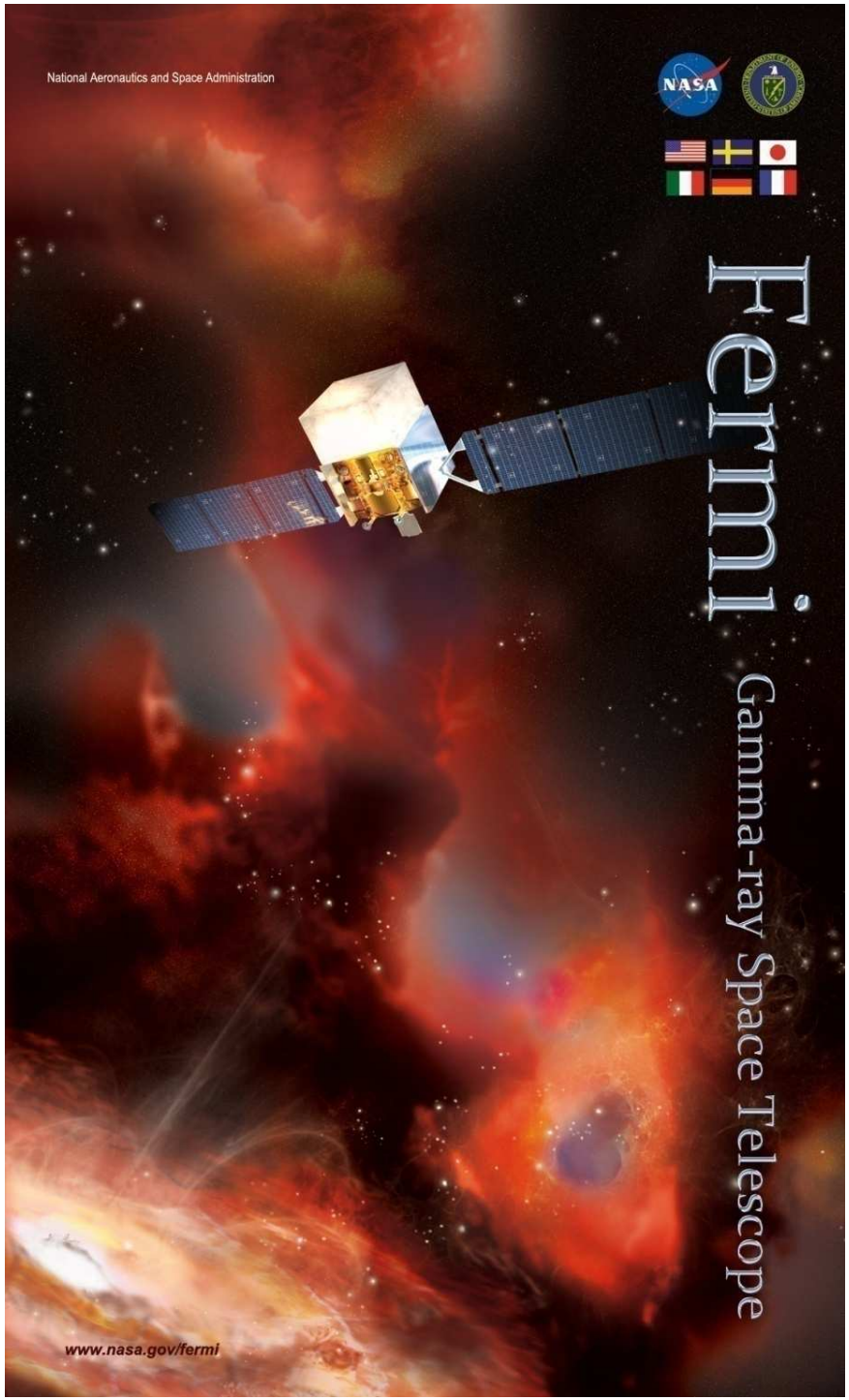


Indirect Dark Matter Searches with the Fermi Large Area Telescope

Andrea Albert (SLAC)
on behalf of
The Fermi LAT Collaboration

Research Progress Meeting
LBNL
December 4th, 2014

Outline

- **Dark Matter Overview**
- **The Fermi Large Area Telescope**
  - **The Gamma-ray Sky**
- **Recent Dark Matter Results**
  - **Lines**
  - **Galactic Center**
  - **Dwarfs**

Outline

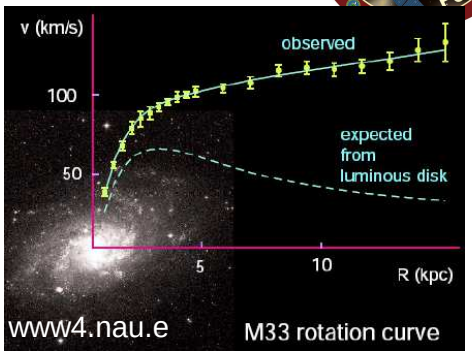
- **Dark Matter Overview**

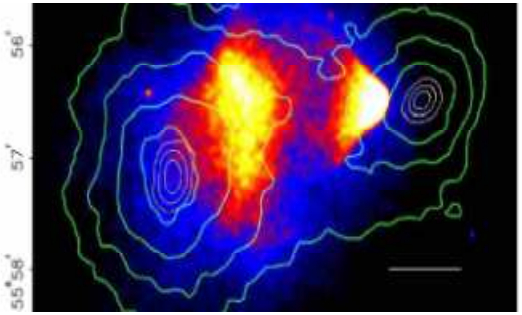
- **The Fermi Large Area Telescope**
  - **The Gamma-ray Sky**

- **Recent Dark Matter Results**
  - **Lines**
  - **Galactic Center**
  - **Dwarfs**

Dark Matter Primer

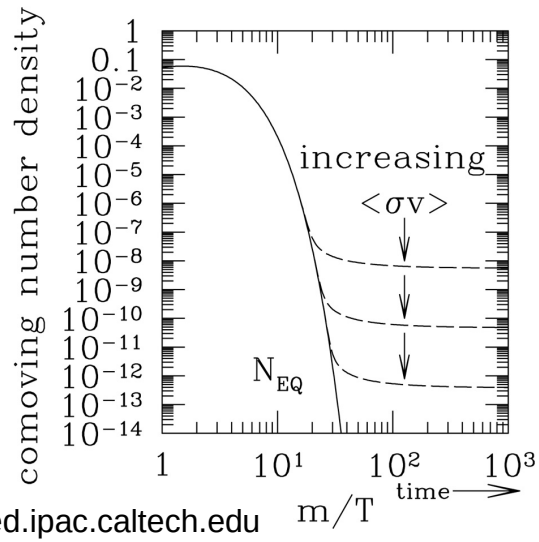
- **Dark Matter clumps in large *halos* around galaxies making up most of their *mass***
  - **Coma Cluster + Virial Theorem, F. Zwicky (1937)**
  - **Galactic Rotation Curves, V. Rubin et al 1980)**





- **Dark Matter is virtually *collisionless* and *non-baryonic***
  - **The Bullet Cluster, D. Clowe et al (2006)**
  - **CMB Acoustic Oscillations, Planck (2013)**

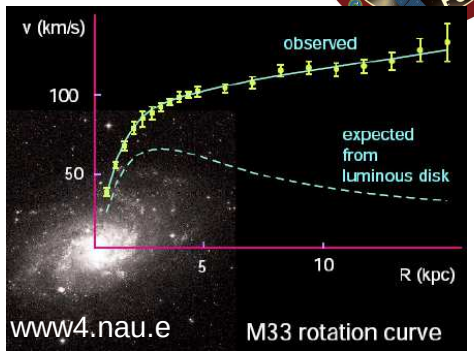
- **Weakly Interacting Massive Particle (WIMP,χ)**
  - **WIMPs may be thermal relics**
    - **WIMP in thermal equilibrium in early universe**
    - **Universe cools enough, amount of DM freezes out**
- **Assume *weak scale* σ_{ann} → observed abundance (~27% of energy density)**
  - **$\langle\sigma v\rangle_{ann}$ ~ 3e-26 cm^3/s (σ_{ann} ~ 3 pb)**



ned.ipac.caltech.edu

Dark Matter Primer

- Dark Matter clumps in large *halos* around galaxies making up most of their *mass*
  - Coma Cluster + Virial Theorem, F. Zwicky (1937)
  - [illegible]ctic Rotation Curves, V. Rubin et al 1980)

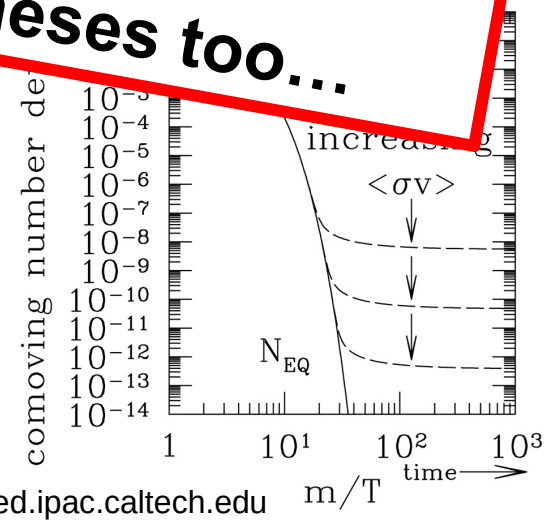


Thermal Relic $\langle\sigma v\rangle_{ann}$ is well-motivated hypothesis
Dan Hooper: "Not a fishing expedition"
Though SUSY gives many other hypotheses too…

[illegible] is virtually *collisionless* and

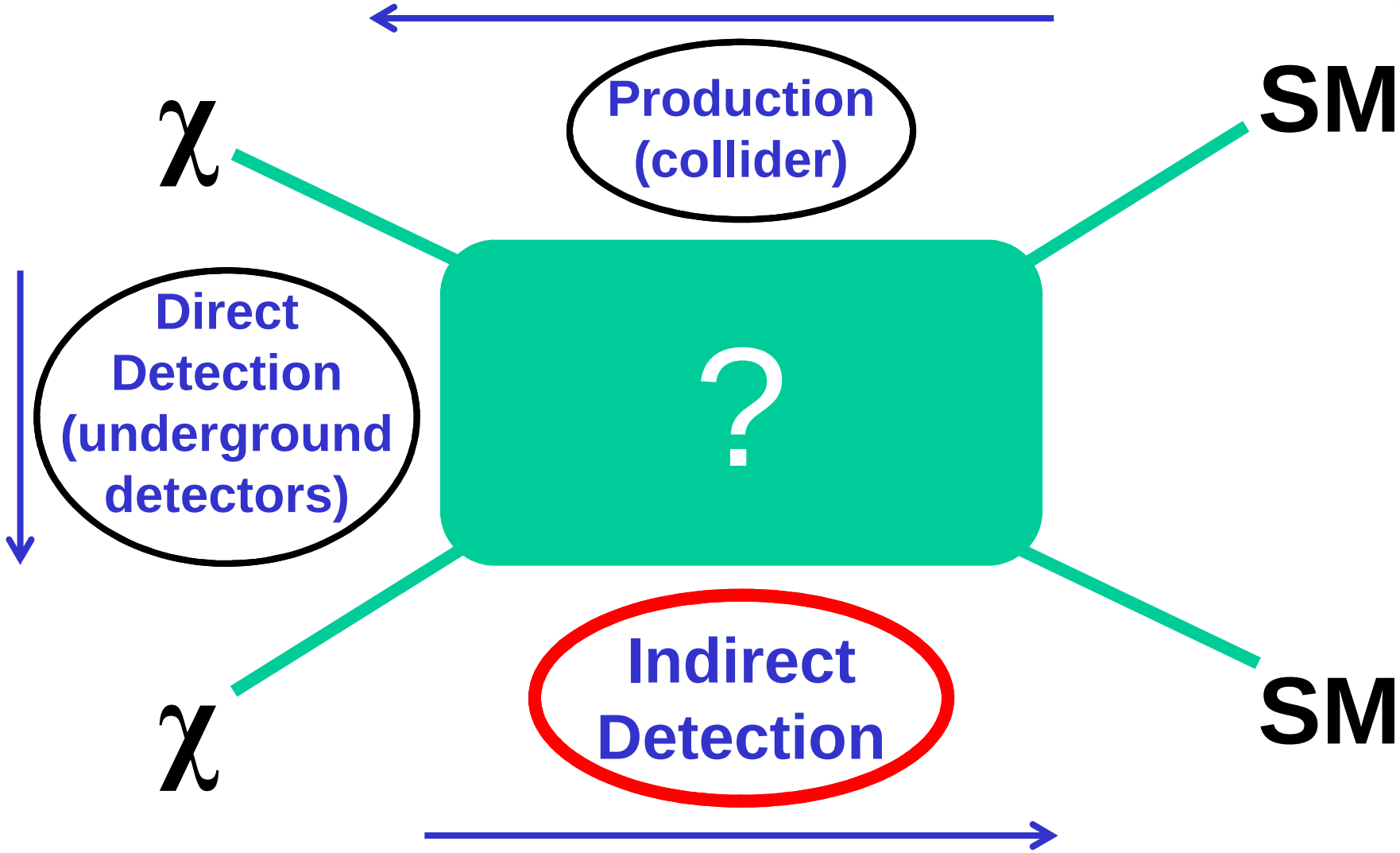
- Weakly Interacting Massive Particle (WIMP, χ)
  - WIMPs may be thermal relics
    - WIMP in thermal equilibrium in early universe
    - Universe cools enough, amount of DM freezes out

- **Assume *weak scale* σ_{ann} → observed abundance (~27% of energy density)**
  - **$\langle\sigma v\rangle_{ann}$ ~ 3e-26 cm^3/s (σ_{ann} ~ 3 pb)**



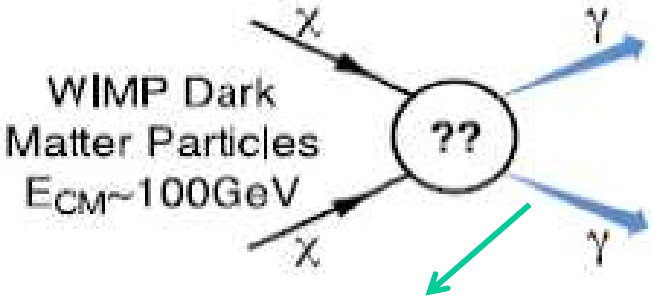
ned.ipac.caltech.edu

How to Detect WIMPs



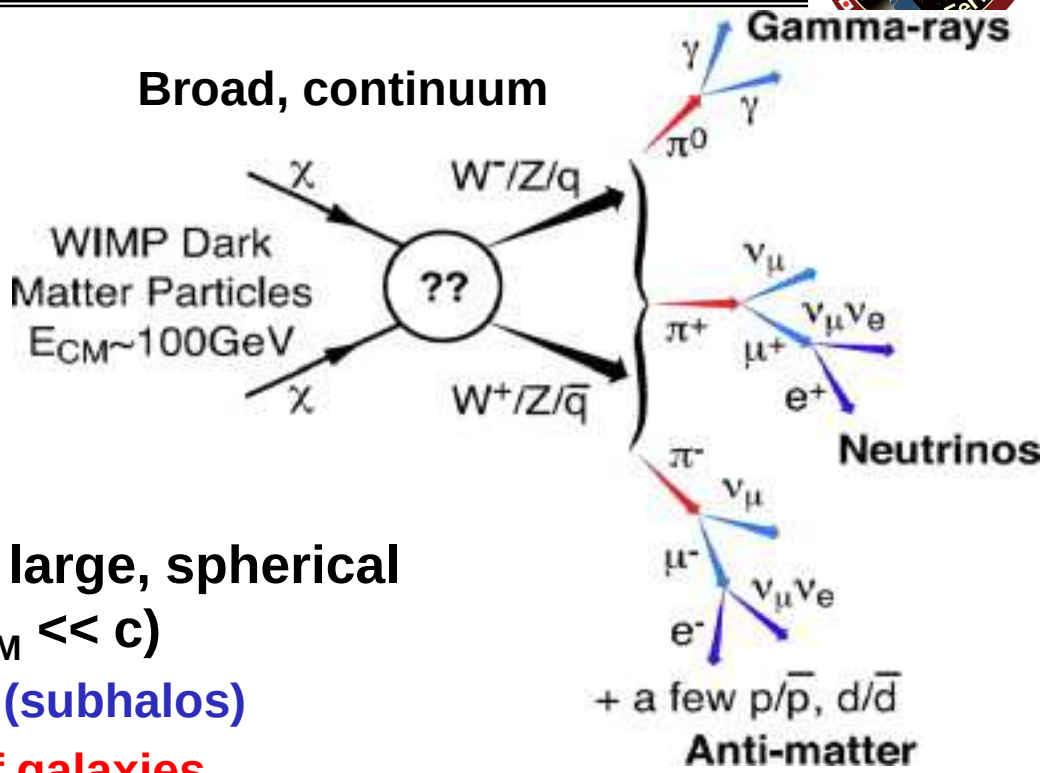
Gamma-rays from WIMPs

Spectral Line



Or Z^0, H^0, etc

Broad, continuum



- **Believe the Milky Way sits in a large, spherical "halo" or cloud of cold DM (v_{DM} << c)**
  - **Expect DM overdensities (subhalos)**
    - **Largest are the dwarf galaxies**
  - **Other extra-galactic DM expected too**
    - **e.g. Galaxy Clusters**
- **WIMPs annihilations (decays) may produce gammas**
  - **Dominant channels -> broad continuum**
  - **Monochromatic channels expected to be rare (loop-suppressed)**

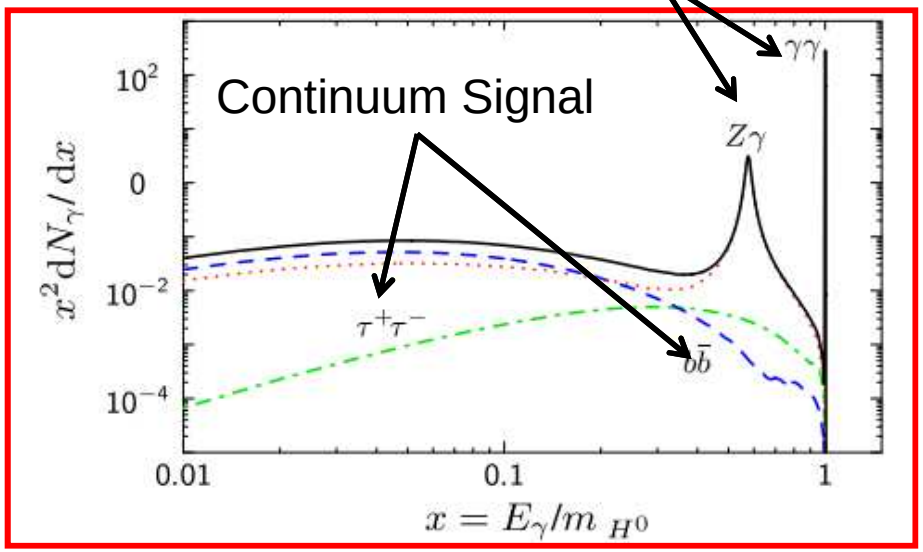
Indirect WIMP Signatures

What we observe | **Intrinsic Particle Properties** | **Astrophysics**

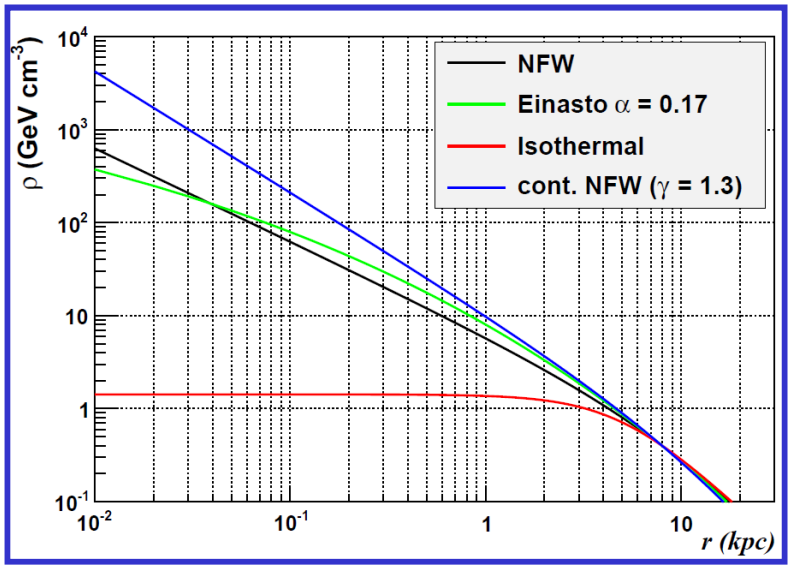
$$\Phi_\chi(E,\psi) = \frac{\langle\sigma_\chi v\rangle}{2}\sum_f \frac{dN_f}{dE} B_f \int_{LOS} dl(\psi)\frac{1}{4\pi}\frac{\rho(l)^2}{m_\chi^2}$$

J-factor – Line of sight integral over a ROI

Monochromatic Signal



Gustafsson et al. PRL 99.041301

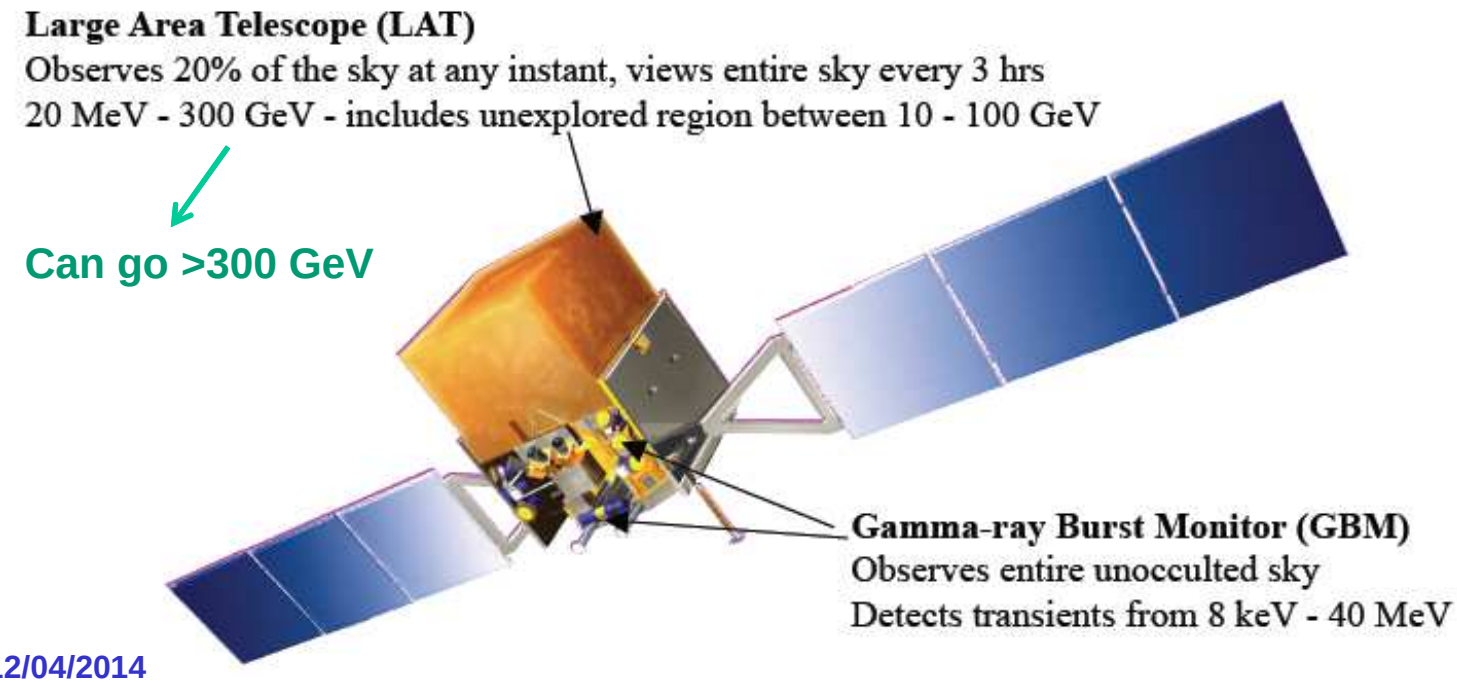


Outline

- Dark Matter Overview
- **The Fermi Large Area Telescope**
  - The Gamma-ray Sky
- Recent Dark Matter Results
  - Lines
  - Galactic Center
  - Dwarfs

Fermi Large Area Telescope (LAT)

- **On board the Fermi Gamma-ray Space Telescope**
  - **Launched June 11, 2008 (science mission started Aug. 2008)**
    - **Mission extended at least through 2016**
    - **No consumables**
      - **Orbit re-entry expected ~2026-2044 (depending on solar activity)**
  - **LAT has triggered on >380 billion events**
    - **Processed >73 billion events (>1 Petabyte!)**

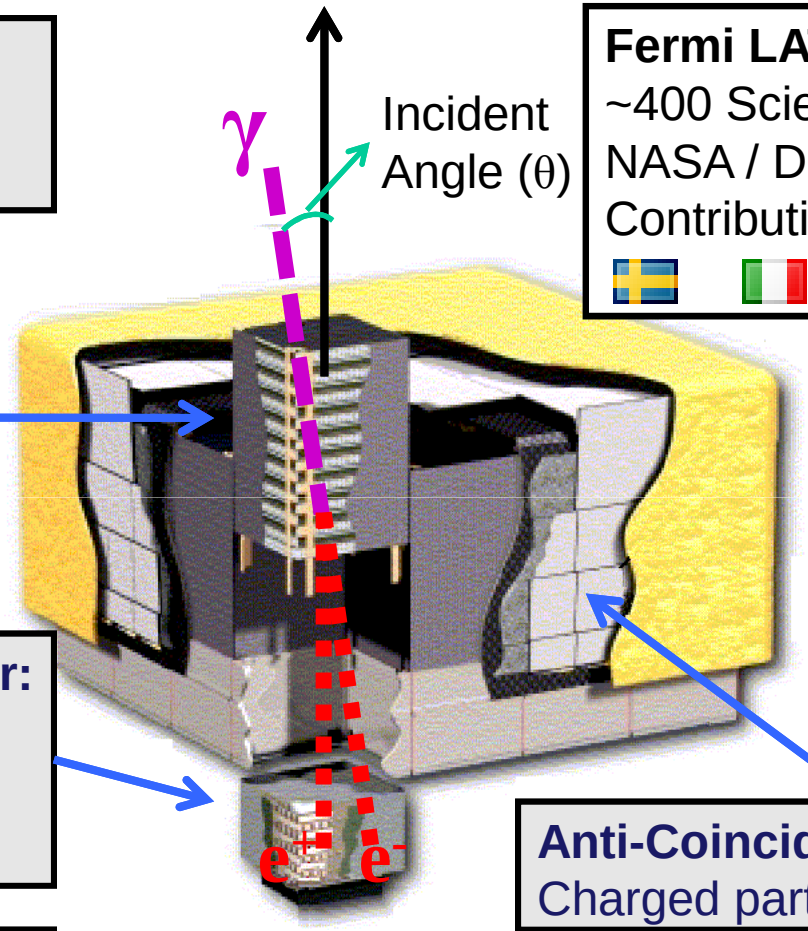


Fermi LAT

Public Data Release:
All γ-ray data made public within 24 hours (usually less)

Fermi LAT Collaboration:
~400 Scientific Members, NASA / DOE & International Contributions

Si-Strip Tracker:
convert $\gamma \rightarrow e^+e^-$
reconstruct γ direction
EM v. hadron separation

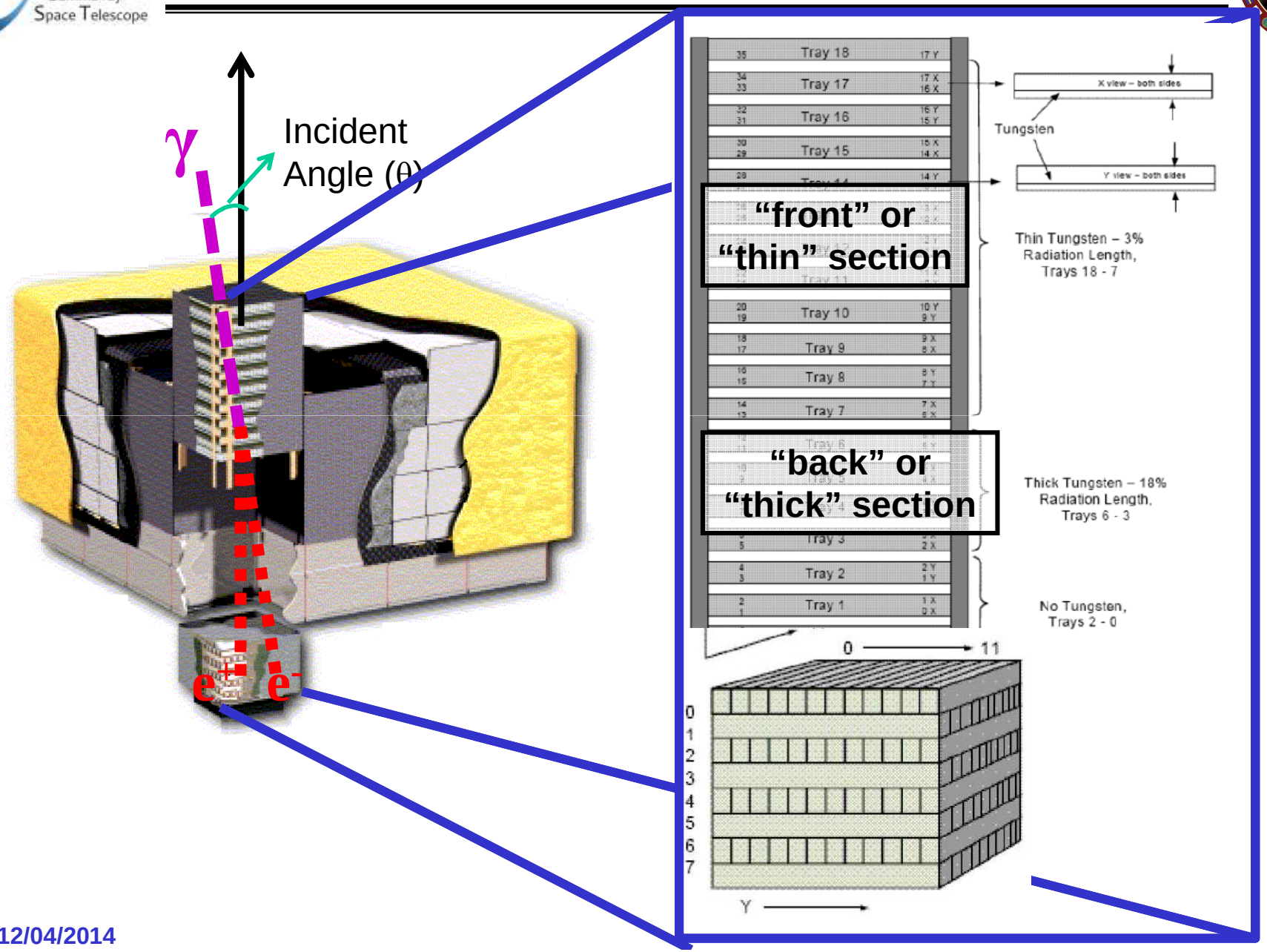


Hodoscopic CsI Calorimeter:
measure γ energy
image EM shower
EM v. hadron separation

Anti-Coincidence Detector:
Charged particle separation

Trigger and Filter:
Reduce data rate from ~10kHz to 300-500 Hz

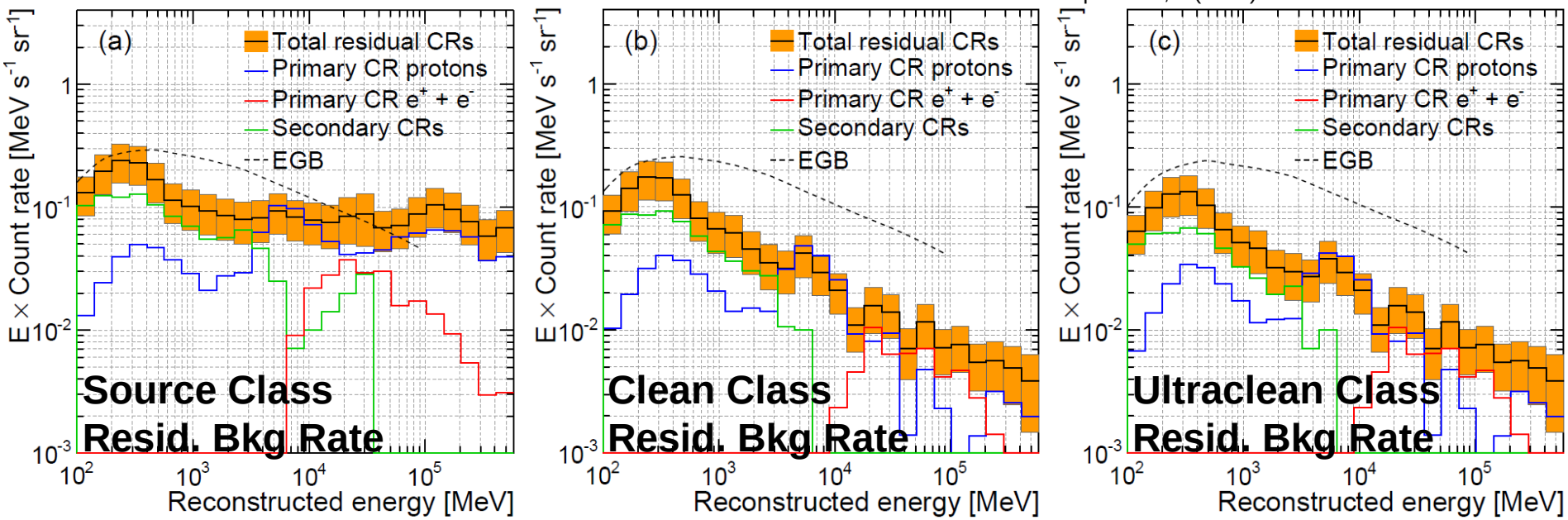
Fermi LAT – “front” vs. “back”



Gamma-ray Event Classes

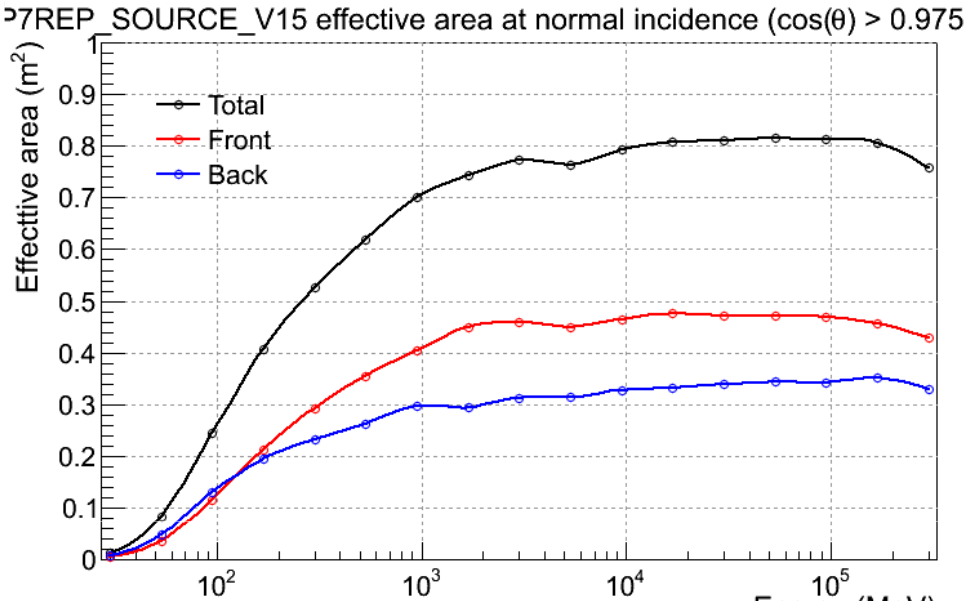
- **Triggered events are dominated by CR background events**
  - **Need to define additional cuts to get γ-ray rich dataset**
- **Nested "event classes" for various types of γ ray sources**
  - **Transient: loosest, for transient sources (< 200 s)**
  - **Source: moderate, for bright sources (cut in space)**
  - **Clean: tight, for γ-ray diffuse**
  - **Ultraclean: tightest, for extragalactic γ rays**

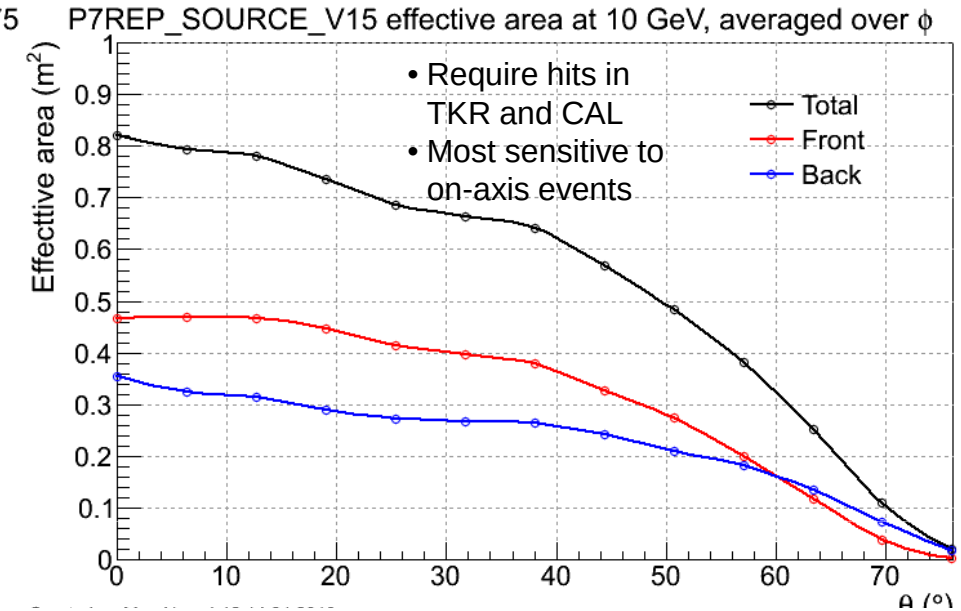
M. Ackermann et al (The Fermi LAT Collaboration)
ApJS 203, 4 (2012) arXiv:1206.1896

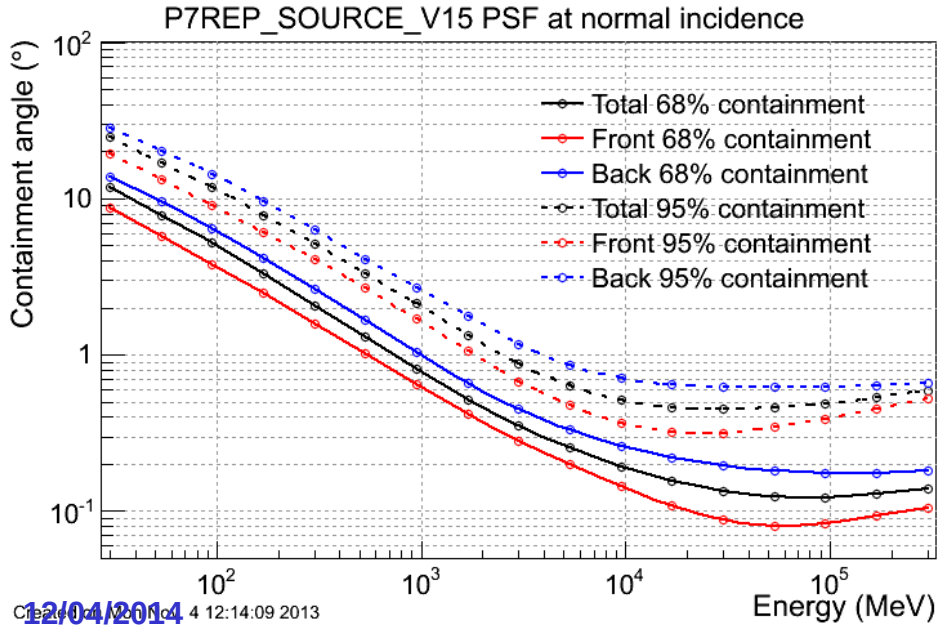


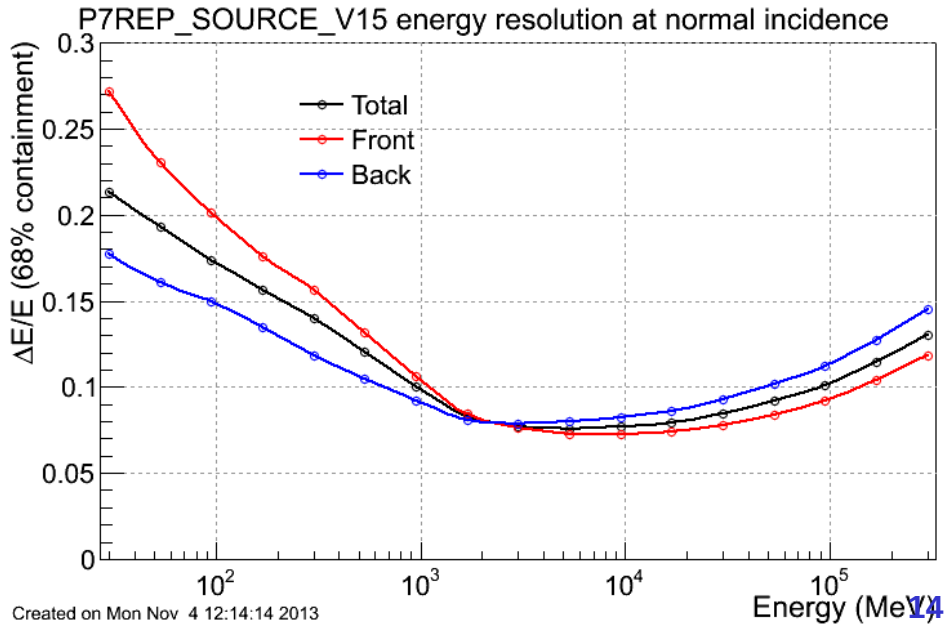
Fermi LAT Performance

see also M. Ackermann et al (The Fermi LAT Collaboration) ApJS 203, 4 (2012) arXiv:1206.1896



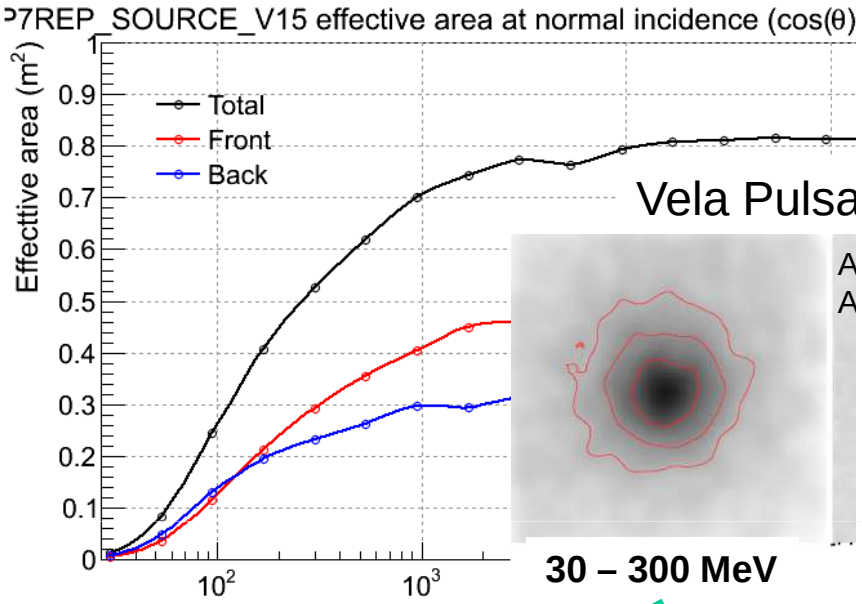


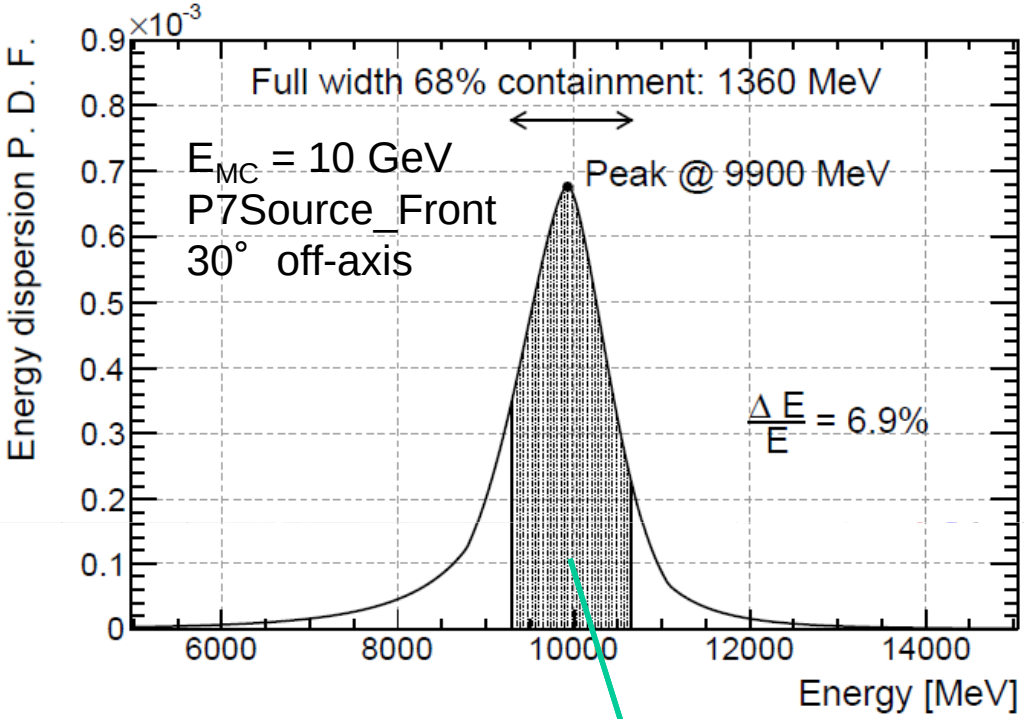


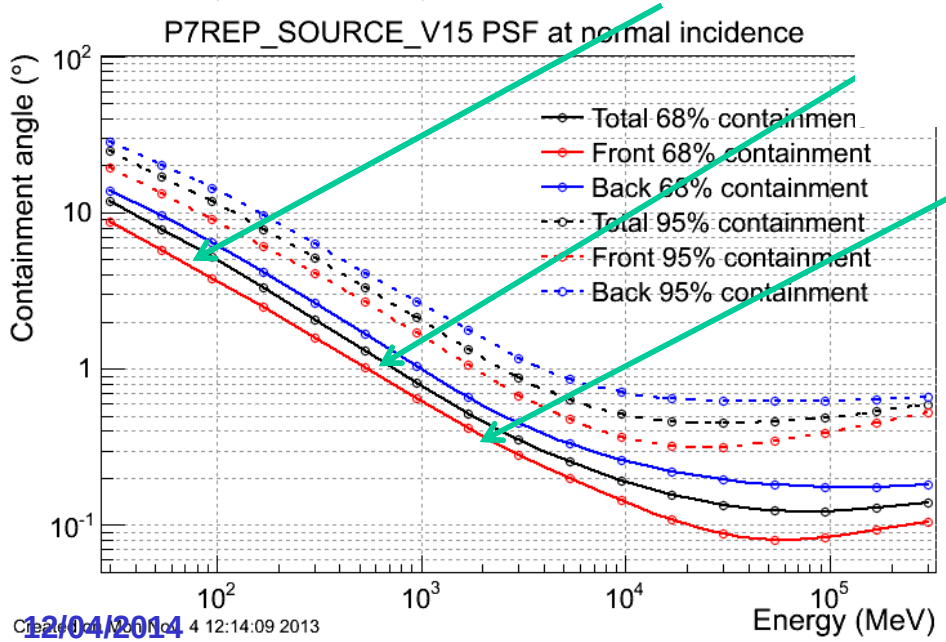


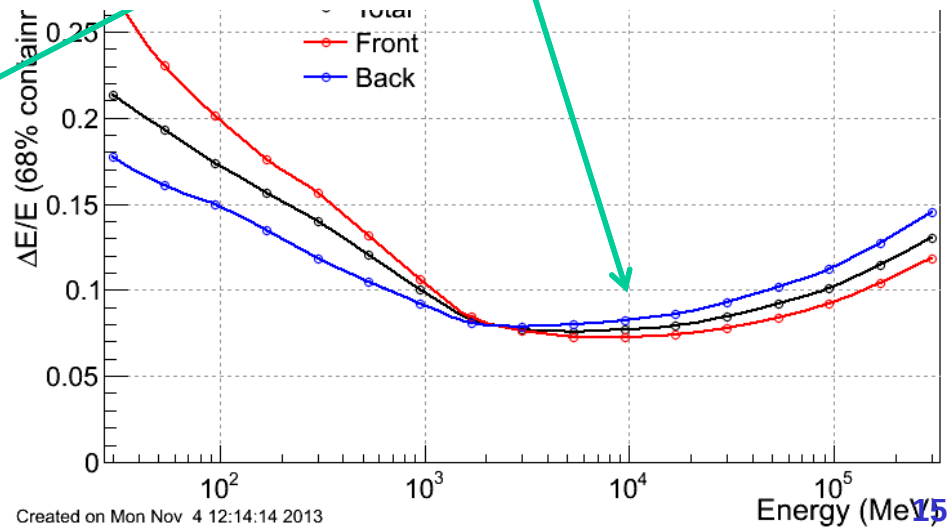
Fermi LAT Performance

M. Ackermann et al (The Fermi LAT Collaboration) ApJS 203, 4 (2012) arXiv:1206.1896



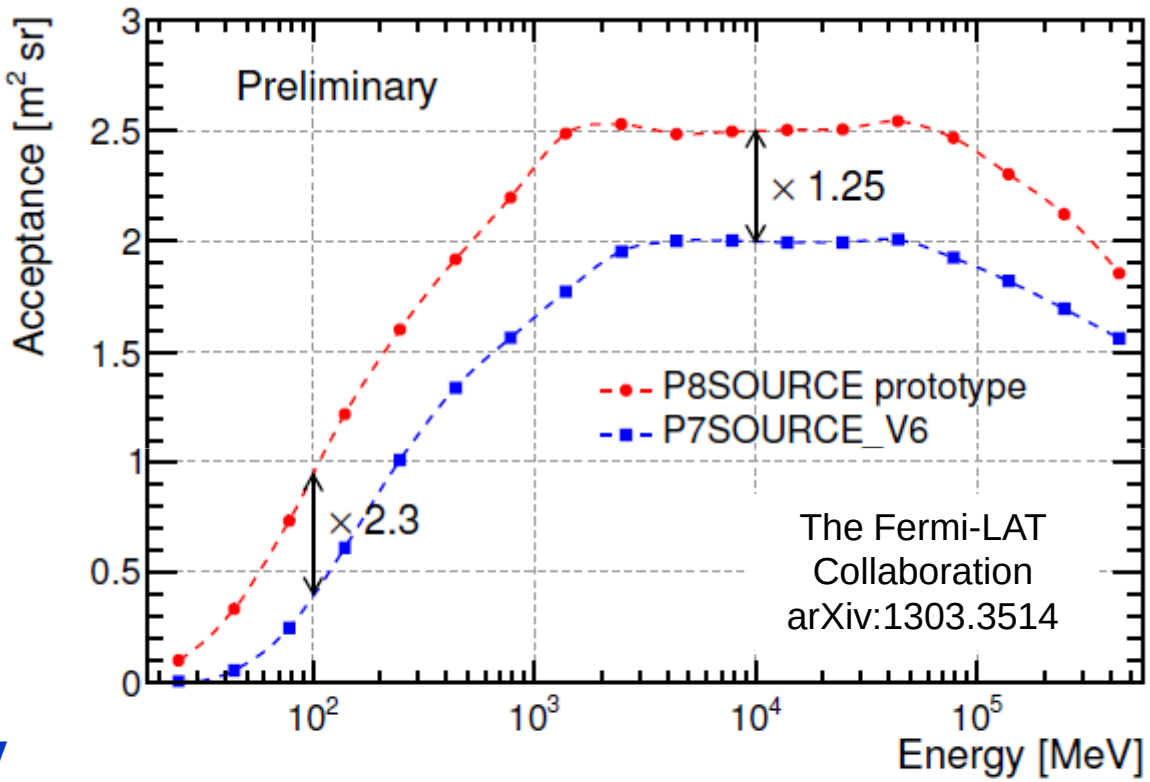






Upcoming Developments -- Pass 8

- **Improvements to LAT performance**
  - **Increased energy range**
  - **Increased effective area**
  - **Improved angular resolution**
  - **Better bkg rejection**
  - **New event classes**
- **Impacts for DM searches**
  - **Explore new high-mass parameter space**
  - **Increased flux sensitivity**
  - **Greater sensitivity to spatially extended sources**
  - **Better handle of systematics**

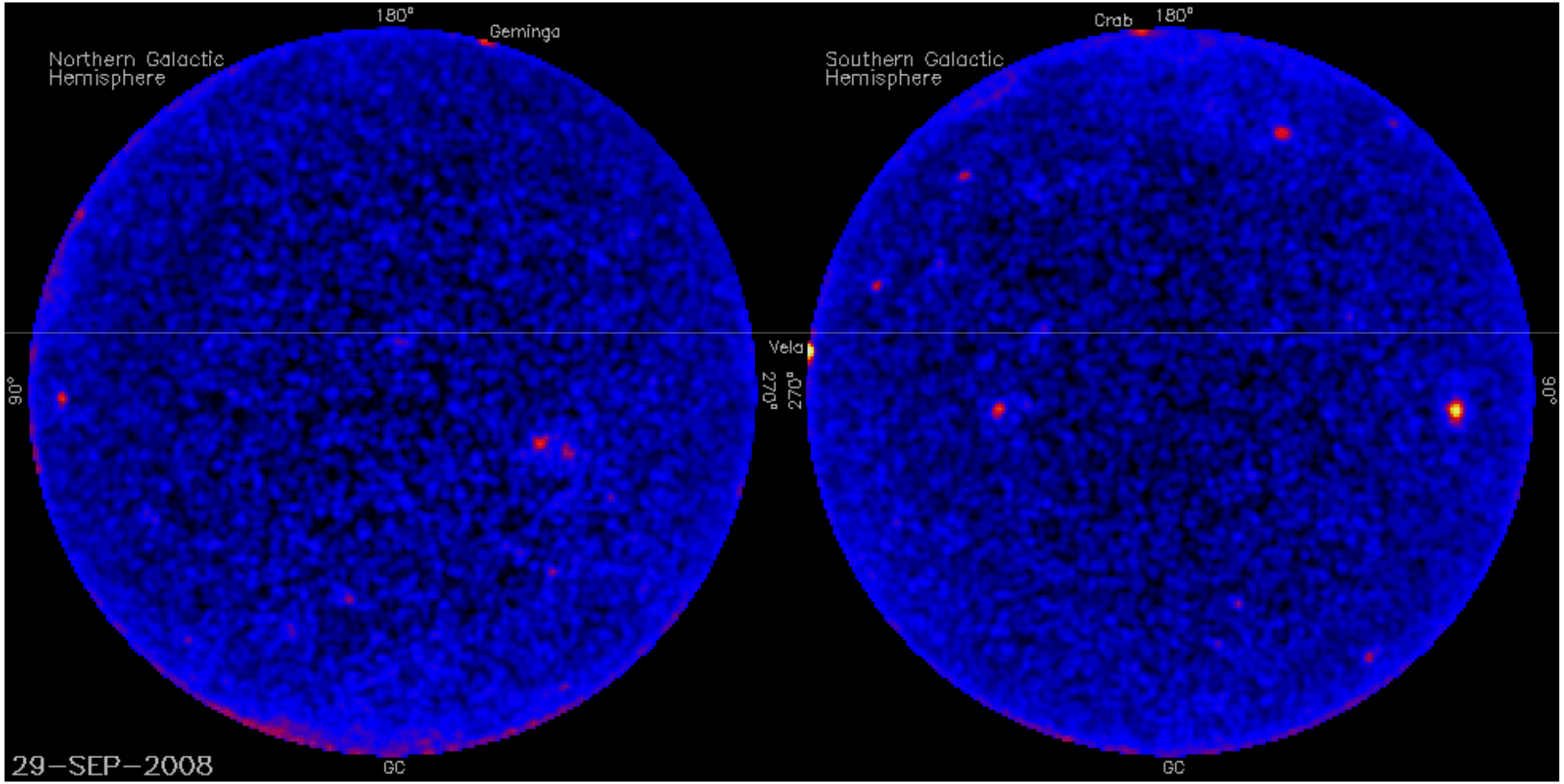


5 Decades in Energy (3 TeV)

Outline

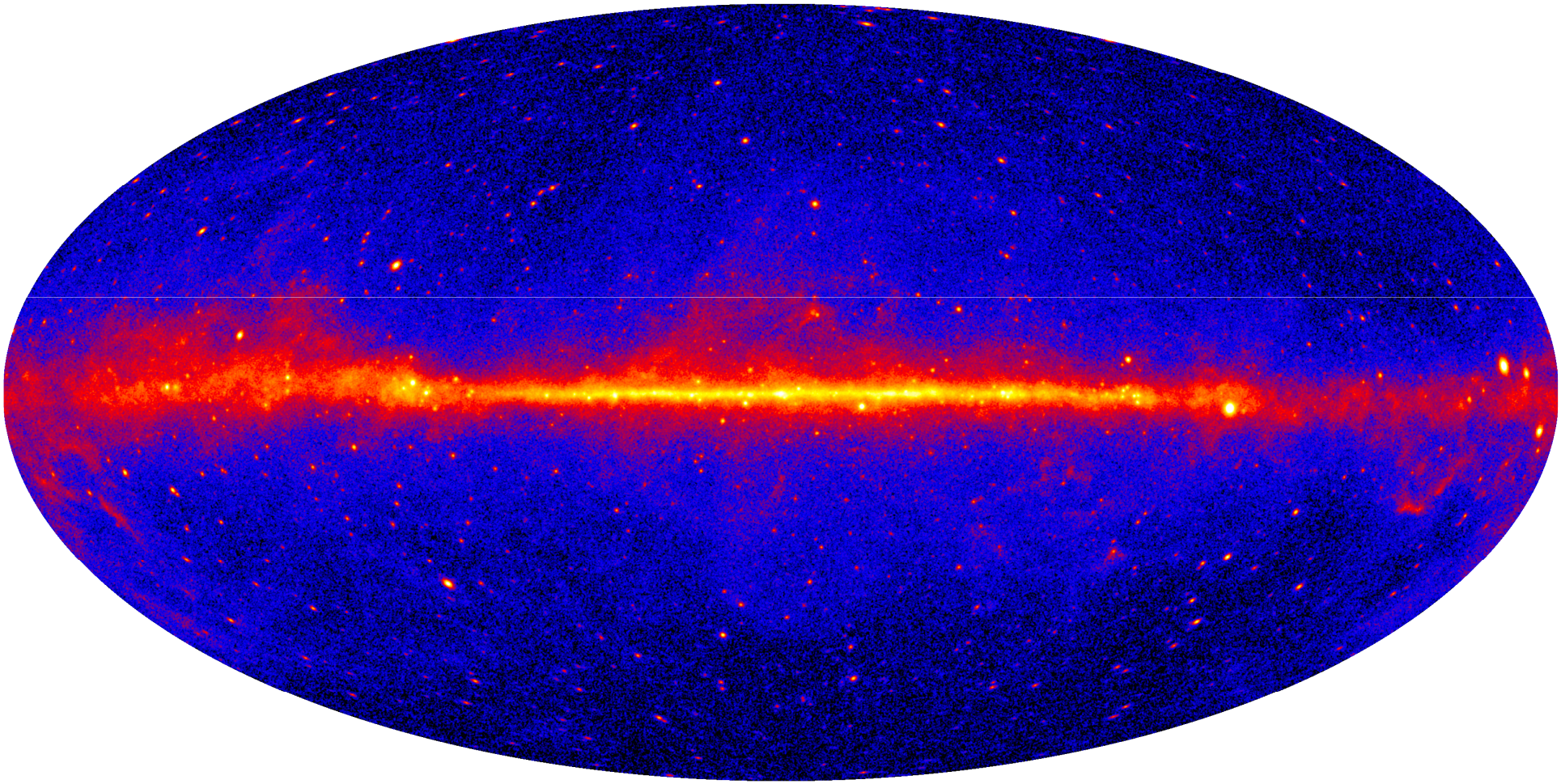
- Dark Matter Overview
- **The Fermi Large Area Telescope**
  - **The Gamma-ray Sky**
- Recent Dark Matter Results
  - Lines
  - Galactic Center
  - Dwarfs

Daily Gamma-ray Sky



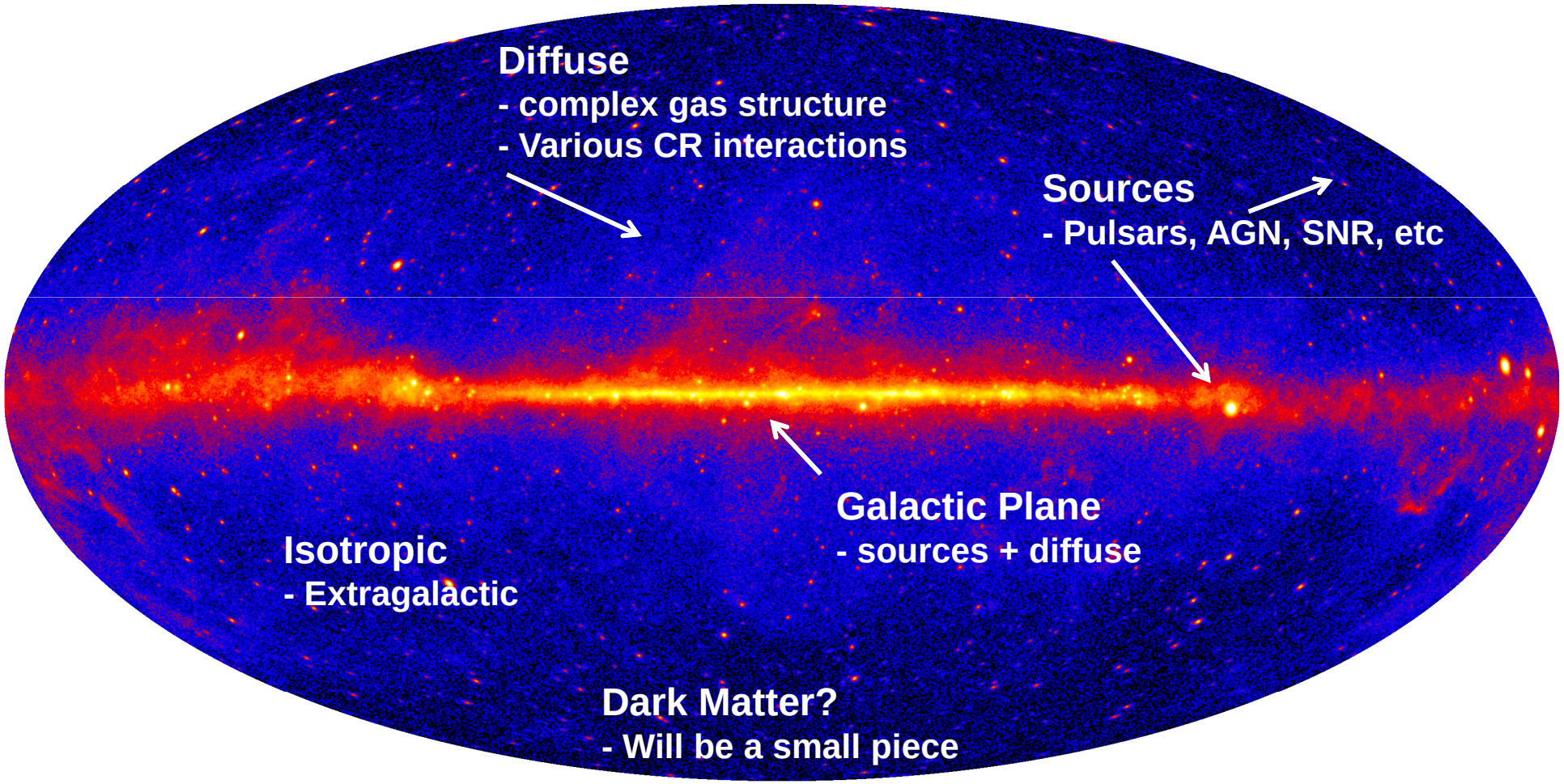
Fermi LAT Gamma-ray Sky

4 year all sky map (E > 1 GeV)



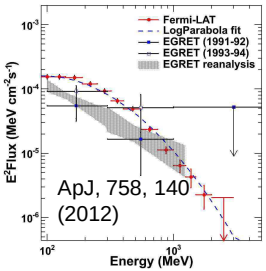
Fermi LAT Gamma-ray Sky

Nature has given us a rich and complicated gamma-ray sky!

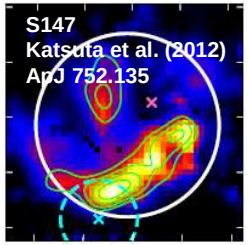


Fermi Gamma-ray Space Telescope Science

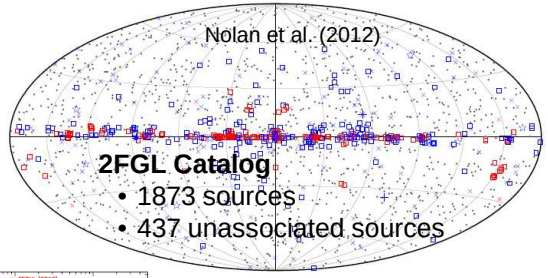
One person's background is another person's source!

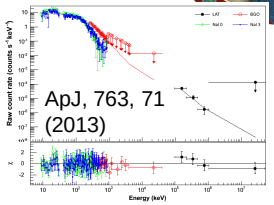


Lunar Gamma rays
- CR hitting surface
- Correlated w/ solar activity

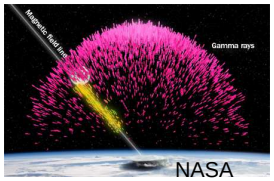


Supernova Remnants
- 25 published SNR + 30 cands in 2FGL
- Multiwavelength objects
- Require good diffuse emission modeling

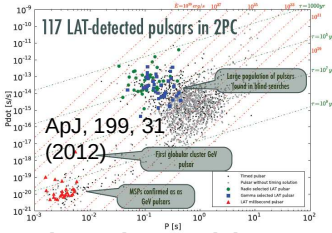




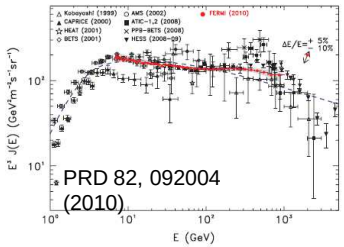
Gamma-ray Bursts
- 35 LAT, 1000+ GBM
- GBM + LAT spectra



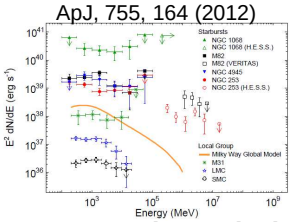
Terrestrial Gamma-ray Flashes
- Associated w/ thunderstorms
- Observed by GBM & LAT



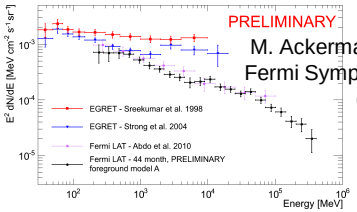
Pulsars (e.g. Vela)
- 117 Fermi-LAT det. pulsars
- Multiwavelength objects
- PSR J2021+4026 shows variablilty



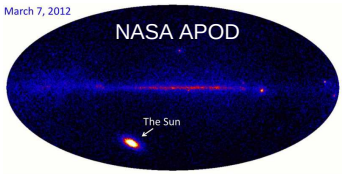
e^-e^+ Energy Spectrum
- LAT can measure e's too
- board high-energy excess



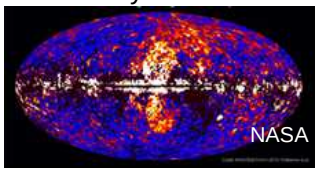
Star-Forming Galaxies
- LAT has seen 7
- Potential LAT-CTA synergy



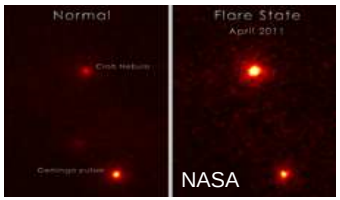
Extragalactic bkg
- Spectrum from 0.2-410 GeV
- Ainsotropy →population info



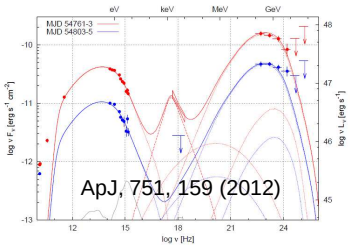
Solar Flares
- Observed by GBM & LAT
- X-class Flare on March 7th, 2012



Fermi Bubbles
- Unexpected high-energy excess lobes



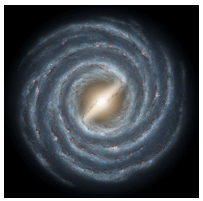
Pulsar Wind Nebula (e.g. Crab)
- 15 candidates found by LAT
- Multiwavelength objects



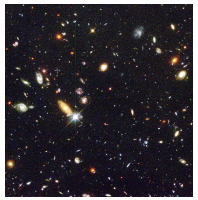
Blazars
- Largest population of LAT known sources
- PKS 1424+240 is harder than expected
- Multiwavelength objects

Solar System

Galactic



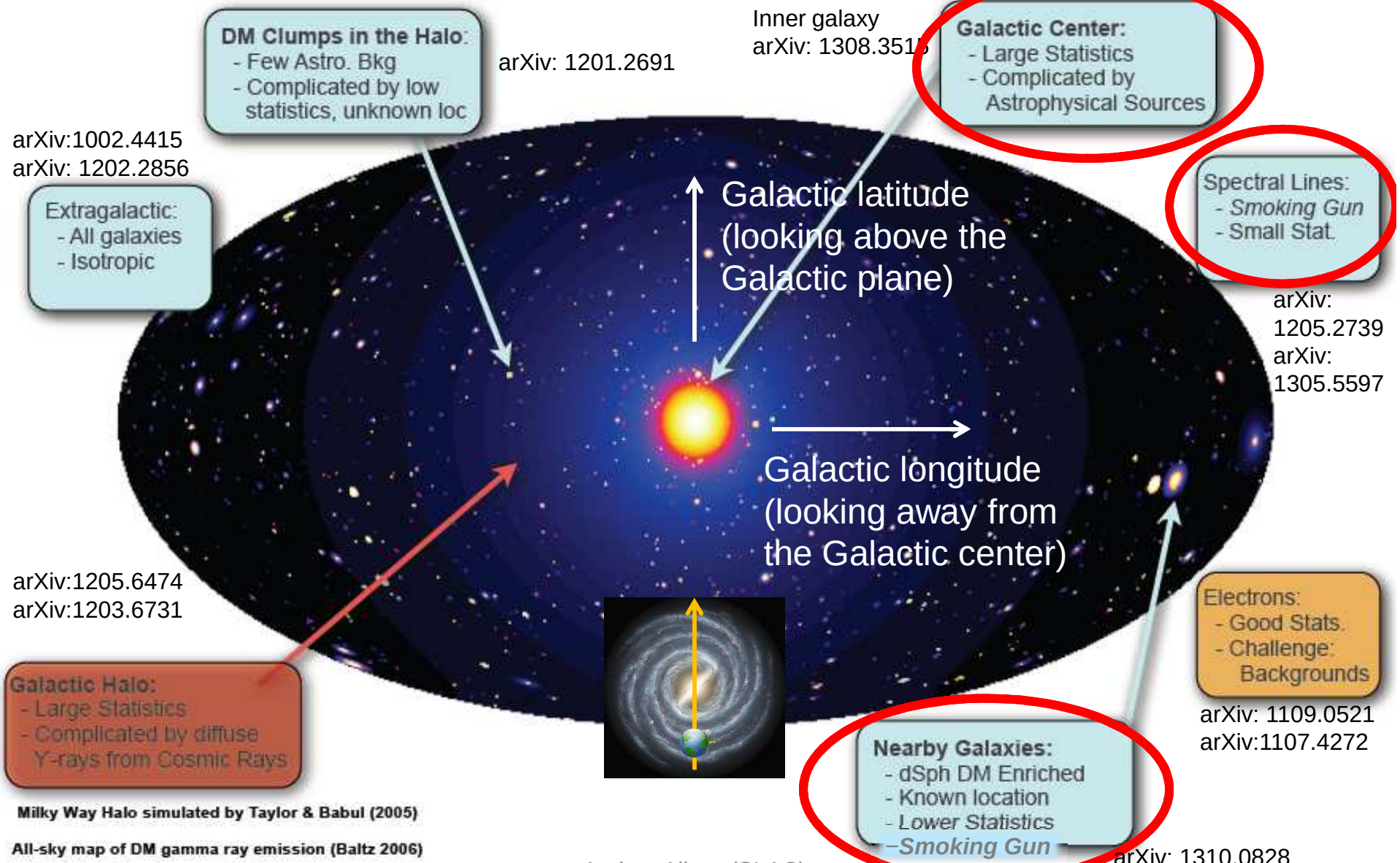
Extragalactic



Outline

- Dark Matter Overview
- The Fermi Large Area Telescope
  - The Gamma-ray Sky
- **Recent Dark Matter Results**
  - Lines
  - Galactic Center
  - Dwarfs

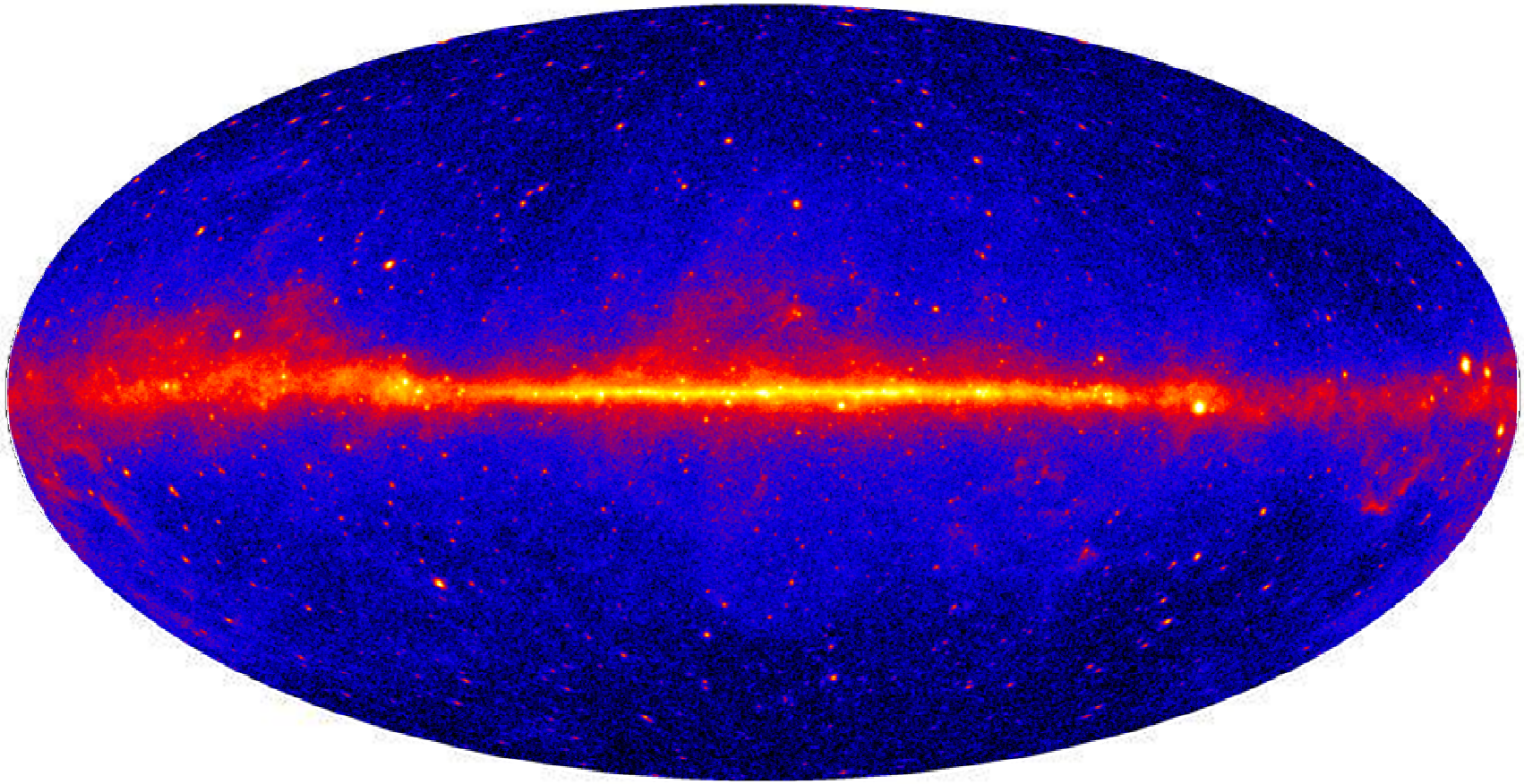
Galactic Distribution of DM



Milky Way Halo simulated by Taylor & Babul (2005)

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

Large Astrophysical Background



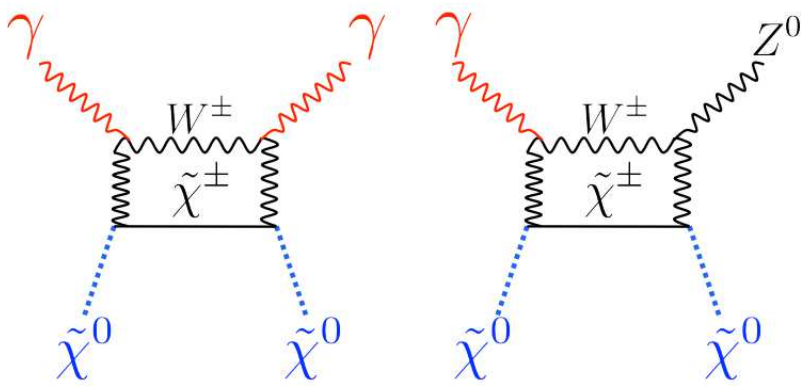
Milky Way Halo simulated by Taylor & Babul (2005)
All-sky map of DM gamma-ray emission (Baltz 2006)

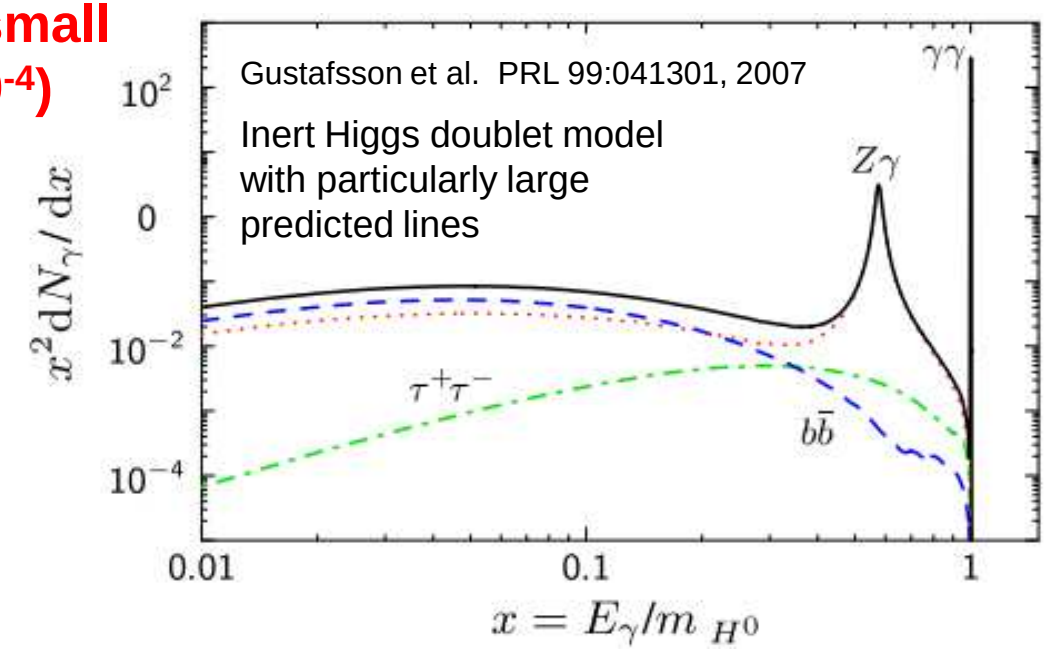
Outline

- Dark Matter Overview
- The Fermi Large Area Telescope
  - The Gamma-ray Sky
- **Recent Dark Matter Results**
  - **Lines**
  - Galactic Center
  - Dwarfs

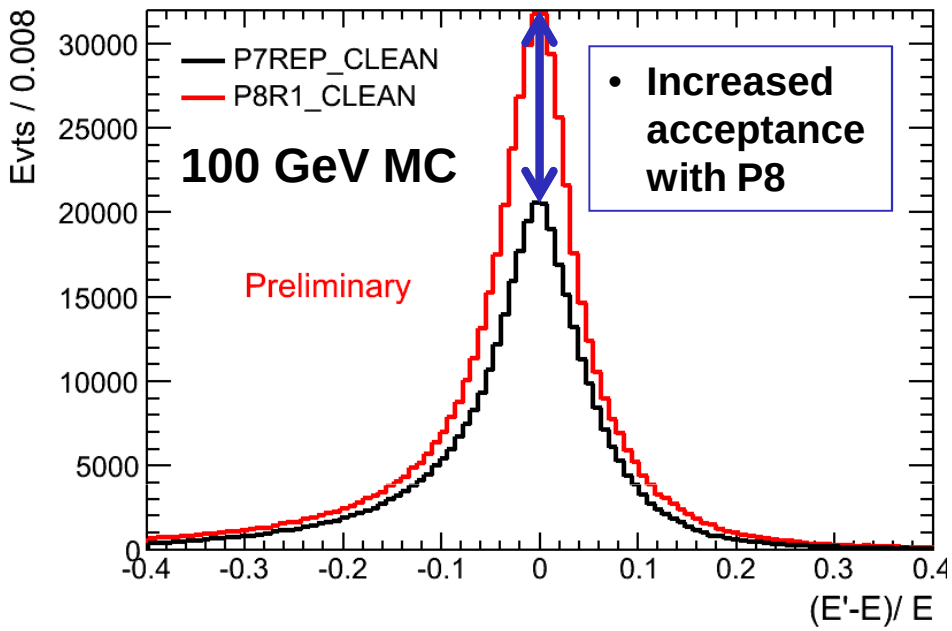
Spectral Lines from WIMP annihilations

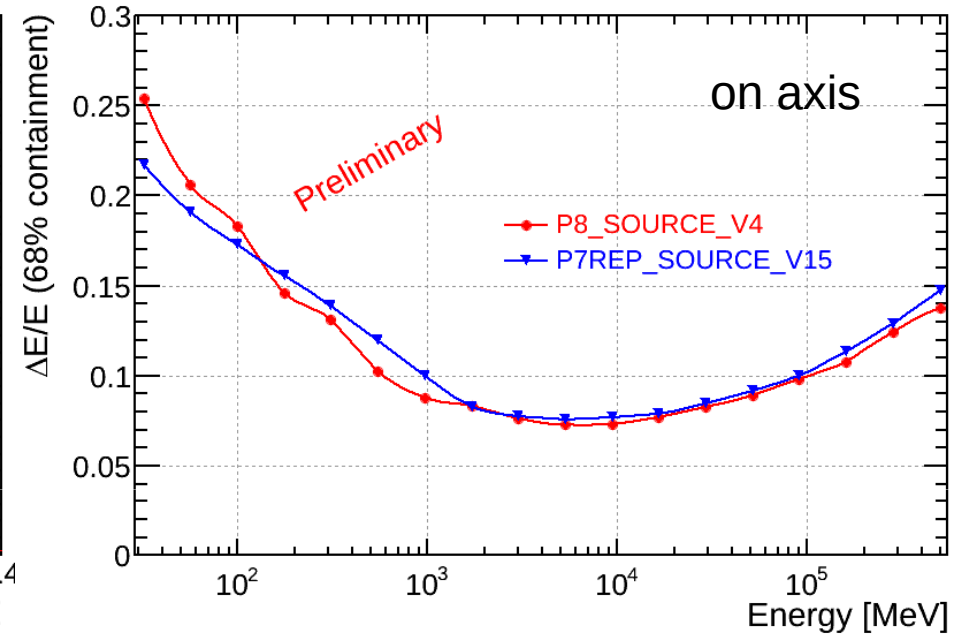
- **Weakly Interacting Massive Particles (WIMPs) are a promising dark matter candidate**
- **WIMP annihilations in the Universe may produce gamma rays detectable by the Fermi Large Area Telescope (LAT)**
- **$\chi\chi \rightarrow \gamma\gamma$, γZ^0, γH^0 would produce a narrow feature**
  - **Sharp, distinct spectral feature ("smoking gun")**
  - **Likely a small branching fraction**
    - **Signal predicted to be small (b.f. typically ~10^{-2} to 10^{-4})**





Pass 8 Improvements Relevant for Line Search

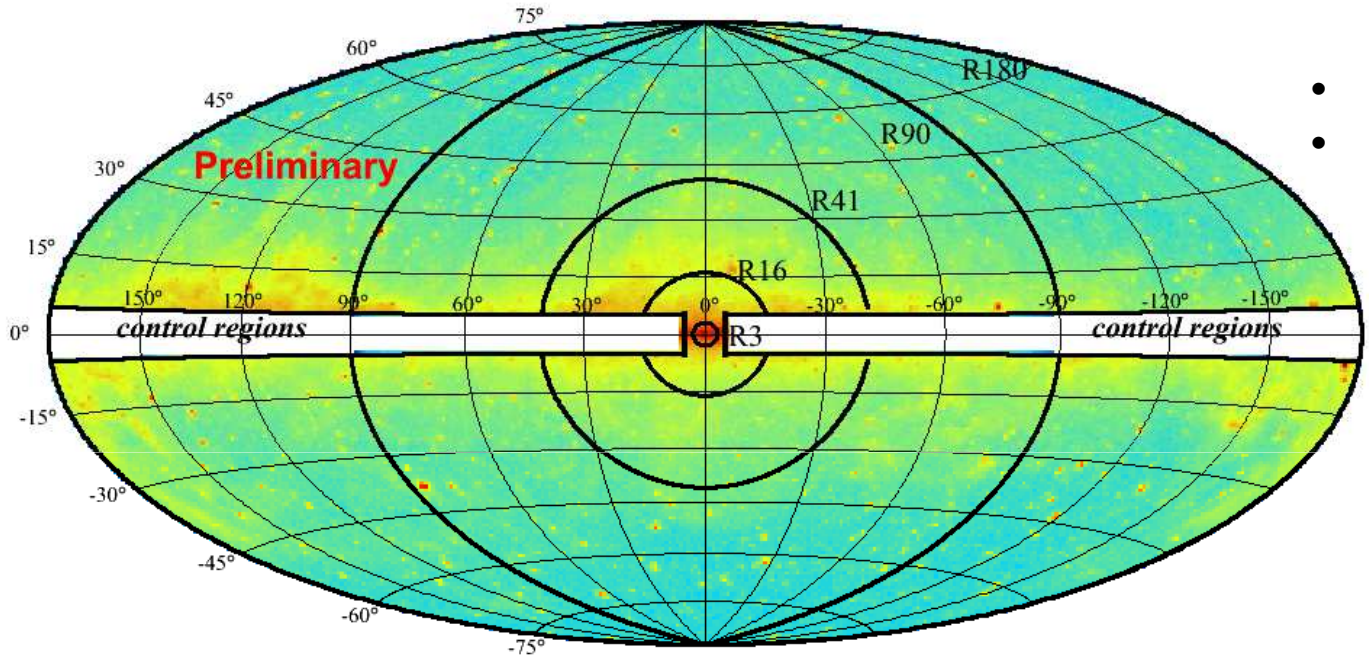




- **Improved energy reconstruction in Pass 8**
  - **Energy recon. above ~1 GeV optimized with better modeling of calorimeter shower (e.g. improve handling of gaps between modules and crystal saturation)**
  - **Increased effective area with equivalent energy resolution**
- **Event reconstruction and selection classes are new in P8**
  - **Pass 8 is a new "lens" we can view lines through**
    - **Important check for tentative 133 GeV feature**

Search for Spectral Lines with Pass 8

5.8 year Counts Map



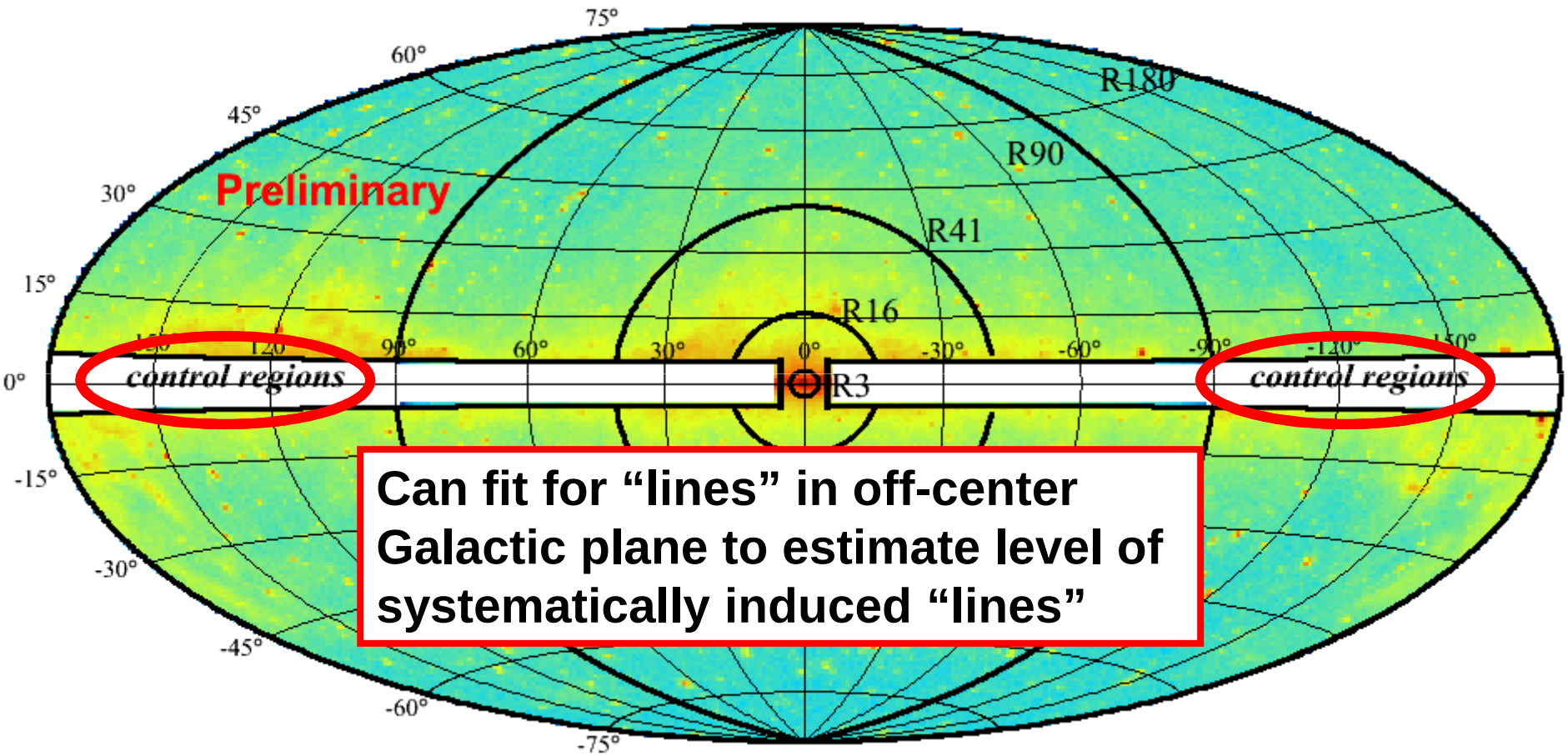
- R3 (contracted NFW, no src masking)
- R16 (Einasto)
- R41 (NFW)
  - R90 (Isothermal)
  - R180 (DM Decay)

ROI optimization motivated by Bringmann et al 2012 (arXiv:1203.1312) and Weniger 2012 (arXiv:1204.2797)

- **Search for lines from 200 MeV – 500 GeV using 5.8 years of data**
  - **Maximum likelihood fit with improved energy dispersion model**
- **Use same 5 ROIs as 3.7 year search**
  - **Ackerman et al. (The Fermi LAT Col.) PRD 88, 082002 (2013)**
- **Use P8_CLEAN event selection**
  - **Clean cuts are recommended for faint diffuse emission analysis**

Search for Spectral Lines with Pass 8

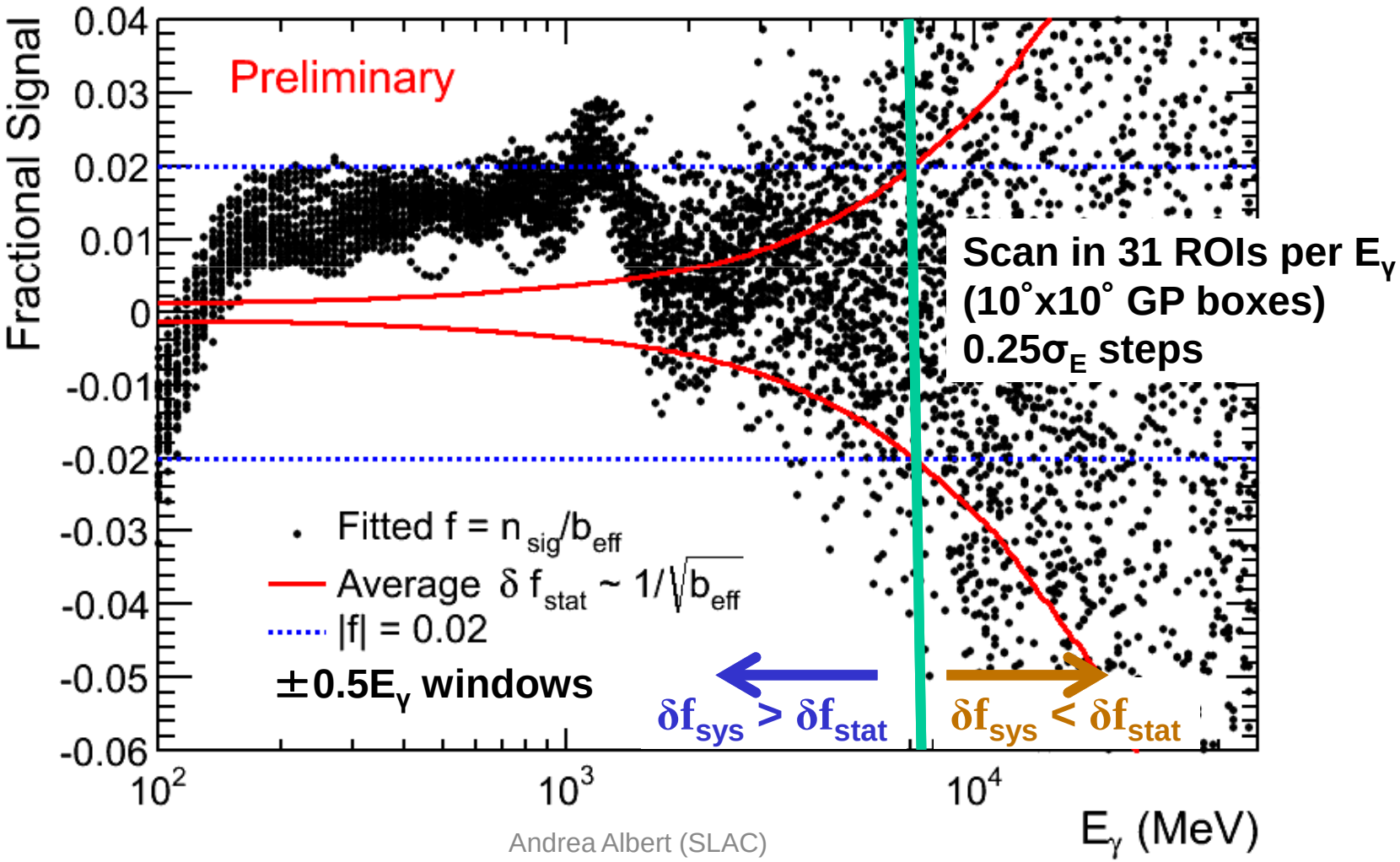
5.8 year Counts Map



Can fit for "lines" in off-center Galactic plane to estimate level of systematically induced "lines"

Pass 8 Line Search
f_{sys} from Galactic Plane Scans

- **There are some common features likely from the effective area (A_{eff})**
- **Displacement from 0 is mostly from A_{eff}, while spread is from bkg. modeling**
- **Larger systematic effect with wider windows (since power-law approx. gets worse)**



P8 Line Search
Accounting for f_{sys} in Likelihood

- **Search with 5.8 years of P8 Clean data for lines from 200 MeV < E_γ < 500 GeV**
  - **Use $\pm 0.5\ E_\gamma$ fit windows to optimize at low energies (where systematic limited) and high energies (where statistical limited)**
- **Include nuisance parameter (n_{sys}) for systematically-induced line-like features**
  - **Only detect a significant line if larger than the line-like features we see in the control regions**
  - **Introduced method in low-energy line paper (A. Albert et al. JCAP10(2014)023)**
  - **Similar technique used to incorporate J-factor uncertainties dSph analysis**
    - **Can be applied whenever accounting for systematic uncertainties is important**

$$C(E,\vec{\alpha}) = \left((n_{sig} + n_{sys})S(E,E_\gamma) + n_{bkg}B(E,\Gamma_{bkg})\right) * G_{sys}$$

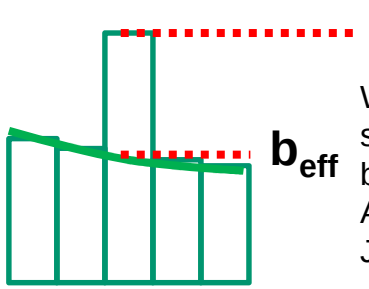
$$\sigma_{sys} = \delta f_{sys} * b_{eff}$$

$$G_{sys} = \frac{1}{\sigma_{sys}\sqrt{2\pi}} e^{-n_{sys}^2/2\sigma_{sys}^2}$$

Gaussian constraint on n_{sys}

n_{sys} is constrained using δf_{sys} estimated with control regions

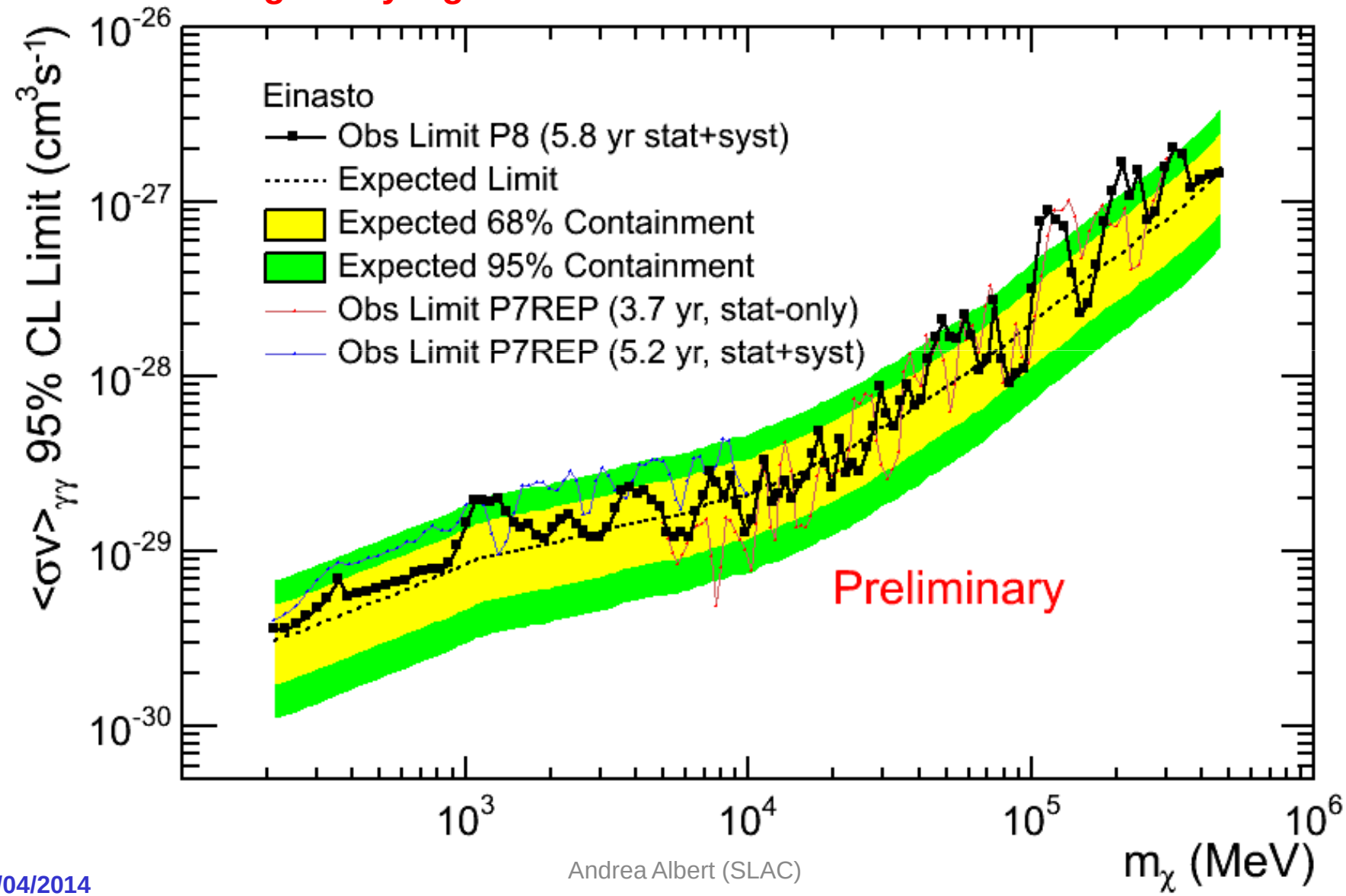
$$f = \frac{n_{sig}}{b_{eff}} \approx \frac{TS}{n_{sig}}$$



Warning: cartoon, see paper for full b_{eff} definition A. Albert et al. JCAP10(2014)023

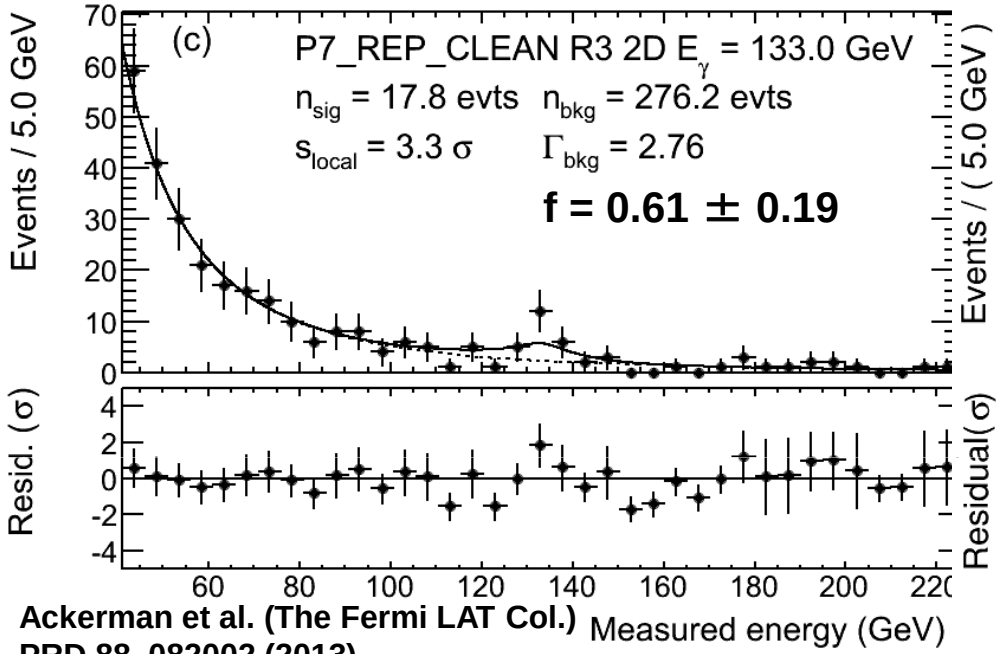
Spectral Line 95% CL Upper Limit R16

- **No globally significant lines found**



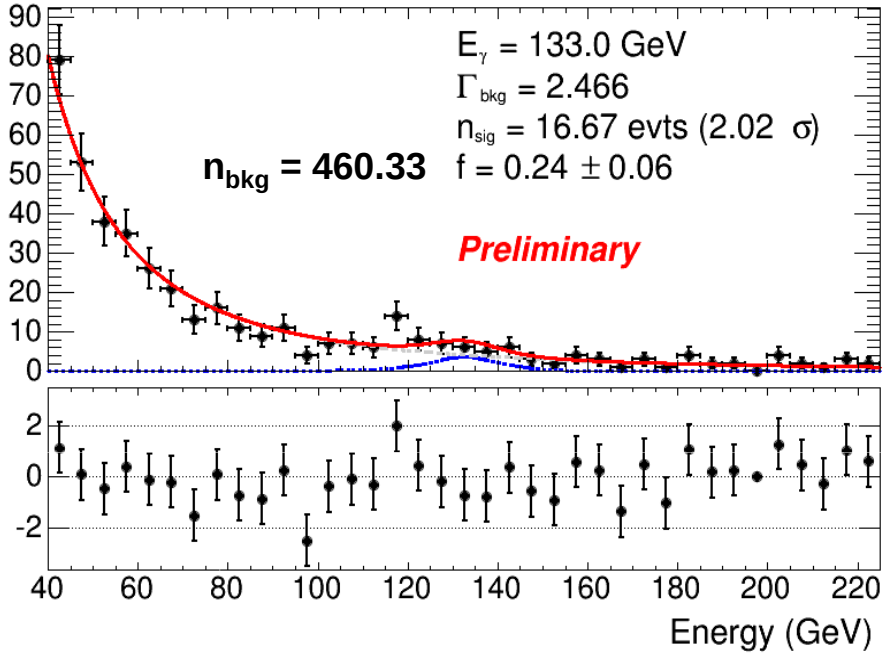
Line-like Feature Near 133 GeV – 3.7 year

P7REP_Clean



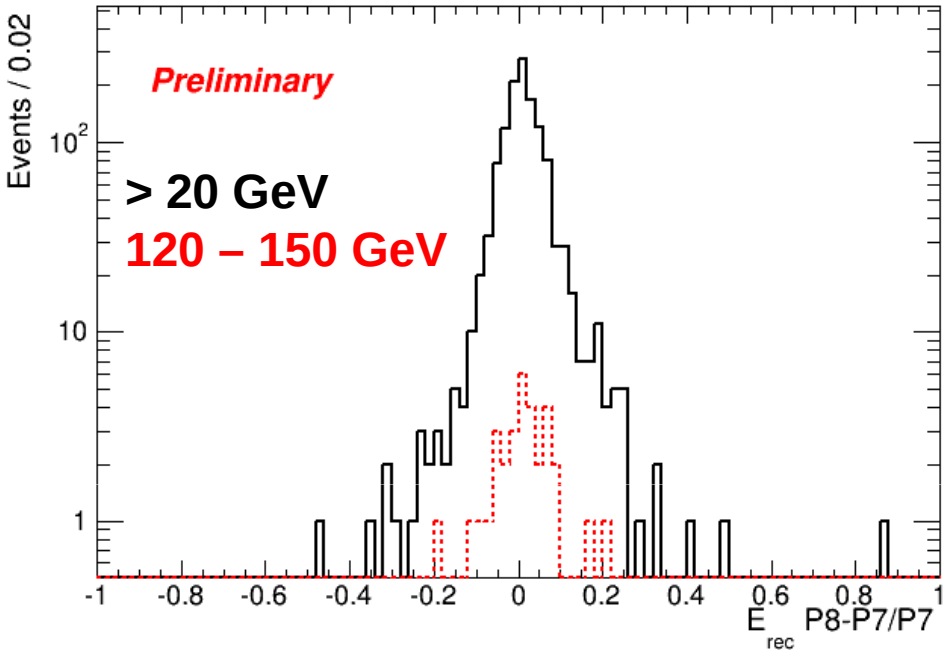
Ackerman et al. (The Fermi LAT Col.) PRD 88, 082002 (2013)

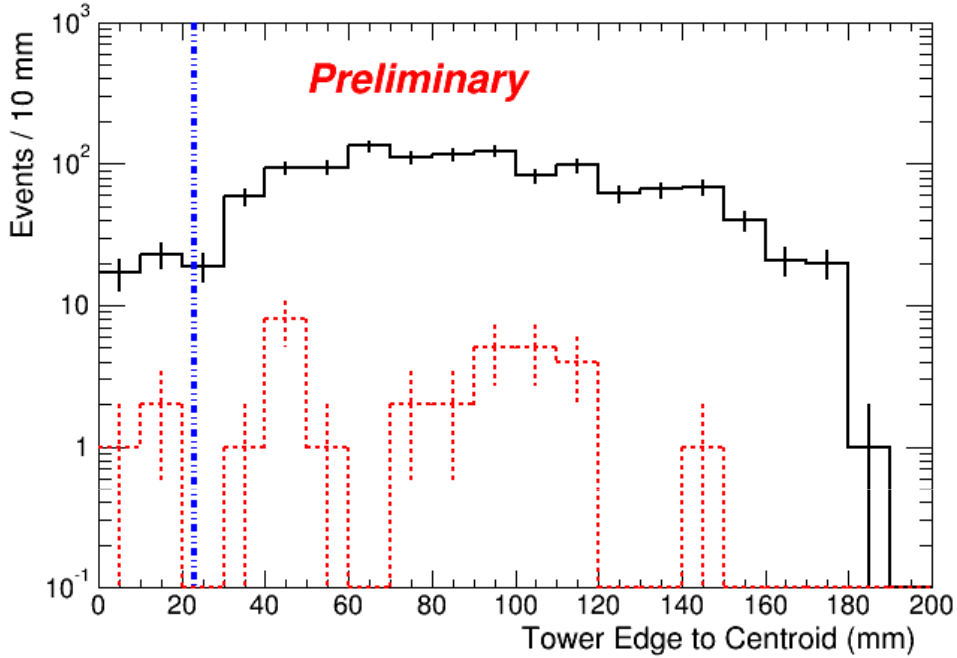
P8_Clean



- **Same fit parameters as 3.7 year line search (Ackerman et al. PRD 88, 082002 (2013))**
  - **Fits in R3, 3.7 year, $\pm 6\sigma_E$ fit window**
- **No strong evidence of 133 GeV Feature in Pass 8**
  - **Lower fractional size and significance**
  - **Energy recon. in P7 vs. P8 changes within expected energy resolution**

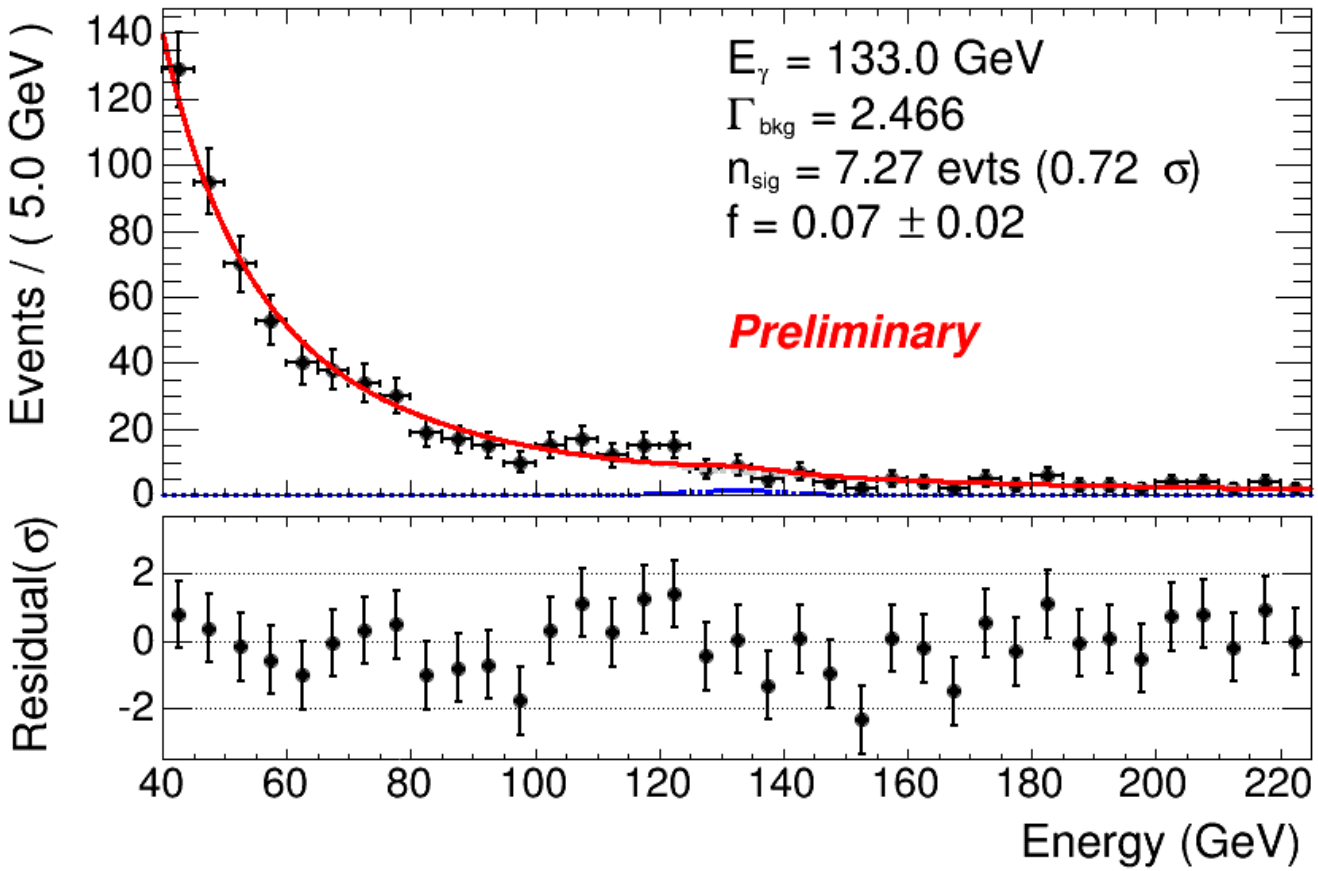
Event Level Investigation Near 133 GeV





- **5.8 year datasets, R3, look at events in both P7REP and P8 Clean**
- **Energy shift from P7REP -> P8 similar near 133 GeV as all event > 20 GeV**
  - **Nothing unique happening at near 133 GeV**
  - **Energy recon. in P7 vs. P8 changes within expected energy resolution**
    - **(gaussian with width ~0.07)**
- **Slight enhancement near 133 GeV where centroid of energy in CAL near tower edge**
  - **These are tricky events to reconstruct since edges of shower lost in gaps**

Line-like Feature Near 133 GeV – 5.8 yr

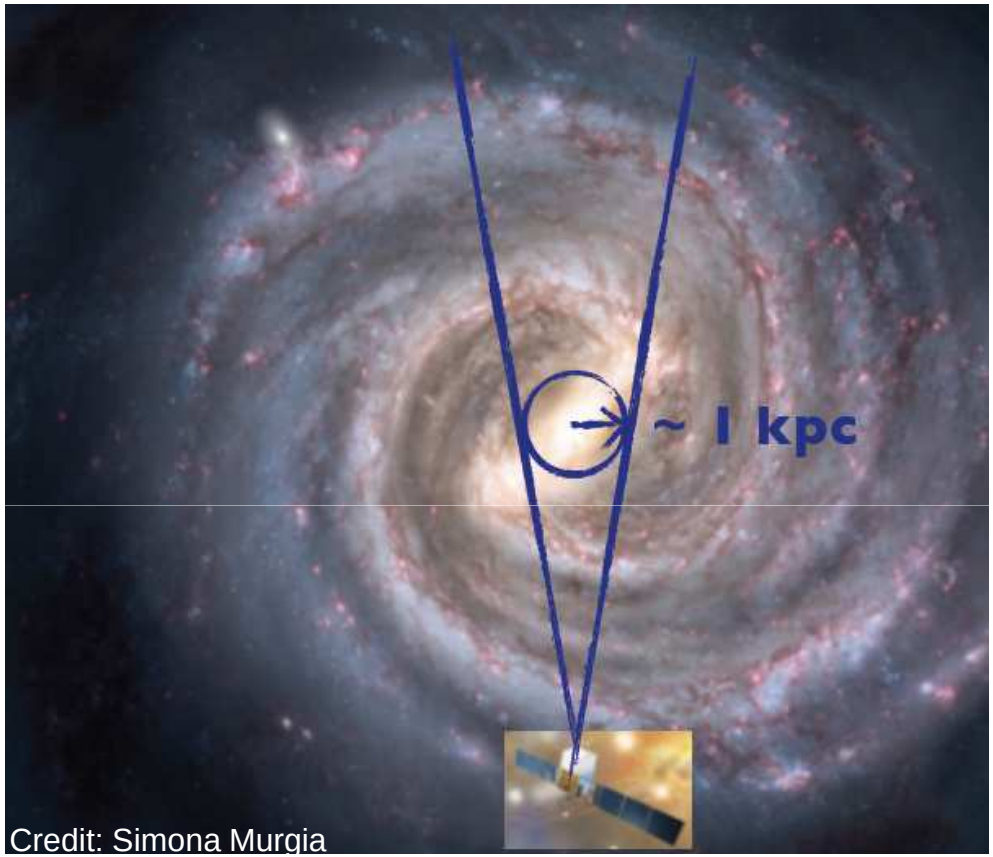


- **Feature is even smaller in 5.8 year P8 Clean dataset**
  - **Consistent with statistical fluctuation in P7 REP 3.7 year dataset**

Outline

- Dark Matter Overview
- The Fermi Large Area Telescope
  - The Gamma-ray Sky
- **Recent Dark Matter Results**
  - Lines
  - **Galactic Center**
  - Dwarfs

The Galactic Center is Really Complicated!



Credit: Simona Murgia

- Focus on 15º x 15º region (~ 1 kpc)
- 1-100 GeV, P7REP Clean, Front-converting
- 62 months
- Significant fore/background emission
- Complex diffuse emission from CR interactions with radiation fields, gas, etc
- Large density of gamma-ray sources that are hard to disentangle from interstellar emission

- LAT team presented preliminary results on a general characterization of the gamma-ray emission in this region
  - Not a DM-focused search
  - Mine is an incomplete, biased summary of a very complex analysis

The Galactic Center is Really Complicated!

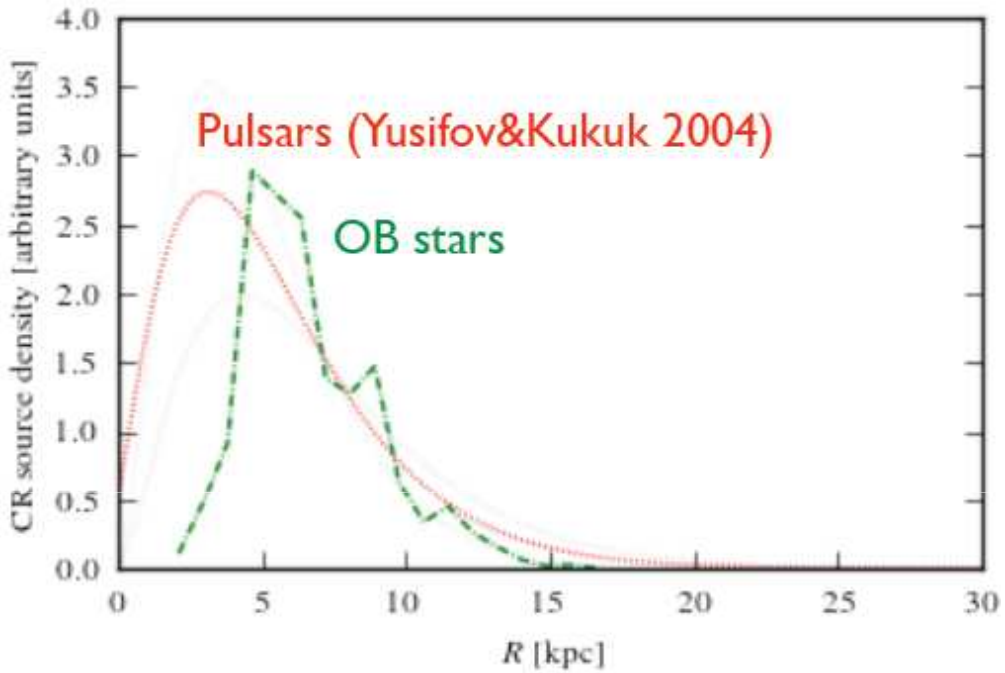
Inner Galaxy publication is in progress
For more details see Murgia and Porter's presentation at the 5th Fermi Symposium

- **Focus on 15º x 15º region (~ 1 kpc)**
- **1-100 GeV, P7REP Clean, Front-converting**
- **62 months**
- **ificant fore/background**
- **n**
- **fields, g**
- **Large density of gam sources that are hard to disentangle from interstellar emission**

- **LAT team presented preliminary results on a general characterization of the gamma-ray emission in this region**
  - **Not a DM-focused search**
  - **Mine is an incomplete, biased summary of a very complex analysis**

Fore/Background Tuning Procedure (1)

- **2 models for CR source distribution**
  - **Pulsars**
  - **OB stars**
- **Use GALPROP to model π^0 and IC in Galactocentric rings**
  - **Tune isotropic, Loop I for each model**
  - **3FGL held constant for tuning**

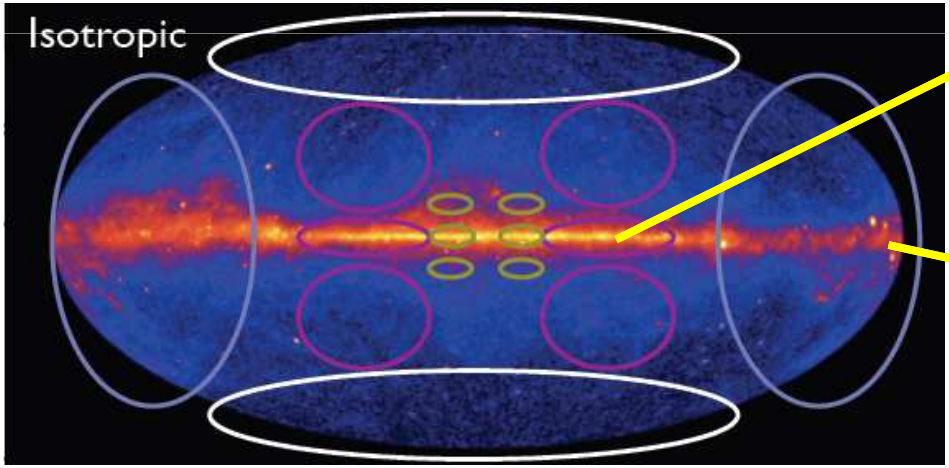


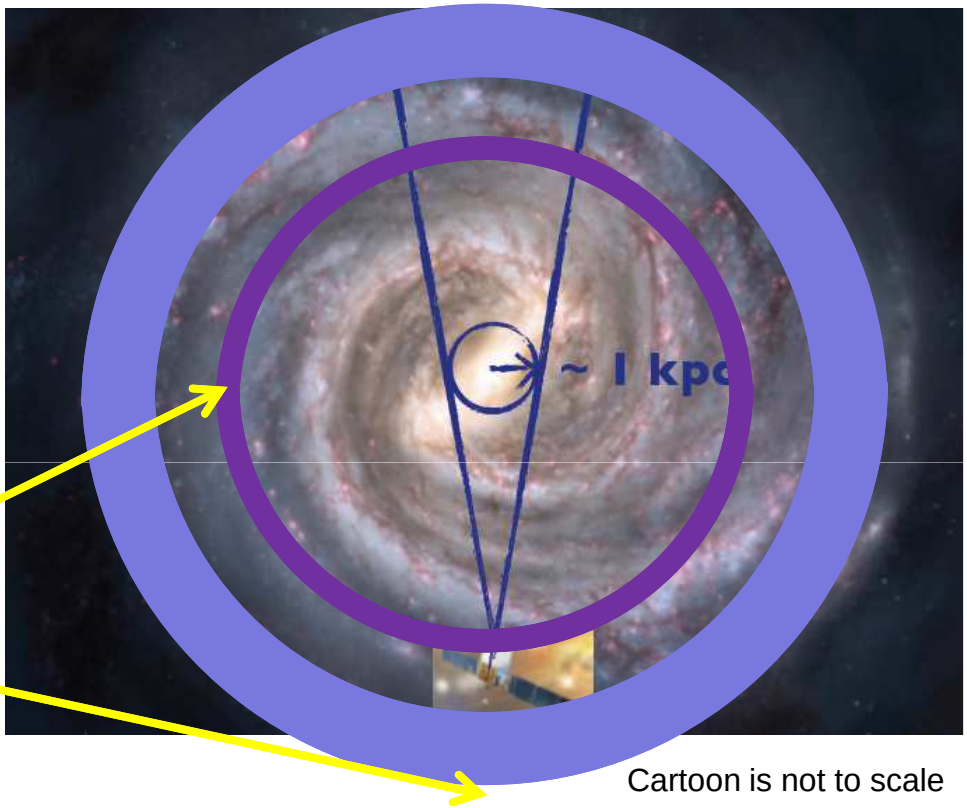
- **Tune from outside in excluding GC with 2 procedures**
  - **adjust intensity only**
  - **adjust intensity *and* spectrum (allow π^0 spectrum to be a broken power law (break at ~2GeV) inside local circle)**
- **4 models in total**
  - **CR src = {Pulsar, OB stars}, {tuned intensity, tuned index}**

Fore/Background Tuning Procedure (2)

Galactocentric ring boundaries.

Ring #	R_{min} [kpc]	R_{max} [kpc]	Longitude Range (Full)
1	0	1.5	$-10° \leq l \leq 10°$
2	1.5	2.5	$-17° \leq l \leq 17°$
3	2.5	3.5	$-24° < l < 24°$
4	3.5	8.0	$-70° < l < 70°$
5	8.0	10.0	$-180 \leq l \leq 180°$
6	10.0	50.0	$-180 \leq l \leq 180°$



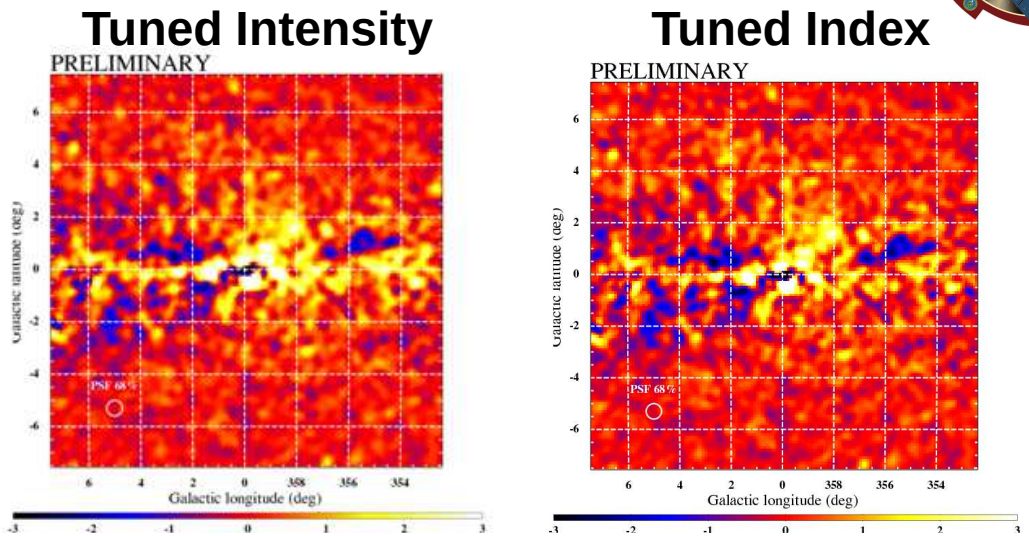


Cartoon is not to scale

- **Tune from outside -> inside excluding GC**
- **Select regions where the ring we're trying to constrain dominates**

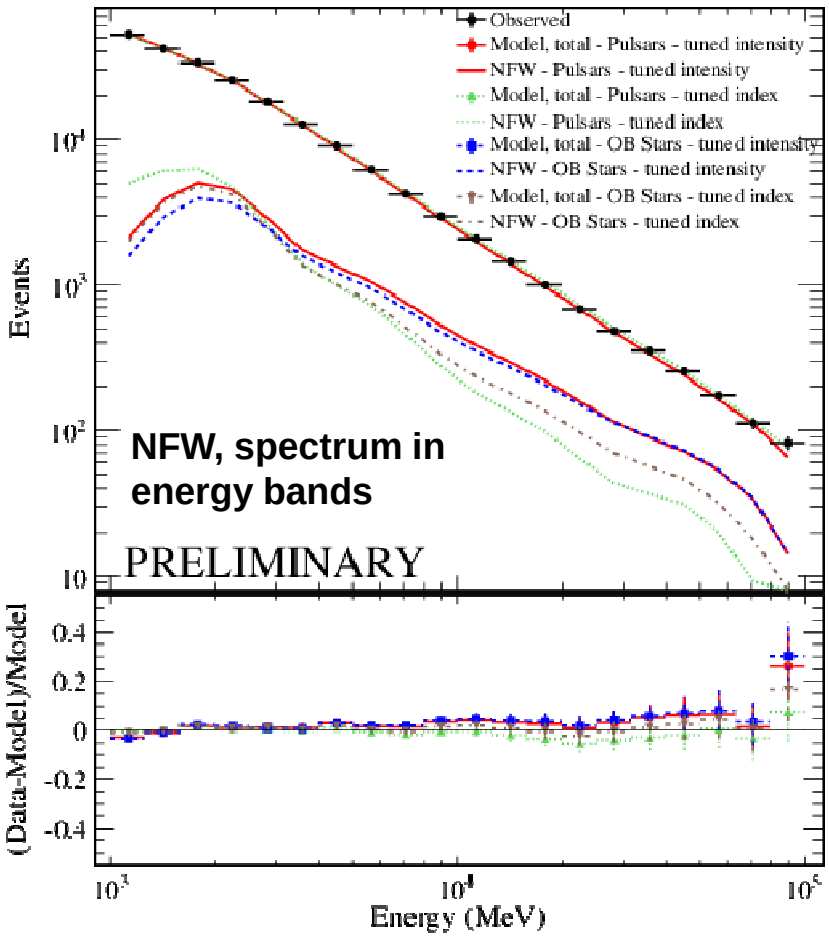
Modeling the Emission in the 15º x 15º ROI

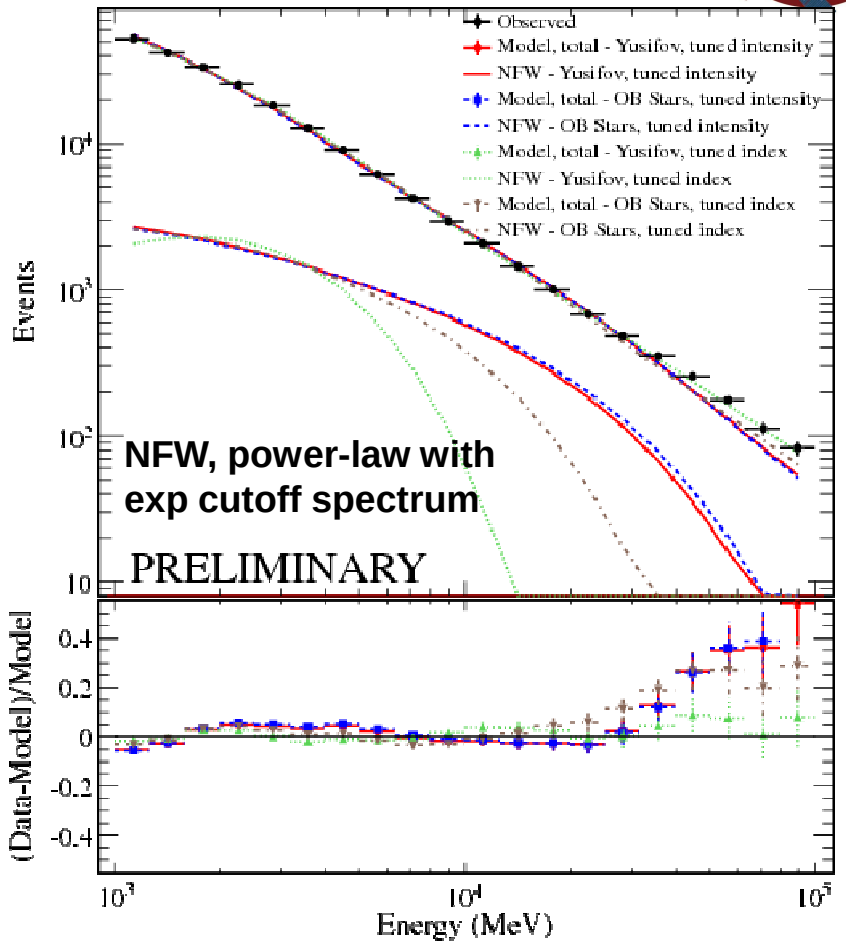
Residual maps from 2-10 GeV for CR Pulsar models



- **Separate modeling for each of the 4 fore/background models**
  - **i.e. point source candidates (TS > 9) in region determined from scratch for *each model***
- **Intensities for π^0 and IC in innermost ring fit using appropriate pt src candidates**
  - **fore/background model assumed is held fixed**
  - **IC emission in GC (ring 1) is larger (~7-30x) than pre-tuned GALPROP baseline model**
    - **Possibly from higher ISRF and/or higher CR lepton intensities in the GC than originally assumed**
    - **Only ~4-15x larger when including NFW template (see next slide)**
      - **π^0 HI component is about ~2x larger with NFW template in fit than without**
- **An excess peaking around a few GeV is seen in all 4 fore/background models**
  - **Morphology & spectrum of excess is strongly dependent on fore/background model**

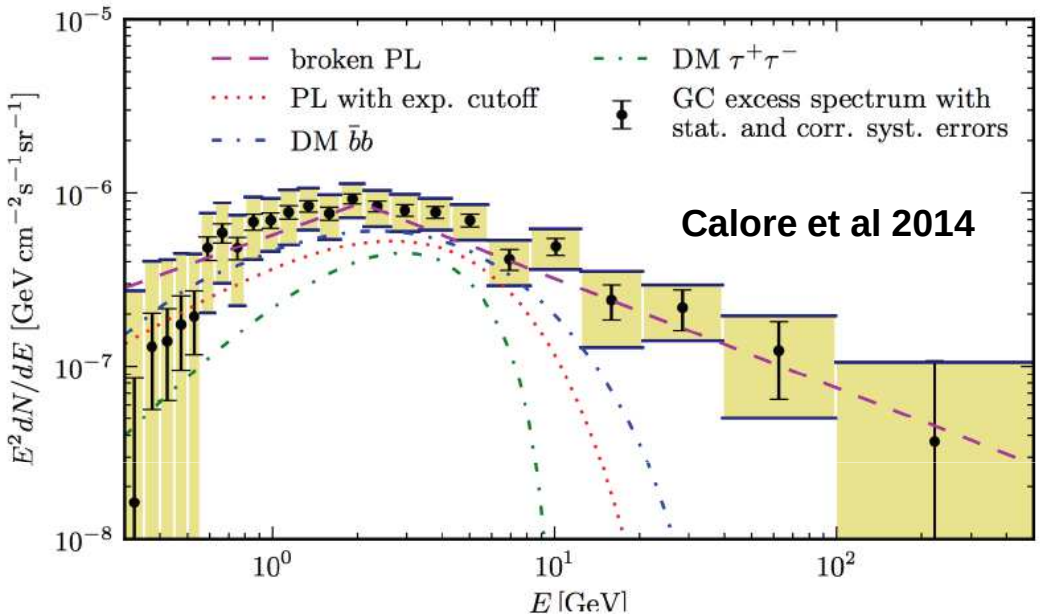
Spectrum of Excess Assuming NFW Template

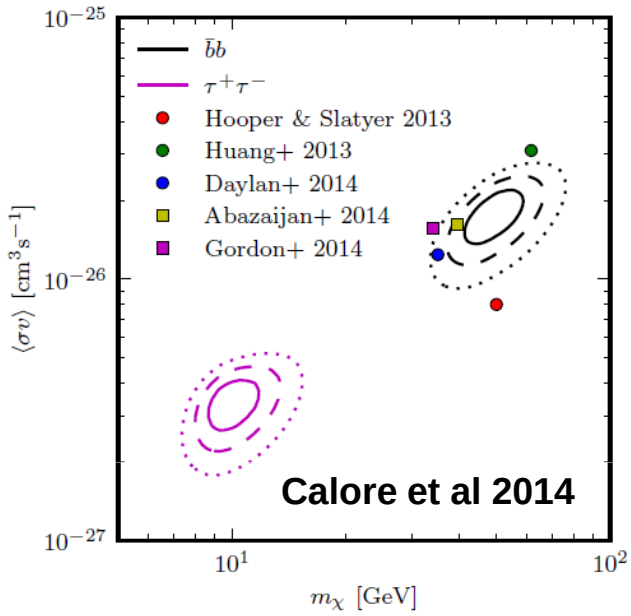




- **Include additional component in fit with an NFW template**
  - **Tried various additional templates, but NFW performed best**
- **Spectrum of emission in NFW model strongly dependent on fore/background models**

What is Causing this Extra High-energy Emission? (1)

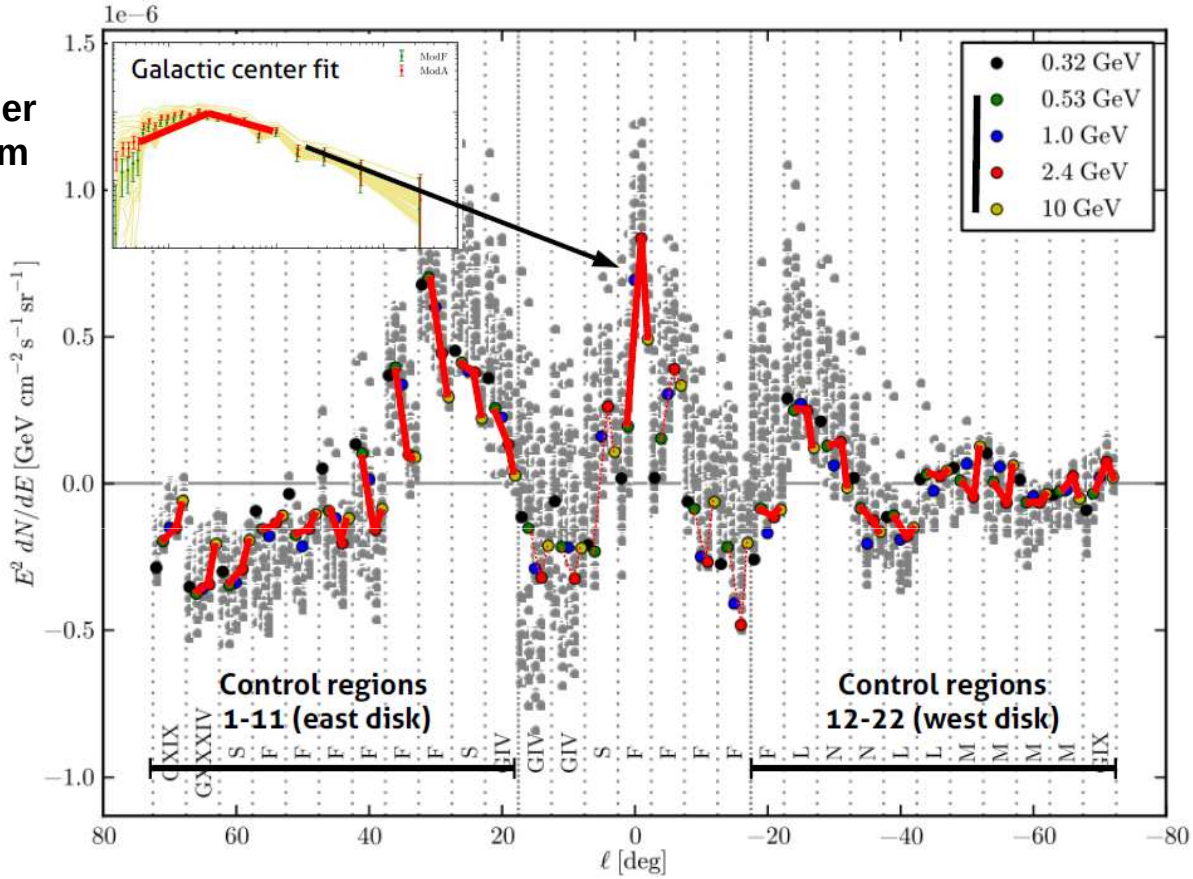




- **Many groups have found a similar excess in the GC and interpreted as gamma rays from DM annihilation**
  - **Expect brightest DM signal from the GC, but modeling other astrophysical components is tricky**
- **Regardless of what it is, any new high-energy gamma-ray source is exciting!**
  - **Much more study is needed to better understand the spectrum and morphology**

What is Causing this Extra High-energy Emission? (2)

Pic credit: C. Weniger
5th Fermi Symposium



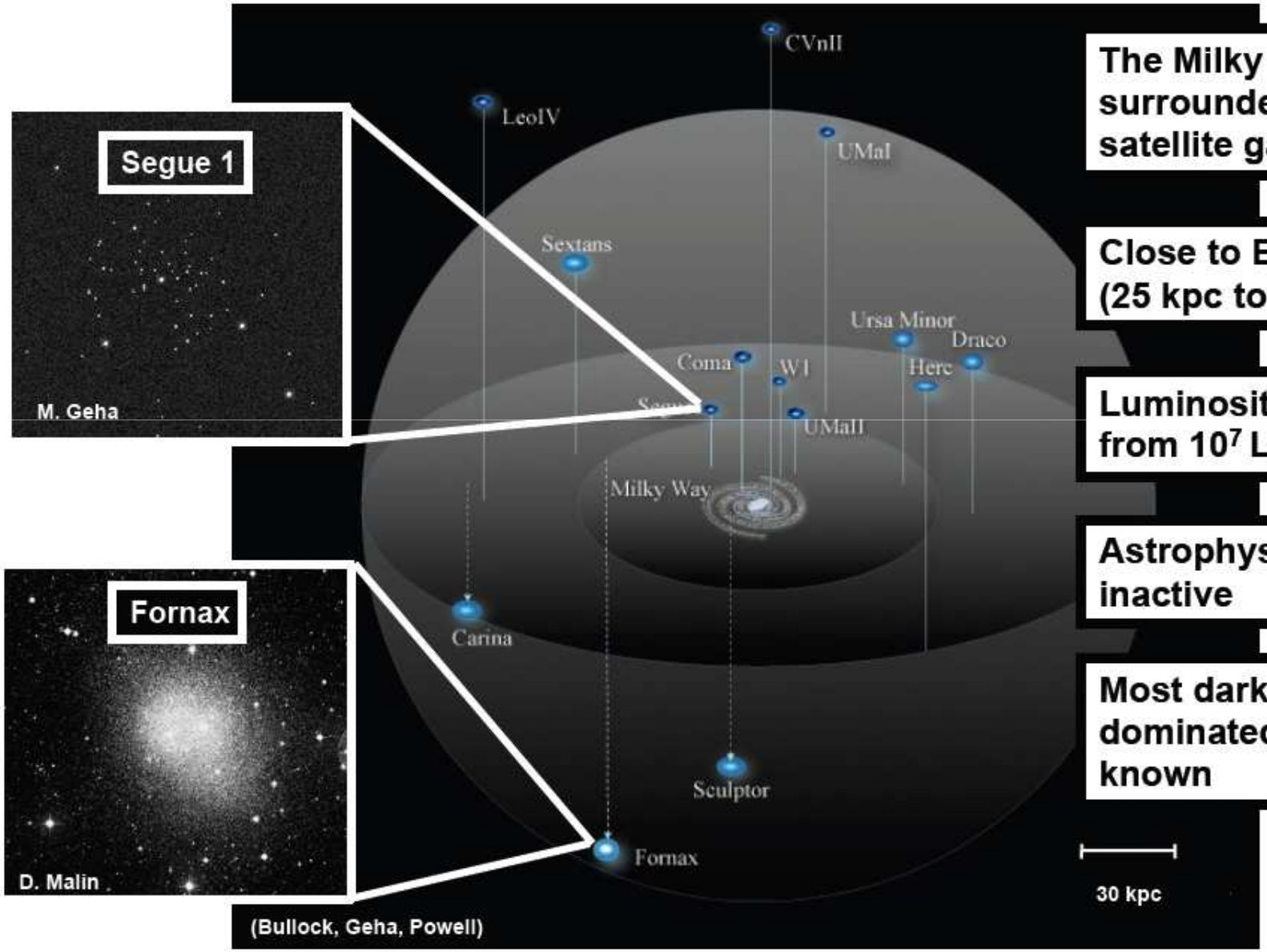
Calore et al 2014

- Calore et al scanned DM template along GP and found other excesses
  - Similar intensities as GC excess, but different spectra
- GC GeV excess story is currently unclear and requires much more study
  - We do have another independent DM search that can test the DM interpretation of the GeV excess: dwarf spheroidal galaxies

Outline

- Dark Matter Overview
- The Fermi Large Area Telescope
  - The Gamma-ray Sky
- **Recent Dark Matter Results**
  - Lines
  - Galactic Center
  - **Dwarfs**

DM Search in MW Dwarf Galaxies



The Milky Way is surrounded by small satellite galaxies

Close to Earth (25 kpc to 250 kpc)

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

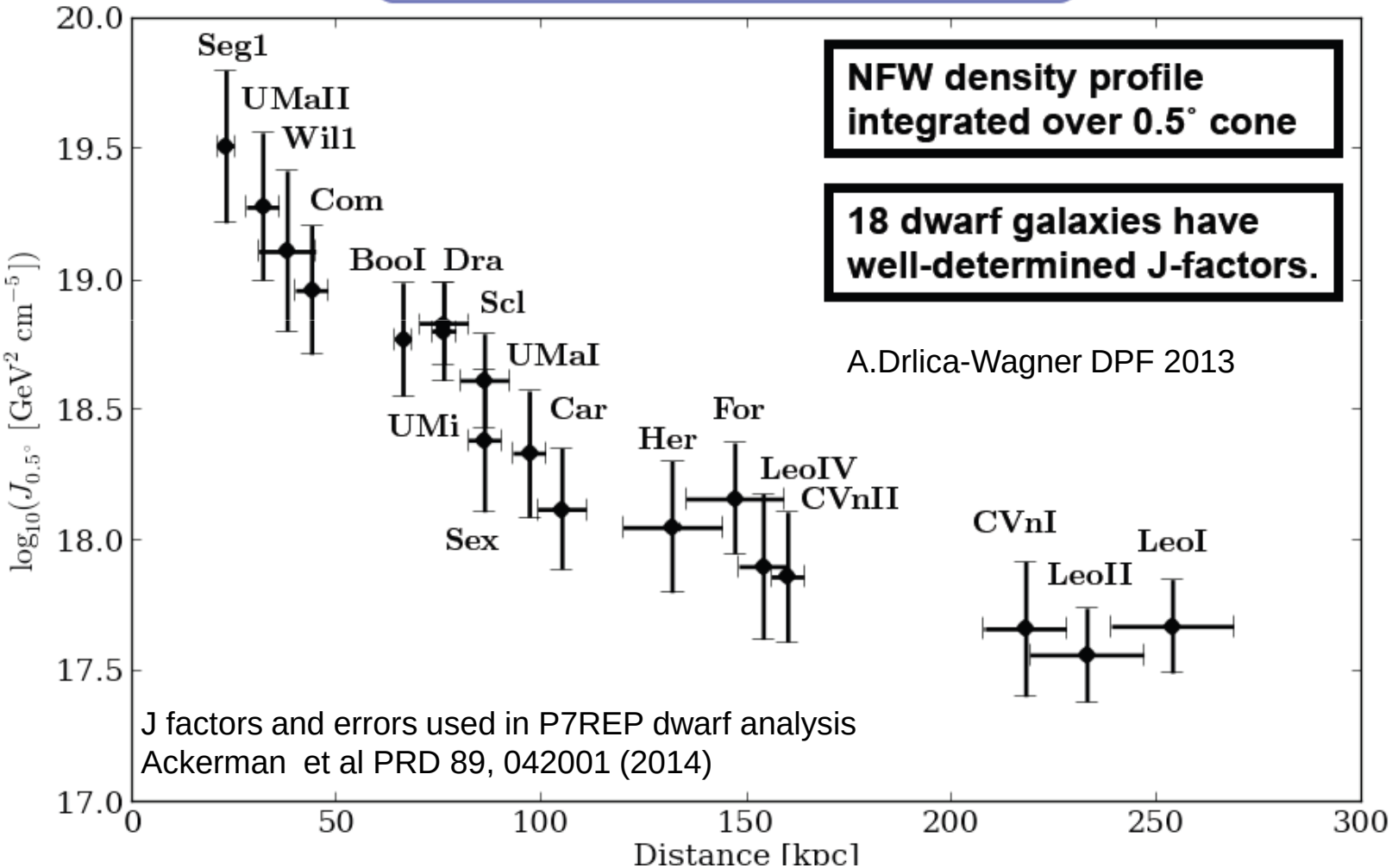
Astrophysically inactive

Most dark matter dominated objects known

A.Drlica-Wagner DPF 2013

J-Factors for Dwarf Galaxies

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



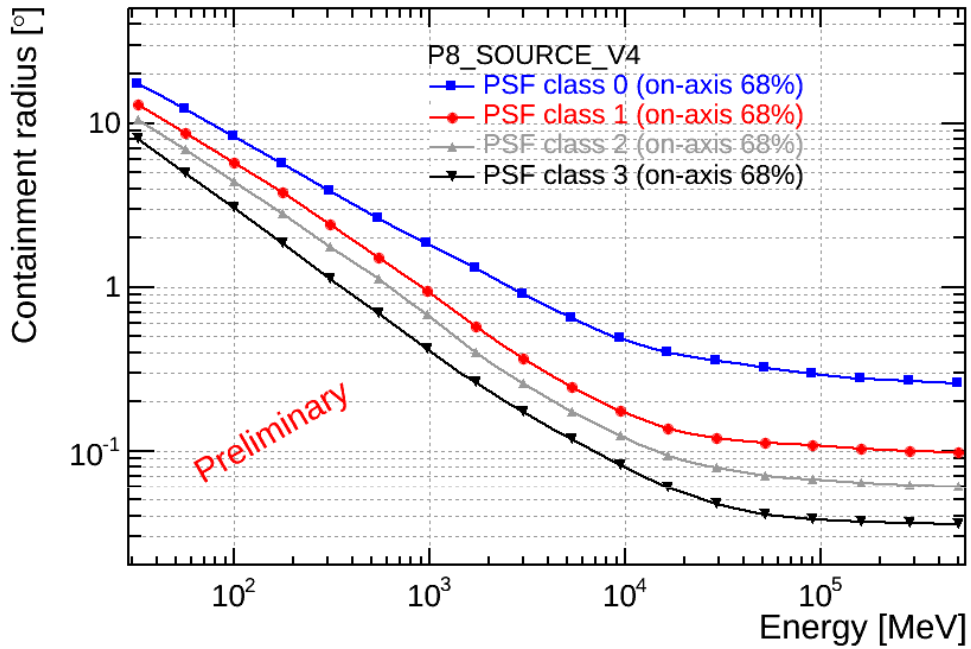
NFW density profile integrated over 0.5° cone

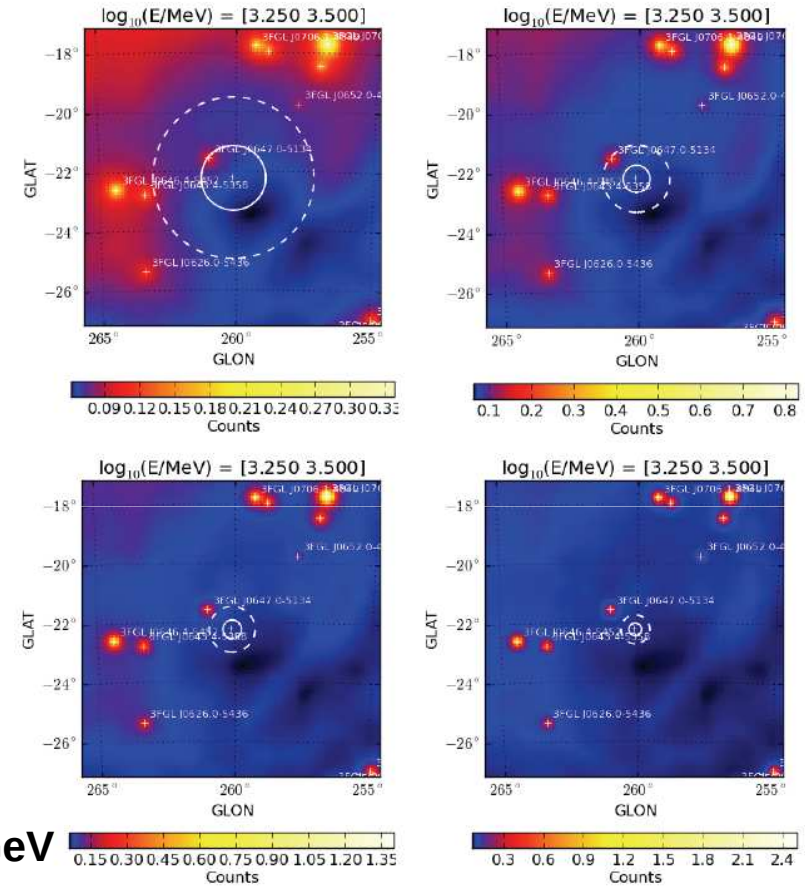
18 dwarf galaxies have well-determined J-factors.

A.Drlica-Wagner DPF 2013

J factors and errors used in P7REP dwarf analysis
Ackerman et al PRD 89, 042001 (2014)

Pass 8 Improvements Relevant for Dwarfs

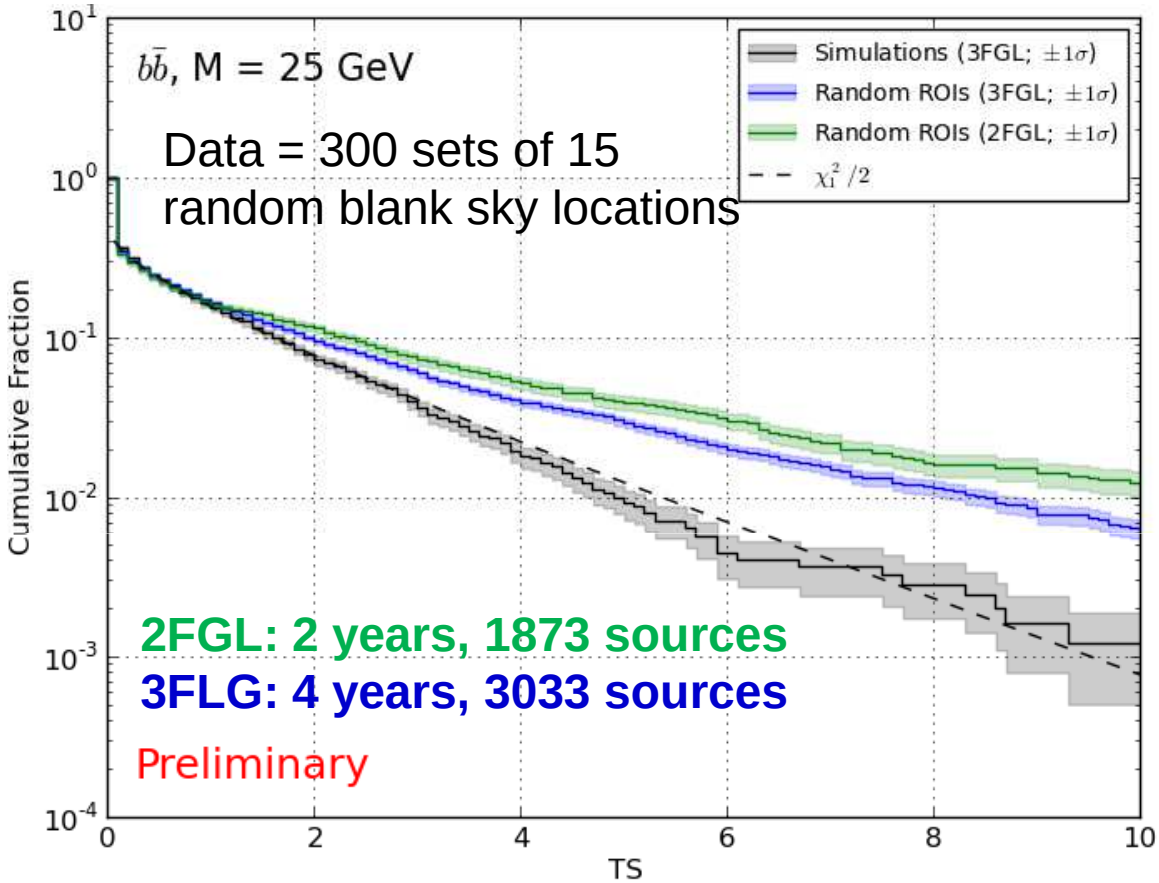




- **Effective area increase by ~25% above 1GeV**
- **Angular resolution improved by ~10-15% above 1 GeV**
- **Point-source sensitivity improved by ~40% for 1-10 GeV**
- **Joint likelihood with all PSFs types improves sensitivity by ~15%**
  - **Similar to EDISP type improvement in line analysis**

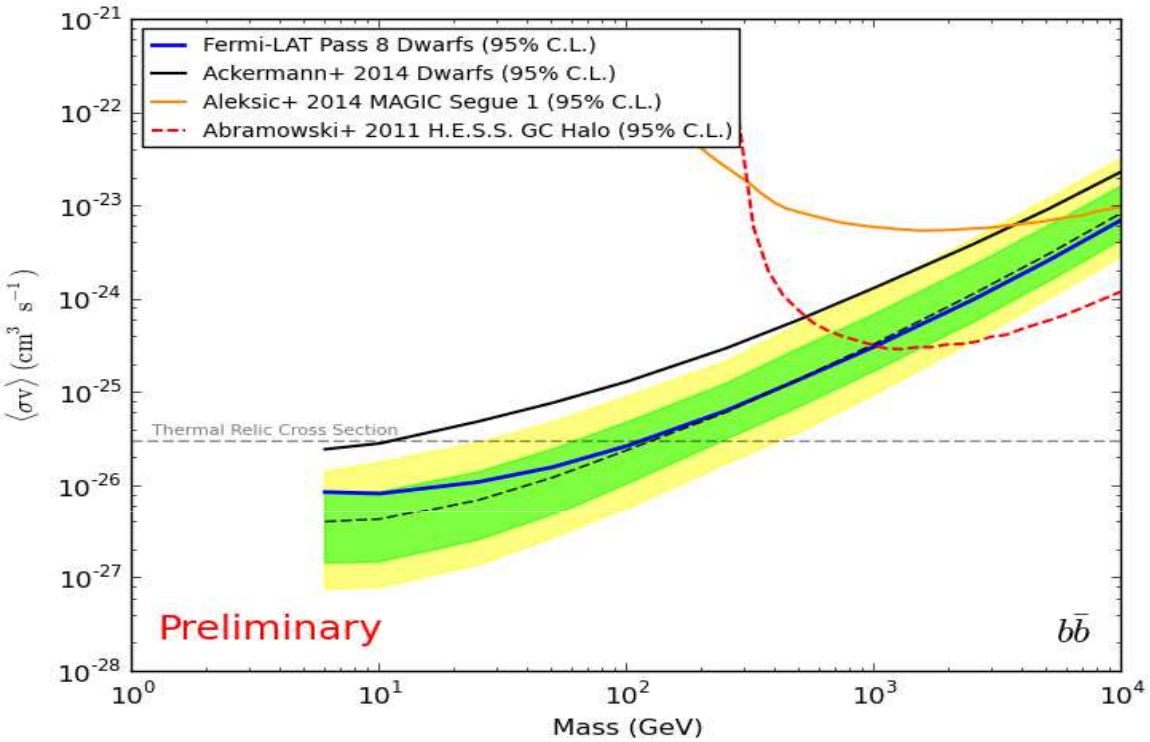
Simulation of region around dwarf

Results from Blank Field Control Regions



- **Using more extensive point-source catalog (3FGL) mitigates some of the MC-data discrepancy**
  - **Suggests discrepancy in TS distributions from MC and random sky data is due in part to unresolved point sources**

Combined dSphs Results

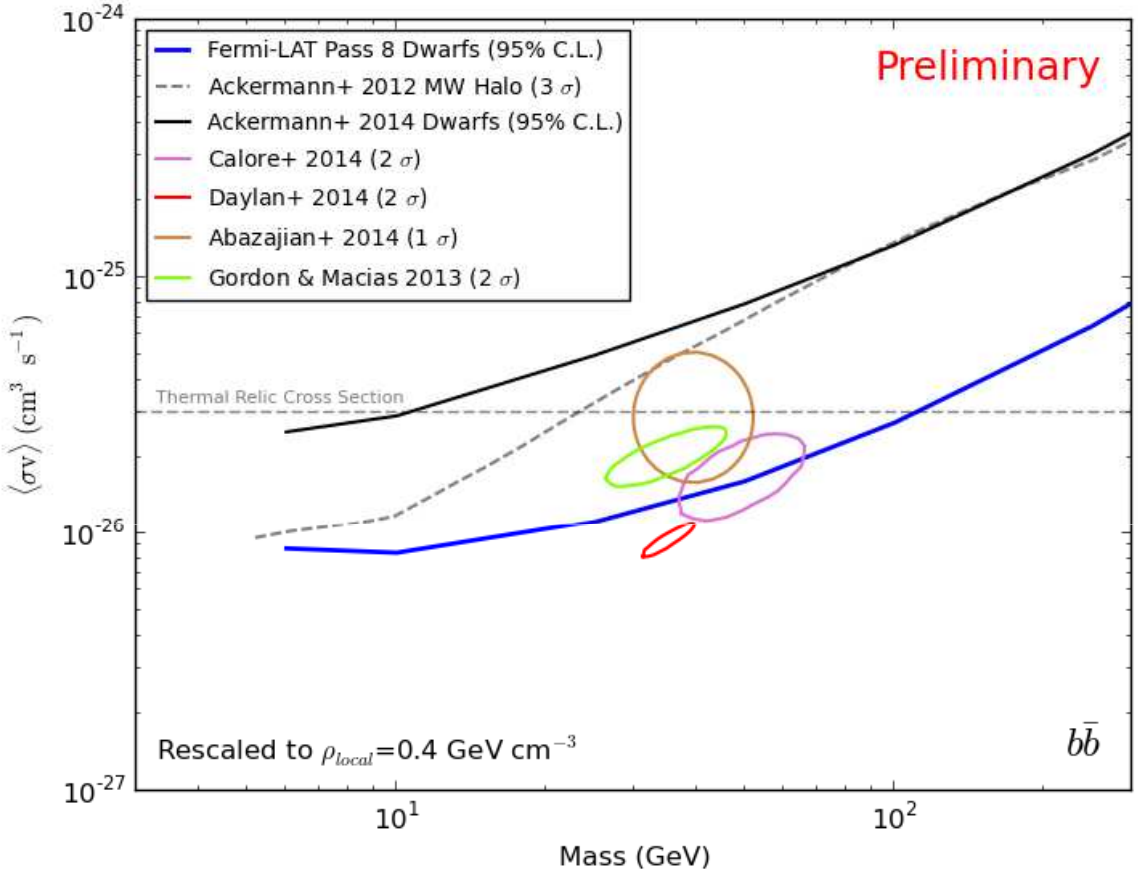


Expected sensitivity estimated from blank sky ROIs

Joint likelihood analysis of 15 dwarf galaxies

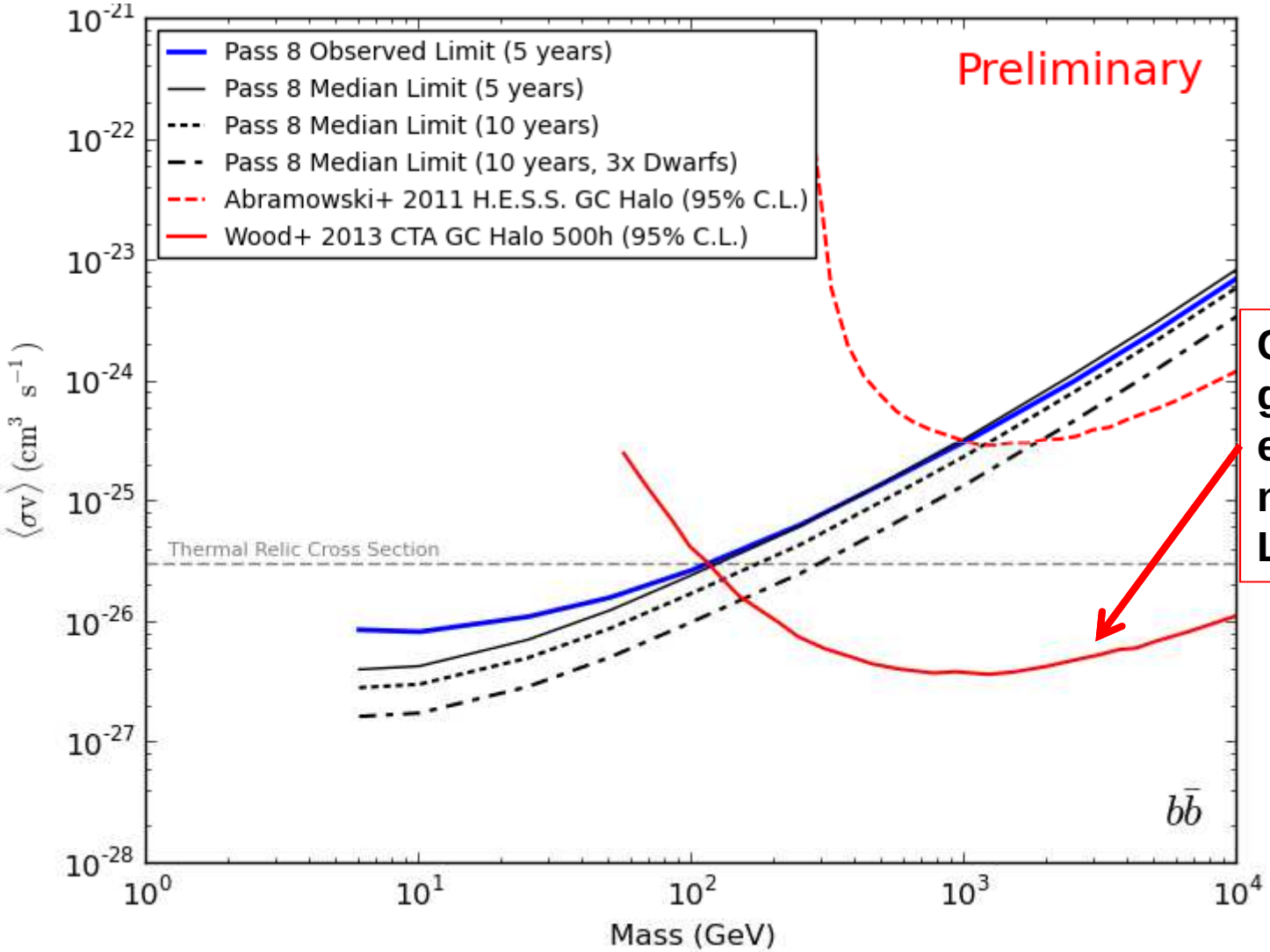
- **5 years of data in energy range 500 MeV – 500 GeV**
- **Account for uncertainties in J-factor**
  - **DM distribution determined using observed stellar velocities**
- **No DM seen**
  - **Exclude canonical thermal relic cross-section for masses less than ~10 GeV (in $b\bar{b}$ and tau's)**

Dwarfs as Check of GC Excess



- **Expect same DM in dwarfs as in GC**
  - **Independent check of DM interpretation of the GeV excess in the GC**
- **No excess seen in dwarfs, limits are starting to exclude some of the DM signal regions from the GeV excess**
  - **Increased exposure and finding new dwarfs will improve limits and help clear up the situation**

Future DM Sensitivity



CTA (future gamma-ray experiment) will nicely complement LAT limits

Summary

- **Fermi continues to be an immensely successful mission (>6 yrs, hope for 10+)**
  - **Unique window to γ–ray sky from 20 MeV to >300 GeV)**
  - **Publically available data and analysis tools (http://fermi.gsfc.nasa.gov/ssc/)**
  - **Expect more exciting results as continue to observe and study the γ–ray sky!**

- **The Fermi LAT team has looked for indirect DM signals using a wide variety of different methods**
  - **So far no signals have been detected and strong constraints have been set**
    - **Exclude thermal relic WIMPs below ~100 GeV in bb̄ and tau channels**

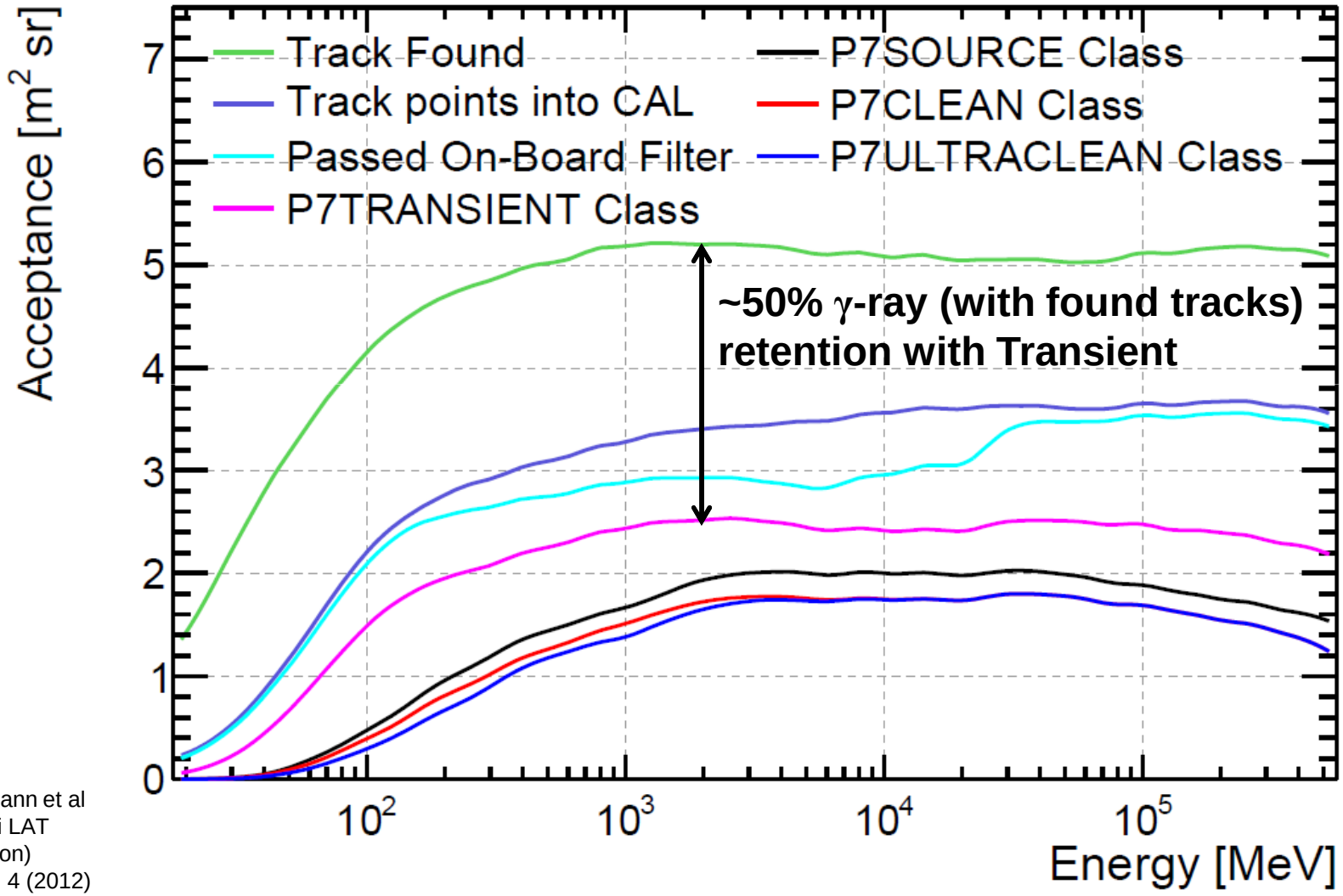
- **No spectral lines detected, 133 GeV feature not significantly present in Pass 8**

- **Evidence for excess in Galactic Center that peaks around 2 GeV**
  - **4 tuned fore/background emission models used**
  - **Spectrum and morphology of excess is strongly dependent on fore/background model assumed**
    - **Much more study is needed to better characterize and understand this excess**

- **No gamma-ray emission observed from dwarf spheroidal galaxies**
  - **Independent check of DM interpretation of GC excess**
    - **Limits starting to rule out possible DM models of the GC excess**

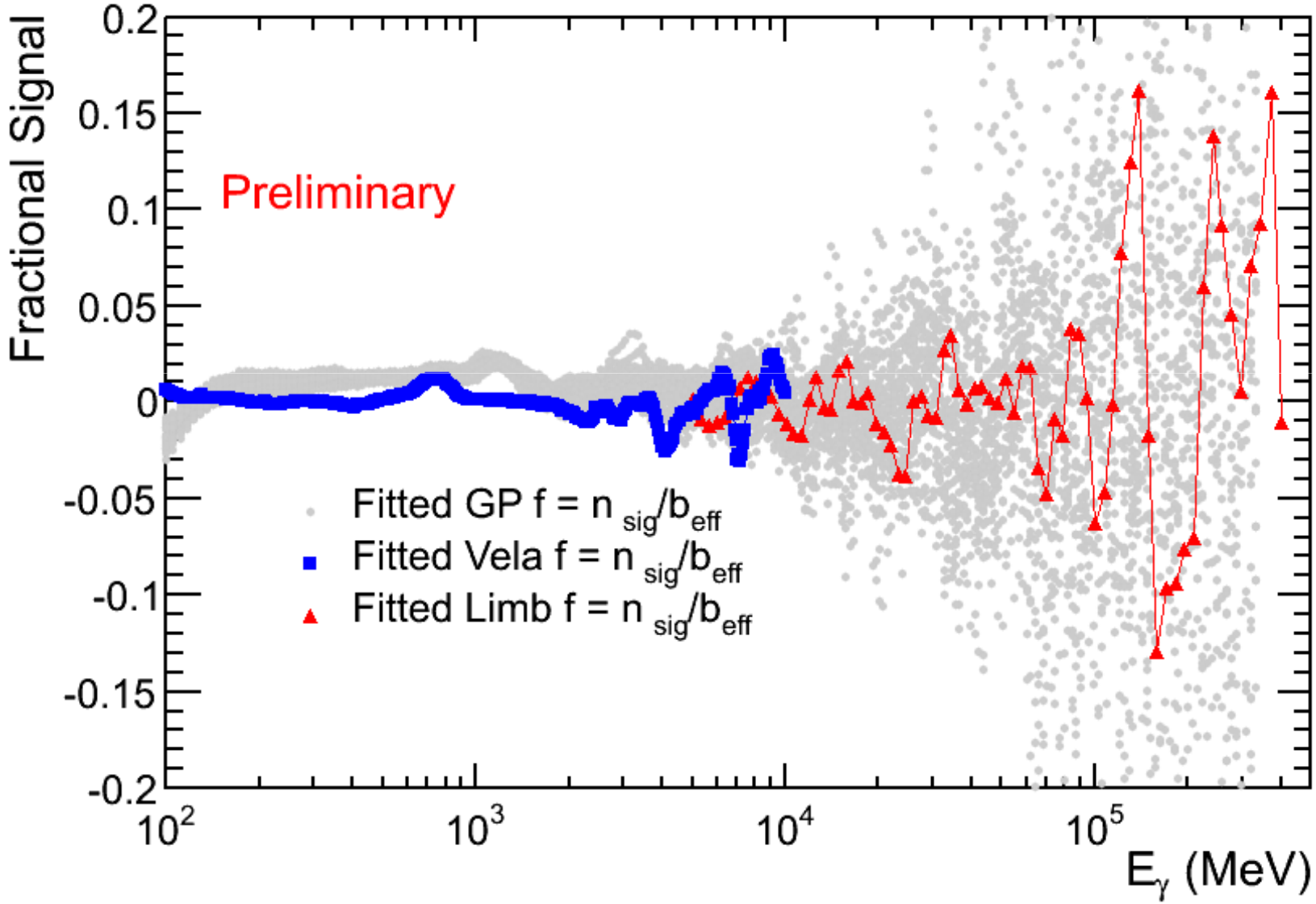
BACKUP SLIDES

Gamma-ray Acceptance

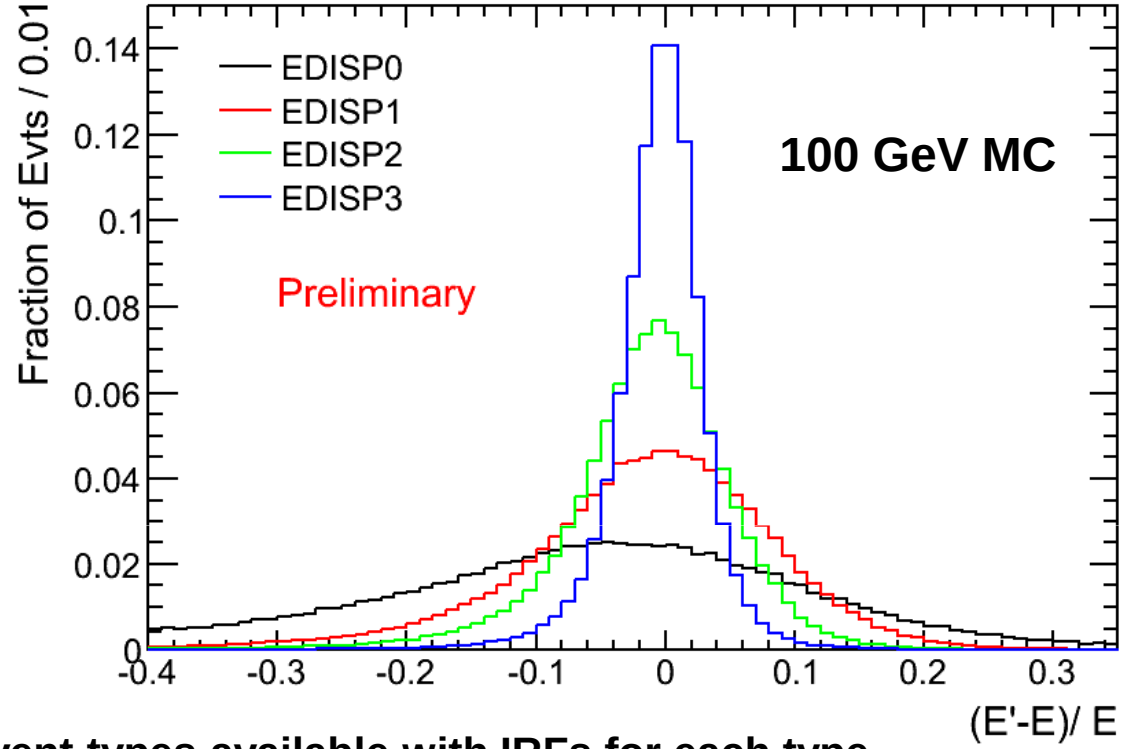


M. Ackermann et al (The Fermi LAT Collaboration) ApJS 203, 4 (2012) arXiv:1206.1896

Pass 8 Line Search
f_{sys} from Control Regions

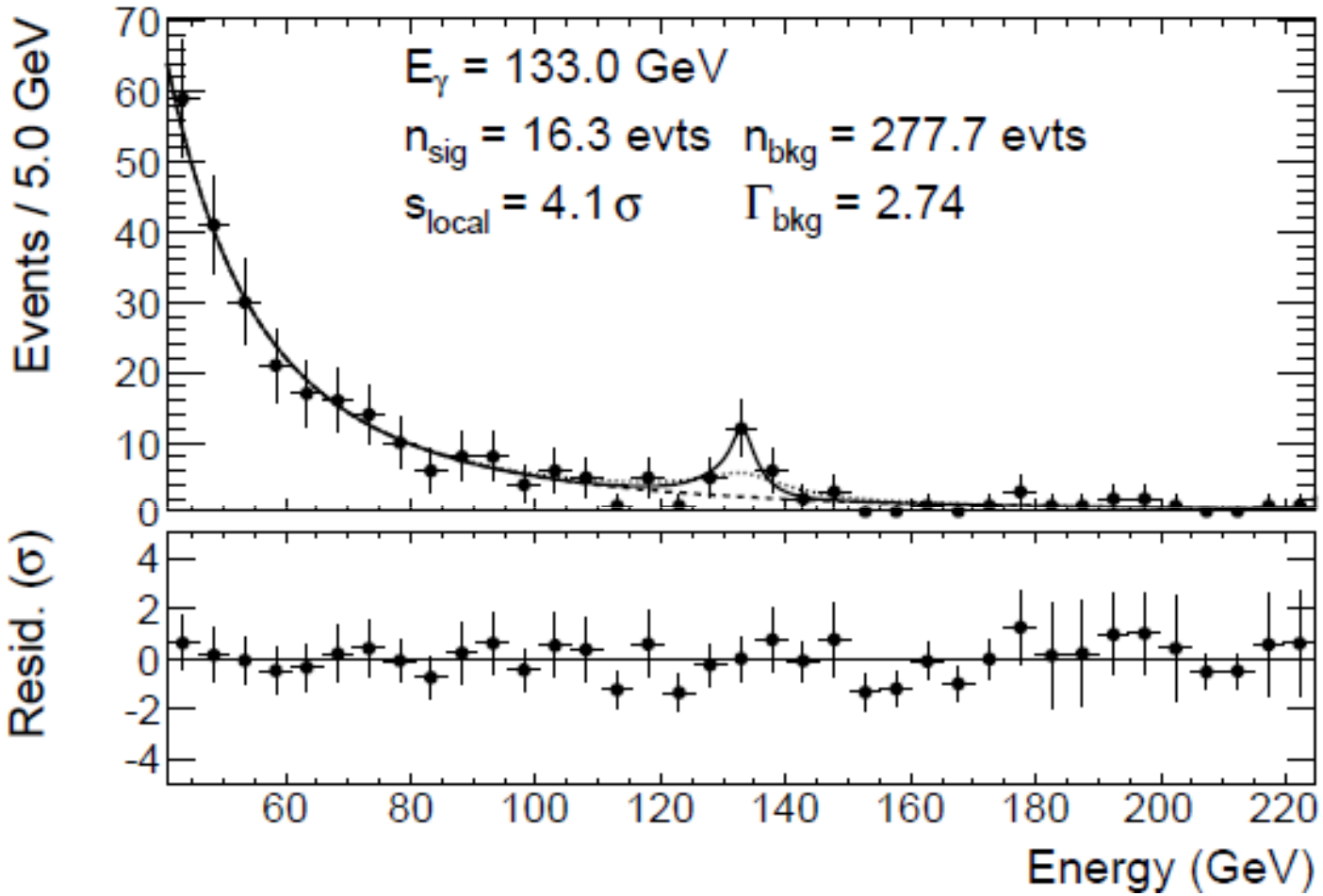


“2D” Line Model with Pass 8



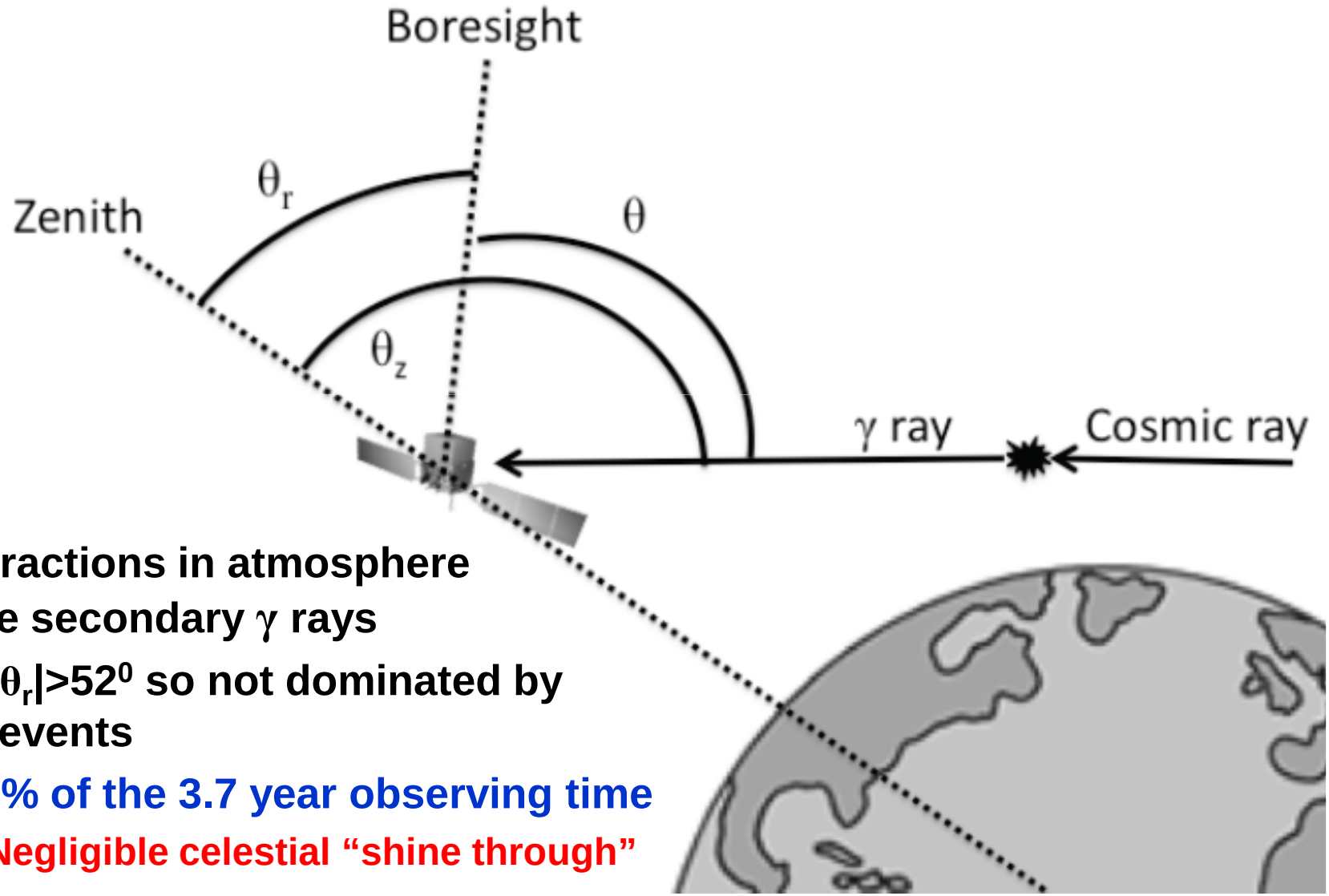
- **P8 has more event types available with IRFs for each type**
  - **Similar to “front” vs. “back” IRFs**
- **EDISP types select events based on energy recon quality**
  - **25% quantiles of “Best Energy Prob” as function of energy**
  - **In given energy range, each EDISP type has ~same acceptance**
- **Including EDISP types → ~10-15% improvement to signal sensitivity**
  - **Amount of improvement depends on energy**
  - **Similar to improvement in P7REP analysis using 10 Best Energy Prob bins**

Width of 133 GeV Feature



- **Let width scale factor float in fit (while preserving shape)**
- $s_\sigma = 0.32^{+0.22}_{-0.07}(95\%CL) \quad \Delta TS = 9.4$
  - **Feature in data is <u>much narrower</u> than expected energy resolution (s_σ=1)**

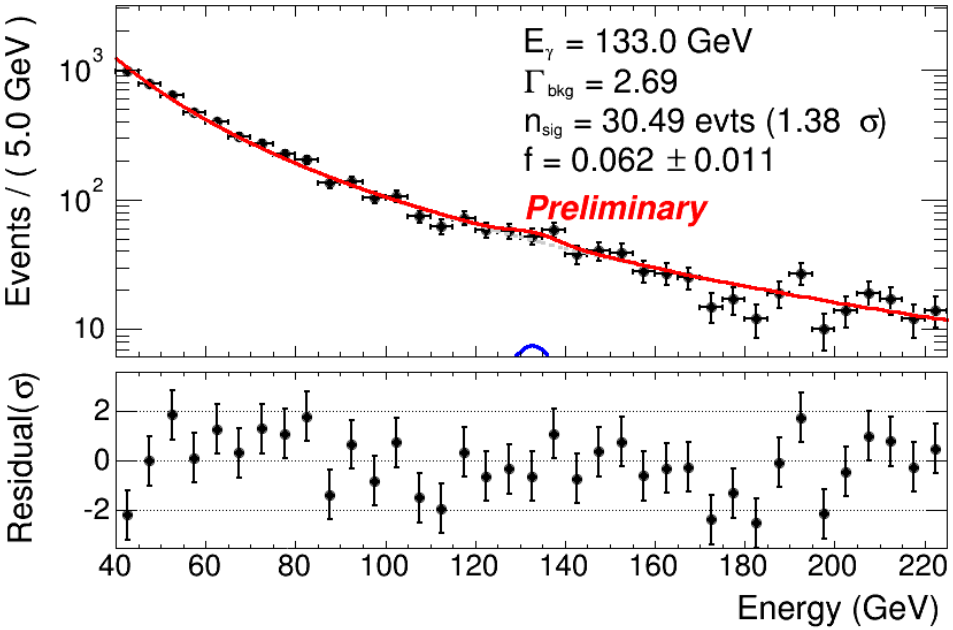
Earth Limb Control Dataset



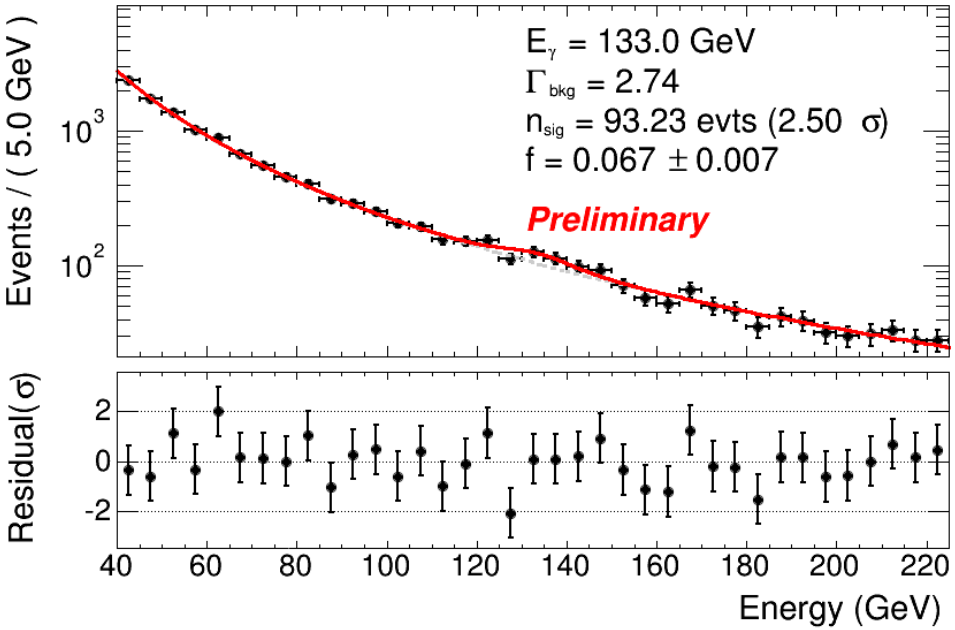
- **CR interactions in atmosphere produce secondary γ rays**
- **Select $|\theta_r|>52^0$ so not dominated by large θ events**
  - **0.03% of the 3.7 year observing time**
    - **Negligible celestial "shine through"**

133 GeV Feature in the Limb with Pass 8

5.8 year P7REP_Clean



5.8 year P8_Clean



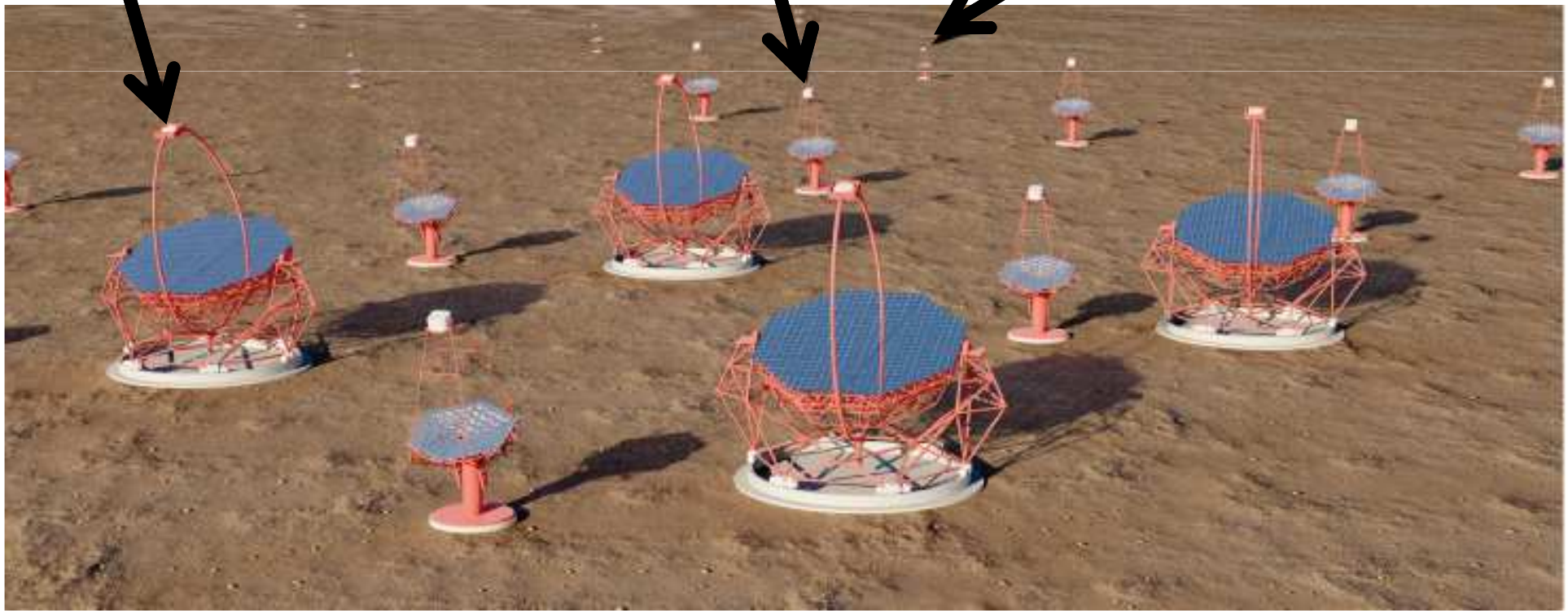
- **Feature still present in limb in Pass 8**
  - **Given small fractional size, would be <1σ in GC**

General CTA Array Design

Low energies
Energy threshold 20-30 GeV
23 m diameter
4 telescopes

Medium energies
100 GeV – 10 TeV
9.5 to 12 m diameter
up to 25 single-mirror telescopes
up to 24 dual-mirror telescopes

High energies
10 km^2 area at few TeV
4 to 6 m diameter
up to 70 telescopes



CTA Performance