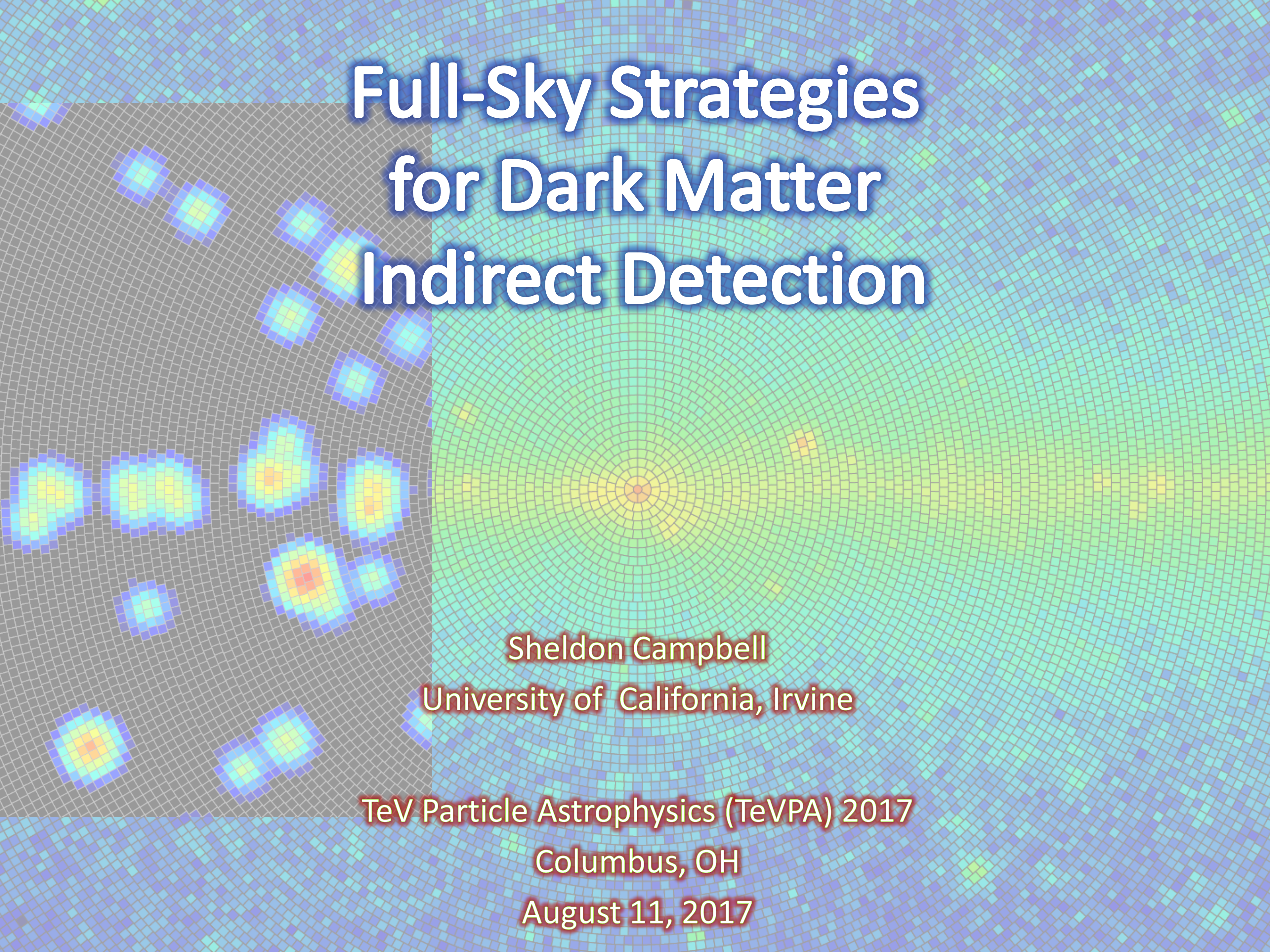
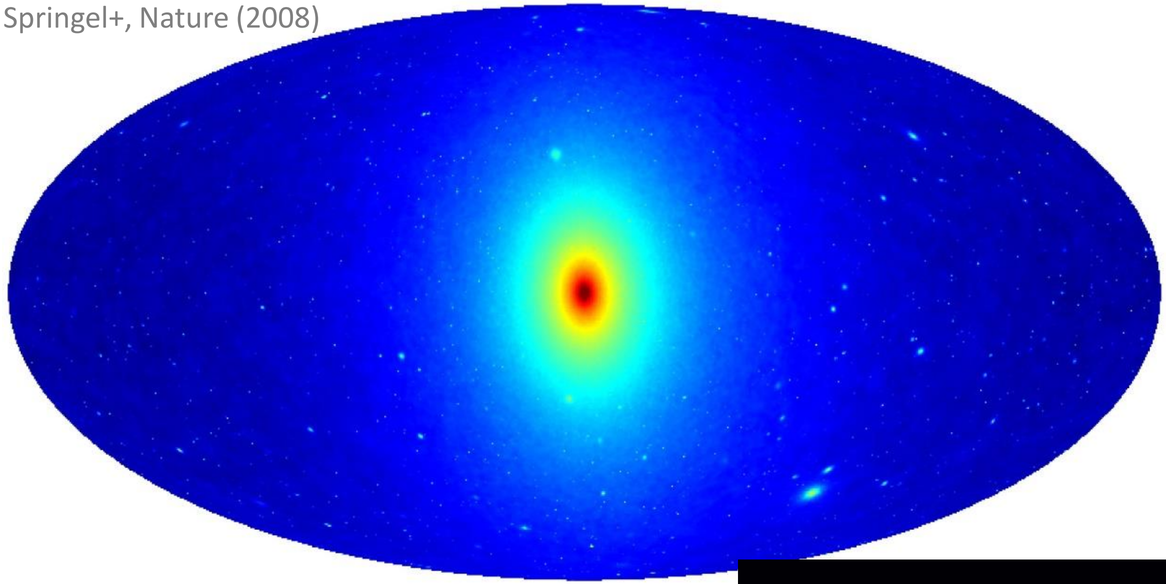


Full-Sky Strategies for Dark Matter Indirect Detection

Sheldon Campbell
University of California, Irvine

TeV Particle Astrophysics (TeVPA) 2017
Columbus, OH
August 11, 2017

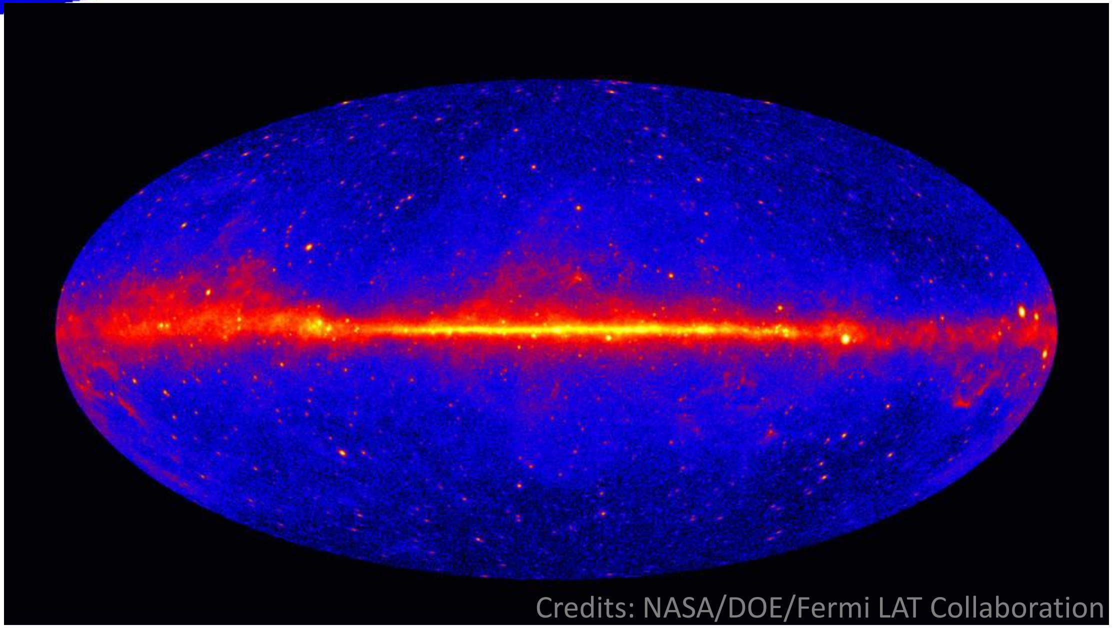
Signal Model vs. Observed γ-ray Sky



Springel+, Nature (2008)

Two main dark matter signal components:

1. galactocentric diffuse
2. small structures



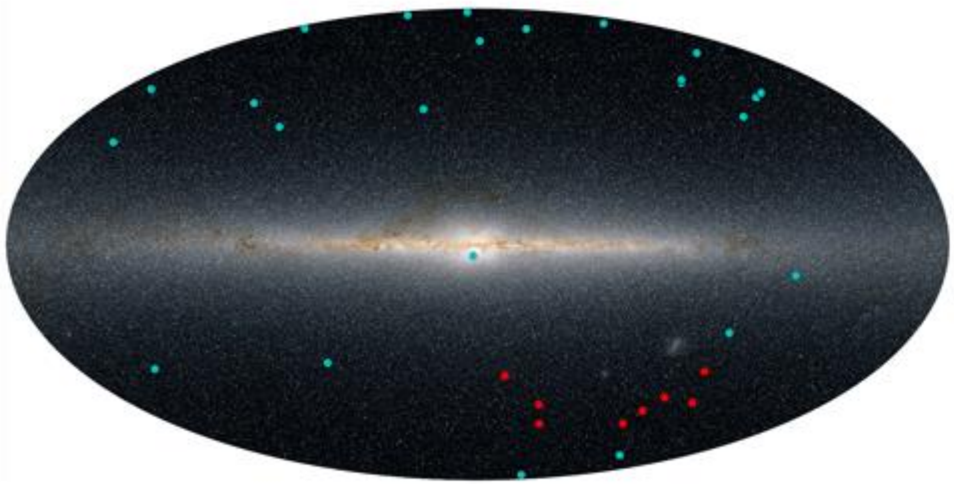
Credits: NASA/DOE/Fermi LAT Collaboration

Observed sky modeled with

- Bremsstrahlung
- π^0 decay
- inverse Compton
- point sources
- Fermi bubbles
- isotropic background

using known gas maps and modeled starlight, cosmic rays.

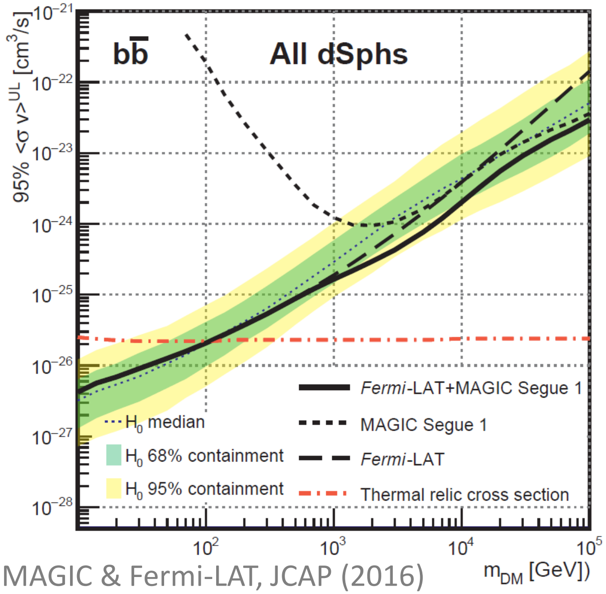
King of ID: Dwarf Satellites



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

The standard all other analyses are measured against.

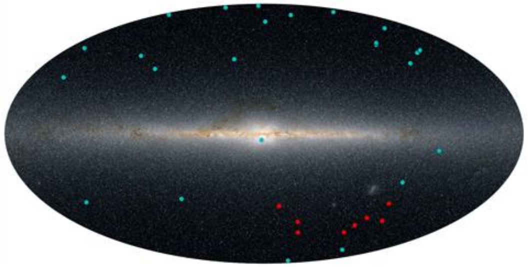
Not necessarily the most sensitive observable,
but likely the most robust constraint.



MAGIC & Fermi-LAT, JCAP (2016)

Central Question

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



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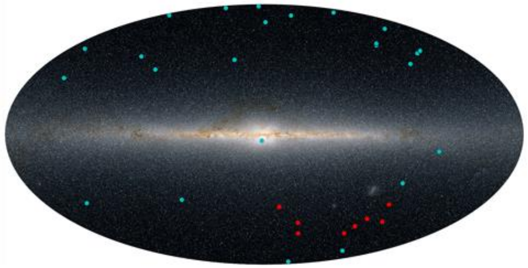

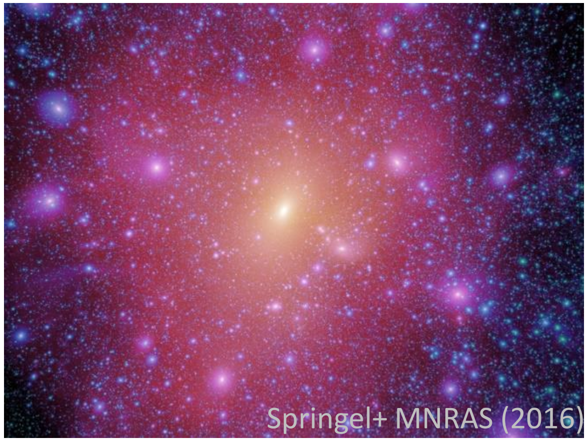

Springel+ MNRAS (2016)

But coherent structures may fill the sky.

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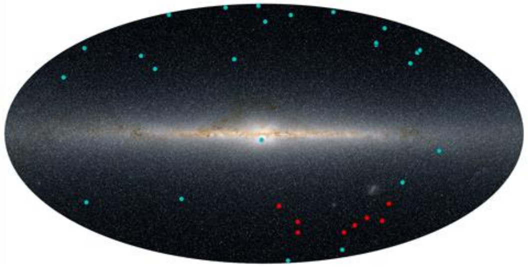
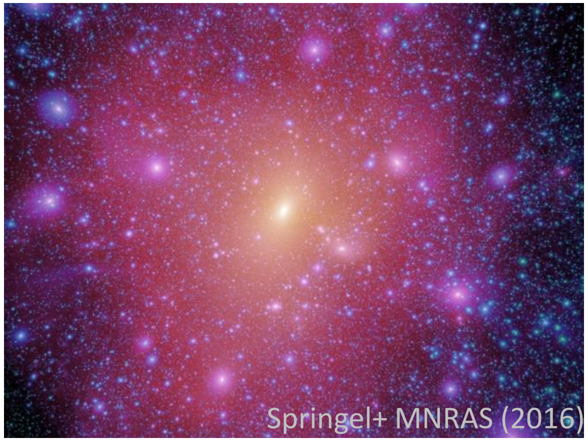
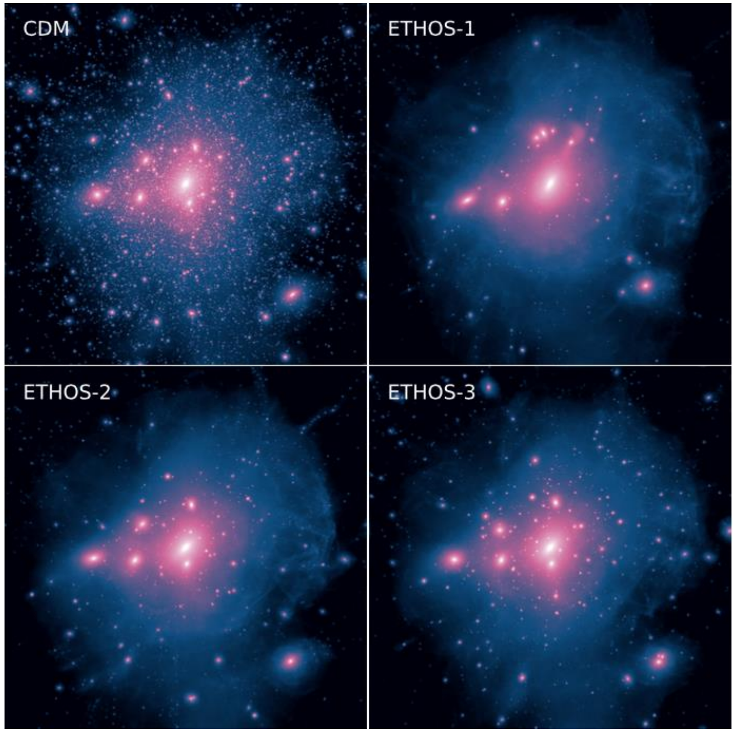




But coherent structures may fill the sky.



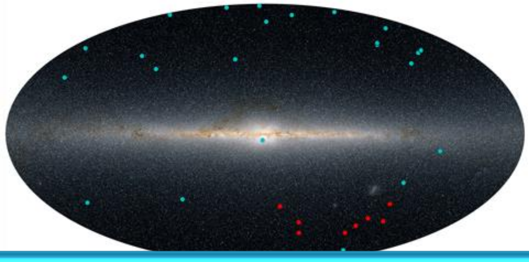
Vogelsberger+ MNRAS (2016)

Detailed structure is sensitive to:

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

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.

Vogelsberger+ MNRAS (2016)

Full Sky Strategies

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

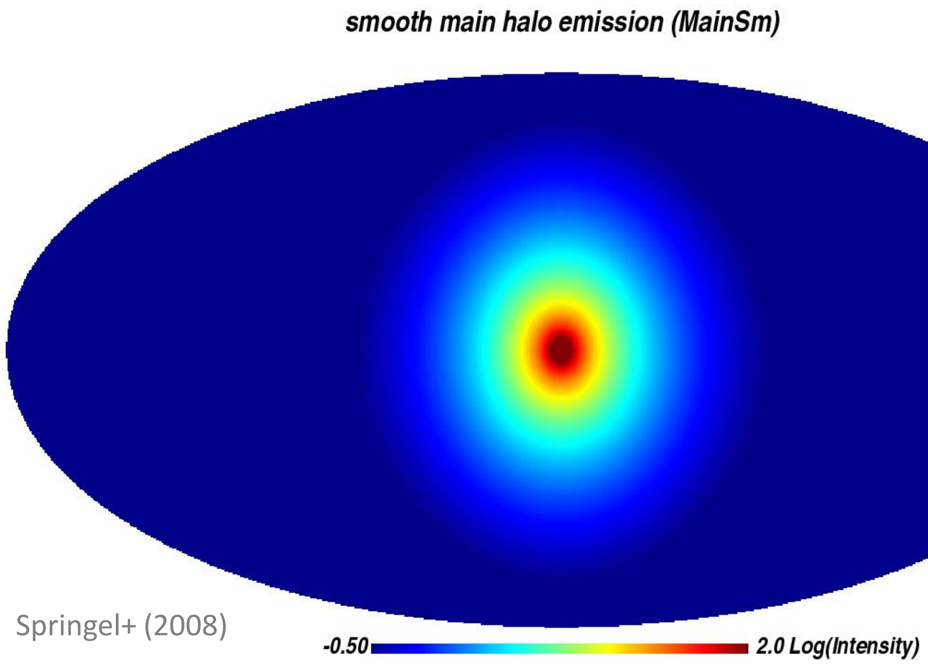
Full Sky Strategies

1. Probe galactocentric diffuse component.
   - Measure **galactoisotropic component**.

Focus for this talk.

2. Probe small structures.
   - Measure **auto-correlations**.
   - Measure **cross-correlations**:
     - between energy bins,
     - with other radiation maps,
     - with point source catalog maps.

More information on small structure searches in the extra slides.

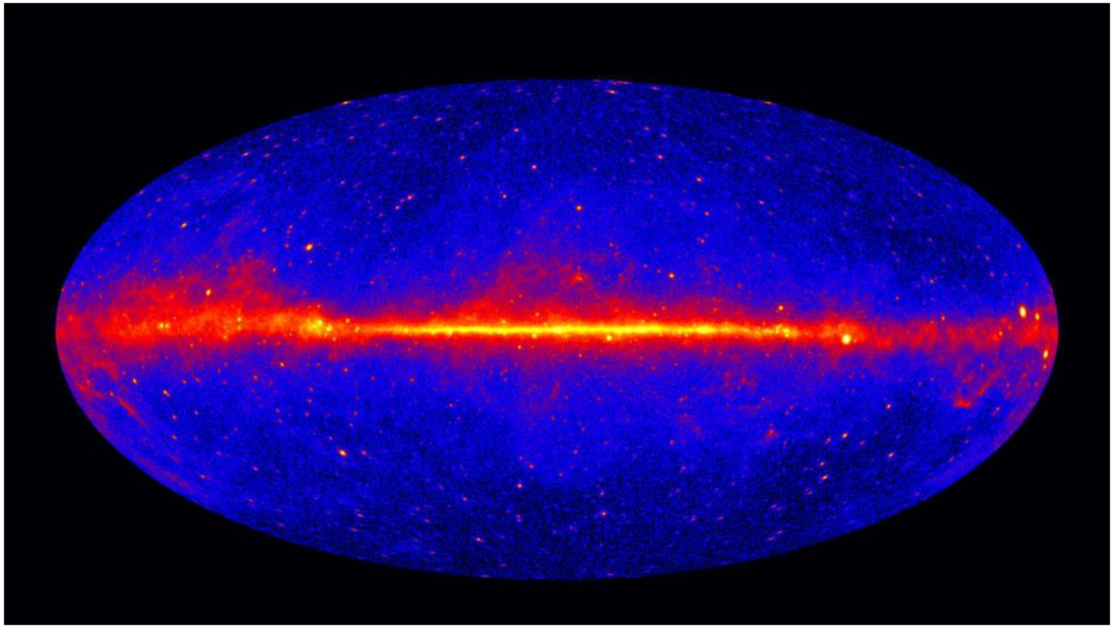


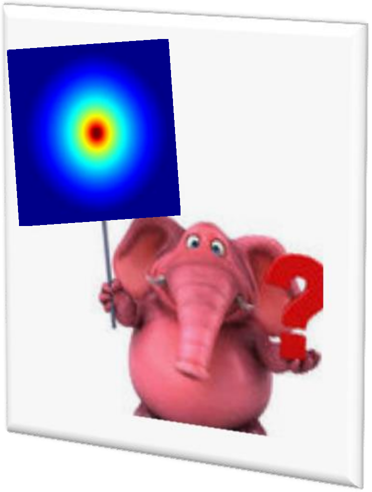
Springel+ (2008)

GALACTOCENTRIC DIFFUSE COMPONENT

New research with collaborators Manoj Kaplinghat and Anna Kwa.

The Elephant in the γ rays

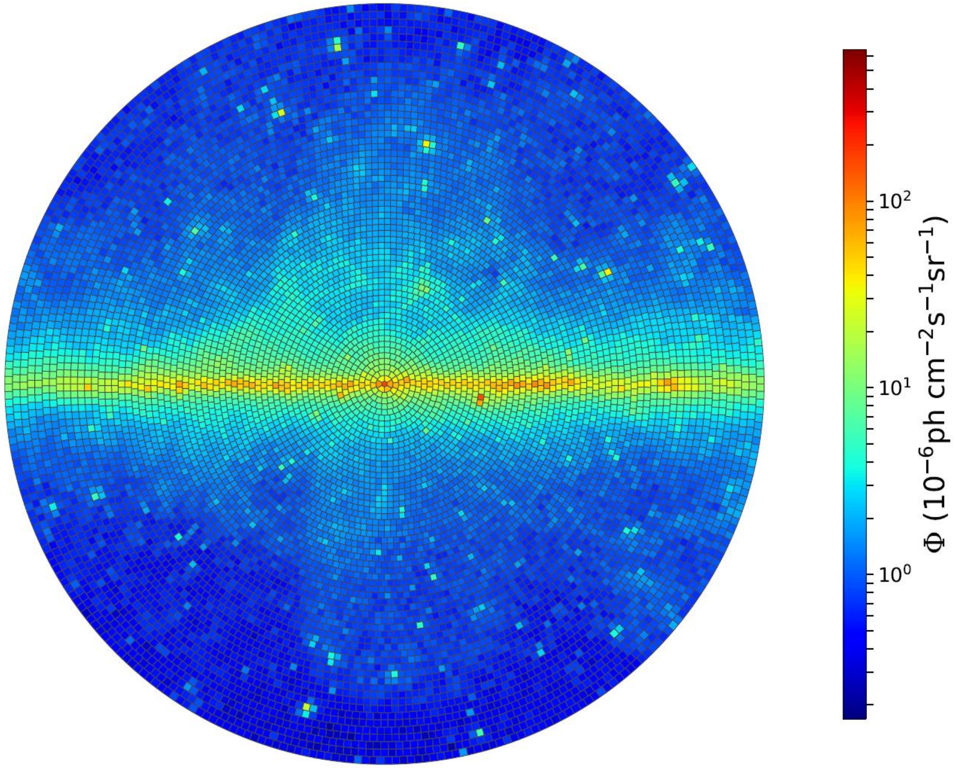




- The **"smooth"** component of the dark matter signal is roughly **galacto-isotropic**.
- The majority of the observed distribution is not.

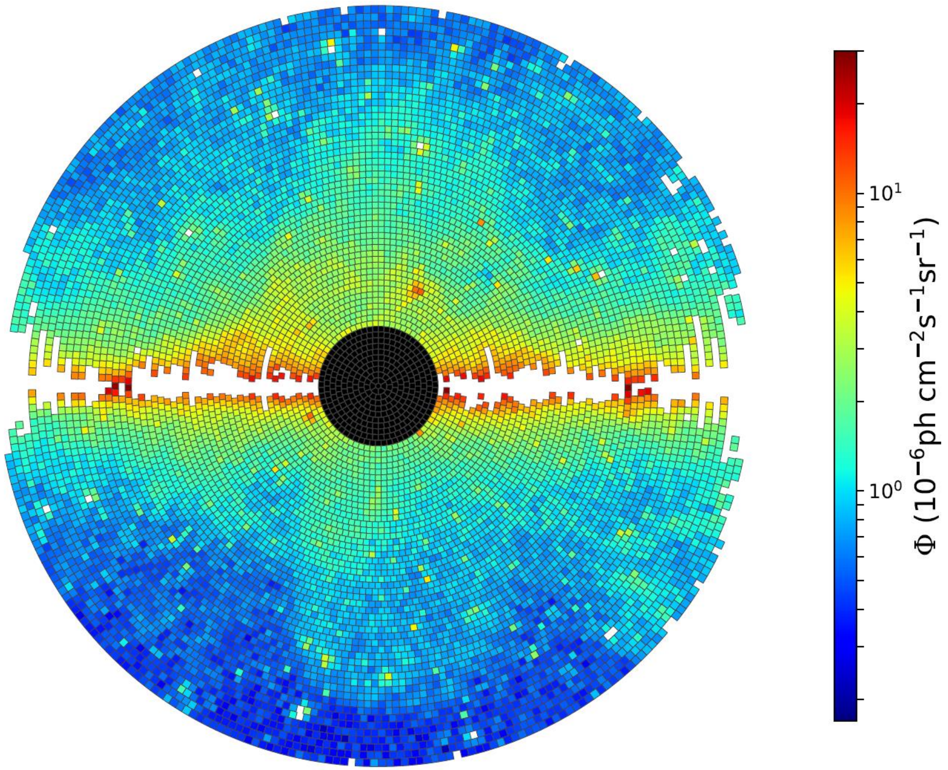
What is the galacto-isotropic component of the γ-ray sky?

Measure Galacto-Isotropic γ Rays
Approach 1: Removing Structure



1° GI Tiling, Inner 60°

Measure Galacto-Isotropic γ Rays Approach 1: Removing Structure

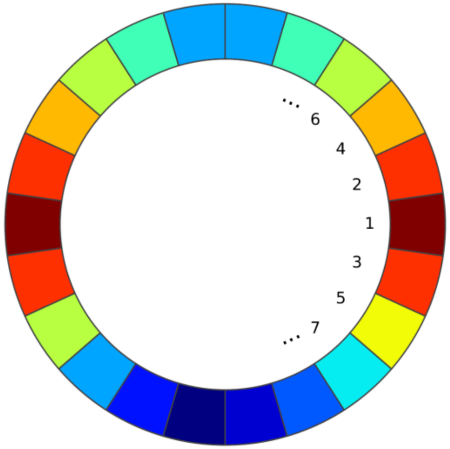


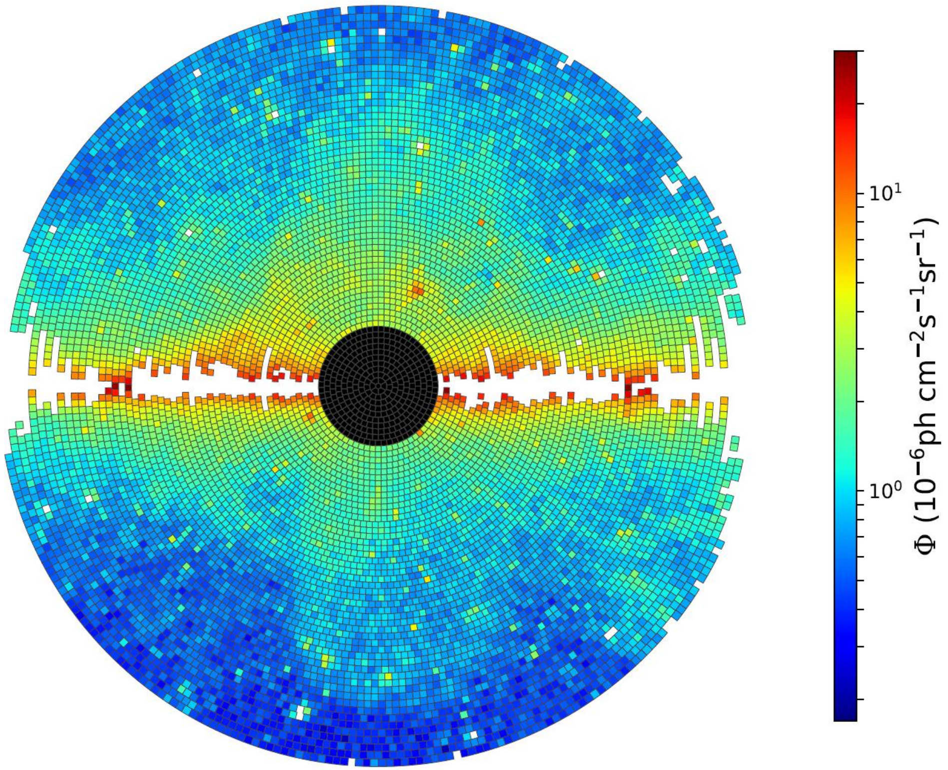
BDS Statistical Test (Baxter, Dodelson 2013)

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

Measure Galacto-Isotropic γ Rays
Approach 1: Removing Structure

Try interleaving.





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Measure Galacto-Isotropic γ Rays
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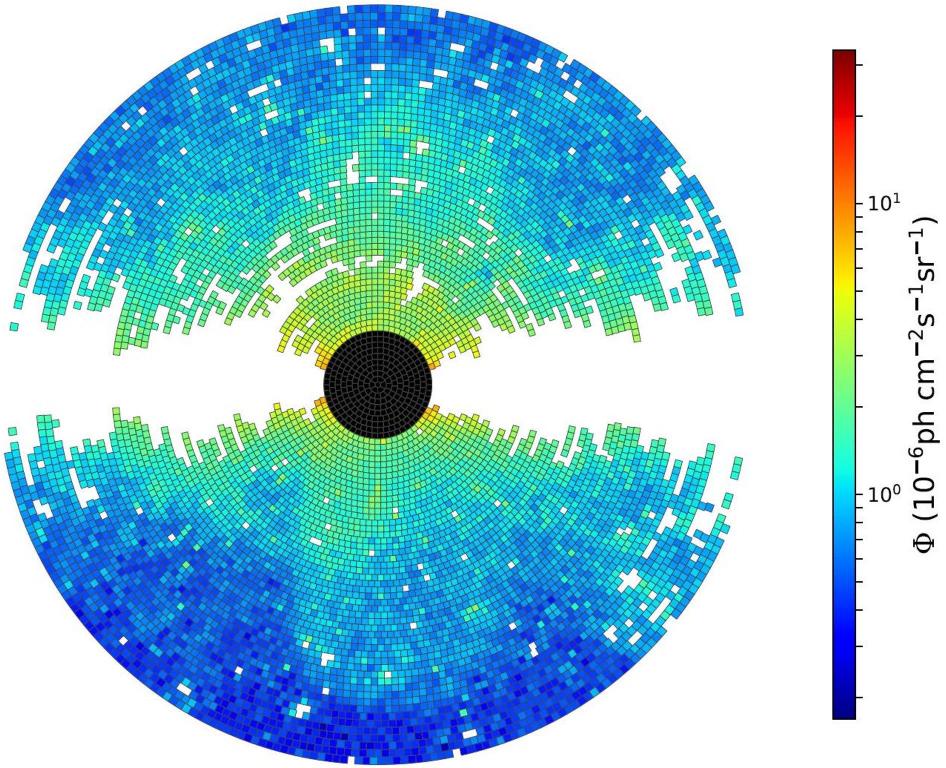
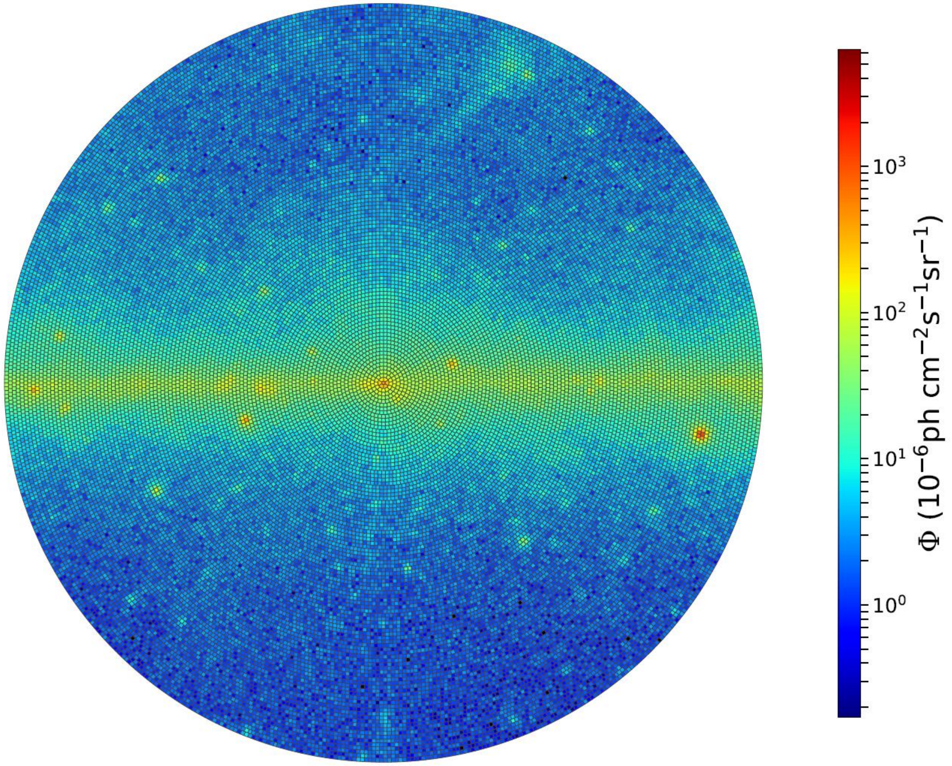


BDS Statistical Test with North-South Interleaving

Structure removal is very effective.

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

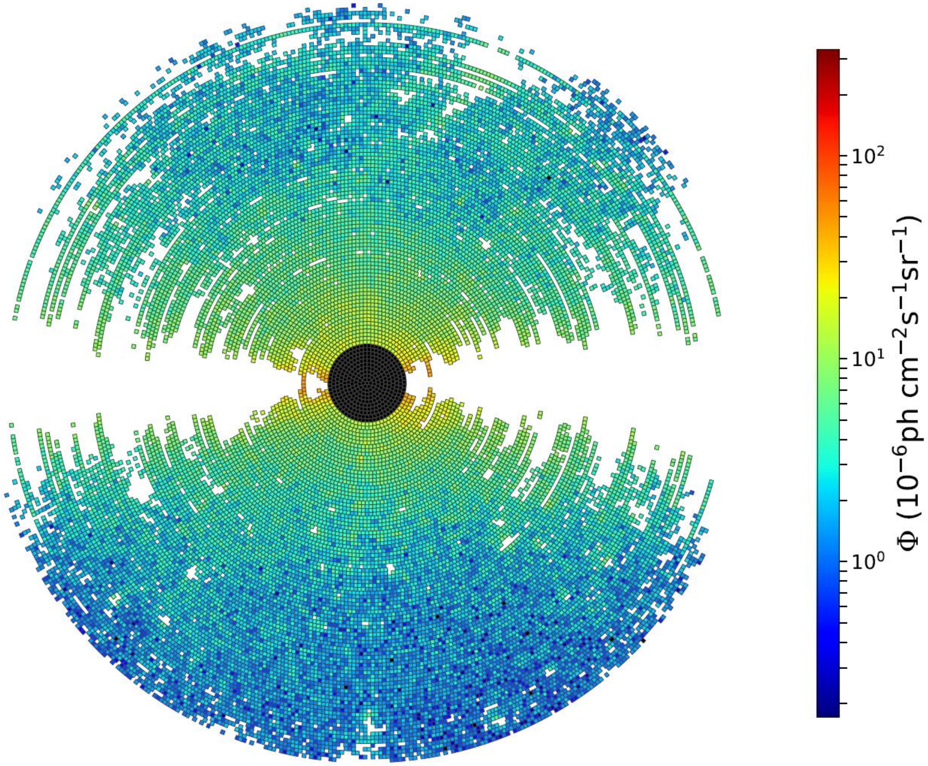
Measure Galacto-Isotropic γ Rays
Approach 1: Removing Structure



0.2° GI Tiling, Inner 20°

Removal of correlated structures is more striking at higher resolution.

Measure Galacto-Isotropic γ Rays Approach 1: Removing Structure



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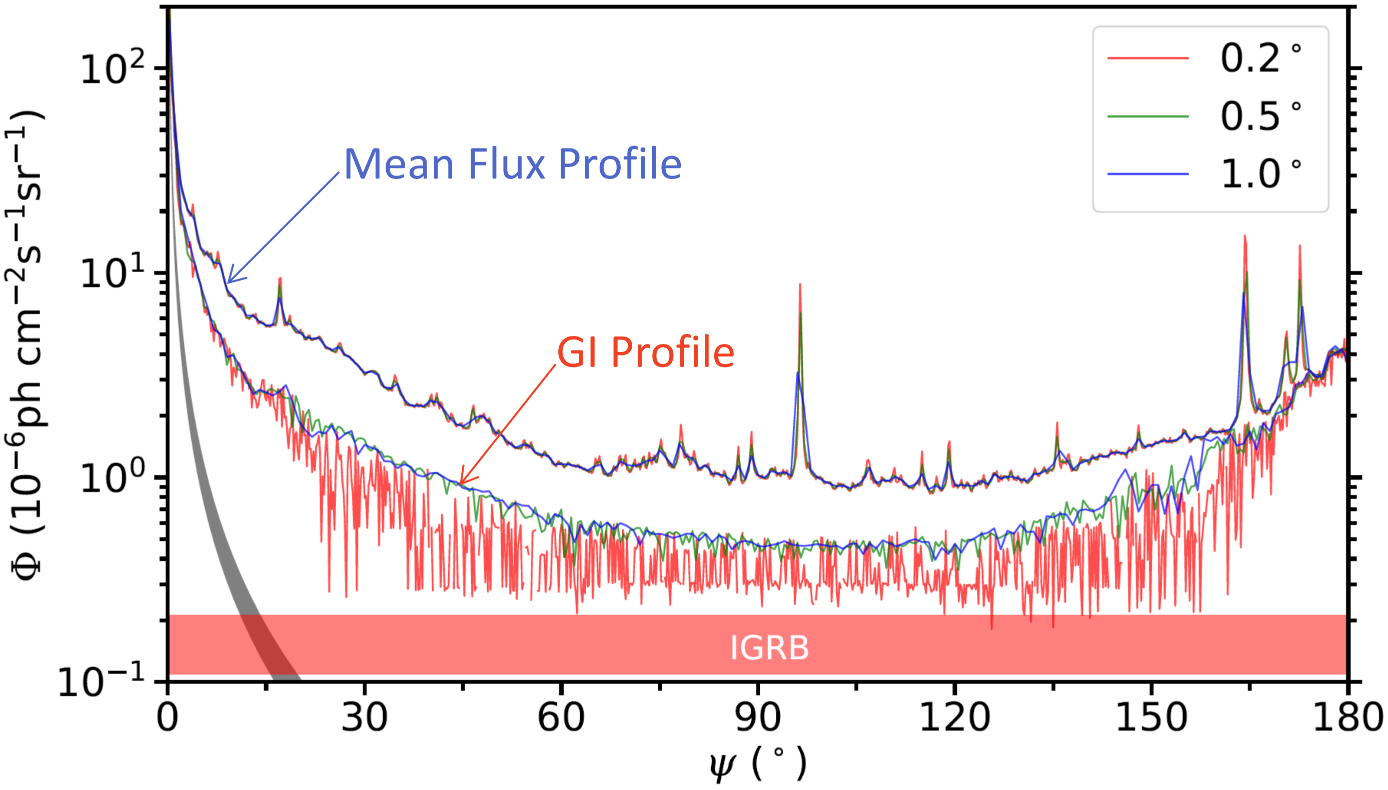
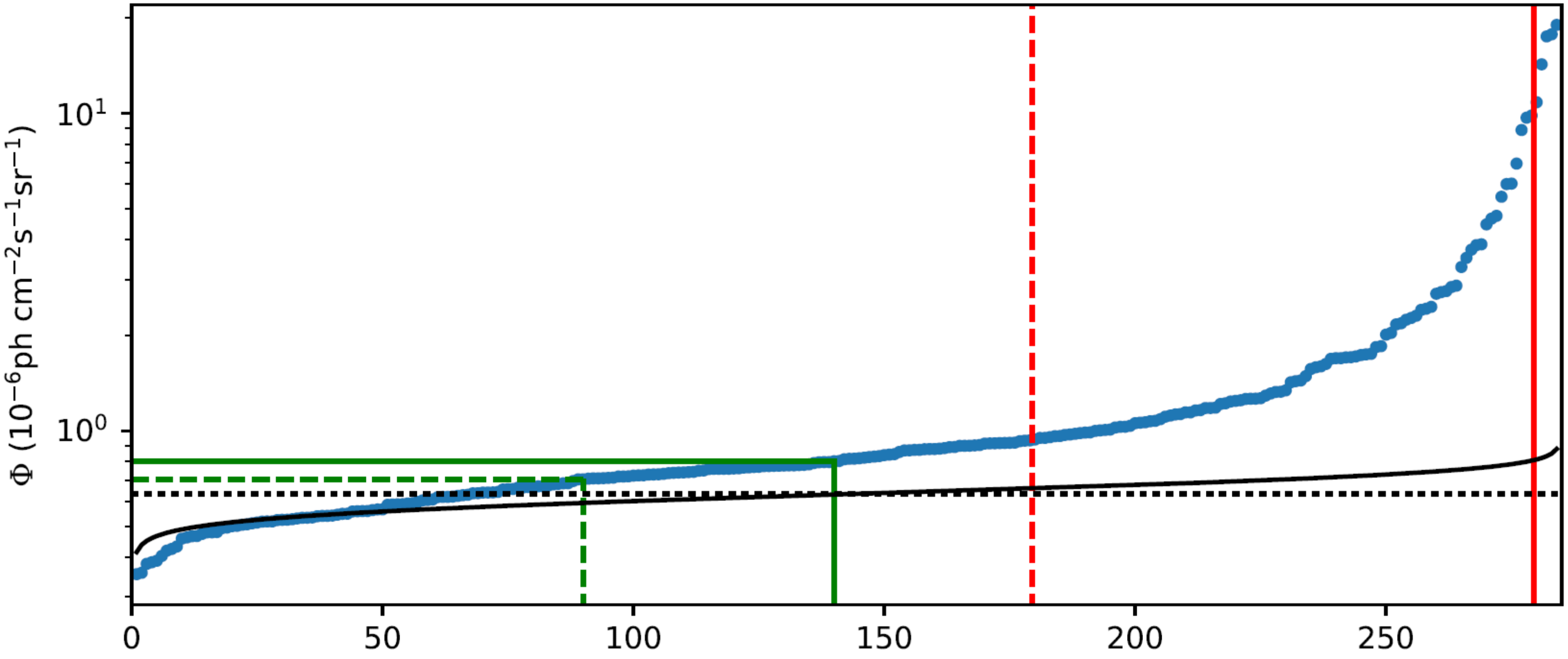


GI Flux Profile

there it is!

Measure Galacto-Isotropic γ Rays

Approach 2: Removing Non-Poissonities



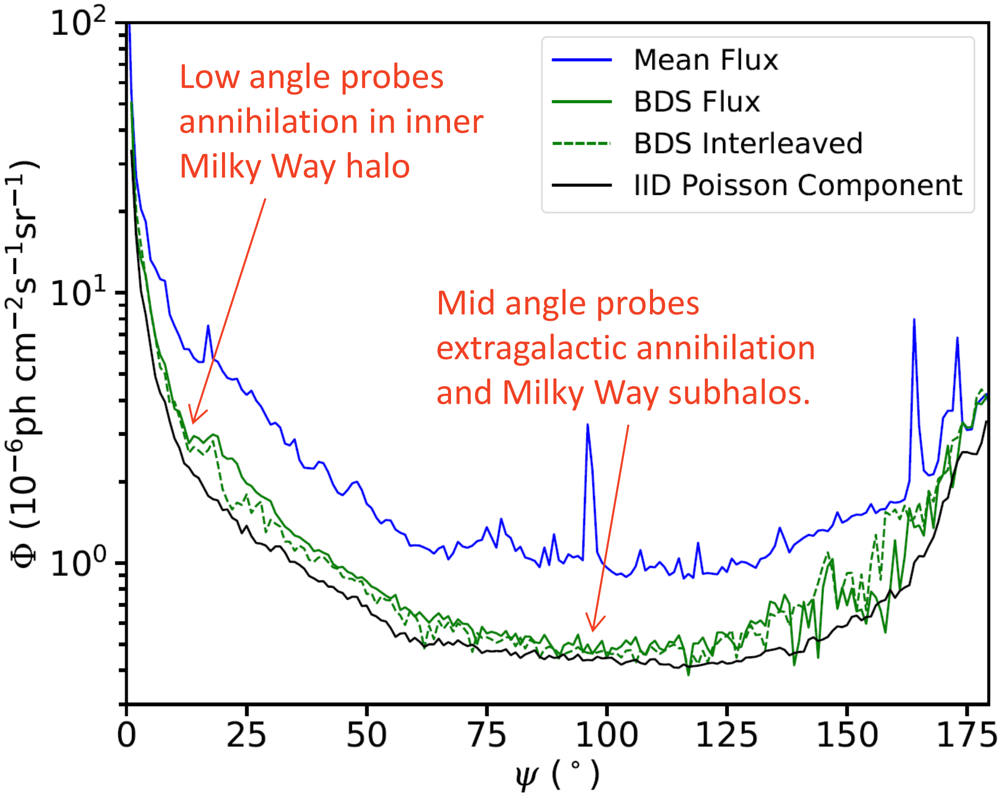
Ordered Pixel Ensemble at 52° with 1° pixels.

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 γ 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 ~30%. Expect ~1% is possible.

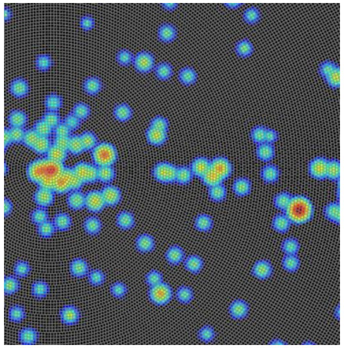
Measure Galacto-Isotropic γ Rays

Approach 2: Removing Non-Poissonities

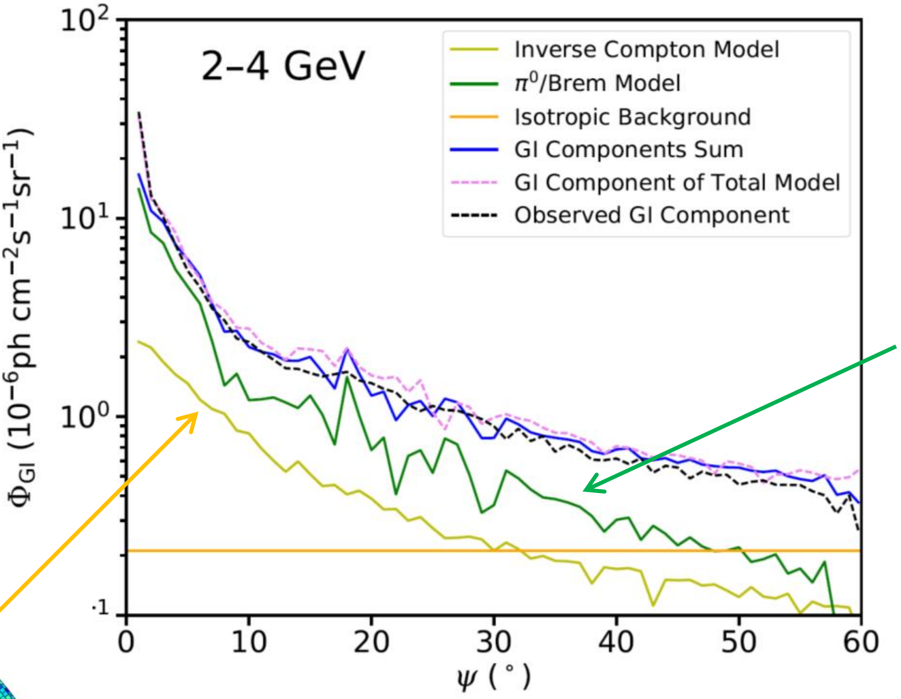
- Exact likelihood functions can be determined for ordered Poisson ensembles, enabling a precise estimate and uncertainty of the GI flux profile.

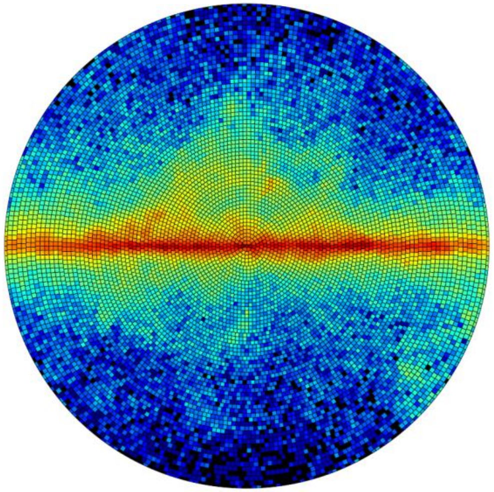
- Full sky models of the γ ray sky must respect this observable.

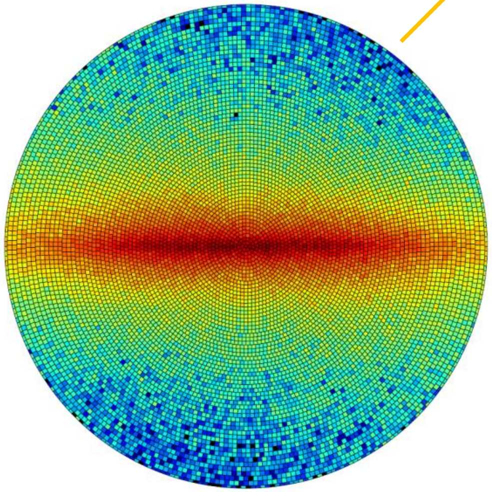
Model the Galacto-Isotropic γ Rays



3FGL Catalog



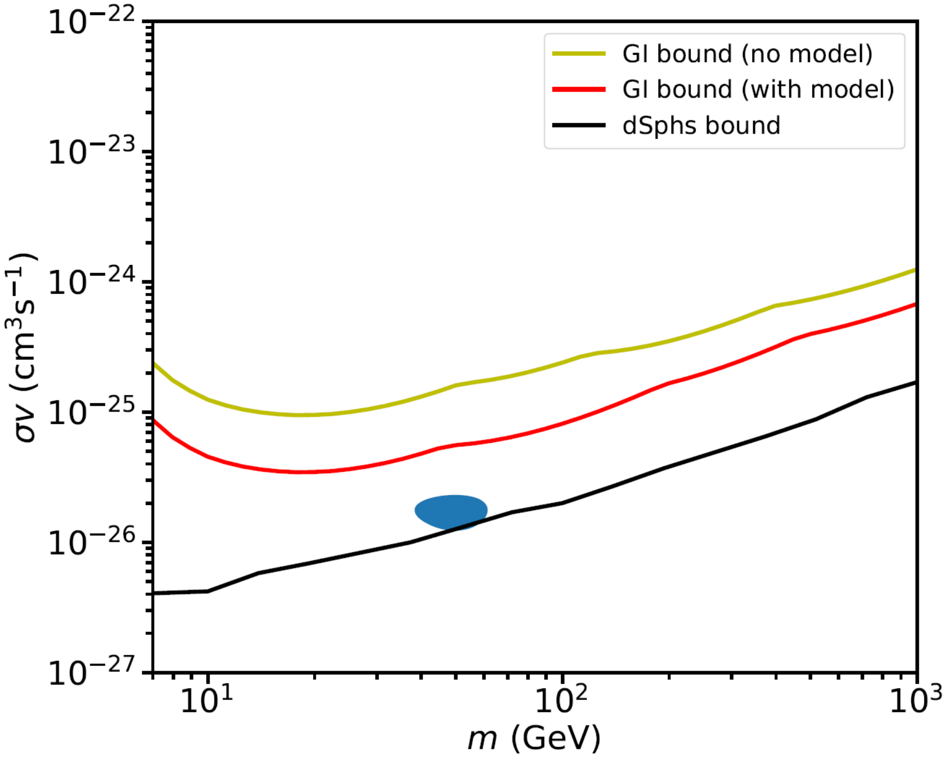




A self-consistent GALPROP-simulated full-sky model.

Calore+ JCAP (2015)
Horiuchi+ JCAP (2016)

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.

“Smooth” full-sky ID Summary

- The γ-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.

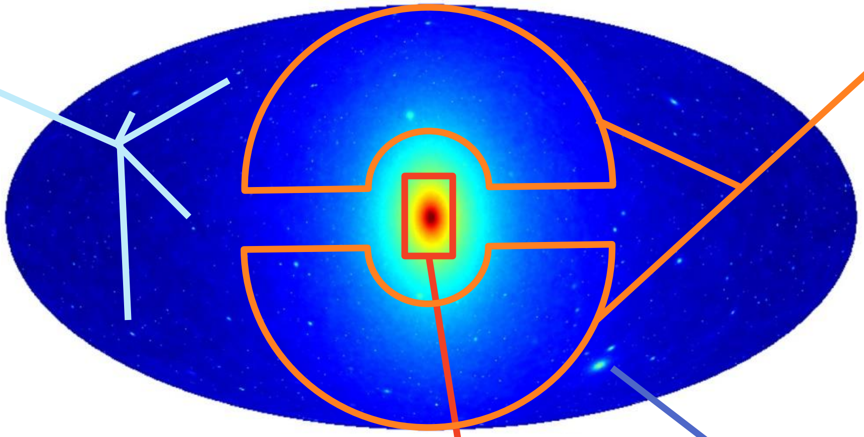
EXTRA SLIDES

Royalty of ID: Targeted Search

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

Does the region's γ-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

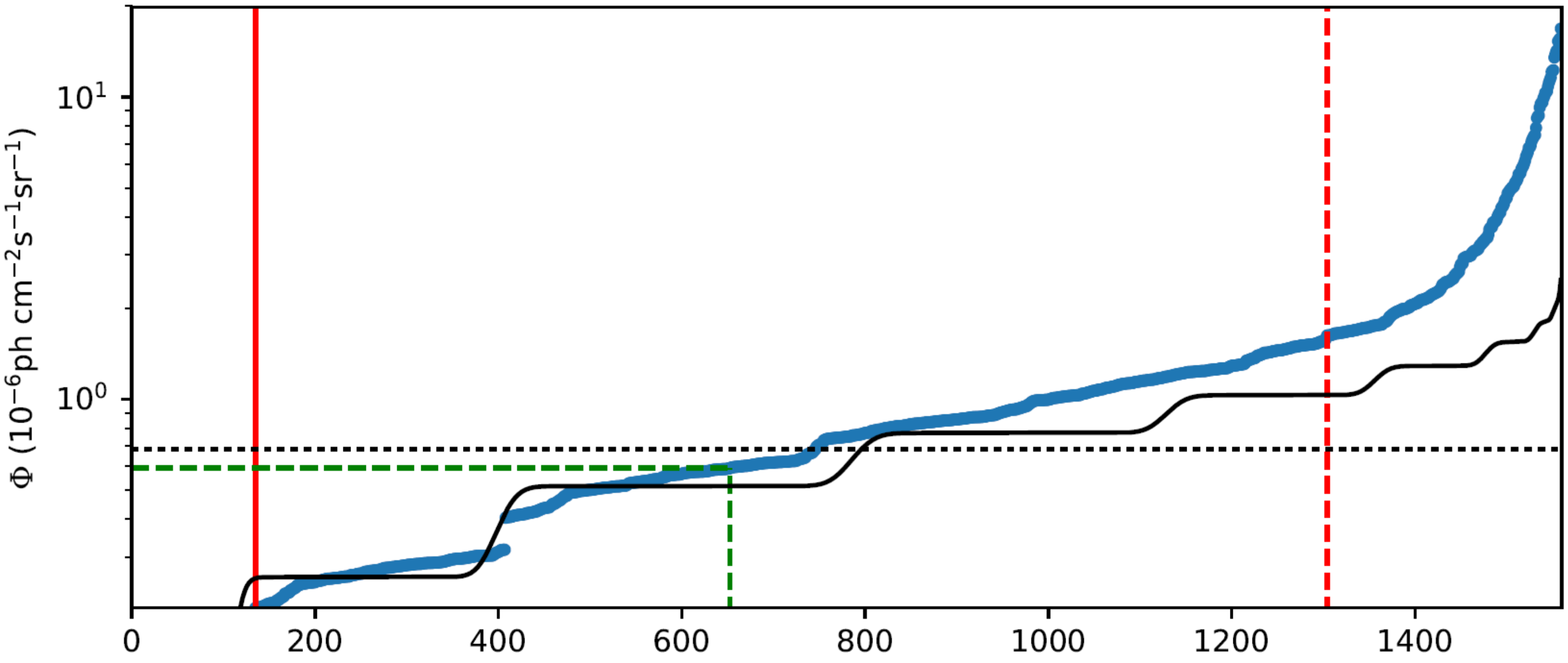
Isotropic Background
- needs big substructure boosts to compete
- large area

Galactic Center
- bright signal
- extended source
- complicated astrophysics

Nearby Galaxies or Clusters
- need very big substructure boosts to compete

Measure Galacto-Isotropic γ Rays

Approach 2: Removing Non-Poissonities

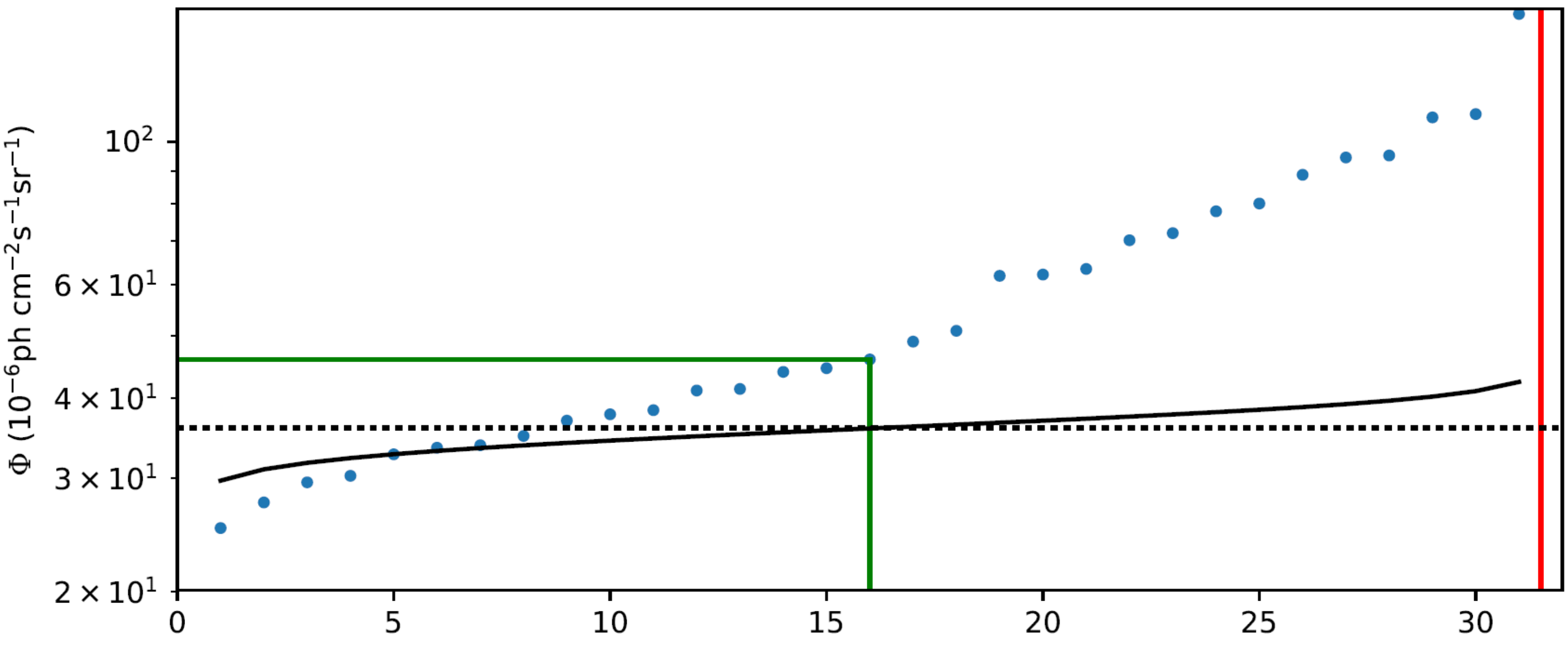


Ordered Pixel Ensemble at 60° with 0.2° pixels.

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

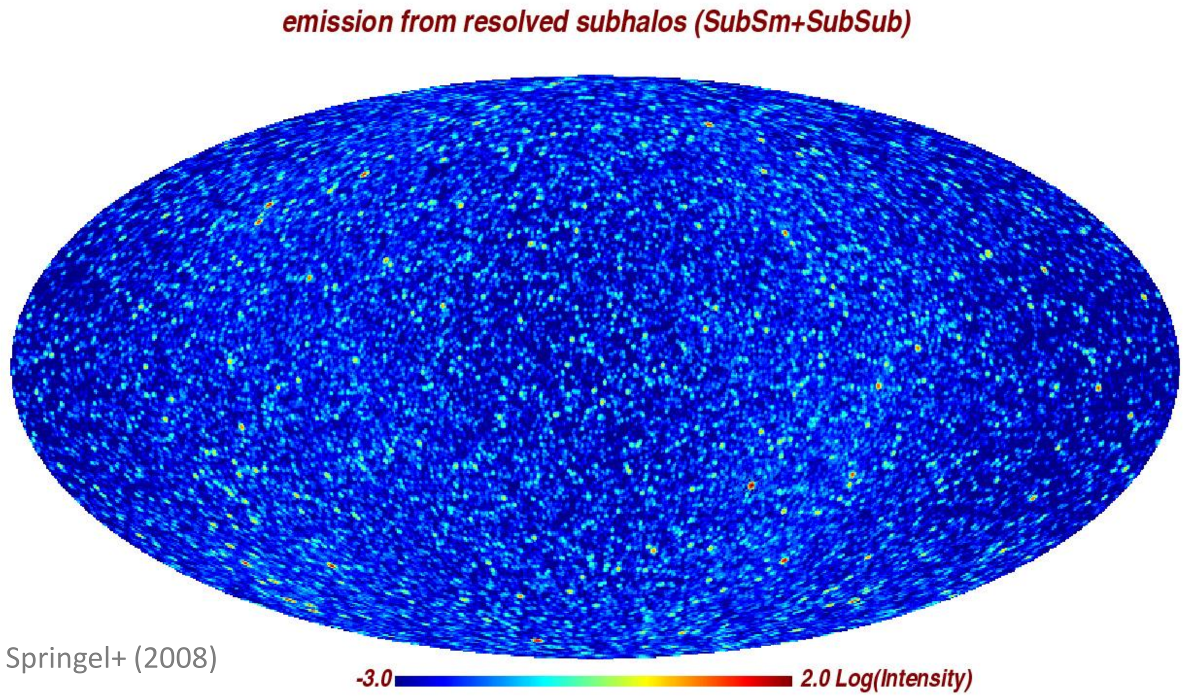
Measure Galacto-Isotropic γ Rays

Approach 2: Removing Non-Poissonities



Ordered Pixel Ensemble at 1° with 0.2° pixels.

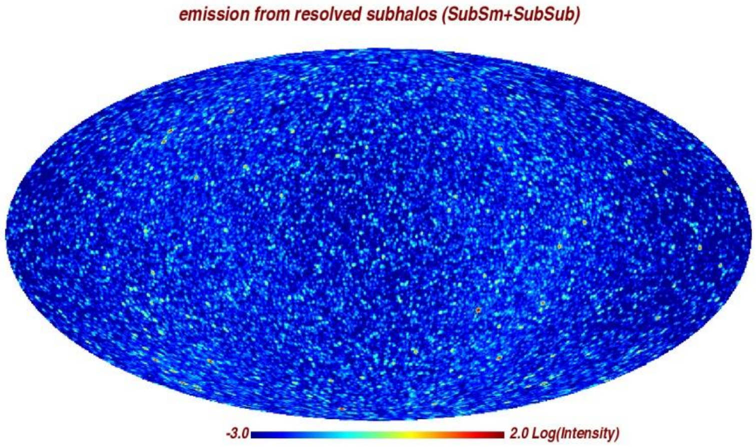
…and works well in annuli with few pixels.



Springel+ (2008)

SMALL STRUCTURE COMPONENT

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 γ rays, and we probably don't need to.

Recommended Strategy for Small Structure ID

Use the fact that γ-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_ℓ of γ Sources

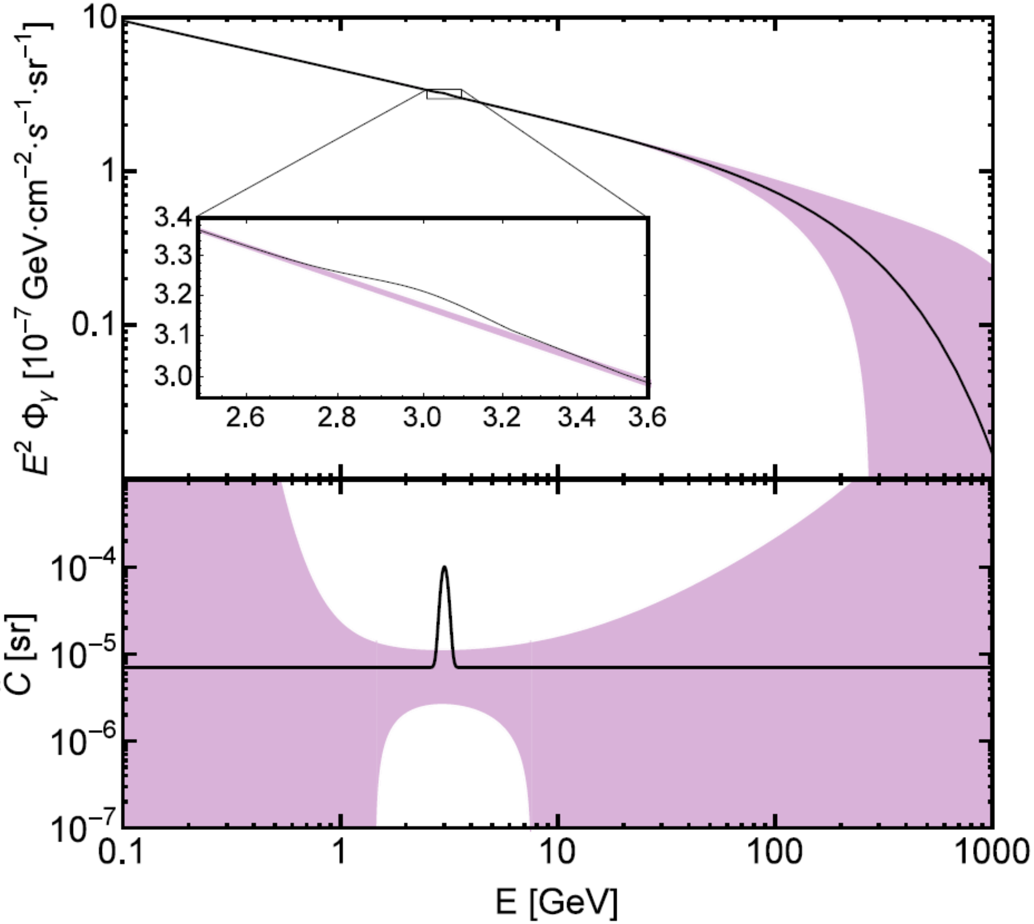
- Power spectrum of γ rays is an estimate of the power spectrum of the sources.
- Sources in our sky are fixed, the γ events received are random.
- The resulting covariance of the power spectrum coefficients is analytic and exact. SC, MNRAS (2014)

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

- 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.

Energy Modulation of Dimensionless Power Spectrum

- Dimensionless power spectrum quantifies clustering of sources independent of intensity.
- The highly clustered (but dim) dark matter annihilation radiation is only present within the energy resolution of the line energy.
- The clustering at each other energy follows the clustering of the sources.



Scenario of dim but highly clustered annihilation to a γ-ray line. The intensity is sensitive to the line at 1.6σ, whereas the dimensionless power spectrum is sensitive at 16σ.

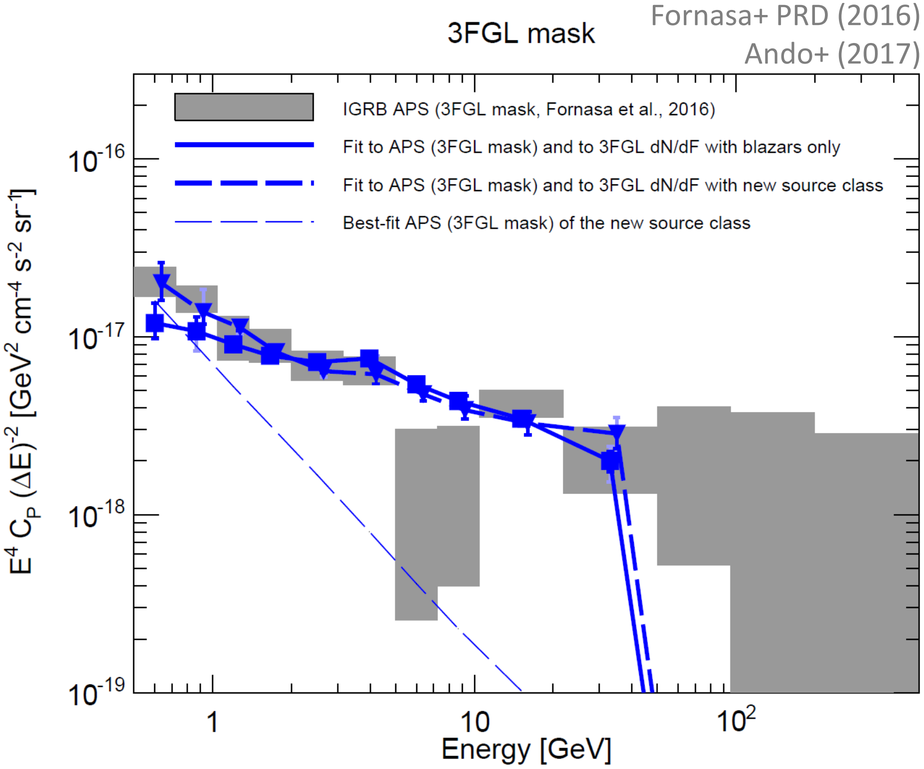
Fermi-LAT Isotropic γ-ray Background (Dimensionful) Power Spectrum

- Mask point sources and subtract Galactic foreground model.

- Power spectrum is consistent with no multipole dependence in each energy bin.

- Measurement is consistent with a population of unresolved blazars, except for lowest energy bins which prefer a second class of source.

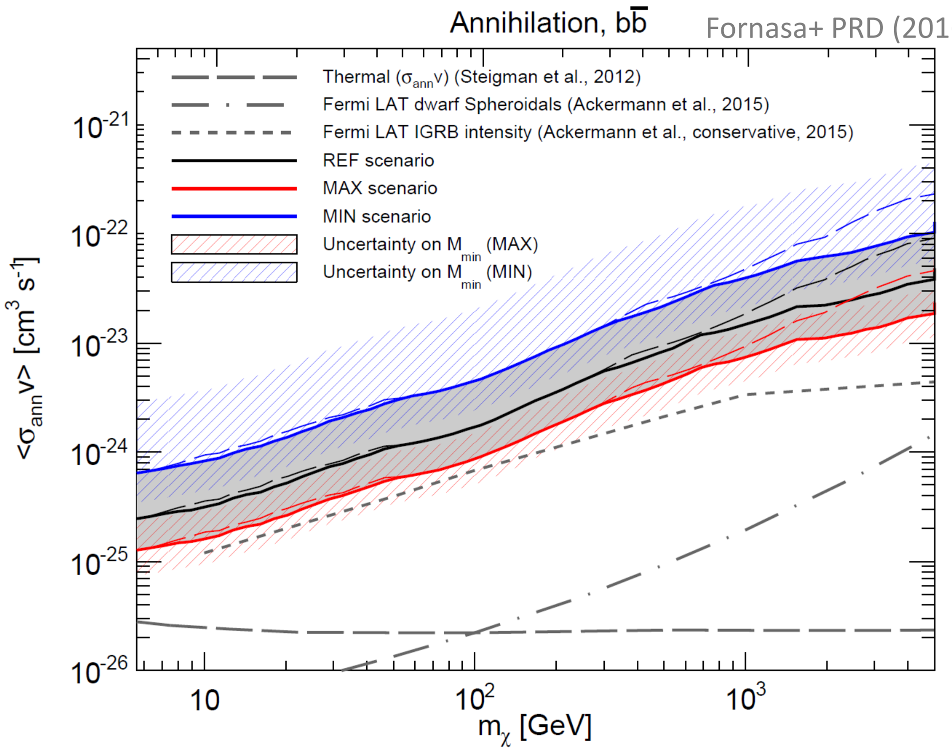
Fornasa+ PRD (2016)
Ando+ (2017)



- The new source class has too soft an energy spectrum (spectral index 2.7-3.2)
to be consistent with known astrophysical sources.

Power Spectrum Constraints

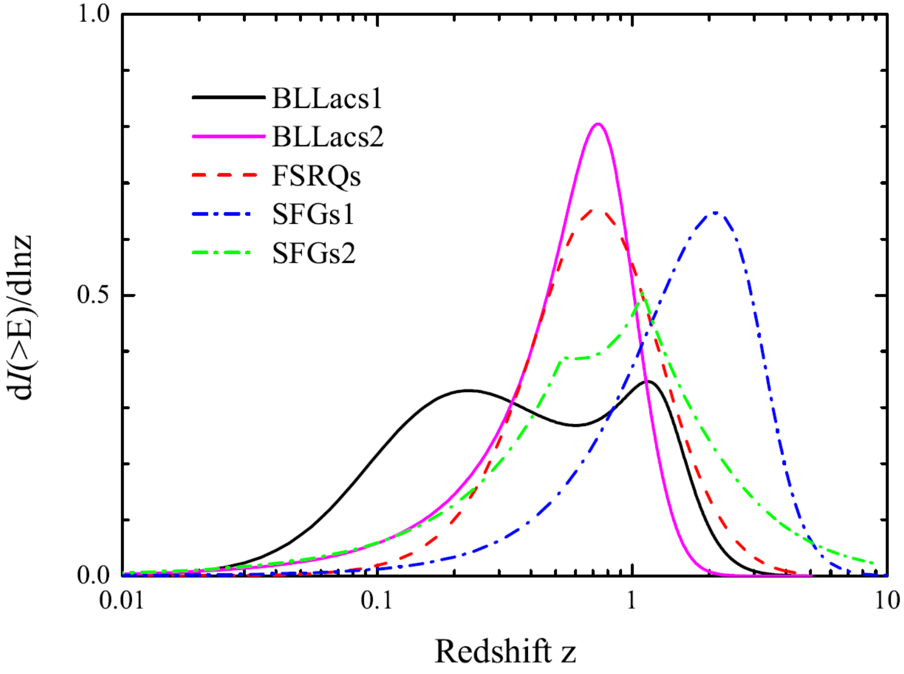
- Annihilation constraints are for the most conservative astrophysics scenario.
  - assume substructure smaller than are resolved in Aquarius simulations are:
    - too small to be resolved in γ rays.
    - are isotropically distributed such that their intensity washes out power from the larger substructure.



Fornasa+ PRD (2016)

- Constraints will be more effective when applied to specific particle physics scenarios and their predicted dark matter clustering.

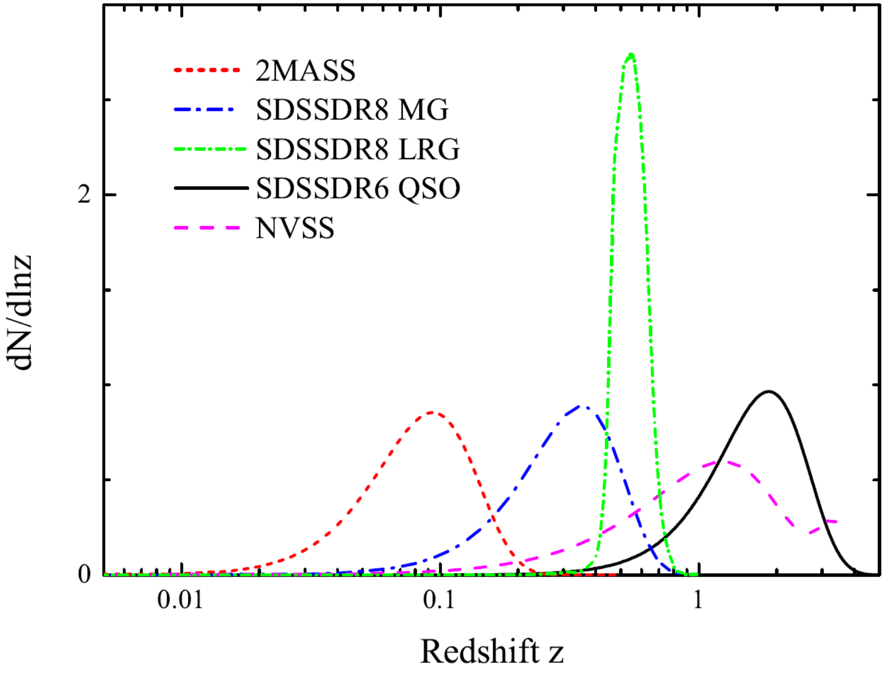
Targeted Full-Sky ID with Cross-Correlations



Different source models contribute γ rays over different ranges of redshifts.

Dark matter annihilation peaks at z=0 and rapidly declines toward higher redshift.

Xia+ ApJS (2015)

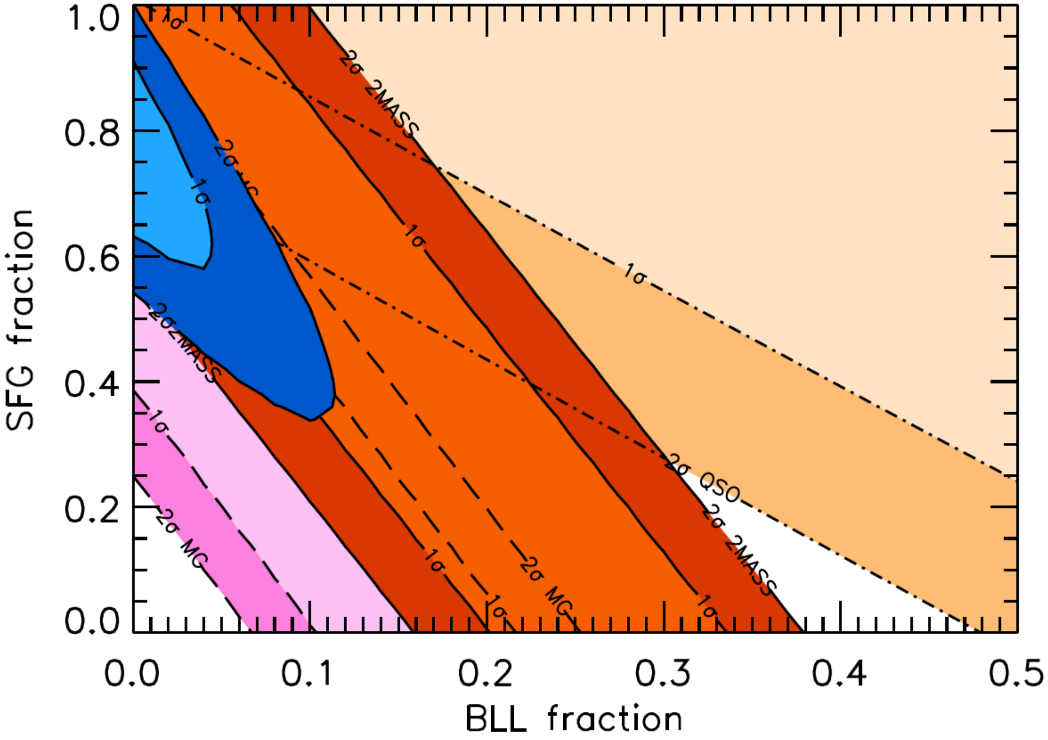


Different source catalogs probe different redshift ranges.

E.g., SDSSDR6 QSO catalog peaks near z=2 making it suitable for probing star-forming galaxies.

Source Model Constraints with Cross-Correlations

What fraction of the istotropic background is due to star-forming galaxies or BL Lacs?



Xia+ ApJS (2015)

Cross-correlations provide new complementary information that constrain source models, helping to make full-sky dark matter constraints even more sensitive.

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 γ-ray astronomy that would be sensitive to dark matter signatures.

3. These observables are already providing new information about γ-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.