A Robust Approach to Constraining Dark Matter with Gamma-Ray Data

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Outline

- Indirect Detection with Gamma-Rays: advantages and challenges
- Our Technique: placing a very robust constraint on dark matter using indirect detection
- Data: gamma-rays measured by the Fermi Gamma-Ray Space Telescope
- Results and Conclusions

Indirect Detection: Advantages and Challenges

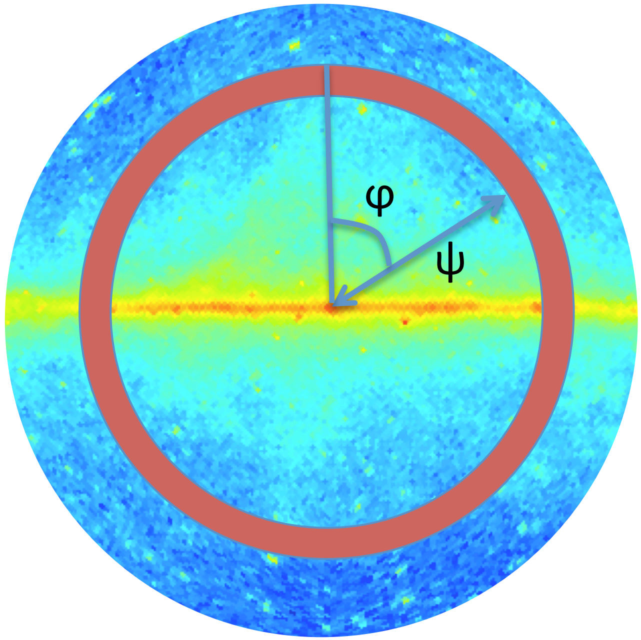
- Indirect detection of dark matter is promising:
  - Annihilation products can be much easier to observe than dark matter (DM) itself (e.g. photons, leptons, etc.)
  - Expected signal is well constrained if DM is a thermal relic → $< \sigma v >_{\mathrm{ann.}} \sim 10^{-26} \mathrm{cm}^3 \mathrm{s}^{-1}$
  - We can learn about the distribution of DM beyond our local environment
  - Identification of dark matter will likely require combination of indirect/direct detection and collider searches (e.g. Bergström et al. 2011, Baltz et al. 2006)
- And challenging:
  - Backgrounds are large and uncertain
    - Gamma-ray backgrounds are typically orders of magnitude larger than predicted signal from dark matter
    - Predicting the galactic gamma-ray background requires knowledge of gas and photon distributions throughout the galaxy, as well as sophisticated cosmic ray propagation codes (e.g. GALPROP, USINE, etc.)
    - Extragalactic backgrounds also uncertain
    - Uncertainty in backgrounds is one of the most significant limitations to indirect detection using gamma-rays
  - Distribution of DM also uncertain
    - Large uncertainties in dark matter density near galactic center where signal is strongest

Developing a Robust Technique for Constraining Dark Matter

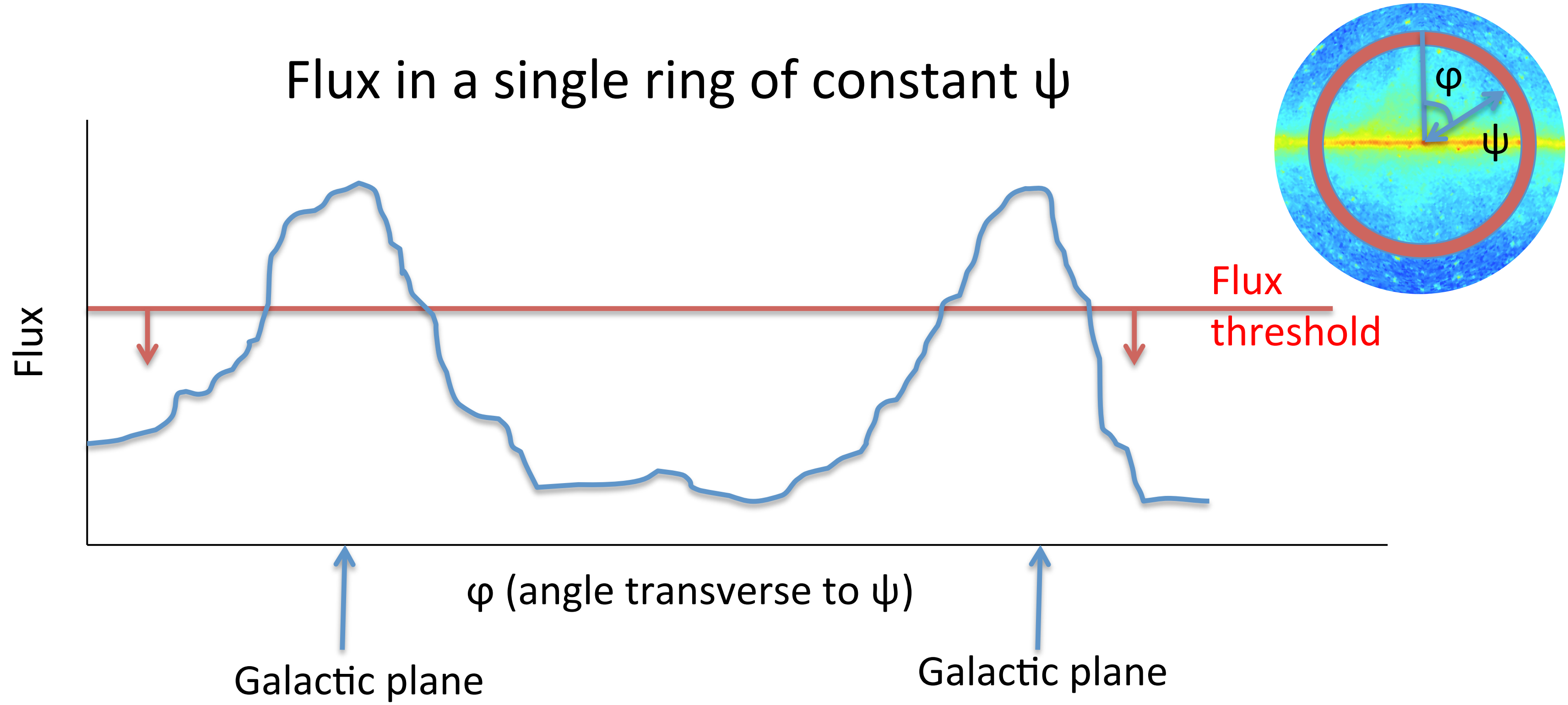
- What is the best constraint we can place on dark matter while making the fewest assumptions about the signal and backgrounds?
- Two reasonable assumptions about the gamma-ray signal from annihilations of smooth (i.e. not in subhalos) galactic dark matter:
    1. The expected signal in any direction is invariant under rotations around the galactic center (since the halo is roughly spherical)
    2. Deviations from the expected signal are uncorrelated from one pixel to the next (since we are considering only smooth dark matter component)
- Of course, neither of these assumptions is exactly true:
    1. The Halo is probably triaxial so the signal is not exactly rotationally symmetric (e.g. Law et al. 2009)
    2. The large point spread function of Fermi correlates the signal in nearby pixels
- We use Monte Carlo techniques to show that breaking these two assumptions (within reasonable limits) minimally degrades our dark matter constraint

The Technique: 'Ring Analysis'

- Consider pixelized data in a ring at constant angle, ψ, from the galactic center
- Our two assumptions constrain the signal in the ring's pixels
  - Rotational symmetry
    → probability distribution function (PDF) of signal in each pixel is the same across the ring
  - Uncorrelated variations from the mean signal
    → signal in each pixel is drawn independently from same PDF
- A sequence of data with these properties is termed independent and identically distributed (i.i.d.)
- Statisticians (actually economists) have developed techniques for determining whether a sequence is i.i.d.
  – Brock, Dechert, and Scheinkman (BDS) statistic (see e.g. Brock and Baek 1991)
  – Tests against null hypothesis that data is i.i.d.
- Adding a non-i.i.d. sequence to an i.i.d. sequence will generally produce a sequence which is non-i.i.d. (for non-pathological distributions)



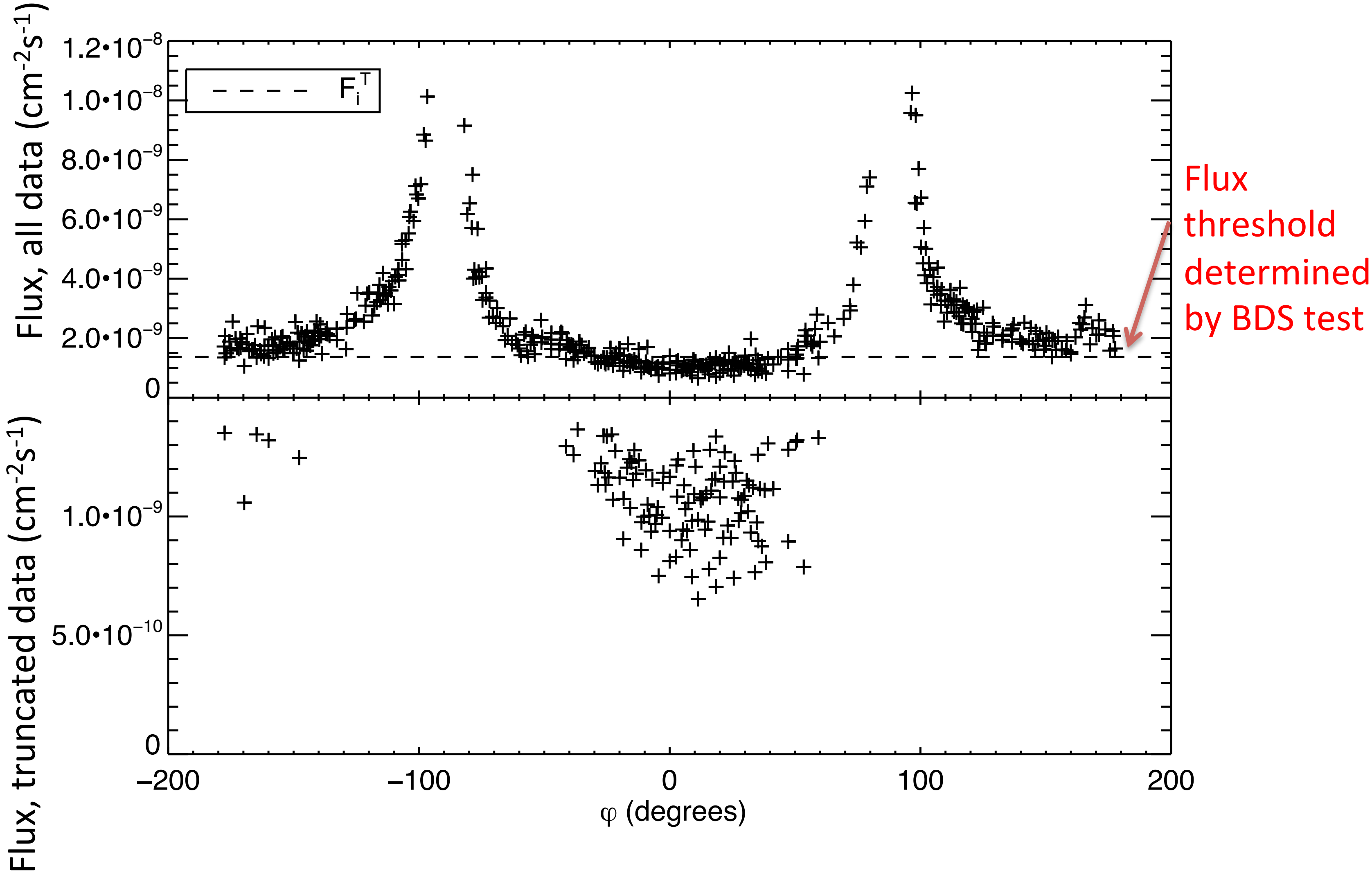
Flux in a single ring of constant ψ



Steps to place limit on the i.i.d. contribution to the observed flux in a ring:

1. Introduce a flux threshold at high flux and consider only those pixels with flux below the threshold
2. Test whether the truncated data is i.i.d. using the BDS statistic
   - IF no THEN i.i.d. contribution must be below the threshold, so lower threshold and repeat
   - IF yes THEN stop
3. The upper limit on the mean flux of the i.i.d. component is then the mean flux of all pixels below the final threshold

Now with real data...

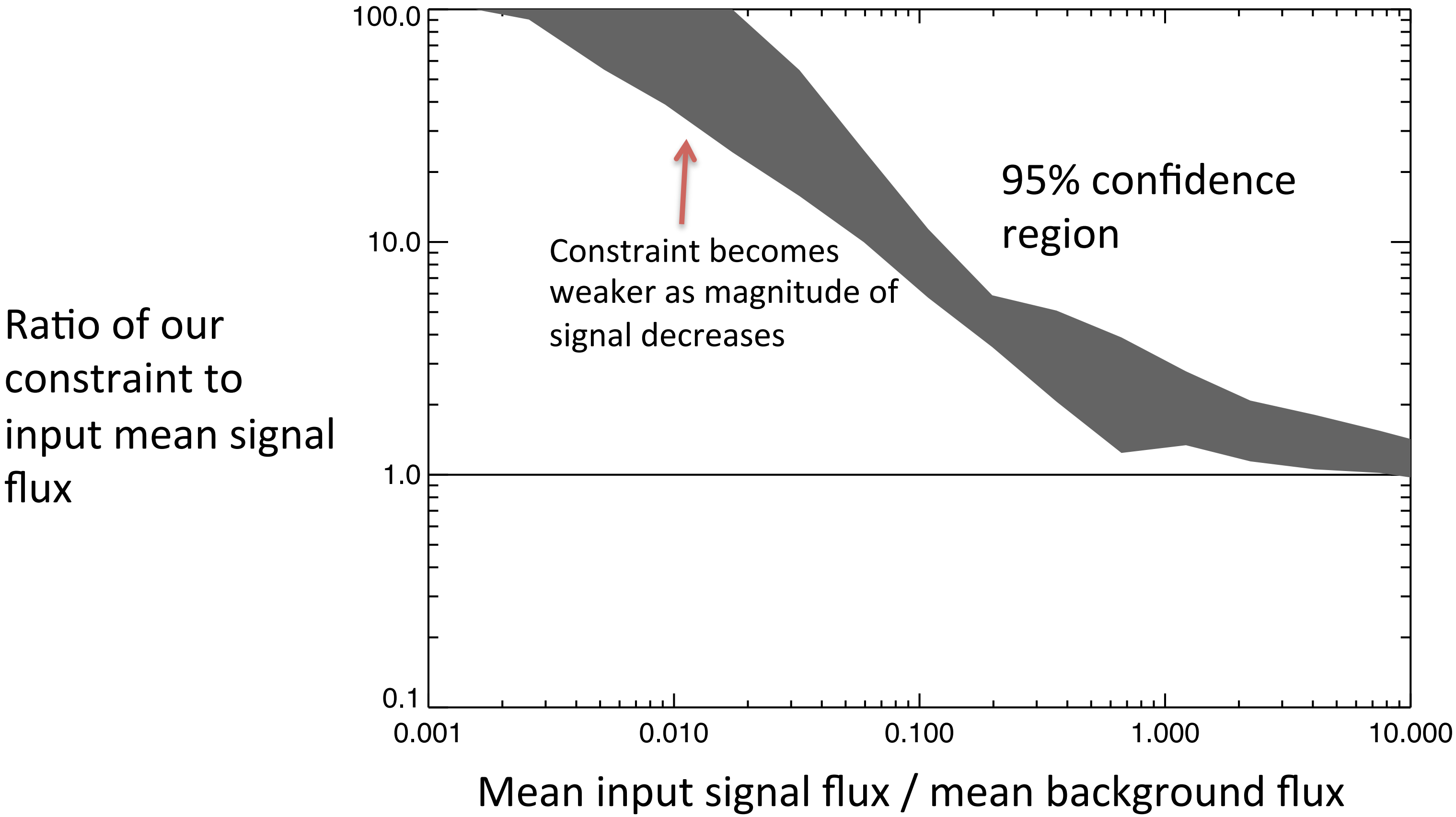


Validating the technique

- How our technique could fail:
  - The i.i.d. limit is lower than the mean signal flux (possible for some pathological photon distributions or by chance)
  - Correlations between pixels due to point spread function invalidate i.i.d. assumption
  - Variation of the mean signal across a ring of pixels invalidates i.i.d. assumption

- We address these issues and determine the power of our technique by running Monte Carlo simulations
  1. Generate artificial signal in a ring by drawing from a Poisson distribution with some particular mean
     - We account for the fact that the expected signal varies slightly across the width of the ring
  2. Generate artificial background (we use data from Fermi as the background model since the data is background dominated)
  3. Apply point spread function to mock data
  4. Do analysis. Is the limit we place always greater than the mean signal flux?

Results of Monte Carlo testing



Result: the limit determined with our technique is always greater than the mean flux of the i.i.d. signal. The technique works! And we've made no assumptions about backgrounds!

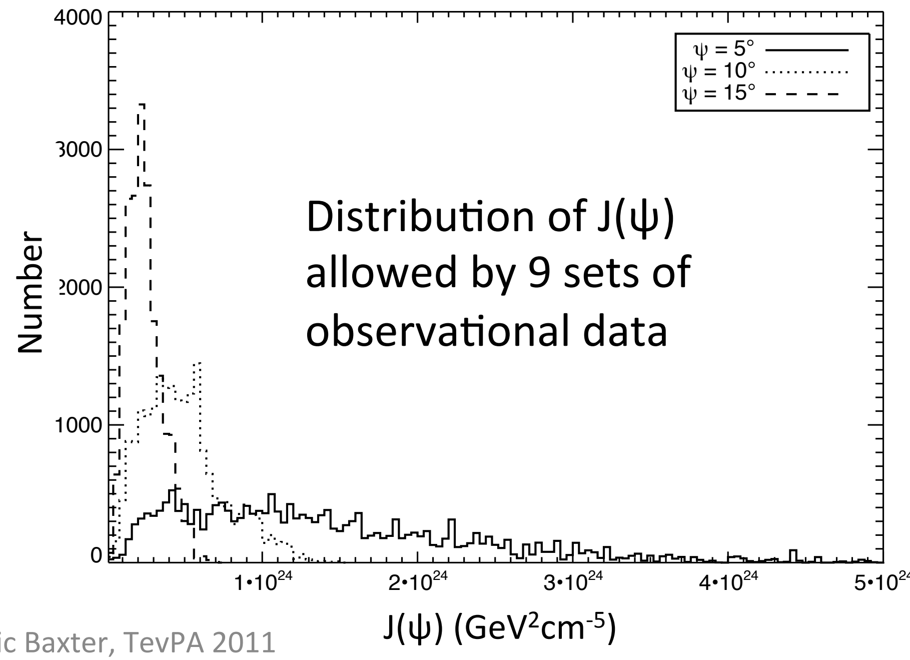
Uncertainties in the dark matter profile

- Uncertainties in the distribution of smooth dark matter → uncertainty in the expected annihilation signal
  - Uncertainty can be large, particularly close to the galactic center
  - Many studies to date have not considered the full range of signals allowed by observation
  - Widrow, Pym, and Dubinski 2008 used nine sets of observational data to constrain galactic dark matter distribution assuming a generalized NFW profile
  - We use their Markov Chains to generate estimate of the uncertainty in the dark matter signal at each value of ψ

Expected Signal ∝

$$J(\psi) = \int dl d\Omega \rho^2(l,\psi)$$

$l =$ line of sight distance

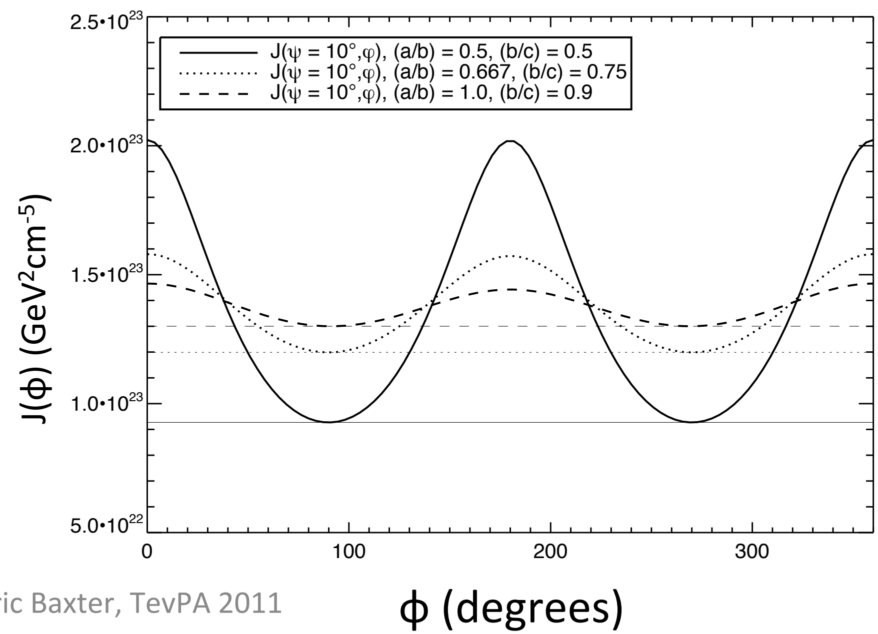


Other Sources of Uncertainty

- Triaxiality of the halo
  - Triaxial halo leads to variation of signal with ϕ
    - There is still some component of signal that *is* i.i.d.
  - We calculate the amount by which i.i.d. component is reduced for triaxial halos drawn from distributions of Jing and Suto 2002
  - Effect is only on the order of 25%

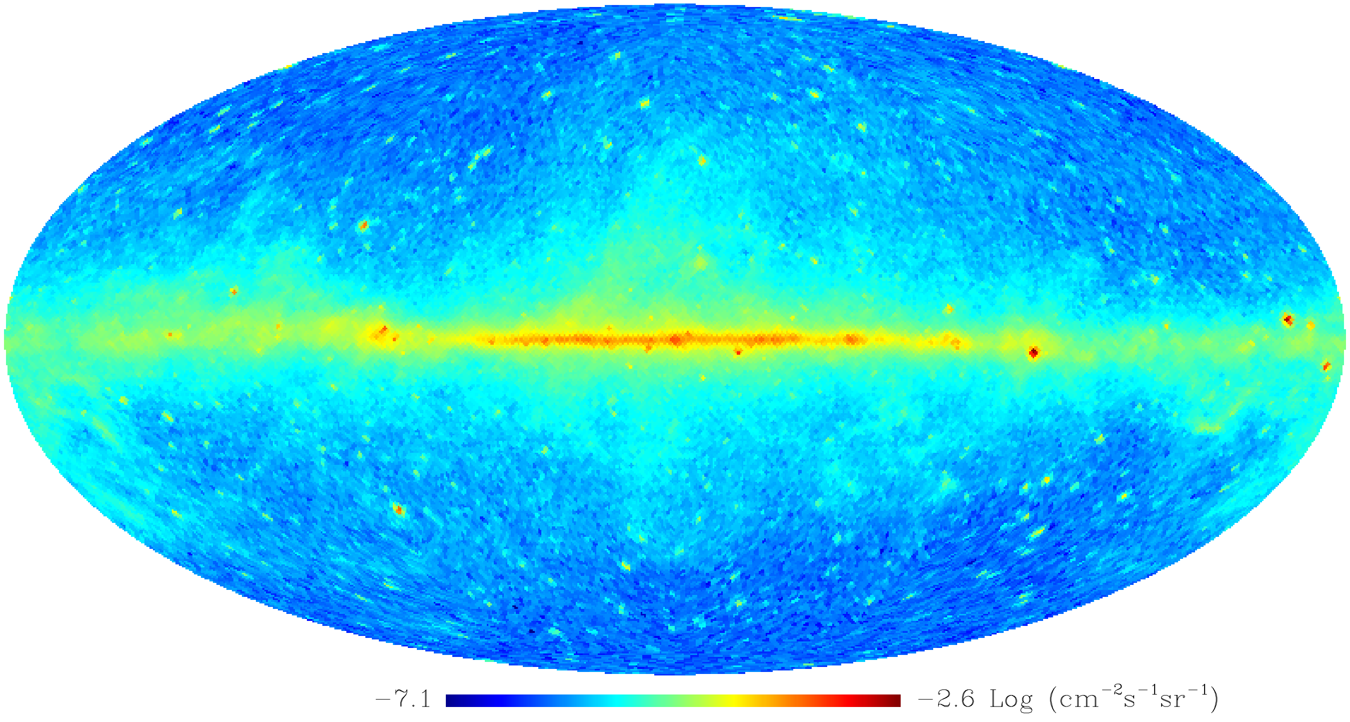
Illustration of the reduction of i.i.d. component of signal when halo is triaxial.

Thick = total signal
Thin = i.i.d. component
Line style = different assumed axis ratios



The Data

- We use over a year's worth of data collected by the Fermi Gamma-Ray Space Telescope with E > 1 GeV
- Use DataClean event class to minimize charged particle contamination
- Use standard Fermi analysis tools to generate flux map (use p6_v3_diffuse)
- Pixelize data using Healpix, each pixel is ~1 degree^2, comparable to size of PSF



Results: the i.i.d. Limit

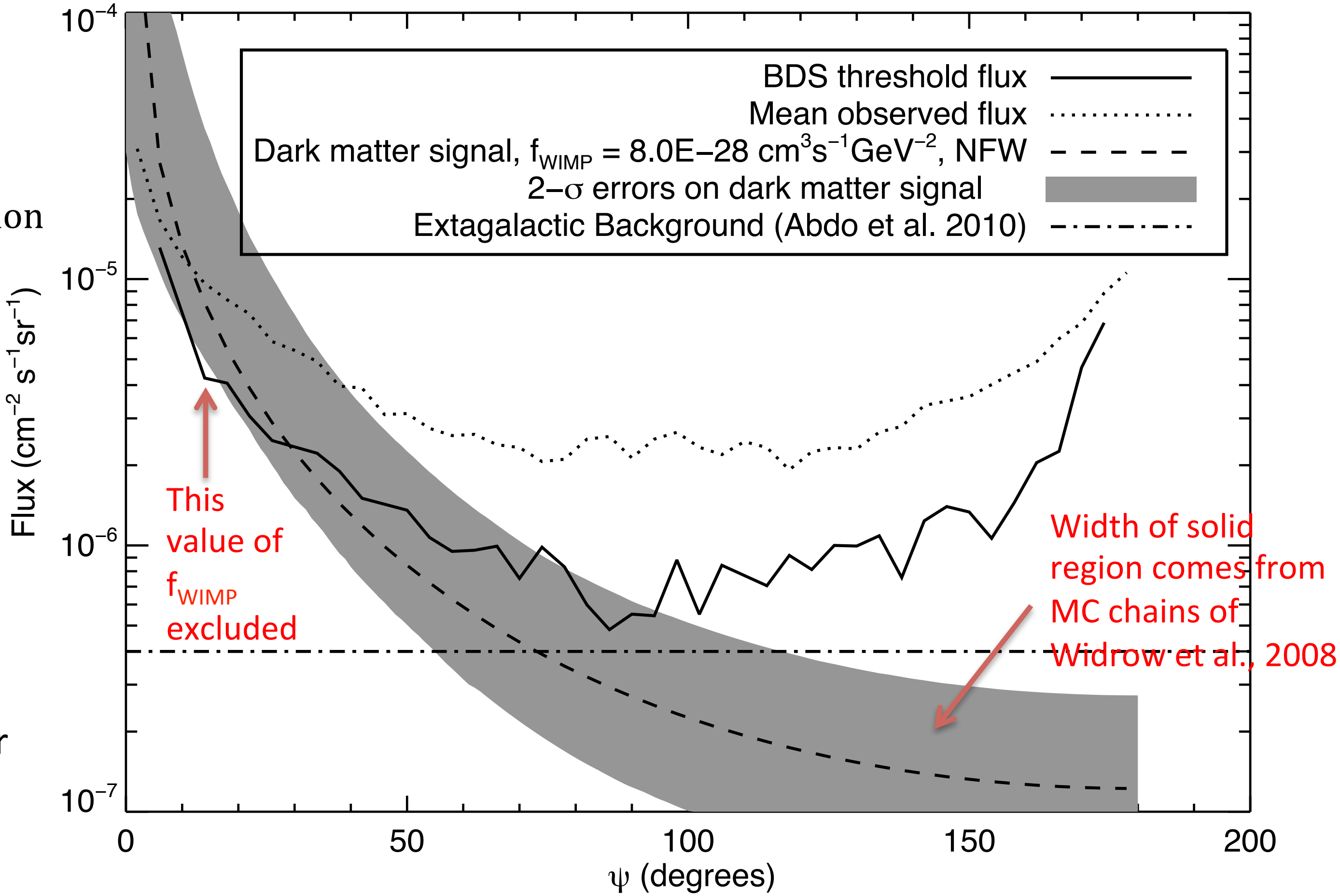
Constraints on *any* component that is i.i.d. in rings of constant ψ (not just dark matter):

$$f_{\mathrm{WIMP}} = \frac{N_\gamma < \sigma v >}{M_\chi^2}$$

N_γ = number of photons per annihilation

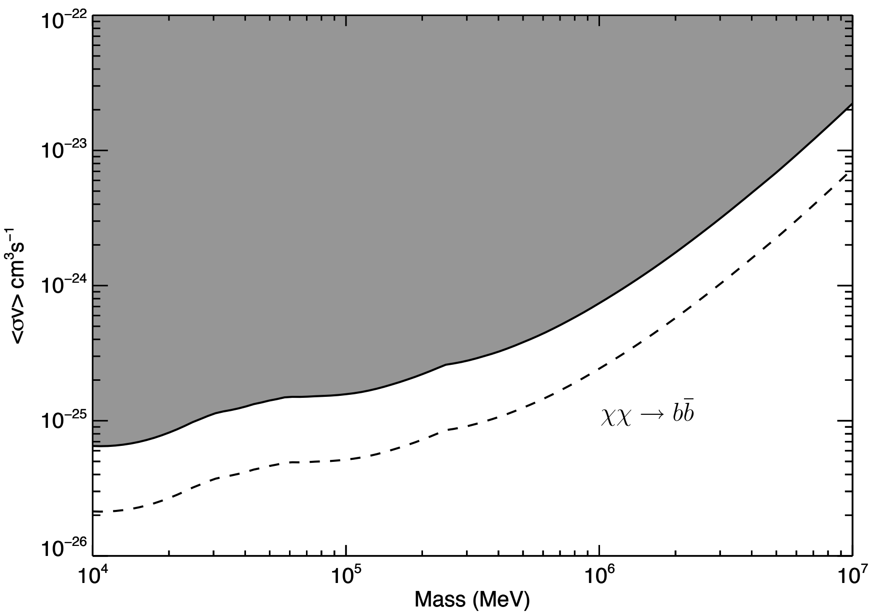
Solid line represents our constraint on i.i.d. flux as a function of ψ

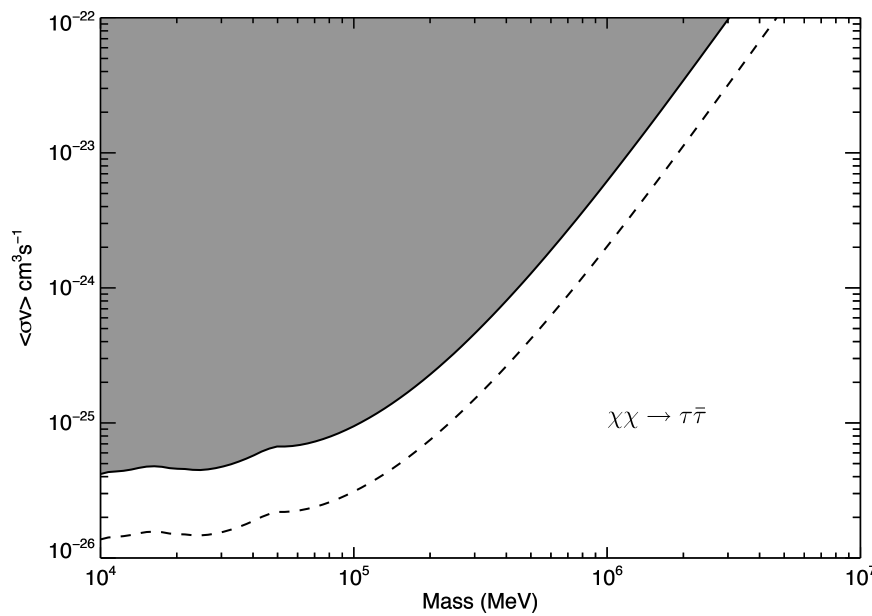
Solid region represents range of allowed dark matter signal for single value of f_{WIMP}



Results: Dark Matter Constraints

- Constraints on i.i.d. flux can be turned into constraints on the dark matter mass and cross section given:
  1. J(ψ): determined from Markov chains of Widrow et al. 2008
  2. N_γ: calculated as a function of M_χ using DarkSUSY package (Gondolo et al. 2004). We consider neutralinos annihilating to b's and to tau's
- We explore several energy cuts on the data to maximize the final constraint





Conclusions

- We have presented a technique for constraining dark matter using gamma-ray data that makes no assumptions about the backgrounds and few assumptions about the signal. It is therefore very robust.
  - We have accounted for the uncertainty in the distribution of smooth dark matter allowed by observations. These uncertainties are significant and need to be taken into account!
- Limitations
  - Not as powerful as more sophisticated techniques incorporating information about backgrounds
  - Technique can only constrain dark matter, not detect it
  - Requires that signal be roughly rotationally symmetric, may not be true if dominant annihilation channel is to light charged particles which are affected by magnetic fields
  - More observation won't necessarily improve constraint
- Future avenues for exploration:
  - Reducing the uncertainty on the dark matter halo will improve limit
  - Better understanding of backgrounds will benefit any attempt at indirect detection