Hands-on session:
How to search for Dark Matter with CTA?

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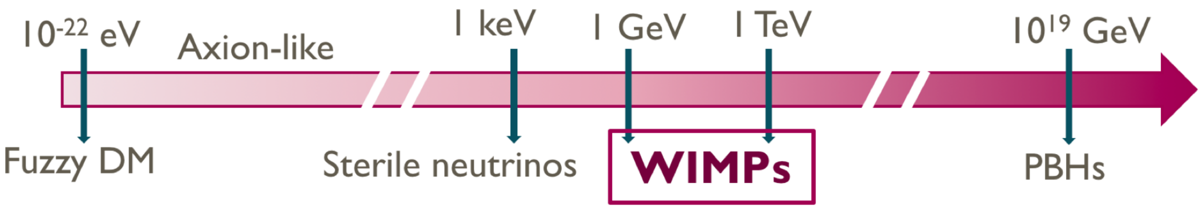
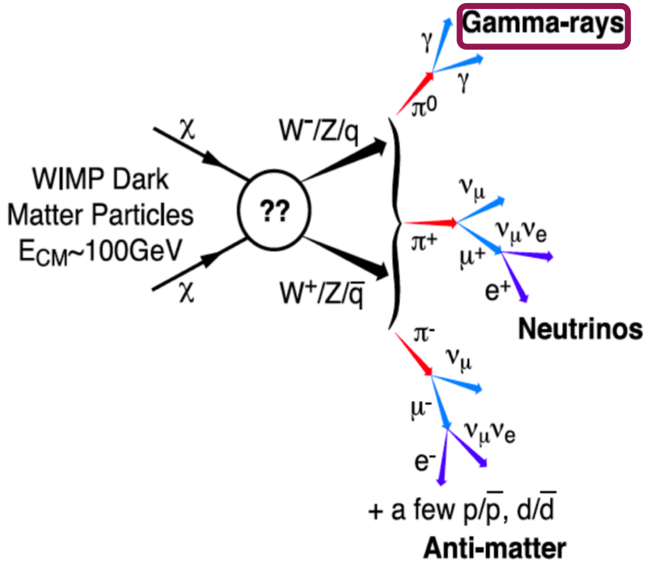
DARK MATTER THROUGH GAMMA-RAYS

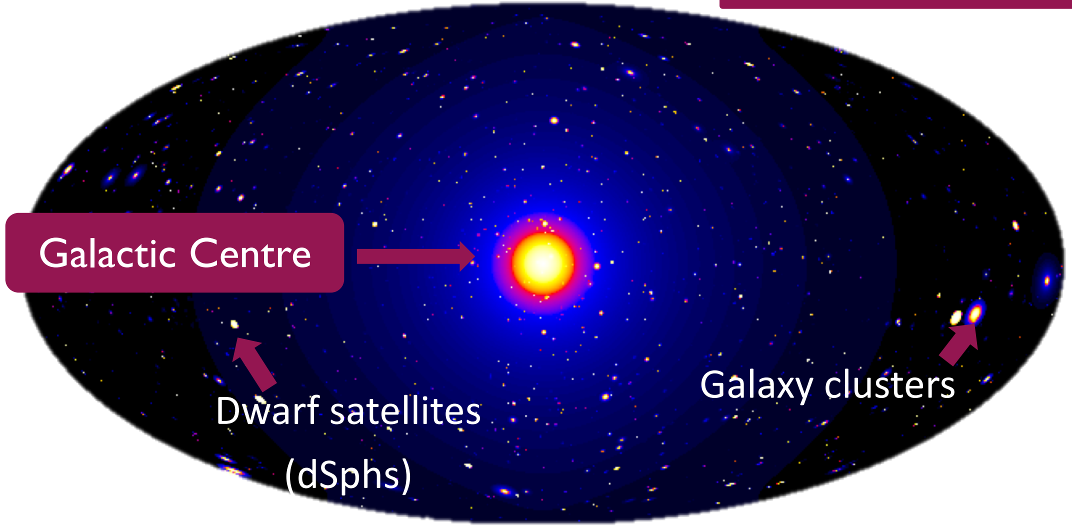
- Different DM candidates:





This γ-ray emission allows to perform Indirect DM Searches with current telescopes

- DM distribution in the Universe **ΛCDM Cosmology**



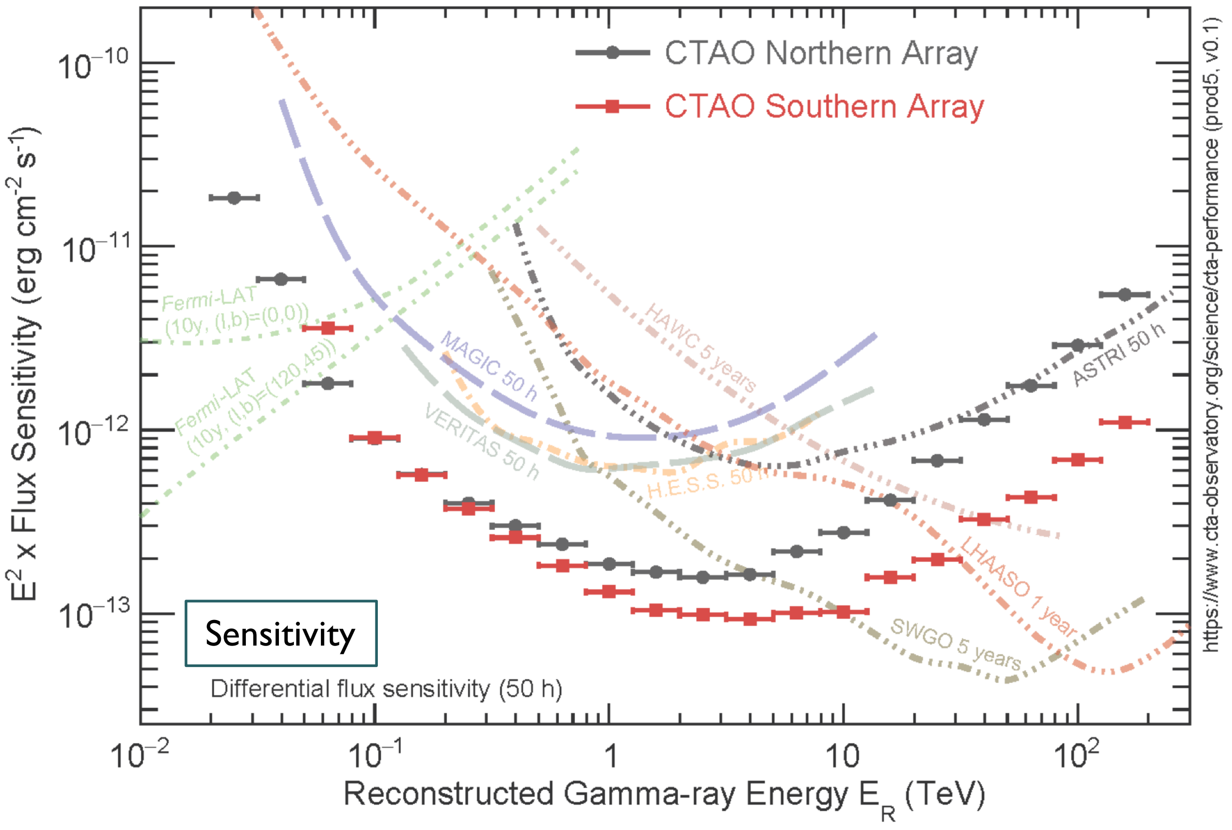
Pieri+09

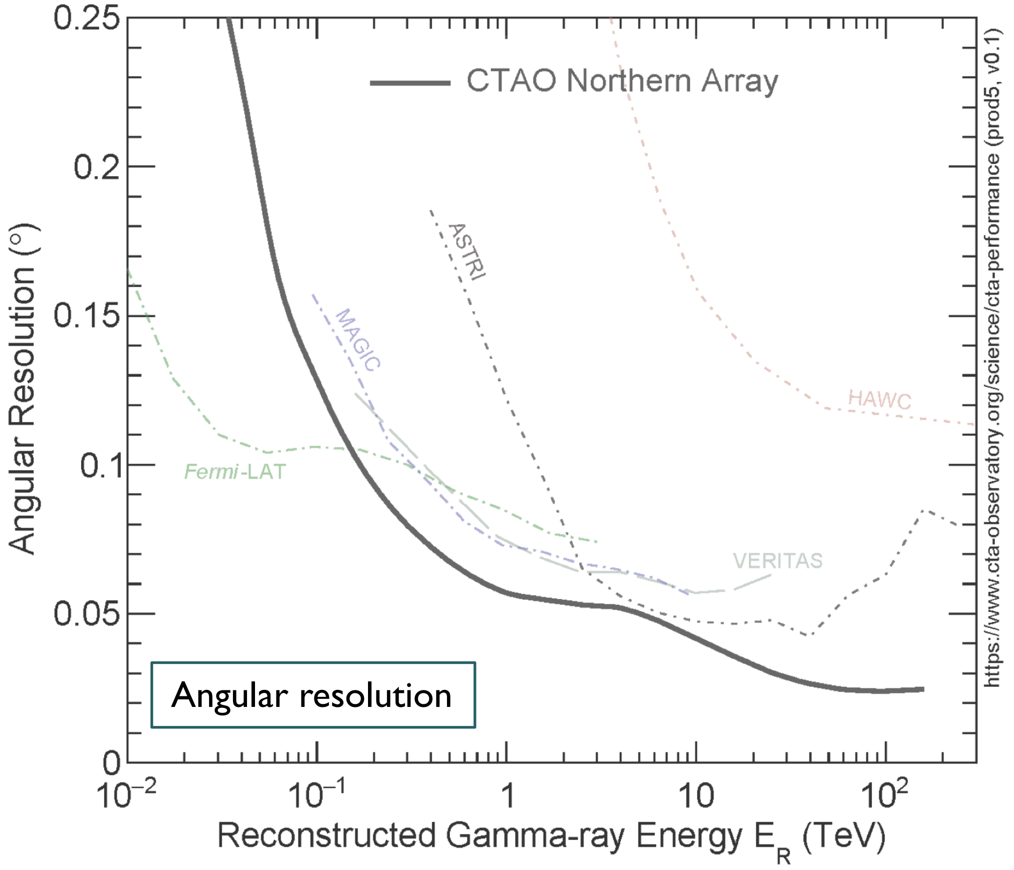
- Which are the optimal targets?
  - High DM density ($\phi_{DM} \propto \rho_{DM}^2$ for annihilation, $\phi_{DM} \propto \rho_{DM}$ for decay)
  - Massive nearby objects ($\phi_{DM} \propto M/d_{Earth}^2$)
  - Low astrophysical background

THE CHERENKOV TELESCOPE ARRAY OBSERVATORY

Preliminary Performance Capabilities

https://www.cta-observatory.org/





CTA has superb capabilities for DM gamma-ray searches

SEARCHING FOR DM WITH CTA

1. Create a simulated observation of the galactic centre with DM signal

2. Analyze datasets provided
   1. Analyze first dataset
   2. Analyze second dataset

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SIMULATING CTA DM OBSERVATION

Basic input information to create **ANY** simulated data:

- Livetime
- Pointing
- Region of Interest (ROI)
- Energy range and/or binning
- Instrument Response Functions (IRFs)
- Model

- Background model: from IRFs
- Source model: can comprehend several sources, each of them has
    - Spectral model
    - Spatial model
    - Time model

SIMULATING CTA DM OBSERVATION

Basic input information to create **OUR** simulated data:

- Livetime: 520 h
- Pointing: galactic centre
- Region of Interest (ROI): 20 deg x 20 deg
- Energy range and/or binning: 10 bins from 20 GeV to 150 TeV
- Instrument Response Functions (IRFs): Prod5-South-20deg-AverageAz-14MSTs37SSTs.180000s
- Model

SIMULATING CTA DM OBSERVATION

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- Background model: from IRFs
- Source model: only one DM source
    - Spectral model: WIMP annihilation
    - Spatial model: Template emission model for the galactic centre
    - ~~Time model~~

SIMULATING CTA DM OBSERVATION

Basic input information to create **OUR** simulated data:

- Model: Annihilation of Weakly Interactive Massive Particles (WIMPs)

$$\frac{d\Phi_\gamma}{dE}(E, l.o.s, \Delta\Omega) = scale \times \boxed{J(l.o.s, \Delta\Omega)} \times \frac{\langle\sigma v\rangle}{4\pi\, m_{\rm DM}^2} \boxed{\sum_i \mathrm{BR}_i \frac{dN_\gamma^{\rm i}}{dE}(E)}$$

Spatial model

- Assumes ΛDCM model
- Encodes how the DM is distributed in the object
- We can use different $\rho_{\rm DM}$ parametrizations
- Ends acting as a multiplicative factor to the overall flux

Spectral model

- Encodes the spectrum of the emission
- We can use the tables computed by *[Cirelli+11]*

  http://www.marcocirelli.net/PPPC4DMID.html

SIMULATING CTA DM OBSERVATION

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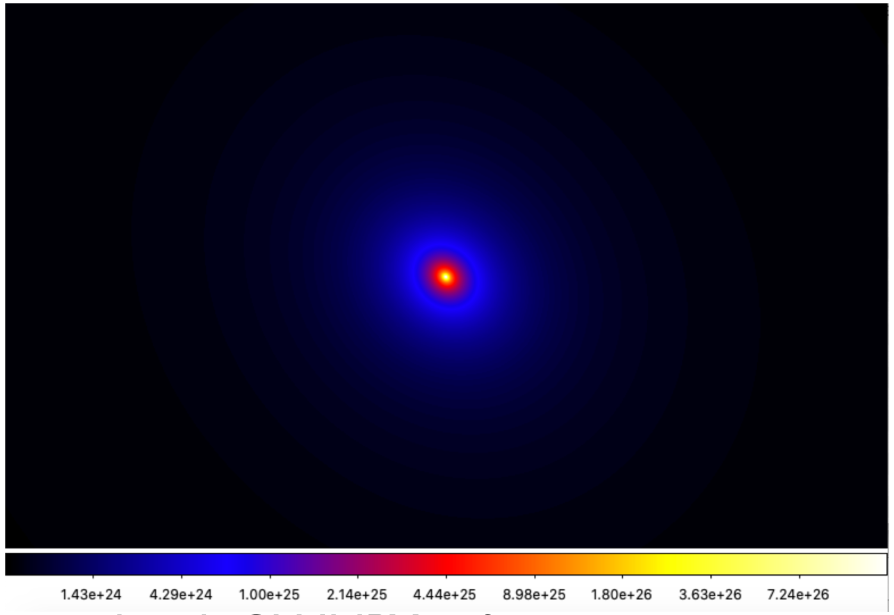
Spatial model

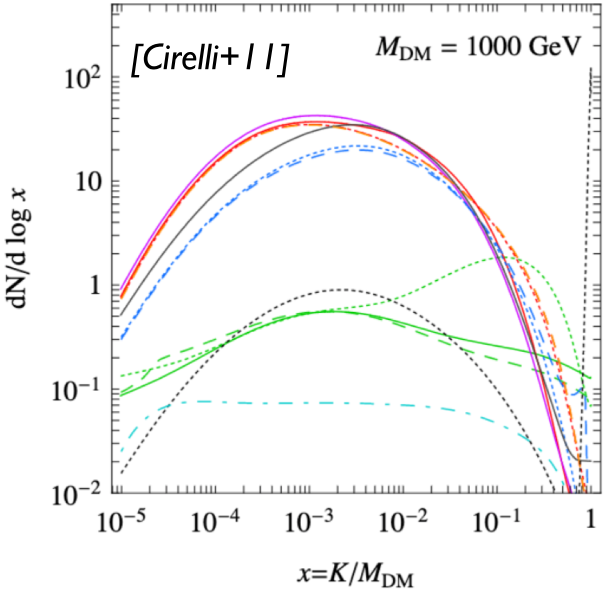


Created with CLUMPY software

[Charbonnier+12, Bonnivard+15, Hütten+18]

https://clumpy.gitlab.io/CLUMPY/

Spectral model



Gamma-ray emission spectrum from:

- WIMP annihilation
- m_{DM} = 5 TeV
- $b\bar{b}$ channel

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ANALYZE CTA DATA SEARCHING FOR DM

- Use maximum likelihood approach with a 3D fitting: 2 dimensions in space and 1 in energy

$$\ln\mathcal{L}(\vec{\theta}|D) = \sum_i M_i(\vec{\theta}) - d_i \ln(M_i(\vec{\theta}))$$

Cash statistics *[Cash 79]*

For the DM model $\rightarrow$ $\vec{\theta} \equiv (scale, norm_{bkg}, tilt_{bkg})$

- In the fit, we obtain as best values the ones maximizing the likelihood function
- To test if a model is better than other to fit a dataset we use the likelihood ratio test (*TS*):

$$TS = 2 \times \frac{\ln\mathcal{L}(H_1)}{\ln\mathcal{L}(H_0)}$$

- If H_0 is the null-hypothesis (only background), we determine a detection when

$\boxed{TS \geq 25}$ $\longrightarrow$ $\sim 5\sigma$ detection *[Li&Ma 83]*

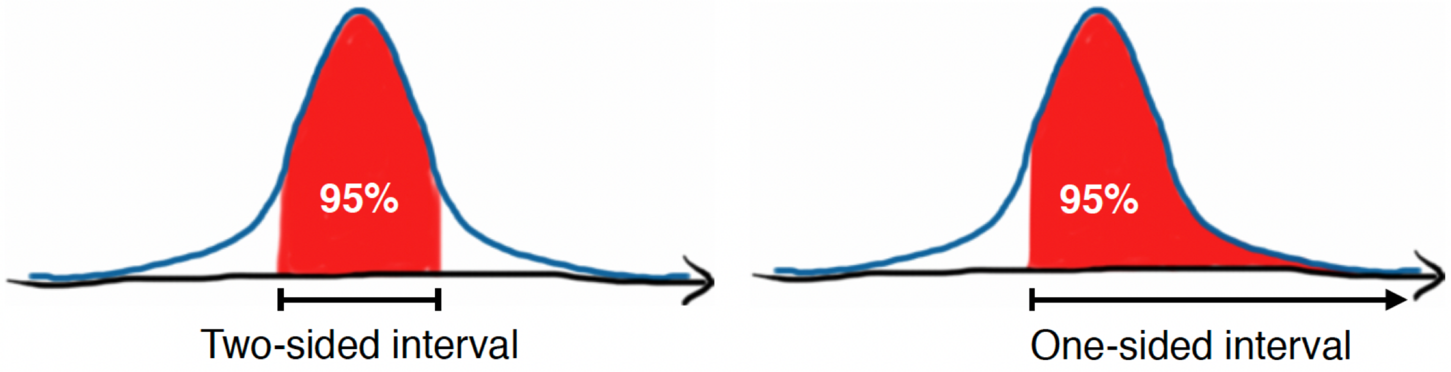
ANALYZE CTA DATA SEARCHING FOR DM

- We have not found a signal… Then let's put constraints!
- The likelihood has several dependencies but we are only interested in *scale*:

Likelihood profile

Project the likelihood to the parameter of interest

- The limits can be one-sided or two-sided:



[picture by S. Fegan for Fermi-LAT school]

- This limits read as: the upper/lower value most probable to get by 95% of the times (if *TS* is distributed following a χ^2)
  - For the one-sided distribution → $\boxed{95\,\%\mathrm{C.L} \rightarrow TS = 2.71}$ *[Rolke+05]*

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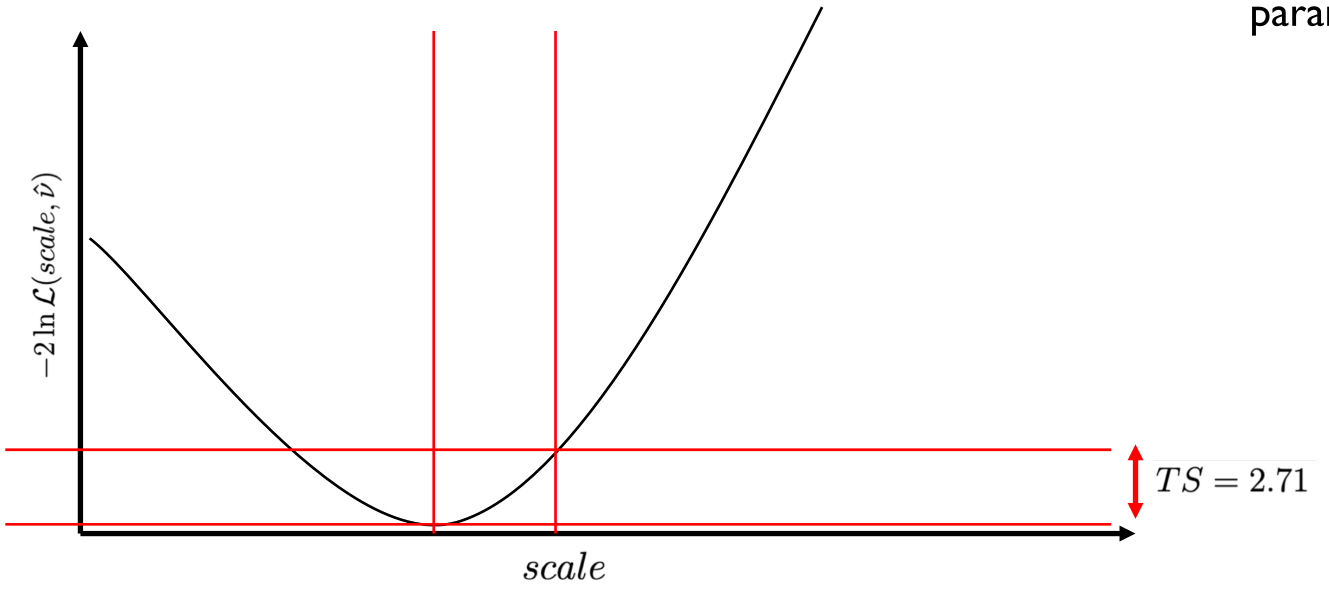
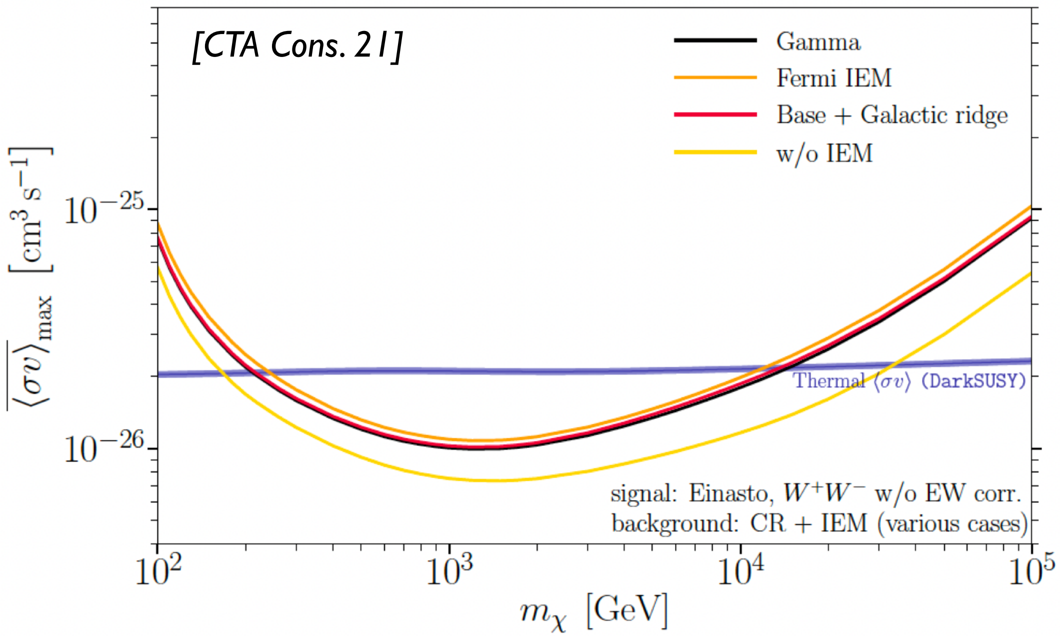


- We need to solve: $-2\ln\frac{\mathcal{L}(scale,\hat{\nu})}{\mathcal{L}(scale_{best},\hat{\nu})} - 2.71 = 0$ *[Rolke+05]*

ANALYZE CTA DATA SEARCHING FOR DM

- Okey but, these are not the cool plots for constraints!



- We have fitted our dataset to one channel and one mass. We will need to loop over the mass range of interest and the available channels to get these lines.

- On top of that, we have only used one Poisson realization. To have statistically meaningful predictions, we need to average over O(300) realizations.

15 mass values x 3 channels x 300 realizations = 13500 fits!

ANALYZE CTA DATA SEARCHING FOR DM

- Most DM projects within CTA with same needs in terms of analysis tools and statistical treatment

Common set of tools

- Unified definitions, methodology
- Avoids repetition of same coding
- Allows easy comparison of results.
- Everyone can potentially contribute

- Creation & coordination of *DMTools Task Force* within CTA
- Gammapy software development

Since v-0.8 to v-1.0
(15 versions)

- Gammapy embedded functions:
  - DarkMatterAnnihilationSpectralModel
- GitHub repository:
  - Gammapy-DMTools
  https://github.com/peroju/dmtools_gammapy
- Gammapy coding sprints

ANALYZE CTA DATA SEARCHING FOR DM

ON-OFF/Wobble Analysis

Standard for IACTs

Point-like

- Lowest complexity
- Most constraining results

Extended

- More complex and realistic than point-like approach
- Benefits from CTA large FoV and angular resolution

Template fitting

State-of-the-art pipeline

Minuit

- Already embedded in Gammapy
- Historically used fitter (iminuit) and very well documented (stability)

MCMC

- Flexible definition of likelihood and priors
- Easy analysis of correlations

ANALYZE CTA DATA SEARCHING FOR DM

Basic functioning of the pipelines

Input DM model
- Spectral (based on *Cirelli+11*)
- Spatial (point-like, analytical, FITS files)

+

Combine with observation set-up
- IRFs
- Observation time
- Backgrounds

→

- Simulated Observation (Poisson realization)
- Observation

Enter the DM fit loop

1. For each realization, consider a list of channels and for each, a list of DM masses
2. Perform a likelihood fit to this specific model
3. Check $TS(H_{null}) \geq 25$
4. Compute $<\sigma v>$ upper limits with $TS(\mathrm{H}_{\text{best-fit}}) = 2.71$, bounded likelihood implemented