Closing In On Dark Matter

Dan Hooper
Fermilab/University of Chicago

American Physical Society Meeting
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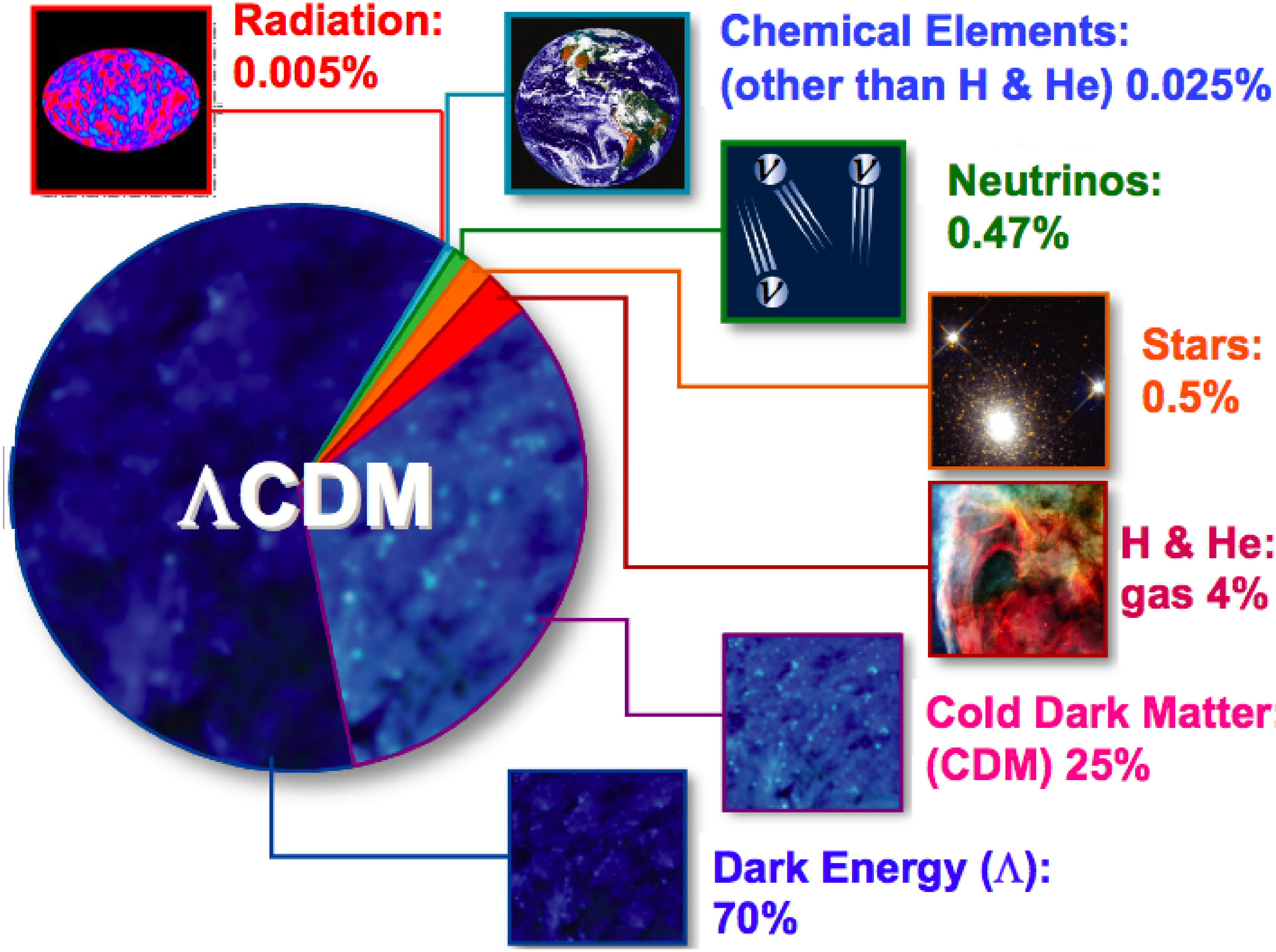

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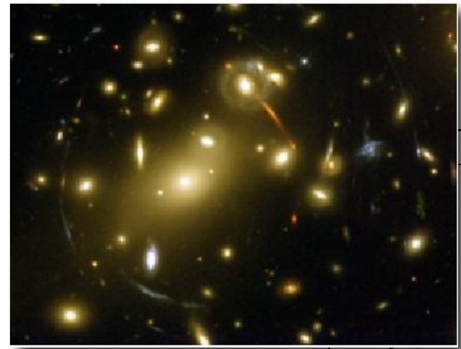
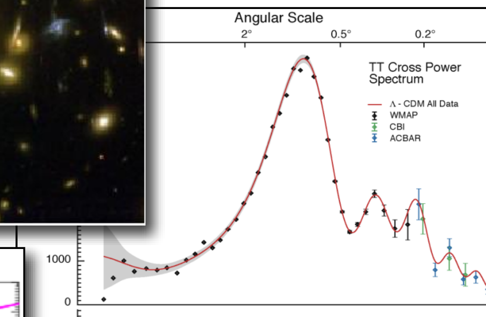
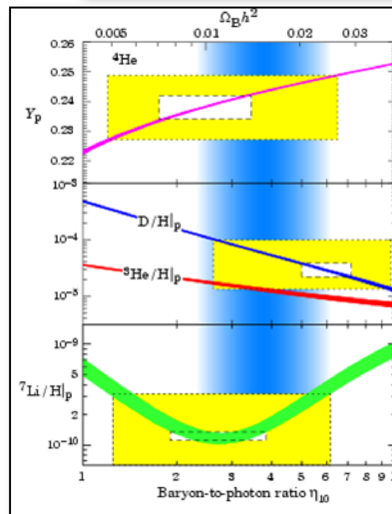
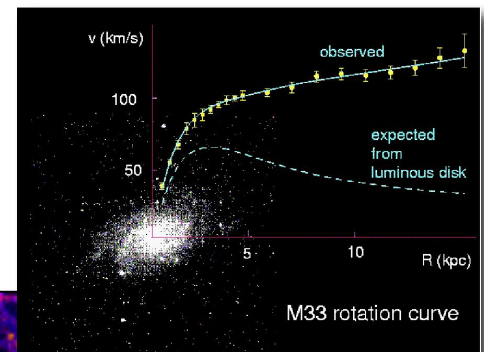
Evidence For Dark Matter

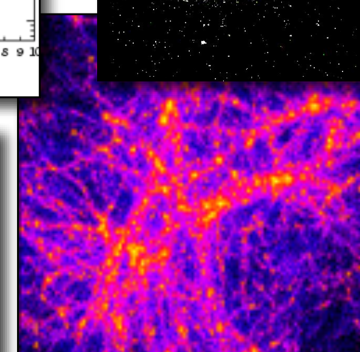
- Galactic rotation curves
- Gravitational lensing
- Light element abundances
- Cosmic microwave background anisotropies
- Large scale structure











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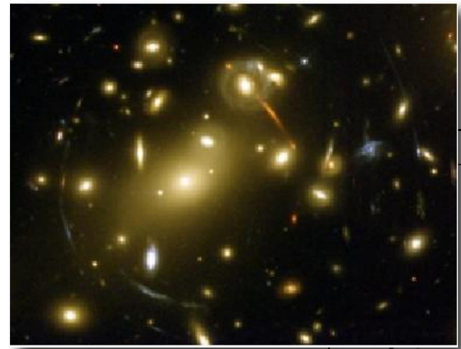
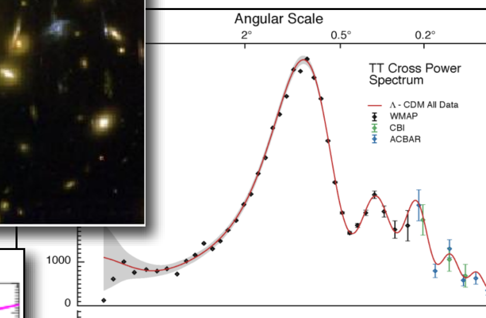
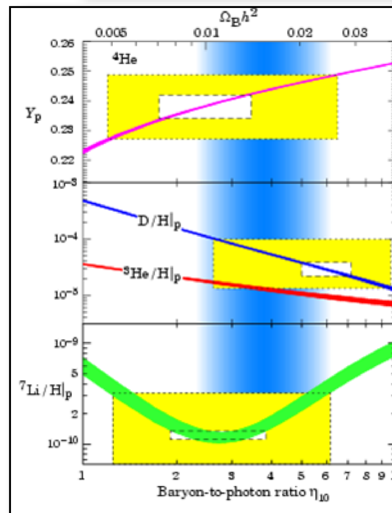
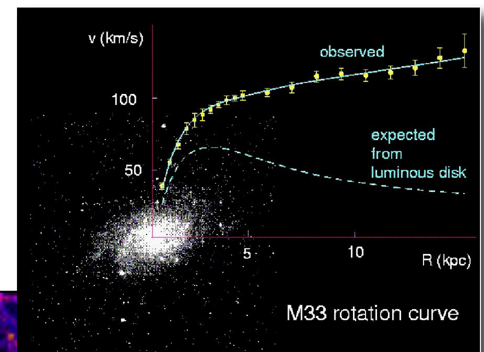
Evidence For Dark Matter

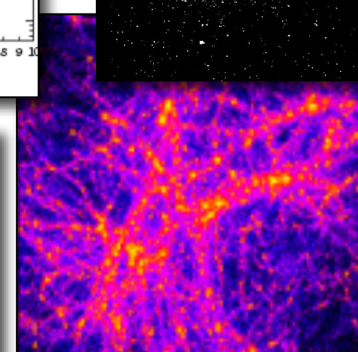
- There is a wide variety of independent evidence that dark matter exists
- Each of these observations infer dark matter’s presence through its gravitational influence
- Still no observations of dark matter’s electroweak interactions (or other non-gravitational interactions)











Why WIMPs?

The thermal abundance of a WIMP

- $T >> M_X$, WIMPs in thermal equilibrium
- $T < M_X$, number density becomes suppressed
- Including the effects of expansion pulls the density away from its equilibrium value:

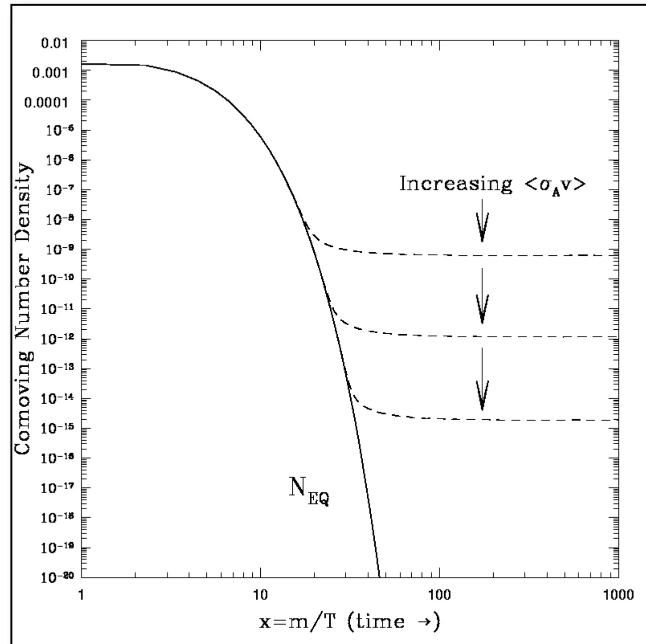
$$\frac{dn_X}{dt} + 3Hn_X = - < \sigma_{X\bar{X}} |v| > (n_X^2 - n_{X,\,\mathrm{eq}}^2)$$

- Numerically, this yield a relic abundance of:

$$\Omega_X h^2 \approx 0.1 \left(\frac{x_{\rm FO}}{20}\right)\left(\frac{g_\star}{80}\right)^{-1/2}\left(\frac{a + 3b/x_{\rm FO}}{3 \times 10^{-26}{\rm cm}^3/{\rm s}}\right)^{-1}$$

- In comparison,

$$\alpha^2/(100\,{\rm GeV})^2 \sim 3\times 10^{-26}\ {\rm cm}^3/{\rm s}.$$



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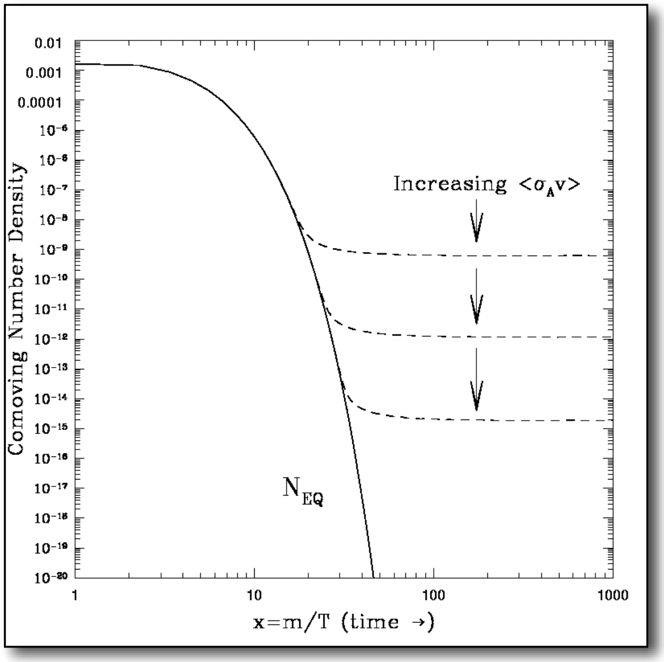
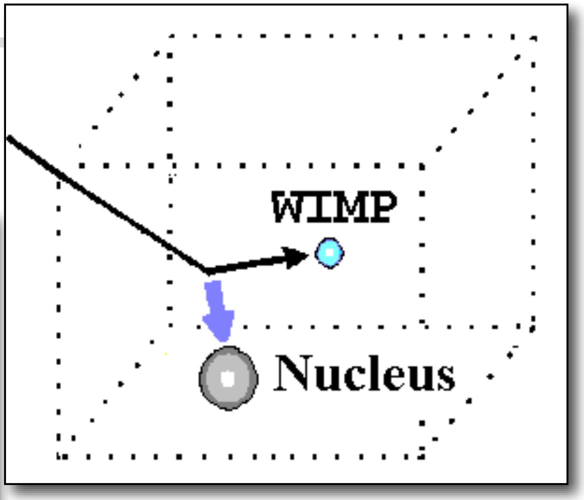
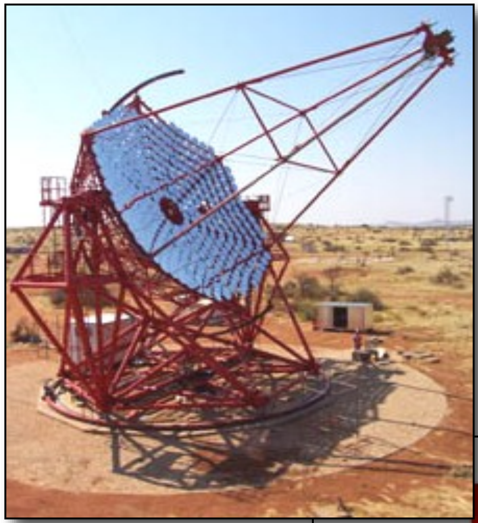


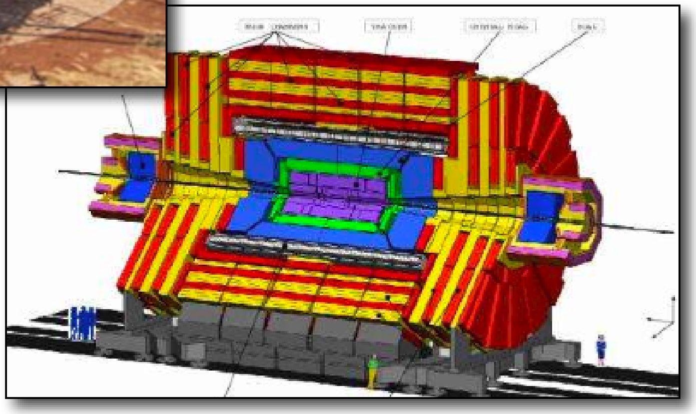
A new species of weakly interacting, stable particles is predicted to be produced with an abundance similar to the observed dark matter density.
-Numerical coincidence?
-WIMP Miracle?

WIMP Hunting

- Direct Detection
- Indirect Detection
- Collider Searches





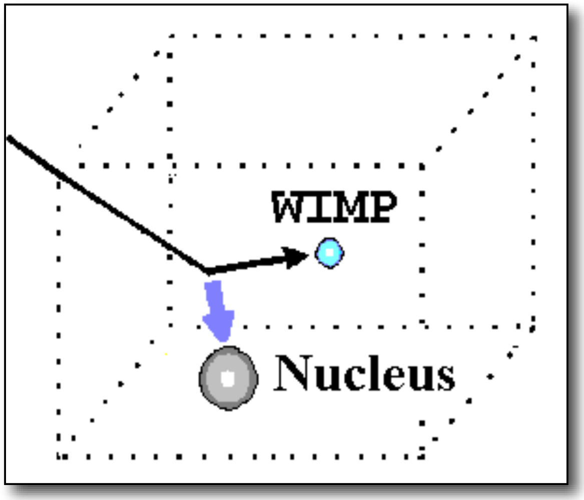


Direct Detection

- A WIMP striking a nucleus will impact a recoil of energy:

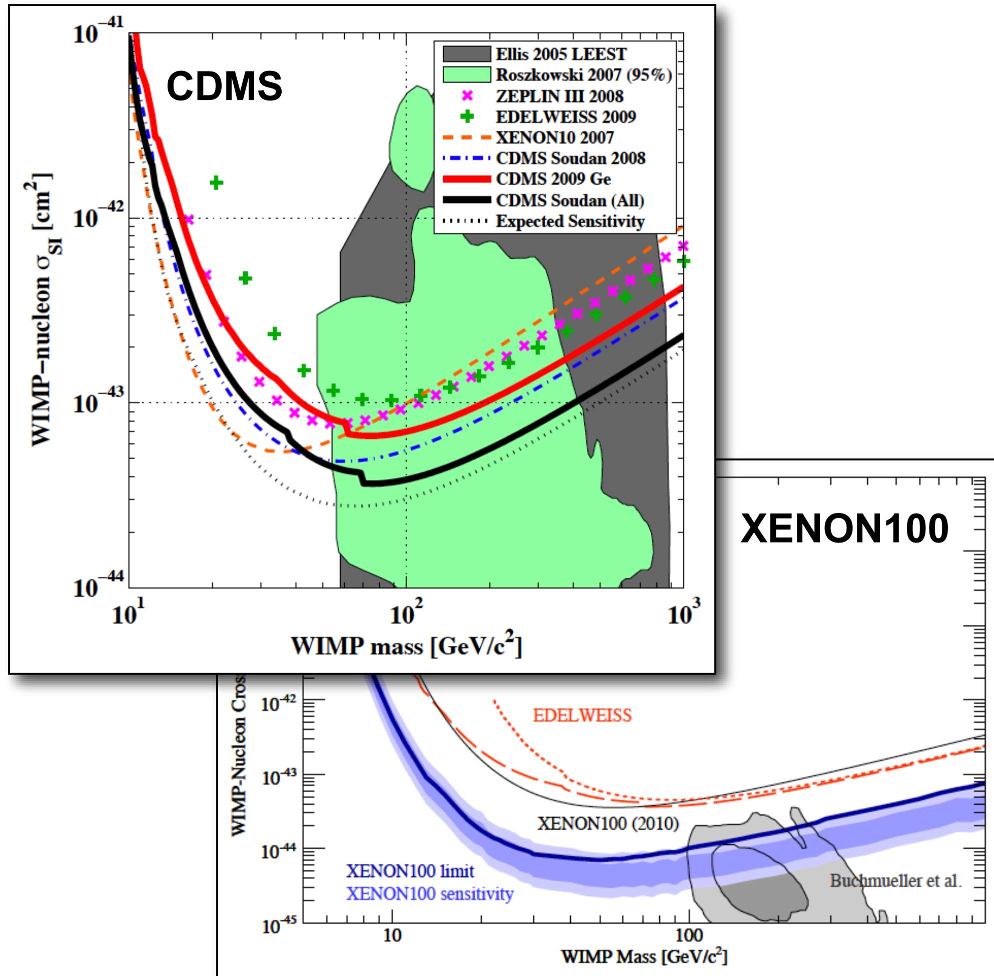
$$E_{\rm recoil} = \frac{|\vec{q}|^2}{2M_{\rm nucleus}} = \frac{2\mu^2 v^2 (1-\cos\theta)}{2M_{\rm nucleus}} = \frac{m_X^2 M_{\rm nucleus}\, v^2 (1-\cos\theta)}{(m_X + M_{\rm nucleus})^2}$$

- For m_X >> $M_{nucleus}$ and v~300 km/s, this corresponds to E_{recoil}~1-100 keV



Direct Detection

- It is often not appreciated how stringent direct detection constraints have become
- A heavy 4th generation neutrino, for example, is ruled out by more than three orders of magnitude



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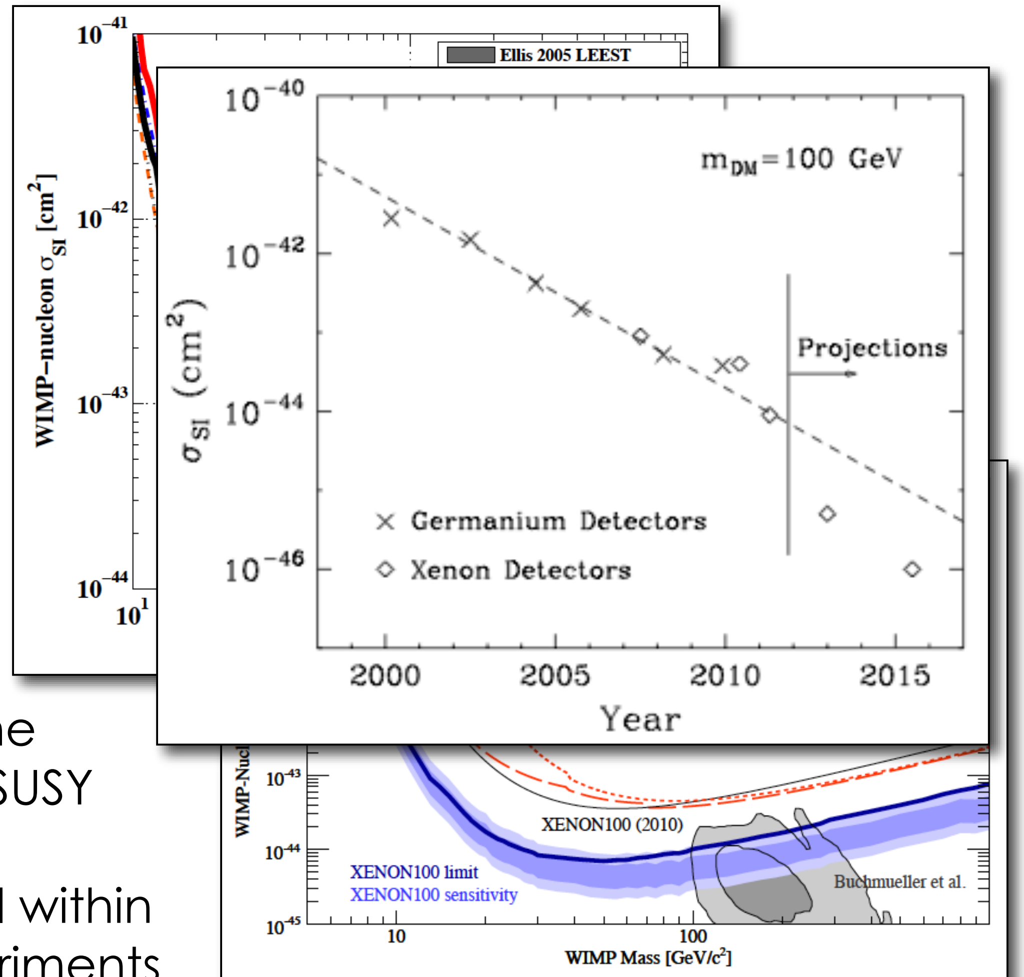
- A heavy 4th generation neutrino, for example, is ruled out by more than three orders of magnitude

- Over the past decade, sensitivity has improved at a rate of an order of magnitude every few years

- Within the next ~5 years, most of the parameter space associated with SUSY and other weak-scale beyond the Standard Model frameworks will fall within the reach of direct detection experiments



Possible Signals From Direct Detection Experiments

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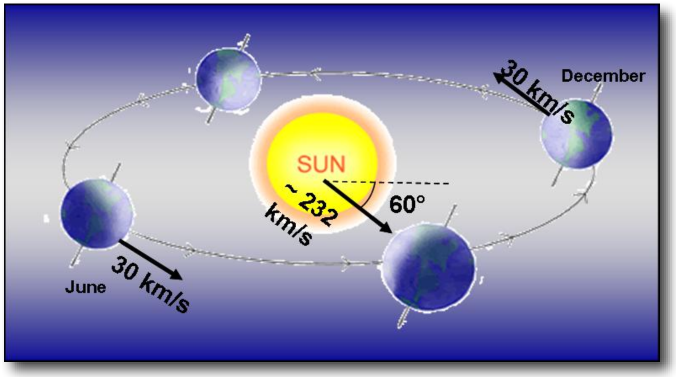
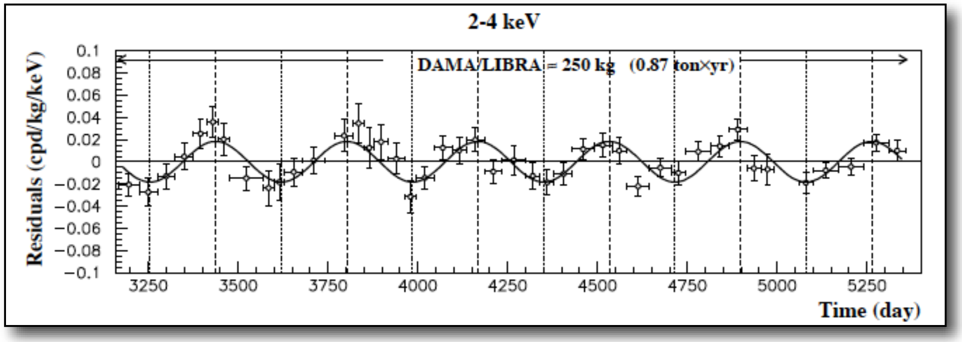
DAMA/LIBRA

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



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



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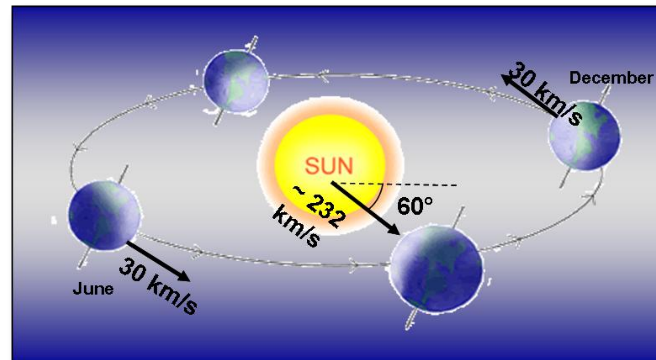

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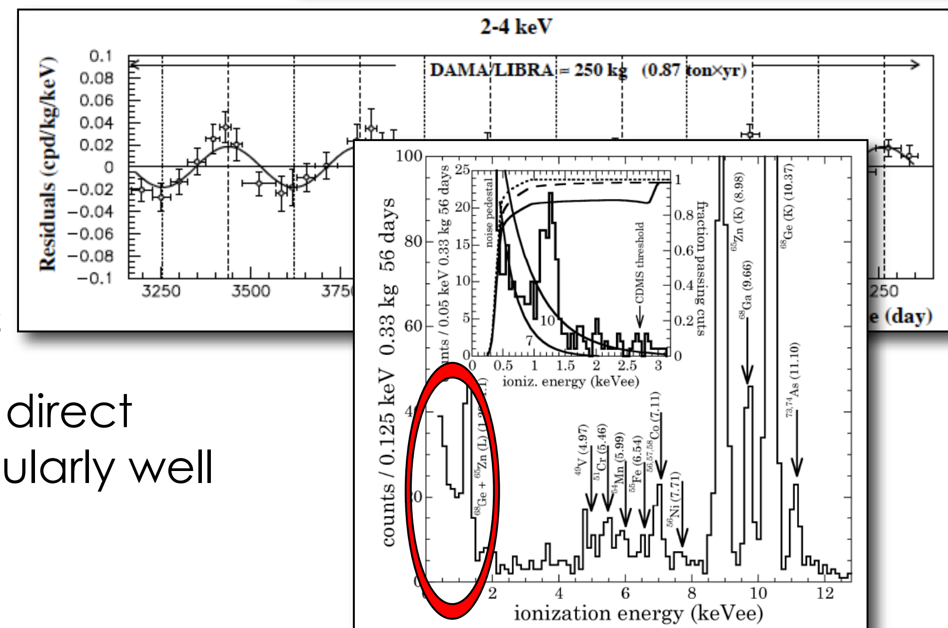

CoGeNT

- The CoGeNT collaboration has also reported 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)

Are CoGeNT and DAMA Detecting Dark Matter?

- The signals reported by CoGeNT and DAMA could be the result of a somewhat light WIMP (~5-10 GeV) with a relatively large cross section with nuclei (~10^{-40} cm^2)
- This interpretation is in some tension with constraints claimed by CDMS and XENON100 - systematic uncertainties?

Are CoGeNT and DAMA Detecting Dark Matter?

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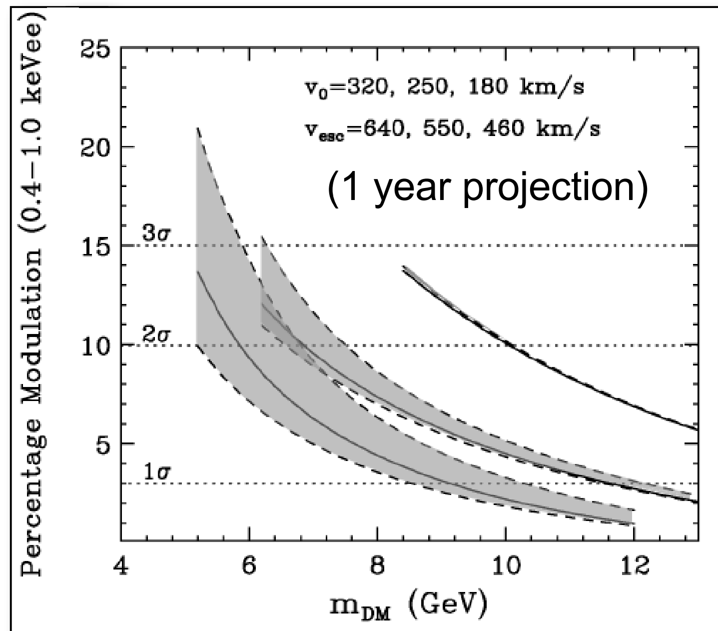
- This interpretation is in some tension with constraints claimed by CDMS and XENON100 - systematic uncertainties?
- If CoGeNT and DAMA are observing dark matter, we predict a ~5-15% modulation at CoGeNT (10-30% higher rate in summer than in winter)
- A 2-3σ detection of this effect should be possible with existing data (alternatively, the dark matter interpretation could be ruled out at 95% to 99% CL)



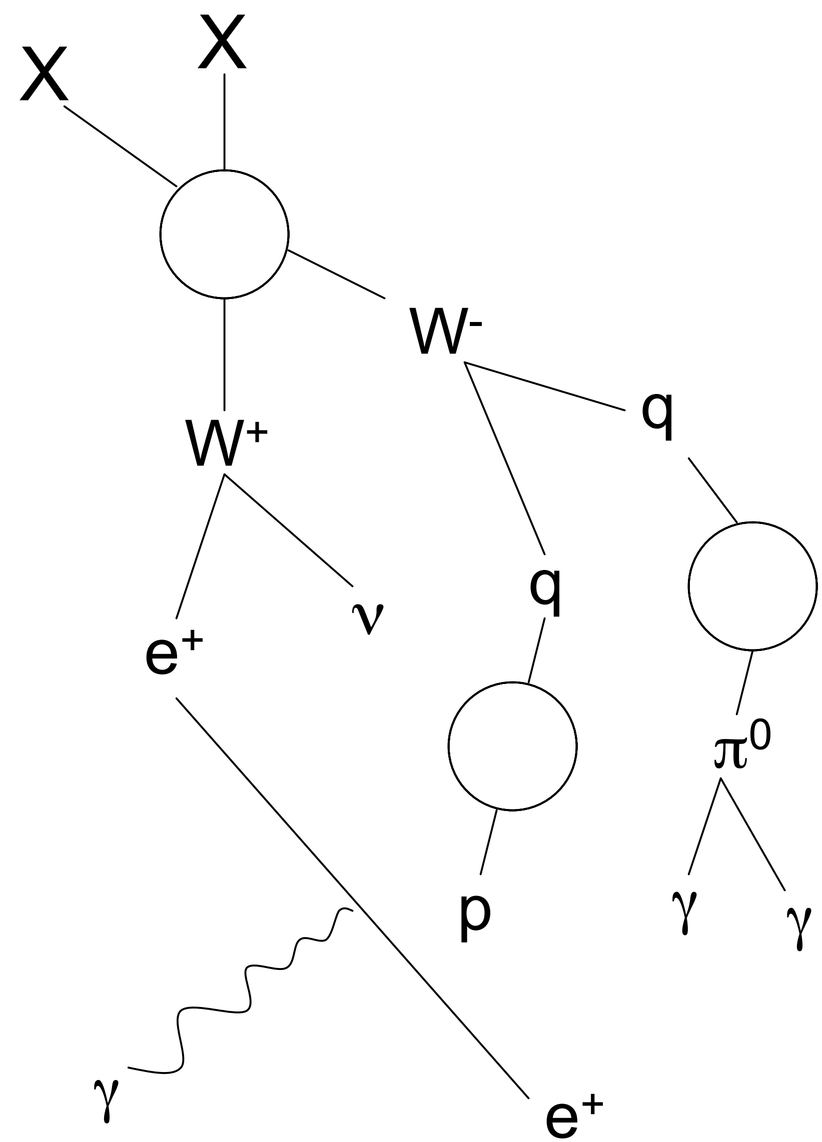
Kelso, Hooper, JCAP, arXiv:1011.3076;
Hooper, Collar, Hall, McKinsey, PRD, arXiv:1007.1005

Indirect Detection

1. **WIMP Annihilation**
   Depending on the model, annihilations can produce Standard Model fermions, gauge or Higgs bosons

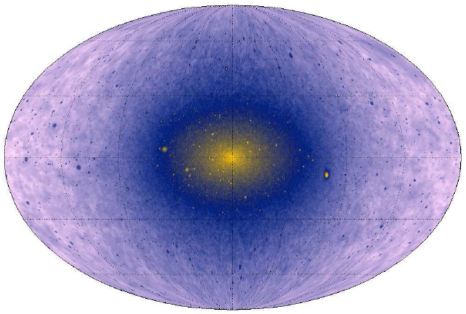
2. **Fragmentation/Decay**
   Annihilation products decay and/or fragment into combinations of electrons, protons, deuterium, neutrinos and gamma-rays

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

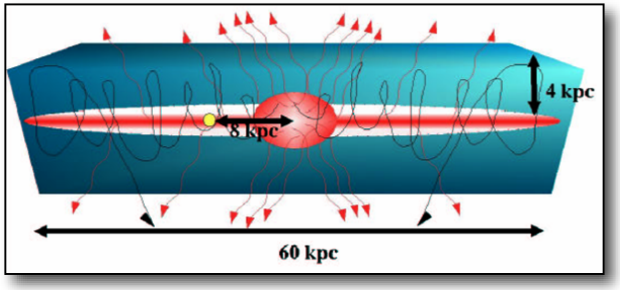


Indirect Detection

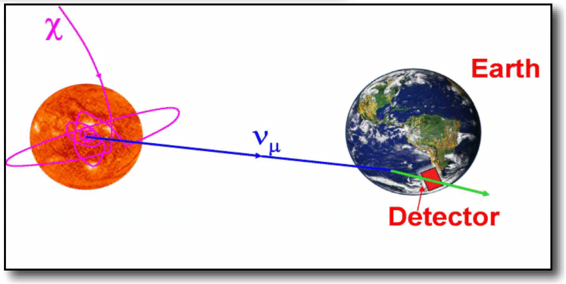
- **Gamma Rays**
  From annihilations in the Galactic Halo, near the Galactic Center, in dwarf galaxies, etc.



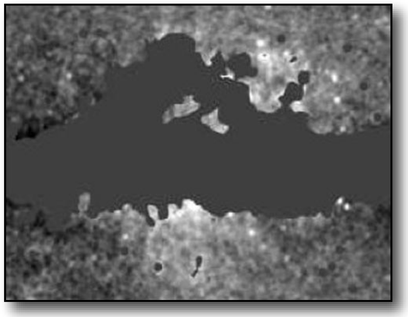
- **Positrons/Antiprotons**
  From annihilations throughout the galactic halo



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



- **Radio and Microwave Synchrotron**
  From electron/positron interactions with the magnetic field of the Milky Way



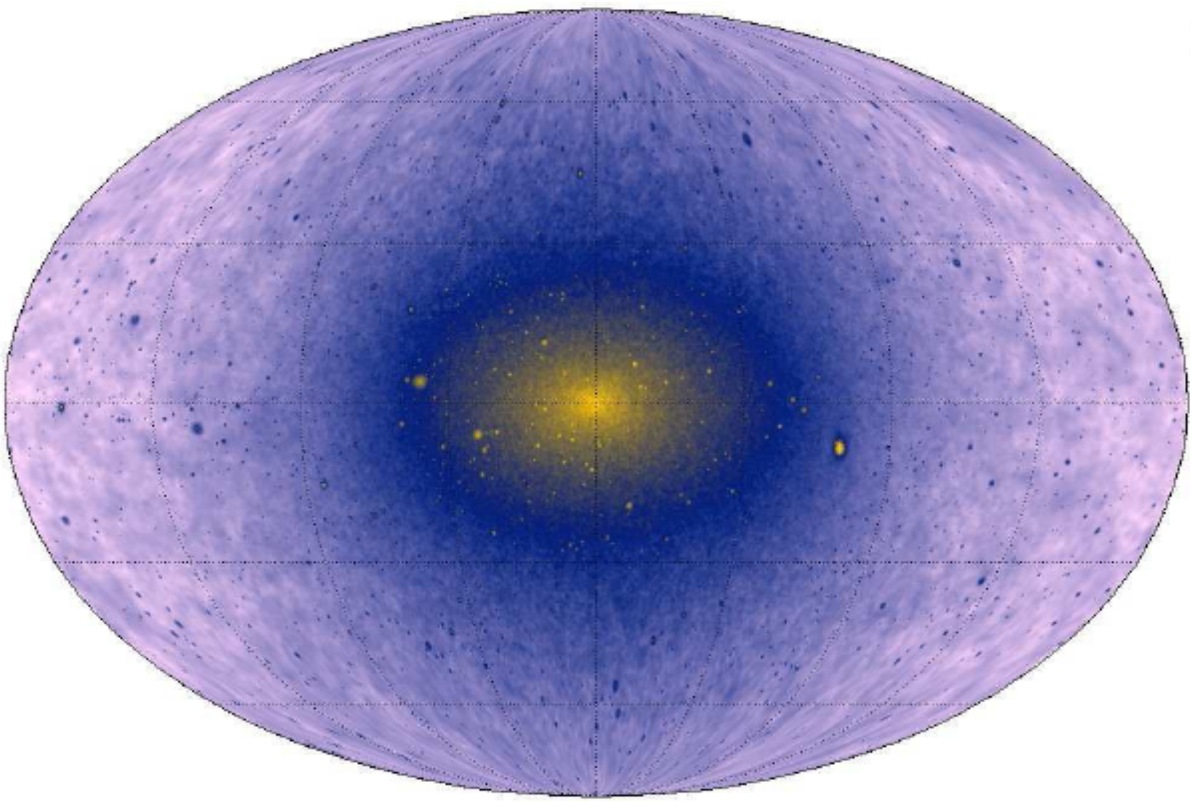
Searches For Gamma Rays From Dark Matter Annihilations With Fermi

- The Fermi Gamma Ray Space Telescope has been collecting data for more than two and a half years

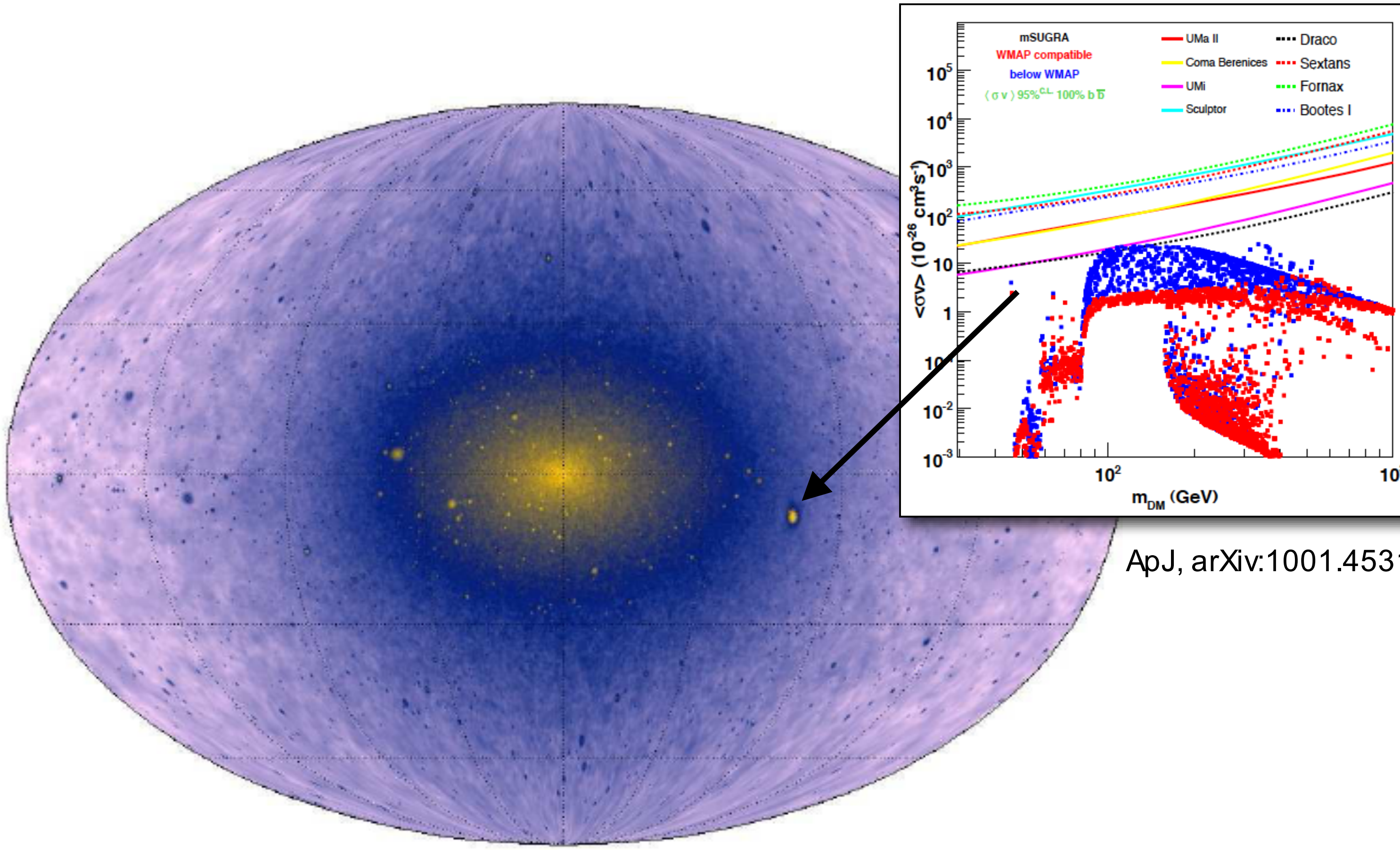
- Fermi's Large Area Telescope (LAT) possesses far superior effective area (~7000-8000 cm^2), angular resolution (sub-degree), and energy resolution (~10%) than its predecessor EGRET

- Unlike ground based gamma ray telescopes, Fermi observes the entire sky, and can study far lower energy emission (down to ~300 MeV)

Dark Matter Searches With Fermi

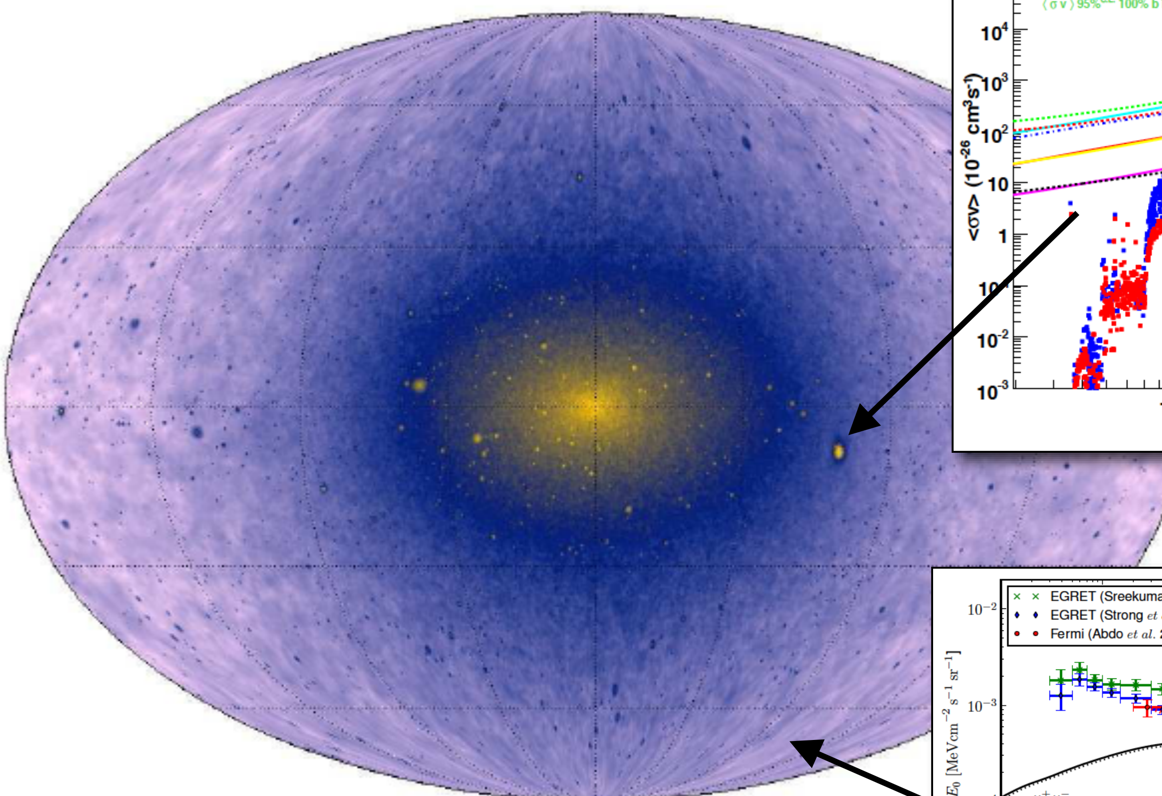


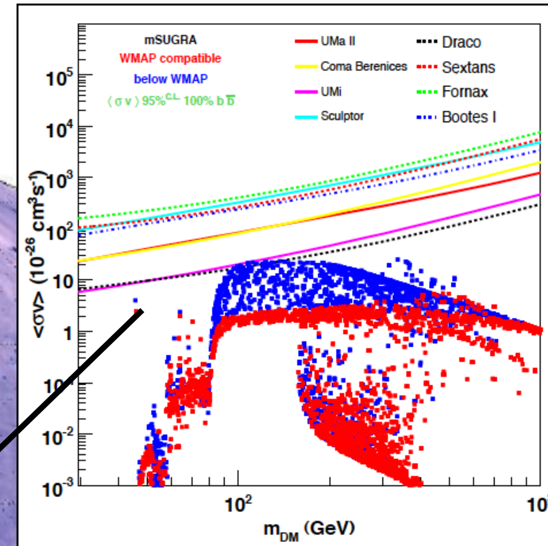
Dark Matter Searches With Fermi



ApJ, arXiv:1001.4531

Dark Matter Searches With Fermi





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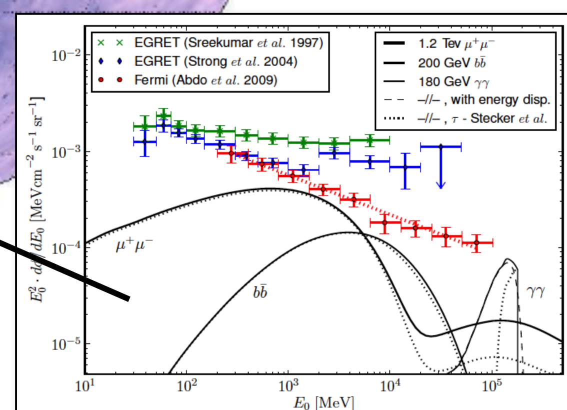

JCAP, arXiv:1002.4415

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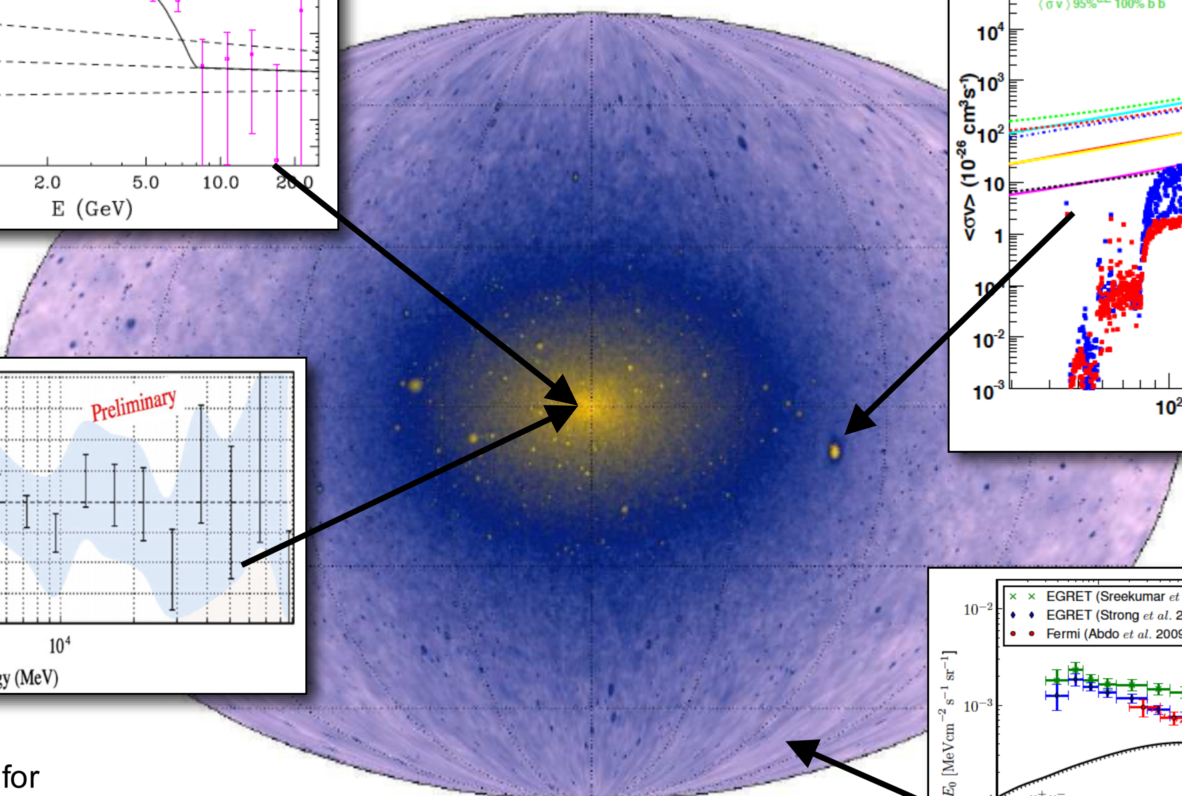
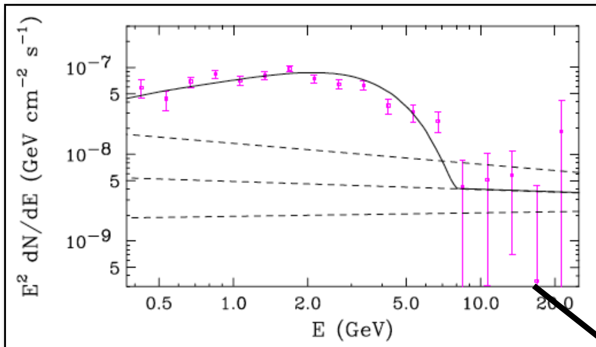
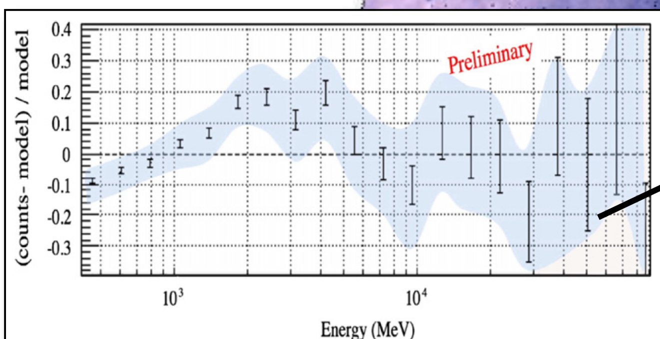
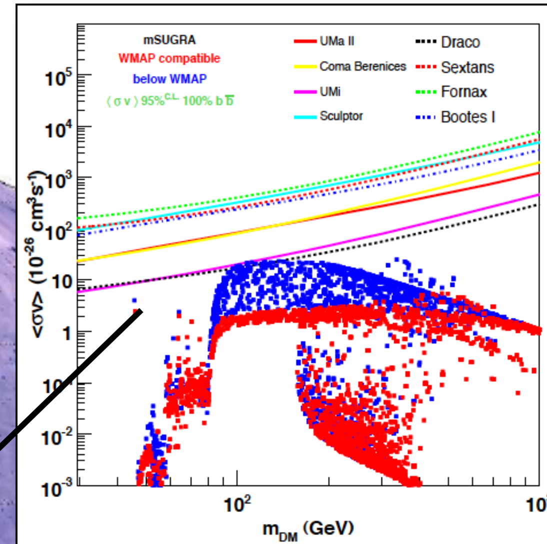




Hooper & Goodenough, PLB, arXiv:1010.2752



Various conference proceedings of V. Vitale for the Fermi Collaboration



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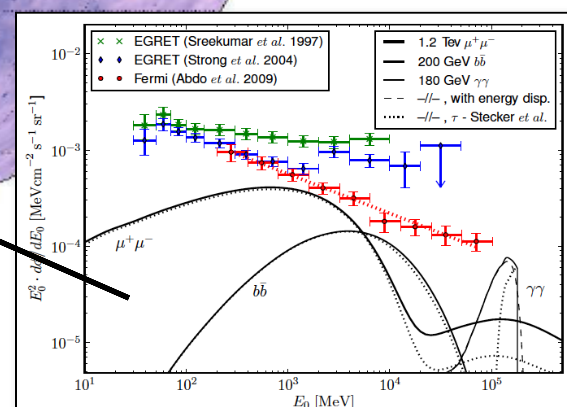


JCAP, arXiv:1002.4415

Dark Matter In The Galactic Center Region

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

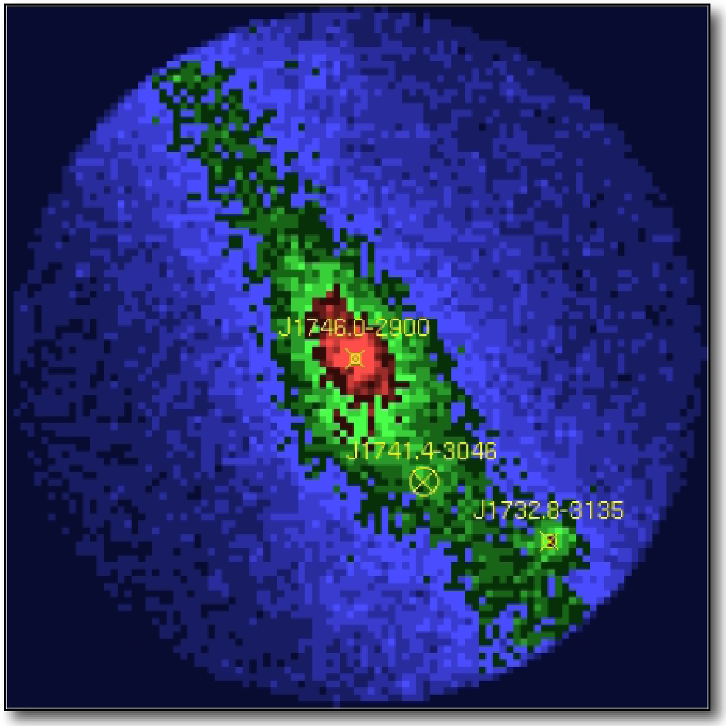
- This does not, however, make searches for dark matter in this region intractable

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

- The signal from dark matter annihilations is predicted to be:

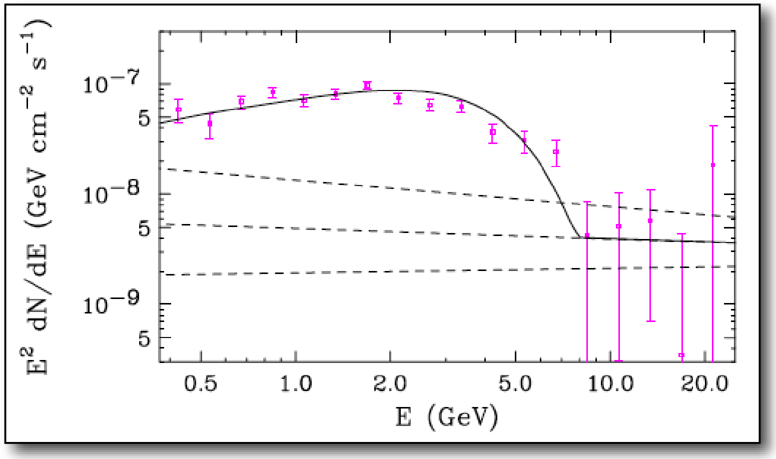
1) Highly concentrated around the Galactic Center (but not entirely point-like)

2) Possess a distinctive “bump-like” spectral feature

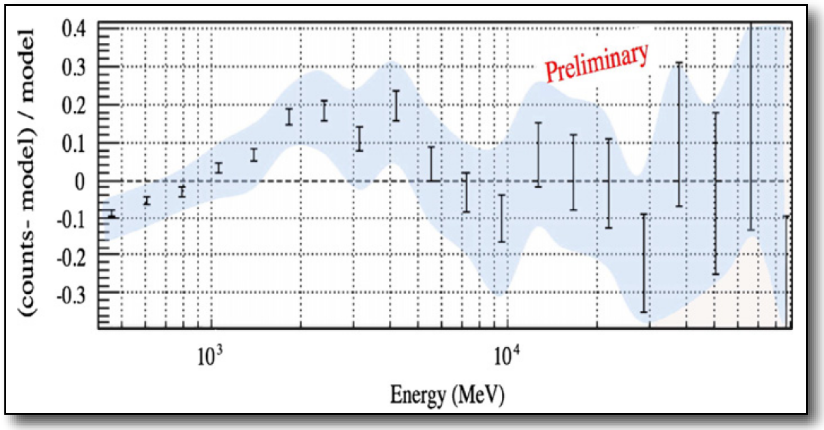


Dark Matter In The Galactic Center Region

- Analysis of Fermi data from the inner galaxy has revealed the presence of a dark matter-like signal
- In conference talks and proceedings, the Fermi collaboration has discussed an excess with similar spectral features (other details, such as the angular distribution of the excess and background modeling have not yet been disclosed by the Fermi Collaboration)
- Both find an excess over backgrounds that peaks at ~2-4 GeV, with no significant excess above ~7 GeV
- The Milky Way's supermassive black hole and pulsars have each been proposed as alternative sources for the observed gamma rays



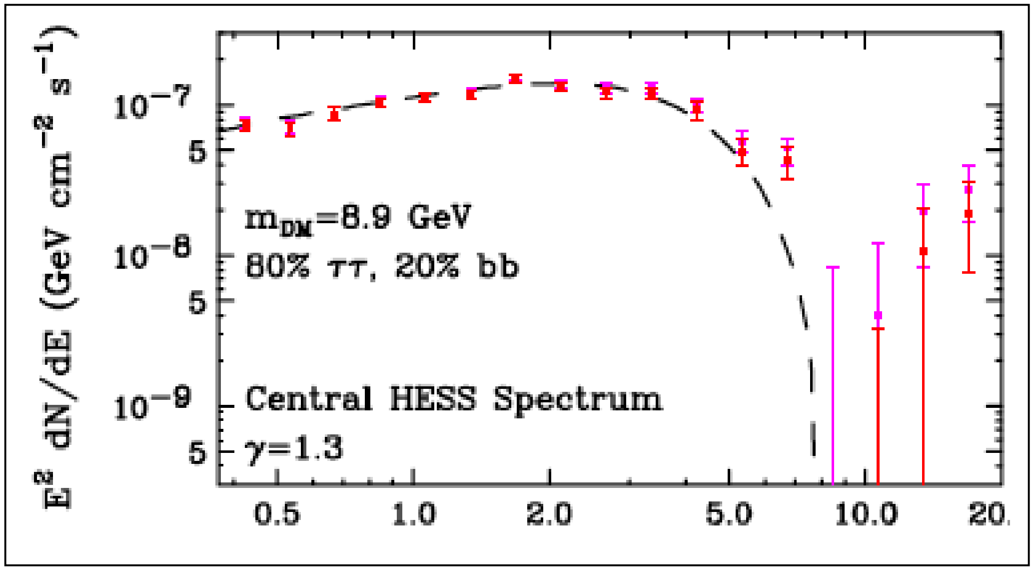
(Hooper, Goodenough, PLB, arXiv:1010.2752)



(V. Vitale, for the Fermi Collaboration)

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 to 10 GeV (similar to that required by CoGeNT and DAMA), annihilating primarily to $\tau^+\tau^-$ (possibly among other leptons)

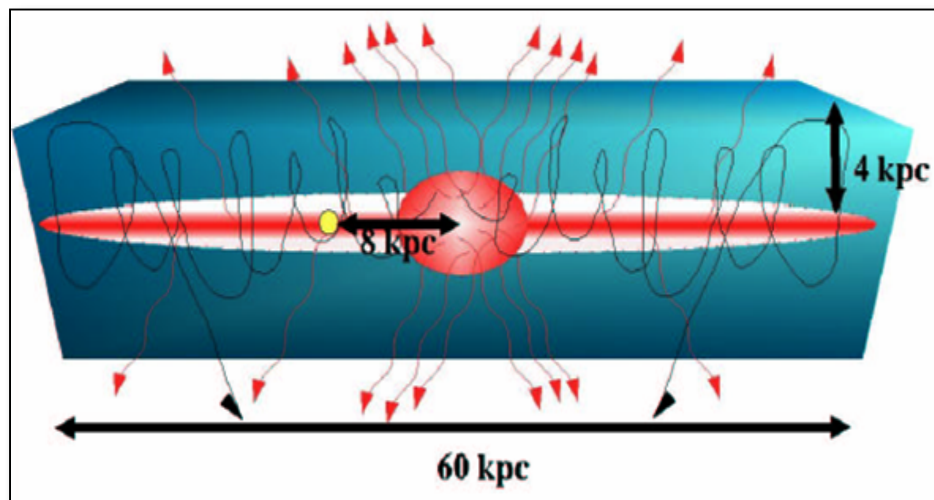


- The angular distribution of the signal is well fit by a flux distribution that scales with $r^{-\alpha}$, with α~2.5; if interpreted as dark matter, this implied an inner profile $\rho(r)$~$r^{-\gamma}$, with γ=1.2-1.3 (*in good agreement with the best fit to the Via Lactea simulation, for example*)

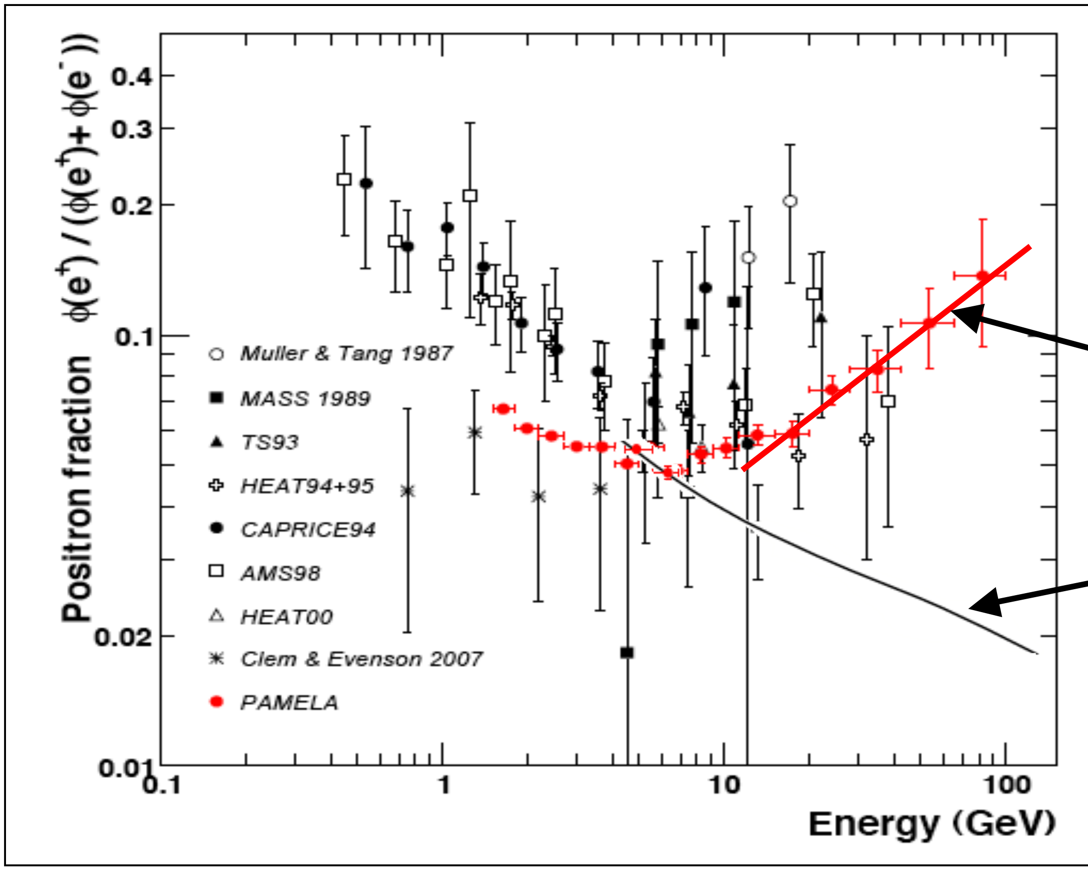
- The normalization of the signal requires the dark matter to have an annihilation cross section (to $\tau^+\tau^-$ and hadronic channels) of σv = (0.5-5)x10^{-26} (*consistent with the value of 3x10^{-26} cm^3/s predicted for a simple thermal relic*)

Dark Matter Searches With Charged Cosmic Rays

- WIMP annihilations are generally predicted to produce equal amounts of matter and antimatter
- Charged particles lose energy as they propagate under the influence of the Galactic Magnetic Field, erasing directional and spectral information
- A large positron/antiproton content in the cosmic ray spectrum could be an indication of dark matter annihilation



Pamela's Positron Measurement



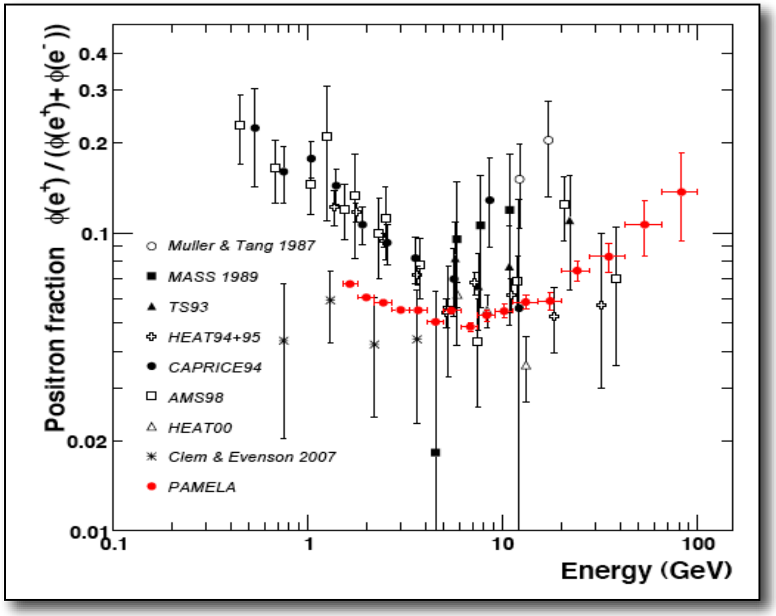
Rapid climb above 10 GeV indicates the presence of a <u>primary source of highly energetic cosmic ray positrons!</u>

Astrophysical expectation (secondary production)

Pamela Collaboration, arXiv:0810.4995

Possible Origins of the PAMELA Positron Excess

- Reacceleration of secondary positrons in or around supernova remnants (P. Blasi, arXiv:0903.2794)
- Astrophysical primary positron sources (ie. pulsars)
- Dark matter annihilations or decays



Dark Matter and PAMELA

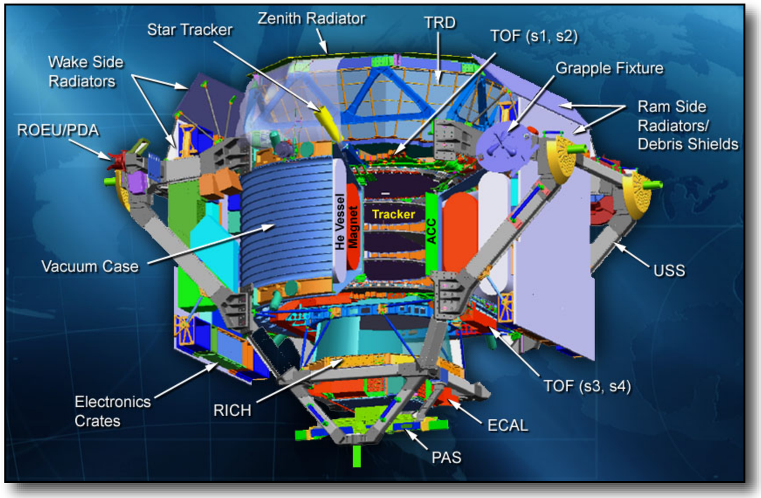
Dark matter annihilations in the halo of the Milky Way could explain the positron excess, although some obstacles exist

- **Hard positron spectrum** - Annihilation to leptons?
  Local overdensity/clump?
- **Lack of excess antiprotons** - Annihilation to leptons?
  Narrow diffusion region?
- **Large positron flux** - Non-thermal dark matter?
  Sommerfeld enhancements?
  Large degree of substructure?

Pamela's positrons cannot be explained by Vanilla Dark Matter, but could be in more complex scenarios

Dark Matter and AMS-02

- AMS-02 will be among the payload of Space Shuttle Endeavor, scheduled for launch on monday
- AMS-02 has ~10^2 times greater acceptance than PAMELA, and is designed to better distinguish cosmic ray electrons, positrons, protons, antiprotons, and various species of nuclei

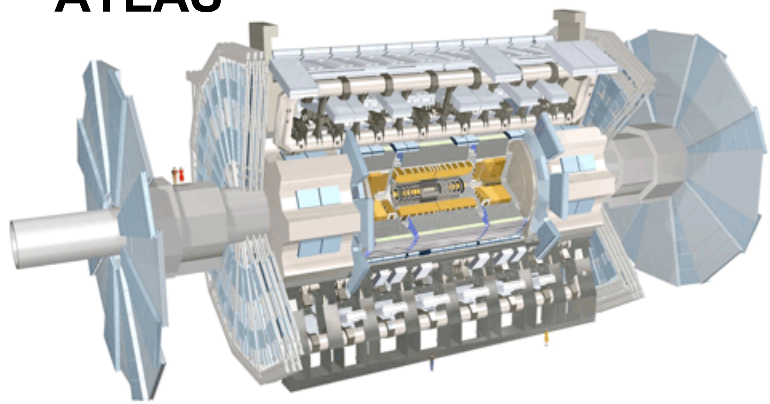


- Capable of measuring the cosmic ray positron fraction up to ~1 TeV
- Represents a major step forward in the advancement of our understanding of GeV-TeV cosmic rays

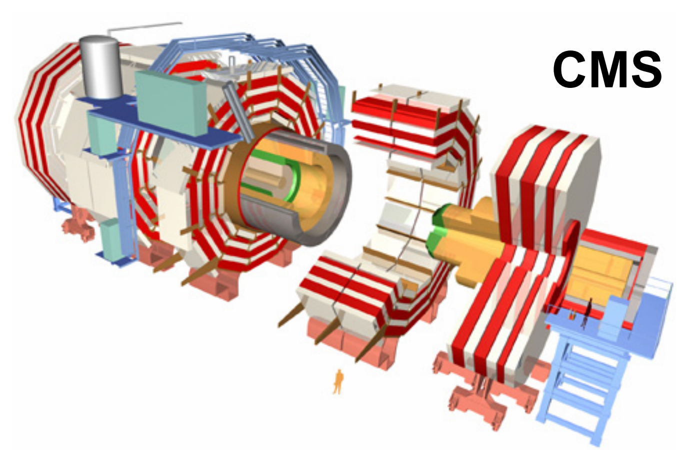
Dark Matter At Particle Colliders

- Machines such as the Large Hadron Collider (LHC) and the Tevatron may be able to produce and observe dark matter particles
- The LHC is currently collecting data at a rapidly accelerating rate - progress over the past year has been staggering
- Within the next year or so, a substantial fraction of weak-scale extensions of the Standard Model will become within the reach of the LHC - Expect new discoveries for the APS 2012 April Meeting

ATLAS



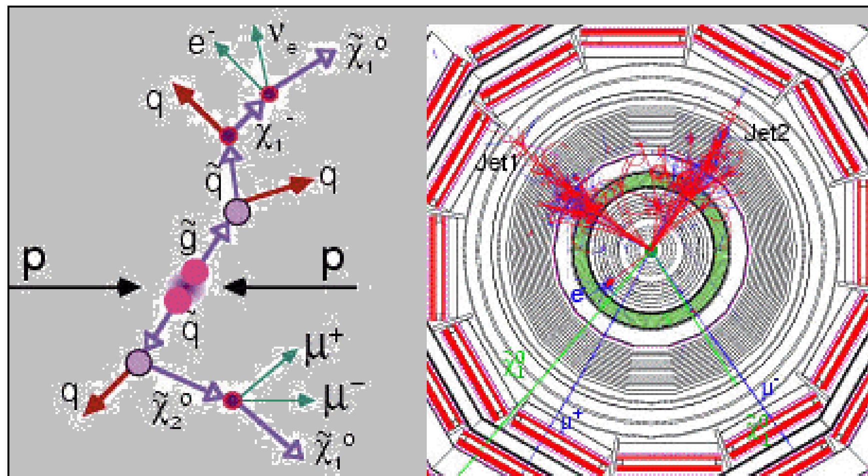
CMS



Dark Matter At Particle Colliders

Two strategies for dark matter hunting at colliders:

- Produce strongly interacting particles which although not dark matter themselves, produce dark matter particles in their decays (study distributions of events with various combinations of jets, leptons and missing energy)



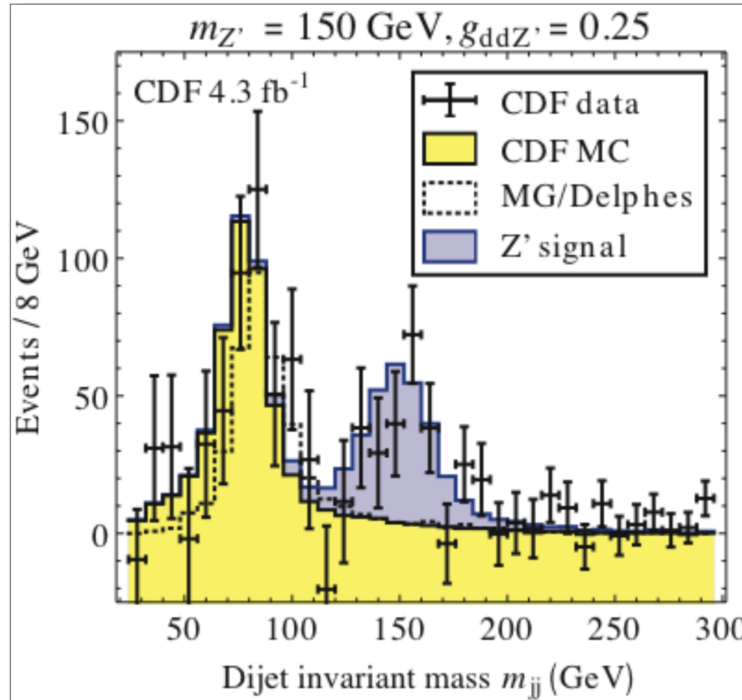
- Produce the dark matter directly (in association with a jet or photon), leading to more model independent constraints

New Physics At The Tevatron!?!

- On April 6th, the CDF collaboration announced the observation of a 3.2σ excess in their distribution of W+dijet events
- If confirmed, this implies the existence of a new particle(s) with a mass of 140-150 GeV
- Two basic explanations has been proposed:

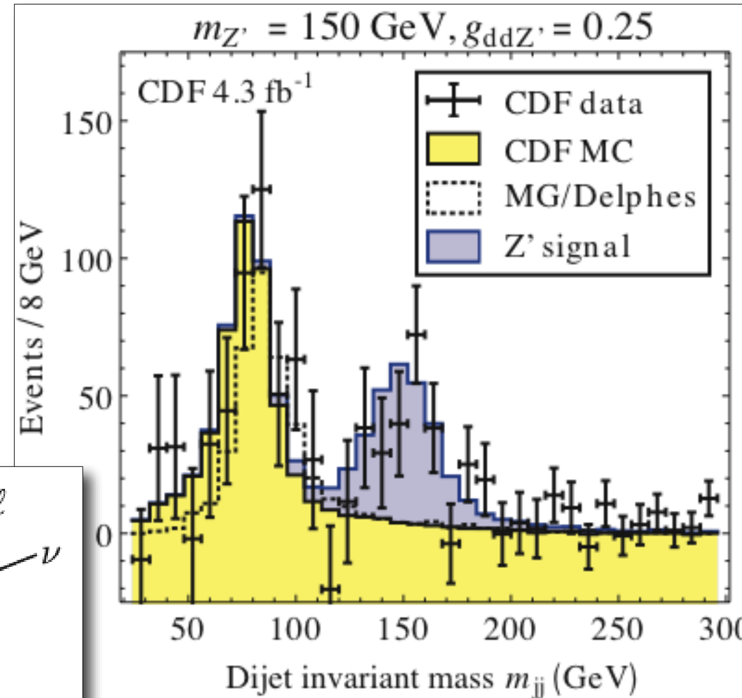
1) A new particle with modest couplings to quarks (g~0.2) but much smaller couplings to leptons (g<0.04, to evade LEP constraints)

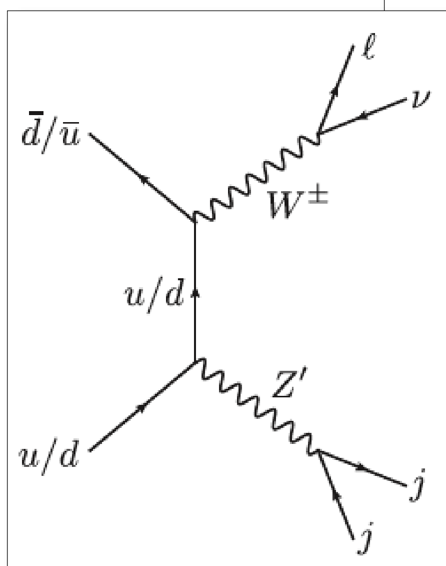
2) Two (or more) new particles lead to the events, the last of which is the ~140-150 GeV state being observed (could appear within the context of technicolor, or R-parity SUSY models, for example)



New Physics At The Tevatron!?!

- Focusing on the first case (only one new particle), the simplest thing we can consider is a new gauge boson (Z′)





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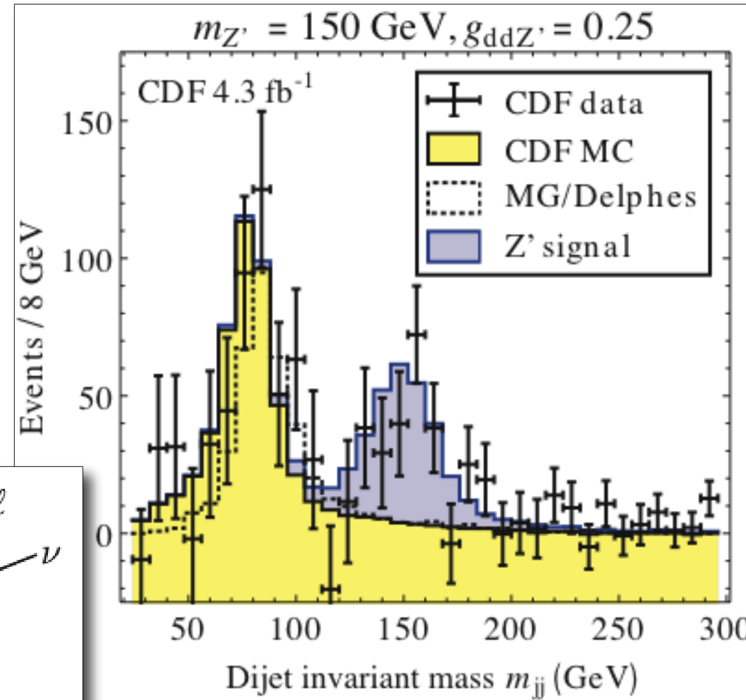
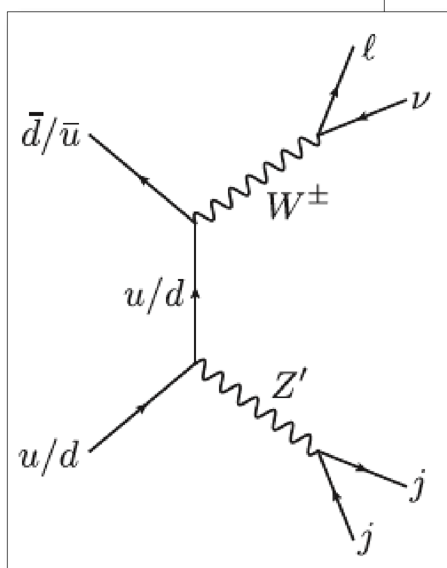
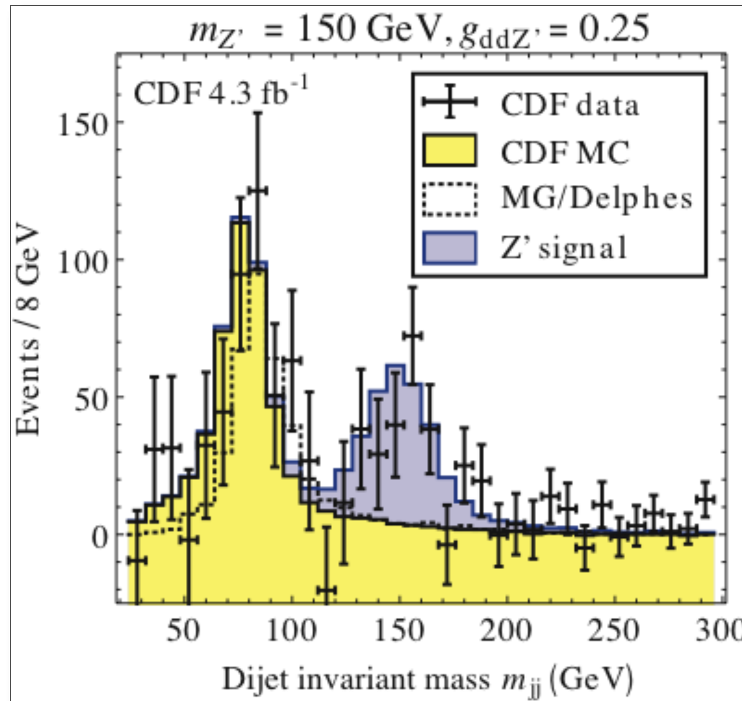
But what does this have to do with dark matter?





Dark Forces at the Tevatron

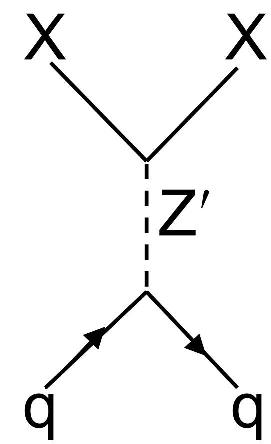
- The new gauge boson must have couplings to quarks, but little or no coupling to leptons - a "leptophobic" Z′
- To cancel the anomalies associated with this new gauge boson, we must to introduce a new particles, including heavy vector-like fermions (called "exotics")
- Within the leptophobic Z′ models in the existing literature, some of the new particles carry baryon number (but do not necessarily have QCD color); the lightest of these will be stable and will couple to the Z′ with approximately (within a factor of a few) the same strength as the Z′ couples to quarks → *provides us with a viable candidate for the dark matter*



Dark Forces at the Tevatron

- If the dark matter (the lightest baryon number charged new state) is a scalar or a Dirac fermion, then its couplings to the Z′ lead to a sizable elastic scattering cross section with nuclei:

$$\sigma^{\rm SI}_{Xp} = \frac{36\, m_X^2\, m_p^2\, g^2_{XXZ'}\, g^2_{qqZ'}}{\pi\, (m_X + m_p)^2\, m^4_{Z'}}$$



- With the coupling and mass of the Z′ that is required to explain the CDF anomaly, this becomes:

$$\sigma^{\rm SI}_{Xp} = 2 \times 10^{-40}\, {\rm cm}^2\ \times \left(\frac{m_X}{m_X + m_p}\right)^2 \left(\frac{g_{XXZ'}}{g_{qqZ'}}\right)^2$$

- For a ~10 GeV-10 TeV WIMP, this is ruled out by direct detection

- For a ~5-10 GeV WIMP, this is approximately the same cross section that is implied by CoGeNT and DAMA

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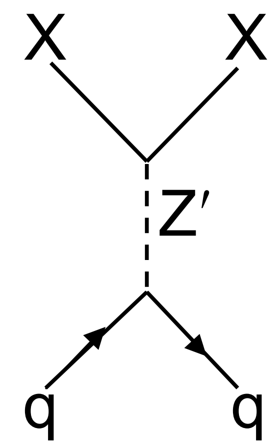

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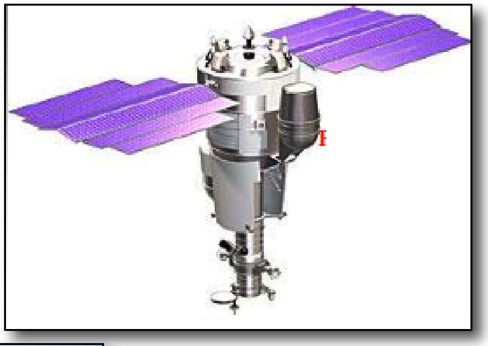
CDF may be observing the force that mediates the interactions between the dark and visible sectors of our universe!

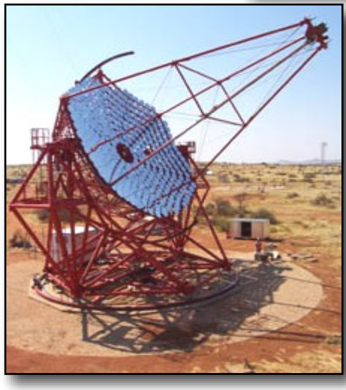
Summary

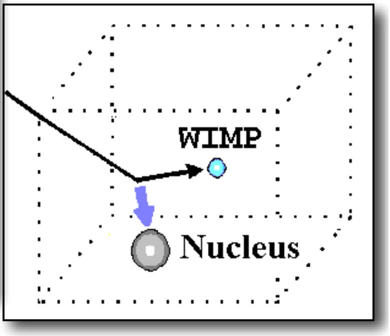
- Weakly interacting massive particles provide a natural class of candidates for dark matter, with a simple and compelling explanation for the observed dark matter abundance

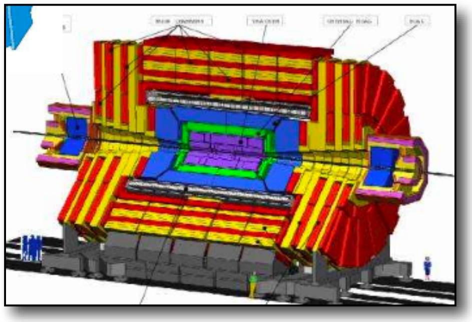
- Searches for dark matter at the LHC, as well as direct and indirect astrophysical searches, are each approaching the sensitivity anticipated to be required to observe dark matter non-gravitationally

- A number of reported signals can be interpreted as possible detections of dark matter (CoGeNT, DAMA, Fermi,…)





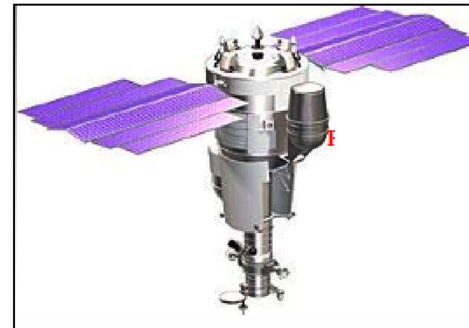


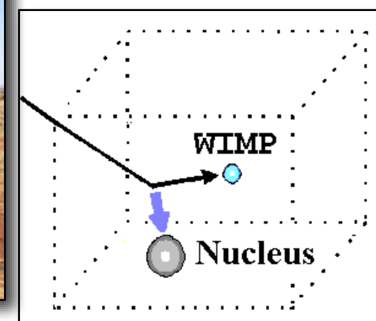


Summary

One Year From Now

- New direct detection results from CRESST, COUPP, CoGeNT, and others
- First data from AMS-02?
- More data from Fermi, and more analysis of Fermi data
- Further input from ground based gamma ray telescopes, and at other wavelengths
- First high luminosity results from the LHC





Five-Ten Years From Now

- Direct detection sensitivity at the level of ~10^{-47} cm^2
- Sensitive indirect searches by Fermi, AMS, IceCube, Planck, CTA, and others
- Broad exploration of the TeV scale by the LHC