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Can We Detect Dark Matter

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Why Do We Need Dark Matter

The story begins in the 1930's with a Cal-Tech astronomy professor. Fritz Zwicky while analyzing his observations of the coma cluster in 1933 was the first to apply the virial theorem to infer the existence of unseen matter in this cluster. This unseen mater is now called dark matter (Zwicky, F., 1933. See also Zwicky, F., 1937). Using the virial theorem he was able to infer the average mass of galaxies within the cluster, and obtained a value as large as 500 times greater than expected from their optical luminosity, and proposed that most of the matter was "dark (cold) matter" (Rubin, V., 2001). Much more work of this type has been done since Zwicky, including the discovery by x-ray space telescopes of large amounts of hot gas in clusters through their x-ray emissions (not seen by Zwicky), and the result is that the missing mass, i.e., dark matter in galaxy clusters, is about 2.5-5 times of the total directly observed luminosity mass (clearly baryonic mass). Thus when these observations are extrapolated to the total mass of Universe this gives a fraction of mass for a flat universe, $\Omega_m \sim 10 – 30$ % (Reiprich, T. H., and Böhringer, H., 2002). On the other hand, big bang nuclear synthesis (BBNS) sets limits on the baryonic matter fractions at, $\Omega_b \sim$ 4-5% (Spergel, D. N., Bean, R., Doré, O., et al., 2007; for an entertaining overview of why we need dark matter see Siegel, E., 2008)

Work has also been done on observing the rotation of individual spiral galaxies. The rotation

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curves of individual stars in spiral galaxies need a large extra dark mass to explain the radial dependence of their velocity around the center of the galaxy to very large distance from the centers of the galaxy (Rubin, V., 1983). These measurements infer a large spherical dark matter halo that encloses the visible galaxy with a radius up to about 10 times the visible disk radius. In typical spiral galaxies the dark matter mass to luminosity mass is about 10, again indicating a strong need for dark matter.

The power density of galaxies over the observable universe can be used to calculate how much total matter (Ω_m) and how much normal matter (Ω_b) there is normalized to the critical mass of the Universe. Using galaxy surveys like the Sloan Digital Sky Survey one finds that Ω_m is about 0.3 and Ω_b is about 0.05 (the rest of the energy density is thought to be in dark energy, Ω_Λ, i.e., $\Omega_{m} + \Omega_\Lambda = 1$). This measurement implies that dark matter constitutes about 25% of the energy budget of the Universe. (Tegmark, M., Blanton, M. R., Strauss, M.A., et al., 2004)

The concordance model of Big Bang Cosmology, or Λ-Cold Dark Matter (ΛCDM), uses measurements of the Cosmic Microwave Background (CMB) (Spergel, D. N., Bean, R., Doré, O., et al., 2007), as well as power density of galaxies observations (Tegmark, M., Blanton, M. R., Strauss, M.A., et al., 2004), supernovae observations of the accelerating expansion of the universe (Perlmutter, S., and Schmidt, B. P., 2003) and x-ray and gravitational lens measurements of galaxy cluster mass yielding direct cluster mass measurements (Allen, S.W., Rapetti, D.A., Schmidt, R.W., et al., 2008; Allen, S.W., 1998). It is the simplest known and generally accepted model that is in excellent agreement with observed phenomena. Fits to ΛCDM of all of this data indicates Ω_m ~27% and Ω_b ~5%.

However, there are a couple of loopholes that need to be closed to fully believe that there exists a non-baryonic dark matter that dominates the mass in the Universe. There is strong evidence these loopholes have been closed, but work is still ongoing:

1. Maybe BBNS is wrong? Can we check for indications of hard to see colder baryonic matter that might fill in the matter deficit? Direct searches for cold baryonic matter, including black holes, via strong lensing have been extensive, e.g., Massive Compact Halo Object (MACHO) searches, and have come to the conclusion that the limits on numbers and mass of “cool bodies” of normal matter fall far short of accounting for the dark matter (MACHO Collaboration, 2000).
2. There are theories of alternative gravity that offer a counter explanation to dark matter. These theories are phenomenological like MOND (Sanders, R.H., 2003) or offer more complex theories of General Relativity (Bekenstein, J.D., 2004). Strong and weak gravitational measurements combined with x-ray measurements of colliding clusters of galaxies make these alternate theories unlikely substitutes for the dark matter paradigm. The first to make it very difficult for a MOND explanation was the “Bullet cluster”, showing a “recent” collision of two clusters, where one observes matter exerting gravity where no normal matter is seen to exist (Clowe, D., Bradač, M., Gonzalez, A.H., et al., 2006). This type of research using colliding clusters is ongoing with a number of additional examples seen since (Mahdavi, A., Hoekstra, H., Babul, A., et al., 2007; Jee, M. J., Ford, H. C., Illingworth, G. D., et al., 2007) which makes it even more impossible for any currently proposed theory of alternative gravity to explain all of the observations without using some form of dark matter.

3. There are future prospects for using gravitational lensing to better constrain dark matter versus alternative gravitational theories. One method directly searches for substructure in dark matter haloes, a strong prediction of the ΛCDM paradigm (see the next section), and not currently predicted by alternative gravities (Metcalf, R. B., Moustakas, L.A., 2003). Another is to constrain the ellipticity of Galaxy-scale Dark Matter Haloes with Weak Lensing (Schrabback, T., 2008). Dark matter haloes can show non-spherically symmetric lensing effects (ellipticity). This is not possible with current alternative gravity theories with no dark matter.

What is the Dark Matter

Currently we have very little idea of what actually constitutes the dark matter from which we clearly see the gravitational effects. Figure 1 shows the broad range of possible particle constituents arising from particle physics theories. There is a huge range of well motivated candidates.

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One of the best motivated candidates is the axion, which is needed to prevent CP violation in the strong interaction and is very light. Then there is the neutralino that arises in super symmetry and is a perennial favorite of a large number of particle theorists. It is relatively heavy, more interactive, and easily and naturally gives the Ω_w ~1 for the dark matter energy density of the Universe. This is particularly true in the case of the “WIMP” miracle for the so called “generic WIMP” that has,

$$M_W \sim 100 \text{ GeV, and } <\sigma_{annihilation} \times v> \sim \text{few } \times 10^{-26} \text{ cm}^3/\text{s}. \qquad \text{(Eq. 1)}$$

Actually, there is no end of “natural” particle candidates for non-baryonic dark matter from particle physics (e.g., little Higgs, sterile neutrinos, excited WIMPs …). For a recent review on constraints on dark matter particle candidates see (Boyanovsky, D., de Vega, H. J., Sanchez, N., 2008).

Besides the very large uncertainty about the micro nature of dark matter there is uncertainty about what is its macro distribution in the Universe. The latter problem has been address by a number of ΛCDM computer simulations. For example, the Via Lactea II dark matter simulation (Kuhlen M., Diemand J., Madau P., 2008; Diemand J., Kuhlen M., Madau P., et al., 2008) has over one billion particles with a mass of only 4.1 thousand solar masses each and uses an improved, physical time-stepping method (Zemp, M., Stadel, J., Moore, B., et al., 2007). Via Lactea II took about one million CPU hours to finish and was run in November 2007 at the Oakridge National Laboratory on the Jaguar supercomputer. These simulations start just after recombination of the Universe with the primordial power spectrum imprinted as an initial condition on the dark matter distribution at that time. Initial conditions were generated with a modified, parallel version of GRAFIC2 (Bertschinger, E., 2001). The program steps through time using only gravitational interactions among the billion dark matter elements to simulate ultimately how the dark matter halo of a Milky Way like galaxy would appear today (if one could actually see and resolve the dark matter structure). Figure 2 shows a picture of the result of these calculations. The dark matter structure formation is hierarchal with small dark matter halos merging to larger ones as the simulation proceeds.

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Thus in figure 2 one sees the Milky Way halo composed of thousands of smaller halos varying in size from very small to very large. "The simulation reveals the fractal nature of dark matter clustering: Isolated halos and sub-halos contain the same relative amount of substructure and both have cuspy inner density profiles" (Diemand J., Kuhlen M., Madau P., et al. 2008).

How Can the Dark Matter Problem Be Solved

Solving the dark matter problem will require continuing the broad interdisciplinary approach that has been ongoing for the past decade. This strategy has encouraged trying to detect dark matter particles as particles in the galaxy via direct and/or indirect detection, continuing to probe the dark matter distribution in the universe using optical telescopes via surveys, stellar velocity dispersion measurements establishing new dark matter structures in the Milky Way, gravitational strong and weak lensing, and working to detect dark matter particles in controlled environments at the Large Hadron Collider (LHC). To accomplish this daunting task, clearly one needs to combine data from astronomy, astrophysics, and high energy physics.

The next decade promises dramatic improvements in implementing this strategy and so greatly improving our understanding as many new facilities have recently come on line, or will soon be on line. These new facilities include the LHC scheduled to begin physics data taking in late 2009: a new generation of indirect detection experiments such as the Fermi Gamma Ray Telescope (Fermi, formally GLAST) that was launched on June 11, 2008 (Fermi-LAT, 2009), PAMELA launched June 15, 2006 (PAMELA, 2009); a relatively new generation of direct detection experiments such as CDMS II (CDMS, 2009), DAMA/LIBRA (DAMA/LIBRA, 2009); XENON (XENON, 2009); and dramatic improvements in optical survey experiments that are beginning operation very soon such as Pan-STARRS (Pan-STARRS, 2009) and DES (DES, 2009) with LSST (LSST, 2009) on the horizon for first light in 2016.

Brief Review of Direct Detection Experiments

Direct detections experiments are a tour-de-force of low noise experiments. The signal is WIMPs scattering elastically (“bumping”) with a nucleus that then recoils with a velocity of ~ 10^{-3} c. The nucleus then excites the nearby atoms by transferring its kinetic energy of ~ 10’s of keV with some efficiency to make observable energy (phonons, light, ionized charge), which is measured in a manner depending on the detector medium (Silicon/Germanium, NaI, Xenon). Unfortunately for direct detection experiments, one estimates that for M_W ~ 100 GeV there is about 1 WIMP per 300 cm^3 at the Earth (~ 0.3 GeV/cm^3), and the WIMP – Nucleus elastic scattering cross section is weak interaction scale, i.e., very tiny. Thus these experiments are a sophisticated and large effort in designing and building for measuring very low signal to noise, and in a very low noise environment. WIMPS are neutral, and so the main backgrounds are (low energy) gamma-rays and neutrons. Also for some detector types, surface electrons from β-decay can mimic nuclear recoils. Gamma rays knock out atomic electrons that have recoil velocity ~ 0.3c. Neutrons recoils only have a mean free path of a few cms. For a recent review of direct detection of dark matter see (Gaitskell, R. J., 2004).

Figure 3 shows a recent status of direct detection searches (Cabrera, B., 2008; Trotta, R., Ruiz de Austri, R., Roszkowski, L., 2007). The most sensitive of the experiments, CDMS II and XENON

10 are beginning to challenge the Minimum Super Symmetric Model (MSSM) phase space (Trotta, R., Ruiz de Austri, R., Roszkowski, L., 2007). However, there are orders of magnitude left in the MSSM phase space, which extends to 3-4 orders of magnitude smaller cross sections, to explore with future experiments. (There are also different models than MSSM to explore.) Another feature to note in this graph is the apparent disagreement between DAMA with ZEPLIN II, XENON 10, and CDMS II. Though MSSM fails to do so, some theories are able to accommodate all of the experimental results, see for example, "Explaining the DAMA signal with WIMPless dark matter" (Feng, J. L., Kumar, J., Strigari, L. E., 2008) also see (Finkbeiner, D. P., and Wiener, N., 2007).

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DAMA/LIBRA (Bernabei, R., Belli, P., Cappella, F., et al., 2008) is an experiment that has been taking data in two configurations for over a decade (DAMA for 7 years, DAMA/LIBRA for 4 years). This experiment is designed to make use of the annual modulation in a direct dark matter signal due to the motion of the Earth through the dark matter field as we go around the Sun (Drukier, A.K., Freese, K., and Spergel, D.N., 1986; Freese, K., Friedman, J., and Gould, J., 1988). With present detector technology the annual modulation is the main model independent signature for the DM signal. Although the modulation effect is expected to be relatively small, a suitably large-mass detector embedded in a low-radioactive environment, with careful control of the running conditions, and over a long enough time, could detect this modulation if dark matter particles exist with a sufficiently large interaction cross section. Optimizing to observe the modulation effect can dramatically improve the sensitivity of a direct detection experiment, and this has been in the design strategy of DAMA/LIBRA from its inception. If the modulation is observed it must modulate according to a cosine through the year. The modulation is observed in a definite (low) energy range in the detector for single hit events in a multi-element detector. The phase maximum should be at about June 2 of each year when the Earth's velocity to the dark matter field is maximum for the year by adding to the Sun's velocity through the galaxy (t_0 = 152.5 days as fit to the data), and with signal modulation amplitude in the region of maximal sensitivity of <7% for usually adopted dark matter halo distributions (but it can be larger in the case of some possible scenarios). DAMA/LIBRA has claimed such a signal that has continued in two experimental setups maintaining the same phase for the past 11 years. This result does not appear to be a statistical fluctuation as it is currently at the ~ 8 σ level statistically. As their many public presentations and their recent publication shows (Bernabei, R., Belli, P., Cappella, F., et al. 2008) they have carefully examined many systematic effects and have found no obvious problems with their measurement. No other independent experiment has reproduced the DAMA/LIBRA result. It is currently left to future experiments to resolve this puzzle.

Brief Review of Indirect Detection Experiments

Figure 4 shows the diversity of experiments that can contribute to the indirect detection of dark matter. The particle physics view is that dark matter is a particle, which is stable or at most very slowly decays during the past 14 billion years. The most popular particle physics models posit annihilation of WIMPs that have been thermally produced in the early Universe, are essentially stable to decay. These annihilations produce final state photons, protons, electrons/positrons, and neutrinos that can be observed as illustrated in the figure. However, there are models in which of WIMPs of a different kind can decay, with long decay constants, and yield the same final state particles, but with different relative probabilities.

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To again illustrate the diversity of theoretical opinions and the resulting challenges to experimentalists, there are theories of dark matter that claim that axions are its main component. Axions that could make up a significant fraction of the dark matter are a product of non-thermal production during the QCD phase transition in the early Universe. At this transition free quarks where bound into hadrons and a very cold Bose condensate of axions formed; therefore, very light axions can also be cold dark matter and are indistinguishable to cosmologists studying galaxy formation and the origin of large scale structure (Kolb, E. W., Turner, M. S., 1990). Axions can be indirectly observed as well in astrophysics experiments (for example, see Simet M., Hooper D. and Serpico P., 2008) as well as in ground based experiments (Asztalos, S.J., Rosenberg, L.J, van Bibber, K., Sikivie, P., and Zioutas. K., 2006). For an informative and easily accessible review of axions see (Wikipedia, 2009).

I will focus on indirect searches for WIMP annihilation here, which is the idea that has generated a very broad range of searches in astrophysical settings (not to mention direct searches and searches at the LHC for WIMPs). Estimating the sensitivity of an experiment to WIMP annihilation somewhere in the Universe (typically in the Milky Way) involves four elements, besides calculating one’s detector intrinsic sensitivity to the particles being measured. The first is the calculation of the integral of the energy spectrum of the particle over the energy range of interest,

$$\int (\sum_i ({}^{dN}\!/_{dE})_i B_i) dE \; . \qquad \text{(Eq. 2)}$$

In equation 2 the index *i* denotes the particle species appearing in the decay that is being observed and B_i is the branching ratio into that species. In the case of WIMP annihilation (or decay), this quantity can be estimated using computer programs like Dark SUSY (Gondolo, P., Edsjö, J., Ullio, P., 2004) combined with PYTHIA (Sjöstrand, T., Mrenna, S., Skands, P., 2009). As the first step, Dark SUSY provides (among other quantities) the branching ratios and momentum distributions from the annihilation into the "fundamental" constituents of the standard model of particle physics, i.e., the various quarks, tau leptons (lighter leptons are neglected at this stage), and intermediate bosons (gluons, W and Z) that can contribute. These branching ratios depend on the nature of the theory and its particular parameters. PYTHIA is then used by Dark SUSY to follow these "fundamental" constituents to their final observable particles by calculating hadronization of the quarks, gluons, …, and decays of the resulting unstable mesons, baryons, and leptons to the finally observed protons/antiprotons, electrons/positrons, photons and neutrinos. As an example, in the case of final state photons, a topic I will review in some detail below for my favorite detector the Fermi – LAT, table 1 shows the high energy photon yield per final state $b\bar{b}$ pair. This example is for the annihilation of two 10, 100, and 1000 GeV WIMPS. Note that in this calculation, it does not matter much which intermediate state fundamental particles contribute; they all give very similar dN/dE distributions for the resulting photons from 100 MeV to the endpoint energy defined by the WIMP mass (for $M_{WIMP} > \sim 100$ GeV). The one exception is decays dominated by tau lepton pairs in which case the spectrum is noticeably harder (Ceasarini, A., Fuctio, F., Lionetto, A., et al., 2004). The potential detection of WIMP annihilation is enhanced as the final photon spectra calculated for this process tend to be harder than most astrophysical spectra and are not power laws. Also note that mono-energetic photon lines can be produced at the mass of the WIMP in annihilations, and for $M_{WIMP} > M_Z/2$ can also have a mono-energetic photon from the γZ final state. This mono-energetic line is considered a "smoking gun" for the discovery of dark matter. The branching fractions to these lines in annihilations and decays theoretically ranges over 0.1 to 10^{-4}, with the most popular SUSY theories giving numbers in the smaller range. This is because in these theories higher loop diagrams are needed (Bergstrom, L., Ullio, P., 1997).

The second element in the calculation is $<\sigma v>$ the annihilation cross section times the relative velocity of the WIMPs. For the "generic" WIMP case $<\sigma v> \sim 3x10^{-26}\ cm^3/s$; however, this cross section varies over orders of magnitude in various parts of the possible theoretical phase space. Recent theoretical speculation has suggested a considerably larger cross section (Arkani-Hamed, N., Finkbeiner, D.P., Slatyer, T. R., et al., 2009) while standard MSSM admits much smaller cross sections (Gondolo, P., Edsjö, J., Ullio, P., 2004).

The third element of the calculation is contribution of the dark matter density distribution. This number density of the dark matter particles is given by,

$$\frac{4\pi}{M_{WIMP}^2}\int \rho^2(r) r^2 dr\,, \tag{3}$$

and depends on the dark matter clustering. $\rho(r)$ is the dark matter density distribution. A popular analytic $\rho(r)$ that was derived from computer simulations is the NFW distribution (Navarro, J., Frenk, C., and White, S., 1996). This form is cuspy near $r = 0$, where $\rho(r) \sim 1/r$; it is also supported by the modern computer simulations that I previously discussed (Diemand J., Kuhlen M., Madau P., et al., 2008). The last element of the puzzle is the distance to the object one is viewing as this gives the inverse square law flux factor, $1/4\pi d^2$. In combining all of these factors there is clearly a great deal of uncertainty in the estimated flux of gamma rays at one's detector. Part of the progress in this field over the next decade will be to better understand and bracket each of the uncertain contributing elements.

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Figure 5 shows the galaxy shining in high energy gamma rays from the annihilation of dark matter assuming a semi-analytic computer simulation of ΛCDM (Taylor, J.E., and Babul, A., 2005), and a generic WIMP dark matter particle. The map is shown as a Hammer-Aitoff projection in galactic coordinates. No normal matter is shown in this picture, and if shown would dominate the gamma ray intensity of the map. The picture is a colorized version of that produced by Baltz (Baltz, E., 2005). In this figure the more intense the radiation the more it is white, while dark is the absence of radiation. The intensity is proportional to the square of the dark matter density. The center of the galaxy is the brightest, and a number of galactic dark matter satellites are prominent. Of course, as I have previously stressed, normal astrophysical sources of radiation at all wavelengths from radio to the highest energy gamma rays dominate what we observe with current instruments. Dark matter radiations, if they exist, are but small fractions of the total and will take considerable time to untangle from the bulk. Setting progressively better limits is the expected outcome for some time. However, the tools we now have in hand and that are close on the horizon are dramatic improvements of past tools. In the next section I will discuss the results from two of these tools, Fermi-LAT and PAMELA in more detail.

GLAST ➔ Fermi, Launch, First Results and Some Dark Matter Prospects

GLAST was launched by NASA on June 11, 2008 from Cape Canaveral Florida. The satellite went to low earth orbit flawlessly and currently is in a circular orbit, 565 km altitude (96 min period), and 25.6 deg inclination. The satellite scans the entire sky every 192 minutes (2 orbits). The standard data collection mode is the all-sky scanning mode where the Fermi-Large Area Telescope (Fermi-LAT) is pointed 35^o towards the north Earth pole relative to Earth zenith at the satellite position on one orbit, and then -35^o towards the south Earth pole on the next. GLAST was renamed Fermi by NASA on August 26, 2008 after on orbit commissioning was complete and nominal science operations had begun. The LAT was constructed and is being operated by the Fermi - LAT Collaboration. The LAT is described in an upcoming publication (Atwood, W.B., Abdo, A.A., Ackermann, M., et al., 2009**)**. The collaboration membership and information about Fermi –LAT science can be found on our website (Fermi - LAT, 2009). The telescope has been optimized to measure gamma rays from 20 MeV to 300 GeV, has unprecedented angular resolution in this energy range compared to previous gamma ray missions, and views 20% of the entire sky at any instant. Fermi-LAT achieves about 30 times the sensitivity of EGRET in the EGRET energy range, 100 MeV – 10 GeV, and extends measurements well beyond the EGRET energy range. The Fermi mission requirement (NASA) is 5 years, with a 10 year goal. 10 years seems quite feasible as the instrument uses no consumables. LAT’s potential for making systematics-limited measurements of CR electrons was recognized during the initial phases of the LAT design (Moiseev, A., Ormes, J. F., and Moskalenko, I. V., 2007), and we have indeed found that Fermi-LAT is an excellent cosmic ray (electron + positron) detector for energies in the range 20 GeV – 1 TeV.

Considering the Fermi-LAT as a telescope, well it really is not one in the standard sense. However, it is an astounding machine – a massive particle physics detector in orbit. It is 1.8 x 1.8 m^2, 3 metric tons, and moving at 17,000 miles/hr. The detector's position is known to a few meters in orbit, its attitude to ~ 10 arc sec., and time to < 10 μs. Yet, as the LAT instrument architect, Bill Atwood, says, "it uses less power than a toaster and we talk to it over a telephone line." Note that the average down linked data rate is considerably higher at an average event rate to the ground of about 500 Hz ~ mega bit/sec. The cosmic – ray background is intense and requires multilevel onboard filtering of events to achieve the data rate to the ground; the average trigger rate before on-board filtering is ~ 2.5 kHz.

Figure 6 shows a Fermi LAT 3-month all-sky map collected in nominal all-sky scanning mode from August 4 – November 4, 2008. The data shown has gamma ray energy > 200 MeV. Some bright sources are indicated on the figure, and many other sources are evident. The galactic disk dominates the picture with many sources seen in the central bulge region. (Fermi-LAT Collaboration, 2008). This is the all - sky image that will get clearer with time, from which one will need to dig out any dark matter signal that might be there.

INSERT FIGURE 6 – this is a color figure

Tables 2 and 3 show active Fermi - LAT Collaboration efforts for dark matter searches using the LAT, and also shows multiwavelength connections other telescopes, as indicated in the tables. The Fermi-LAT prelaunch sensitivity estimates for most of the searches listed in the tables have been published (Baltz, E.A., Berenji, B., Bertone, G., et al., 2008). The various telescopes listed in the last column of the tables contribute complementary multi – wavelength information for the dark matter searches. In table 2 the Milk Way satellite search and the WIMP line search stand out as potential “smoking guns” for dark matter if a signal is discovered. In the case of dark matter satellites, optical telescope surveys can find dark matter satellites by the peculiar motions of their stars also giving mass/light ratios and accurate locations (e.g. see, Simon, J. D. and Geha, M., 2007). With bigger telescopes, e.g., Keck, one learns more details about the putative dark matter distribution of the satellite from much better spectrographic observations of the associated stars. Fermi can examine the locations of these known satellites and set limit on dark matter models improved by the more detailed knowledge of the dark matter distribution. Also, Fermi can search the sky for unknown dark matter satellites (Baltz, E.A., Berenji, B., Bertone, G., et al. 2008). If found, optical follow-up would be important in understanding the structure of these Fermi found dwarf galaxies.

Most of the Fermi dark matter searches using photons will take deep exposures over 5 years or more and considerable work in other wavelengths to produce significant limits on current theories of dark matter. If the LHC were to discover a particle candidate in this time frame with a well specified mass, this could dramatically improve Fermi’s, as well as other telescopes, chances for establishing this potential candidate as the dark matter particle of the Universe . On the other hand, the LHC alone cannot do this. LHC experiments cannot measure the lifetime of a putative dark matter candidate particle, and can only set lifetime limits that are on the order of μ seconds, less than the age of the Universe by many orders of magnitude.

Cosmic Ray Results from ATIC, Fermi, and PAMELA

The indirect search for dark matter has been the subject of recent excitement with the release of new results from the PAMELA experiment on the antiproton/(proton + antiproton) ratio (Adriani, O., Barbarino , G. C., Bazilevskaya, G. A., et al., 2009, PRL) and positron/(electron + positron) ratio from 1 to 100 GeV (Adriani, O., Barbarino , G. C., Bazilevskaya, G. A., et al., 2009, Nature). The antiproton ratio measurements fit the expectations of cosmic ray models assuming pure secondary production of antiprotons during the propagation of cosmic rays in the galaxy (Ptuskin, V. S., Moskalenko, I. V., Jones, F. C., et al., 2006). However, the positron ratio does not fit the currently favored cosmic ray model. (Moskalenko, I. V. & Strong, A. W., 1998). The PAMELA positron ratio increases from 0.055 at 10.2 GeV to 0.14 at 82.6 GeV, or an increase of a factor of ~2.5, while in this energy range the Moskalenko and Strong model shows a rapid decrease in the ratio. In their Nature paper, the PAMELA collaboration concludes that to explain this data “a primary source, be it an astrophysical object or dark matter annihilation, is necessary.” The experiment is continuously taking data and the increased statistics will allow the measurement of the positron fraction to be extended up to about 300 GeV in the future.

Since the NV400 conference took place in October 2008, and before this writing (May 8, 2009) two new developments have heated up interest in the indirect search for dark matter ignited by the PAMELA results considerably. Though the PAMELA results were published after the conference, first reports were made in the summer conferences of 2008 and so were known at the time of NV400. First, the ATIC balloon experiment reported observing a peak in the (electron + positron) cosmic ray spectrum at an energy of about 600 GeV (Chang, J., Adams, J. H., Ahn, H. S., 2008). In their Nature paper the ATIC collaboration “report an excess of galactic cosmic-ray electrons at energies of, 300–800 GeV, which indicates a nearby source of energetic electrons [plus positrons]. Such a source could be an unseen astrophysical object (such as a pulsar or micro-quasar) that accelerates electrons to those energies, or the electrons could arise from the annihilation of dark matter particles (such as a Kaluza–Klein particle with a mass of about 620 GeV)".

INSERT FIGURE 7 – this is a color figure

The second development comes from the Fermi LAT. The Fermi-LAT Collaboration has measured the (electron + positron) spectrum from 20 GeV to 1 TeV with very high statistical precision (Abdo, A. A., Ackermann, M., Ajello, M., et al., 2009). Figure 7 shows the results of the cosmic ray ($e^- + e^+$) measurement from the Fermi-LAT collaboration from 20 GeV to 1 TeV. This spectrum contains more than 4 million ($e^- + e^+$) events, and so the statistical errors are very small compared to the systematic errors indicated in the figure. The details of the analysis and how the systematic errors were estimated is discussed in some detail in the Fermi – LAT publication. The main conclusion to be drawn from this data is two fold: First, the Fermi-LAT does not confirm the ATIC peak at about 600 MeV. If this peak were present at the strength reported by ATIC, the Fermi-LAT analysis would have reproduced it, but with ~ 7000 ($e^- + e^+$) in a peak above the spectrum shown in Figure 7. Second, the Fermi-LAT spectrum is much harder than expected in conventional galactic diffusive models (Strong, A. W., Moskalenko, I. V., and Reimer, O.,2004). A simple power law fit to the data in the Fermi-LAT energy band gives a spectral index of -3.04 with small errors, and a $\chi^2 = 9.7$ for 24 degrees of freedom; this is a very good fit. The reason the fit is seemingly too good, χ^2/d.o.f = 0.4, is that the Fermi team has taken the systematic errors, represented by the grey band in the figure, and added them in quadrature with the statistical errors. The team considers this to be the conservative thing to do at this time. A future long paper using more data will explore this issue again.

Combined with the PAMELA positron fraction discussed above, the Femi result still posses a serious problem to the conventional galactic diffusive models, and strongly reinforces the need for relatively local galactic sources of electrons and positrons. Two such sources of electrons and positrons have so far been considered – pulsars, and dark matter annihilation or decays. An example of comparisons of these two very different models with the Fermi and PAMELA data can be found in a recent LAT-Collaboration publication (Grasso, D., Profumo, S., Strong, A.W., et al., 2009). Good fits are obtained in both models, but much more needs to be learned from the experiments before a choice of mechanism is finally made.

Summary and Conclusions

A number of new experiments have recently come online, or are coming on line over the next few years that will greatly enhance the discovery space for direct and indirect detection of dark matter. These experiments include new gravitational strong and weak lensing techniques that will soon be making an impact on understanding DM structure in galaxies and in particular Milky Way dwarf galaxies. The LHC will also start beam collisions for doing science in late 2009, and the potential discovery of new high mass particles would give strong impetus to targeted astrophysical dark matter searches. Thus, the next five to 10 years should be a “golden age” for expanding our knowledge of the nature of dark matter. We hope we will actually discover what the stuff of this mysterious dark matter is! Maybe DAMA, Fermi, and Pamela are close?? Tune in next week as the adventure unfolds.

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Tables

M_{WIMP}	**Total# γ**	**>100MeV**	**>1GeV**	**>10GeV**
10 GeV	17.3	**12.6**	1.0	0
100GeV	24.5	22.5	**12.4**	1.0
1TeV	31.0	29.3	22.4	**12.3**

Table 1. The gamma ray yield per final state $b\bar{b}$ pair as a function of the mass of the WIMP. The table shows the total number of γ-rays produced in the decay, and with energy > 100 MeV, > 1 GeV, and > 10 GeV. The numbers in bold approximately show the constant multiplicity contour.

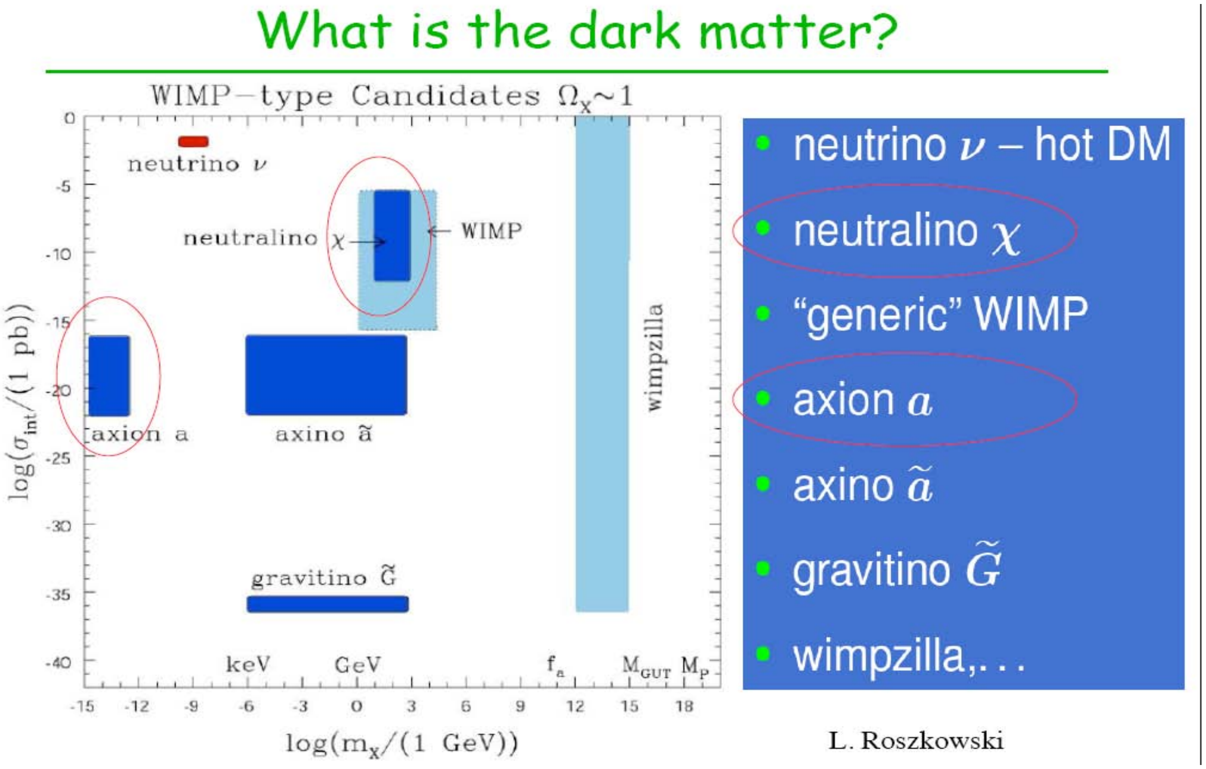
Focus of Search	**Advantages**	**Challenges**	**Experiments**
Galactic Center Region - WIMP	good statistics	source confusion, astrophysical background	ACTs, Fermi, WMAP (Haze), Integral, X-ray, radio
DM Galactic Satellites/Dwarfs/BH Mini Spikes-WIMP	low background	low statistics, follow –up multi-wavelength observations, astrophysical uncertainties	ACTs (guided by Fermi), Fermi, Optical telescopes
Milky Way Halo-WIMP	high statistics	galactic diffuse modeling	Fermi
Spectral Lines-WIMP	no astrophysical backgrounds	low statistics in many models	Fermi, ACTs (GC)
Extra Galactic Background-WIMP	high statistics	galactic diffuse modeling, instrumental backgrounds	Fermi

Table 2. Ongoing indirect dark matter searches using photons. The searches, a brief description of the pros and cons for each search, and the multi – wavelength contributions are indicated. Details of the potential sensitivity for these searches for Fermi-LAT have been published (Baltz, E.A., Berenji, B., Bertone, G., et al. 2008).

Focus of Search	Advantages	Challenges	Experiments
High latitude Neutron stars – KK graviton	low background	astrophysical uncertainties, instrument response ~ 100 MeV	Fermi
AGN Jet Spectra - Axions	many point sources, good statistics	understanding details of AGN Jet physics and spectra.	ACTs, Fermi, X-ray, radio (Multi-wavelength).
$e^+ + e^-$, or e^+/e^-	very high statistics	charge particle propagation in galaxy, astrophysical uncertainties	Fermi, PAMELA, AMS
Antiproton/Proton	“	“	PAMELA, AMS

Table 3. Ongoing searches for dark matter using different sorts of astrophysical photon sources, and cosmic rays. This table considers two searches for dark matter with photons that are a bit unusual compared to those in table 1. The searches, a brief description of the pros and cons for each search, and the multi – wavelength contributions are indicated. The first is a search for large extra dimensions using older neutron pulsars (Hannestad, S., and Raffelt, G. G., 2003), and the second uses AGN jet spectra to search for axions (Sánchez-Conde, M. A., Paneque, D., Bloom, E.D., et al., 2009). The last two searches use e^+ and e^-, antiproton and proton from cosmic rays.

Figures



What is the dark matter?

- neutrino ν – hot DM
- neutralino χ
- “generic” WIMP
- axion a
- axino $\tilde{a}$
- gravitino $\tilde{G}$
- wimpzilla,. . .

L. Roszkowski

Figure 1. What constitutes the dark matter? This figure shows a range of options for elementary particle constituents of dark matter based on particle physics ideas. It may be that more than one of these (or none) are what actually makes up dark matter. The abscissa shows the log of the normalized mass of the particle candidate and the ordinate shows the log of the normalized coupling. In the case of a “generic” WIMP, M_w ~100 GeV, $<\sigma_{annihilation} \times v>$ ~ few x10^{-26} cm^3/s, and Ω_X ~1, for its contribution to the dark matter energy density of the universe.

Figure 2. Projected dark matter density map of “Via Lactea II”. About an 800 kpc cube is shown. The Via Lactea II simulation has a mass resolution of 4,100 $M_\odot$ and a force resolution of 40 pc. It used over a million processor hours on the “Jaguar” Cray XT3 supercomputer at the Oak Ridge National Laboratory. A new method was employed to assign physical, adaptive time-steps equal to 1/16 of the local dynamical timescale (but not shorter than 268,000 yr), which allows to resolve very high density regions (Diemand J., Kuhlen M., Madau P., et al., 2008)

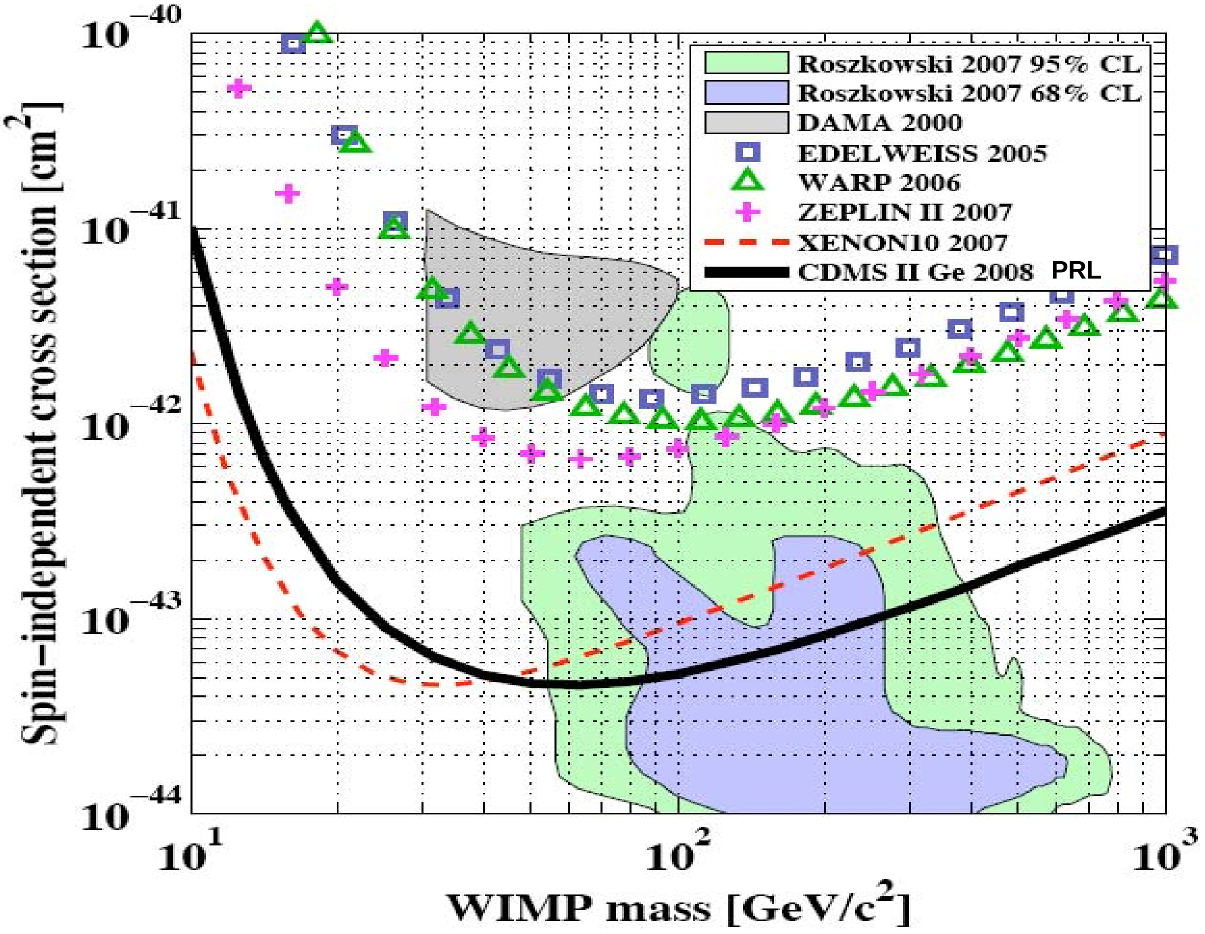


Figure 3. Status of direct detection searches from a number of competitive experiments. There is an apparent disagreement between DAMA, ZEPLIN II, XENON10, and CDMS II, which is currently being explored by the theorists as described in the text.

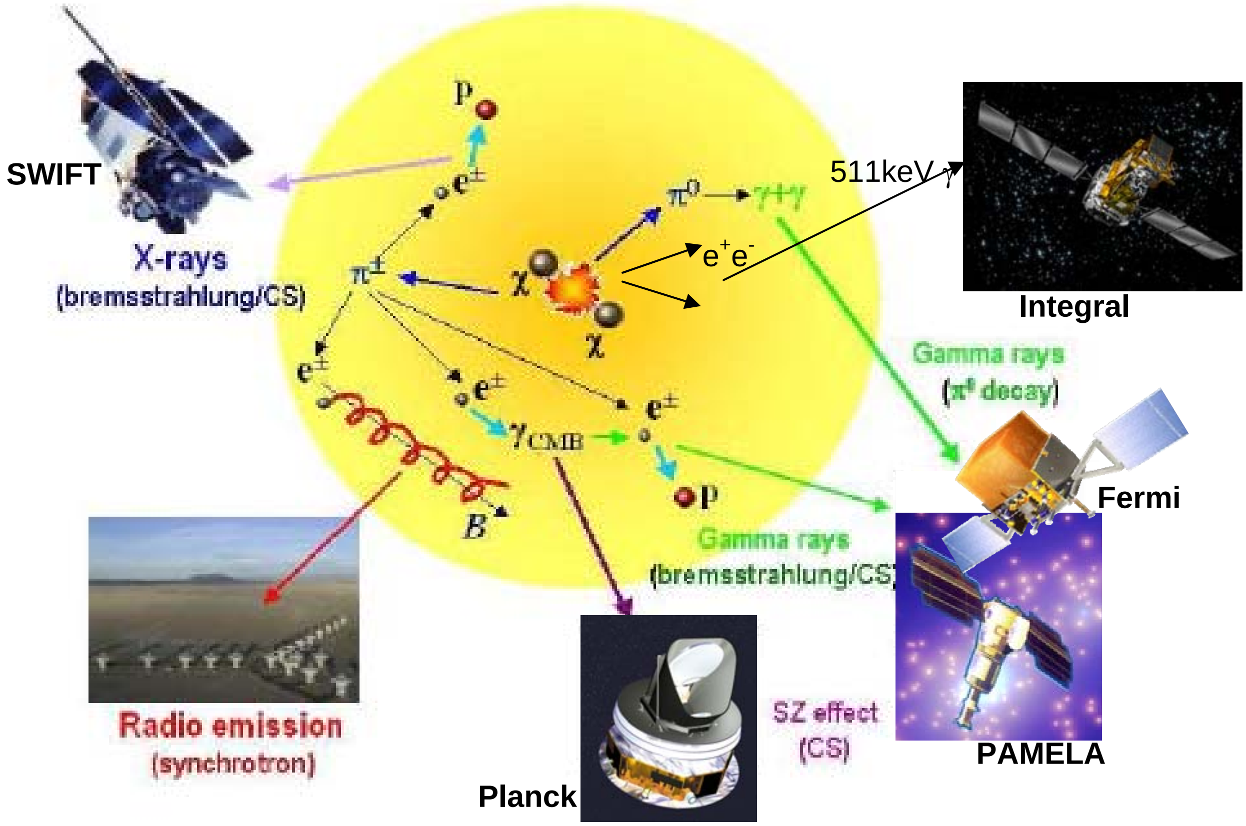


Figure 4. Representation of indirect detection. Dark matter annihilation in situ in the Universe via particle physics generic model feeds a large number of indirect detection methods. In these particle physics models, $<\sigma v>$ and the mass of dark matter particle are highly uncertain. The indirect detection methods shown span the electro-magnetic spectrum from radio to very high energy gamma rays (Air Cherenkov telescopes, such as CANGAROO III, Hess, and VERITAS also contribute observations of > ~ 100 GeV photons and ~ TeV (e- + e+), but are not shown explicitly in the figure). The presence of magnetic fields and or stellar radiation fields is needed to generate the lower energy signals. In addition, there are charged cosmic ray signals in protons and electrons at high energy. PAMELA is focused more on the charged particles, while Fermi has been focused more on gamma rays; however, each can observe both, and in fact, Fermi has excellent electron capability from the GeV range up to and greater than 1 TeV.

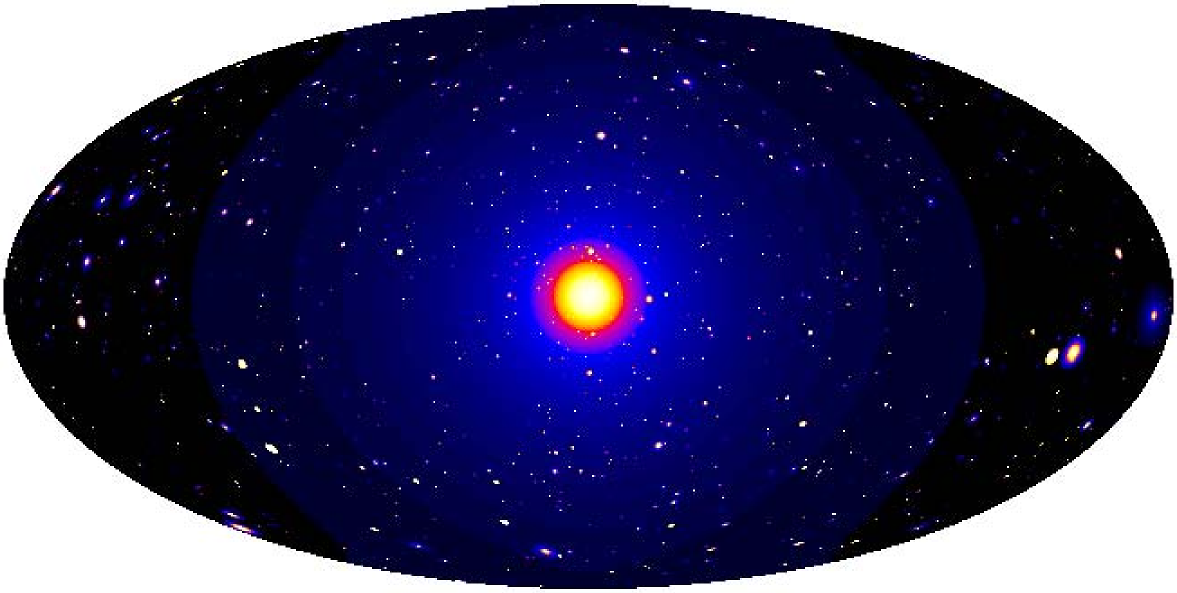


Figure 5. A far view of the galaxy shining from dark matter annihilations only. The galaxy shines in high energy gamma rays from the annihilation of dark matter assuming a semi-analytic computer simulation of ΛCDM (Taylor, J.E., and Babul, A., 2005), and a generic WIMP dark matter particle. The picture is for an "average" Milky Way Galaxy as determined by these computer simulations. The scale of the central part of the picture, i.e., the brightest part, yellow-red-light blue at the center, roughly corresponds to the visible Milky Way diameter in optical wavelengths. The rest of the picture is the dark matter halo dominated at larger distances by the dark matter clumps. The radius of the visible part of the Milky Way is about 20 kpc, the entire dark matter halo is ~ 100 kpc. The WIMP annihilation is proportional to density squared of the dark matter density and that is what is visualized in this figure. The map is shown as a Hammer-Aitoff projection in galactic coordinates. No normal matter is shown in this picture, and if shown would dominate the gamma ray intensity of the map for the Milky Way proper. The picture is a colorized version of that produced by Baltz (Baltz, E.,2005).

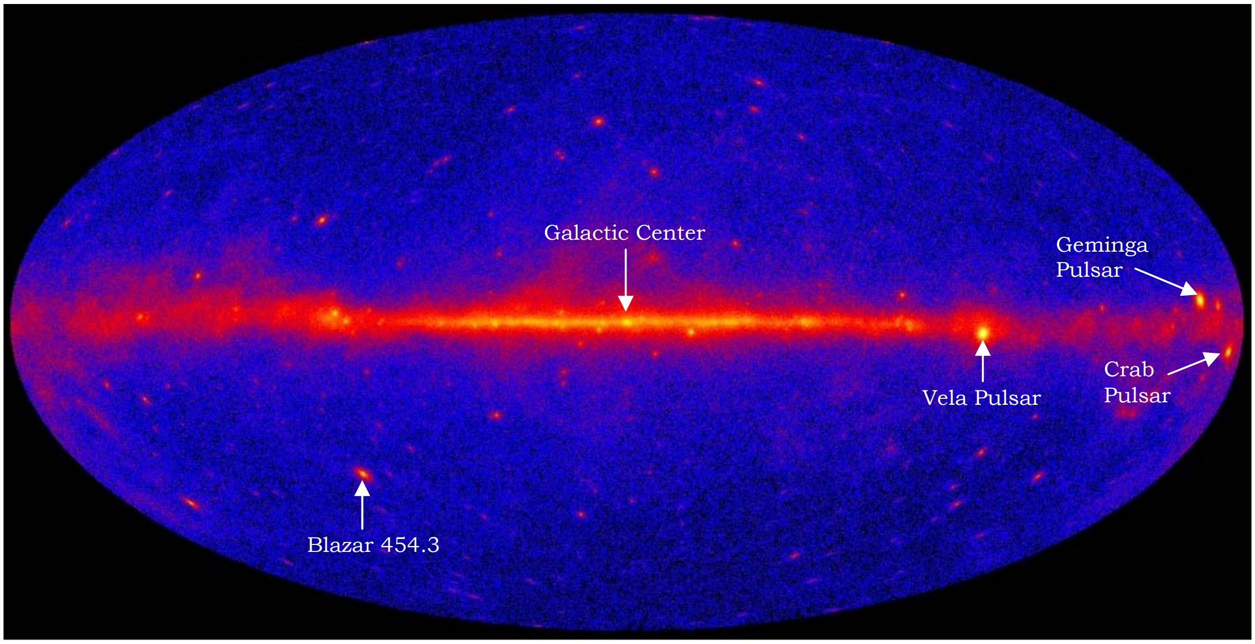


Figure 6. Fermi LAT 3-month all-sky map collected in nominal all-sky scanning mode from August 4 – November 4, 2008. Some bright sources are indicated on the figure. The data shown has gamma ray energy > 200 MeV. This is a count map (1131x617) with 0.3° pixels, with Log scaling over the entire range, and is shown as a Hammer-Aitoff projection in galactic coordinates. The map is corrected for exposure at 1 GeV (Fermi-LAT collaboration, 2008).

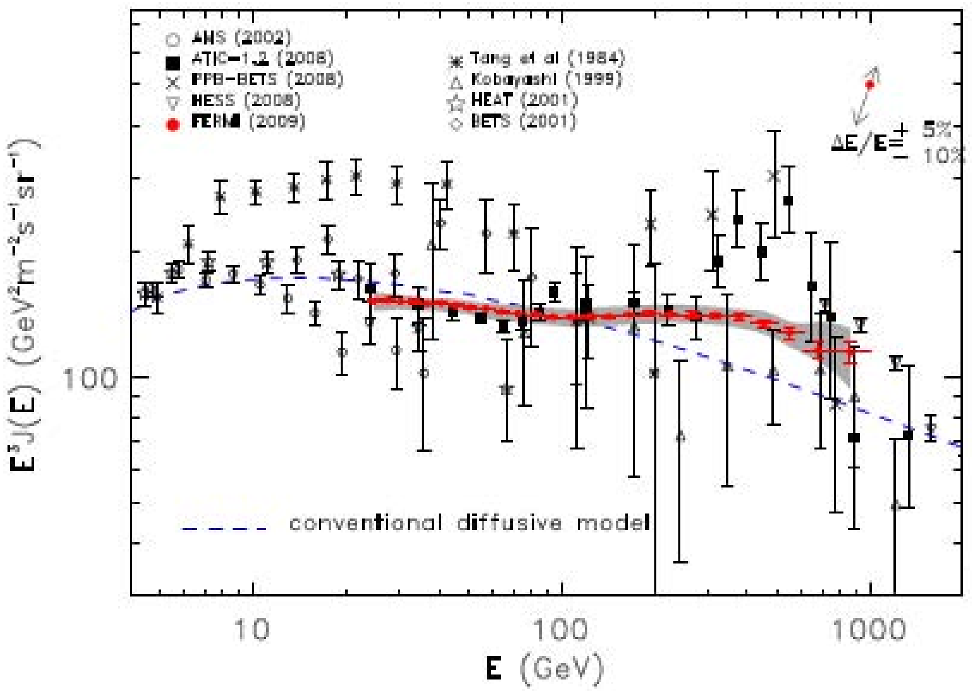


Figure 7. The Fermi LAT CR electron spectrum (red filled circles). Systematic errors are shown by the gray band. The two-headed arrow in the top-right corner of the figure gives size and direction of the rigid shift of the spectrum implied by a shift of +5% −10% of the absolute energy, corresponding to the present estimate of the uncertainty of the LAT energy scale. Other high-energy measurements and a conventional diffusive model (Strong, A. W., Moskalenko, I. V., and Reimer, O., 2004) are shown.

Document Control Sheet—List of Elements in Chapter

Tables *(add rows as needed)* [1]

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