Title: Constraints on Dark Matter Models from a Fermi-LAT Search for Cosmic-Ray Electrons from the Sun

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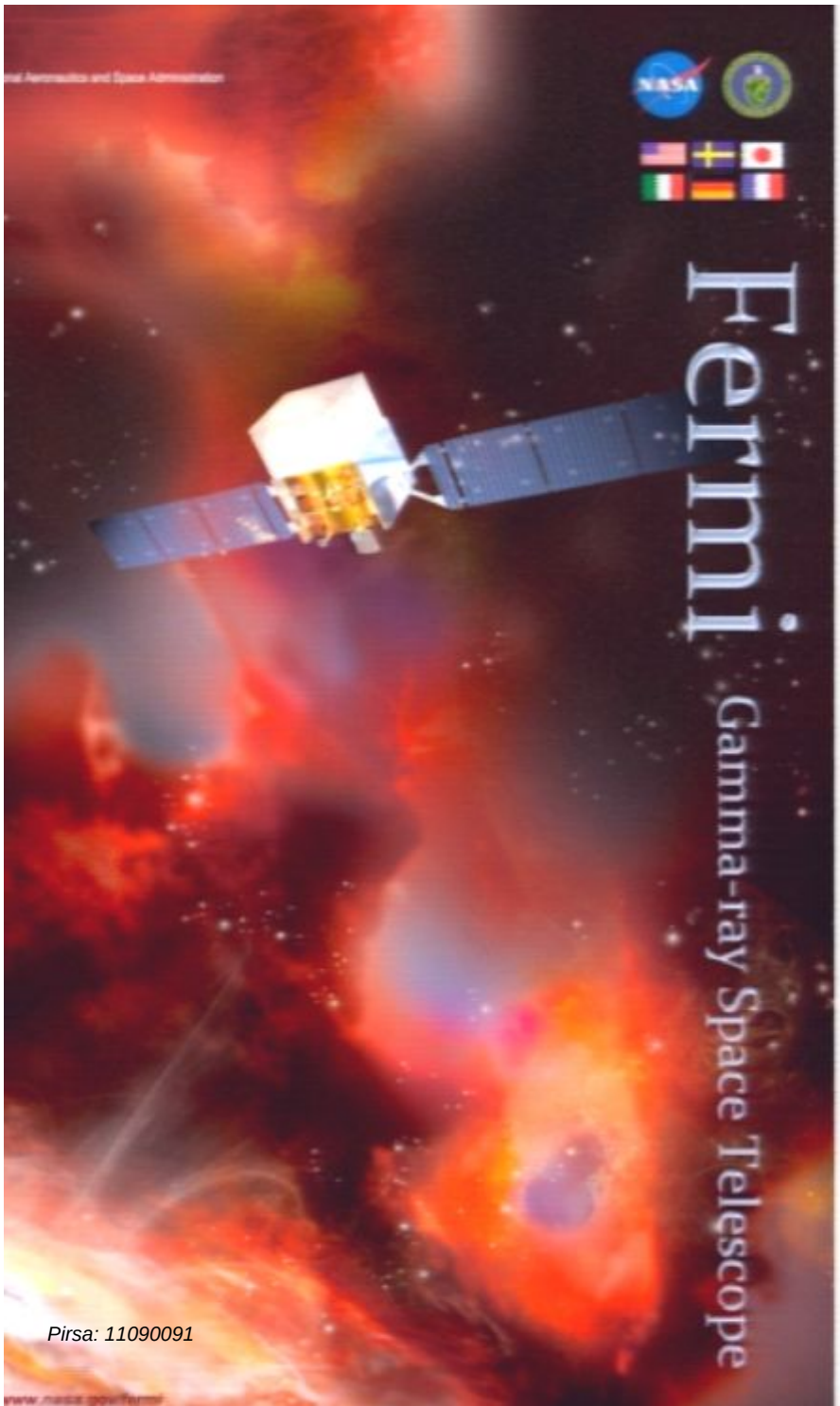
Abstract: No known astrophysical mechanisms are expected to generate a significant high-energy flux of cosmic-ray electrons and positrons (CREs) from the Sun. However, some recently considered classes of dark matter models predict such a signal. We analyzed the CRE events collected by the Fermi-LAT during its first year of operation to search for a flux excess correlated with the Sun's direction, and found no evidence of a significant signal. I will discuss the constraints these results place on secluded dark matter models and inelastic dark matter models.



Constraints on dark matter models from a Fermi LAT search for cosmic-ray electrons from the Sun

J. Siegal-Gaskins
(OSU → Caltech)

with
F. Loparco and M.N. Mazziotta

on behalf of
the Fermi LAT Collaboration

based on
PRD 84, 032007 (2011)
arXiv:1107.4272

Unexpected features in the cosmic-ray $e^{\pm}$ spectra?

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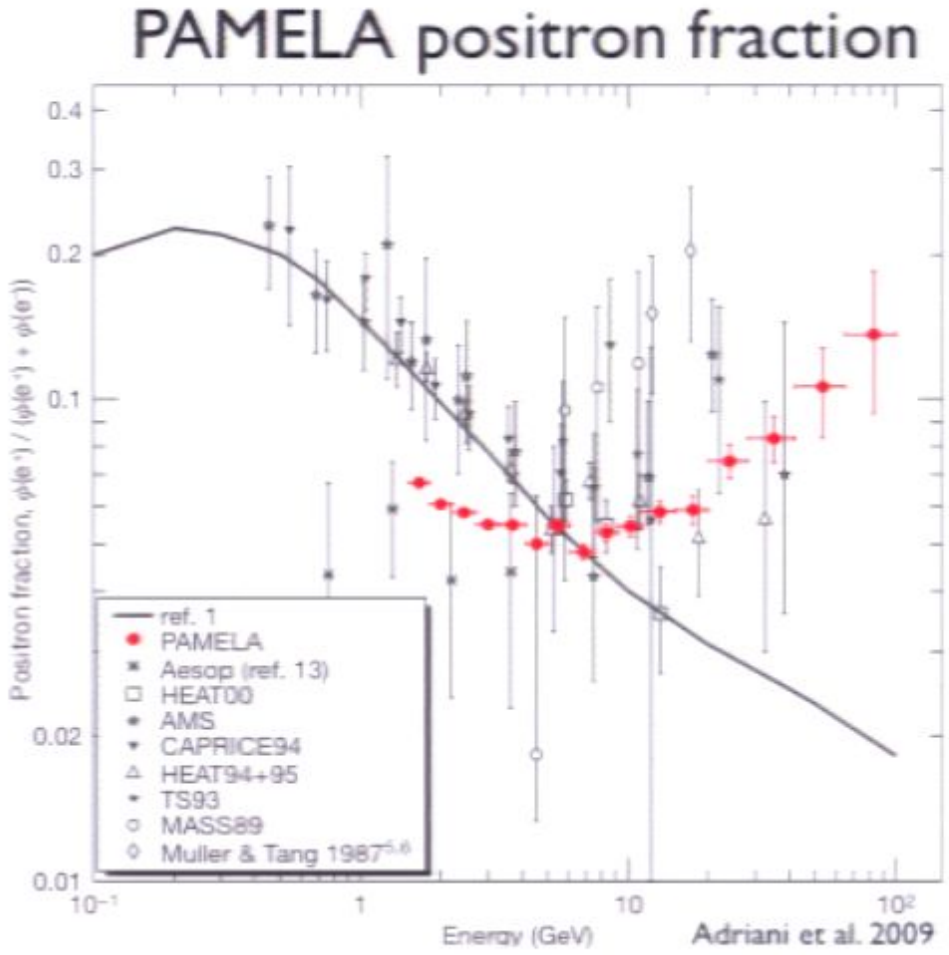
- rise in local positron fraction above ~10 GeV disagrees with conventional model for cosmic rays (secondary positron production only)



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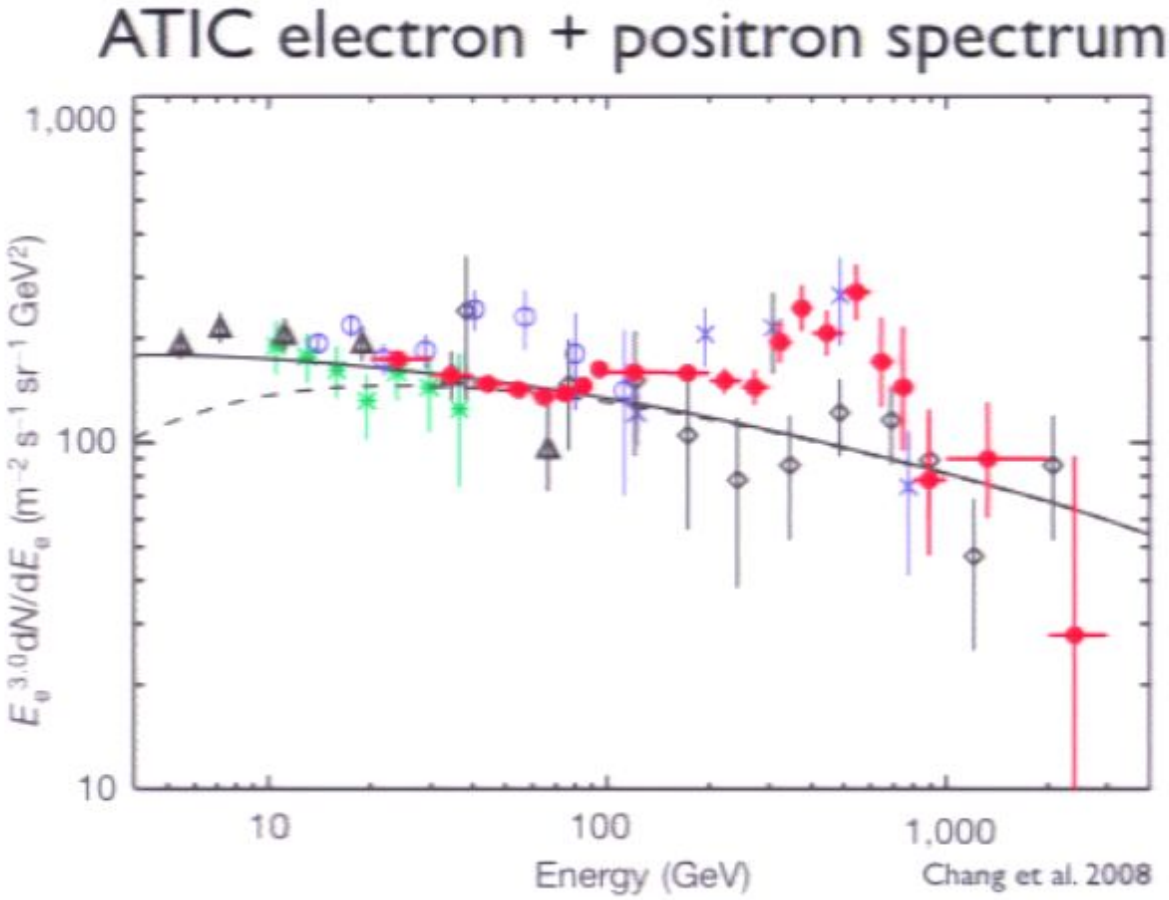

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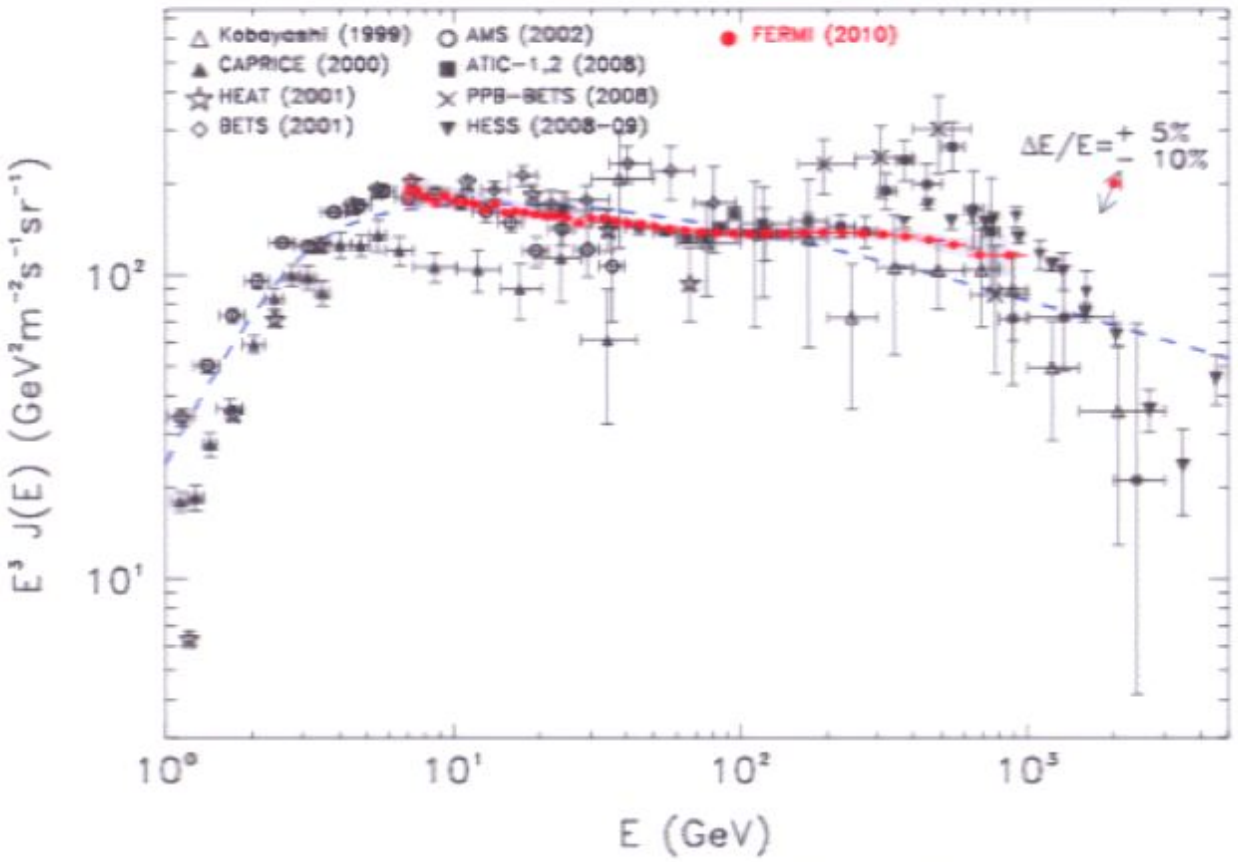
Fermi electron + positron spectrum



Ackermann et al. [Fermi LAT Collaboration] 2010

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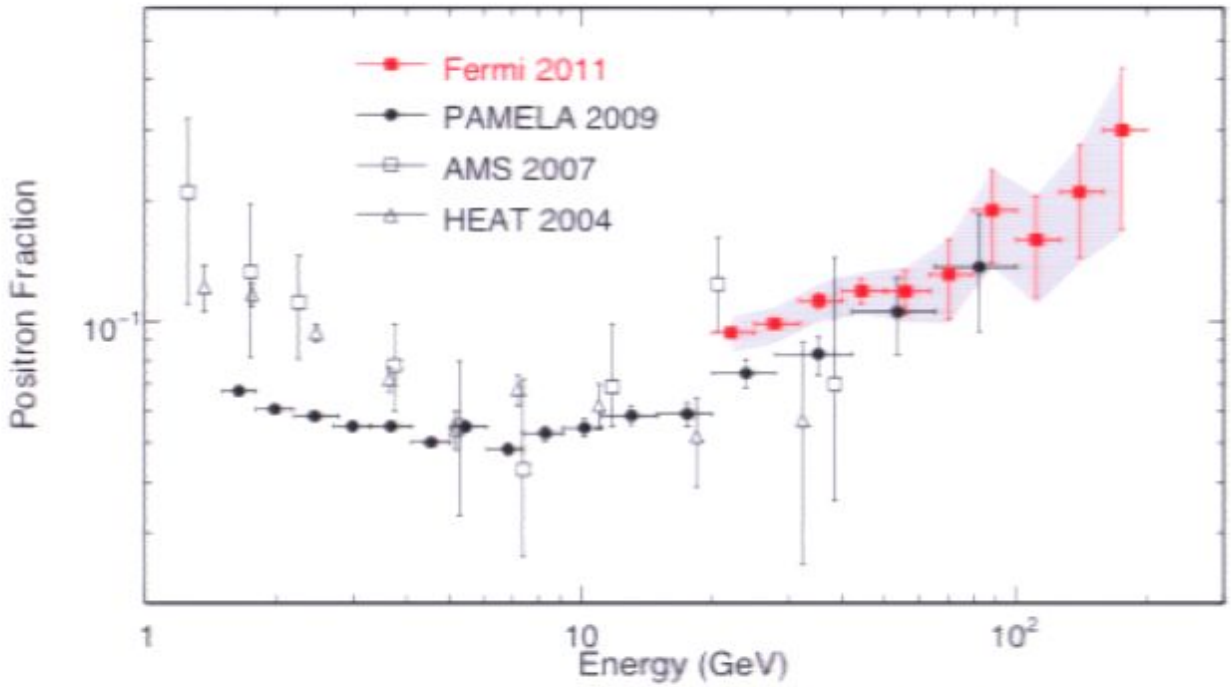
- Fermi positron fraction agrees with PAMELA result, extends to higher energies

Fermi positron fraction



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Hints of a dark matter signal?

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- 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;...)
  - leptophilic models
  - large annihilation cross-sections (e.g., via Sommerfeld)

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]

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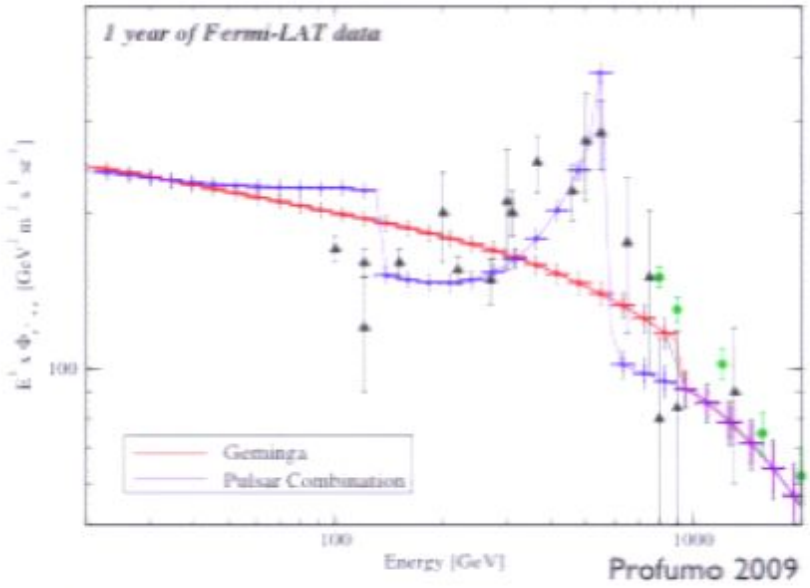
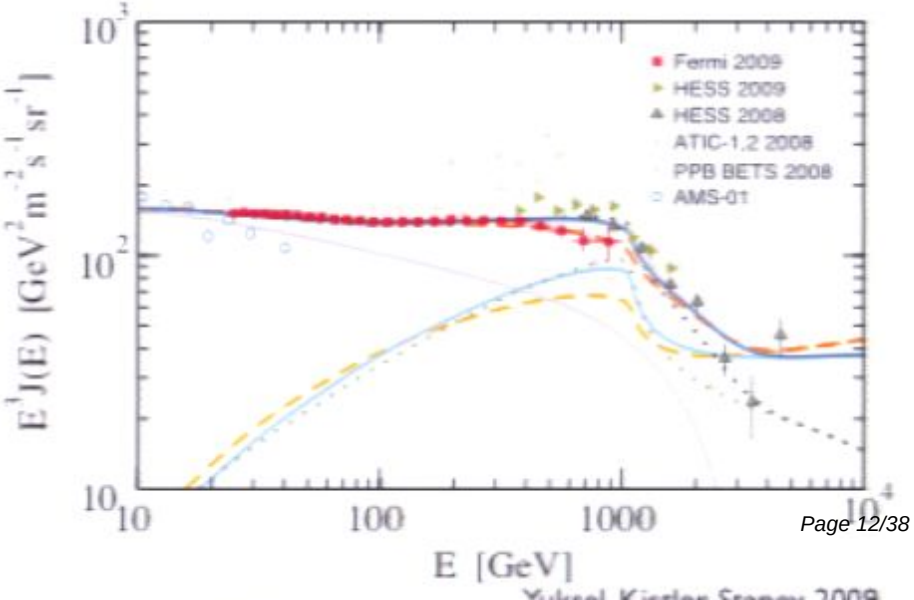
  - leptophilic models
  - large annihilation cross-sections (e.g., via Sommerfeld)
- astrophysical explanations: pulsars (e.g., Yuksel, Kistler, & Stanev 2009; Hooper, Blasi, & Serpico 2009; Profumo 2009; Grasso et al. 2009;...), SNR (e.g., Blasi & Serpico 2009), etc.

Pulsar contributions to CRE spectra



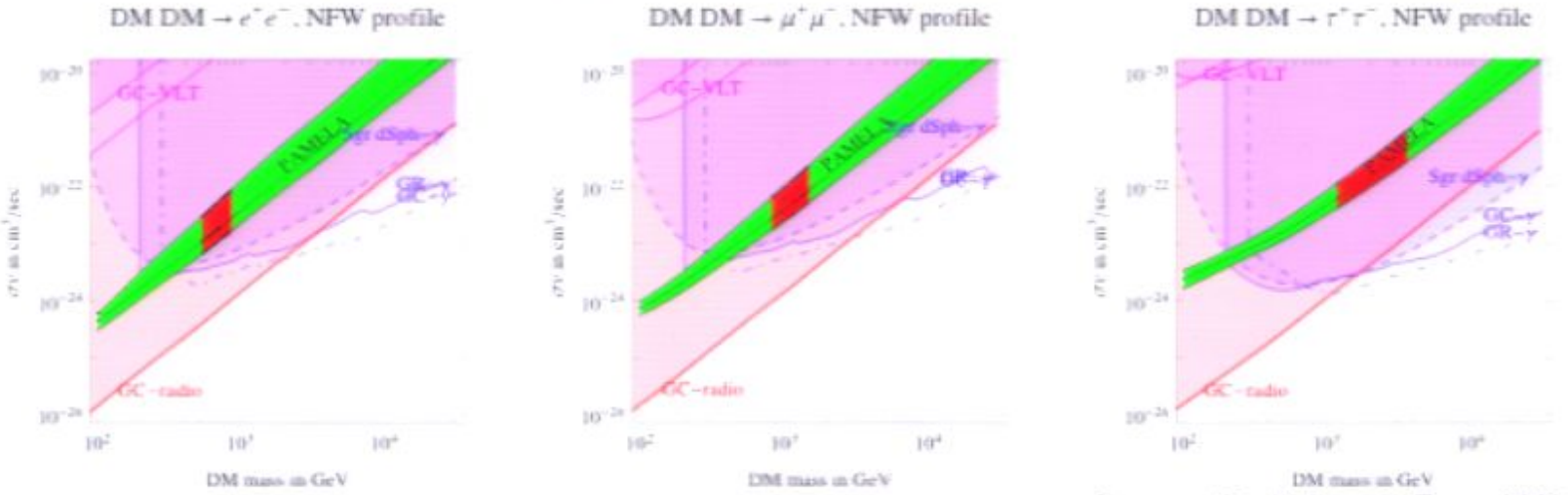
Profumo 2009



Yuksel, Kistler, Stanev 2009

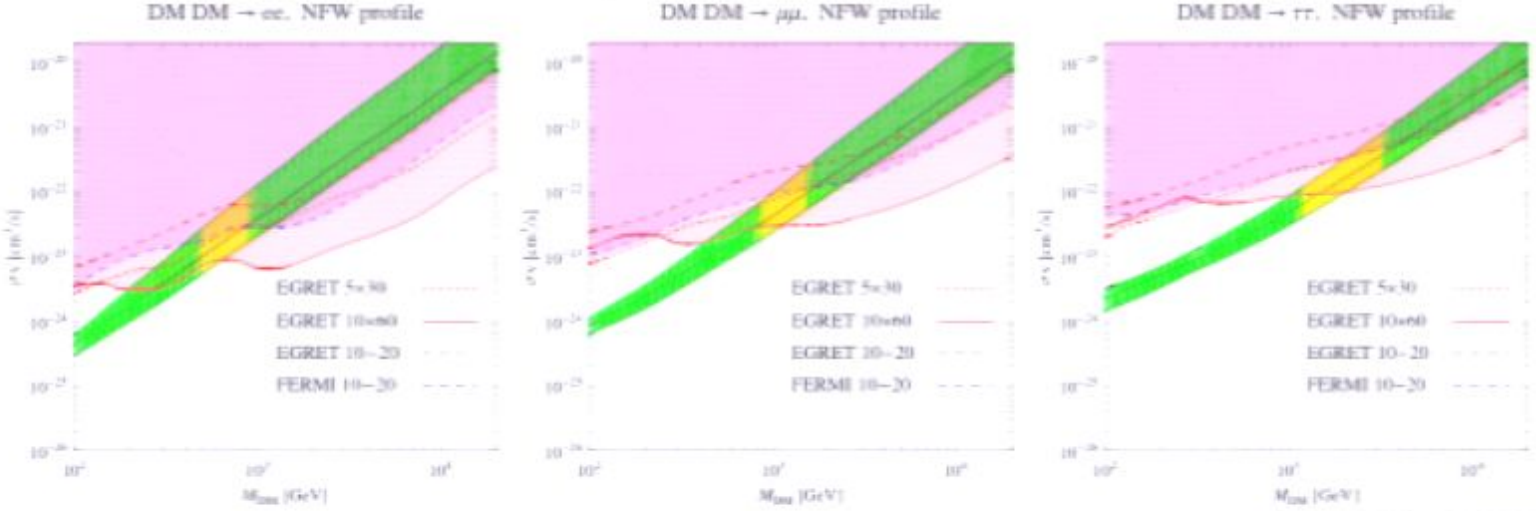
Multiwavelength constraints on dark matter explanations

GC & GR gamma-ray (continuum and FSR), GC radio (synchrotron)



Bertone, Cirelli, Strumia, Taoso 2009

Inverse Compton scattering in the inner Galaxy

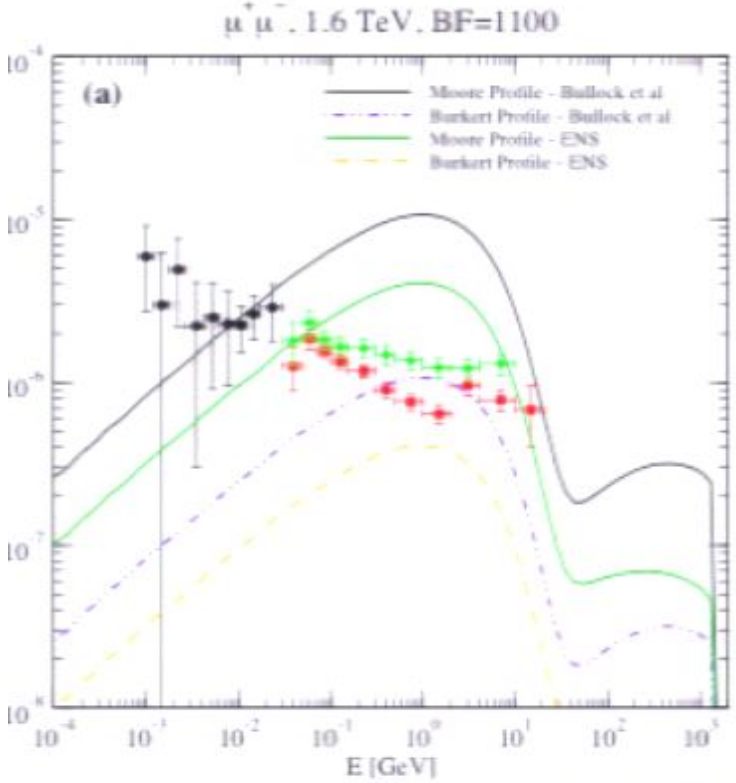


Cirelli & Panci 2009

see also Cirelli, Panci, Serpico 2009, ...

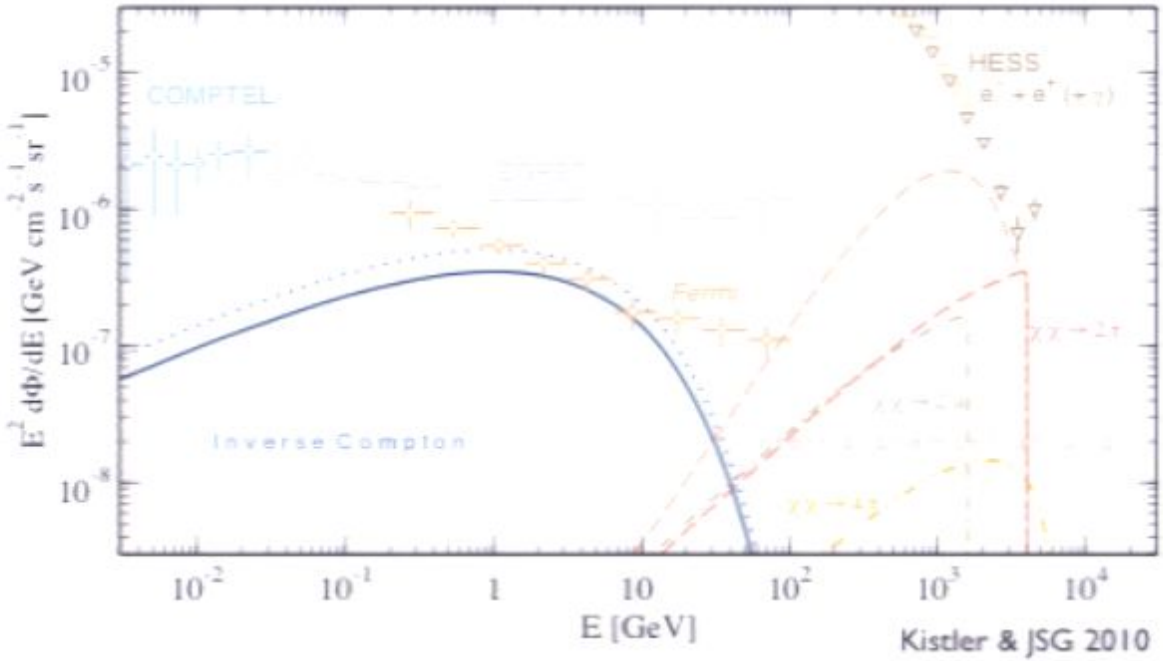
Constraints from the diffuse gamma-ray background

Annihilation in extragalactic DM halos



Profumo & Jeltema 2009

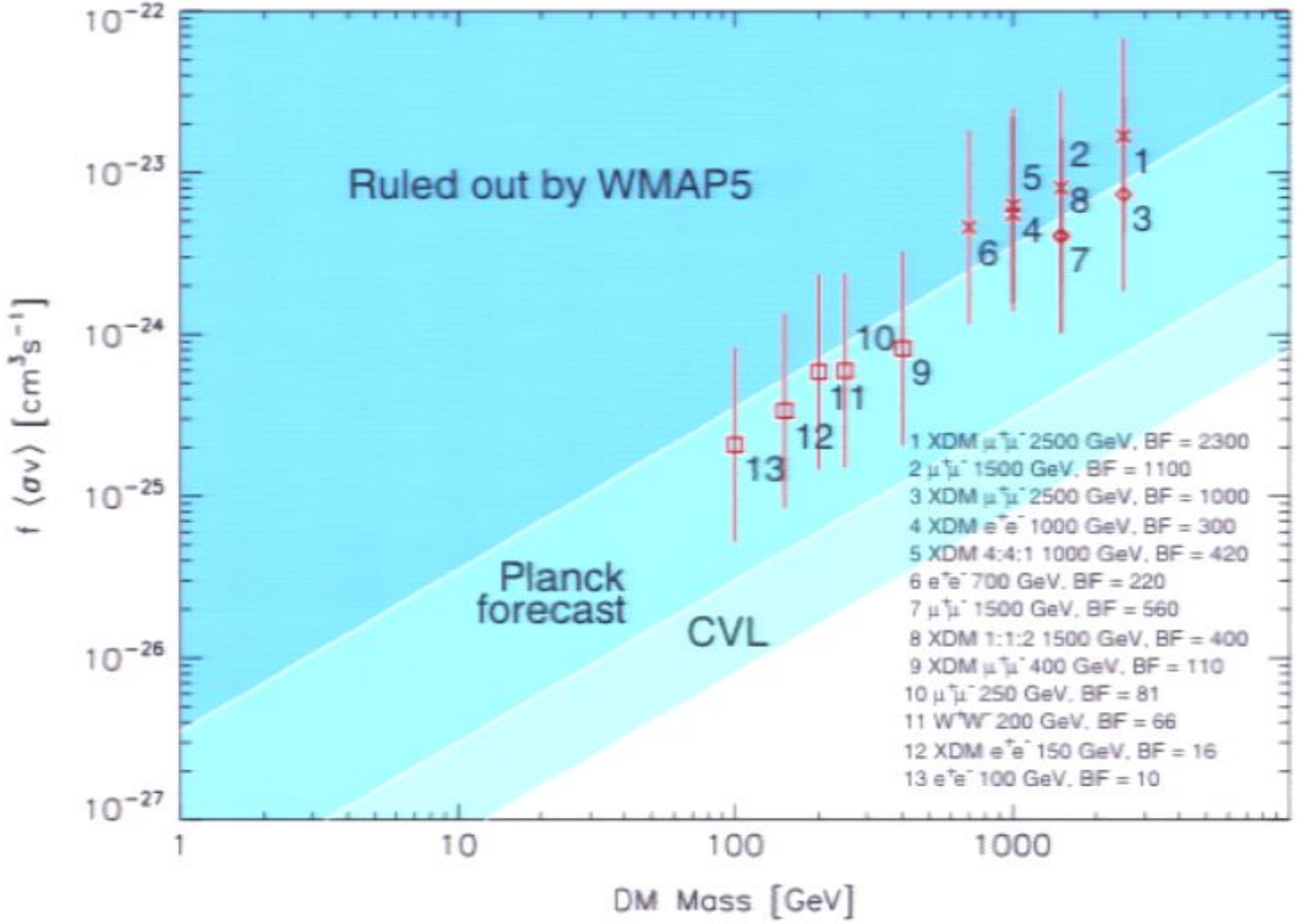
Annihilation in Galactic DM subhalos



Kistler & JSG 2010

see also Belikov & Hooper 2009;
Slatyer, Toro, Weiner 2011; ...

Constraints from the CMB



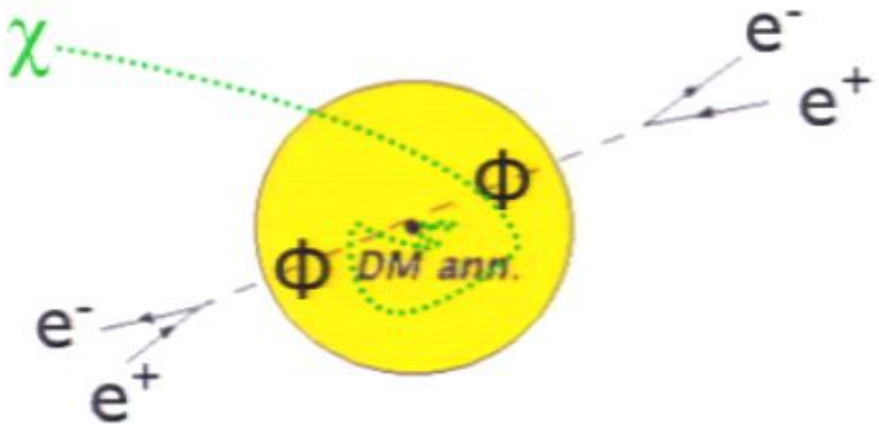
Slatyer, Padmanabhan, Finkbeiner 2009

see also Galli, Iocco, Bertone, Melchiorri 2009; Zavala, Vogelsberger, White 2010...

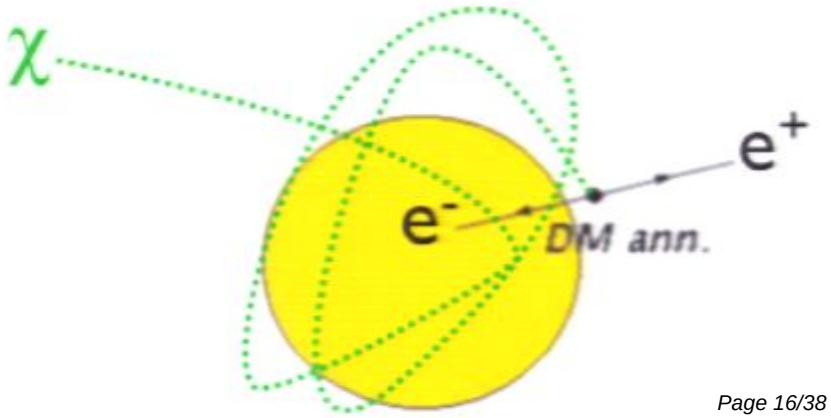
Solar CREs from DM annihilation

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



The Fermi Gamma-ray Space Telescope

- pair-production detector: detects charged particle events as well as gamma rays
- can identify cosmic-ray electron and positron events; in general cannot determine charge on an event-by-event basis*

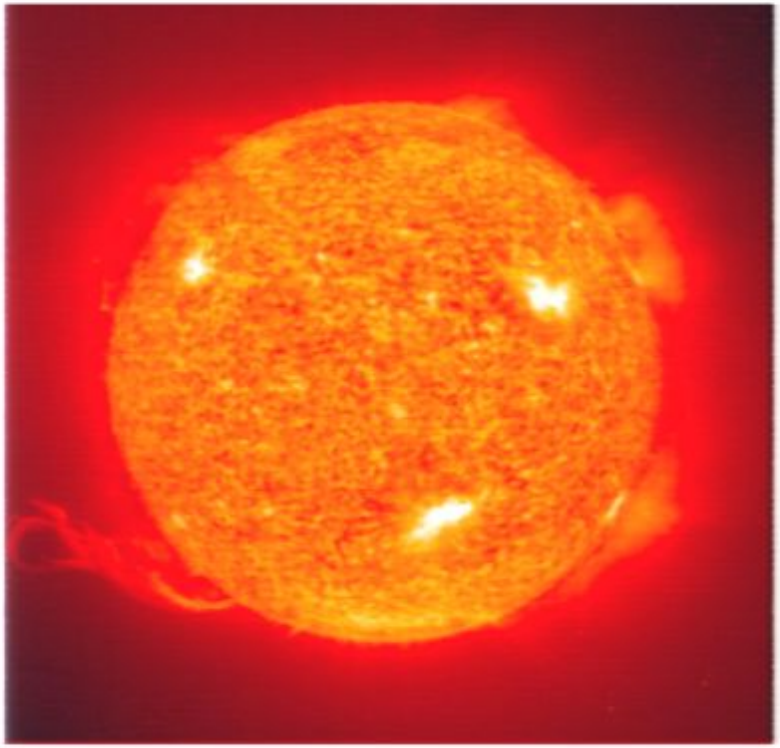
*position in the geomagnetic field can be used to select events by charge, as in Fermi positron spectrum measurement (Ackermann et al., 2011)

Credit: NASA/General Dynamics

Data selection

- ~10^6 CRE events (E > 60 GeV), from 1st year of operation

- analysis performed in ecliptic coordinates, in reference frame centered on the Sun



Data analysis

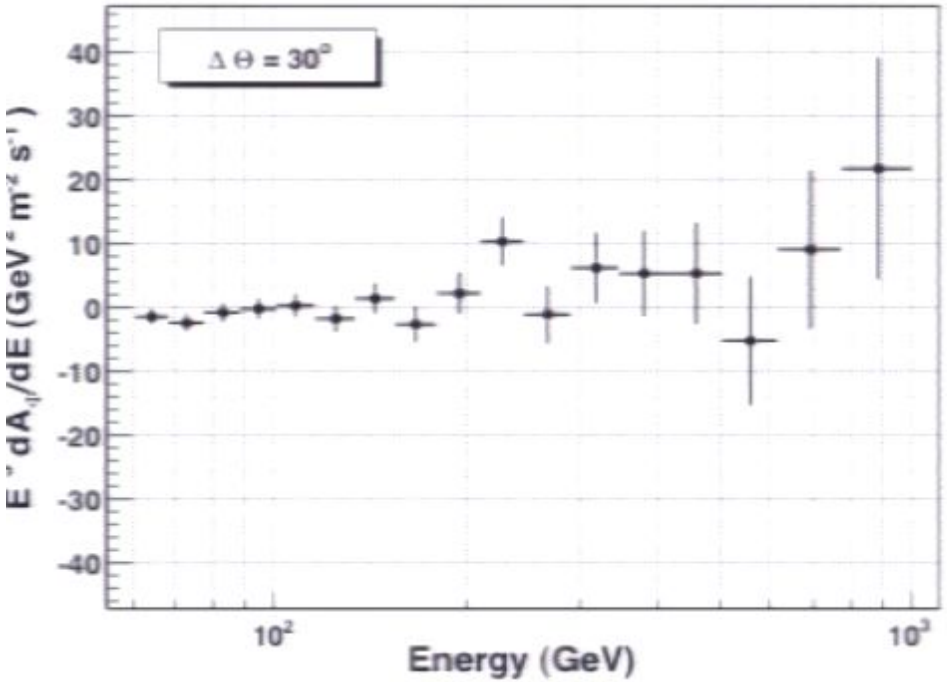
3 approaches used to search for flux excesses:

- flux asymmetry search: compare flux from the Sun and from a "fake" Sun in the opposite sky direction
- comparison with isotropic flux: a sample of isotropic CRE events was simulated using an event-shuffling technique; the real flux from the Sun and the simulated isotropic flux is compared
- spherical harmonics analysis: tests for CRE flux variations correlated with any sky direction and on different angular scales

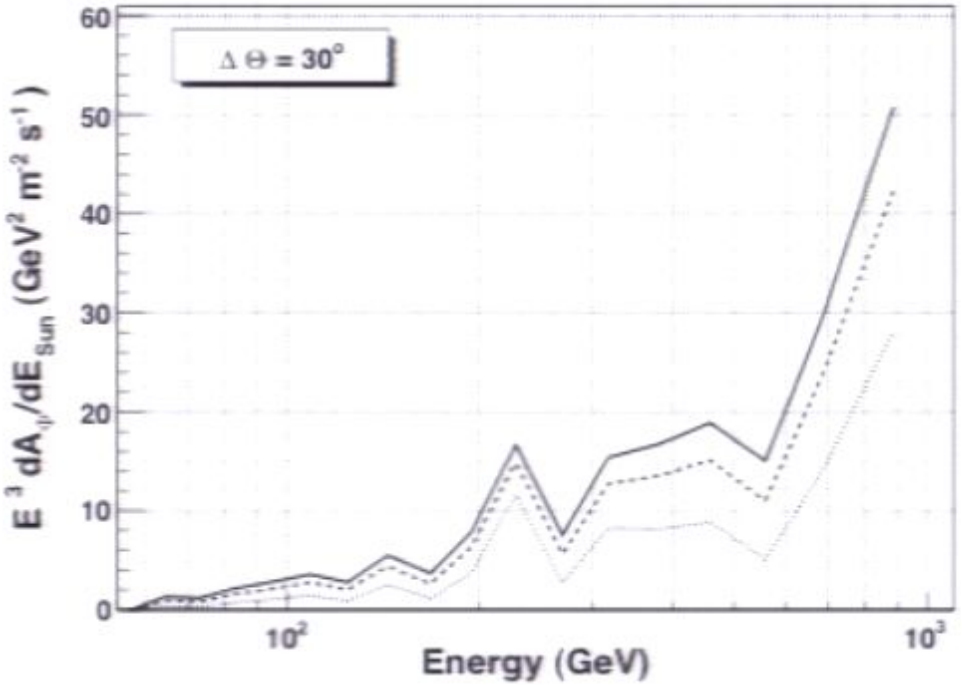
Flux asymmetry (real vs. fake Sun)

fluxes evaluated in a cone of 30° angular radius centered on the real or fake Sun

flux difference (real Sun - fake Sun)



flux upper limits (68%, 95%, 99% CL)

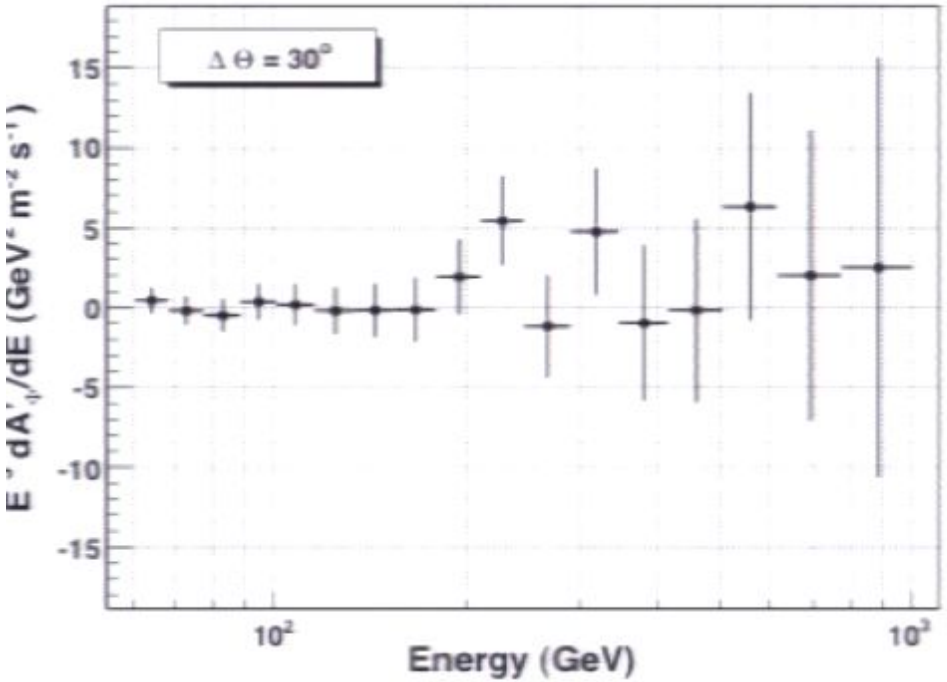


no flux excess detected in any energy bin at > 3σ

Comparison with isotropic flux

fluxes evaluated in a cone of 30° angular radius centered on the real Sun

lux difference (real Sun - simulated isotropic)



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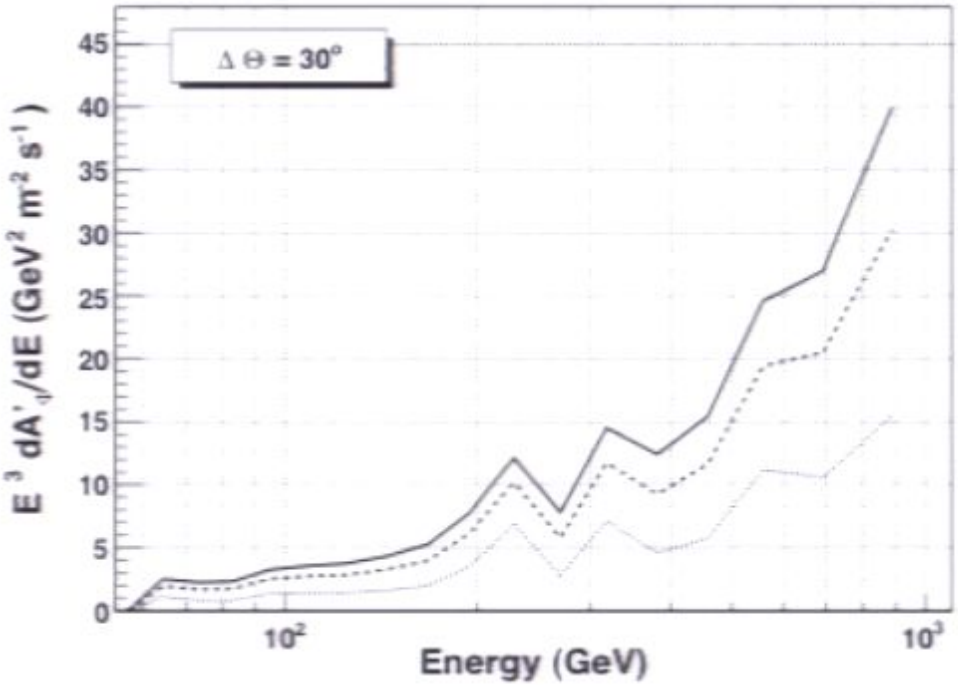

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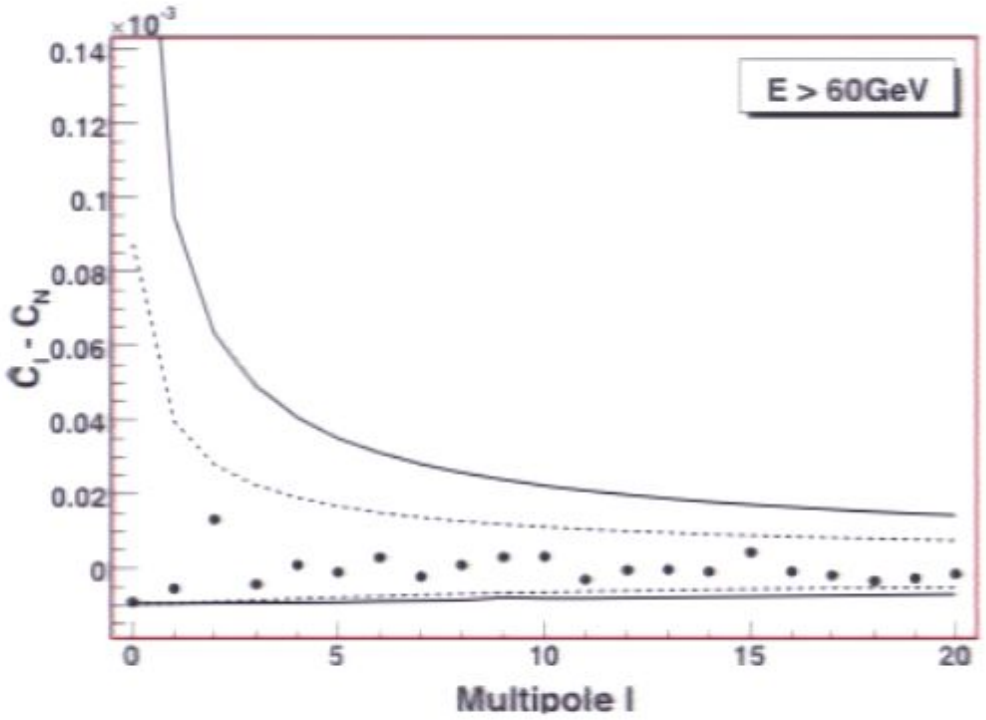
Spherical harmonics analysis

fluctuation angular power spectrum of events E>60 GeV



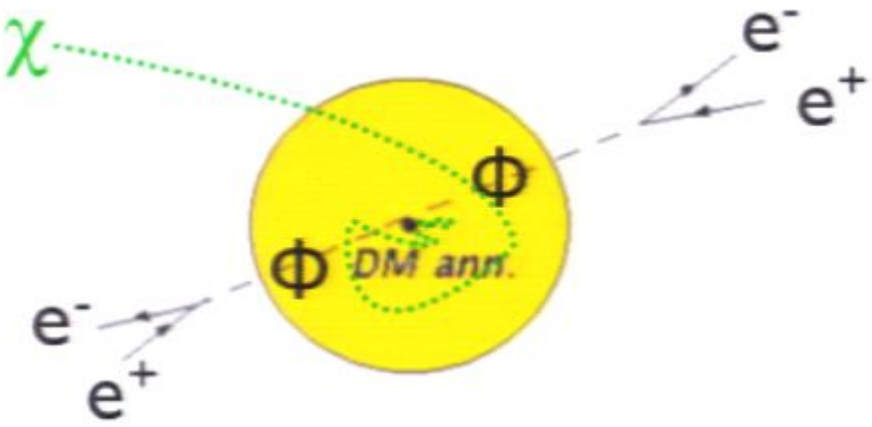
dotted and dashed lines show 3σ and 5σ limits on probability distribution of shot noise C_N

no significant angular power detected in this multipole range

Solar CRE fluxes from dark matter

Intermediate state scenario: overview

- DM is captured by the Sun via elastic scattering, continues to scatter and lose energy, and sinks to the core where it annihilates



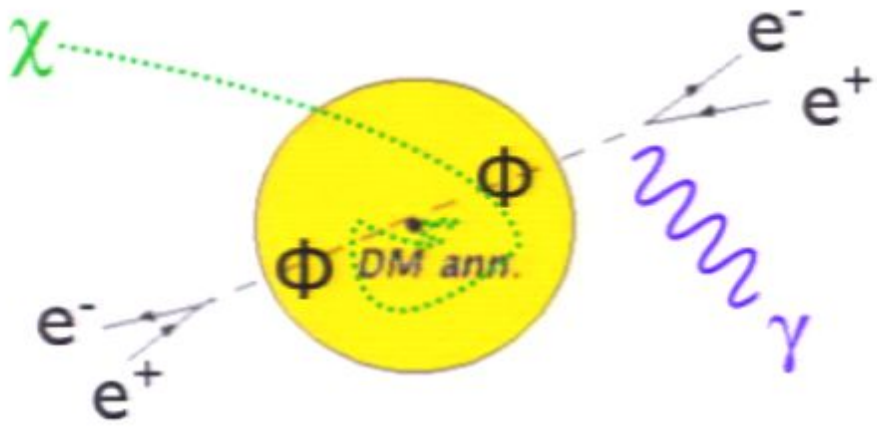
- assume DM annihilates to a new light scalar Φ which then decays to an electron and positron pair

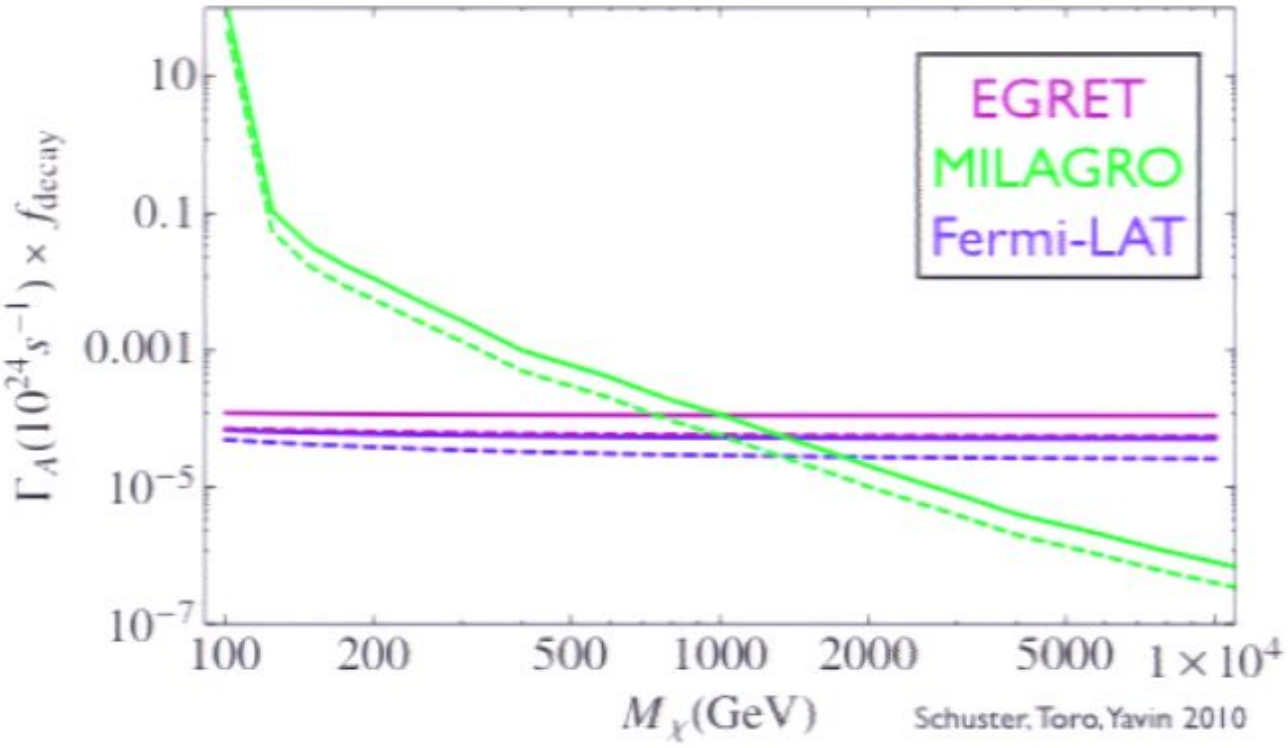
$$\chi\chi \rightarrow \phi\phi \qquad \phi \rightarrow e^+e^-$$

- the Φ are assumed to have mass less than a few GeV, while the DM has mass of ~ 100 GeV - few TeV, so the Φ are relativistic
- many Φ escape the Sun before decaying, so the CREs they produce are observable
- the addition of the new light scalar is related to the mechanism used to generate Sommerfeld enhancement; this class of models is often considered as a possible explanation for the observed excesses in CREs by PAMELA and ATIC/Fermi

Existing gamma-ray constraints

- *observable* gamma-rays from the Sun (from FSR) are also produced in this scenario
- solar gamma-ray measurements constrain decay rate of Φ outside sun





see also Batell, Pospelov, Ritz, Shang 2010; ...

CRE flux from intermediate state scenario

decay rate of Φ per volume

selects energy of observed CREs

$$\frac{dN}{dt\,dA\,d\cos\theta_{\rm det}dE_{\rm det}}(\theta_{\rm det}, E_{\rm det}) = \int_0^\infty dR\,\frac{dN}{dV\,dt}\,\frac{d\Gamma}{d\cos\theta_{\rm det}}\delta(E_{\rm det} - E),$$

line-of-sight distance

angular distribution of CREs

Φ decay rate per volume

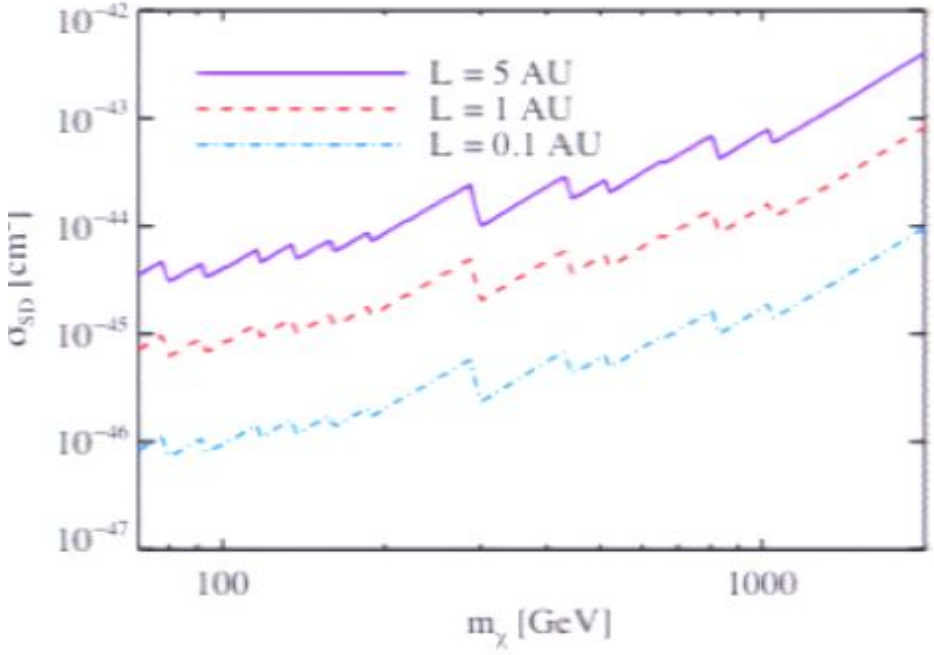
$$\frac{dN}{dV\,dt}\left(r\left(\theta_{\rm det}, R\right)\right) = 2\,\frac{C_{\odot}e^{-r/L}}{4\pi r^2 L}$$

- assume equilibrium (for every 2 particles that are captured, 2 annihilate)
- calculate solar capture rate with DarkSUSY
  - proportional to the elastic scattering cross-section
  - depends on DM particle mass
- L is decay length, set by lifetime of Φ and energy of Φ

Limits on elastic scattering cross-section

assuming annihilation to CREs via an intermediate state

spin-dependent scattering



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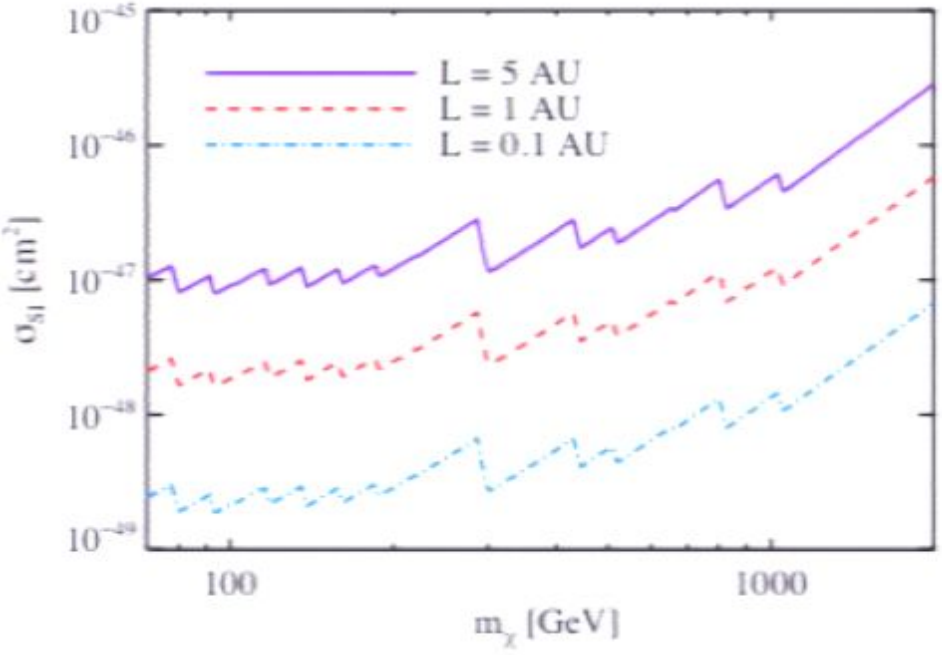

solar CRE flux limits correspond to constraints on the rate of decay to CREs outside the Sun that are ~ 2-4 orders of magnitude stronger than constraints on the associated FSR derived from solar gamma-ray data


f decay to
onger than
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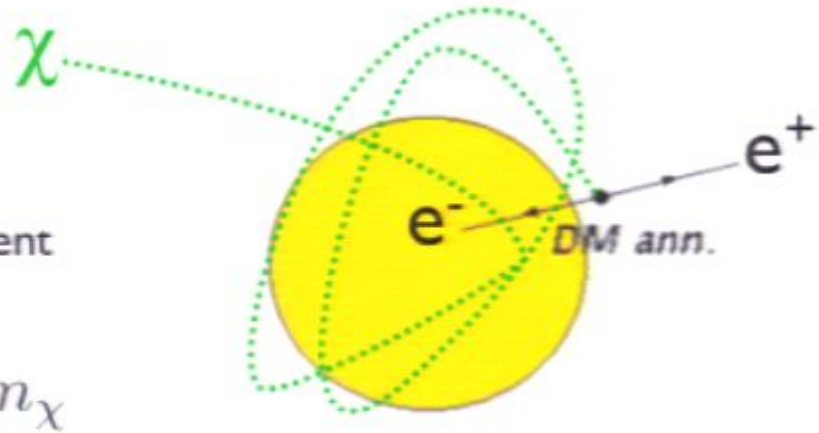
Inelastic dark matter scenario: overview

- DM is captured by the Sun via inelastic scattering

$$\chi + N \to \chi^\star + N$$



- inelastic scattering can only occur if the DM has sufficient energy:

$$E \geq \delta(1 + m_\chi/m_N) \qquad \delta = m_{\chi^\star} - m_\chi$$

- the mass splitting (delta) is typically assumed to be ~ 100 KeV
- after only a few scatterings the DM doesn't have enough energy to continue scattering and so, rather than sink to the core, it remains on large orbits which take it outside the surface of the Sun
- a non-negligible fraction of DM can be accumulated outside the surface of the Sun in this scenario, and annihilations outside the Sun can produce an observable CRE flux
- iDM models could potentially explain the inconsistent results of DAMA/LIBRA and CDMS (and other direct-detection experiments), e.g. Smith & Weiner 2001; Chang, Kribs, Tucker-Smith, Weiner 2009

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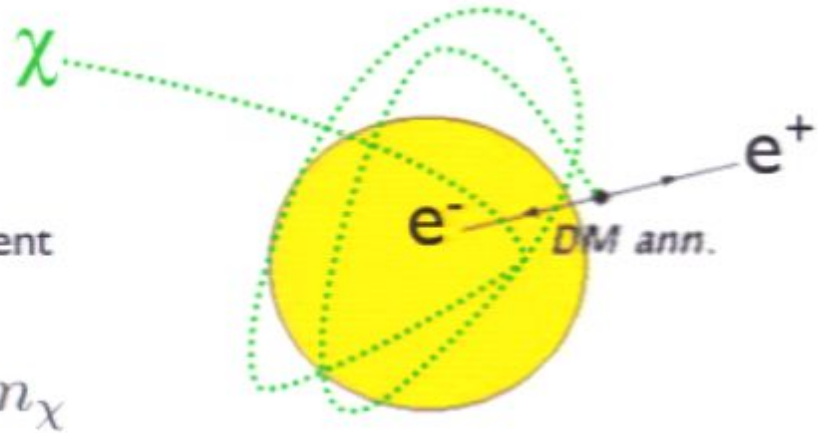

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Flux from iDM outside the Sun

- isotropic flux (but *observable* flux is a factor of 2 smaller b/c CREs produced on the opposite side of Sun can't reach us)

$$F = 2\,\frac{\Gamma_{\mathrm{A,out}}}{4\pi D_{\odot}^{2}}$$

- annihilation rate is proportional to fraction of captured dark matter particles outside the Sun at a given time; assume capture/annihilation are in equilibrium

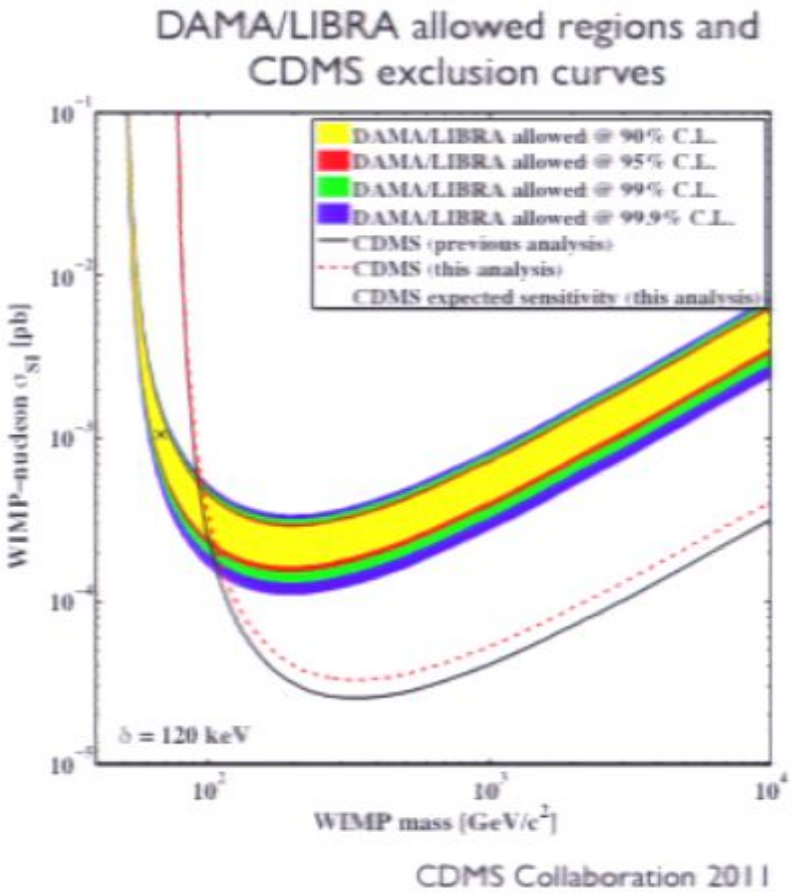
$$\Gamma_{\mathrm{A,out}} = f_{\mathrm{out}}\Gamma_{\mathrm{A}} = \frac{1}{2} f_{\mathrm{out}} C_{\odot}$$

- f_{out} has been calculated by Schuster et al. 2010, iDM capture rate calculated by Nussinov et al. 2009 and Menon et al. 2010

- dark matter assumed to annihilate at rest so CRE flux is mono-energetic with E = mass of the dark matter particle

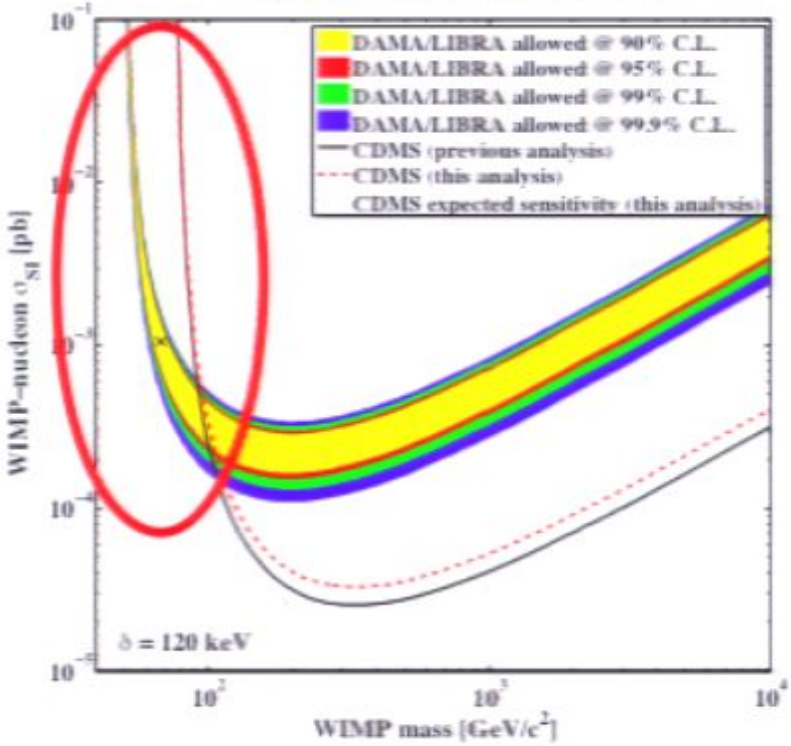
- in this scenario we account for the energy resolution of the LAT since the limits for masses near the energy bin edges are weakened by spreading the signal over more than one bin

Limits on inelastic scattering cross-section



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:

$m_\chi \leq 100$ GeV

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

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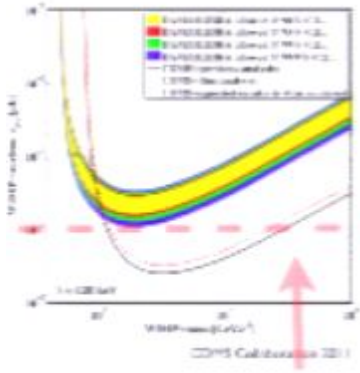
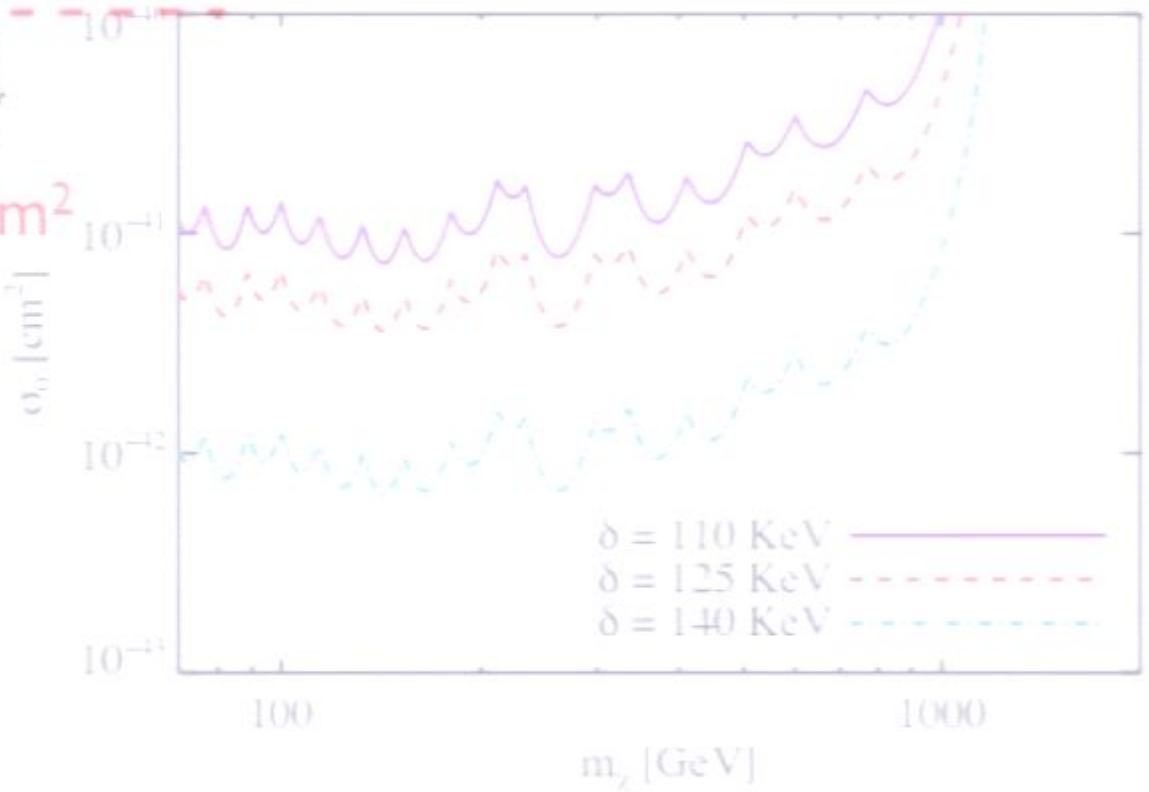


10^{-40} cm^2

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



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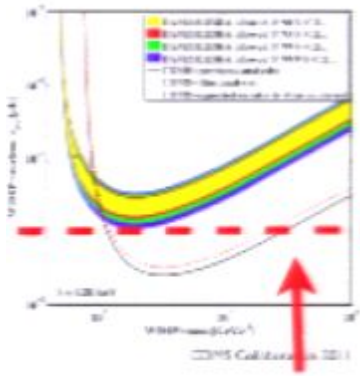
solar CRE constraints exclude by ~ 1-2 orders of magnitude all of the parameter space compatible with an inelastic DM explanation of DAMA/LIBRA and CDMS for DM masses greater than ~ 70 GeV, assuming DM annihilates to CREs

Limits on inelastic scattering cross-section



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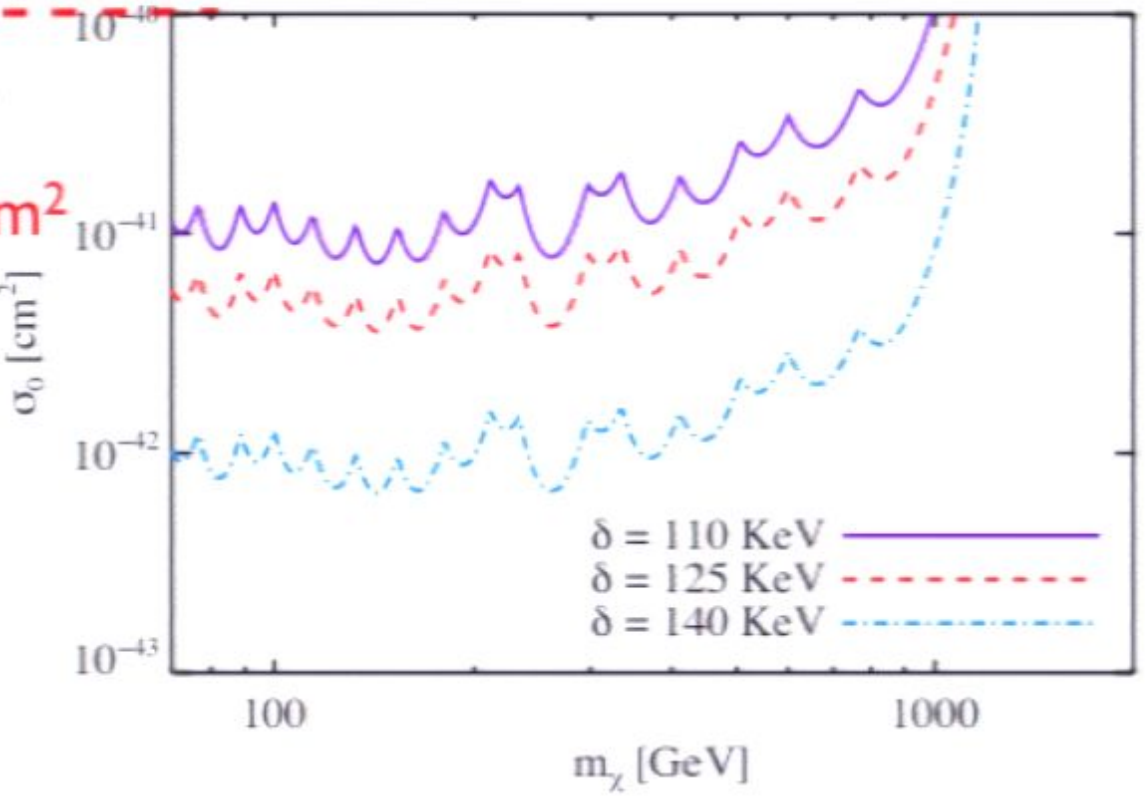

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Summary

- for models in which dark matter annihilates to CREs via an intermediate state:

  solar CRE constraints on the DM-nucleon elastic scattering cross-section correspond to significantly stronger bounds on the rate of CRE decay outside the Sun than existing constraints on associated FSR emission from solar gamma-ray data

- for inelastic dark matter models:

  the CRE constraints exclude all of the parameter space for DM masses above ~ 70 GeV that can reconcile the results of DAMA/LIBRA and CDMS, assuming DM annihilates to CREs