Indirect dark matter searches with the MAGIC telescopes

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MAGIC

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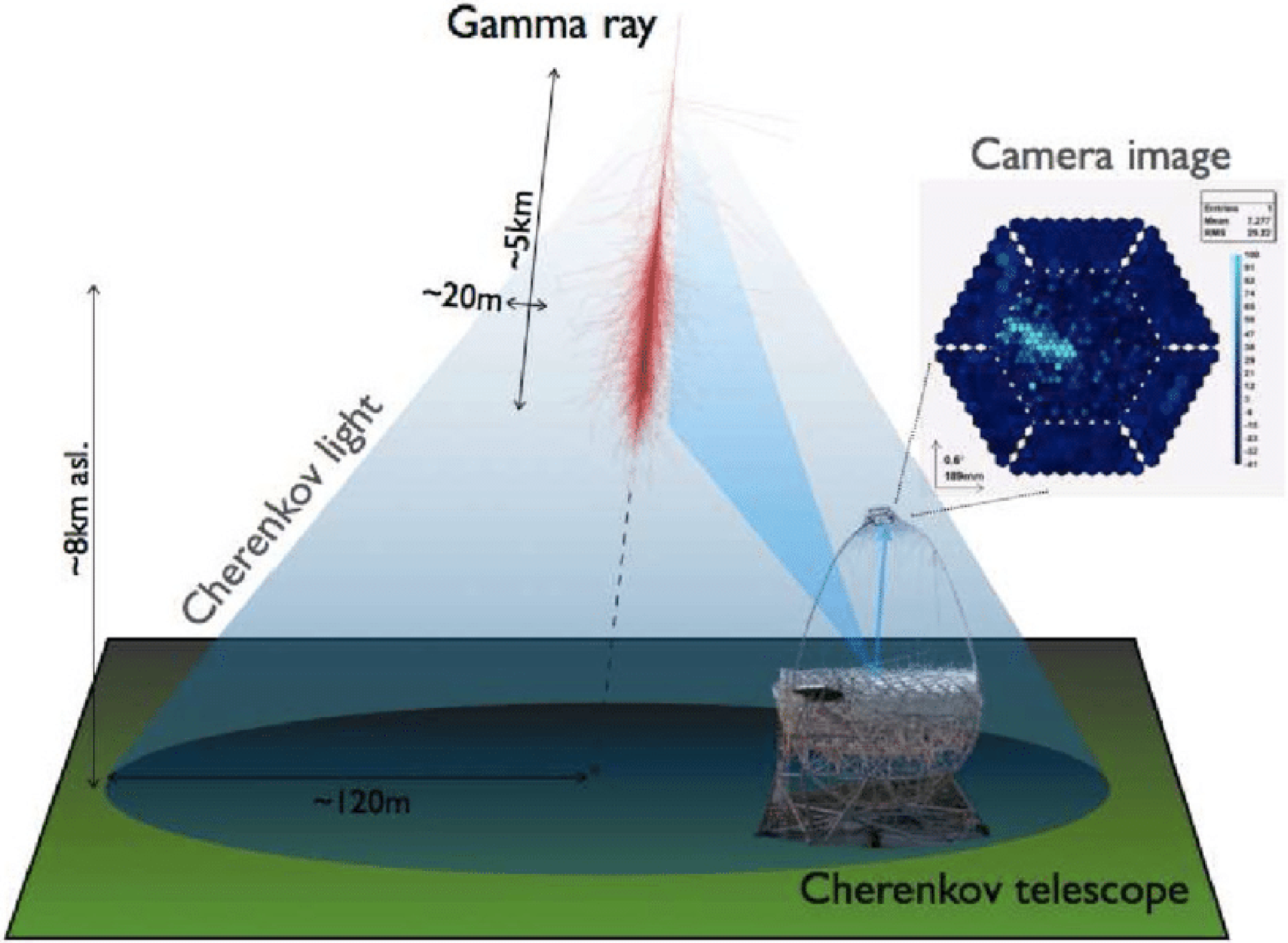
The MAGIC experiment

- **Two Imaging Atmospheric Cherenkov Telescopes located in the Observatory Roque del Muchachos at La Palma, Canary Islands (Northern hemisphere):**
  - Altitude: ~ 2200 m asl
  - Detects gamma rays between ~20 GeV and ~100 TeV
  - Field of view of ~3.5°
  - Angular resolution ~ 0.1° (energy dependent)

See also C. Nigro’s talk on Thursday!

Atmospheric showers

IATCs are designed to detect gamma rays



Indirect dark matter search with gamma-rays

- **Gamma-rays are not deflected by magnetic fields and trace back to original source**

  → Critical to identify the (physical) origin of the signal and study DM spatial distribution

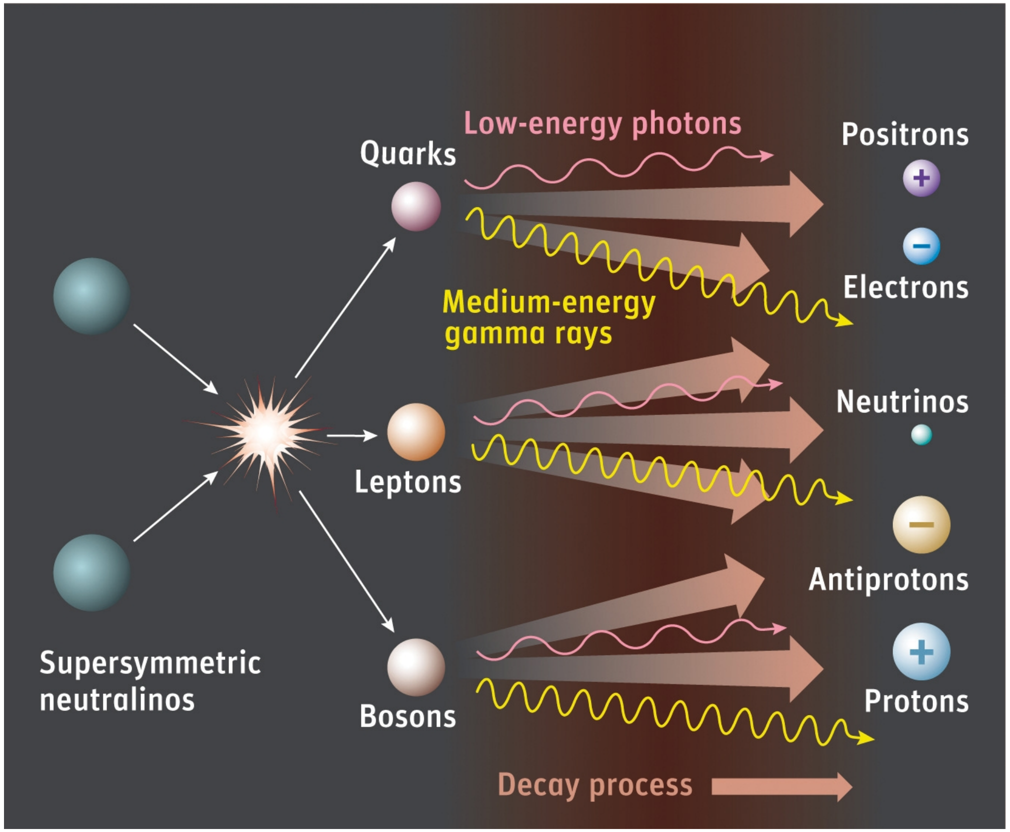
- **Classical targets for gamma-ray experiments include among others:**
  - The Galactic Center (high DM content with high uncertainties)
  - Dwarf spheroidal galaxies (lower DM content with smaller uncertainties)
  - Galaxy clusters

- **Looking for Dark Matter particles self-annihilating (or decaying) into Standard Model particles**

  → Weakly Interacting Massive Particles (WIMP) scenario

Expected Dark Matter flux

$$\frac{d\Phi(\Delta\Omega)}{dE} = \frac{1}{4\pi}\frac{\langle\sigma_{\mathrm{ann}}v\rangle}{2m_{\mathrm{DM}}^2}\frac{dN}{dE} \times \int_{\Delta\Omega} d\Omega' \int_{\mathrm{l.o.s.}} dl\,\rho^2(l,\Omega')$$



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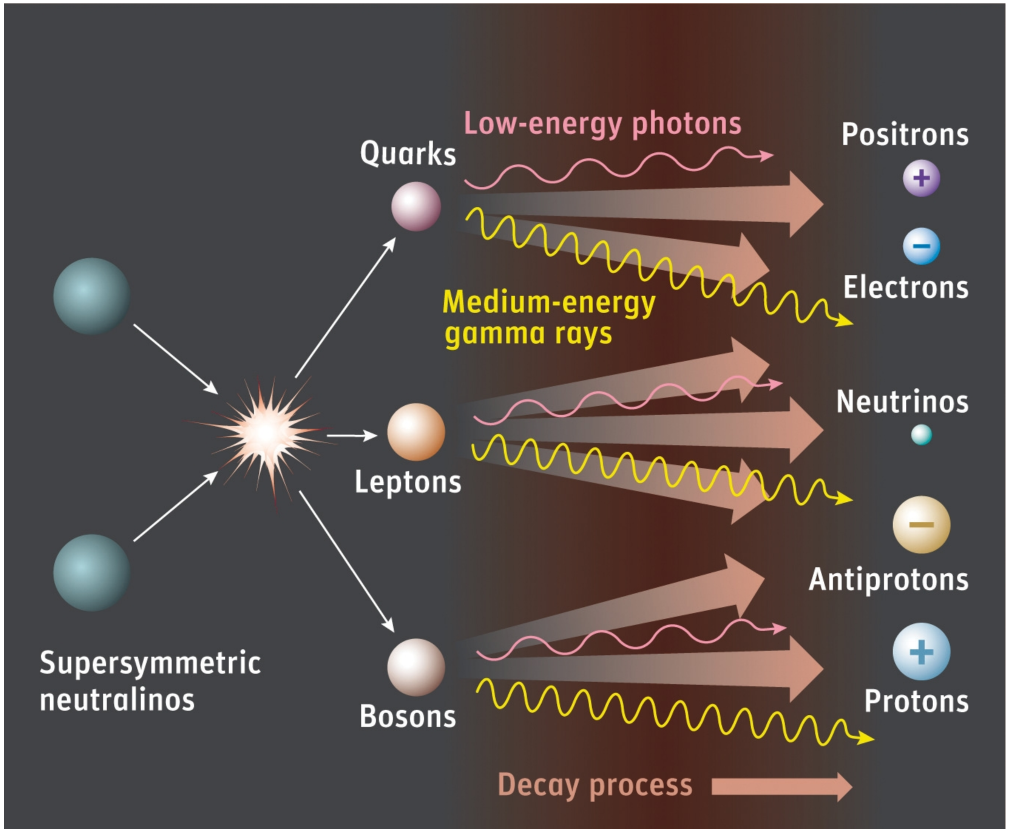

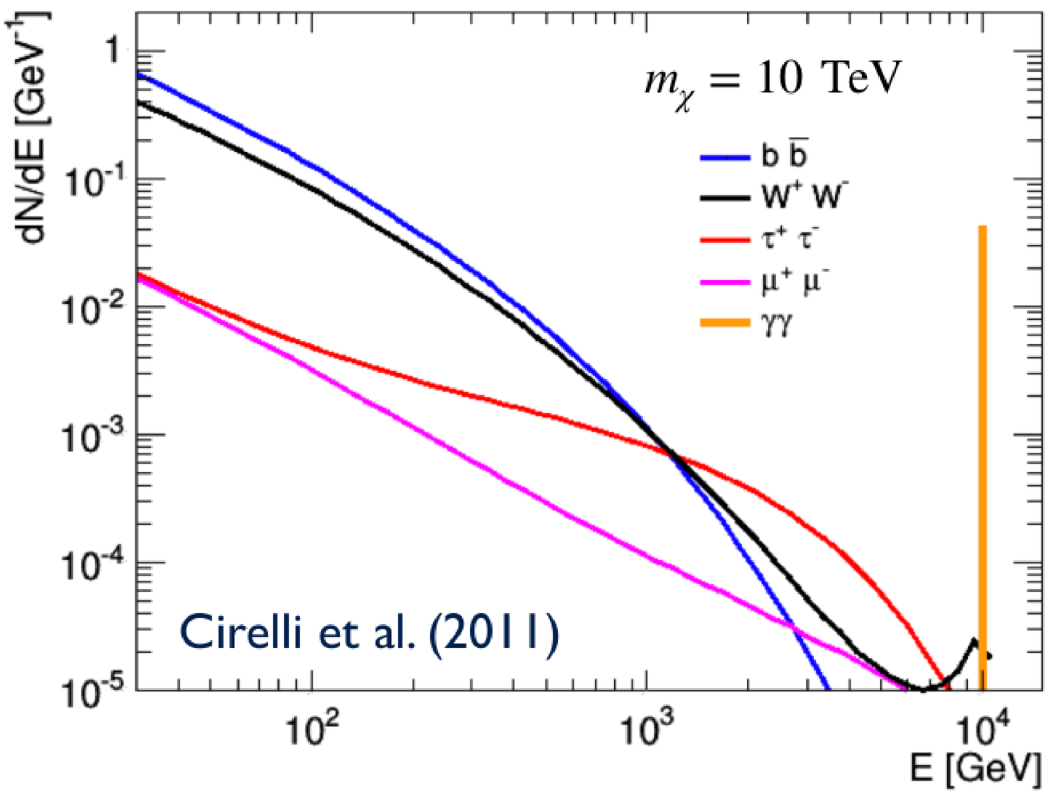

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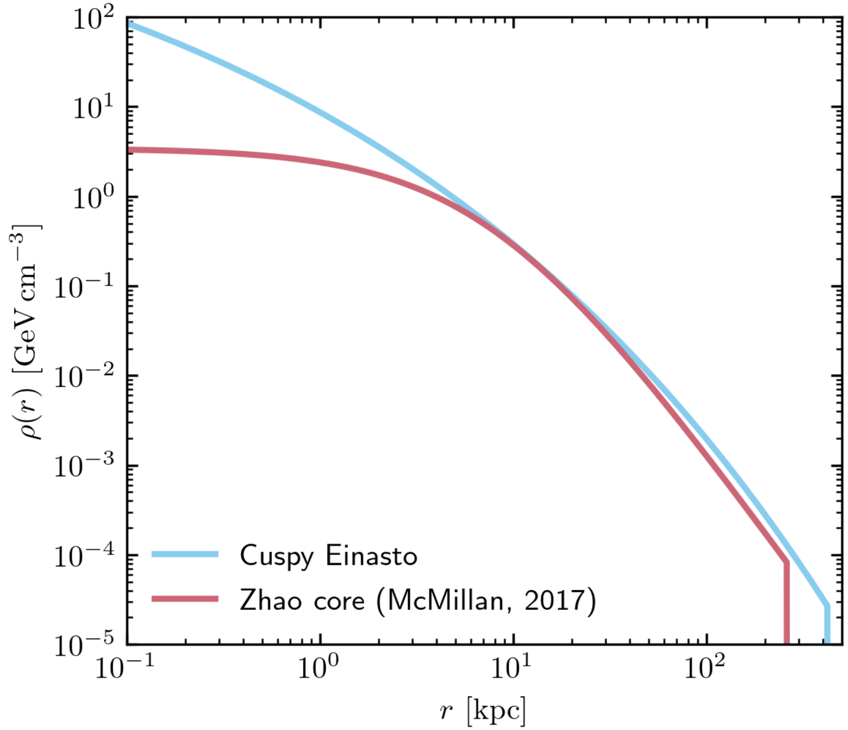

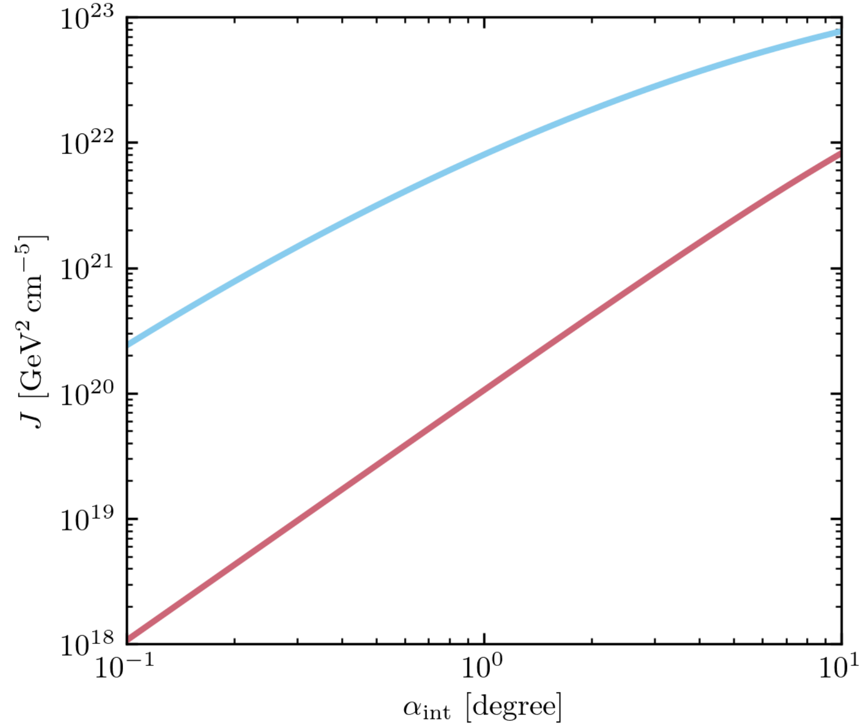

Examples of DM content profiles for the Galactic Centre

State of the art likelihood analysis

$$
\begin{aligned}
\mathcal{L}_i(\langle\sigma v\rangle;\boldsymbol{\nu}_i\,|\,\boldsymbol{\mathcal{D}}_i) &= \mathcal{L}_i(\langle\sigma v\rangle;\{b_{ij}\}_{j=1,\dots,N_{\mathrm{bins}}},J,\tau_i\,|\,(N_{\mathrm{ON},ij},N_{\mathrm{OFF},ij})_{j=1,\dots,N_{\mathrm{bins}}}) \\
&= \prod_{j=1}^{N_{\mathrm{bins}}}\Bigg[\frac{(g_{ij}(\langle\sigma v\rangle)+b_{ij})^{N_{\mathrm{ON},ij}}}{N_{\mathrm{ON},ij}!}e^{-(g_{ij}(\langle\sigma v\rangle)+b_{ij})} \\
&\qquad\times\frac{(\tau_i b_{ij})^{N_{\mathrm{OFF},ij}}}{N_{\mathrm{OFF},ij}!}e^{-(\tau_i b_{ij})}\Bigg] \\
&\qquad\times\mathcal{T}(\tau_i|\tau_{\mathrm{obs},i},\sigma_{\tau,i})\times\mathcal{J}(J|J_{\mathrm{obs}},\sigma_{\log_{10}J}) \quad ,
\end{aligned}
$$

- **Binned (in energy) likelihood**

  → Poisson PDF for the ON region (where signal is expected)

  → Poisson PDF for the OFF region (where background is estimated)

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$$= \prod_{j=1}^{N_{\rm bins}}\left[\frac{(g_{ij}(\langle\sigma v\rangle)+b_{ij})^{N_{{\rm ON},ij}}}{N_{{\rm ON},ij}!}e^{-(g_{ij}(\langle\sigma v\rangle)+b_{ij})}\right.$$
$$\left.\times\frac{(\tau_i b_{ij})^{N_{{\rm OFF},ij}}}{N_{{\rm OFF},ij}!}e^{-(\tau_i b_{ij})}\right]$$
$$\times\,\mathcal{T}(\tau_i|\tau_{{\rm obs},i},\sigma_{\tau,i})\times\mathcal{J}(J|J_{\rm obs},\sigma_{\log_{10}J})\quad,$$

- **PDF for the ON/OFF normalization factor**

  → taken into account as nuisance parameter in the likelihood

  → allow proper treatment of instrumental systematic errors, important in the case of Cherenkov telescopes

  → no overestimation of the limits

State of the art likelihood analysis

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$$\times\,\mathcal{T}(\tau_i|\tau_{\text{obs},i},\sigma_{\tau,i})\times\mathcal{J}(J|J_{\text{obs}},\sigma_{\log_{10}J}),$$

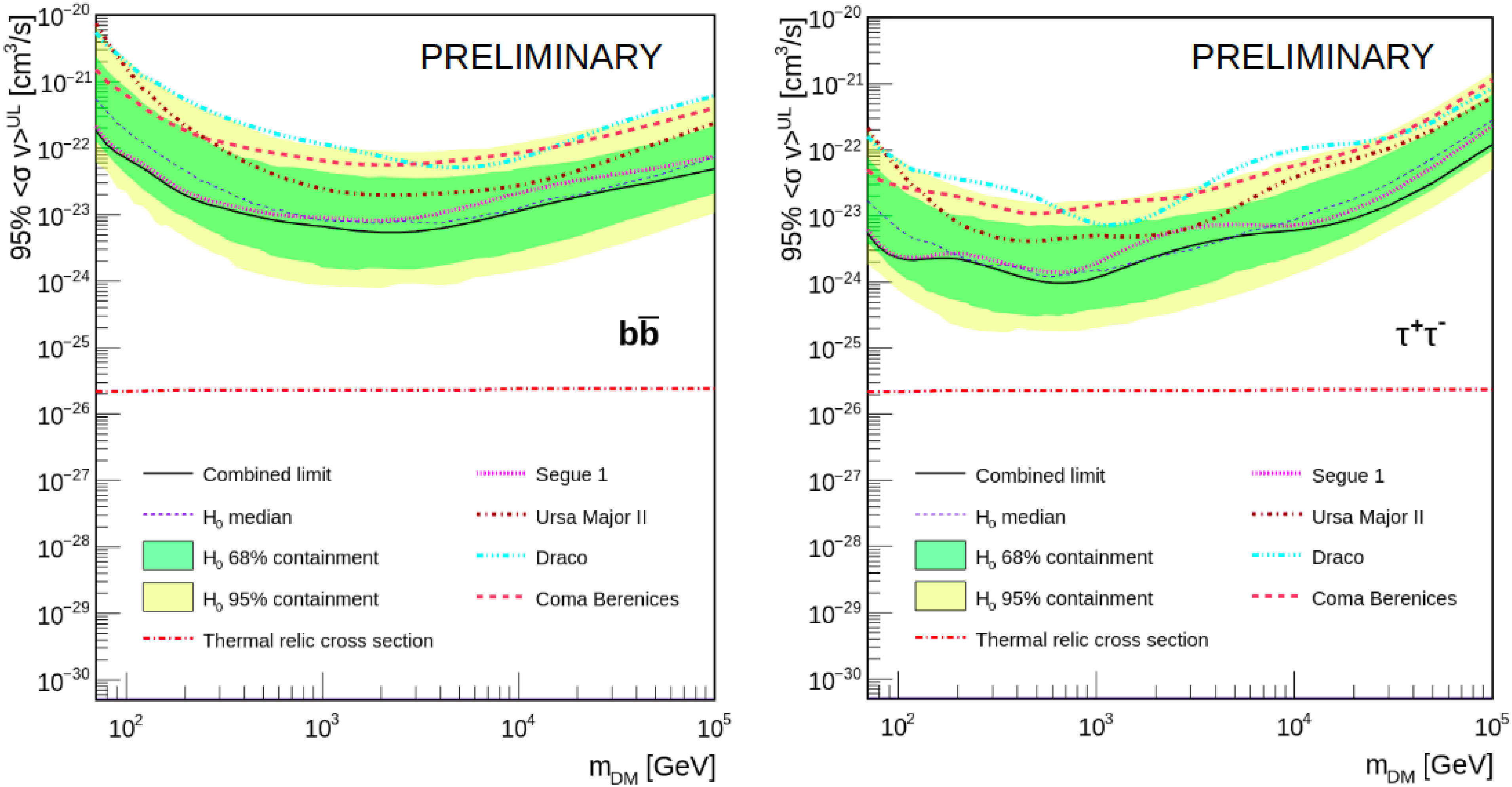
- **J-factor (ie Dark matter content) PDF**
  → taken into account as nuisance parameter in the likelihood
  → no overestimation of the limits

Observation of dSphs with MAGIC

- **Combination of data from multiple dSphs observations**
  - maximize the sensitivity to a potential DM signal by increasing the statistics
  - 4 dSphs observed for a total of **354.3** hours

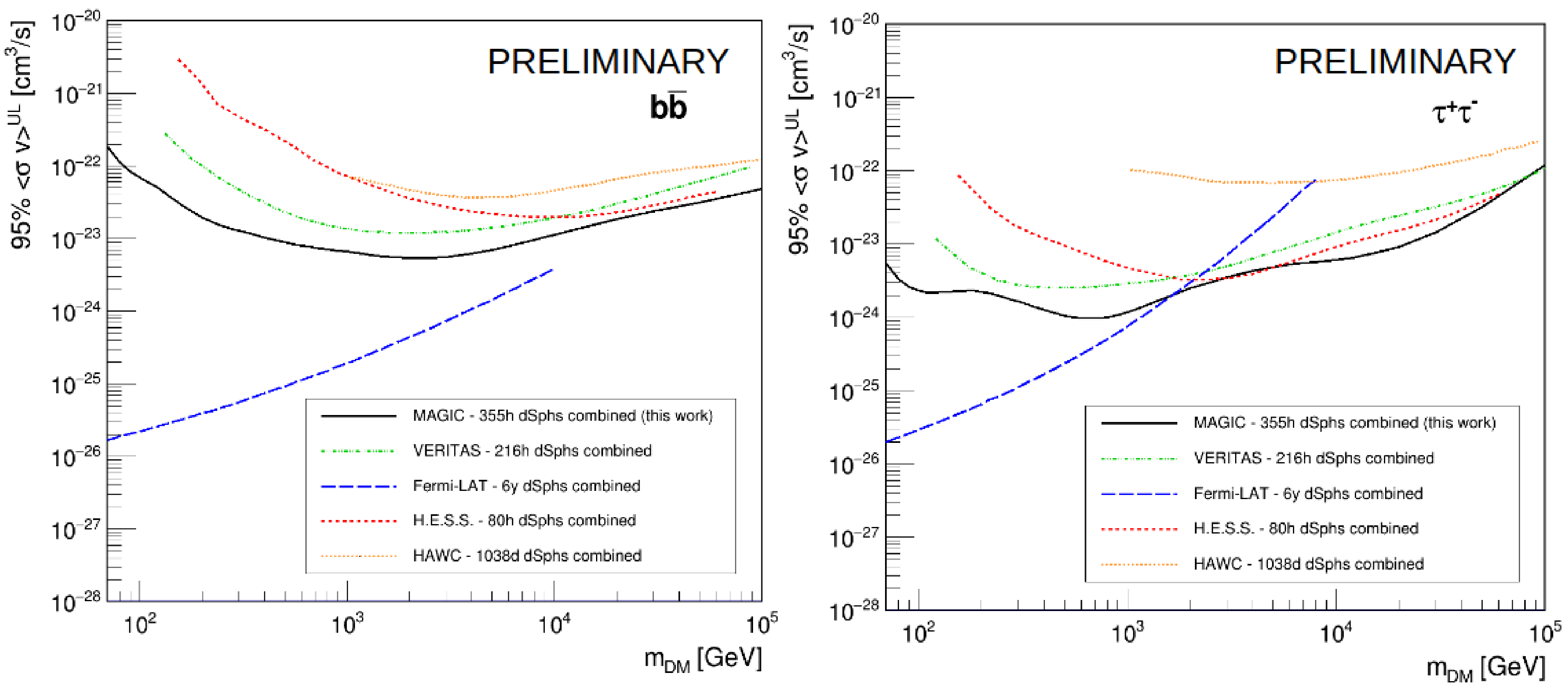
Target	$\log_{10} J(\theta_{max})$ [$GeV^2 cm^{-5}$]	θ_{max} [deg]	$\theta_{0.5}$ [deg]	T_{eff} [h]	Year
Coma Berenices	$19.02^{+0.37}_{-0.41}$	0.31	$0.16^{+0.02}_{-0.05}$	49.5	2019
Draco	$19.05^{+0.22}_{-0.21}$	1.30	$0.40^{+0.16}_{-0.15}$	52.1	2018
Ursa Major II	$19.42^{+0.44}_{-0.42}$	0.53	$0.24^{+0.06}_{-0.11}$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

Observation of dSphs with MAGIC



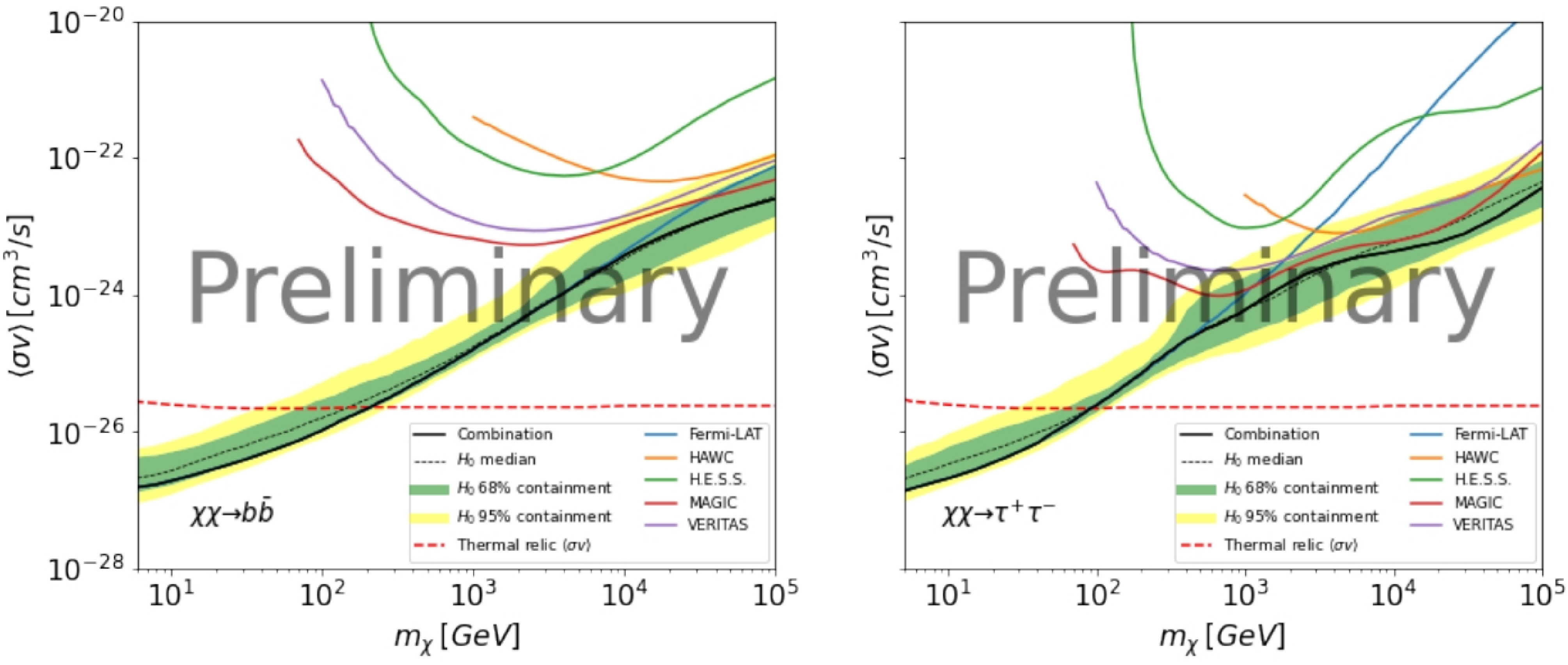
- **Combined limits yield an improvement by a factor up to 40-50%**

Observation of dSphs with MAGIC



- **Largest data set from Cherenkov telescopes**
- **Limits from various gamma-ray experiment nicely complement each other**

Combined limits from 5 experiments



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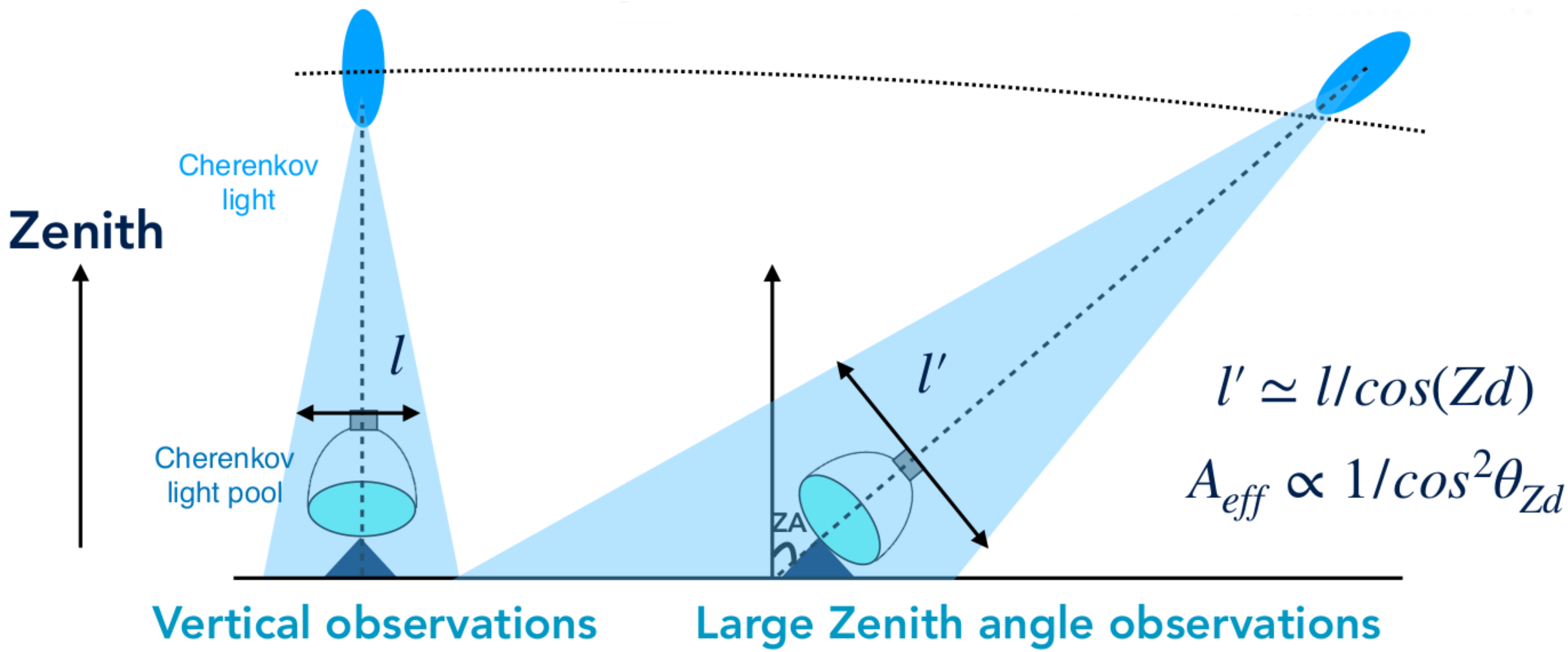
- **Combined limits are up to a factor 2-3 more constraining!**

The Galactic Centre as seen by MAGIC

- Optimal observation conditions (ie low zenith) is from the Southern hemisphere
- But MAGIC is located in the Northen hemisphere, so Galactic Centre can only be seen from a zenith of ~50 degrees

  → larger effective area but higher energy threshold



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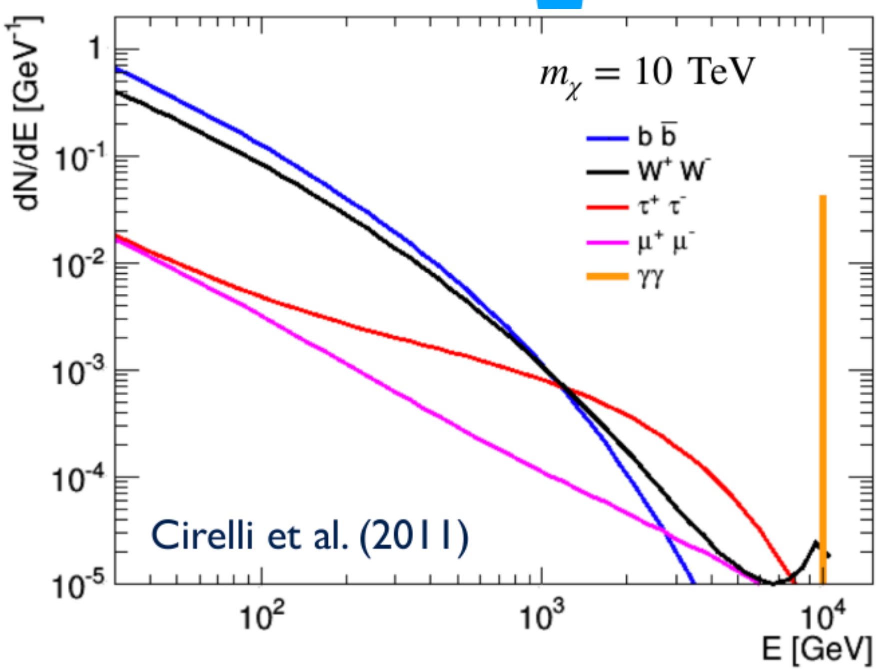

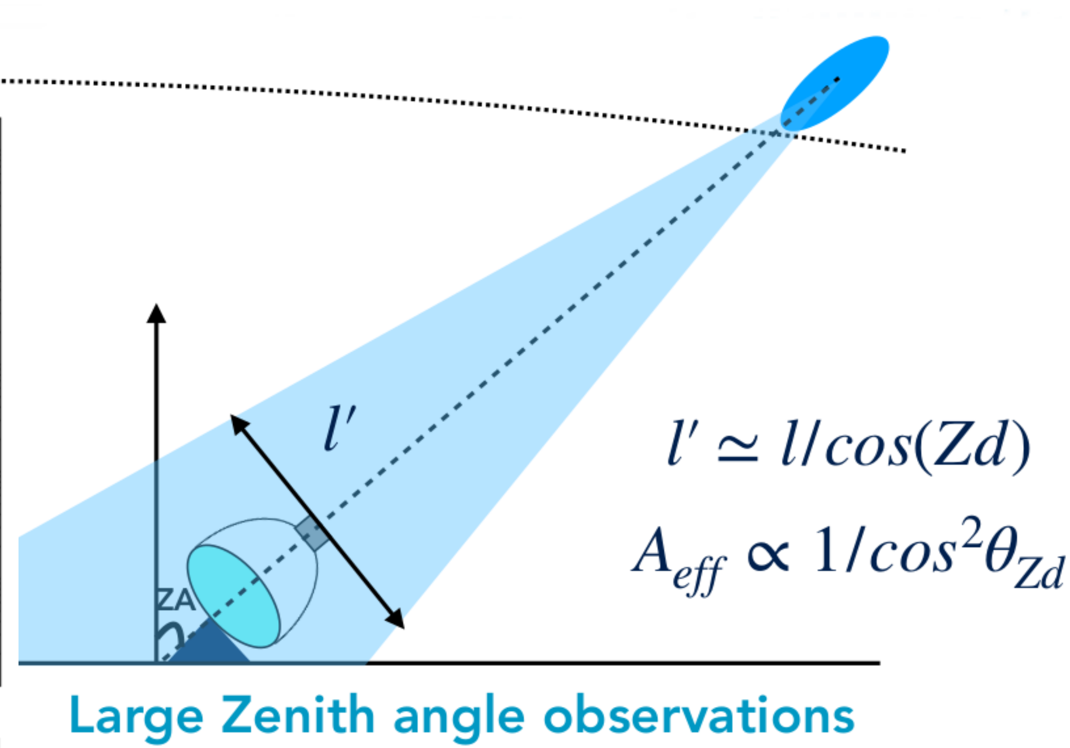

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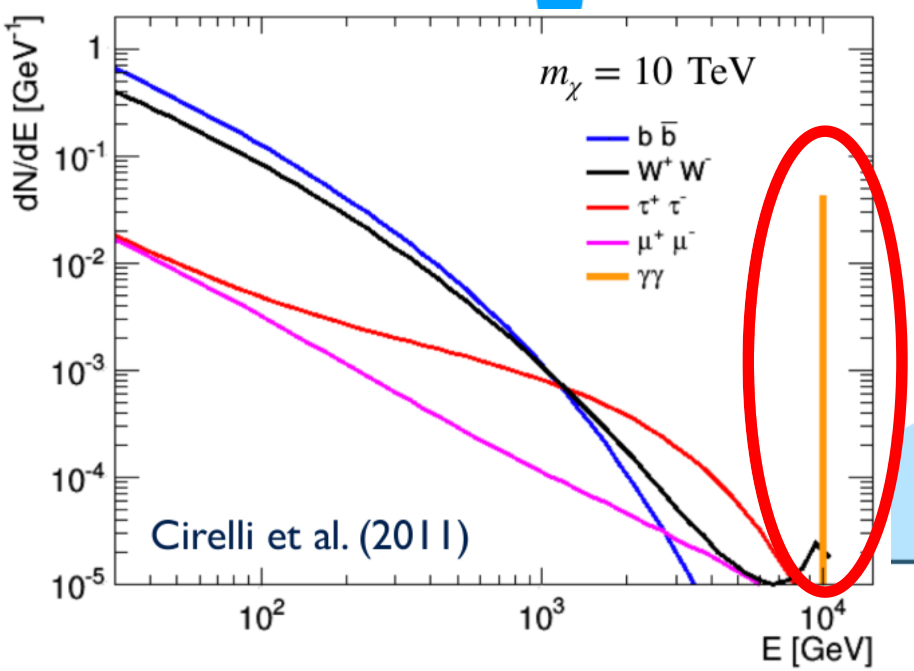
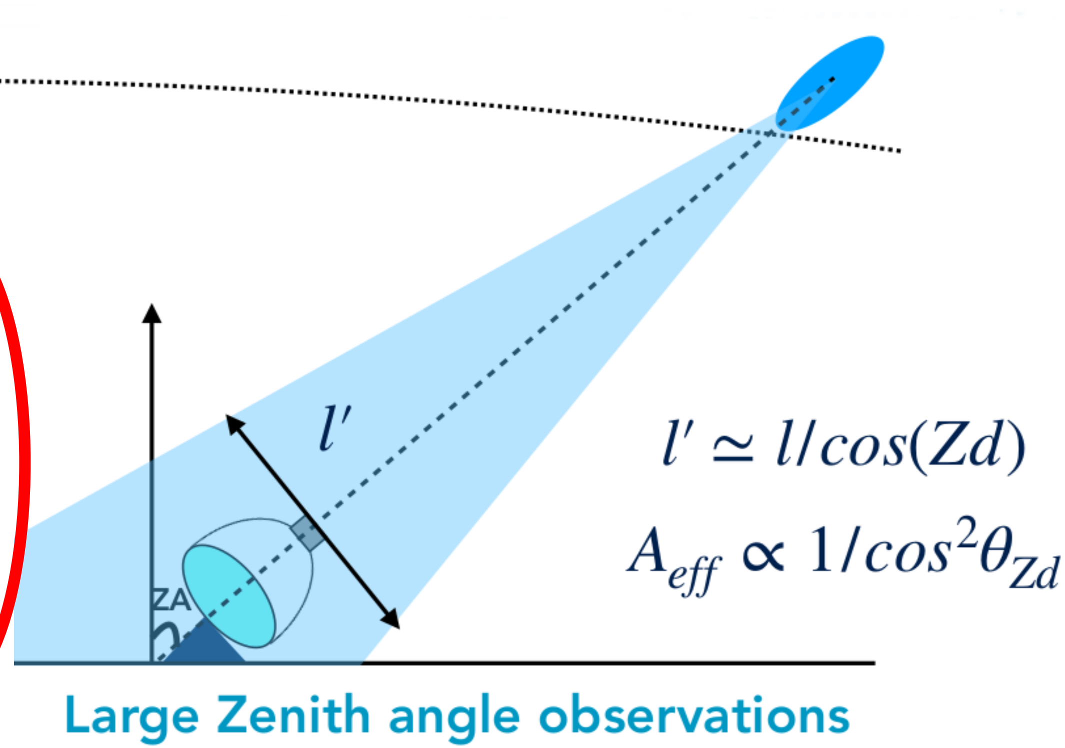
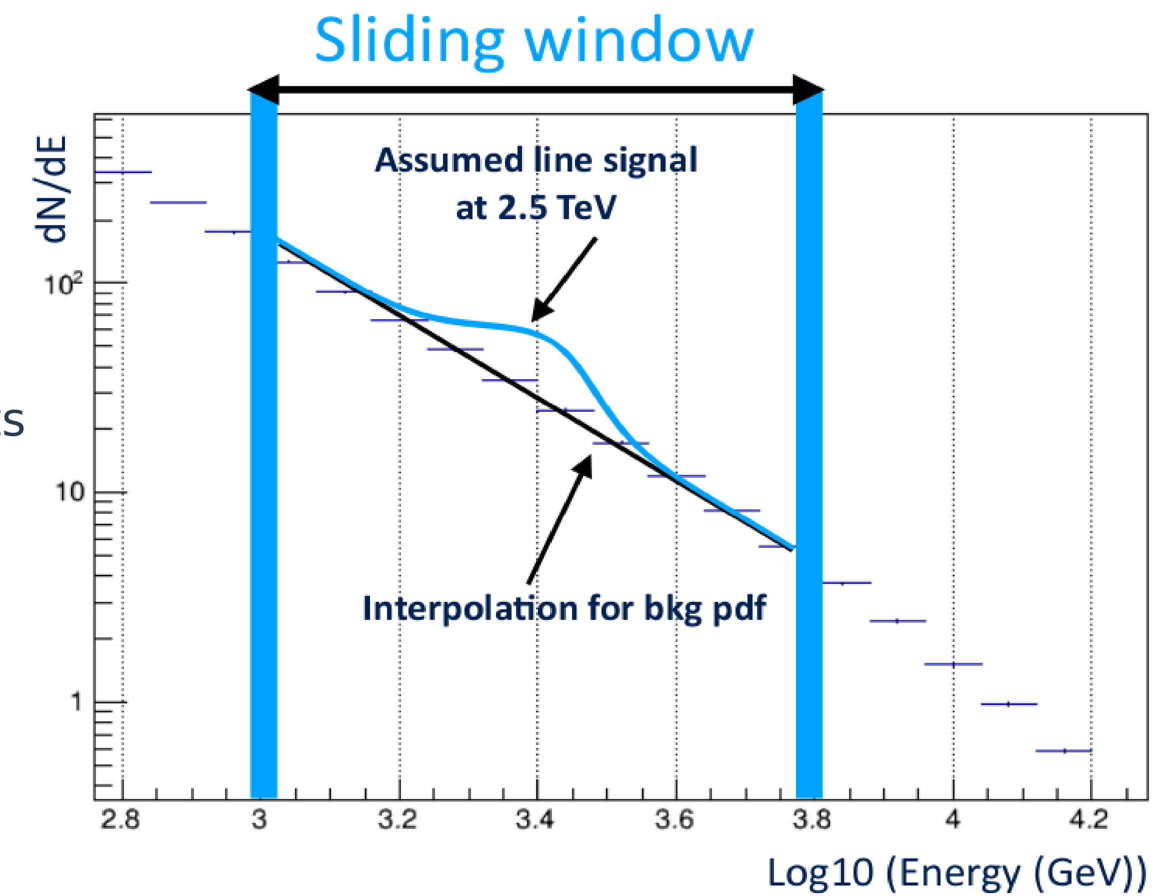




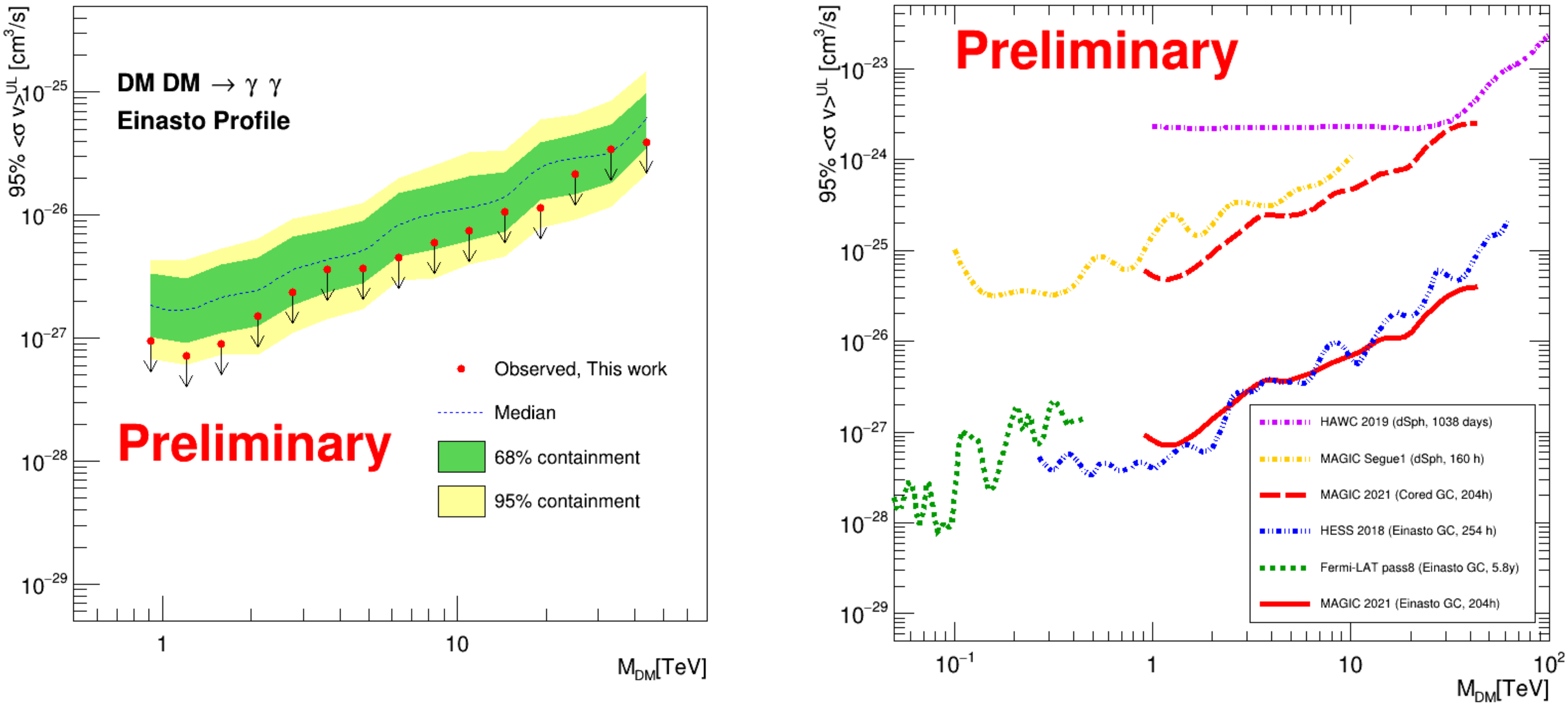
Unbinned likelihood analysis

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

- N_ON: observed number of events
- Index i run over different data samples
- G: estimated number of signal events
- B: estimated number of background events
- Tau: normalization factor for background model
- f_g: line signal PDF
- f_b: background PDF

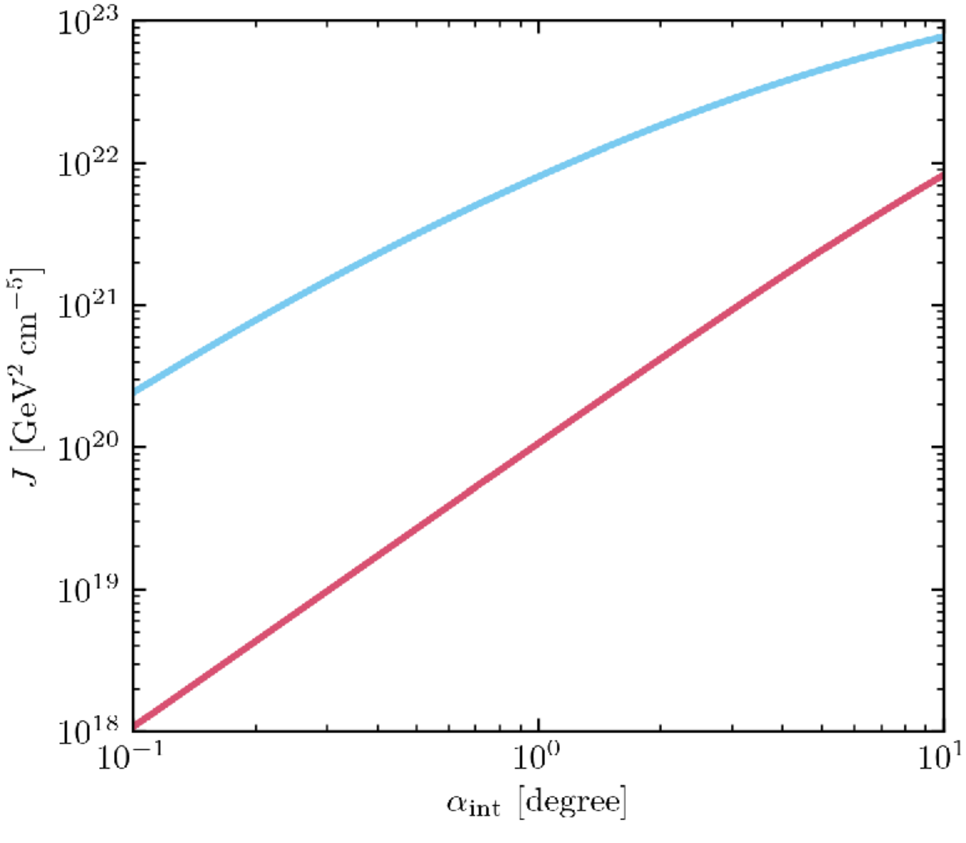


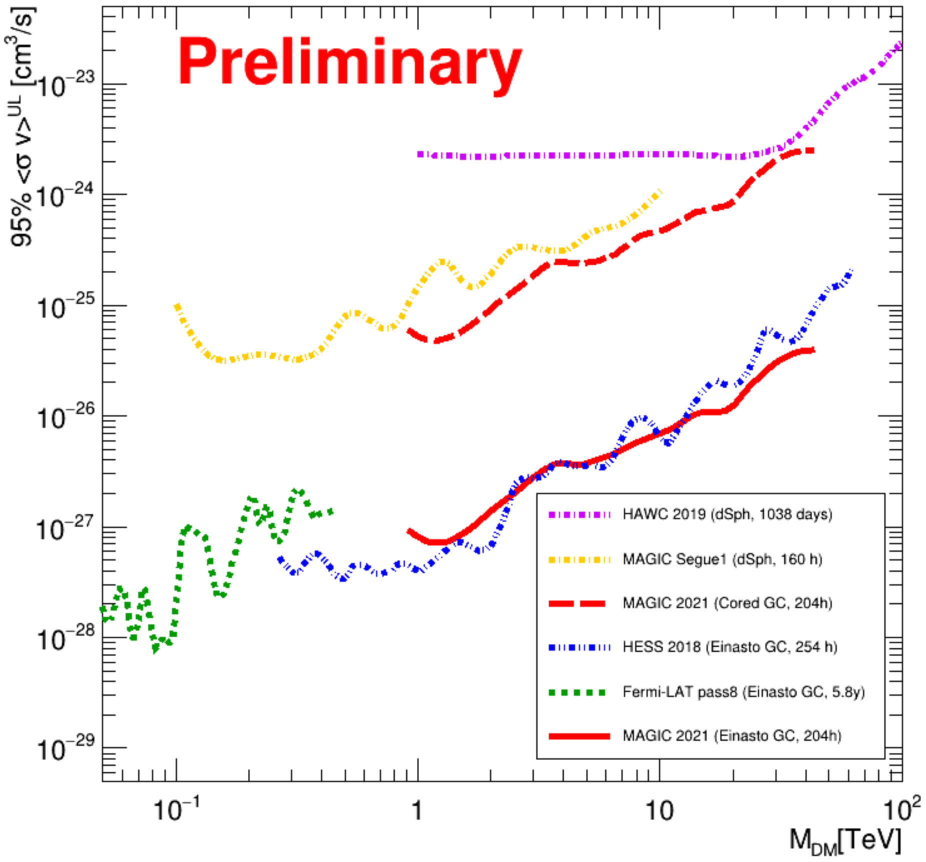
Search for line-like signals in the Galactic Centre



- **Results from ~204 hours of data**
- **No significant excess detected**

Search for line-like signals in the Galactic Centre





- **Results from ~204 hours of data**
- **Limits for cuspy profile comparable to H.E.S.S. and limits for core profile comparable to limits from dSphs**

Conclusion

- Gamma-ray experiments can probe very efficiently the GeV to multi-TeV DM mass range

- Robust results can be achieved with “clean” targets such as dSphs
  → large dataset of 4 dSphs and a total of ~354 hours of observations
  → most stringent limits from dSphs in the TeV regime
  → results nicely complements with other gamma-ray experiments

- Analyses are now both highly sophisticated and highly standardized
  → allows us to perform multi-instruments and multi-targets analysis
  → combined limits from Fermi-LAT, HAWC, H.E.S.S., MAGIC, and VERITAS range from 5 GeV to 100 TeV and improve individual limits up to a factor 2 to 3

- Observations of the Galactic Centre from the MAGIC site are done at large zenith angle
  → larger effective area but higher energy threshold
  → search of TeV DM line-like signals is boosted!
  → analysis technique allow to constrain both cuspy and core profiles