ICRR
Institute for Cosmic Ray Research
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MAGIC

Search for Gamma-ray Line emission from Dark Matter annihilation in the Galactic Centre with the MAGIC telescopes

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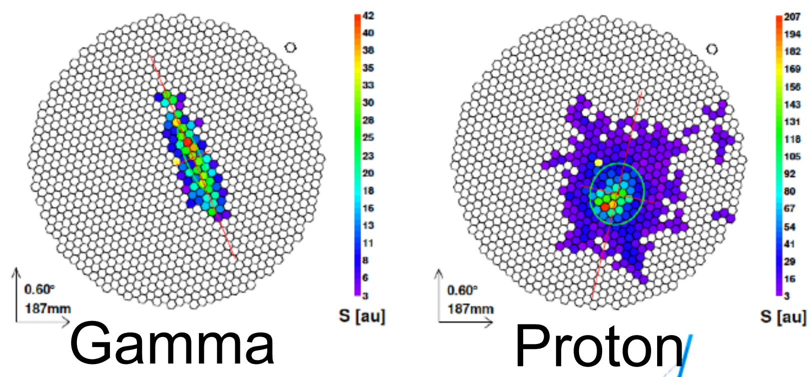
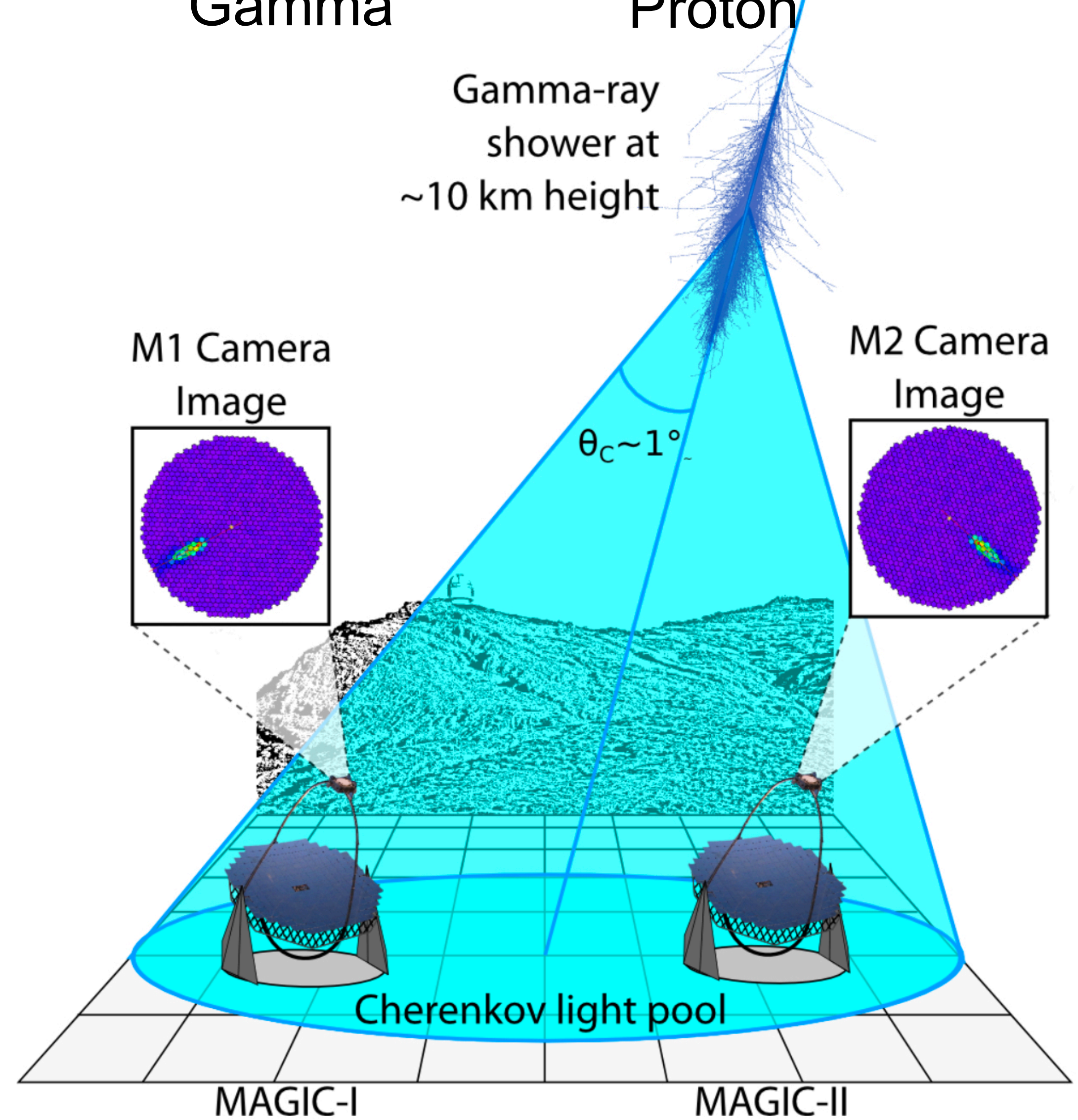
The MAGIC telescopes

MAGIC (Major Atmospheric Gamma Imaging Cherenkov telescopes)

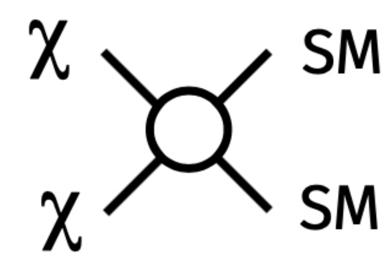
- Observatorio del Roque de los Muchachos (ORM)
  - ~ 2200 m a.s.l., La Palma, Canary Islands, Spain
- 2-telescope stereoscopic system
  - 17m diameter
- Energy : 50 GeV - 50 TeV (Low Zd ~20°)
- FoV : 3.5°
- Angular resolution : 0.06° @ 1 TeV
- Energy resolution : 15 % - 25 %





Gamma-ray Signal from Dark Matter (DM)

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



σv : annihilation cross-section

m_χ : Mass of DM particle

BR_i : branching ratio of each channel

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

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

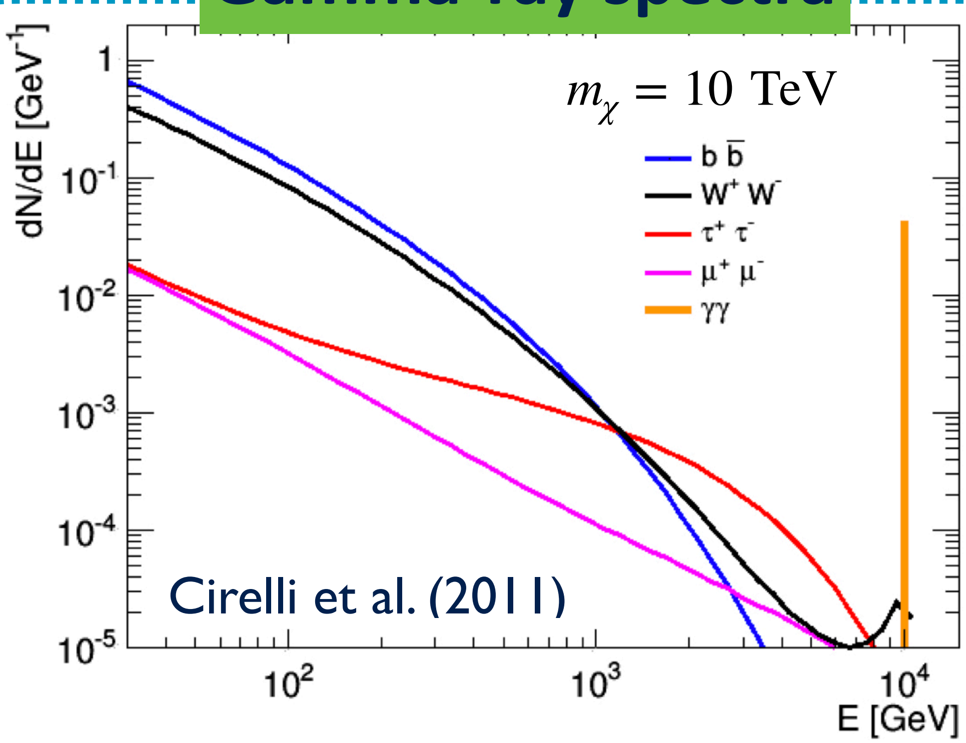
ρ : dark matter (DM) density

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

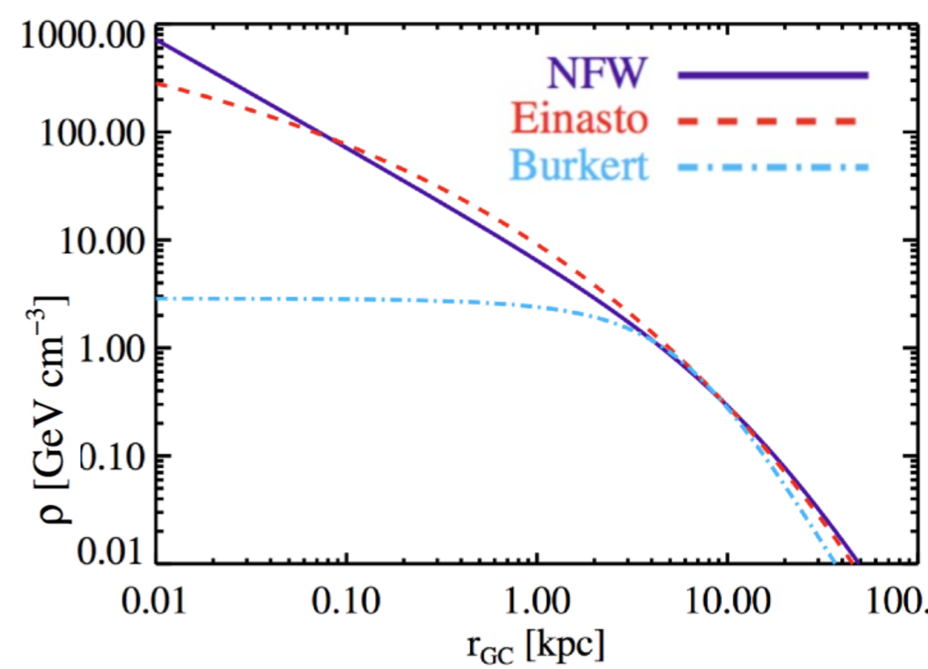
J-factor :

- Integrated DM density along the line of sight

Gamma-ray spectra



DM density profile models



J. M. Gaskins (2016)

Motivation for line search

The expected cross section derived from thermal relic

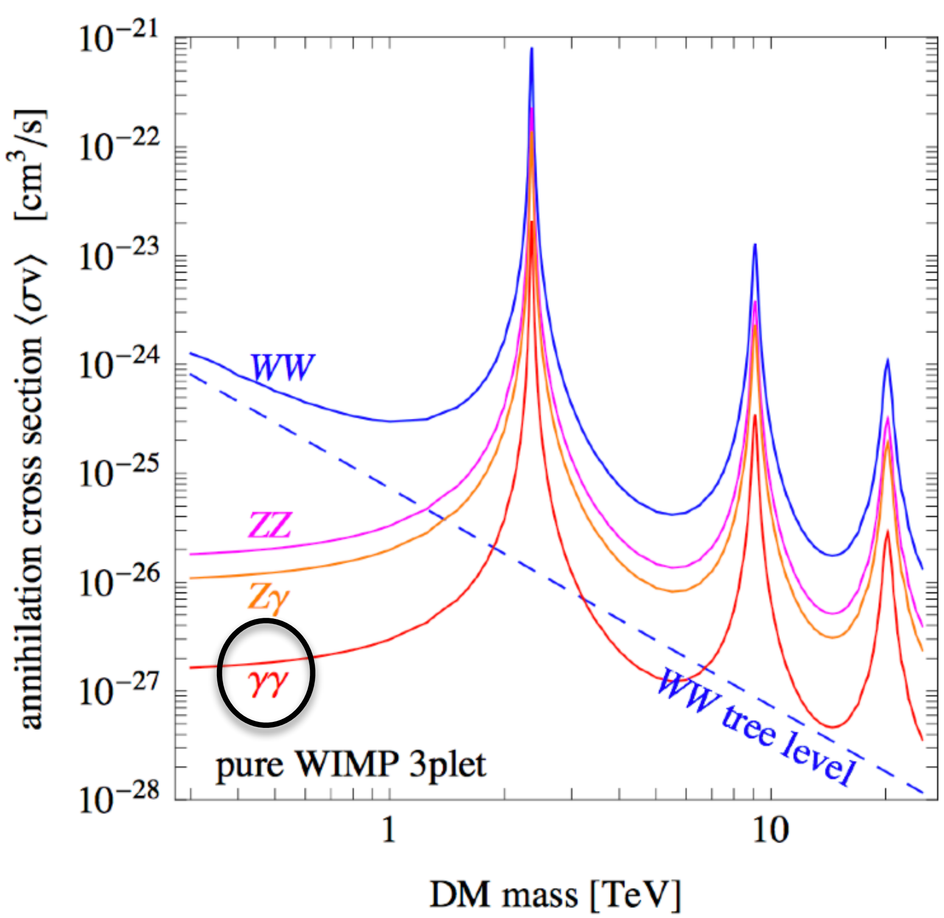
$$\langle \sigma v \rangle = \langle \sigma v_{\tau\tau} \rangle + \langle \sigma v_{bb} \rangle + \langle \sigma v_{\gamma\gamma} \rangle \quad \ldots$$

$$\langle \sigma v \rangle \simeq 3 \times 10^{-26}\,\mathrm{cm}^3\,\mathrm{s}^{-1}$$

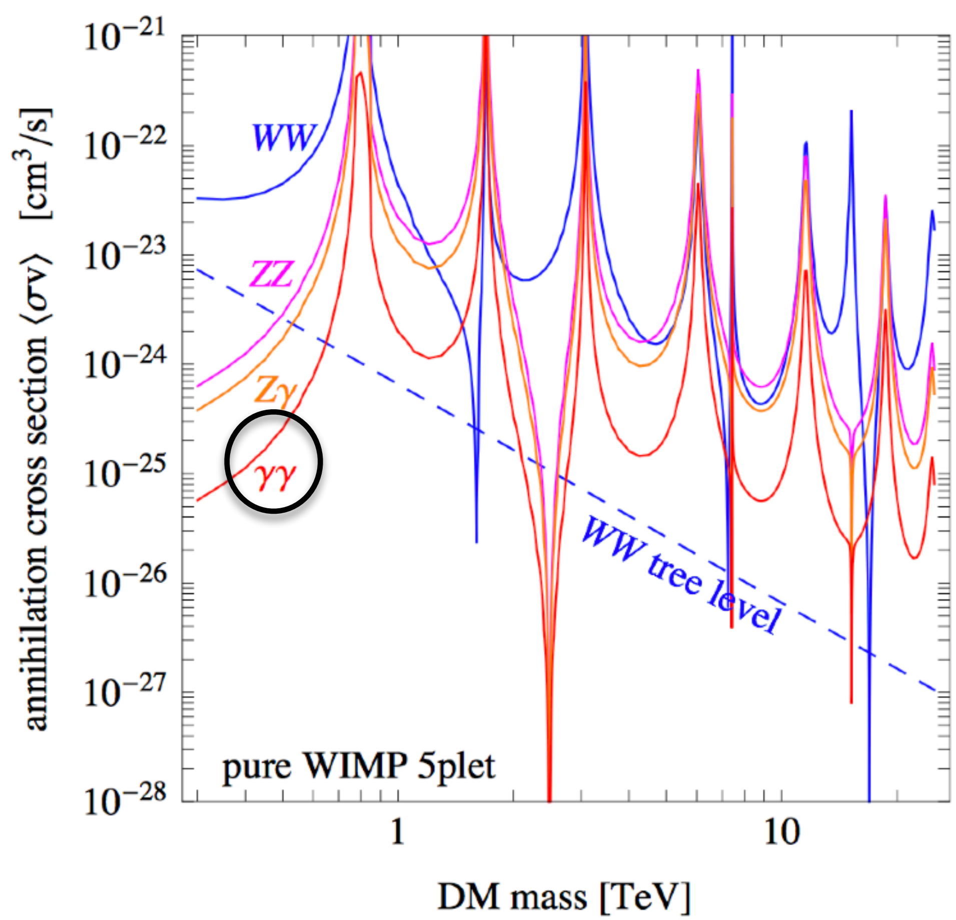
The Branching ratio for 2 γ is suppressed by factor α^2, though…

Interesting models show their cross-sections are enhanced by non-perturbative phenomenon (the Sommerfeld effect)

3plet (wino-like in SUSY)



5plet (minimal DM model)



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

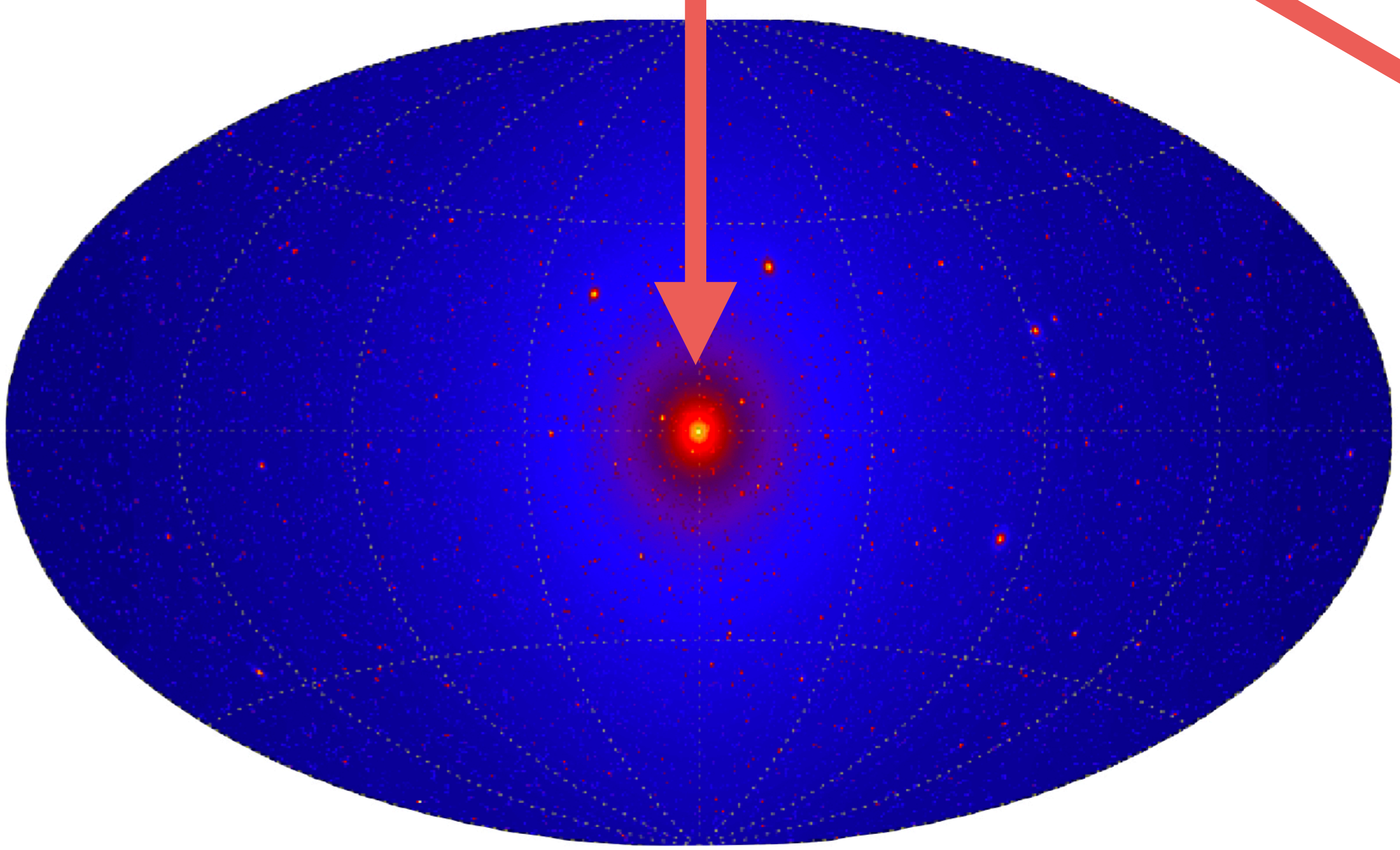
Galactic Centre (GC) and Halo

- The largest J-factor
- Extended
- Source confusion, diffuse bkg and Cuspy/core differences in DM profiles

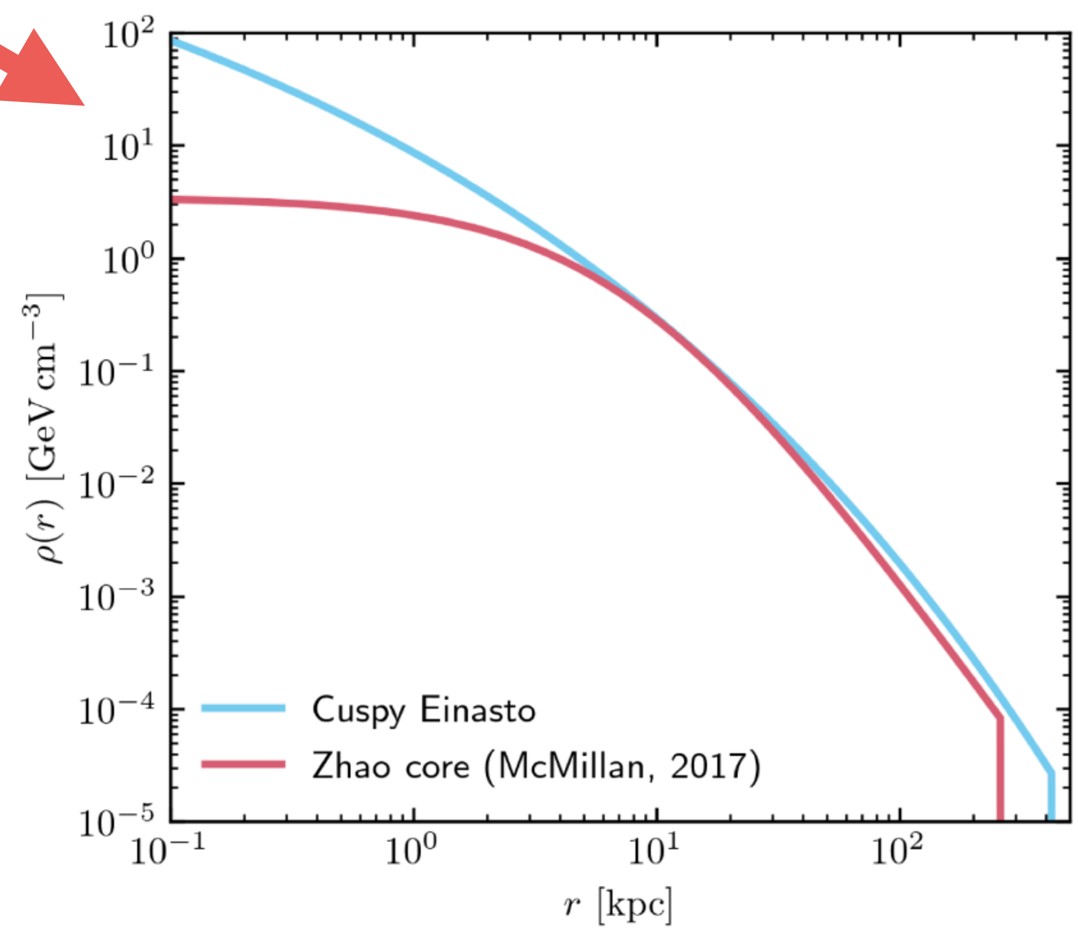
$$\rho_{\mathrm{Einasto}}(r) = \rho_s \exp\left\{\frac{-2}{\alpha}\left[\left(\frac{r}{r_s}\right)^{\alpha} - 1\right]\right\}$$

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

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



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!

The GC observation by MAGIC

The GC observation by MAGIC

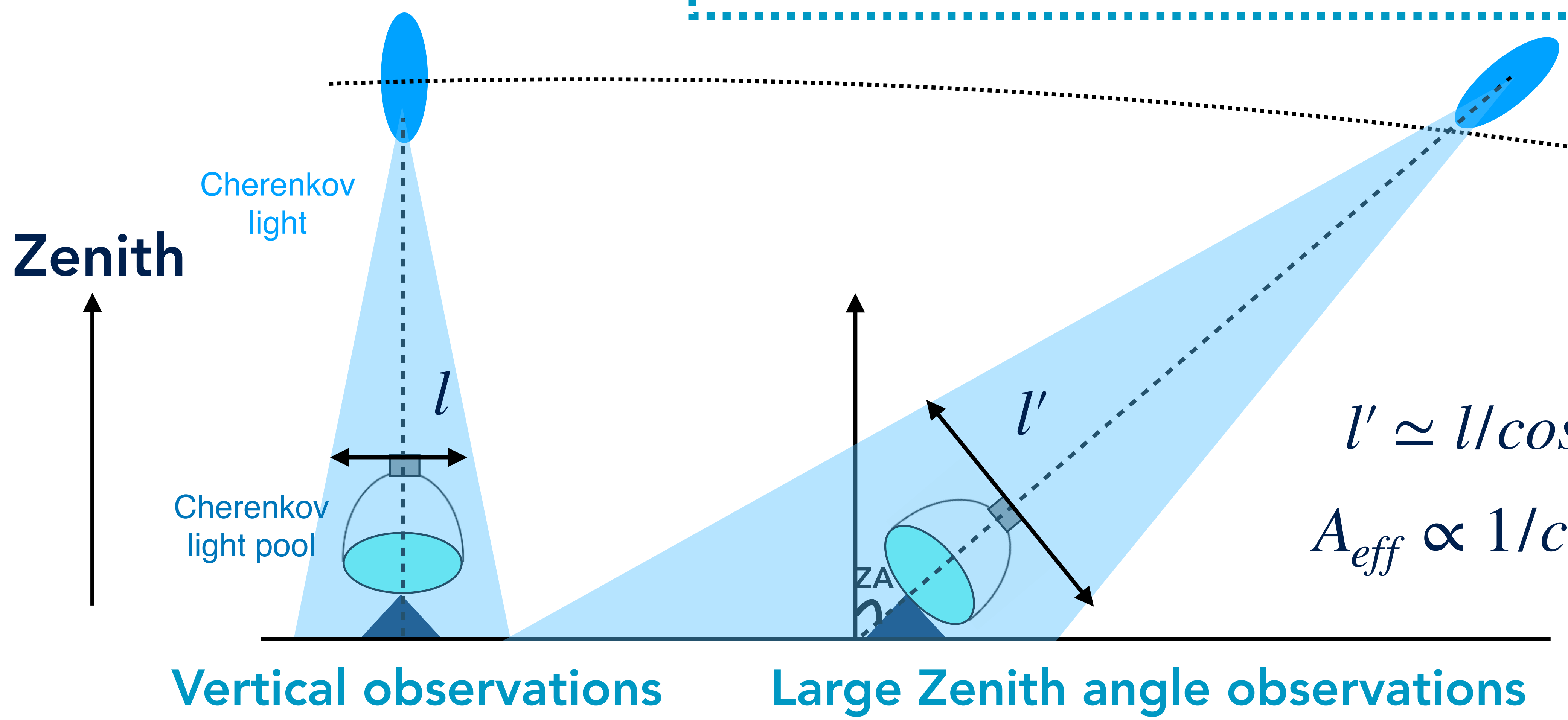
- Zenith angle : 58 - 70 [deg]
  - Large zenith angle observation, LZA

Pros

- Increase the γ-ray detectable area
  - Get larger statistics in higher energies

Cons

- Increase the energy threshold



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

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

Large Zenith angle observations boost the sensitivity for line signals from TeV DM!!

Dataset

Data : March 2013 - August 2019

- **Zd range : 58° < Zd < 70°**
- **Total observation time : 204 hours**
  - After quality cuts

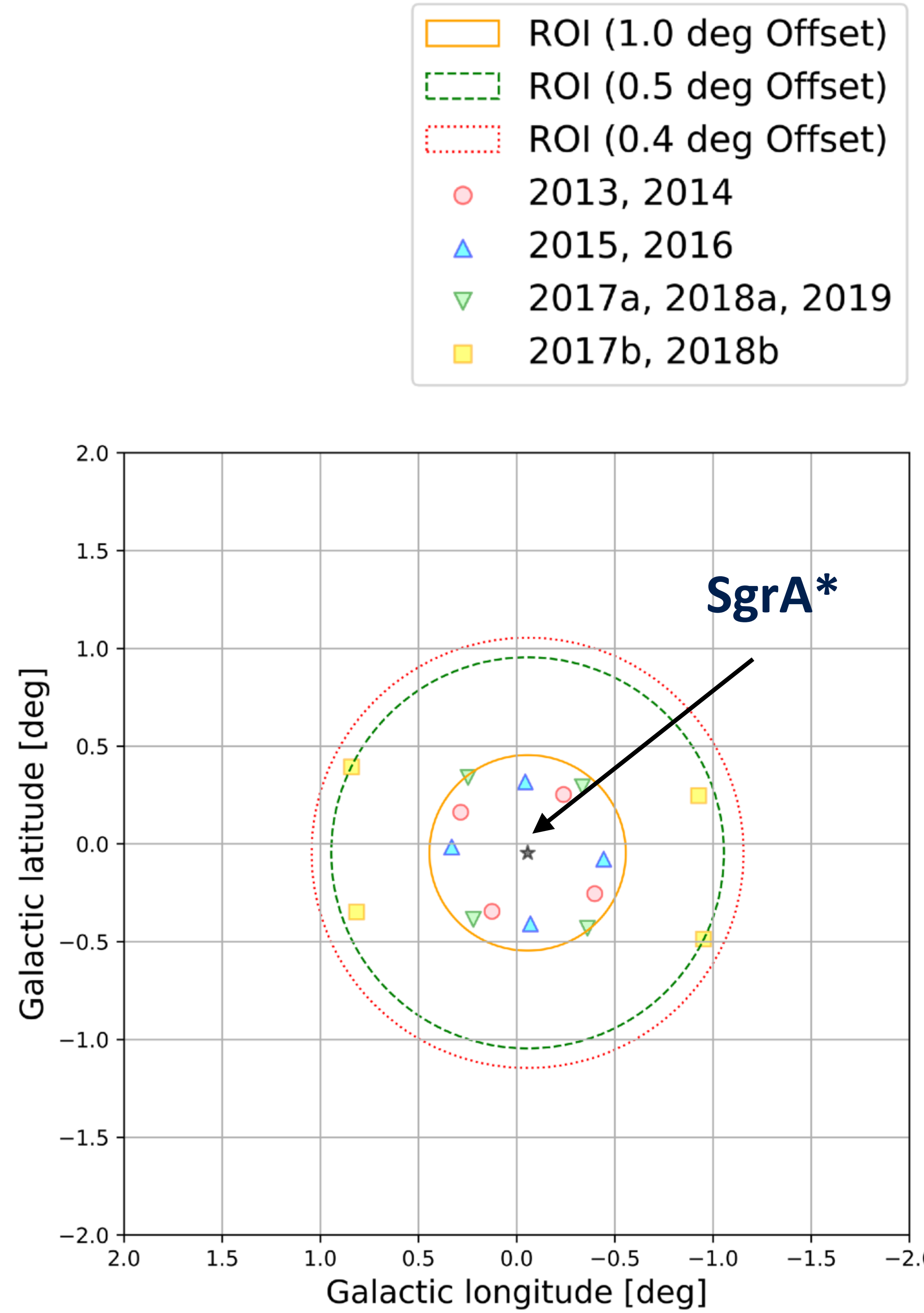
Analysis region (ROI)

- Regions within 1.5° away from the camera center
- different ROI sizes used
  - due to the variation in pointing directions

J-factor

- computed with each ROI
  - For both a cuspy and core profile

Profile name	$J(0.5°)$	$J(1.0°)$	$J(1.1°)$
Cuspy Einasto	3.14×10^{21}	8.01×10^{21}	9.03×10^{21}
Zhao γ=0 core	2.66×10^{19}	1.06×10^{20}	1.28×10^{20}



Likelihood analysis for line search

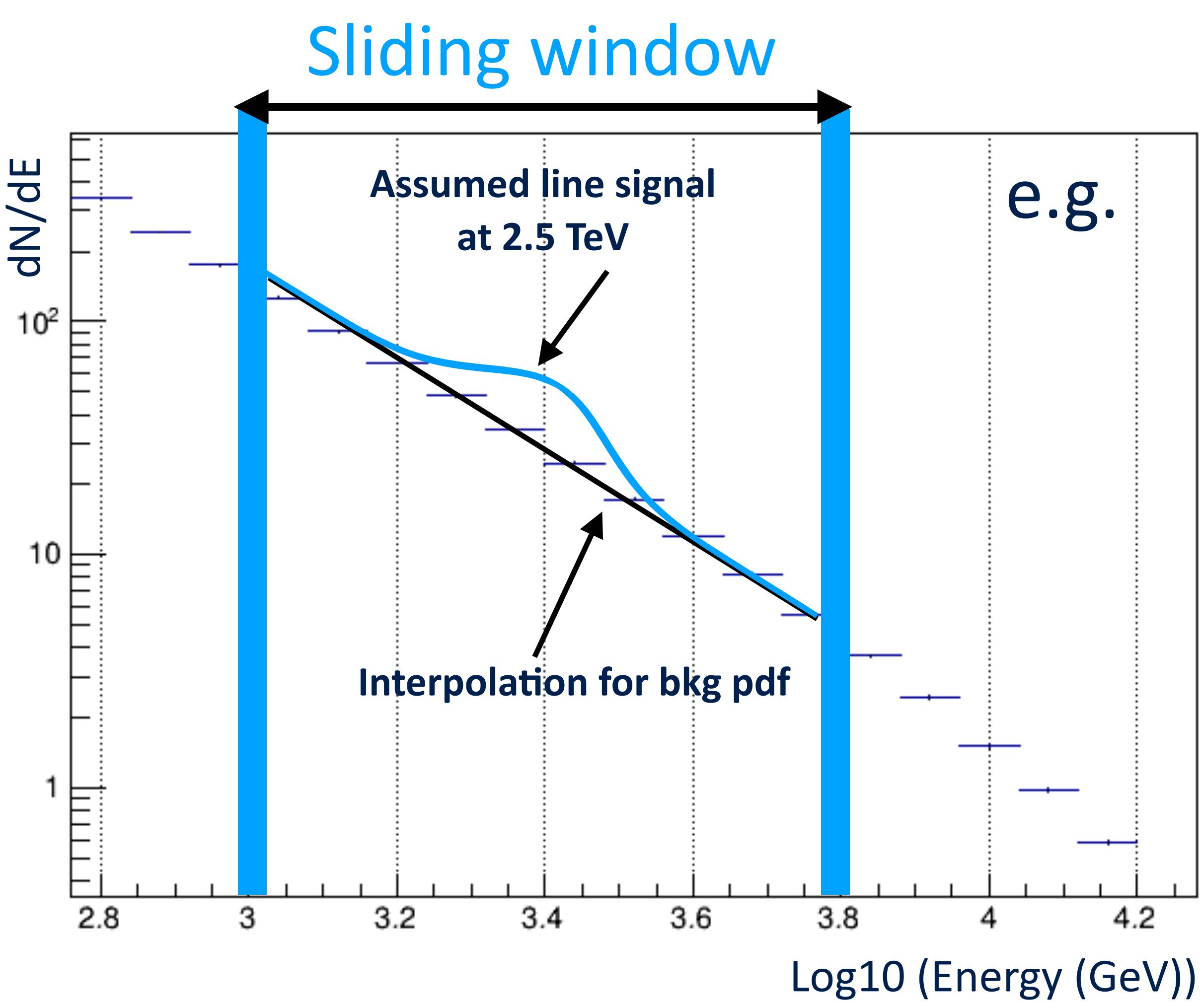
Unbinned likelihood analysis with a sliding window

Our strategy : Search a tiny peak on a smooth background curve

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

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

$$\times \mathcal{T}(\tau_i|\tau_{\mathrm{obs},i},\sigma_{\tau,i})$$ for systematic uncertainty of a bkg model

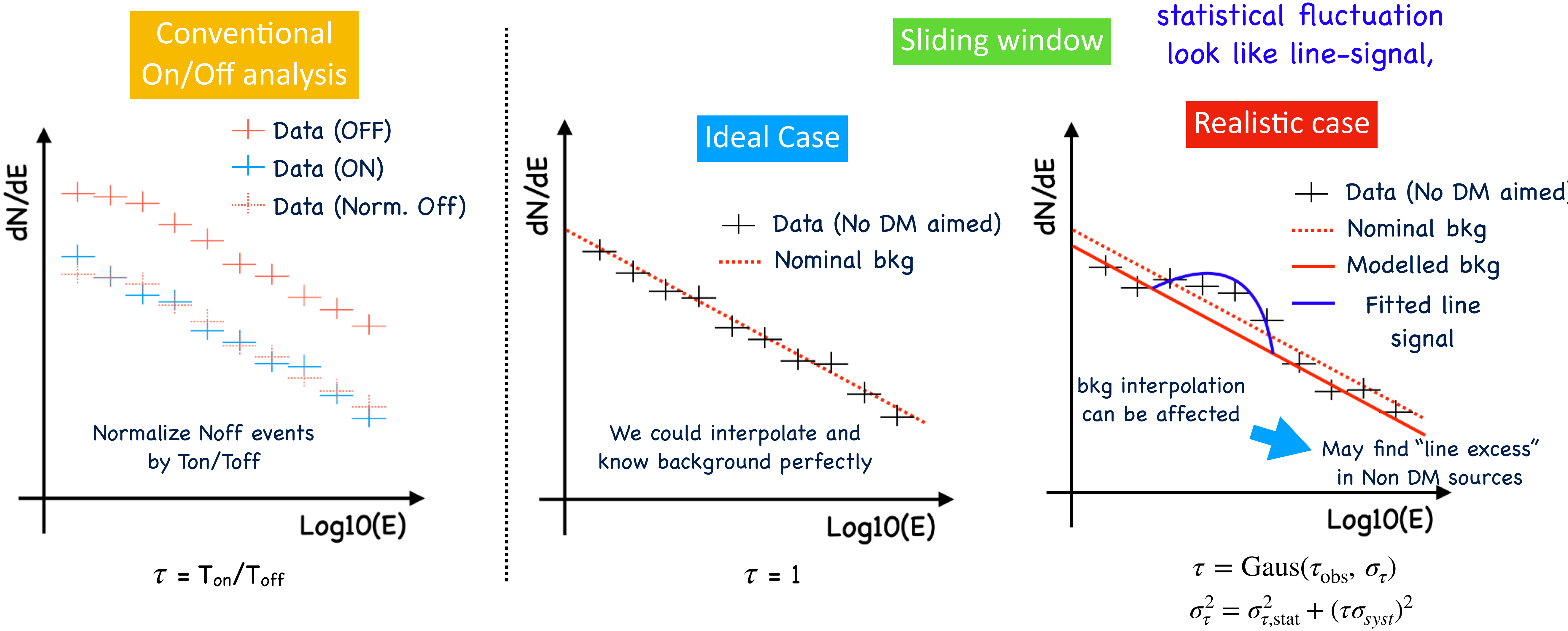


- Index i : Data samples
- N_{on} : Observed events in a ROI
- g : **Estimated signal events** — **Parameter of interests**
- b : Estimated background events — Nuisance parameters
- τ : Normalization factor for bkg model — Nuisance parameters
- f_g : Line signal pdf
  - δ-function convoluted with the response function
- f_b : Background pdf
  - Interpolated from energy spectra
    - Assumption : background behaves smooth curve in a sliding window

Uncertainty in background model ?

- How to obtain a background model?

If systematic offsets or statistical fluctuation look like line-signal,



- Systematic uncertainty in a background pdf is included to Likelihood

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

given by Gaussian

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

Need to estimate!!

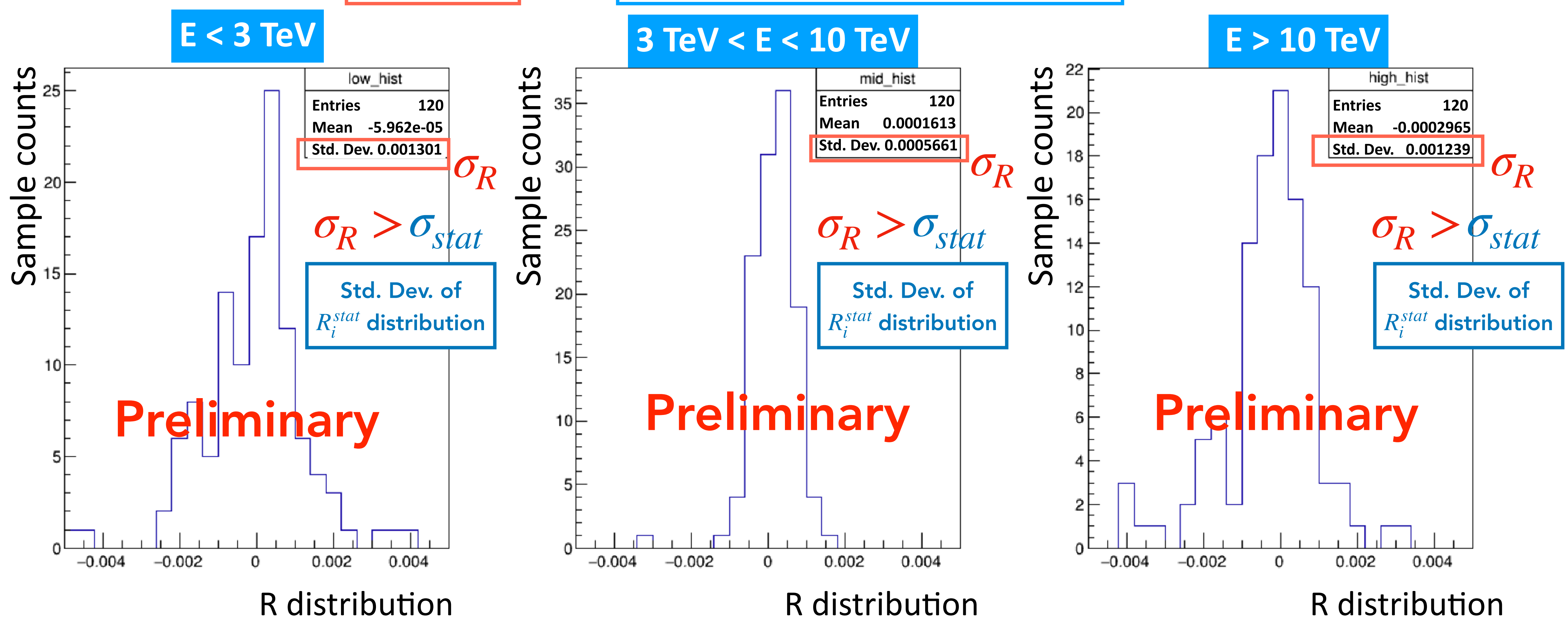
Study for Systematic uncertainty

Estimated systematic uncertainty in a bkg pdf determination

- Applied the line search analysis to non-DM aimed sources with 120 samples
  - Divided into 3 energy categories, E < 3 TeV, 3 TeV < E < 10 TeV, E > 10 TeV
- Computed residual R_i and its statistical error size R_i^{stat} with error propagation

$$R_i = \frac{N_i^{ex}}{N_i^{tot}}$$

$$R_i^{stat} = \sqrt{\left(\frac{\partial R_i}{\partial N_i^{ex}} \cdot \sigma_{N_i^{ex}}\right)^2 + \left(\frac{\partial R_i}{\partial N_i^{tot}} \cdot \sigma_{N_i^{tot}}\right)^2}$$



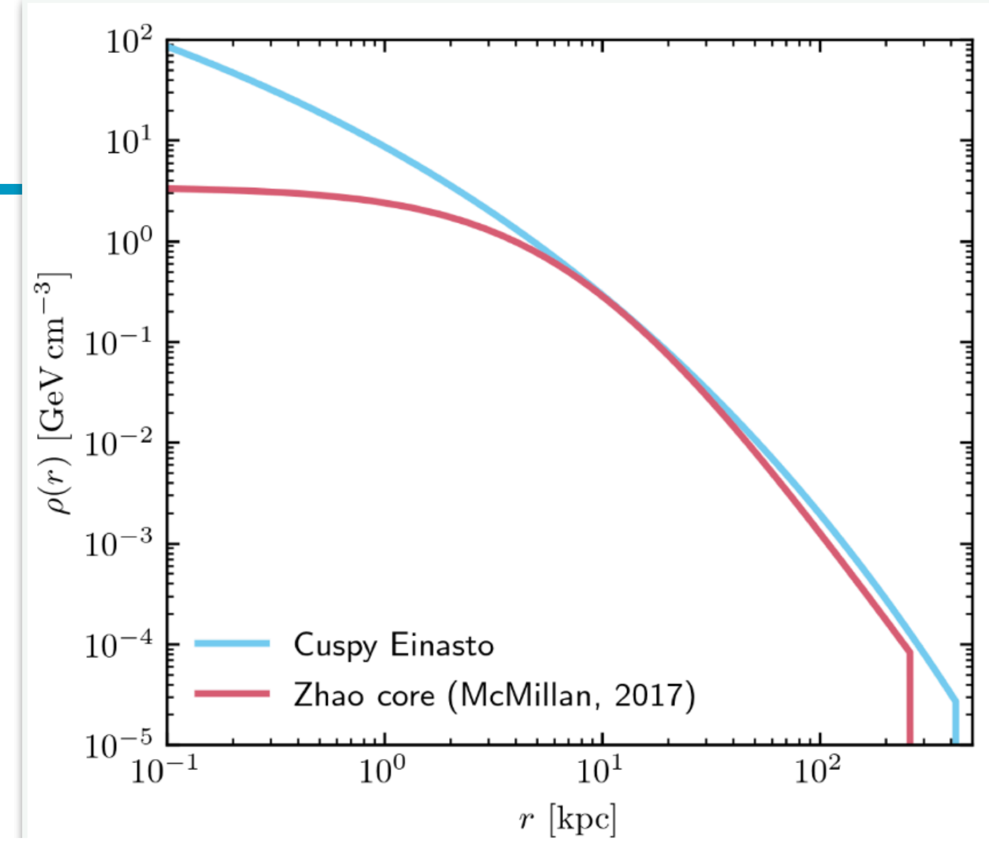
$$\sigma_R^2 = \sigma_{\text{tot}}^2 = \sigma_{\text{stat}}^2 + \sigma_{\text{syst}}^2$$

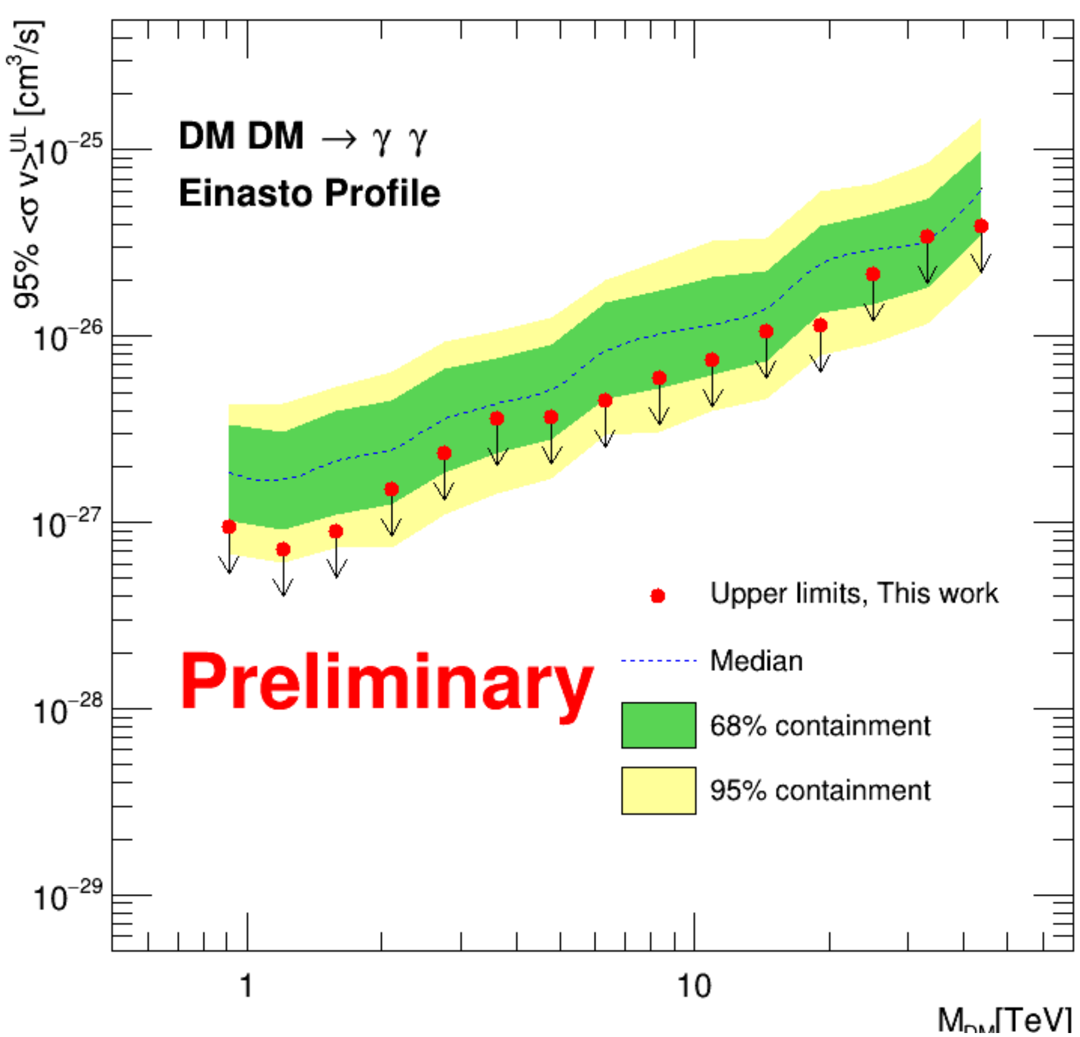
→ $\sigma_{\text{syst}}^2 < 1\ \%$ level : included likelihood eq.

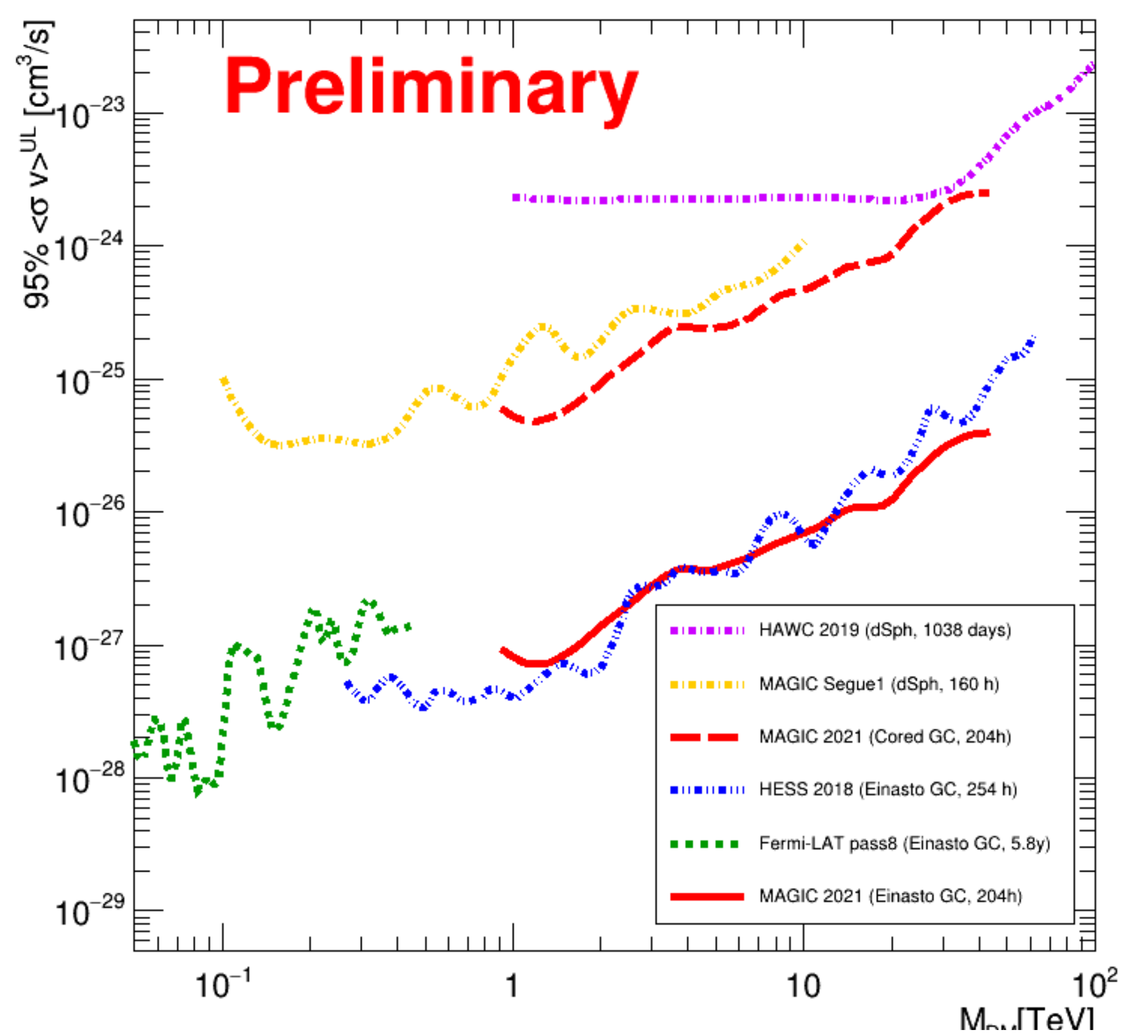
Results

No significant excess

- Set upper limits with 95% C.L. on 15 masses
- 912 GeV - 43 TeV
- with Einasto (cuspy) and cored profile.
- <u>E > 10 TeV : competitive</u>







Summary

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

- We reported observations with the MAGIC telescopes located on La Palma, Spain
  - Performed large zenith angle observations to focus on TeV DM
  - First search for DM lines at the GC with MAGIC

- No significant excess was found and upper limits were set on the annihilation cross section $\chi\chi \rightarrow \gamma\gamma$
  - Competitive limits for both cuspy and core DM profiles

- For the future (CTA era)
  - 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