Searching for Dark Matter in the Large Magellanic Cloud with the *Fermi*-LAT

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with:
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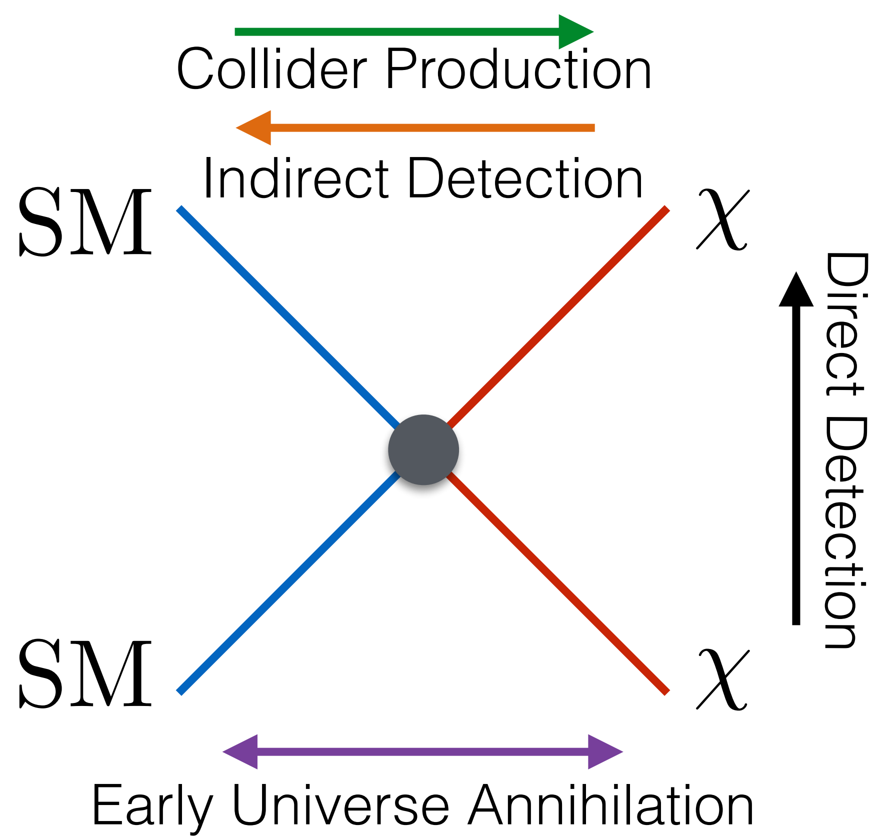
and the *Fermi*-LAT Collaboration

(Preliminary Results)

Indirect Detection



- Complimentary probe of DM/SM interactions
- Models without large direct detection cross sections can have significant indirect detection rates, and *vice versa*
- Intriguing hints from the Galactic Center.
  - I'd like to know what's going on there.

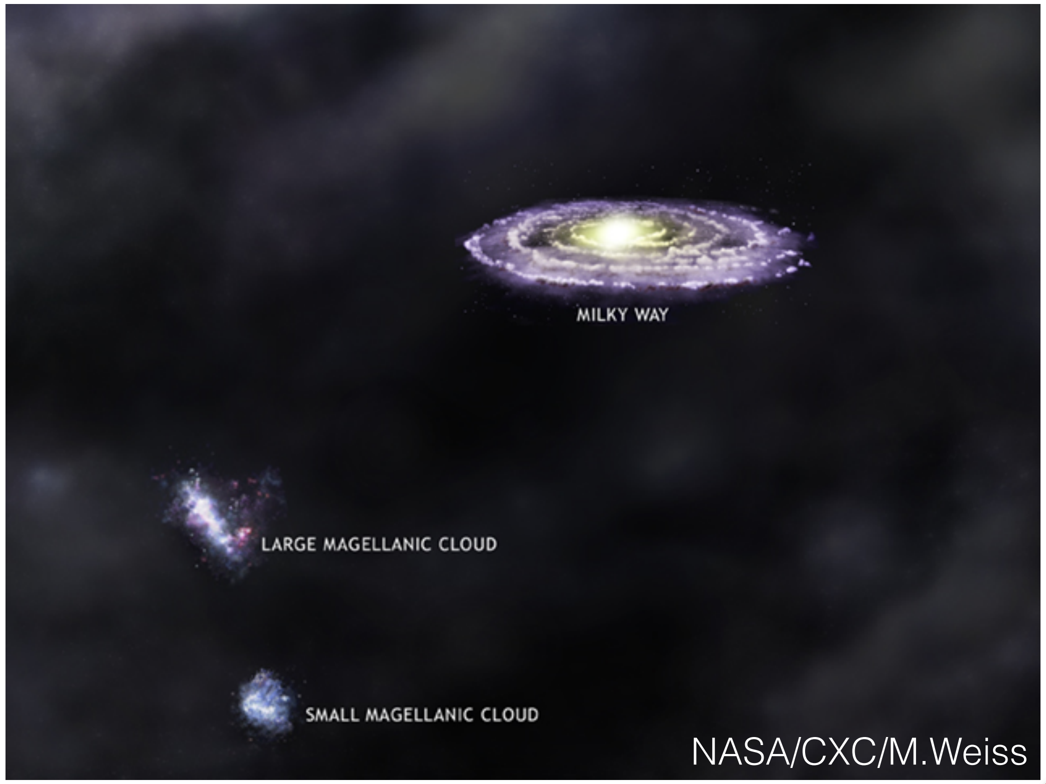
Indirect Detection

$$\frac{d\phi}{dE_\gamma} = \left(\frac{\langle\sigma v\rangle}{8\pi}\frac{dN_\gamma}{dE_\gamma}\frac{1}{m_\chi^2}\right)\left(\int_{\mathrm{l.o.s.}}\rho_\chi^2(\vec{r})d\ell d\Omega\right)$$

- Nearby over-densities give a boost through the 2nd term
  - a.k.a. the *J*-factor
- Notable targets:
  - dwarf spheroidals: $J \sim 10^{18-19.5}\ \mathrm{GeV}^2/\mathrm{cm}^5$
  - Galactic Center: $J \sim 10^{21}\ \mathrm{GeV}^2/\mathrm{cm}^5$ (within 1°)
  - Can also look at all-sky, galactic clusters, dark satellites (unidentified gamma-ray sources), *etc*
- What additional good sources are out there?

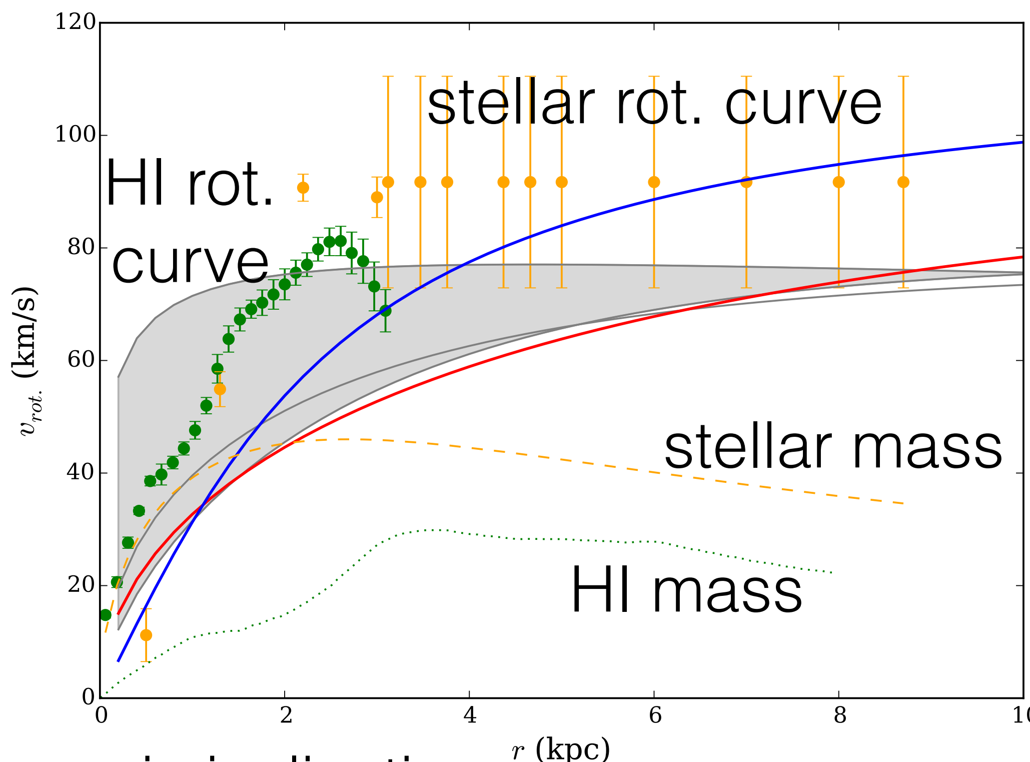
The Magellanic Clouds

- The Milky Way's largest satellite galaxies
  - Not dwarf spheroidal galaxies.
  - LMC: 50 kpc distant, 8-9 kpc radius, $\sim 1.7 \times 10^{10}\ M_{\odot}$
  - Consistent with first approach to Milky Way.



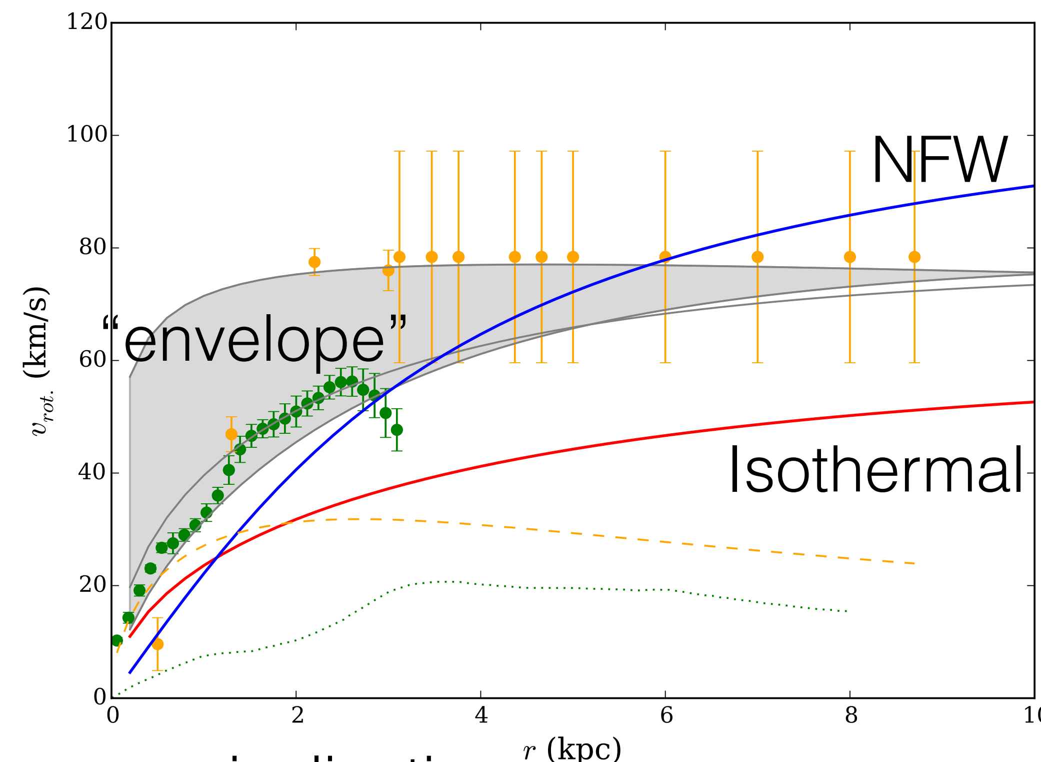
Dark Matter Content

- Two approaches to determine the dark matter distribution
  - Use rotation curve measurements, fit to a particular profile (blue & red lines). Need to assume an inclination angle.
  - Take simulations of LMC-type galaxies. Derive dark matter profile using mass/luminosity of LMC. (grey shaded region)



min inclination
max dark matter

$i = 26.2^{\circ}$



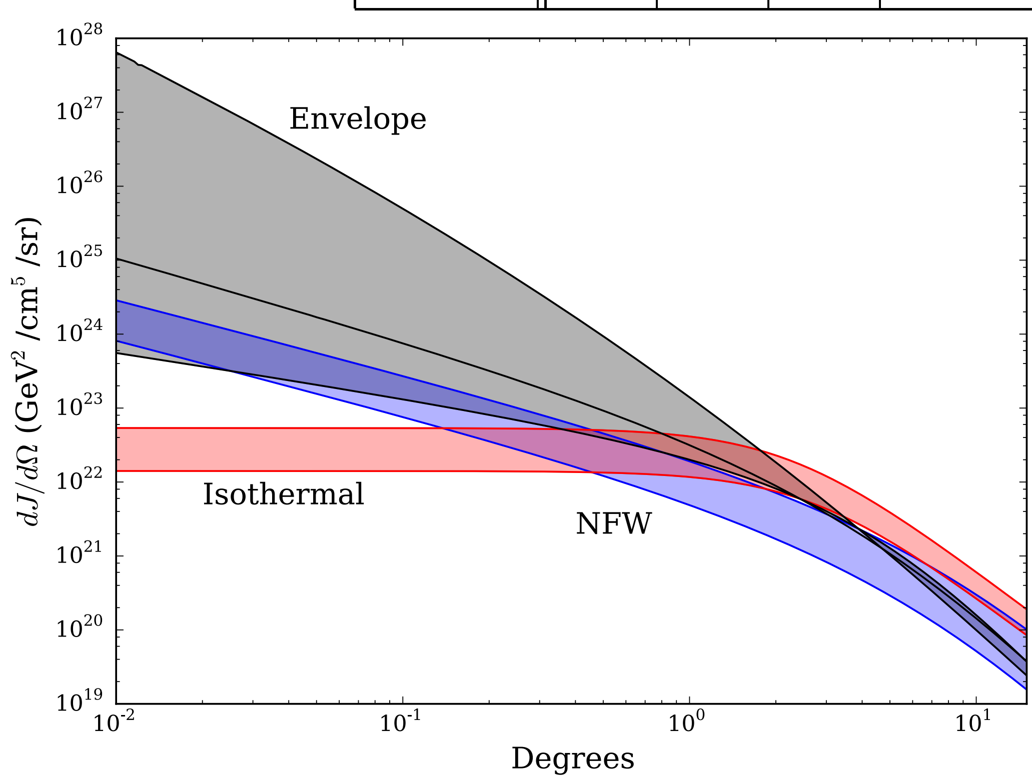
max inclination
min dark matter

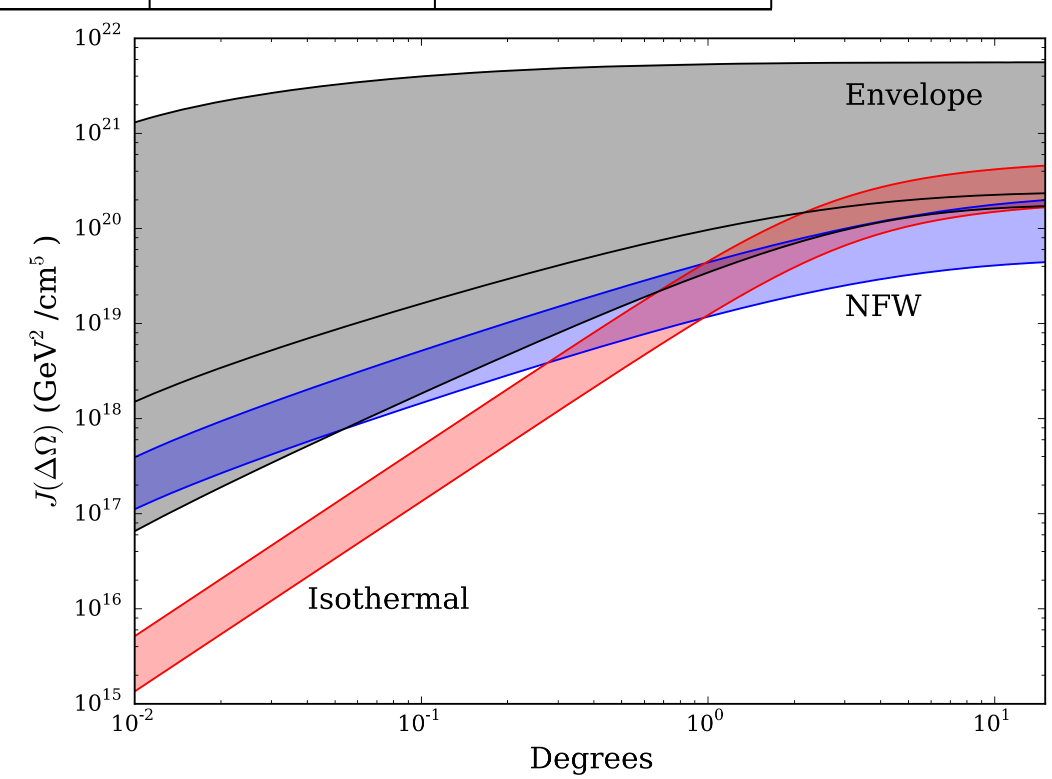
$i = 39.6^{\circ}$

J-factor

- Adopt 3 sets of profiles: NFW, isothermal, “envelope”
- “Best” Dwarfs: $J \sim 10^{18-19}\ \mathrm{GeV^2/cm^5}$
- Galactic Center: $J \sim 10^{21}\ \mathrm{GeV^2/cm^5}$ inside 1°

Profile	α	β	γ	r_S (kpc)	ρ_0 ($M_\odot/\mathrm{kpc}^3$)	J ($\mathrm{GeV^2/cm^5}$)	$M(8.7\ \mathrm{kpc})$ ($M_\odot$)
nfwmax	1	3	1	17.0	2.5×10^6	2.0×10^{20}	1.1×10^{10}
nfwmin	1	3	1	12.6	1.8×10^6	4.4×10^{19}	5.3×10^9
isomax	2	2	0	2.0	6.2×10^7	4.6×10^{20}	2.0×10^{10}
isomin	2	2	0	2.4	2.9×10^7	1.7×10^{20}	1.2×10^{10}
envmax	0.35	3	1.3	5.4	1.1×10^8	5.6×10^{21}	1.6×10^{10}
envmean	0.96	2.85	1.05	7.2	8.4×10^6	2.3×10^{20}	1.4×10^{10}
envmin	1.56	2.69	0.79	4.9	1.2×10^7	1.7×10^{20}	1.3×10^{10}





Event Selection

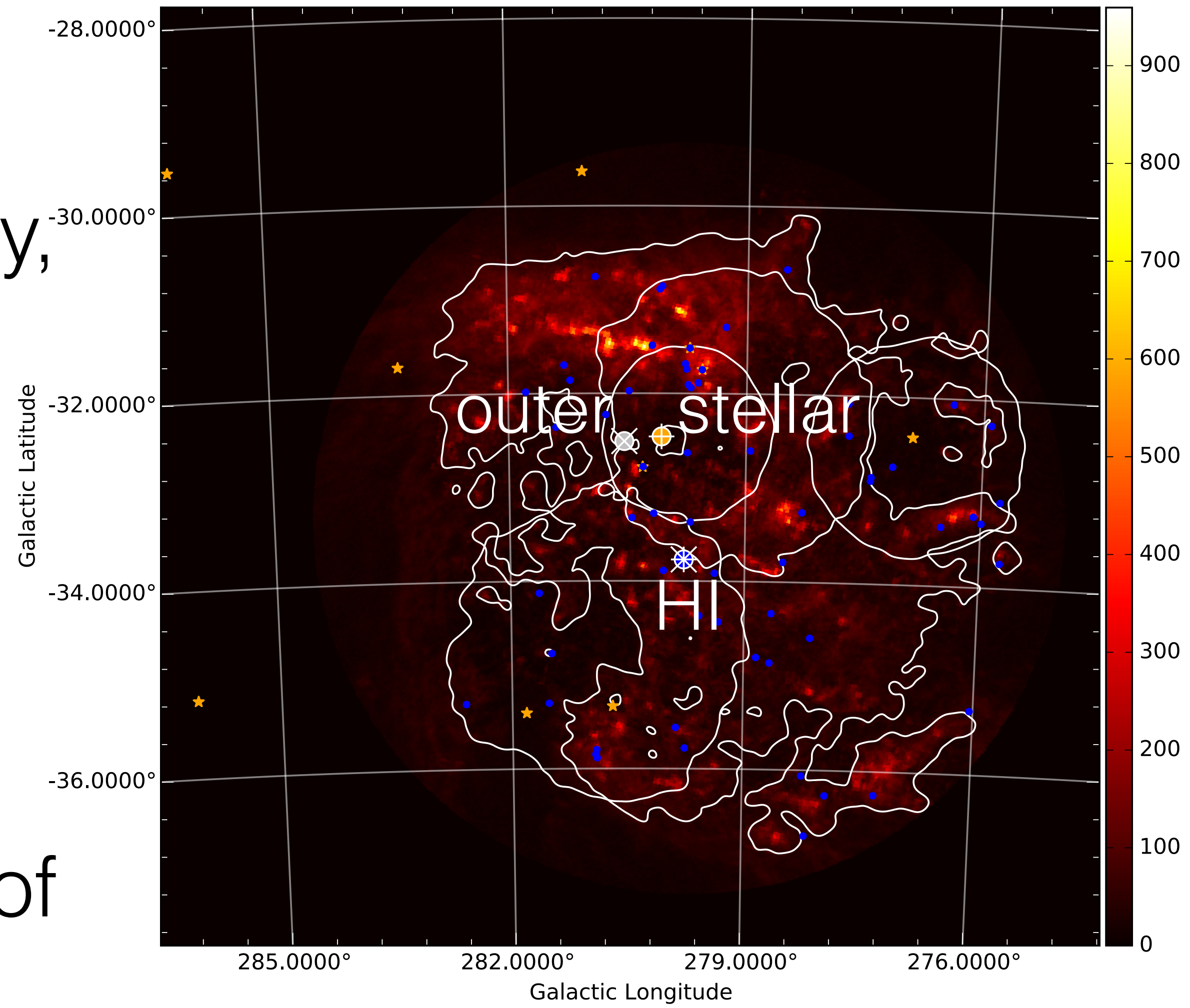
- Data from Aug 4, 2008 and Aug 4, 2013
  - P7REP-CLEAN event selection
  - Standard data quality cuts

$$\texttt{DATA\_QUAL} == 1 \ \&\& \ \texttt{LAT\_CONFIG} == 1$$

Selection	Criteria
Observation Period	2009 Aug. 4 to 2013 Aug. 4
Mission Elapsed Time (s)	239557414 to 397345414
Energy range (GeV)	0.5 to 500
Fit Region	$10^\circ \times 10^\circ$ centered on $(l, b) = (277.86^\circ, -32.41^\circ)$
Zenith range (deg)	$\theta_{\rm z} < 100$
Rocking angle range (deg)	$\lvert\theta_{\rm r}\rvert < 52$

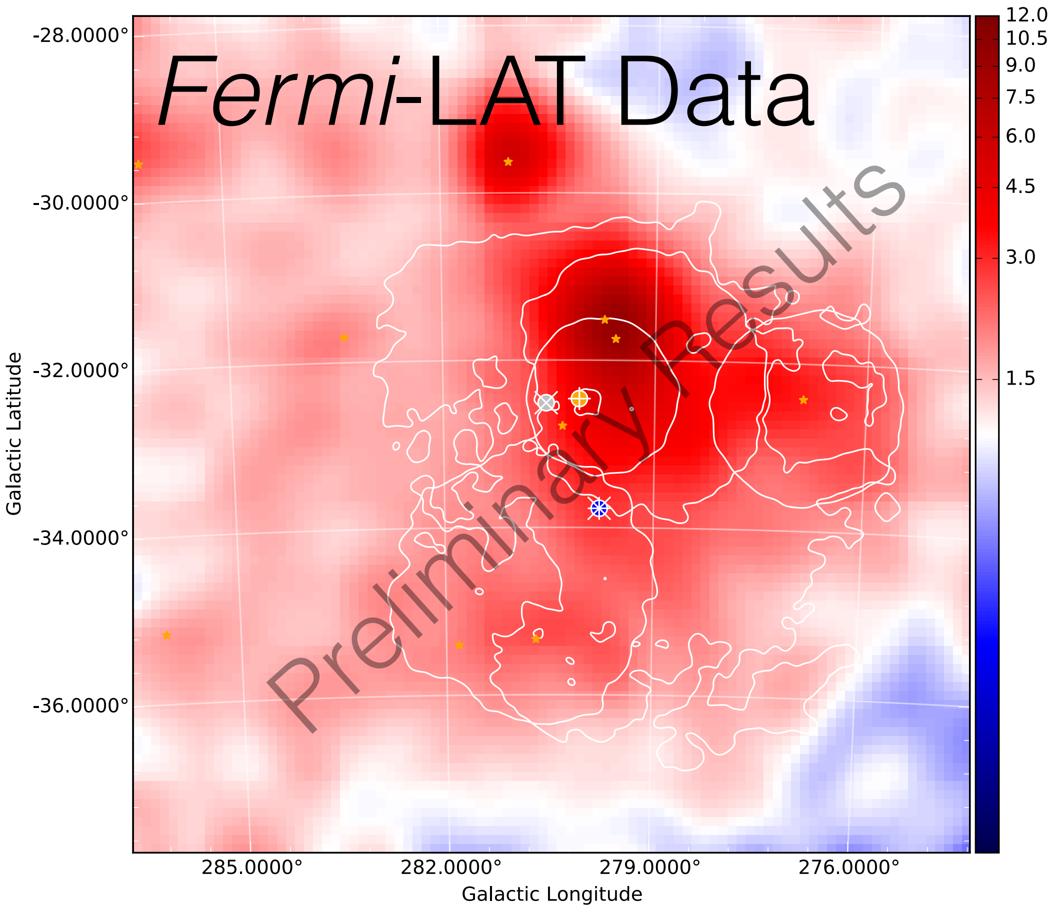
Backgrounds

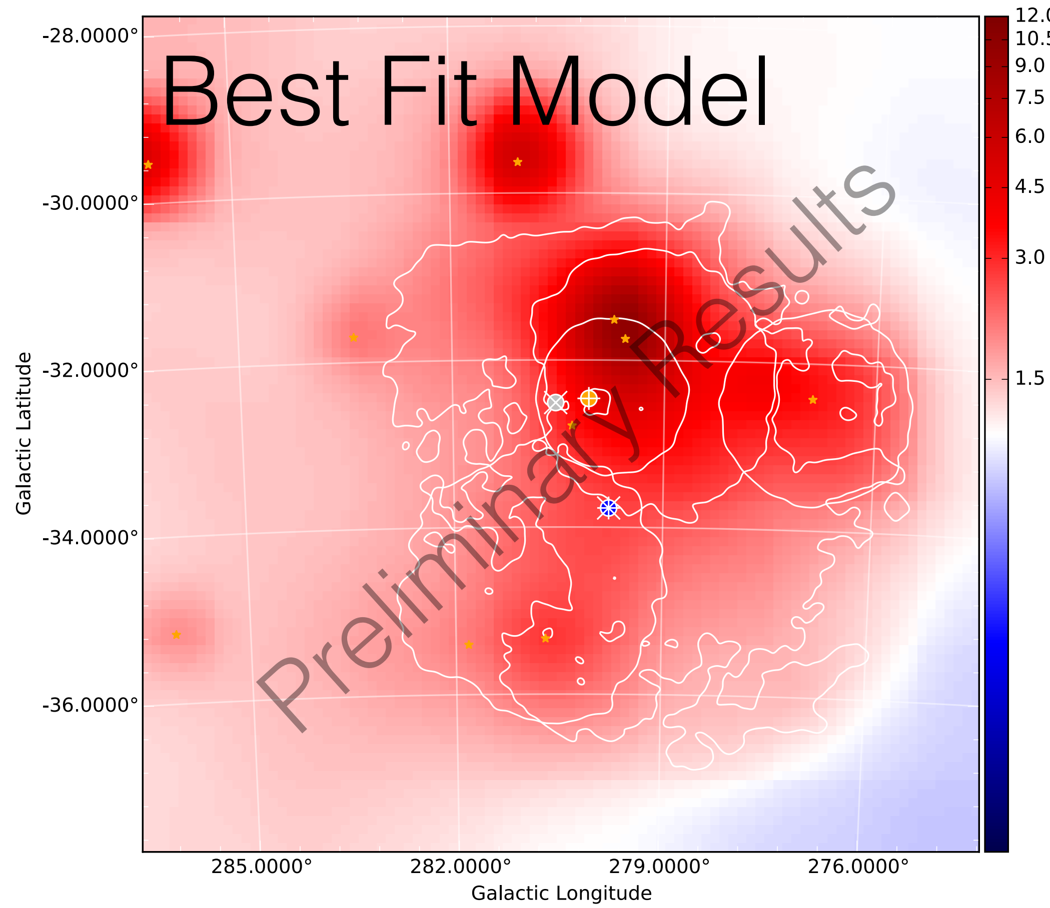
- Backgrounds built iteratively from *LAT* gamma-ray data
- Assume emission of cosmic rays with gaussian morphology, power law spectrum.
  - Gamma ray flux set by convolution of CR injection, measured HI gas column density.
- *Fermi*-LAT gamma-ray model of LMC. Publication pending
- Broadband fit to get spectra



Backgrounds

- Background model contains both extended components and point sources
  - Some previously unidentified in *Fermi*-LAT catalog

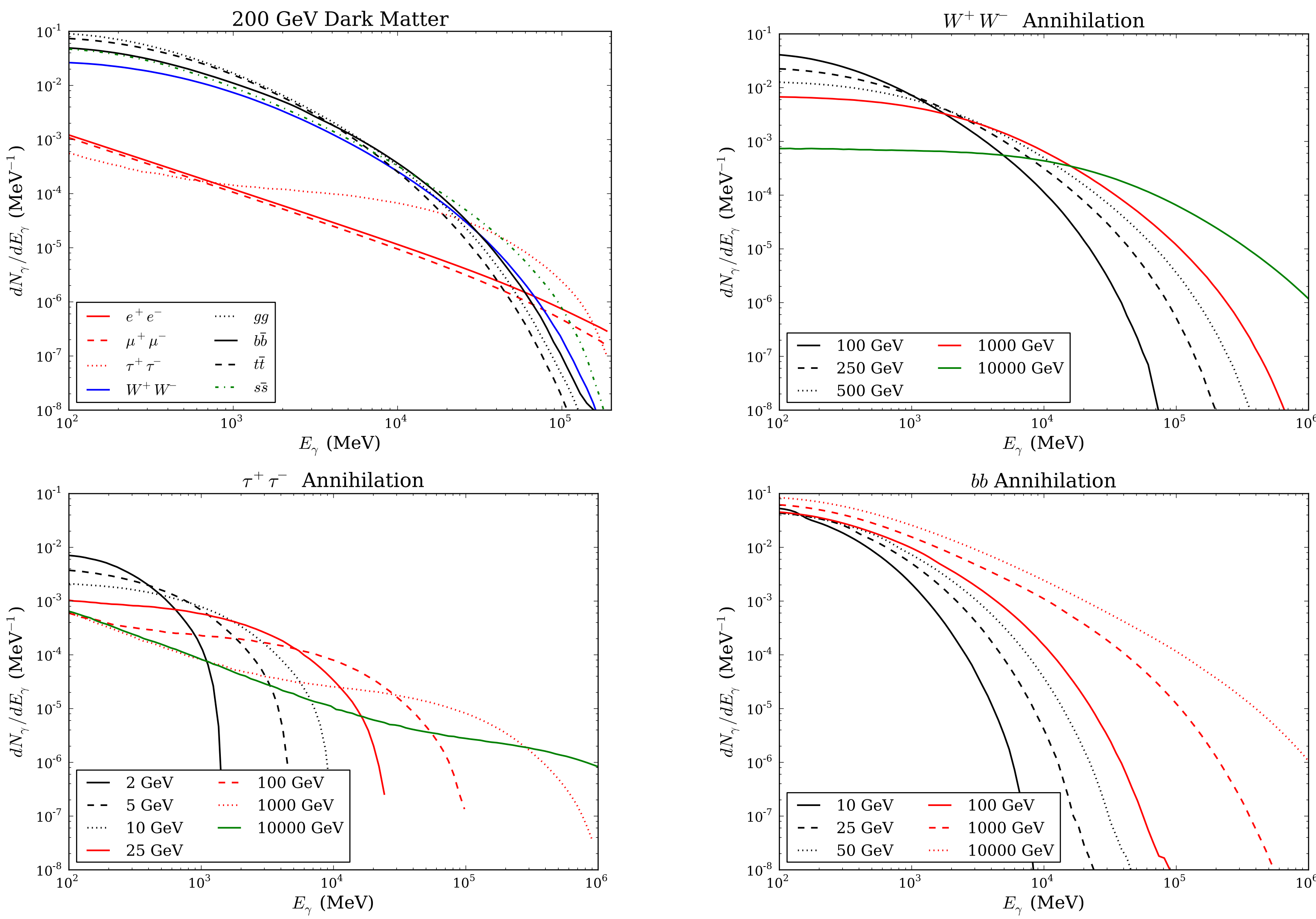




800 MeV-12.6 GeV

Dark Matter Spectra

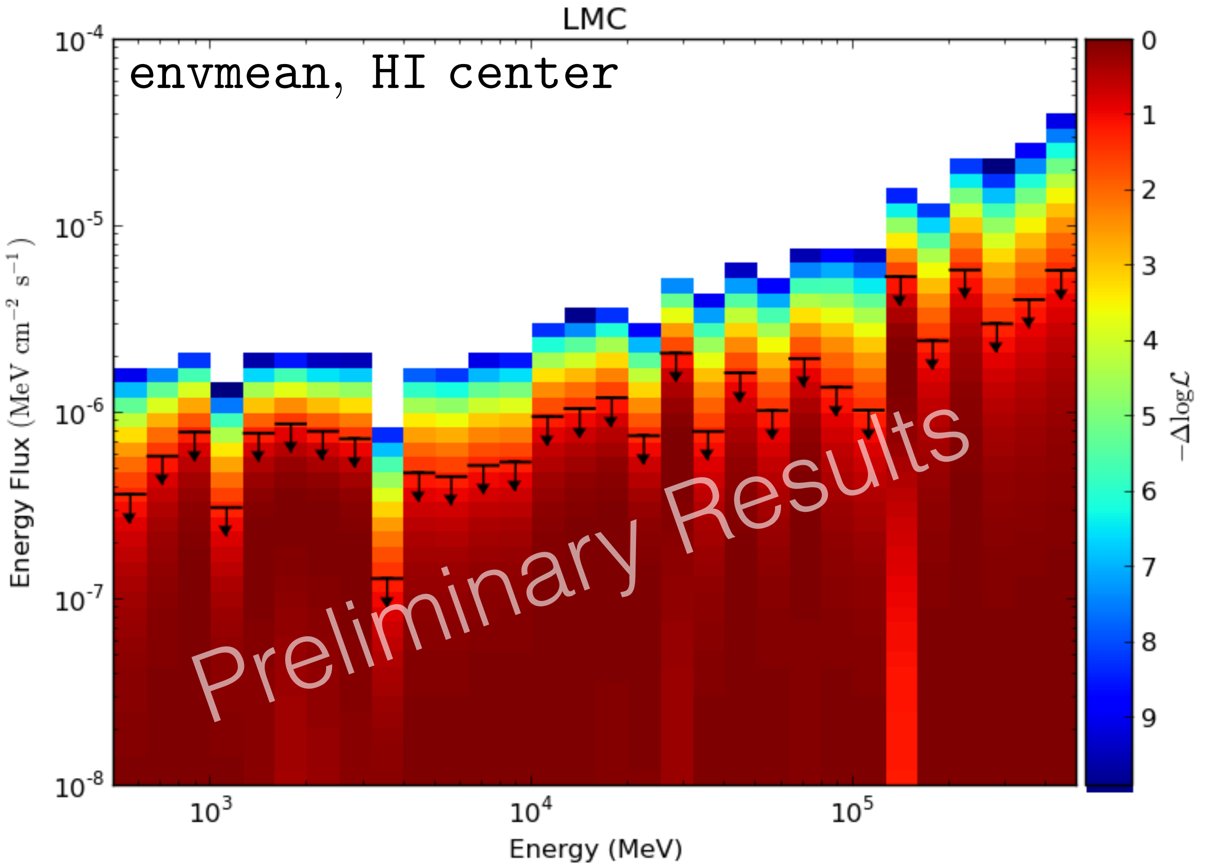
- Test dark matter annihilating into 1 species of Standard Model particles at a time.
    - Code developed by LAT Team & Stefano Profumo



Fitting Procedure

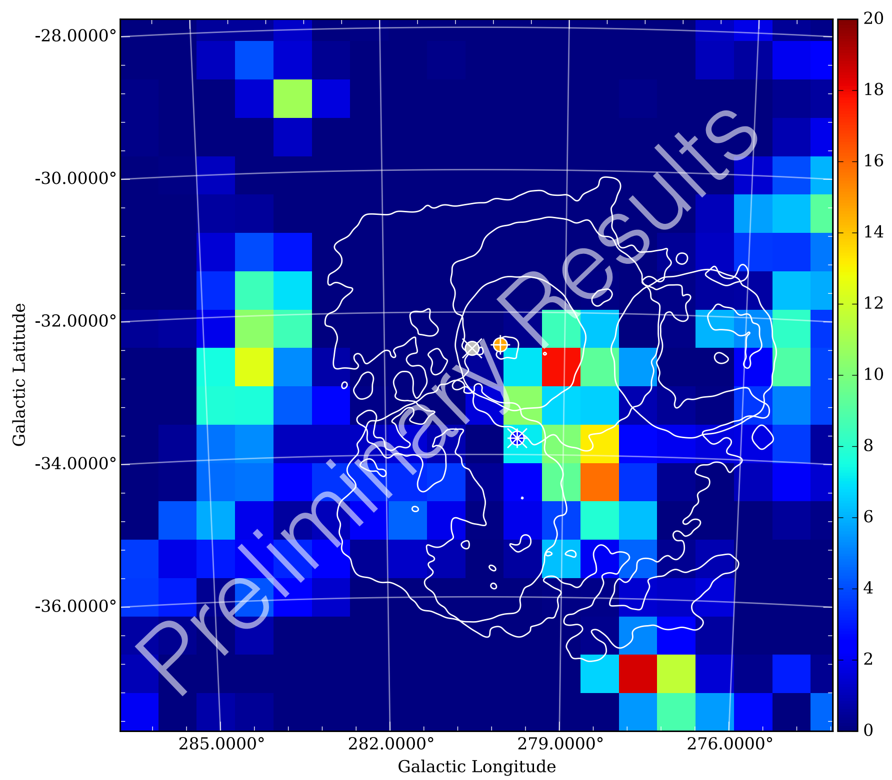
- Binned likelihood (30 log bins 500 MeV-500 GeV)
- Parameter inputs from “broadband” best fit
- Likelihood constructed assuming specific spatial morphology for a signal (*i.e.* assuming a dark matter profile and center location)
  - Construct a spectral energy distribution, independent of annihilation channel.
- Then can quickly build a test statistic for a particular choice of spectrum

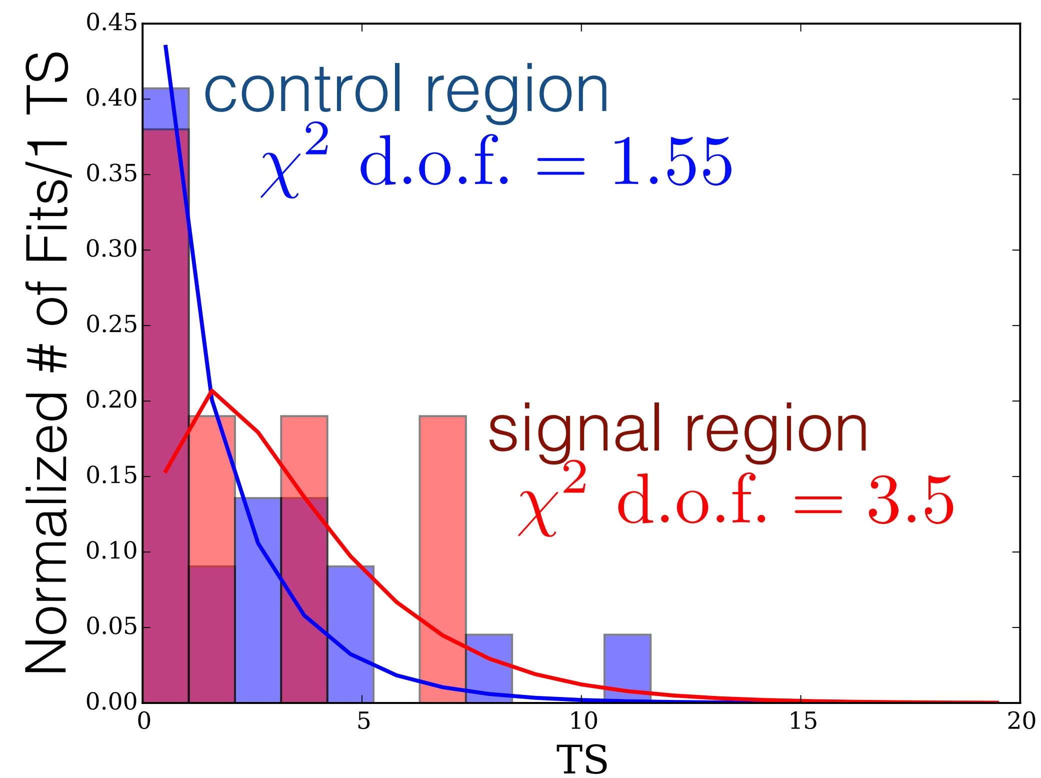
$$\mathrm{TS} = 2\ln\frac{\mathcal{L}(\boldsymbol{\mu},\boldsymbol{\theta}|\mathcal{D})}{\mathcal{L}_{\mathrm{null}}(\boldsymbol{\theta}|\mathcal{D})}$$



Systematics

- Model not perfect. Would like control region to estimate systematics. No similar region exists in the sky.
  - Use LMC outside 3° as control.
- First: Using test statistic (TS), we assumed χ^2 with 1 d.o.f.
  - Refit TS distribution to find TS value for 95% exclusion

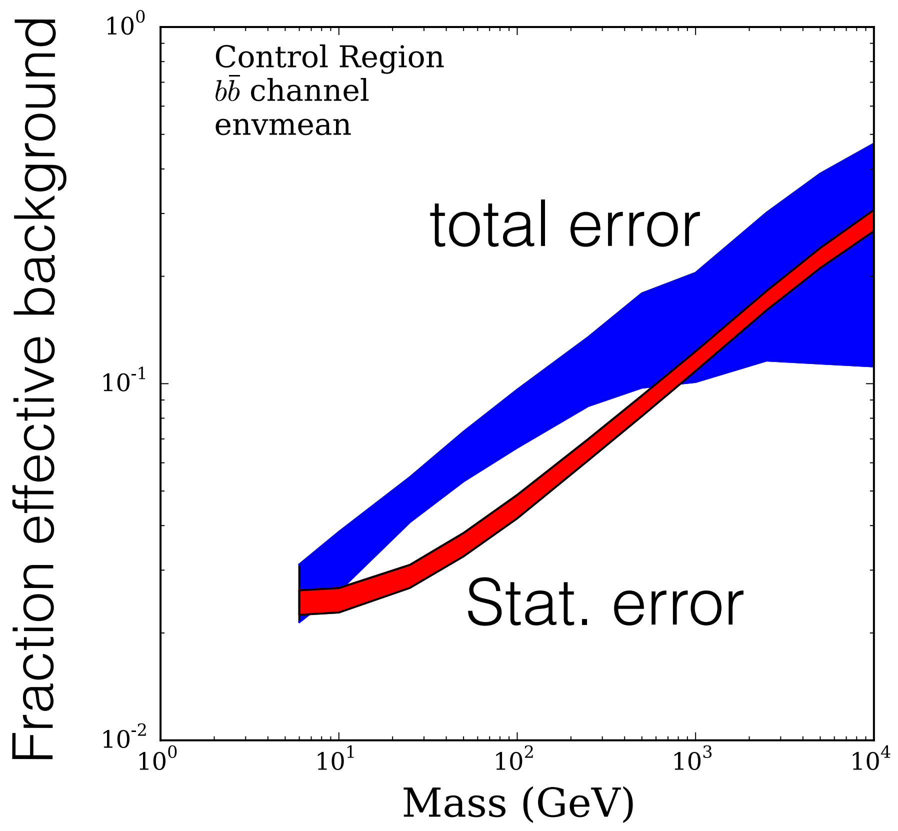


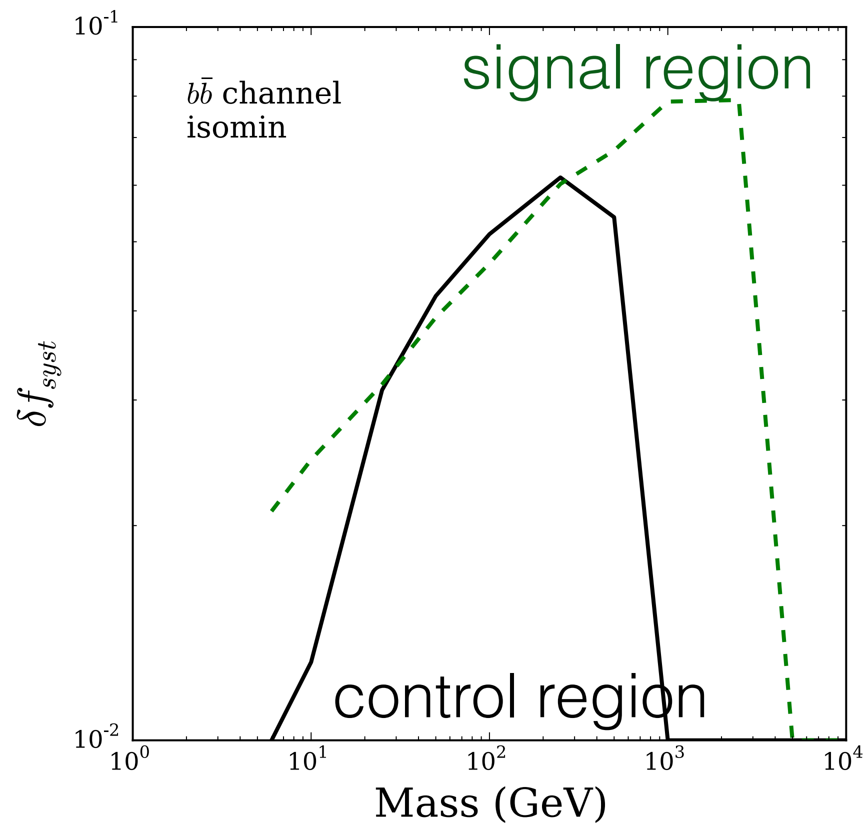


Systematics

- Second: Estimate statistical and total errors from number of photons, derive estimate of systematics from this.

$$f_{\text{sig}} = \frac{N_{\text{sig}}}{b_{\text{eff}}} \qquad f_{\text{stat}} = \frac{1}{\sqrt{b_{\text{eff}}}}$$



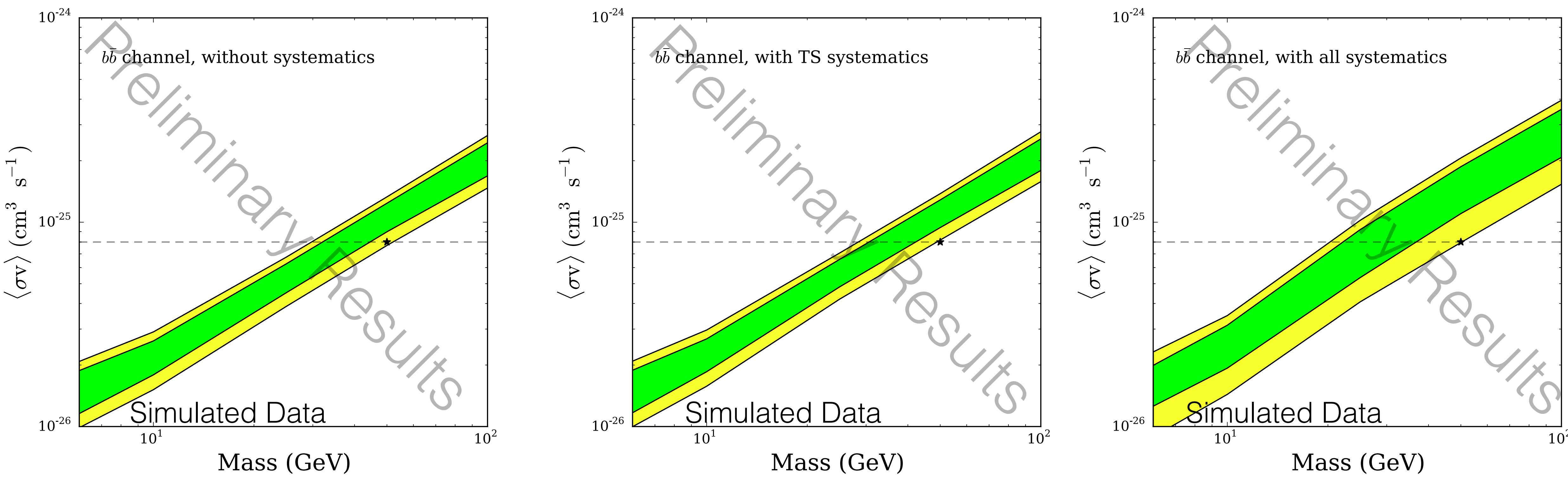


Coverage

- Test that injecting signals will return reasonable results.
- Inject signal of 50 GeV DM annihilating into $b\bar{b}$ with

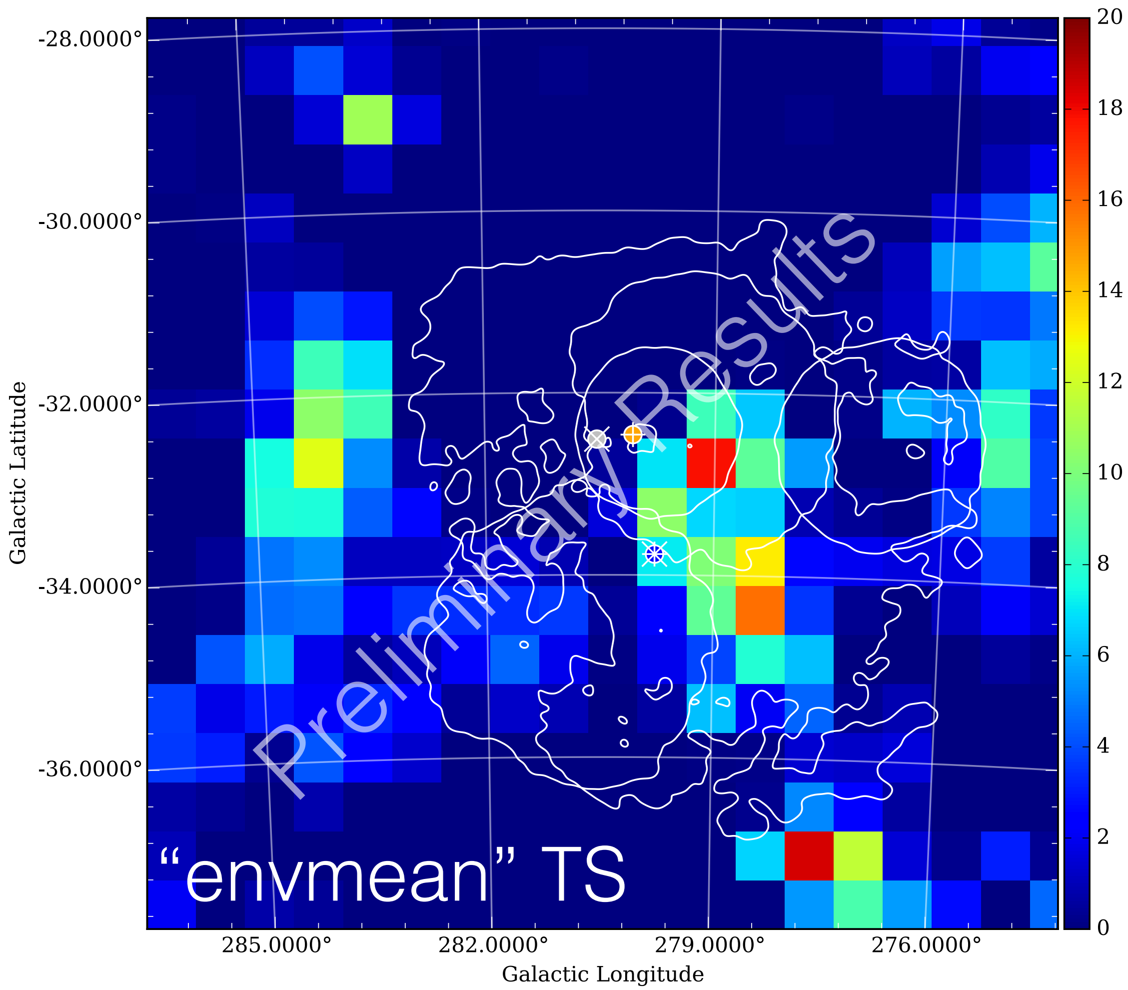
$$\langle \sigma v \rangle = 8 \times 10^{-26}\ \mathrm{cm}^3/\mathrm{s}$$

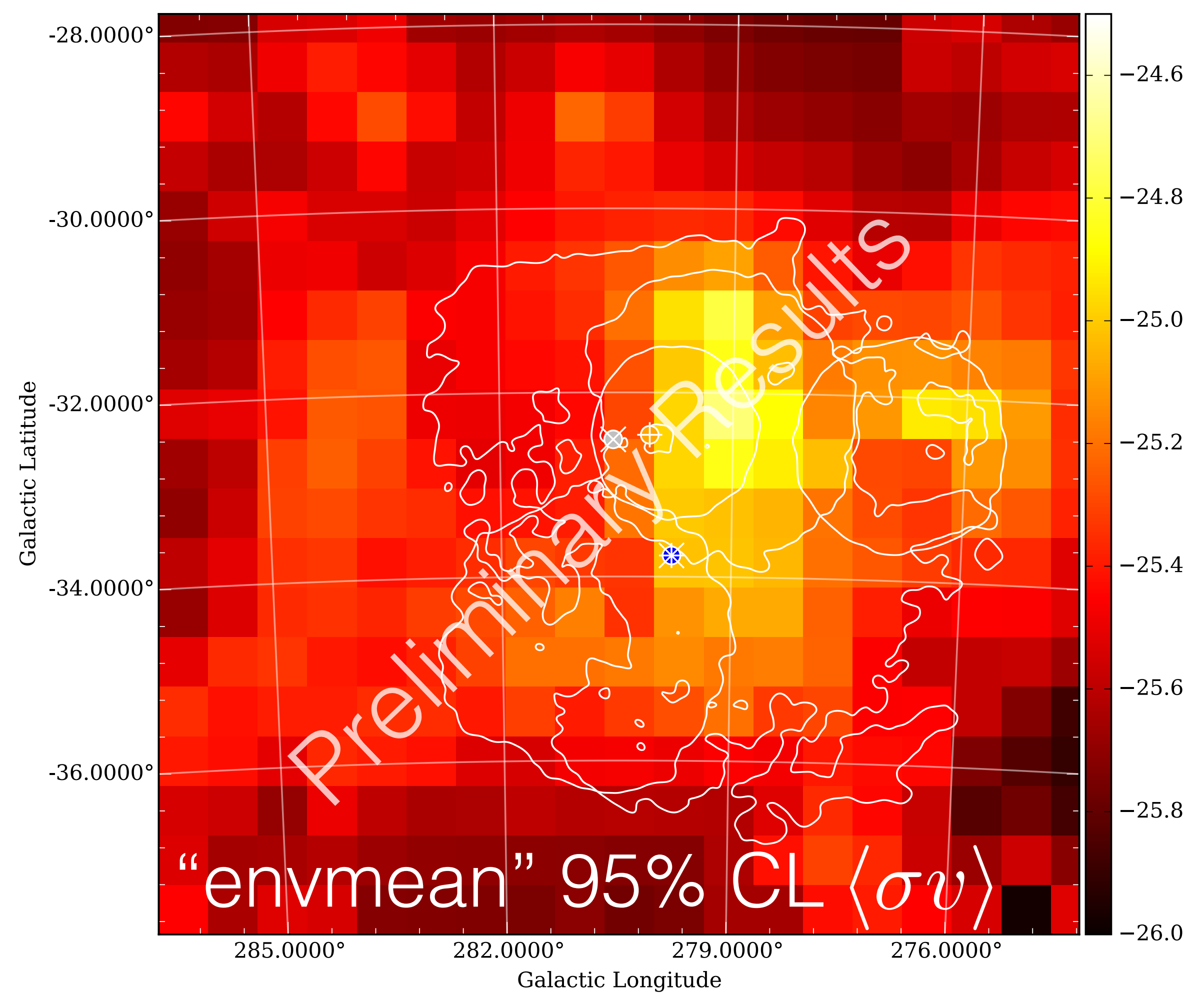
  - Test both fits to “correct” and “wrong” profile/centers



Results

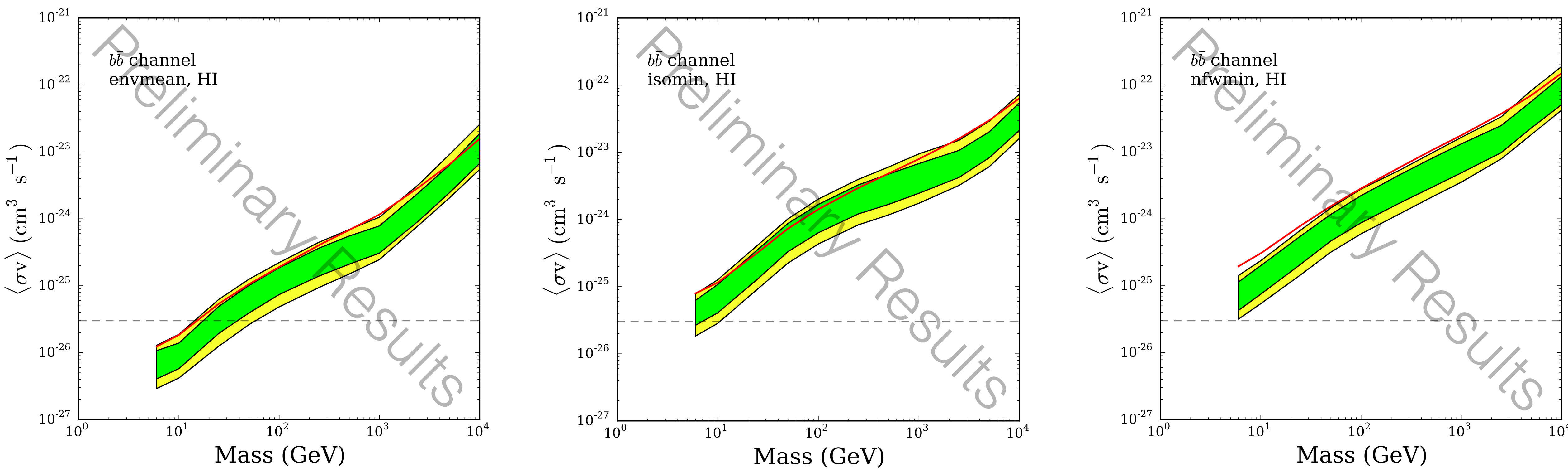
- Consider the bounds for minimum isothermal, minimal NFW, and mean envelope profile.
  - Scan over possible center locations.





Results

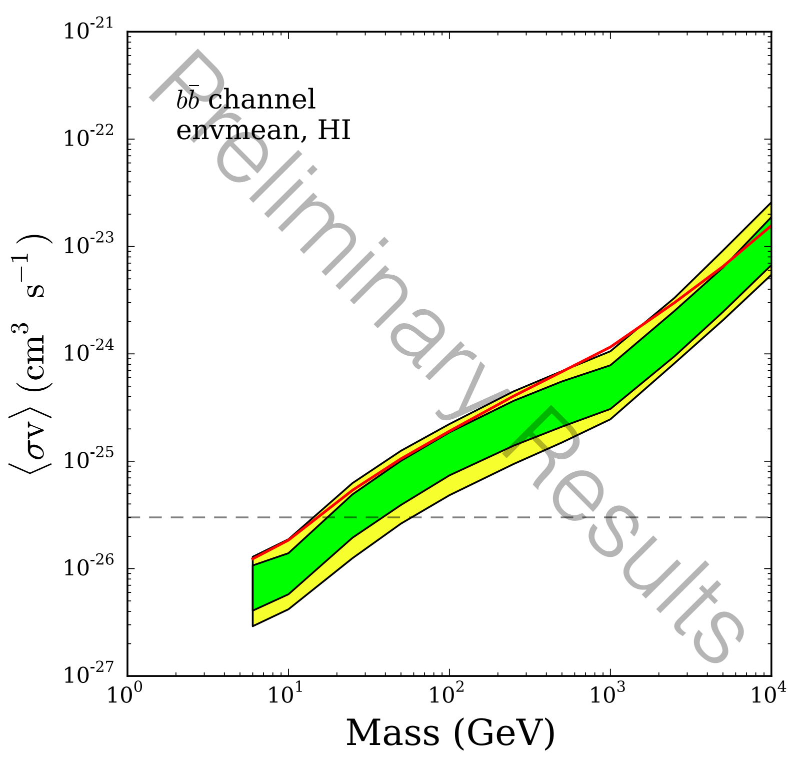
- Of our pre-selected center locations, the center of the HI gas has the most conservative bounds. Use this for our limits.

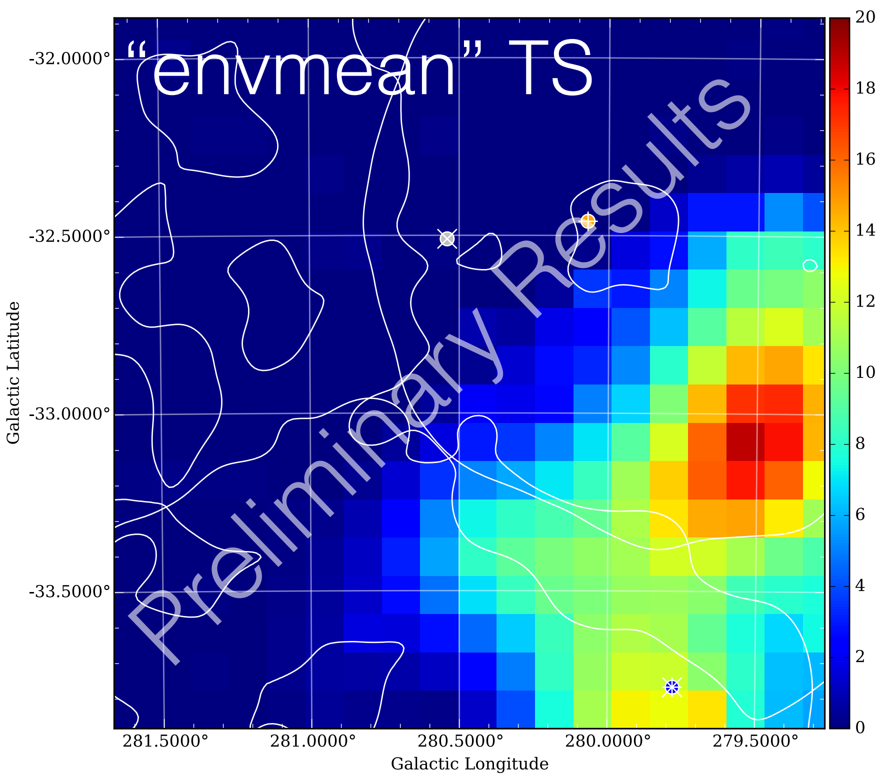


- Lower edge of brazil band is pushed upward by addition of systematic errors for spectra with $\mathcal{O}(100 \text{ MeV} - \text{GeV})$ photons

A Possible Excess

- Our bounds are $3-4\sigma$ weaker than expected from statistical uncertainties only, $1-2\sigma$ with all systematics.
  - A 15-18 TS near to expected DM centers.
  - Depends on morphology of DM signal injection





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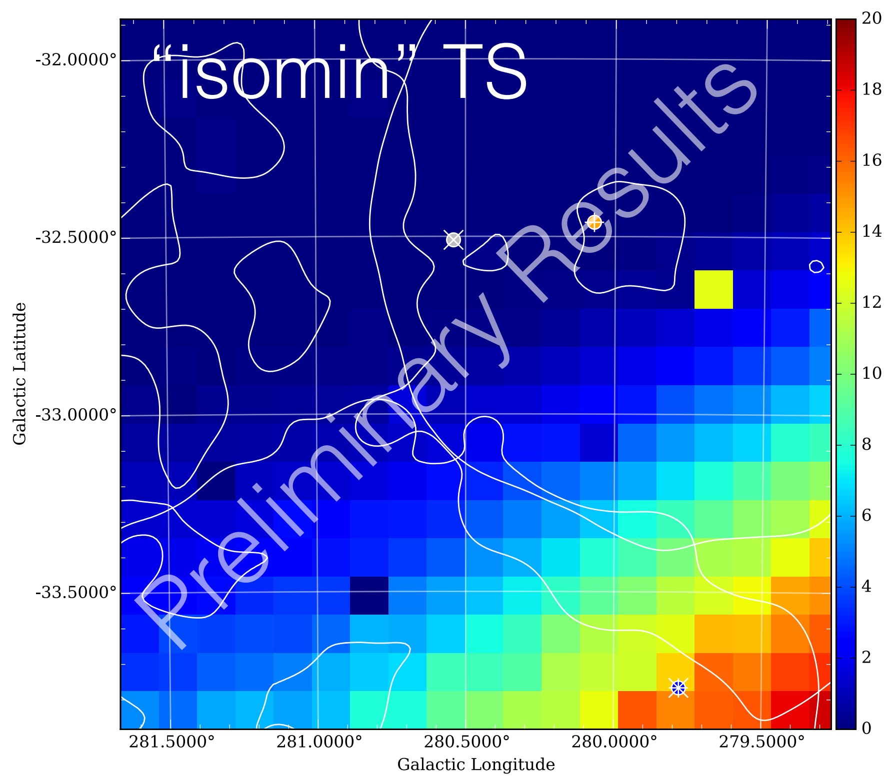
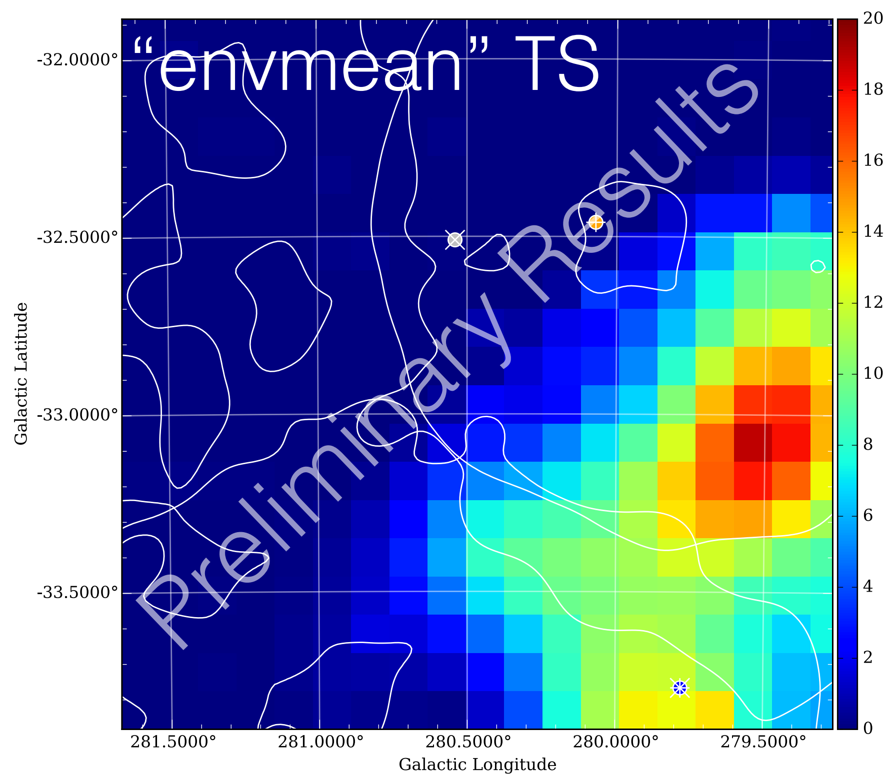
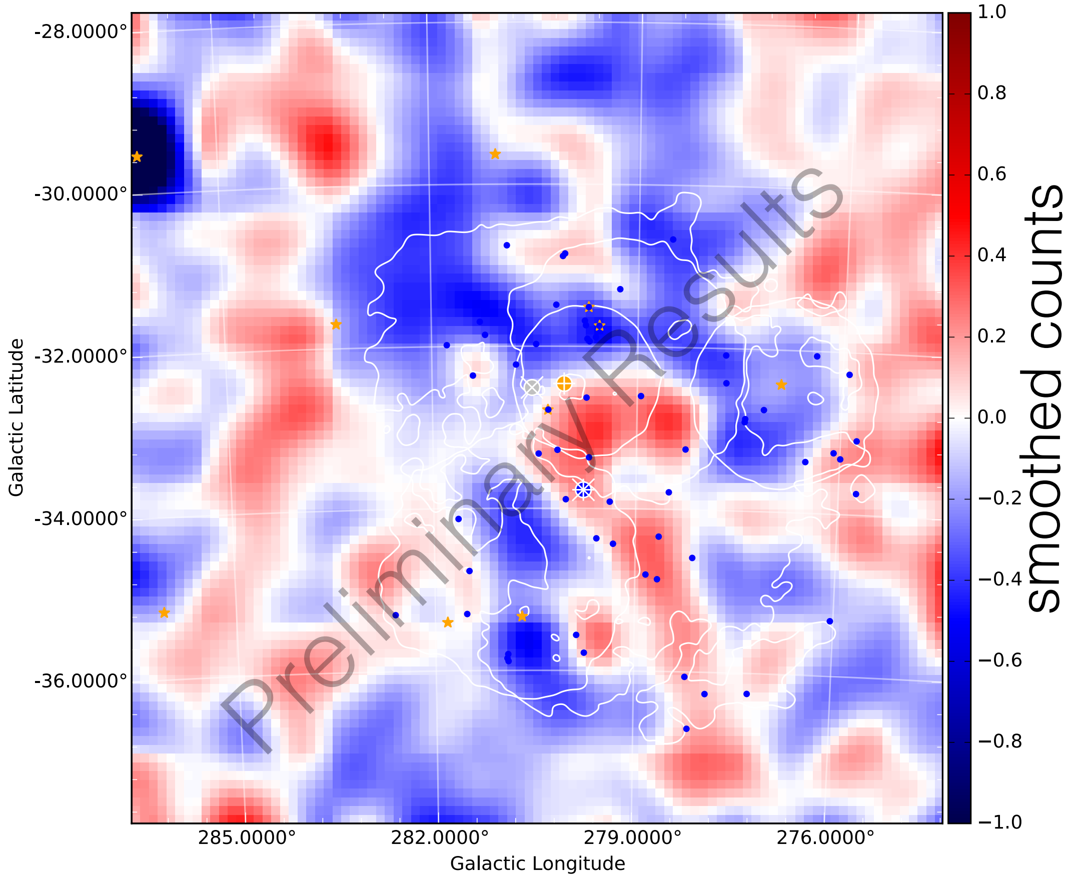


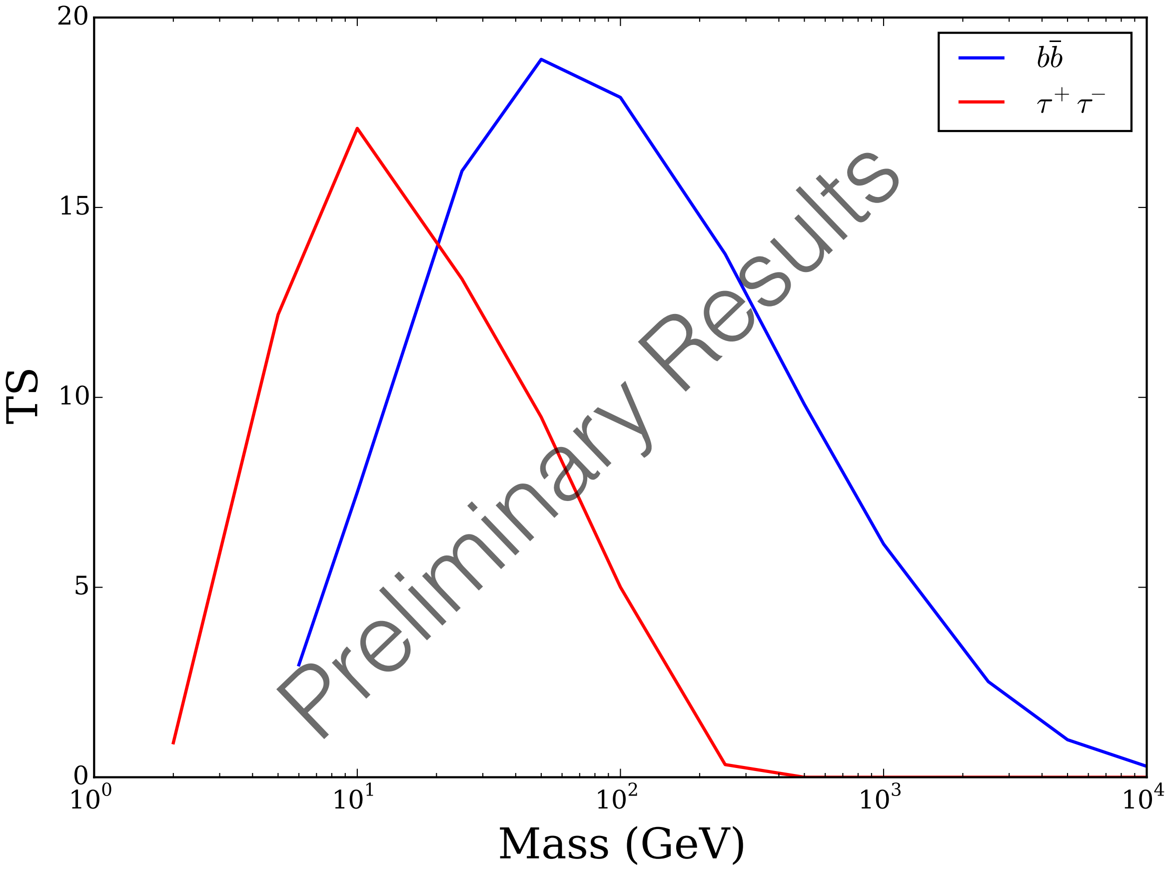


A Possible Excess

- Most likely explanation is this is an unmodeled baryonic background (non-gaussian, TS < 25 not in model)
  - However, also the parameters of the claimed anomaly in the Galactic Center (which does look baryonic)



Background Residual



Conclusions

- Stacking up against dwarf spheroidals galaxy bounds, and Galactic Center excess.
    - Weaker than expected
    - Comparable with Pass 7 dwarf, if profile similar to simulation results
- Future Improvements/Work:
    - Reduce uncertainties in DM profile
        - Need collaboration with astronomers.
    - Small Magellanic Cloud