fermi
Gamma-ray
Space Telescope

Results from the Fermi Large Area Telescope

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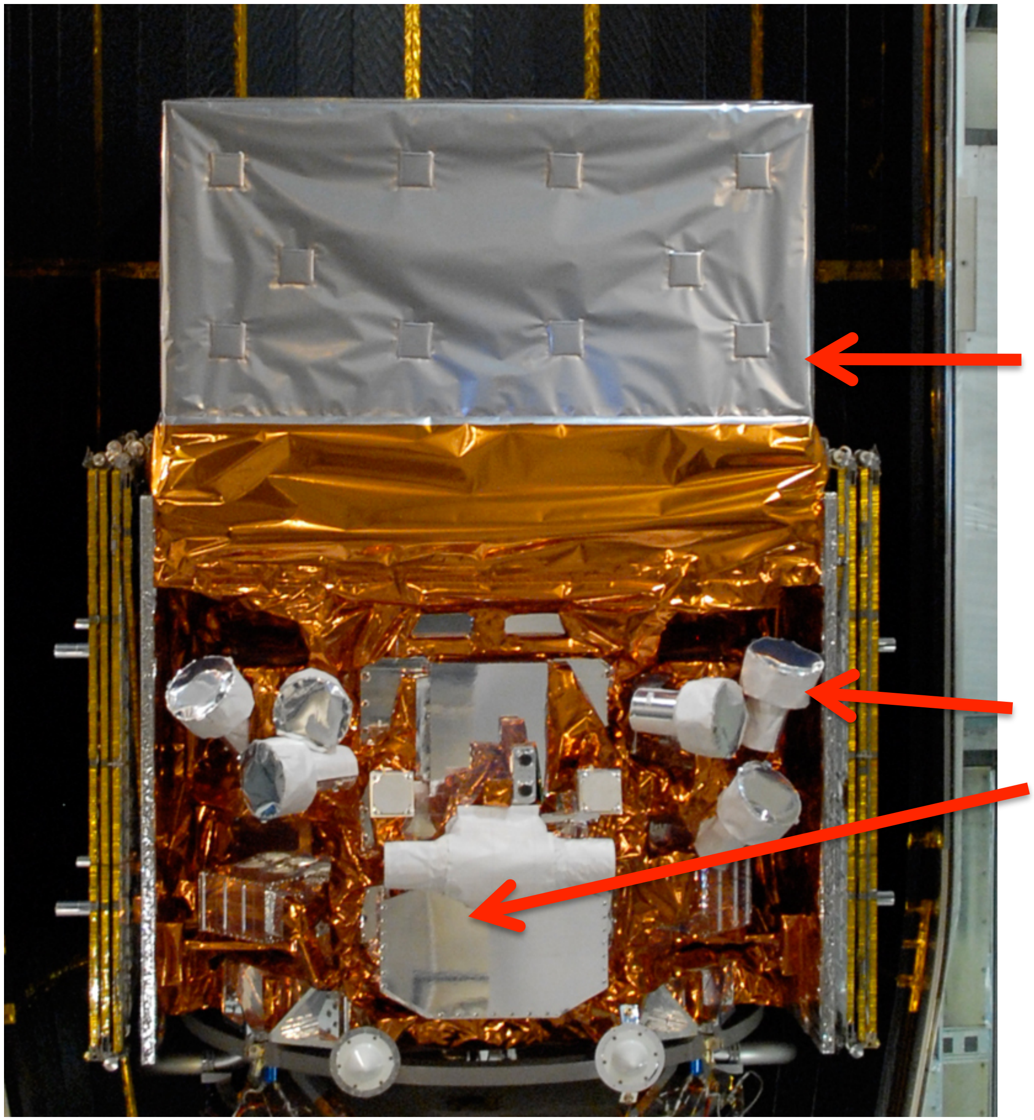
SLAC Summer Institute
July 16, 2013

SLAC
NATIONAL ACCELERATOR LABORATORY

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

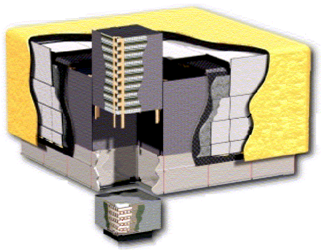
Gamma-ray Burst Monitor (GBM):

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

Fermi Gamma-ray Space Telescope

Overview of the Large Area Telescope

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

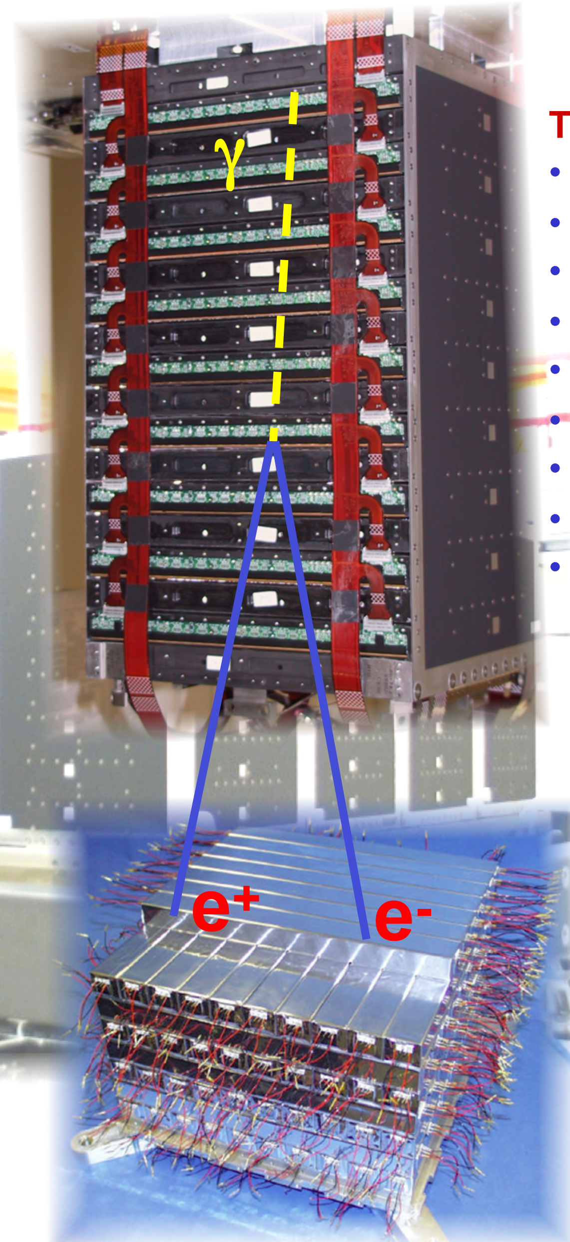


LAT:

- modular - 4x4 array
- 3ton – 650watts

Anti-Coincidence (ACD):

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



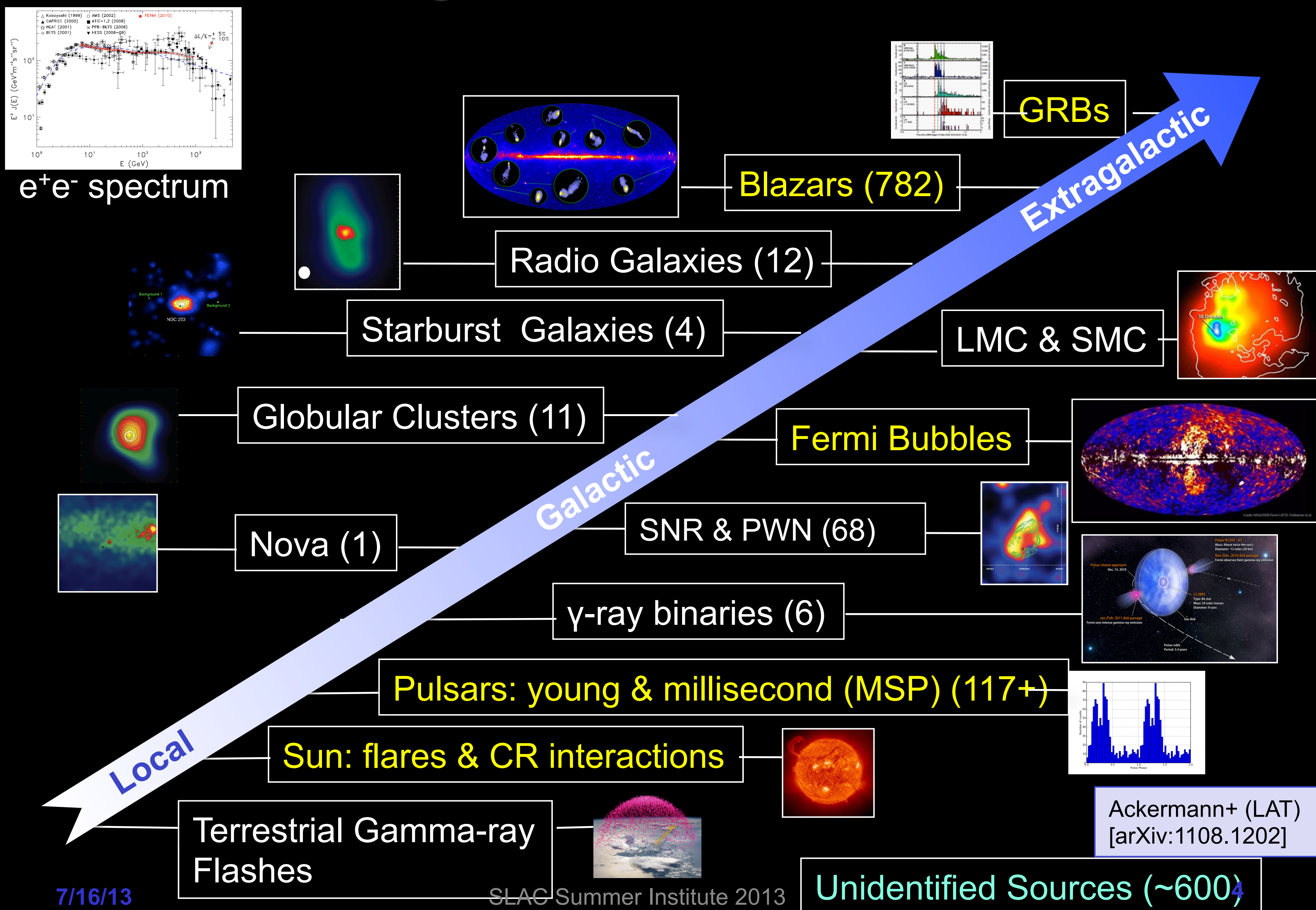
Tracker/Converter (TKR):

- 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):

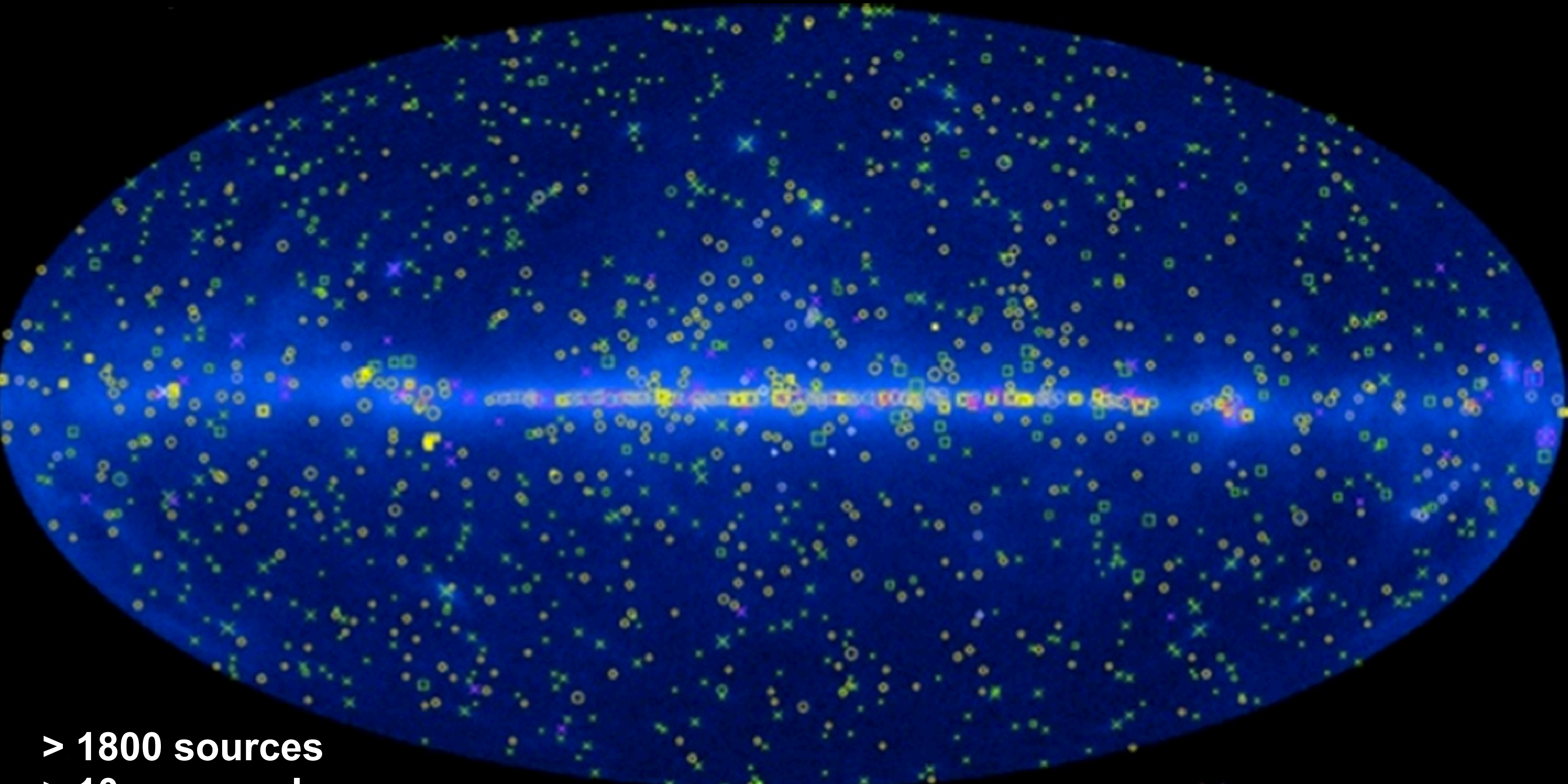
- 1536 CsI(Tl) crystals
- **8.6 X0 on-axis**
- large elx dynamic range (2MeV-60GeV per xtal)
- **Hodoscopic (8x12)**
- Shower profile recon
- EM vs HAD separation

Increasing Classes of Fermi-LAT Sources



Fermi 2FGL catalog

Nolan et al.: 2012ApJS..199...31N

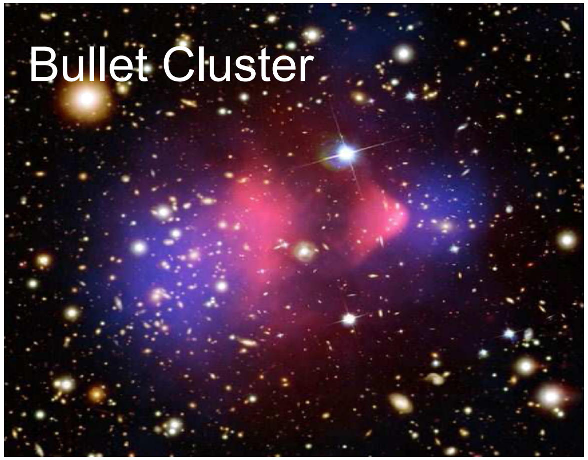


- > 1800 sources
- > 10 source classes
- known classes (AGN, Pulsars, PWN, SNR...)
- New emitters (Novae, ms PSR, starbursts)
- ~30% unidentified

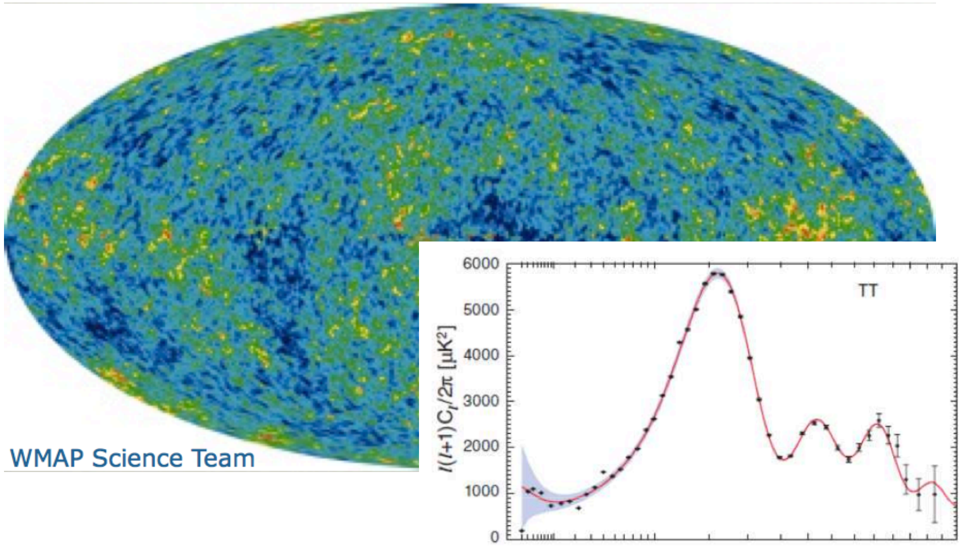
3FGL in preparation

Evidence for Dark Matter

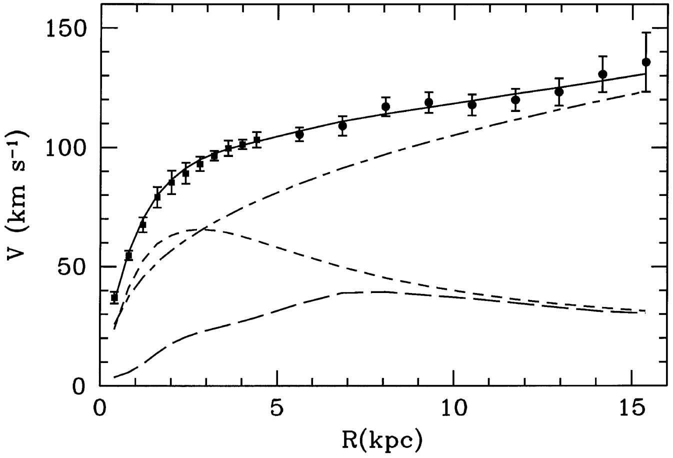
Gravitational Lensing



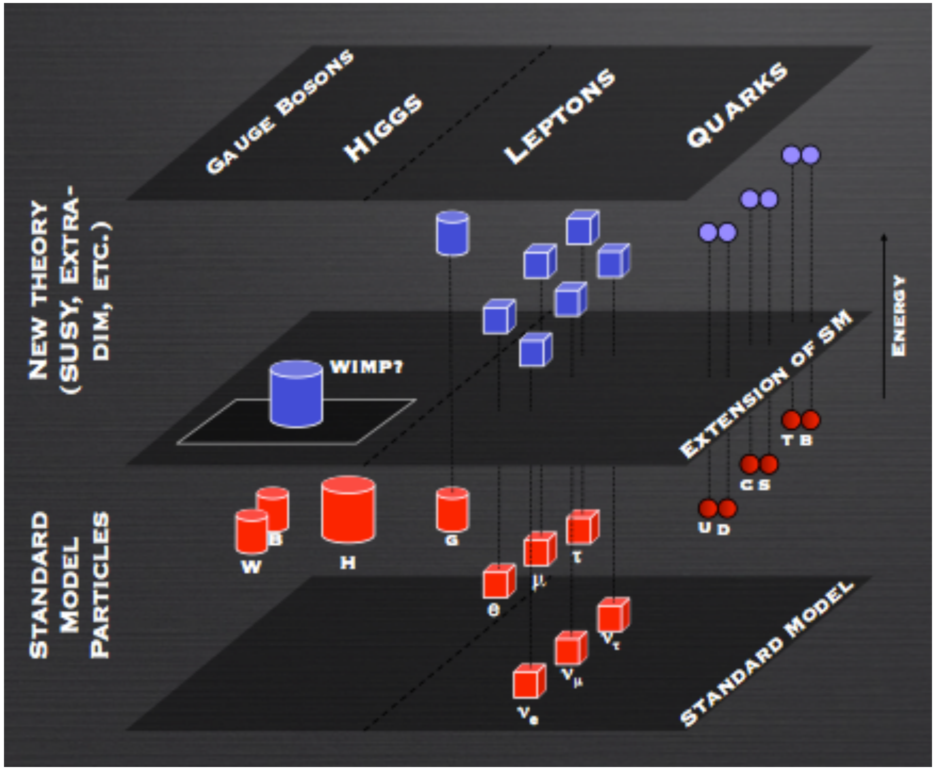
CMB Power Spectrum



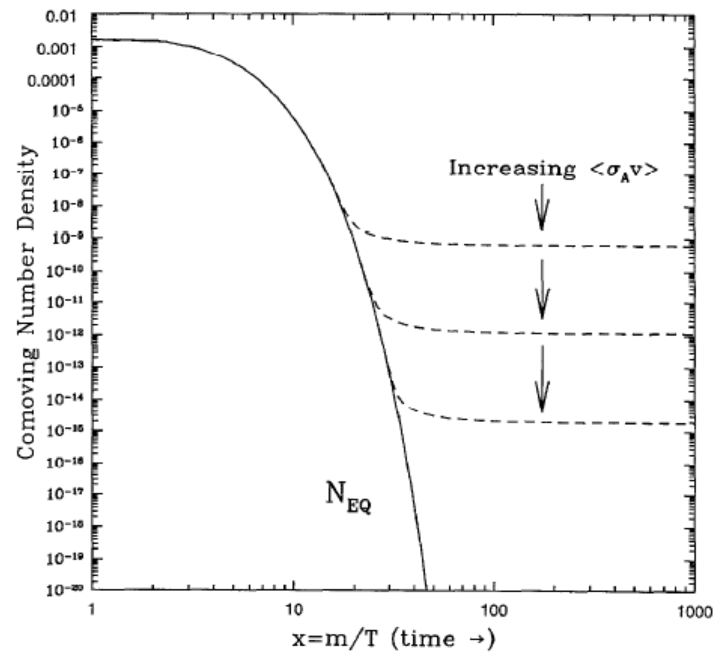
Kinematics of Galaxies and Galaxy Clusters



Particle Physics offers Dark Matter Candidates



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

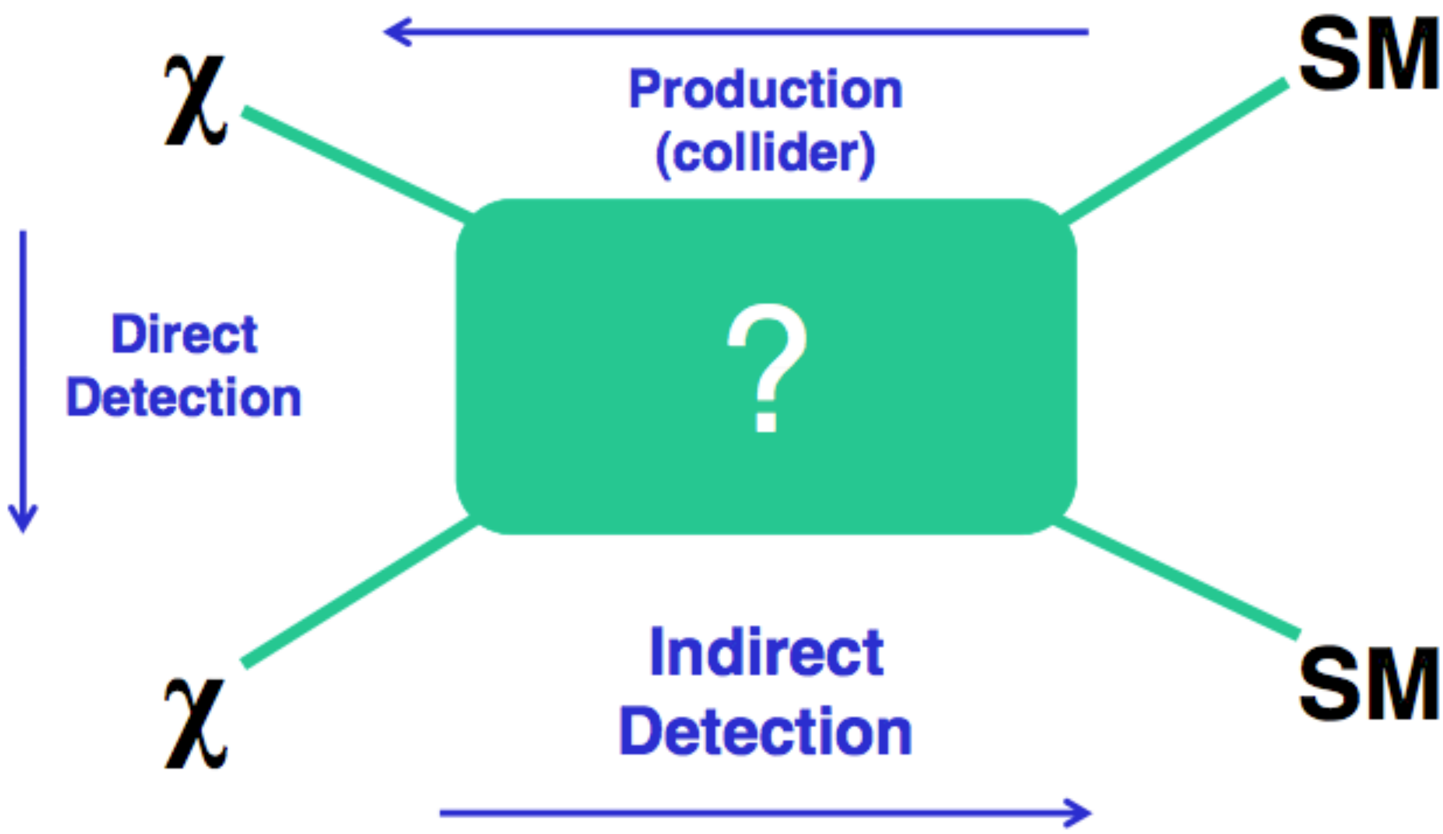


Weakly Interacting Massive Particles (WIMPs) are an interesting DM candidate

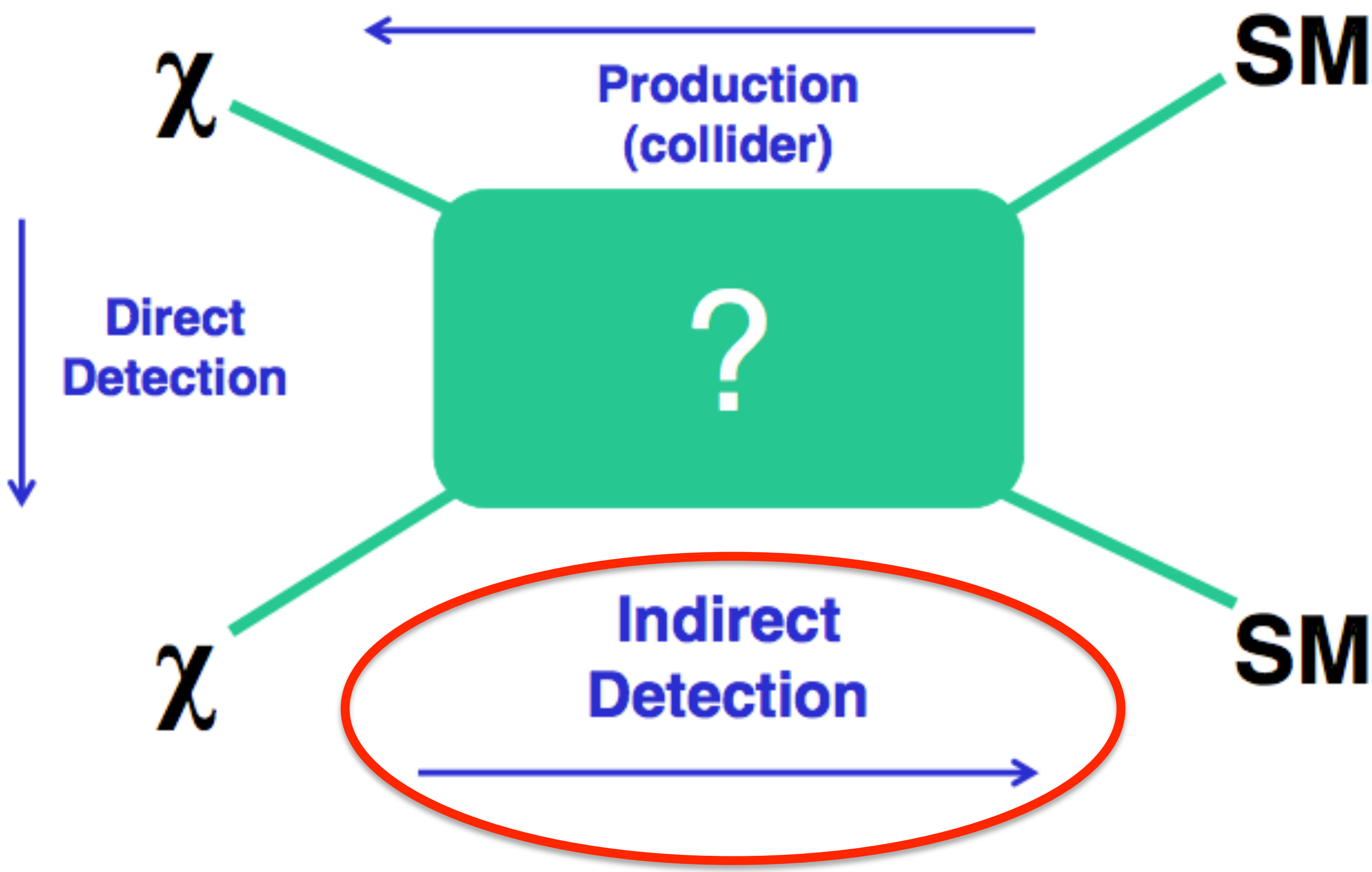
"WIMP Miracle", WIMPs as thermal relic:
Mass scale ~ 100 GeV
$\langle\sigma v\rangle \sim 3\ 10^{-26}\ \mathrm{cm}^3\ \mathrm{s}^{-1}$

Thermal freezeout process connects WIMP cross section to relic density

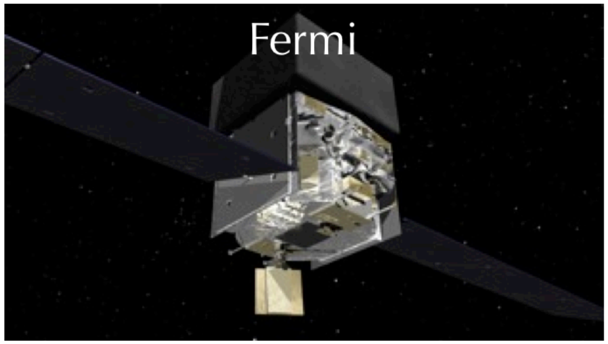
Dark Matter Searches



Dark Matter Searches

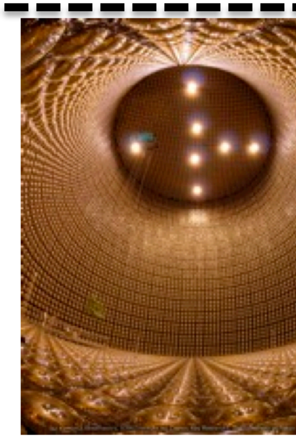


Indirect Dark Matter Searches

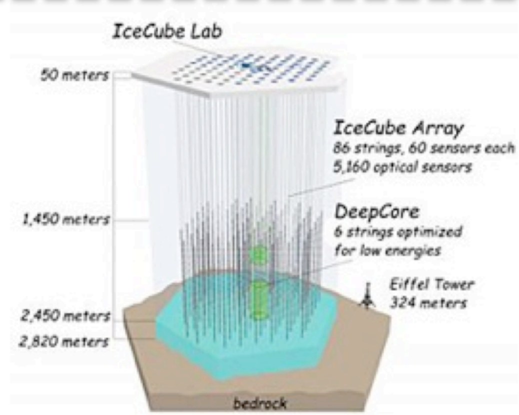


γ

Super-K



ν



ICECUBE

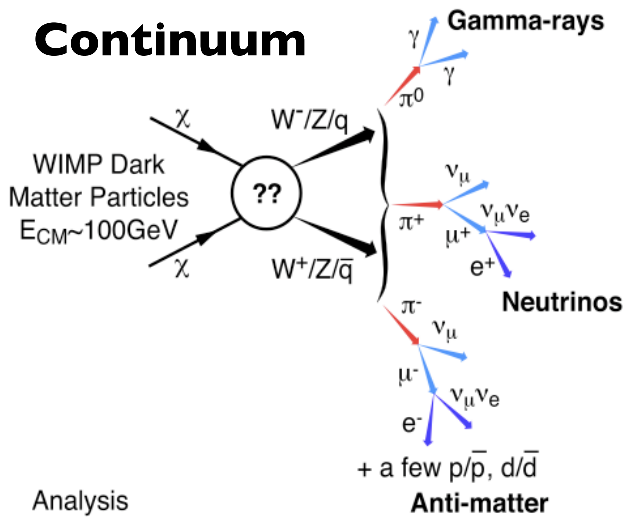
PAMELA

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

AMS

Gamma-ray Signature of Dark Matter

Continuum

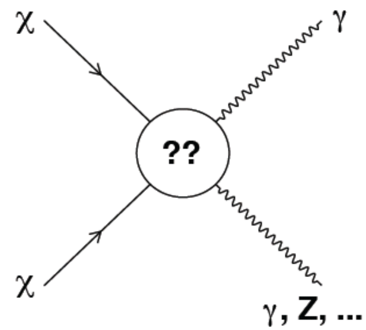


Analysis

+

Spectral line

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



Gamma-ray Flux

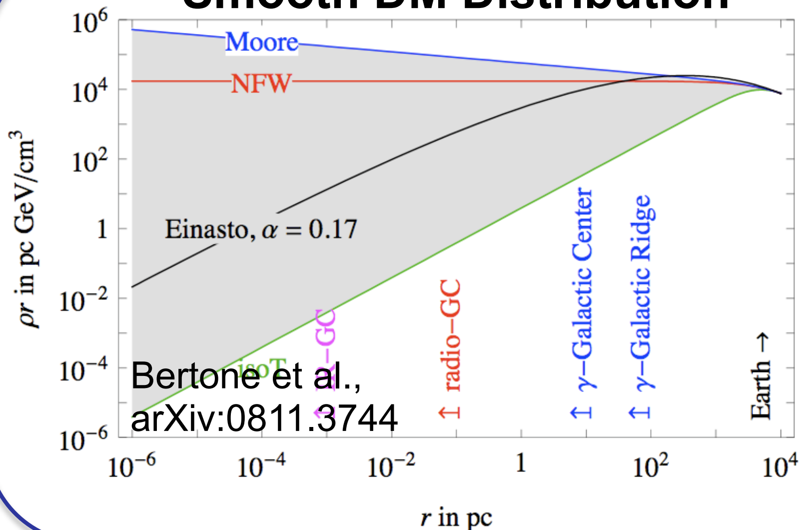
Particle Physics

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

DM Distribution (J-Factor)

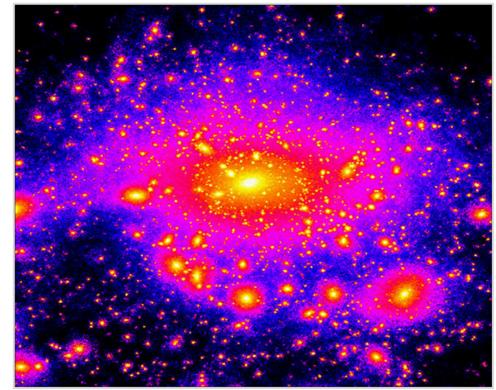
Gamma-ray Signature of Dark Matter

Smooth DM Distribution



X

Boost Factor



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)

Fermi-LAT DM Search Targets

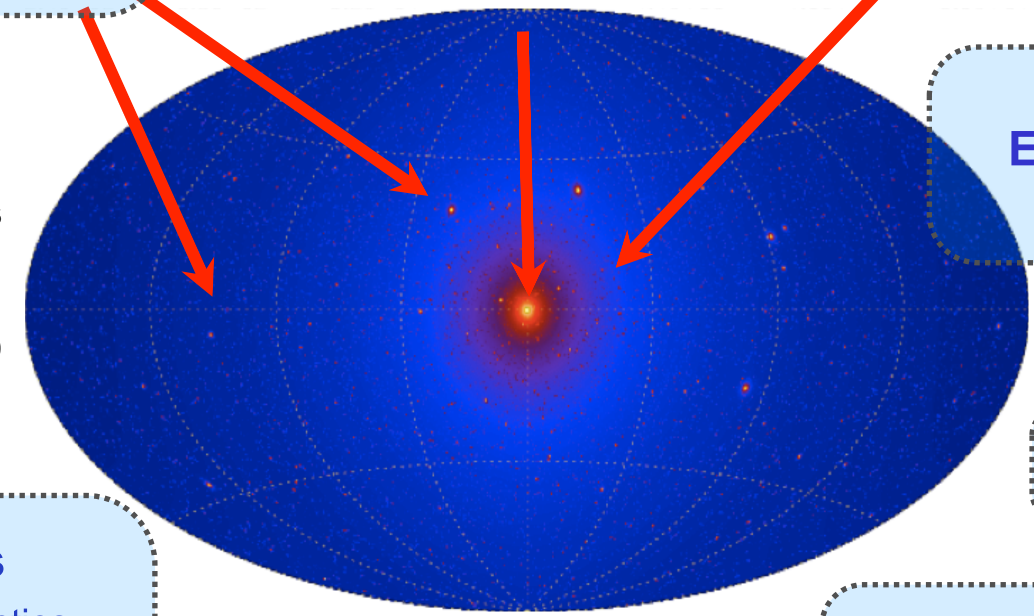
Satellites
Low background and good source id, but low statistics, astrophysical background

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)



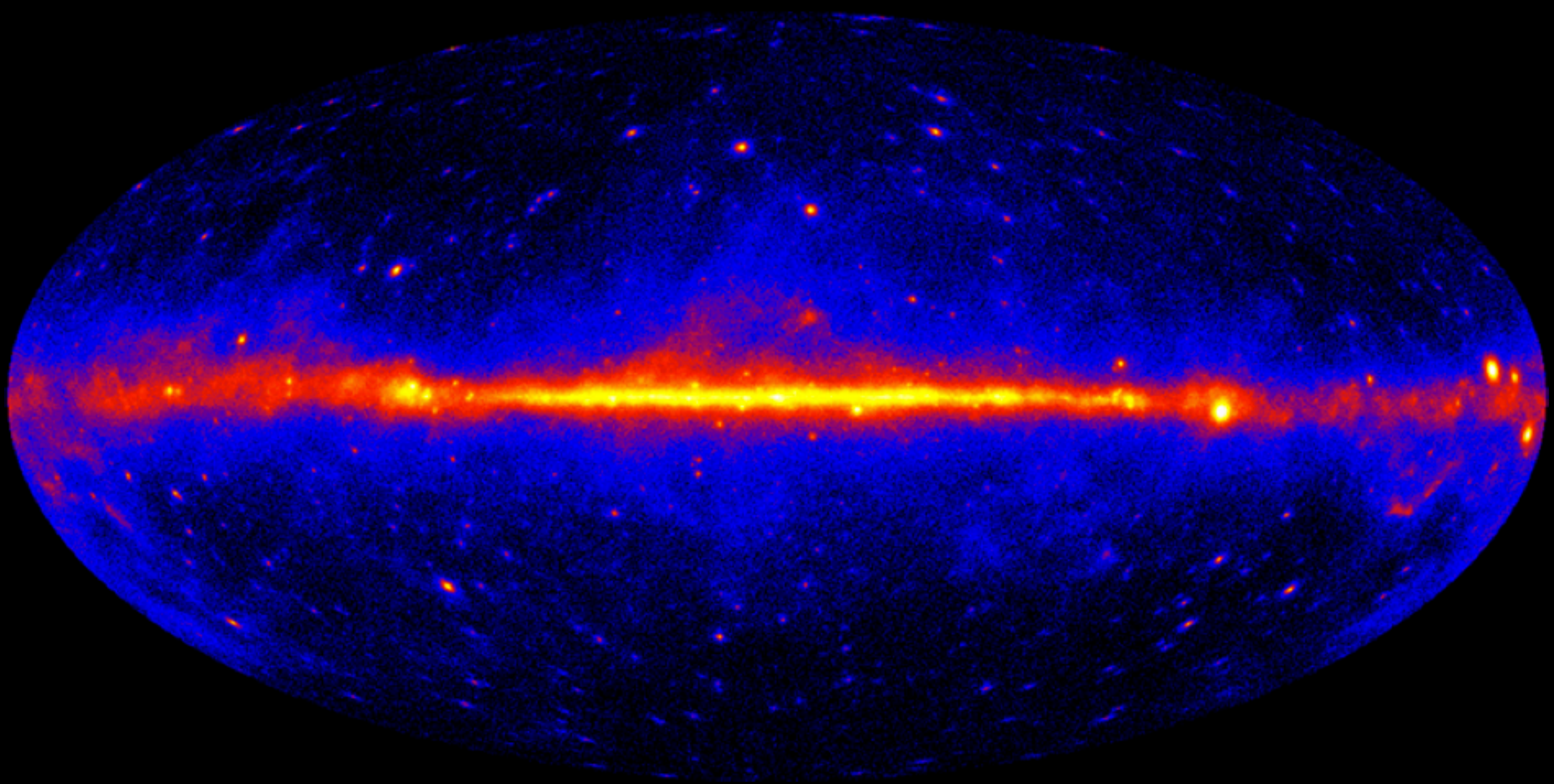
The Sun

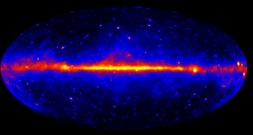
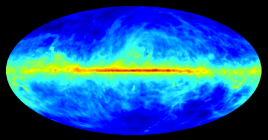
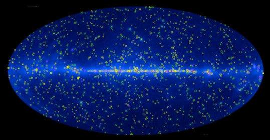
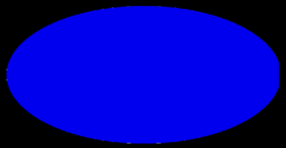
Spectral Lines
No astrophysical uncertainties, good source id, but low sensitivity because of expected small BR

Extra-galactic
Large statistics, but astrophysics, galactic diffuse background

Galaxy Clusters
Low background, but low statistics

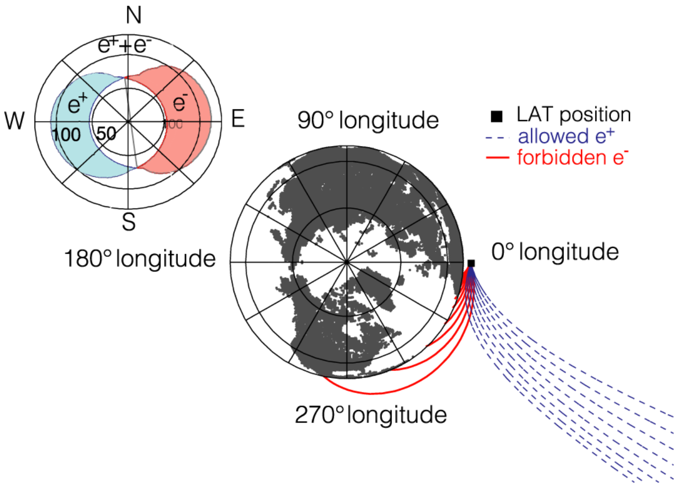
Searching Dark Matter in the gamma-ray sky

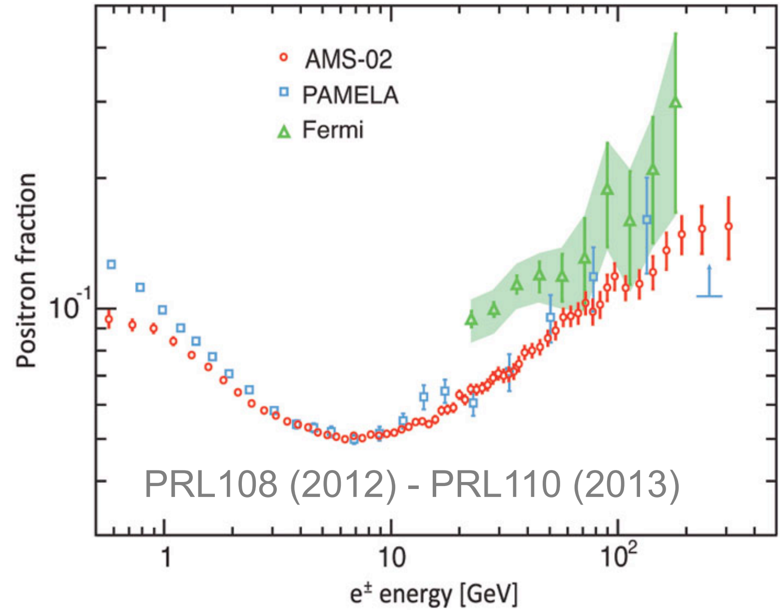


 =  +  +  + ???

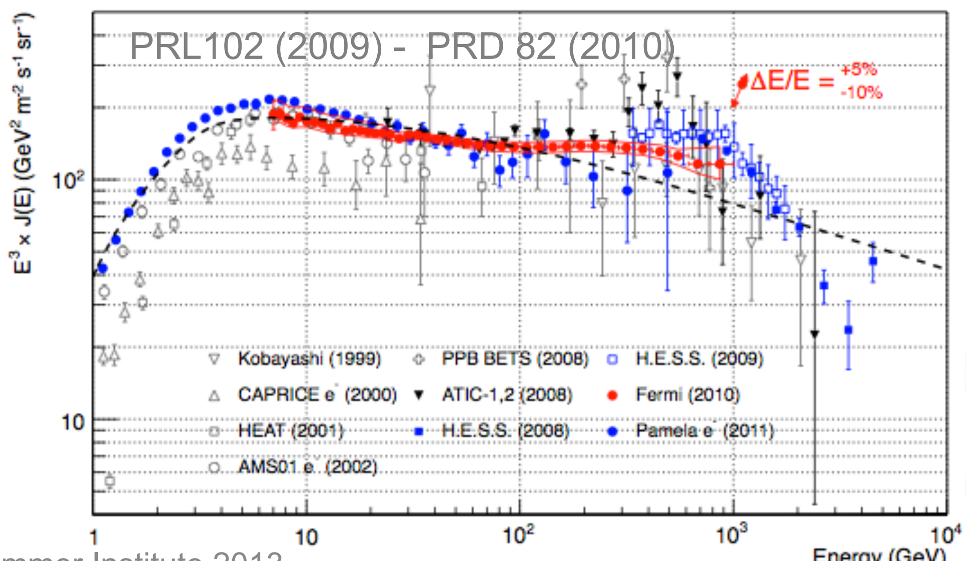
GeV Sky   Galactic   Point Sources   Isotropic

Cosmic Ray Electron/Positron Measurements



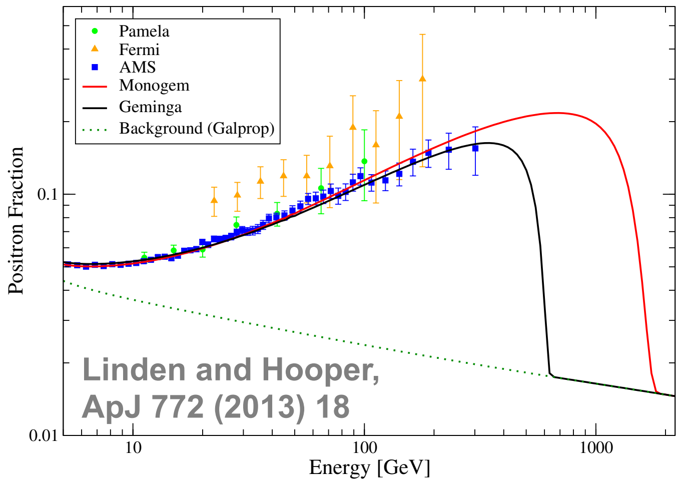


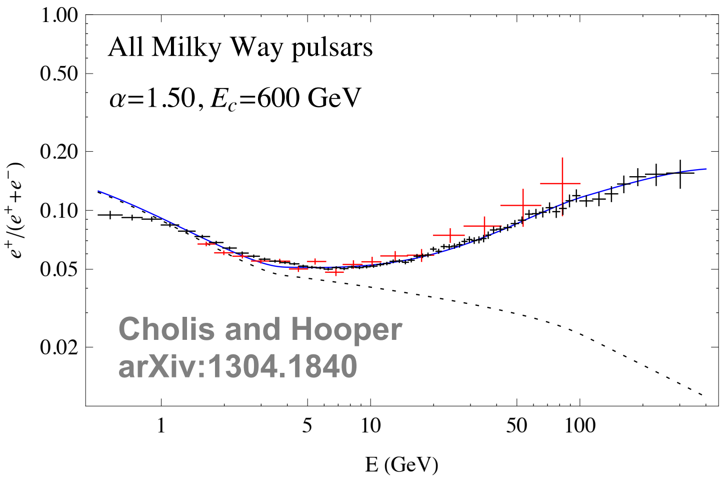
- **Creative use of a γ-ray telescope**
  - **Dedicated event selection**
  - **Same event reconstruction**
  - **Earth magnetic field**
- **Surprising results with independent confirmations**
  - **Hard inclusive spectrum**
  - **Rising positron fraction**



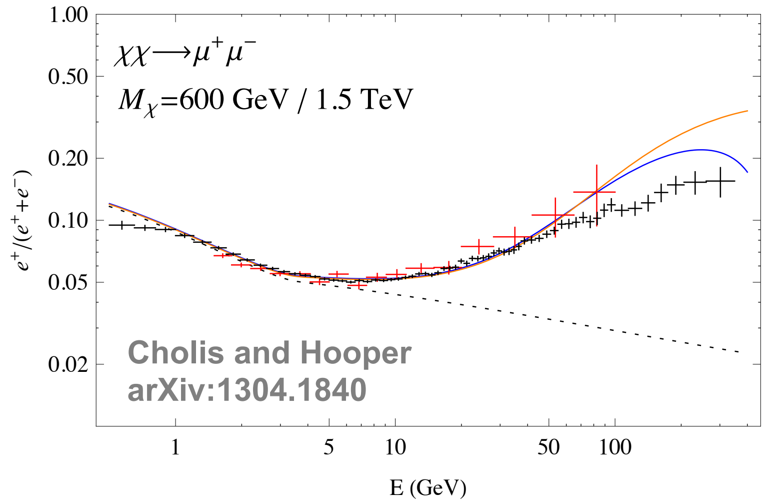
Explaining the Positron Excess

Pulsars



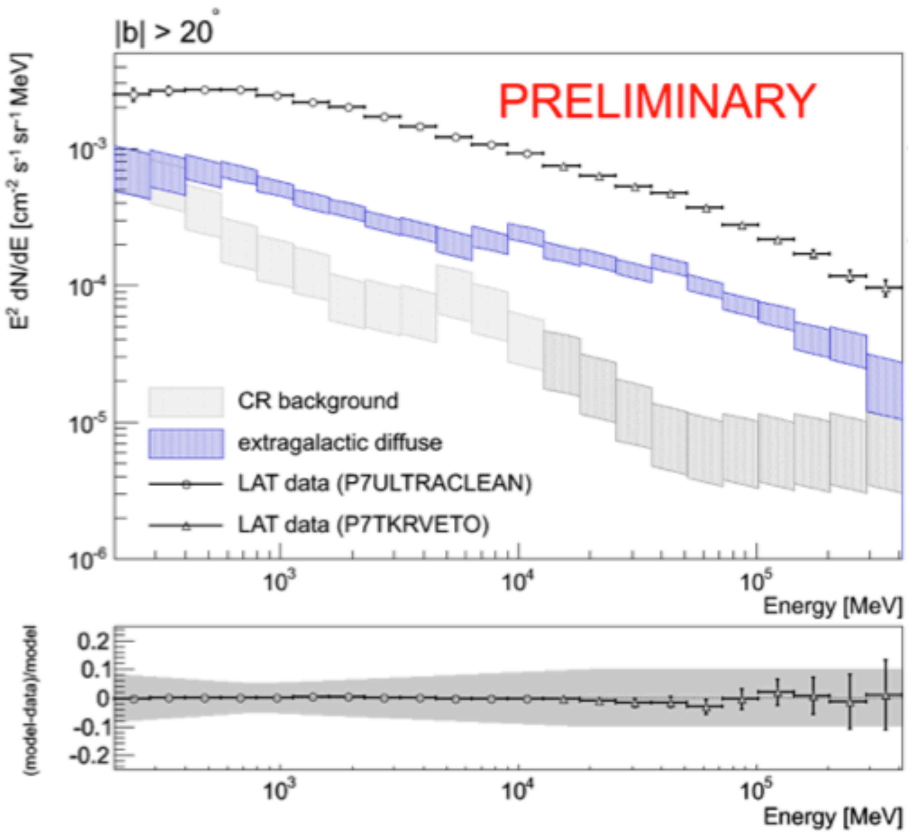


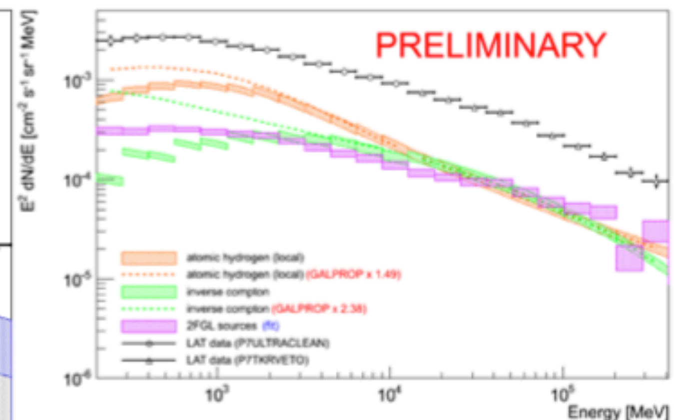
Dark Matter



- **Many astrophysical models have been proposed**
  - **Pulsars**
  - **Secondary Production in SNR**
- **Pure DM models are increasingly difficult to reconcile with experimental data**
  - **Spectral shape in AMS-02 data is not well matched to DM annihilation spectrum**
  - **Absence of anomalies in gamma rays and other charged particle fluxes**

Extragalactic Gamma-ray Background





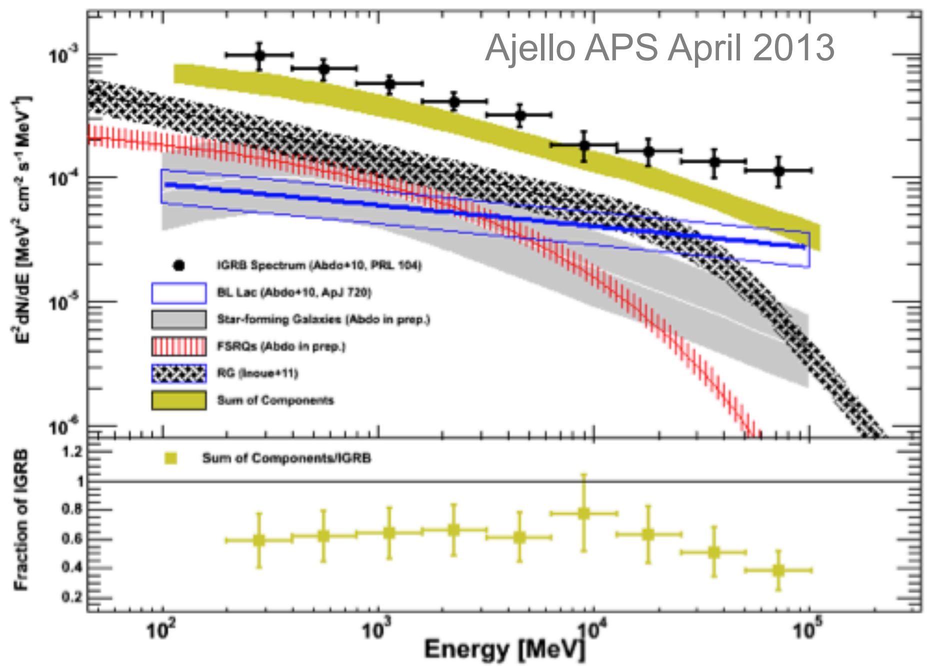
- Preliminary EGB spectrum between 200 MeV to 410 GeV for default foreground model.
- Error bands include systematics from effective area uncertainty and CR background subtraction.
- ... but **NOT** systematics from foreground model uncertainties. (still under evaluation).
- Publication in preparation for EGB spectrum up to 820 GeV.

Markus Ackermann | Fermi Symposium, Monterey | 11/01/2012 | Page 15

Will follow earlier publication Abdo, A. A. et al. 2010, Phys. Rev. Lett., 104, 101101

EGB – modeling source contributions

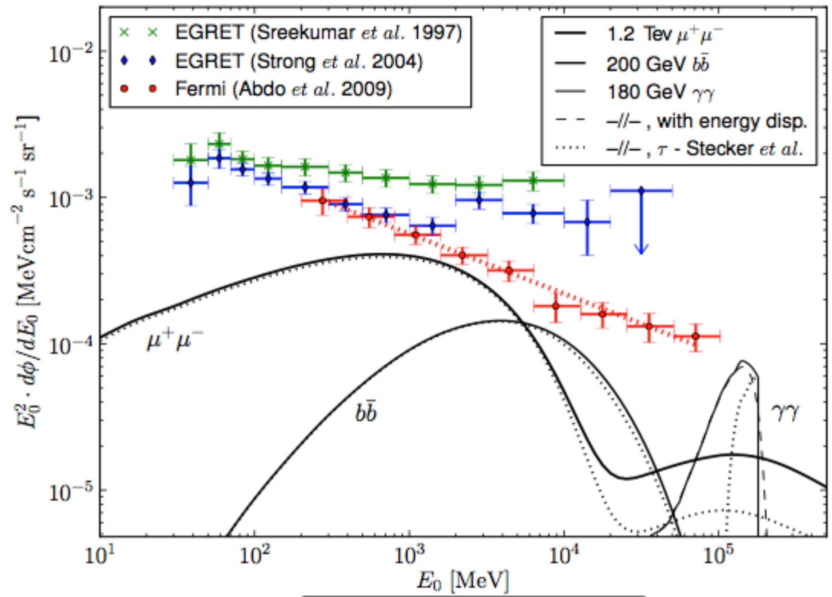
- Undetected sources
  - AGN, Star-Forming Galaxies, ms PSR, Gamma-Ray Bursts
- Diffuse processes
  - Shocks, Dark Matter, UHECR scattering EBL, large CR halo
- Large theoretical uncertainties
- For some classes no gamma-ray luminosity functions
  - Using radio / IR correlation functions

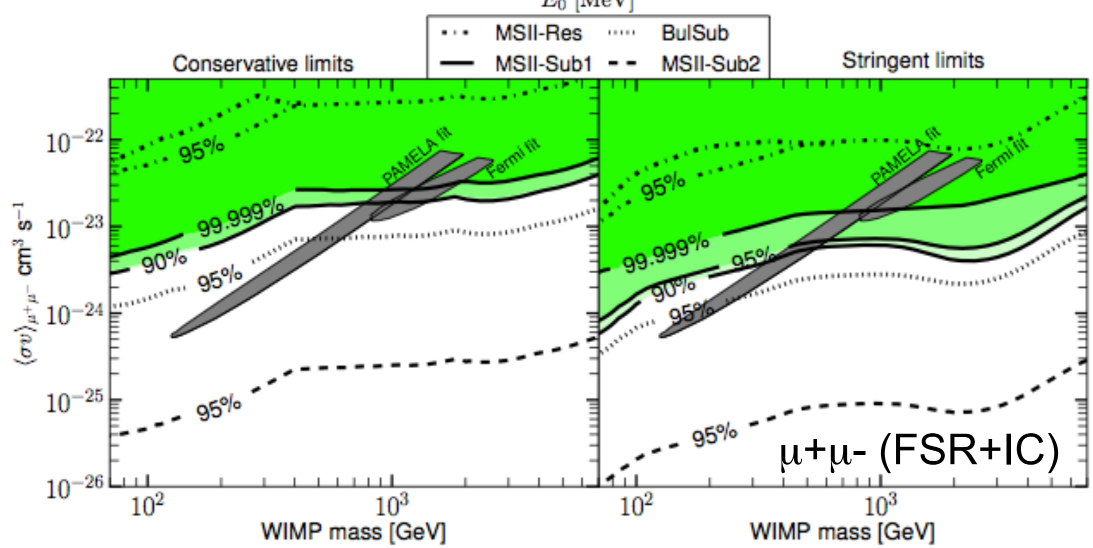


Constraints on Cosmological DM

Ackermann, M. et al. 2011, ApJ, 726, 81

- Use Fermi EGB to search for a DM signal from all halos at all redshifts
- Predictions affected by
  - DM distribution
  - γ-ray opacity
- Under reasonable assumptions can exclude most DM models explaining CR lepton excess from Fermi and Pamela

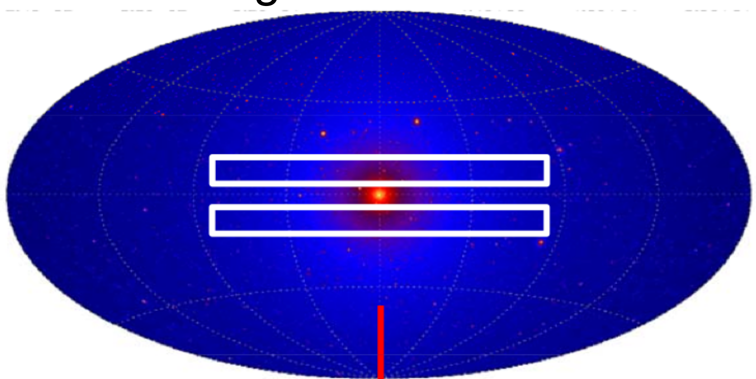




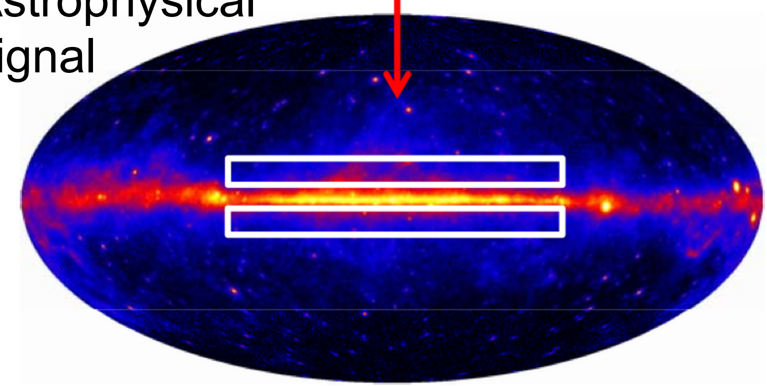
Constraints from Milky Way Halo

Ackermann+ ApJ 761 (2012) 91

Expected DM signal



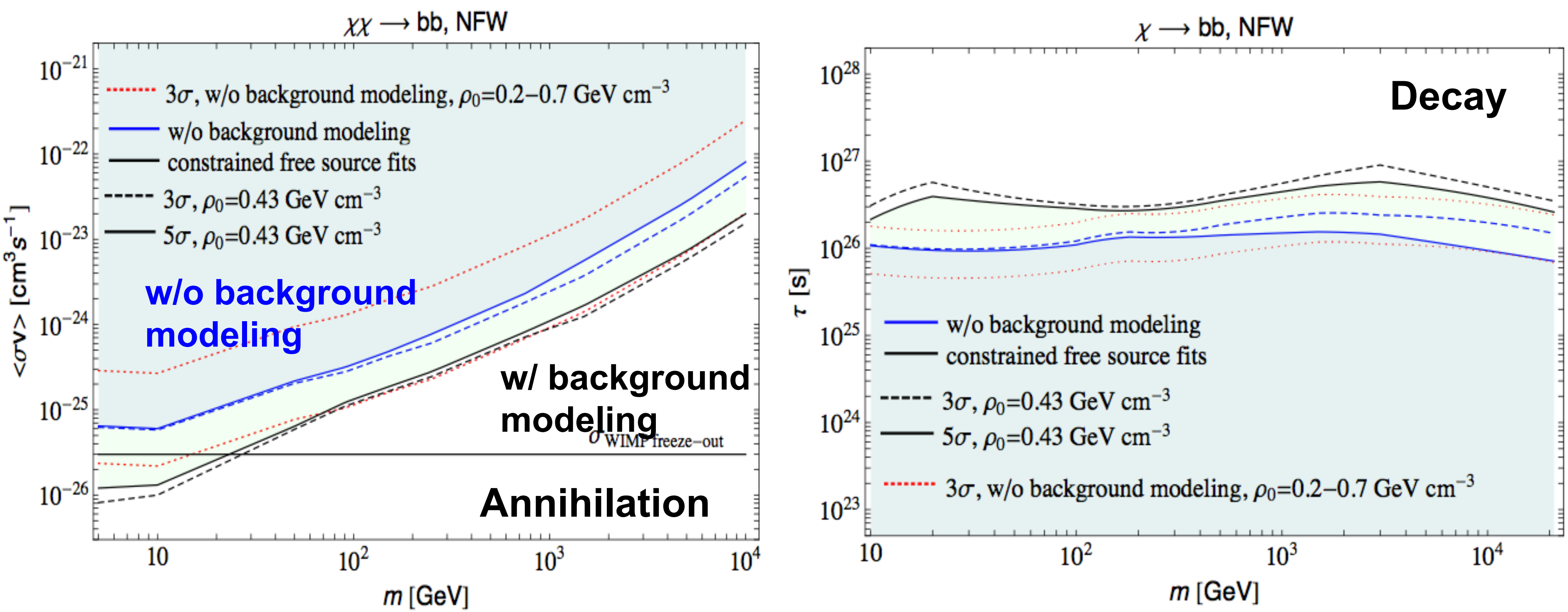
Astrophysical signal



- **two 10^o bands 5^o off the plane**
  - **minimize astrophysical background**
  - **mitigate uncertainties from inner DM density profile**
- **Two approaches to set limits:**
  1. **more conservative: assume emission only from DM**
  2. **more accurate: fit the DM and astrophysical emission simultaneously**
- **Explores systematics of diffuse emission modeling**

Constraints from Milky Way Halo

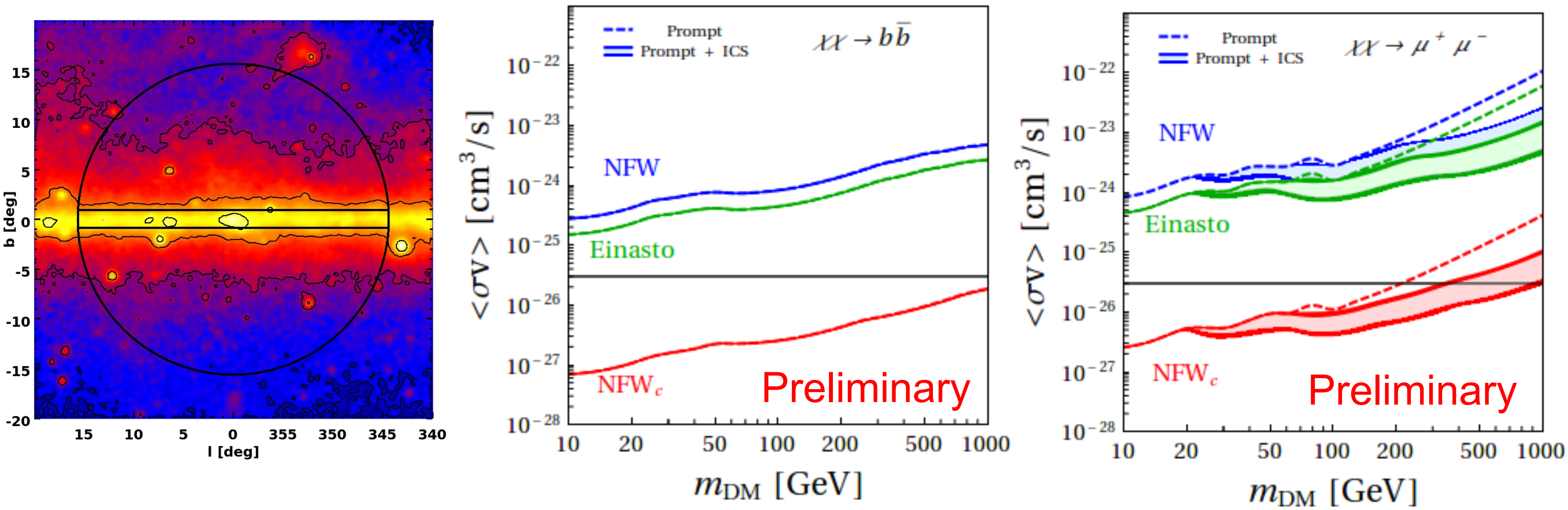
Ackermann+ ApJ 761 (2012) 91



- **Including modeling of the astrophysical emission improves the DM constraints by a factor of ~5**
- **With inclusion of astrophysical backgrounds, the limit constrains a canonical thermal annihilation cross section into b-quarks to a WIMP mass $\gtrsim$ 30 GeV**
- **Marginalizes over many different diffuse emission models to take into account uncertainties in astrophysical foreground subtraction**

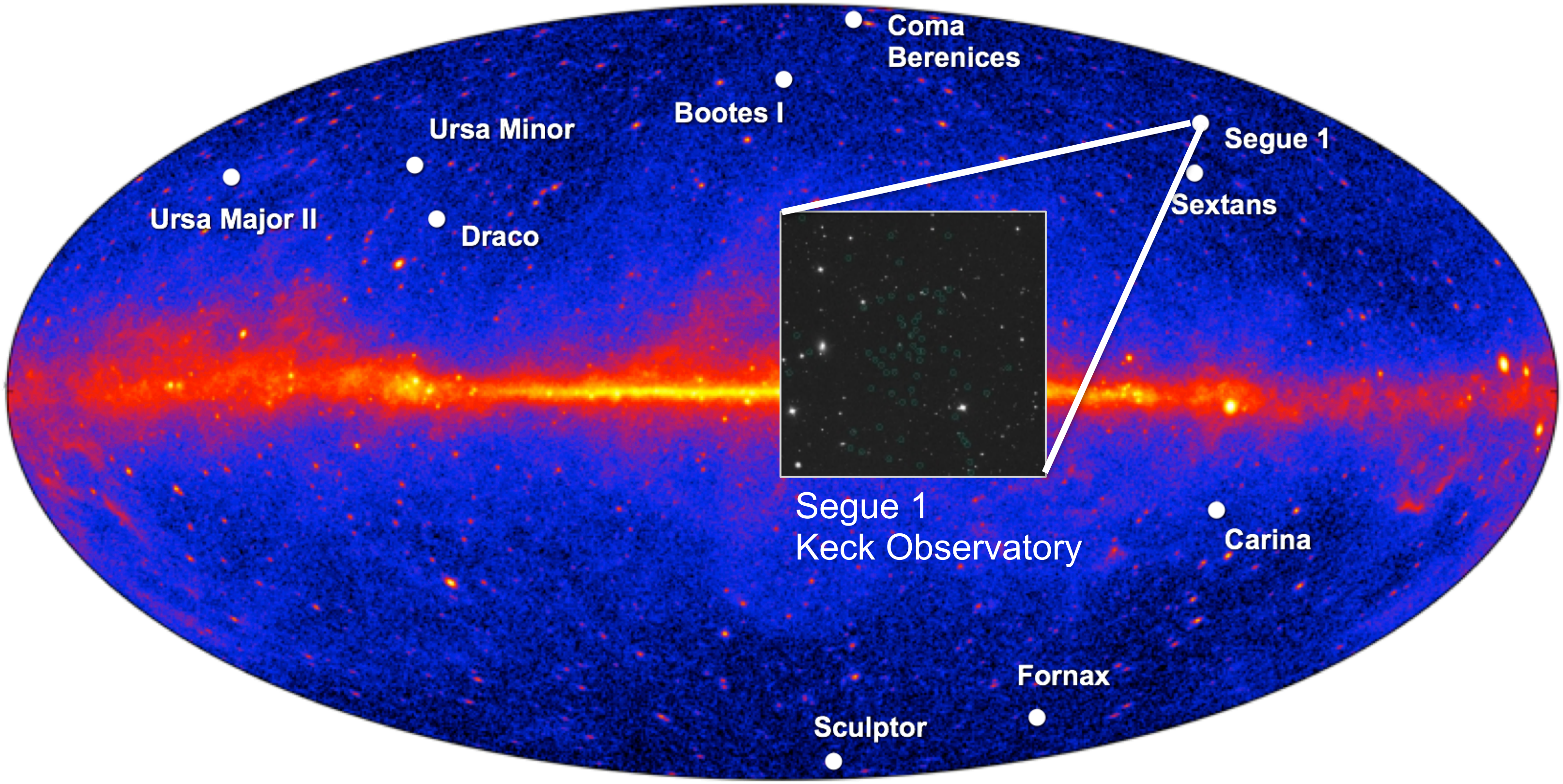
Constraints from the Inner Galaxy

Gómez-Vargas+ in preparation



- **Inner galaxy should be the brightest DM annihilation source in the sky**
- **Systematics make the inner galaxy a challenging target for DM searches**
  - **Crowded region with many point-sources and strong diffuse foreground emission**
  - **Large uncertainty on the shape and normalization of the DM distribution in the inner galaxy**
- **Set conservative upper limits by requiring that DM annihilations not exceed the inclusive spectrum of the inner galaxy region (R < 15 deg)**

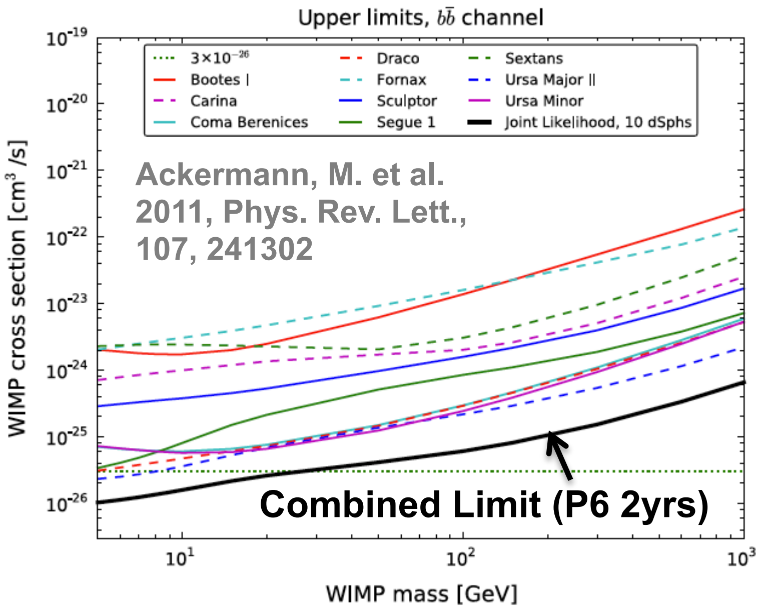
Dwarf Spheroidal Galaxies

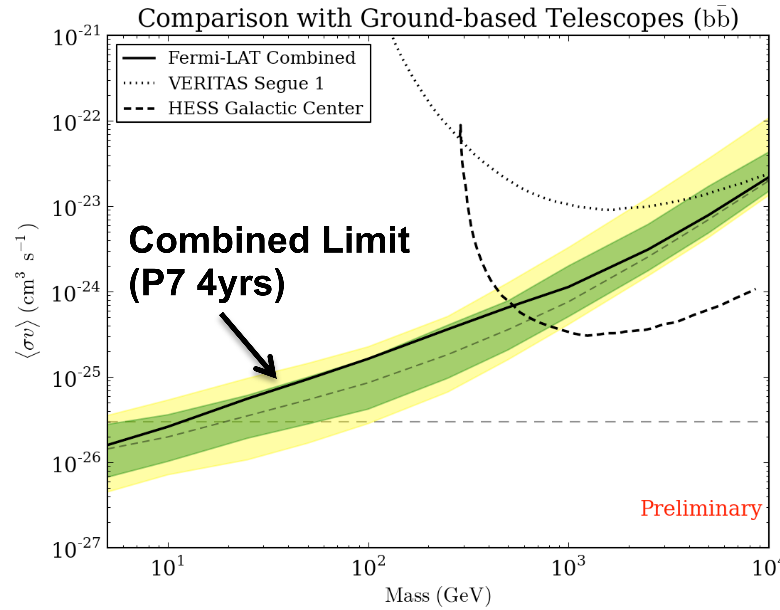


- **Faint satellites of the MW with typical distances of 30-100 kpc**
- **Ideal search targets due to high DM content, low astrophysical foregrounds, and absence intrinsic gamma-ray emission**
- **This is as a low-signal, low-background search strategy**

Dwarf Stacking Limits

Ackermann+ PRL 107, 241302 (2011)

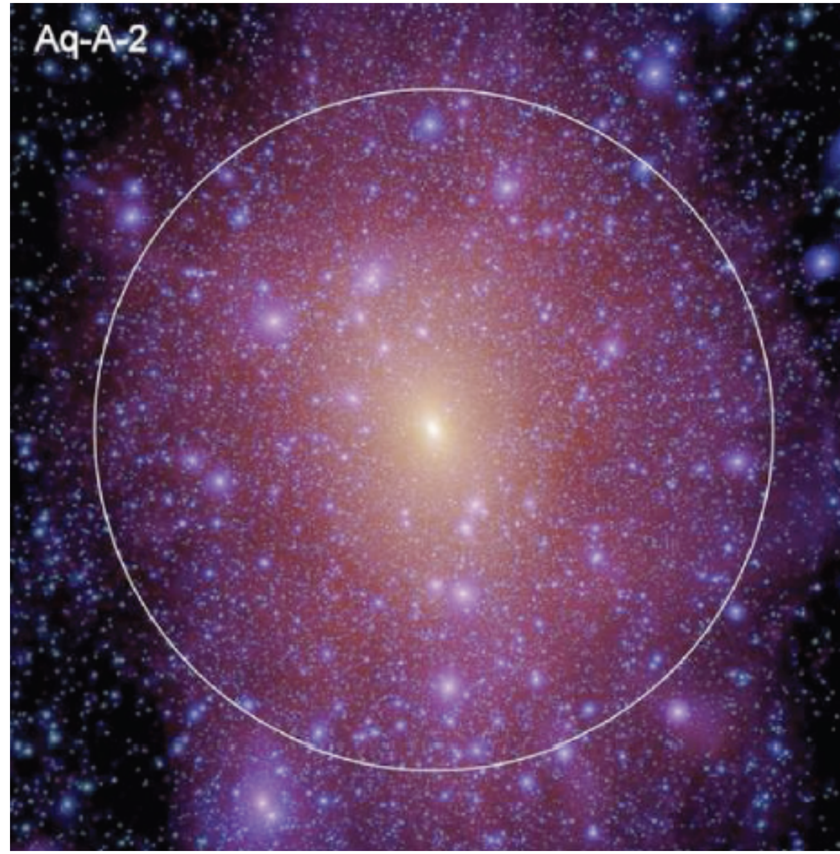




- **No detection – combined limit from 10 dSphs is close to thermal WIMP cross section for masses below ~30 GeV (bb and ττ channels)**
- **Comparable to limits from ACT observations of dwarf galaxies at high DM masses (> 1 TeV)**

Galactic DM Substructures

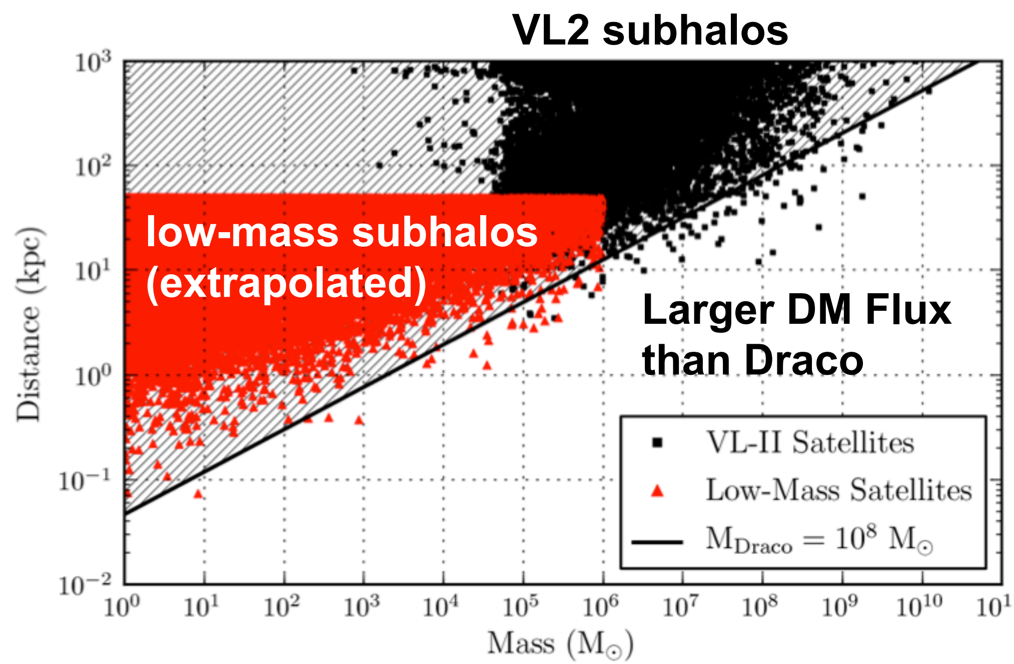
- CDM simulations predict the existence of abundant DM subhalos in the Milky Way
- Fermi-LAT can look for ‘dark’ subhalos by searching for unassociated sources with the expected characteristics of DM
  - Spectral Curvature
  - Spatially Extended
  - Steady emission (no variability)



Unassociated Satellite Search

Ackermann+ ApJ 747 (2012) 121

- Look for unassociated LAT sources from 1FGL with properties consistent with DM substructure
- Use Via Lactea II (VL2) simulations to model the properties of the MW subhalo population
- Extrapolate subhalo properties below resolution limit (~10^6 M_{sun})
- Results
  - No subhalo candidates found
  - From VL2 expectations derive limits on the DM annihilation cross section



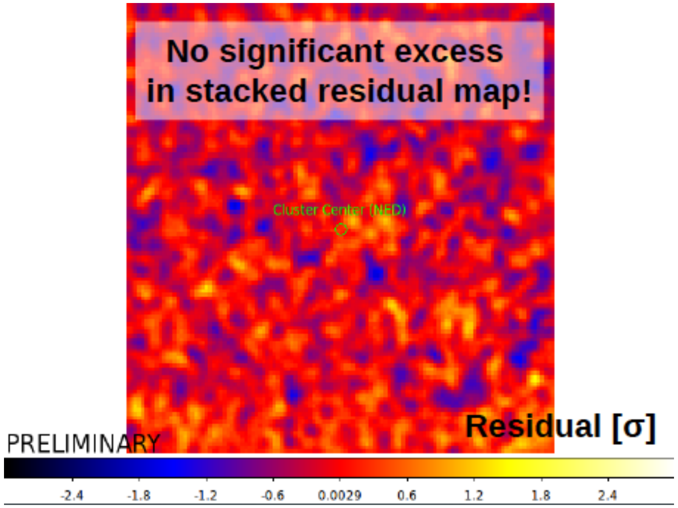
$\langle \sigma v \rangle \lesssim 2 \times 10^{-24}\ cm^3\ s^{-1}$

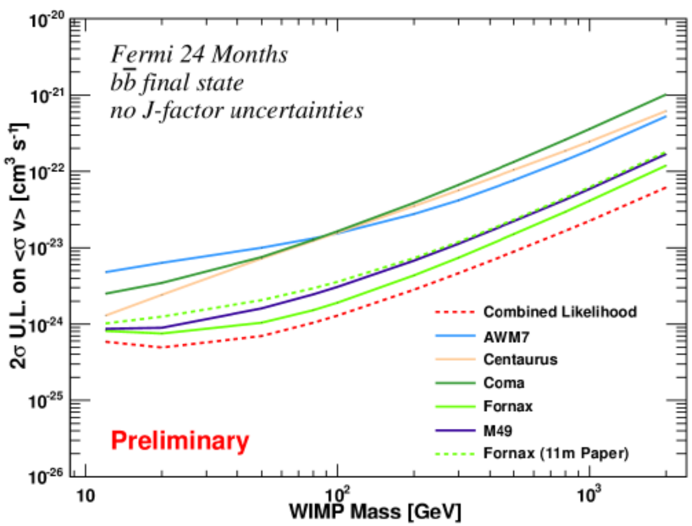
(100 GeV WIMP, $b\bar{b}$ channel)

Galaxy Clusters

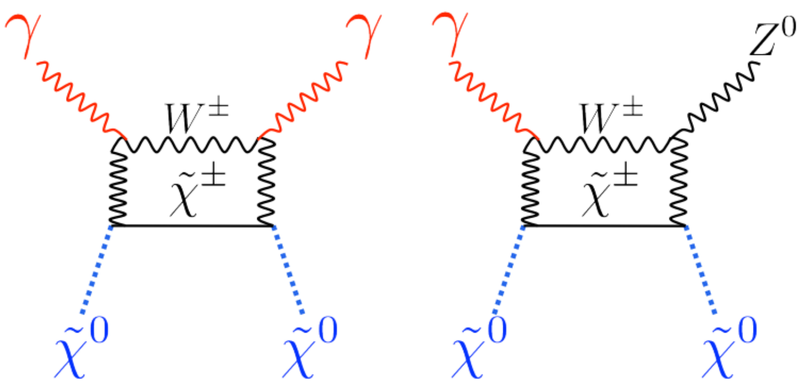
Zimmer and Conrad 2011, arXiv: 1110.6863

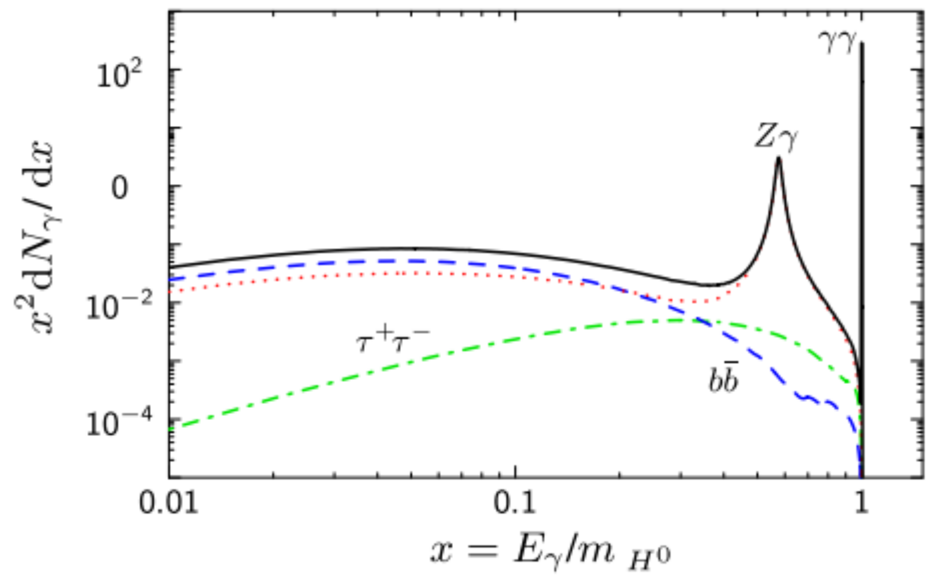
- Largest virialized and most massive structures in the universe
  - Radio emission suggests relativistic cosmic ray (CR) population
  - Lensing and X-ray observations indicate large dark matter (DM) content
- Data Analysis
  - 24 Months of Fermi-LAT data (p6v11 Diffuse Class)
  - 10 deg ROI for each source, 200 MeV to 100 GeV
  - Clusters modeled as point sources
- Combined Likelihood Analysis
  - CR and DM have a common parameter in all clusters
  - No detection in 24 months data





Search for Gamma-ray Spectral Lines

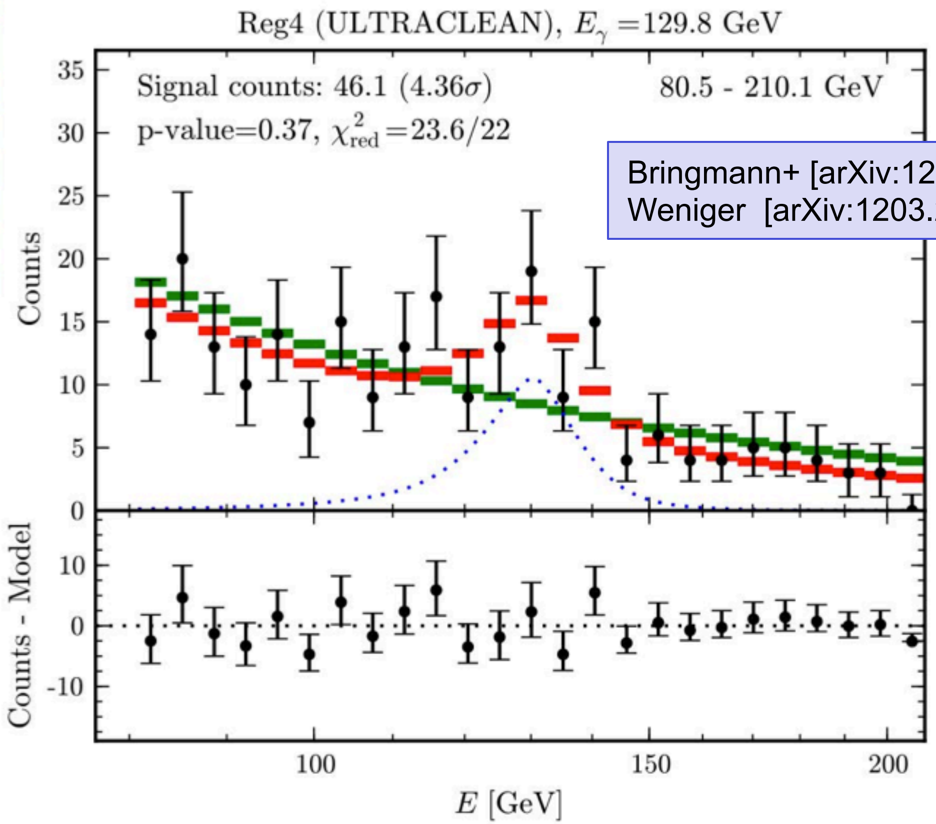




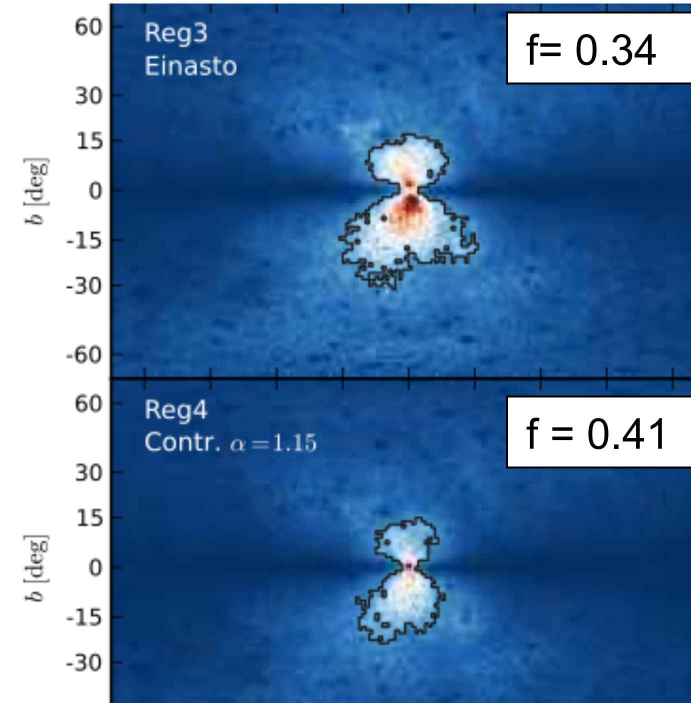
Gustafsson et al. PRL 99.041301

- **Annihilation/decay directly into γγ or Xγ (X = Z^0, H^0, …)**
- **"Smoking Gun" channel**
- **Advantage: sharp, distinct feature**
- **Disadvantage: low predicted counts**

The Context: Narrow Feature at 130 GeV



Bringmann+ [arXiv:1203.1312]
Weniger [arXiv:1203.2797]



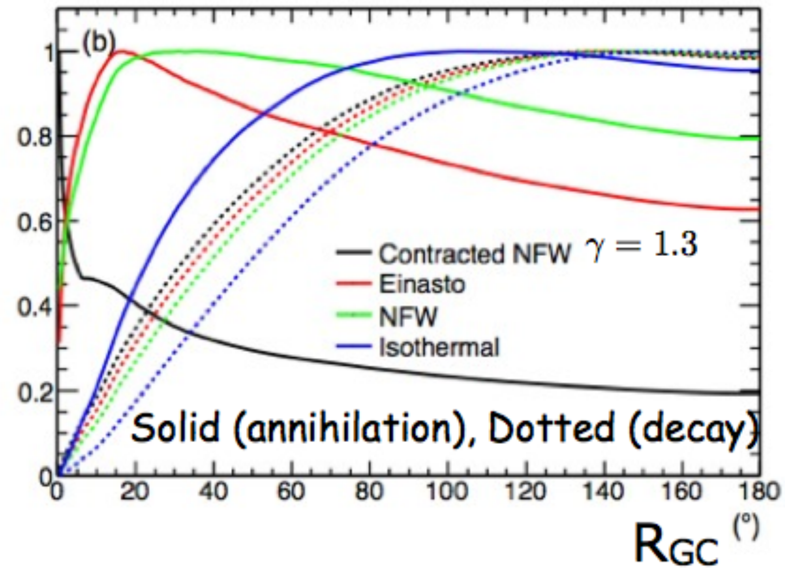
Frac Residual (i.e., S/N):
$f = s_{local}^2 / n_s$

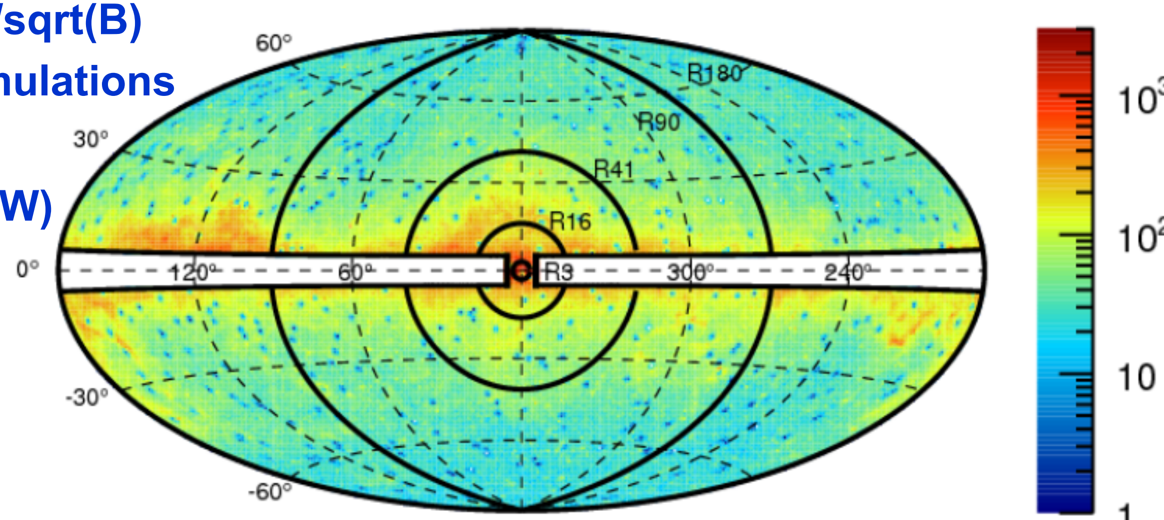
- **Bringmann et al. and Weniger showed evidence for a narrow spectral feature near 130 GeV near the Galactic center (GC)**
- **Signal is particularly strong in 2 out of 5 test regions, shown above**
- **Over 4σ, with S/N > 30%, up to ~60% in optimized regions of interest (ROI)**

Fermi-LAT Line Search - 4 years data

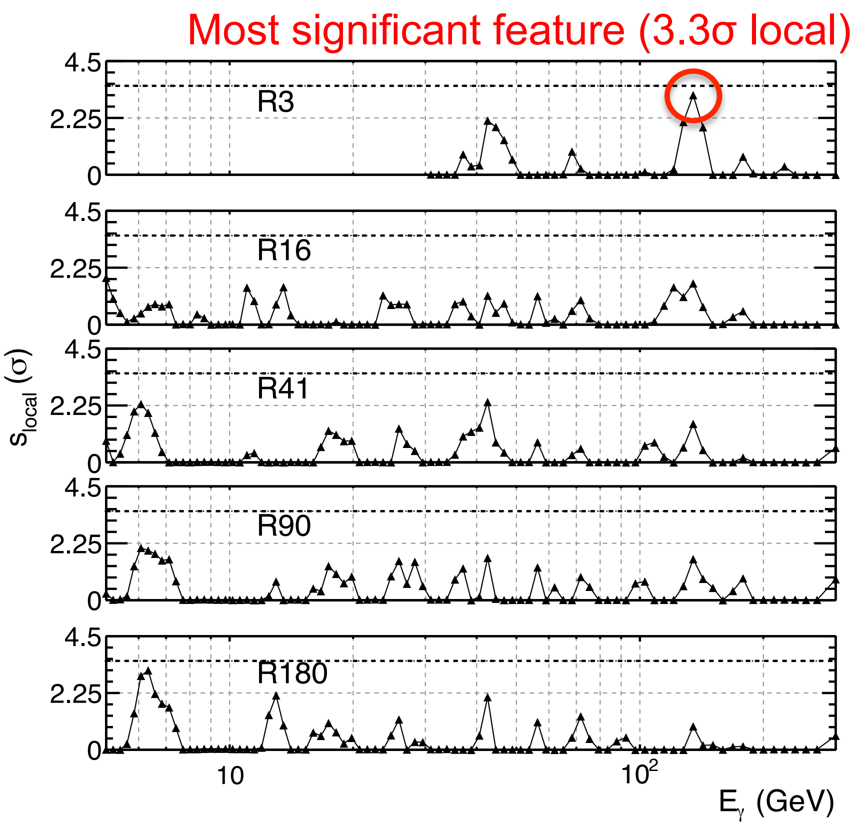
arXiv:1305.5597

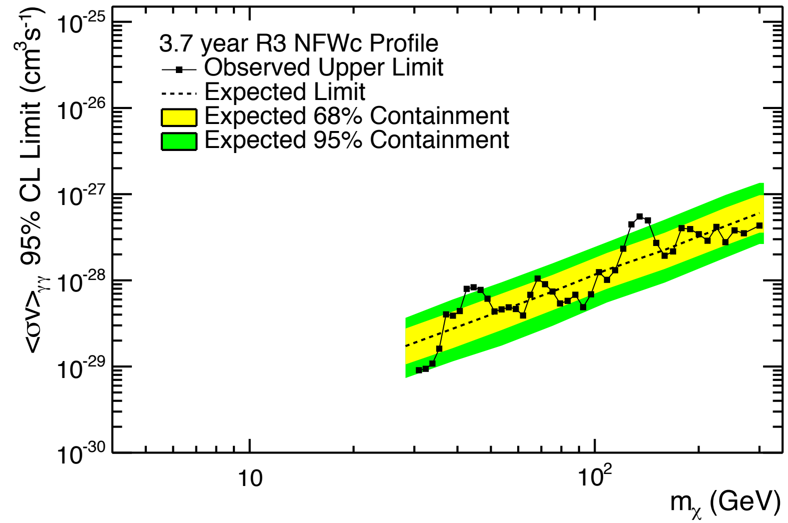
- Search for lines from 5 – 300 GeV using 3.7 years of data
- Use P7REP_CLEAN (REP = "reprocessed")
  - Updates to CAL calibration and reconstruction
    - Improved PSF
    - Energy shifts upwards ~3-4%
  - Mask bright (>10σ for E > 1 GeV) 2FGL sources
- Optimize ROI for a variety of DM profiles
  - Find R_{GC} that optimizes S/sqrt(B)
  - Background from LAT simulations
- Search in 5 ROIs
  - R3 (3° GC Circle, cont. NFW)
  - R16 (Einasto)
  - R41 (NFW)
  - R90 (Isothermal)
  - R180 (DM Decay)

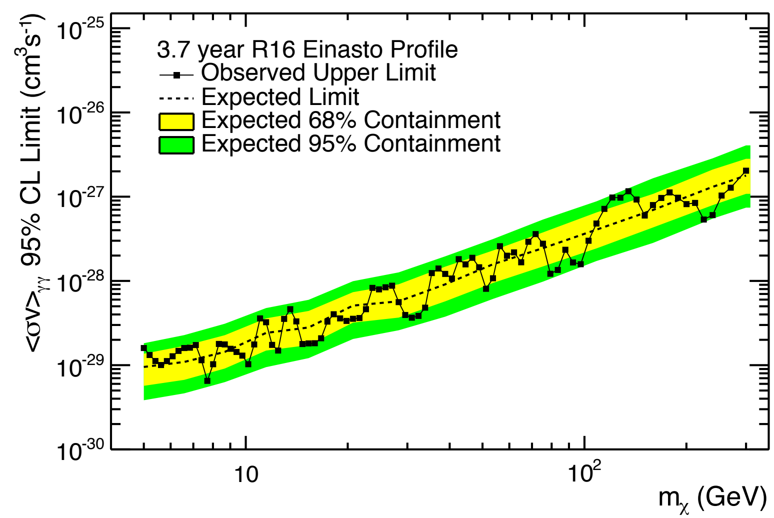




95% CL $\langle\sigma v\rangle_{\gamma\gamma}$ Upper Limit R3-R16



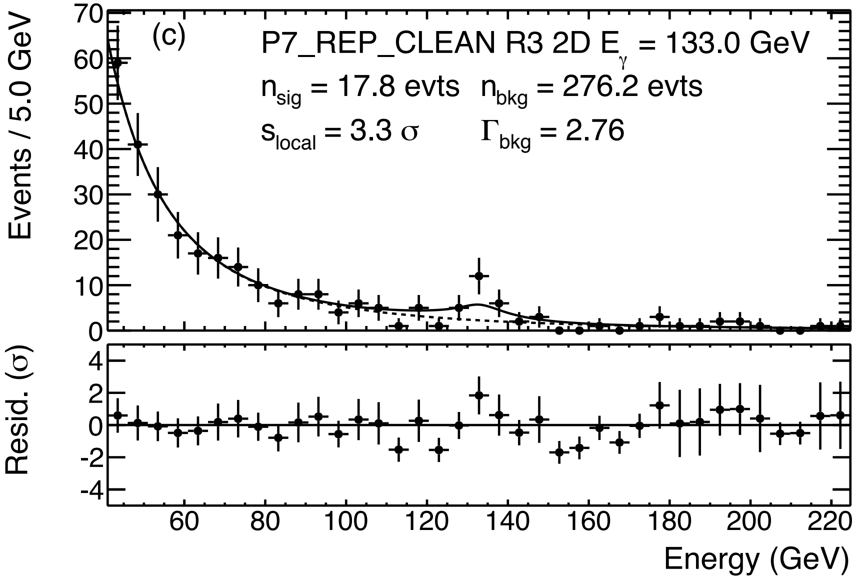




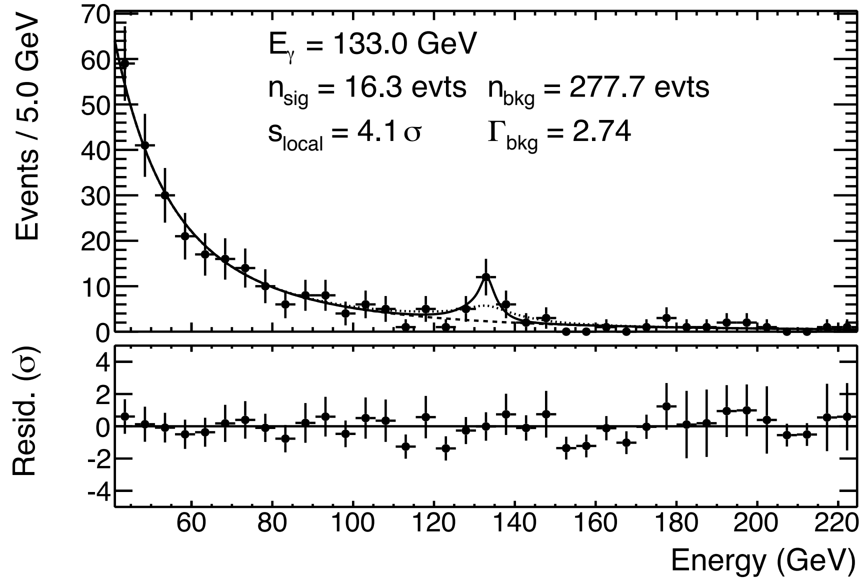
- **No globally significant lines detected**
  - **All fits have global significance < 2σ**
  - **Most significant feature found at 133 GeV in R3 ROI (3.3σ local significance)**

Feature at 133 GeV

Fit in R3 ROI



Fit in R3 ROI with rescaled energy dispersion

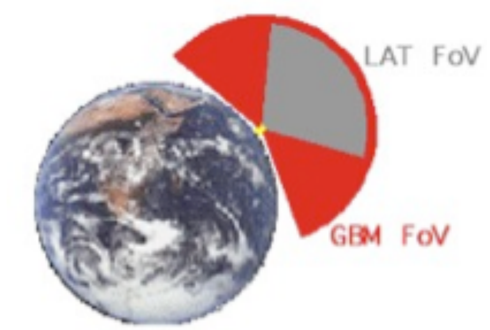


- **Let width scale factor float in fit (while preserving shape)**
- **s_σ = 0.32±0.17 (95% CL)**
  - **Feature in data is much narrower than expected energy resolution**
- **Width of 133 GeV feature as well as the presence of a similar feature in the Earth Limb control sample points to a systematic effect – further study with more data is required for a full understanding**

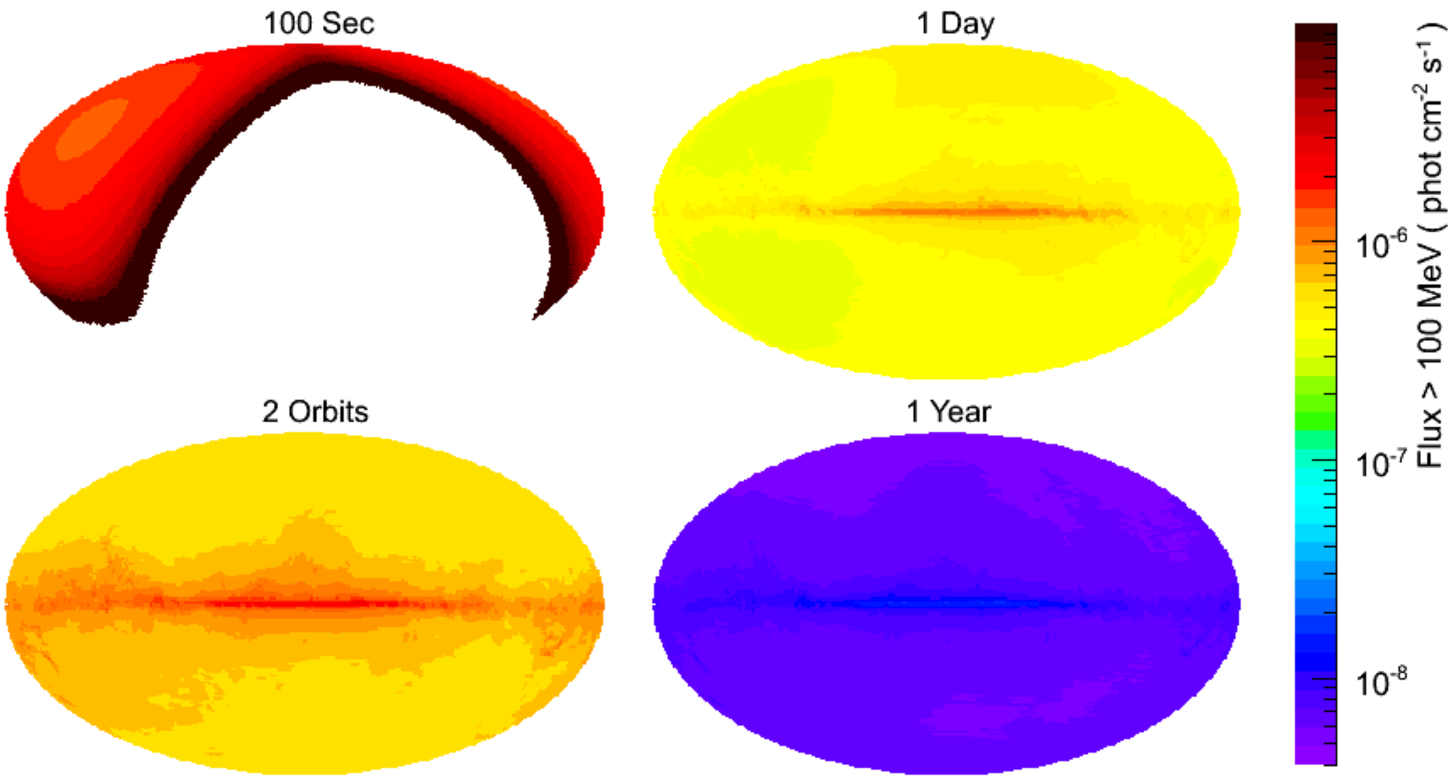
Conclusions

- Fermi-LAT addresses a diverse range of science topics
  - Searches for new physics (DM, LIV)
  - Understanding of different gamma-ray source populations (pulsars, AGN, SNR, etc.)
  - Studying the nature of galactic and extragalactic diffuse gamma-ray emission
- The Fermi-LAT has made great progress toward constraining/identifying the nature of DM
  - Many independent search strategies (dSphs, clusters, MW halo, etc.)
  - No clear signals despite several hints (135 GeV line)
  - LAT constraints from dwarf stacking and MW halo searches are beginning to rule out some interesting areas of parameter space for WIMP masses below 30 GeV
- Fermi-LAT should continue to yield exciting discoveries in the future
  - Improved understanding of astrophysical backgrounds
  - Increased exposure (sensitivity gain linear in time at high energies)
  - Improvements in analysis and understanding of detector response (Pass8)

Fermi Survey Mode



LAT sees 1/5 of the sky at any time
GBM sees entire un-occulted sky



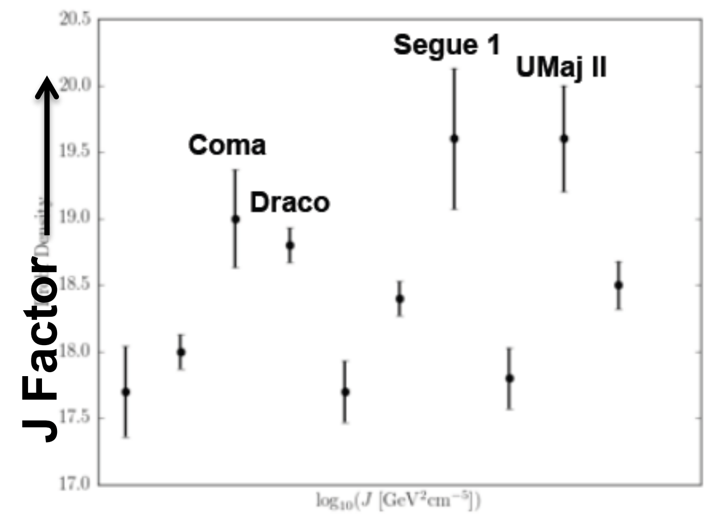
Fermi spends every other orbit rocked either north or south.

3 hours to survey entire sky

Dwarf Spheroidal Galaxies

- **Dwarf spheroidal galaxies are ideal systems in the context of indirect DM searches**
  - **No intrinsic gamma-ray emission**
  - **Mostly located at high latitudes (low astrophysical background)**
  - **DM content can be unambiguously inferred from stellar kinematics (large M/L)**
- **Many new dSphs discovered in optical surveys (SDSS) – more than two dozen now identified**
- **Stacking can increase discovery potential**

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 et al. PRL 107, 241302 (2011)

Dwarf Stacking

- **Sensitivity to a DM signal can be enhanced by combining data from multiple dwarfs**
- **Compute a joint likelihood incorporating both LAT data and uncertainty of the J-factor for each dwarf**
- **Remove nuisance parameters (J-factors, gamma-ray background amplitudes, etc) by likelihood profiling**

Joint dSph Likelihood

LAT Likelihood

$$L(D|\mathbf{p_W}, \{\mathbf{p}\}_i) = \prod_i L_i^{\mathrm{LAT}}(D|\mathbf{p_W}, \mathbf{p}_i)$$

J-Factor Posterior

$$\times \frac{1}{\ln(10) J_i \sqrt{2\pi}\sigma_i} e^{-[\log_{10}(J_i) - \overline{\log_{10}(J_i)}]^2/2\sigma_i^2}$$

DM Particle Parameters

Projected Stacking Limits

- **Dwarf stacking limits are projected to improve**
  - **Increase in observing time (10 year mission lifetime)**
  - **Discovery of new dwarfs**
  - **Analysis improvements increase LAT performance at high energy**
- **Fermi-LAT has the potential to push below thermal relic cross section at ~100 GeV**