Indirect detection of dark matter

HEPAP-DAS 2023
SAHA Institute of Nuclear Physics

Daniel Nieto
(d.nieto@ucm.es)
Institute for Particle and Cosmos Physics
IPARCOS-UCM

https://apod.nasa.gov/apod/ap200724.html

Syllabus

- Dark matter paradigm and searches (Day 1)
- Indirect searches with gamma rays (Day 2)
- Data analysis: specific methodologies (Day 3)

Credit: NASA, HST, Webb

Syllabus: Day 3

- Data analysis: specific methodologies
  - Profile likelihood method (IACTs)
  - Event-weighting method (IACTs)
  - Full likelihood method
- Detection prospects
- Proposals for hands-on session

Credit: NASA, HST, Webb

Annihilation (DM DM → SM SM → secondary γ)

$$\frac{\Phi_{\rm ann}}{{\rm d}E_\gamma}(E_\gamma,\Delta\Omega) = \underbrace{\frac{\langle\sigma v\rangle}{8\pi\, m_{\rm DM}^2}\frac{{\rm d}N}{{\rm d}E}}_{\text{Particle Physics factor}}\ \underbrace{\int_0^{\Delta\Omega}\int_{\rm l.o.s.} \rho(l,\Omega)^2\,{\rm d}l\,{\rm d}\Omega}_{\text{Astrophysical factor}}$$

Decay (DM → γ γ , DM → SM SM → secondary γ)

$$\frac{\Phi_{\rm decay}}{{\rm d}E_\gamma}(E_\gamma,\Delta\Omega) = \underbrace{\frac{1}{4\pi\, t_{\rm DM}\, m_{\rm DM}}\frac{{\rm d}N}{{\rm d}E}}_{\text{Particle Physics factor}}\ \underbrace{\int_0^{\Delta\Omega}\int_{\rm l.o.s.} \rho(l,\Omega)\,{\rm d}l\,{\rm d}\Omega}_{\text{Astrophysical factor}}$$

Local volume, DM mass below few TeV: attenuation not relevant

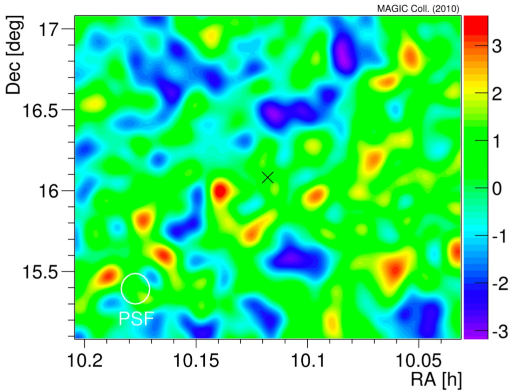
Galaxies 2022, 10, 92

Annihilation (DM DM → SM SM → secondary γ)

$$\frac{\Phi_{\mathrm{ann}}}{dE_\gamma}(E_\gamma,\Delta\Omega) = \frac{\langle\sigma v\rangle}{8\pi\, m_{\mathrm{DM}}^2}\,\frac{dN}{dE}\int_0^{\Delta\Omega}\int_{\mathrm{l.o.s.}}\rho(l,\Omega)^2\,dl\,d\Omega$$

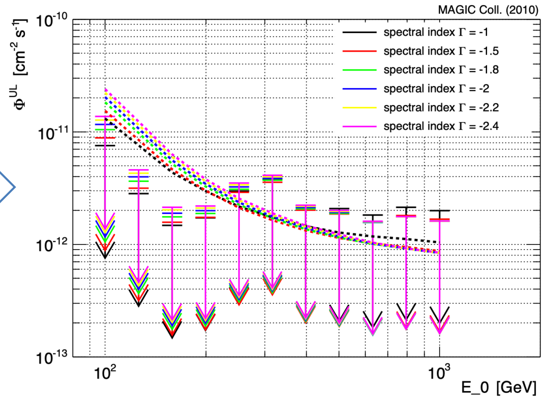
Particle Physics factor — Astrophysical factor

No significant emission

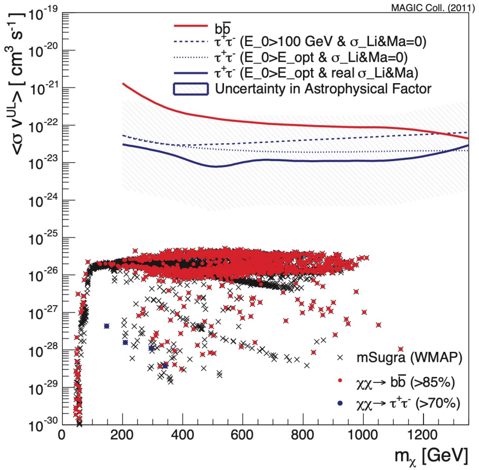


Segue 1 – MAGIC I – JCAP 1106:035,2011

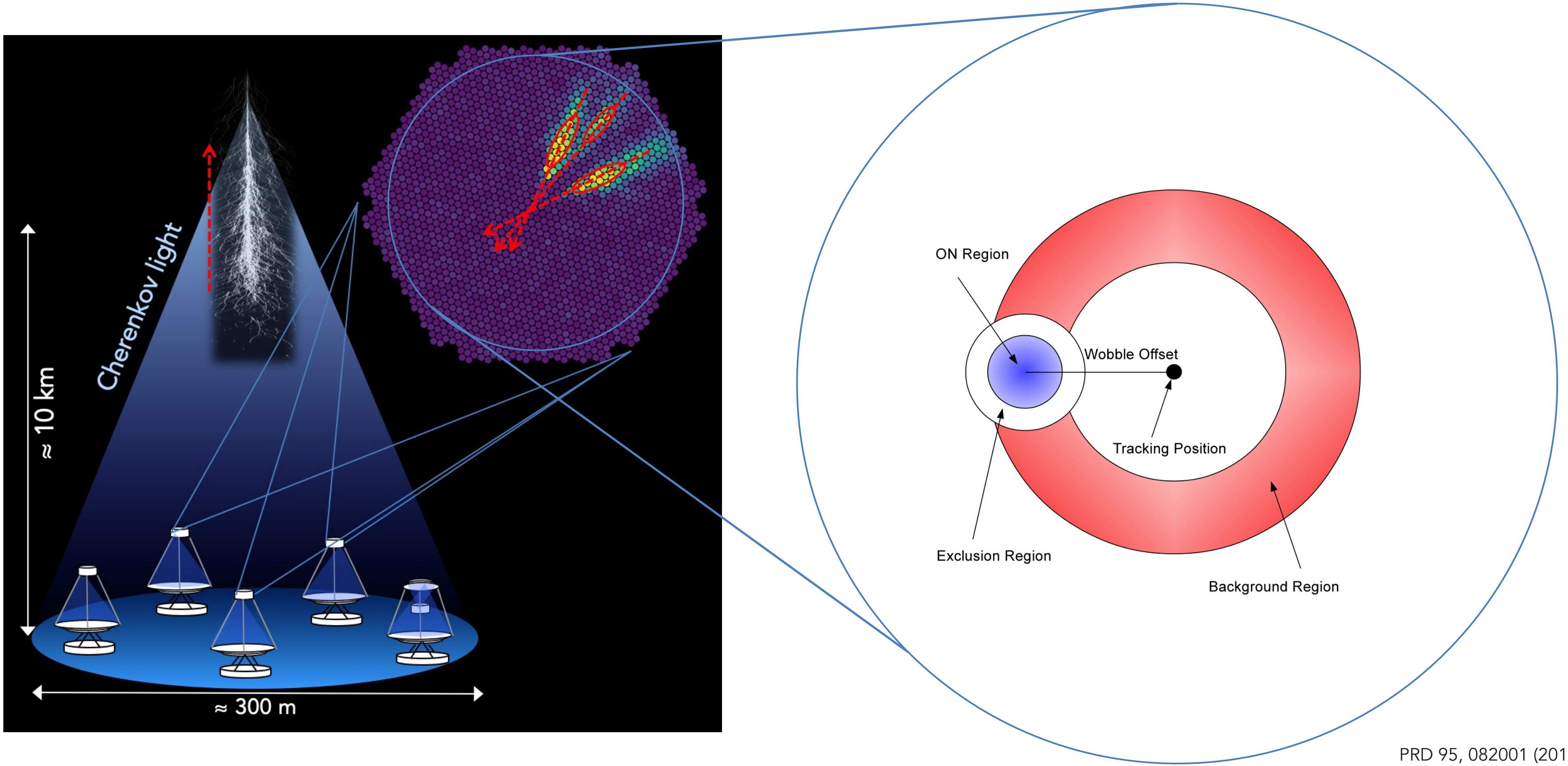
Flux upper limits



DM model constraints



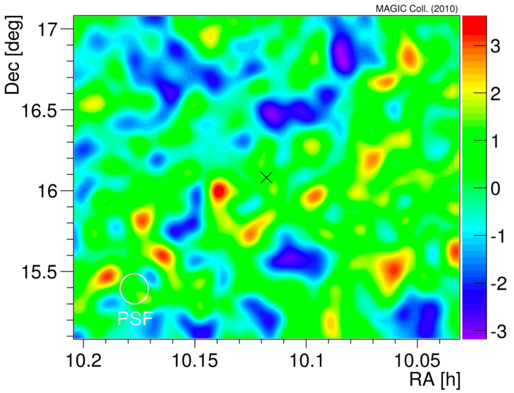
Profile likelihood method (IACTs)

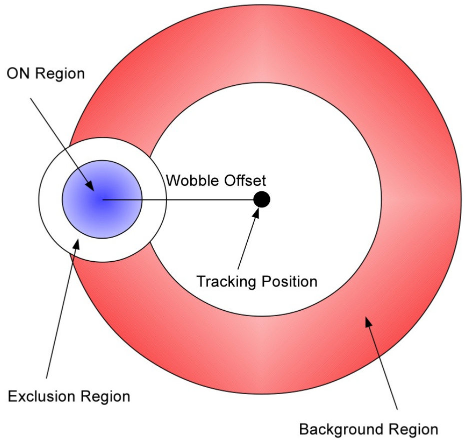


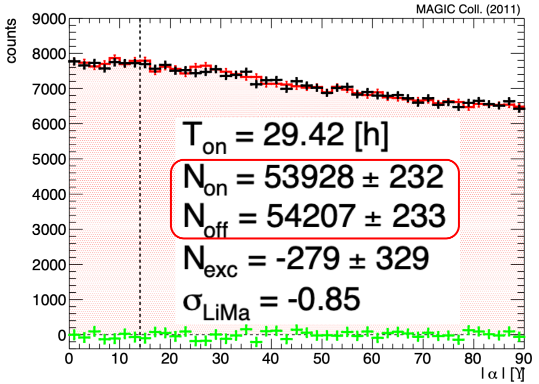
PRD 95, 082001 (2017)

Profile likelihood method (IACTs)

No significant emission







Integral flux upper limits

Expected differential spectrum

$$\Phi^{UL}(>E_0) = \frac{N_{exc}^{UL}(E_{rec} > E_0)}{t_{eff}} \frac{\int_{E_0}^{\infty} S(E)dE}{\int_0^{\infty} A_{eff}(E; E_{rec} > E_0)\, S(E)dE}$$

Segue 1 – MAGIC I – JCAP 1106:035,2011

Profile likelihood method (IACTs)

Profile likelihood (Rolke et al. 2009)

Likelihood

PDF

$$L(\boldsymbol{\pi},\boldsymbol{\theta}|X) = \prod_{i=1}^{n} f(X_i|\boldsymbol{\pi},\boldsymbol{\theta})$$

Parameters of interest

Nuisance parameters

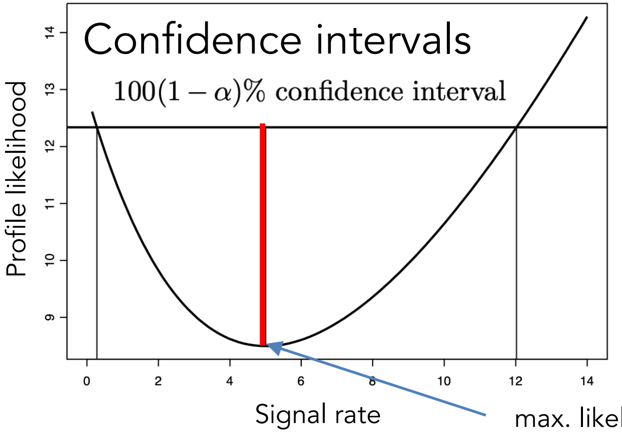
Indep. observations

Profile likelihood

$$\lambda(\boldsymbol{\pi}_0|X) = \frac{\sup\{L(\boldsymbol{\pi}_0,\boldsymbol{\theta}|X);\boldsymbol{\theta}\}}{\sup\{L(\boldsymbol{\pi},\boldsymbol{\theta}|X);\boldsymbol{\pi},\boldsymbol{\theta}\}}$$

$$-2\log\lambda \sim \chi^2$$

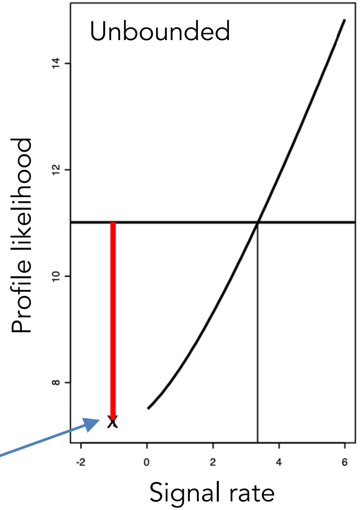
(with *k* degrees of freedom, for *k* parameters of interest)

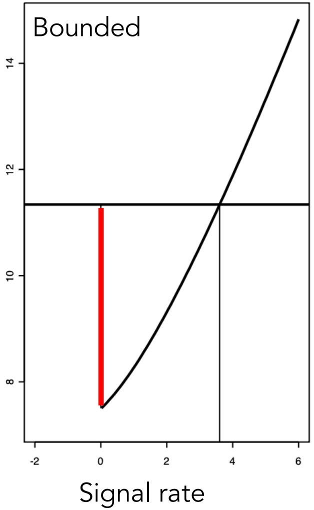


α percentile of a χ^2

max. likelihood estimator (MLE)

Limits





Segue 1 – MAGIC I – JCAP 1106:035,2011

Profile likelihood (Rolke et al. 2009)

Likelihood

$$L(\boldsymbol{\pi}, \boldsymbol{\theta}|X) = \prod_{i=1}^{n} f(X_i|\boldsymbol{\pi}, \boldsymbol{\theta})$$

PDF

Parameters of interest

Nuisance parameters

Indep. observations

Profile likelihood

$$\lambda(\boldsymbol{\pi}_0|X) = \frac{\sup\{L(\boldsymbol{\pi}_0, \boldsymbol{\theta}|X); \boldsymbol{\theta}\}}{\sup\{L(\boldsymbol{\pi}, \boldsymbol{\theta}|X); \boldsymbol{\pi}, \boldsymbol{\theta}\}}$$

$$-2\log\lambda \sim \chi^2$$

(with *k* degrees of freedom, for *k* parameters of interest)

IACTs

Signal rate

Bkg rate

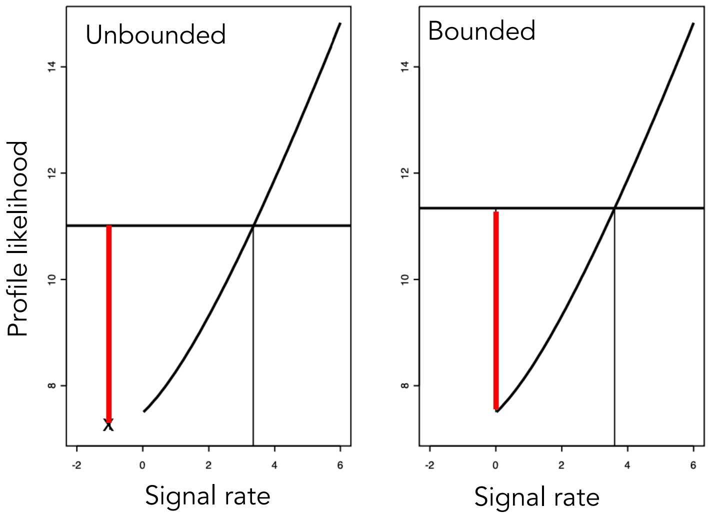
$$X \sim Pois(\mu + b), \quad Y \sim Pois(\tau b)$$

N_{on} N_{off}

$$f(x, y|\mu, b) = \frac{(\mu+b)^x}{x!} e^{-(\mu+b)} \cdot \frac{(\tau b)^y}{y!} e^{-\tau b}$$

$$\lambda(\mu|x, y) = \frac{L(\mu, \hat{b}(\mu)|x, y)}{L(\widehat{\mu}, \widehat{b}|x, y)}$$

Limits



Segue 1 – MAGIC I – JCAP 1106:035,2011

Profile likelihood method (IACTs)

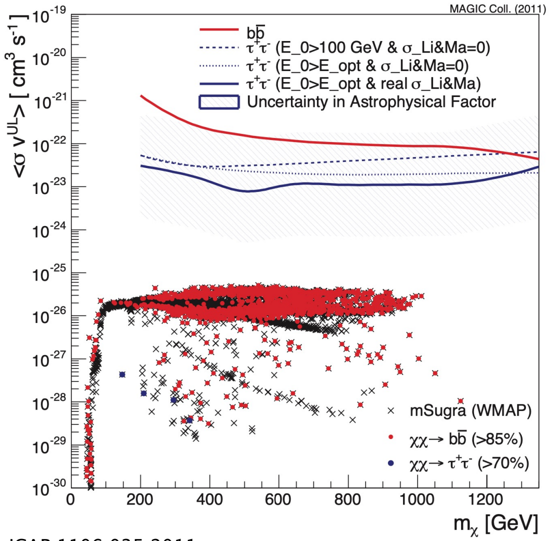
$$\Phi(> E_0, \Delta\Omega) = \Phi_{\epsilon}^{PP}(> E_0)\; J\,(\Delta\Omega)$$

$$\Phi_{\epsilon}^{PP}(> E_0) = \frac{1}{4\pi}\,\frac{\langle\sigma_{\rm ann} v\rangle}{2m_\chi^2} \int_{E_0}^{m_\chi} \sum_{i=1}^{n} B^i \frac{dN_\gamma^i}{dE}\, dE$$

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

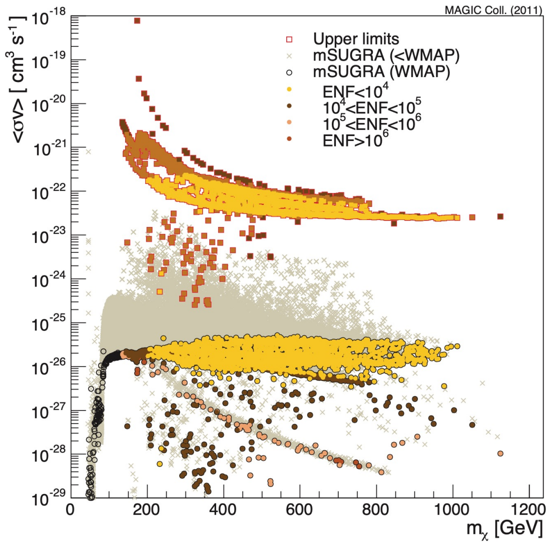
$$\langle\sigma_{\rm ann} v\rangle^{UL} = \frac{8\,\pi\, m_\chi^2\, \Phi^{UL}(> E_0)}{\widetilde{J}(\Delta\Omega)\; \int_{E_0}^{m_\chi} \frac{dN_\gamma}{dE} dE}$$

Model-agnostic limits

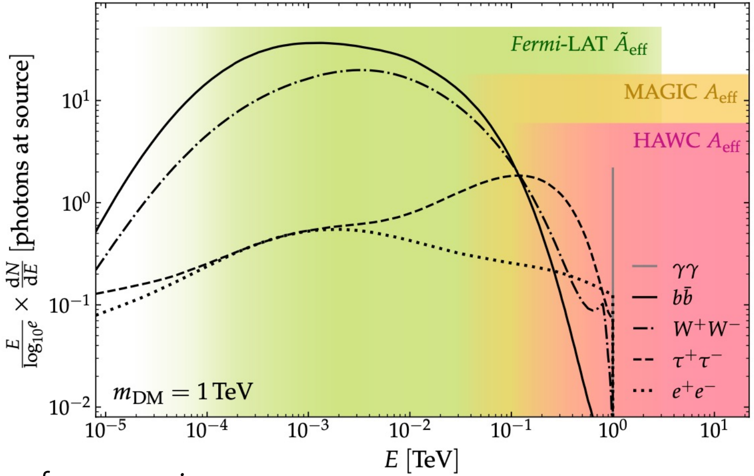


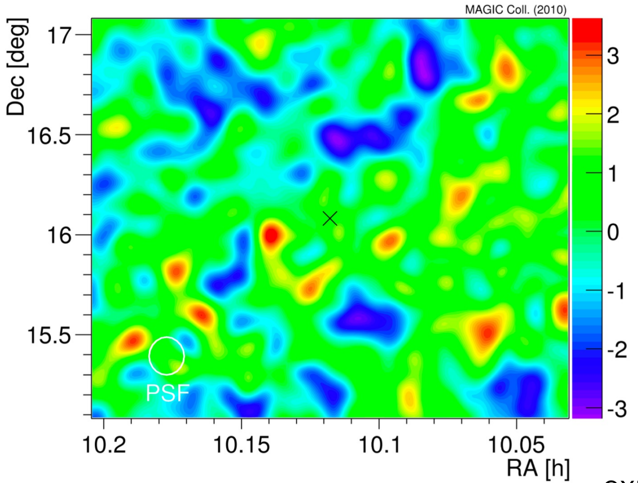
Segue 1 – MAGIC I – JCAP 1106:035,2011

Model-dependent limits



Not all events are equally informative → assign relevance based on event weights





(Rec.) Energy for event *i*

(Rec.) Distance to target for event *i*

$$w_i = w(\nu_i, E_i, \theta_i)$$

Astro. target for event *i*

Weight for event *i*

Test statistic

$$T = \sum_i w_i$$

Likelihood ratio method

Optimized weight

$$w = \log\left[1 + \frac{s}{b}\right]$$

expected # signal events

$$s(\nu, E, \theta)$$

$$b(\nu, E, \theta)$$

expected # bkg events

Galaxies 2022, 10, 92 JCAP 1106:035, 2011 PRD 95, 082001 (2017)

Event-weighting method (IACTs)

(Rec.) Energy for event *i*

(Rec.) Distance to target for event *i*

$$w_i = w(\nu_i, E_i, \theta_i)$$

Astro. target for event *i*

Weight for event *i*

Test statistic

$$T = \sum_i w_i$$

Likelihood ratio method

Optimized weight

$$w = \log\left[1 + \frac{s}{b}\right]$$

expected # signal events

$$s(\nu, E, \theta)$$

$$b(\nu, E, \theta)$$

expected # bkg events

Estimation of *s*

$$s(\nu, E, \theta) = \frac{dN(\nu, E, \theta)}{dEd\Omega} dE 2\pi \sin(\theta) d\theta$$

DM spectrum

$$\frac{dN(E, \hat{\mathbf{n}})}{dEd\Omega} = \int_{E_t}\int_{\Omega_t} dE_t d\Omega_t \frac{dF(E_t, \hat{\mathbf{n}}_t)}{dE_t d\Omega_t} R(E, \hat{\mathbf{n}} | E_t, \hat{\mathbf{n}}_t)$$

Obs. time

Angular res.

Energy res.

$$R(E, \hat{\mathbf{n}} | E_t, \hat{\mathbf{n}}_t) = \sum_{\text{runs}} \tau A_{\text{eff}}(E_t) \text{PSF}(\hat{\mathbf{n}} | E_t, \hat{\mathbf{n}}_t) D(E | E_t)$$

Instrument response

Effective area

Galaxies 2022, 10, 92 JCAP 1106:035, 2011 PRD 95, 082001 (2017)

(Rec.) Energy for event *i*

(Rec.) Distance to target for event *i*

$$w_i = w(\nu_i, E_i, \theta_i)$$

Astro. target for event *i*

Weight for event *i*

Test statistic

$$T = \sum_i w_i$$

Likelihood ratio method

Optimized weight

$$w = \log\left[1 + \frac{s}{b}\right]$$

expected # signal events

$$s(\nu, E, \theta)$$

$$b(\nu, E, \theta)$$

expected # bkg events

Estimation of *s*

$$s(\nu, E, \theta) = \frac{dN(\nu, E, \theta)}{dE d\Omega} dE 2\pi \sin(\theta) d\theta$$

DM spectrum

$$\frac{dN(E, \hat{\mathbf{n}})}{dE d\Omega} = \int_{E_t} \int_{\Omega_t} dE_t d\Omega_t \frac{dF(E_t, \hat{\mathbf{n}}_t)}{dE_t d\Omega_t} R(E, \hat{\mathbf{n}} | E_t, \hat{\mathbf{n}}_t)$$

Estimation of *b*

$$b(\nu, E, \theta)$$

empirical energy distribution of the OFF events
+ assuming isotropy within the ON region

Obs. time

Angular res.

Energy res.

$$R(E, \hat{\mathbf{n}} | E_t, \hat{\mathbf{n}}_t) = \sum_{\text{runs}} \tau A_{\text{eff}}(E_t) \text{PSF}(\hat{\mathbf{n}} | E_t, \hat{\mathbf{n}}_t) D(E | E_t)$$

Instrument response

Effective area

Galaxies 2022, 10, 92 JCAP 1106:035, 2011 PRD 95, 082001 (2017)

Computation of upper limits

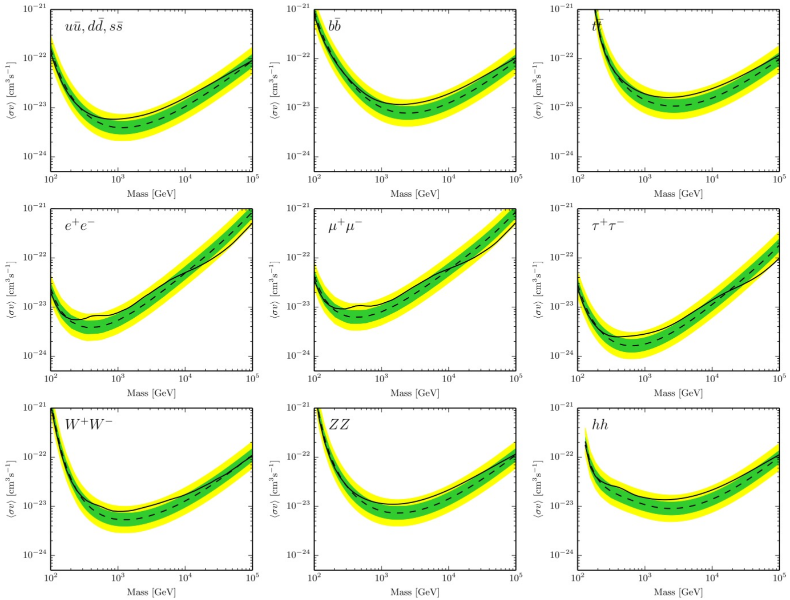
Hypothesis test is performed at every value of $<\sigma v>$, for each DM mass and channel:

$$P(T < T_{obs}) < \alpha \rightarrow \text{hypothesis rejected at } 1-\alpha \text{ confidence level} \rightarrow <\sigma v>^{UL}$$

bkg only

VERITAS

Dwarf	Zenith [deg]	Azimuth [deg]	Exposure [hours]	Energy Range [GeV]
Segue 1	15–35	100–260	92.0	80–50000
Draco	25–40	320–40	49.8	120–70000
Ursa Minor	35–45	340–30	60.4	160–93000
Boötes 1	15–30	120–249	14.0	100–41000
Willman 1	20–30	340–40	13.6	100–43000



PRD 95, 082001 (2017)

Full likelihood method

Profile likelihood for $N_{targets}$ and $N_{instruments}$

Dataset

Value maximizing joint likelihood for a given <σv>

$$\lambda_P(\langle\sigma v\rangle \,|\, \boldsymbol{\mathcal{D}}) = \frac{\mathcal{L}(\langle\sigma v\rangle; \hat{\hat{\boldsymbol{\nu}}} \,|\, \boldsymbol{\mathcal{D}})}{\mathcal{L}(\widehat{\langle\sigma v\rangle}; \hat{\boldsymbol{\nu}} \,|\, \boldsymbol{\mathcal{D}})}$$

Values maximizing joint likelihood

Nuisance parameters

Uncertainty on J_{obs}

$$\mathcal{L}(\langle\sigma v\rangle; \boldsymbol{\nu} \,|\, \boldsymbol{\mathcal{D}}) = \prod_{i=1}^{N_{\mathrm{target}}} \mathcal{L}_i(\langle\sigma v\rangle; J_i, \boldsymbol{\mu}_i \,|\, \boldsymbol{\mathcal{D}}_i) \cdot \mathcal{J}(J_i \,|\, J_{\mathrm{obs},i}, \sigma_i)$$

Likelihood for J

Observed J

$$\mathcal{L}_i(\langle\sigma v\rangle; J_i, \boldsymbol{\mu}_i \,|\, \boldsymbol{\mathcal{D}}_i) = \prod_{j=1}^{N_{\mathrm{instrument}}} \mathcal{L}_{ij}(\langle\sigma v\rangle; J_i, \boldsymbol{\mu}_{ij} \,|\, \boldsymbol{\mathcal{D}}_{ij})$$

$$\mathcal{J}(J_i \,|\, J_{\mathrm{obs,i}}, \sigma_i) = \frac{1}{\ln(10) J_{\mathrm{obs,i}} \sqrt{2\pi}\sigma_i} \times e^{-\left(\log_{10}(J_i) - \log_{10}(J_{\mathrm{obs,i}})\right)^2 / 2\sigma_i^2}$$

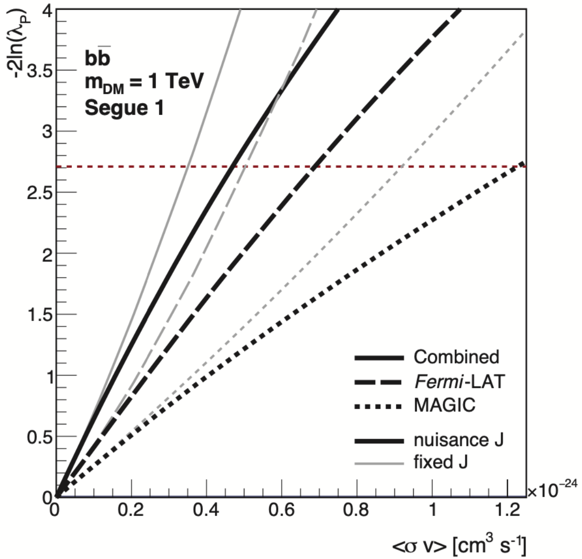
Likelihood for J

JCAP02(2016)039

Full likelihood method

Example: MAGIC (Segue 1) + Fermi-LAT (15 dSph)

$$-2\ln\lambda_P(\langle\sigma v\rangle_{2.71}\,|\,\boldsymbol{\mathcal{D}}) = 2.71$$



Fermi-LAT $(j \equiv F)$

$$\mathcal{L}_{iF}(\langle\sigma v\rangle; J_i, \hat{\boldsymbol{\mu}}_{iF}\,|\,\boldsymbol{\mathcal{D}}_{iF}) = \prod_{k=1}^{N_{\mathrm{E-bins}}} \mathcal{L}_{iFk}\left(\overline{E\Phi}_k(\langle\sigma v\rangle, J_i)\right)$$

$$\overline{E\Phi}_k(\langle\sigma v\rangle, J_i) = \int_{E_{\min,k}}^{E_{\max,k}} dE\, E\, \frac{d\Phi}{dE}(\langle\sigma v\rangle, J_i)$$

MAGIC $(j \equiv M)$

Number of different datasets for Segue 1 (→ N)

$$\mathcal{L}_{iM}(\langle\sigma v\rangle; J_i, \boldsymbol{\mu}_{iM}\,|\,\boldsymbol{\mathcal{D}}_{iM}) = \prod_{k=1}^{N} \mathcal{L}_{iMk}(\langle\sigma v\rangle; J_i, \boldsymbol{\mu}_{iMk}\,|\,\boldsymbol{\mathcal{D}}_{iMk})$$

Expected #bkg events; ON/OFF ratio

$$\mathcal{L}(\langle\sigma v\rangle; J, \boldsymbol{\mu}\,|\,\boldsymbol{\mathcal{D}}) = \frac{(g + b/\tau)^{N_{\mathrm{ON}}}}{N_{\mathrm{ON}}!} e^{-(g+b/\tau)} \frac{b^{N_{\mathrm{OFF}}}}{N_{\mathrm{OFF}}!} e^{-b} \prod_{l=1}^{N_{\mathrm{ON}}} f(g; b, \tau\,|\,E'_l) \prod_{m=1}^{N_{\mathrm{OFF}}} h(E'_m)$$

Expected #signal events with E′

PDF measured ON

PDF measured OFF

$$g(\langle\sigma v\rangle, J) = T_{\mathrm{obs}} \int_{E'_{\min}}^{E'_{\max}} dE' \int_0^{\infty} dE \frac{d\Phi}{dE}(\langle\sigma v\rangle, J)\, A(E)\, G(E; E')$$

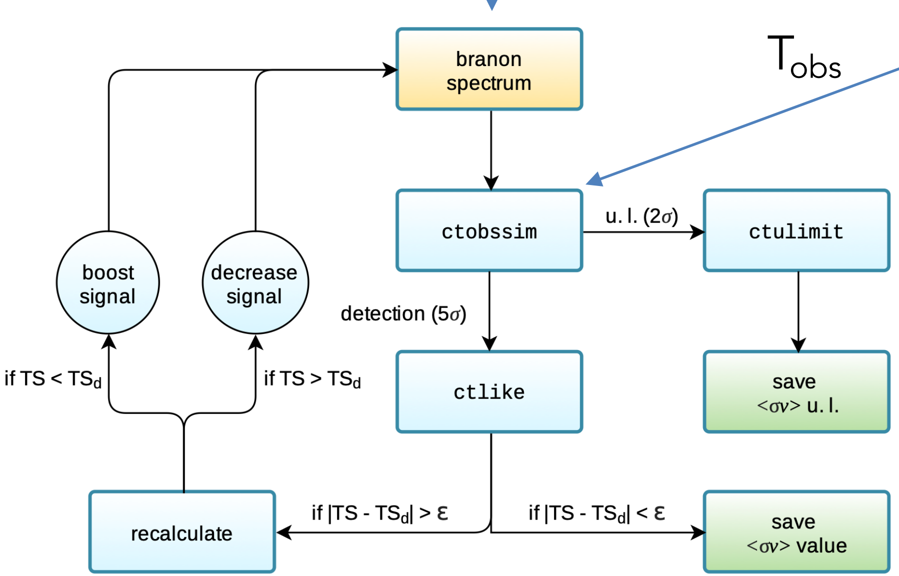
$$f(g; b, \tau\,|\,E') = \frac{\frac{b}{\tau} h(E') + g\, p(E')}{\frac{b}{\tau} + g}$$

$$p(E') = \frac{T_{\mathrm{obs}} \int_0^{\infty} dE \frac{d\Phi}{dE}(\langle\sigma v\rangle, J)\, A(E)\, G(E; E')}{g}$$

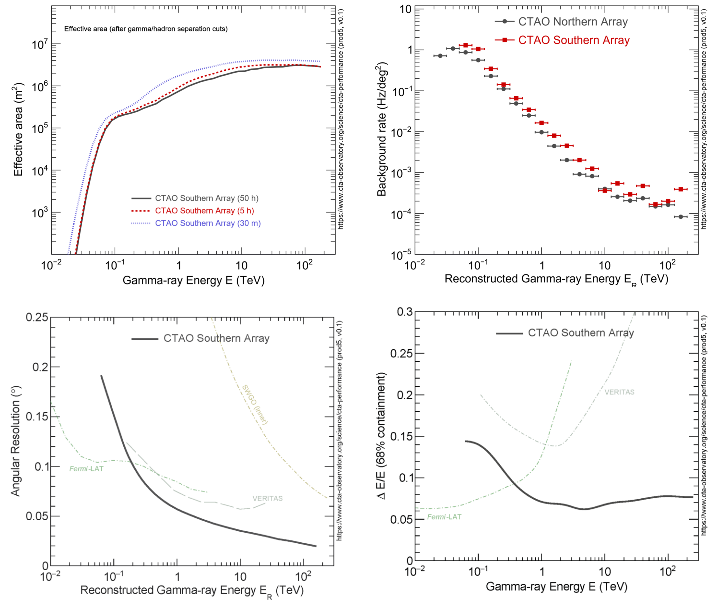
JCAP02(2016)039

Detection prospects

$$\frac{\Phi_{\rm ann}}{dE_\gamma}(E_\gamma,\Delta\Omega) = \frac{\langle\sigma v\rangle}{8\pi\, m_{\rm DM}^2}\,\frac{dN}{dE}\int_0^{\Delta\Omega}\int_{\rm l.o.s.}\rho(l,\Omega)^2\, dl\, d\Omega$$



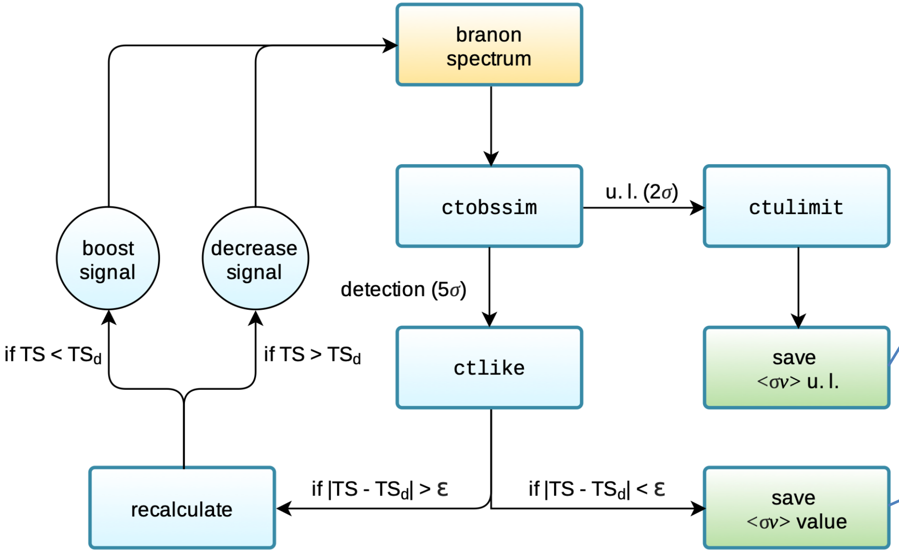
Instrument response functions

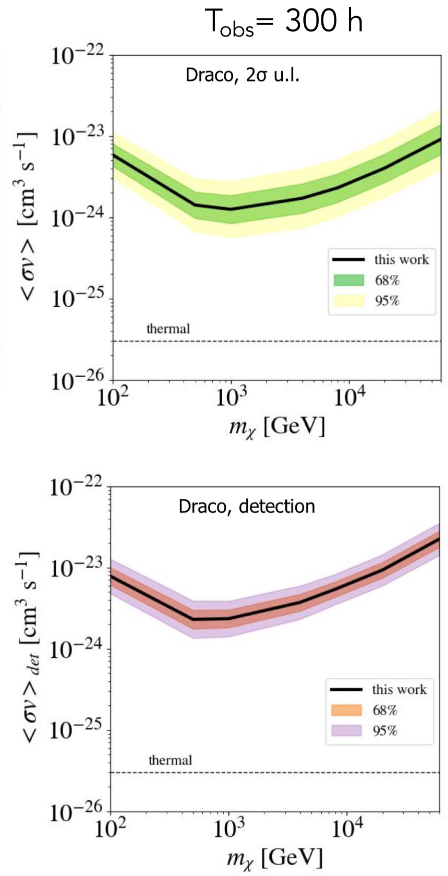


cta cherenkov telescope array — the observatory for ground-based gamma-ray astronomy

JCAP10(2020)041

Detection prospects





JCAP10(2020)041

Proposal 1 for hands-on session

Analyze Fermi-LAT data on Draco dSph and obtain $< \sigma v >^{UL}$

You will be using Fermipy and this tutorial(*):

https://github.com/fermiPy/fermipy-extra/blob/master/notebooks/draco.ipynb

Exercises:

- Compute $< \sigma v >^{UL}$ vs DM mass for different annihilation channels
- Increase exposure from 6 years to 14 years

(*) For recent installations of Fermipy one should update gll_iem_v06.fits to gll_iem_v07.fits in the config.yaml

Compute photon yield for branon DM using PPPC 4 DM ID:

Photon yields per annihilation channel can be found here:
http://web.mit.edu/lns/research/CascadeSpectra.tar.gz
Read `CascadeSpectraExample.py` to learn how to use the Python interface

Branching ratios can be computed following equations 2.2-2.4 in JCAP05(2022)005

Then, one can compute the model-dependent photon yield per annihilation like:

$$\frac{dN}{dE} = \sum_i B_i \left.\frac{dN}{dE}\right|_i$$

Some examples of the photon yield from branon annihilation can be found in Fig. 1 in JCAP05(2022)005

Proposal 3 for hands-on session

Compute astrophysical factors using pyCLUMPY:

The goal would be to compute the astrophysical factor of a user-defined halo and test how it depends on the integration angle

1.- Install CLUMPY: https://clumpy.gitlab.io/CLUMPY/v3.1.1/install.html

2.- Load Tutorial.ipynb in CLUMPY/python_helperscripts/pyClumpy_Tutorial

3.- Import necessary packages and go to Haloes section

4.- Run Haloes section picking your halo preformatted example from list_generic.txt

5.- Using the code in J-Factors (1D) subsection compute J factors and fluxes for an angle of 0.5° (typical for Fermi-LAT) and 0.1° (typical for IACTs). Compare the results

Further readings

TASI Lectures on the Particle Physics and Astrophysics of Dark Matter
https://arxiv.org/abs/2303.02169

TeV Dark Matter Searches in the Extragalactic Gamma-ray Sky
https://doi.org/10.3390/galaxies10050092

Les Houches Lectures on Indirect Detection of Dark Matter
https://arxiv.org/abs/2109.02696

TASI Lectures on Indirect Searches For Dark Matter
https://arxiv.org/abs/1812.02029

Particle Dark Matter: Observations, Models, and Searches
Bertone et al., Cambridge University Press (2010)

The Review of Particle Physics (2023)
https://pdg.lbl.gov

Credit: NASA, HST, Webb

Further readings: analysis methods

Searches for dark matter annihilation signatures in the Segue 1 satellite galaxy with the MAGIC-I telescope
https://doi.org/10.1088/1475-7516/2011/06/035

Optimized dark matter searches in deep observations of Segue 1 with MAGIC
https://doi.org/10.1088/1475-7516/2014/02/008

Limits to dark matter annihilation cross-section from a combined analysis of MAGIC and Fermi-LAT observations of dwarf satellite galaxies
https://doi.org/10.1088/1475-7516/2016/02/039

Comprehensive search for dark matter annihilation in dwarf galaxies
https://doi.org/10.1103/PhysRevD.91.083535

Dark matter constraints from a joint analysis of dwarf Spheroidal galaxy observations with VERITAS
https://doi.org/10.1103/PhysRevD.95.082001

Fermi Large Area Telescope Fourth Source Catalog (Appendix B)
https://doi.org/10.3847/1538-4365/ab6bcb

Credit: NASA, HST, Webb

Useful tools

Clumpy (Astrophysical factor)
https://clumpy.gitlab.io/CLUMPY

PPPC 4 DM (Particle Physics factor)
http://www.marcocirelli.net/PPPC4DMID.html

gLike (combined likelihood analysis)
https://github.com/javierrico/gLike

LlkCom (combined likelihood analysis)
https://github.com/TjarkMiener/likelihood_combiner

Credit: NASA, HST, Webb