Indirect Dark Matter Searches with the *Fermi* Large Area Telescope

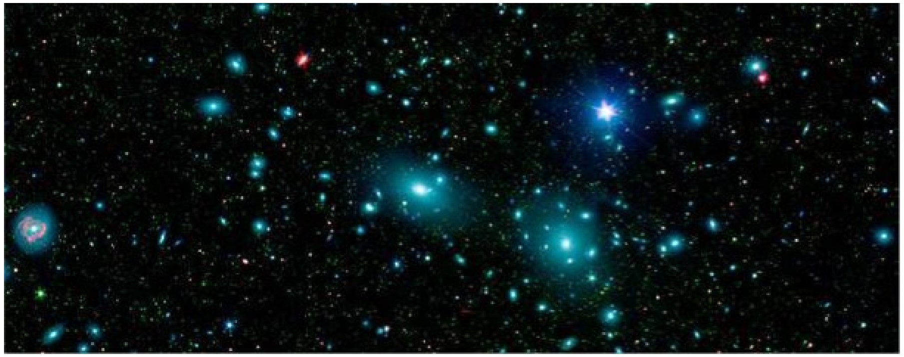
Johann Cohen-Tanugi

on behalf of the *Fermi*-LAT collaboration

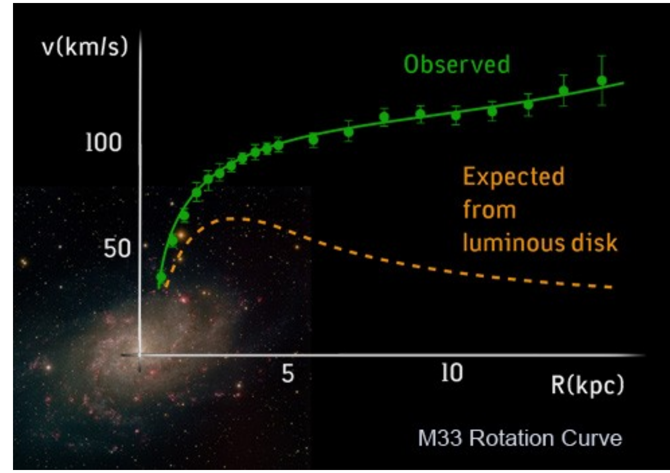
28th Texas Symposium on Relativistic Astrophysics, Geneva

Dec. 13-18, 2015

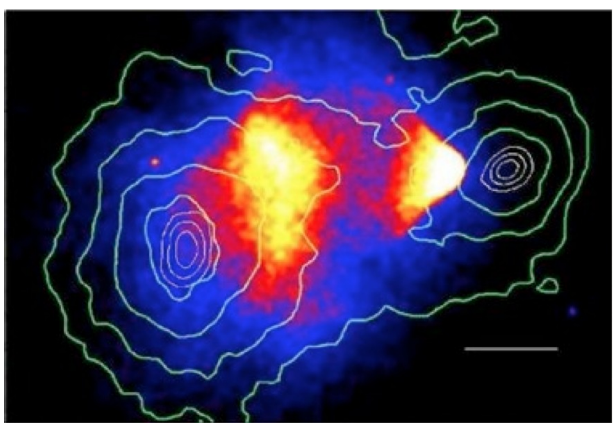
Evidence for / Salient Features of Dark Matter



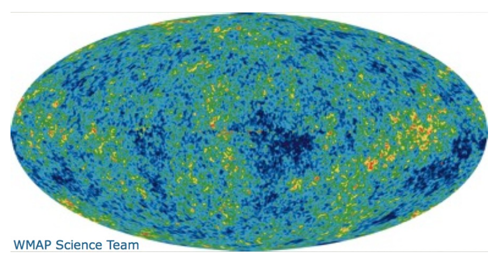
*Comprises **majority** of **mass** in Galaxies*
Missing mass on Galaxy Cluster scale
Zwicky (1937)

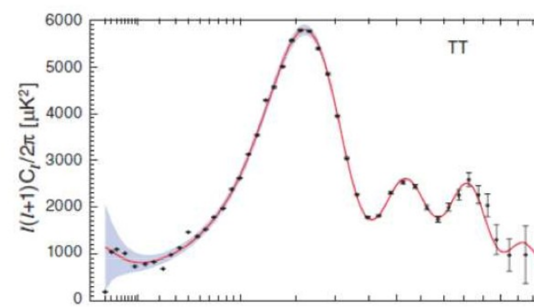


*Large **halos** around Galaxies*
Rotation Curves
Rubin+(1980)



*Almost **collisionless***
Bullet Cluster
Clowe+(2006)

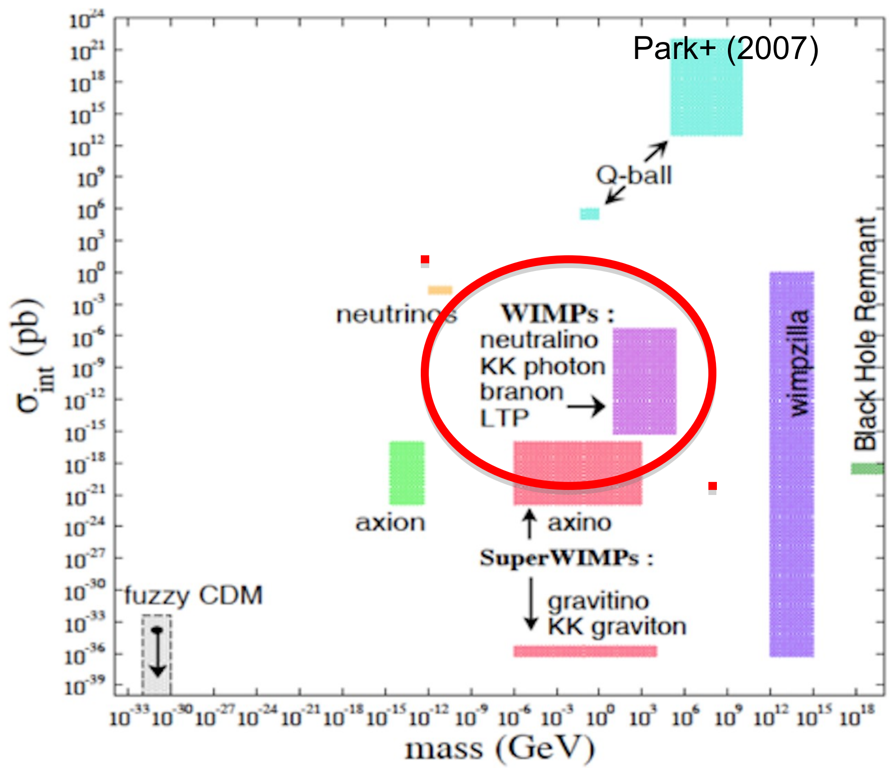




Non-Baryonic
Big-Bang Nucleosynthesis,
CMB Acoustic Oscillations
WMAP(2010), Planck(2015)

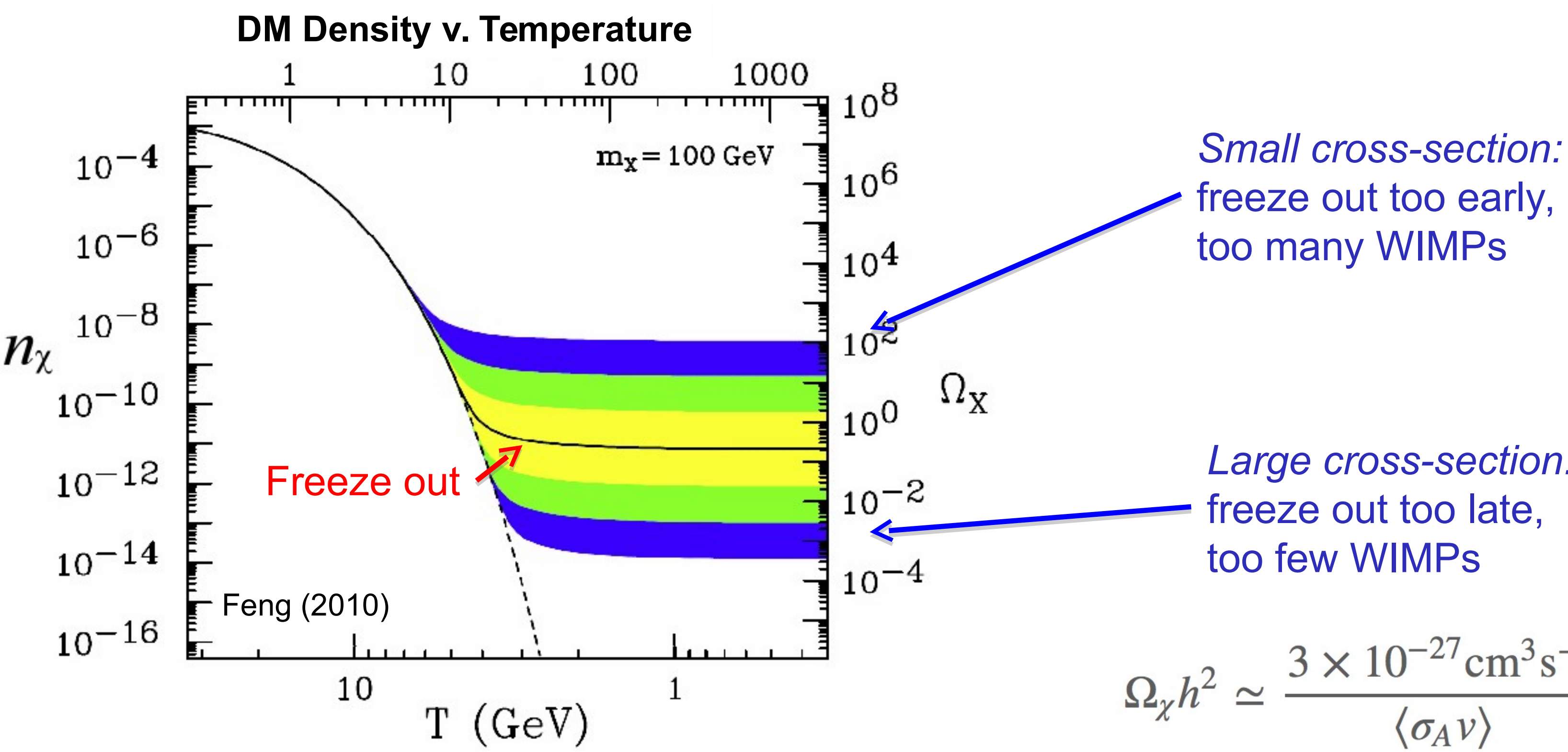
Cosmological Constraints on Dark Matter

DM Candidates by Mass & Cross Section



- No Standard Model particle matches the known properties of dark matter
- Many candidate particles have been proposed:
  - LAT searches (and my talk) focus on WIMPs
  - LAT is also sensitive to signals from axion-like particles, primordial black holes and gravitinos, not necessarily in the phase space where these could be candidates

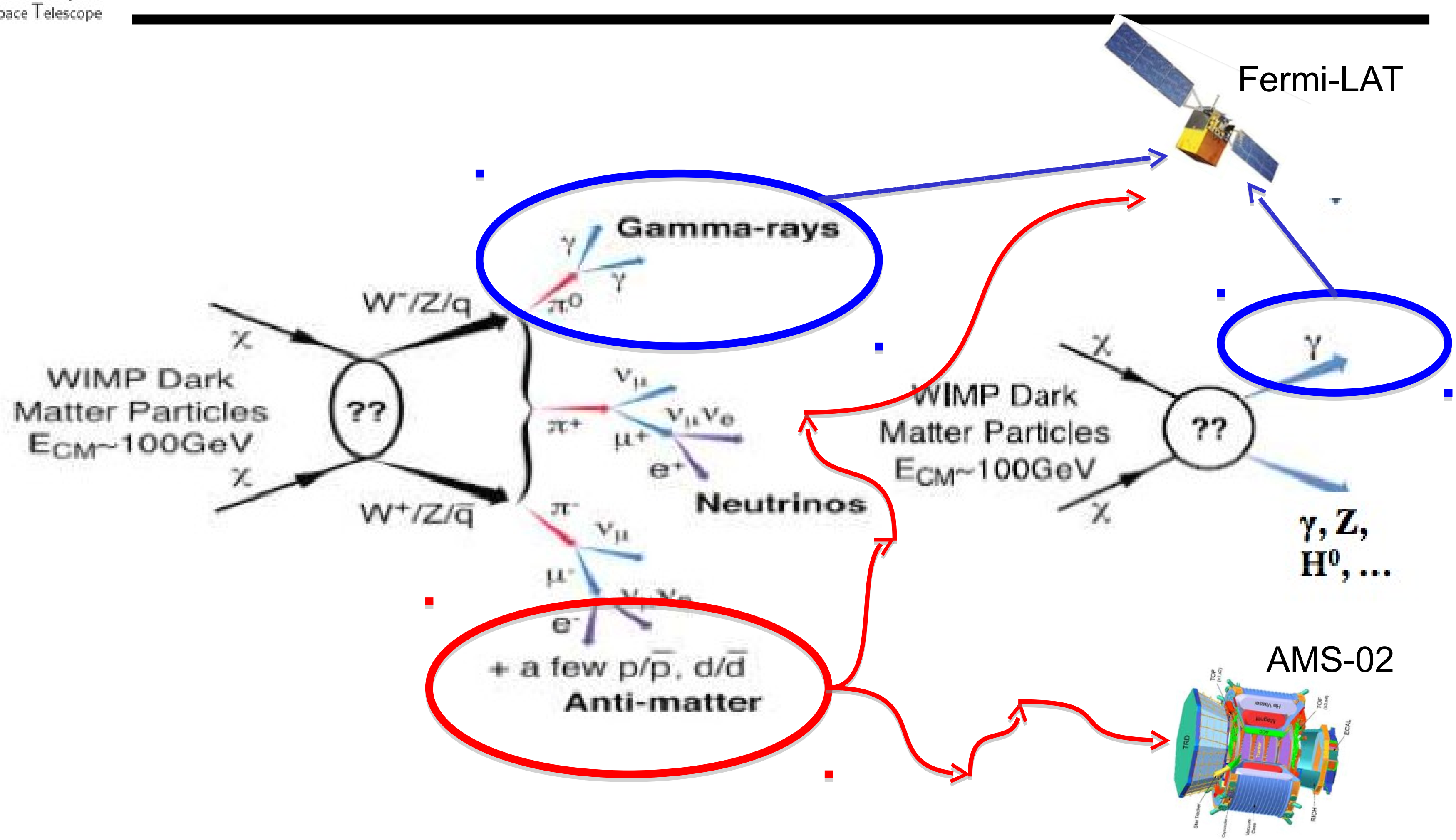
WIMP Dark Matter as a Thermal Relic



$$\Omega_\chi h^2 \simeq \frac{3 \times 10^{-27} \mathrm{cm}^3 \mathrm{s}^{-1}}{\langle \sigma_A v \rangle}$$

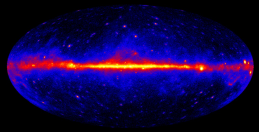
- The calculation of the thermal-averaged cross-section <σv> needed to obtain the relic density is robust and gives <σv> ~ 3 10^{-26} $cm^3 s^{-1}$
- At that cross-section we are probing the entire class of particle models that would generate GeV-to-TeV dark matter

Indirect Detection of WIMPs

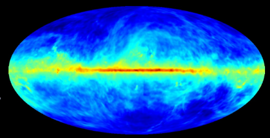


- What we observe are stable final-state annihilation products
  - Neutral particles (γ; ν, observed by IceCube) travel directly to us
  - Charged particles (e^+,e^-,p,anti-p) diffuse in Galactic magnetic fields

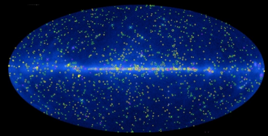
Indirect Searches for DM in the Fermi Sky



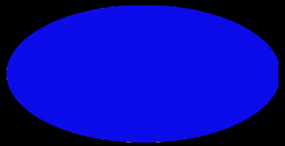
Fermi Sky =



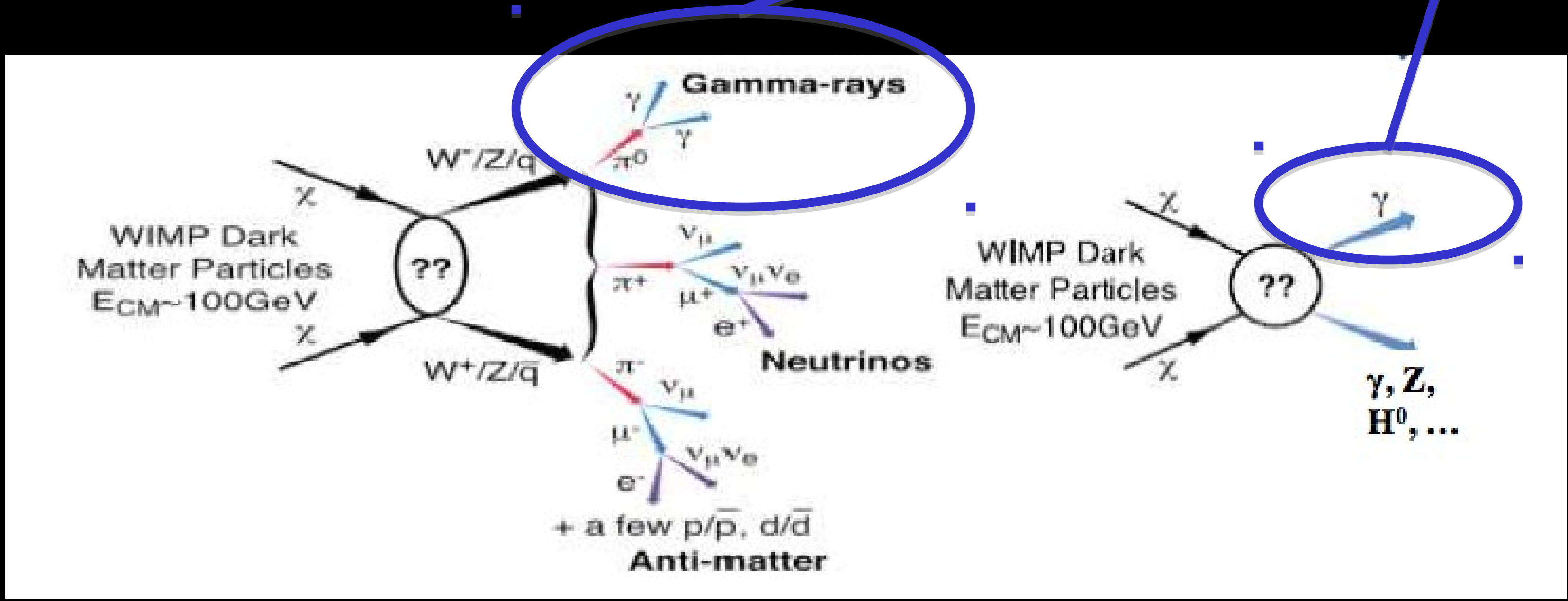
Galactic +



Point Sources +



Isotropic + ???

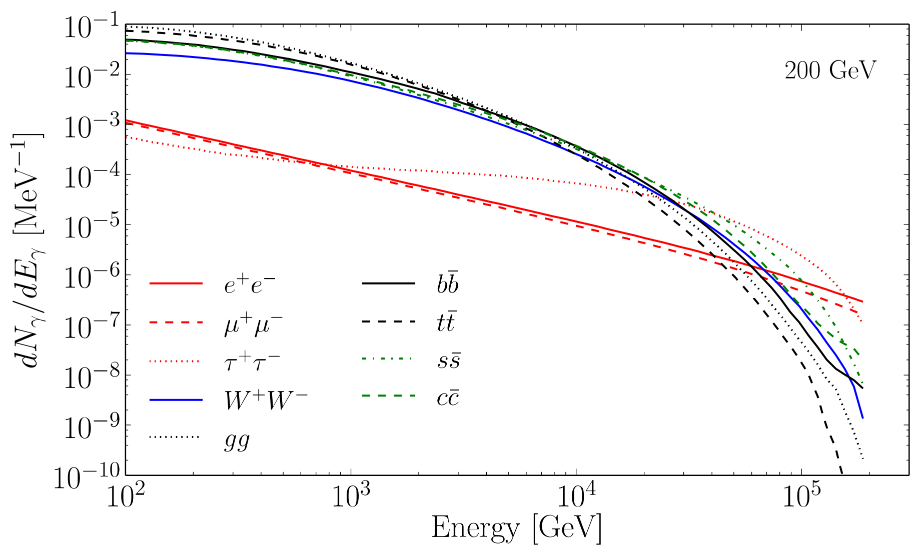


The Key Formula for WIMP Searches

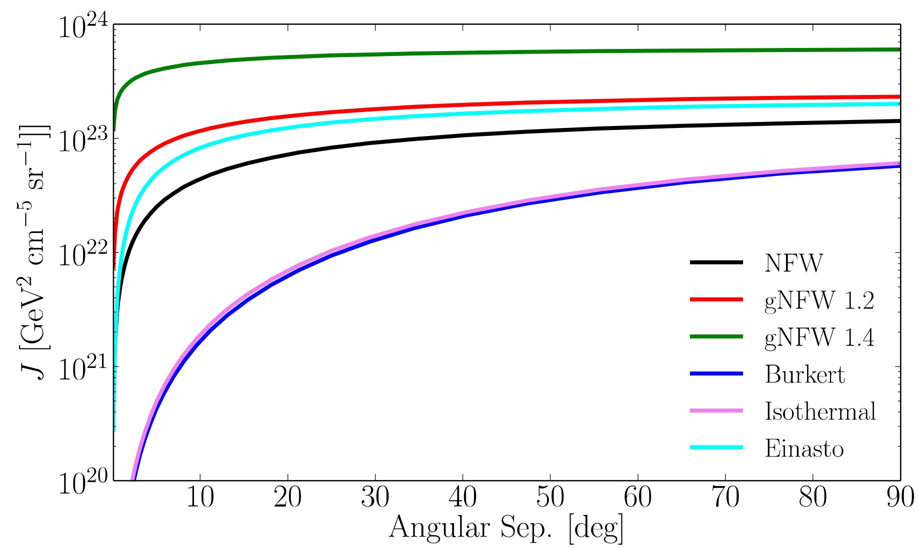
Particle Physics | **Astrophysics (*J*-Factor)**

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

dN/dE for 200 GeV DM

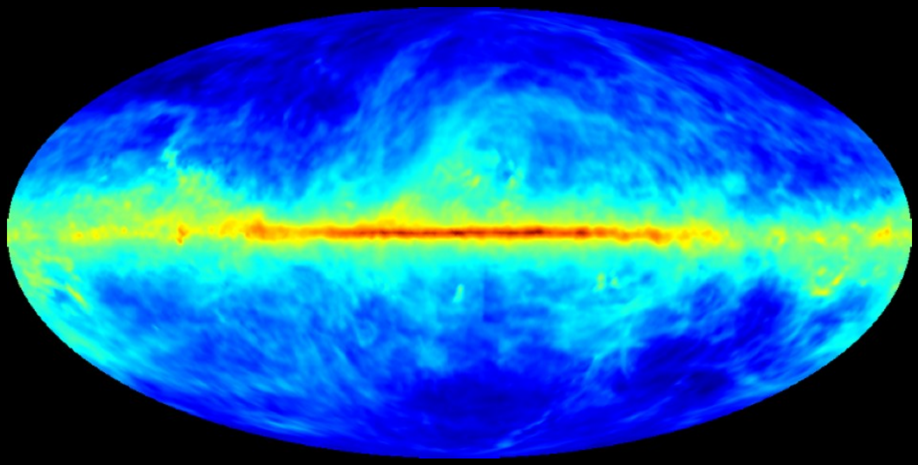


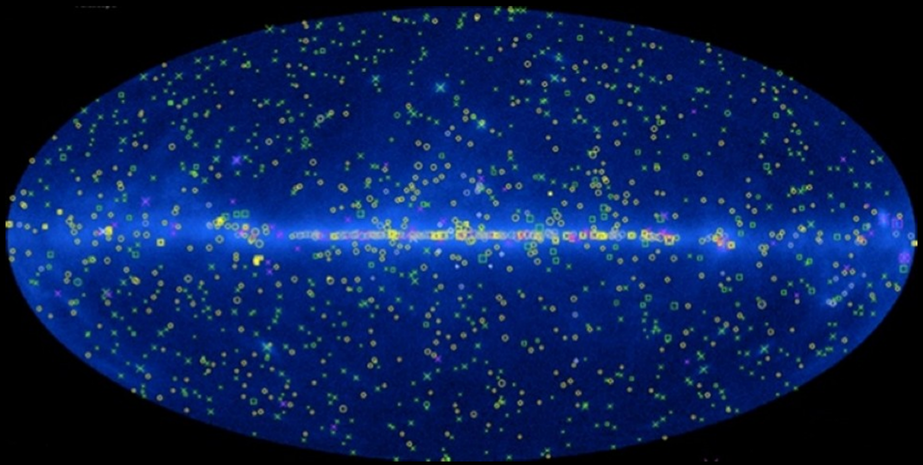
J-factor for the Galactic Center



- *Note*: *J*-factor includes distance, i.e., *J*-factor would decrease by four if a point-like source were twice as far away
- *Note*: the key factor of $1/m_\chi^2$ is b/c we express the *J*-factor as a function of mass density (which we can measure), not number density

Astrophysical Backgrounds (GeV)





- Diffuse Backgrounds:
  - Cosmic-ray interactions with interstellar matter and radiation fields
- Source Backgrounds:
  - ***Pulsars***
  - Blazars and Active Galactic Nuclei
  - Supernova Remnants
  - Galaxies (starburst galaxies)
- Unresolved Sources

Search Strategies (against the γ-ray Sky)

Satellites

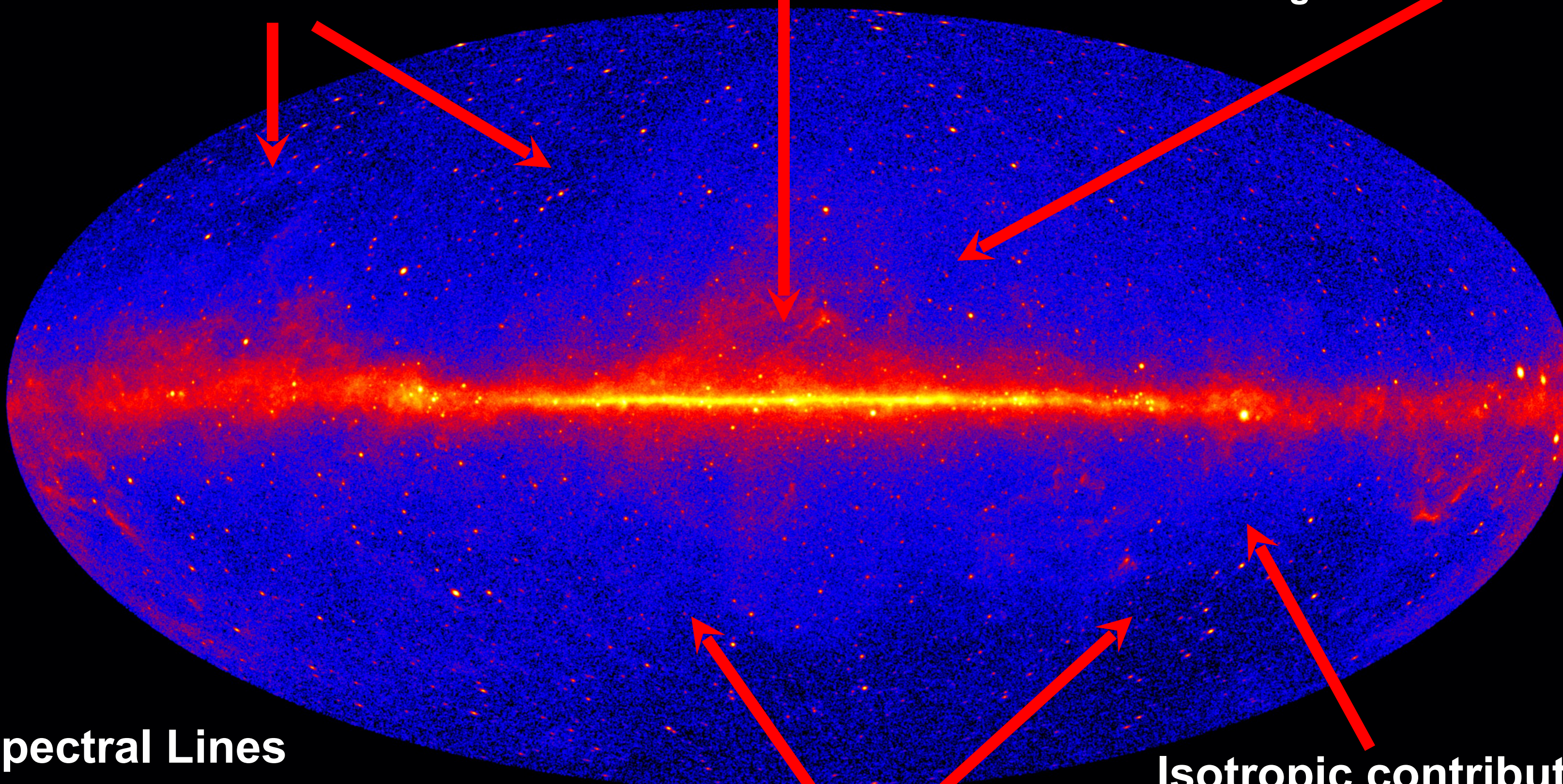
Low background and good source id, but low statistics

Galactic Center

Good statistics, but source confusion/diffuse background

Milky Way Halo

Large statistics, but diffuse background



Spectral Lines

Little or no astrophysical uncertainties, good source id, but low sensitivity because of expected small branching ratio

Galaxy Clusters

Low background, but low statistics

Isotropic contributions

Large statistics, but astrophysics, galactic diffuse background

LAT 7 Year Sky > 1 GeV

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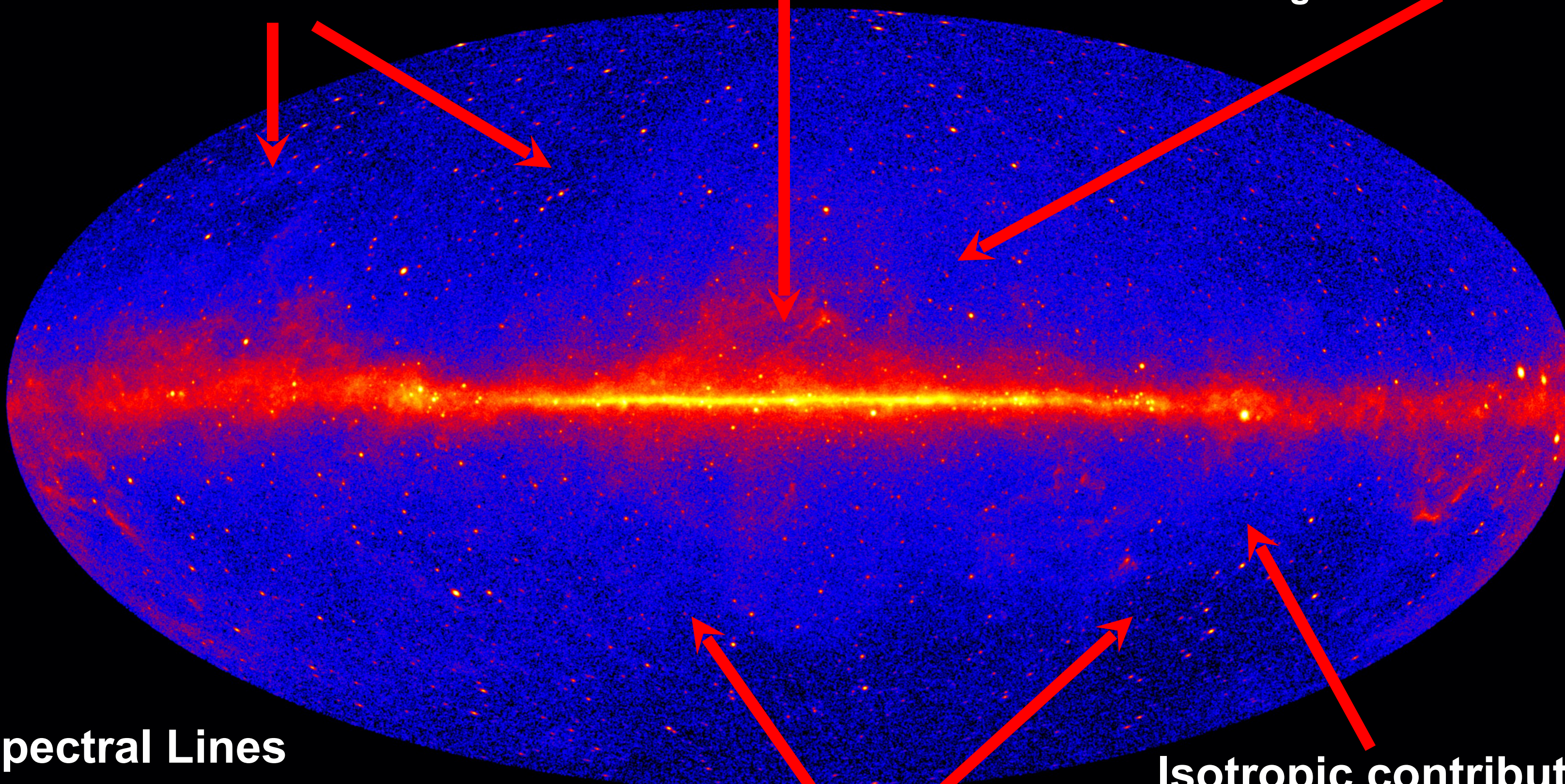

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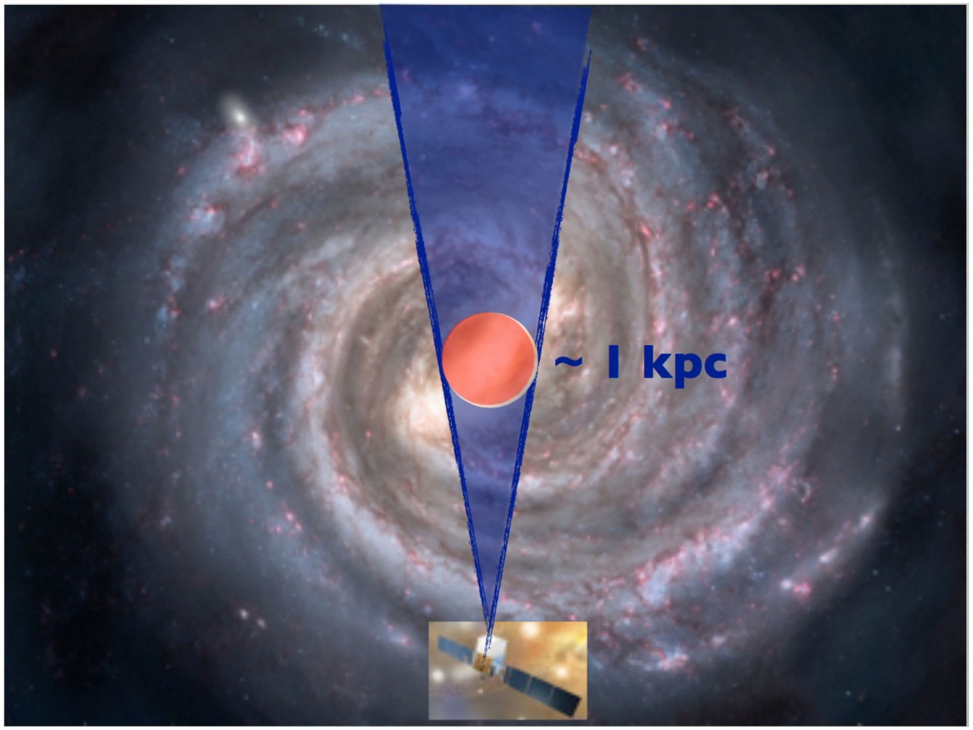
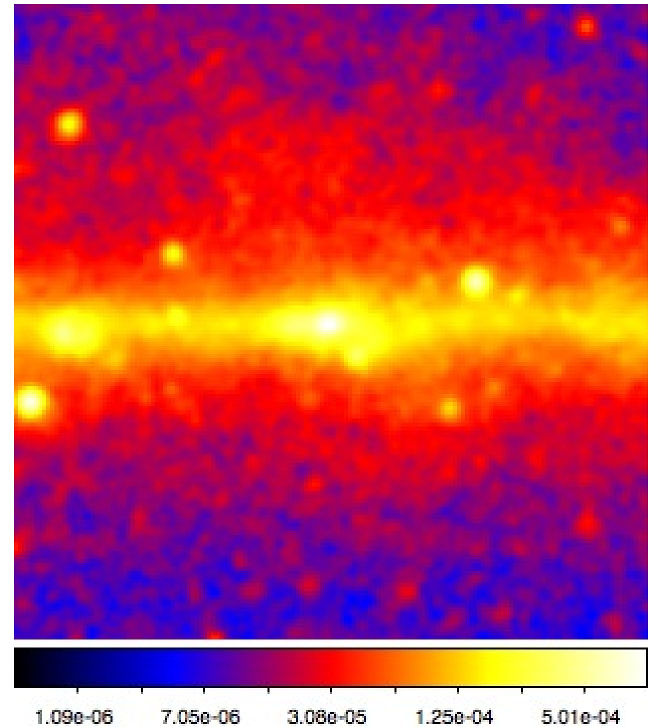
Observing the Inner Galaxy

Fermi-LAT collaboration arxiv 1511.02938 in press to ApJ



LAT Intensity: 7 years, > 1 GeV, 15°x15°



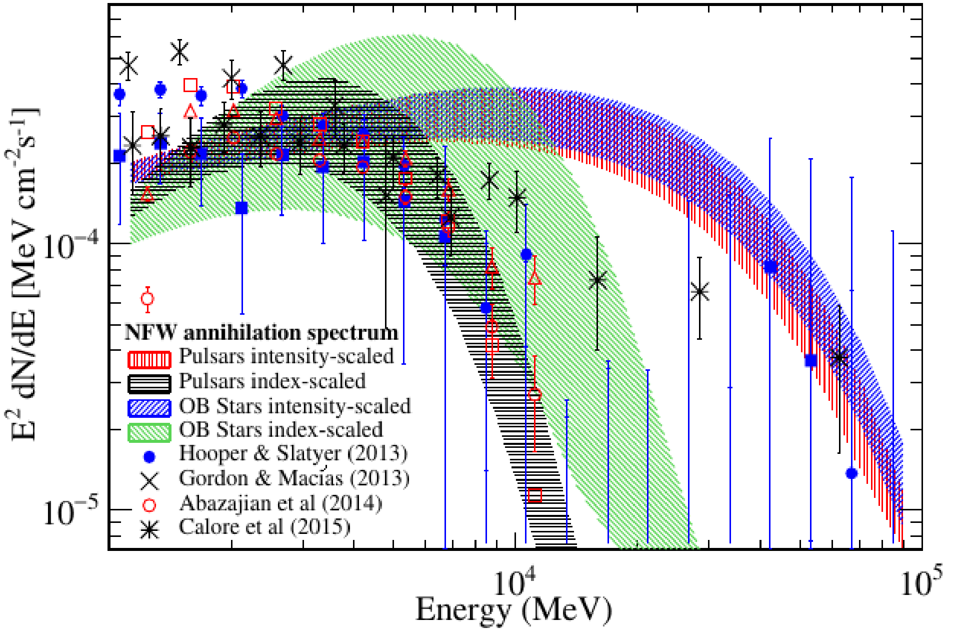
- Observations of the inner Galaxy include strong astrophysical foreground and backgrounds along the line of sight
  - In the 1-100 GeV energy band these account for ~85% of the γ-rays in a 15°x15° box around the Galactic center

Observing the Inner Galaxy

Fermi-LAT collaboration arxiv 1511.02938 in press to ApJ

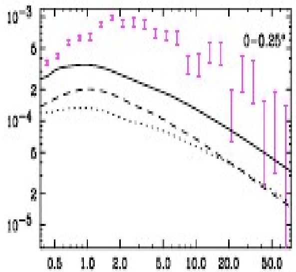
- Use 4 GALPROP models tuned to large scale, excluding IG, then fit inner ring HI/CO component and IC, together with an ab initio and self-consistent source extraction and fitting
- In IG, IC higher and pi0 lower than baseline models
  - incomplete gas census, and artifacts present when transforming from survey data to the ring column density maps.
    - Different Xco factor and/or CR nuclei intensities (true for CMZ anyway)
  - Incomplete knowledge of ISRF, electron intensity underestimated

- An extended GC residual persists in all cases, **but its spectrum depends on the IEM used in the analysis** →
- Its spatial extension can be modeled with a centrally peaked profile, however there are other positive (and negative) residuals also over the region **with similar magnitude**. A simple centrally peaked profile model is **not** a complete description for the residual emissions!

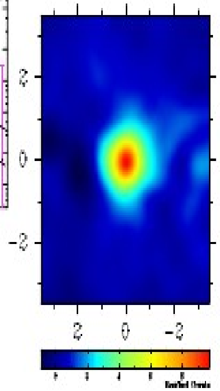


The Galactic Center (GC) excess

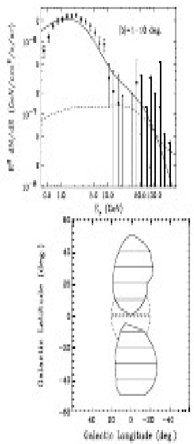
Excess emission



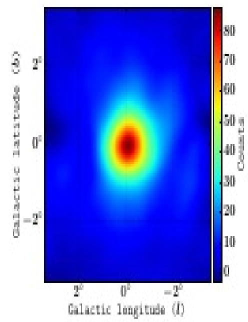
Goodenough & Hooper arxiv:1010.2752



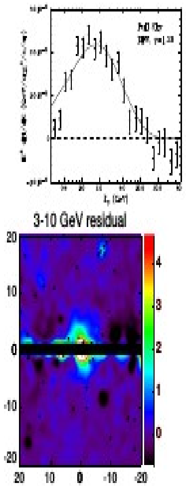
Abazajian & Kaplinghat arxiv:1207.6047



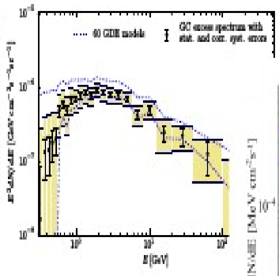
Hooper & Slatyer arxiv:1302.6589



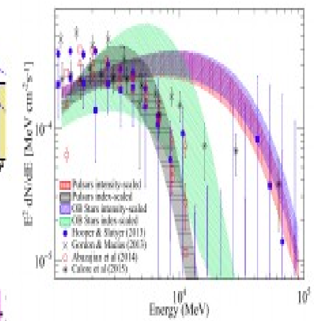
Gordon & Macias arxiv:1306.5725



Daylan et al. arxiv:1402.6703



Calore et al. arxiv:1409.004



Ajello et al. arxiv:1511.02938

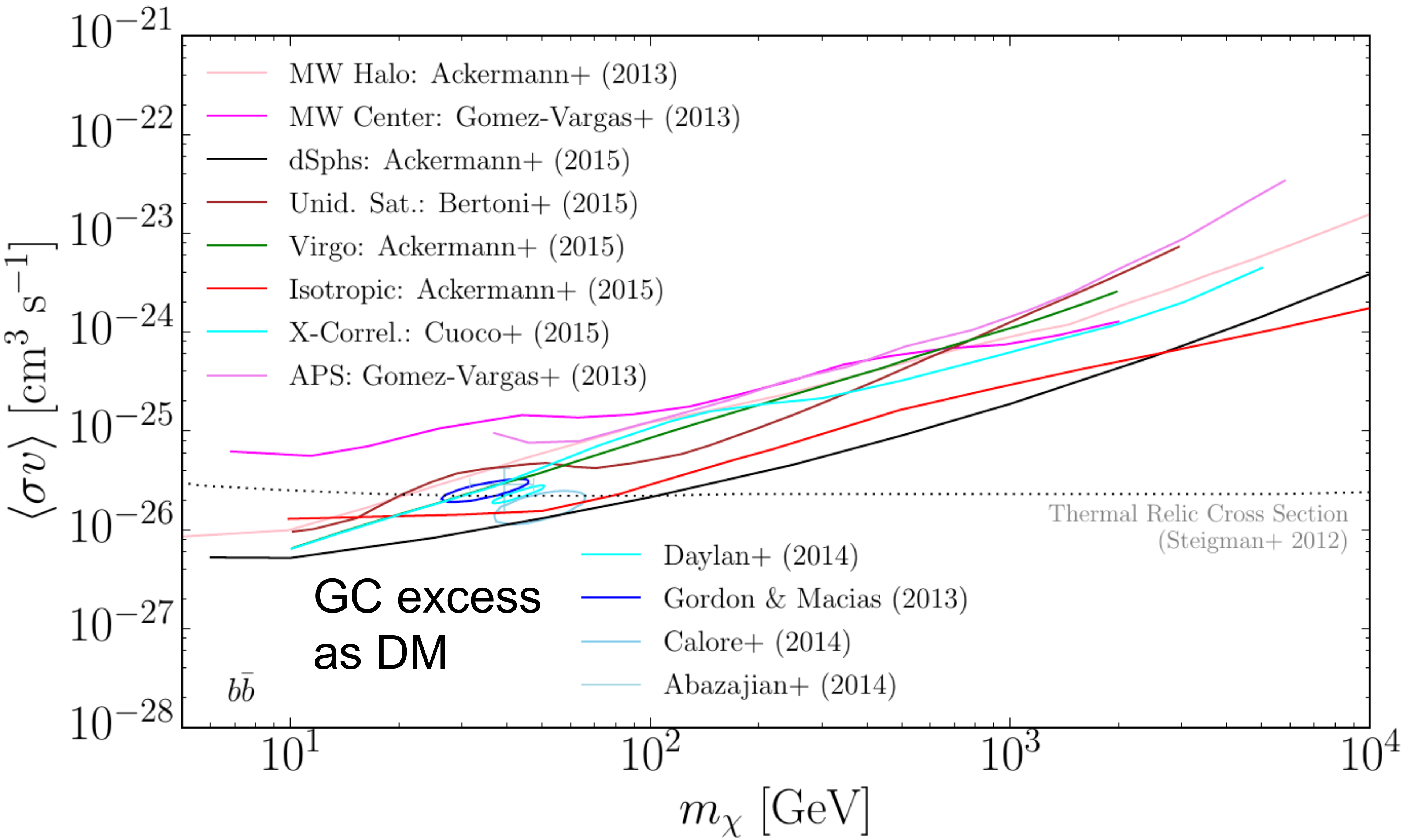
and counting

Dark matter annihilation, unresolved sources, CR electrons?

- Mirabal (arxiv:1309.3428), Petrovic et al. (arxiv:1411.2980), Cholis et al. (arxiv:1506.05119), Lee et al. (arxiv:1506.05124), Bartels et al. (arxiv:1506.05104), Brandt & Kocsis (arxiv:1507.05616), Carlson et al. (arXiv:1510.04698) etc.

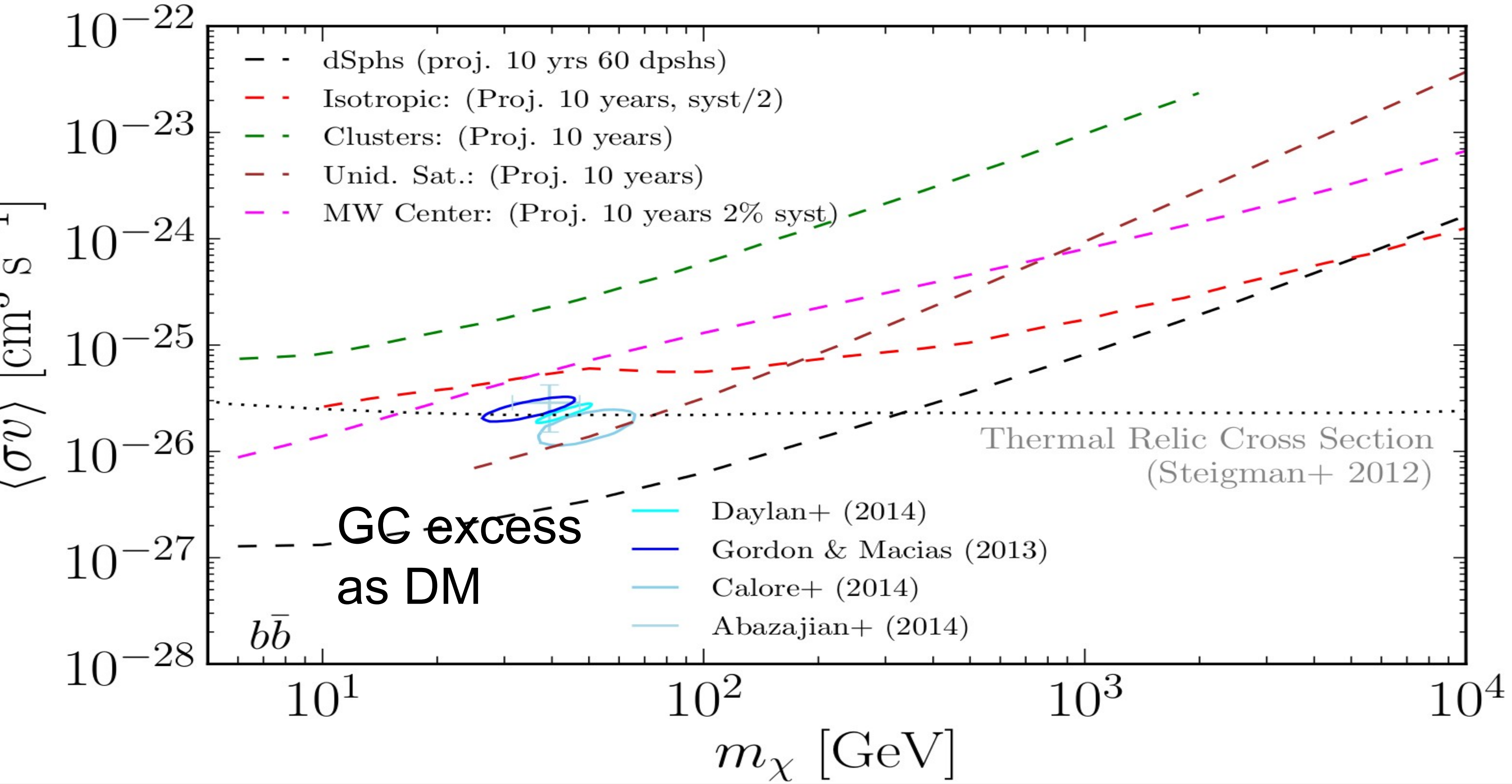
A Sample of Published Results from Indirect DM Searches with LAT Data

Representative Results for Different Search Targets for the b-quark Channel



A Sample of Published Results from Indirect DM Searches with LAT Data

Projections as computed for a recently submitted white paper



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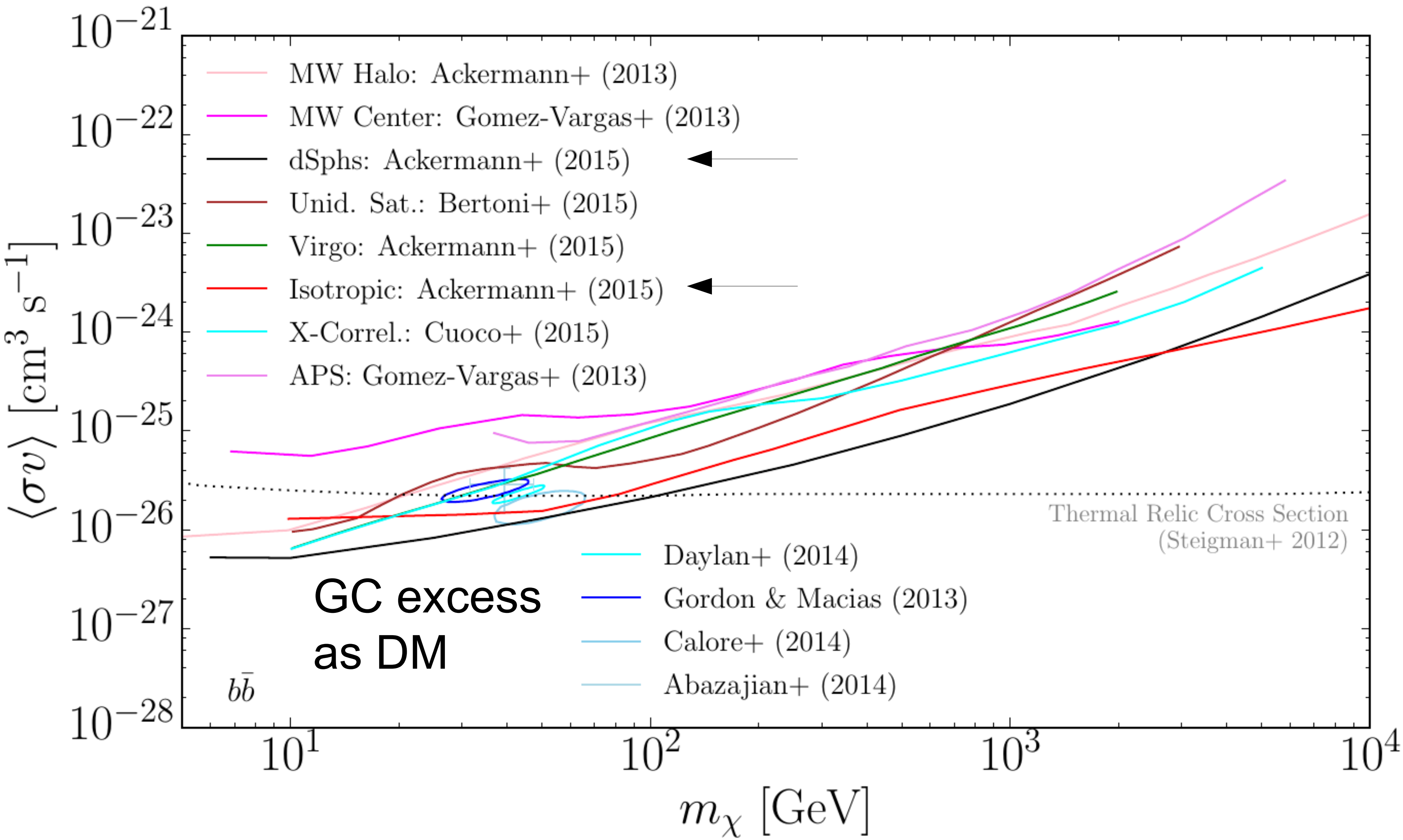


DM search in a cosmological isotropic signal

- Take all halo/subhalo DM contribution at all z

$$\frac{d\phi}{dE_0} = \frac{\langle \sigma v \rangle}{8\pi} \frac{c\,(\Omega_{\rm DM}\rho_c)^2}{m_{DM}^2} \int dz\, e^{-\tau(E_0,z)} \frac{(1+z)^3}{H(z)} \zeta(z) \left.\frac{dN}{dE}\right|_{E=E_0(1+z)}$$

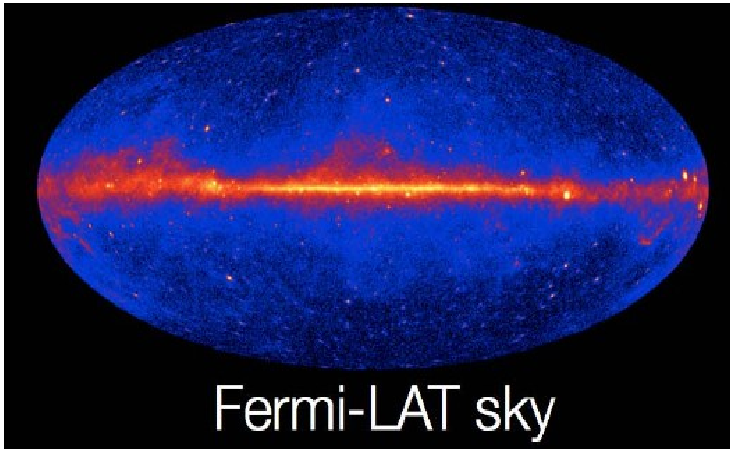
WIMP annihilation cross-section | EBL attenuation (Domínguez+11) | "Flux multiplier" | WIMP-induced spectrum

- "flux multiplier" : encodes the clumpiness of the DM in the Universe; large uncertainties at small masses (extrapolations to simulations)
- Use 2 different modeling of the halo distributions to investigate theoretical uncertainties

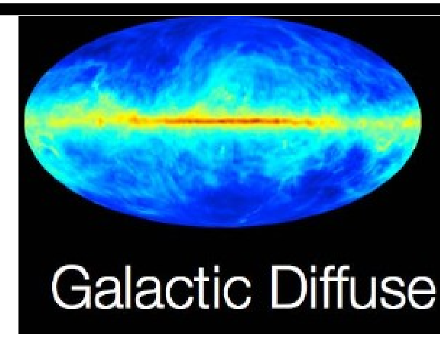
Ackermann+15, JCAP09(2015)008 [astro--ph/1501.05464]

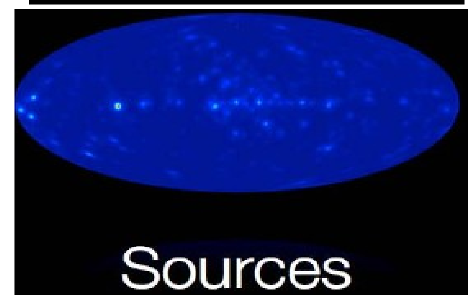
Search in the isotropic gamma-ray background

Take

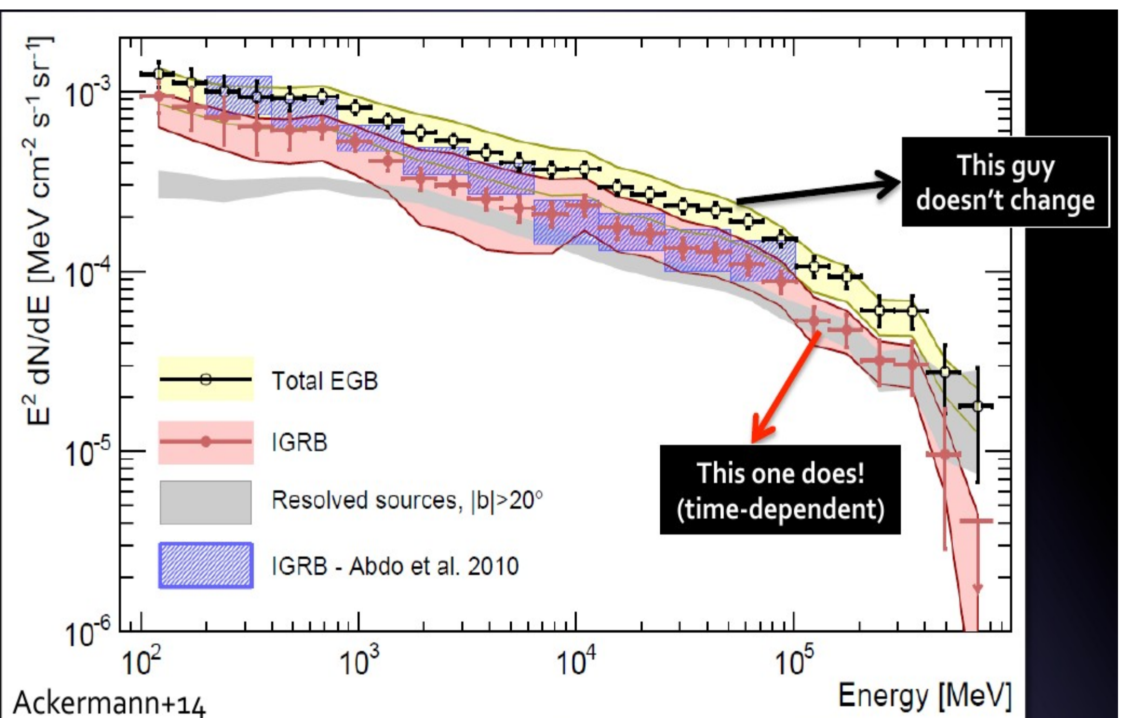


and remove





(and isotropic contribution of CR...)



could there be a DM signal lurking in this isotropic diffuse emission?

DM limits to the isotropic signal

2 extremes (taken from Sanchez-Conde, Fermi Symposium 2015):

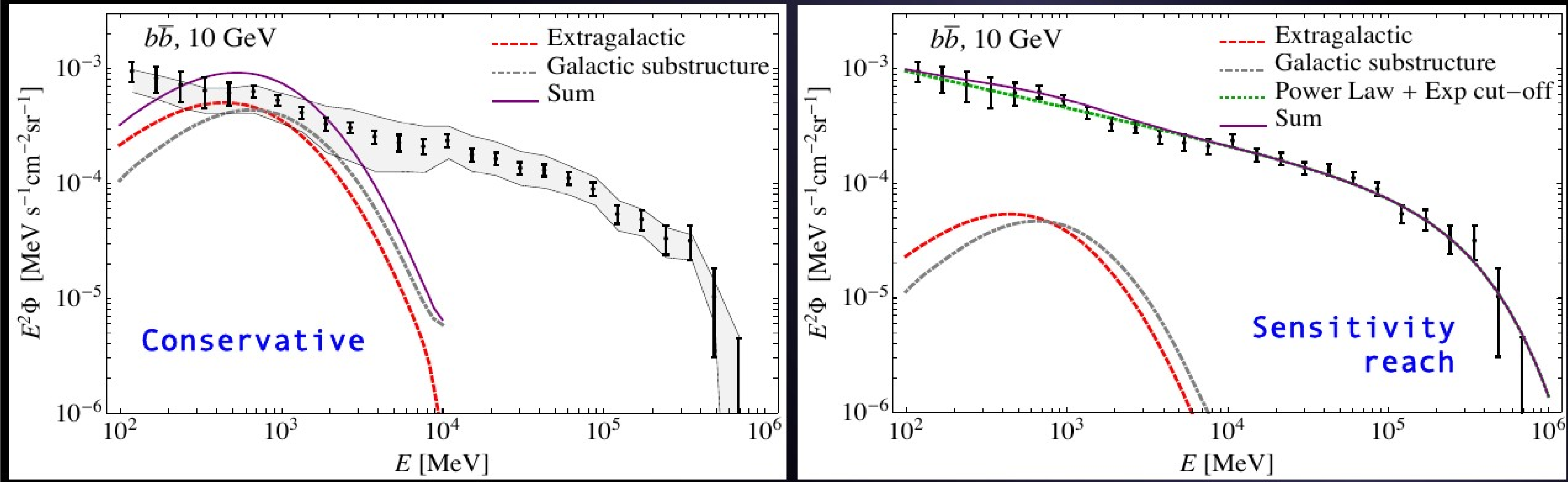
Conservative limits

- Only DM. No astrophysical contributions to the measured IGRB.
- Not preferred Galactic diffuse model among those tested in IGRB measurement paper.

Sensitivity reach

- Total astrophysical contribution fully explains the measured IGRB at all energies.
- We can entirely rely on a Galactic diffuse model to derive the IGRB.

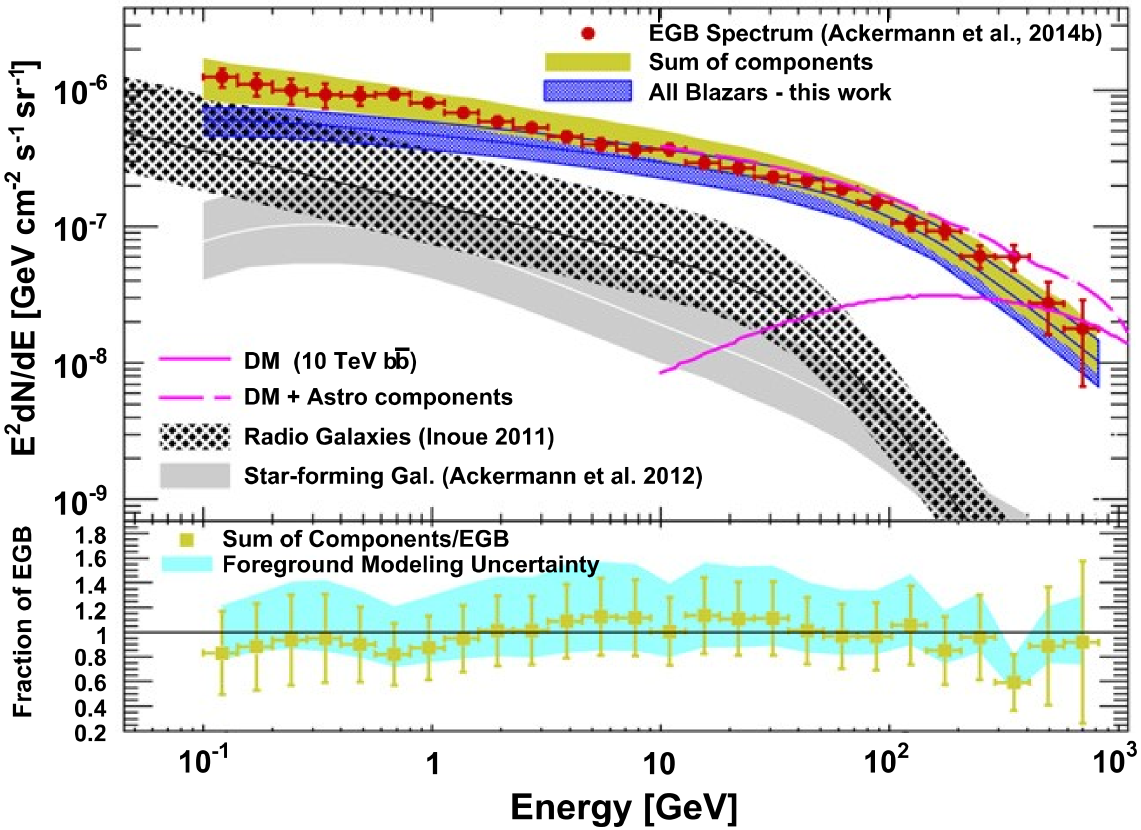
Ackermann+15, JCAP09(2015)008 [astro-ph/1501.05464]



Examples of DM-produced gamma-ray spectra which are at the border of being excluded at 2σ level in our two procedures to set DM limits

And a more realistic estimate

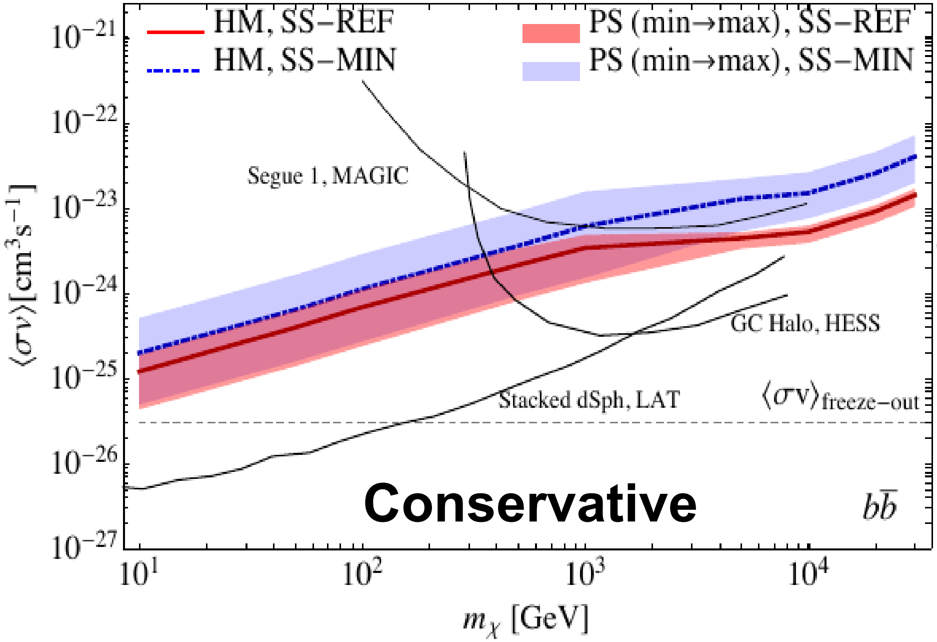
Comparison of Extragalactic Gamma-ray Background to Contributions from Sources

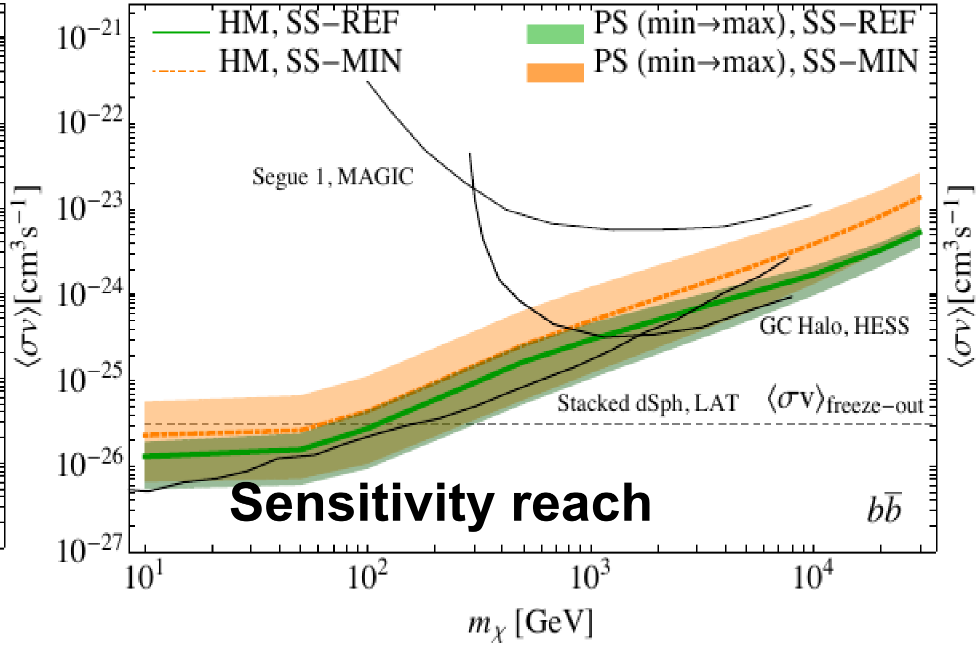


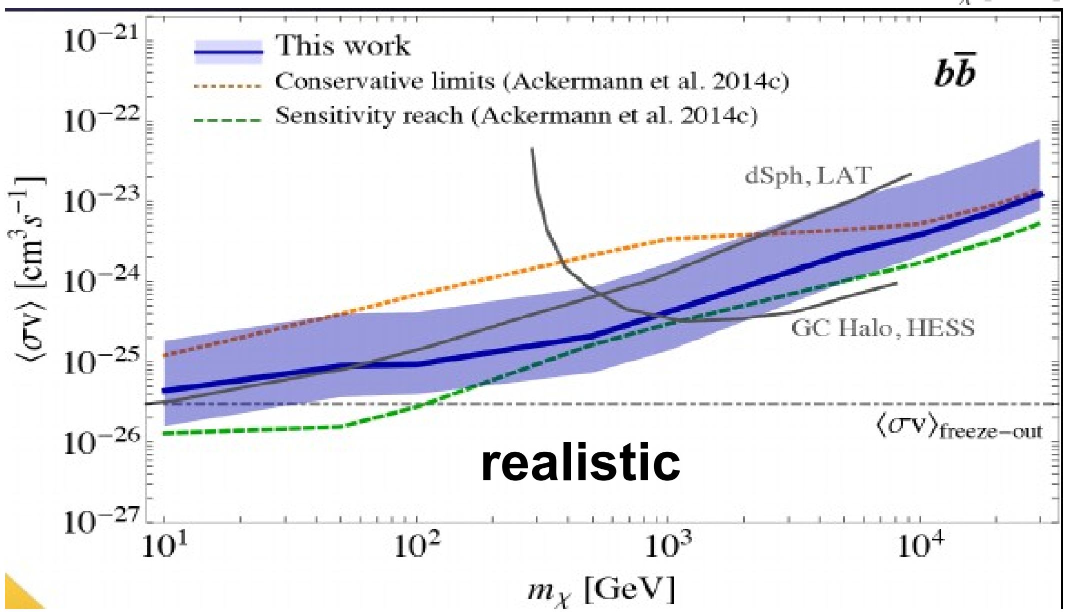
Ajello et, PRL 2015 arXiv:1501.05301

- Estimating the contribution from unresolved sources requires deriving the cumulative luminosity function N(Flux > Threshold) as a function of the threshold (log N – log S in astronomy parlance)
- Knowledge of the log N – log S can also constrain the DM emission from local DM halos

Results : DM limits

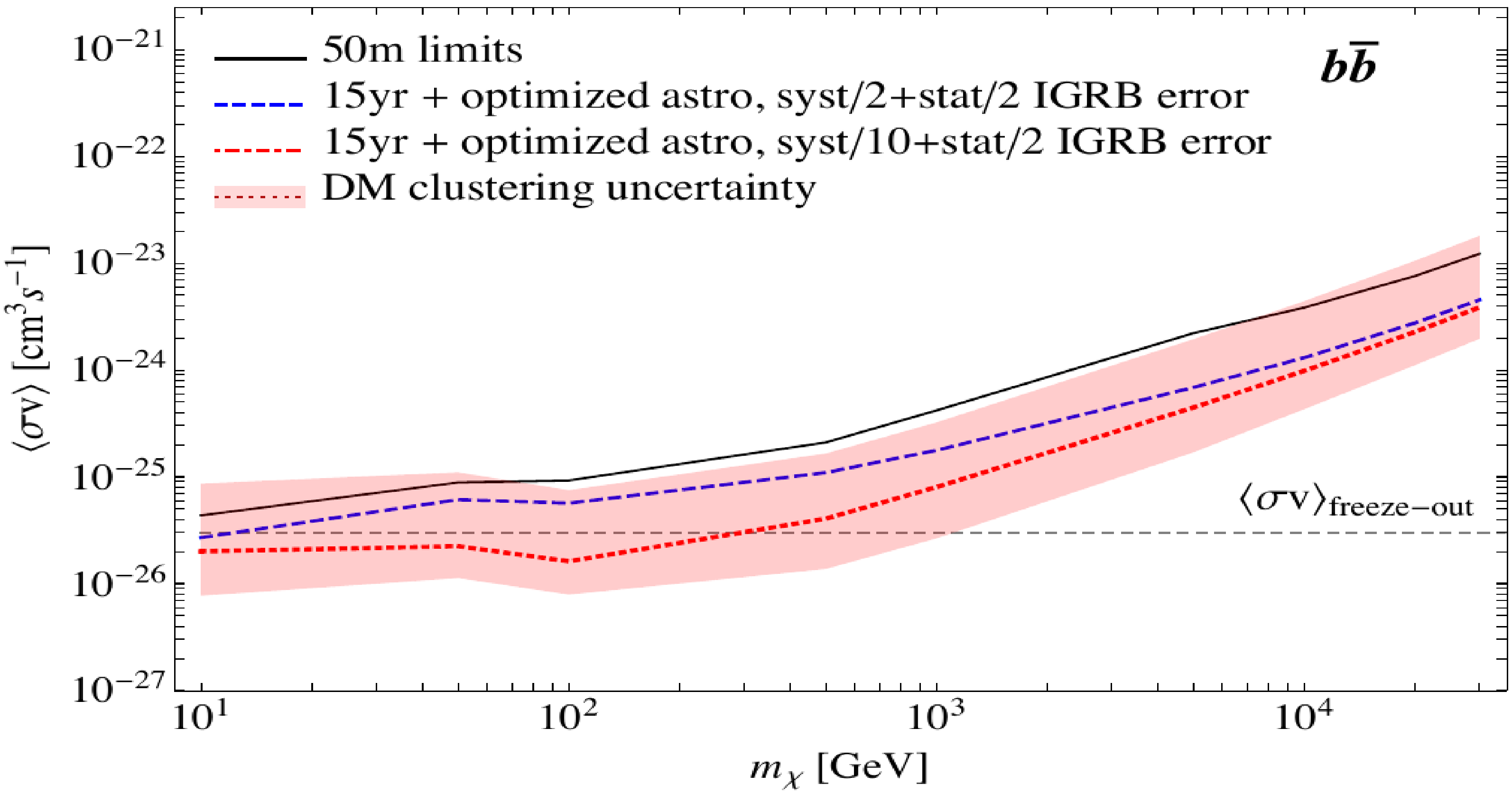






Projected Sensitivity from Studies of the EGB & IGRB

Projected Upper Limits From for 15 Years of data, in the realistic case



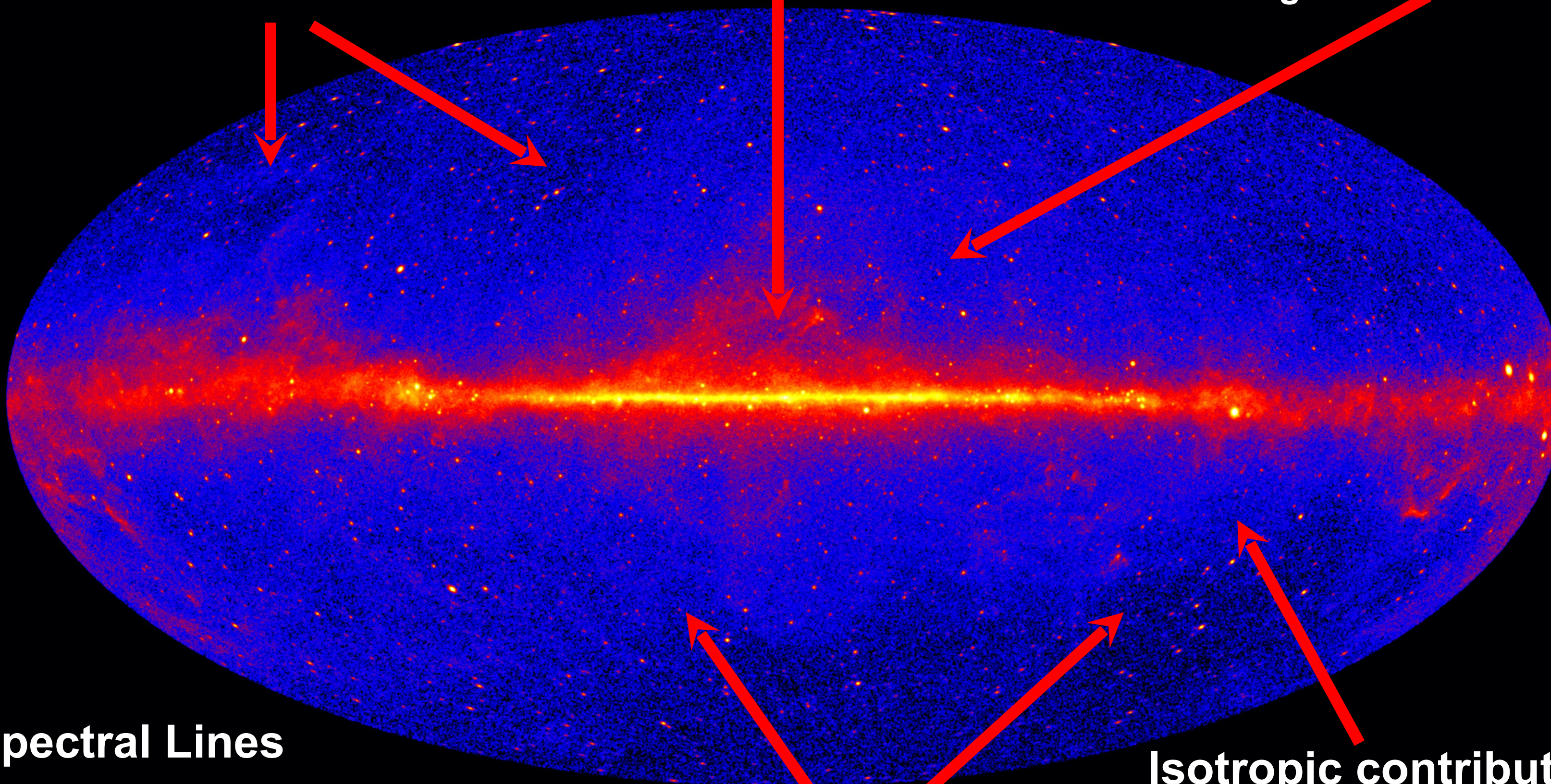
- These limits are calculated by comparing the sum of contributions form the known γ-ray emitting source classes to the measured IRGB
- To make projections we must estimate how the IGRB measurement will improve with additional data (including Planck microwave data)

Search Strategies (against the γ-ray Sky)

Satellites
Low background and good source id, but low statistics

Galactic Center
Good statistics, but source confusion/diffuse background

Milky Way Halo
Large statistics, but diffuse background



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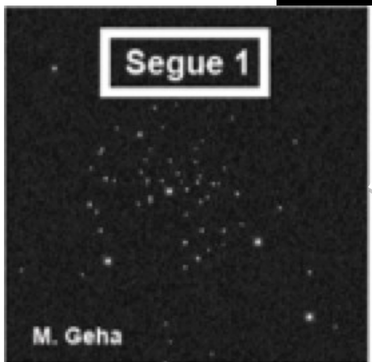
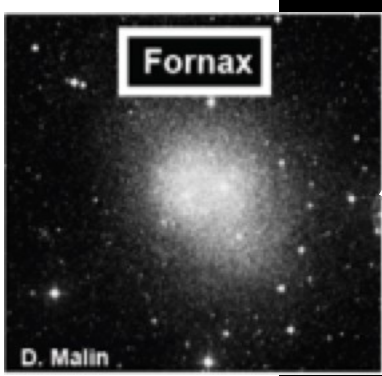
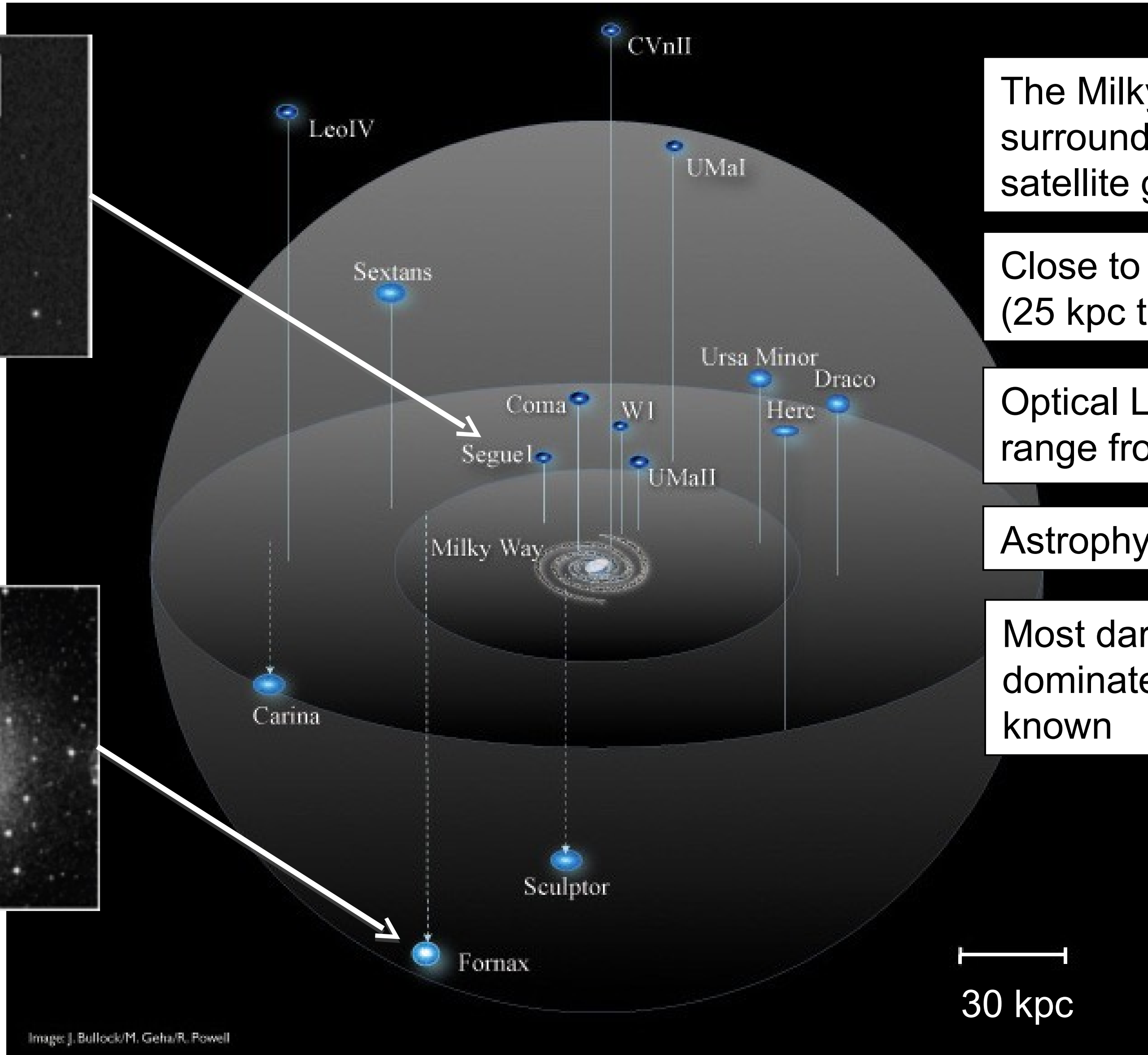
LAT 7 Year Sky > 1 GeV

Some Dwarf Spheroidal Satellites of the Milky Way







The Milky Way is surrounded by small satellite galaxies

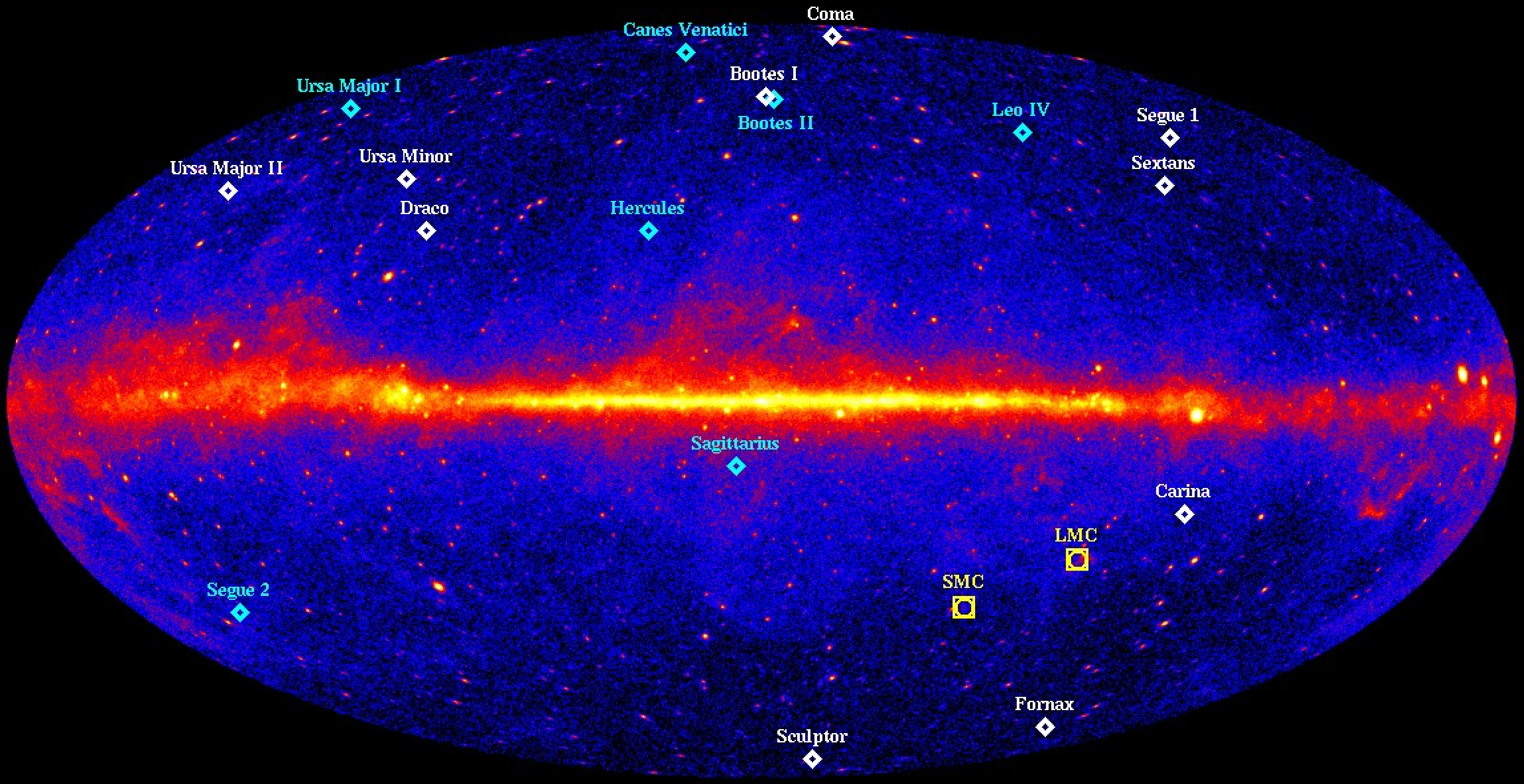
Close to Earth (25 kpc to 250 kpc)

Optical Luminosities range from 10^3 to 10^7 $L_{\odot}$

Astrophysically inactive

Most dark matter dominated objects known

Searches for DM in MW Satellites



- Roughly two dozen Dwarf spheroidal (dSph) satellite galaxies of the Milky Way known up to the DES era
- Negligible astrophysical γ-ray production expected

Joint Likelihood Analysis

- Assume same dark matter particle present in all dwarf spheroidal galaxies (same spectrum)
- Use all dwarf galaxies with well-determined J-factors in non-overlapping regions (N=15)
- Perform a combined likelihood analysis:
  - Predicted flux for each dwarf will depend on individual dark matter content (J-factor)
  - Include statistical uncertainties from stellar kinematic data.
  - Fit backgrounds independently
- Joint likelihood function:

$$\frac{d\Phi}{dE}(E,\phi,\theta) = \frac{1}{4\pi}\frac{\langle\sigma_{ann}v\rangle}{2m_{\rm DM}^2}\sum_f \frac{dN^f}{dE}B_f \times \int_{\Delta\Omega(\phi,\theta)} d\Omega' \int_{los} \rho^2(r(l,\phi'))dl(r,\phi')$$

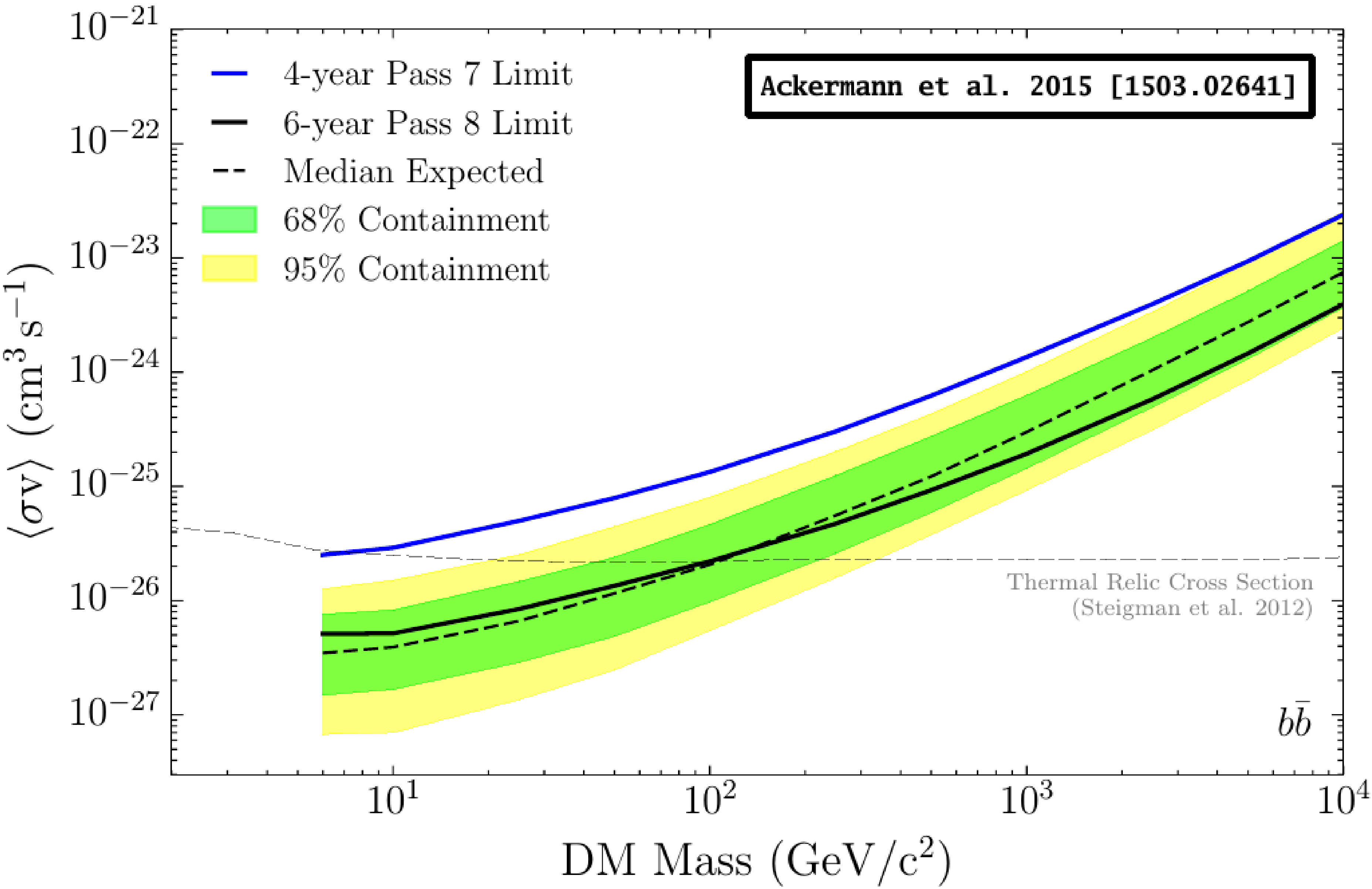
$$L(D\,|\,\mathbf{p_m},\{\mathbf{p_k}\}) = \prod_k L_k^{\rm LAT}(D_k\,|\,\mathbf{p_m},\mathbf{p_k}) \times \frac{1}{\ln(10)J_k\sqrt{2\pi}\sigma_k} e^{-(\log_{10}(J_k)-\overline{\log_{10}(J_k)})^2/2\sigma_k^2}$$

Shared by all dwarfs (dark matter particle parameters) — $\mathbf{p_m}$

Fit for each dwarf (background sources) — $\{\mathbf{p_k}\}$

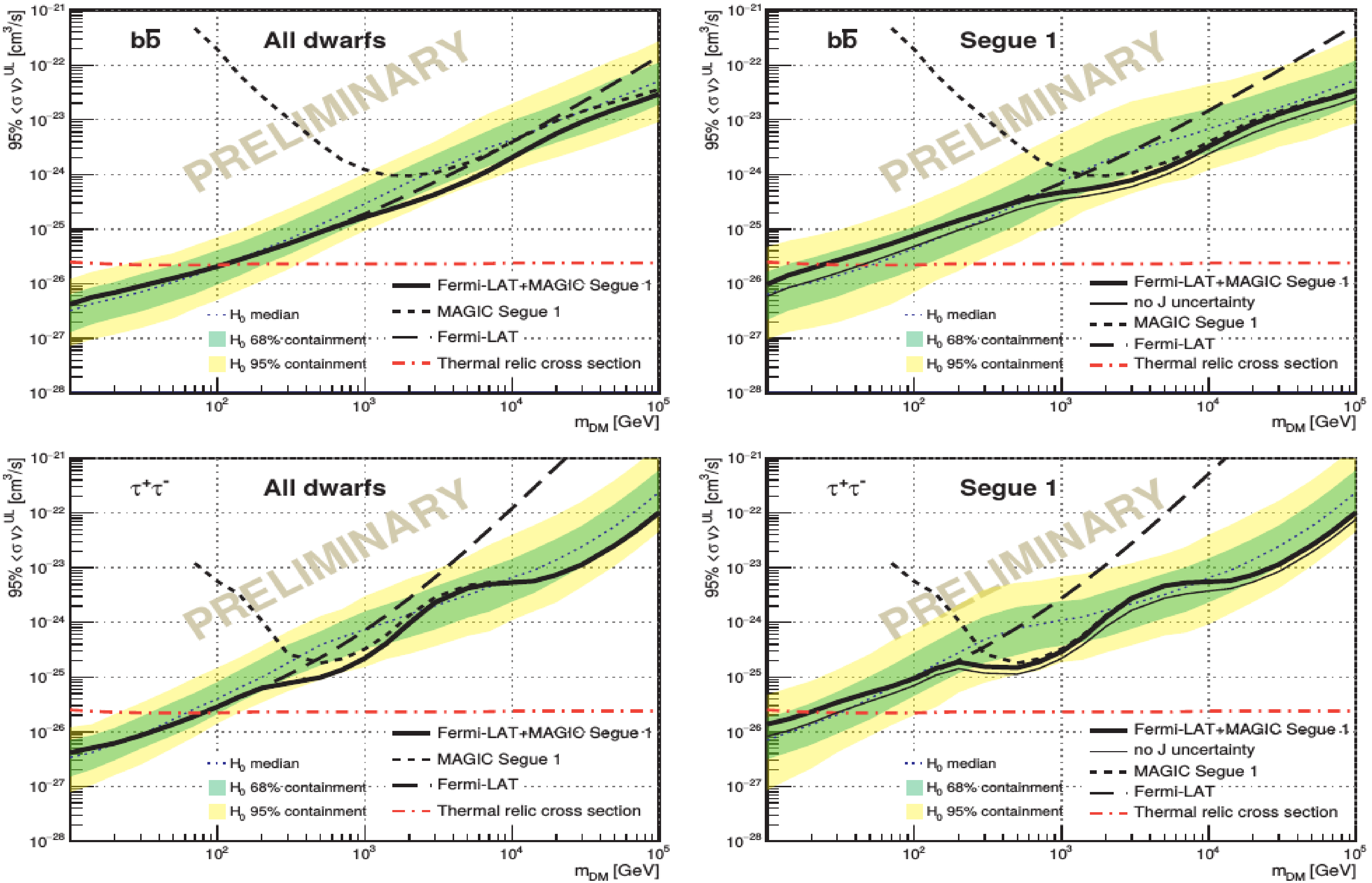
Uncertainty in J-factor

Pass 8 15 dwarf LAT analysis

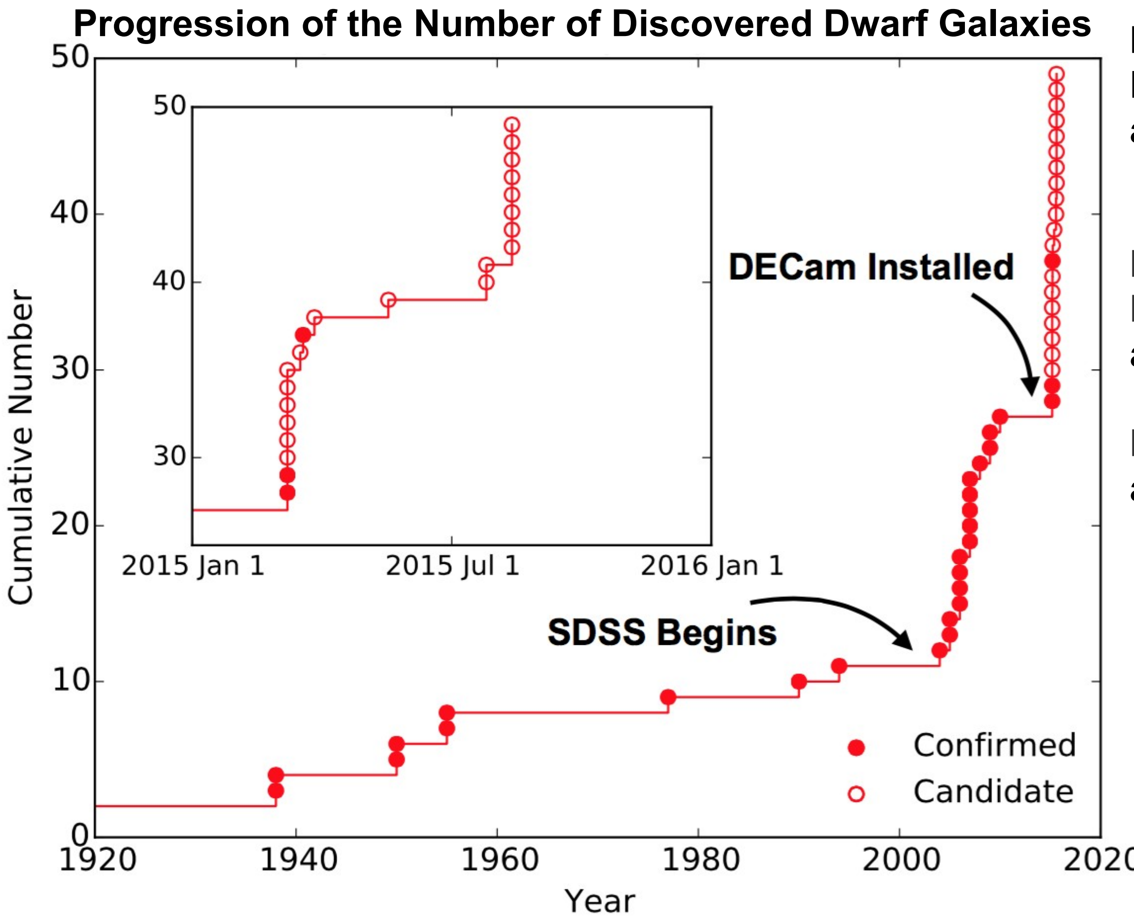


Combined LAT + MAGIC (Segue 1) analysis

J. Rico et al. arXiv:1508.05827



Growing Number of Known Dwarf Galaxies



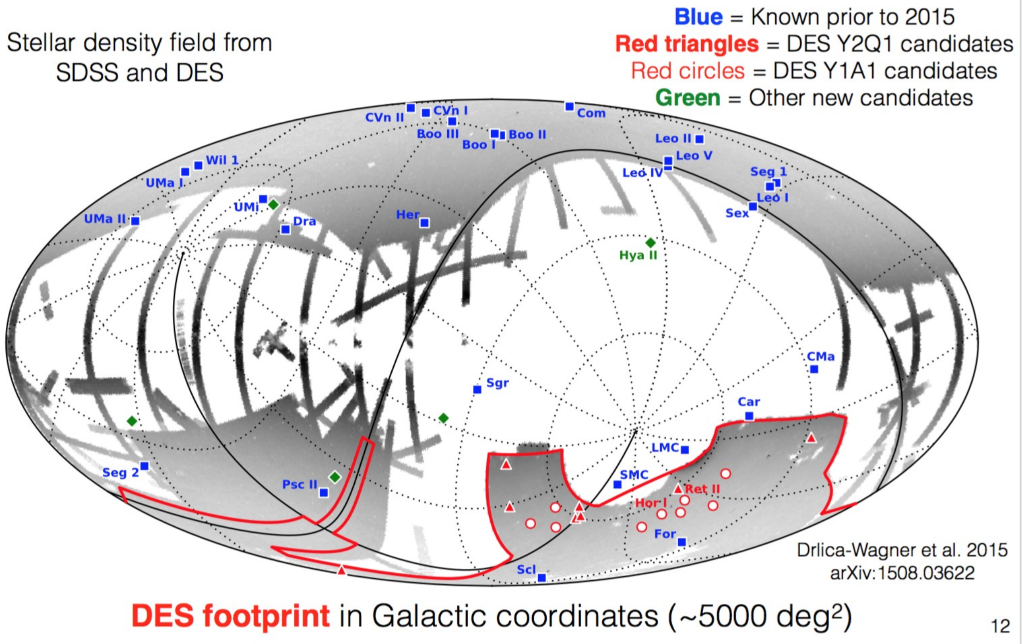
DES Year 2 Data: Drlica-Wagner+, arXiv:1508.03622

DES Year 1 Data: Bechtol+: arXiv:1503.02584

Koposov+: arXiv:1503.02079

- Advent of deep, digital survey era in optical astronomy has led to the discovery of numerous new Milky Way-satellite dwarf galaxies
- LSST & other surveys will continue to find new dwarf galaxies after the *Fermi* mission

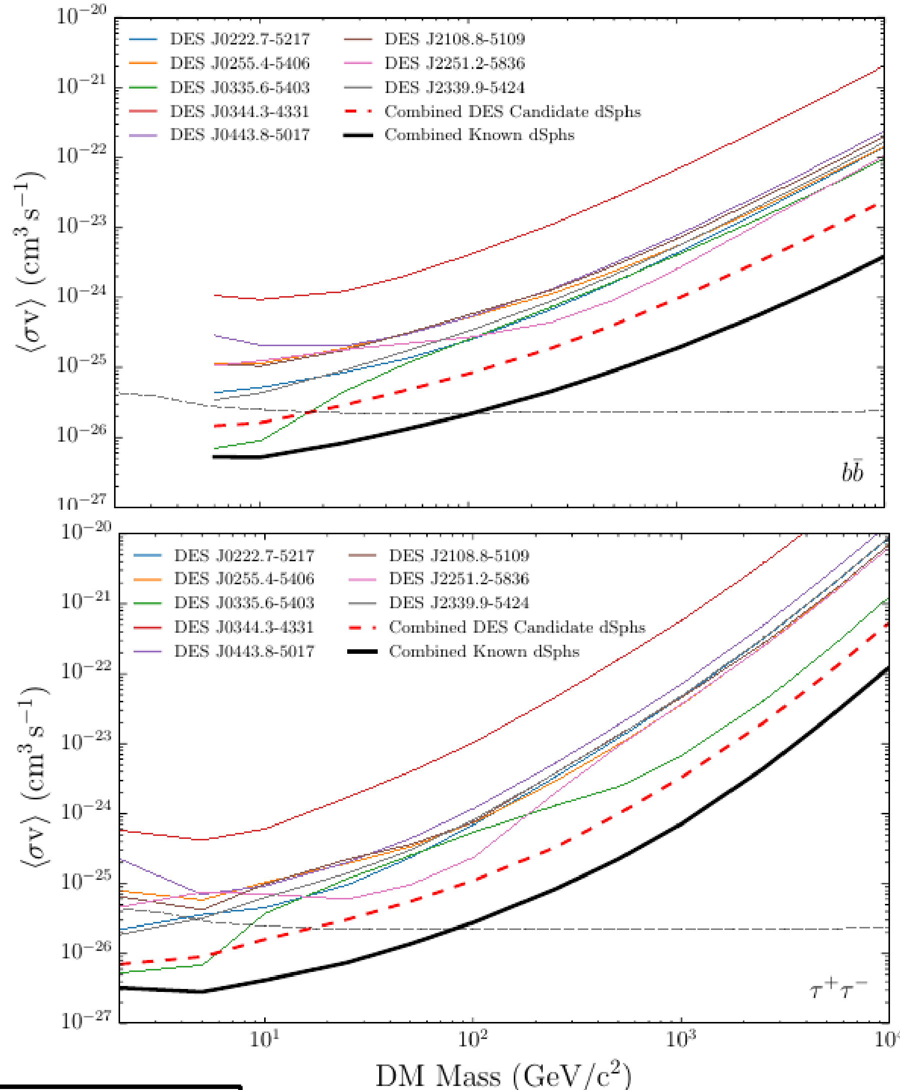
Discovery Volume for DM Signals from Dwarf Galaxies



- Optical surveys are quickly improving in both sky-coverage and depth, potentially giving us even better dSph targets
- 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)$^{1.5}$ ~ 4.0***

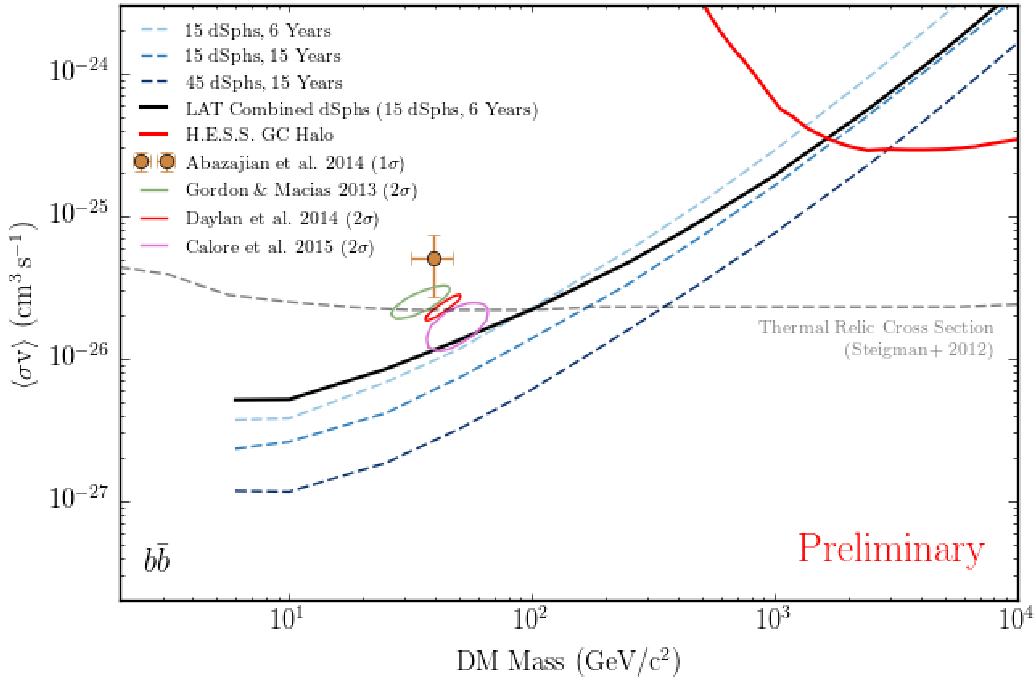
DES Y1 and LAT analysis

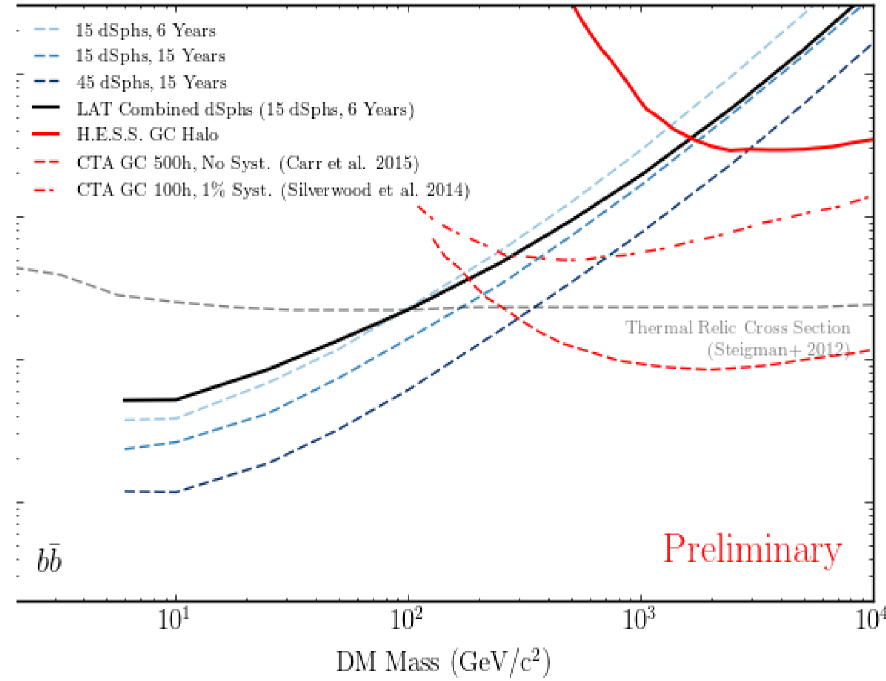
- Spectroscopic observations are targeted and expensive
- Expected J-factors can be predicted assuming:
  1. New systems are dwarf galaxies
  2. All dwarf galaxies inhabit dark matter halos of similar mass (Strigari et al. 2008)
  3. A characteristic uncertainty on the accuracy of J-factor measurements (taken to be 0.4 dex here)
  4. The photometrically-determined distance to each system
- Candidates discovered in DES Y1 alone are expected to be sensitive to the thermal relic cross section.
- Analysis of all new systems discovered in 2015 is ongoing.



LAT & DES Collaborations [1503.02584]

15-year projections





- 45 dwarfs and 15 years of data (assuming same analysis)
- But 3FGL source list and current IEM and isotropic model....
- Take-away message : the dSphs, by their cumulative effect in the era of large optical surveys, will remain a major DM targets!
- CTA will have plenty of new dSph in the South, and the TeV community has now taken the road to combined analyses.

Summary

- Indirect detection is the only detection technique that searches for DM in the distant astrophysical targets where it is known to exist.
- The LAT has reached sensitivity to DM annihilation at the thermal relic cross section in the present-day universe.
  - Mind the s-wave only assumption, among other subtleties...
- For dSphs, the LAT sensitivity scales as better than √t with more data. With 15 years of data:
  - The dSphs would allow us to exclude the thermal relic cross section for masses up to > 400GeV for the b-quark channel,
  - The dSphs would reach below 2×10^{-27} cm^3 s^{-1} for masses of ~ 50 GeV in the b-quark channel *allowing us to confirm or rule out the DM interpretation of the Galactic center excess*
- Searches targeting "dark satellites" and the unresolved component of the EGB will also scale better than √t with more data and will probe the thermal relic cross section up to ~100 GeV.