Latest results from indirect dark matter searches from space-based observations

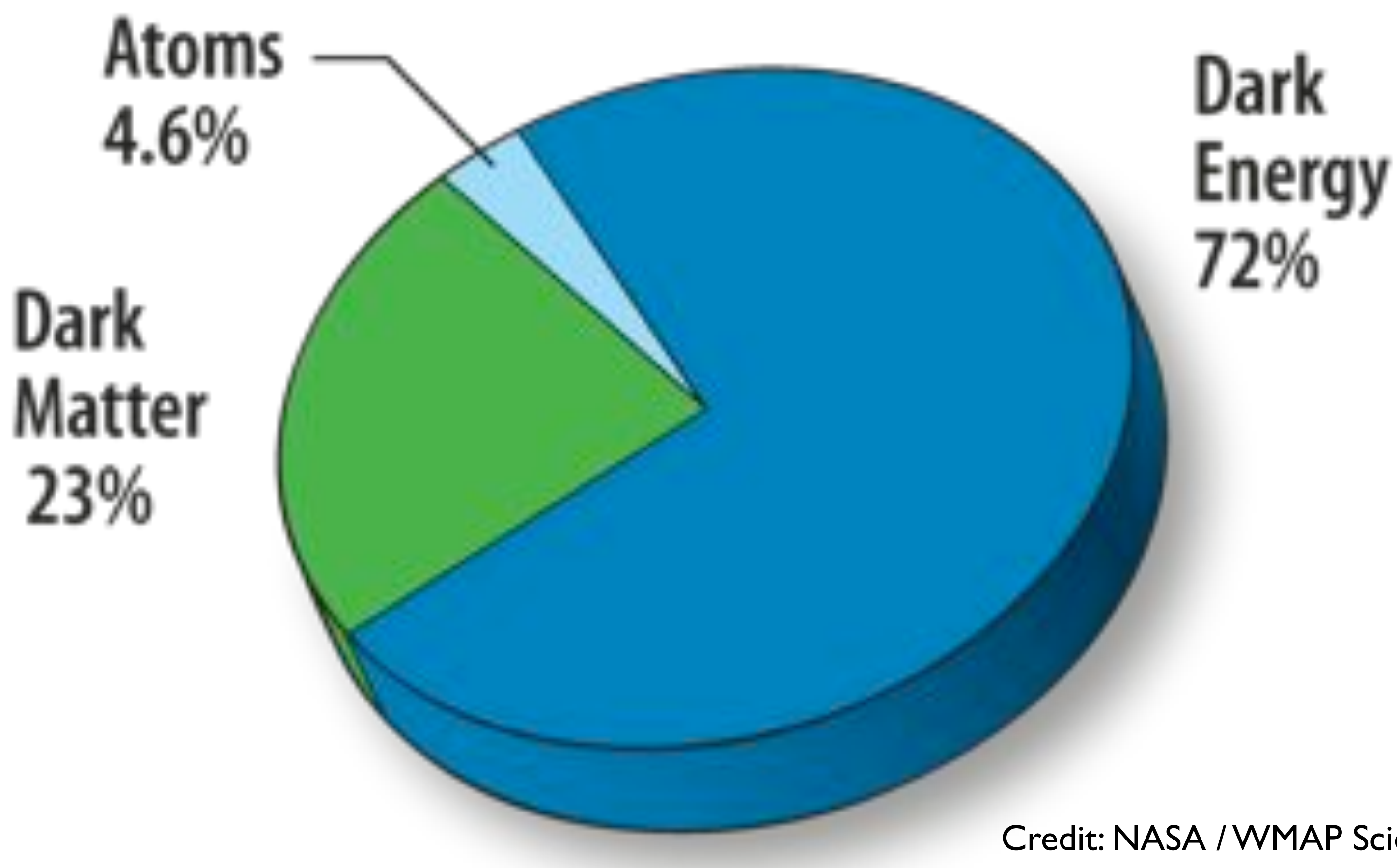
Jennifer Siegal-Gaskins
(Caltech)

on behalf of
the Fermi LAT Collaboration

The nature of dark matter

Observational evidence indicates:

- non-baryonic
- neutral
- virtually collisionless

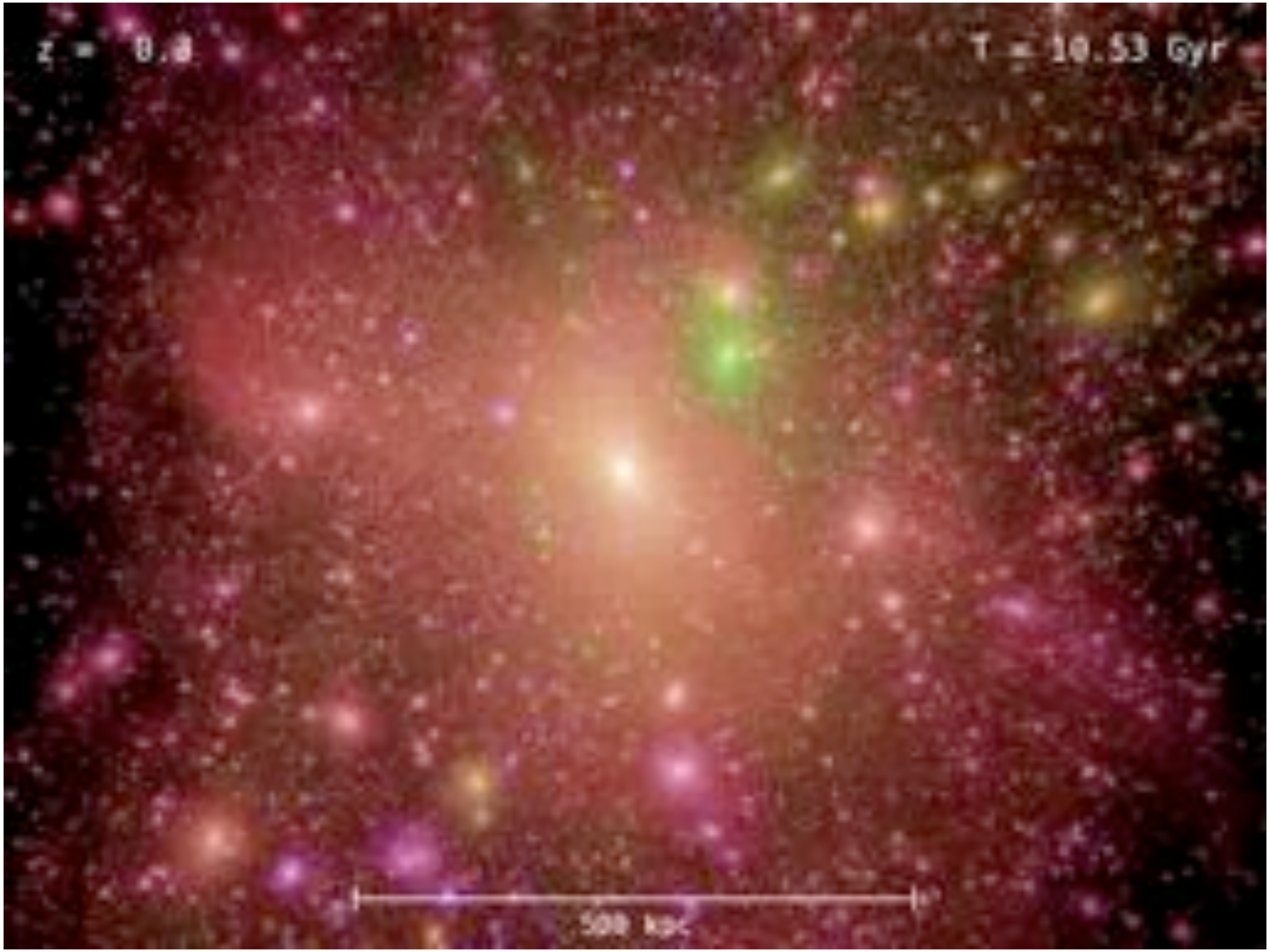


Credit: NASA / WMAP Science Team

Additional assumptions for this talk:

- dark matter is a weakly-interacting massive particle (WIMP)
- GeV - TeV mass scale
- can pair annihilate or decay to produce standard model particles
- accounts for the measured dark matter density

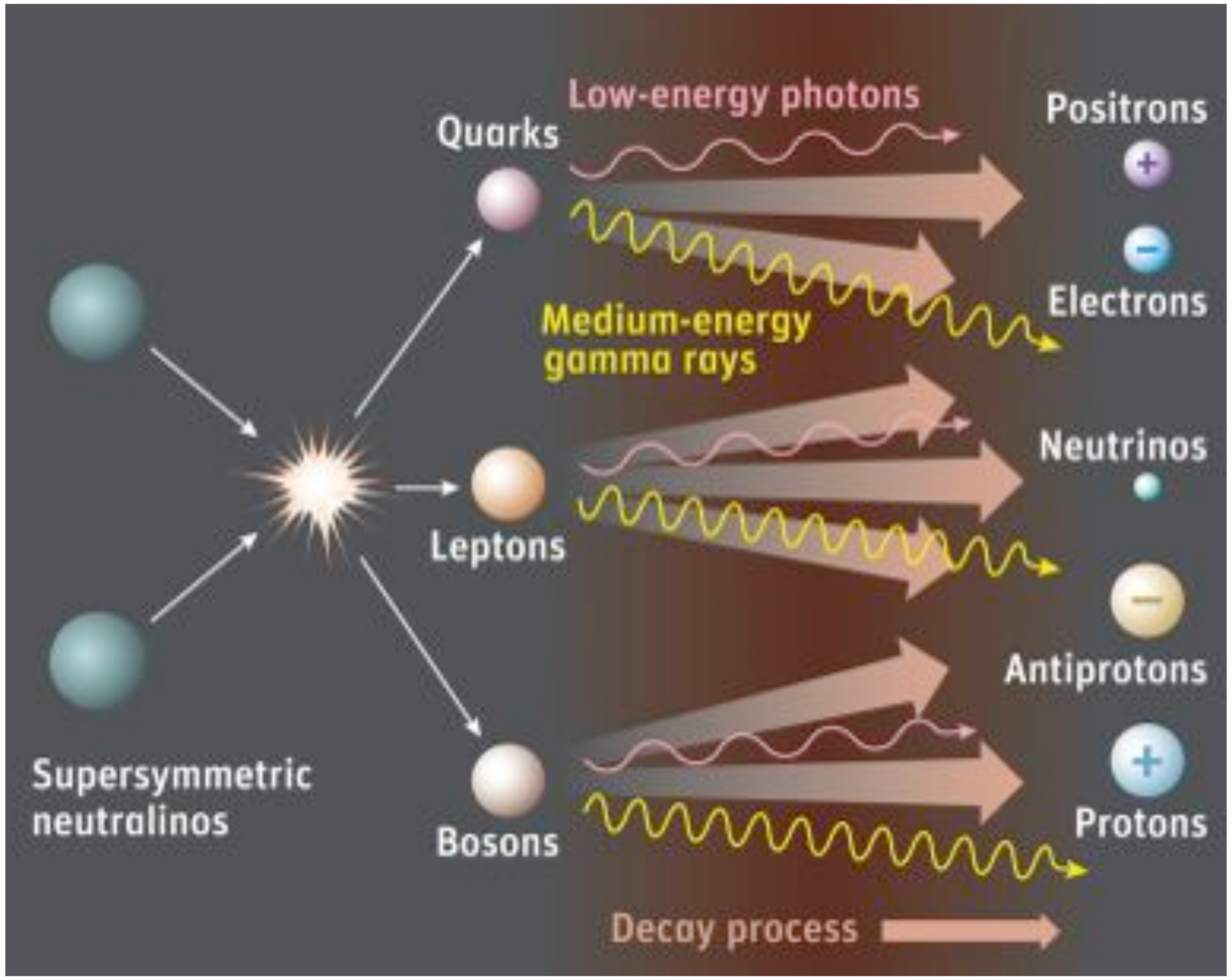
The dark matter distribution



Credit: Springel et al. (Virgo Consortium)

Indirect dark matter signals

- annihilation or decay of dark matter can produce a variety of potentially detectable Standard Model particles
- spectrum of annihilation (or decay) products encodes info about intrinsic particle properties
- variation in the intensity of the signal along different lines of sight is determined exclusively by the distribution of dark matter



Credit: Sky & Telescope / Gregg Dinderman

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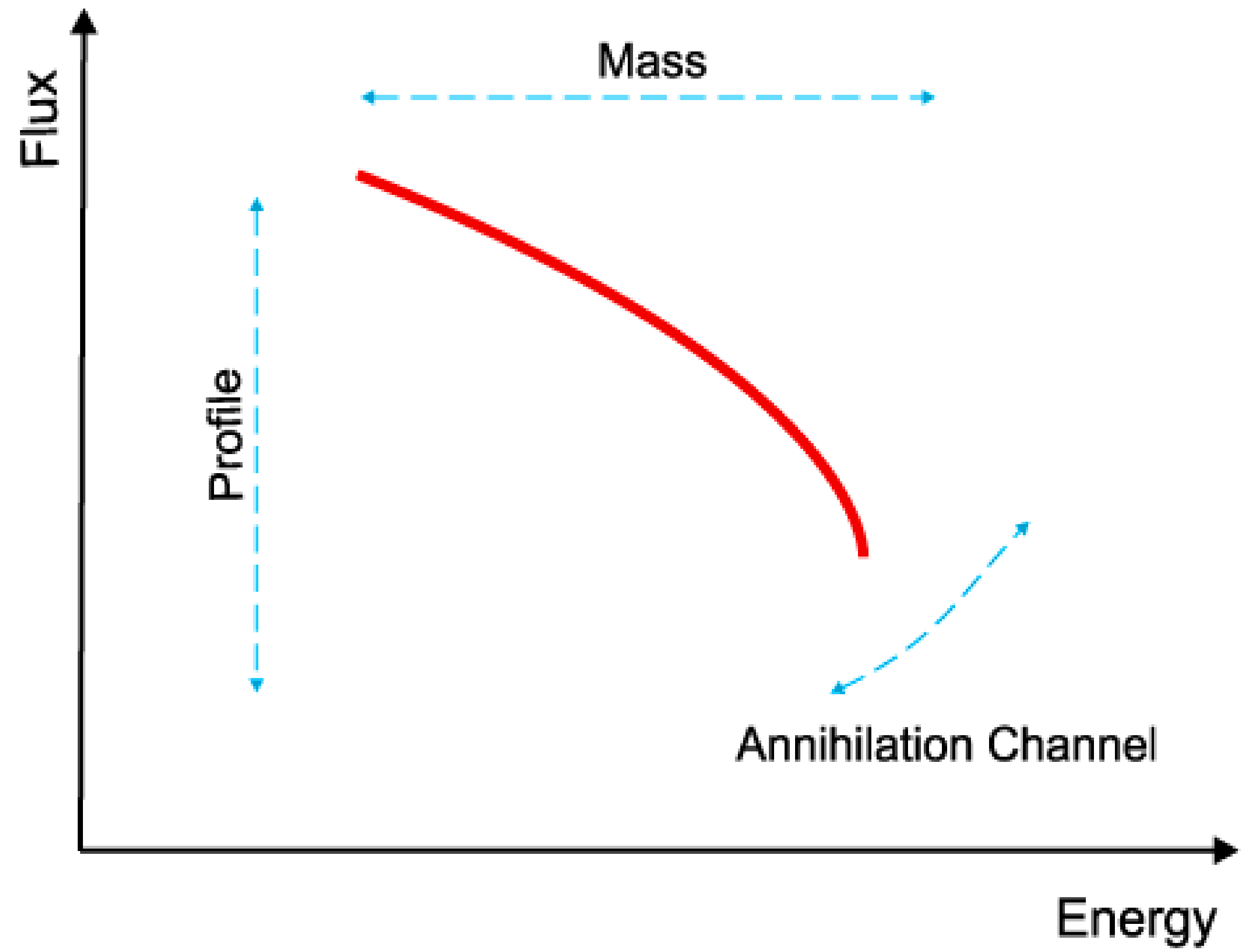

Bertone 2007

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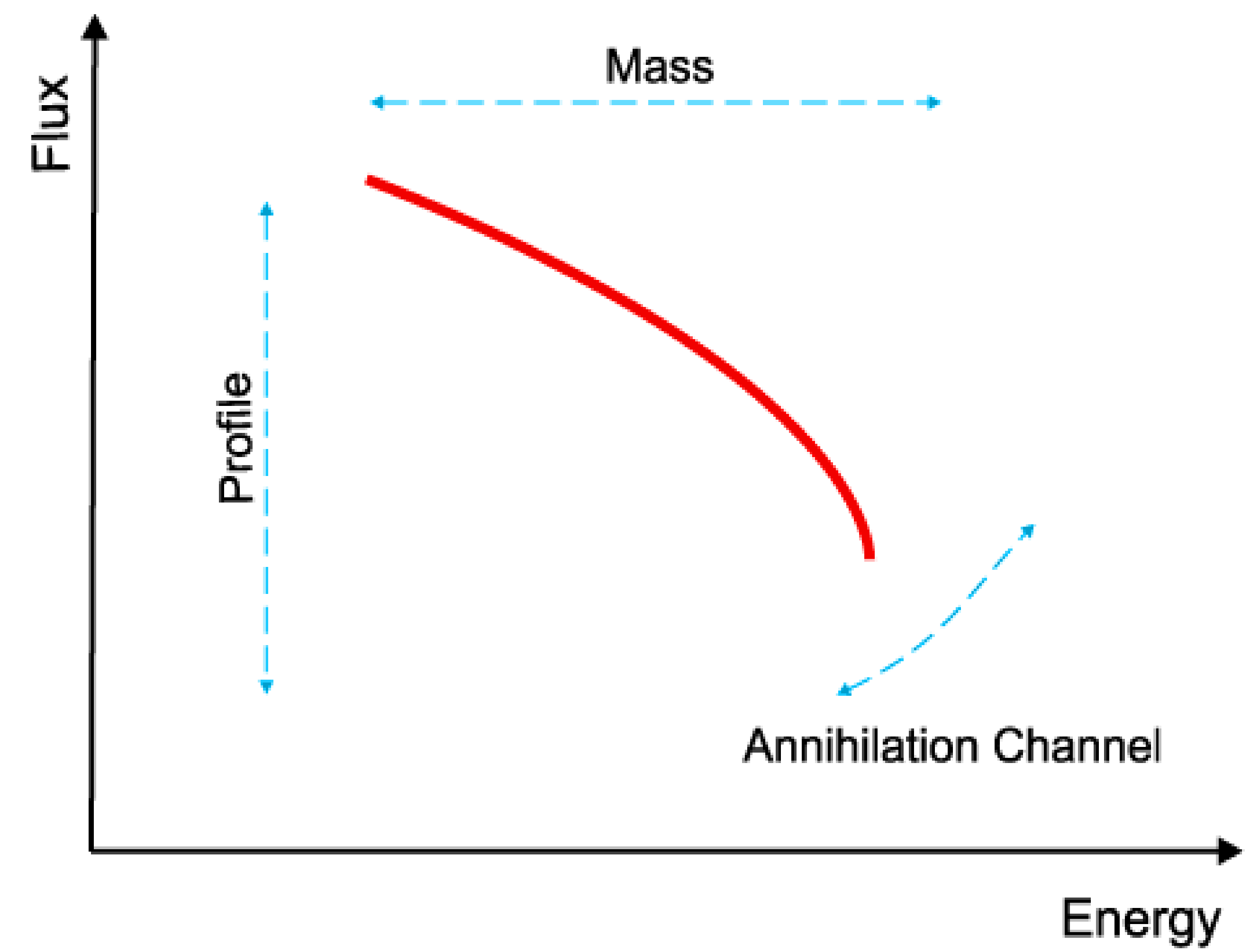

Bertone 2007

$$I(\psi) = \frac{K}{4\pi} \int_{los} \mathrm{d}s \; \rho^2(s, \psi) \qquad K = \frac{N_\gamma \langle \sigma v \rangle}{2 m_\chi^2}$$

(annihilation)

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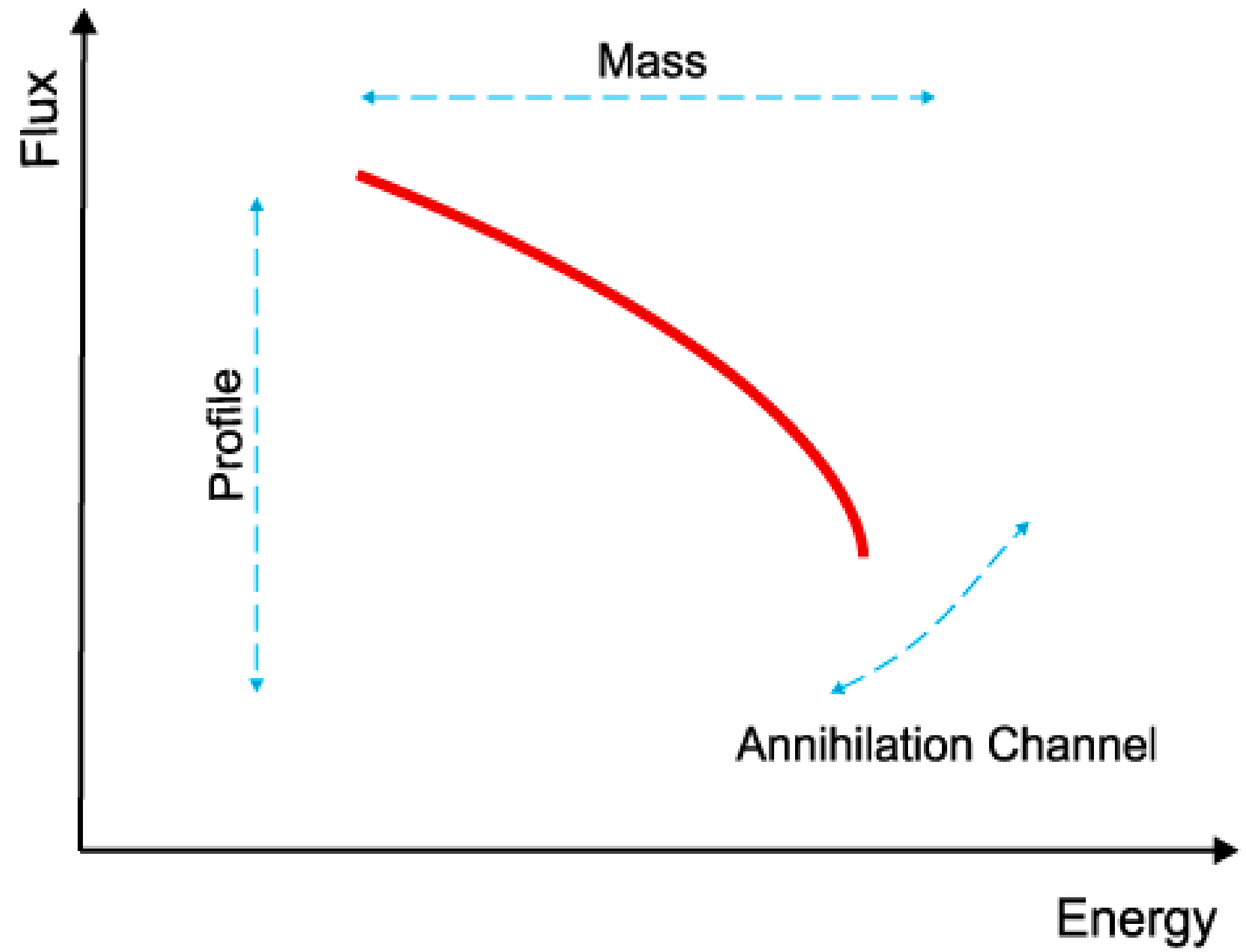

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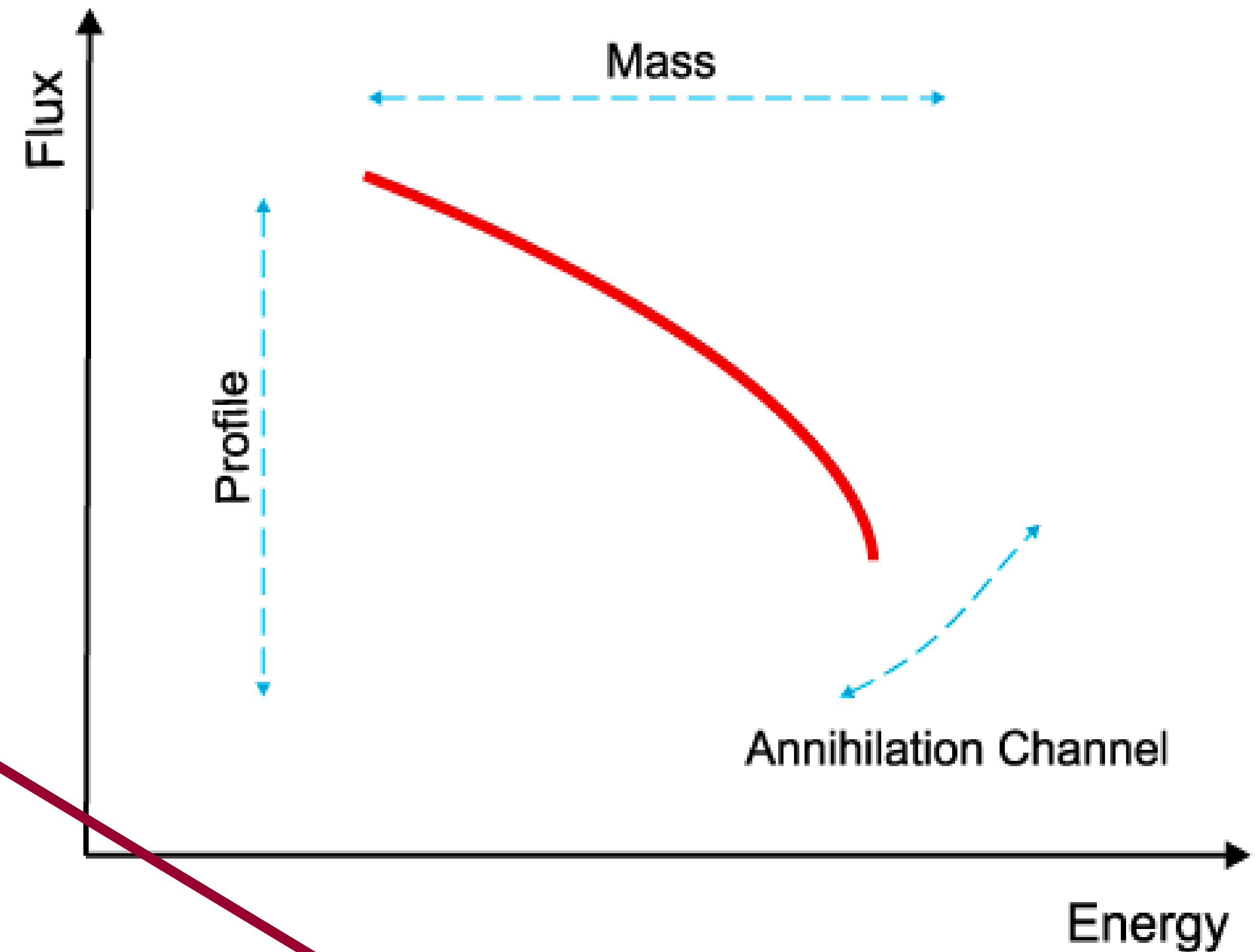

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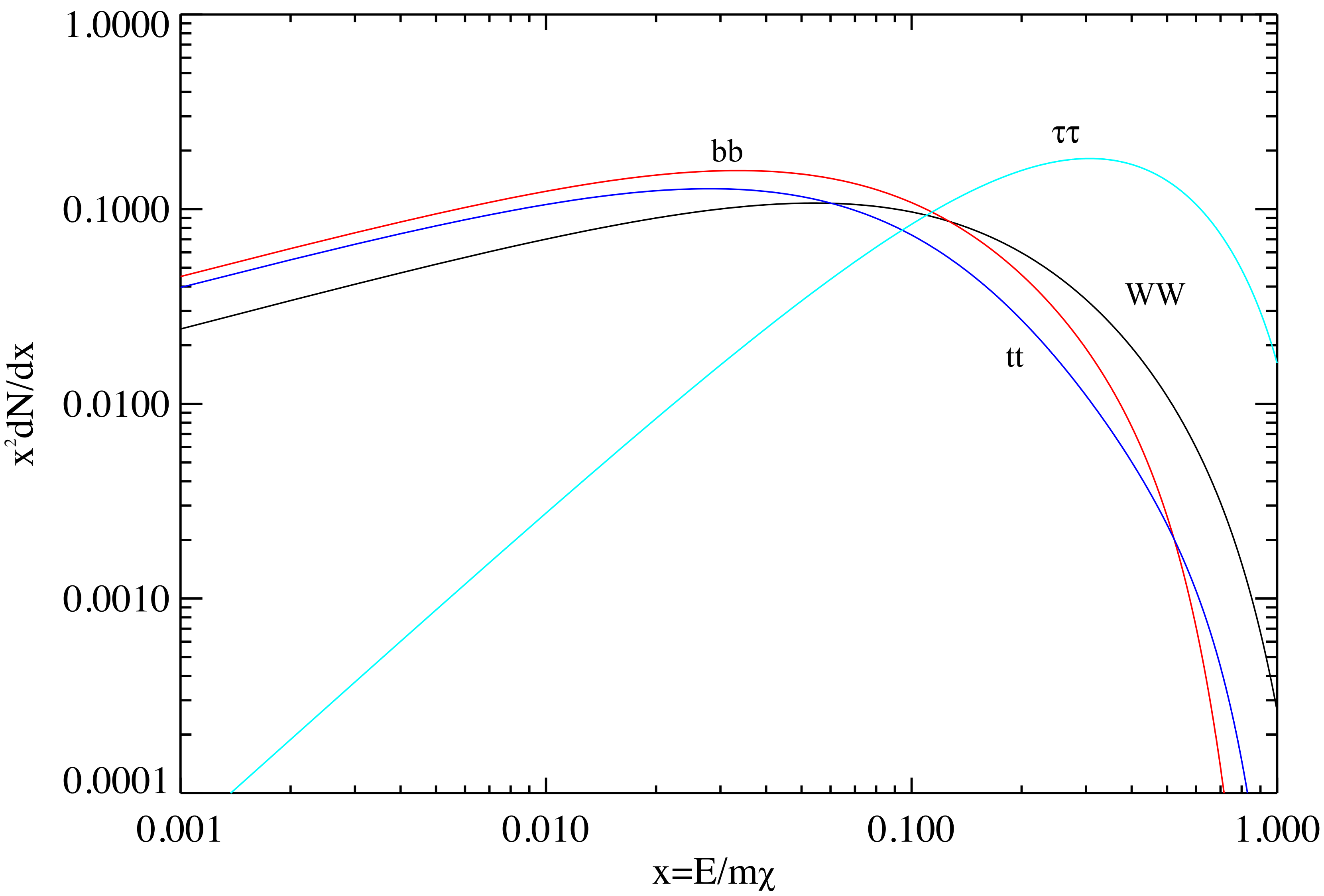
Dark matter photon spectra

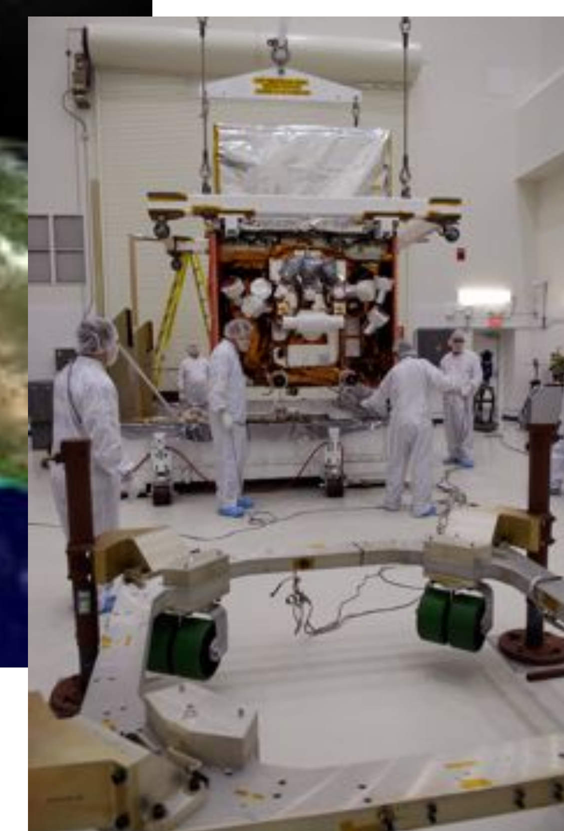
- soft channels produce a continuum gamma-ray spectrum primarily from decay of neutral pions
- internal bremsstrahlung radiation from charged lepton final states (much harder)
- line emission ($\gamma\gamma$, $Z\gamma$)



The Fermi Large Area Telescope (LAT)

- pair-production detector: detects charged particles as well as gamma rays
- excellent charged particle event identification and background rejection
- 20 MeV to > 300 GeV
- angular resolution ~ 0.1 deg above 10 GeV
- uniform sky exposure of ~ 30 mins every 3 hrs

Credit: NASA/General Dynamics



The Fermi LAT gamma-ray sky

3-year all-sky map
E > 1 GeV

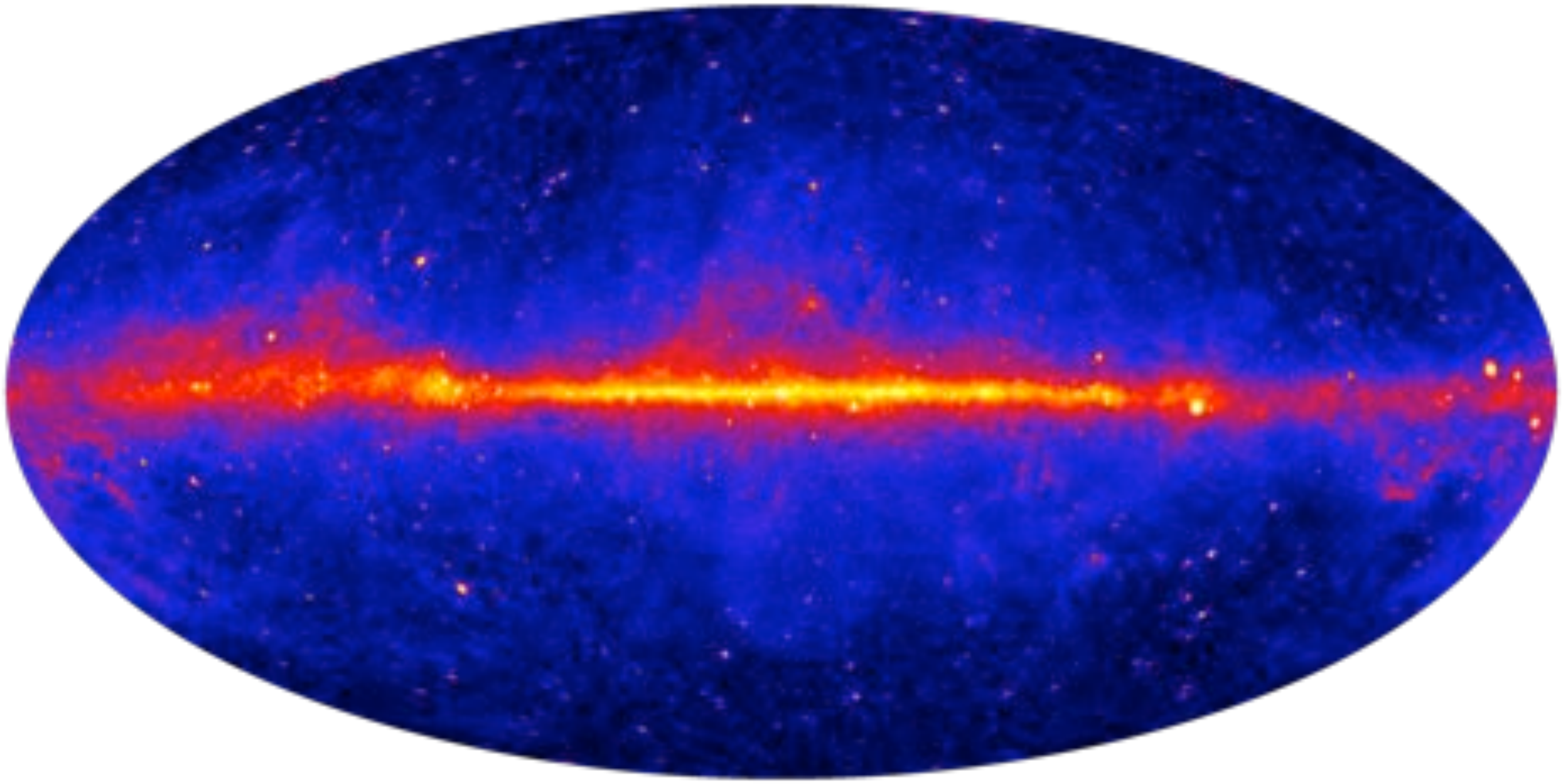


Image Credit: NASA/DOE/International LAT Team

Fermi LAT dark matter search targets

The Milky Way halo

The inner galaxy

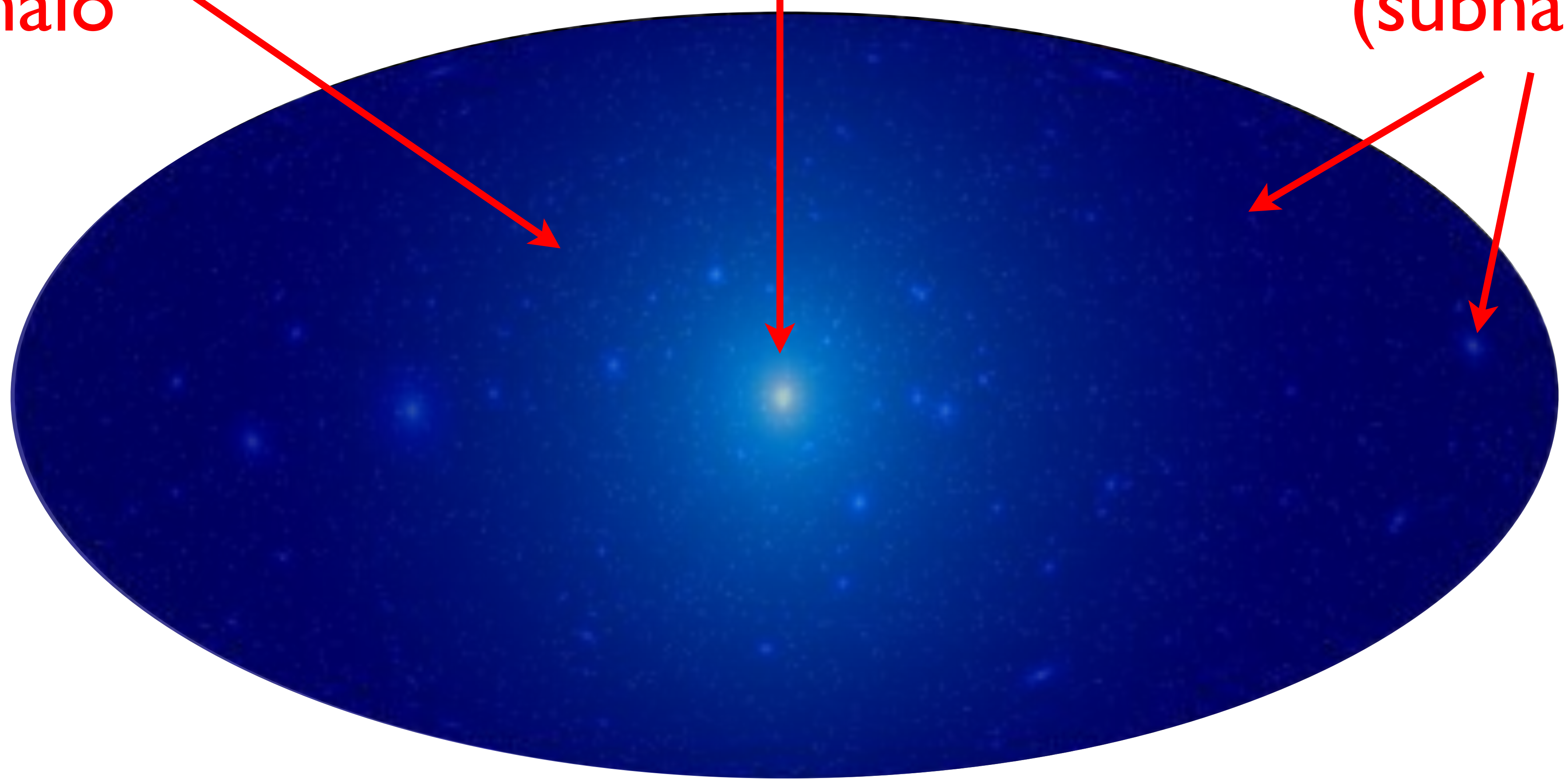
Unassociated sources (subhalos?)

Galaxy clusters

Dwarf galaxies

The Sun

Spectral lines



Gamma rays from dark matter annihilation

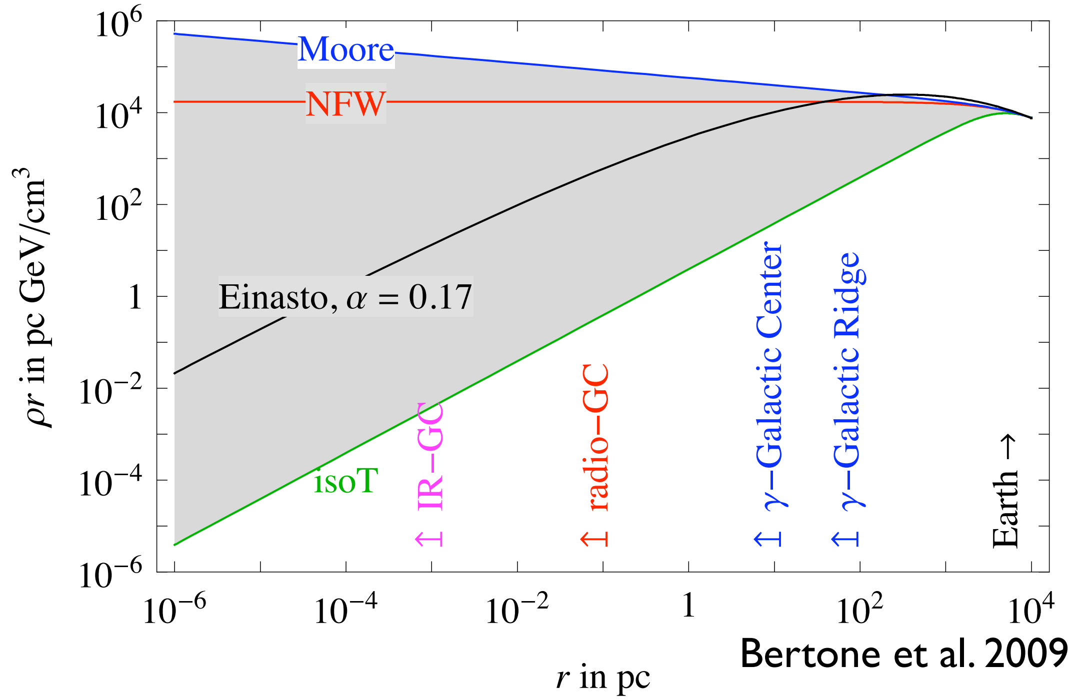
Cosmic-ray electrons and positrons

Anisotropies

The isotropic gamma-ray background

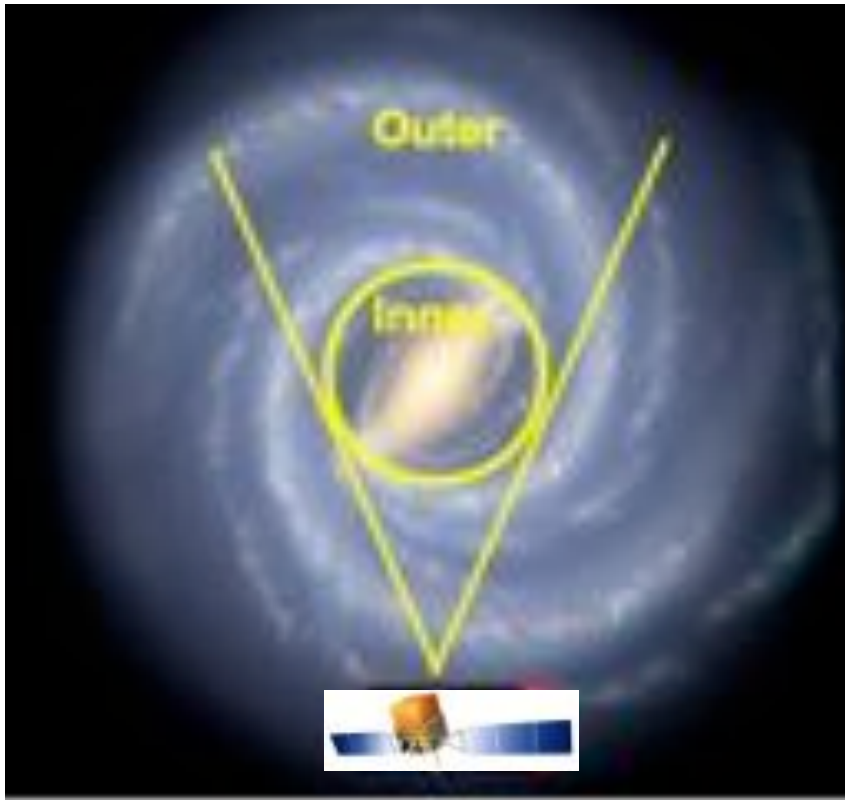
Dark matter in the inner galaxy

- steep inner density profiles predicted by CDM imply large annihilation (and decay) signals from the GC
- substantial sources of backgrounds make the inner galaxy a complex region of the sky:
  - source confusion: many energetic sources near to or in the line of sight of the GC
  - 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



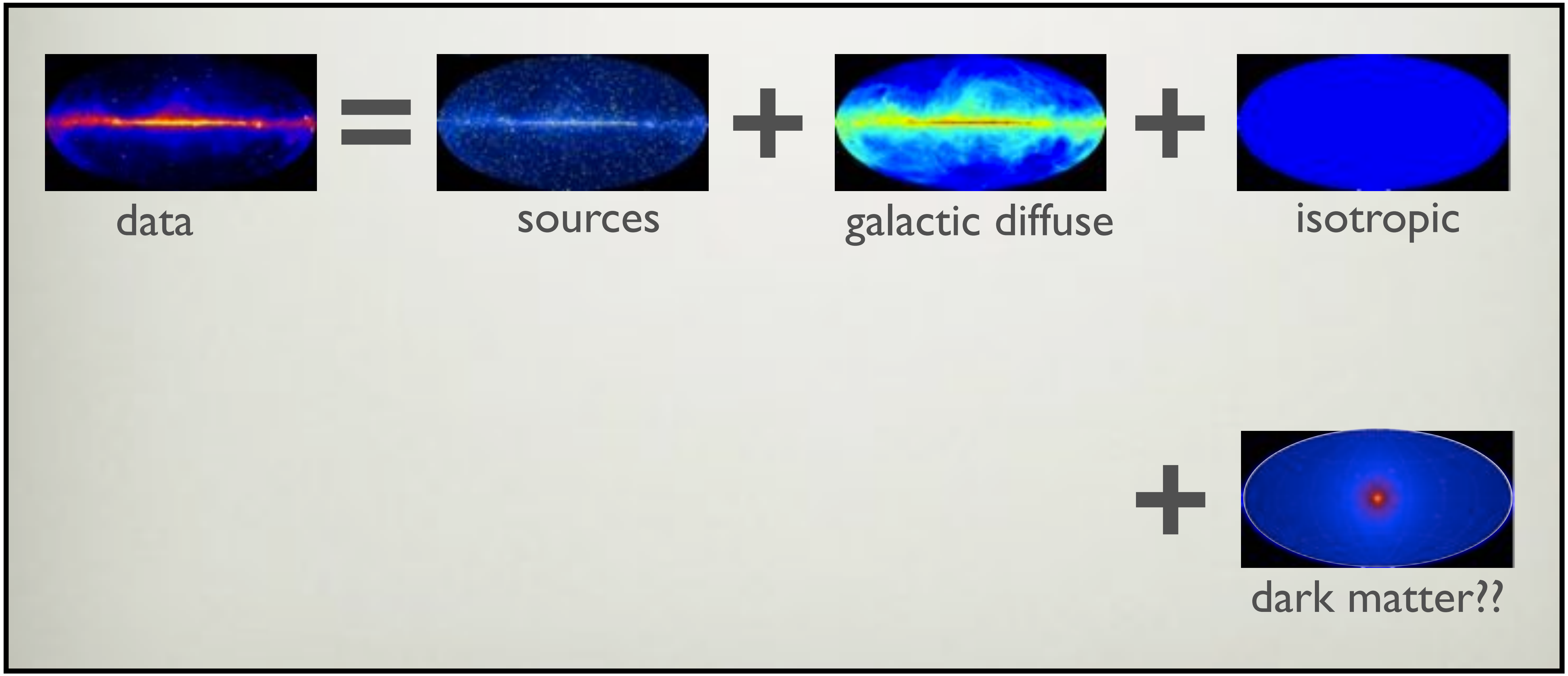
Bertone et al. 2009

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



see also: Hooper & Goodenough, Phys. Lett. B 697 (2011) 412-428; Abazajian JCAP 1103 (2011) 010

Modeling the inner galaxy

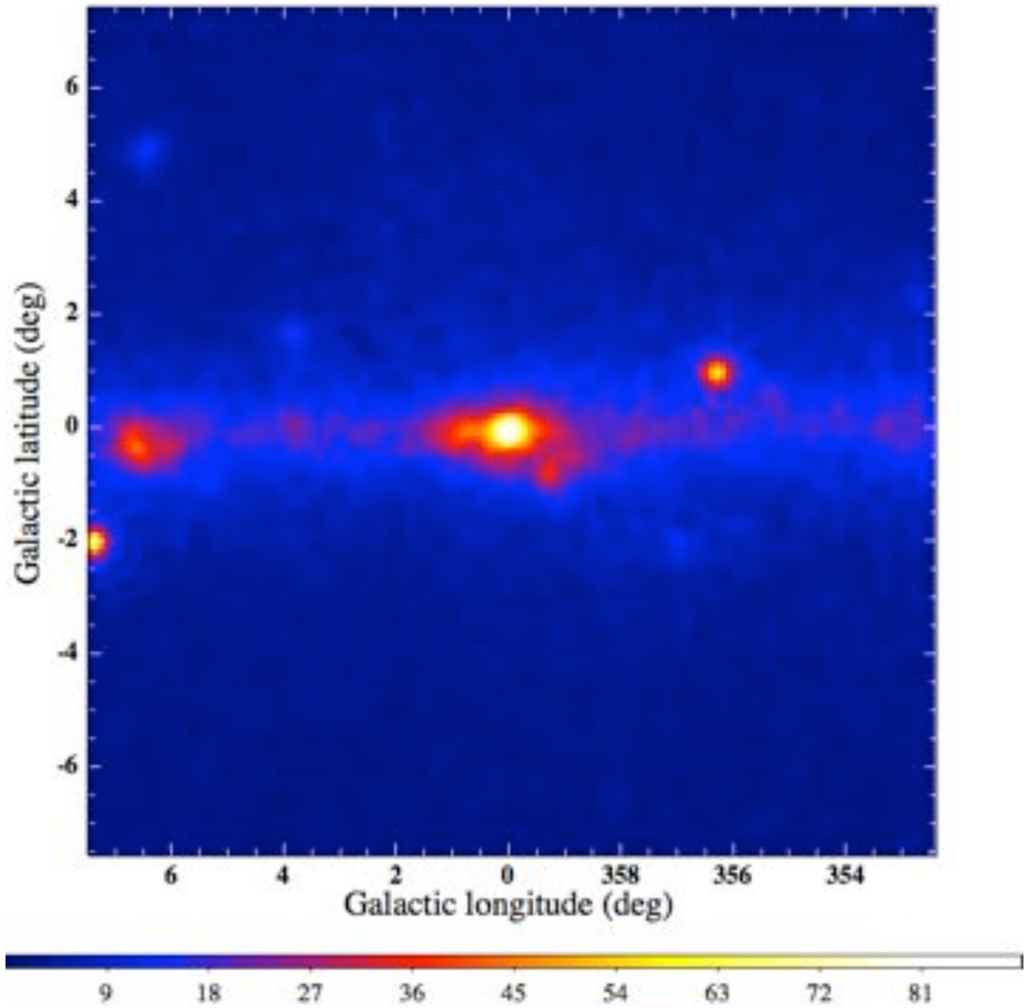


Fermi's view of the inner galaxy

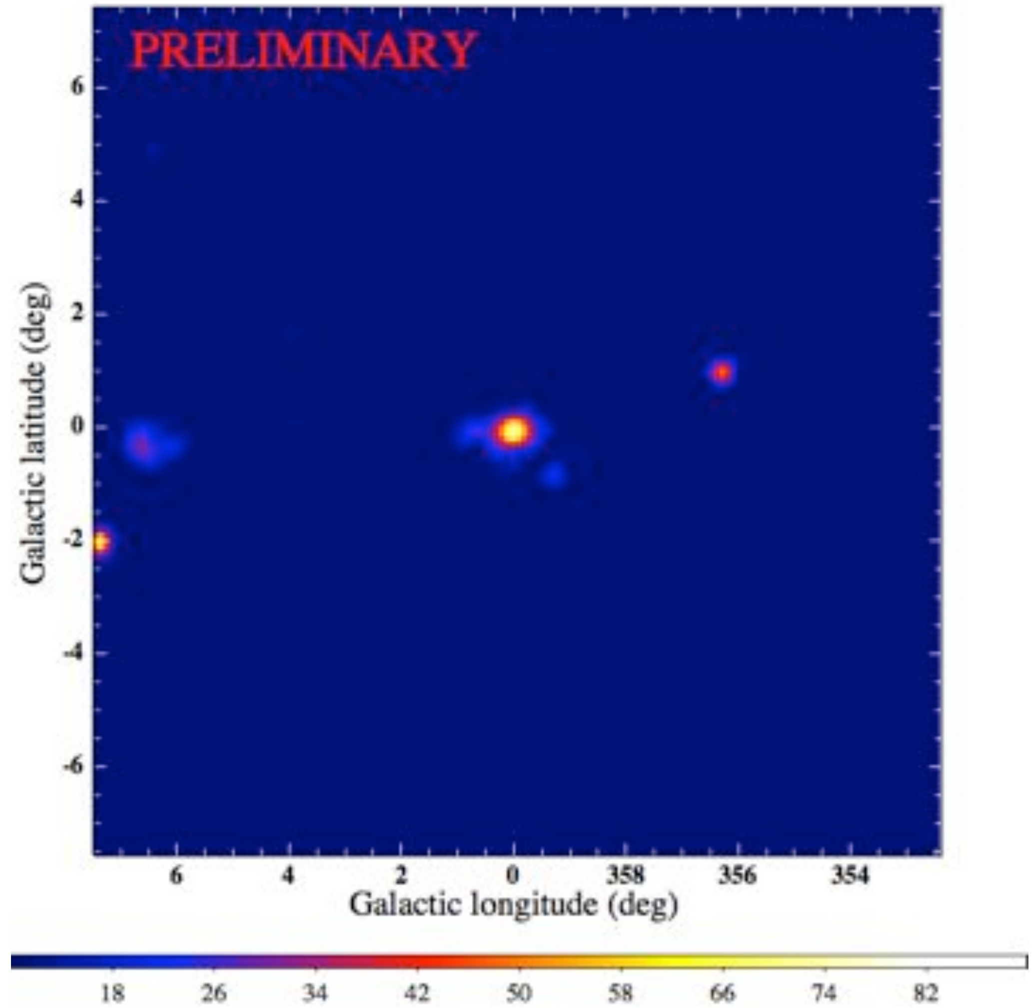
15° x 15° region

Fermi LAT preliminary results with 32 months of data, E>1 GeV (P7CLEAN_V6, FRONT):

DATA



DATA - MODEL (diffuse)



Galactic diffuse emission model = all-sky GALPROP model tuned to the inner galaxy

bright excesses after subtracting diffuse emission model are consistent with known sources

Fermi's view of the inner galaxy

15° x 15° region

Fermi LAT preliminary results with 32 months of data, E>1 GeV (P7CLEAN_V6, FRONT):

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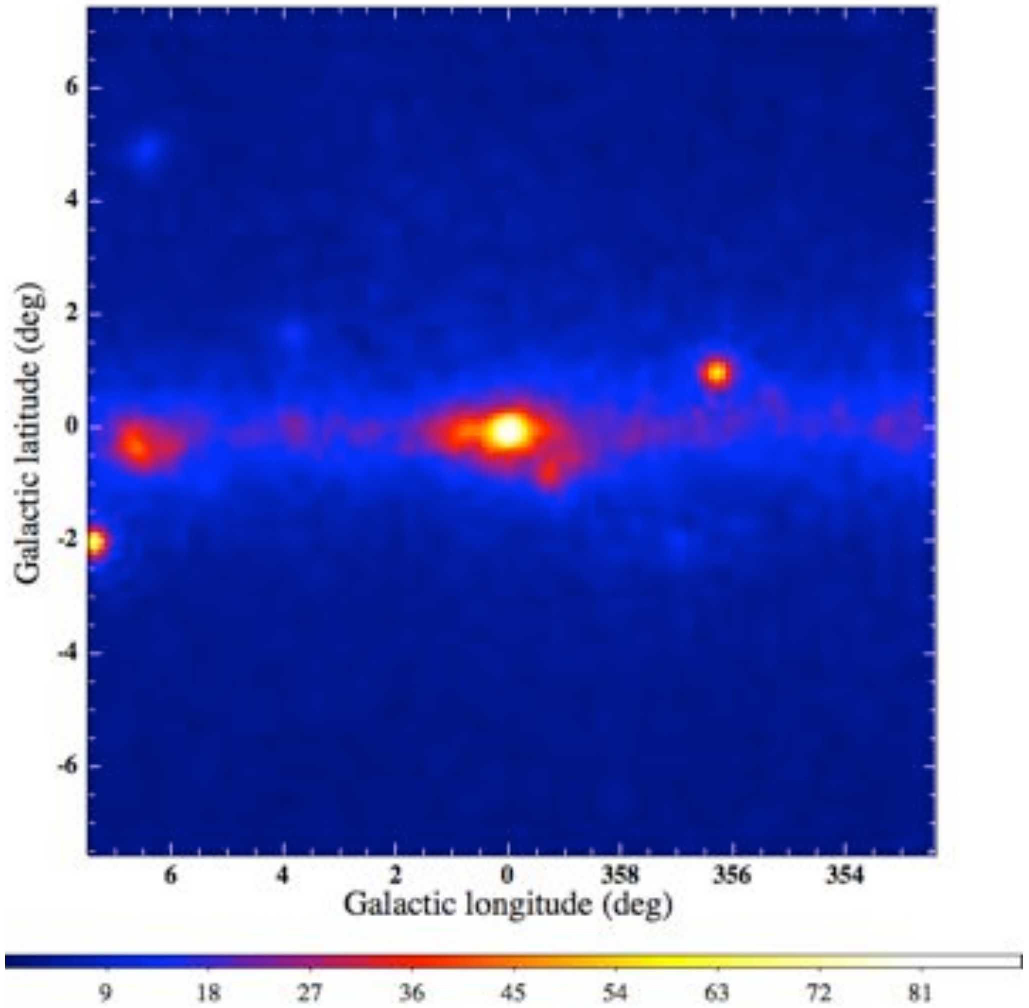
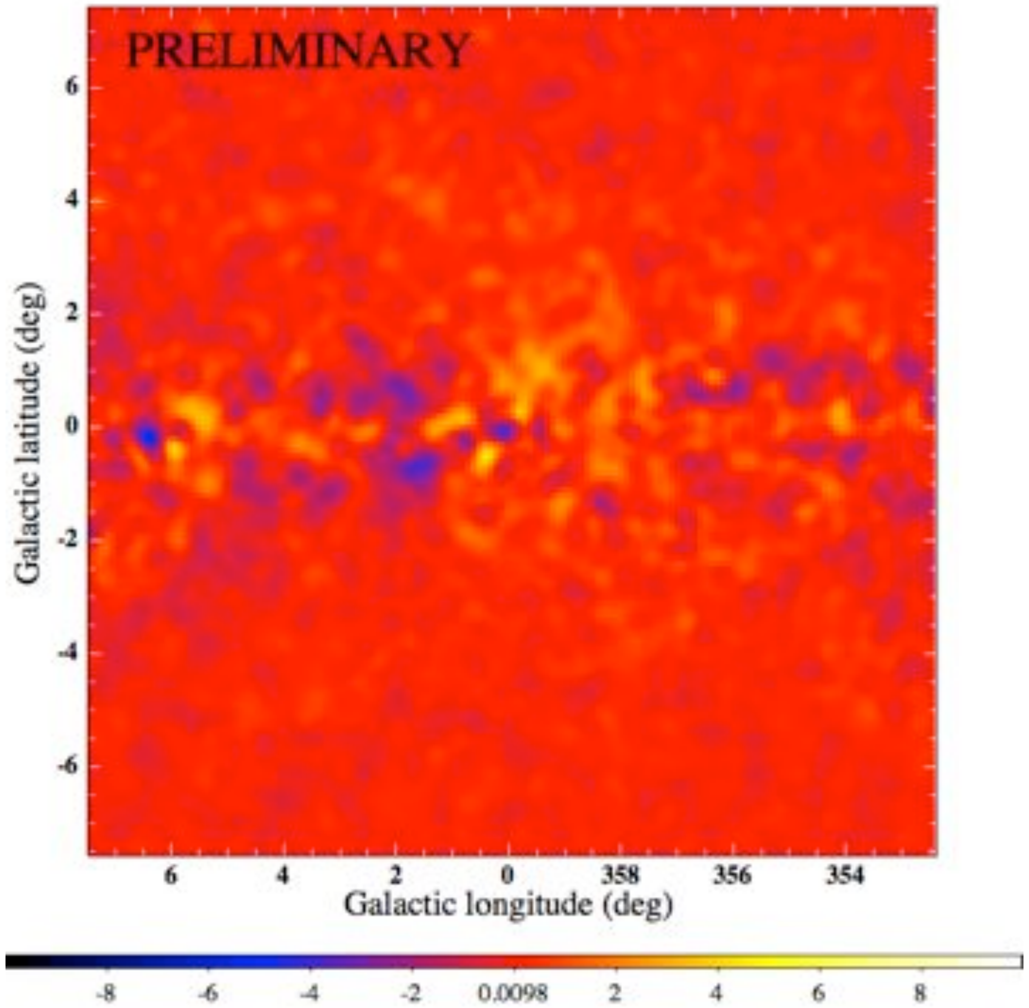


DATA - MODEL (diffuse+sources)

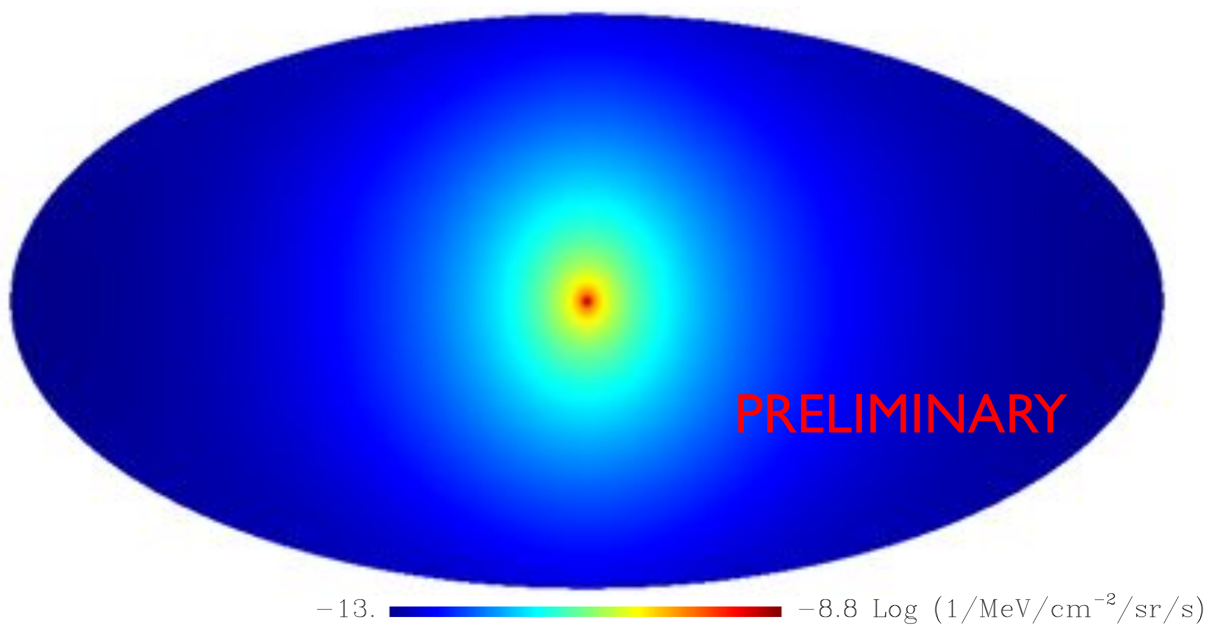


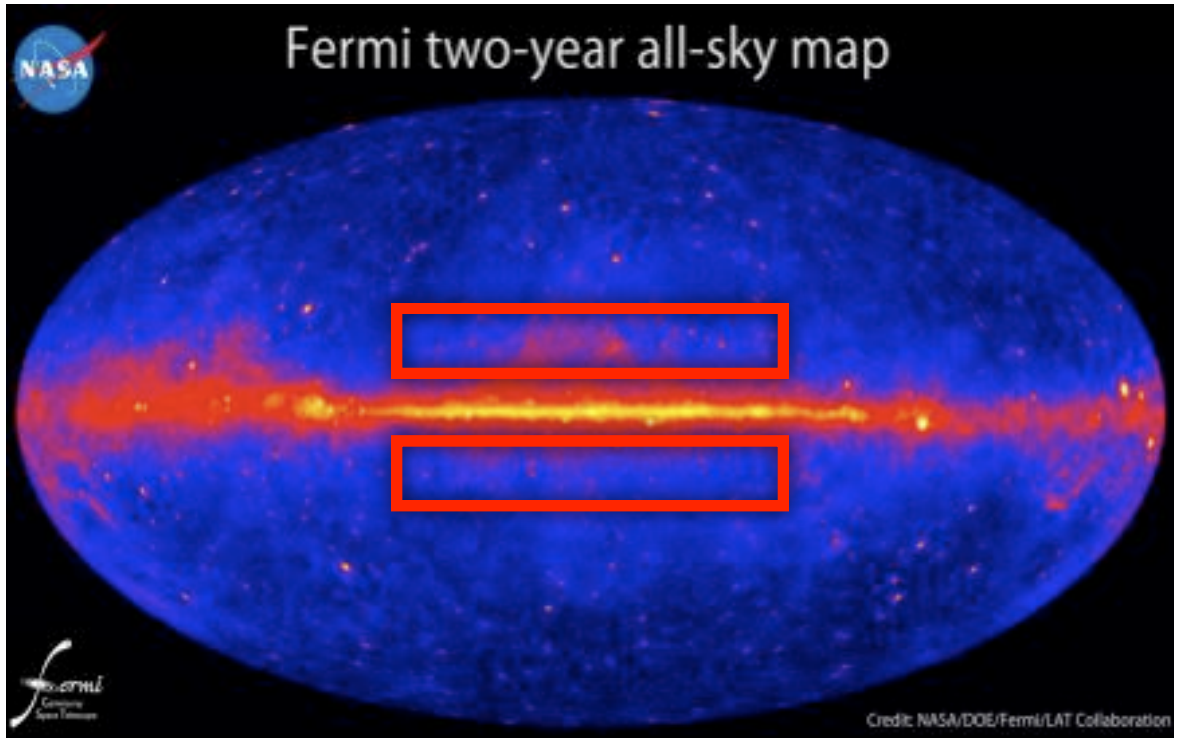
diffuse emission model and point sources account for most of the emission observed in the region

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





- 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 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:

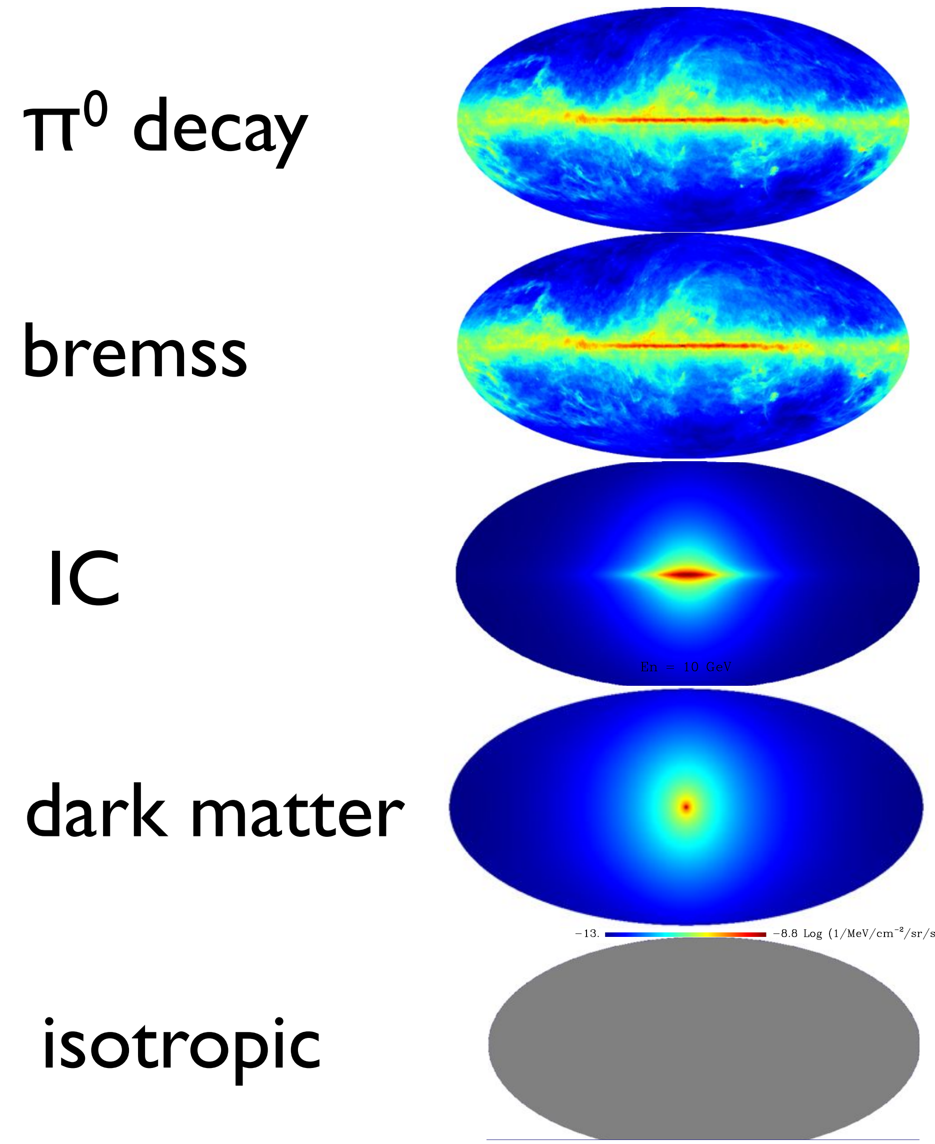
  $n_{DM} - 3(5)\ \sqrt{n_{DM}} > n_{data}$

  in at least one energy bin

Halo analysis: method 2

DM limits with simultaneous modeling of astrophysical signal:

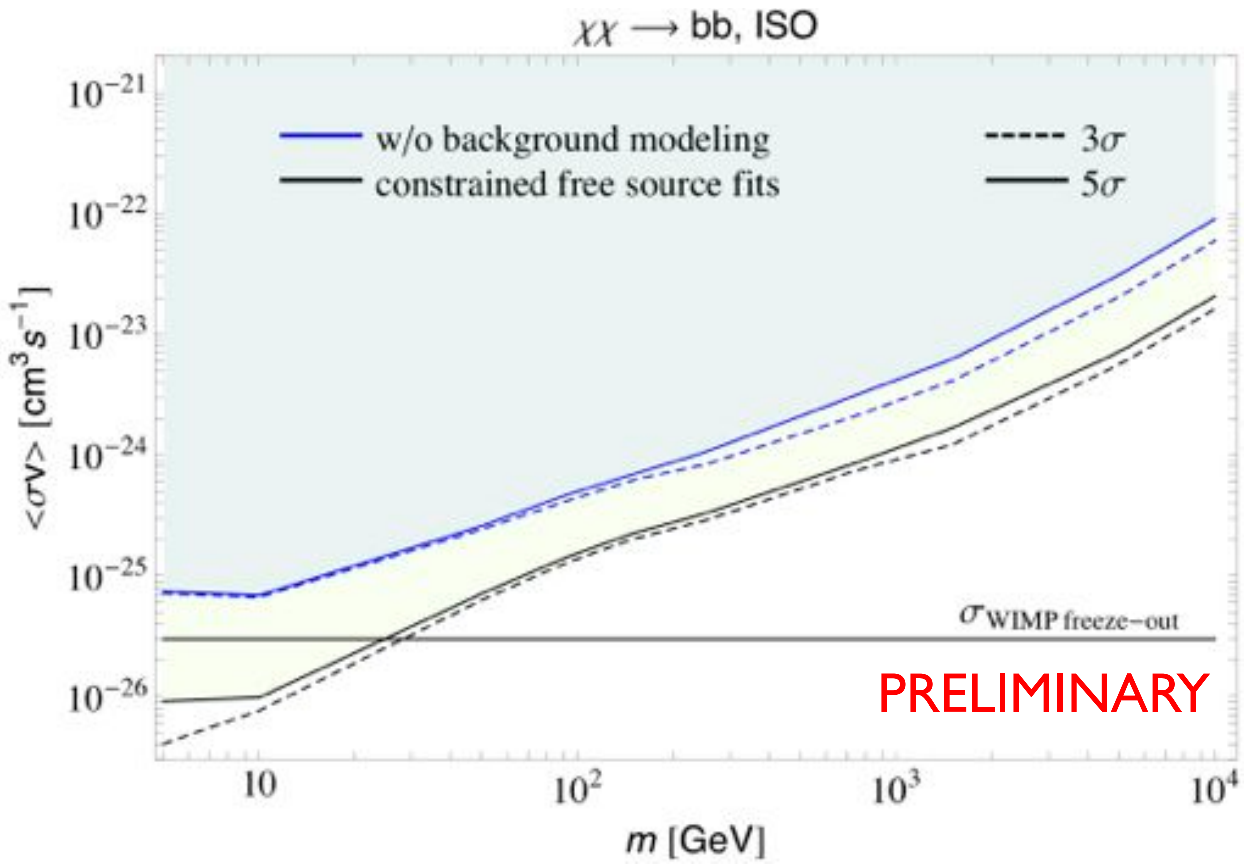
- uncertainties from diffusion models and gas maps taken into account by scanning over a grid of GALPROP models
- for each GALPROP (+DM) model, maps of different components of diffuse emission are generated and fit to the Fermi LAT data, incorporating both morphology and spectra
- the distribution of 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



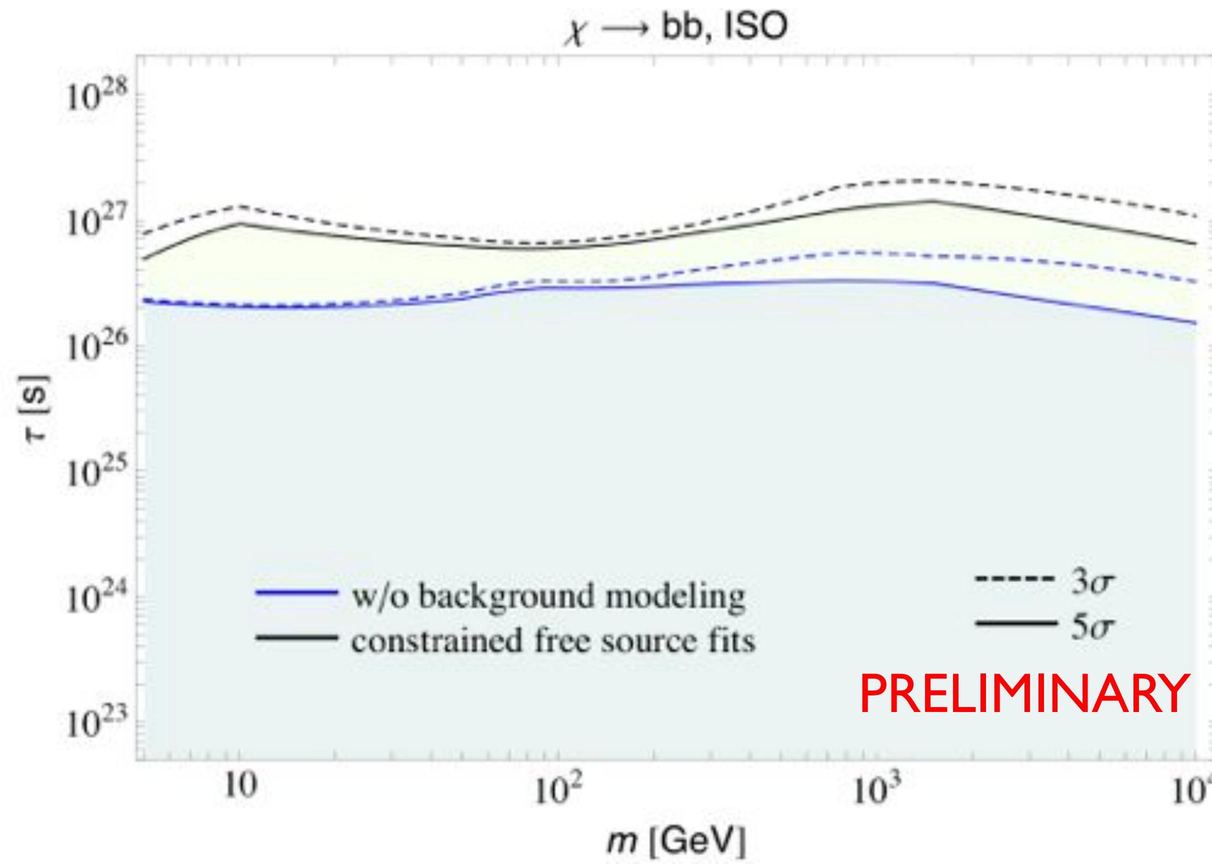
PRELIMINARY

Constraints from the halo: bb channel

Annihilation



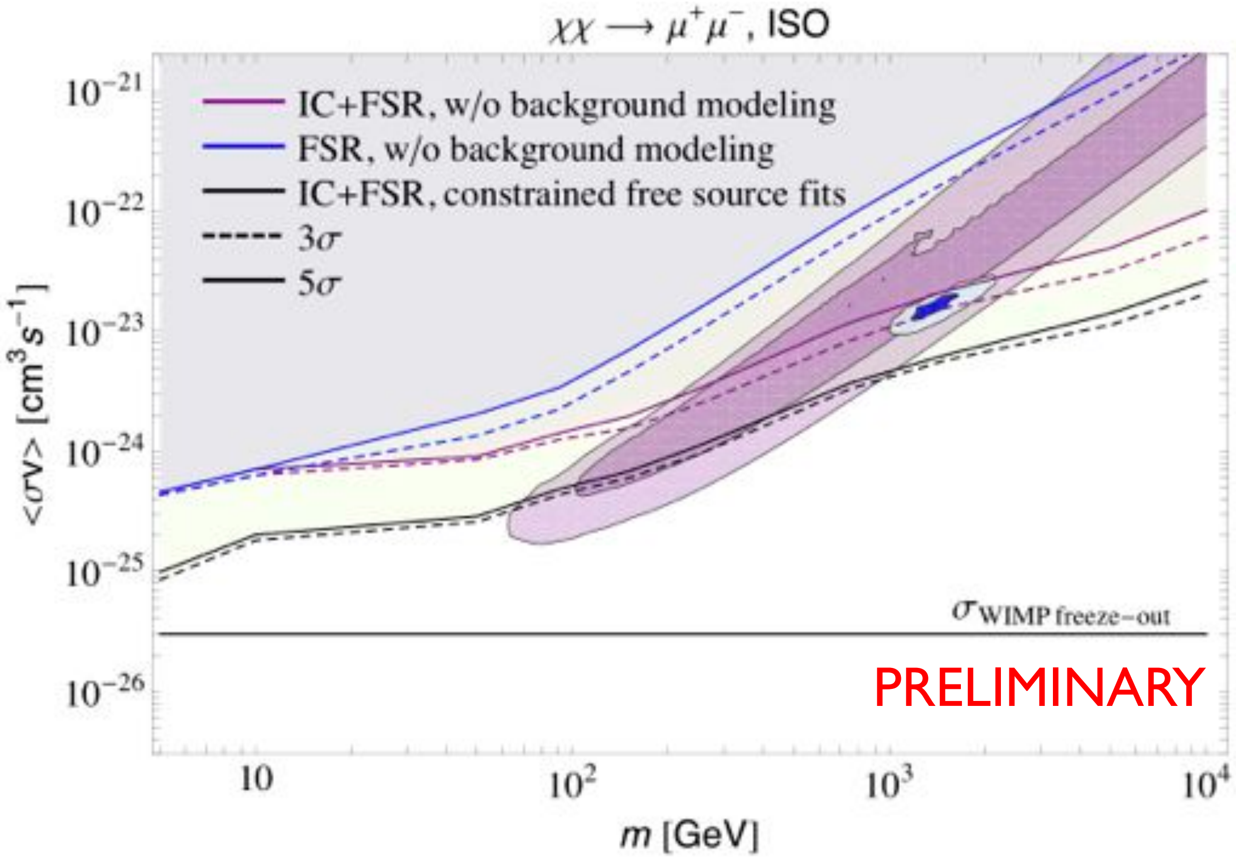
Decay



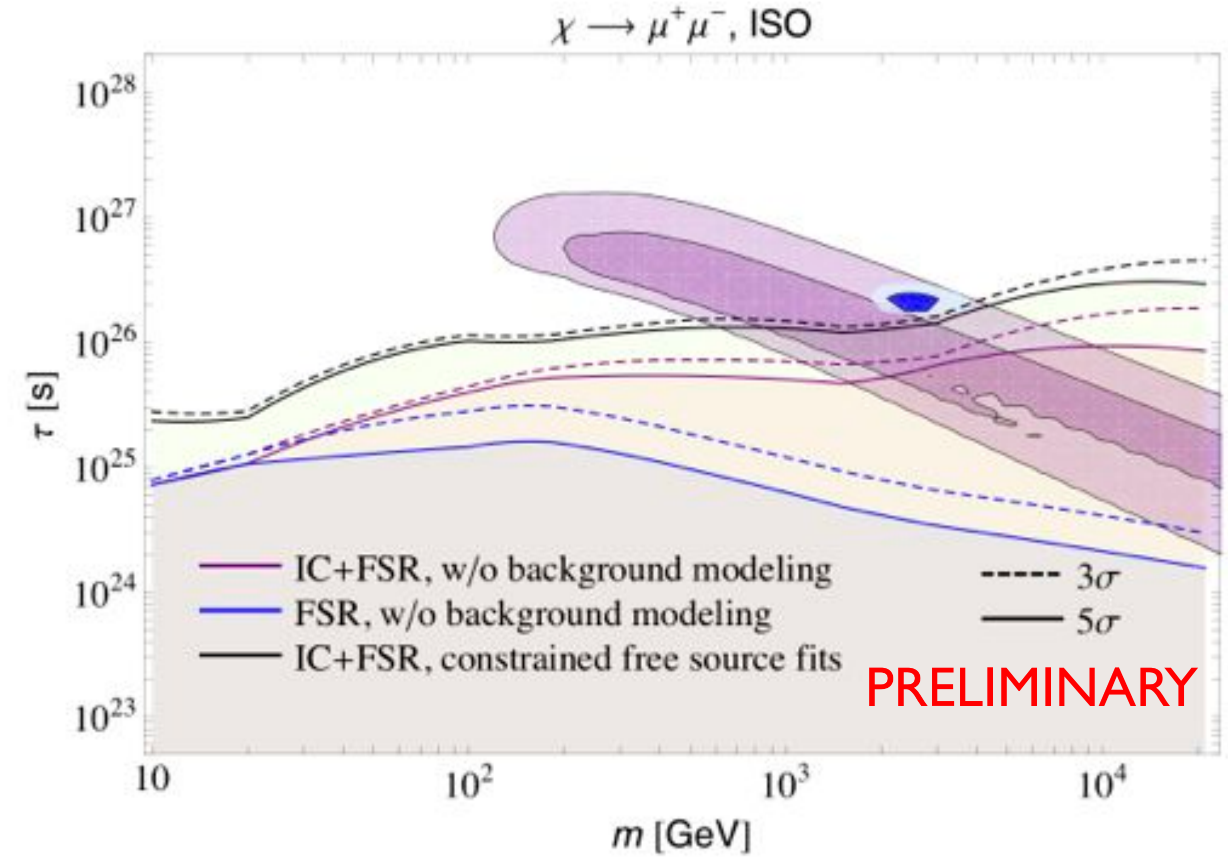
- blue = "no-background limits"
- black = limits obtained by marginalization over the CR source distribution, diffusive halo height and electron injection index, gas to dust ratio, and in which CR sources are held to zero in the inner 3 kpc
- limits with NFW density profile (not shown) are only slightly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

Constraints from the halo: μμ channel

Annihilation



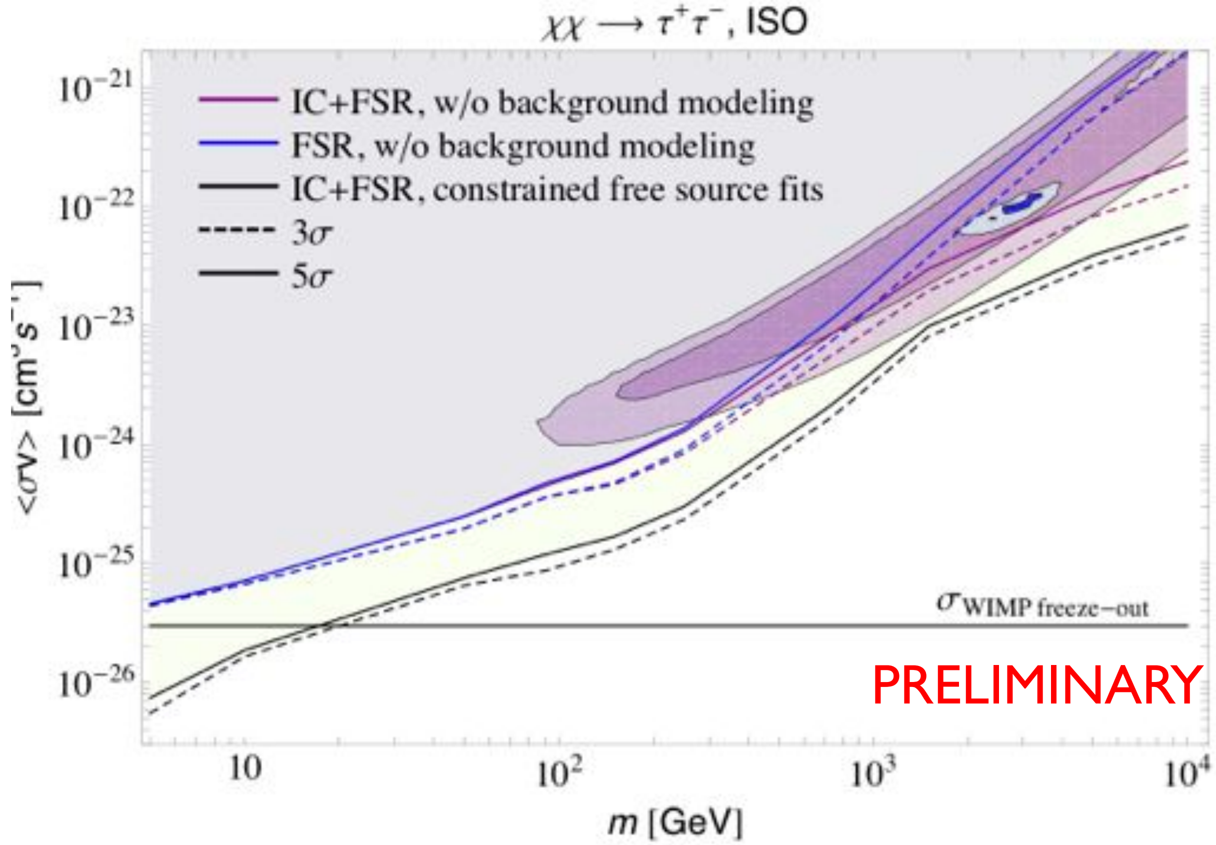
Decay



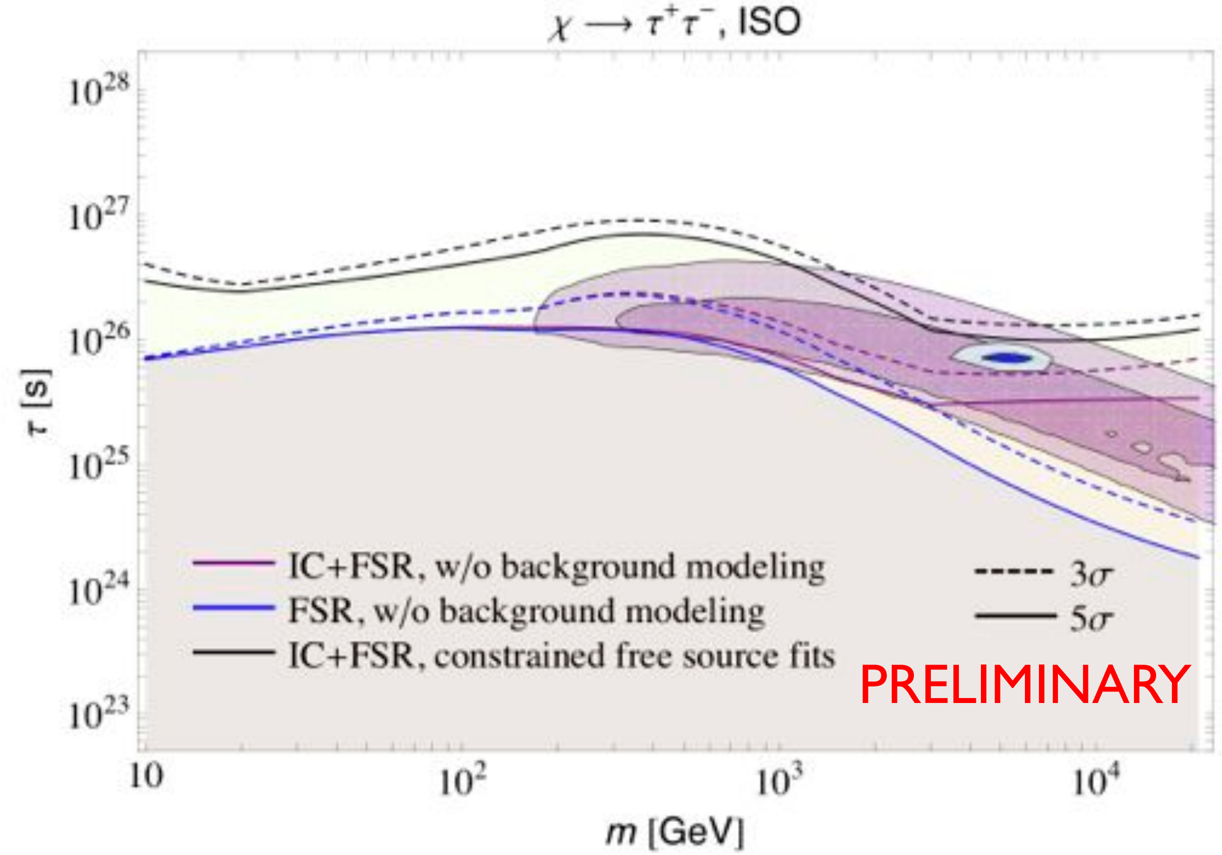
- blue = only photons produced by muons (no electrons) to set "no-background limits", i.e., only including Final State Radiation (FSR)
- violet = "no-background limits" including FSR + Inverse Compton (IC) from dark matter
- black: limits from profile likelihood and CR sources set to zero in the inner 3 kpc
- DM interpretation of PAMELA/Fermi CR anomalies strongly disfavored (for annihilating DM)

Constraints from the halo: $\tau\tau$ 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
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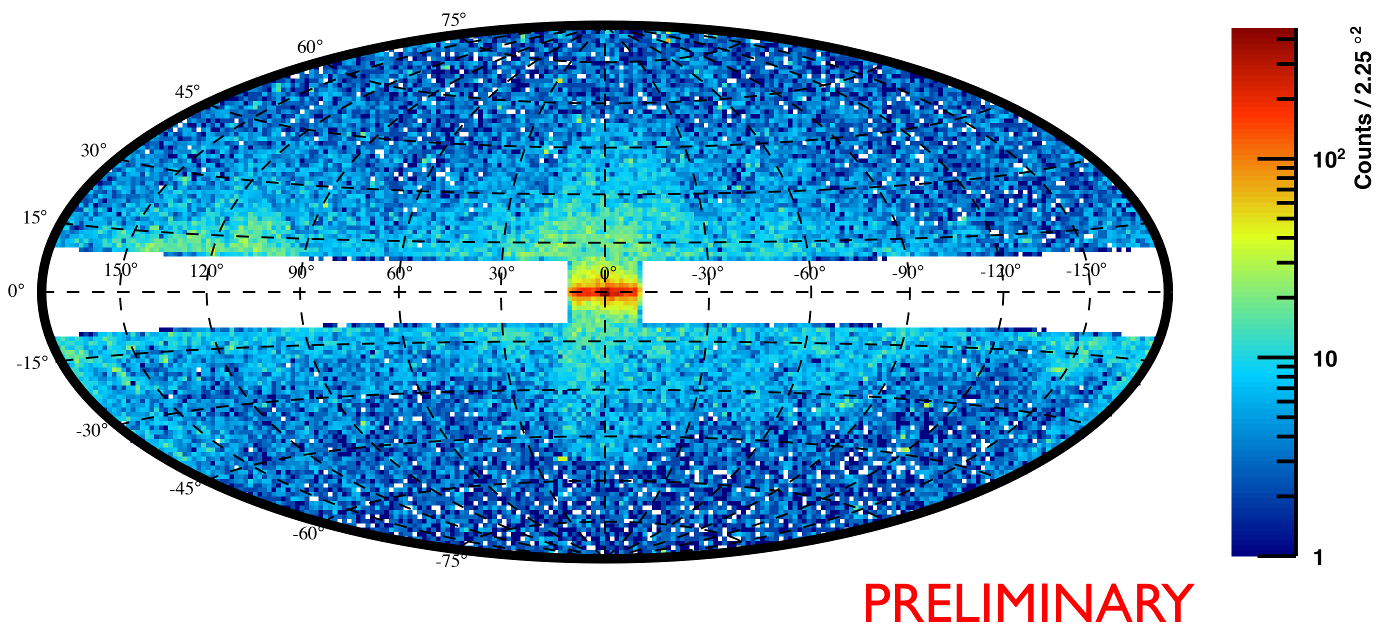
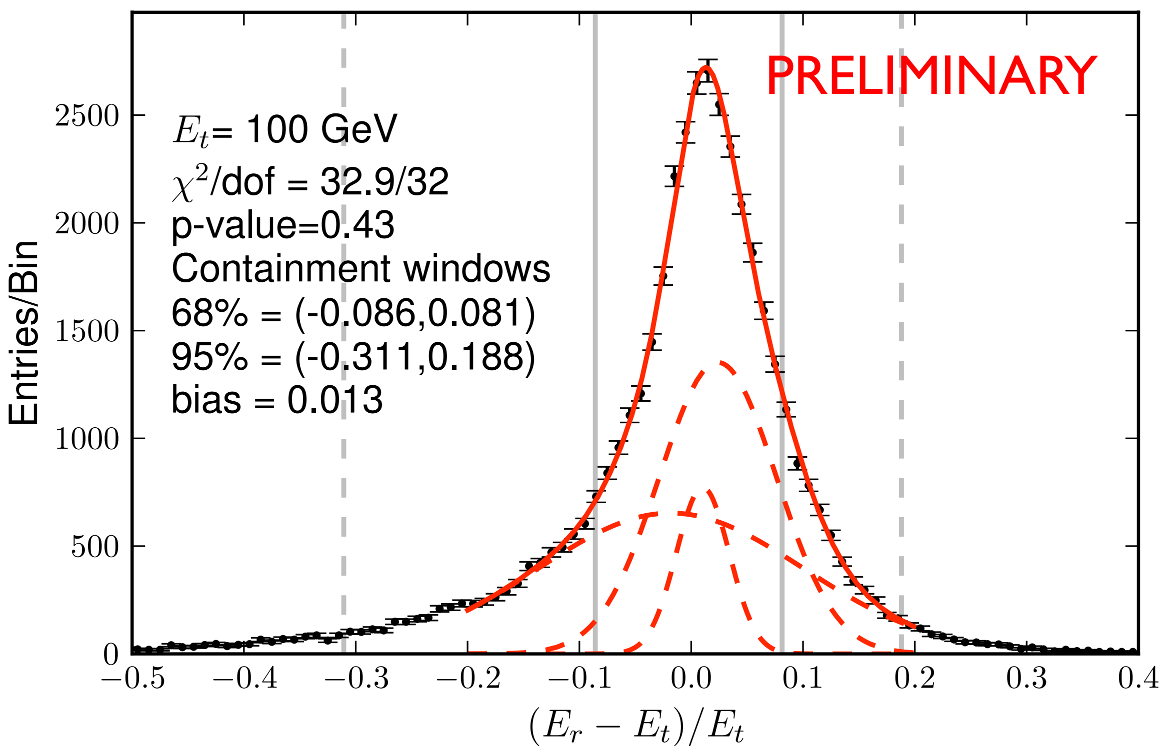
Search for spectral lines

Region-of-interest for line search



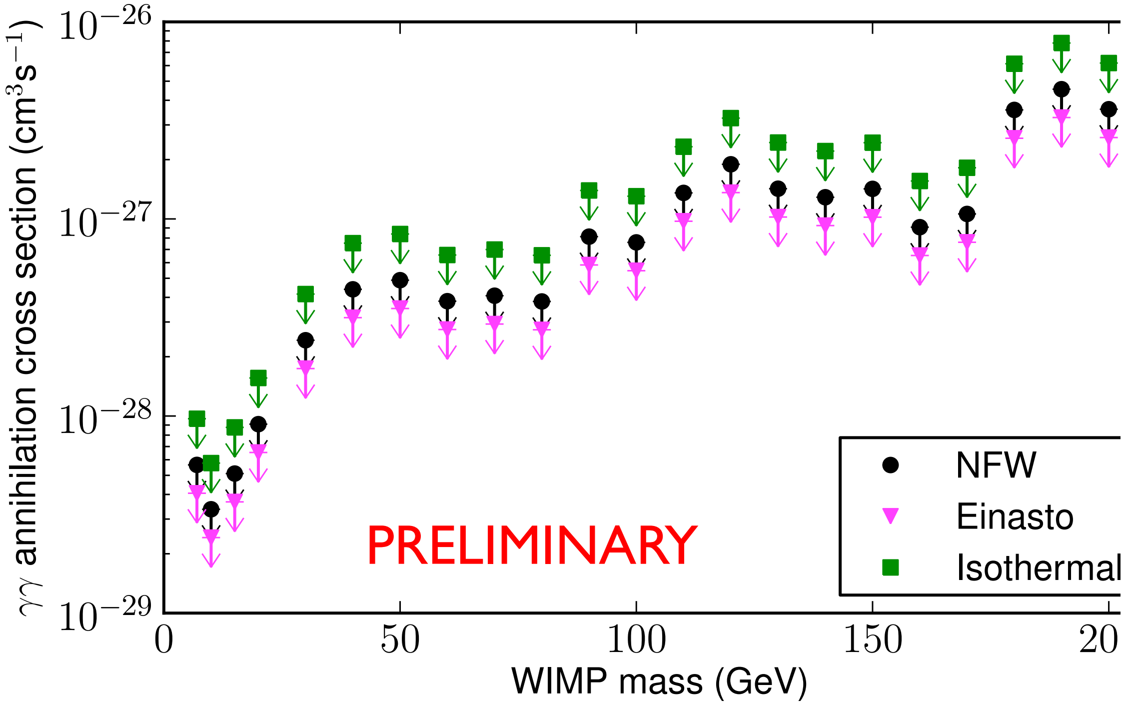
LAT energy response to 100 GeV line

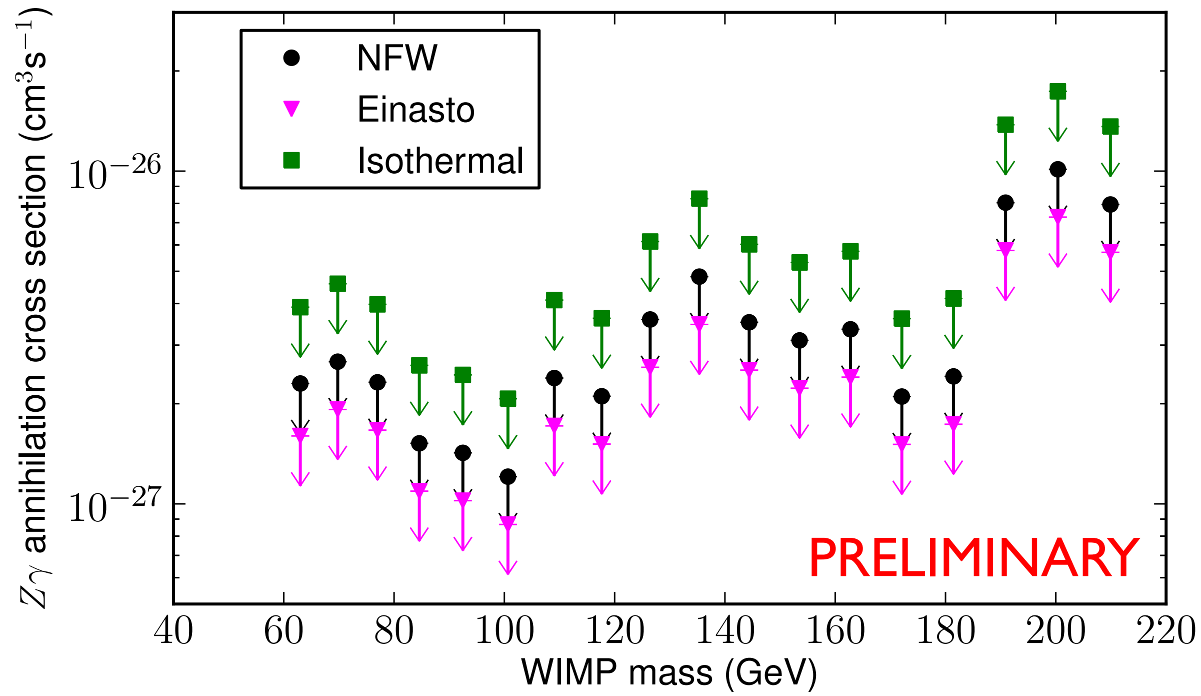


- search for line emission from dark matter annihilation or decay ($\gamma\gamma$ and $Z\gamma$ channels)
- exclude Galactic plane and 1FGL sources
- assume power-law background (spectral index free to vary) in each energy window

Constraints from line search

Annihilation cross-section constraints



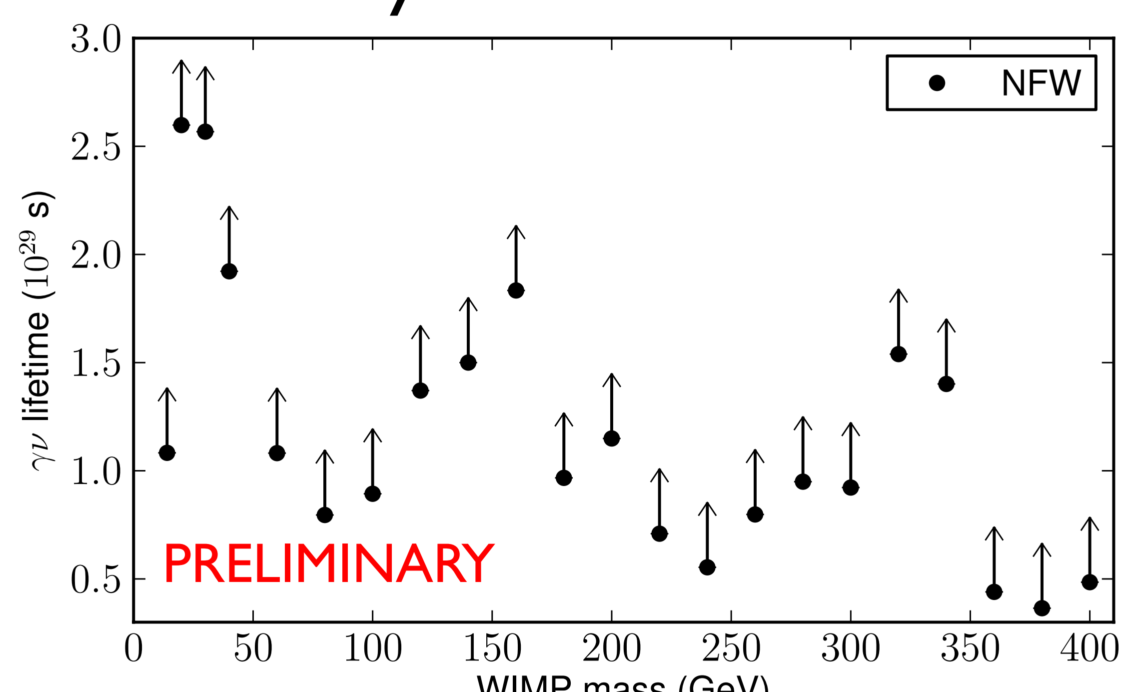


Ackermann et al. [Fermi LAT Collaboration], submitted to PRD

- non-detection places limits on annihilation cross section or decay lifetime to **γγ** and $Z\gamma$
- recent results in the literature claim detection of lines or hard spectral features consistent with DM predictions -- stay tuned!

see also: Vertongen & Weniger, JCAP 1105(2011)027; Bringmann et al., arXiv: 1203.1312

Decay lifetime constraints



Unassociated source analysis

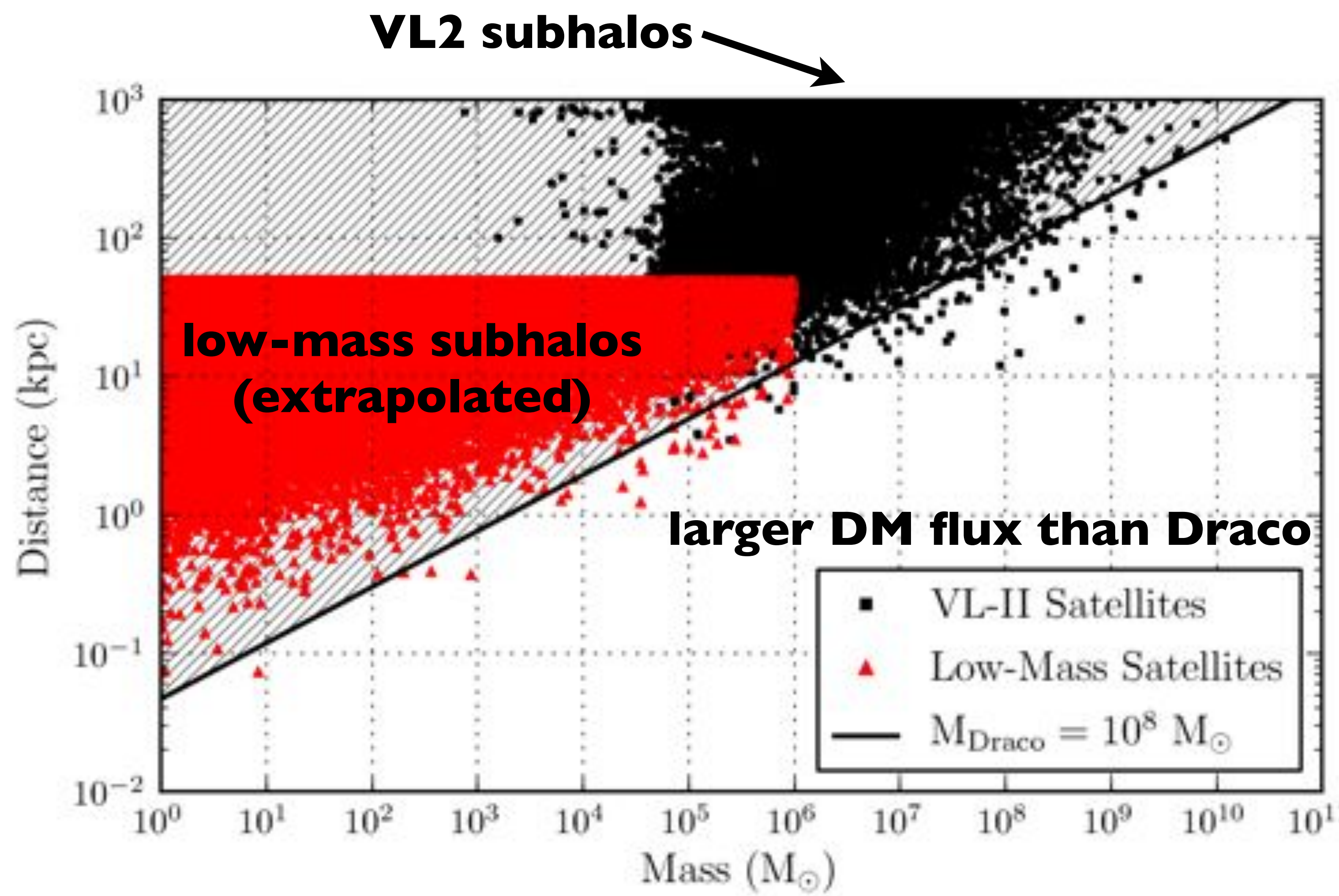
- dark matter satellites are expected to have
  - hard γ-ray spectra
  - finite angular extent
  - lack of counterparts at other wavelengths

no viable DM satellite candidates found in unassociated LAT sources using 1 year of data

- used N-body simulations to determine probability of not detecting viable sources to place constraints 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)

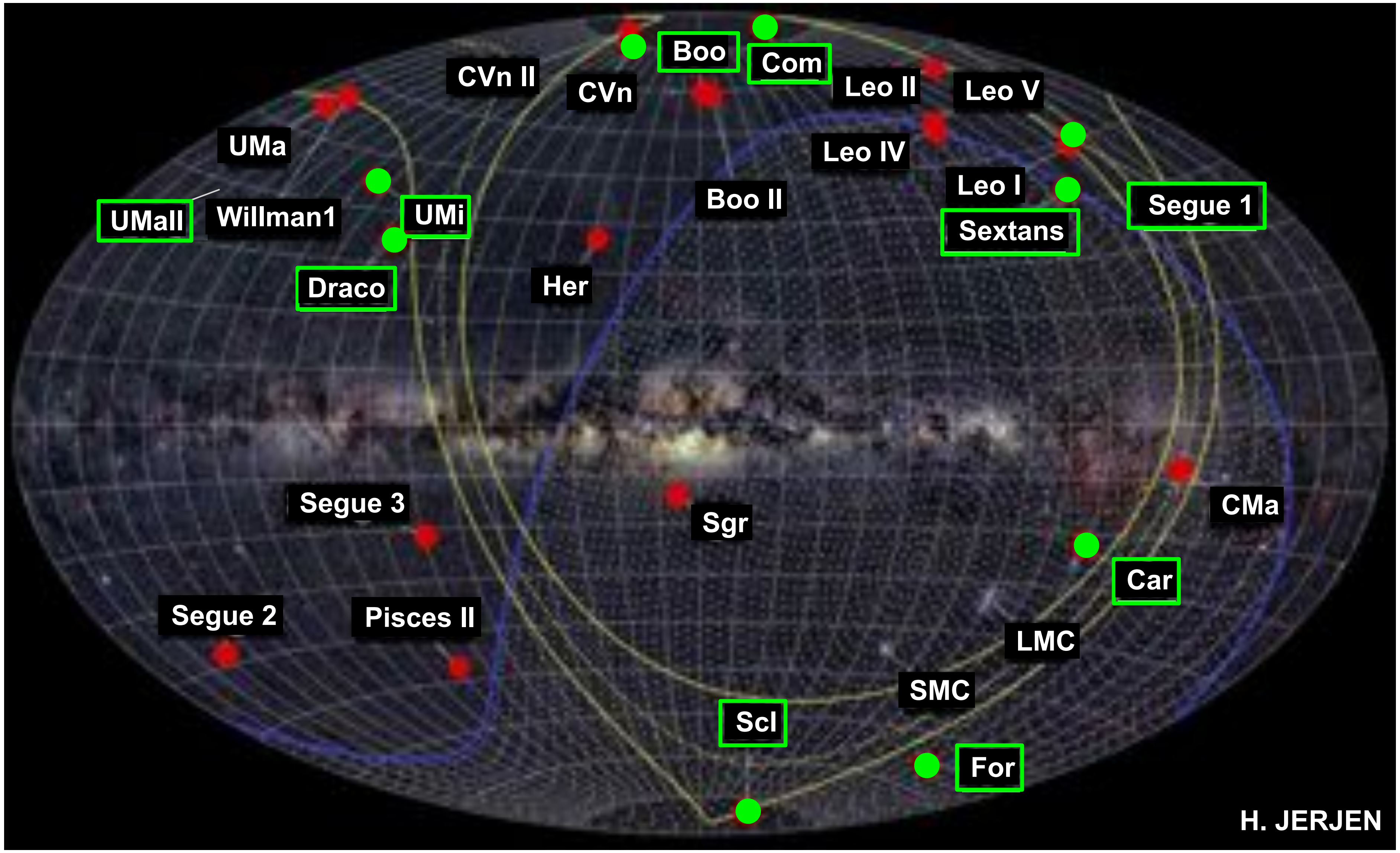


Ackermann et al. [Fermi LAT Collaboration], ApJ 747 (2012)121

Elliott Bloom's talk (Sunday)!

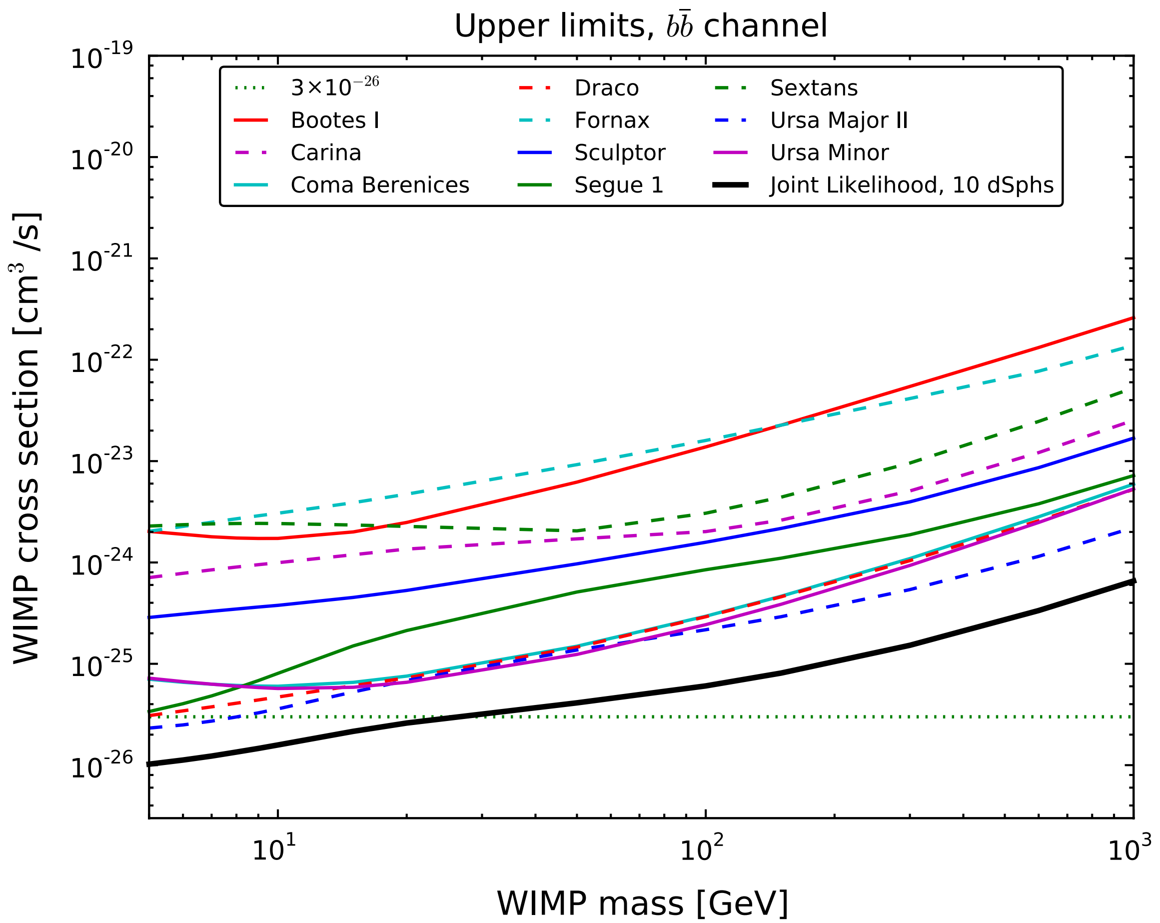
see also: Buckley & Hooper, PRD 82 (2010) 063501; Belikov et al., arXiv:1111.2613; Zechlin et al., arXiv:1111.3514

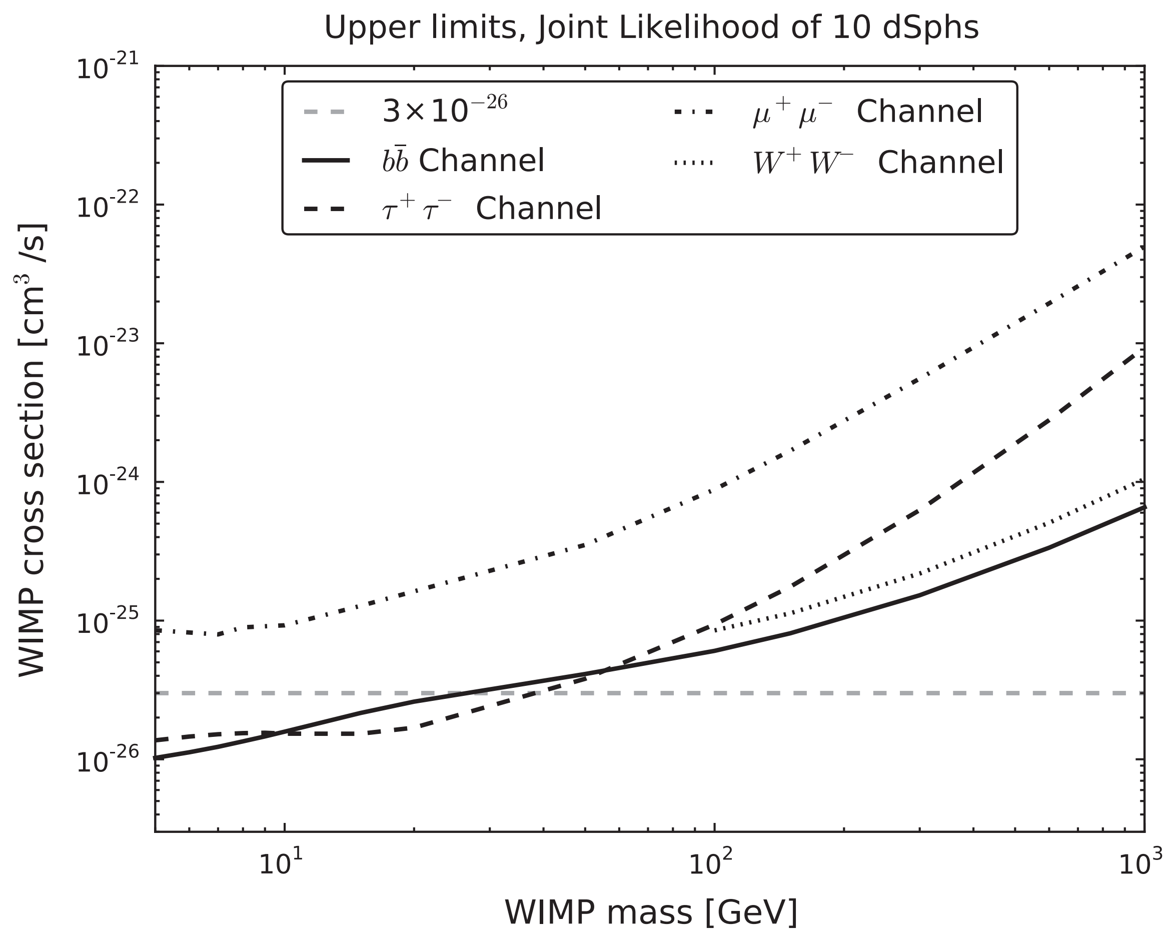
Search for gamma rays from dwarf galaxies



- there are roughly two dozen known dwarf spheroidal galaxies (dSphs) of the Milky Way
- some of the most dark-matter--dominated objects in the Universe
- no astrophysical gamma-ray production expected

DM limits from combined analysis of dSphs





M. Ackermann et al. [Fermi LAT Collaboration], PRL 107, 241302 (2011)

Joint likelihood analysis of Fermi LAT data:

- 10 dwarf galaxy targets
- 2 years data, energy range: 200 MeV - 100 GeV, P6_V3_diffuse
- 4 annihilation channels
- incorporates statistical uncertainties in the solid-angle-integrated "J-factor"

  ("astrophysical factor" in the predicted signal, set by the dark matter distribution)

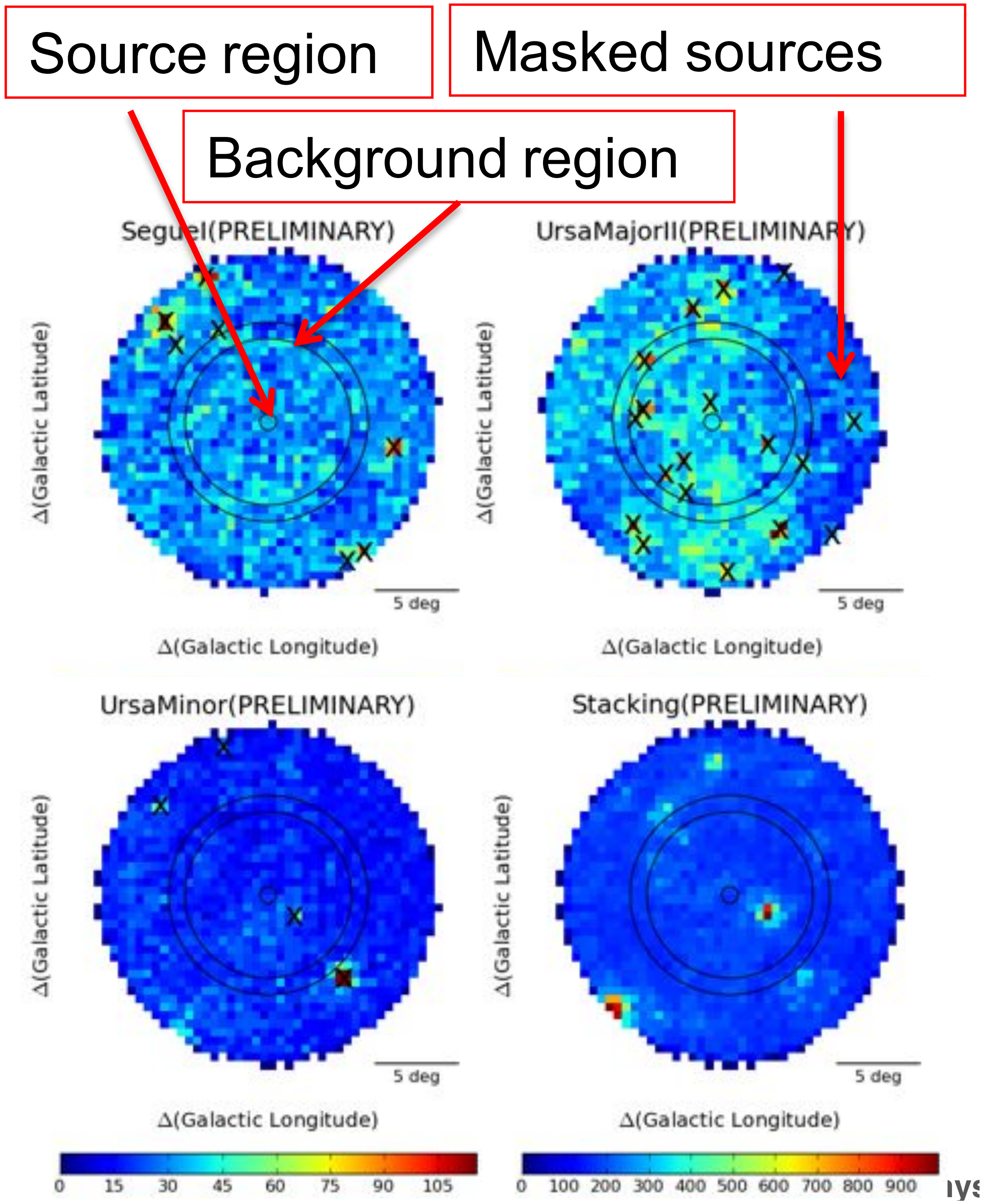
results exclude the canonical WIMP thermal relic cross-section for annihilation to $b\bar{b}$ or $\tau^+\tau^-$ for masses below ~ 30 GeV

Alex Drlica-Wagner's talk (Sunday)!

see also: Geringer-Sameth & Koushiappas, PRL 107, 241303 (2011); Cholis & Salucci, arXiv:1203.2954

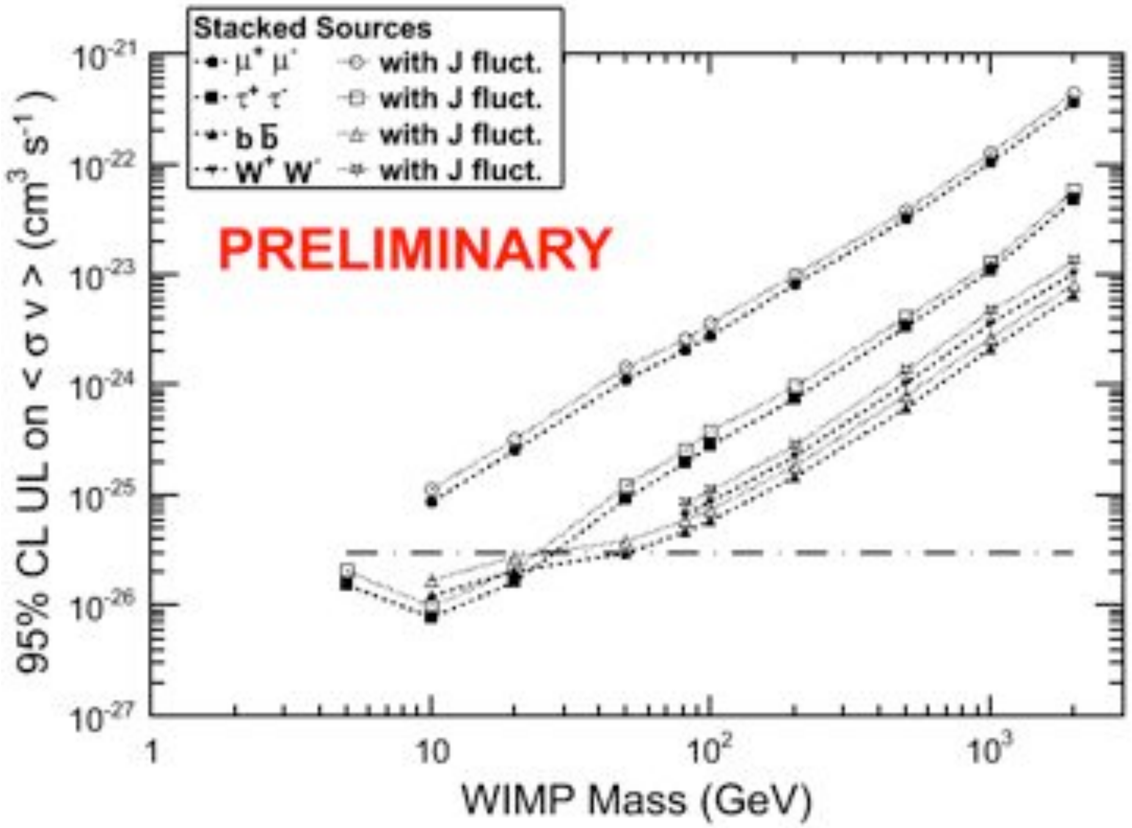
Model-independent dwarf analysis

- data set: 3 years of SOURCE_P7V6 data, 2FGL sources masked
- the background is evaluated in an annulus around each source (the diffuse model is not used)
- the expected gamma-ray flux from the DM was evaluated using the DMFIT package



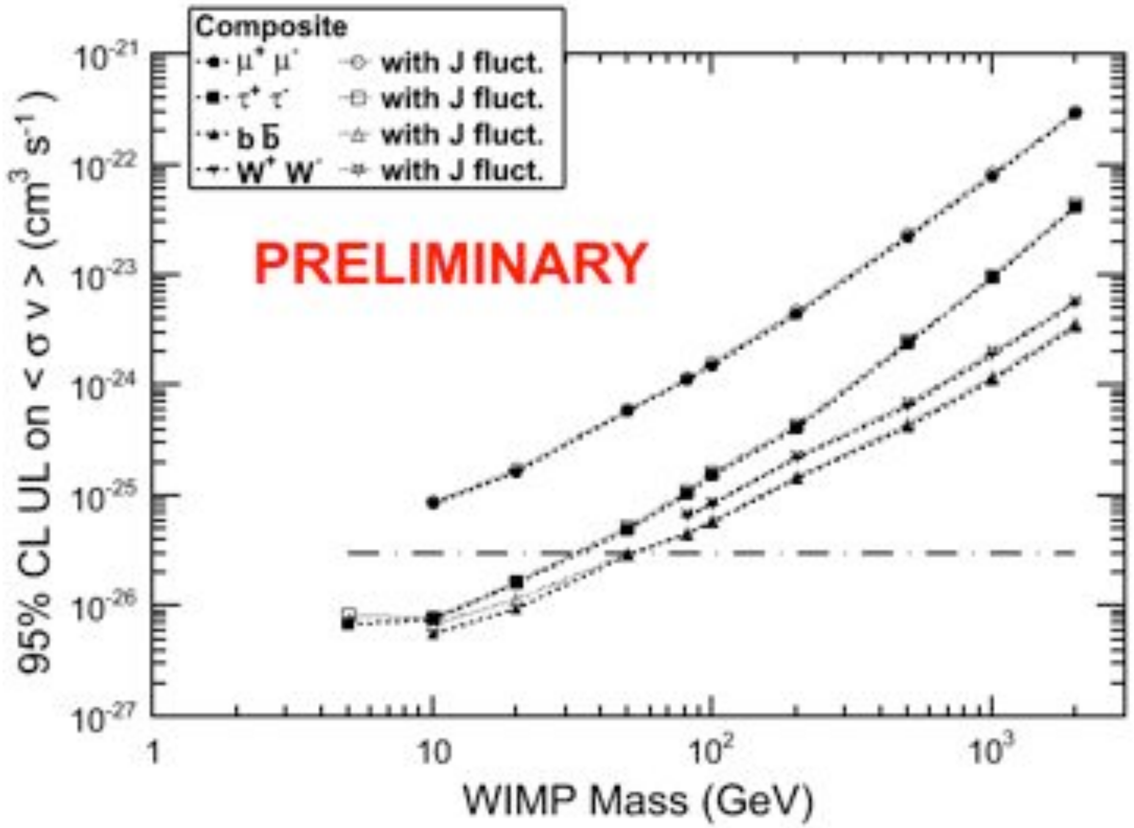
Model-independent limits from dwarfs

STACKING METHOD



- all 10 dSphs are stacked and the stacked J factor is determined by averaging weighting by the individual exposures
- standard Bayesian method for UL evaluation with a flat prior is used

COMPOSITE LIKELIHOOD

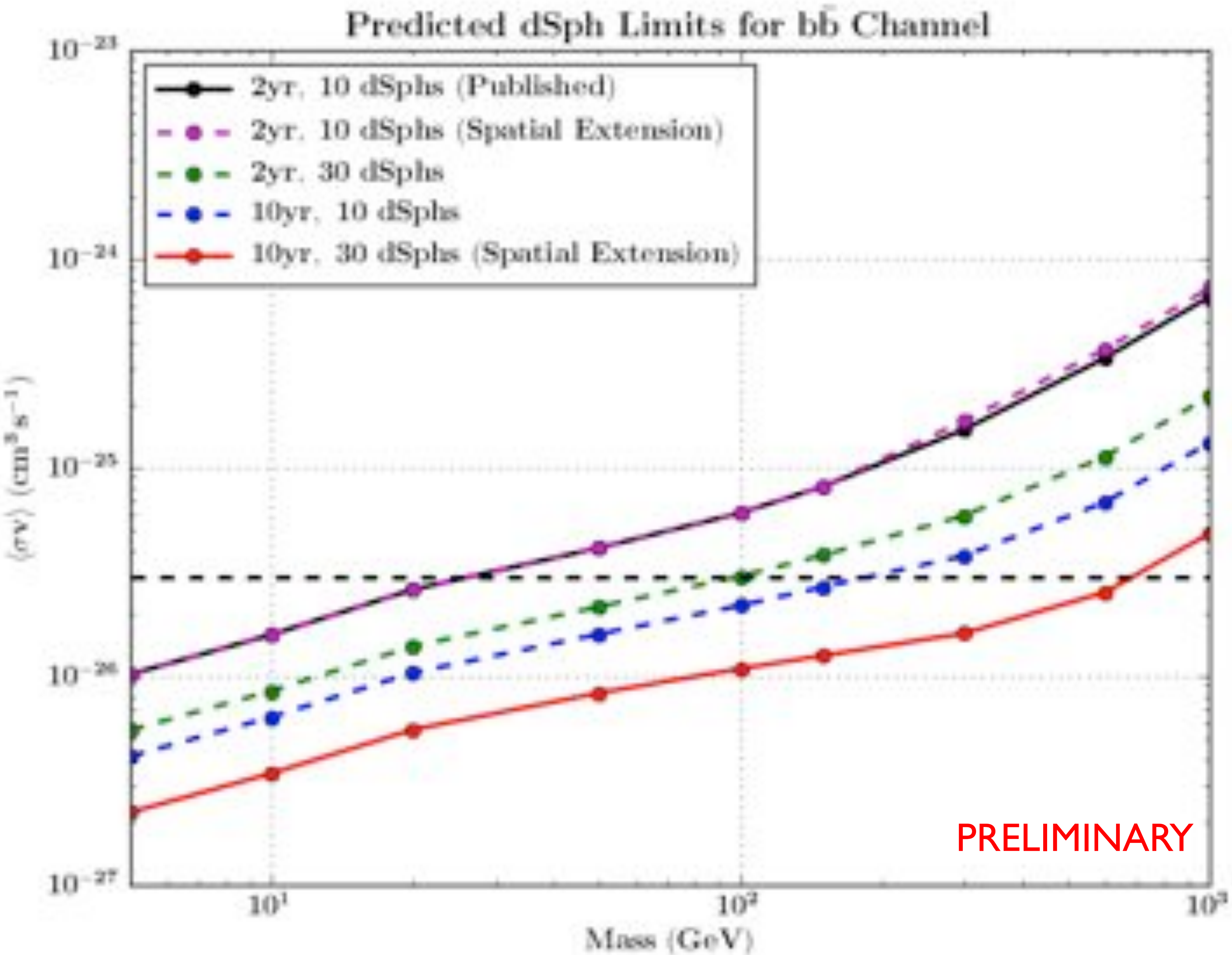


- weight dSph with different J values differently
- each posterior pdf is combined and the upper limit is evaluated

Future prospects for dwarf spheroidals

future DM limits from dSph projected to improve due to:

- increased observation time
- discovery of new dwarfs



Limits from stacking clusters

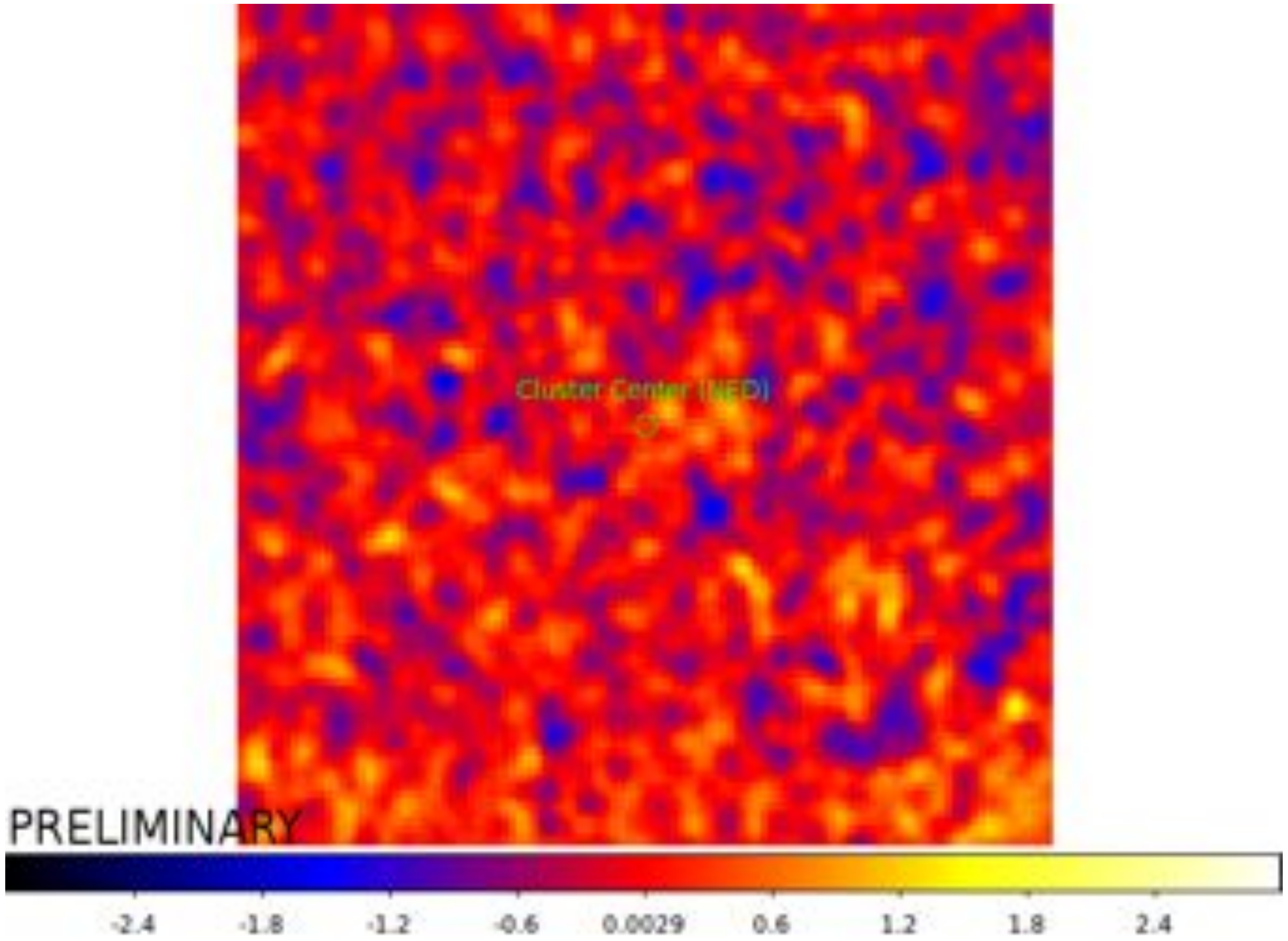
clusters are the largest and most massive structures in the universe:

- lensing and x-ray observations indicate large DM content → large predicted DM signals!
- radio emission suggests relativistic cosmic-ray population → potentially large backgrounds!
- recent claims of detection of gamma-ray signals

data analysis:

- 24 months of Fermi-LAT data, p6v11 diffuse class events
- binned analysis
- 10 deg ROI
- 20 energy bins spanning 200 MeV – 100 GeV
- clusters modeled as point sources!

Stacked residual map



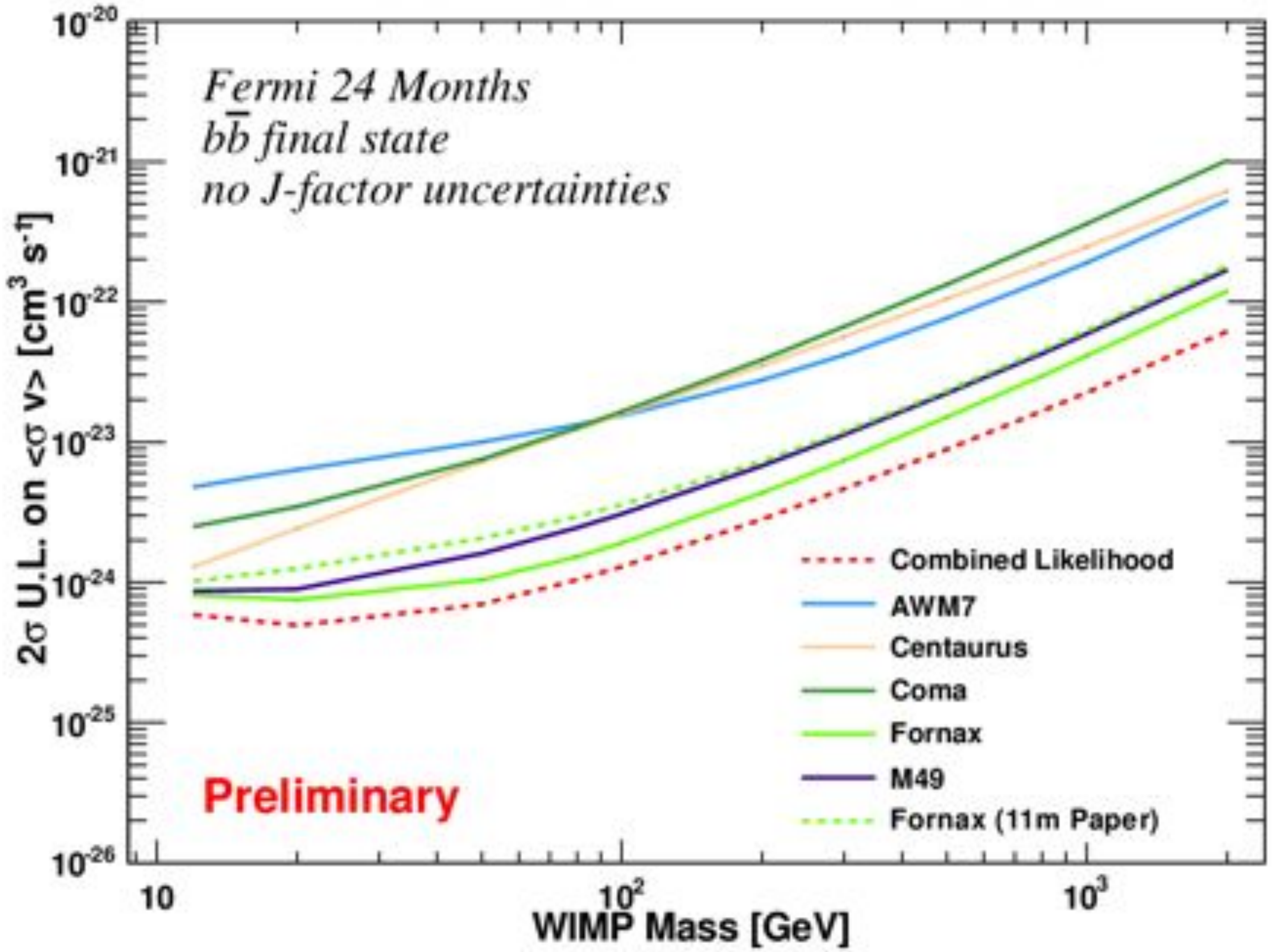
no significant detection in 24 months of data using combined likelihood analysis

for more details on this analysis, see Zimmer, Conrad [for Fermi LAT] & Pinzke, arXiv:1110.686

see also: Huang et al., arXiv:1110.1529; Ando & Nagai, arXiv:1201.0753; Han et al., arXiv:1201.1003

Limits from stacking clusters

DM annihilation constraints



combined limits on DM are a factor of ~ 2 stronger than individual limits

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

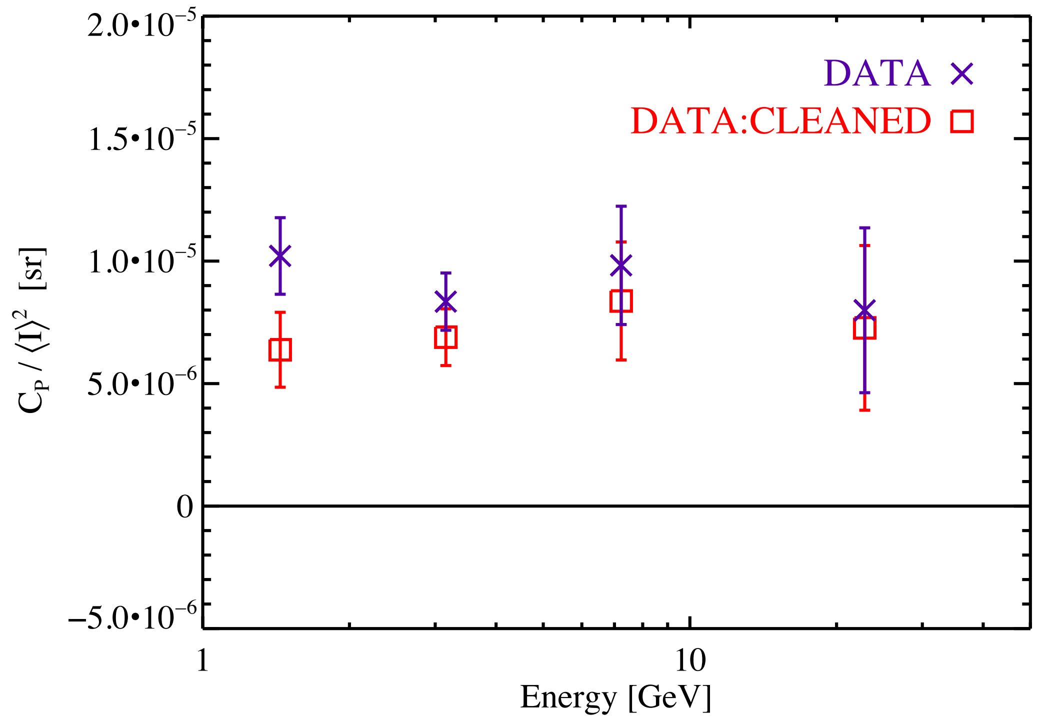
after convolving with 0.1° beam

JSG, JCAP 10(2008)040

Anisotropy constraints on dark matter

- angular power spectrum analysis of the large-scale isotropic gamma-ray background (IGRB):
  - yielded a significant (>3σ) detection of angular power in energy bins spanning 1-10 GeV
  - lower significance power measured at 10-50 GeV
- the measured (dimensionless) fluctuation angular power is consistent with a constant value in the four energy bins spanning 1-50 GeV
- fluctuation angular power measurement constrains fractional contribution of individual source classes, including DM, to the IGRB intensity

Fluctuation anisotropy energy spectrum



Ackermann et al. [Fermi LAT Collaboration] 2012 (to appear in PRD)

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

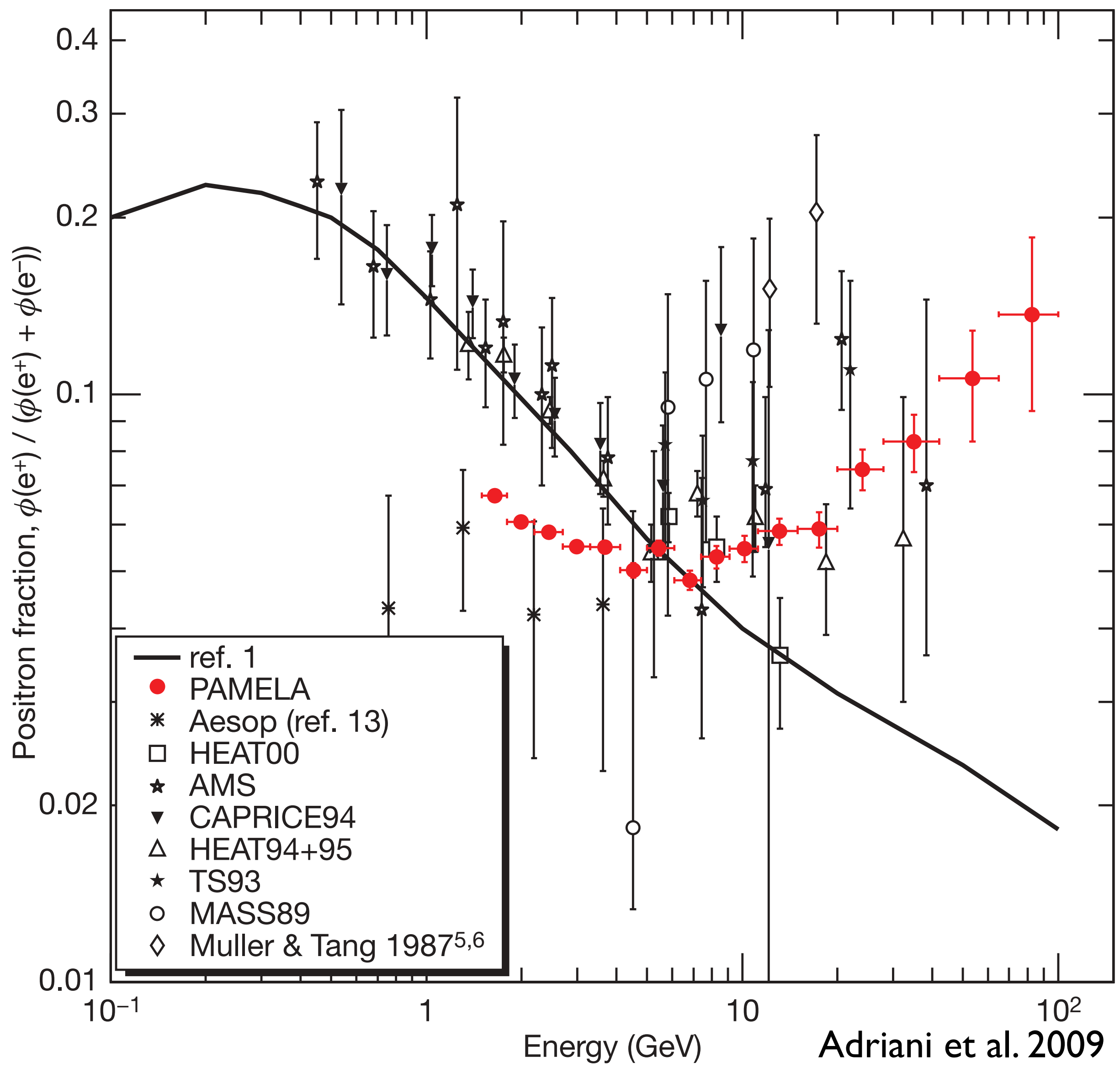
Source class	Predicted $C_{100}/\langle I \rangle^2$ [sr]	Maximum fraction of IGRB intensity DATA	DATA:CLEANED
Blazars	2×10^{-4}	21%	19%
Star-forming galaxies	2×10^{-7}	100%	100%
Extragalactic dark matter annihilation	1×10^{-5}	95%	83%
Galactic dark matter annihilation	5×10^{-5}	43%	37%
Millisecond pulsars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

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)

PAMELA positron fraction

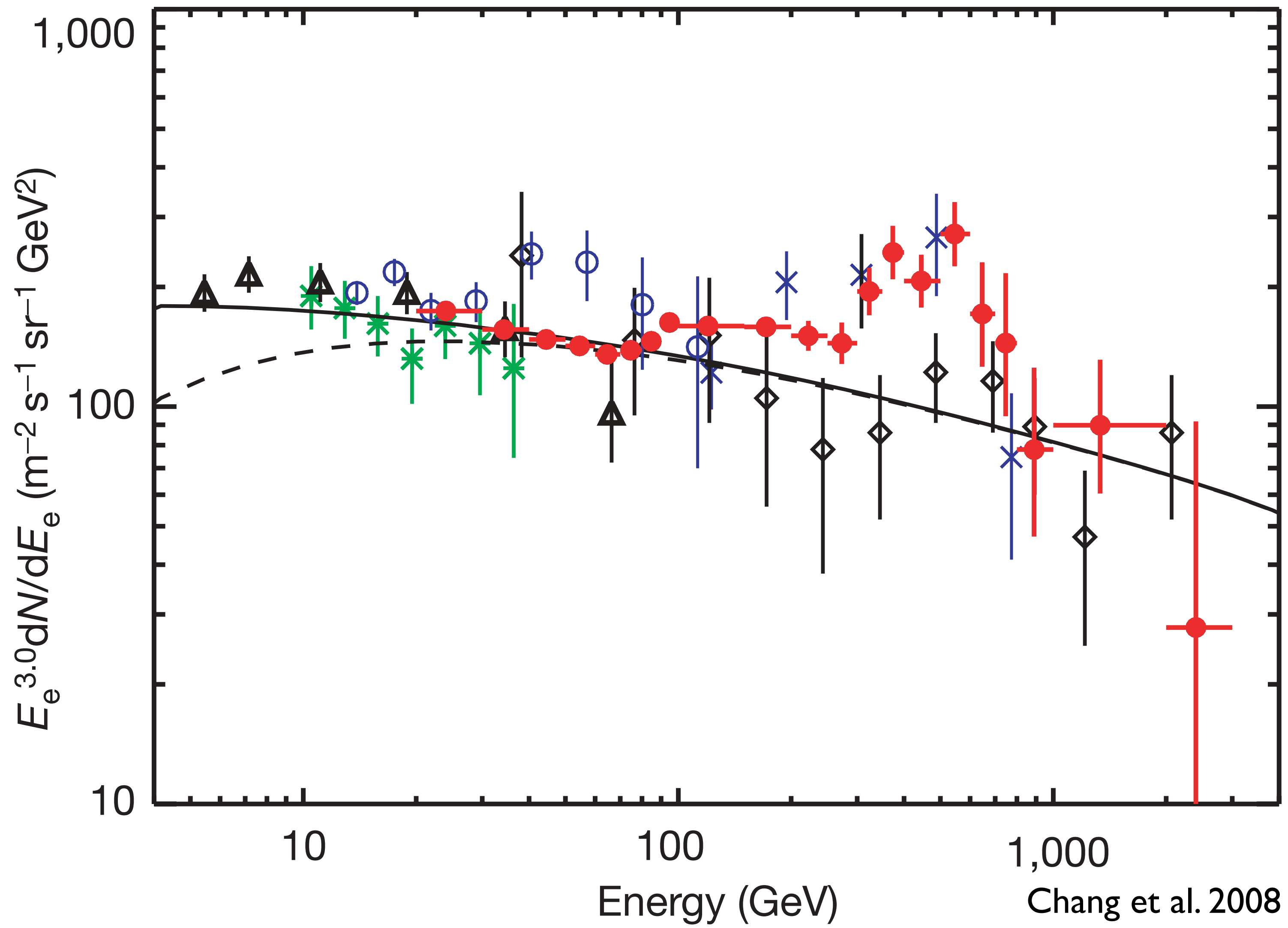


Adriani et al. 2009

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

ATIC electron + positron spectrum

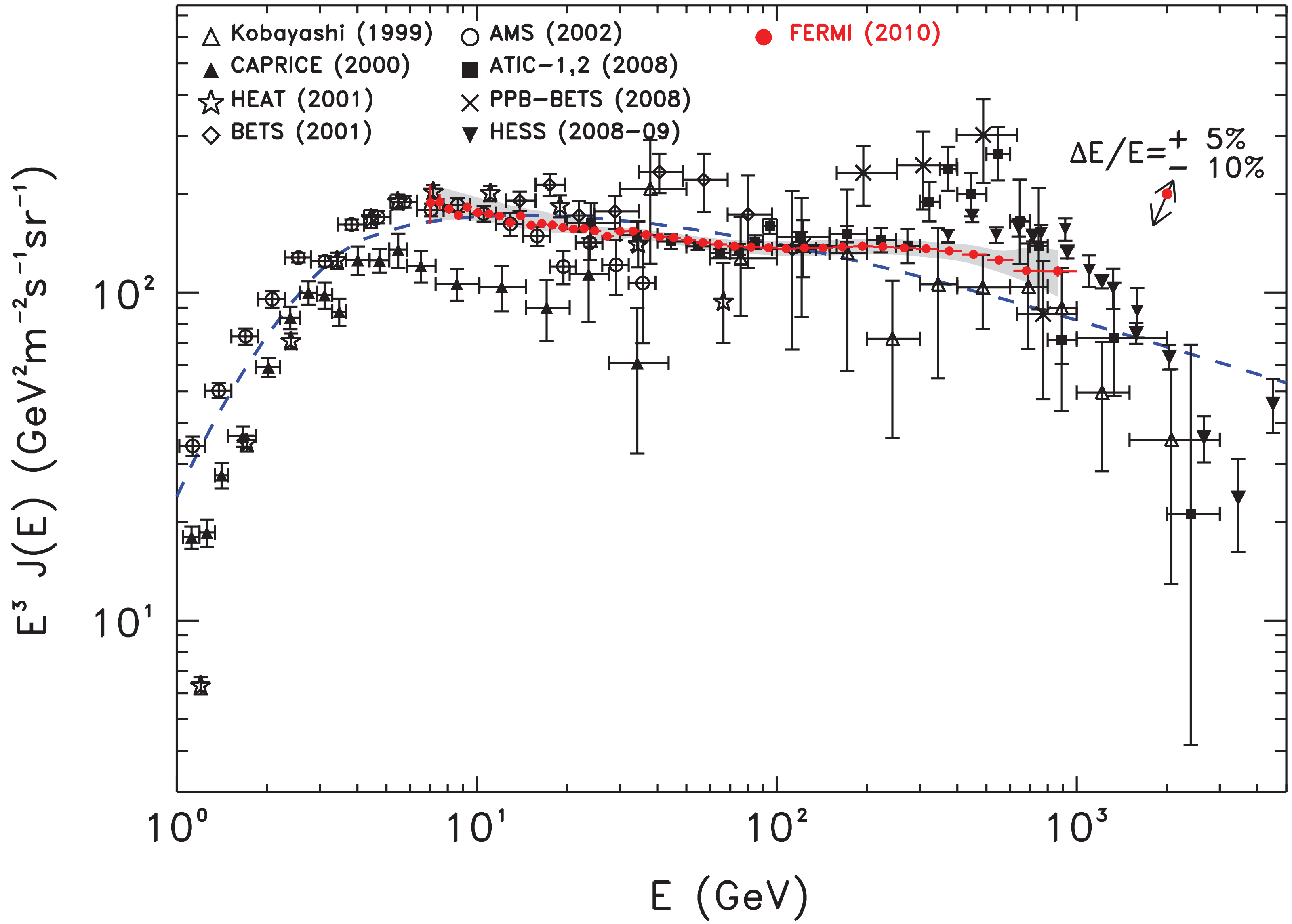


Chang et al. 2008

Unexpected features in the cosmic-ray e± spectra?

- rise in local positron fraction above ~10 GeV disagrees with conventional model for cosmic rays (secondary positron production only)
- 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



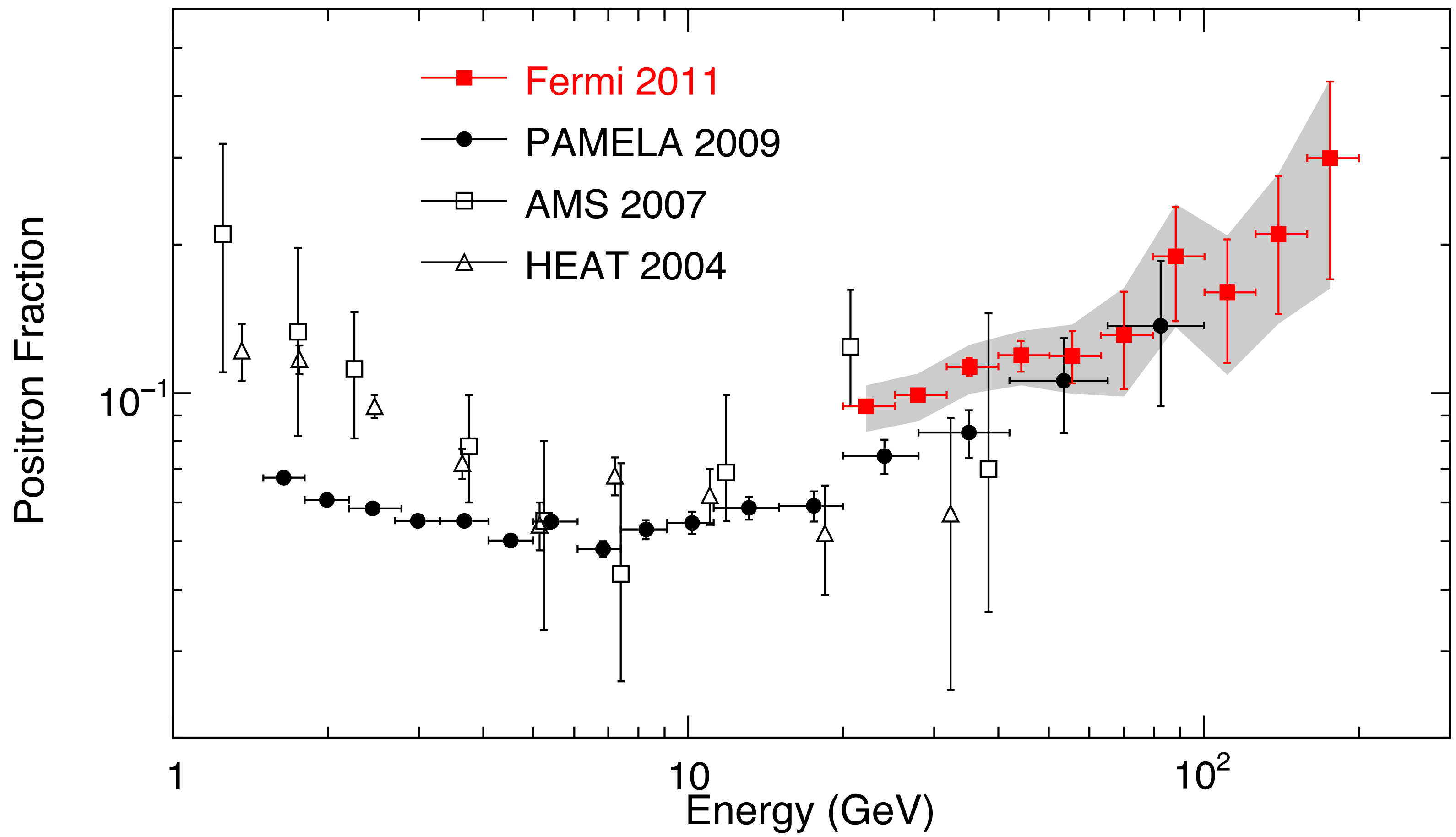
Ackermann et al. [Fermi LAT Collaboration] 2010

Unexpected features in the cosmic-ray e± spectra?

- rise in local positron fraction above ~10 GeV disagrees with conventional model for cosmic rays (secondary positron production only)
- 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

Stefan Funk's talk (Sunday)!

Fermi positron fraction



Ackermann et al. [Fermi LAT Collaboration] 2011

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:

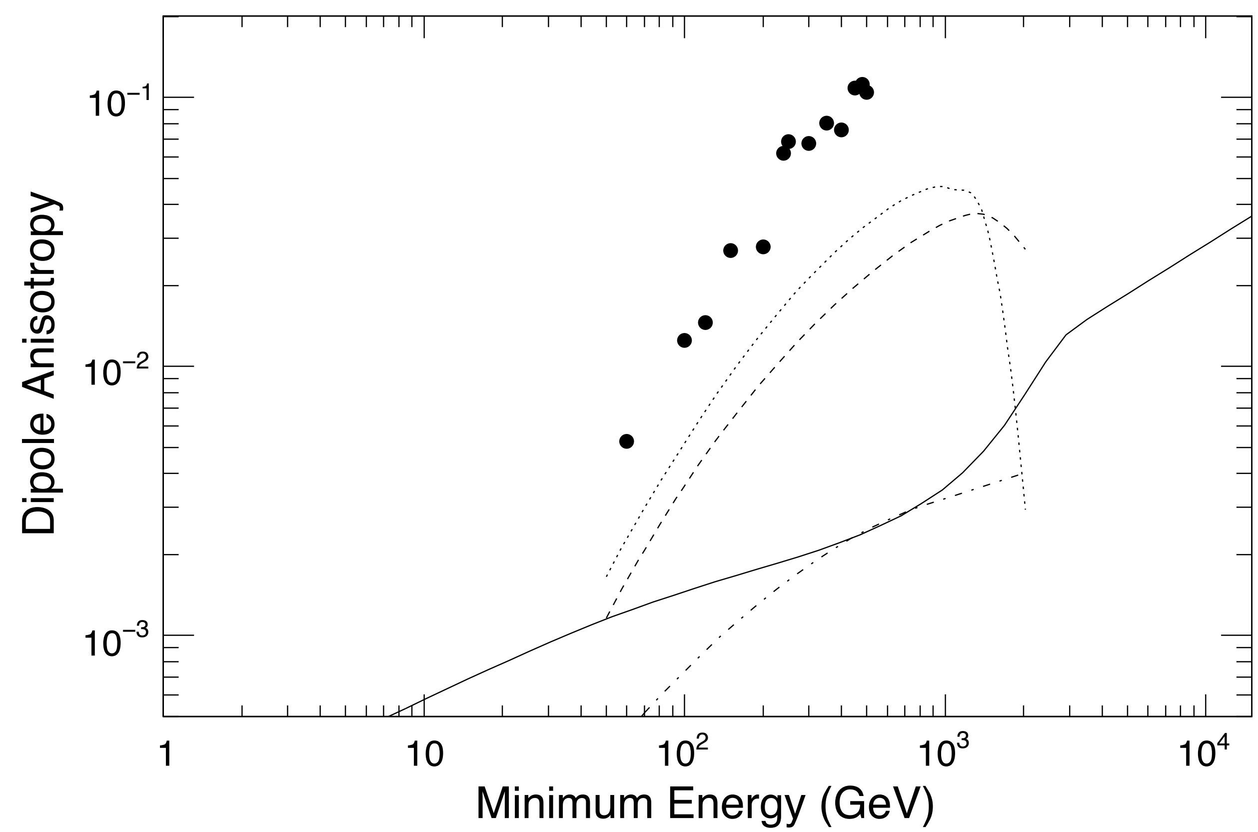
- leptophilic models
- large annihilation cross-sections; this can arise in "secluded" or "intermediate state" models, in which DM interacts with SM via a new particle (typically a light scalar)

Stefano Profumo's talk (this session)!

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 limits on CRE can constrain scenarios explaining CRE measurements

CRE dipole anisotropy limits and predictions for some DM scenarios



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

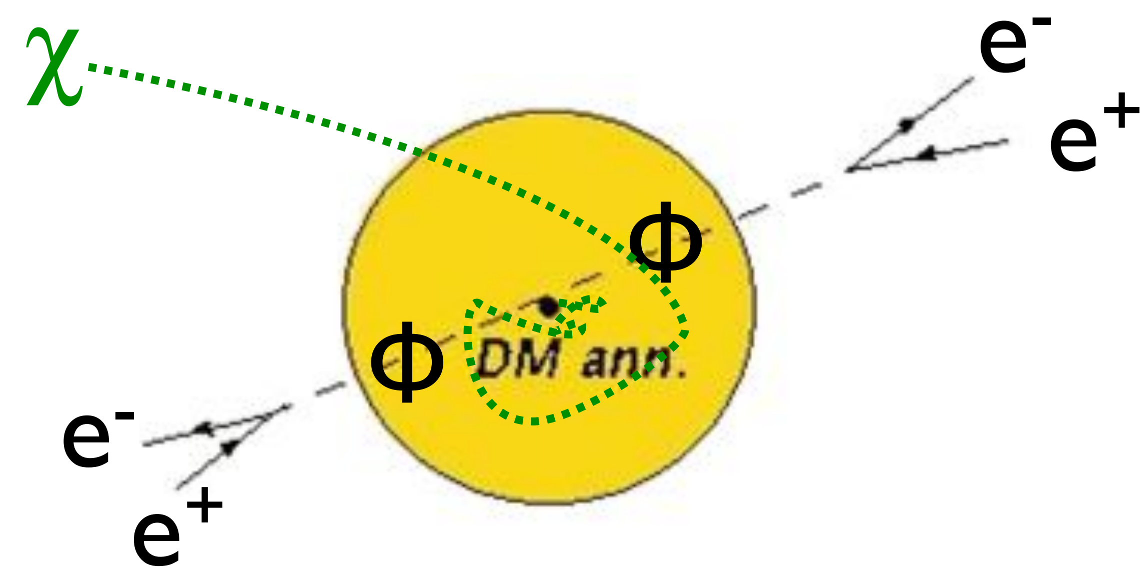
Stefano Profumo's talk (this session)!

Cholis et al 2008

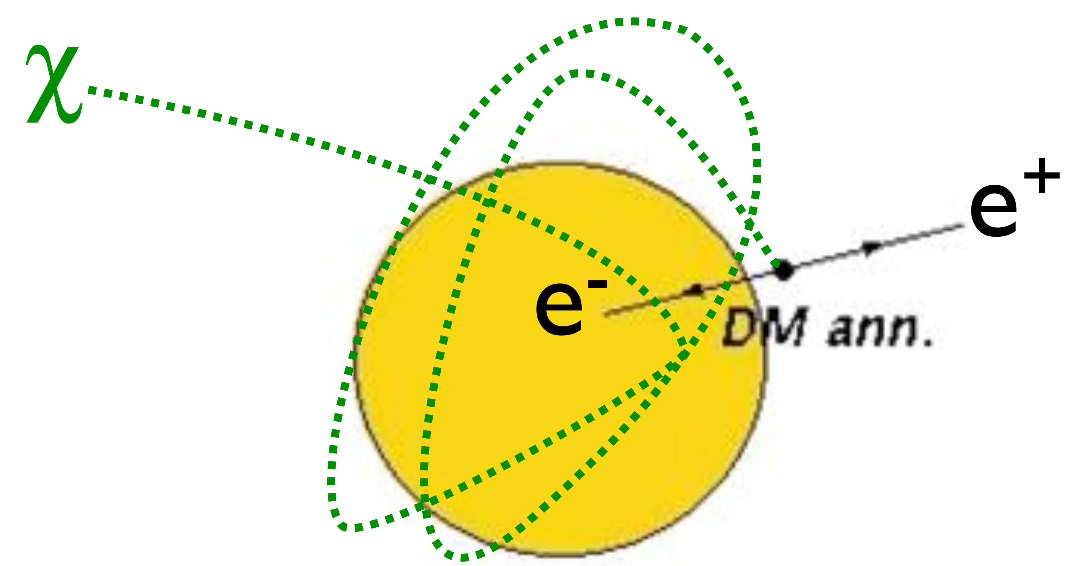
Solar CREs from DM annihilation

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

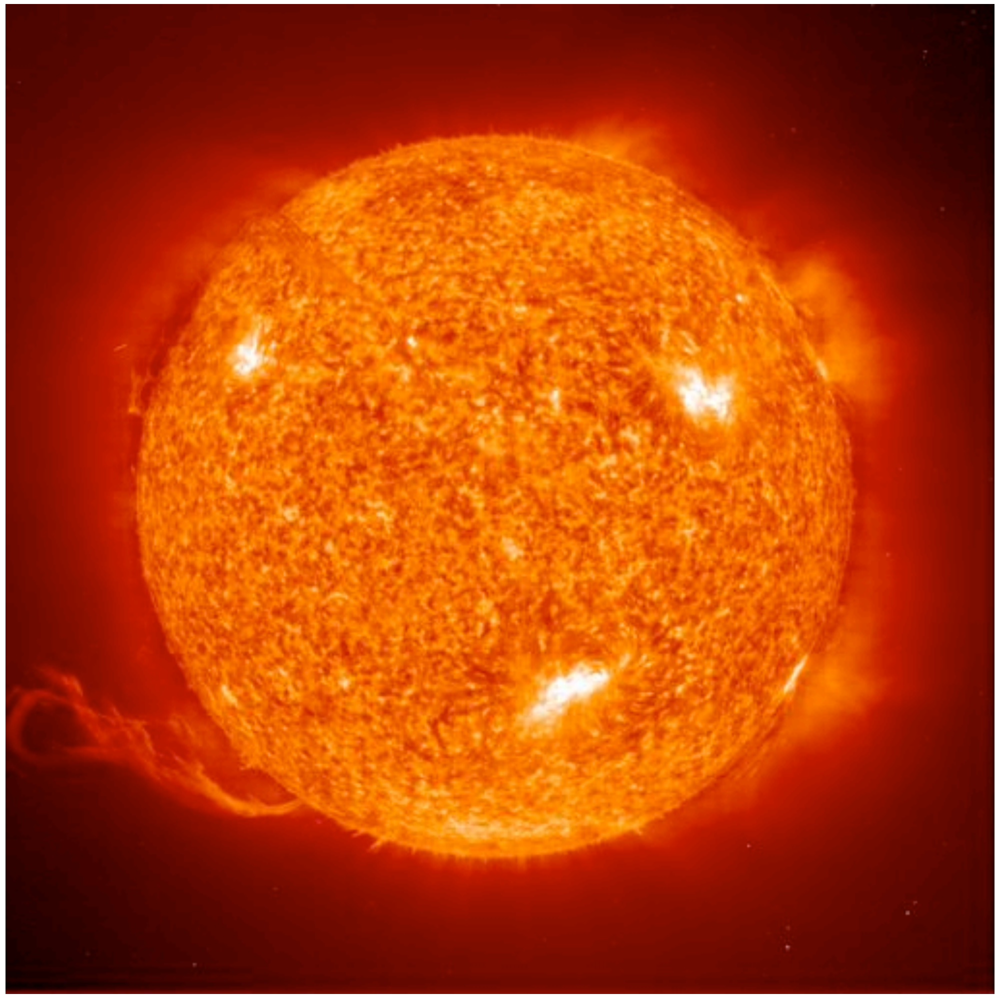


- iDM scenario: Inelastic dark matter (iDM) captured by the Sun remains on large orbits, then annihilates directly to CREs outside the surface of the Sun



Fermi LAT search for CREs from the Sun

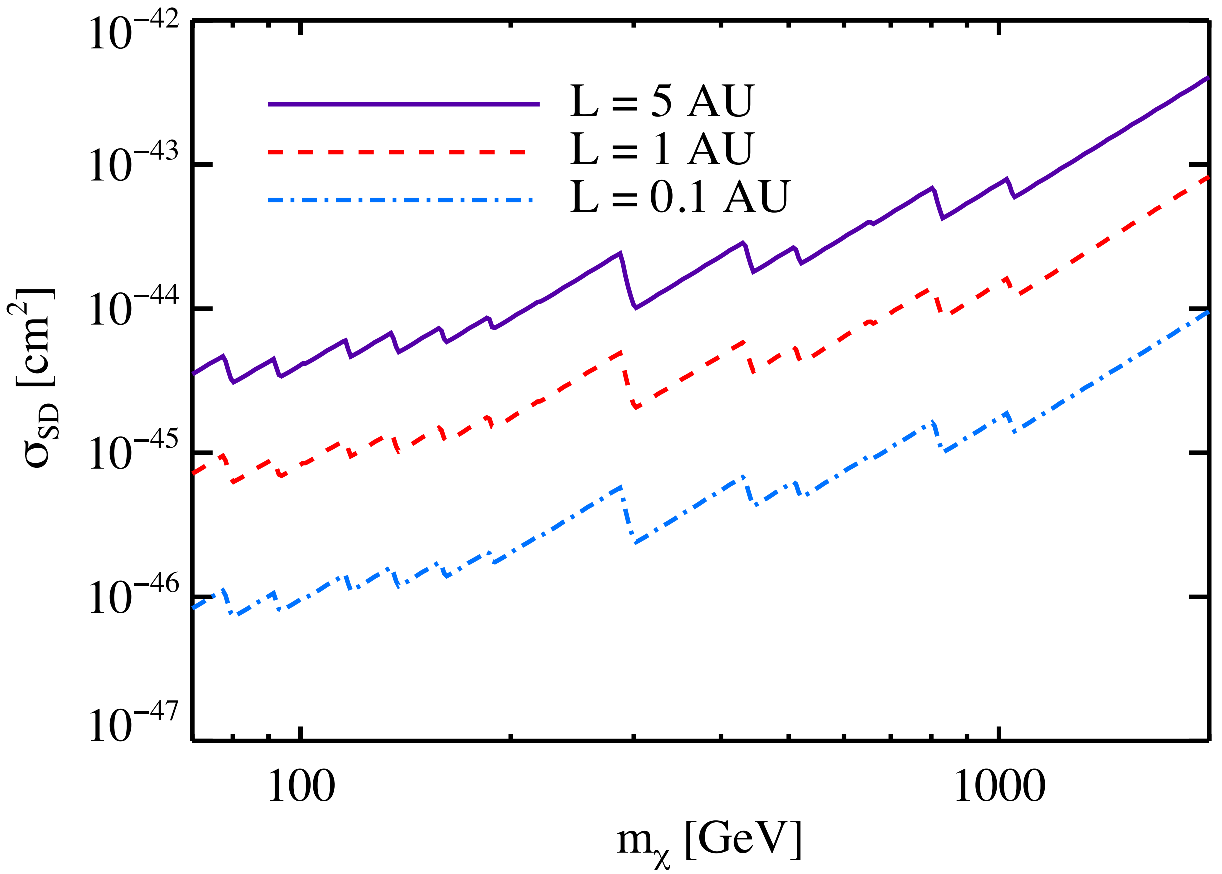
- ~10^6 CRE events (E > 60 GeV), from 1st year of operation
- analysis performed in ecliptic coordinates, in reference frame centered on the Sun
- search for a flux excess correlated with Sun's direction yielded no significant detection, flux upper limits placed



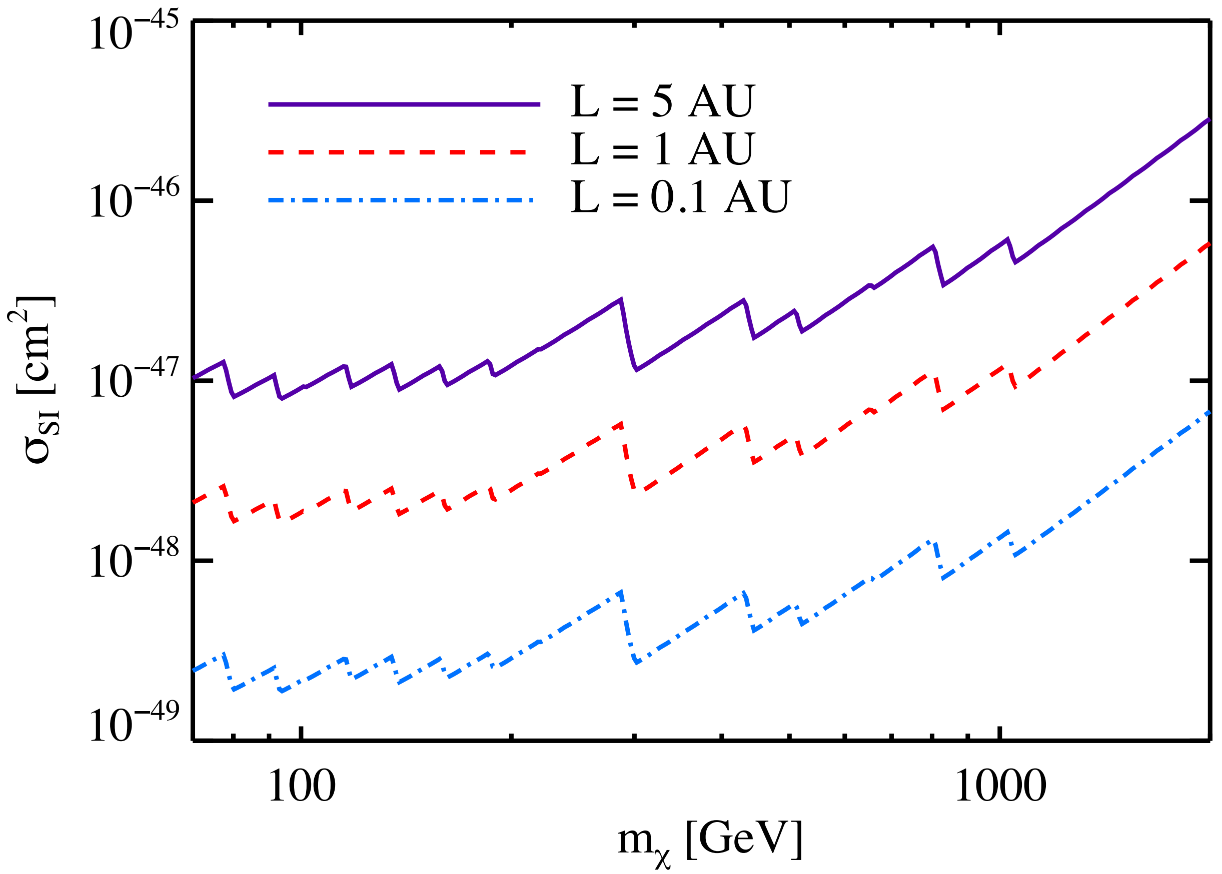
Limits on elastic scattering cross-section

assuming annihilation to CREs via an intermediate state

spin-dependent scattering



spin-independent scattering

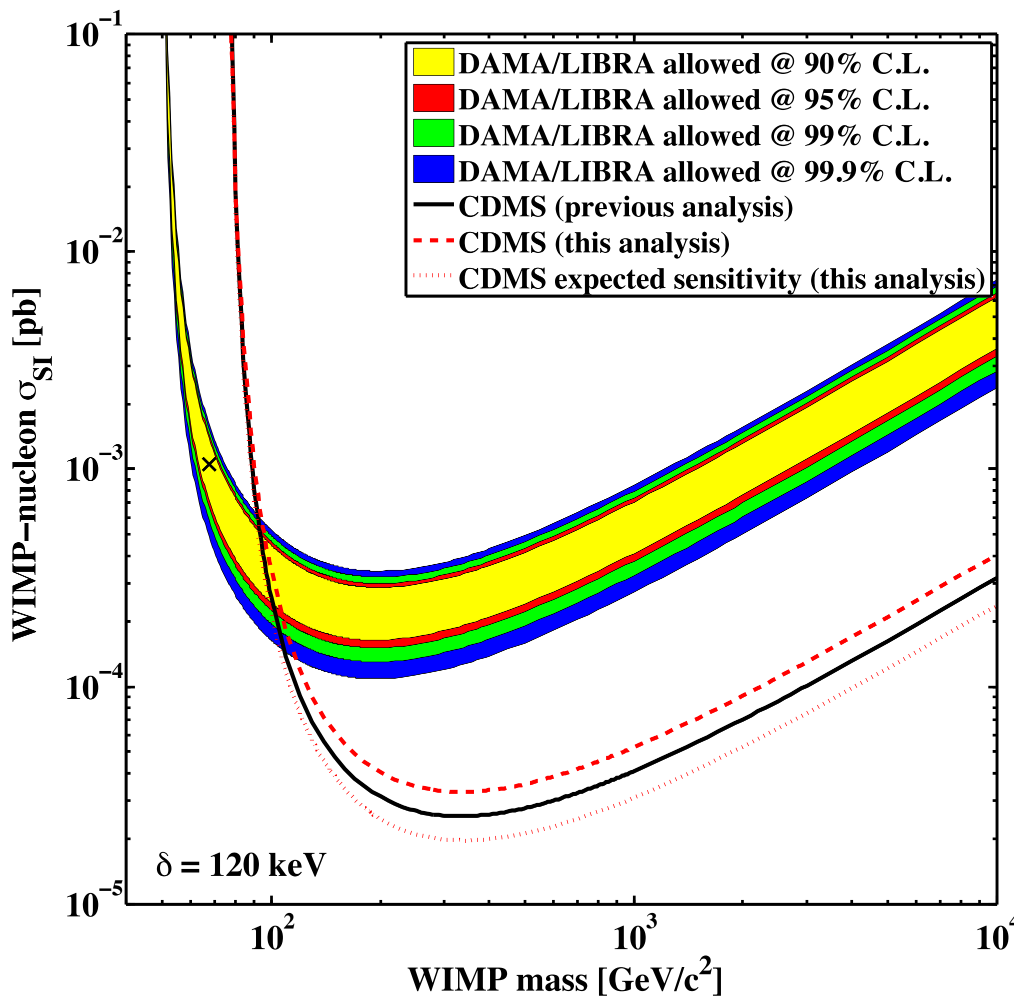


Ajello et al. [Fermi LAT Collaboration], PRD 84, 032007 (2011)

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

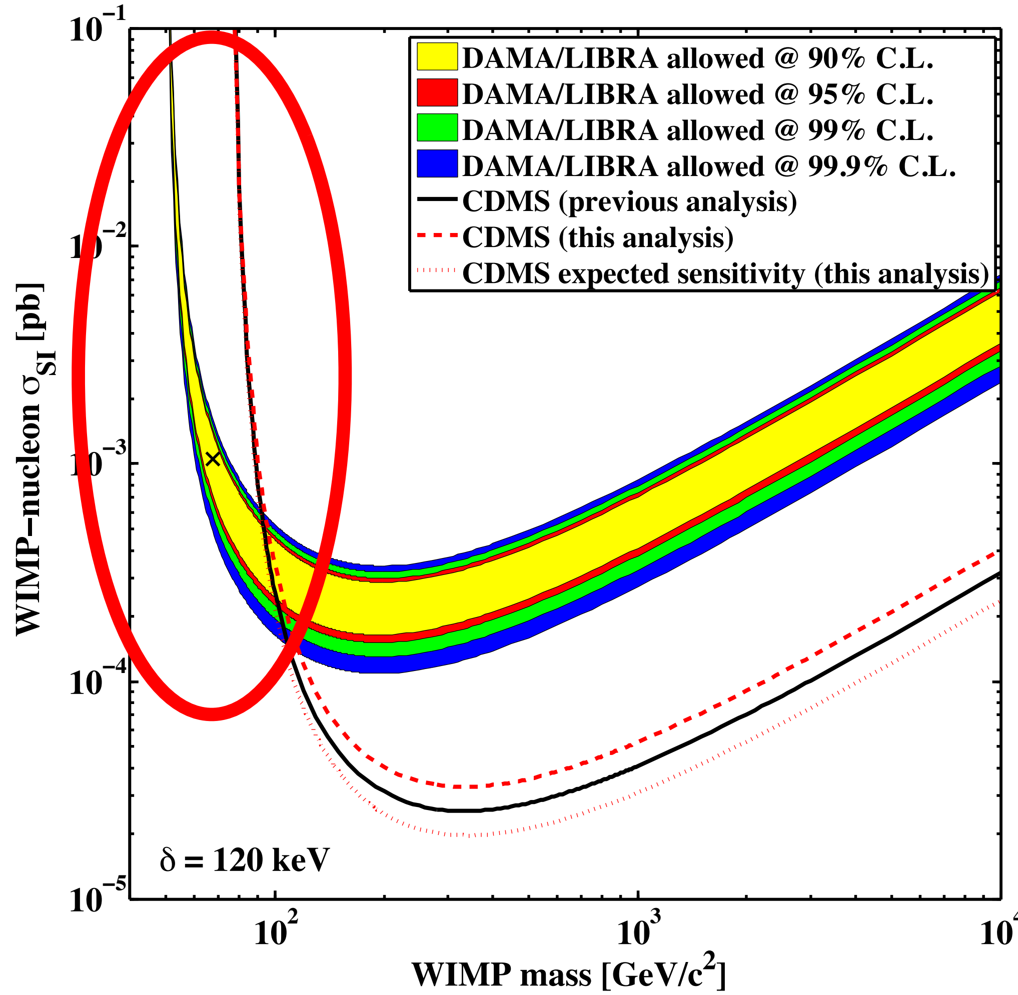
DAMA/LIBRA allowed regions and CDMS exclusion curves



CDMS Collaboration 2011

Limits on inelastic scattering cross-section

DAMA/LIBRA allowed regions and
CDMS exclusion curves

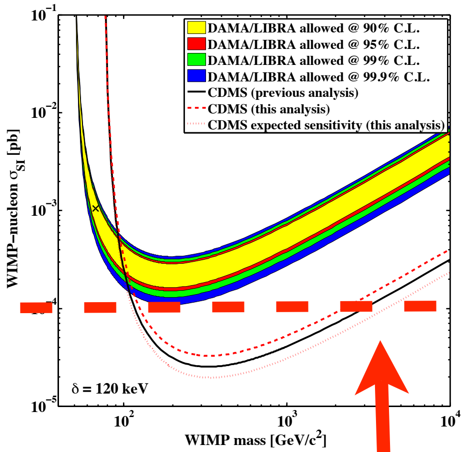


CDMS Collaboration 2011

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

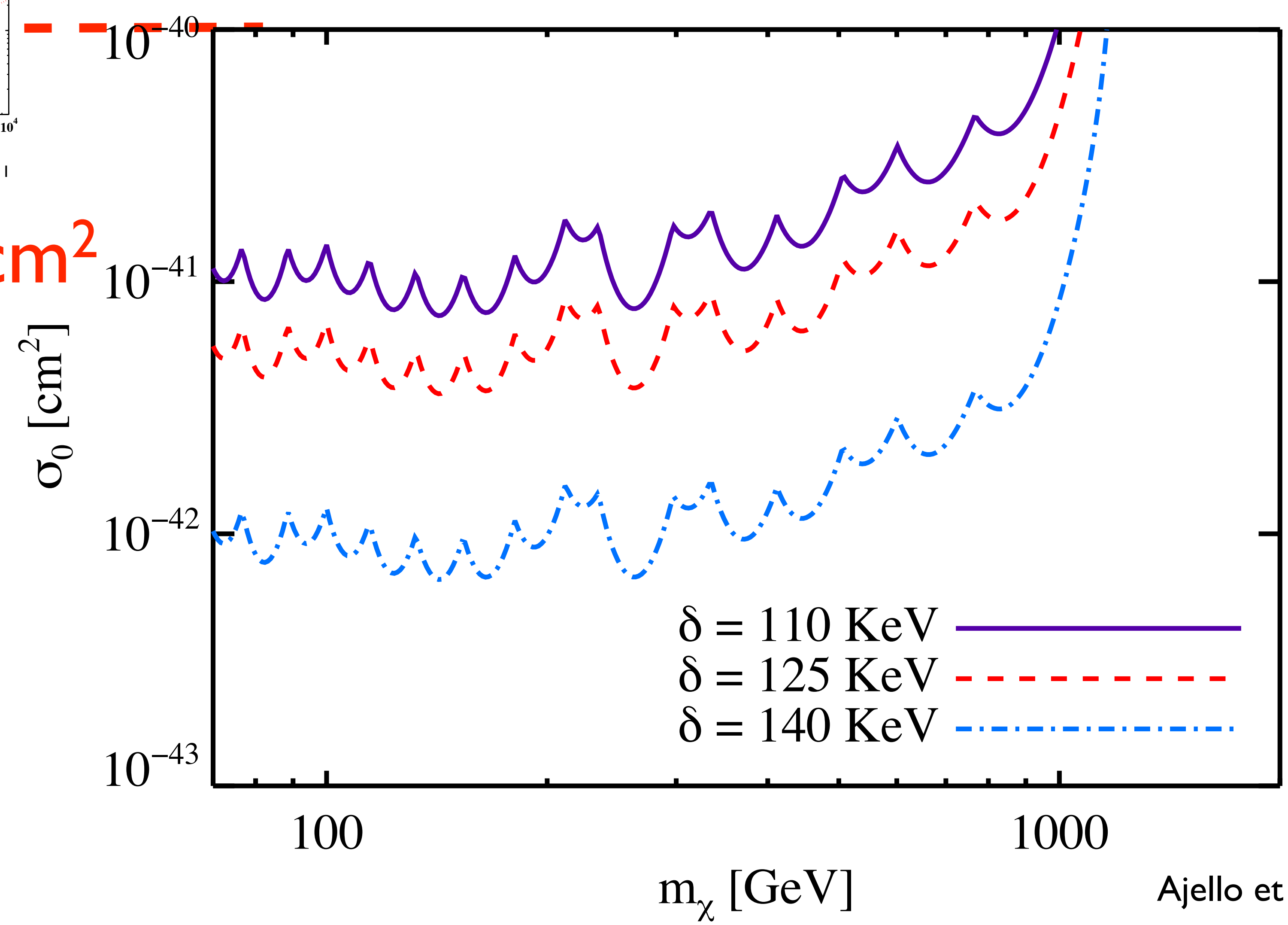
Limits on inelastic scattering cross-section



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

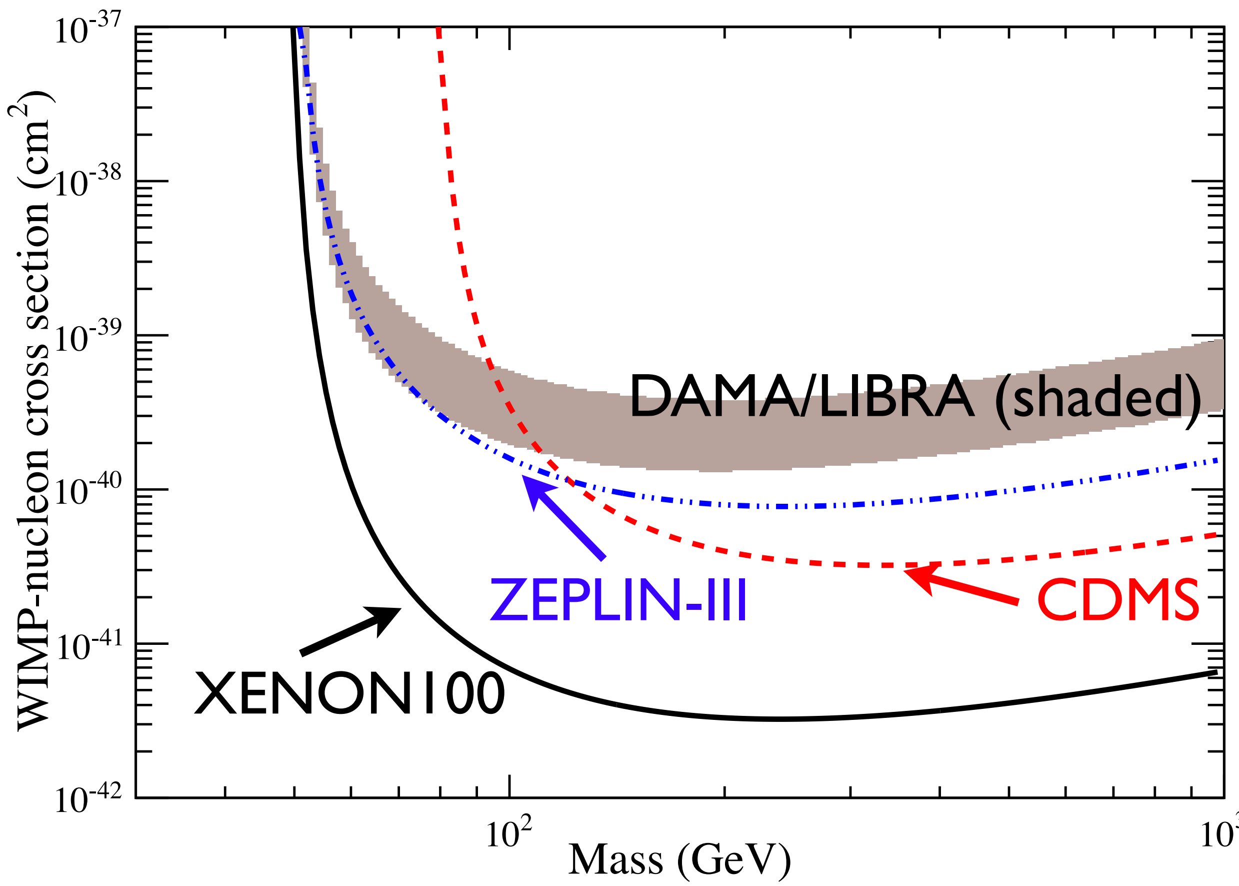
$\sigma_{SI} \sim 10^{-39}$ - 10^{-40} cm^2

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

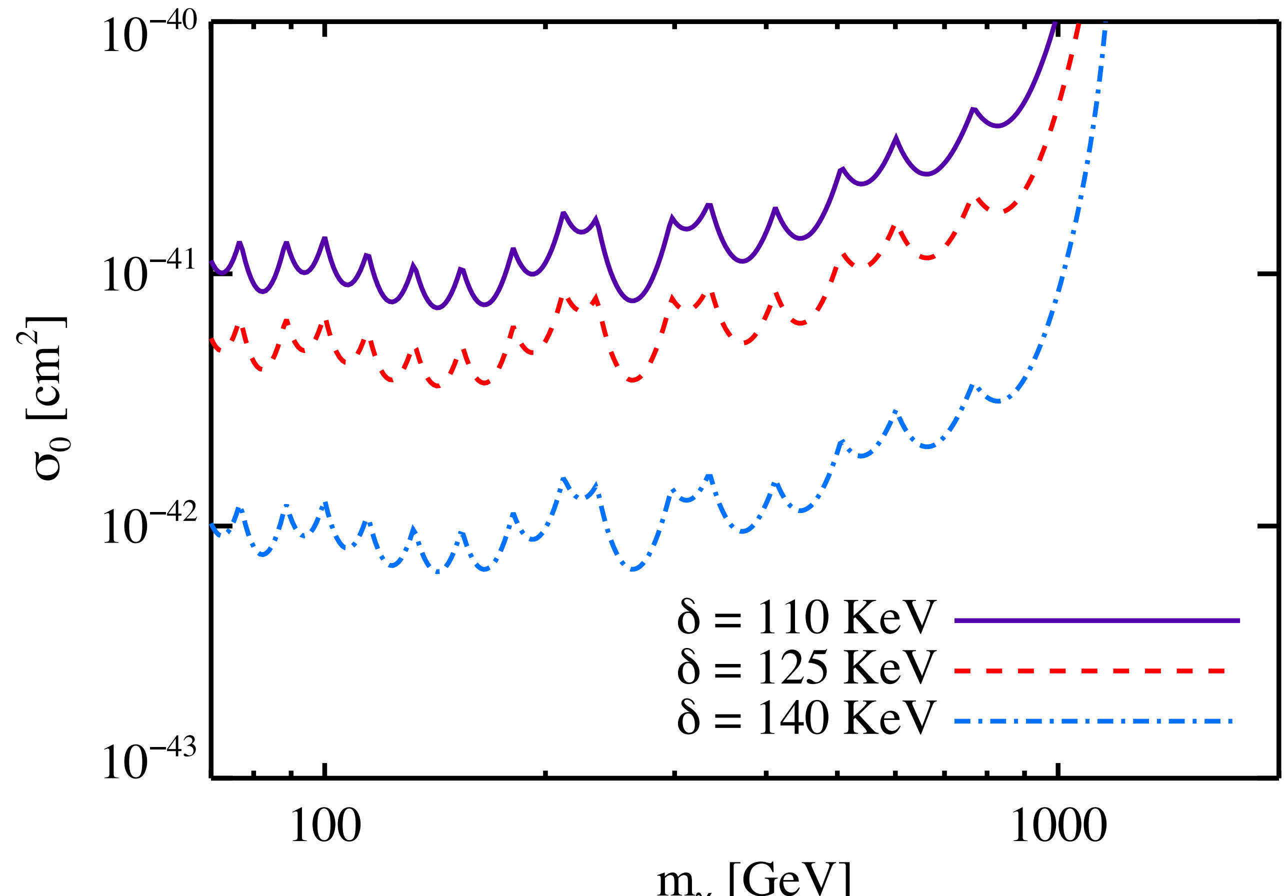
Complementarity with direct searches

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

Summary

- 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
- 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
- current searches are already testing canonical WIMP dark matter models; there is great potential for discovery in future dark matter searches with the Fermi LAT!