Fermi ガンマ線衛星による暗黒物質探査

2014年10月3日@東京大学
柏キャンパス
(高エネルギーガンマ線でみる
極限宇宙2014)

水野恒史
(広島大学　宇宙科学センター)
On behalf of the Fermi-LAT collaboration

Dark Matter Search with Fermi Large Area Telescope

Oct. 3, 2014@Kashiwa

(The Extreme Universe viewed in very high-energy γ-rays)

T. Mizuno

(Hiroshima Univ.)

On behalf of the Fermi-LAT collaboration

Fermi Gamma-ray Space Telescope

Dark Matter (DM) Search with γ-rays

- **Gamma-rays may encrypt the DM signal**

Gamma Ray Flux (measured by Fermi-LAT)

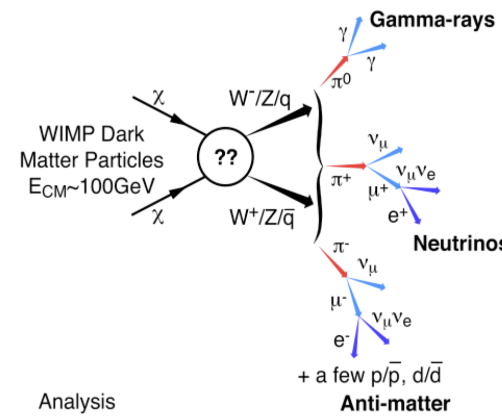
Particle Physics (photons per annihilation)

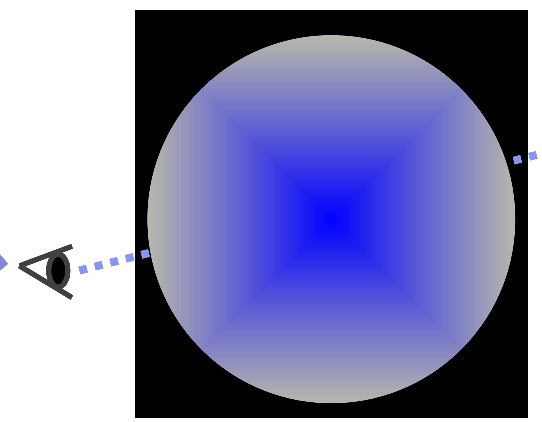
$$\frac{d\Phi_\gamma}{dE_\gamma}(E_\gamma,\phi,\theta) = \frac{1}{4\pi}\frac{<\sigma_{ann}v>}{2m^2_{WIMP}}\sum_f \frac{dN^f_\gamma}{dE_\gamma}B_f$$

$$\times$$

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

DM Distribution (line-of-sight integral)





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$<\sigma v> \sim 3\times10^{-26}$ cm^3 s^{-1} to reproduce the matter density (if DM is a thermal relic)

×

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

(J-factor)

DM Distribution (line-of-sight integral)

NFW profile is usually assumed

$$\rho(r) = \rho_0 \frac{r_0}{r}\frac{(1 + r_0/a_0)^2}{(1 + r/a_0)^2}$$

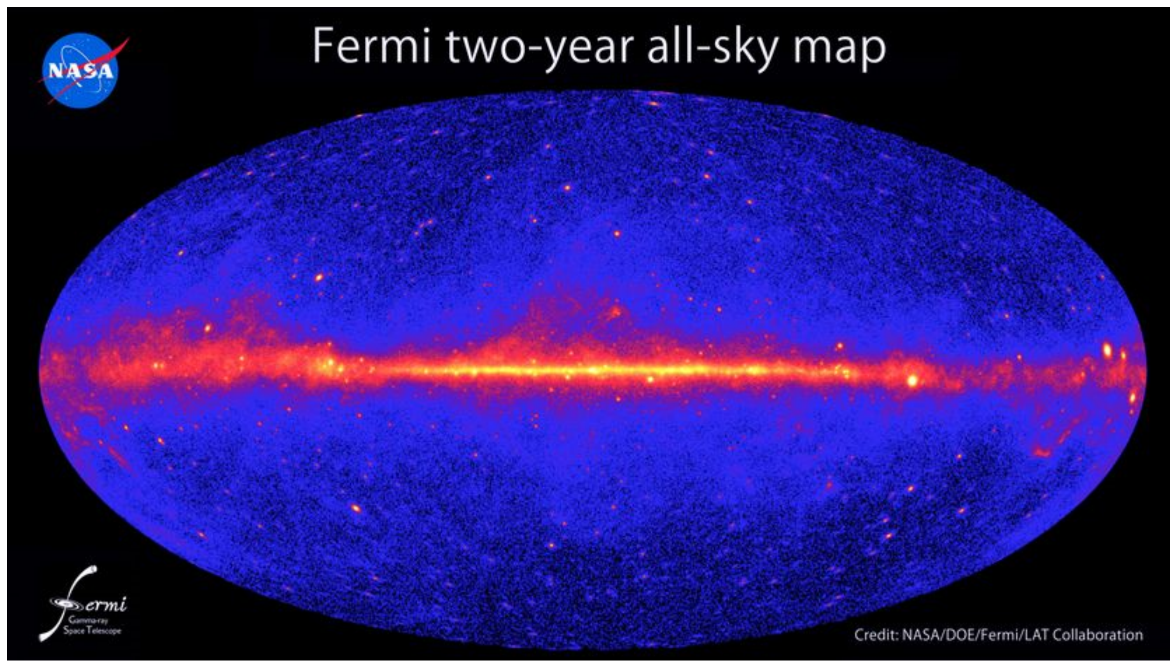
($\rho_0 \sim 0.3$ GeV cm^{-3}, $a_0 \sim 20$ kpc, $r_0 = 8.5$ kpc for the MW)

indirect search of a DM signal is complementary to direct detection (e.g., distribution of DM)

Fermi Gamma-ray Space Telescope

- Fermi = LAT + GBM
- LAT = GeV Gamma-ray Space Telescope (20 MeV ~ >300 GeV; All-Sky Survey)

Cape Canaveral, Florida



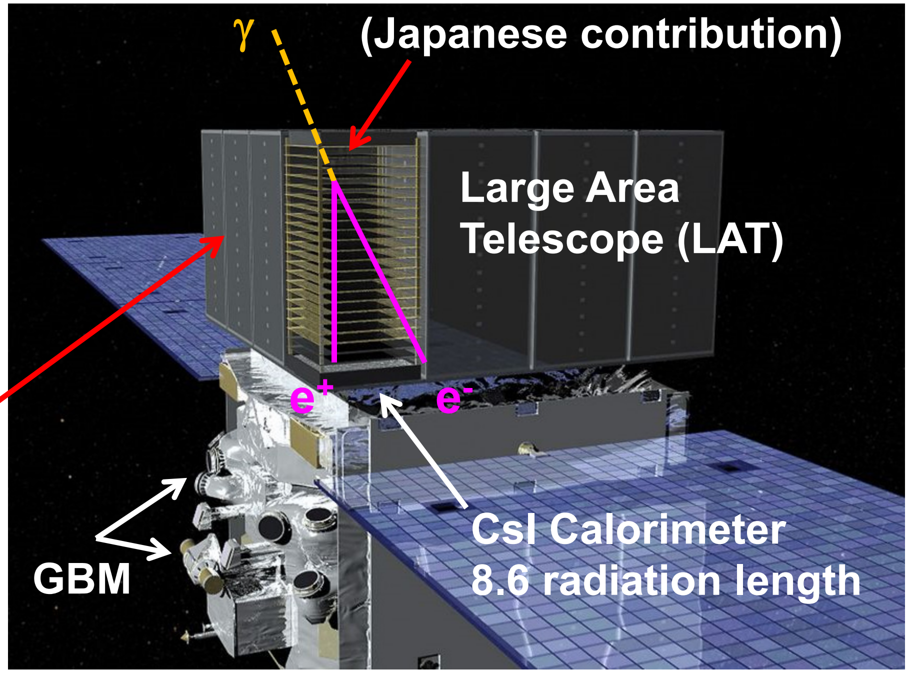
1873 sources
Nolan+12

Fermi LAT

- Pair-conversion telescope (TKR+CAL+ACD)
  - good background rejection due to "clear" γ-ray signature
  - (also sensitive to CR electrons)
- Tracker (TKR): pair conversion, tracking
  - angular resolution is dominated by multiple scattering below ~GeV
- Calorimeter (CAL):
  - use shower profile to compensate for the leakage
- Anti-coincidence detector (ACD):
  - efficiency>99.97%

Si Tracker
70 m^2, 228 μm pitch
~0.9 million channels
(Japanese contribution)

Atwood+09



energy band: 20 MeV to >300 GeV
effective area: ~8000 cm^2 (>1 GeV)
FOV: >2.4 sr
angular resolution: <1 deg (>1 GeV)
energy resolution: ~10% (@1 GeV)

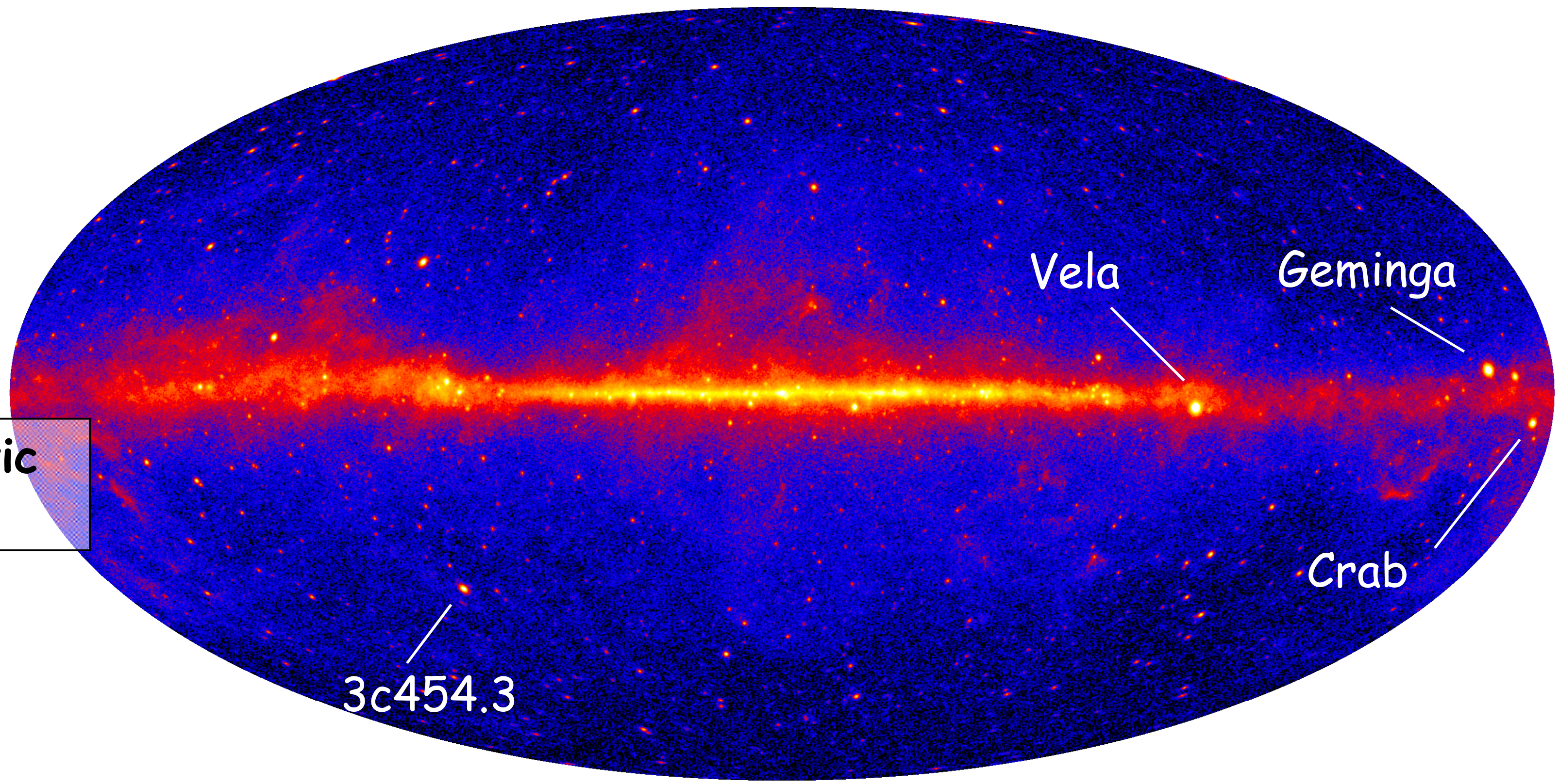
Anti-coincidence Detector
Segmented scintillator tiles

T. Mizuno et al.

Gamma-ray Sky

- **GeV gamma-ray sky**

  = Galactic Diffuse + astrophysical objects + unresolved sources + <u>others</u>



Fermi-LAT 4 year all-sky map

DM Search Strategies with γ-rays (1)

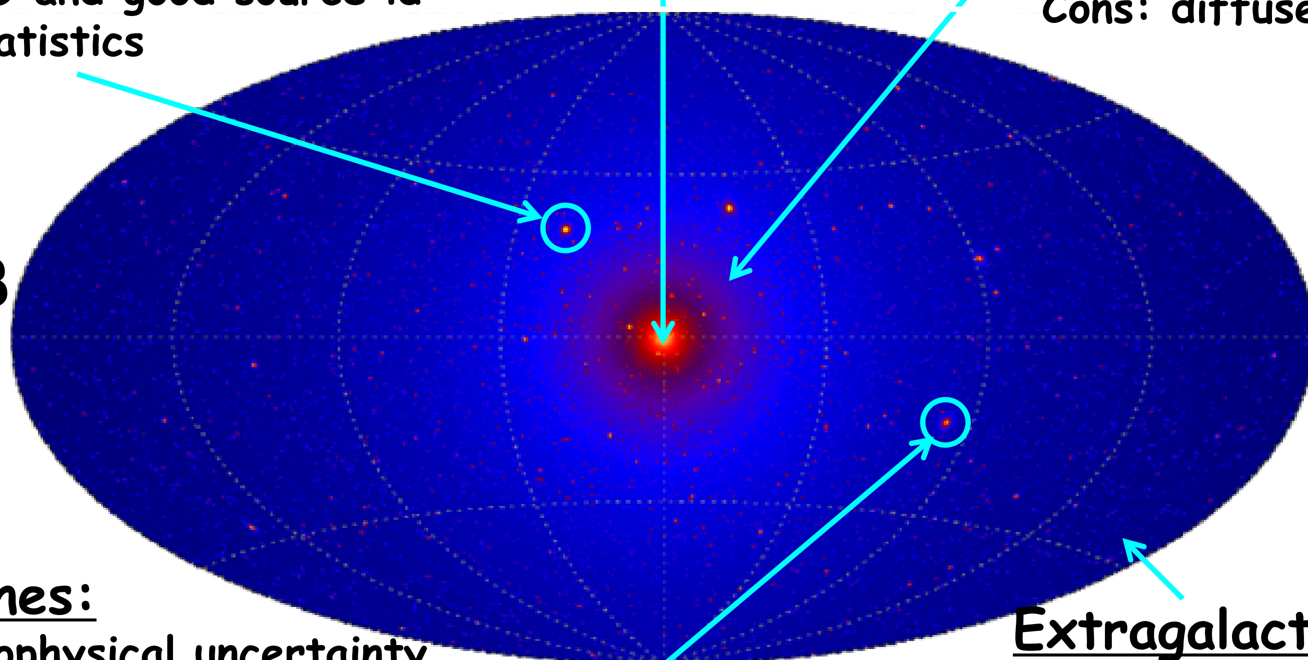
(Figure taken from Pieri+11)

Galactic Center:
Pros: Good statistics
Cons: confusion, diffuse BG

Satellites:
Pros: Low BG and good source id
Cons: low statistics

MW halo:
Pros: very good statistics
Cons: diffuse BG

Baltz+08



Spectral lines:
Pros: no astrophysical uncertainty (Smoking gun)
Cons: low statistics

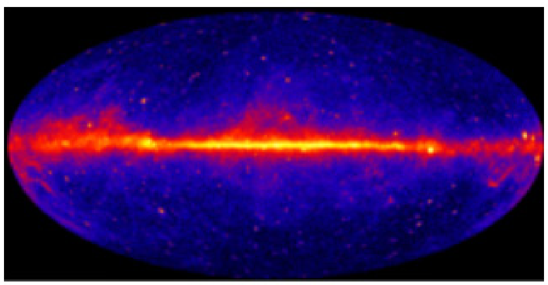
Extragalactic:
Pros: very good statistics
Cons: diffuse BG, astrophysical uncertainties

Clusters:
Pros: low BG and good source id
Cons: low statistics, astrophysical uncertainties

DM Search Strategies with γ-rays (2)

- In short, we search for DM signal in γ-rays by utilizing their spatial and/or spectral signatures

Fermi-LAT data



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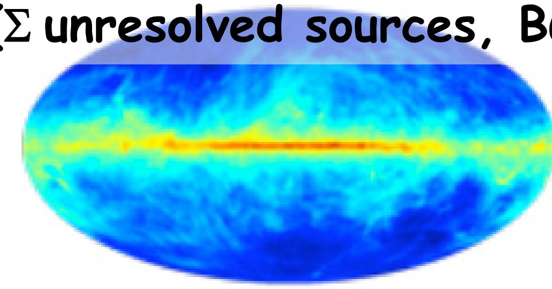
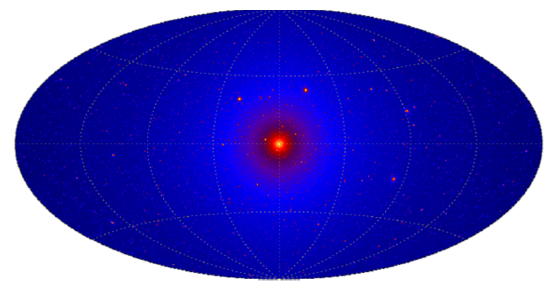
Galactic Diffuse, Sources, isotropic (Σ unresolved sources, BG)

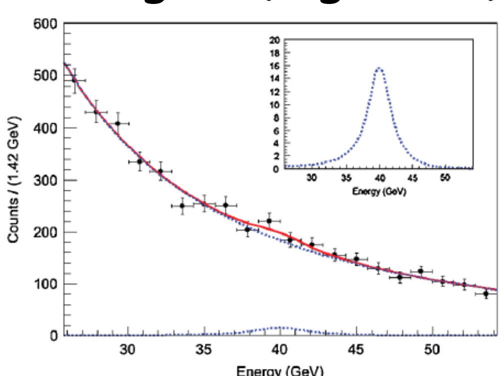


+

DM signal (e.g., MW halo)?



DM signal (e.g., line)?



(Figure taken from Abdo+10)

Good understanding of Galactic diffuse emission and the instrument is crucial

DM Search Strategies with γ-rays

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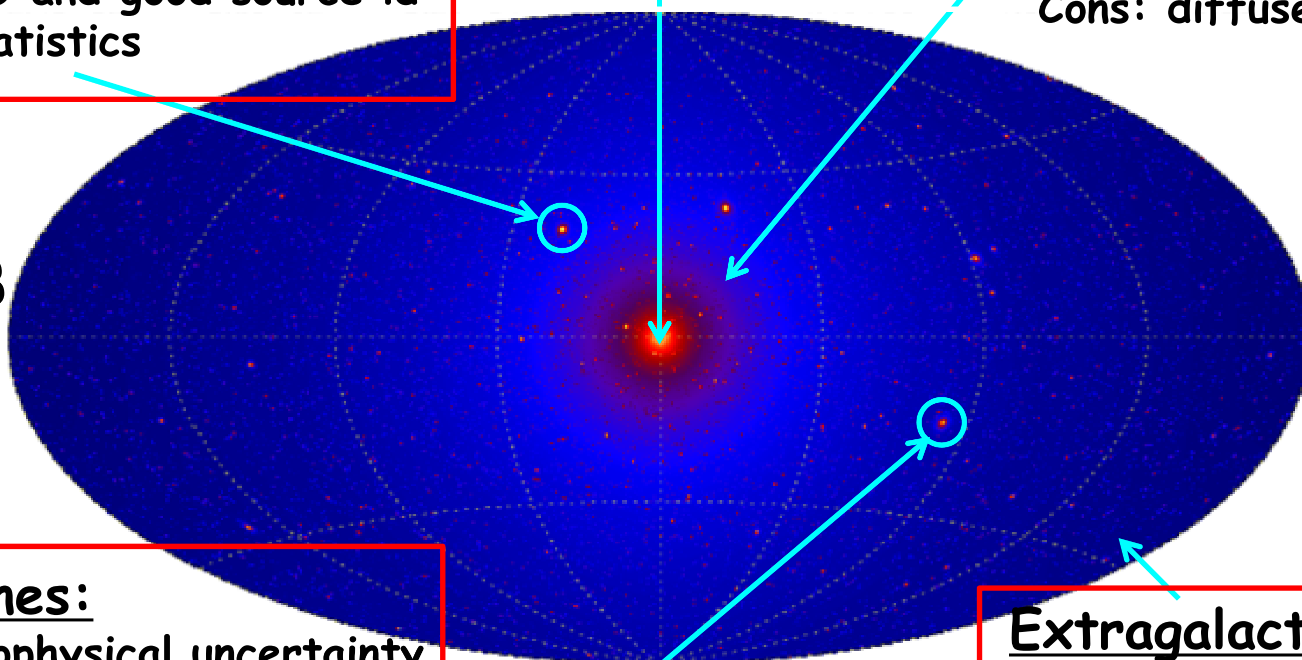

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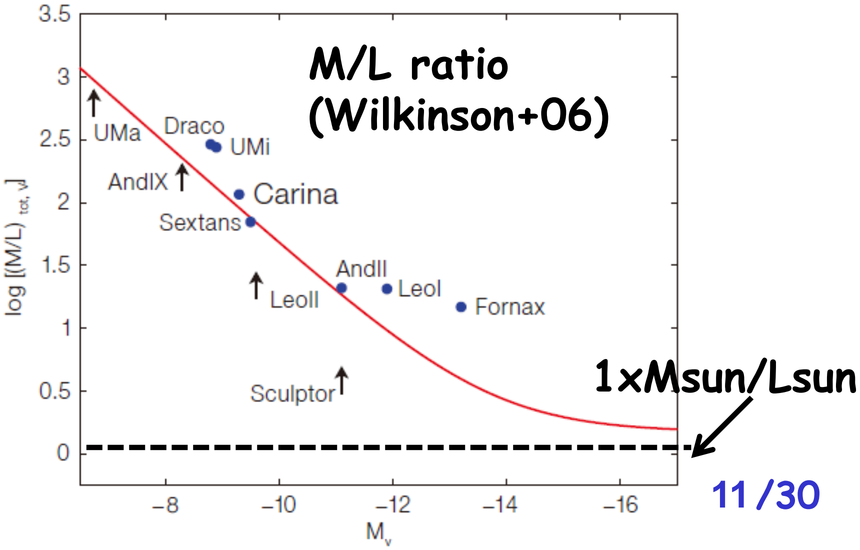
[1] Search for a Galactic DM Substructure

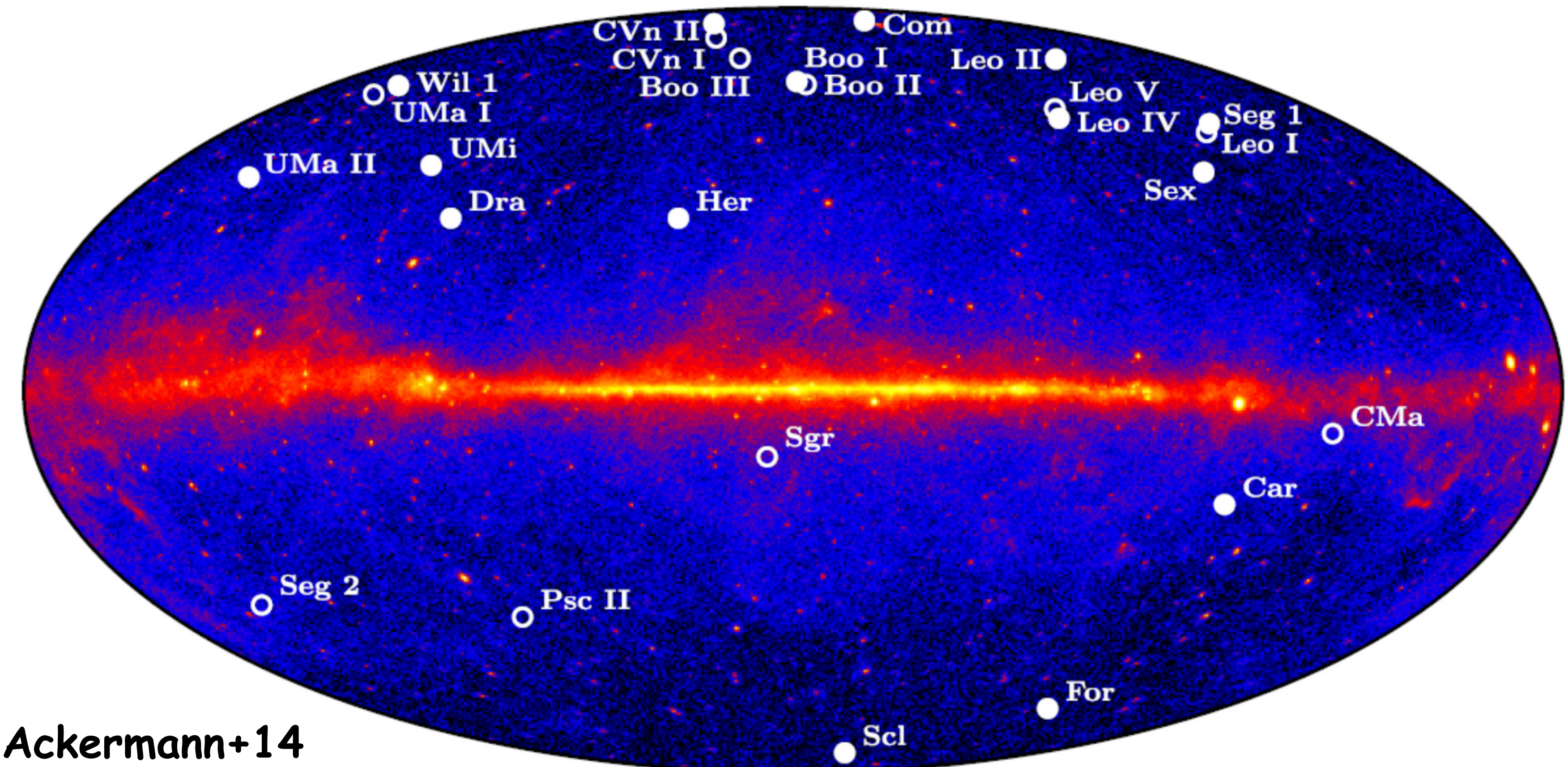
- In the standard cosmological model, structures form from bottom up. Numerical simulations predict that the MW should be surrounded by smaller structures.
- Optically observed Dwarf Spheroidal (dSph) galaxies are the most attractive candidate subhalo objects
  - relatively nearby
  - known position and mass (stellar velocity dispersion)
  - very high M/L ratio (>=100 Msun/Lsun)
  - low astrophysical gamma-ray background

Ursa Minor
(Credit:Mischa Schirmer)



Fermi-LAT Study of dSphs

- No significant γ-ray emission if found to be coincident with any of the 25 known dSphs



Ackermann+14

(CA: Cohen-Tanugi, Conrad, Drlica-Wagner, Llena Garde and Mozaiotta)

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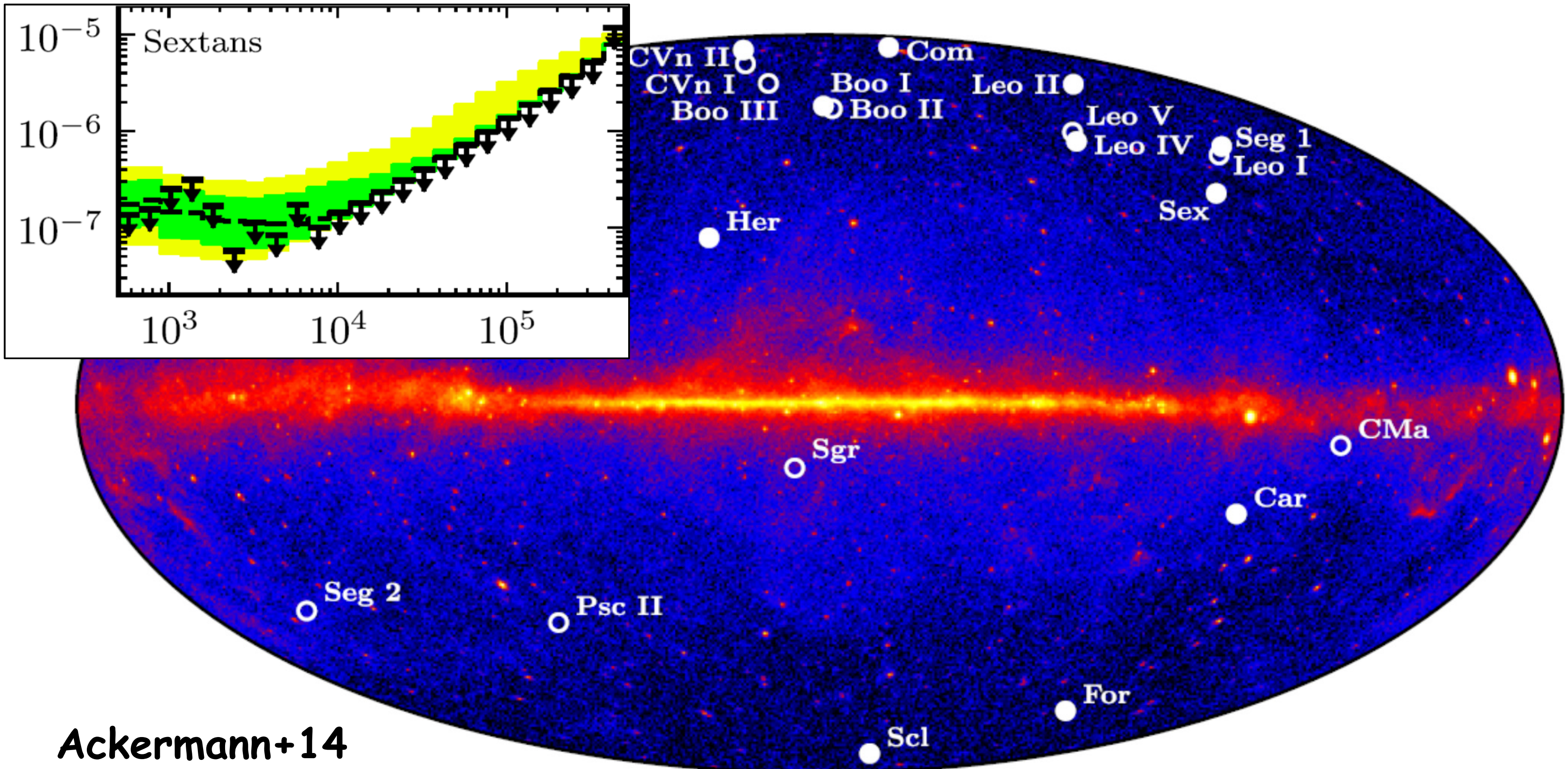
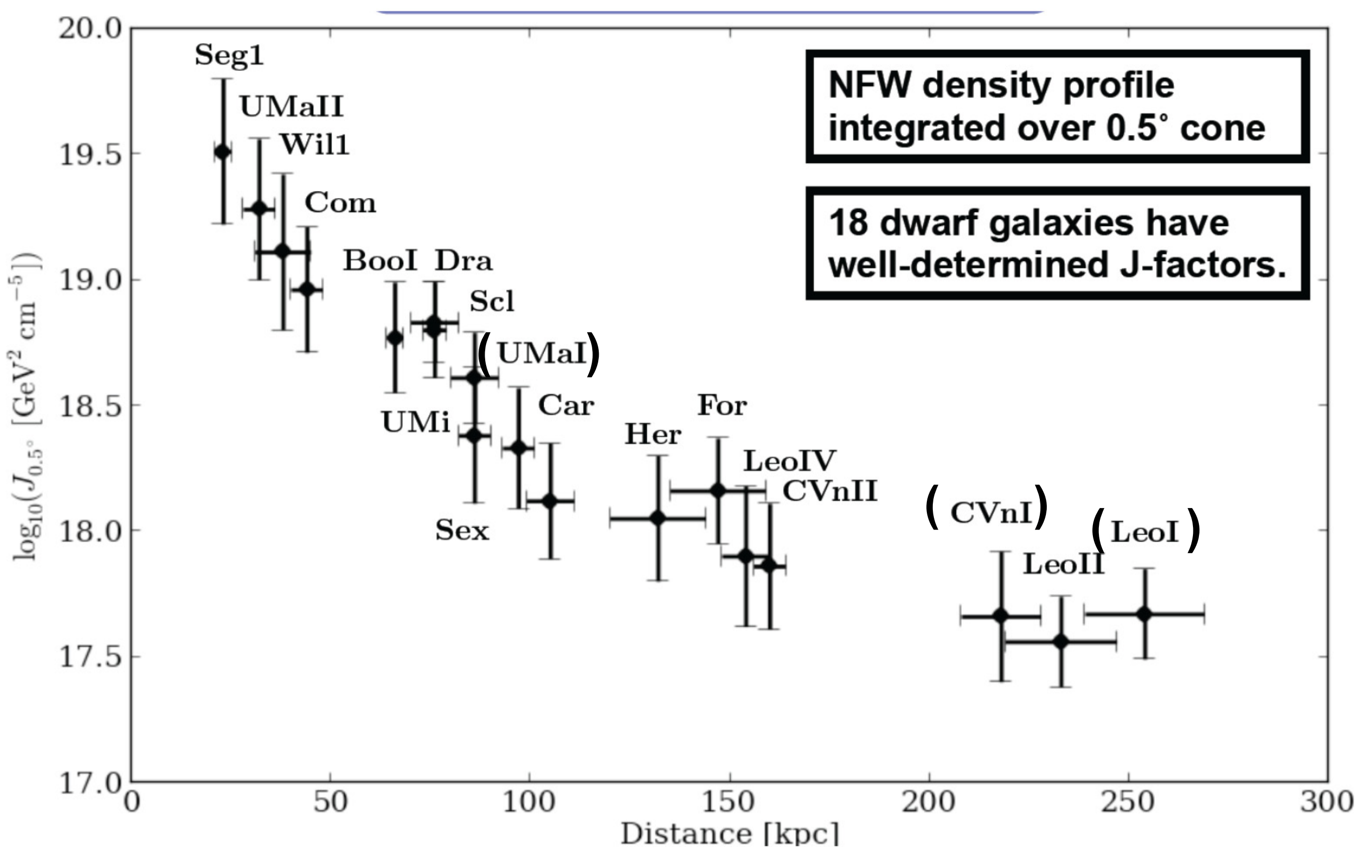


Ackermann+14
(CA: Cohen-Tanugi, Conrad, Drlica-Wagner, Llena Garde and Mozaiotta)

J-Factors of dSphs

- 18 dSphs with kinematically determined J-factors
- 15 “nonoverlaping” dSphs used for a combined analysis



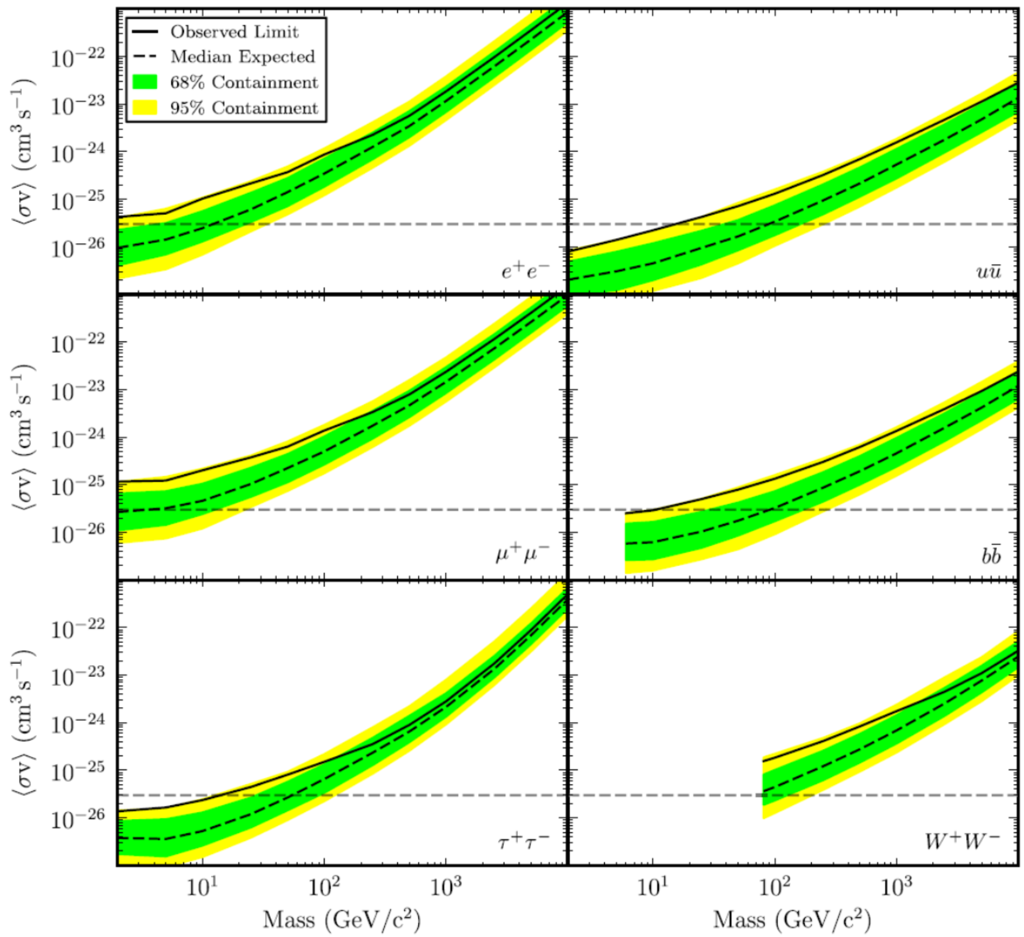
A.Drlica-Wagner DPF 2013

Combined Limits by 15 dSphs

- 4 years of data, 500 MeV-500 GeV
- J-factor uncertainties accounted for
- Expected sensitivity calculated from the data:
  - choose 25 blank-sky locations as a control sample (high Galactic lat. (|b|>30deg), >1deg from 2FGL)
  - combined analysis on 300 randomly selected sets of blank fields

Ackermann+14

(CA: Cohen-Tanugi, Conrad, Drlica-Wagner, LlenaGarde, Mazziotta)

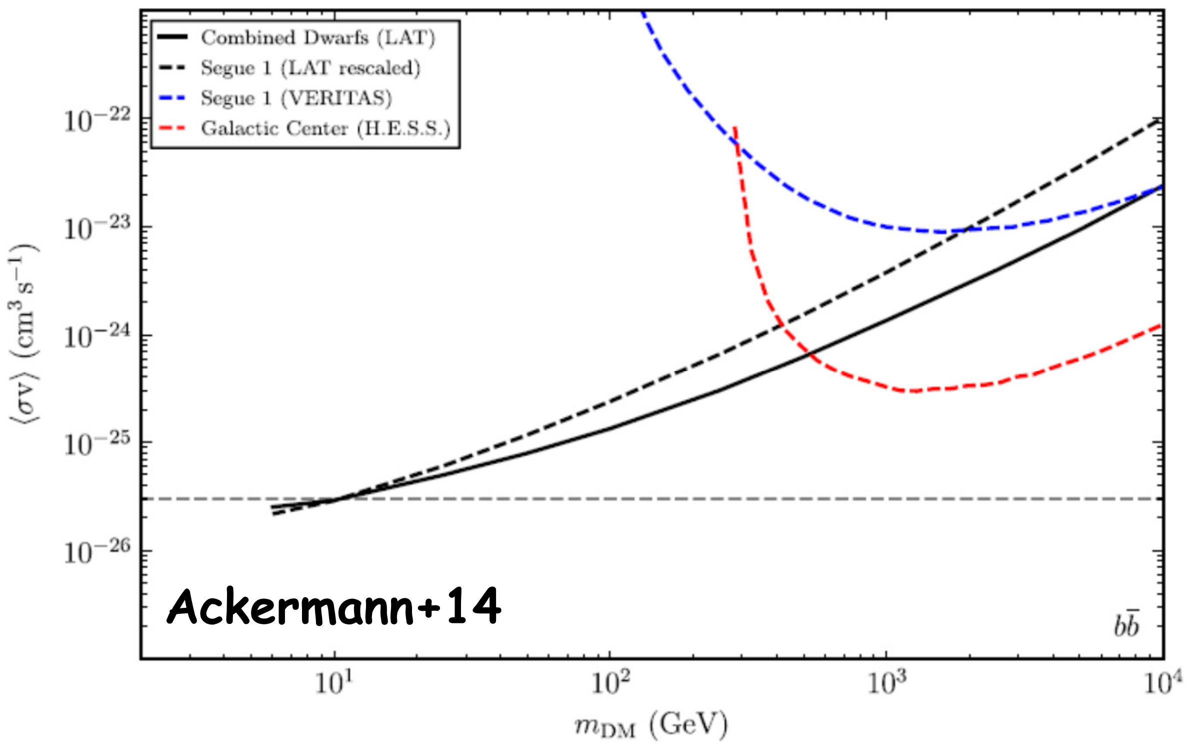


M_{WIMP}>=10 GeV to satisfy $\langle\sigma v\rangle = 3\times10^{-26}$ cm^3 s^{-1}

Largest excess (TS=8.7) for 25 GeV WIMP to bb (global p-value ~ 0.08 or 1.4σ)

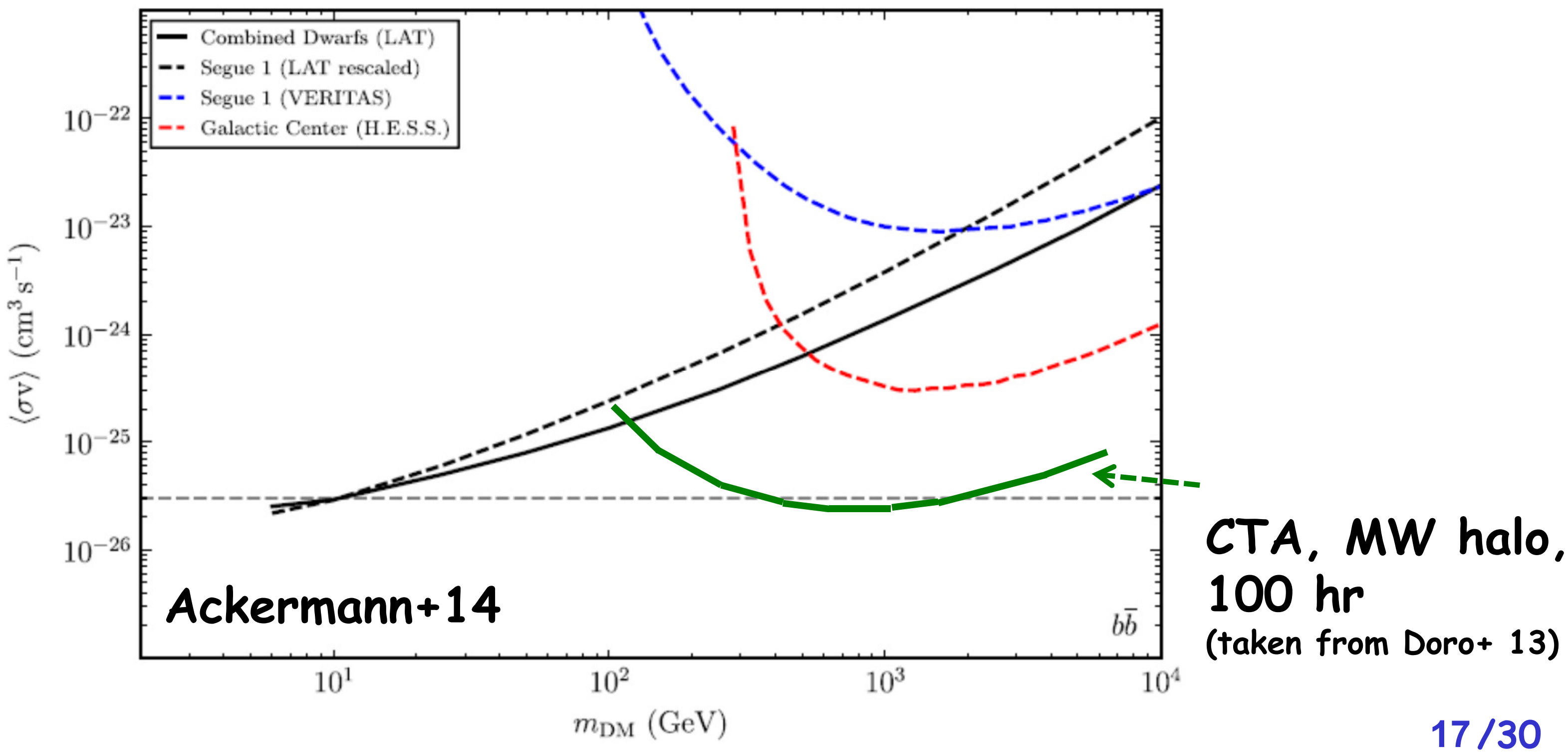
Synergy with Cherenkov Telescopes (1)

- **Although not so constraining (yet), ground Cherenkov Telescopes gave limits complementary to Fermi-LAT results**



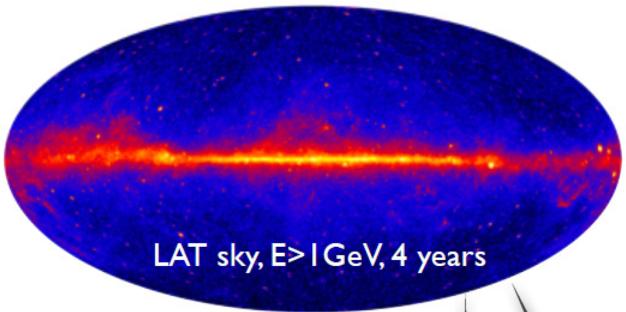
Synergy with Cherenkov Telescopes (2)

- Although not so constraining (yet), ground Cherenkov Telescopes gave limits complementary to Fermi-LAT results
- CTA is able to exclude (or detect) WIMP of M>=300 GeV
- With a factor of 3 improvement of the Fermi-LAT (more exposure, improved response, more dSphs), WIMP mass of 10 GeV ~ >1 TeV will be covered with sensitivity at $\langle\sigma v\rangle \sim 3\times10^{-26}$ cm^3 s^{-1}



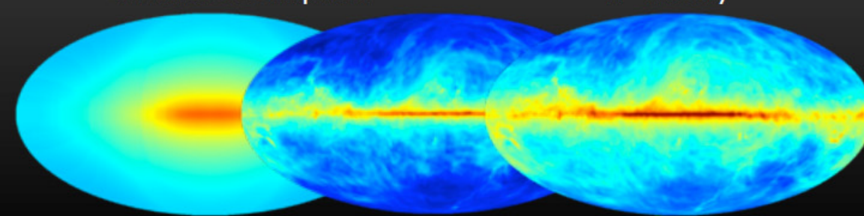
[2] Extragalactic Gamma-ray Background (EGB)

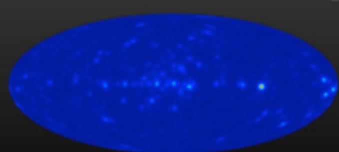
(taken from M. Ackermann's talk)



Galactic diffuse emission

(CR interactions with the interstellar medium)





Resolved point sources

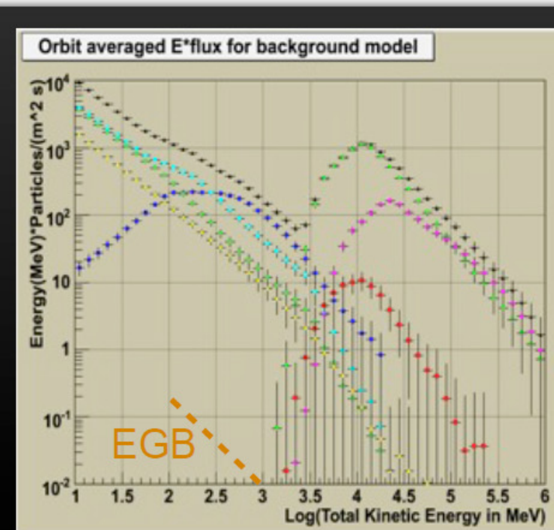
Isotropic extragalactic diffuse emission

Residual charged cosmic rays

Protons, nuclei, electrons + positrons, misclassified as gamma-rays by event selection filters

γ-rays from the Earth limb

γ-rays << 1GeV with poor directional reconstruction

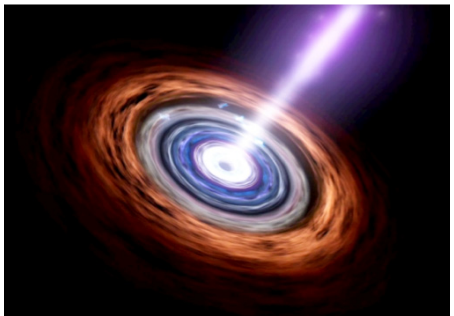


dedicated event class to obtain "clean" γ-rays

Y. Mizuno et al.

Origin of EGB/IGRB

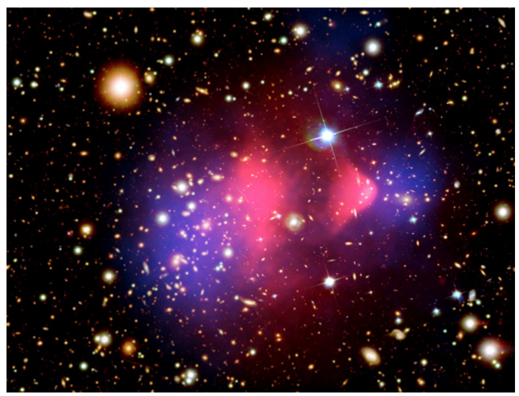
- **The EGB may encrypt the signature of the most powerful processes in astrophysics**



Blazars contribute 20-100% of the EGB

Star forming galaxies, etc.

Particles accelerated in Intergalactic shocks



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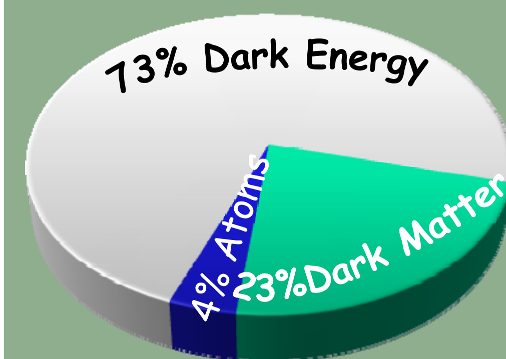
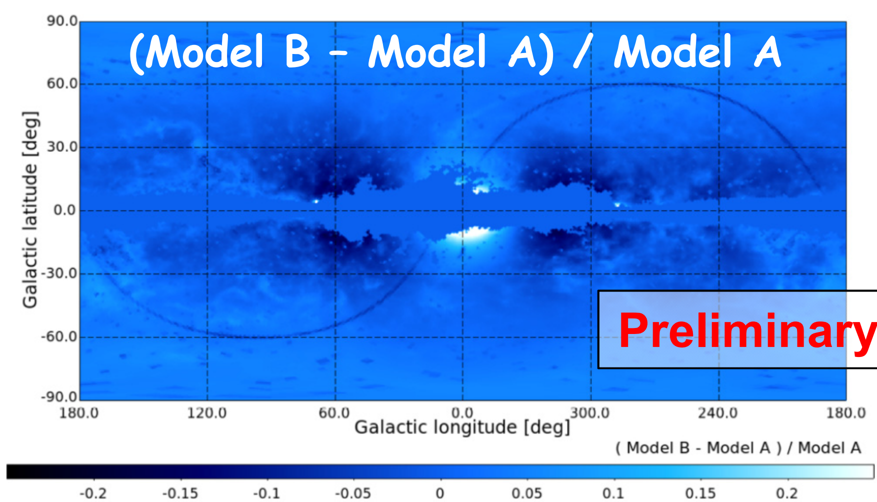


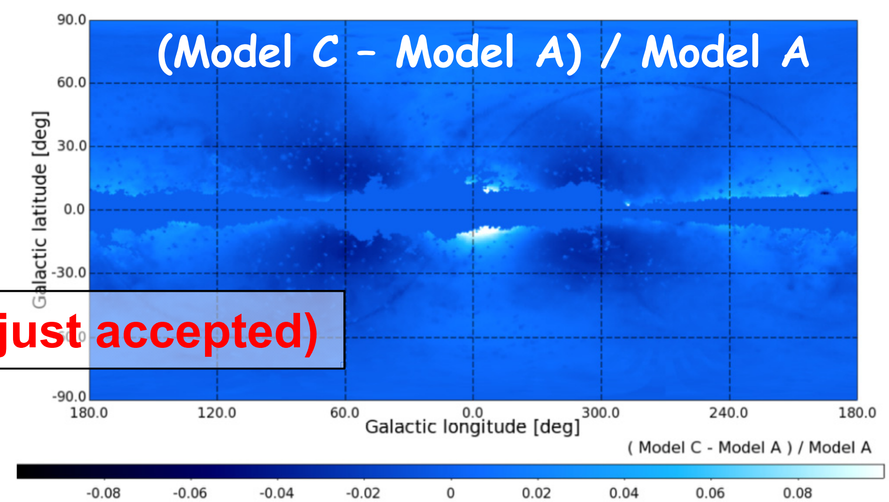
Annihilation of Cosmological Dark Matter

Total EGB = Isotropic Gamma-Ray Background (IGRB)+resolved sources
Possible Cosmological WIMP contribution to IGRB

Systematic Uncertainty from Galactic Diffuse

- **Galactic Diffuse dominates γ-ray sky, hence is the most significant source of uncertainty for EGB/IGRB**
- **Three Diffuse models are considered to gauge uncertainty**
  - **ModelA: similar to a model in Ackermann+12 (baseline model)**
  - **ModelB: add population of electron-only sources near GC (better match to IC)**
  - **ModelC: non-uniform CR diffusion rate (better reproduce flat emissivity)**
- **Variation of diffuse model parameters (e.g., halo size) also considered**



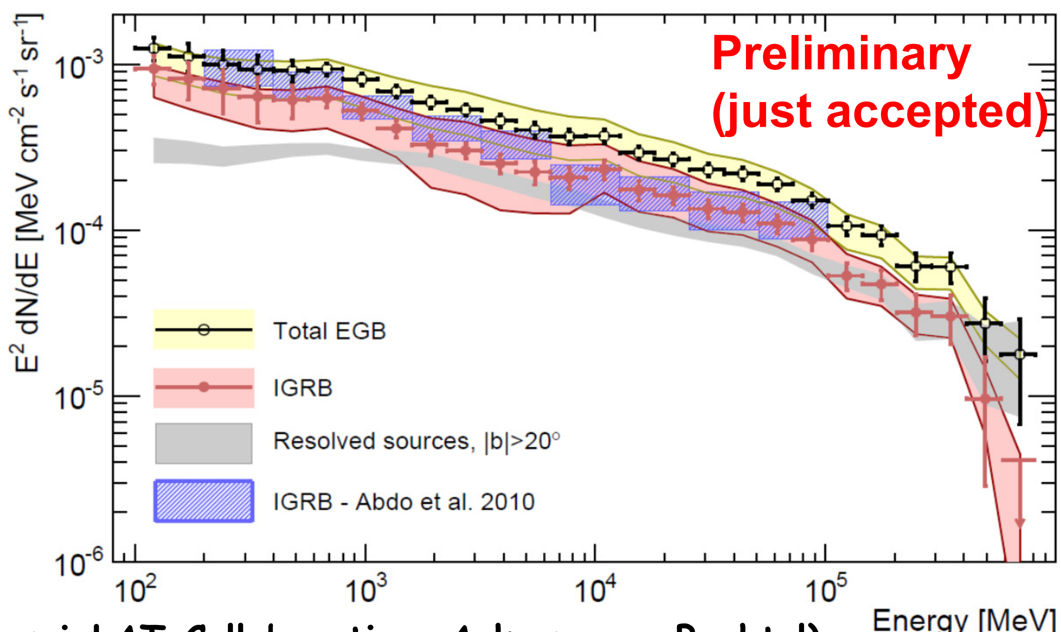


Preliminary (just accepted)

(Fermi-LAT Collaboration, Ackermann, Bechtol)

The Fermi EGB/IGRB

- Updated LAT measurement of IGRB
  - 200 MeV-100 GeV (Abdo+10) -> 100 MeV – 820 MeV
- Significant high-energy cutoff feature in IGRB
  - Consistent with simple source population attenuated by EBL
- Roughly half of total EGB intensity above 100 GeV now resolved into individual sources
- Then, how about constraints on DM?



(Fermi-LAT Collaboration, Ackermann, Bechtol)

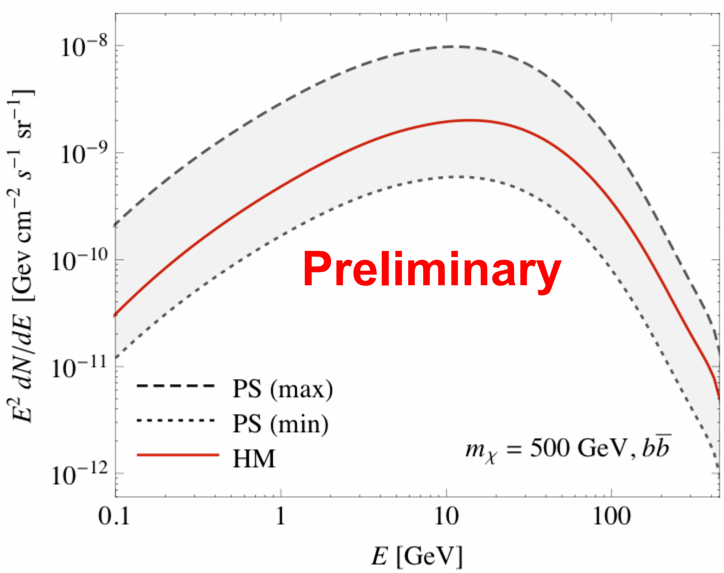
Contribution of Cosmological WIMP

- **Flux from cosmological WIMP annihilation**

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

Flux multiplier (clumpiness of DM) — WIMP-induced spectrum

- **Clumpiness of DM is the main source of uncertainty. Two independent and complementary approaches to compute ζ(z)**

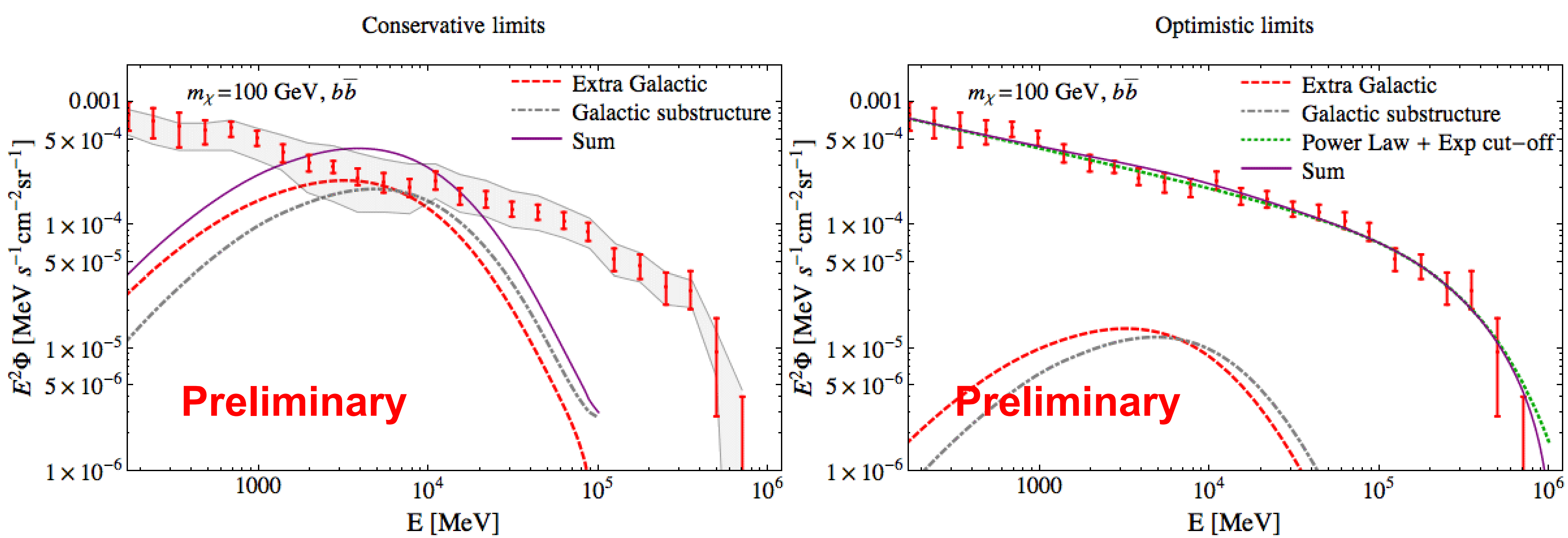


- **Use Halo Model as a Benchmark model** (Sánchez-Conde and Prada 14, Prada+12)
- **Use non-linear matter power spectrum to gauge uncertainty** (Sefusatti+14)

(Fermi-LAT Collaboration, Franckowiak, Gustafsson, Sánchez-Conde, Zaharijas)

Limits on Cosmological DM (1)

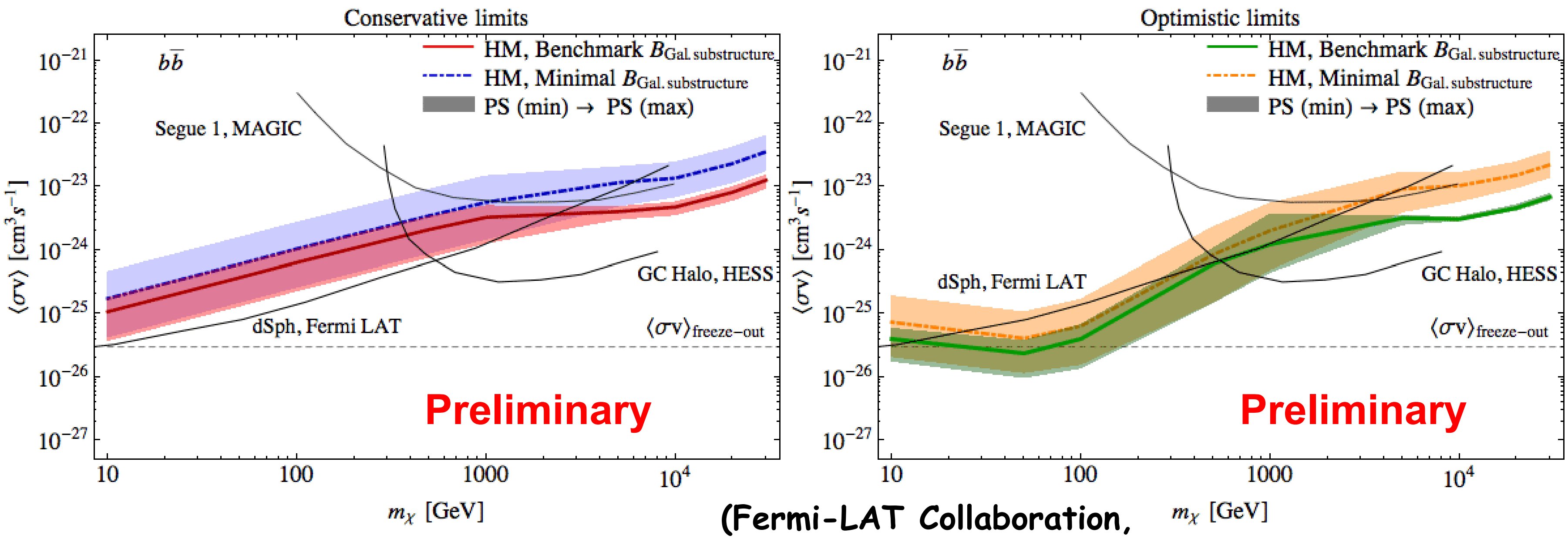
- **Two types of "extreme" limits (they bracket the true limit)**
  - **Conservative, no assumed astrophysical contributions to IGRB**
  - **Optimistic, 100% of the IGRB assumed to be of astrophysical origin**
- **Galactic substructure taken into account (based on our Halo Model) to derive limits on cosmological WIMP**



(Fermi-LAT Collaboration,
Franckowiak, Gustafsson, Sánchez-Conde, Zaharijas)

Limits on Cosmological DM (2)

- Two types of “extreme” limits (conservative and optimistic)
- Min/Max Galactic substructure considered to gauge uncertainty

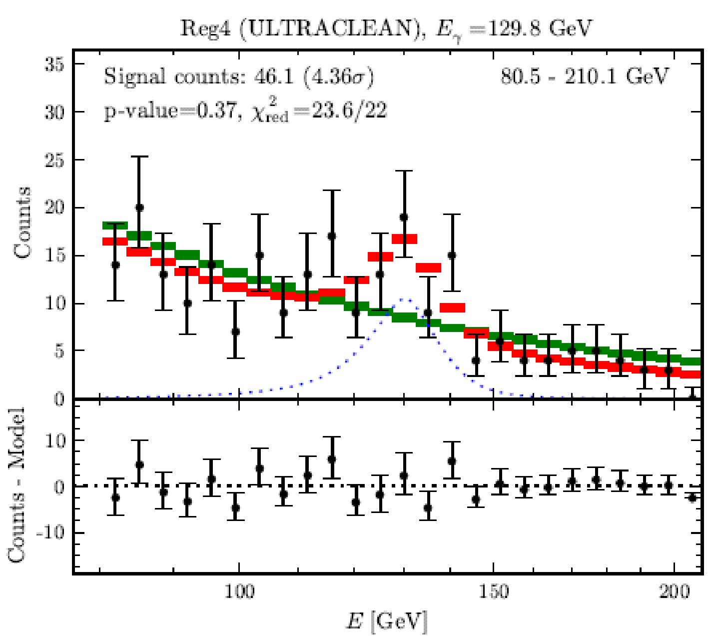


(Fermi-LAT Collaboration, Franckowiak, Gustafsson, Sánchez-Conde, Zaharijas)

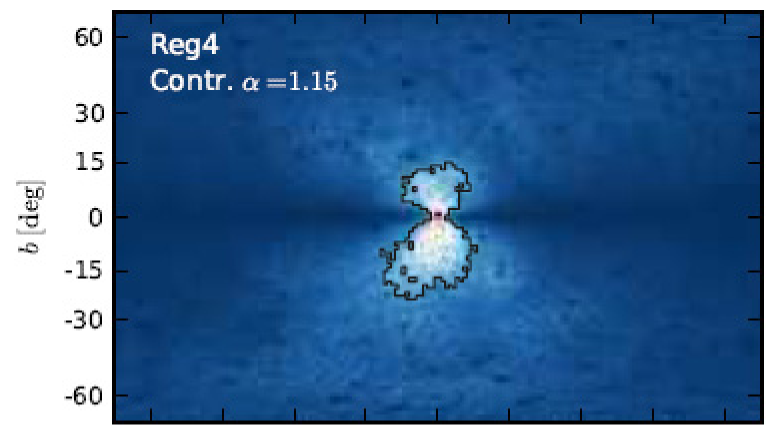
- Strongest Fermi-LAT limits in the >-5 TeV range
- Good sensitivity to WIMPs in 10-100 GeV range – potentially offer a possibility to check the signal detected elsewhere

[3] Narrow Feature at ~130 GeV

- Several groups showed evidence for a narrow spectral feature at ~ 130 GeV near the Galactic Center (GC)
- (E.g., Weniger+12) Over 4σ, S/N>30%, up to ~60% in optimized region of interest

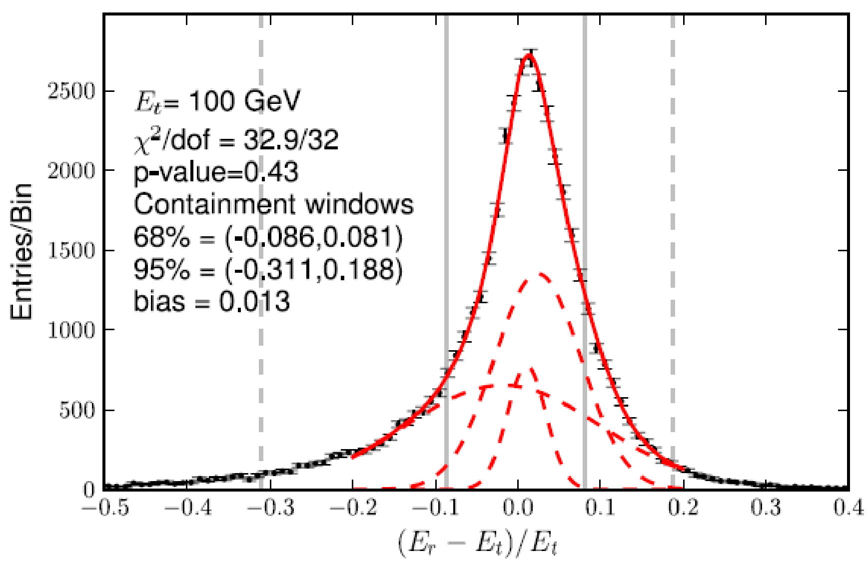


Weniger+12

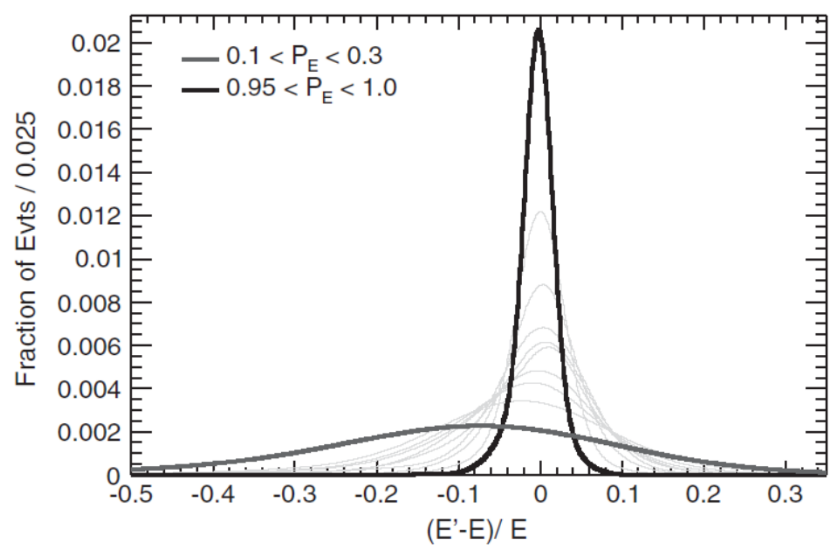


Improve the Model of Energy Dispersion

- Use full MC to get Fermi-LAT energy dispersion
- Previously modeled line with a triple Gaussians (1D PDF)
- Updated analysis add a 2nd dimension to line model P_E (probability that measured energy is close to the true value)
- Including P_E improves line sensitivity by ~15%



Ackermann+12
(CA: Bloom, Edomonds, Essig)

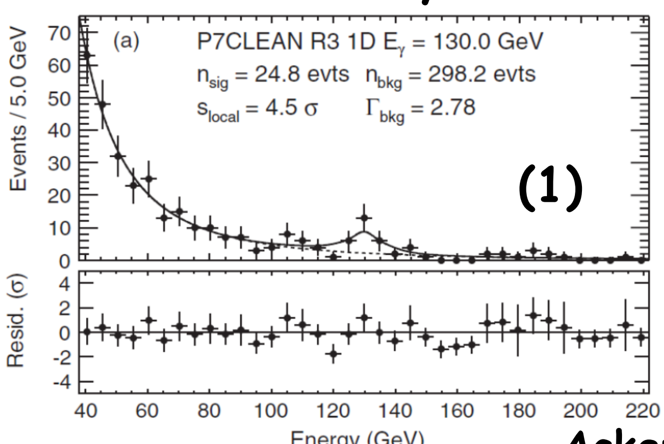


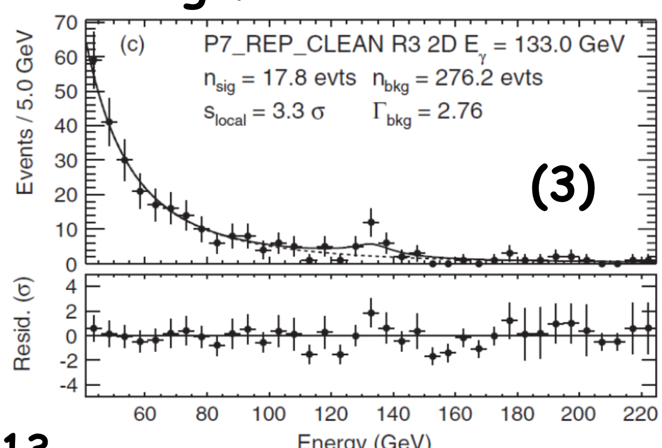
Ackermann+13
(CA: Albert, Bloom, Charles, Winer)

Evolution of line-like Feature near 133 GeV

- 1) 1D PDF, unreprocessed data (public data)
  - 4.5σ (local) 1D fit at 130 GeV
- 2) 1D PDF, reprocessed data (better energy calibration)
  - 4.1σ (local) at 133 GeV
- 3) 2D PDF, reprocessed data
  - 3.3σ (local) at 133 GeV (Energy dispersion in data is narrower than expected when P_E is taken into account)
  - <2σ global

4 year data, look in r=3deg from GC

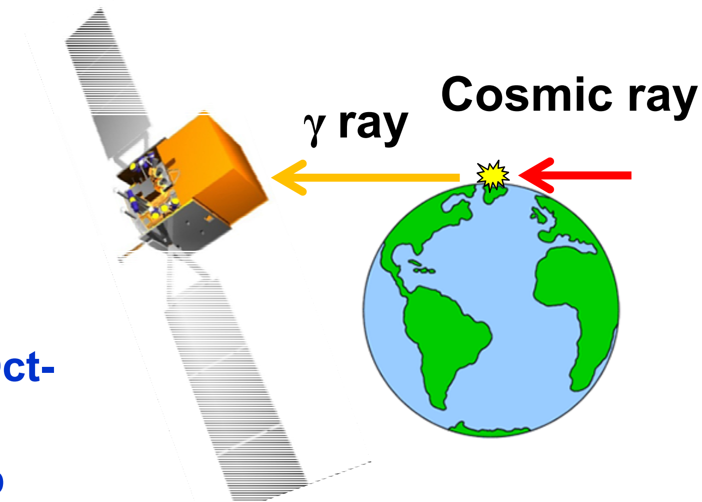




Ackermann+13
(CA: Albert, Bloom, Charles, Winer)

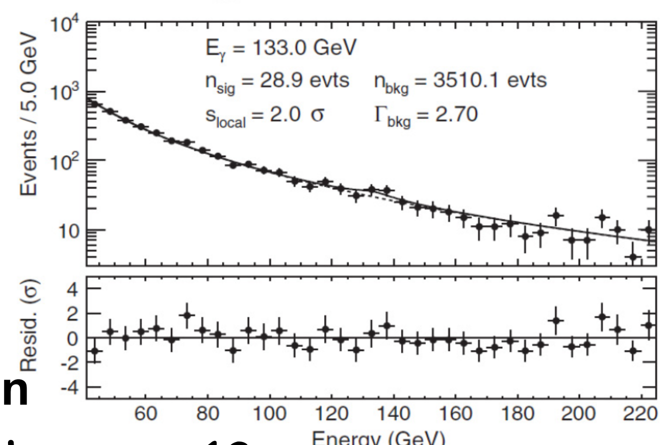
Search 133 GeV in Earth Limb Data

- Earth Limb is bright and well understood
  - γs are from CR interaction with atmosphere
  - Can be used to study instrumental effects
- Need to cut on time when the LAT was pointing at the limb
- Have made changes to increase our Limb dataset
  - Pole-pointed observation each week (2012 Oct-2013 Oct)
  - Extended target of opportunity (tracing Limb while target is occulted)



- Excess is seen (likely due to dips in efficiency below/above 130 GeV)
- Not at the level of GC (S/N_{limb}~15% while S/N_{GC}=30-60%)

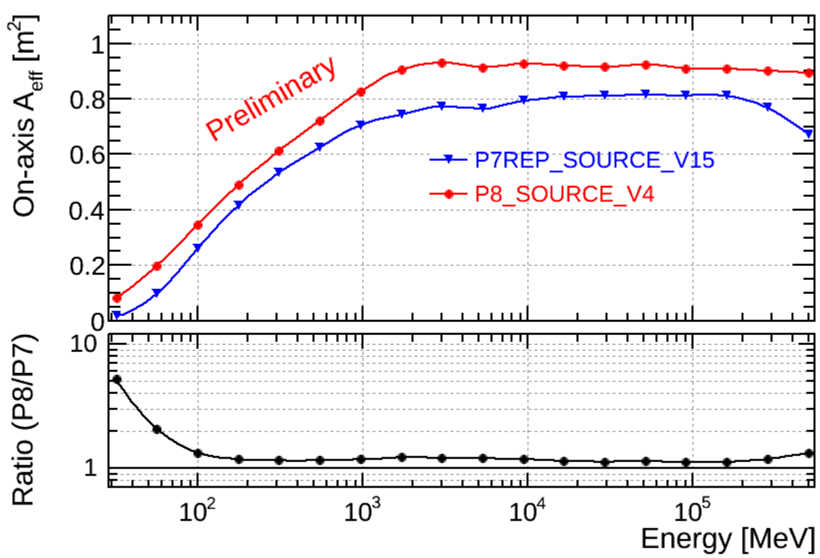
More data and study are needed to clarify the origin of 133 GeV feature (physical or systematic)

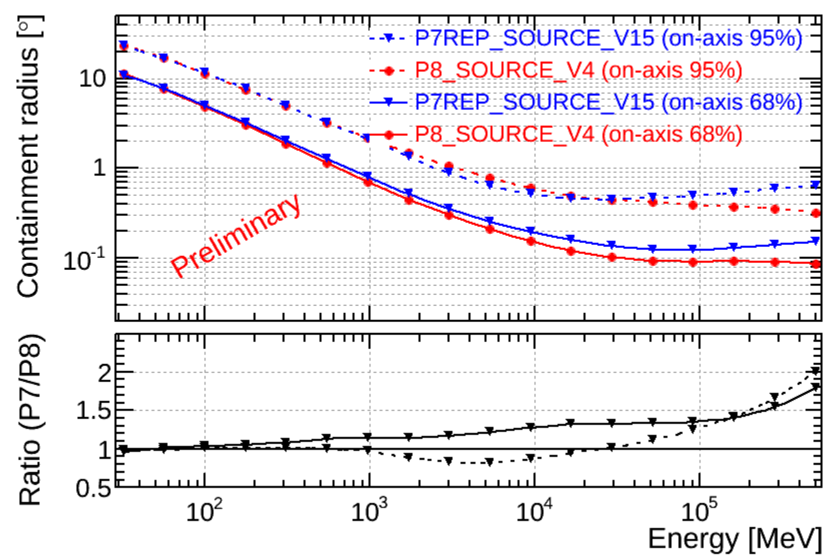


Ackermann+13
(CA: Albert, Bloom, Charles, Winer)

Future Prospects: Pass 8

- **dSphs are promising targets for DM search. Sensitivity is expected to be improved**
  - **more data, more dSphs, improved response**
- **Pass 8 is a comprehensive revision of the Fermi-LAT response**
- **Impact on scientific analysis (including DM search)**
  - **increased energy range (new mass parameter space)**
  - **Increased effective area (flux sensitivity)**





Summary

- γ-ray observation is a powerful probe to investigate the DM property
- No significant detection of the signal yet
  - (130 GeV line not significant globally with reprocessed data and new Edisp model. Significance has declined since 2012 Spring)
- Constraints on the nature of DM have been placed (dSphs, IGRB)
  - start to reach thermal-relic cross section
- Future improvement of Fermi-LAT study (more data/dSphs and improved response) and CTA will cover WIMP mass of 10 GeV-1 TeV with good sensitivity

Thank you for your Attention

Reference

- Nolan et al. 2012, ApJS 199, 31
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- Baltz et al. 2008, JCAP 7, 13
- Abdo et al. 2010, PRL 104, 091302
- Pieri et al. 2011, PRD 83, 023518
- Wilkinson et al. 2006, Messenger 124, 28
- Ackermann et al. 2014, PRD 89, 042001
- Doro et al. 2013, Astroparticle Physics 43, 189
- Abdo et al. 2010, PRL 104, 101101
- Sánchez-Conde and Prada 2014, MNRAS 442, 2271
- Prada et al. 2012, MNRAS 423, 3018
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- Weniger et al. 2012, JCAP 8, 7
- Ackermann et al. 2012, PRD 86, 2012
- Ackermann et al. 2013, PRD 88, 082002

Backup Slides

Fermi-LAT Collaboration

France

Italy

Japan

- Hiroshima Univ.
- ISAS/JAXA
- Tokyo Tech
- Waseda Univ.
- Kyoto Univ.
- Nagoya Univ.
- Aoyama Gakuin Univ.
- Ibaraki Univ.

Sweden

US

PI: Peter Michelson (Stanford)

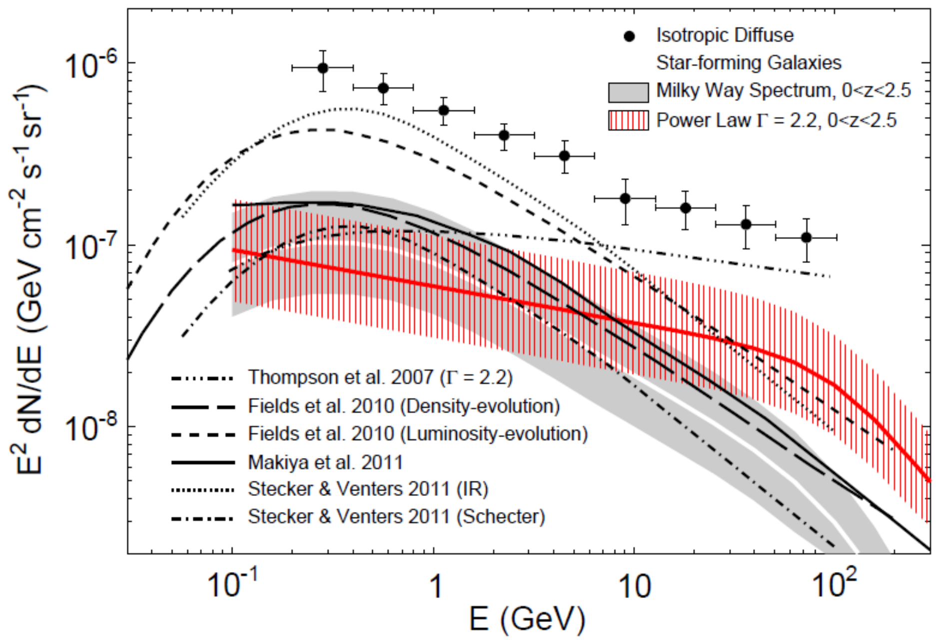
~400 Scientific Members

Cooperation between NASA and DOE, with key international contributions from France, Italy, Japan and Sweden.

Project managed at SLAC.

Contribution of Star-forming Galaxies

- Use $L\gamma$-L_{IR} scaling to estimate contribution
- Star-forming galaxies account for 4-23% of the EGB (~60% at the maximum if we add Blazars and SFGs)

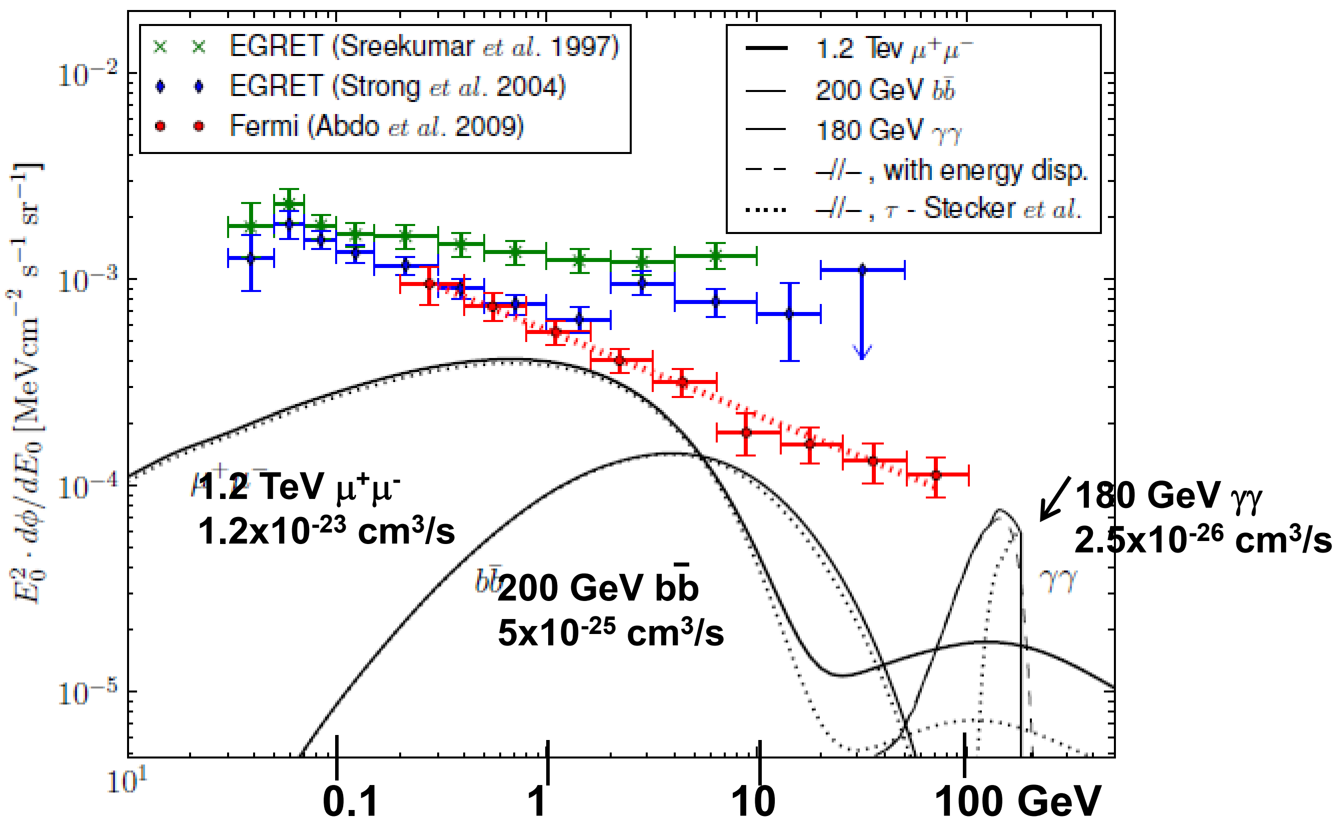


Ackermann+12, ApJ 755, 164 (CA: Bechtol, Cillis, Funk, Torres)

- Radio galaxies can account for ~25% (e.g., Inoue+11). Still some room for other source type or truly diffuse emission.

DM Signal Example

- **Example of DM signal (for extragalactic gamma-ray background)**

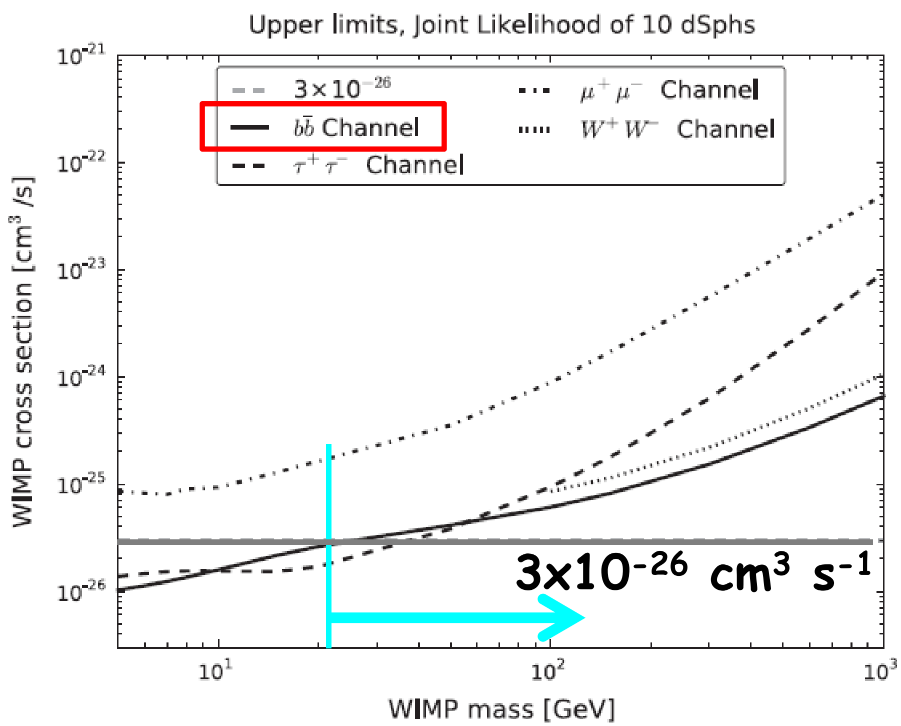


Abdo+10, JCAP 4, 14

(CA: Conrad, Gustafsson, Sellerholm, Zaharijas)

Stacking Analysis with Old Response (Pass6)

- **Stacking analysis using 10 dSphs and 2 years data**
  - **conservative limit on DM cross section (no "boost factor")**



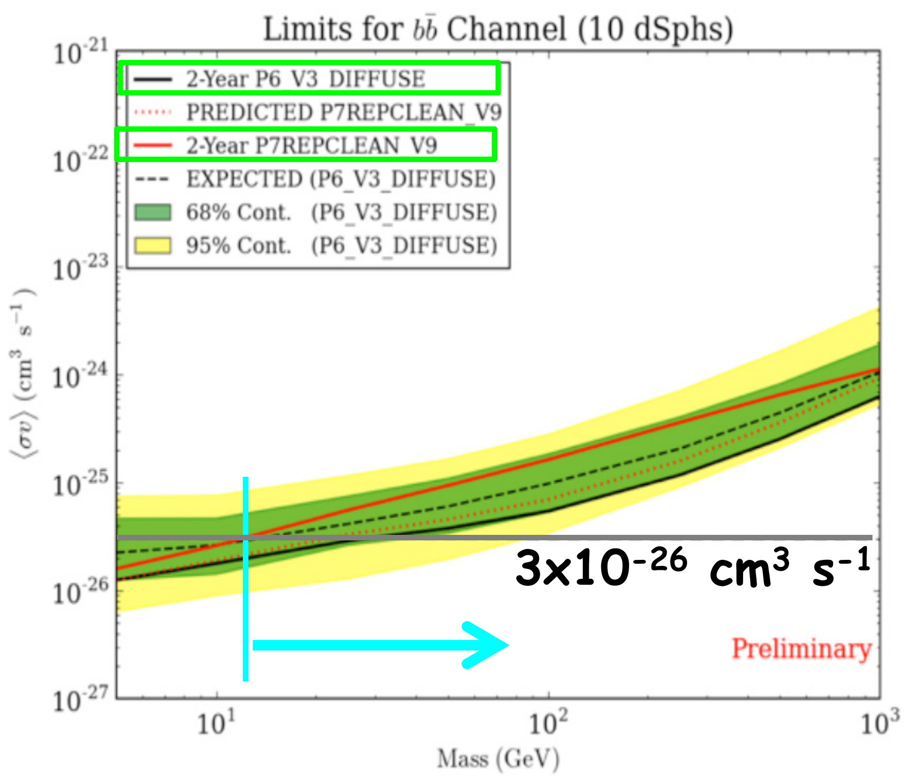
Name	l (degree)	b (degree)	d (kpc)	$\overline{\log_{10}(J)}$ ($\log_{10}$[GeV^2 cm^{-5}])	σ
Bootes I	358.08	69.62	60	17.7	0.34
Carina	260.11	−22.22	101	18.0	0.13
Coma Berenices	241.9	83.6	44	19.0	0.37
Draco	86.37	34.72	80	18.8	0.13
Fornax	237.1	−65.7	138	17.7	0.23
Sculptor	287.15	−83.16	80	18.4	0.13
Segue 1	220.48	50.42	23	19.6	0.53
Sextans	243.4	42.2	86	17.8	0.23
Ursa Major II	152.46	37.44	32	19.6	0.40
Ursa Minor	104.95	44.80	66	18.5	0.18

Ackermann+11, PRL 107, 241302
(CA: Cohen-Tanugi, Conrad, Garde)

M_{WIMP}>=20 GeV to satisfy <σv>=3×10^{-26} cm^3 s^{-1}
Rule out models with generic cross section using γ-rays for the first time

Stacking Analysis with New Response (Pass7)

- **Update analysis with Pass 7**
  - **take account of an improved understanding of the instrument**

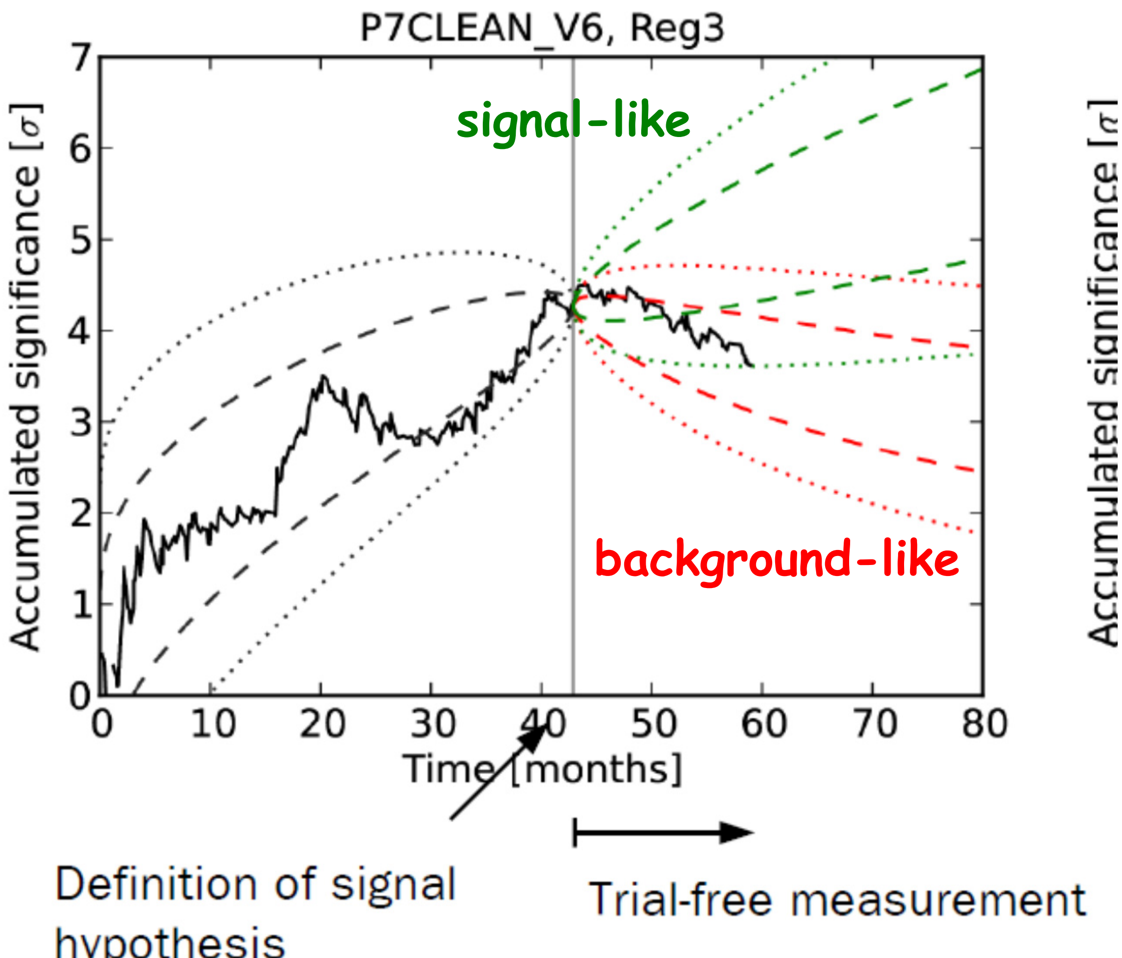


- **Use new response (P6->P7) and redo the analysis**
- **This leads to a statistical reshuffling of γ-ray-classified events (only ~50% events are common in two dataset above 10 GeV)**
- **Two limits are statistically consistent**

dSphs still constrain generic cross section for M_{WIMP}<=10 GeV and will remain a prime target for DM search

Evolution of line-like Feature near 135 GeV

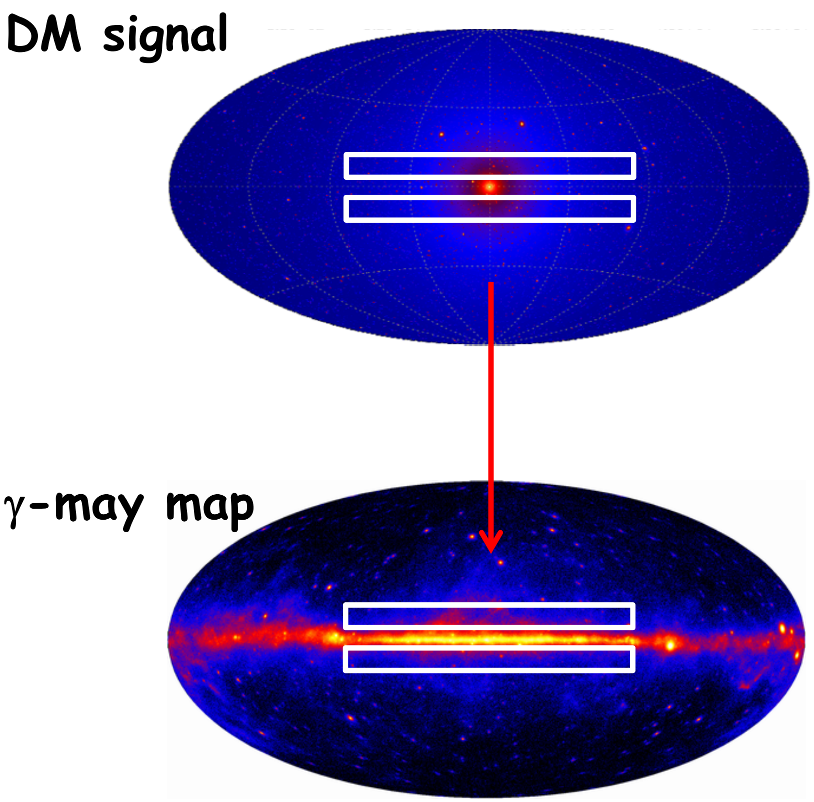
- **Since Spring 2012, the significance of the feature has declined**



Weniger+13
(http://fermi.gsfc.nasa.gov/ssc/proposals/alt_obs/white_papers_eval.html)

[4] Milky Way DM Halo

- Another recent and complementary DM search for MW halo
  - Search for continuous emission from DM annihilation/decay in the smooth MW halo



- Analyze bands 5deg off the plane
  - ➢ decrease astrophysical BG
  - ➢ mitigate uncertainty from inner slope of DM density profile
- Two approaches:
  - ➢ 1) more conservative - assume all emission are from DM (no astrophysical BG)
  - ➢ 2) more accurate – fit DM source and astrophysical emission simultaneously

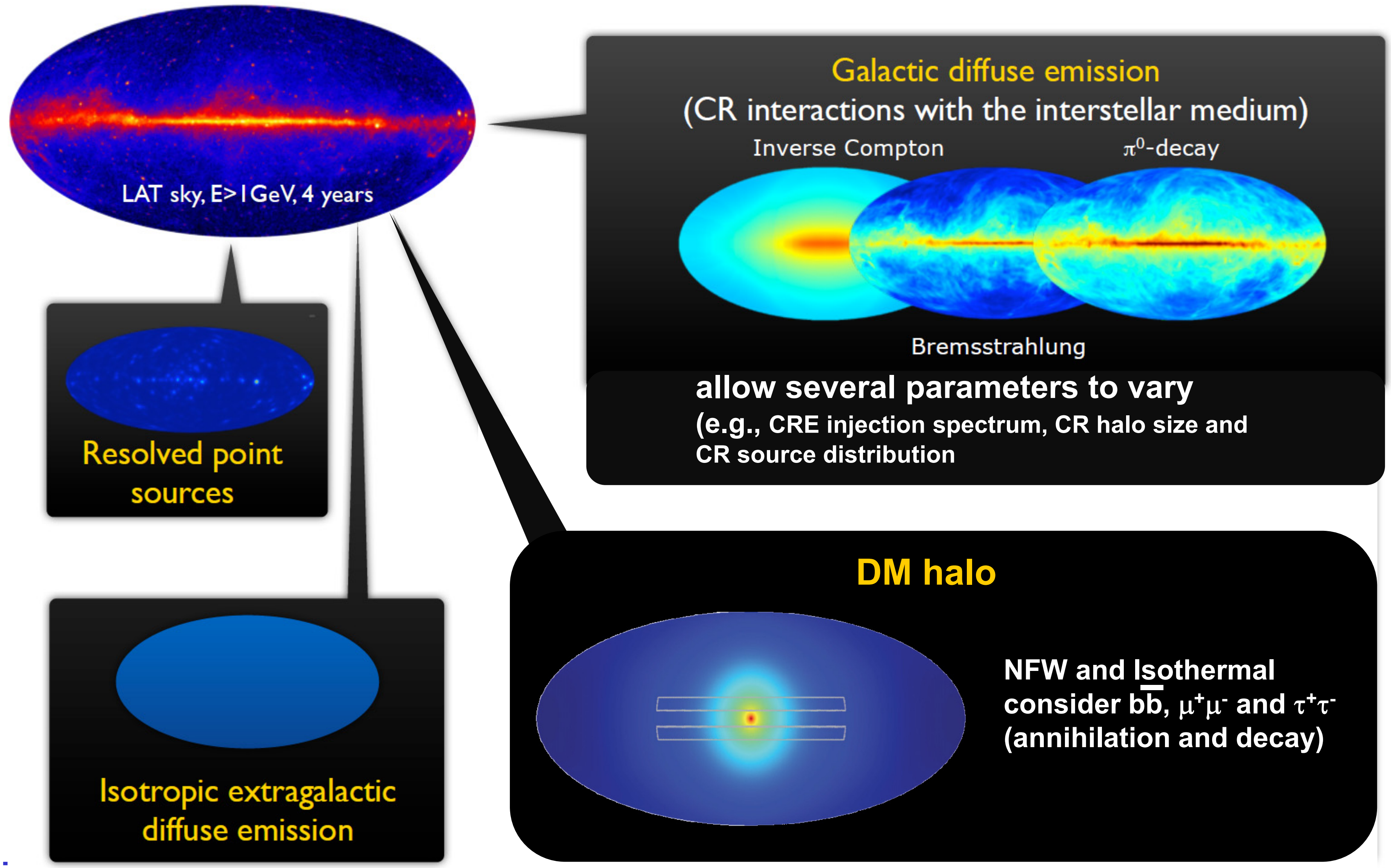
Ackermann+12, ApJ 761, 91
(CA: Conrad, Yang, Zaharijas, Cuoco)

DM Halo Search: Method I

- Assume all γ-rays are from DM and give upper limits
  - conservative, robust to uncertainty
- Expected DM counts (n_{DM}) compared to observed counts (n_{data}) and 3σ upper limit are set using (in at lease one energy bin)

$$n_{DM} - 3\sqrt{n_{DM}} \geq n_{data}$$

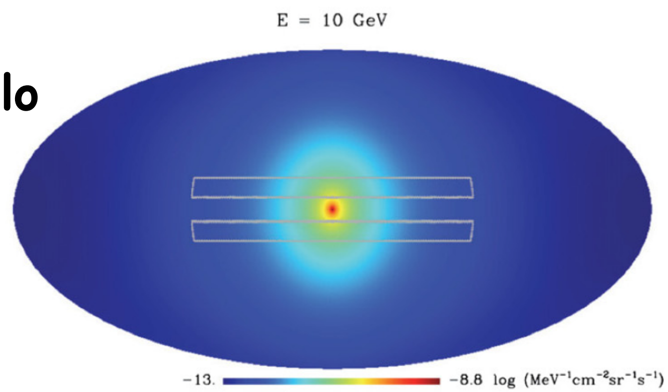
DM Halo Search: Method II

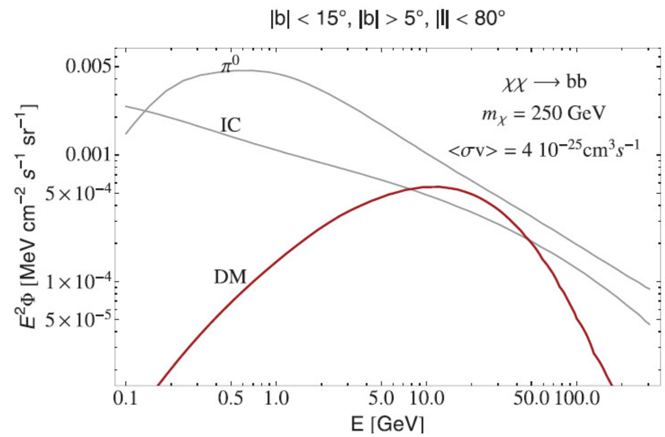


DM Halo Search: Method II

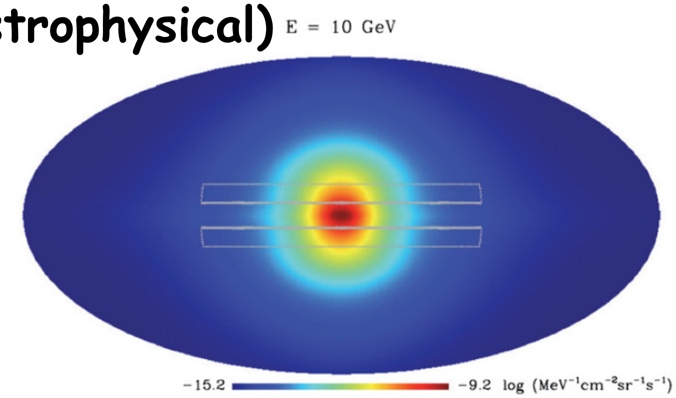
- **Disentangle DM signal from foreground by utilizing spatial and spectral shapes (good diffuse model is important)**

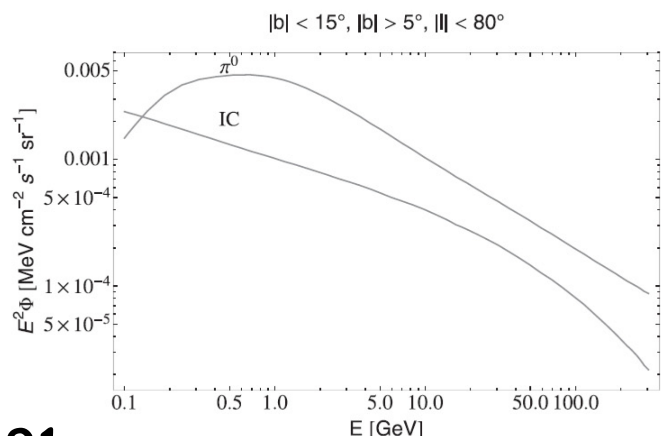
DM halo





IC (astrophysical)



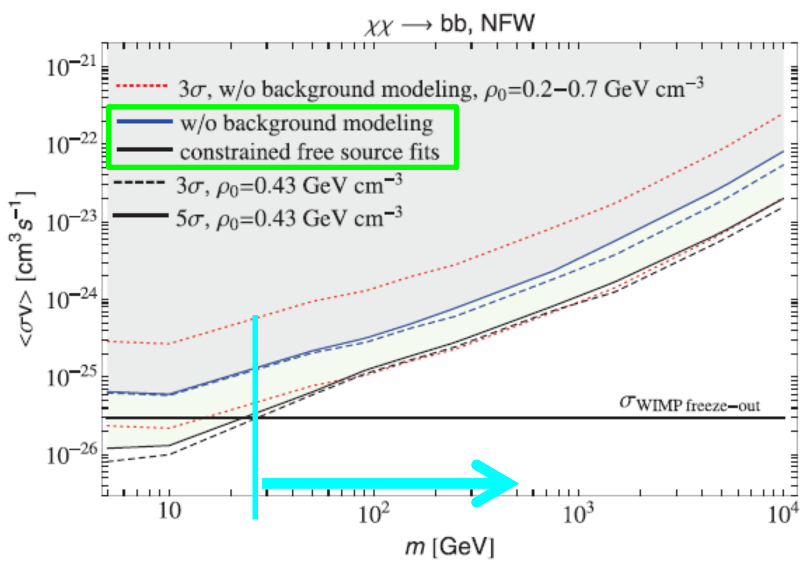


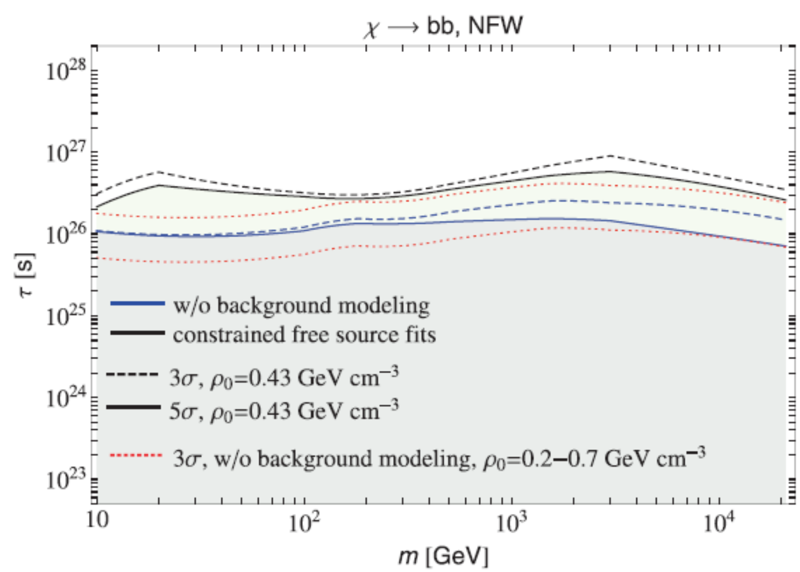
Ackermann+12, ApJ 761, 91

(CA: Conrad, Yang, Zaharijas, Cuoco)

Constraints on DM Model

- Modeling the astrophysical emission improves DM constraints by a factor of ~5
- w/ astrophysical BG, the limit constrains the thermal relic cross section for <u>WIMP with mass > 30 GeV</u> (comparable to dSphs)

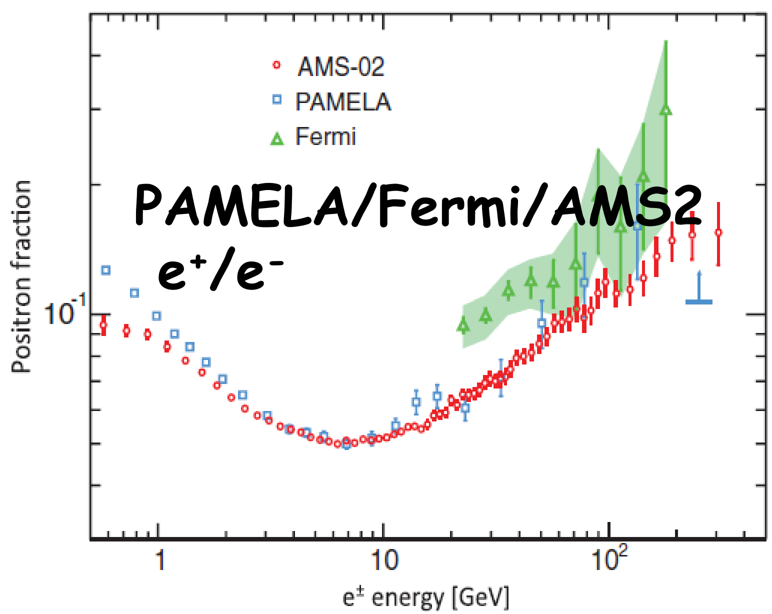




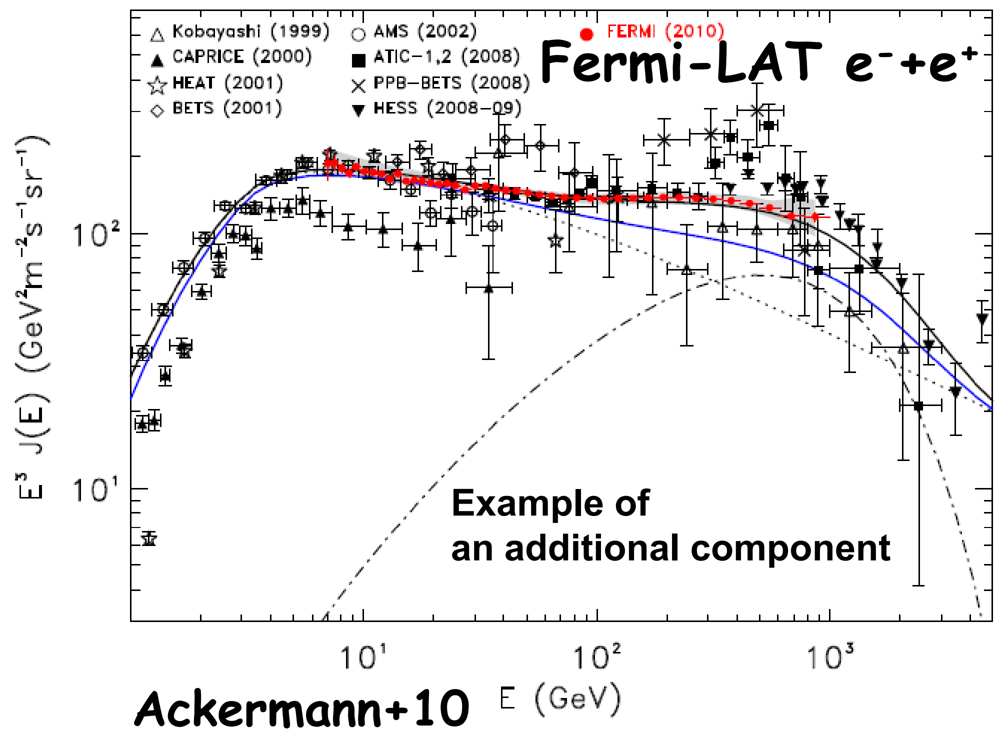
Ackermann+12, ApJ 761, 91
(CA: Conrad, Yang, Zaharijas, Cuoco)

Cosmic-ray Electrons/Positrons

- e^+/e^- is not compatible with a standard scenario (2ndary production)
  - Additional e^-/e^+ sources (astrophysical or exotic) can provide a good fit to Fermi CRE and $e^+/(e^- + e^+)$



Aguilar+13,
PRL 110, 141102



Ackermann+10
PRD 82, 092004