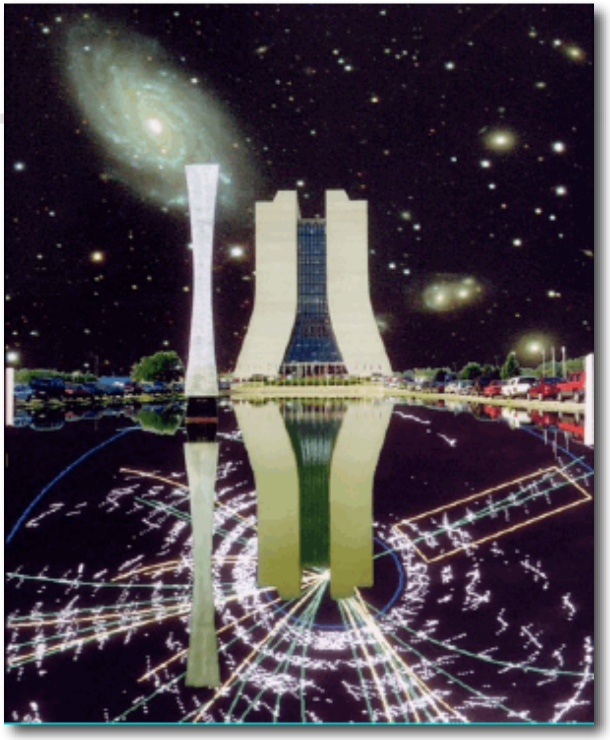
The Observational Case For 7-8 GeV Dark Matter:
Fermi, CoGeNT and DAMA

Dan Hooper
Fermilab/University of Chicago



Southern Methodist University
Webinar

October 25, 2010

Based on…

Dark matter annihilation in the Galactic Center as seen by the Fermi Gamma Ray Space Telescope

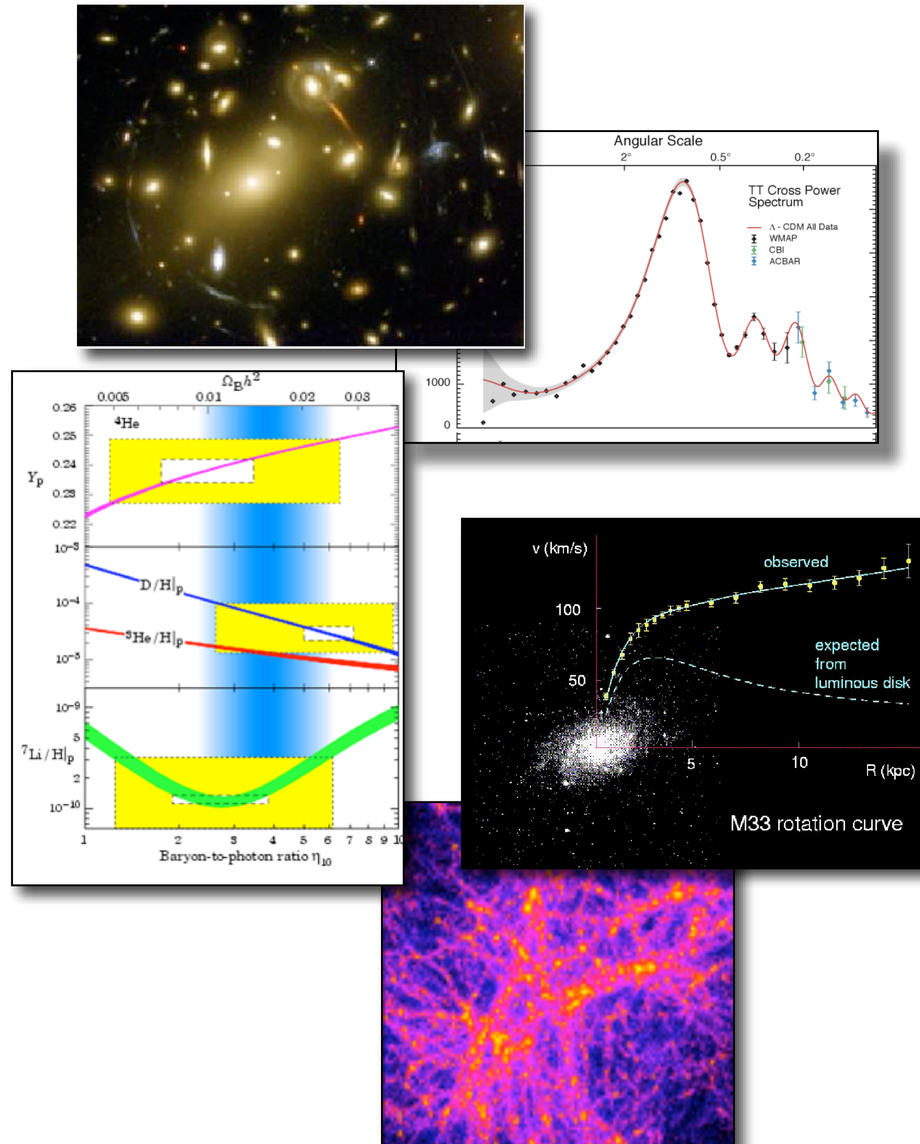
Dan Hooper and Lisa Goodenough
arXiv:1010.2752

A consistent dark matter interpretation for CoGeNT and DAMA/LIBRA

Dan Hooper, Juan Collar, Jeter Hall, and Dan McKinsey
PRD (in press), arXiv:1007.1005

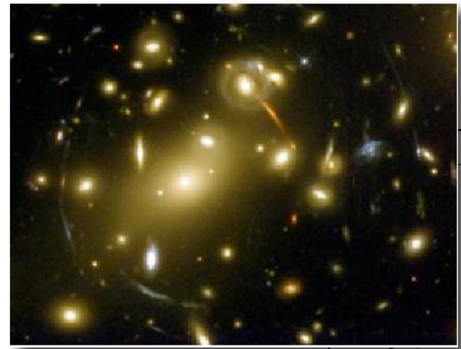
Evidence For Dark Matter

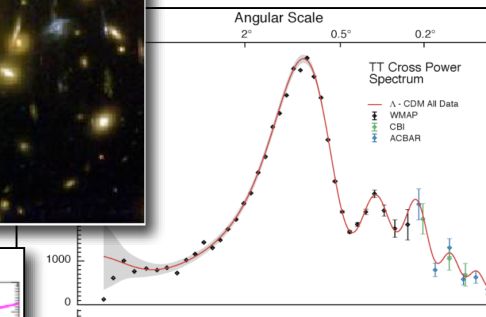
- Galactic rotation curves
- Gravitational lensing
- Light element abundances
- Cosmic microwave background anisotropies
- Large scale structure

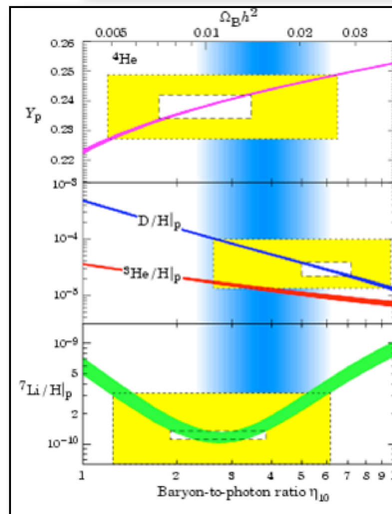


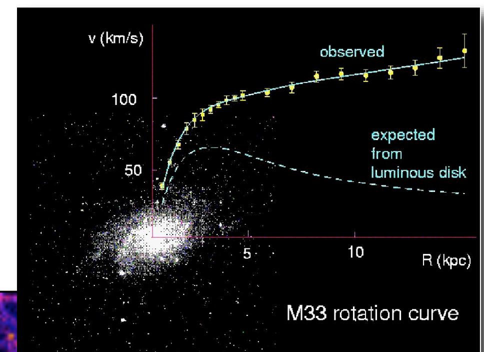
Evidence For Dark Matter

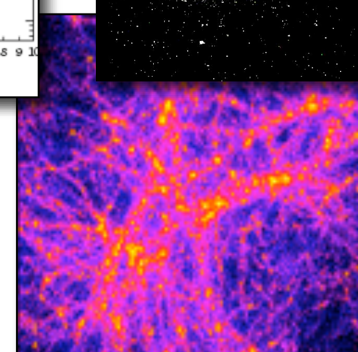
- There exists a wide variety of independent indications that dark matter exists
- Each of these observations infer dark matter's presence through its gravitational influence
- Without observations of dark matter's electroweak or other non-gravitational interactions, we are unable to determine its particle nature





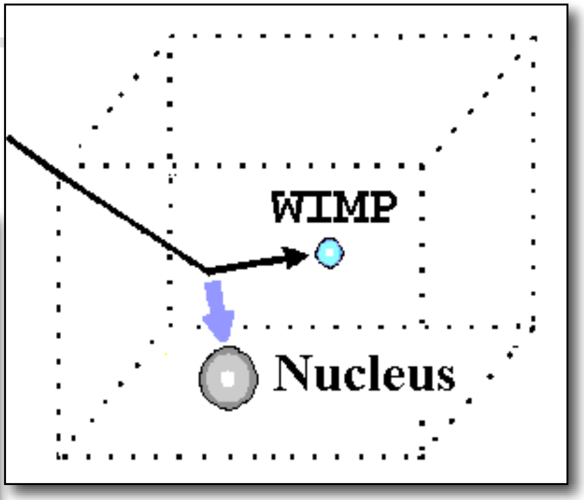


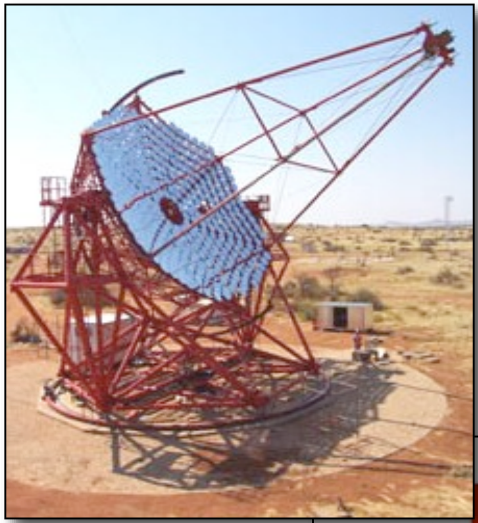


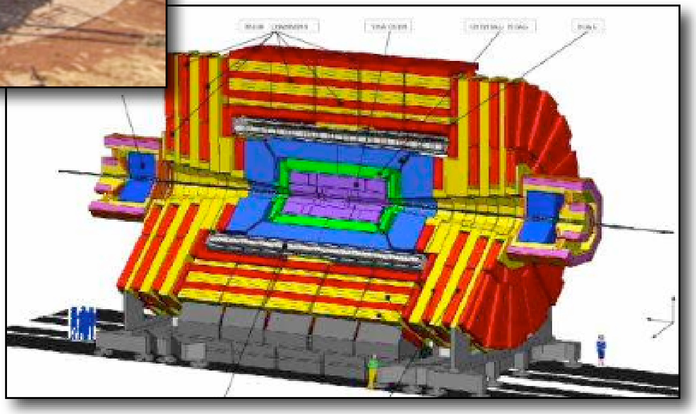


WIMP Hunting

- Direct Detection
- Indirect Detection
- Collider Searches

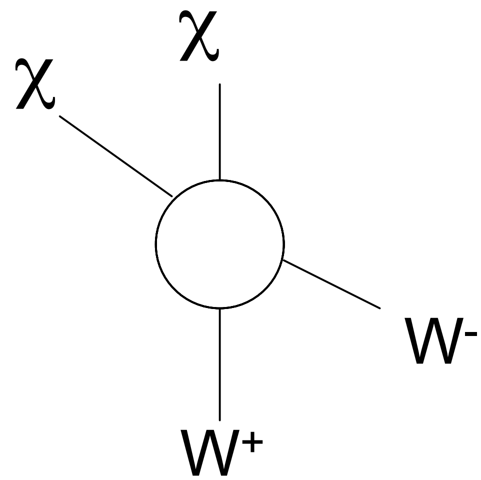






The Indirect Detection of Dark Matter

1. **WIMP Annihilation**
   Typical final states include heavy fermions, gauge or Higgs bosons



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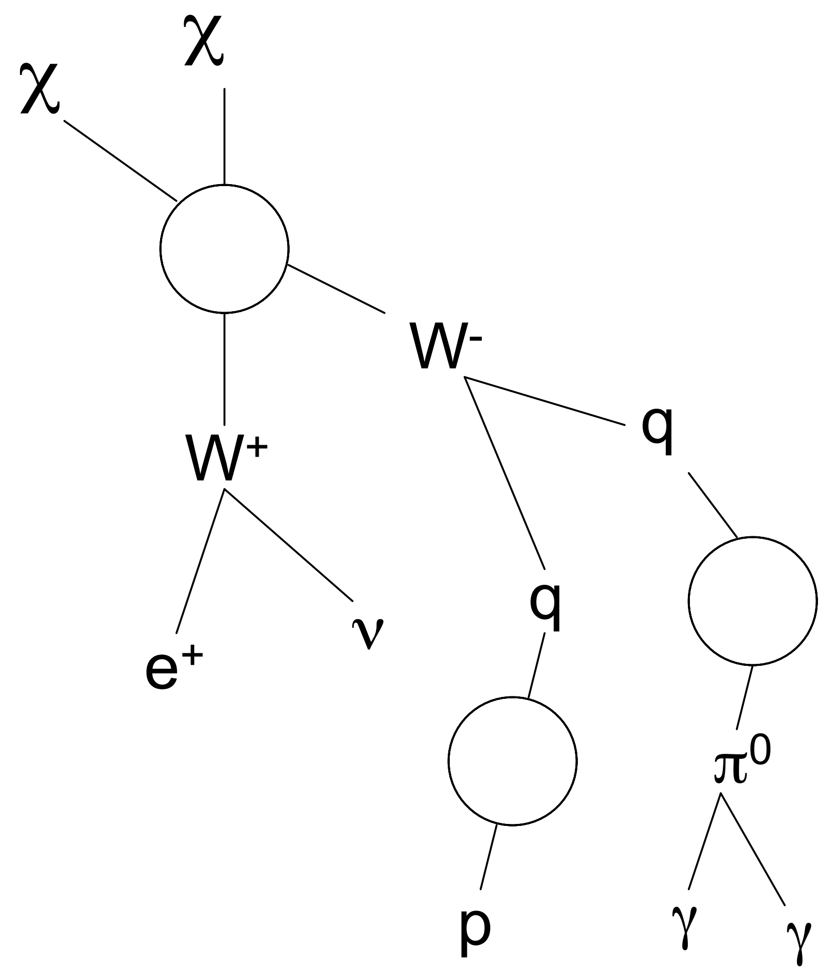
   Annihilation products decay and/or fragment into combinations of electrons, protons, deuterium, neutrinos and gamma-rays



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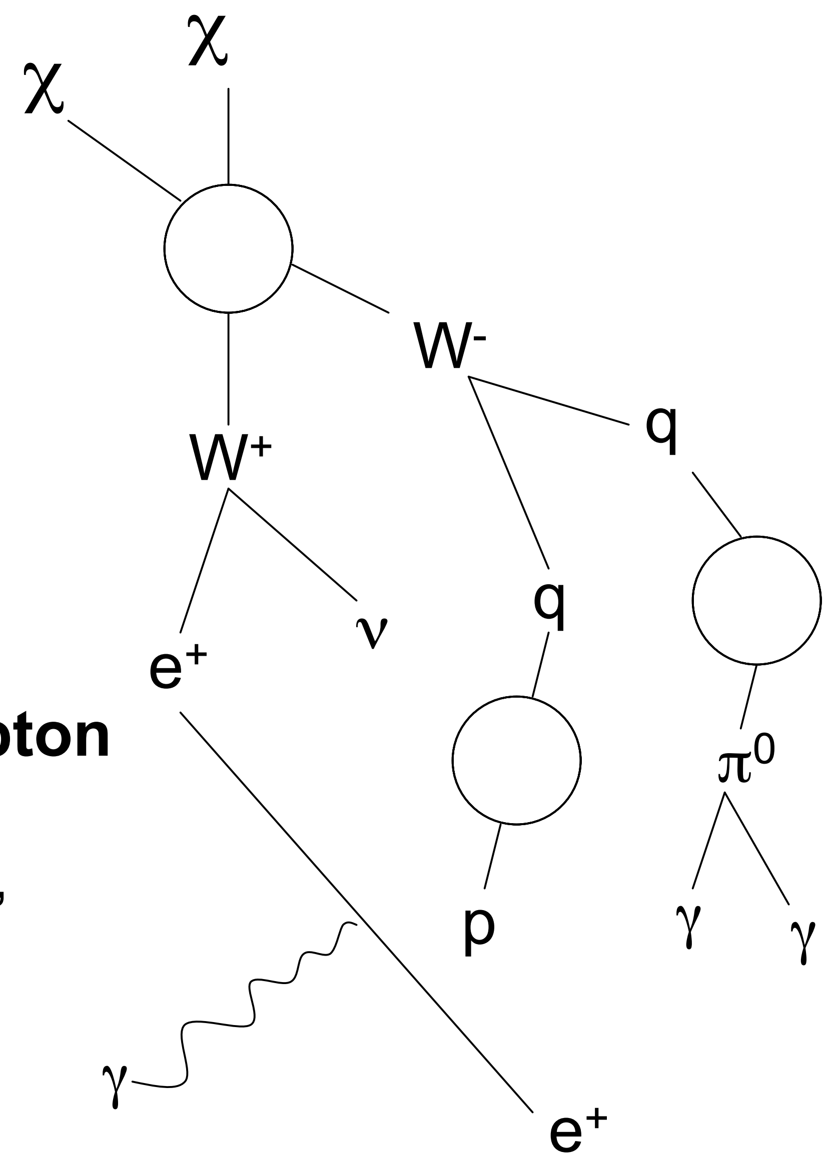
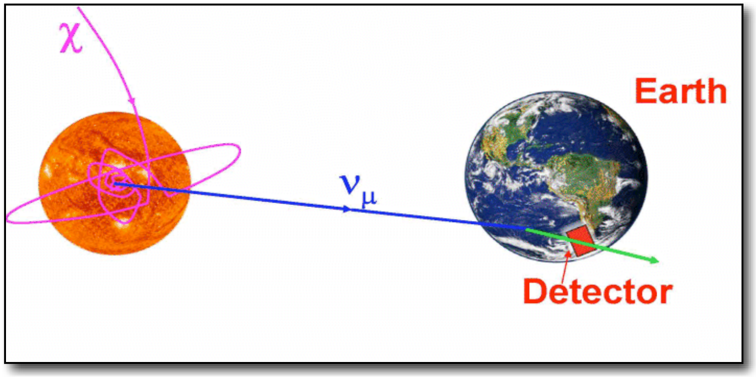
3. **Synchrotron and Inverse Compton**
   Relativistic electrons up-scatter starlight/CMB to MeV-GeV energies, and emit synchrotron photons via interactions with magnetic fields



The Indirect Detection of Dark Matter

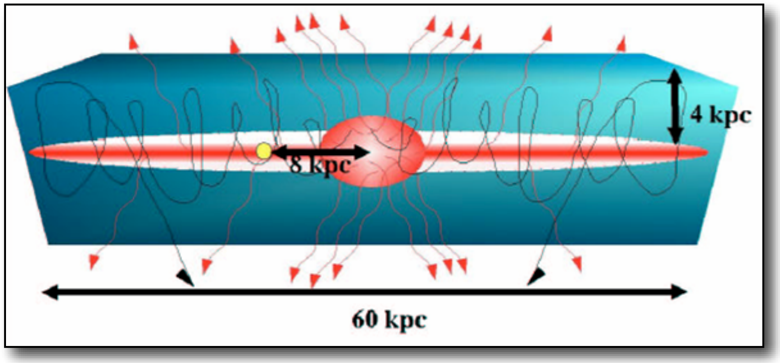
- **Neutrinos** from annihilations in the core of the Sun



- **Gamma Rays** from annihilations in the galactic halo, near the galactic center, in dwarf galaxies, etc.

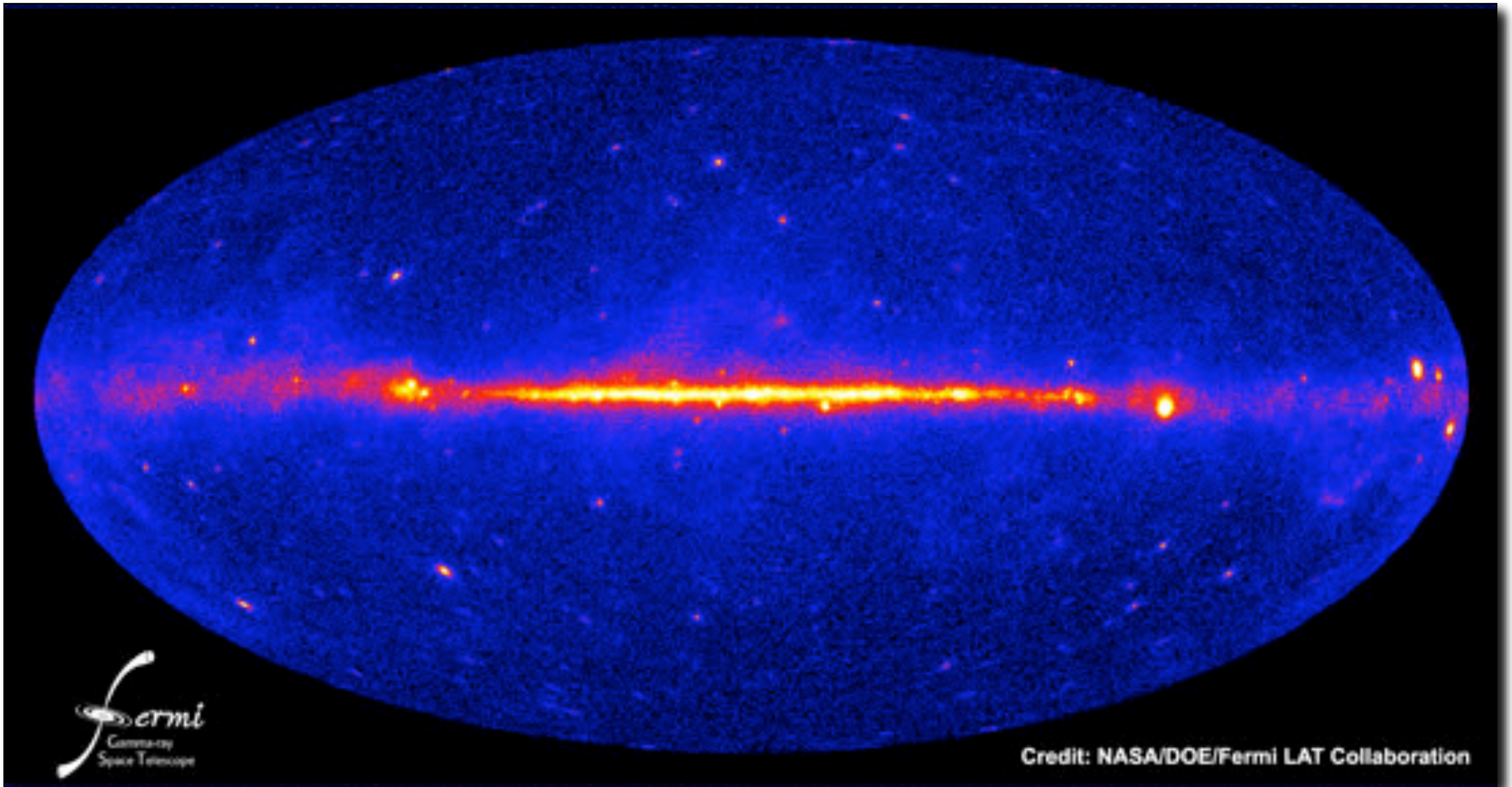
- **Positrons/Antiprotons** from annihilations throughout the galactic halo

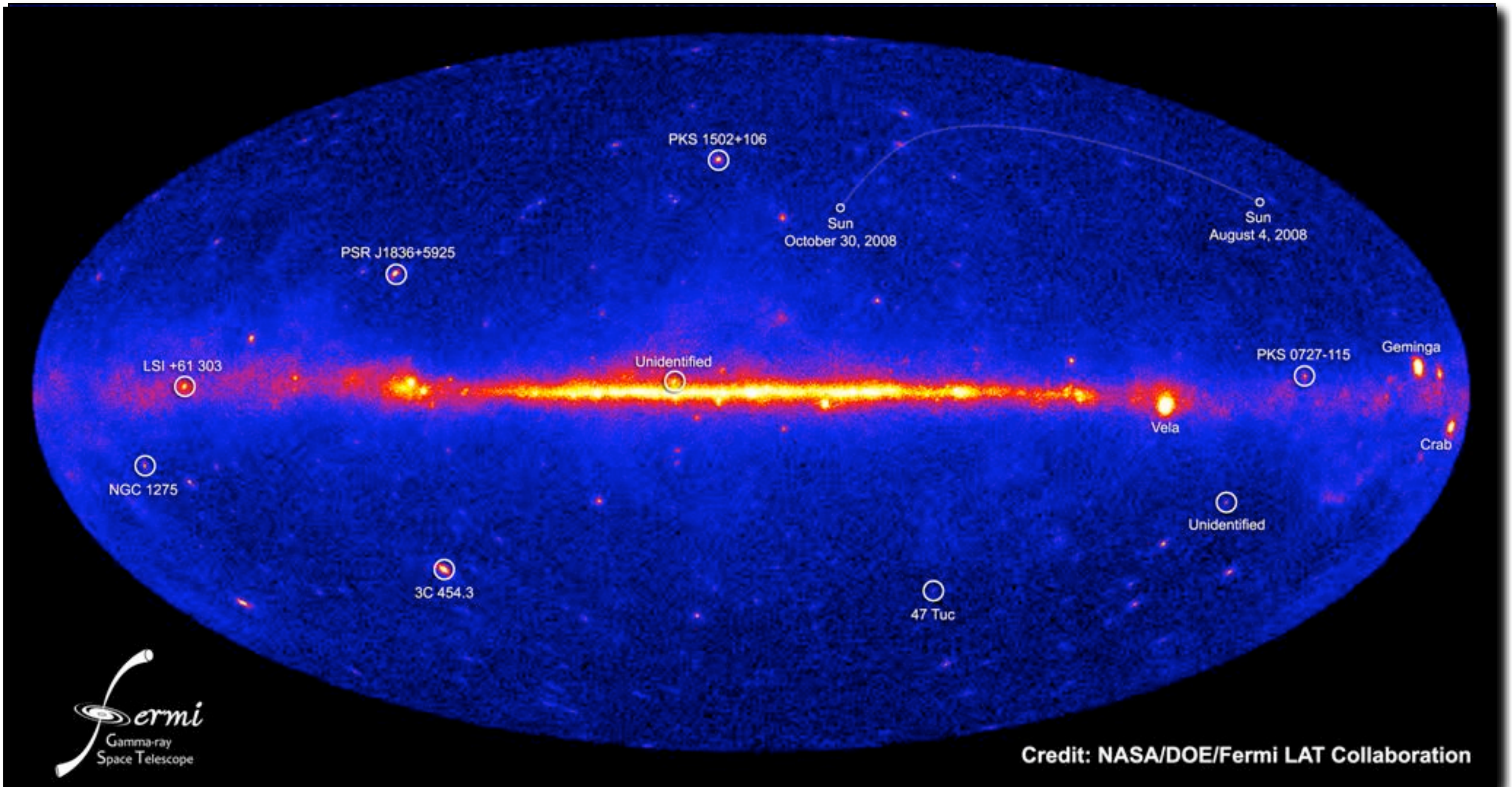
- **Synchrotron and Inverse Compton** from electron/positron interactions with the magnetic fields and radiation fields of the galaxy



An Essential Test:
Searches For Gamma Rays From Dark Matter Annihilations With Fermi

- The Fermi Gamma Ray Space Telescope has been collecting data for more than two years
- In August 2009, their first year data became publicly available
- Fermi's Large Area Telescope (LAT) possesses superior effective area (~7000-8000 cm^2), angular resolution (sub-degree), and energy resolution (~10%) than its predecessor EGRET
- Unlike ground based gamma ray telescopes, Fermi observes the entire sky, and can study far lower energy emission (down to ~300 MeV)


Fermi
Gamma-ray
Space Telescope
Credit: NASA/DOE/Fermi LAT Collaboration


PKS 1502+106
Sun
October 30, 2008
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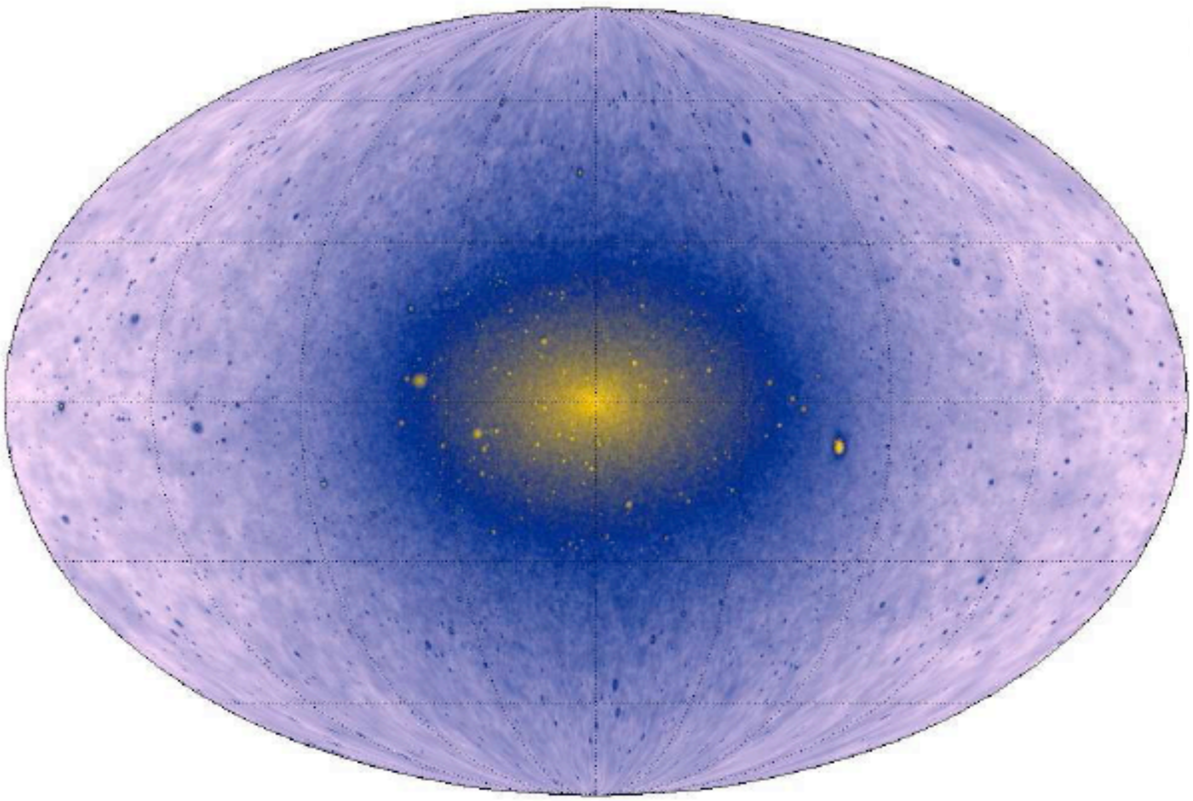
PSR J1836+5925
LSI +61 303
Unidentified
PKS 0727-115
Geminga
Vela
Crab
NGC 1275
Unidentified
3C 454.3
47 Tuc
Fermi
Gamma-ray
Space Telescope
Credit: NASA/DOE/Fermi LAT Collaboration

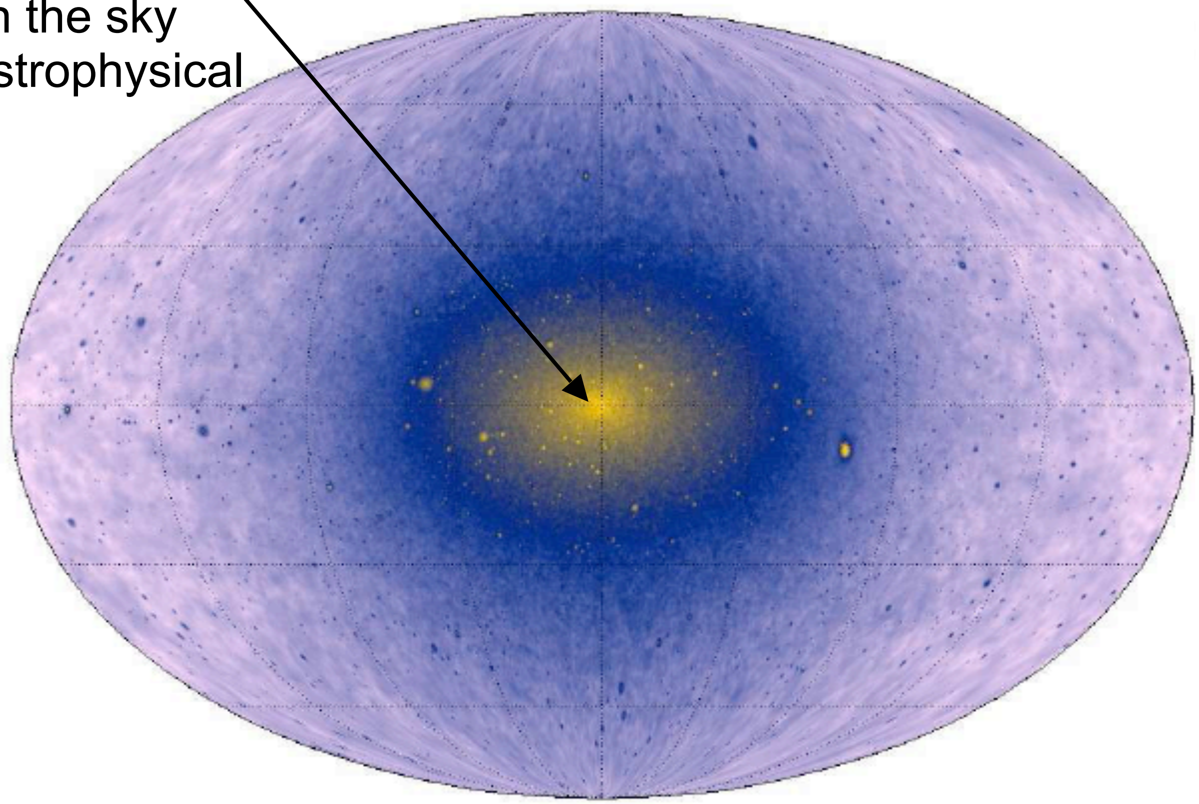
Where To Look For Dark Matter With Fermi?



Where To Look For Dark Matter With Fermi?

The Galactic Center

-Brightest spot in the sky
-Considerable astrophysical backgrounds



Where To Look For Dark Matter With Fermi?

The Galactic Halo

-High statistics
-Requires detailed model of galactic backgrounds

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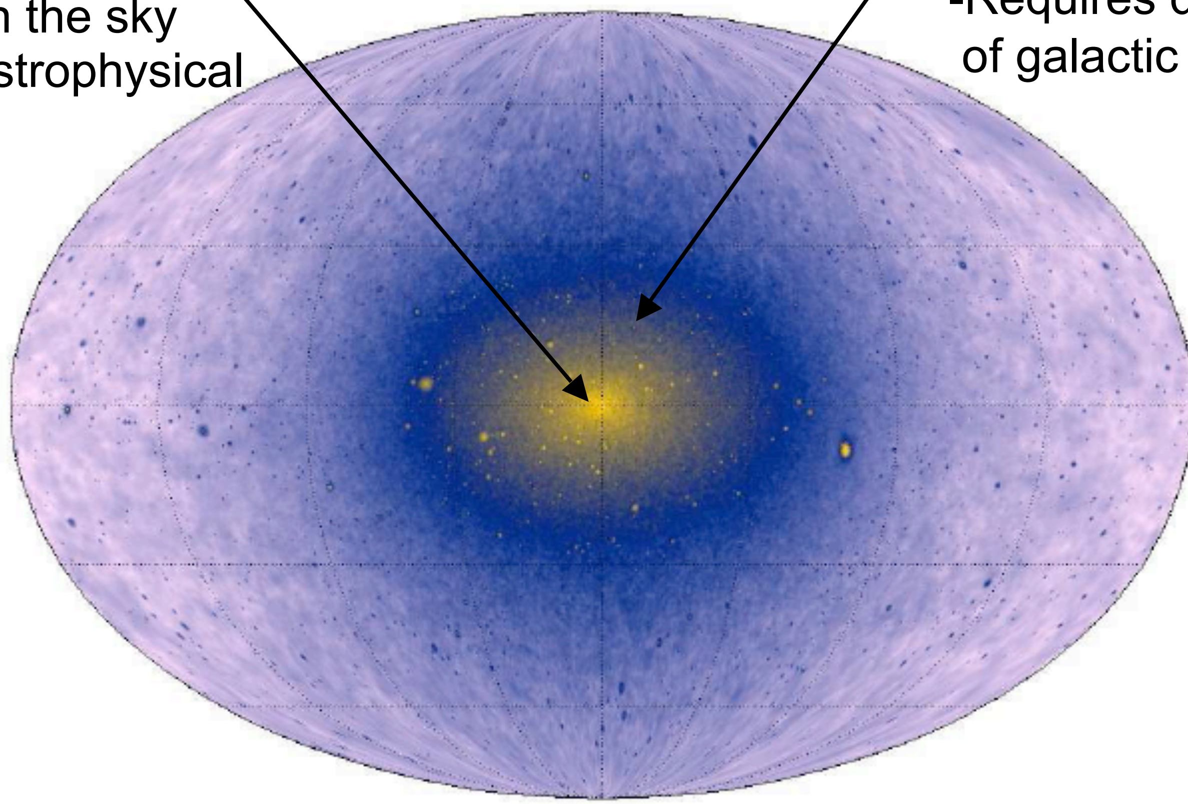

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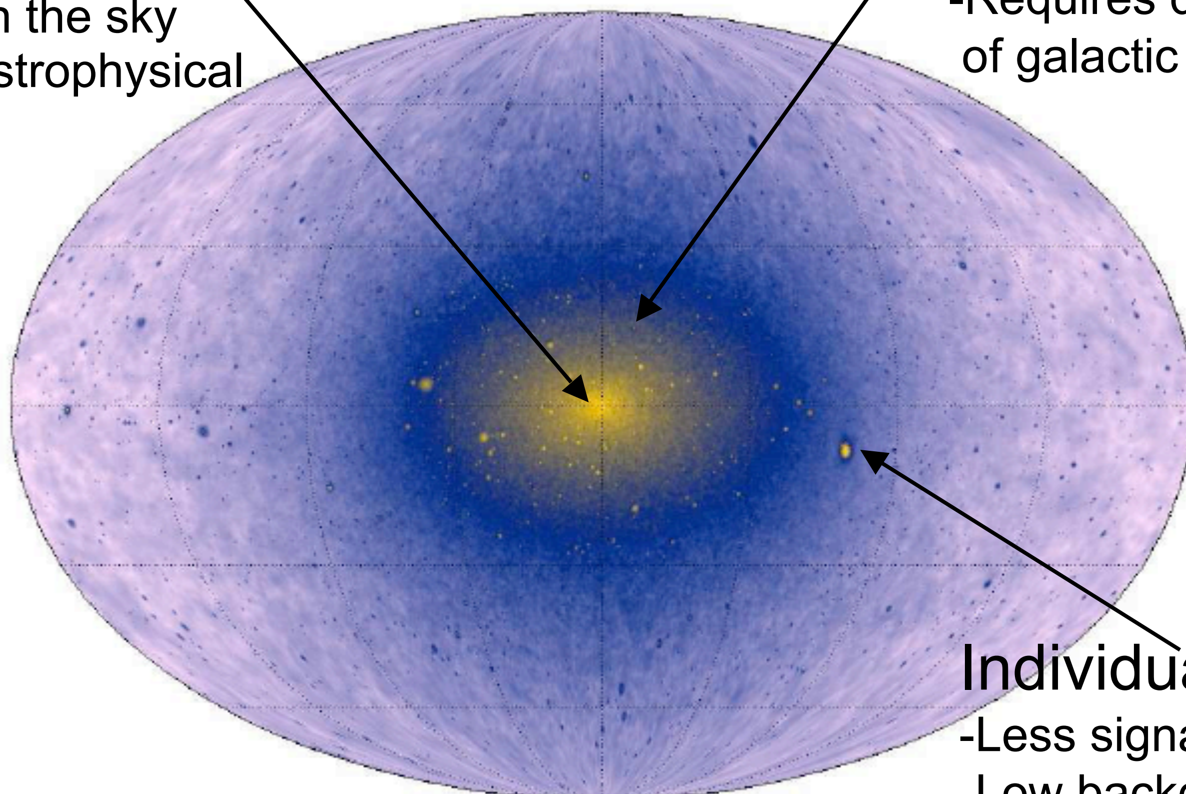

Individual Subhalos

-Less signal
-Low backgrounds

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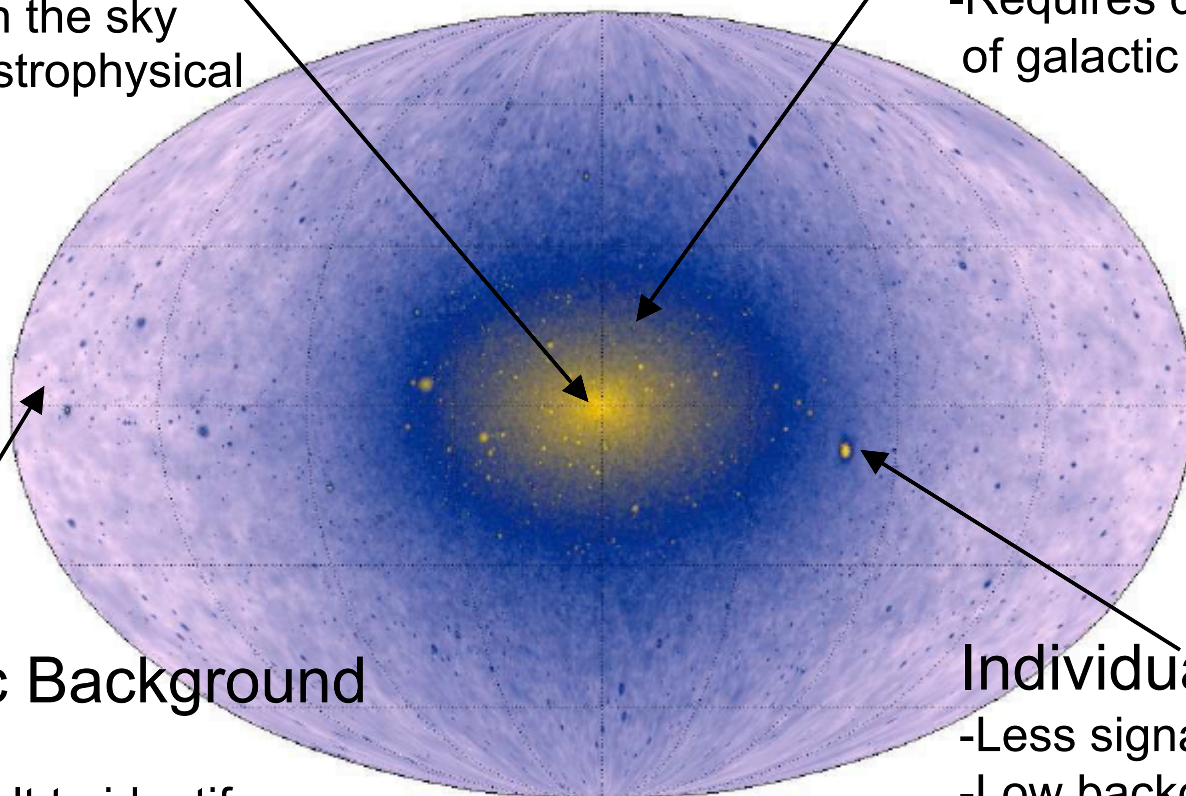


The Galactic Halo
-High statistics
-Requires detailed model of galactic backgrounds

The Galactic Center
-Brightest spot in the sky
-Considerable astrophysical backgrounds

Extragalactic Background
-High statistics
-potentially difficult to identify

Individual Subhalos
-Less signal
-Low backgrounds

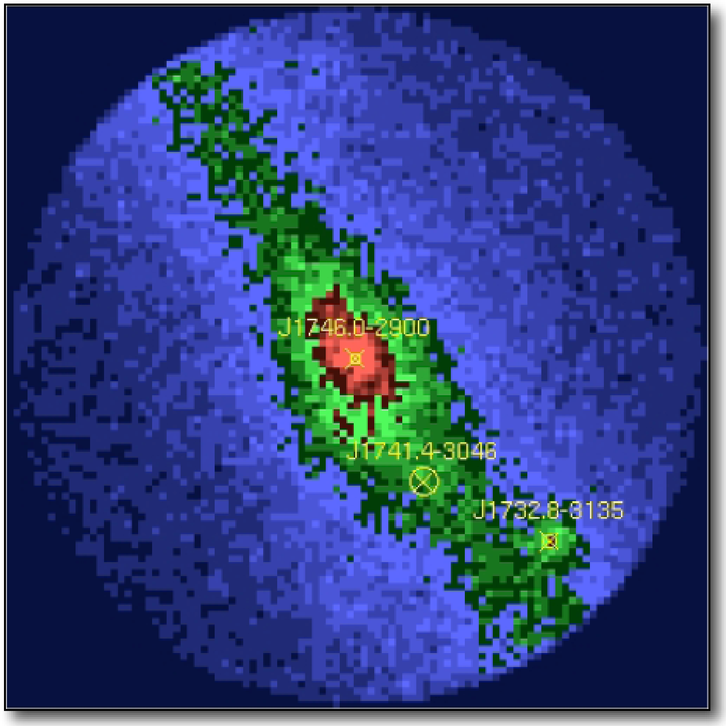
Dark Matter In The Galactic Center Region

- The region surrounding the Galactic Center is complex; backgrounds present are not necessarily well understood

- This does not, however, necessarily make searches for dark matter in this region intractable

- The signal from dark matter annihilation is large in most benchmark models (typically hundreds of events per year)

- To separate dark matter annihilation products from backgrounds, we must focus on the distinct observational features of these components

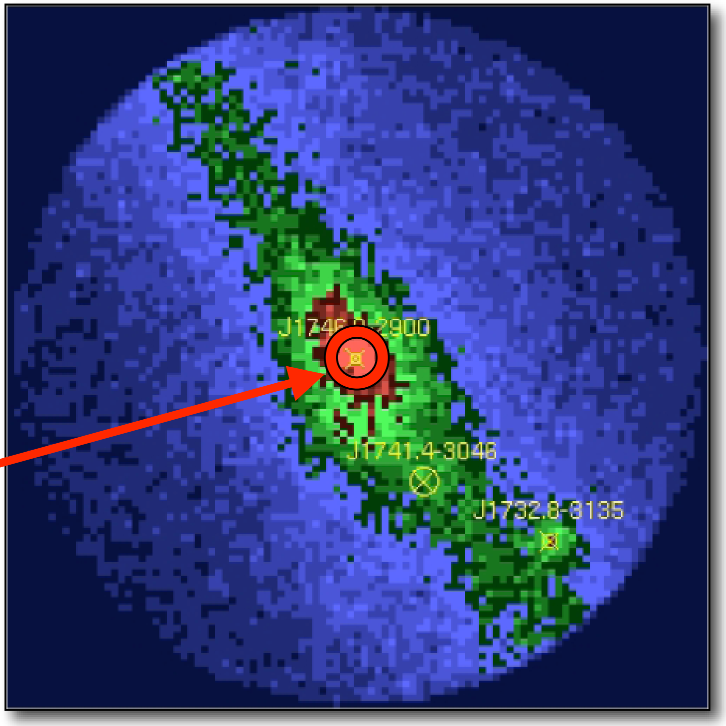


Dark Matter In The Galactic Center Region

The characteristics of a signal from dark matter annihilations:

$$\Phi_\gamma(E_\gamma, \psi) = \frac{\mathrm{d}N_\gamma}{\mathrm{d}E_\gamma} \frac{\langle \sigma v \rangle}{8\pi m_X^2} \int_{\mathrm{los}} \rho^2(r) \mathrm{d}l$$

1) Signal highly concentrated around the Galactic Center (but not entirely point-like)



2) Distinctive “bump-like” spectral feature

Astrophysical Backgrounds In The Galactic Center Region

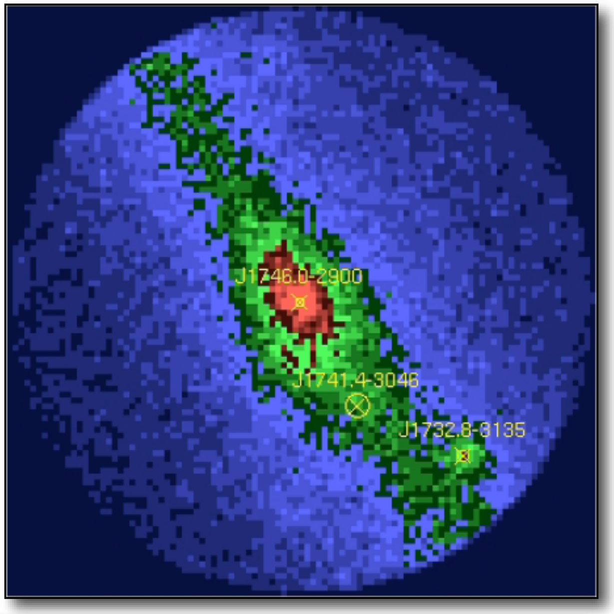
Known backgrounds of gamma rays from Inner Galaxy include:

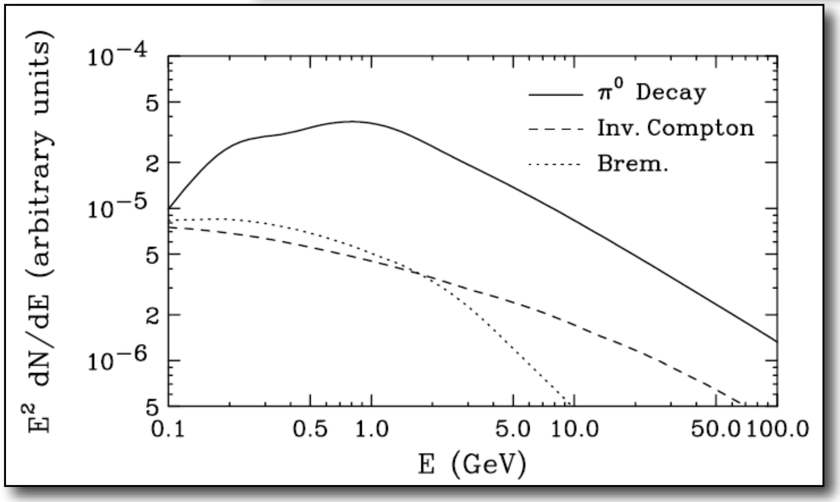
1) Pion decay gamma rays from cosmic ray proton interactions with gas ($p+p \rightarrow p+p+\pi^0$)

2) Inverse Compton scattering of cosmic ray electrons with radiation fields

3) Bremsstrahlung

4) Point sources (pulsars, supernova remnants, the supermassive black hole)



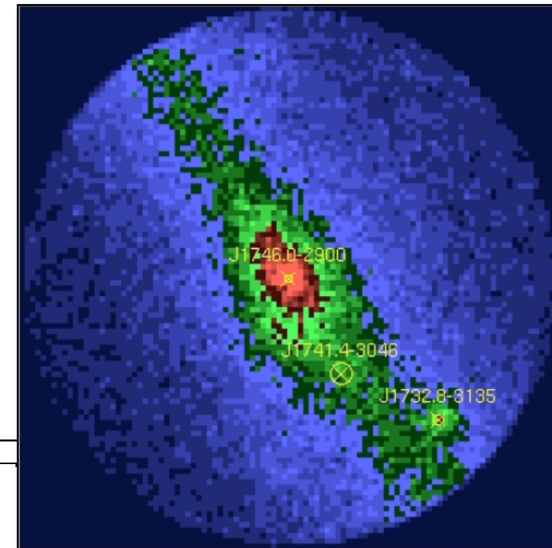


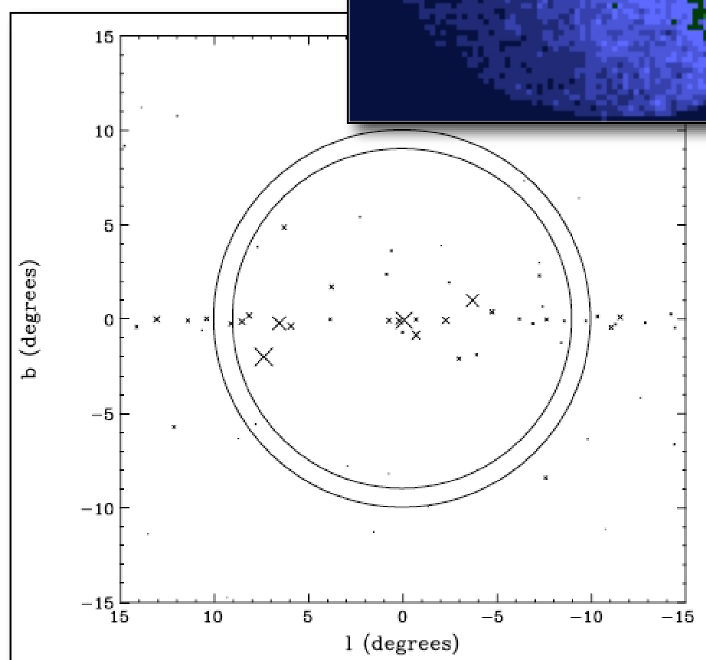
Astrophysical Backgrounds In The Galactic Center Region

- Much of the emission is concentrated along the disk, but a spherically symmetric component (associated with the Galactic Bulge) is also to be expected

- The Fermi First Source Catalog contains 69 point sources in the inner +/-15° of the Milky Way

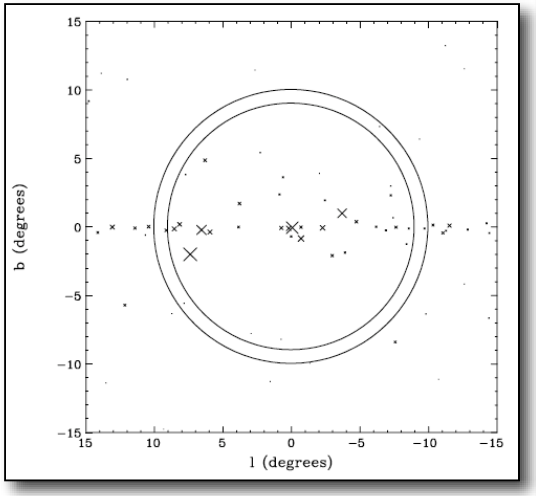
- Build a background model with a morphology of disk+bulge+known point sources

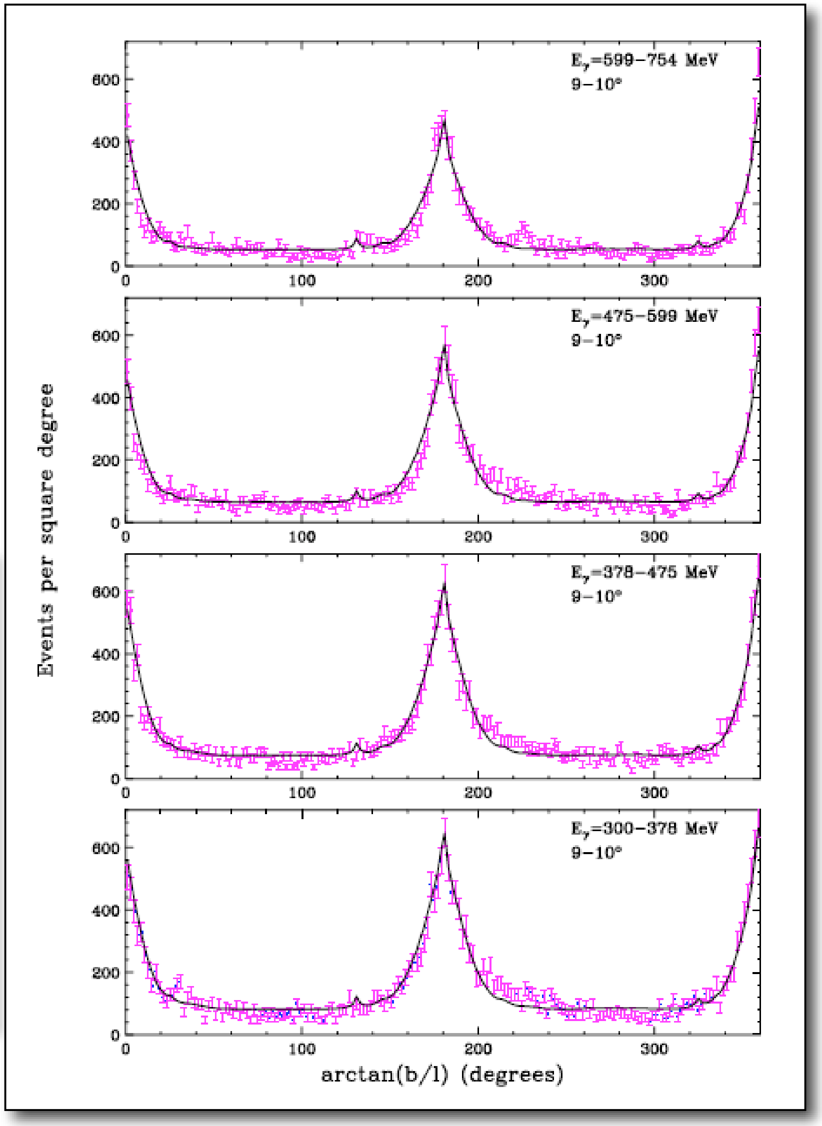




Astrophysical Backgrounds In The Galactic Center Region

- Fit one energy bin at a time, and one angular range around the Galactic Center (no assumptions about spectral shape, or radial dependance)
- Fit to intensity of the disk (allow to vary along the disk), width of the disk (gaussian), intensity of the flat (spherically symmetric) component
- Include point sources, but do not float
- Provides a very good description of the overall features of the observed emission (between ~2-10° from the Galactic Center)





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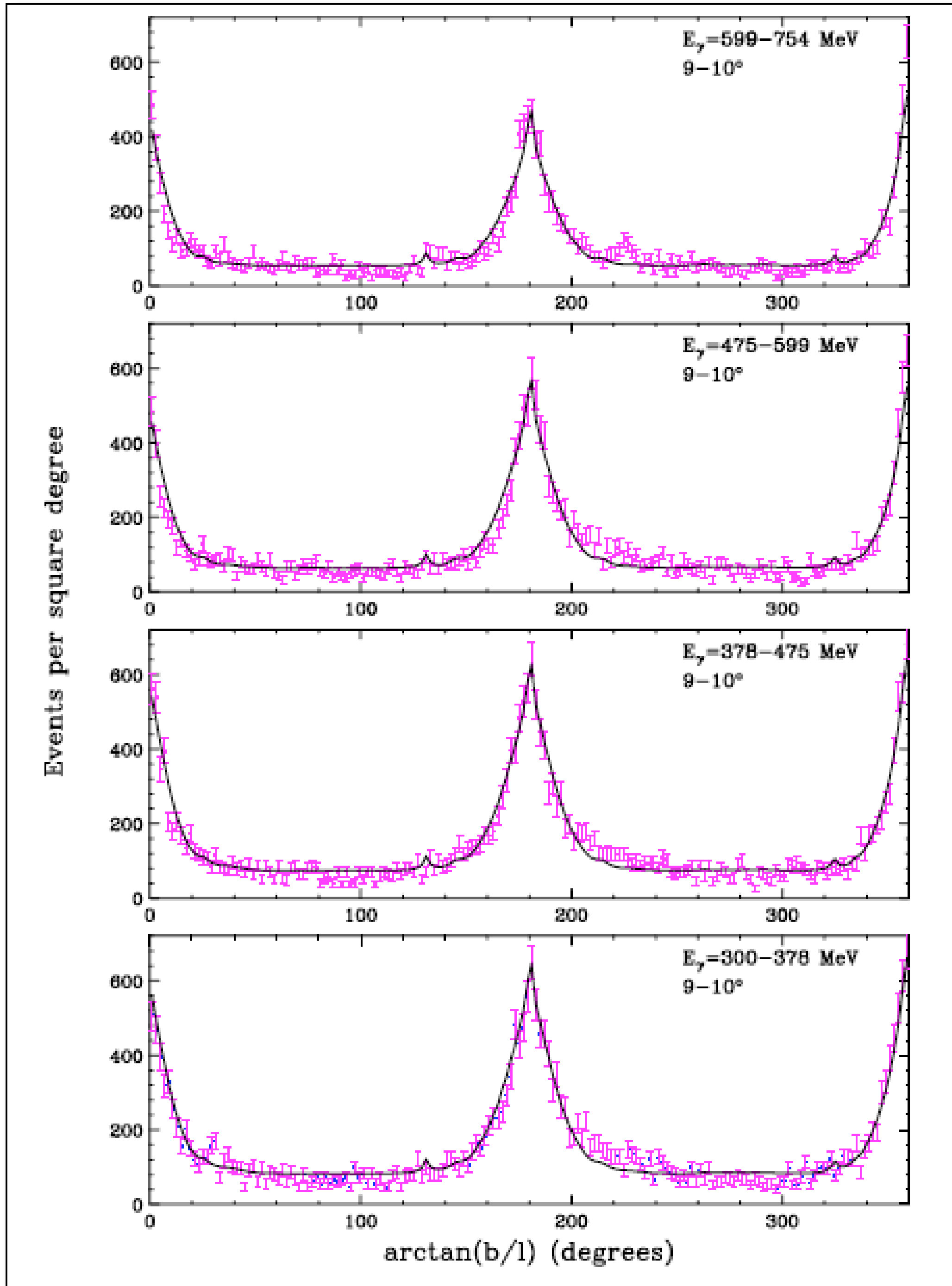
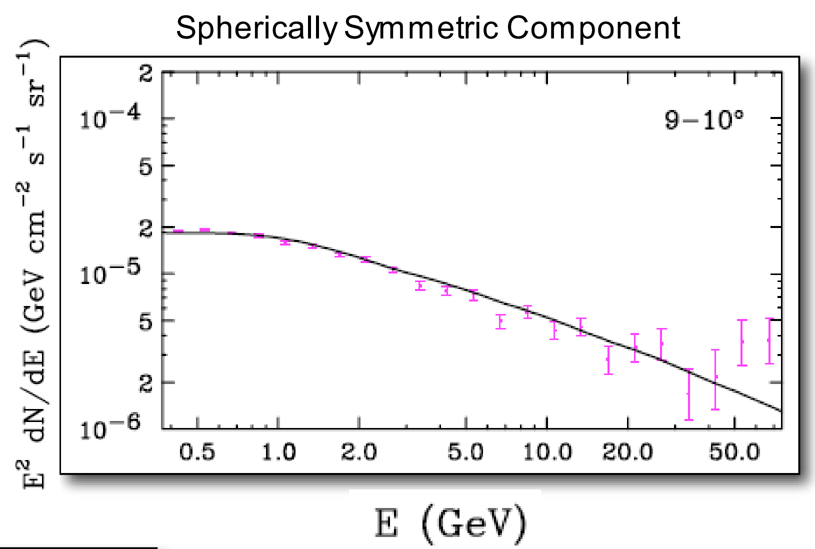
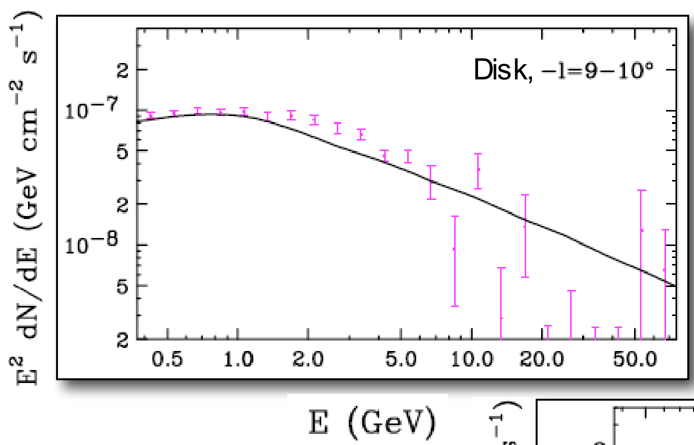


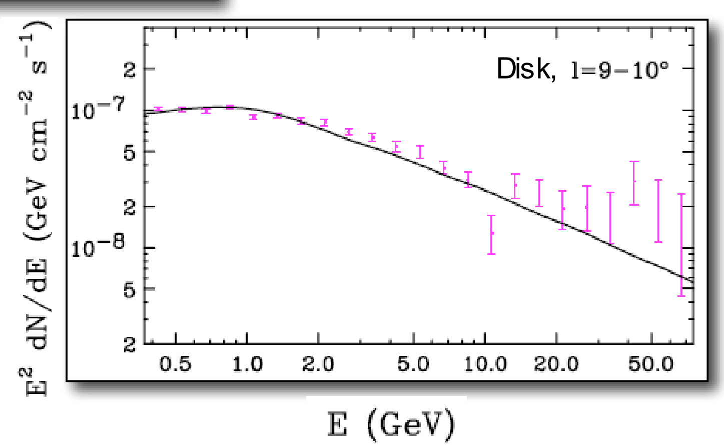
Astrophysical Backgrounds In The Galactic Center Region

- By combining the results from all energy bins, we can extract the spectrum of emission from the disk and bulge components

- Spectral shapes consistent with gamma rays from pion decay and ICS

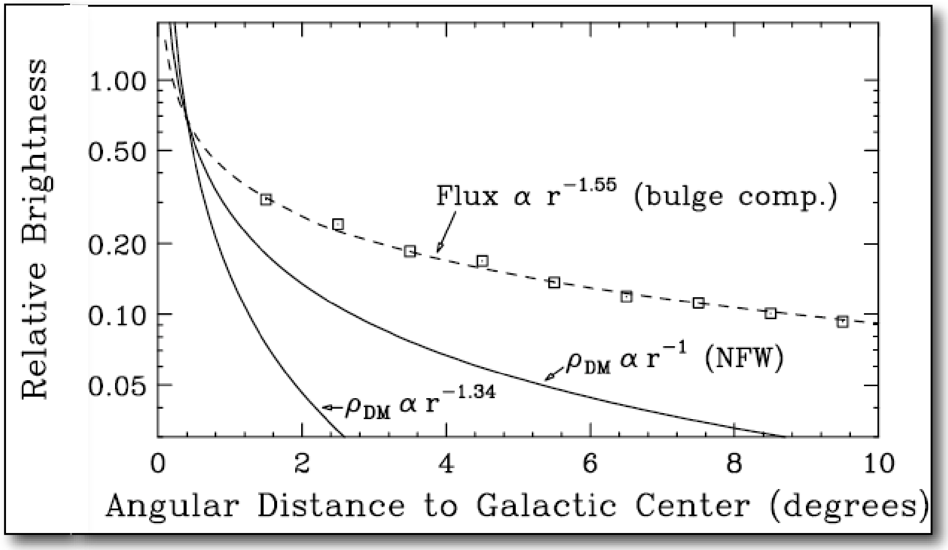






Astrophysical Backgrounds In The Galactic Center Region

- By combining the results from all energy bins, we can extract the spectrum of emission from the disk and bulge components
- Spectral shapes consistent with gamma rays from pion decay and ICS
- Spectrum of disk emission does not discernibly vary along the disk; disk intensity fluctuates by ~30%
- Spectral shape of the spherically symmetric component also does not vary, but intensity does (brighter closer to the Inner Galaxy)



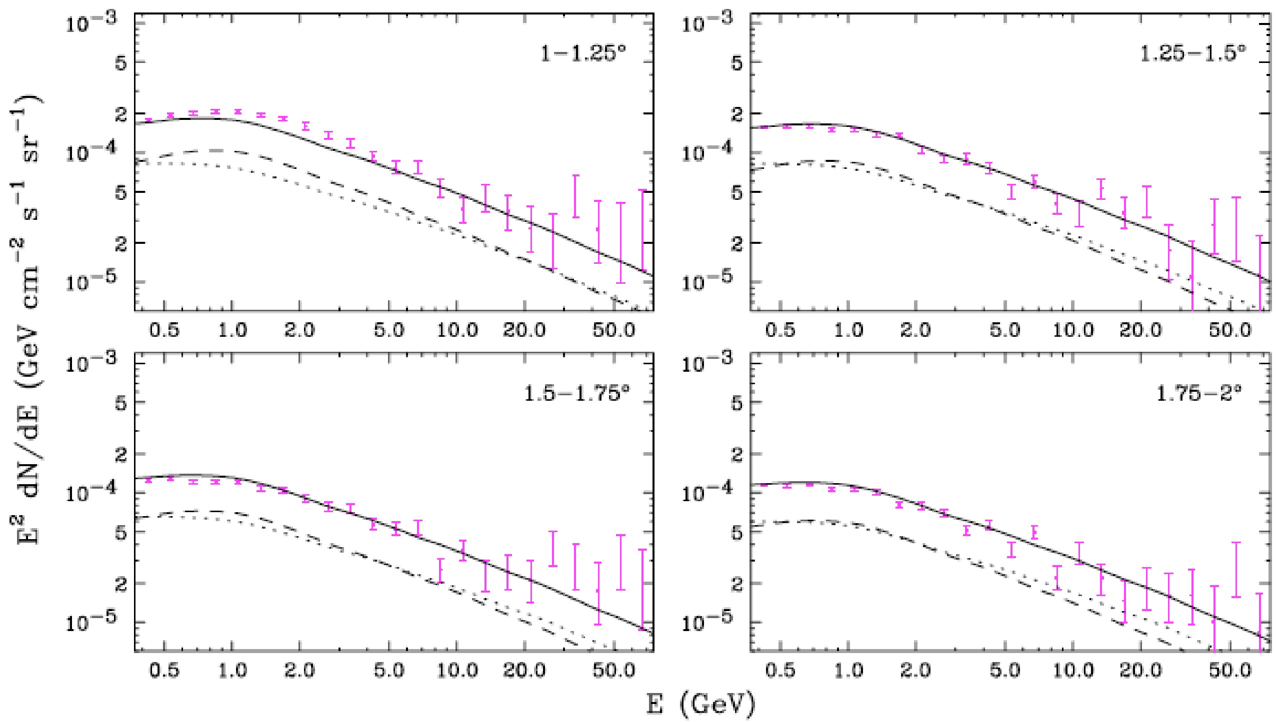
- Well described by a distribution of source emission that scales with $r^{-1.55}$
- In contrast, dark matter annihilation products are predicted to be more centrally concentrated r^{-2} for NFW (γ=1), or even steeper if adiabatic contraction is taken into account

The Inner Two Degrees Around The Galactic Center

- If the Fermi data contains a signal from dark matter annihilations in the Galactic Center, we should expect to see departures from the background model within the inner ~1 degree
- The key will be to observe both the morphological and spectral transitions in the data

Dashed=disk
Dotted=bulge
Solid=disk+bulge

- Outside of ~1 degrees from GC, background model does very well



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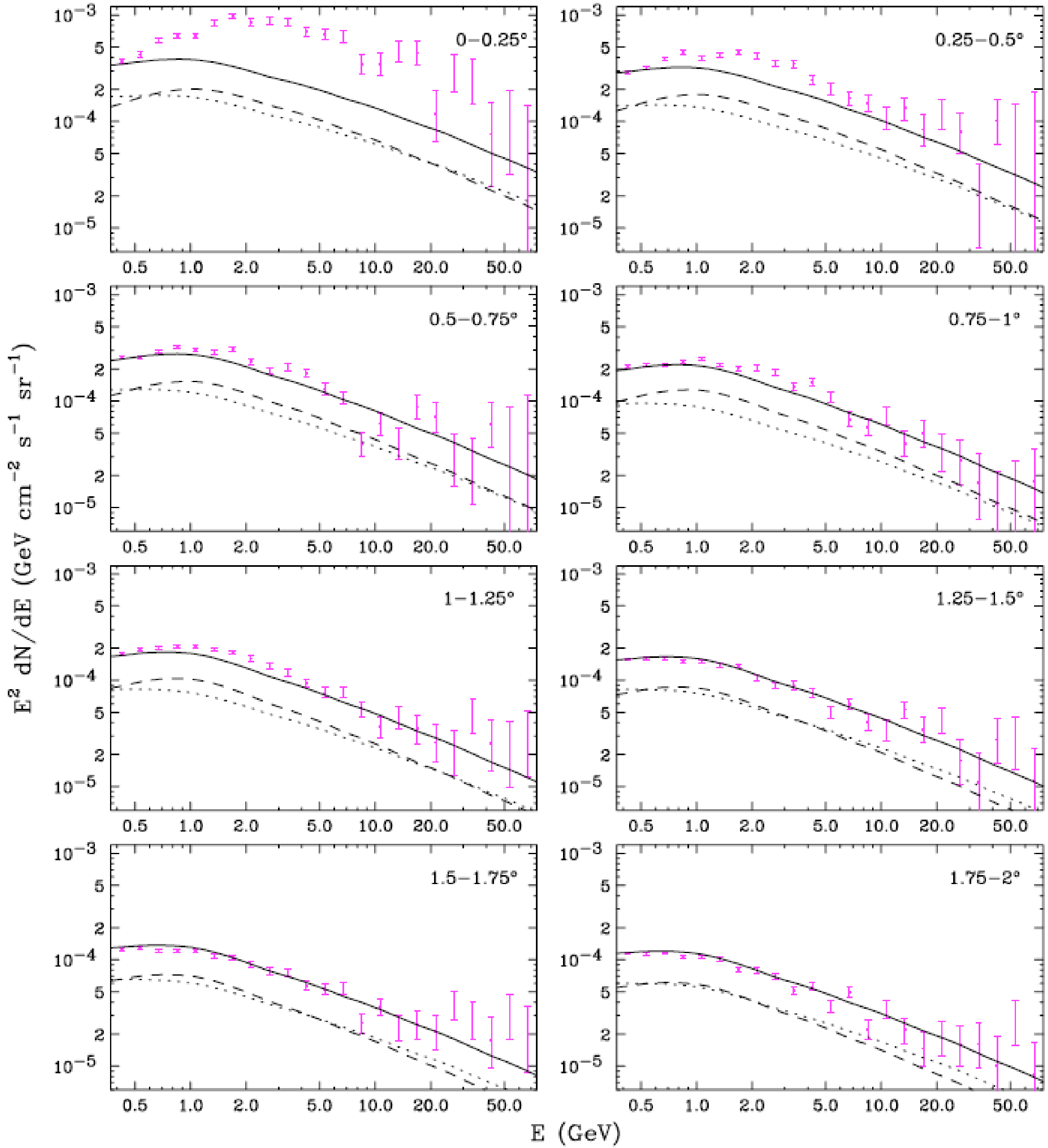
- Outside of ~1 degrees from GC, background model does very well
- Inside of ~0.5°, backgrounds utterly fail to describe the data
- A new component is clearly present in this inner region, with a spectrum peaking at ~2-4 GeV



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- By studying the angular profile of the observed emission, we determine the intensity of the new component to scale with $r^{-2.60}$ to $r^{-2.76}$
- If interpreted as dark matter annihilations, this implies a dark matter distribution that scales as $\rho(r) \propto r^{-1.34}$

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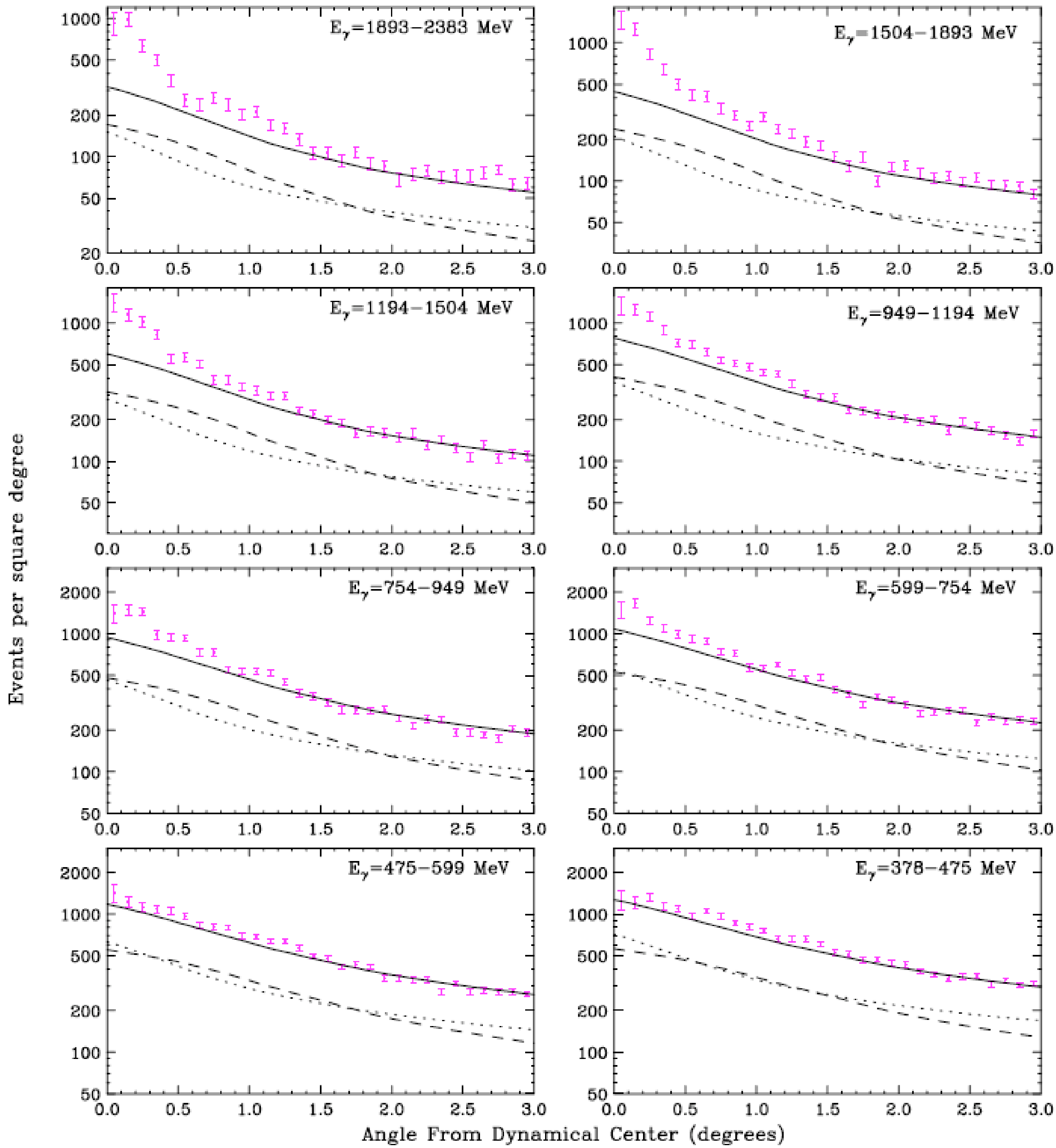

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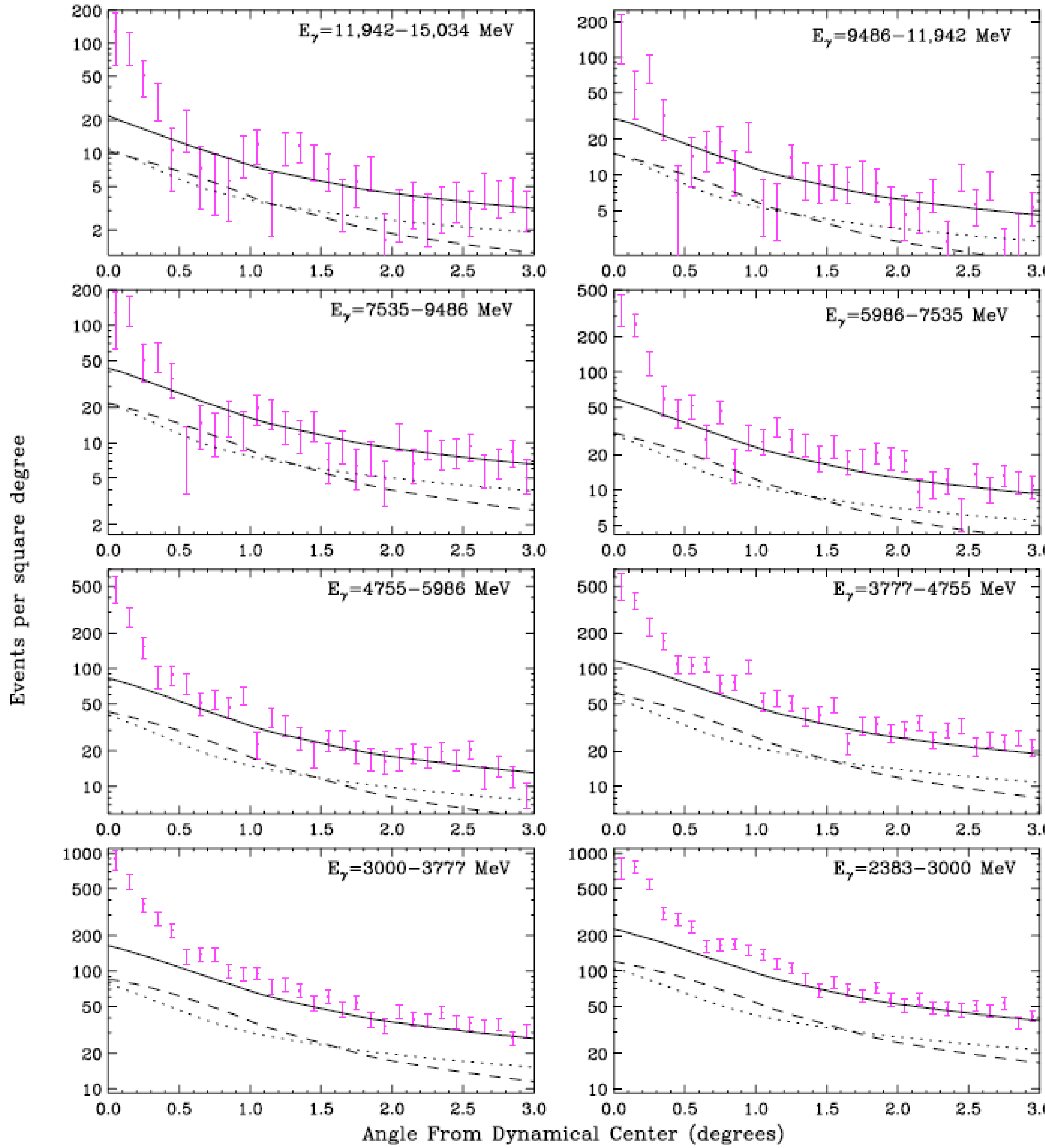
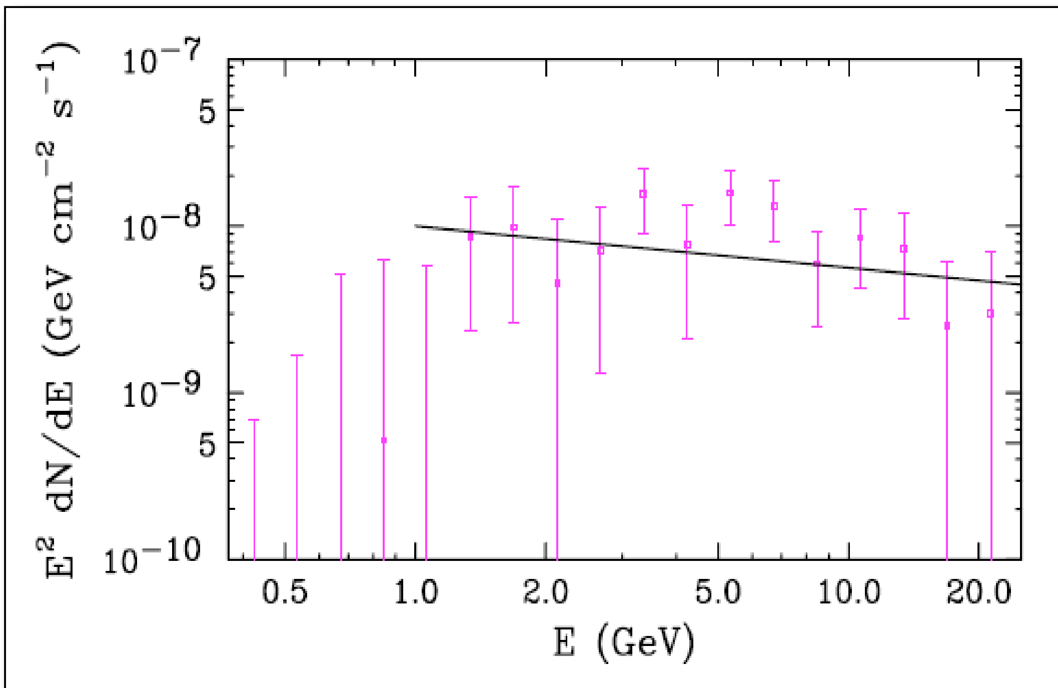
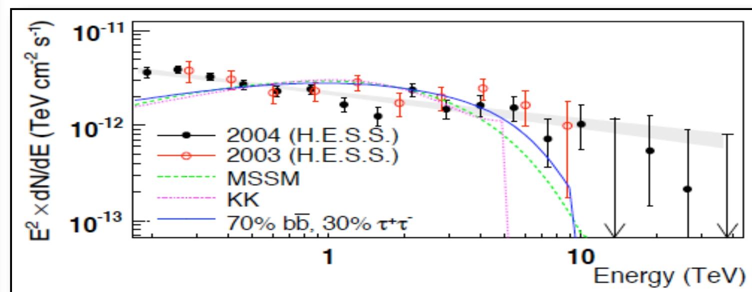


Emission From Our Galaxy's Supermassive Black Hole

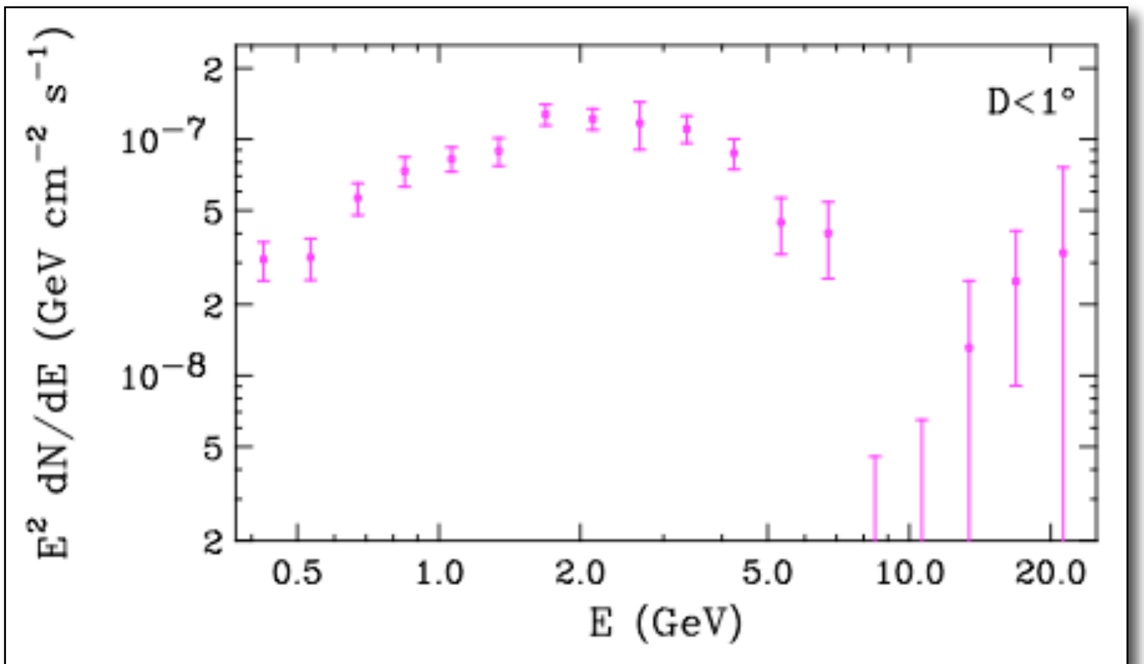
- We were able to separate the point-like emission from the center of the Milky Way (presumably associated with the SMBH)
- Above ~1 GeV, the observed spectrum agrees very well with an extrapolation of the power-law emission reported by HESS (above ~200 GeV)





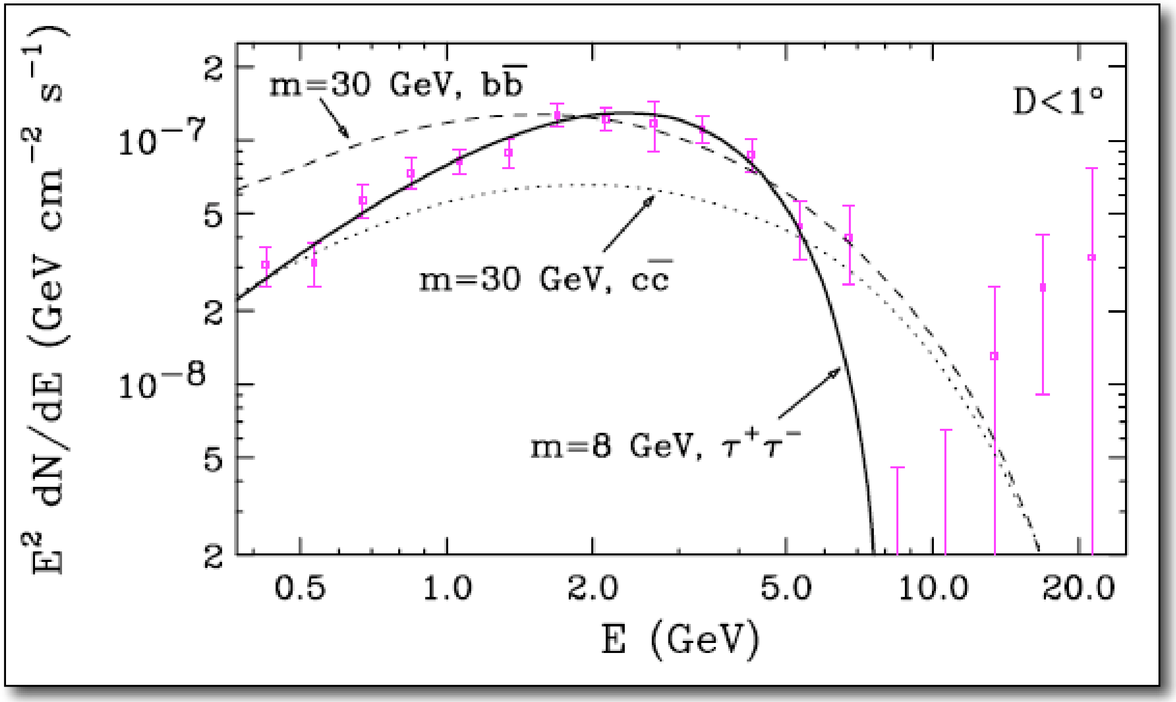
The Spectrum Of The Excess Emission

- We have been able to cleanly extract the spectrum of the excess emission (not disk, bulge, or known point sources)
- Sharply peaked emission around 1.5 to 4 GeV
- No statistically significant excess above ~6-7 GeV



The Dark Matter Interpretation

- The spectral shape of the excess can be well fit by a dark matter particle with a mass in the range of 7.3 to 9.2 GeV, annihilating primarily to $\tau^+\tau^-$ (up to ~20% to hadronic channels is OK)
- No other dark matter annihilation channels provide a good fit
- The normalization of the signal requires the dark matter to have an annihilation cross section of σv = 3.3x10^{-27} to 1.5x10^{-26} cm^3/s



Other Interpretations?

Challenges:

- Very concentrated emission (scales with $r^{-2.68}$)
- Very strong spectral peak

Other Interpretations?

Unresolved Point Sources?

Perhaps a population of ~50 or more unresolved points sources distributed throughout the inner tens of parsecs of the Milky Way could produce the observed signal - millisecond pulsars have been suggested

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Two problems:
1) Why so many in the inner 20 pc, and so few at 100 pc?
    -With typical pulsar kicks of 250-500 km/s, millisecond pulsars should escape the inner region of the galaxy, and be distributed no more steeply than r^{-2} (assuming that *none* are born outside of the inner tens of parcecs!)

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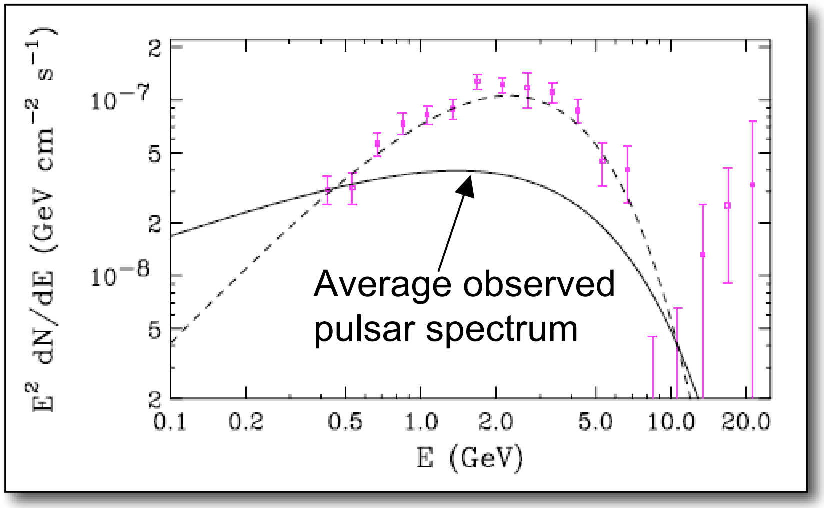
-With typical pulsar kicks of 250-500 km/s, millisecond pulsars should escape the inner region of the galaxy, and be distributed no more steeply than r^{-2} (assuming that *none* are born outside of the inner tens of parcecs!)

2) Of the 46 pulsars in FGST's catalog, none has a spectrum as sharply peaked as is observed in the Inner Galaxy



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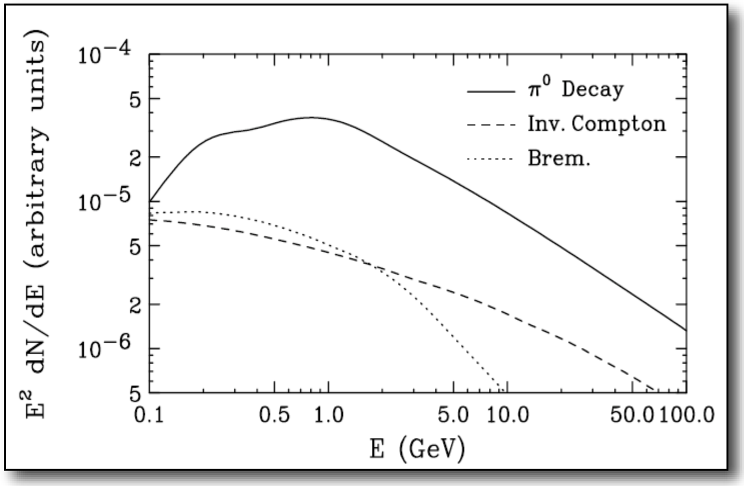
- Typical models (such as that contained in GALPROP) predict a shape like:



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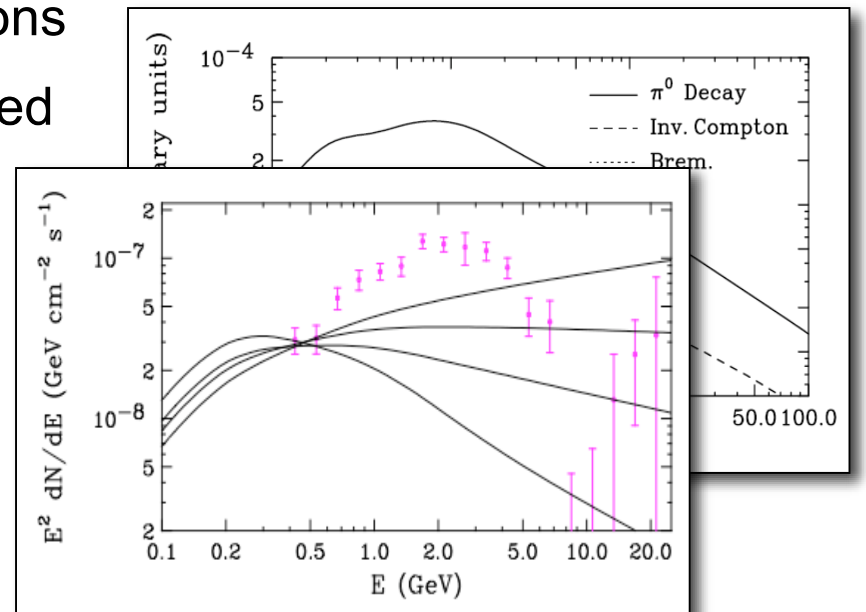

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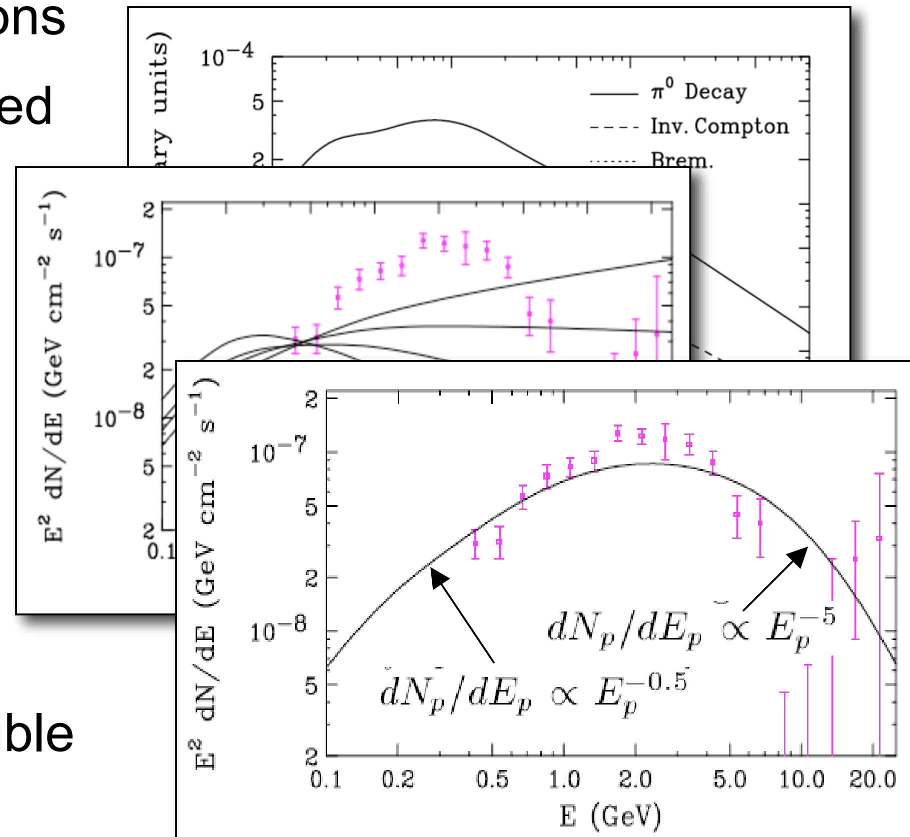
- Power-law proton spectra lead to: (unable to generate observed peak)
- To produce a 2-4 GeV peak, the proton spectrum must break strongly at ~50 GeV (essentially requires a delta function at E_p=50 GeV)
- This solution appears highly implausible



Other Interpretations?

Confusion With The Galactic Center Point Source?

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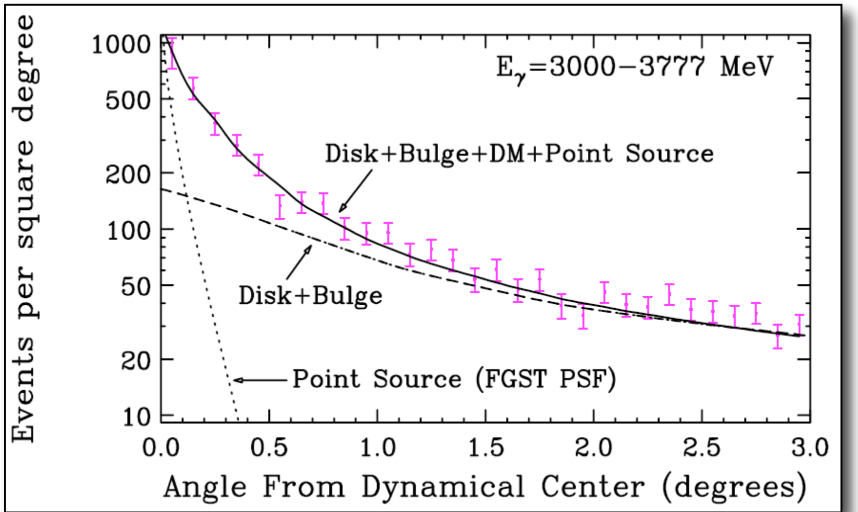

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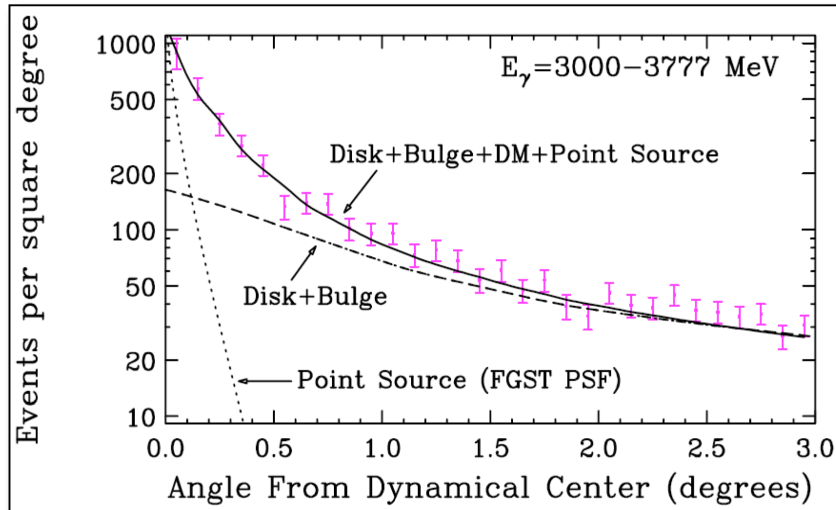


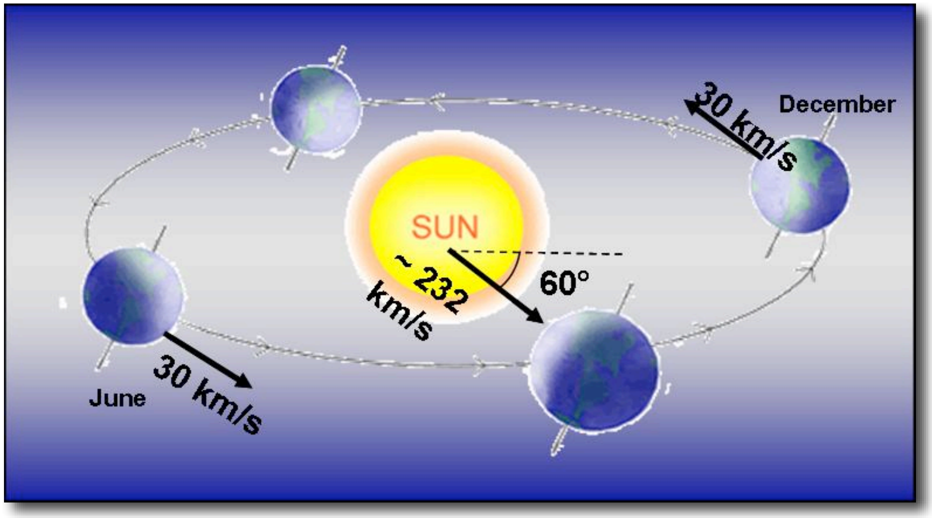
- Any instrumental explanation would have to somehow impact the inner 0.5°, but not the rest of the region we studied (or the rest of the sky)

No known astrophysical sources or mechanisms, and no plausible instrumental effects can account for the observed excess

Evidence From Direct Detection

DAMA/LIBRA

- Over the course of a year, the motion of the Earth around the Solar System is expected to induce a modulation in the dark matter scattering rate



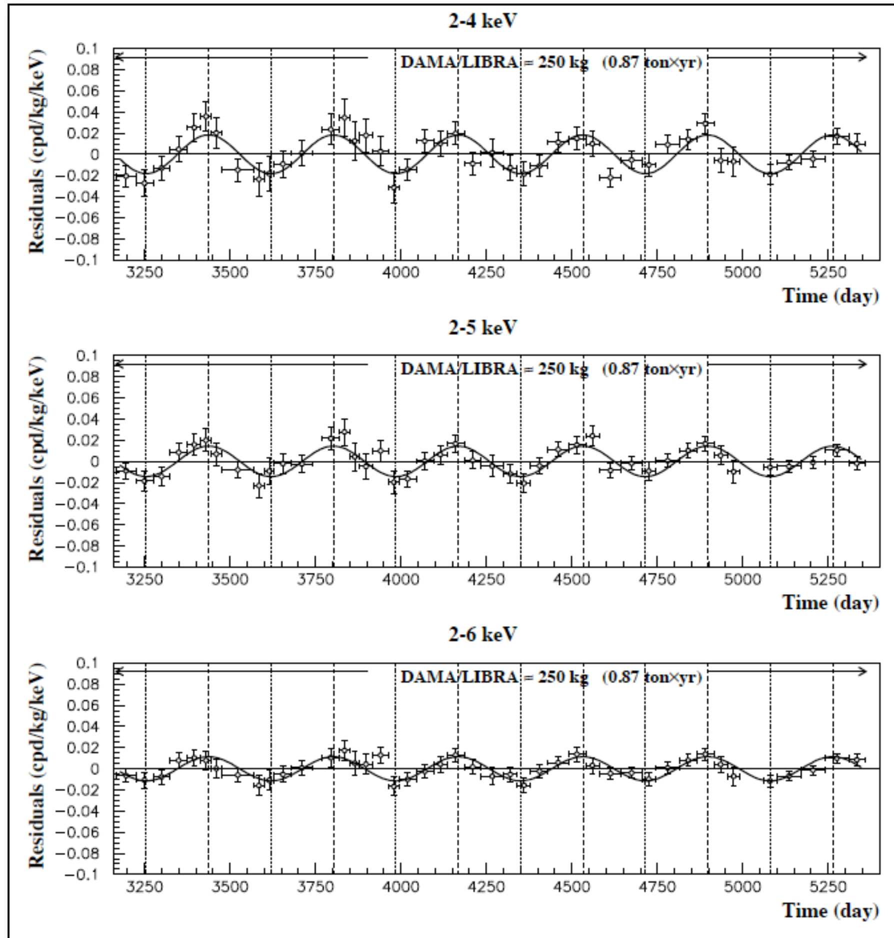
Drukier, Freese, Spergel, PRD (1986)

Evidence From Direct Detection

DAMA/LIBRA

- Over the course of a year, the motion of the Earth around the Solar System is expected to induce a modulation in the dark matter scattering rate

- The DAMA collaboration reports a modulation with a phase consistent with dark matter, and with high significance (8.9σ)

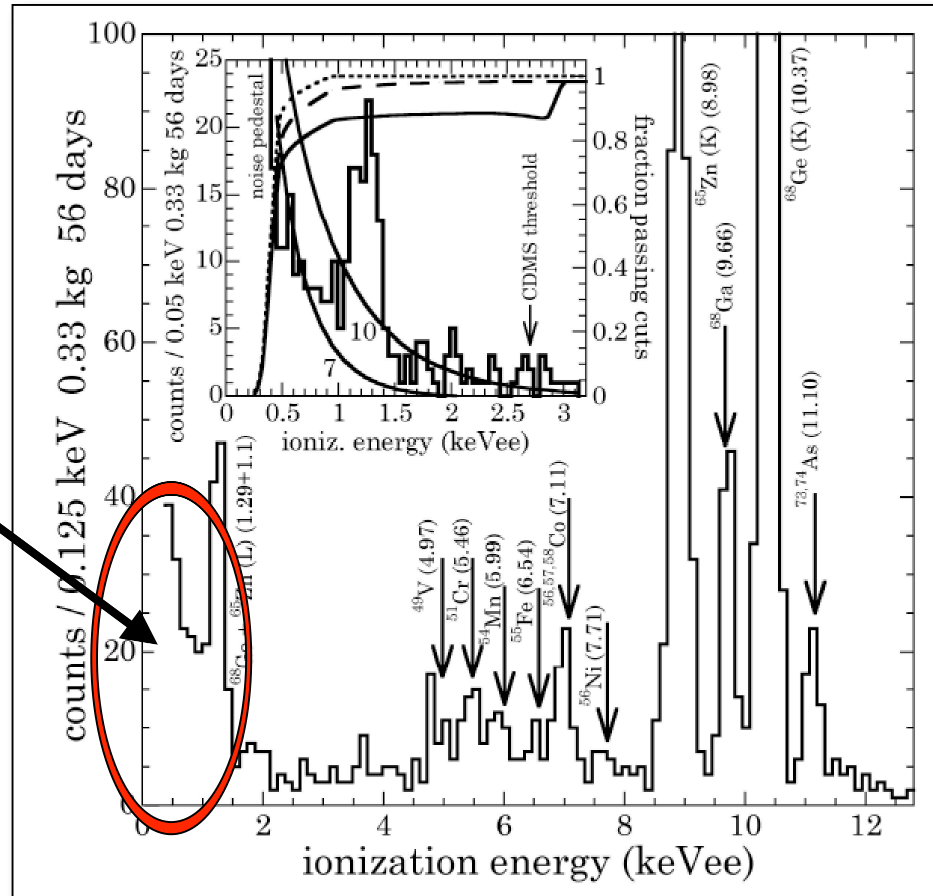


Evidence From Direct Detection

CoGeNT

- The CoGeNT collaboration recently announced their observation of an excess of low energy events

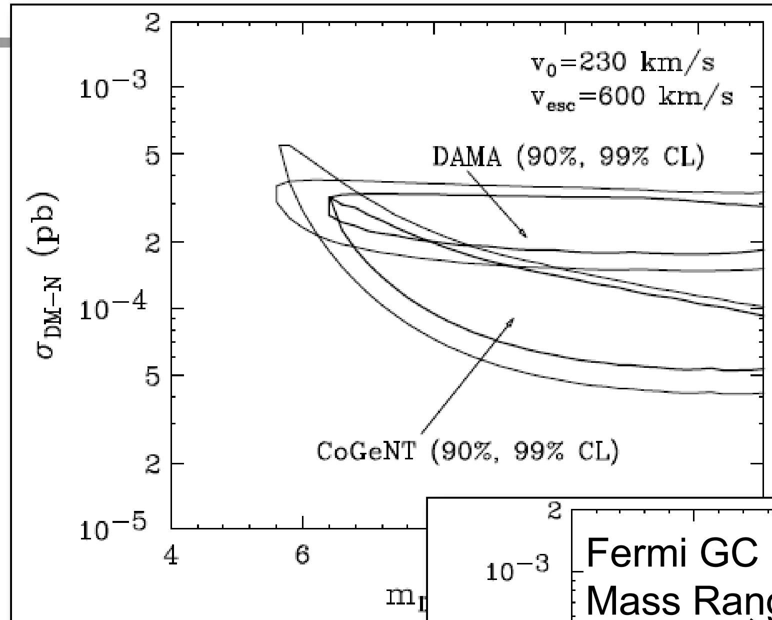
- Although it has less exposure than other direct detection experiments, CoGeNT is particularly well suited to look for low energy events (and low mass WIMPs)



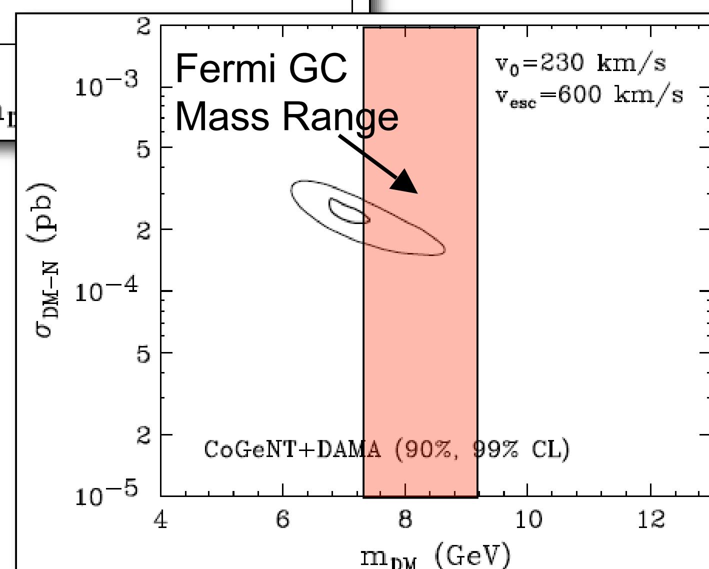
CoGeNT Collaboration, arXiv:1002.4703

CoGeNT and DAMA

- Intriguingly, if the CoGeNT and DAMA signals are interpreted as the elastic scattering of dark matter, they point to a region of parameter space with mass of ~6-8 GeV



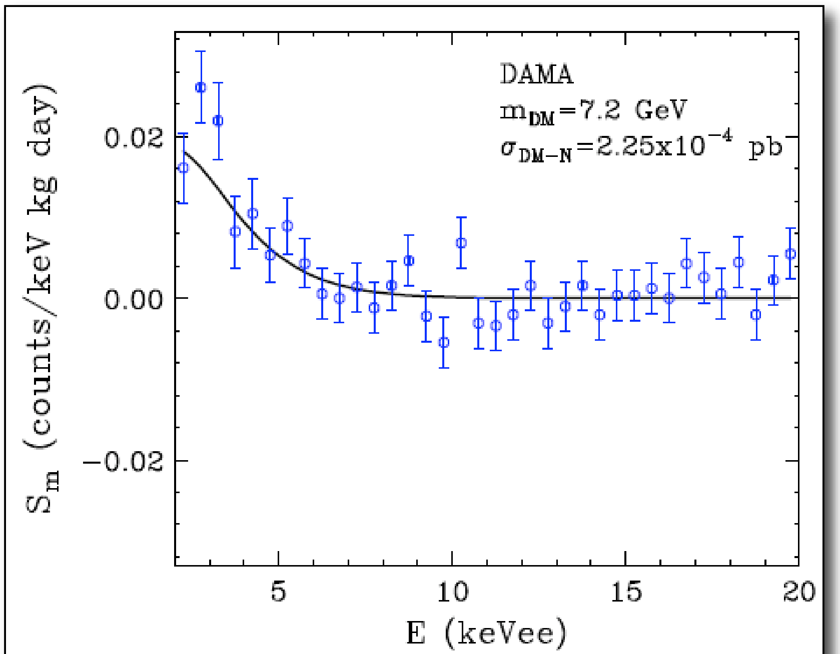
- Recall that our analysis of the Galactic Center gamma rays requires dark matter with a mass of 7.3-9.2 GeV

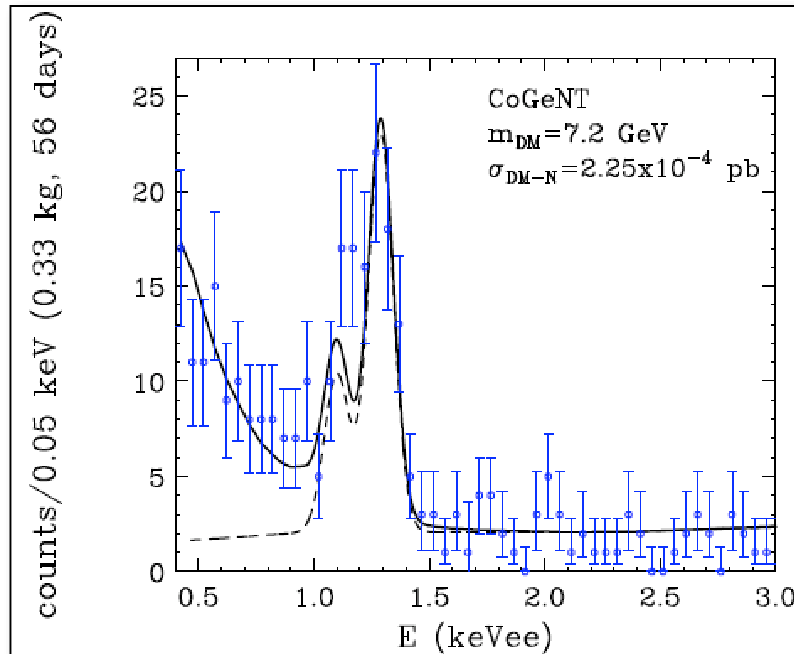


Hooper, J. Collar, J. Hall, D. McKinsey, PRD

CoGeNT and DAMA

- An example of a good fit:

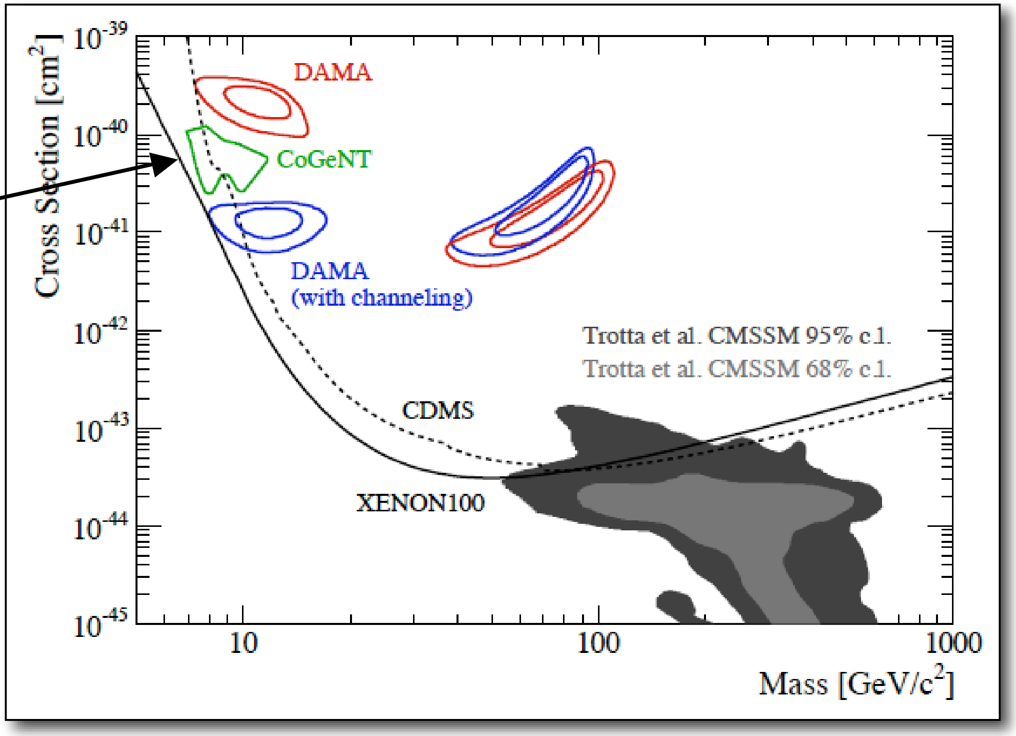




Hooper, J. Collar, J. Hall, D. McKinsey, PRD

CoGeNT and DAMA

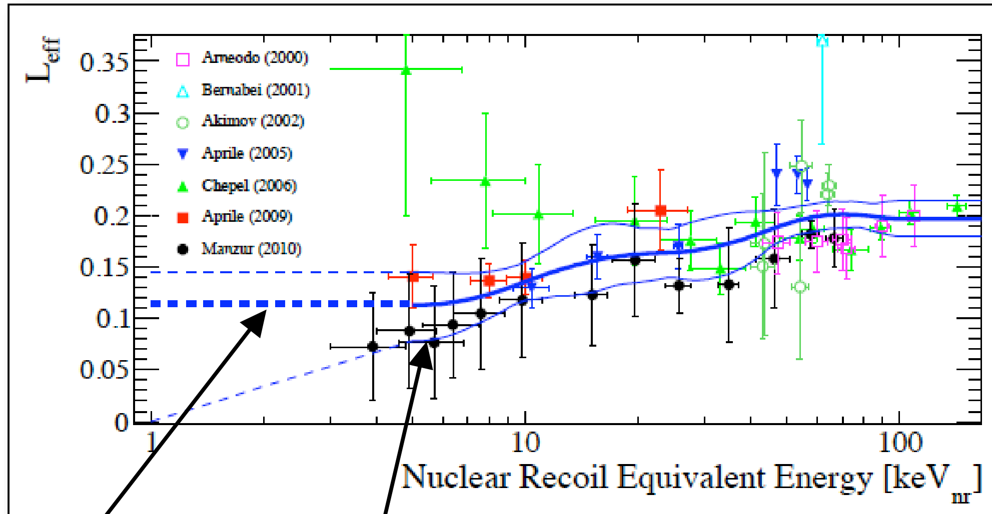
- But what about the null results of XENON and CDMS?
- Don't these rule out the DAMA/CoGeNT regions?
- A very heated discussion has surrounded this question in recent months…



XENON 100 Collaboration, March 2010

CoGeNT and DAMA

- But what about the null results of XENON and CDMS?
- Don't these rule out the DAMA/CoGeNT regions?
- This depends critically on the scintillation efficiency of liquid xenon - large uncertainties, no measurements below 4 keV

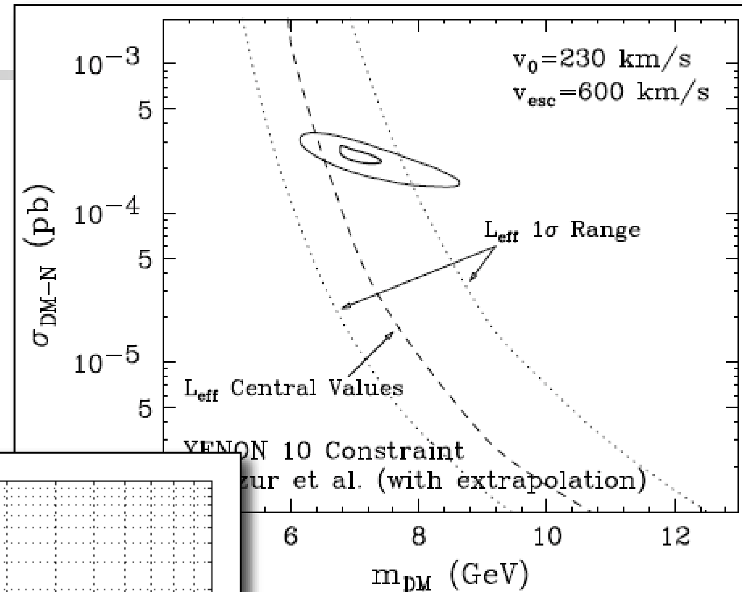


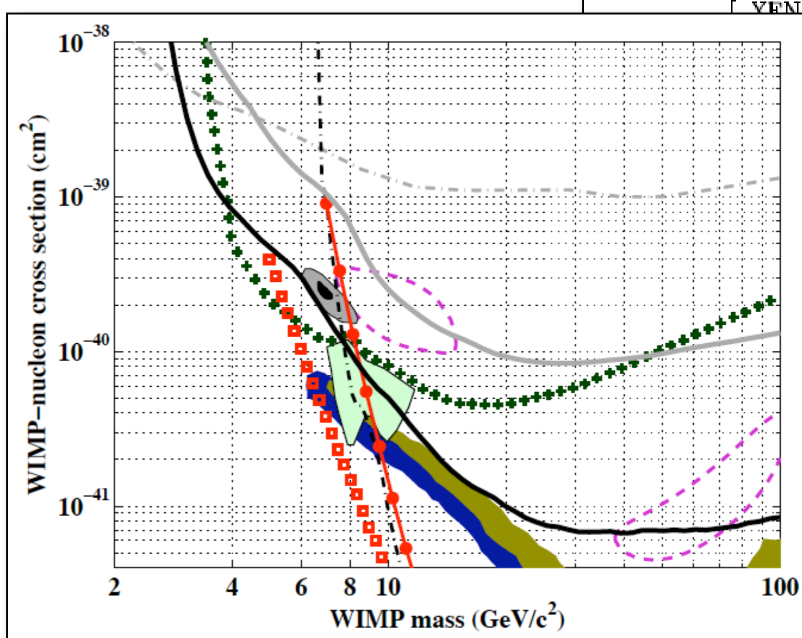
XENON 100 Collaboration, March 2010

- The XENON 100 collaboration initially used a set of (unreasonably) optimistic values for L_{eff}
- More moderate values do not lead to a strong constraint on the CoGeNT/DAMA region

CoGeNT and DAMA

- More stringent constraints come from XENON10 and CDMS
- Both appear in tension with most of the best fit CoGeNT/DAMA region, but at only ~1σ
- Better determinations of L_{eff} may clarify this situation in the future





See Savage, Freese, et al. (2010); J. Filippini thesis (2008); CDMS arXiv:1010.4290

What Has Been Discovered Here? (comments on model building)

Requirements

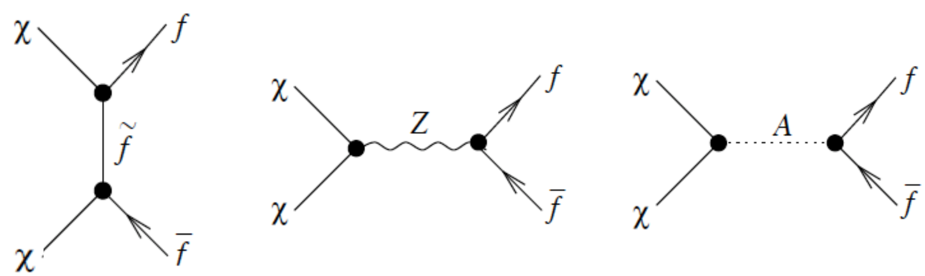
- Stable particle with a mass of ~7-8 GeV
- At non-relativistic velocities, annihilates primarily to $\tau^+\tau^-$ (perhaps among other leptonic final states)
- Non-relativistic annihilation cross section (to $\tau^+\tau^-$) of $\sigma v \sim 3.3\times10^{-27}$ cm^3/s to 1.5×10^{-26} cm^3/s
- Elastic scattering cross section with nucleons of $\sigma_{SI} \sim 2\times10^{-40}$ cm^2 (from CoGeNT+DAMA)

Are these requirements difficult to accommodate?

What Has Been Discovered Here? (comments on model building)

Using SUSY as a example…

- In the MSSM, neutralinos can annihilate to fermions (including $\tau^+\tau^-$) through sfermion, *Z*, or *A* exchange



- *Z* couplings are limited by LEP, and *A* leads to mostly $b\bar{b}$ final states

- $\sigma v_{\chi\chi\rightarrow\tilde{\tau}\rightarrow\tau\tau} \sim 4\times10^{-27}\ \mathrm{cm^3/s} \times |N_{11}|^4\,(85\ \mathrm{GeV} / m_{\tilde{\tau}})^4$

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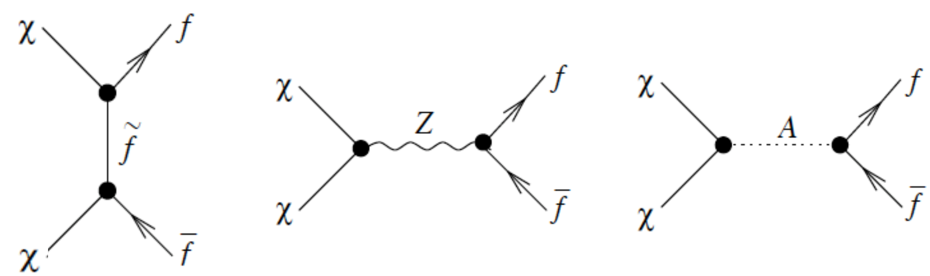

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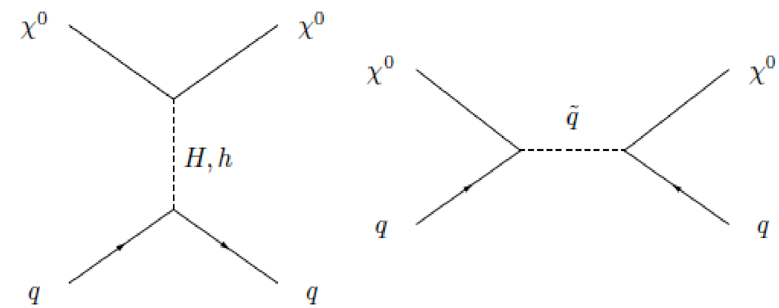
Gamma Ray signal is easy to accommodate

What Has Been Discovered Here? (comments on model building)

Using SUSY as a example…

- The elastic scattering of neutralinos with nucleons can result from scalar higgs or squark exchange

- Amplitude for quark exchange is much too small, and in the MSSM, even higgs diagrams lead to values of σ_{SI} that fall short by a factor of ~10 or more



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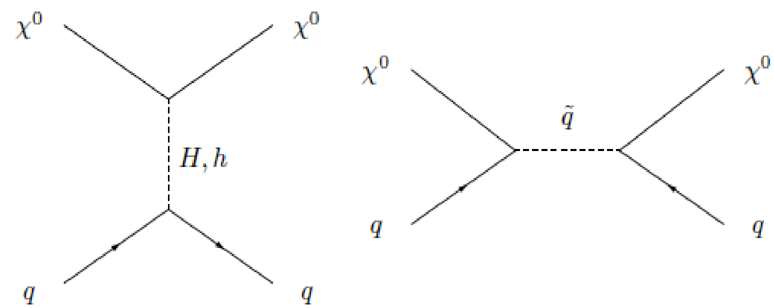


- If we extend the MSSM by a chiral singlet, however, the lightest neutralino can scatter much more efficiently with nucleons

$$\sigma_{\chi^0 p,n} \approx 2.2 \times 10^{-40}\,\mathrm{cm}^2 \times \left(\frac{\kappa}{0.6}\right)^2 \left(\frac{\tan\beta}{50}\right)^2 \left(\frac{45\,\mathrm{GeV}}{m_{h_1}}\right)^4 \left(\frac{F_s^2}{0.85}\right)\left(\frac{F_d^2}{0.15}\right)$$

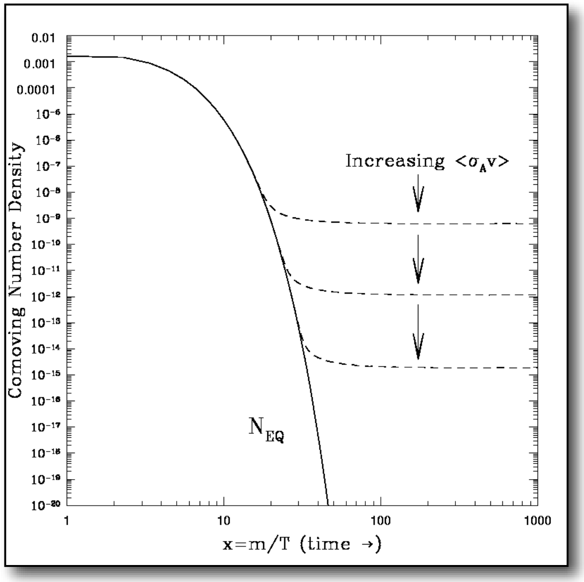
Light singlet-like higgs

Belikov, Gunion, Hooper, Tait, arXiv:1009.0549

What Has Been Discovered Here? (comments on model building)

Using SUSY as a example…

- This model can also be used to predict the abundance of neutralino dark matter, resulting from thermal freeze-out in the early universe
- Stau exchange diagrams alone would lead to the overproduction of neutralino dark matter by a factor of ~10 ($\Omega_\chi h^2 \sim 1$)
- The higgs exchange diagrams, however, are more efficient, and lead to $\Omega_\chi h^2 \sim 0.1$



In this simple SUSY model, the cross section implied by CoGeNT and DAMA forces us to the prediction of $\Omega_\chi h^2 \sim 0.1$

Belikov, Gunion, Hooper, Tait, arXiv:1009.0549

What Has Been Discovered Here? (comments on model building)

More generally speaking…

- Relatively large couplings and/or light mediators are needed to provide the large cross section implied by CoGeNT and DAMA
- Preferential annihilation to $\tau^+\tau^-$ requires either exchanged particles which share the quantum numbers of tau leptons (*ie.* staus) or that possess leptophillic couplings
- MSSM does not provide a dark matter candidate that can produce these signals, but (slightly) extended supersymmetric models can
- Simple models can accommodate these signals, but they are not the models most particle theorists have been studying

Buckley, Hooper, Tait, in preparation

Predictions and Implications

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1) An annual modulation at CoGeNT

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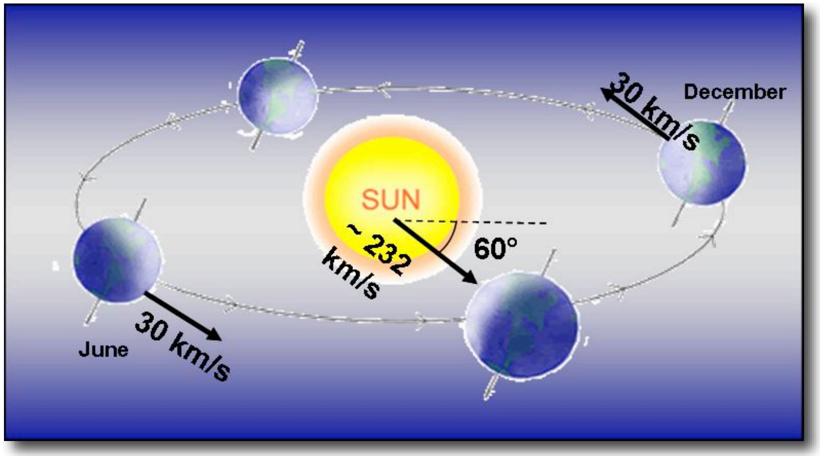


- Published CoGeNT excess consists of ~10^2 events, from winter season; insufficient to observe any annual variation in rate
- If CoGeNT and DAMA are observing elastically scattering dark mater, we predict a ~10% annual modulation at CoGeNT (20% higher rate in summer than in winter)
- 3σ detection of this effect should become possible with ~40 kg-days exposure in both summer and winter
- Confirmation possible by end of year

Hooper, Collar, Hall, McKinsey, PRD, arXiv:1007.1005

Predictions and Implications

1) An annual modulation at CoGeNT

2) Other dark matter annihilation signals for Fermi

Predictions and Implications

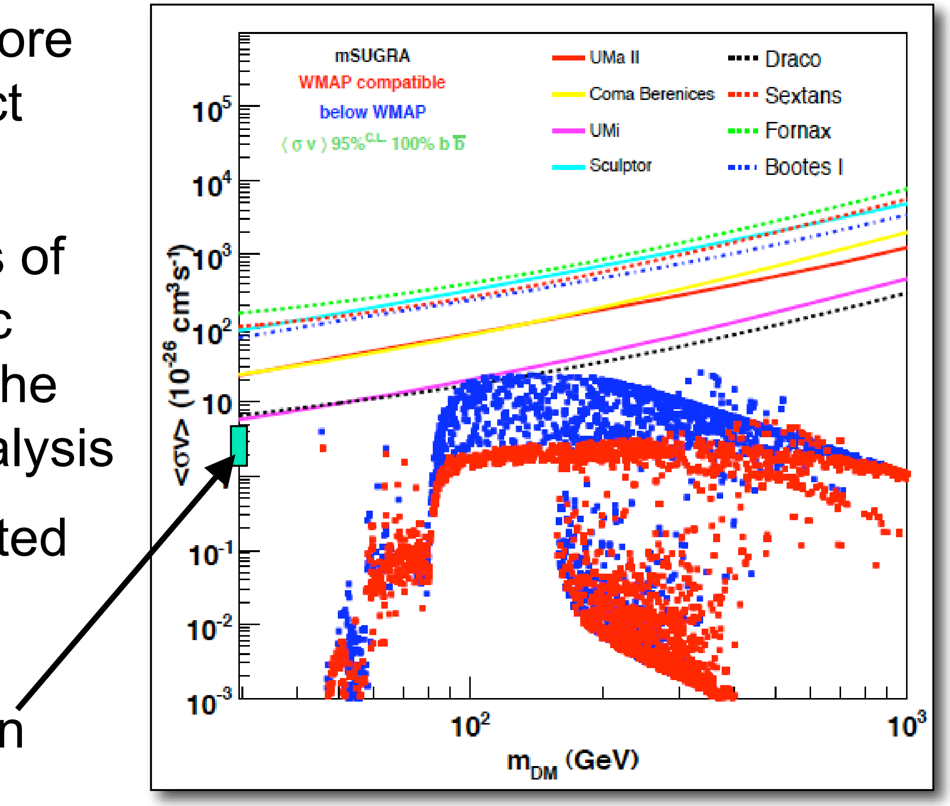
1) An annual modulation at CoGeNT

2) Other dark matter annihilation signals for Fermi

- Light dark matter particles produce more annihilation power, and brighter indirect detection signals

- Current constraints from observations of dwarf spheroidal galaxies and isotropic diffuse emission are not very far from the signals predicted in light of our GC analysis

- Although limits have not been presented for masses as low as 7-8 GeV, or for annihilations to $\tau^+\tau^-$, predicted signal should look very much like that found in this region



Fermi Collaboration arXiv:1001.4531
(First 11 months of data)

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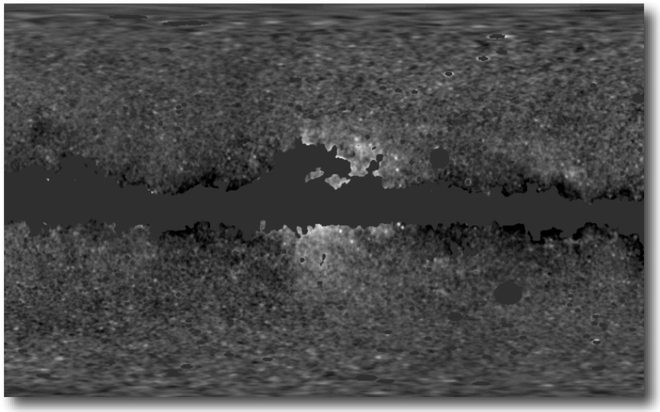

WMAP Haze (22 GHz)

- For years, it has been argued that the WMAP data contains an excess synchrotron emission from the inner ~20° around the Galactic Center, and that this cannot be explained by known astrophysical mechanisms
- Previous studies have shown that this emission could be accounted for with roughly ~20-60 GeV electrons produced in dark matter annihilations
- Very recently, however, evidence has appeared in favor of ~100μG magnetic fields in the inner several hundred parsecs of the Milky Way (Crocker *et al.*, Nature, 2010), which shifts the energy of the required electrons to around a few GeV
- The observed spectral shape and intensity of the WMAP Haze appear easy to accommodate with the dark matter implied by our GC analysis

Finkbeiner, astro-ph/0409027;
Hooper, Finkbeiner, Dobler, PRD (2007);
Dobler, Finkbeiner, ApJ (2008)

Predictions and Implications

1) An annual modulation at CoGeNT

2) Other dark matter annihilation signals for Fermi

3) Synchrotron emission from the Inner Milky Way

4) Neutrinos from the Sun

Predictions and Implications

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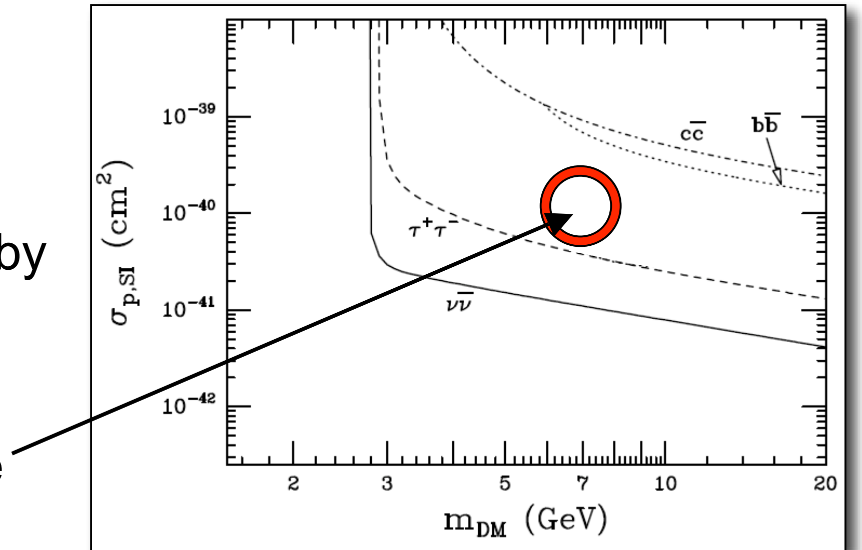
- The large elastic scattering cross section implied by CoGeNT and DAMA will lead to dark matter being captured very efficiently by the Sun (~10^{24} per second)

- Subsequent annihilations to $\tau^+\tau^-$ should yield a flux of few GeV neutrinos near the upper limit based on Super-K data (might favor additional annihilation final states?)



Hooper, Petriello, Zurek, Kamionkowski, PRD, arXiv:0808.2464;
Fitzpatrick, Hooper, Zurek, PRD, arXiv:1003.0014

Predictions and Implications

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5) White dwarf heating

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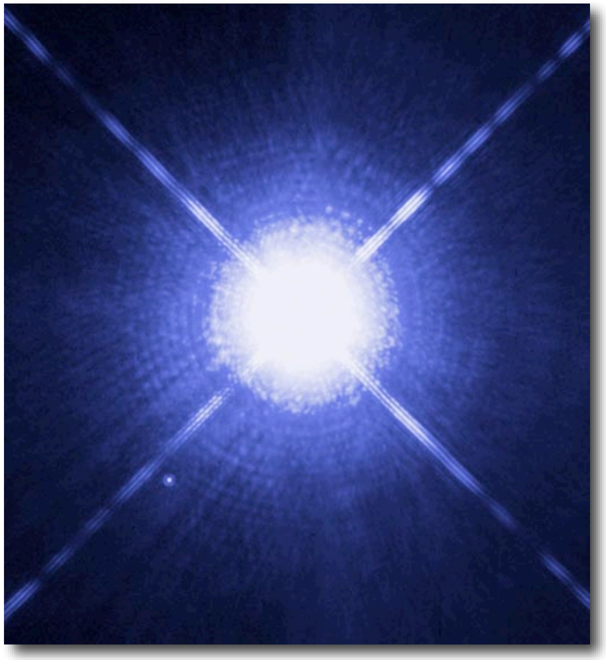
5) White dwarf heating

- High capture rates of dark matter are also predicted for white dwarfs; subsequent annihilation could provide an observationally relevant heat source

- Old white dwarfs in regions with high densities of dark matter (dwarf spheroidal galaxies, etc.) will be prevented from cooling below a few thousand degrees



Hooper, Spolyar, Vallinotto, Gnedin, PRD, arXiv:1002.0005

Summary

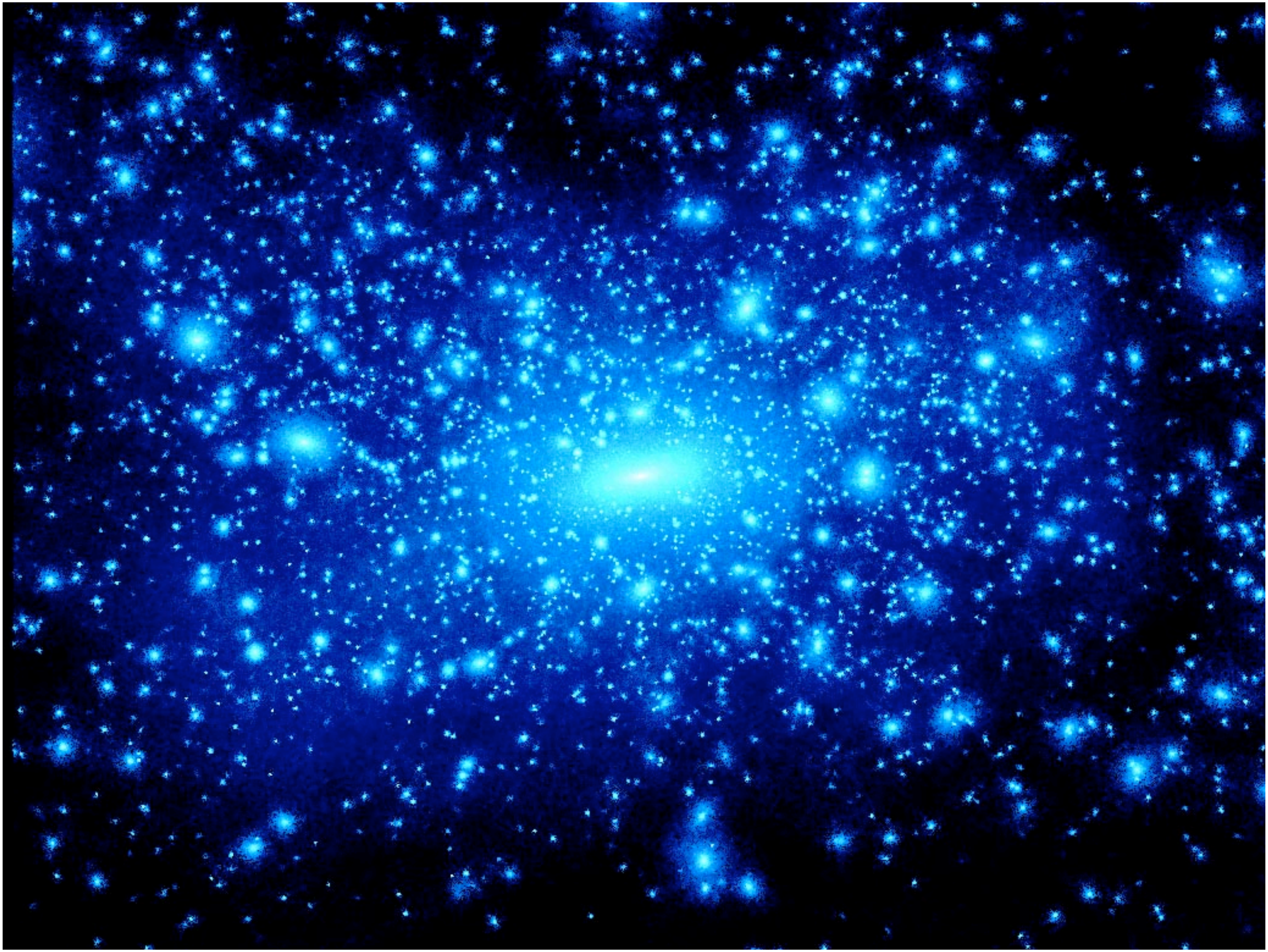
- From the first two years of publicly available FGST data, we have identified a component of gamma rays concentrated around the inner 0.25-0.5° around the Galactic Center, with a spectrum sharply peaked at 2-4 GeV
- This component does not appear to be consistent with any plausible astrophysical source or mechanism
- The spectrum and morphology of the observed emission can be easily accounted for with annihilating dark matter distributed with a cusped (and perhaps adiabatically contracted) profile ($\rho \propto r^{-1.34}$), with a mass of 7.3-9.2 GeV, and an annihilation cross section of $\sigma v \sim 3.3 \times 10^{-27}$ cm^3/s to 1.5×10^{-26} cm^3/s, primarily to $\tau^+\tau^-$ (possibly among other leptonic final states)
- The required mass range is remarkably similar to that inferred from the combination of signals reported by CoGeNT and DAMA/LIBRA

Moving Forward

We welcome criticism and aggressive vetting

The first claimed observation of the detailed particle properties of dark matter calls for great scrutiny

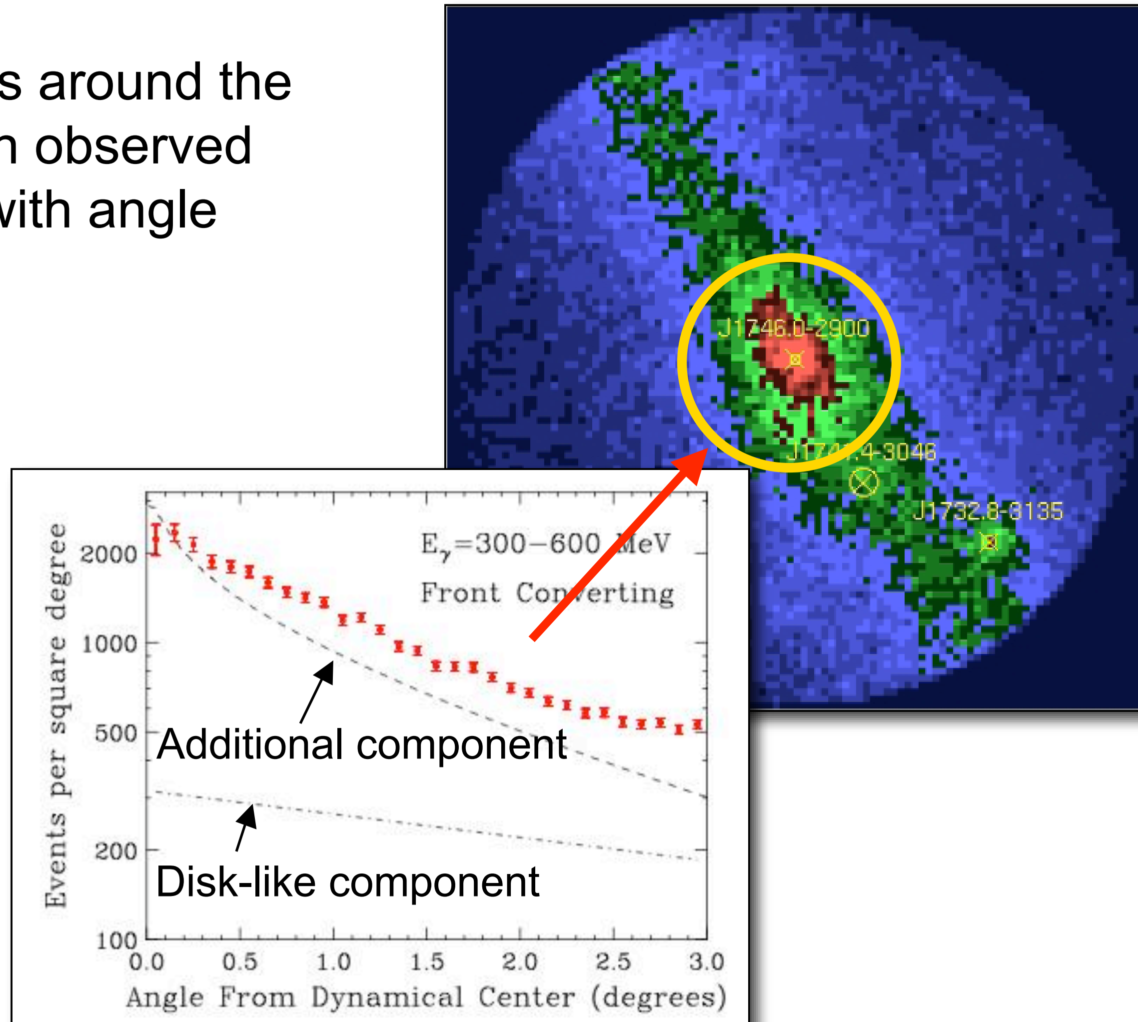
- Independent analysis of Galactic Center morphology and spectrum
- Consideration of any and all possible astrophysical sources or mechanisms
- Instrumental effects (Fermi Collaboration)
- Input from other potentially sensitive experiments (CRESST, CoGeNT annual modulation, CDMS low threshold, Super Kamiokande, Planck, etc.)



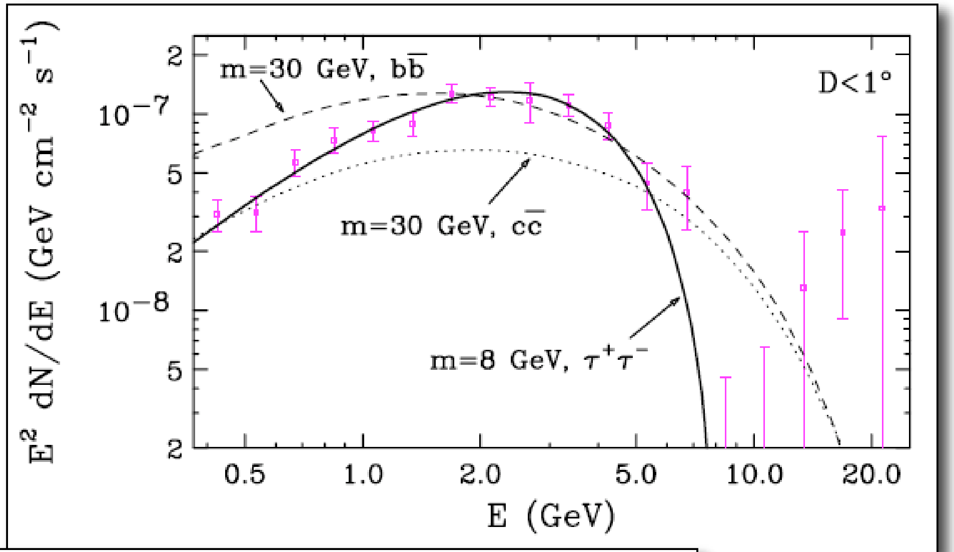
Dark Matter In The Galactic Center Region

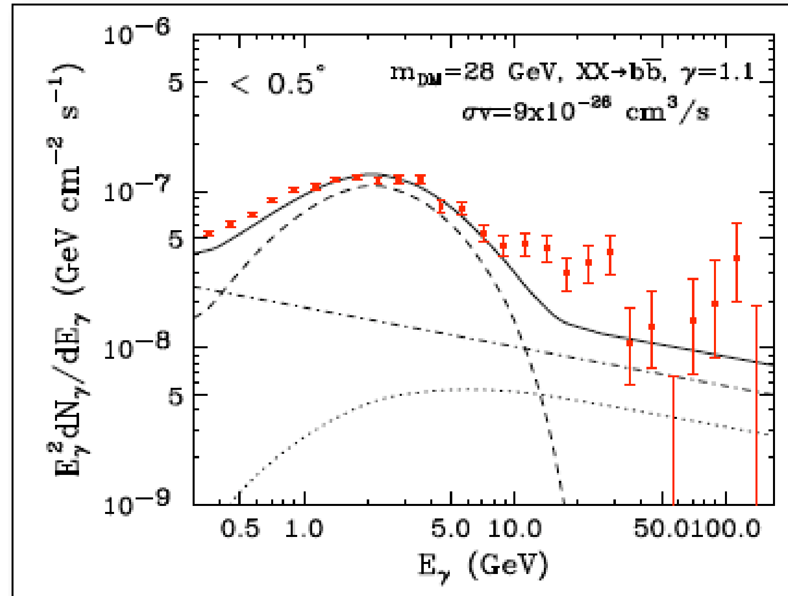
- Within the inner few degrees around the Galactic Center, the emission observed by FGST steeply increases with angle

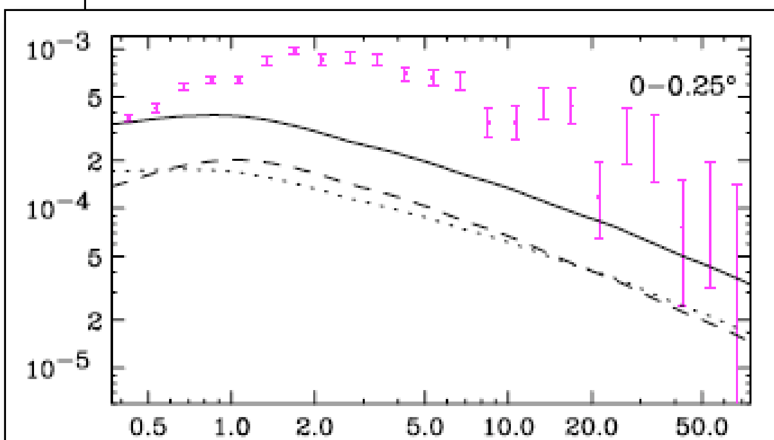
- If the diffuse background is modeled with the shape of the disk emission between 3° and 6°, another component is required that is more concentrated and spherically symmetric

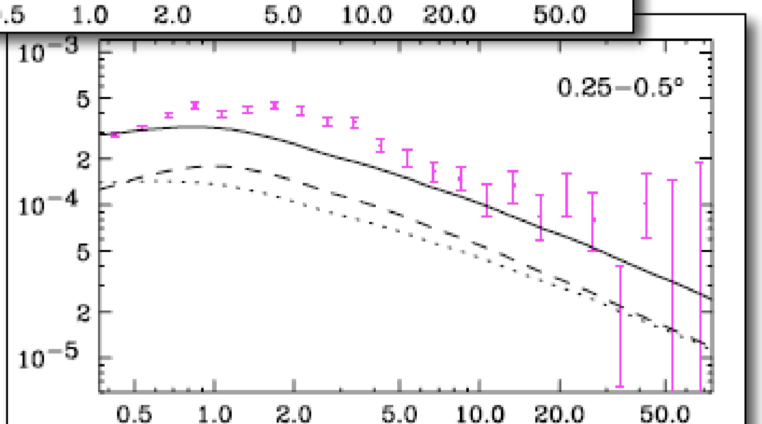


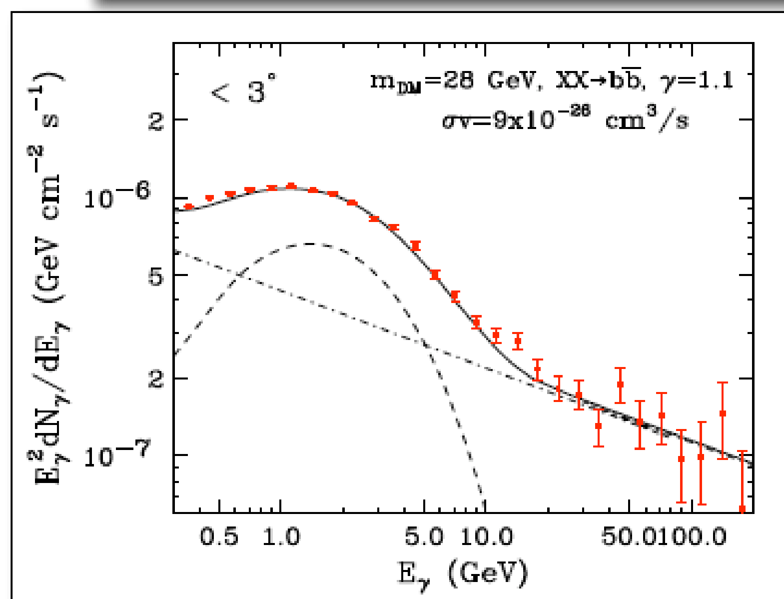
L. Goodenough, D. Hooper, arXiv:0910.2998





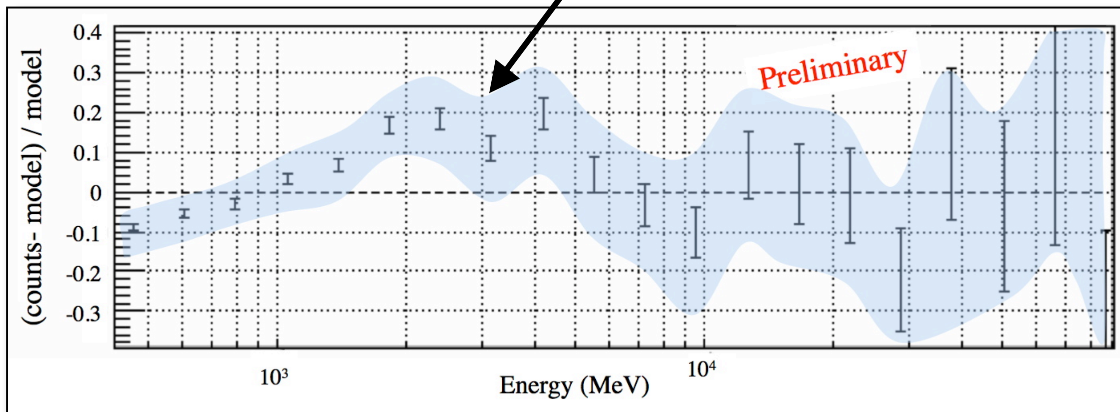




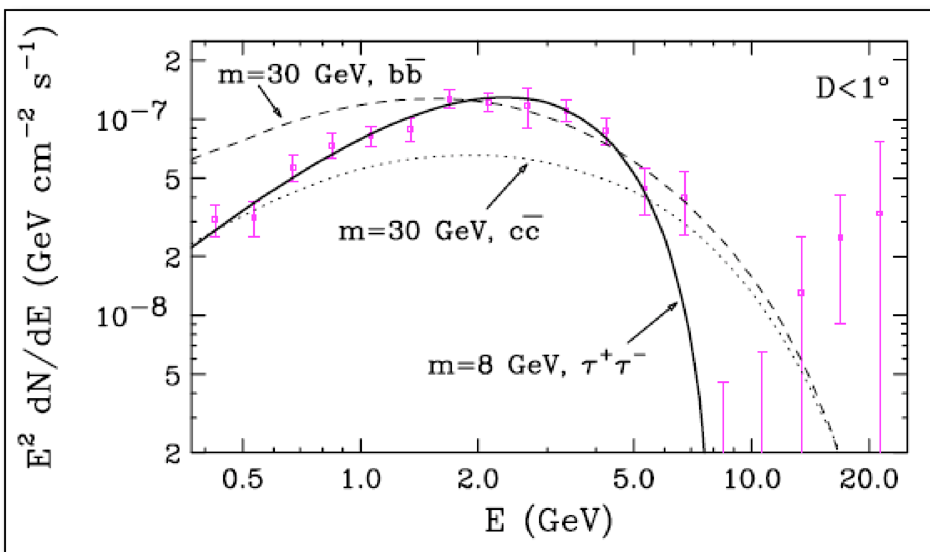


L. Goodenough, D. Hooper, arXiv:0910.2998

- Recent presentations by the Fermi collaboration confirm the presence of this feature



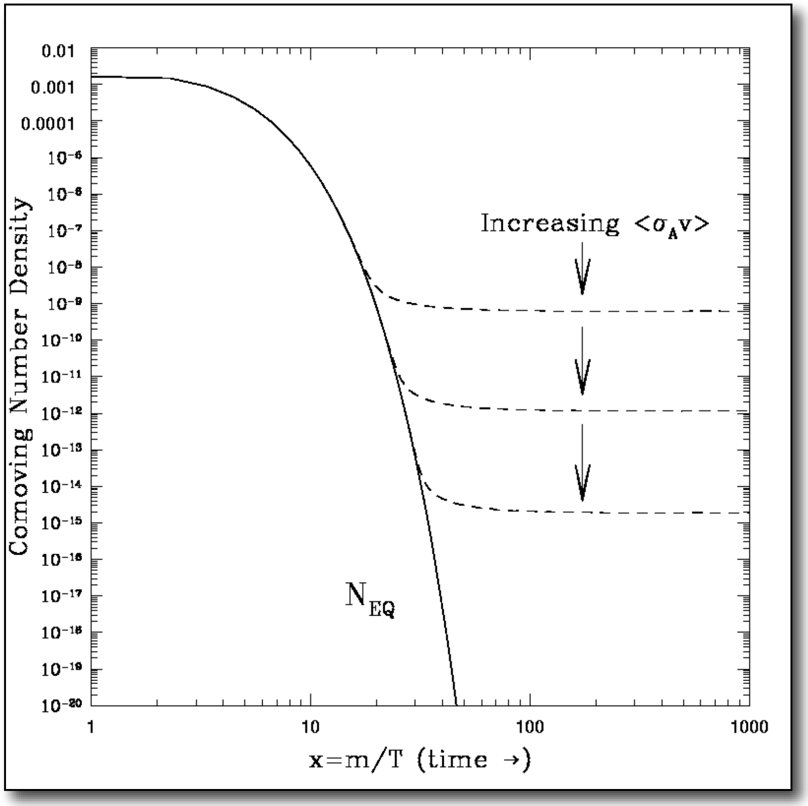
(Fermi Collaboration, Preliminary)



Why WIMPs?

The thermal abundance of a WIMP

- T >> M, WIMPs in thermal equilibrium
- T < M, number density becomes Boltzmann suppressed
- T ~ M/20, Hubble expansion dominates over annihilations; freeze-out occurs
- Precise temperature at which freeze-out occurs, and the density which results, depends on the WIMP's annihilation cross section



Why WIMPs?

The thermal abundance of a WIMP

- As a result of the thermal freeze-out process, a relic density of WIMPs is left behind:

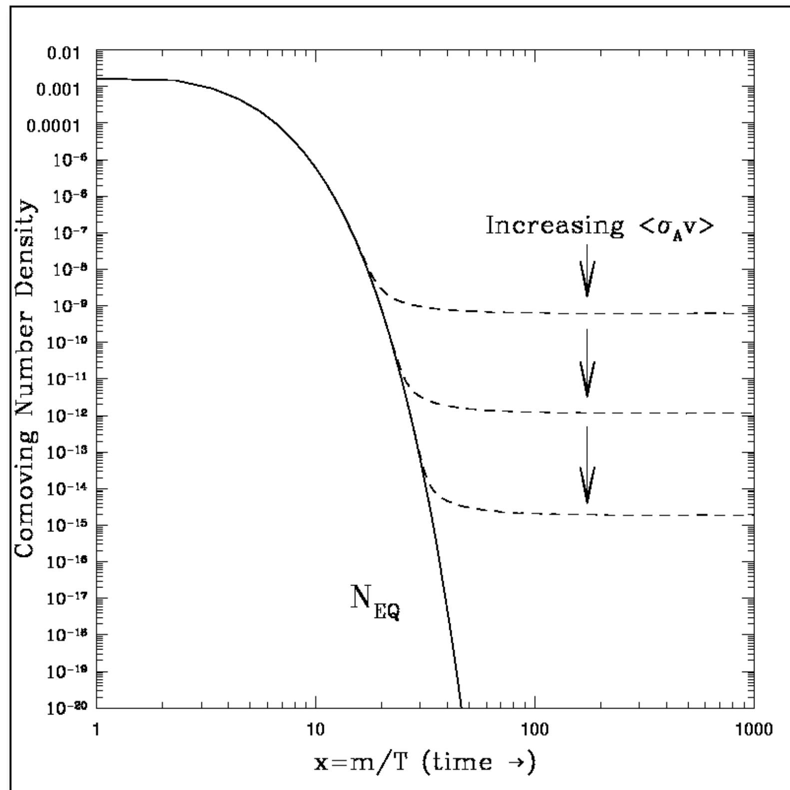
$$\Omega h^2 \sim x_F / \langle\sigma v\rangle$$

- For a GeV-TeV mass particle, to obtain a thermal abundance equal to the observed dark matter density, we need an annihilation cross section of:

$$\langle\sigma v\rangle \sim 3\times10^{-26}\ \mathrm{cm}^3/\mathrm{s}$$

- Generic weak interaction yields:

$$\langle\sigma v\rangle \sim \alpha^2\ (100\ \mathrm{GeV})^{-2} \sim 3\times10^{-26}\ \mathrm{cm}^3/\mathrm{s}$$



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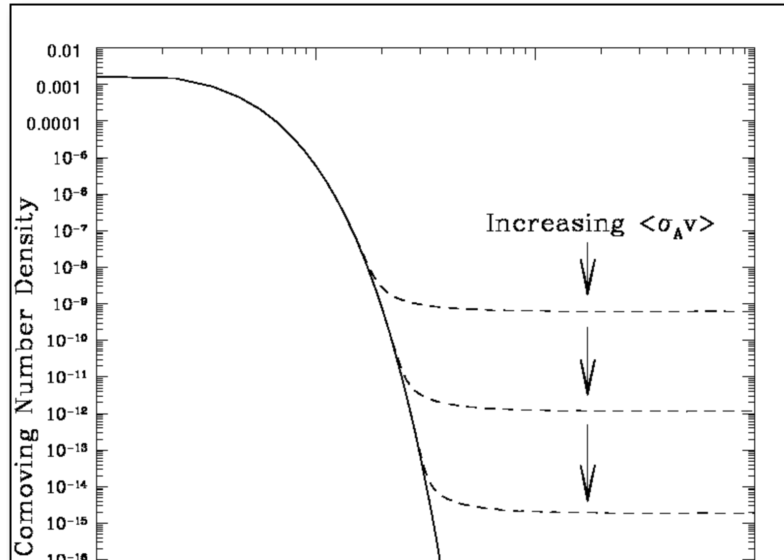

Numerical coincidence? Or an indication that dark matter originates from electroweak-scale physics?