MAGIC
Major Atmospheric
Gamma Imaging
Cerenkov Telescopes

Dark Matter searches with the MAGIC telescopes

Image Credit: Urs Leutenegger (@urs.leutenegger)

FAKULTET ZA FIZIKU
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On behalf of the MAGIC collaboration

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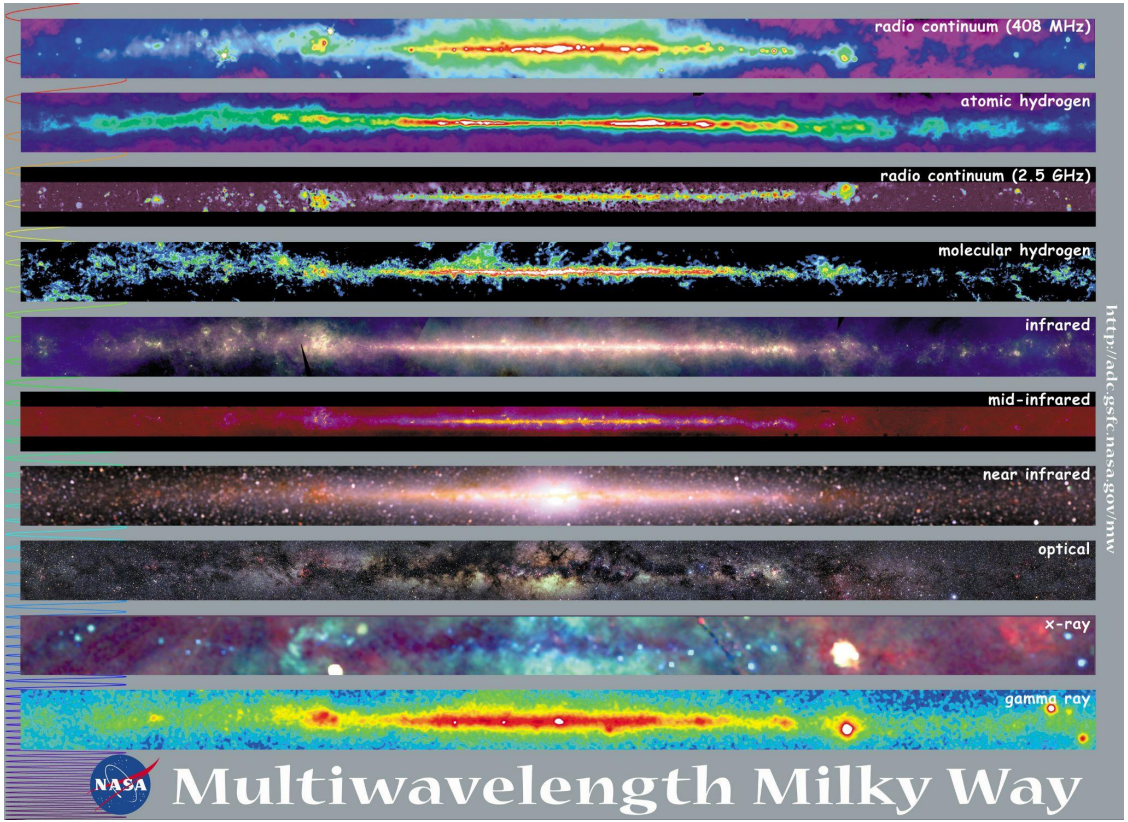
Observations across the electromagnetic spectrum…



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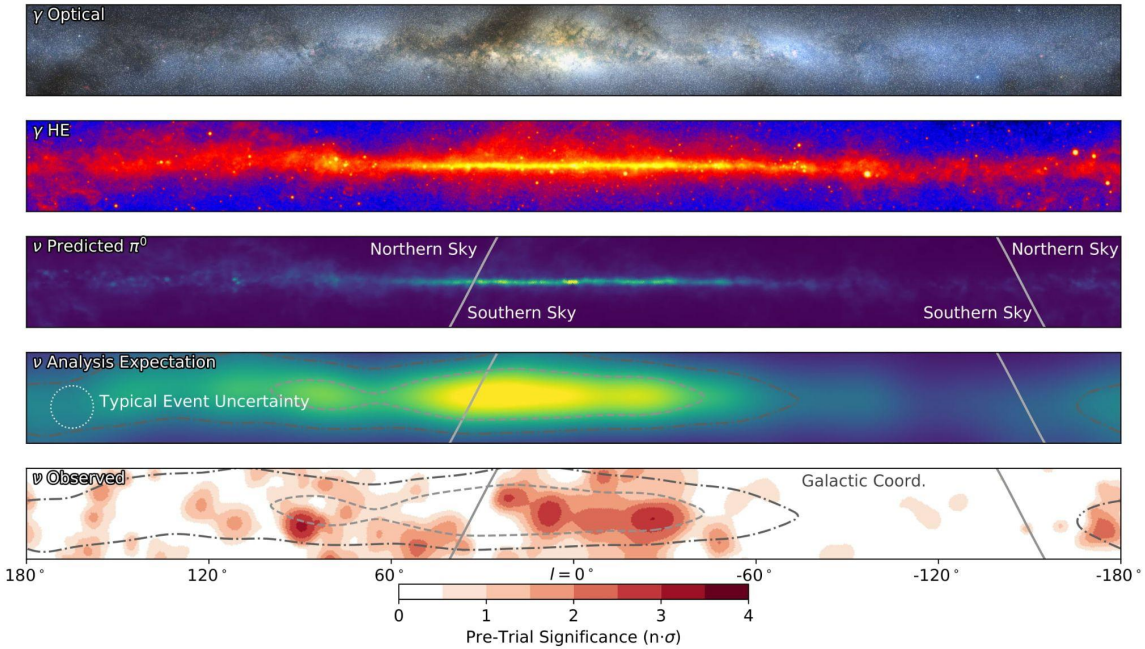
And beyond!



IceCube collaboration, 2023, Vol. 380, No. 6652

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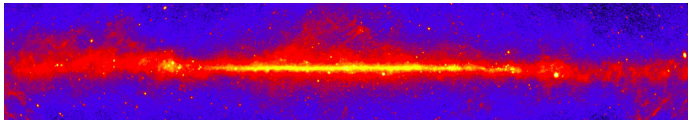
Gamma rays

High-energy gamma rays (HE)

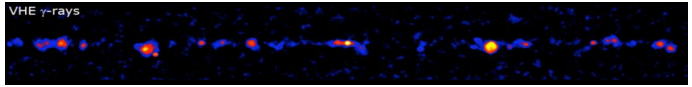
0.1 GeV < E < 100 GeV



Credit: NASA/DOE/Fermi LAT Collaboration

Very-high-energy gamma rays (VHE)

Energy: > 100 GeV



Credit: Dmitry V. Semikoz, lectures on High Energy astroparticle physics (observations by the H.E.S.S. telescopes)

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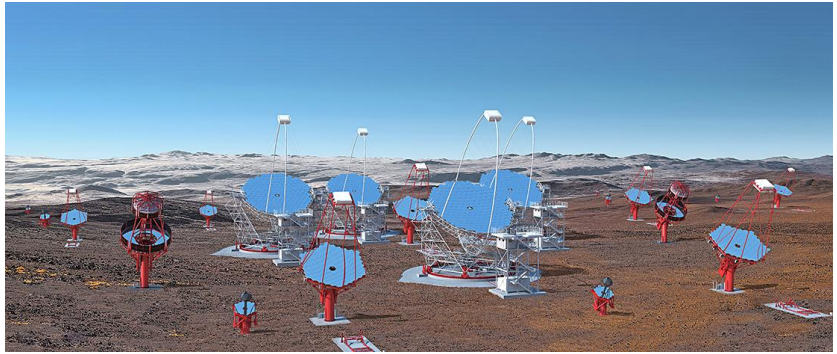
Imaging Atmospheric Cherenkov telescopes

Credit: FACT collaboration

Credit: Daniel Lopez, IAC

Credit: Klepser, DESY, H.E.S.S. collaboration

Credit: VERITAS collaboration



Credit: CTAO (Cherenkov Telescope Array Observatory, under construction)

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Extensive Air Showers (EAS)

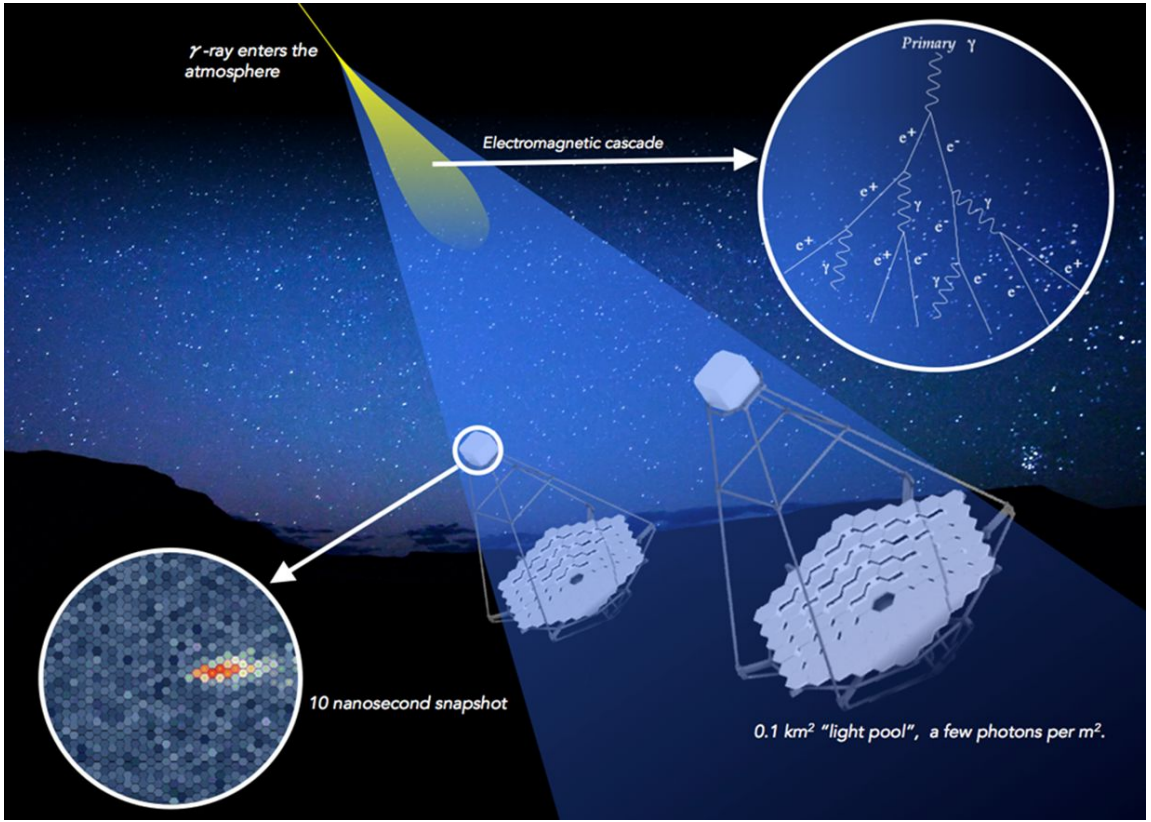

Image credit: CTAO

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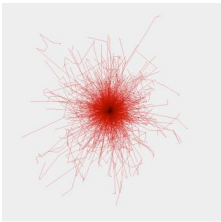
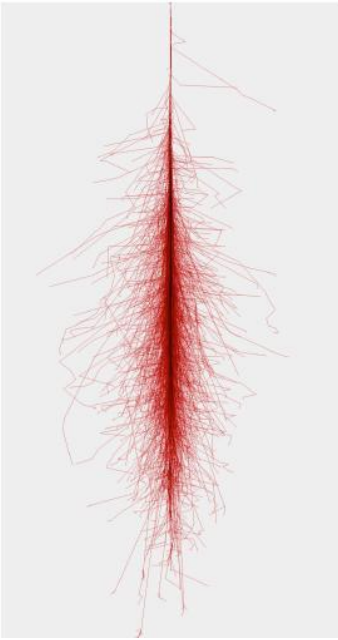
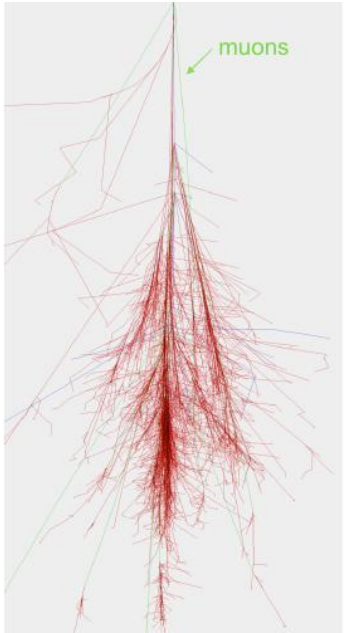
Extensive Air Showers

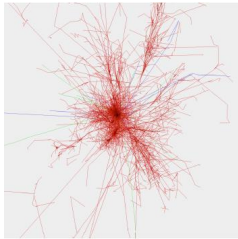
50 GeV gamma







100 GeV proton



Credit: CorsiKa Air shower simulation program – https://www.iap.kit.edu/corsika/

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MAGIC (Major Atmospheric Gamma ray Imaging Cherenkov telescopes)

Credit: Giovanni Ceribella

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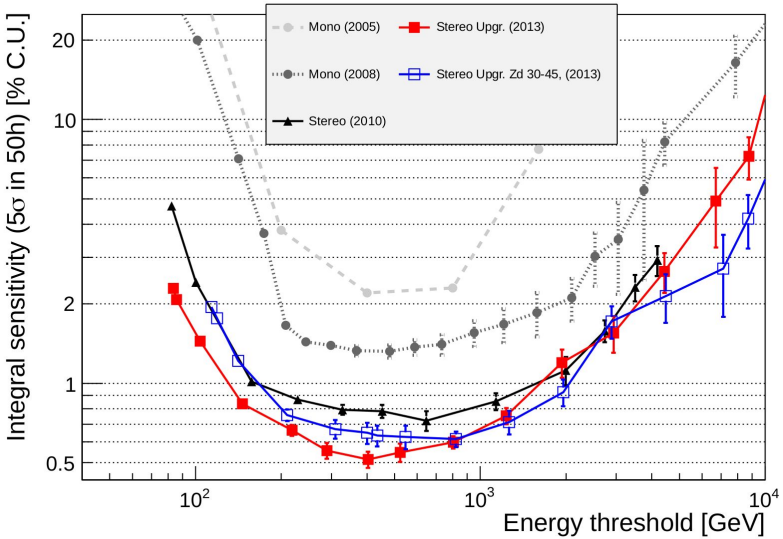
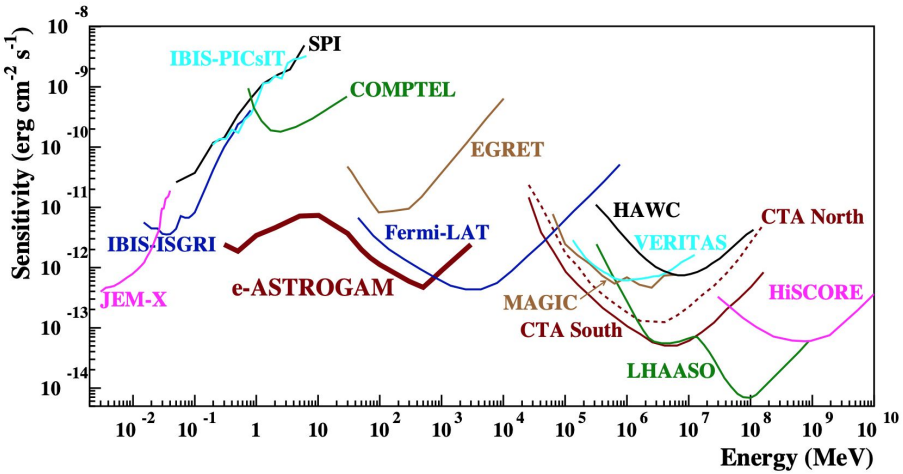
MAGIC telescopes: Characteristics

- MAGIC I from 2004, MAGIC II from 2009
- Located in the Canary island of La Palma, 2200m a.s.l
- Mirror dish diameter: 17 m
- Active reflective mirror surface: 236^2 m
- Upgrade of MAGIC I camera and readout system in 2012
- 1039 PMTs cameras (FoV 3.5°)
- Energy range: 30 GeV to 100 TeV
- Fast repositioning (180° in less than 30s)
- Energy threshold can be lowered to 15 GeV
- Sensitivity above 220 GeV is ~0.66% of the Crab nebula flux (for 50 hs)
- In total 300 MAGICians from 12 countries

MAGIC telescopes: Sensitivity



-Aleksić et al. 2016, Astroparticle Physics 72, 76-94



-De Angelis et. al, 2017, Experimental Astronomy 44, 25-82

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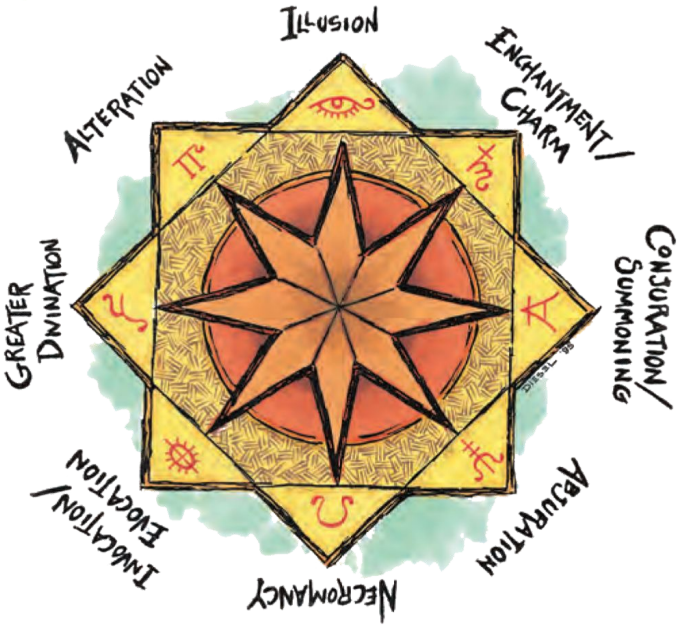
Schools of MAGIC



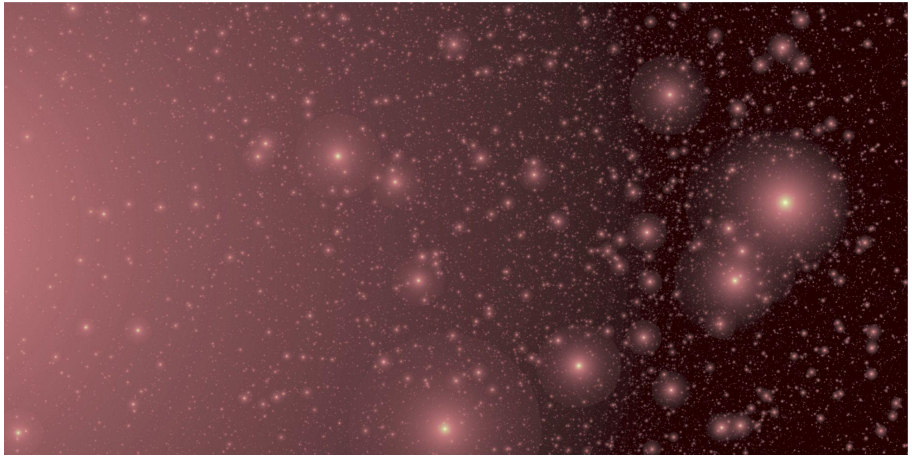
Physics working groups

- Astroparticle and Fundamental Physics
- Transients objects
- Galactic objects
- Extragalactic objects

Image Credit: Mikolaj Lasota

Dark MAGIC

Dark matter studies in MAGIC are pursued by many different projects:



http://clumpy.gitlab.io/CLUMPY/_images/DMsky_pink.png

- Dark Matter lines in the Galactic Center
- Dwarf spheroidal satellite galaxies observations
- Multi-dSphs combined analysis
- Galaxy clusters
- Axion-like particles hunting

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Indirect Dark Matter searches

WHAT?

WIMPs vs. WISPs

HOW?

- Dark matter signal is expected to be embedded in the spectrum of the astrophysical sources
- Observations of gamma-rays spectra
- Annihilation and decay in the Standard Model particles and other signatures in the spectra

WHERE?
Classical targets

- The Galactic Centre
- Dwarf spheroidal galaxies
- Galaxy clusters

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Dark Matter flux and J-factors

Annihilation

$$\frac{d\Phi}{dE\,d\Omega} = \frac{1}{4\pi}\frac{\langle\sigma v\rangle}{2\,m_{DM}^2}\frac{dN_\gamma}{dE}\frac{dJ_{ann}}{d\Omega}$$

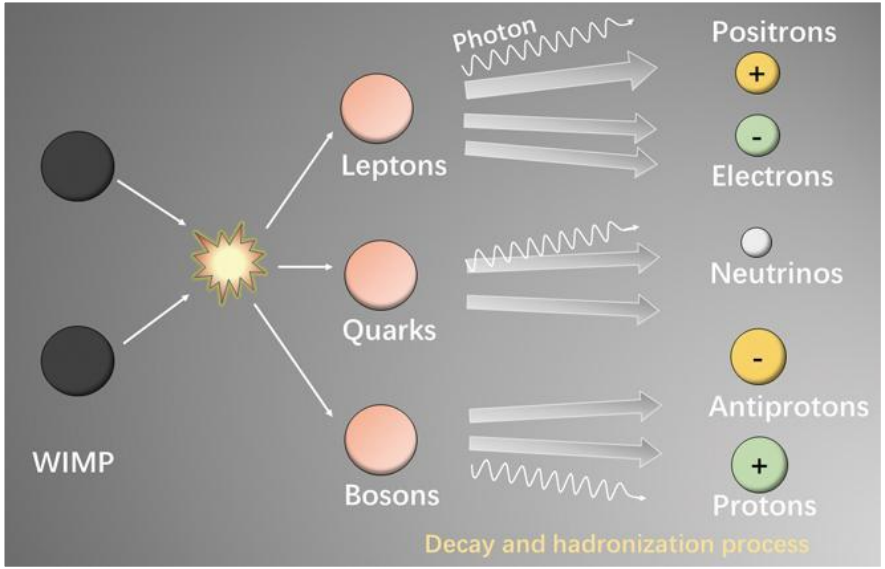
$$\frac{dJ_{ann}}{d\Omega} = \int_{l.o.s} dl\,\rho^2(l,\Omega)$$

Decay

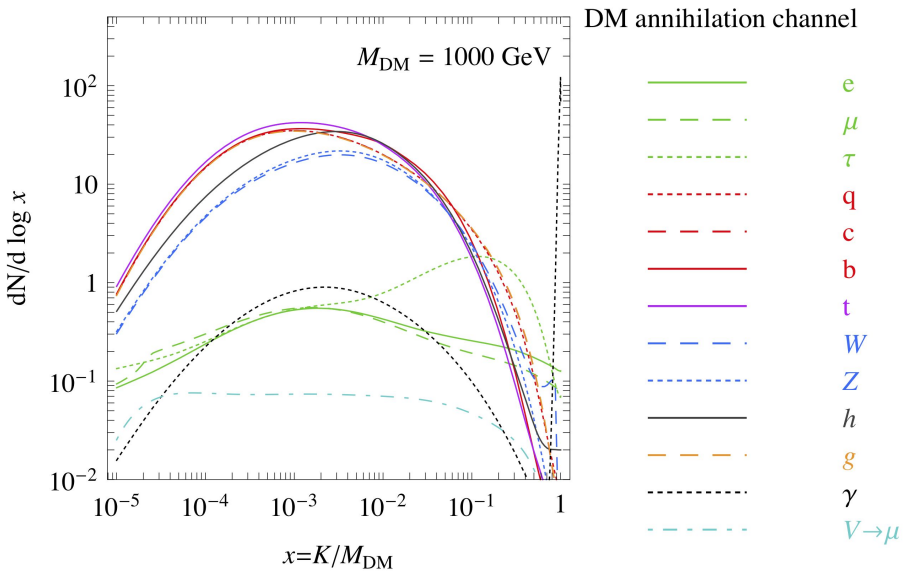
$$\frac{d\Phi}{dE\,d\Omega} = \frac{1}{4\pi}\frac{1}{\tau_{DM}m_{DM}}\frac{dN_\gamma}{dE}\frac{dJ_{dec}}{d\Omega}$$

$$\frac{dJ_{dec}}{d\Omega} = \int_{l.o.s} dl\,\rho\,(l,\Omega)$$

Dark Matter flux and J-factors

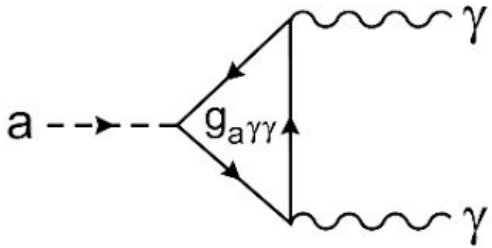


Principle of indirect detection of dark matter, credit: GAO Linqing and LIN Sujie



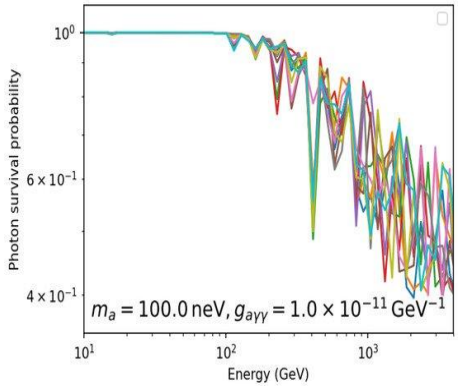
Primary DM gamma-ray spectra for various annihilation models, extracted from: Cirelli et al., JCAP 2011, 1103, 051

WISPs-ALPs



Feynman diagram of photon-axion interaction

- ALPs □ axion - solution to the Strong CP problem
- Photon-ALP mixing in the external magnetic field
- Irregularities (wiggles) in the spectra of astrophysical targets
- Knowledge of the magnetic fields is fundamental for producing the ALPs models



Photon survival probability
(https://github.com/me-manu/gammaALPs)

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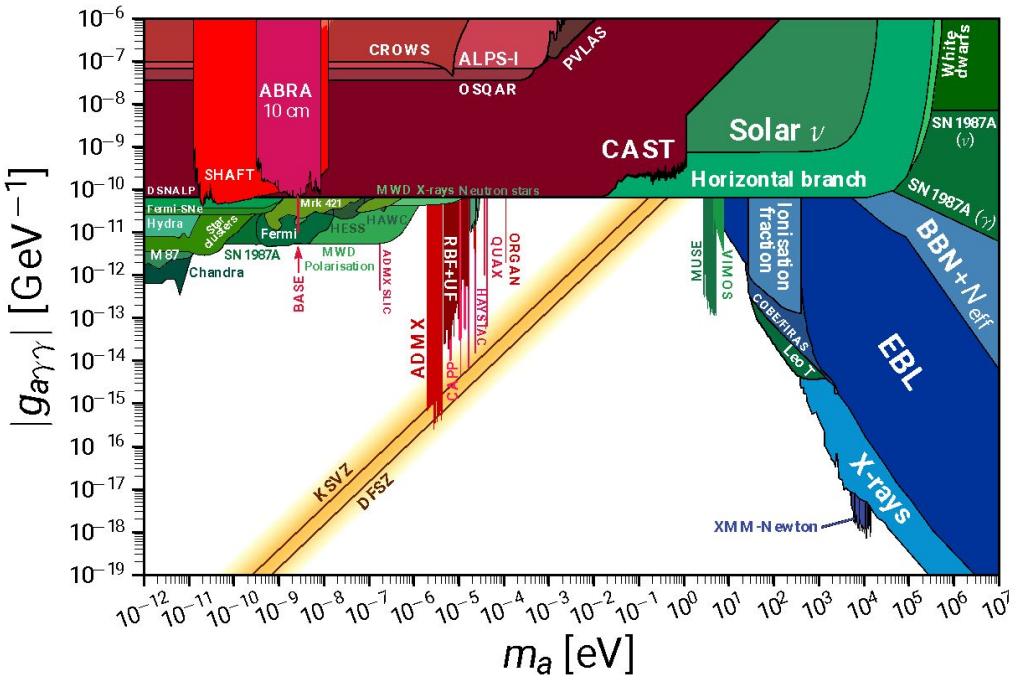
WISPs-ALPs



ALPs parameter space with current constraints, (https://cajohare.github.io/AxionLimits/), on the date 16/05/2022

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Target sources

Dwarf spheroidal galaxies (dSphs)

Image credit: ESO/Digitized Sky Survey 2

Milky-Way center (GC)

Image credit: X-ray: NASA/CXC/SAO; Optical: Detlef Hartmann; Infrared: NASA/JPL-Caltec

Galaxy clusters

Image credit: NASA/CXC/SAO/E.Bulbul, et al.

MAGIC campaigns for DM searches

Target	Year	Time (h)	Constraint	Reference
The Milky Way				
MW Outer Halo	2018	10	Decay	Ninci et al., PoS, 2019, ICRC2019, 538
MW inner Halo	2023	204	Annihilation–DM lines	Abe et al., Phys. Rev. Letters, 130, 061002 (2023)
Dwarf Satellite Galaxies				
Draco*	2007	7.8	Annihilation	Albert et al., ApJ 200, 679, 428–431
Draco	2018	52.6	Annihilation	Acciari et al., Phys. Dark Univ. 2022, 35, 100912
Wilman 1	2008	15.5	Annihilation	Aliu et al., ApJ 2009, 697, 1299–1304
Segue 1*	2008 - 2009	29.4	Annihilation	Aleksić et al., J., Cosmology Astropart. Phys. 2011, 1106, 035
Segue 1	2010 - 2013	157.9	Annihilation + Decay	Aleksić et al., J. Cosmology Astropart. Phys. 2014, 1402, 008
			Annihilation	Ahnen et al., J. Cosmology Astropart. Phys. 2016, 1602, 039
Coma Berenices	2018	50.2	Annihilation	Acciari et al., Phys. Dark Univ. 2022, 35, 100912
Ursa Major II	2014 - 2016	94.8	Annihilation	Ahnen et al., JCAP 951, 2018, 1803, 009
Triangulum II	2014 - 2016	62.4	Annihilation	Acciari et al., Phys. Dark Univ. 2020, 28, 100529

Extracted from: arXiv:2111.01198,
* monoscopic observations

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MAGIC campaigns for DM searches

Target	Year	Time (h)	Limit	Reference
Dark Satellites				
1FGL J2347.3+0710	2010	8.3	–	Nieto et al. arXiv e-prints 2011, p. arXiv:1109.5935
1FGL J0338.8+1313	2010 - 2011	10.7	–	Nieto et al., arXiv e-prints 2011, p. arXiv:1109.5935
Intermediate Mass Black Holes				
Galactic Plane*	2005 -2006	25	Annihilation	Doro et al., Proceedings of the 30th ICRC, 2007
Galaxy Clusters				
Perseus (Abell 426)	2008	24.4	Annihilation	Aleksić et al., ApJ 2010, 710, 634–647
Perseus (Abell 426)*	2009 - 2017	202.2	Decay	Acciari et al., Phys. Dark Univ. 2018, 22, 38–47

Extracted from: arXiv:2111.01198,
* monoscopic observations

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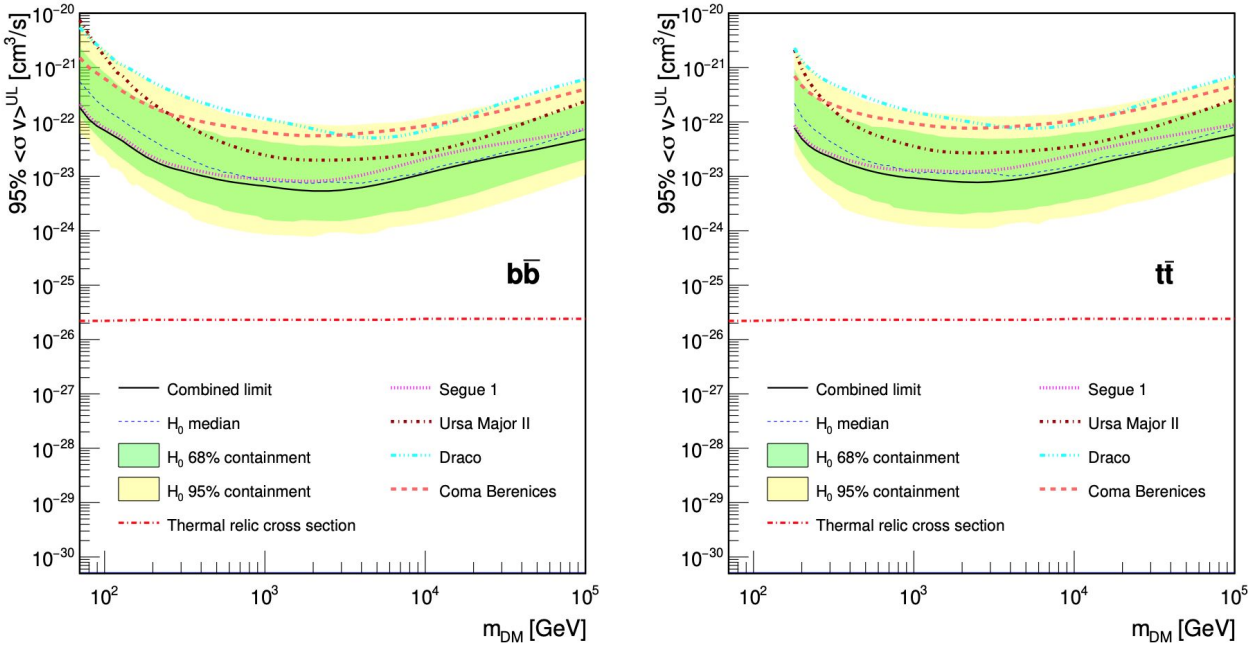
Searches for DM in dSphs with MAGIC

- 4 dSphs, combination of data from a multi-year observation program
- Total of 354.3 hours of good quality data
- Increasing the statistics □ better sensitivity
- 95% CL upper limits on velocity – averaged annihilation cross section for 9 channels are obtained

Target	$\log_{10} J(\theta_{\max})$ [$\mathrm{GeV^2 cm^{-5}}$]	$\theta_{\max}$ [deg]	$\theta_{0.5}$ [deg]	T_{eff} [h]	Year
Coma Berenices	$19.02^{+0.37}_{-0.41}$	0.31	$0.16^{+0.02}_{-0.05}$	49.5	2019
Draco	$19.05^{+0.22}_{-0.21}$	1.30	$0.40^{+0.16}_{-0.15}$	52.1	2018
Ursa Major II	$19.42^{+0.44}_{-0.42}$	0.53	$0.24^{+0.06}_{-0.11}$	94.8	2016–2017
Segue 1	$19.36^{+0.32}_{-0.35}$	0.35	$0.13^{+0.05}_{-0.07}$	157.9	2011–2013

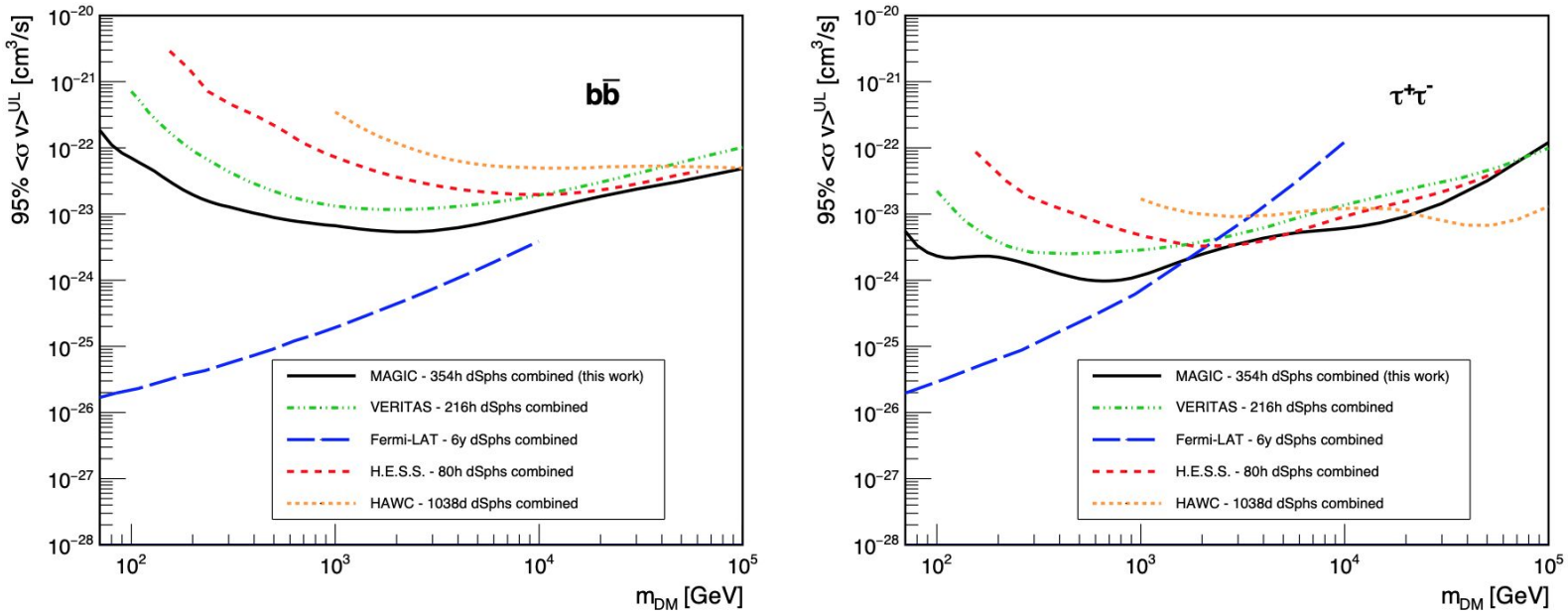
Table of sources and corresponding info,
Acciari at al. 2022, Phys. Dark Universe 35, 100912, leading author: Camilla Maggio

Searches for DM in dSphs with MAGIC



95% C.L. ULs for $<\sigma_{ann}v>$ for DM annihilation into bb and tt channels, Acciari et al. 2022, Physics of the Dark Universe 35, 100912, leading author Camilla Maggio

Searches for DM in dSphs with MAGIC



95% C.L. ULs for $<\sigma_{ann}v>$ for DM annihilation into bb and tau+tau- pairs, in comparisons with the results from other experiments , Acciari et al. 2022, Physics of the Dark Universe 35, 100912, leading author Camilla Maggio

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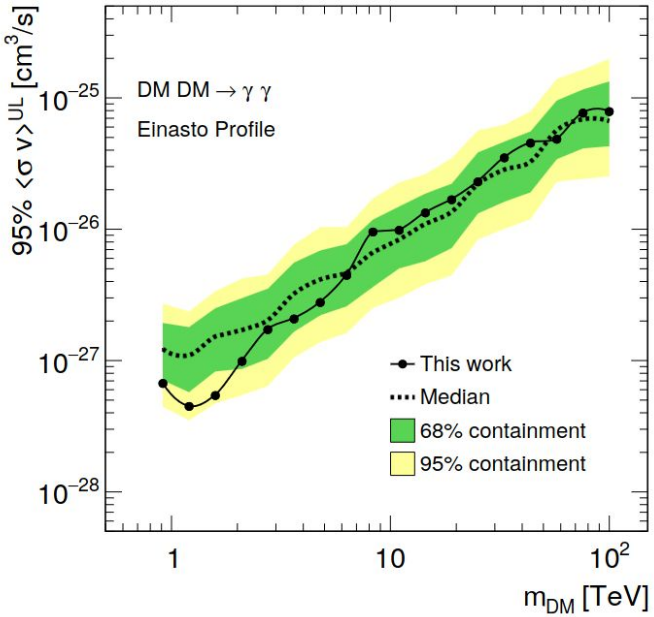
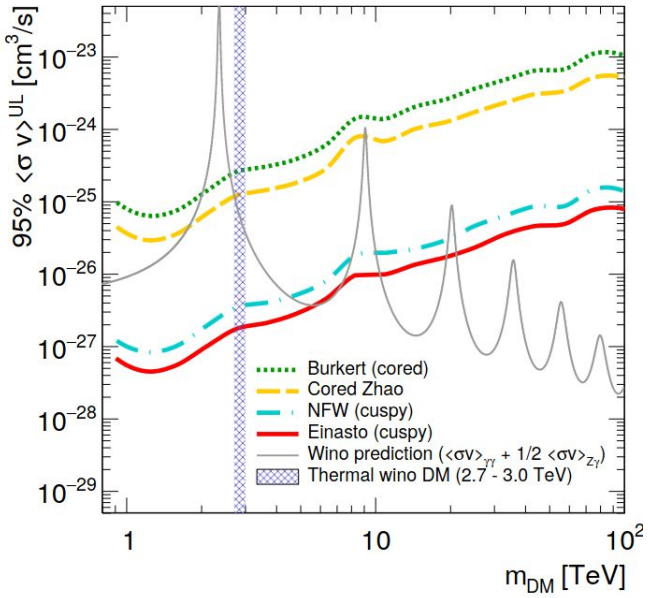
Line-like features in the GC with MAGIC

- 223 hours of observations of the Galactic Centre region
- Energies reaching up to 100 TeV
- High zenith angles increase the energy threshold
- Unbinned likelihood analysis
- No significant excess detected
- Constraints on the cross section for dark matter annihilation into two photons are obtained

Line-like features in the GC with MAGIC

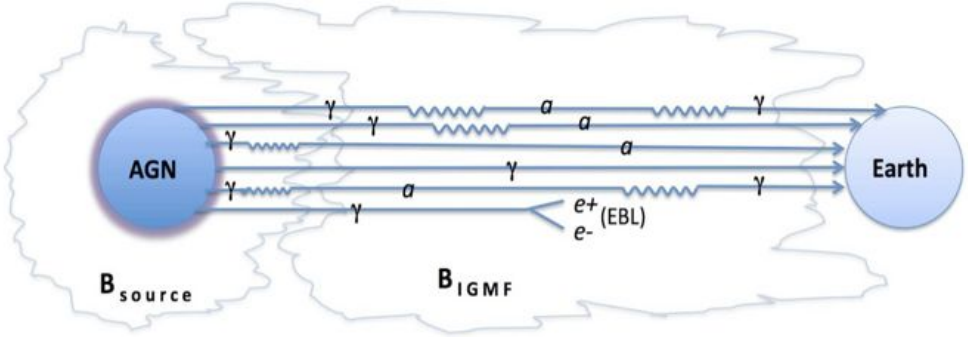




95% CL upper limits on the annihilation cross section (left) and upper limits for the four DM density profiles (right) credit: Abe et al. 2023, Phys. Rev. Letters 130, 061002, leading author: Tomohiro Inada

ALPs searches in the Perseus cluster

- Photon – ALP mixing external magnetic field
- Flaring states increased constraining power
- 40.2 hours of NGC1275 data & 3.5 hours of IC310 data

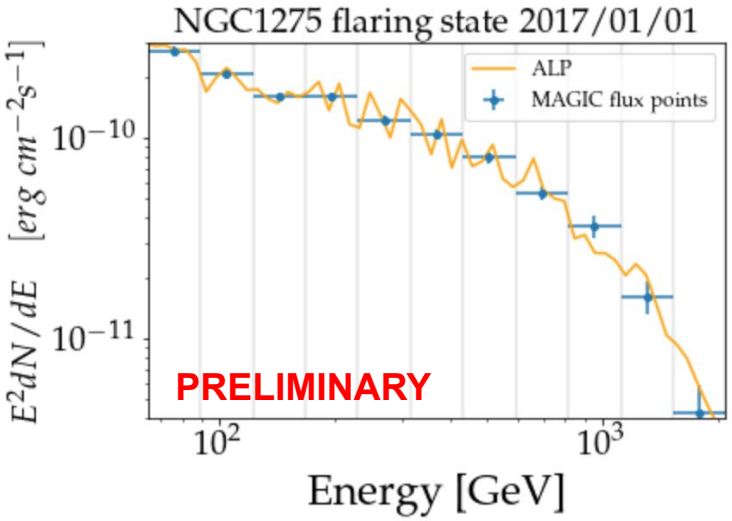


- mixing in the blazar + jet
- mixing in the magnetic field of the galaxy cluster
- mixing in the extragalactic magnetic field + ($\gamma + \gamma \rightarrow e^+ + e^-$)
- back-conversion in the galactic magnetic field

Photon-ALP mixing in the magnetic field, credit: M.A. Sanchez Conde et al., 2009, Phys.Rev.D79:123511

ALPs searches in the Perseus cluster

Binned likelihood $-\mathcal{L}(\theta, b) = \mathcal{L}(m_a, g_{a\gamma}; B, \Gamma, \Phi_0, E_c | b)$



- Model with fixed magnetic field realisation
- In the case of ALPs, due to the unknown magnetic field, random magnetic field realisations have to be employed to calibrate the test statistics for excluding the ALPs parameters.

Comparison of the MAGIC flux points with and w/out the ALPs model included.
MAGIC collaboration, in preparation, 2023, leading author Ivana Batković

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Conclusions

- MAGIC has been very active in the DM searches with several DM campaigns over the years
- Study of the data from dSphs gave the most stringent limits in the TeV regime
- Results agree with the constraints set with other gamma-ray experiments
- Advancement of the multi-instrument analysis allows for more detailed studies
- Studies of the galactic centre are limited by the high energy threshold, but result in the boosted DM line-like signal
- Constraints on both cuspy and core profiles are set
- Axion-like particle searches show the potential on constraining the ALPs parameter space
- Irregularities (wiggles) in the spectra of astrophysical targets are investigated
- Knowledge of the magnetic fields is fundamental for producing the ALPs models

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Thanks for your attention!

Image Credit: Chiara Righi (@chirighi)

@MAGICtelescopes