Fermi Gamma-ray Space Telescope

Searches for New Physics with the Fermi Large Area Telescope

Eric Charles (SLAC)

SLAC Summer Institute

2012 August 1

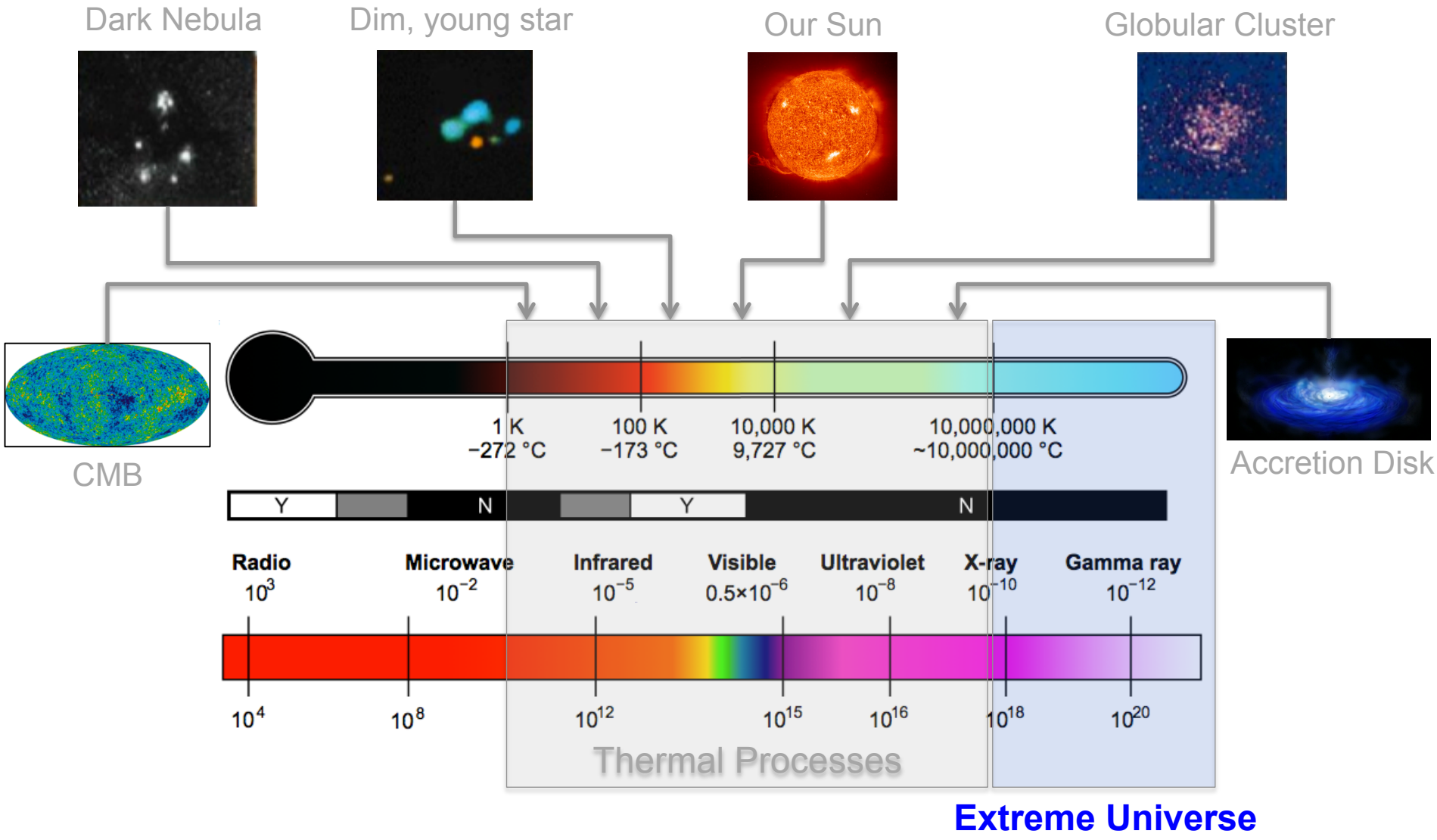
Searches for New Physics with the Fermi-LAT

- γ-ray Astronomy and the Fermi-LAT
- Indirect Searches for Dark Matter
- Fermi-LAT Search Strategies and Results
- Status and Summary

Searches for New Physics with the Fermi-LAT

- **γ-ray Astronomy and the Fermi-LAT**
- Indirect Searches for Dark Matter
- Fermi-LAT Search Strategies and Results
- Status and Summary

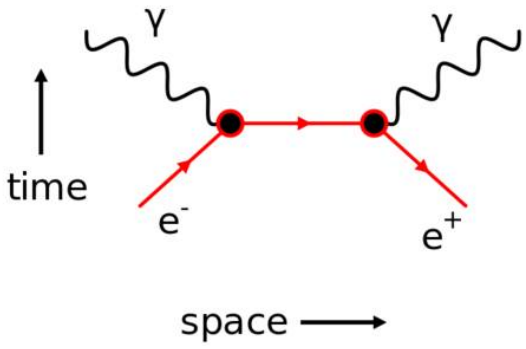
γ-rays Probe the Extreme, Non-Thermal, Universe



Non-thermal γ ray emission

Energy source

Acceleration mechanism



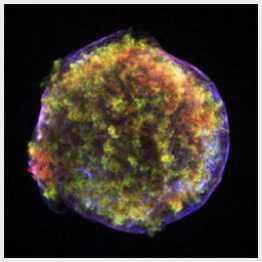
γ-ray production mechanism

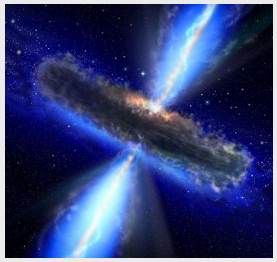
Foreground absorption

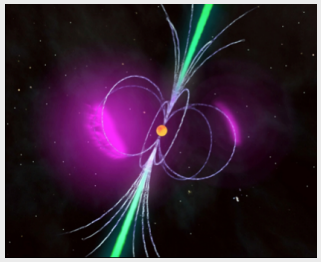
γ rays

Many Mechanisms Involved in Producing γ rays

Energy Sources

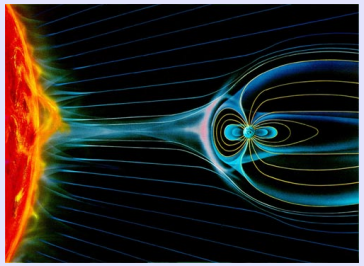

Explosions

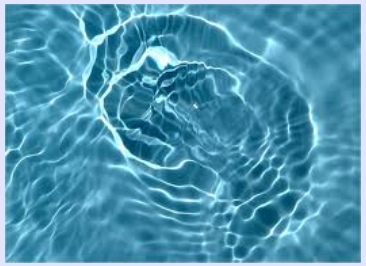

Accretion

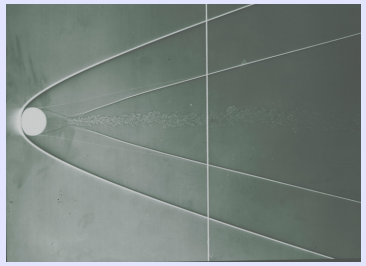

Rotating Fields

Many of these mechanisms will produce radiation at other, non γ-ray, wavelengths

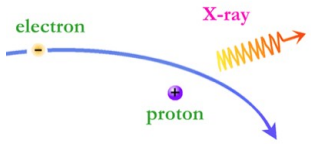
Acceleration Mechanisms


Reconnection


Caustics

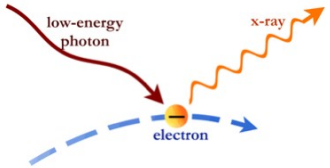

Other Shocks

γ-ray Emission Mechanisms

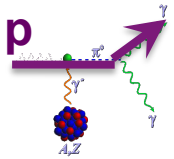


bremsstrahlung

synchrotron

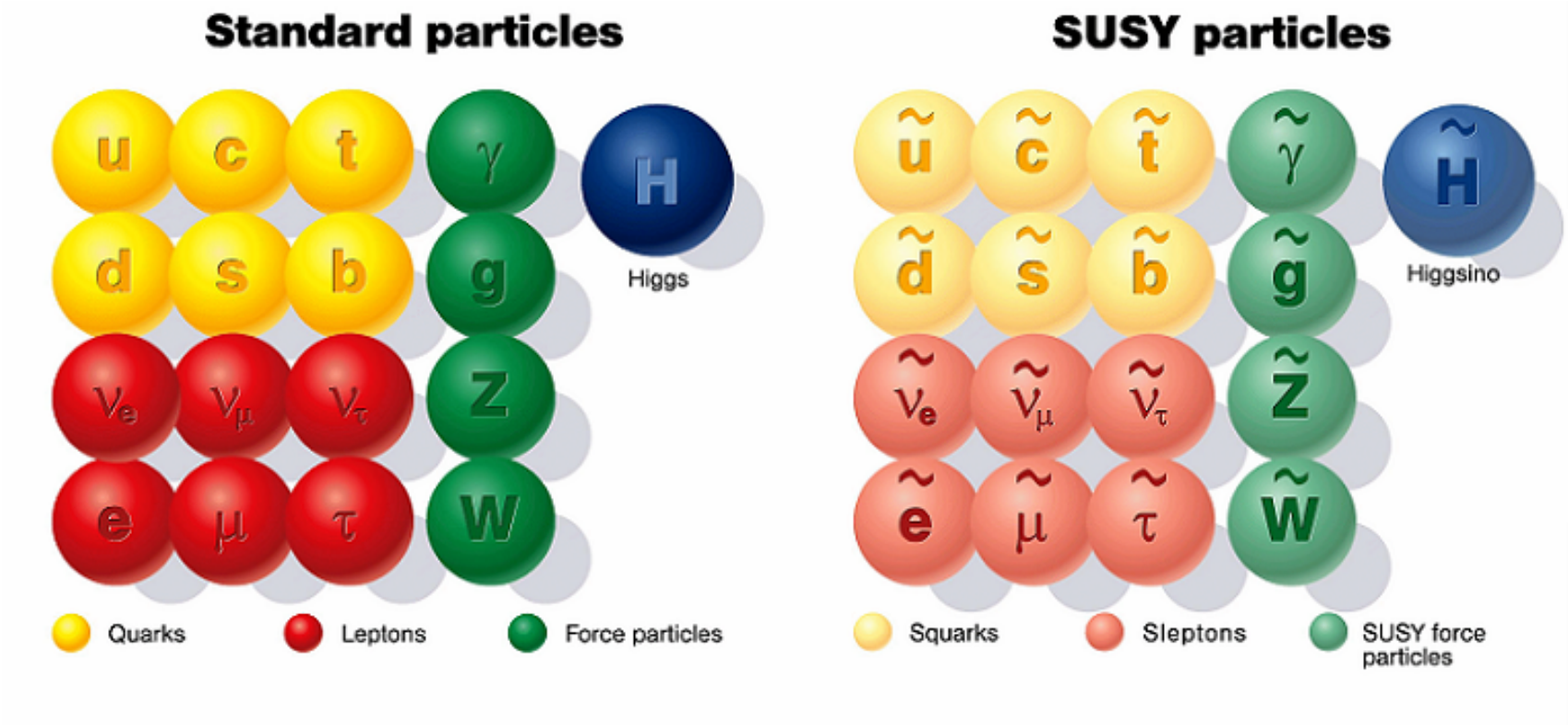


inverse Compton



π^0 production

One More Potential Mechanism to make γ rays



Exotic particle rest mass

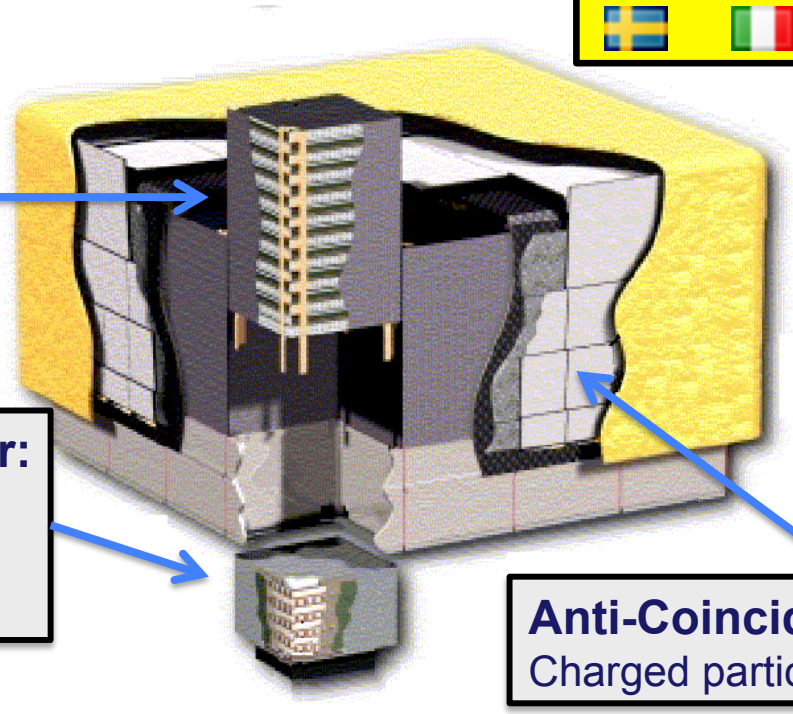
The mechanism is "cleaner" in that it does not require external energy sources, particle acceleration or target material and fields to produce γ rays

The Fermi Large Area Telescope

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 γ->e^+e^-
reconstruct γ direction
EM v. hadron separation



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

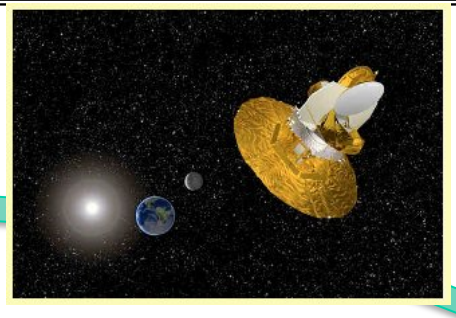
Anti-Coincidence Detector:
Charged particle separation

Sky Survey:
With 2.5 sr Field-of-view LAT sees whole sky every 3 hours

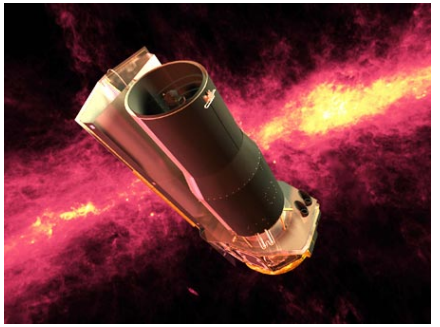
Trigger and Filter:
Reduce data rate from ~10kHz to 300-500 HZ

Synergy with Other Instruments

Radio: pulsations, synchrotron emission, ISM maps, high resolution imaging of jets AGN host galaxies…



Microwave: diffuse maps & morphology, Galaxy characteristics…

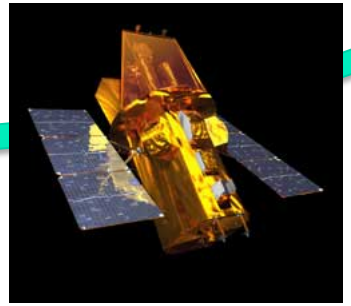


IR: ISM maps, AGN/GRB host galaxies…

LAT Source Localization ~0.1°--0.01° comparable to many field-of-views
LAT: 4+ decades energy band provides lever-arm for spectral fits

Energy

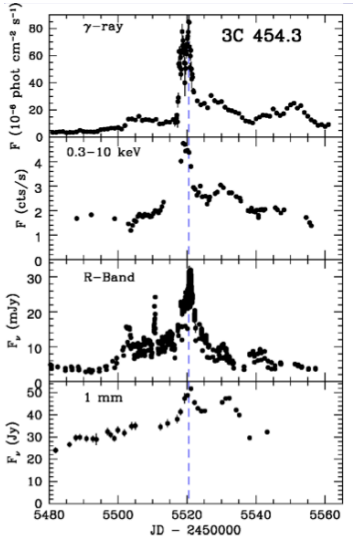
TeV: High-energy spectral breaks, SNR/ PWN morphology…



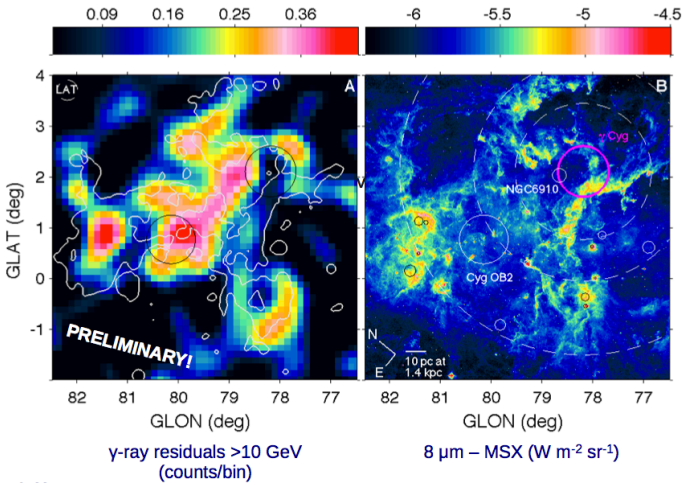
X-ray:
GRB & Flare afterglows, morphology & pulsar association…

Optical:
GRB afterglows, AGN/ GRB redshits…

Wide Variety of Analysis Techniques



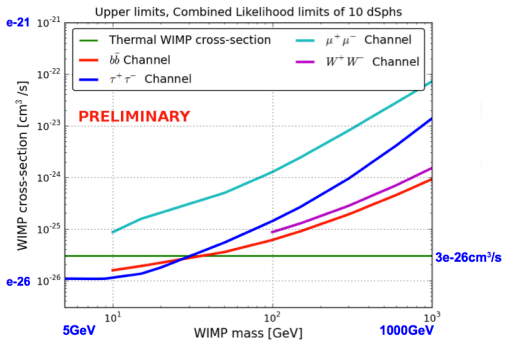
MW Variability & Pulsations



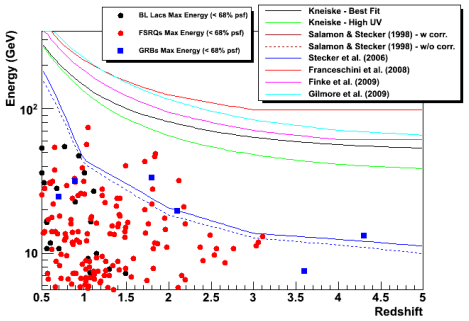
γ-ray residuals >10 GeV (counts/bin)

8 μm – MSX (W m^{-2} sr^{-1})

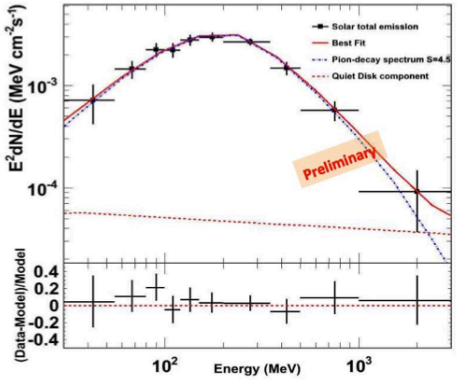
Morphology, Source Extension and Counterpart Identification



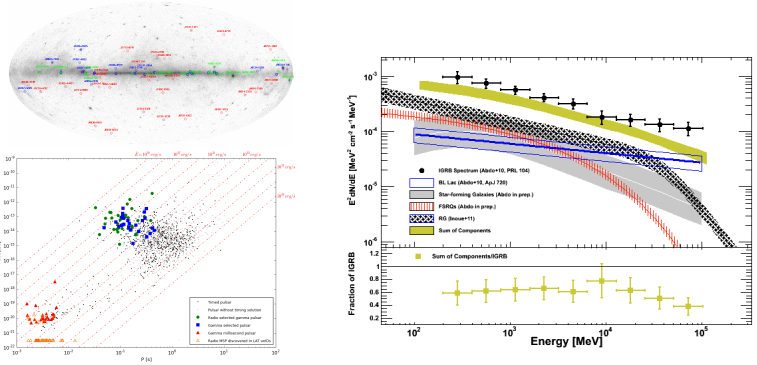
DM Searches



Single Photon Studies



Spectra and Spectral Components



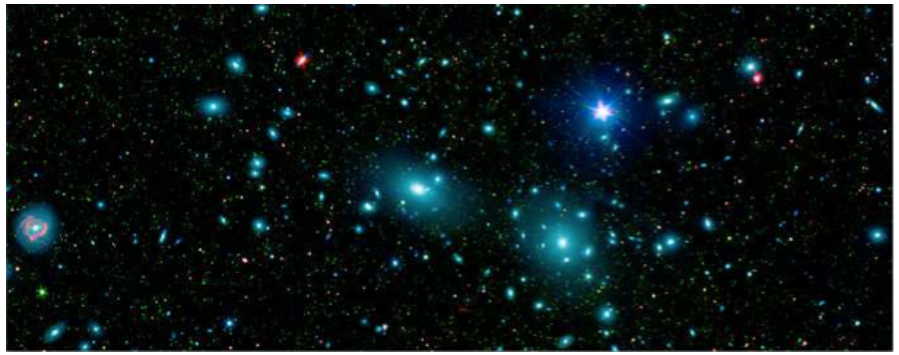
Catalogs, Population Studies and Luminosity Functions

No real "standard" analysis. Many complementary ways to extract information about the γ-ray sky

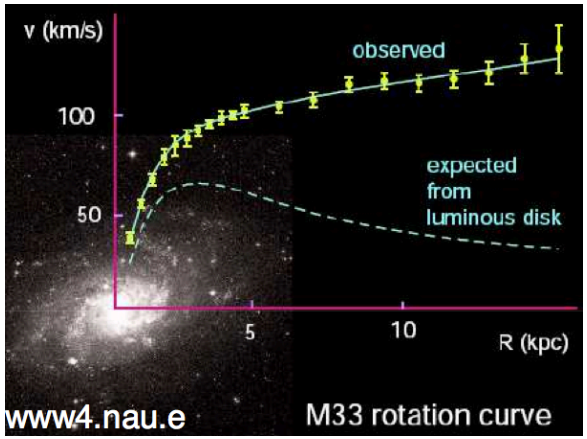
Searches for New Physics with the Fermi-LAT

- γ-ray Astronomy and the Fermi-LAT
- **Indirect Searches for Dark Matter**
- Fermi-LAT Search Strategies and Results
- Status and Summary

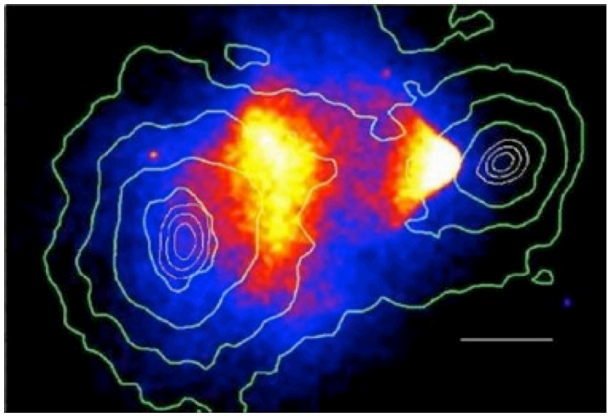
Evidence for / Salient Features of Dark Matter



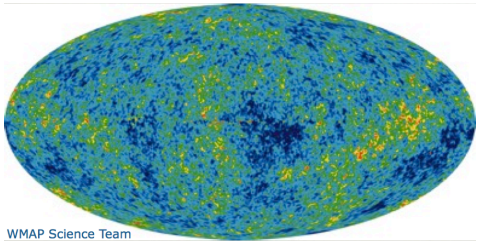
*Comprises **majority** of **mass** in Galaxies*
Coma Cluster + Virial Theorem
Zwicky (1937)

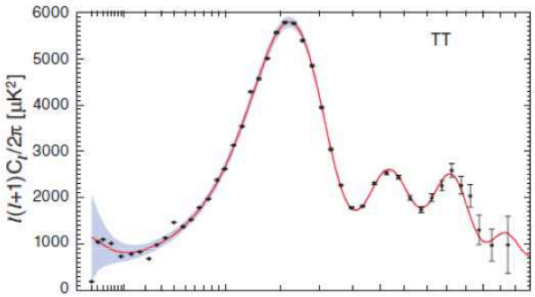


*Large **halos** around Galaxies*
Rotation Curves
Rubin+(1980)



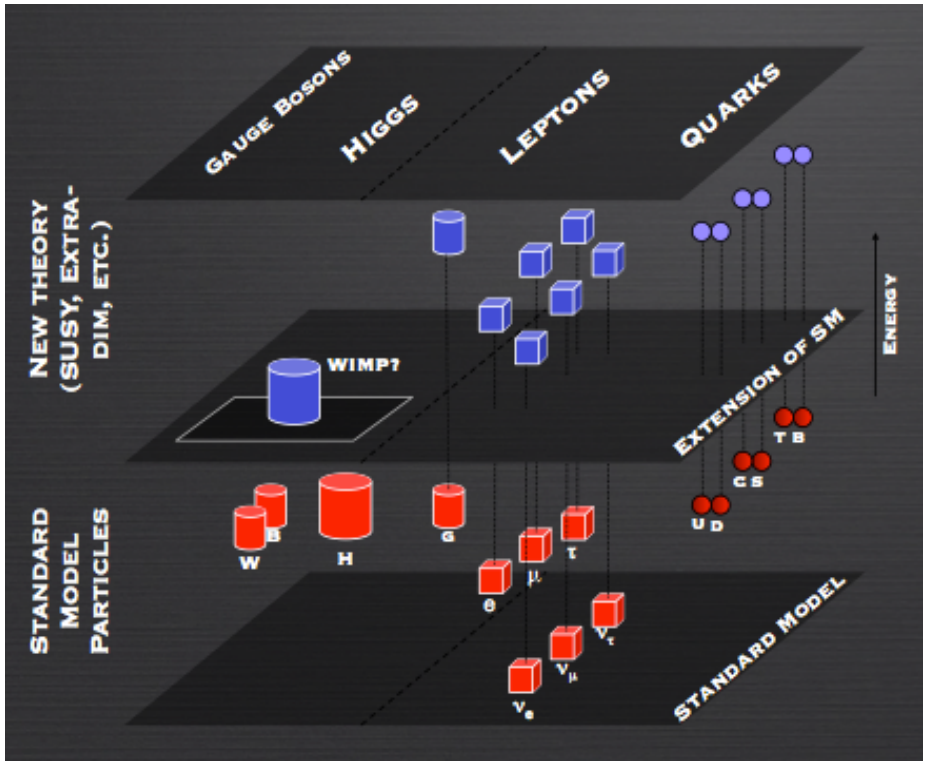
*Almost **collisionless***
Bullet Cluster
Clowe+(2006)

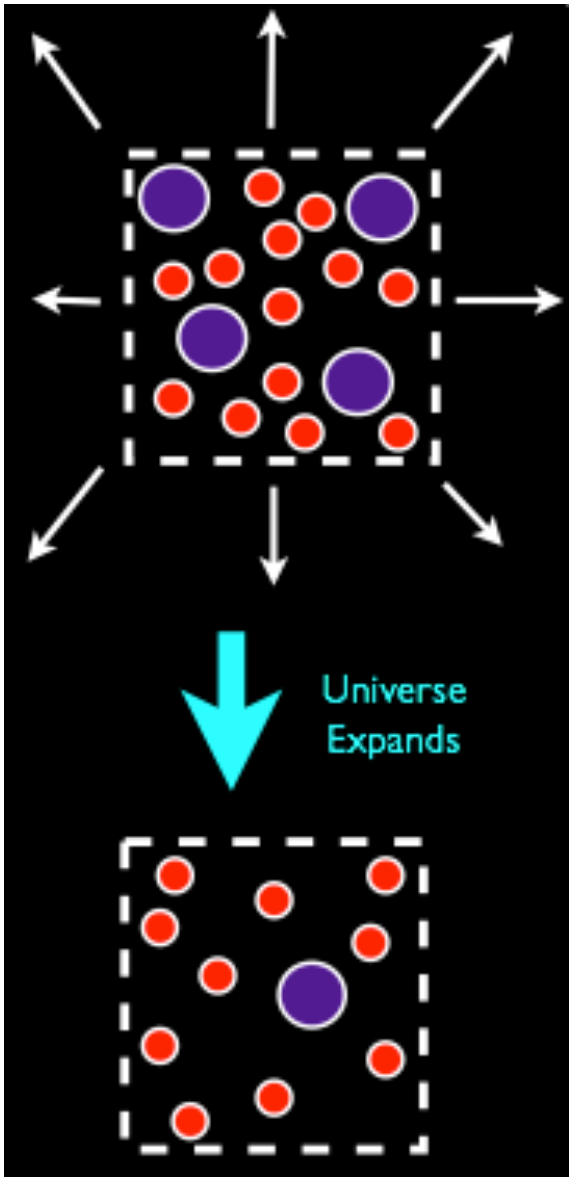




Non-Baryonic
CMB Acoustic Oscillations
WMAP(2010)

Particle Physics offers Dark Matter Candidates

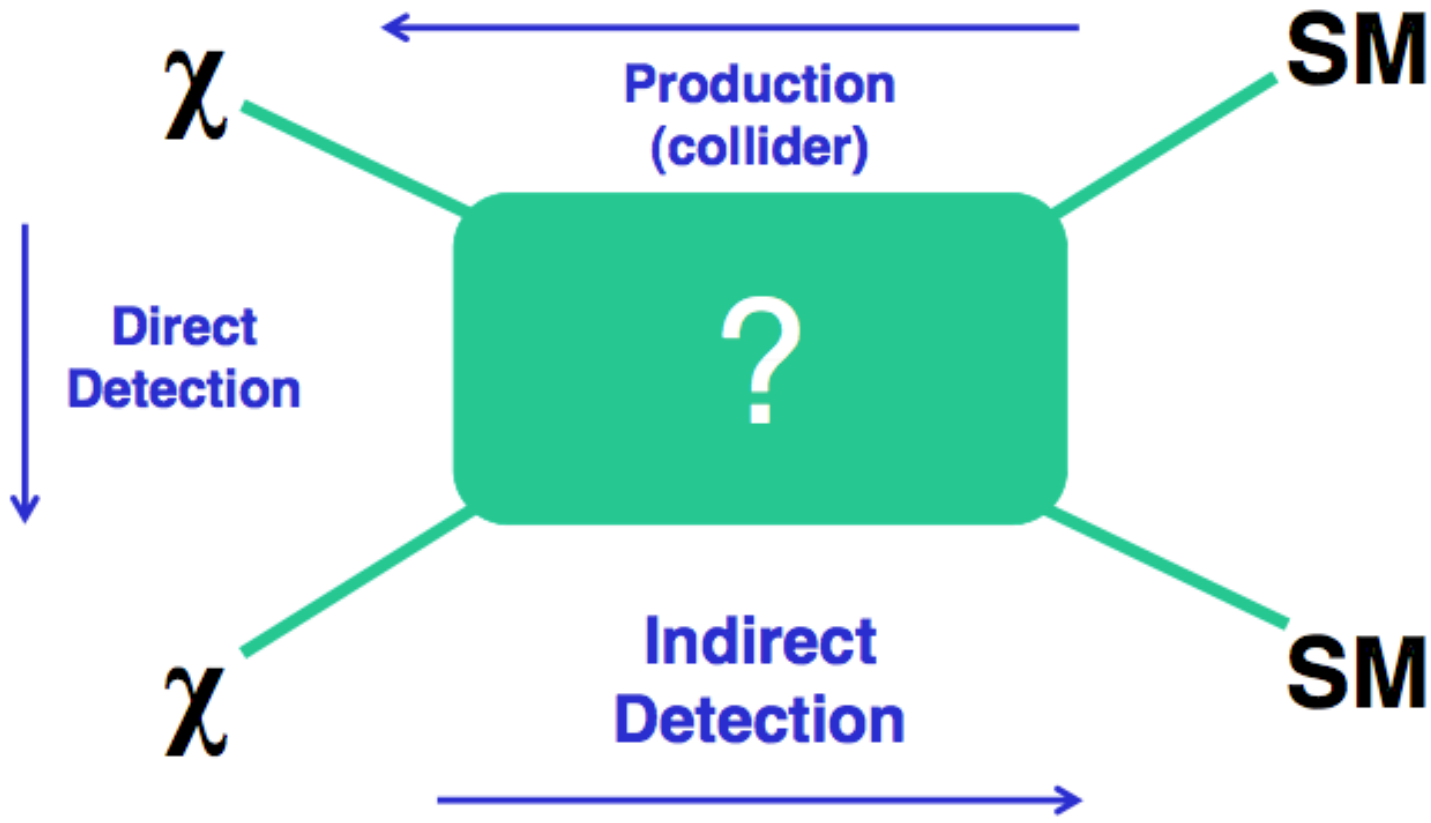




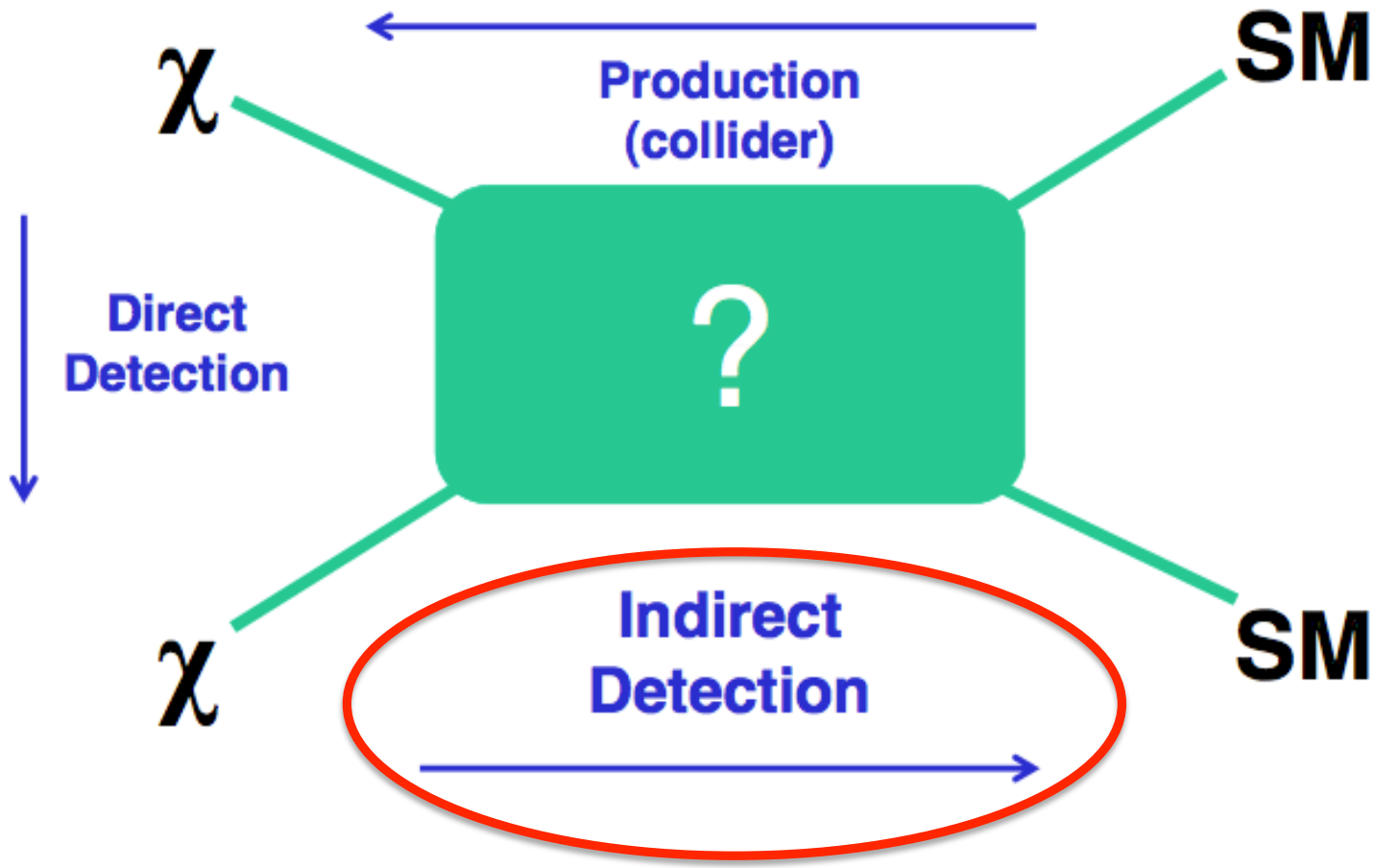
Weakly Interacting Massive Particles (WIMPs) are an interesting DM candidate

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

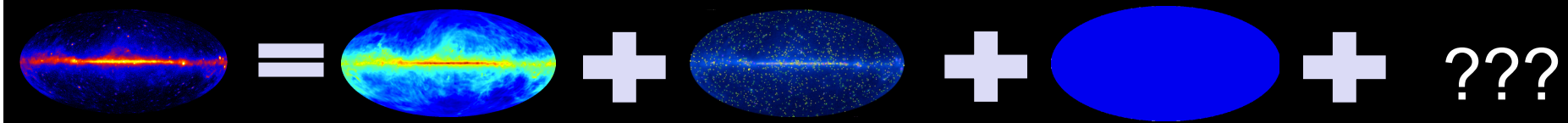
Dark Matter Searches



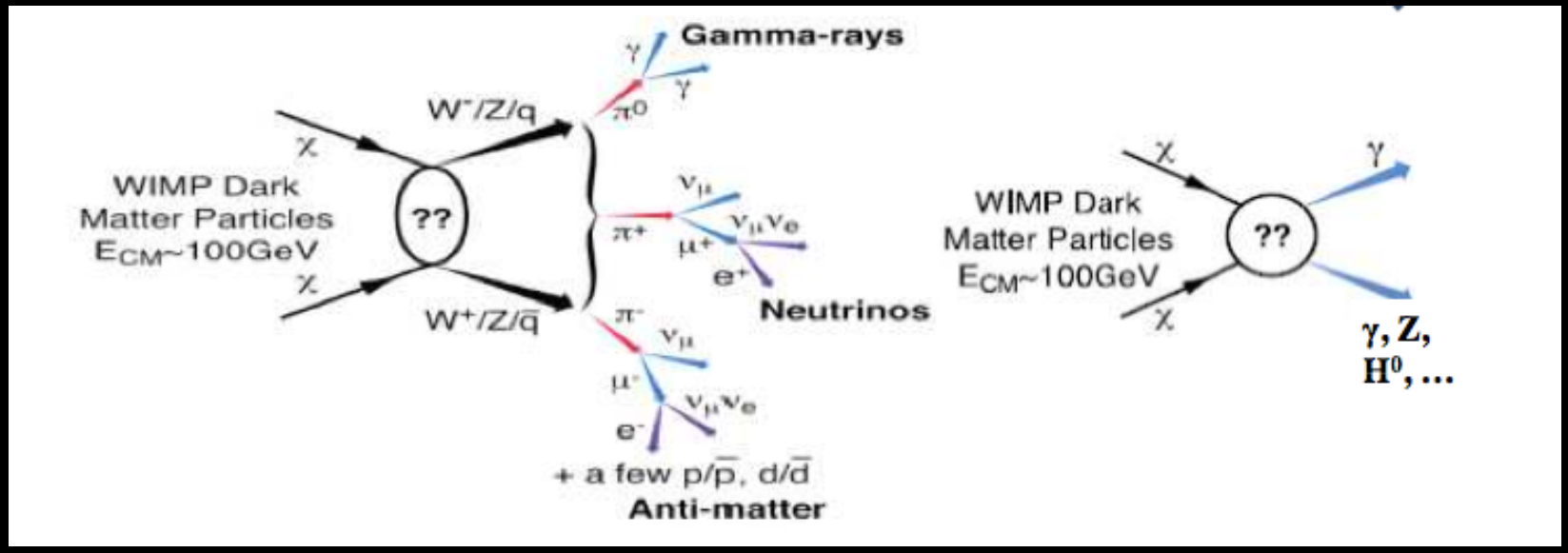
Dark Matter Searches



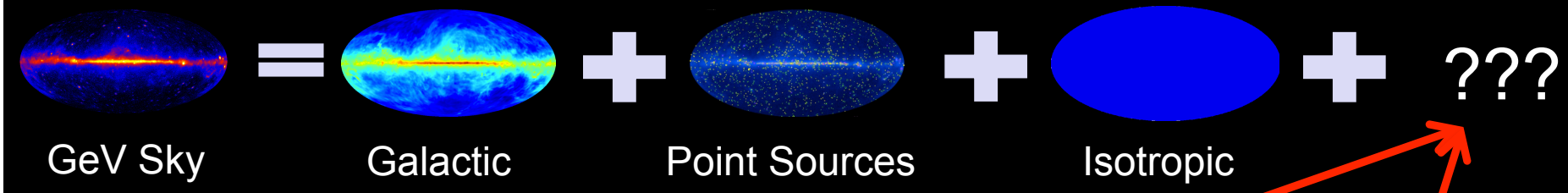
Indirect Searches for DM in the GeV Sky

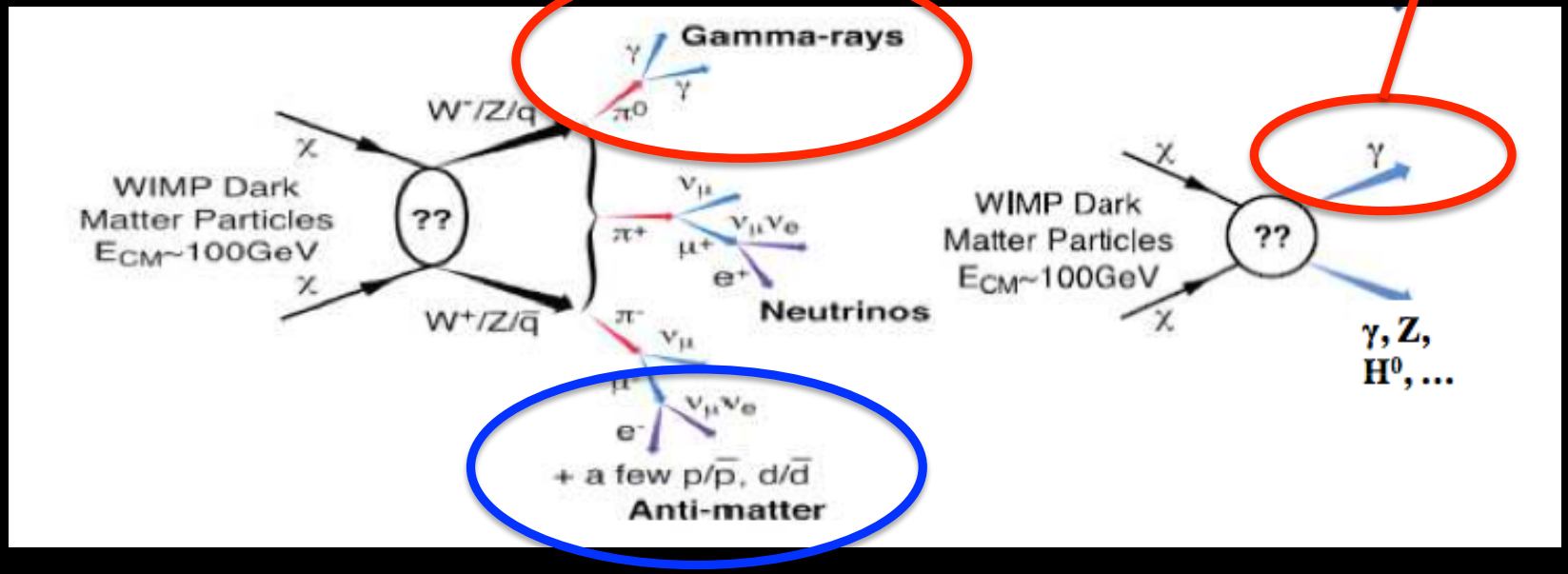


GeV Sky | Galactic | Point Sources | Isotropic

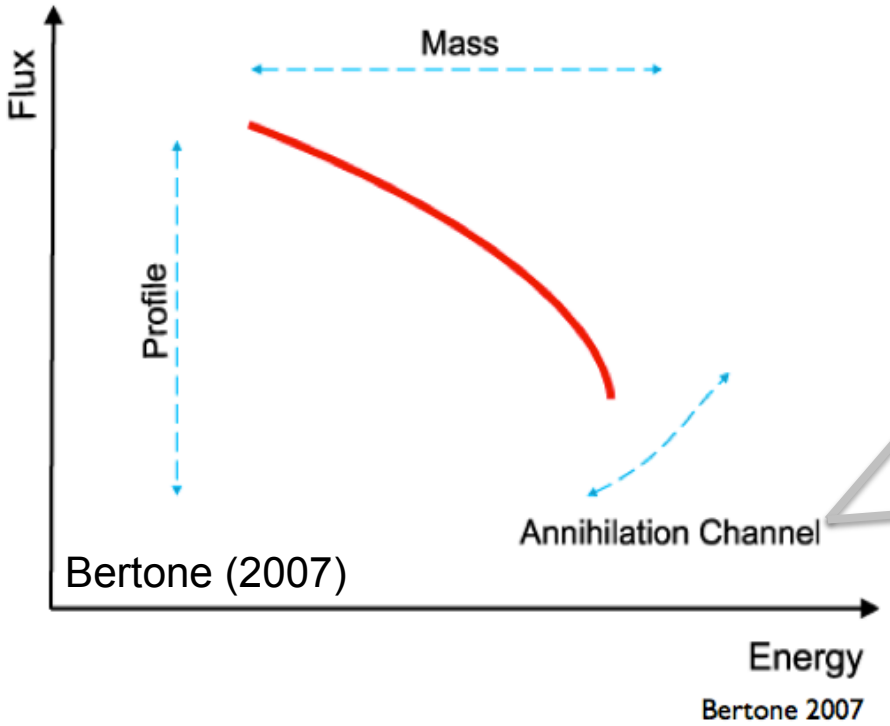


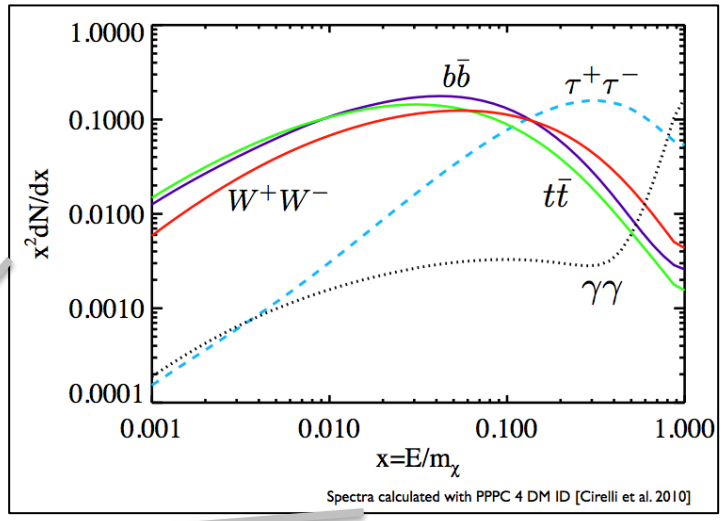
Indirect Searches for DM in the GeV Sky





Dark Matter Signatures in γ-ray Sky





Particle Physics

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

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

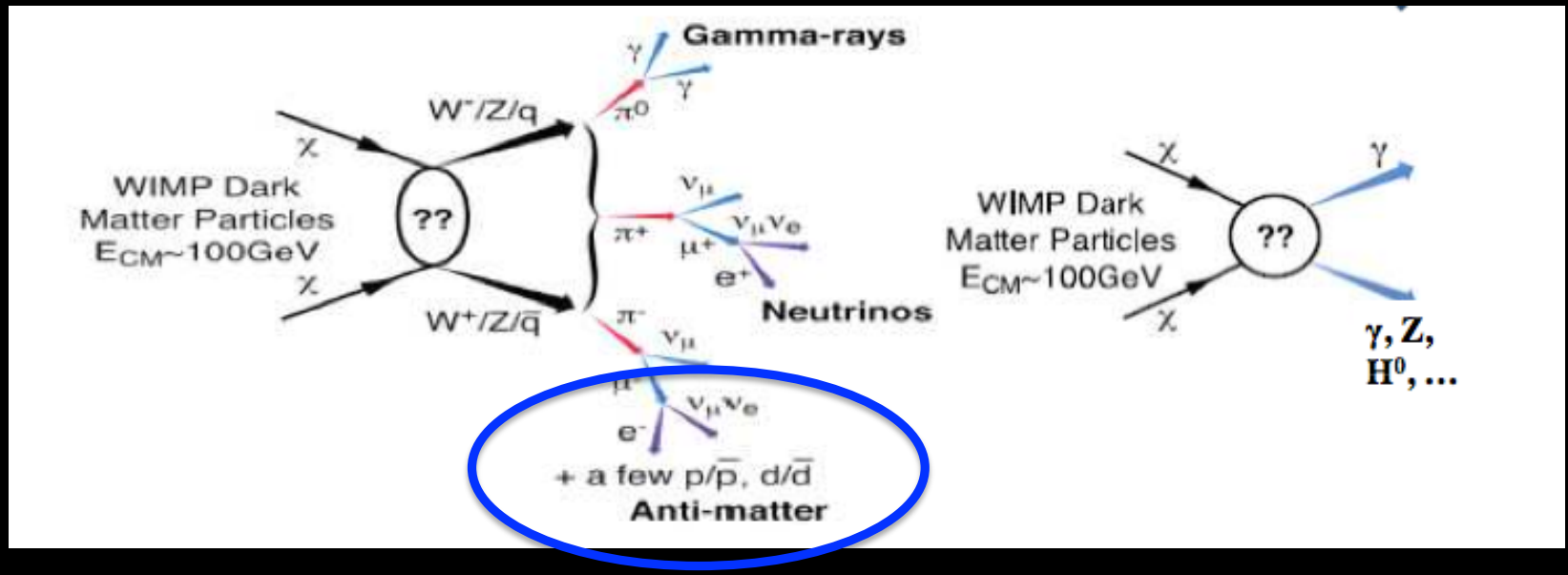
Astrophysics (J-Factor)

Searches for New Physics with the Fermi-LAT

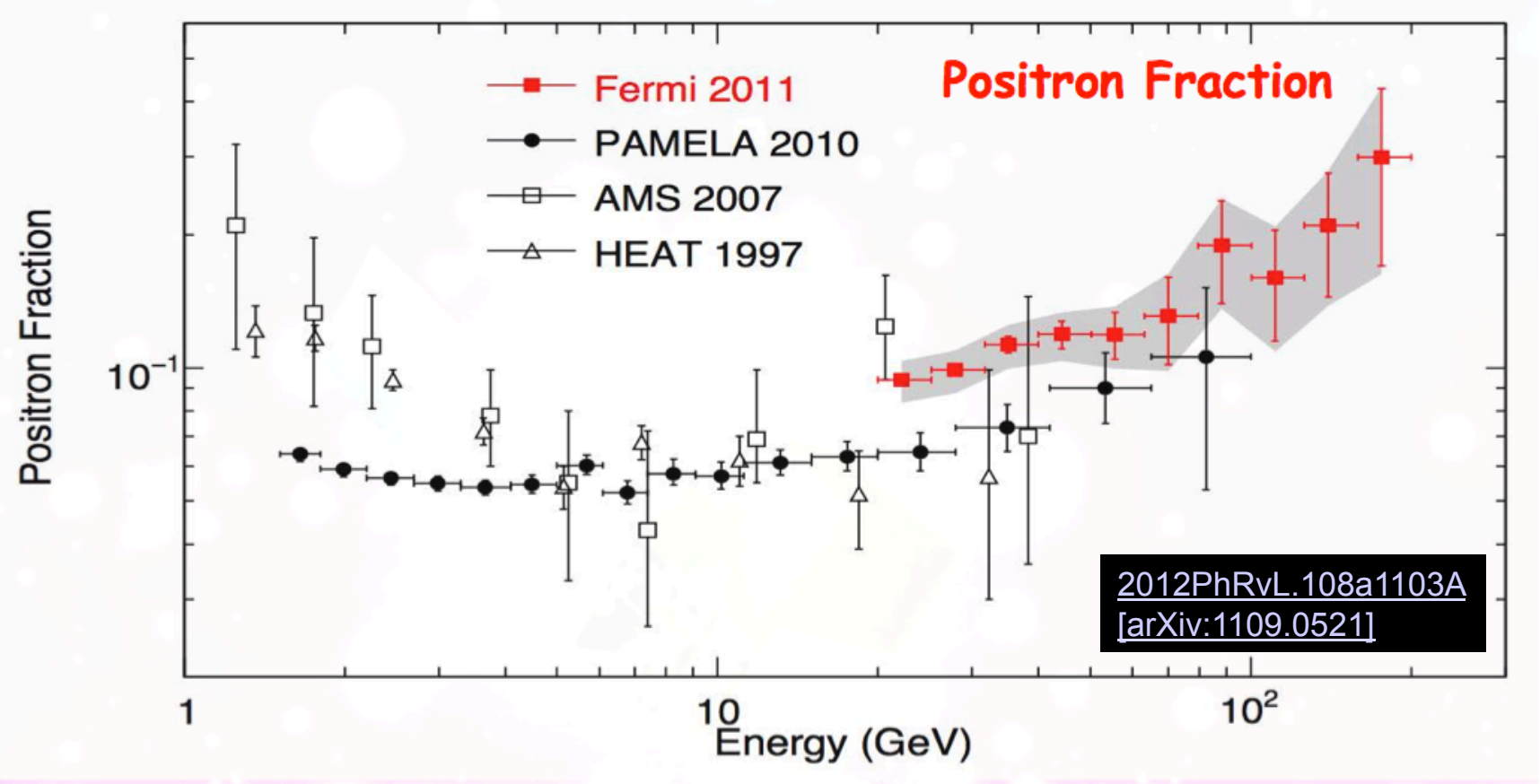
- γ-ray Astronomy and the Fermi-LAT
- Indirect Searches for Dark Matter
- **Fermi-LAT Search Strategies and Results**
- Status and Summary

Searches for DM in Cosmic Rays

- WIMP Interactions can produce charged cosmic-ray particles
- Although charged particles carry little or no directional information, we can look for signs of DM in cosmic-ray spectra

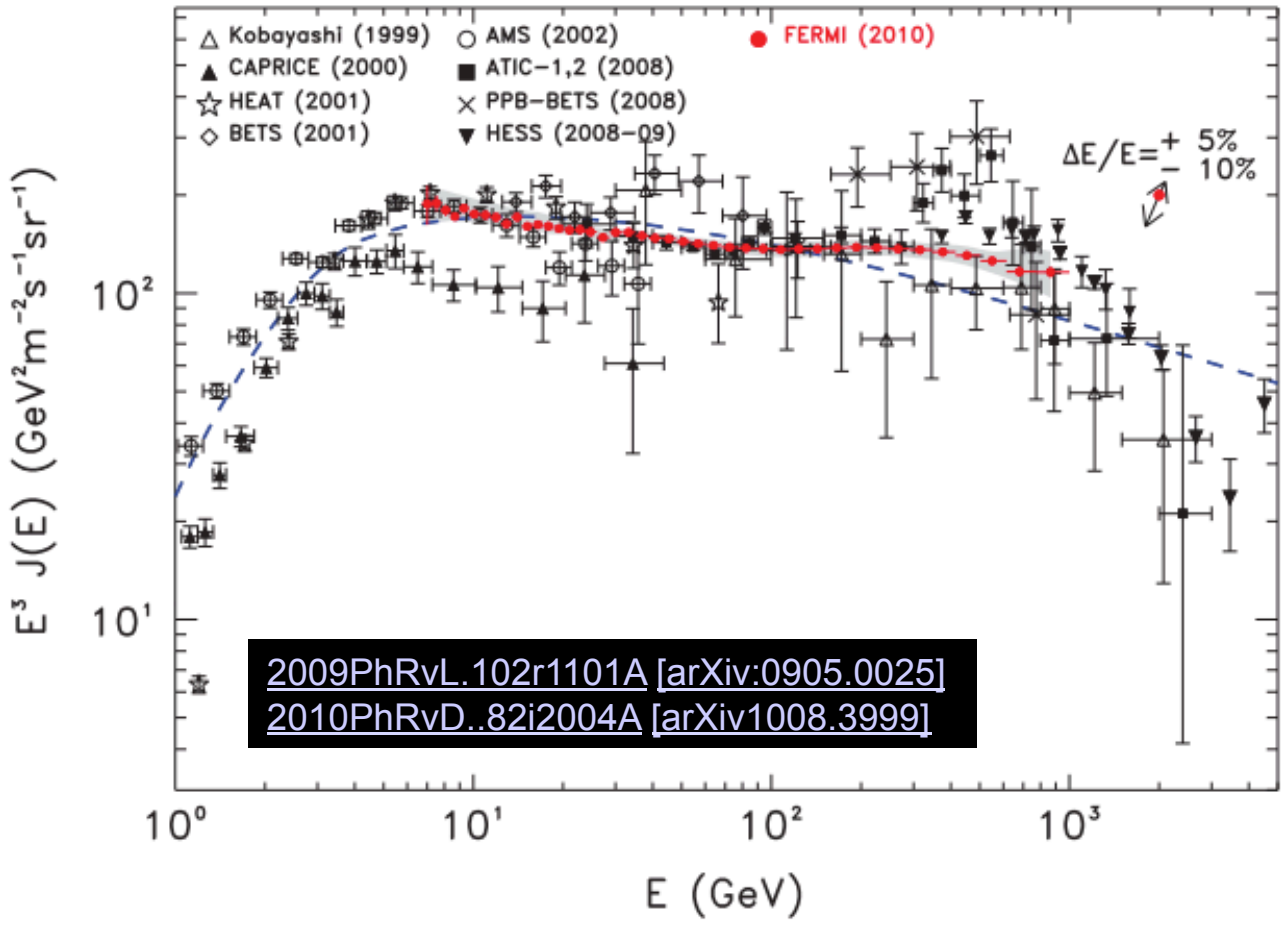


Positron Fraction Measurements



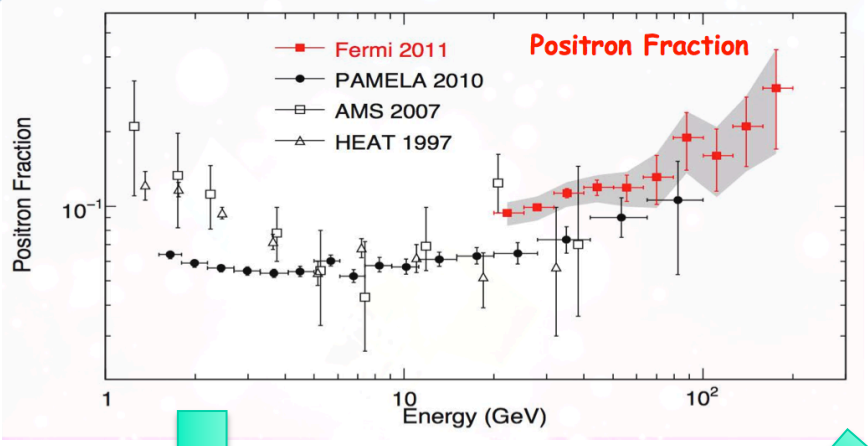
- PAMELA and Fermi-LAT observe a rise in local e^+ fraction above ~10 GeV
- This disagrees with conventional models (e.g., GALPROP) for cosmic rays (secondary e^+ production only)
- No similar rise is seen in anti-proton fraction

e^+e^- Combined Spectrum



•Fermi-LAT also observes a small, wide, spectral feature in the combined e^+e^- spectrum between 100GeV and 1 TeV

New Fundamental Physics or New Astrophysics?

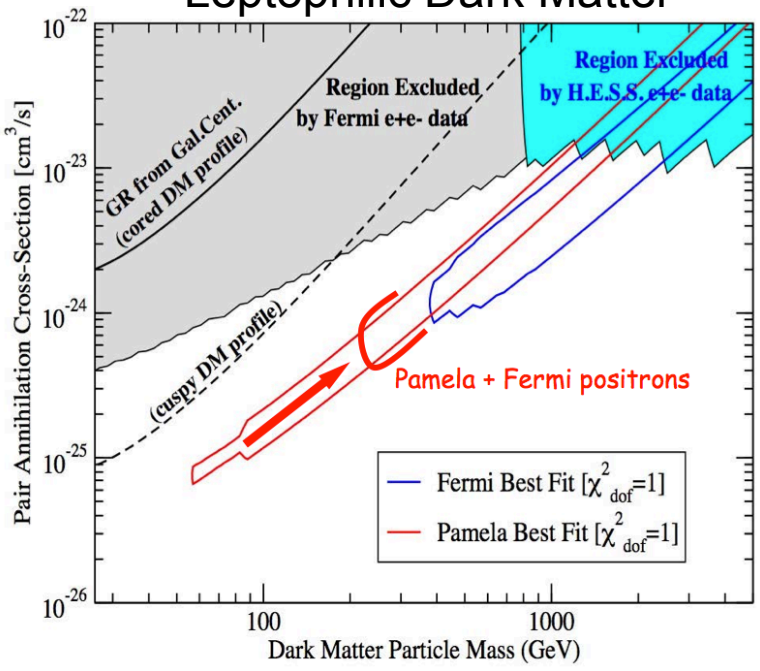


Understanding γ-ray sources is key to disentangling fundamental physics from astrophysics

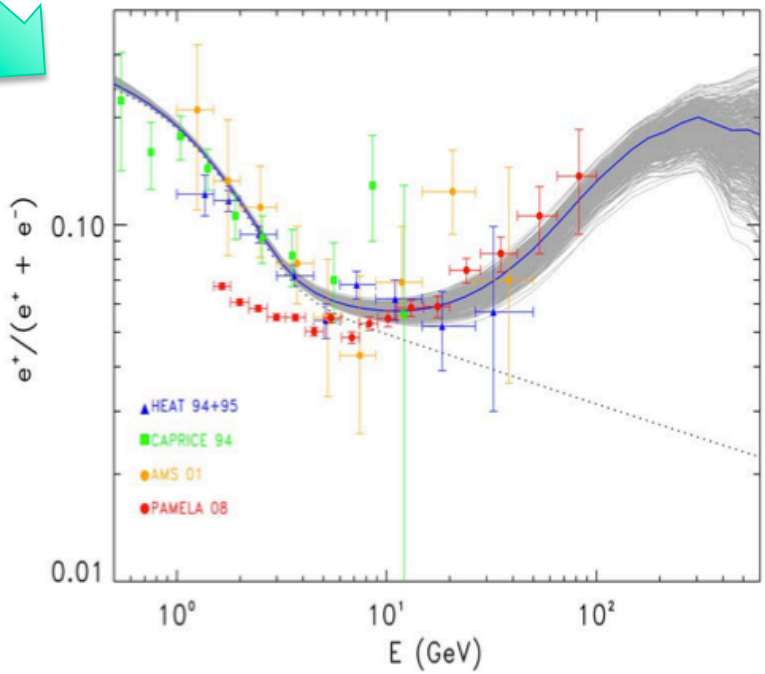
Increases discovery potential and allows more stringent constraints on DM

2009APh....32..140G [arXiv:0905.0636]

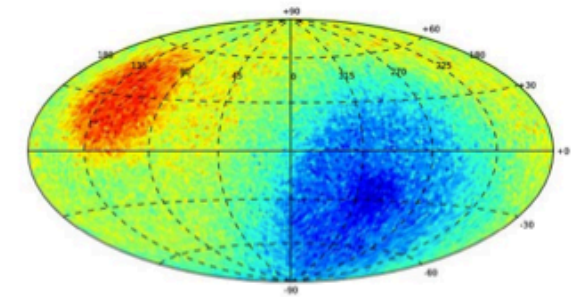
Leptophilic Dark Matter

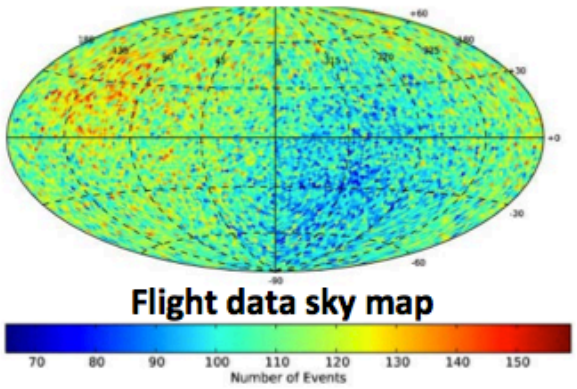


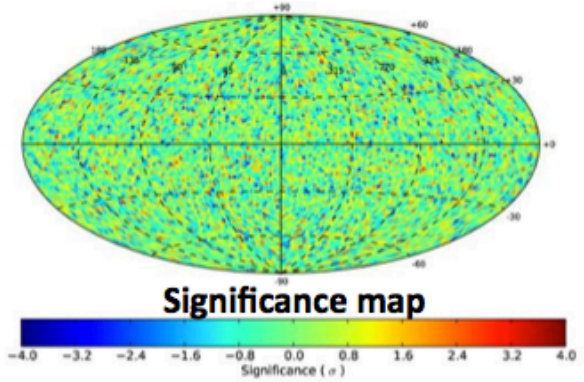
Pulsars

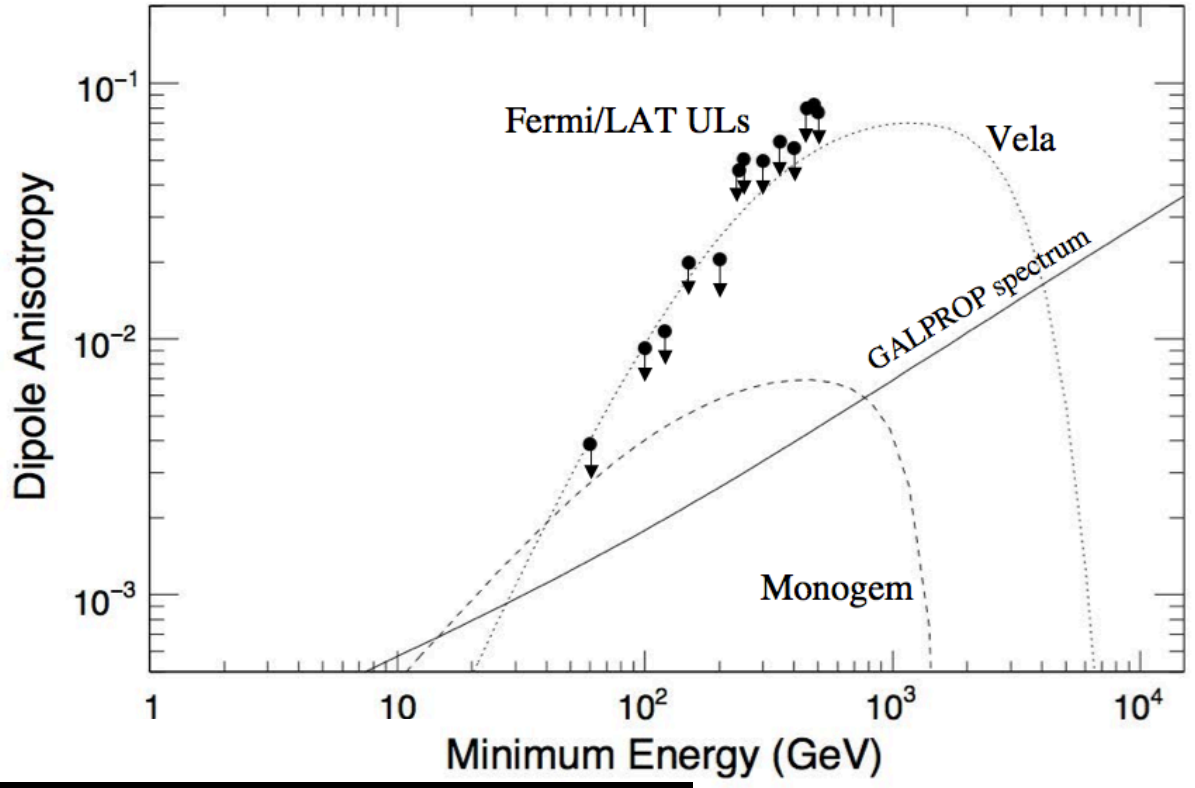


$e^+ + e^-$ Anisotropy





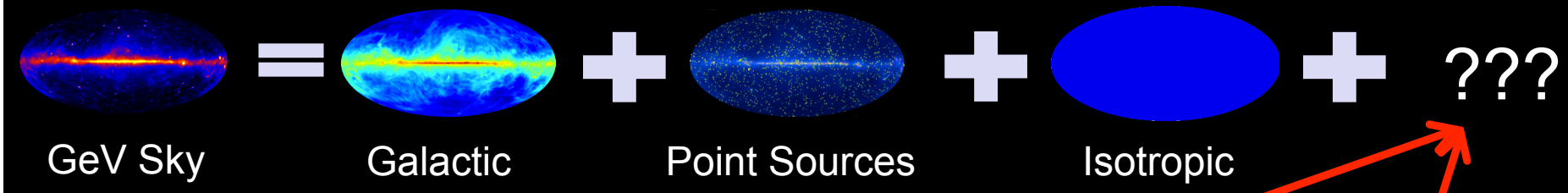


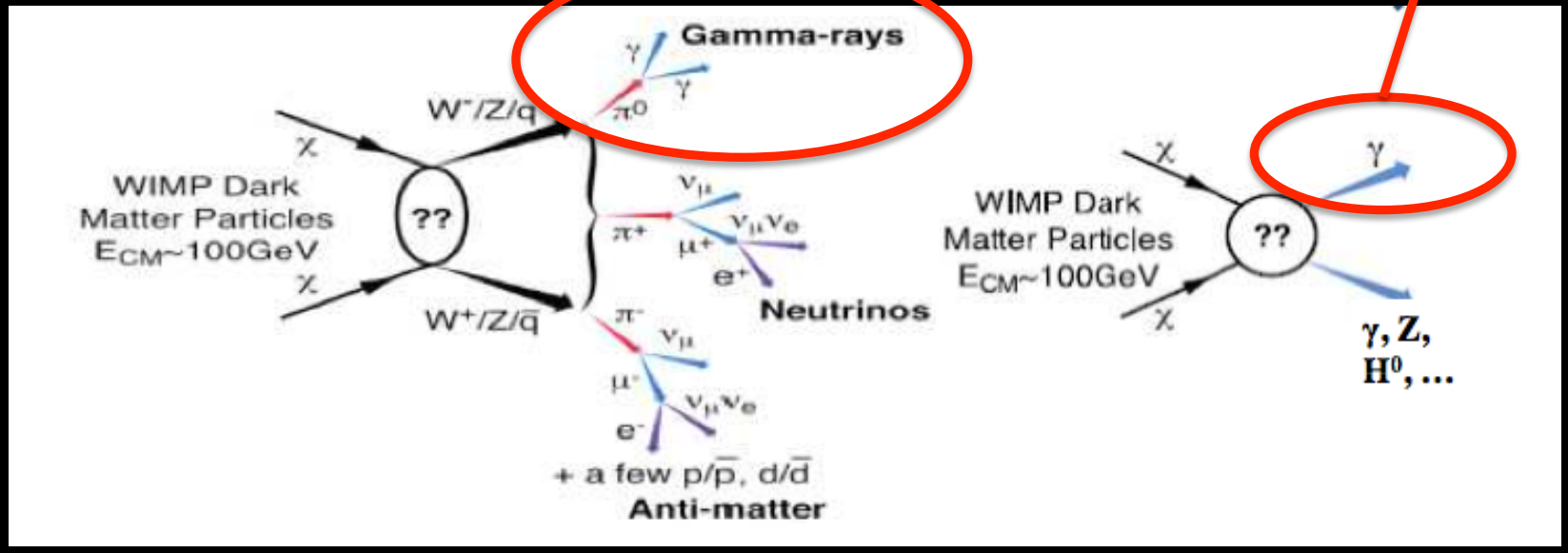


2010PhRvD..82i2003A [arXiv:1008.5119]

- **Search for large scale anisotropies in e^+e^- data yield null results**
- **However, the upper-limits are not stringent enough to rule out nearby pulsars as source for high energy leptons**

Indirect Searches for DM in the γ-ray Sky





Dark Matter Search Strategies

Satellites

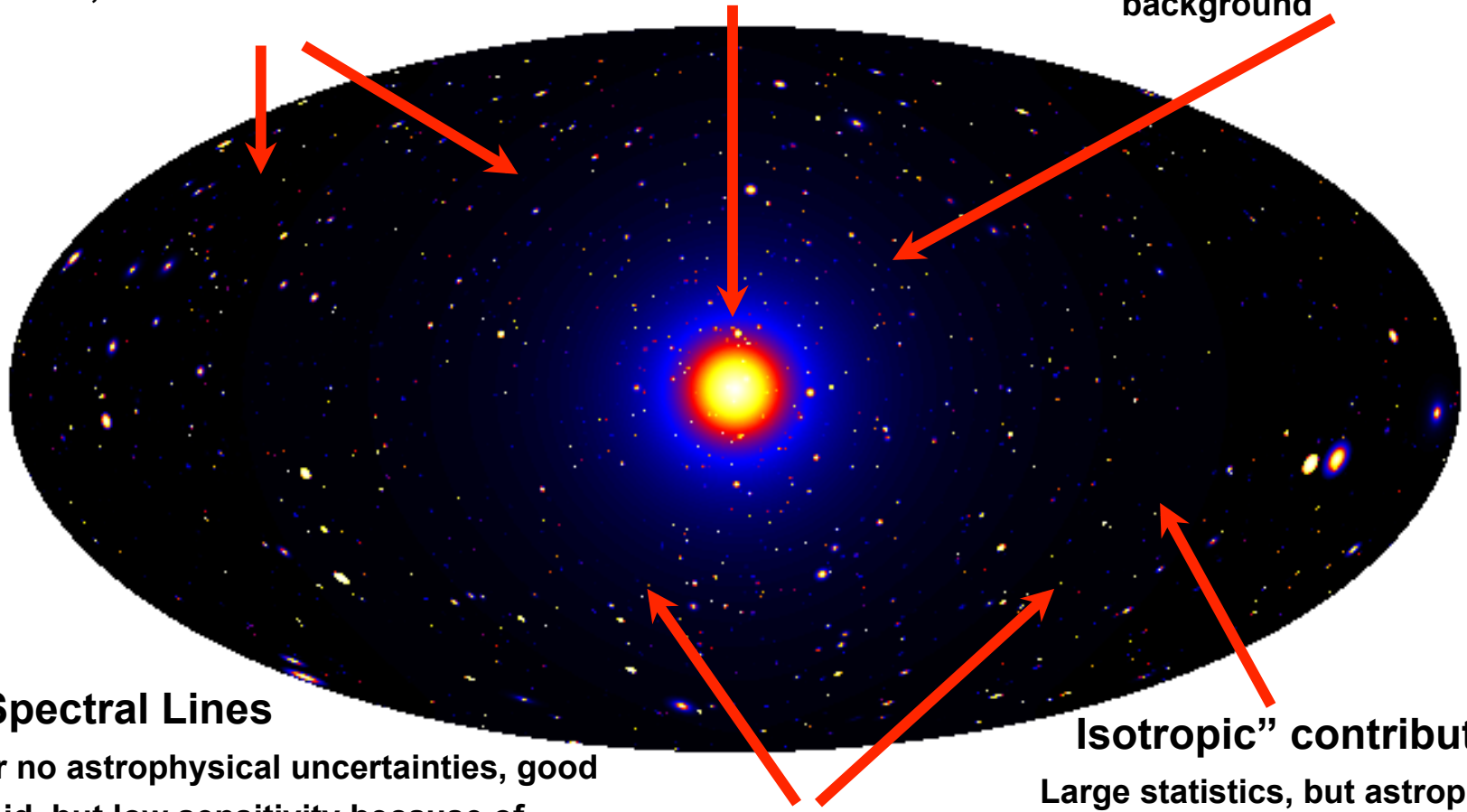
Low background and good source id, but low statistics

Galactic Center

Good Statistics, but source confusion/diffuse background

Milky Way Halo

Large statistics, but diffuse background



Spectral Lines

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

Isotropic" contributions

Large statistics, but astrophysics, galactic diffuse background

Galaxy Clusters

Low background, but low statistics

Dark Matter simulation: Pieri+(2009) arXiv:0908.0195

Search Strategies (against the γ-ray Sky)

Satellites

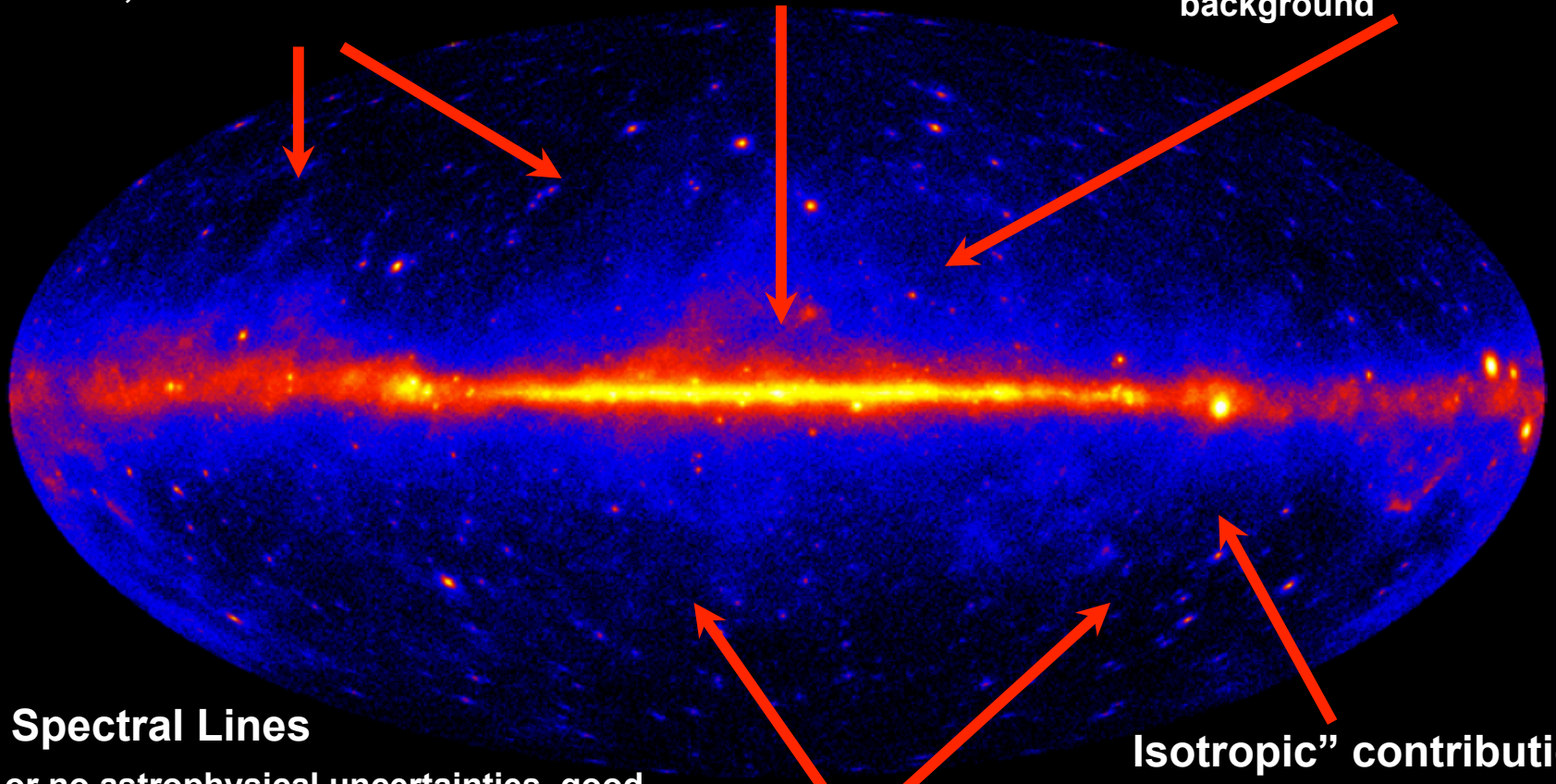
Low background and good source id, but low statistics

Galactic Center

Good Statistics, but source confusion/diffuse background

Milky Way Halo

Large statistics, but diffuse background



Spectral Lines

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

Galaxy Clusters

Low background, but low statistics

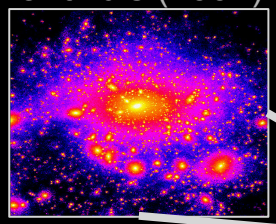
Isotropic" contributions

Large statistics, but astrophysics, galactic diffuse background

3 Years Sky > 1 GeV

Searches for DM Satellites in Unid. LAT Sources

Simulated DM Satellite
Kazantzidis (2007)



2012ApJ...747..121A [arXiv:1201.2691]

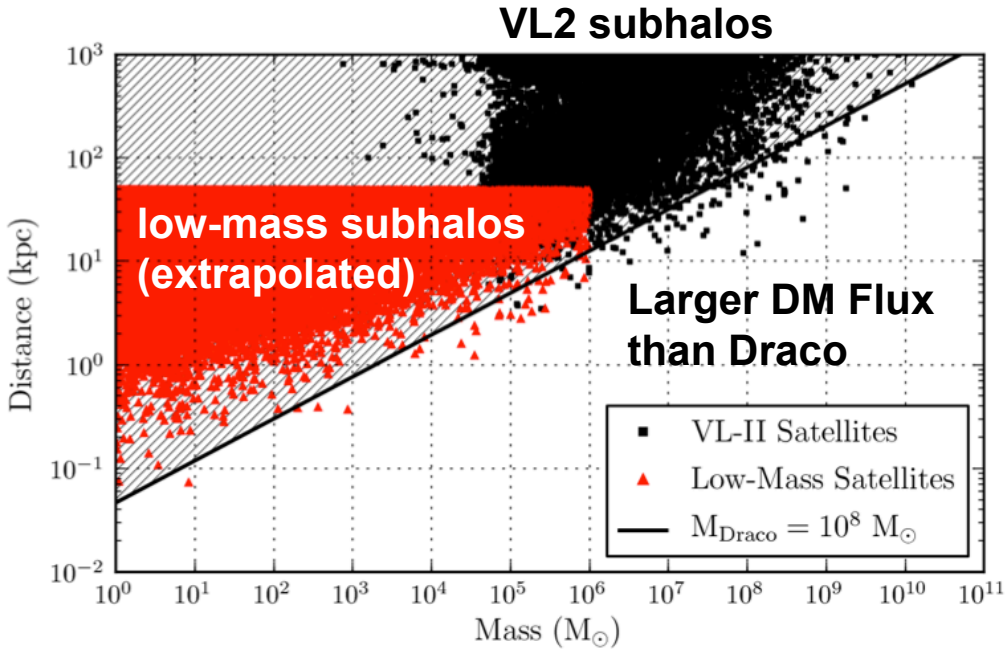
- **Look for LAT Catalog Sources that are consistent with DM signatures and inconsistent with known astrophysical sources classes**

DM in Unid. Sources: Results and Developments

- **Search criteria:**
  - **Catalog Sources**
  - **Off-plane: |b| > 10°**
  - **No counterpart at other wavelengths**
  - **Steady emission**
  - **Spatially extended**
  - **Spectrum consistent with DM**
- **Results:**
  - **No sources pass criteria**
  - **From N-body simulations we infer constrains on annihilation cross-section:**

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

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



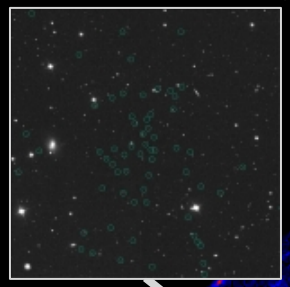
See also:
Buckley & Hooper, PRD 82 (2010) 063501;
Belikov+ [arXiv:1111.2613];
Zechlin+ [arXiv:1111.3514];

Mirabel+ [arXiv:1205.4825] use Random Forest Classifier to identify DM-like sources in 2FGL Catalog

2012ApJ...747..121A [arXiv:1201.2691]

Searches for DM in Dwarf Spheroidal Galaxies

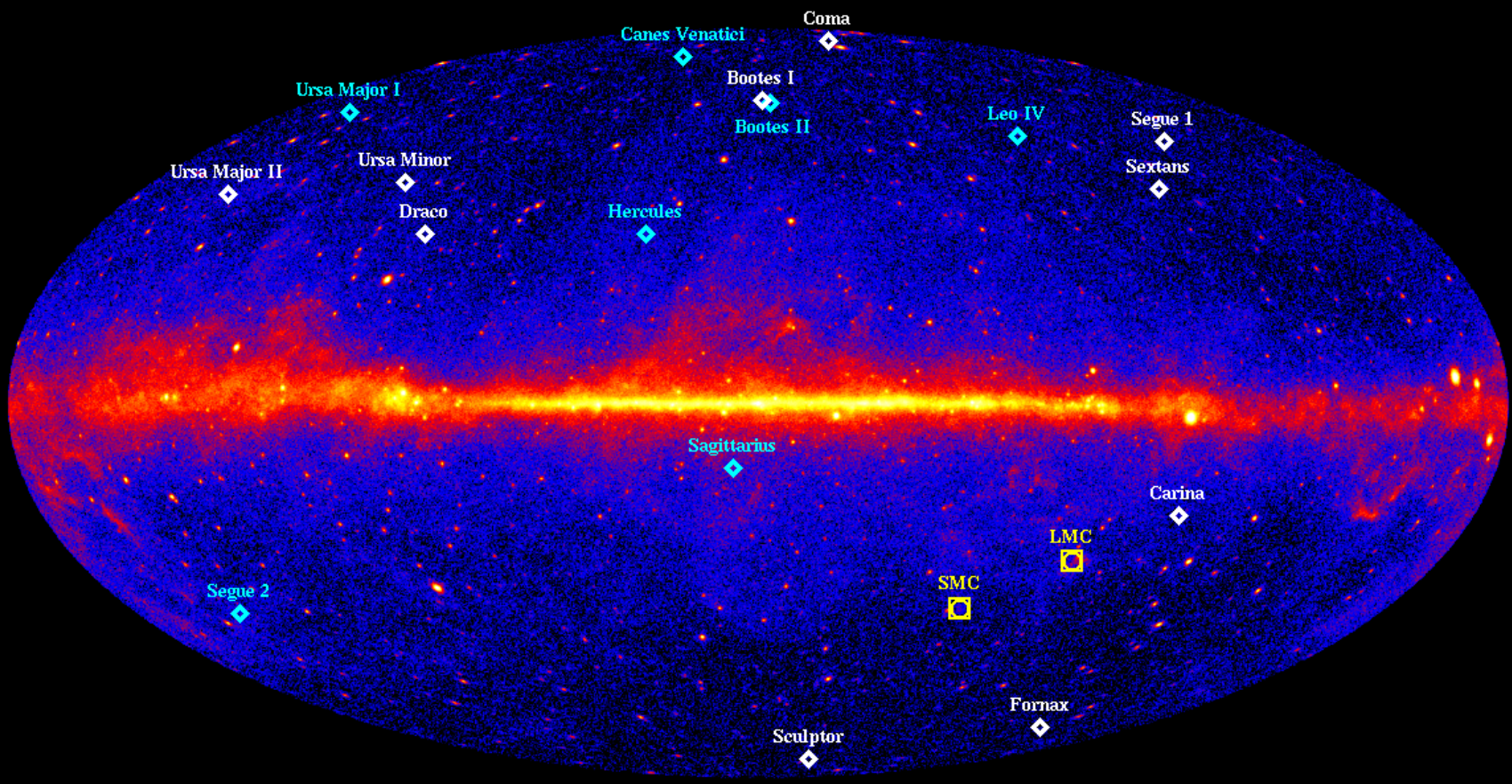
Segue 1
Keck Observatory



2010ApJ...712..147A [arXiv:1001.4531]
2011PhRvL.107x1302A [arXiv:1108.3546]
2012JCAP...04..016C [arXiv:1111.2604]
arXiv:1205.3620 arXiv:1203.6731

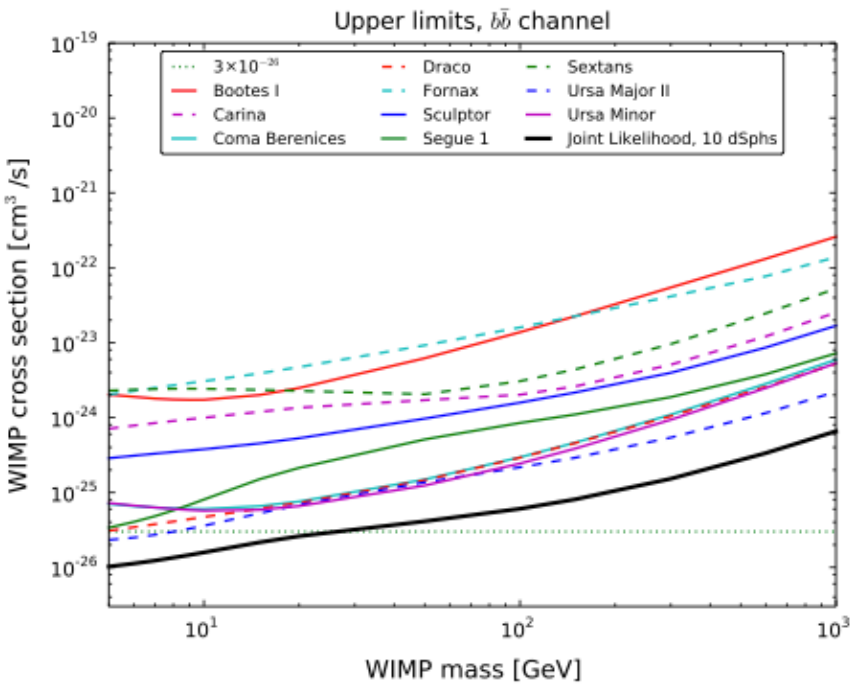
- Look for γ-ray emission from Dwarf Spheroidal galaxies with large, well measured, J-factors at high Galactic latitudes
- This is as a low-signal, low-background search strategy

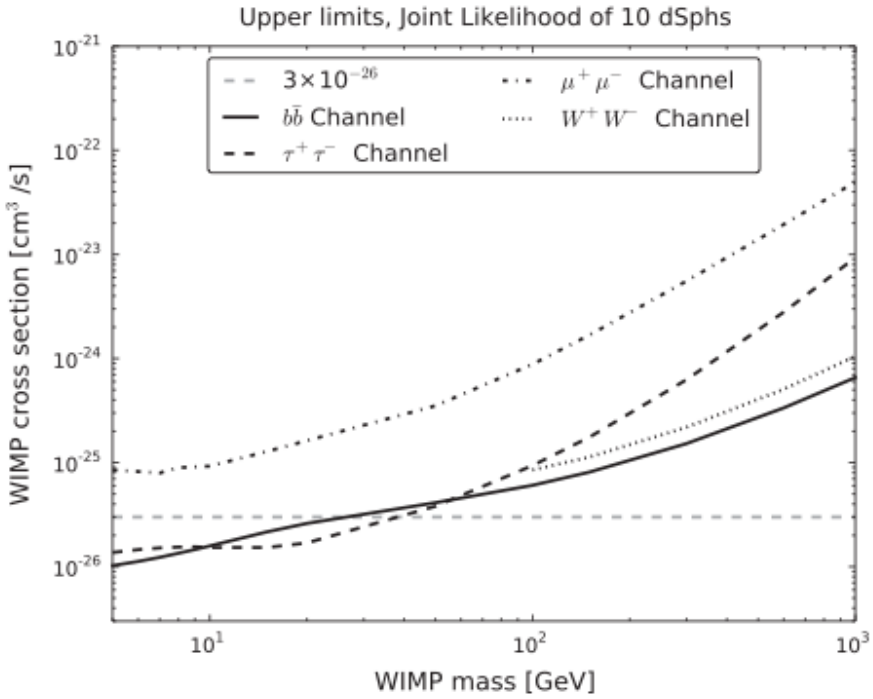
DM in dSph: Search Targets



- Roughly two dozen Dwarf Spheroidal satellite galaxies of the Milky Way
- Some of the most dark matter dominated objects in the Universe
- Negligable astrophysical γ-ray production expected

DM in dSph: Results

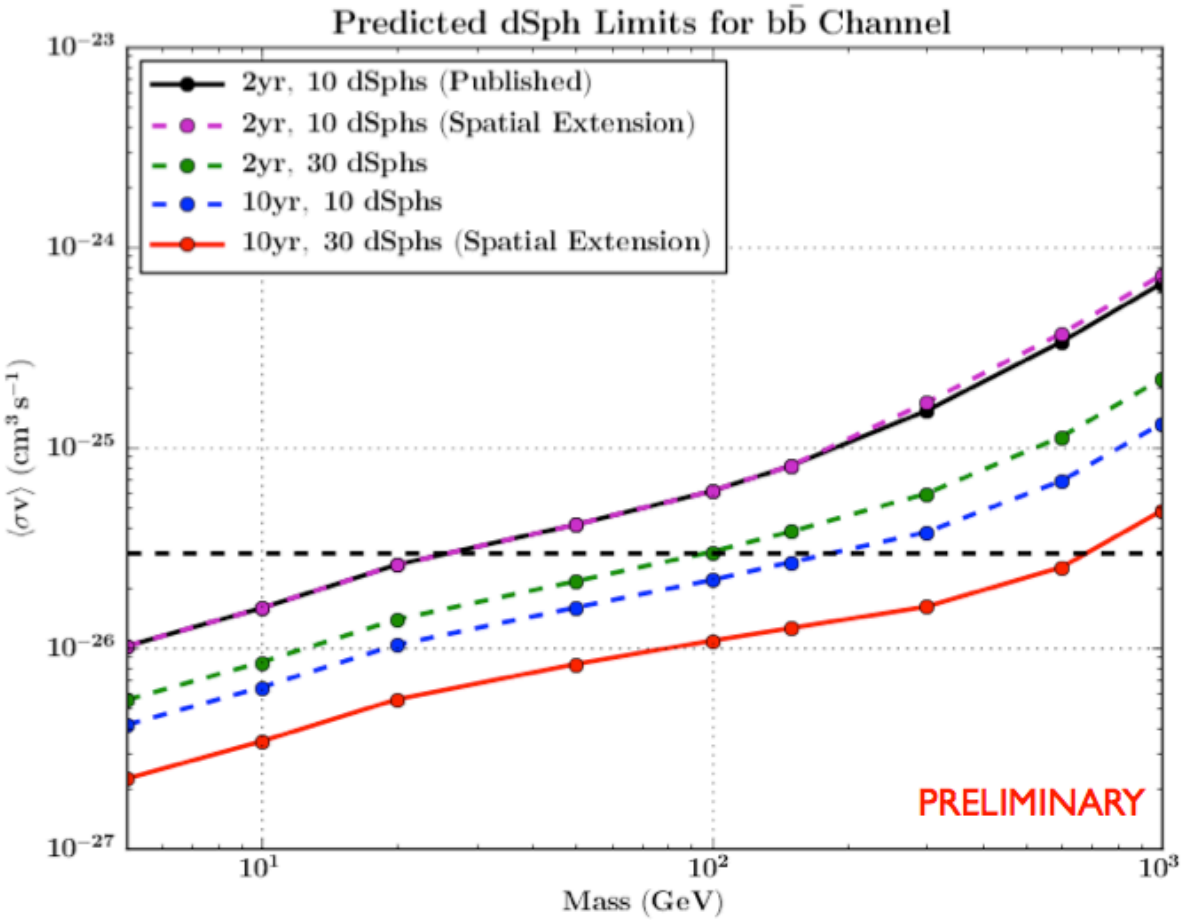




Combined upper limit excludes "canonical" thermal relic cross-section for annihilation into bb or $\tau^+\tau^-$ for masses below ~ 30GeV

2011PhRvL.107x1302A [arXiv 1108.3546]

DM in dSph: Prospects

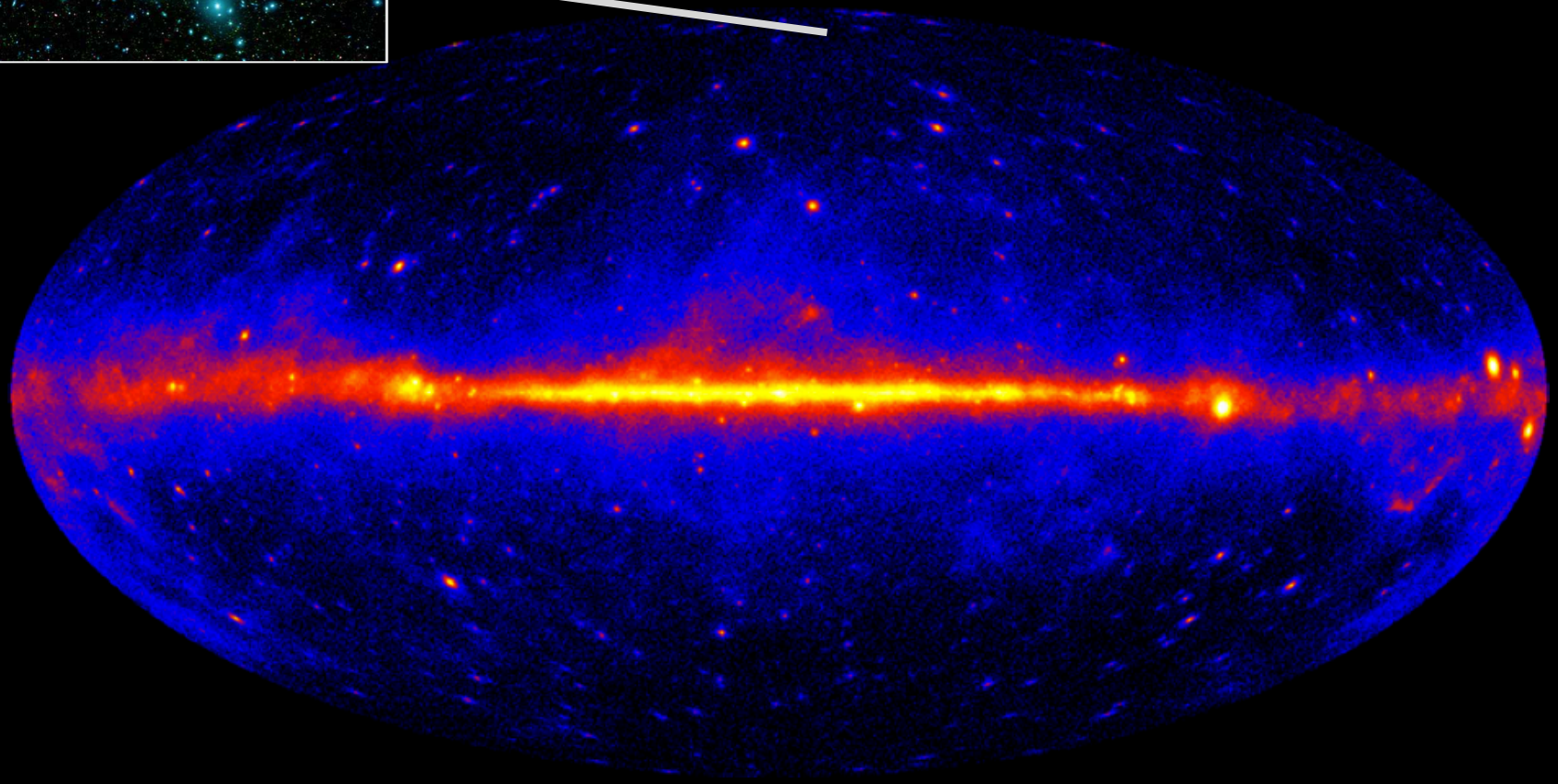


Discovery of new dSph and increased observing time should allow us to explore the thermal relic cross section up to almost 1TeV by the end of the mission

Search for DM in Galaxy Clusters

Coma Cluster
Spitzer/ SDSS/ JPL/ NASA

2010JCAP...05..025A [arXiv:1002.2239]

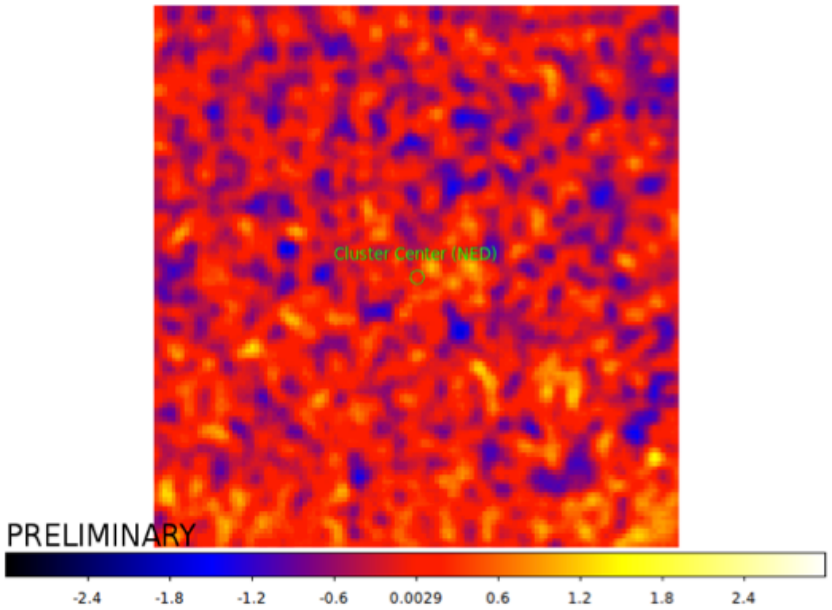


- Look for γ-ray emission from Galaxy Clusters with high missing mass and no γ-ray blazars (or other AGN)
- This is a low-signal, potentially low-background search strategy

DM in Galaxy Clusters: Search Strategy

- Clusters are largest and most massive structures in universe
  - Lensing / X-ray data imply high DM content
    - High DM signal
  - Radio data implies relativistic CR
    - Potential γ-ray backgrounds

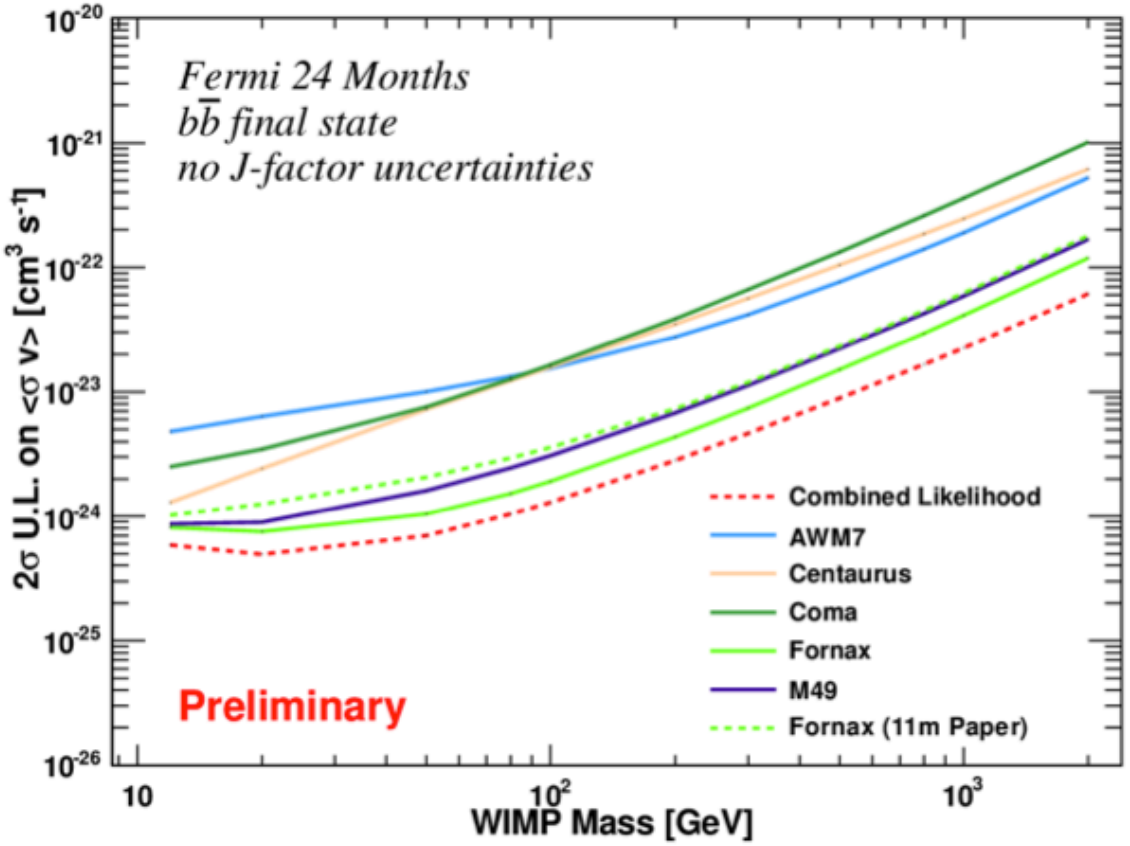
Stacked Cluster Counts Map



- **Results:**
  - No significant detection
  - Infer limits from individual clusters and for the stacked sample

2010JCAP...05..025A [arXiv:1002.2239]

Limits from Galaxy Clusters

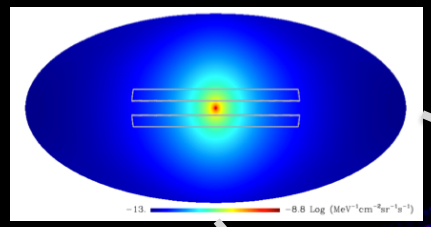


- Combined cluster limits are less stringent than dSph
- However, there is significantly more uncertainty about DM distributions
- Galaxy Clusters can be competitive with dSph for constraining models with enhanced DM rates

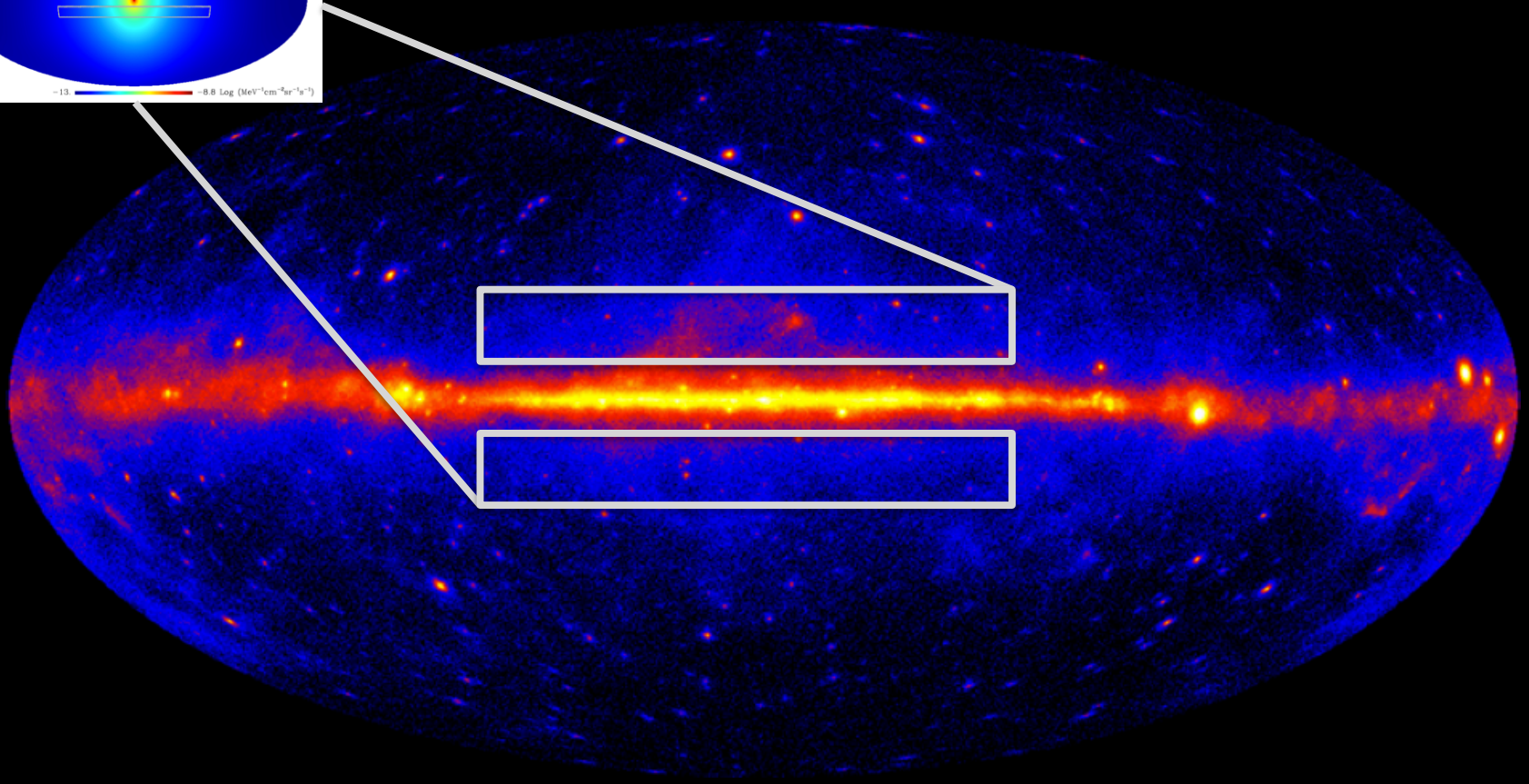
2010JCAP...05..025A [arXiv:1002.2239]

Search for DM in the Galactic Halo

Simulation of 250 GeV WIMP into b bbar



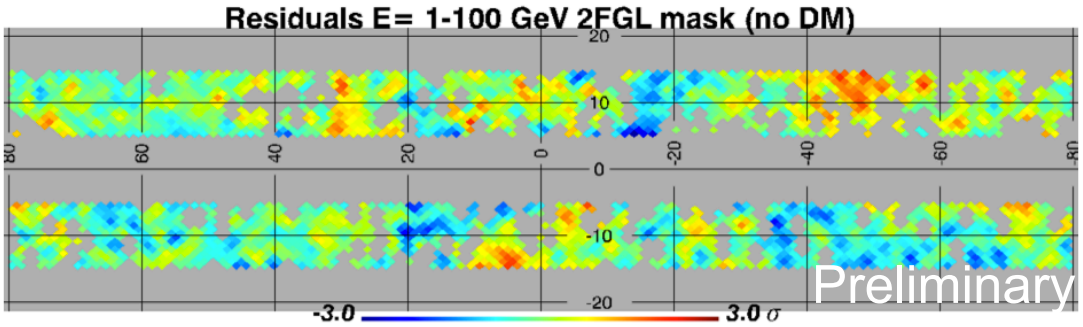
arXiv:1205.6474v1



- Look for a hard-spectral excess near (but slightly off) the Galactic plane
- This is a trade-off between larger signals in the plane and smaller astrophysical foregrounds away from the plane

Halo Method I: "No-background" Limits

- **No non-DM background modeling**
  - **Robust to many uncertainties (models leave many structured residuals in ROI)**



- **Expected DM counts (n_{DM}) compared to observed counts (n_{data})**
  - **3σ and 5σ upper limits are set using**

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

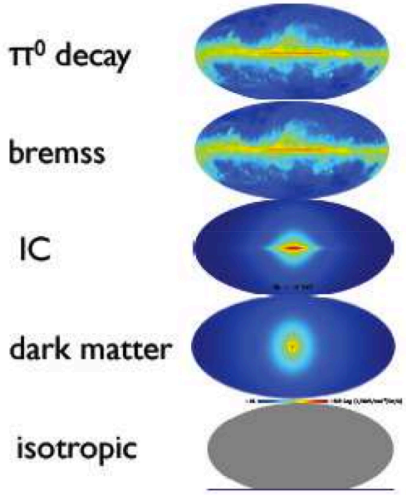
  - **in at least one energy bin**

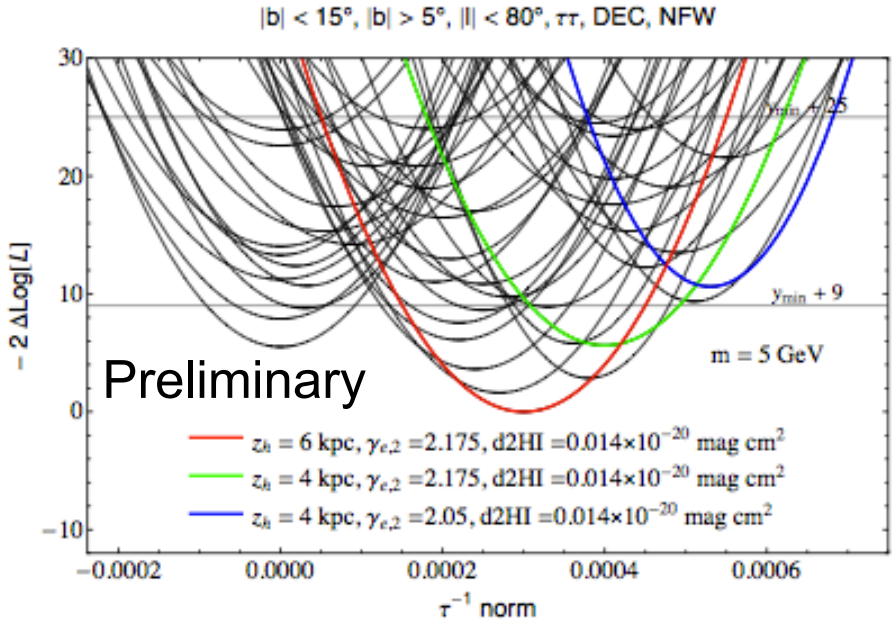
arXiv:1205.6474v1

Halo Method II: "Marginalize over Diffuse Models"

- **Template-based profile likelihood fit:**
  - **Diffuse components, some GALPROP-based**
  - **Isotropic component**
  - **DM component**

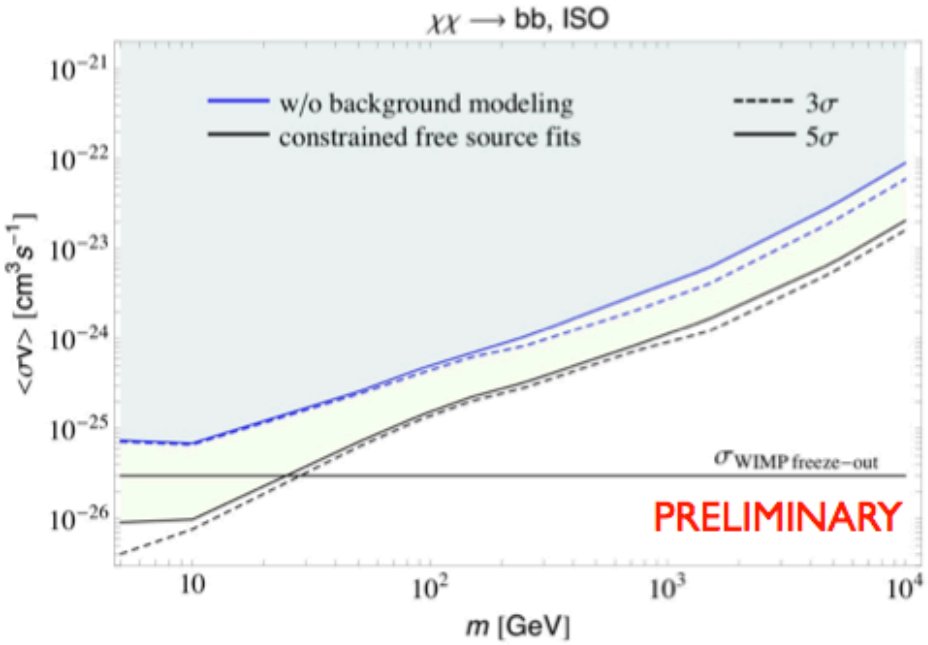
- **Sample ranges of several key bkg. parameters:**
  - **CRE injection index**
  - **diffuse halo height**
  - **gas (HI) to dust ratio**
  - **CR source distribution**
  - **local H2 to CO factor**
  - **isotropic normalization**

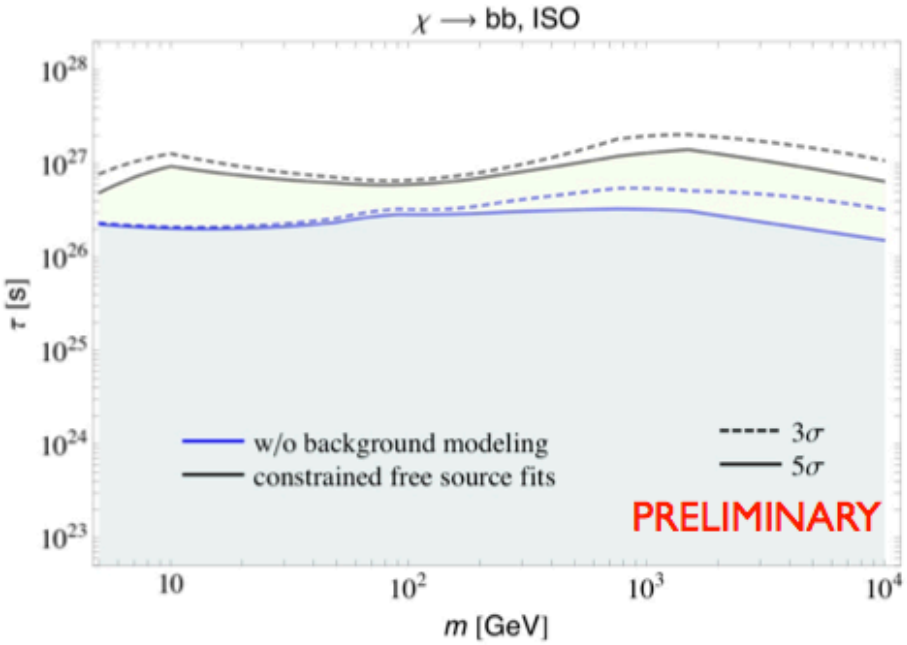




arXiv:1205.6474v1

Halo Search Results: bb Channel

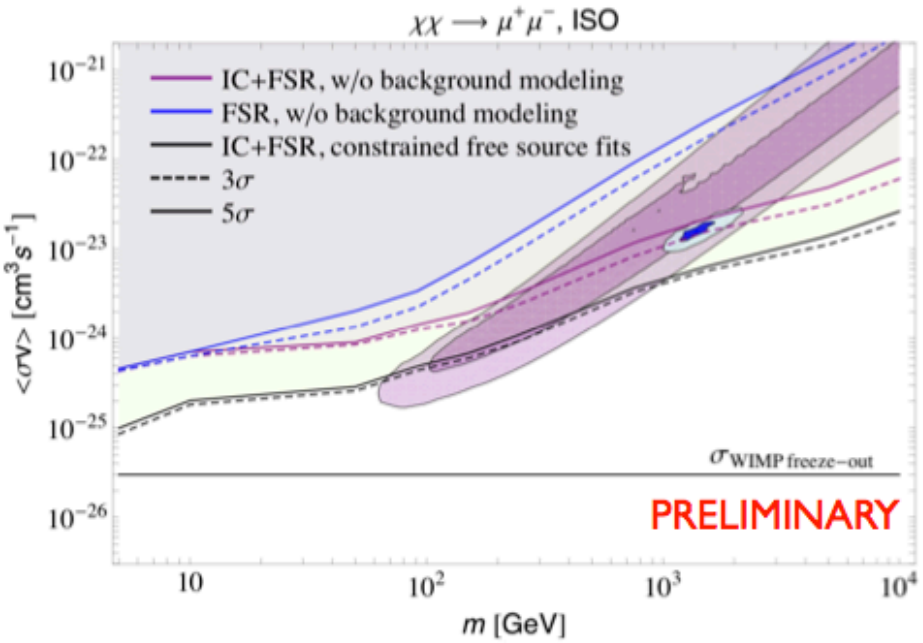


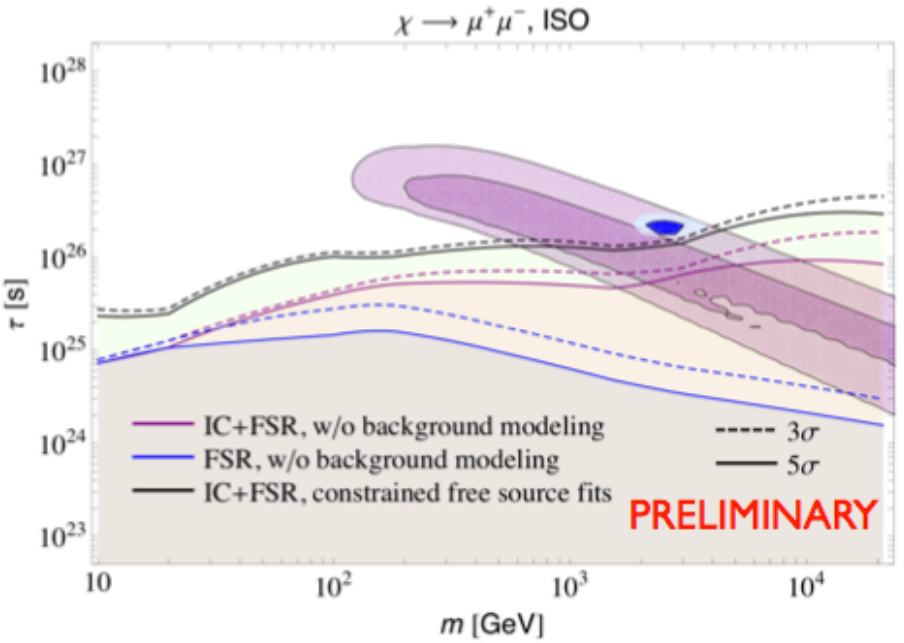


- **Method II (marginalize over astrophysical models) limits are about an order of magnitude deeper than conservative limits**
- **Similar to saying that we understand about 90% of the diffuse emission in the Galactic Halo region**

arXiv:1205.6474v1

Halo Search Results: $\mu^+\mu^-$ Channel



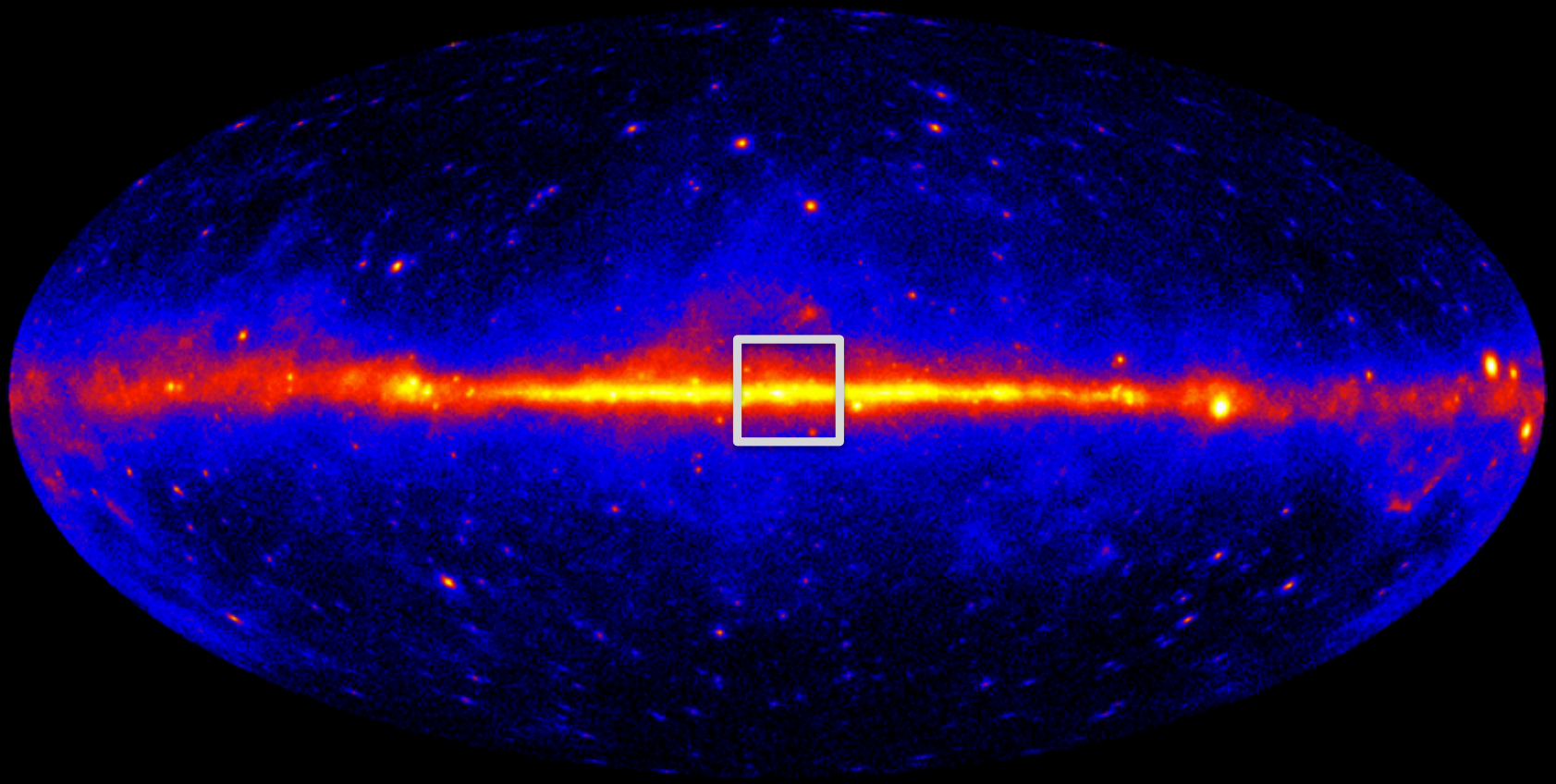


- **blue: only γ rays produced by $\mu^+\mu^-$ (no e^+e^-) to set "no-background limits", i.e., only including Final State Radiation (FSR)**
- **violet: "no-background limits" including FSR + Inverse Compton (IC) from DM**
- **black: limits from profile likelihood + CR sources set to zero in the inner 3 kpc**

DM interpretation of PAMELA/Fermi CR anomalies in tension with limits derived by including background modeling

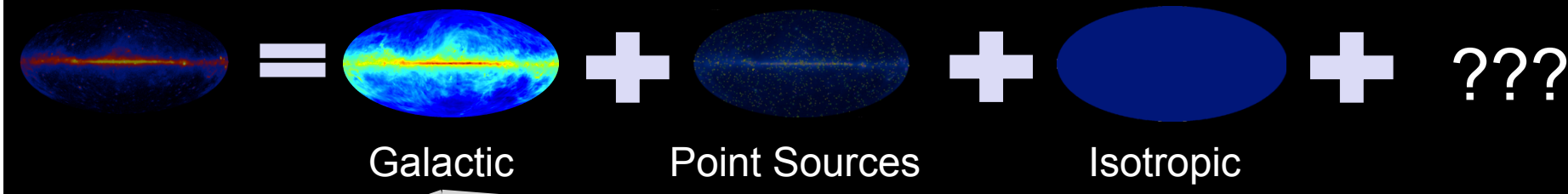
arXiv:1205.6474v1

Search for DM in the Inner Galaxy

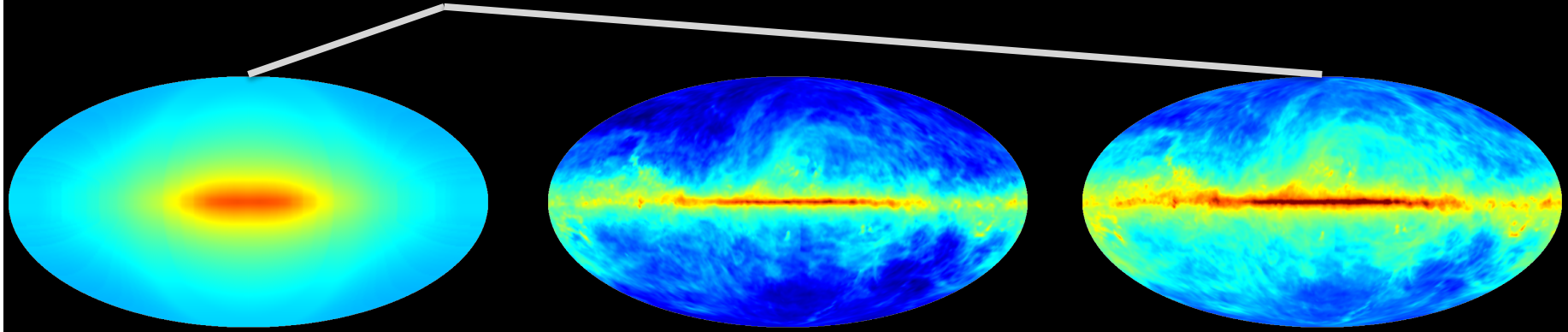


- The eventual goal is to look for DM in the inner Galaxy
- Because of the large astrophysical foregrounds, we must first understand the γ-ray emission from the Galaxy and from known source classes

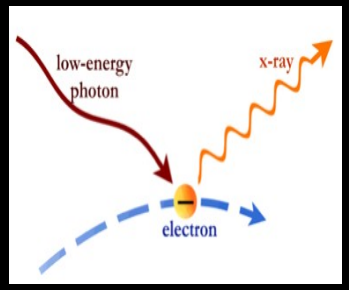
IG Analysis: Refitting the Diffuse Model

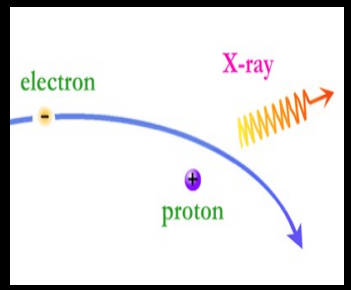


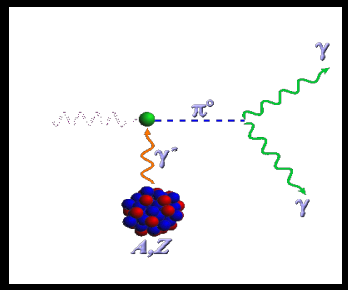
Galactic | Point Sources | Isotropic



Inverse Compton | Bremsstrahlung | π^0 decay

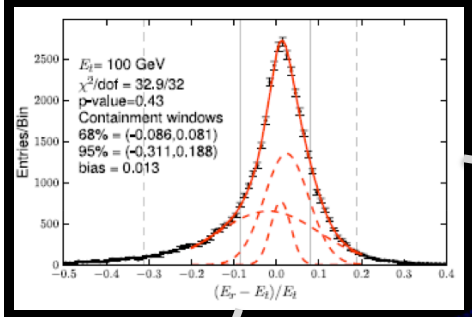




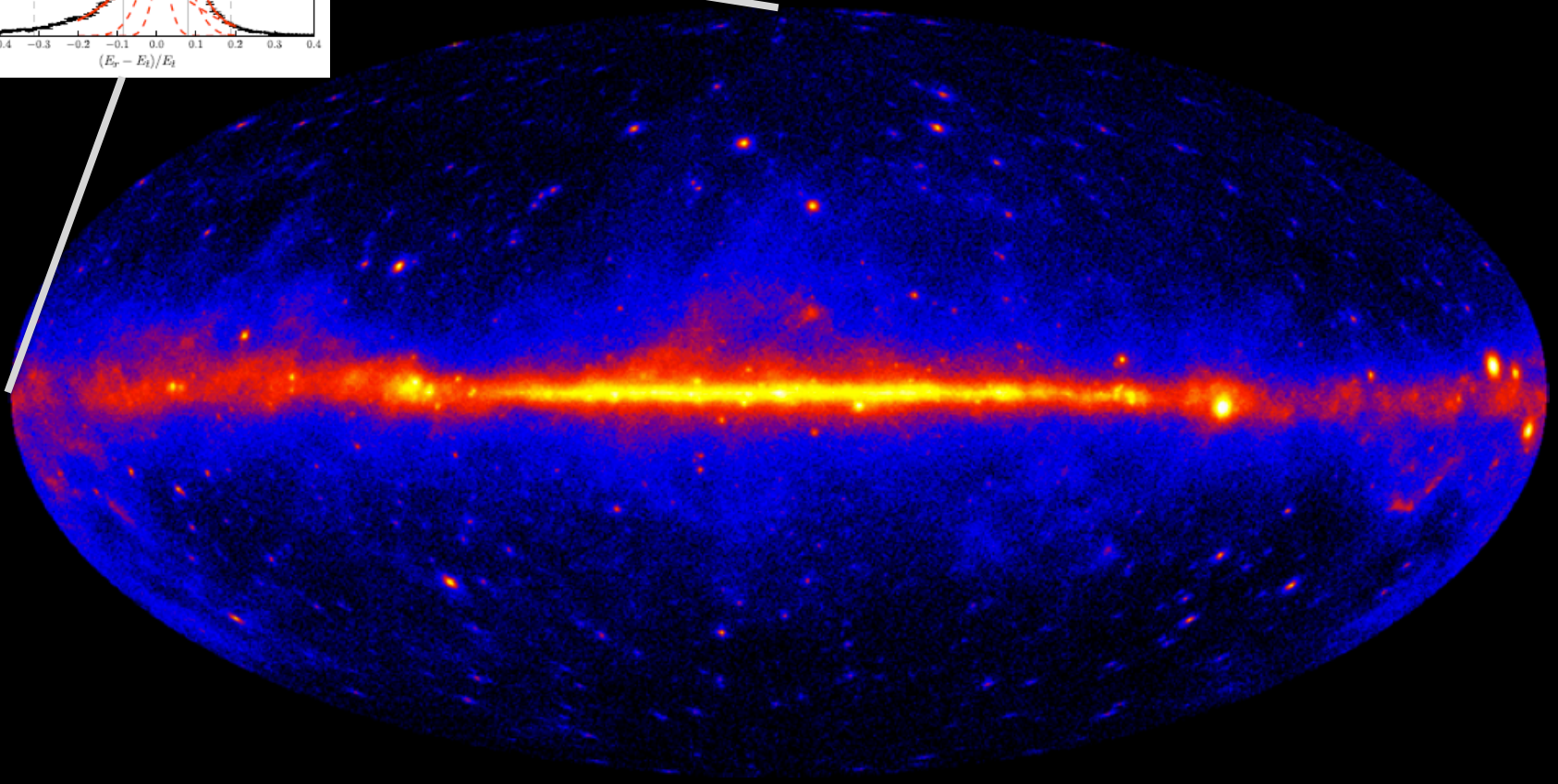


- **Start with diffuse emission model which is tuned to the inner 45°x45° of the Galaxy**
- **Analysis in progress, stay tuned**

Search for γ-ray Line(s)



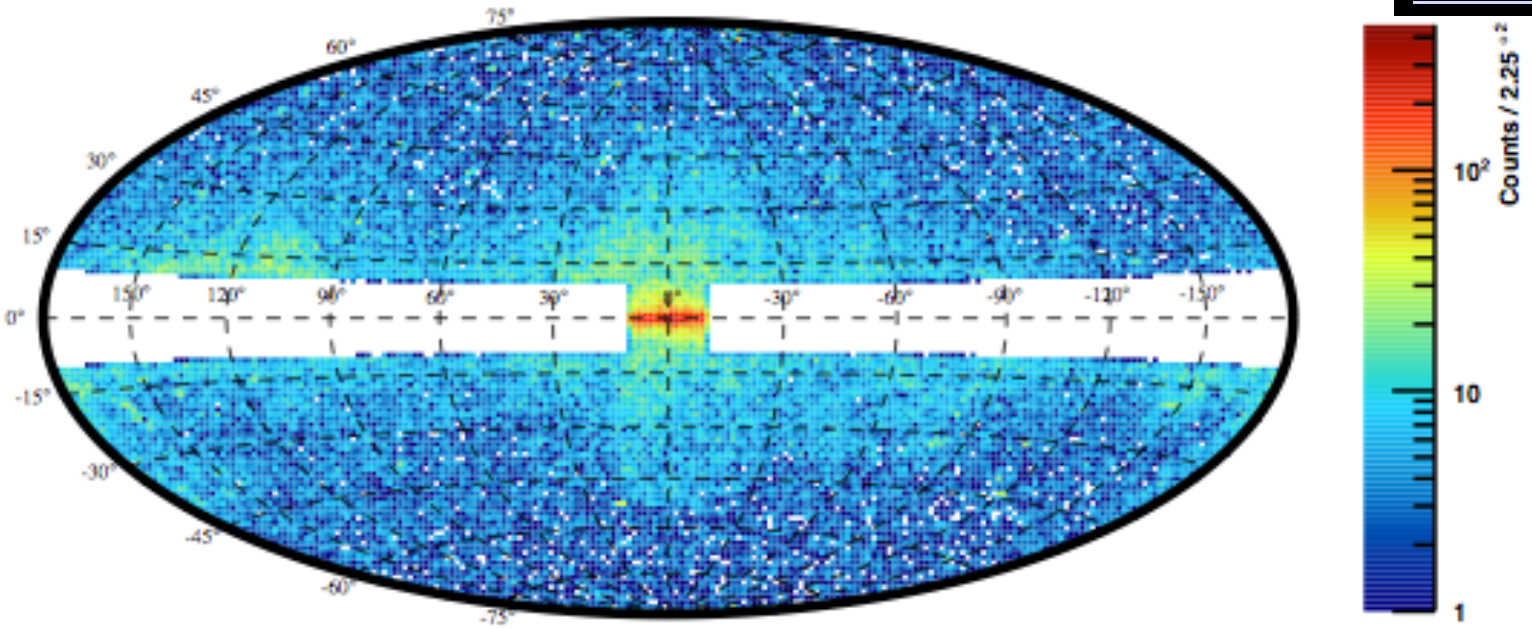
2010PhRvL.104i1302A [arXiv:1108.0501]
arXiv:1205.2739



- Look for spectral features consistent with the instrumental energy resolution
- A very clean signal, but highly suppressed in many WIMP scenarios

Search for γ-ray Line(s): Data Analysis

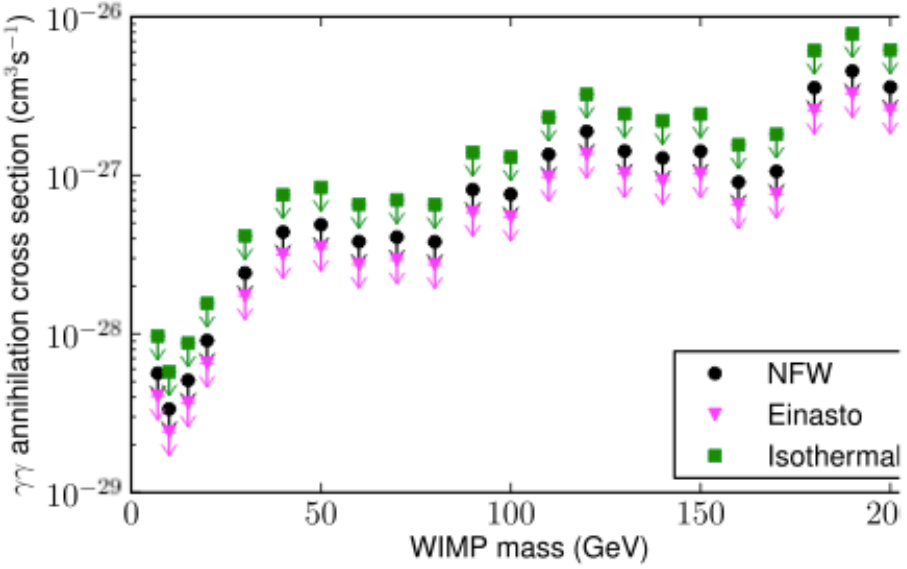
arXiv:1205.2739

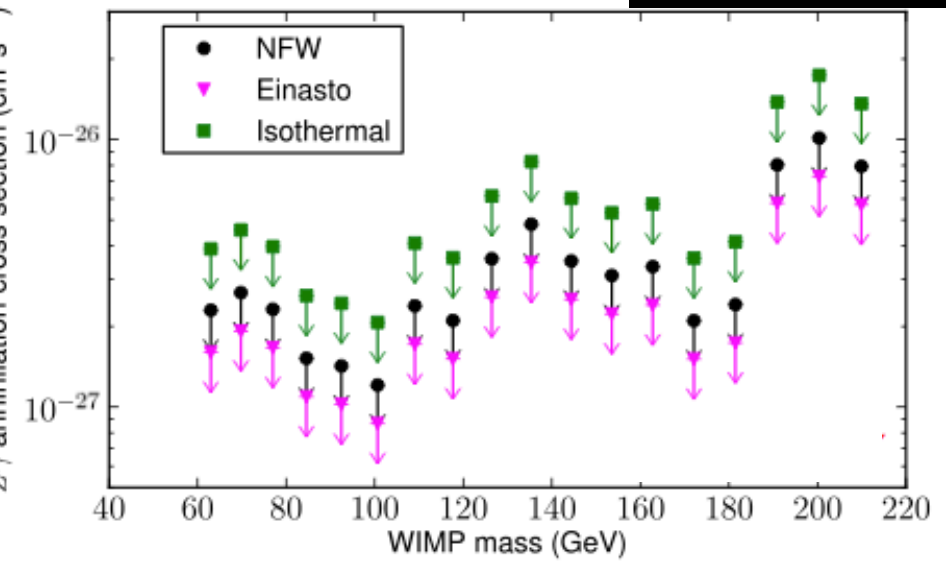


- Search for γ-ray line for DM annhilation or decay (γγ and γZ channels)
- Data Analysis:
  - Exclude Galactic plane and mask 1FGL catalog sources
  - Fit in sliding windows to powerlaw background (index free) + energy resolution PDF
- Extract limits for Einasto, NFW and Isothermal DM profiles

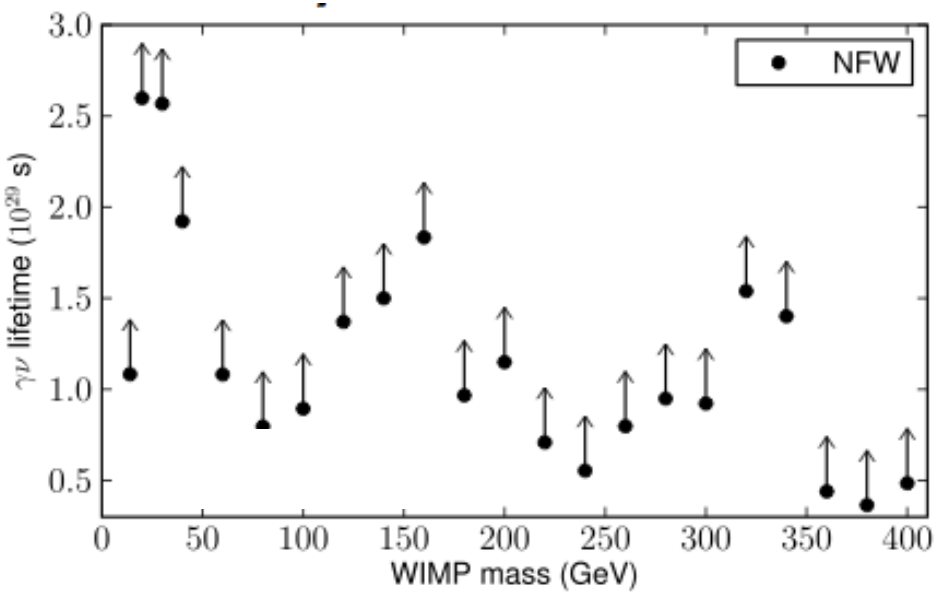
Line Search Upper Limits

arXiv:1205.2739

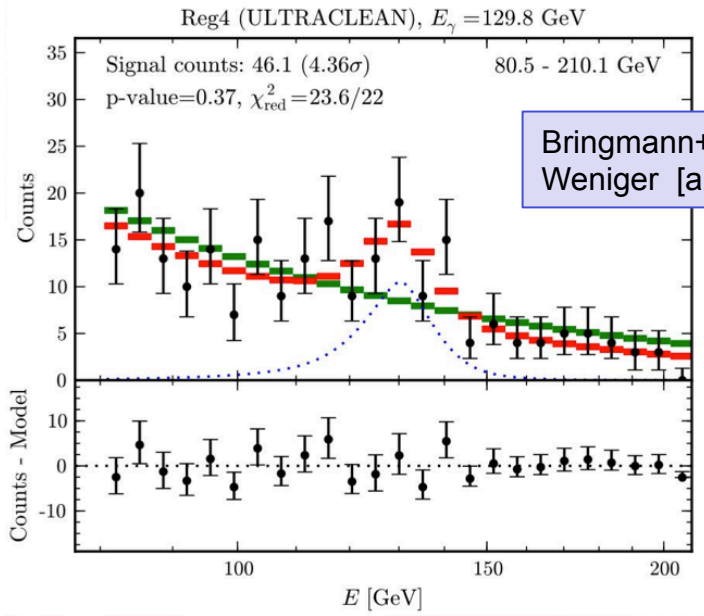




- **Non-detection used to place limits on annihilation cross section for 3 DM profiles**



Reprise: New Physics or New Astrophysics



Bringmann+ [arXiv:1203.1312]
Weniger [arXiv:12.2797]

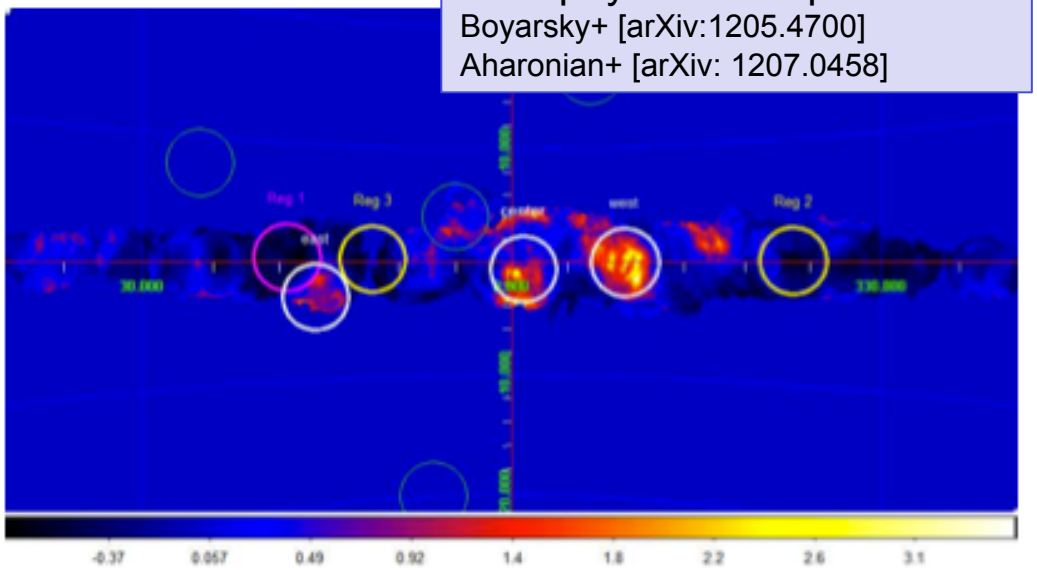
Interpretations and follow up analyses:
Tempel+ [arXiv:1205.1045]
Kyae & Park [arXiv:1205.4151]
Dudas+ [arXiv:1205.1520]
Lee+ [arXiv:1205.4700]
Acharya+ [arXiv:1205.5789]
Buckley & Hooper [arXiv:1205.6811]
Su & Finkbeiner [arXiv:1206.1616]
Chu,Hambye + [arXiv:1206.2279]
& many others

Narrow excess ~130GeV associated with Inner Galaxy

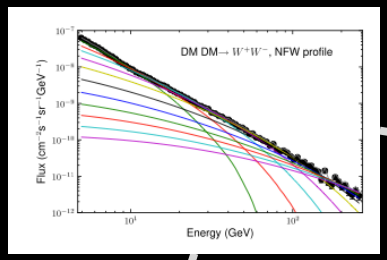
Many DM models, but also models of spectra features from astrophysics

Need to extract more information from *morphology* and *MW observations*

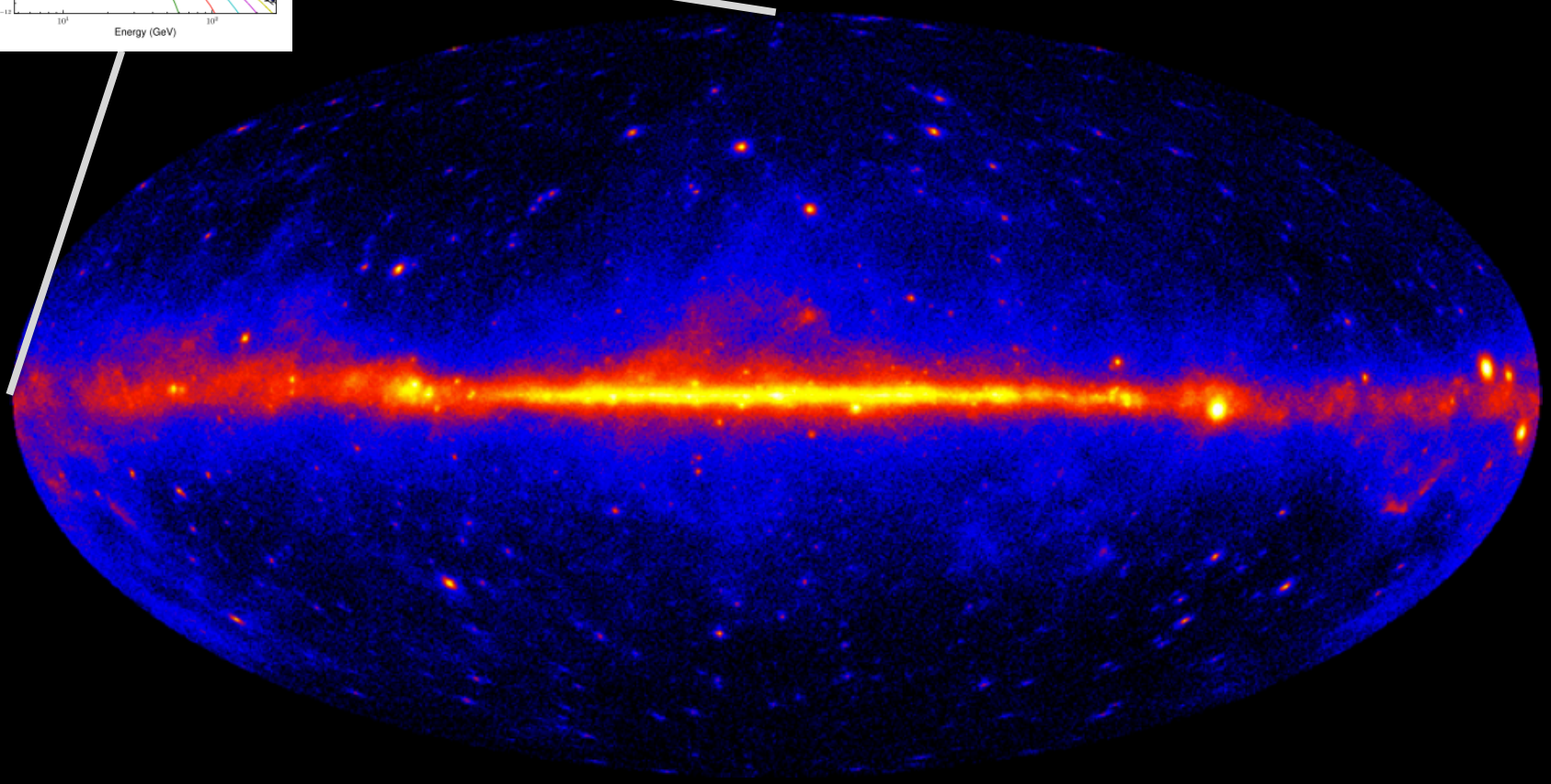
Astrophysical Interpretations:
Boyarsky+ [arXiv:1205.4700]
Aharonian+ [arXiv: 1207.0458]



DM Limits from Inclusive Spectrum



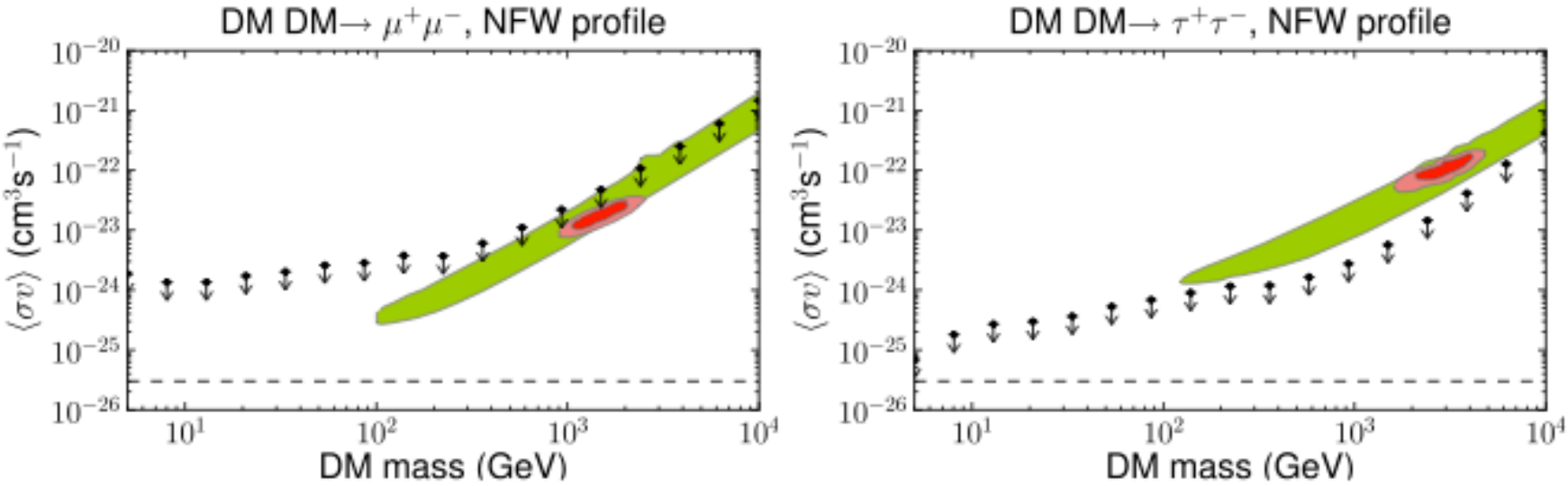
2010PhRvL.104i1302A [arXiv:1108.0501]
arXiv:1205.2739



- Limit DM to avoid saturating the observed spectrum in the line search ROI
- Very conservative limits, no model subtraction

Inclusive Spectrum Limits

arXiv:1205.2739



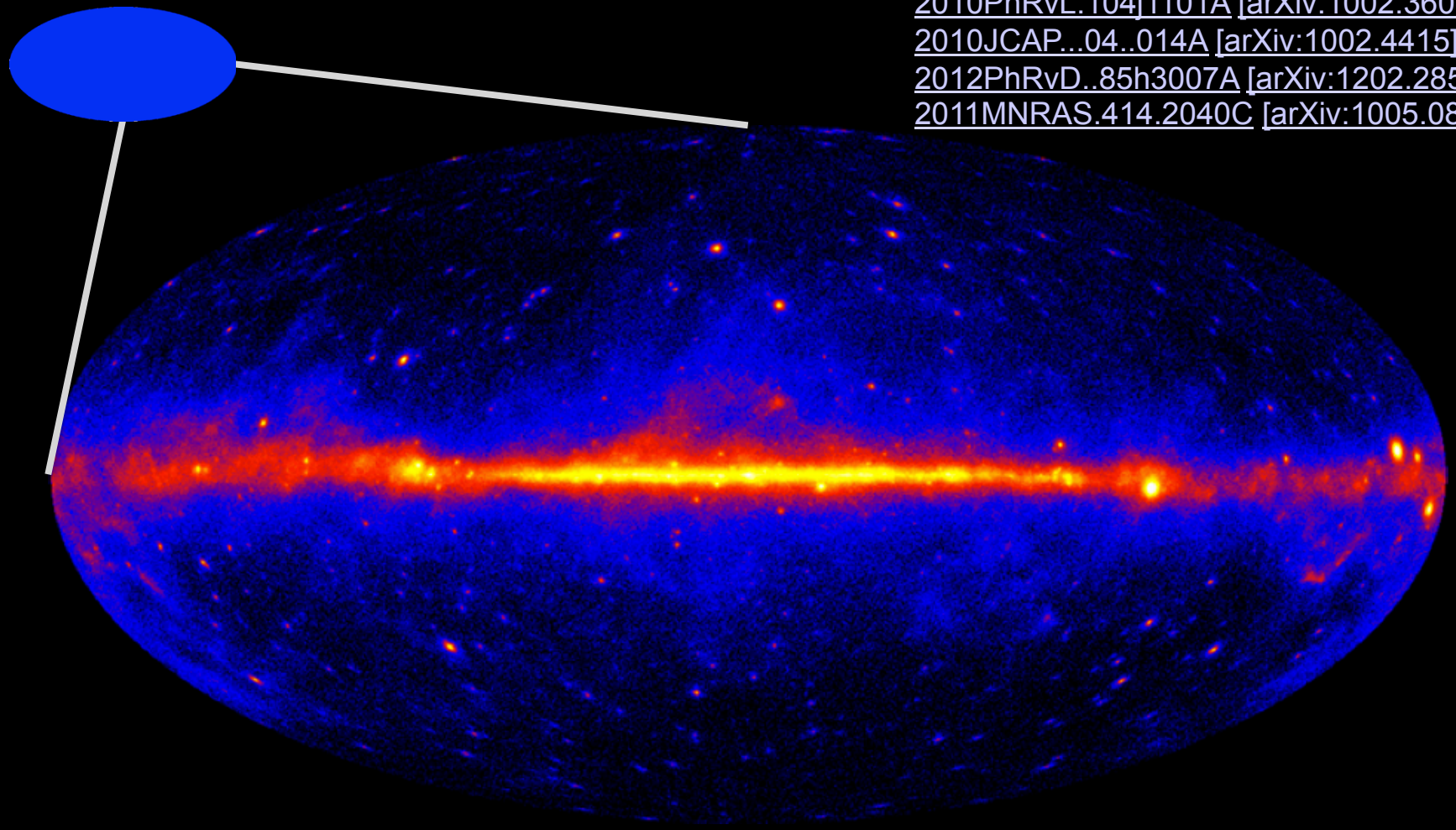
•Similar to Halo analysis "Method I", simply ask how much DM signal we can have without saturating the observed spectrum in the line-search ROI

•20°x20° at Galactic Center + |b| > 10°

The limits from the $\tau^+\tau^-$ channel in particular are at odds with DM interpretations of features in the e^+e^- spectrum and the rise in the positron fraction

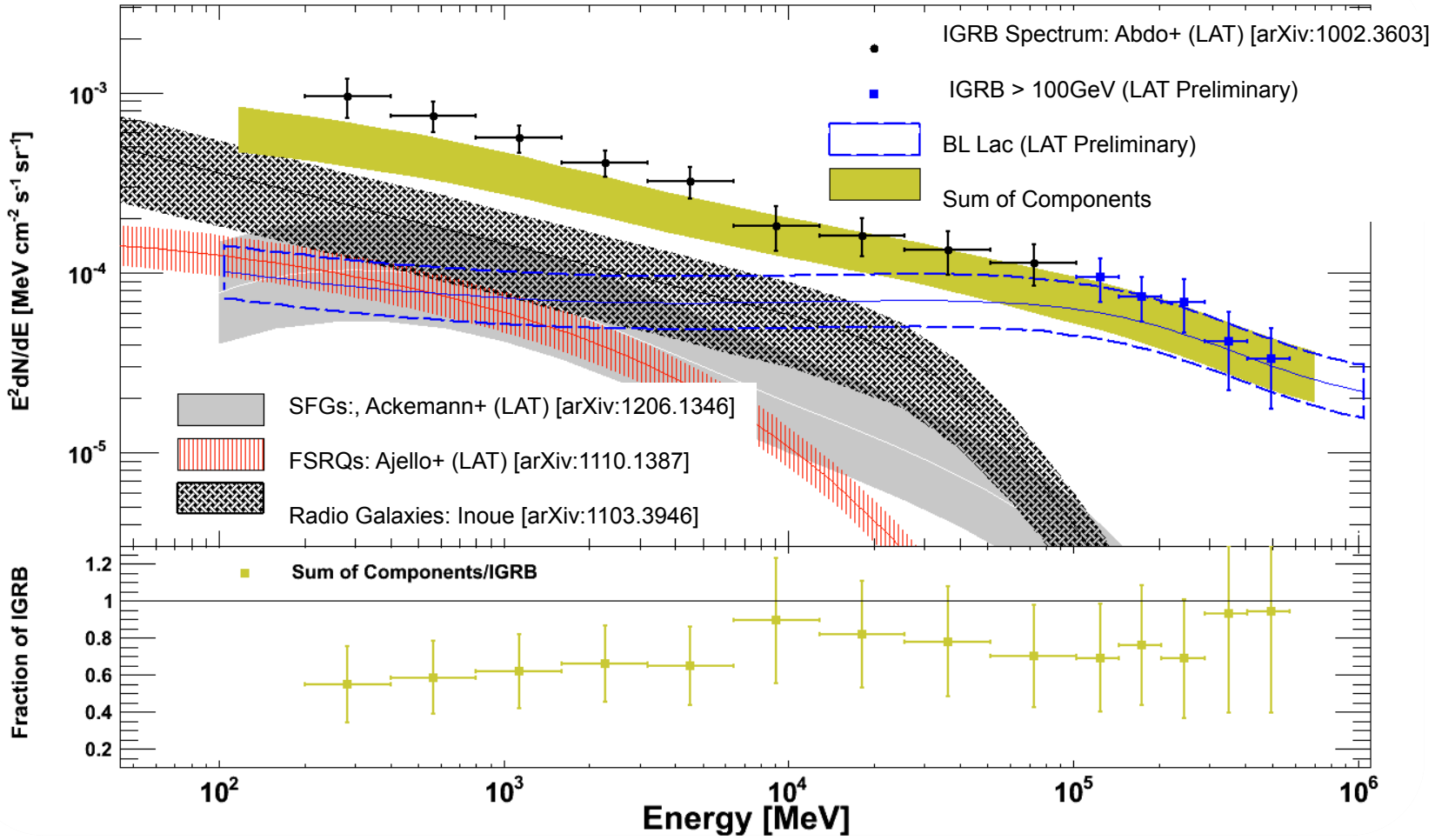
DM Contributions to the "Isotropic" Background

2010PhRvL.104j1101A [arXiv:1002.3603]
2010JCAP...04..014A [arXiv:1002.4415]
2012PhRvD..85h3007A [arXiv:1202.2856]
2011MNRAS.414.2040C [arXiv:1005.0843]



- Look for signatures of Dark Matter in the Isotropic background
- This requires good knowledge of all the astrophysical foregrounds

Summing Contributions to the γ-ray Sky

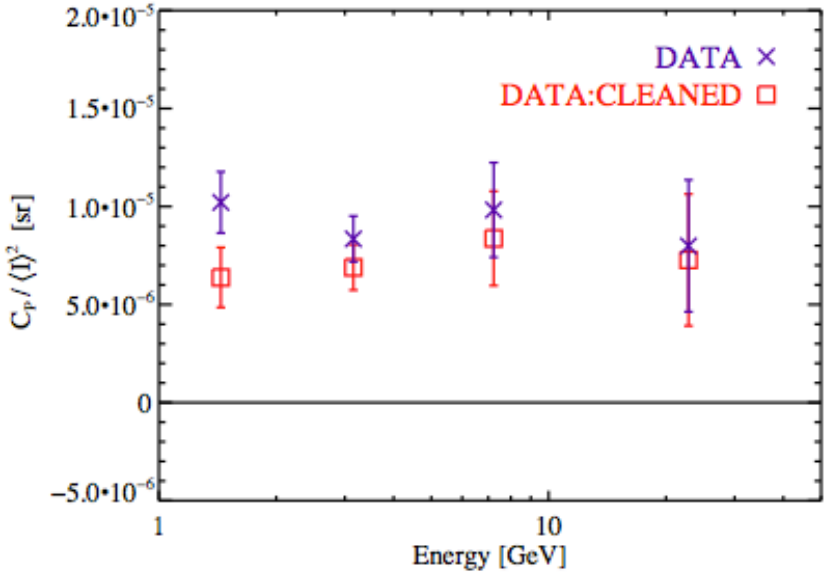


By estimating and modeling the contributions of unresolved sources in known source classes to the IGRB, we can constrain the potential contribution for unknown source classes (such as DM)

See other studies by: Stecker&Salomon+96, Pavlidou&Fields+02, Narumoto&Totani06,Dermer07, Bhattacharya+09, Inoue&Totani09, Fields+10, Makiya+10, Inoue+11,Abazajian+10, Ghirlanda+11,Stecker&Venters11,Malyshev&Hogg11

Constraining DM with γ-ray Anisotropies

- **Measure the angular power spectrum of large-scale isotropic γ-ray bkg.**
  - **Significant (3σ) detection of angular power from 1-10 GeV**
- **Fluctuation angular power is consistent with constant from 1-50GeV**
  - **Constrains fractional contribution of individual sources classes (including DM)**



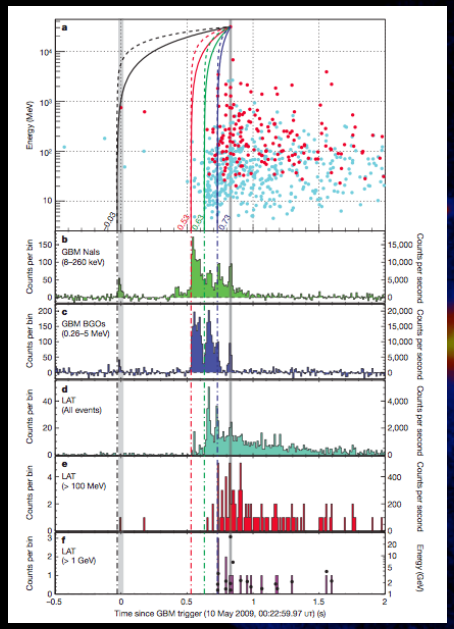
Fornasa+(2012) [arXiv:1207.0502]

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^{-5}	43%	37%
Millisecond pulsars	3×10^{-2}	1.7%	1.5%

See also: Ando+ (2007), Miniati+ (2007), Siegal-Gaskins (2008), Cuoco+ (2008), Fornasa+(2009), Zavala+(2010) , Cuoco+(2011), Campbell & Dutta (2011)

Other Searches for DM and New Physics

Limits on Lorentz Invariance Violation from arrival times of high energy γ rays in GRB 090510
2009Natur.462..331A [arXiv:0908.1832]



Limits on Large Extra Dimensions from non-detection of γ rays from Neutron Stars
2012JCAP...02..012F [arXiv:1201.2460]

Cosmic-ray electrons from the Sun
2011PhRvD..84c2007A [arXiv:1107.4272]

Searches for Axions from Galaxy Clusters
(E.g., Sanchez-Conde+ 2009 arXiv:0905.3270)

STATUS AND SUMMARY

Summary and Status

- The Fermi-LAT collaboration has searched for DM in a wide variety of ways
  - We have not observed any DM signals to date
  - We have placed constraints on many DM scenarios
- Fermi-LAT e^+e^- data disagree with conventional models
  - Explanation may or may not involve DM
- The search for DM in dSphs has excluded the canonical thermal relic annihilation cross section below ~30 GeV
  - With 10 years data and more dSphs we expect to be able to search for signals from WIMP with masses up to 1 TeV
- DM search in the Galactic halo also puts strong constraints on thermal relic WIMPs below ~30 GeV
  - Analysis depends on knowledge of diffuse emission