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

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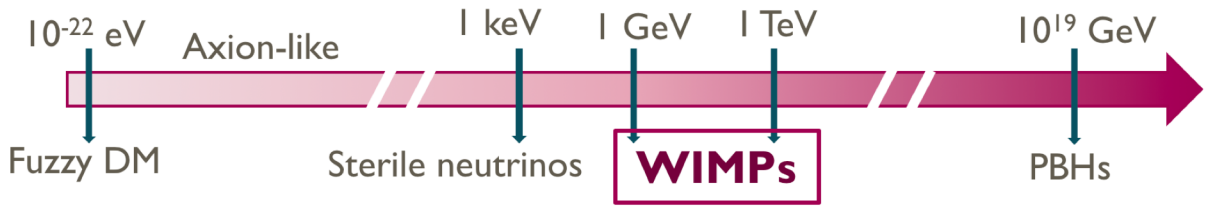
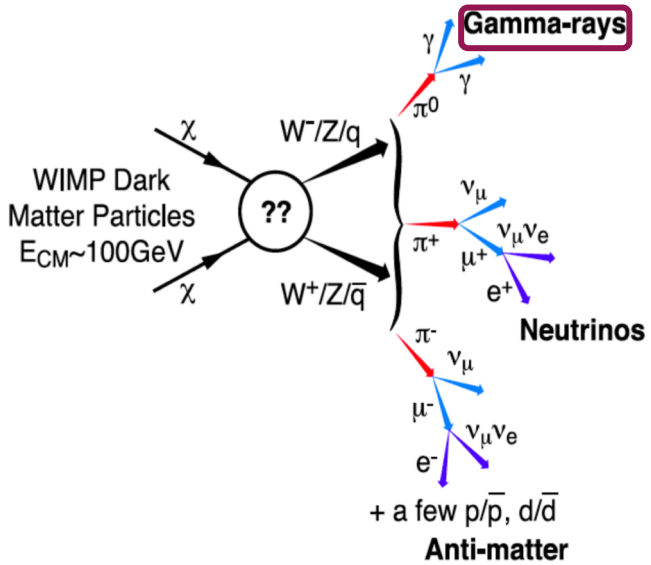
DARK MATTER THROUGH GAMMA-RAYS

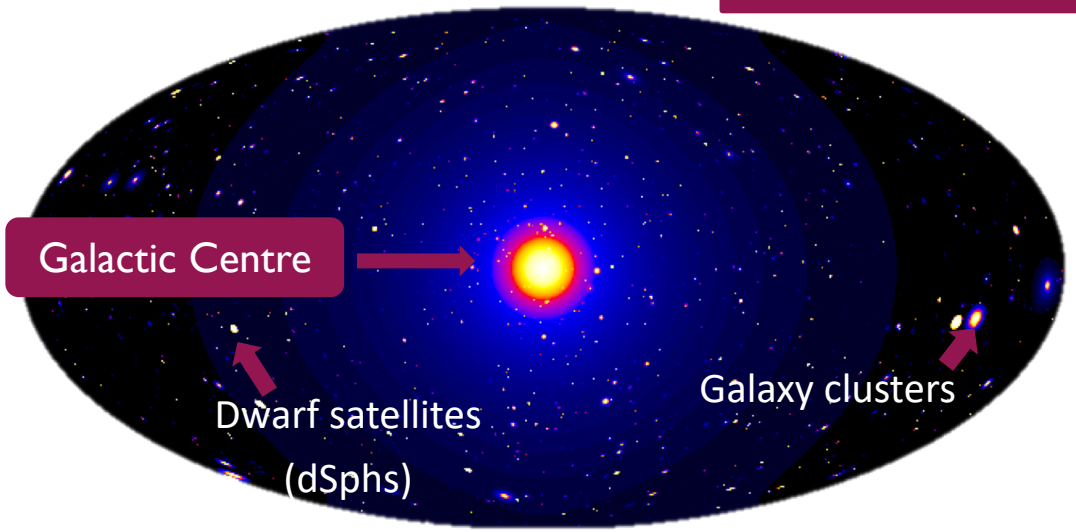
- Different DM candidates:





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

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



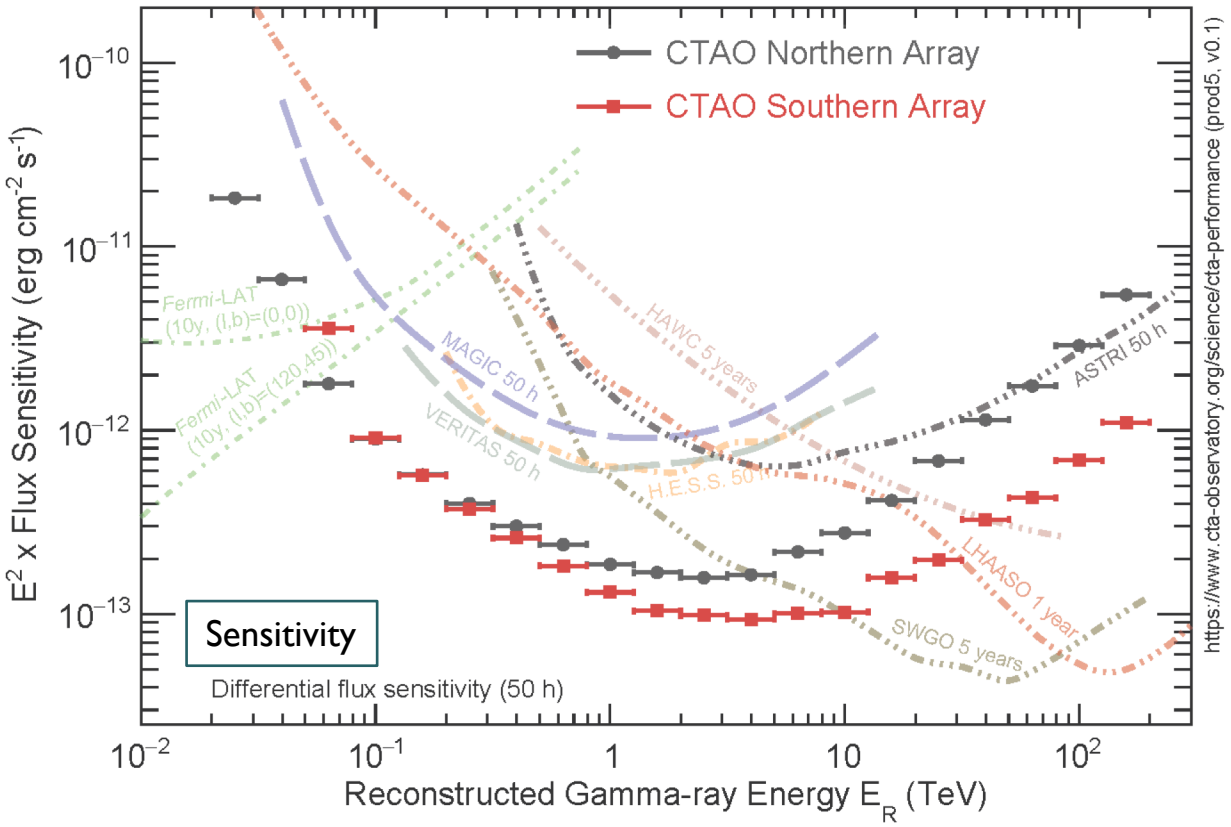
- Which are the optimal targets?
  - High DM density ($\phi_{DM} \propto \rho_{DM}^2$ for annihilation, $\phi_{DM} \propto \rho_{DM}$ for decay)
  - Massive nearby objects ($\phi_{DM} \propto M/d_{Earth}^2$)
  - Low astrophysical background

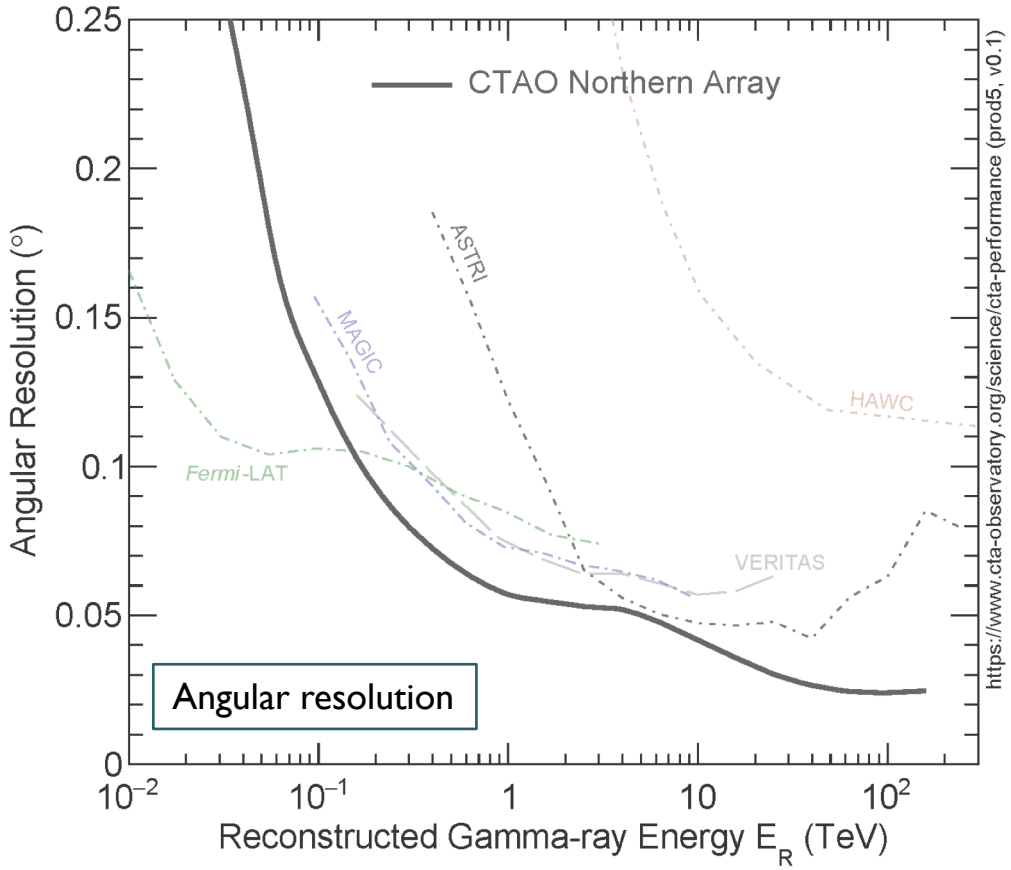
Pieri+09

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

SEARCHING FOR DM WITH CTA

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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

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
  - 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)

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

Spatial model

Spectral 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

- Encodes the spectrum of the emission
- We can use the tables computed by *[Cirelli+11]*
  http://www.marcocirelli.net/PPPC4DMID.html

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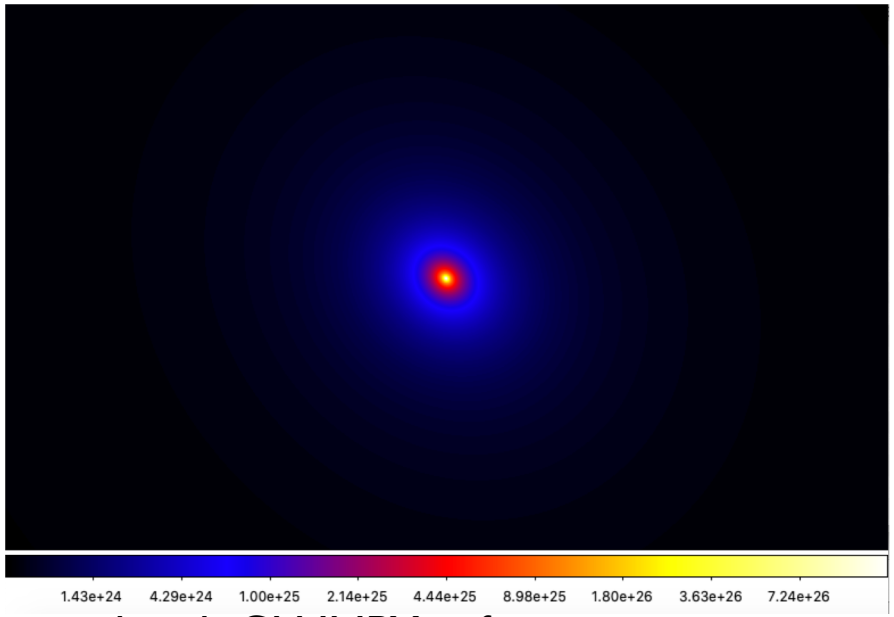
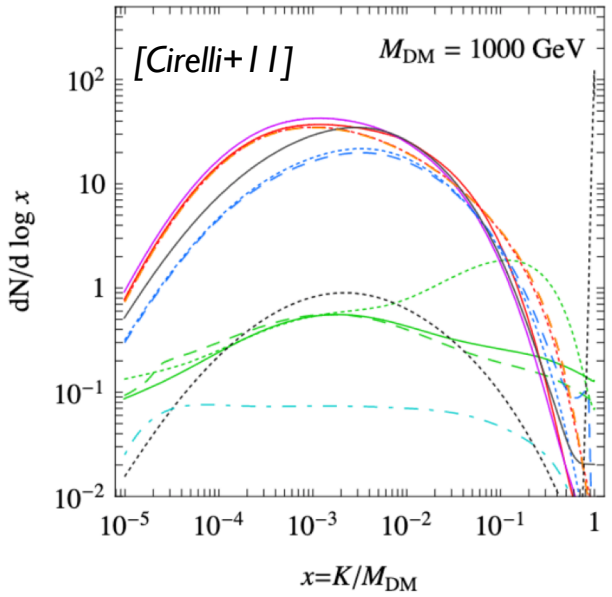


Created with CLUMPY software

[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 → $\vec{\theta} \equiv (scale, norm_{bkg}, tilt_{bkg})$

- 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

$$\boxed{TS \geq 25} \longrightarrow \sim 5\sigma \text{ detection}$$

[Li&Ma 83]

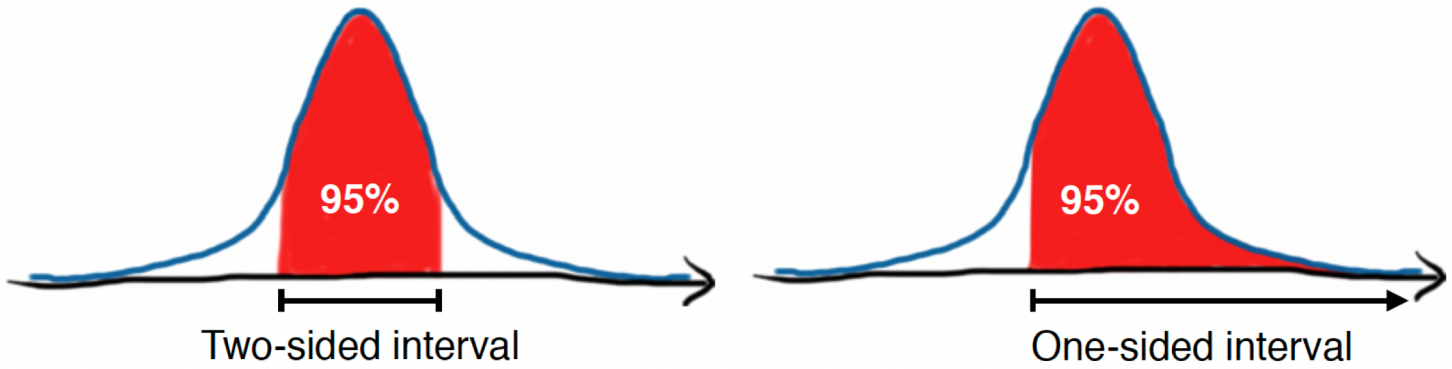
ANALYZE CTA DATA SEARCHING FOR DM

- 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 → $95\,\%\mathrm{C.L} \rightarrow TS = 2.71$ *[Rolke+05]*

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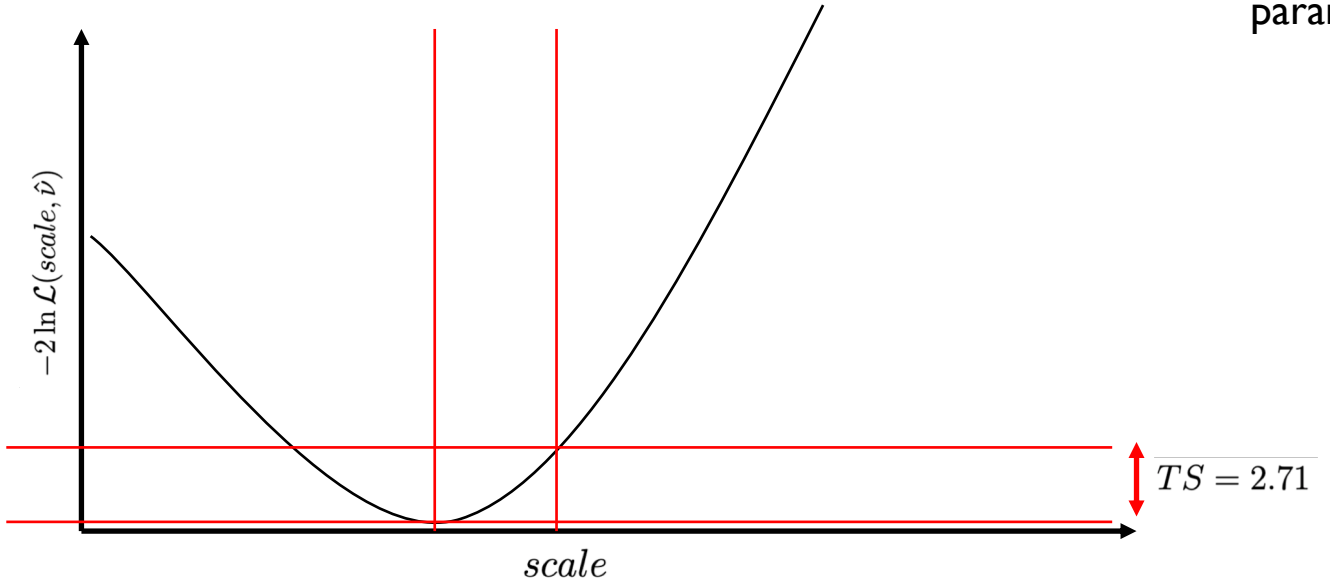

- We need to solve: $-2\ln\dfrac{\mathcal{L}(scale,\hat{\nu})}{\mathcal{L}(scale_{best},\hat{\nu})} - 2.71 = 0$ *[Rolke+05]*