Fermi Gamma-ray Space Telescope

Searching for Dark Matter in Dwarf Spheroidal Satellite Galaxies with the Fermi-LAT

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on behalf of the
Fermi-LAT Collaboration

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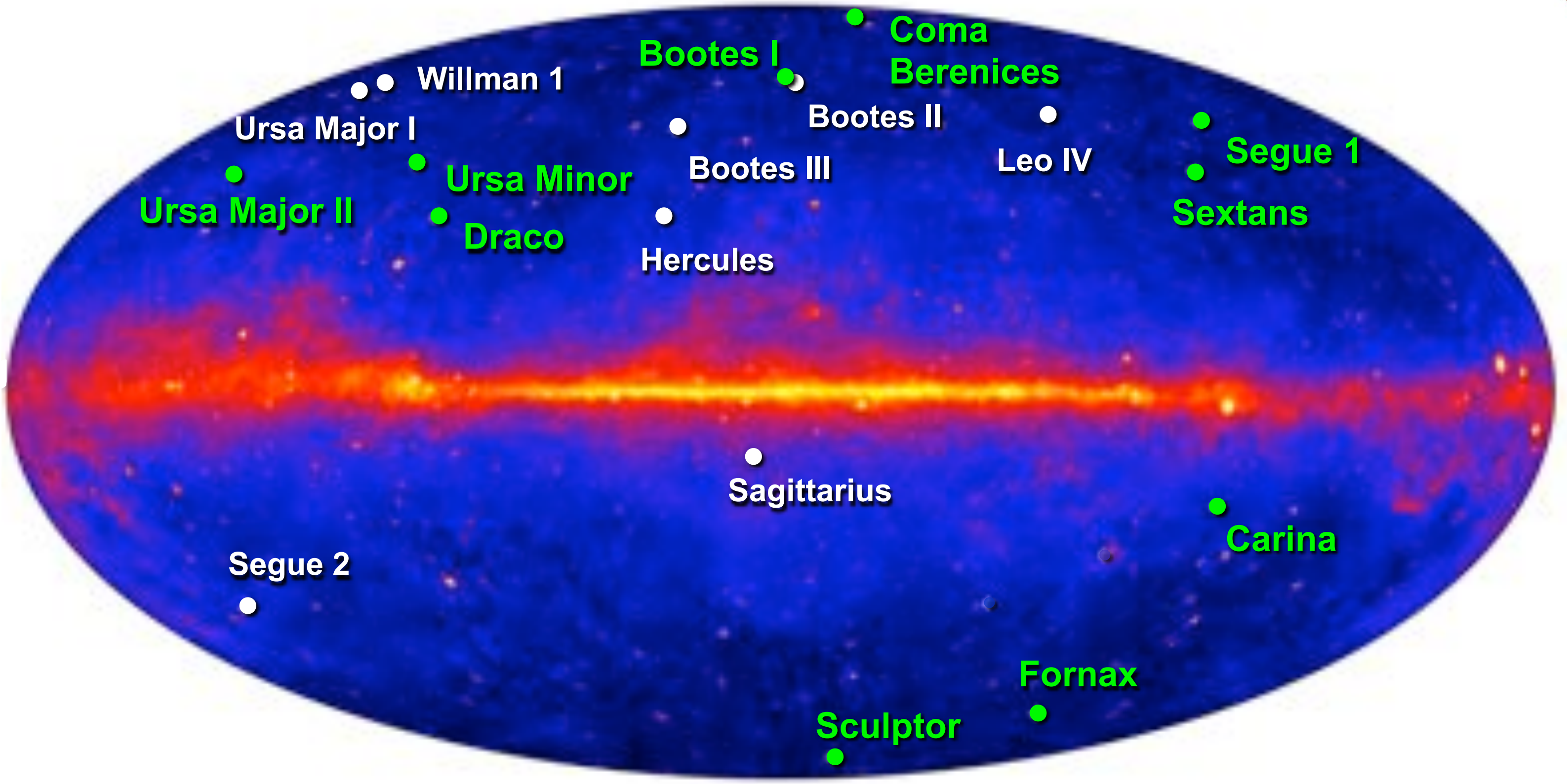
SLAC KIPAC STANFORD UNIVERSITY

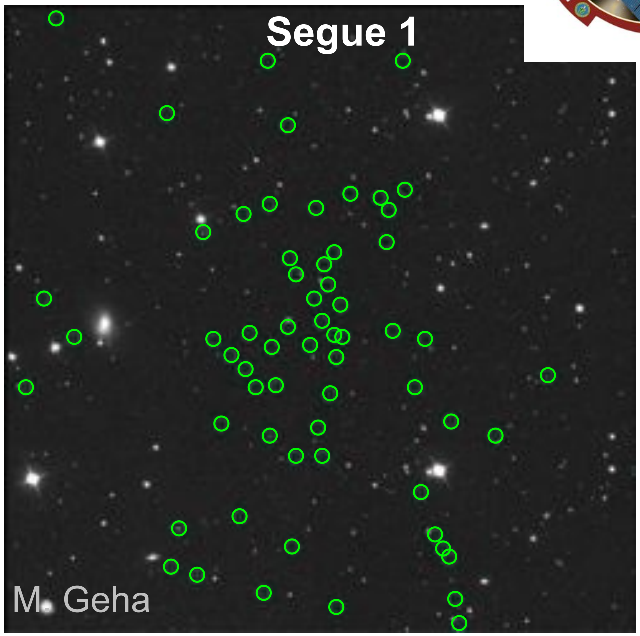
Dwarf Spheroidal Satellite Galaxies

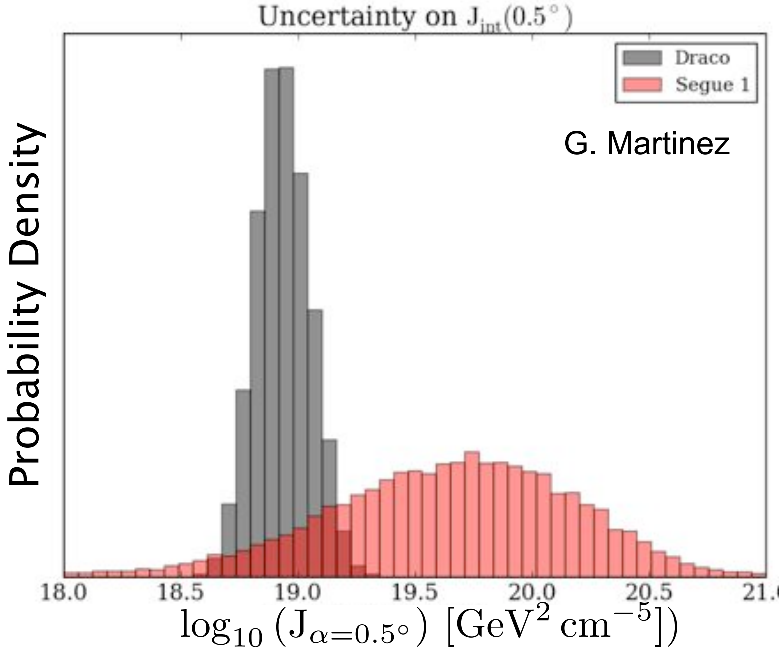


- Most dark-matter dominated objects in the universe
- Relatively nearby (25 - 150 kpc)
- High galactic latitudes, minimize astrophysical foregrounds
- Multi-wavelength observations show no basis for astrophysical gamma-ray production

Dark Matter Content

- **Dark matter content determined from stellar velocity dispersion**
  - **Classical dwarfs: spectra for several thousand stars**
  - **Ultra-faint dwarfs: spectra for fewer than 100 stars**
- **Fit stellar velocity distribution of each dwarf (assuming an NFW profile)**
- **Calculate the J-factor by integrating out to a radius of 0.5 deg.**
  - **Comparable to the half-light radius of many dwarfs**
  - **Minimizes the uncertainty in the J-factor**
  - **Large enough to be insensitive to the inner profile behavior (core vs. cusp)**
- **Include the J-factor uncertainty as a nuisance parameter in the joint likelihood**





Joint Likelihood Analysis

- Assume the same particle makes up dark matter in all dwarfs.
- The relative flux of each dwarf will differ due to its J-factor (dark matter content and distance)
- Create a joint likelihood (not data stacking) -- product of the likelihood fits to each region assuming the dark matter cross section as a shared parameter

$$L(D \mid \mathbf{p_m}, \{\mathbf{p_k}\}) = \prod_k L_k^{\mathrm{LAT}}(D_k \mid \mathbf{p_m}, \mathbf{p_k}) \times \frac{1}{\ln(10) J_k \sqrt{2\pi}\sigma_k} e^{-(\log_{10}(J_k) - \overline{\log_{10}(J_k)})^2/2\sigma_k^2}$$

Shared by all dwarfs (dark matter particle parameters)

Fit for each dwarf (background sources)

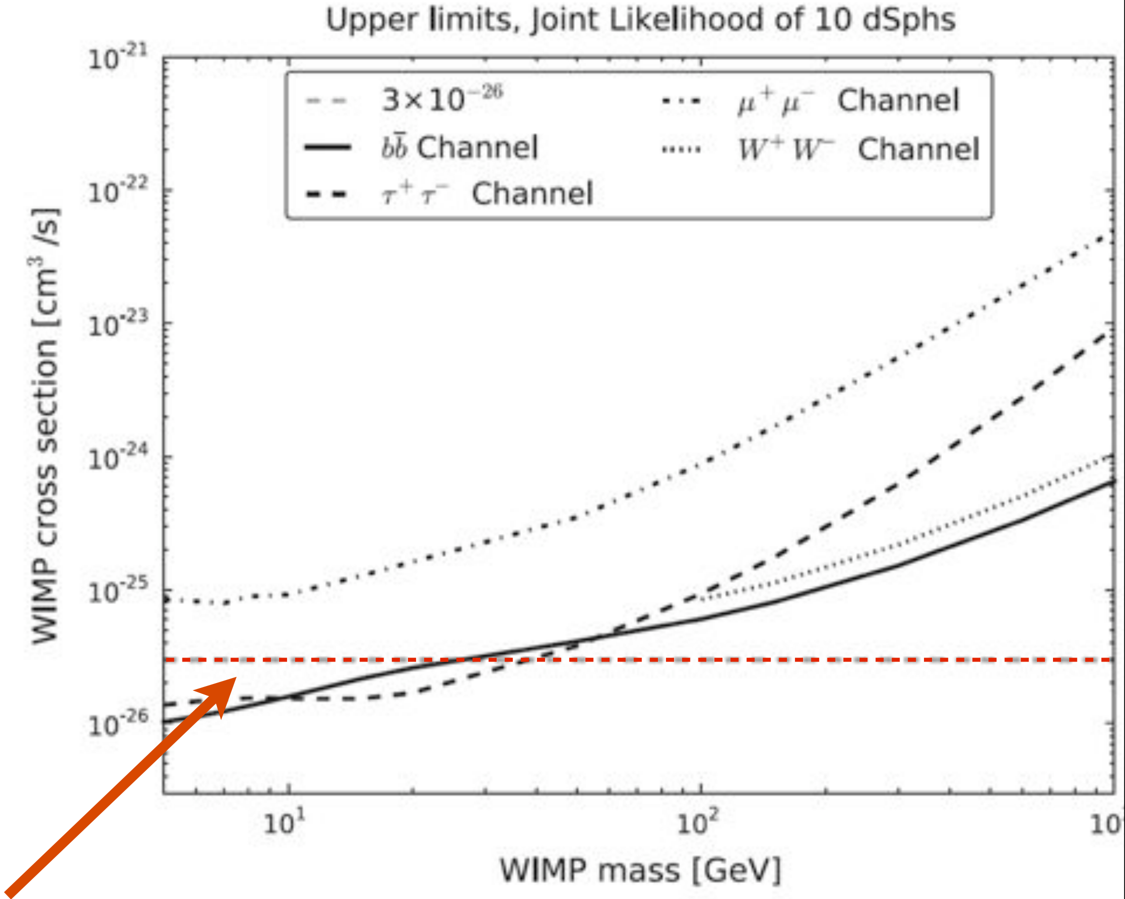
Statistical Uncertainty in J-factor

- Allows astrophysical backgrounds and J-factor uncertainties to be incorporated on a dwarf-by-dwarf basis.

2-Year Pass 6 Analysis

PRL 107, 241302; arXiv:1108.3546

- **Constraints from a joint likelihood analysis of:**
  - **10 dwarf galaxies**
  - **200 MeV - 100 GeV gamma rays**
  - **2 years of P6_V3_DIFFUSE data and IRFs (derived from Monte Carlo)**
- **Astrophysical model:**
  - **Point-like source from the 1FGL**
  - **Diffuse backgrounds from 1 year Galactic and Isotropic models**
- **Include statistical uncertainties in the solid-angle-integrated J-factor**
- **Constrain the conventional thermal relic cross section for a WIMP with mass < 30 GeV annihilating to** $b\bar{b}$ **or** $\tau^+\tau^-$



*** Also see:**
Talk by A. Geringer-Sameth
Poster 5 by F. Loparco

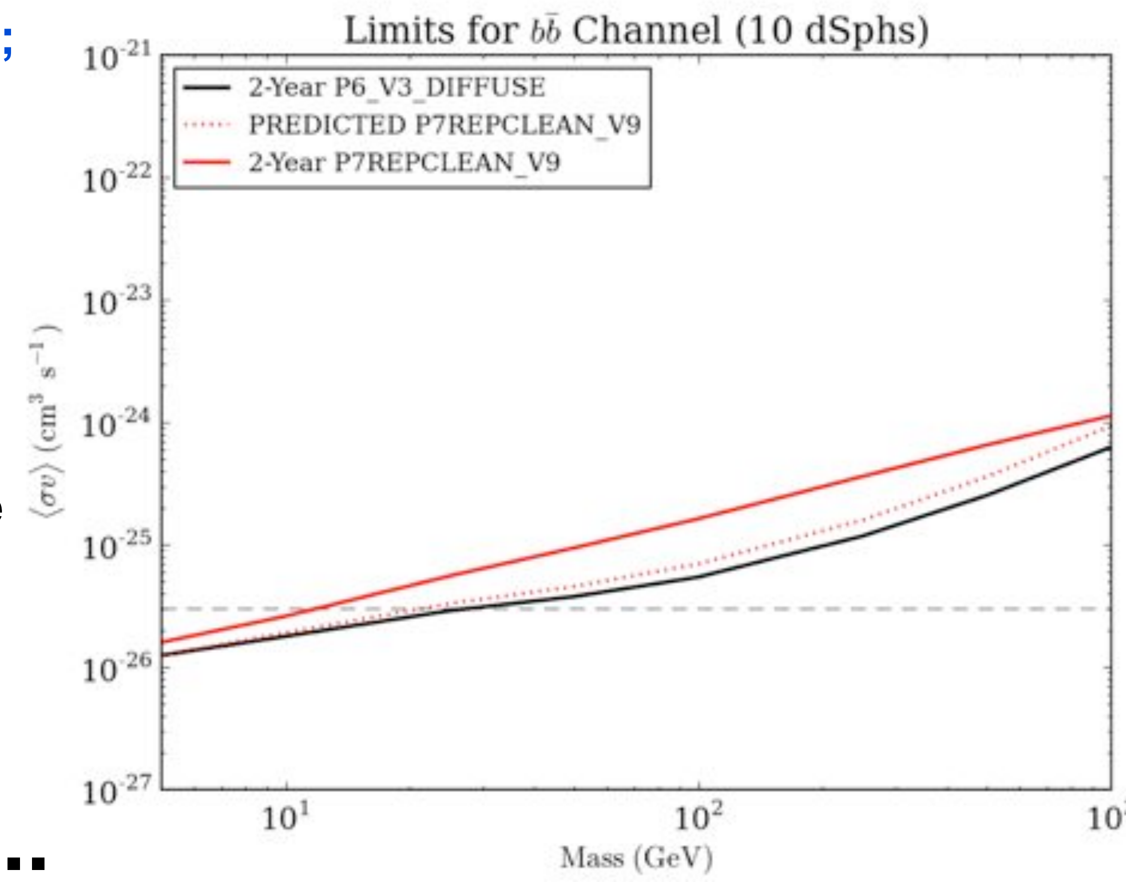
Pass 7 Analysis

- **Pass 7 reflects a better understanding of the LAT***
  - **Retraining of event classification; low background classes**
  - **In-flight PSF still slightly worse than simulation**

- **Predict ~50% increase in limits due to in-flight PSF vs simulated PSF**

- **Observed Pass 7 limits are increase by a factor of 1.5 to 3.5**

- **This is unexpected...**



*** Pass 7 refers to the reprocessed data (see Poster 5.4 by J. Bregeon)**

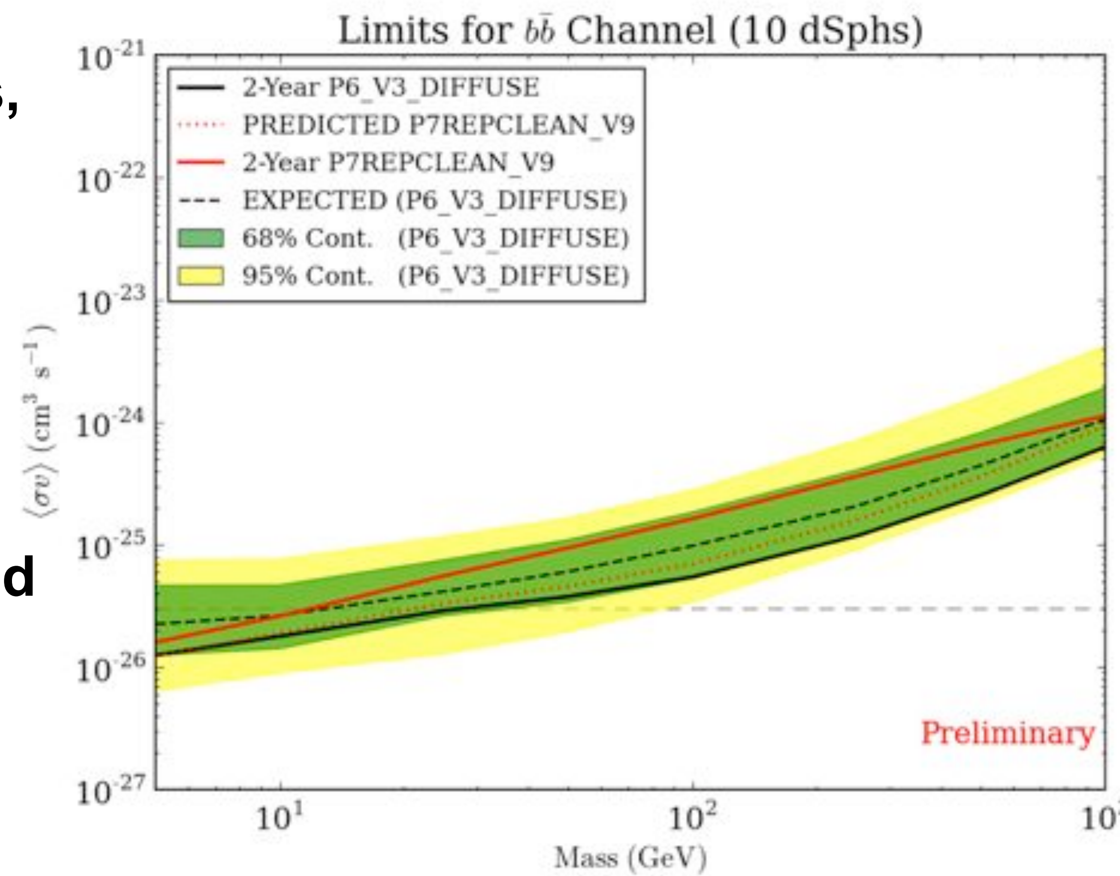
Expected Limits

- **...or is it?**

- **100 realistic sky simulations, replicating Pass 6 analysis:**
  - **All catalog sources**
  - **Galactic and isotropic diffuse backgrounds**
  - **No dark matter**

- **Run full analysis pipeline and calculate upper limits**

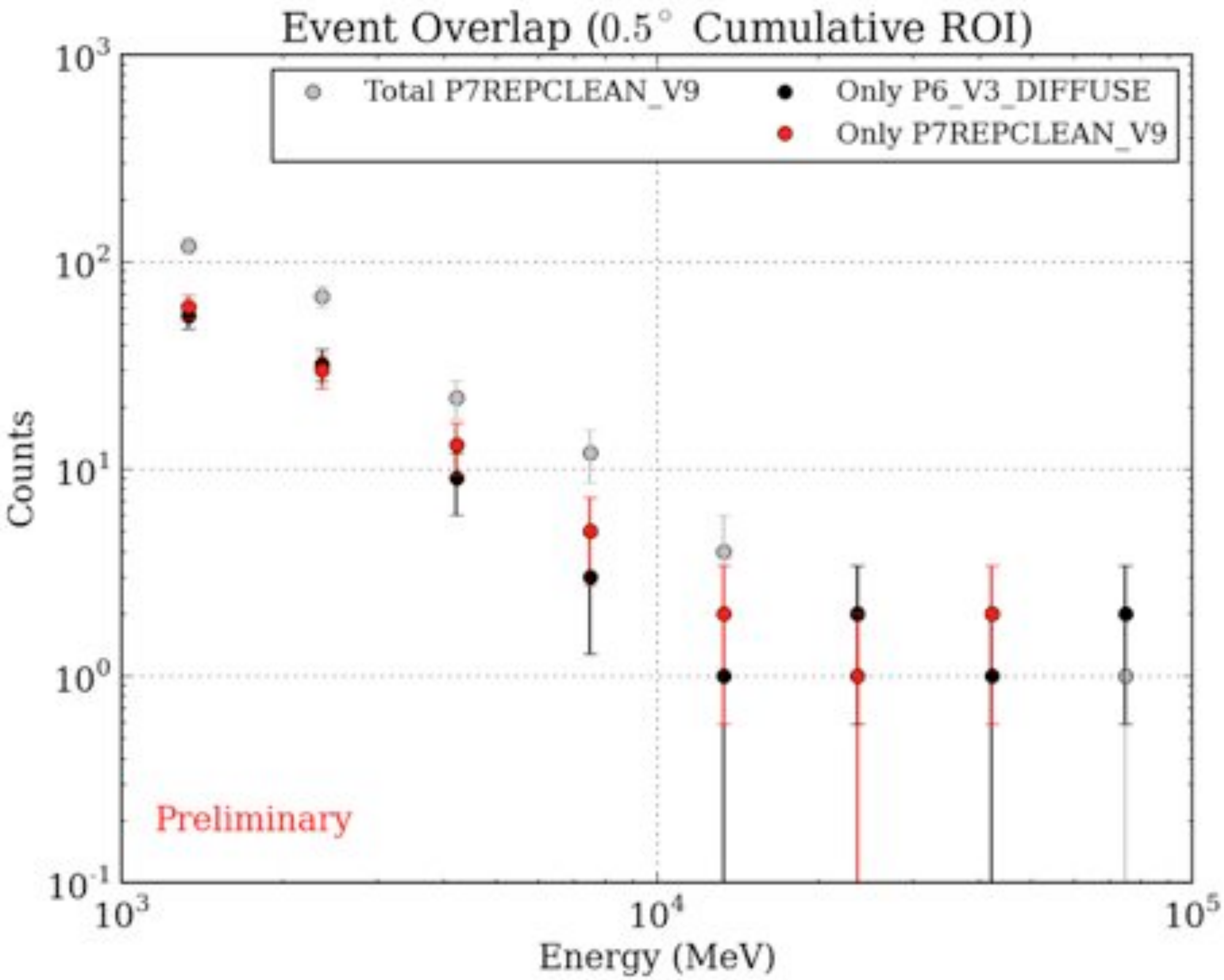
- **Both Pass 6 and Pass7 measurements lie within the 68% containment region of a statistical sample**



Statistical Fluctuations

- **The P6_V3_DIFFUSE and P7REPCLEAN_V9 differ on an event-by-event basis**
  - **Only ~70% of events above 1 GeV shared by the two event classes**
  - **Only ~50% of events above 10 GeV and within 0.5 deg. of the dwarfs are shared by the event classes**

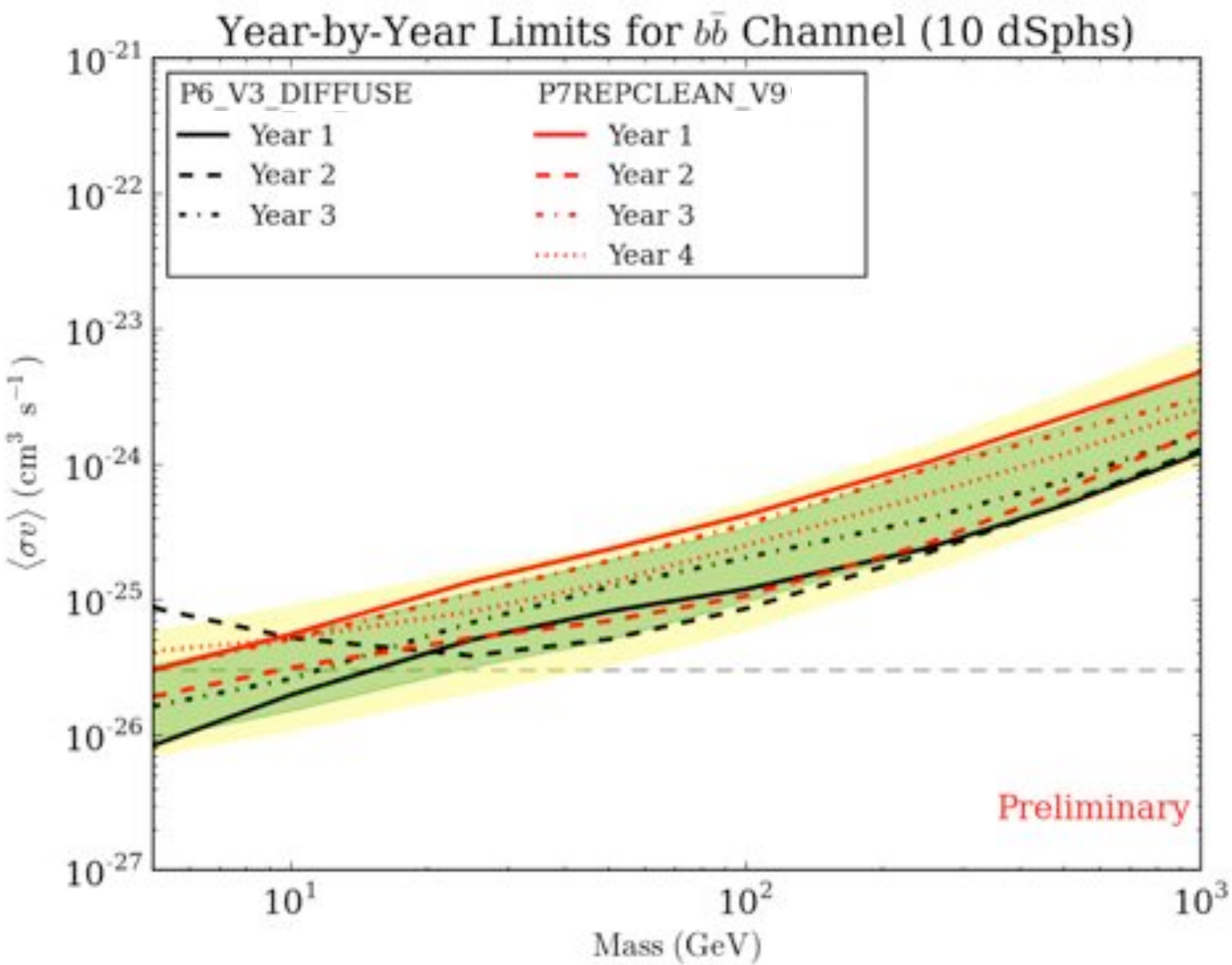
- **What accounts for this difference?**
  - **Pass 7 does a better job of mitigating instrumental pile-up**
  - **Required retraining of multivariate classification**
  - **Results in a statistical re-shuffling of events**



Statistical Fluctuations

- **Statistical fluctuations on year-by-year limits**
  - **3 year-by-year limits from Pass 6**
  - **4 year-by-year limits from Pass 7**
  - **Fluctuations consistent with the range of expected limits**

- **Median expected limits behave as predicted.**
  - **At high mass, Pass 7 limit ~50% higher than Pass 6 limit**
  - **Decrease as better than $1/\sqrt{\text{time}}$ (not background dominated)**

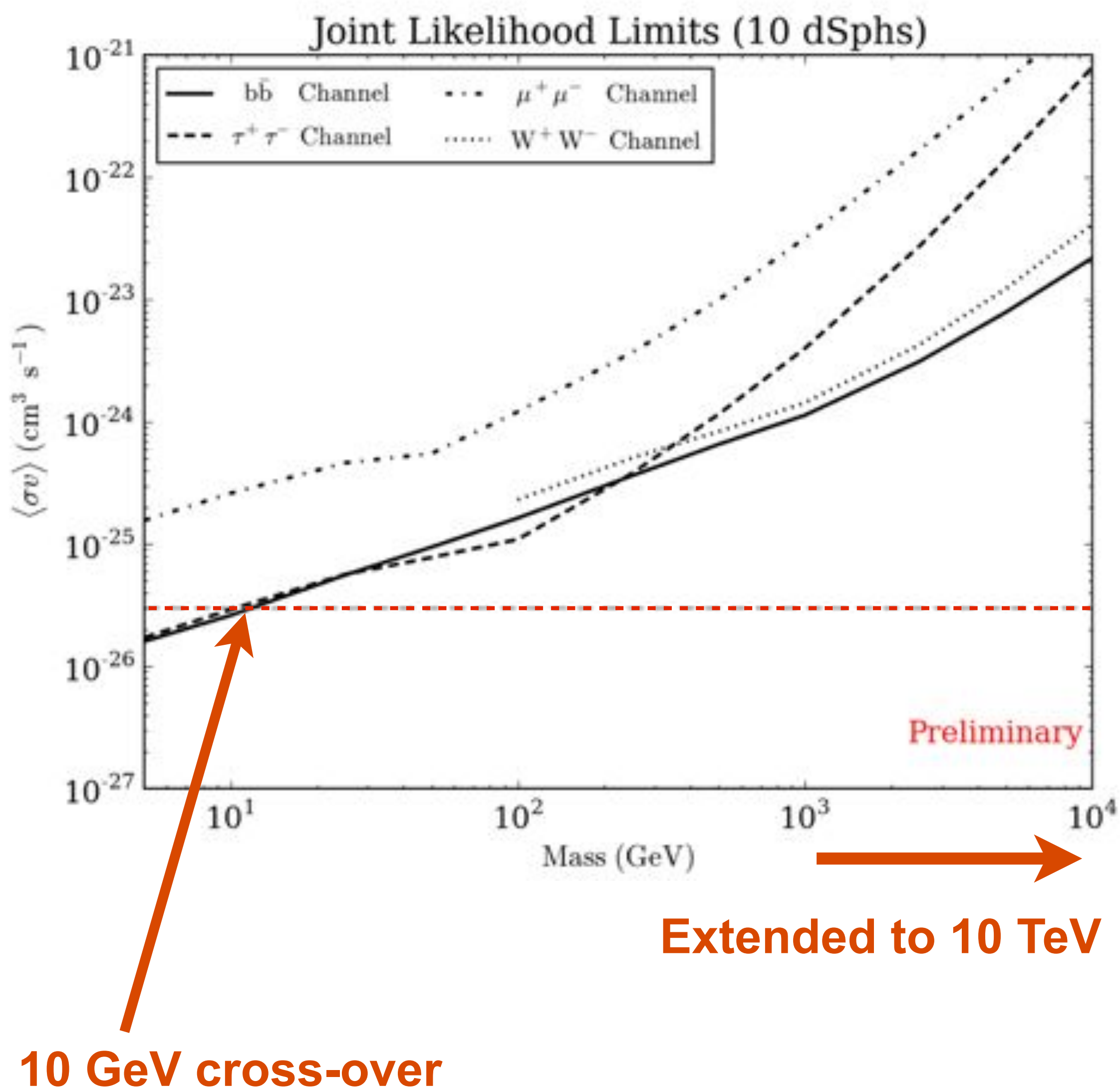


4-Year Pass 7 Analysis

- **Joint likelihood analysis of:**
  - Extended time period: 4 years
  - Improved instrument response: P7REPCLEAN_V9
  - Expanded photon energy range: 100 MeV - 500 GeV
  - Constrain higher WIMP masses: 5 GeV - 10 TeV
  - Same 10 dwarf galaxies

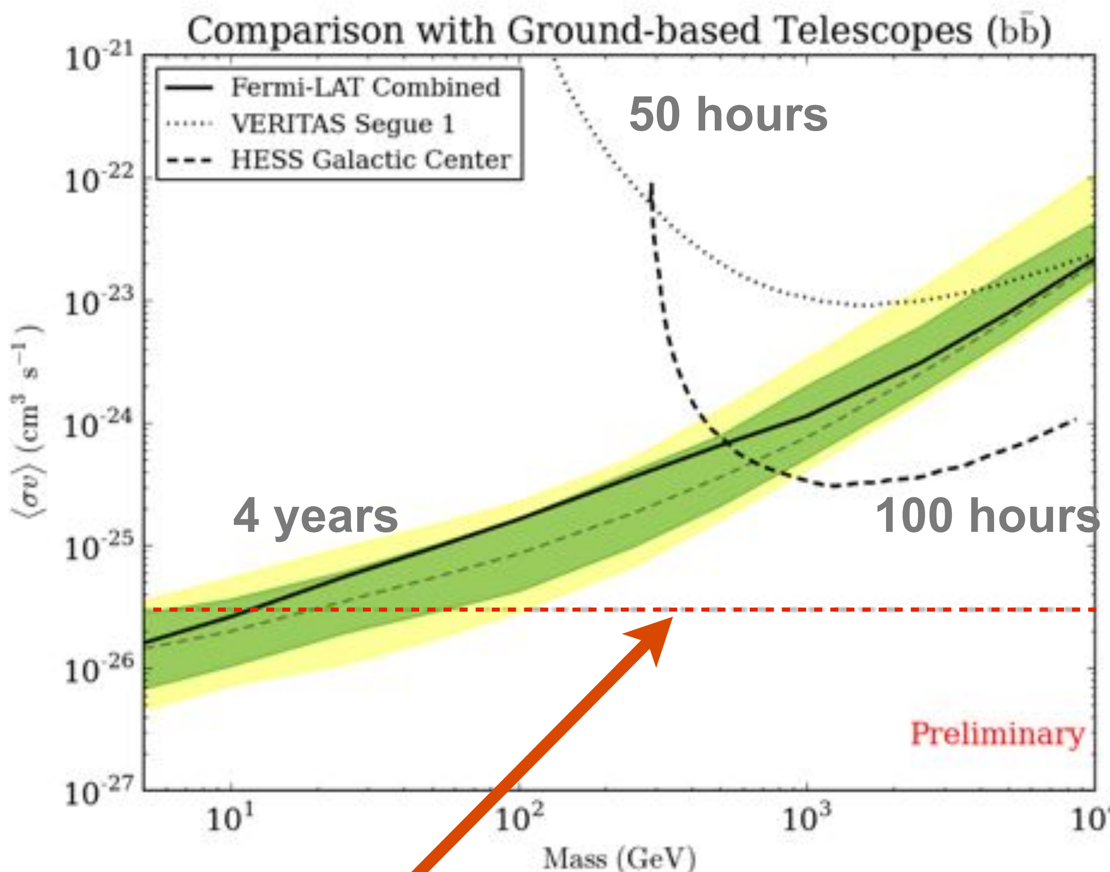
- **Model astrophysical backgrounds based on 2 years of Pass 7 data**
  - 2FGL catalog sources (normalization free within 5˚)
  - 2-year diffuse background models (normalization free)

- **Include statistical uncertainties in the solid-angle-integrated J-factor**



Conclusions

- 4 years of Pass 7 data yields higher limits than 2 years of Pass 6 data; however, the two are statistically consistent with predictions.
- Change in the Fermi-LAT dwarf limits are due to statistical fluctuations in the event classification.
- Still no evidence for a dark matter signal from these objects.
- Immediate improvements are expected from updated diffuse and point source background models.
- Eventual improvements are expected from instrument performance (Pass 8).



Thermal Relic Cross Section

$$\langle\sigma v\rangle = 3\times10^{-26}\mathrm{cm}^3\,\mathrm{s}^{-1}$$

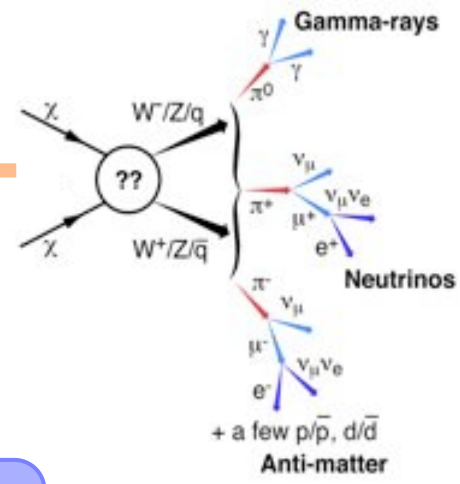
Back-up Slides

Dark Matter Annihilation

Gamma-Ray Flux
(measured by Fermi-LAT)

Particle Physics
(photons per annihilation)

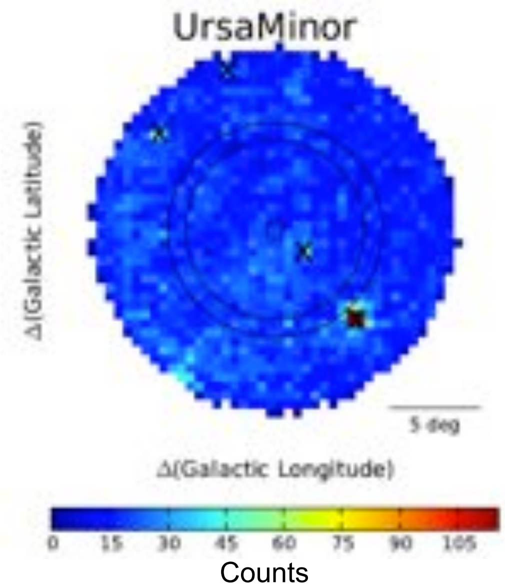
$$\frac{d\Phi_\gamma}{dE_\gamma}(E_\gamma,\phi,\theta) = \frac{1}{4\pi}\frac{<\sigma_{ann}v>}{2m^2_{WIMP}}\sum_f \frac{dN^f_\gamma}{dE_\gamma}B_f$$

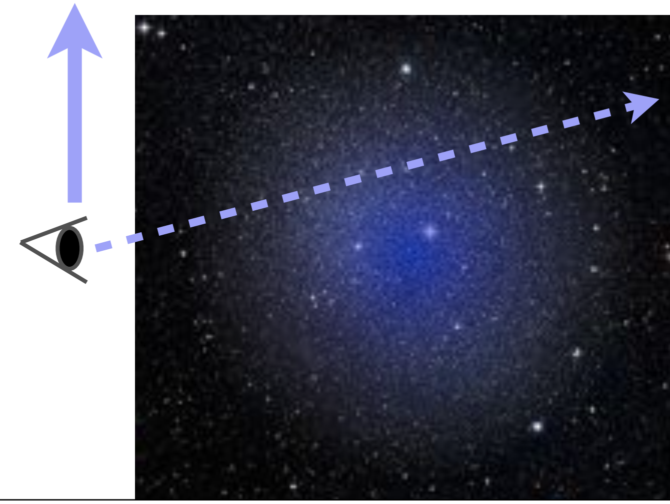


$$\times$$

$$\int_{\Delta\Omega(\phi,\theta)} d\Omega' \int_{los} \rho^2(r(l,\phi'))dl(r,\phi')$$

Dark Matter Distribution
(line-of-sight integral)





Joint Likelihood Function

PRL 107, 241302; arXiv:1108.3546

- Perform a combined analysis of 10 dwarf spheroidal galaxies.
- Approximate integrated J-factor with 0.5 deg. radius as a point-source contribution at the location of each dwarf
- J-factor derived from statistical fit to stellar kinematic data
- Statistical uncertainty (σ_k) is propagated to the LAT data analysis
- Joint likelihood function:

$$\frac{d\Phi_\gamma}{dE_\gamma}(E_\gamma,\phi,\theta) = \frac{1}{4\pi}\frac{<\sigma_{ann}v>}{2m^2_{WIMP}}\sum_f \frac{dN^f_\gamma}{dE_\gamma}B_f \times \int_{\Delta\Omega(\phi,\theta)} d\Omega' \int_{los} \rho^2(r(l,\phi'))dl(r,\phi')$$

J-Factor

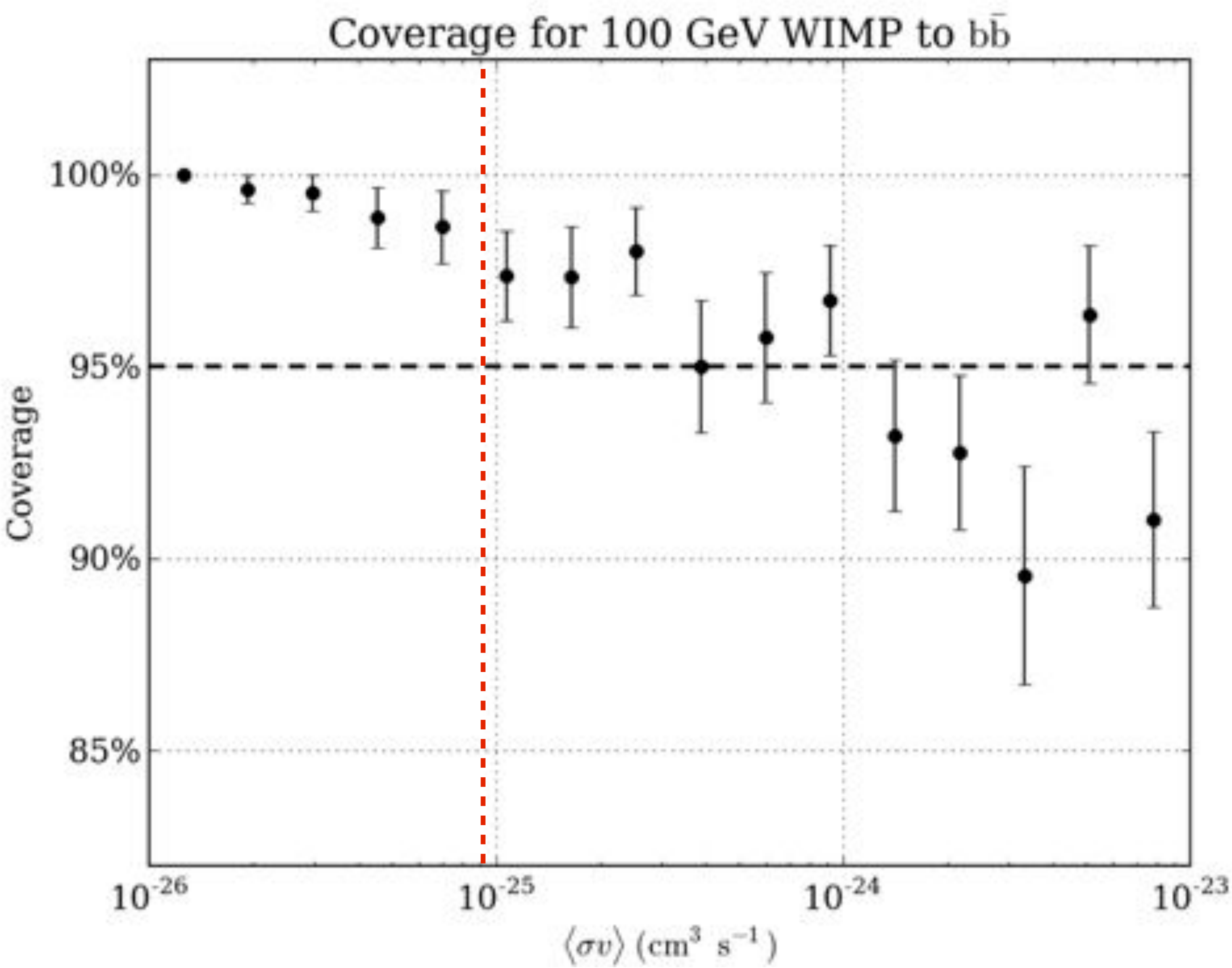
$$L(D\,|\,\mathbf{p_m},\{\mathbf{p_k}\}) = \prod_k L_k^{\rm LAT}(D_k\,|\,\mathbf{p_m},\mathbf{p_k}) \times \frac{1}{\ln(10)J_k\sqrt{2\pi}\sigma_k}e^{-(\log_{10}(J_k)-\overline{\log_{10}(J_k)})^2/2\sigma_k^2}$$

Shared by all dwarfs (dark matter particle parameters)

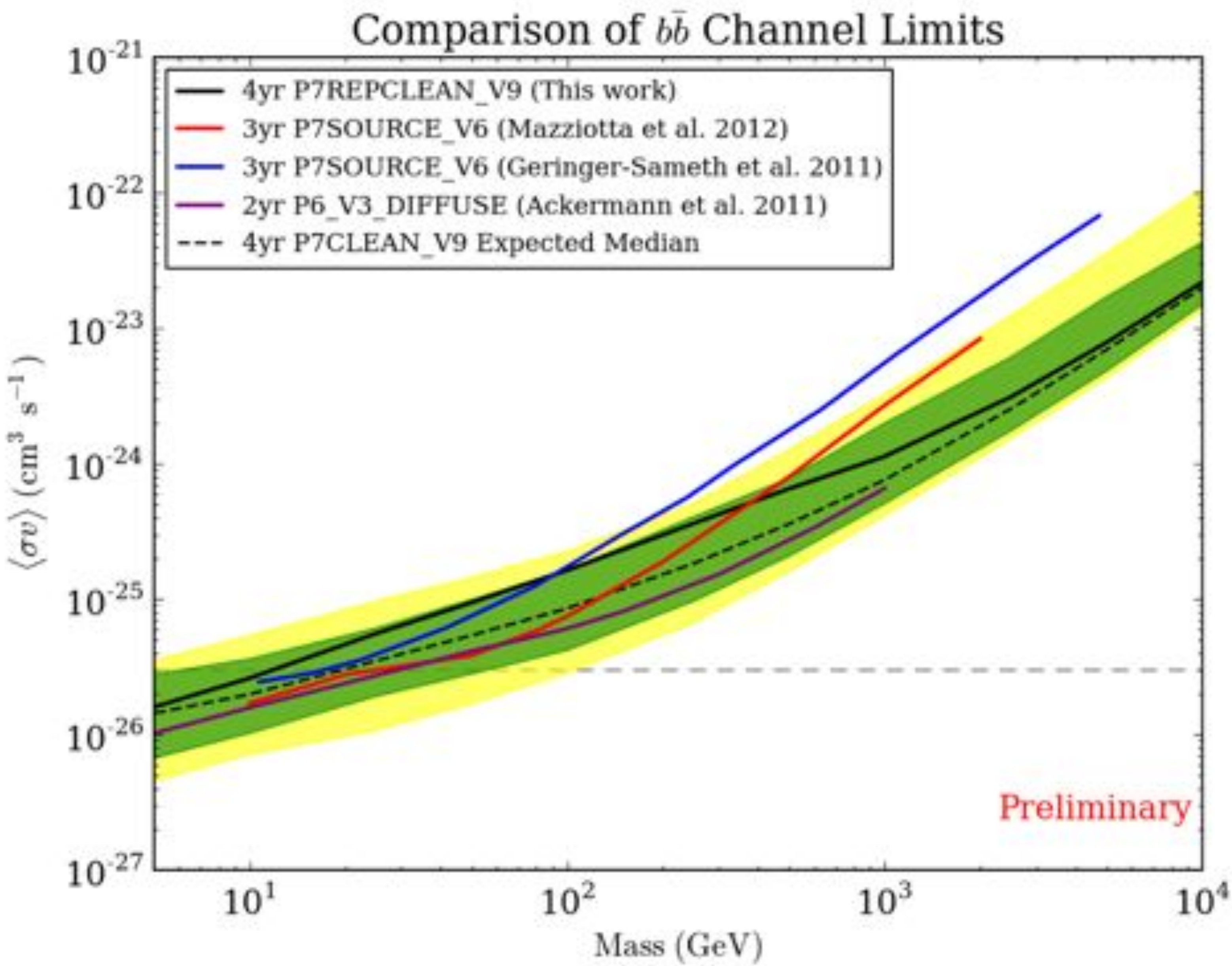
Fit for each dwarf (background sources)

Statistical Uncertainty in J-factor

Coverage

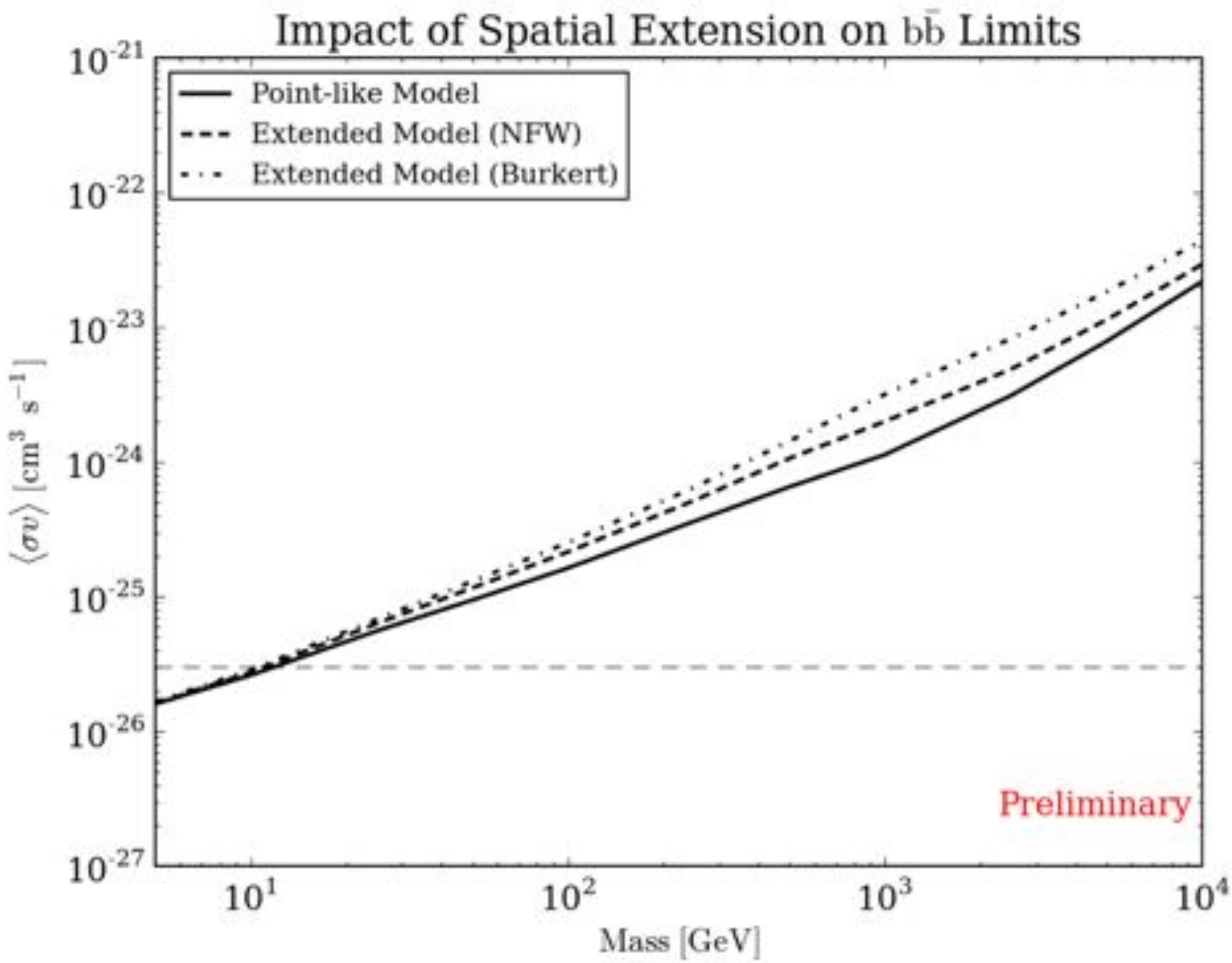

Coverage for 100 GeV WIMP to $b\bar{b}$
100%
95%
90%
85%
Coverage
10^{-26}
10^{-25}
10^{-24}
10^{-23}
$\langle \sigma v \rangle$ (cm^3 s^{-1})

Comparison



Comparison of $b\bar{b}$ Channel Limits
4yr P7REPCLEAN_V9 (This work)
3yr P7SOURCE_V6 (Mazziotta et al. 2012)
3yr P7SOURCE_V6 (Geringer-Sameth et al. 2011)
2yr P6_V3_DIFFUSE (Ackermann et al. 2011)
4yr P7CLEAN_V9 Expected Median
Preliminary
$\langle \sigma v \rangle$ (cm^3 s^{-1})
Mass (GeV)
10^{-21}
10^{-22}
10^{-23}
10^{-24}
10^{-25}
10^{-26}
10^{-27}
10^1
10^2
10^3
10^4

Spatial Extension



Uncertainties in J-factors

PRL 107, 241302; arXiv:1108.3546

- Examine systematic uncertainties in deriving the dwarf J-factors

- Choice of profile:
  - J-factors integrated over a cone with radius 0.5 degrees
  - Comparable to or larger than the half-light radii of the dwarfs
  - The choice of cored or cusped profile at small radii has little effect

- Change of stellar kinematic analysis:
  - J-factors determined using the methodology of Strigari et al. (2008) and Martinez et al. (2009)
  - Replacing 6 conventional dwarfs with J-factors calculated independently by Chabonnier et al. (2011), results in a ~ 10% effect

- Impact of ultra-faint dwarfs:
  - The dark matter distributions of Segue 1 and Ursa Major II are calculated from 71 and 24 stars, respectively
  - Removing both Segue 1 and Ursa Major II from combined analysis impacts the results by a ~50%

Dwarf Galaxies