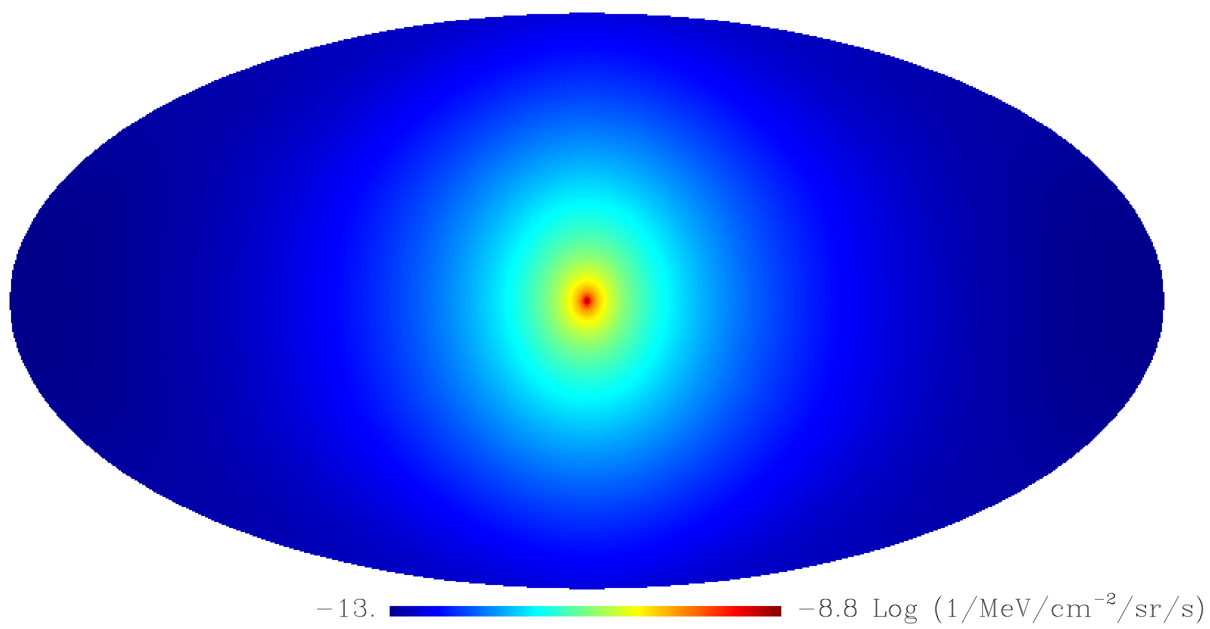
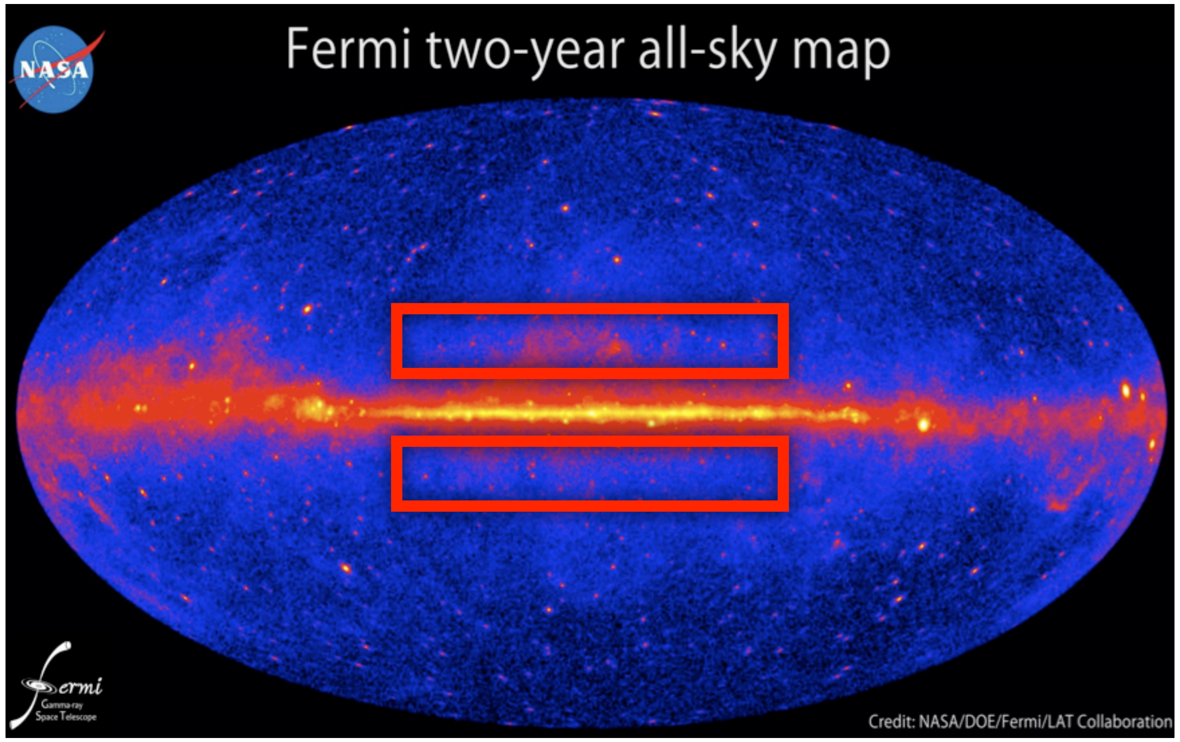
Constraints from the Milky Way halo

testing the LAT diffuse data for a contribution from a
Milky Way DM annihilation/decay signal

DM annihilation signal





M. Ackermann et al. [Fermi LAT Collaboration] (2012)

- data set: 24 months, p7 clean event selection (front+back) in the 1-100 GeV energy range
- ROI: 5° <|b|<15° and |l|<80°, 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 from the Fermi lobes and Loop I

see also: Malyshev, Bovy, & Cholis, PRD 84 (2011) 023013

Halo analysis: method 1

Conservative 'no-background' limits:

- these limits do not involve any modeling of the non-DM astrophysical background, and are robust to that class of uncertainties (i.e. they are *conservative*)

- the expected counts from DM, (n_{DM}) are compared with the observed counts (n_{data}) and the upper limits at 3(5) sigmas is set from the requirement:

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

  in at least one energy bin

Halo analysis: background modeling

DM limits with simultaneous modeling of non-DM astrophysical signal:

- uncertainties from diffusion models and gas maps taken into account by scanning over a grid of GALPROP models
- for each GALPROP (+DM) model, maps of different components of diffuse emission are generated and fit to the Fermi LAT data, incorporating both morphology and spectra
- the distribution of CR sources is highly uncertain, so is left free to vary in radial Galactic bins. To get more conservative DM constraints, *the distribution is set to zero in the inner 3 kpc*
- the profile likelihood method is used to combine all the models in the grid, and to derive the DM limits marginalized over the astrophysical uncertainties

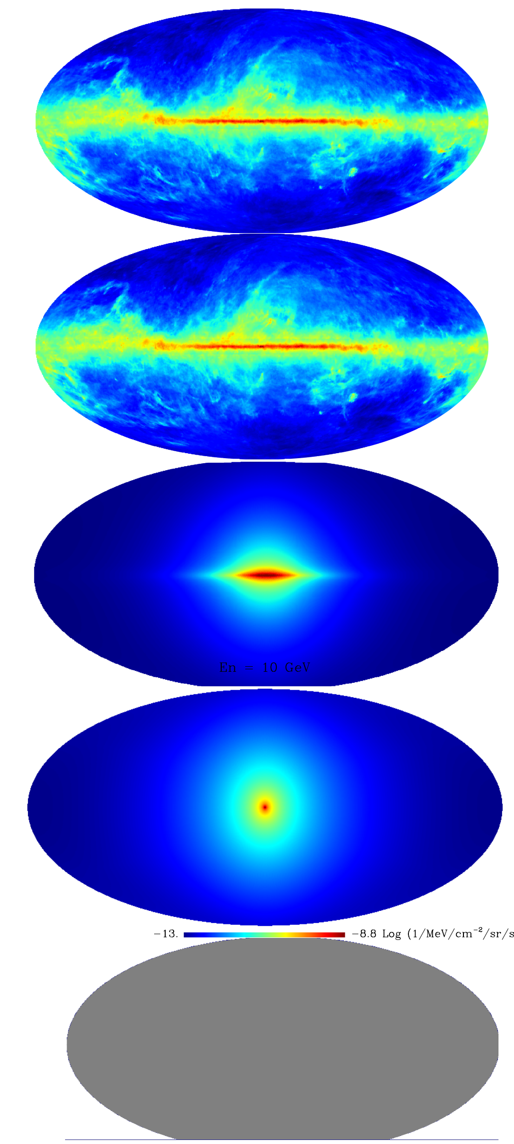
π^0 decay

bremss

IC

dark matter

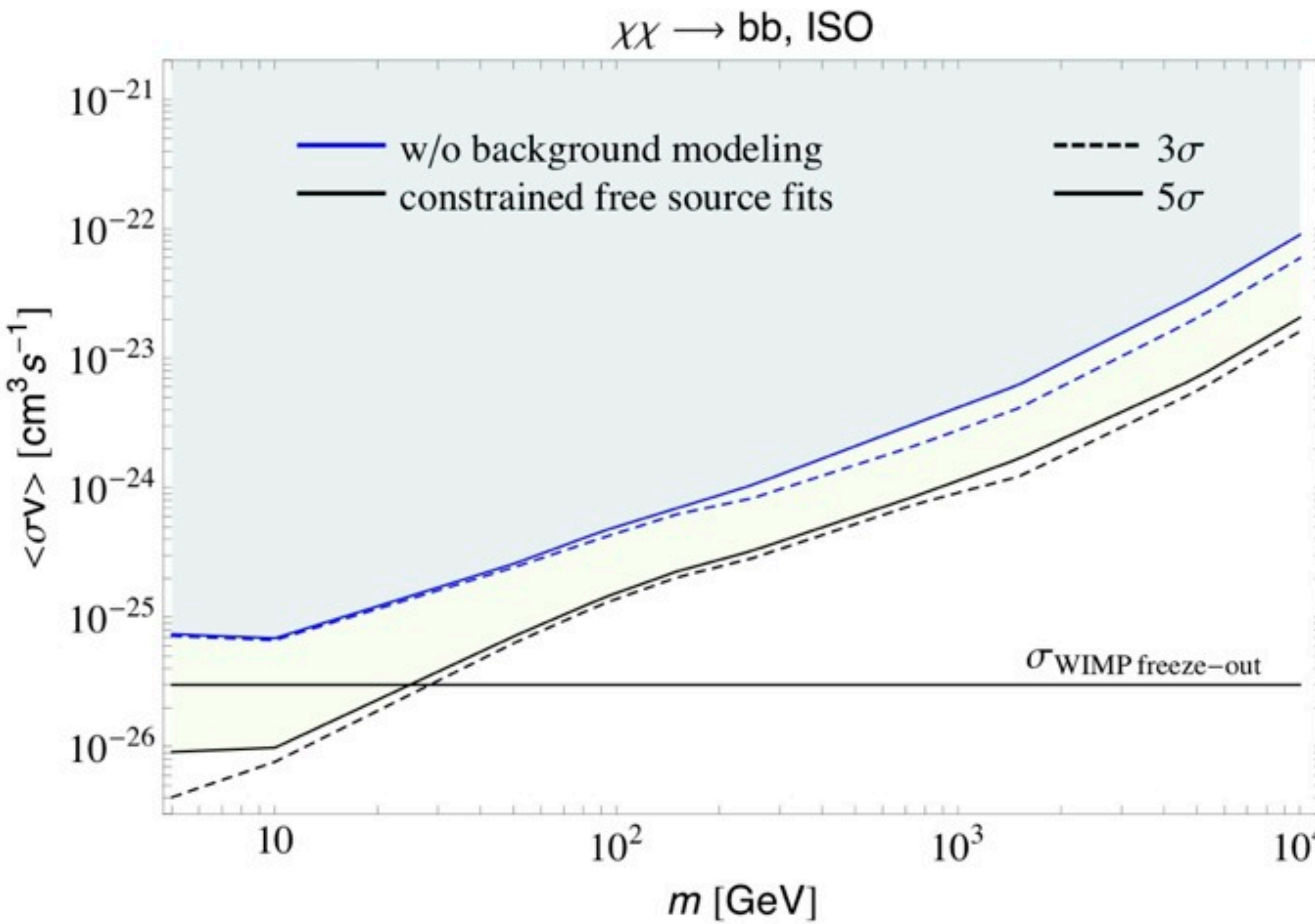
isotropic



Constraints from the halo: bb channel

- 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, and in which CR sources are held to zero in the inner 3 kpc
- limits with NFW density profile (not shown) are only slightly stronger

Annihilation

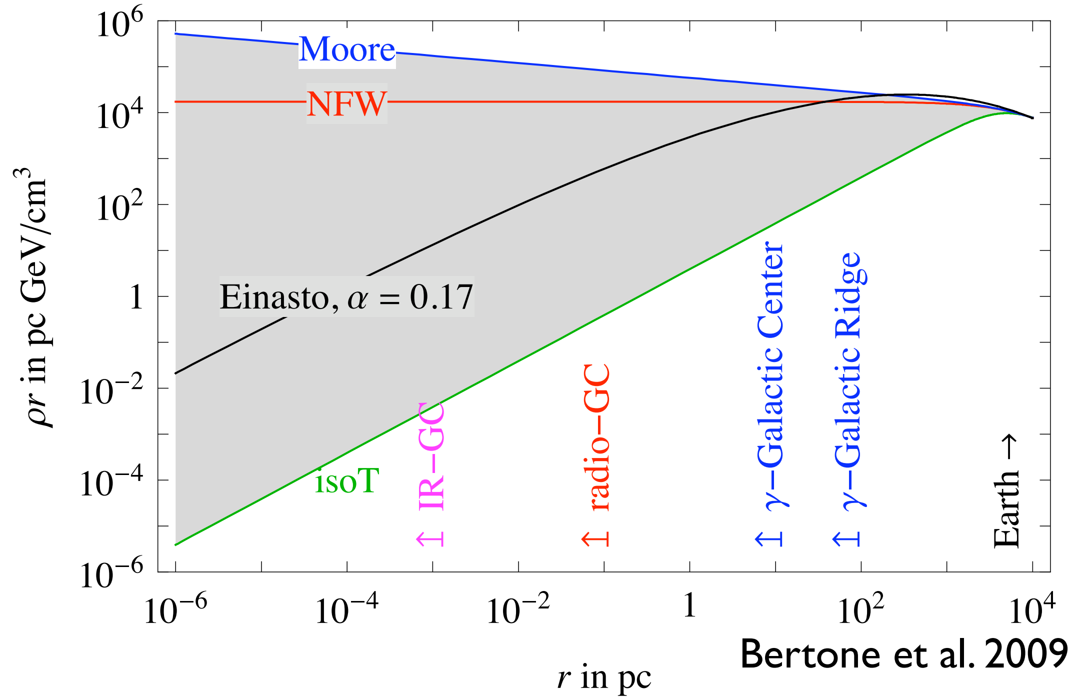


M. Ackermann et al. [Fermi LAT Collaboration] (2012)

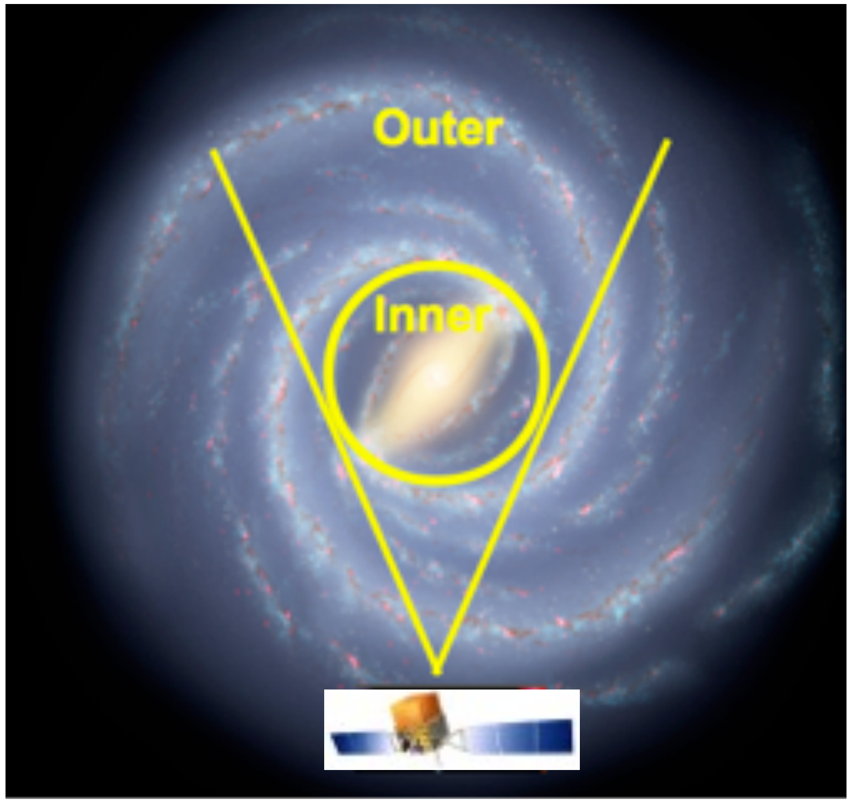
Dark matter in the Inner Galaxy

- steep inner density profiles predicted by CDM imply large annihilation (and decay) signals from the inner galaxy
- substantial sources of backgrounds make the inner galaxy a complex region of the sky:
  - resolved sources: many energetic sources near to or in the line of sight
  - unresolved source populations: may provide an important contribution to the gamma-ray emission from the inner galaxy
  - diffuse emission modeling: large uncertainties due to the overlap of structures along the line of sight, difficult to model

good understanding of the conventional astrophysical background is crucial to extract a potential DM signal!

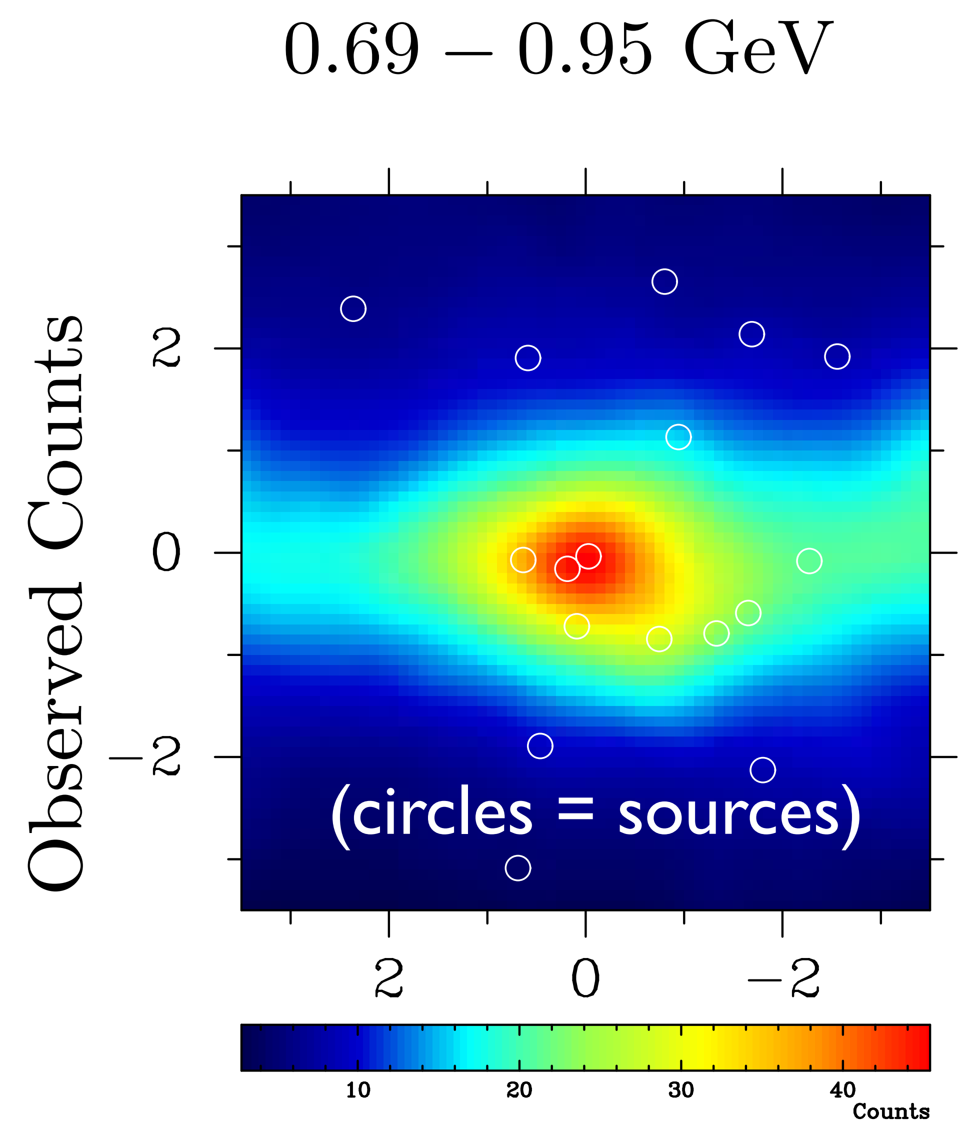


Bertone et al. 2009



Dark matter in the Inner Galaxy

- robust constraints can be derived from total measured emission
- there have been claimed GeV excesses consistent with a DM signal from multiple studies *which include background modeling*
- improved astrophysical source modeling could significantly improve sensitivity to dark matter and robustness of claimed excesses

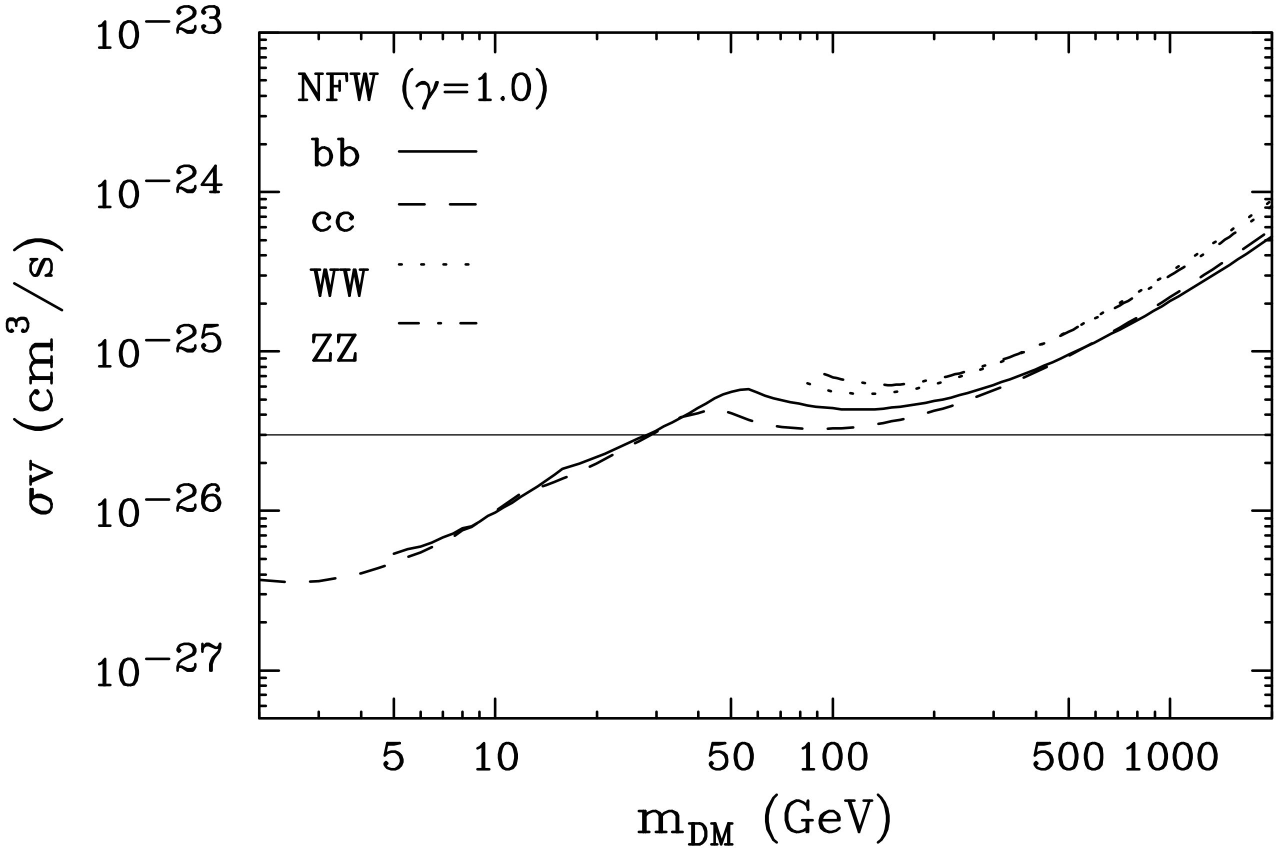


Abazajian & Kaplinghat 2012

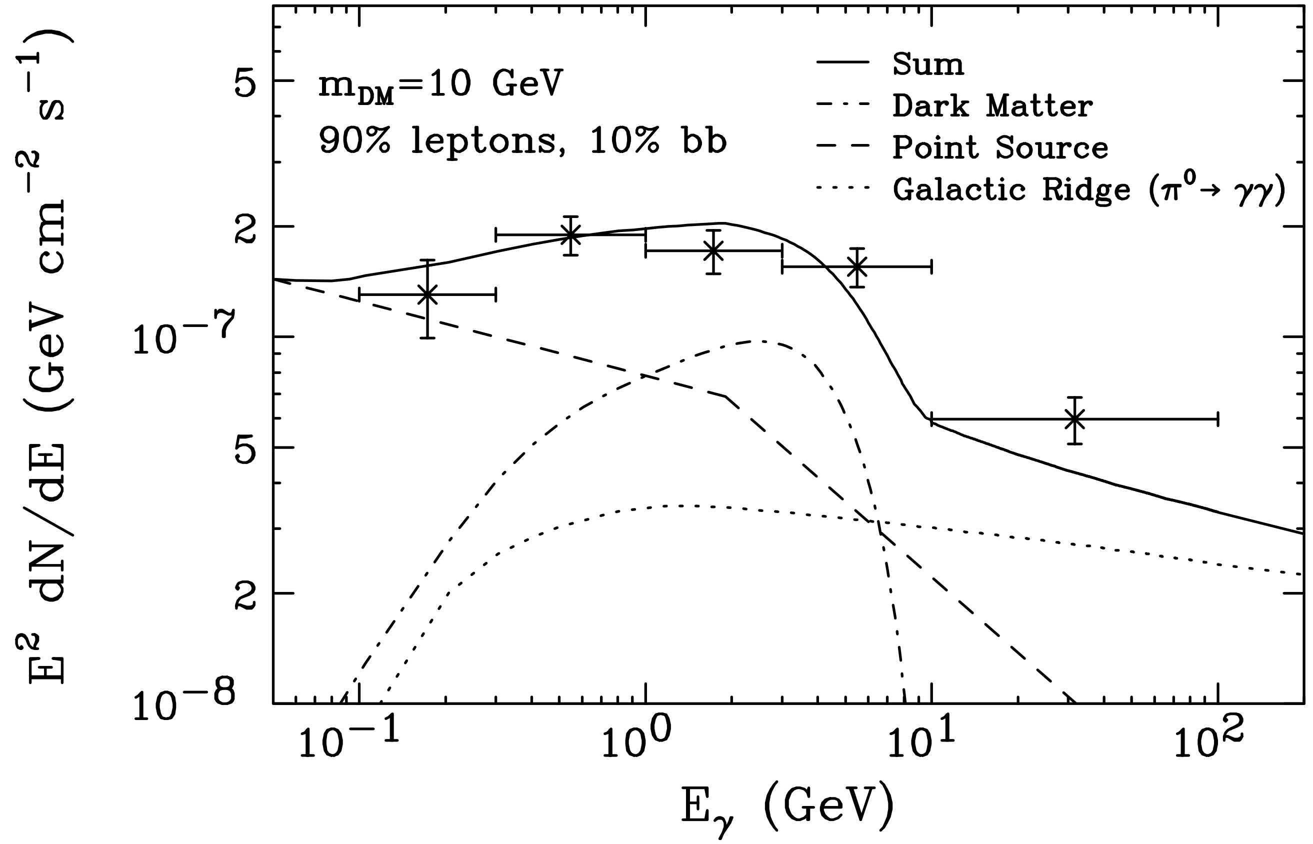
see also: Hooper & Goodenough 2011, Hooper & Linden 2011, Abazajian & Kaplinghat 2012, Hooper & Slatyer 2013 (IG excess), Gordon & Macías 2013

Dark matter in the Inner Galaxy

constraints from residual emission
after subtracting sources
and diffuse model



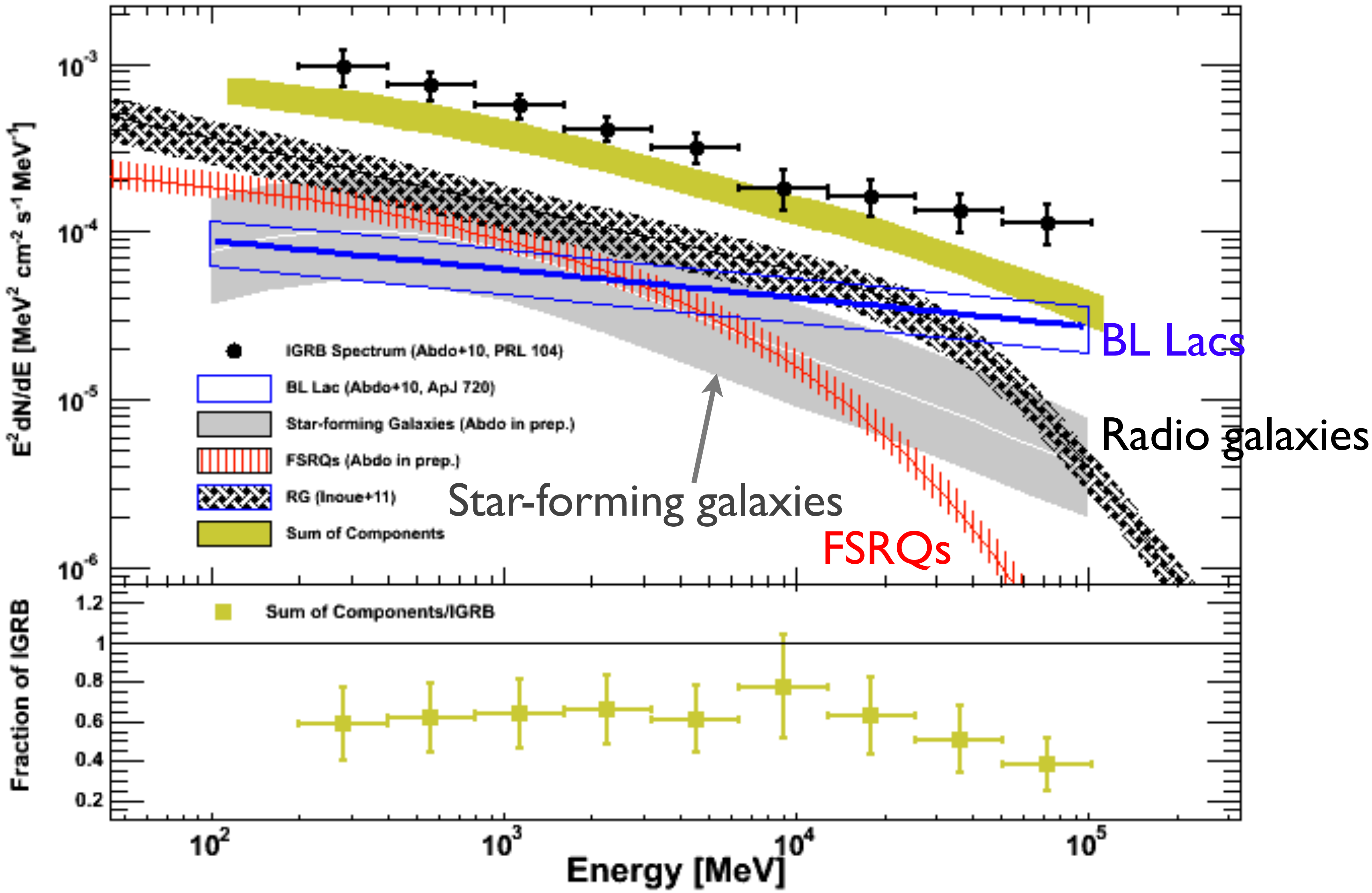
possible signal?



Hooper & Linden 2011

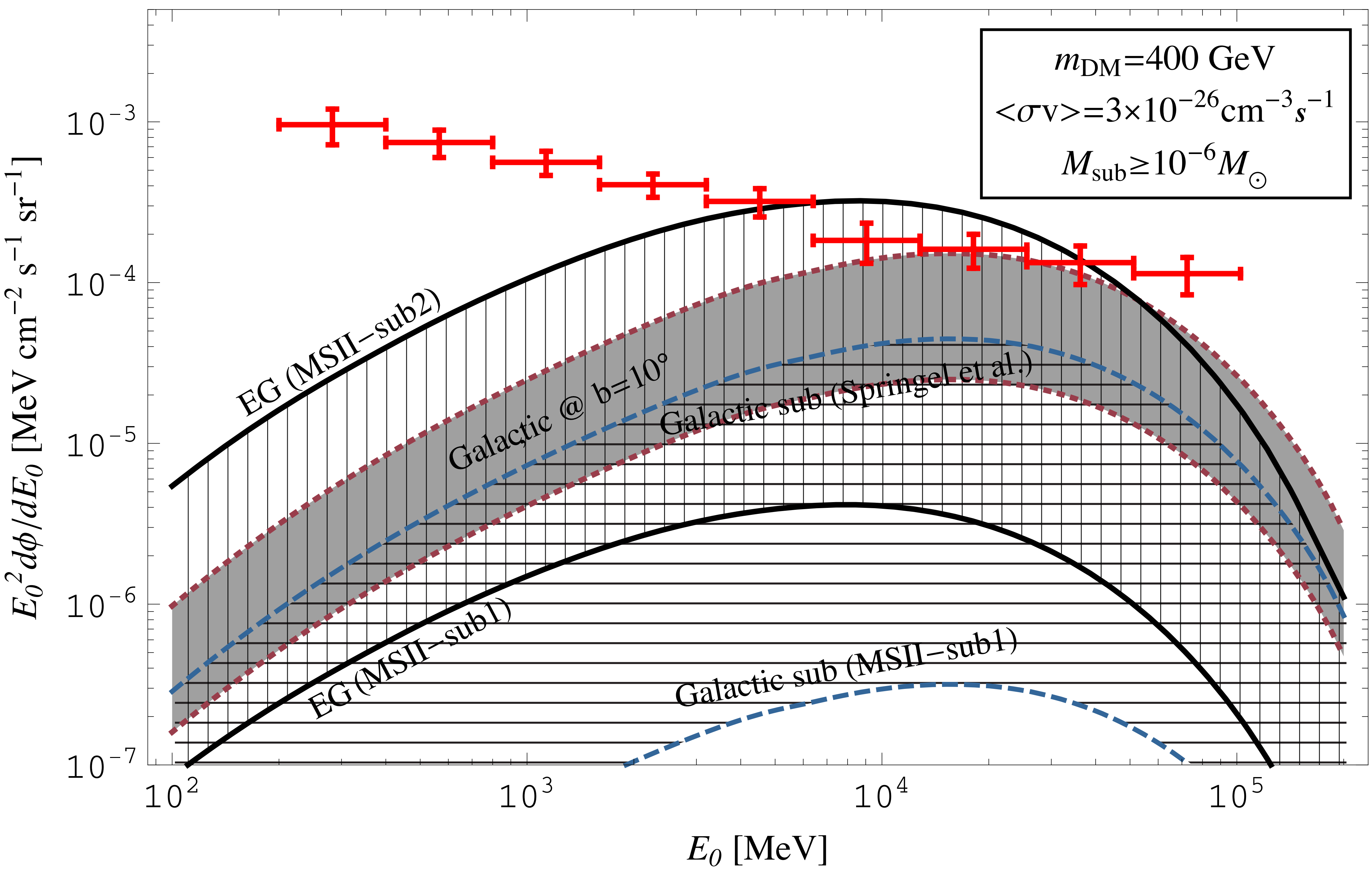
What is making the diffuse gamma-ray background?

Expected contribution of source populations to the IGRB



Sum is ~ 60-100% of IGRB intensity (energy-dependent)

Dark matter signals in the IGRB

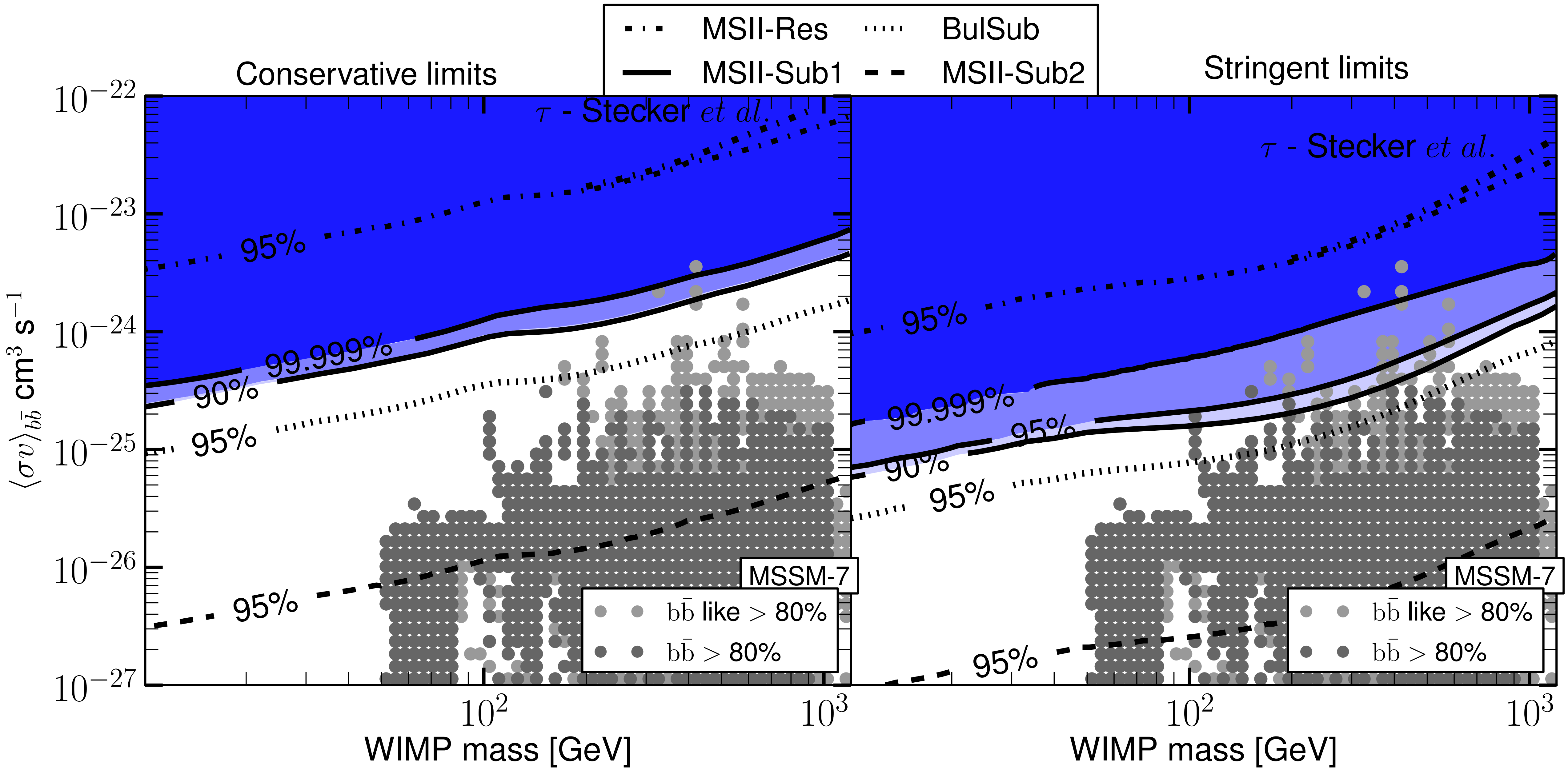


Abdo et al., JCAP 04 014 (2010)

Constraints from the IGRB

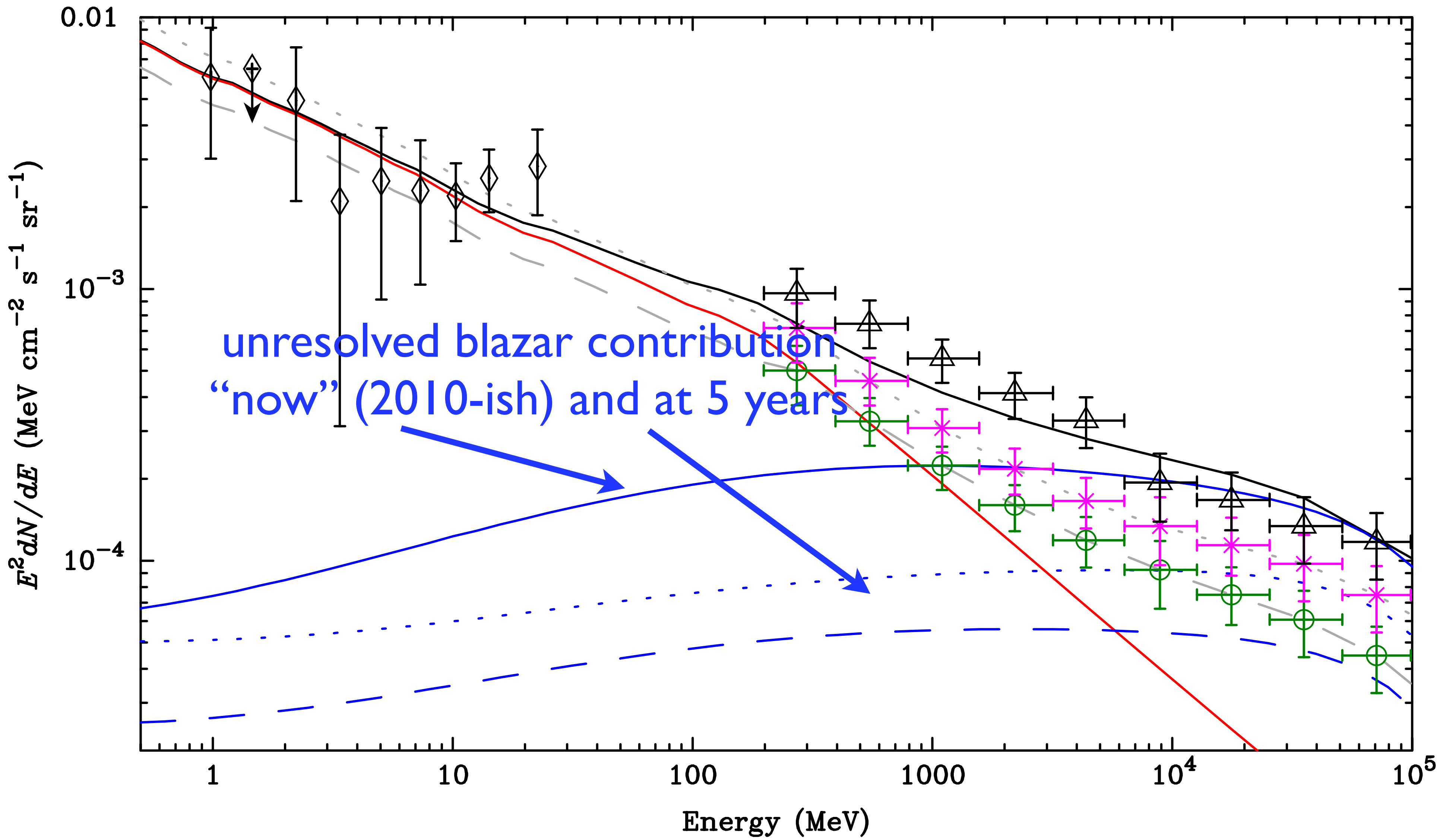
No background modeling

With background modeling and multi-component fit



Abdo et al., JCAP 04 014 (2010)

Getting rid of the IGRB



Abazajian, Blanchet, Harding 2011

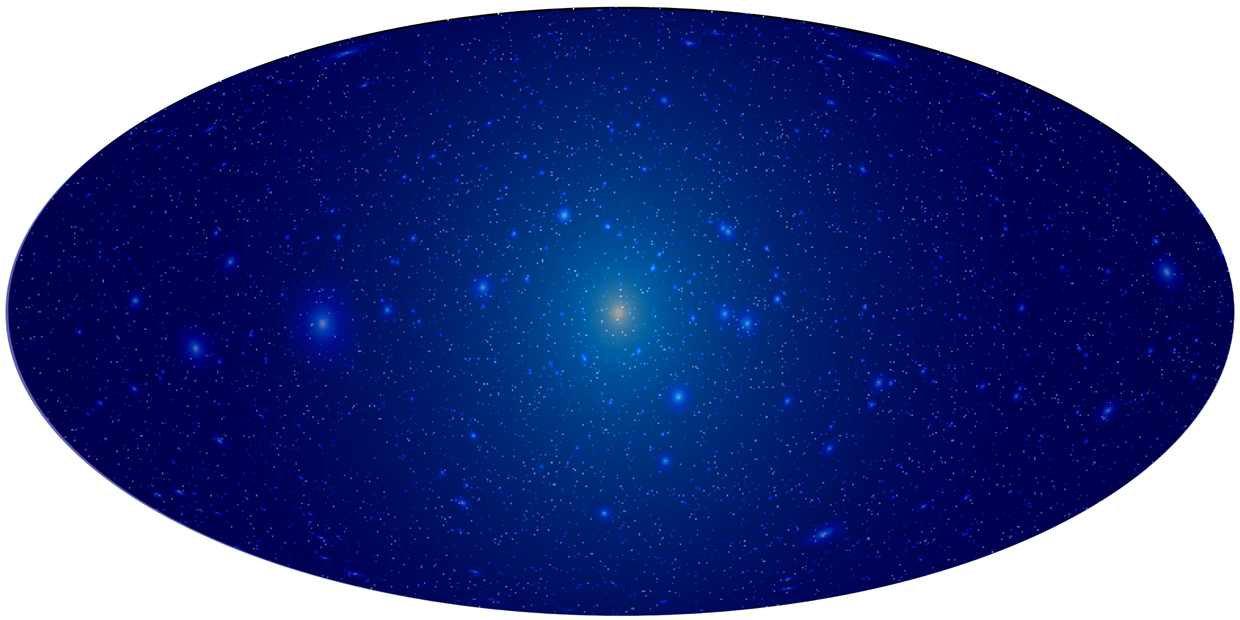
- the IGRB is time-dependent: will get smaller as more sources are resolved
- future IGRB measurements will lead to improved DM sensitivity

see also Abazajian, Blanchet, Harding 2012

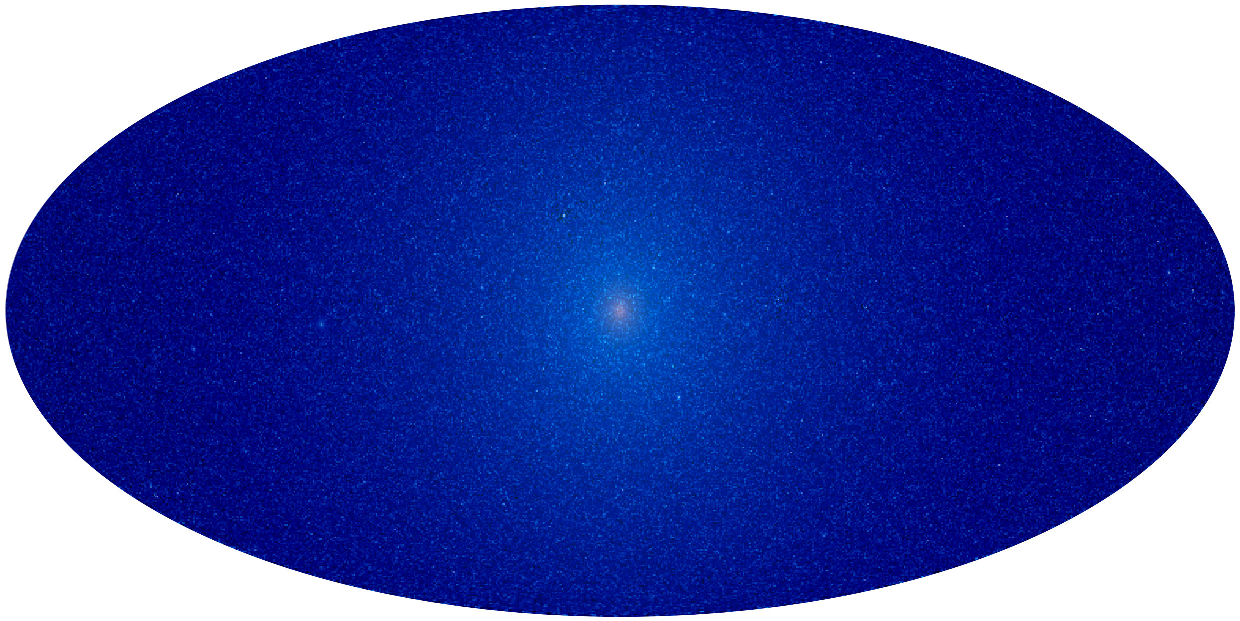
Gamma-ray anisotropies from dark matter

gamma rays from DM annihilation and decay in Galactic and extragalactic dark matter structures could imprint small angular scale fluctuations in the diffuse gamma-ray background

Gamma rays from Galactic DM



before accounting for instrument PSF



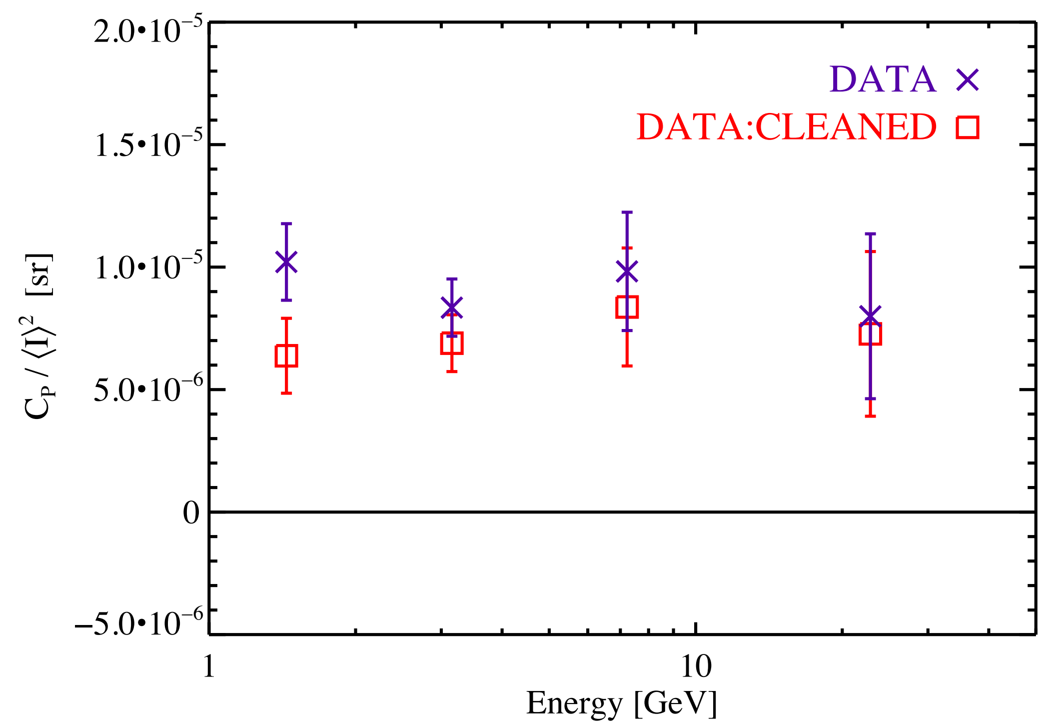
after convolving with 0.1° beam

JSG, JCAP 10(2008)040

Anisotropy constraints on dark matter

- small angular scale IGRB anisotropy measured for the first time with the Fermi LAT
- angular power measurement constrains contribution of individual source classes, including DM, to the IGRB intensity

Fluctuation anisotropy energy spectrum



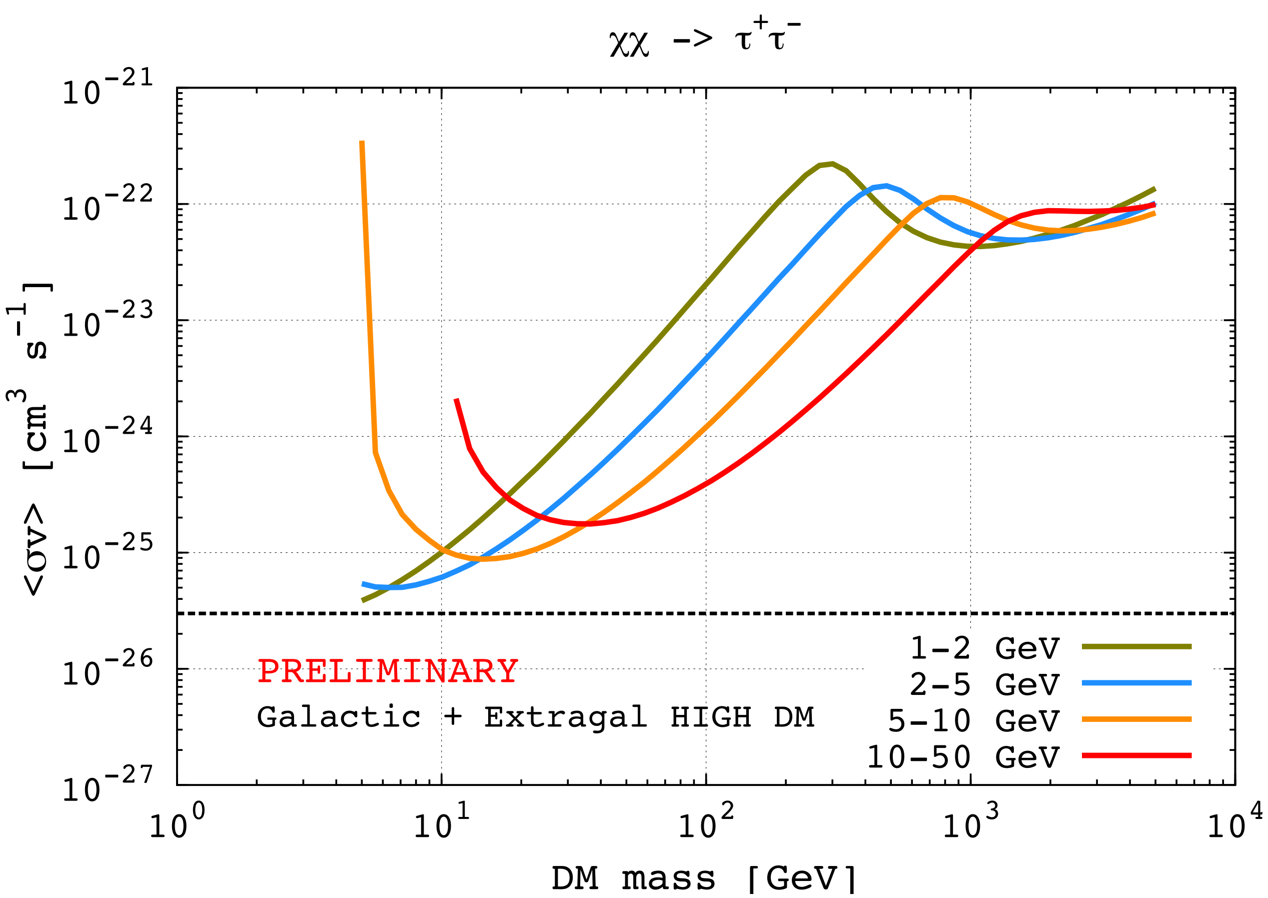
Ackermann et al. [Fermi LAT Collaboration] 2012

Constraints from best-fit constant fluctuation angular power (l ≳ 150) measured in the data and foreground-cleaned data

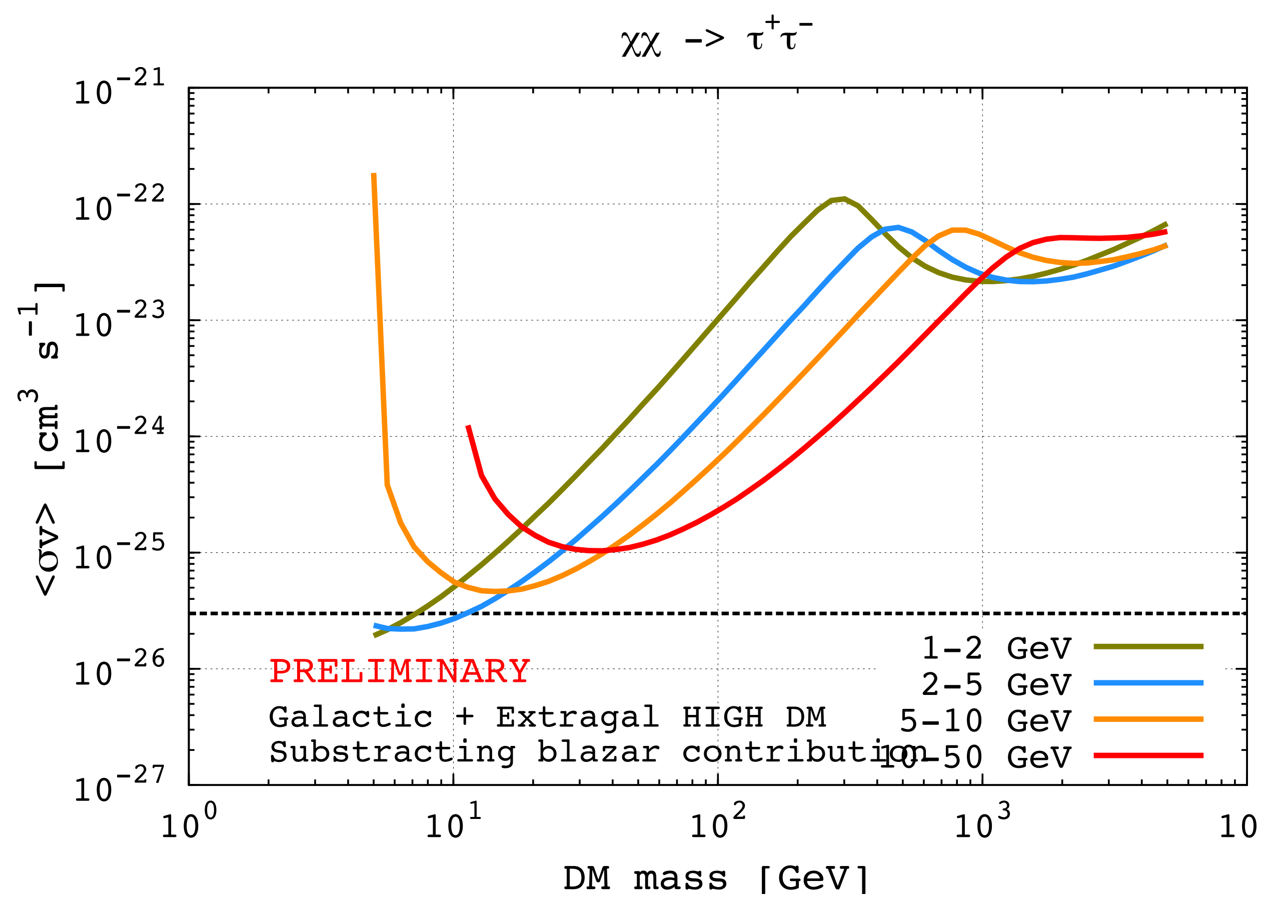
Source class	Predicted $C_{100}/\langle I \rangle^2$ [sr]	Maximum fraction of IGRB intensity DATA	DATA:CLEANED
Blazars	2×10^{-4}	21%	19%
Star-forming galaxies	2×10^{-7}	100%	100%
Extragalactic dark matter annihilation	1×10^{-5}	95%	83%
Galactic dark matter annihilation	5×10^{-5}	43%	37%
Millisecond pulsars	3×10^{-2}	1.7%	1.5%

Anisotropy constraints on dark matter models

Constraints using 2-sigma upper limit on total measured anisotropy



Constraints using 2-sigma upper limits on non-blazar anisotropy

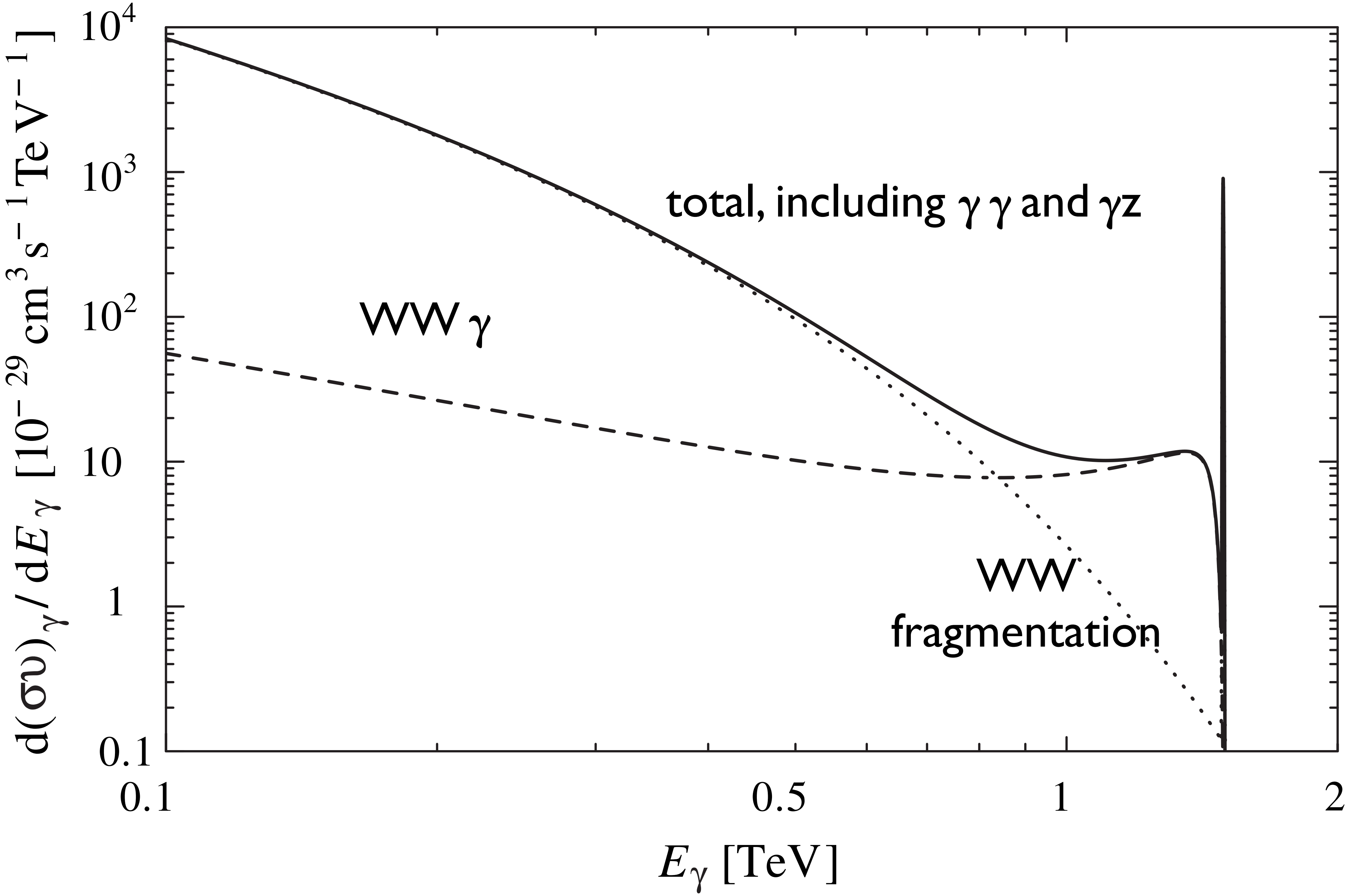


Fermi LAT collaboration and MultiDark, in prep

- preliminary dark matter constraints from published anisotropy measurement
- updated measurement should yield improved sensitivity due to more energy bins and improved statistics

A 130 (135) GeV line from dark matter in the Fermi LAT data?

Photon spectrum from a MSSM model



Bergstrom et al. 2005

10. **A Tentative Gamma-Ray Line from Dark Matter Annihilation at the Fermi Large Area Telescope**

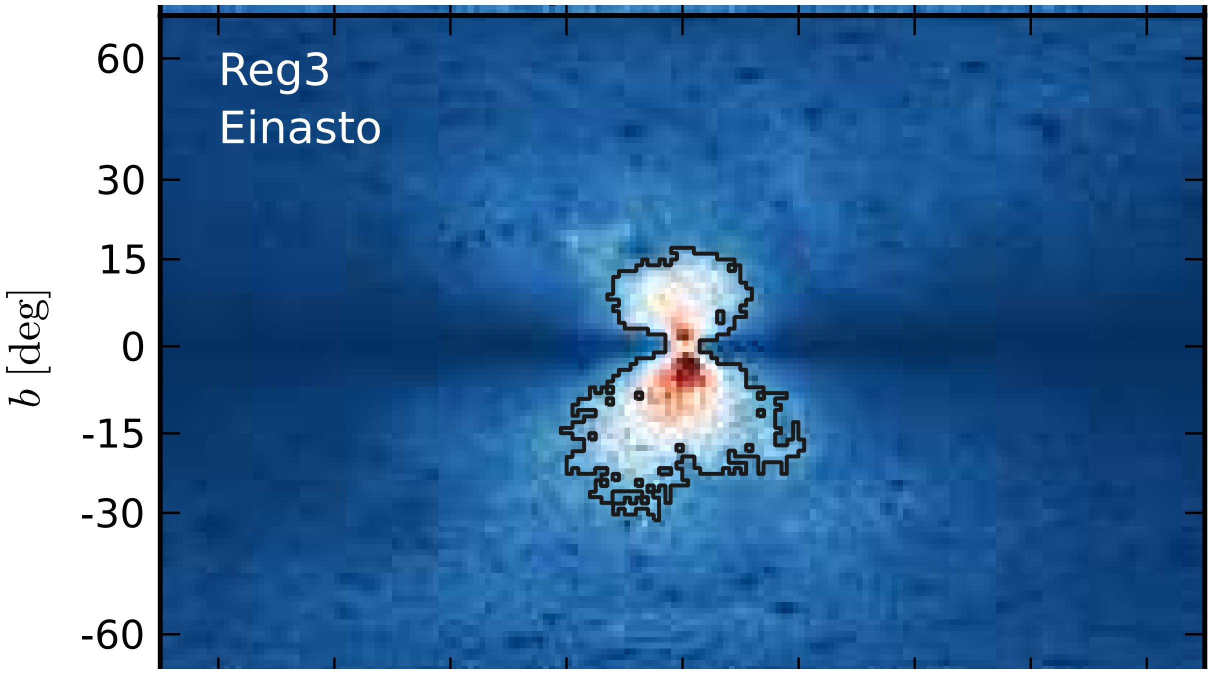
Christoph Weniger (Munich, Max Planck Inst.). Apr 2012. 21 pp.
Published in **JCAP 1208 (2012) 007**
MPP-2012-73
DOI: 10.1088/1475-7516/2012/08/007
e-Print: **arXiv:1204.2797 [hep-ph]** | PDF

References | BibTeX | LaTeX(US) | LaTeX(EU) | Harvmac | EndNote
ADS Abstract Service; physicsworld.com article

Detailed record - Cited by 196 records 100+

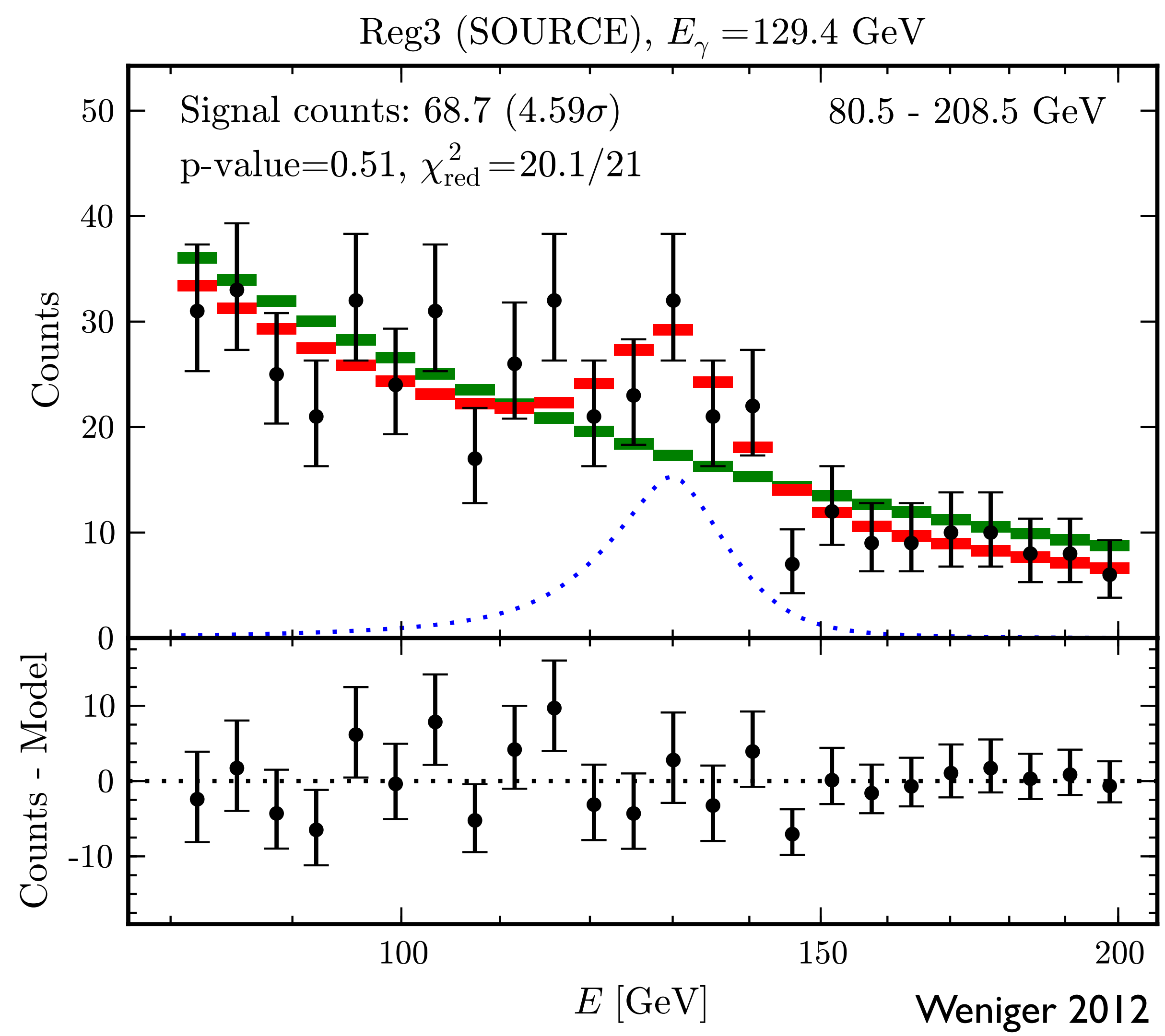
A 130 GeV line from dark matter?

One region-of-interest for Weniger's line search



Weniger 2012

Spectrum of ROI with power-law and power-law+line fits



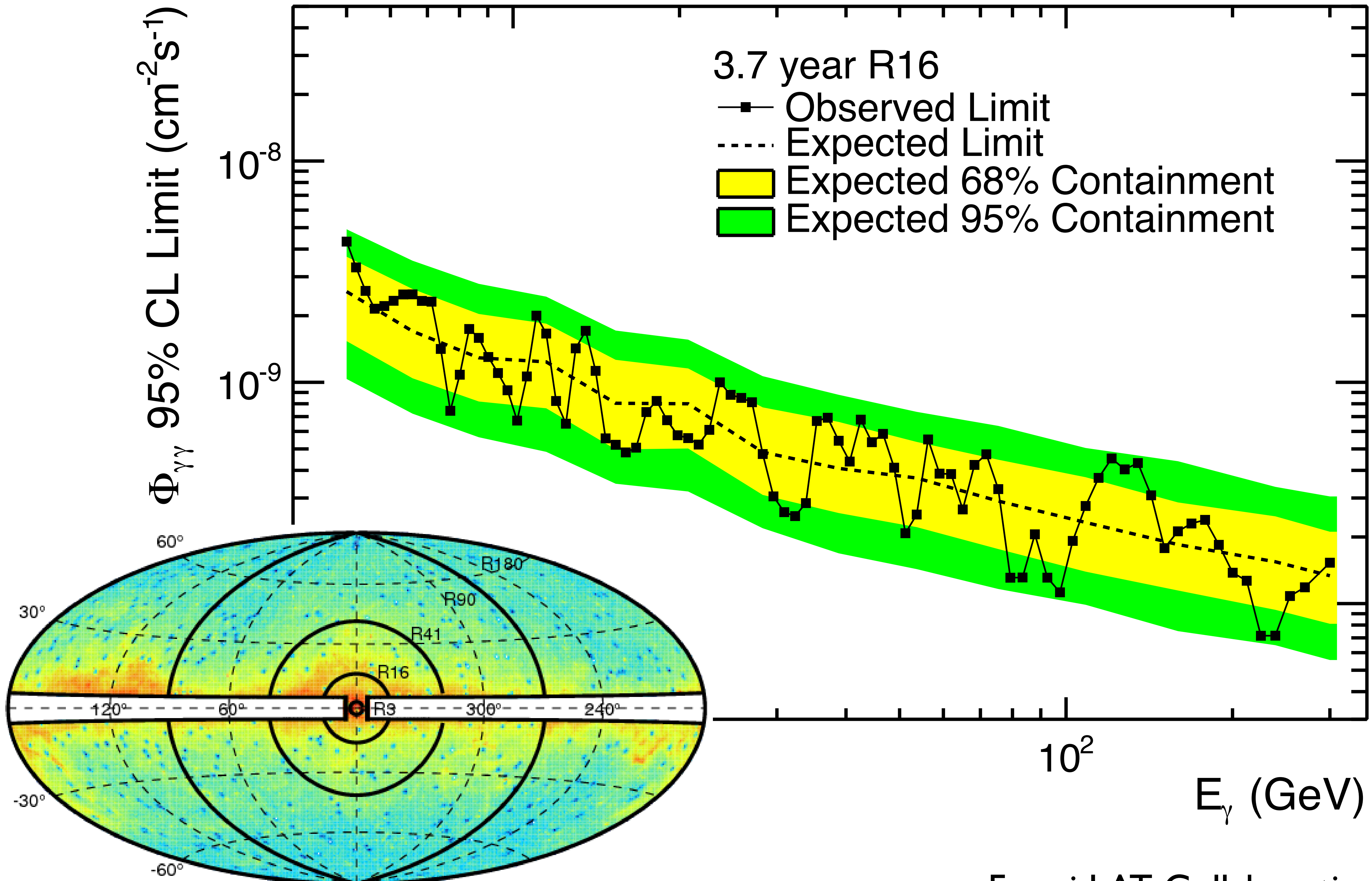
Weniger 2012

- Bringmann et al. find weak indication of a feature consistent with IB emission from DM annihilation
- Weniger claims a tentative gamma-ray line

see also: Bringmann, Huang, Ibarra, Vogl, Weniger, arXiv:1203.1312; Weniger, arXiv:1204.2797; Tempel, Hektor, Raidal, arXiv:1205.1045; Boyarsky, Malyshev, Ruchayskiy, arXiv:1205.4700; Geringer-Sameth & Koushiappas, arXiv:1206.0796; Su & Finkbeiner, arXiv:1206.1616, Aharonian, Khangulyan, Malyshev, arXiv:1207.0458 ...

Fermi LAT collaboration 3.7-yr results

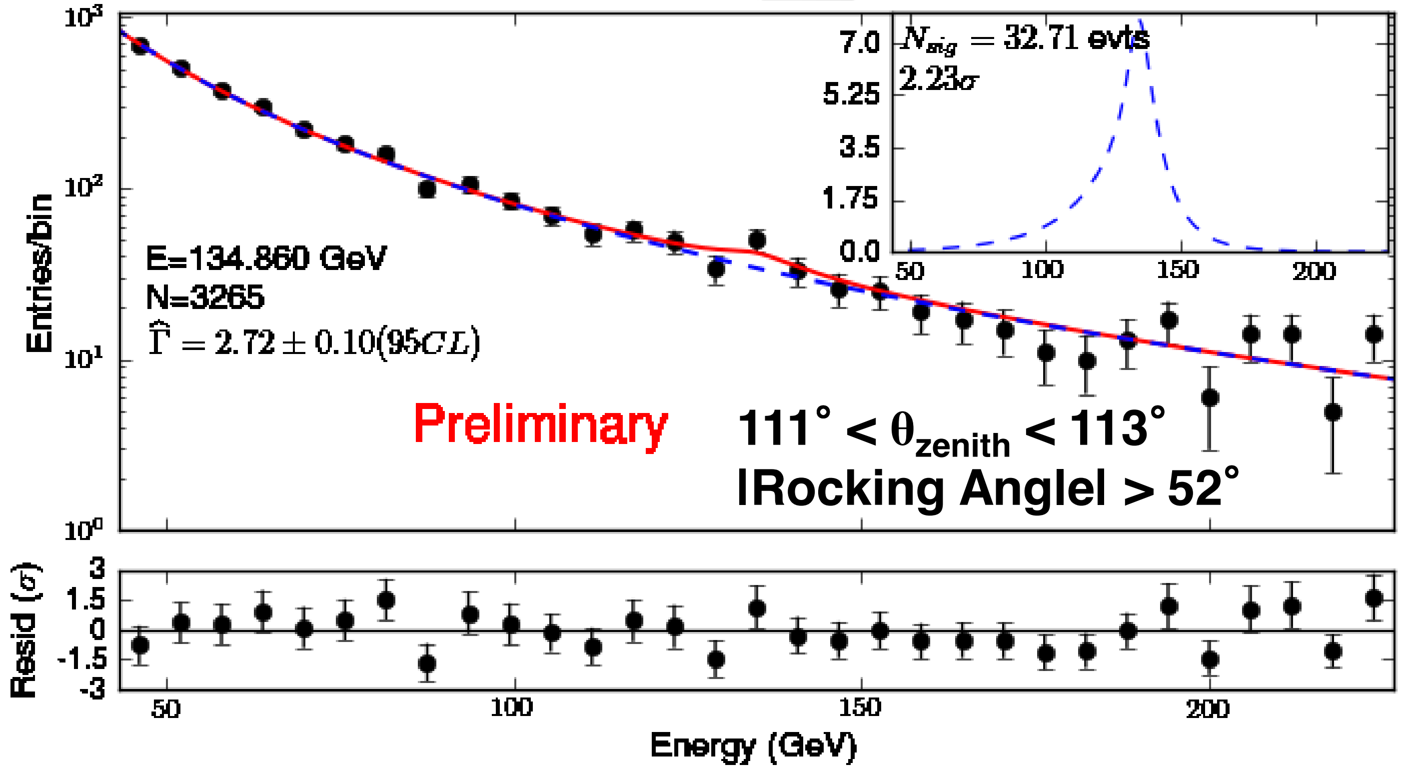
No globally significant lines found (all less than 2σ global)



Fermi LAT Collaboration 2013

Is it instrumental?

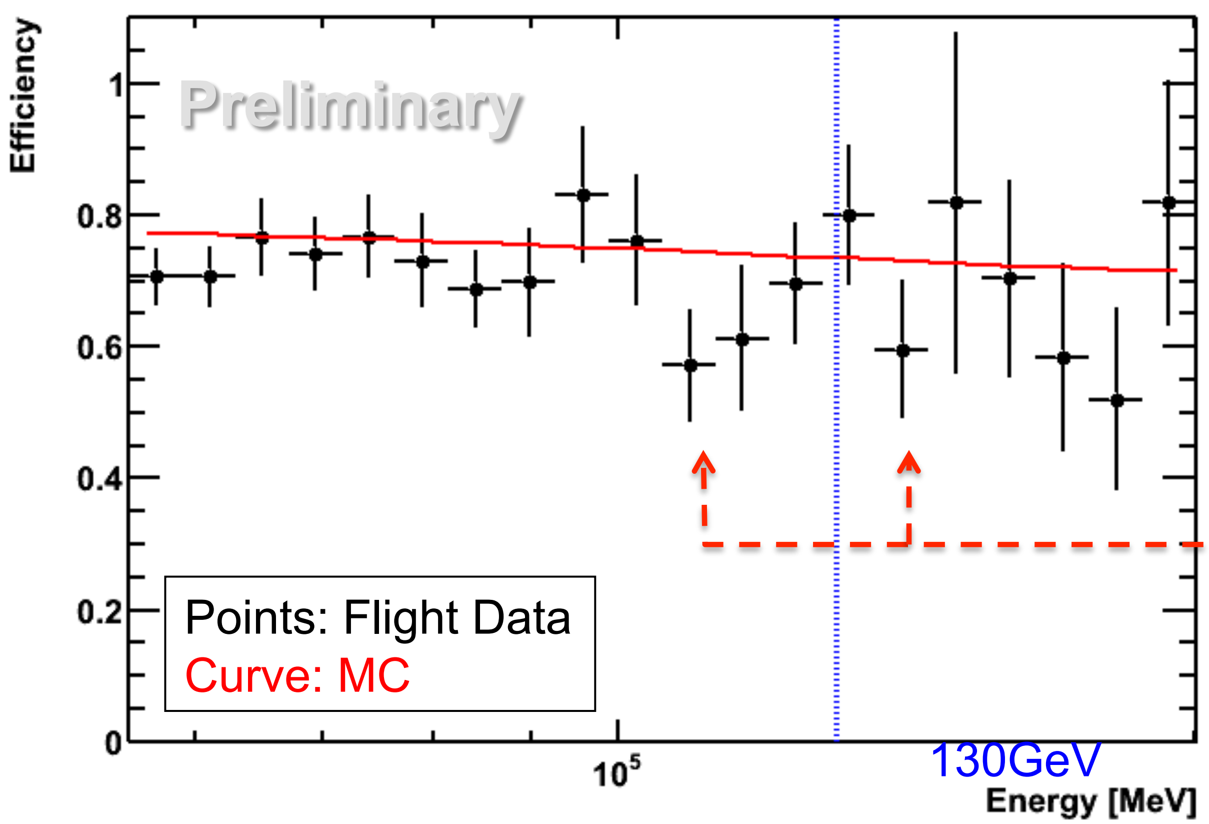
Earth's limb spectrum



E. Charles' and A. Albert's talks at Fermi Symposium 2012

Efficiency:

transient to clean class in Earth's limb

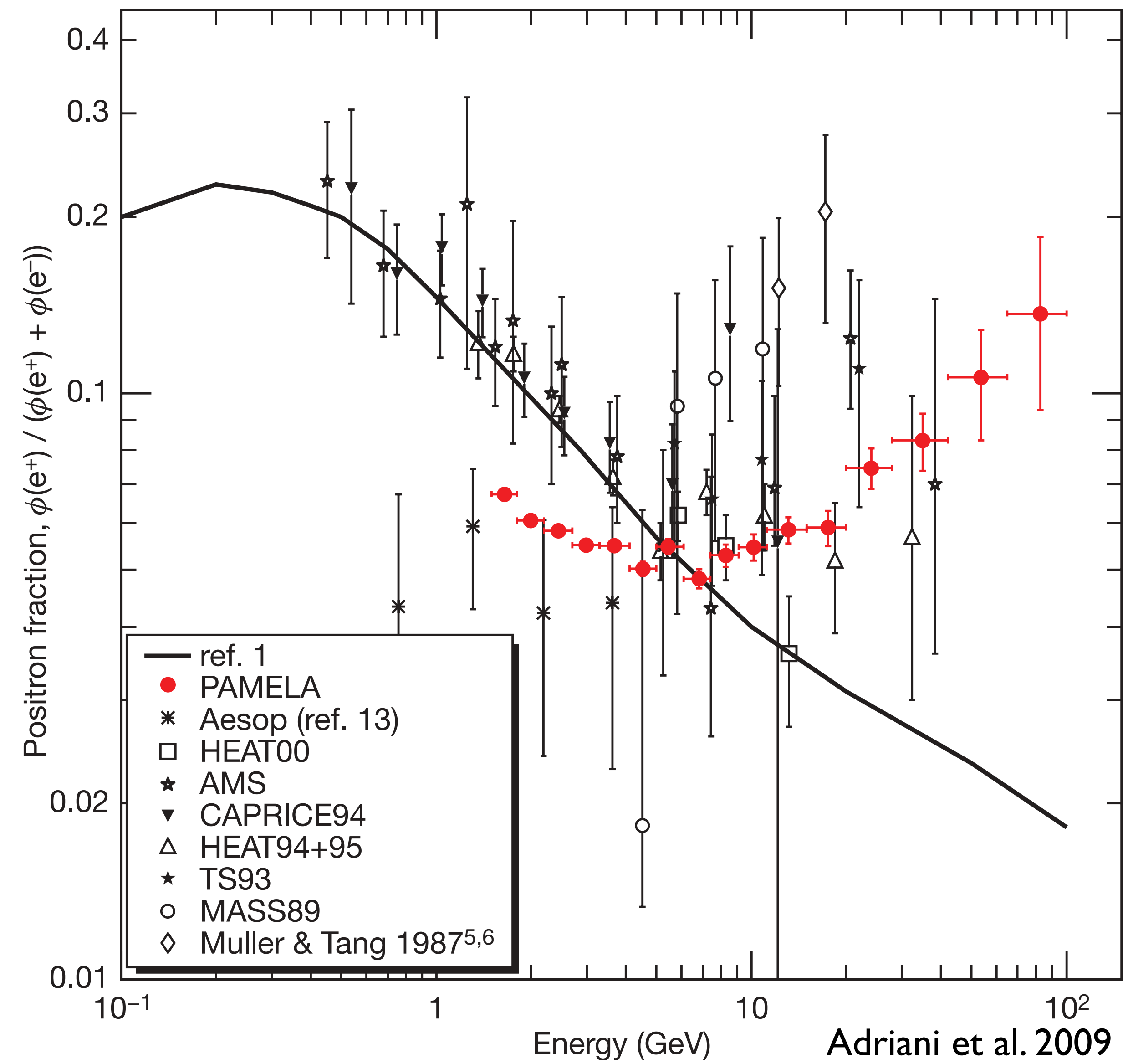


Unexpected features in the cosmic-ray e± spectra?

Unexpected features in the cosmic-ray e± spectra?

- rise in local positron fraction above ~10 GeV disagrees with conventional model for cosmic rays (secondary positron production only); see also arXiv: 1011.4843 for low-energy discrepancy

PAMELA positron fraction



Adriani et al. 2009

Unexpected features in the cosmic-ray e± spectra?

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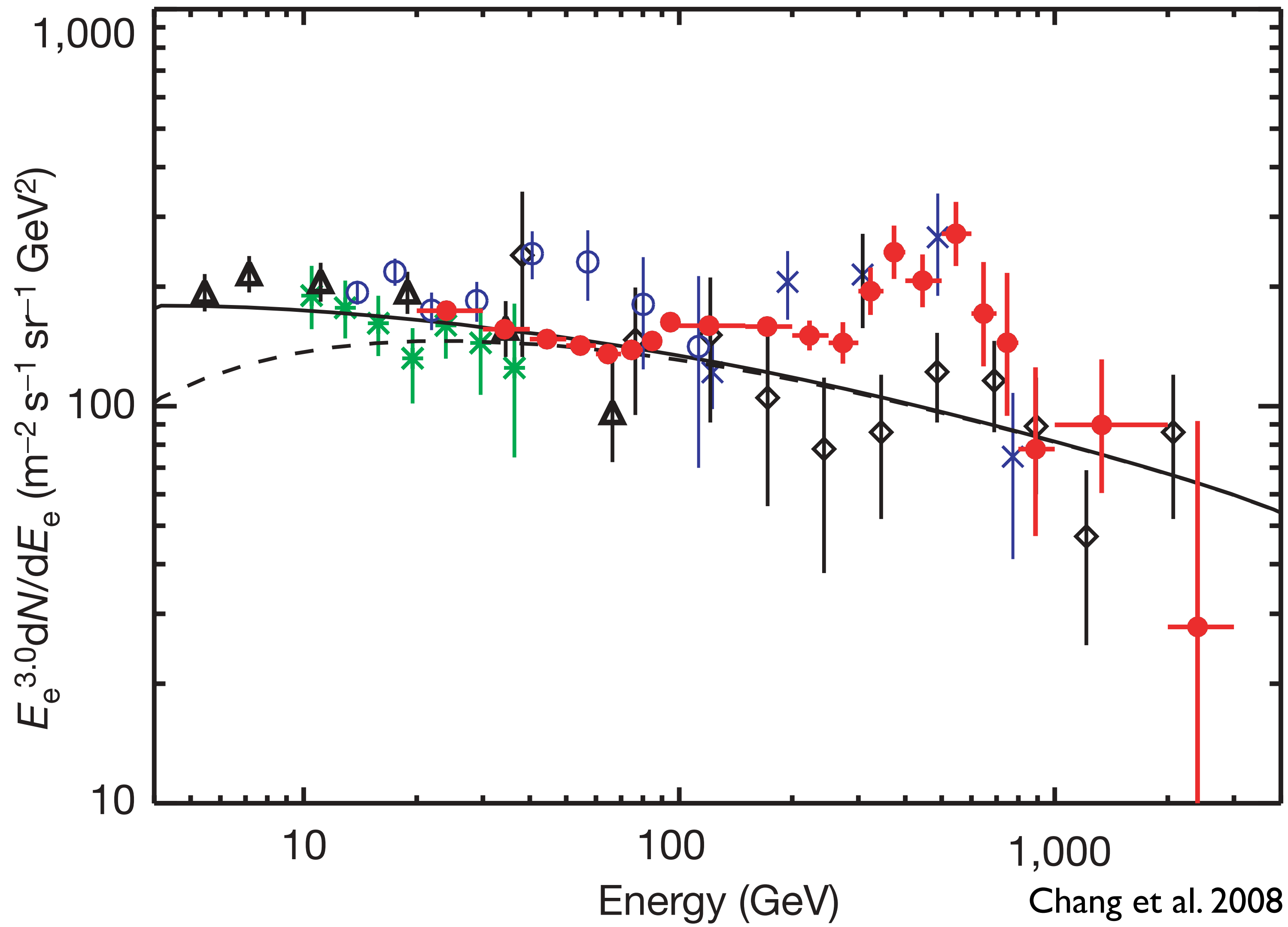
- unexpected bump in total electron + positron spectrum measured by ATIC

ATIC electron + positron spectrum



Chang et al. 2008

Unexpected features in the cosmic-ray e± spectra?

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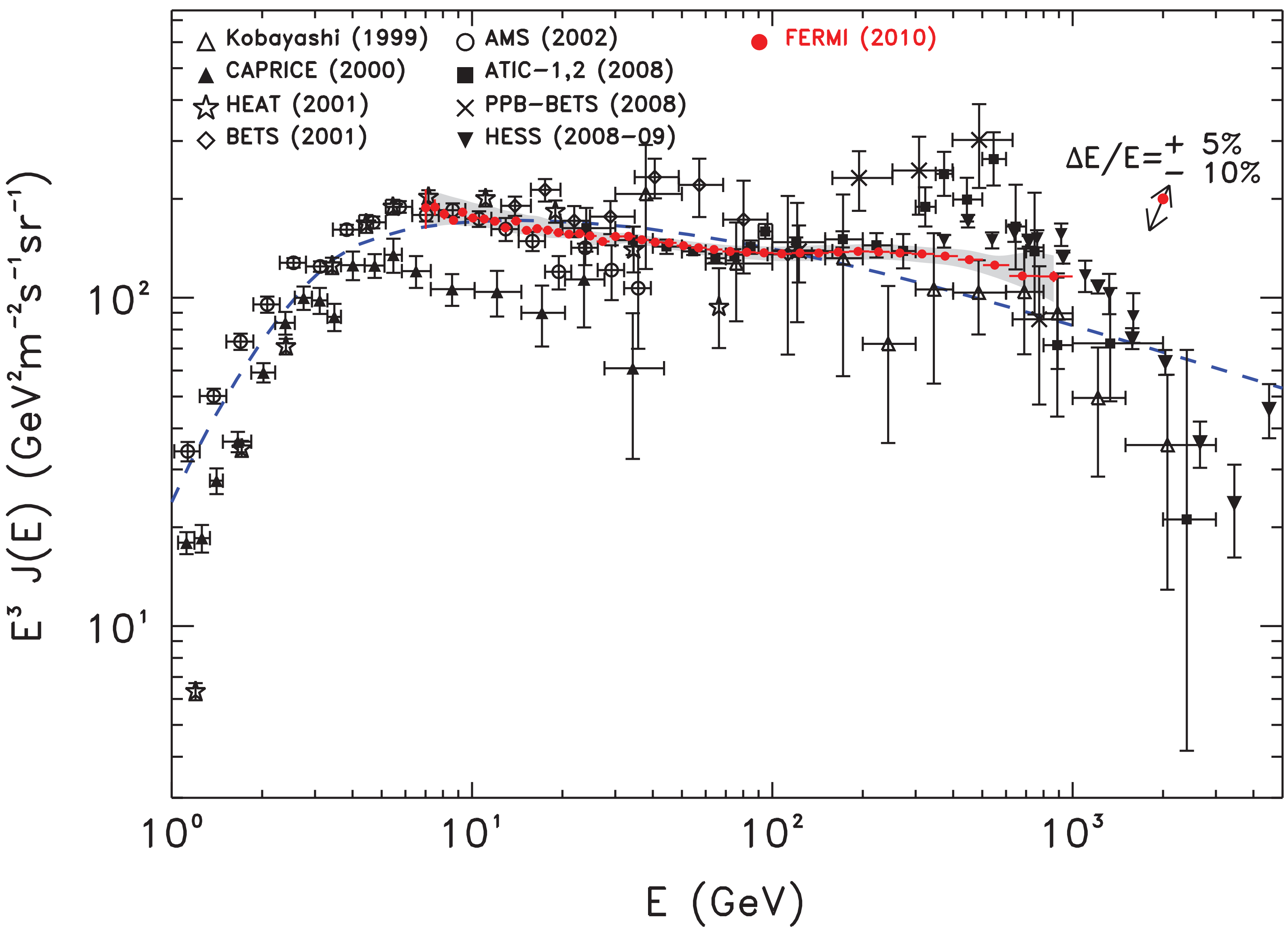
- unexpected bump in total electron + positron spectrum measured by ATIC
- less prominent feature seen in Fermi cosmic ray electron/ positron spectrum

Fermi electron + positron spectrum



Ackermann et al. [Fermi LAT Collaboration] 2010

Unexpected features in the cosmic-ray e± spectra?

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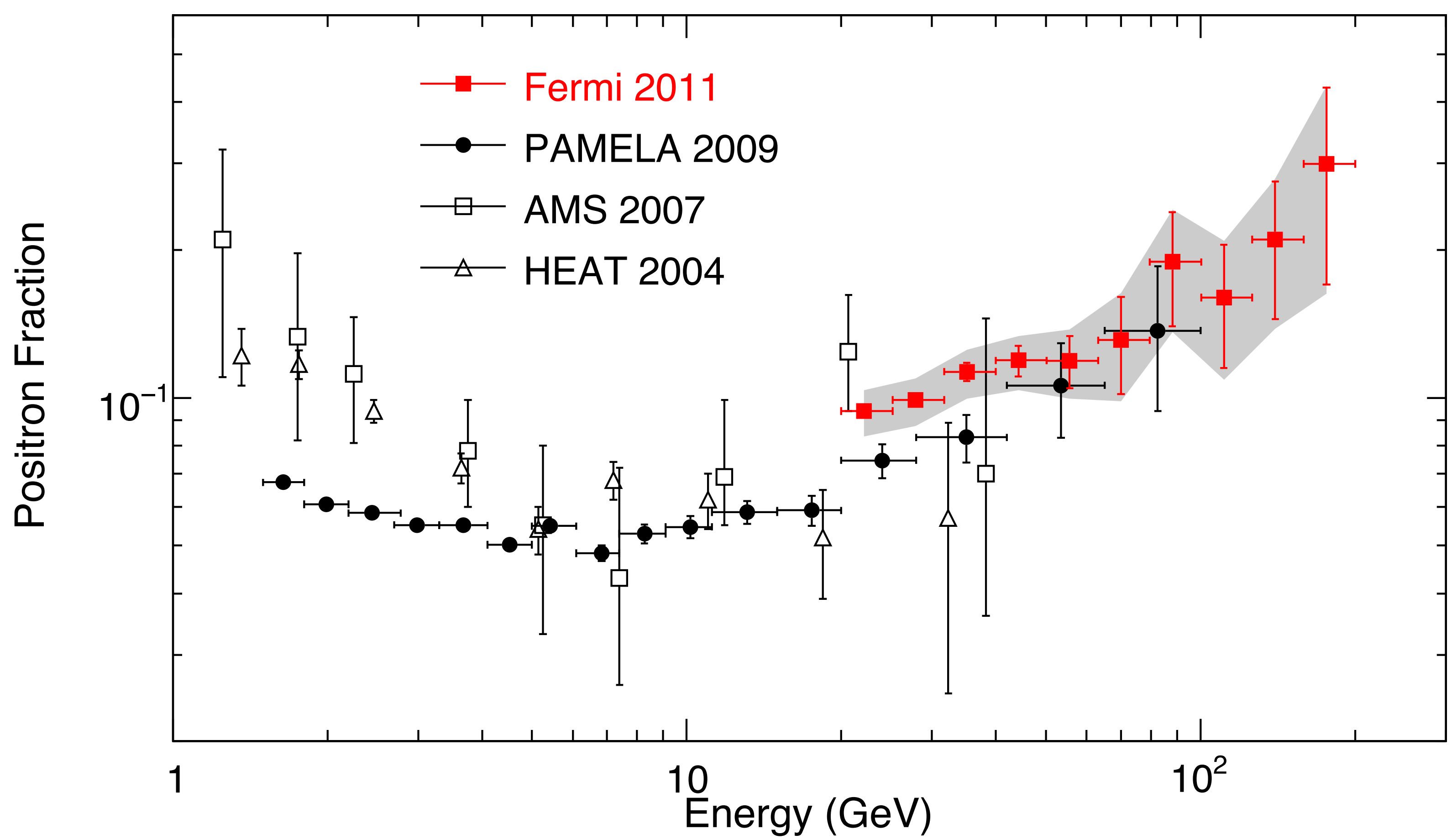
- unexpected bump in total electron + positron spectrum measured by ATIC
- less prominent feature seen in Fermi cosmic ray electron/positron spectrum
- Fermi positron fraction agrees with PAMELA result, extends to higher energies

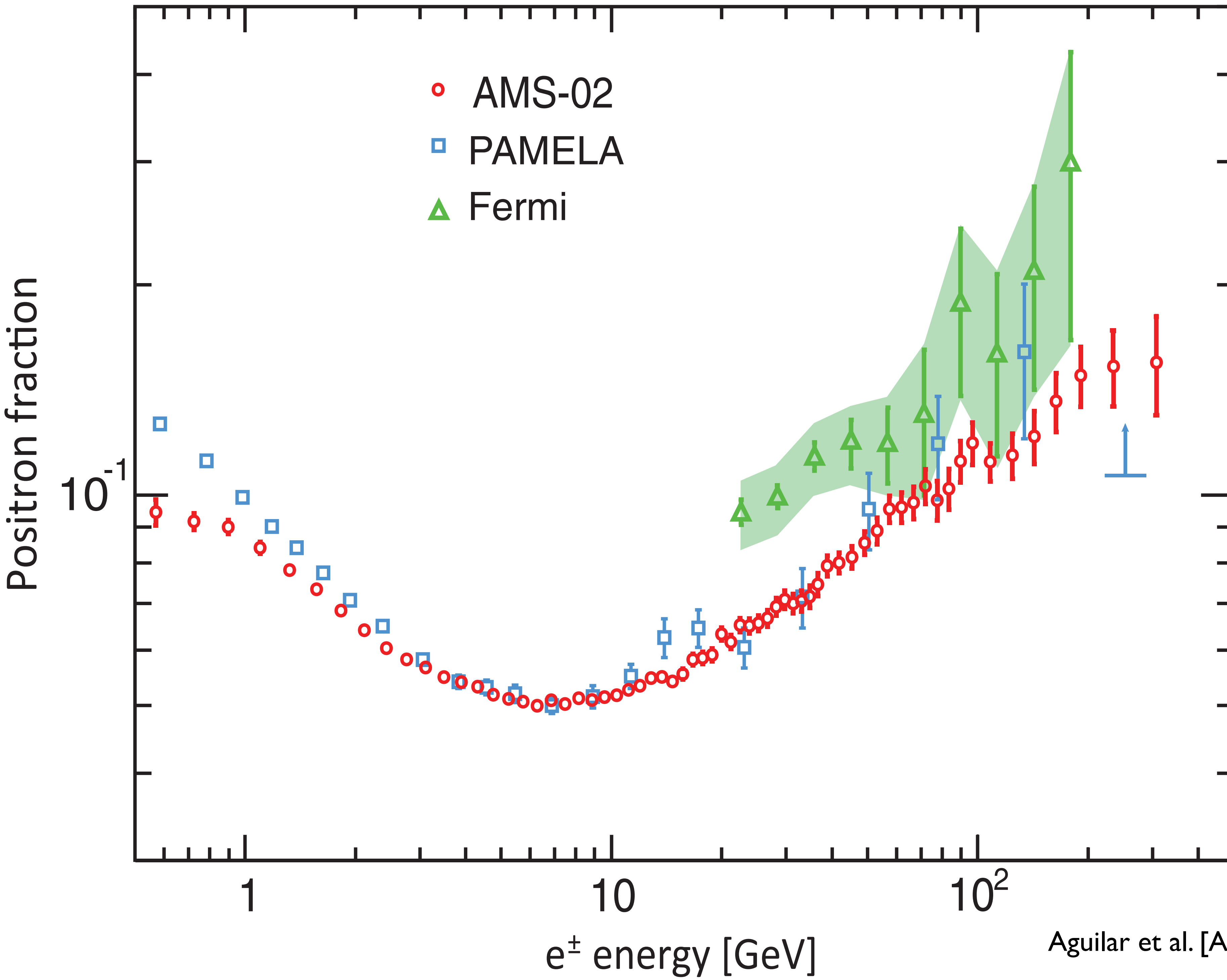
Fermi positron fraction



Ackermann et al. [Fermi LAT Collaboration] 2011

The positron excess persists...

AMS-02 positron fraction measurement



Aguilar et al. [AMS-02 Collaboration] 2013

Hints of a dark matter signal?

The Case for a 700+ GeV WIMP: Cosmic Ray Spectra from ATIC and PAMELA

Ilias Cholis,[1] Gregory Dobler,[2] Douglas P. Finkbeiner,[2] Lisa Goodenough,[1] and Neal Weiner[1]

Recent cosmic-ray electron and positron (CRE) results sparked interest in DM explanations (e.g., Arkani-Hamed et al. 2009; Lattanzi & Silk 2009; Cirelli et al. 2009; Cholis et al. 2008; Grasso et al. 2009;...)

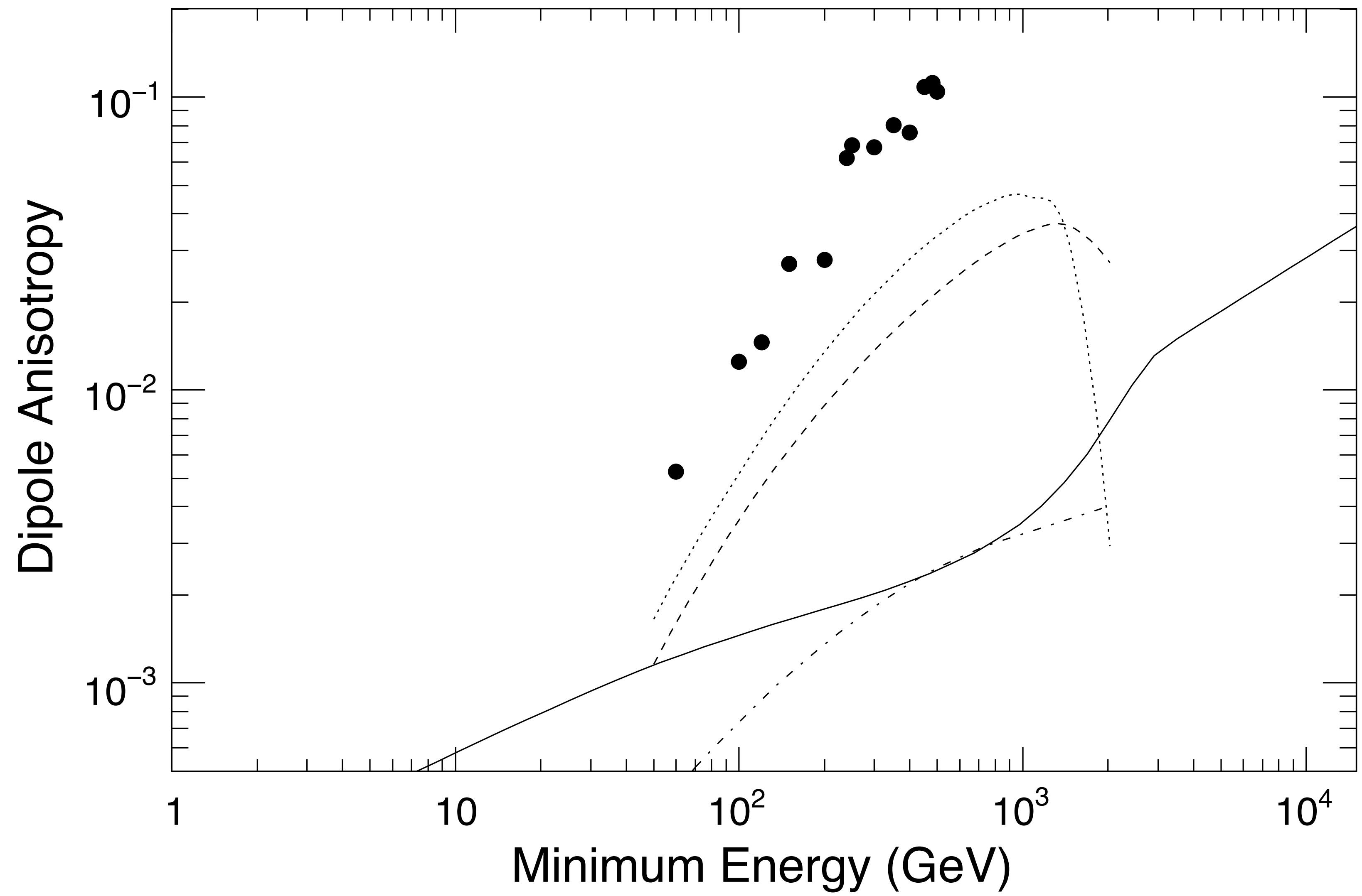
To explain the CRE data with DM generally requires:

- leptophilic models
- large annihilation cross-sections; this can arise in "secluded" or "intermediate state" models, in which DM interacts with SM via a new particle (typically a light scalar)

Constraints from CRE dipole anisotropy

- high-energy positrons should originate from "local" sources (within ~ 1 kpc)
- distribution of nearby sources could produce a detectable asymmetry in the arrival direction of CREs
- Fermi LAT / AMS-02 limits on CRE anisotropy could constrain scenarios explaining CRE measurements

Fermi LAT limits on CRE dipole anisotropy and predictions for some DM scenarios

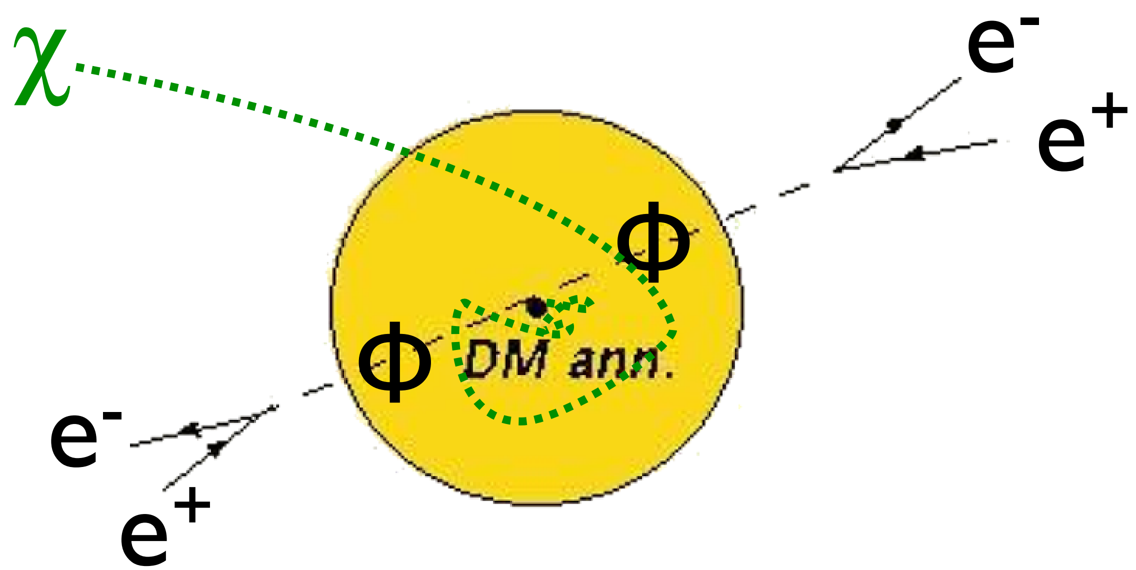


Ackermann et al. [Fermi LAT Collaboration] 2010
(Phys.Rev.D 82, 092003)

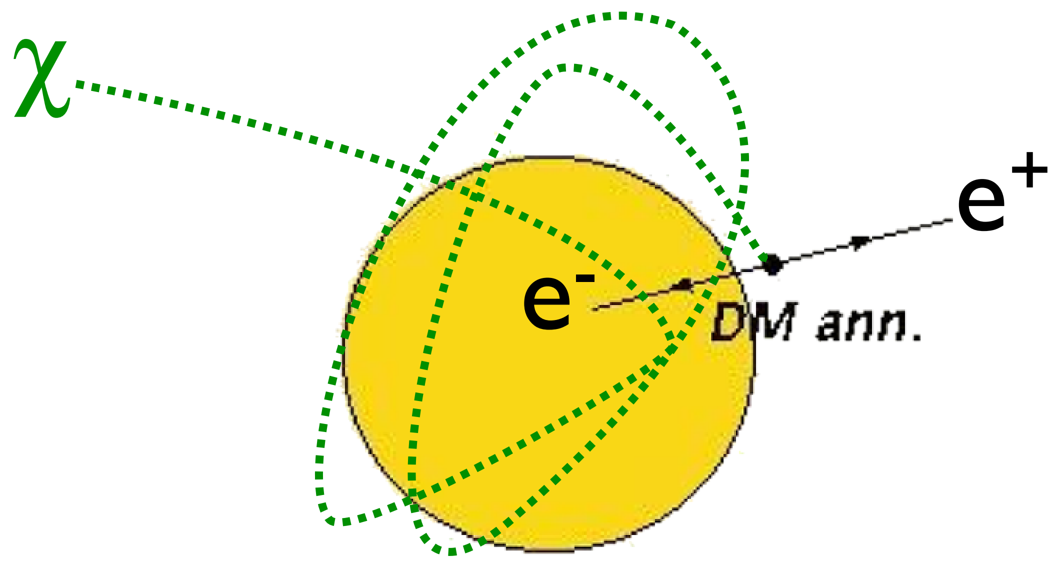
Solar CREs from DM annihilation

Schuster, Toro, Weiner, Yavin 2010 discuss 2 scenarios in which dark matter annihilation leads to cosmic-ray electron and positron (CRE) fluxes from the Sun:

- 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

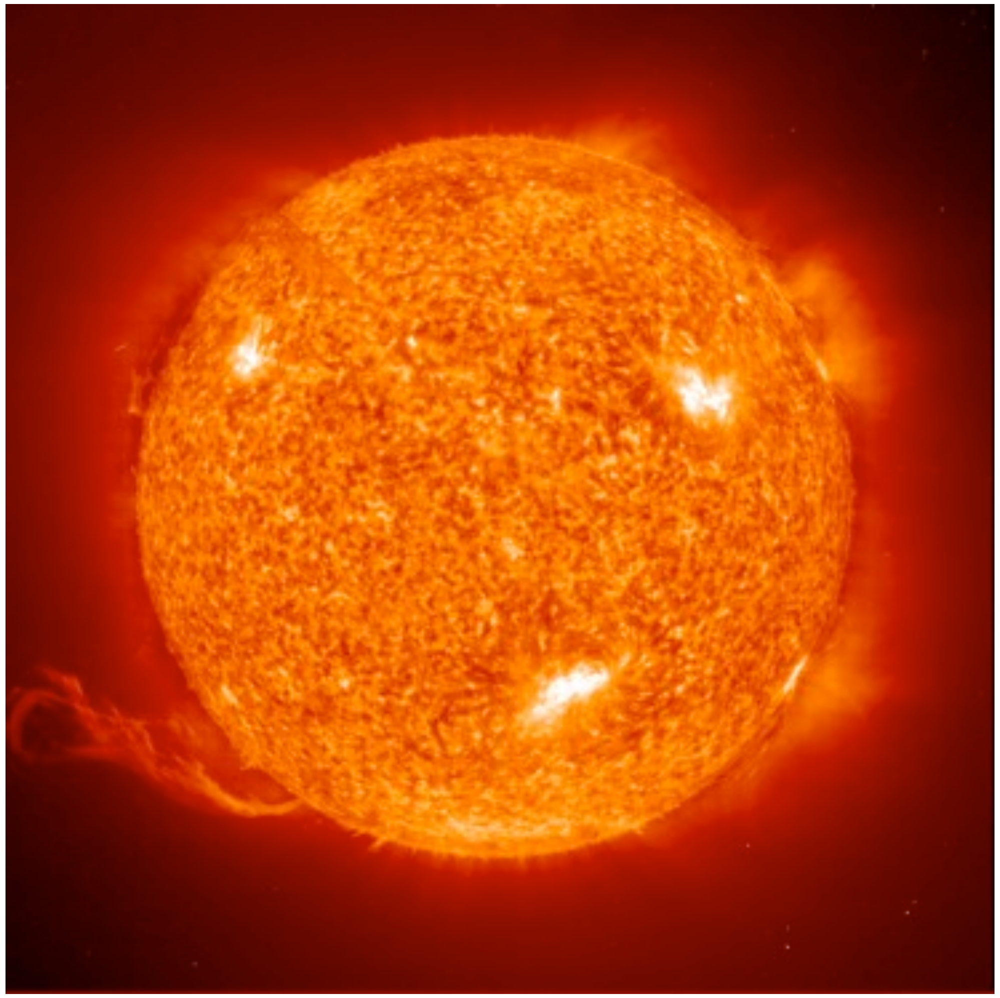


- iDM scenario: Inelastic dark matter (iDM) captured by the Sun remains on large orbits, then annihilates directly to CREs outside the surface of the Sun



Fermi LAT search for CREs from the Sun

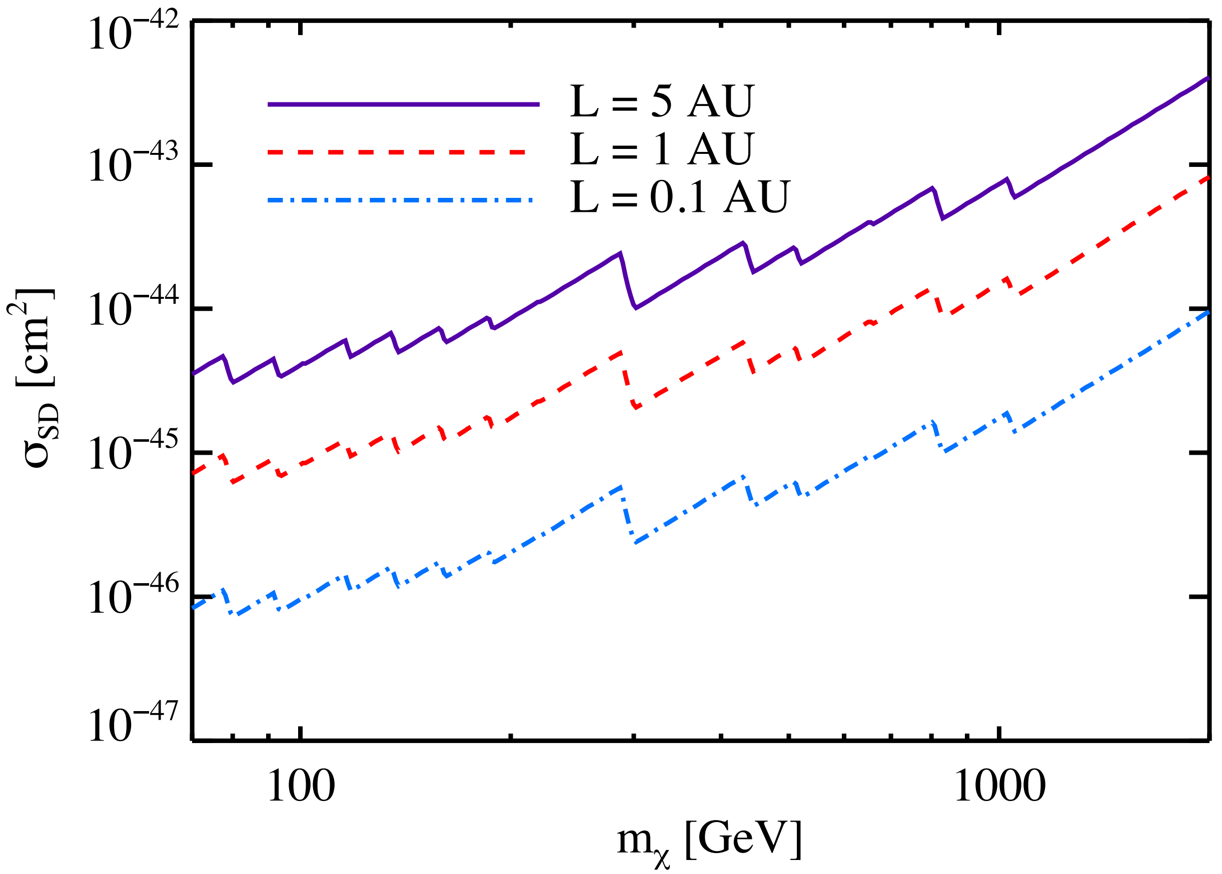
- ~10^6 CRE events (E > 60 GeV), from 1st year of operation
- analysis performed in ecliptic coordinates, in reference frame centered on the Sun
- search for a flux excess correlated with Sun's direction yielded no significant detection, flux upper limits placed



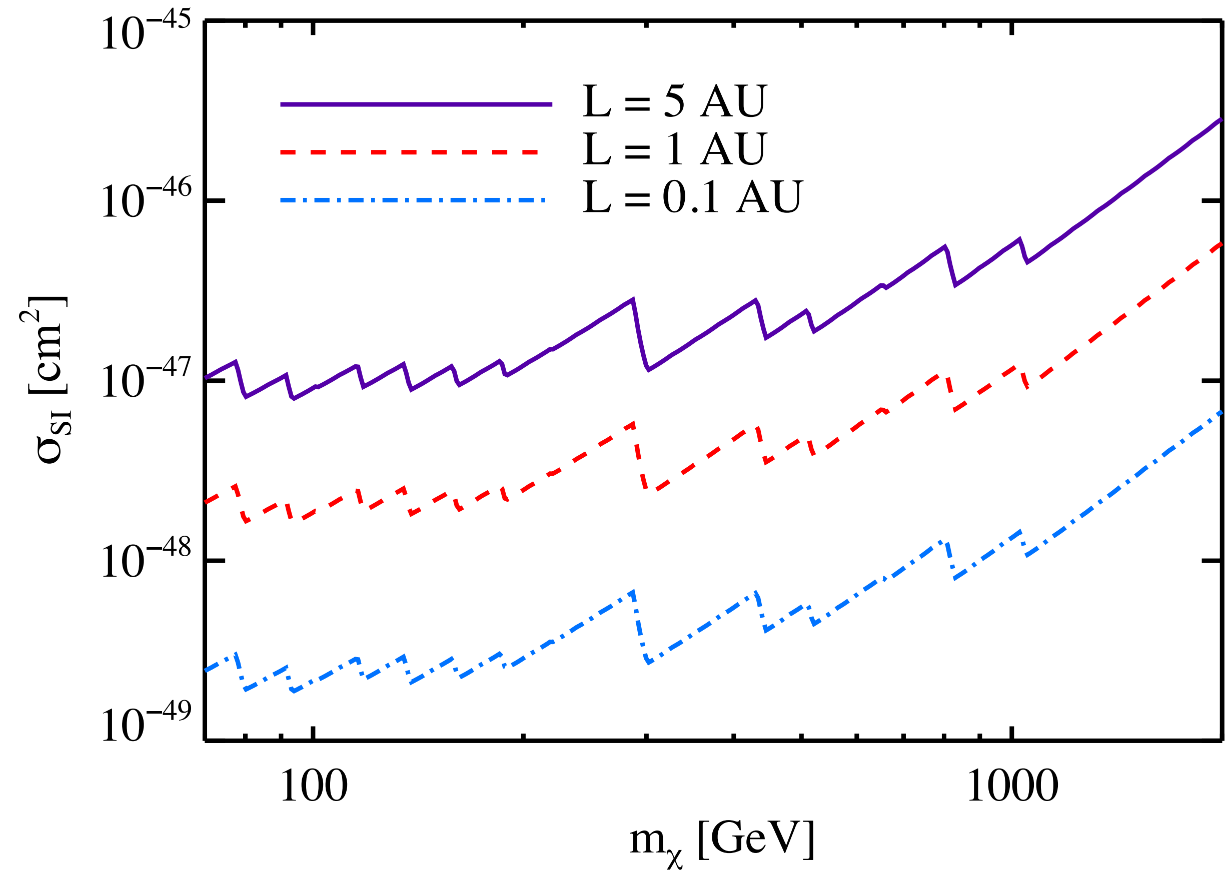
Limits on elastic scattering cross-section

assuming annihilation to CREs via an intermediate state

spin-dependent scattering



spin-independent scattering

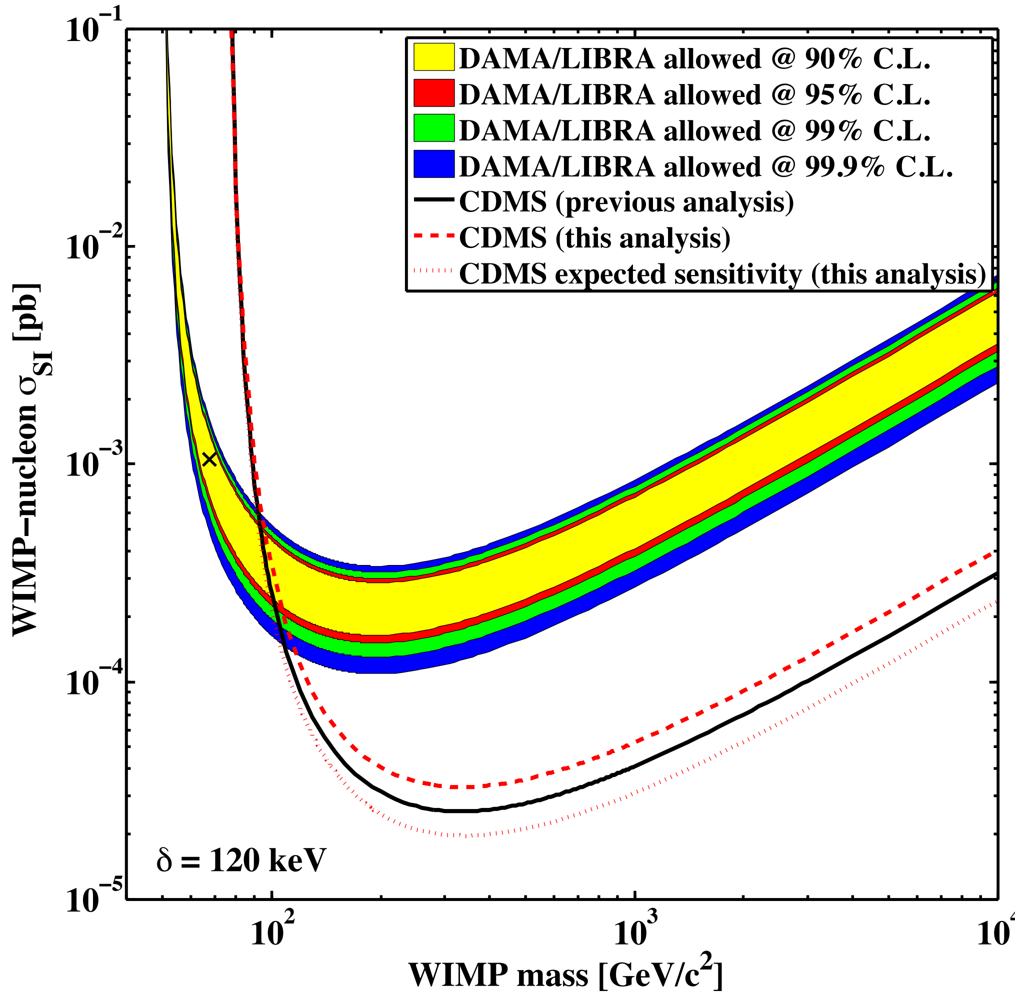


Ajello et al. [Fermi LAT Collaboration], PRD 84, 032007 (2011)

solar CRE flux limits correspond to constraints on the rate of decay to CREs outside the Sun that are ~ 2-4 orders of magnitude stronger than constraints on the associated FSR derived from solar gamma-ray data

Limits on inelastic scattering cross-section

DAMA/LIBRA allowed regions and
CDMS exclusion curves



CDMS Collaboration 2011

Limits on inelastic scattering cross-section

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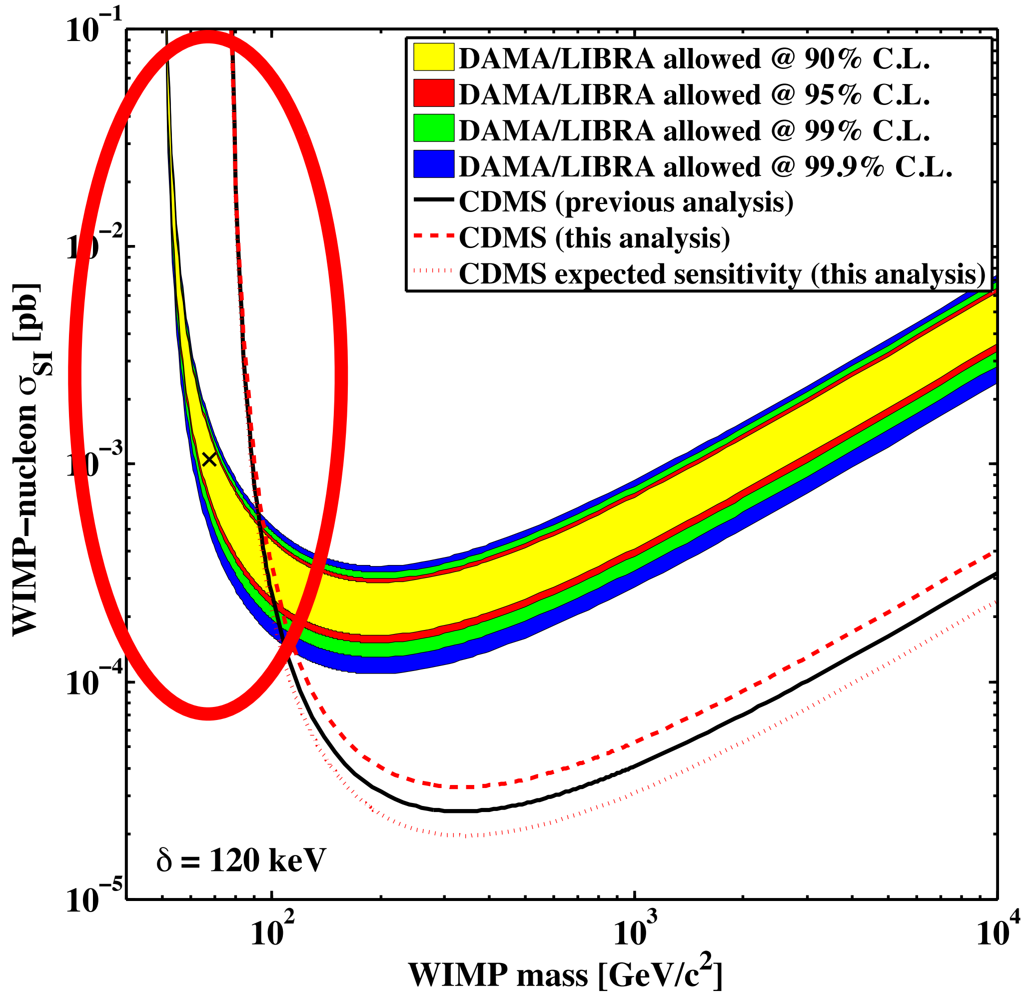


CDMS Collaboration 2011

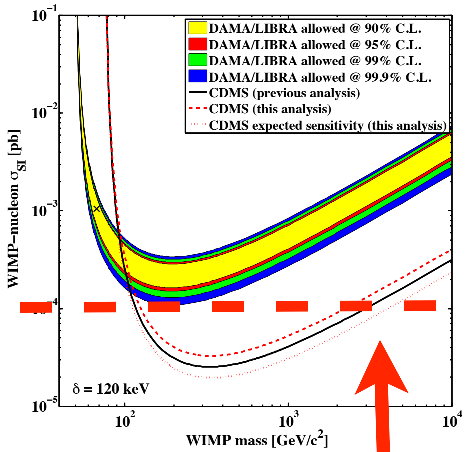
only parameter space compatible with DAMA/LIBRA and CDMS:

$m_\chi \lesssim 100$ GeV

$\sigma_{SI} \sim 10^{-39} - 10^{-40}$ cm^2

compatible models require the mass splitting parameter $\delta \sim 120$ keV

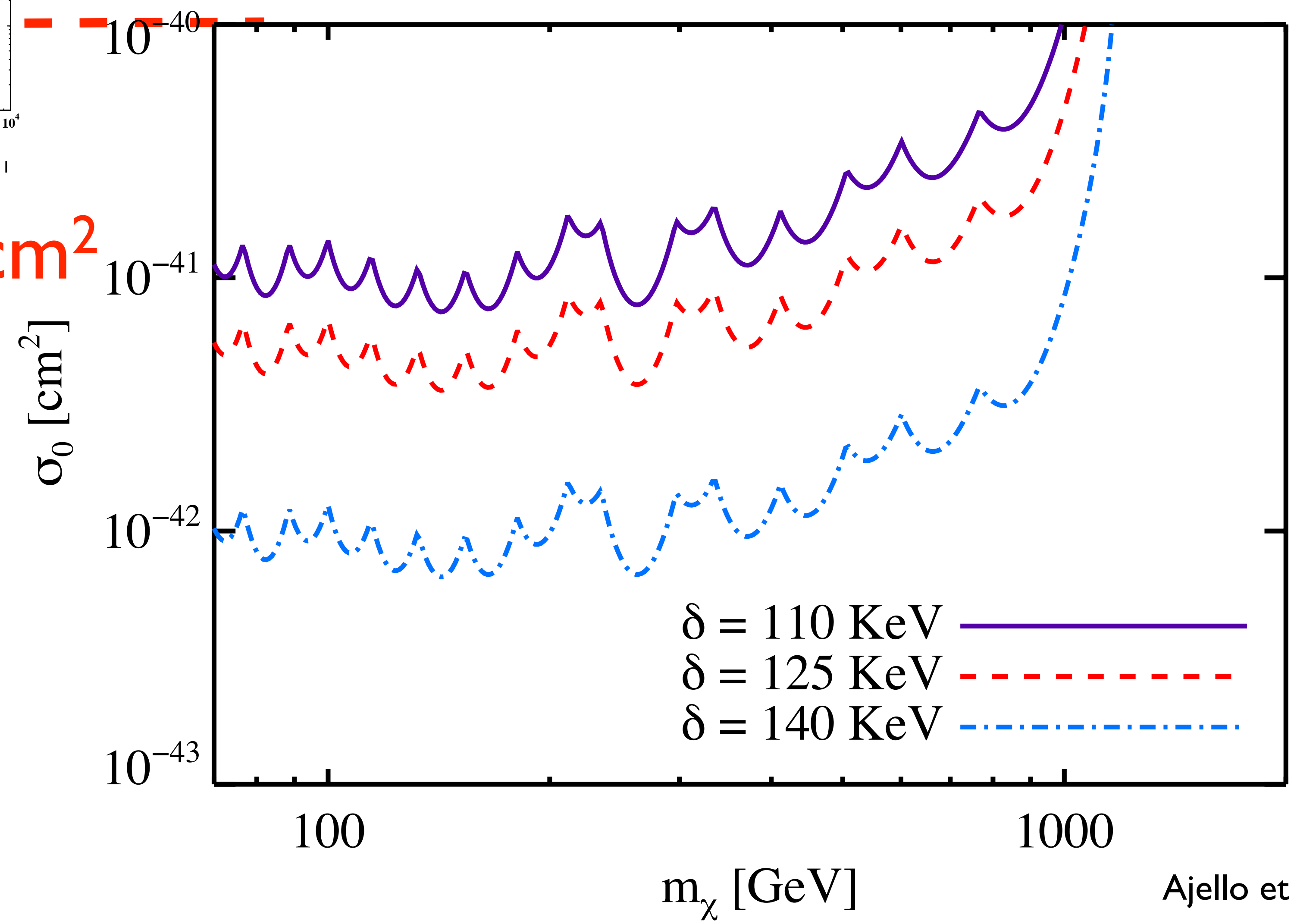
Limits on inelastic scattering cross-section



CDMS Collaboration 2011

10^{-40} cm^2

Parameter space above curves excluded at 95% CL for CRE final state



Ajello et al. [Fermi LAT Collaboration] (2011)

only parameter space compatible with DAMA/LIBRA and CDMS:

$m_\chi \lesssim 100$ GeV

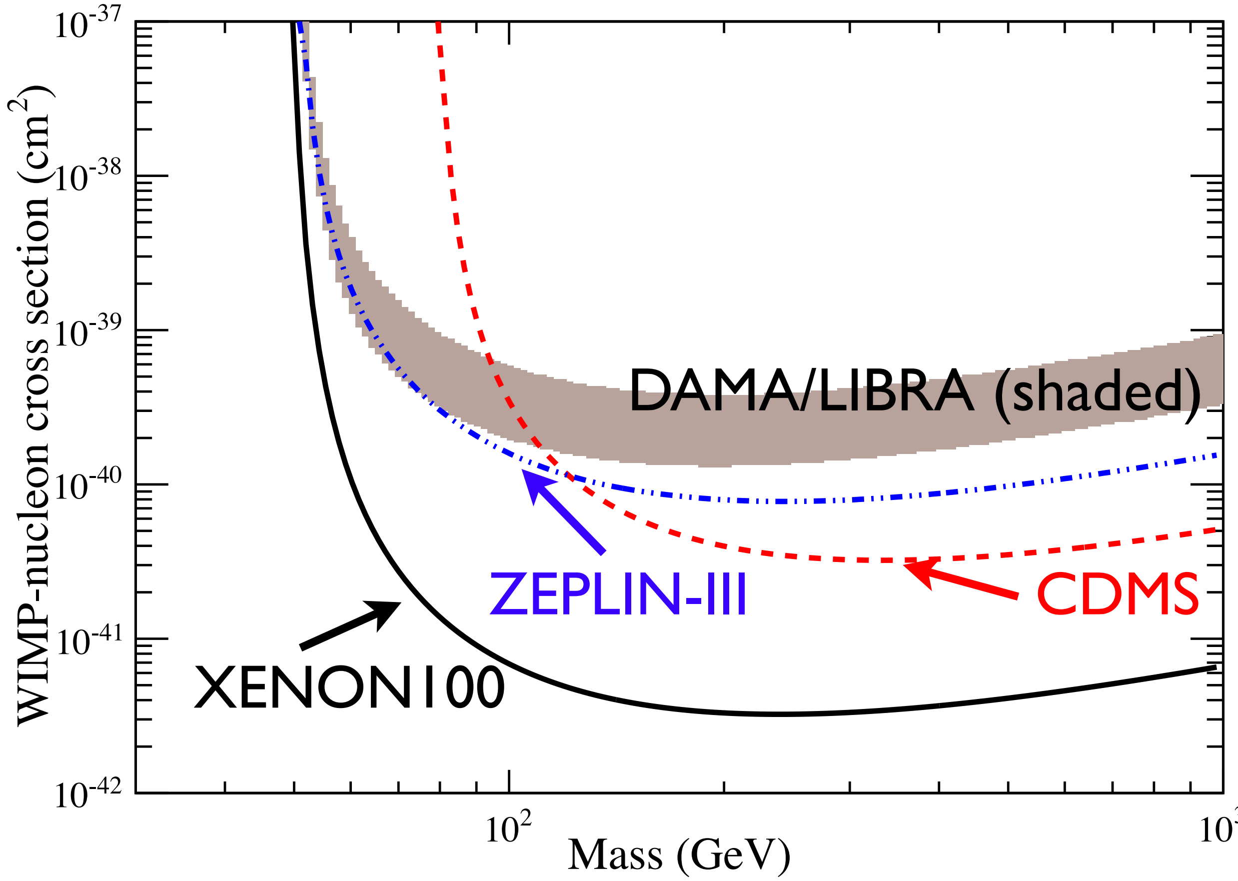
$\sigma_{SI} \sim 10^{-39}$ - 10^{-40} cm^2

compatible models require the mass splitting parameter $\delta \sim 120$ keV

solar CRE constraints exclude by ~ 1-2 orders of magnitude all of the parameter space compatible with an inelastic DM explanation of DAMA/LIBRA and CDMS for DM masses greater than ~ 70 GeV, assuming DM annihilates to CREs

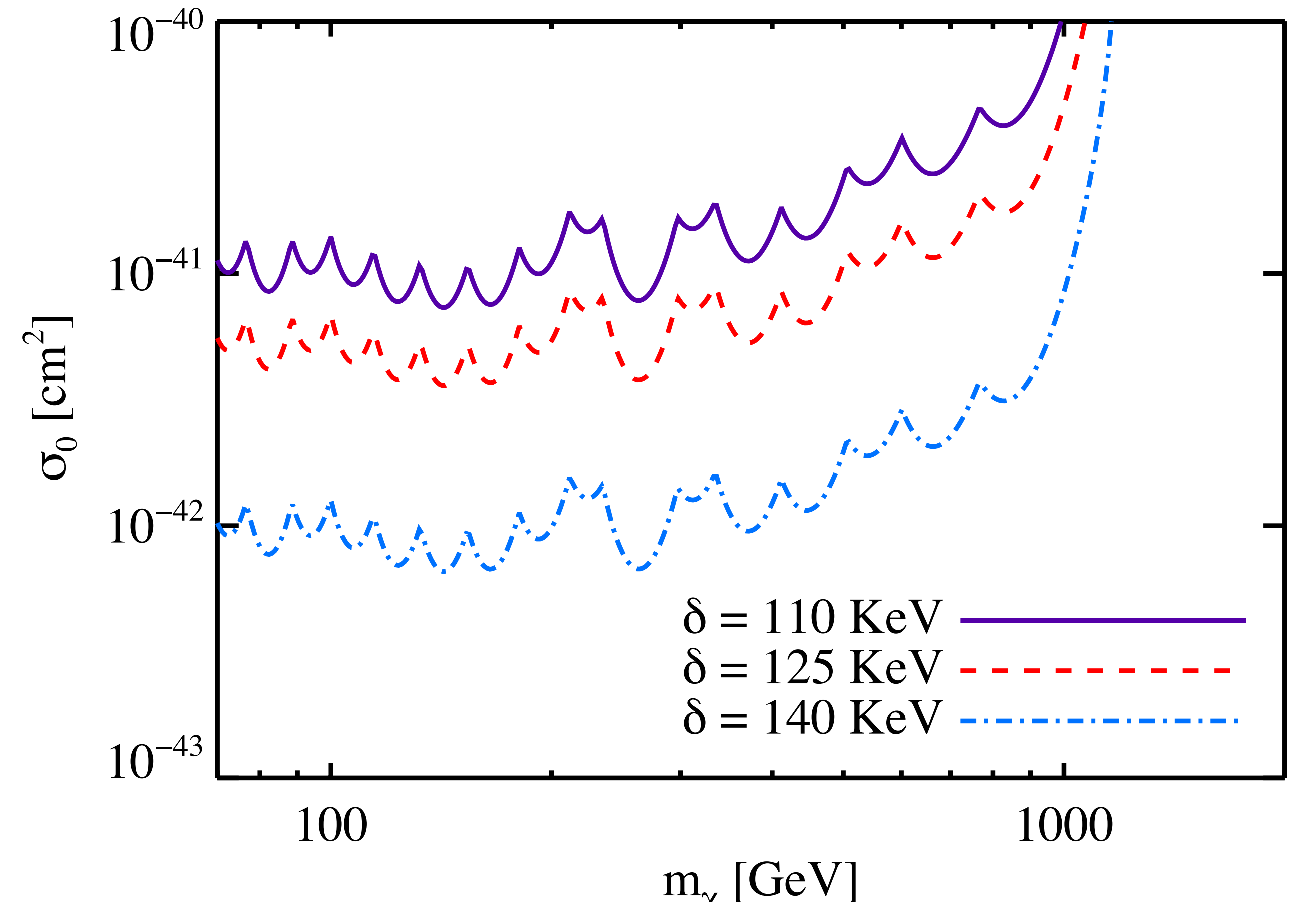
Complementarity with direct searches

Signal and exclusion regions for direct detection experiments at 90% CL (for δ = 120 keV)



Aprile et al. [XENON100 Collaboration] (2011)

Parameter space above curves excluded at 95% CL for CRE final state by Fermi LAT CRE analysis



Ajello et al. [Fermi LAT Collaboration] (2011)

Fermi solar CRE constraints are competitive with and complementary to direct detection results

- tests for a unique astrophysical signal arising from specific dark matter models
- different sources of uncertainties make solar CRE limits a valuable cross-check

Instruments and analyses:
Cherenkov Telescope Array (CTA)

The Cherenkov Telescope Array (CTA)

- array of many telescopes of various sizes to balance need for effective area while reducing energy threshold
- relatively large FOV ~ 10 deg (current ACTs ~ 5 deg)
- will trigger as low as ~ few tens of GeV (compared to ~ 100 GeV for current ACTs)

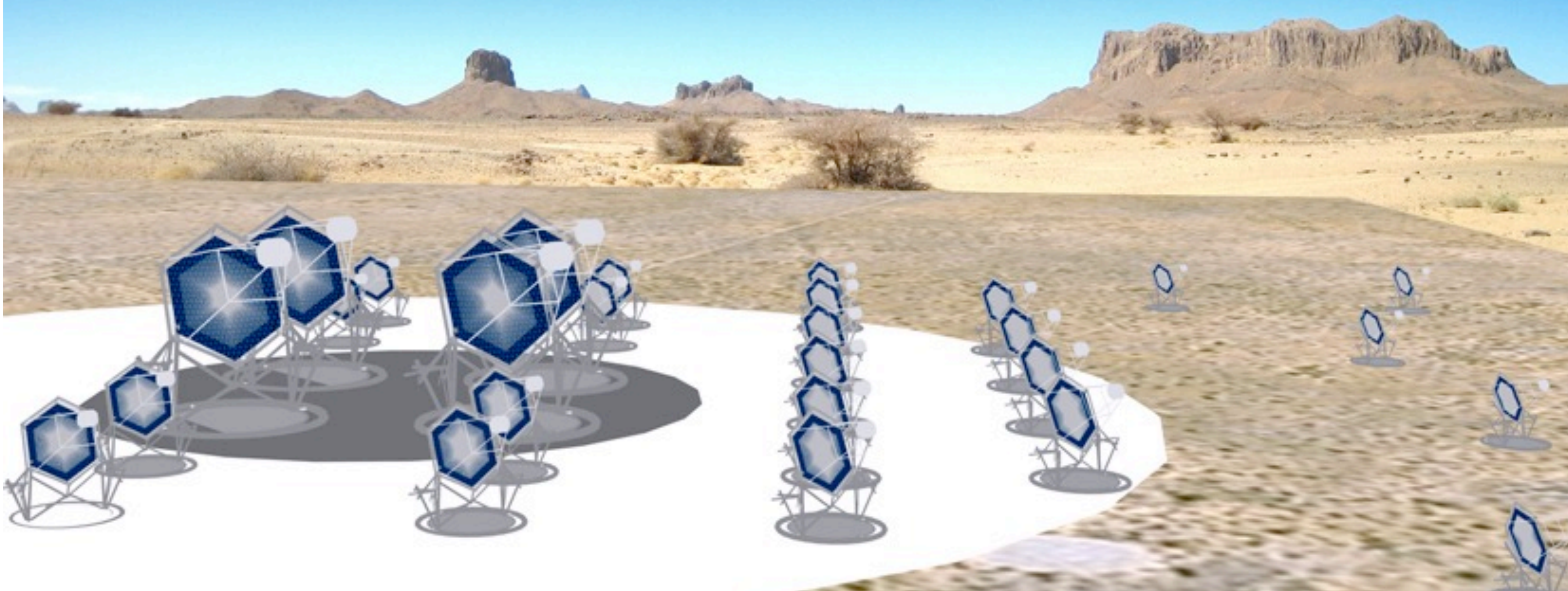


Image credit: CTA Collaboration

The Cherenkov Telescope Array (CTA)

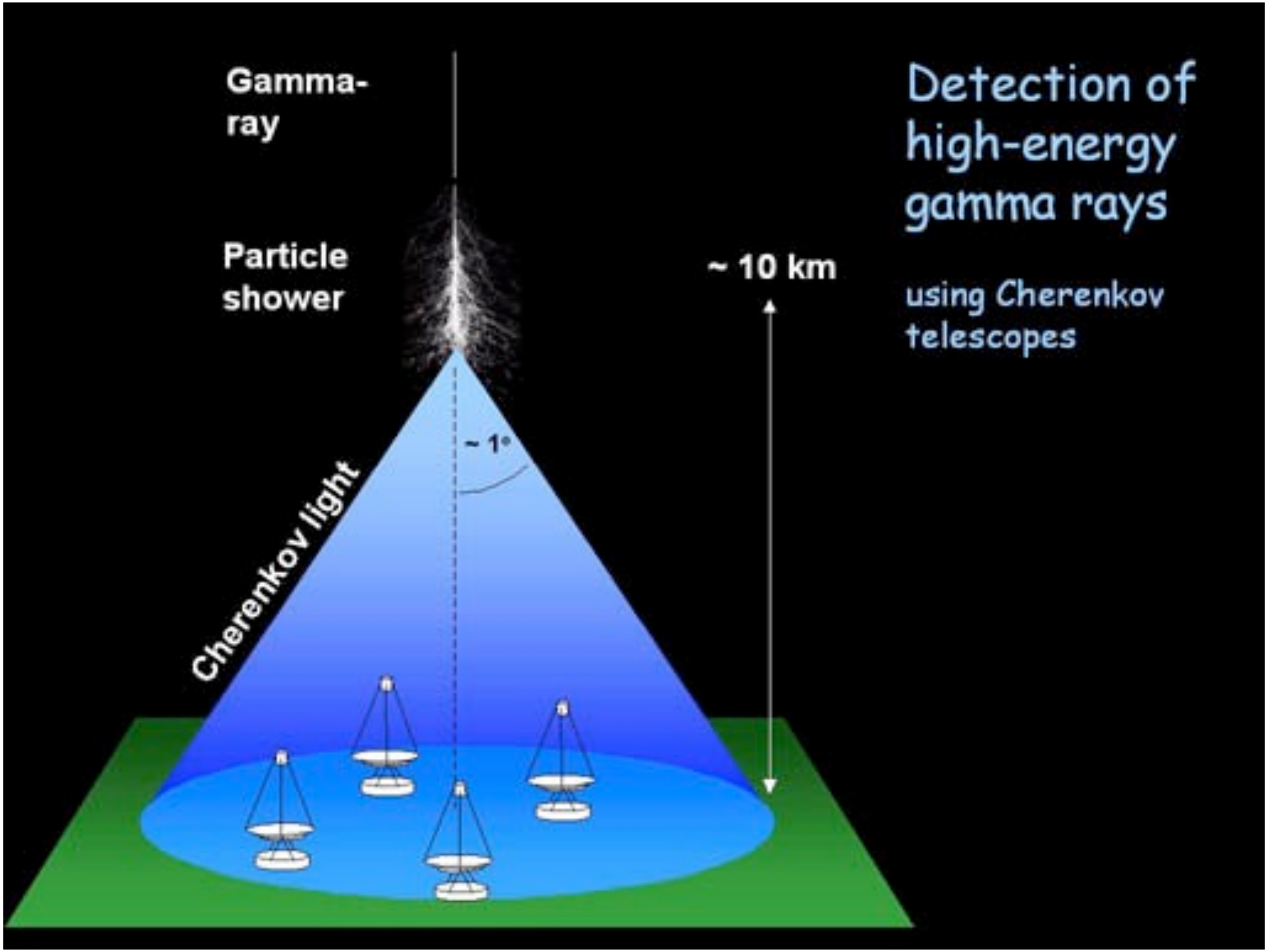
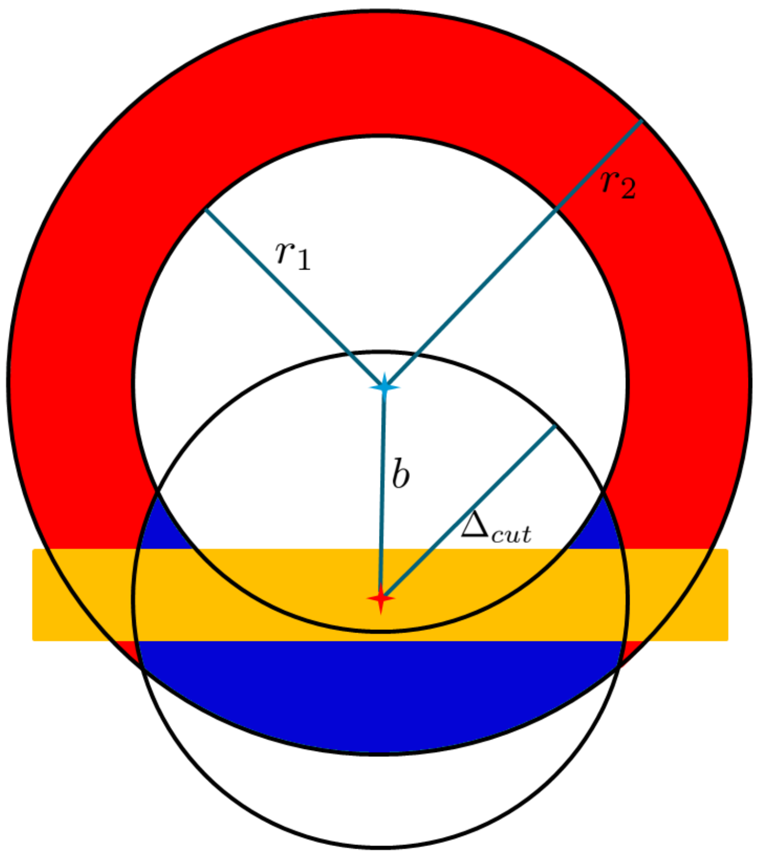


Image credit: H.E.S.S. Collaboration

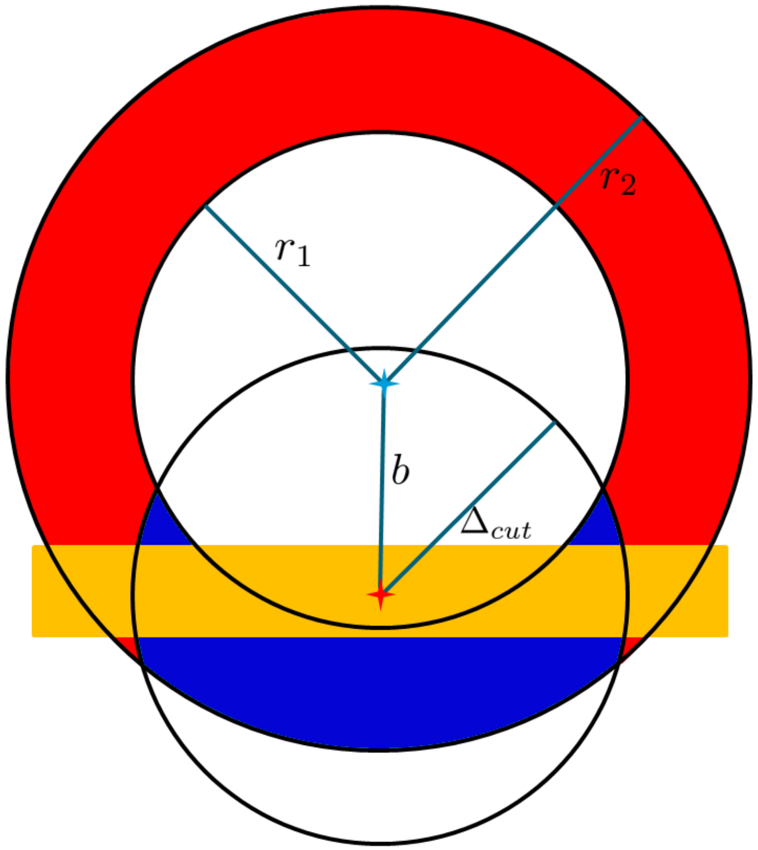
Sensitivity to dark matter annihilation



"Ring Method"

ACTs use "on-off" methods to search for signals due to large irreducible cosmic-ray electron background

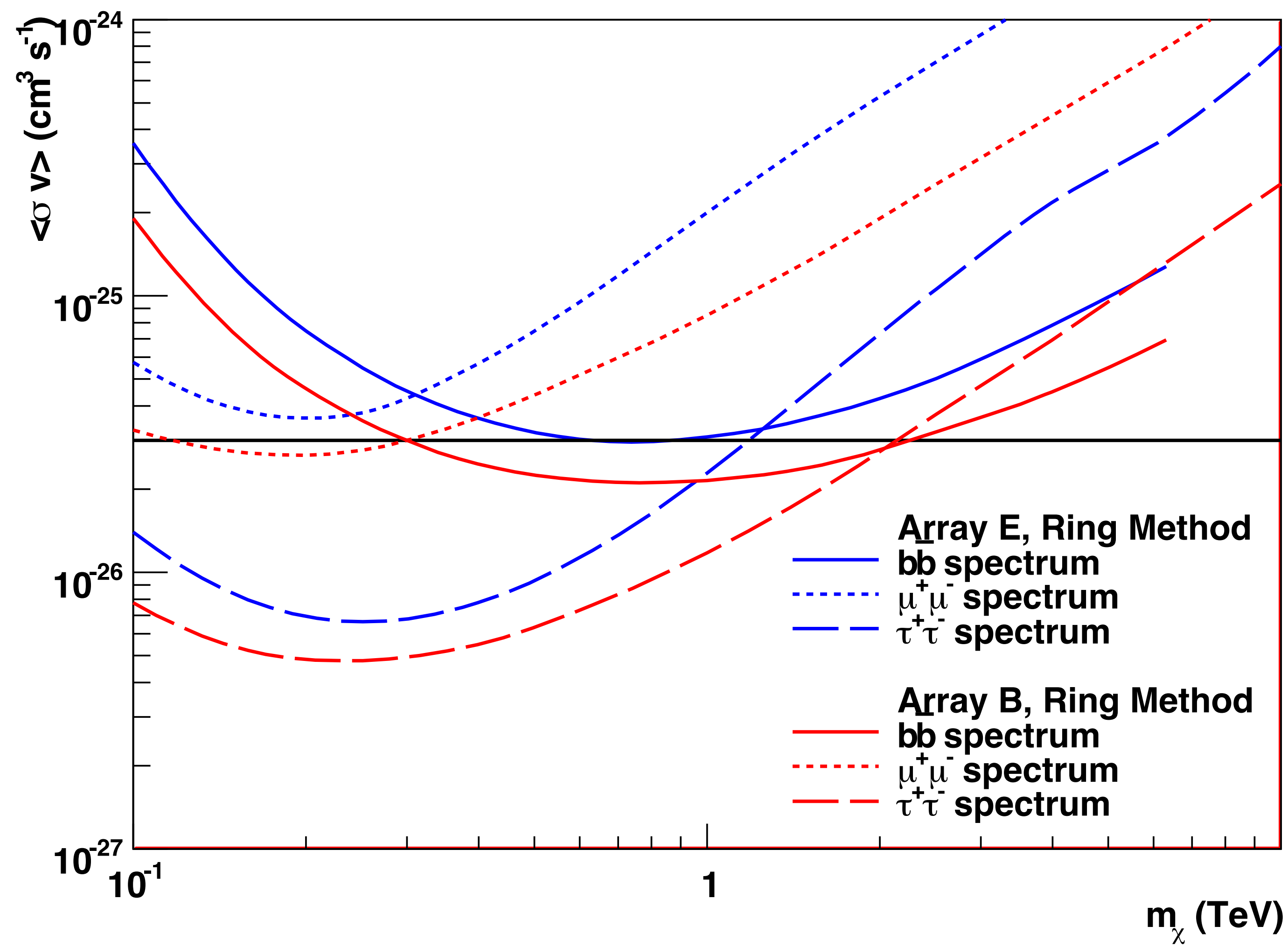
Sensitivity to dark matter annihilation



"Ring Method"

ACTs use "on-off" methods to search for signals due to large irreducible cosmic-ray electron background

projected sensitivity for Galactic Center (100h)



Doro et al. [CTA Collaboration] 2012

Summary

- Several hints of possible dark matter signals have been uncovered in gamma-ray and cosmic-ray data! This is a very interesting time for indirect detection!
- New constraints on dark matter models have been obtained from null searches for indirect dark matter signals in Fermi LAT data using a variety of targets
- Searches for dark matter signatures in gamma rays from the Milky Way halo and dwarf galaxies exclude canonical thermal relic dark matter annihilation cross-sections for masses less than a few tens of GeV for some channels
- Fermi LAT CRE data provide a valuable probe of dark matter models that could explain the measured rise in the local cosmic-ray positron fraction
- Non-observation of CREs from the Sun places strong limits on inelastic and secluded dark matter models; inelastic dark matter constraints are complementary to those from direct searches
- CTA will provide new, strong sensitivity to dark matter signals, especially at high WIMP masses
- Current searches are already testing canonical WIMP dark matter models; there is great potential for discovery in future dark matter searches with gamma rays and cosmic rays!
- Fermi data are public!!! Please (continue to) use them!!!