Fermi Gamma-ray Space Telescope

New Fermi-LAT Results on the Search for Dark Matter Annihilation in Dwarf Spheroidal Galaxies

Matthew Wood
on behalf of the Fermi-LAT Collaboration

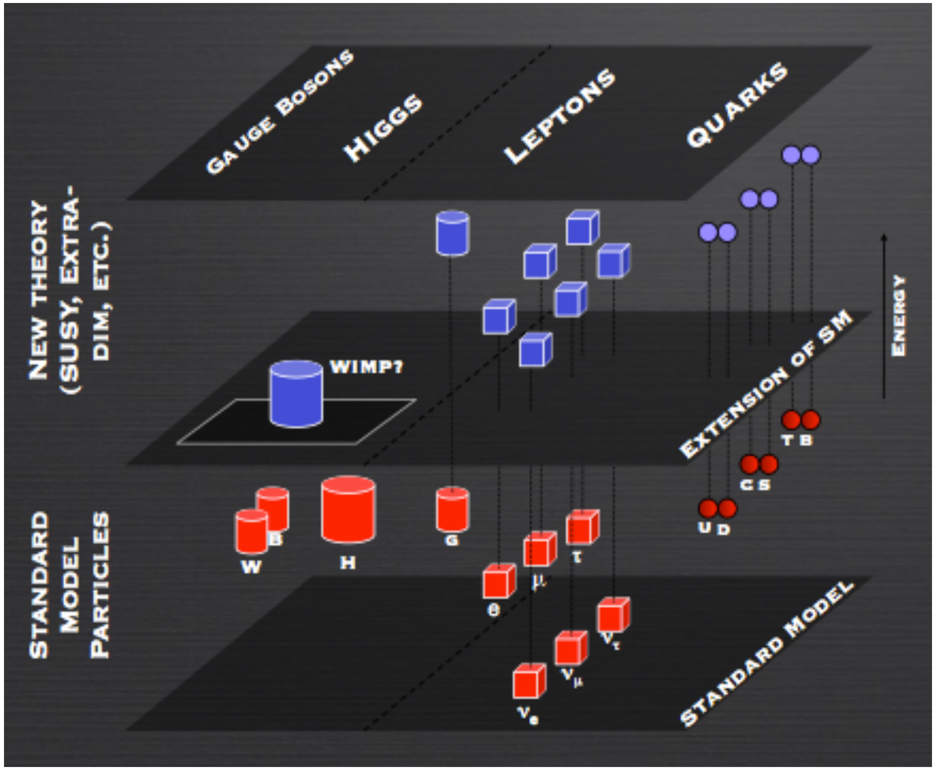
SLAC Experimental Physics Seminar

October 14, 2014

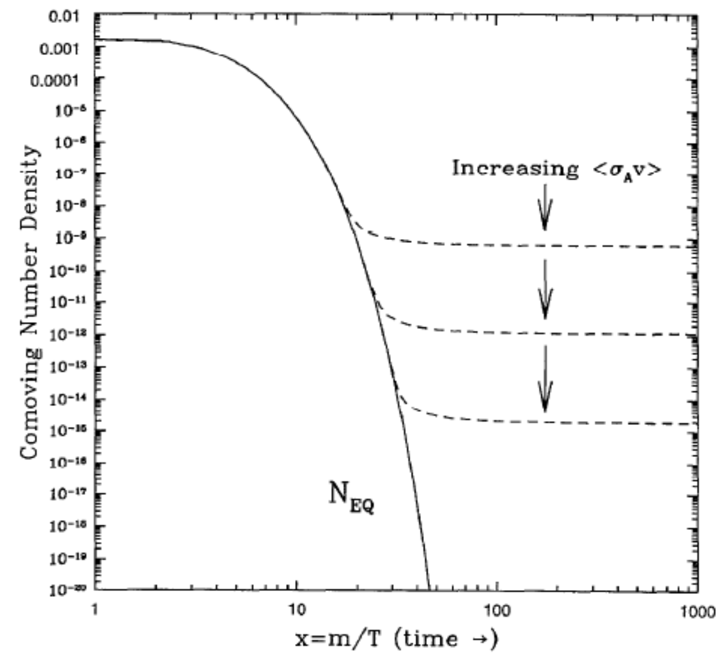
SLAC NATIONAL ACCELERATOR LABORATORY

KIPAC

Weakly Interacting Massive Particles



$$\frac{\Omega_\chi h^2}{0.1} \simeq \frac{3 \times 10^{-26}\ \mathrm{cm}^3\ \mathrm{s}^{-1}}{\langle \sigma v \rangle}$$

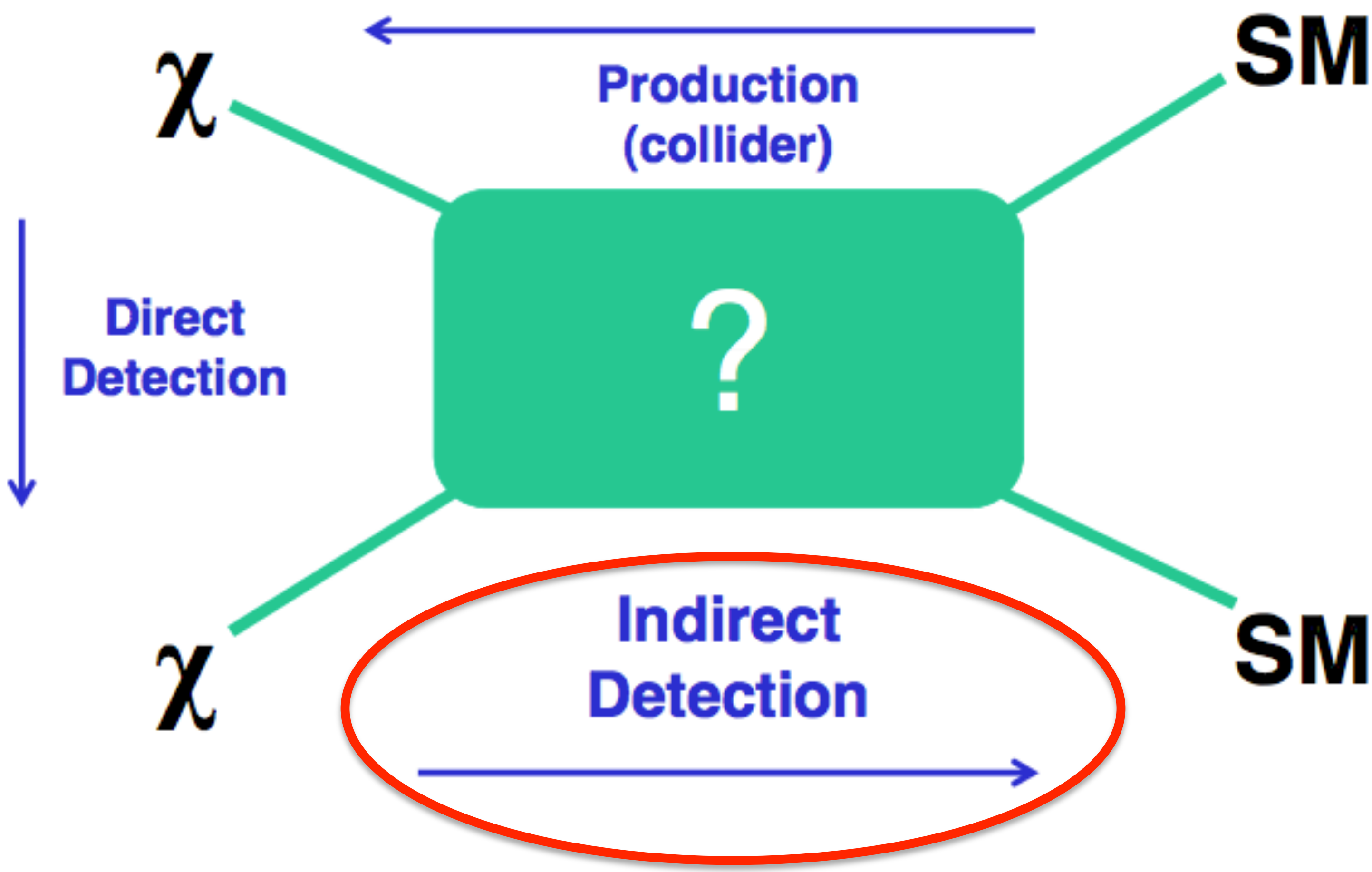


WIMPs arise naturally in extensions to the standard model (e.g. SUSY)

"WIMP Miracle", WIMPs as thermal relic:
Mass scale ~ 100 GeV
$\langle \sigma v \rangle \sim 3 \times 10^{-26}\ \mathrm{cm}^3\ \mathrm{s}^{-1}$

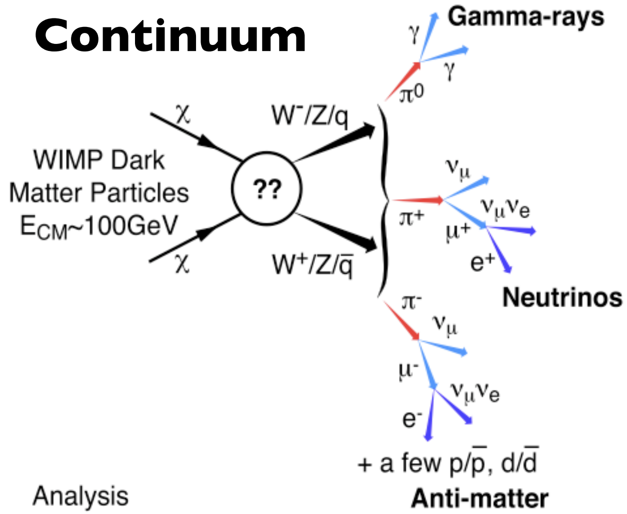
Thermal freezeout process connects WIMP cross section to relic density

Dark Matter Searches



Gamma-ray Signature of Dark Matter

Continuum

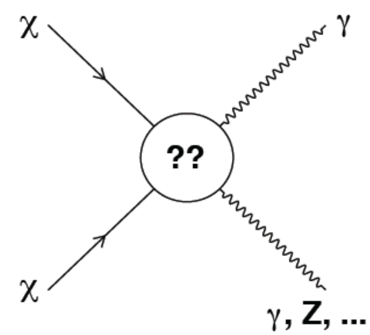


Analysis

+

Spectral line

Prompt annihilation into γγ, γZ, γH⁰...
(also prompt decay into photons)



Gamma-ray Flux

Particle Physics

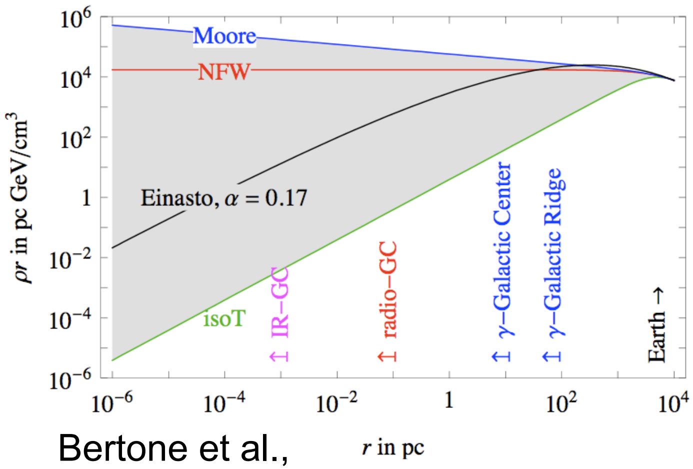
$$\frac{d\Phi_\gamma}{dE_\gamma}(E_\gamma, \phi, \theta) = \frac{1}{4\pi}\frac{< \sigma_{ann} v >}{2m^2_{WIMP}}\sum_f \frac{dN^f_\gamma}{dE_\gamma}B_f$$

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

DM Distribution (J-Factor)

Gamma-ray Signature of Dark Matter

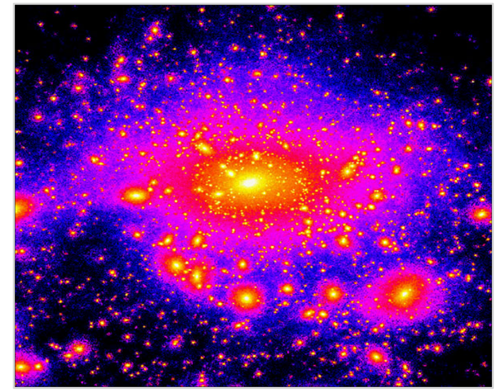
Smooth DM Distribution



Bertone et al.,
arXiv:0811.3744

X

Boost Factor



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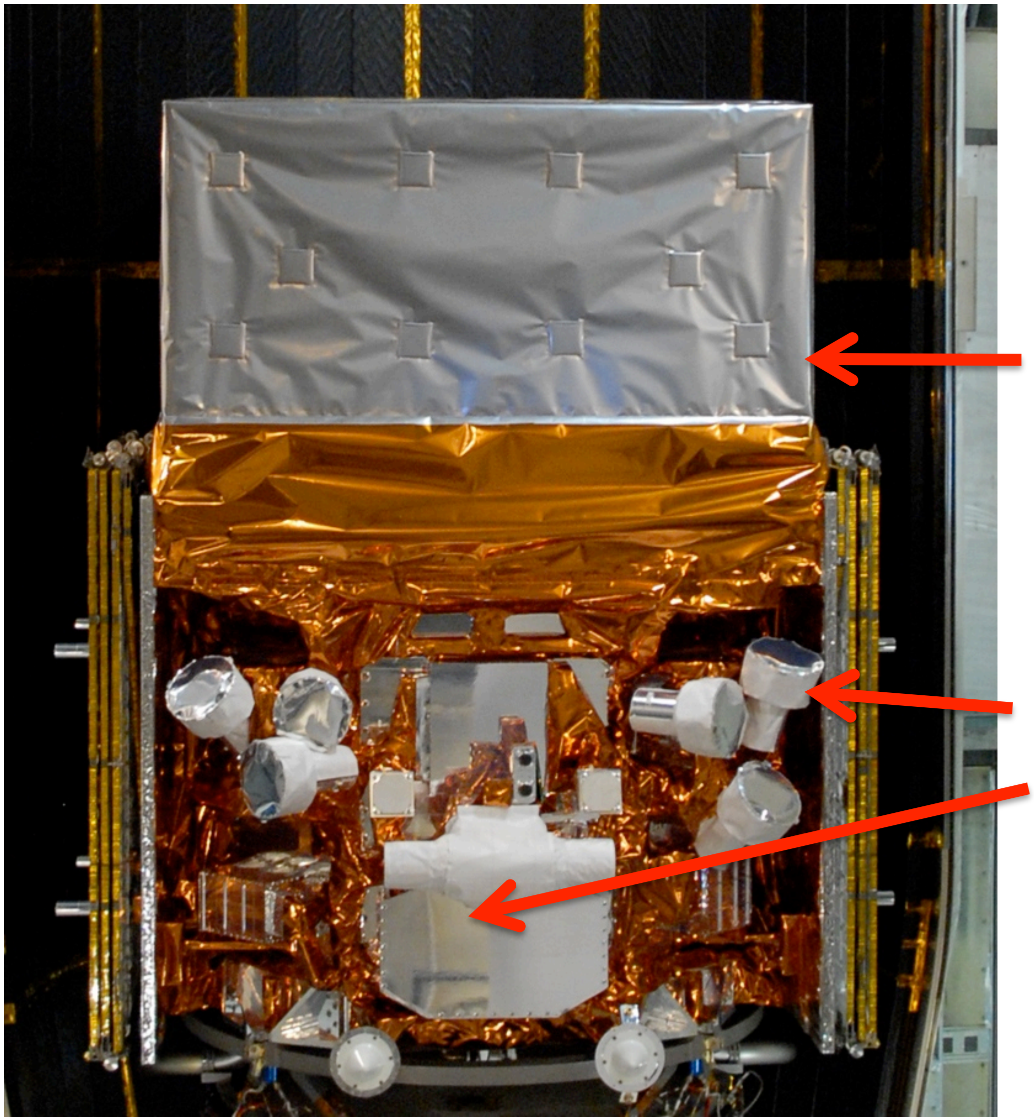
DM Distribution (J-Factor)

Fermi Observatory



Launch: June 11 2008
Nominal Operations: Aug 4 2008
Mission Approved through 2016

Large Area Telescope (LAT)

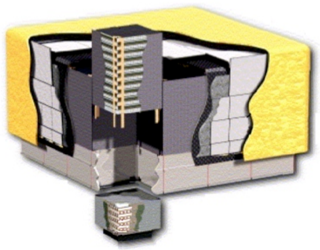
- 20 MeV - > 300 GeV
- 2.4 sr FoV

Gamma-ray Burst Monitor (GBM):

- 12 x NaI (8 keV – 1 MeV)
- 2 x BGO (200 keV – 40 MeV)
- Views entire un-occulted sky

Overview of the Large Area Telescope

Atwood, W. B. et al. 2009, ApJ, 697, 1071

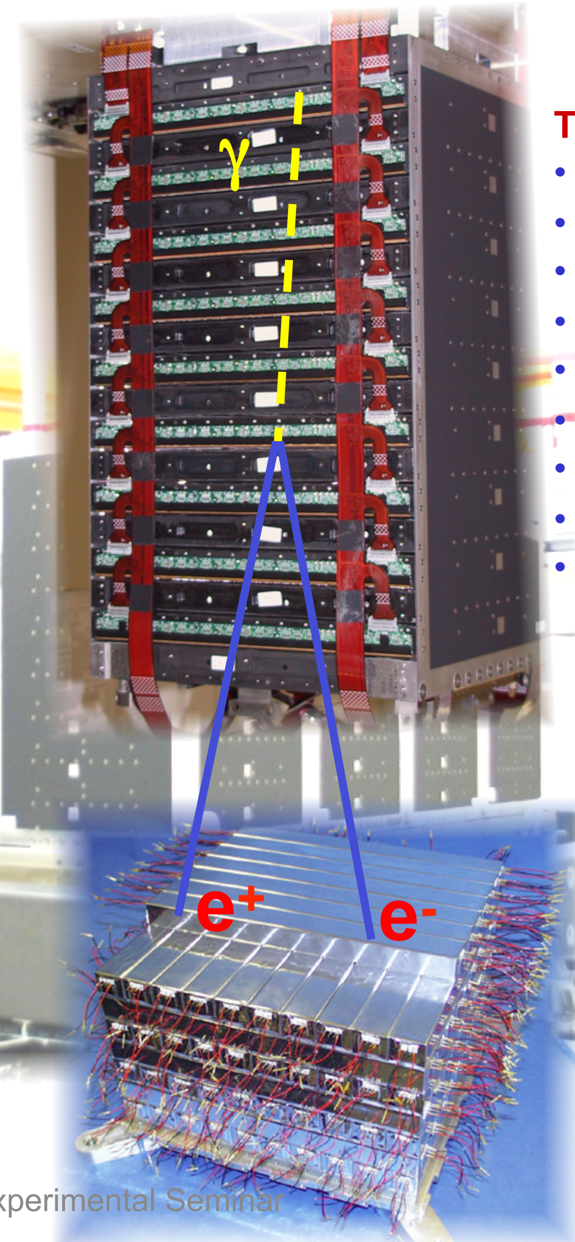


LAT:

- modular - 4x4 array
- 3 tons – 650 W

Anti-Coincidence (ACD):

- Segmented (89 tiles + 8 ribbons)
- Self-veto @ high energy limited
- **0.9997 detection efficiency**



Tracker/Converter (TKR):

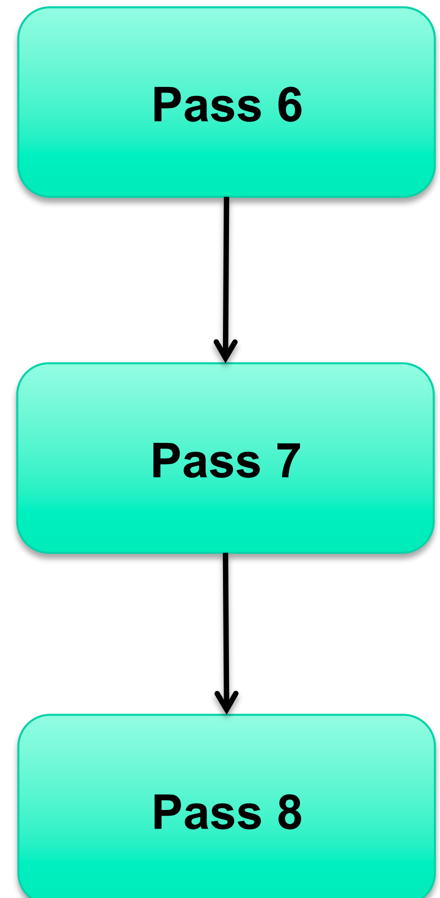
- Si-strip detectors
- ~80 m^2 of silicon (total)
- W conversion foils
- **1.5 X0 on-axis**
- 18XY planes
- **~10^6 digital elx chans**
- Highly granular
- High precision tracking
- Average plane PHA

Calorimeter (CAL):

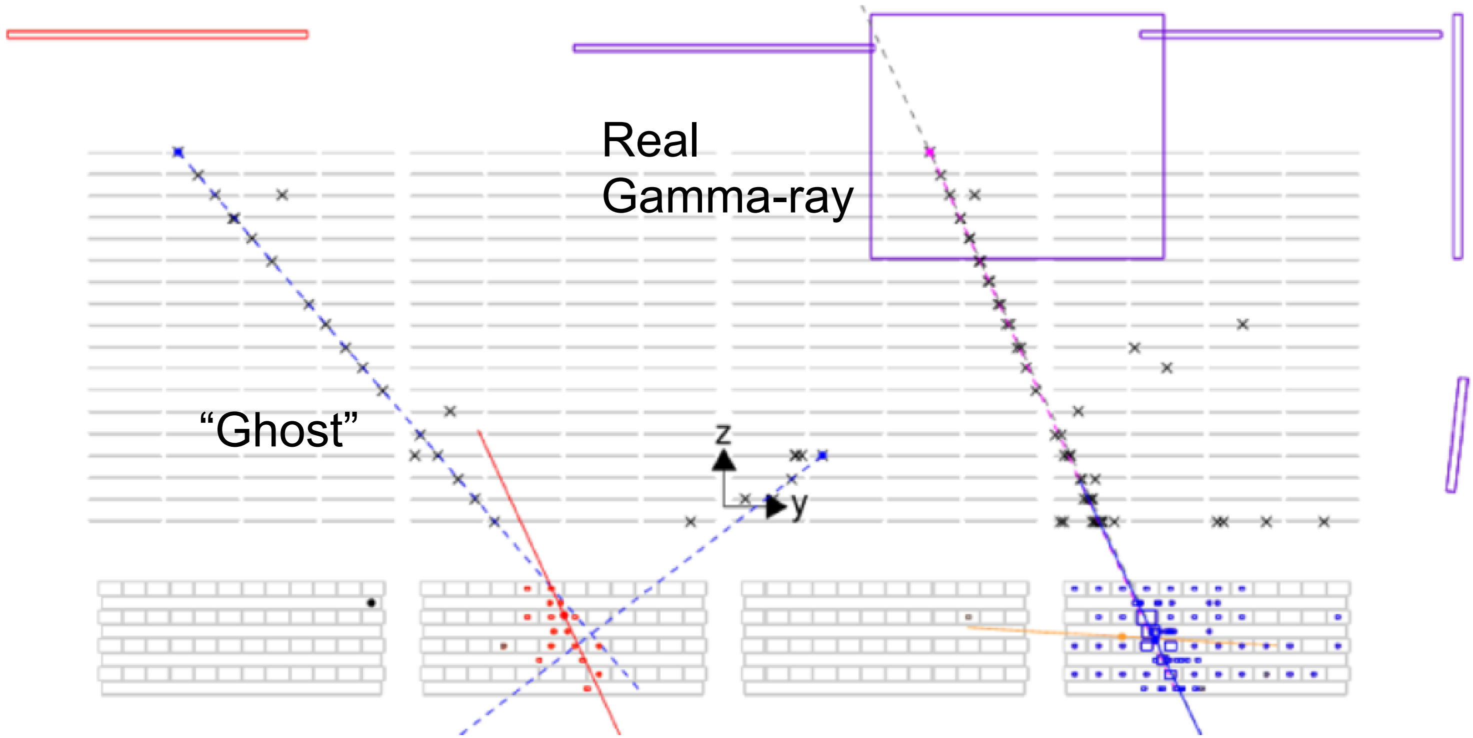
- 1536 CsI(Tl) crystals
- **8.6 X0 on-axis**
- large elx dynamic range (2MeV-60GeV per xtal)
- **Hodoscopic (8x12)**
- Shower profile recon
- EM vs HAD separation

Pass 8: Improving the LAT Event Reconstruction

- Since launch there has been a continuous effort to update and refine the LAT event-level reconstruction
- **Pass 6**: Event analysis developed prior to launch and based primarily on MC models of the instrument performance
- **Pass 7/Pass 7 Reprocessed**: Improved event analysis developing with experience operating the LAT in its orbital environment and accounting for on-orbit effects
- **Pass 8**: Complete revision of entire event analysis chain from reconstruction to classification



Dealing with Ghosts

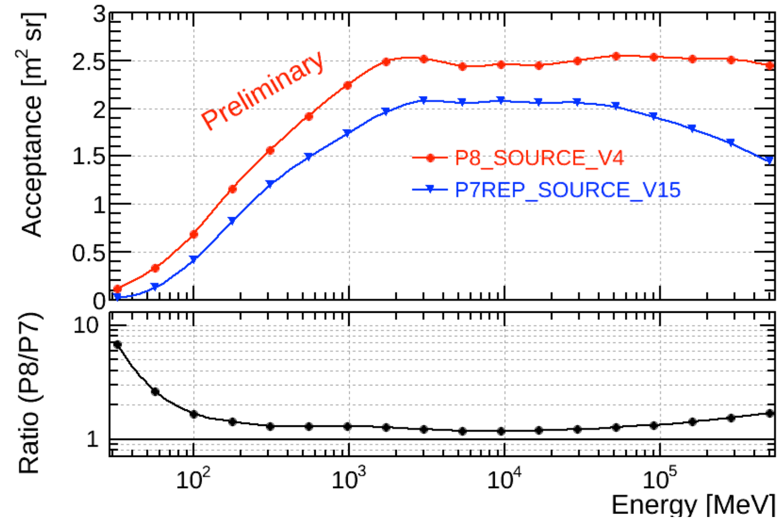


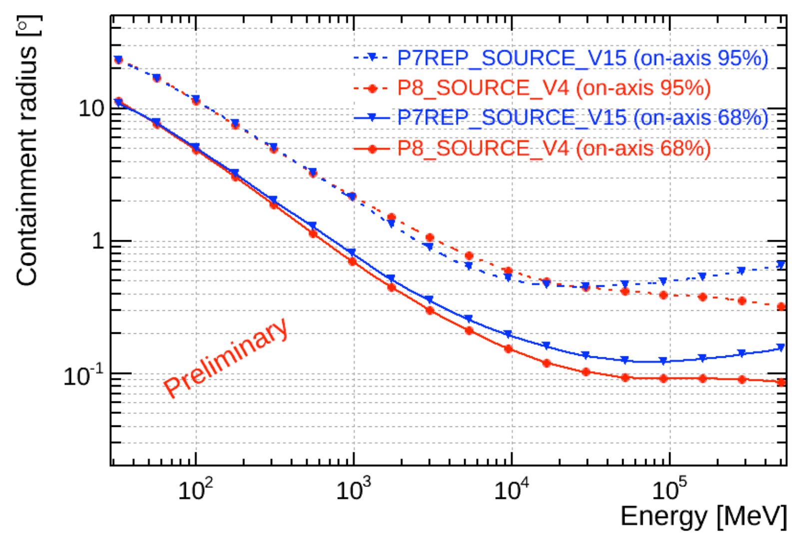
- One of the main improvements made in Pass 8 was the development of algorithms to identify and remove "ghosts"– out-of-time signals left by CRs that arrive just before a real gamma ray
- Ghost removal allows us to reconstruct gamma rays which would have been previously misidentified as background events

Pass 8: Improving the LAT Performance

- Many improvements relative to Pass 7
  - Increased point-source sensitivity at all energies (30-40% at 1-10 GeV)
  - Large increase in acceptance at very low and very high energies (< 100 MeV and > 100 GeV)
  - Better control of systematic uncertainties in the instrument response
  - New event classes which allow information about the event-wise reconstruction quality to be better utilized

- Impact on dark matter searches
  - Energy Range: Extend reach to lower and higher masses
  - Angular Resolution: Better sensitivity to angular extension





Fermi-LAT DM Search Targets

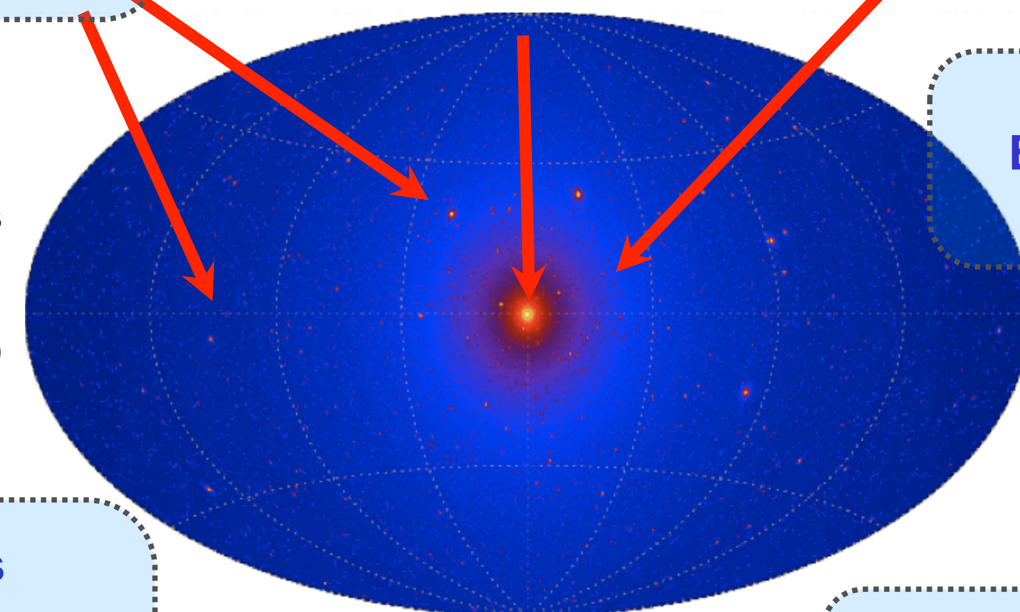
Satellites
Low background and good source id, but low statistics, astrophysical background

Galactic Center
Good Statistics but source confusion/diffuse background

Milky Way Halo
Large statistics but diffuse background

Cosmic-ray Electrons and Positrons

All-sky map of gamma rays from DM annihilation arXiv:0908.0195 (based on Via Lactea II simulation)



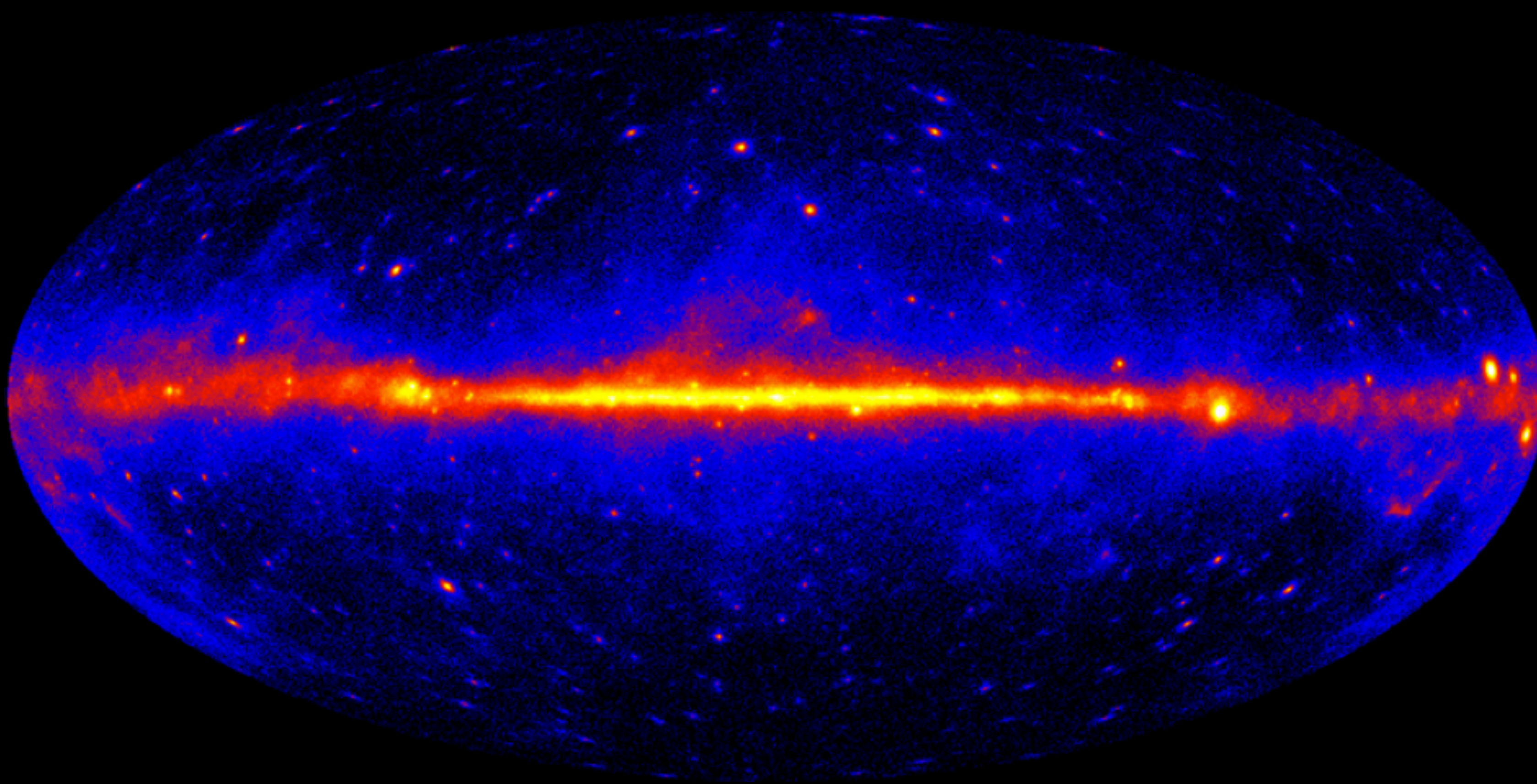
The Sun

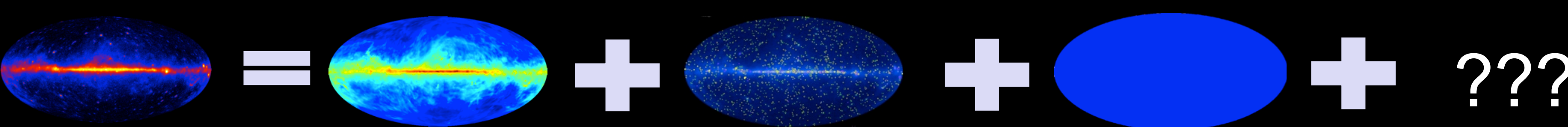
Spectral Lines
No astrophysical uncertainties, good source id, but low sensitivity because of expected small BR

Galaxy Clusters
Low background, but low statistics

Extragalactic
Large statistics, but astrophysics, galactic diffuse background

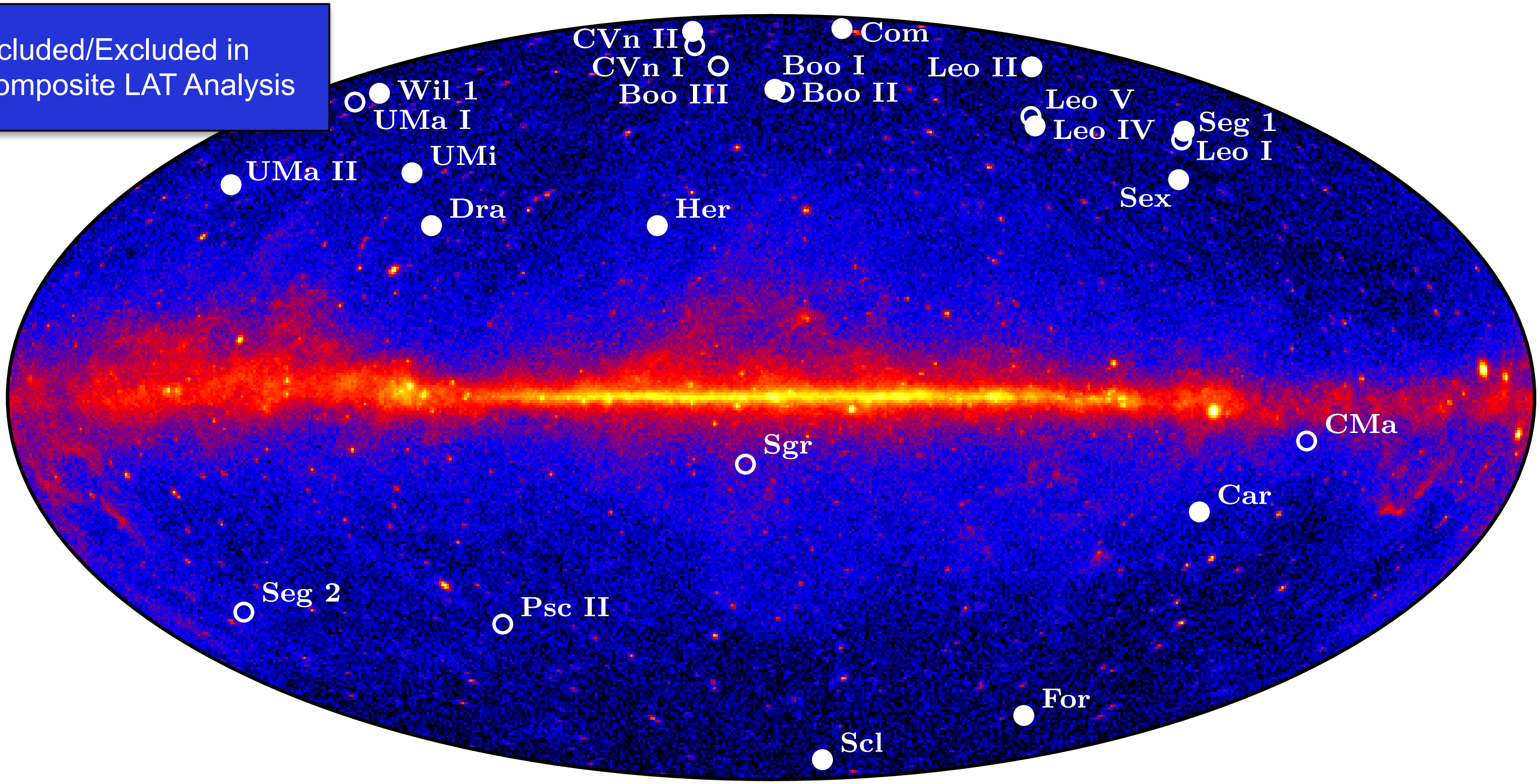
Searching for Dark Matter in the Gamma-ray Sky





Dwarf Spheroidal Galaxies

●/○ Included/Excluded in Composite LAT Analysis



Dwarf spheroidal galaxies (dSphs) are **dark** and highly **DM-dominated** systems
Most are found at high latitude where astrophysical foregrounds are low
Low backgrounds make these a very clean target for indirect DM searches

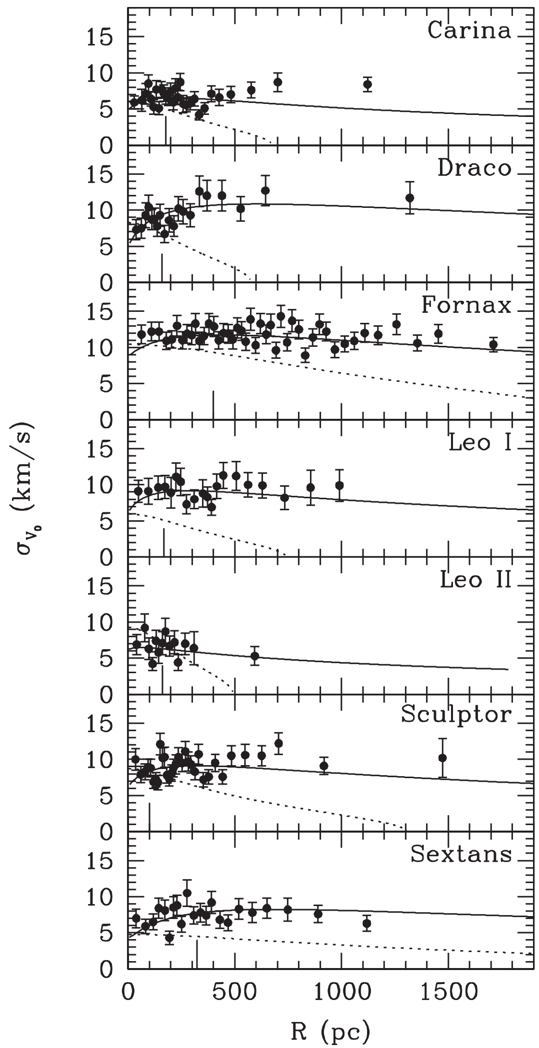
Measuring DM Content of dSphs

Gamma-ray signal from each dwarf is proportional to its **J-Factor:**

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

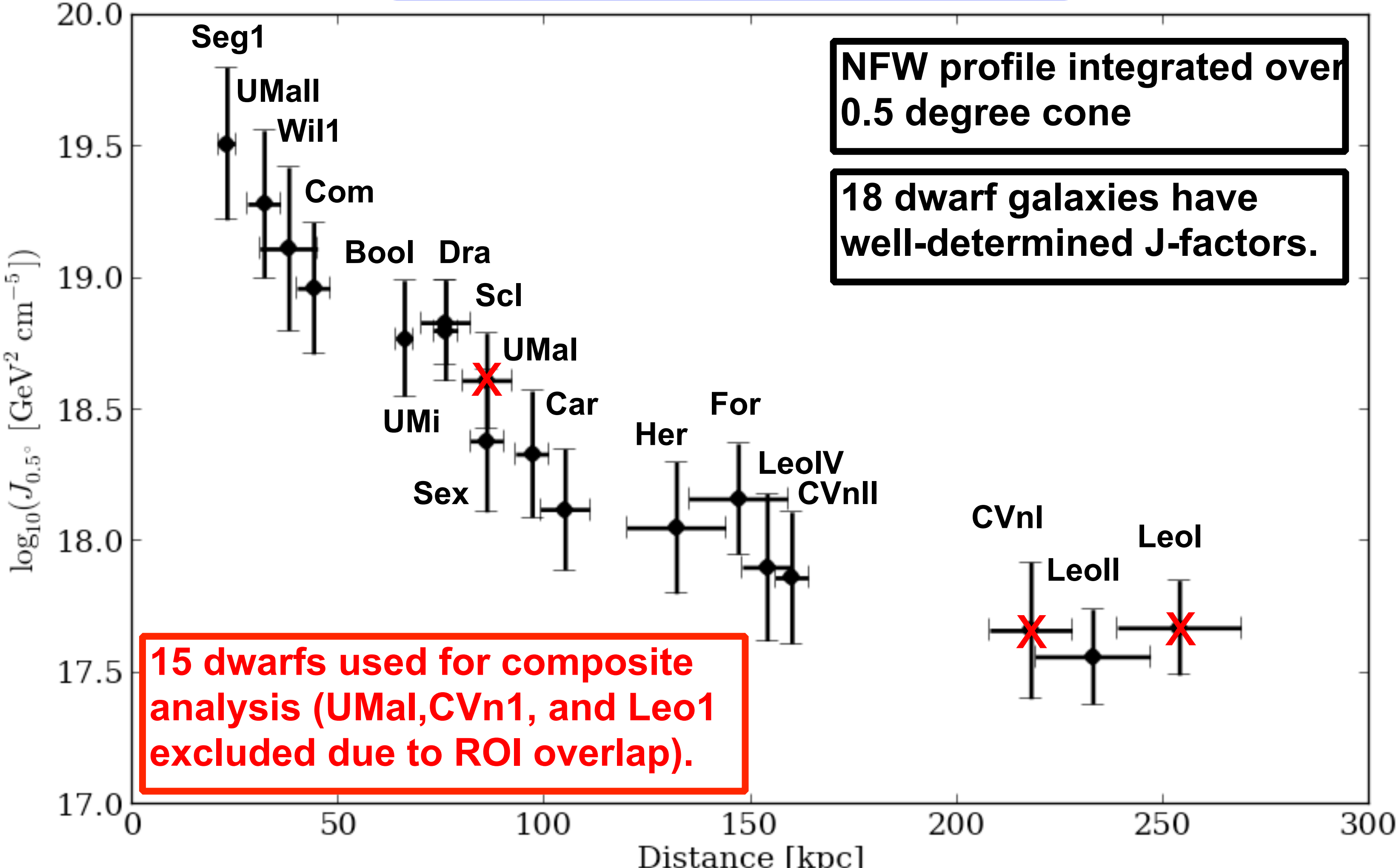
- Dwarf J-factors are determined **spectroscopically** from stellar velocity dispersions
  - Classical dwarfs: spectra for several thousand stars
  - Ultra-faint dwarfs: spectra for fewer than 100 stars
- Using the LOS velocity dispersion and an assumed DM density profile (NFW) we can calculate a J-factor for each dwarf (Martinez, 2013)
- Statistical uncertainty in the J-factor is folded into the gamma-ray analysis

Walker et al. 2007

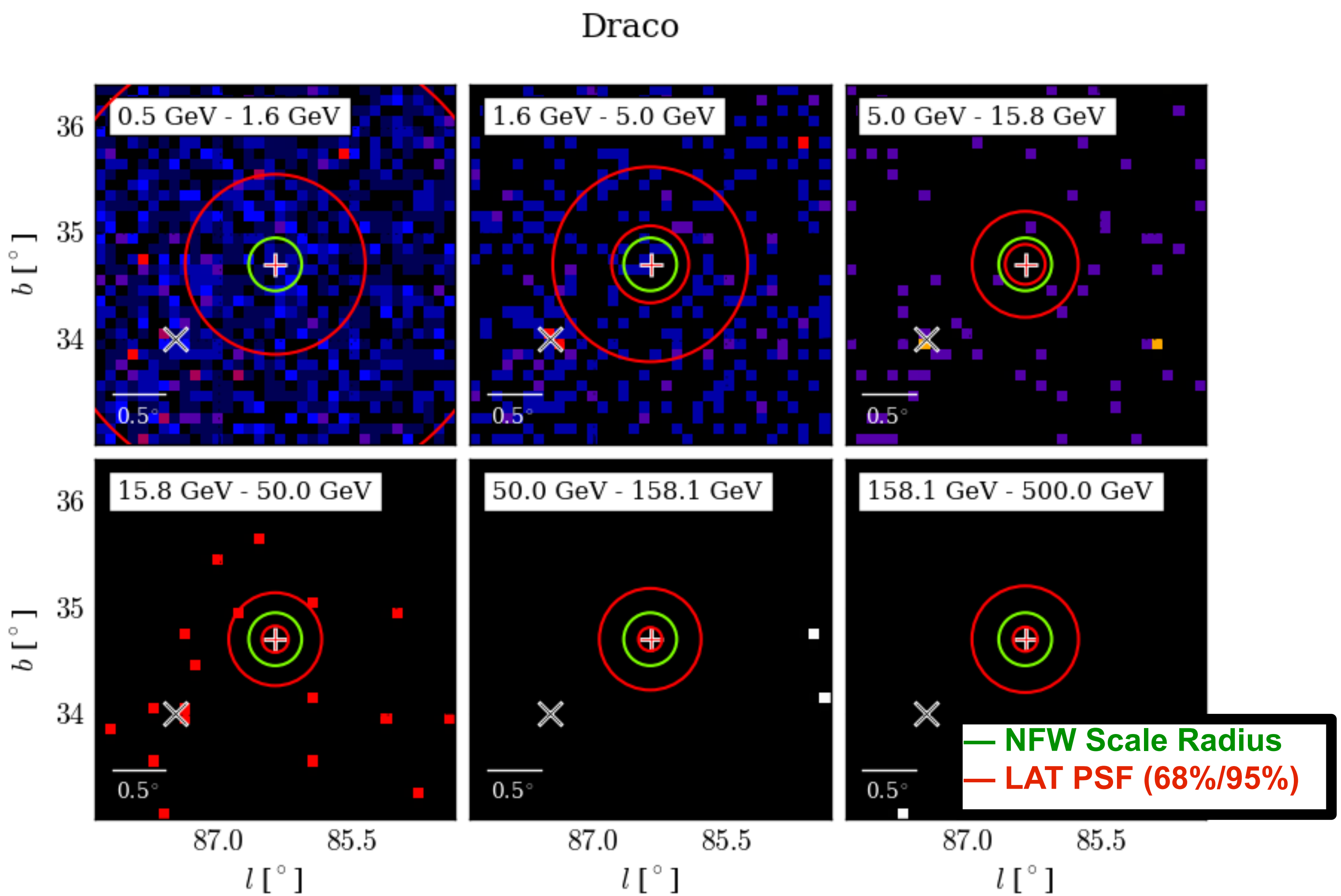


J-Factors for 18 Dwarf Galaxies

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



Gamma-ray Count Maps



Joint Likelihood Analysis

A **joint likelihood analysis** provides the most sensitive technique to test the hypothesis of a common DM signal in our sample of dwarf galaxies

Joint DM Likelihood

Product of LAT DM Likelihoods for each target k (15 dwarfs total)

$$L(D \,|\, \mathbf{p_m}, \{\mathbf{p_k}\}) = \prod_k L_k^{\mathrm{LAT}}(D_k \,|\, \mathbf{p_m}, \mathbf{p_k})$$

$$\times \frac{1}{\ln(10) J_k \sqrt{2\pi}\sigma_k} e^{-(\log_{10}(J_k) - \overline{\log_{10}(J_k)})^2 / 2\sigma_k^2}$$

Dark Matter Particle Parameters
(shared by all dwarfs)

Background Nuisance Parameters
(fit individually for each dwarf)

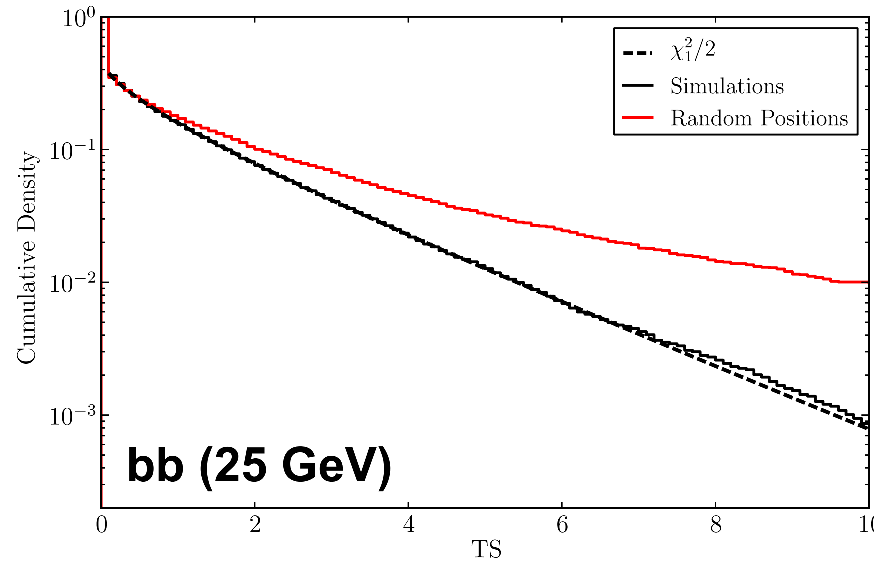
Uncertainty in J-factor

P7REP Dwarf Stacking Analysis

Ackermann et al. PRD 89 042001 (2014), arXiv: 1310.0828

- Ackermann+ 2014 is the most recent publication from the LAT collaboration on dwarf stacking using the **P7REP** data release and **four years** of LAT data
- Validity of the P7REP analysis was cross-checked by running the same analysis on a large number of randomized **control regions** in which no DM signal was expected
- Ackermann+ 2014 found a significant deviation between the control region TS distribution and the one expected from simulations
- Several explanations were postulated for this deviation
  - Error in diffuse model
  - Unresolved/Unmodeled point sources
  - Systematic uncertainties in the instrument response

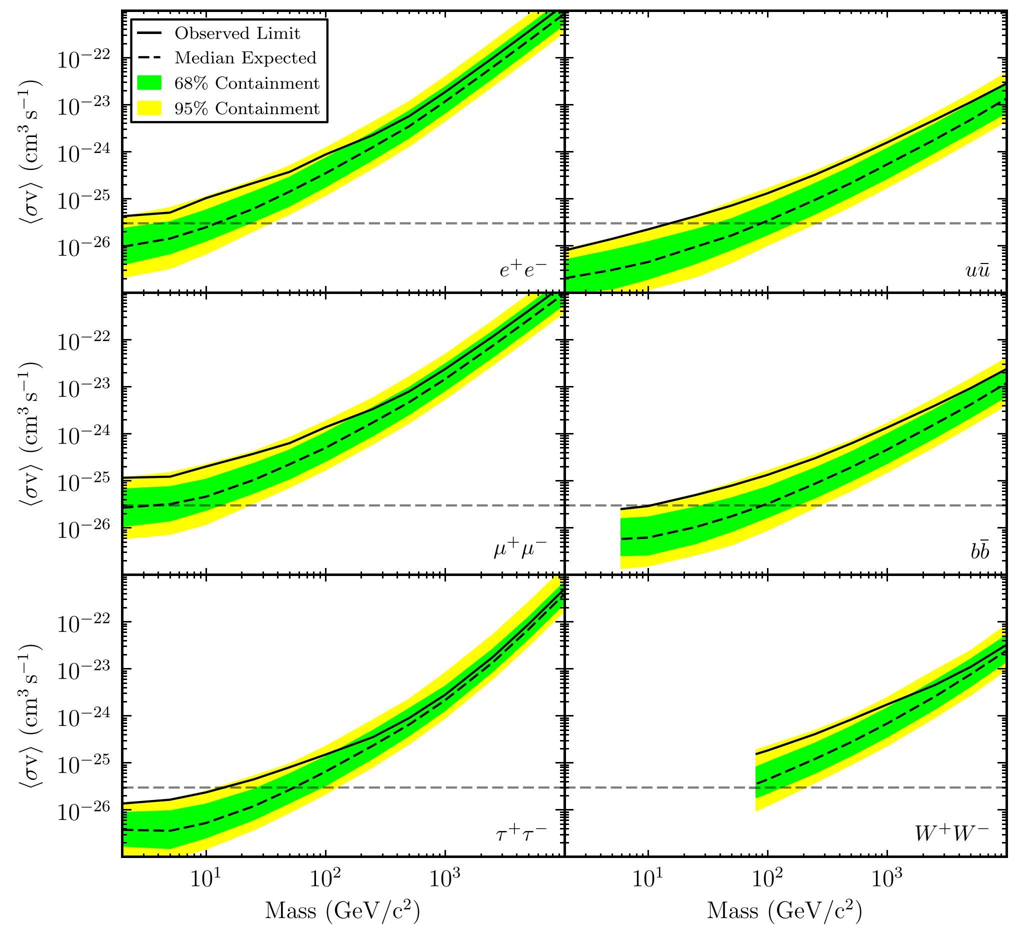
Randomized Control Region TS Distribution



P7REP Dwarf Stacking Analysis

Ackermann et al. PRD 89 042001 (2014), arXiv: 1310.0828

- No detection in 4 years of LAT data
- Largest excess with TS=8.7 observed at 25 GeV for the bb channel
  - **Local Significance (Sims):** 2.95σ (p=1.6x10^{-3})
  - **Global Significance (Sims):** 2.05σ (p=0.02)
  - **Global Significance (Data):** 1.41σ (p=0.08)
- Upper limit expectation bands computed from analysis of randomized high-latitude control regions
- Upper limits exclude WIMP models with the thermal relic cross section and M < 10 GeV



Pass 8 Dwarf Stacking Analysis

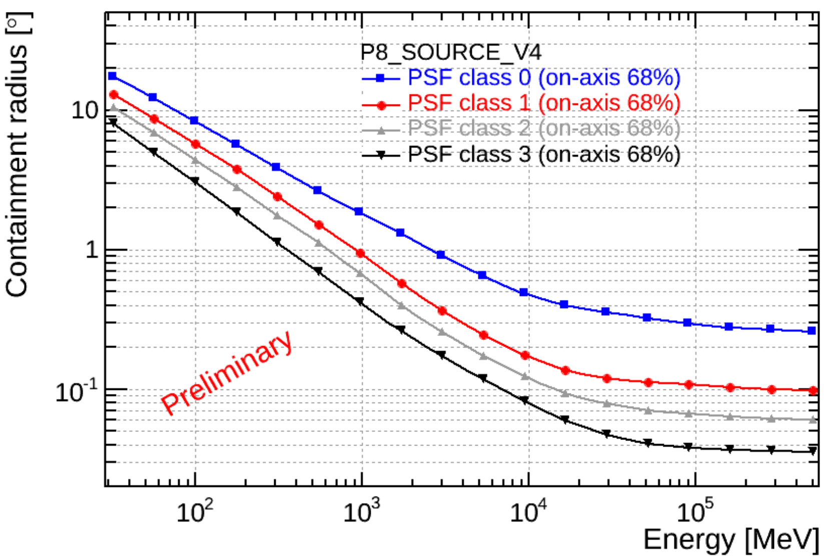
- **Pass 8 Dwarf Analysis:** Apply the same methodology developed in Ackermann+ 2014 to Pass 8 data
  - Composite likelihood with 15 dwarfs
  - P8SOURCE event selection with 5 years of data and events with reconstructed energy between 562 MeV and 316 GeV
  - Likelihood for each dwarf is composed of a joint likelihood with four PSF event subclasses

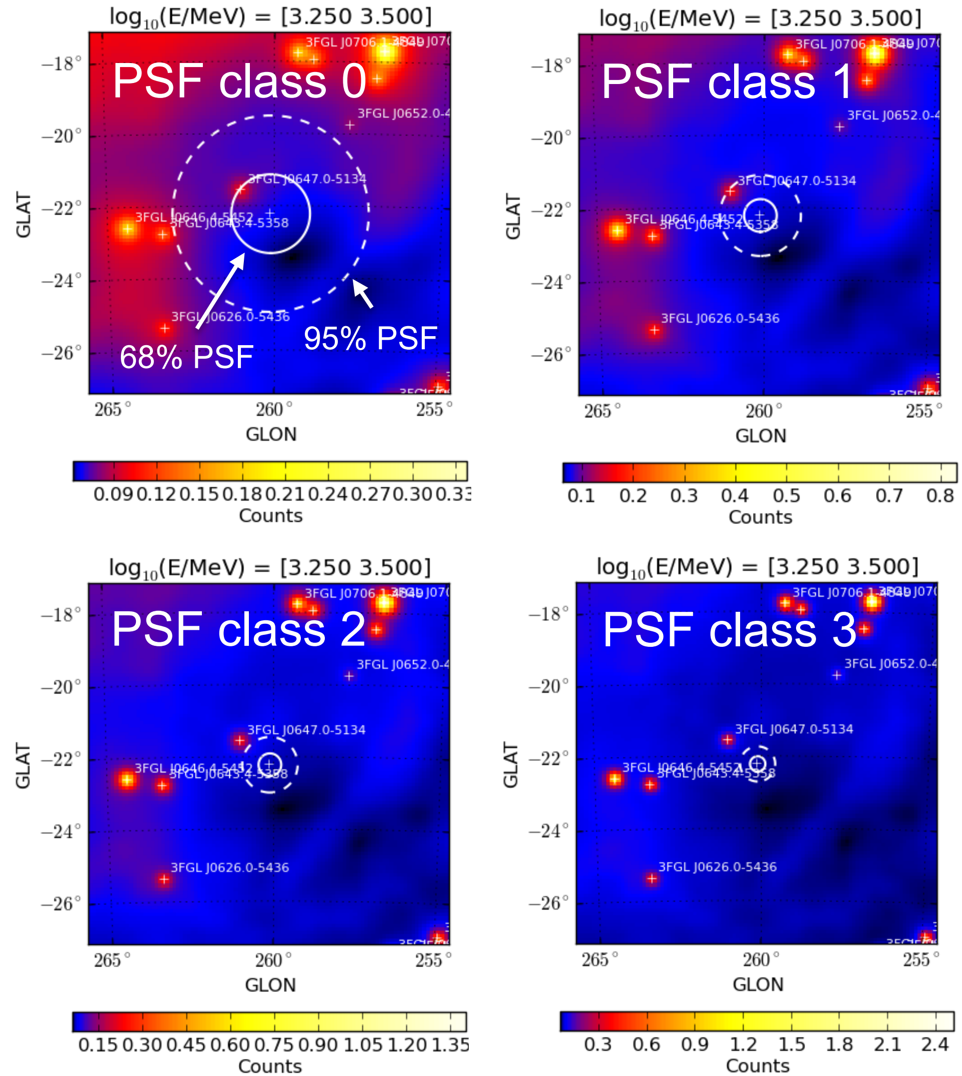
- Pass 8 Dwarf Stacking Analysis improves on the Pass 7 analysis in several respects
  - **Improved Event Reconstruction:** Pass7 → Pass8
  - **Larger Data Sample:** 4 → 5 years
  - **Improved Background Model:** 2FGL→ 3FGL
  - **New Likelihood Technique:** Events weighted by quality of their angular reconstruction (PSF event classes)

Pass 8 Joint Likelihood with PSF Event Classes

In the Pass8 analysis events are weighted according to the quality of their angular reconstruction in four subclasses

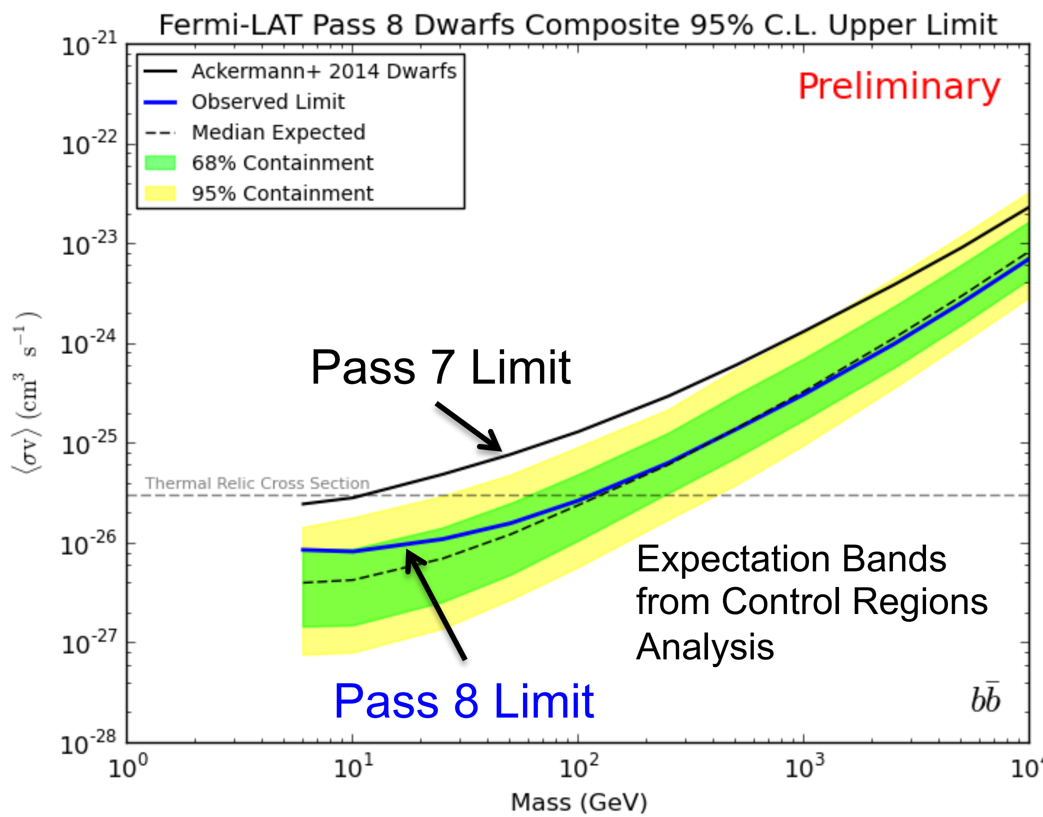
This provides an additional handle by which DM signals can be discriminated from diffuse and point-like backgrounds



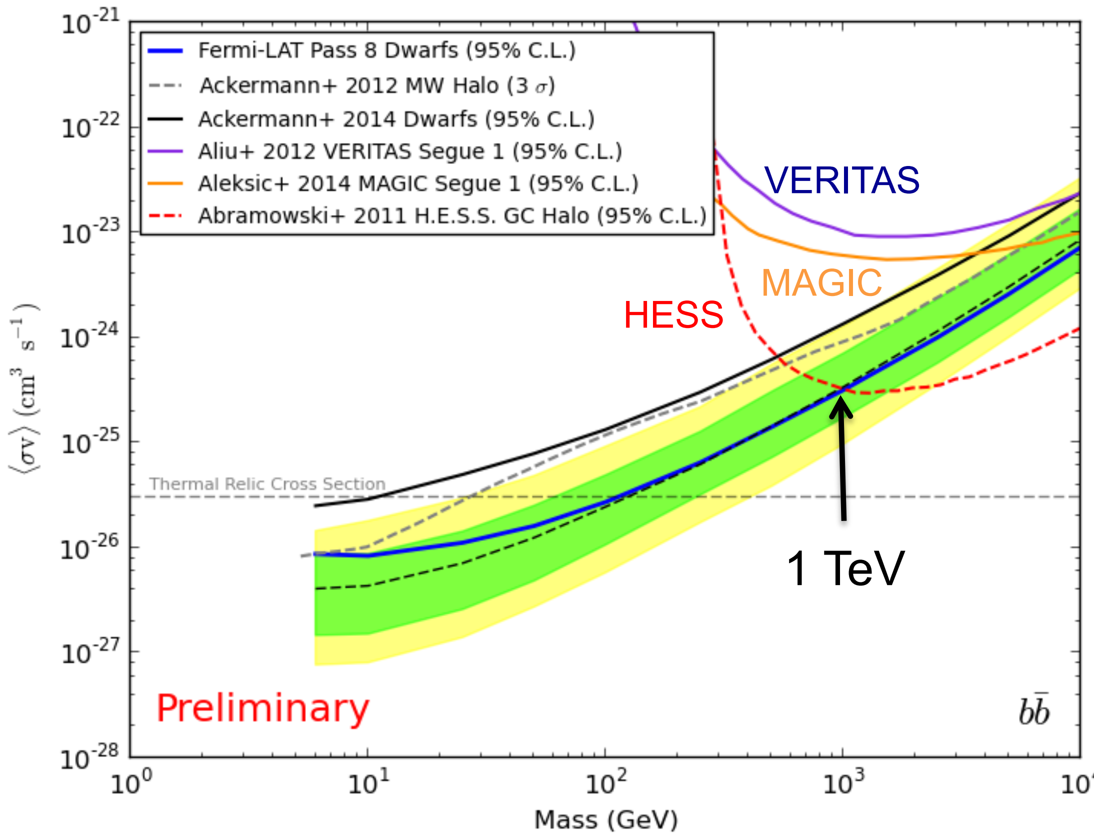


Results for the Pass 8 Composite Analysis

- No significant detections for any mass or annihilation channel
- Largest excess for the bb annihilation channel (TS=0.84) occurs for M = 6 GeV
- Observed limits are in good agreement with expectation bands from randomized control regions
- Pass 8 limits improve on Pass 7 limits (Ackermann + 2014) by a factor of 2-4



Comparison with IACT DM Limits

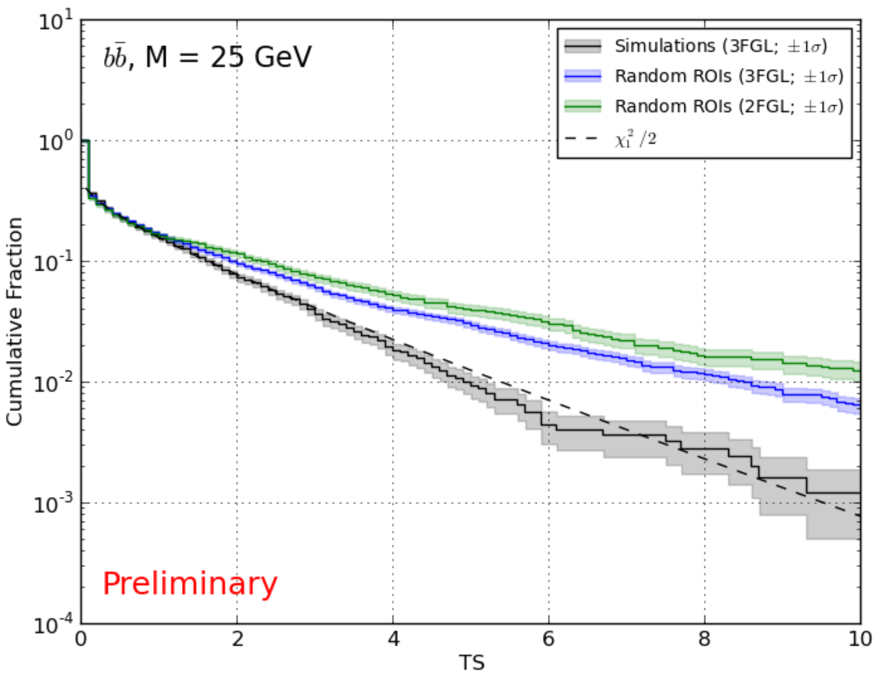


- DM Limits from the LAT Dwarf Stacking analysis are highly competitive with those provided by ground-based gamma-ray observatories (HESS, MAGIC, and VERITAS)
- LAT Dwarf limits are more constraining for WIMP models with mass below 1 TeV

Analysis of Randomized Control Regions

- Pass 8 analysis confirms the deviation in the TS distribution reported in Ackermann+ 2014
  - Frequency of large TS values in randomized control regions is found to be significantly greater than expected from simulations
- We have also conducted a comparative analysis with different point-source catalogs
  - 2FGL (1873 sources; 2-year catalog)
  - 3FGL (3033 sources; 4-year catalog)
- Our analysis indicates that unmodeled point sources are at least a partial contributor to the deviation in the TS distribution

Randomized Control Region
TS Distribution (Pass 8)



Systematics

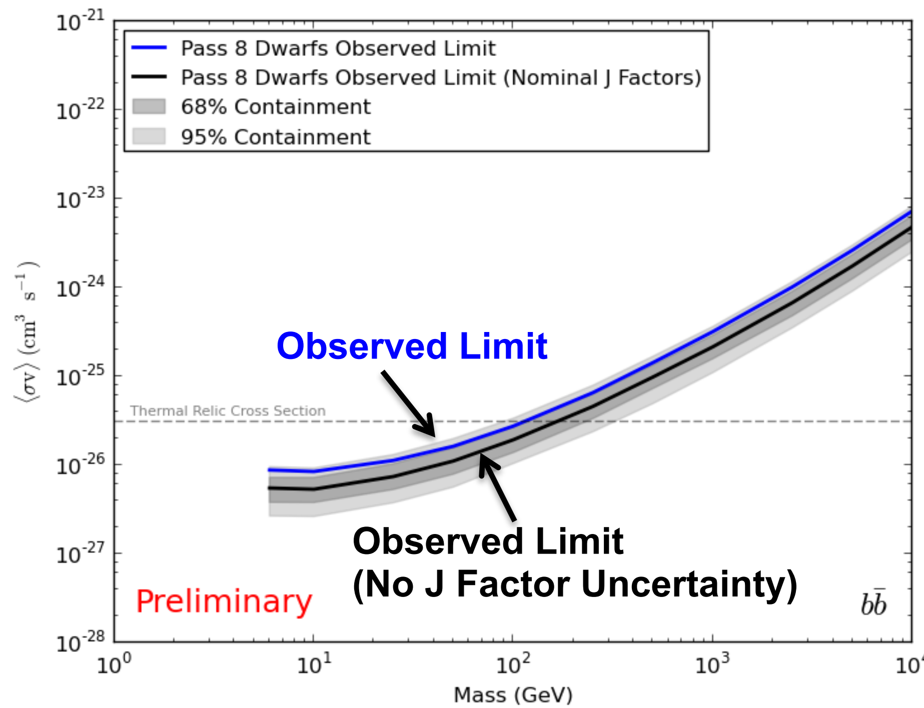
- Comprehensive investigation of systematics was performed that considered the uncertainties in the following:
  - **Diffuse Background Models**
  - **Instrument Response**
  - **Dwarf Astrophysical Factors**

- Uncertainties from diffuse modeling and instrument response affect the limits at the 5-10% level

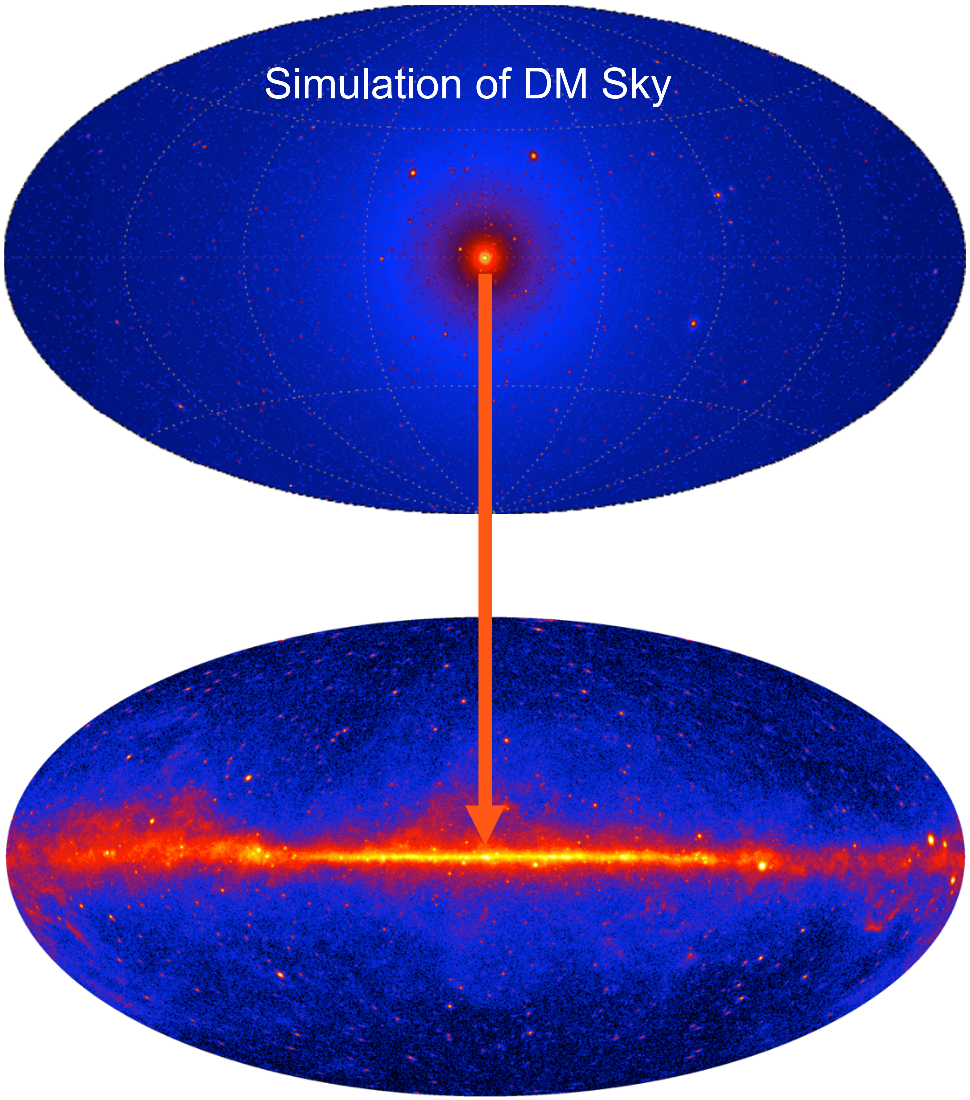
- Largest uncertainties enter in the determination of the astrophysical factors
  - Uncertainty on J factors is already incorporated into limit calculation procedure but assumes dwarfs are well described by an NFW profile
  - A cored DM profile (Burkert) would worsen our limits by an additional 20%

Impact of J factor Uncertainties

- Astrophysical J Factors enter linearly in the expected signal amplitude and their uncertainty is an important consideration when evaluating DM upper limits
- Large range in J factor uncertainties in the dwarf sample
  - 0.15-0.20 dex (classical dwarfs)
  - 0.2-0.3 dex (ultra-faint dwarfs)
- We treat the J factors as additional **nuisance parameters** in the likelihood analysis and profile over them when evaluating the DM test statistic
- Incorporating the J factor uncertainty worsens our limits relative to what we would obtain if we knew the J factors perfectly



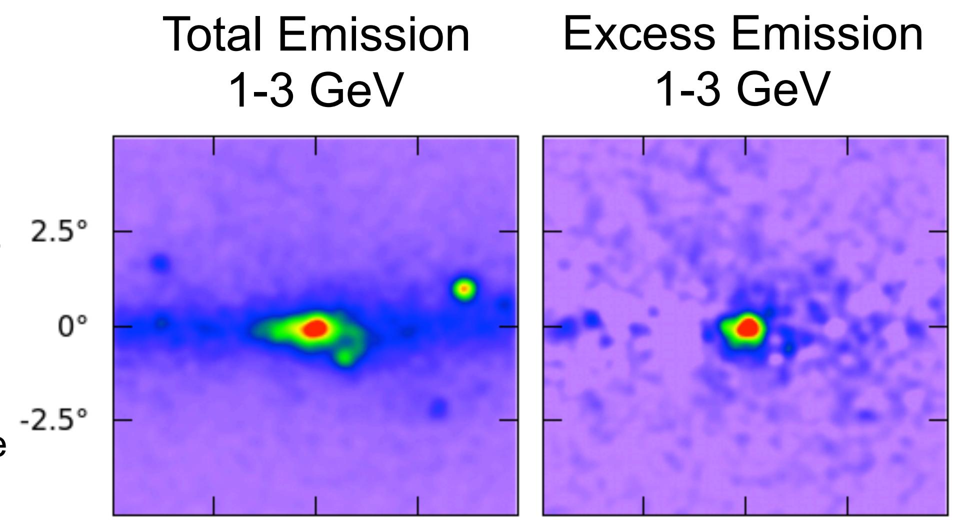
Comparison of dSph Limits with the Inner Galaxy

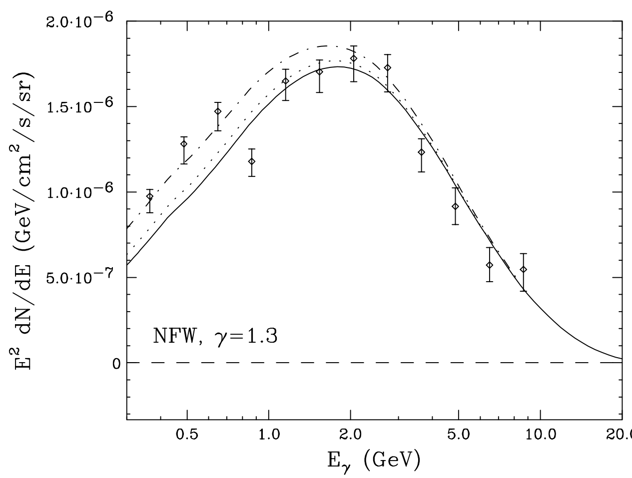


- The center of the Galactic dark matter halo is a promising target
  - Deep gravitational potential
  - Relatively nearby
- However, it is extremely complicated
  - Diffuse emission from cosmic-ray interactions with Galactic gas and dust
  - Densely populated by astrophysical sources (e.g., pulsars, SNR)
  - Detected in other wavelengths (e.g., radio, X-ray, TeV)
- Dwarf Spheroidal Galaxies are a powerful consistency check for DM signals in the Galactic center
  - A WIMP signal in the GC should also appear in dwarf spheroidal galaxies with the same mass and cross section
  - Relatively small uncertainty on the astrophysical factors (unlike the GC)

GeV Excess in the Galactic Center?

- Many recent papers report the detection of a diffuse gamma-ray excess in the Galactic Center (GCE) in LAT data; see e.g. Goodenough & Hooper 2009, Abazajian & Kaplinghat 2012, Gordon & Macias 2013, Daylan+ 2014, Abazajian+ 2014, Calore+ 2014
- SED peaks at 1-3 GeV but with large systematic uncertainties on its precise spectral shape (Abazajian+ 2014, Calore + 2014)
- Spherically symmetric spatial distribution extending at least 10-20 degrees above and below the plane (Daylan+ 2014, Calore+ 2014)
- Spatial and spectral properties are robust to changes in the assumed galactic diffuse emission model (Calore+ 2014)





Daylan+ 2014, 1402.6703

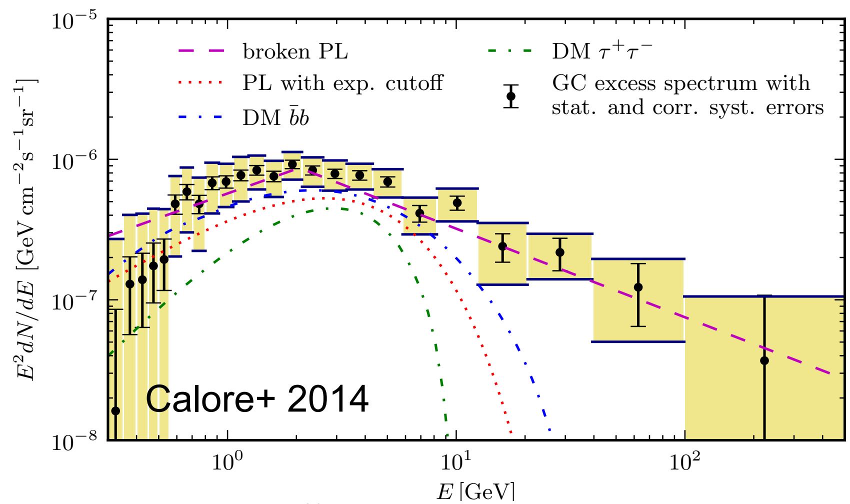
GCE WIMP Interpretation

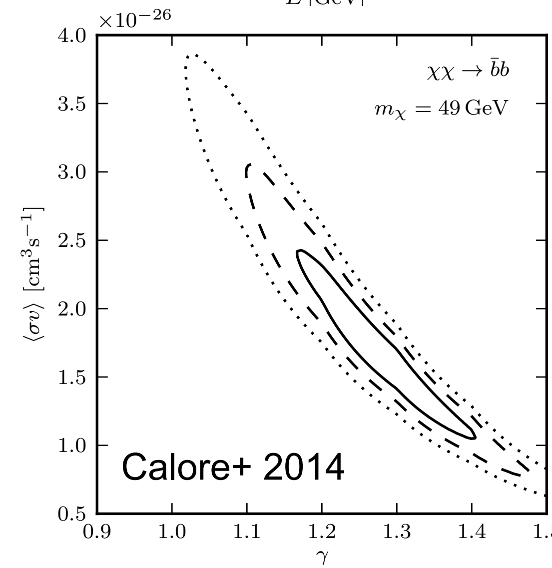
- WIMP annihilations in the MW halo have been suggested as an potential model for the GCE

- Spectrum and morphology of the GCE has been reported to be consistent with the signal of WIMP annihilations in the MW halo

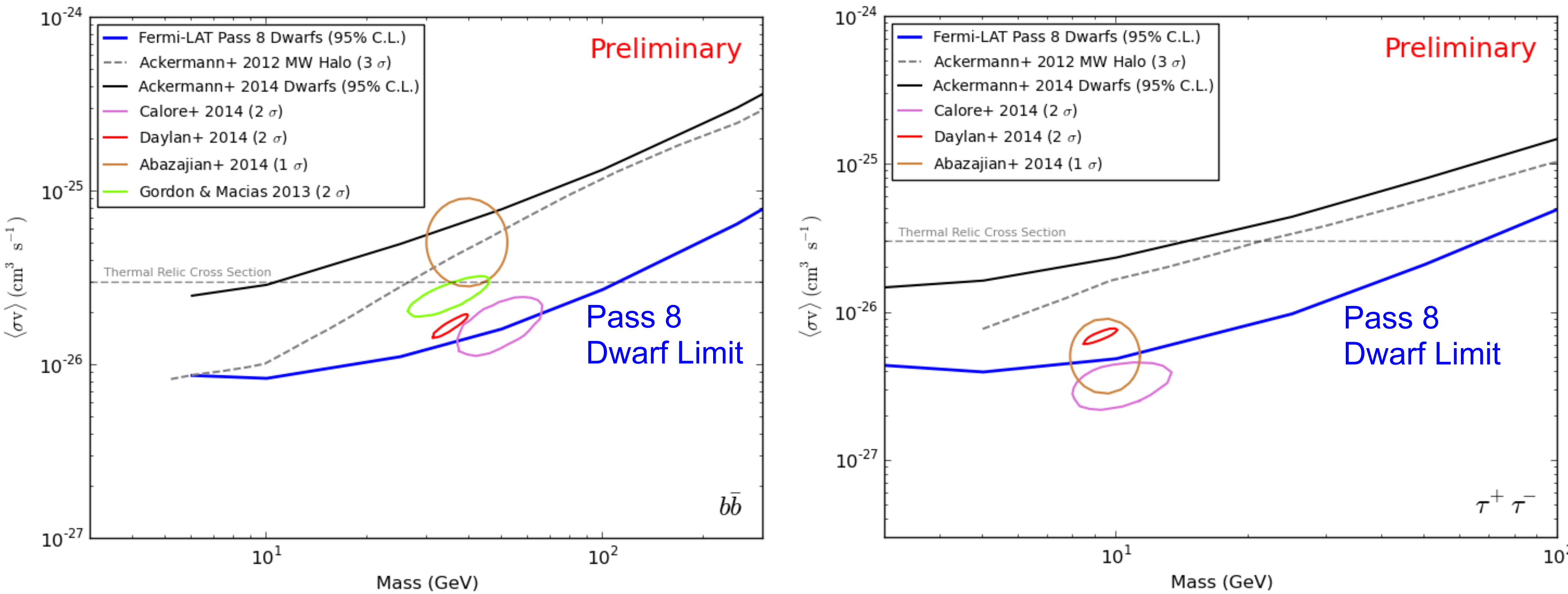
- Spectrum can be well fit by either quark (M=30-60 GeV) or tau lepton (M=5-15 GeV) annihilation spectrum

- Spatial profile can be modeled with a generalized NFW profile with inner slope of 1.1-1.4

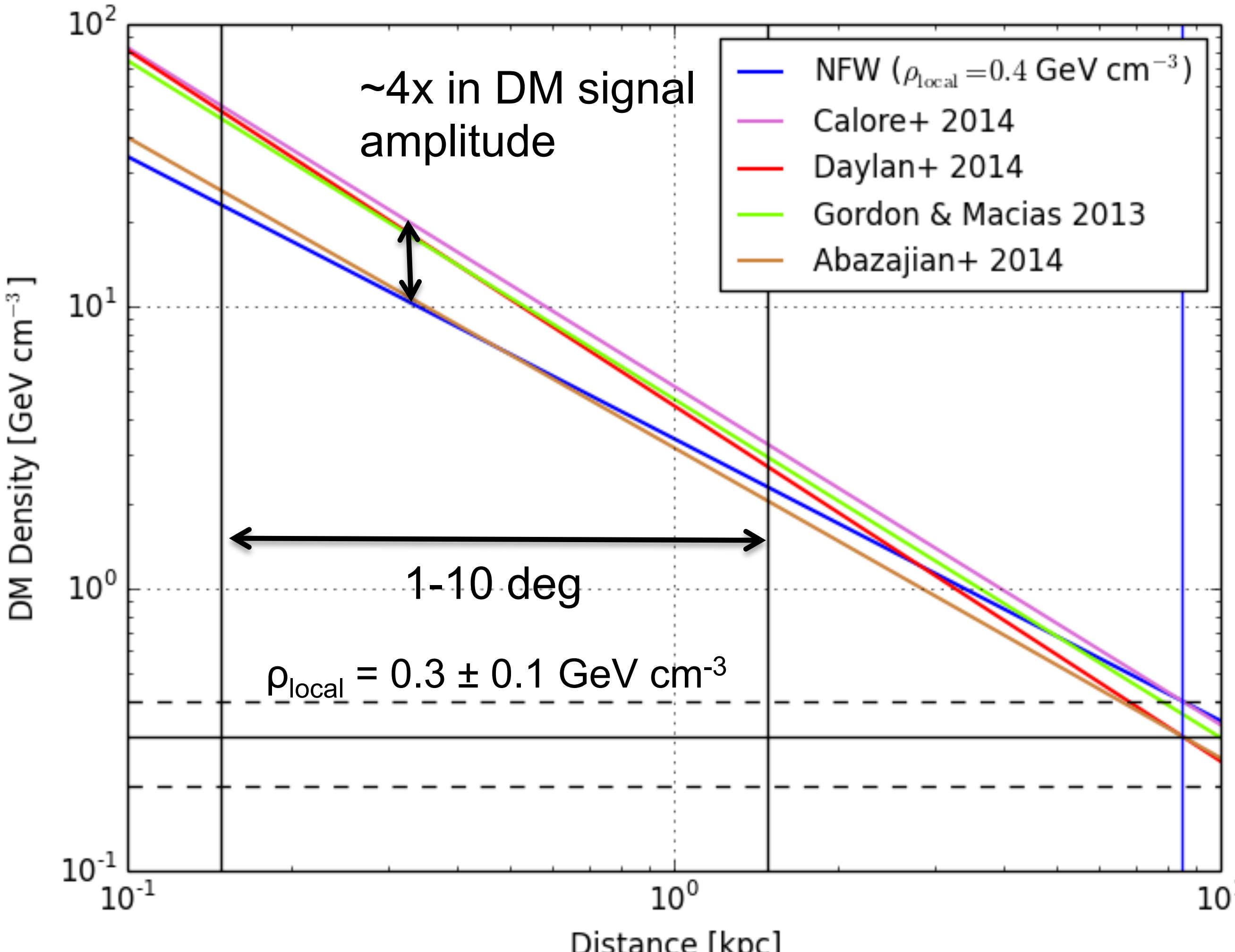




Consistency of the GCE WIMP with Pass 8 Dwarf Limits



Uncertainty from the MW Halo



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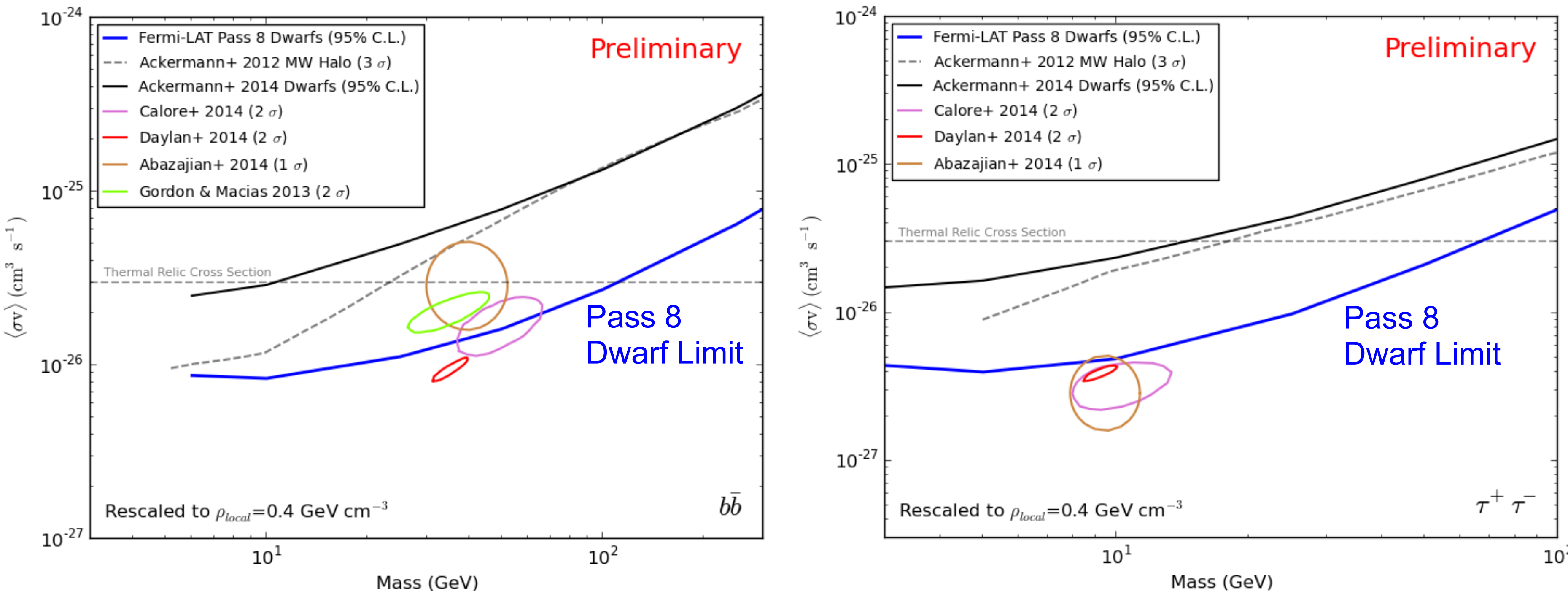

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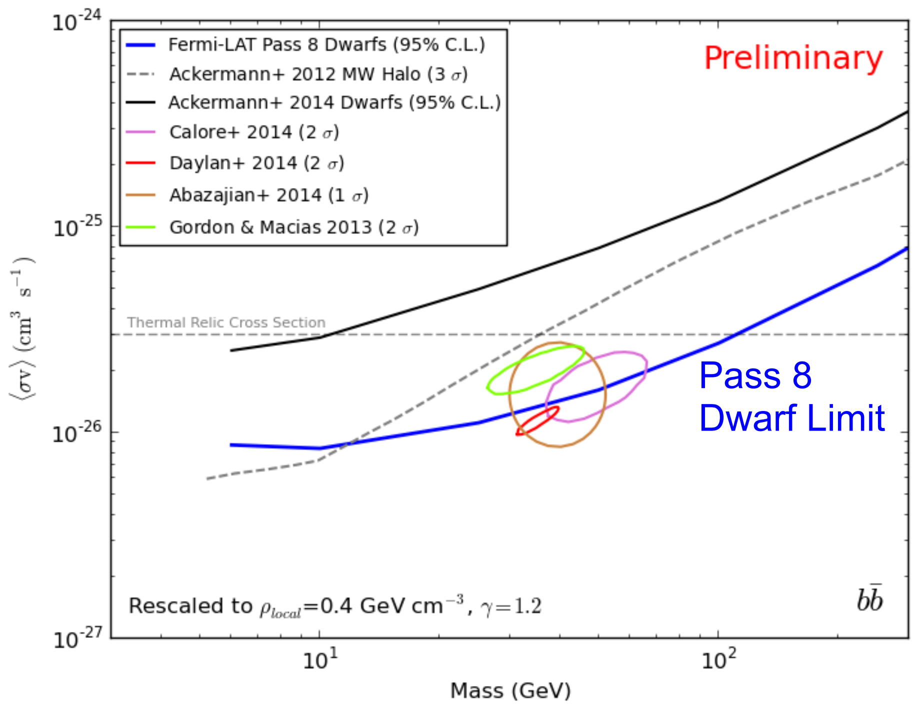
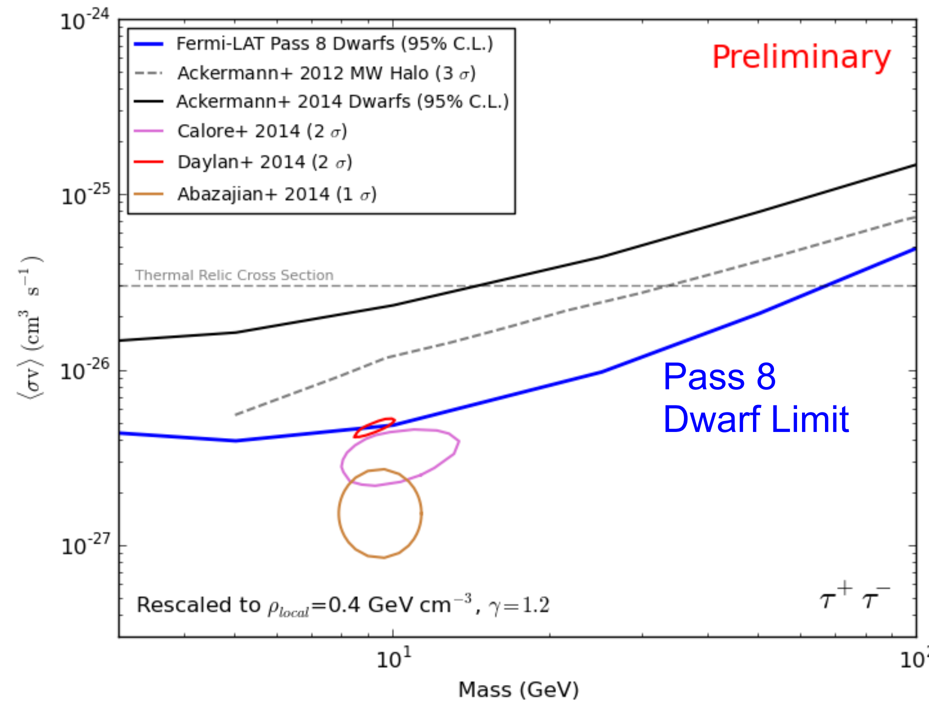




Implications for WIMP Interpretations of the GCE

- Mild tension now exists between the Fermi-LAT Dwarf Limits and WIMP interpretations of the GCE
  - Some freedom in the normalization of GCE cross sections is allowed by changing the MW density profile
  - Pass 8 dwarf limits may point to a MW density profile with a steeper inner slope (> 1.2) or a local DM density at the upper end of the allowed range (0.4-0.5 GeV cm^{-3})

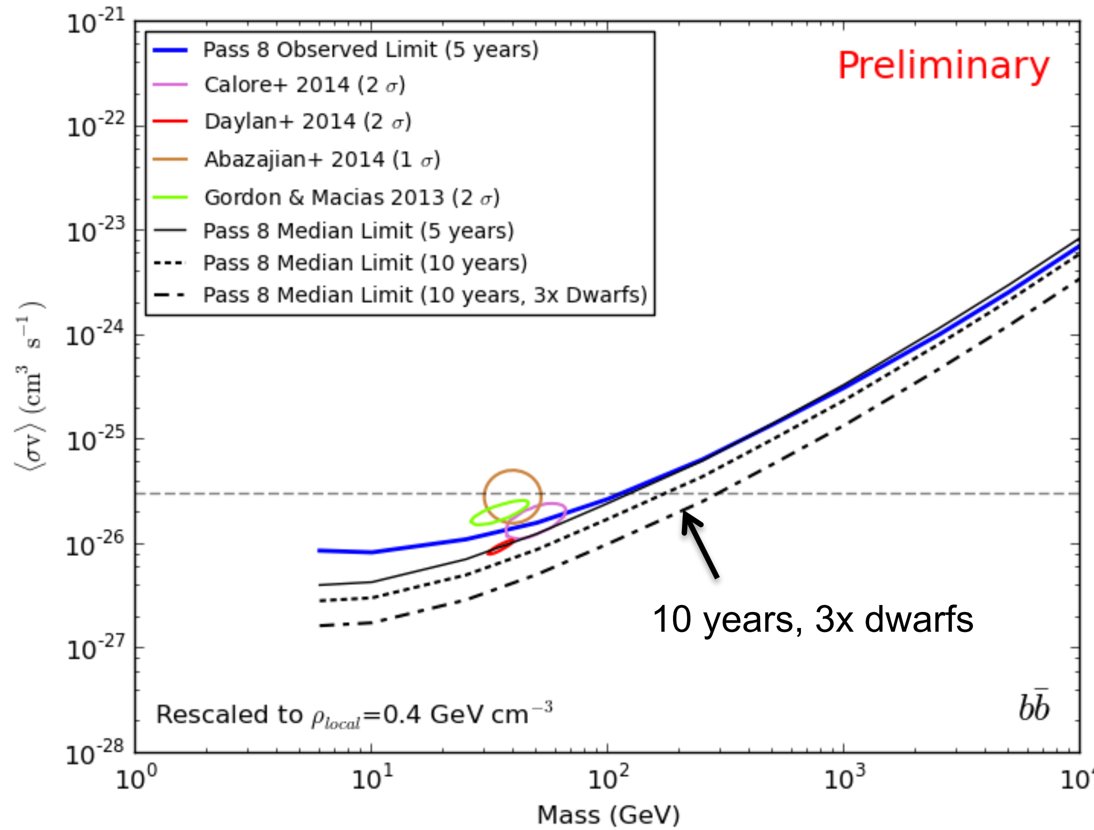
- May also point to an astrophysical explanation
  - Population of unresolved MSPs (Abazajian+ 2011, Abazajian & Kaplinghat 2012)
  - Systematic uncertainties in the modeling of the standard astrophysical production mechanisms in the ISM

Projected Dwarf Stacking Limits

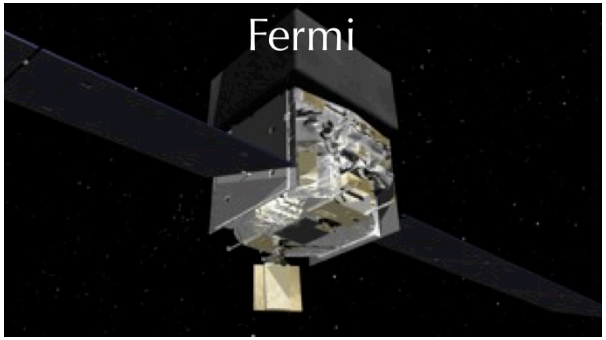
- Future analyses will improve primarily in two areas
  - **More Data**: Fermi-LAT is anticipated to operate for at least 10 years (formally approved through 2016)
  - **Larger Dwarf Sample**: Future optical surveys (DES, LSST) will enlarge the sample of dwarf galaxy targets

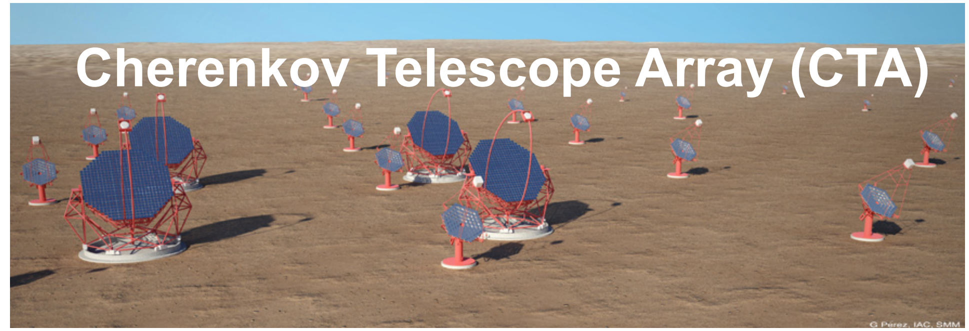
- Projected Limits with 10 years of data and 3x more dwarfs should conclusively confirm or exclude the WIMP interpretation of the GCE

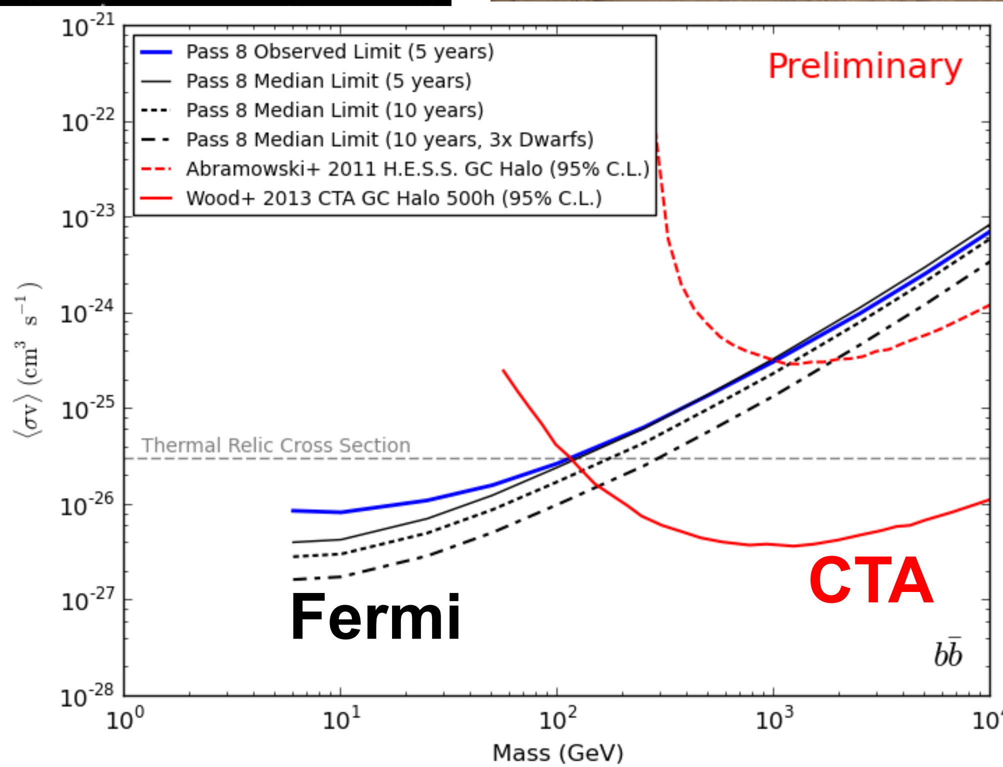
DARK ENERGY SURVEY



Future for Gamma-ray DM Searches



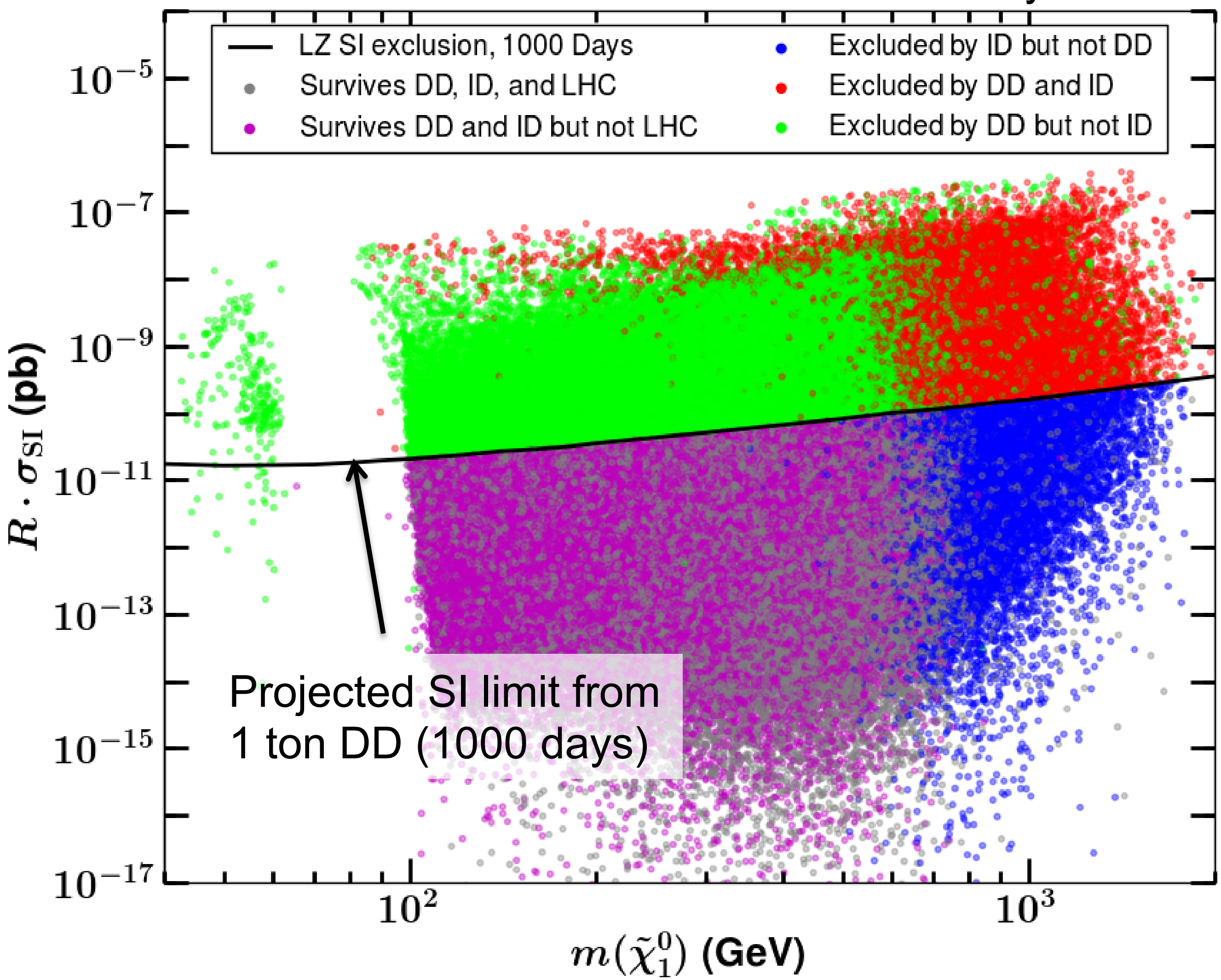




Together Fermi and CTA will probe the entire space of WIMP models with thermal relic annihilation cross section

Complementarity of DM Searches

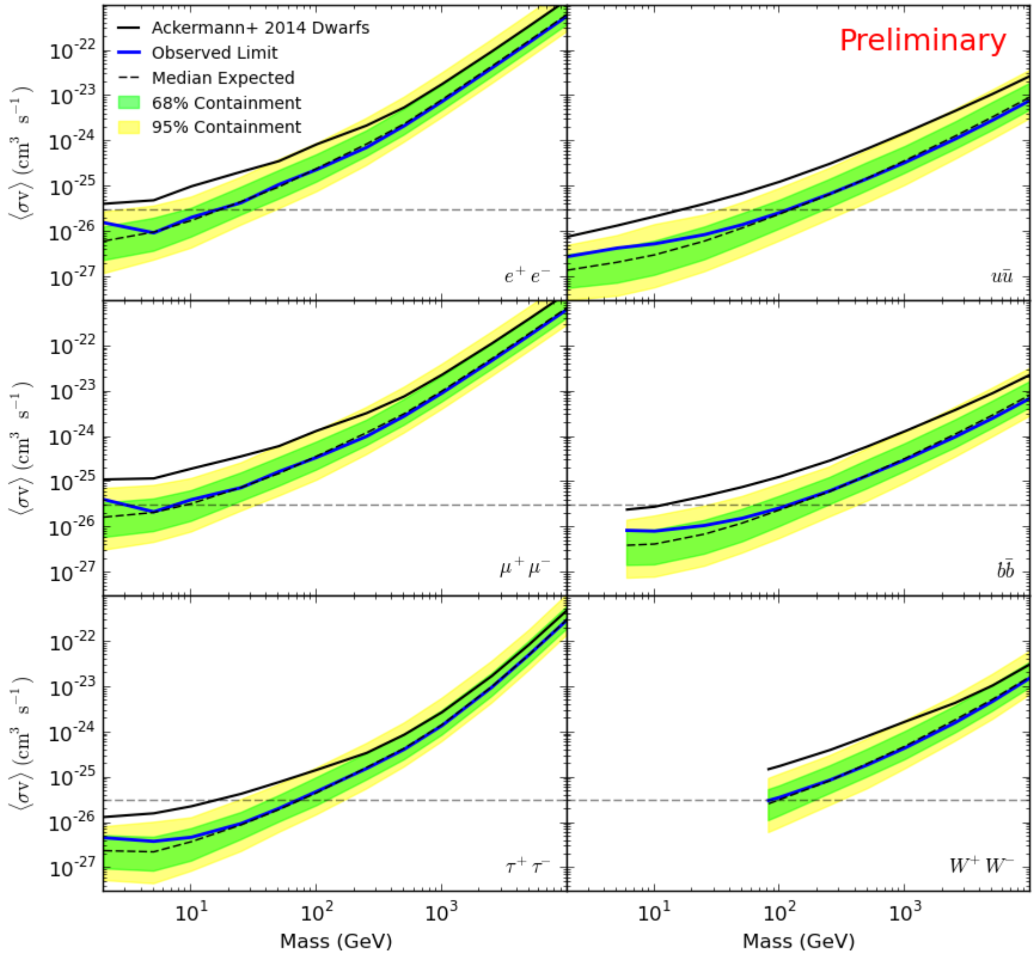
Cahill-Rowley+ 2014



Summary/Conclusions

- LAT Pass 8 dwarf analysis provides robust constraints on the annihilation cross section of the WIMP
  - Improve on previously published LAT limits by a factor of 2-4
  - Probe new phase space for thermal relic WIMP models with mass less than 100 GeV
- LAT Pass 8 dwarf limits are in mild tension with the WIMP interpretation of the GCE
- Further improvement in sensitivity can be expected with the addition of new dwarfs discovered in optical surveys (DES,LSST) which should allow the GCE WIMP interpretation to be conclusively excluded (or confirmed)
- Future indirect DM searches with both Fermi and CTA will continue to explore interesting parts of the WIMP DM phase space

All Annihilation Channels



Comparison with IACT DM Limits