Indirect Searches for Dark Matter with the Fermi Large Area Telescope

Andrea Albert

(The Ohio State University)

on behalf of

The Fermi LAT Collaboration

"LHC Now"

Santa Fe 2012

- **Dark Matter Overview**

- **The Fermi Large Area Telescope**

- **Recent Results**

- **Dark Matter Overview**

- The Fermi Large Area Telescope

- Recent Results

Astrophysical Evidence for Dark Matter

- **Majority of mass in galaxies is *dark***
  - **Coma Cluster + Virial Theorem**
    F. Zwicky (1937)

- **Dark Matter clumps in large *halos* around galaxies**
  - **Galactic Rotation Curves**
    V. Rubin et al (1980)

- **Dark Matter is virtually *collisionless***
  - **The Bullet Cluster**
    D. Clowe et al (2006)

- **Dark Matter is *non-baryonic***
  - **CMB Acoustic Oscillations**
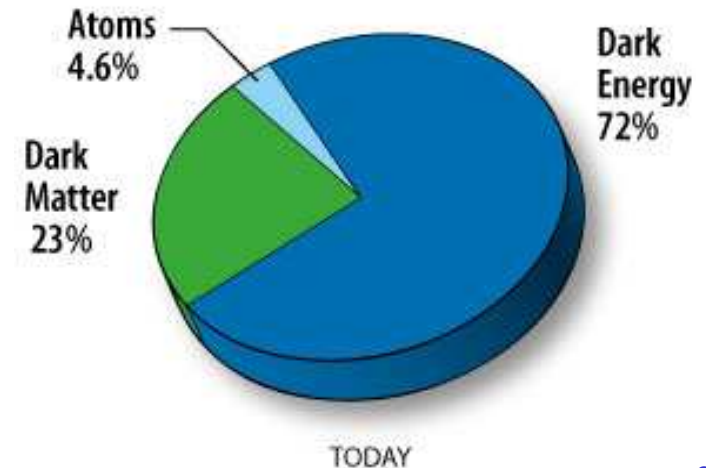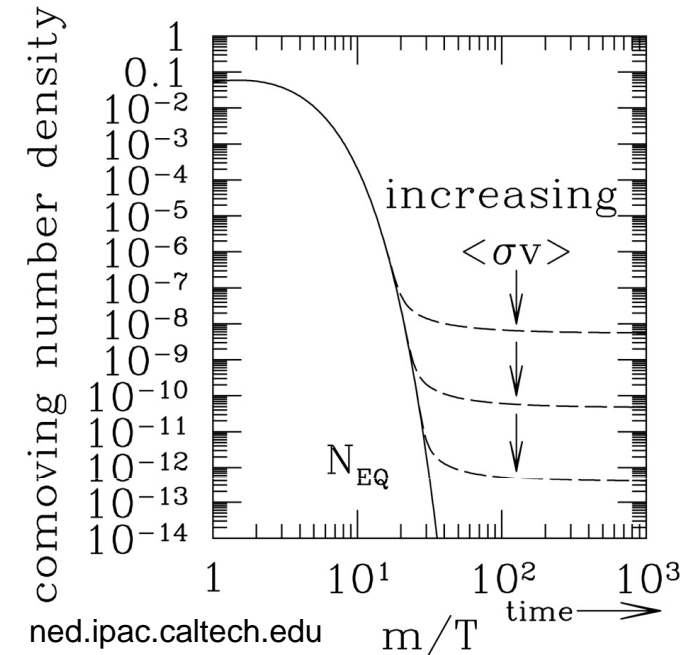   **WMAP (2010)**

Andrea Albert (OSU)
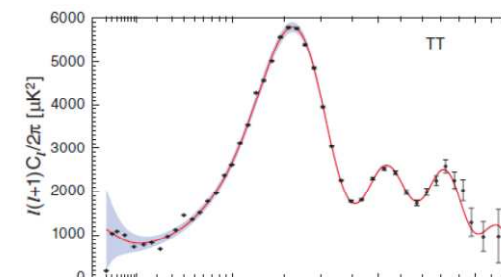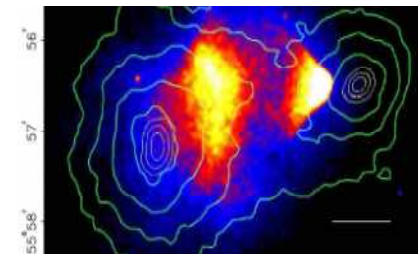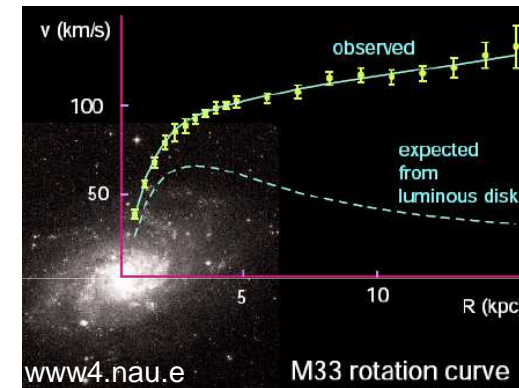
- **Weakly Interacting Massive Particle (WIMP)**

- **GeV-TeV mass scale**

- *Assume*: **Can annihilate or decay into SM particles**

- *Assume*: **Accounts for measured DM density**

- **Ex) Neutralino**
  - **Predicted by many SUSY models**
  - **Electrically neutral**
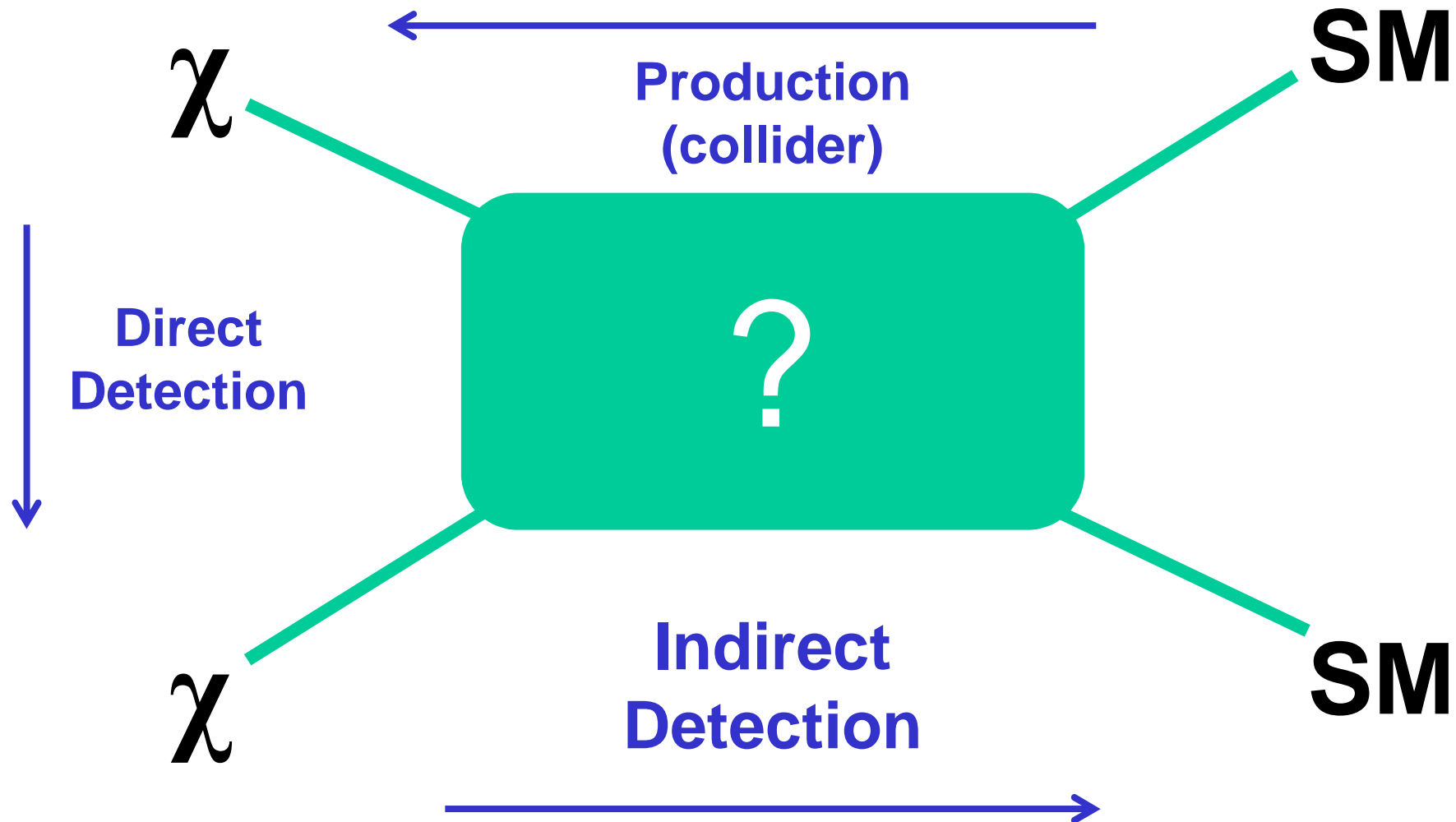 - **LSP → stable particles**
  - **GeV-TeV mass**
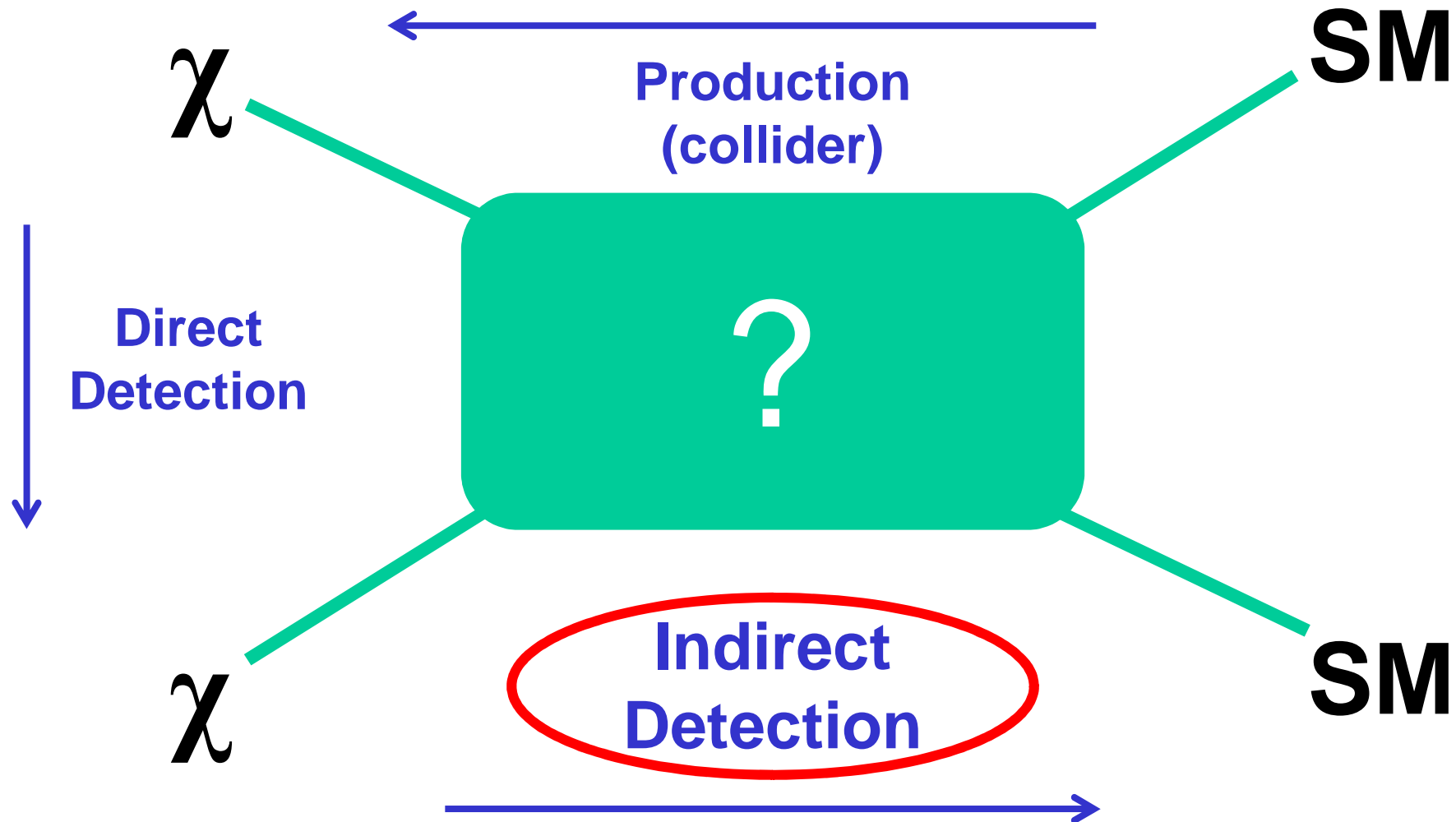
WIMPs as a Thermal Relic

- **If WIMP was a thermal relic, then it was in creation/annihilation equilibrium in early universe**

- **Once universe cools enough, amount of dark matter freezes out**
  - **No longer created, and expansion causes annihilation rate to drop to ~0**

- **Assume *weak scale* σ_{ann} → observed abundance (~23%)**
  - **$<\sigma v>_{ann}$ ~ 3e-26 cm^3/s (σ_{ann} ~ 3 pb)**
  - **v_{CDM} ~ 0.3c**
    - **Virial theorem -> to form stable halos around galaxies, DM particle should be non-relativistic (cold dark matter)**

ned.ipac.caltech.edu

Andrea Albert (OSU/Fermi LAT)

χ

SM

← **Production (collider)**

Direct Detection ↓

?

χ

SM

Indirect Detection →

Andrea Albert (OSU)

χ SM

Production (collider)

Direct Detection

?

Indirect Detection

χ SM

Andrea Albert (OSU)
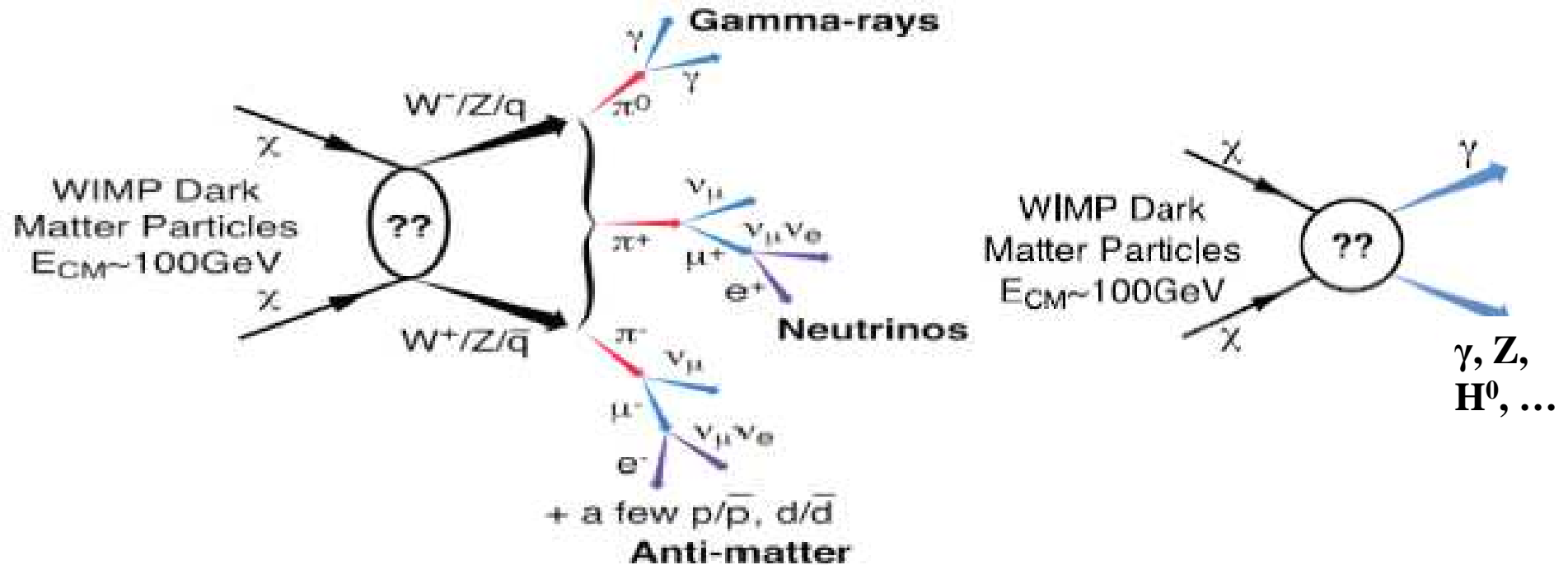
- **WIMP annihilation or decay can produce a variety of detectable SM particles**

- **Goal is to detect these particles and disentangle intrinsic WIMP properties**

What we observe

$$\Phi_\chi(E,\psi) = \frac{\langle \sigma_\chi v \rangle}{4\pi} \sum_f \frac{dN_f}{dE} B_f \int_{LOS} dl(\psi) \frac{1}{2} \frac{\rho(l)^2}{m_\chi^2}$$

DM Flux (events/cm^2/s)

Region of Interest (ROI)
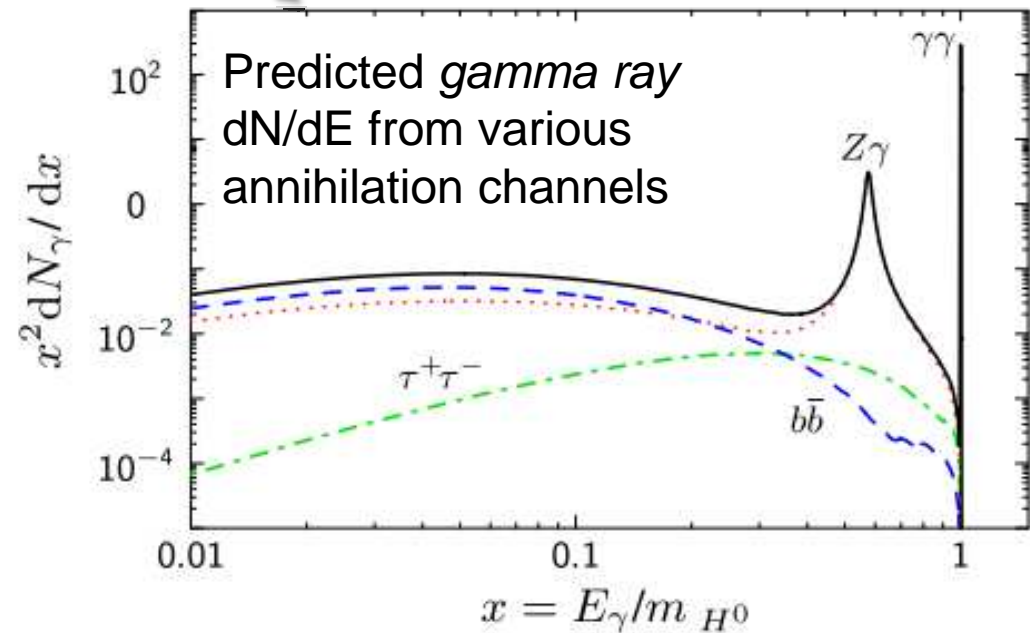(dwarf galaxy, the whole sky, etc)

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Intrinsic Particle Properties

$$\Phi_\chi(E,\psi) = \frac{\langle \sigma_\chi v \rangle}{4\pi} \sum_f \frac{dN_f}{dE} B_f \int_{LOS} dl(\psi) \frac{1}{2} \frac{\rho(l)^2}{m_\chi^2}$$

Annihilation Cross Section * velocity
(v ~ 0.3c)
$\langle \sigma v \rangle_{ann}$ ~ 3e-26 cm^3/s (σ_{ann} ~ 3 pb)

Note: large fraction of predicted gamma's have $E_\gamma < m_{DM}$

Predicted *gamma ray* dN/dE from various annihilation channels

Gustafsson et al. PRL 99.041301

Astrophysics

$$\Phi_\chi(E,\psi) = \frac{\langle\sigma_\chi v\rangle}{4\pi} \sum_f \frac{dN_f}{dE} B_f \int_{LOS} dl(\psi) \frac{1}{2} \frac{\rho(l)^2}{m_\chi^2}$$

J-factor – Line of sight integral over a ROI

Dark matter density distribution (example simulation)

z = 0.3   T = 10.53 Gyr

500 kpc

Credit: Springel et al. (Virgo Consortium)

North Galactic Pole
90⁰ lat

90° long

LOS

lat

long

180° long
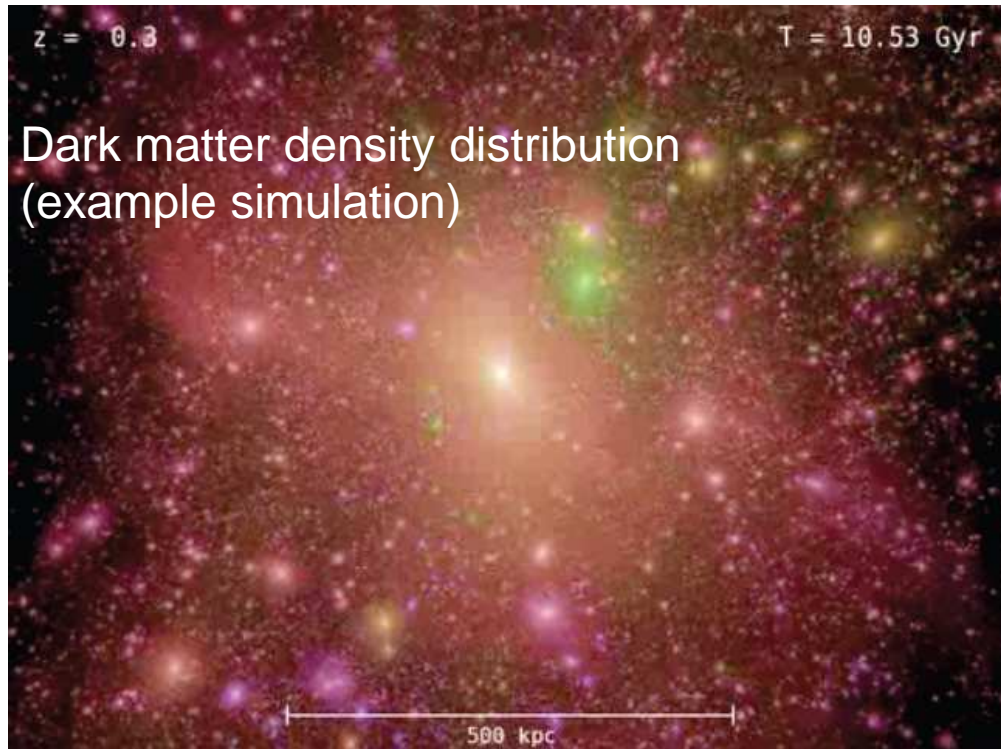
Sun

0° long

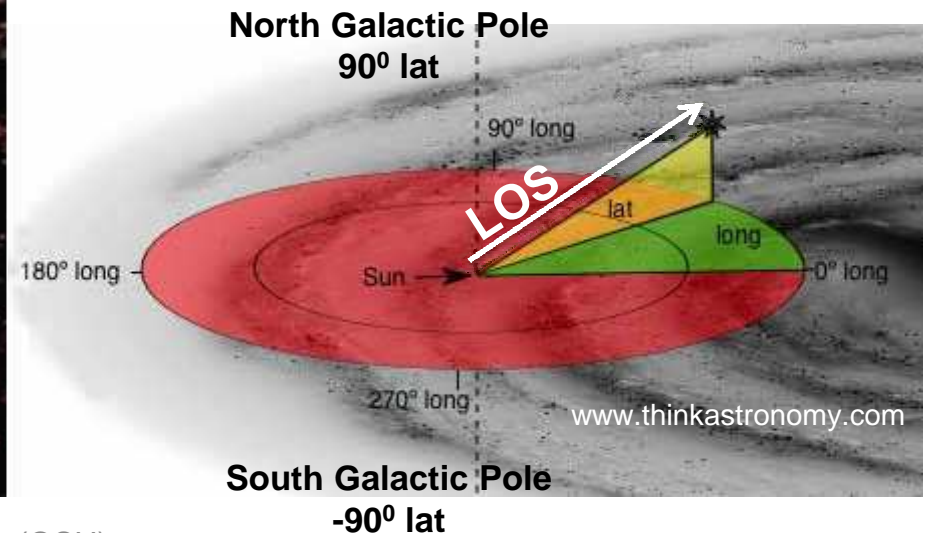270° long

www.thinkastronomy.com

South Galactic Pole
-90⁰ lat

Astrophysics

$$\Phi_\chi(E,\psi) = \frac{\langle\sigma_\chi v\rangle}{4\pi} \sum_f \frac{dN_f}{dE} B_f \int_{LOS} dl(\psi) \frac{1}{2}\frac{\rho(l)^2}{m_\chi^2}$$
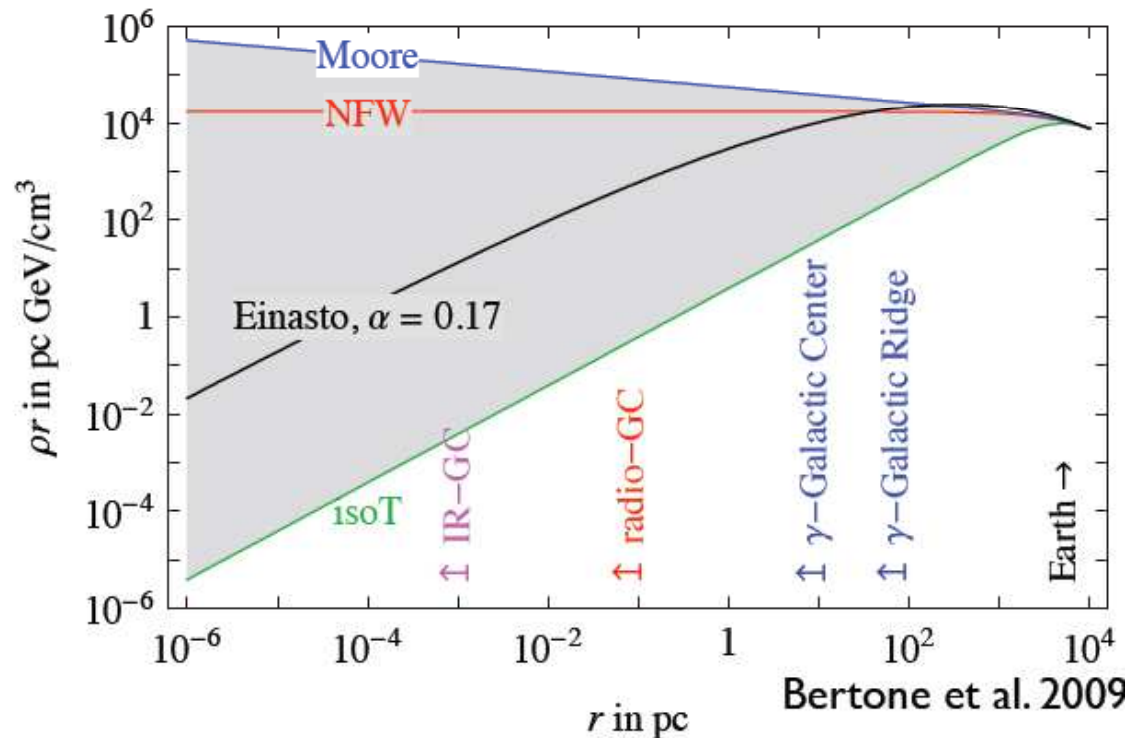
"J-factor" – Line of sight integral over a ROI

Various models for the smooth DM density as a function of distance from galactic center (r) Derived from fits to N-body simulations

Moore
NFW
Einasto, $\alpha = 0.17$
isoT
↑ IR–GC
↑ radio–GC
↑ γ–Galactic Center
↑ γ–Galactic Ridge
Earth →

ρr in pc GeV/cm^3

r in pc

Bertone et al. 2009

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- Dark Matter Overview

- **The Fermi Large Area Telescope**

- Recent Results

Fermi Large Area Telescope (LAT)
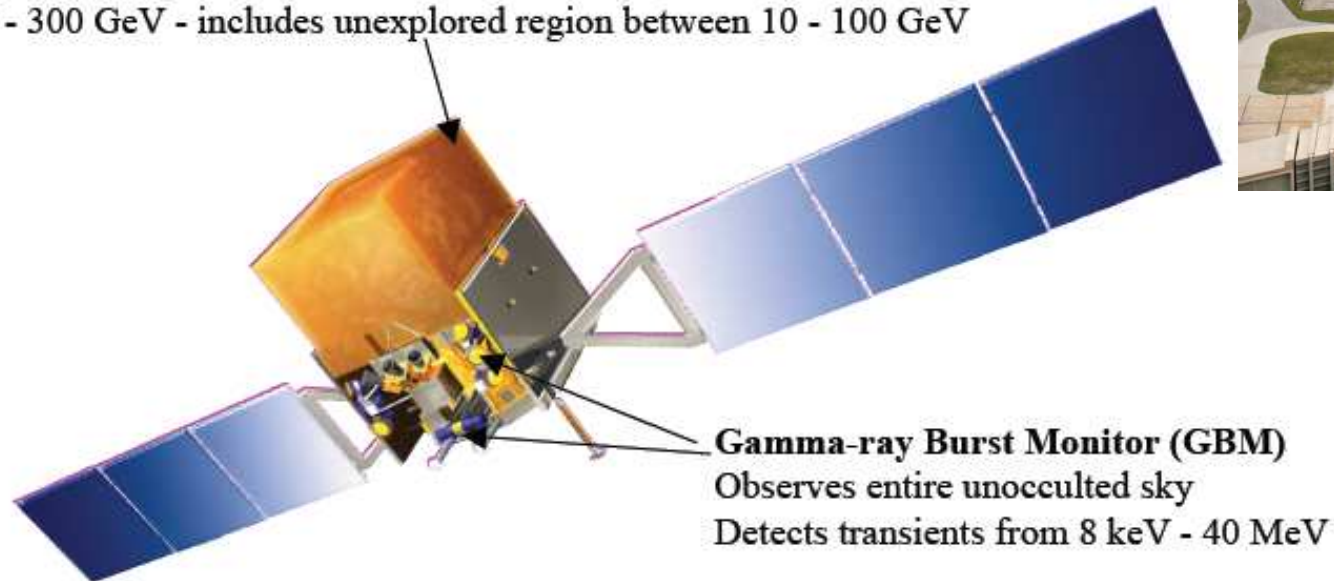
- **On board the Fermi Gamma-ray Space Telescope**
  - **Launched June 11, 2008**
    - **Started taking data Aug 2008**
  - **5 year mission**
    - **Hope to run for 10 years**

Large Area Telescope (LAT)
Observes 20% of the sky at any instant, views entire sky every 3 hrs
20 MeV - 300 GeV - includes unexplored region between 10 - 100 GeV

Gamma-ray Burst Monitor (GBM)
Observes entire unocculted sky
Detects transients from 8 keV - 40 MeV

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Energy loss mechanisms

Cross section (L_{rad}^{-1}) vs E (MeV)

- 0.6
- 0.4
- 0.2
- 0

Compton

Pair

Photo-electric

Pair Cross-Section saturates at $E_\gamma > 1$ GeV
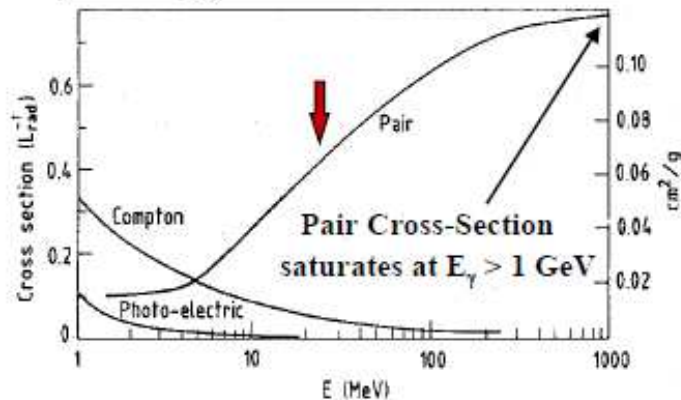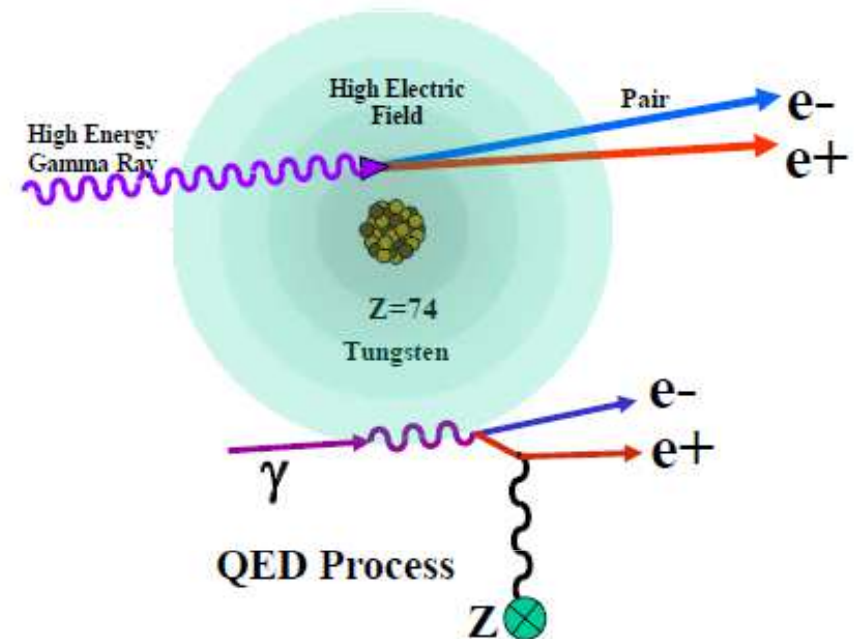
cm^2/g : 0.10, 0.08, 0.06, 0.04, 0.02

Fig. 2: Photon cross-section σ in lead as a function of photon energy. The intensity of photons can be expressed as $I = I_0 \exp(-\sigma x)$, where x is the path length in radiation lengths. (Review of Particle Properties, April 1980 edition).
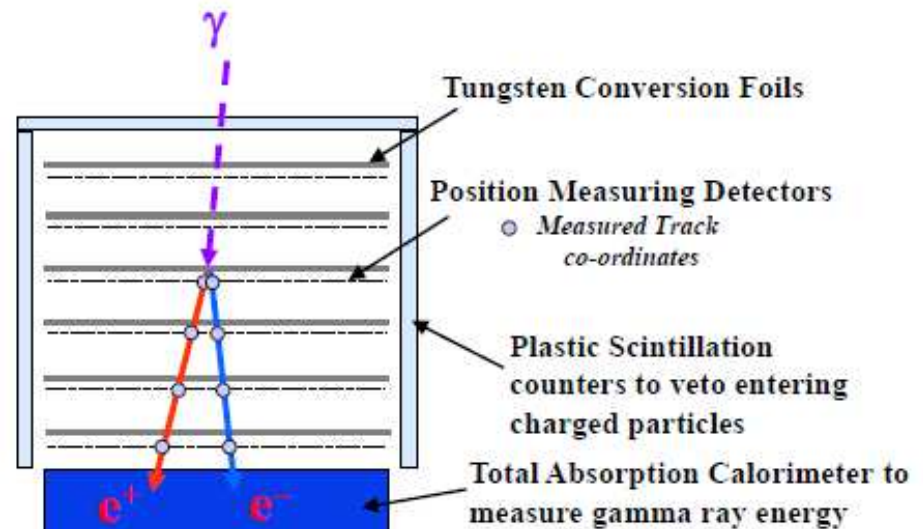
High Energy Gamma Ray

High Electric Field

Pair → e–, e+

Z=74 Tungsten

γ → e–, e+

QED Process

Z⊗

Opening Angle

$$\theta_{Open} \approx \frac{4m_e}{E_\gamma}$$

At 100 MeV
$\theta_{Open} \sim 1°$

NASA

γ

Tungsten Conversion Foils

Position Measuring Detectors
○ Measured Track co-ordinates

Plastic Scintillation counters to veto entering charged particles

Total Absorption Calorimeter to measure gamma ray energy
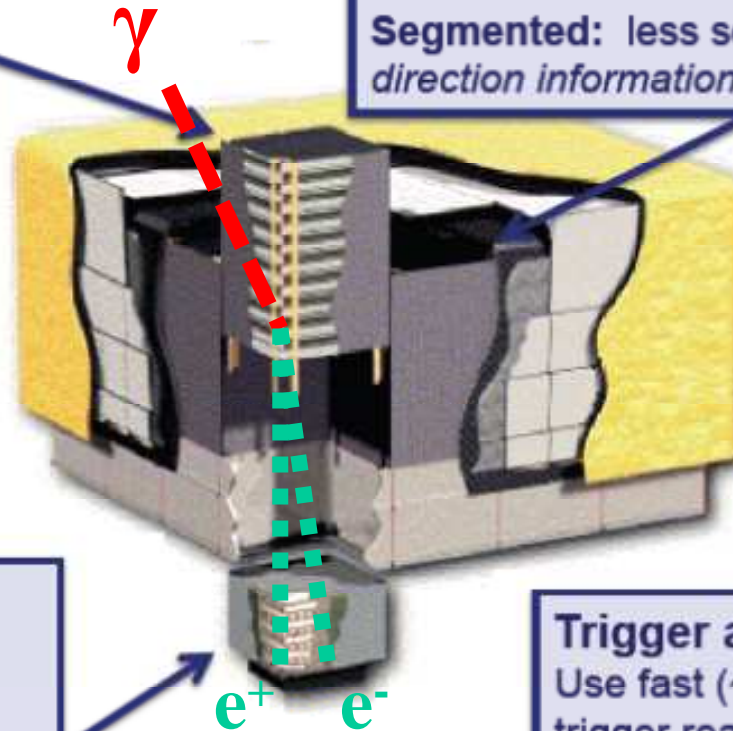
e+   e–

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Fermi LAT

Tracker (TKR):
18 Si bi-layers
Front- 12 layers (~60% X_o)
Back-   6 layers (~80% X_o)

Angular resolution ~2x
better for front
Many EM showers start in TKR

Anti-Coincidence Detector (ACD):

$\varepsilon = 0.9997$ for MIPs
Segmented: less self-veto *when good direction information is available*
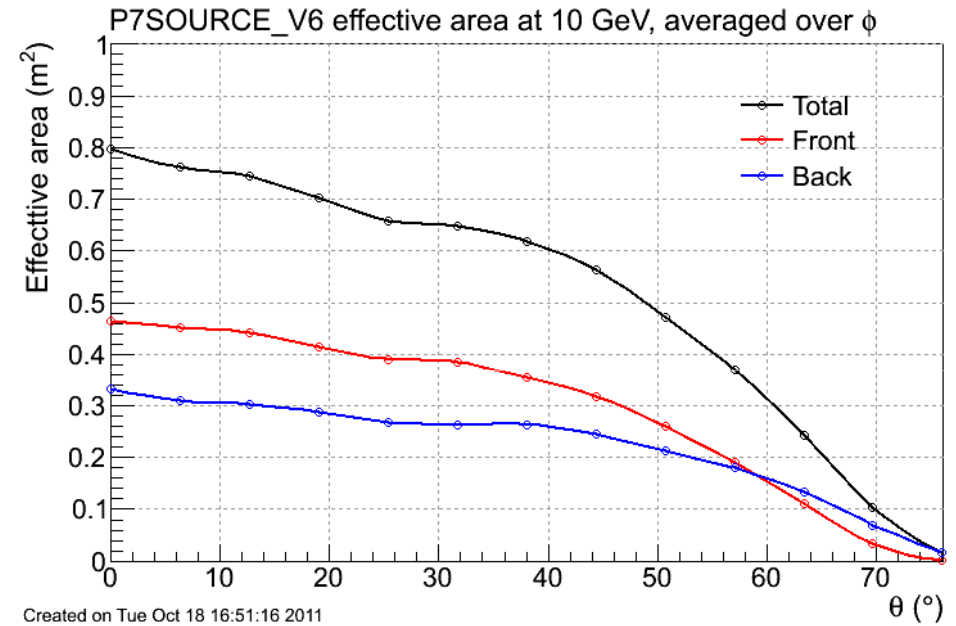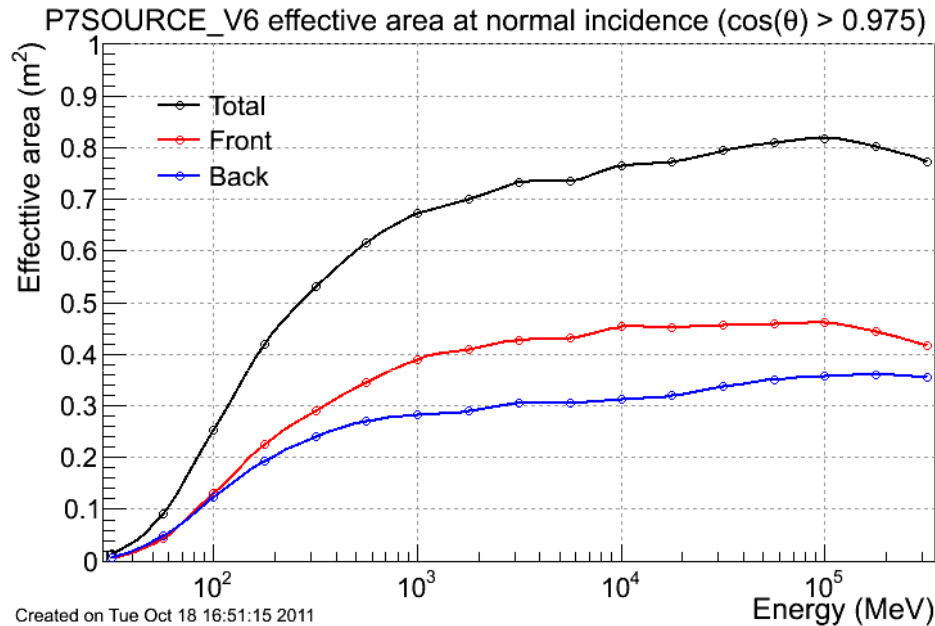
γ

e^+ e^-

Calorimeter (CAL):
8 layers (8.6 X_o on axis)

$\Delta E/E \sim 5\text{-}20\%$
Hodoscopic, shower profile
and *direction* reconstruction
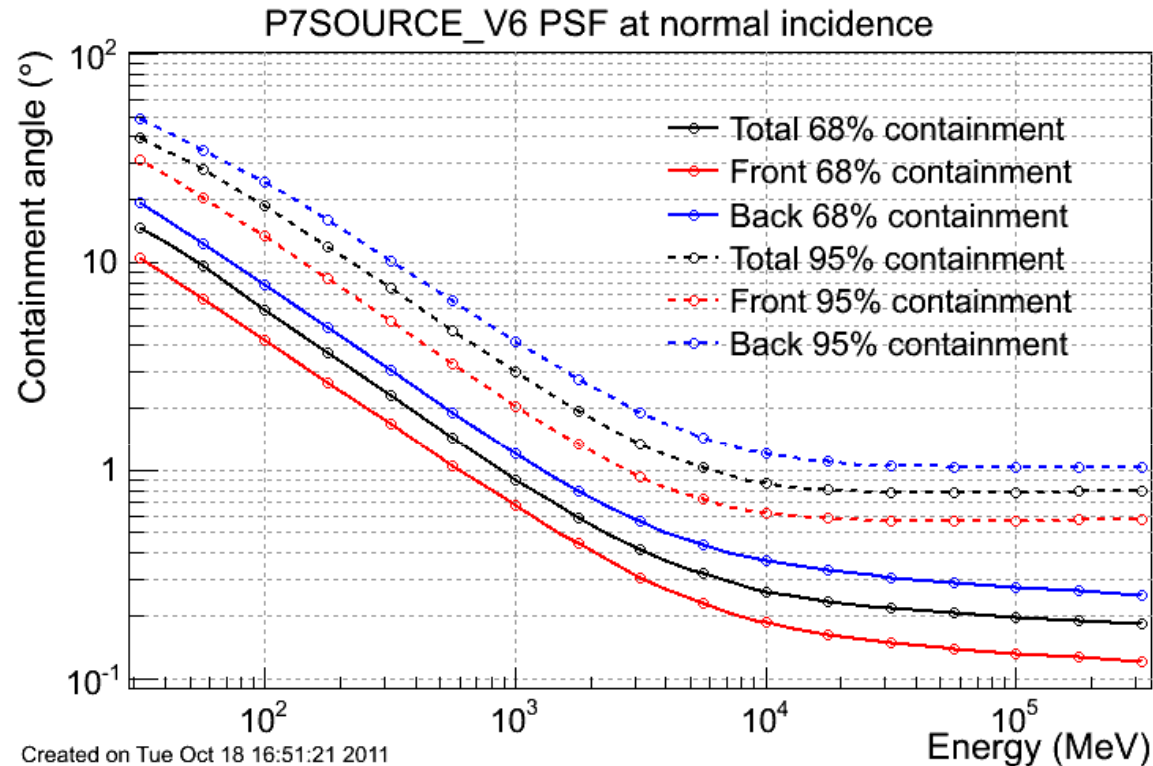above ~200 MeV

Trigger and Filter
Use fast (~0.1 μs) signals to trigger readout and reject cosmic ray (CR) backgrounds
Ground analysis uses slower (~10μs) shaped signals

Andrea Albert (OSU)

P7SOURCE_V6 effective area at normal incidence (cos(θ) > 0.975)

P7SOURCE_V6 effective area at 10 GeV, averaged over φ

Created on Tue Oct 18 16:51:15 2011

Created on Tue Oct 18 16:51:16 2011

- **< 100 MeV limited by 3 in-a-row trigger requirement**

- **> 100 GeV limited by backsplash**

- **See arXiv:1206.1896 for more info on Fermi LAT performance/validation**

P7SOURCE_V6 PSF at normal incidence

- **Limited by multiple scattering at low E**
- **Limited by strip pitch at high E (pitch = 228 μm)**
- **See arXiv:1206.1896 for more info on Fermi LAT performance/validation**

Fermi LAT Energy Dispersion
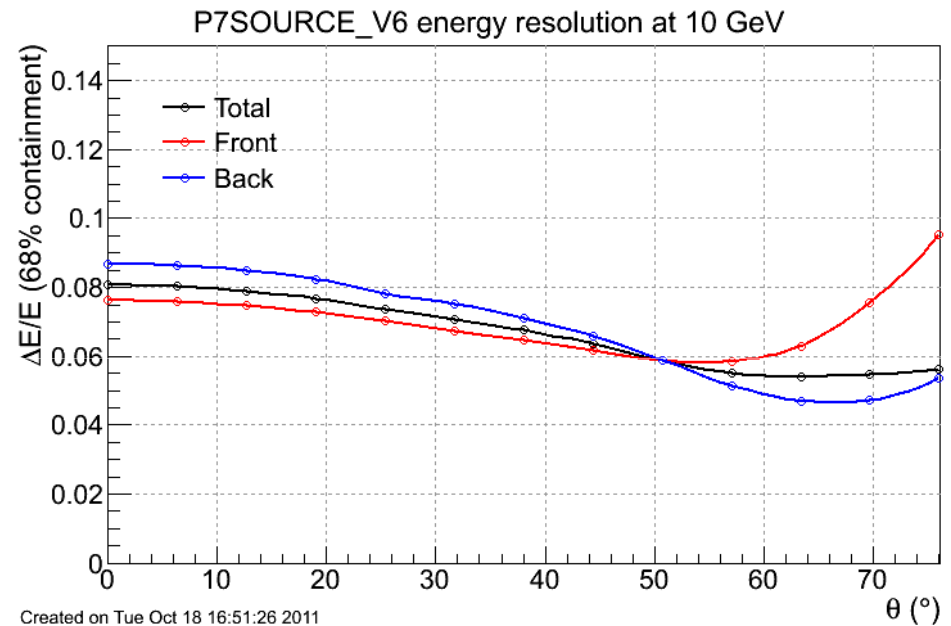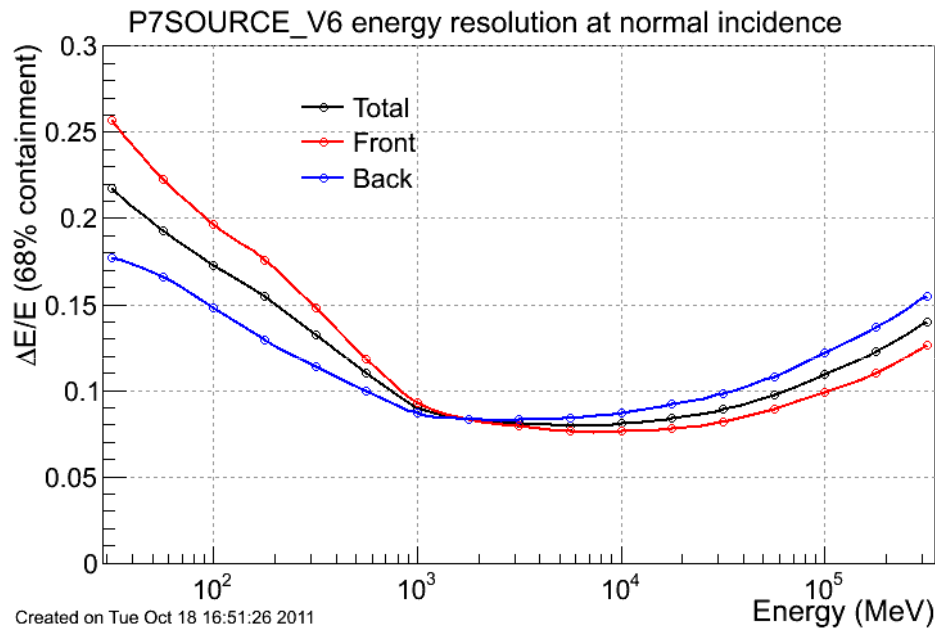
- **Limited by energy loss in tracker at low E**
- **Limited by leakage and CAL saturation at high E**
- **See arXiv:1206.1896 for more info on Fermi LAT performance/validation**

1 year all sky map (E > 1 GeV)

Andrea Albert (OSU)
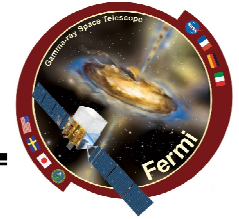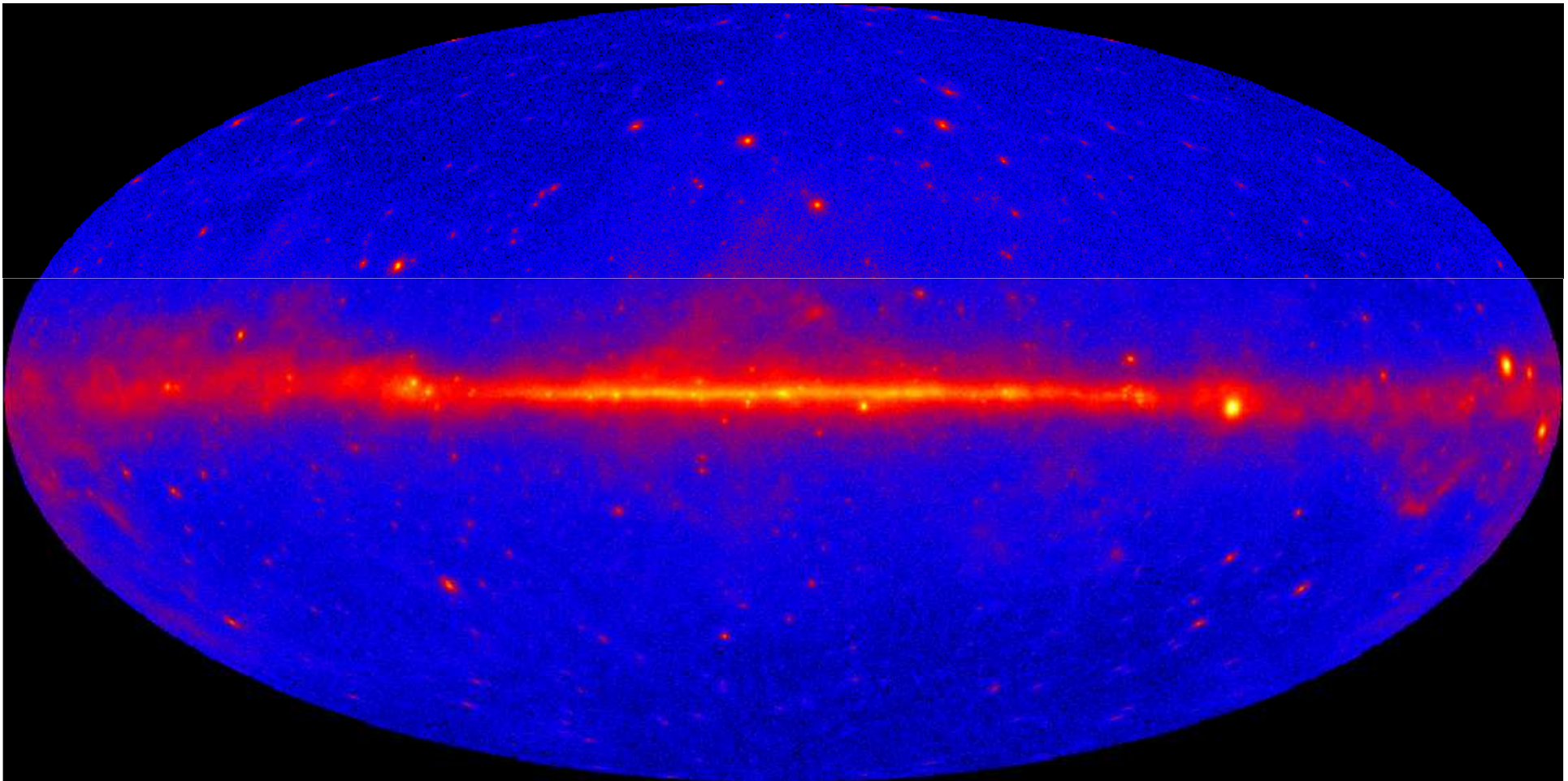
3 year all sky map (E > 1 GeV)

Andrea Albert (OSU)
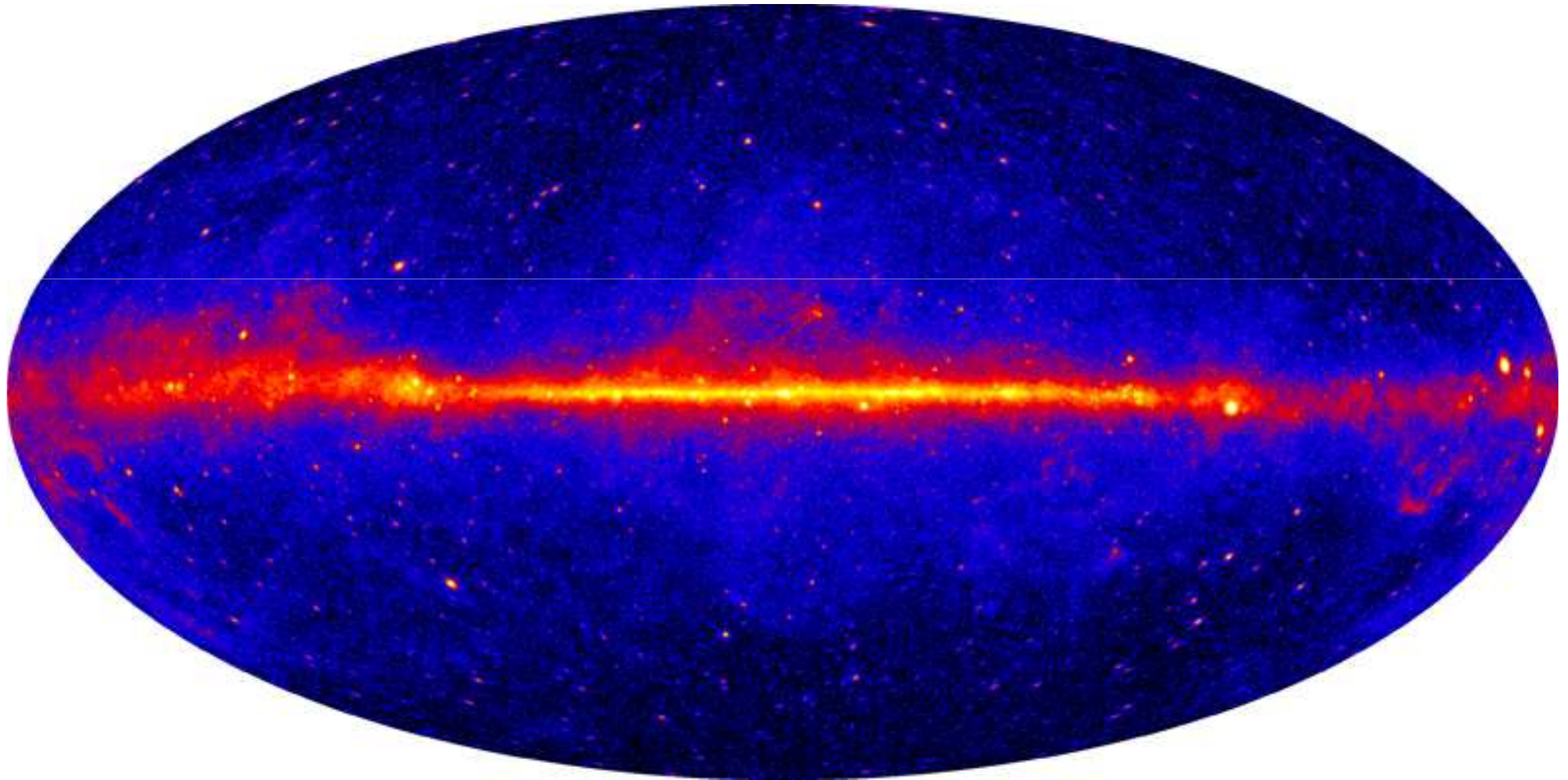
Nature has given us a rich and complicated gamma-ray sky!

Diffuse
- complex gas structure
- Various CR interactions

Sources
- Pulsars, AGN, SNR, etc

Active Plane
- sources + diffuse

Isotropic
- Extragalactic

Dark Matter?
- Will be a small piece

- Dark Matter Overview

- The Fermi Large Area Telescope

- **Recent Results**

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DM Clumps in the Halo:
- Few Astro. Bkg
- Complicated by low statistics, unknown loc

Galactic Center:
- Large Statistics
- Complicated by Astrophysical Sources

Extragalactic:
- All galaxies
- Isotropic

Spectral Lines:
- *Smoking Gun*
- Small Stat.

Galactic Halo:
- Large Statistics
- Complicated by diffuse γ-rays from Cosmic Rays

Electrons:
- Good Stats.
- Challenge: Backgrounds

Nearby Galaxies:
- dSph DM Enriched
- Known location
- Lower Statistics

Milky Way Halo simulated by Taylor & Babul (2005)

All-sky map of DM gamma ray emission (Baltz 2006)

Andrea Albert (OSU)

- **ATIC observed an unexpected bump in the CR e± spectrum**

- **Fermi observes a broader excess around the same energy**

- **This feature can be accounted for by adjusting the CR injection spectrum or nearby pulsars**

- **Has been explained with leptophillic DM annihilation models**
  - **Requires large $\langle\sigma v\rangle_{ann}$ to explain excess**


Fermi electron + positron spectrum
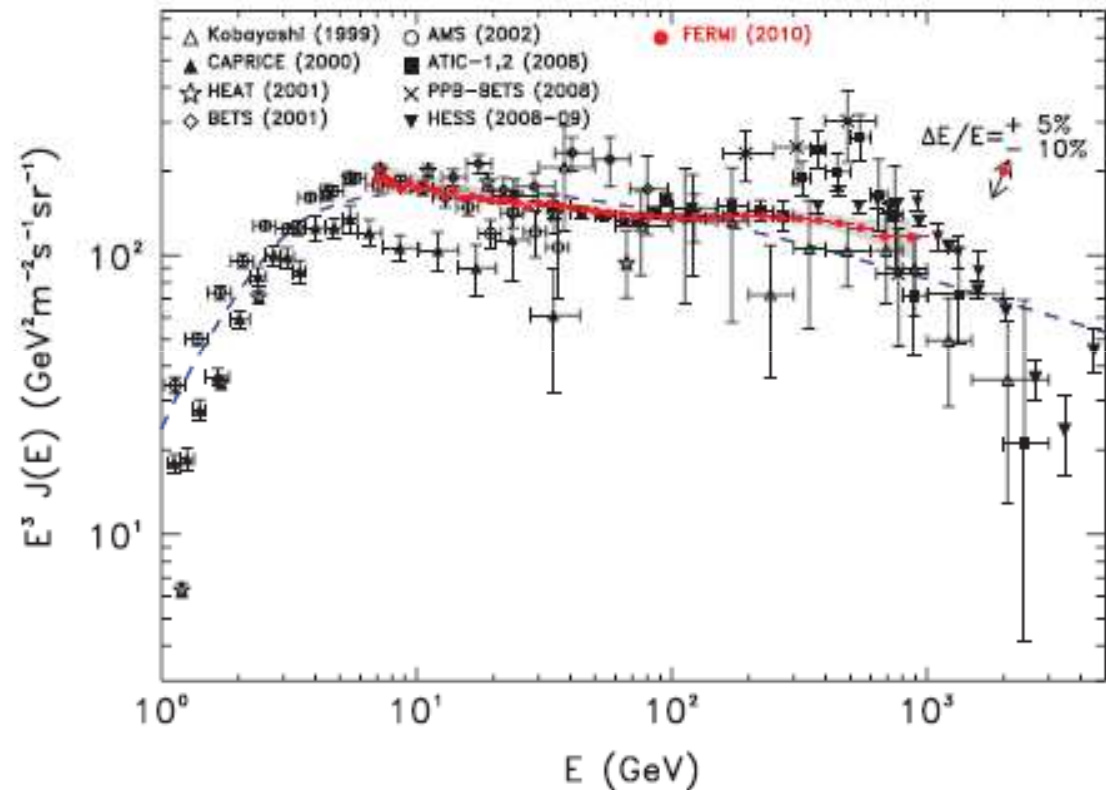
Ackermann et al. [Fermi LAT Collaboration] 2010

# Unexpected Rise in local CR Positron Fraction

- **Fermi measures a rise in the local high-energy CR positron fraction, consistent with the PAMELA results**

- **No magnet on-board, so use Earth's magnetic field**

- **Rise in local positron fraction disagrees with conventional model for cosmic rays**
  - **Local positrons are secondaries created by CR nuclei interactions (this should cause fraction to *decrease*)**

- **This can be explained with leptophilic annihilating/decaying DM**
  - **Requires large $\langle \sigma v \rangle_{ann}$ to explain excess**
  - **Antiproton fraction does *not* rise; need to suppress hadronic modes**
  - **see T. A. Porter et al. (2011) arXiv:1104.2836v1; D. Grasso et al. (2009) arXiv:0905.0636v3 for more**

events arriving from West:
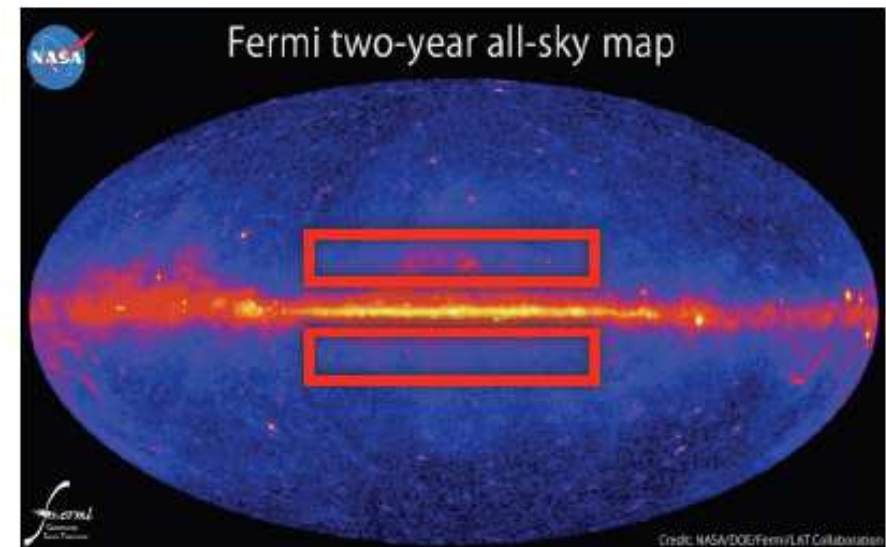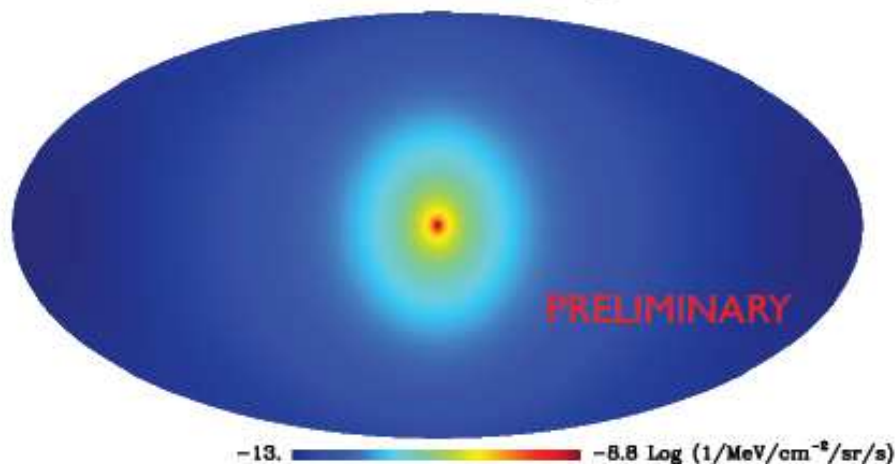e^+ allowed, e^- blocked

Fermi positron fraction

Ackermann et al. [Fermi LAT Collaboration] 2011
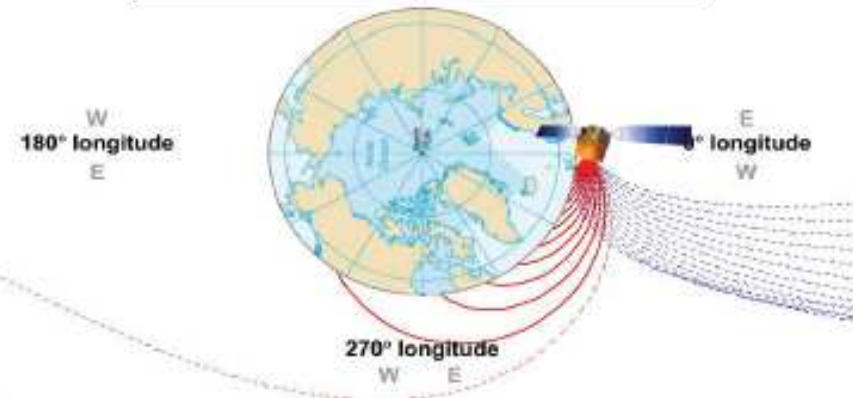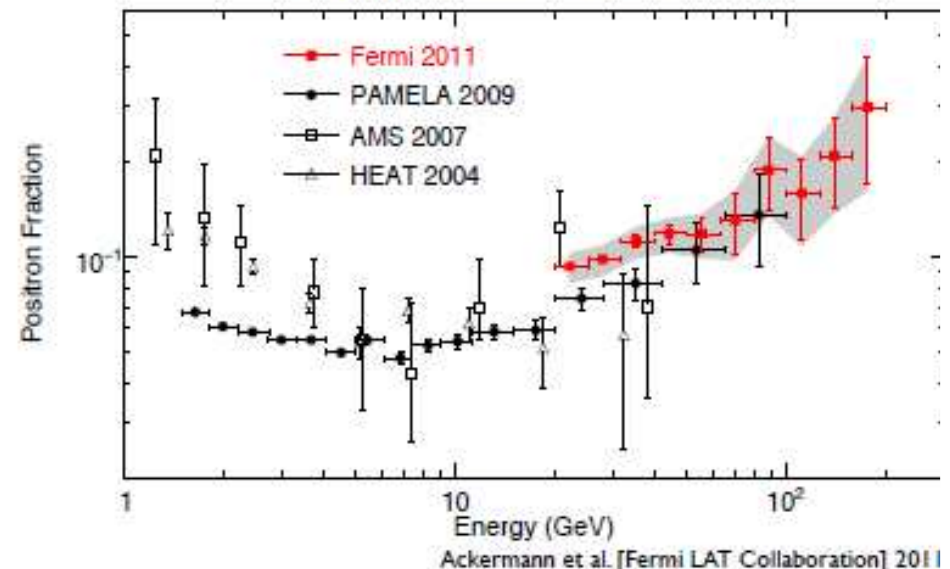
DM Constraints from the Milky Way Halo

- **Look in 2 year diffuse from 1 – 100 GeV**
  - **Mask out known gamma-ray sources**
- **Region of Interest: two off-plane rectangles ($5^0 < |b| < 15^0$ & $|l| < 80^0$)**
  - **Minimizes DM profile uncertainties (central cuspiness varies)**
  - **Limits astrophysical uncertainties (mask bright plane, avoid high latitude Fermi lobes and Loop I)**
- **This analysis focuses on setting limits on possible DM signals**
  - **See non-DM like residuals (e.g. not centrally peaked)**
  - **DM search in MW Halo is ongoing**

DM annihilation signal

PRELIMINARY

−13. −8.8 Log (1/MeV/cm^{-2}/sr/s)

Fermi two-year all-sky map

Credit: NASA/DOE/Fermi/LAT Collaboration

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- **Conservative**
  - **Method II w/detailed bkg modeling on next slide**
- **No non-DM background modeling**
  - **Robust to many uncertainties**
- **Expected DM counts (n_{DM}) compared to observed counts (n_{data}) and 3σ and 5σ upper limits are set using**

$$n_{DM} - 3(5)\sqrt{n_{DM}} > n_{data}$$

  in at least one energy bin

- **Profile likelihood fit combining several GALPROP diffusion models with DM**
  - **Derives DM limits marginalized over astrophysical uncertainties**

- **Allow several bkg parameters to vary**
  - **CRE injection index, diffuse halo height, gas (HI) to dust ratio, CR source distribution, local H_2 to CO factor, and isotropic normalization**

- **Distribution of CR sources is uncertain, so left free in radial Galactic bins.**
  - **To be conservative to DM constraints, CR source distribution set to zero in the inner 3 kpc**

- **Maps of each GALPROP + DM model are made and fit to the Fermi LAT data, incorporating both morphology and spectra**

π^0 decay
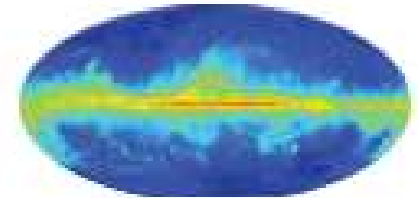
bremss
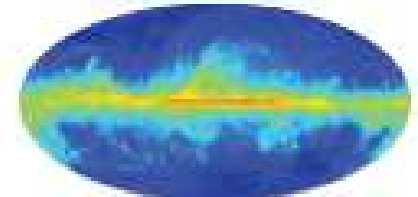
IC
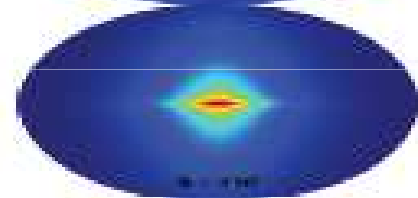
dark matter

isotropic

PRELIMINARY

Annihilation

$\chi\chi \longrightarrow bb$, ISO

Decay

$\chi \longrightarrow bb$, ISO

M. Ackermann et al. [Fermi LAT Collaboration], submitted
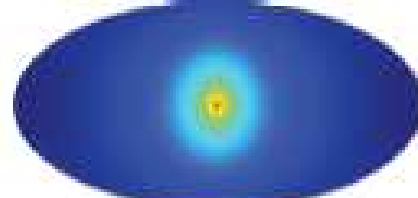
M. Ackermann et al. [Fermi LAT Collaboration], submitted
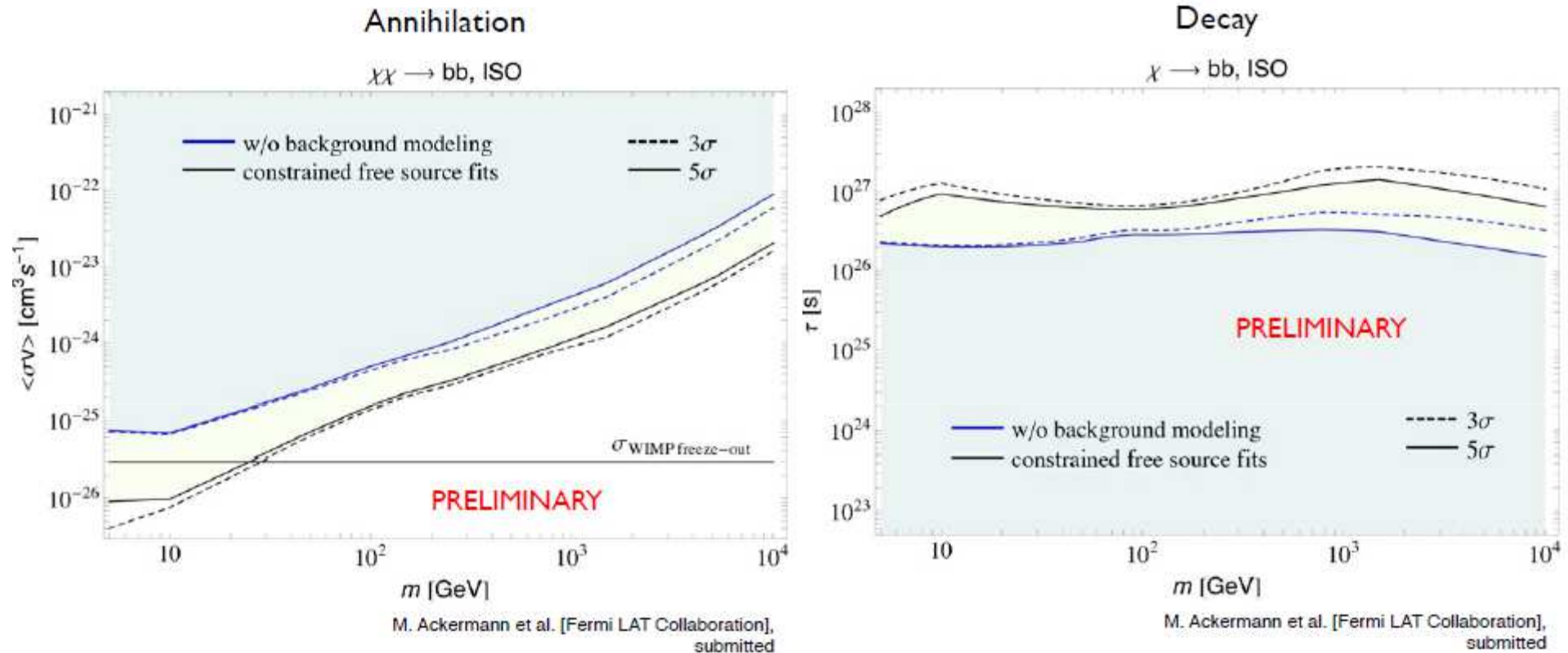
- bb̄ annihilation spectrum is similar in shape to DM annihilations/decays producing heavy quarks and gauge bosons in this energy range

Andrea Albert (OSU)

M. Ackermann et al. [Fermi LAT Collaboration], submitted

- **Set limits assuming only Final State Radiation and FSR + Inverse Compton**
  - **Only FSR = only photons produced by muons (no electrons)**
  - **"FSR + IC" includes IC gamma rays from electrons produced via DM annihilation/decay**
- **Contours show 2σ and 3σ CL fits to PAMELA (purple) and Fermi (blue) positron fraction**
  - **DM interpretation of positron fraction strongly disfavored (for annihilating DM)**

Andrea Albert (OSU)

Annihilation

$\chi\chi \rightarrow \tau^+\tau^-$, ISO

- IC+FSR, w/o background modeling
- FSR, w/o background modeling
- IC+FSR, constrained free source fits
- - - - 3σ
- —— 5σ

PRELIMINARY

$\langle \sigma v \rangle$ [cm³s⁻¹]

WIMP freeze-out

m [GeV]

Decay

$\chi \rightarrow \tau^+\tau^-$, ISO

PRELIMINARY

- IC+FSR, w/o background modeling
- FSR, w/o background modeling
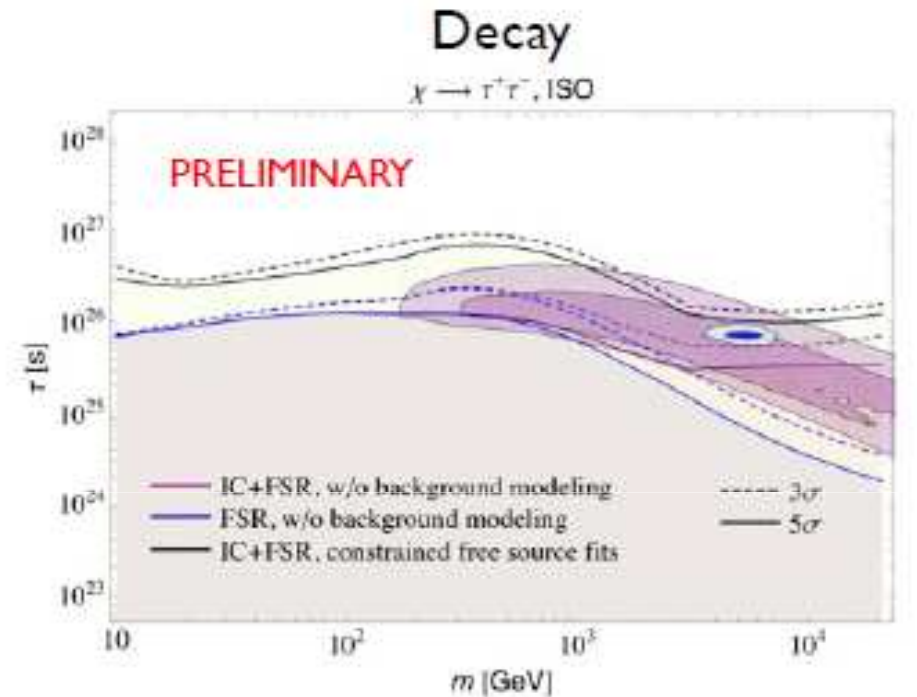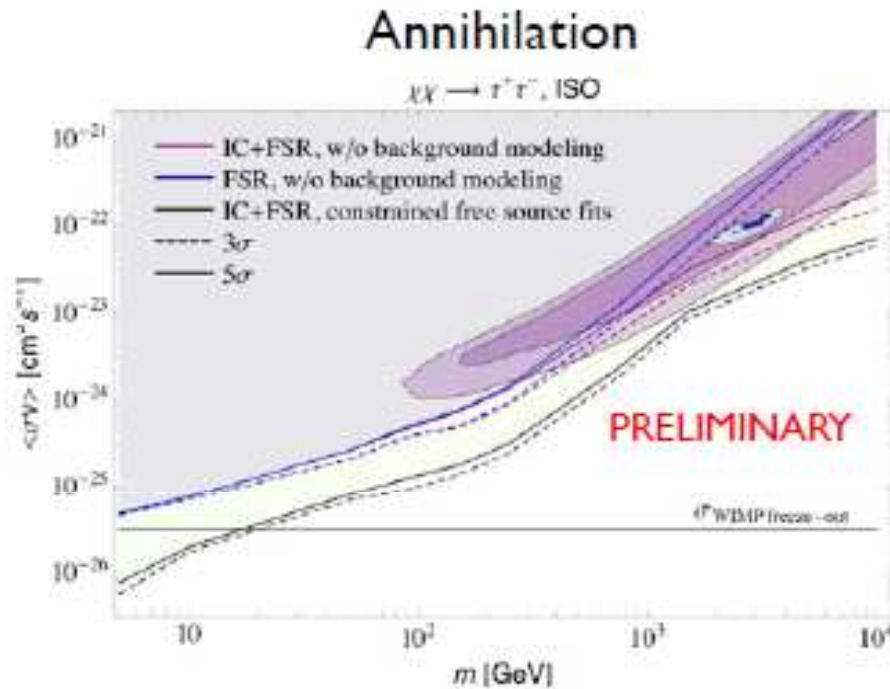- IC+FSR, constrained free source fits
- - - - 3σ
- —— 5σ

τ [s]

m [GeV]

M. Ackermann et al. [Fermi LAT Collaboration], submitted

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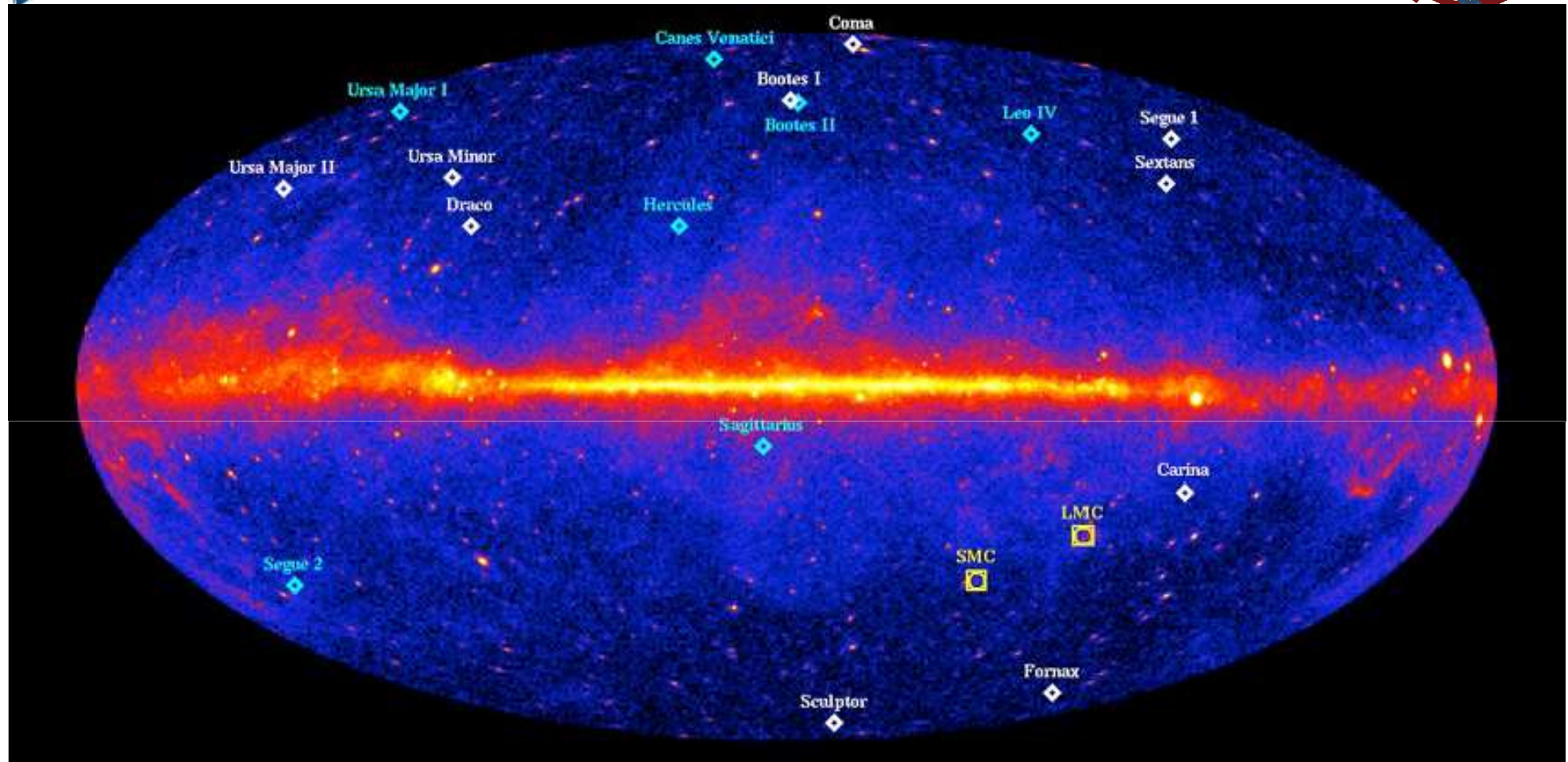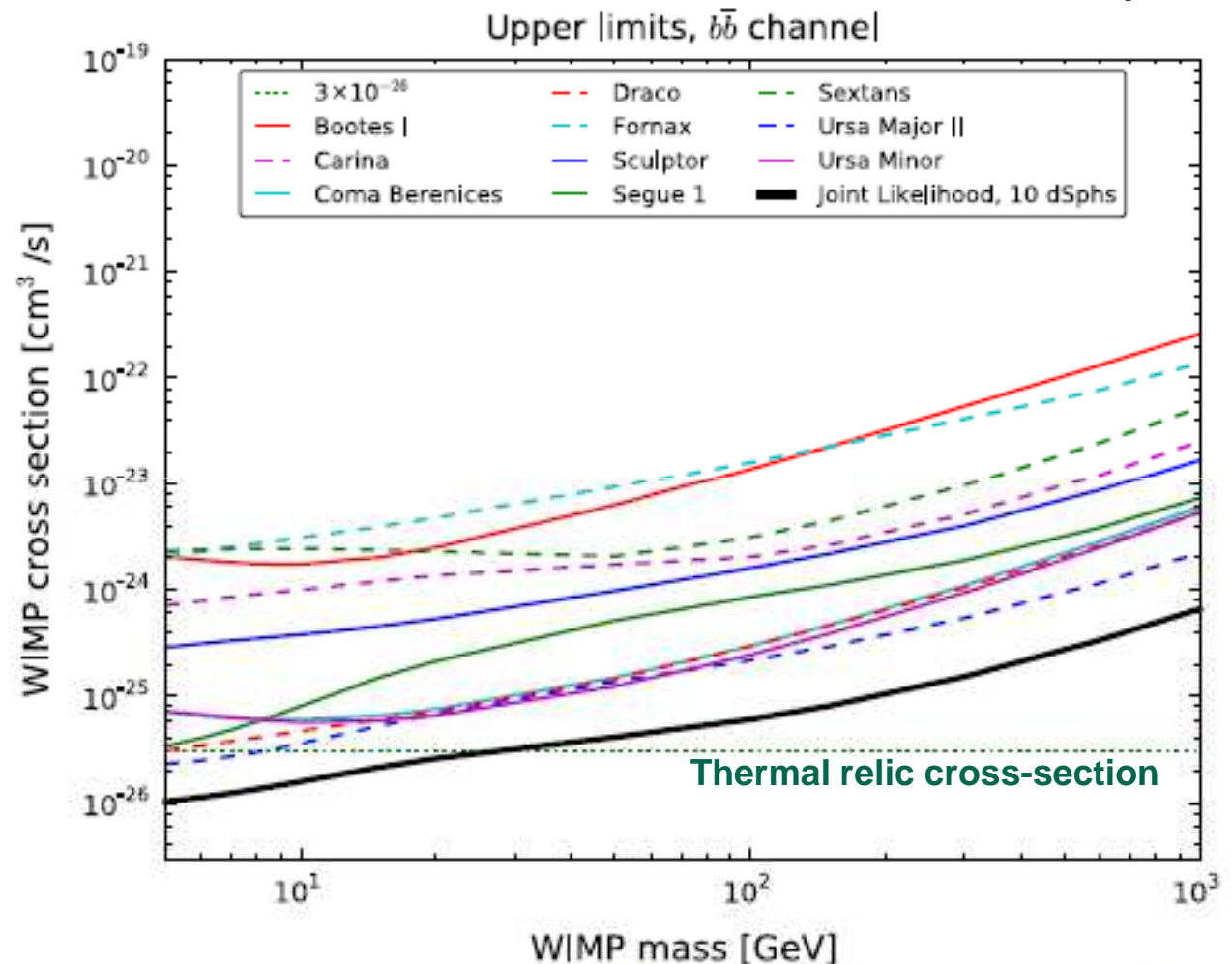
- **Dwarf galaxies have a large mass-to-light ratio**
- **Good signal-to-noise for a DM search**

Andrea Albert (OSU)

- **Joint likelihood analysis of 10 dwarf galaxies**

- **2 years of data in energy range 200 MeV – 100 GeV**

- **Account for uncertainties in J-factor**
  - **DM distribution determined using observed stellar velocities**

- **4 annihilation channels considered**

- **No DM seen**
  - **Exclude canonical thermal relic cross-section for masses less than ~30 GeV (in $b\bar{b}$ and tau's)**

Upper limits, $b\bar{b}$ channel

Legend:
- 3×10^{-26}
- Bootes I
- Carina
- Coma Berenices
- Draco
- Fornax
- Sculptor
- Segue 1
- Sextans
- Ursa Major II
- Ursa Minor
- Joint Likelihood, 10 dSphs

WIMP cross section [cm^3/s]

WIMP mass [GeV]

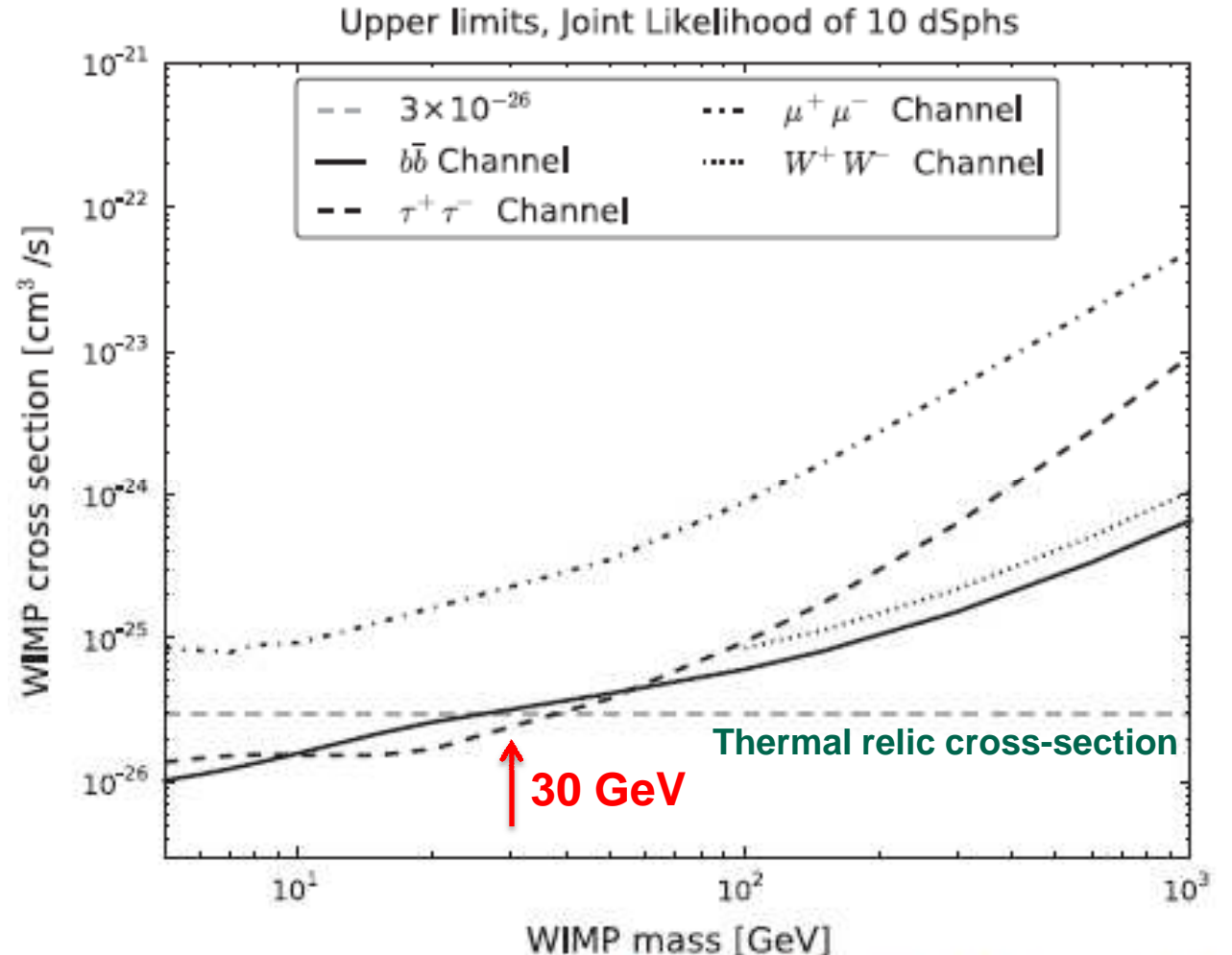**Thermal relic cross-section**

M. Ackermann et al. [Fermi LAT Collaboration], PRL 107, 241302 (2011)
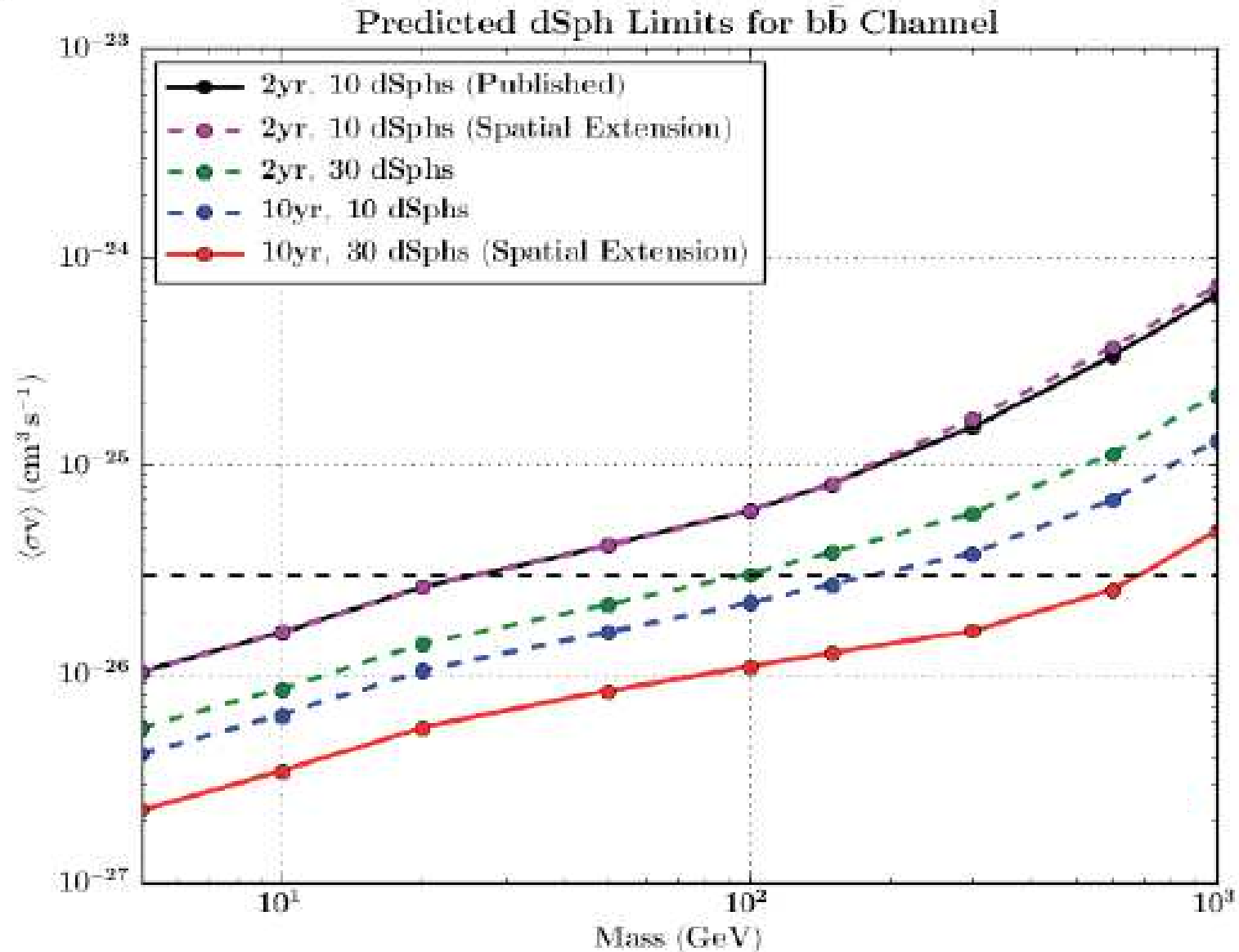
Combined dSphs Results

- **Joint likelihood analysis of 10 dwarf galaxies**

- **2 years of data in energy range 200 MeV – 100 GeV**

- **Account for uncertainties in J-factor**
  - **DM distribution determined using observed stellar velocities**

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- **No DM seen**
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Upper limits, Joint Likelihood of 10 dSphs

Legend:
- $- -$ 3×10^{-26}
- $\cdots$ $\mu^+\mu^-$ Channel
- $\underline{\quad}$ $b\bar{b}$ Channel
- $\cdots\cdots$ W^+W^- Channel
- $- - -$ $\tau^+\tau^-$ Channel

WIMP cross section [cm³ /s]

30 GeV

Thermal relic cross-section

WIMP mass [GeV]

M. Ackermann et al. [Fermi LAT Collaboration], PRL 107, 241302 (2011)

Andrea Albert (OSU)

Predicted dSph Limits for b$\bar{\text{b}}$ Channel

Legend:
- 2yr. 10 dSphs (Published)
- 2yr. 10 dSphs (Spatial Extension)
- 2yr. 30 dSphs
- 10yr. 10 dSphs
- 10yr. 30 dSphs (Spatial Extension)

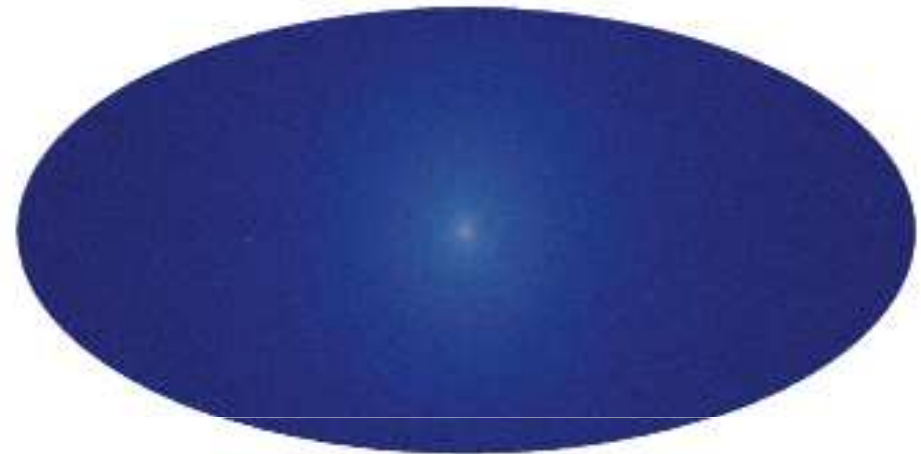y-axis: $\langle \sigma v \rangle$ (cm^3 s^{-1})

x-axis: Mass (GeV)

Gamma rays from Galactic DM

before accounting for instrument PSF

after convolving with 0.1° beam

- **Study the Isotropic Gamma-ray Background (IGRB)**
    - **Composed of unresolved sources from various classes (blazars, star-forming galaxies, MSPs, dark matter, …)**

- **Galactic DM subhalos (clumps of DM) may not be resolved by the LAT, but may be detected via anisotropy signature**
    - **Simulation above is one of several realizations, we don't know where the subhalos actually are**
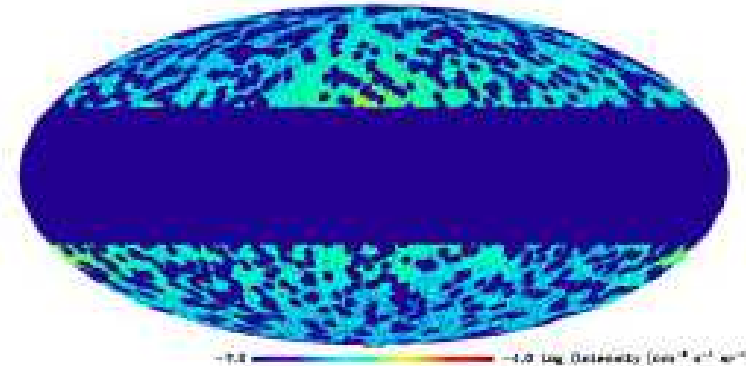
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- **ROI = $\pm 30^0$ off plane, mask out known sources**
  - **Look at whole dataset (DATA) and dataset minus Galactic Diffuse model (DATA:CLEANED)**
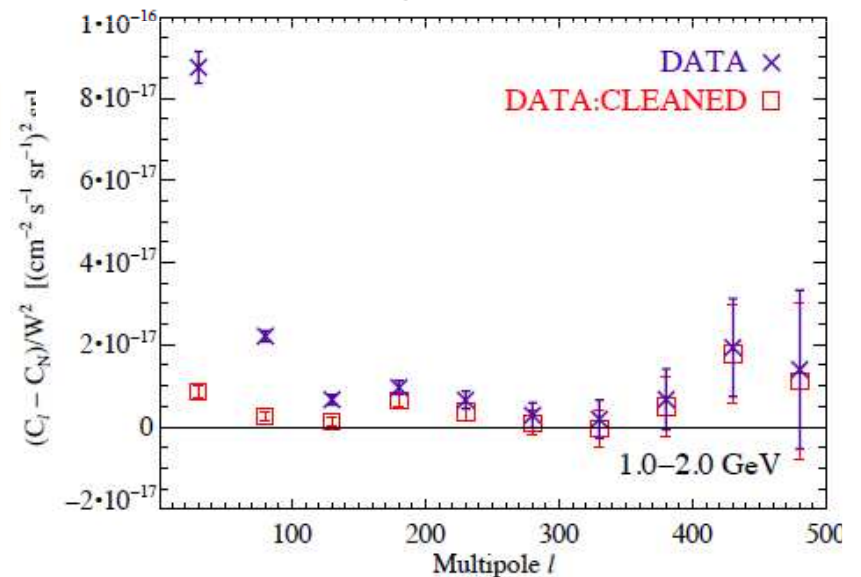
- **Measure the IGRB angular power spectrum in 4 energy bins from 1-50 GeV**

$$I(\psi) = \sum_{\ell,m} a_{\ell m} Y_{\ell m}(\psi) \qquad C_\ell = \langle |a_{\ell m}|^2 \rangle$$

- **For 155 < l < 504, angular power is roughly constant in multipole in all four energy bins**
  - **Poisson-like, characteristic of unclustered point sources**
  - **Constrains DM subhalo models**

1 - 2 GeV Angular Power Spectrum

DATA ×
DATA:CLEANED □

1.0–2.0 GeV

Multipole l

Ackermann et al. [Fermi LAT Collaboration] 2012
(to appear in PRD)

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Constraints from Observed Anisotropy (1)

- **Angular power spectrum analysis of the isotropic gamma-ray background (IGRB) found a >3σ detection of angular power up to 10 GeV (lower significance measure at 10-50 GeV bin)**

- **Observed fluctuation angular power is roughly constant from 1-50 GeV**
  - **Well described by coming from single source class with spectral index Γ = -2.4±0.07**
  - **Constrains some DM subhalo models**

- **Can constrain fractional contribution of individual source classes to the IGRB intensity**

Fluctuation Anisotropy Energy Spectrum
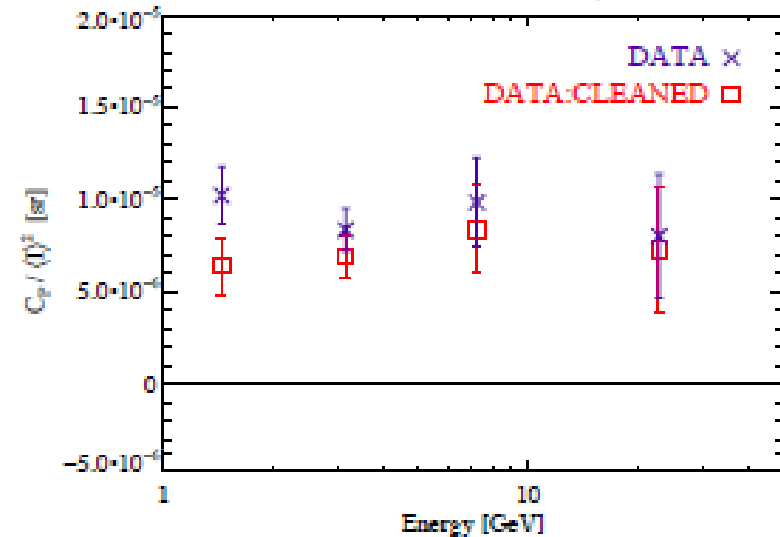
Ackermann et al. [Fermi LAT Collaboration] 2012
(to appear in PRD)

Constraints from best-fit constant fluctuation angular power (l ≈ 150) measured in the data and foreground-cleaned data

Source class	Predicted $C_{100}/\langle I \rangle^2$ [sr]	Maximum fraction of IGRB intensity	
		DATA	DATA:CLEANED
Blazars	2×10^{-4}	21%	19%
Star-forming galaxies	2×10^{-7}	100%	100%
Extragalactic dark matter annihilation	1×10^{-5}	95%	83%
Galactic dark matter annihilation	5×10^{-6}	43%	37%
Millisecond pulsars	3×10^{-2}	1.7%	1.5%

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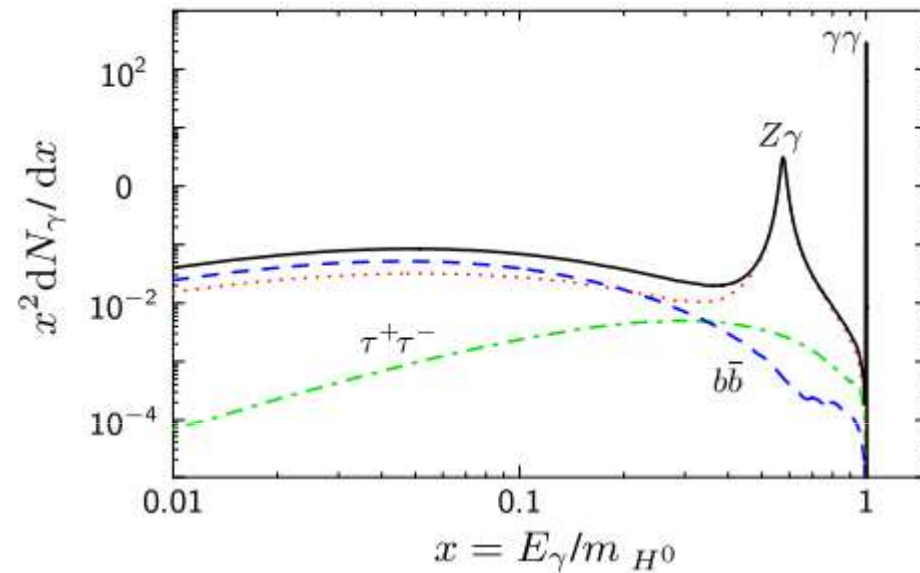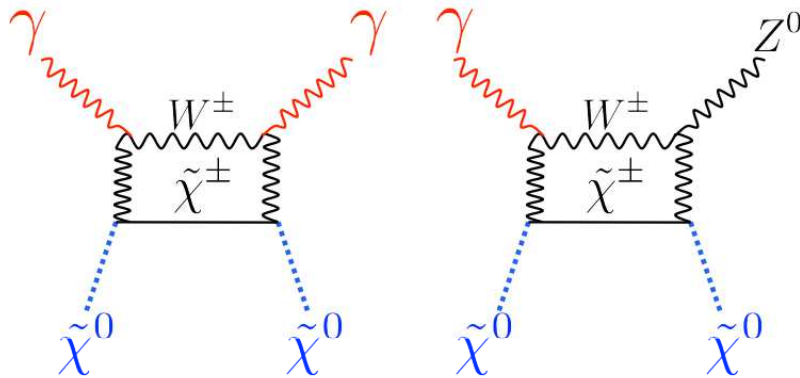
Gustafsson et al. PRL 99.041301

- **Annihilation/decay directly into γγ or Xγ (X = Z⁰, H⁰, …)**
- **"Smoking Gun" channel**
- **Advantage: sharp, distinct feature**
- **Disadvantage: low predicted counts**

Fermi Line Search

2 yr Analysis ROI
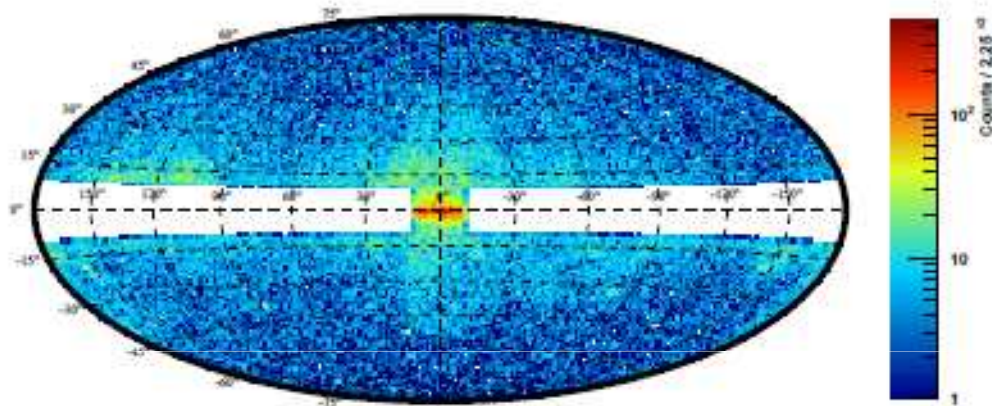
LAT energy response to 100 GeV Line

$E_l = 100$ GeV
$\chi^2/dof = 32.9/32$
p-value=0.43
Containment windows
68% = (−0.086,0.081)
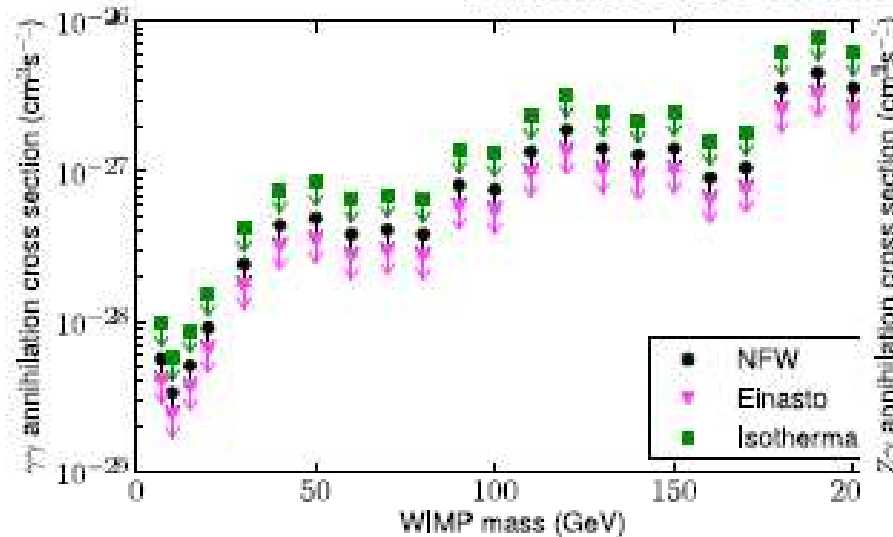95% = (−0.311,0.188)
bias = 0.013
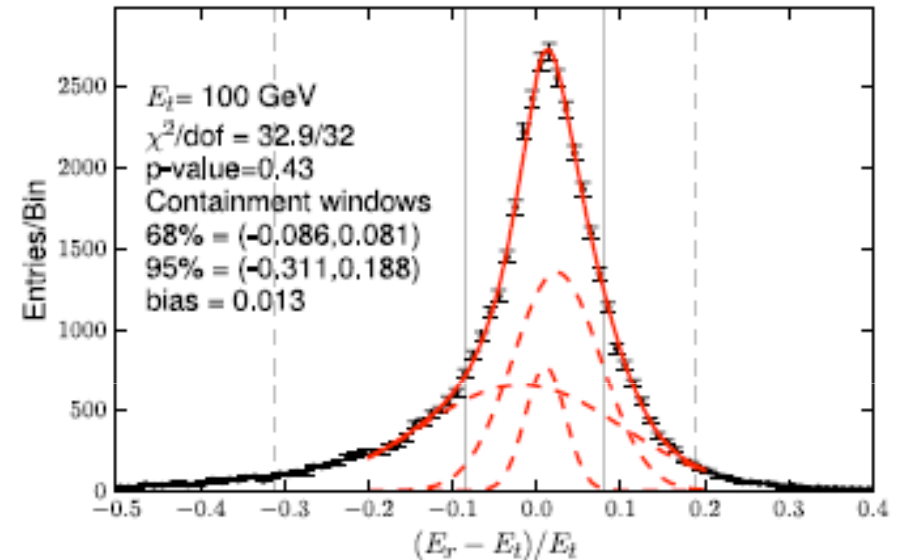
- **Model energy dispersion using full detector GEANT simulation**
- **ROI = 10^0 off plane + galactic center (mask out known sources)**
- **Likelihood fit in sliding energy windows**
  - **Assume single power-law background**
  - **Background spectral index and DM signal fraction free to vary in each window**
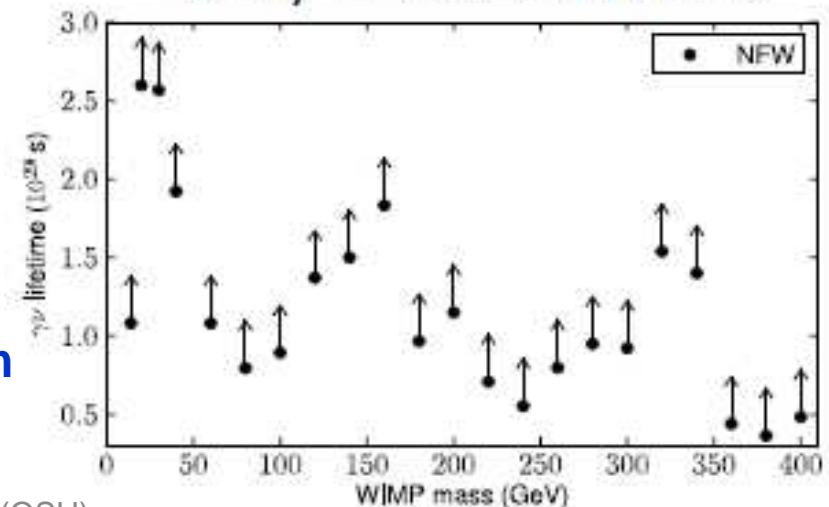
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Annihilation cross-section constraints
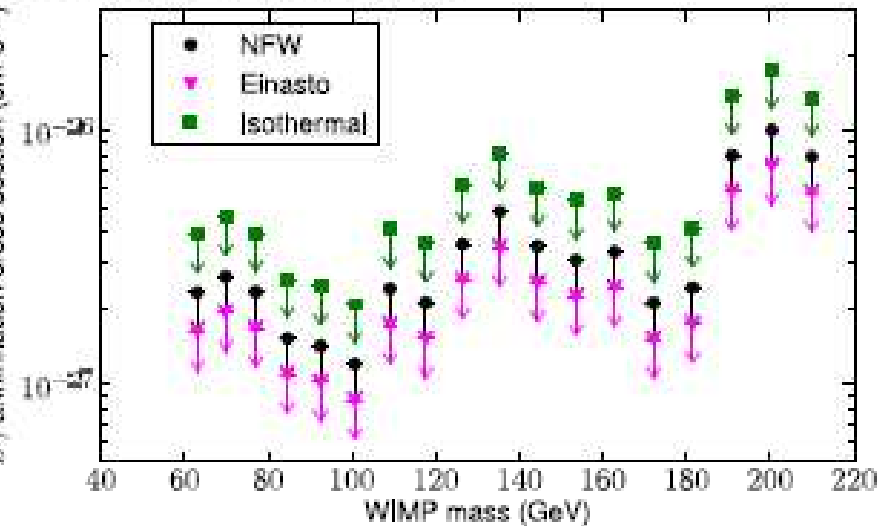
Ackermann et al. [Fermi LAT Collaboration], accepted to PRD

- **No lines detected in the 2 yr analysis**
- **Follow up analysis is ongoing**
  - **More data**
  - **Exploring ROI optimization**
  - **Design better E_{disp} model**
 - **In-depth exploration of 130 GeV claim**

Decay lifetime constraints

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DM Line at 130 GeV?

- **Feature found in gamma-ray spectrum at ~130 GeV**
  - Bringmann et al. find weak indication that feature is consistent with internal brem. emission from DM annihilation
  - Weniger claims a tentative gamma-ray line

- **Feature seems to come from galactic center**
  - Slightly offset though

- **In-depth Fermi investigation is ongoing**

- **See also: Bringmann et al. arXiv: 1203.1312; Weniger arXiv: 1204.2797; Tempel et al. arXiv 1205.1045; Boyarsky et al. atXiv:1205.4700; Geringer-Sameth & Koushiappas arXiv: 1206.0796; Su & Finkbeiner arXiv: 1206.1616; Aharonian et al. arXiv: 1207.0458**

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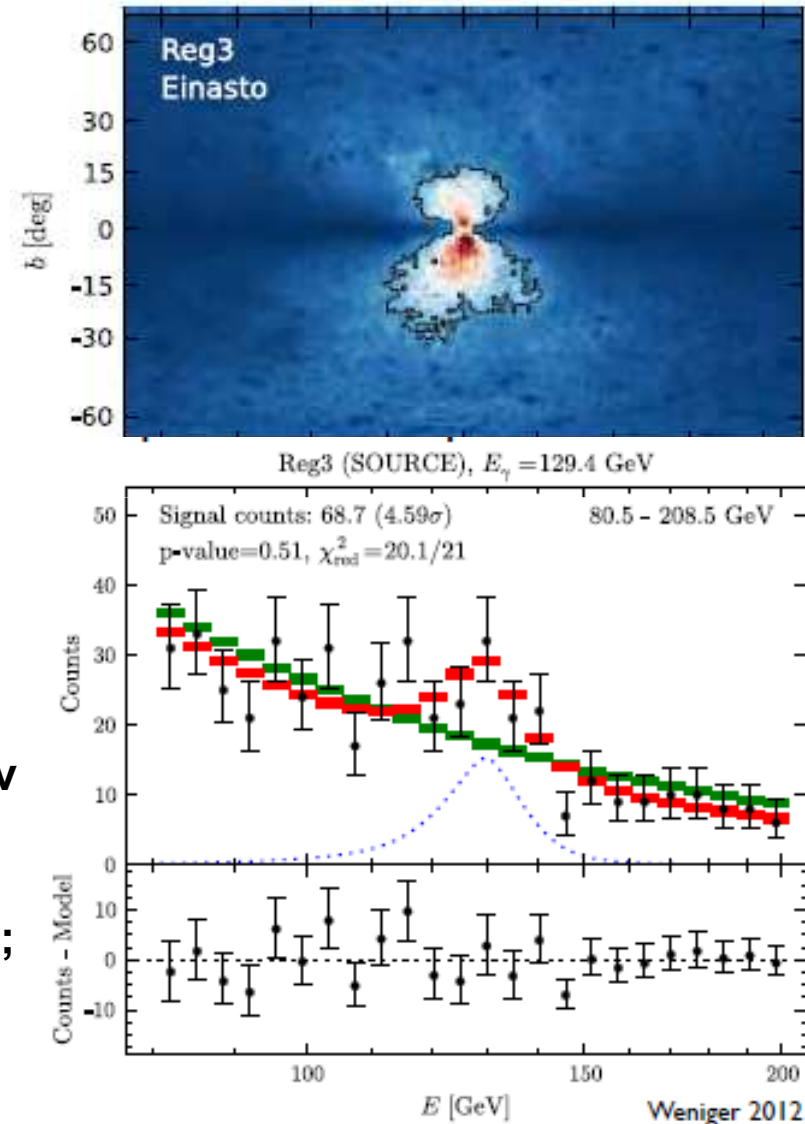
- **Profumo & Linden show how a broken power-law source could produce a line-like feature**
  - **Non DM astrophysical sources can produce such a break**

- **Aharonian et al. argue that a cold ultrarelativistic pulsar wind could produce a line-like feature**

- **May be an instrumental or reconstruction issue**

- **Many unresolved questions remain so stay tuned!**

Profumo & Linden 2012
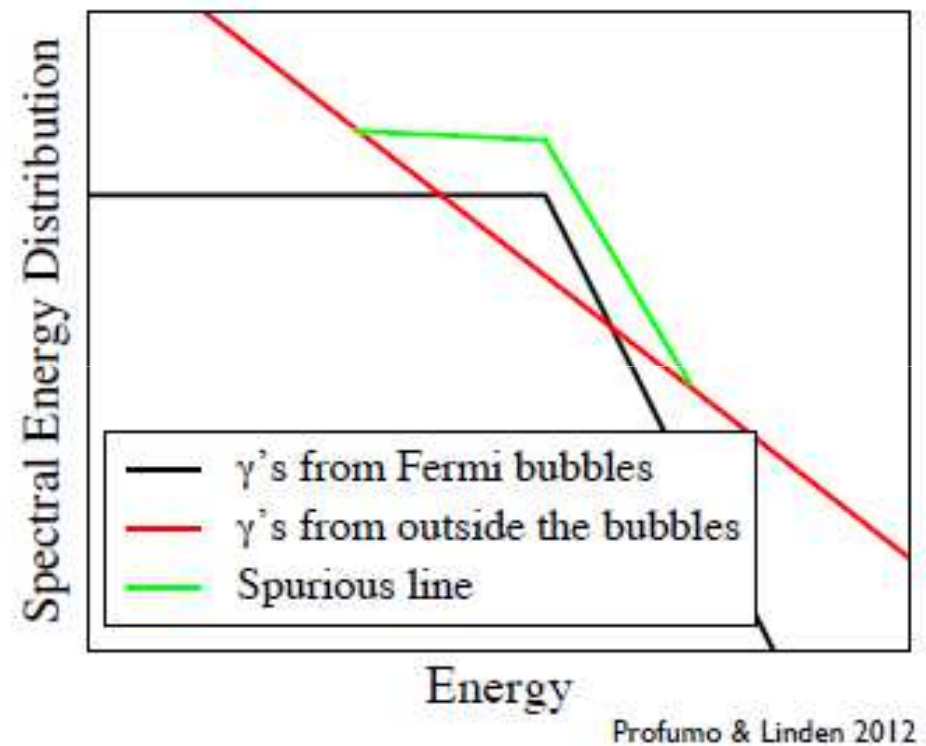
Summary

- **The Fermi LAT has placed strong constraints on dark models from null detections in several indirect DM searches**

- **Searches in the Milky Way Halo and Dwarf Galaxies have excluded the canonical thermal relic cross-section for masses less than ~30 GeV (in b$\bar{\text{b}}$ and tau annihilation channels)**

- **Searches in the Milky Way Halo have also strongly disfavored DM models explaining the electron-positron anomalies**

- **Sensitivity of the LAT is expected to keep improving**
  - **Improved understanding of astrophysical background**
  - **Increased exposure**
  - **Improvements in analysis and understanding of detector response**

- **Current searches are already exploring interesting parts of DM phase space and will just keep getting more sensitive; stay tuned for more exciting Dark Matter results from the Fermi LAT!**

Fermi LAT Collaboration References

- **For a list of Fermi LAT collaboration publications**
    - **see http://www-glast.stanford.edu/cgi-bin/pubpub**

- **"The Fermi Large Area Telescope On Orbit: Event Classification, Instrument Response Functions, and Calbration**
    - **arXiv: 1206.1896**

- **"Fermi LAT observations of cosmic-ray electrons from 7 GeV to 1 TeV"**
    - **arXiv: 1008.3999**

- **"Measurement of separate cosmic-ray electron and positron spectra with the Fermi Large Area Telescope"**
    - **arXiv: 1109.0521**

- **"Constraints on the Galactic Halo Dark Matter from Fermi-LAT Diffuse Measurements"**
    - **arXiv: 1205.6474**

- **"Constraining Dark Matter Models from a Combined Analysis of Milky Way Satellites with the Fermi Large Area Telescope"**
    - **arXiv: 1108.3546**

- **"Anisotropies in the diffuse gamma-ray background measured by the Fermi LAT"**
    - **arXiv: 1202.2856**

- **"Fermi LAT Search for Dark Matter in Gamma-ray Lines and the Inclusive Photon Spectrum"**
    - **arXiv: 1205.2739**

- **Profumo and Linden, "Gamma-ray Lines in the Fermi Data: is it a Bubble?"**
    - **arXiv: 1204.6047**