Search for features in the cosmic-ray electron and positron spectrum measured by the Fermi Large Area Telescope

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on behalf of the Fermi LAT Collaboration

The Fermi mission

- Launched by NASA on 2008 June 11, from Cape Canaveral, Florida
  - Almost circular orbit, at 565 km altitude and 25.6° inclination
- Science mission started on August 2008
- Fermi is celebrating its 10th birthday!

The Fermi satellite

- The Fermi Gamma-Ray Space Telescope is an international Science Mission exploring the gamma-ray sky by means of its two main instruments:
  - GLAST Burst Monitor (GBM): 8 keV → 40 MeV
  - Large Area Telescope (LAT): 20 MeV → > 300 GeV
- Huge energy range: including largely unexplored band for a total of >7 energy decades!

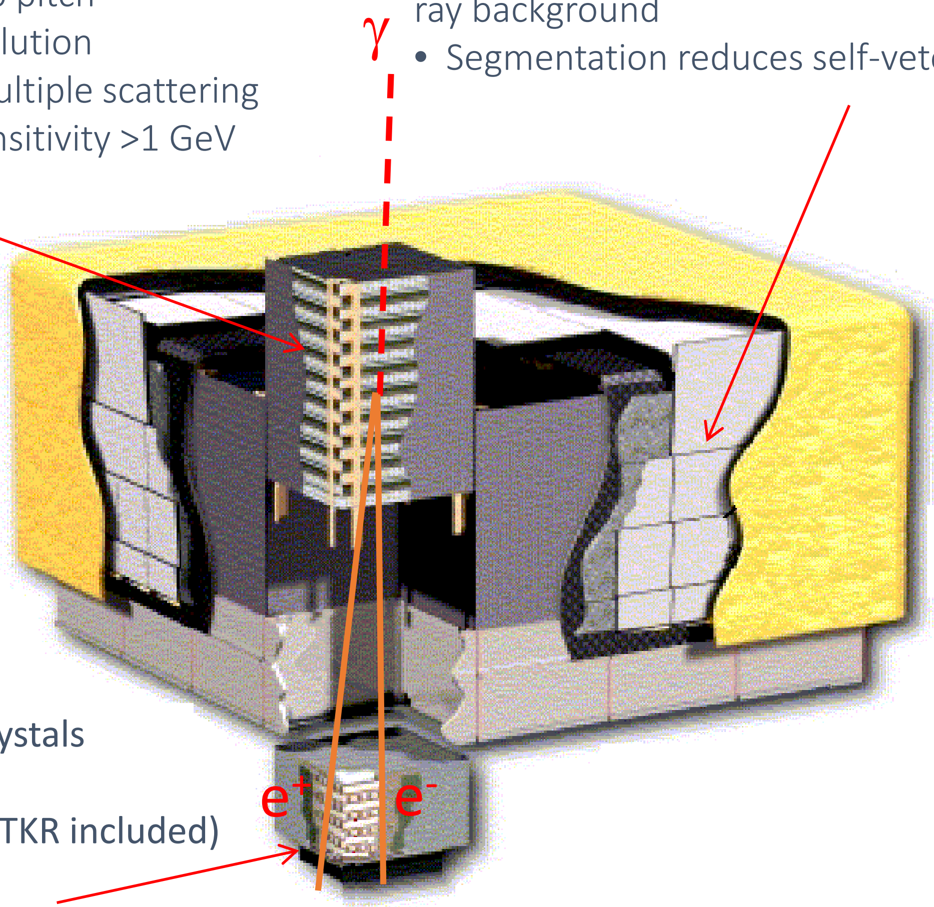
The Fermi LAT

Precision Si-strip Tracker (TKR)

- Measures incident γ-ray direction
- 18 XY tracking planes: 228 μm strip pitch
- High efficiency. Good position resolution
- 12x 0.03 X_0 front end → reduce multiple scattering
- 4x 0.18X_0 back-end → increase sensitivity >1 GeV

Anticoincidence Detector (ACD)

- 89 scintillator tiles
- First step in the reduction of large charged cosmic ray background
- Segmentation reduces self-veto at high energy



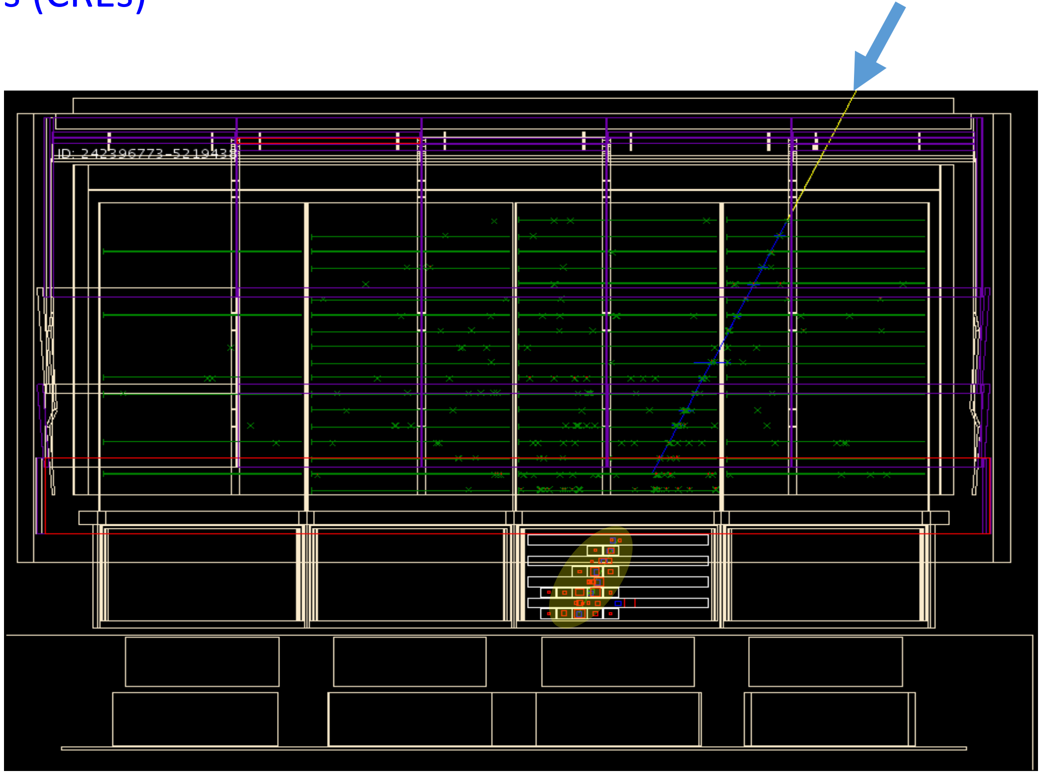
Hodoscopic CsI Calorimeter

- Segmented array of 1536 CsI(Tl) crystals
- 8.6 X_0: shower max contained
  - ~ 200 GeV normal (1.5X_0 from TKR included)
  - ~ 1TeV @ 40° (CAL-only)
- Measures the incident γ-ray energy
- Rejects cosmic-ray background

The LAT as an e^+/e^- detector

- Gamma-ray detection:
  - Look for an electromagnetic cascade
  - Reject incident charged particles with ACD
- Electron (positron) detection:
  - Also an electromagnetic cascade!
    - Removed charge veto, tighten the other cuts
  - The LAT cannot distinguish between e^- and e^+ ➔ we refer to both as “Cosmic Ray Electrons (CREs)”

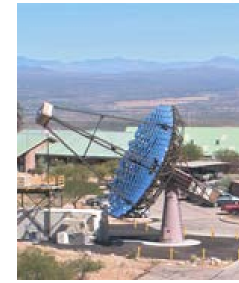
Candidate electron event

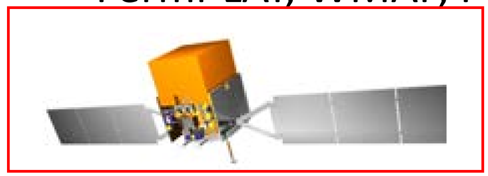


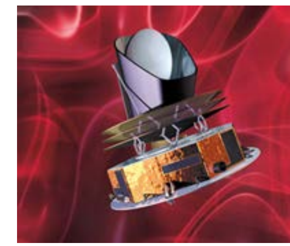
Indirect Dark Matter Search

γ

Ground-based instruments:
Cherenkov detector as HESS; MAGIC, VERITAS, …
Satellite-borne detectors:
Fermi-LAT, WMAP, PLANK, …

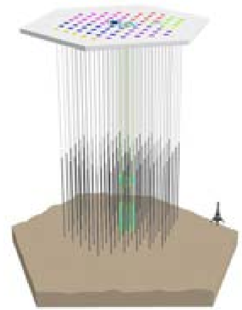


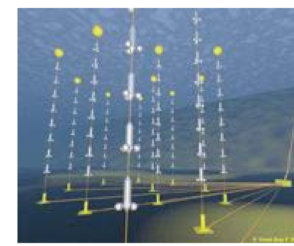




ν

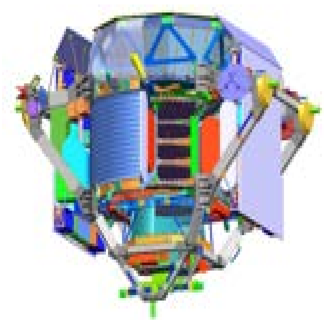
IceCube
Antares
…





B-field

$e^{\pm}$, anti-p,

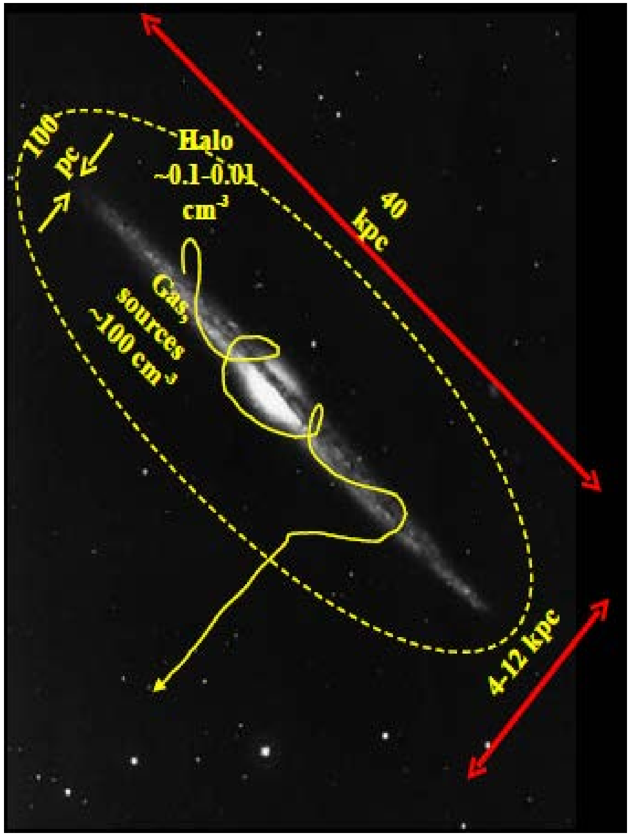


PAMELA
Fermi-LAT
AMS-02
DAMPE
CALET

- Annihilation or decay of dark matter can produce a variety of potentially detectable Standard Model particles
    - Contribute to cosmic rays
- Spectrum of annihilation (or decay) products encodes info about intrinsic particle properties
- Variations in the intensity of the signal along different lines of sight depend exclusively on the distribution of dark matter

Galactic cosmic rays

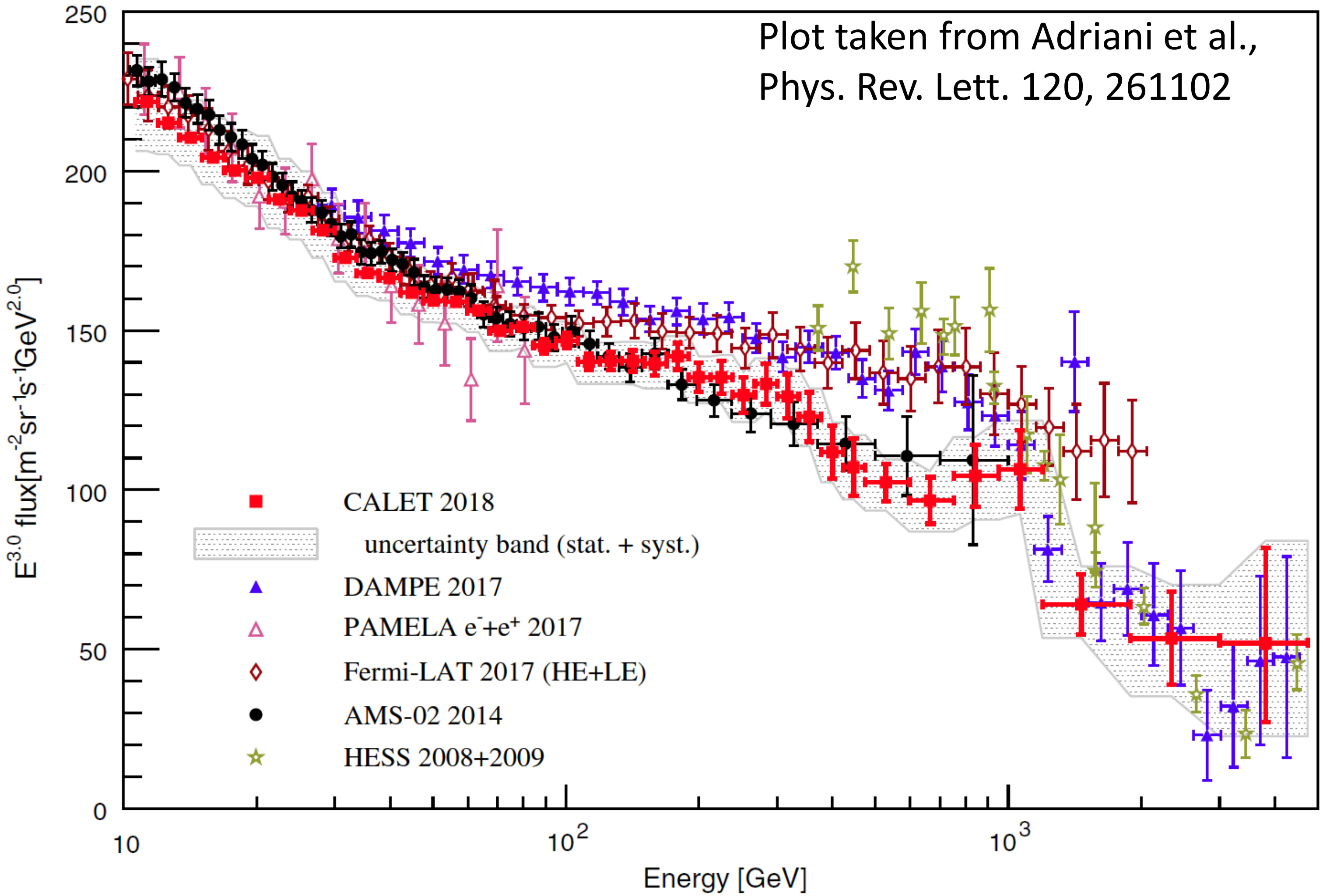
- High-energy (GeV–TeV) charged Cosmic Rays (CRs) are originated within our Galaxy
  - Sources: Supernova Remnants (SNRs), Pulsar Wind Nebulae (PWN)
- CR propagation:
  - Well described by a diffusion-loss equation
  - Escape time ≈ 1My
- CR interactions with interstellar gas, radiation and magnetic fields produce various secondaries:
  - EM radiation (from radio to gamma rays)
  - Nuclei
  - Electrons and positrons
  - …



Cosmic-ray electrons and positrons (CREs)

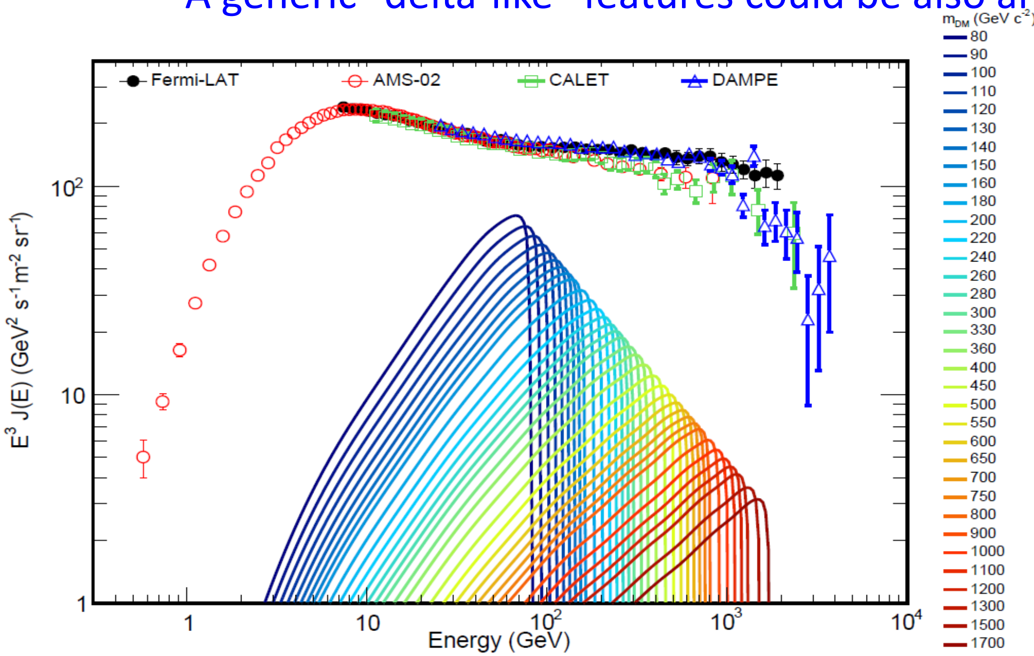
- CREs suffer significant energy losses during their propagation
  - Synchrotron radiation in the Galactic Magnetic Field (GMF)
  - Inverse Compton scattering with the low-energy photons of the Interstellar Radiation Field (IRF)
- Cooling time:
  - Average time needed for a CRE to lose all its energy
  - $T \approx 2 \times 10^5$ yrs/E(TeV)
- Travel distance (due to diffusion):
  - $R = (2DT)^{1/2}$
  - $R \approx 1.6$ (0.75) kpc for E=100 GeV (1 TeV)
  - The CRE horizon is small compared to the size of our Galaxy
  - High-energy CREs originate from a few nearby sources

Summary of the current measurements of the CRE energy spectrum at Earth



Features in the CRE energy spectrum?

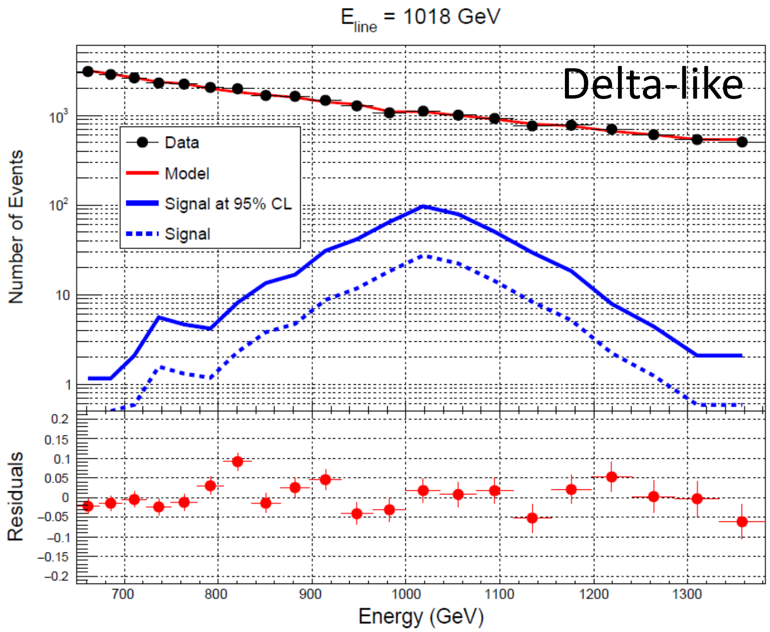
- High-energy CREs at Earth
  - Their energy spectrum reflects the production spectra at the sources
    - Individual sources are expected to yield power-law spectra
    - The final spectrum results from the superposition of individual source contributions
    - Local bumps/dips expected in the spectrum
- CREs could be also produced by DM annihilations within the Galaxy
  - Direct annihilation into e^+e^- pairs would yield a “edge-like” feature in the CRE energy spectrum with a cut-off at the DM mass value
  - The amplitude of the feature depends on the velocity-averaged annihilation cross section $\langle\boldsymbol{\sigma v}\rangle$ (and local DM density)
  - A generic “delta-like” features could be also an hint of a “nearby” DM clump

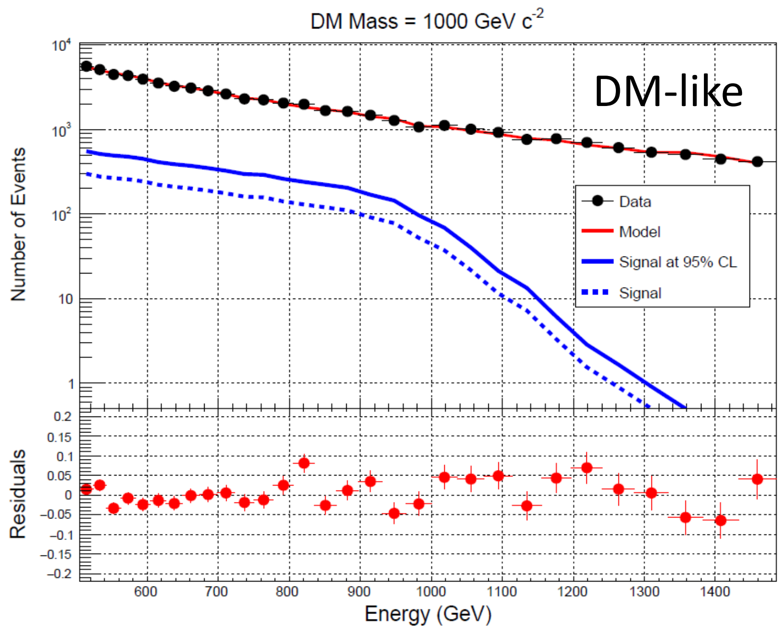


- Diffuse DM source in the Milky Way
  - A NFW DM profile is assumed
    - The choice of the DM profile does not significantly affect the CRE spectrum at the Earth
  - DM spectra evaluated with $\langle\sigma v\rangle = 3 \times 10^{-25} cm^3 s^{-1}$

Search for features in the CRE energy spectrum (1)

- Analysis of the spectrum of CREs detected by the LAT
  - CRE energy range: 40 GeV – 2 TeV
- Fits of the spectrum in sliding energy windows with:
  - $\Phi(E) = \Phi_{smooth}(E) + \Phi_{feat}(E)$
  - Smooth power-law component: $\Phi_{smooth}(E) = k\left(\frac{E}{1GeV}\right)^{-\gamma}$
  - Feature (delta-like or edge-like, from DM model)
- Energy resolution of the LAT is included in the fit procedure

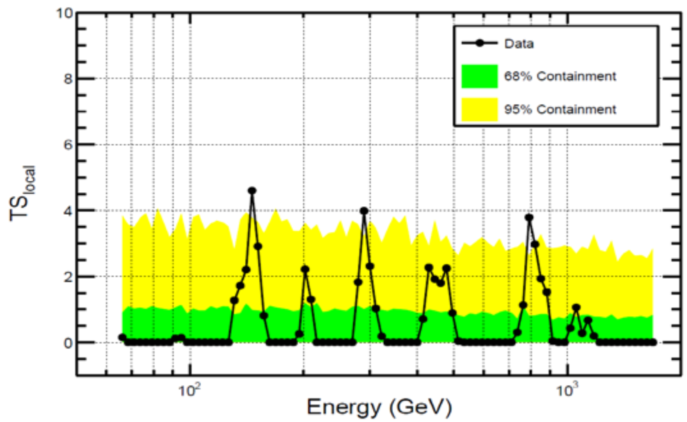


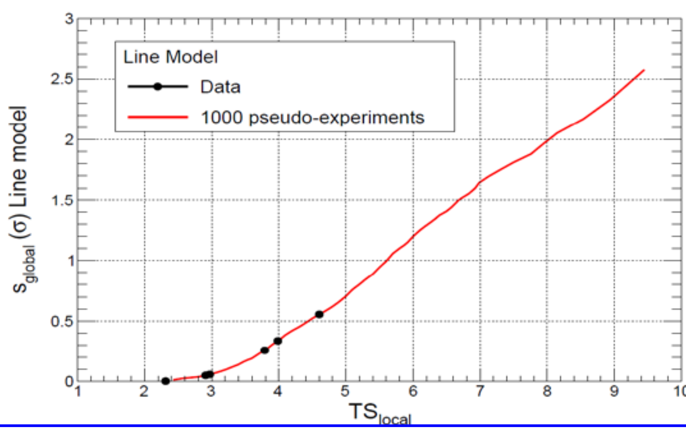


Search for features in the CRE energy spectrum (2)

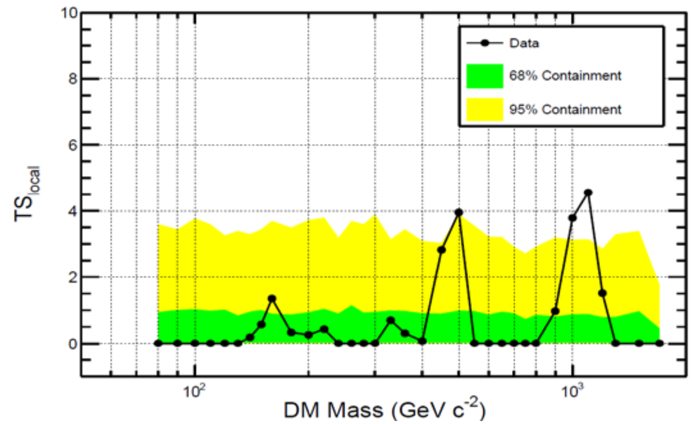
- No significant features found
- Results are consistent with expectations from null hypothesis

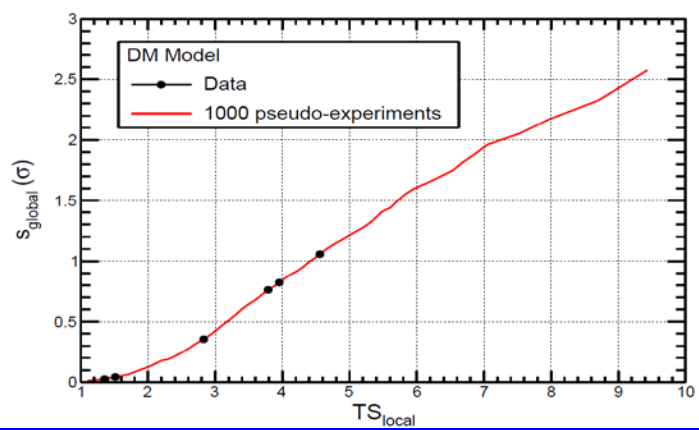
Delta-like





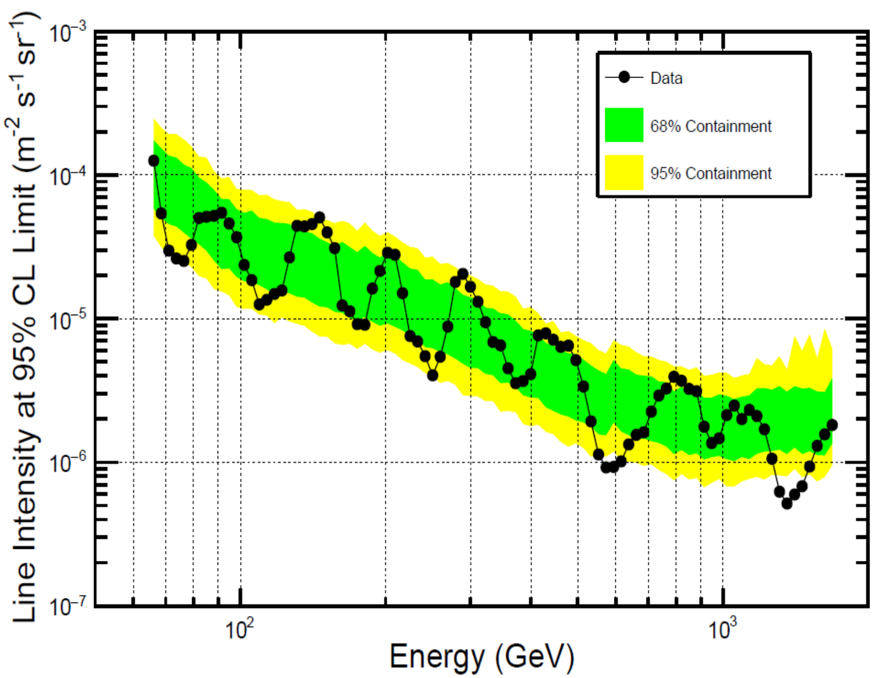
DM-like

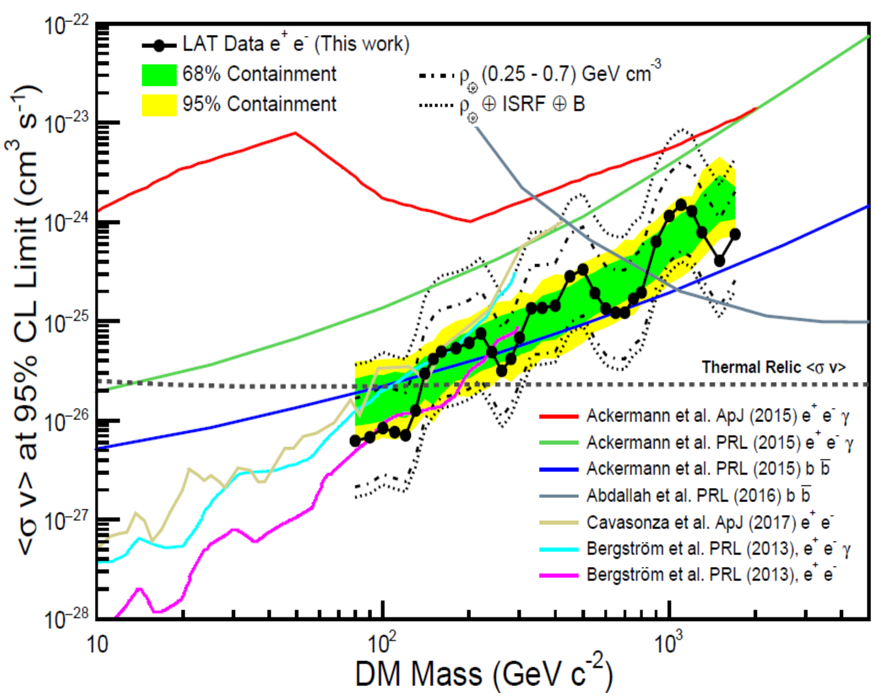




DM constraints from the analysis of the CRE spectrum

- Thermal relic <σv> excluded below 150 GeV/c²
- Limits on DM mass are consistent with those obtained by the LAT with gamma rays
  - Limits also consistent with HESS (TeV) and AMS-02 (<300 GeV)





Conclusion

- The current analysis yields no evidence for a line or a DM feature in the in the CRE spectrum up to 1.7 TeV
  - The thermal relic cross section is excluded up to about 150 GeV for Galactic DM halo
  - Further details in Mazziotta et al., Phys. Rev. D 98 (2018), 022006
- The LAT has looked for indirect DM signals using a wide variety of methods
  - Searches using gamma rays and CREs have been performed
    - More searches than the one presented in this report
  - No DM signals have been detected, but strong constraints have been set
  - DM searches are still ongoing and results will be updated as new data will be collected by the LAT

BACKUP

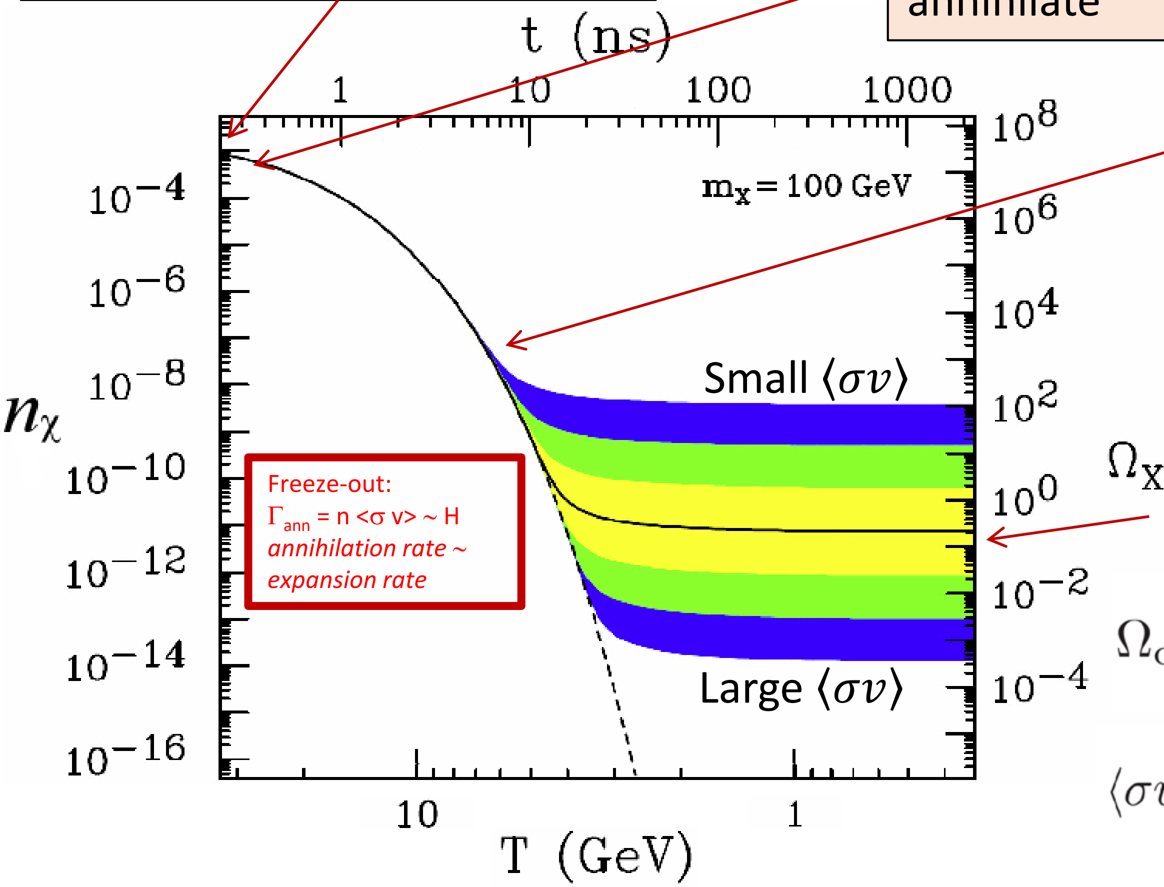
DM as a thermal relic of the Big Bang

For the first 0.1 ns of the Universe it is hot enough to produce exotic particles

After about 0.1 ns, the Universe has cooled enough that exotic particles are no longer produced, but can annihilate

For about 10 ns, the density is so high that almost all the exotic particles do annihilate

Only about 1 in 100 billion of the exotic particles survive, these account for all the dark matter that exists today

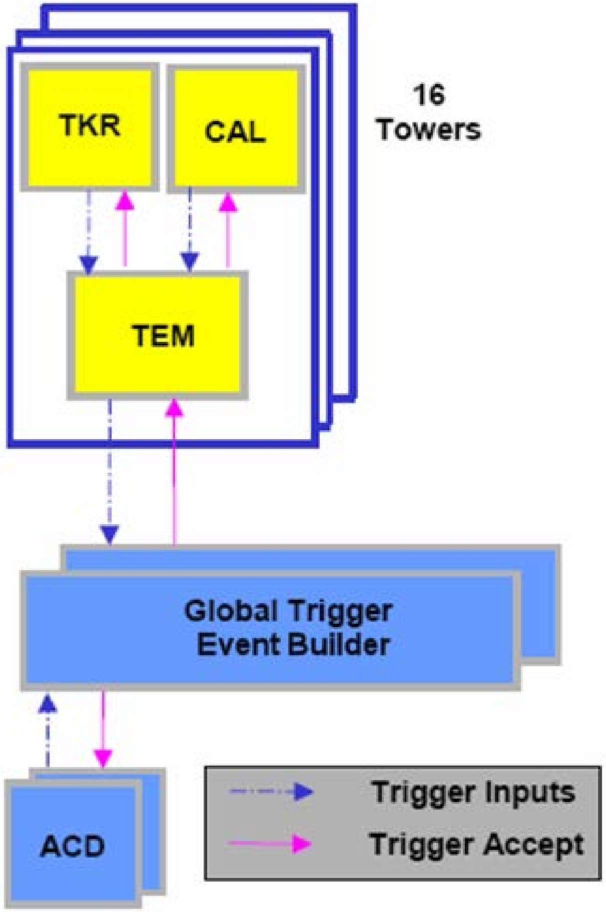


$$\Omega_{\rm dm} h^2 \approx \frac{3\times 10^{-27}\mathrm{cm}^3\mathrm{s}^{-1}}{\langle\sigma v\rangle} \simeq 0.1$$

$$\langle\sigma v\rangle \sim \frac{\alpha^2}{(200\mathrm{GeV})^2} \sim 10^{-26}\mathrm{cm}^3\mathrm{s}^{-1}$$

The surviving fraction depends critically on the annihilation cross section: small differences would yield very different dark matter densities today

LAT Triggering



- Five hardware trigger primitives (at the tower level)
  - TKR: 3 x + 3 y tracker planes hit in a row
  - CAL LO: single log with more than 100 MeV
  - CAL HI: single log with more than 1 GeV
  - ROI: MIP signal in a ACD tiles close to a triggering tower
  - CNO: heavy ion signal in the ACD
- Upon L1 trigger the entire detector is read out
- Need onboard filtering to fit the data volume within the allocated bandwidth
  - GAMMA: the purpose is to select γ-ray candidates and events that deposit at least 20 GeV in the CAL
    - High energy events, including electrons, are available for analysis on the ground
  - Heavy Ions: the purpose is to perform calibration on high-energy scales;
  - Diagnostic: the purpose is to select an unbiased event sample for filter and background performance studies
  - MIP: the purpose is to select non interacting charged particles (protons)

CRE performance

- S. Abdollahi et al. “Cosmic-ray electron-positron spectrum from 7 GeV to 2 TeV with the Fermi Large Area Telescope”, PRD 95, 082007 (2017)

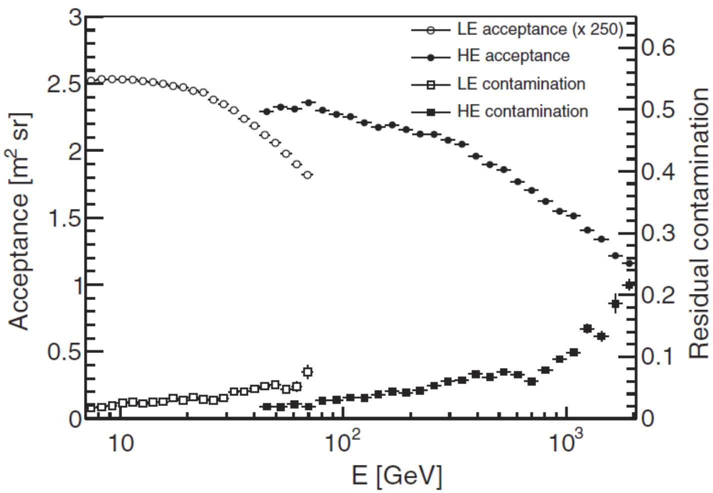


FIG. 6. Acceptance and residual background contamination as a function of energy. The displayed LE acceptance is multiplied by 250 (as if there were no prescale factor due to the on-board filter).

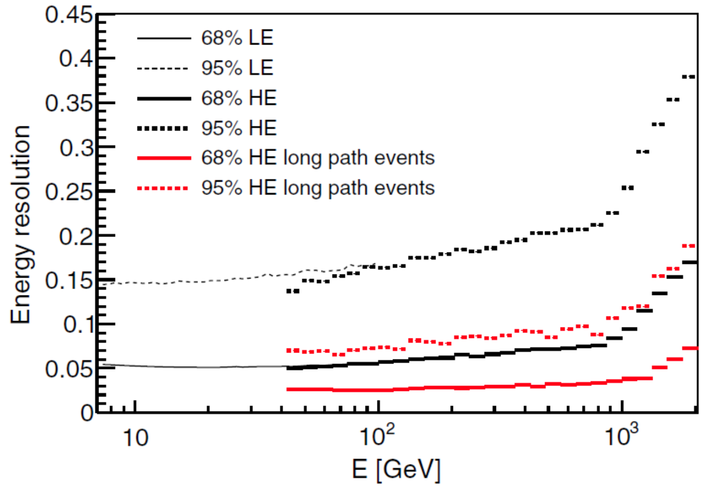


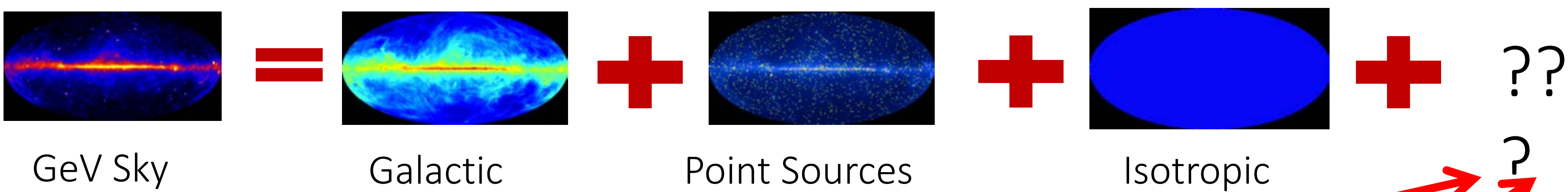
FIG. 10. Energy resolution for various selections: all events (black), events with more than 12 radiation lengths in the CAL (red). Solid (dotted) lines correspond to the 68% (95%) containment halfwidth. Thin and thick lines correspond to the LE and the HE analysis, respectively.

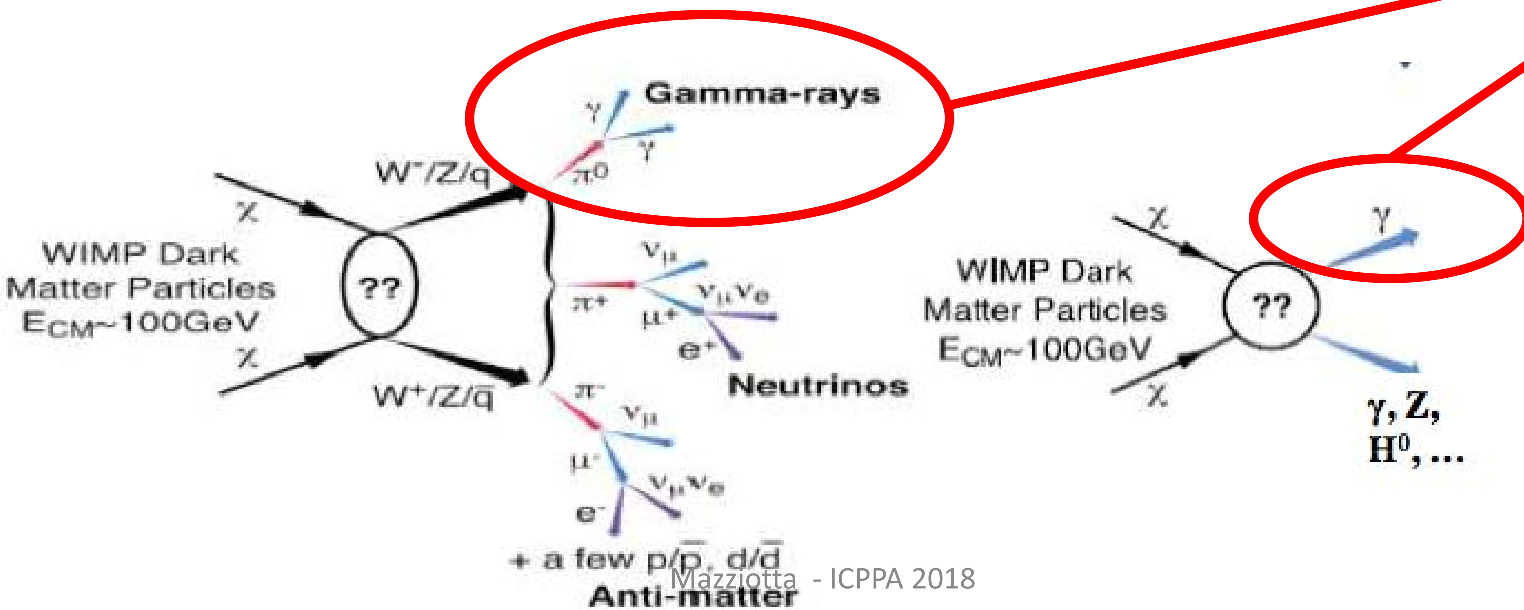
DM searches with the Fermi LAT

- The LAT can perform DM searches with two different probes:
  - Gamma rays
  - Cosmic-ray electrons and positrons (CREs)
- The results of these searches are complementary
- DM search strategy:
  - DM is usually expected to yield a signal excess
    - The signal excess is often correlated to some particular directions in the sky
    - Variation in the intensity of the signal along different lines of sight is determined exclusively by the distribution of dark matter
    - Spectrum of annihilation (or decay) products encodes info about intrinsic particle properties
  - The possible DM signal must be disentangled from all known astrophysical backgrounds

DM searches in the GeV gamma-ray sky

- Indirect detection (i.e. astrophysical) searches for DM in the astrophysical targets where it is known to exist
- The LAT is sensitive to DM annihilation at the present-day thermal relic cross section





DM signatures in gamma rays

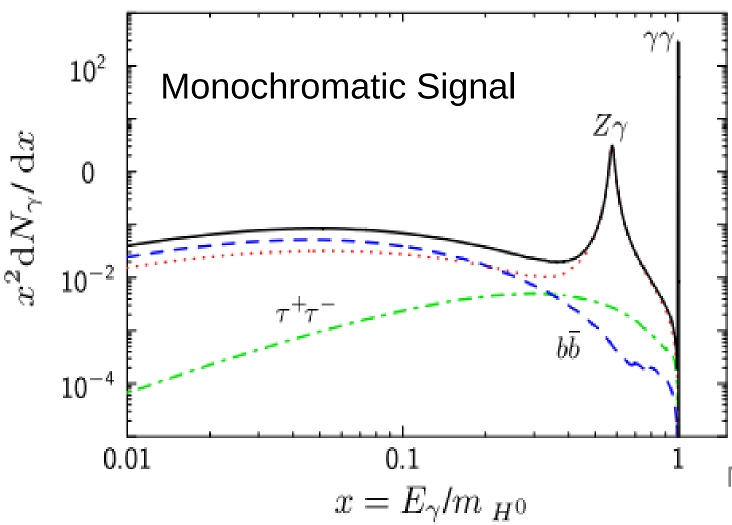
Observed flux — Intrinsic Particle Properties — Astrophysics

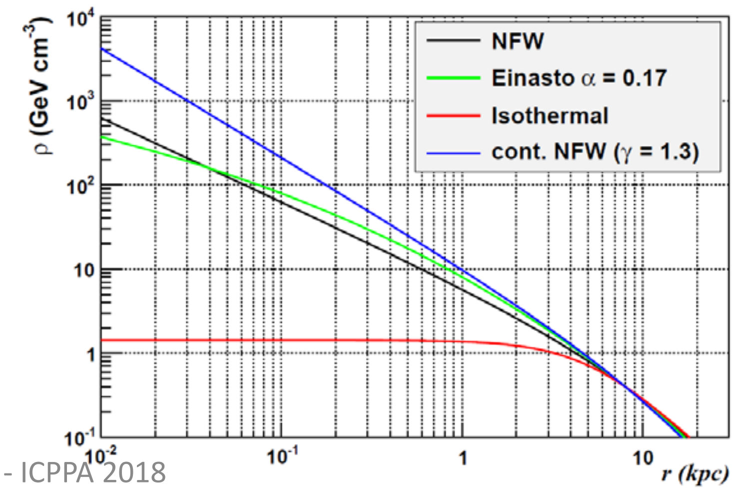
Annihilation: $$\underbrace{\phi(E,\Delta\Omega)}_{\text{Observed flux}} = \underbrace{\frac{1}{4\pi}\frac{\langle\sigma v\rangle}{2\,m_\chi^2}\sum_f \frac{dN_f}{dE}B_f}_{\text{Intrinsic Particle Properties}}\,\underbrace{\int_{\Delta\Omega} d\Omega \int_{l.o.s.} dl\,\rho^2(l(\Omega))}_{\text{Astrophysics}}$$

$<\sigma v>_{ann} \sim 3\times10^{-26} cm^3/s$ for thermal relic

J-factor – DM distribution (line-of-sight integral)

Decay: $$\phi(E,\Delta\Omega) = \frac{1}{4\pi}\frac{1}{\tau\,m_\chi}\sum_f \frac{dN_f}{dE}B_f \int_{\Delta\Omega} d\Omega \int_{l.o.s.} dl\,\rho(l(\Omega))$$





DM search targets

Satellites

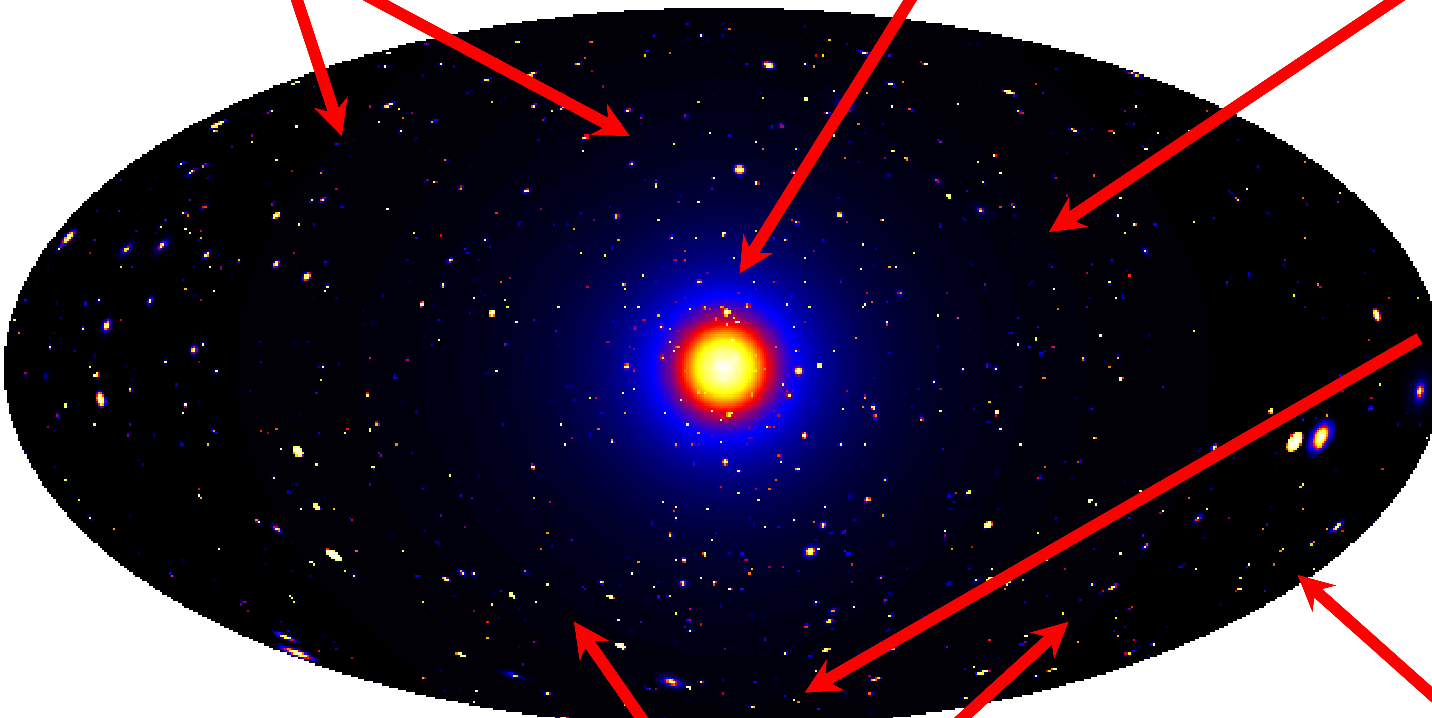
Low background and good source id, but low statistics

Galactic Center

Good Statistics, but source confusion/diffuse background

Milky Way Halo

Large statistics, but diffuse background



Dwarf Galaxies

Known location and DM content
Low statistics

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

Power law spectral index