



Fermi
Gamma-ray Space Telescope



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

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with
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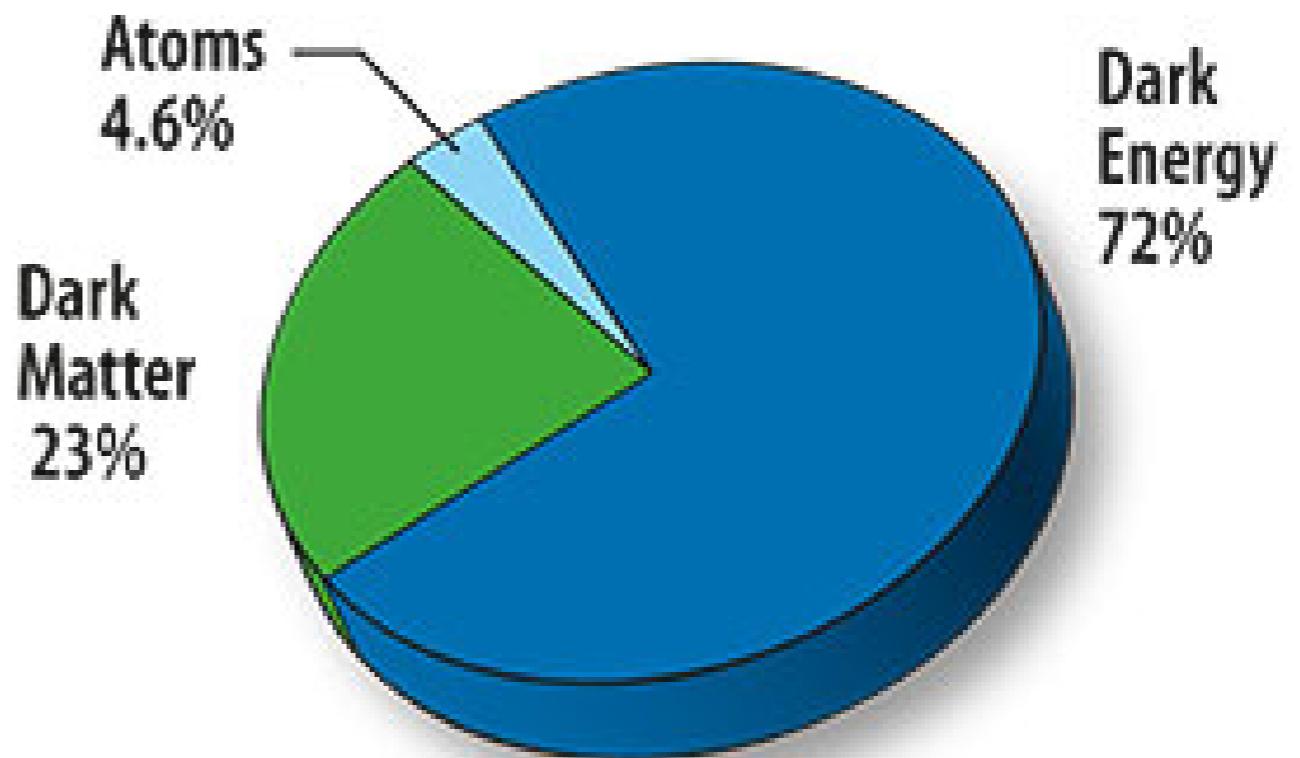
on behalf of
the Fermi LAT Collaboration

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

The nature of dark matter

Observational evidence indicates:

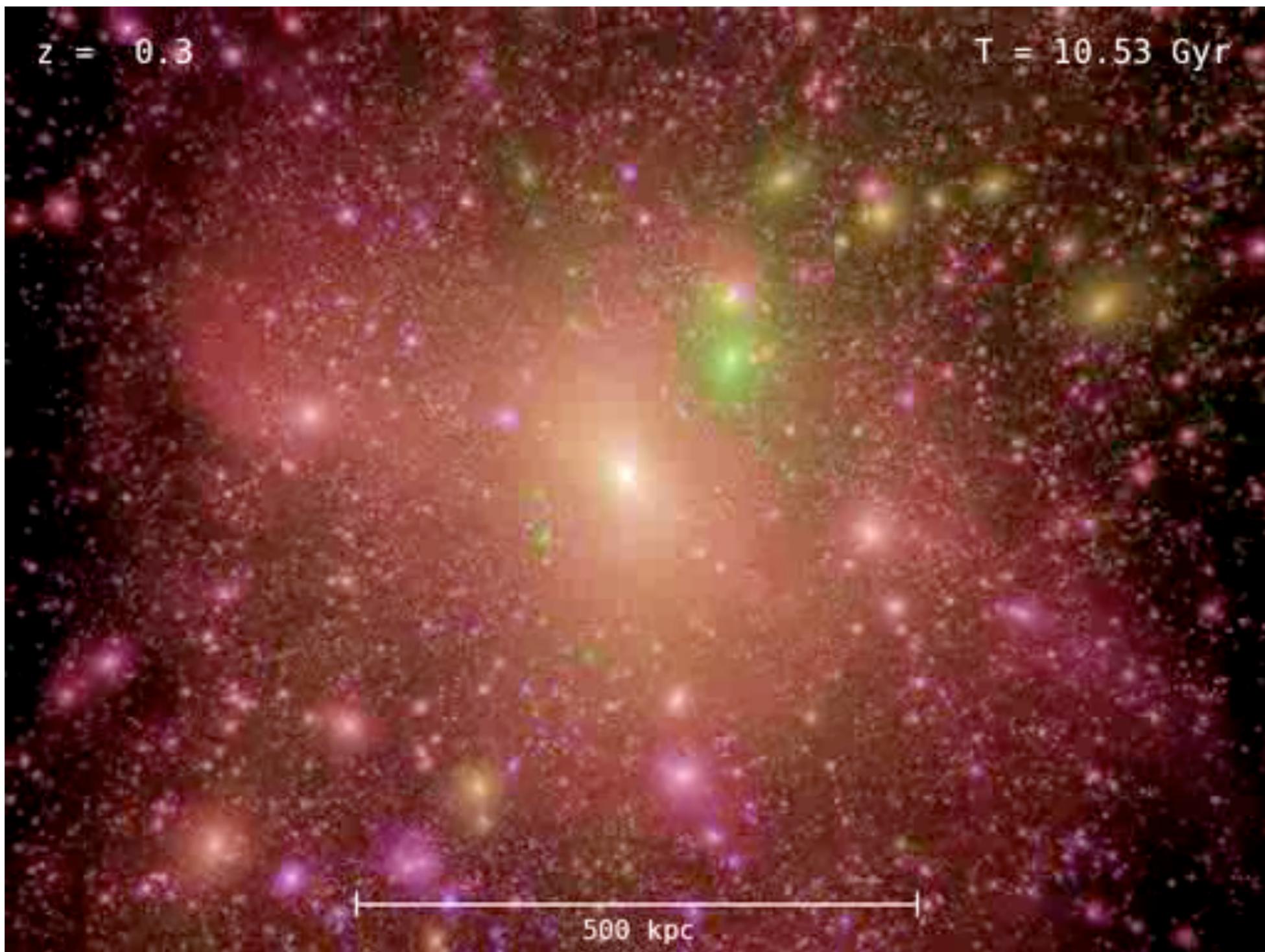
- non-baryonic
- neutral
- virtually collisionless



Credit: NASA / WMAP Science Team

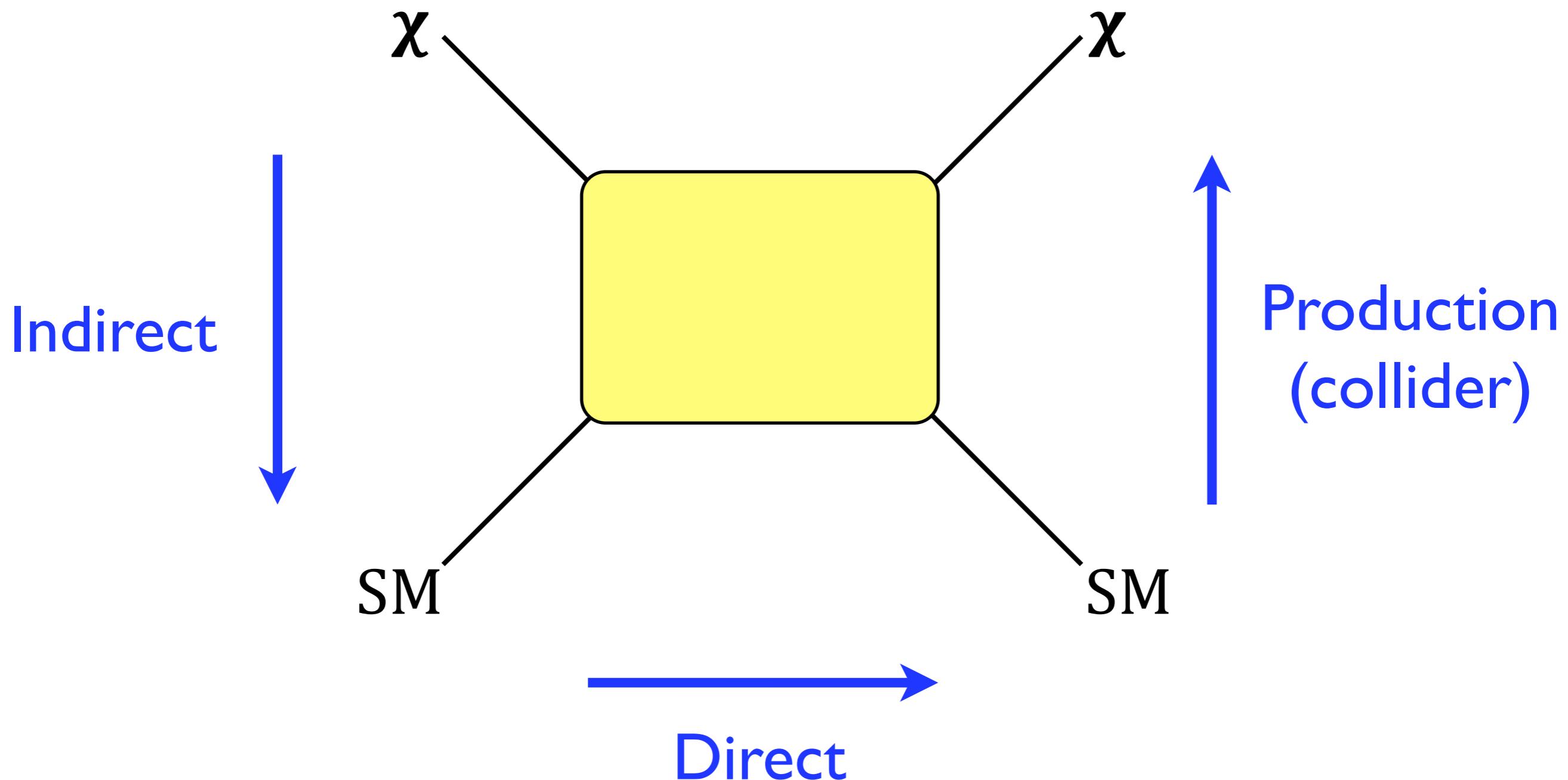
- Additional assumptions for this talk:
 - dark matter is a weakly-interacting massive particle (WIMP)
 - GeV - TeV mass scale
 - can pair annihilate to produce standard model particles

The dark matter distribution

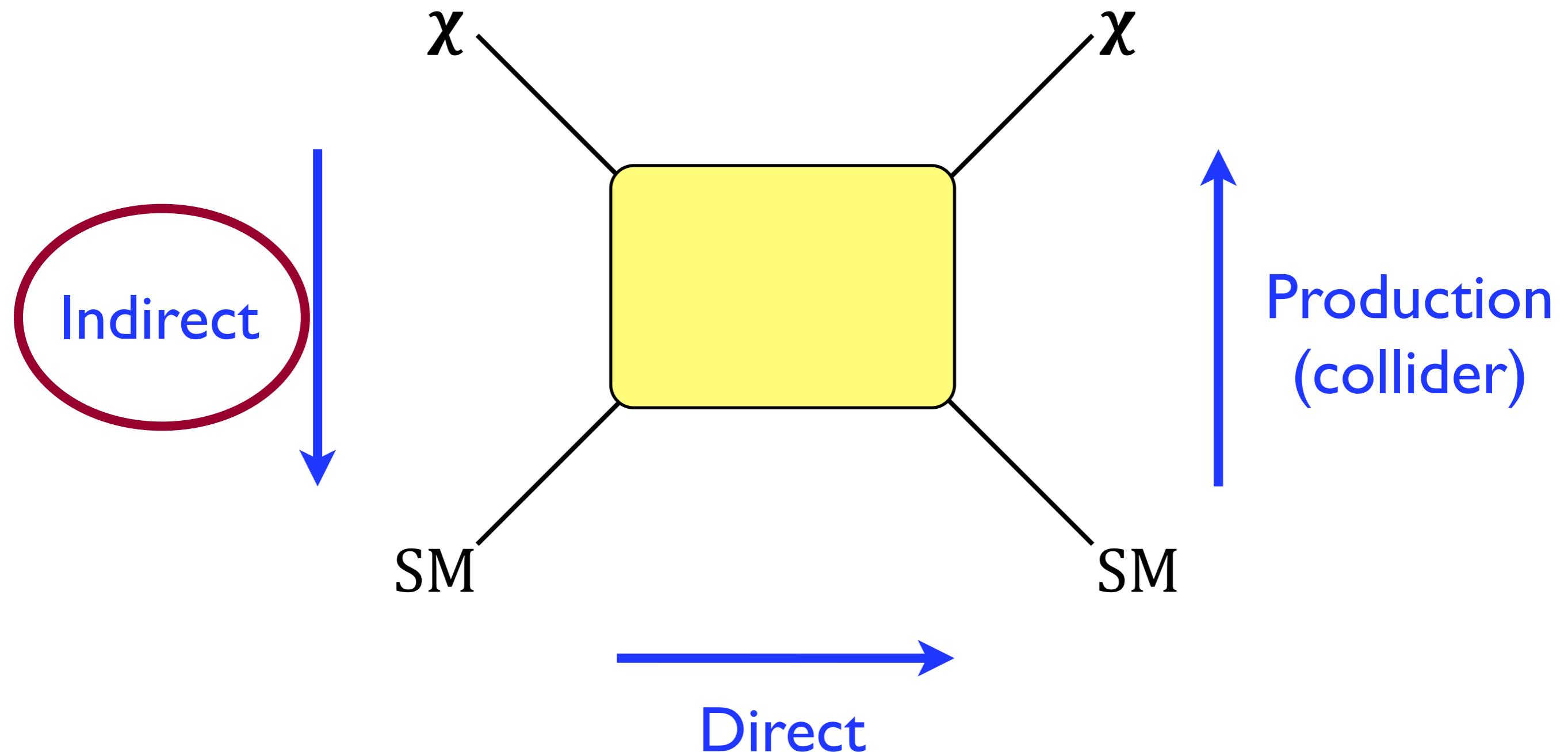


Credit: Springel et al. (Virgo Consortium)

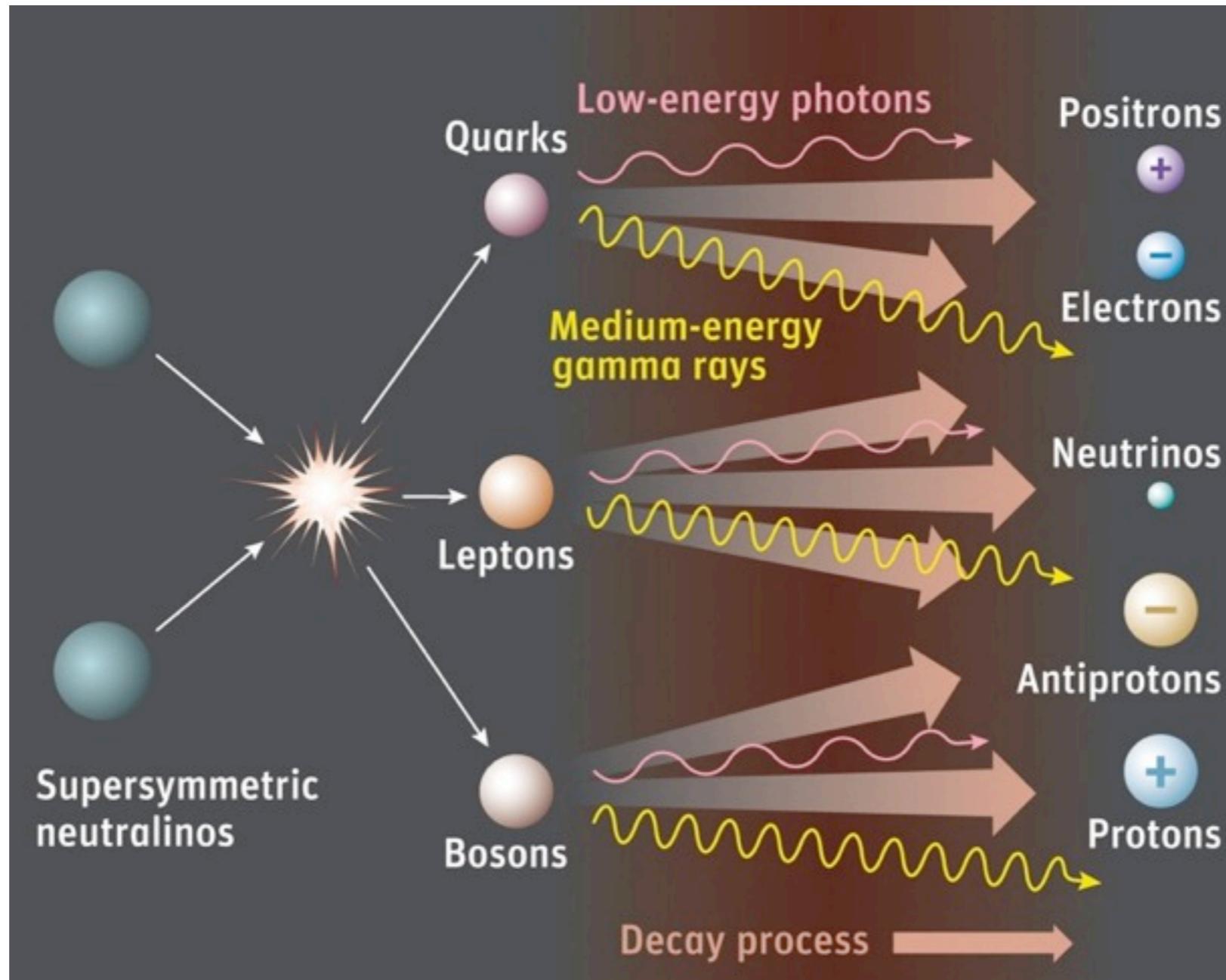
How to detect particle dark matter?



How to detect particle dark matter?



Indirect dark matter signals



Credit: Sky & Telescope / Gregg Dinderman

- annihilation or decay of dark matter can produce a variety of potentially detectable Standard Model particles

Indirect messengers

	Instruments	Advantages	Challenges
Gamma-ray photons	Fermi, ACTs (HESS, VERITAS, MAGIC)	point back to source, spectral signatures	backgrounds, attenuation
Neutrinos	IceCube, Super-K	point back to source	low statistics, backgrounds
Charged particles	PAMELA, AMS(-02), ATIC, HESS (and other ACTs), Fermi	antimatter hard to produce astrophysically	diffusion, propagation uncertainties, don't point back to sources

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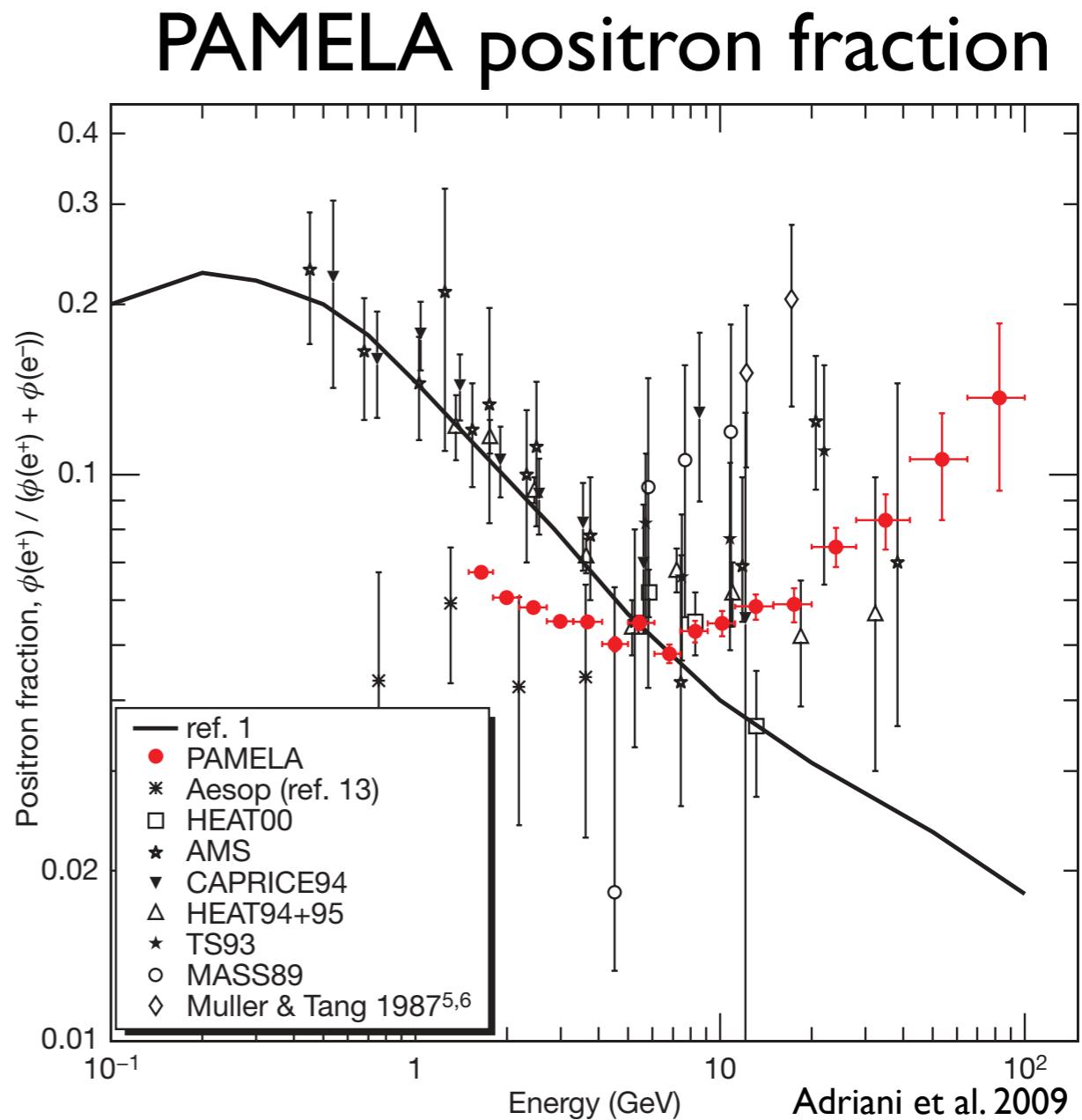
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Unexpected features in the cosmic-ray e^\pm spectra?

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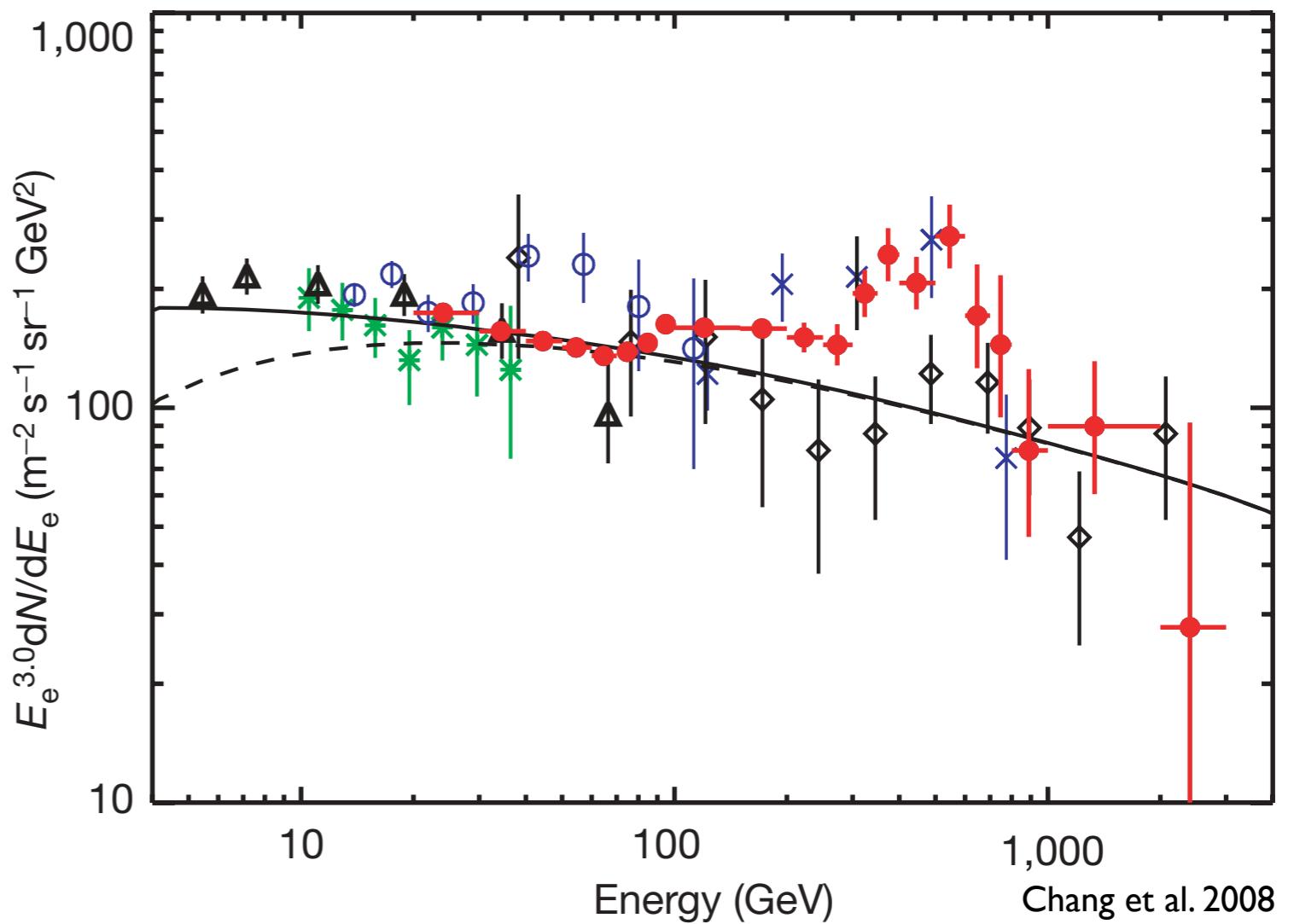
- rise in local positron fraction above ~ 10 GeV disagrees with conventional model for cosmic rays (secondary positron production only)



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

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

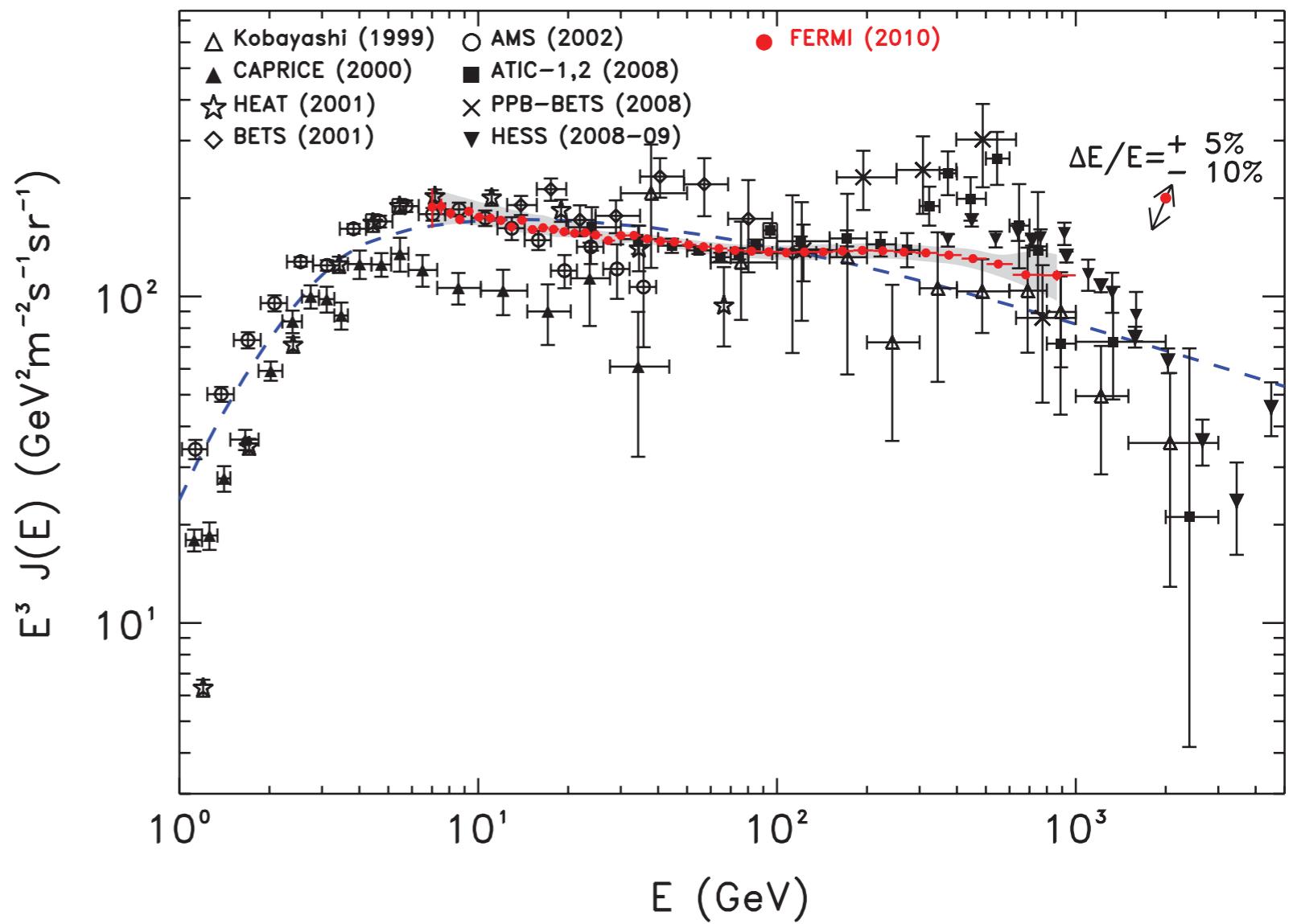
ATIC electron + positron spectrum



Unexpected features in the cosmic-ray e^\pm 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

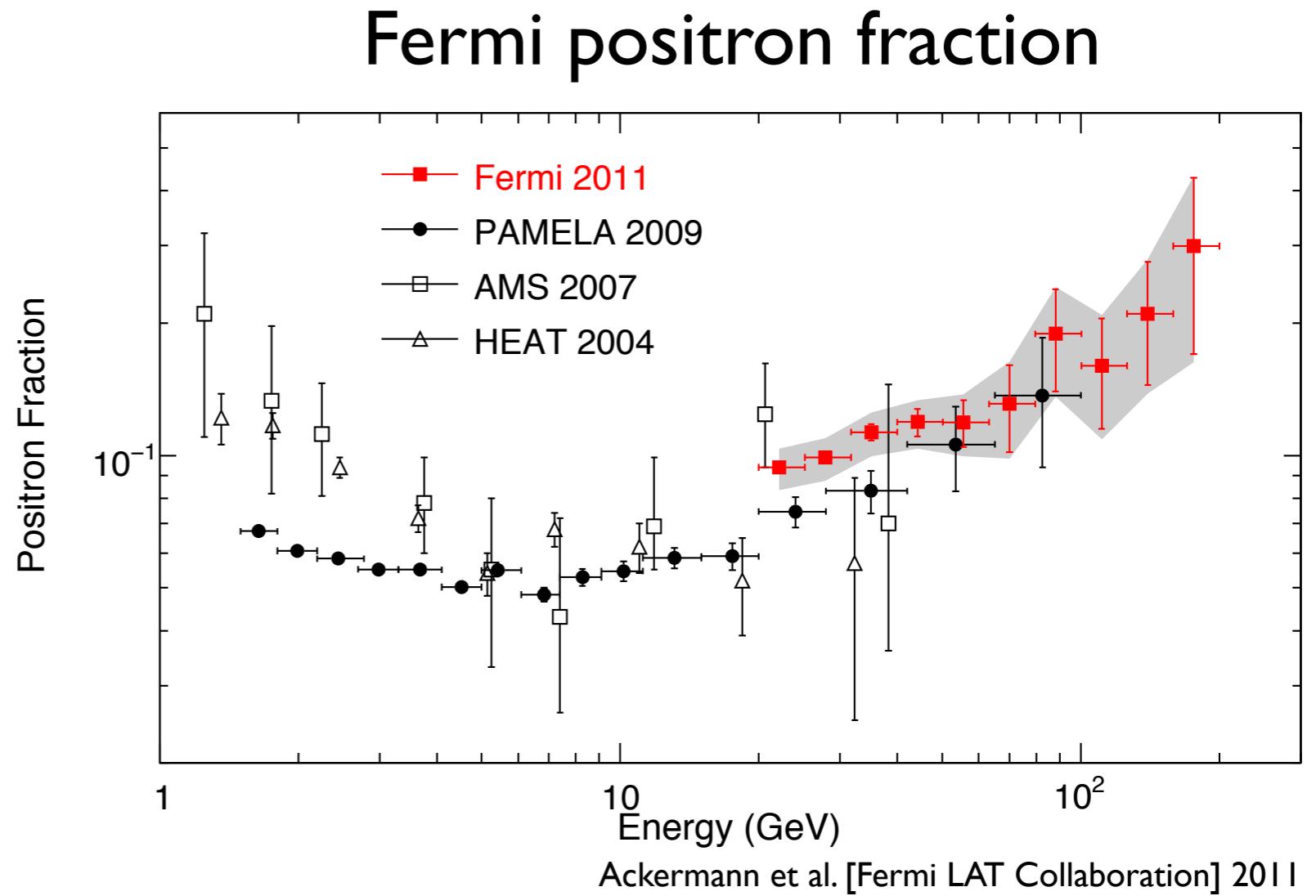
Fermi electron + positron spectrum



Ackermann et al. [Fermi LAT Collaboration] 2010

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

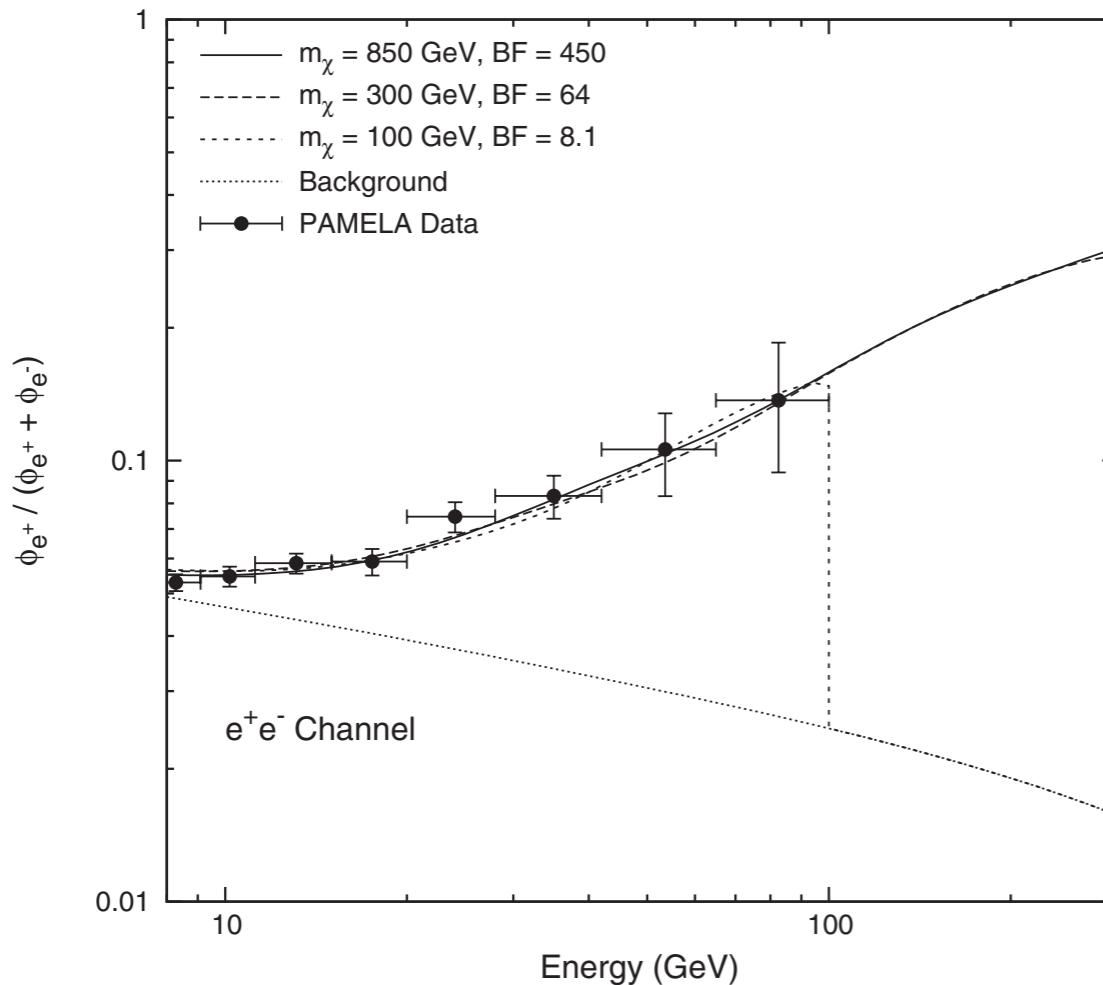
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- less prominent feature seen in Fermi cosmic ray electron/positron spectrum
- Fermi positron fraction agrees with PAMELA result, extends to higher energies



Hints of a dark matter signal?

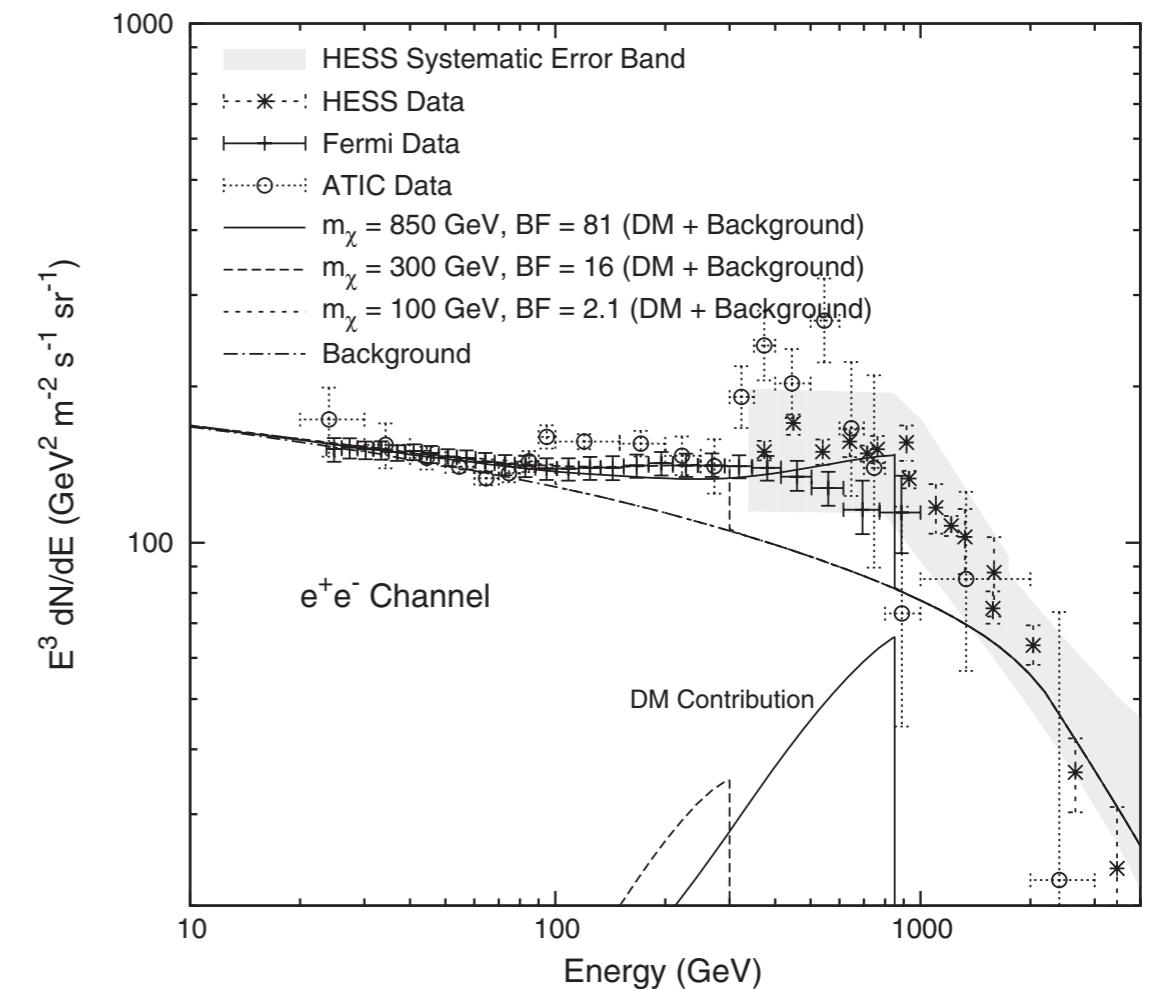
sparked interest in DM explanations (e.g., Arkani-Hamed et al. 2009; Lattanzi & Silk 2009; Cirelli et al. 2009; Cholis et al. 2008; Grasso et al. 2009;...)

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



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

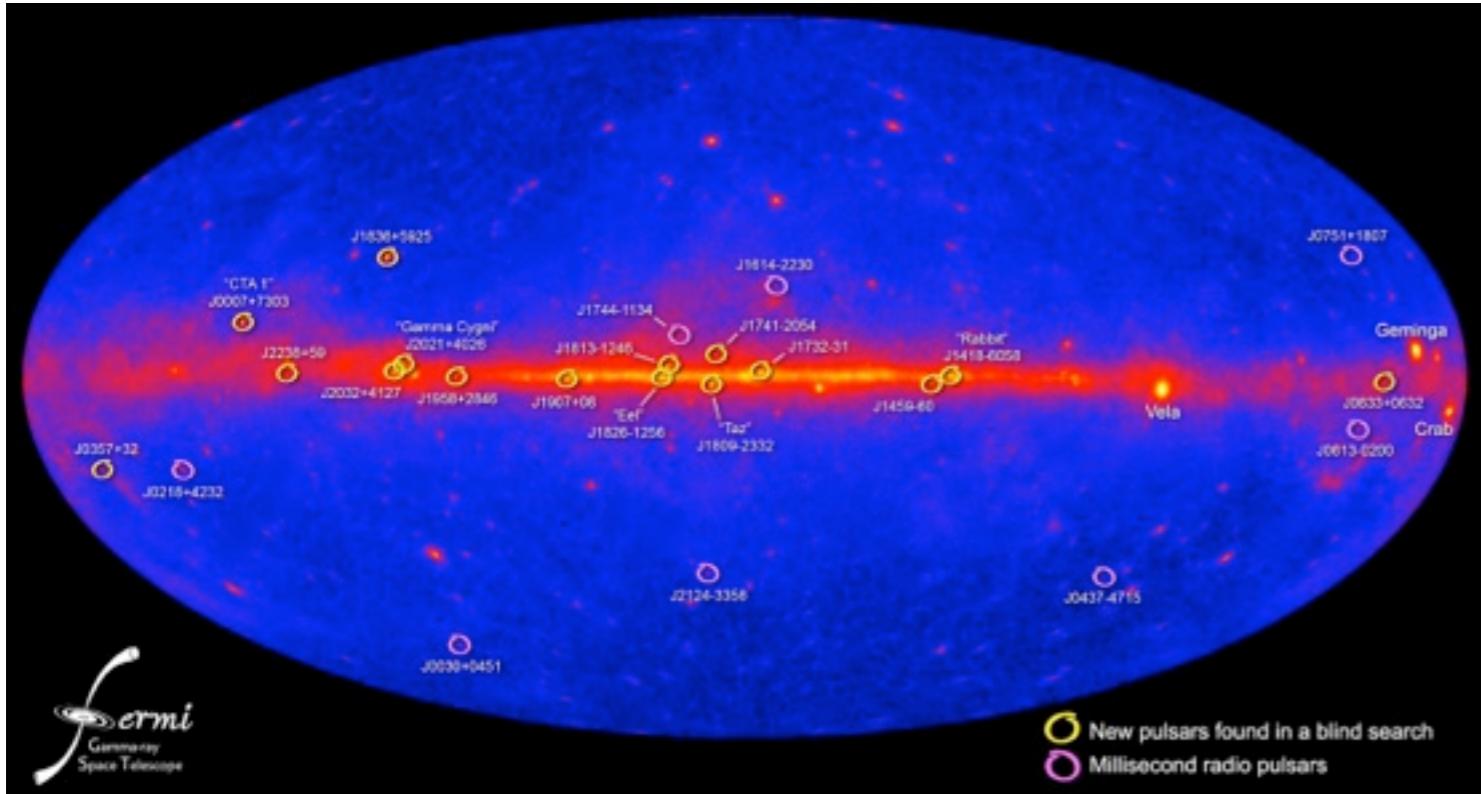
Ilias Cholis,¹ Gregory Dobler,² Douglas P. Finkbeiner,² Lisa Goodenough,¹ and Neal Weiner¹



Cholis et al 2008

Non-DM explanations?

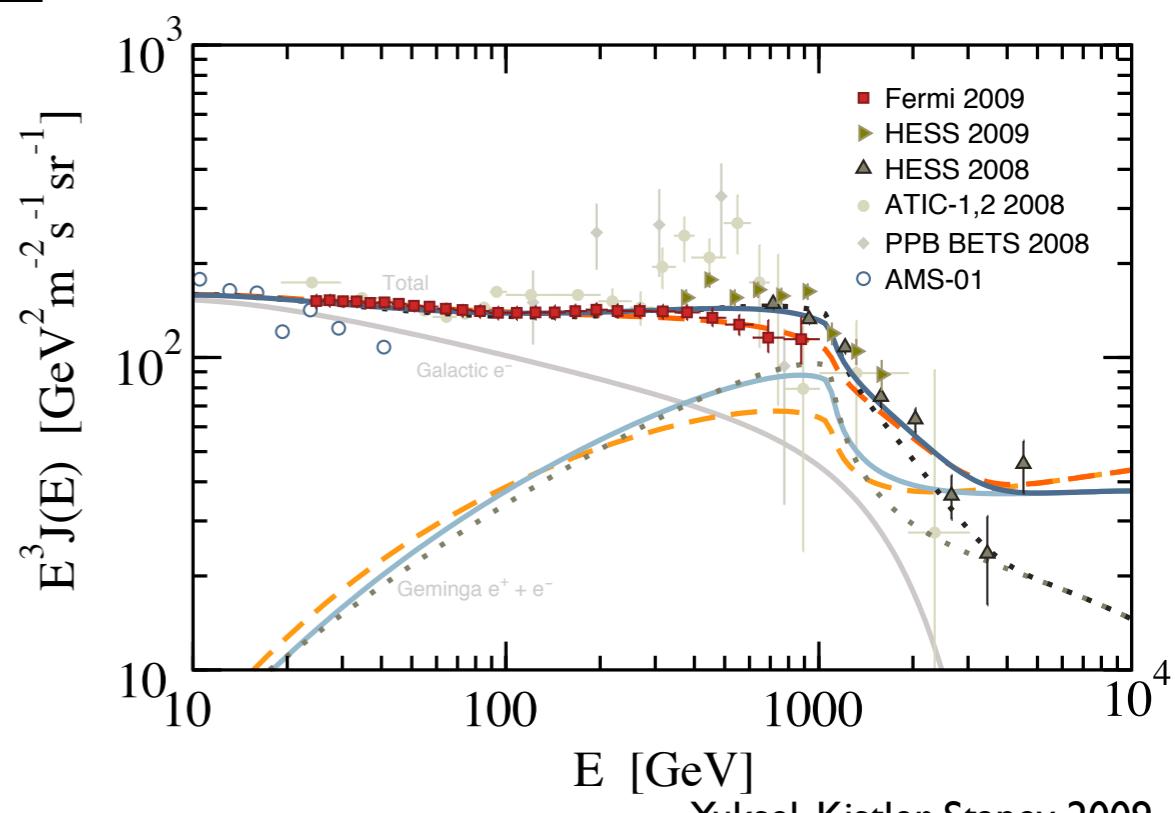
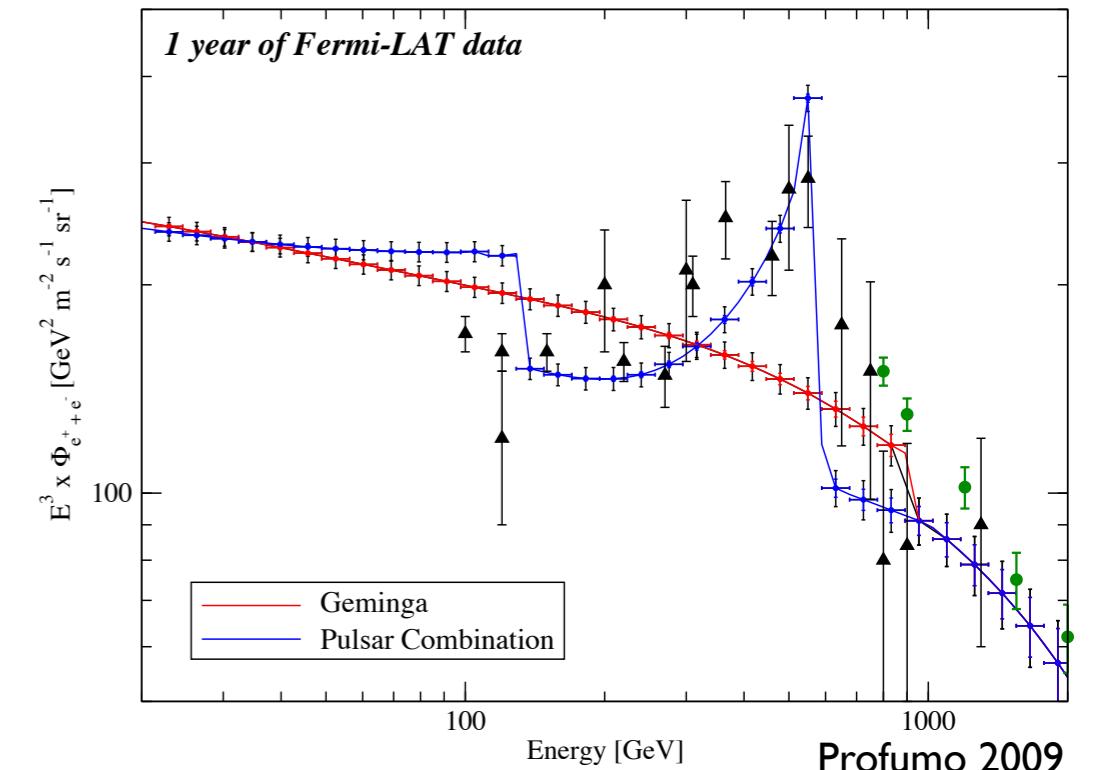
Pulsar contributions to CRE spectra



Credit: NASA/DOE/Fermi LAT Collaboration

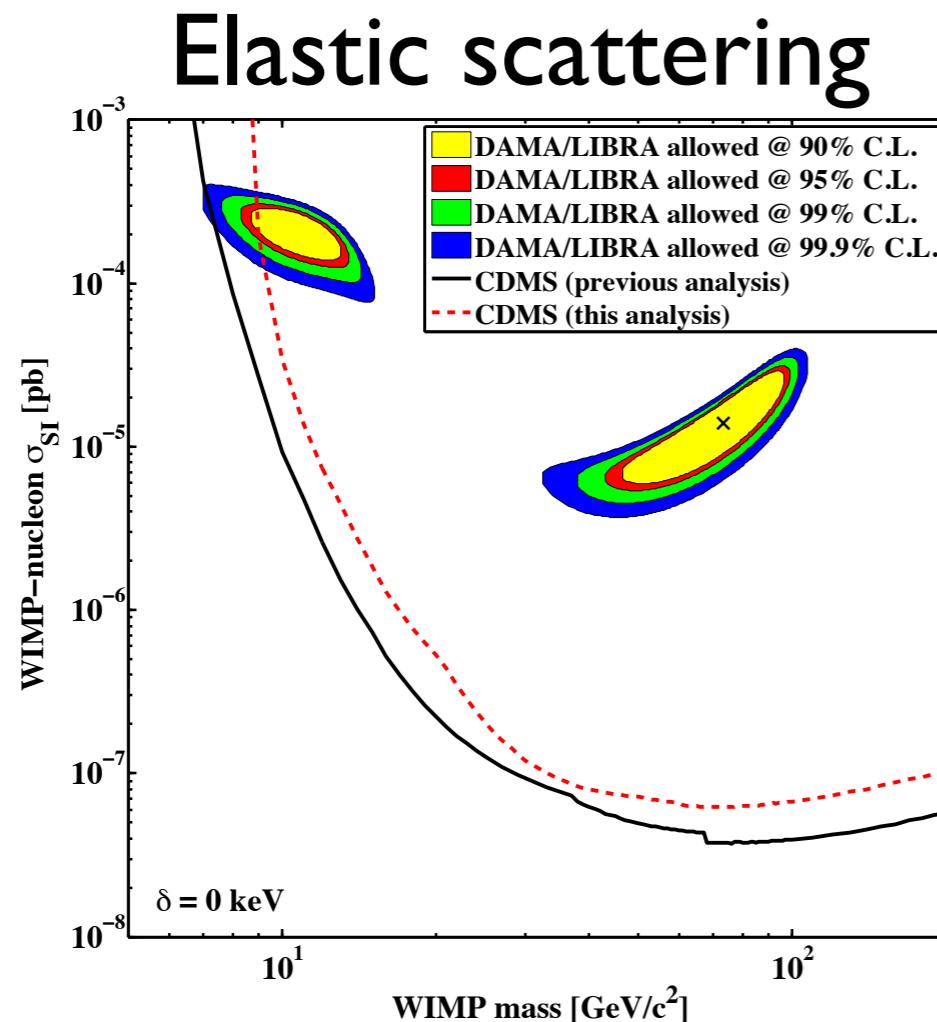
astrophysical explanations:

- pulsars (e.g., Yuksel, Kistler, & Stanev 2009; Hooper, Blasi, & Serpico 2009; Profumo 2009; Grasso et al. 2009;...)
- SNR (e.g., Blasi & Serpico 2009)



Yuksel, Kistler, Stanev 2009

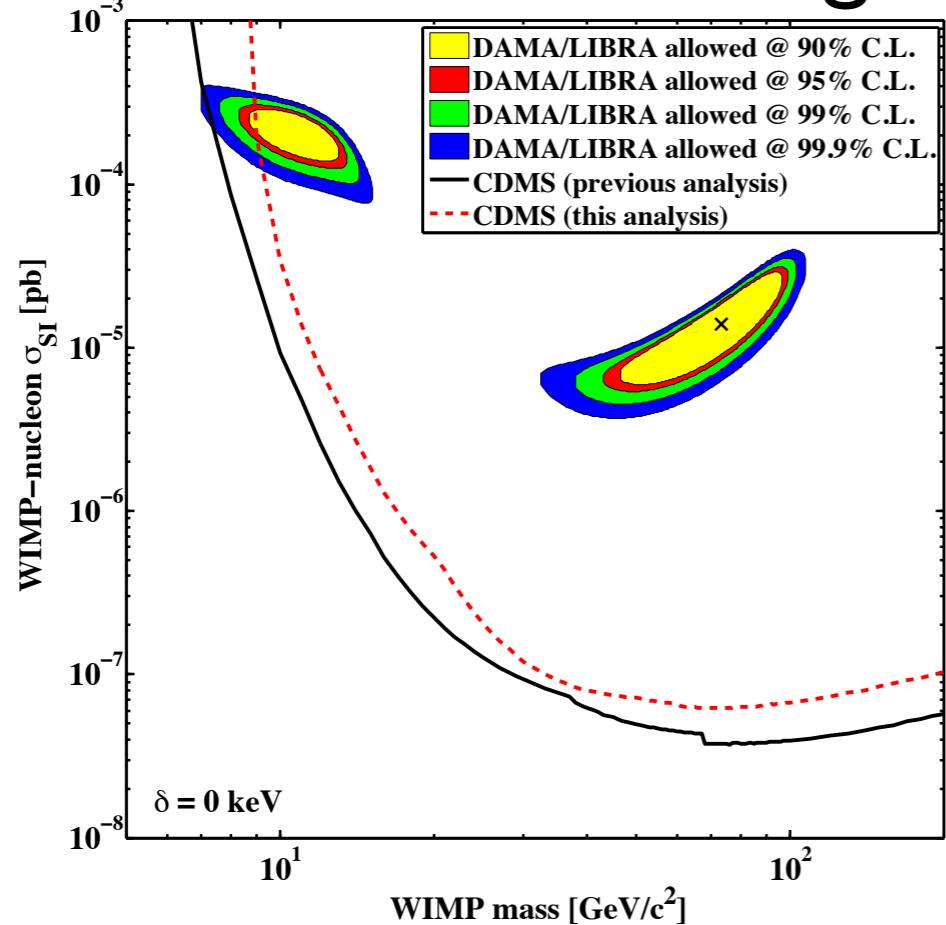
Meanwhile... in direct detection news



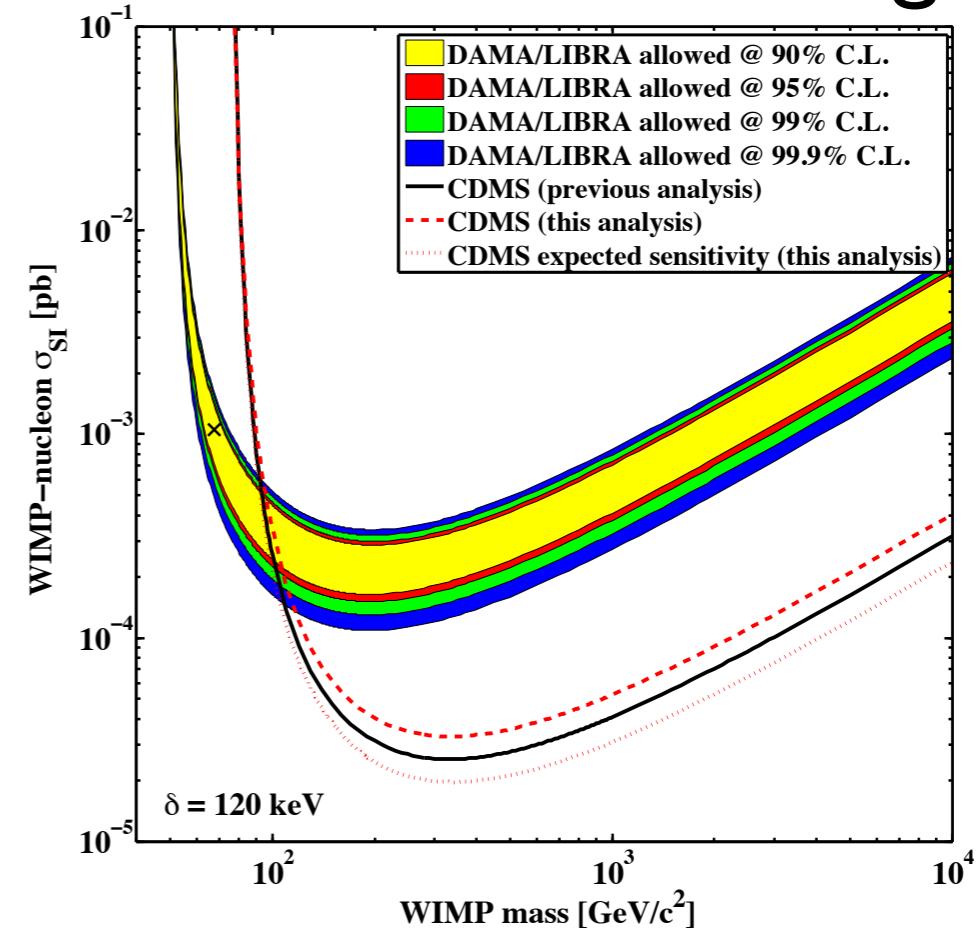
- CDMS limits exclude DAMA/LIBRA signal region for standard WIMP scenario

Meanwhile... in direct detection news

Elastic scattering



Inelastic scattering



Ahmed et al. [CDMS Collaboration] 2011

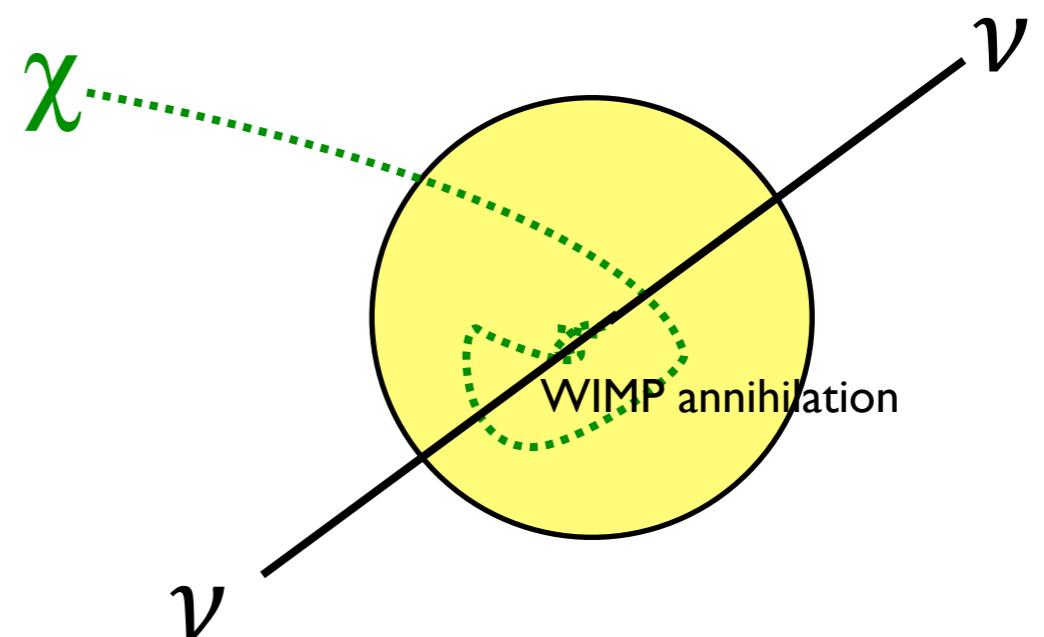
- CDMS limits exclude DAMA/LIBRA signal region for standard WIMP scenario

- it was proposed that the experiments could be reconciled if dark matter scatters *inelastically* (Tucker-Smith and Weiner, 2001)

Solar CREs from DM annihilation

the standard WIMP capture/annihilation scenario

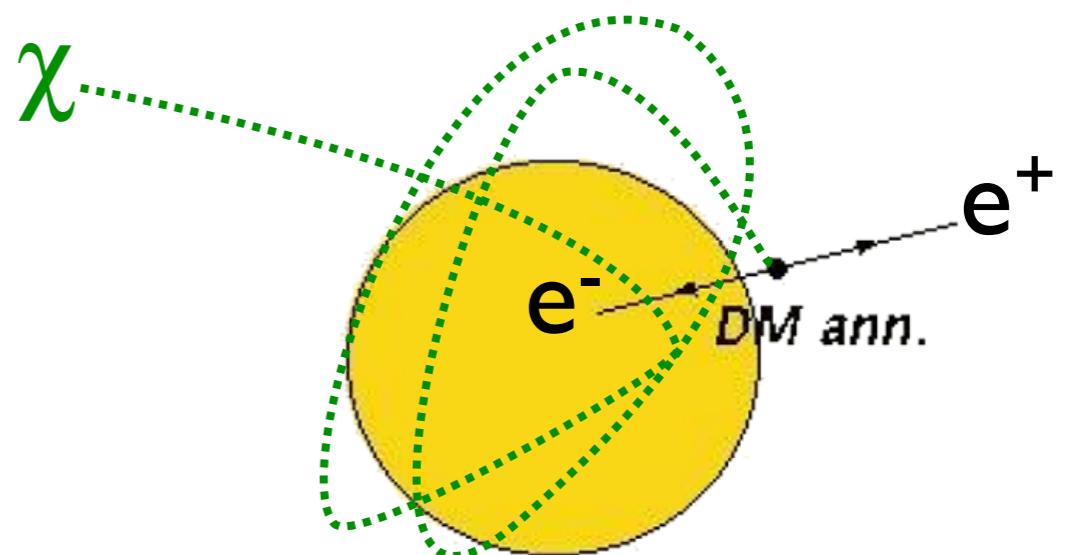
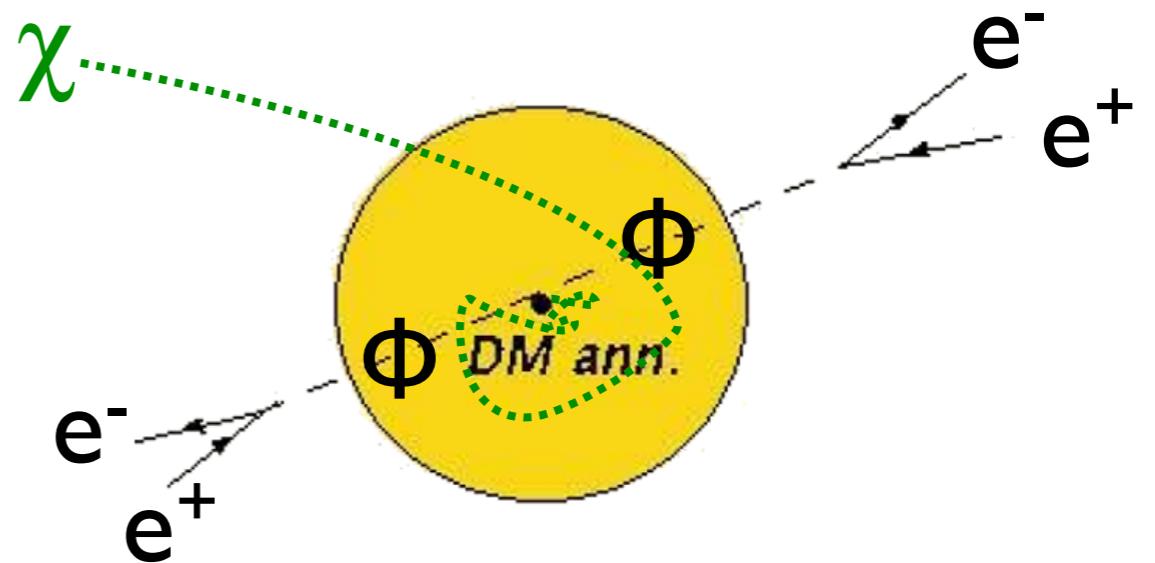
- DM particles are **captured by the Sun via elastic scattering with nucleons**
- the DM particles lose energy with each scattering, and quickly **sink to the core of the Sun** where they annihilate into SM particles
- neutrinos are the only observable signal from DM annihilations in the Sun since they are the only SM particle that can escape from the Sun



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

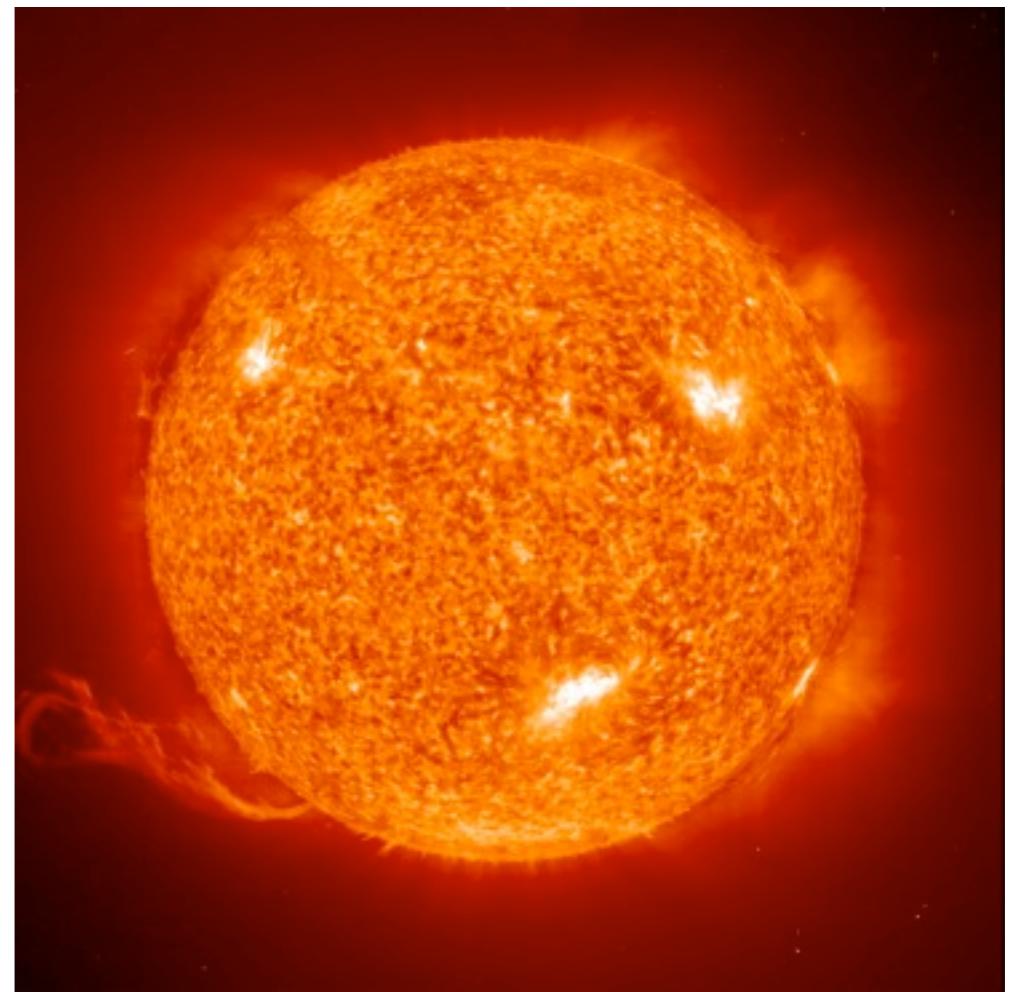
- pair-production detector: detects charged particle events as well as gamma rays
- can identify cosmic-ray electron and positron events; in general cannot determine charge on an event-by-event basis*

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



Data selection

- $\sim 10^6$ CRE events ($E > 60$ GeV), from 1st year of operation
- analysis performed in ecliptic coordinates, in reference frame centered on the Sun



Data analysis

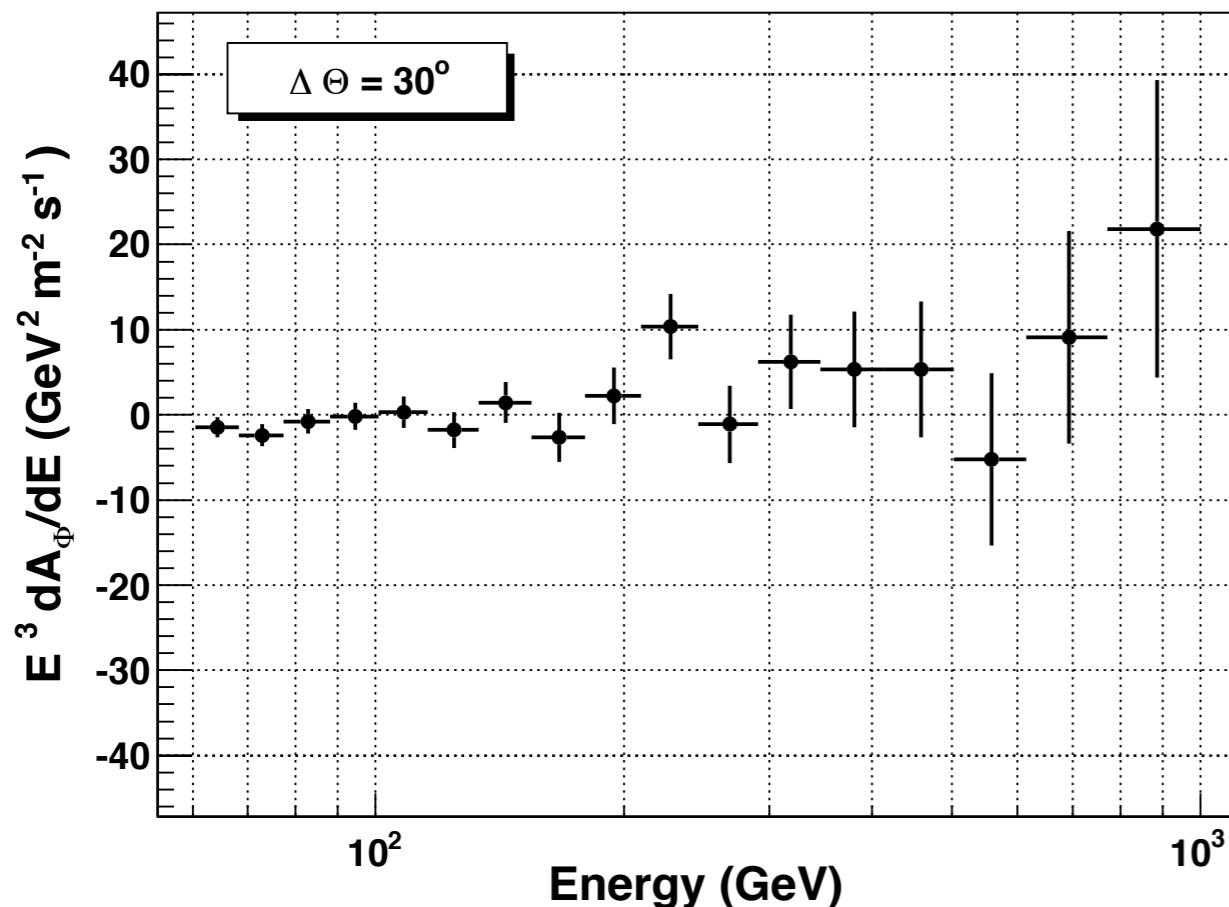
3 approaches used to search for flux excesses:

- 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

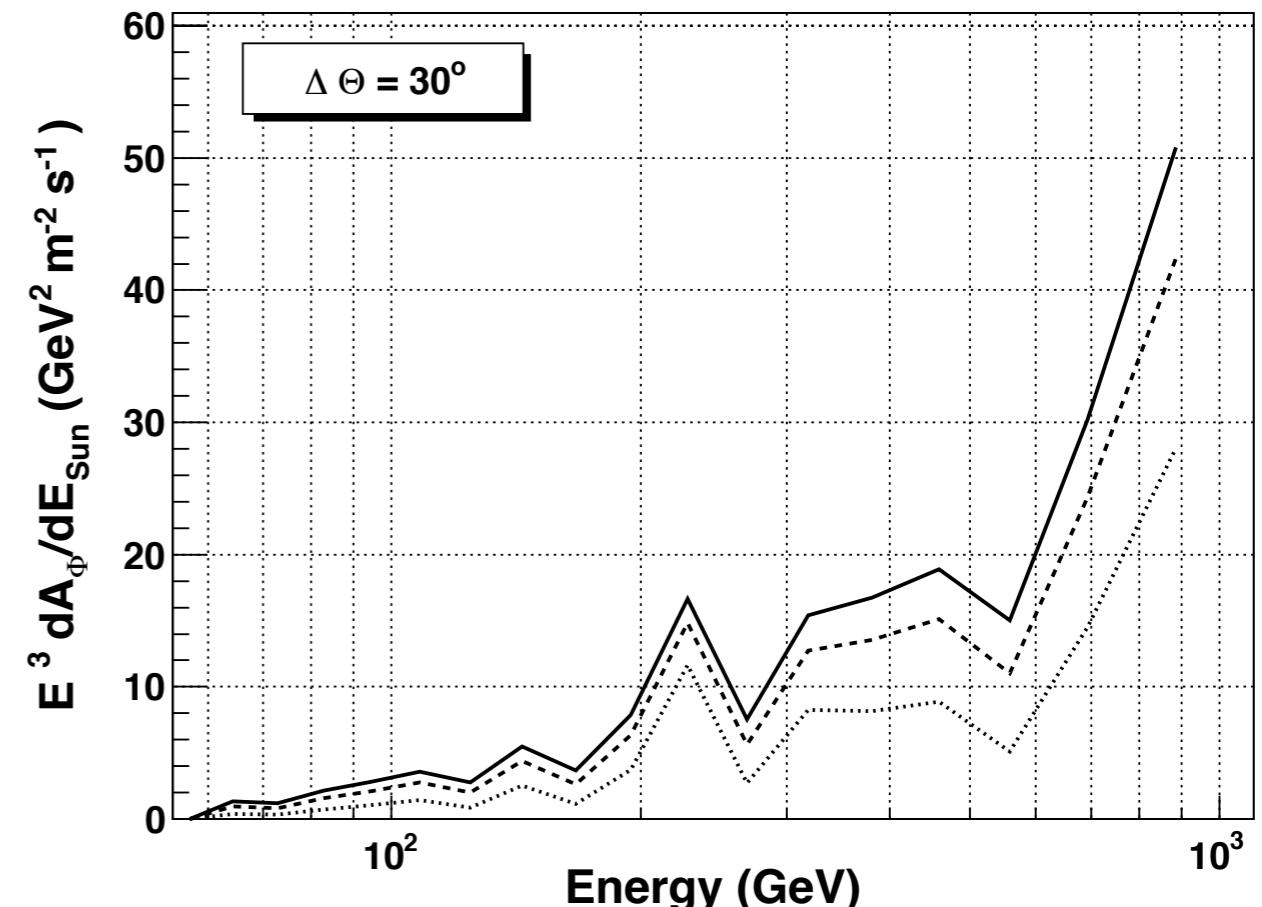
Flux asymmetry (real vs. fake Sun)

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)

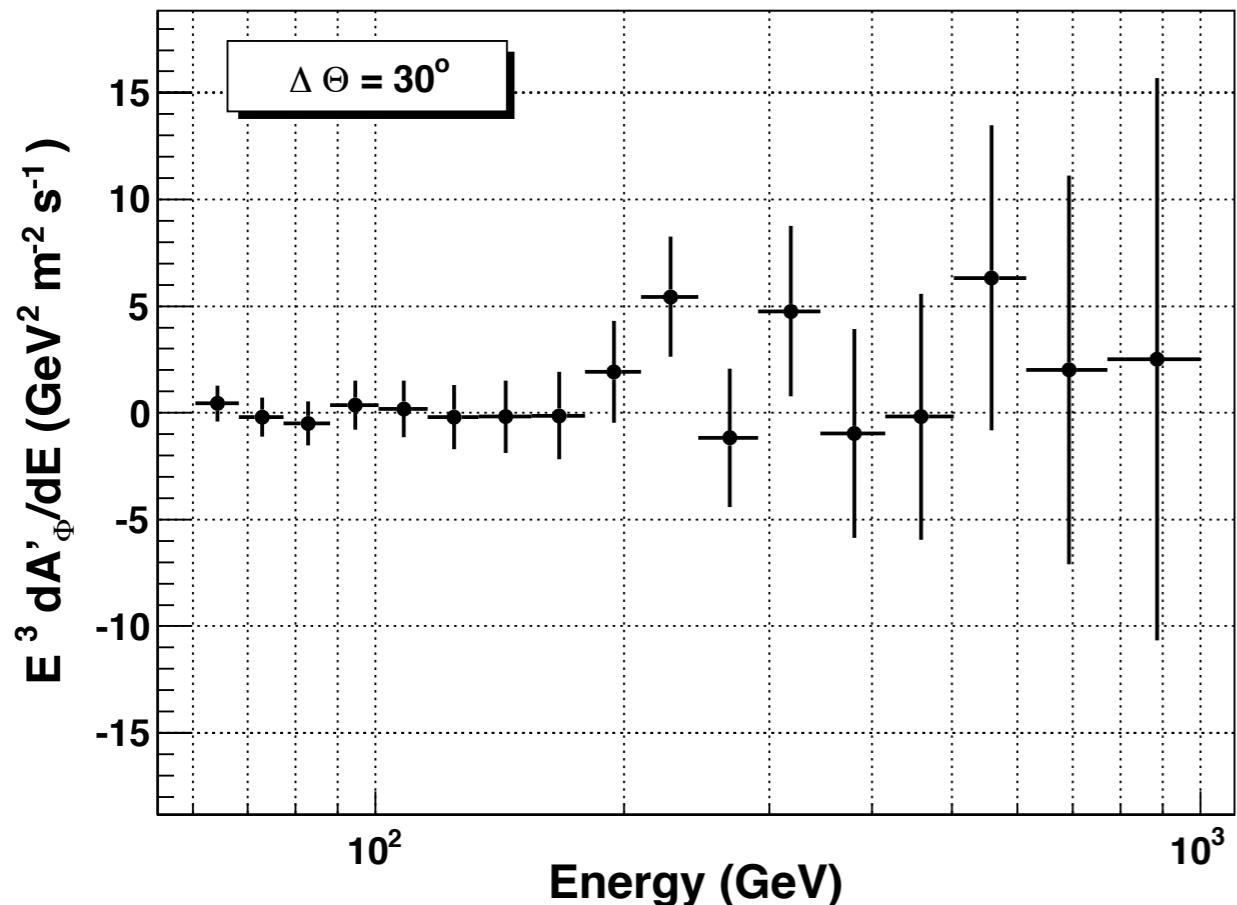


no flux excess detected in any energy bin at $> 3\sigma$

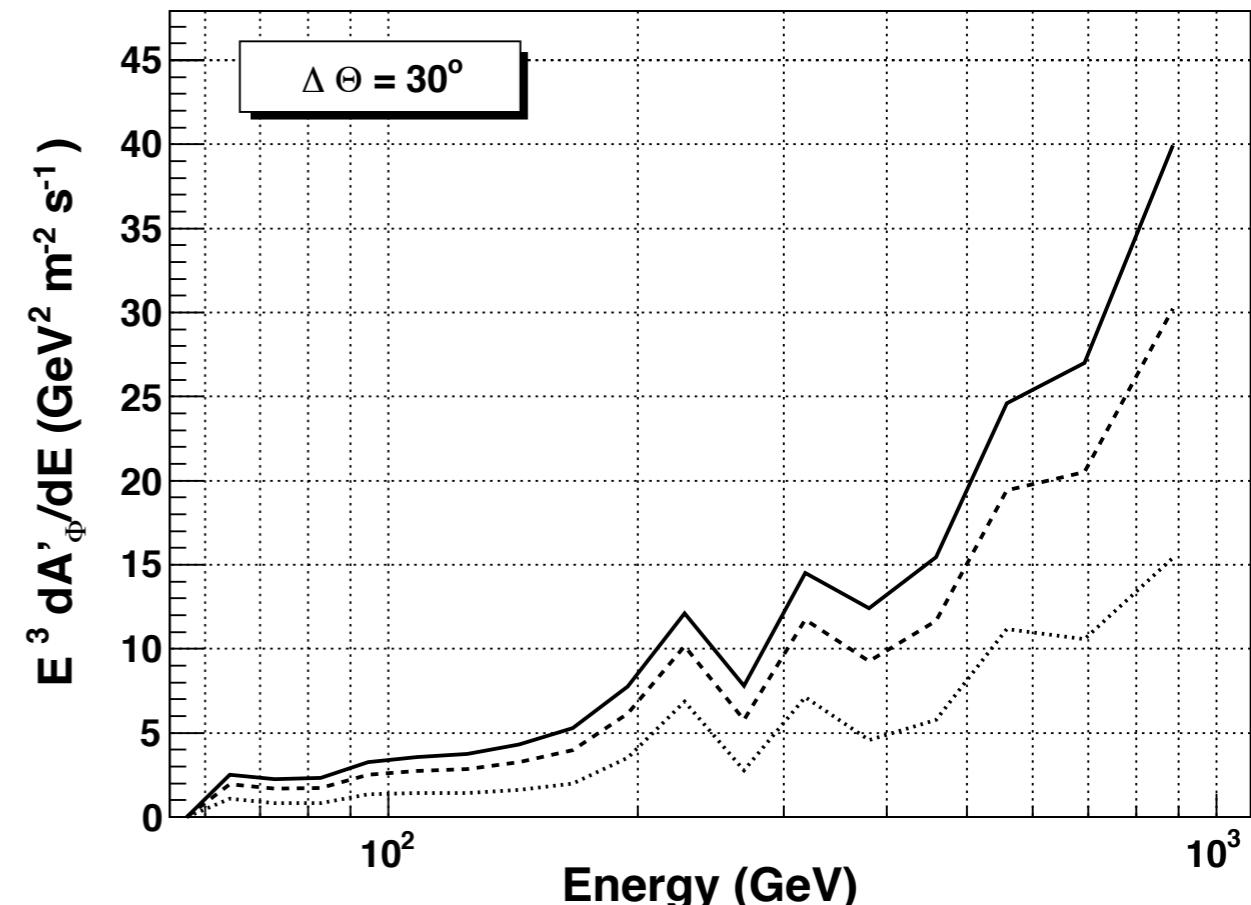
Comparison with isotropic flux

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

flux difference (real Sun - simulated isotropic)



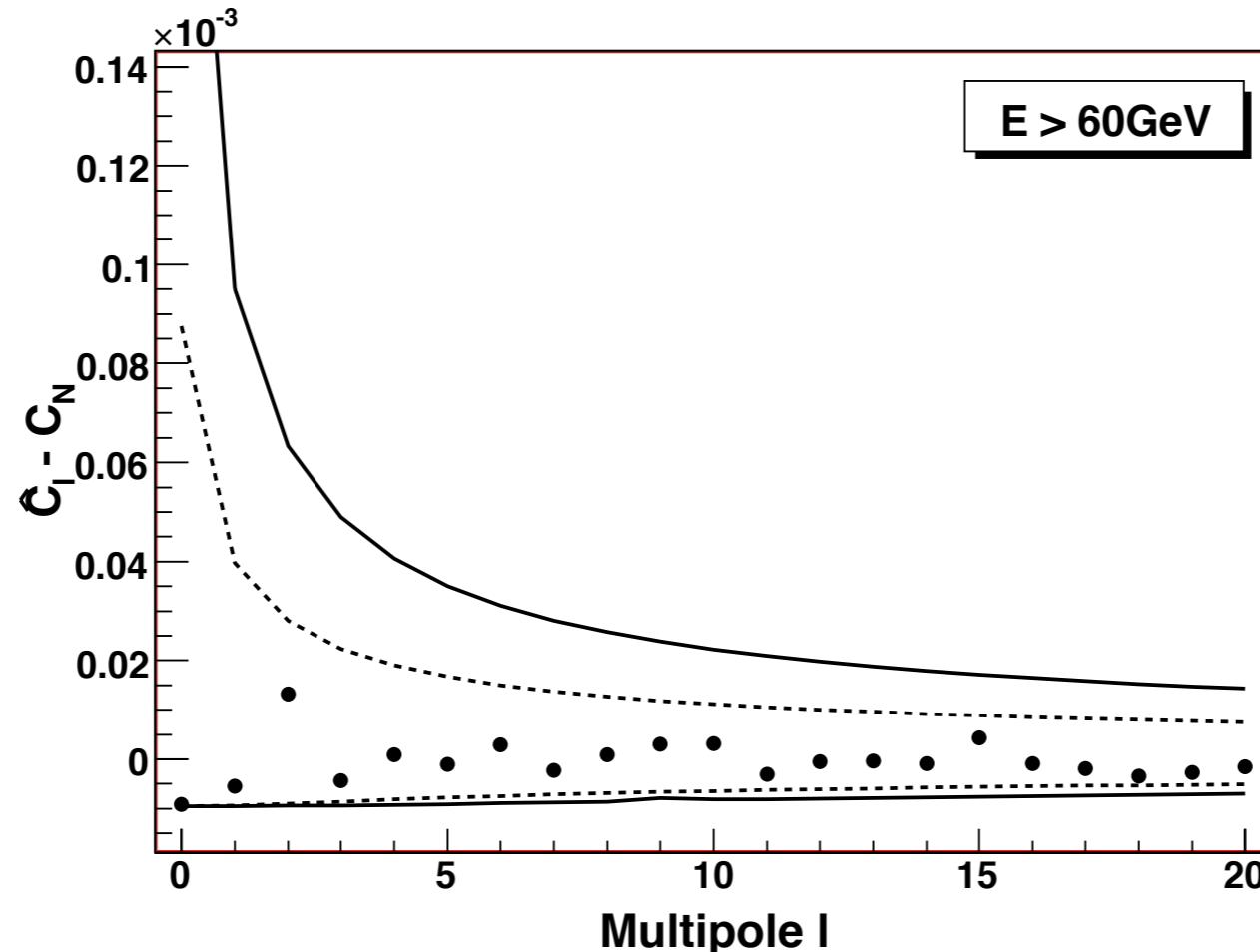
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Spherical harmonics analysis

fluctuation angular power spectrum of events $E > 60 \text{ GeV}$



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

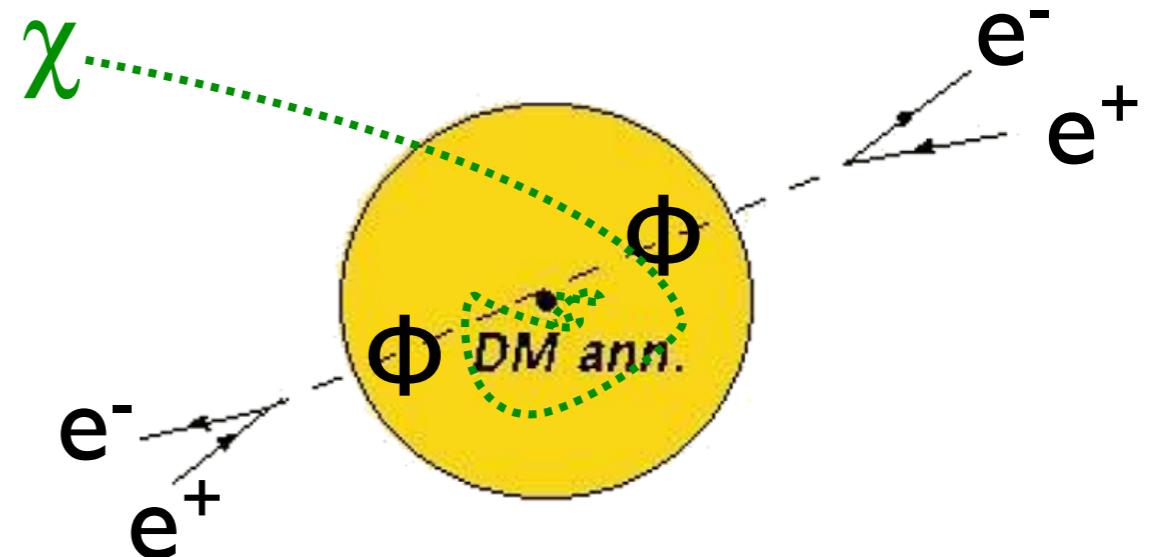
Solar CRE fluxes from dark matter

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

$$\chi\chi \rightarrow \phi\phi$$

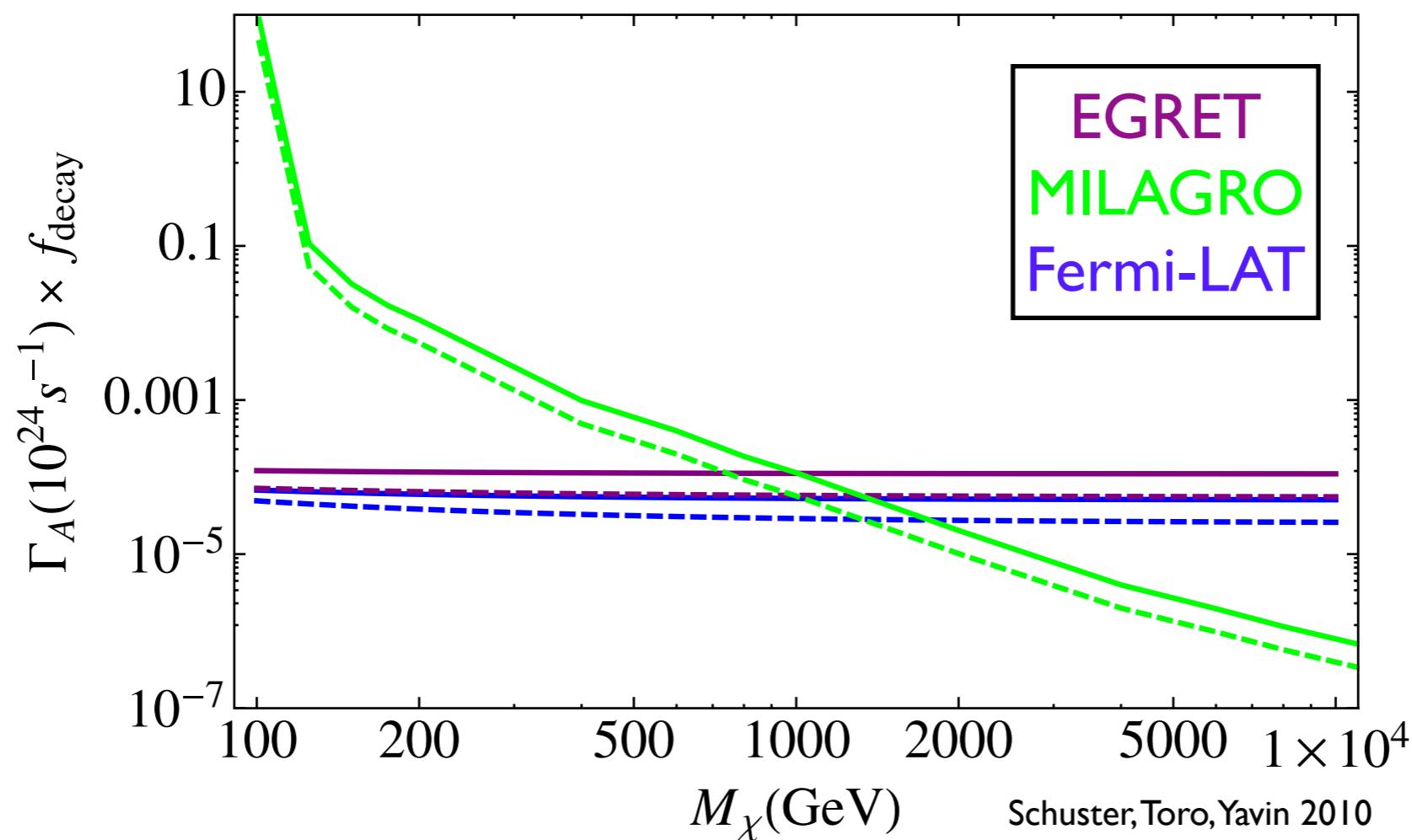
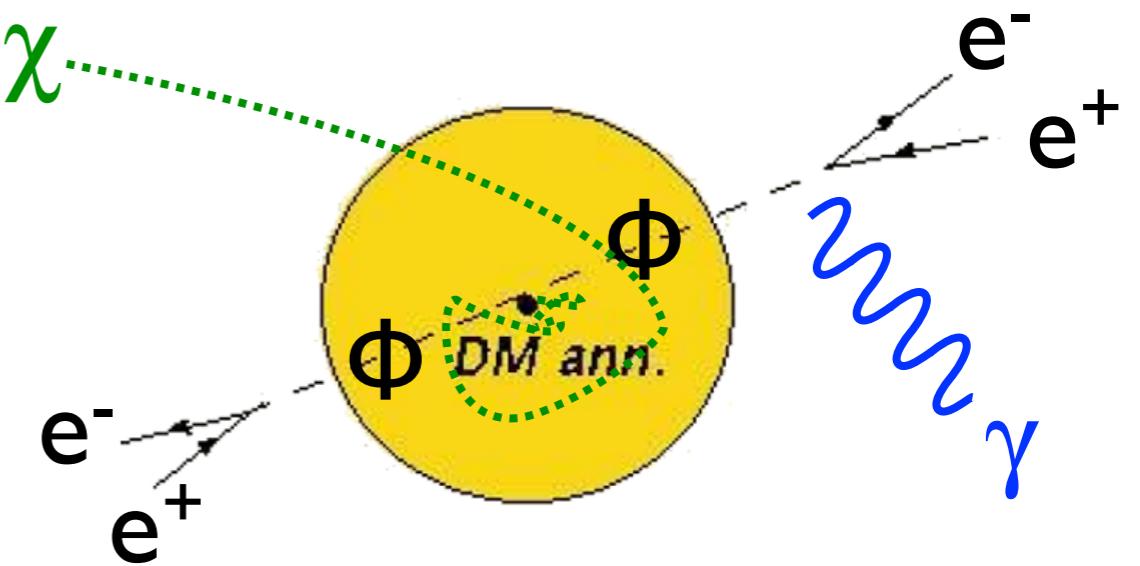
$$\phi \rightarrow e^+e^-$$



- the Φ are assumed to have mass less than a few GeV, while the DM has mass of \sim 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



CRE flux from intermediate state scenario

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

decay rate of Φ
per volume

selects energy of
observed CREs

line-of-sight
distance

angular
distribution of
CREs

```
graph TD; Eq["dN / (dt dA d cos theta_det dE_det) = ..."] -- "decay rate of Φ per volume" --> TopLeft["decay rate of Φ per volume"]; Eq -- "selects energy of observed CREs" --> TopRight["selects energy of observed CREs"]; LeftArrow[("line-of-sight distance")] --> DR["dR"]; RightArrow[("angular distribution of CREs")] --> dGammadet["dΓ / d cos theta_det"]
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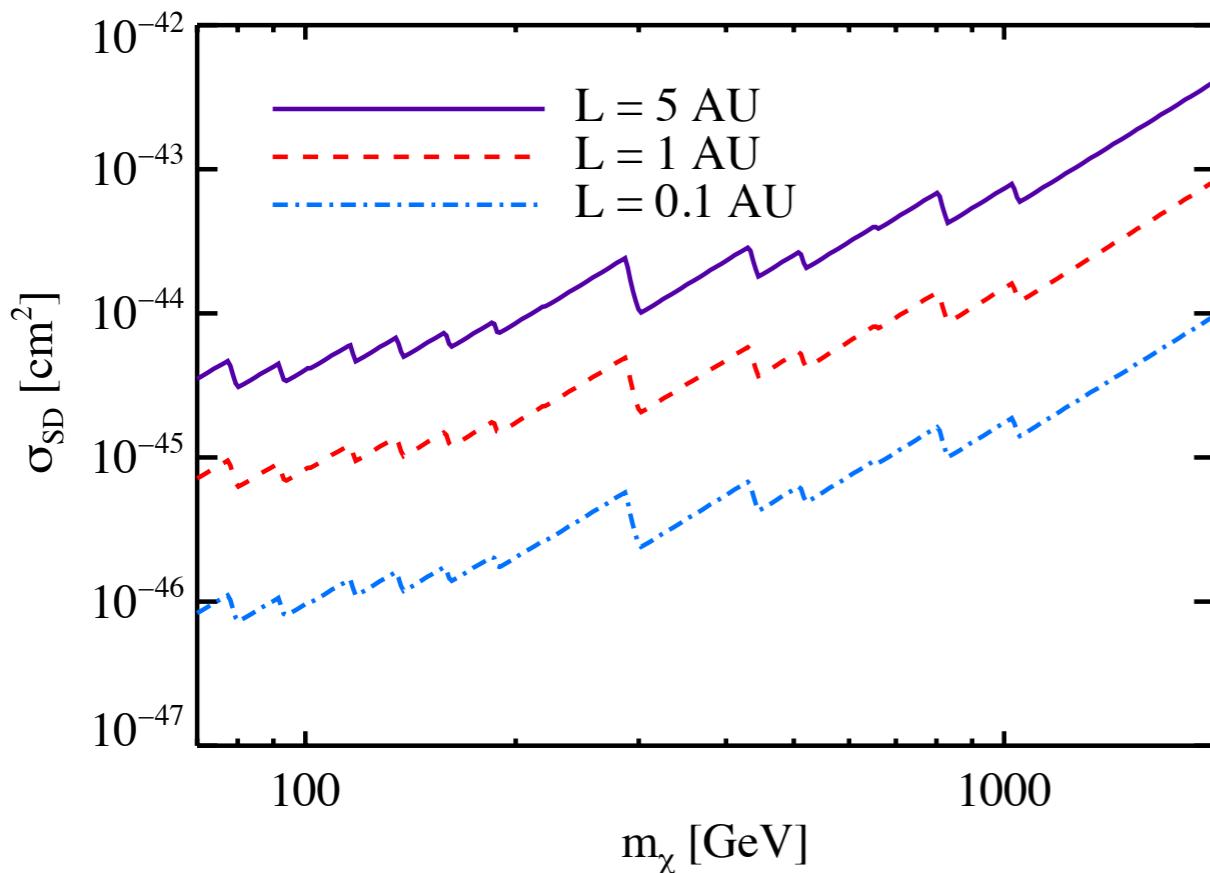
Φ decay rate per volume

$$\frac{dN}{dVdt} (r (\theta_{\text{det}}, R)) = 2 \frac{C_{\odot} e^{-r/L}}{4\pi r^2 L}$$

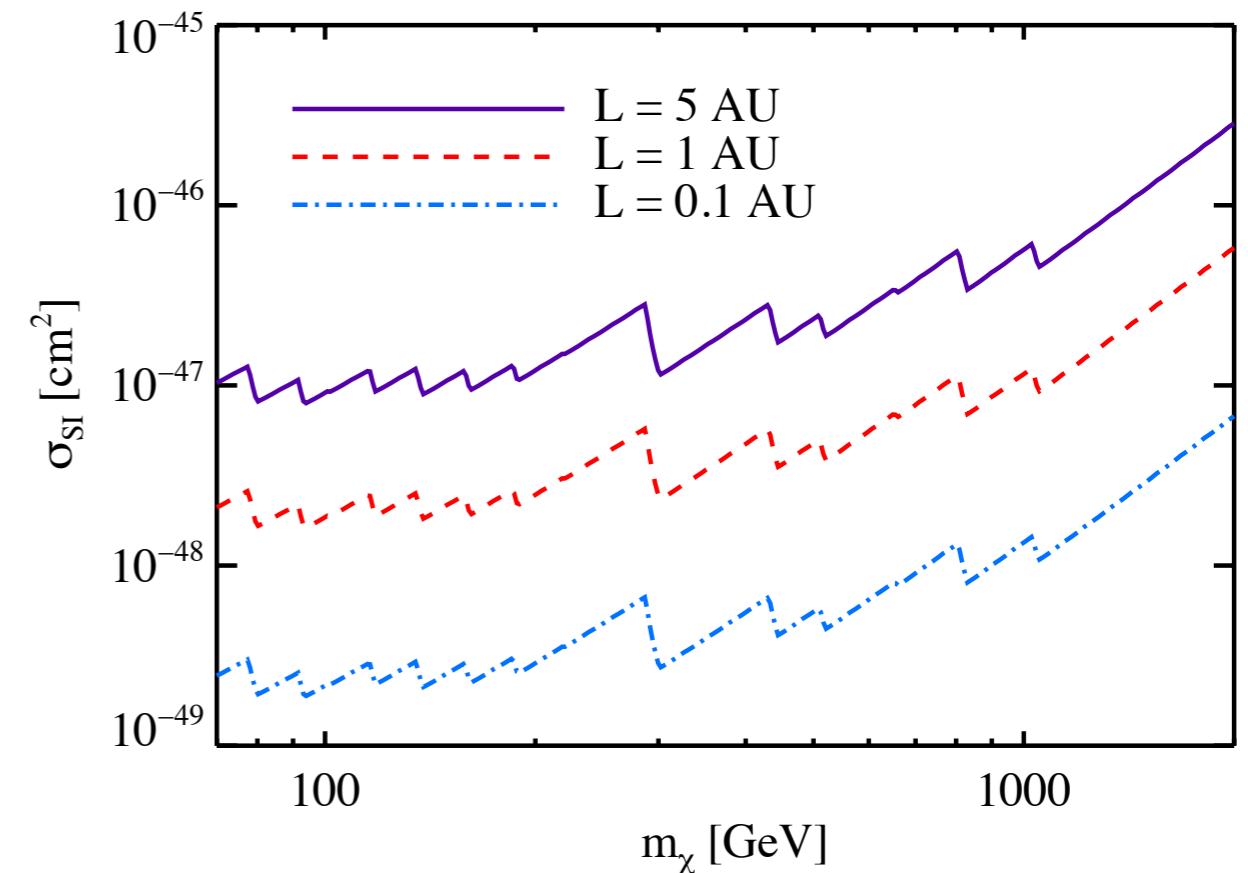
- assume equilibrium (for every 2 particles that are captured, 2 annihilate)
- calculate solar capture rate with DarkSUSY
 - proportional to the elastic scattering cross-section
 - depends on DM particle mass
- L is decay length, set by lifetime of Φ and energy of Φ

Limits on elastic scattering cross-section assuming annihilation to CREs via an intermediate state

spin-dependent
scattering



spin-independent
scattering



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

Inelastic dark matter scenario: overview

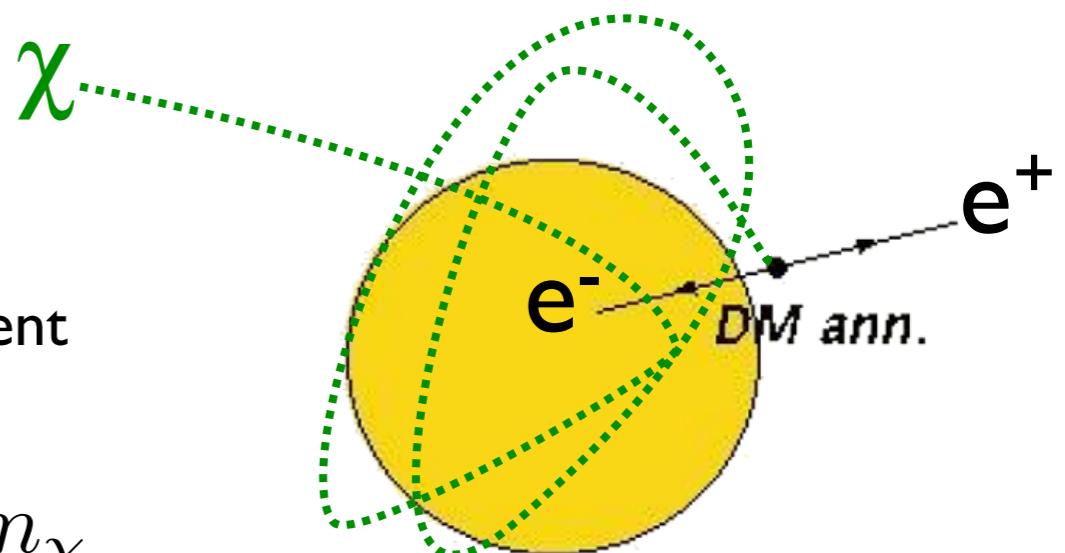
- DM is captured by the Sun via inelastic scattering

$$\chi + N \rightarrow \chi^* + N$$

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

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

- 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



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)

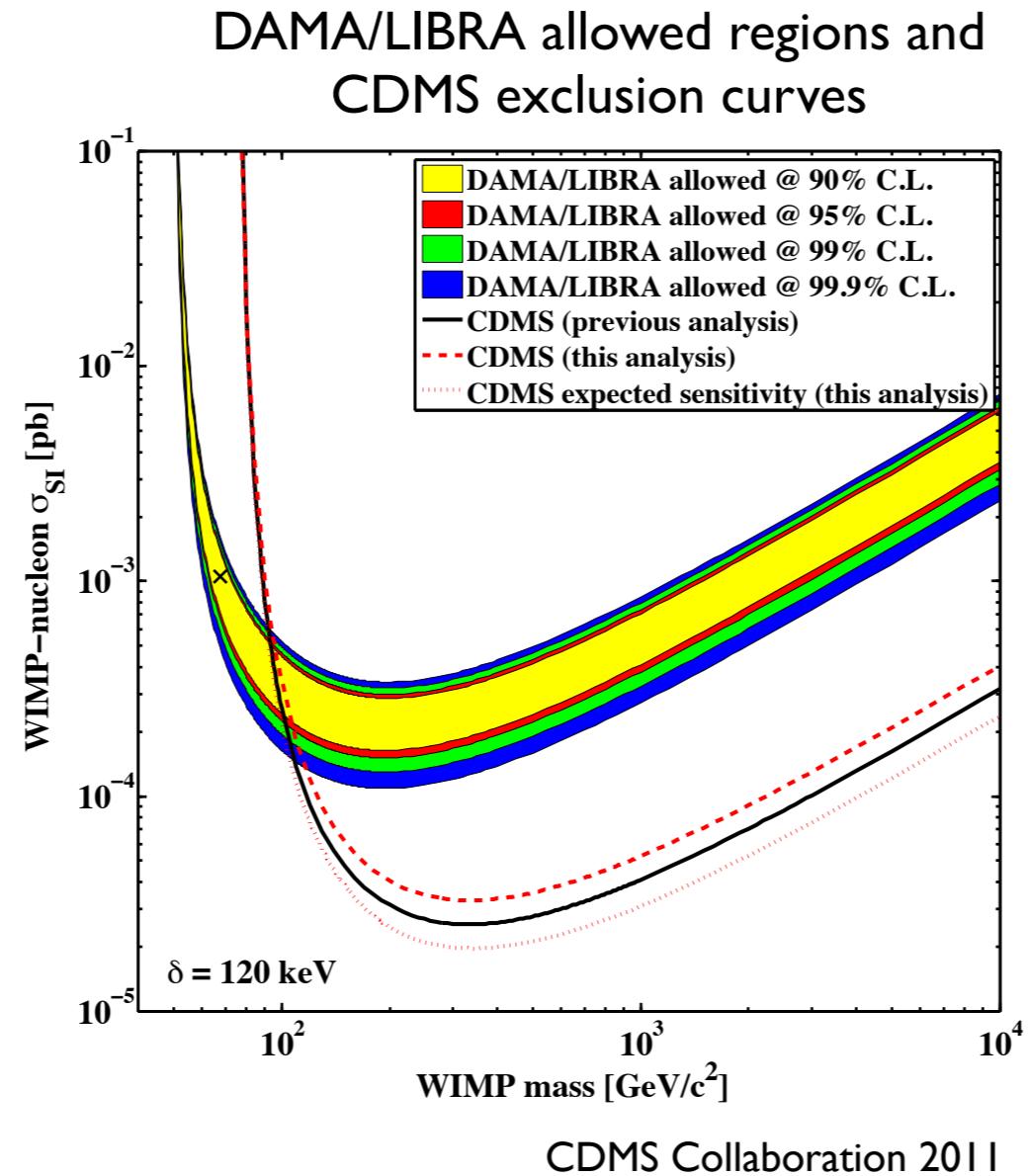
$$F = 2 \frac{\Gamma_{A,\text{out}}}{4\pi D_\odot^2}$$

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

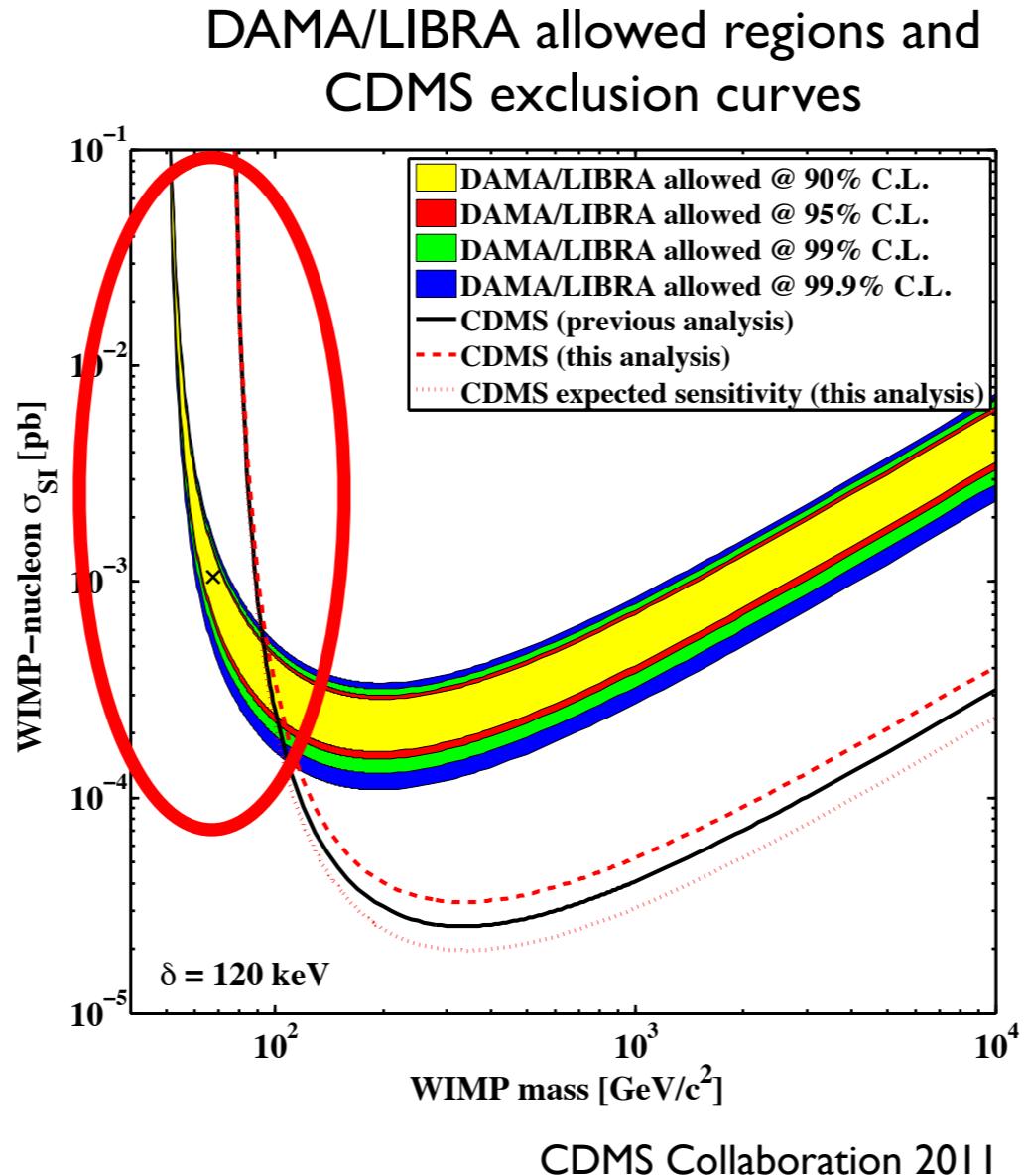
$$\Gamma_{A,\text{out}} = f_{\text{out}} \Gamma_A = \frac{1}{2} f_{\text{out}} C_\odot$$

- 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

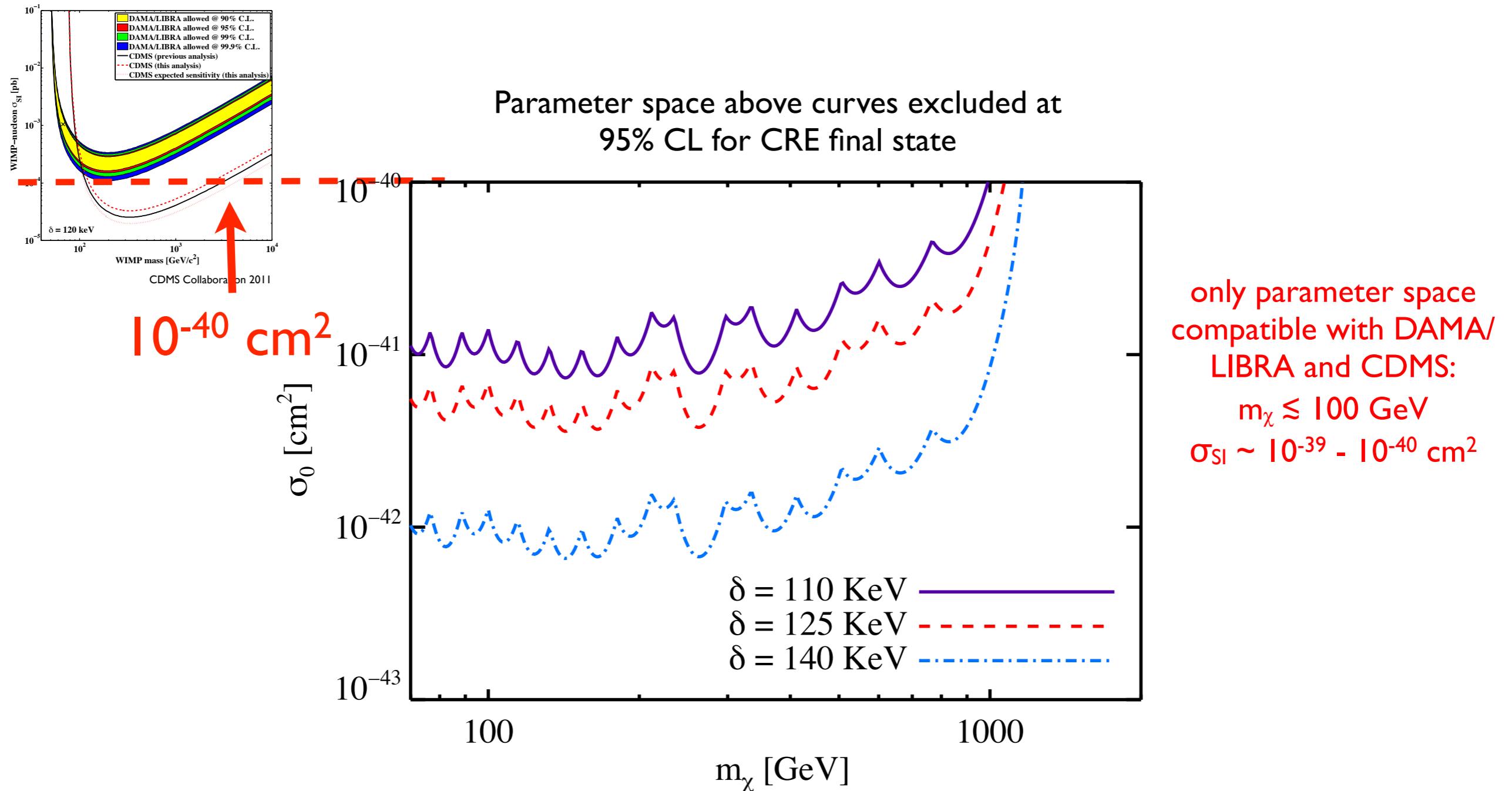


Limits on inelastic scattering cross-section



only parameter space compatible with DAMA/
LIBRA and CDMS:
 $m_\chi \lesssim 100 \text{ GeV}$
 $\sigma_{\text{SI}} \sim 10^{-39} - 10^{-40} \text{ cm}^2$

Limits on inelastic scattering cross-section



solar CRE constraints exclude by $\sim 1\text{-}2$ 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

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