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An optimized analysis approach for
Indirect Dark Matter Searches



darkattack2012

DM searches with IACTs

$$\frac{d\Phi_G}{dE'} = \frac{d\Phi_G^{PP}}{dE'} \times \tilde{J}(\Delta\Omega)$$

$$\frac{d\Phi_G^{PP}}{dE'} = \frac{1}{4\pi} \frac{\langle\sigma v\rangle}{2m_\chi^2} \frac{dN_\gamma}{dE'}$$

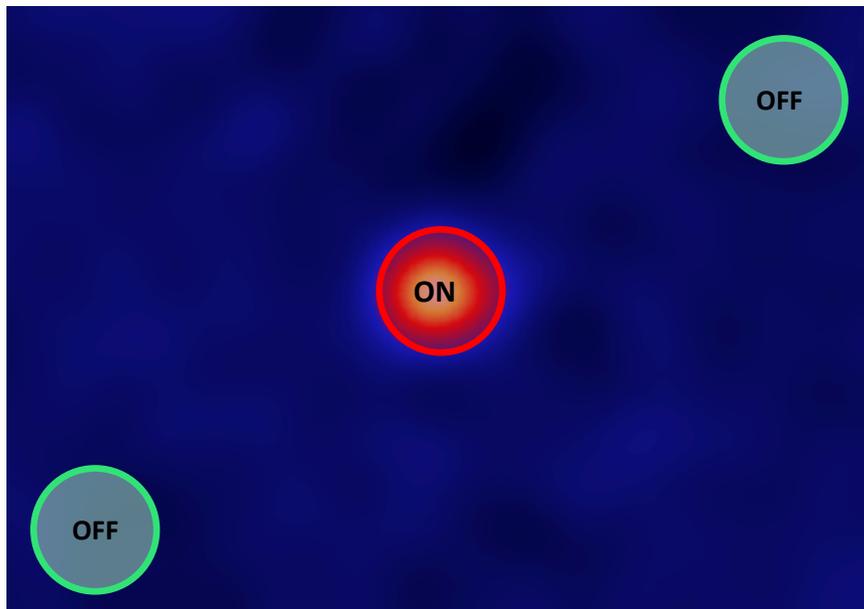
$$\tilde{J}(\Delta\Omega) = \int_{\Delta\Omega} d\Omega \int_{los} \rho^2(r) ds$$

- ✦ Search based on detection of characteristic spectral features
- ✦ Shape of gamma-ray spectrum fixed for a given DM model
→ optimization of the analysis approach

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THE METHOD

Classical method



ON = gamma + bkg

OFF = $\tau \times$ bkg

τ – bkg normalization

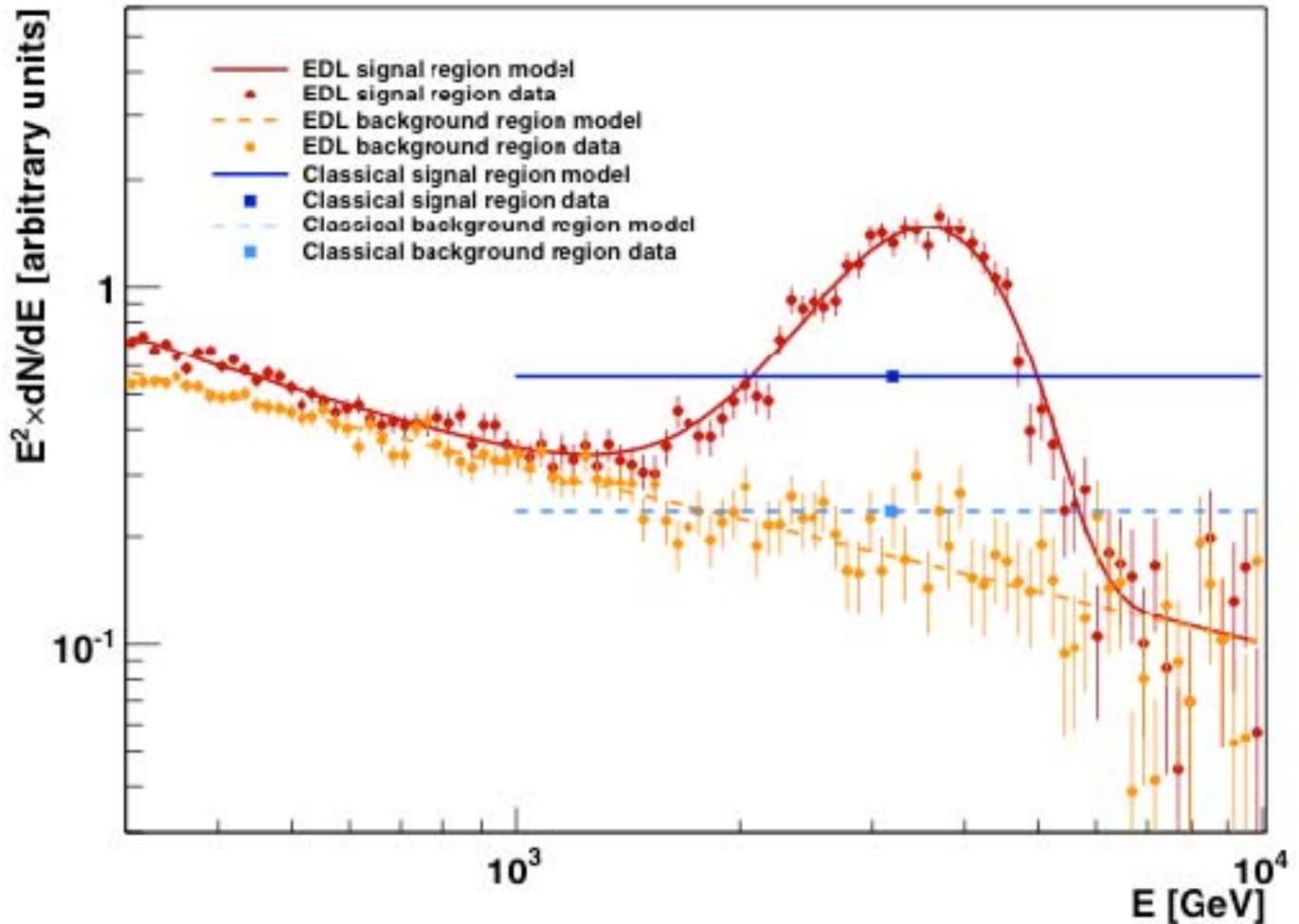
n, m – measured number of events from
signal/bkg regions

g, b – estimated number of γ /bkg events

✦ Not optimized for spectra with features

$$\mathcal{L}(g, b | n, m) = \underbrace{\frac{(g+b)^n}{n!} e^{-(g+b)}}_{\text{ON}} \times \underbrace{\frac{(\tau b)^m}{m!} e^{-(\tau b)}}_{\text{OFF}}$$

EDL vs Classical



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CHARACTERIZATION

Characterization of the EDL

✦ Response function

$$R_{G,B}(E;E') = A_{eff_{G,B}}(E')G_{G,B}(E;E')$$

✦ Spectral functions

✦ Background

directly measure bkg rate

✦ Signal

- Monochromatic Line

$$d\Phi_G/dE' = A_L \delta(E' - l)$$

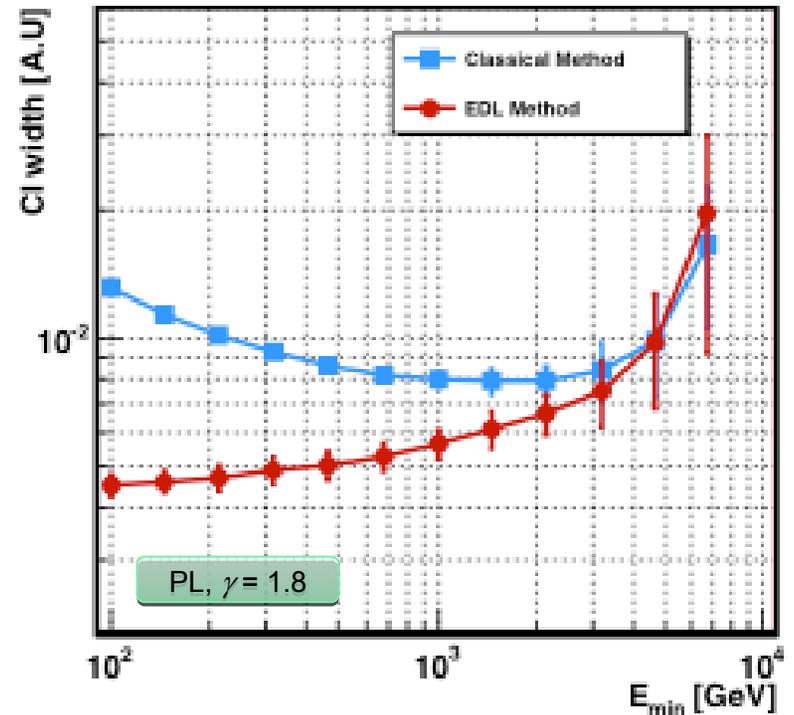
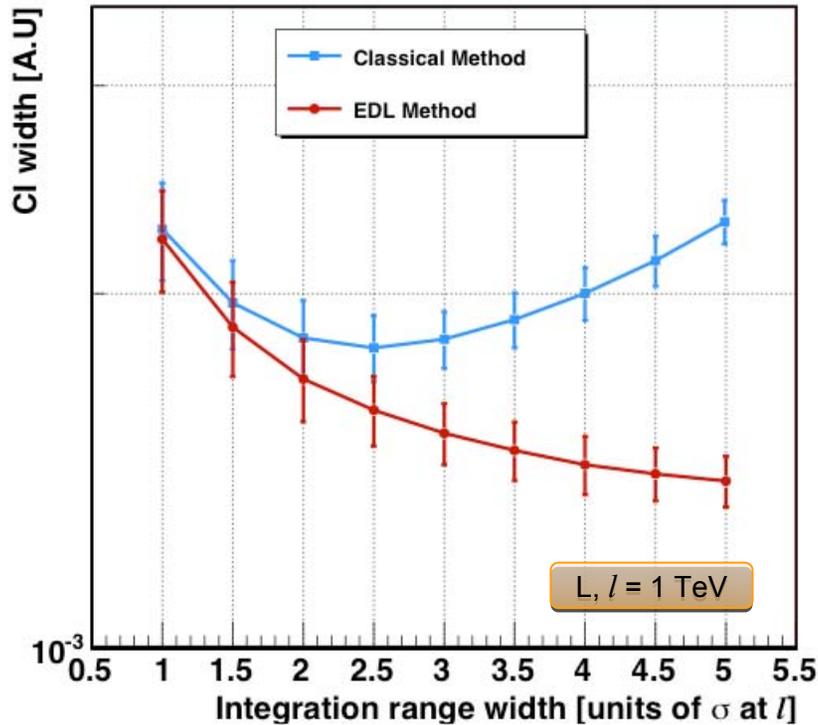
- Power Law

$$d\Phi_G/dE' = A_{PL} E'^{-\gamma}$$

✦ Improvement Factor

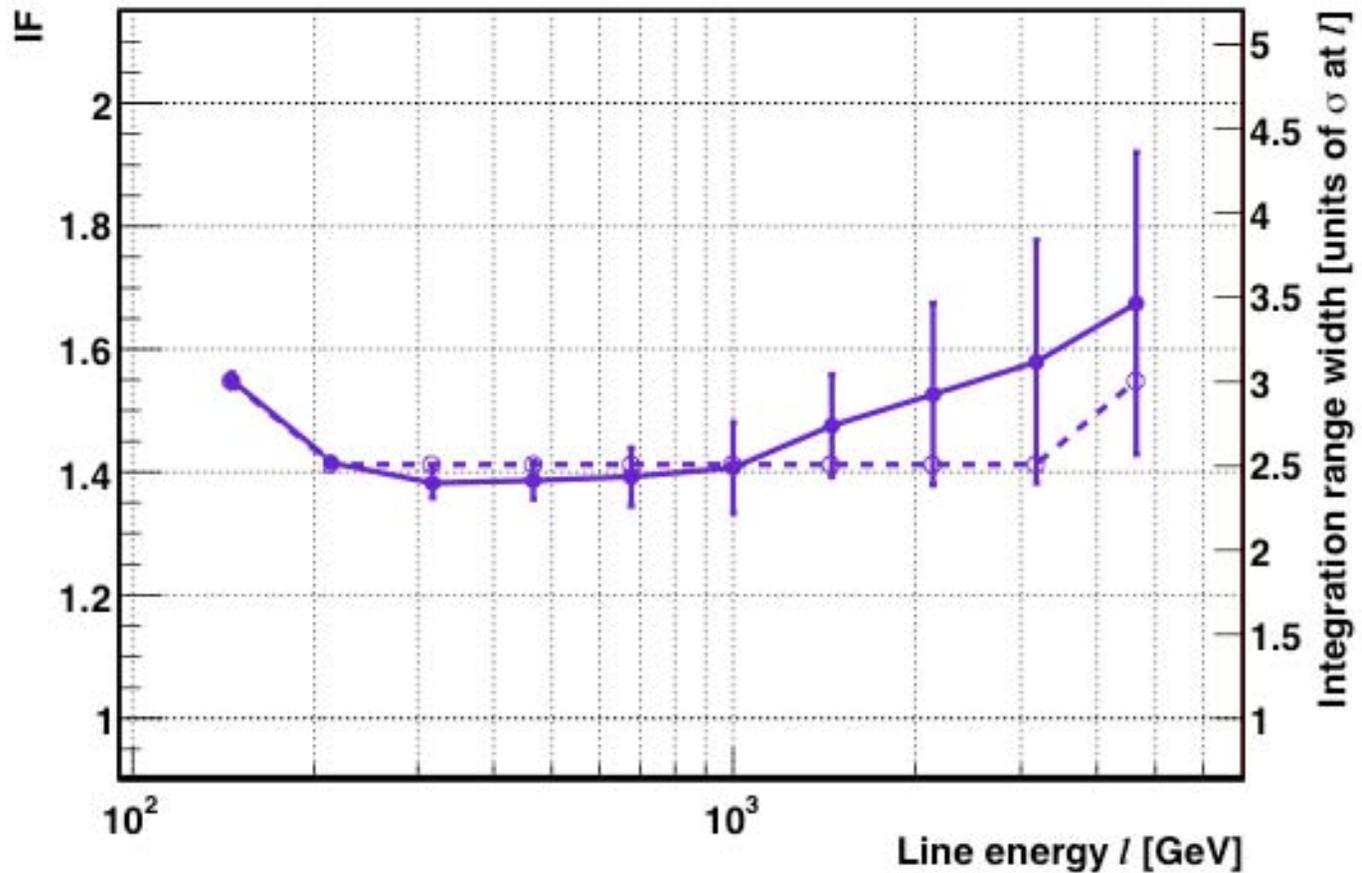
$$IF(M(\theta)) = \langle CI_{class} / CI_{EDL} \rangle$$

Optimal Integration Range



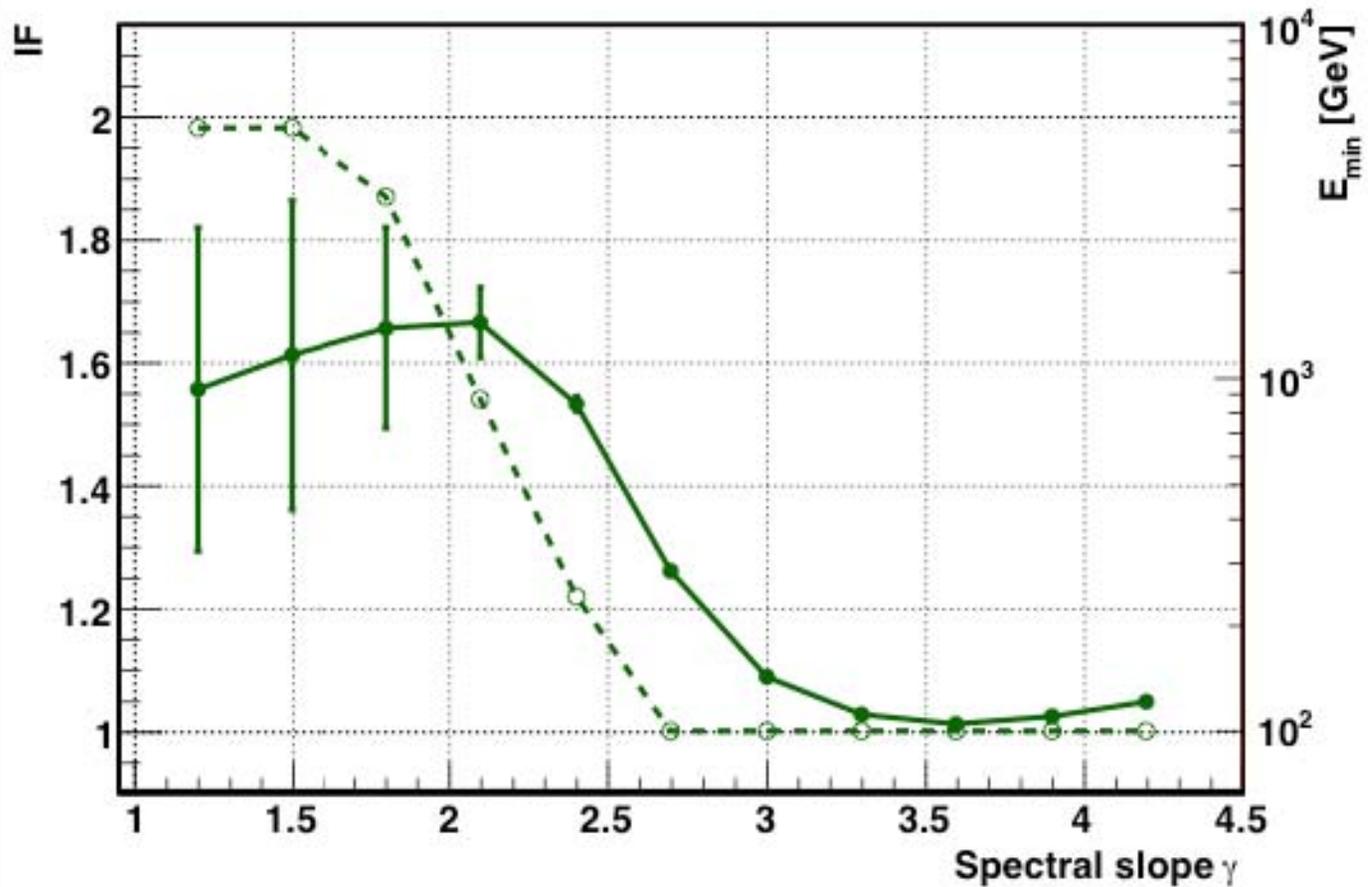
* Error bars are the RMS of the distribution

IF for different Signal Models



Line Energy (l)

IF for different Signal Models



Spectral slope (PL)

Stability & Robustness

Parameter	Variation Range [units of the parameter]	IF		
		PL, $\odot = 1.8$ L, $l = 1$ TeV	PL, $\odot = 3.6$	
/	1 - 5	1.91 - 1.47	1.02 - 1.01	1.63 - 1.26
# of events	$5 \times 10^4 - 5 \times 10^6$	1.76 - 1.72	1.03 - 1.02	1.43 - 1.41
f [% of f_{MAGIC}]	50 - 500	1.65 - 1.66	1.01 - 1.11	1.37 - 2.83
E_{max} [TeV]	10 - 50	1.66 - 1.82	1.01 - 1.02	1.40 - 1.41

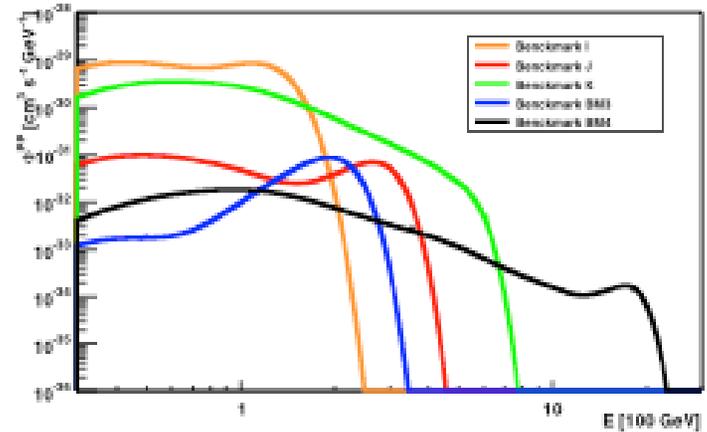
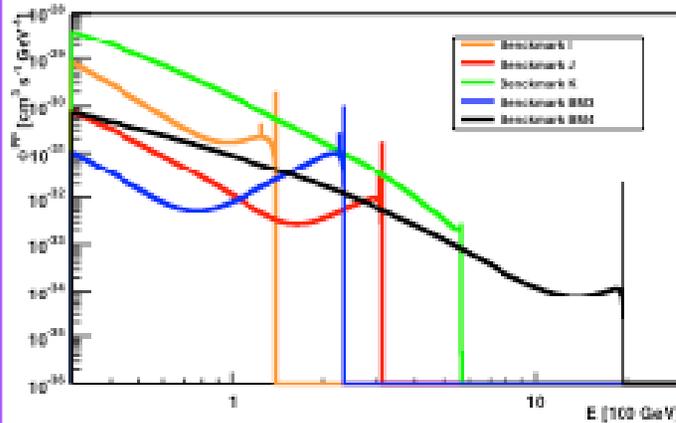
- ✦ Robustness tests: Response function of the detector is not perfectly known
- ✦ Extreme mismatch between the actual and R used in analysis - up to 10% sensitivity degradation
 - Loss smaller than the gain, EDL is robust

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DM SEARCHES

Benchmark Models

Bringmann, Doro & Fornasa (2009)



MAGIC

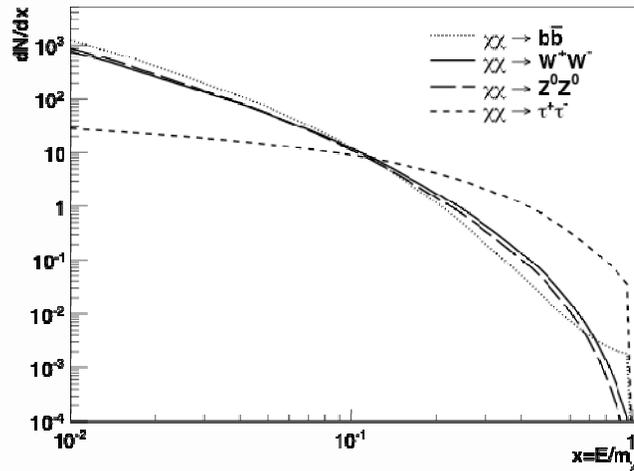
CTA

BM	m_x [GeV]	σv [$cm^3 s^{-1}$]	IF	$\langle\sigma v\rangle_{EDL}$ [$cm^3 s^{-1}$]	IF	$\langle\sigma v\rangle_{EDL}$ [$cm^3 s^{-1}$]
I'	141	3.6×10^{-27}	1.57	5.65×10^{-23}	1.48	1.39×10^{-23}
J'	315	3.2×10^{-28}	1.80	1.01×10^{-23}	1.65	1.91×10^{-24}
K'	565	2.6×10^{-26}	1.23	3.91×10^{-23}	1.58	8.39×10^{-24}
BM3	233	9.2×10^{-29}	1.89	7.21×10^{-25}	1.61	1.35×10^{-25}
BM4	1957	2.6×10^{-27}	2.10	2.87×10^{-23}	3.81	4.82×10^{-24}

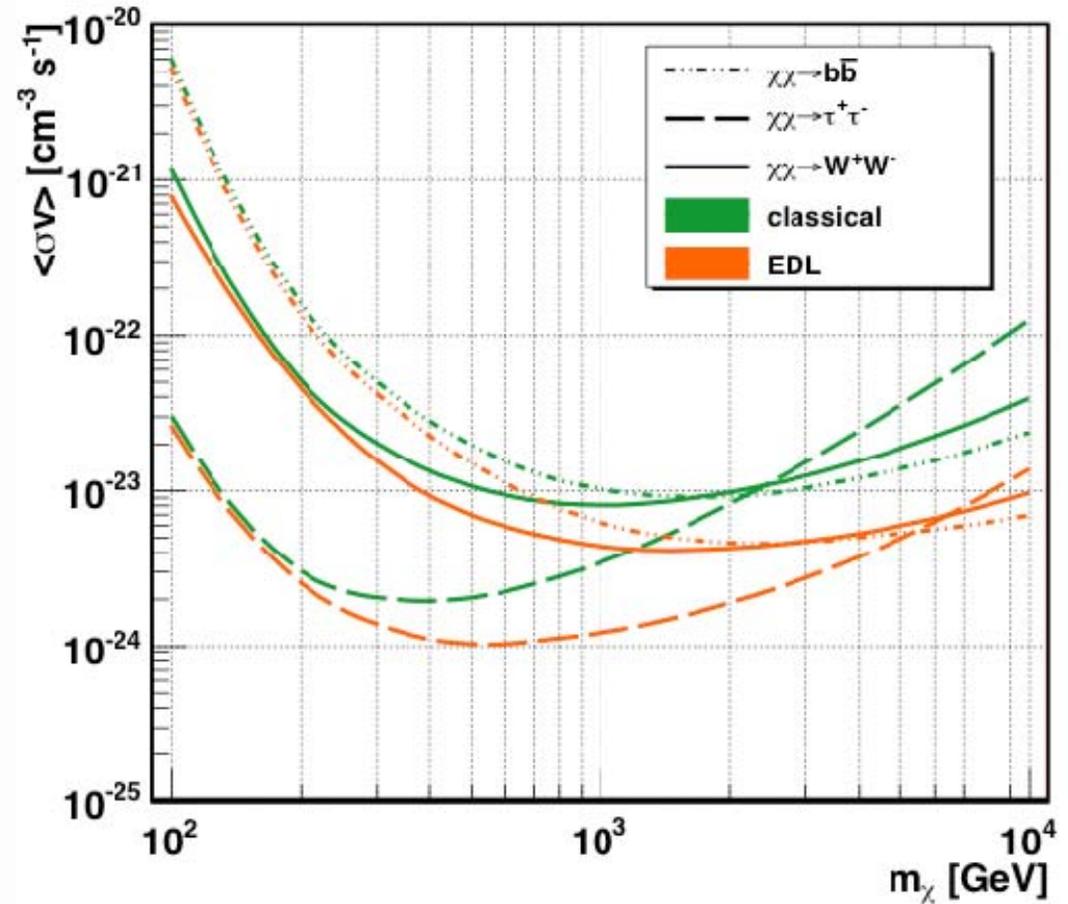
IF: $E^* - m_x$

Secondary γ s

VERITAS Coll (2012)



- 50 h of Segue 1 data
- no optimization of the energy range
- channels $b\bar{b}$, $\tau^+\tau^-$ and W^+W^-
- $\text{Br} = 100\%$
- $J = 7.7 \times 10^{18} \text{ GeV}^2 \text{ cm}^{-5}$, $f = 1/0.084$



Secondary γ s: $b\bar{b}$

$m_\chi = 100$ GeV

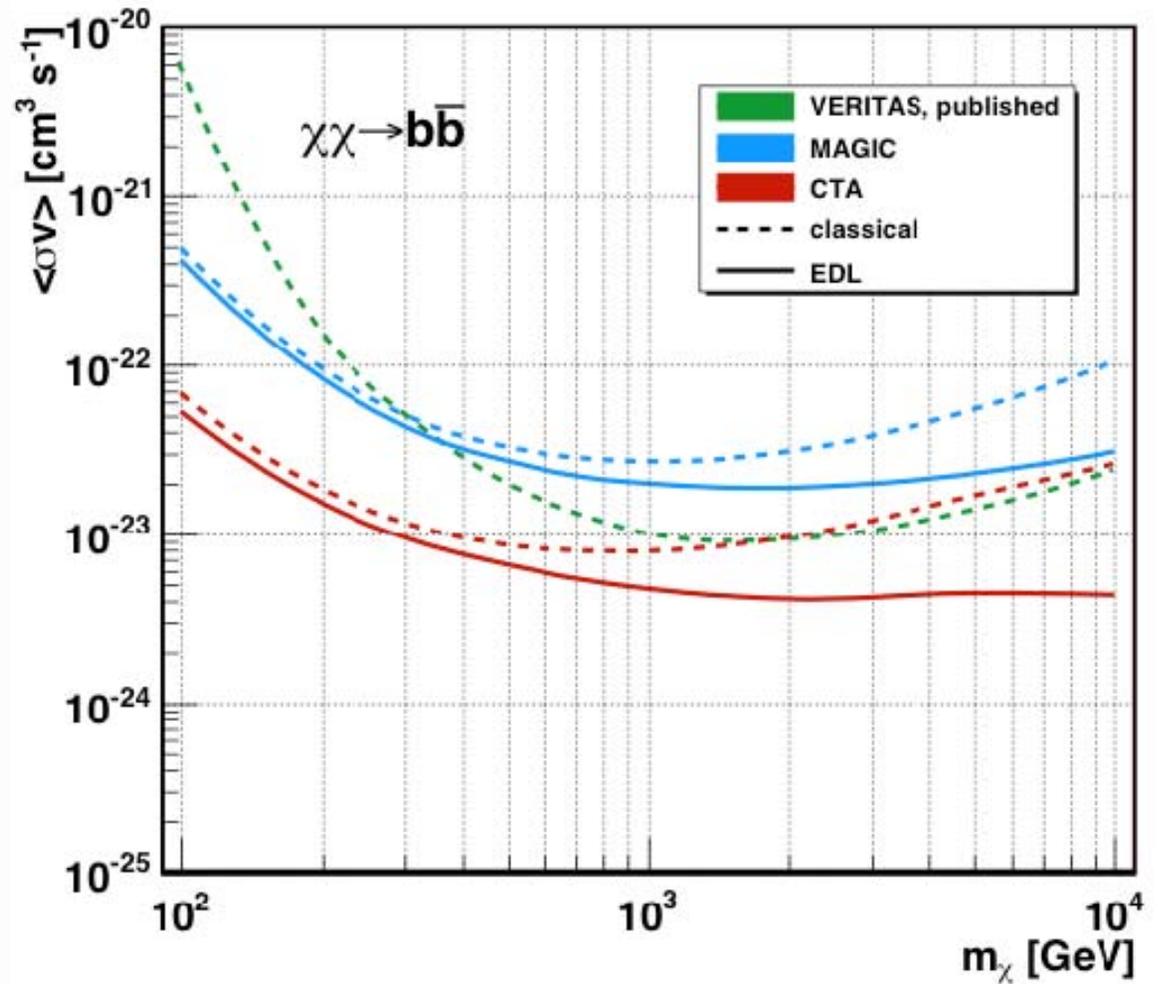
1.16 / 1.27

$m_\chi = 1$ TeV

1.37 / 1.66

$m_\chi = 10$ TeV

3.43 / 5.99



- same conditions and analysis settings as done by VERITAS

Secondary γ s: W^+W^-

$m_\chi = 100$ GeV

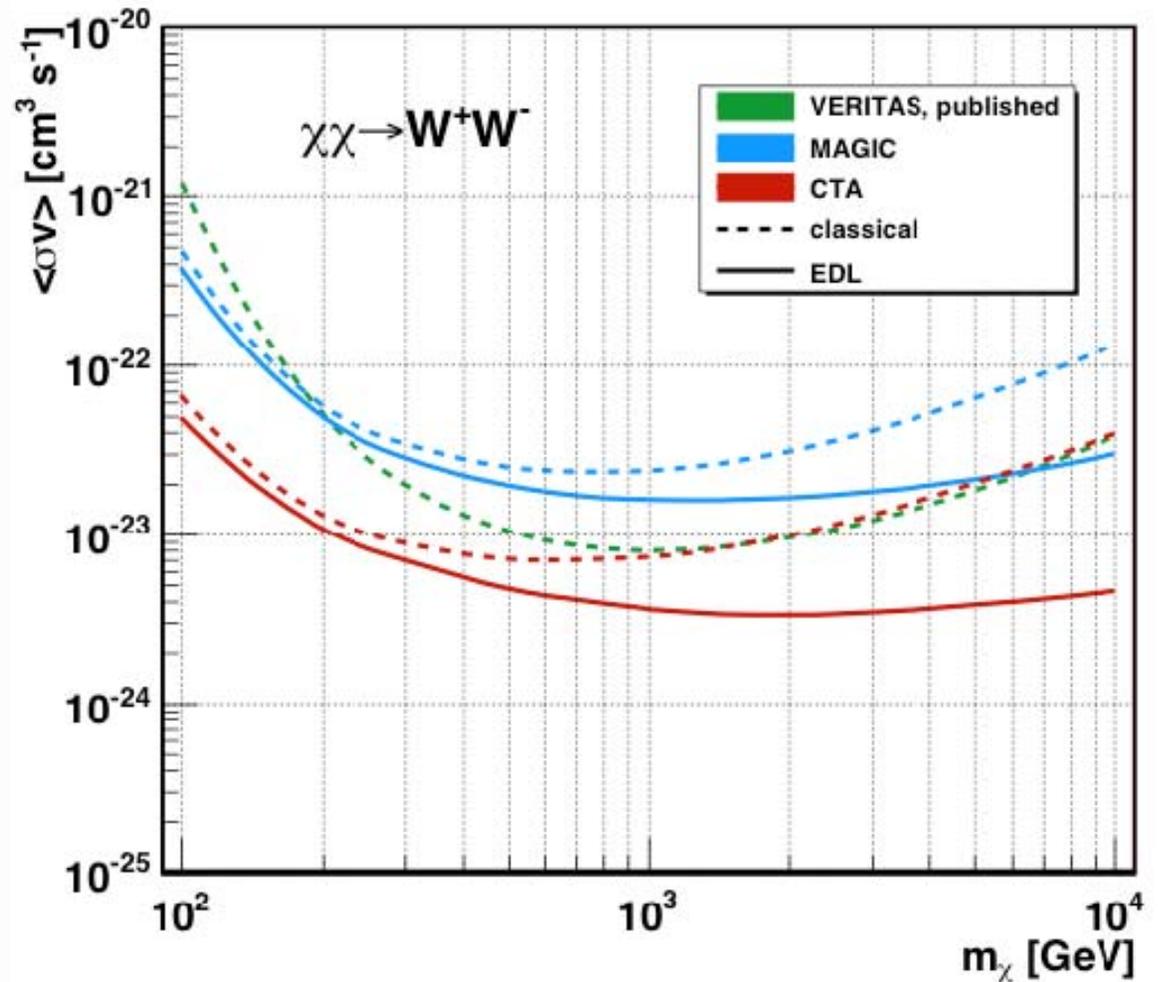
1.26 / 1.36

$m_\chi = 1$ TeV

1.52 / 2.02

$m_\chi = 10$ TeV

4.52 / 8.51



- same conditions and analysis settings as done by VERITAS

Secondary γ s: $\tau^+\tau^-$

$m_\chi = 100$ GeV

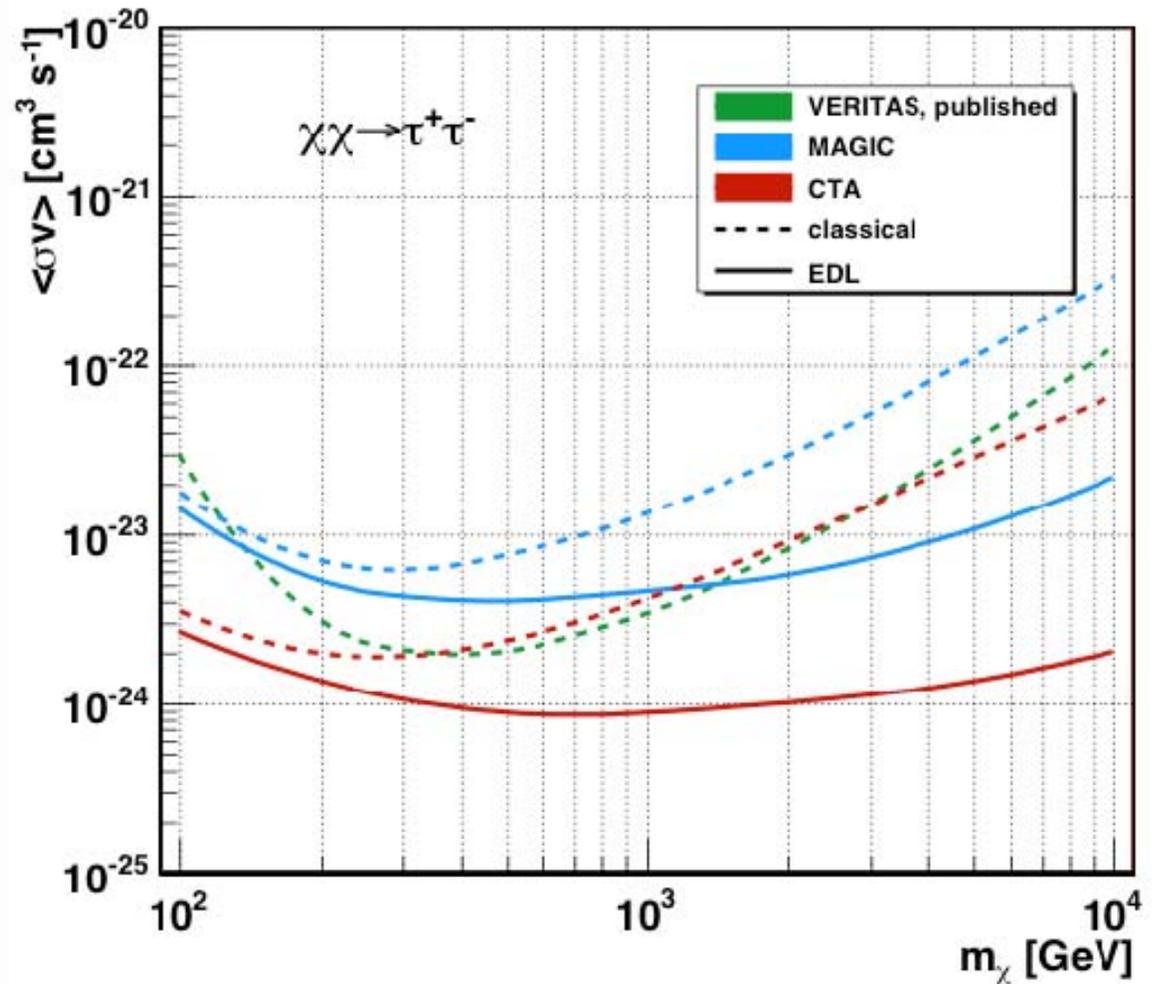
1.25 / 1.33

$m_\chi = 1$ TeV

2.94 / 4.84

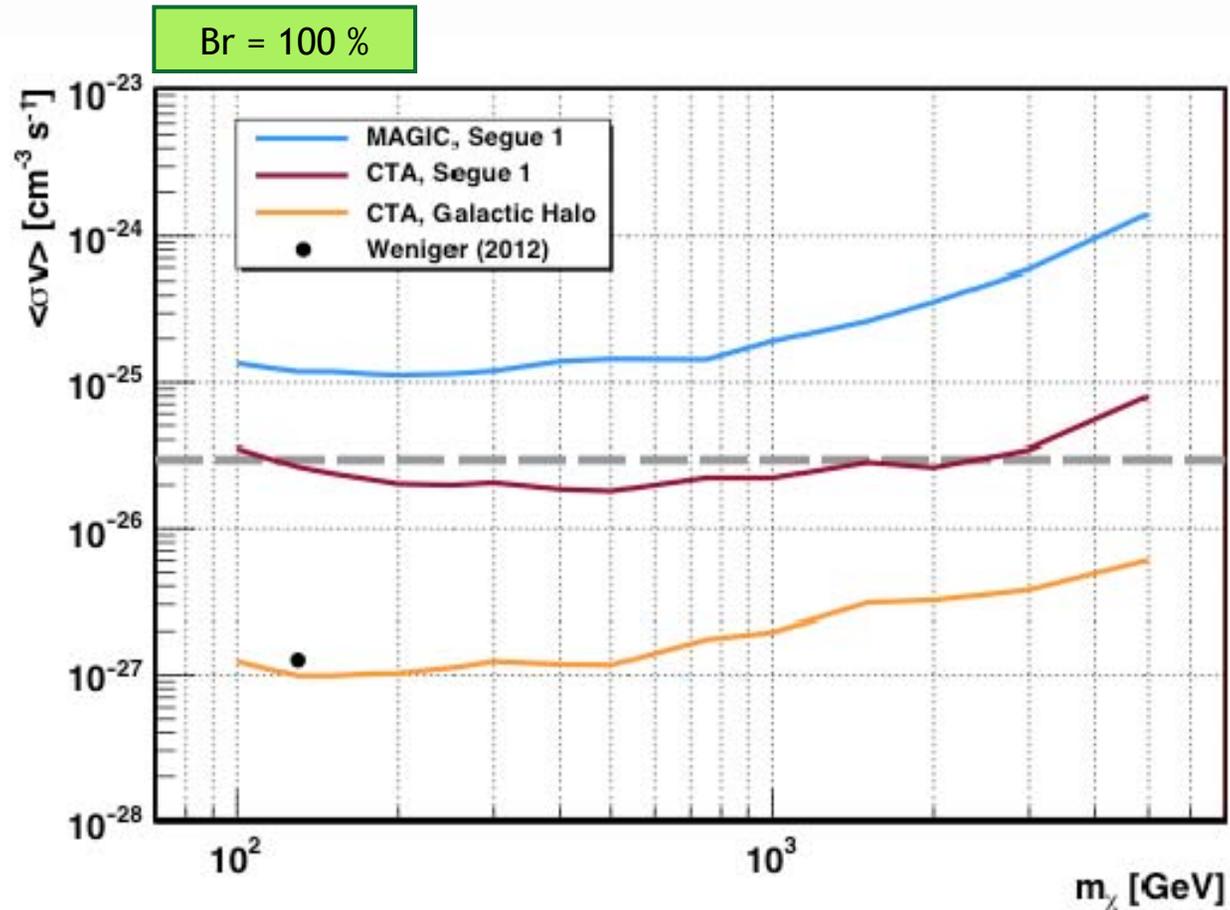
$m_\chi = 10$ TeV

15.75 / 33.14



- same conditions and analysis settings as done by VERITAS

Annihilation into $\gamma\gamma$



5σ detection in 50 h

Segue 1: $\tau = 12$; $J = 1.7 \times 10^{19} \text{ GeV}^2 \text{ cm}^{-5}$

Galactic Halo: $\tau = 2$; $J = 3.3 \times 10^{21} \text{ GeV}^2 \text{ cm}^{-5}$

Discussion

- ✦ EDL: a priori knowledge on the expected gamma-ray spectrum
- ✦ Maximum advantage of the spectral information
- ✦ Up to order of 10 better sensitivity than the classical approach
- ✦ Improvement insensitive to other analysis characteristics
- ✦ It is general: applicable to other instruments and physics cases
- ✦ Straight-forward combination of different data (instruments/sources)

$$\mathcal{L}_T(M(\theta)) = \prod_{i=1}^{N_{\text{inst}}} \mathcal{L}_i(M(\theta))$$

- ✦ Potential for the most sensitive DM search through the combination of the data from the IACTs of the present generation

Energy-dependent likelihood: an optimized analysis method for indirect dark matter searches

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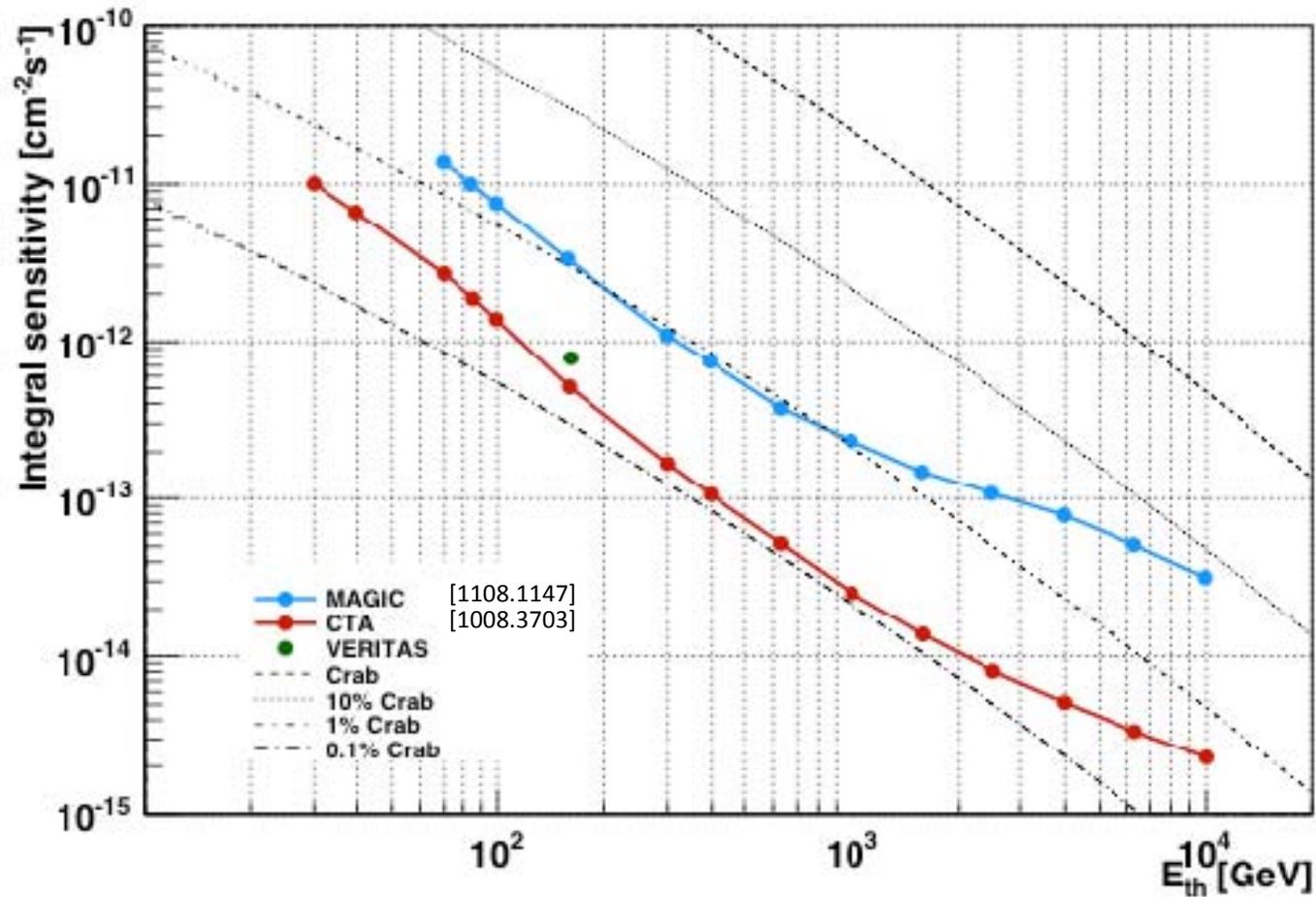
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