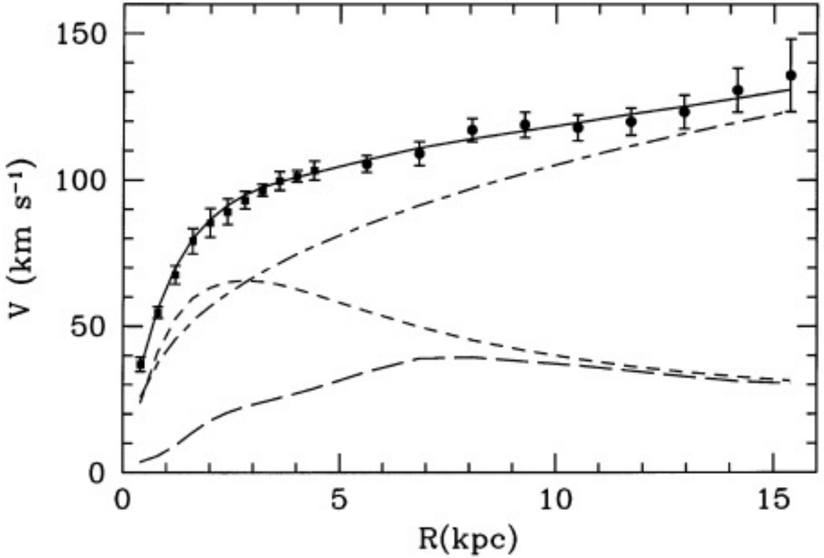
MONASH University

A Bayesian dark matter analysis pipeline for the CTA

Liam Pinchbeck

Supervisors: Csaba Balazs and Eric Thrane

Dark Matter



Corbelli, E. & Salucci, P. (Jan. 2000).

NASA/CXC/CfA/ M. Markevitch et al.
ESO WFI; Magellan/U.Arizona/ D.Clowe et al.
Magellan/U.Arizona/D.Clowe et al.

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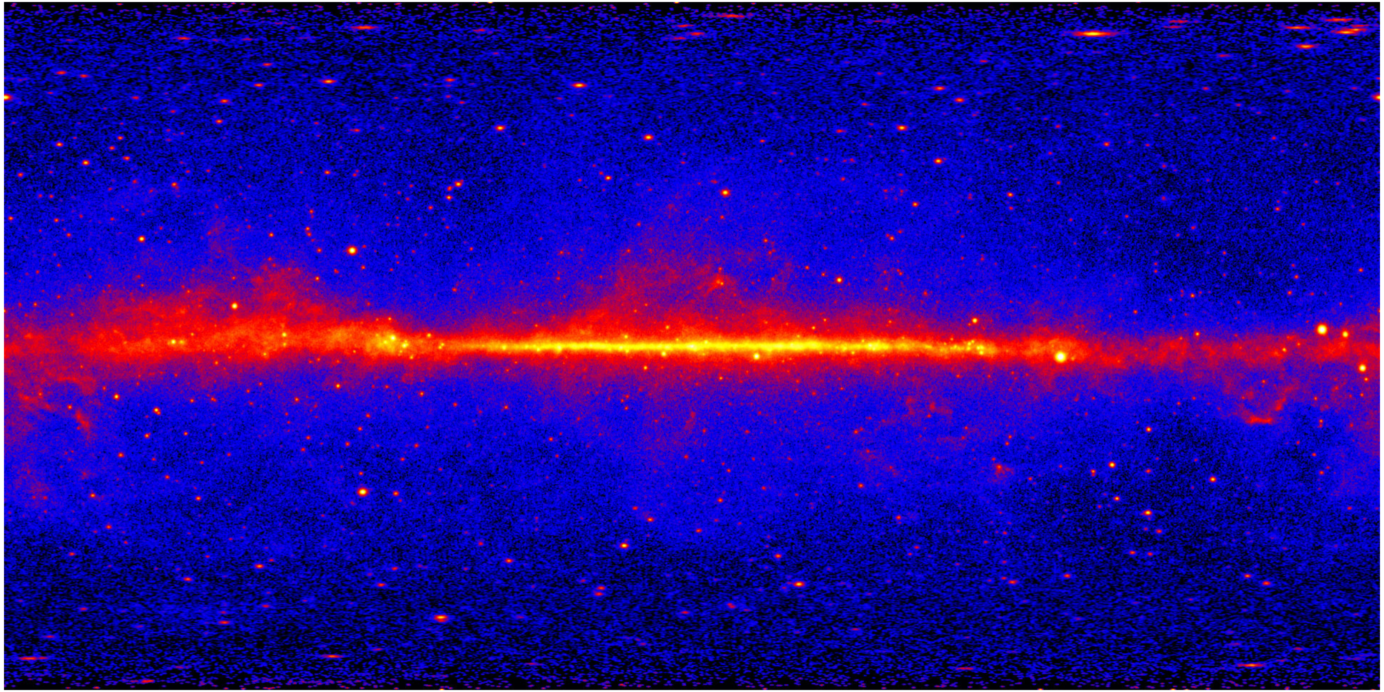
Dark Matter



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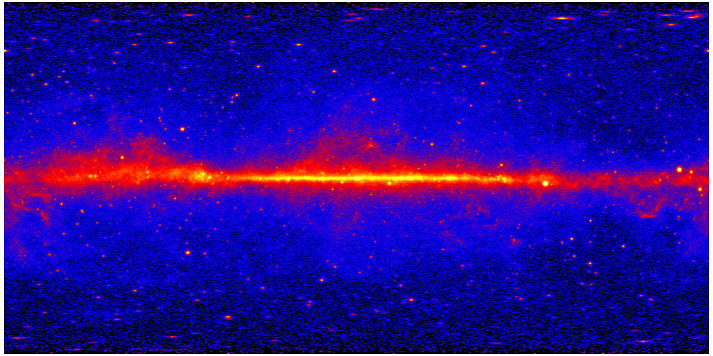
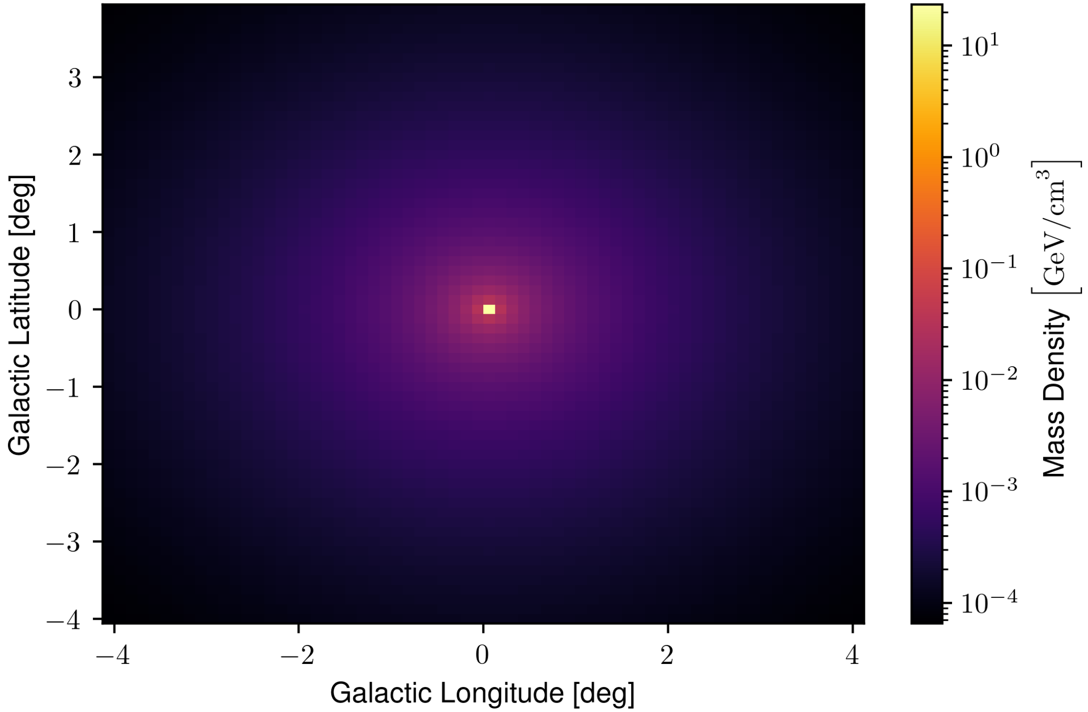
Dark Matter





Made with data taken from the Gammapy package,
Deil et al. 2017

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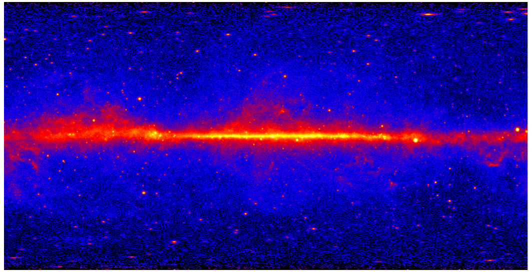
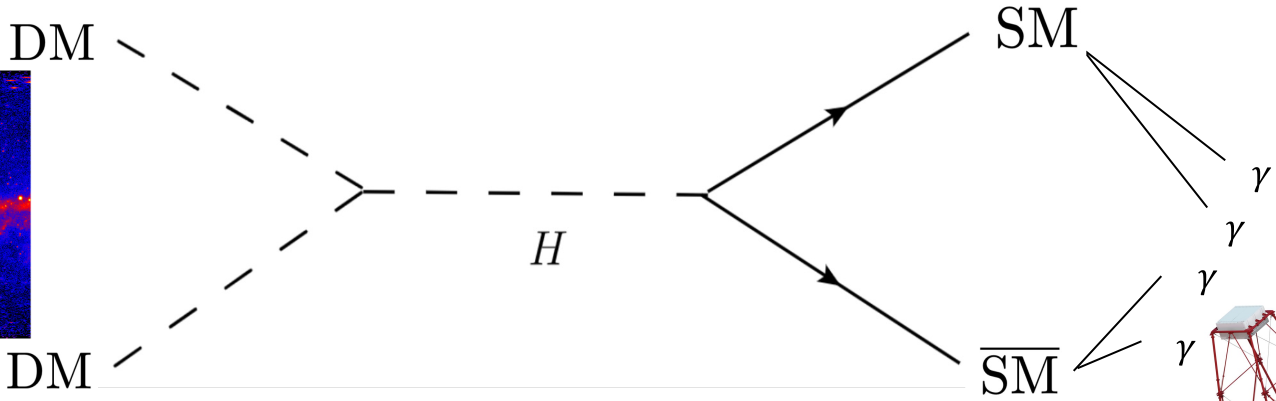
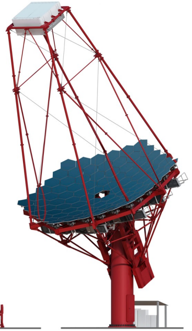
Dark Matter



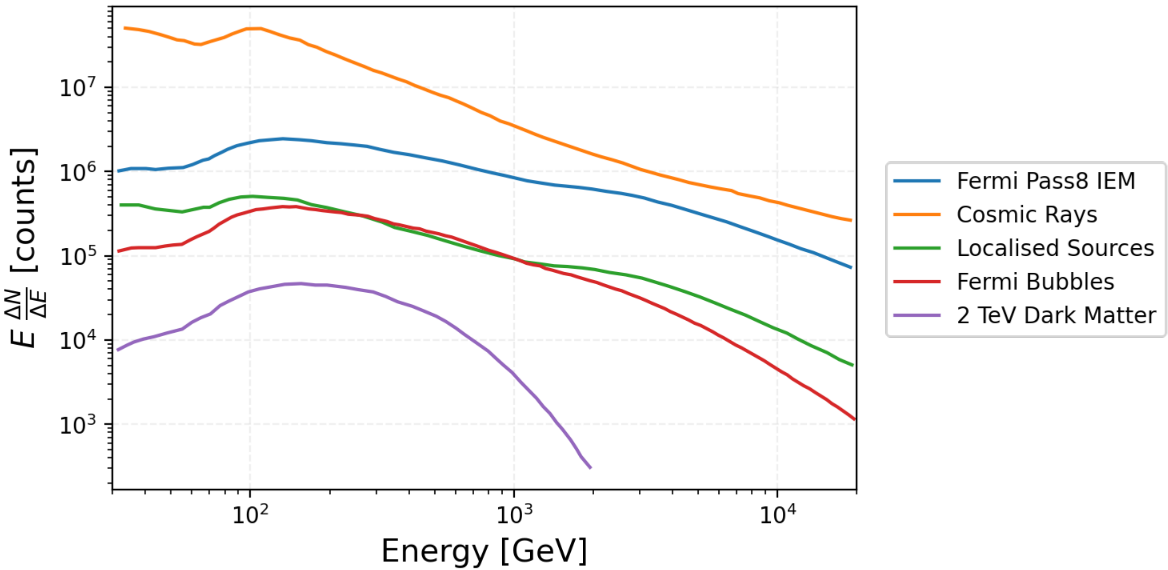


Adapted from Das, P., Kumar Das, M., Khan, N., (Mar. 2021)

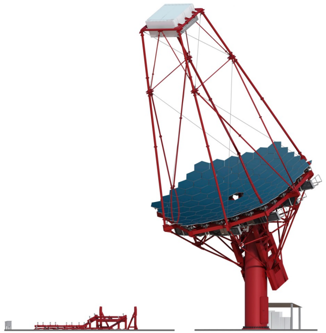


cta cherenkov telescope array

Dark Matter



Adapted from the CTA Consortium 2021 “Sensitivity of the Cherenkov Telescope Array to a dark matter signal from the Galactic centre”



cherenkov telescope array

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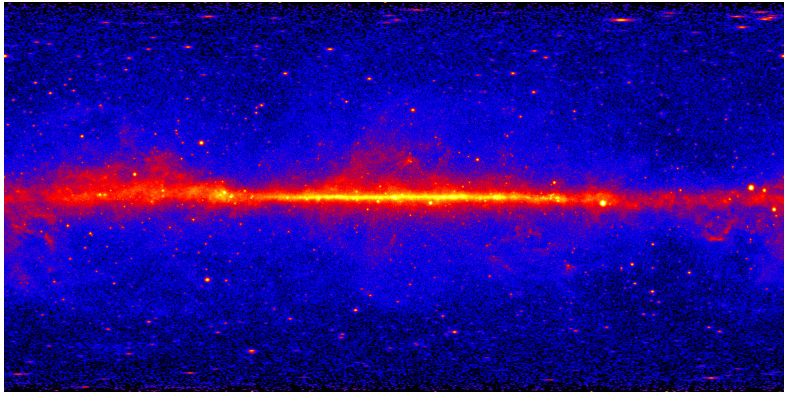
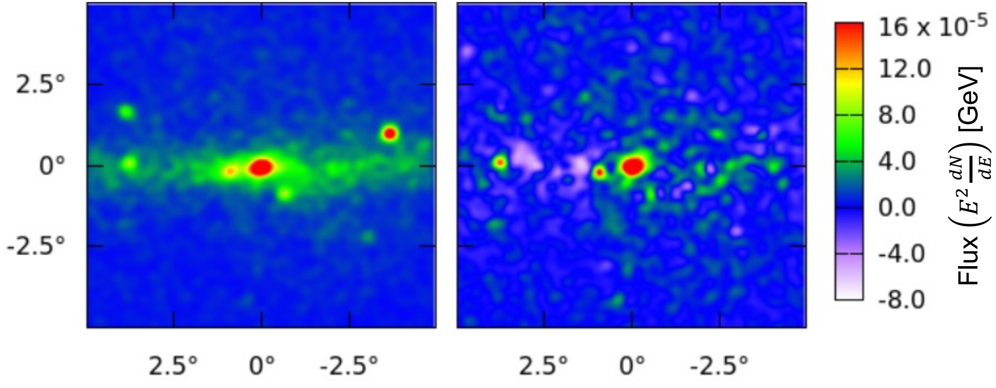
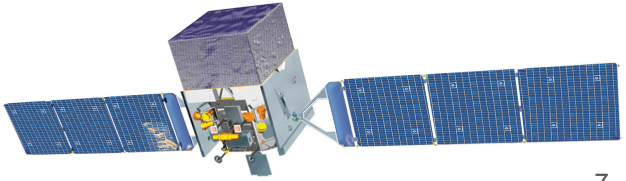
Dark Matter





Daylan et. al (Mar. 2015), ArXiv:1402.6703

Fermi
Gamma-ray
Space Telescope



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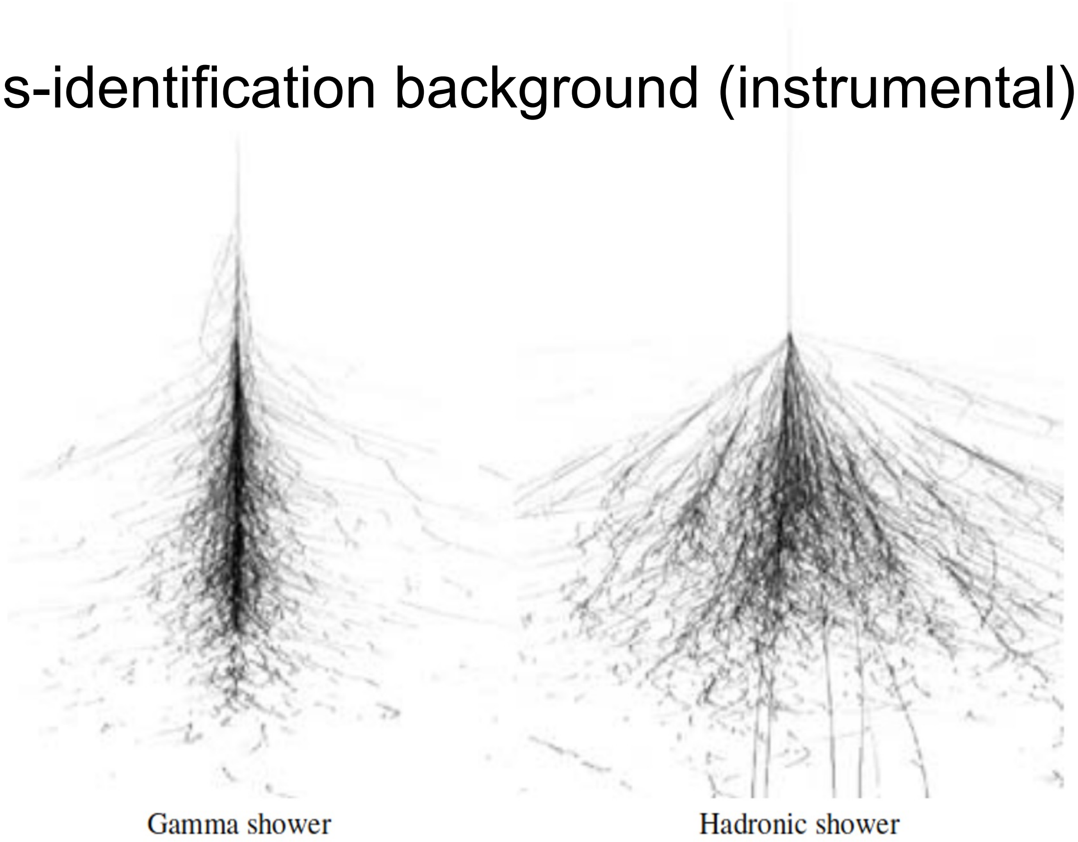
Mis-identification background (instrumental)



Völk & Bernlöhr (2009)

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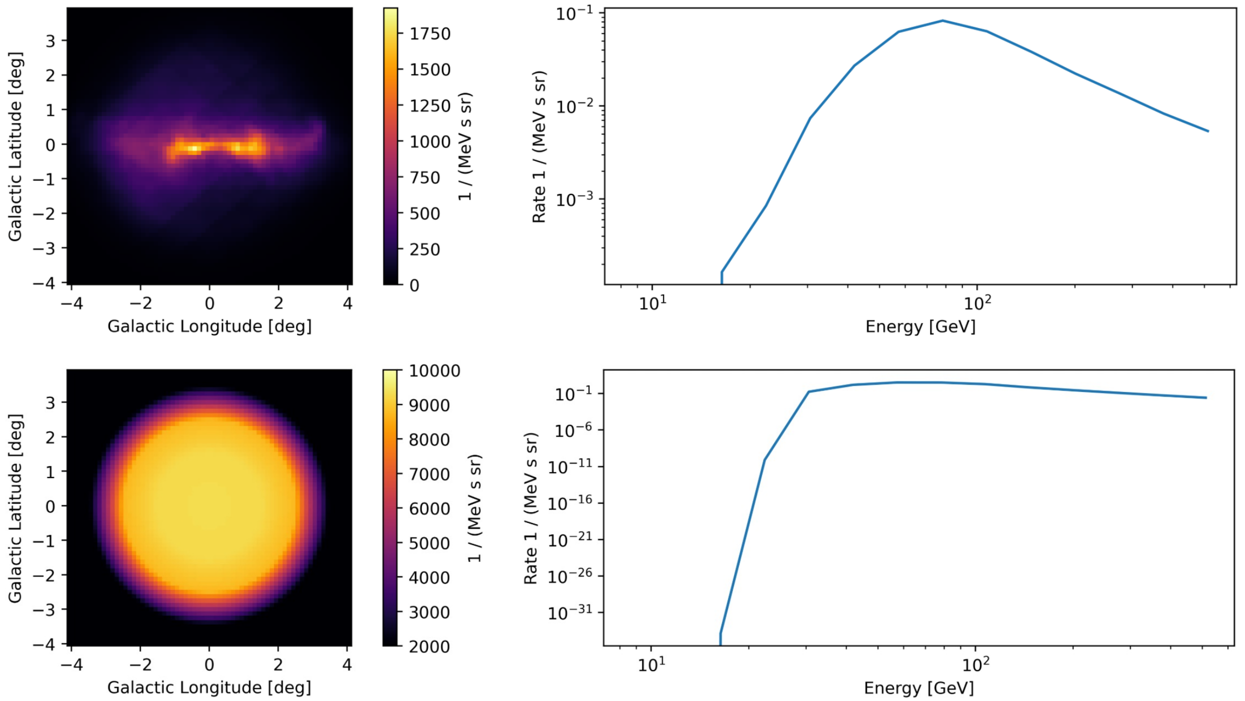
Backgrounds



Plots made with data taken from the Gammapy package, Deil et al. 2017

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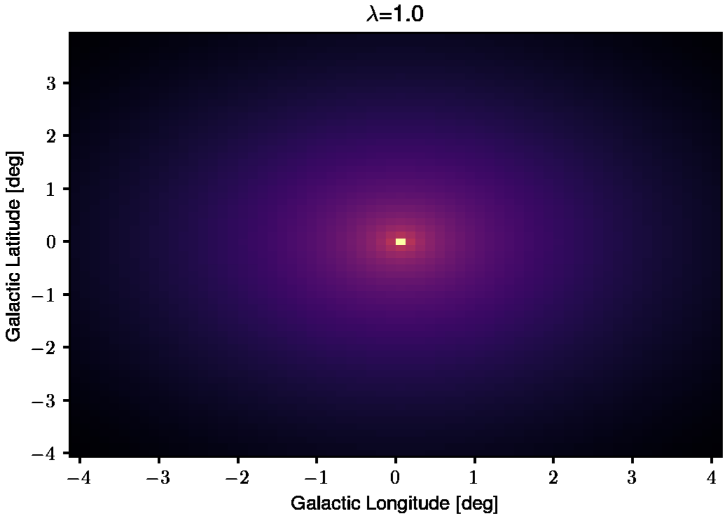
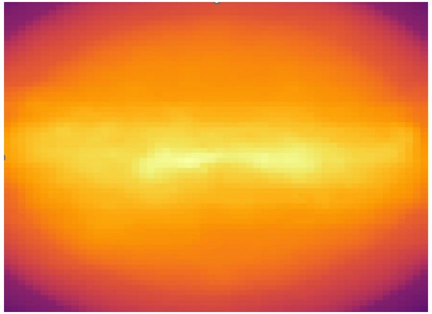
The model

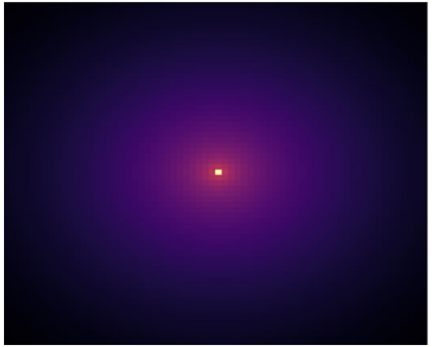


$=$

$(1-\lambda)$



$+\lambda$



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Bayesian framework

Good things!

- Provides a very natural way of dealing with uncertainties
- Marginalize over systematic uncertainties relating to the IRFs
- Robust and efficient model comparison

Not so good things

- Need some foreknowledge of the background

Grinder Meat Vector Icon. Stock Vector - Illustration of cartoon, household: 178168613

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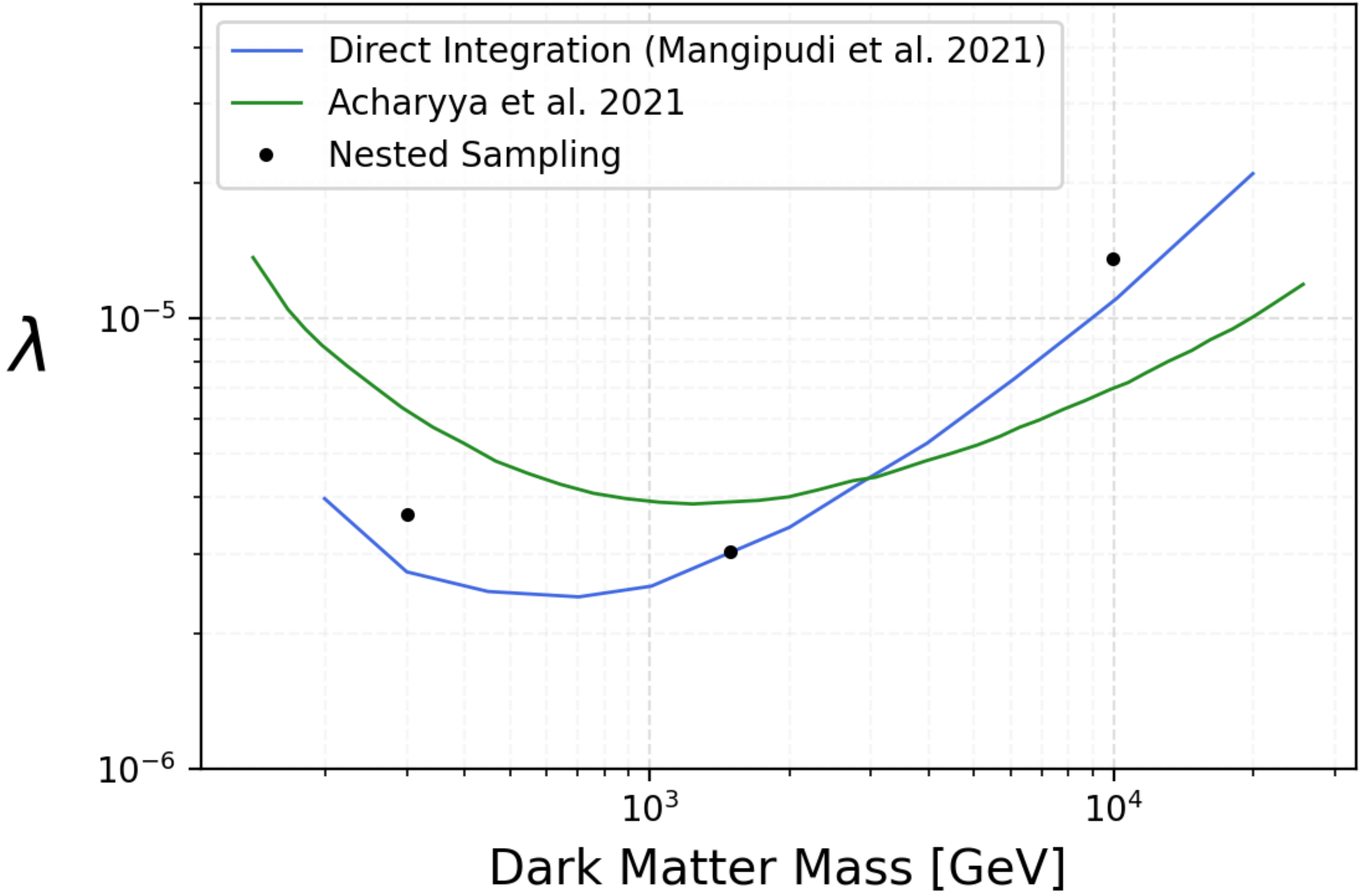

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Dark Matter detection at the Galactic Centre with the Cherenkov Telescope Array

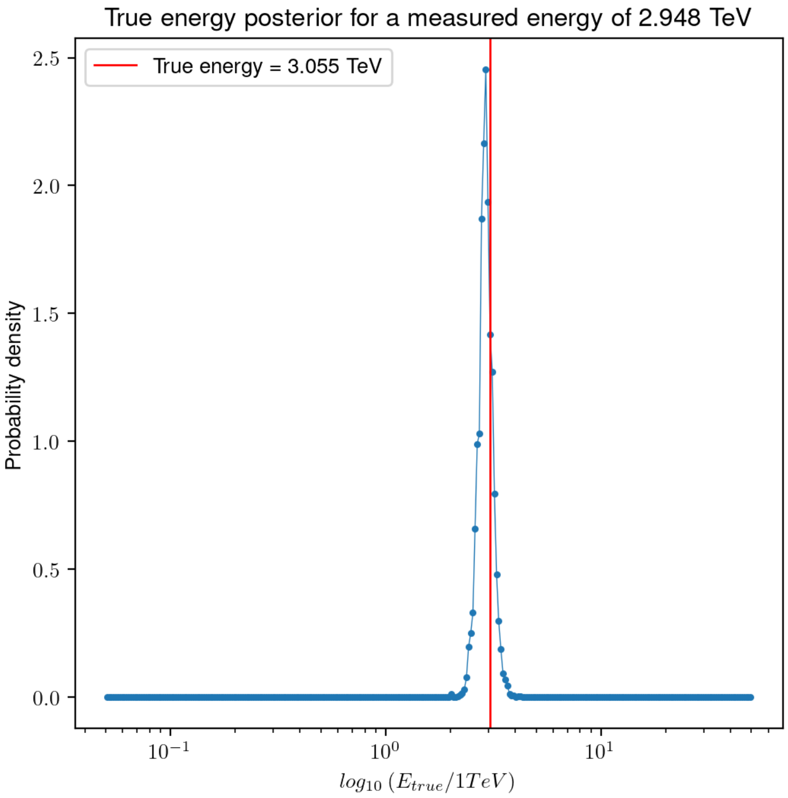
Main points:

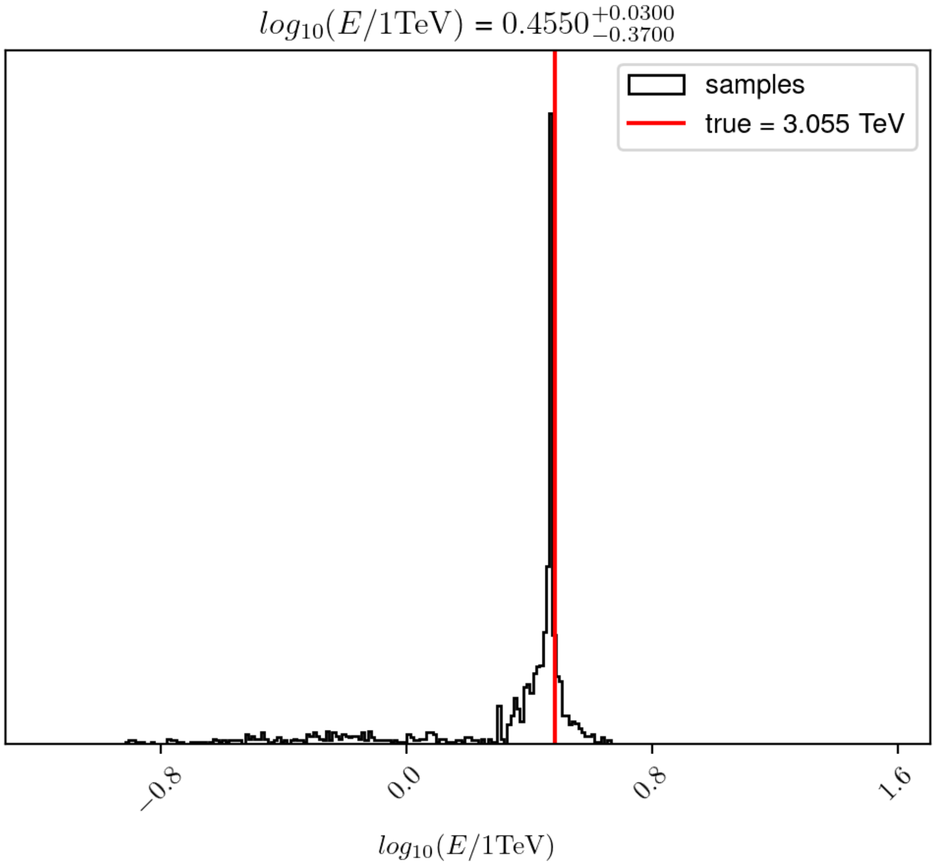
- We have developed a Bayesian inference framework that can predict dark matter parameters based on future observations of the galactic centre by the CTA
- We currently are developing the sensitivity of this pipeline to dark matter parameters
- This approach offers a complementary approach to the analysis pipeline stored in Gammapy
- Further study will generalize the models considered and the number of variables we fit for

Marginalisation

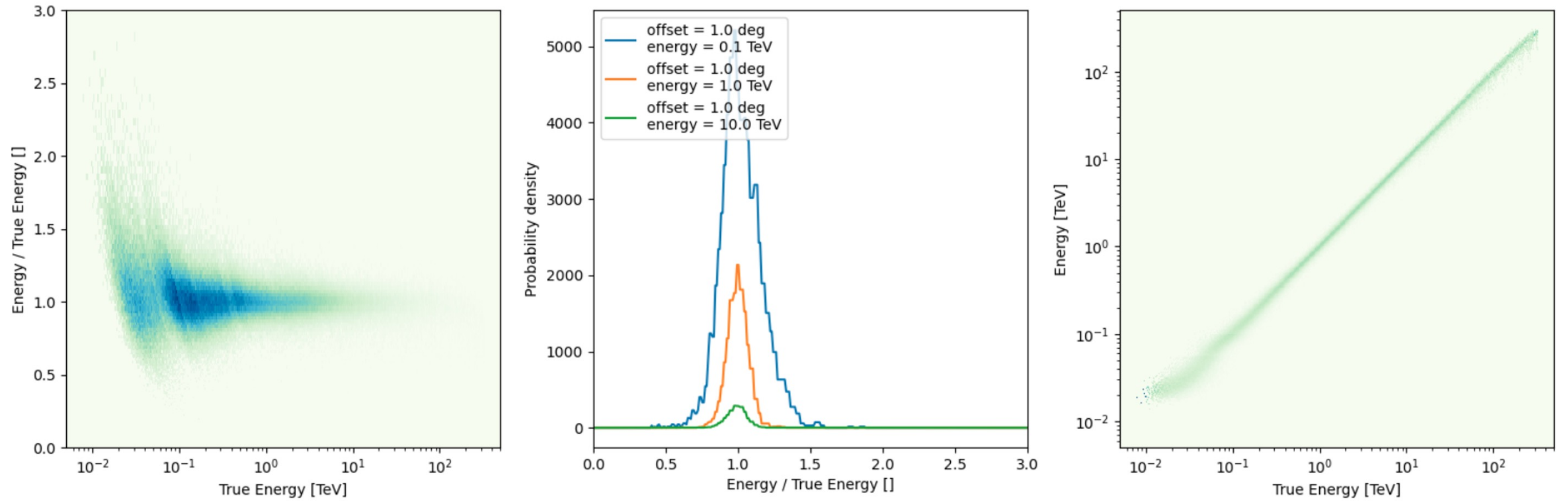
$$p(\theta|d,\mathcal{M}) = \frac{p(d|\theta)p(\theta|\mathcal{M})}{\mathcal{Z}}$$

$$p(d|\theta,\mathcal{M}) = \int p(d|\alpha,\theta)p(\alpha|\mathcal{M})d\alpha$$

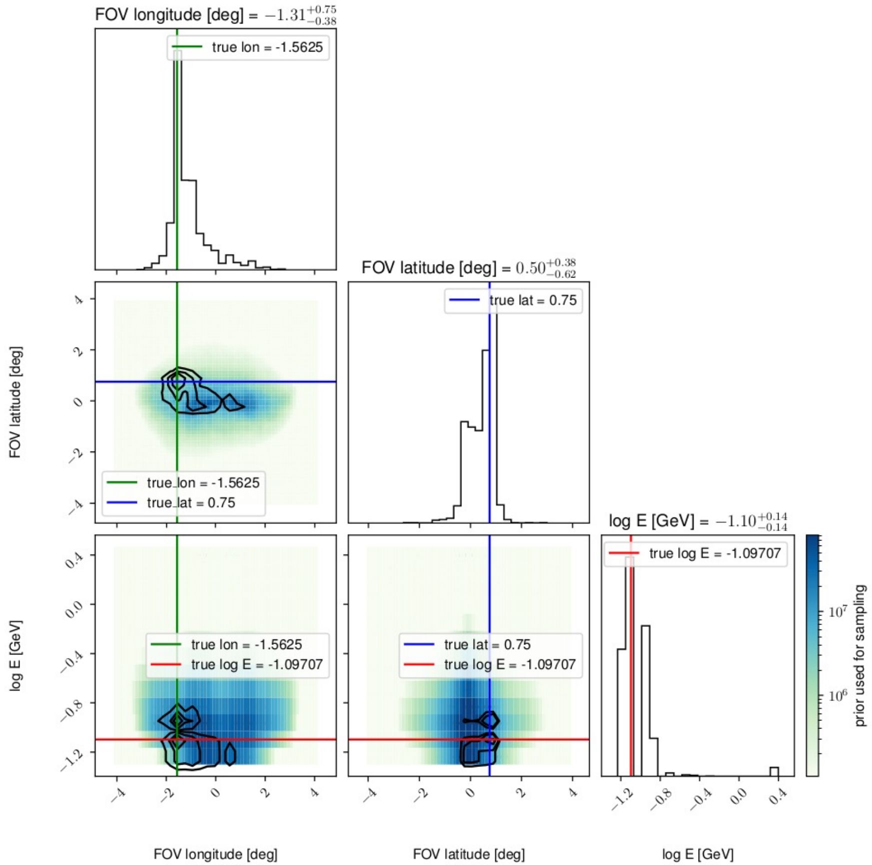

True energy posterior for a measured energy of 2.948 TeV
True energy = 3.055 TeV
Probability density
2.5
2.0
1.5
1.0
0.5
0.0
10^{-1}
10^{0}
10^{1}
$log_{10}\left(E_{true}/1TeV\right)$

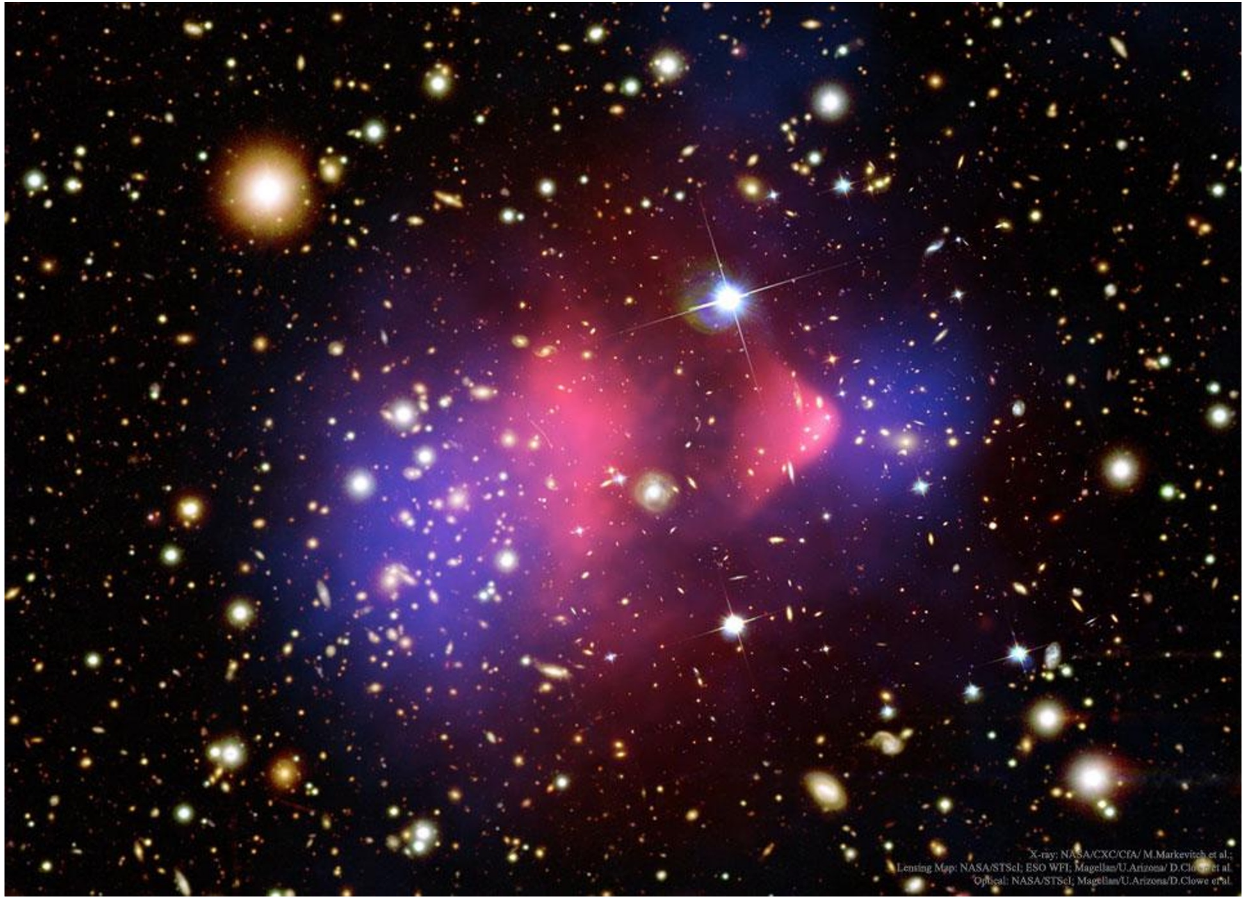

$log_{10}(E/1\text{TeV}) = 0.4550^{+0.0300}_{-0.3700}$
samples
true = 3.055 TeV
−0.8
0.0
0.8
1.6
$log_{10}(E/1\text{TeV})$

Simulated Energy Dispersion of the CTA

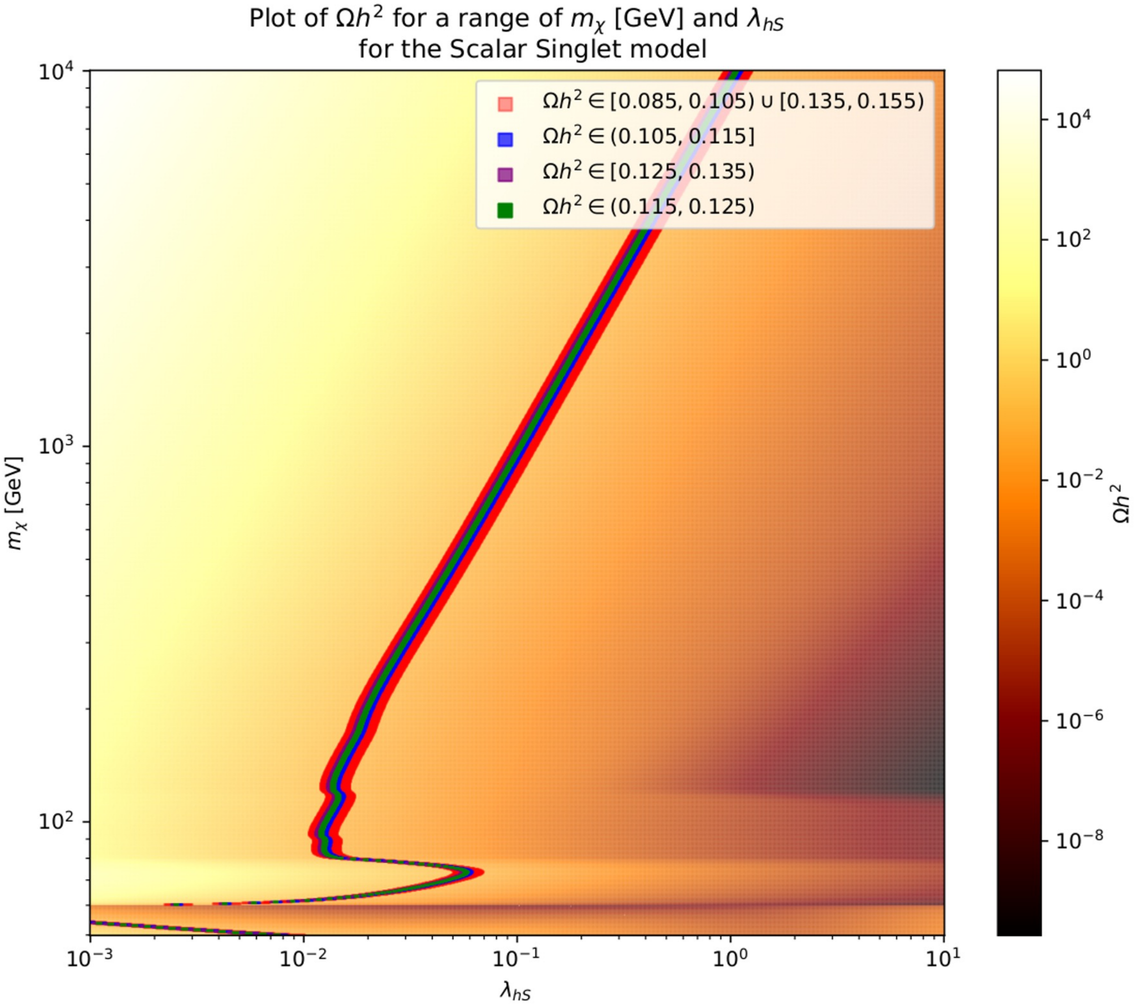


$$\mathcal{L}(E_m, \psi_m | \lambda, S, B) = \prod_i^N \lambda \mathcal{L}(E_{mi}, \psi_{mi} | S) + (1-\lambda) \mathcal{L}(E_{mi}, \psi_{mi} | B)$$



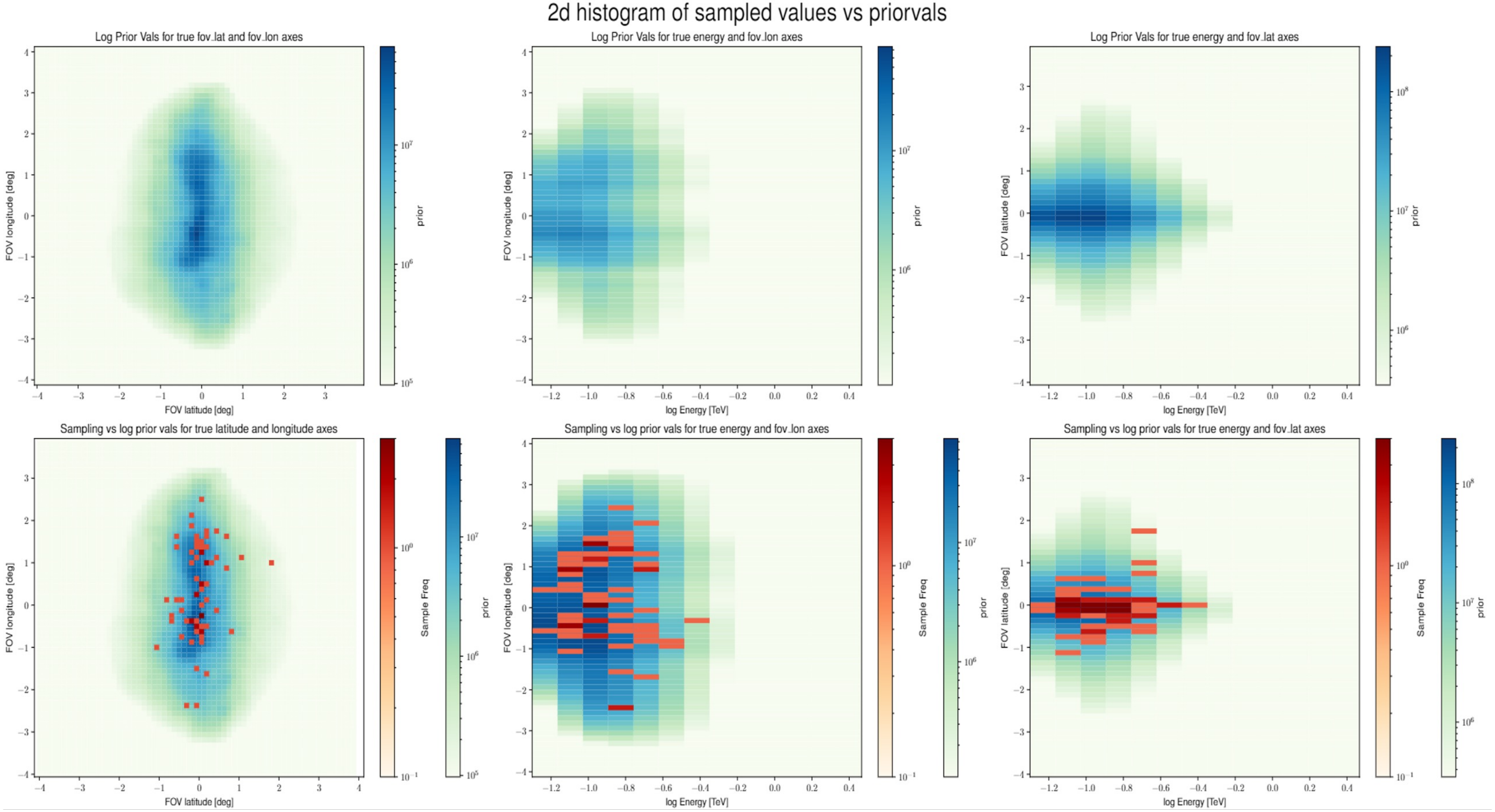


NASA/CXC/CfA/ M. Markevitch et al.
ESO WFI; Magellan/U.Arizona/ D.Clowe et al.
Magellan/U.Arizona/D.Clowe et al.


Plot of Ωh^2 for a range of m_χ [GeV] and λ_{hS}
for the Scalar Singlet model
$\Omega h^2 \in [0.085, 0.105) \cup [0.135, 0.155)$
$\Omega h^2 \in (0.105, 0.115]$
$\Omega h^2 \in [0.125, 0.135)$
$\Omega h^2 \in (0.115, 0.125)$
m_χ [GeV]
10^4
10^3
10^2
10^{-3}
10^{-2}
10^{-1}
10^0
10^1
λ_{hS}
Ωh^2
10^4
10^2
10^0
10^{-2}
10^{-4}
10^{-6}
10^{-8}

Inverse Transform Sampling

Sample the priors (the true values) → Given the true energy and sky position, mess them up with **IRFs**



Recycling samples

$$p_{\text{tot}}(\Lambda|\vec{d}) = \frac{\mathcal{L}_{\text{tot}}(\vec{d}|\Lambda)\,\pi(\Lambda)}{\int d\Lambda\,\mathcal{L}_{\text{tot}}(\vec{d}|\Lambda)\,\pi(\Lambda)}$$

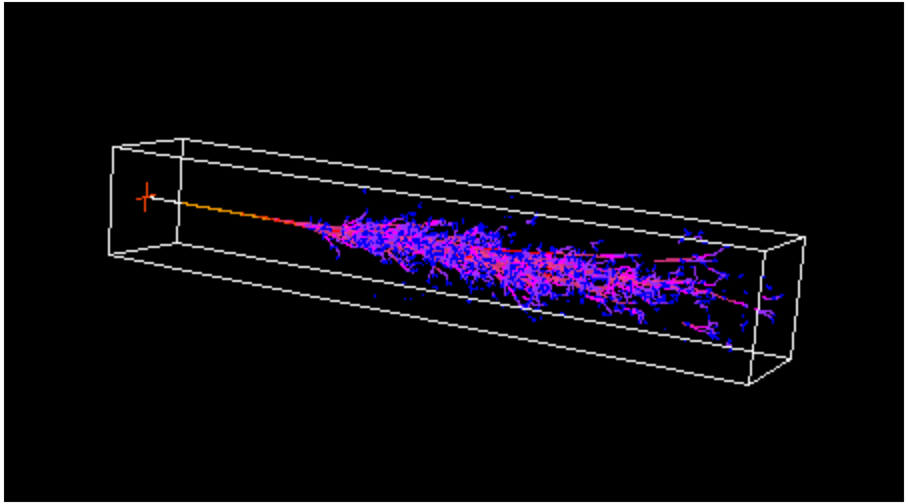
$$\mathcal{L}_{\text{tot}}(\vec{d}|\Lambda) = \prod_{i}^{N} \int d\theta_i\,\mathcal{L}(d_i|\theta_i)\,\pi(\theta_i|\Lambda)$$

$$\mathcal{L}_{\text{tot}}(\vec{d}|\Lambda) = \prod_{i}^{N} \frac{\mathcal{Z}_{\varnothing}(d_i)}{n_i} \sum_{k}^{n_i} \frac{\pi(\theta_i^k|\Lambda)}{\pi(\theta_i^k|\varnothing)}$$

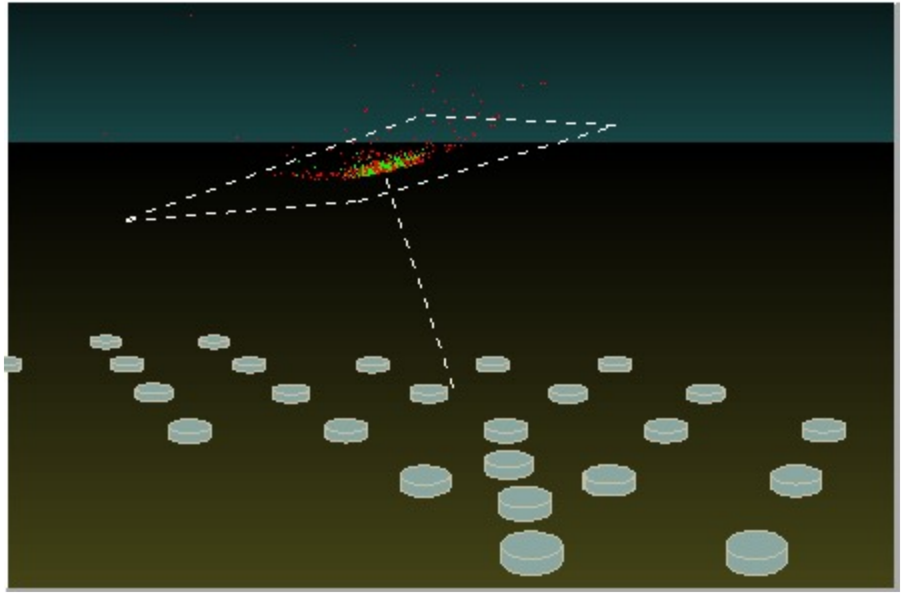
Thrane, E. & Talbot, C. (2019).

$$\frac{d\Phi}{dE_\gamma}(E_\gamma, \psi) = J\left(\frac{\langle\sigma v\rangle}{2m_\chi^2}\sum_f B_f \frac{dN\gamma^f}{dE_\gamma}\right)$$

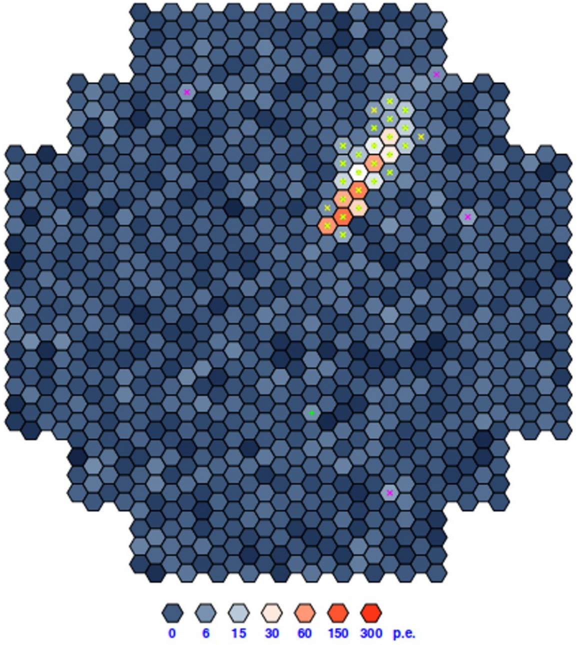
The CTA



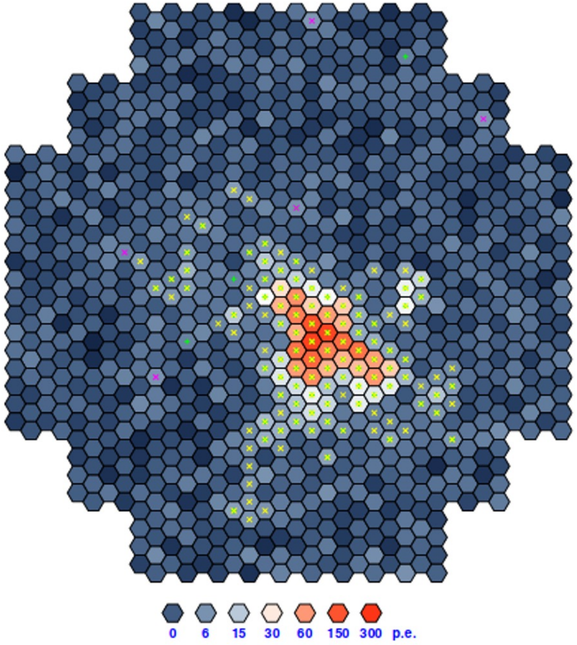
The Electromagnetic Shower Simulator, Last accessed 25/10/22, https://www.mpp.mpg.de/~menke/elss/anim1.shtml?unwrap



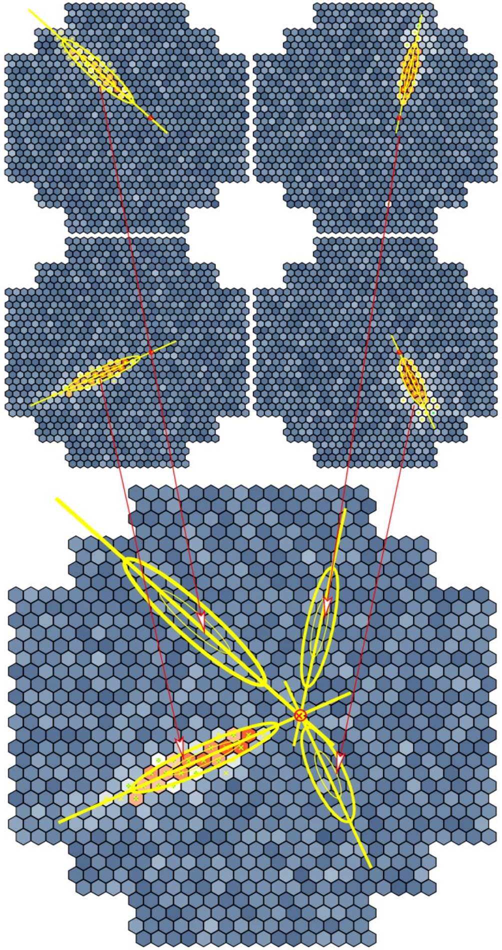
RELEVANT and IRRELEVANT (to “Introduction to Cosmic Rays”), http://theor.jinr.ru/~vnaumov/Eng/UHECR/Relevant.html



1.0 TeV gamma shower



2.6 TeV proton shower



Völk & Bernlöhr (2009)

To Do

- Cosmic ray background probability density plot (spatial and spectrum)
- Annihilation diagram
- Egret logo (GeV excess)
- My sensitivities
- Conclusion slide