15 years of Dark Matter searches with MAGIC

Michele Doro*

*University and INFN Padova michele.doro@pd.infn.it

J. Aleksic, J. A. Barrio, A. Biland, A. Dominguez, D. Elsaesser, M. Gaug, P. Giammaria, S. Lombardi, C. Maggio, M. Martinez, D. Nieto, D. Ninci, S. Paiano, J. Palacio, F. Prada, M. Persic, J. Rico, M. Rissi, M. A. Sanchez-Conde, K. Satalecka, S. Stark, G. Vanzo, M. Vazquez, F. Zandanel

Thanks!

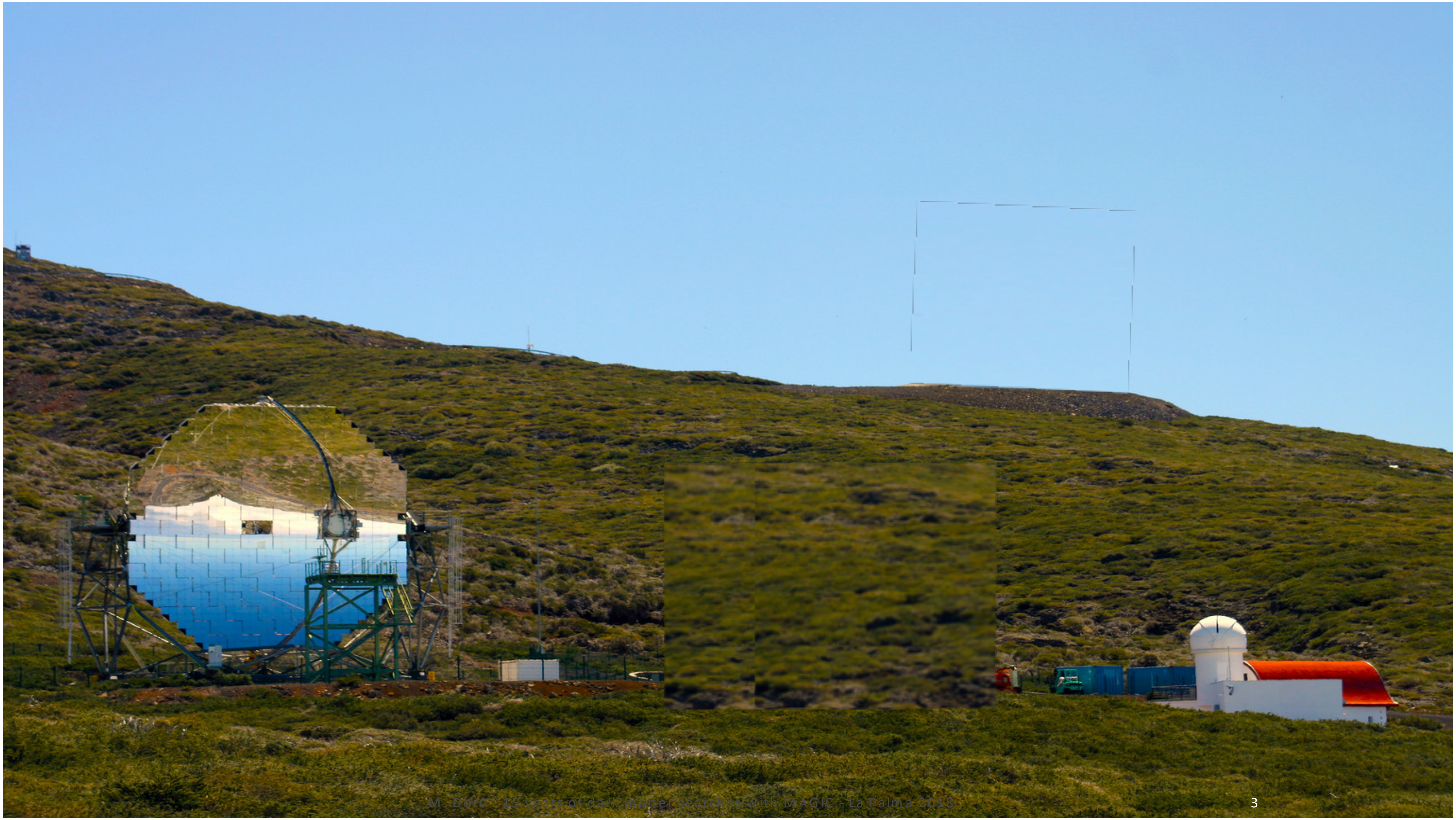
PHYSICAL REVIEW D **72,** 103517 (2005)

New signature of dark matter annihilations: Gamma rays from intermediate-mass black holes

Gianfranco Bertone,[1] Andrew R. Zentner,[2] and Joseph Silk[3]
[1]*Particle Astrophysics Center, Fermi National Accelerator Laboratory, Batavia, Illinois 60510-0500, USA*
[2]*Kavli Institute for Cosmological Physics and Department of Astronomy and Astrophysics, The University of Chicago, Chicago, Illinois 60637, USA*
[3]*Astrophysics, Denys Wilkinson Building, Keble Road, Oxford OX1 3RH, United Kingdom*
(Received 21 September 2005; published 16 November 2005)

We study the prospects for detecting gamma rays from dark matter (DM) annihilations in enhancements of the DM density (mini-spikes) around intermediate-mass black holes (IMBH) with masses in the range $10^2 \lesssim M/M_\odot \lesssim 10^6$. Focusing on two different IMBH formation scenarios, we show that, for typical values of mass and cross section of common DM candidates, mini-spikes, produced by the adiabatic growth of DM around pregalactic IMBHs, would be bright sources of gamma rays, which could be easily detected with large field-of-view gamma-ray experiments such as GLAST, and further studied with smaller field-of-view, larger-area experiments like Air Cherenkov Telescopes CANGAROO, HESS, MAGIC, and VERITAS. The detection of many gamma-ray sources not associated with a luminous component of the Local Group, and with identical cutoffs in their energy spectra at the mass of the DM particle, would provide a potential smoking-gun signature of DM annihilations and shed new light on the nature of intermediate and supermassive black holes.

DOI: 10.1103/PhysRevD.72.103517 PACS numbers: 95.35.+d, 97.60.Lf, 98.62.Js, 98.70.Sa



CACTUS claim

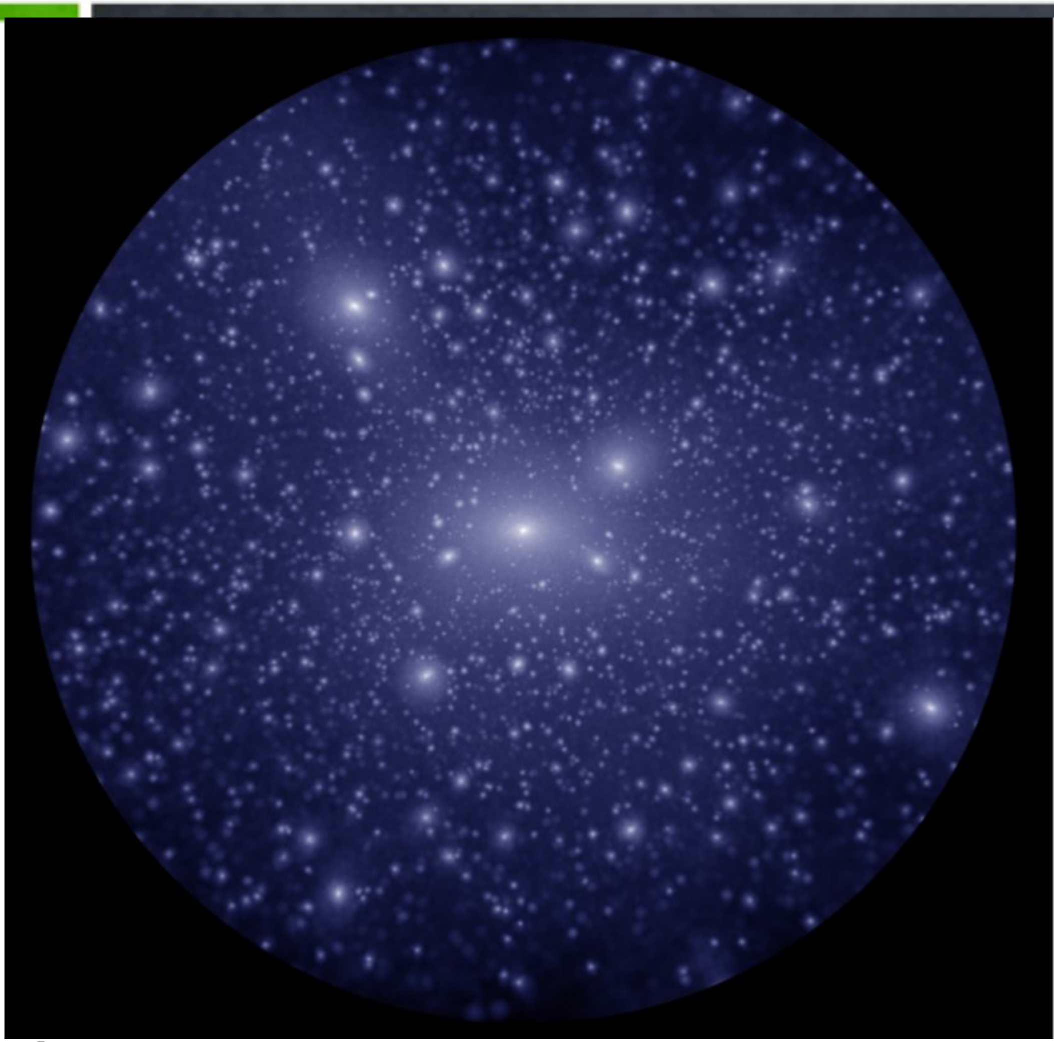
TABLE II. The approximate energy distribution of events reported by CACTUS compared to the prediction from various annihilating dark matter scenarios. The CACTUS observations appear to be consistent with a ~500 GeV dark matter particle annihilating to $b\bar{b}$, a ~300 GeV dark matter particle annihilating to W^+W^-, or a ~200 GeV dark matter particle annihilating to $\tau^+\tau^-$. In the last column, the number of events which EGRET should have seen is given for each case.

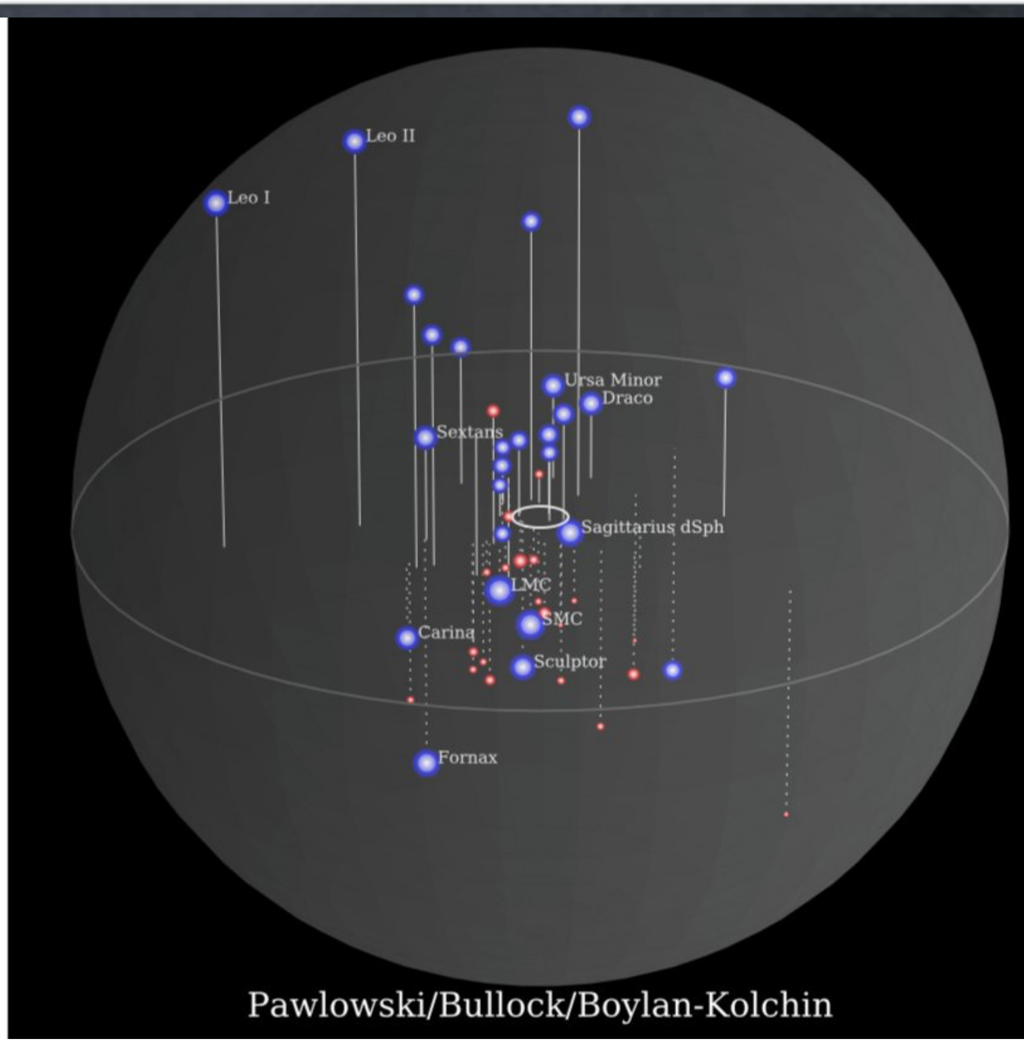
	Total	>100 GeV	>125 GeV	EGRET
CACTUS observation	30000	7000	4000	–
600 GeV, $b\bar{b}$	30000	9000	5000	290
500 GeV, $b\bar{b}$	30000	7700	3900	400
400 GeV, $b\bar{b}$	30000	6000	2700	630
400 GeV, W^+W^-	30000	9200	5100	280
300 GeV, W^+W^-	30000	7100	3500	470
200 GeV, W^+W^-	30000	4000	1300	1100
300 GeV, $\tau^+\tau^-$	30000	15000	9500	2.8
200 GeV, $\tau^+\tau^-$	30000	9200	4200	7.2
150 GeV, $\tau^+\tau^-$	30000	5000	1300	16

- CACTUS (Converted Atmospheric Cherenkov Telescope Using Solar-2) was a ACT located in California.
- It was originally a solar power plant called Solar Two, converted to an observatory in 2001, installing a 6 meter secondary that imaged the field onto an array of 80 PMTs.

Bergstrom Hooper 2015

Dwarf Spheroidal Galaxies (dSphs)



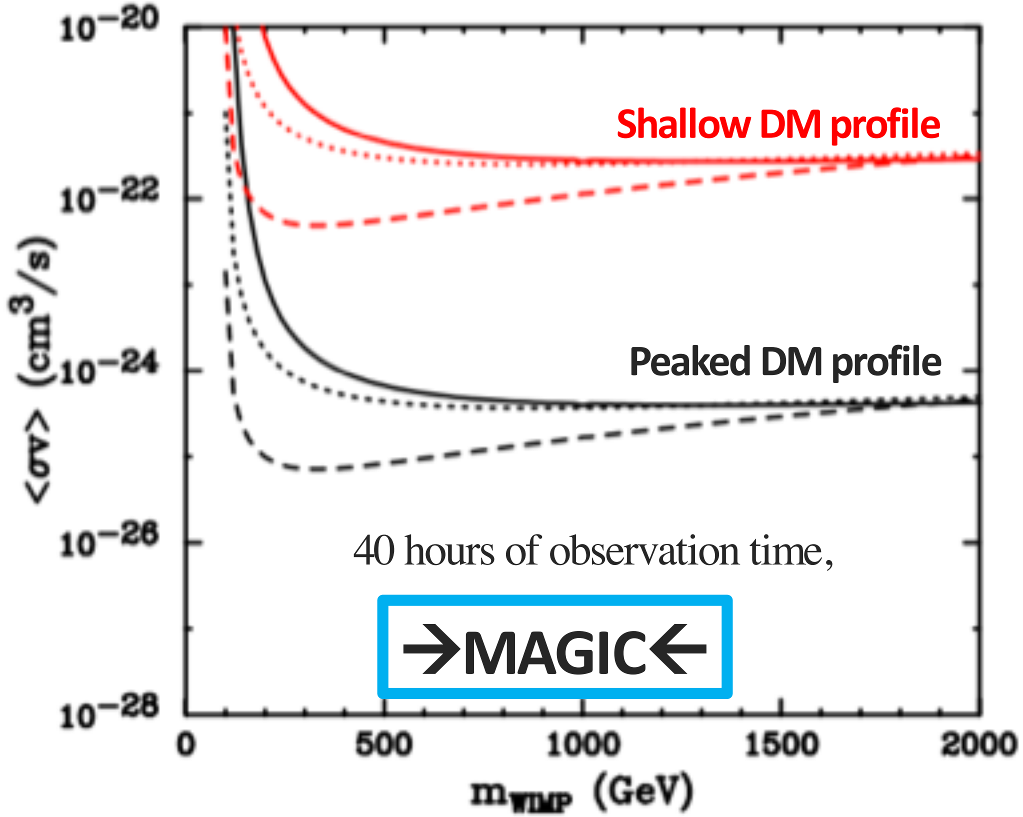


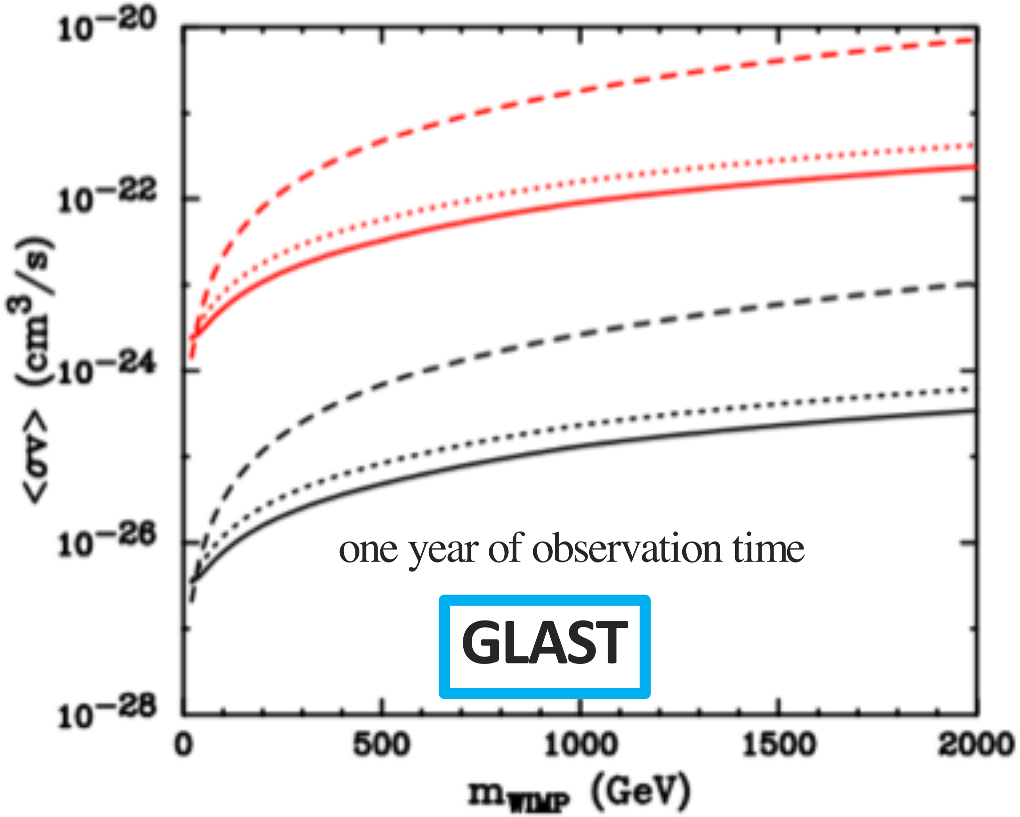
12 years ago

PHYSICAL REVIEW D **73**, 063510 (2006)

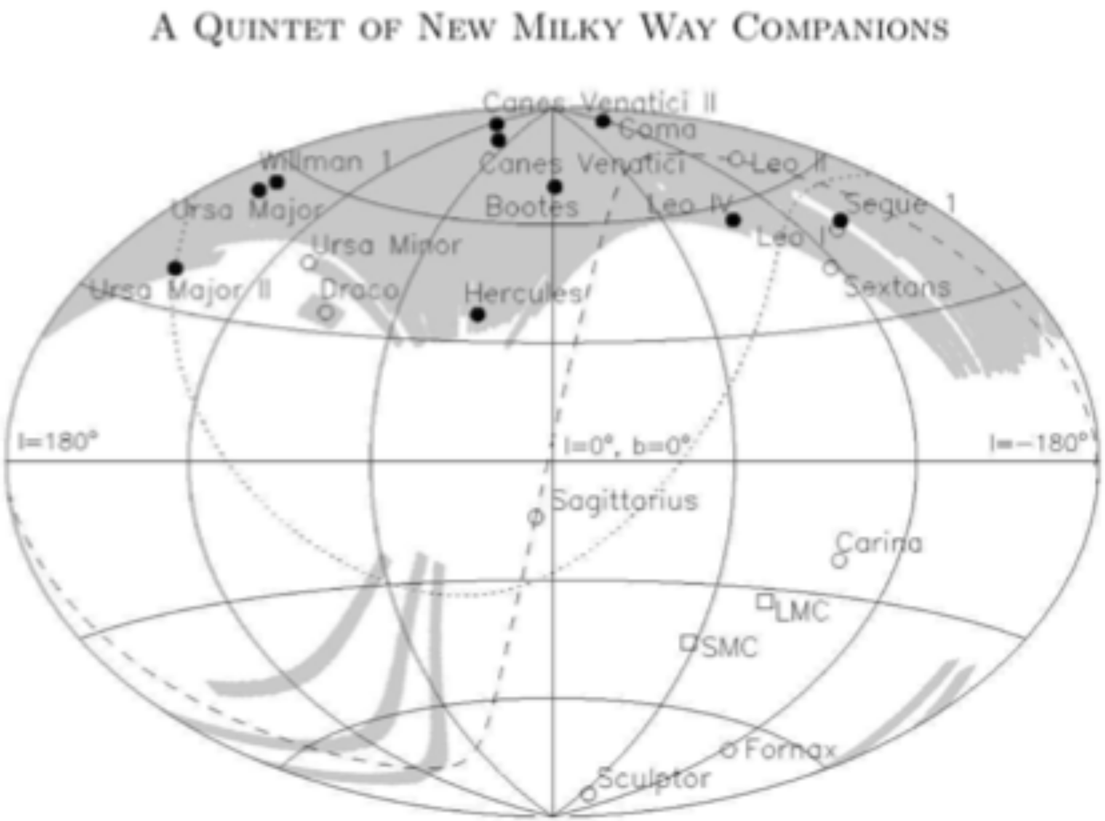
Dark matter and gamma rays from Draco: MAGIC, GLAST and CACTUS

Lars Bergström[1] and Dan Hooper[2]

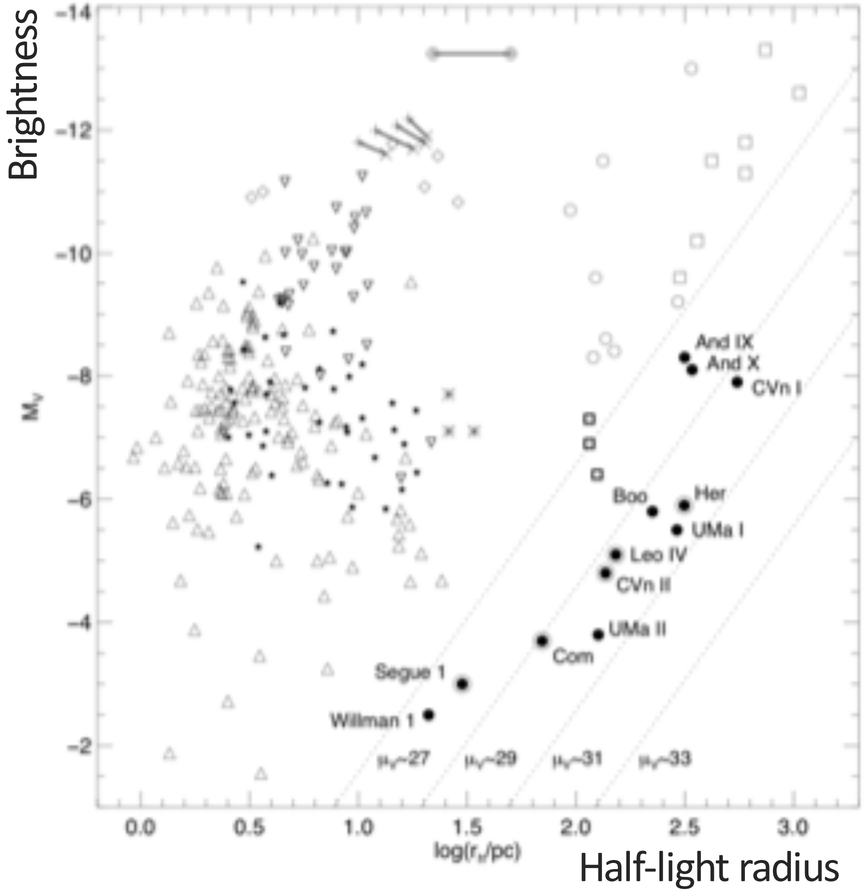




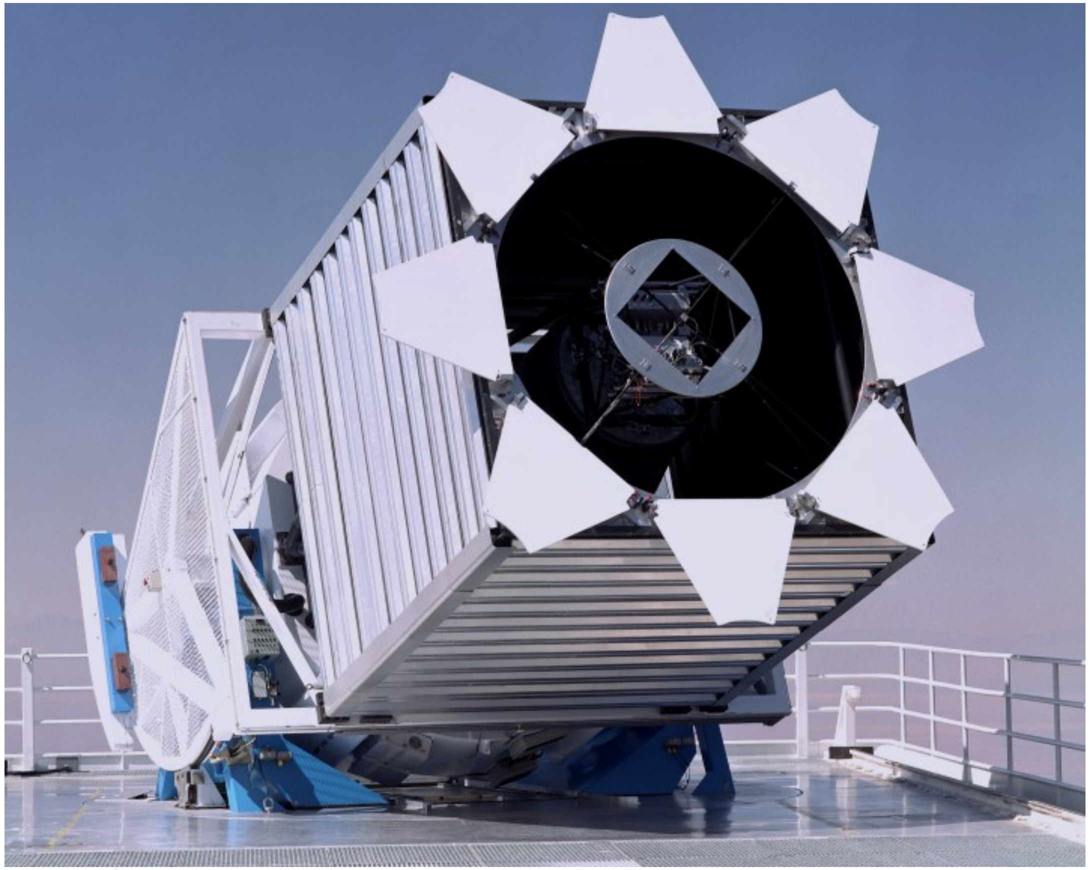
Classical and Ultra-faint dwarf spheroidal galaxies

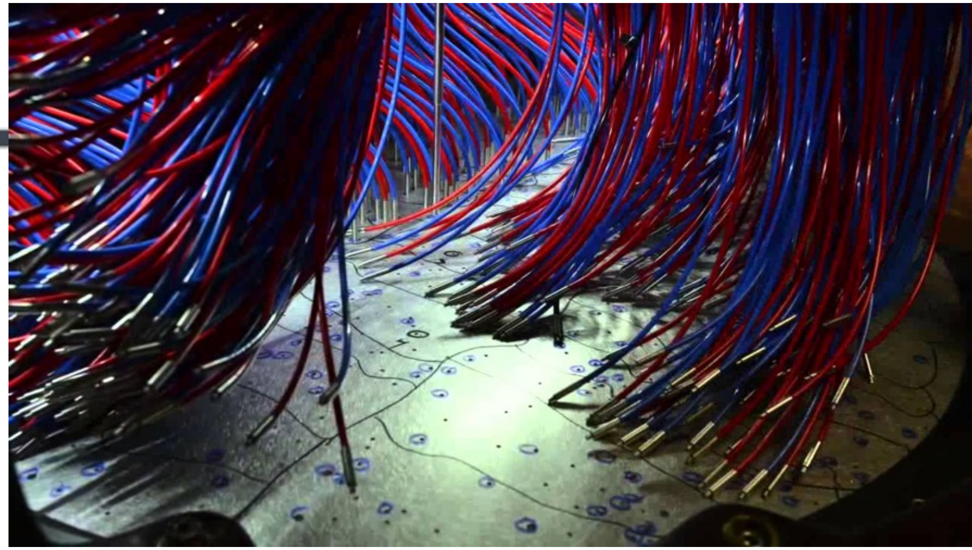


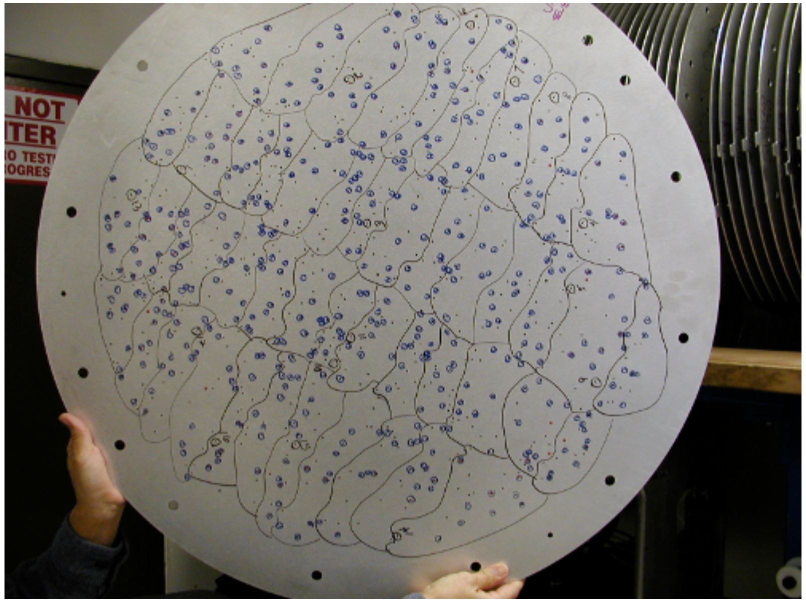
Belokurov+ (SDSS) Astrophys.J. 654 (2007) 897-906



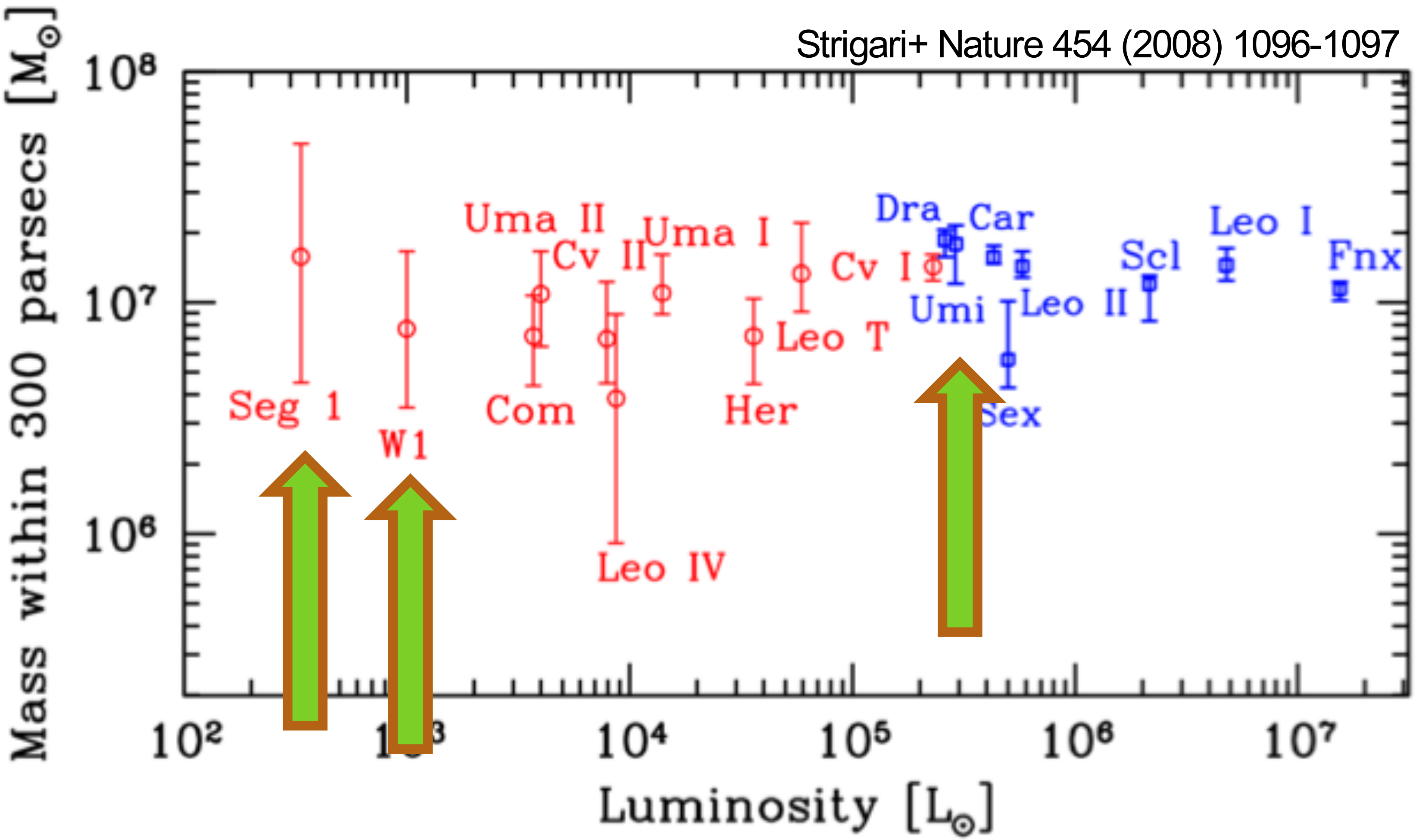
Sloan Digital Sky Survey







Excitement for the ultra-faints



Crazy for dSphs

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

Target	Year	Time	Experiment
Dwarf Satellite Galaxies			
Draco	2003		Whipple
	2007		MAGIC
	2007		VERITAS
Ursa Minor	2003		Whipple
	2007		VERITAS
Sagittarius	2006		H.E.S.S.
Canis Major	2007		H.E.S.S.
Willman 1	2007		VERITAS
	2008		MAGIC
Sculptor	2008		H.E.S.S.
Carina	2009		H.E.S.S.
	2012		H.E.S.S.
Boötes	2009		VERITAS
Coma Berenices	2013		H.E.S.S.
Fornax	2012?		H.E.S.S.

MD, NIM A 742 (2014)

Draco & Willman 1 with MAGIC

THE ASTROPHYSICAL JOURNAL, 679:428–431, 2008 May 20

7.8 h of data!

UPPER LIMIT FOR γ-RAY EMISSION ABOVE 140 GeV FROM THE DWARF SPHEROIDAL GALAXY DRACO

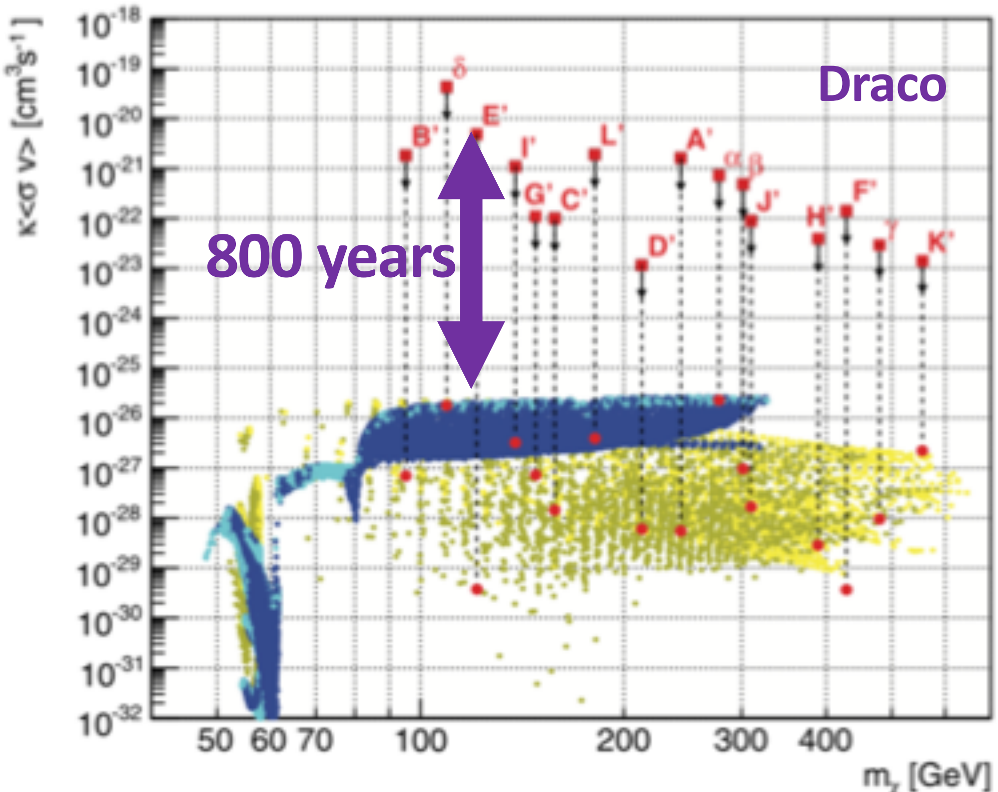
J. Albert,[1] E. Aliu,[2] H. Anderhub,[3] P. Antoranz,[4] M. Backes,[5] C. Baixeras,[6] J. A. Barrio,[4] H. Bartko,[7] D. Bastieri,[8] J. K. Becker,[5] W. Bednarek,[9] K. Berger,[1] C. Bigongiari,[8] A. Biland,[3] R. K. Bock,[7,8] P. Bordas,[10] V. Bosch-Ramon,[10] T. Bretz,[1] I. Britvitch,[3] M. Camara,[4] E. Carmona,[7] A. Chilingarian,[11] S. Commichau,[3] J. L. Contreras,[4] J. Cortina,[2] M. T. Costado,[12,13] V. Curtef,[5] …

THE ASTROPHYSICAL JOURNAL, 697:1299–1304, 2009 June 1

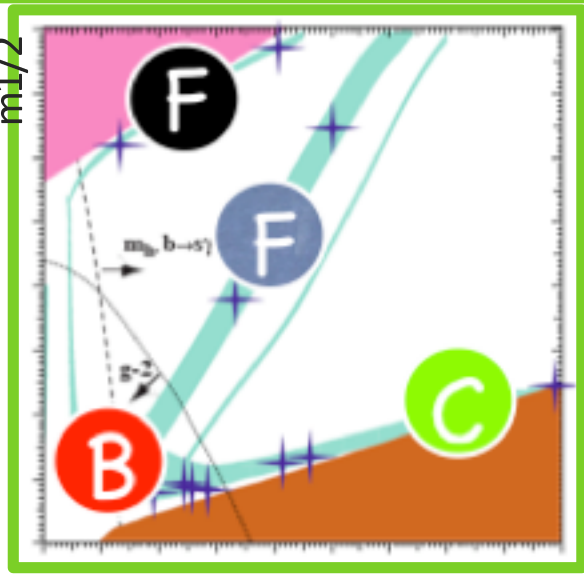
13.7 h of data!

UPPER LIMITS ON THE VHE GAMMA-RAY EMISSION FROM THE WILLMAN 1 SATELLITE GALAXY WITH THE MAGIC TELESCOPE

E. Aliu[1], H. Anderhub[2], L. A. Antonelli[3], P. Antoranz[4], M. Backes[5], C. Baixeras[6], S. Balestra[4], J. A. Barrio[4], H. Bartko[7], D. Bastieri[8], J. Becerra González[9], J. K. Becker[5], W. Bednarek[10], K. Berger[10], E. Bernardini[11], …



$$\chi = n_{11}\widetilde{B}^0 + n_{12}\widetilde{W}_3^0 + n_{13}\widetilde{H}_d^0 + n_{14}\widetilde{H}_u^0$$



Battaglia Eur.Phys.J.C33:273-296,2004

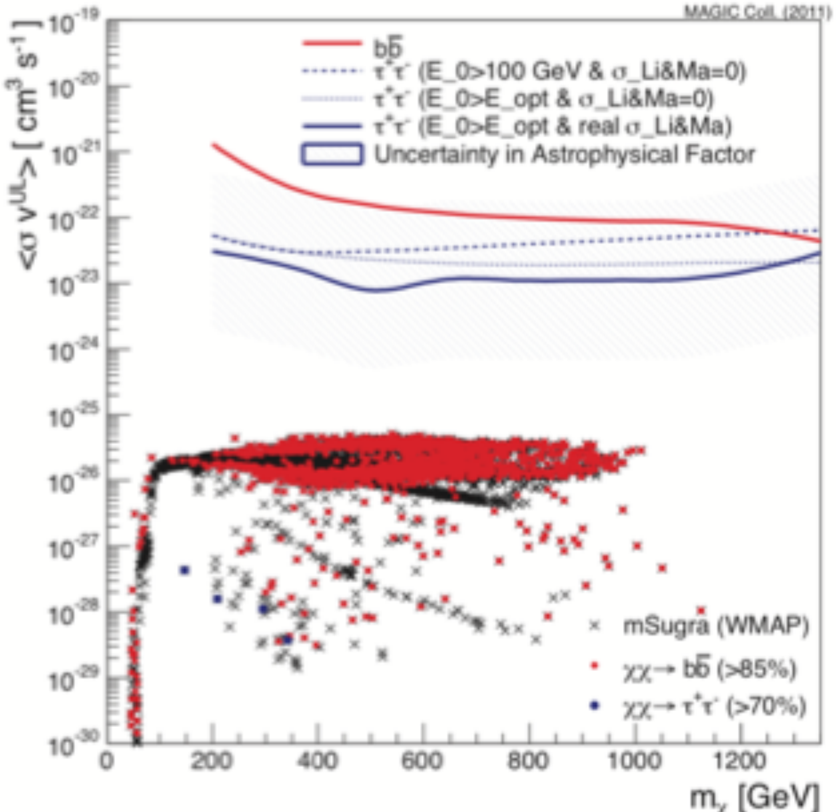
Then Segue1 came

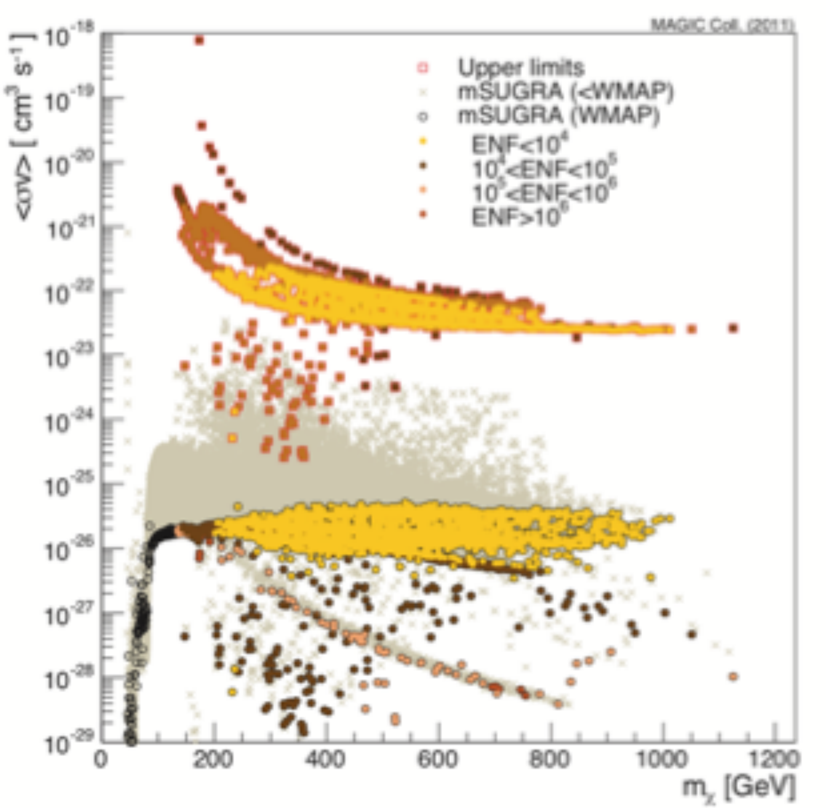
Journal of Cosmology and Astroparticle Physics

Searches for dark matter annihilation signatures in the Segue 1 satellite galaxy with the MAGIC-I telescope

MAGIC collaboration

Segue 1 performed by the MAGIC-I ground-based gamma-ray telescope between 2008 and 2009 for a total of **43.2 hours**.





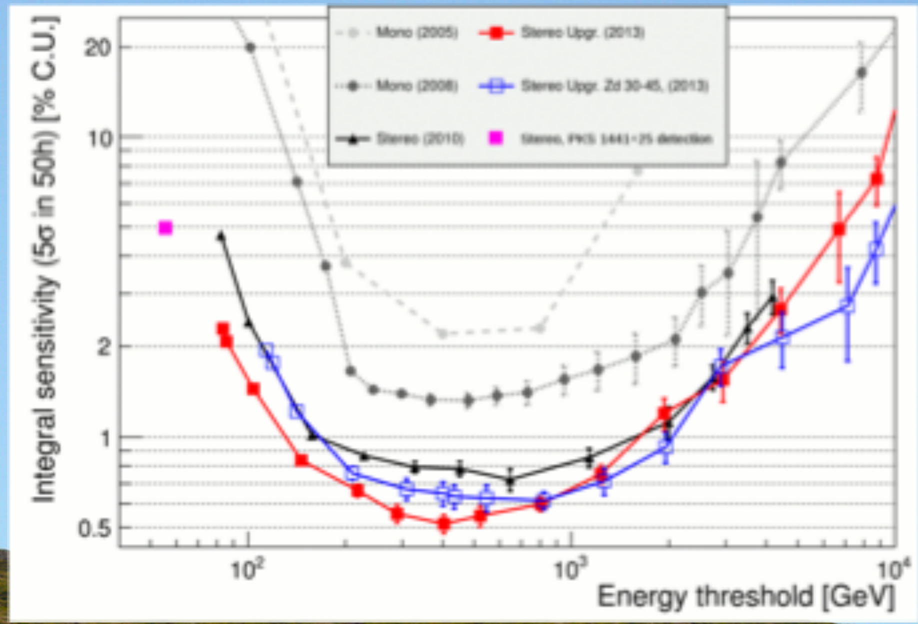
Custom scan ofthe parameter space with DarkSusy within mSugra

2009: Two (MAGIC) is better than one

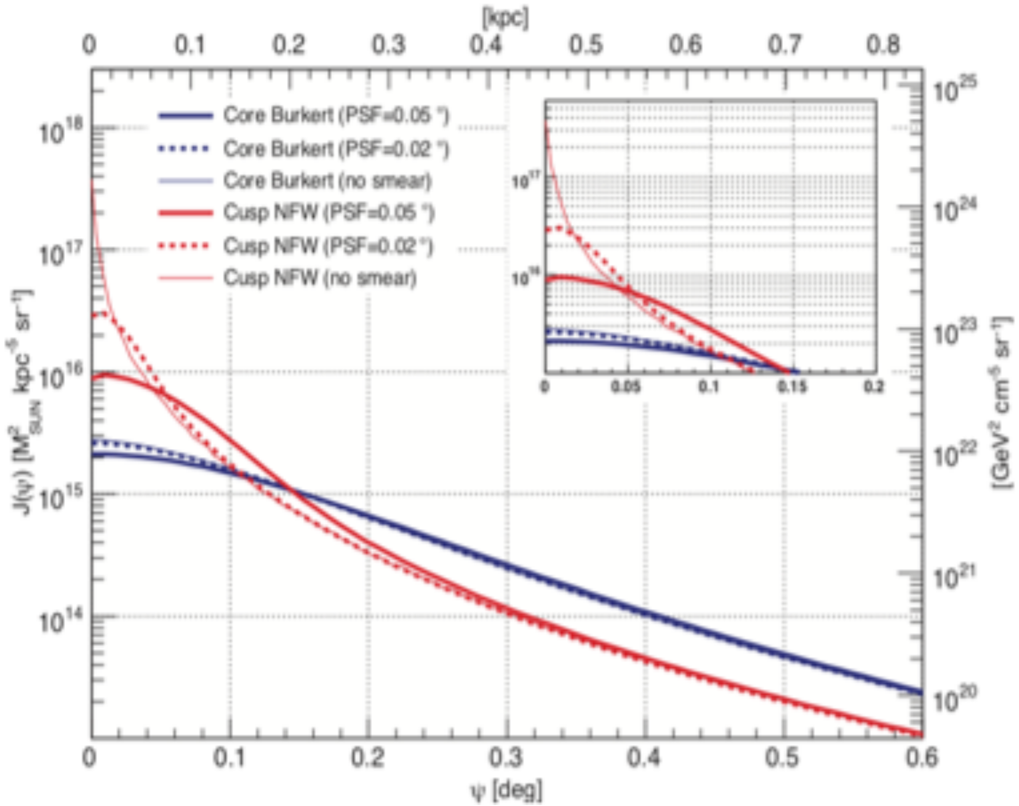
- **4-fold improvement in sensitivity**

↑16 times less needed observation time!

- **10-fold at lowest energies**



Some expectations for M-stereo: Draco and Willman1



$\tilde{J}$	Draco-Burkert	Draco-NFW	Willman 1-NFW
(GeV^2/cm^5)	3.84×10^{17}	4.71×10^{17}	9.55×10^{17}
($M_\odot$/kpc^5)	8.63×10^{10}	1.06×10^{11}	2.15×10^{11}

	Draco-NFW			
	MAGIC II		CTA_{30}	
I'	0.75	$(1.9{\cdot}10^4, 1.3{\cdot}10^4, \mathbf{2900})$	4.7	$(3100, 2100, \mathbf{490})$
J'	0.10	$(1.4{\cdot}10^5, 3.2{\cdot}10^4, \mathbf{7600})$	0.52	$(2.8{\cdot}10^4, 4900, \mathbf{1200})$
K'	7.0	$(2000, 2000, \mathbf{470})$	35	$(410, 260, \mathbf{61})$
F^*	0.45	$(3.1{\cdot}10^4, 1.6{\cdot}10^4, \mathbf{3800})$	1.1	$(1.3{\cdot}10^4, 2800, \mathbf{670})$
J^*	0.37	$(3.8{\cdot}10^4, 7400, \mathbf{1700})$	0.42	$(3.4{\cdot}10^4, 1200, \mathbf{290})$

Dark matter signals from Draco and Willman 1: prospects for MAGIC II and CTA Bringmann, MD, Fornasa JCAP01(2009)016

How many gamma-rays from DM annihilation/decay?

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

Particle Physics factor:

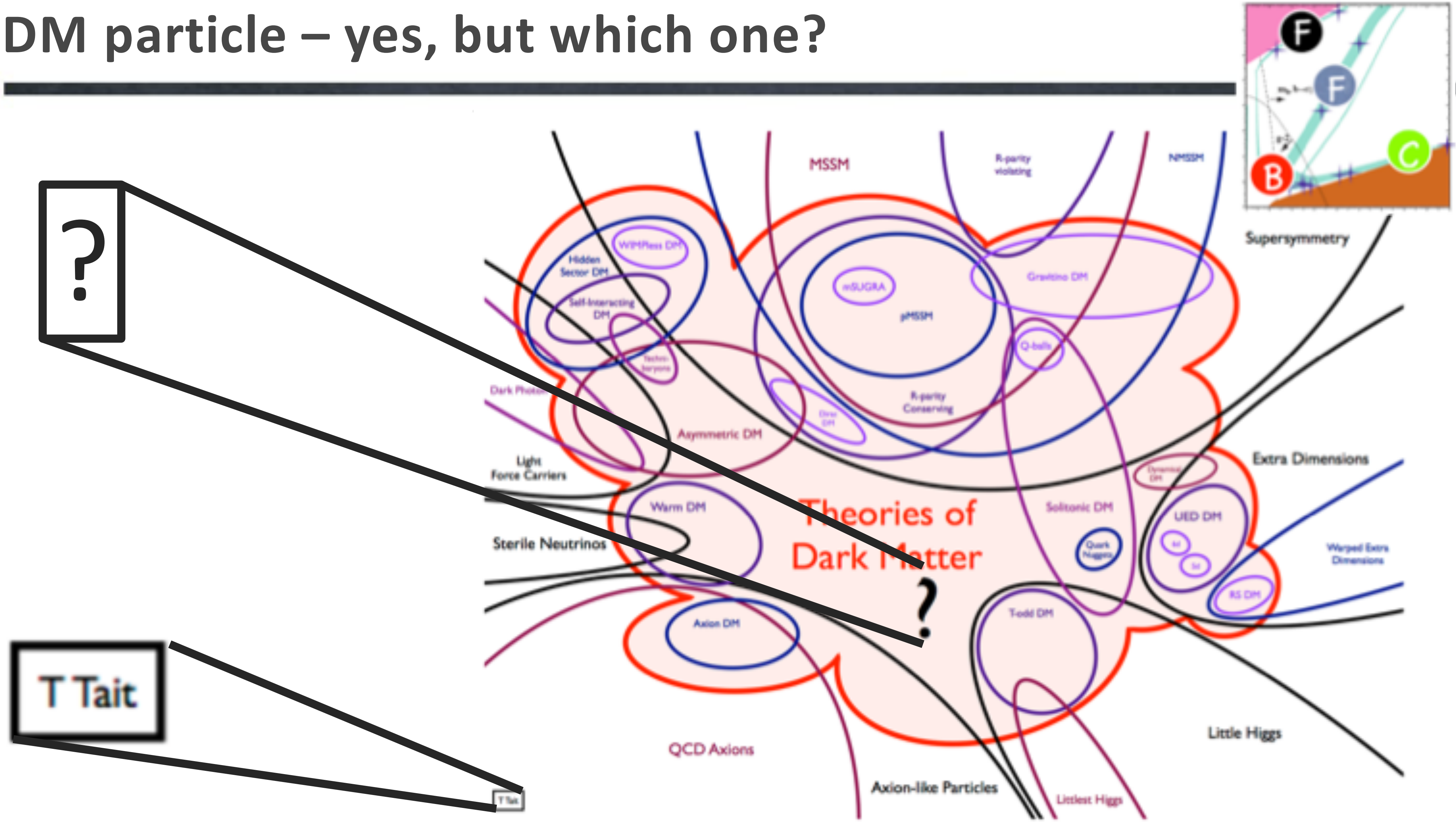
Annihilation: $$\frac{d\Phi^{\mathrm{PP}}}{dE'} = \frac{1}{4\pi}\frac{\langle\sigma_{\mathrm{ann}}v\rangle}{2m_\chi^2}\frac{dN}{dE'}$$

Decay: $$\frac{d\Phi^{\mathrm{PP}}}{dE'} = \frac{1}{4\pi\,\tau_\chi m_\chi}\frac{dN}{dE'}$$

Large uncertainties from Fund. Phys.
No target dependences
(straightforward stacking analysis)

- Hunting the **highest J-factor**
- Huge **uncertainties in the particle physics**

DM particle – yes, but which one?

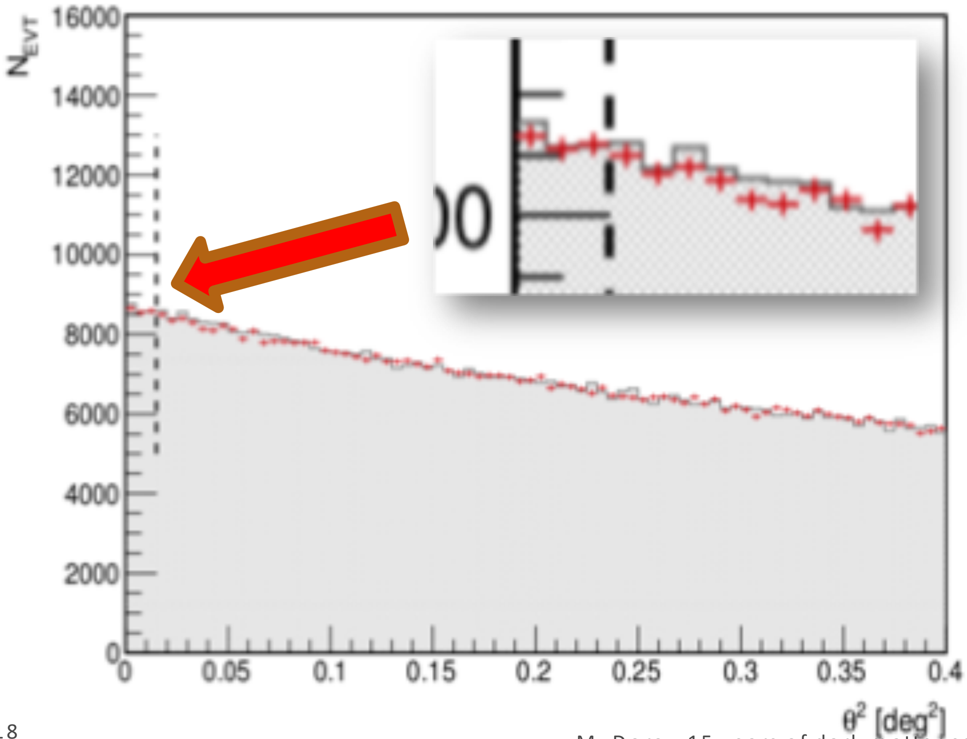


Segue1 with HiFi system

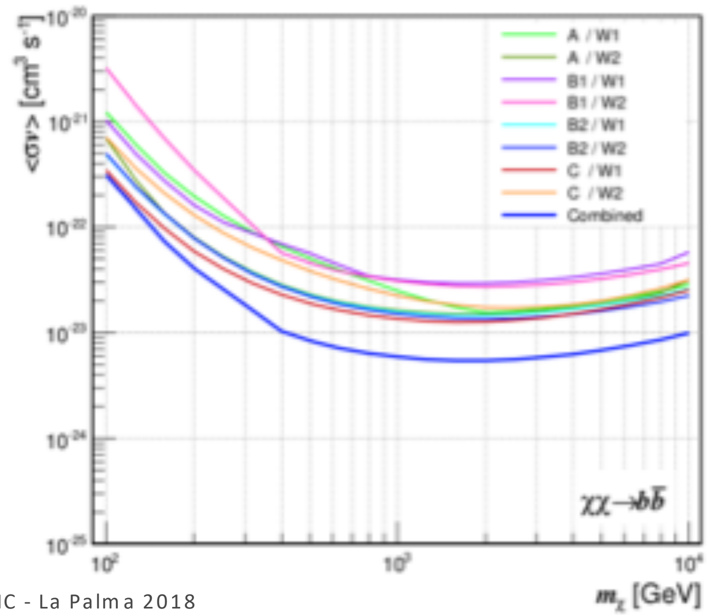
Journal of Cosmology and Astroparticle Physics
An IOP and SISSA journal

Optimized dark matter searches in deep observations of Segue 1 with MAGIC

Segue 1 with the MAGIC Telescopes, carried out between 2011 and 2013.
With almost 160 hours

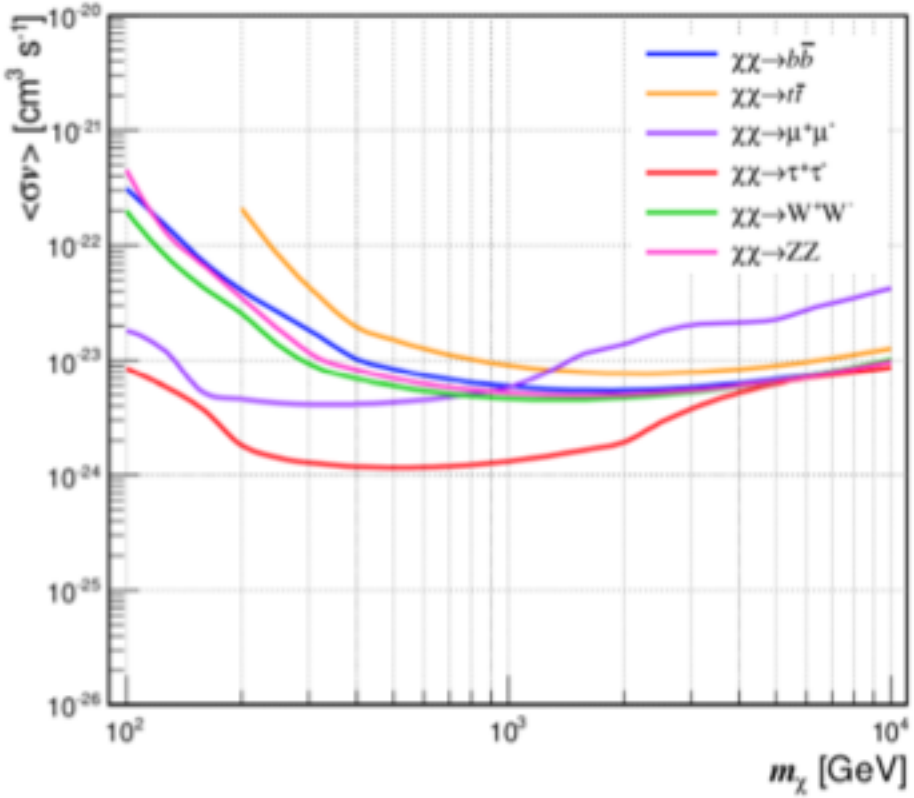


	Sample A	Sample B1	Sample B2	Sample C
Readout	DRS2	DRS4	DRS4	DRS4
MAGIC-I camera	old	old	old	new
Obs. period	Jan–May 2011	Jan–Feb 2012	Mar–May 2012	Nov 2012–Feb 2013
Obs. time [h]	64	24.28	59.77	55.05
Zd range [deg]	13–33.7	13–32.5	13–35.7	13–37
Az range [deg]	104.8–250.2	120.2–252.0	115.4–257.2	103.8–259.4

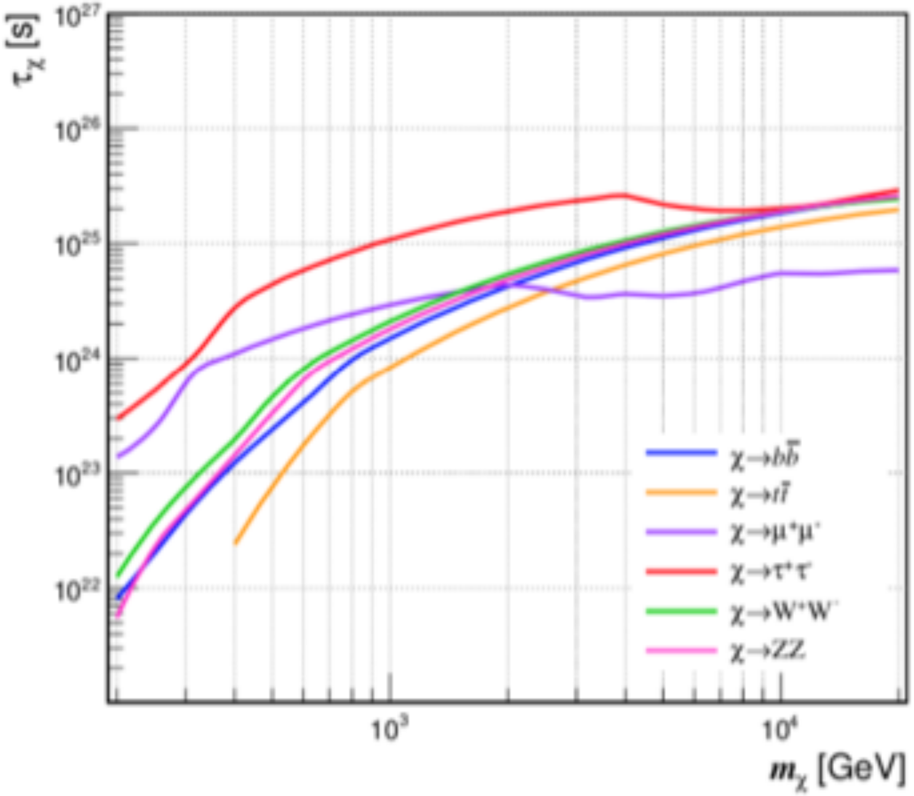


Annihilating and decaying dark matter

Annihilation cross-section



Decay lifetime

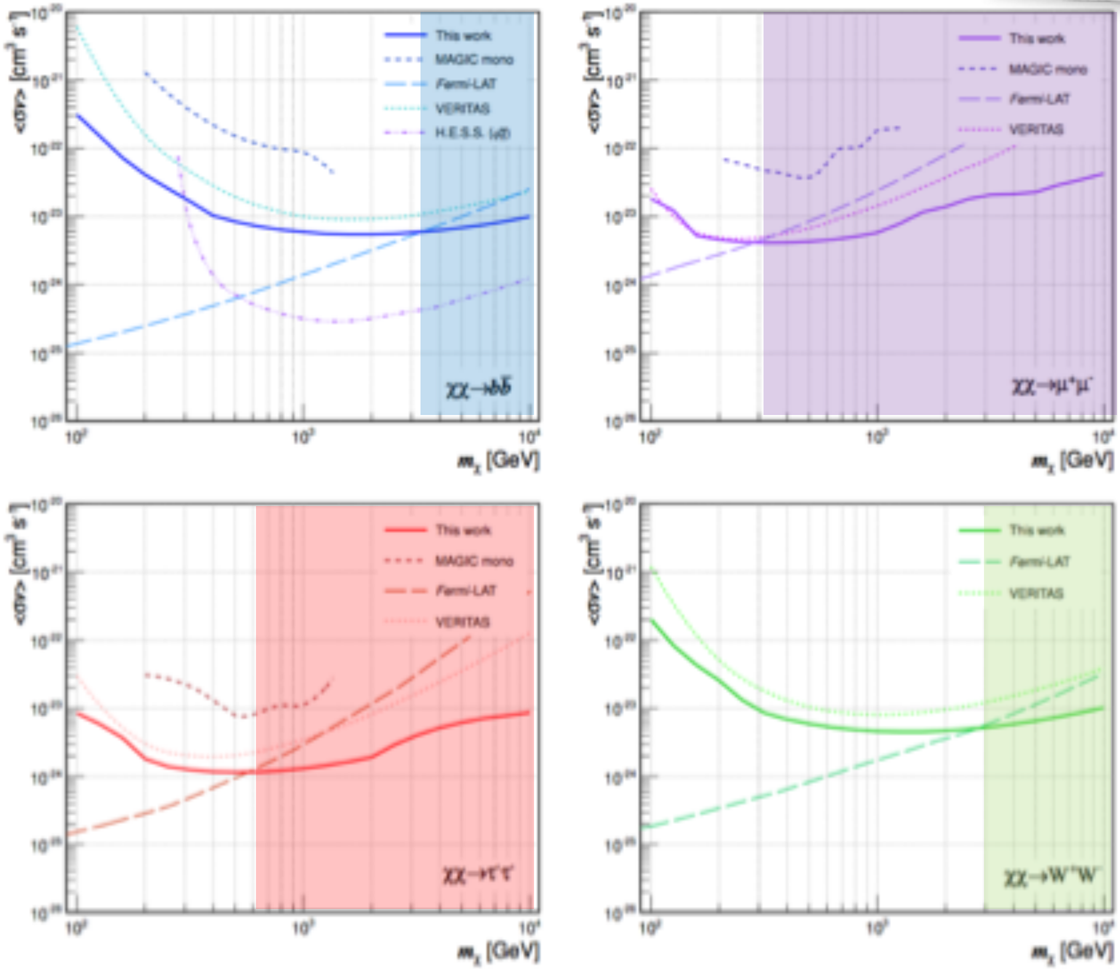


Segue 1 – stereo results

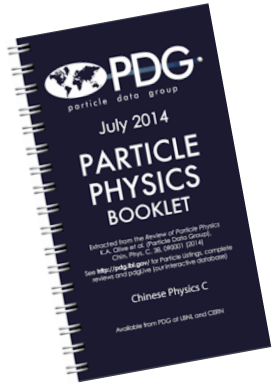
Best limits from dwarfs in high-mass range

- 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

Aleksic, Rico, Martinez JCAP 1210 (2012) 032

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

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

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

$$J_{\rm ann}(\Delta\Omega) = \int_{\Delta\Omega}\int_{los} \rho^2(l,\Omega)\,dl\,d\Omega.$$

- **Aim: combine measurements** of $<\sigma v>$ 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

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

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

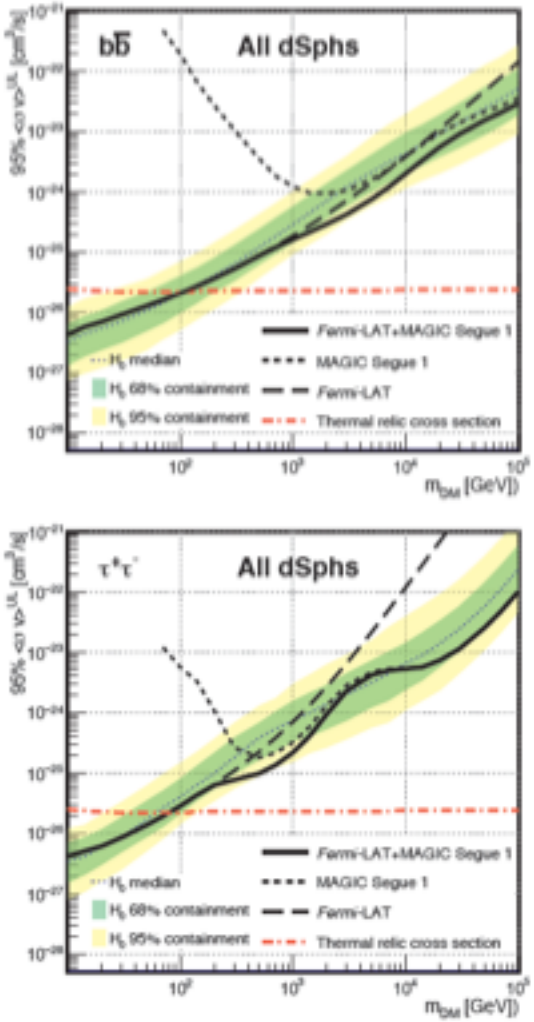
RESULTS FROM DIFFERENT INSTRUMENTS AND DIFFERENT TARGETS CAN BE NOW COMBINED TO IMPROVE SENSITIVITY

MAGIC + Fermi combined

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

- **Effective combination (2x stronger constraints) in the range 300-500 GeV**

JCAP 02 (2016) 039

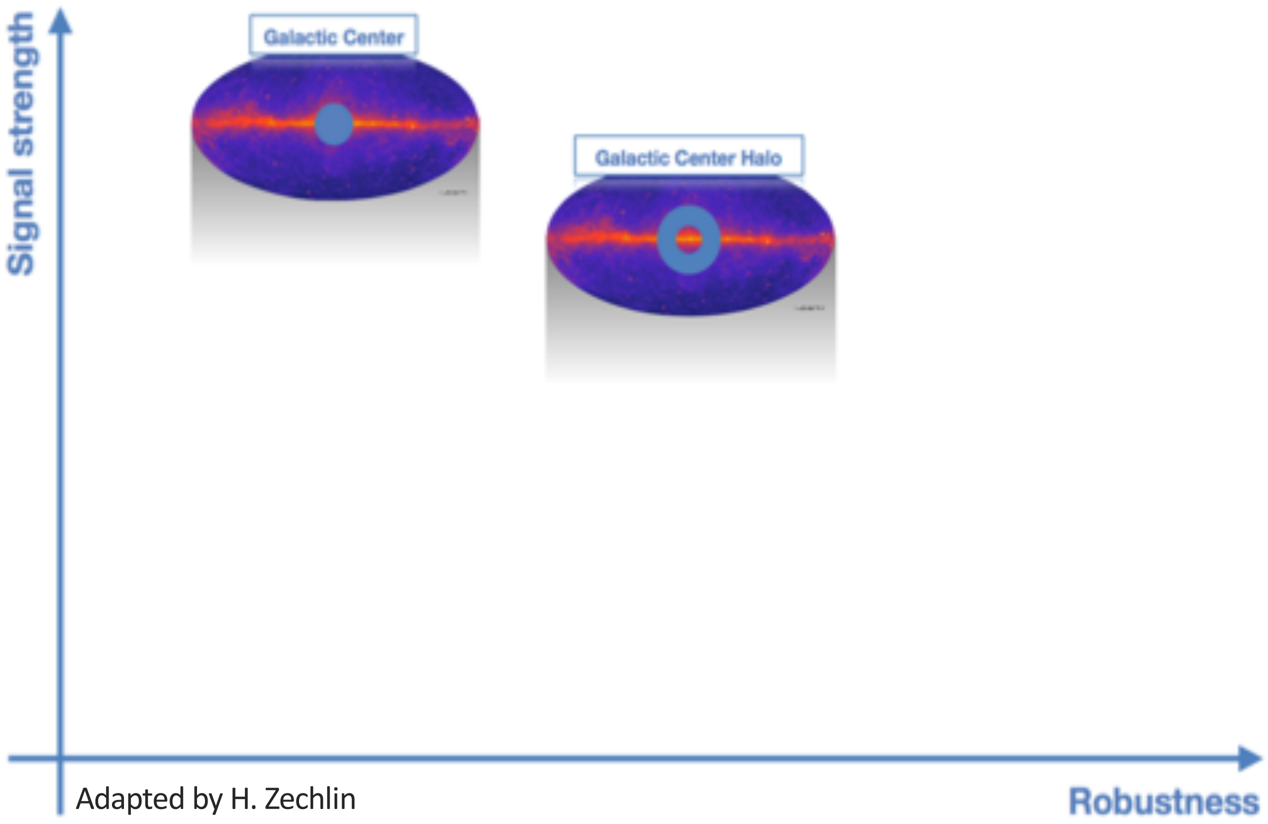


JCAP02(2016)039

«Gather them all»

- **A project between MAGIC, VERITAS, HESS and Fermi started *to gather them all***
  - 300+ h MAGIC
  - 300+ h VERITAS
  - 100+ h HESS
  - Fermi-dSph
- Great expectations!

Not only dSphs



Adapted by H. Zechlin

❖ ***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

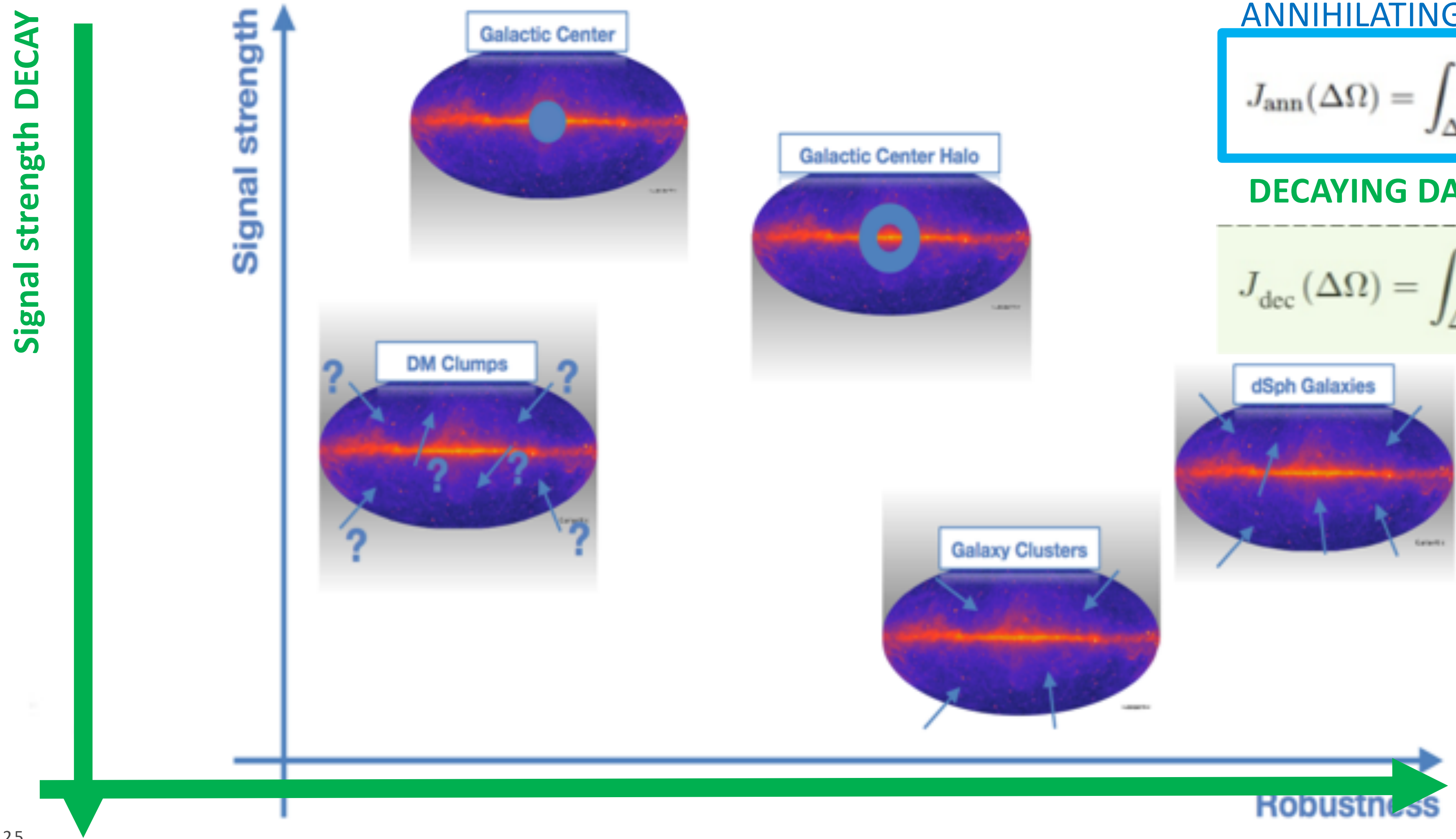
❖ ***Dark Clumps?***

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

❖ ***DM anisotropies***

+ In principle possible with IACTs although challenging

Decay DM case



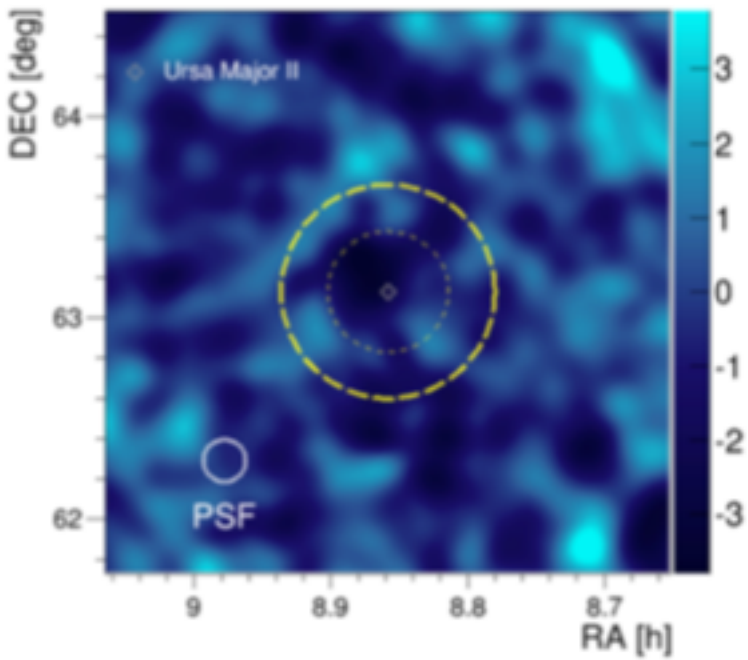
ANNIHILATING DARK MATTER

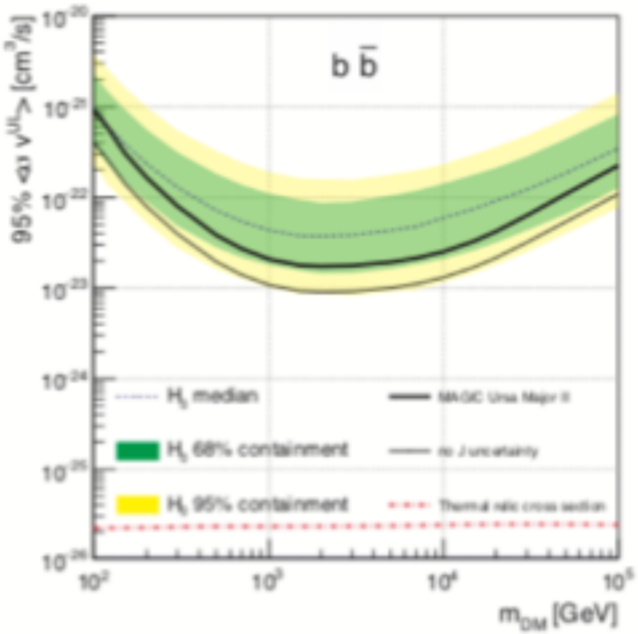
$$J_{\rm ann}(\Delta\Omega) = \int_{\Delta\Omega}\int_{los} \rho^2(l,\Omega)dl d\Omega.$$

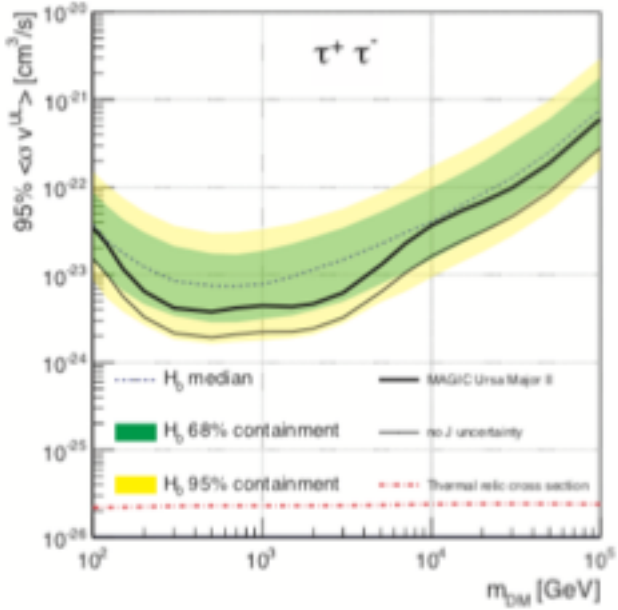
DECAYING DARK MATTER

$$J_{\rm dec}(\Delta\Omega) = \int_{\Delta\Omega}\int_{los} \rho\,(l,\Omega)dl d\Omega.$$

2018: another dSph in the portfolio: Ursa Maior 2







$\log_{10}(J(\theta_{\max})\ [\mathrm{GeV}^2\ \mathrm{cm}^{-5}])=19.42^{+0.44}_{-0.42}$

$\mathrm{M/L} \sim 4000^{+3700}_{-2000}\ M_\odot/L_\odot$

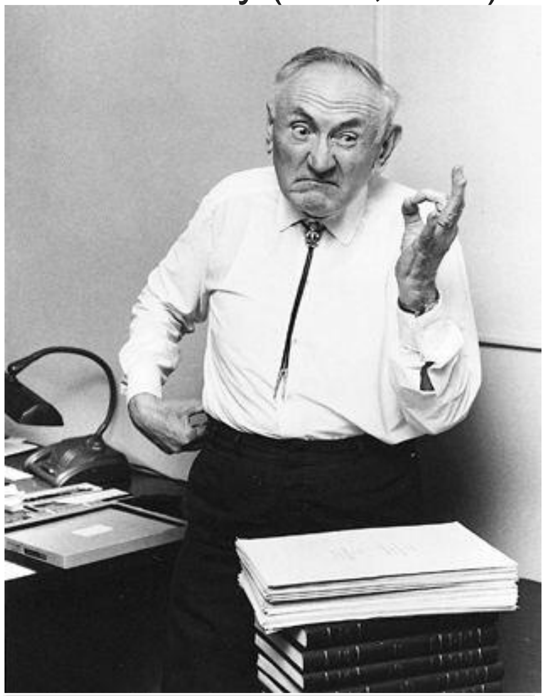
distance of ~ 30 kpc

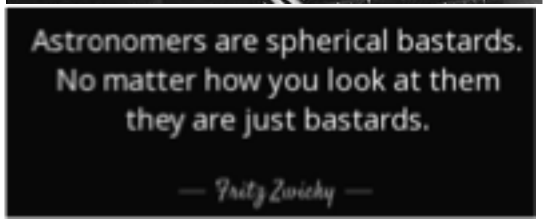
Indirect dark matter searches in the dwarf satellite galaxy Ursa Major II with the MAGIC Telescopes
MAGIC Collaboration (M.L. Ahnen (ETH, Zurich (main)) *et al.*). Dec 7, 2017. 21 pp.
Published in **JCAP 1803 (2018) no.03, 009**


MAG
ter
TODAY on ARXIV 1806.11063

It all started with cluster

Fritz Zwicky (1898, 1974)



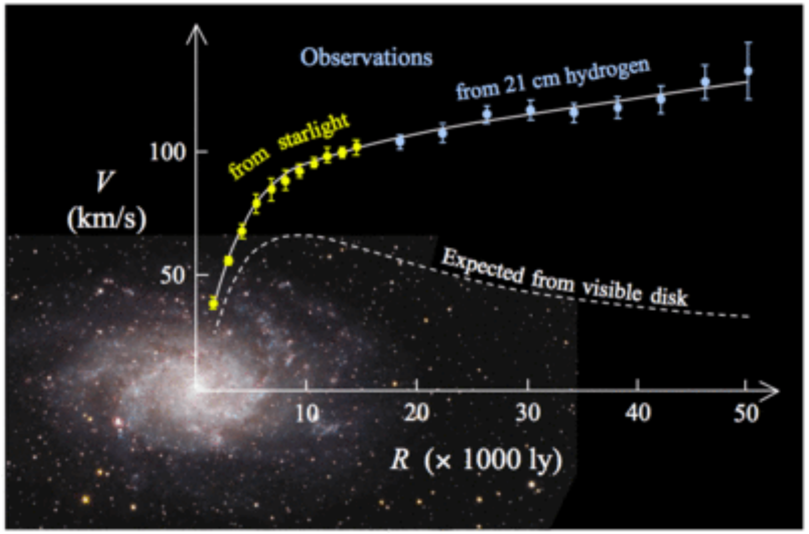


- F. Zwicky, while examining the Coma galaxy cluster in 1933, was the first to use the **virial theorem** to infer the existence of unseen matter, which he referred to as **dunkle Materie 'dark matter'**.

$$2\,E_K = -U \quad \rightarrow \quad v(r) = \sqrt{\frac{GM(<r)}{r}}$$

- He calculated the gravitational mass of the galaxies within the cluster and obtained a value at **least 400 times greater than expected from their luminosity**

The technique was refined by Vera Cooper (Rubin) for galaxies in the '60s



A long campaign

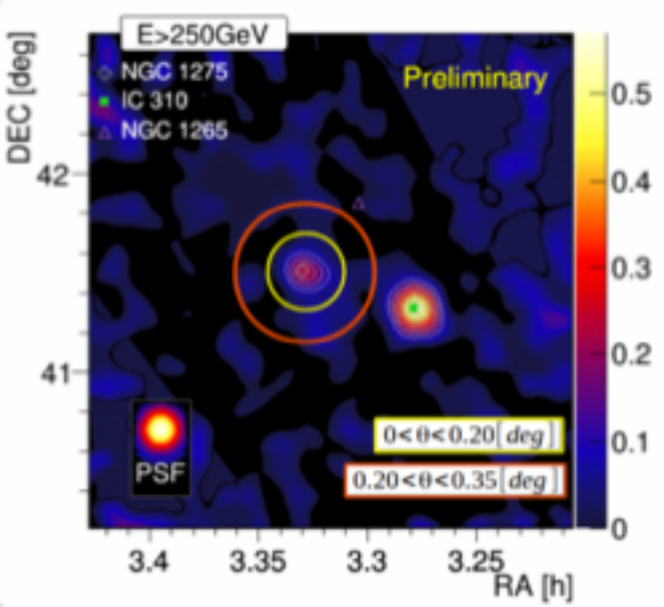
Period	Dates	Telescope Pointing 𝒜 All data [h]	𝒜 Data Selection quality [h]	𝒜 Data Selection quality + specific [h]	ℬ All data [h]	ℬ Data Selection quality [h]	ℬ Data Selection quality + specific [h]
𝒫1	2009.11.01-2011.06.01	94.7	56.4	45.4	-	-	-
𝒫2	2012.09.01-2013.01.17	9.2	9.1	9.1	59.4	40.2	36.8
𝒫3	2013.07.27-2014.08.05	17.5	16.7	14.8	55	30.2	28.9
𝒫4	2014.08.31-2014.11.22	16.6	10.4	10.1	21.7	21.7	7.5
𝒫5	2014.11.24-2016.04.28	6.8	3.9	3.9	29.3	22.32	21.9
𝒫6	2016.04.29-2017.08.02	44.1	41.9	12.2	20.5	16.02	11.1
TOTAL		185.9	138.4	106.1	188.9	119.2	96.2

Global sample selected	202.2 h

- Consider duty cycle is roughly 1000h/year

A very fruitful campaign

See Paneque talk



J. Aleksić et al. *Astrophys. J.*, 710:634–647, 2010a.
J. Aleksić et al. *Astrophys. J.*, 723:L207, 2010b
J. Aleksić et al. *Astron. Astrophys.*, 541:A99, 2012c.
J. Aleksić et al. *Astron. Astrophys.*, 539:L2, 2012d.
J. Aleksić et al. *Astron. Astrophys.*, 563: A91, 2014a.
J. Aleksić et al. *Astron. Astrophys.*, 564:A5, 2014b.
J. Aleksić et al. *Science*, 346:1080–1084, 2014d

- MAGIC campaign on Perseus CG proved to be very fruitful:
  - the strongest limits on **Cosmic Ray (CR) acceleration** in the core of the cluster and on the CR to thermal pressure (Aleksić et al., 2010a, 2012c);
  - the **radio-galaxy NGC 1275**, at the center of the cluster, was clearly detected and modelled (Aleksić et al., 2012d, 2014b); and
  - the **peculiar radio-galaxy IC 310**, located at 0.6 deg from the Perseus CG center, was detected and provided important evidences related to the acceleration of CRs close to black holes (Aleksić et al., 2010b, 2014a,d).

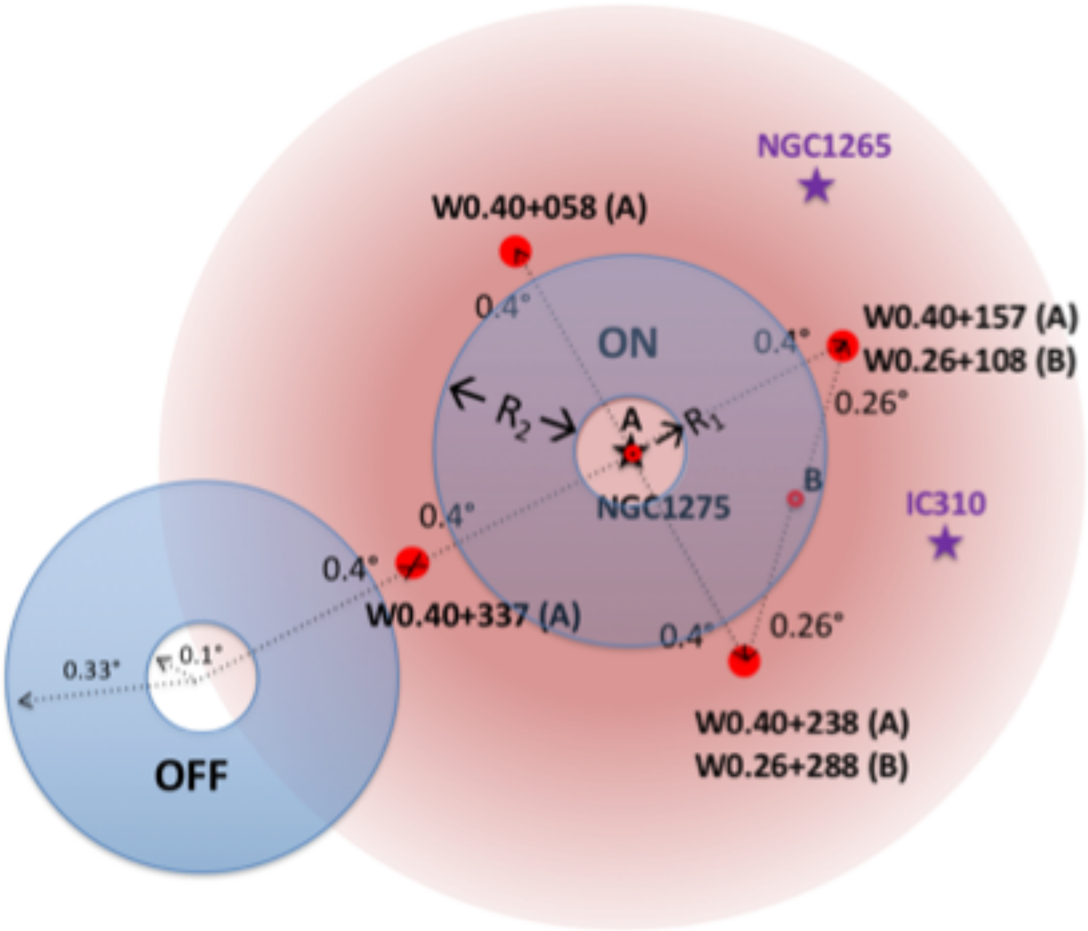
See backup slides

Complex observing region

- Two radio galaxies: NGC1275 and IC310
- Variability of these sources
- Extension of DM signal
- Signal leakeage into background control region

- **Development of a specific tailored MC to estimate IRFs properly (J. Palacio Phd 2018)**

- **DECAYING DARK MATTER CASE**



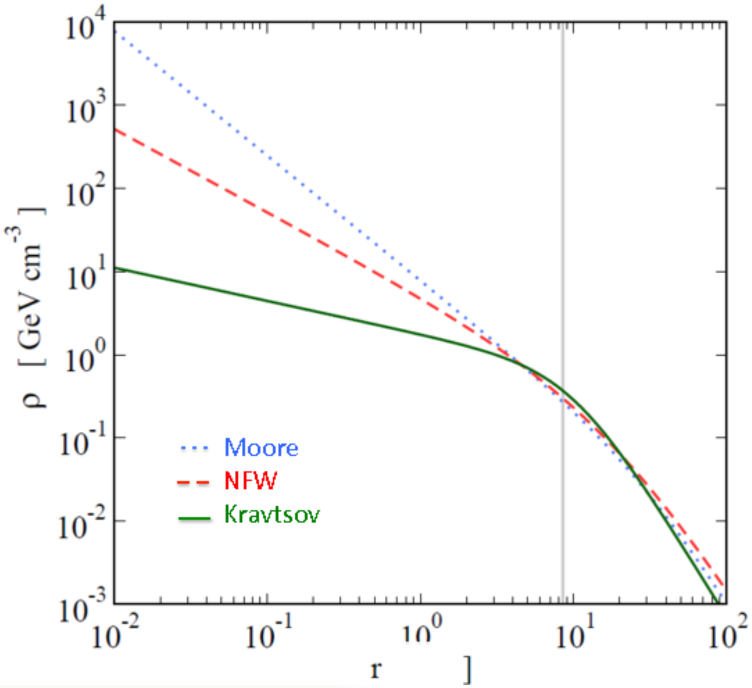
Dark matter profile

$$\rho(r) = \frac{\rho_0}{\left(\frac{r}{r_s}\right)^\gamma \left[1+\left(\frac{r}{r_s}\right)^\alpha\right]^{(\beta-\gamma)/\alpha}},$$

$r_s = 0.477$ Mpc and

$\rho_0 = 7.25 \times 10^{14}\ \mathrm{M_\odot\ Mpc^{-3}}$.

Zhao-Hernquist profile with $\alpha = 1$
$\beta = 2$ and $\gamma = 1$ Navarro et al., 1996



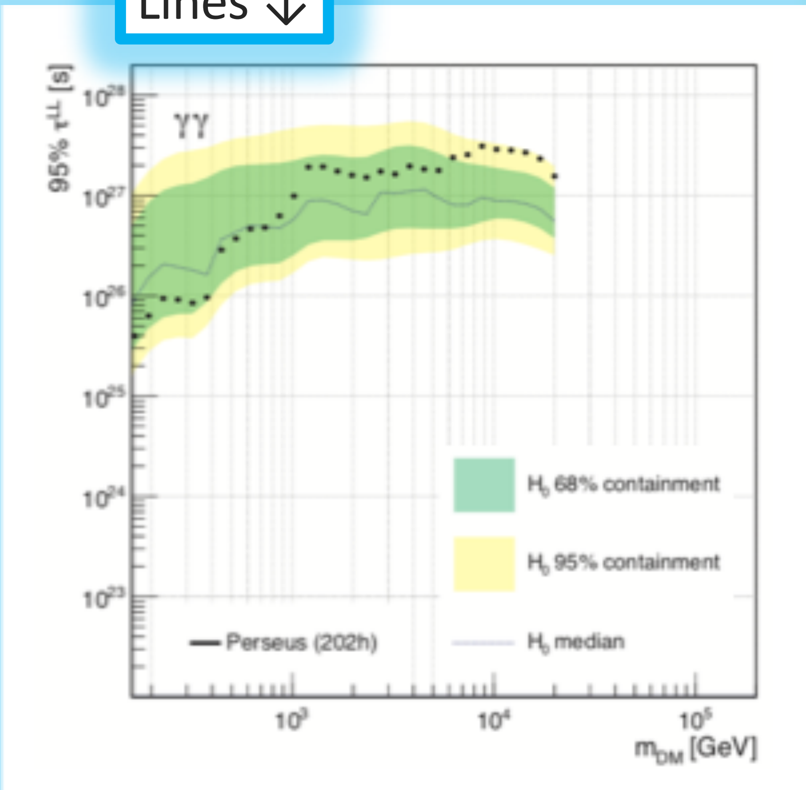
decay J-factor of 1.5×10^{19} GeV cm^{-2}.

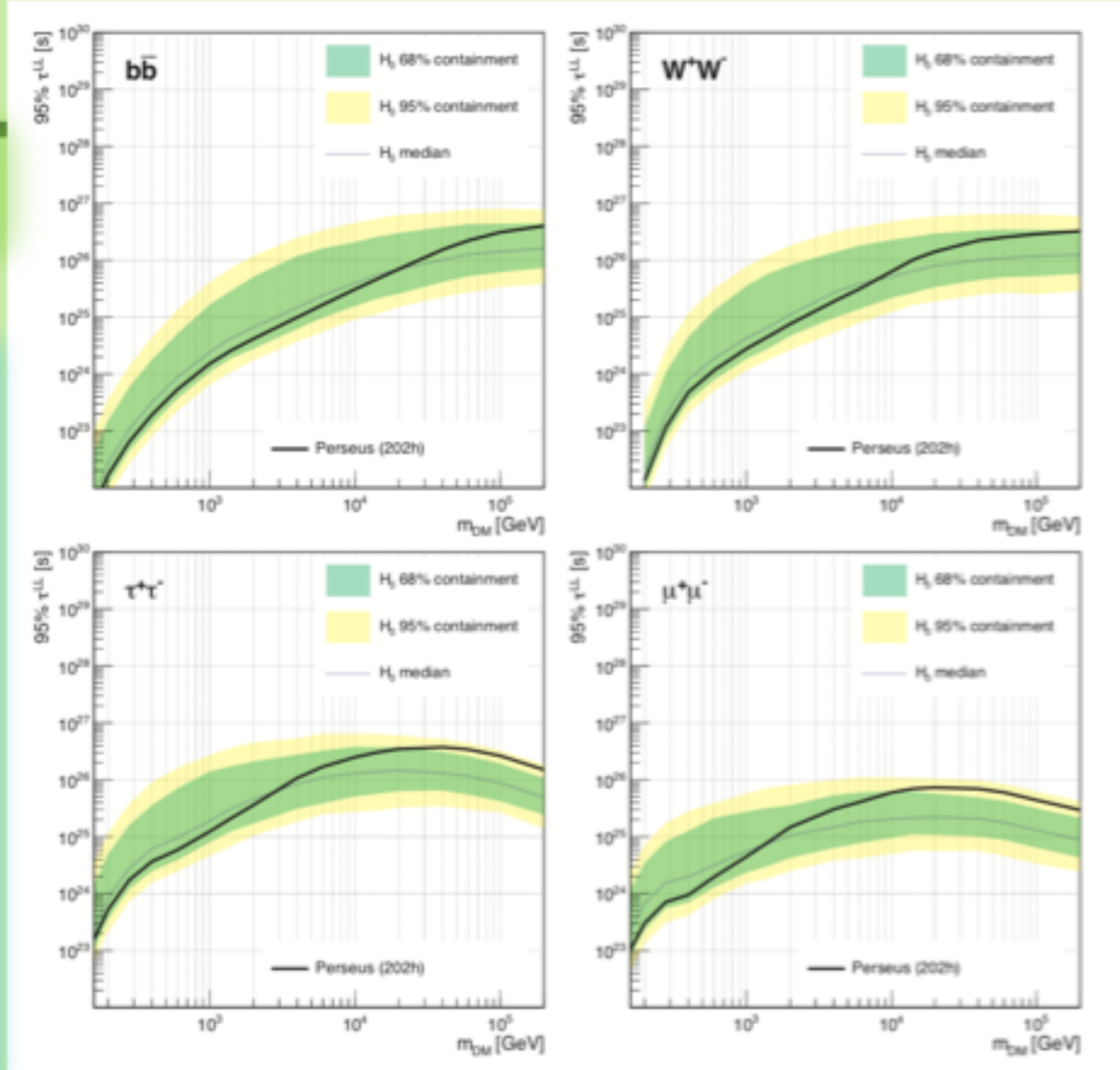
- We follow the prescription in **Sanchez-Conde et al**. (2011)
- We use **30% systematics on mass estimation** for Perseus CG (Reiprich and Boehringer, 2000; Chen et al., 2007)

Results

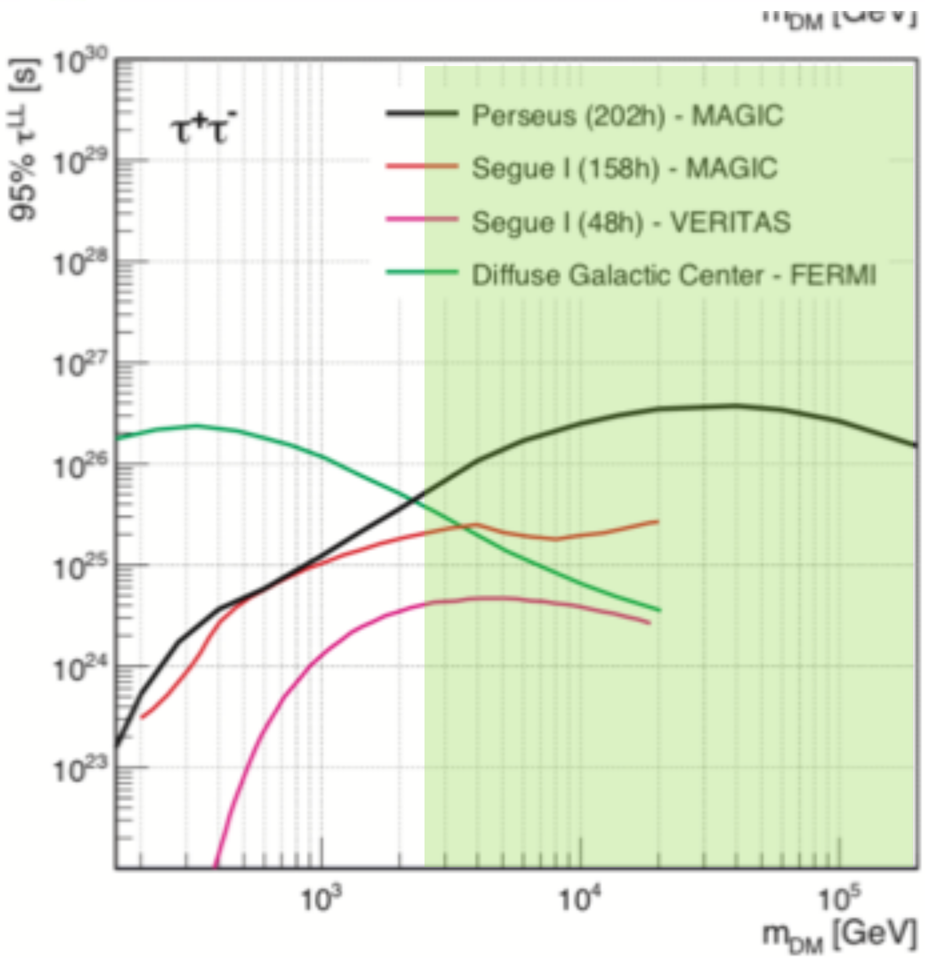
Continuum→

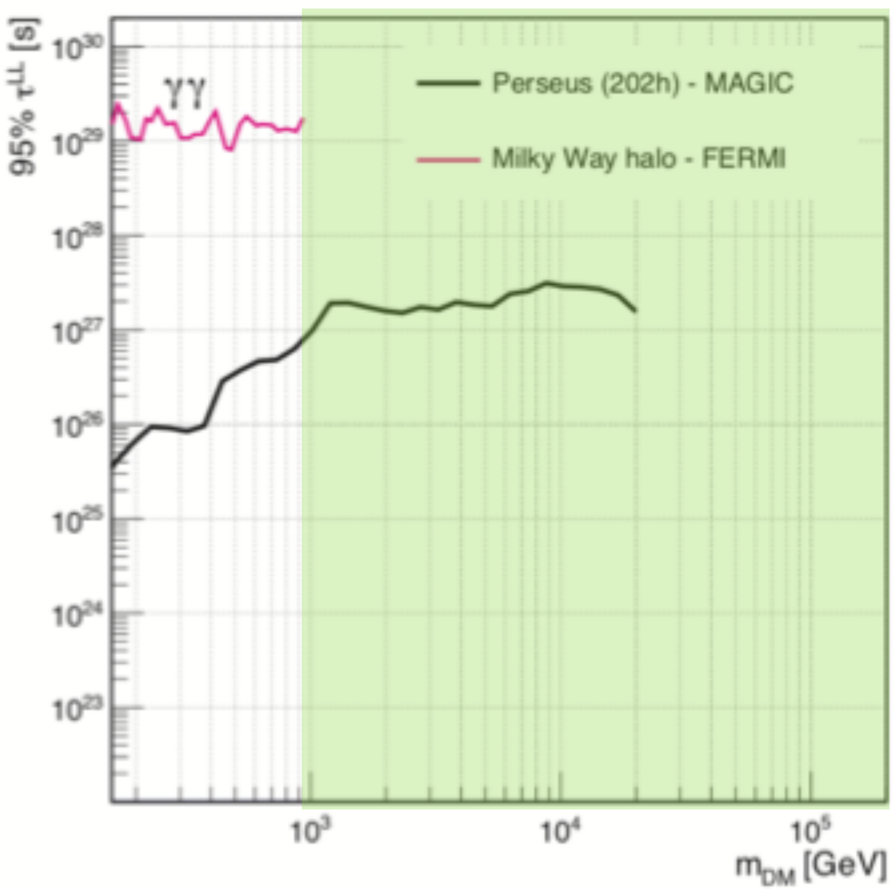
Lines ↓





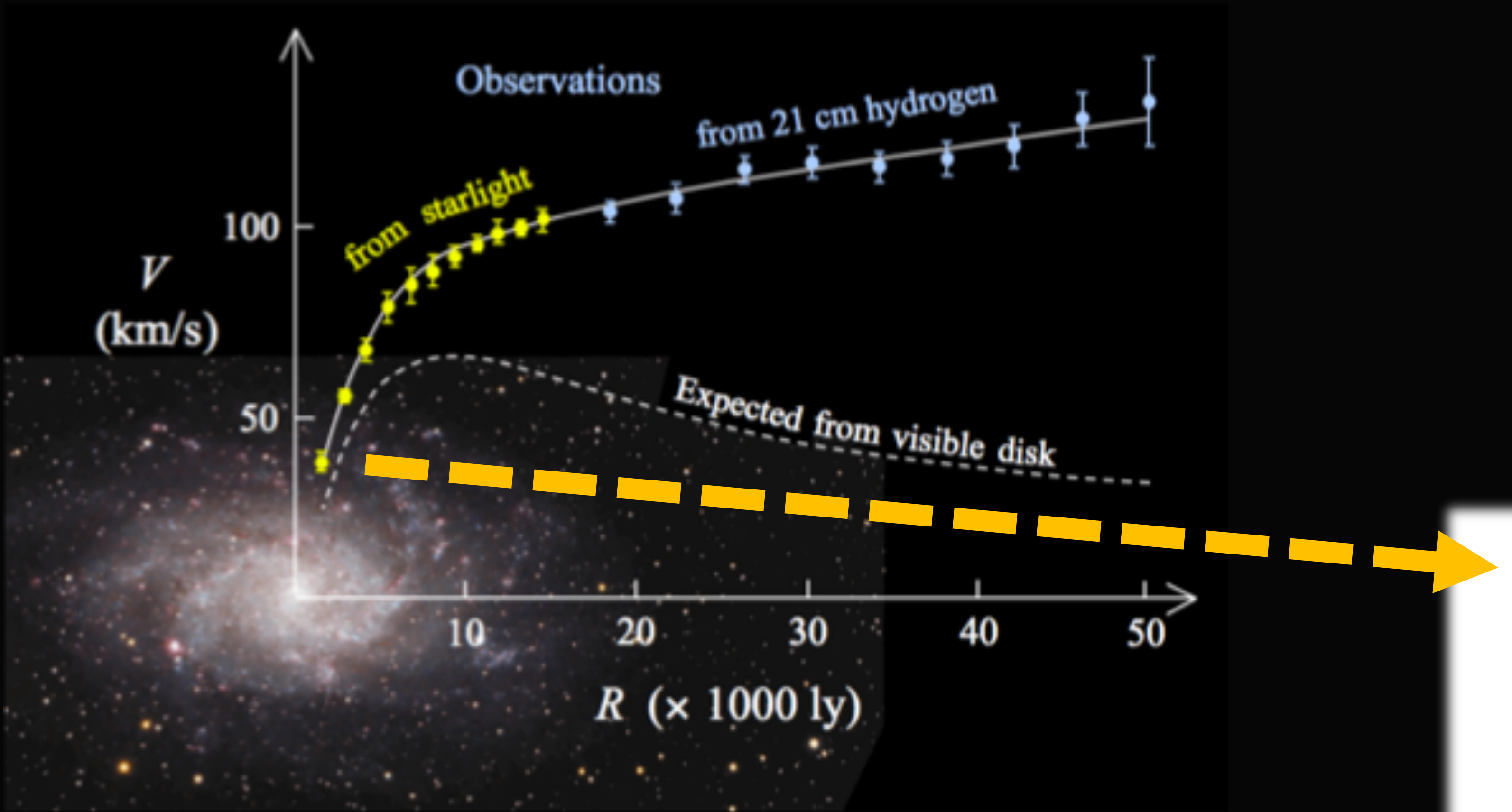
MAGIC results put into context



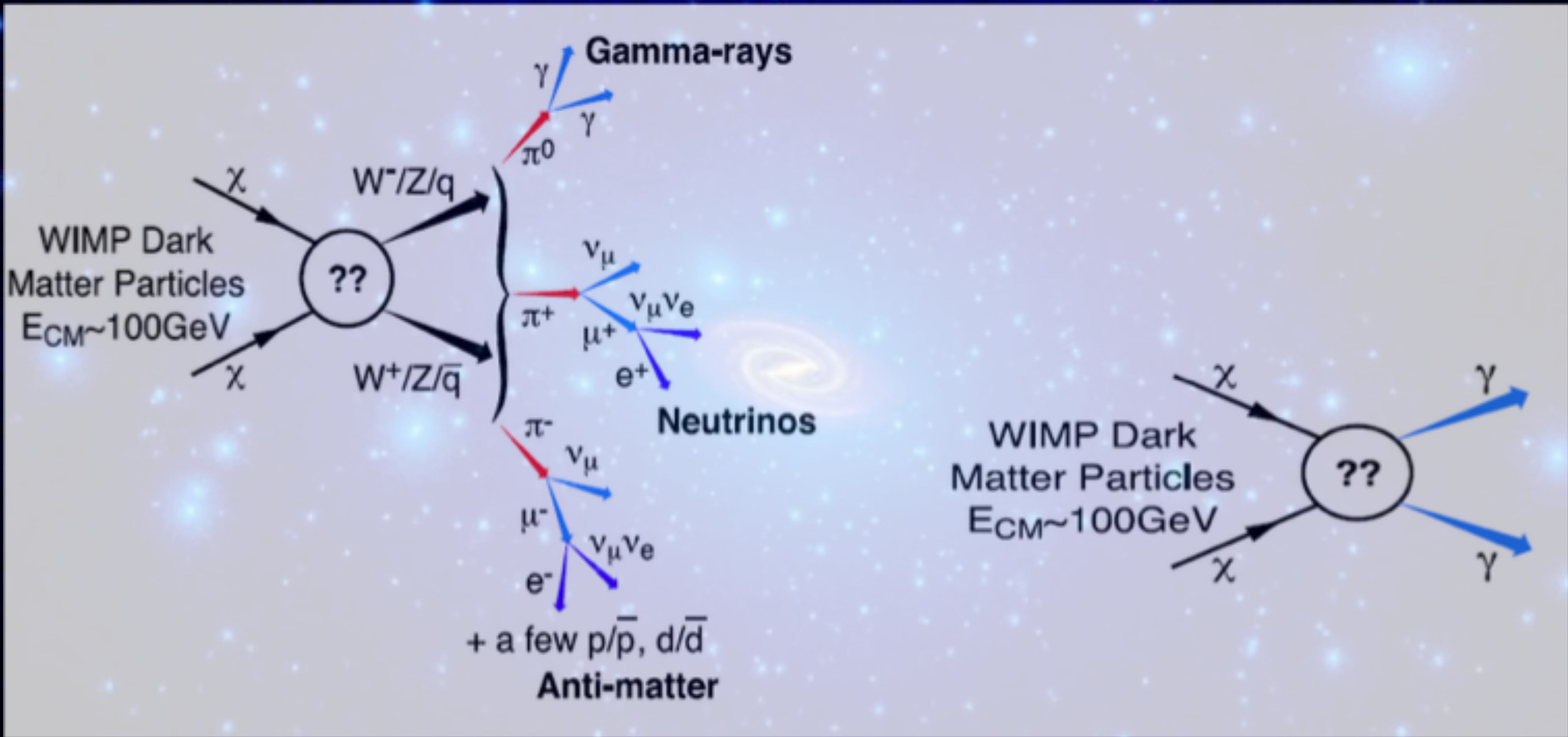


Why should be using IACT time for DM?

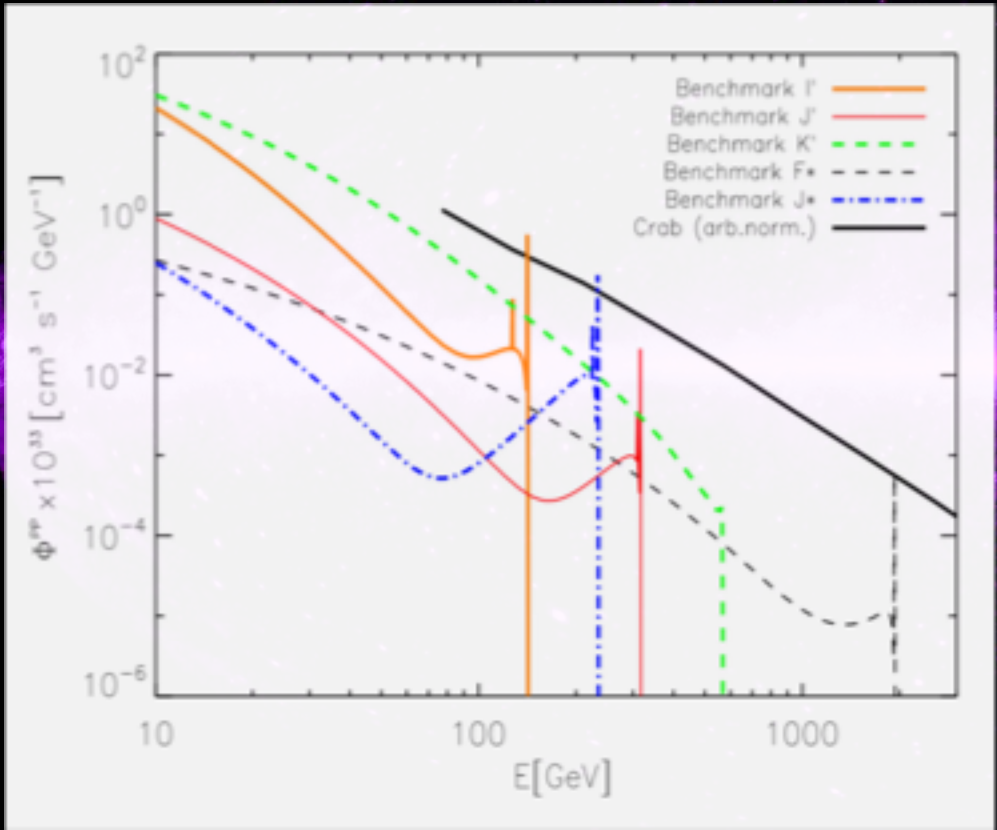
0/ DM is gravitational!

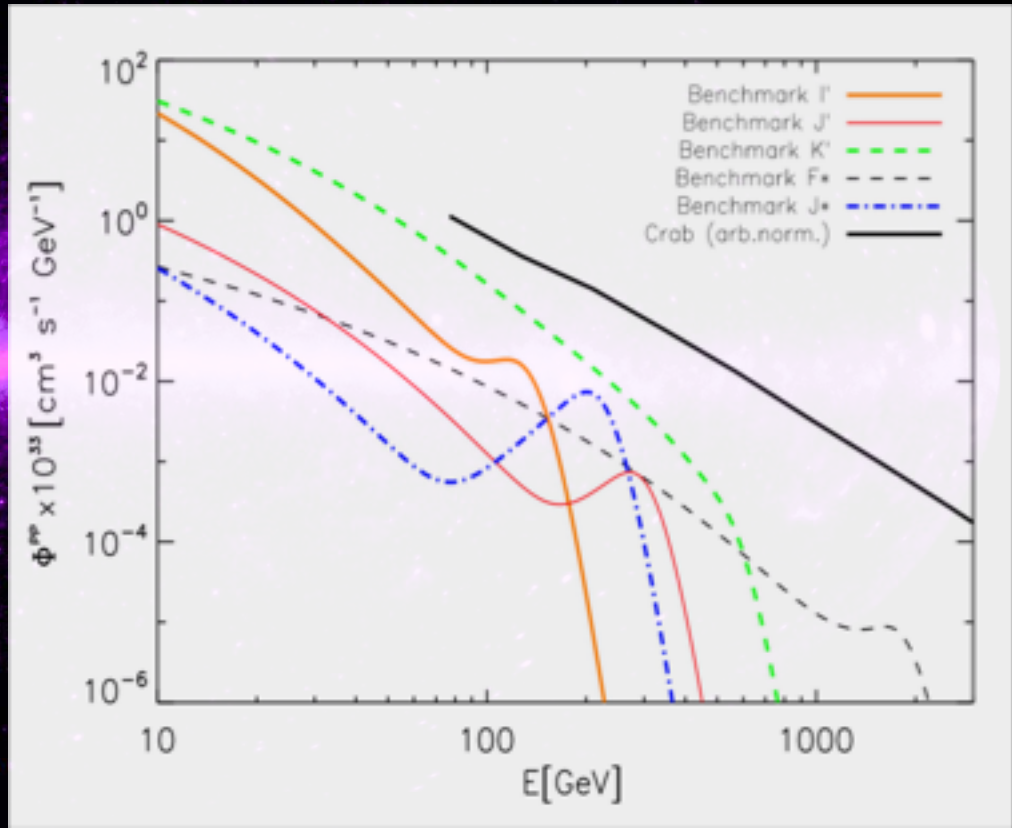


1/ We do expect gamma-rays



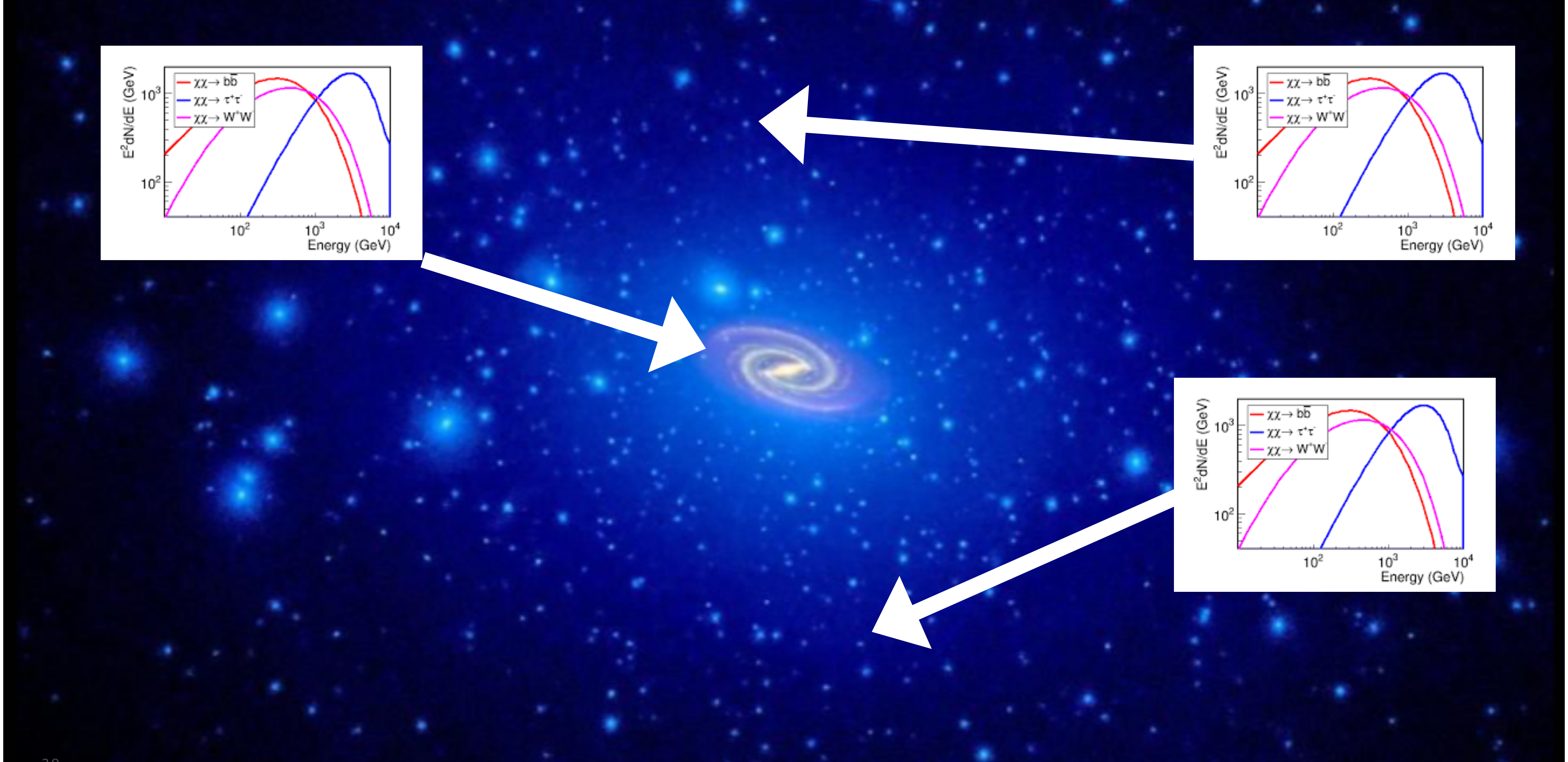
2/ Dark Matter identification

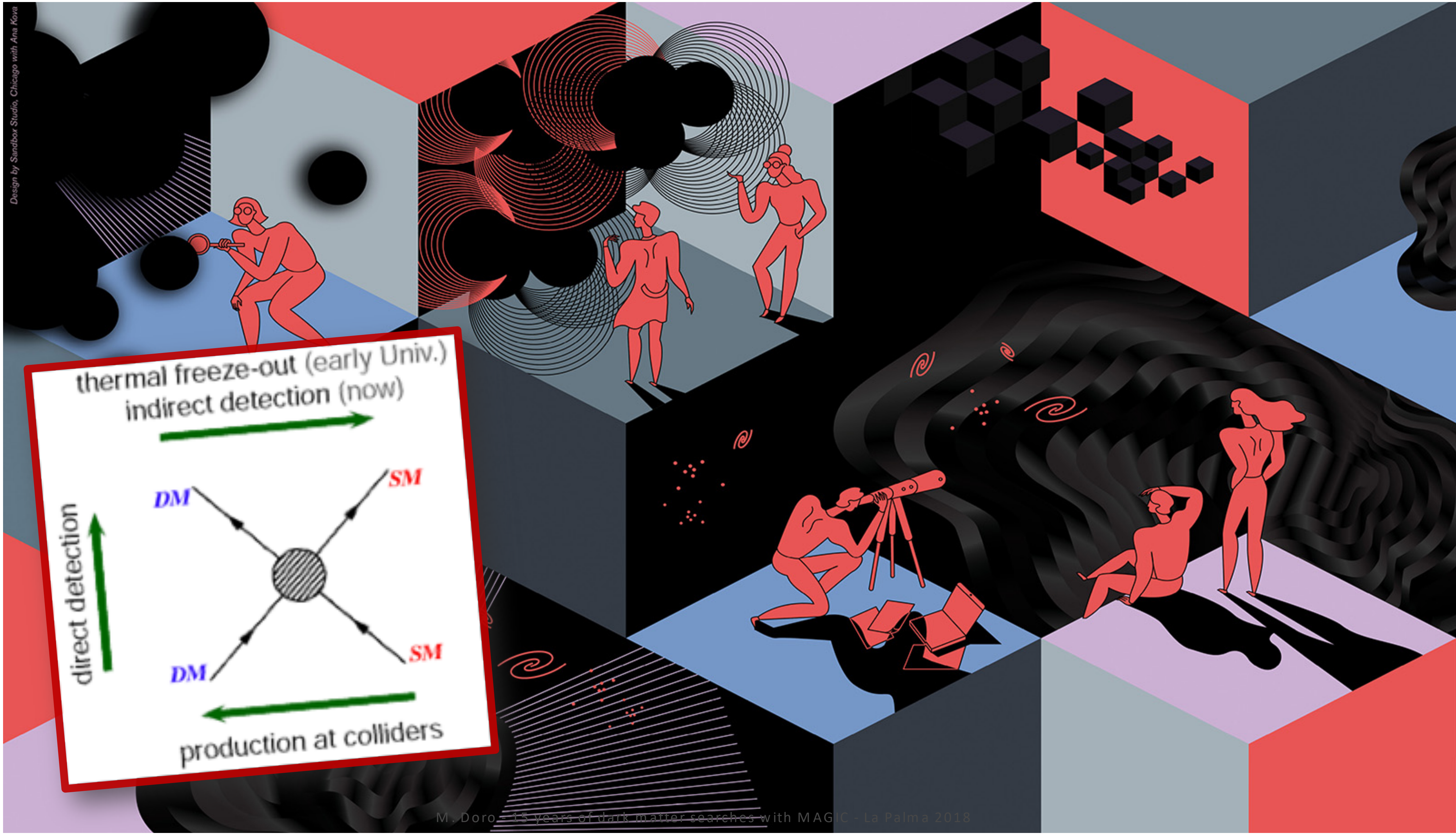




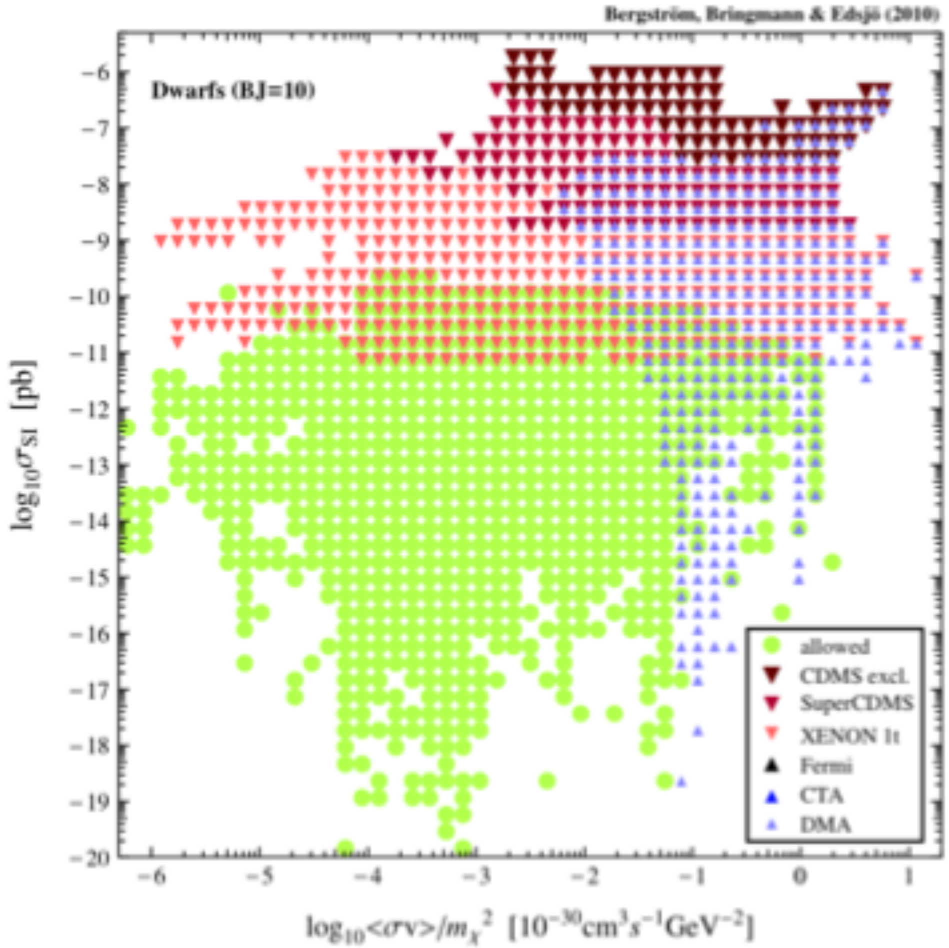
Bringmann, MD, Fornasa JCAP01(2009)016

3/ Universality of Dark Matter Spectra



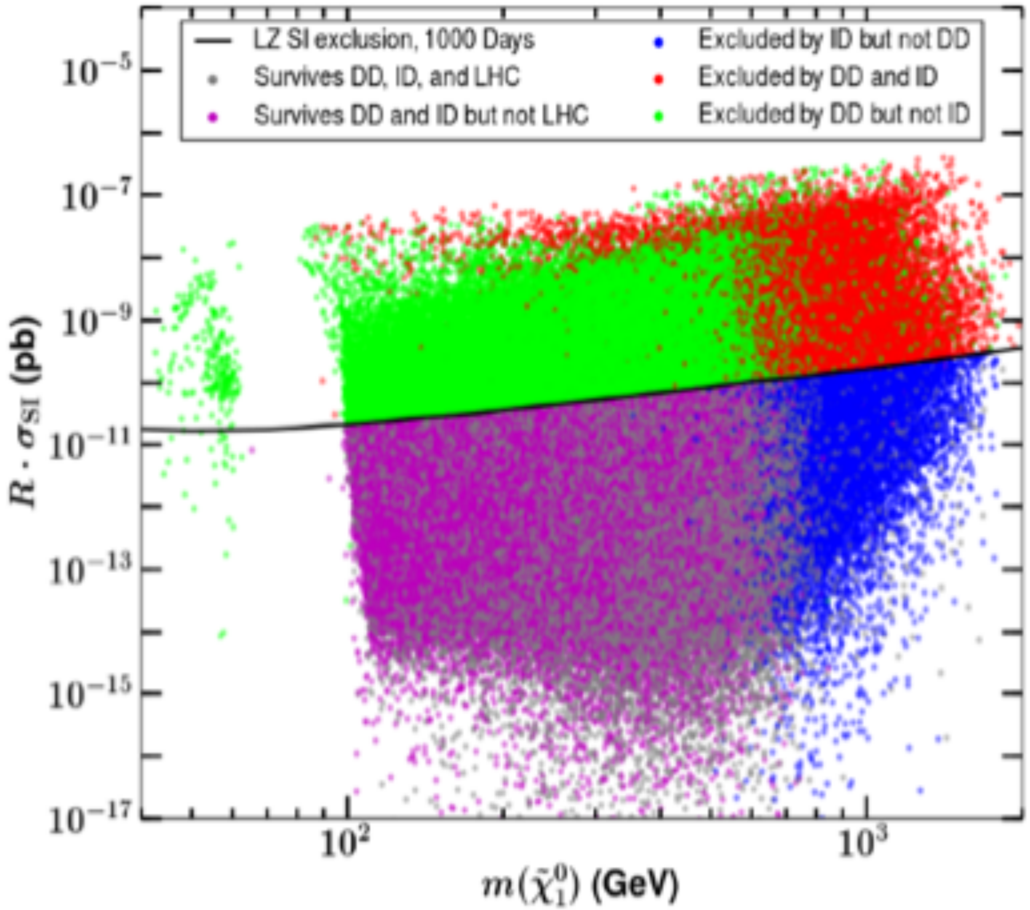

Design by Sandbox Studio, Chicago with Ana Kova
thermal freeze-out (early Univ.)
indirect detection (now)
DM
SM
DM
SM
direct detection
production at colliders

4/ Complementarity



PHYSICAL REVIEW D 83, 045024 (2011)

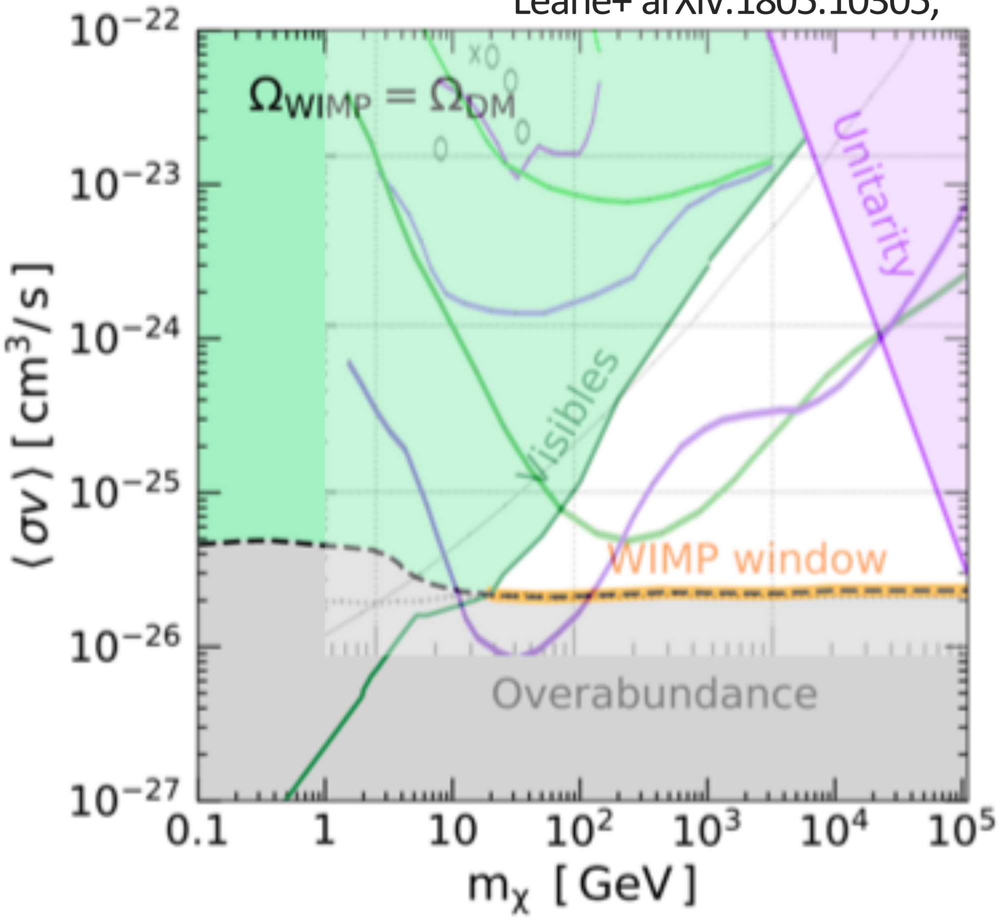
M. Cahill-Rawley 1411.3353

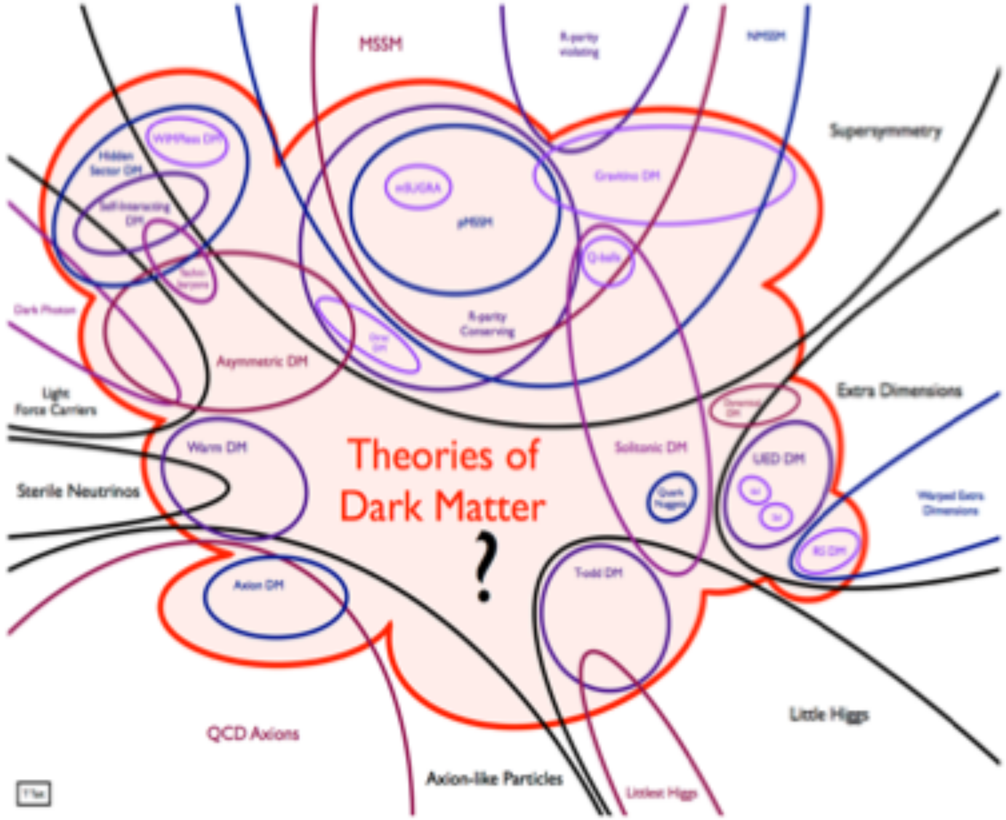


Are we close or far?

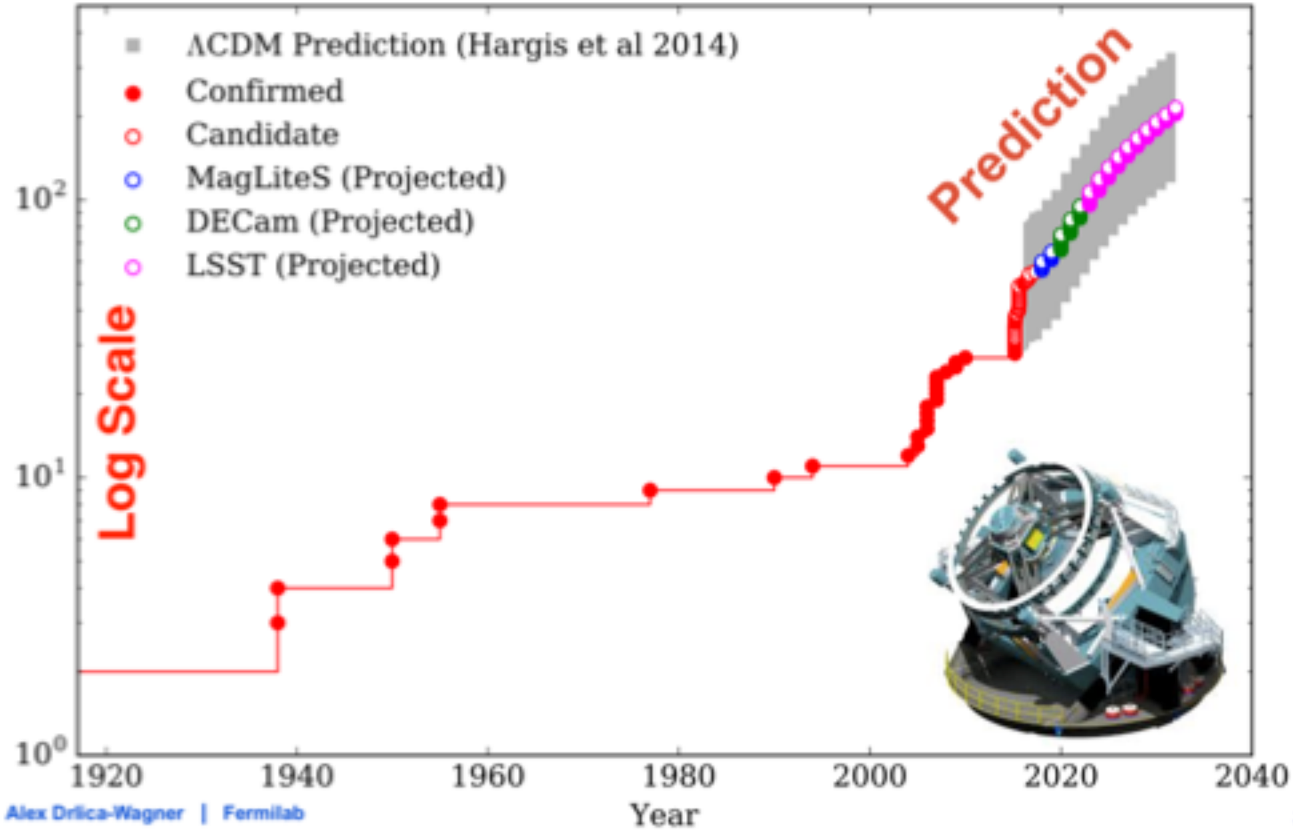
MAGIC on 10xSegue1 in 500h

Leane+ arXiv:1805.10305,





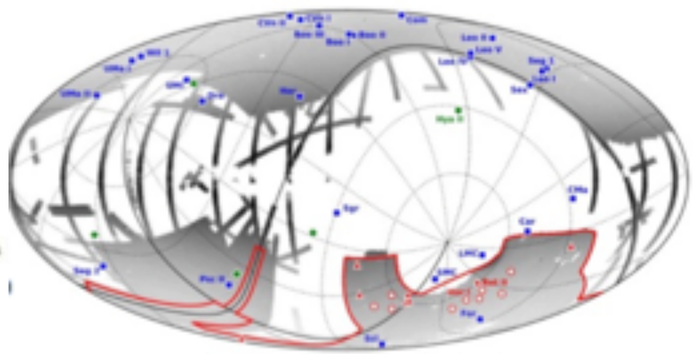
More visible dSphs coming



Alex Drlica-Wagner | Fermilab

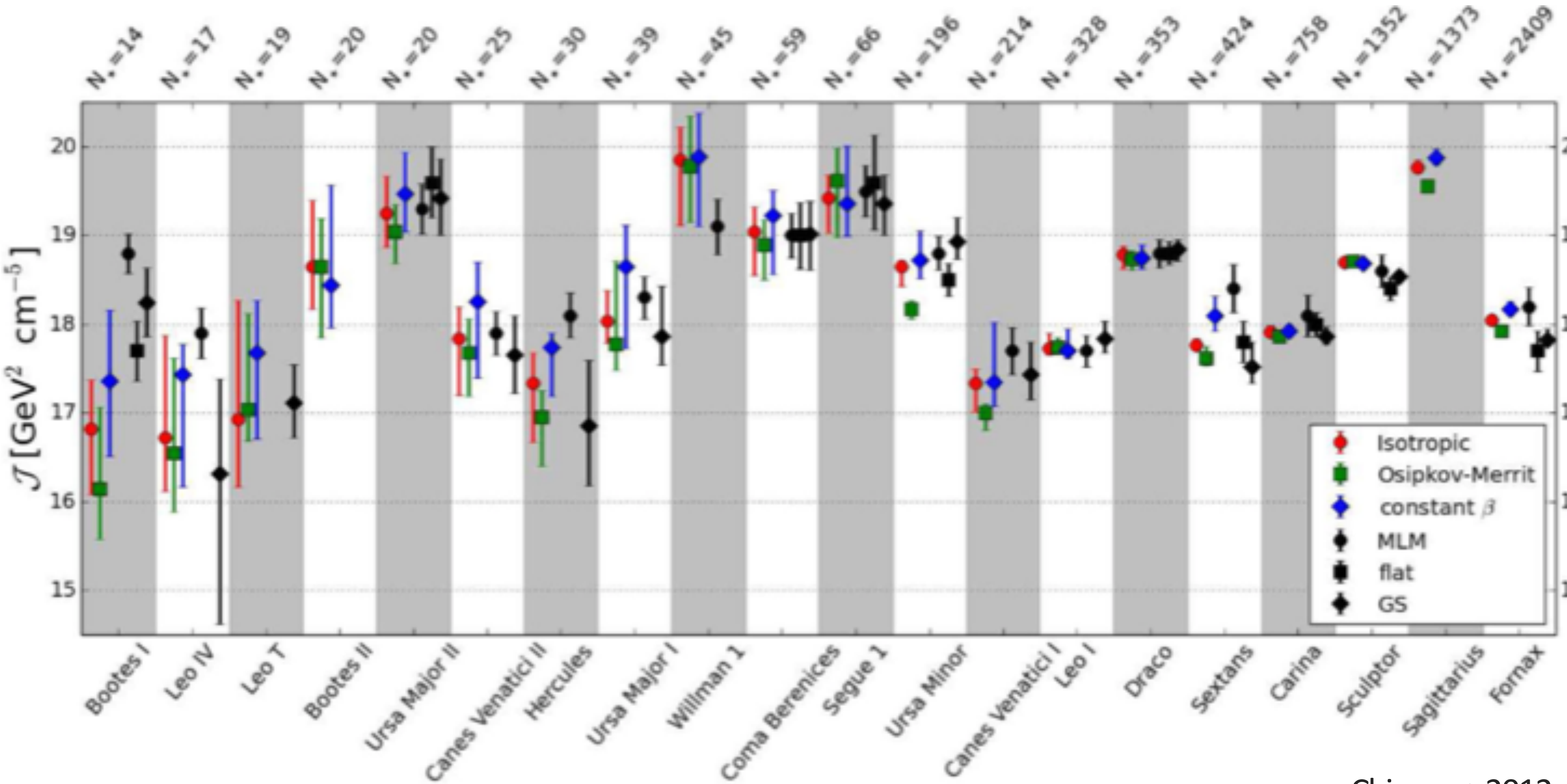
New instruments are discovering new dSphs: some very promising.

Expect results from MAGIC!



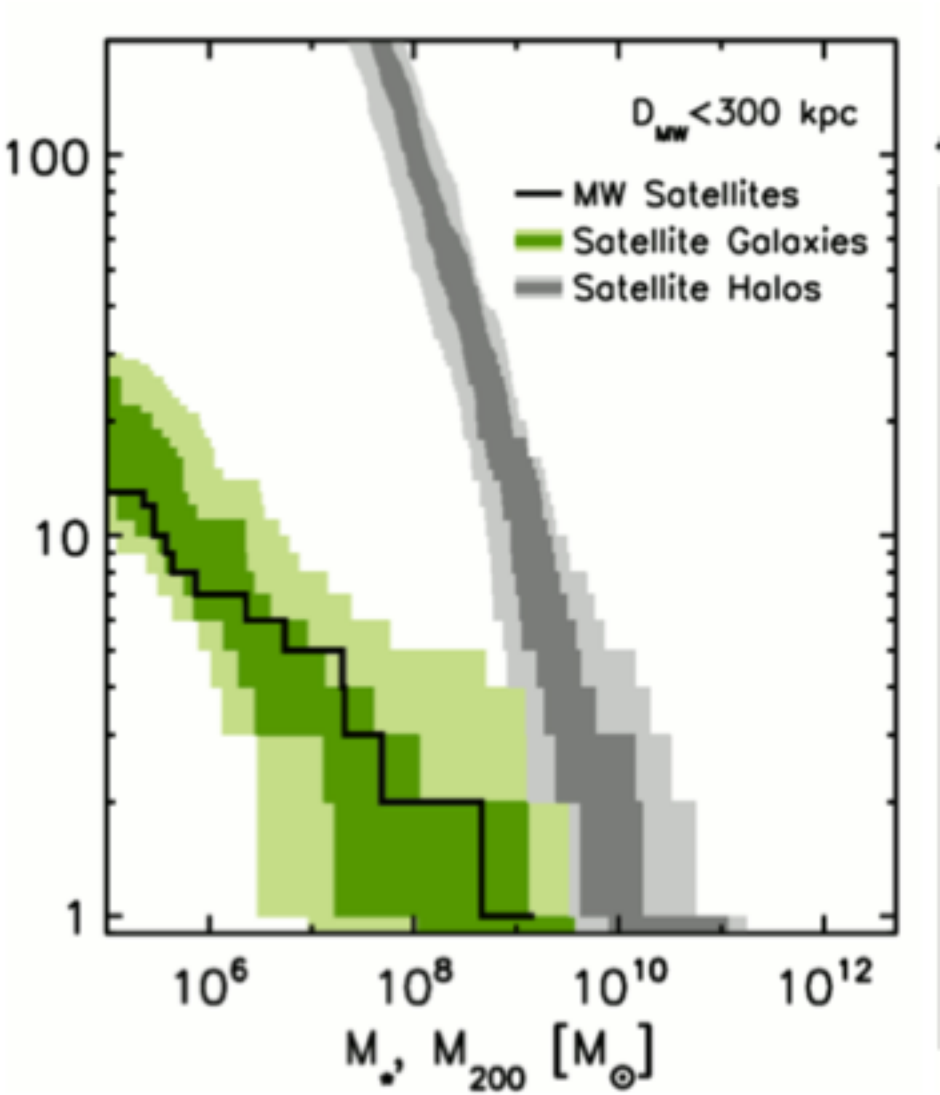
Credit: Dark Energy Survey Collaboration

We need accurate J-factors (more than precise)



Chiappo+ 2012

Dark subhaloes?

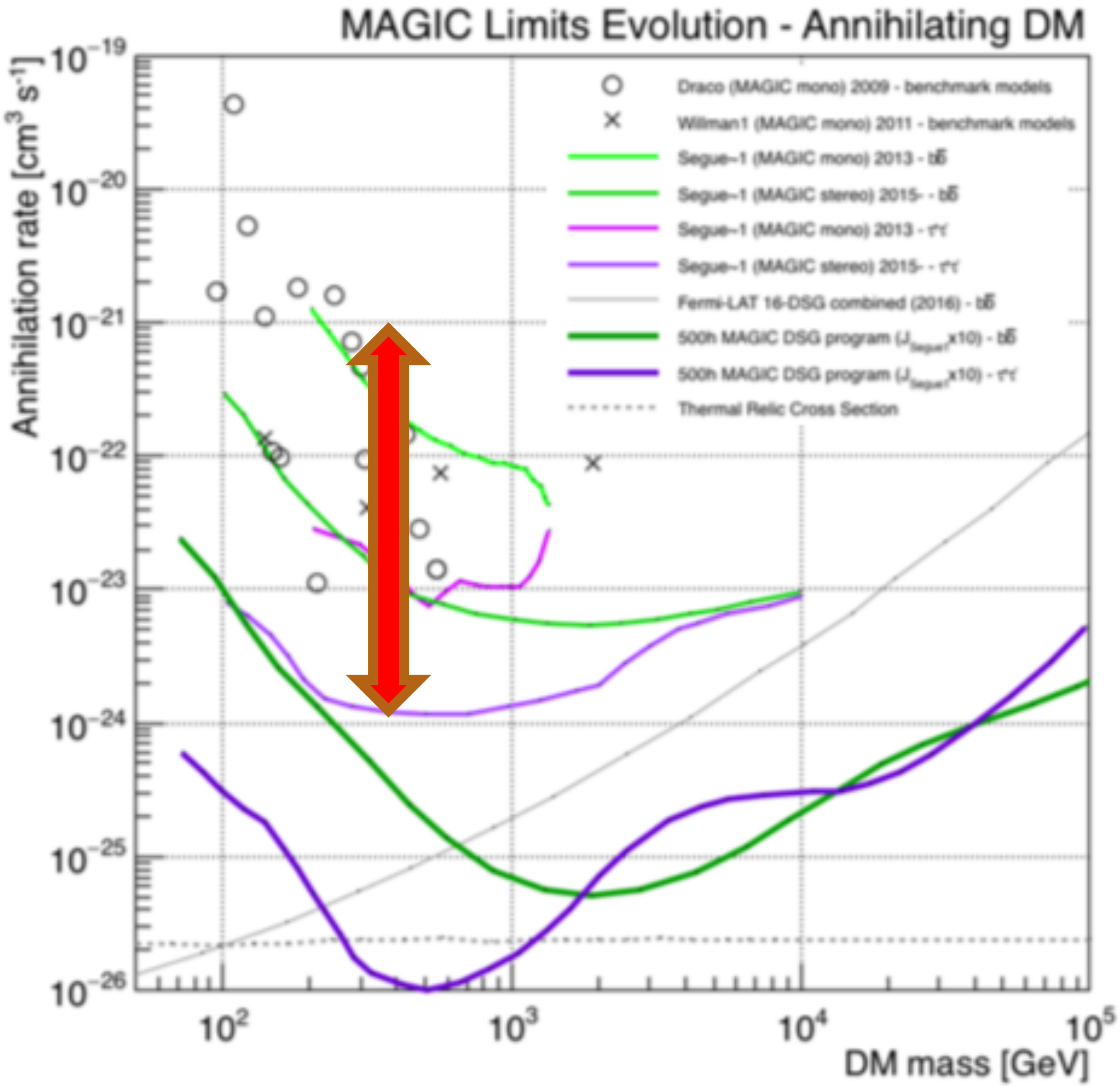


Savala+ MNRAS 457 (2016)

Conclusions

MAGIC

- 3 orders of magnitude from first to latest limits!



Can be a long journey to discovery

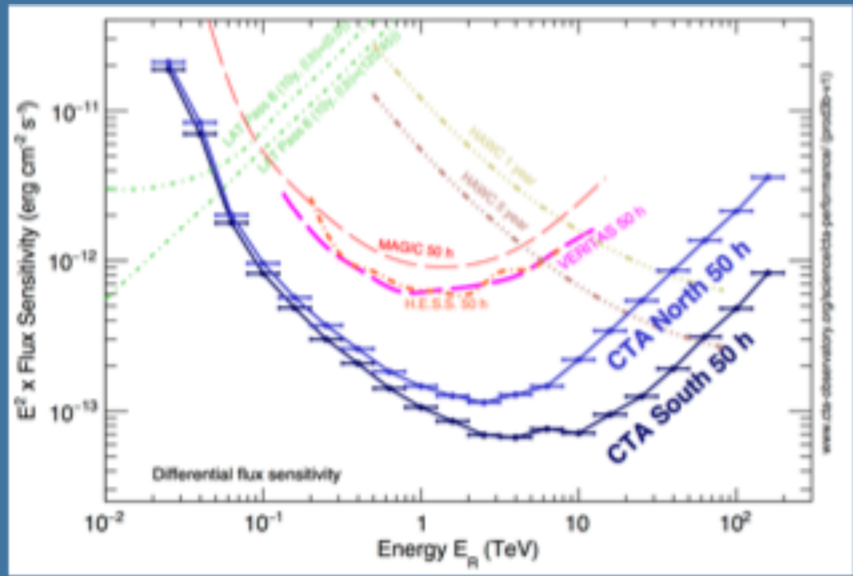
- The bus that Bruno Rossi set-up to carry the experimental equipment to measure Cosmic Rays to the summit of Mount Evans in Colorado (4,348 m).

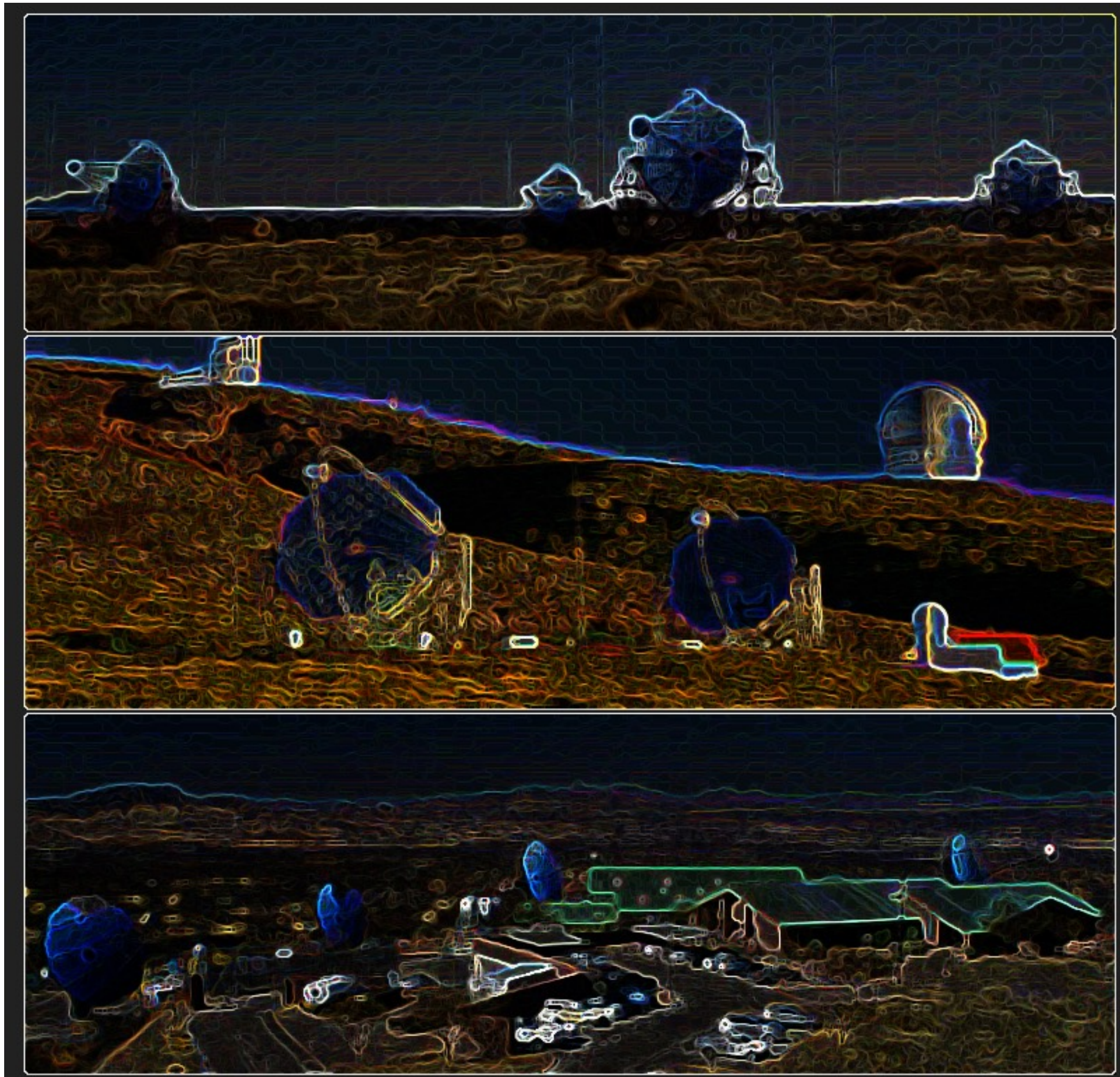
- *He brought his family too!*

Figure 3. The bus equipped for the measurements at different altitudes up to the summit of Mount Evans. Here at Echo Lake, 1939, together with Nora Rossi (reproduced from B. Rossi, *Moments in the Life of a Scientist*, Cambridge University Press, New York 1990).

What about ν, h, GW ?

CTA is happening right here: high expectations for DM searches





Before their light is switched off

Use MAGIC VERITAS and HESS
for dSph deep field?


Happy 15th Birthday!
Major Atmospheric Gamma-Ray Imaging Cherenkov Telescopes
MAGIC