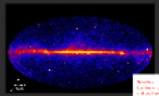
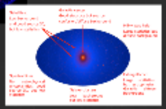
The "Doubly Indirect" Detection of Dark Matter

Last Week.....

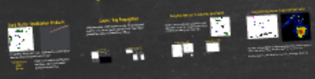


Studied dark matter in gamma-rays



Gamma-Rays travel directly from annihilation event to our detector

Doubly Indirect Detection



Antiparticle Searches

Antiproton Flux

Positron Fraction

Heavier Nuclei

Radio Searches

Galactic Center

Tim Linden

Conclusions

Doubly Indirect Dark Matter detection is very promising, but also very difficult!

Easy to find anomalies, and when you find them, somebody will model them with dark matter

Some hints may last (antiprotons, ARCADE-II excess, positron fraction?) Careful modeling will be necessary!

Lecture 8

Fall 2014 Compton Lectures

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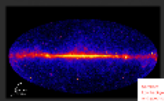

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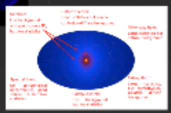

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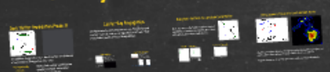

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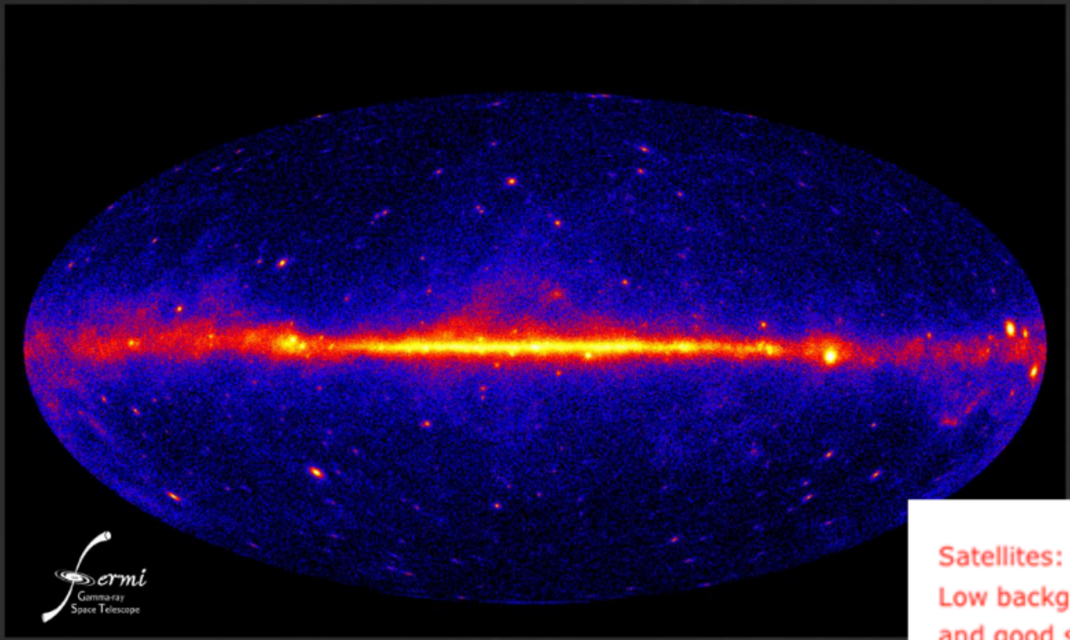

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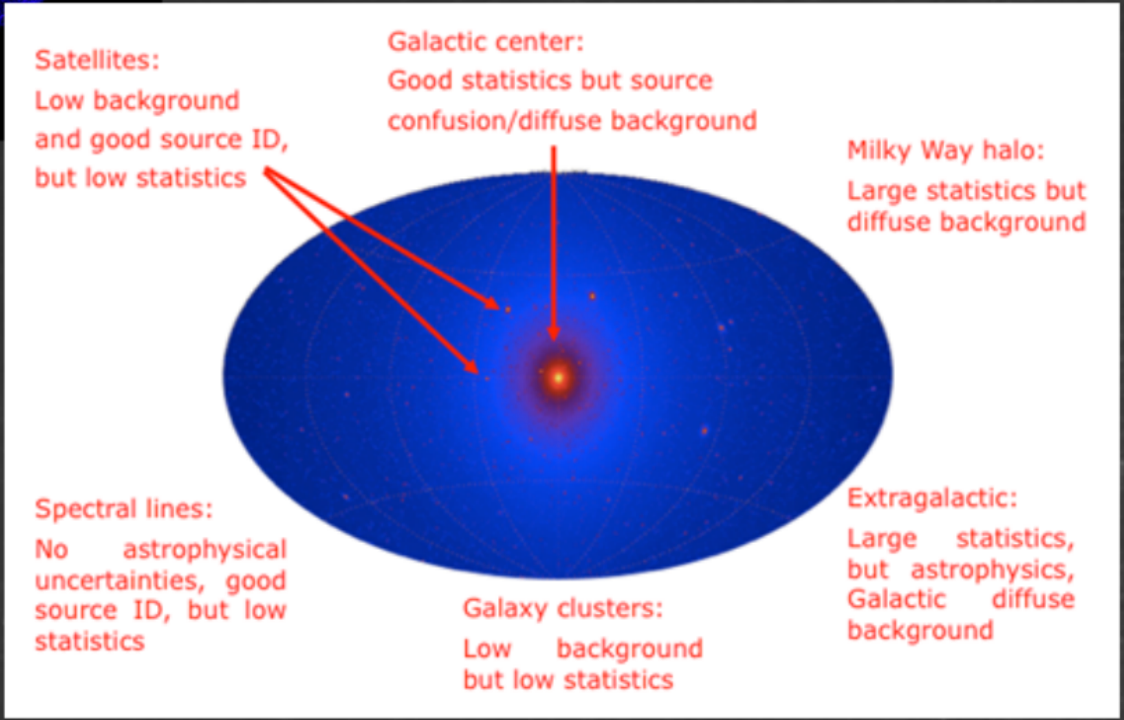
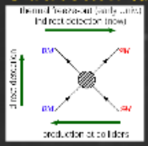
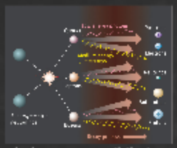


background background
ut low statistics

Doubly Indirect Detection

Dark Matter Annihilation Products





In addition to gamma-rays, dark matter annihilation also produces charged cosmic-rays

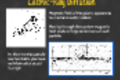
Most Importantly:
- Protons
- Electrons

Note dark matter annihilation produces equal antimatter particles as particles

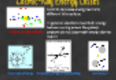
Cosmic-Ray Propagation

Unfortunately, unlike gamma-rays, these charged cosmic-rays do not go straight to Earth from their proudction point, instead they diffuse

Cosmic-Ray Diffusion



Cosmic-Ray Energy Losses



Using Anti-Particles to Constrain Dark Matter

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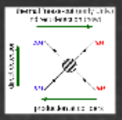

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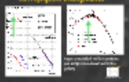

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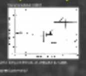

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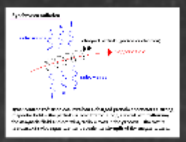

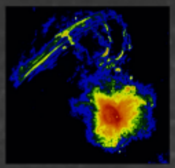

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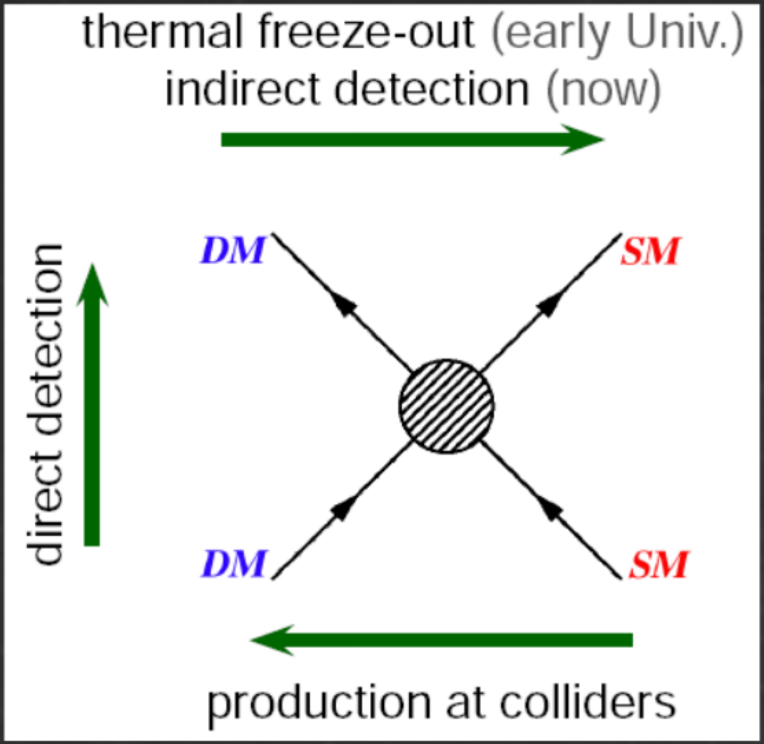

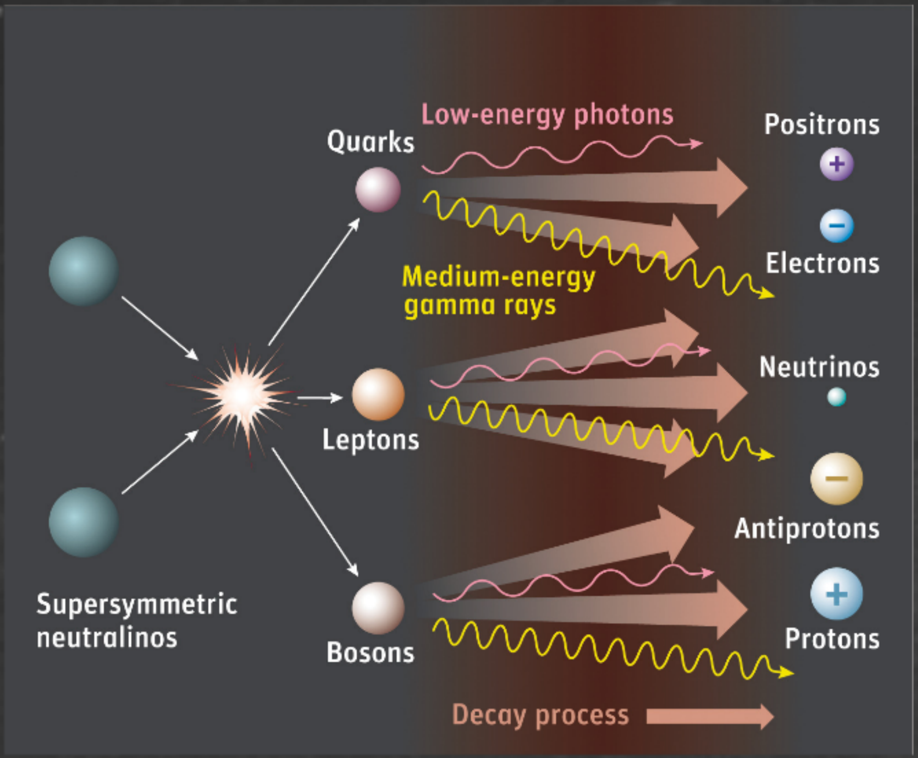

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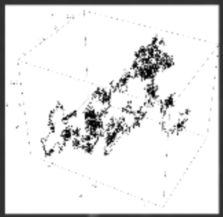
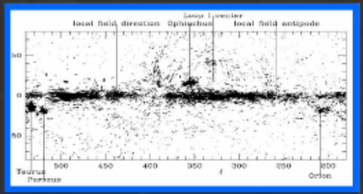


Magnetic field of the galaxy appears to be predominantly random

Moving through the random magnetic field leads to large deflections of each particle

By the time the particle reaches Earth, you have no information about its origin



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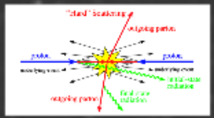
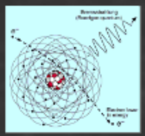


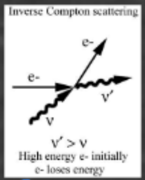
Hadronic Interactions

Cosmic-rays lose energy to many different interactions

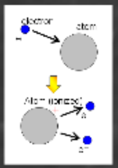
In general, electrons lose their energy before moving across the galaxy, protons do not lose much energy during transit



Bremsstrahlung

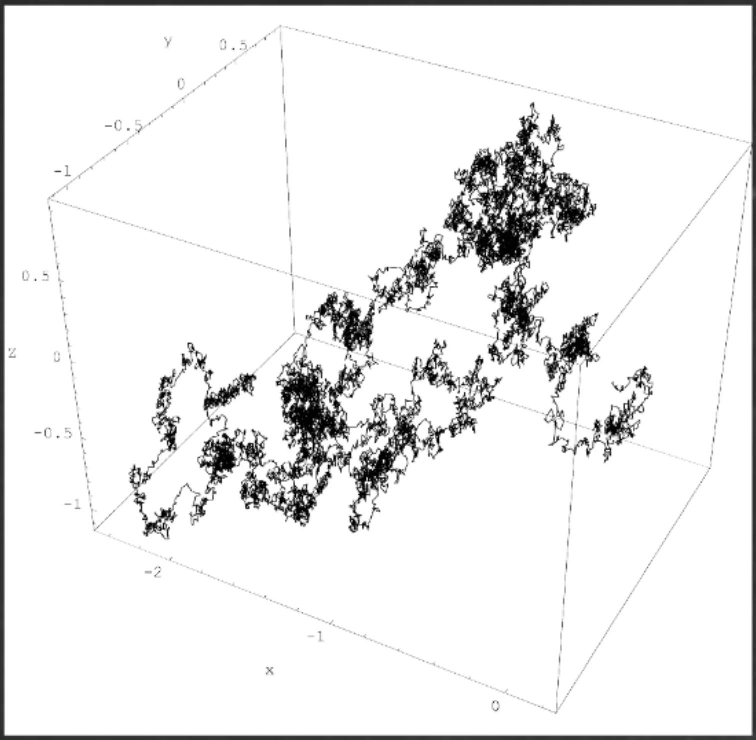


inverse Compton scattering



ionization

Cosmic-Ray Diffusion



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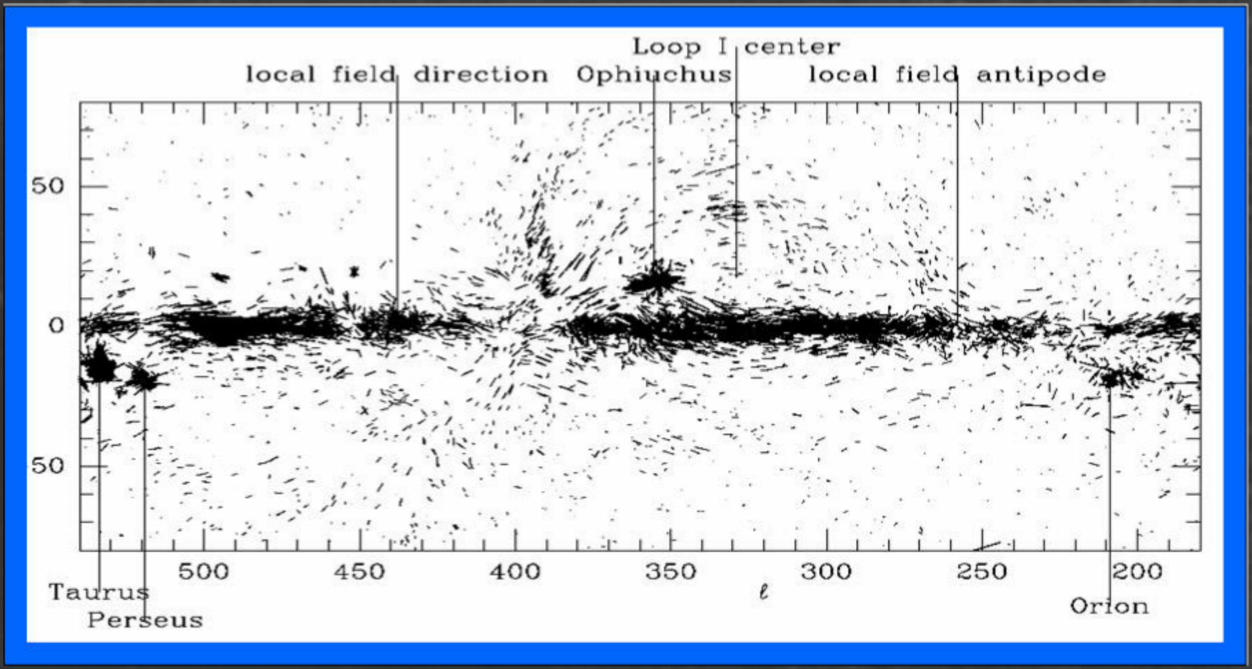

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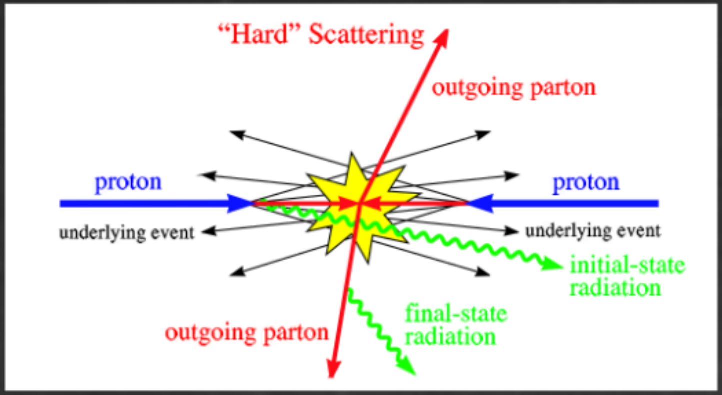

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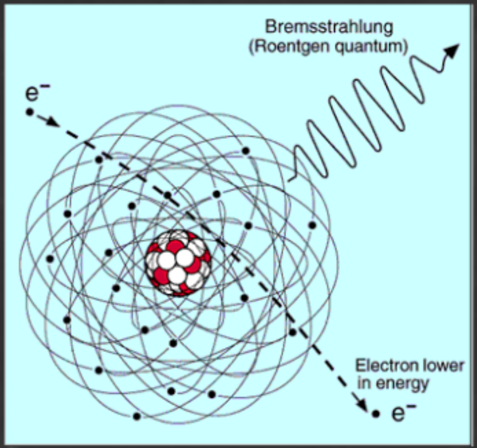

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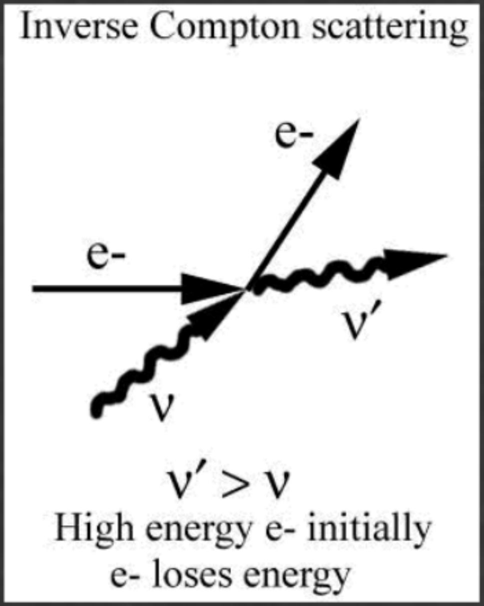

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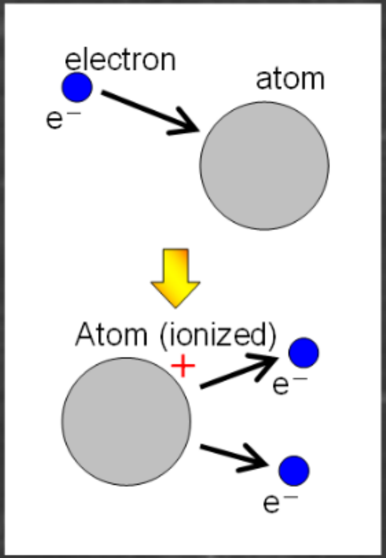

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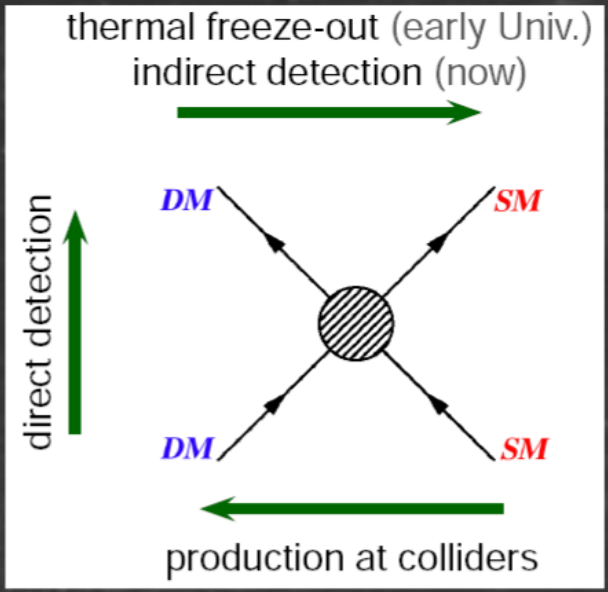

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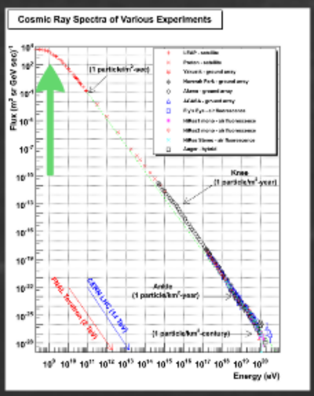
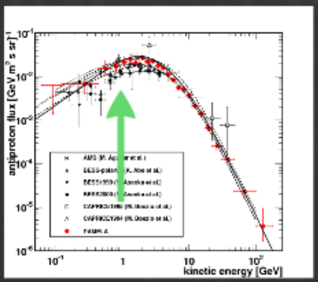
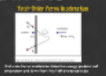


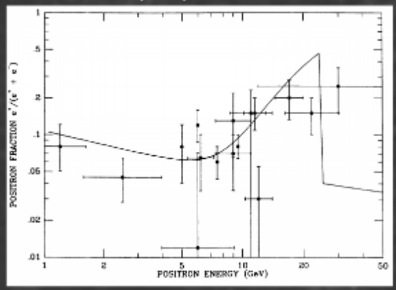


Approximately 1 million protons per antiproton observed in the galaxy



Bumps in the Background

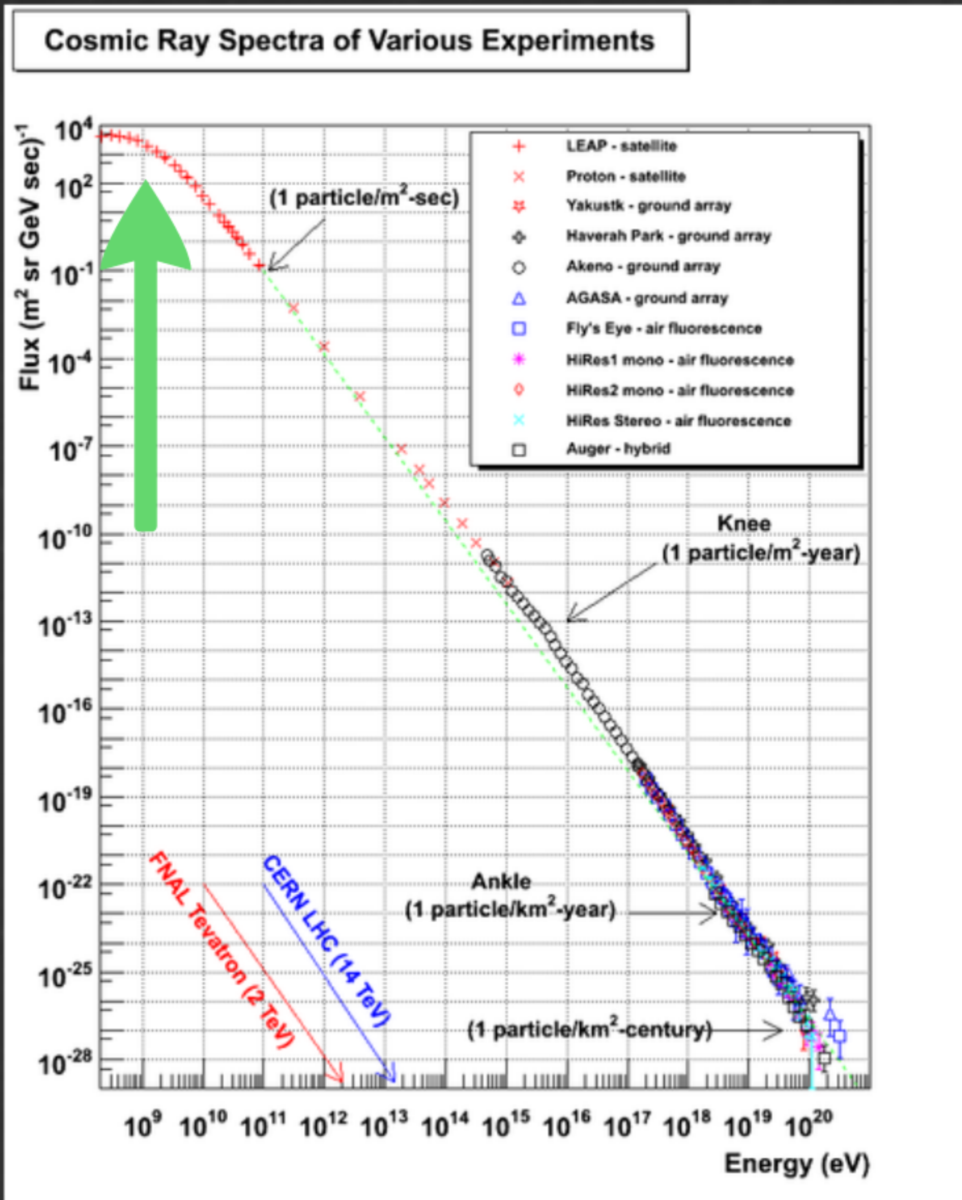
Turner & Wilczek (1990)

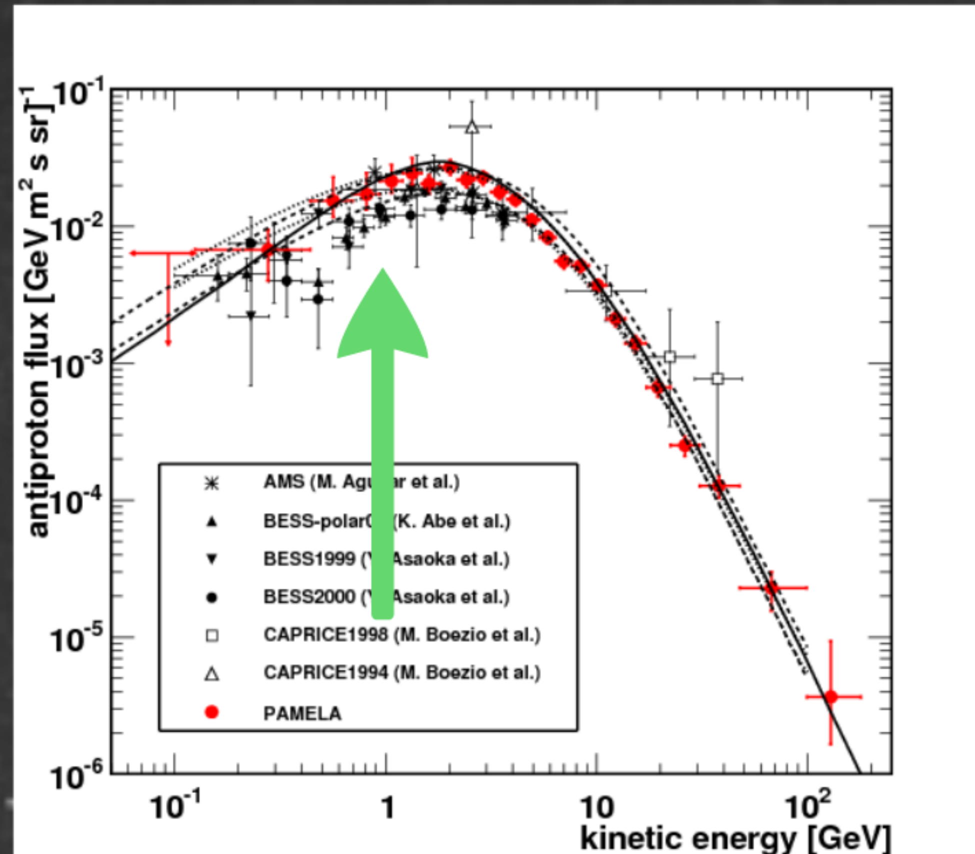


Can look for bumps in the ratio of antimatter to matter.

Helps control systematics!

Astrophysical Backgrounds





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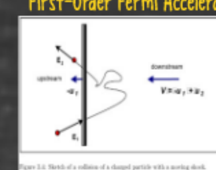
First-Order Fermi Acceleration



First order Fermi acceleration takes low energy protons and antiprotons and turns them into high energy particles

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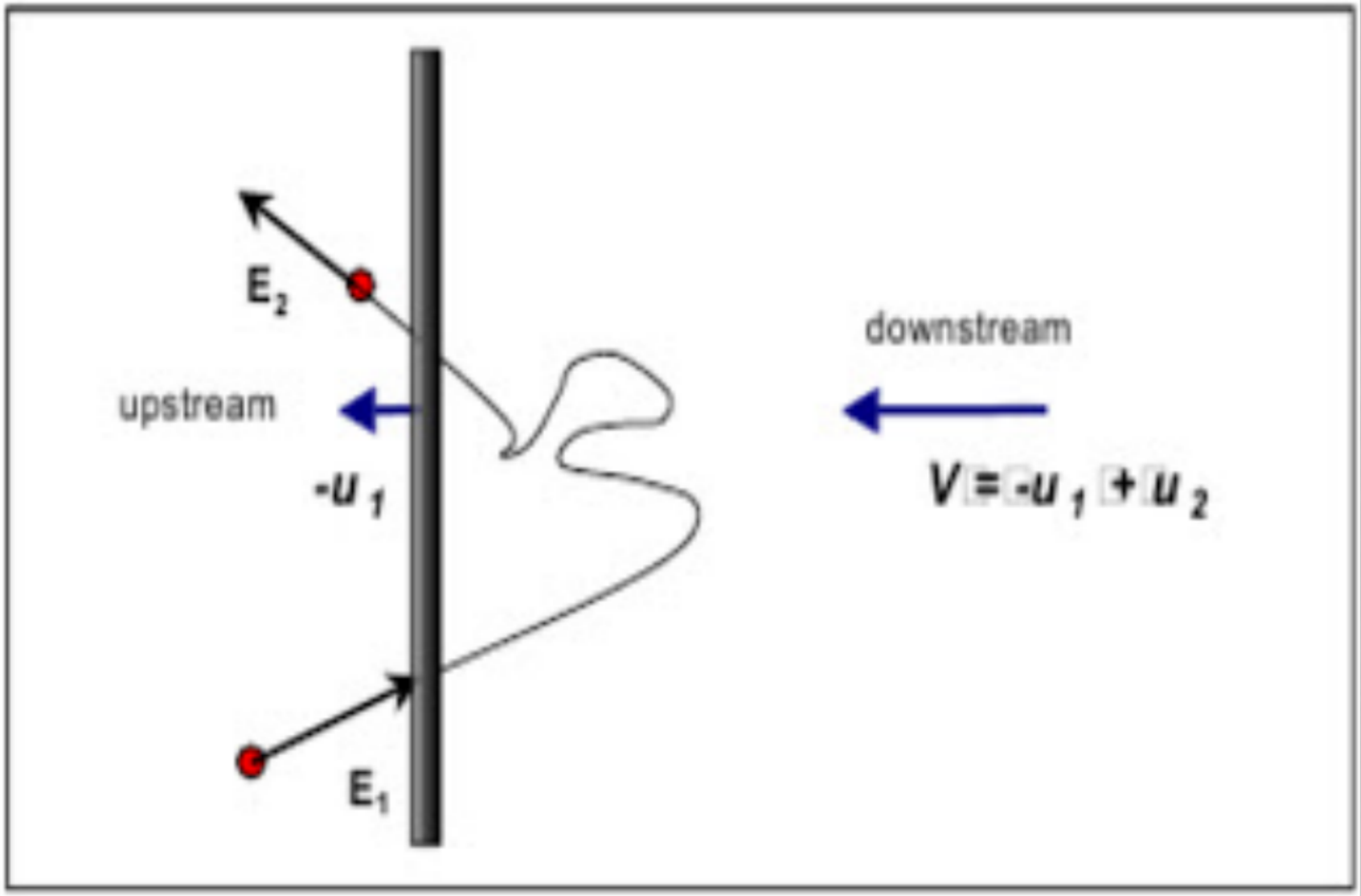

Figure 3.4: Sketch of a collision of a charged particle with a moving shock.

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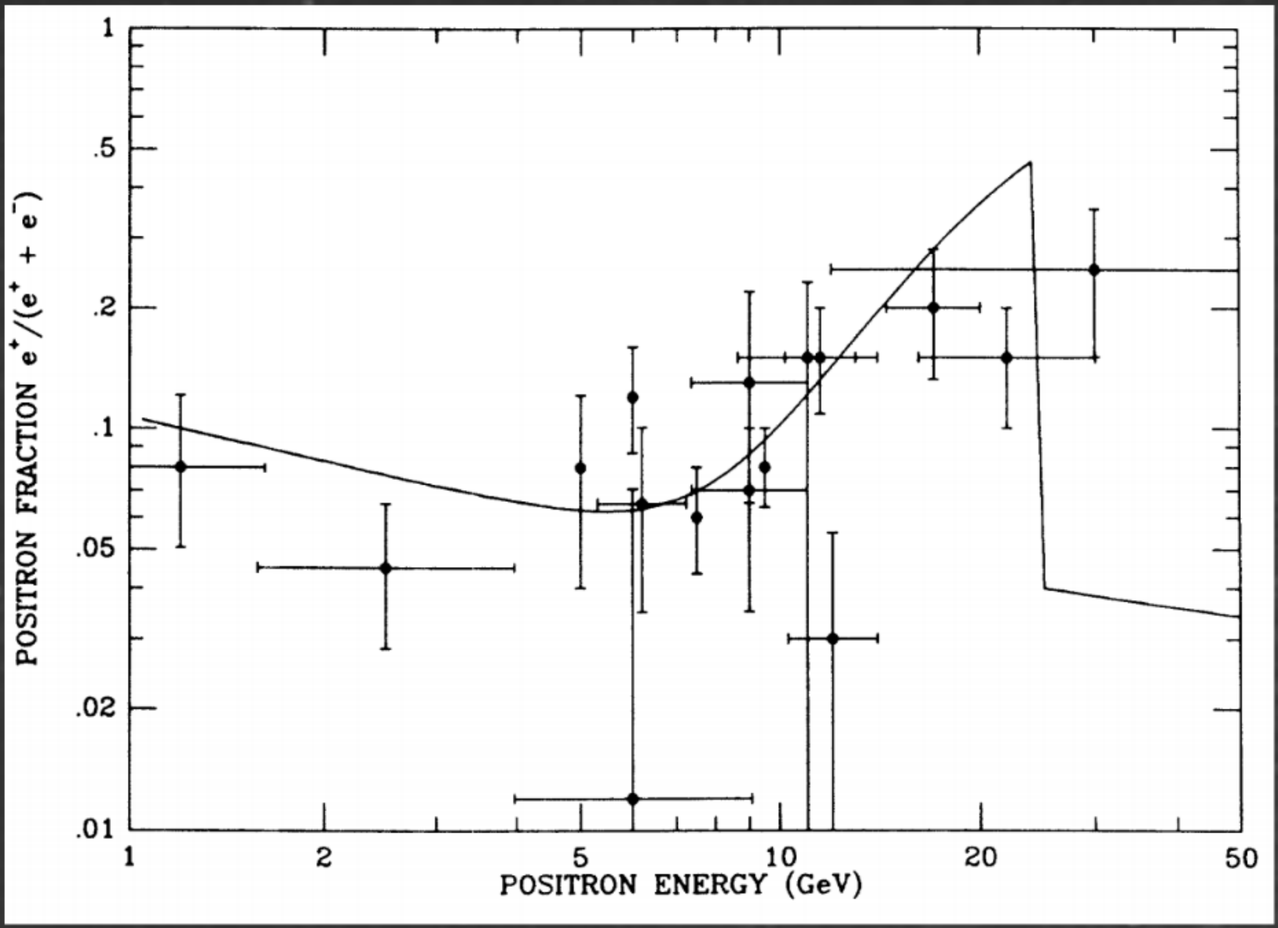

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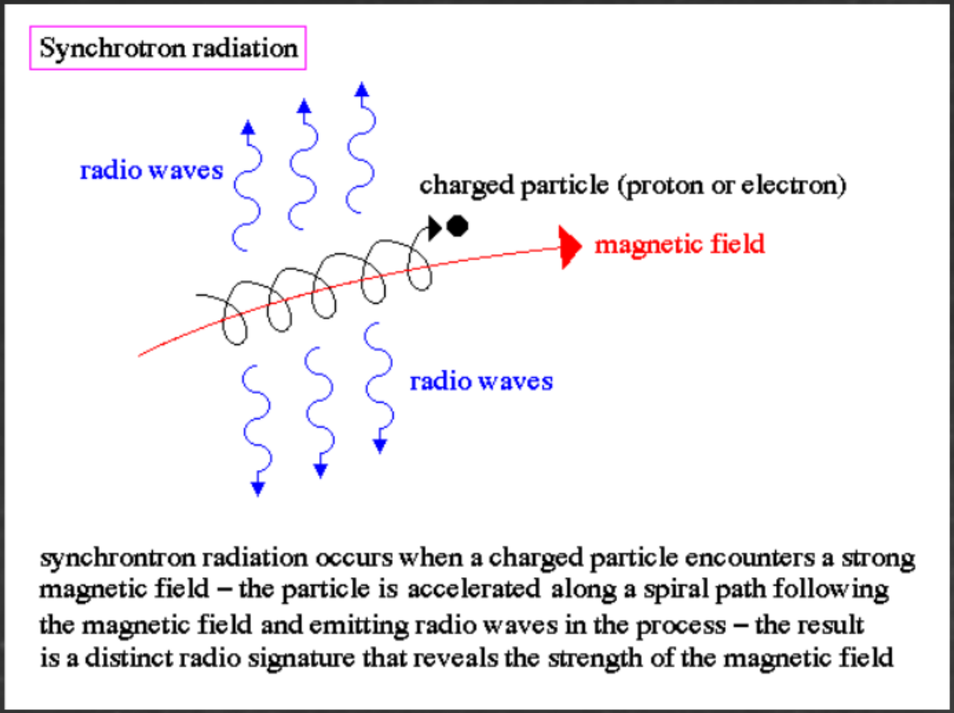

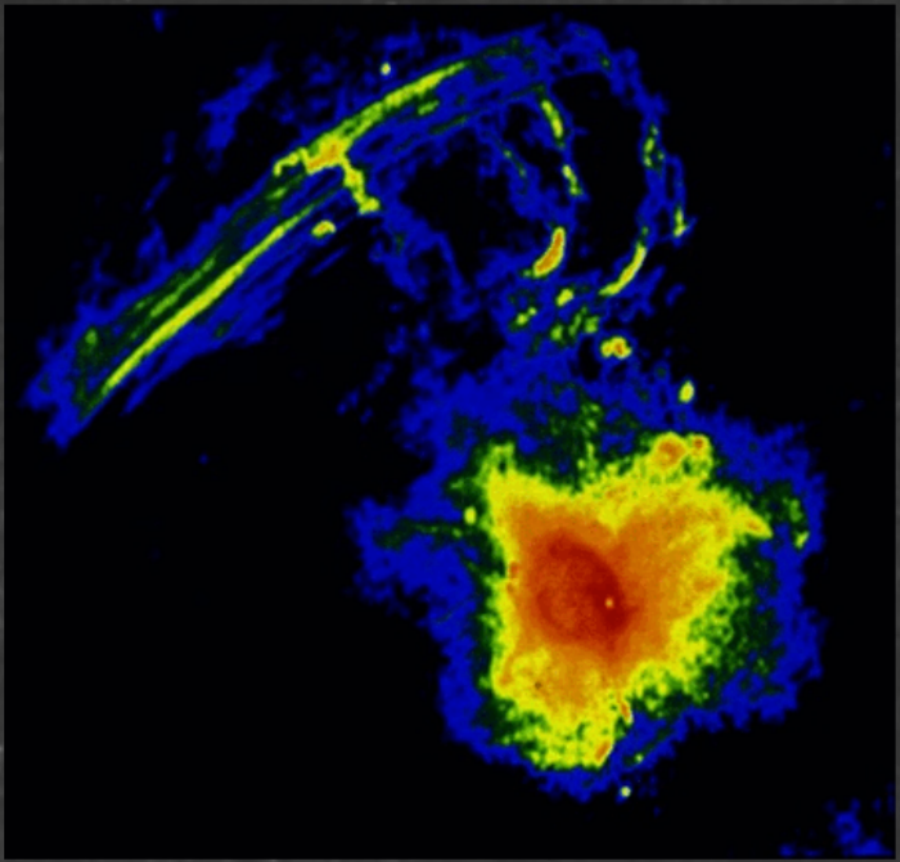

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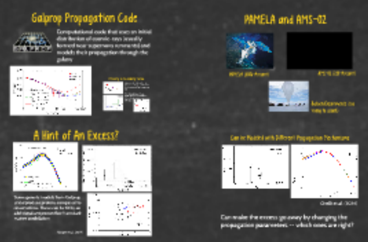
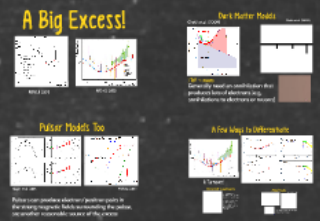
Antiparticle Searches

Antiproton Flux

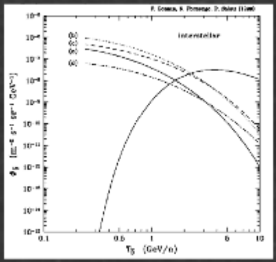


Positron Fraction

Look for a bump in the flux of positrons (compared to electrons) in satellites orbiting Earth



Heavier Nuclei



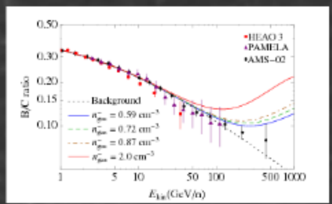
Can look for heavier anti-neuclei (like antideuterium or anti-helium). These are essentially never made in astrophysics.

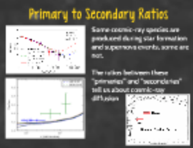
Unfortunately, rare from dark matter too.

Antiproton Flux

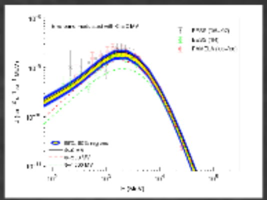
Galprop Propagation Code

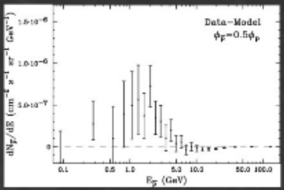
Computational code that uses an initial distribution of cosmic-rays (usually formed near supernova remnants) and models their propagation through the galaxy



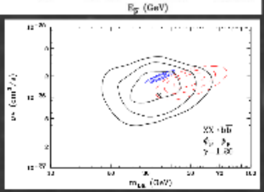


A Hint of An Excess?





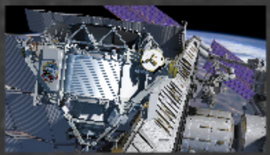
Some generic models from Galprop underproduce protons compared to observations. These can be fit by an additional antiproton flux from dark matter annihilation



Hooper et al. (2014)

PAMELA and AMS-02

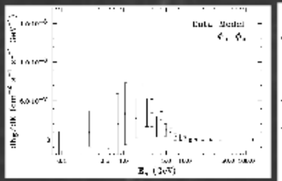
PAMELA (2006-Present)

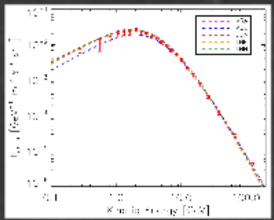


AMS-02 (2011-Present)

Balloon Experiments (too many to count)

Can be Modeled with Different Propagation Mechanisms





Cirelli et al. (2014)

Can make the excess go away by changing the propagation parameters -- which ones are right?

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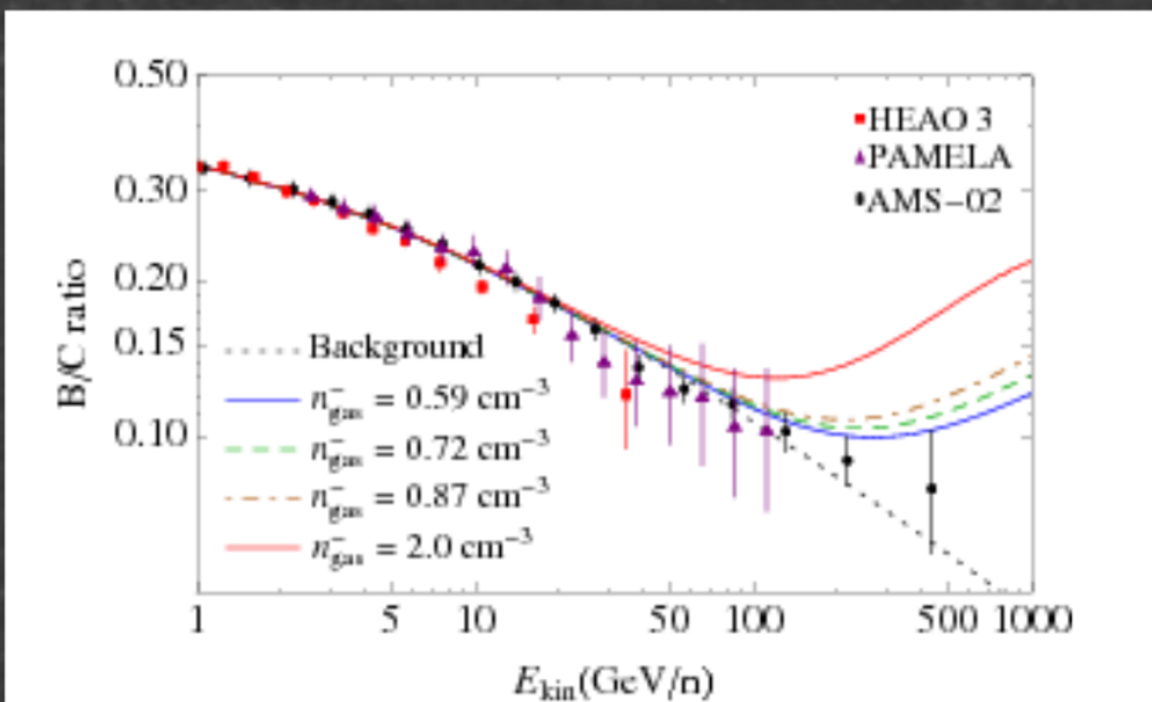
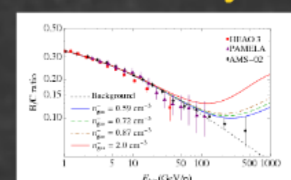
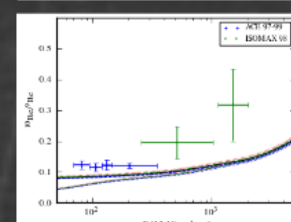


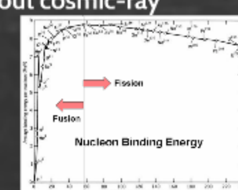
Primary to Secondary Ratios





Some cosmic-ray species are produced during star formation and supernova events, some are not.

The ratios between these "primaries" and "secondaries" tell us about cosmic-ray diffusion



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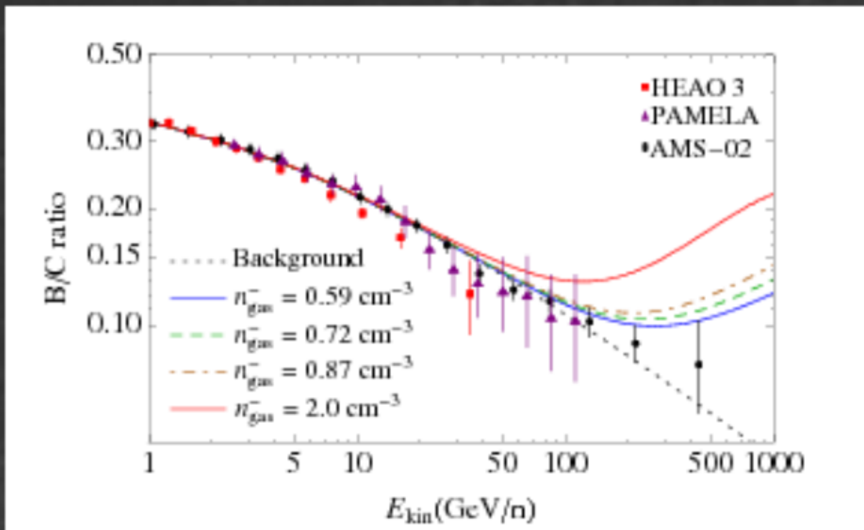

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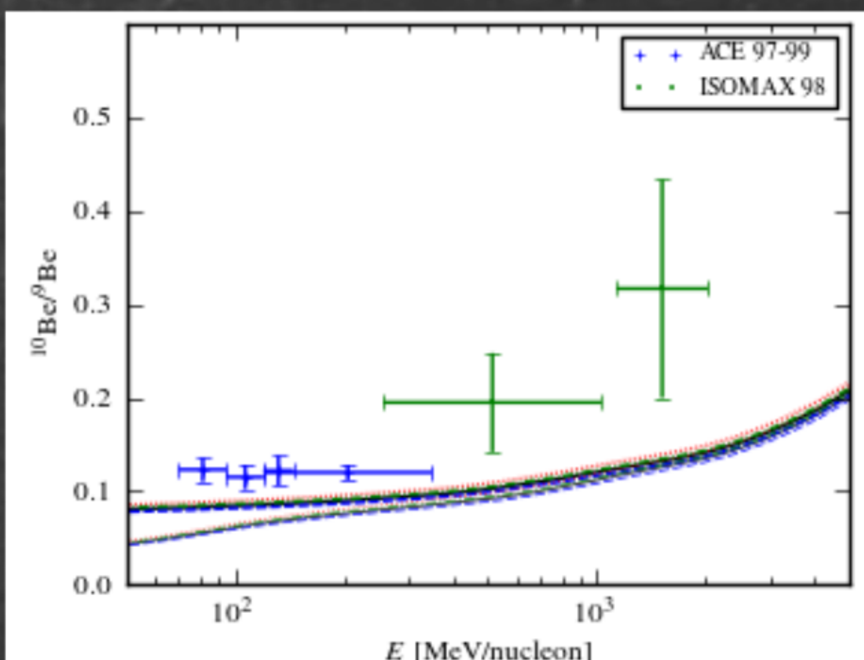

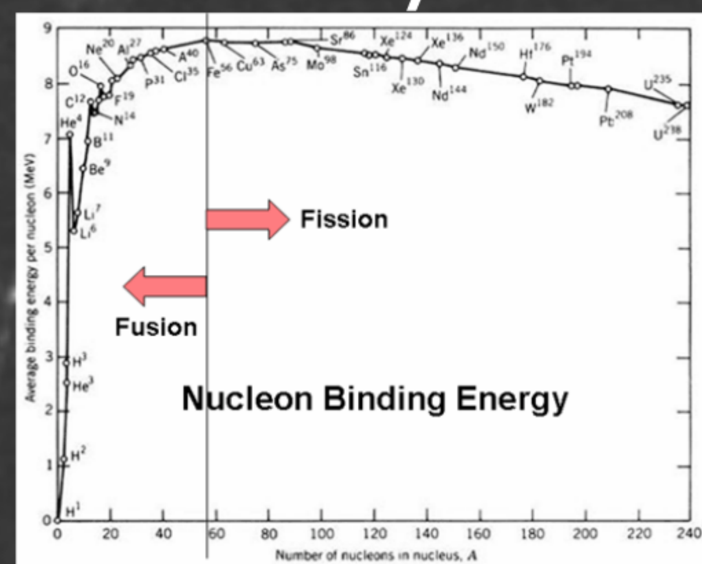

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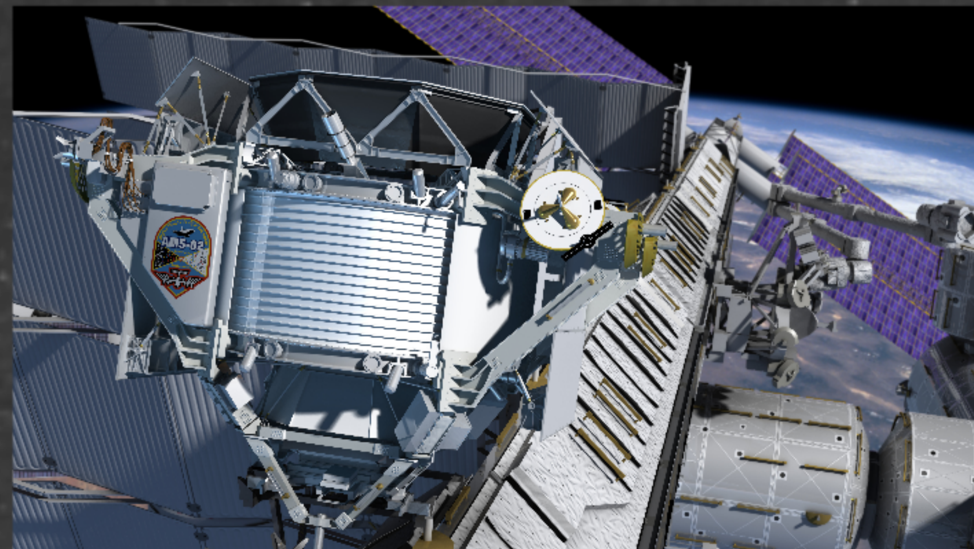

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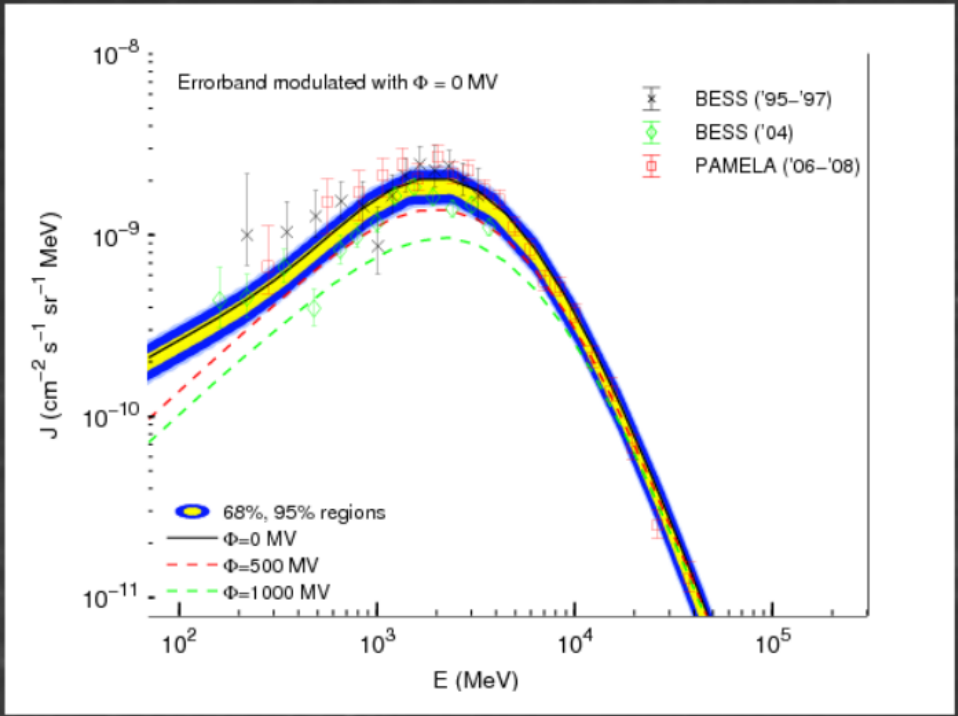
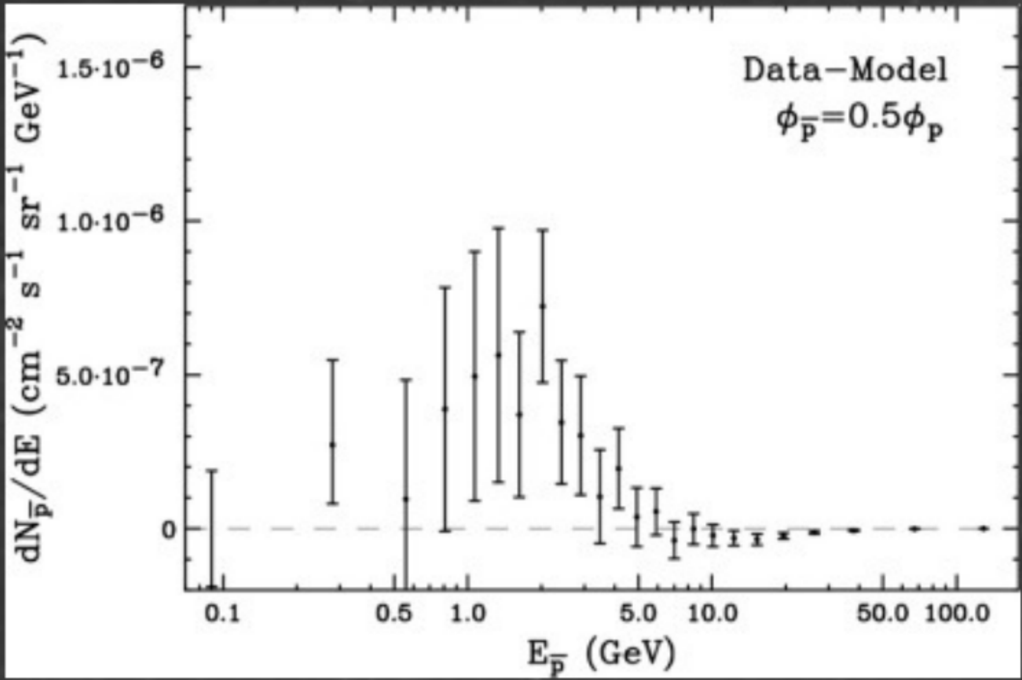
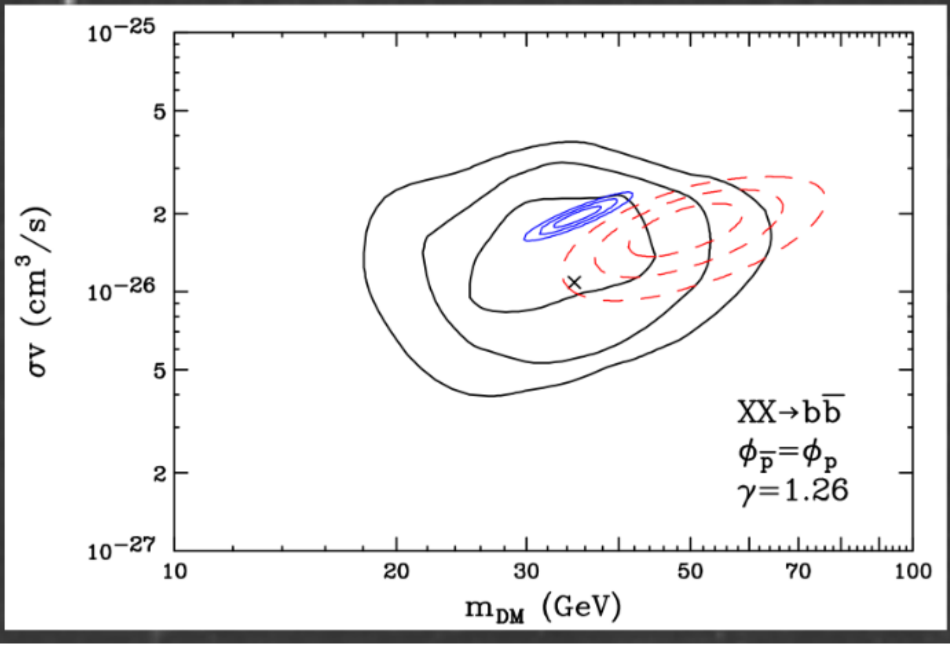
Balloon Experiments (too many to count)

A Hint of An Excess?



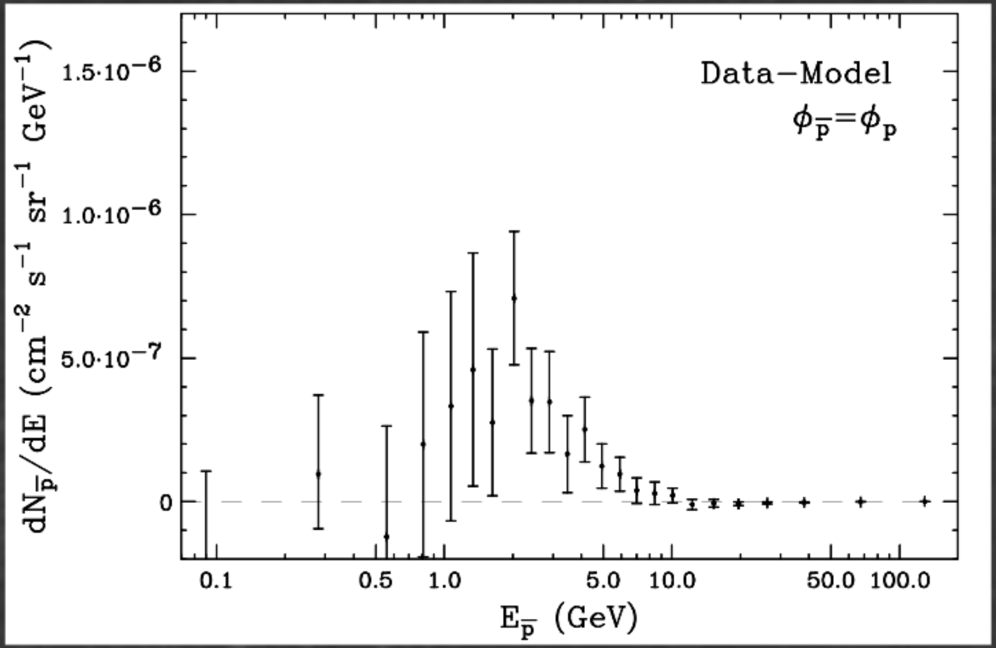


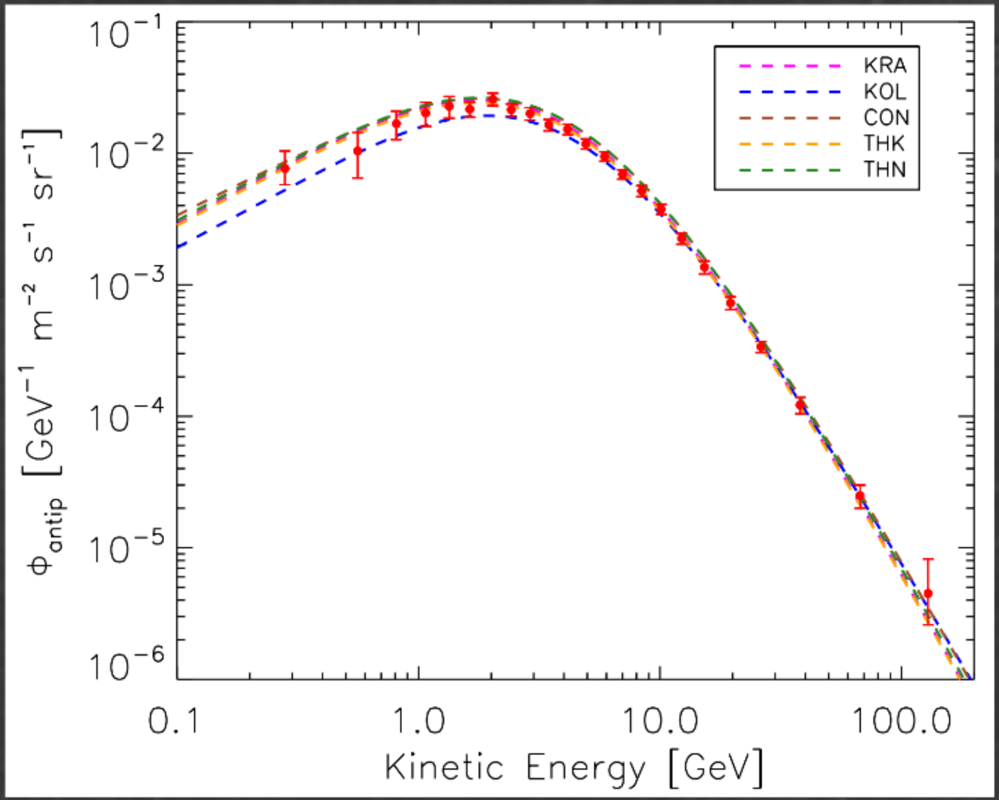
Some generic models from Galprop underproduce protons compared to observations. These can be fit by an additional antiproton flux from dark matter annihilation



Hooper et al. (2014)

Can be Modeled with Different Propagation Mechanisms





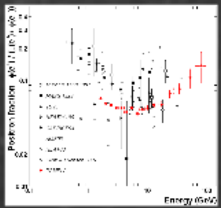
Cirelli et al. (2014)

Can make the excess go away by changing the propagation parameters -- which ones are right?

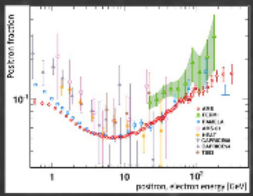
Positron Fraction

Look for a bump in the flux of positrons (compared to electrons) in satellites orbiting Earth

A Big Excess!



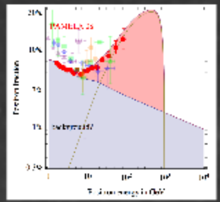
PAMELA (2009)



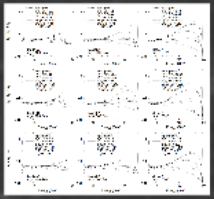
AMS-02 (2013)

Dark Matter Models

Cirelli et al. (2009)



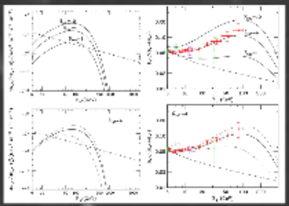
Cholis et al. (2009)



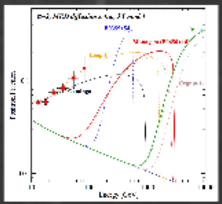
1 TeV -> muons

Generally need an annihilation that produces lots of electrons (e.g. annihilations to electrons or muons)

Pulsar Models Too



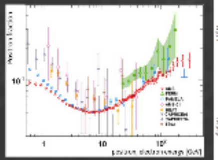
Hooper et al. (2009)



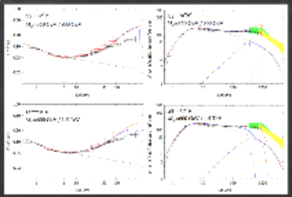
Profumo (2009)

Pulsars can produce electron/positron pairs in the strong magnetic fields surrounding the pulsar, are another reasonable source of the excess

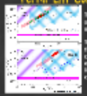
A Few Ways to Differentiate



A Turnover!



Fermi-LAT Constraints



Anisotropies

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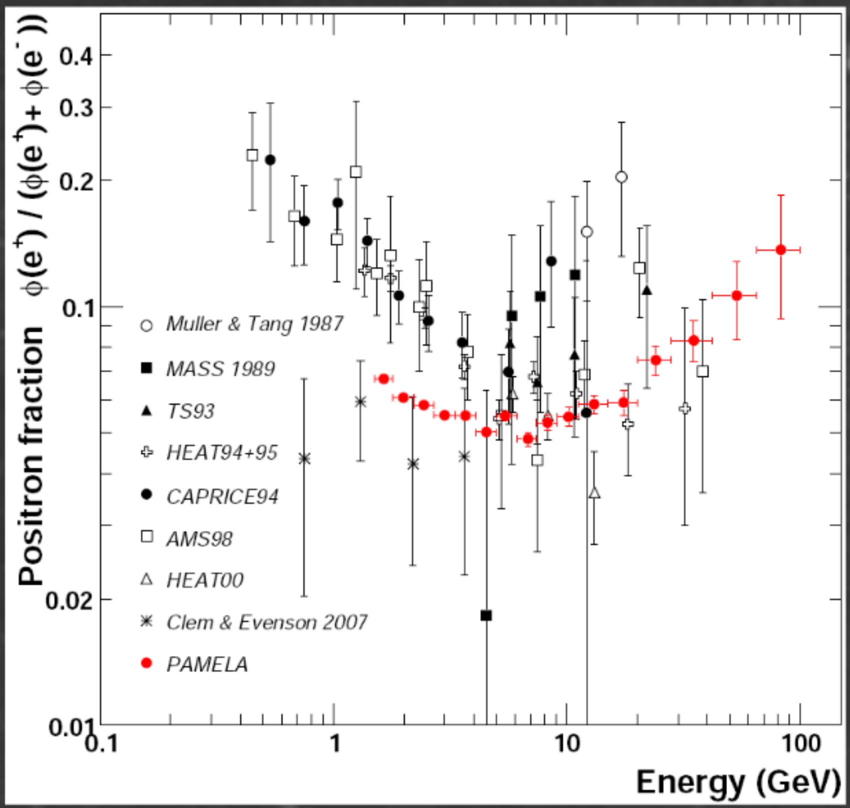

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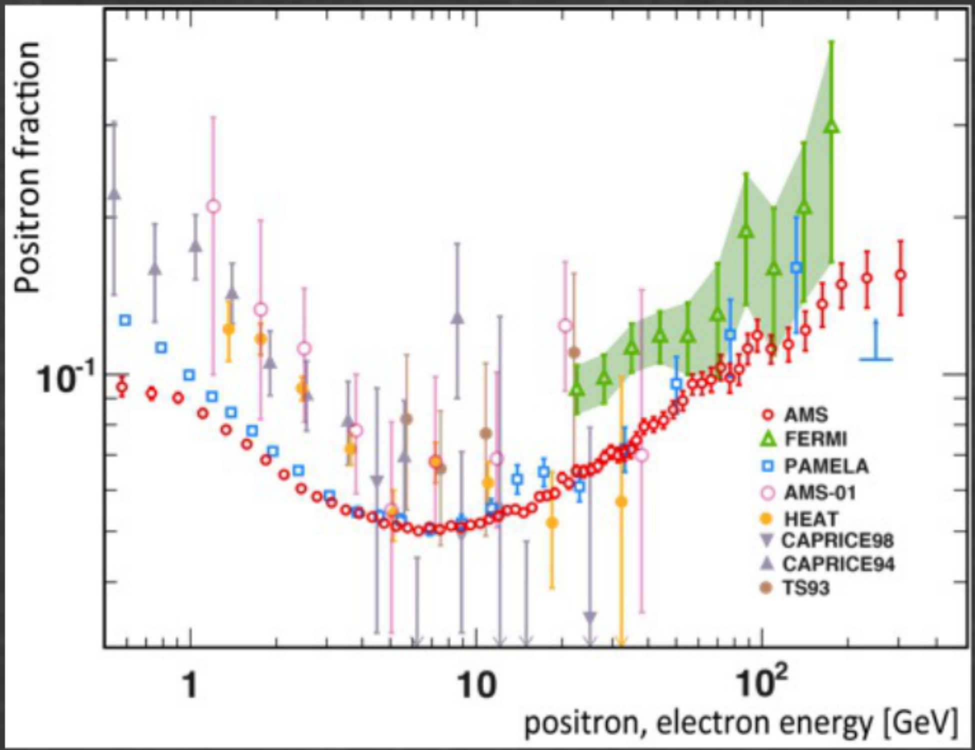

AMS-02 (2013)

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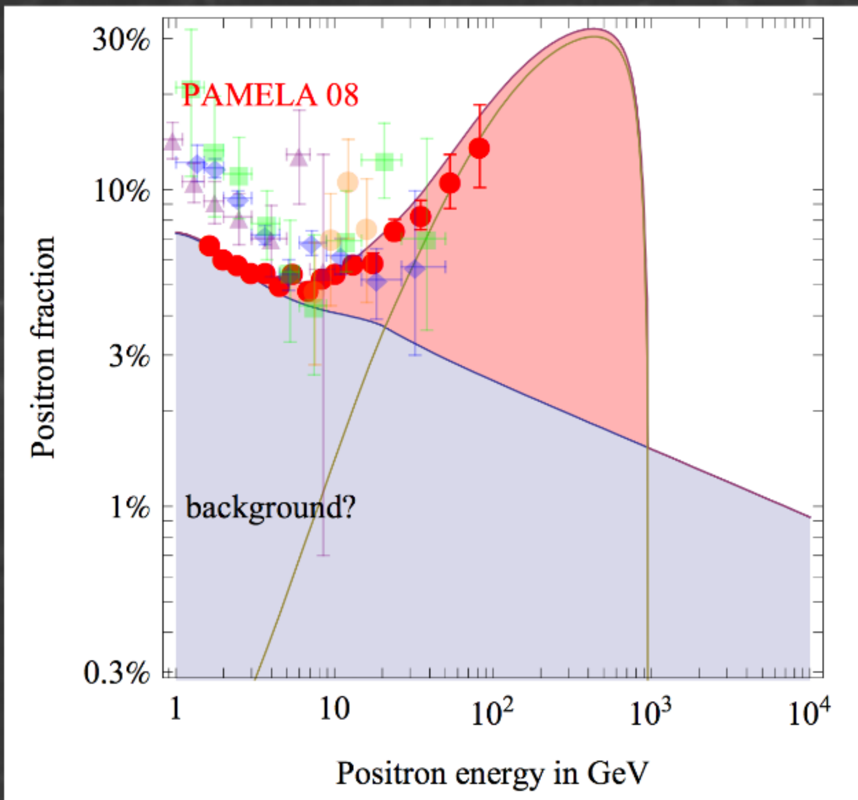

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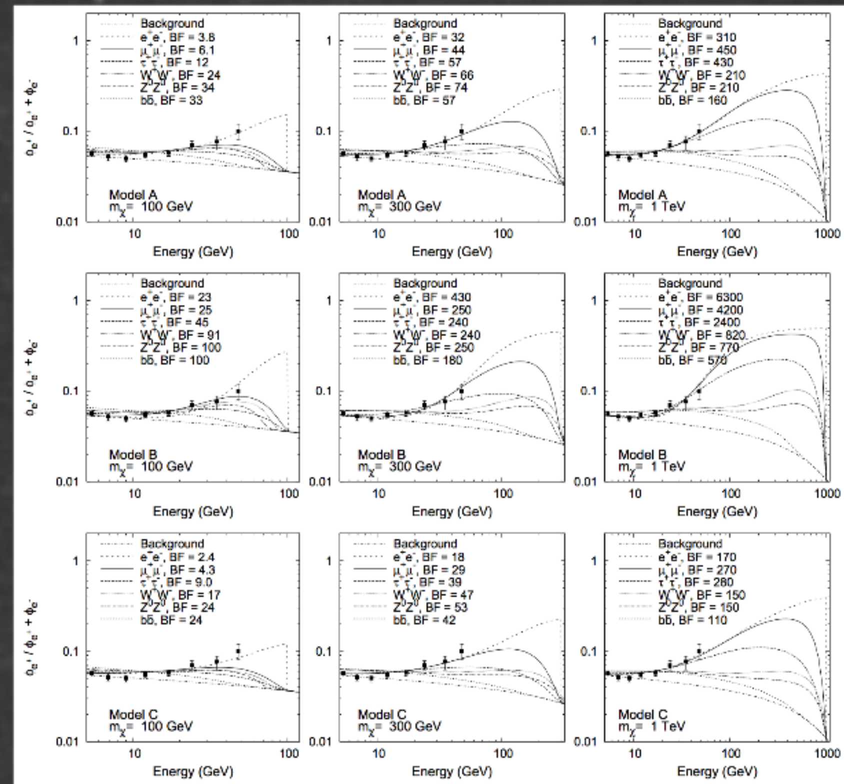

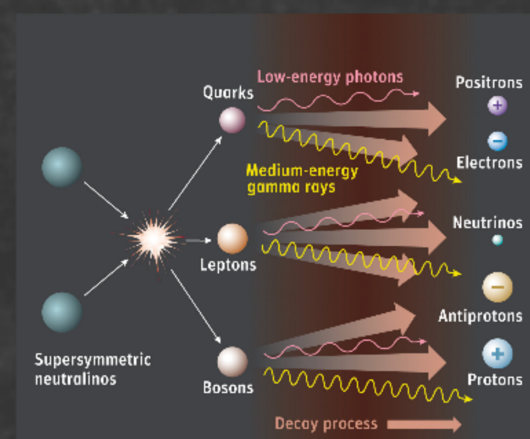

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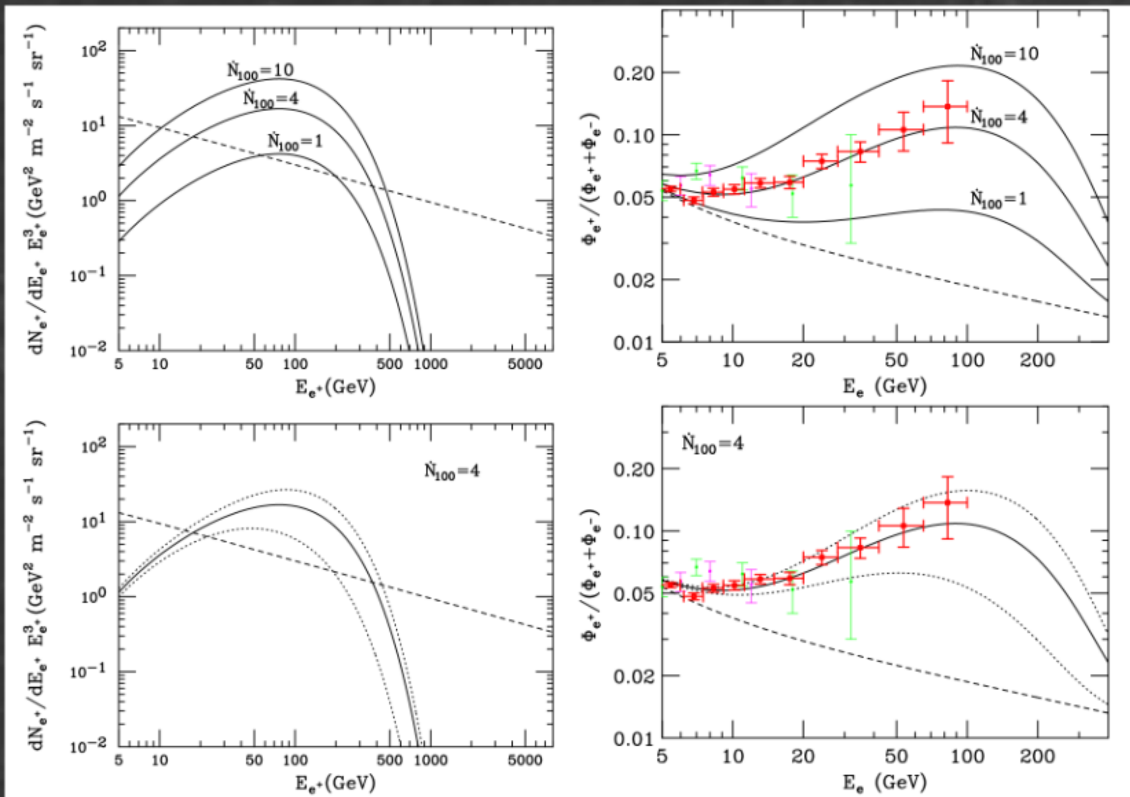

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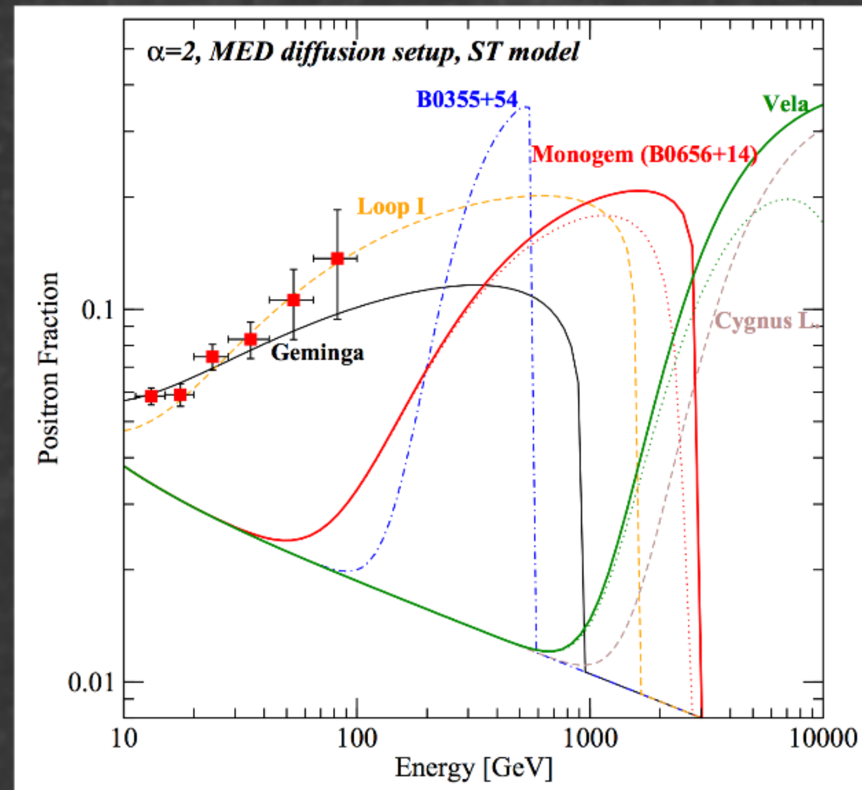

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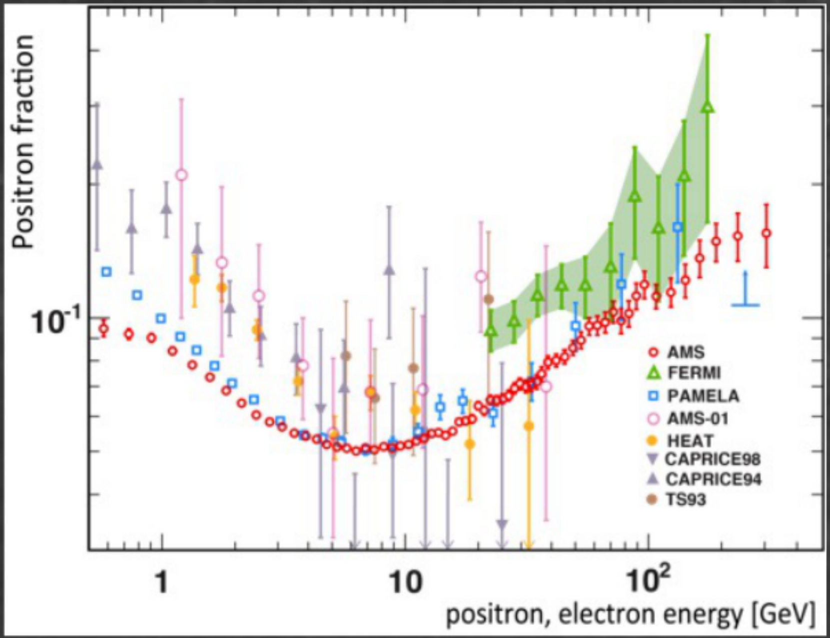

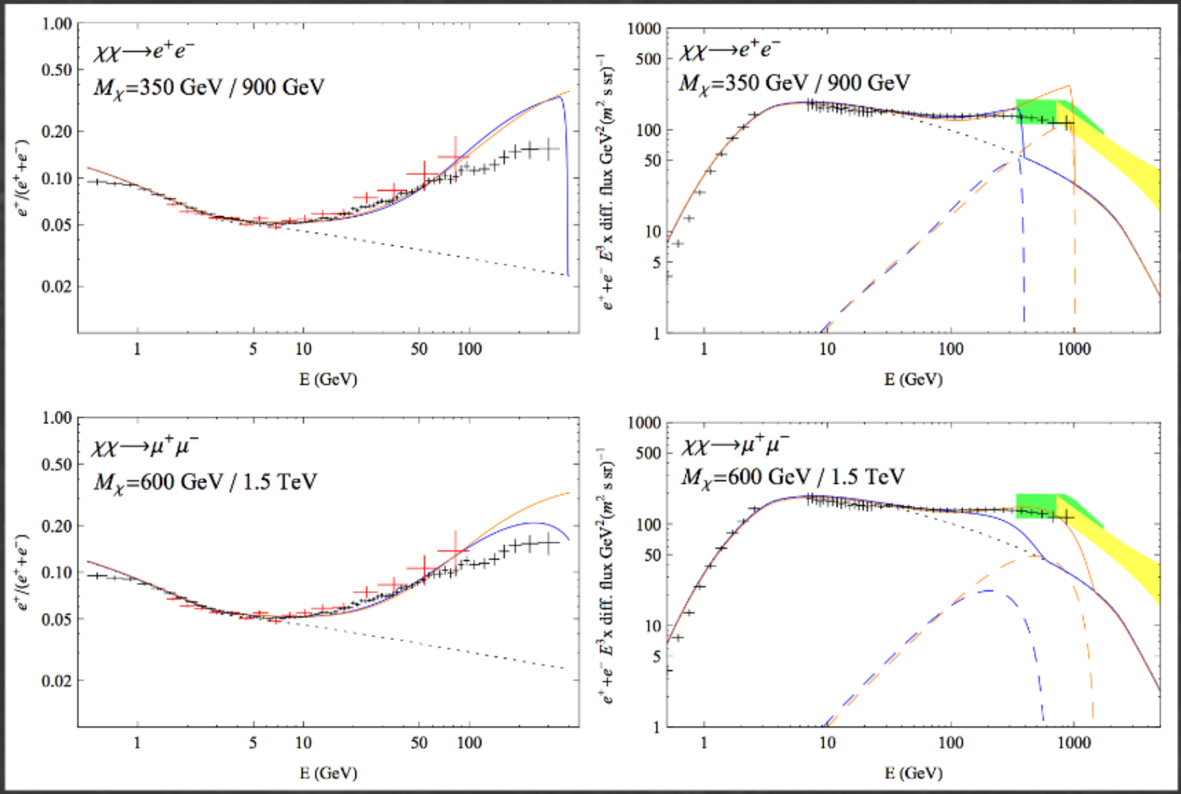

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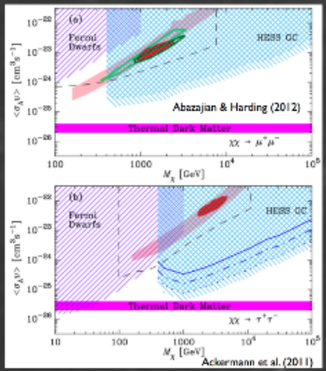
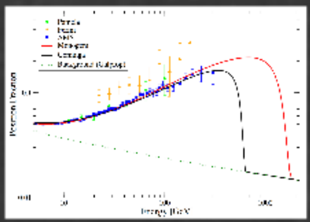


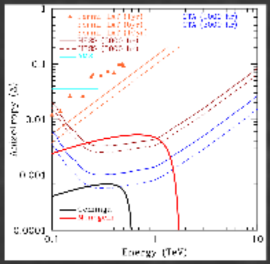
The majority of these annihilation states should also produce gamma-rays.

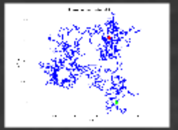
There is tension between the high dark matter cross-sections needed to explain PAMELA, and the limits from dwarf constraints

Anisotropies

Linden & Profumo (2013)

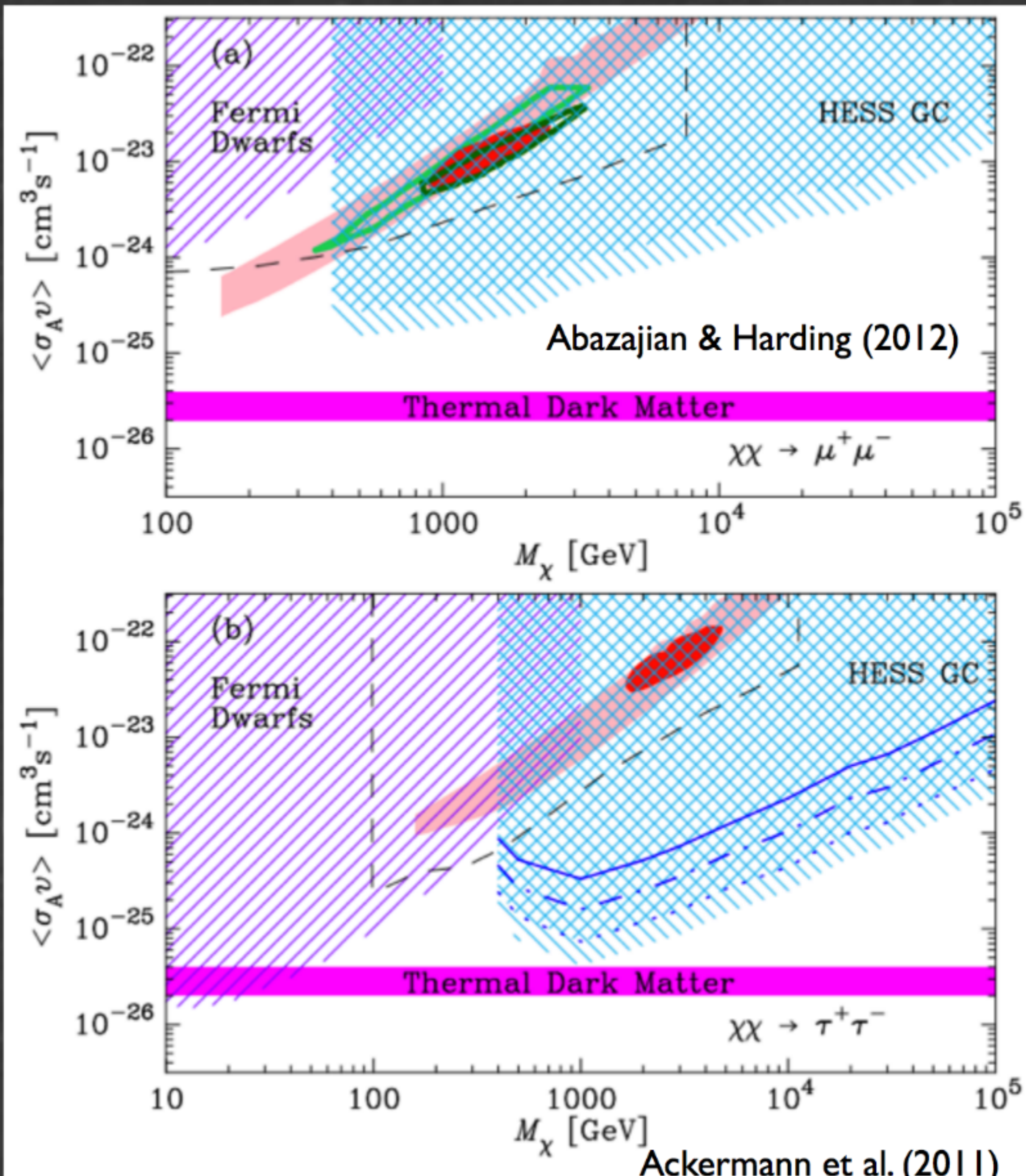






Can search for small anisotropies if the signal is made by a single, nearby source

Fermi-LAT Constraints



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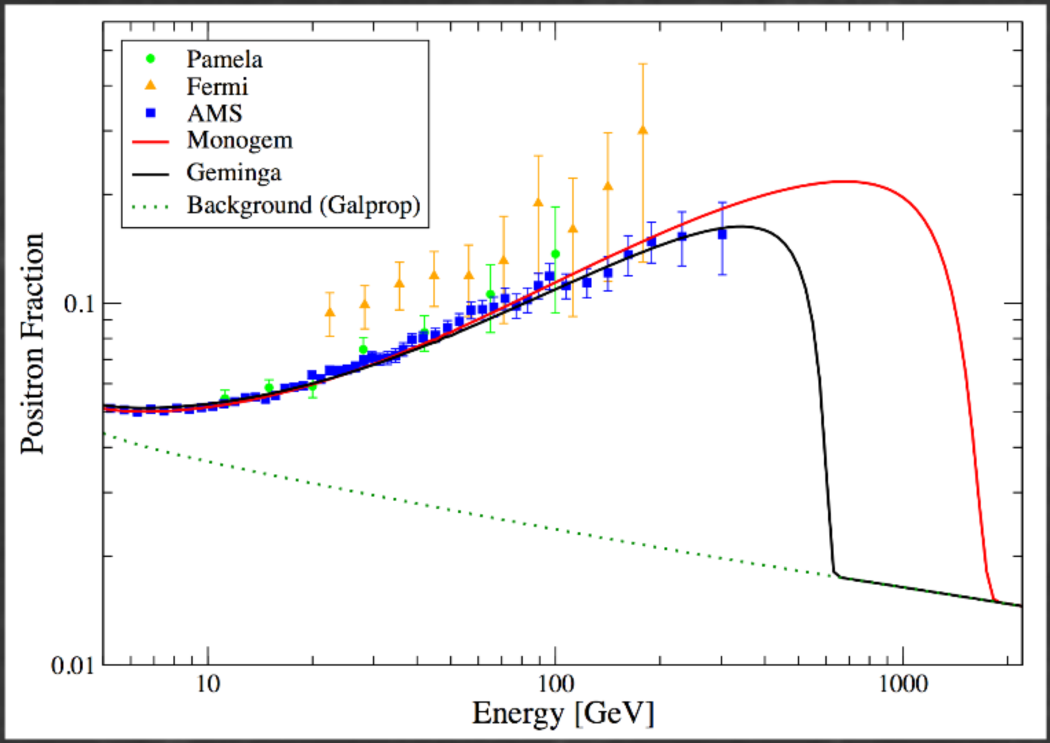

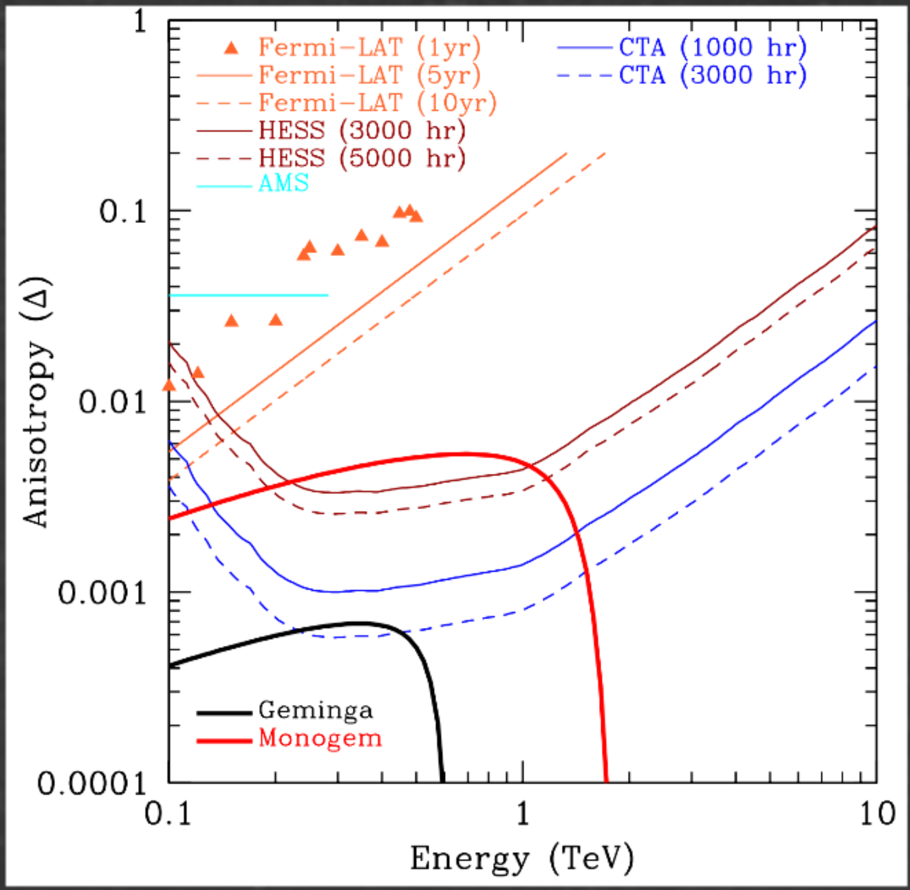

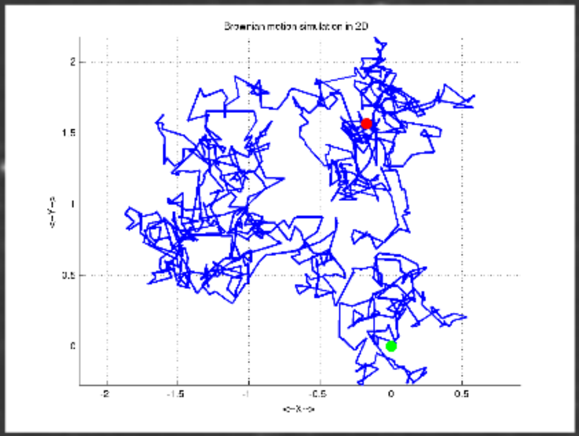

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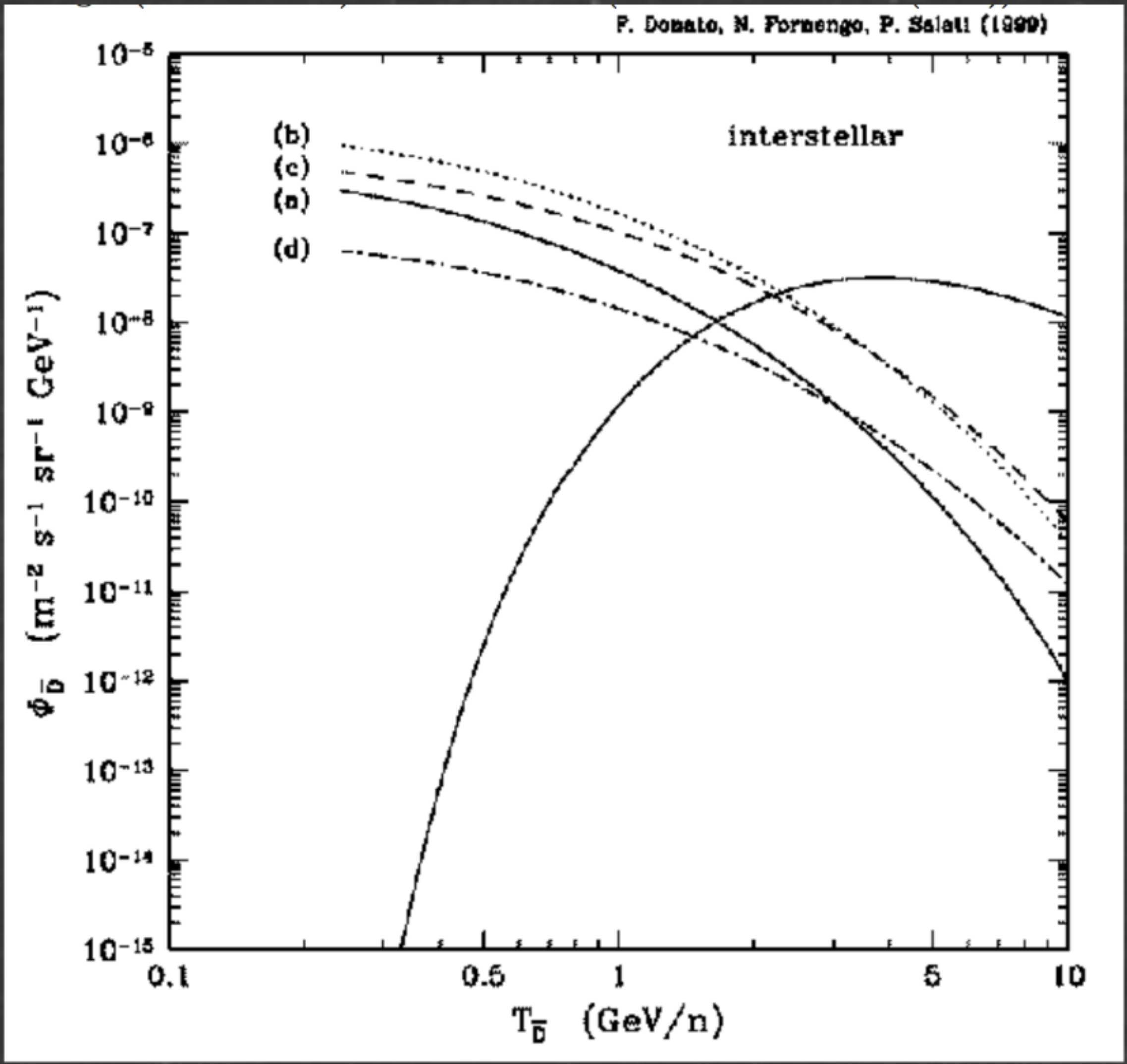
Heavier Nuclei

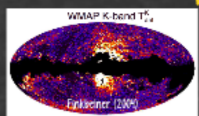


Can look for heavier anti-neuclei (like antideuterium or anti-helium). These are essentially never made in astrophysics.

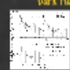
Unfortunately, rare from dark matter too.

Radio Searches

WMAP Haze



Dark Matter Models



Dark Matter Annihilation can explain both the spectrum and intensity of the WMAP Haze

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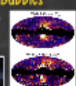
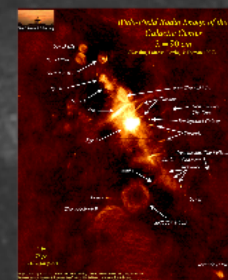
WMAP haze was found to be correlated with the Fermi bubbles, which are not thought to be the product of dark matter annihilation



Galactic Center



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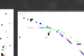
Strong Constraints!



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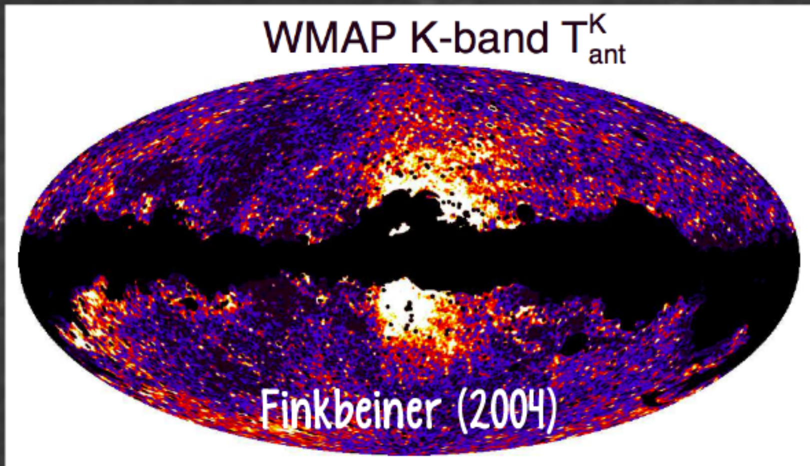
Are these Constraints too Strong?

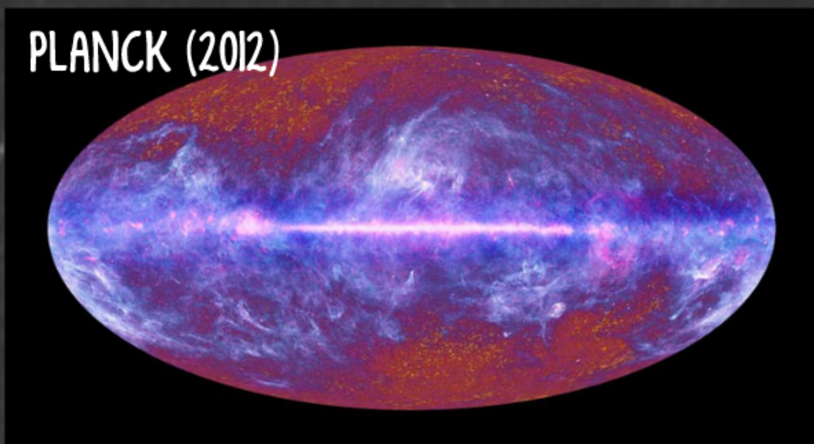
Recently, we showed that the electrons in this region do not produce much synchrotron radiation. Instead they lose energy from inverse-Compton scattering.

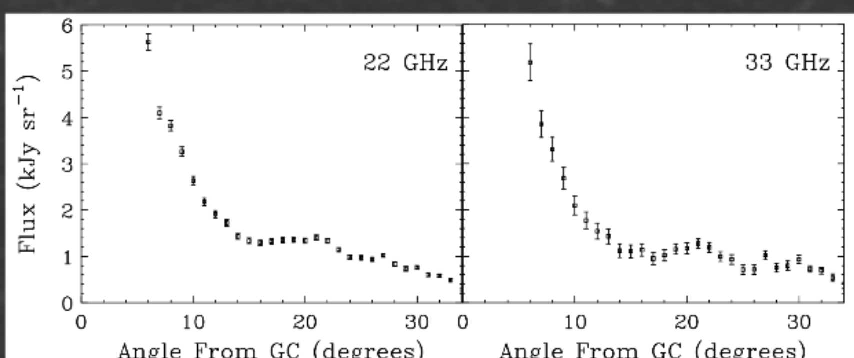
This weakens the limits considerably.

Hooper et al. (2014)

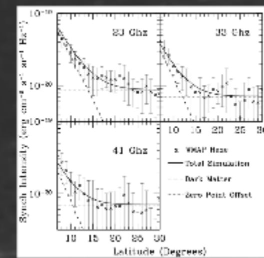
WMAP Haze







Dark Matter Models



Hooper & Linden (2011)

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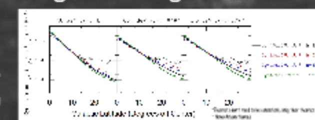

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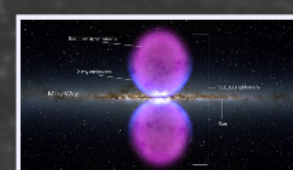

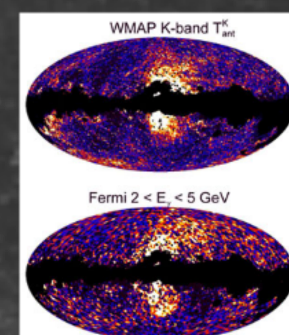

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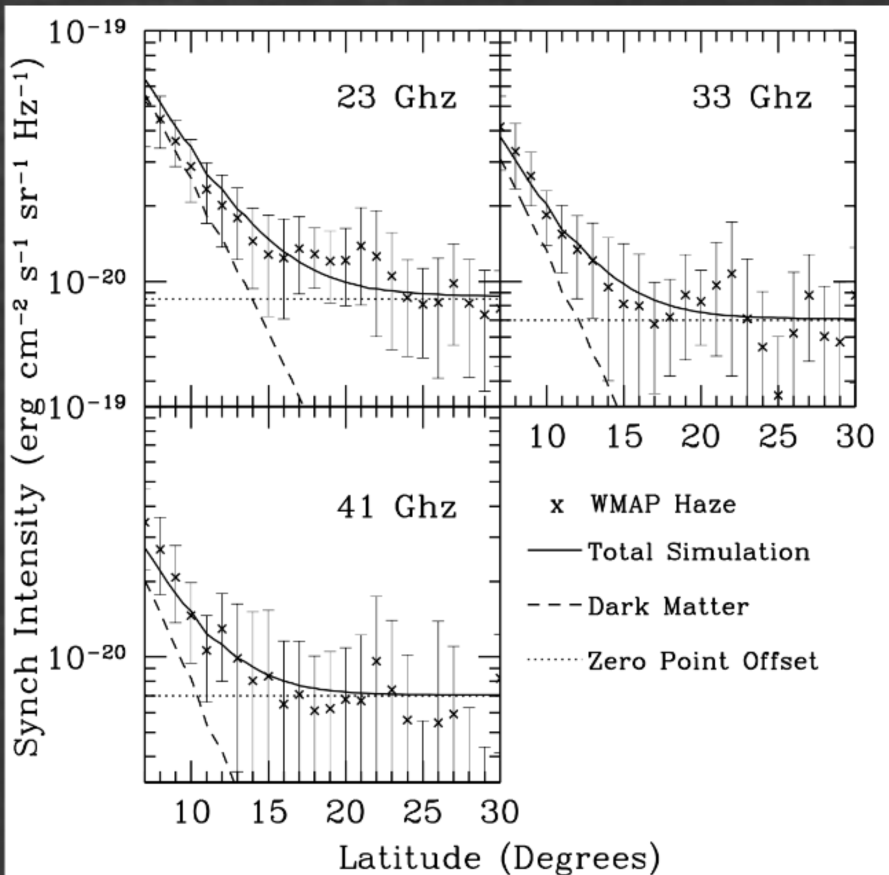

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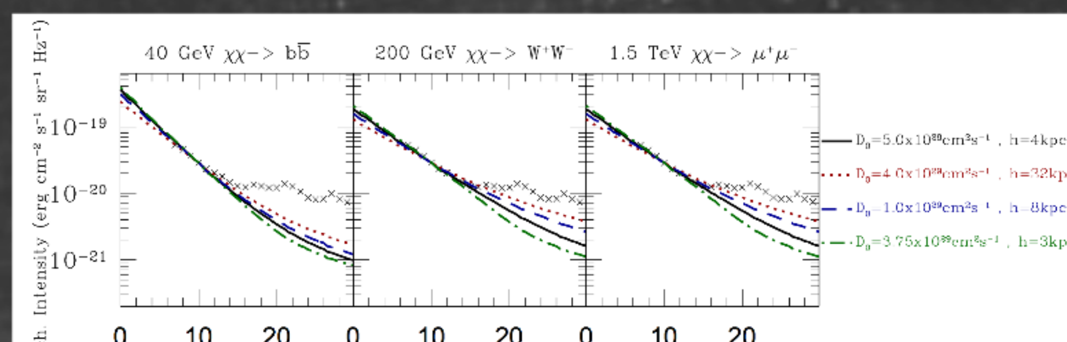

"Theorists don't need to be consistent; only their theories do."
– Nima Arkani-Hamed

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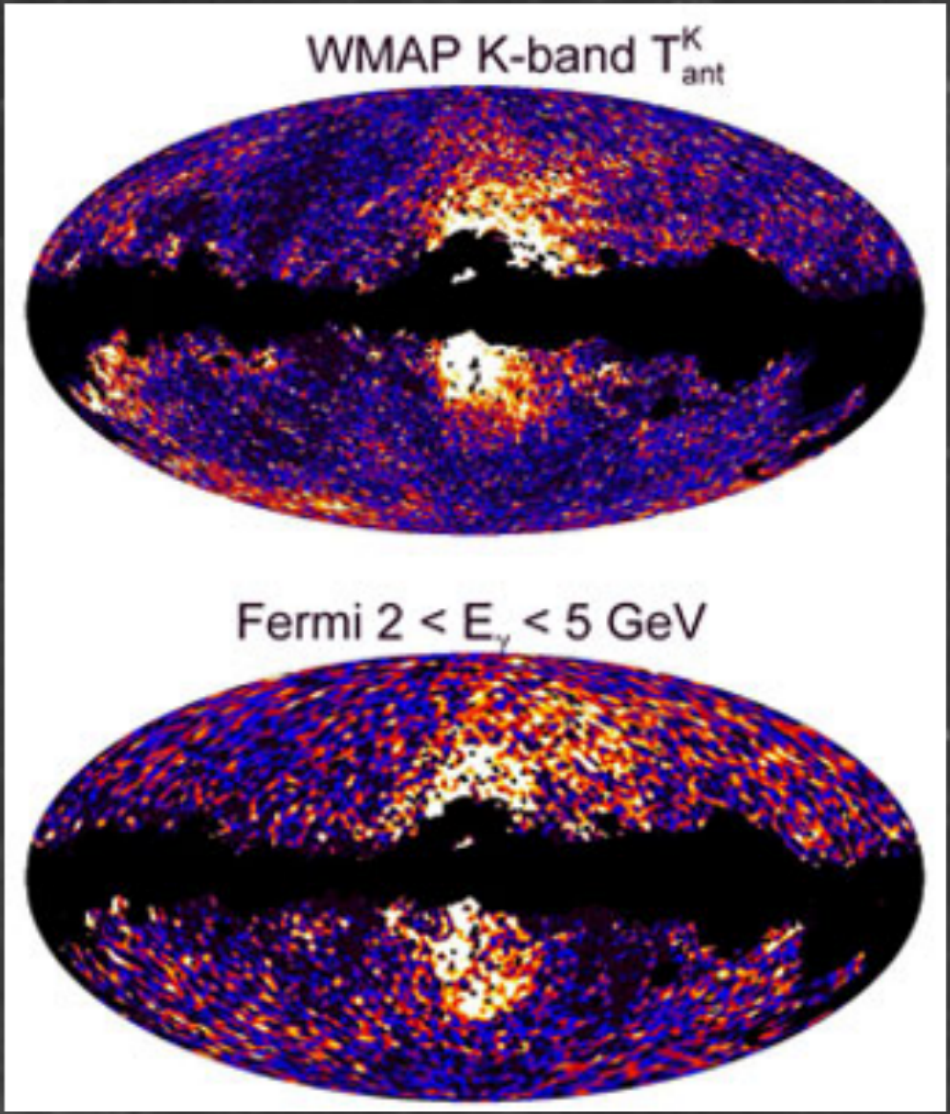

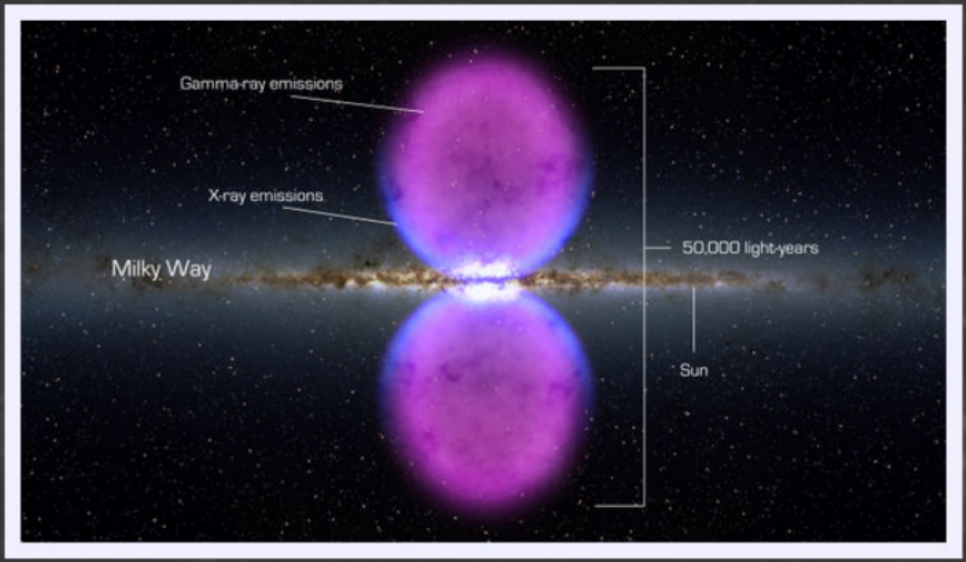

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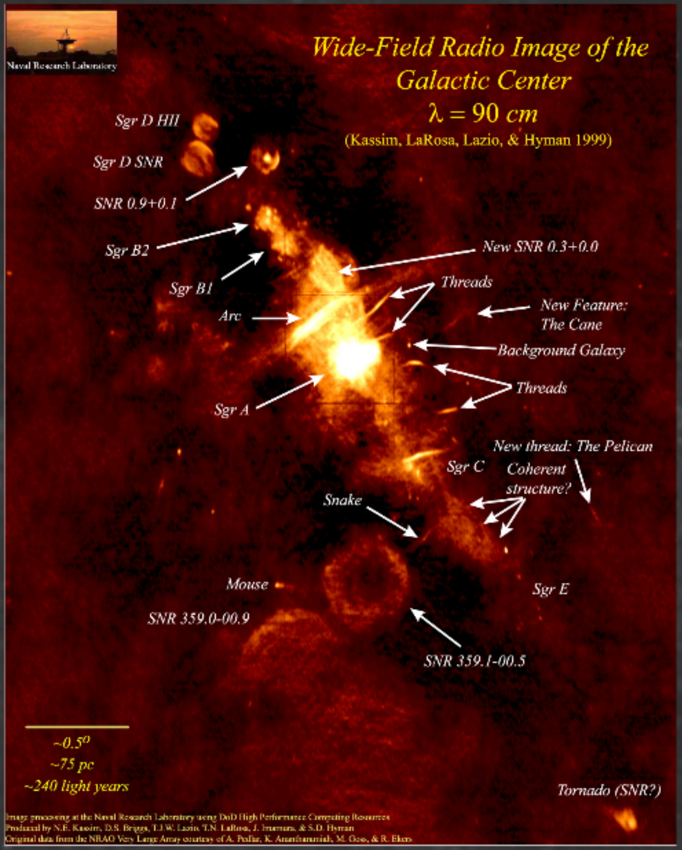

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Strong Constraints!

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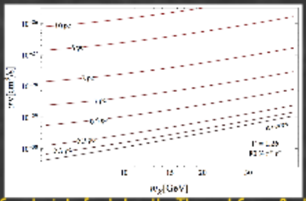
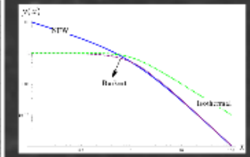


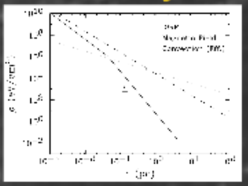


Constraints far below the Thermal Cross-Section!

This is because there is lots and lots of dark matter in the galactic center. If the electrons in this region produce radio emission, you should see a very very bright radio source

Are these Constraints too Strong?

Recently, we showed that the electrons in this region do not produce much synchrotron radiation. Instead they lose energy from inverse-Compton scattering.



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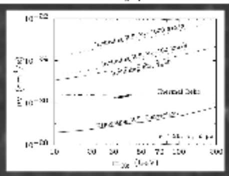
Hooper et al. (2014)



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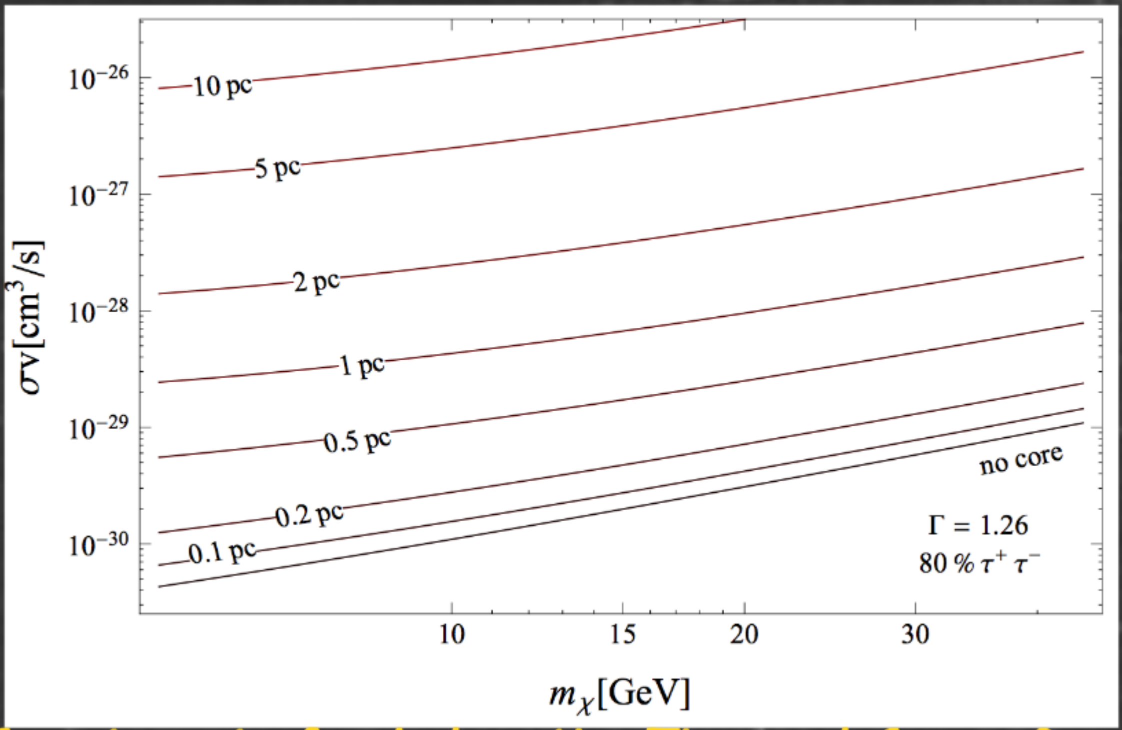

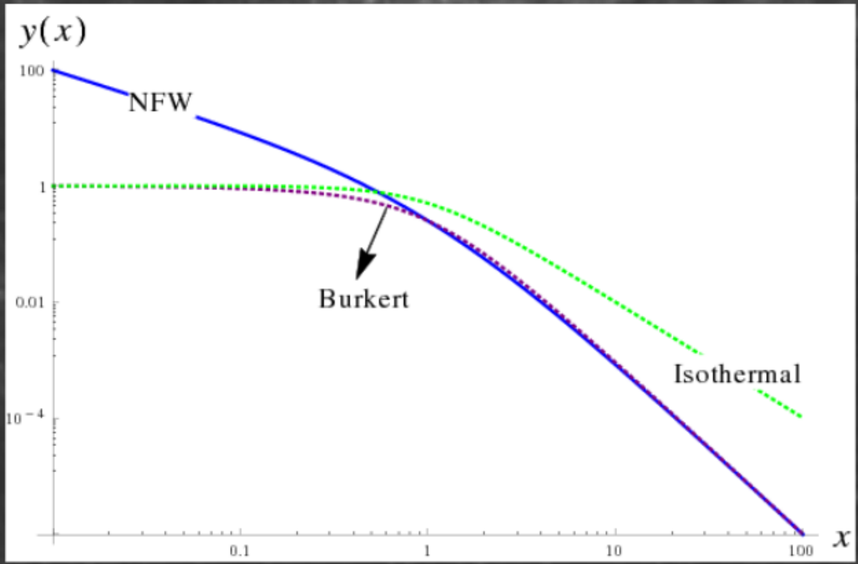

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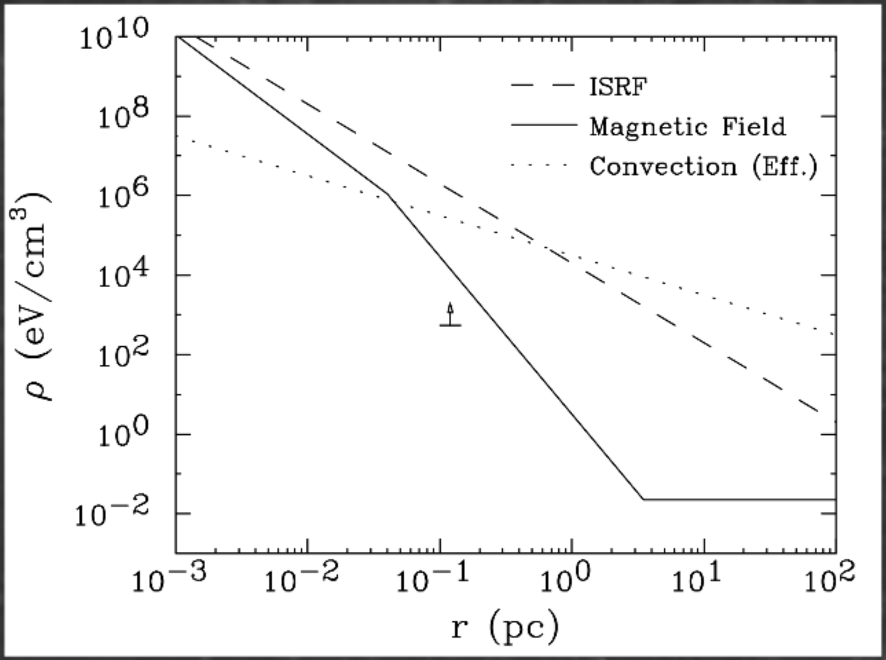

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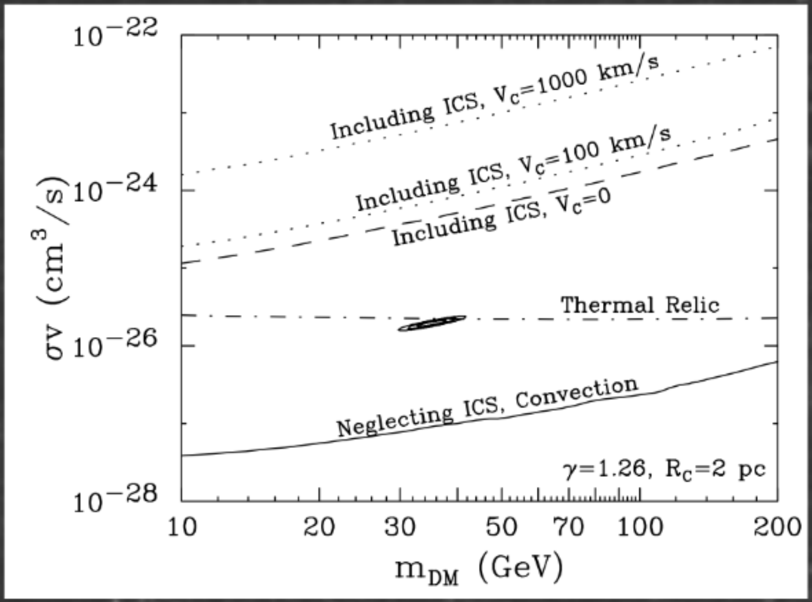


Hooper et al. (2014)

Conclusions

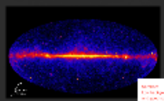
Doubly Indirect Dark Matter detection is very promising, but also very difficult!

Easy to find anomalies, and when you find them, somebody will model them with dark matter

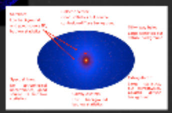
Some hints may last (antiprotons, ARCADE-II excess, positron fraction?) Careful modeling will be necessary!

The "Doubly Indirect" Detection of Dark Matter

Last Week.....



Studied dark matter in gamma-rays



Gamma-Rays travel directly from annihilation event to our detector

Doubly Indirect Detection

Antiparticle Searches

Antiproton Flux

Positron Fraction

Heavier Nuclei

Radio Searches

Galactic Center

Tim Linden

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Lecture 8

Fall 2014 Compton Lectures