Fermi
Gamma-ray Space Telescope

Indirect Dark Matter Searches with the Fermi Large Area Telescope

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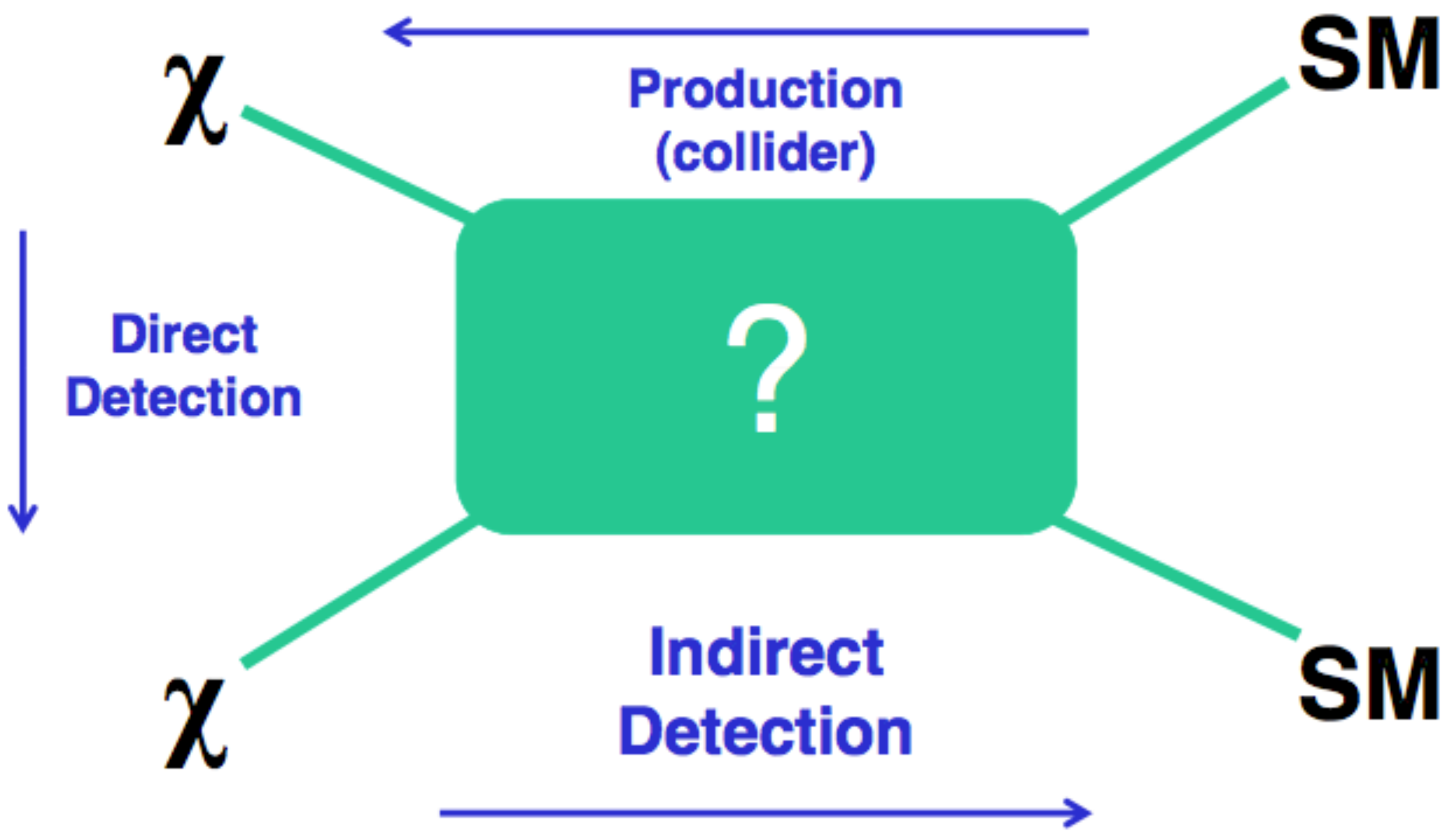
on behalf of the Fermi-LAT Collaboration

Mitchell Workshop
College Station, Texas
May 25th, 2016

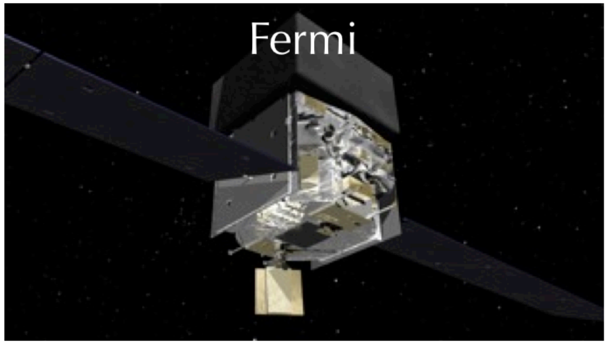
SLAC NATIONAL ACCELERATOR LABORATORY

KIPAC

Dark Matter Searches

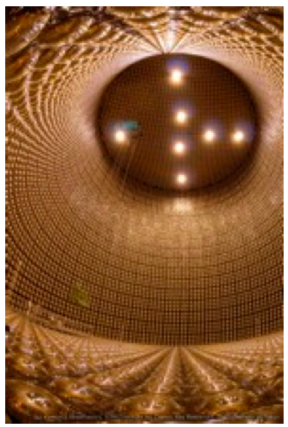


Indirect Dark Matter Searches

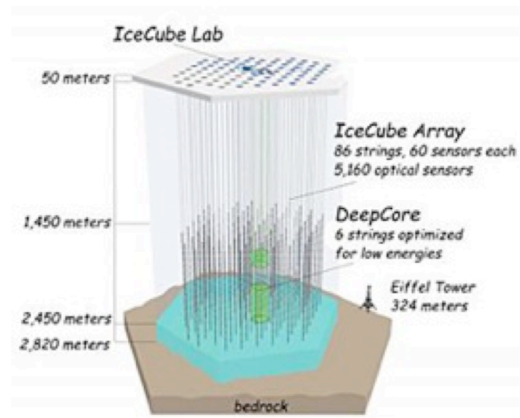


γ

Super-K



ν



ICECUBE

PAMELA

$$e^-, e^+, p, \bar{p}$$

AMS

Fermi Observatory

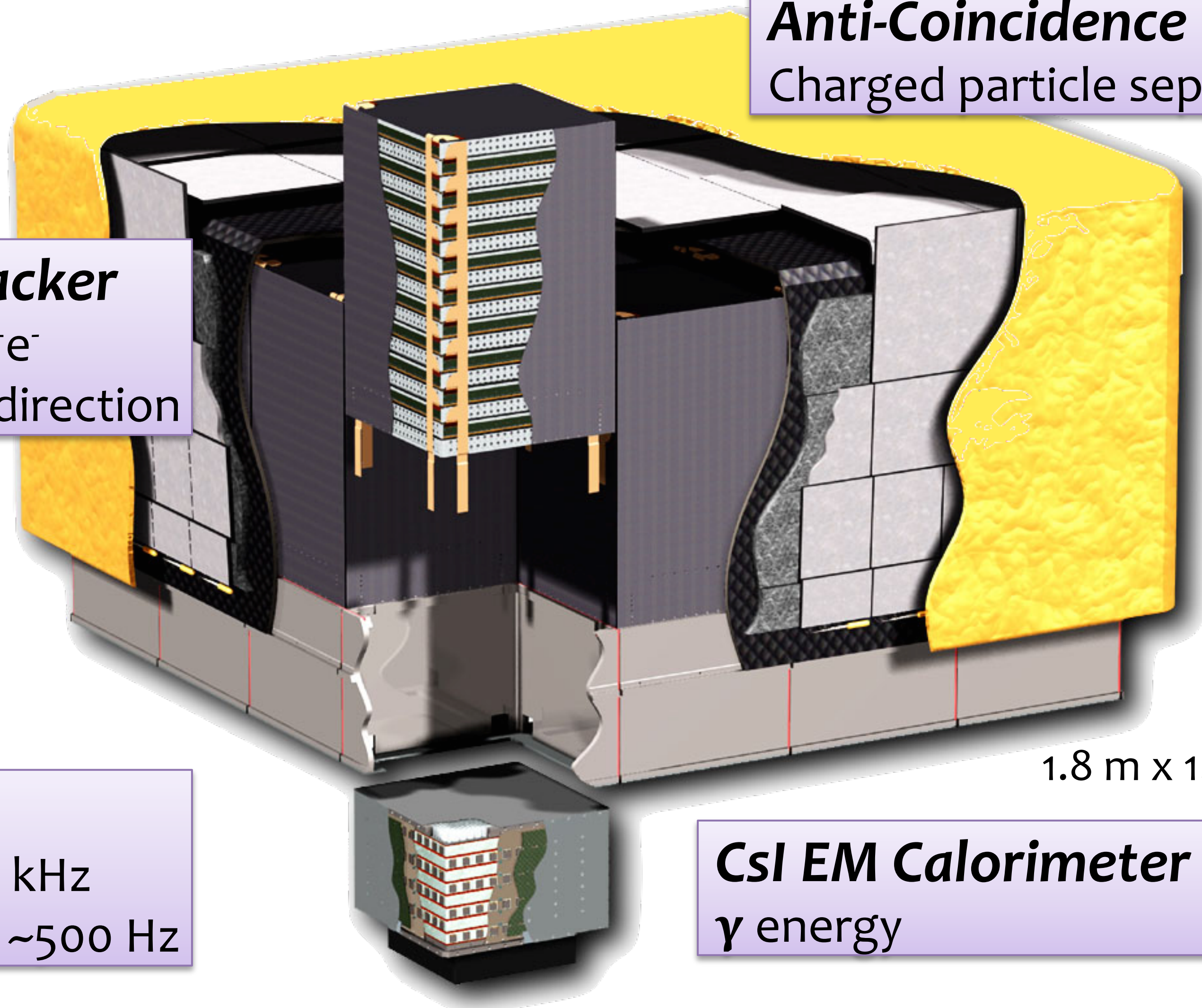
Launch: June 11 2008

Nominal Operations: Aug 4 2008

Large Area Telescope
20% sky at once
full sky every 3 hours
20 MeV -> 300 GeV

Gamma-ray Burst Monitor
Full-sky continuous
8 keV - 40 MeV

Fermi Large Area Telescope



Anti-Coincidence Detector
Charged particle separation

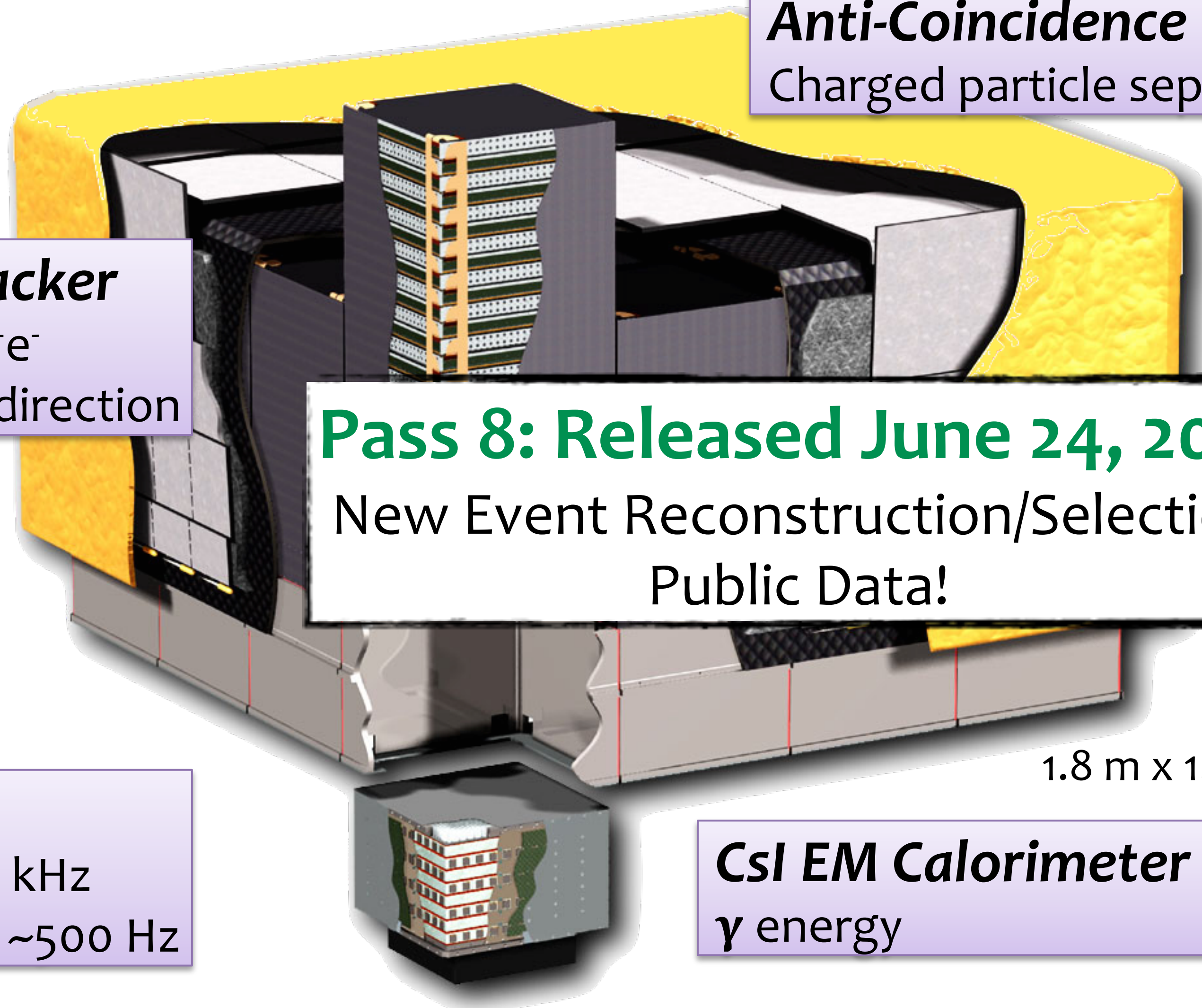
Si-Strip Tracker
convert $\gamma \rightarrow e^+e^-$
reconstruct direction

1.8 m x 1.8 m x 0.7 m

Trigger
rate: ~2.5 kHz
read out: ~500 Hz

CsI EM Calorimeter
γ energy

Fermi Large Area Telescope



Fermi-LAT DM Search Targets

Satellites

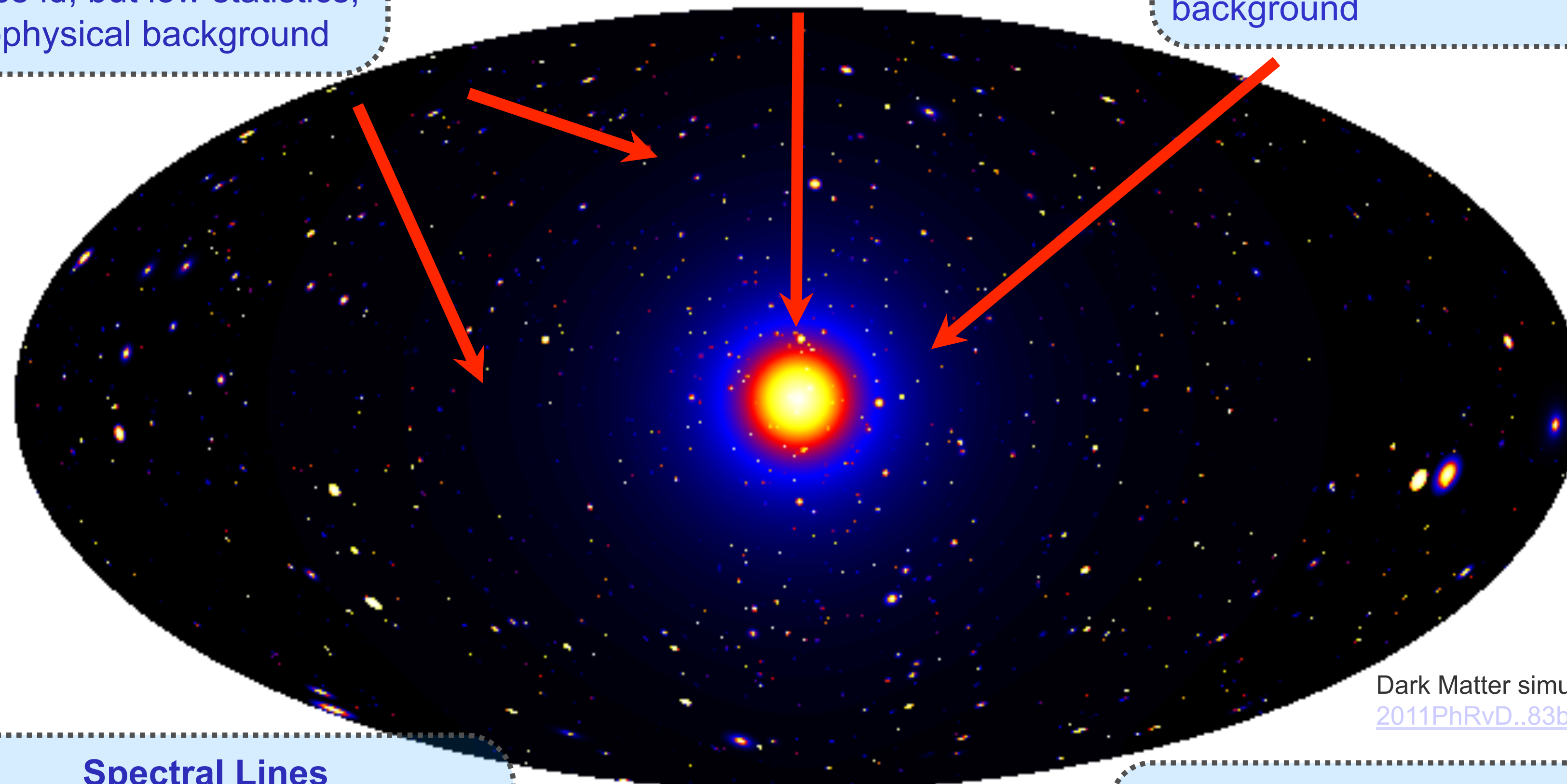
Low background and good source id, but low statistics, astrophysical background

Galactic Center

Good Statistics but source confusion/diffuse background

Milky Way Halo

Large statistics but diffuse background



Dark Matter simulation: Pieri+ 2011PhRvD..83b3518P

Spectral Lines

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

Galaxy Clusters

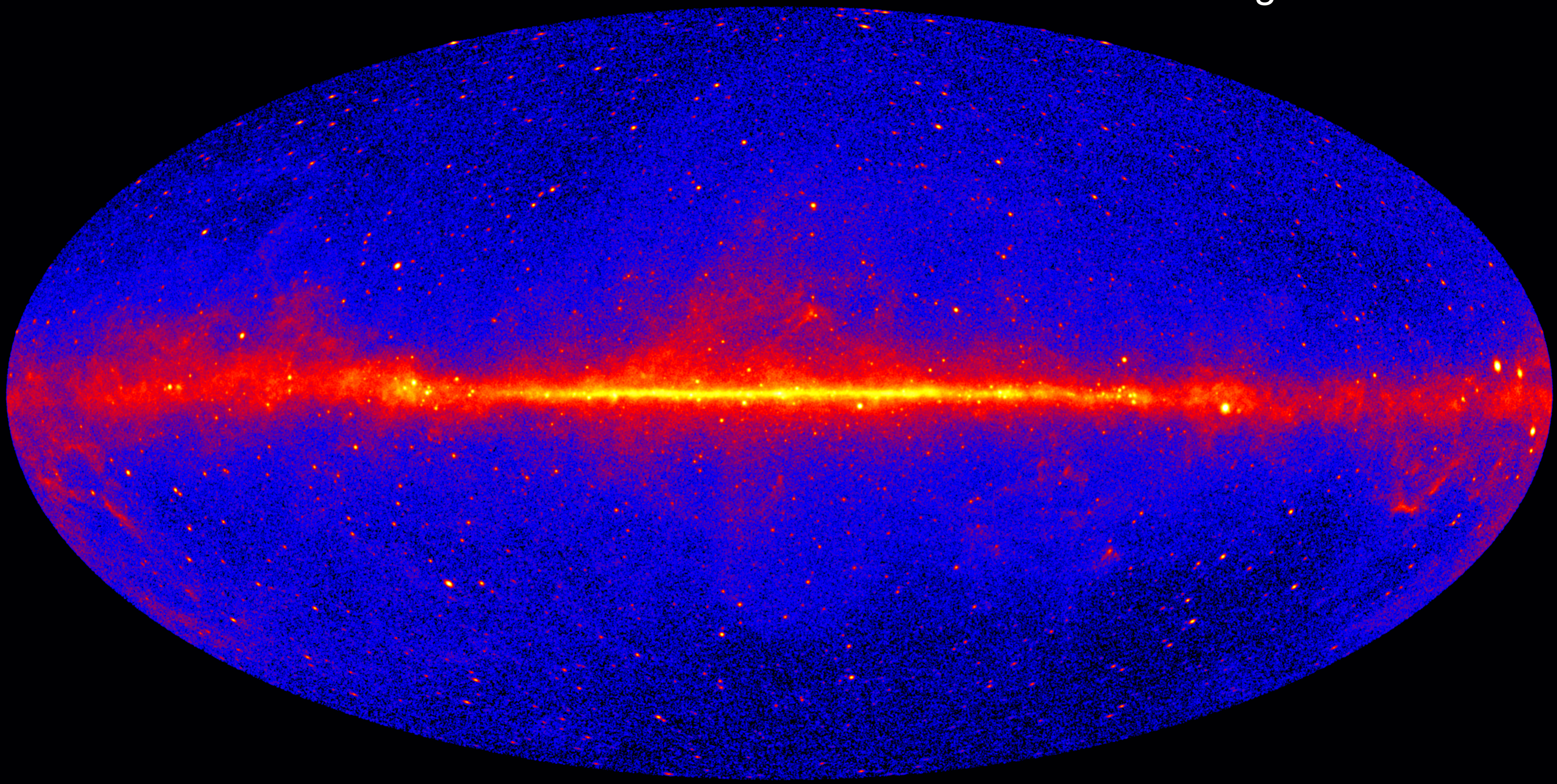
Low background, but low statistics

Extragalactic

Large statistics, but astrophysics, galactic diffuse background

Gamma-ray Sky

Fermi-LAT: 7 Year Sky,
Front-converting events > 1 GeV



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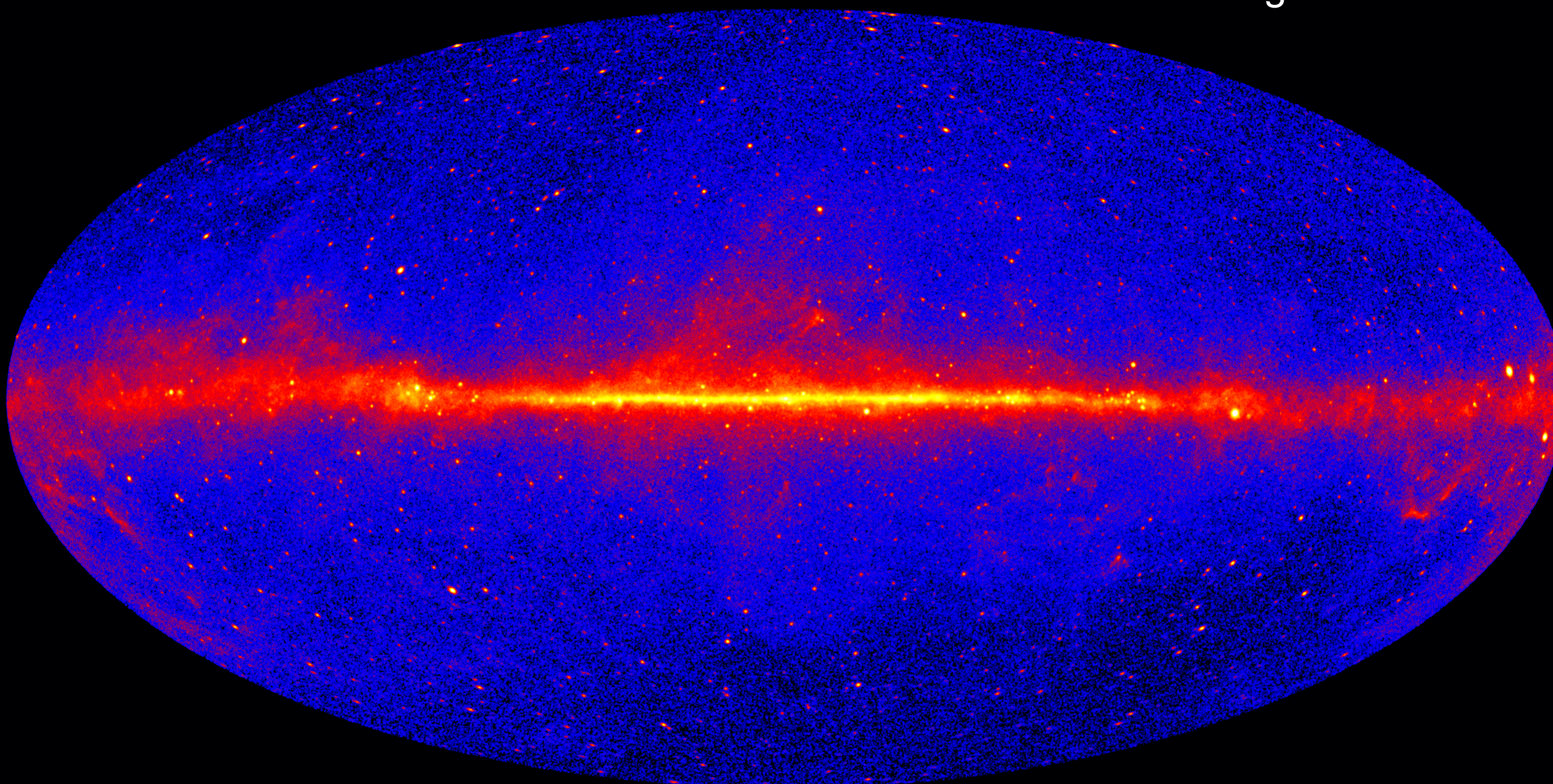
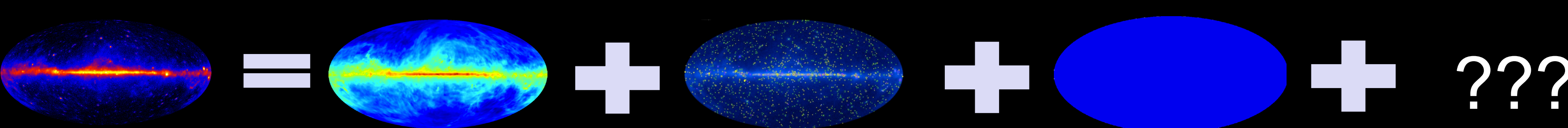
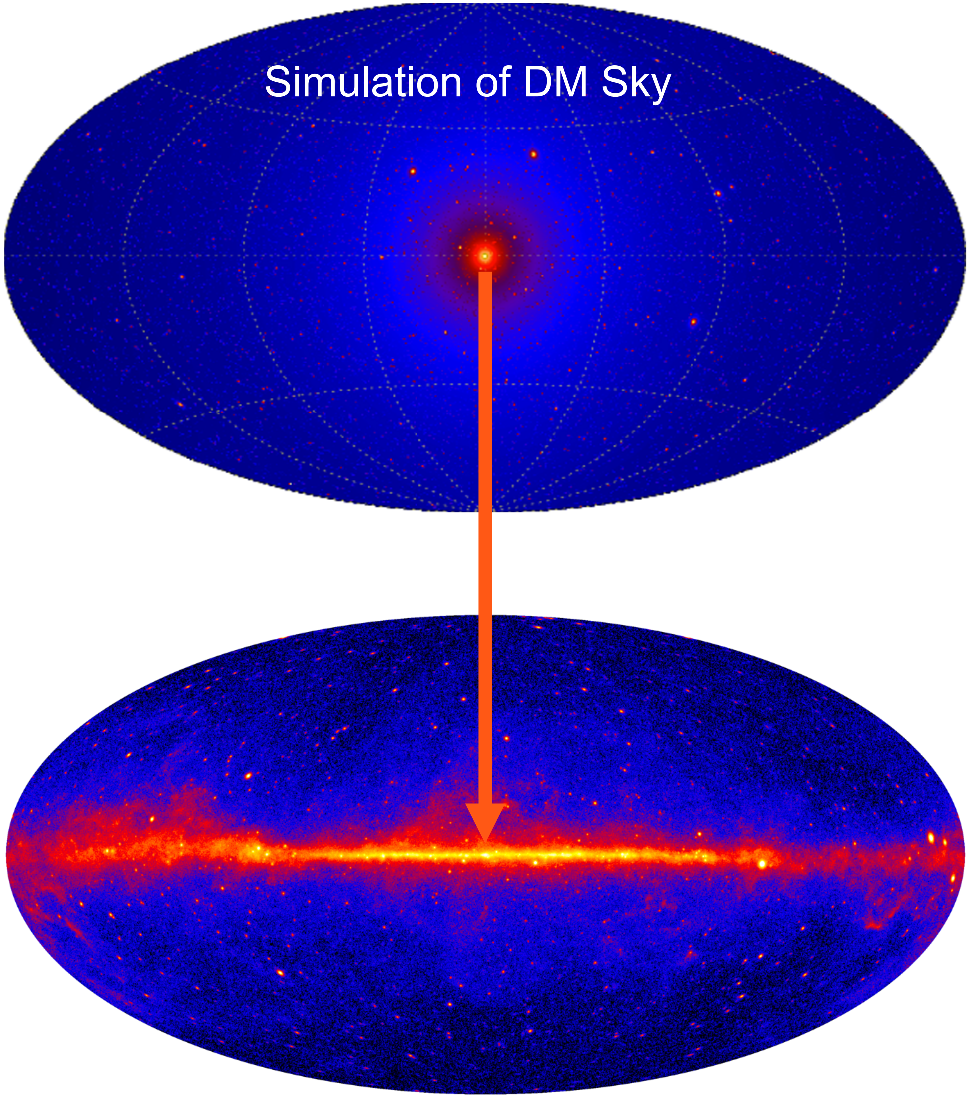




GeV Sky   Galactic   Point Sources   Isotropic

The Inner Galaxy

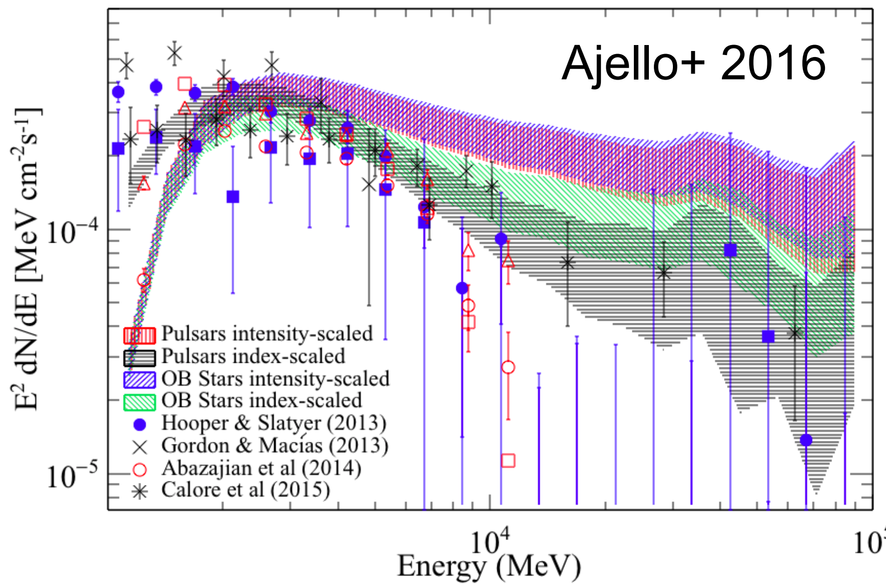


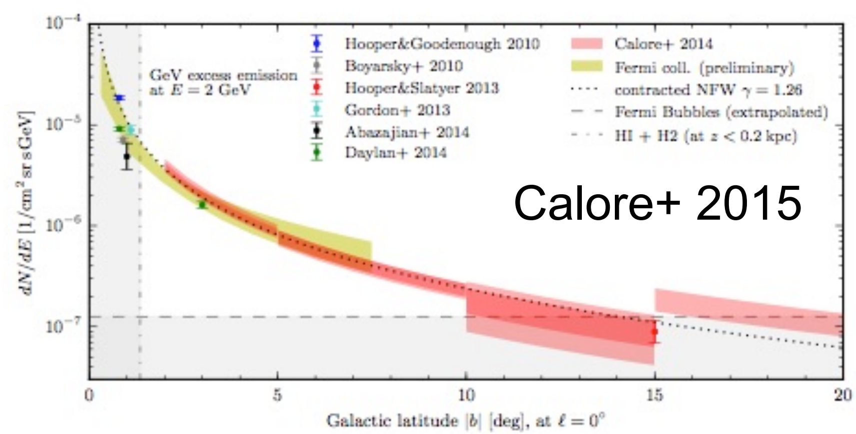
- The center of the Galactic dark matter halo is a promising target
  - Deep gravitational potential
  - Relatively nearby
- However, it is extremely complicated
  - Diffuse emission from cosmic-ray interactions with Galactic gas and dust
  - Densely populated by astrophysical sources (e.g., pulsars, SNR)
  - Detected in other wavelengths (e.g., radio, X-ray, TeV)
- Topic of much study, both inside and outside the collaboration…
  - Hooper & Linden (2011)
  - Boyarski et al. (2011)
  - Abazajian & Kaplinghat (2012)
  - Gordon & Macias (2013)
  - Abazajian et al. (2014)
  - Daylan et al. (2014)
  - etc.

GeV Excess in the Galactic Center

- Existence of a diffuse gamma-ray excess in the Galactic Center (GCE) with respect to standard astrophysical models is now well-established; see e.g. Goodenough & Hooper 2009, Abazajian & Kaplinghat 2012, Gordon & Macias 2013, Daylan+ 2014, Abazajian+ 2014, Calore+ 2014, Ajello+ 2016

- Some consistencies have emerged for the properties of the GCE
  - SED with peak at 1-3 GeV but with large systematic uncertainties on its precise shape
  - Hard spectral tail extending to ~100 GeV
  - Spherically symmetric spatial distribution extending 10-20 degrees from the GC

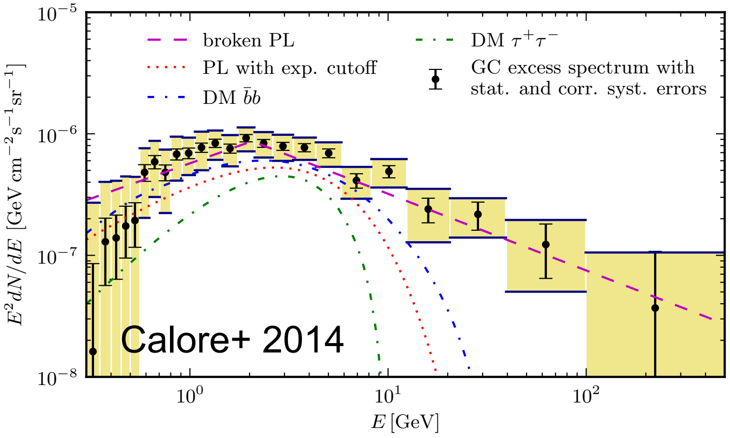


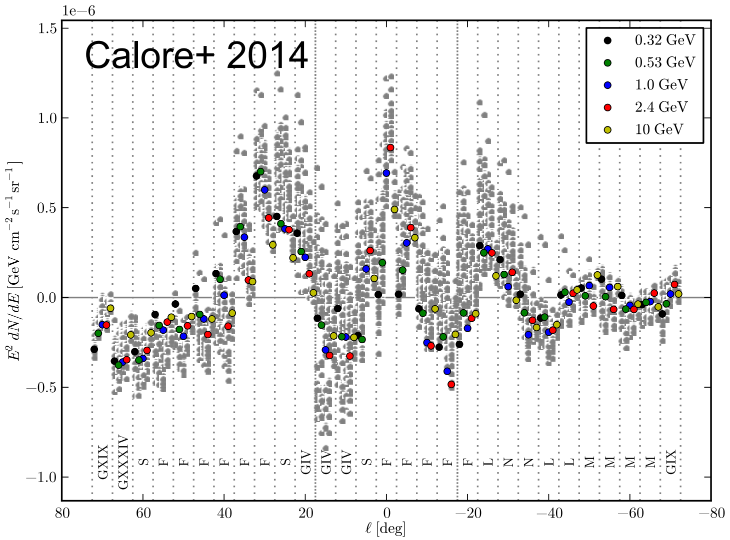


Diffuse Modeling Systematics in the Inner Galaxy

- Improved understanding of the systematic uncertainties in the galactic diffuse emission is needed before the nature of the GCE can be conclusively determined
  - Many uncertainties are unique to the Galactic Center
  - Impact of simplifications made in CR propagation models (e.g. GALPROP) are difficult to quantify

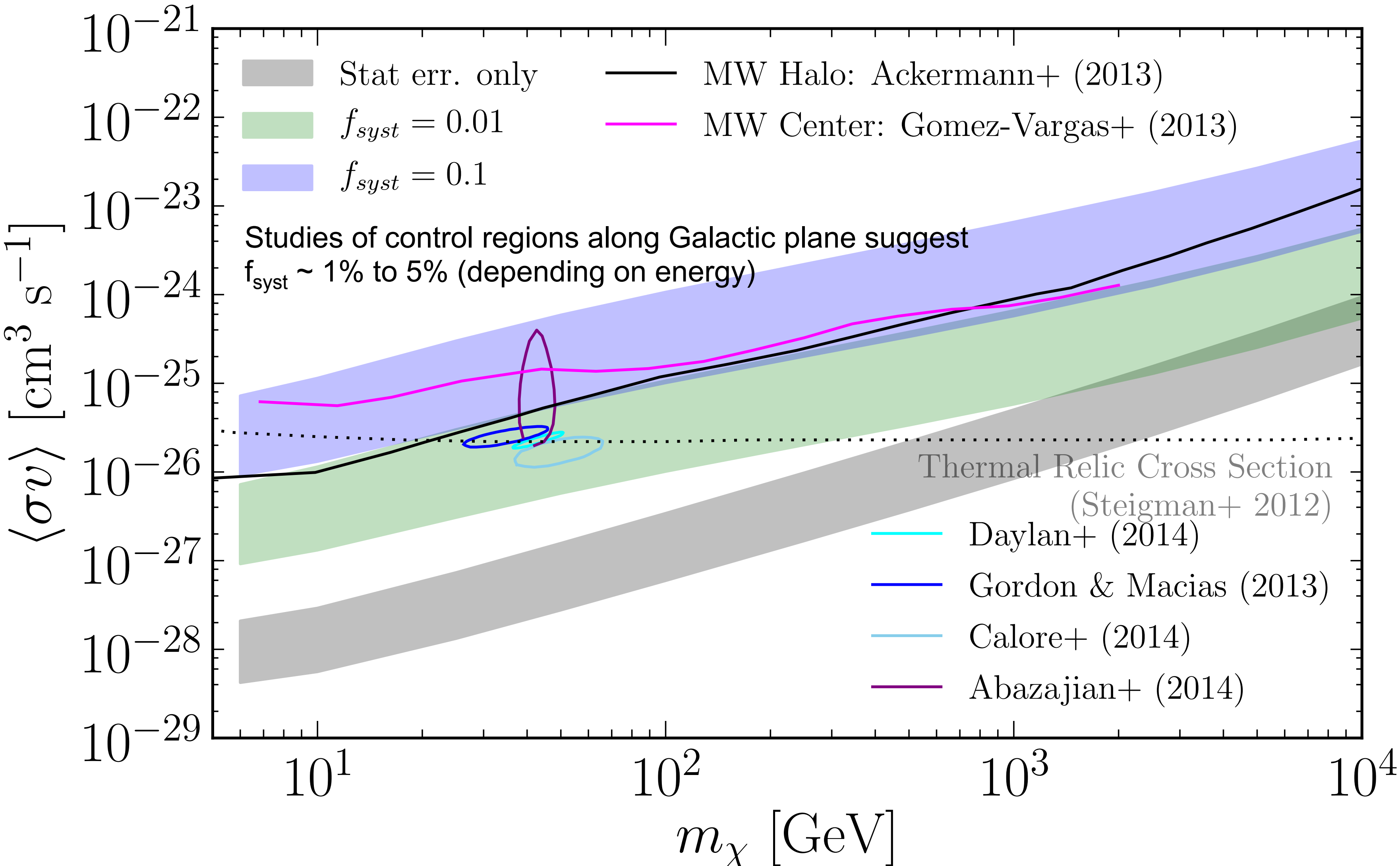
- Models for astrophysical backgrounds produce residuals along the Galactic plane that are comparable in magnitude to the GCE





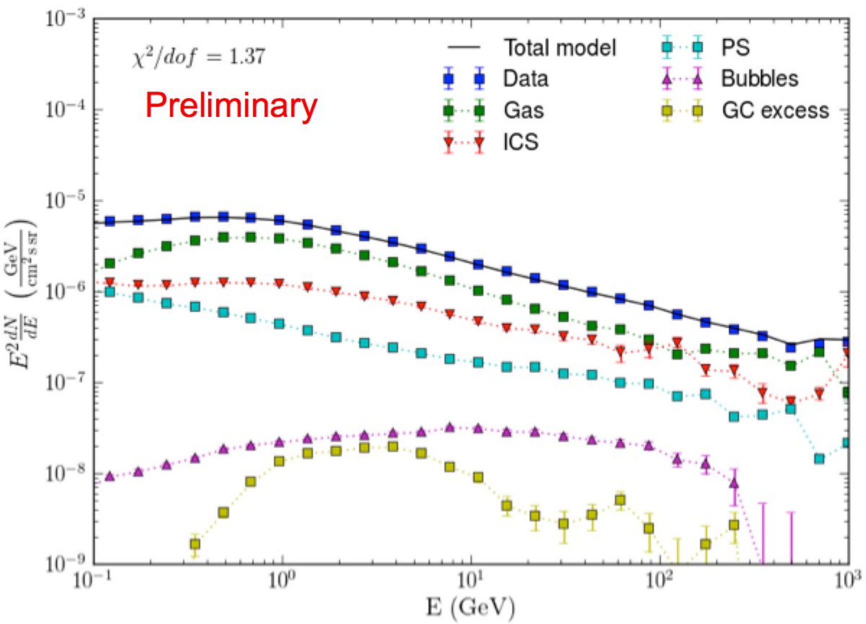
Dark Matter Interpretations of GC Excess

Projected Upper Limits from a 15-year GC Analysis for Different Levels of Modeling Uncertainty

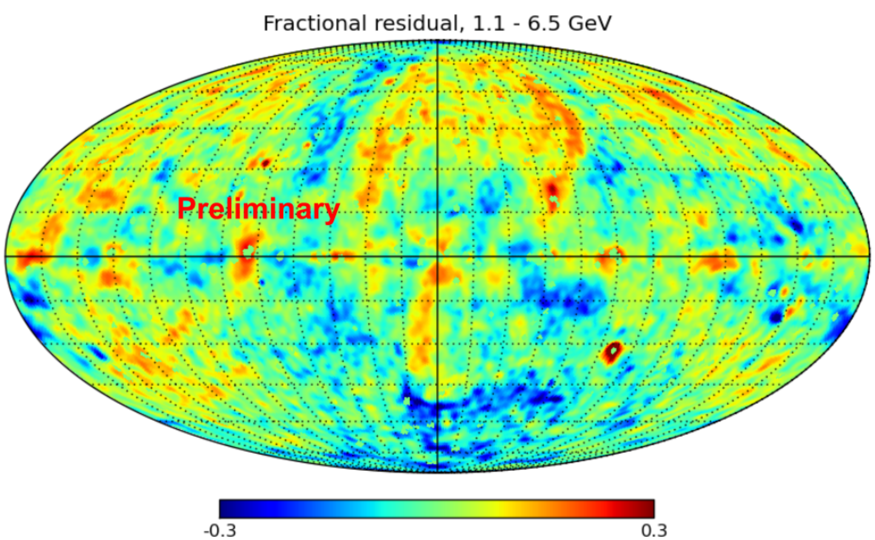


Modeling the GCE with Pass 8

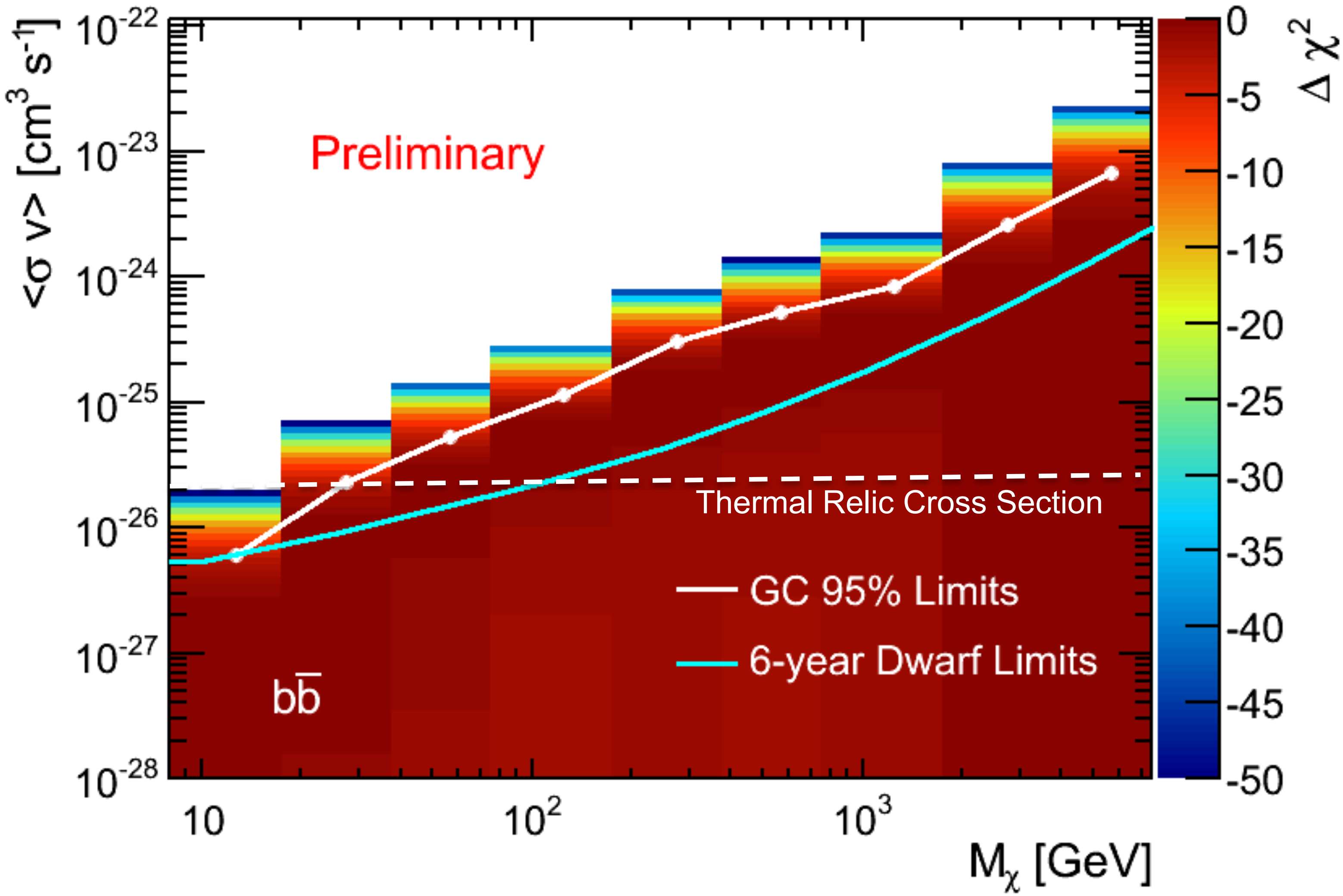
- Inner Galaxy analysis based on 6.5 years of Pass 8 data
- Background modeling uncertainties are explored by studying templates for different diffuse astrophysical emission components in the inner Galaxy
- DM interpretation of the GCE evaluated using an assessment of the background model systematics derived from control regions along the Galactic plane



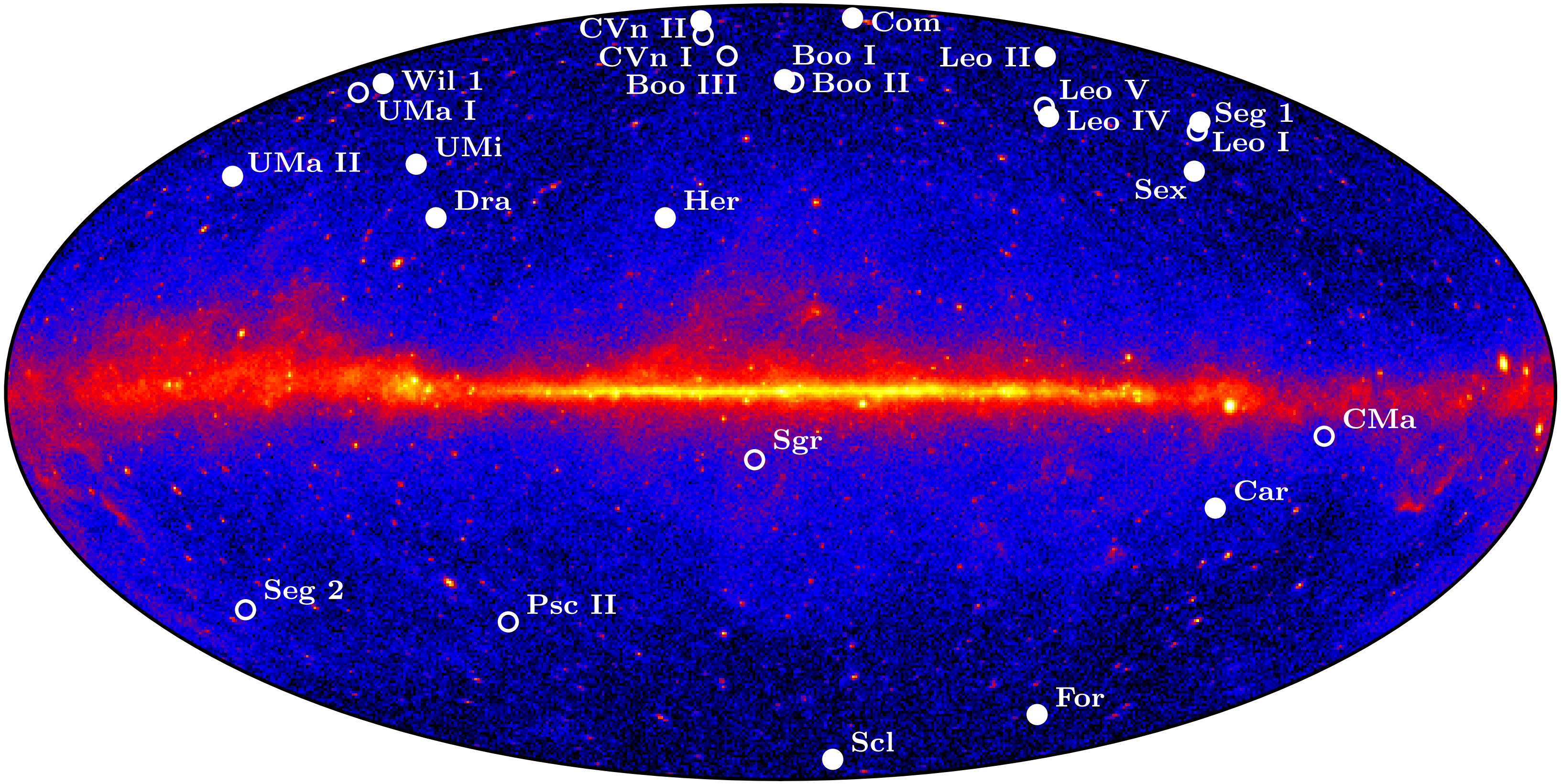
Baseline Model Residuals



Inner Galaxy DM Limits



Dwarf Spheroidal Galaxies



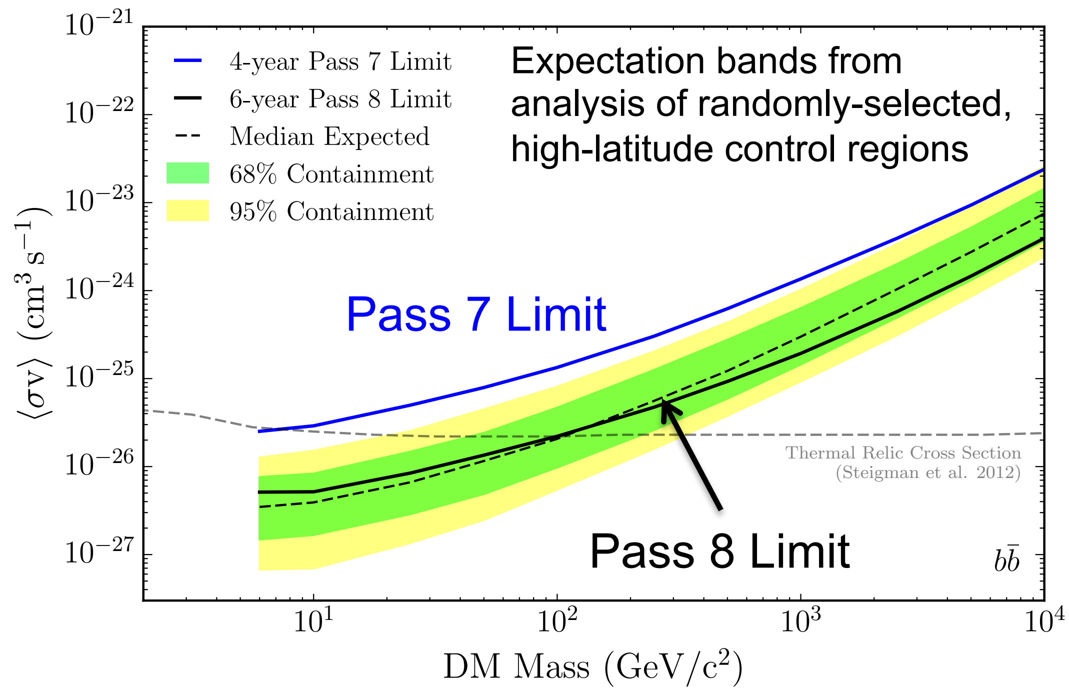
Dwarf spheroidal galaxies (dSphs) are highly **DM-dominated** systems orbiting the MW at typical distances of 25-100 kpc

Dwarf Search with Six Years of LAT Data

Ackermann+ PRL 115 231301 (2015)

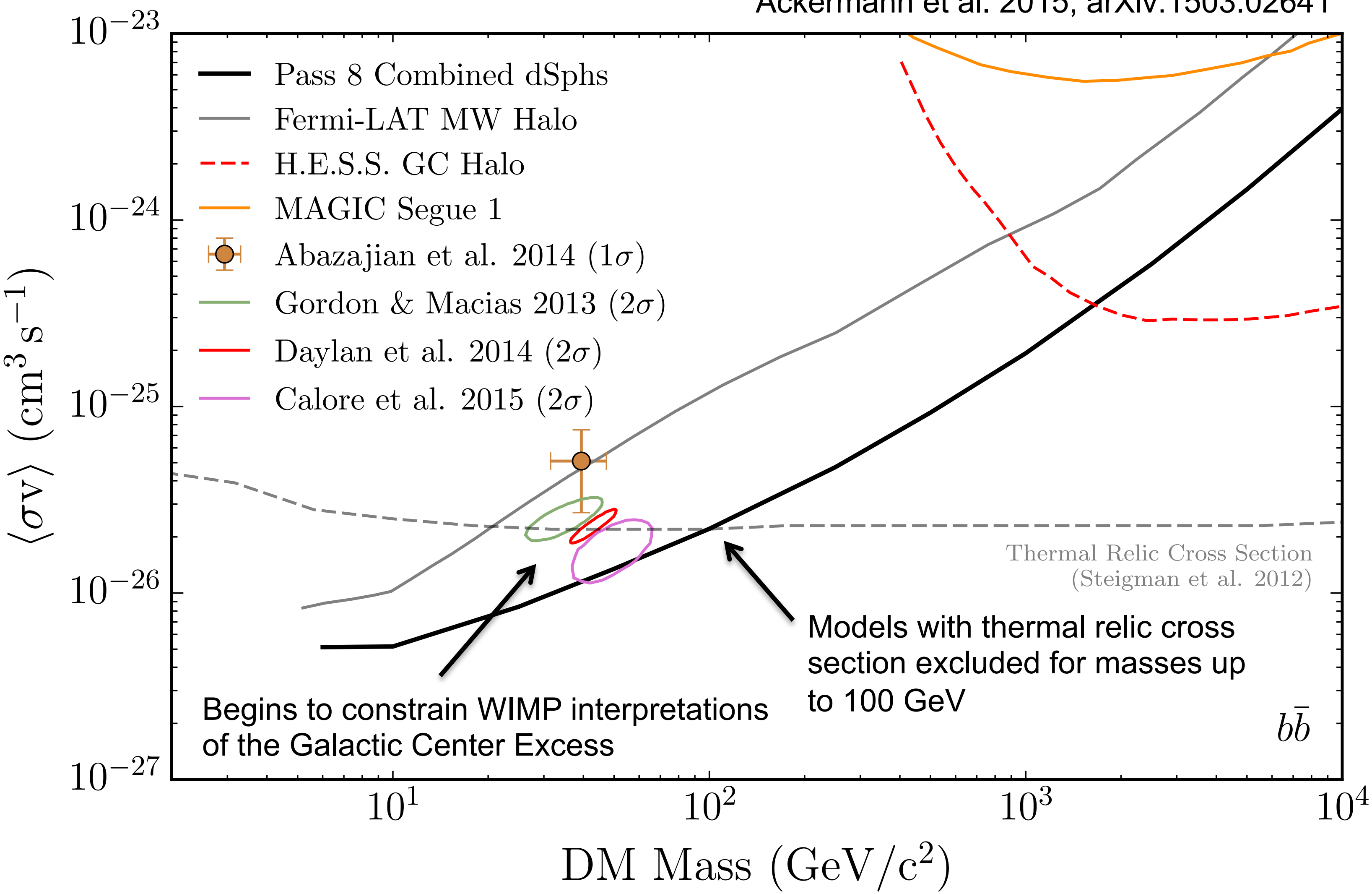
- A sample of 15 known dSphs were analyzed for evidence of DM annihilation signals using **6 years** of **Pass 8** LAT data
- No detection in the combined sample or from any individual dSph
- Observed limits are in good agreement with expectation bands from randomized control regions

Ackermann et al. 2015, arXiv:1503.02641



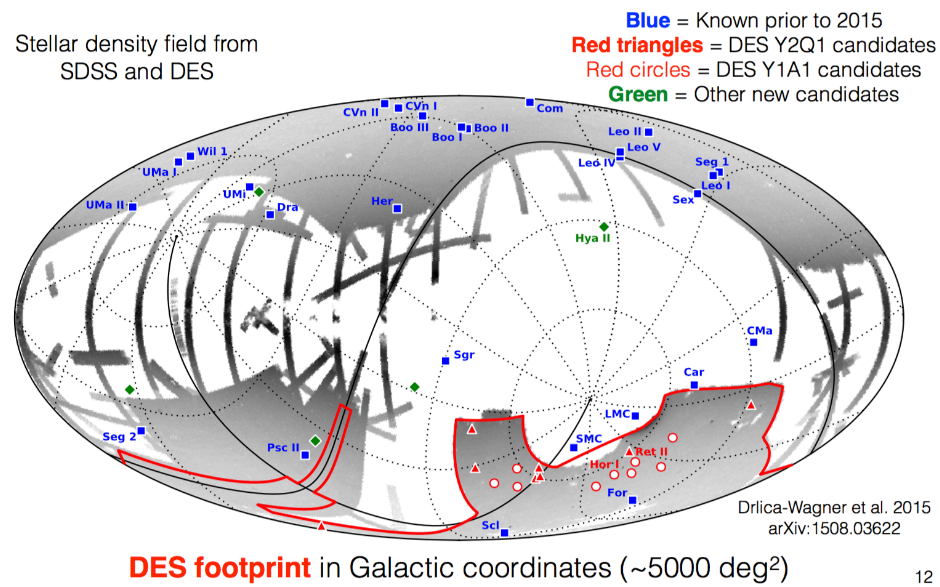
Comparison with other Searches

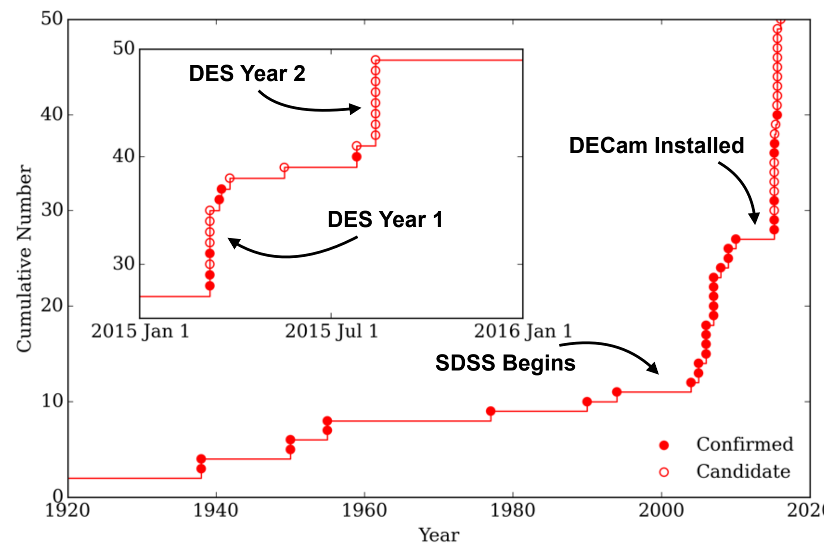
Ackermann et al. 2015, arXiv:1503.02641



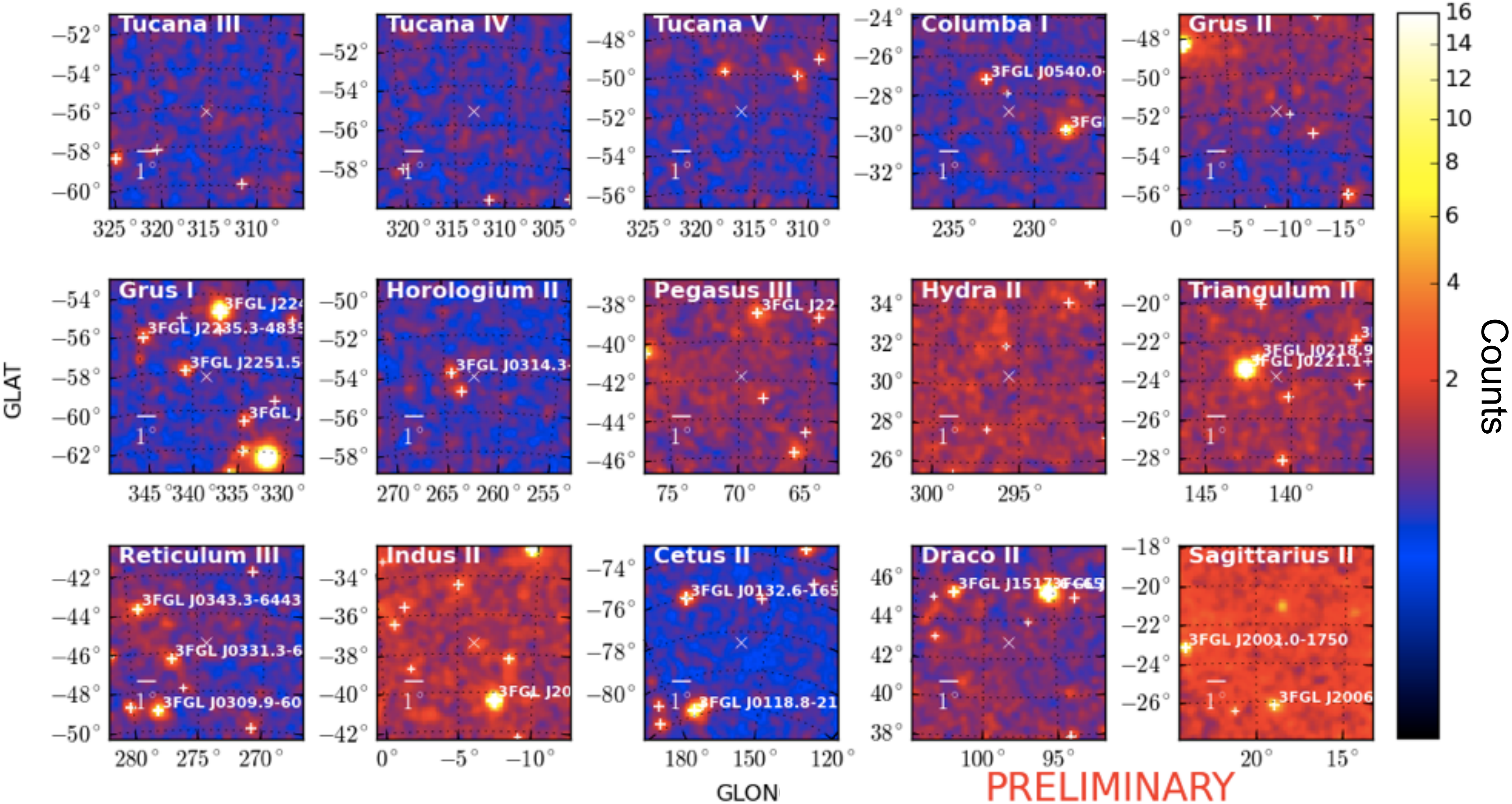
Finding New Satellites

- New optical surveys such as DES and PanSTARRS are rapidly increasing the number of dSphs
- Because the LAT surveys the entire sky these systems can be immediately incorporated into future stacking analyses





Gamma-ray Follow-up of New Candidates



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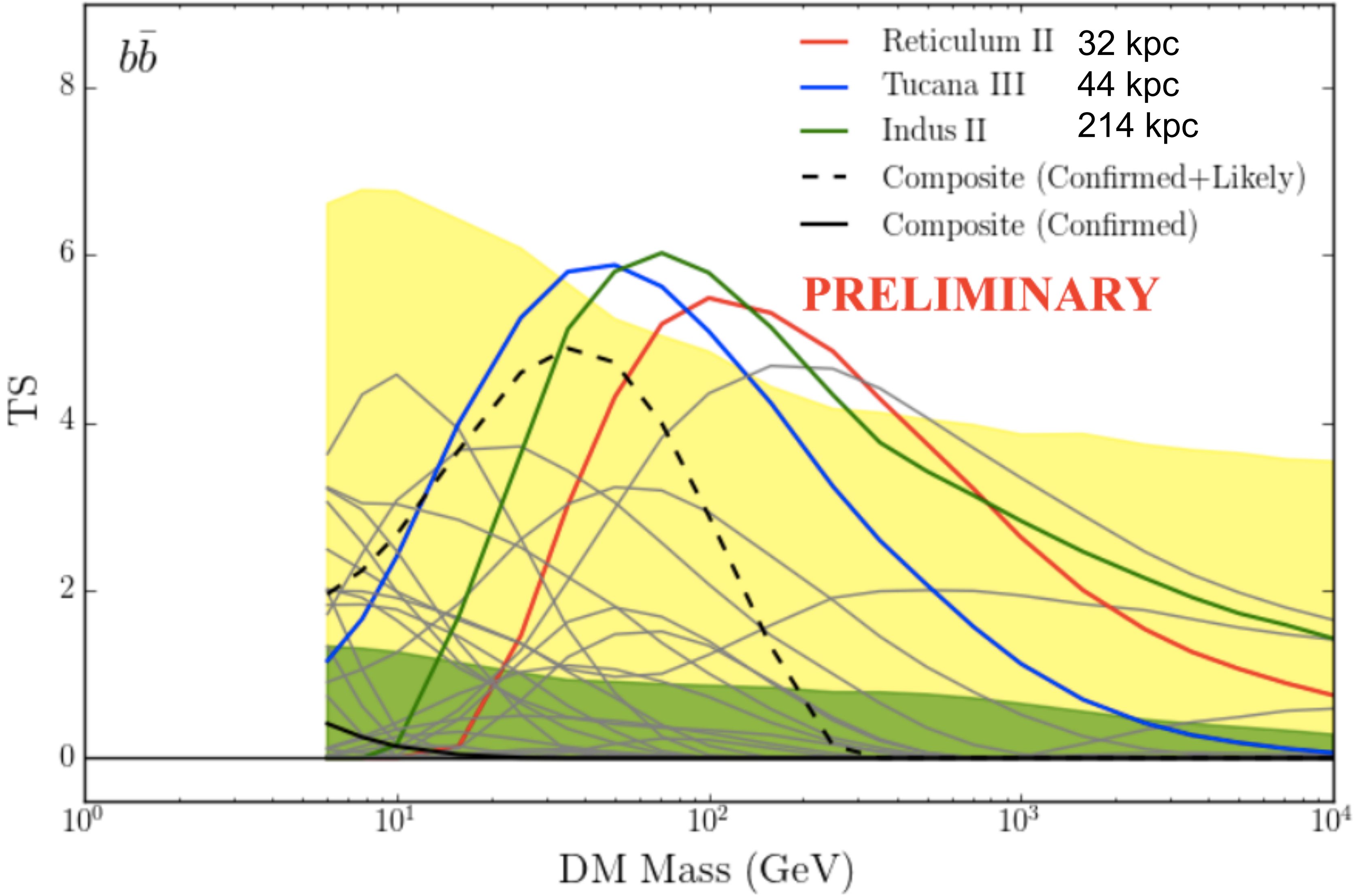
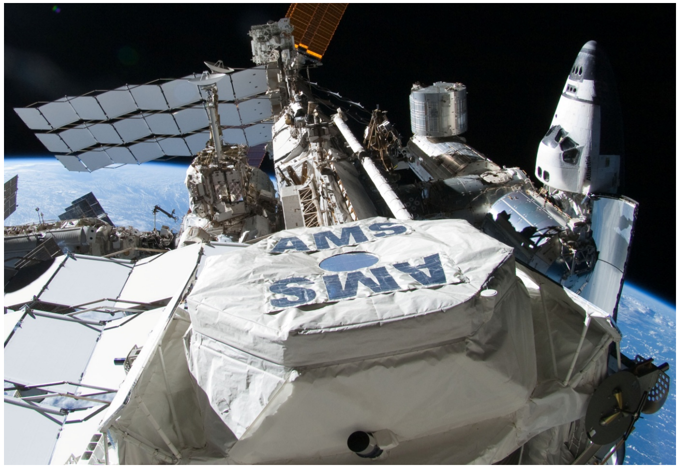
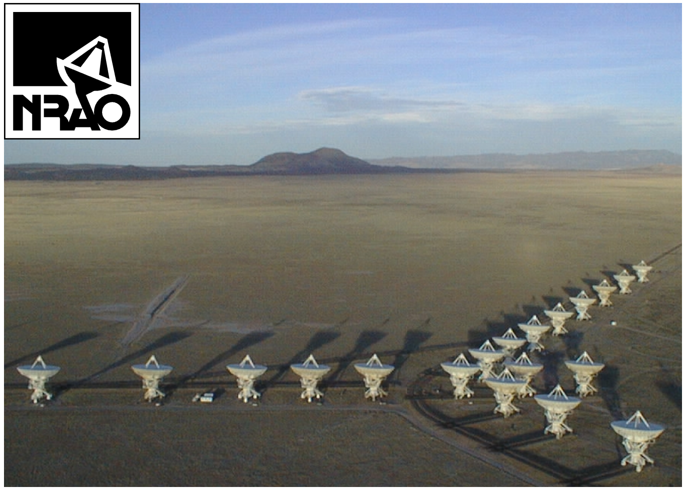


Multi-messenger Constraints

- Multi-messenger and multi-wavelength data are an important ingredient in a comprehensive DM search strategy
  - Positrons
  - Antiprotons
  - Neutrinos
  - Radio
  - X-ray

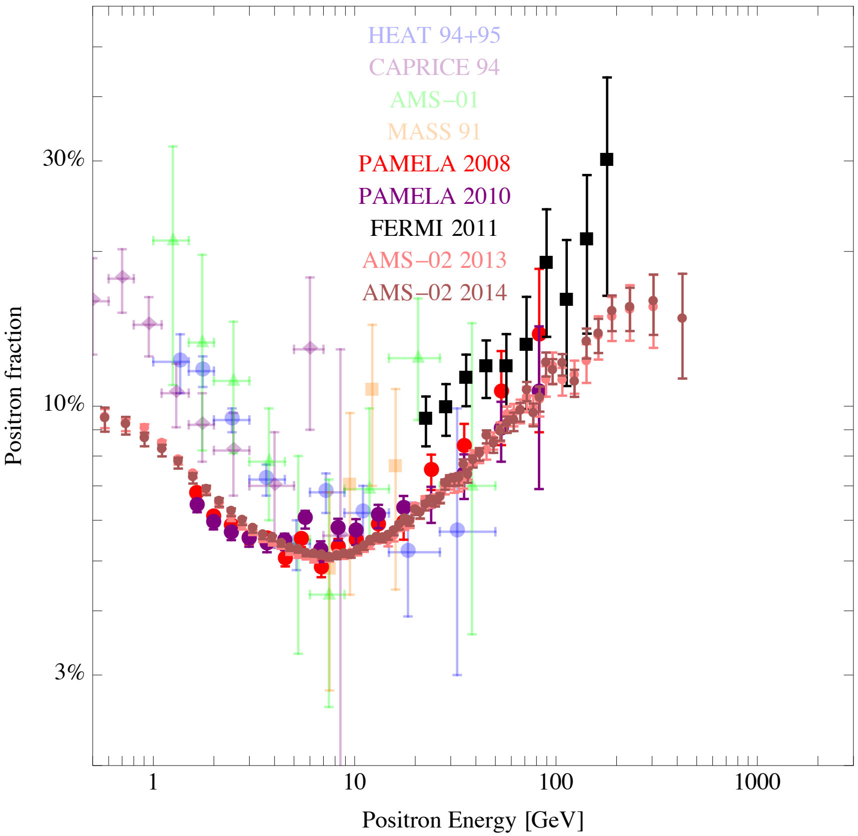
- These data also provide an additional avenue for confirming or disproving gamma-ray signals





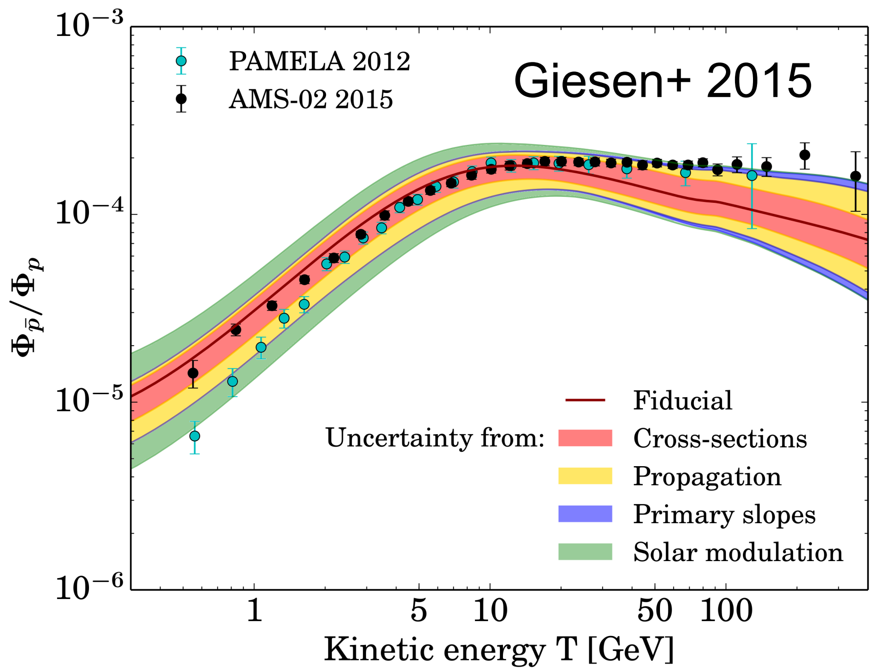
Positrons

- AMS-02 confirms the rise in the positron fraction first measured by PAMELA and Fermi-LAT with high statistical precision
- Challenges for DM interpretation
  - Require Leptophilic models
  - Large non-thermal cross sections
  - Tension with gamma-ray constraints (Lopez+ 2016, arxiv:1501.01618)
- Astrophysical models can also explain a rising fraction
  - Local pulsar sources
  - Acceleration of secondaries in SNR



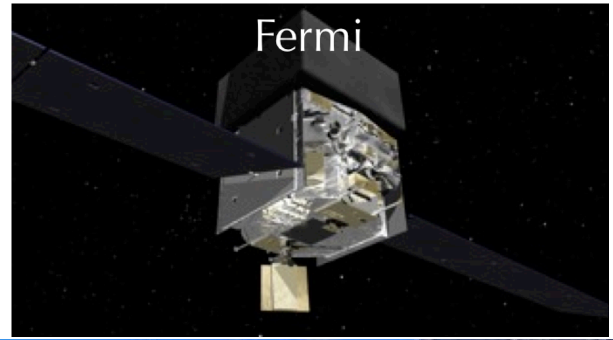
Antiprotons

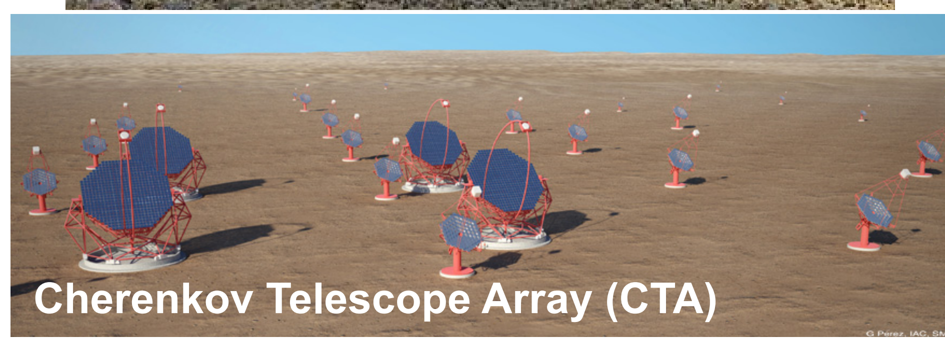
- PAMELA and AMS-02 antiproton spectra are both compatible with secondary production models
- Several papers report limits from antiprotons that exclude or are in strong tension with the GCE WIMP interpretation (Cirelli+ 2014, Bringmann+ 2014)
- **However**, there are large uncertainties in modeling both expected signal and background fluxes
  - Galactic Propagation model
  - Solar modulation



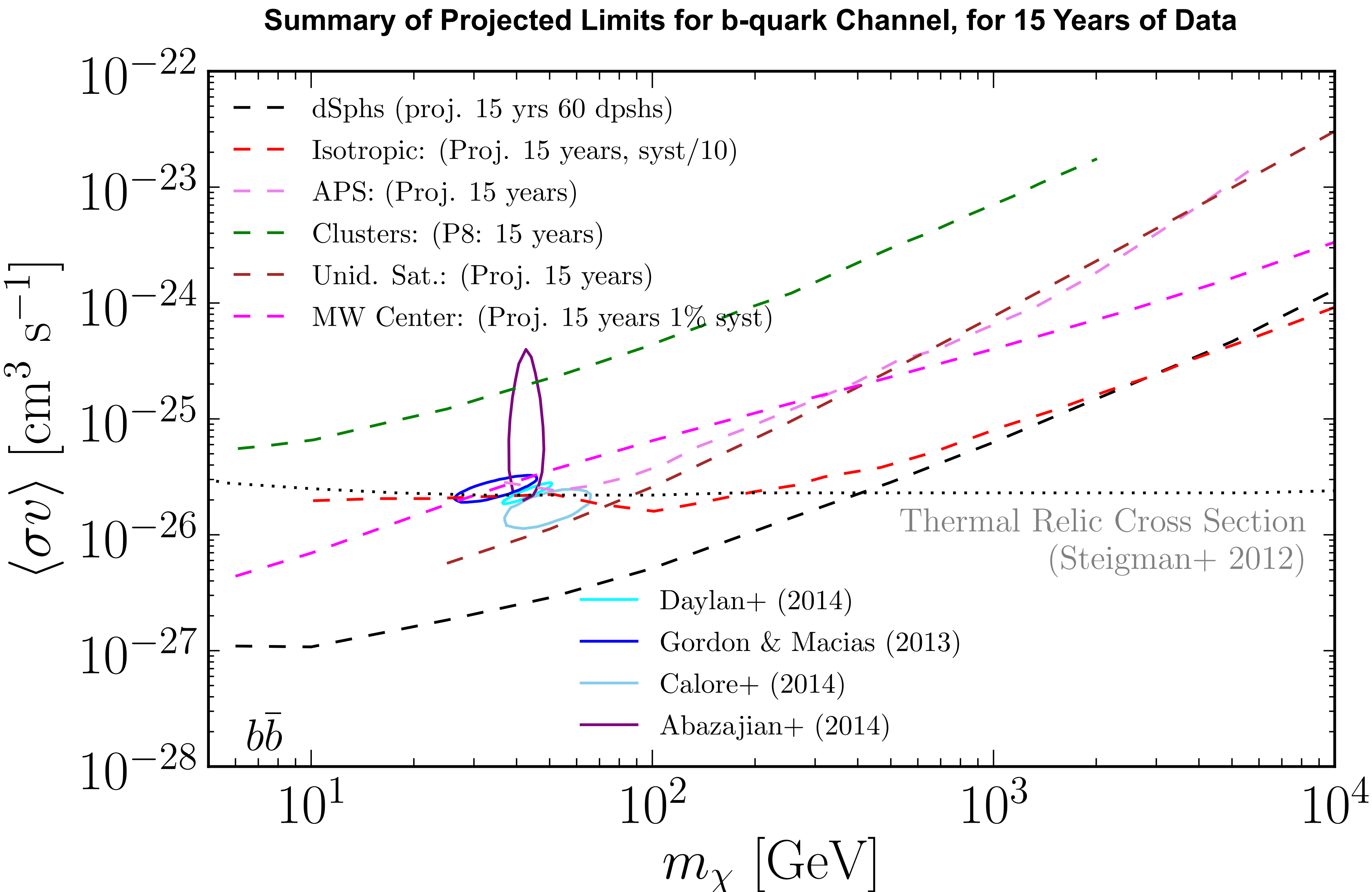
Future for Indirect Searches

- **More Data**
  - Fermi-LAT is anticipated to operate for at least 10 years
  - AMS-02 will continue to collect data and provide improved precision at higher energies
- **New Targets**
  - Current and upcoming optical surveys (DES, LSST) will enlarge the sample of dwarf galaxy targets
- **New and Future Instruments**
  - HAWC
  - Cherenkov Telescope Array
  - GAPS (Antideuteron Search)
  - DAMPE (Gamma-ray Space Telescope)



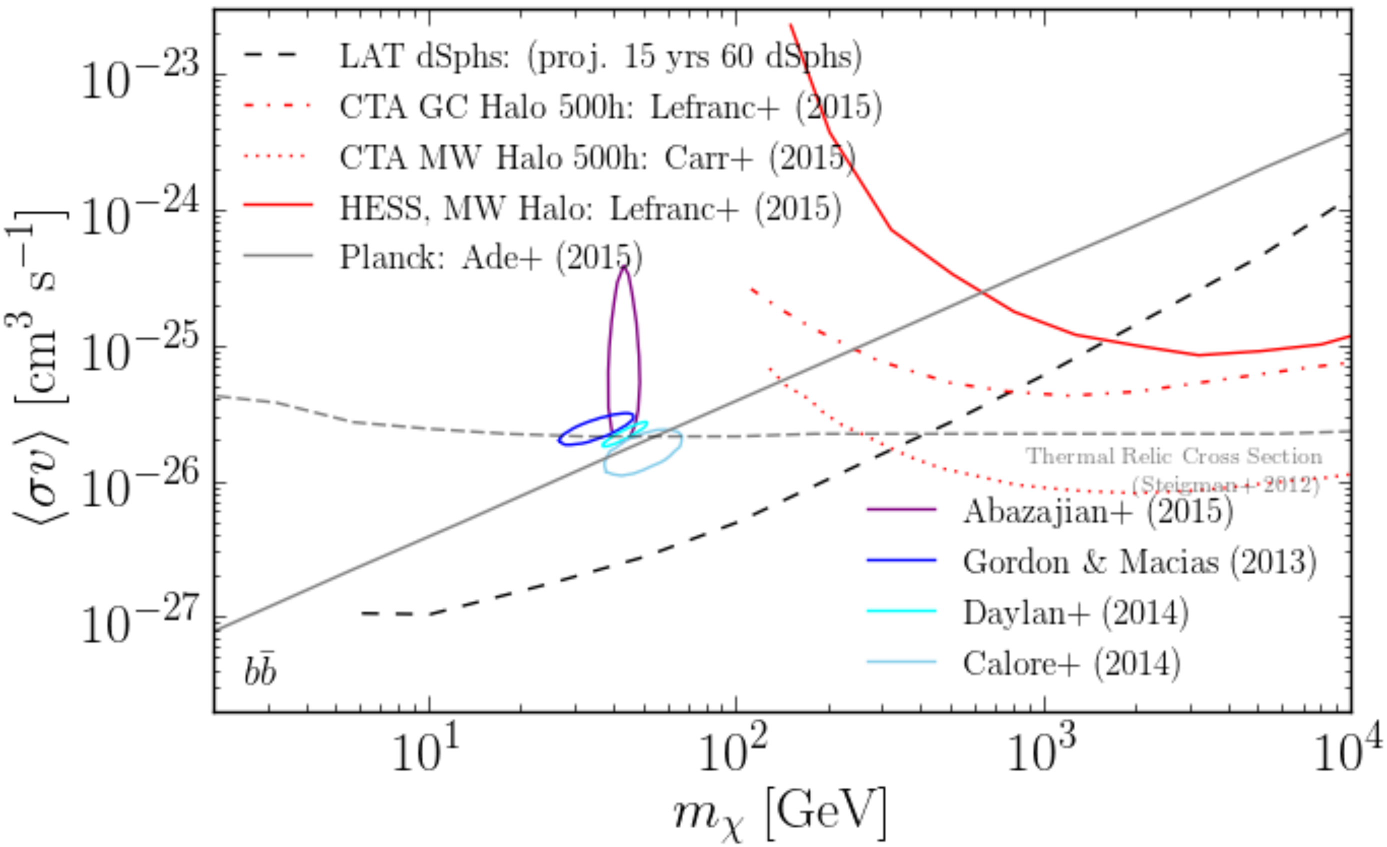


Summary of Projected Sensitivity (15 Years)



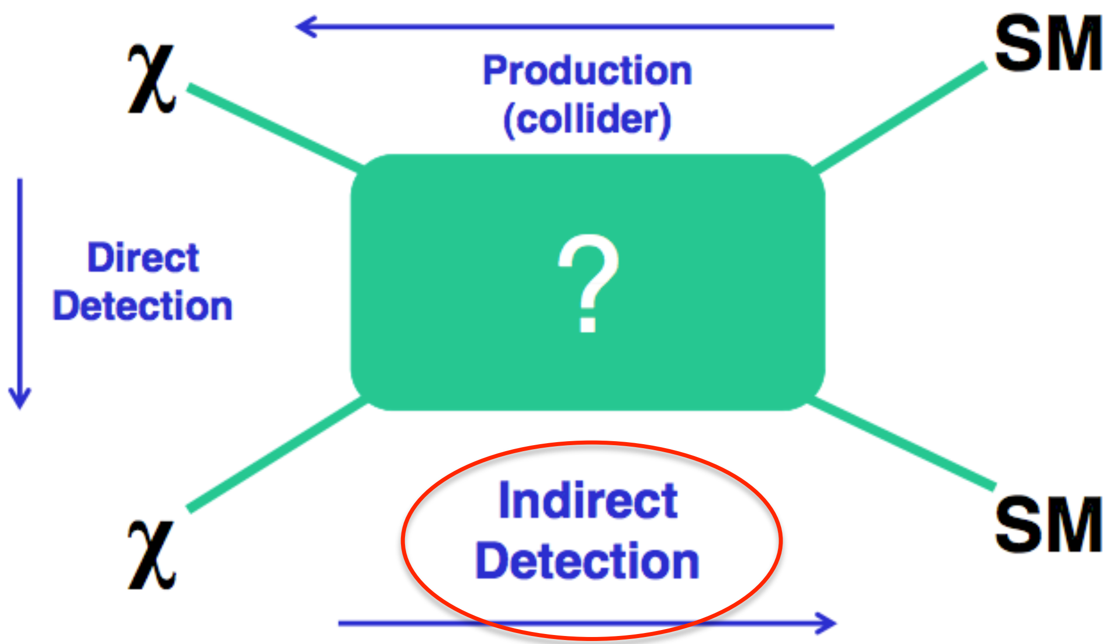
Comparison with Other Indirect-Detection Methods

Comparison of LAT Projected Limits with Other Indirect-detection Limits for b-quark Channel



- With 15 years of data the LAT would:
  - Have the best sensitivity for indirect detection up to 800 GeV (b-quark channel)
  - Probe the thermal relic cross section up to > 400 GeV (b-quark channel)
  - Confirm or rule out a DM-interpretation of the GeV excess

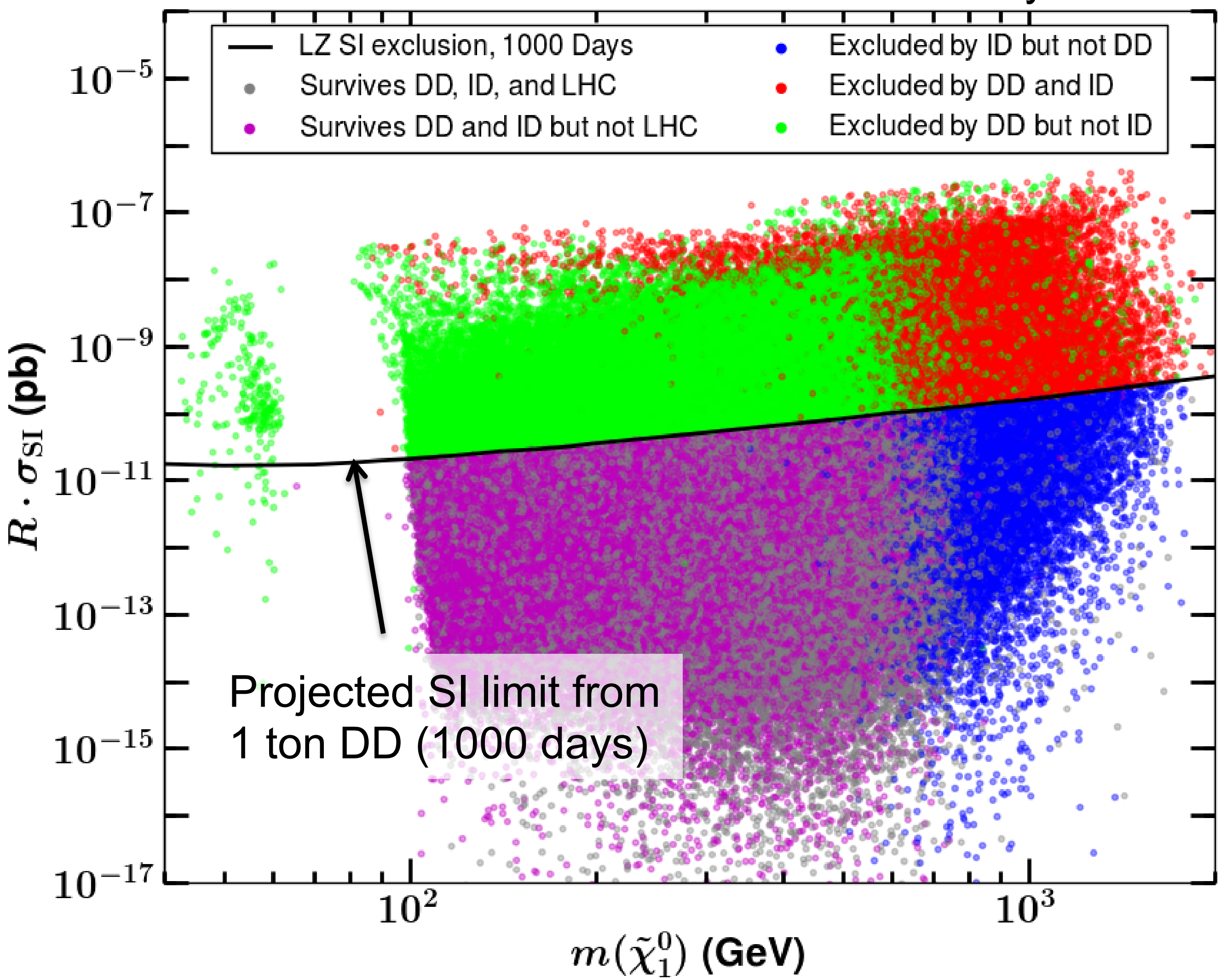
Role of Indirect Detection Dark Matter Searches



- *Compared to collider searches*: indirect detection is sensitive to high mass scales (particles already exist, stable final state particle spectrum peaks at ~10% of m_χ)
- *Compared to direct detection*: indirect detection is sensitive to annihilation rather than scattering off of nuclei (i.e., more sensitive when χ couples more to heavy quarks and vector bosons than to light quarks and gluons)

Complementarity of DM Searches

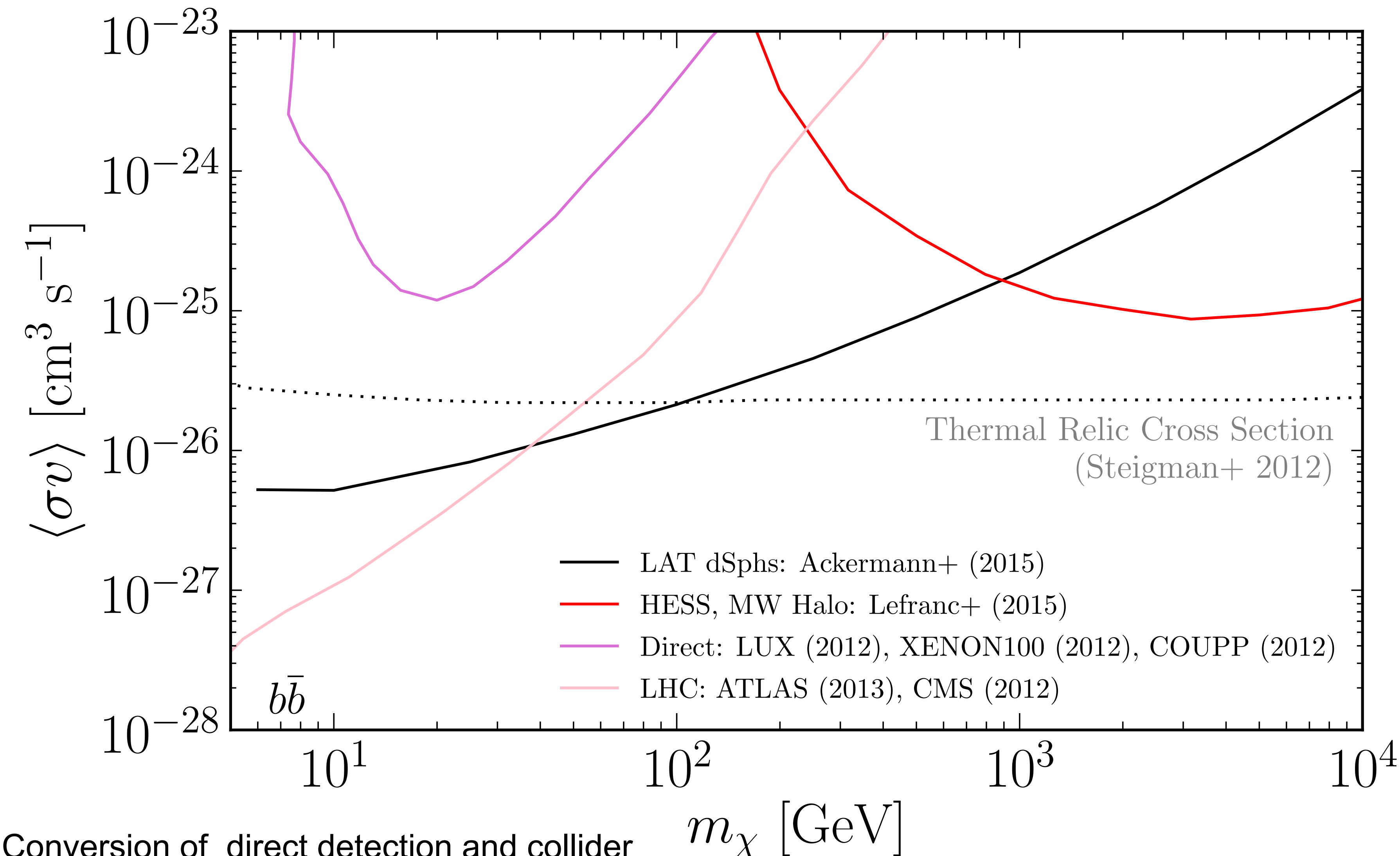
Cahill-Rowley+ 2014



Importance of Indirect-Detection Searches

Charles+ 2016, arxiv:1605.02016

Comparison of LAT Current Limits with Direct-Detection and Collider Limits for b-quark Channel

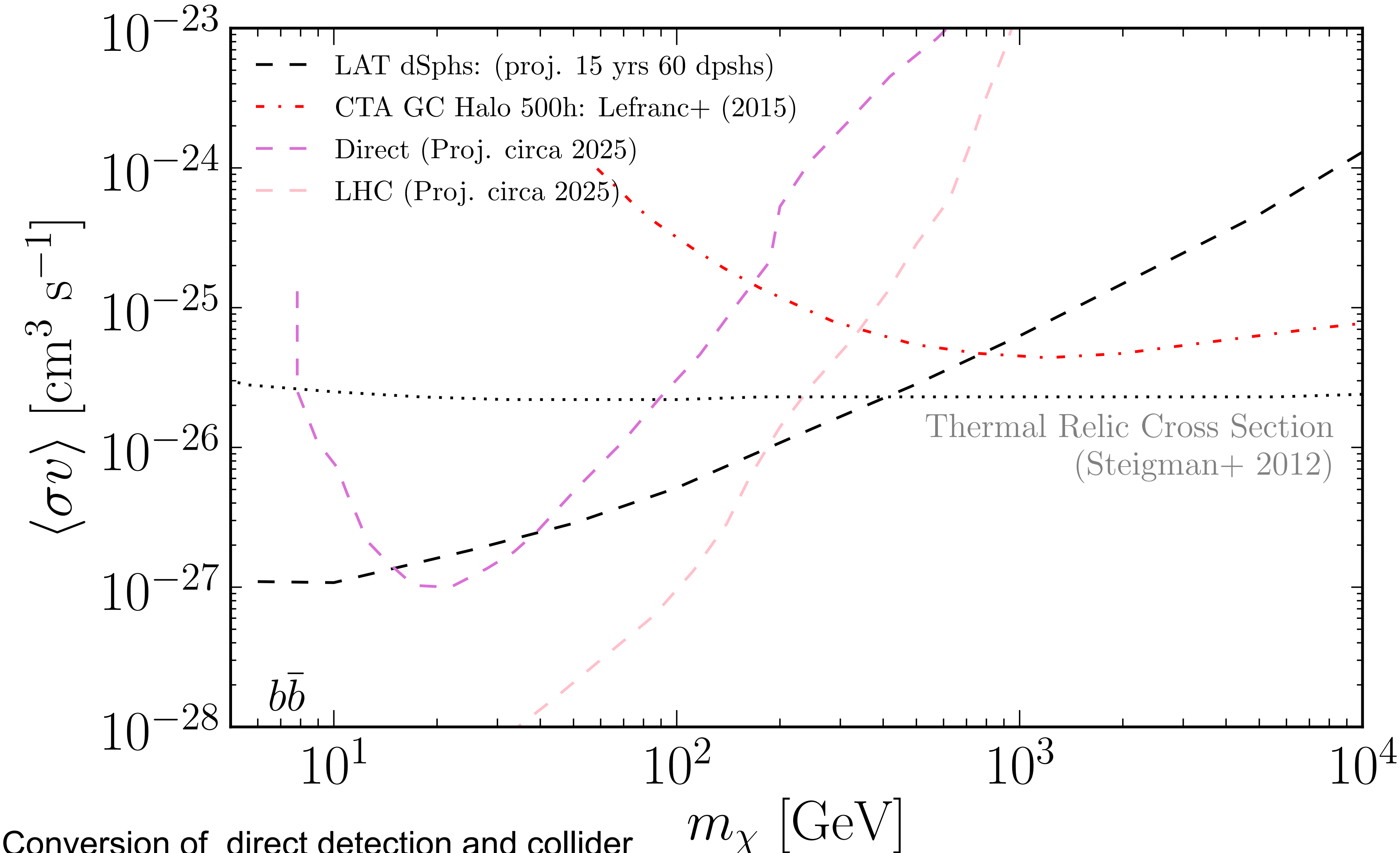


Conversion of direct detection and collider limits following EFT methodology of Bauer+ 2015PDU.....7...16B

Dark Matter Sensitivity, circa 2025

Charles+ 2016, arxiv:1605.02016

Comparison of LAT Projected Limits with Direct-Detection and Collider Limits for b-quark Channel



Conversion of direct detection and collider limits following EFT methodology of Bauer+ 2015PDU.....7...16B

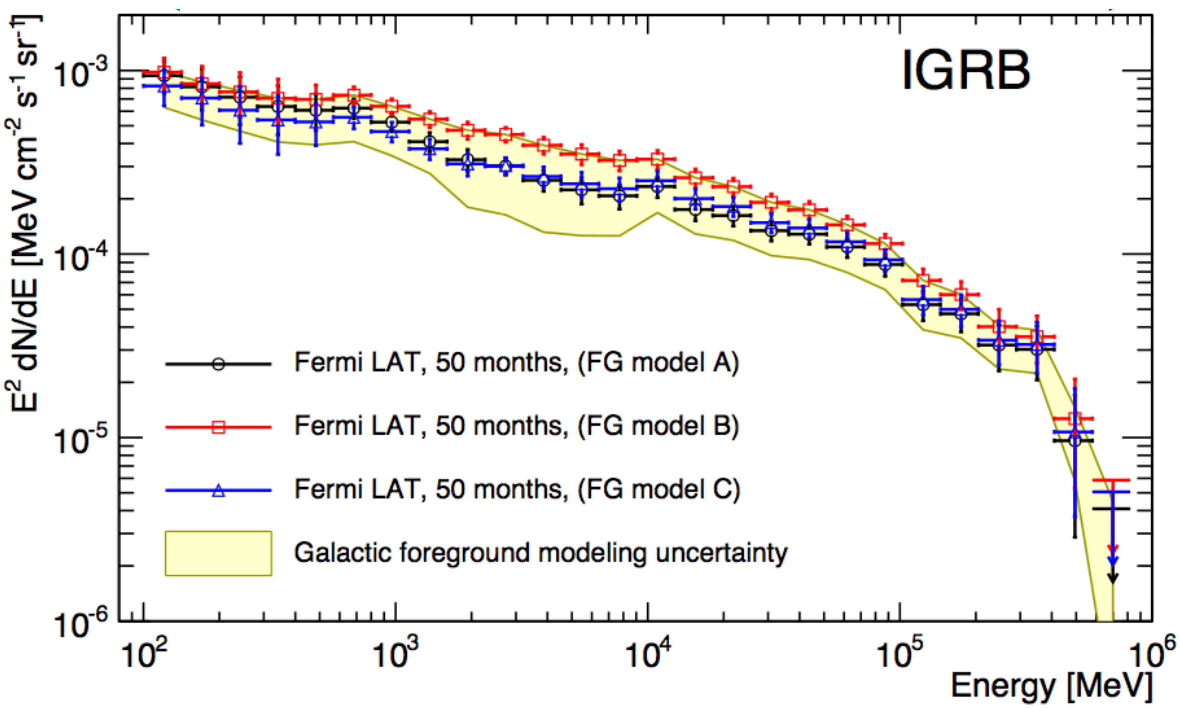
Conclusions

- This is an exciting era for indirect DM searches
  - Many targets are now probing the preferred phase space of thermal relic WIMP models
  - Conclusive evidence will probably require confirmation with multiple targets and/or messengers
- Interpretation of the GCE remains challenging
  - WIMP interpretation in mild tension with dwarf galaxy limits and antiproton measurements
  - Further progress will require more accurate models for the galactic diffuse emission and quantification of its uncertainties
- Indirect Detection will continue to play a complementary role in the hunt for DM with direct and collider searches

Isotropic Gamma-ray Background

Ackermann+ 2015 ApJ, 799, 86

- The **Isotropic Gamma-ray Background (IGRB)** is the residual intensity that remains after subtracting all known sources of gamma-ray emission (diffuse and pointlike)
- Latest measurement using 4 years of P7REP data
  - Extends energy range to 100 MeV – 820 GeV
  - Careful analysis of systematics including uncertainties from galactic foreground modeling
  - A high-energy cutoff is significantly detected at ~250 GeV



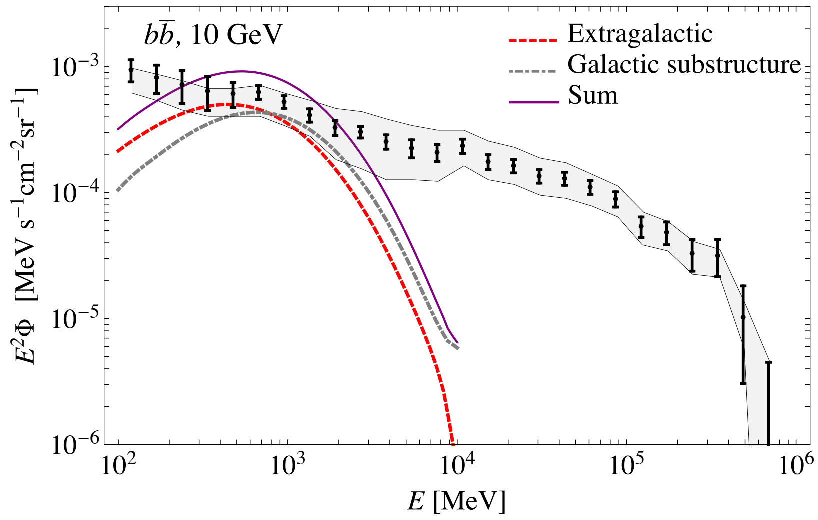
DM Limits from the IGRB

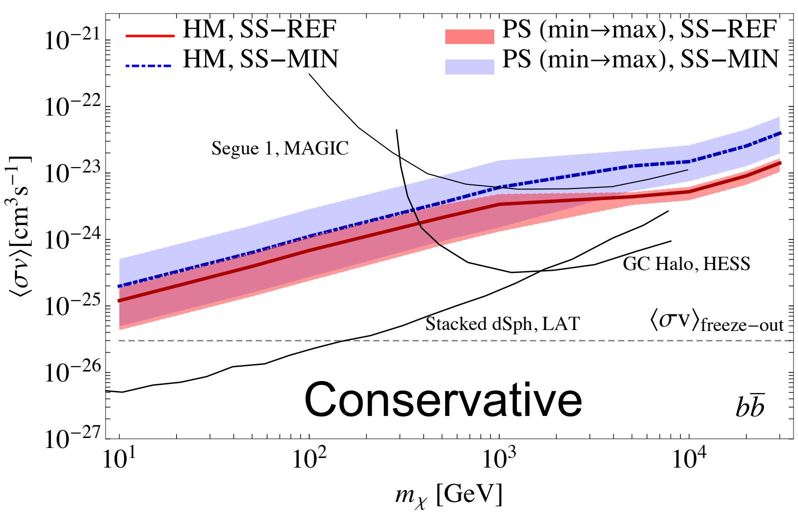
Ackermann+ JCAP (2015) 09, 008

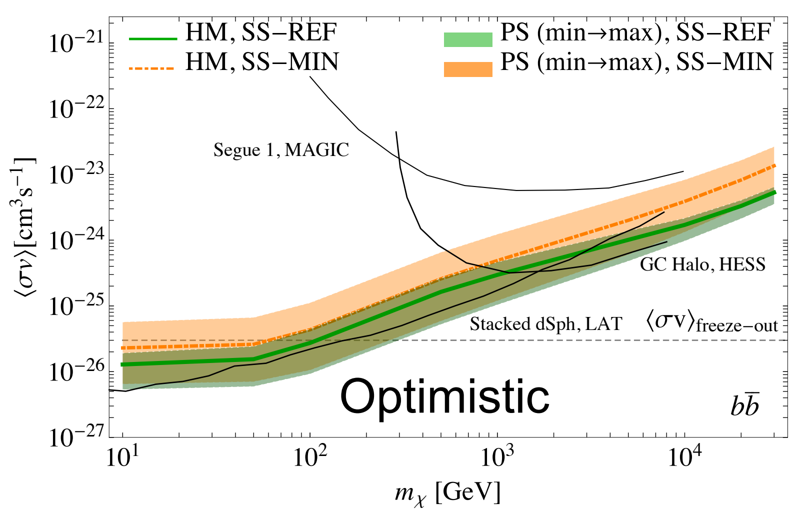
Use two independent approaches (Halo Model and Power Spectrum) to estimate the cosmological flux multiplier → **theoretical uncertainty reduced from ~10^3 to ~17**

Conservative Limits: No background subtraction

Optimistic Limits: Assume that all Galactic and extragalactic astrophysical contributions can be accurately modeled



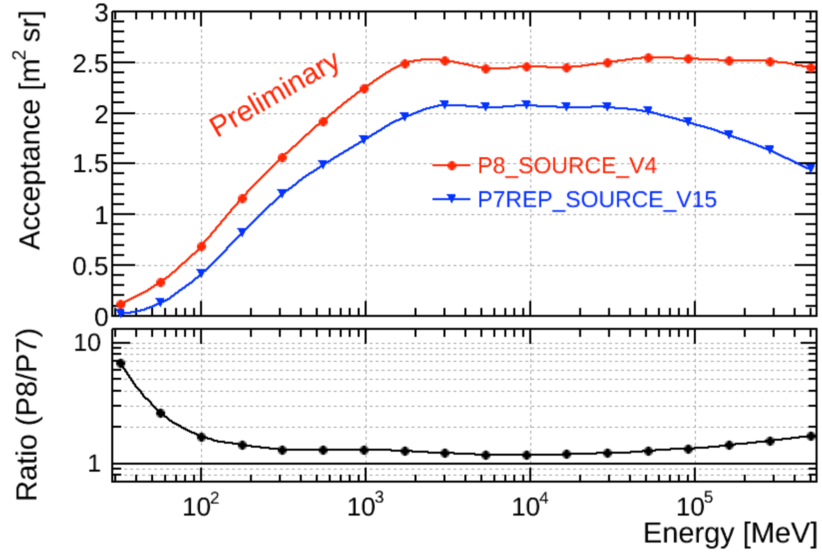


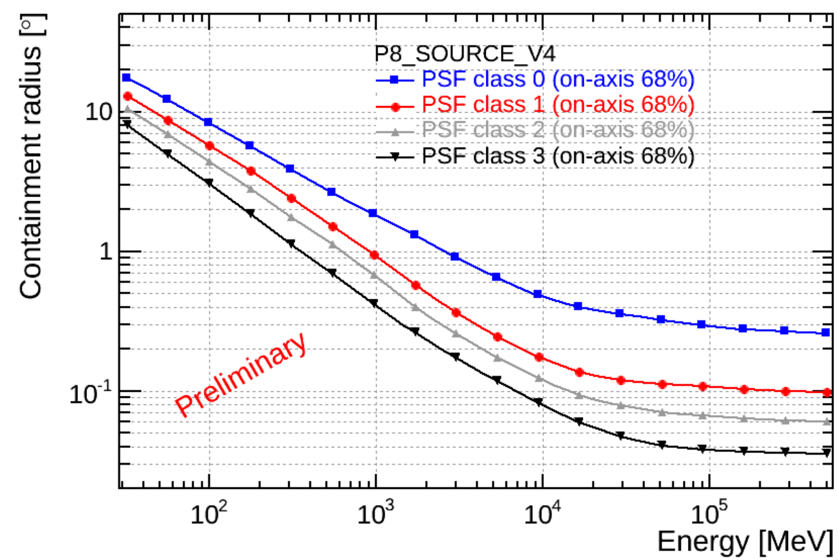


Pass 8: Improving the LAT Performance

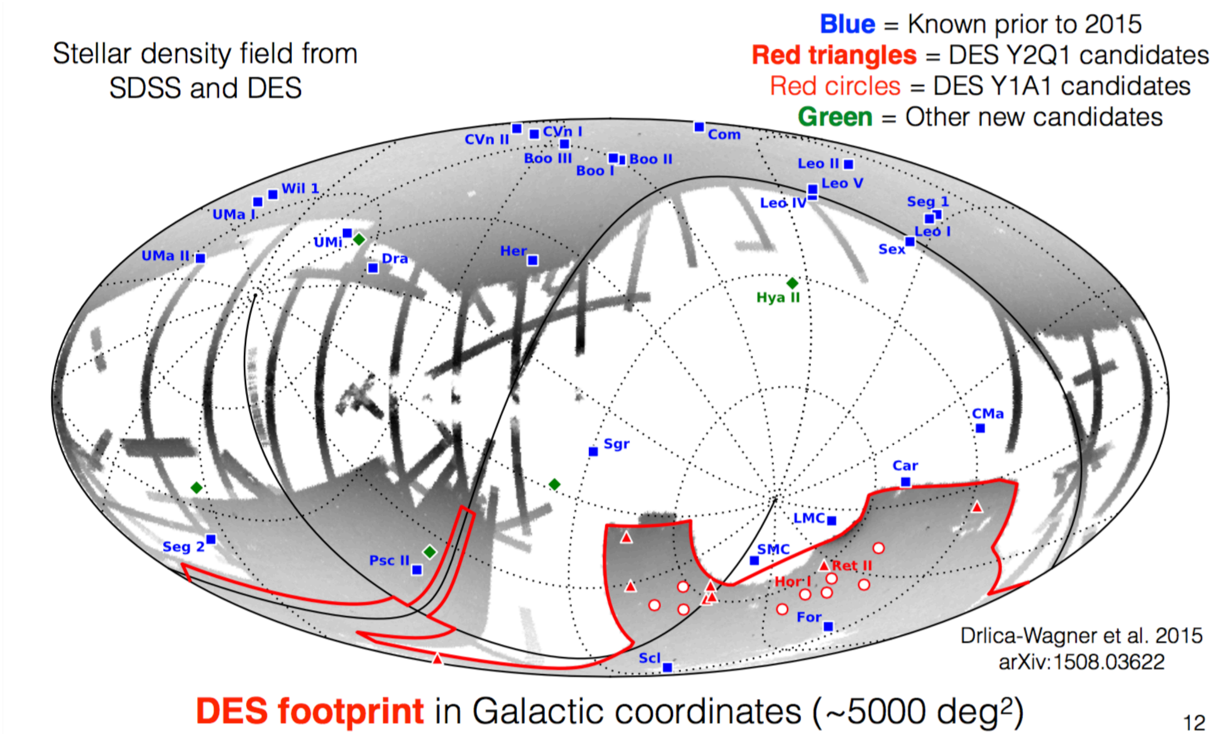
- **Pass 8** is a complete revision of the LAT event-level reconstruction and classification
  - Increased point-source sensitivity at all energies (30-40% at 1-10 GeV)
  - Large increase in acceptance at very low and very high energies (< 100 MeV and > 100 GeV)

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





Discovery Volume for DM Signals from Dwarf Galaxies



- Assuming dSph *J*-factor scaling with distance we could currently expect a 5σ signal for 100 GeV DM at the thermal relic cross section in the b-quark channel for any new dSph within 8 kpc (a volume of 2100 kpc^3)
- With 15 years of data that increases to V > 4200 kpc^3; i.e., doubles the discovery volume.
- At higher masses, where the sensitivity is signal limited, doubling the data increases the discovery volume by $(15/6)^{1.5} \sim 4.0$