

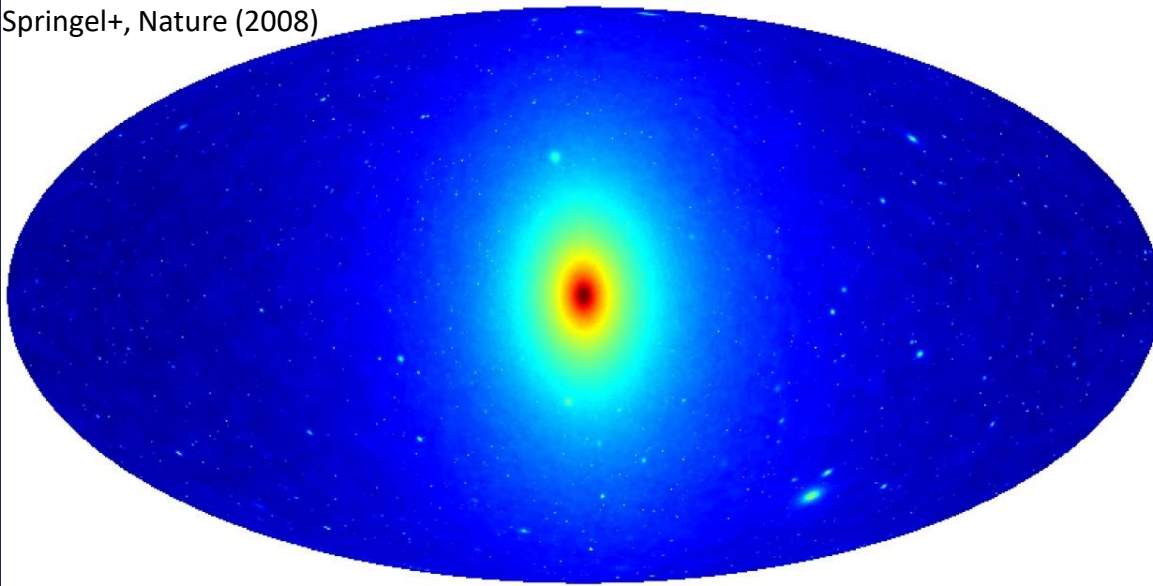
# Lessons Learned Taking Indirect Detection To The Full Sky

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# Signal Model vs. Observed $\gamma$ -ray Sky

Springel+, Nature (2008)



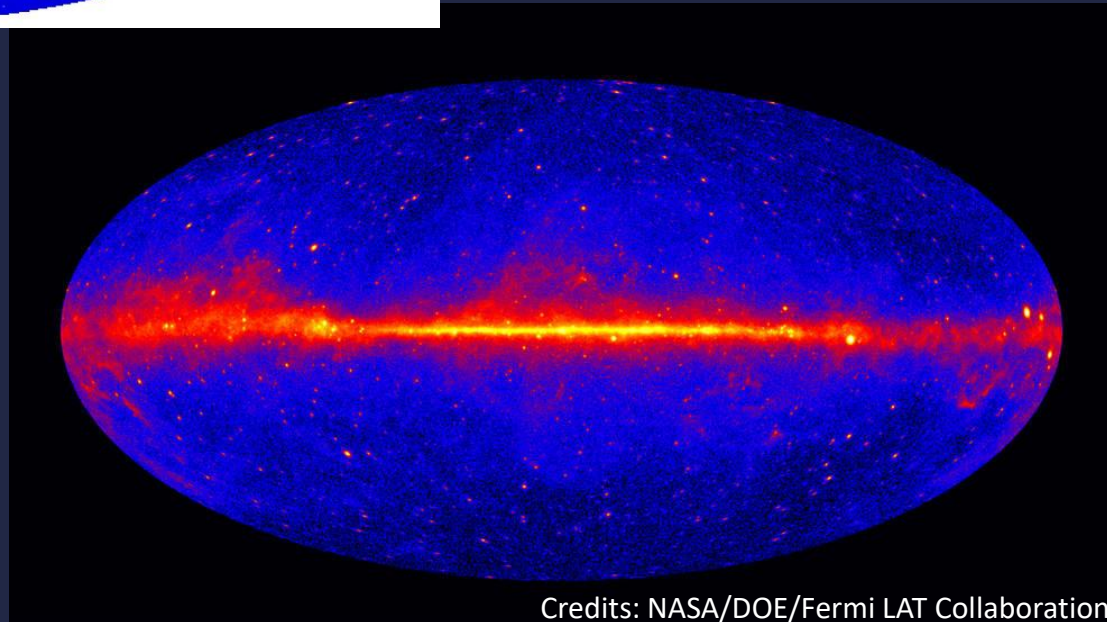
Two main signal components:

1. galactocentric diffuse
2. small structures

Observed sky modeled with

- bremsstrahlung
- $\pi^0$  decay
- up-scattered light
- point sources
- Fermi bubbles
- isotropic background

using known gas maps and modeled starlight, cosmic rays.



Credits: NASA/DOE/Fermi LAT Collaboration

# Royalty of ID: Targeted Search

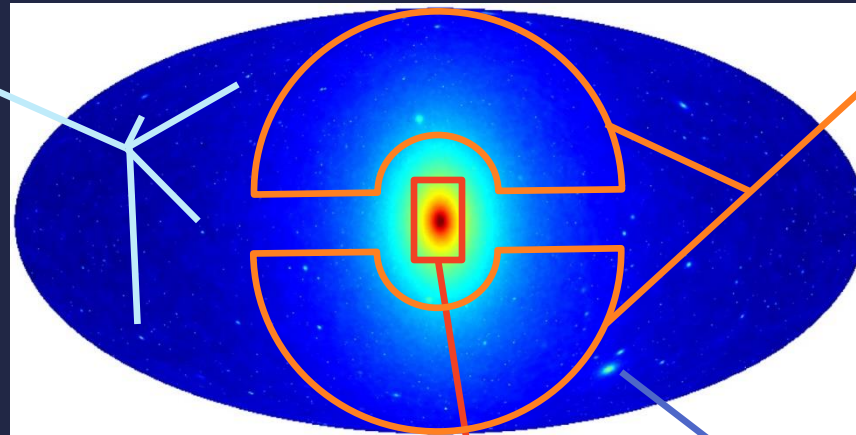
## Dwarf Satellites

- most robust signal model
- low astrophysics
- satellite population for stacking analysis

Does the region's  $\gamma$ -ray spectrum have a bump that astrophysics can't account for?

## Halo

- needs big substructure boost to compete
- large area



## Unassociated Point Sources

- invisible subhalos
- no obvious detections yet

## Isotropic Background

- needs big substructure boosts to compete
- large area

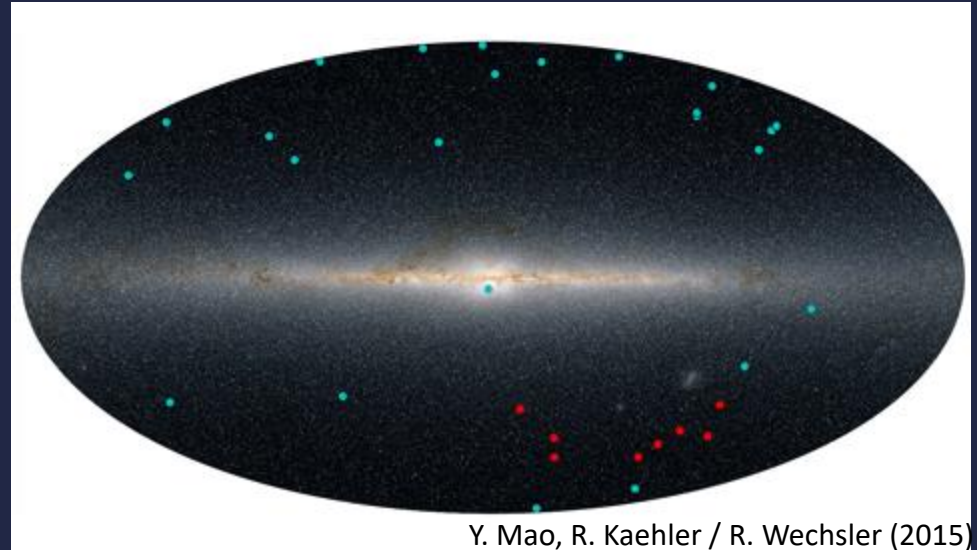
## Galactic Center

- bright signal
- extended source
- complicated astrophysics

## Nearby Galaxies or Clusters

- need very big substructure boosts to compete

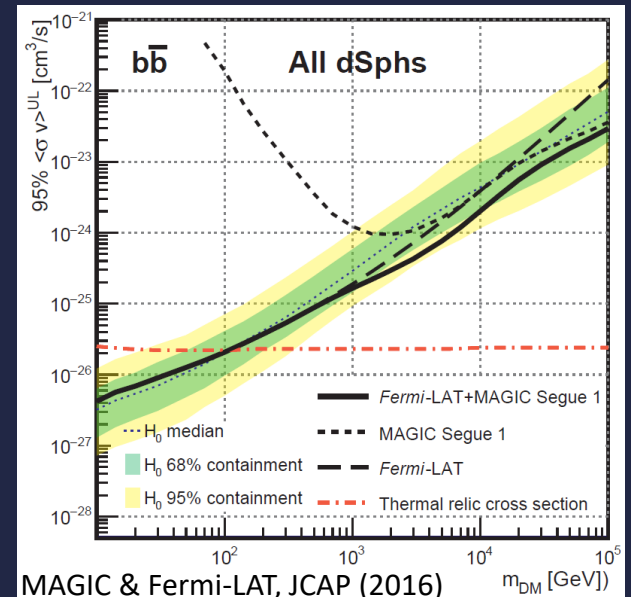
# King of ID: Dwarf Satellites



Y. Mao, R. Kaehler / R. Wechsler (2015)

The standard all other analyses are measured against.

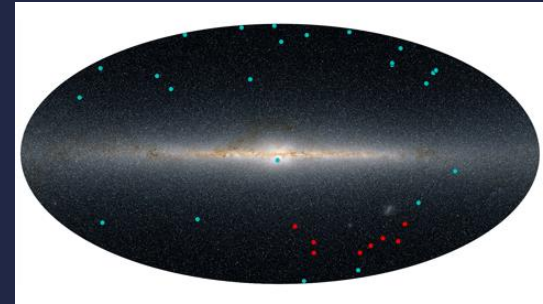
Not necessarily the most sensitive observable, but likely the most robust constraint.





# Central Question

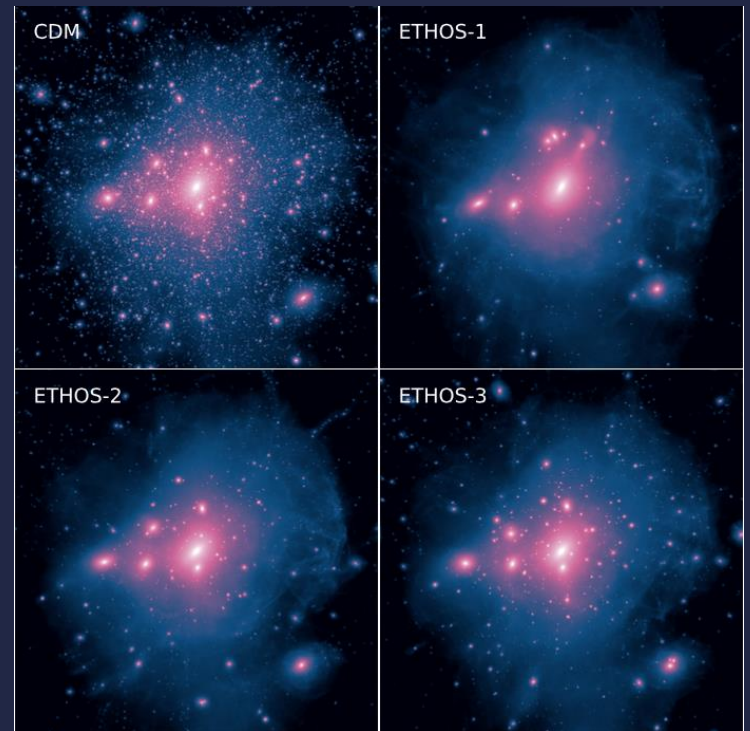
Known dwarf satellites produce great constraints using only a very small fraction of the sky.



But coherent structures may fill the sky.

Detailed structure is sensitive to:

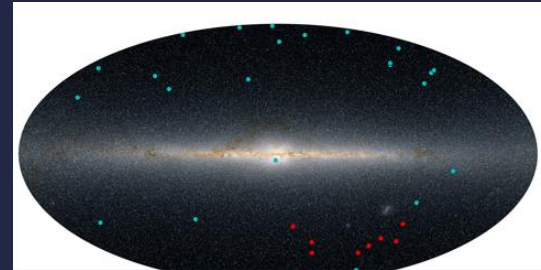
- dark matter interactions and thermal/freezeout history,
- Milky Way merger history,
- sensitivity to stellar feedback.



Vogelsberger+ MNRAS (2016)

# Central Question

Known dwarf satellites produce great constraints using only a very small fraction of the sky.



How can we access the information content of the unknown invisible structure for indirect detection?

Can full-sky statistics significantly improve sensitivity over dwarf satellites alone?

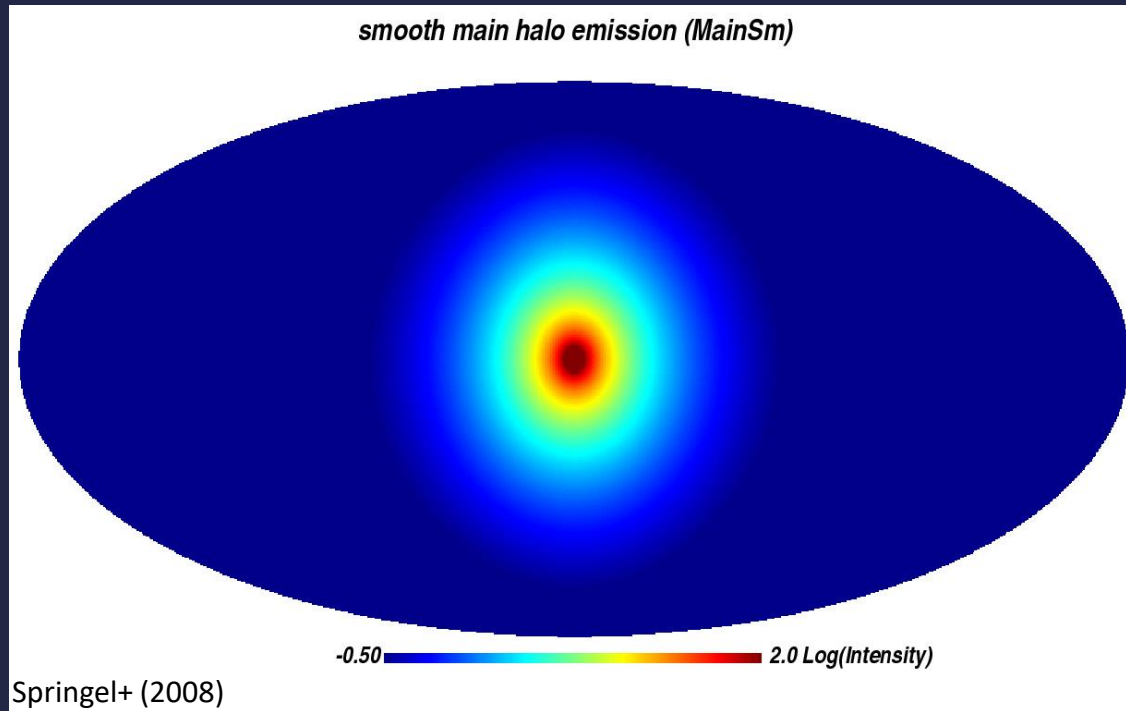
thermal/freezeout history,

- Milky Way merger history,
- sensitivity to stellar feedback.



# Full Sky Strategies

1. Probe galactocentric diffuse component.
  - Measure **galactoisotropic component**.
2. Probe small structures.
  - Measure **auto-correlations**.
  - Measure **cross-correlations**:
    - with other radiation maps,
    - with point source catalog maps.

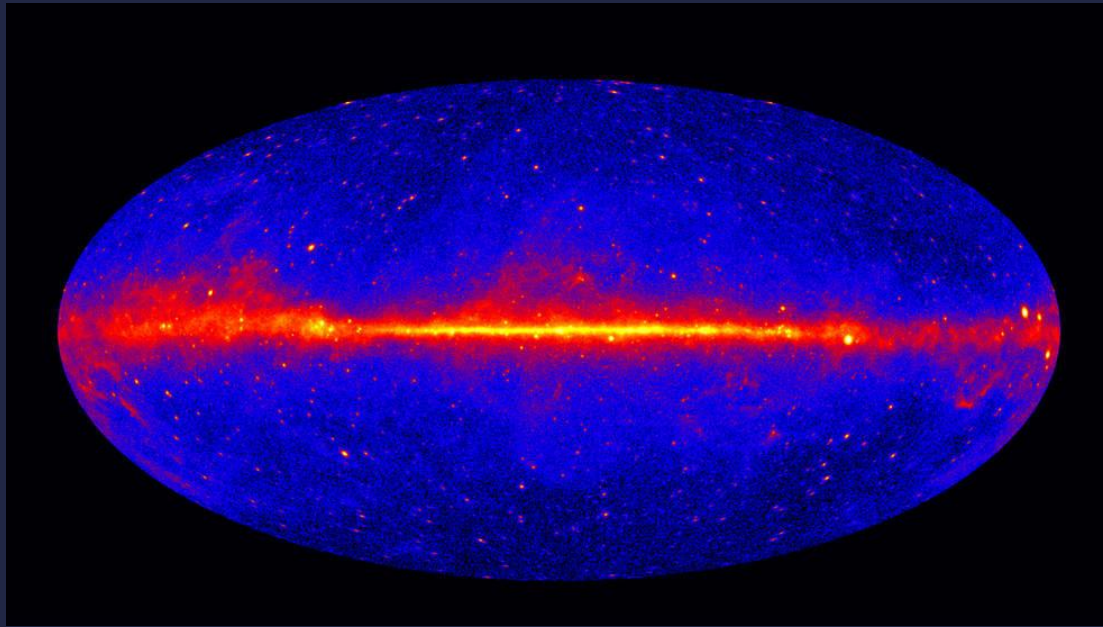


# GALACTOCENTRIC DIFFUSE COMPONENT

New research with collaborators Manoj Kaplinghat and Anna Kwa.



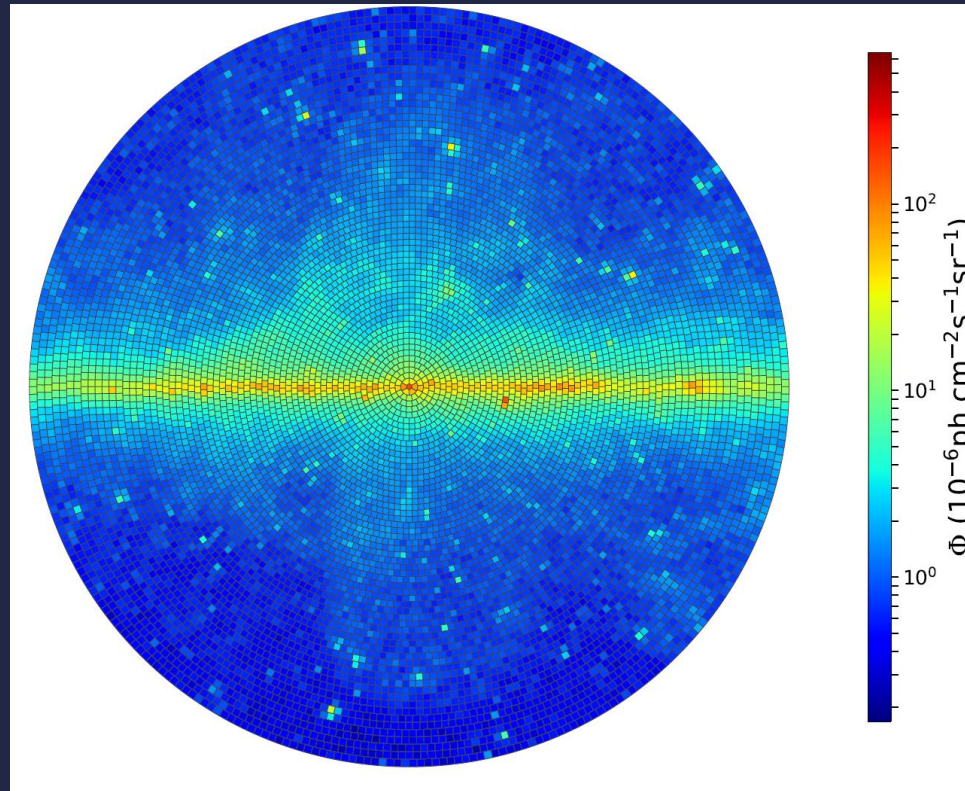
# The Elephant in the $\gamma$ rays



- The “smooth” component of the dark matter signal is roughly galacto-isotropic.
- The majority of the observed distribution is not.
- What is the galacto-isotropic component of the  $\gamma$ -ray sky?

# Measure Galacto-Isotropic $\gamma$ Rays

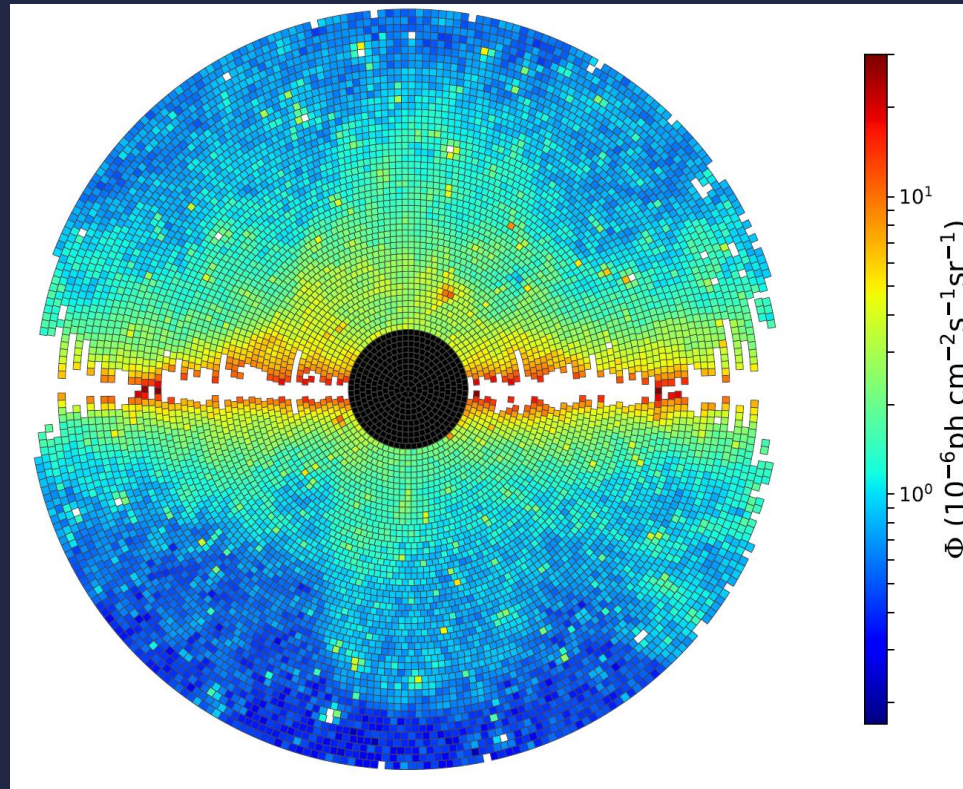
## Approach 1: Removing Structure



$1^\circ$  GI Tiling, Inner  $60^\circ$

# Measure Galacto-Isotropic $\gamma$ Rays

## Approach 1: Removing Structure



### BDS Statistical Test (Baxter, Dodelson 2013)

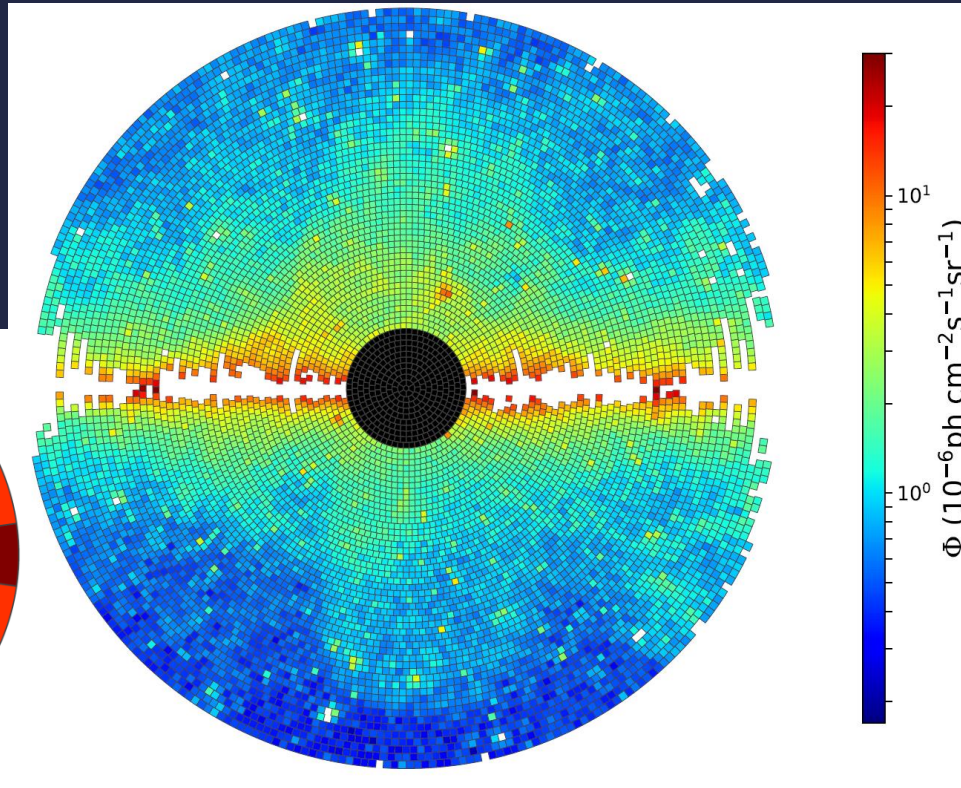
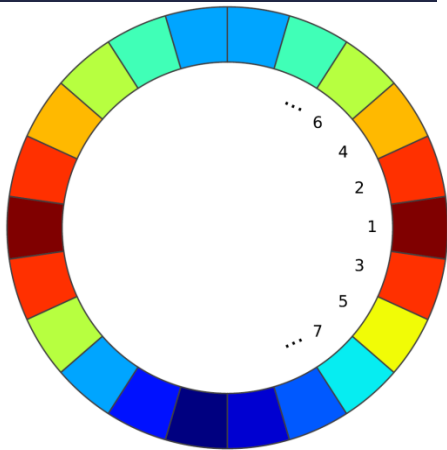
In each annulus, remove brightest pixels until remaining pixels are consistent with being drawn independently from a common probability distribution function.



# Measure Galacto-Isotropic $\gamma$ Rays

## Approach 1: Removing Structure

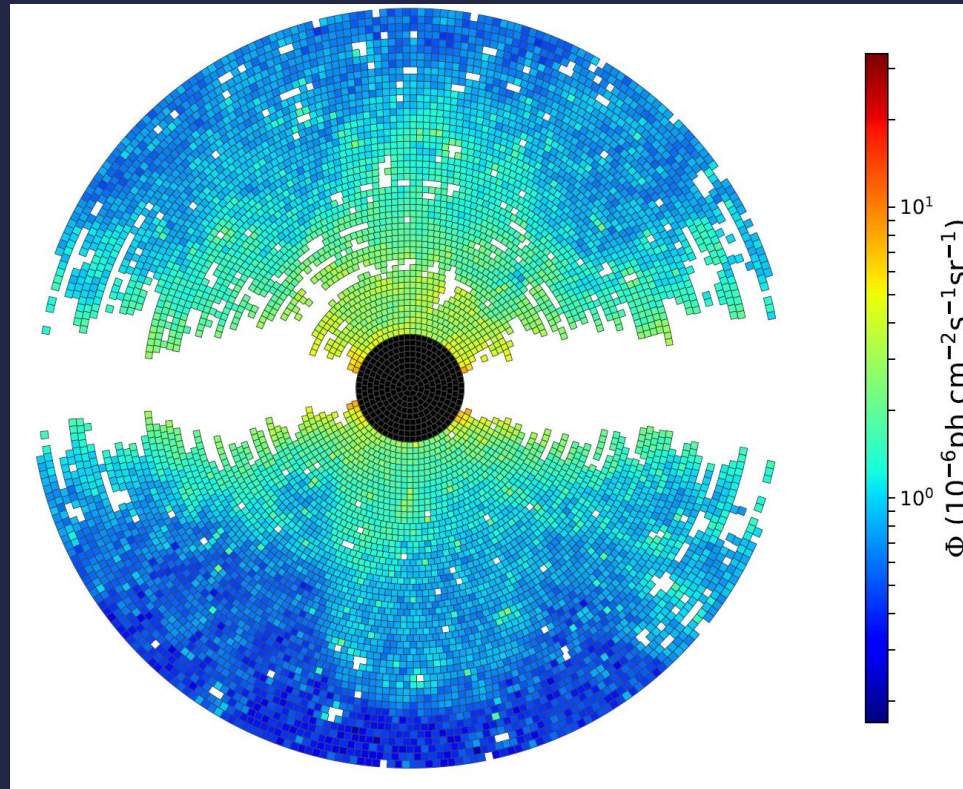
Try interleaving.



In each annulus, remove brightest pixels until remaining pixels are consistent with being drawn independently from a common probability distribution function.

# Measure Galacto-Isotropic $\gamma$ Rays

## Approach 1: Removing Structure



## BDS Statistical Test with North-South Interleaving

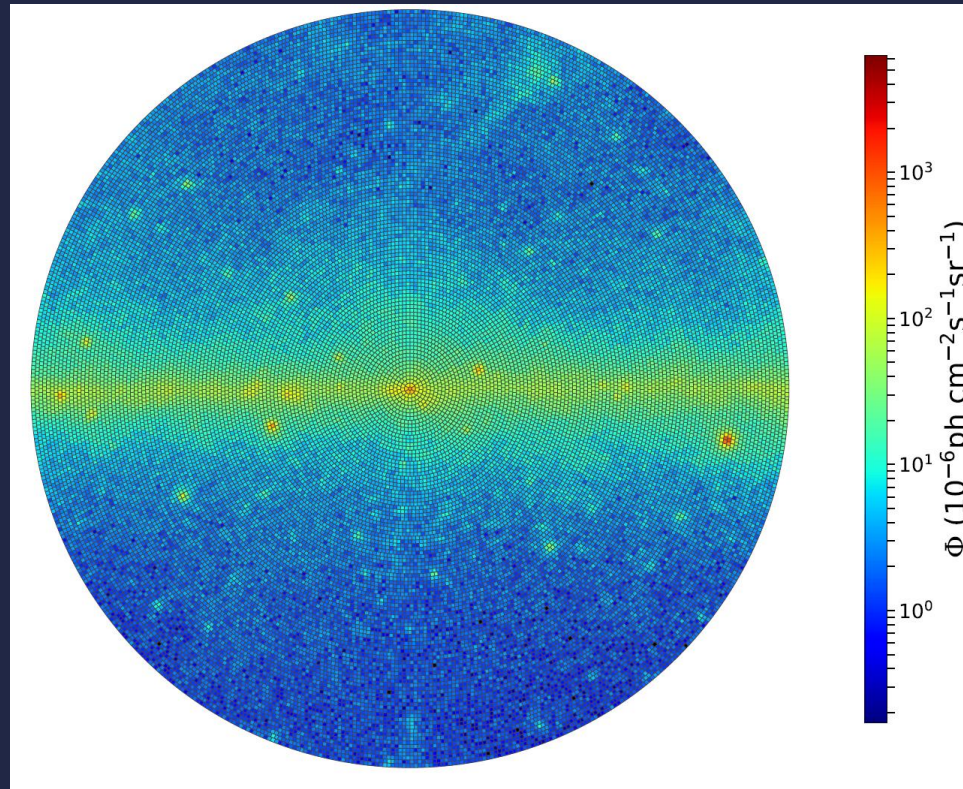
Structure removal is very effective.

Median remaining pixel of each annulus estimates the GI flux at that radius.



# Measure Galacto-Isotropic $\gamma$ Rays

## Approach 1: Removing Structure

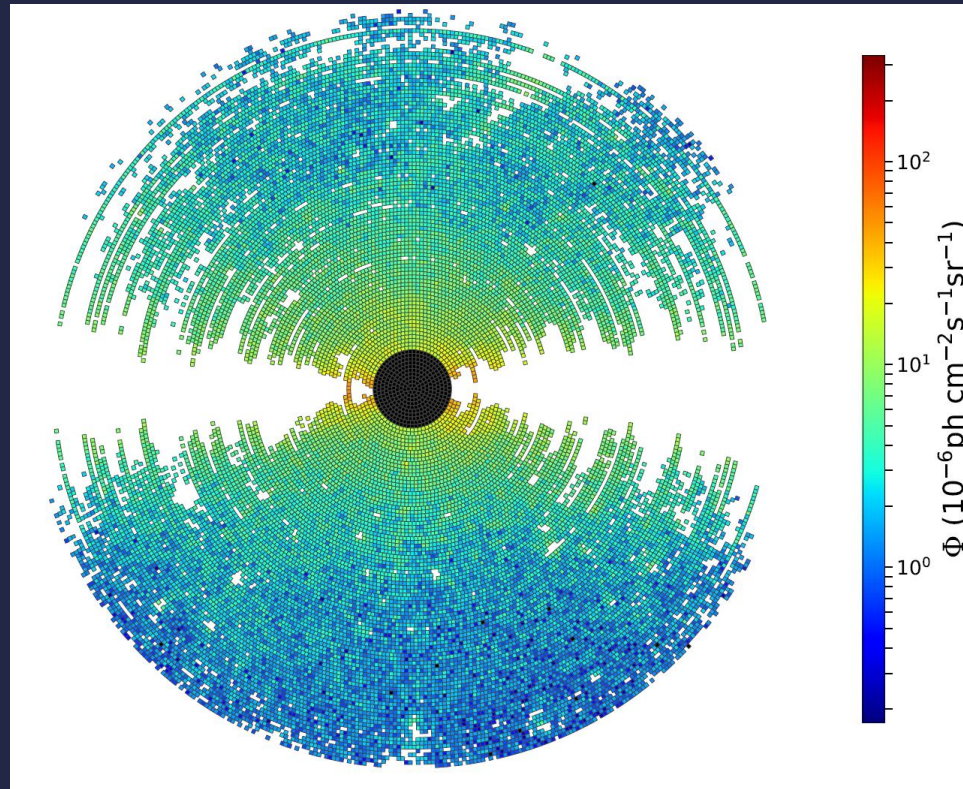


0.2° GI Tiling, Inner 20°

Removal of correlated structures is more striking at higher resolution.

# Measure Galacto-Isotropic $\gamma$ Rays

## Approach 1: Removing Structure

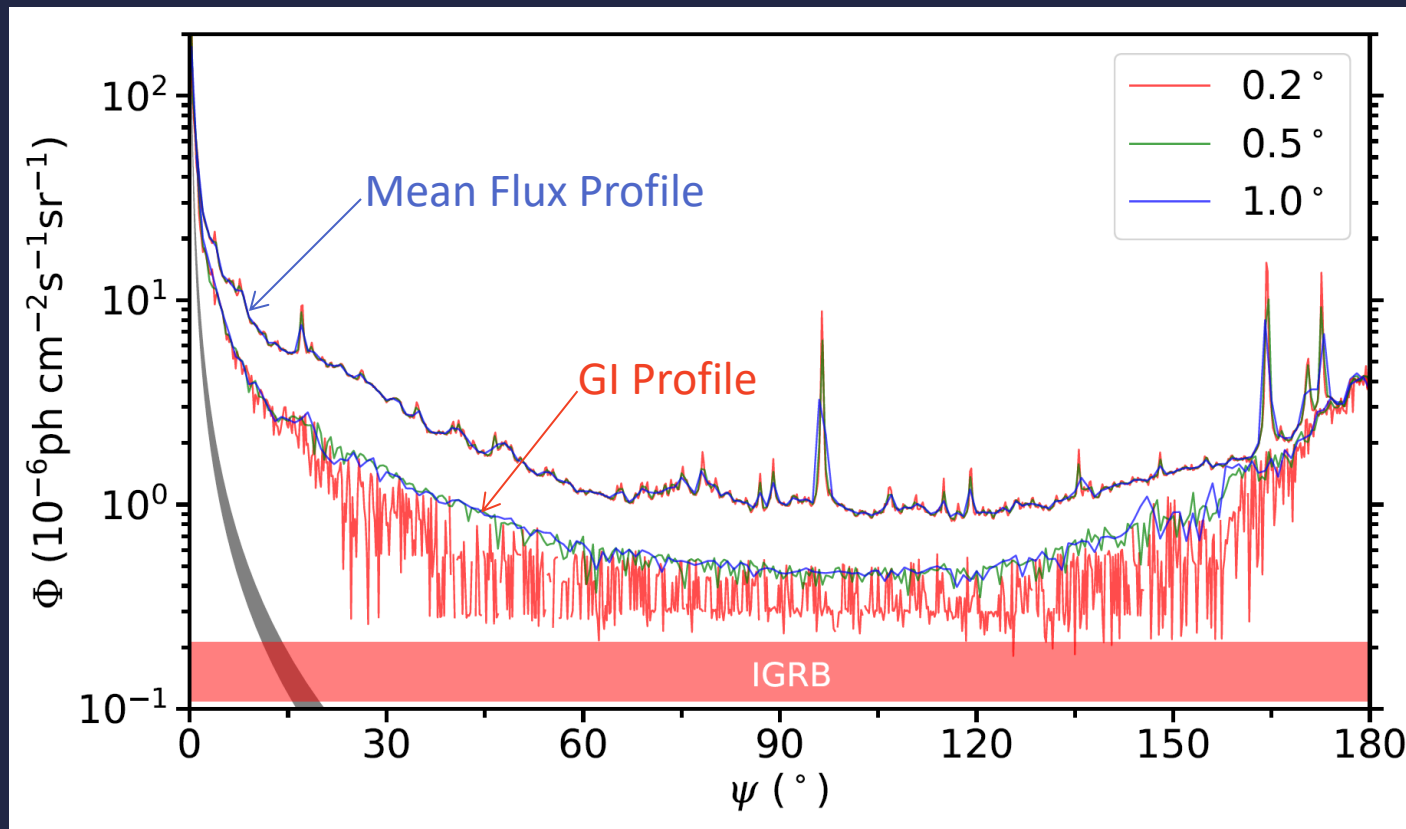


0.2° GI Tiling, Inner 20°

Removal of correlated structures is more striking at higher resolution.

# Measure Galacto-Isotropic $\gamma$ Rays

## Approach 1: Removing Structure



GI Flux Profile

there it is!

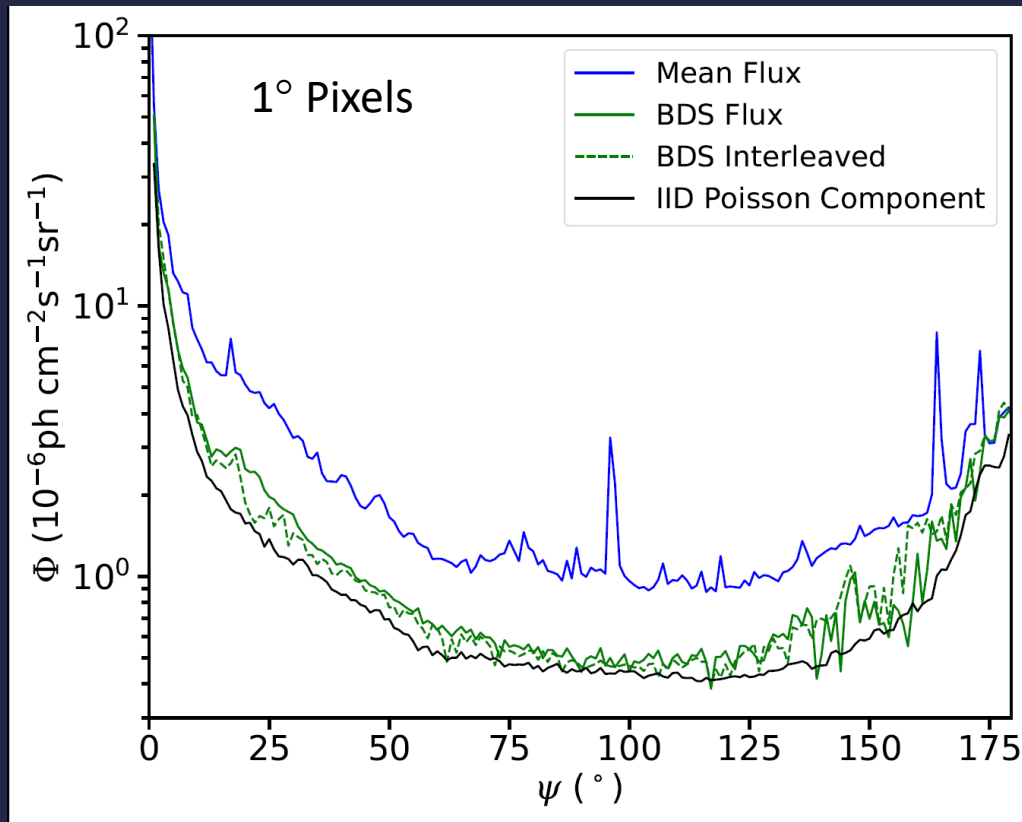


# Measure Galacto-Isotropic $\gamma$ Rays

## Approach 2: Removing Non-Poissonities

# Measure Galacto-Isotropic $\gamma$ Rays

## Approach 2: Removing Non-Poissonities



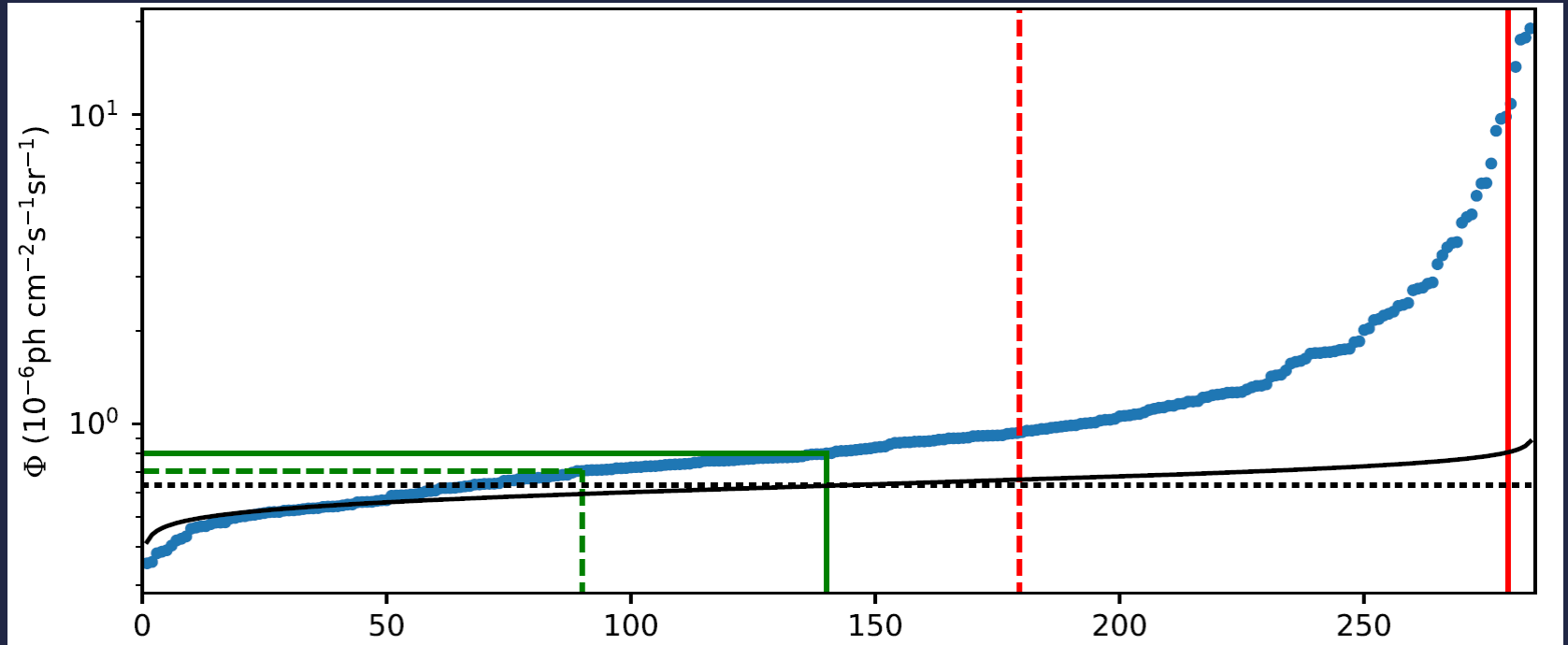
## GI Flux Profiles

The extra structure removed by interleaving does not significantly decrease the measured galacto-isotropic flux. WHY?



# Measure Galacto-Isotropic $\gamma$ Rays

## Approach 2: Removing Non-Poissonities



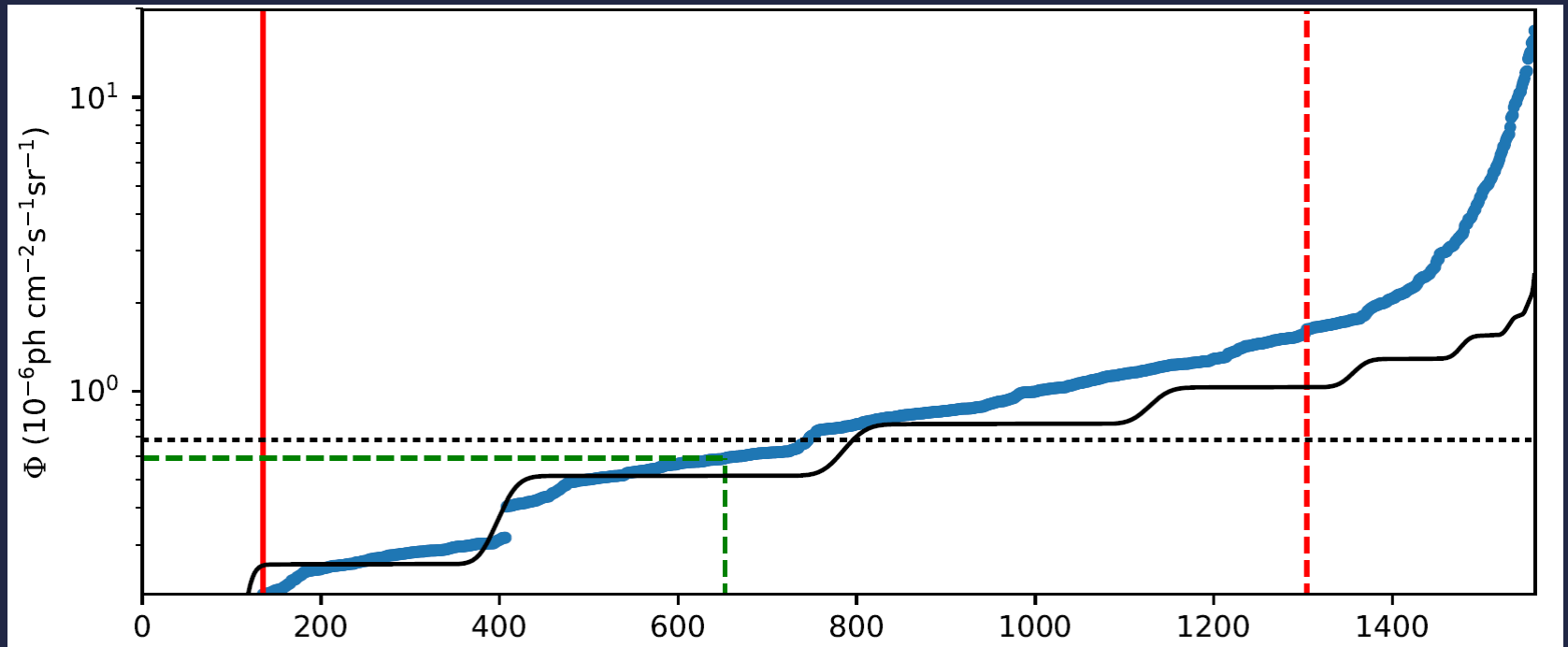
Ordered Pixel Ensemble at  $52^\circ$  with  $1^\circ$  pixels.

Pixel brightness is flat in the middle of the ordered distribution.

We can fit a median ordered Poisson profile to the dim pixels of the annulus.

# Measure Galacto-Isotropic $\gamma$ Rays

## Approach 2: Removing Non-Poissonities

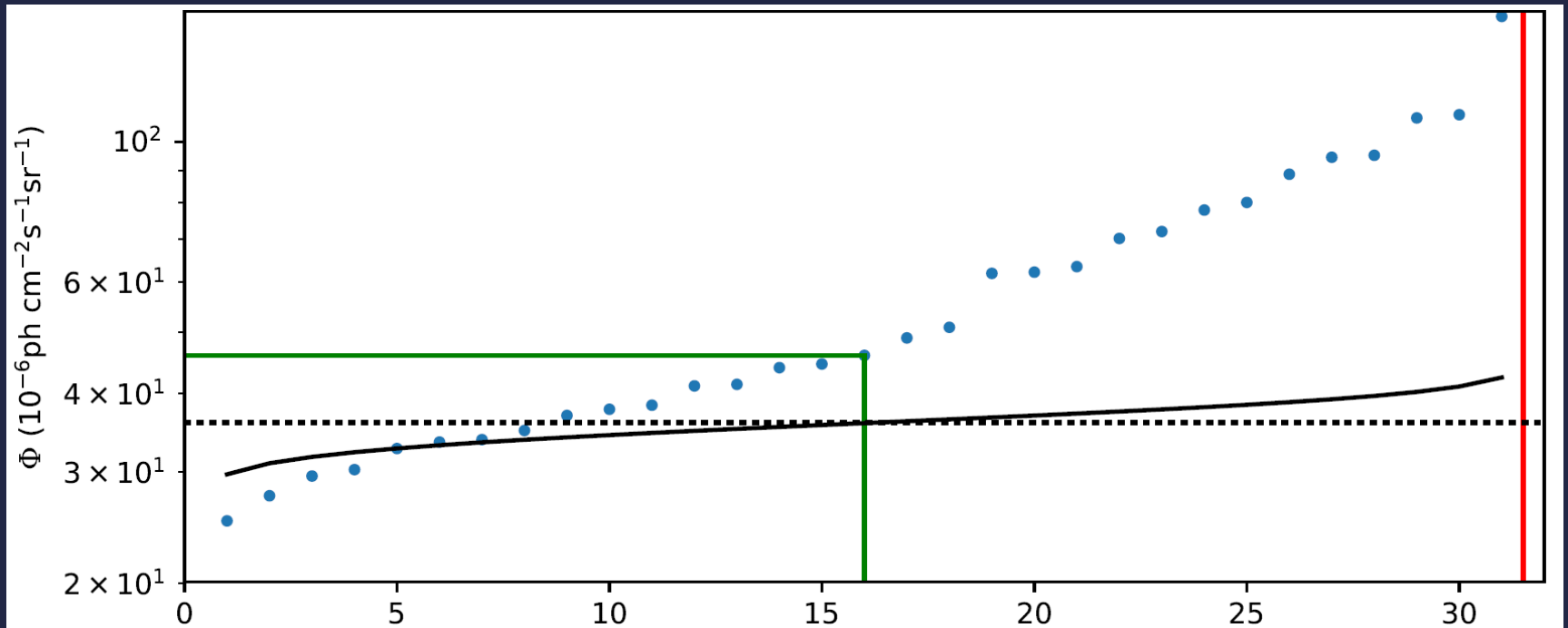


Ordered Pixel Ensemble at  $60^\circ$  with  $0.2^\circ$  pixels.

Unlike the BDS test, this method works perfectly well for annuli with low-count pixels...

# Measure Galacto-Isotropic $\gamma$ Rays

## Approach 2: Removing Non-Poissonities

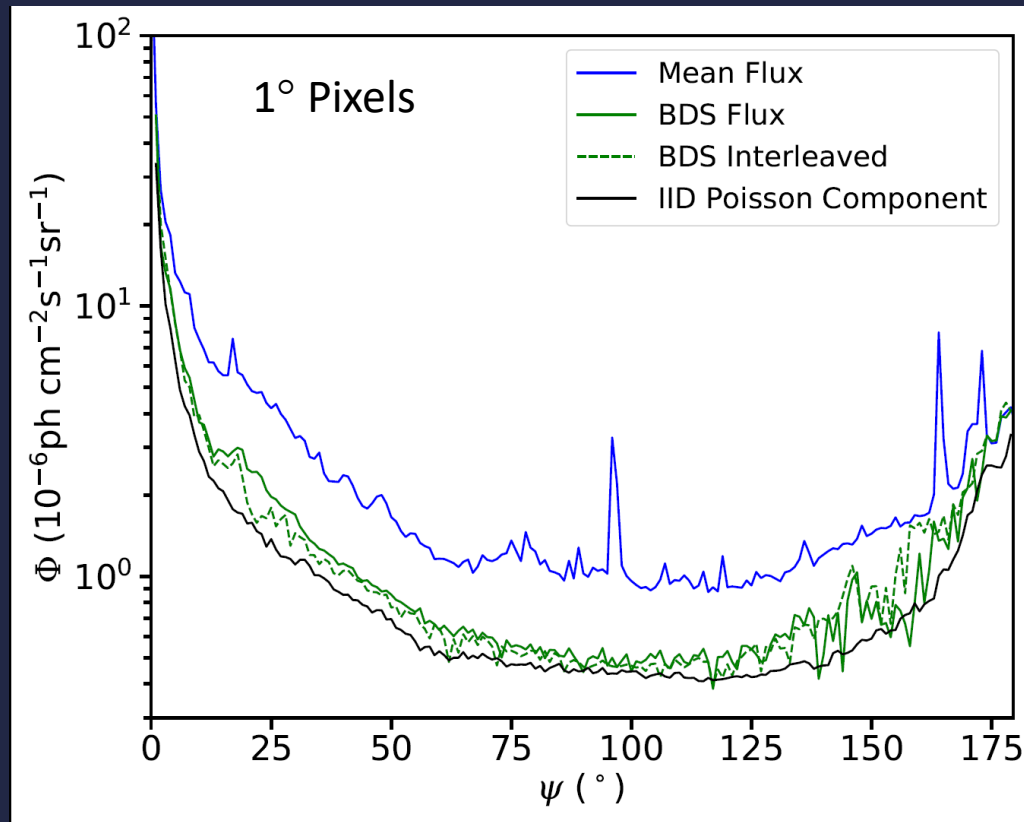


Ordered Pixel Ensemble at  $1^\circ$  with  $0.2^\circ$  pixels.

...and works well in annuli with few pixels.

# Measure Galacto-Isotropic $\gamma$ Rays

## Approach 2: Removing Non-Poissonities



## GI Flux Profiles

Consistency between removing spatial correlations or removing non-Poissonities.

The variation between the different methods is  $\sim 30\%$ . Expect  $\sim 1\%$  is possible.

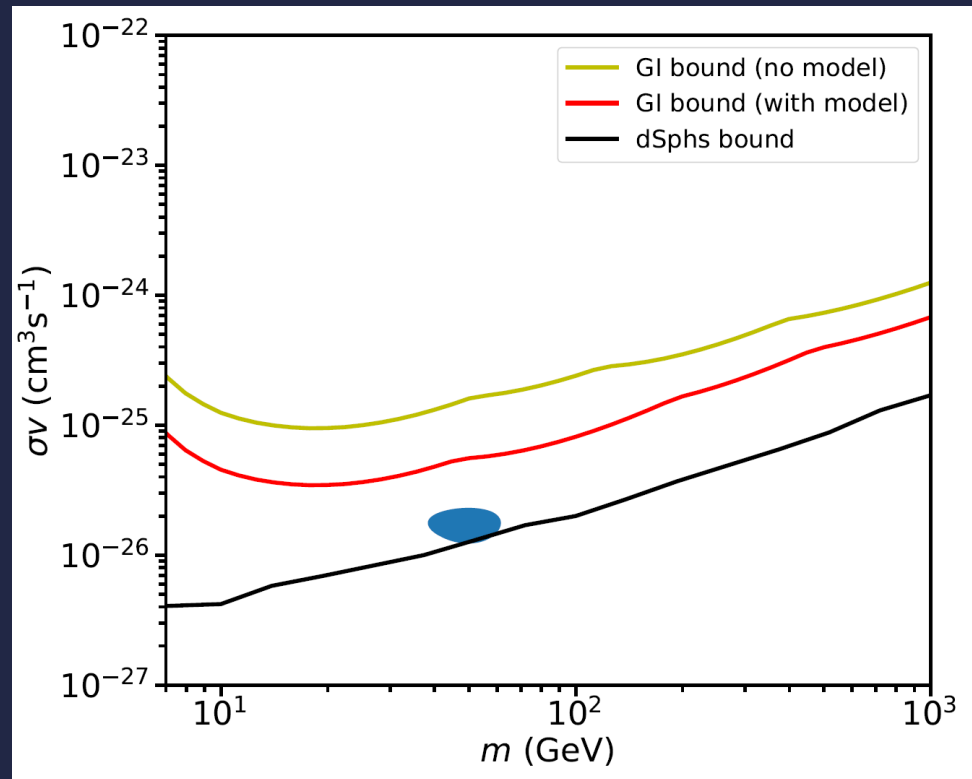
# Measure Galacto-Isotropic $\gamma$ Rays

## Approach 2: Removing Non-Poissonities

- Exact likelihood functions can be determined for ordered Poisson ensembles, enabling a precise estimate and uncertainty of the GI flux profile.
- Full sky models of the  $\gamma$  ray sky must respect this observable.
- Dark matter annihilation constraints include the halo profile, substructure content, and extragalactic annihilation.



# GI Constraint for 30% Uncertainty



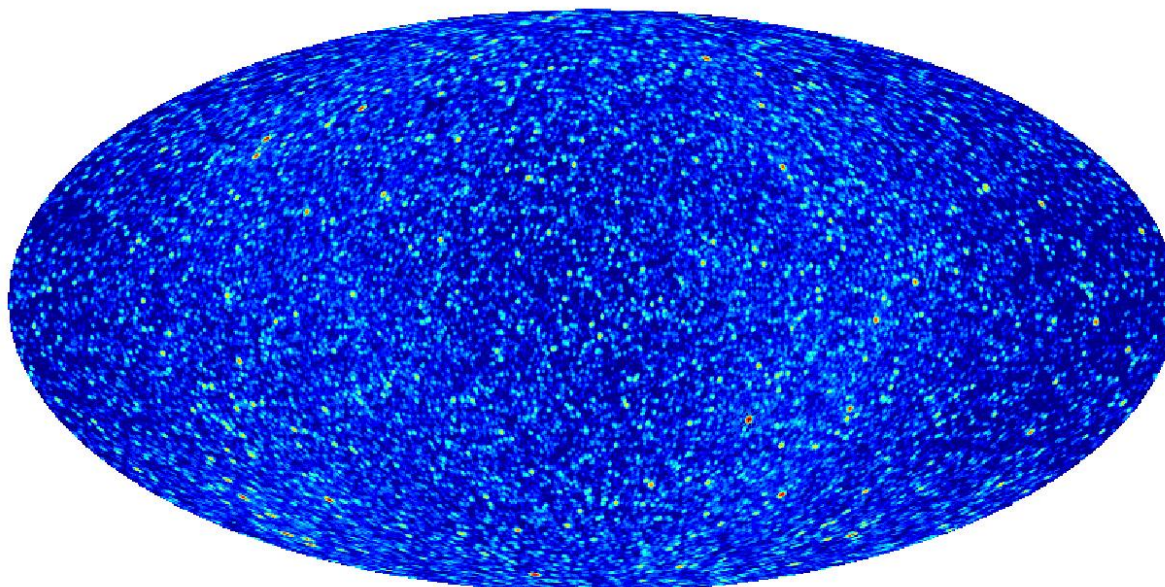
Analyses that observe the Galactic center GeV excess use the same information (model) as we use here. Only the large uncertainty in the GI flux profile prevents sensitivity to the GeV excess.

From an information consideration, it must be possible to reduce the GI flux uncertainty to at least be sensitive to the GeV excess. This predicts the curvature of the likelihood function for the GI flux using ordered Poisson ensembles.

# Lessons from “smooth” full sky ID

- The  $\gamma$ -ray sky has a significant, well-defined, galacto-isotropic component. Full-sky models must adhere to this decomposition.
- The non-GI component is both non-Poisson and spatially correlated, to a good approximation.
- The Galactic center GeV excess is also mostly galacto-isotropic, and so GI measurements and modeling should be sensitive to the GeV excess.
- The GI profile at high latitudes will have implications for constraining particularly clumpy and annihilating dark matter models.

*emission from resolved subhalos (SubSm+SubSub)*



-3.0  2.0 Log(Intensity)

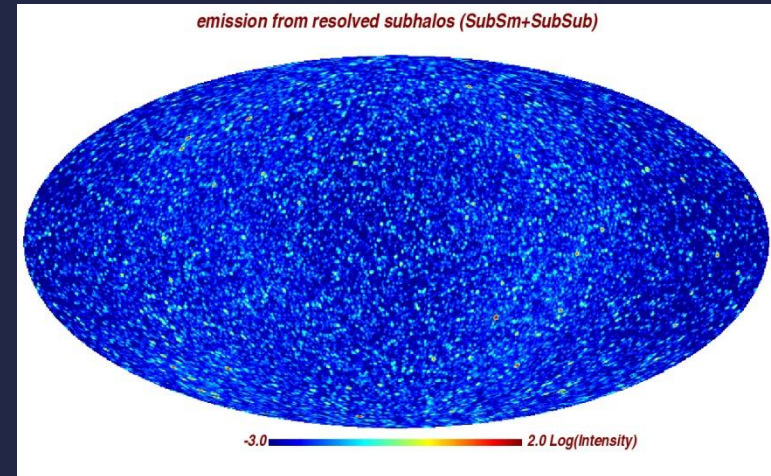
Springel+ (2008)

# SMALL STRUCTURE COMPONENT

2 Minute Version

# How Should We “Measure” or Quantify Small Structure?

- There is a literature from cosmologists tackling this conundrum when the CMB was discovered.
- In the end, Gaussianity of CMB means the **power spectrum** contains all information about CMB anisotropies.
- Unfortunately, structure formation is not a Gaussian process.
- It is probably incorrect to assume Gaussianity of  $\gamma$  rays, and we probably don't need to.



# Lesson from Small Structure ID

Use the fact that  $\gamma$ -ray observing is a  
**Poisson Point Process**

The probability of observing a point in an area of the sky is proportional to the intensity and the exposure of observation.

**This turns out to be  
very powerful.**



# Case Study: Angular Power Spectrum

## $C_\ell$ of $\gamma$ Sources

- Power spectrum of  $\gamma$  rays is an estimate of the power spectrum of the sources.
- Sources in our sky are fixed, the  $\gamma$  events received are random.
- The resulting covariance of the power spectrum coefficients is analytic and exact. SC, MNRAS (2014)

$$\text{Cov}[C_\ell, C_{\ell'}] = \frac{A_{\ell\ell'}}{N_\gamma^2} + \frac{B_{\ell\ell'}}{N_\gamma}$$

- Both  $A$  and  $B$  depend on the power spectrum.
- $B$  also depends on the bispectrum.
- Similar results can be determined for any large-area observable: correlation functions, wavelet transforms, etc.

# General Conclusions

1. Observation of dark matter annihilation would provide access to the sub-dwarf structure of astrophysical dark matter, probing the cosmological history and particle nature of dark matter and possible dark sector.
2. This motivates new large-area observables in  $\gamma$ -ray astronomy that would be sensitive to dark matter signatures.
3. These observables are already providing new information about  $\gamma$ -ray sources making models more constrained, and dark matter analyses more robust.
4. Proper full-sky indirect detection constraints must be as good as the dwarf satellite constraint (since dwarf satellites are included) and are one of few windows available to potentially improve them significantly.