Dark Matter and the Galactic Centre with the MAGIC telescope

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for the MAGIC Collaboration

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[Submitted on 20 Dec 2022]

Search for Gamma-ray Spectral Lines from Dark Matter Annihilation up to 100 TeV towards the Galactic Center with MAGIC

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Line-like features in TeV γ-rays constitute a "smoking gun" for TeV-scale particle dark matter and new physics. Probing the Galactic Center region with ground-based Cherenkov telescopes enables the search for TeV spectral features in immediate association with a dense dark matter reservoir at a sensitivity out of reach for satellite γ-ray detectors, and direct detection and collider experiments. We report on 223 hours of observations of the Galactic Center region with the MAGIC stereoscopic telescope system reaching γ-ray energies up to 100 TeV. We improved the sensitivity to spectral lines at high energies using large-zenith-angle observations and a novel background modeling method within a maximum-likelihood analysis in the energy domain. No line-like spectral feature is found in our analysis. Therefore, we constrain the cross section for dark matter annihilation into two photons to $\langle\sigma v\rangle \lesssim 5\times10^{-28}\ \mathrm{cm^3\ s^{-1}}$ at 1 TeV and $\langle\sigma v\rangle \lesssim 1\times10^{-25}\ \mathrm{cm^3\ s^{-1}}$ at 100 TeV, achieving the best limits to date for a dark matter mass above 20 TeV and a cuspy dark matter profile at the Galactic Center. Finally, we use the derived limits for both cuspy and cored dark matter profiles to constrain supersymmetric wino models.

Comments: Accepted in Phys. Rev. Lett., includes Supplemental materials. 9+4 pages, 3+3 figures, 3 tables. Corresponding authors: T. Inada, D. Kerszberg, M. Hütten
Subjects: **High Energy Astrophysical Phenomena (astro-ph.HE)**
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Mainly based on this paper, recently accepted in PRL

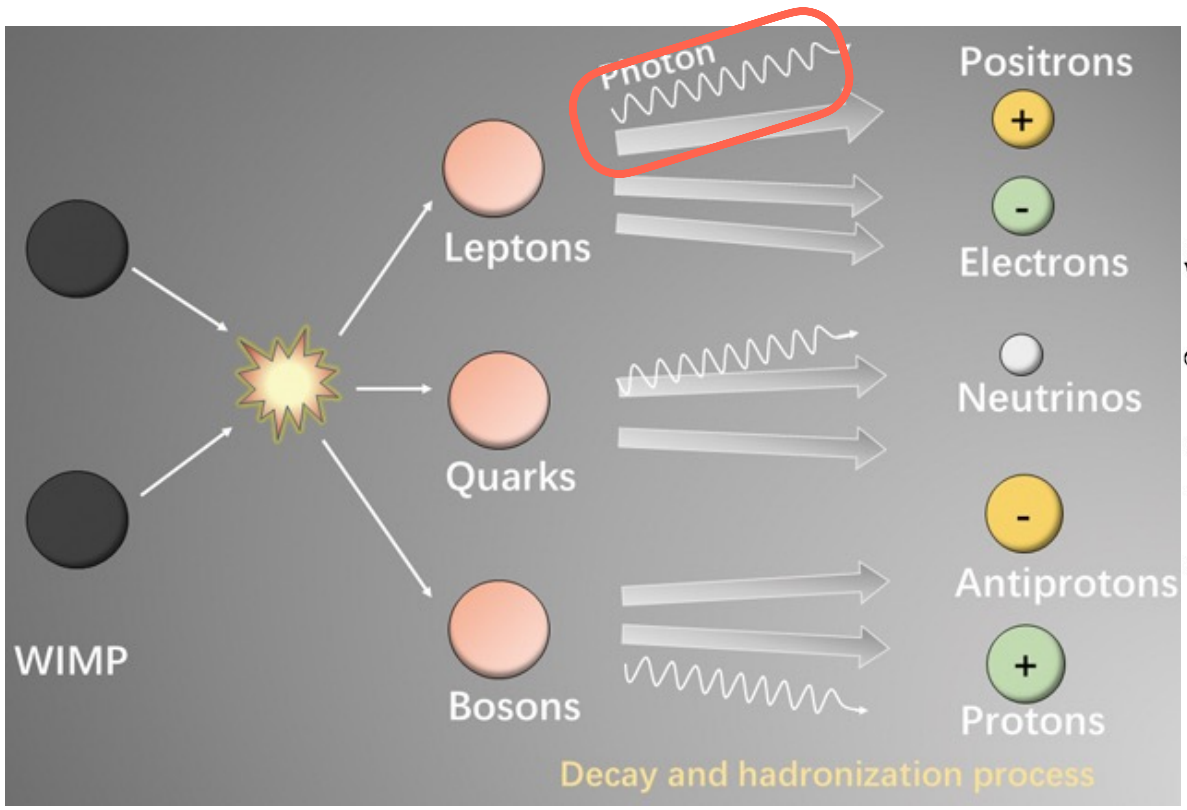
Indirect dark matter search with gamma-ray

Indirect dark matter search

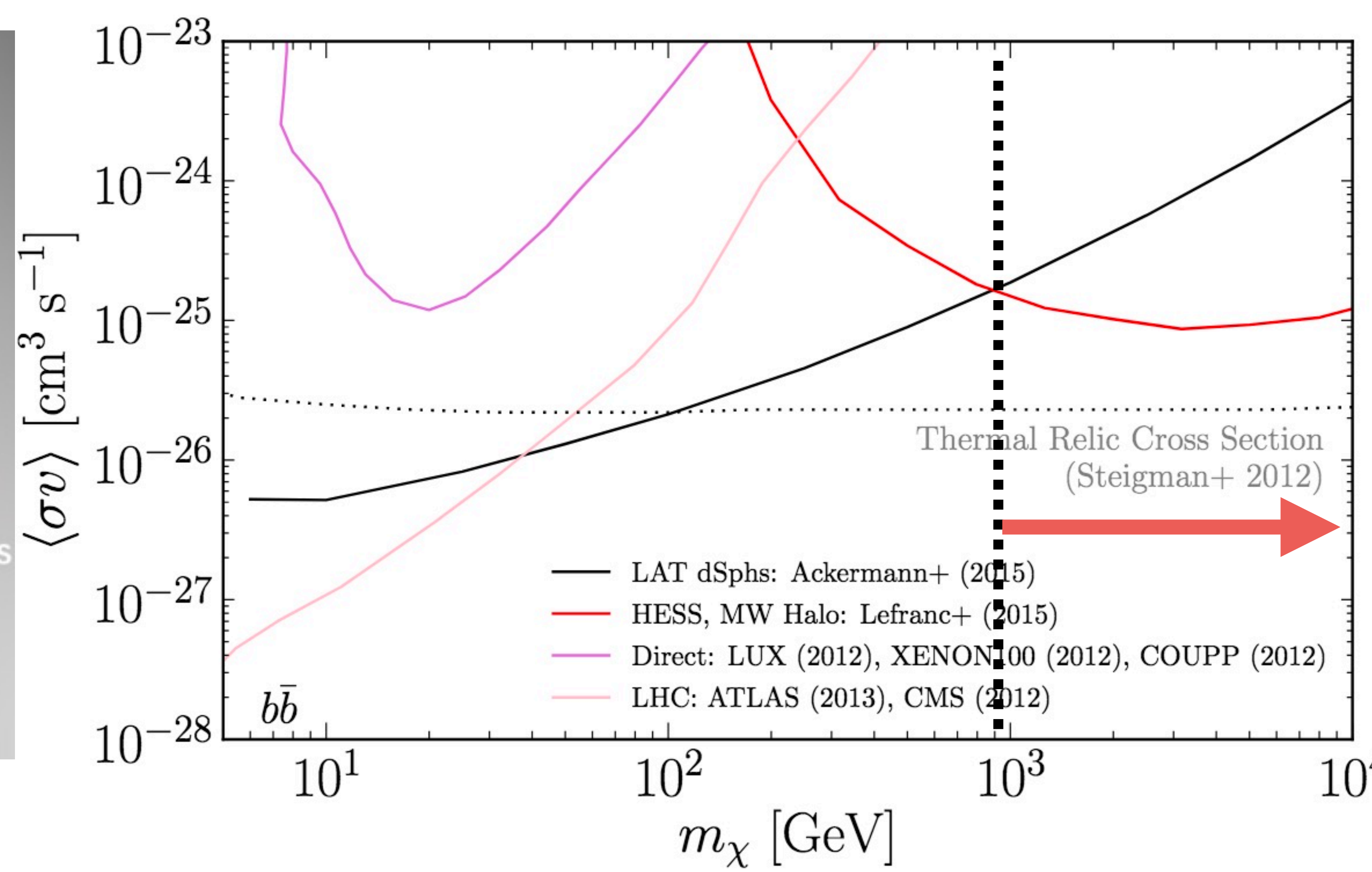
- searches for products ($\gamma, e^{\pm}, \nu, p^{\pm}$) from dark matter annihilation/decay

Complementarity of WIMP DM Searches

- Complementary to direct detection and collider searches.
- Cherenkov telescopes are useful to search for DM at TeV-scale due to the good sensitivity for very-high energy gamma-ray



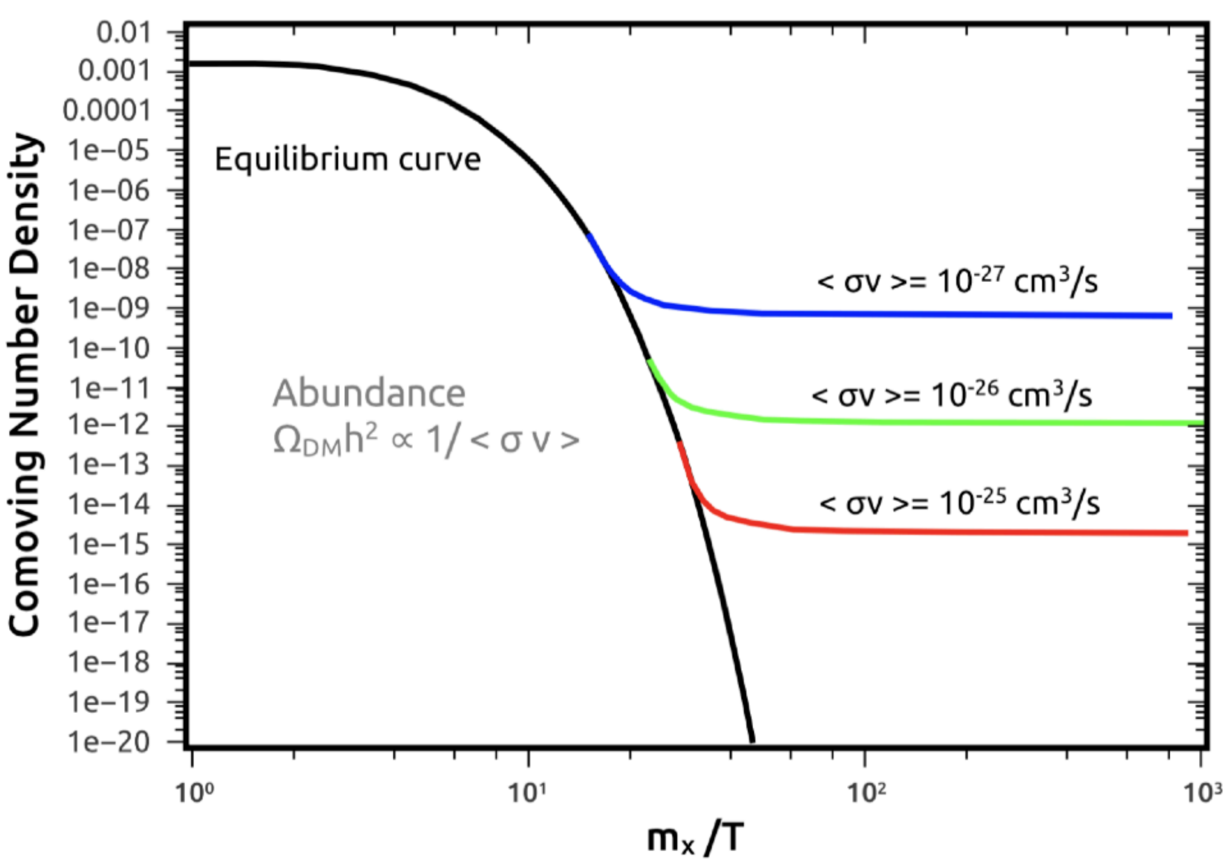
credit: GAO Linqing and Lin Sujie



arXiv:1605.02016

Why the indirect way?

- **Test of particle DM**
  - information on the parameter (DM mass, a coupling constant, cross-section…)
- **Test of DM production via thermal freeze-out (Unique!!)**
  - DM interaction rate equals the Hubble expansion rate of the universe.



- DM is in thermal equilibrium.
- DM is diluted by the cosmic expansion
- DM annihilation stops
- The DM number in comoving volume **freezes out**

$$\boxed{<\sigma v> \sim 3 \times 10^{-26} \mathrm{cm}^3 \mathrm{s}^{-1}}$$

So-called **“thermal relic” cross-section**

Gamma-ray Signal from Dark Matter (DM)

Why gamma rays?

- DM is expected to annihilate into SM products, among which gamma-rays
  - easy to associate with the source for being a neutral particle, not affected by B-fields
    - can determine DM abundance and distribution in the universe
  - characteristic spectral features
    - can identify the characteristics of DM particles (e.g. mass and cross-section/lifetime)

Expected gamma-ray flux from DM annihilation

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

σv : annihilation cross-section

$m\chi$: mass of DM particle

BR_i : branching ratio of each channel

dN^i/dE : differential gamma-ray yield of each channel

Line signal : $\frac{dN_\gamma}{dE} = 2\delta(E - m_\chi)$

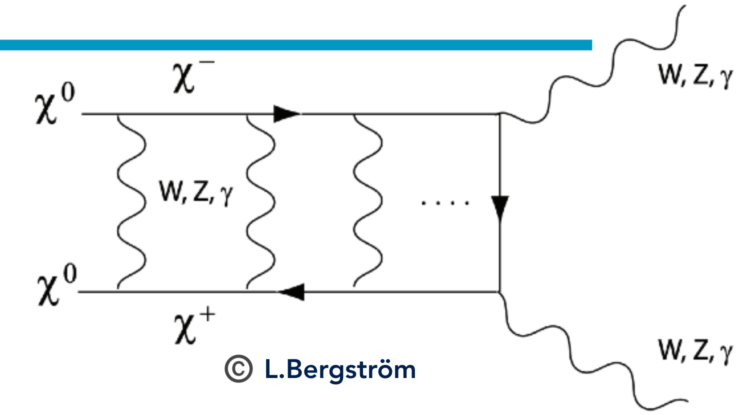
ρ : dark matter (DM) density

- depends on source type, DM profile of a source, etc.

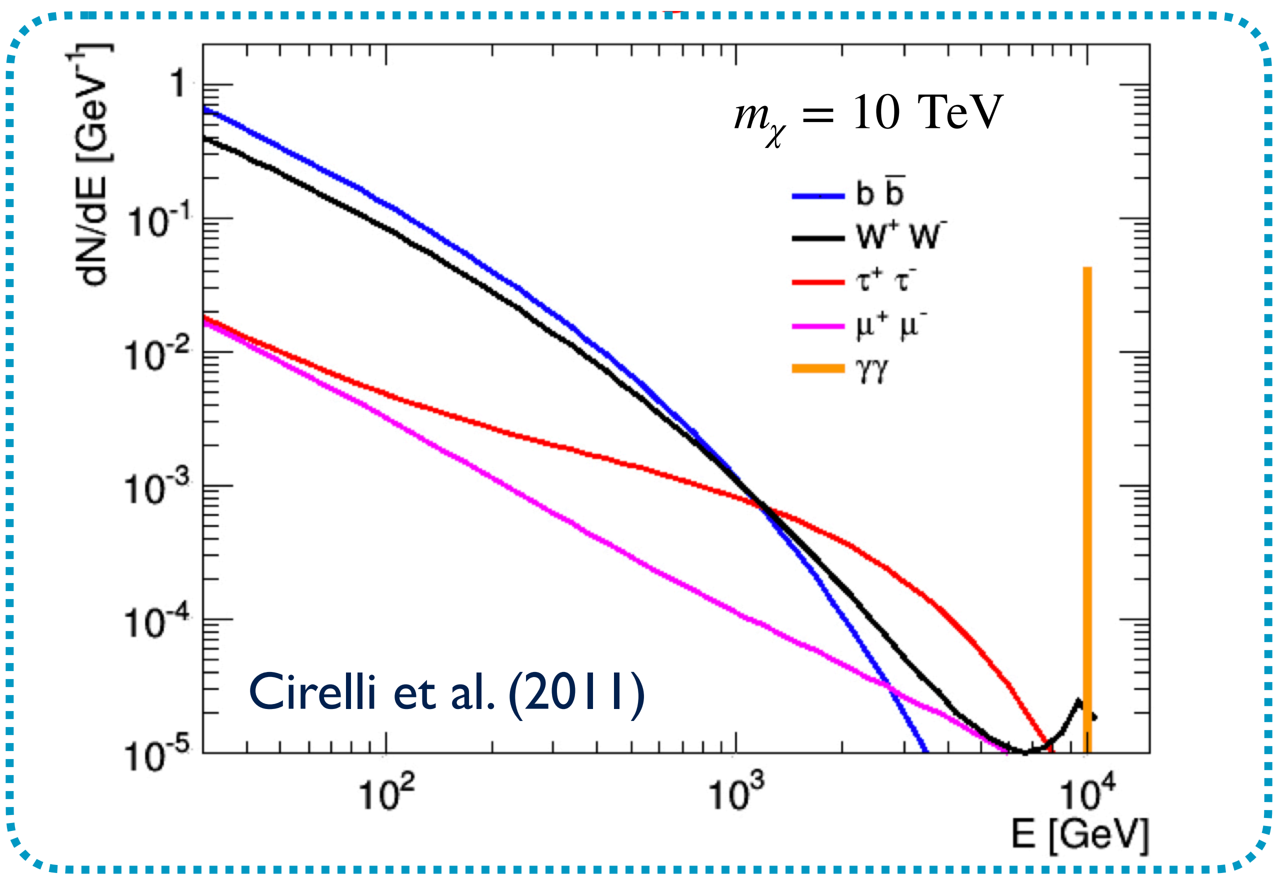
J-factor :

- integrated square DM density

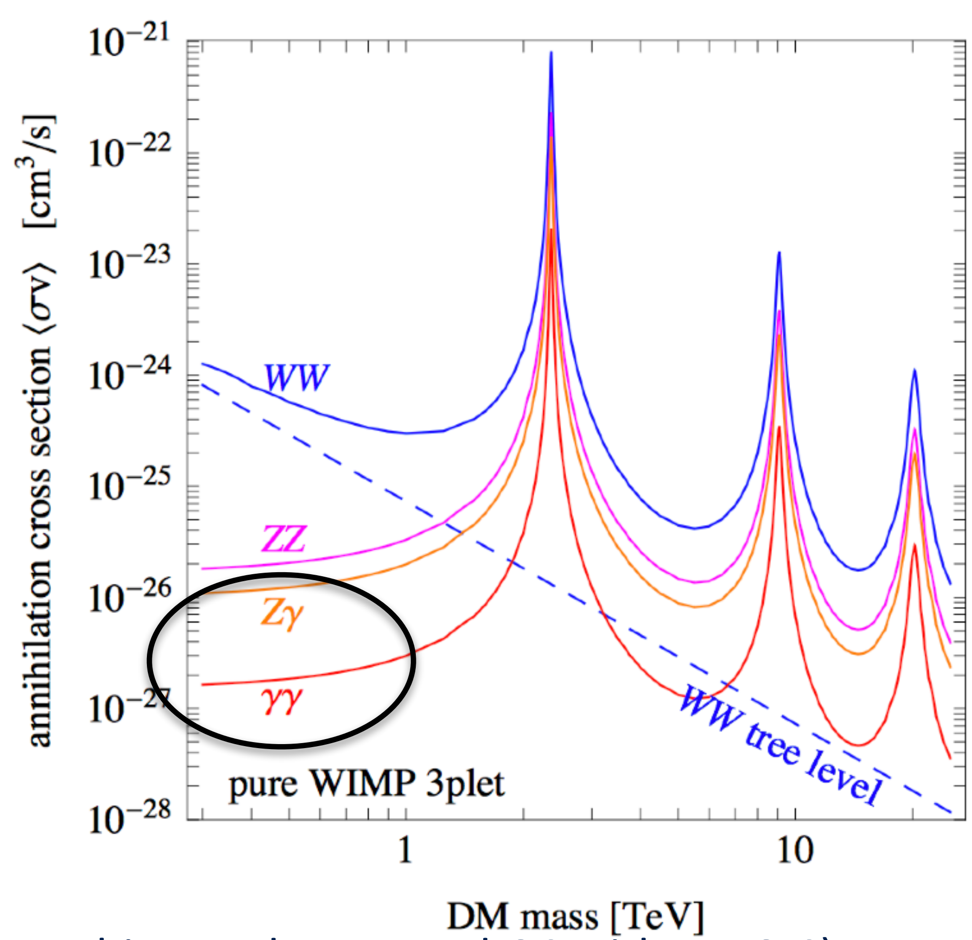
Motivation for line search



- **Clear peak at DM mass:** No astrophysical contamination
- **Test interesting particle models**
  - $\chi\chi \rightarrow \gamma\gamma, Z\gamma$: loop-suppressed by α^2 (i.e. the fine-structure constant)
  - Annihilation cross-section of heavy DM models are expected an order-of-magnitude increase for the Sommerfeld enhancement



SUSY-Wino



J. Hisano, S. Matsumoto, M. M. Nojiri and O. Saito 2005
M. Cirelli, N. Fornengo and A. Strumia (2006)
H. E.S.S. collaboration JCAP11(2018)

DM searches with the Galactic Centre

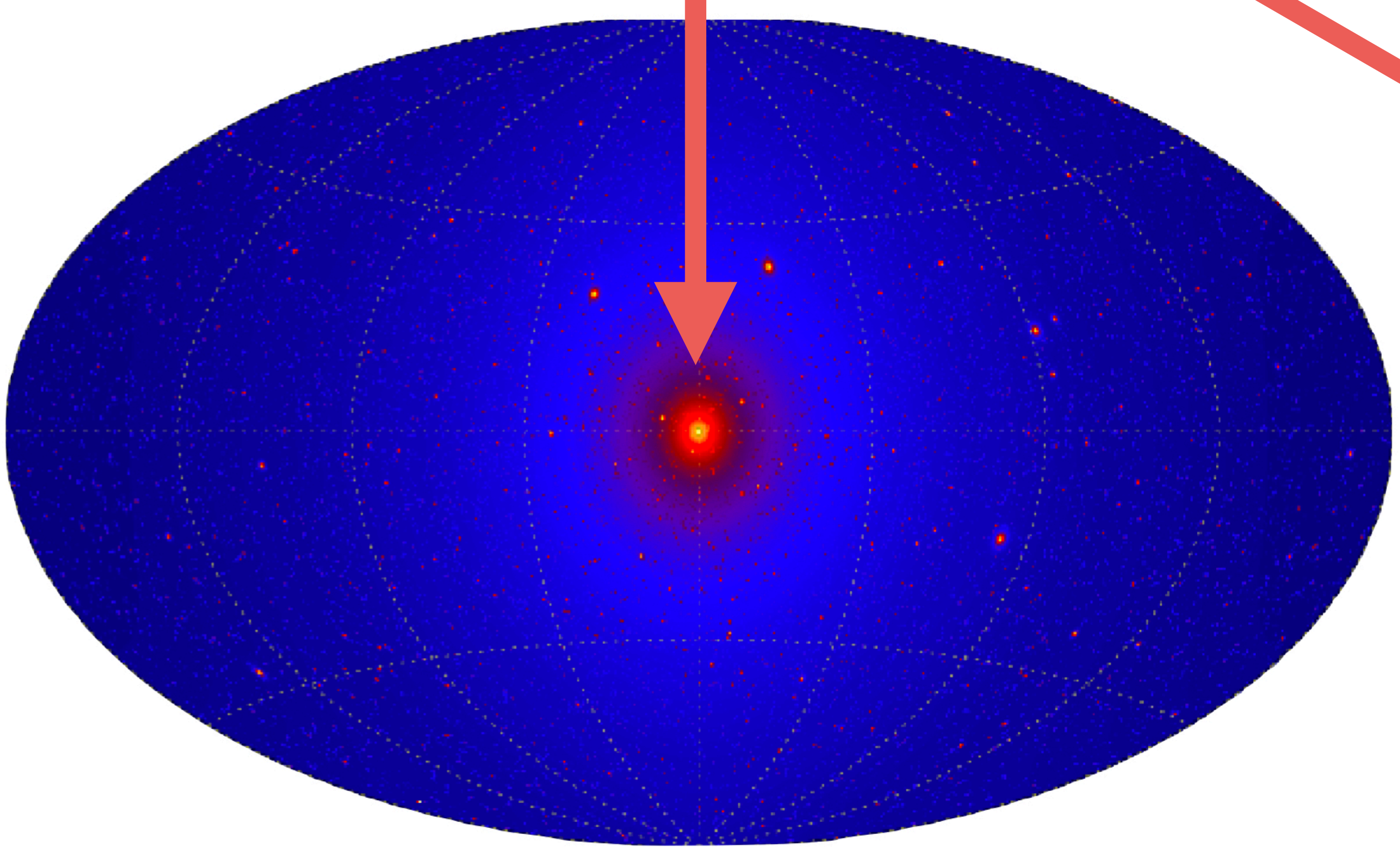
Galactic Centre (GC) and Halo

- the largest J-factor
- extended
- source confusion, diffuse bkg and Cusp/core differences in DM profiles

$$\rho_{\mathrm{Einasto}}(r) = \rho_s \exp\left\{\frac{-2}{\alpha}\left[\left(\frac{r}{r_s}\right)^{\alpha} - 1\right]\right\}$$

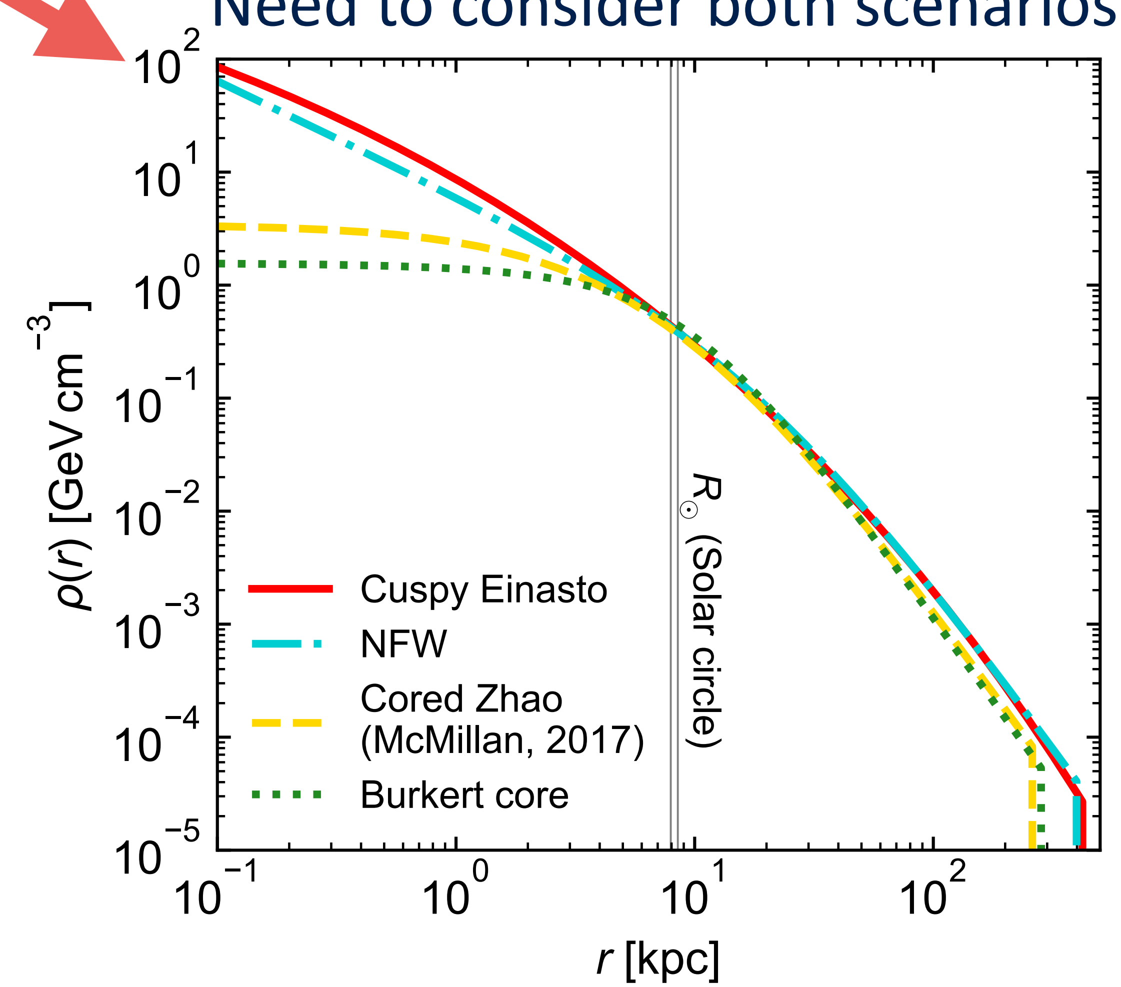
$$\rho_{\mathrm{Zhao}}(r) = \frac{2^{\frac{\beta-\gamma}{\alpha}}\rho_s}{\left(\frac{r}{r_s}\right)^{\gamma}\left[1+\left(\frac{r}{r_s}\right)^{\alpha}\right]^{\frac{\beta-\gamma}{\alpha}}}$$

$$(\alpha, \beta, \gamma) = (1,3,0)$$



Simulated all-sky map of gamma-rays from DM annihilation (Galactic coordinates) PRD 83, 023518 (2011) N-Body simulation Via Lactea II

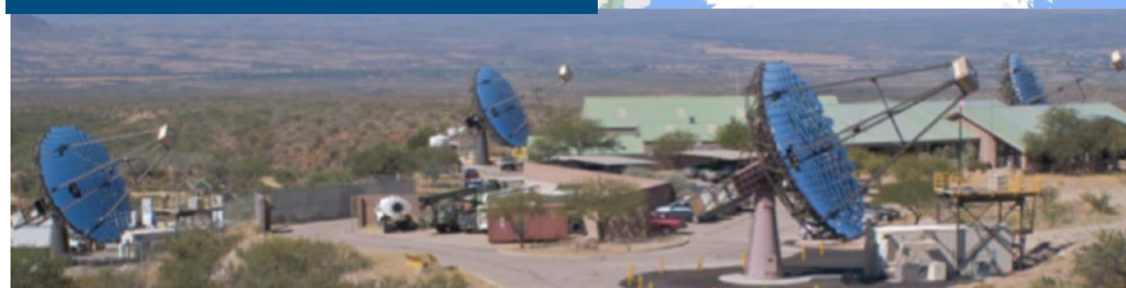
Need to consider both scenarios



arXiv2212.10527

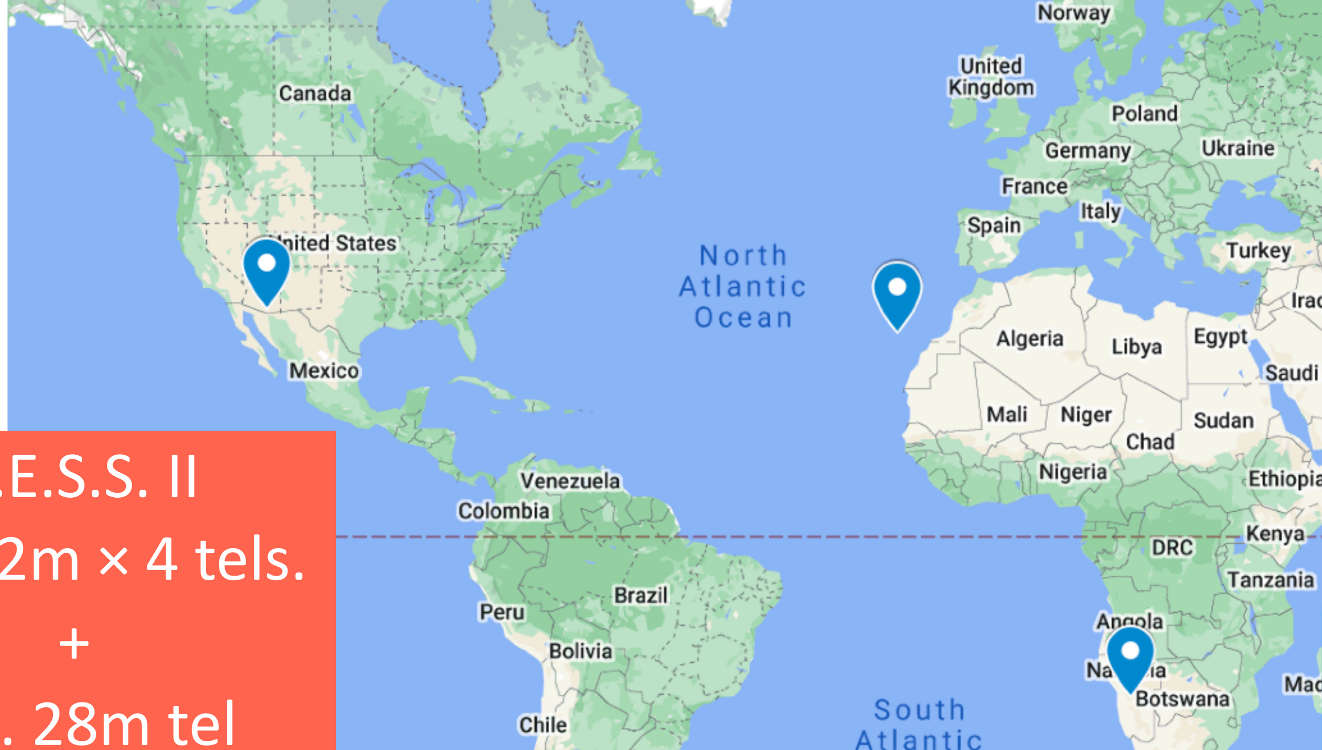
Imaging Atmospheric Cherenkov Telescopes (IACTs)

VERITAS
Dia. 12m × 4 tels.



MAGIC
Dia. 17m × 2 tels.

CTA-LST
Dia. 23m × 4 (1) tels.



H.E.S.S. II
Dia. 12m × 4 tels.
+
Dia. 28m tel

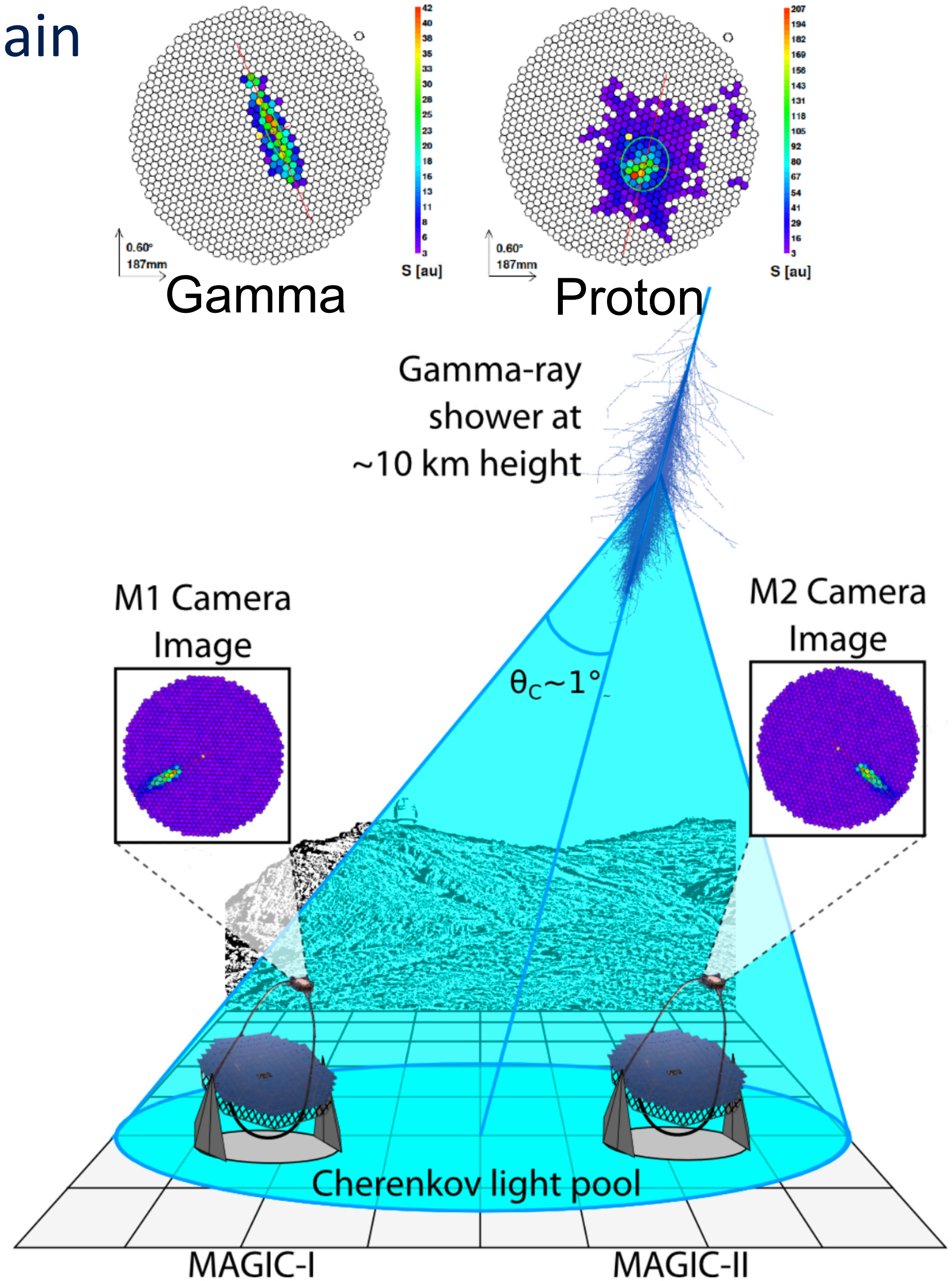
Typical performance

- Energy range: 20 GeV - 100 TeV
- Energy resolution: 10 - 15 %
- Angular resolution: 0.1 deg
- Field of view: 3 - 5 deg
- Duty cycle: about 10 - 20 %
  - dark time: about 1000 h/year
- Different sky coverage between N and S

The MAGIC telescopes

MAGIC (Major Atmospheric Gamma Imaging Cherenkov telescopes)

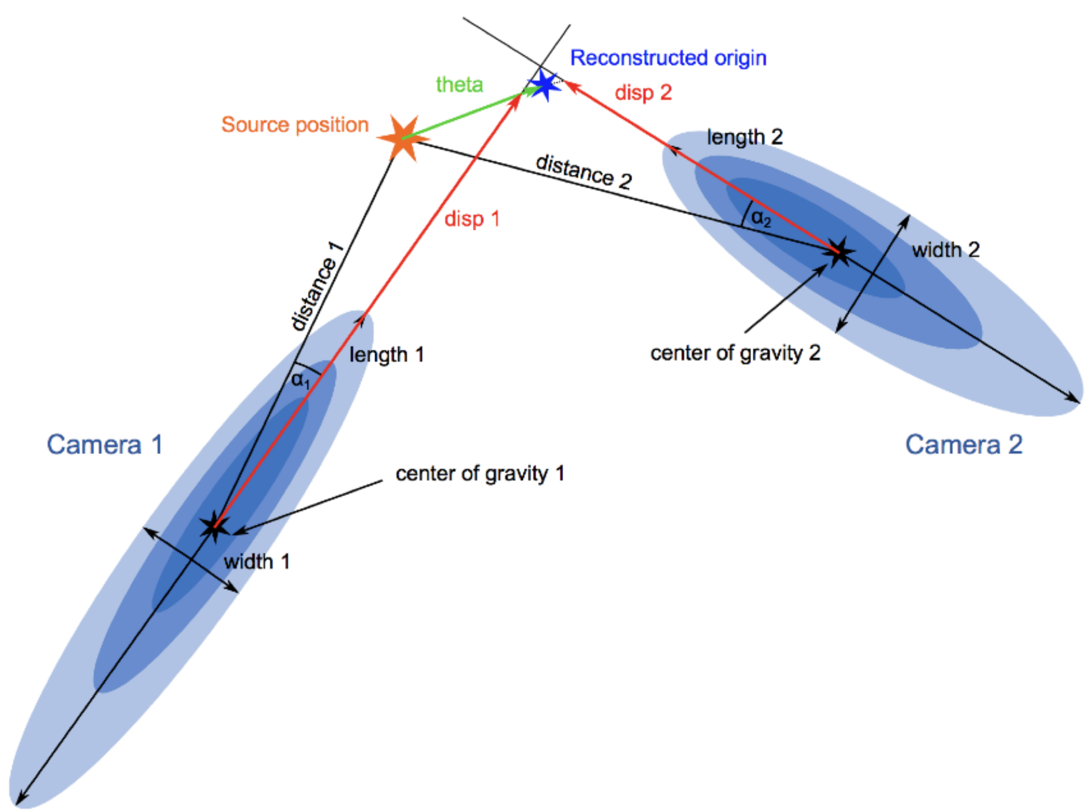
- Observatorio del Roque de los Muchachos (ORM)
  - ~ 2200 m a.s.l., La Palma, Canary Islands, Spain
- 2-telescope stereoscopic system
  - 17m diameter
- Energy : 50 GeV - 50 TeV (Low Zd ~20°)
- FoV : 3.5°
- Angular resolution : 0.06° @ 1 TeV
- Energy resolution : 15 % - 25 %



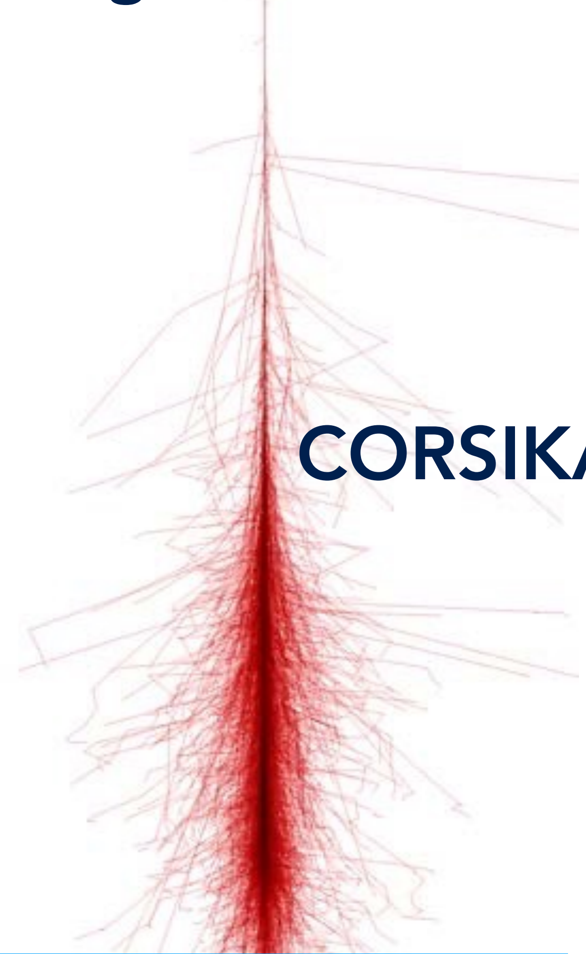
IACT technique

Image analysis with shower images
- Orientation
- Size/length/width
- Time gradient

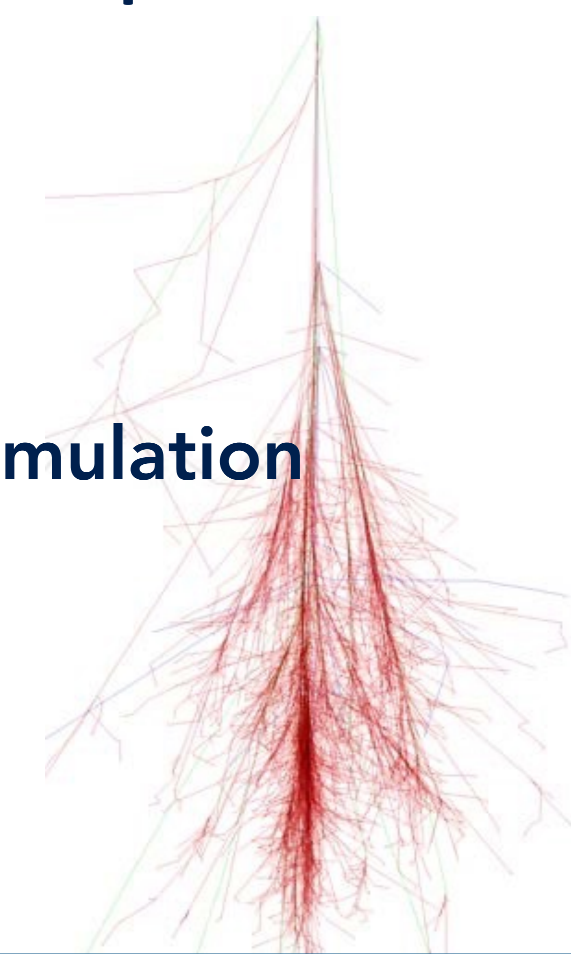
Output on primary particles info
- Energy, direction, arrival time
- Types of particles



MC gamma shower



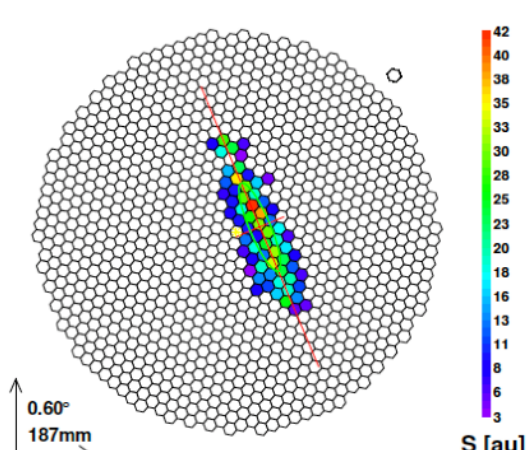
MC proton shower

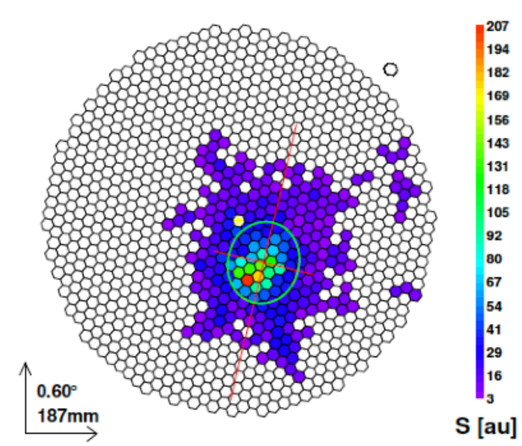


CORSIKA simulation

Gamma (signal)

Hadron(background)





IACT technique

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- Energy, direction, arrival time
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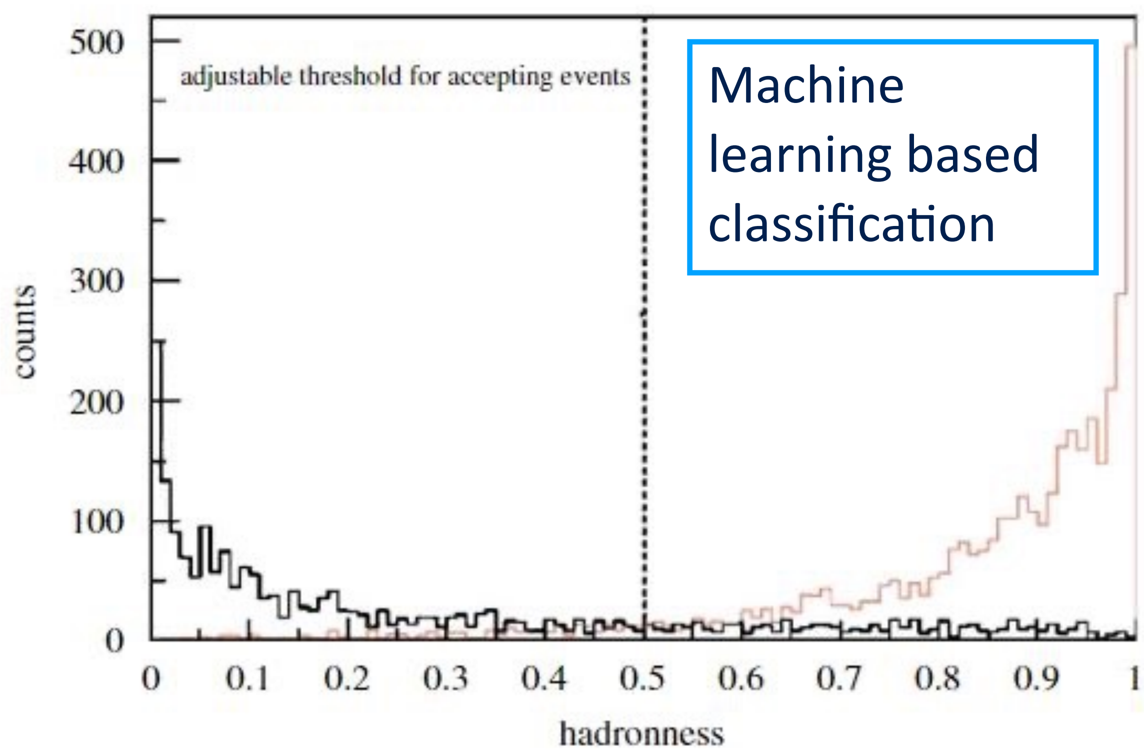
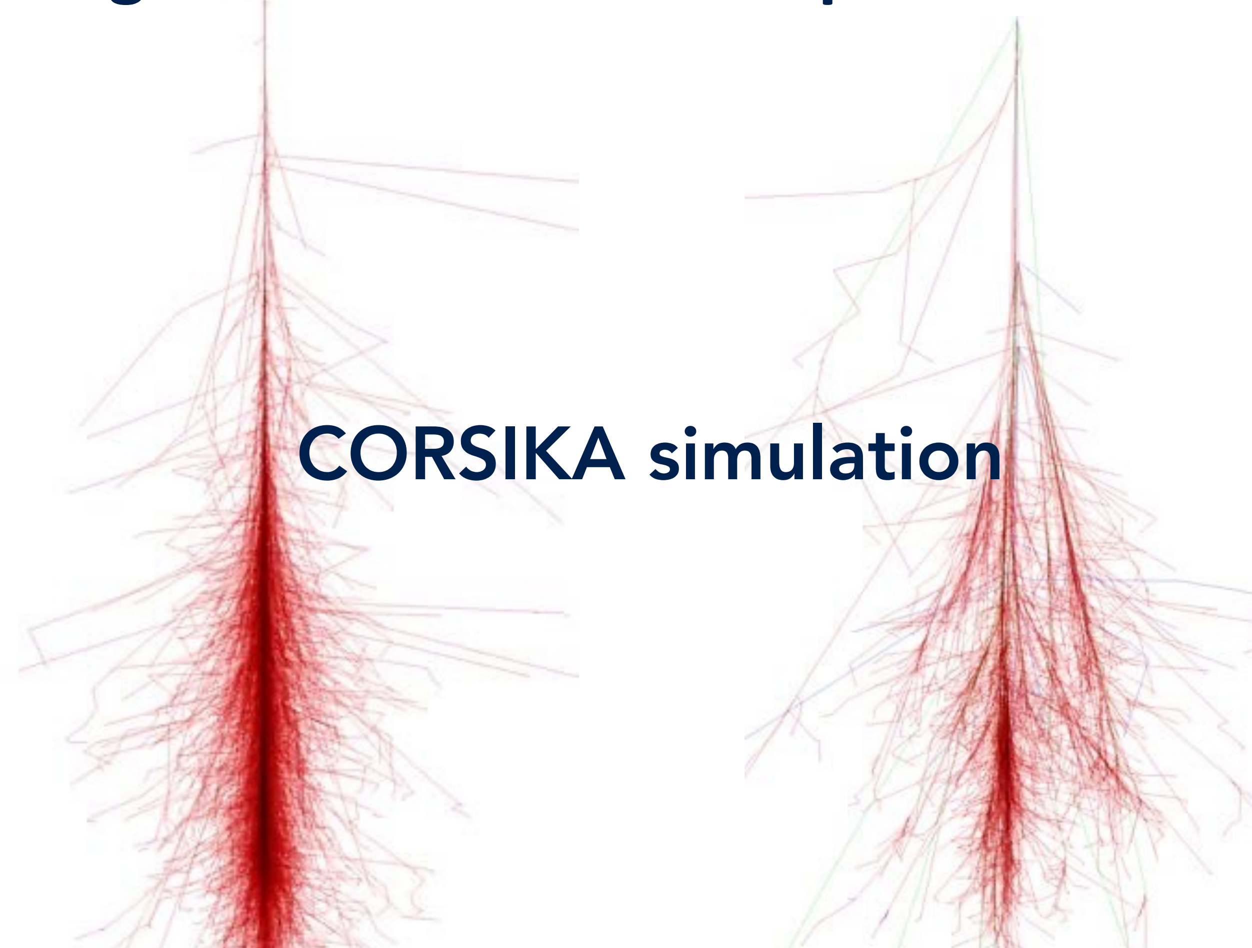
Nucl.Instrum.Meth.A588:424-432,2008



MC gamma shower

MC proton shower



CORSIKA simulation

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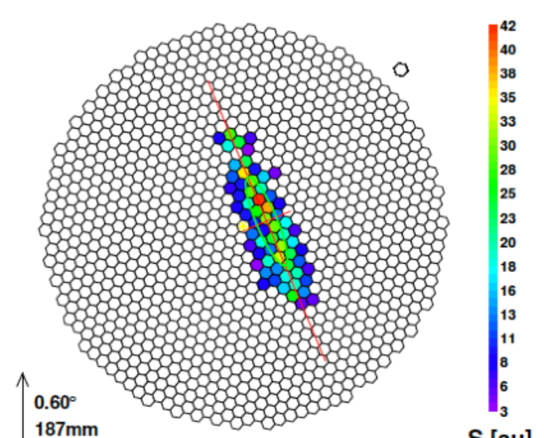
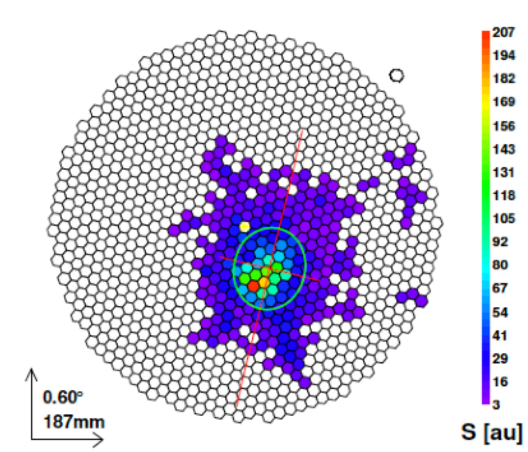
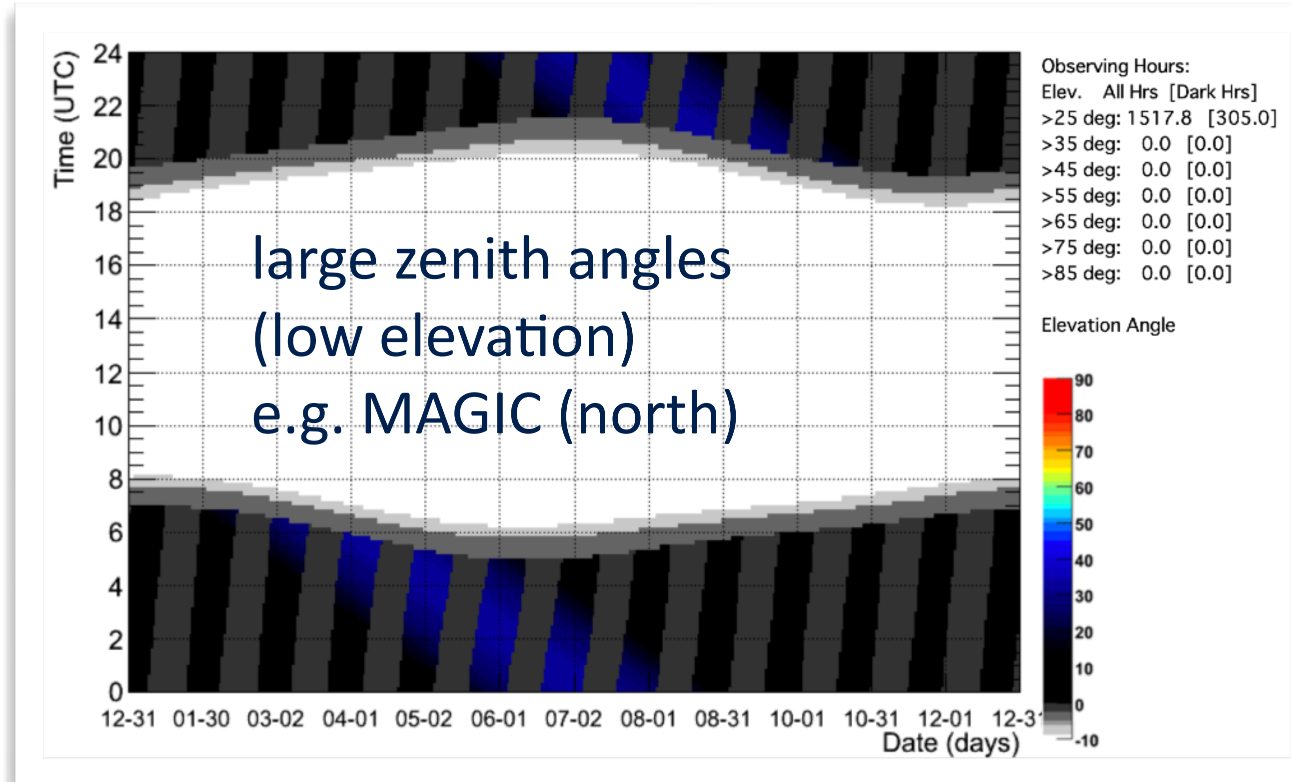




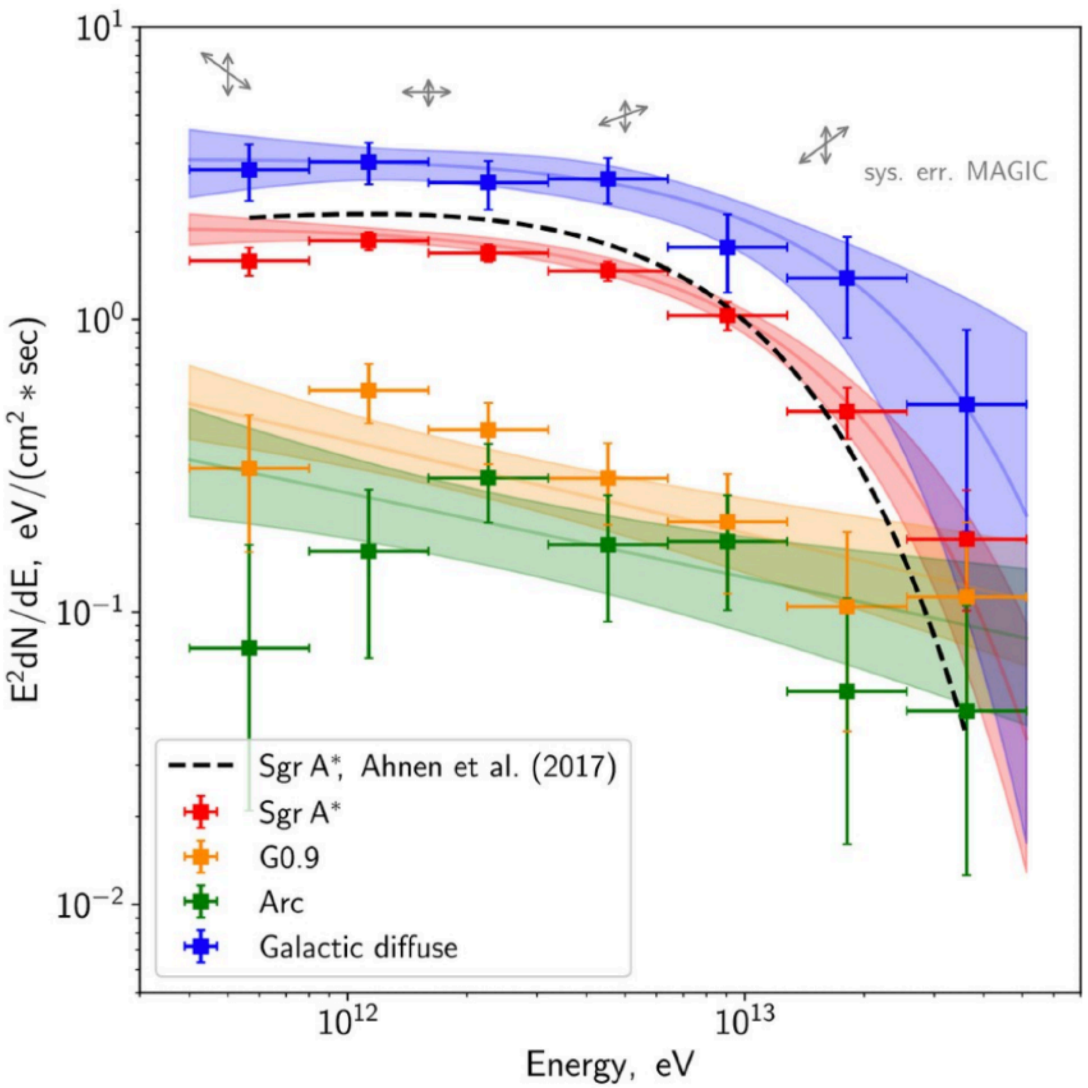
The Galactic Centre with MAGIC

The most complex source

- many bright sources
- the largest DM density expected
- For MAGIC, the GC is passing close to the horizon (zenith > 50°)

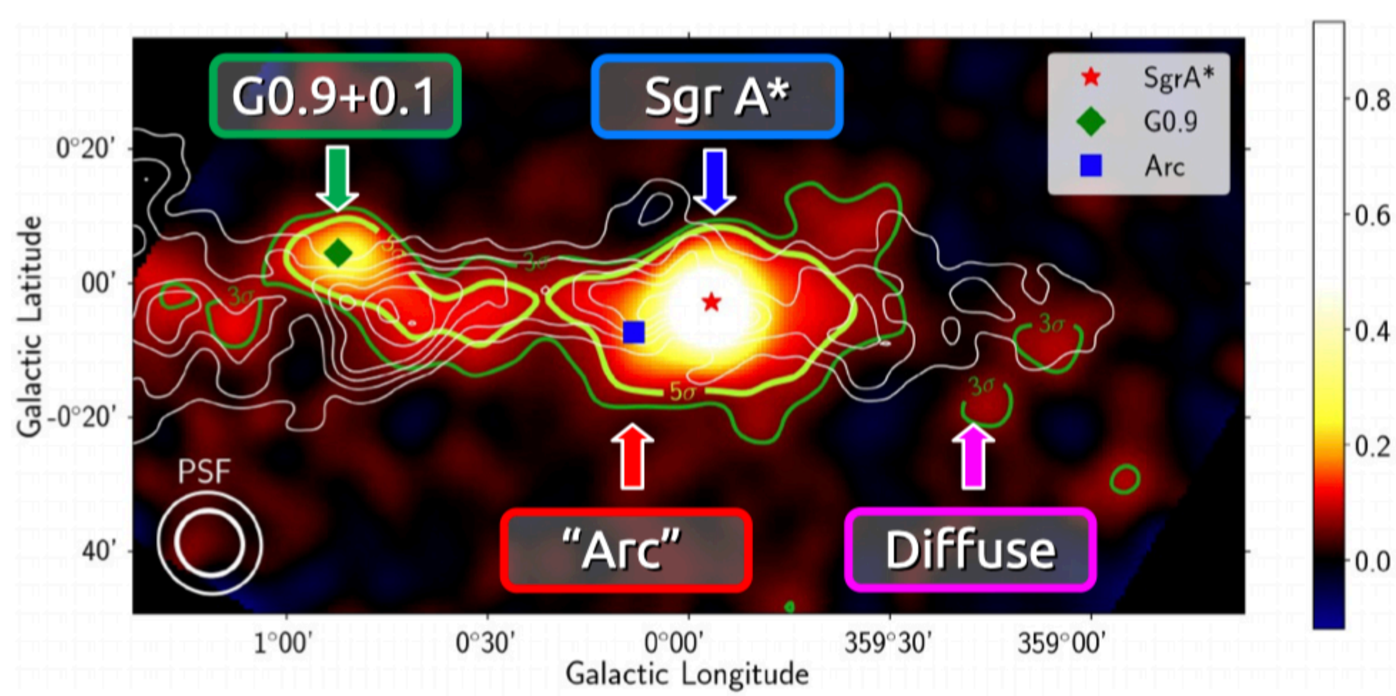


http://tevcat.uchicago.edu



A&A 642, A190 (2020)

MAGIC collaboration A&A 642, A190 (2020)



Large Zenith Angle observations

The GC observation by MAGIC

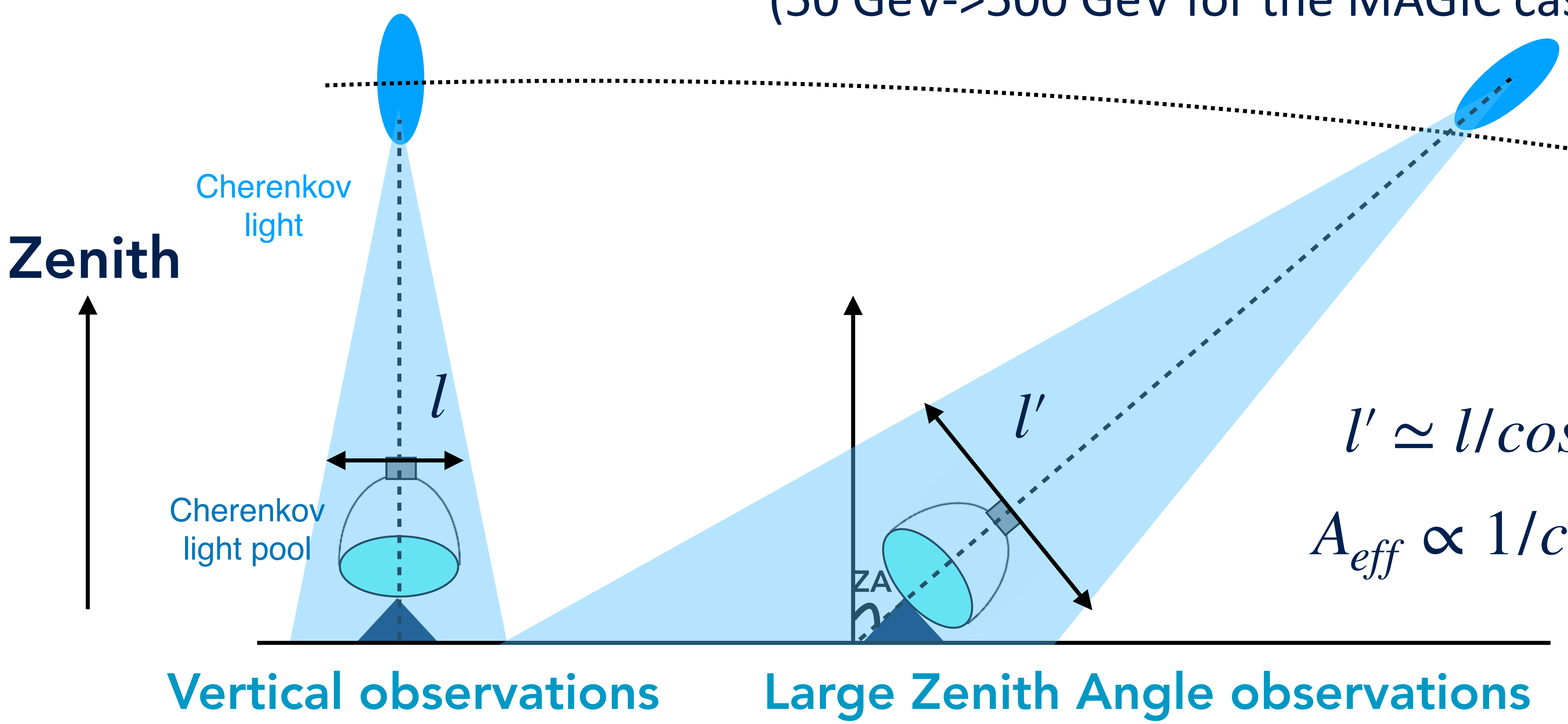
- zenith angle : 58 - 70 [deg]
  - large zenith angle observation, LZA

Pros

- increase the effective area for γ-ray detection to get more statistics at TeV energies

Cons

- increase the energy threshold (50 GeV->500 GeV for the MAGIC case)



$$l' \simeq l/cos(Zd)$$

$$A_{eff} \propto 1/cos^2\theta_{Zd}$$

Large Zenith Angle observations boost the sensitivity to line signals from TeV DM!!

Data set

Data : March 2013 - August 2020

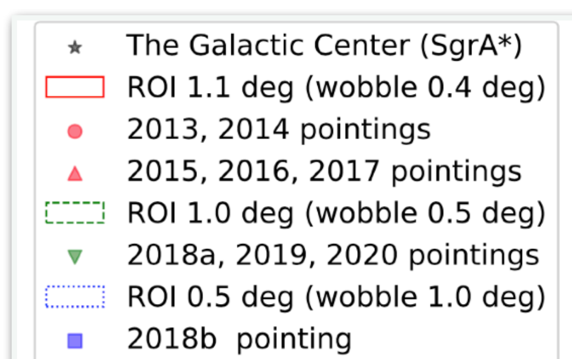
- Zd range : 58° < Zd < 70°
- total observation time (after cuts) : 223 h

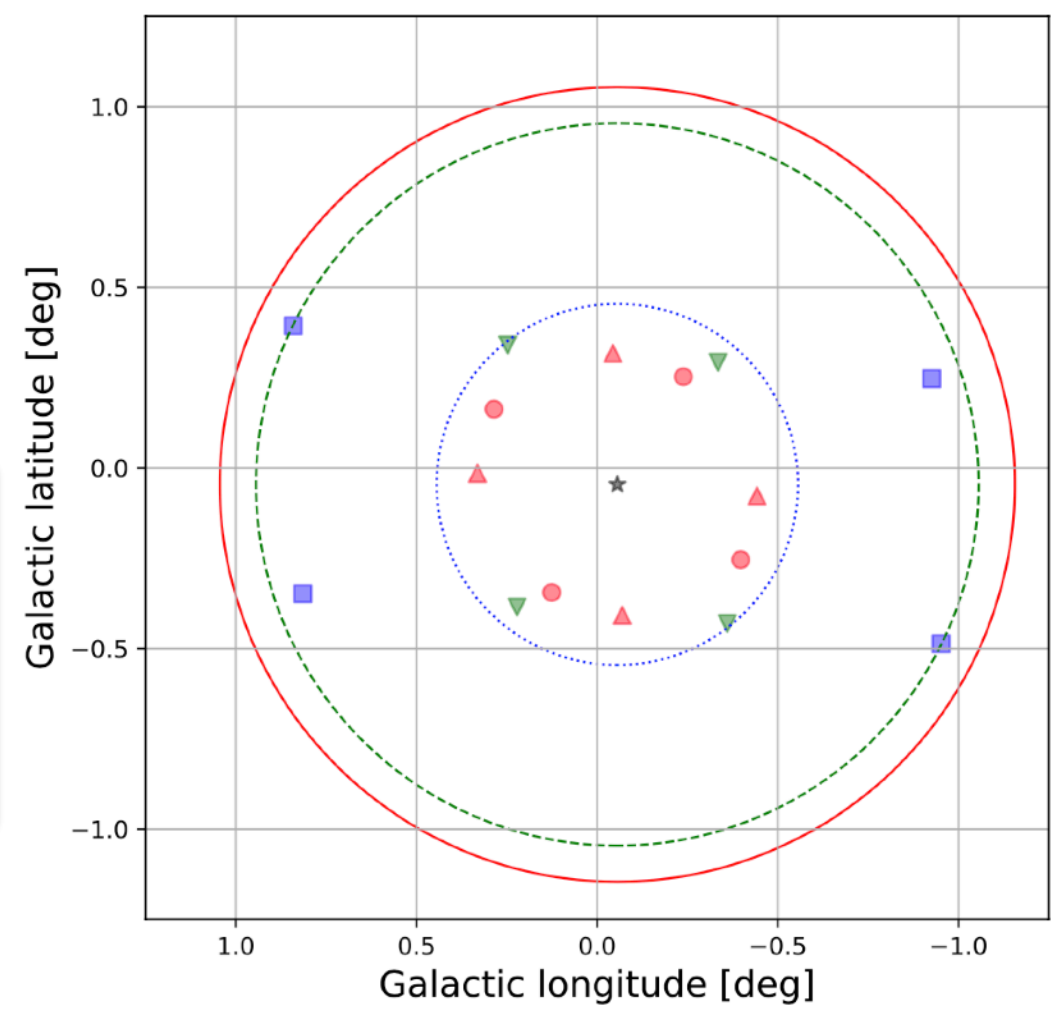
Dates	Label	Total observation time [h] (before quality cuts)	Effective live time [h] (after quality cuts)
2013/03/10 – 2013/07/18	2013	47.1	38.8
2014/03/01 – 2014/07/07	2014	37.3	30.1
2015/03/29 – 2016/04/13	2015	27.0	18.9
2016/05/02 – 2016/08/05	2016	24.8	17.3
2017/03/26 – 2017/06/24	2017	26.0	22.1
2018/02/19 – 2018/09/30	2018a	26.3	19.1
	2018b	7.0	5.8
2019/03/11 – 2019/08/04	2019	54.4	52.0
2020/06/19 – 2020/08/21	2020	22.9	19.1
Total		272.8	223.2

Analysis region (ROI)

- Regions within 1.5° away from the camera center
- Different ROI sizes used due to the variation in pointing directions
- J-factors are computed in each case

Profile name	$J(0.5^\circ)$	$J(1.0^\circ)$	$J(1.1^\circ)$
Cuspy Einasto	3.14×10^{21}	8.01×10^{21}	9.03×10^{21}
NFW	2.18×10^{21}	4.55×10^{21}	5.02×10^{21}
Cored Zhao	2.66×10^{19}	1.06×10^{20}	1.28×10^{20}
Burkert core	1.26×10^{19}	5.04×10^{19}	6.10×10^{19}





Each DM profile shape is taken into account of telescope's acceptance calculation

Likelihood analysis for line search

Unbinned likelihood analysis with a sliding window

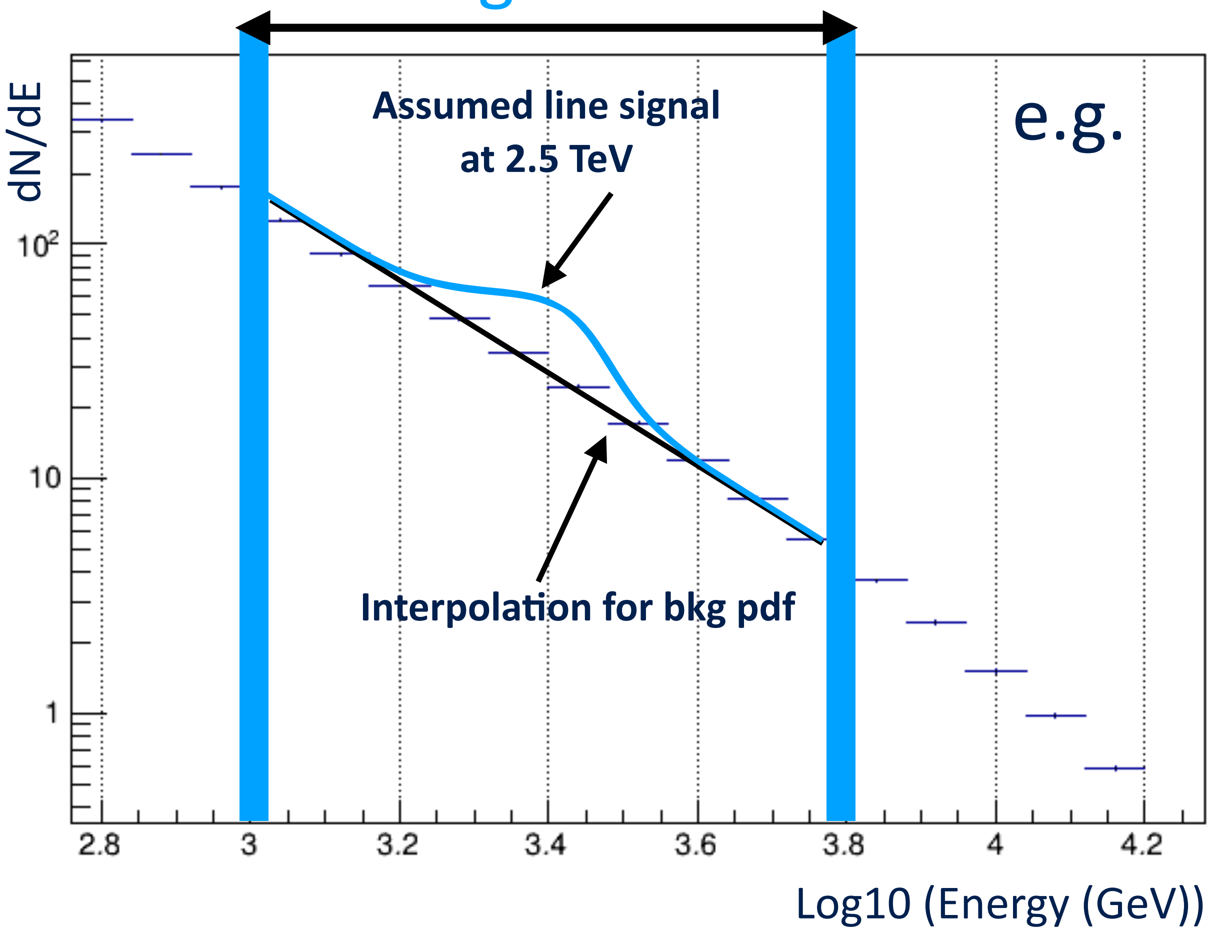
$$\mathcal{L}_i(g_i; \nu_i \,|\mathcal{D}_i) = \mathcal{L}_i(g_i; b_i, \tau_i \,|\{E'_j\}_{j=1,\ldots,N_{\mathrm{ON},i}}, N_{\mathrm{ON},i})$$

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

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

to treat systematic uncertainty of a bkg model

Sliding window

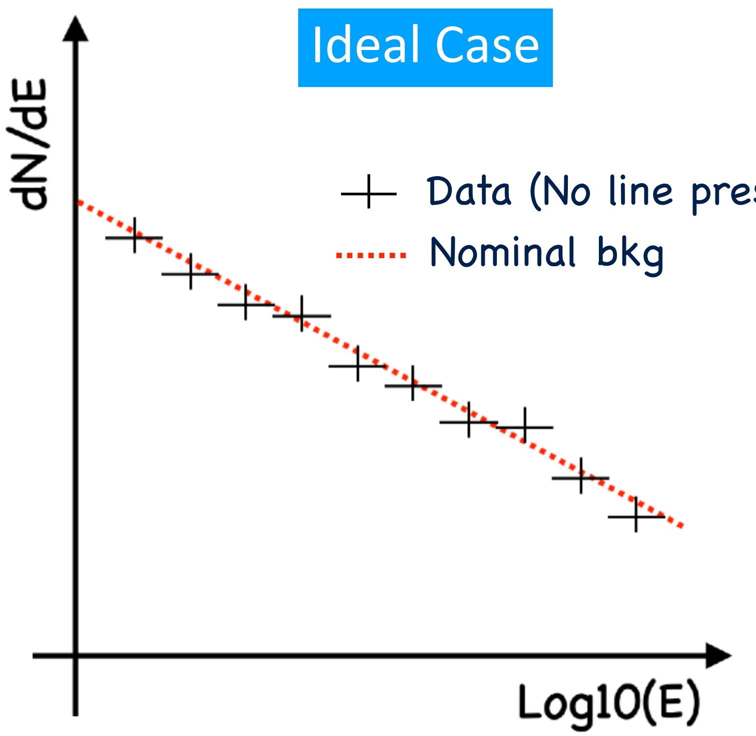


- Index i : data samples
- N_{on} : observed events in a ROI
- g : **estimated signal events** — **Parameters of interest**
- b : estimated background events
- τ : normalization factor for bkg model — Nuisance parameters
- f_g : line signal pdf
  - δ-function convolved with the response function
- f_b : background pdf
  - interpolated from energy spectra, assuming background behaves as power-law spectrum in a sliding window

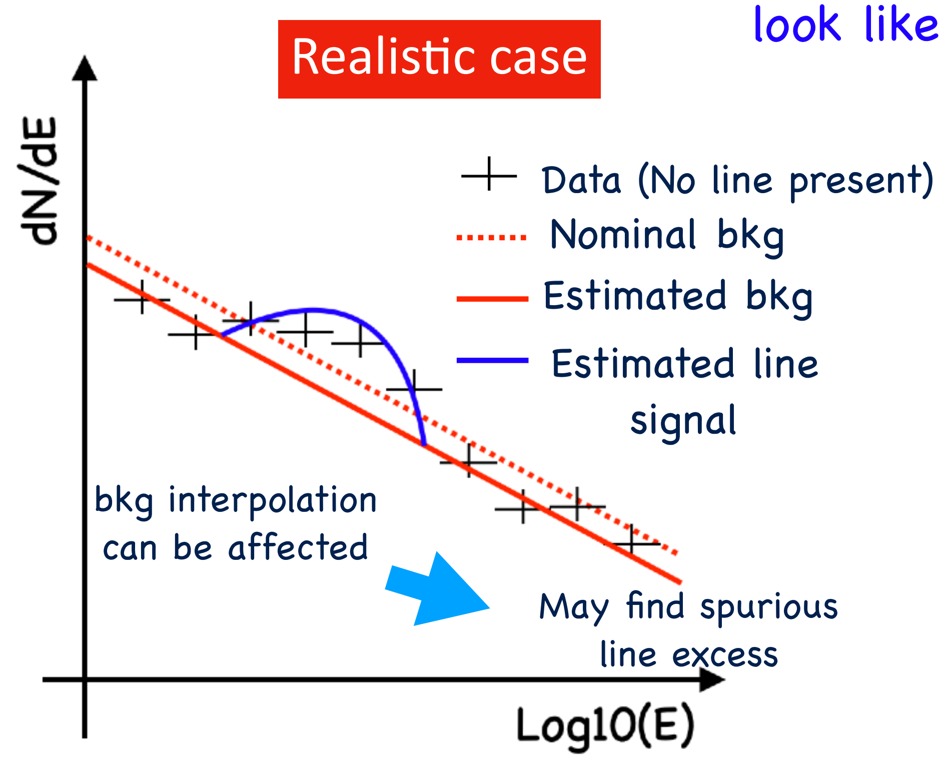
Background model uncertainty?

Potential to under/overestimation number of signals
by the systematic uncertainty of bkg model

If systematic offsets
look like line-signal



τ = 1



$$\tau = \mathrm{Gaus}(\tau_{\mathrm{obs}},\ \sigma_\tau)$$

$$\sigma_\tau^2 = \sigma_{\tau,\mathrm{stat}}^2 + (\tau\sigma_{syst})^2$$

- systematic uncertainty in the background pdf is included in likelihood

Need to estimate

given by Gaussian

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

$$= \frac{(g_i + \boxed{\tau_i} b_i)^{N_{\mathrm{ON},i}}}{N_{\mathrm{ON},i}!} e^{-(g_i + \boxed{\tau_i} b_i)} \times \frac{1}{g_i + \boxed{\tau_i} b_i} \prod_{j=1}^{N_{\mathrm{ON}}} (g_i f_g(E'_j) + \boxed{\tau_i} b_i f_b(E'_j)) \times \boxed{\mathcal{T}(\tau_i | \tau_{obs,i}, \sigma_{\tau,i})}$$

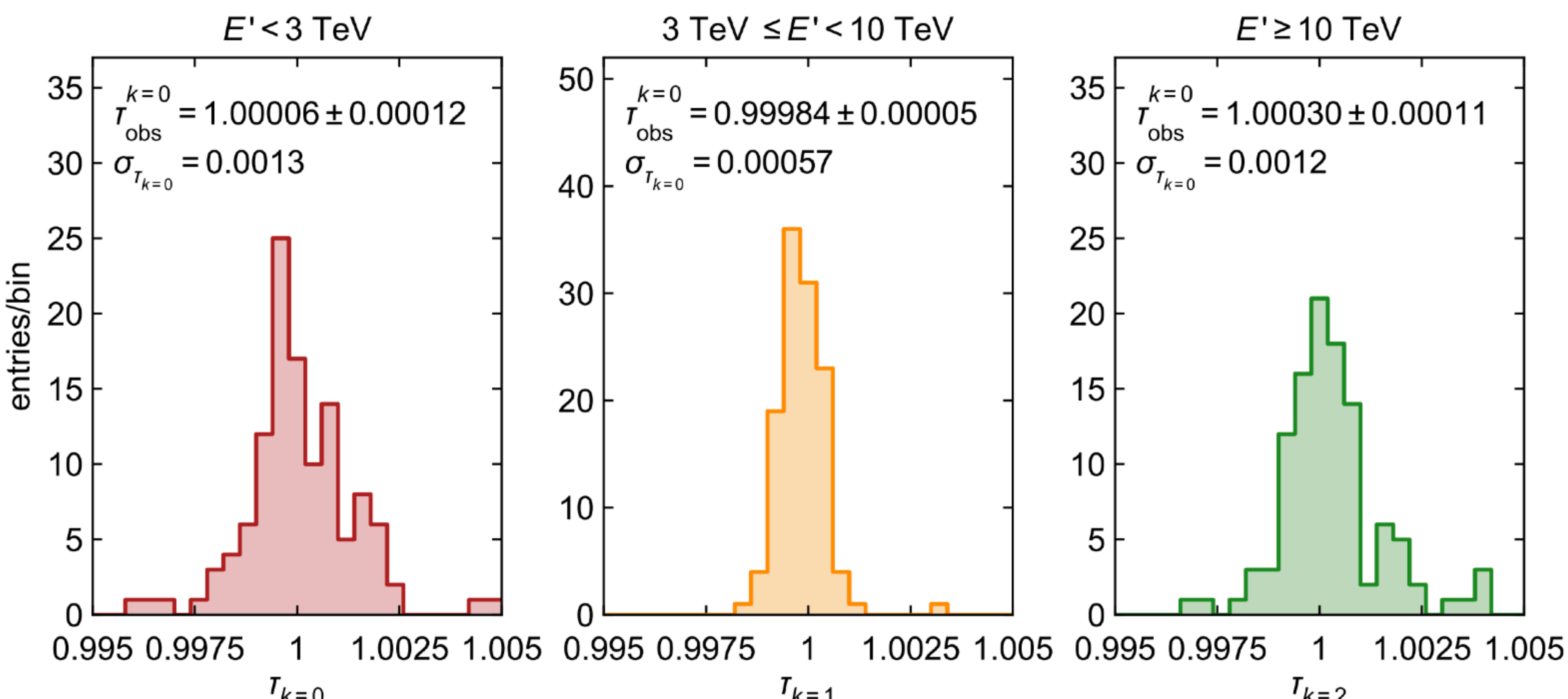
Study for systematic uncertainty

Estimated systematic uncertainty in a bkg pdf determination

- applied the line search analysis to data without DM target sources with 120 samples divided into 3 energy categories, E < 3 TeV, 3 TeV < E < 10 TeV, E > 10 TeV

$$\tau = \frac{N_{\mathrm{ON}} - N_{\mathrm{sig}}}{N_{\mathrm{ON}}} \qquad \sigma_{\tau,\mathrm{stat}}^2 = \left(\frac{\partial \tau}{\partial N_{\mathrm{sig}}} \times \sigma_{N_{\mathrm{sig}}}\right)^2 + \left(\frac{\partial \tau}{\partial N_{\mathrm{ON}}} \times \sigma_{N_{\mathrm{ON}}}\right)^2$$

τ_{obs}^k is the mean of the distribution, which is included as the bias to likelihood eq.



arXiv2212.10527

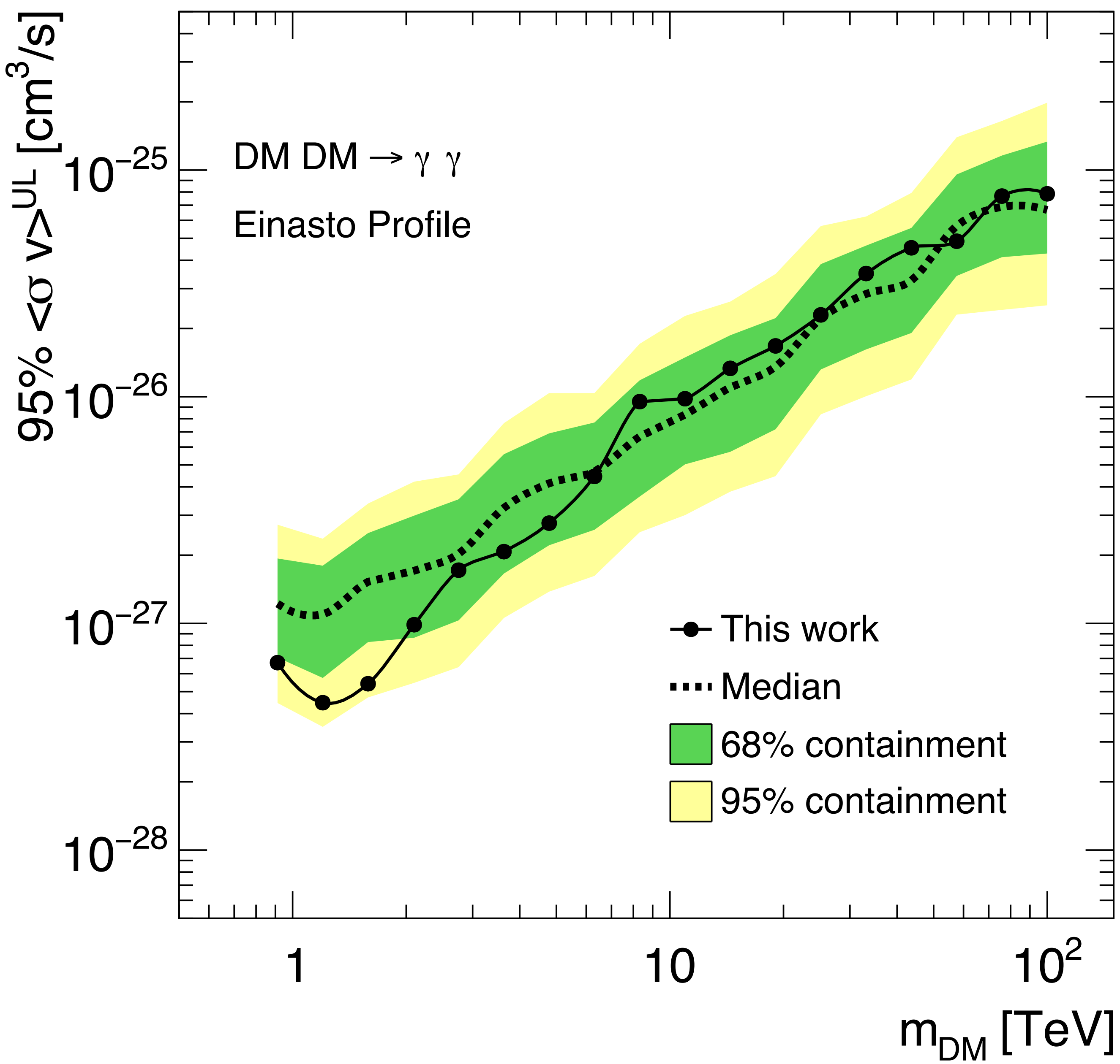
$$\sigma_{\tau^k}^2 = \sigma_{\tau^k,\mathrm{stat}}^2 + \sigma_{\tau^k,\mathrm{syst}}^2$$

$\sigma_{\tau^k,\mathrm{syst}} < 1\ \%$: included likelihood eq.

Results

No significant line-like excess found

- set upper limits at 95% C.L. on 18 masses in the range 0.9 TeV - 100 TeV
- uncertainty on sensitivity calculated with 300 realizations (trade-off between statistical convergence and calculus speed)



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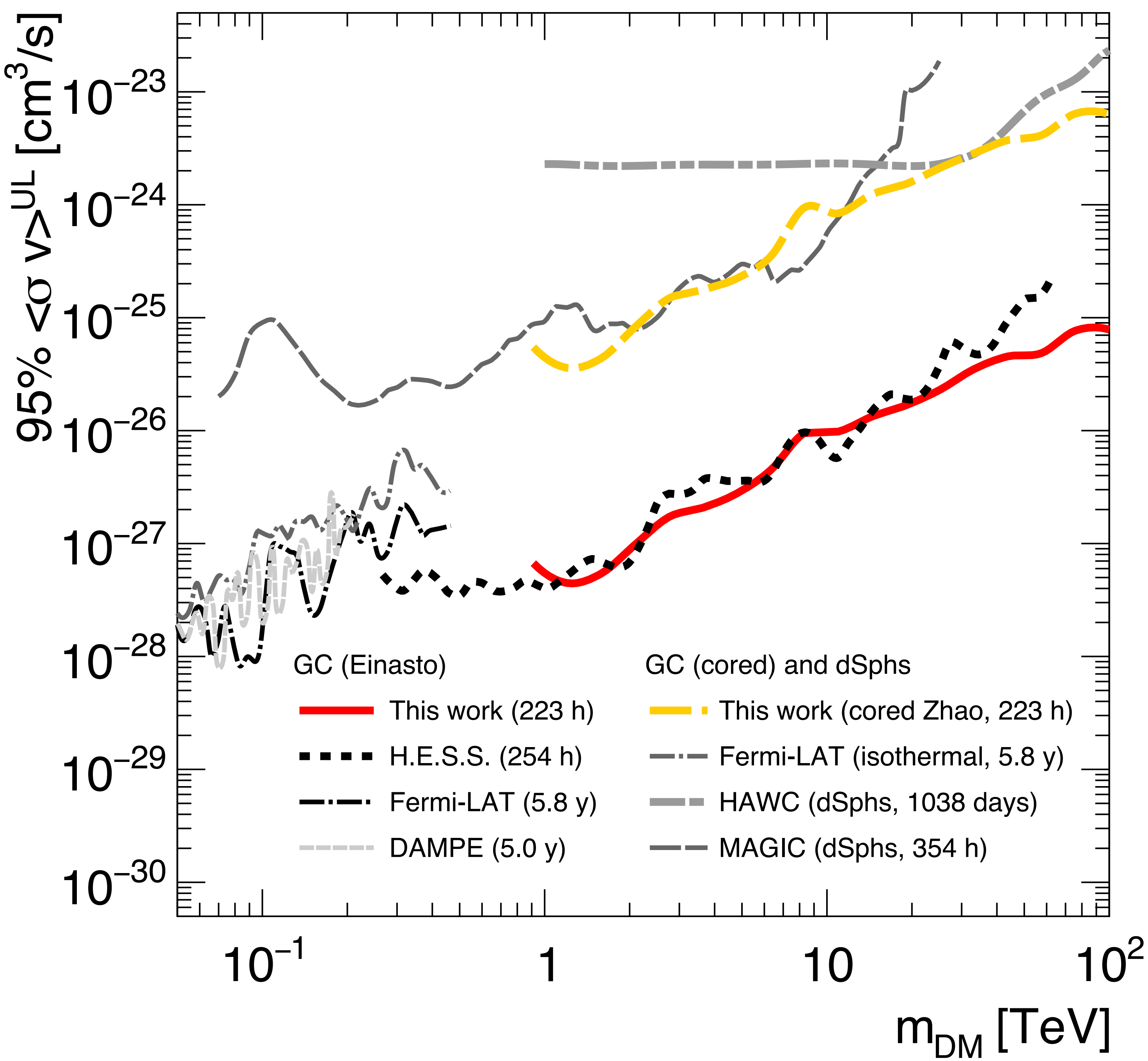
Comparison of limits with other experiments

No significant excess: 0.9 TeV - 100 TeV

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



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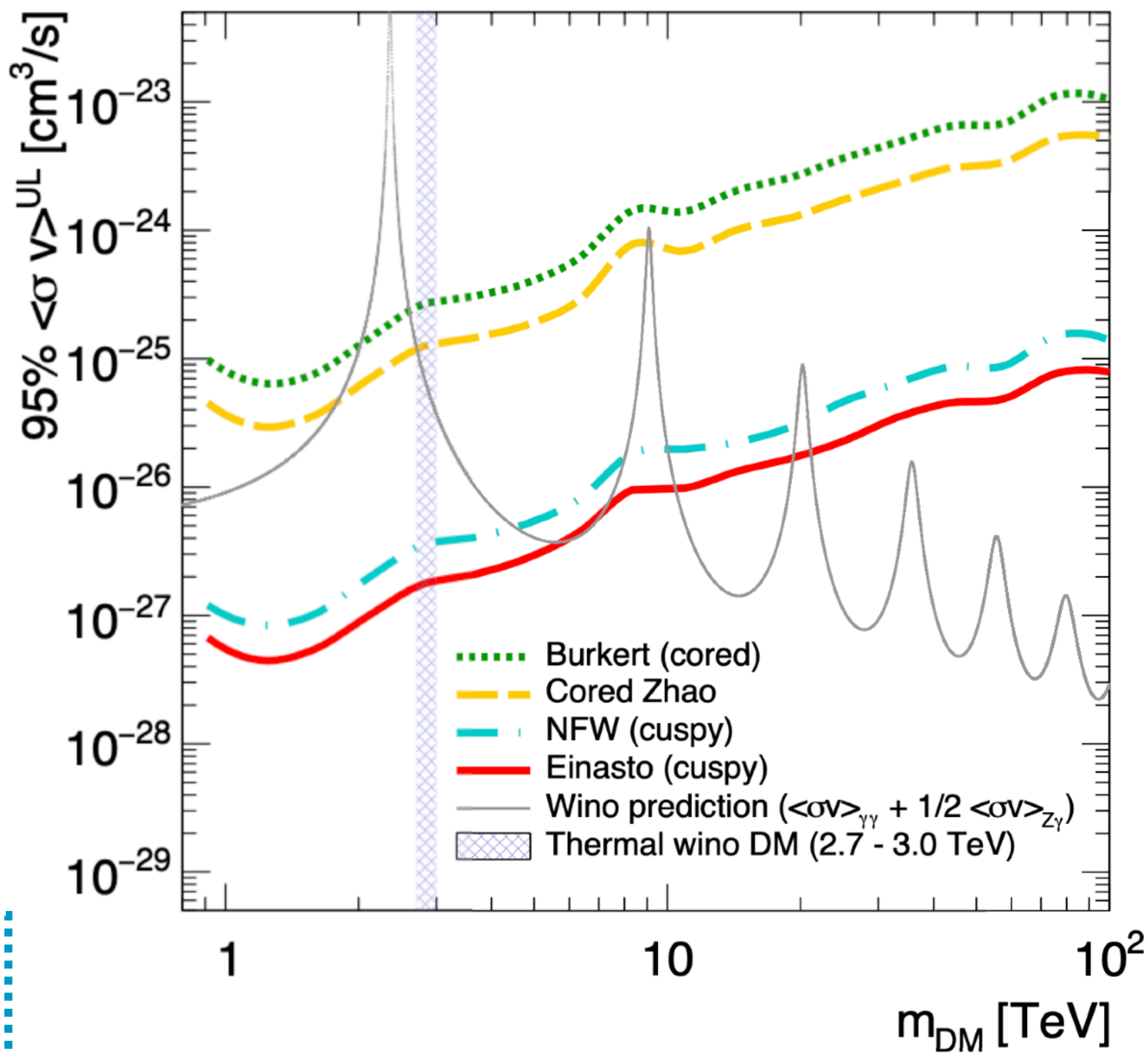
Testing SUSY-Wino with various DM profiles

The Neutralino

$$\chi = a_1\tilde{B} + a_2\tilde{W}^0 + a_3\tilde{H}_1^0 + a_4\tilde{H}_2^0$$

bino $\tilde{B}$ wino $\tilde{W}^0$ higgsino $\tilde{H}_1^0, \tilde{H}_2^0$

- If **SUSY-Wino** exists in the range of masses between **2.7 - 3.0 TeV**, it can be DM
- Up to 2.8 TeV rejected by **Cored Zhao** (the reasonable cored profile), **Einasto and NFW**.



The first time to constrain SUSY-wino DM with both cuspy and cored profiles!

arXiv2212.10527

Summary

- Search for **line-like signals in VHE gamma rays** can test promising TeV DM particle models

- We reported observations with **the MAGIC telescopes** located on La Palma, Spain
  - **large zenith angle observations to focus on DM detection at (multi-)TeV masses**
  - **first search for DM lines at the GC with MAGIC**

- No significant excess was discovered
- Upper limits were set on the annihilation cross section
  - the best limits > 20 TeV, competitive with low masses as well
  - **constraint on well motivated SUSY-Wino to be DM with various DM profiles**

- For the future
  - **large zenith angle observations of the GC are well suited to search for heavy DM candidates**
  - high potential of the northern site to contribute to next-generation DM searches