Latest results from the Fermi Large Area Telescope

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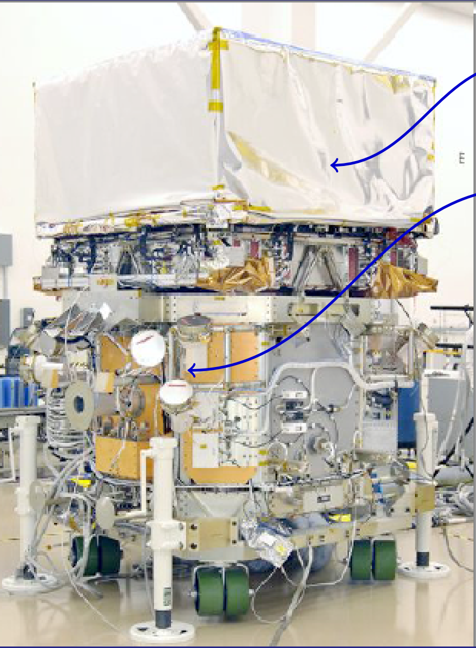
on behalf of the Fermi LAT collaboration

PPC 2012

The Fermi Observatory



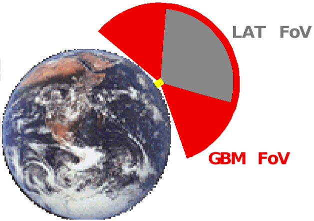
Large Area Telescope (LAT)

- Pair conversion telescope
- Energy range: 20 MeV – >300 GeV

Gamma-ray Burst Monitor (GBM)

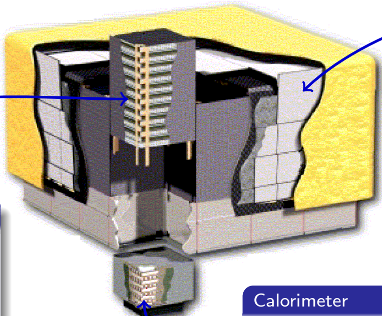
- 12 NaI and 2 BGO detectors
- Energy range: 8 keV – 30 MeV

- Launched by NASA on 2008 June 11
- Almost circular orbit, at 565 km altitude and 25.6° inclination



Large Area telescope

- Overall modular design
- 4×4 array of identical towers (each one including a tracker and a calorimeter module)
- Tracker surrounded by an Anti-Coincidence Detector (ACD)



Anti-Coincidence Detector

- Segmented (89 tiles) as to minimize self-veto at high energy
- 0.9997 average detection efficiency

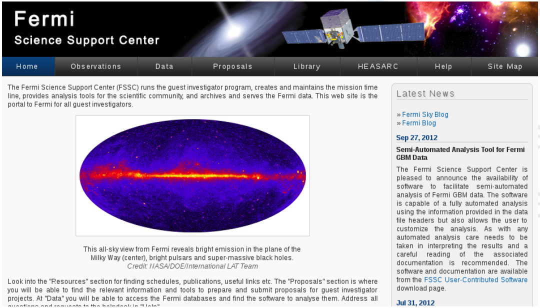
Tracker

- Silicon strip detectors, W conversion foils; 1.5 radiation lengths on-axis
- 10k sensors, 73 m^2 of silicon active area, 1M readout channels
- High-precision tracking, short dead time

Calorimeter

- 1536 CsI(Tl) crystals; 8.6 radiation lengths on-axis
- Hodoscopic, 3D shower profile reconstruction for leakage correction

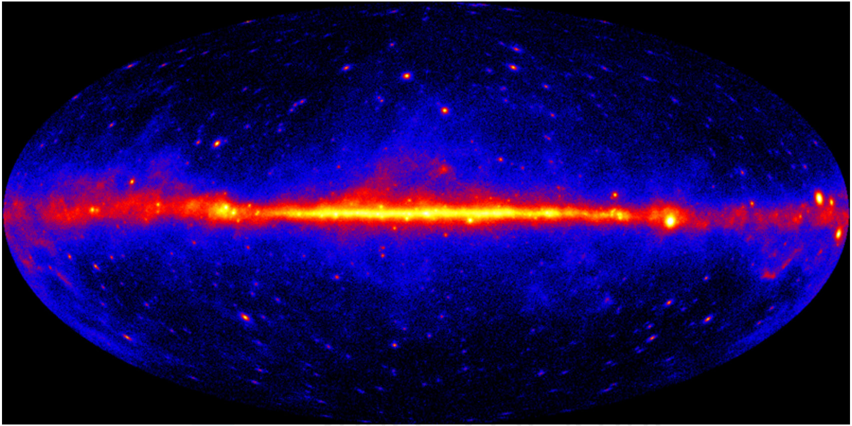
- All subsystem working properly, no performance degradation
- More than 99% up-time collecting science data (out of the SAA)
  - Including detector calibrations/hardware issues
  - Fraction of time in side SAA is $\sim 13\%$
- Data taking trivia:
  - > 250 B LAT readouts in orbit
  - > 50 B events down-linked to ground
  - > 700 M γ-ray candidates made public



All LAT photon data go public *immediately*

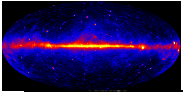
- Data access at `http://fermi.gsfc.nasa.gov/ssc/`
- Average latency ~ 8 hr

Dissecting the gamma-ray sky



- The γ-ray sky
  - Rate map (exposure corrected) of γ-candidates above 200 MeV collected during the first year of data taking.

DISSECTING THE GAMMA-RAY SKY



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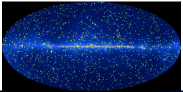
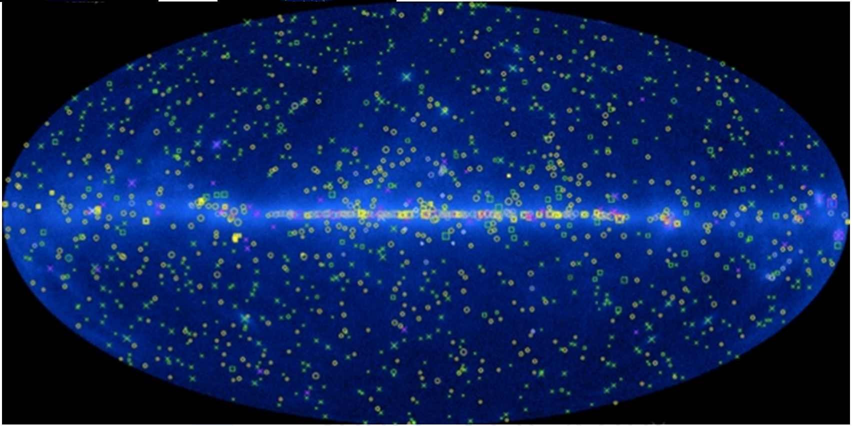
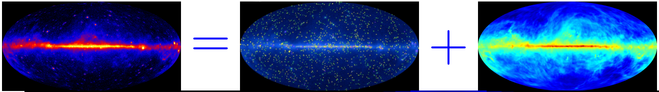
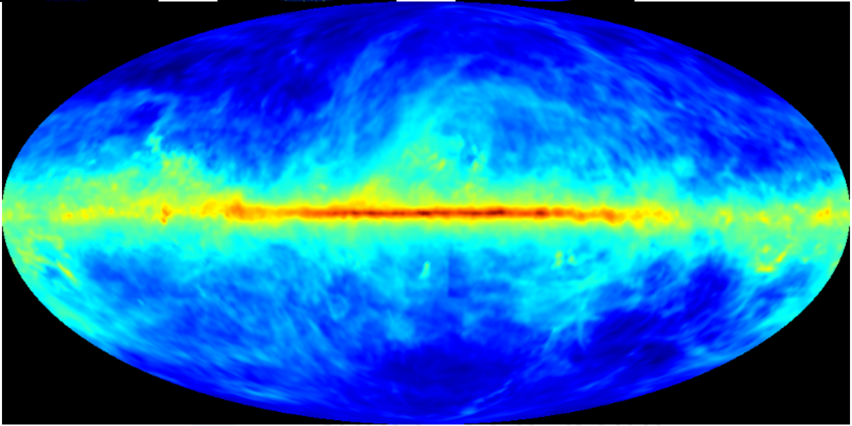




- Resolved point sources
  - The catalogs are among the most important collaboration science products

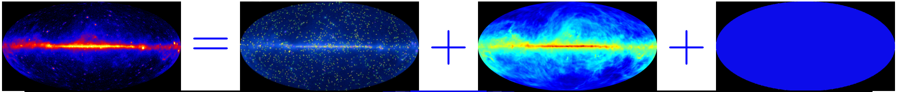
Dissecting the gamma-ray sky

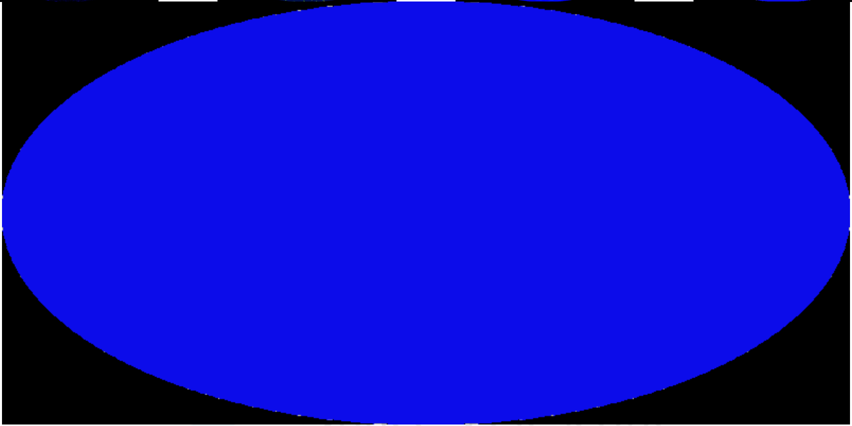




- Galactic diffuse radiation (accounts for the vast majority of photons)
  - Cosmic-ray interactions with the interstellar medium (Bremsstrahlung, Inverse Compton, π^0 decay)

Dissecting the gamma-ray sky



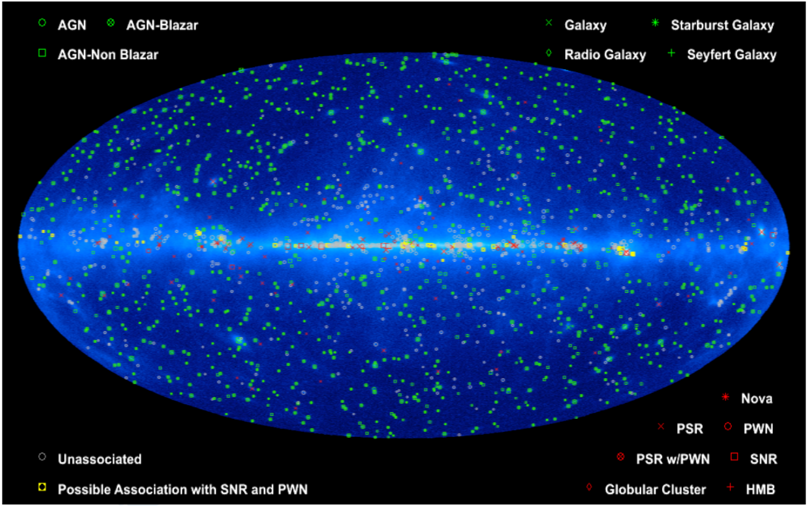


- Isotropic diffuse
  - Unresolved sources and truly diffuse (extragalactic) emission
  - Residual cosmic-rays surviving background rejection filters

The Second Fermi Catalog (2FGL)

Nolan, P. L. et al. 2012, ApJS, 199, 31,

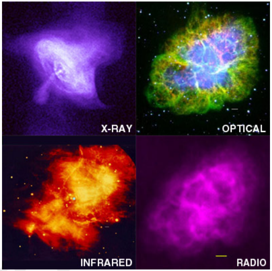
http://fermi.gsfc.nasa.gov/ssc/data/access/lat/2yr_catalog/

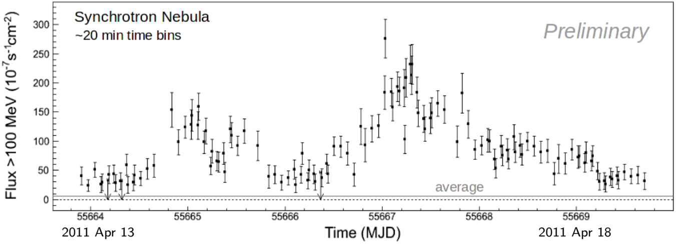


- Dataset: 24 months of data (100 MeV–100 GeV), 35.7 M events
- 1873 sources (the deepest catalog ever in this energy range)

Variability: the Crab flare case
Standard Candle no more

- Many of the point sources show temporal variability...
- ...but the flare of the Crab nebula was a surprise
  - 5 episodes from 2007 up to now
- The wind emanating from a rotating neutron star (Crab Nebula) produces strong γ-ray flux
- Those γ rays are produced by energetic (PeV) electrons (via synchrotron), but not clear how to accelerate them
- Rapid variability ($\sim$hours) constrains the size of electron acceleration region





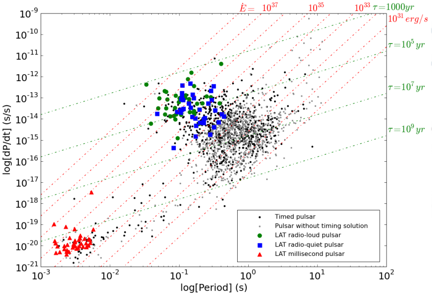
Tavani et al. 2012 Science 331 736-739 (AGILE)

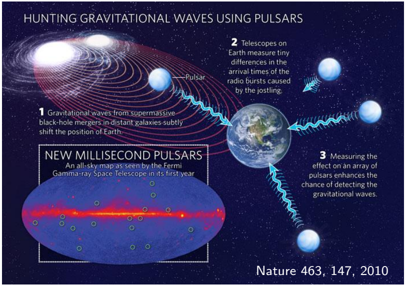
Abdo A.A. et al. 2011 Science 331 739-742

Buehler R. et al. 2012 ApJ 749 26

Atel 4239 on 2012 July 4th (to celebrate the "Higgs discovery")

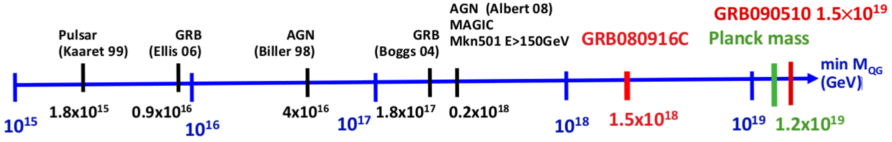
- Huge increase in number of known γ-ray pulsars
  - From $\sim$ 6 pre-Fermi-LAT to over 117 now
- Large fraction ($\sim$ 1/2) of young γ-ray pulsars are radio-quiet
  - γ-ray beam is wider than radio beam
- Radio searches on LAT sources discovered $>$ 40 MSPs
  - Potential for nHz, kilo-parsec scale gravitational wave detection array, i.e. Pulsars Timing Arrays





Nature 463, 147, 2010

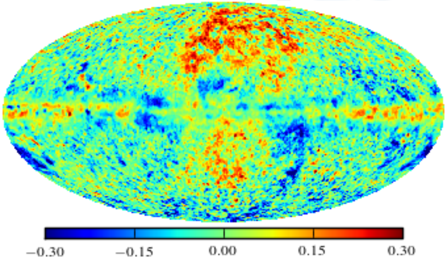
- Quantum gravity predicts Lorentz Invariance Violation (LIV) near Planck scale (10^{19} GeV)
- GRB emits short light pulse at great distance: can probe variation in arrival time (light speed) as function of energy
- *GRB 090510* (z=0.9): we see a 31 GeV photon less than 1 second after the first X-ray photons, after traveling >7 billion light years
- This requires the quantum–gravity mass scale to be at least 1.2 times the Planck mass
- Assuming dispersion: $\nu = \delta E/\delta P \sim c(1-(E/E_{QG})^n)$ with $n = 1$
- Assuming that the GeV photons are not emitted *before* the X-ray burst



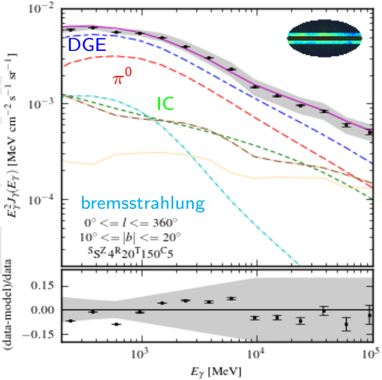
Galactic Diffuse Emission

- Produced by CR interacting with the interstellar gas and radiation field
- Carries important information on the acceleration, distribution, and propagation of cosmic rays
- Cosmic ray origin, propagation, and properties of the interstellar medium can be constrained by comparing the data to predictions
- Generate models (in agreement with CR data) varying CR source distribution, CR halo size, gas distribution and compare with data

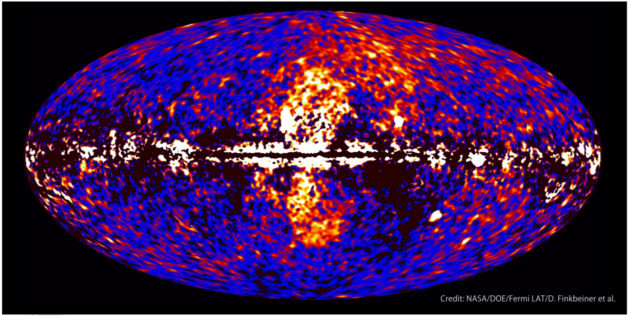
Example of residual map (data - model)/model



Fermi LAT Collab. 2012, ApJ 750, 3

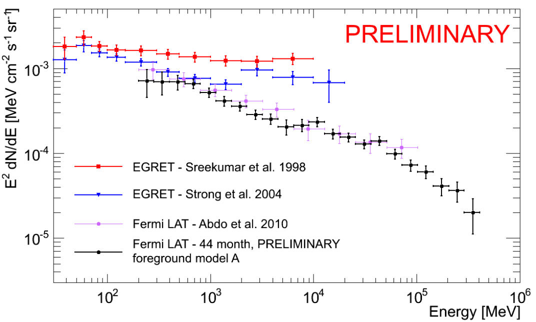


- Large "bubbles" seen projecting from Galactic Center
  - very extended ($\sim 50^\circ$ from plane)
  - hard spectrum ($\sim E^{-2}$, 1-100 GeV)
  - possible counterparts in other wavelengths (ROSAT, WMAP, and Planck)
- What is the origin of this emission?
- What are the consequences for other observations?

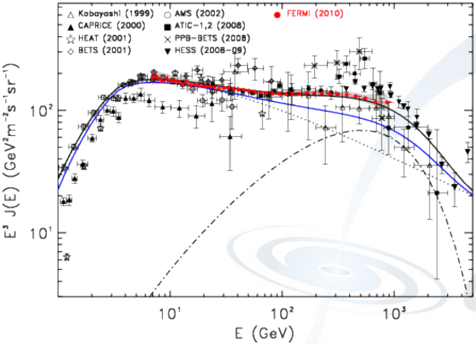


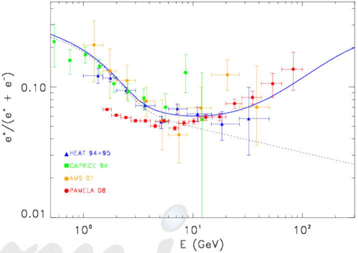
Su et al 2010, ApJ 724, 1044

Isotropic Gamma-Ray Background
M. Ackermann at Fermi Symposium 2012



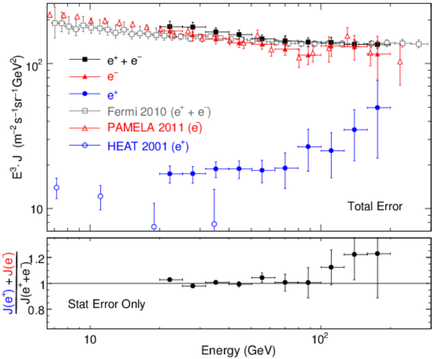
- Fermi-LAT is measuring isotropic γ-ray spectrum to > 400 GeV
  - Published up to 100 GeV in Abdo A. A. et al. 2010, PRL, 104, 101101
  - New, preliminary, analysis on 44 months of LAT data up to 410 GeV
- Can compare measurements to expected unresolved contributions from sources
- Sub-degree scale (high-multipole) anisotropies sensitive to unresolved sources as well as DM sub-structures
- Work ongoing in extending the spectrum to ~ 1 TeV (arXiv:1210.2558)

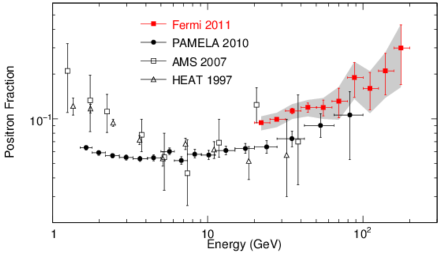




From D.Grasso et al. Astropart. Phys. 32, 140-151 (2009)

- Systematics limited spectrum from 7 GeV to 1 TeV
- Spectrum is harder than in pre-Fermi GALPROP model
  - Compatible with a single power-law → diffusive model
- Adding an extra component nicely fits the Fermi spectrum
  - Together with PAMELA positron fraction
- Several possibilities for an additional source of e^+/e^-
  - Either astrophysical or exotic (or both)

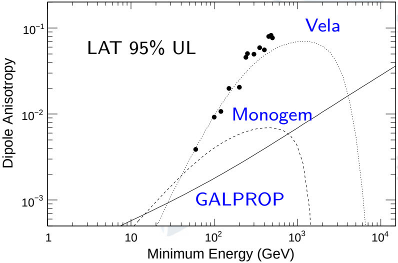




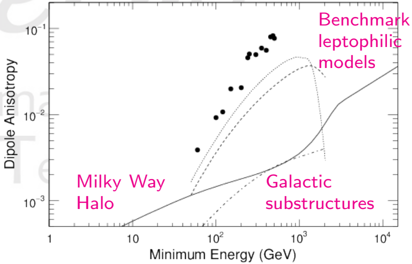
- First measurement of separate electron and positron spectra in this energy range
  - Using the Earths magnetic field as charge discriminator
  - Limited by statistics at high-energy, as we need special data-taking runs (*looking down* for this analysis)
- Positron fraction increasing with energy (consistent with PAMELA)
- The complete explanation has probably to wait for future measurements with greater sensitivity and energy reach

- Fermi offers a unique opportunity for the measurement of possible anisotropies
  - Large exposure and complete sky coverage
- Current results based on one year of data, more than 1.6 M CRE candidate above 60 GeV
- Limits on dipole anisotropy is a valuable tool to constrain models
  - Dominance of a single, very bright nearby source is disfavored
  - Dark Matter models predict a smaller effect

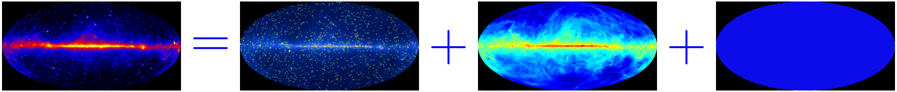
Astrophysical sources



Dark Matter models



Dissecting the gamma-ray sky



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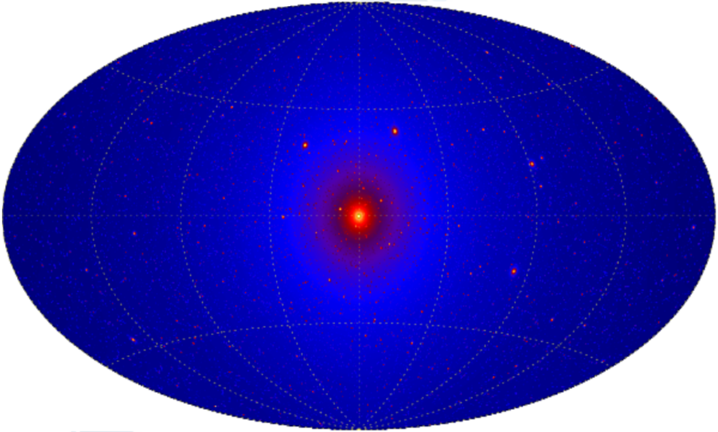


γ rays from Dark Matter?

Image from Pieri arXiv:0908.0195

Fermi LAT DM search target

Spectral lines

Phys. Rev. D, 86, 022002 (2012)

Phys. Rev. Lett. 104, 091302 (2010)

The inner galaxy

Dwarf galaxies

Phys. Rev. Lett. 107, 241302 (2011)

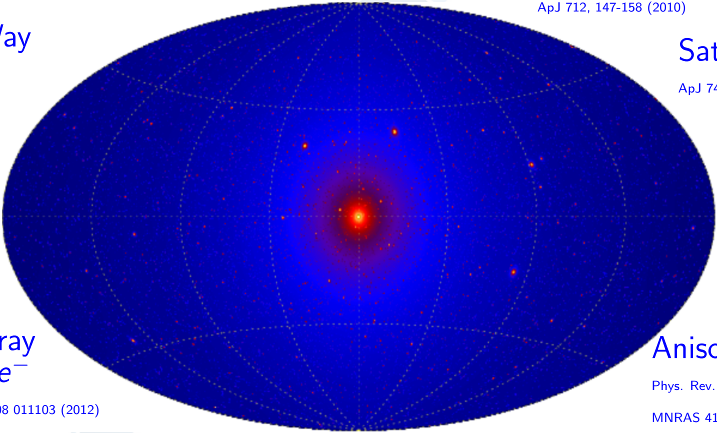
ApJ 712, 147-158 (2010)

Milky Way halo

arXiv:1205.6474

Satellites

ApJ 747, 121 (2012)



The Sun

Phys. Rev. D 84, 032007 (2011)

Cosmic-ray e^+ and e^-

Phys.Rev.Lett., 108 011103 (2012)

Phys. Rev. D84, 032007 (2011)

Phys. Rev. D82, 092003 (2010)

Phys.Rev.Lett., 102 181101 (2009)

Anisotropies

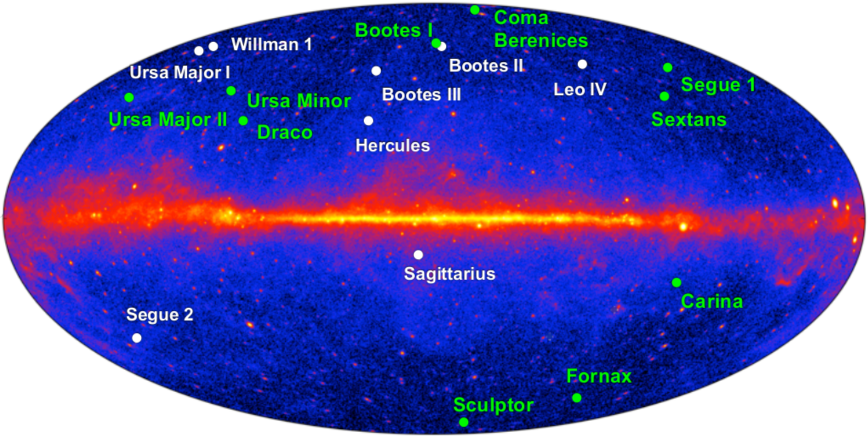
Phys. Rev. D,85, 3007 (2012)

MNRAS 414, 2040 (2011)

Isotropic gamma-ray background

JCAP 04 (2010) 014

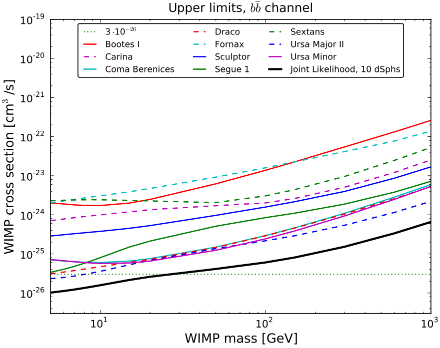
Dwarf Spheroidal Galaxies

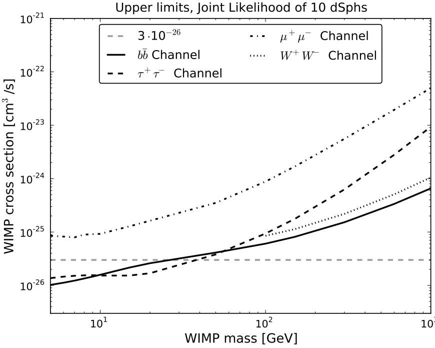


- Roughly two dozen dwarf spheroidal satellite galaxies (dSphs) of the Milky Way
- Some of the most dark matter dominated objects in the Universe
  - Very large M/L ratio: 10 to $\sim>$ 1000 (M/L$\sim$10 for Milky Way)
- No astrophysical gamma-ray production expected

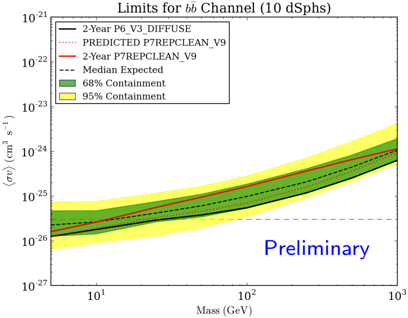
DM limits from combined analysis of dSphs
Ackermann M. et al. 2011, Phys. Rev. Lett. 107, 241302

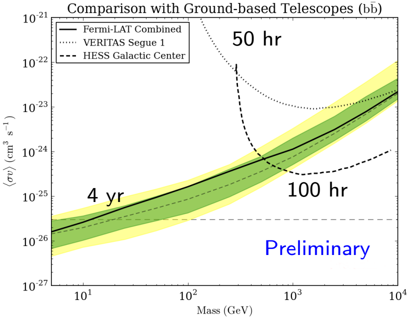
- Joint likelihood analysis of Fermi LAT data:
  - 10 dwarf galaxy targets
  - 2 years data, energy range: 200 MeV –100 GeV
  - 4 annihilation channels
- Exclude the conventional thermal cross section for a WIMP with mass < 30 GeV annihilating to $b\bar{b}$ or $\tau^+\tau^-$

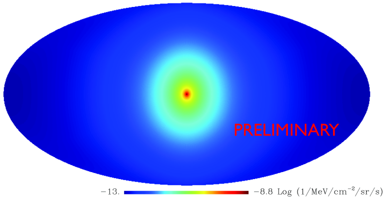


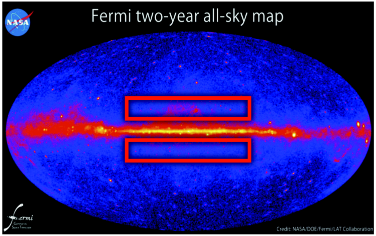


- 2 years of Pass 7 data, reprocessed with updated calibrations (left plot)
  - Observed limits are increased by a factor of 1.5 to 3.5
  - Evaluating statistical fluctuations with 100 realistic sky simulations, replicating Pass 6 analysis
  - Both Pass 6 and Pass 7 measurements lie within the 68% containment region of statistical sample
- Updated analysis with 4 years of Pass 7 data (right plot)
  - Expanded energy range: constrain WIMP masses up to 10 TeV
  - New limits are consistent with prediction (within statistical fluctuations)





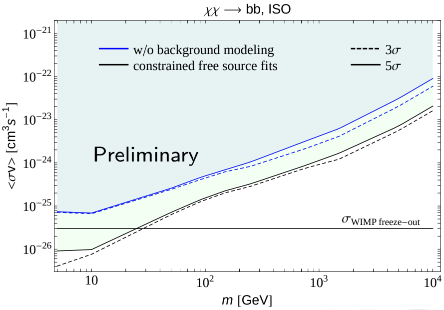




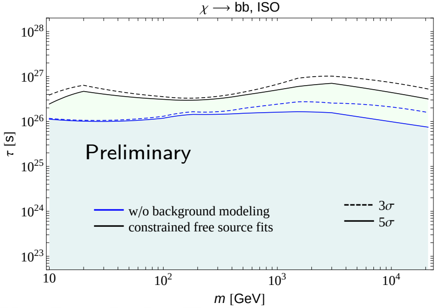
- Testing the LAT diffuse data for a contribution from a Milky Way DM annihilation/decay signal
- ROI: $5^\circ < |b| < 15^\circ$ and $|l| < 80^\circ$, chosen to:
  - Minimize DM profile uncertainty (highest in the Galactic Center region)
  - Limit astrophysical uncertainty by masking out the Galactic plane and cutting-out high latitude emission
- Two methods:
  - Conservative "no-background" limits:
    - Upper limits are set from the requirement that a DM contribution not overpredict the data
  - Simultaneous modeling of non-DM astrophysical signal:
    - Scanning over a grid of GALPROP models to take into account uncertainties from diffusion models and gas maps

CONSTRAINT FROM THE HALO: *bb* CHANNEL

Annihilation



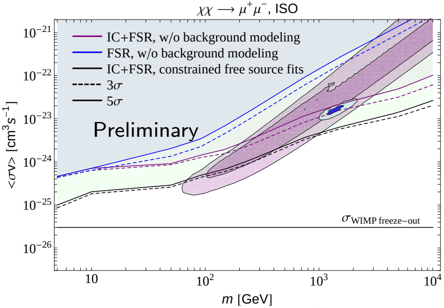
Decay



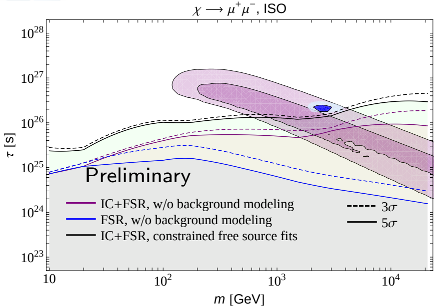
- Blue: "no-background limits"
- Black: limits obtained by marginalization over the CR source distribution, diffusive halo height and electron injection index, gas to dust ratio, in which CR sources are held to zero in the inner 3 kpc
- Limits with NFW profile (not shown) are only slightly better

Constraint from the halo: $\mu^+\mu^-$ and $\tau^+\tau^-$ channel

Annihilation



Decay

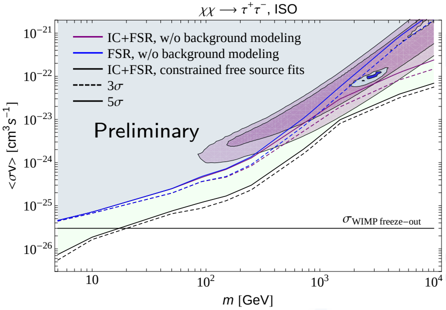


- Blue: only photons produced by muons (no electrons) to set "no-background limits" ("FSR only")
- Violet: "no-background limits" including FSR+IC from dark matter
- Black: modeling astrophysical signal
- DM interpretation of PAMELA/Fermi CR anomalies strongly disfavored (for annihilating DM)

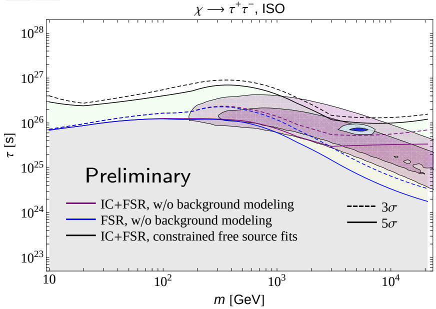
Paper submitted [arXiv:1205.6474]

Constraint from the halo: $\mu^+\mu^-$ and $\tau^+\tau^-$ channel

Annihilation



Decay



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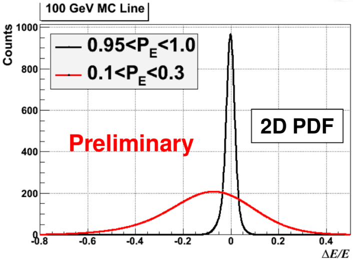
Paper submitted [arXiv:1205.6474]

Search for spectral lines

A. Albert, Fermi Symposium 2012

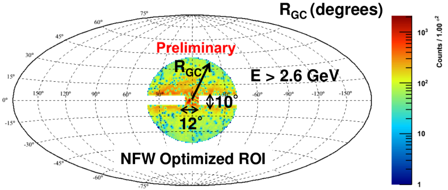
- Search for line emission from dark matter annihilation or decay ($\gamma\gamma$ and $Z\gamma$ channels)
- New analysis with 4 years of data
  - Similar method as in published results
- Pass 7 data, reprocessed with updated calibrations
  - Shifts energy scale by 1-4% to account for slight radiation damage to calorimeter

- Better modeling of Energy dispersion
  - Adding a 2nd dimension to line model: P_E, the probability of a good energy measurement

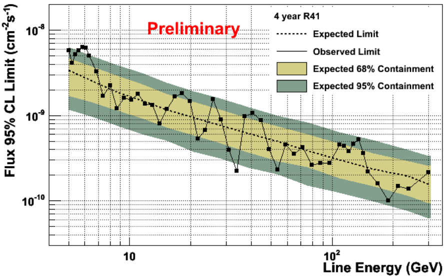


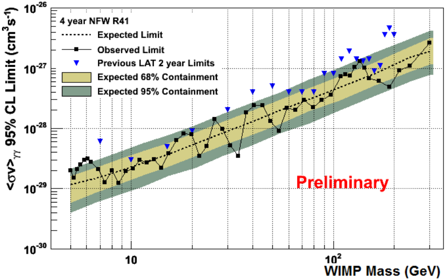
- Region of Interest (ROI) Optimization
  - Find R_{GC} that optimizes $sig/\sqrt{bkg}$
  - Search in 5 ROIs:

R0 ($12^{\circ} \times 10^{\circ}$ GC box)
R16 (Einasto Optimized)
R41 (NFW Optimized)
R90 (Isothermal Optimized)
R180 (2 year Analysis ROI)



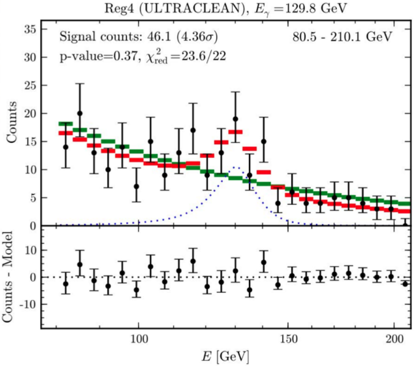
- Search for lines from 5 to 300 GeV
  - Maximum Likelihood Fit
  - Use sliding $\pm 6\sigma_E$ windows
  - Fit for energies in σ_E steps
- No globally significant lines found
  - Most significant fit was in R0 at 5 GeV, 1.75 (3.70 local)
- Expected limits calculated from powerlaw-only pseudo experiments. No systematic errors applied
- Plots show an example of the results for the NFW-optimized ROI

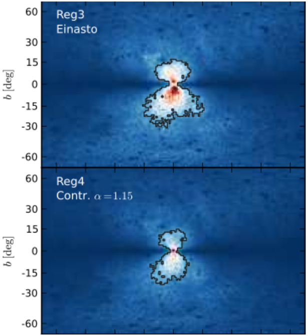




A GAMMA-RAY LINE AT 130 GEV ?

- Recent claim of a narrow spectral feature at $\sim$ 130 GeV near the Galactic center (GC)
- Triggered a huge interest in the community
- Comprehensive Fermi LAT team analysis on line searches based on 4 years of data ongoing (see, e.g. A. Alberts, E. Bloom, E. Charles at Fermi Symposium 2012)
  - Line significance decreases with reprocessed data
  - Line-like feature observed in Earth Limb

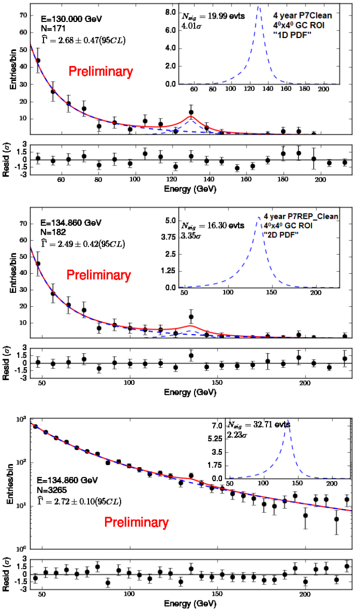




Bringmann+ [arXiv:1203.1312], Weniger [arXiv:1204.2797]

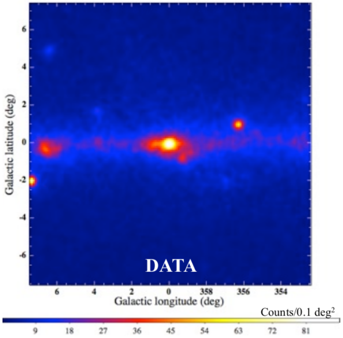
A Gamma-Ray Line at 130 GeV ?

- 4.01σ (local) 1D fit at 130 GeV with 4 year unreprocessed data
  - Look in $4^\circ \times 4^\circ$ GC ROI
  - Use 1D PDF (no use of P_E)
- 3.35σ (local) 2D fit at 135 GeV with 4 year reprocessed data
  - Look in $4^\circ \times 4^\circ$ GC ROI
  - Use 2D PDF
- Line-like feature in the limb at 135 GeV
  - Appears when LAT is pointing at the Limb
    - $|RockAngle| > 52^\circ$
  - Surprising since limb should be smooth
  - Orbit profile changed to increase our Limb dataset

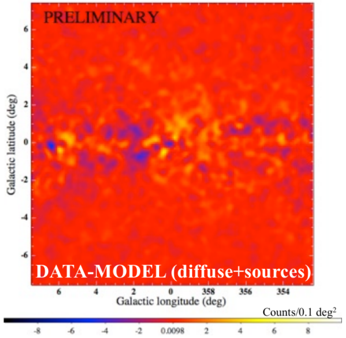


Fermi LAT view of the Galactic Center region

- Fermi LAT preliminary results for a $15^\circ \times 15^\circ$ region around the direction of the Galactic center, with 32 months of data, 1-100 GeV
- Diffuse emission model and contribution from detected point sources account for most of the emission observed in the region
- Good agreement between data and model within 5-10%. Investigating low level residuals
- Dark matter analysis ongoing

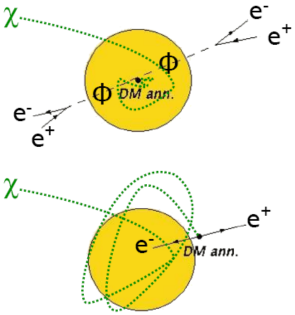


Fermi LAT Collaboration, paper in preparation



- Dark matter model predicts cosmic-ray electron and positron (CRE) fluxes from the Sun
- Search for a flux excess correlated with Sun's direction yielded no significant detection, flux upper limits placed

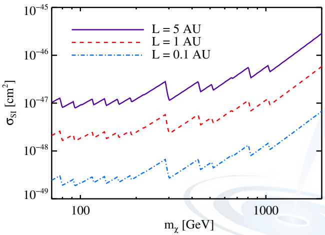
- Intermediate state scenario: dark matter annihilates in the center of the Sun into an intermediate state Φ which then decays to CREs outside the surface of the Sun
- iDM scenario: inelastic dark matter (iDM) captured by the Sun remains on large orbits, then annihilates directly to CREs outside the surface of the Sun



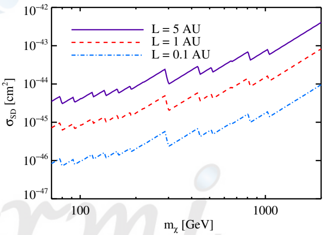
from J. Siegal-Gaskins

Annihilation through an intermediate state

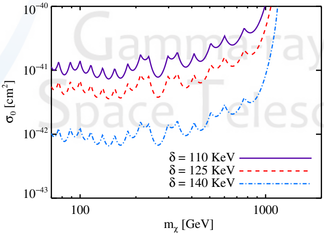
spin-dependent



spin-independent



Inelastic scattering cross-section

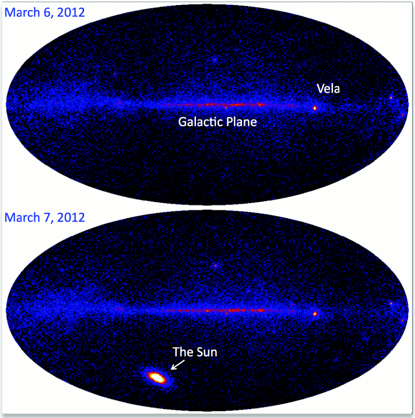


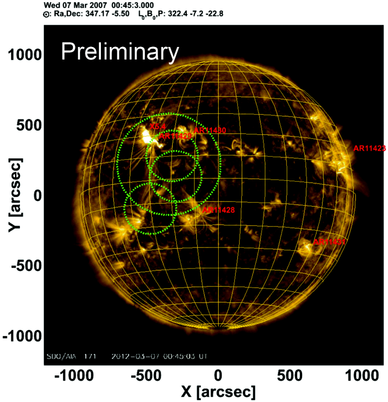
Summary

- Fermi is about to begin its extended phase in 2013
  - The observatory performed extremely well, both from the operational and the scientific standpoint
  - Good example of a HEA/HEP joint venture
- Fermi is changing our knowledge of high energy astrophysics with large statistics, high resolution gamma-ray data made publicly available to the interested community at large
- New constraints on dark matter models have been obtained for indirect dark matter signals using a variety of targets
- Fermi LAT cosmic ray data provide a valuable probe of dark matter models
- Looking forward: Fermi continues to survey the sky!
  - NASA Senior Review recommended extending operations through 2016, at least

EXTRA

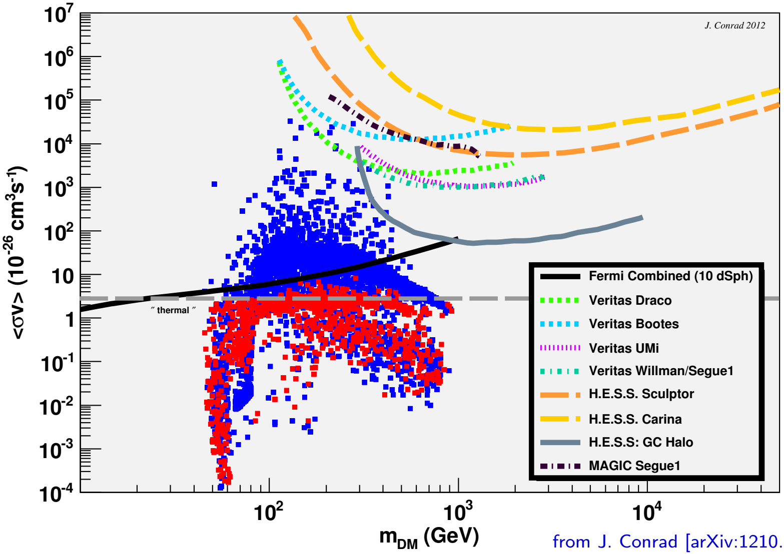
γ-RAY FLARES FROM THE SUN





- We are close to maximum of the Sun 11-yr cycle
- A very bright Solar Flare was detected on March 7, exceeding 1000 times the γ-ray flux of the steady Sun and 100 times the flux of Vela
- High energy emission (>100 MeV, up to 4 GeV) lasted for $\sim$ 20 hours
  - Continuous particle acceleration lasting almost 1 day challenges acceleration models

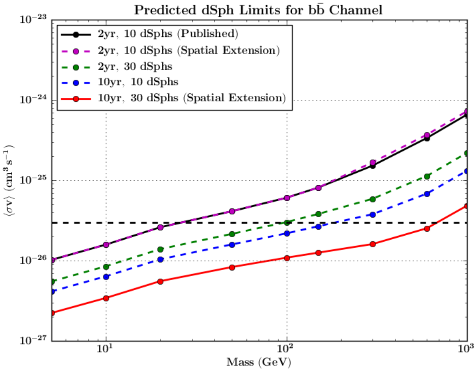
Current Best constraints on Indirect detection with γ rays



from J. Conrad [arXiv:1210.4392v1]

Prospects for dwarf spheroidal

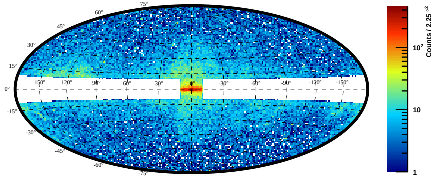
Thermal relic cross section



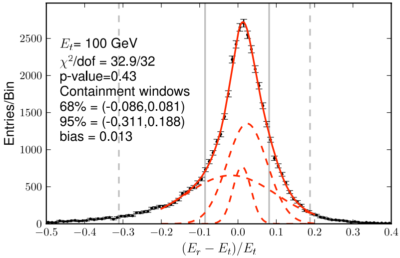
- Future dwarf spheroidal limits:
  - Extracted from published results
  - Increased observation time
  - Discoveries of new dwarfs
    - New optical surveys will discover more dSphs
  - Gains at high energy
- Potential for stringent constraints on WIMP models

- Search for line emission from dark matter annihilation or decay ($\gamma\gamma$ and $Z\gamma$ channels)
- Exclude Galactic plane and point sources
- Assume power-law background (spectral index free to vary) in each energy window

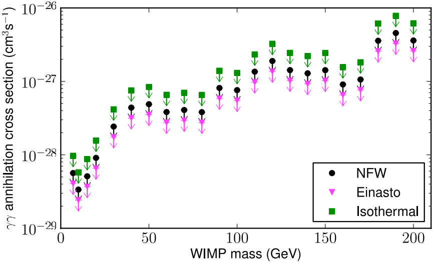
Region-of-interest for line search

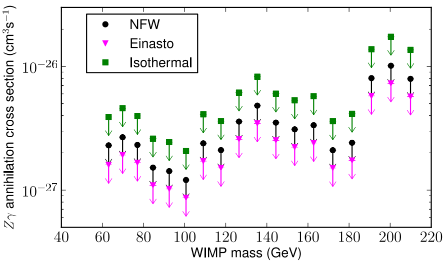


LAT energy response to 100 GeV line



Annihilation cross-section constraints





Decay lifetime constraints

- No line detection. 95% CL flux upper limits, 7–200 GeV energy range
- With assumptions on the dark matter density distribution, we extract constraints on the dark matter annihilation cross-section and decay lifetime