# Dark Matter Searches with the MAGIC Telescopes

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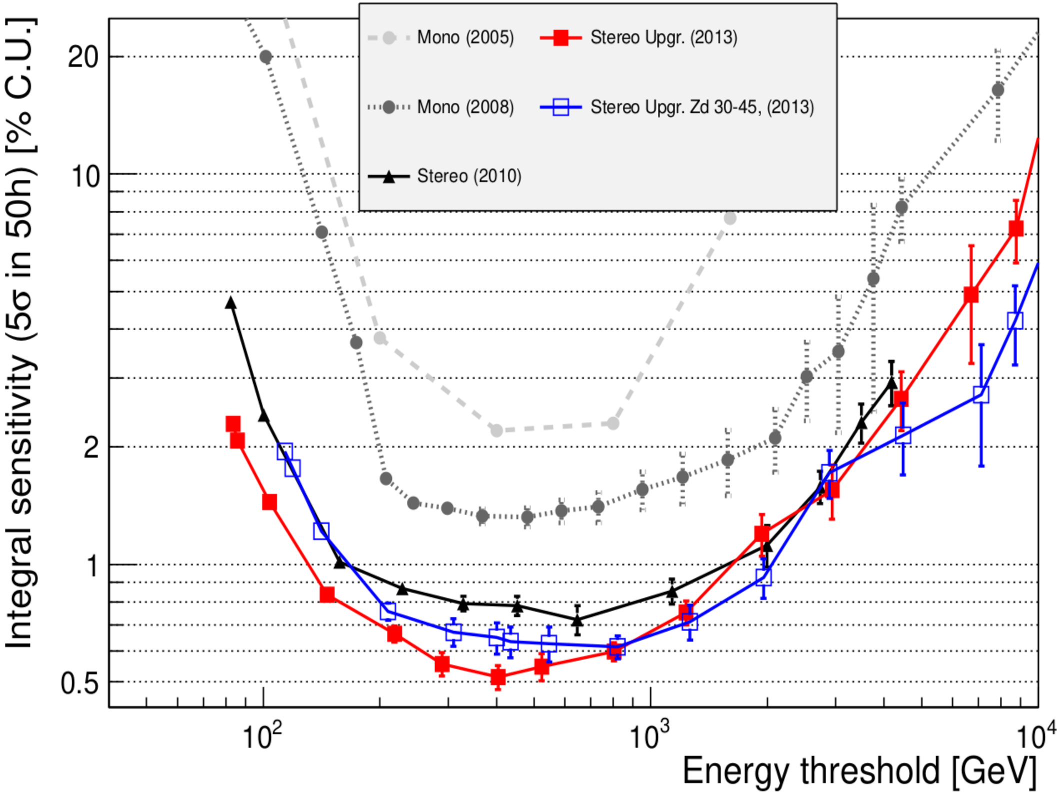
MAGIC

# Outline

- The MAGIC telescopes
- WIMP Dark Matter Searches
- MAGIC combined Search with dSphs
- MAGIC observation of Galactic Centre
- ALP Searches
- Summary

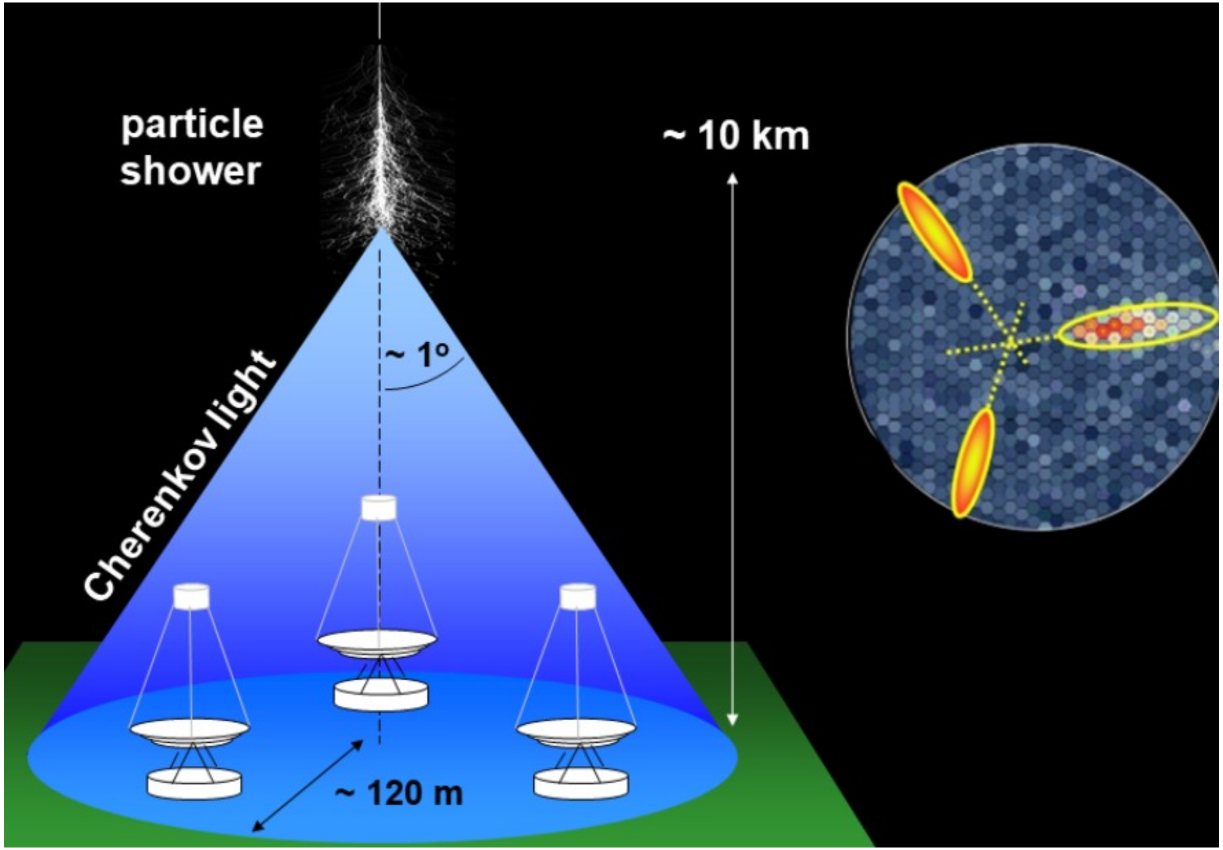
# MAGIC Telescopes

- A system of two Imaging Atmospheric Cherenkov Telescopes
- International collaboration of about 300 members from 13 countries
- Working since 2 decades ! in stereo mode from 2009
- 25GeV-100TeV energy range
- 17m reflector → low energy thresh.
- light structure → fast repositioning for GRB
- field of view of ~3.5°
- angular resolution ~ 0.1° (energy dependent)
- energy  resolution 15-25 %
- At Obs. Roque de los Muchachos, La Palma, Canarias (~2200 m asl)



# Imaging Atmospheric Cherenkov Telescopes

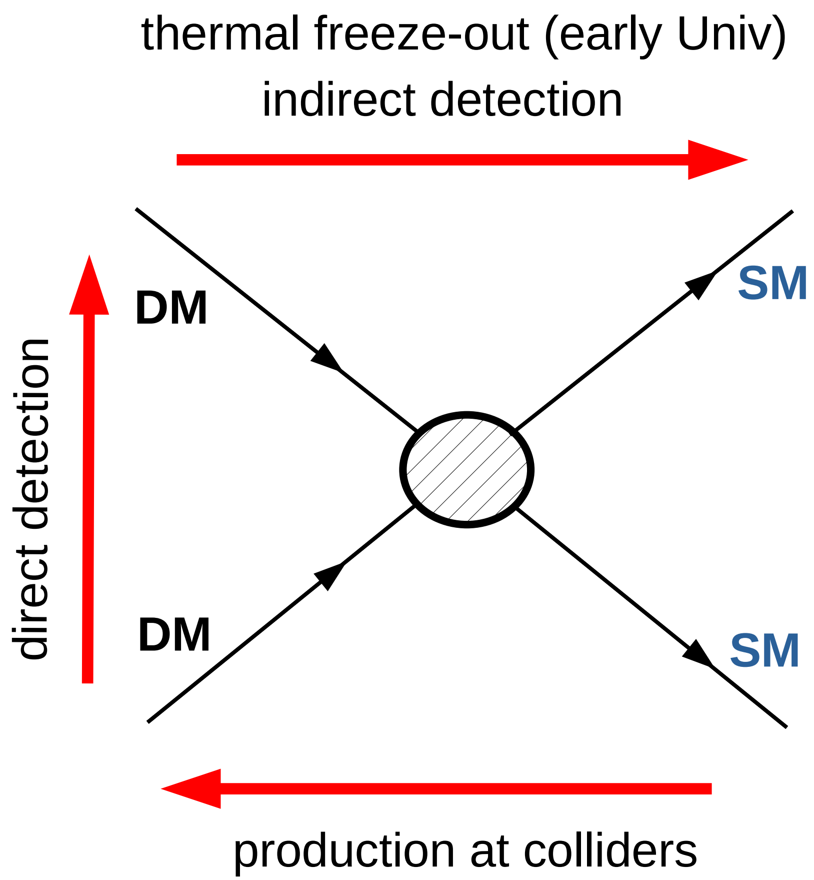
- Very High energy gamma rays (charged cosmic rays) enter the atmosphere and produce extensive air showers
- IACTs detect the photo emission of secondary electrons and record images of the air showers
- Energy, orientation and classification (gamma/hadron) of the primary particle  are obtained with a detailed image analysis



# WIMP Dark Matter Searches

- Weakly interacting massive particles
- relic density from freeze-out mechanism
- weak coupling and electroweak mass scale $\rightarrow$ correct relic density

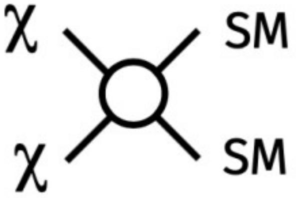
$$\frac{\Omega_\chi h^2}{0.1} \approx \frac{3 \times 10^{-26} \mathrm{cm}^3 \mathrm{s}^{-1}}{\langle \sigma v \rangle}$$



# Gamma-ray flux from DM

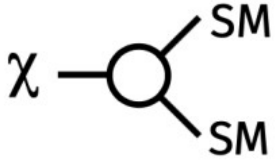
self-annihilation

$$\frac{d\Phi^{ann.}}{dE_\gamma} = \frac{1}{4\pi}\frac{\sigma v}{2m_\chi^2} \times \sum_i BR_i \frac{dN_\gamma^i}{dE} \times \int_{\Delta\Omega}\int_{los} ds\ \rho^2(s,\ \Omega)$$




decay

$$\frac{d\Phi^{dec.}}{dE_\gamma} = \frac{1}{4\pi}\frac{1}{m_\chi \tau_\chi} \times \sum_i BR_i \frac{dN_\gamma^i}{dE} \times \int_{\Delta\Omega}\int_{los} ds\ \rho(s,\ \Omega)$$

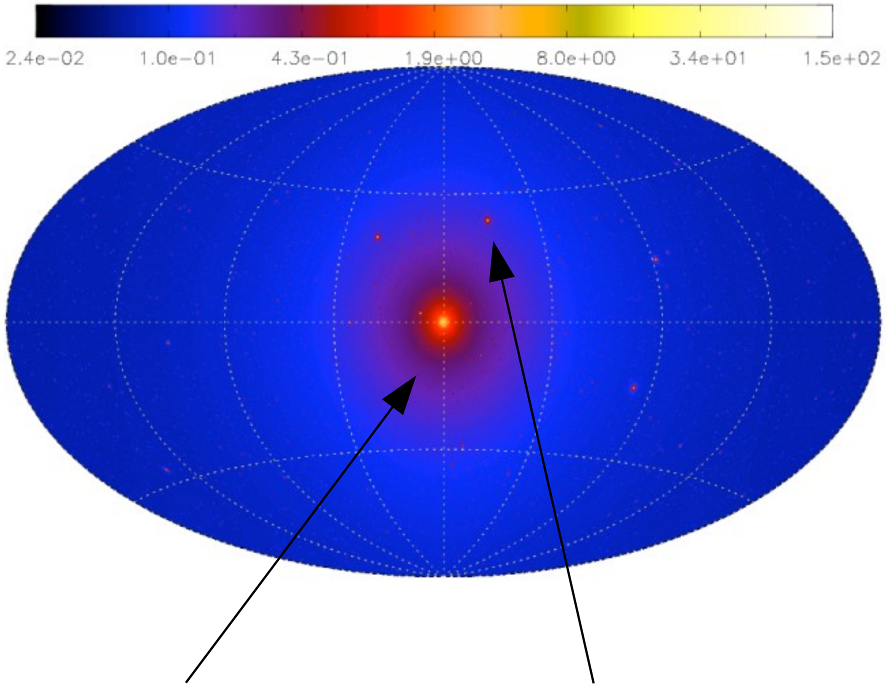



particle ph. Astroph.

- Gamma emission from large  DM over-densities
- via self-annihilation or decay

# DM Density Distribution

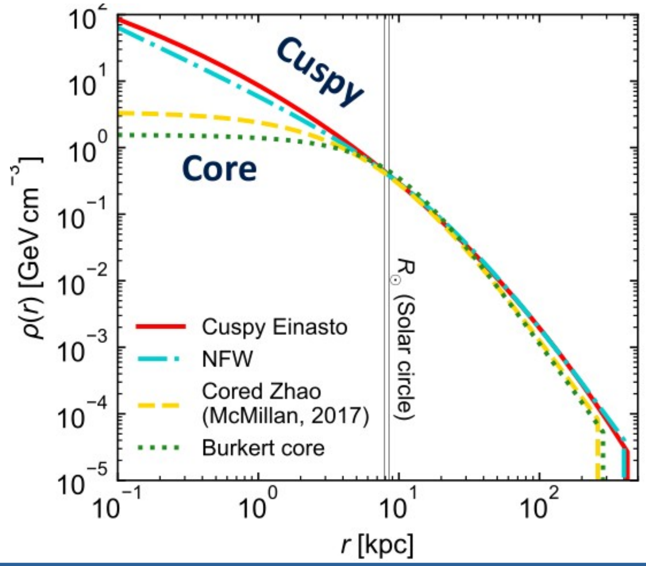
- DM forms halos
- Density distribution in the central halo region not directly observed
- Strong effect on the expected gamma ray flux
- Galactic Centre: highest J-Factor, but large astrophysical background and source confusion
- Milky Way satellites: reasonable  J-Factor, almost clean from background




GC

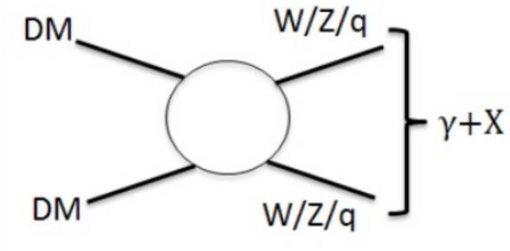
dwarf spher. gal

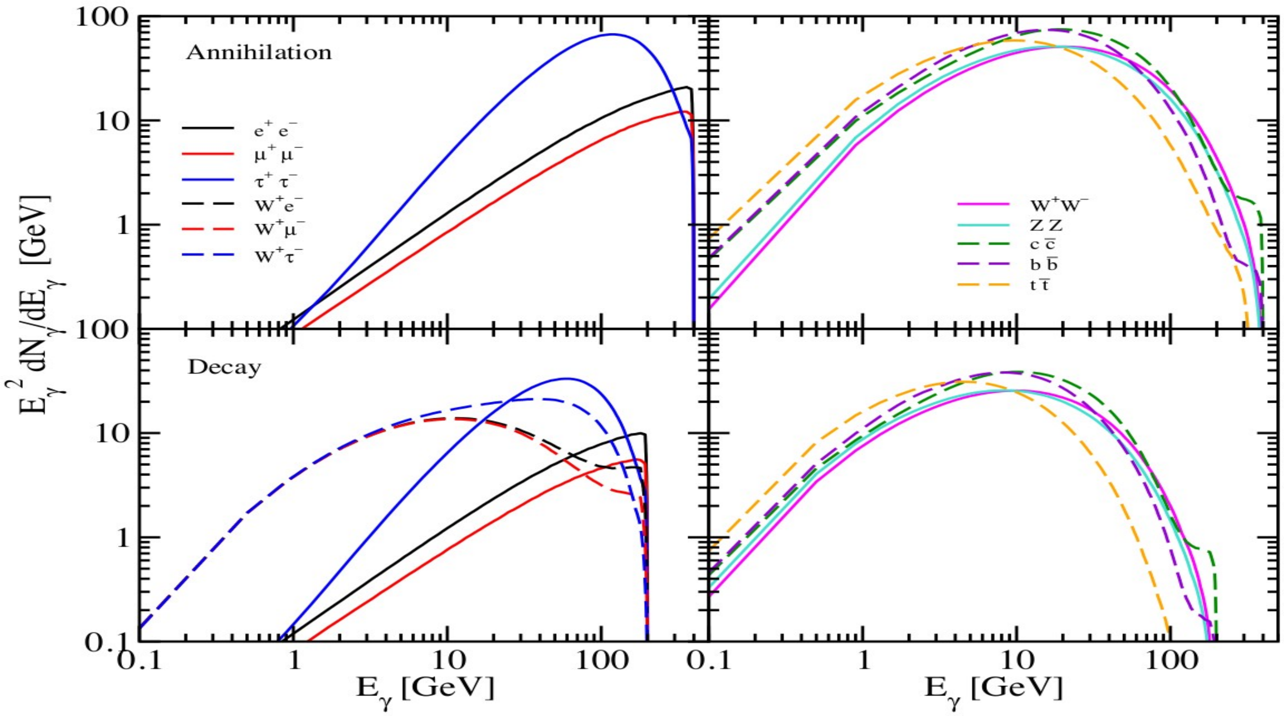
GC J-factor



# Annihilation Photon Yields

- Annihilation in SM pairs
- SM primaries → secondary gamma rays (via meson production and decay, final state gamma radiation, etc..)
- For each channel → channel photon yield
- Total photon yield of a specific DM candidate is the sum of each channel photon yield weighted for the branching ratio




S.Palomares-Ruiz, J.Siegal-Gaskins
JCAP 1007:023,2010

# MAGIC DM Searches

- **Galactic Center, large signal**

  - H. Abe, et al. Physical Review Letters, 130, 6 (Lines from Dark Matter toward the GC)

- **Dwarf Spheroidal Galaxies, clean environment**

  -J. Albert et al. ApJ, 679:428–431, 2008 (Draco),

  -E. Aliu et al. ApJ, 697 (Willmann1),

  -Aleksić et al.JCAP 1402:008, 2014 (Segue I),

  -JCAP 03(2018) 009 (UrsaMajor II),

  -PDU 28 (2020) 100529 (Triangulum II),

  -PDU 35, 2022,100912 (combined 350+h, 4 dSphs)

- **Galaxy Clusters, MW Halo, Fermi sources**

  -J. Aleksić et al. ApJ, 710:634–647, 2010(NGC 1275)
  -V.Acciari et al, PDU 22, 2018, (decay in Perseus Cluster )
  -D. Ninci, et al. PoS, ICRC2019:538, 2019 (decay in MW galactic halo)
  -D. Nieto et al, arXiv:1109.5935, Sep 2011 (1FGL J2347.3+0710, 1FGL J0338.8+1313 )

- **AGNs/axions:**

  - ongoing works

# Combined Search with dSphs

- Combination of data from all observed dSph
- Maximize sensitivity
- J-factor and experimental effects to be carefully taken in account
- 350+ hours of observation
- J factors from Geringer-Sameth, et al ApJ 801,74, 2015
- $\theta_{max}$: maximum angular extension
- $\theta_{0.5}$: angular distance containing 50% of the DM emission

| Target | $\log_{10} J(\theta_{max})$ [$GeV^2 cm^{-5}$] | $\theta_{max}$ [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 |

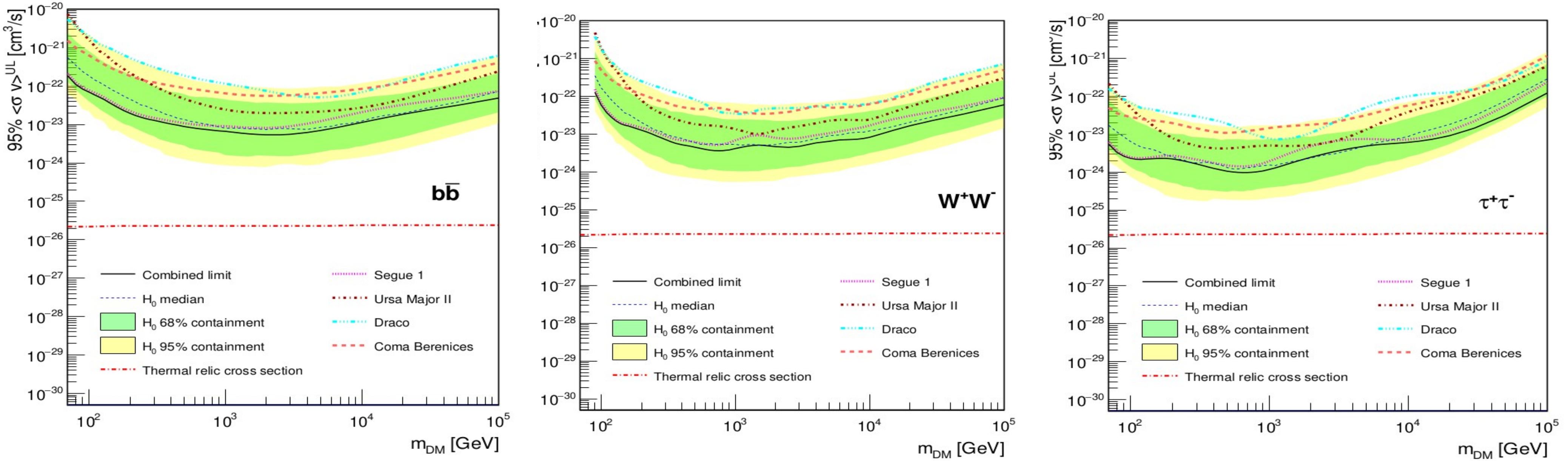
# State of the art likelihood analysis

$$\mathcal{L}(\langle\sigma_{\text{ann}}v\rangle;\boldsymbol{\nu}|\boldsymbol{\mathcal{D}}) = \prod_{t=1}^{N_{\text{target}}}\prod_{k=1}^{N_t}\prod_{i=1}^{2}\mathcal{L}_{tki}(\langle\sigma_{\text{ann}}v\rangle;\boldsymbol{\nu_{tki}}|\boldsymbol{\mathcal{D}_{tki}}).$$

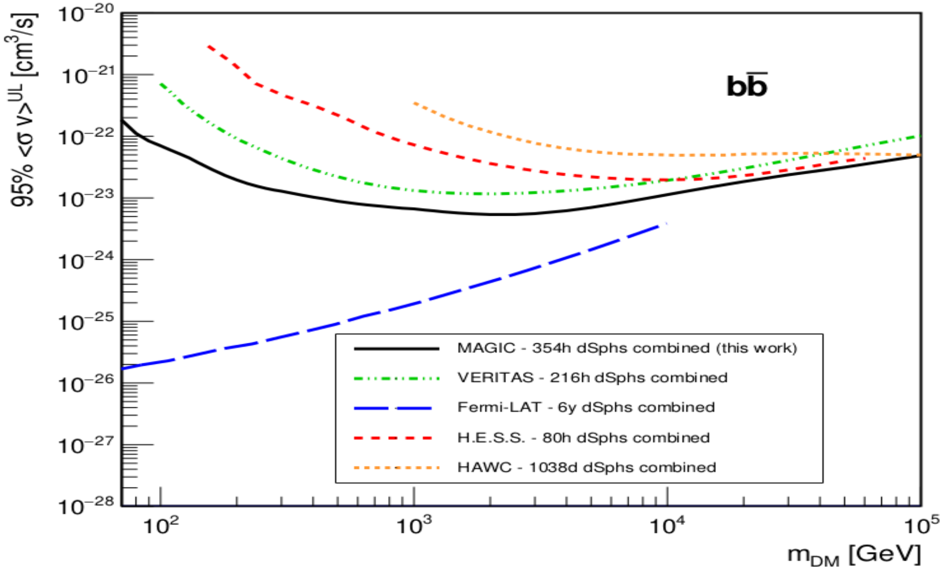
$$\mathcal{L}_{tki}(\langle\sigma_{\text{ann}}v\rangle;\boldsymbol{\nu}|\boldsymbol{\mathcal{D}}) = \prod_{j=1}^{N_{\text{bins}}}\left[\frac{(g_j(\langle\sigma_{\text{ann}}v\rangle,J)+b_j)^{N_{\text{ON},j}}}{N_{\text{ON},j}!}e^{-(g_j(\langle\sigma_{\text{ann}}v\rangle,J)+b_j)} \times \frac{(\tau b_j)^{N_{\text{OFF},j}}}{N_{\text{OFF},j}!}e^{-\tau b_j}\right]$$
$$\times\,\mathcal{T}(\tau|\tau_{\text{obs}},\sigma_\tau)$$
$$\times\,\mathcal{J}(J|\log_{10}J_{\text{obs}},\sigma_{\log_{10}J}),$$

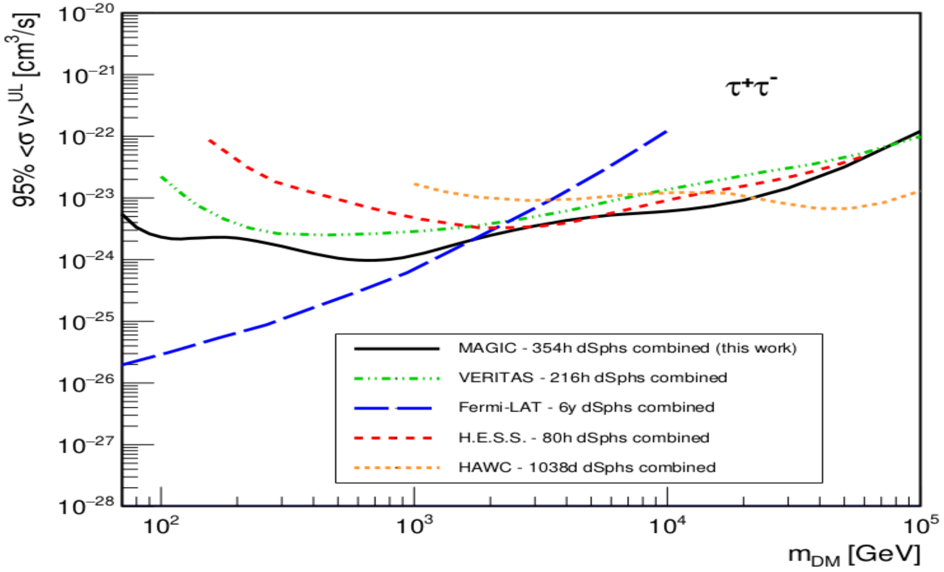
- Used to properly combine different data sets (glike package)
- Likelihood: $N_{on}$ signal counts ($N_{off}$ bck counts), for a given σv and a set of J factors
- t runs over different targets, k over IRFs, I over pointing directions
- Nuisance parameters: τ (ON/OFF normalization), J-factors
- 3 terms: counts prob., τ , J-factors
- From likelihood minimization → sensitivity to a given σv → upper limits
- … used for multi-experiment combination (Glory Duck project)

# Limits on Selected Channels



# Comparison with Existing Limits

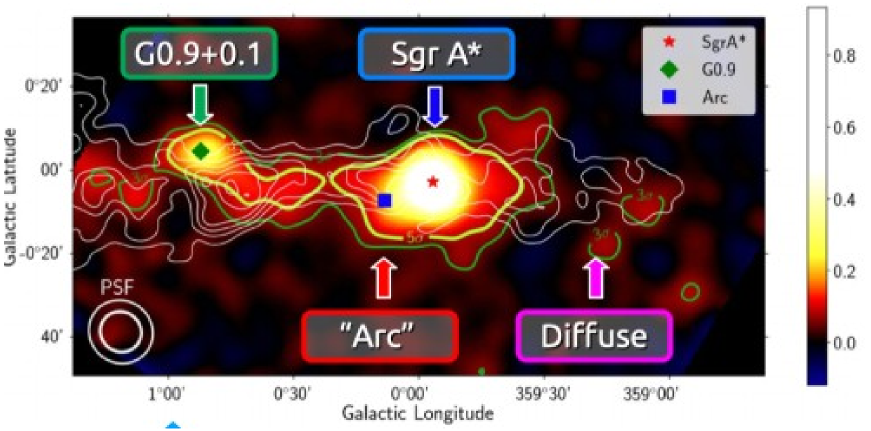


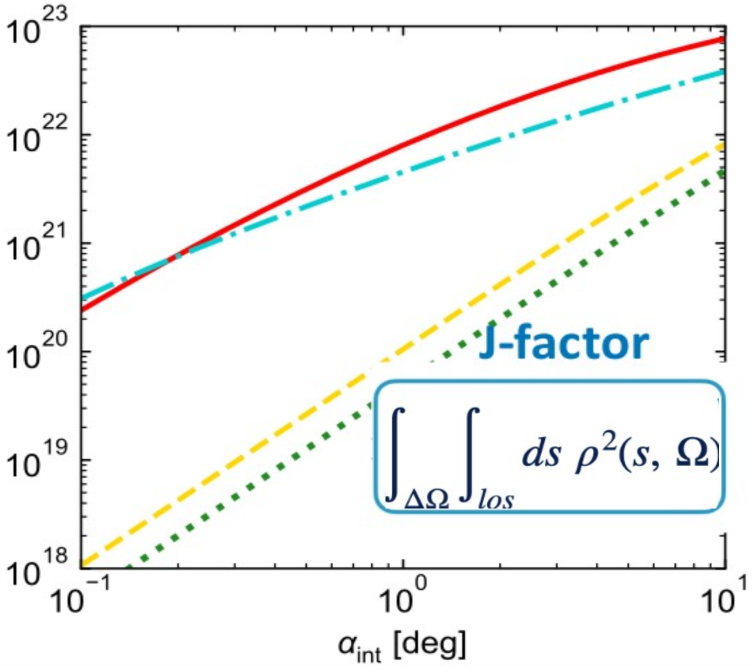



# Galactic Centre

- Pro:  largest J-factor
- Contra: source confusion, extension
- Visible  at low ZA from southern detectors
- MAGIC can observe it only at Large zenith angle:
  - higher energy threshold
  - larger effective collection area,
  specially interesting  for multi-TeV gamma rays

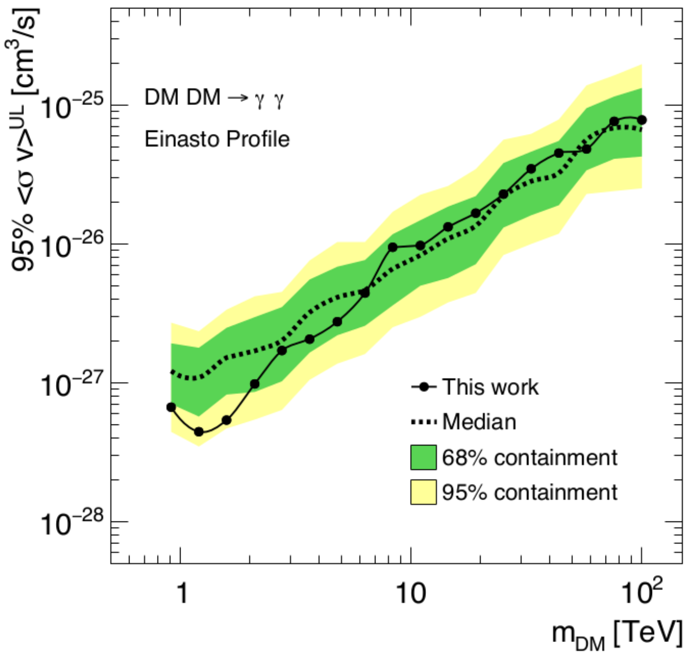
A&A 642, A190 (2020)



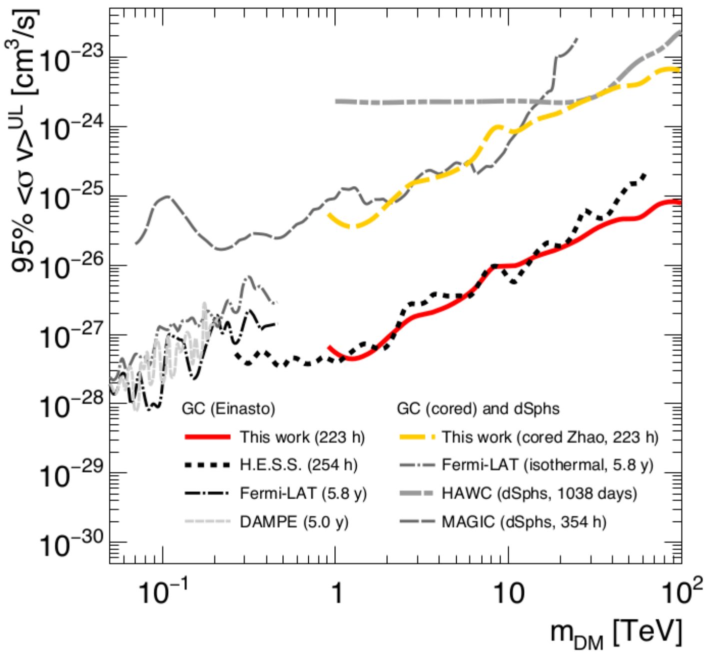
# DM Annihilation Lines from the GC

- search for spectral lines in γ-ray from 0.9 TeV to 100 TeV
- 223 h. exposure
- sensitivity boosted by the LZA observations.
- sliding-window technique in the energy domain to search for a line-like signal
- both cuspy or cored Galactic DM halo studied
- up to a factor 2 better sensitivity above 20 TeV then previous measure-ments
- first time probed up to 100 TeV with IACTs



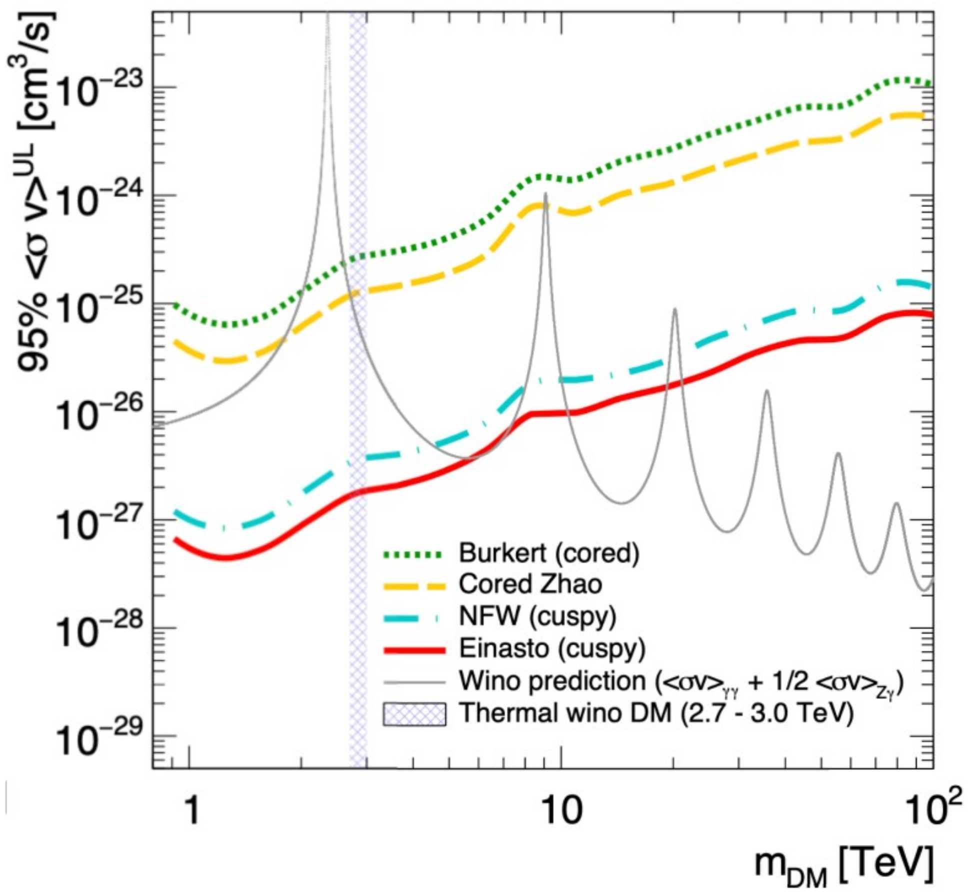

No significant line-like excess found

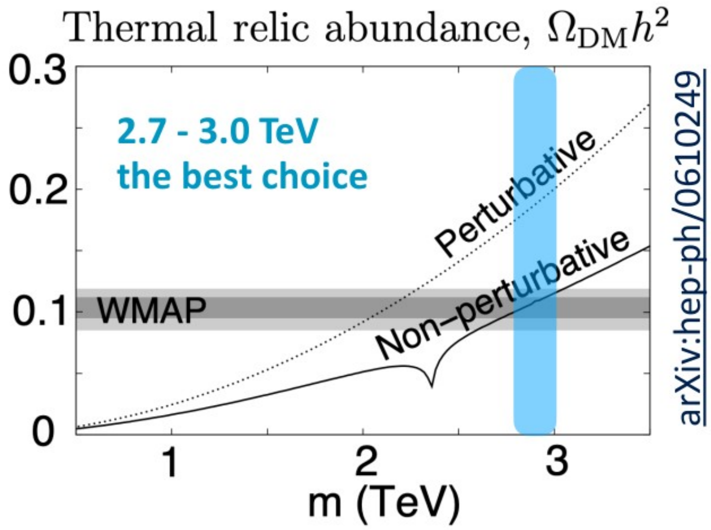
- Set upper limits at 95% C.L. on 18 masses in the range **0.9 TeV - 100 TeV**




- **Einasto : the best limits above 20 TeV**
- **Cored** : competitive with **dSph** results

# Testing SUSY-Wino

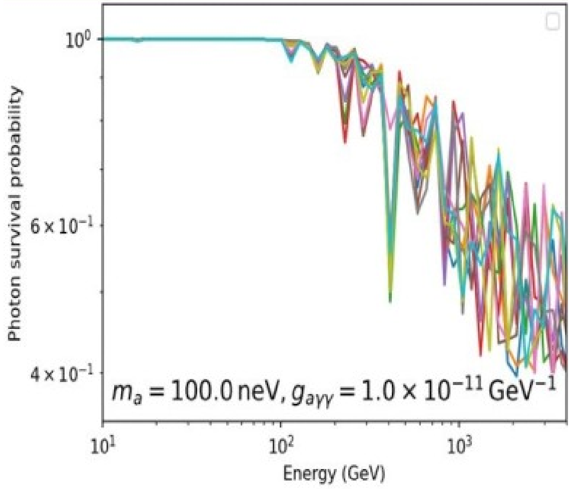


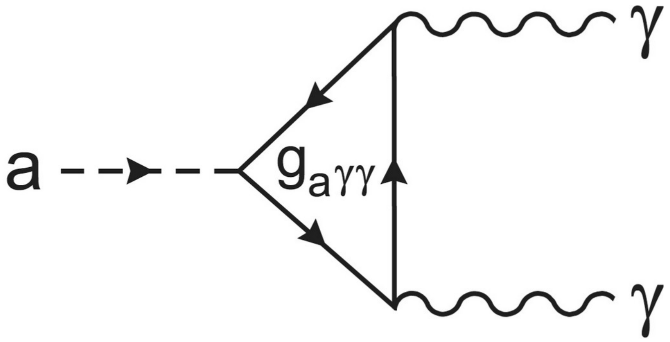



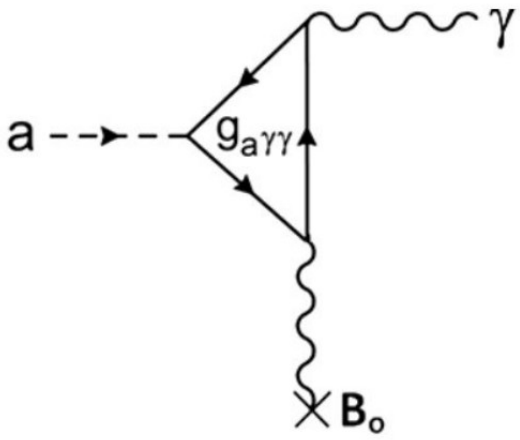

- Rejected up to 2.8 TeV with Cored Zhao, Einasto and NFW
- First time SUSY-wino DM constrained with both cuspy and cored profilles!

# Axion-Like Particles

- Axions. Light pseudo-scalar (postulated to explain the CP conservation in QCD).
- Axions can be cold, both thermal and non thermal production possible
- Axion-Like Particles. Axion generalization by releasing the mass coupling constraint
- Photon-ALP mixing → wiggles in the spectra of astrophysical gamma-ray sources



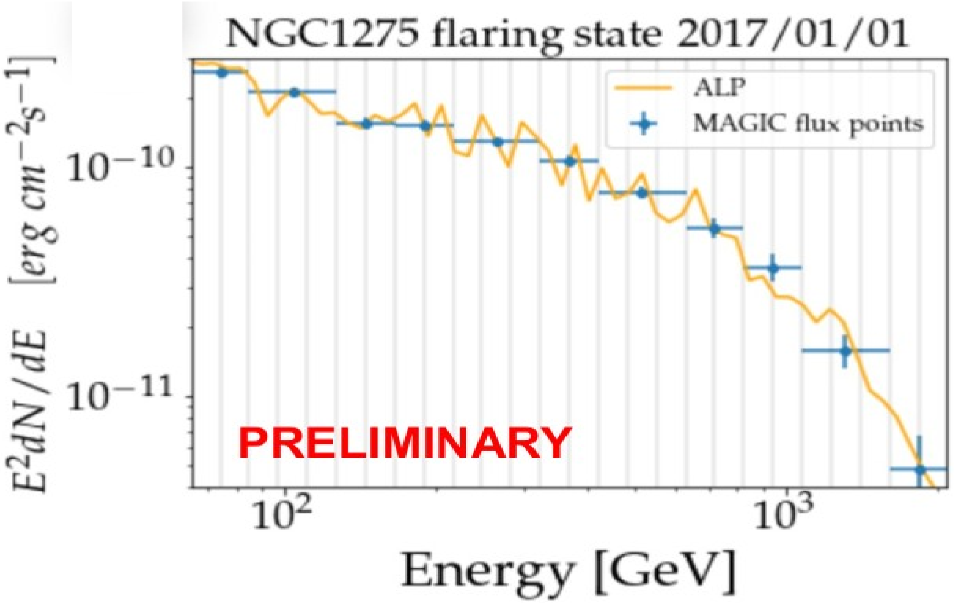



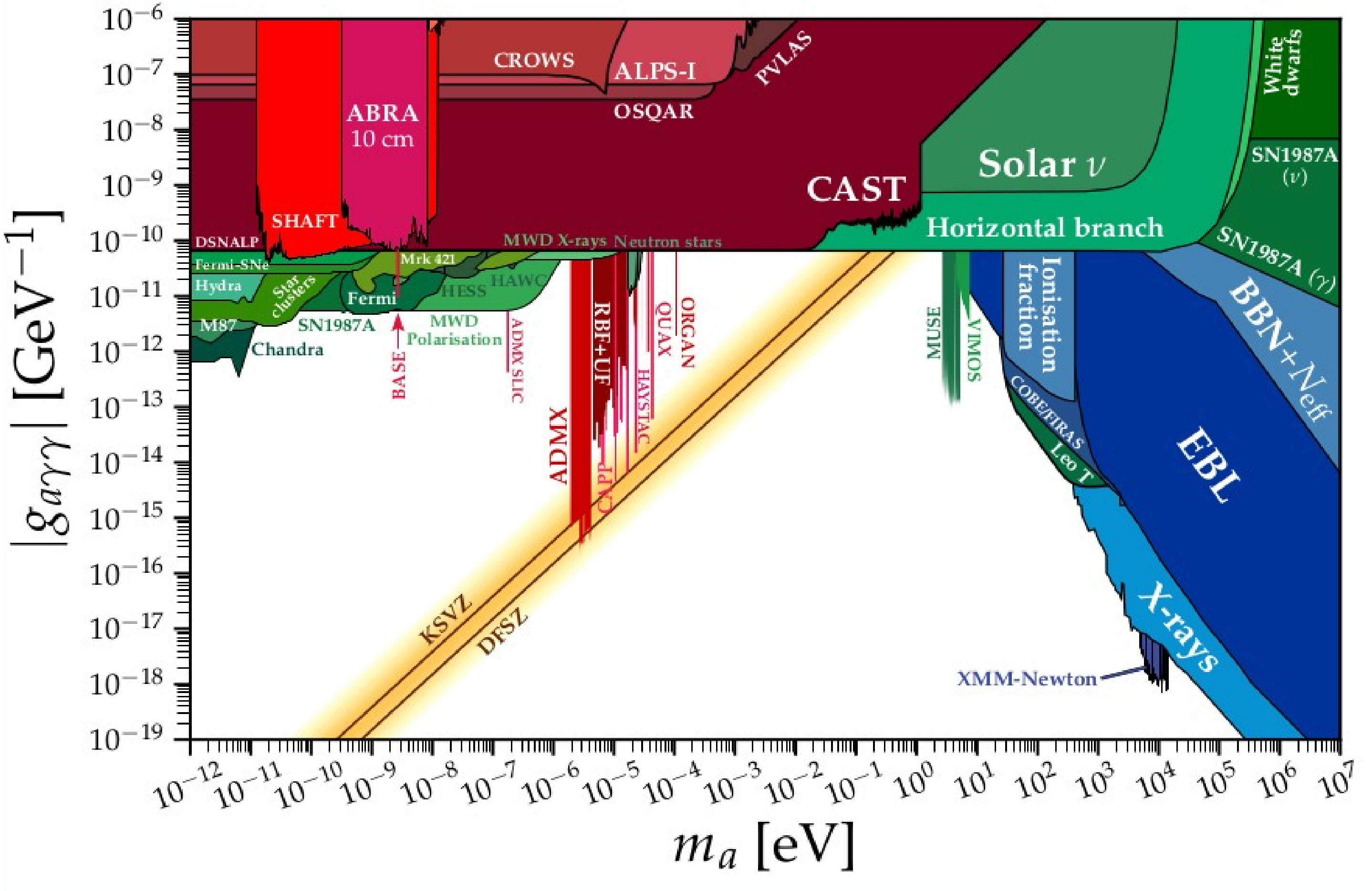

Primakov

# ALPs searches in Perseus cluster

- Wiggles are searched for in NGC1275 and IC310 gamma-ray spectra
- blazar  jet, galaxy cluster, extra -galactic and Milky Way  magnetic fields
- Spectra are compare to models with fixed magnetic field realization



# ALPs Exclusion



# Summary

- MAGIC WIMP DM search strategy: diversification of targets
- Dwarf Spheroidal Gal.:

  - cleanest object, multi year campaign exploited with combined analysis

  - strongest constraint for masses above few TeV

  - further improvements with multi experiment combined analysis
- Galactic Centre: performed with large zenith angle obs.

  -constraint on Wino with several density profiles

  -strong upper limits for lines, specially in multi-TeV regime
- Galaxy Clusters: strong constraint on decay lifetime for masses > 10TeV
- MAGIC ALPs: search for wiggles in AGN spectra

  - magnetic fields fundamental for  ALPs models

# Backup

# Dark Matter

THE ASTROPHYSICAL JOURNAL

AN INTERNATIONAL REVIEW OF SPECTROSCOPY AND ASTRONOMICAL PHYSICS

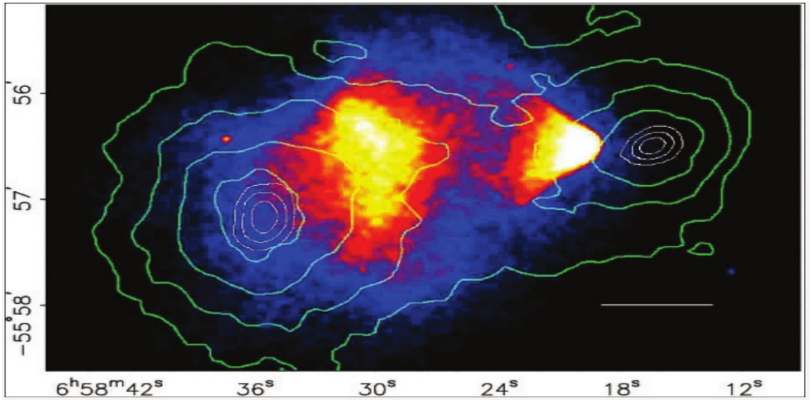
VOLUME 86 OCTOBER 1937 NUMBER 3

ON THE MASSES OF NEBULAE AND OF CLUSTERS OF NEBULAE

F. ZWICKY

ABSTRACT

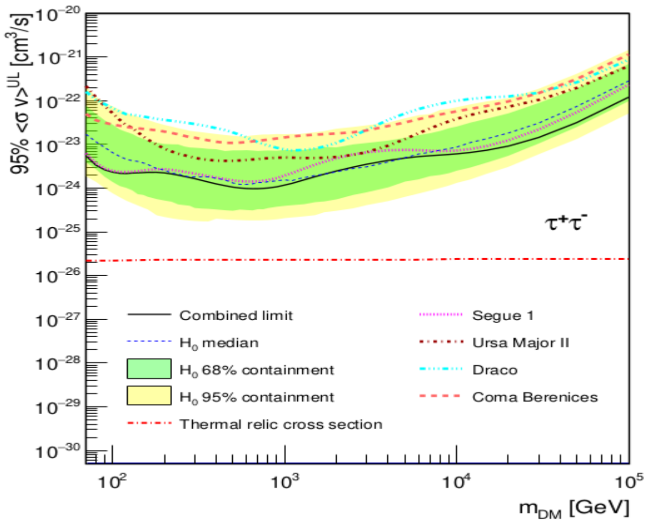
Present estimates of the masses of nebulae are based on observations of the *luminosities* and *internal rotations* of nebulae. It is shown that both these methods are

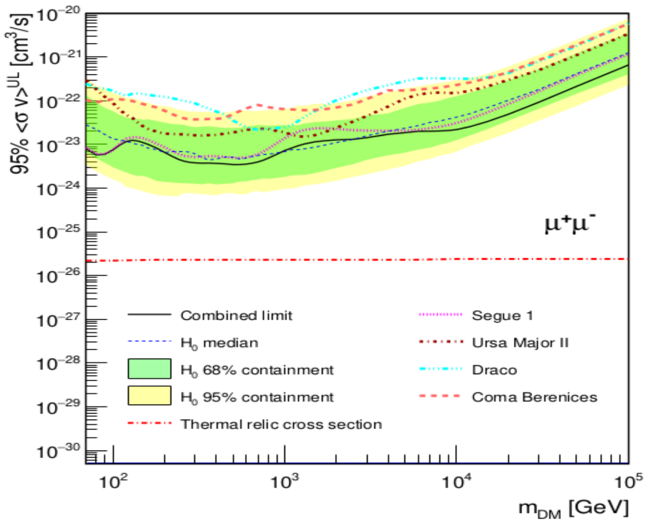


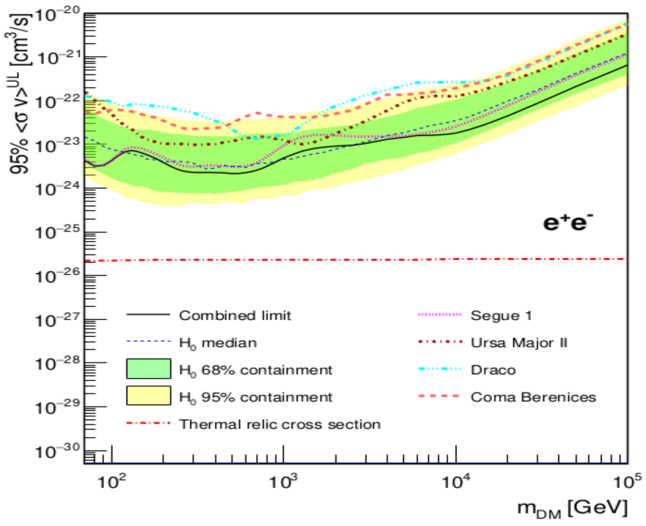

the Bullet cluster (1E 0657-56). X-ray images (red, Chandra), and the DM mass (blue,lensing)

- Dark Matter (DM):
  - firstly required in kinematic studies of galaxy clusters;
  - several indications of missing matter in cosmology and astrophysics;
  - ΛCDM → DM main fraction of the Universe matter, 5 times more than baryons;
  - indirectly inferred (gravitational effects), not directly observed .

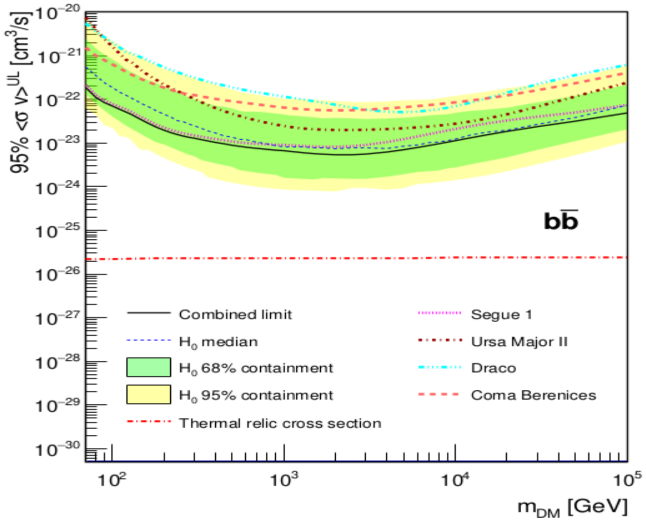
# Limits on Leptonic channels

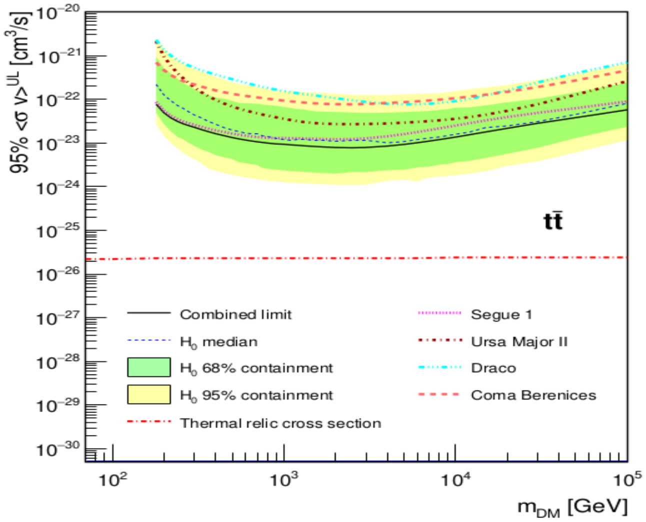


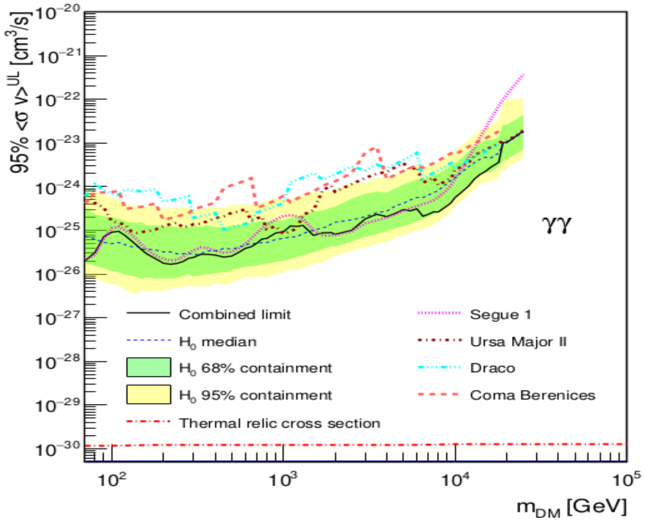



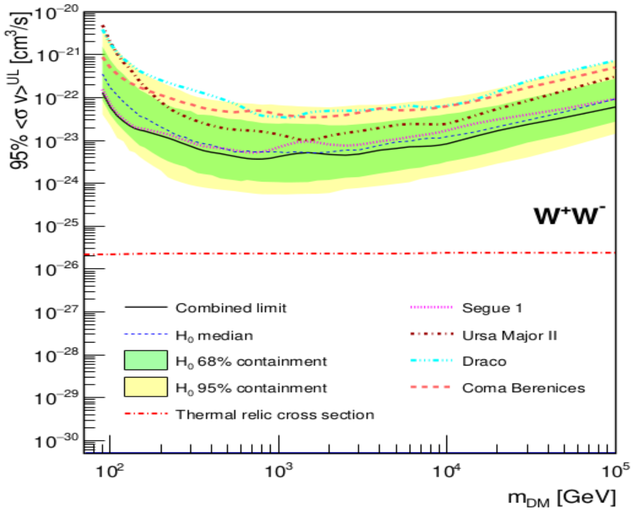
# Limits on Quark and γ channels

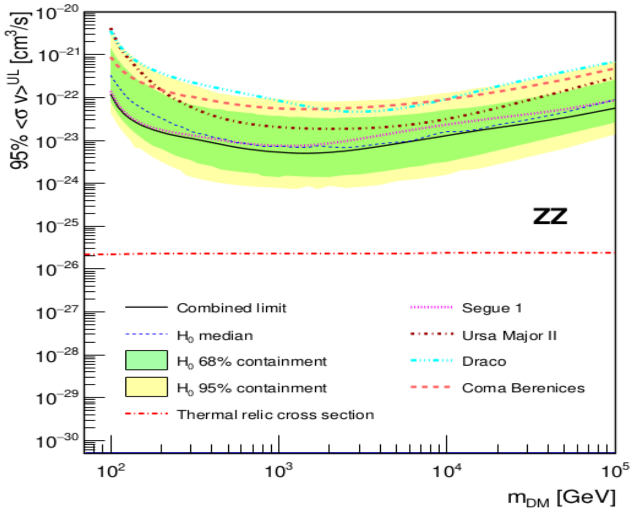


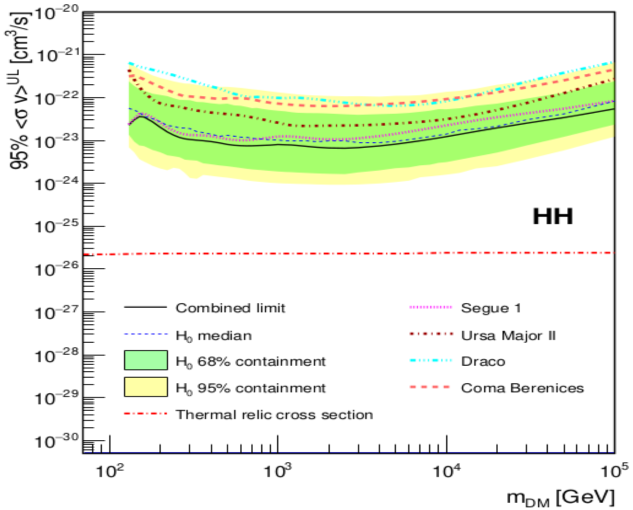



# Limits on Boson channels

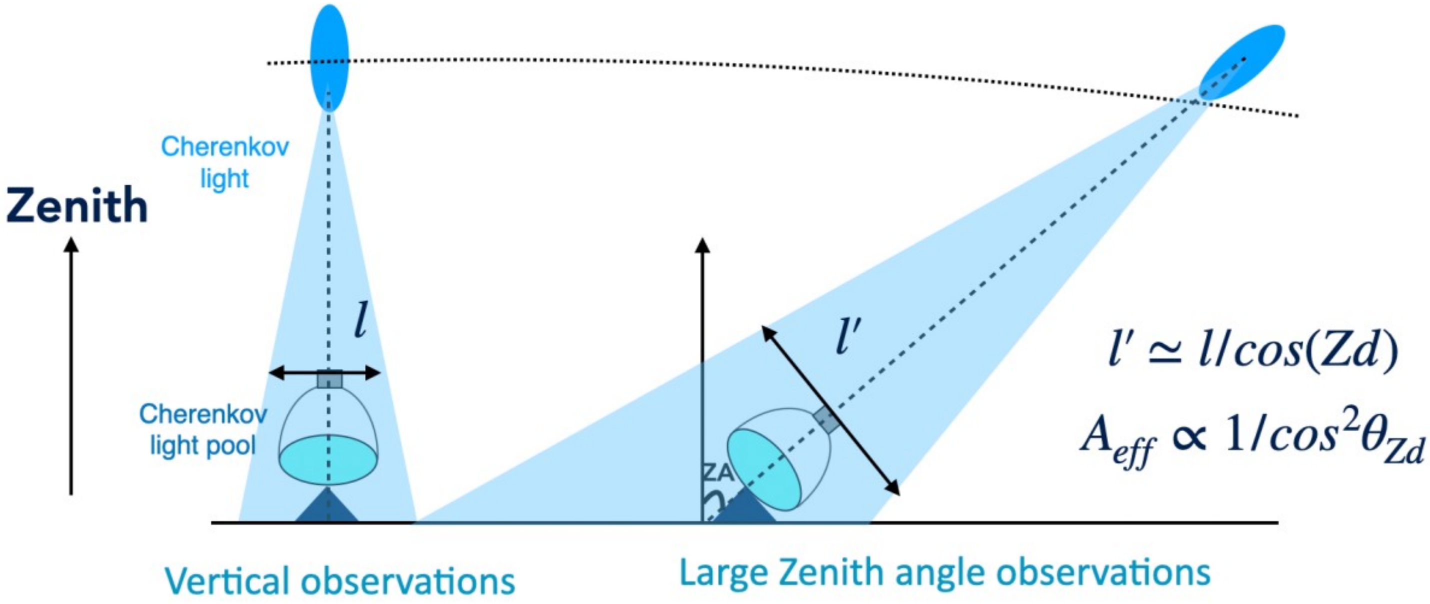


# Large Zenith Angle Observations

- vertical observation: lowest energy threshold and atmospheric effects
- LZA: large effective collection area



# Likelihood analysis for line search

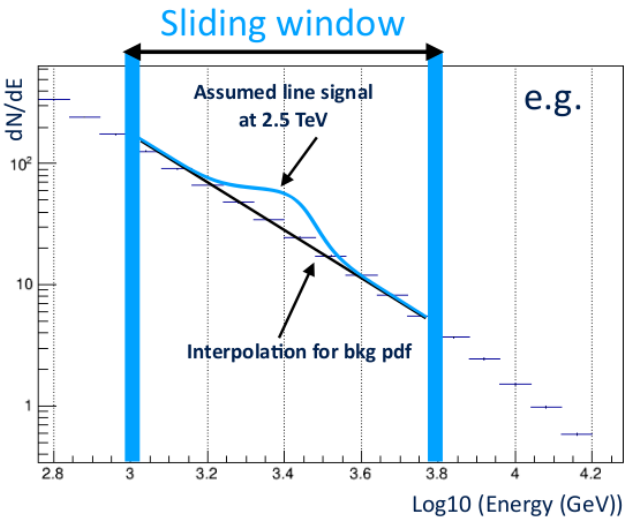
## Unbinned likelihood analysis with a sliding window

$$\mathcal{L}_i(g_i;\nu_i\,|\mathcal{D}_i) = \mathcal{L}_i(g_i;b_i,\tau_i\,|\{E'_j\}_{j=1,\ldots,N_{\mathrm{ON},i}}, N_{\mathrm{ON},i})$$

$$= \frac{(g_i+\tau_i b_i)^{N_{\mathrm{ON},i}}}{N_{\mathrm{ON},i}!} e^{-(g_i+\tau_i b_i)} \times \frac{1}{g_i+\tau_i b_i} \prod_{j=1}^{N_{\mathrm{ON}}} (g_i f_g(E'_j) + \tau_i b_i f_b(E'_j))$$

$$\times \mathcal{T}(\tau_i|\tau_{\mathrm{obs},i},\sigma_{\tau,i})$$

to treat systematic uncertainty of a bkg model




Index $i$ : data samples

$N_{\mathrm{on}}$ : observed events in a ROI

$g$ : **estimated signal events** — **Parameters of interest**

$b$ : estimated background events

$\tau$ : normalization factor for bkg model — Nuisance parameters

$f_g$ : line signal pdf

- $\delta$-function convolved with the response function

$f_b$ : background pdf

- interpolated from energy spectra
  - assumption : background behaves as power-law spectrum in a sliding window

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