MAGIC

ICRR Institute for Cosmic Ray Research University of Tokyo

ICHEP 2022 BOLOGNA

Search for gamma-ray spectral line emission from dark matter annihilation up to 100 TeV towards the Galactic Centre with MAGIC

Tomohiro Inada (ICRR, UTokyo)

Daniel Kerszberg, Moritz Hütten, Masahiro Teshima, Javier Rico, Kazunori Kohri, Nagisa Hiroshima for the MAGIC Collaboration

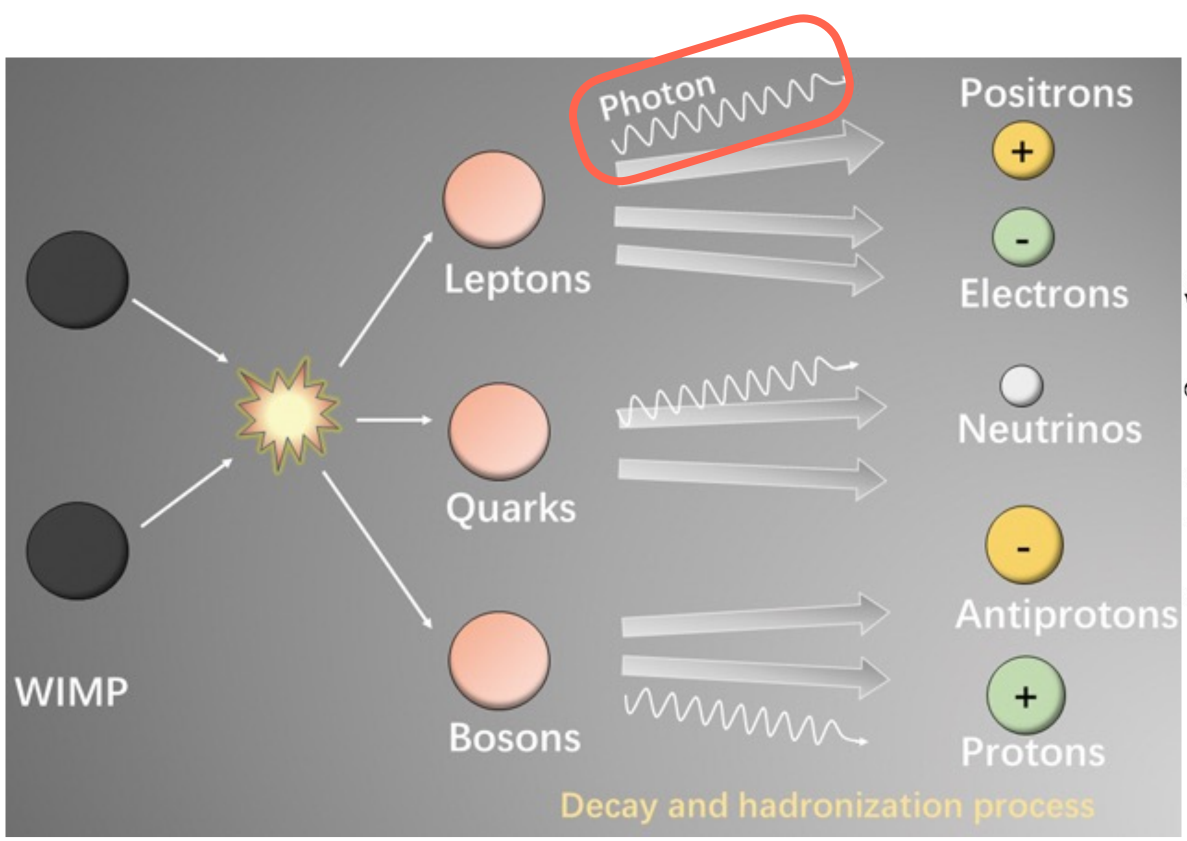
Indirect dark matter search with gamma-ray

Indirect dark matter search

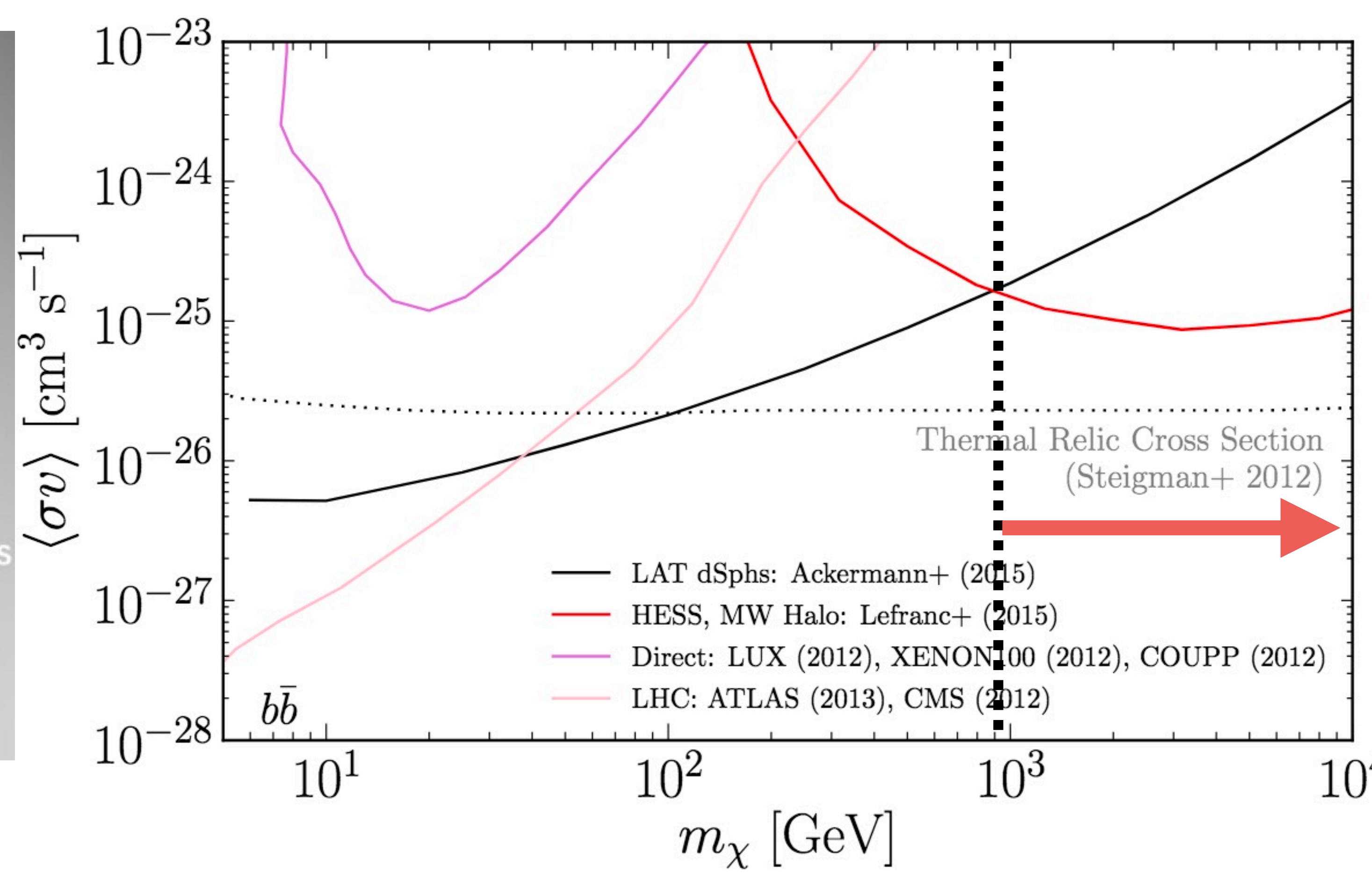
- searches for products ($\gamma, e^{\pm}, \nu, p^{\pm}$) from dark matter annihilation/decay

Complementarity of WIMP DM Searches

- Cherenkov telescopes would be useful to search for DM at TeV-scale due to the good sensitivity for high-energy gamma-ray



credit: GAO Linqing and Lin Sujie

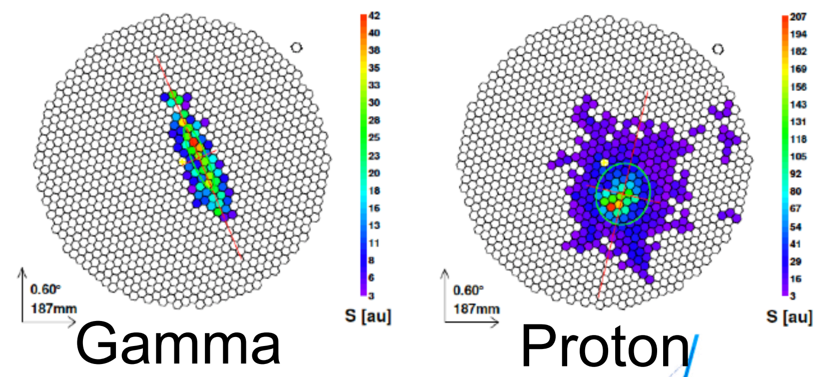


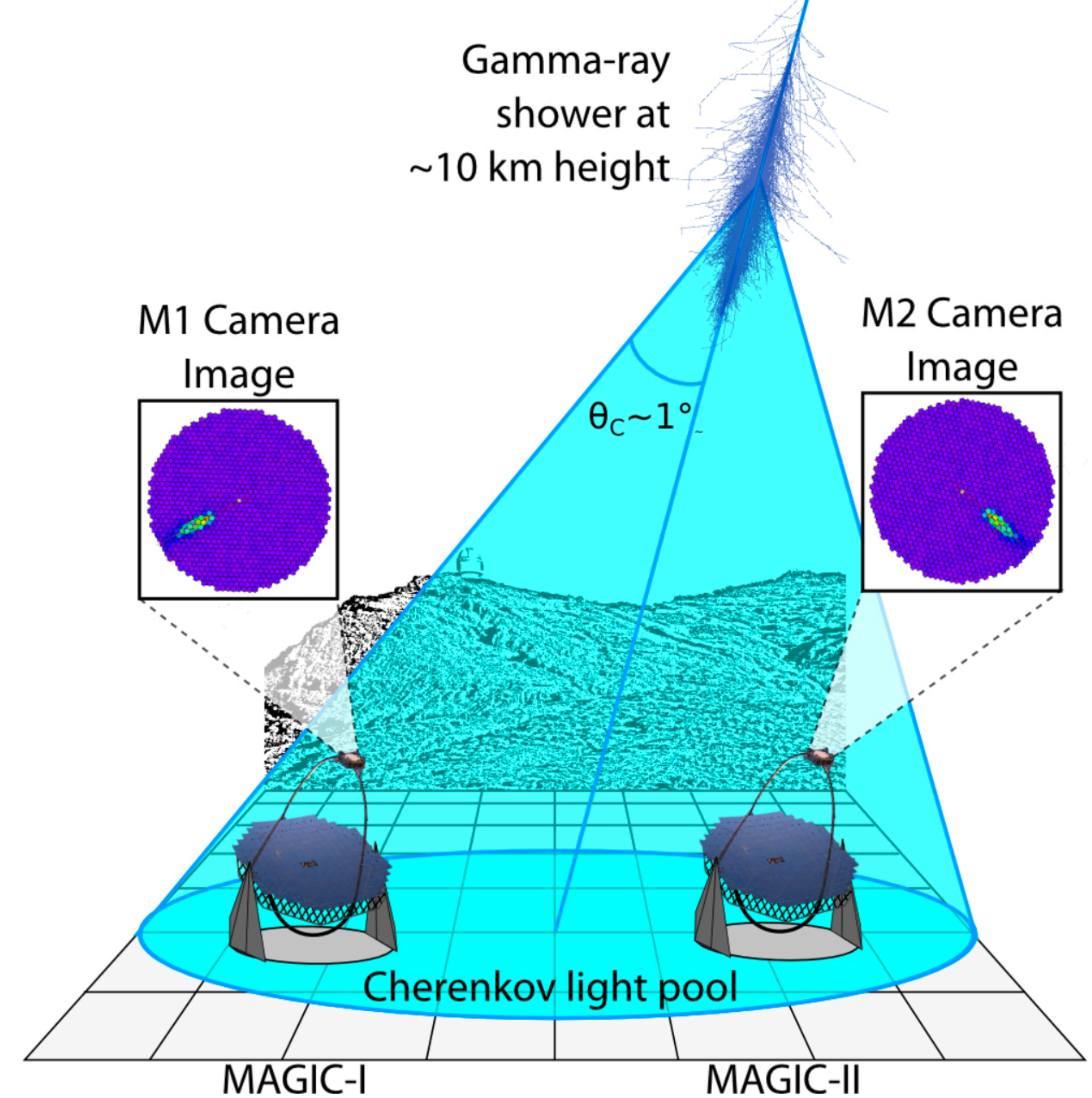
arXiv:1605.02016

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)

Why gamma rays?

- DM is expected to annihilate into SM products, among which gamma-rays
  - easy to associate with the source due to 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

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

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

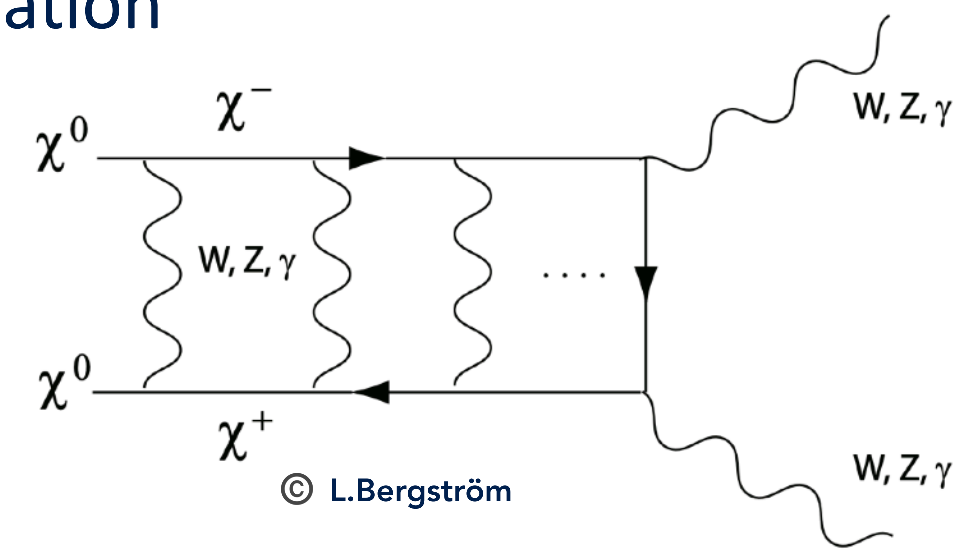
- depends on source type, DM profile of a source, etc.

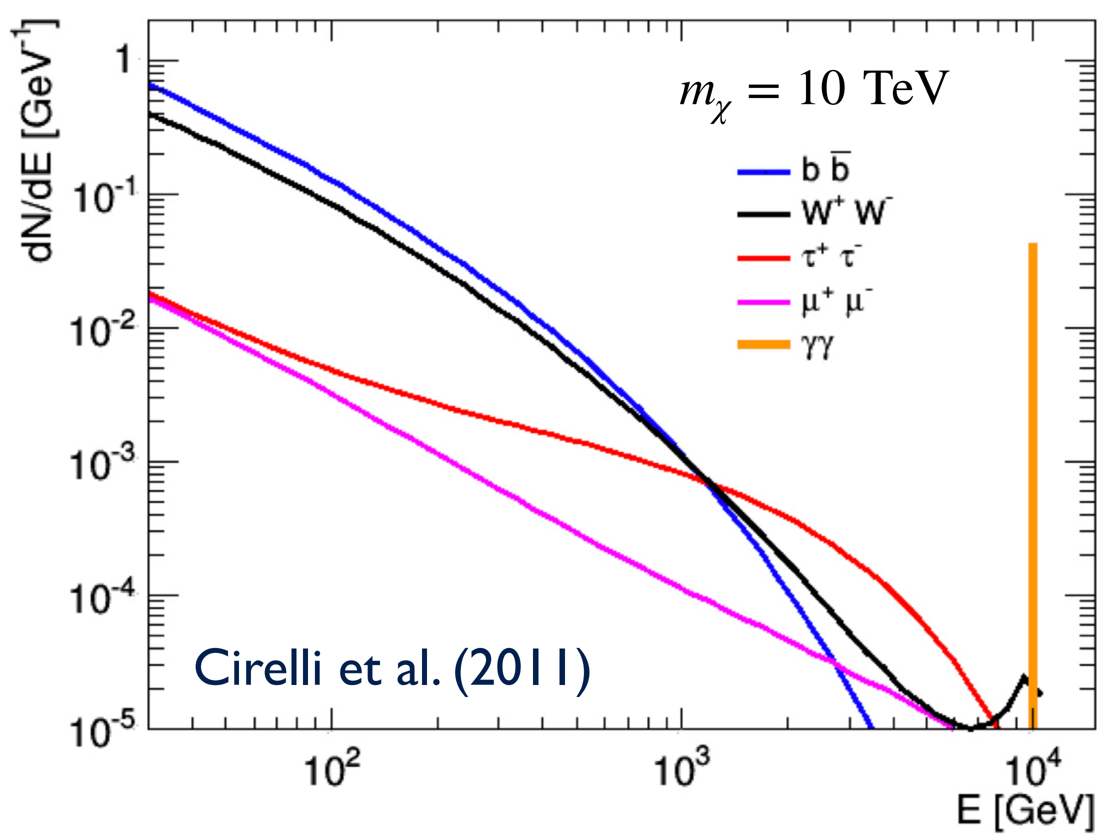
J-factor :

- integrated DM density along the line of sight

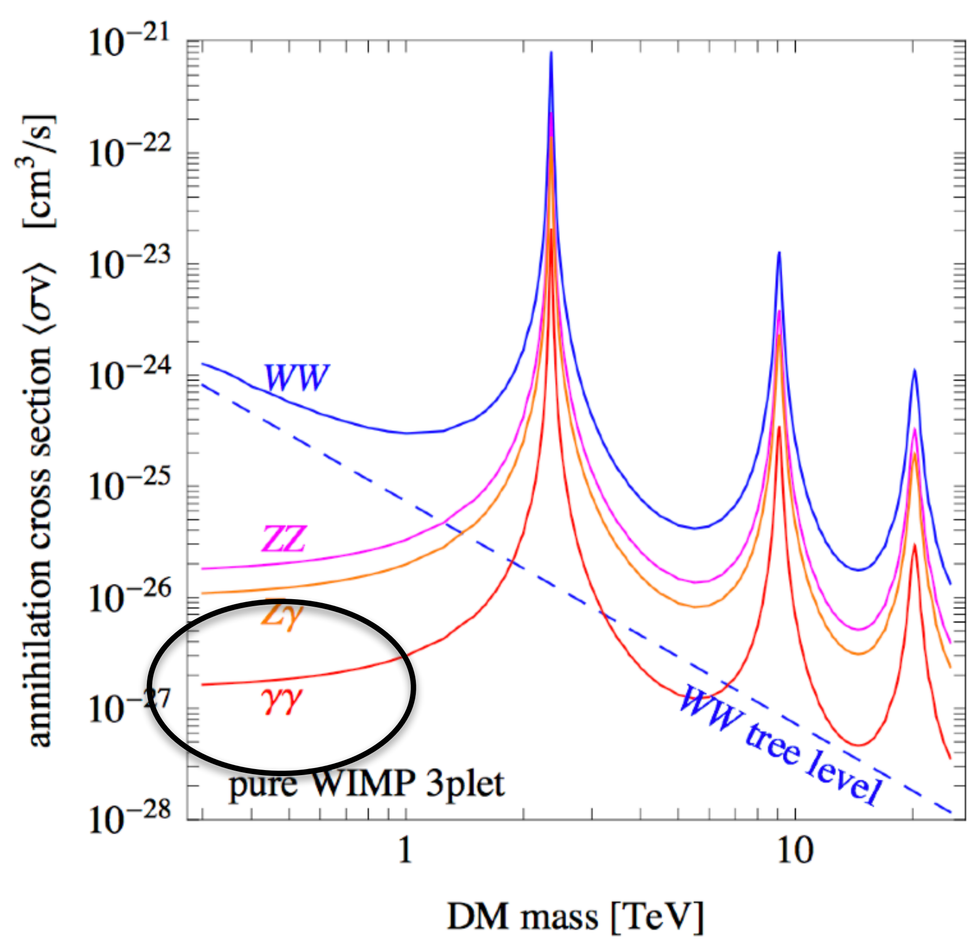
Motivation for line search

- **Clear peak at DM mass:** No astrophysical contamination
- **Test interesting particle models**
  - $\chi\chi \to \gamma\gamma, Z\gamma$: loop-suppressed by α^2
  - heavy DM models are expected to increase $\langle\sigma v\rangle$ by 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

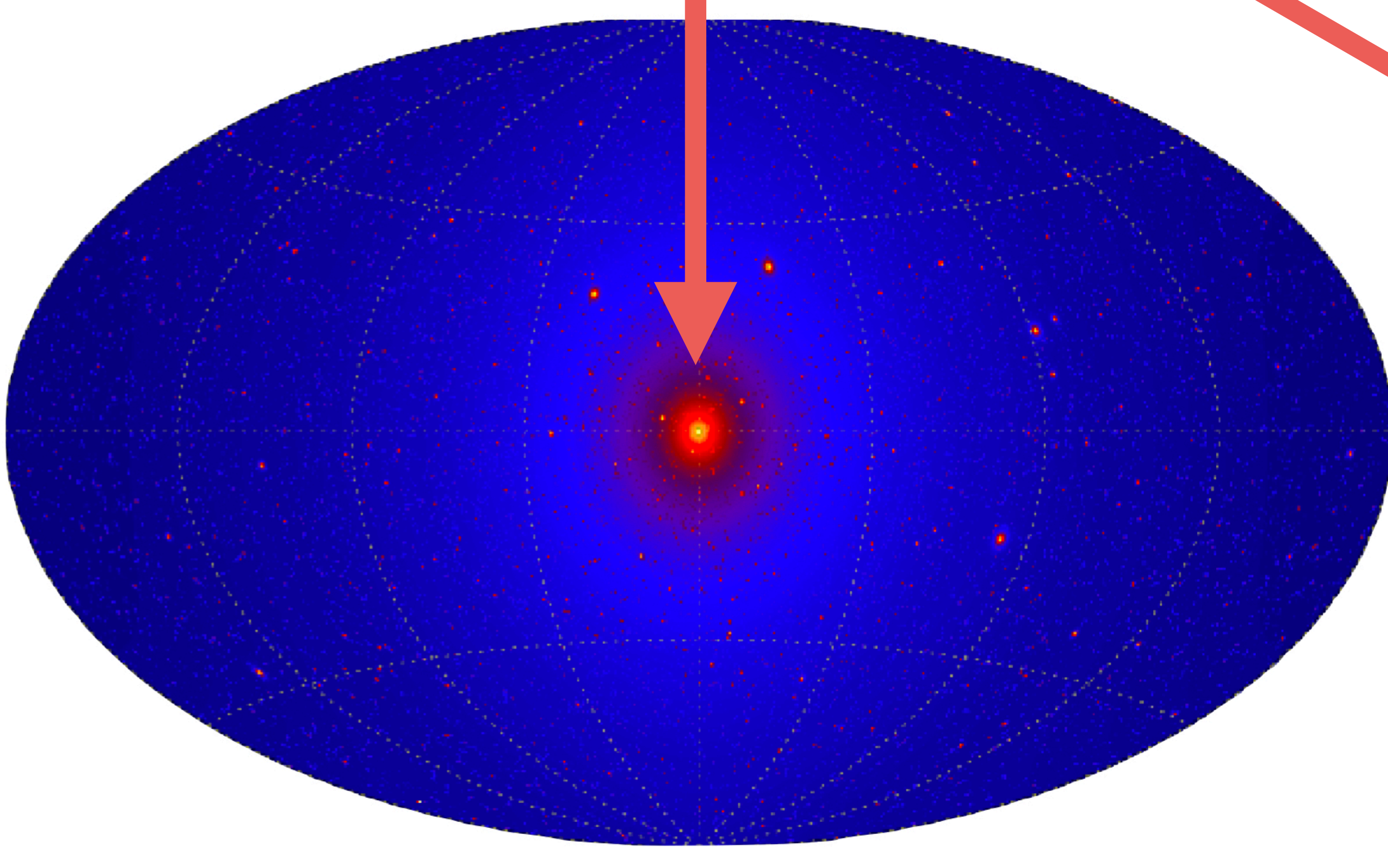
Galactic Centre (GC) and Halo

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

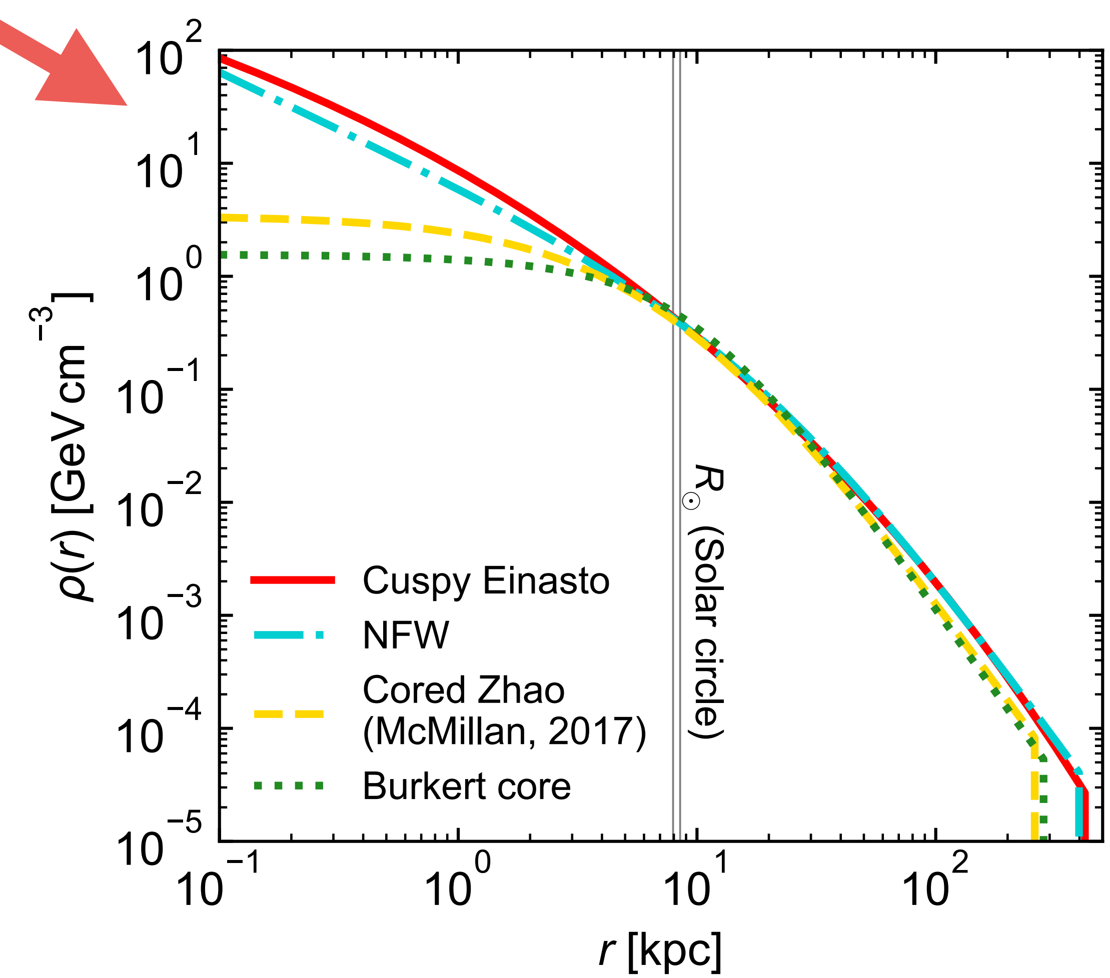
$$\rho_{\mathrm{Einasto}}(r) = \rho_s \exp\left\{\frac{-2}{\alpha}\left[\left(\frac{r}{r_s}\right)^{\alpha} - 1\right]\right\}$$

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

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



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

The GC observation with MAGIC

The GC observation by MAGIC

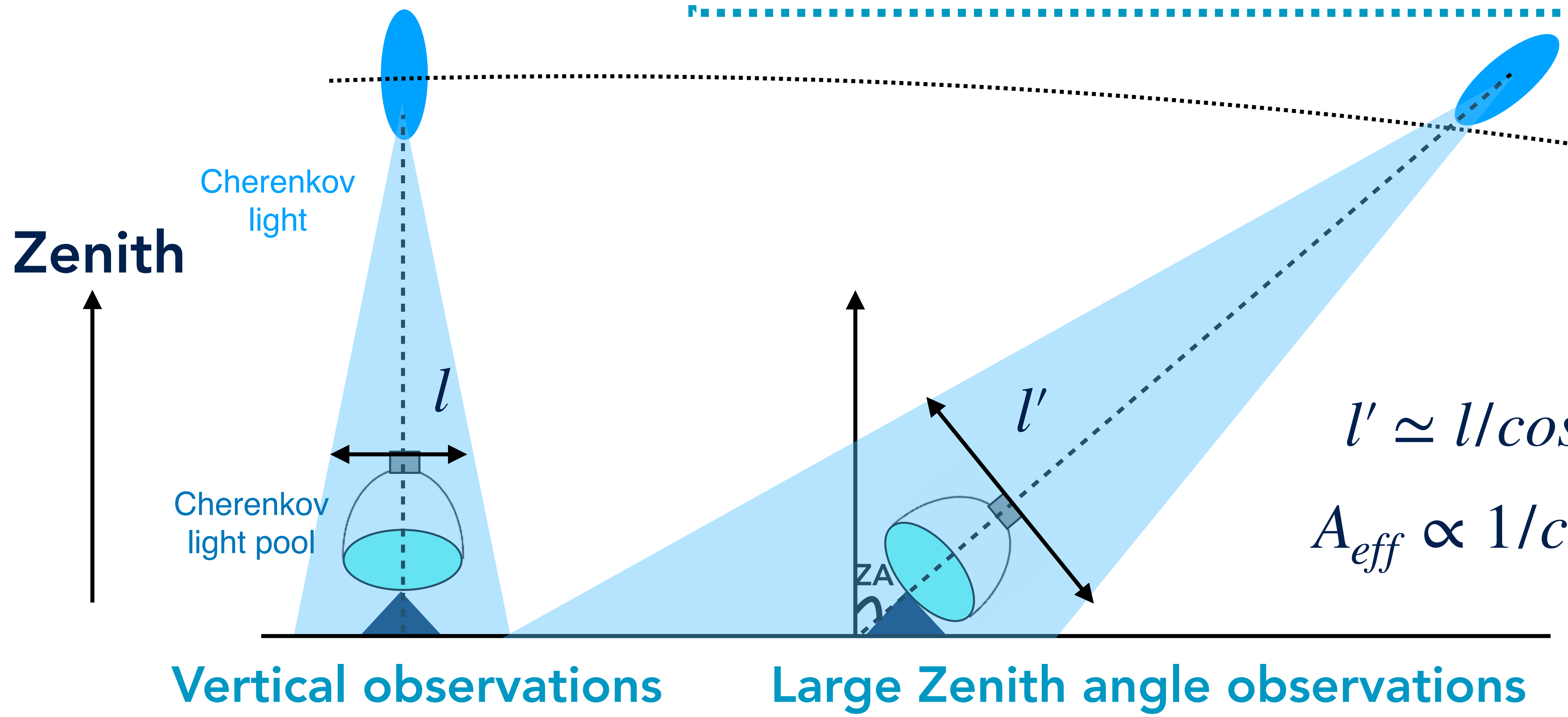
- zenith angle : 58 - 70 [deg]
  - large zenith angle observation, LZA

Pros

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

Cons

- increase the energy threshold



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

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

<u>Large Zenith angle observations boost the sensitivity to line signals from TeV DM!!</u>

Data set

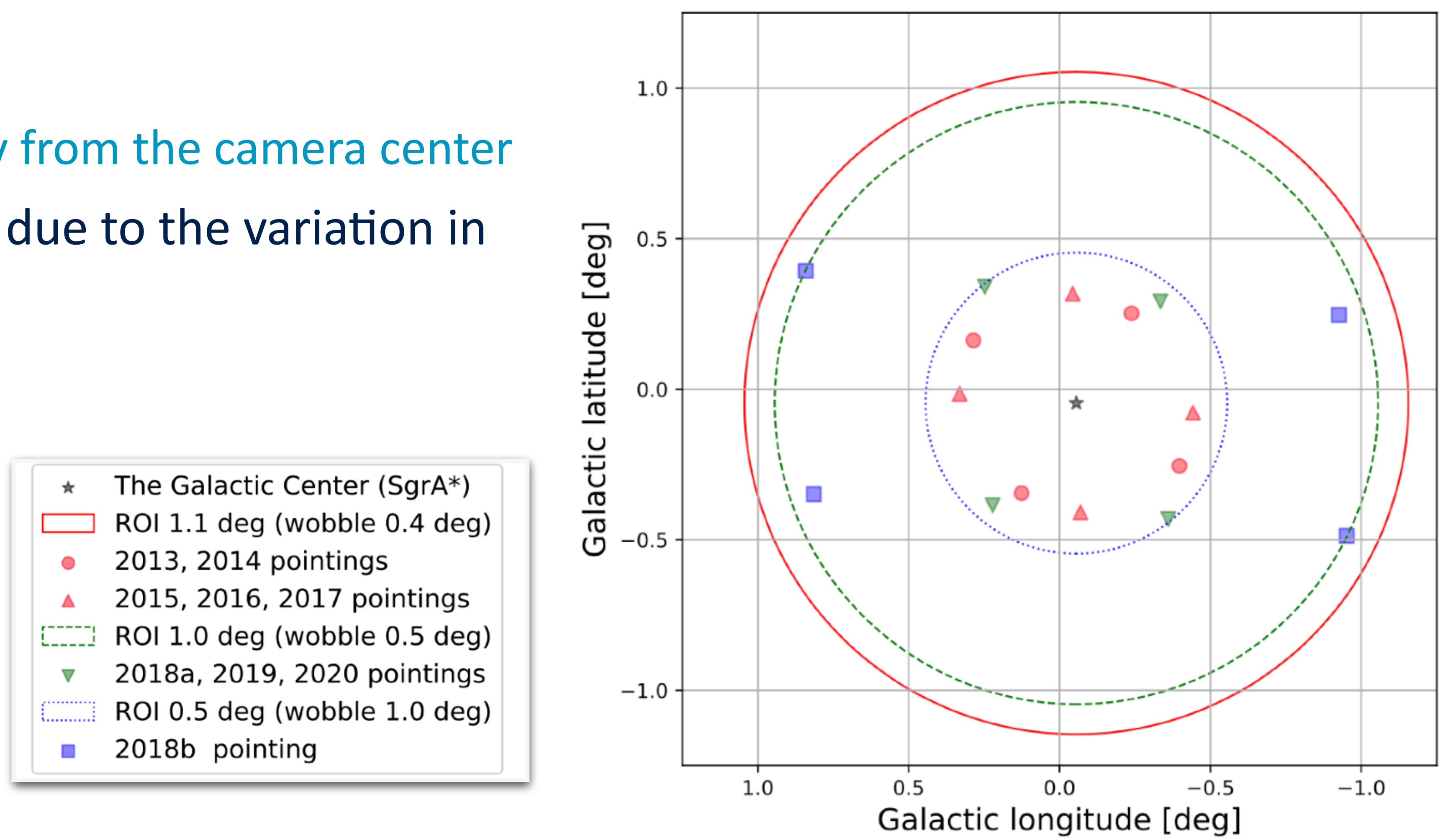
Data : March 2013 - August 2020

- 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



Likelihood analysis for line search

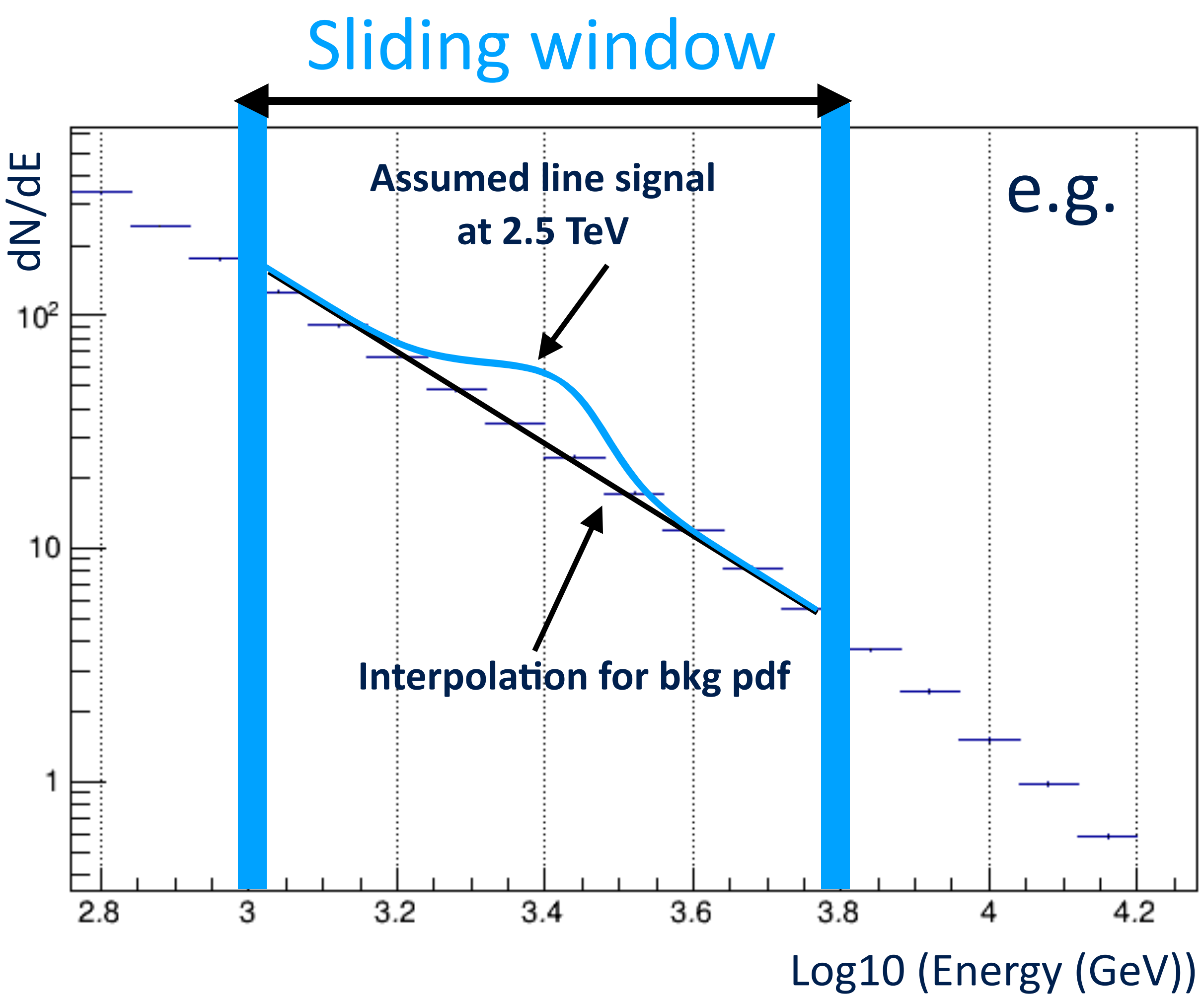
Unbinned likelihood analysis with a sliding window

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

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

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

to treat systematic uncertainty of a bkg model

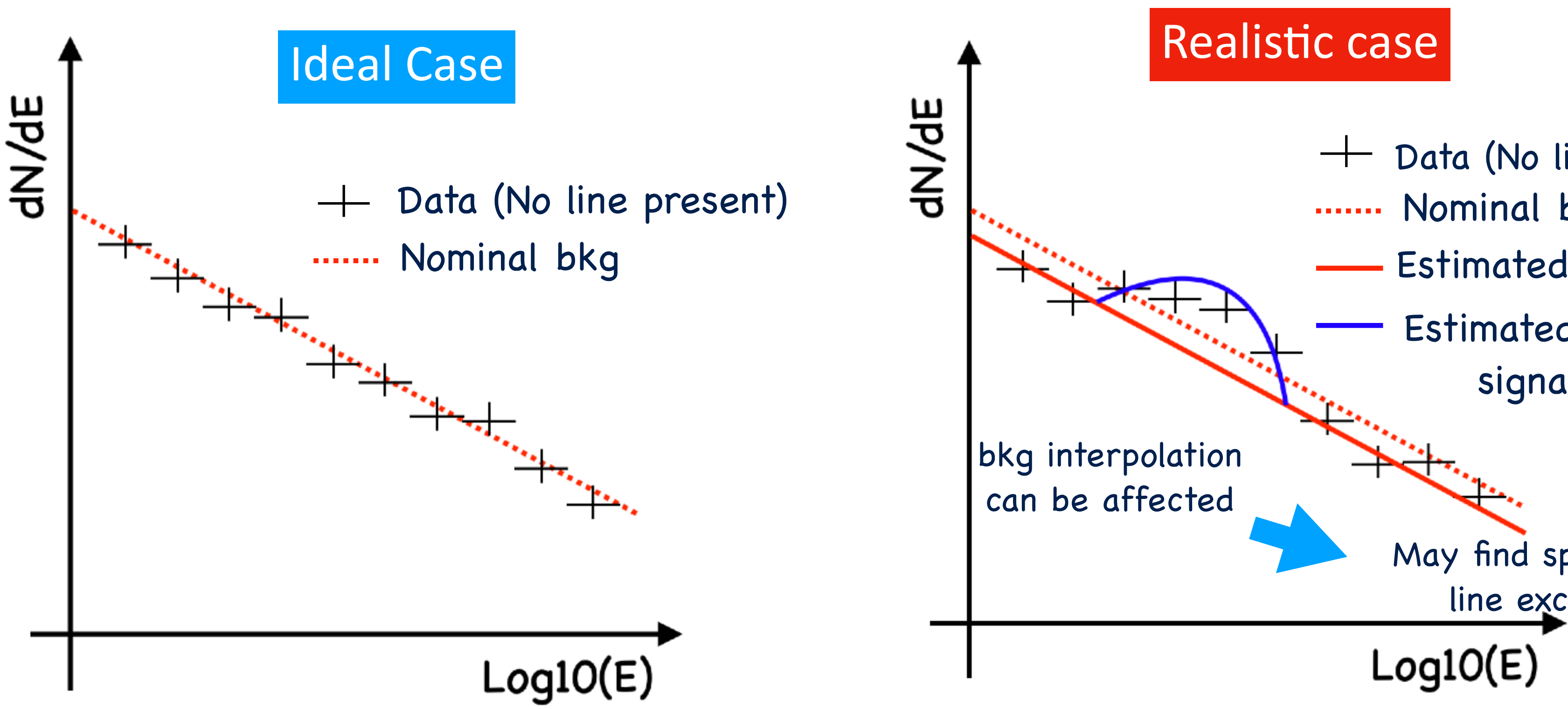


- Index i : data samples
- N_{on} : observed events in a ROI
- g **: estimated signal events** — **Parameters of interest**
- b : estimated background events — Nuisance parameters
- τ : normalization factor for bkg model
- f_g : line signal pdf
  - δ-function convolved with the response function
- f_b : 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



$\tau = 1$

$$\tau = \text{Gaus}(\tau_{\text{obs}},\ \sigma_\tau)$$
$$\sigma_\tau^2 = \sigma_{\tau,\text{stat}}^2 + (\tau\sigma_{syst})^2$$

- systematic uncertainty in the background pdf is included in Likelihood

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

given by Gaussian

Need to estimate

Study for systematic uncertainty

Estimated systematic uncertainty in a bkg pdf determination

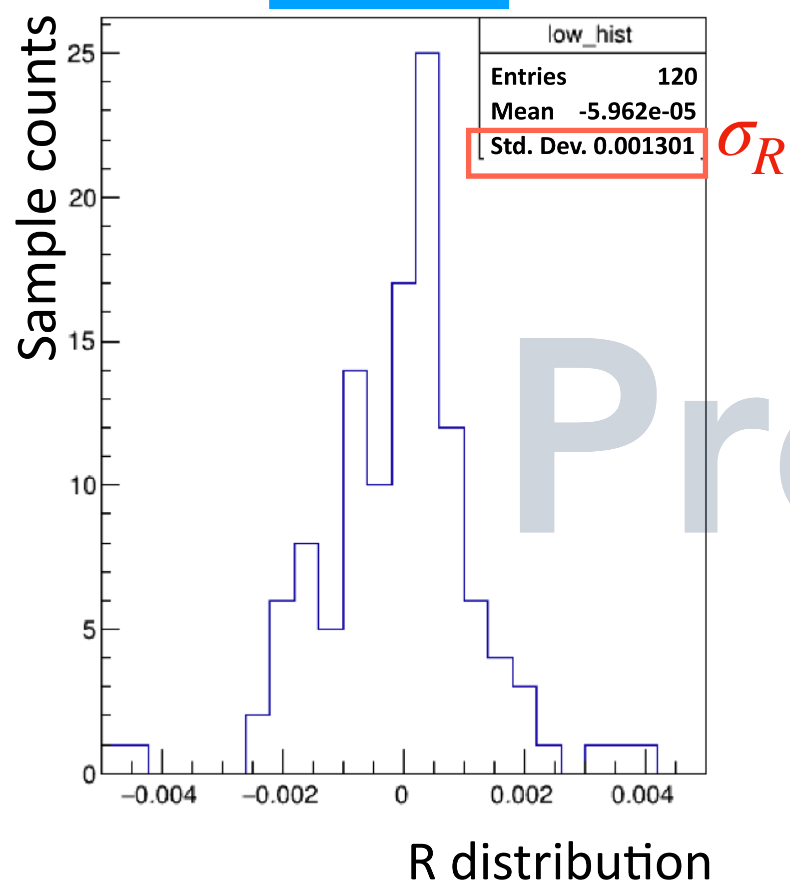
- applied the line search analysis to data without DM target sources with 120 samples divided into 3 energy categories, E < 3 TeV, 3 TeV < E < 10 TeV, E > 10 TeV
- computed residual R_i and its statistical error size R_i^{stat} with the error propagation

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

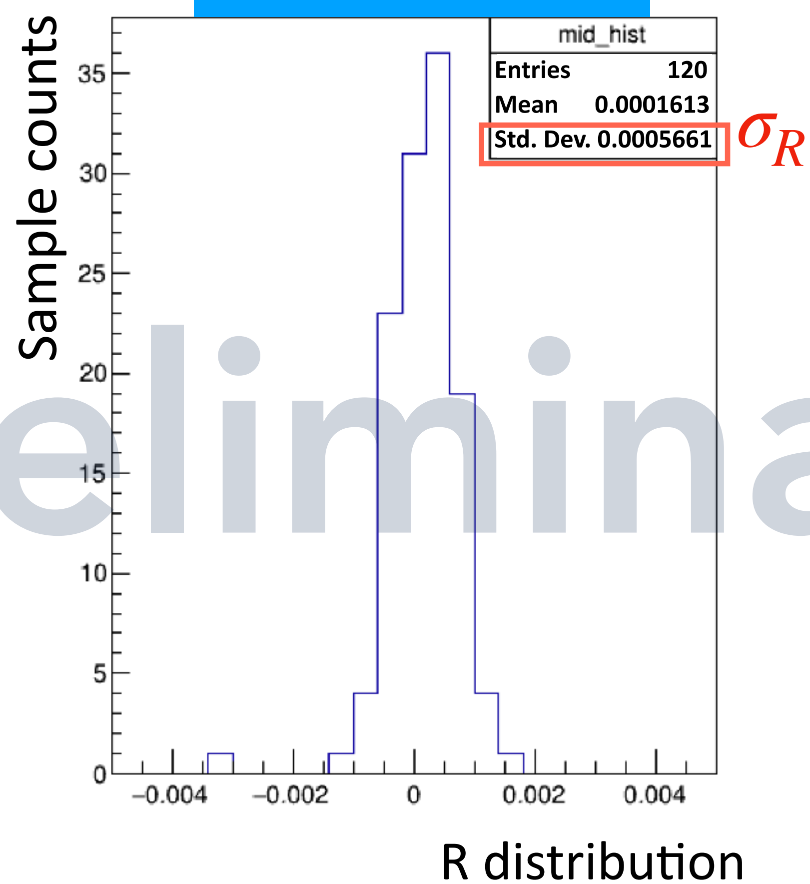
$$R_i^{stat} = \sqrt{\left(\frac{\partial R_i}{\partial N_i^{ex}} \cdot \sigma_{N_i^{ex}}\right)^2 + \left(\frac{\partial R_i}{\partial N_i^{tot}} \cdot \sigma_{N_i^{tot}}\right)^2}$$

Std. Dev. of R_i^{stat} distribution

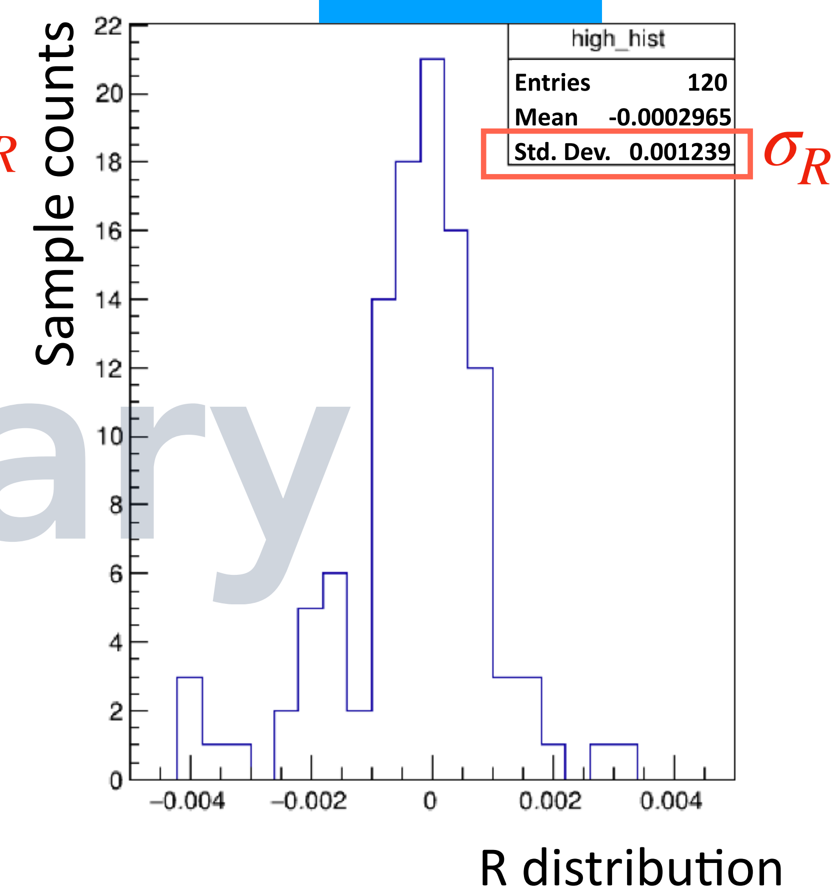
E < 3 TeV



3 TeV < E < 10 TeV



E > 10 TeV



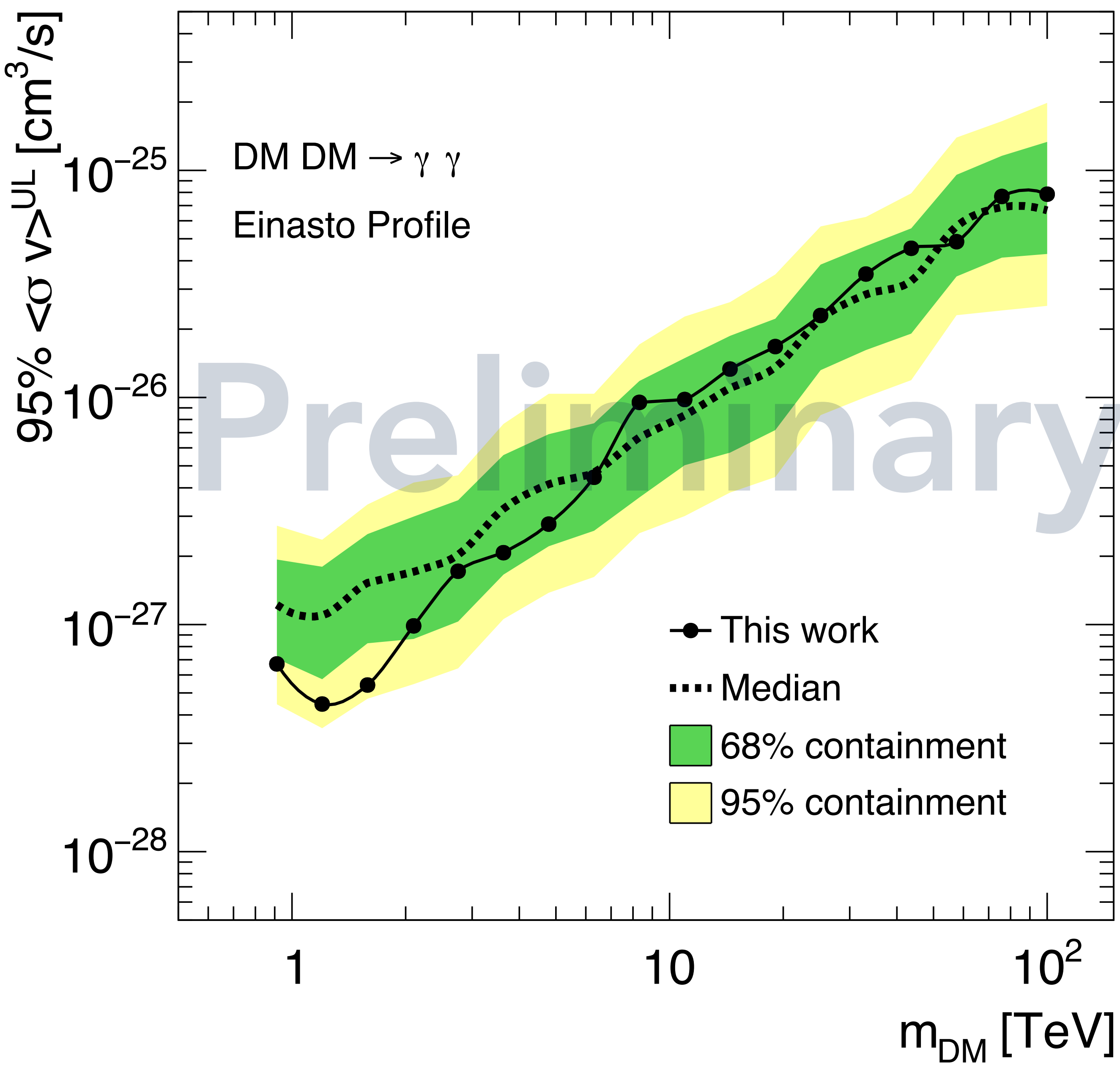
$$\sigma_R^2 = \sigma_{\rm stat}^2 + \sigma_{\rm syst}^2$$

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

Results

No significant line-like excess found

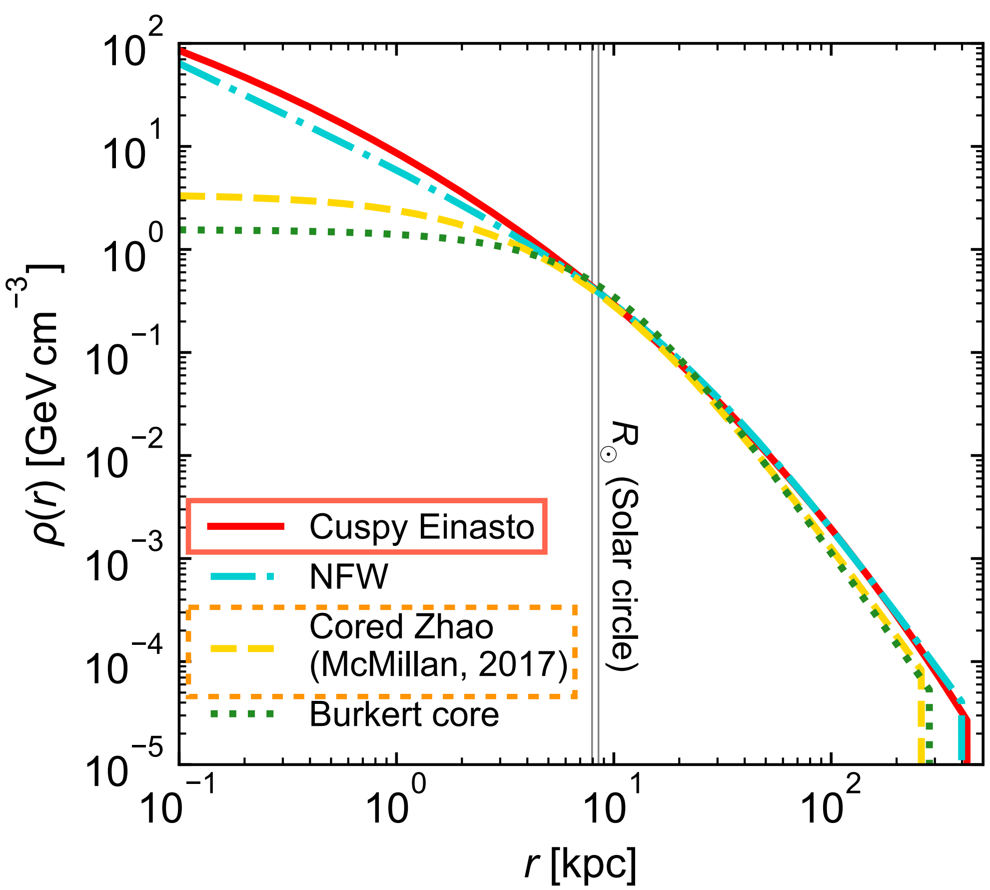
- set upper limits at 95% C.L. on 18 masses in the range 0.9 TeV - 100 TeV
- uncertainty on sensitivity calculated with 300 realizations

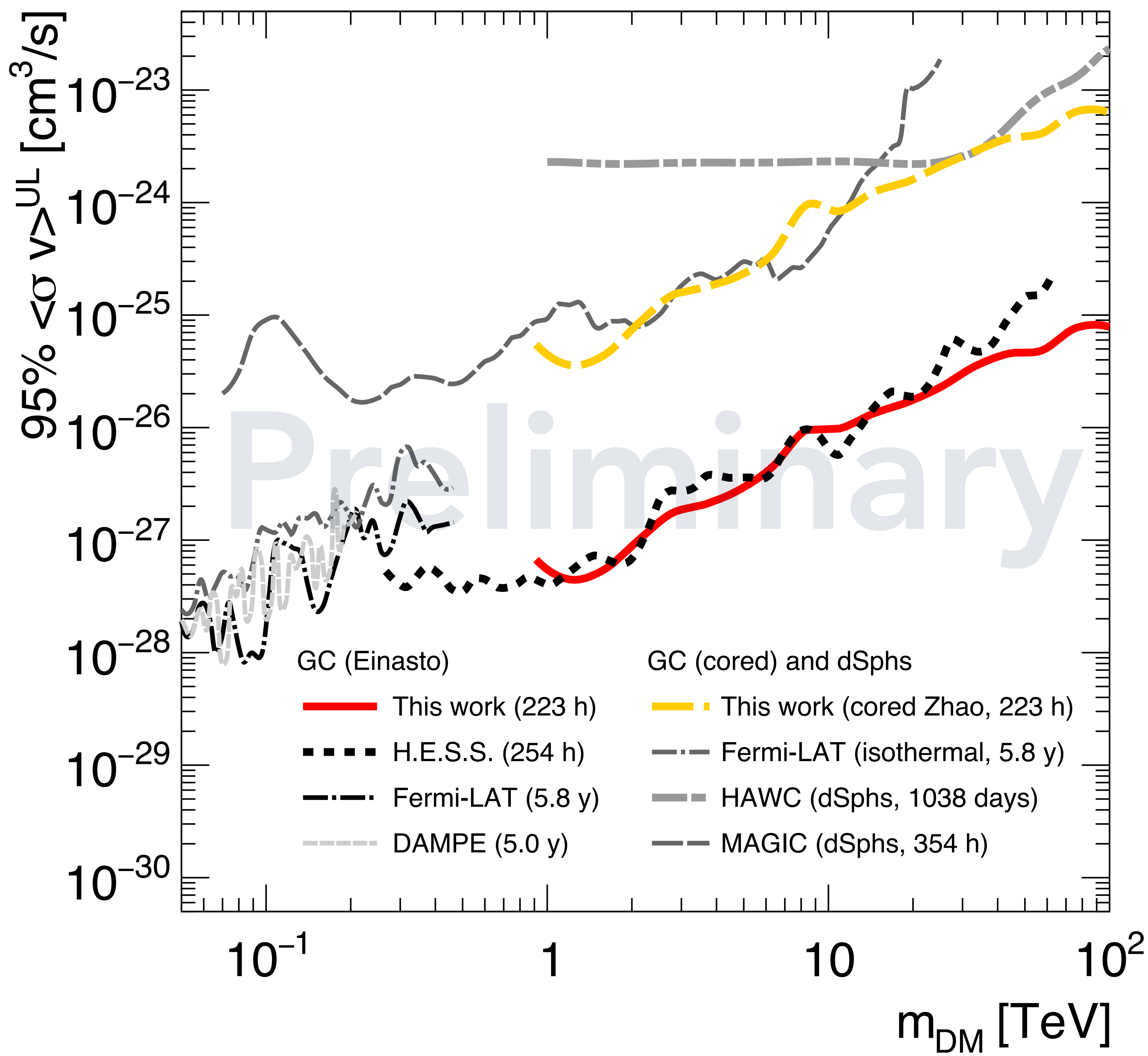


Comparison with the literature

No significant excess: 0.9 TeV - 100 TeV

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

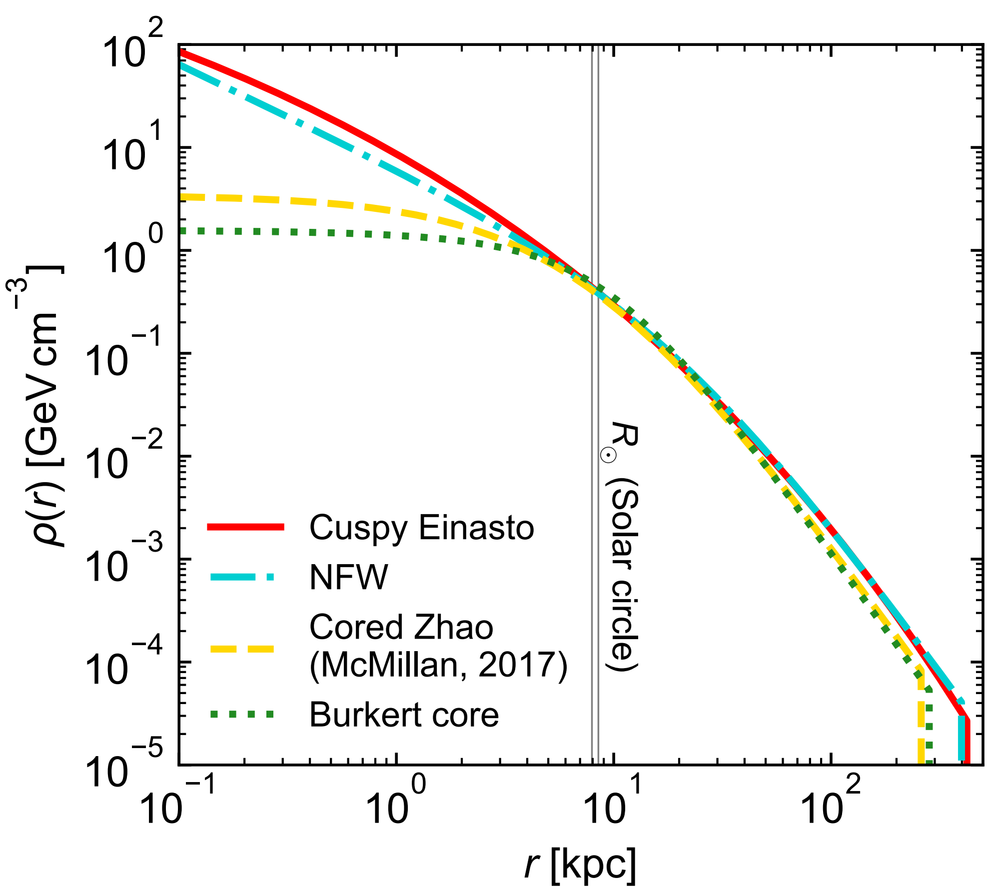


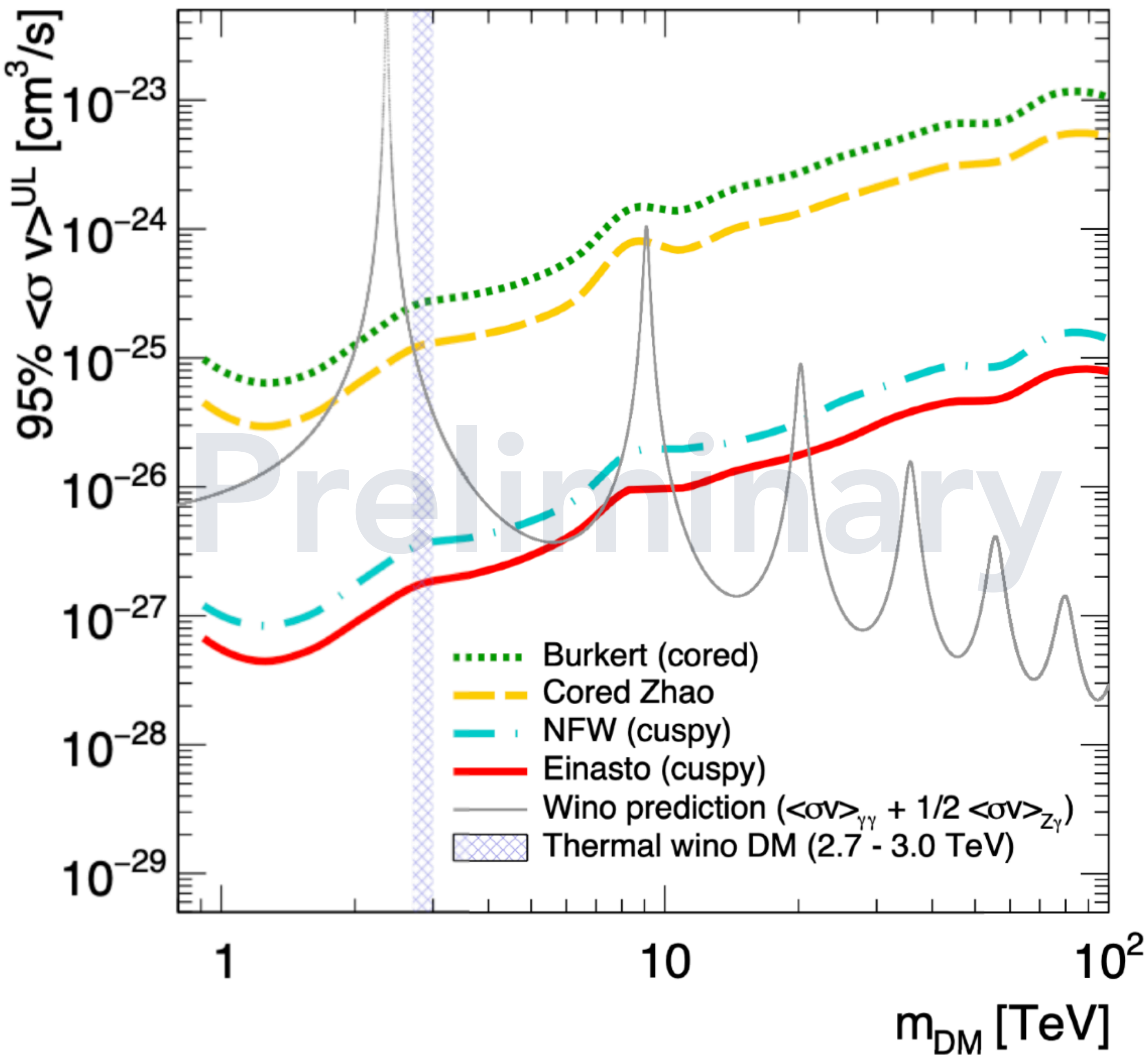


Constraints on SUSY-Wino

- Constraints on SUSY-Wino with 4 DM profiles
  - cuspy :
    - < 4 - 10 TeV and 20 TeV
  - cored
    - < 2.7 - 2.8 TeV

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





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

- 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