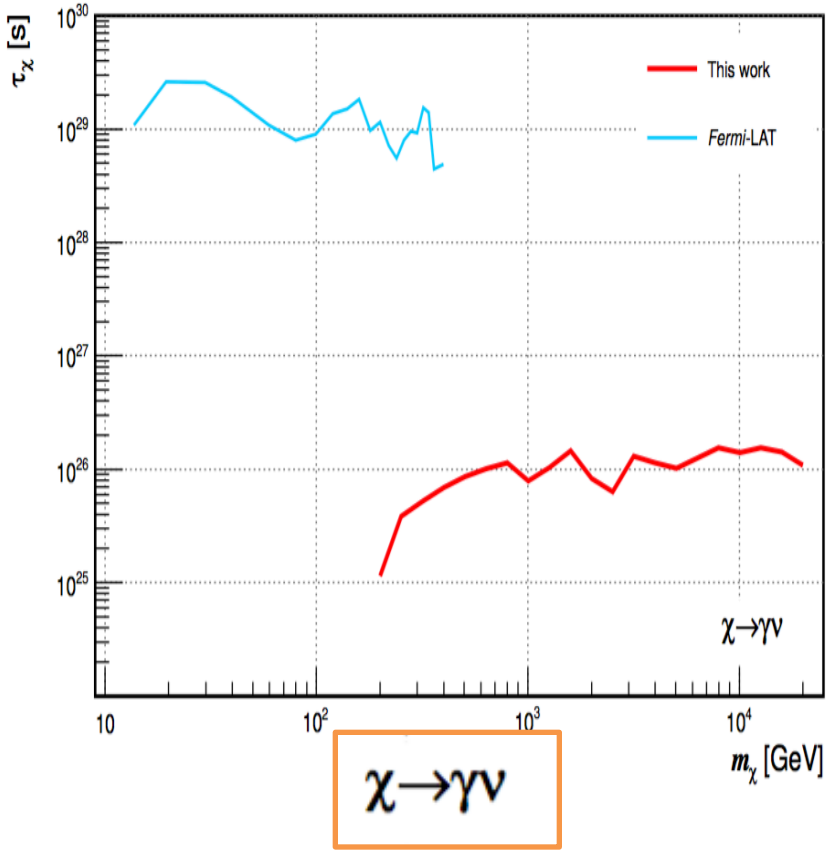
MAGIC, JCAP 02 (2014) 008



$\chi\chi\to\gamma\gamma$



$\chi\chi\to\gamma Z$

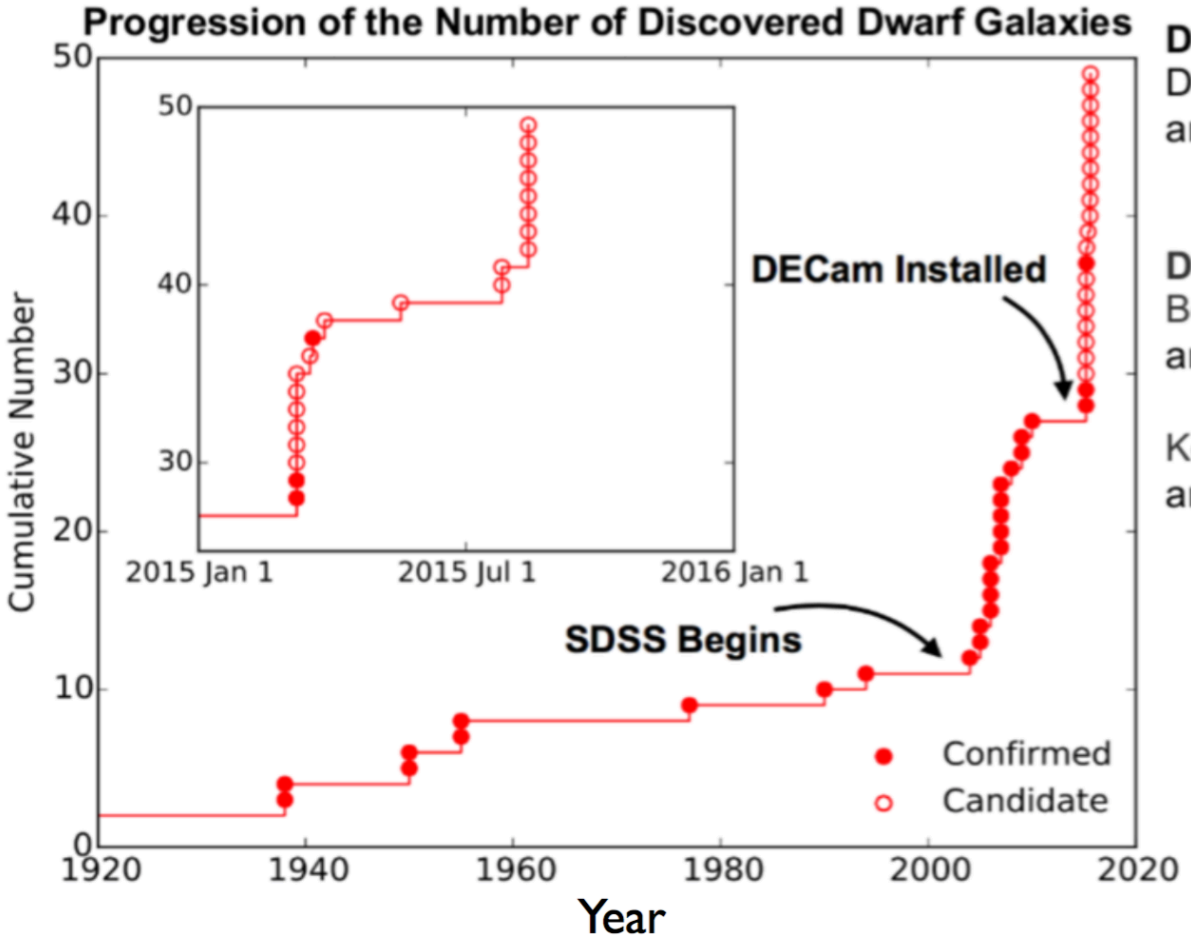


$\chi\to\gamma\nu$

- Limits were produced for narrow-band emissions (smoking guns) with 160 hours of Segue1

A look ahead

MAGIC program



DES Year 2 Data:
Drlica-Wagner+,
arXiv:1508.03622

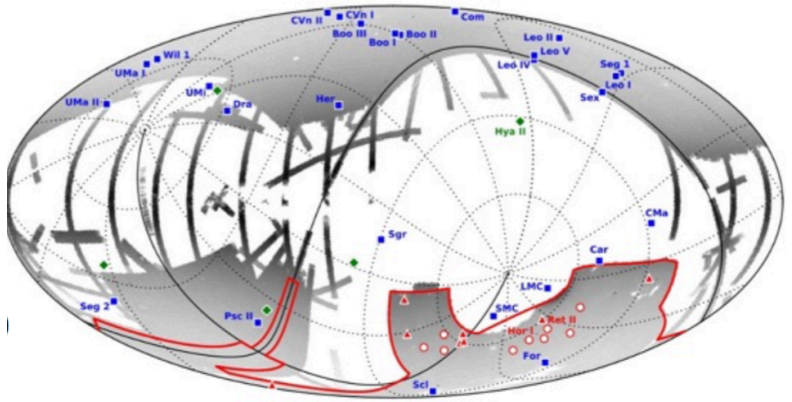
DES Year 1 Data:
Bechtol+:
arXiv:1503.02584

Koposov+:
arXiv:1503.02079

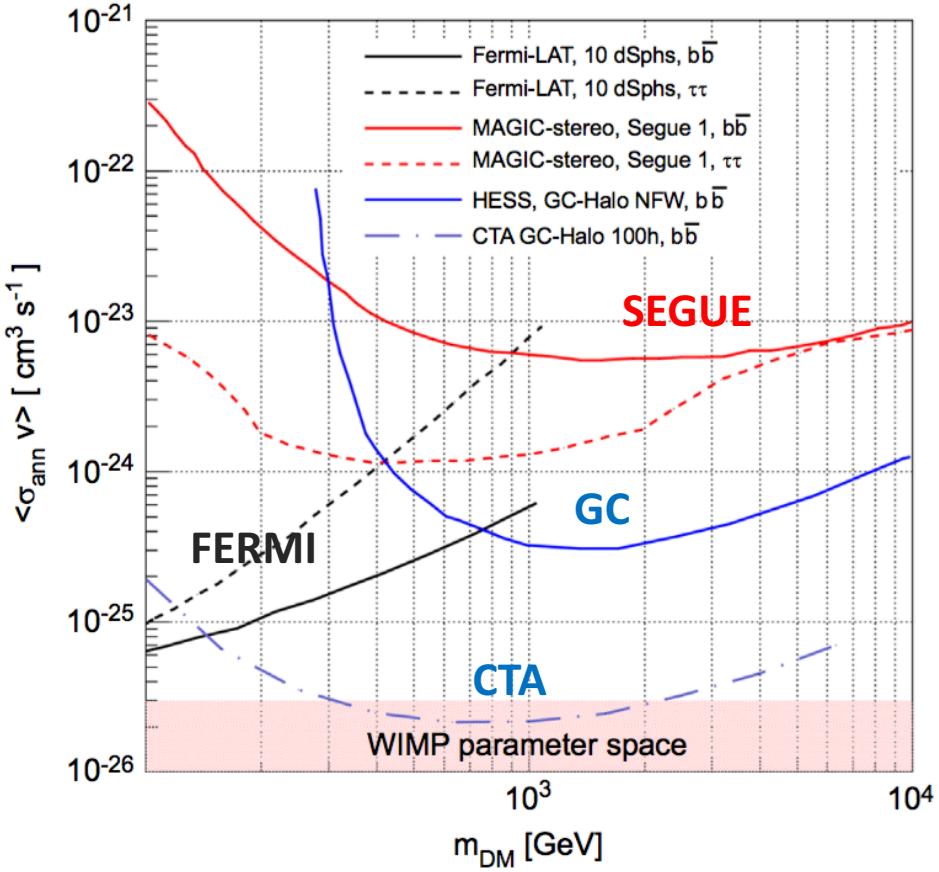
New instruments are discovering new dSphs: some very promising.

Expect results from MAGIC!

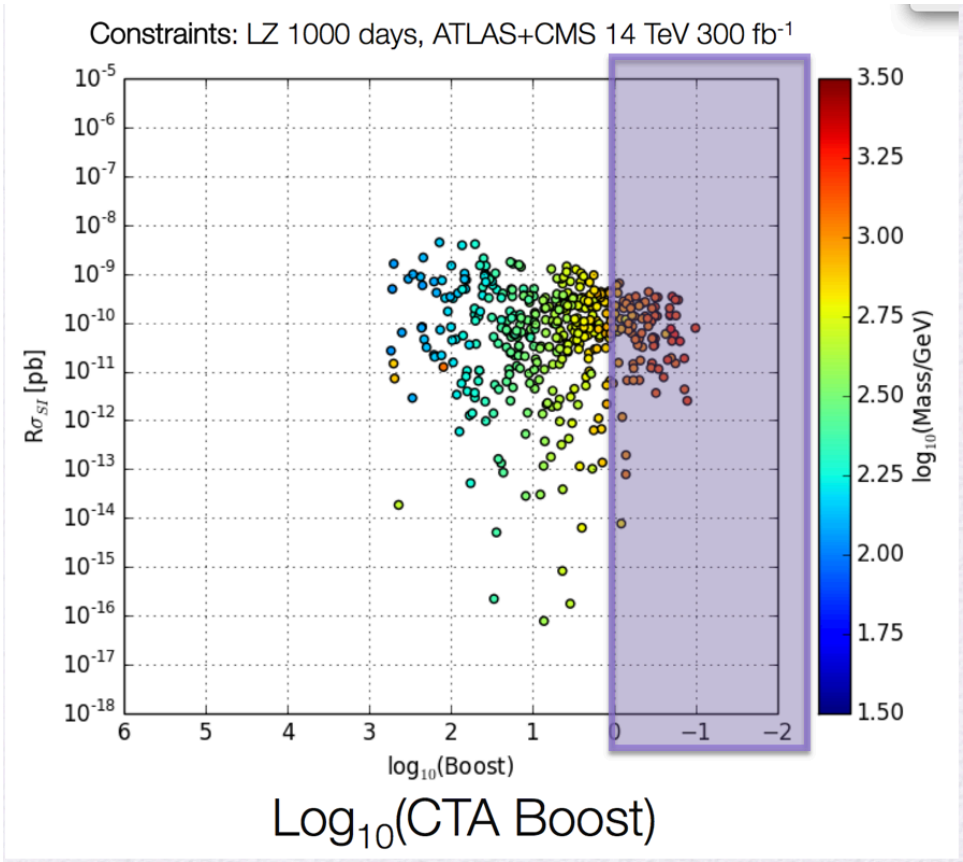
Catching up with Λ_{CDM} predictions:
until 2004: 9 “classical”
2005: +15 (SDSS)
2015: +>20 (DES + Pan-Starrs)



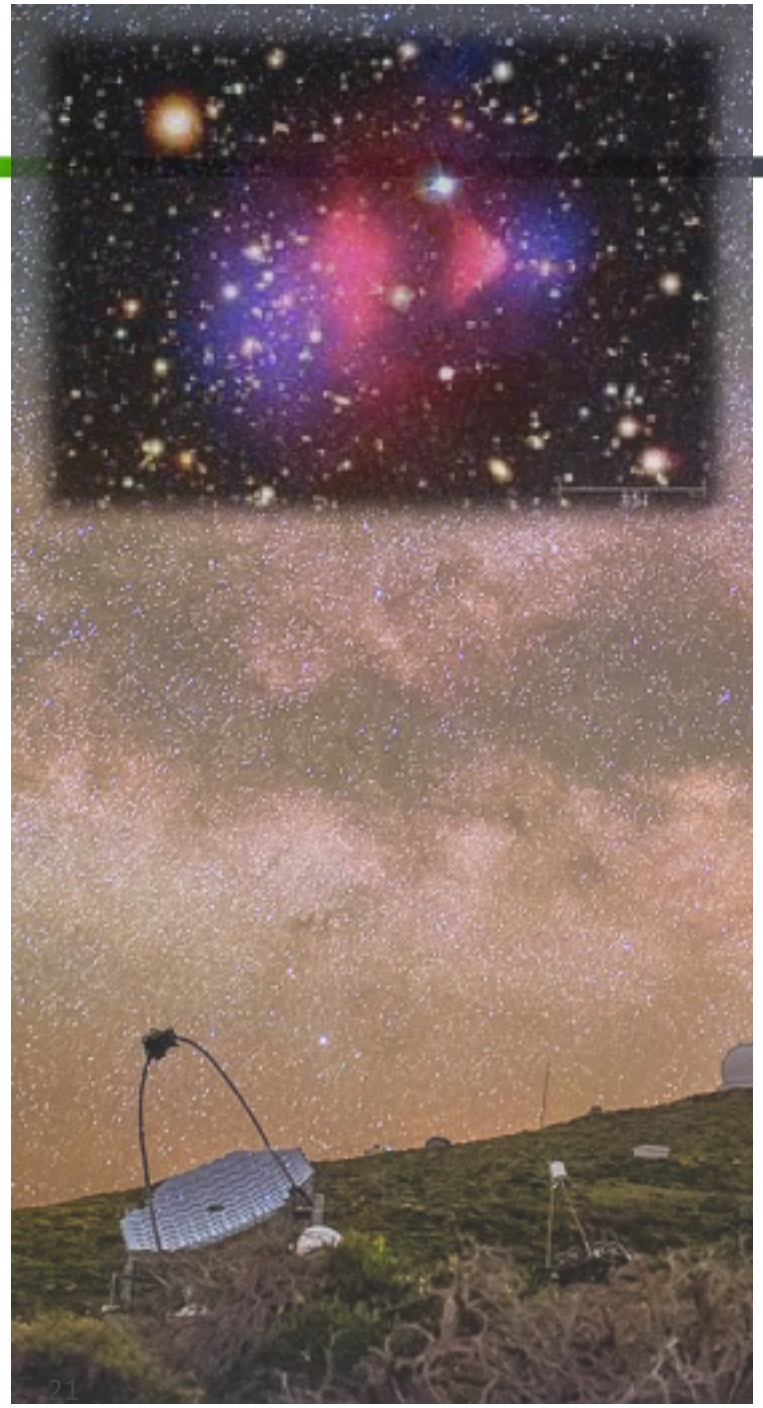
MAGIC results into the times of CTA



1/ The galactic center results are more slippery, because the **core-cusp** effect can be very relevant there. For some years at least dSph results are robust



2/ Even after LHC-14 and LZ, still space left in DM space, **if DM is above TeV**, IACTs are probably the sole player



Conclusions

- **MAGIC is hunting DM** for a decade now, at first with moderate effort, and now **with strong commitment**
- Chances of detection are hard to claim: DM can be round the corner or out of reach, no way to know it now
- MAGIC aims at providing the **strongest legacy before CTA** with well-performing statistical treatment that allow **multiple-target combination and multiple-instruments combination**
- CTA will improve by a factor of 10 the sensitivity and decrease the energy threshold, this is good for DM!
  - ***GC will be sampled for long****: good but robustness of results will be moderate* unless our knowledge improves on the baryon-DM feedback there
  - ***CTA may not invest time in the early years toward dSphs*****:** MAGIC results will remain the strongest at the TeV for some time

therefore **MAGIC legacy could survive for about a decade**