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Estimating the CTAO Sensitivity to the Fermi Bubbles

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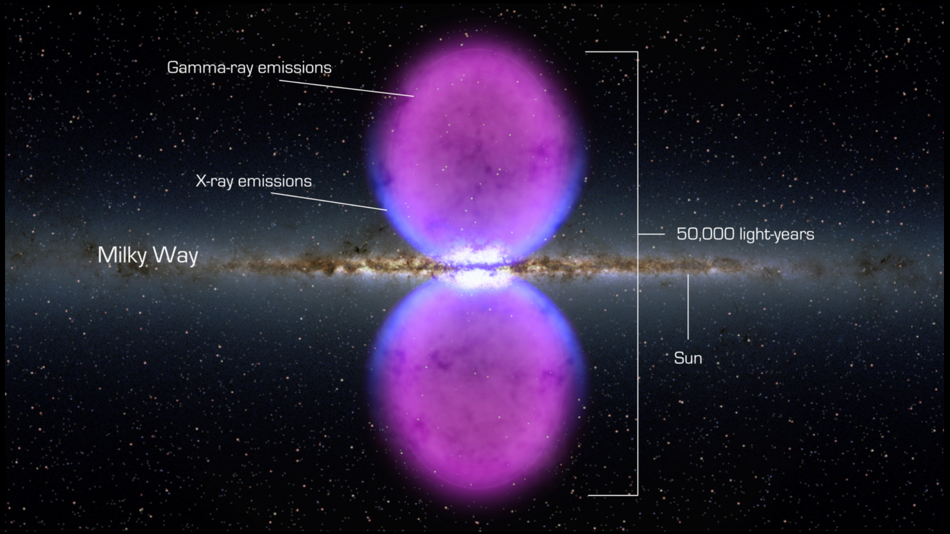
What are the Fermi Bubbles?

- Discovered in 2010 with *Fermi*-LAT data [Su *et al.*, 2010, 1005.5480], upper limits have later been put by H.E.S.S. [Moulin *et al.*, 2021, 2108.10028]
- Surrounded by X-Ray bubbles observed by eROSITA [Predehl *et al.*, 2020, 2012.05840]
- Possibly connected to WMAP and Planck microwave haze, seen by WMAP [Finkbeiner, 2003, 0311547; Planck Collaboration, 2012, 1208.5483]
- Gamma-ray emitting lobes extending up to 55° in latitude above and below the Galactic Center (GC)
- Gamma rays are produced either in hadronic interactions or in leptonic inverse Compton scattering

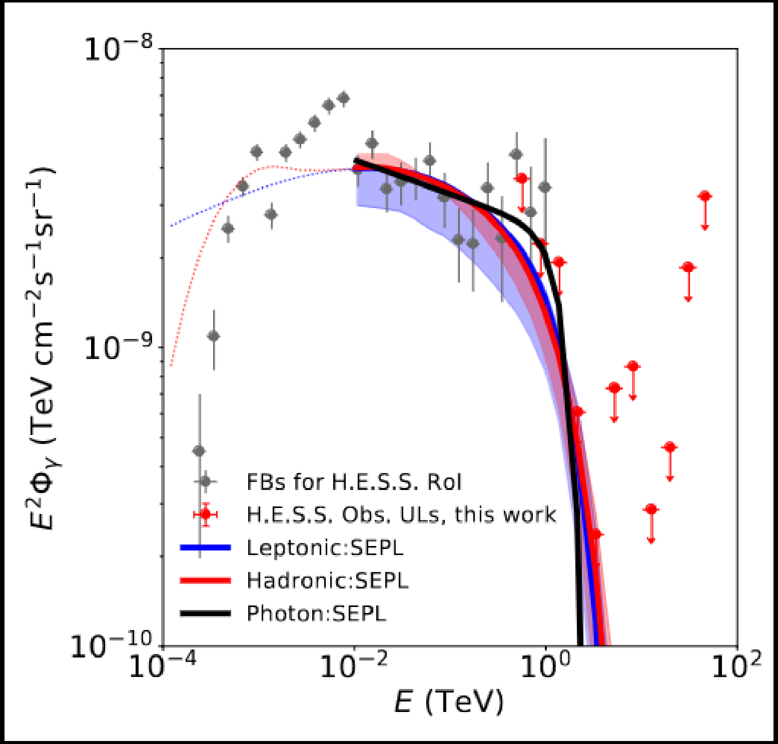
Artistic depiction of the Fermi Bubbles



https://www.nasa.gov/universe/nasas-fermi-telescope-finds-giant-structure-in-our-galaxy/

Fermi Bubbles Spectrum

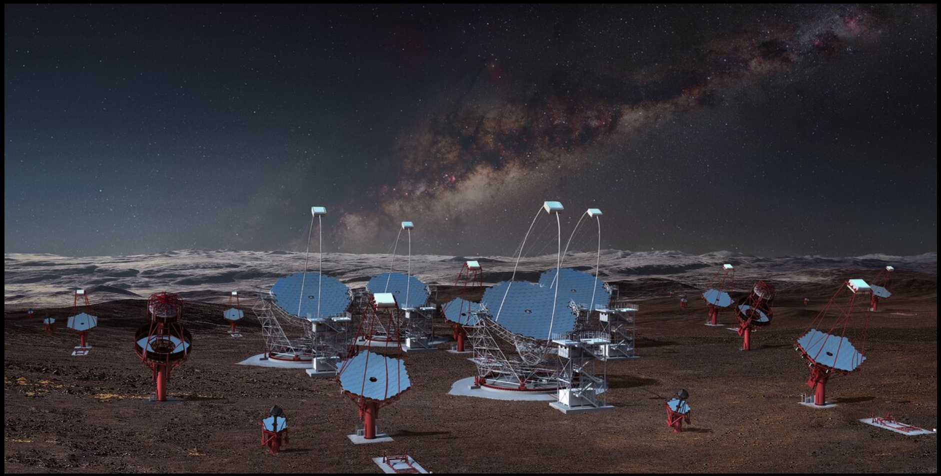
- Existing data between ~0.1 GeV and ~1 TeV
- Spectrum consistent with an Exponential Cutoff Power Law (EPL) or a (Super)EPL
- Softening at 100 GeV for high latitudes
- Lack of detection above 1 TeV, best energy for sensitivity of CTAO



Moulin *et al.*, 2021, 2108.10028

The Cherenkov Telescope Array Observatory

- CTAO is an array of Imaging Air Cherenkov Telescopes (IACTs), able to detect Cherenkov light from showers initiated by gamma-rays colliding with the atmosphere
- CTAO will be composed of three kind of telescopes:
  - Large-Sized Telescope (LST): ~30 GeV to ~200 GeV
  - Medium-Sized Telescope (MST): ~200 GeV to ~5 TeV
  - Small-Sized Telescope (SST): ~5 TeV to ~300 TeV
- CTAO will be the most sensitive tool around ~1 TeV, where it is one order of magnitude more sensitive than other IACTs
- CTAO will have a large field of view and best angular resolution (~0.05 deg at 1 TeV)



https://www.eso.org/public/teles-instr/paranal-observatory/ctao/

This Project

GOALS:

- Study the sensitivity of CTAO to detect the Fermi Bubbles in a realistic manner
- Find the optimal observational strategies for the Fermi Bubbles

HOW TO DO IT:

- Simulate the observation:

  Galactic Centre Survey [The CTAO Consortium, 2021, 2007.16129],

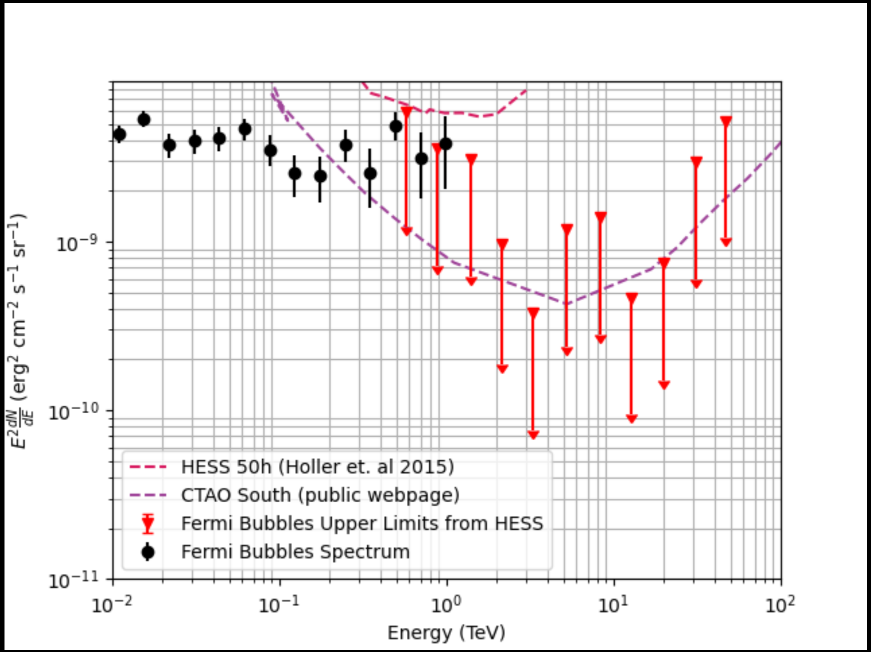
  525 hours, 12°x12° RoI
- Template Fitting with Standard Likelihood approach

  To create the simulations and for fitting we use the official CTAO science tool:

  Gammapy [Donath *et al.*, 2023, 2308.13584]

  We will consider systematics using our own fitting code following:

  [The CTAO Consortium, 2021, 2007.16129]



Galactic Centre Survey for Fermi Bubbles

- We consider two set-ups:

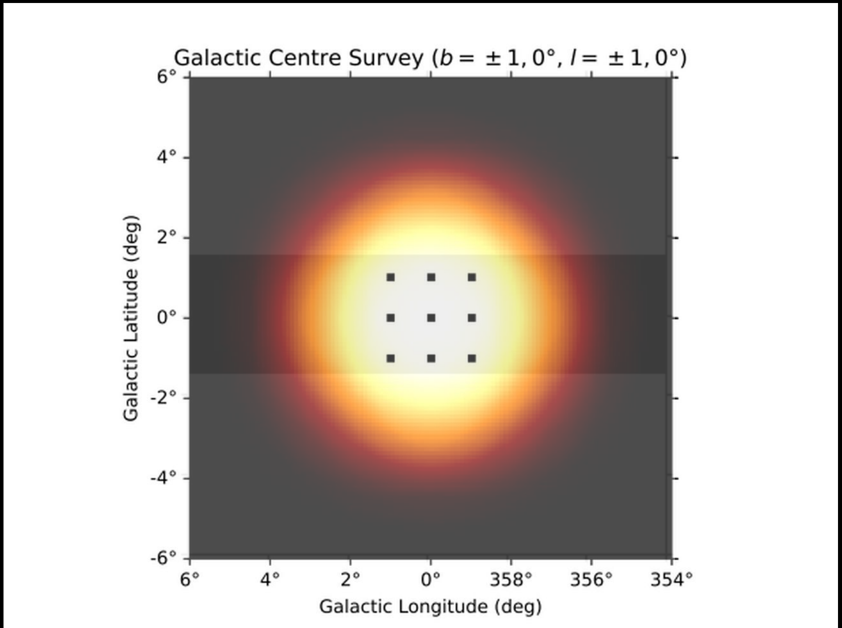
  1. Galactic Centre Survey, no mask

  2. Galactic Centre Survey, mask on Galactic Plane

- Galactic Centre Survey [The CTAO Consortium, 2021, 2007.16129]

- GP Mask: |*b*|<1.5°

- Observation time: 525 h, split in 9 points as in figure (~58 h each)

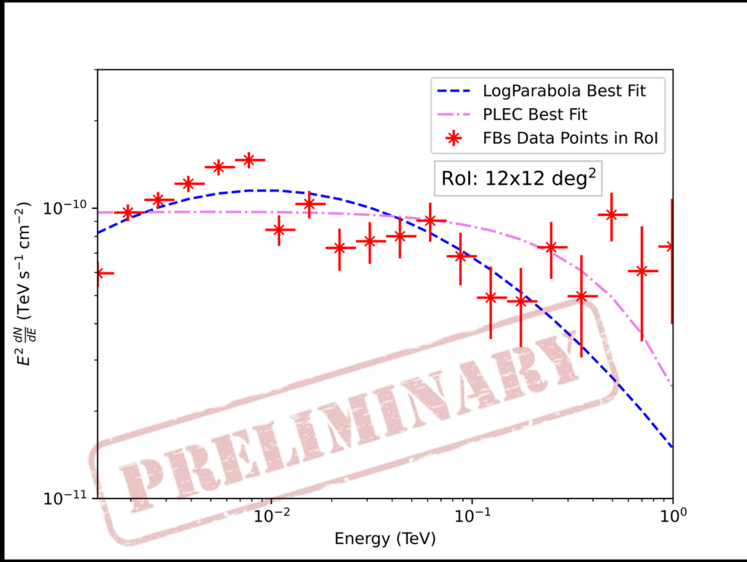


Fermi Bubbles Emission Model

To model the FB emission, we fit the FB data points [The *Fermi*-LAT Collaboration, 2017, 1704.03910]

- To a LogParabola
- To a power law with exponential cutoff (PLEC)

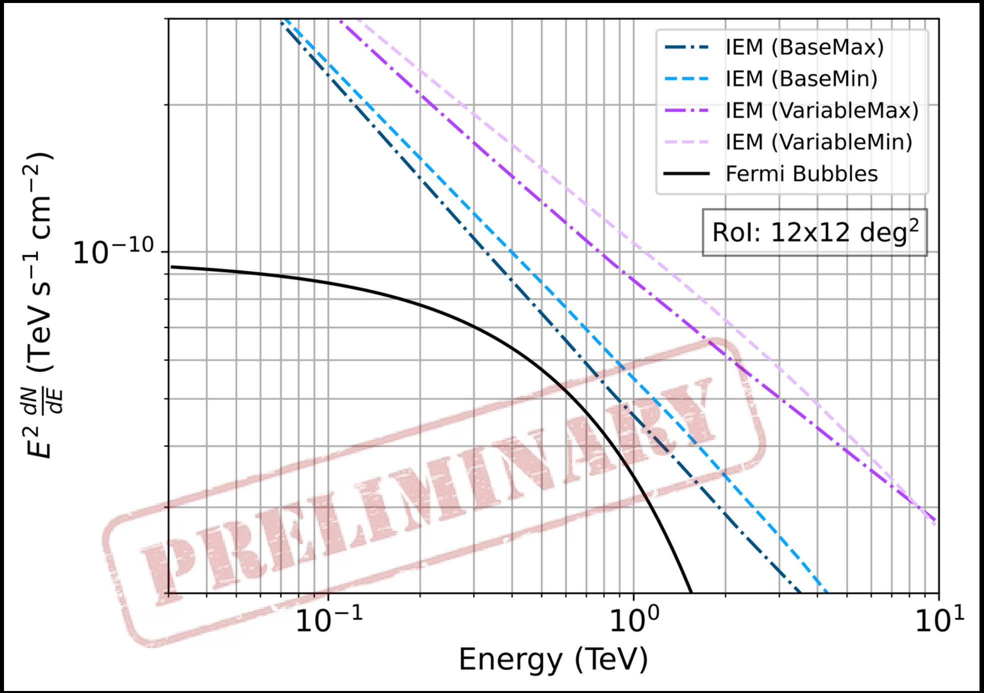
$$\frac{dN}{dE} = I\left(\frac{E}{1\mathrm{GeV}}\right)^{-\gamma} e^{-E/E_{\mathrm{cut}}}$$



Parameter	Value
Amplitude	9.77e-5 $cm^{-2}\ s^{-1}\ TeV^{-1}$
Spectral Index	2.00
Cut-Off Energy	1 TeV

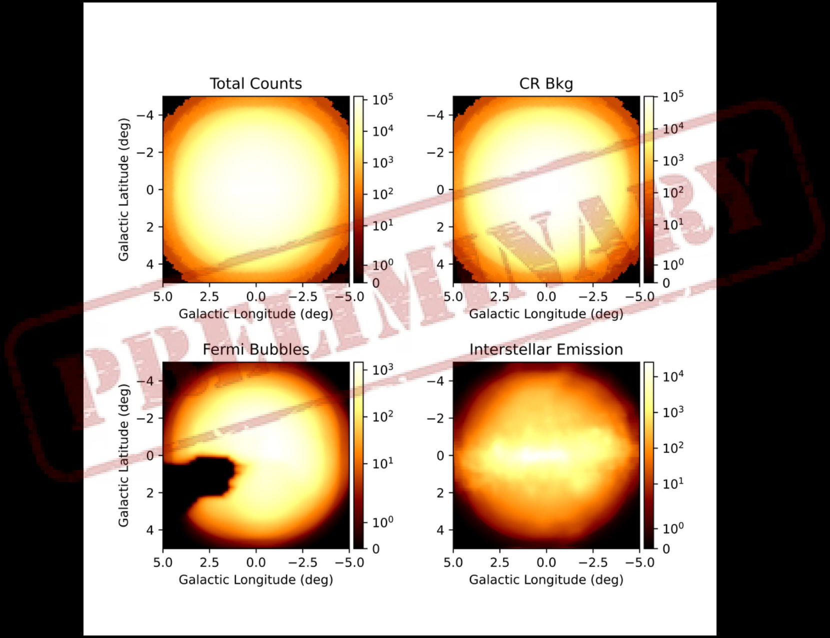
Emission Models

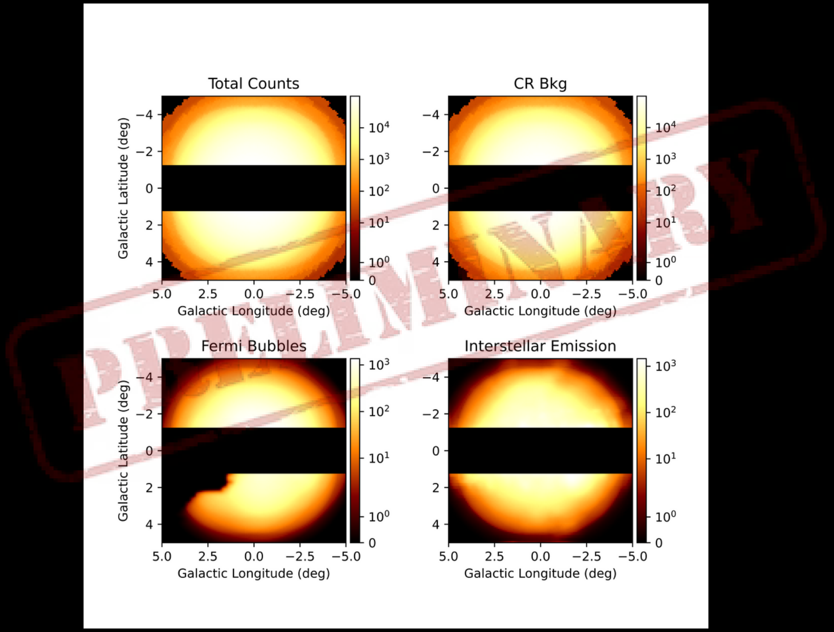
- FB model from [The *Fermi*-LAT Collaboration, 2017, 1704.03910]
- Different Interstellar Emission (IE, emission of gamma-rays coming from the interaction of particles with the interstellar medium) models are used both for simulations and fitting
- Max and Min depend on the CR spectral indexes
- Variable and Base depend on the CR Diffusion coefficient
- IE Models from [De la Torre, 2022, 2203.15759]
- Instrument CR Background



Characterization of the Simulation

- Left Plot: Cumulative counts in each energy bin between 30 GeV and 100 TeV, GC survey
- Right Plot: Cumulative counts in each energy bin between 30 GeV and 100 TeV, GC survey, GP mask

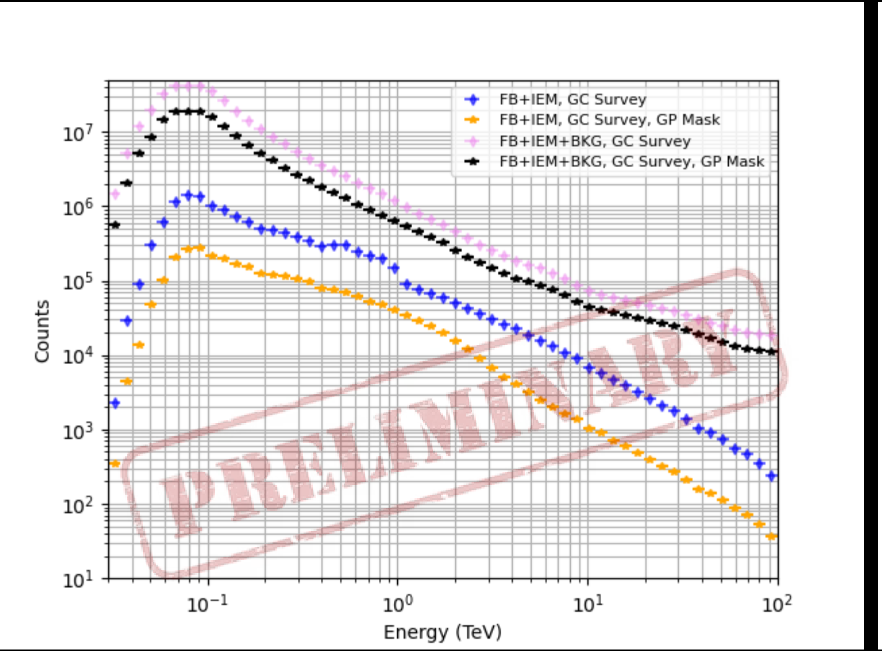


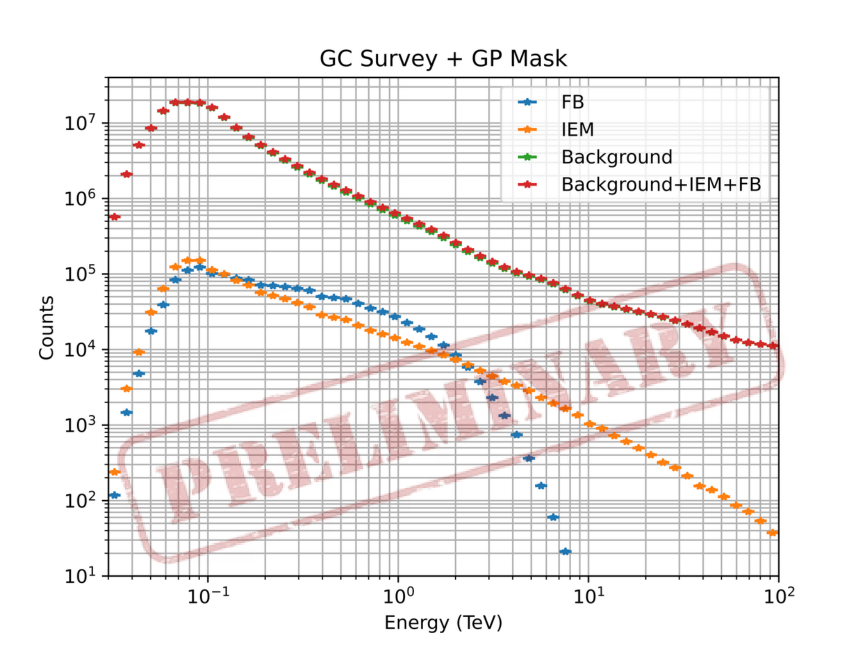


- Shown simulations assume BaseMax benchmark model for IE

Characterization of the Simulation

- Left Plot: Emission with and without the GP mask
- Right Plot: counts for the different emission components assuming Galactic Centre Survey + Galactic Plane Mask

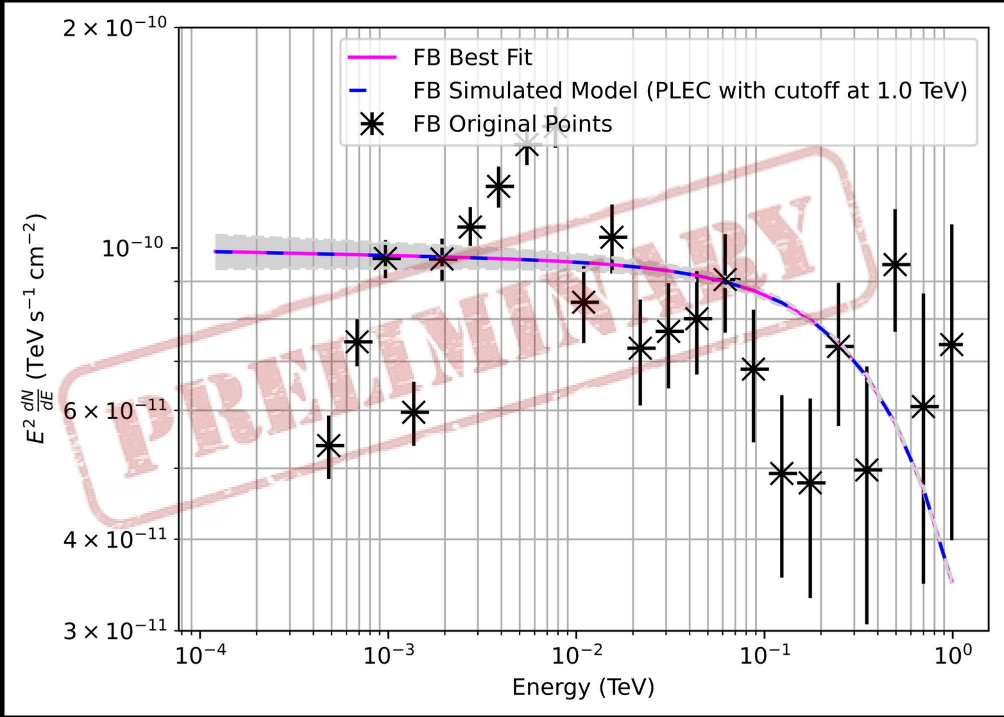




Global Fit Results

- Fit and Simulated with BaseMax with Gammapy
- GC +GP Mask

Parameter Name	Value	Error
FB Norm	1.0	4.1e-2
FB Tilt	2.6e-05	4.0e-2
IEM Norm	1.0	1.4e-2
IEM Tilt	-3.7e-5	2.9e-2
BKG Norm	1.0	3.2e-4
BKG Tilt	8.6e-8	1.1e-4

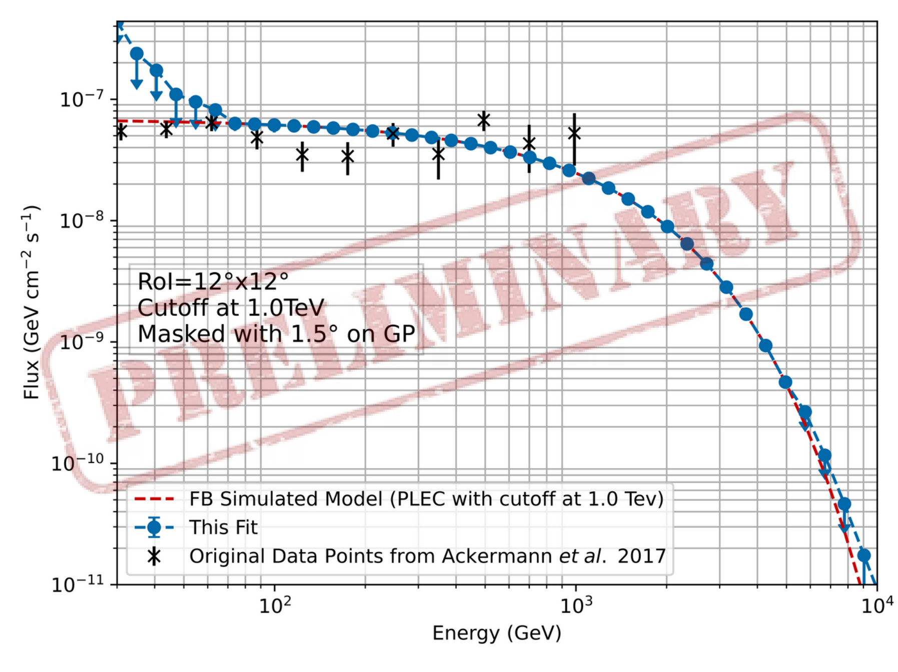


- We are able to recover input model

Bin-by-bin Fit

- Bin-by-bin fit for the normalization of the FB PLEC model
- Fit with our code
- IEM is fixed to BaseMax
- Detection of the FBs from ~80 GeV to ~5 TeV for a model with a cutoff at 1 TeV

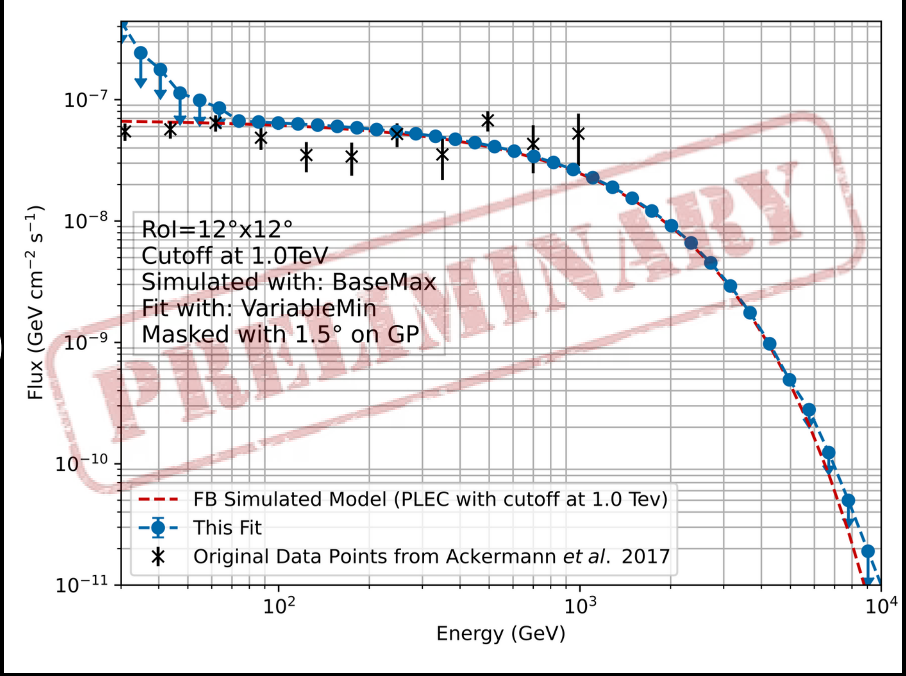
CTAO will investigate the spectrum from ~80 GeV to few TeV energies



Bin-by-bin Fit: Fitting with different IEMs

- Bin-by-bin fit for the normalization of the FB PLEC model
- Simulate with BaseMax
- Fit with VariableMin
- Detection of the FBs from ~80 GeV to ~5 TeV for a model with a cutoff at 1 TeV

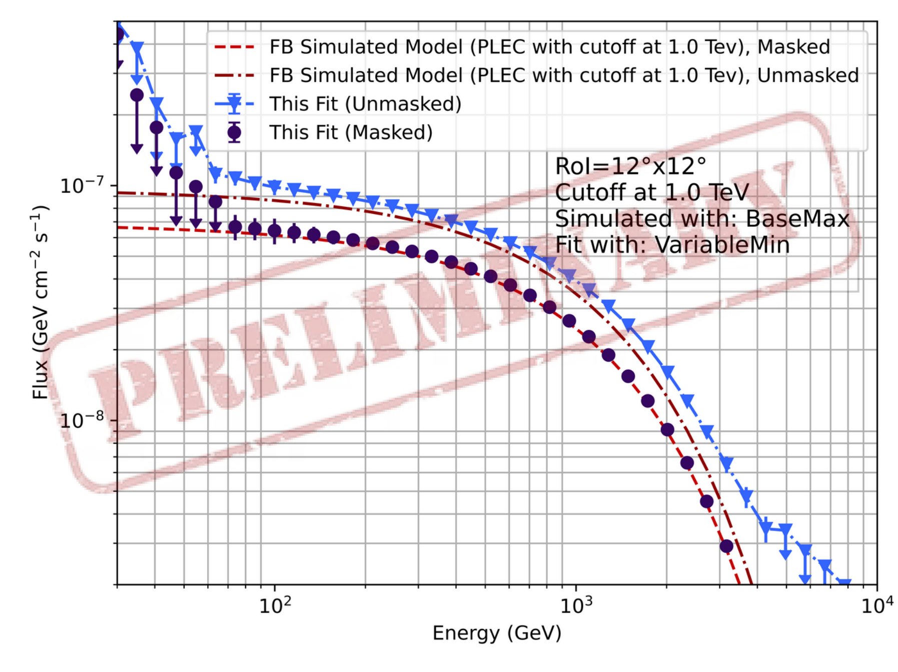
CTAO will investigate the spectrum from ~80 GeV to few TeV energies



Bin-by-bin Fit: impact of the mask

- Bin-by-bin fit for the normalization of the FB PLEC model
- Simulate with BaseMax
- Fit with VariableMin
- Detection of the FBs from ~80 GeV to ~5 TeV for a model with a cutoff at 1 TeV

Even if the errors of the fit are nearly invisible above 300 GeV, the fit with the mask shifts the fitted values, making them more in agreement with the original simulation



Addressing Systematic Uncertainties for the Telescope

Correlated systematic uncertainties may partially degrade morphological differences of the background/signal templates

- spatial bin-spatial bin
- energy bin-energy bin
- energy bin-spatial bin

$$\mathcal{L}(\boldsymbol{\mu}, \boldsymbol{\alpha}, \boldsymbol{\beta}|\boldsymbol{n}) = \prod_i \frac{1}{\sqrt{2\pi}\sigma_\beta} e^{-\frac{(1-\beta_i)^2}{2\sigma_\beta^2}} \prod_j \frac{(\mu_{ij}\alpha_{ij}\beta_i)^{n_{ij}}}{\sqrt{2\pi}\sigma_\alpha \cdot n_{ij}!} e^{-\mu_{ij}\alpha_{ij}\beta_i} e^{-\frac{(1-\alpha_{ij})^2}{2\sigma_\alpha^2}}$$

Gaussian Nuisance for beta

Gaussian Nuisance for alpha

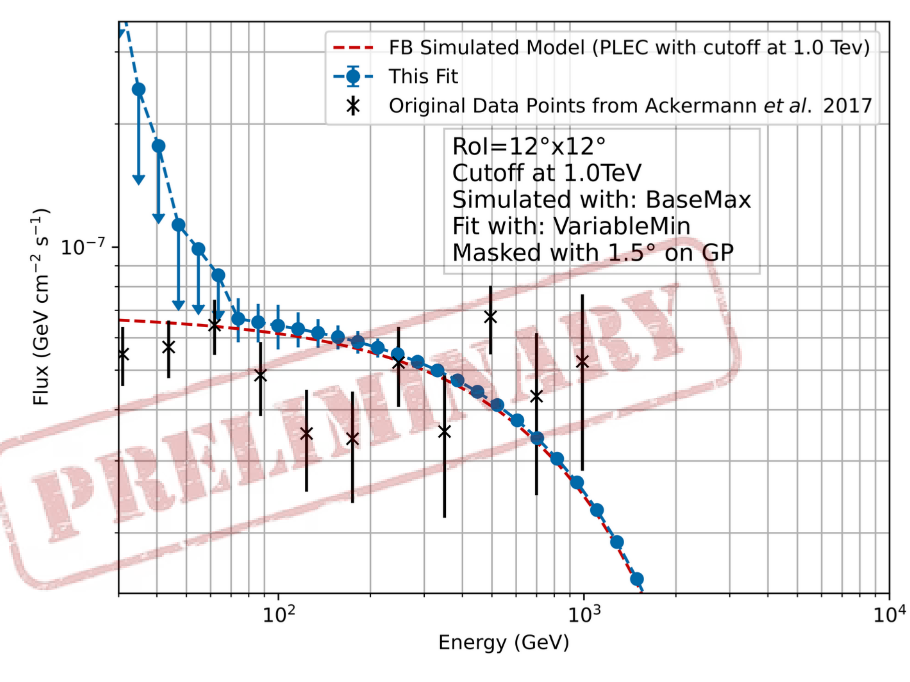
Silverwood *et al., 2016, 1408.4131*

Parameter	Values
σ_α	0.03-0.1
β	1

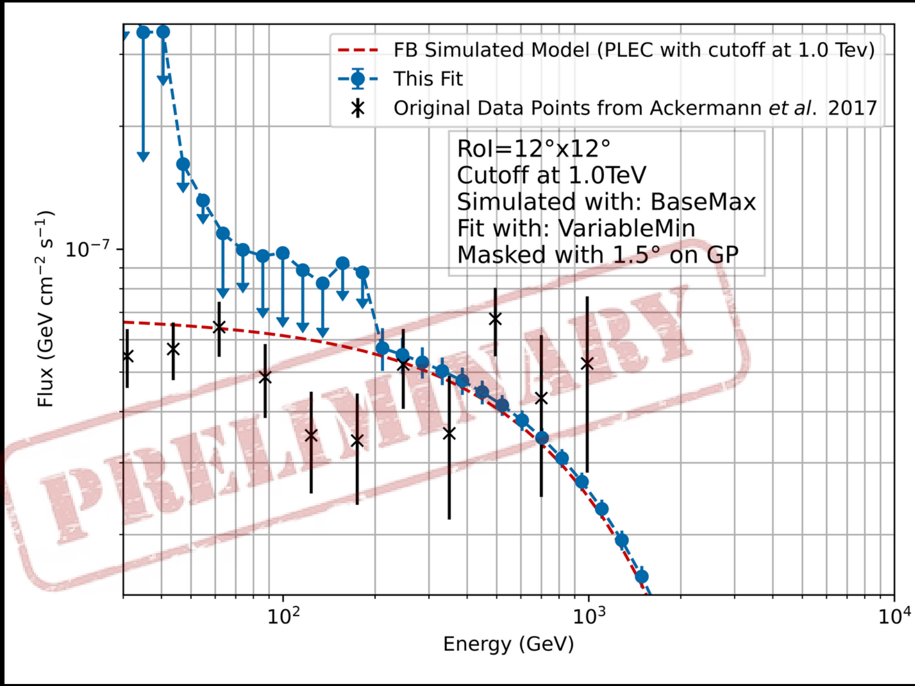
Systematics may hinder the robust detection of the FB, worsening the results we have just obtained

Addressing Systematic Uncertainties for the Telescope

σ_α=0.03



σ_α=0.1



Even including different benchmark values for the systematics, we are still able to reach detection for the FBs at energies ~200 GeV, increasing the uncertainty of the detected flux.

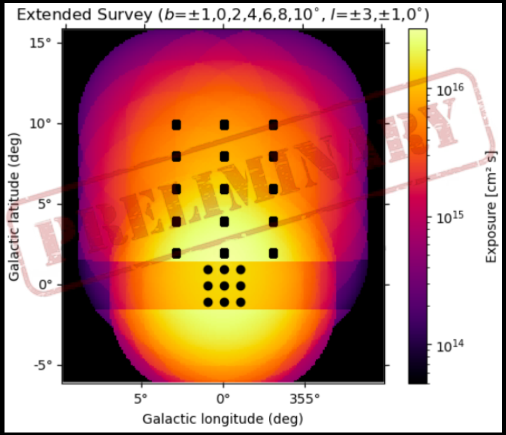
Summary and Future Prospects

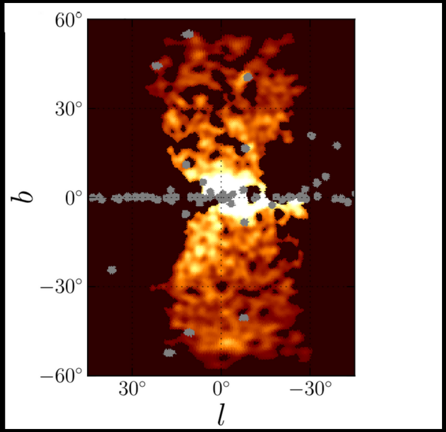
Summary

- CTAO is expected to detect the emission of Fermi Bubbles
- Fitting with a different IEM still allows us to recover the FB input model
- Adding the GP mask improves the recovery of the FB input model
- The results seem to be stable even with the inclusion of benchmark values for systematic uncertainties

Future Work

- Use the Extended Galactic Survey [The CTAO Consortium, 2021, 2007.16129]:
  - To check high latitude properties of FBs
  - To study the transition between high latitude and low latitude
- (Maybe) Use Extragalactic Survey [The CTAO Consortium, 2018, 1709.07997]
- Further quantify the role of systematic uncertainties
- Explore how sensitive CTAO will be to the cut-off of the FB





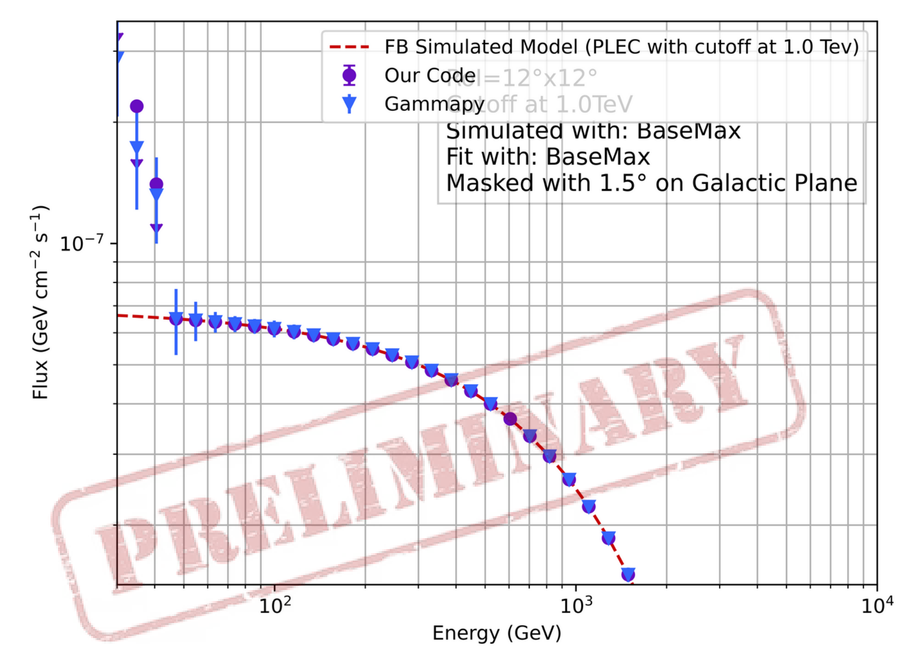
[The *Fermi*-LAT Collaboration,2017, 1704.03910]


Thank You!

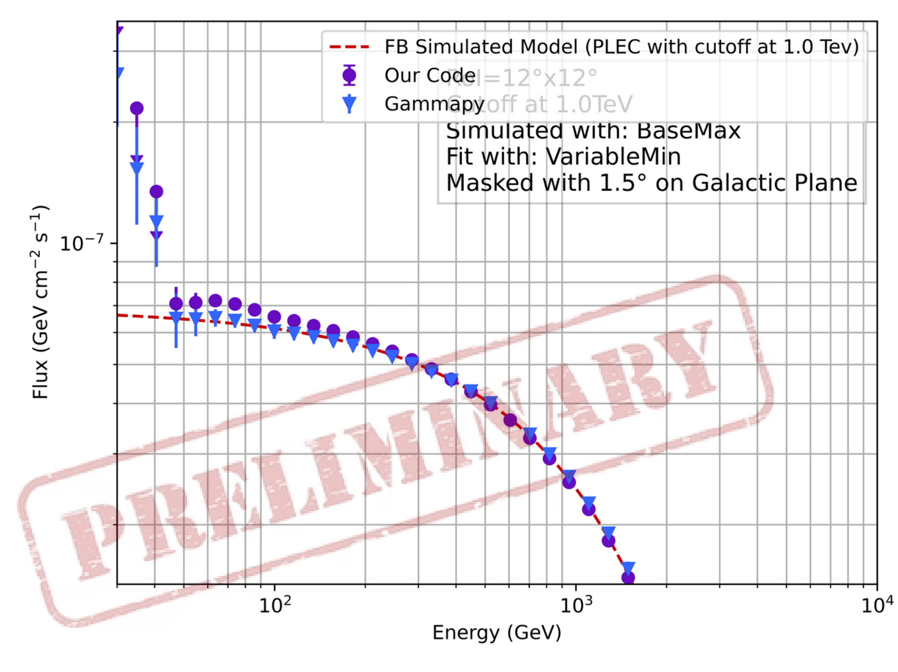
Fit Results: Gammapy vs. Minuit (Our Code)

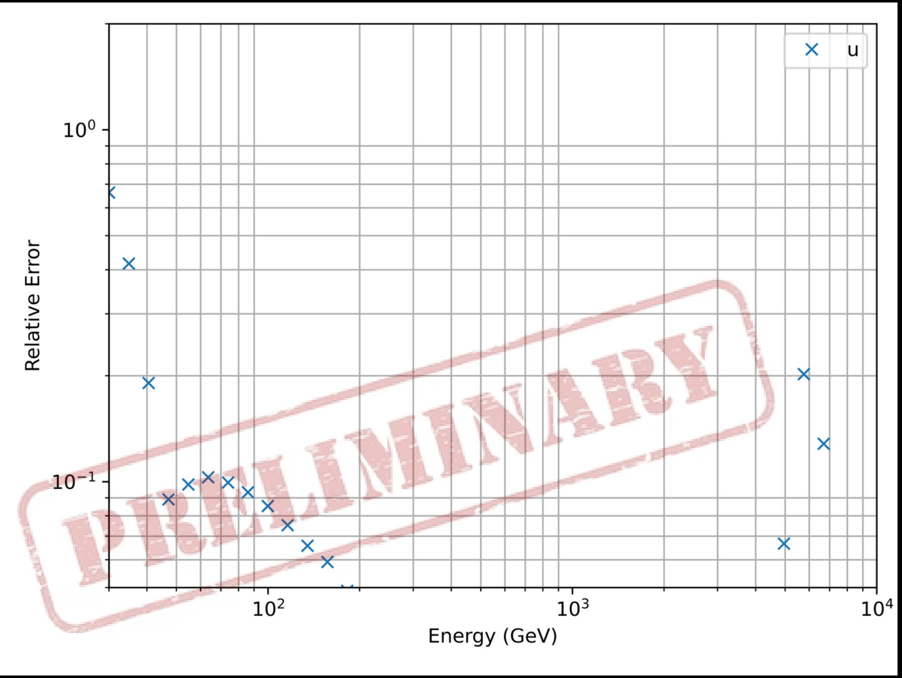
Since we cannot include systematic uncertainties in Gammapy, we check that the results from the fit in our code (using minuit) are in agreement with the ones produced by Gammapy following the same set-up:

- Global Fit
- Bin-by-bin Fit using the global fit normalizations
- Same model for simulations and fit (this slide)



Fit Results: Gammapy vs. Minuit (Our Code)





Here we show the second set-up, where we consider:

- Different model for simulation than for fitting

In conclusion we see that our results are compatible with gammapy

Extended Survey

Extended Survey may allow us:

- To study morphological properties of the FBs
- To study the transition between high and low latitude