

Fermi

Gamma-ray Space Telescope



Dark Matter Constraints with the First Year of Fermi LAT Data

Tomi Ylinen

on behalf of the Fermi LAT collaboration

Royal Institute of Technology (KTH)

Linnaeus University

Oskar Klein Centre for Cosmoparticle Physics



Outline

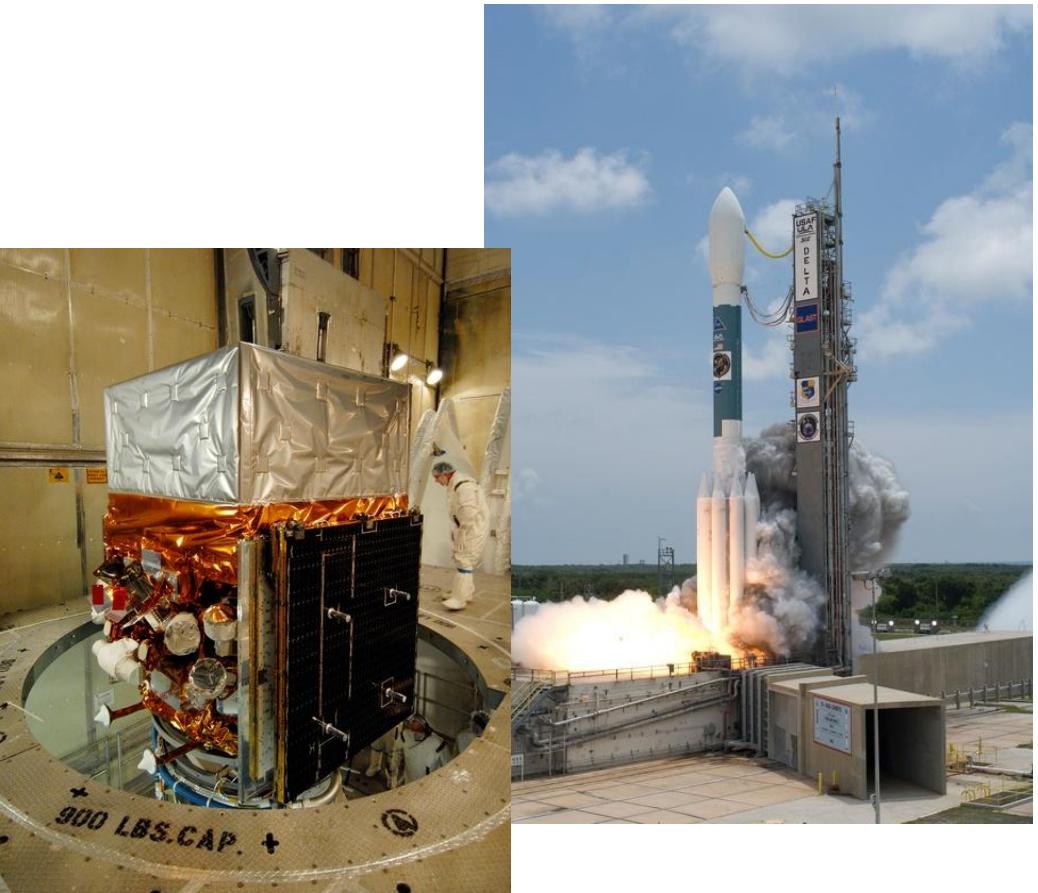


- Fermi mission
- Dark matter
- Fermi LAT searches:
 - Clusters of galaxies
 - Cosmological dark matter
 - Dark matter subhalos
 - Dark matter satellites
 - Dwarf spheroidal galaxies
 - Spectral lines
- Fermi LAT electrons
- Summary and outlook

Fermi mission



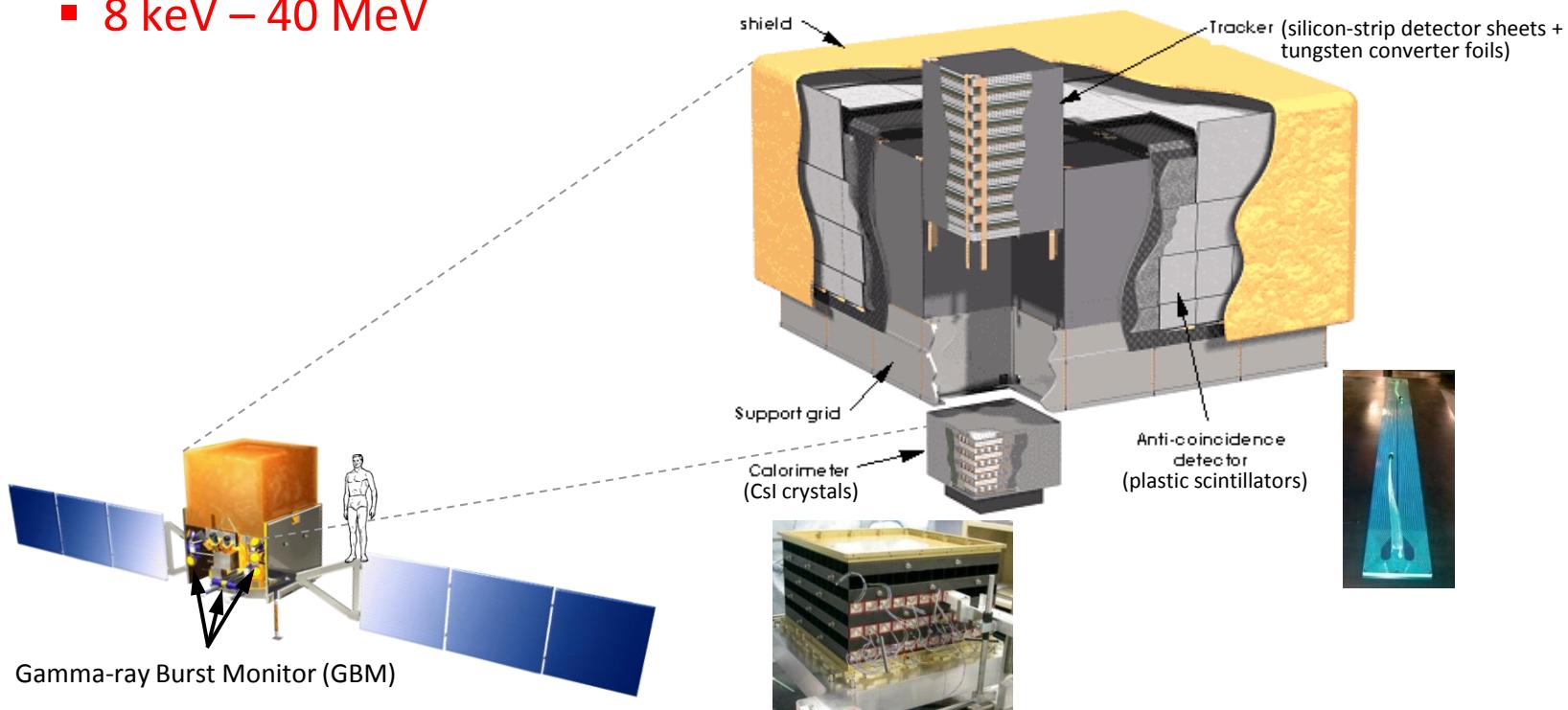
- Fermi Gamma-ray Space Telescope was launched by NASA on June 11, 2008, from Cape Canaveral, Florida
- Circular orbit:
 - 565 km altitude
 - 25.6° inclination
- Life expectancy:
 - 5 years (minimum)
 - 10 years (design goal)
- About 60 published collaboration papers so far



Fermi detectors



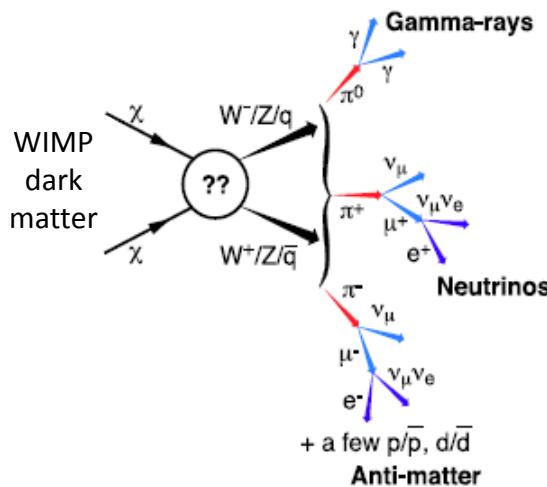
- Two instruments:
 - Large Area Telescope (LAT)
 - 20 MeV – >300 GeV
 - Gamma-ray Burst Monitor (GBM)
 - 8 keV – 40 MeV





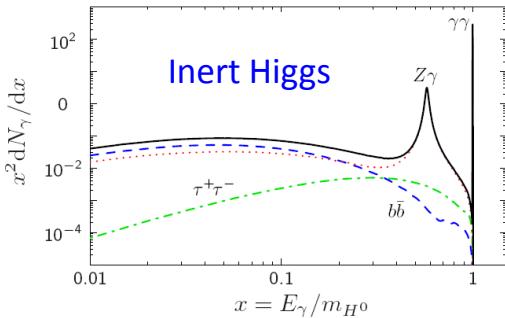
- For γ -rays, dark matter (DM) signals come as:
 - Continuum spectrum with cutoff at m_χ
 - Spectral lines at m_χ

Continuum signal



$$E_\gamma = m_\chi \left(1 - \frac{m_\chi^2}{4m_\chi^2}\right)$$

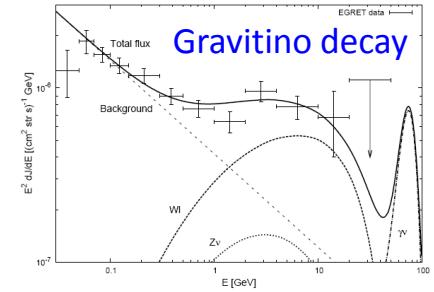
M. Gustafsson, et al.,
Phys. Rev. Lett., 99 (2007) 041301.



$$E_\gamma = \frac{m_\chi}{2} \left(1 - \frac{m_Z^2}{m_\chi^2}\right)$$

WIMP
dark
matter

A. Ibarra & D. Tran,
Phys. Rev. Lett., 100 (2008) 061301.



Dark matter annihilations



- Total flux from DM annihilations:

$$\frac{d\Phi}{dE_\gamma}(E_\gamma, \phi, \theta) = \boxed{\frac{1}{4\pi} \frac{\langle \sigma v \rangle}{2m_\chi^2} \sum_f \frac{dN_\gamma^f}{dE_\gamma} B_f} \times \boxed{\int_{\Delta\Omega(\phi, \theta)} d\Omega' \int_{LoS} \rho^2(\vec{r}(l, \phi', \theta')) dl}$$

- DM distribution:

$$\rho(r) = \frac{\rho_s}{(r/r_s)^\gamma [1 + (r/r_s)^\alpha]^{(\beta-\gamma)/\alpha}}$$

$$\rho(r) = \rho_s e^{-(2/a)[(r/r_s)^a - 1]}$$

Popular choices for (α, β, γ):

NFW: (1, 3, 1)

Moore: (1.5, 3, 1.5)

Isothermal with core: (2, 2, 0)

Einasto profile

Dark matter sources



- Where to look?

Search	Advantages	Challenges
Galactic center	Good statistics	Source confusions Uncertainty in diffuse background prediction
Satellites	Low background Good source identification	Astrophysical uncertainties
Galactic halo	Very good statistics	Uncertainties in galactic diffuse background
Extragalactic	Very good statistics	Uncertainties in galactic diffuse contribution Astrophysical uncertainties
Spectral lines	No astrophysical uncertainties “Smoking gun” signal	Potentially low statistics

E.A. Baltz, et al., JCAP 07 (2008) 013.

Clusters of galaxies



- Distant source type but dark matter dominated and typically at high galactic latitudes
- 6 clusters selected from the HIGFLUCS catalog of brightest X-ray clusters
- Unbinned likelihood fit with both spatial and spectral models

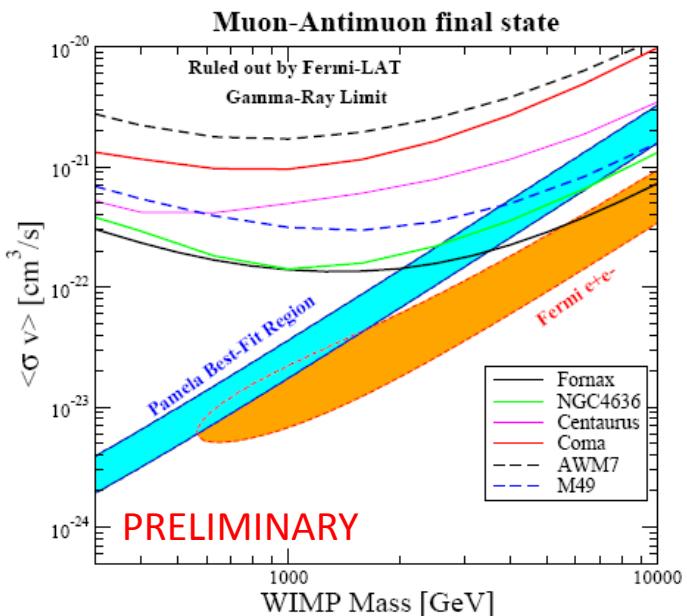
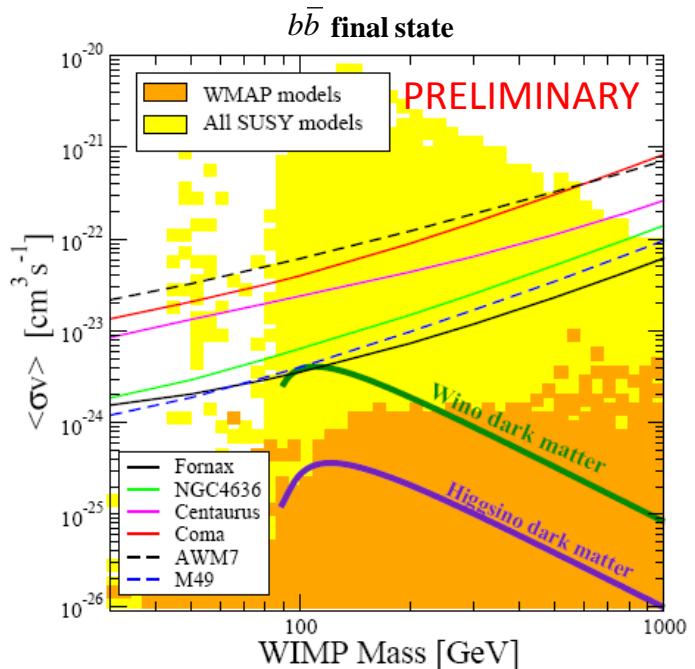
Cluster	RA	Dec.	z	$J (10^{17} \text{ GeV}^2 \text{ cm}^{-5})$
AWM 7	43.6229	41.5781	0.0172	$1.4_{-0.1}^{+0.1}$
Fornax	54.6686	-35.3103	0.0046	$6.8_{-0.9}^{+1.0}$
M49	187.4437	7.9956	0.0033	$4.4_{-0.1}^{+0.2}$
NGC 4636	190.7084	2.6880	0.0031	$4.1_{-0.3}^{+0.3}$
Centaurus (A3526)	192.1995	-41.3087	0.0114	$2.7_{-0.1}^{+0.1}$
Coma	194.9468	27.9388	0.0231	$1.7_{-0.1}^{+0.1}$

Fermi LAT Collaboration, arXiv:1002.2239v2, submitted to JCAP.

Clusters of galaxies



- No significant γ -ray emission detected from the selected clusters for 11 months of data
- 95% limits begin to probe the available phase space



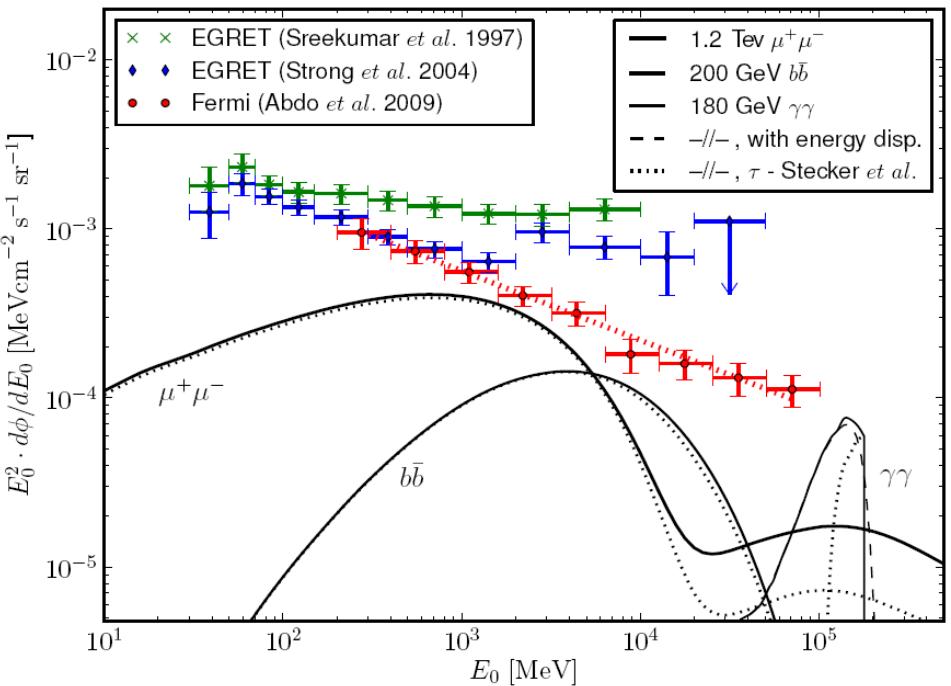
Fermi LAT collaboration, arXiv: 1002.2239v2, submitted to JCAP.

Cosmological dark matter



- Search for DM from all halos at all redshifts
- Based on the measured isotropic diffuse gamma-ray background emission
Fermi LAT collaboration, Phys. Rev. Lett., 104 (2010) 101101, [arXiv: 1002.3603v1].
- Cases considered:
 - 4 annihilation clustering enhancement models
 - 3 particle physics models for dark matter
 - 2 absorption models
 - 2 upper limit calculations (conservative, stringent)

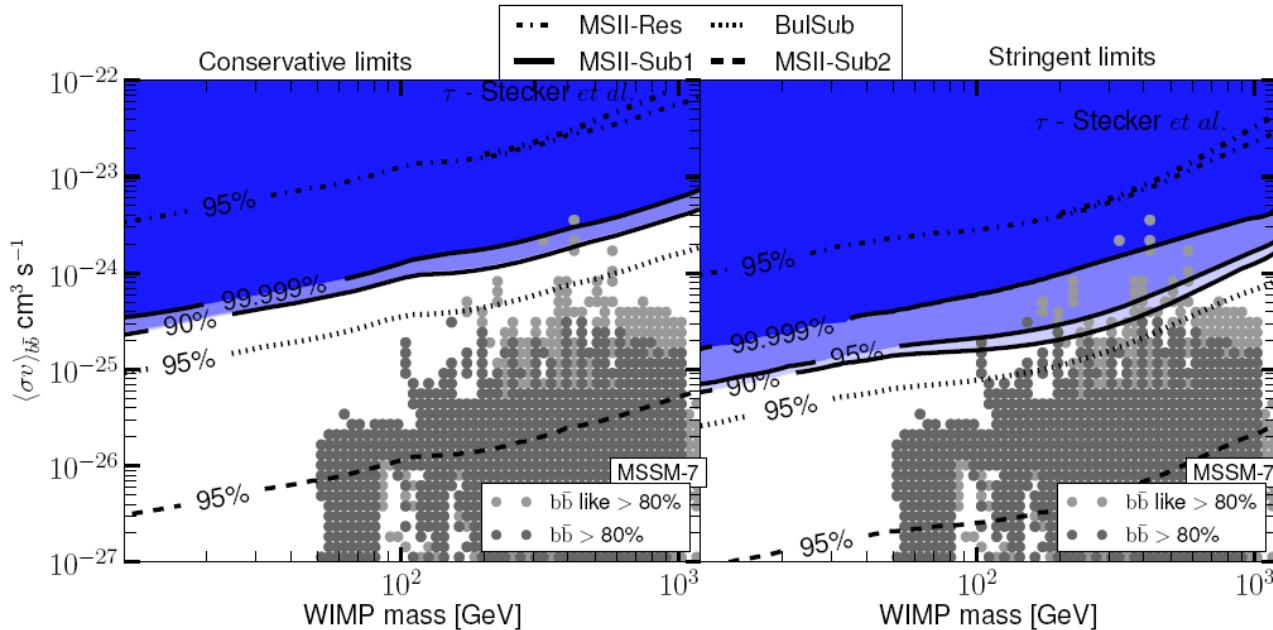
Fermi LAT collaboration, arXiv:1002.4415, accepted by JCAP.



Cosmological dark matter



- Limits can be very constraining for some cases
- However, large uncertainties in:
 - Modeling of the evolution of DM structure and substructure
 - Estimation of the isotropic background



Fermi LAT collaboration, arXiv:1002.4415, accepted by JCAP.

Dark matter subhalos



- Two types of DM subhalos:
 - DM satellites
 - Substructures with only DM
 - May shine in radiation from DM annihilations/decays
 - Ongoing analysis, no detection in 10 months of Fermi LAT data (Preliminary)
 - Optically observed dwarf spheroidal galaxies

Dwarf spheroidal galaxies



- Low luminosity optically observed galaxies that are companions to a larger host galaxy
 - High mass-to-light ratios (M/L) of 10-1000
→ dark matter dominated
 - Many are nearby
 - Predicted by N-body simulations
- 14 selected based on:
 - Proximity
 - High galactic latitude
 - Dark content based on recent stellar velocity measurements

Name	Distance (kpc)	year of discovery	$M_{1/2}/L_{1/2}$ ref. 8	l	b
Ursa Major II	30 ± 5	2006	4000^{+3700}_{-2100}	152.46	37.44
Segue 2	35	2009	650	149.4	-38.01
Willman 1	38 ± 7	2004	770^{+930}_{-440}	158.57	56.78
Coma Berenices	44 ± 4	2006	1100^{+800}_{-500}	241.9	83.6
Bootes II	46	2007	18000??	353.69	68.87
Bootes I	62 ± 3	2006	1700^{+1400}_{-700}	358.08	69.62
Ursa Minor	66 ± 3	1954	290^{+140}_{-90}	104.95	44.80
Sculptor	79 ± 4	1937	18^{+6}_{-5}	287.15	-83.16
Draco	76 ± 5	1954	200^{+80}_{-60}	86.37	34.72
Sextans	86 ± 4	1990	120^{+40}_{-35}	243.4	42.2
Ursa Major I	97 ± 4	2005	1800^{+1300}_{-700}	159.43	54.41
Hercules	132 ± 12	2006	1400^{+1200}_{-700}	28.73	36.87
Fornax	138 ± 8	1938	$8.7^{+2.8}_{-2.3}$	237.1	-65.7
Leo IV	160 ± 15	2006	260^{+1000}_{-200}	265.44	56.51

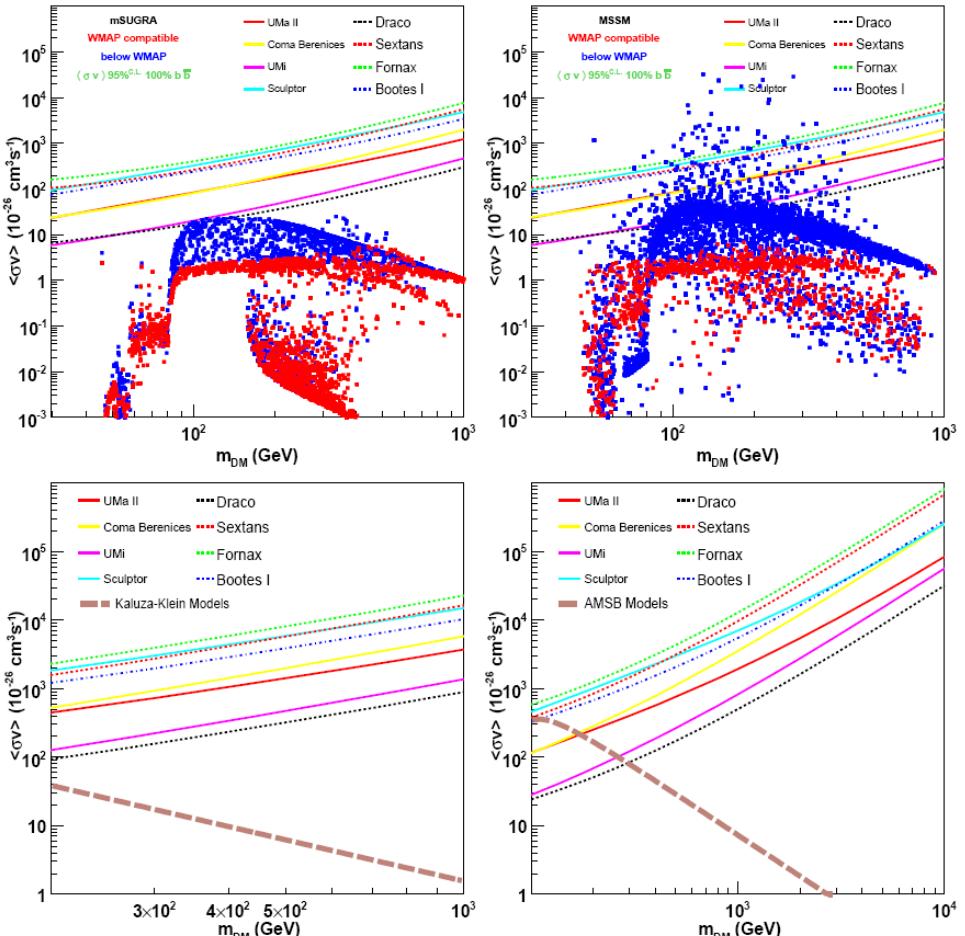
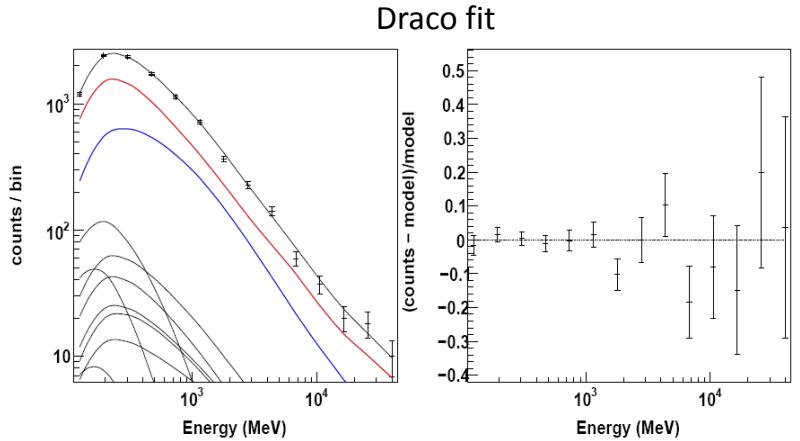
Fermi LAT collaboration, ApJ, 712 (2010) 147, [arXiv:1001.4531].

Dwarf spheroidal galaxies



- Binned likelihood search on 11 months of data assuming NFW halo profile
- No γ -ray excesses observed
- 8 limits combined with DM density inferred from stellar data*. 95% upper limits start to constrain mSUGRA, MSSM and AMSB parameter spaces

*G.D. Martinez, et al., JCAP, 6 (2009) 14.



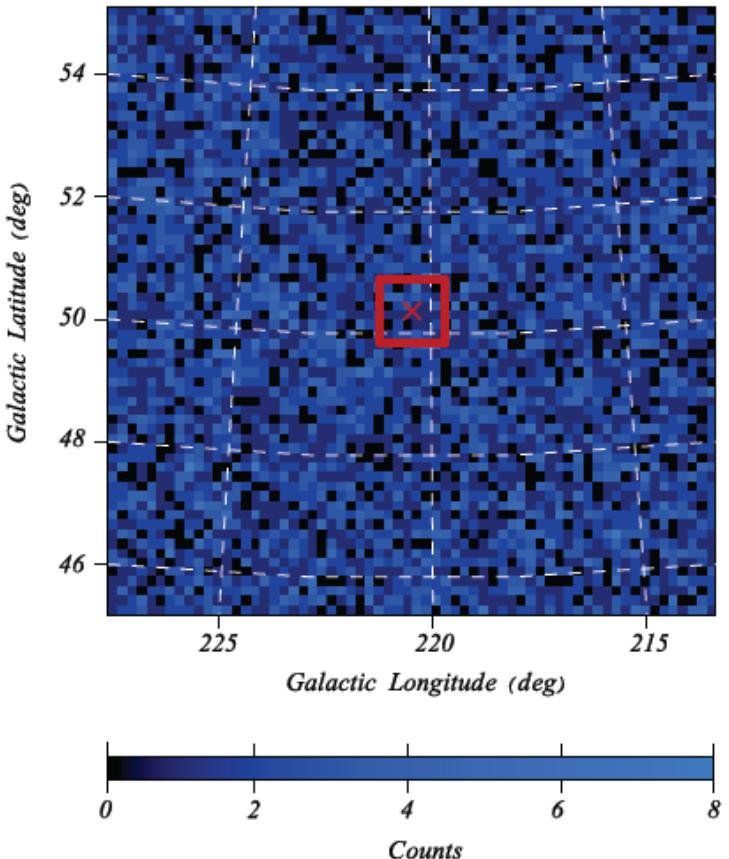
Fermi LAT collaboration, ApJ, 712 (2010) 147, [arXiv:1001.4531].

Dwarf spheroidal galaxies



- Dedicated analysis of Segue 1
 - Ra: 151.763, Dec: 16.074
 - M/L \approx 1320
 - Distance: 23 kpc
- Binned likelihood analysis combined with DarkSUSY and a CMSSM parameter scan based on nested sampling from **MultiNest** in **SuperBayeS** and assuming Einasto profile
- Instrumental response with uncertainty, internal bremsstrahlung and secondary decay is taken into account

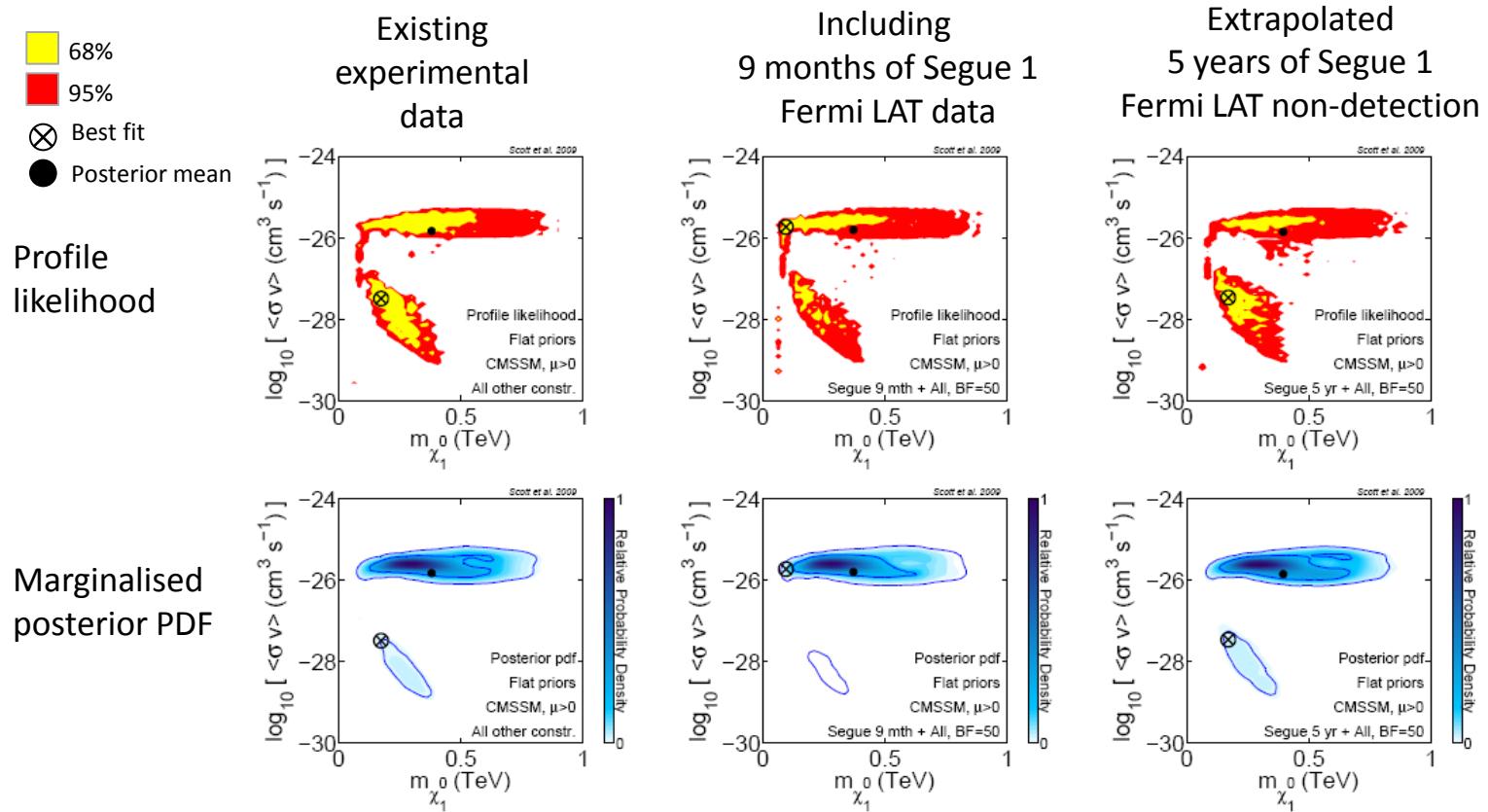
P. Scott, et al., JCAP, 01 (2010) 031.



Dwarf spheroidal galaxies



- Allowed regions for CMSSM (with 4 free continuous parameters + 1 sign)
- Disfavoured models already strongly disfavoured by relic density constraints

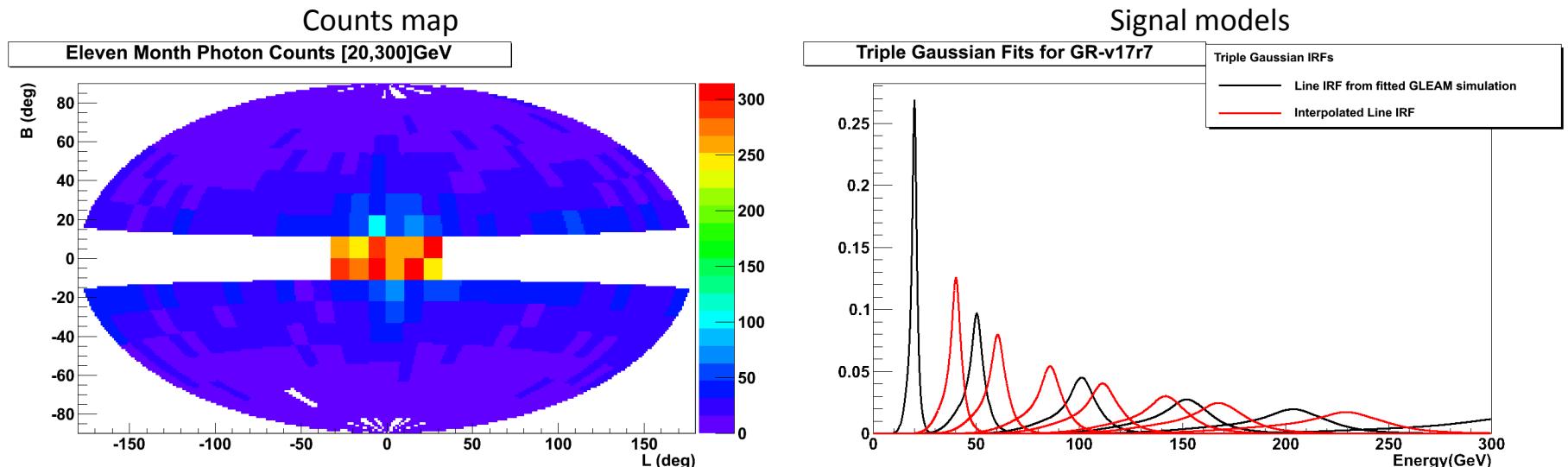


P. Scott, et al., JCAP, 01 (2010) 031.

Spectral lines



- Unbinned likelihood that can be used for both detection and upper limits, constructed within the **RooFit** framework and minimized with MINOS
- Line shapes determined from full detector simulations and interpolations
- Additional cuts w.r.t. public data event class, to reduce charge particle contamination, and profile energy used instead of standard energy
- Point sources from 11 month catalogue are masked

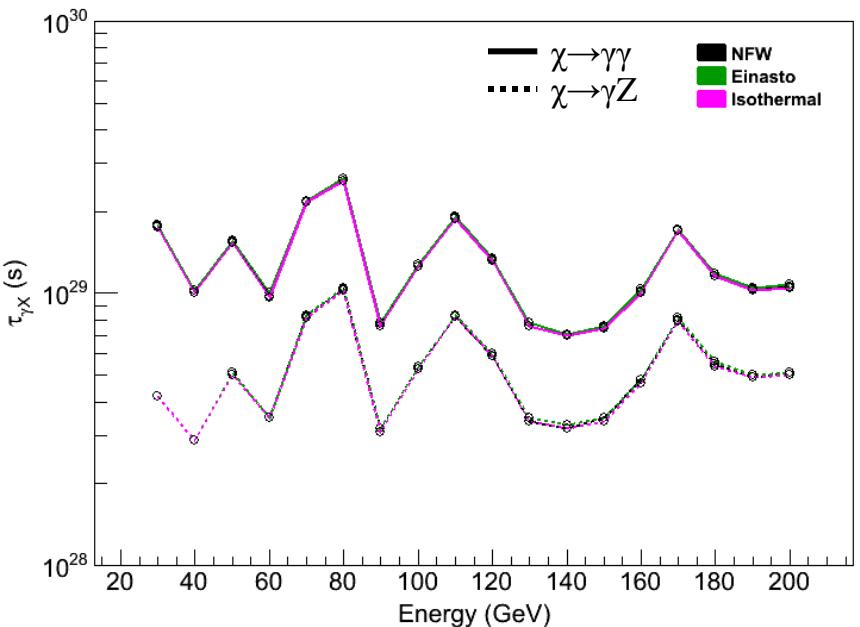
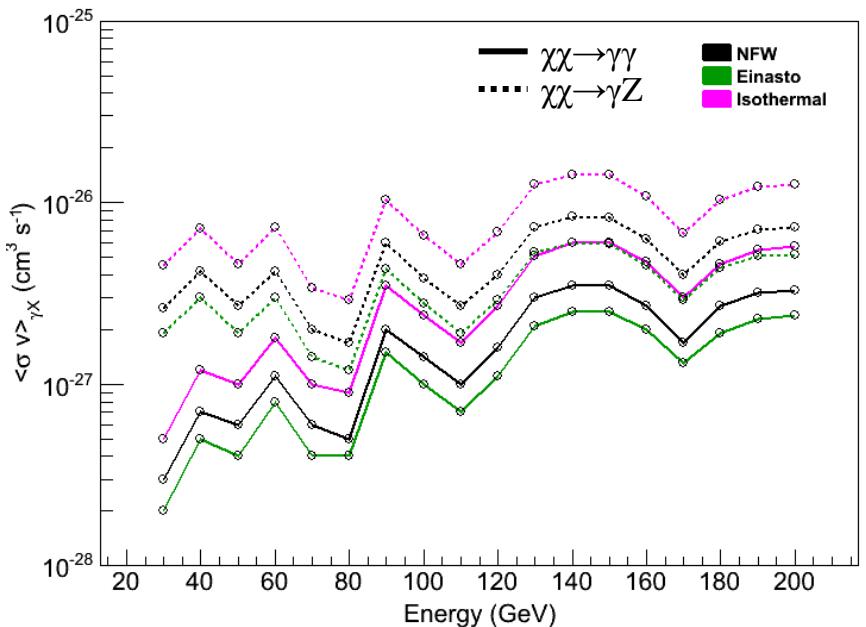


Spectral lines



- No detection at 95% CL. Upper limits still factor of ≈ 10 from more interesting MSSM and mSUGRA parameter spaces
- Disfavours "Wino LSP" model by factor of $\approx 2\text{-}5$
 - Prediction*: $\langle \sigma v \rangle_{\gamma Z} \approx 1.4 \times 10^{-26} \text{ cm}^3 \text{ s}^{-1}$ at 170 GeV

*G. Kane, et al., Physics Letters B 681 (2009) 151.



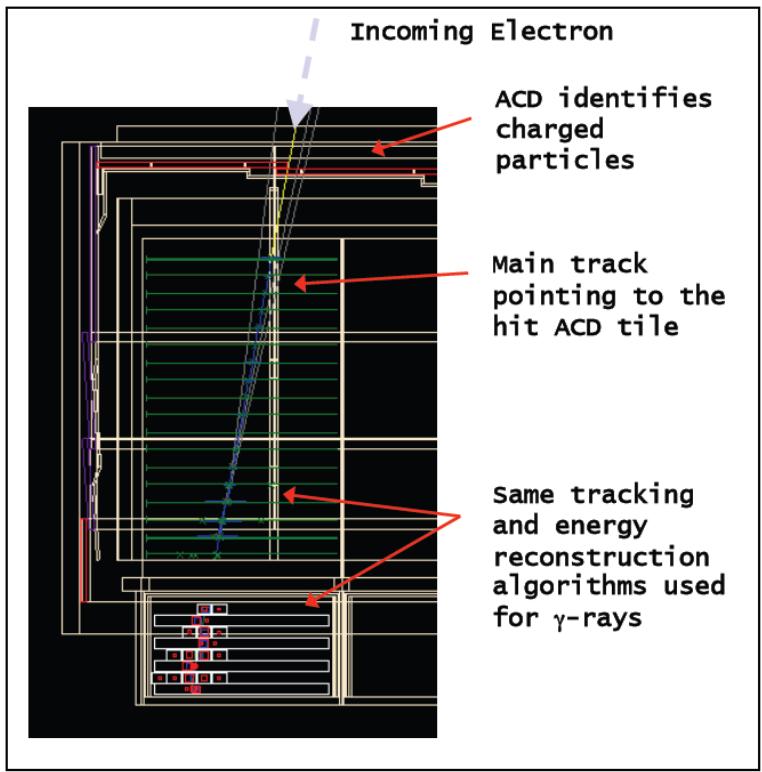
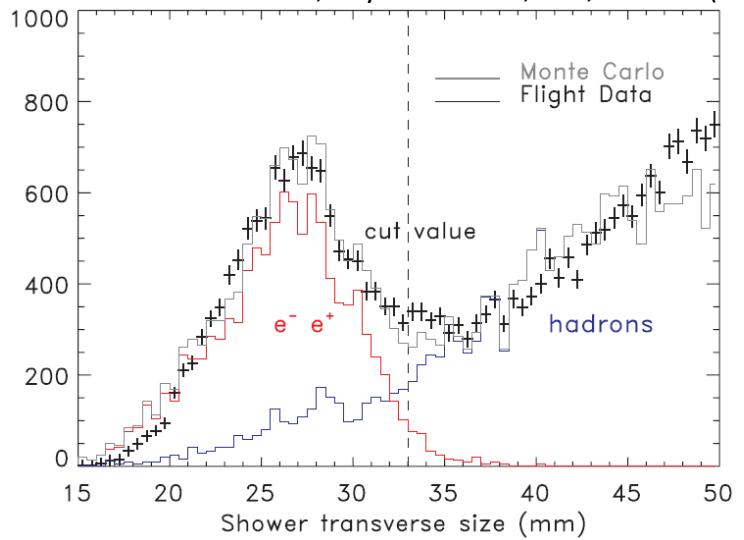
Fermi LAT Collaboration, Phys. Rev. Lett., 104 (2010) 091302, [arXiv:1001.4836].

Electron results



- *Fermi* LAT can also be used to measure e^- and e^+ (no separation)
- Relevant for cosmic-ray propagation models and possible nearby sources
- Rejection power of 10^3 - 10^4 required for protons, achieved via separate series of trigger settings and cuts on detector variables

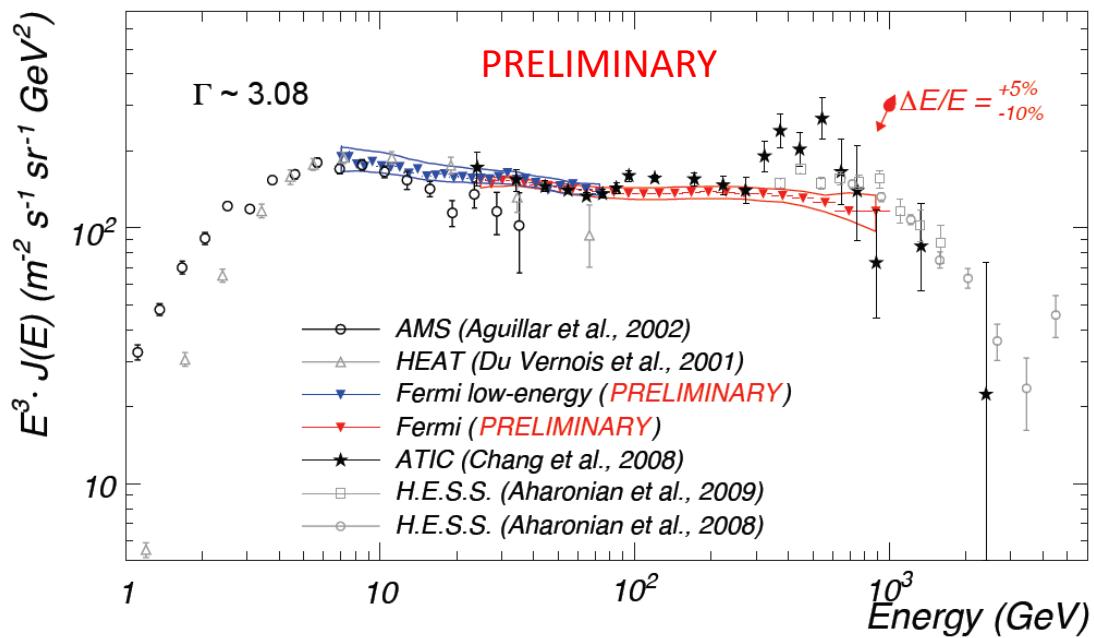
Fermi LAT Collaboration, Phys. Rev. Lett., 102, 181101 (2009)



Electron results



- Full spectrum combination of two separate analyses:
 - Low-energy and high energy
- Deviates visually from flat spectrum but is well fit by simple power-law when including systematic uncertainties

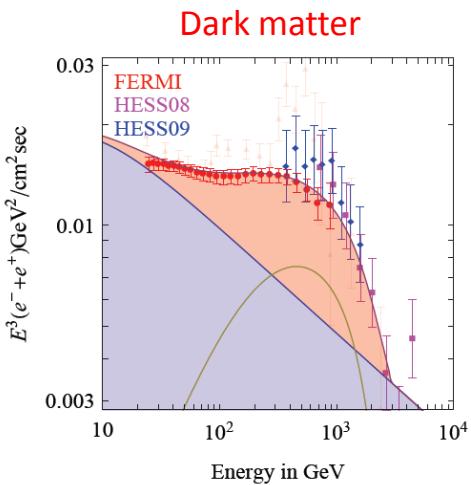


L. Latronico, Cosmic-ray backgrounds in dark matter searches, Stockholm, 2010

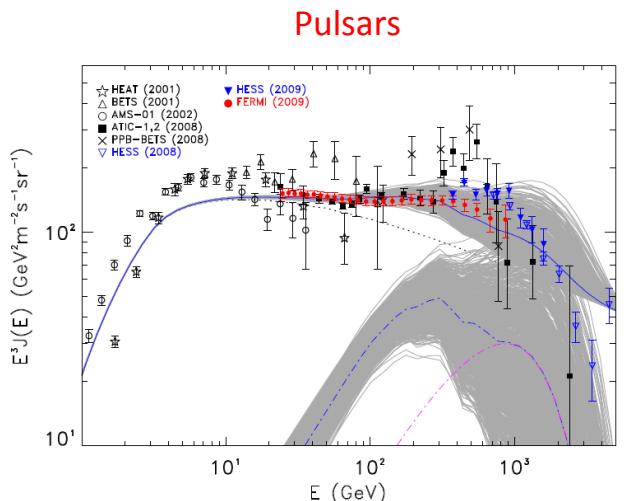
Electron results



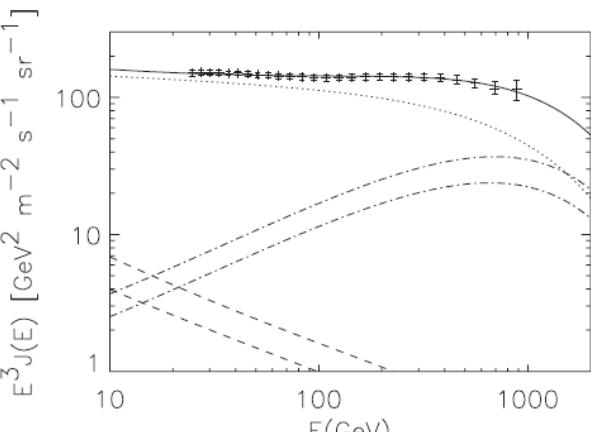
- Many possible interpretations to the shape of the e^-e^+ spectrum, when also considering other measurements like the positron fraction and the diffuse gamma-ray spectrum



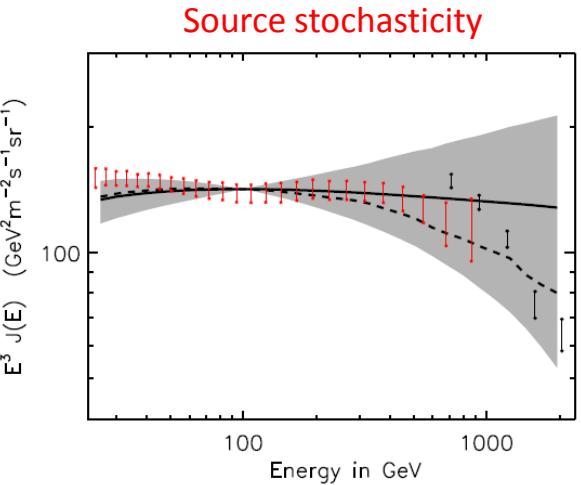
P. Meade, et al., [arXiv:0905.0480v1].



D. Grasso, et al., Astroparticle Physics 32 (2009) 140–151.



P. Blasi, Phys. Rev. Lett. 103 (2009) 051104.



Summary and outlook

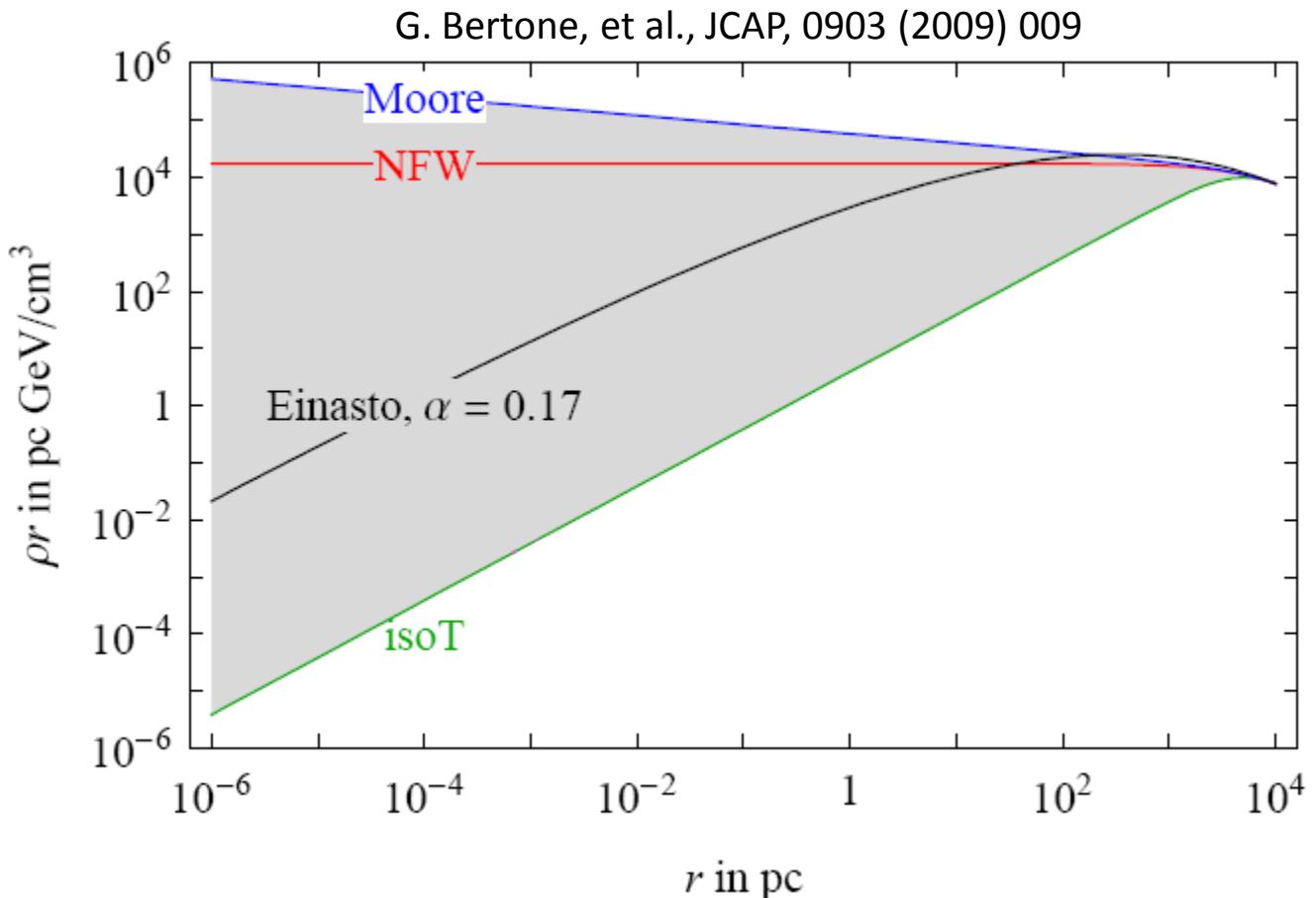


- Fermi Gamma-ray Space Telescope has opened a new era in DM searches
- A large variety of analyses have been developed for clusters of galaxies, DM subhalos, cosmological DM and spectral lines
 - No significant detections have been made, so constraints have been put on the annihilation cross-section and decay life times
- Several ongoing analyses are now being finalized, including studies of dark matter satellites and the complicated galactic center region
- Exciting times ahead, *Fermi* mission is 5-10 years

Backup slide – Halo profiles



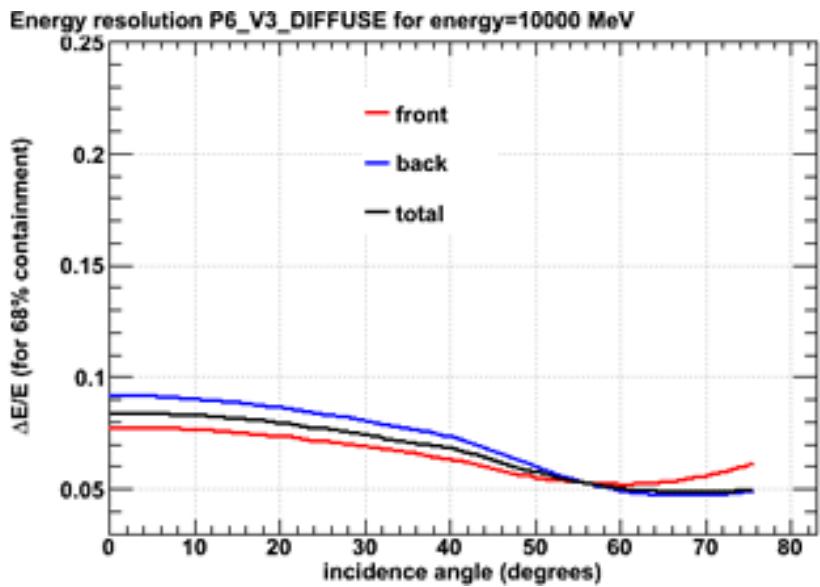
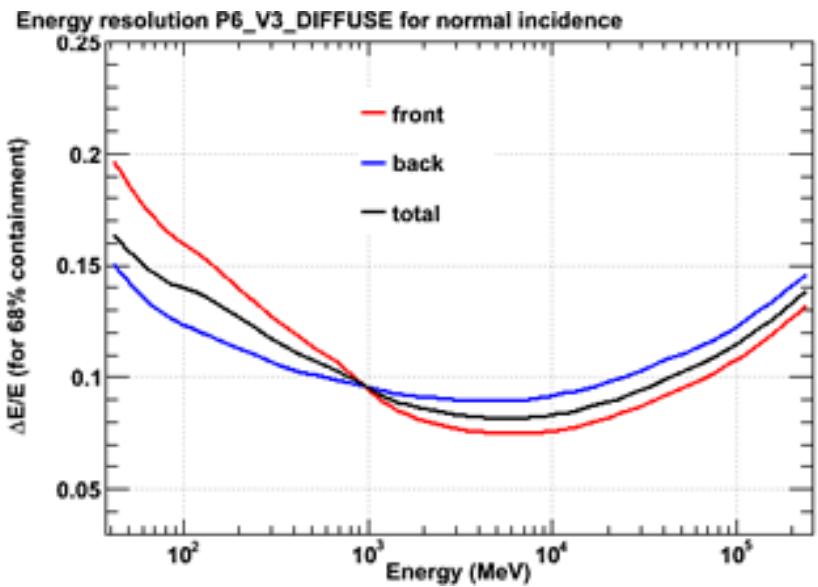
- Differences in halo profiles



Backup slide – Halo profiles



- Fermi LAT performance
 - Energy resolution



http://www-glast.slac.stanford.edu/software/IS/glast_lat_performance.htm

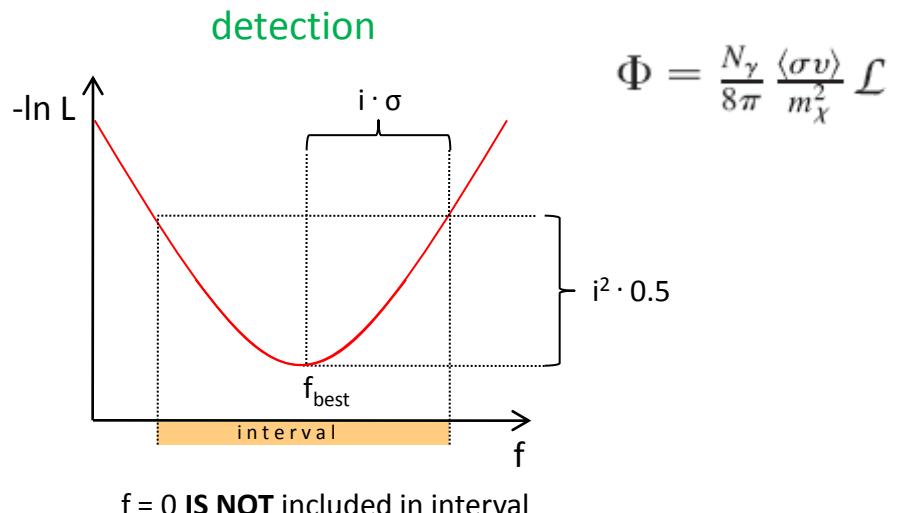
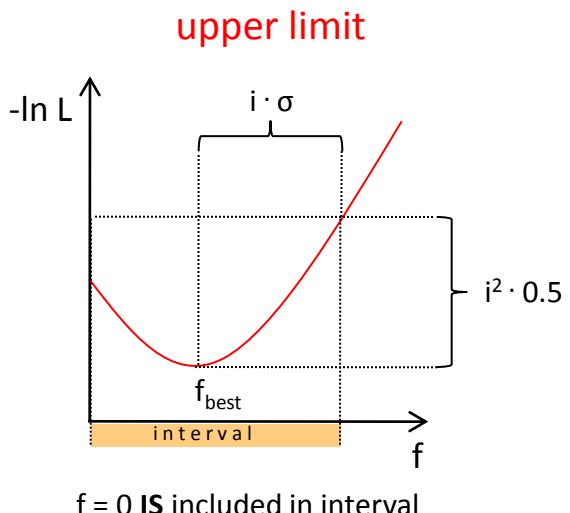
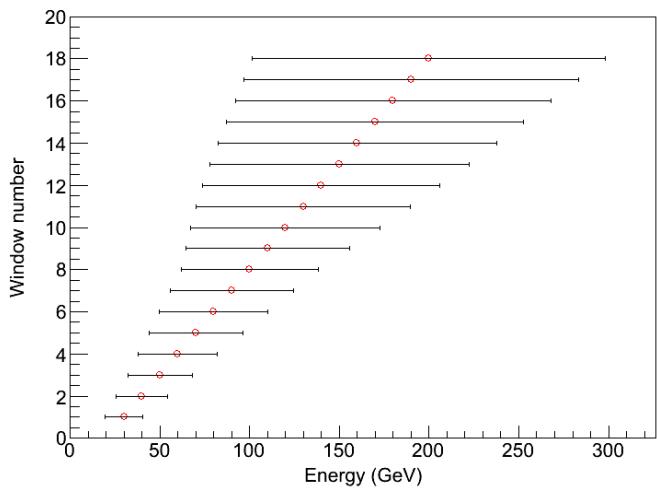
Backup slide - Lines



- Composite unbinned likelihood model

$$L(x_i|f, \gamma) = \prod_{i=0}^{n_{tot}} f S(x_i) + (1-f)B(x_i, \gamma)$$

- Sliding window in energy with overlapping windows determined by energy resolution
- Profile likelihood method:



Backup slide - CosmoWIMPs



- Flux from DM induced extragalactic photons:

$$\frac{d\phi_\gamma}{dE_0} = \frac{\langle \sigma v \rangle}{8\pi} \frac{c}{H_0} \frac{\bar{\rho}_0^2}{m_{DM}^2} \int dz (1+z)^3 \frac{\Delta^2(z)}{h(z)} \frac{dN_\gamma(E_0(1+z))}{dE} e^{-\tau(z,E_0)},$$

average density today
 redshift
 parametrization of energy content
 Hubble constant
 $100 h \text{ km s}^{-1} \text{ Mpc}^{-1}$
 enhancement of annihilation signal due to substructure
 $\sqrt{\Omega_M(1+z)^3 + \Omega_\Lambda}$
 optical depth (absorption)
 γ -ray spectrum at emission

Fermi LAT collaboration, arXiv:1002.4415, accepted by JCAP.

Backup slide - Satellites



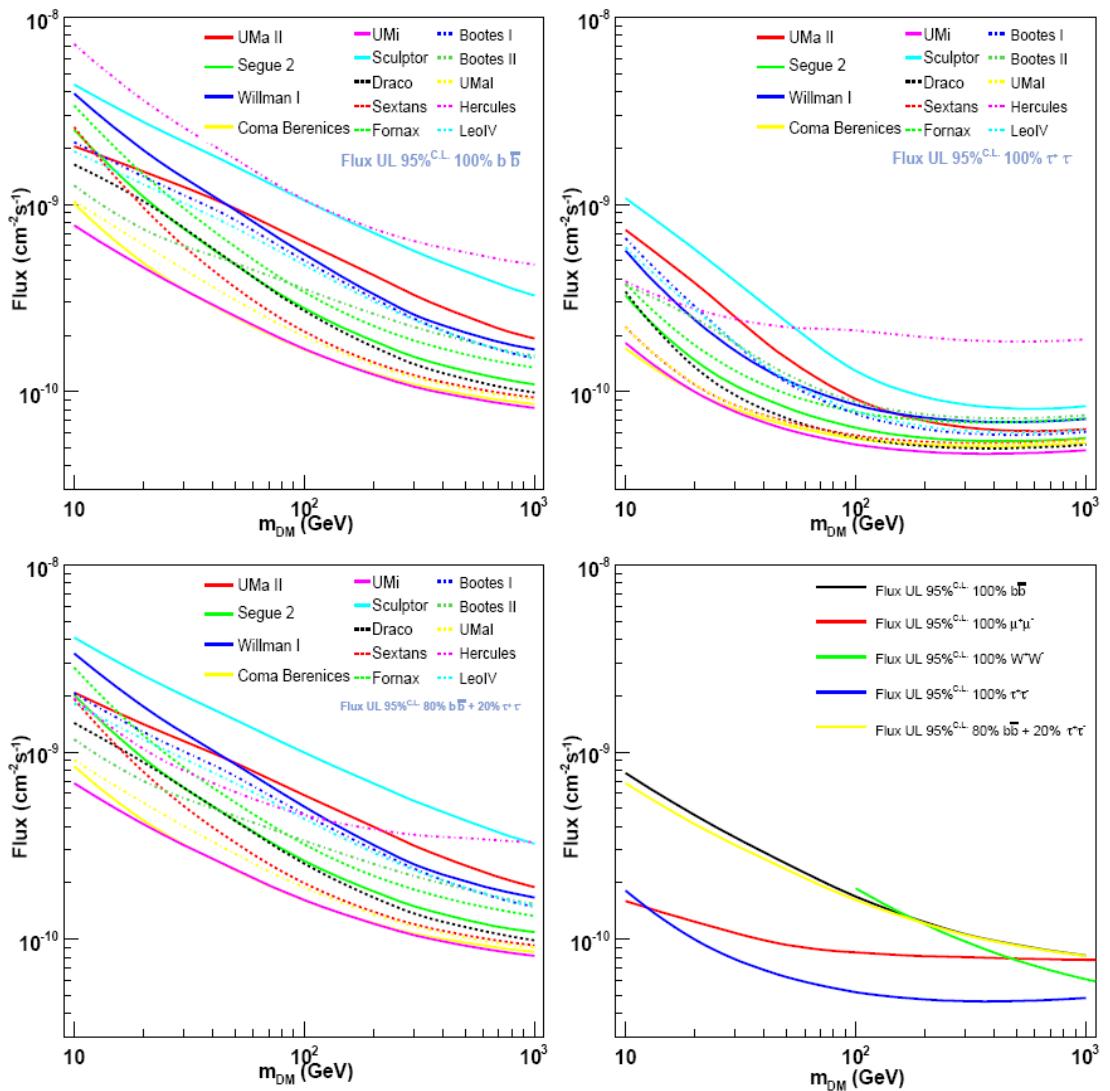
- Search criteria:
 - More than 10° from the galactic plane
 - No counterpart at other wavelengths
 - Emission constant in time (1 week interval)
 - Spatially extended: ~ 10 average radial extension for nearby, detectable clumps
 - Spectrum determined by DM (both b-bbar and FSR spectra are tested vs a (soft) power law hypothesis)
- Search for sources ($>5\sigma$ significance) passing these criteria in the 100 MeV to 300 GeV energy range.
- Background: point sources+diffuse galactic and isotropic emission

Backup slide - dSph



- Flux limits of all dwarf spheroidals

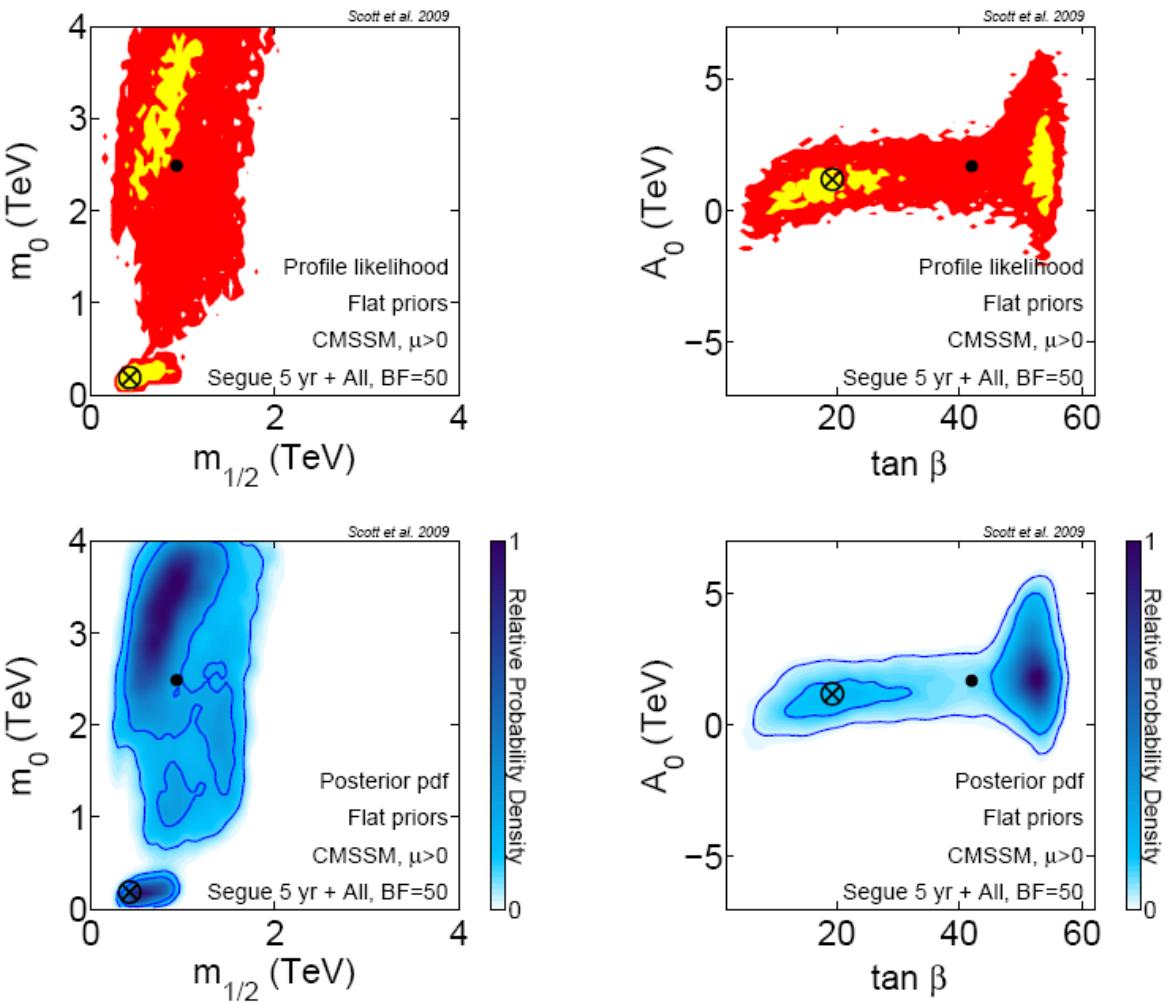
Fermi LAT collaboration, ApJ, 712 (2010) 147, [arXiv:1001.4531].



Backup slide - Segue 1



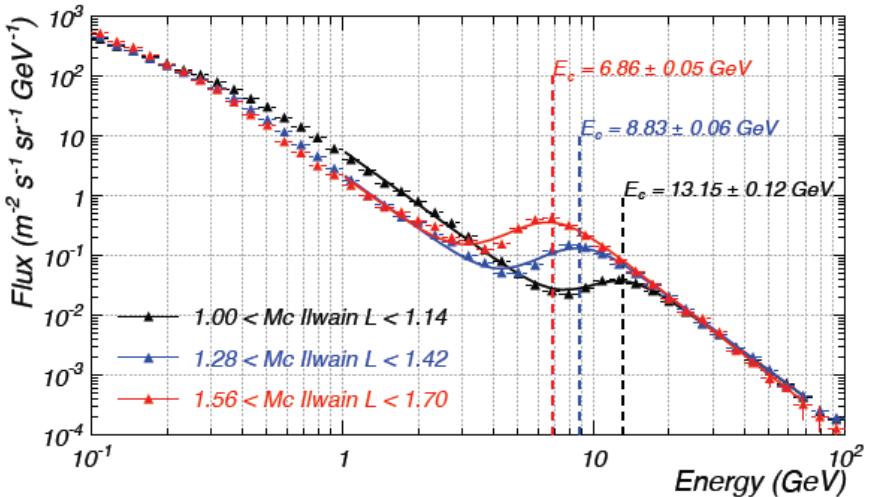
- Preferred CMSSM parameter regions



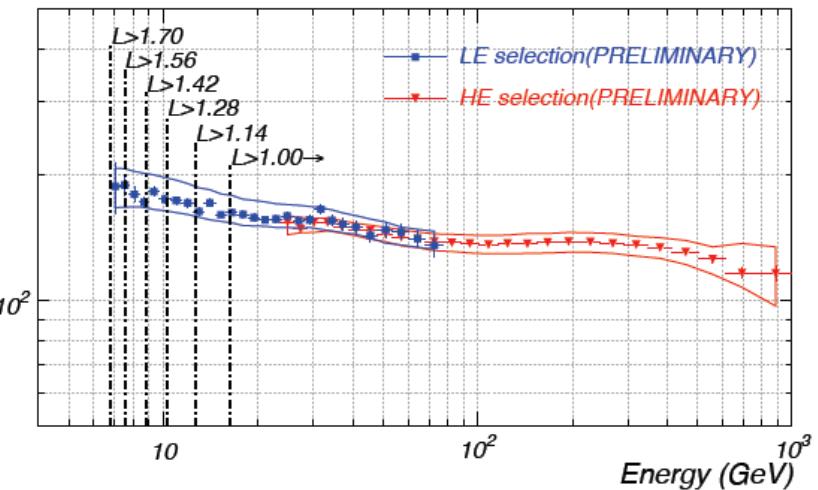
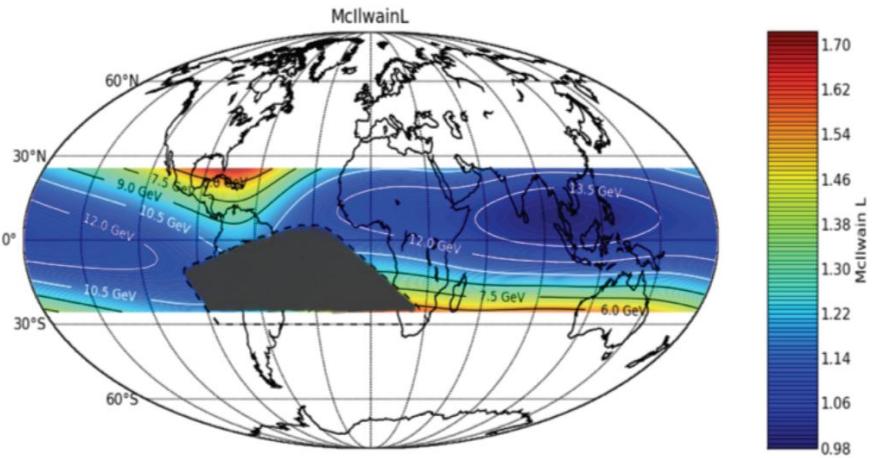


Backup slide - Electrons

- Determine geomagnetic cutoff energy as a function of geomagnetic orbital coordinates
 - Higher McIlwain L, lower cutoff energy



PRELIMINARY



L. Latronico, Cosmic-ray backgrounds in dark matter searches, Stockholm, 2010