Characterization of Galaxy Cluster Gamma-Rays

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CUNY Graduate Center, American Museum of Natural History, Flatiron Institute

Detecting gamma rays in galaxy clusters

Galaxy clusters (GCs) are the largest bound structures in the universe and host many energetic processes. Some of this activity, such as AGN jets, starburst supernovae, and galaxy mergers, can form large-scale shocks that can accelerate charged particles to relativistic speeds. These cosmic rays interact with the intra-cluster medium and radiation, producing high-energy gamma-rays that we analyze in this study through two different key mechanisms.

- Inverse Compton Scattering: $e^-_{CR} + \gamma_{ISM} \longrightarrow e^{-\prime}_{CR} + \gamma_\gamma$
- Proton-Proton Collisions: $p^+_{CR} + p^-_{CR} \longrightarrow \pi^+,\ \pi^-,\ \pi^0 \longrightarrow 2\gamma$

The cosmic ray electrons are evidently present in GCs from radio observations, but little is known about their cosmic ray proton prevalence. In spite of theory, barring one or two potential exceptions, galaxy clusters have yet to be confirmed observationally as gamma-ray sources.

Our main objectives:
- Detect gamma rays in these clusters
- Investigate the spectral properties of the gamma-ray cluster population

Detecting gamma rays in galaxy clusters

- We analyze 207 galaxy clusters within redshift z < 0.1, identified in the Planck Sunyaev–Zeldovich catalog, using 16 years of Fermi-LAT data between 300 MeV–100 GeV
- A binned maximum likelihood analysis is performed with *fermipy*. Each cluster is modeled with a point source spatial distribution and a power-law spectral model, yielding a Test Statistic (TS):

$$TS = 2\ln\left(\frac{L}{L_0}\right)$$

- L is the likelihood of a point source being present at the target's location
- $L0$ is the null hypothesis that there is no source.

- $\sqrt{TS} \approx$ source significance. (TS > 25 is considered a strong detection)
- Likelihood analysis was run on all 207 GC locations
- We expect galaxy clusters to be spatially modeled best as extended sources.
- Modeling our GC targets as extended sources can help validate the origin of detected γ-rays and identify embedded point source contaminants like AGN.
- Extension tests add an extra degree of freedom, slightly raising the TS detection threshold. This is shown by the blue dashed line in Figure 1.
- When our targets are refit as extended sources, we find a consistent increase in the likelihoods. This confirms the emissions we are detecting are from the Galaxy clusters and not embedded point sources!

Results

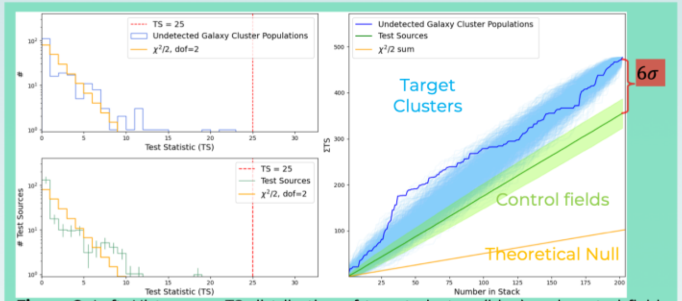
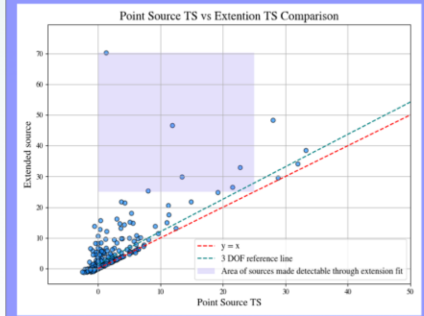


Figure 2: Left: Histograms TS distribution of target clusters (blue) and control fields (green) compared to the theoretical null (orange).
Right: Cumulative TS stack for the target clusters in random orders (blue) and Cumulative TS stack for control fields (green). Where the Green line is the mean cumulative CF TS and the Green envelope is the spread of CF realizations.



Fitting targets as extended sources bumps up our individual detections from 4 to 10 sources!

Figure 1: The effect of the two spatial models fit on the likelihoods of our galaxy clusters. The plot compares point-source TS (x-axis) with extended-source TS (y-axis). The purple box highlights clusters that cross the detection threshold when fit as extended sources.

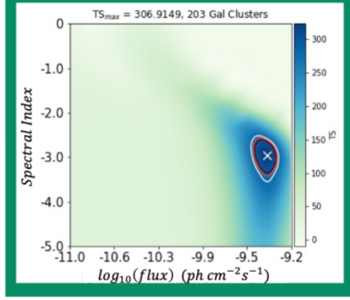


Figure 1: Stacked likelihood analysis across flux and spectral index (**γ**) parameter space. The color scale shows the cumulative Test Statistic (TS), with the maximum significance (TSmax ≈ 307) marked by the white cross. Contours denote 3**σ** and 5**σ** confidence regions. The peak indicates the best-fit average **γ**-ray properties of the cluster population, demonstrating a coherent stacked signal above background noise.

Getting above the noise

Individual galaxy clusters are often too faint in γ-rays to stand out from the extragalactic γ-ray background. To uncover a cumulative signal, we apply a **likelihood stacking technique**. This produces a cumulative Test Statistic (TS) that could detect a population's γ-ray emission.

- We compare our stacked targets to two sets of stacked control fields, designed to match the spatial distribution of our target clusters, to get the significance of our detections.
  - CF1: 361 random sky positions.
  - CF2: 400 higher-redshift (z = 0.2–0.4) clusters (undetectable by Fermi)
- The stacking routine was applied to all Target GC and Control Fields.
- The Difference in the Cumulative TS for these samples was used to find the significance of the population's detection using methods developed in [Henery et al. 2024].
- We find that our stacked Target TS values are consistently higher than the cumulative control field TS values with a significance of 6σ, making our galaxy cluster population well-detected in γ-rays.

Investigating spectral properties

To get a better understanding of our galaxy cluster population's spectral properties, we perform a **TS stack in spectral parameter space.**

- Sources are fit with a power law spectral model whose parameters include the index (spectral slope) and flux.
- We run our likelihood pipeline over a grid of flux and index values.
- By choosing one of the grid spaces as our null likelihood, we can produce a TS map in spectral parameter space for a given source.
- This process was done on all 207 of our sources, and the resultant TS maps were stacked to create a cumulative spectral parameter stack (Figure 3).
- We find that the most likely index value for our population of galaxy clusters is: $\gamma = -3.0$
- The average spectral index can help inform emission mechanisms taking place in the cluster.

Future work/continuation of the study

- Run the parameter stack on our control fields to find the significance of our detections.
- Use parameter stacks for likelihood correlation analysis of our sub-threshold population, comparing their γ-ray luminosities to their x-ray and radio luminosities.
- Model the SED with, e.g., naima, to gauge the prominence of whether radiation is dominated by hadronic or leptonic processes. Stack plots

Galaxy Clusters

- The largest bound structures in our universe!
  - Most of its baryonic mass is in hot plasma → seen in X-ray
- Full of very high-energy interactions!

- AGN Jets
- Starburst Supernova
- Galaxy Mergers

→ **SHOCKS** → *Cosmic Rays*

Credit: ESO/M. Kornmesser

Comic Ray → Gamma Ray

Inverse Compton Scattering:

$$e^{-}_{CR} + \gamma_{\mathrm{CMB}} \longrightarrow e^{-\prime}_{CR} + \gamma_{\gamma}$$

Proton-Proton Collisions:

$$p^{+}_{CR} + p^{+}_{ICM} \rightarrow \pi^{+},\ \pi^{-},\ \pi^{0}$$

$$\pi^{+}, \pi^{-} \rightarrow \mu^{\pm} \rightarrow e^{\pm},\ \nu$$

$$\pi^{0} \longrightarrow 2\gamma$$

Cosmic ray electrons:

- See them in GC through radio observations
- Short energy loss timescale

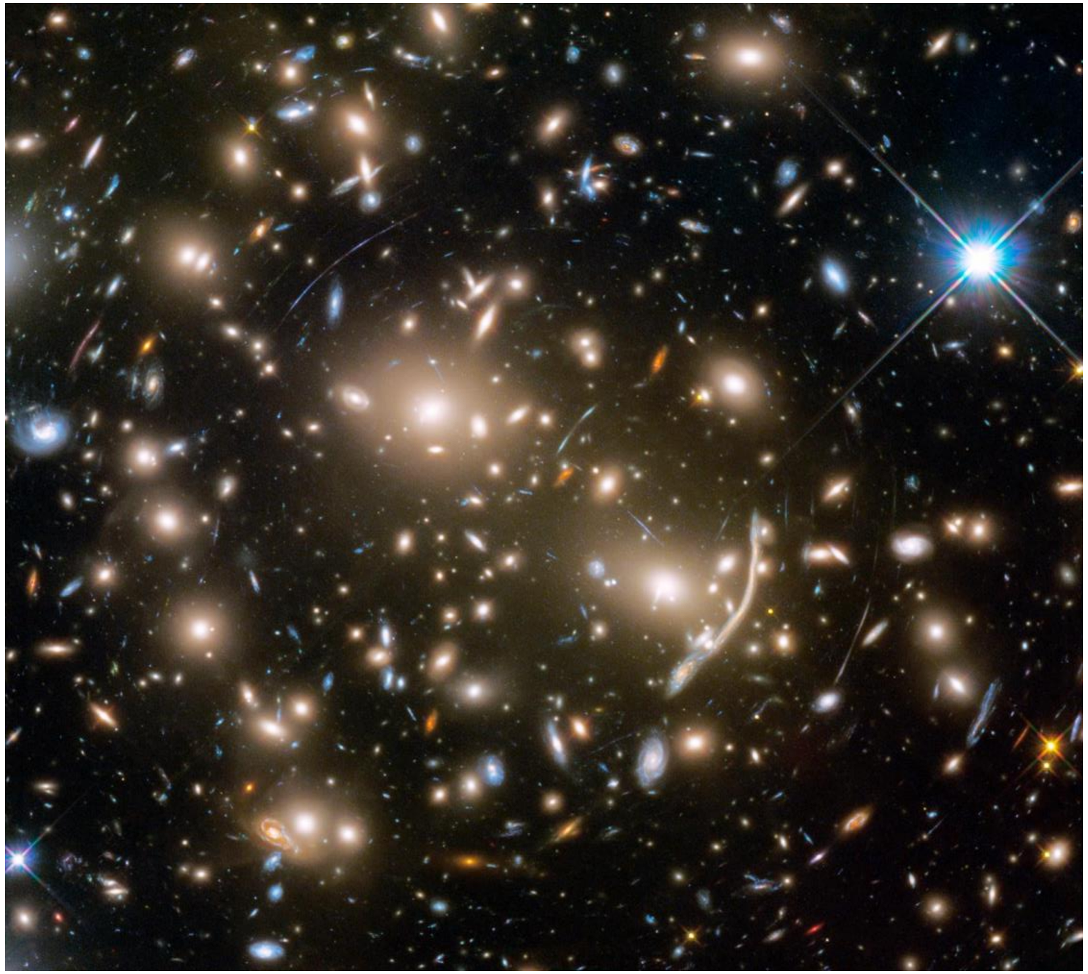
Cosmic Ray Protons:

- Long high energy lifetime
- Prevalence in galaxy clusters remains uncertain

Galaxy clusters are not observationally confirmed gamma-ray sources!?

~ Barring a few exceptions

- Ex. Coma Galaxy Cluster [**Adam et al (2021)**]

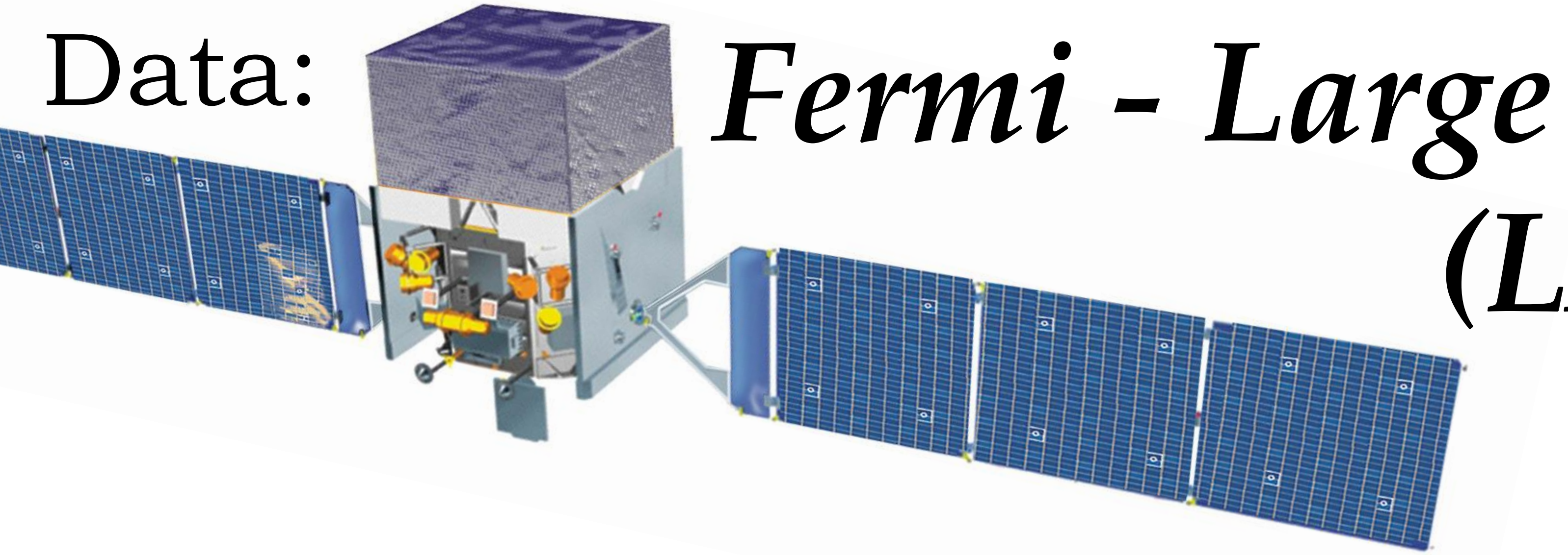


➢ **Main objectives in this study:**

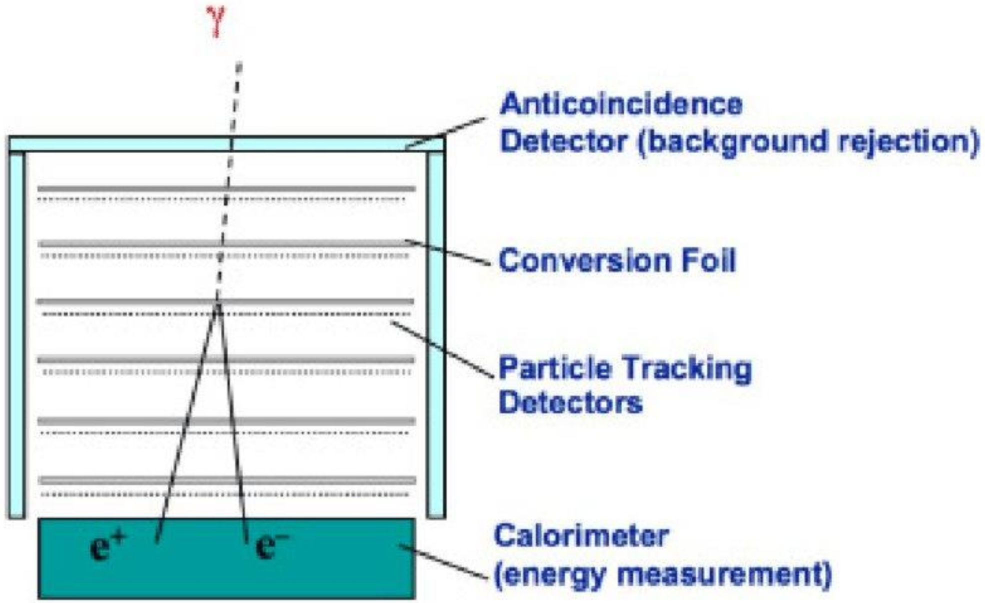
- **Detect gamma rays in these clusters**
- **Investigate galaxy cluster gamma rays spectral properties**

- Ultimately, try to CR protons' role in gamma ray emission

Data: *Fermi - Large Area Telescope (LAT)*



- ➢16 years of Fermi-LAT data
  - Photon energy ranges from 300 MeV–100 GeV
- ➢We analyze 207 galaxy clusters identified in the Planck Sunyaev–Zeldovich Catalog
  - redshift $z < 0.1$
- ❖Photon sparsity at this energy requires special analysis



Lopez-Oramas 2015

Maximum likelihood analysis

1. Look at the photon data at the location of galaxy clusters.
2. Built a source model and fit it to our data
   - spatial component
   - spectral component
3. Use likelihood to measure how well the model fits our data
4. Maximize the likelihood to get the best-fit model parameters.
5. Find the **TS** value to gauge detection significance.

Likelihood (Poisson):

$$L(\theta) = \prod_{ij} \frac{\theta_{ij}^{n_{ij}} e^{-\theta_{ij}}}{n_{ij}!}$$

Log Likelihood:

$$ln\, L\,(\theta) = \sum_{ij} n_{ij}\, ln\, \theta_{ij} - \sum_{ij} \theta_{ij}$$

Pixel

Observed counts

Modeled counts

Test Statistic

$$\mathrm{TS} = 2 \times (ln\, L - ln\, L_0)$$

(Mattox+ 1996)

TEST STATISTIC = *Best Statistic*

$$TS = 2\ln\left(\frac{L}{L_0}\right)$$

- L is the likelihood of a source being present at the target's location
- $L0$ is the null hypothesis, the likelihood that there is no source at a target's location.

➢ TS value reflects the significance of a source's emission

$\sqrt{TS} \approx$ Source Significance

➢ For Fermi-LAT analysis

$TS > 25$ = strong detection (5σ)

Initial run

Source Model

Spectral model: Power law

$$\frac{dN}{dE} = N_0 \left(\frac{E}{E_0}\right)^{\gamma}$$

Spatial model: Point Source

⇨ Results: 4 detected sources

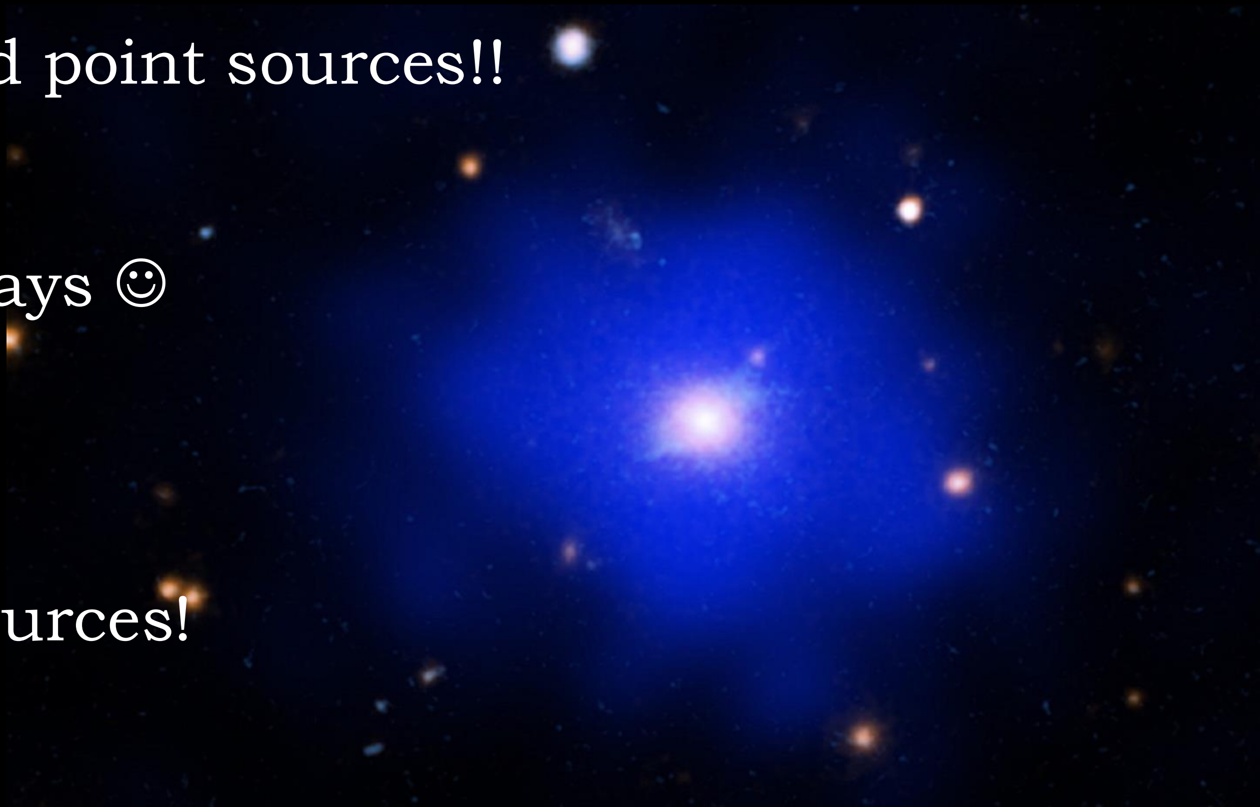
~Does this model construction best represent our GC gamma-rays?

GC Gamma - Ray = Extended Source?

- Galaxy clusters are HUGE! Emissions spatial extent > Fermi's point spread function
- Gamma-ray emission from GC should be throughout the volume of the cluster.
- Don’t want emissions from embedded point sources!!

Extension Fit:

- Confirms the source of our gamma-rays ☺
- Quantifies point source ☺
- Adds a degree of freedom ☹
- Lets refit our clusters as extended sources!



Galaxy Clusters TS values

Results:

- ✓ Refitting GC targets as extended sources consistently increases the likelihoods!
- ✓ Extension fit bumped up our individual detections from 4 to 10 sources!!

We are seeing these Galaxy clusters with gamma rays!!!

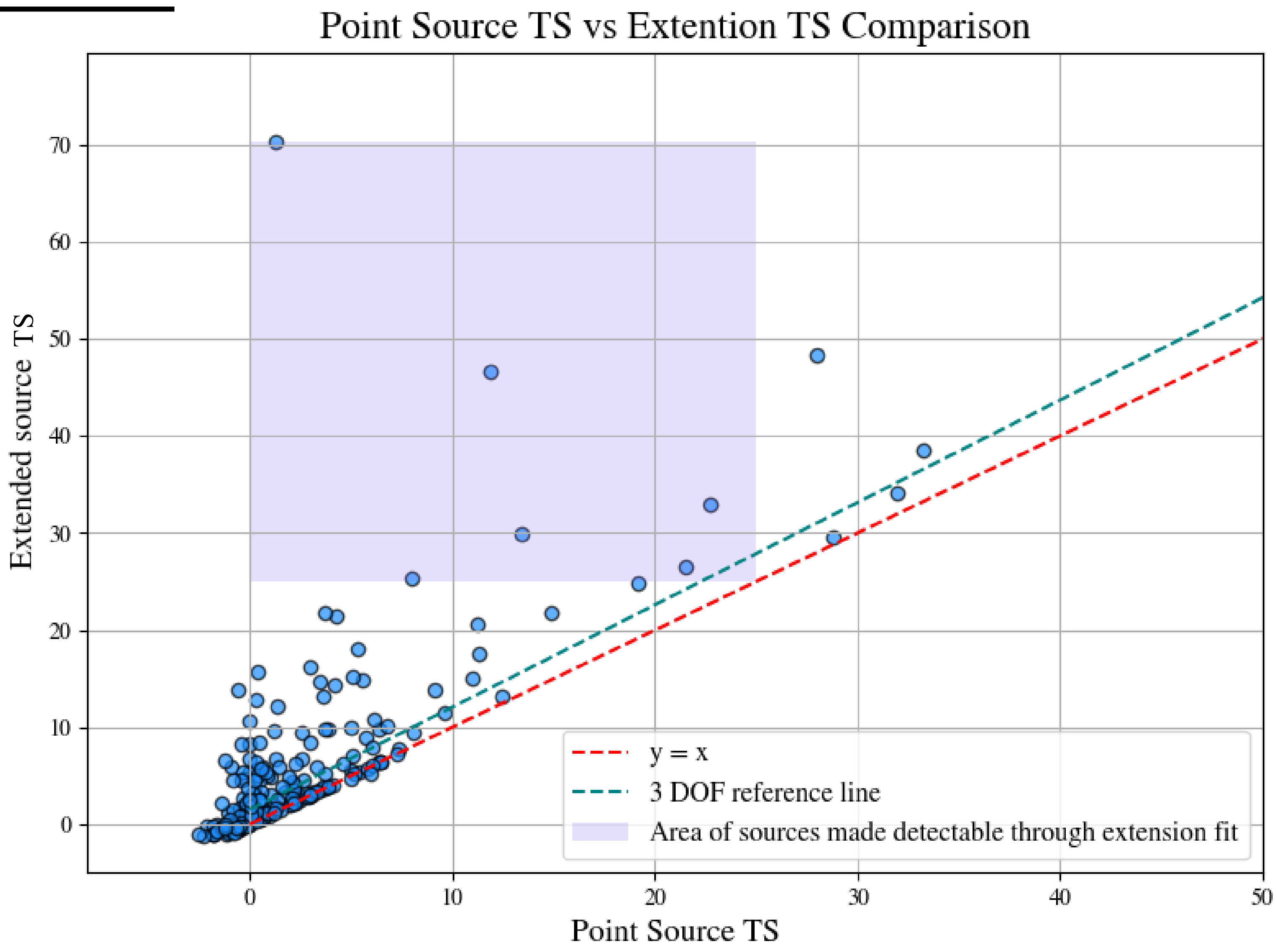


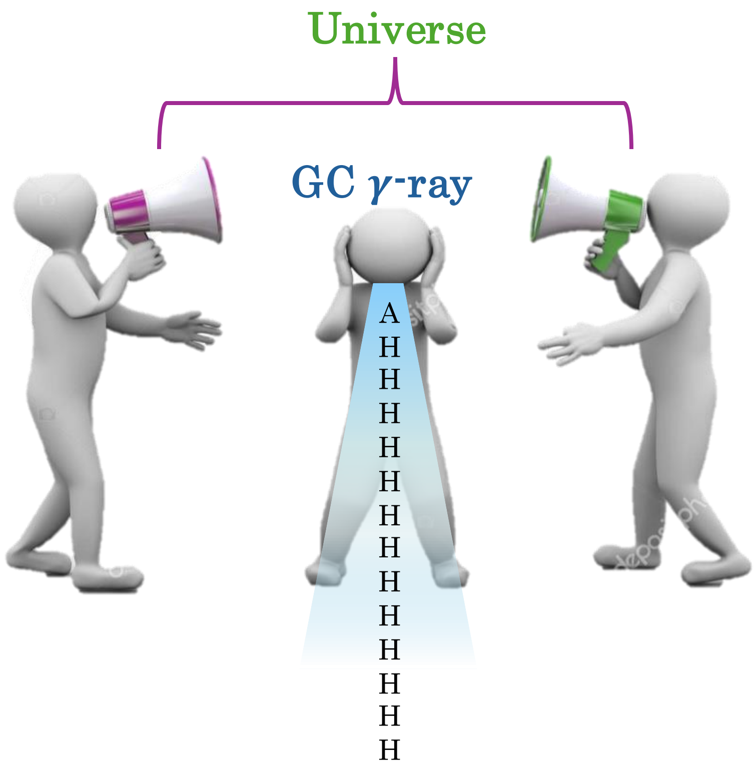
Figure 1: The effect of the two spatial models fit on the likelihoods of our galaxy clusters.

But what about the other 194 clusters? ☹

- Hard to see above all the extragalactic γ-ray background noise

- Special analysis technique

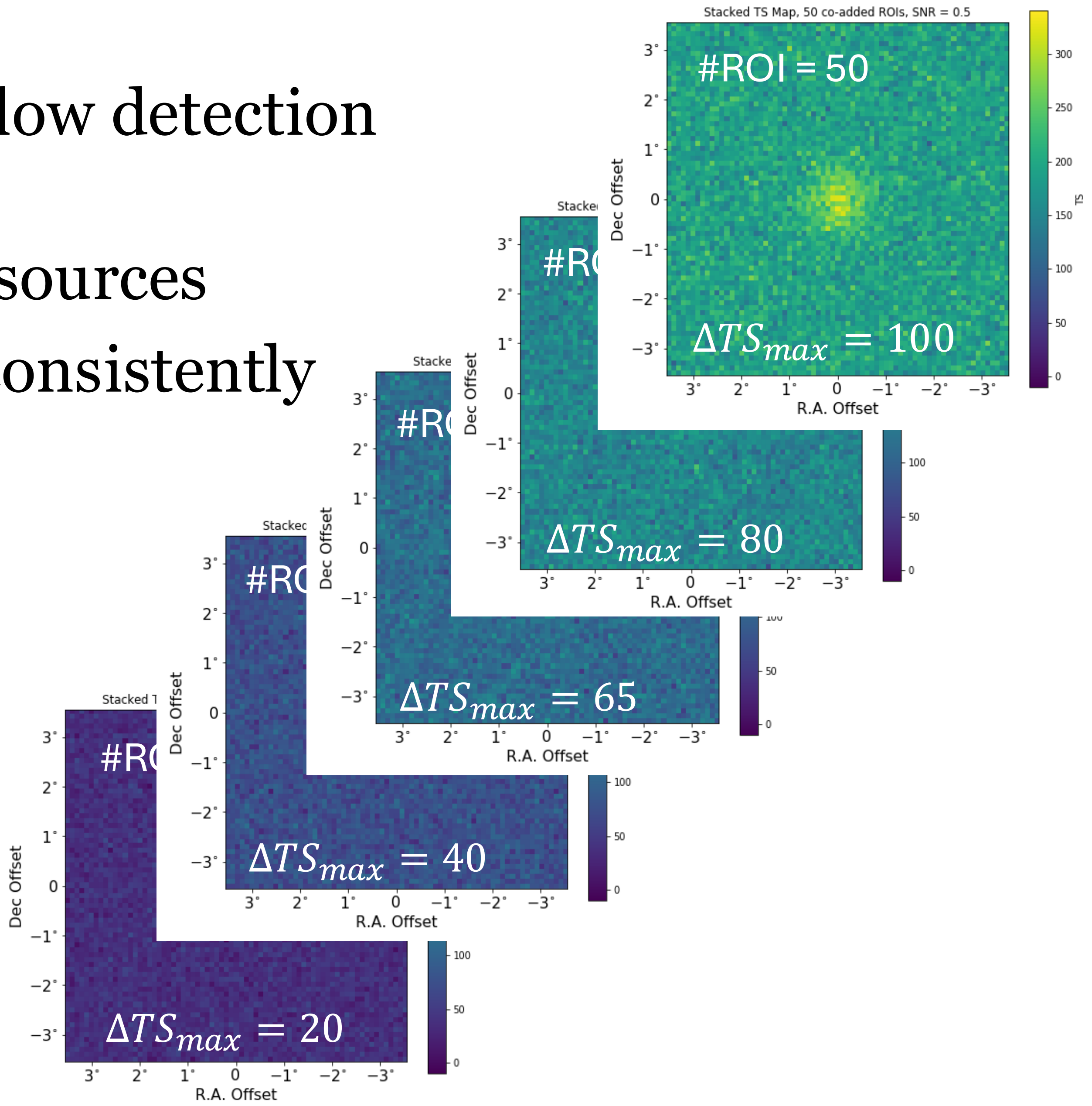
- Likelihood stacking → cumulative signal



Likelihood stacking

~A similar idea to stacking photon counts

- An individual cluster's signal falls below detection thresholds
- Stack several of these sub-threshold sources
- Persistent gamma-ray signal stacks consistently
- Random background noise will not (average out)
- The Cumulative gamma ray signal stacks above the noise
- Detect a population's γ-ray emission
- Compare to background for detection significance

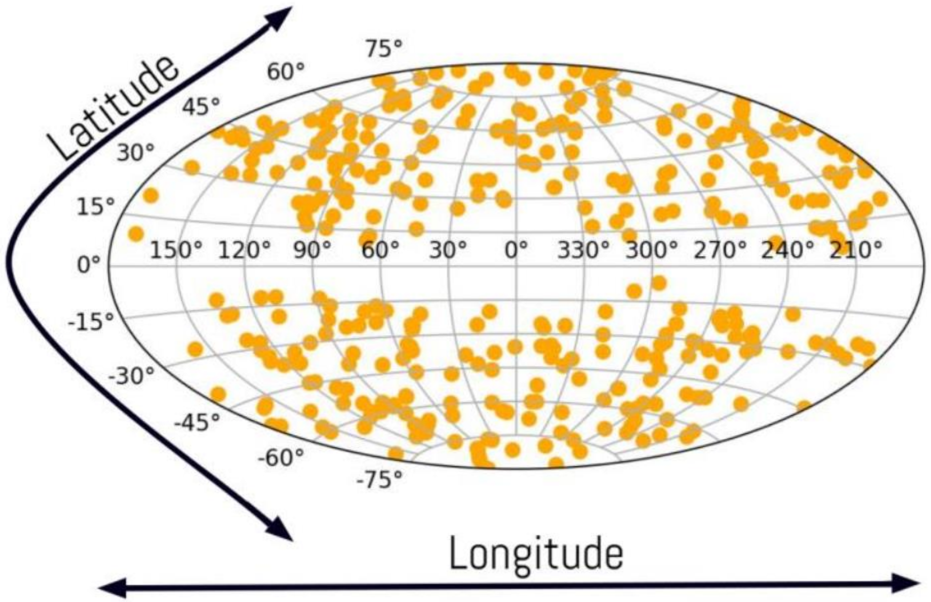


Background = Control Fields (CF)

~CF Spatial distribution designed to model GC background distribution

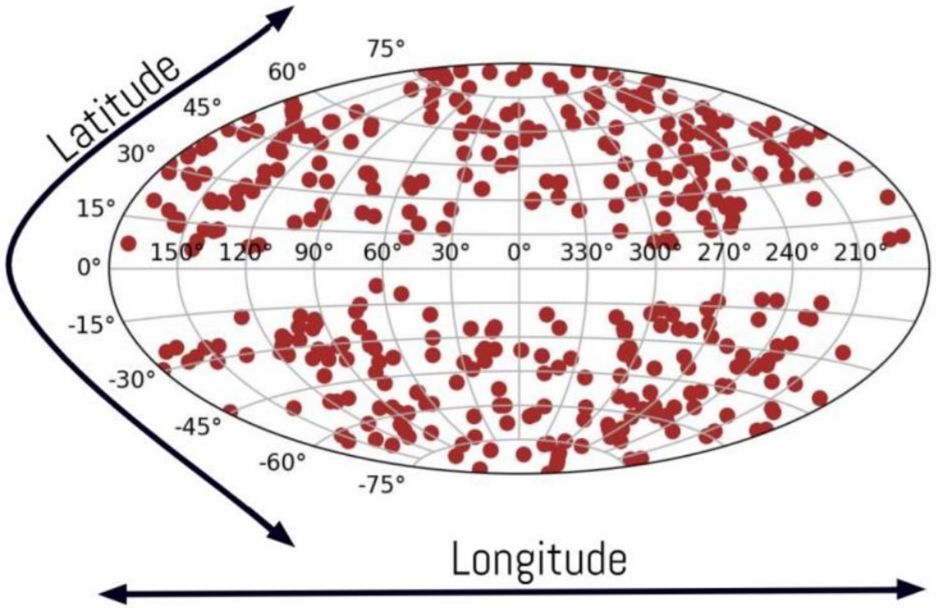
CF 1 → empty source pop

- 361 sources
- Random sky positions.



CF 2 → Reference clusters

- 400 sources
- higher-redshift (z = 0.2–0.4)



The Cumulative TS Stack

- Apply the resampling scheme to estimate uncertainty

Blue lines: cumulative stacks of target clusters in random orders.

Green line: mean cumulative CF TS.

Green envelope: standard deviation of CF realizations.

Orange line: the theoretical $\chi^2/2$ null distribution

Red Box: Source detection significance (Kullback-Leibler)

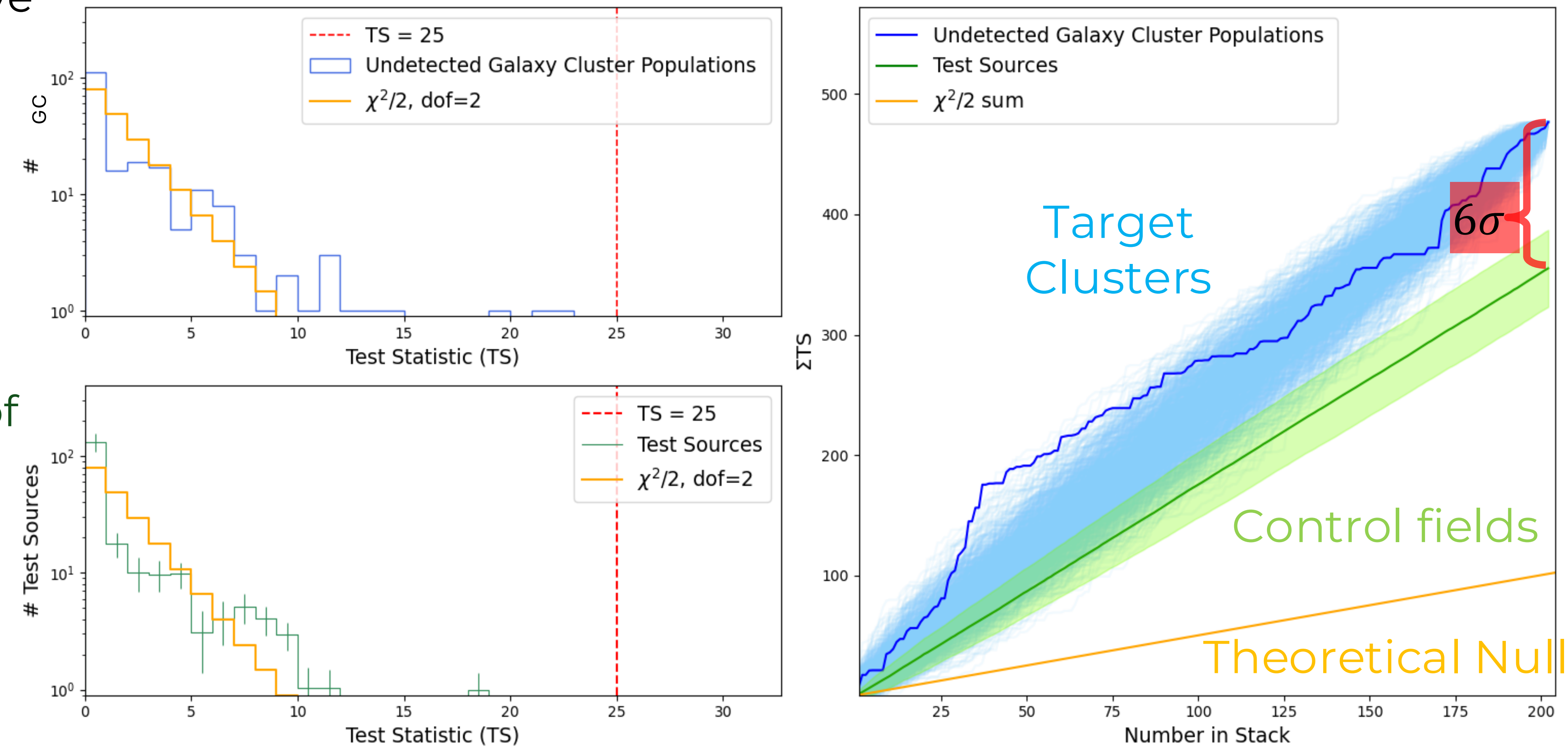
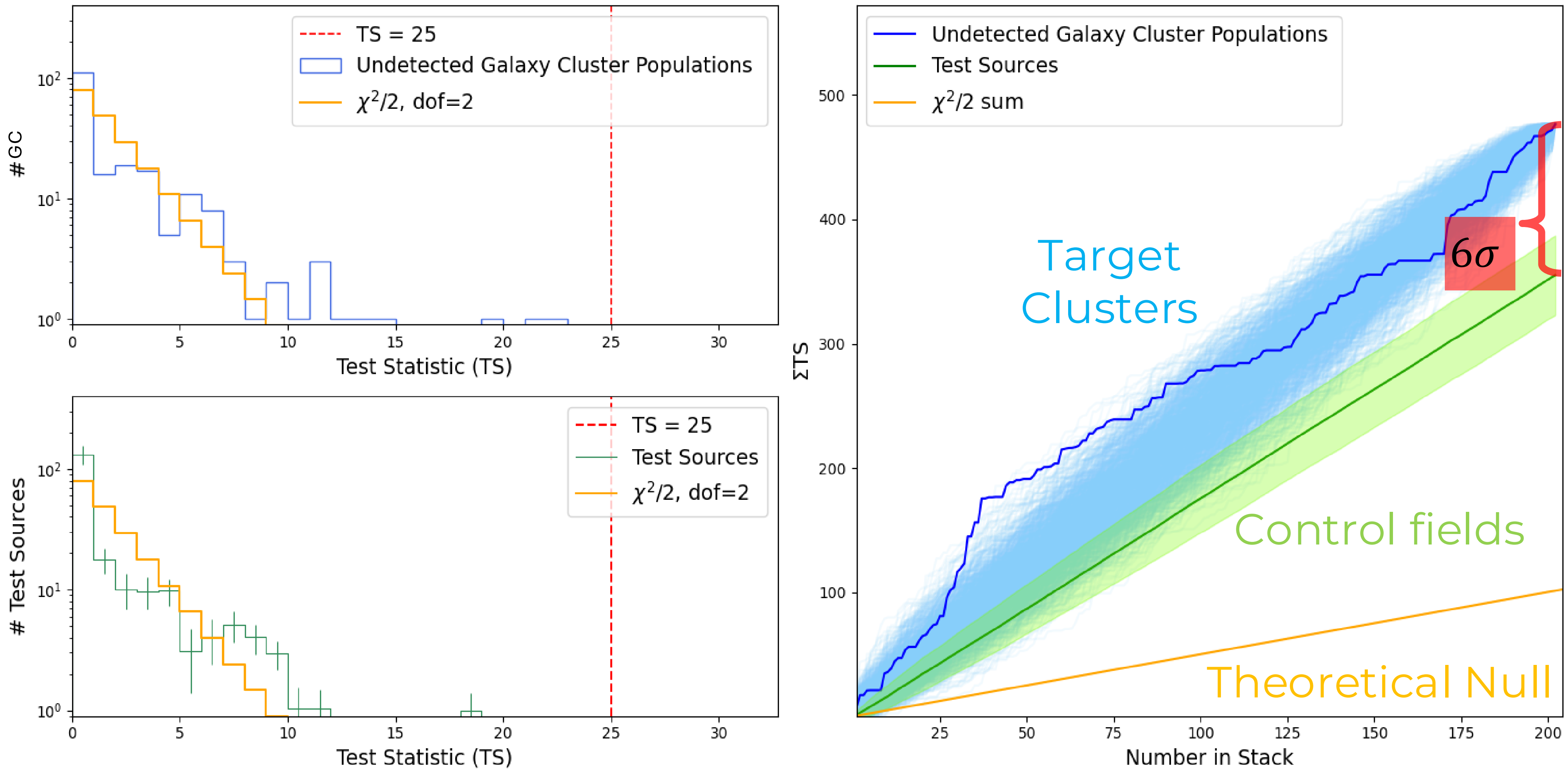


Figure 4. A histogram of the TS values of the undetected targets (upper left), the control fields (lower left), and the cumulative TS values (right) using the reference clusters.

Galaxy clusters are well detected in gamma-ray!!



We know they are there!! Lets learn more!

Investigating spectral properties

~Perform a TS stack in spectral parameter space.

- Sources fit with a power law spectral model, parameters include:
  - N_0 = Perfector (flux)
  - γ = Spectral Index (spectral slope)
- Normally:
  - Spectral parameters remain free to be fit
  - Find best model parameter values
- Now: re-run our likelihood pipeline and for a specific index and flux value.

$$\frac{dN}{dE} = N_0 \left(\frac{E}{E_0}\right)^{\gamma}$$

ILLUSTRIS

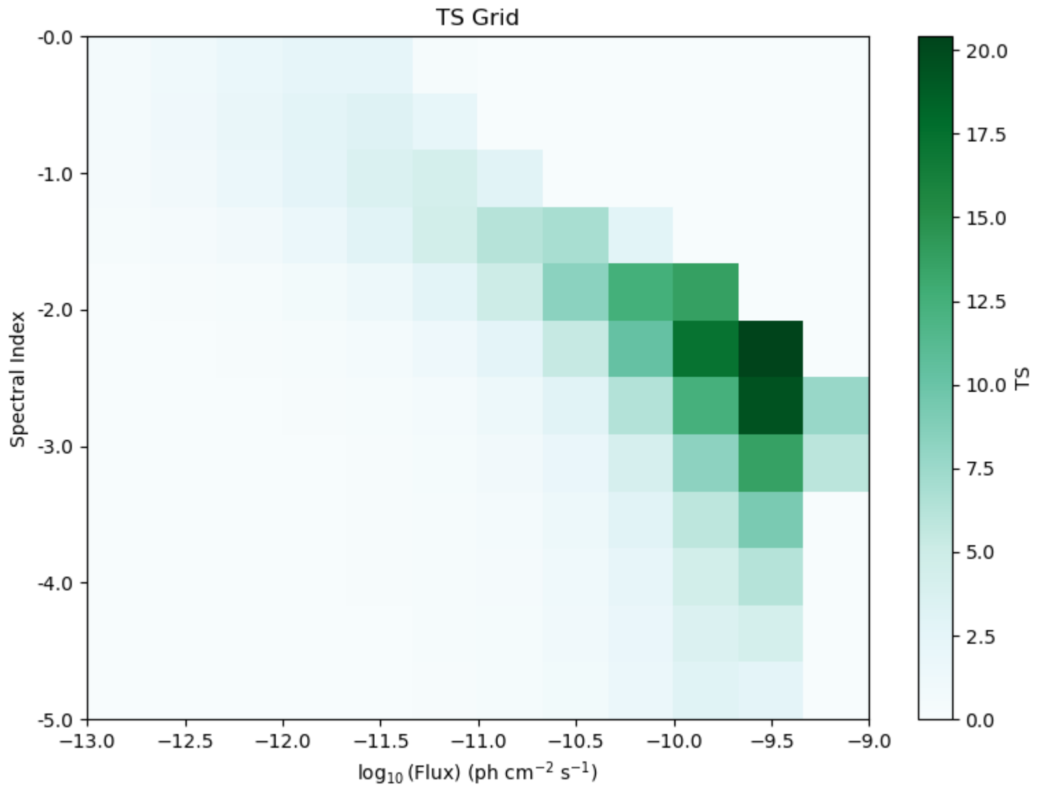
Investigating spectral properties

- Repeat likelihood pipeline over a grid of flux and index values

- Choose null likelihood grid block

- Produce a TS map in spectral parameter space for a given source.

  ✓Best parameters for the model
  ✓Degeneracy and uncertainties



- Repeat parameter map process for the entire population

- Stack resultant TS maps were stacked to create a **Cumulative Spectral Parameter Stack.**

Cumulative Spectral Parameter Stack

- Improves faint sources detection sensitivity
- Constrain model parameter
- Gauge parameter uncertainties
- Find most likely spectral index value

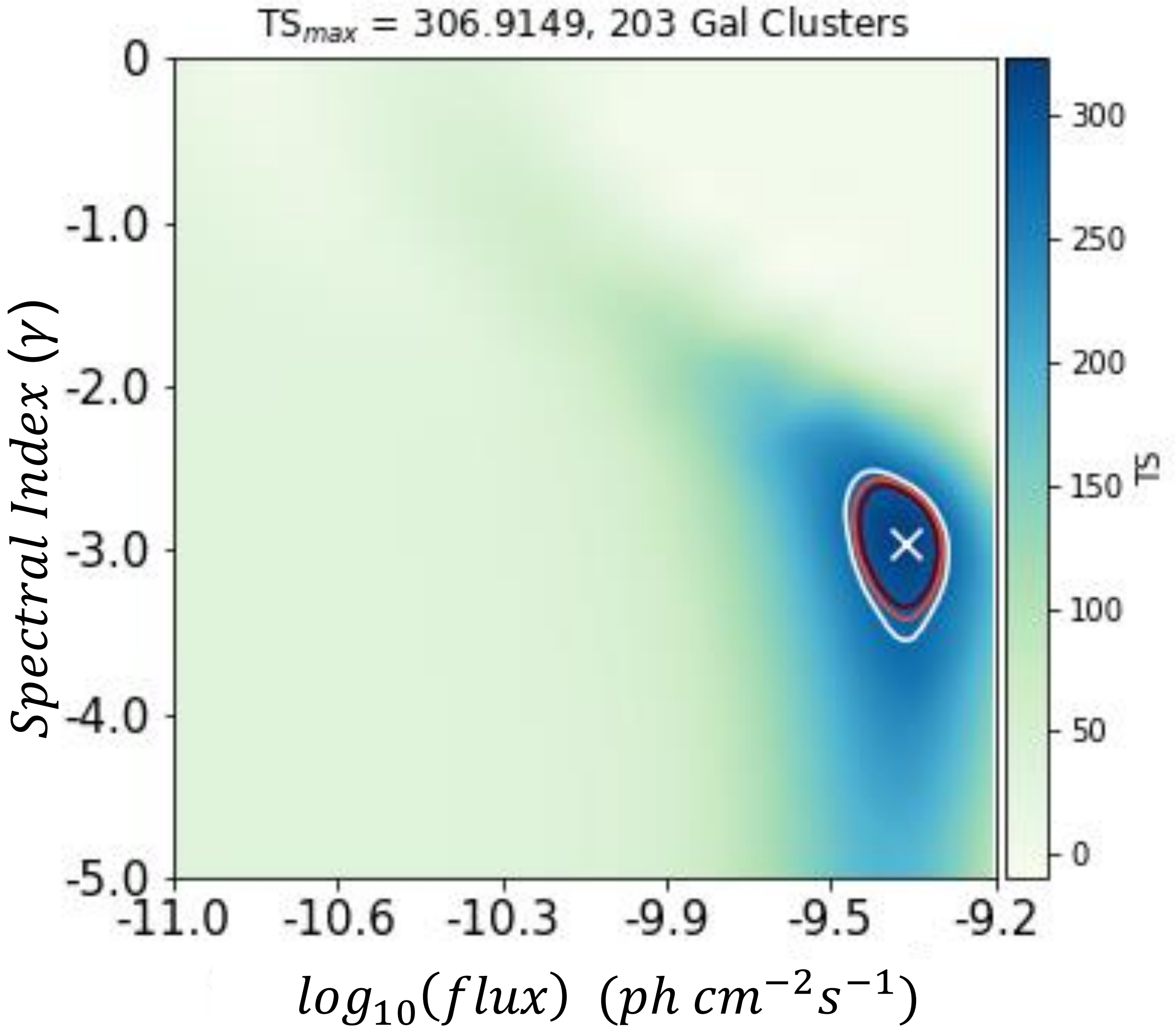
→Informs the dominant Galaxy Cluster γ-Ray Emission mechanism

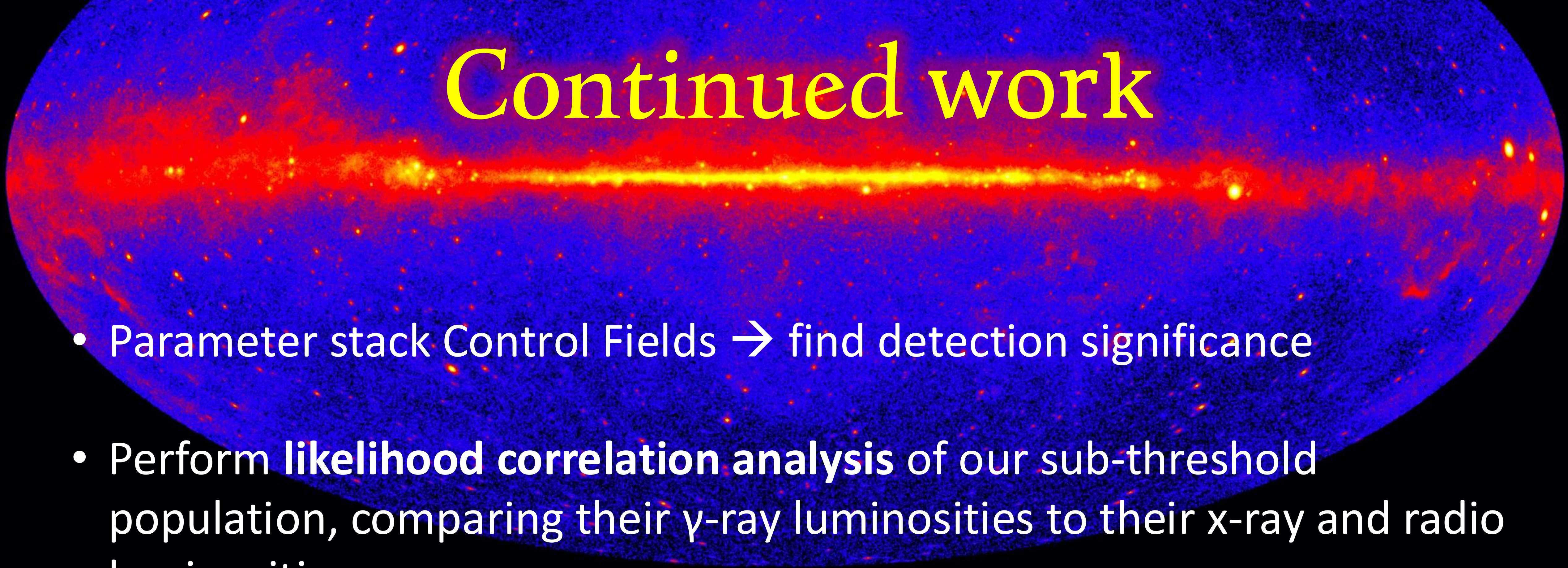
Result:

- Most likely index value for our population of galaxy clusters is:

$$\gamma = -3.0$$

- Well isolated
- below the sensitivity limit of the LAT (not an upper limit)





Continued work

- Parameter stack Control Fields → find detection significance
- Perform **likelihood correlation analysis** of our sub-threshold population, comparing their γ-ray luminosities to their x-ray and radio luminosities
- Model the Spectral Energy Distribution with Naima, to gauge the dominance of hadronic or leptonic radiation processes.

Questions?

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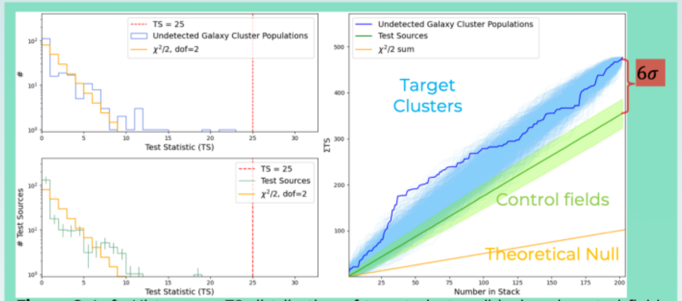

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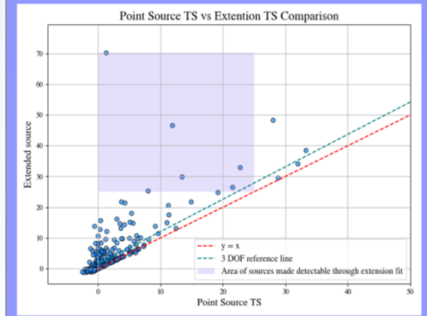

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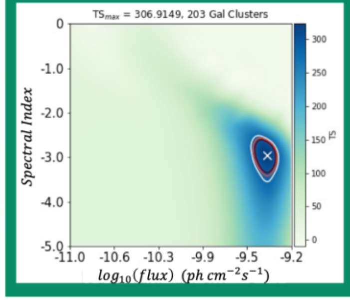

Figure 1: Stacked likelihood analysis across flux and spectral index (**γ**) parameter space. The color scale shows the cumulative Test Statistic (TS), with the maximum significance (TSmax ≈ 307) marked by the white cross. Contours denote 3**σ** and 5**σ** confidence regions. The peak indicates the best-fit average **γ**-ray properties of the cluster population, demonstrating a coherent stacked signal above background noise.

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