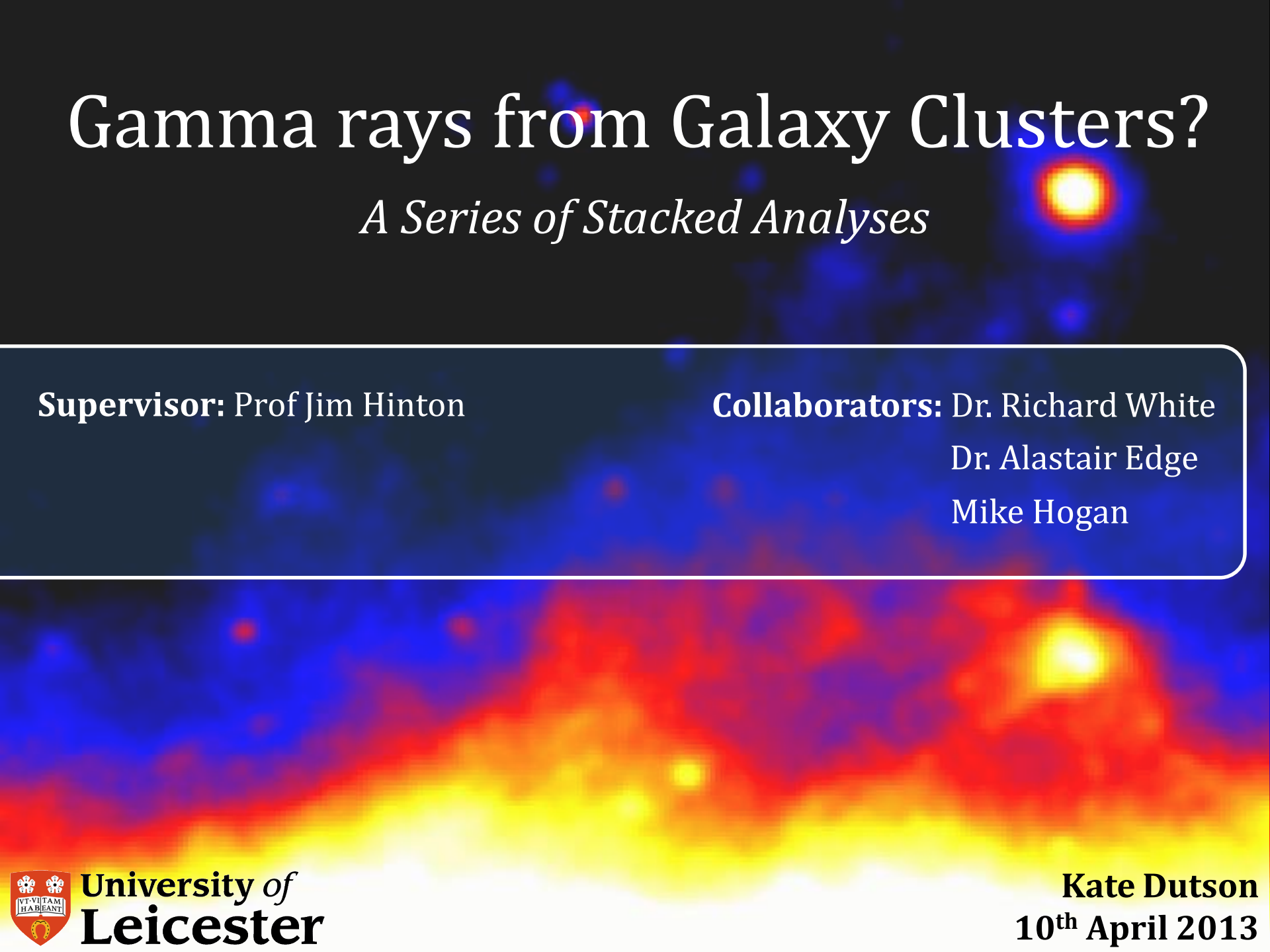
Gamma rays from Galaxy Clusters?

A Series of Stacked Analyses

Supervisor: Prof Jim Hinton

Collaborators: Dr. Richard White
Dr. Alastair Edge
Mike Hogan



University *of* Leicester

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An Outline…

- Galaxy Clusters
  - Emission scenarios and scales
- Some words about *Fermi*
  - The LAT instrument
  - The analysis procedure
- The work
  - Three samples
  - Preliminary results and interpretation

Galaxy Clusters

- Largest gravitationally-bound structures in the Universe
- Bremsstrahlung X-rays reveal hot intra-cluster gas (10^7 – 10^8 K)
- Presence of dark matter inferred
- *Cooling flows* where

$$t_{\text{cool}} < t_{\text{age}}$$

Pandora's Cluster

Galaxy Clusters - Dark Matter

- Indirect detection of dark matter through annihilation signatures in the γ-ray band proposed
- Neutralino is the popular WIMP candidate
- Clusters good targets due to high theoretical dark matter content

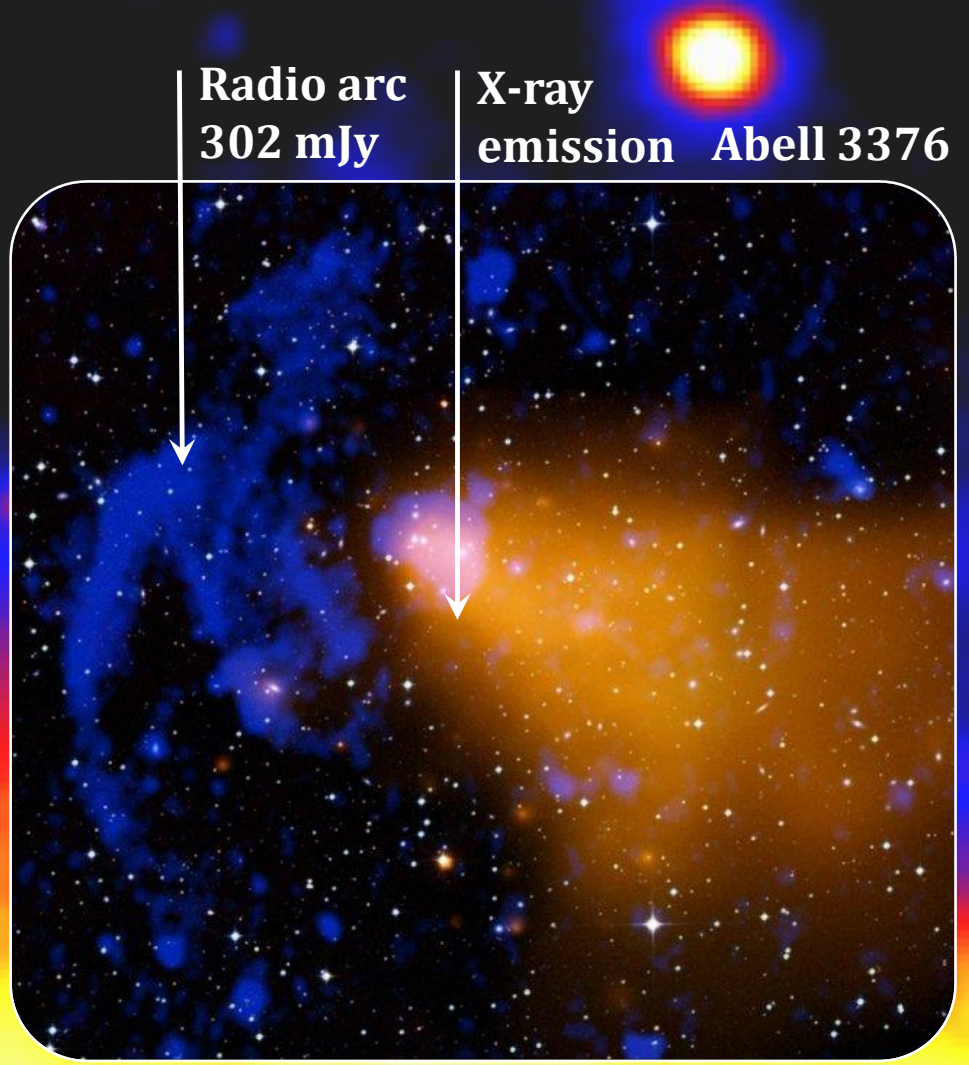
Pandora's Cluster

Galaxy Clusters - BCGs

- In *cooling-core* clusters suppression of the cooling flow is observed, necessitating some reheating mechanism…
- Feedback from the central Brightest Cluster Galaxy (BCG) suggested.
- Gamma rays from AGN-driven processes

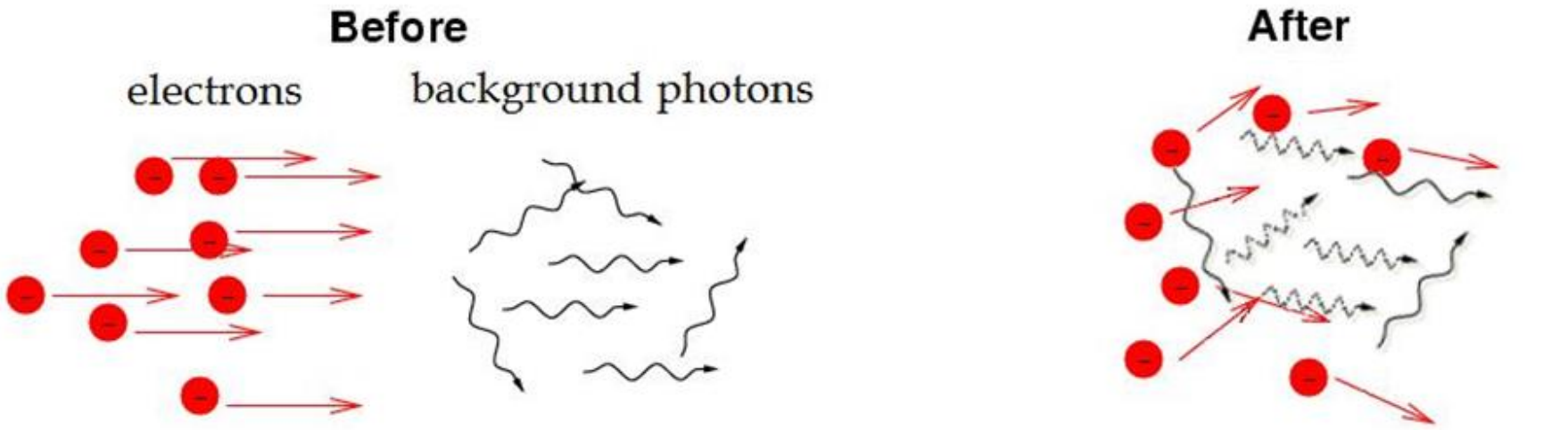
Galaxy Clusters - Diffuse Sources

- Zoo of diffuse baryonic sources observed in massive clusters:
  - *Radio halos*
  - *AGN relics*
  - *Radio phoenixes*
  - *Radio gischts*
  - *Mini-halos*
  - *Confined cluster cores*
- Associated with merger shocks; past AGN activity



γ-rays from Clusters?

- Gamma radiation is a tracer of Cosmic-ray acceleration.
- Clusters of galaxies are reservoirs of non-thermal particles and dark matter
- HE Emission via inverse Compton scattering:



γ-rays from Clusters?

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- Clusters of galaxies are reservoirs of non-thermal particles and dark matter
- HE Emission via inelastic proton-proton collisions:

$$p + p \rightarrow p + p + \pi^0 \qquad \pi^0 \rightarrow \gamma\gamma$$

$$p + p \rightarrow p + n + \pi^+$$

$$\pi^+ \rightarrow \mu^+ + \nu_\mu \rightarrow e^+ + \nu_e + \nu_\mu + \bar{\nu}_\mu$$

$$\pi^- \rightarrow \mu^- + \bar{\nu}_\mu \rightarrow e^- + \bar{\nu}_e + \nu_\mu + \bar{\nu}_\mu$$

γ-rays from Clusters?

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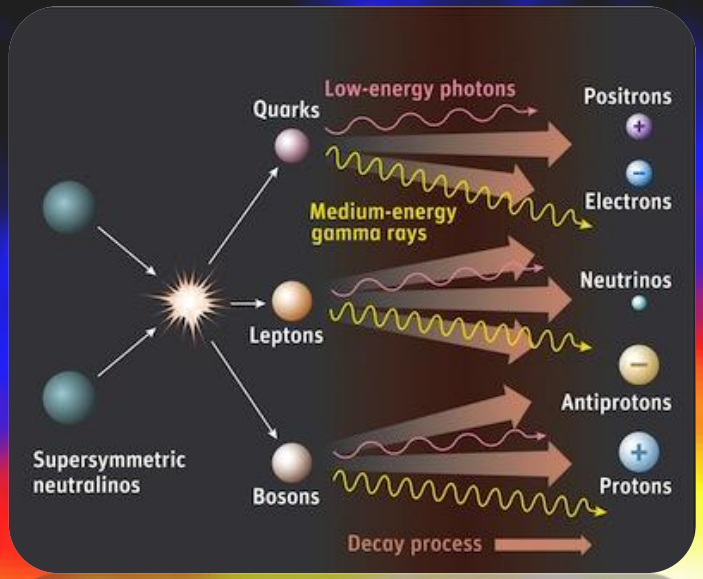
- HE Emission via dark matter annihilation:



- Supersymmetric neutralino self-annihilation
- Leptonic and hadronic channels both produce γ-ray signal

The *Fermi Gamma-ray Space Telescope*

- Launched in 2008
- Carries the **Large Area Telescope** (LAT), which is sensitive to γ-rays of energy **20 MeV – 300 GeV**
- Surveys whole sky every ~3 hours (two orbits)

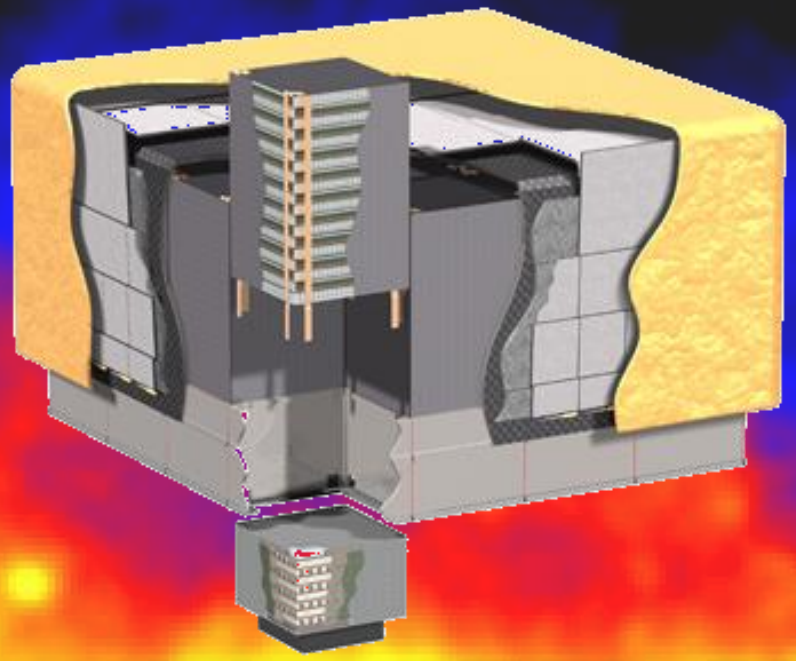
The *Fermi Gamma-ray Space Telescope*

The LAT:

- FoV 2.4 sr
- Energy-dependent angular resolution of 0°.15 – 3°.5

Inside the LAT:

- Background rejection (ACD)
- Pair production in tracker
- Electromagnetic cascade in calorimeter: 8.6+ radiation lengths
- Event reconstruction



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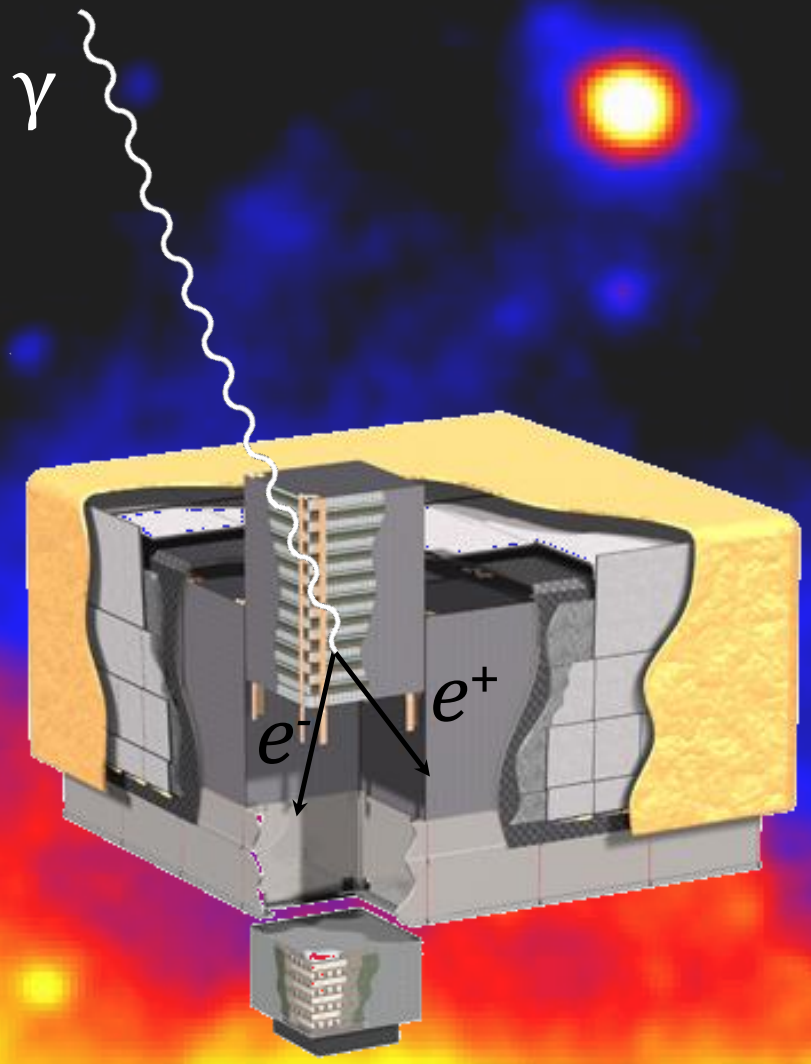

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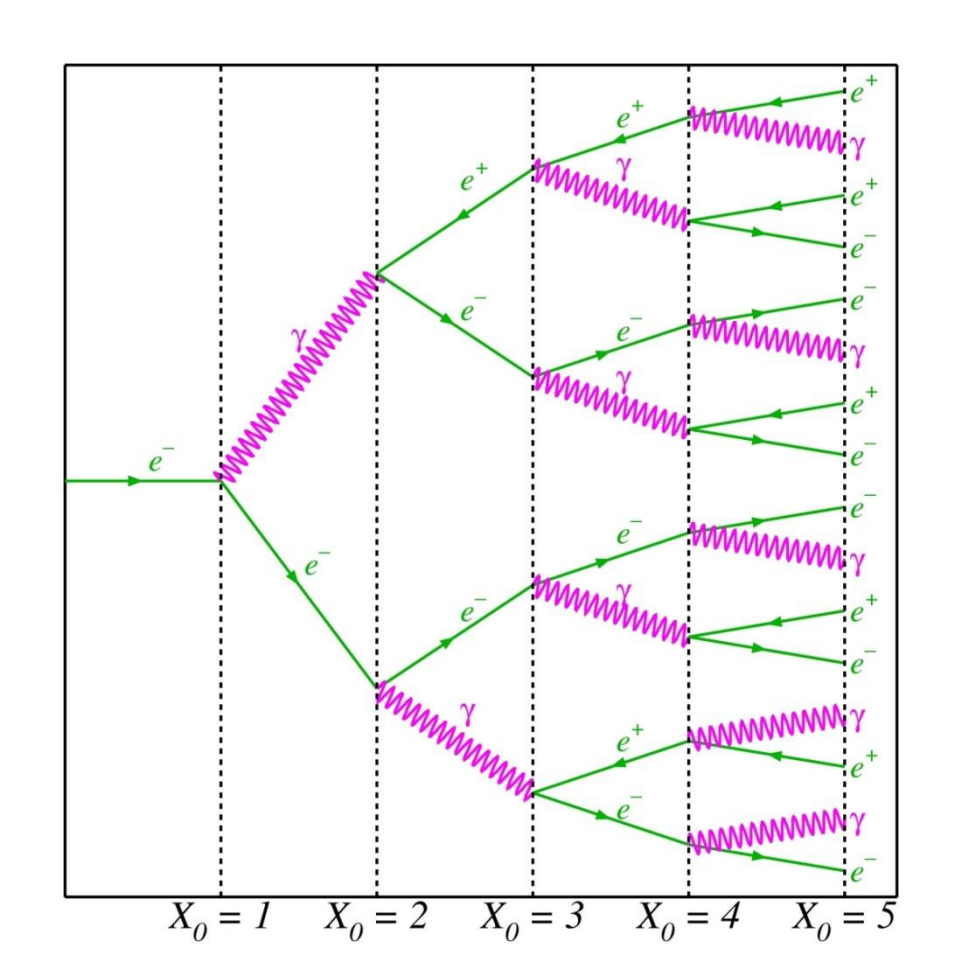
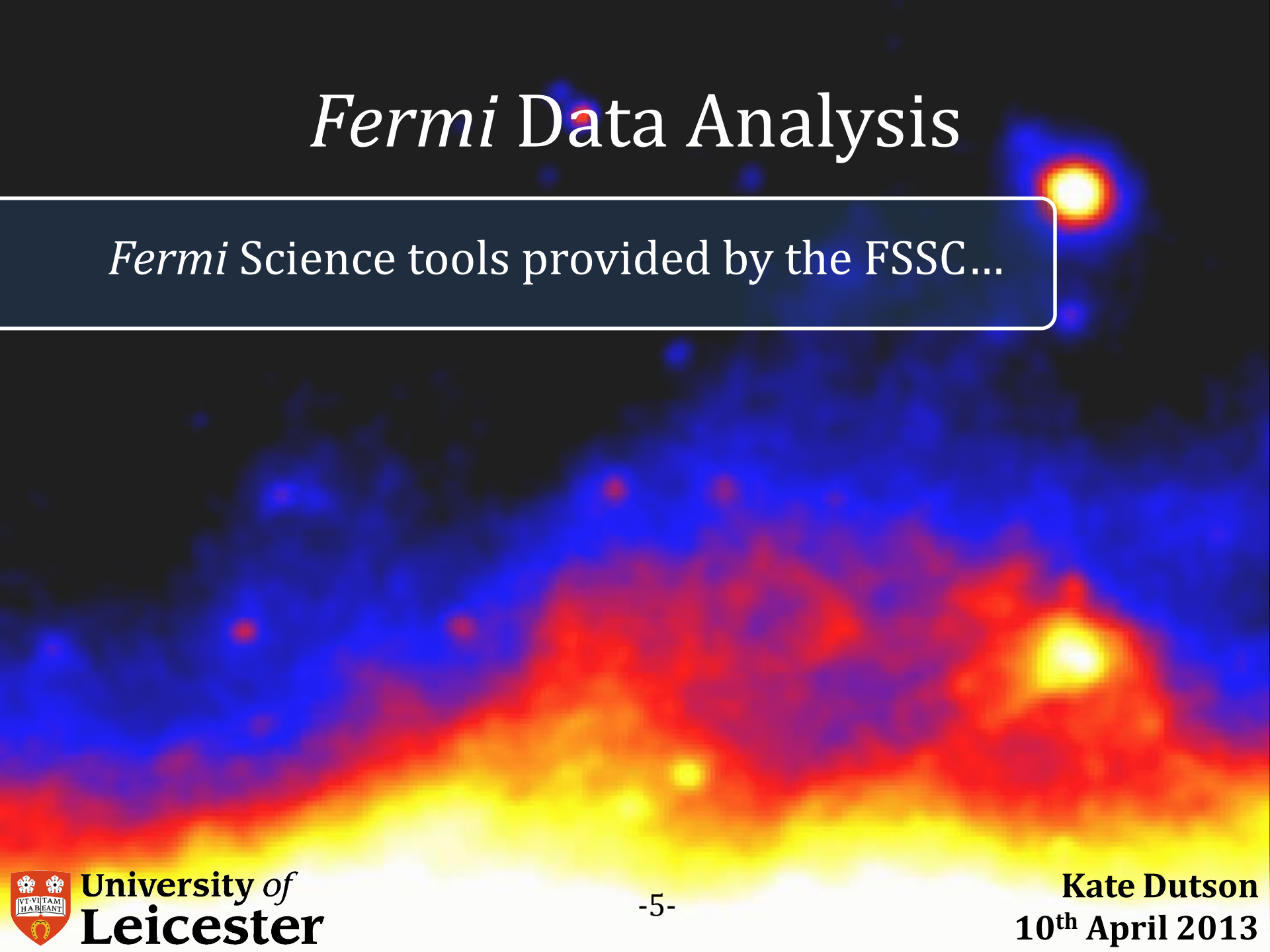
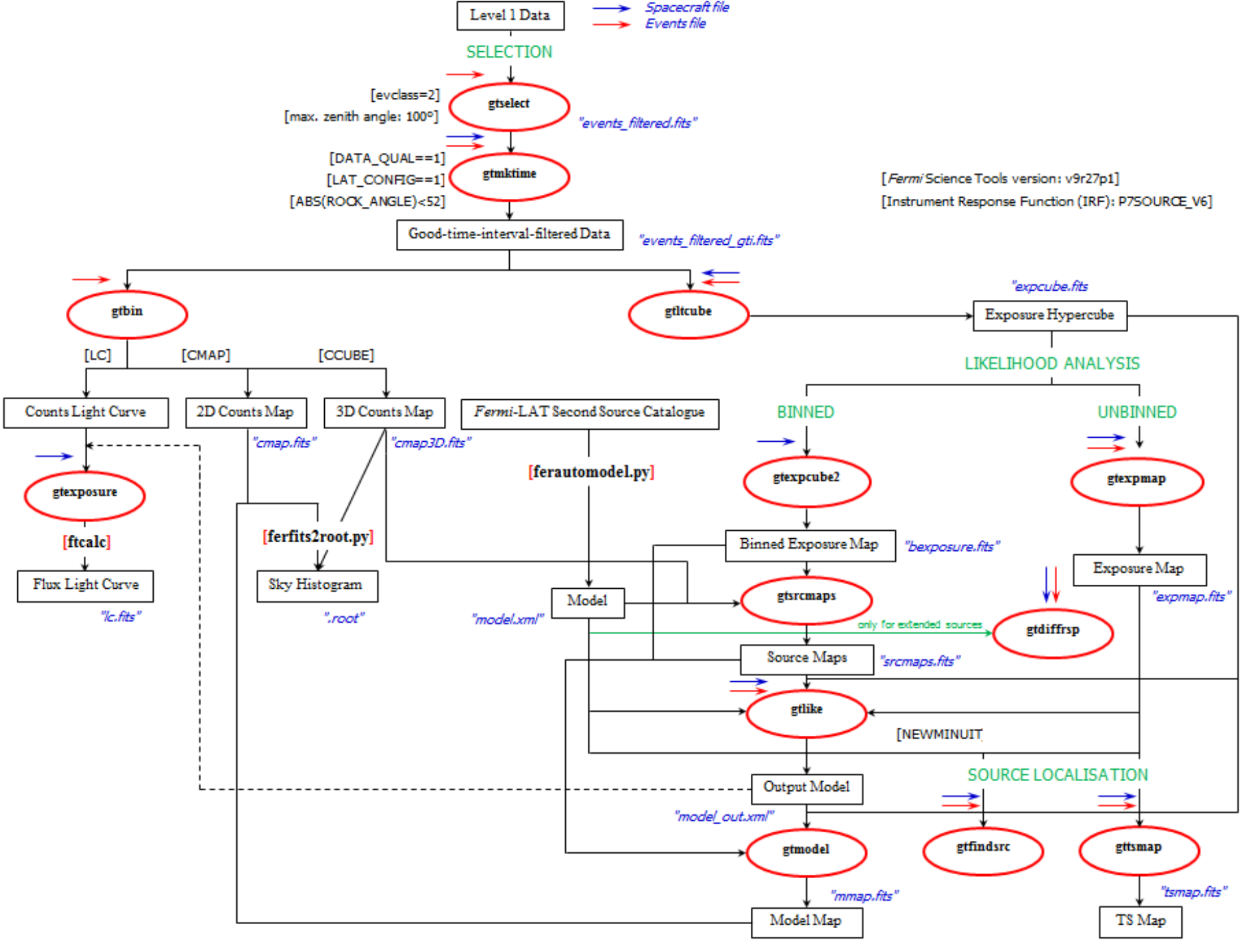


Fermi Data Analysis

Fermi Science tools provided by the FSSC…

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Spacecraft file
Events file
SELECTION
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[max. zenith angle: 100°]
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"events_filtered.fits"
[DATA_QUAL==1]
[LAT_CONFIG==1]
[ABS(ROCK_ANGLE)<52]
gtmktime
[Fermi Science Tools version: v9r27p1]
[Instrument Response Function (IRF): P7SOURCE_V6]
Good-time-interval-filtered Data
"events_filtered_gti.fits"
gtbin
gtltcube
"expcube.fits"
Exposure Hypercube
[LC]
[CMAP]
[CCUBE]
LIKELIHOOD ANALYSIS
Counts Light Curve
2D Counts Map
3D Counts Map
Fermi-LAT Second Source Catalogue
BINNED
UNBINNED
"cmap.fits"
"cmap3D.fits"
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gtexposure
gtexpcube2
gtexpmap
[ftcalc]
[ferfits2root.py]
Binned Exposure Map
"bexposure.fits"
Exposure Map
Flux Light Curve
Sky Histogram
Model
gtsrcmaps
"expmap.fits"
"lc.fits"
".root"
"model.xml"
only for extended sources
gtdiffrsp
Source Maps
"srcmaps.fits"
gtlike
[NEWMINUIT]
SOURCE LOCALISATION
Output Model
"model_out.xml"
gtmodel
gtfindsrc
gttsmap
"mmap.fits"
"tsmap.fits"
Model Map
TS Map

Likelihood Analysis

- Poissonian statistics for arrival of photons at the LAT
- Requires model and null hypothesis
- Maximising the likelihood is similar to minimising χ^2
- *Fermi* tool **gtlike**

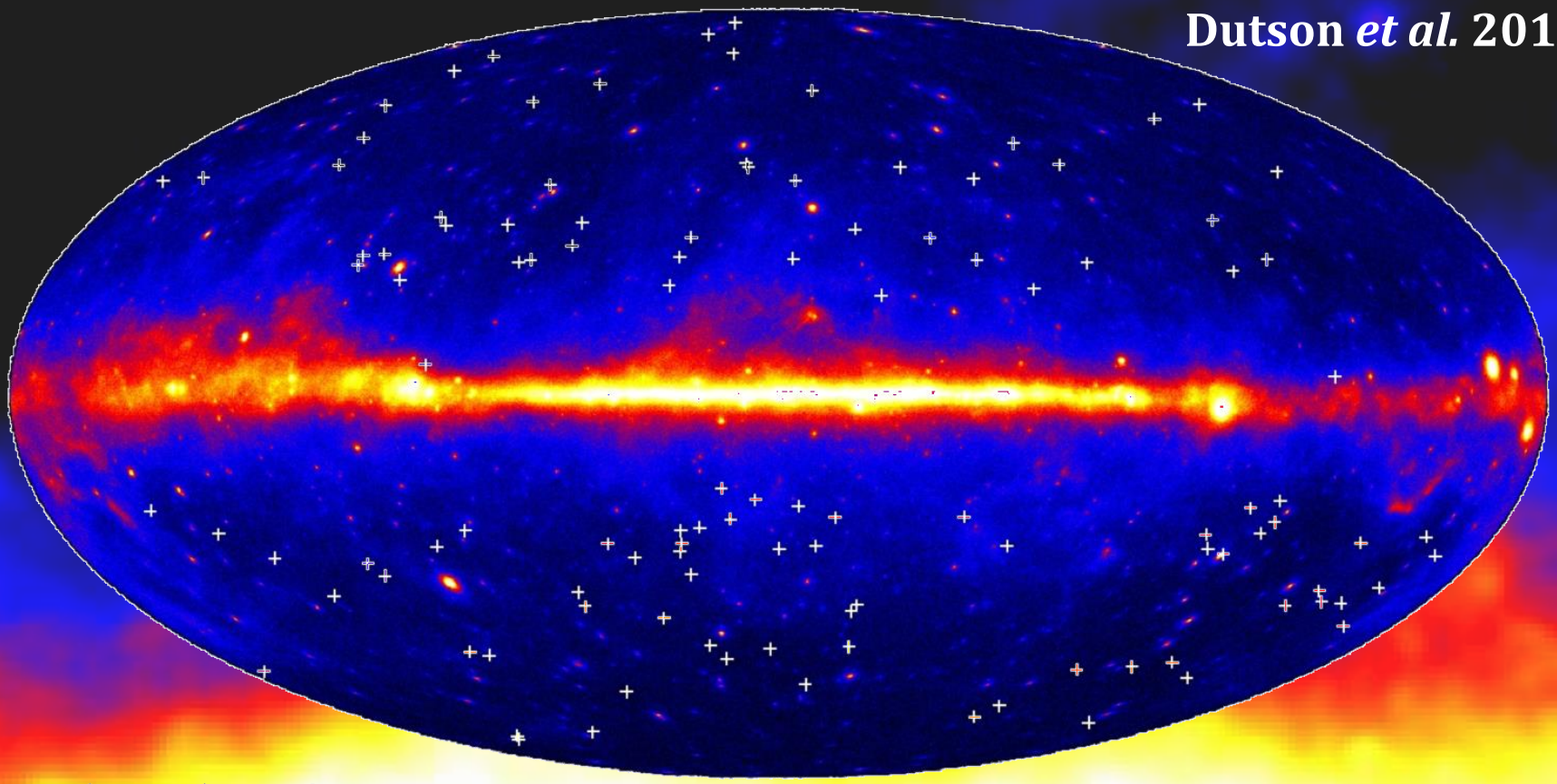
$$L = \prod_{i=1}^{n} P(k_i; \lambda_i)$$

$$\ln L = \sum_{i=1}^{n} P(k_i; \lambda_i) = \sum_{i=1}^{n} \left(\frac{e^{-\lambda_i} \lambda_i}{k_i!} \right)$$

$$TS = -2\ln\Lambda = -2(\ln L_0 - \ln L_1)$$

Three Cluster Samples

- 114 radio-bright, X-ray flux-limited BCGs



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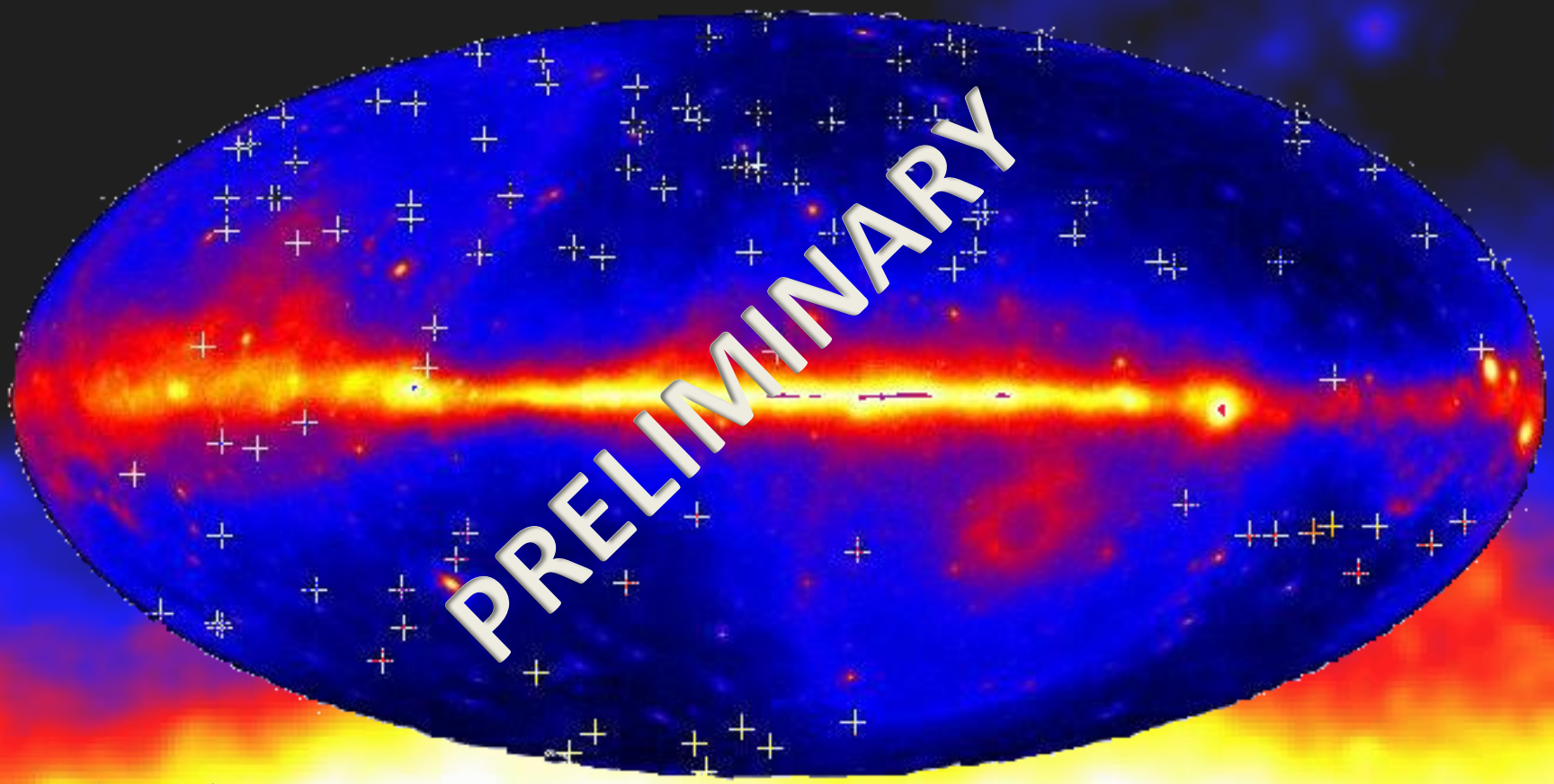
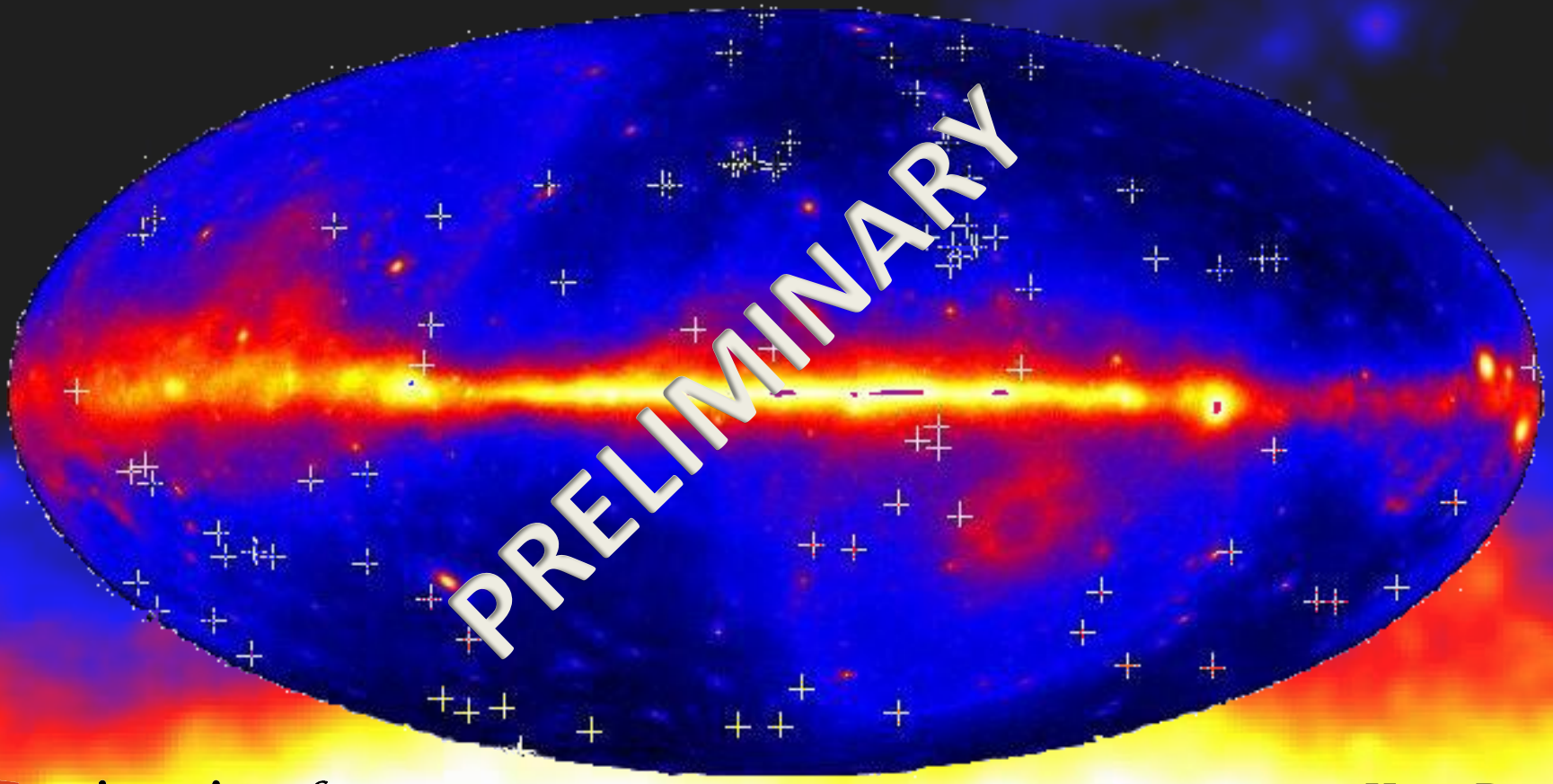
Three Cluster Samples

- 101 hosts of relics and halos from the literature



Three Cluster Samples

- 90 dark matter candidate clusters



Significance Distribution

- BCG sample (and controls)

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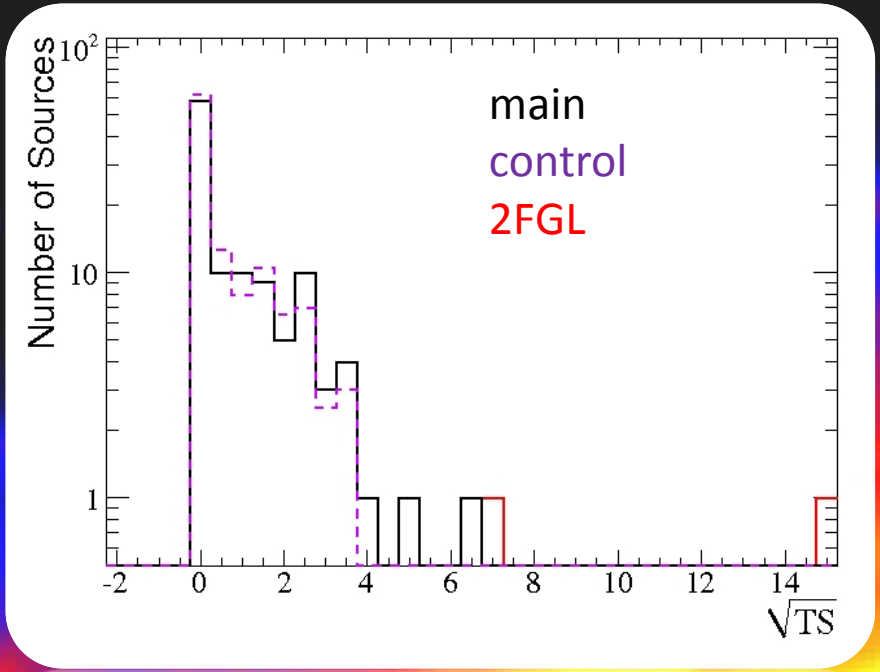
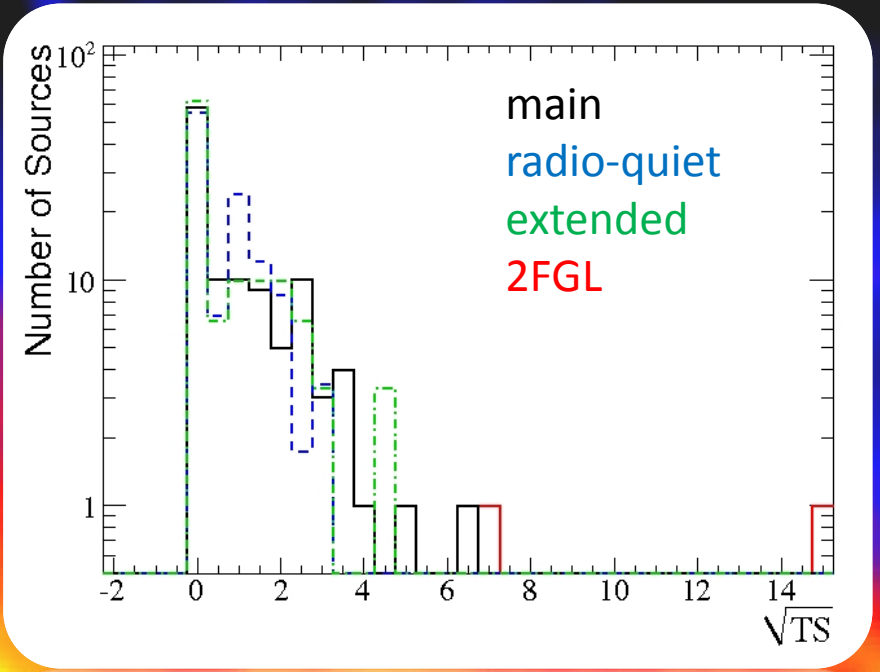
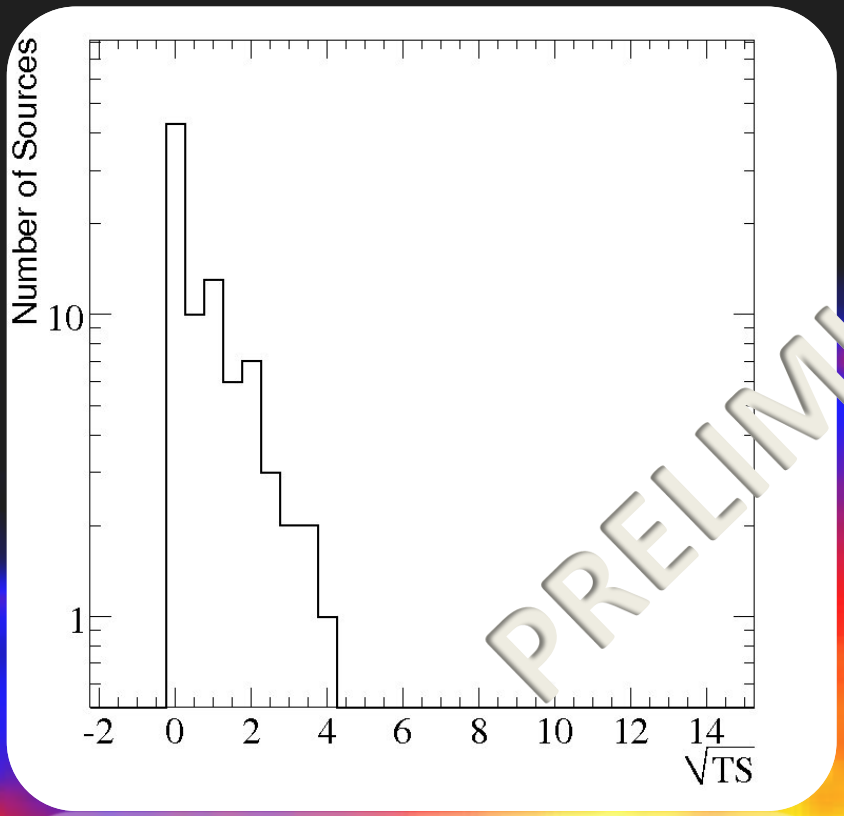


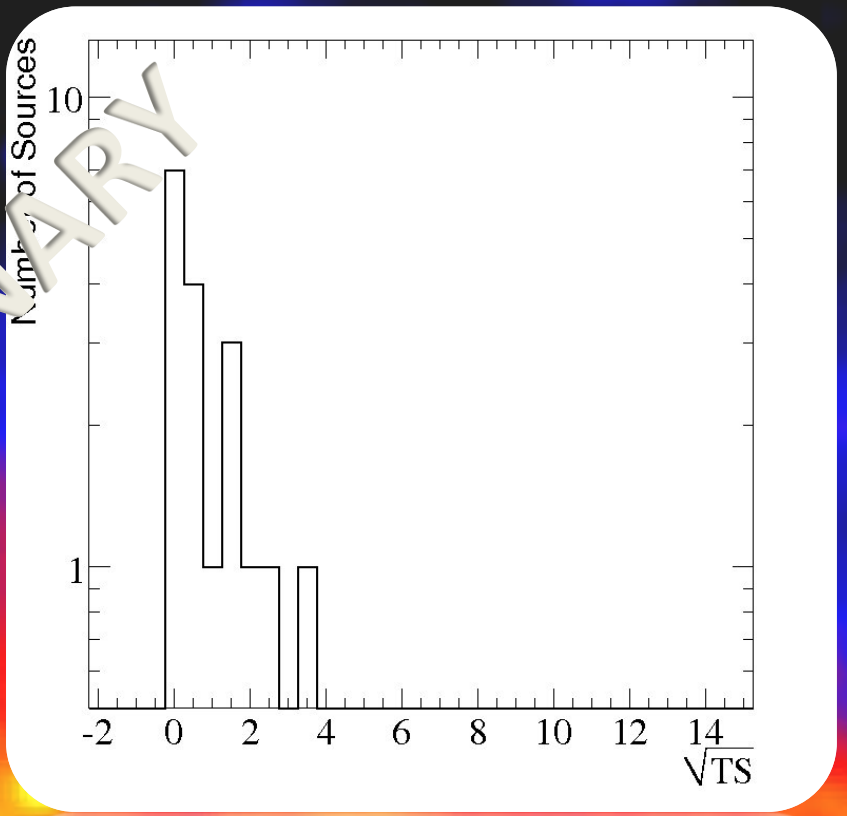


Significance Distribution

Dark Matter cut >2GeV

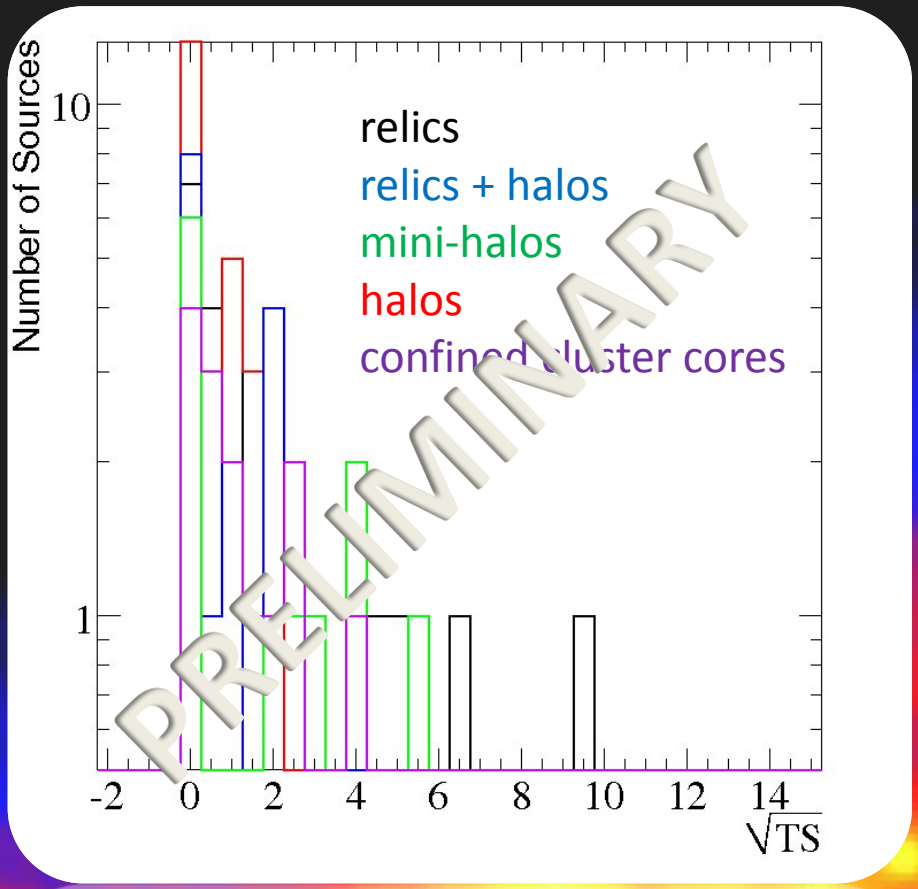


Dark Matter cut >0.9GeV



Significance Distribution

Diffuse sources



Sources of Note…

In the field of A 2055 (above 3GeV)

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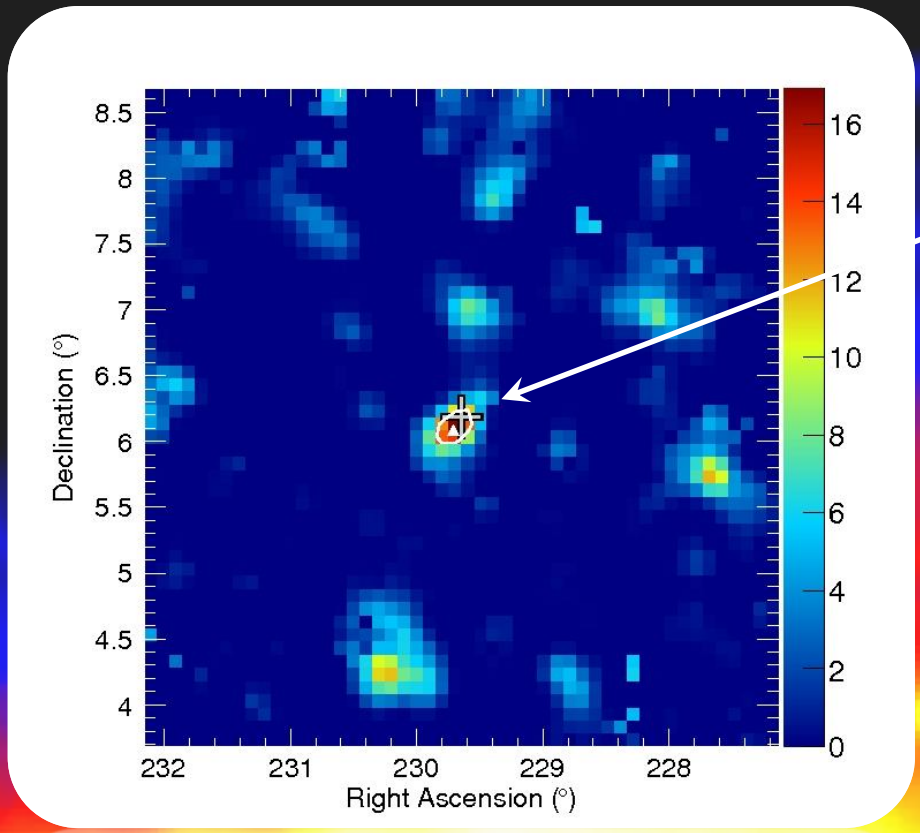
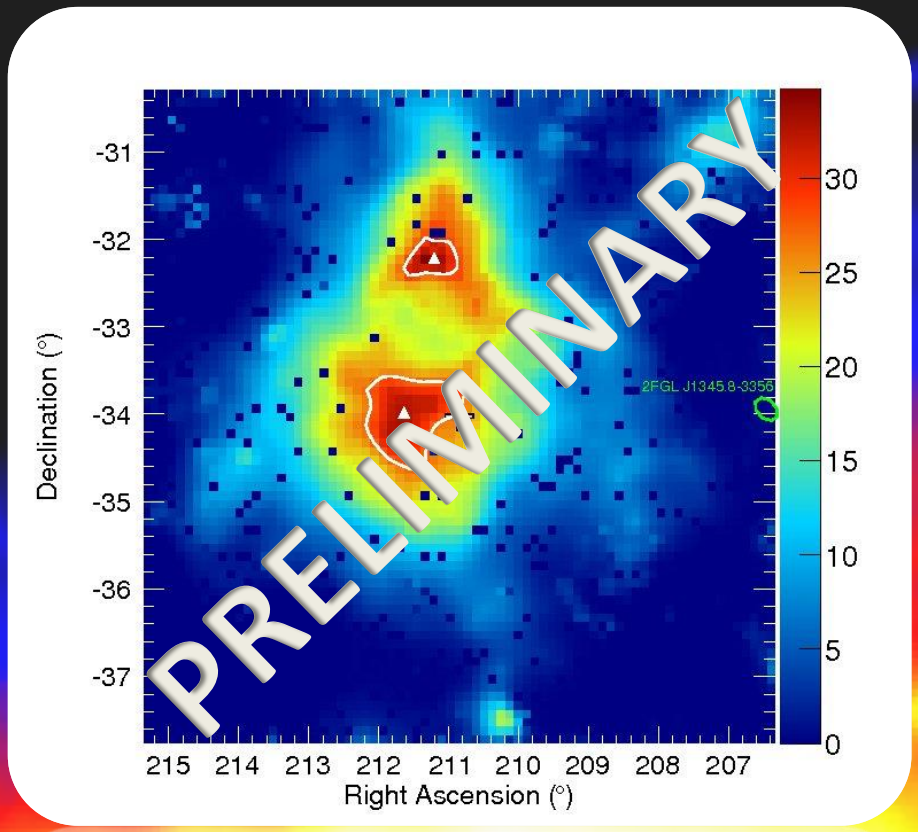


TS = 15.2

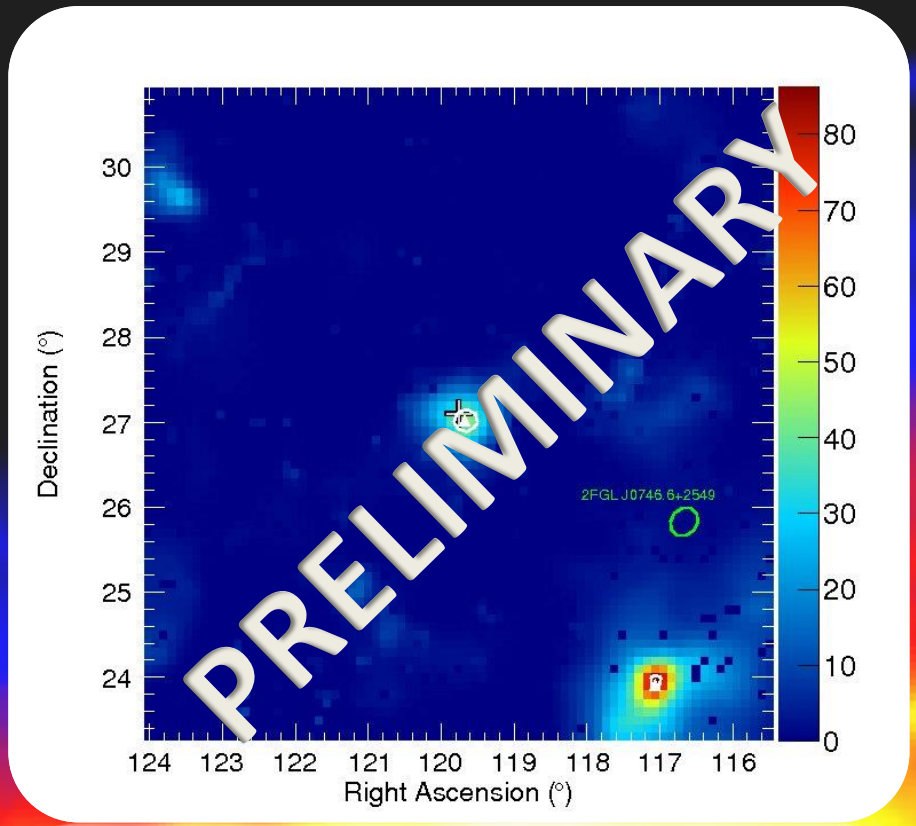
Sources of Note…

In the field of AS753



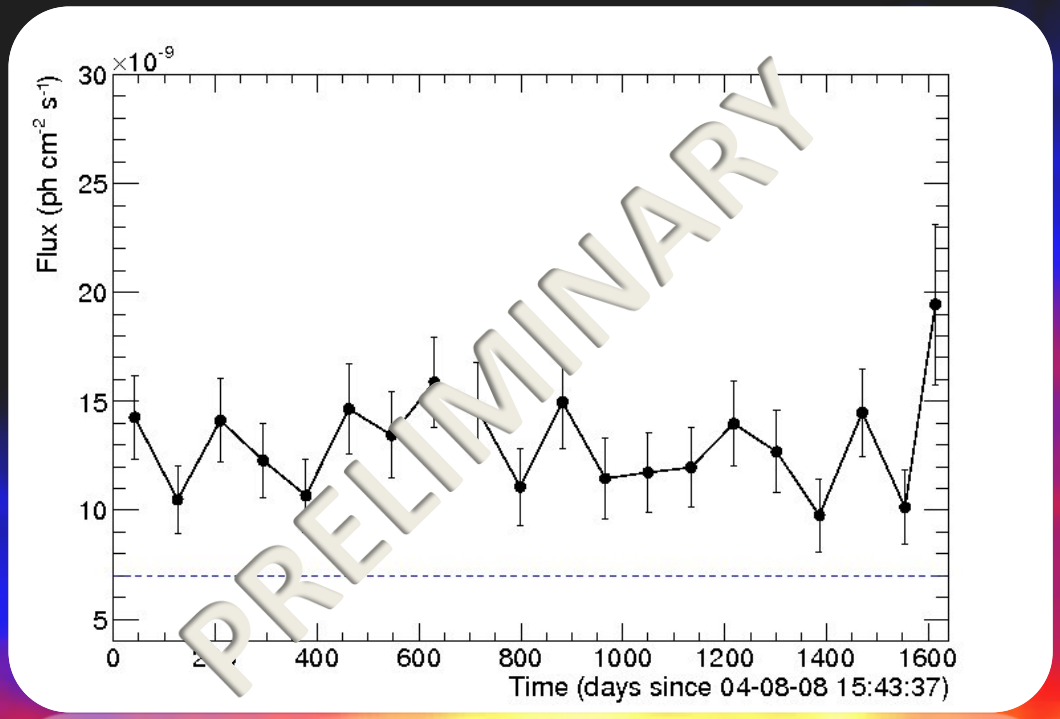
Sources of Note…

In the field of A 610



Sources of Note…

In the field of A 610



Stacking Analysis

Integrated BCG flux upper limit: $F_\gamma < 5.5 \times 10^{-11}$ ph cm^{-2} s^{-1}

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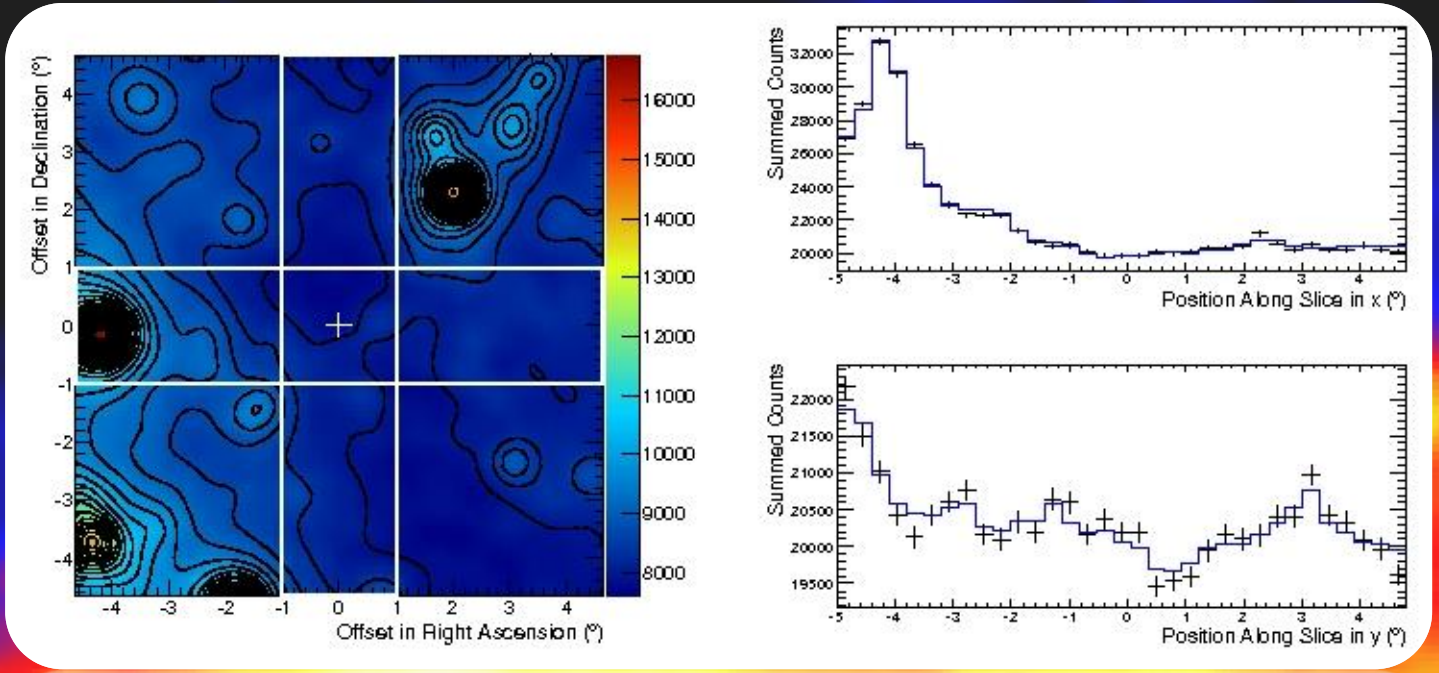
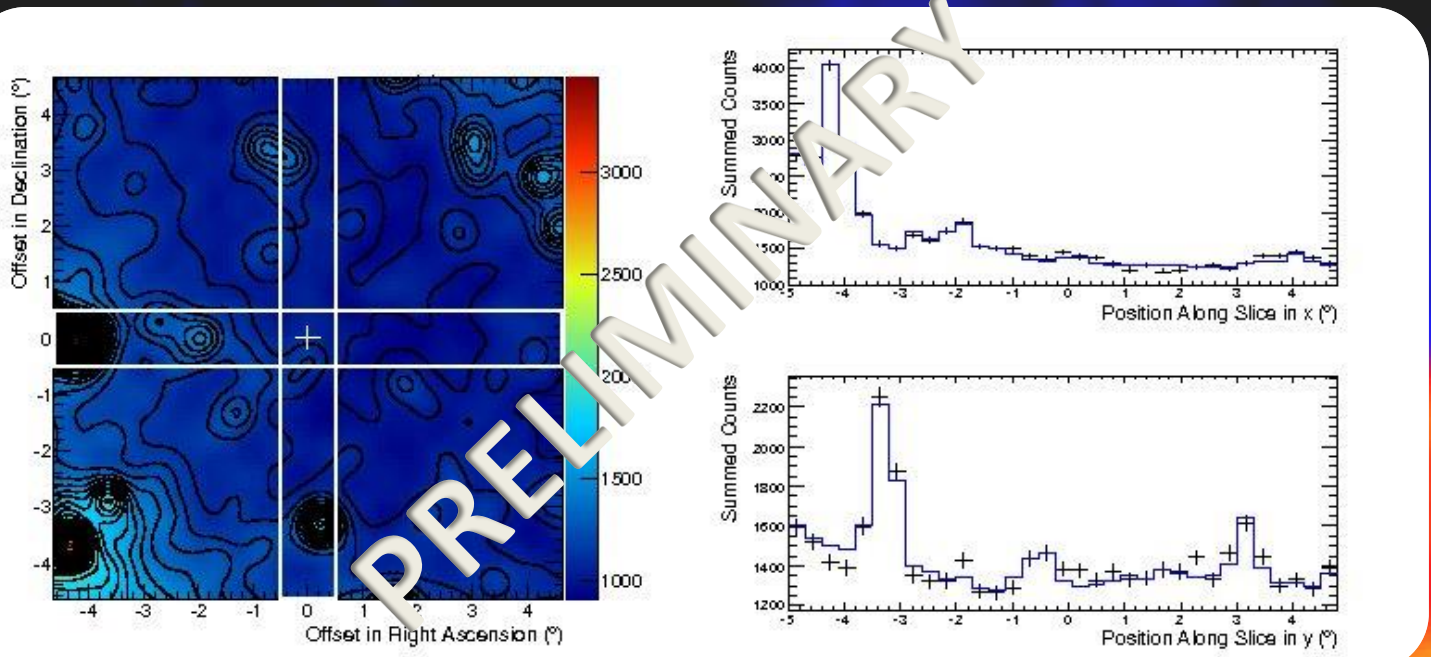


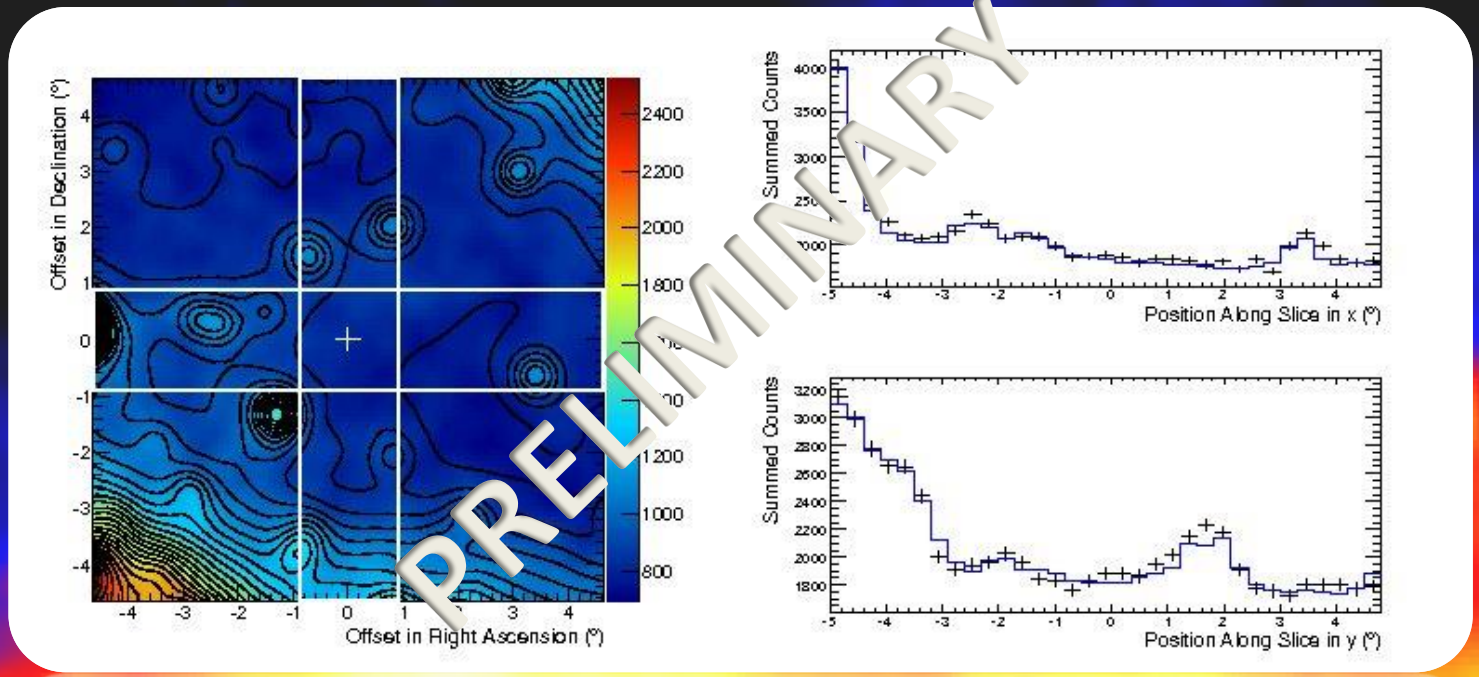
Stacking Analysis

Integrated DM flux upper limit >2GeV: $F_\gamma < 2.6 \times 10^{-10}$ ph cm^{-2}s^{-1}



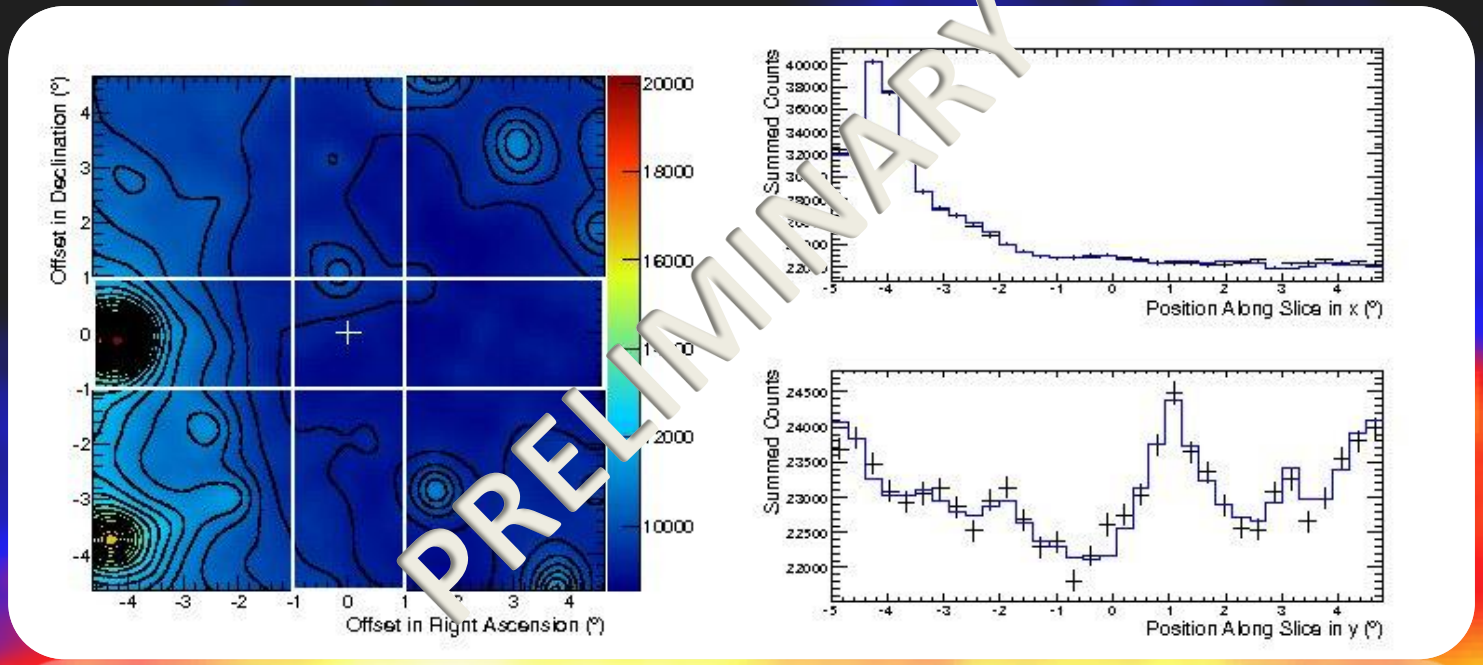
Stacking Analysis

Integrated DM flux upper limit >0.9GeV: $F_\gamma < 1.1 \times 10^{-11}$ ph cm^{-2}s^{-1}



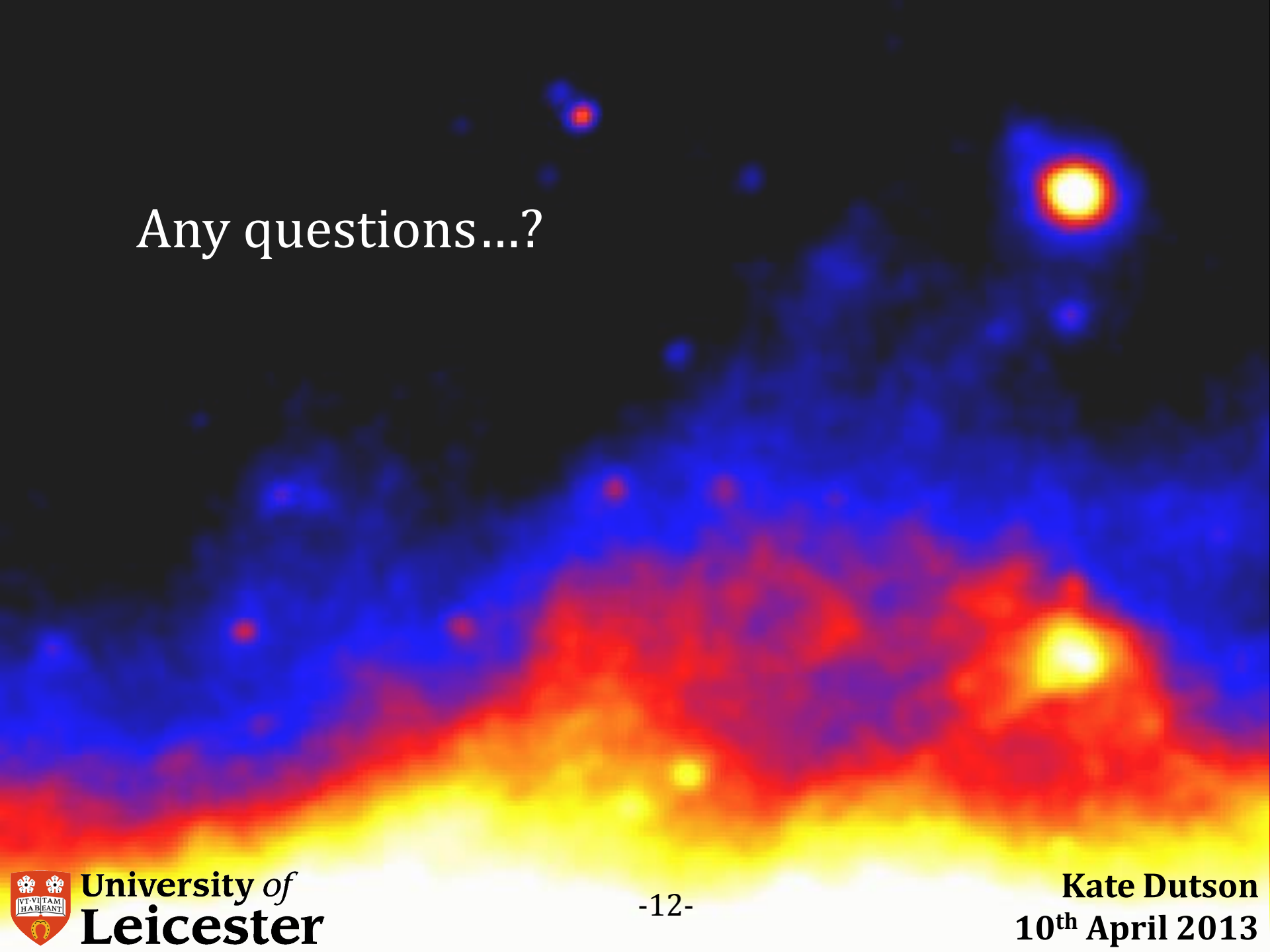
Stacking Analysis

Integrated Diffuse flux upper limit: $F_\gamma < 1.27 \times 10^{-10}$ ph cm^{-2} s^{-1}



In Summary

- No evidence of a signal in the stacked data.
- Upper limits on the γ-ray flux of an average candidate source cluster represent at least an order-of-magnitude improvement on individual limits.
- Expected scaling:
  $\sim {}^{1}/_{\sqrt{N_{\mathrm{obj}}}}$ (background-limited) $\sim {}^{1}/_{N_{\mathrm{obj}}}$ (signal-limited)
- Detections of a number of new *Fermi* sources.
- Suggestion that point-like *beamed* emission from member galaxies comprise the dominant bright γ-ray sources in clusters at present.
- Diffuse emission?


Any questions…?