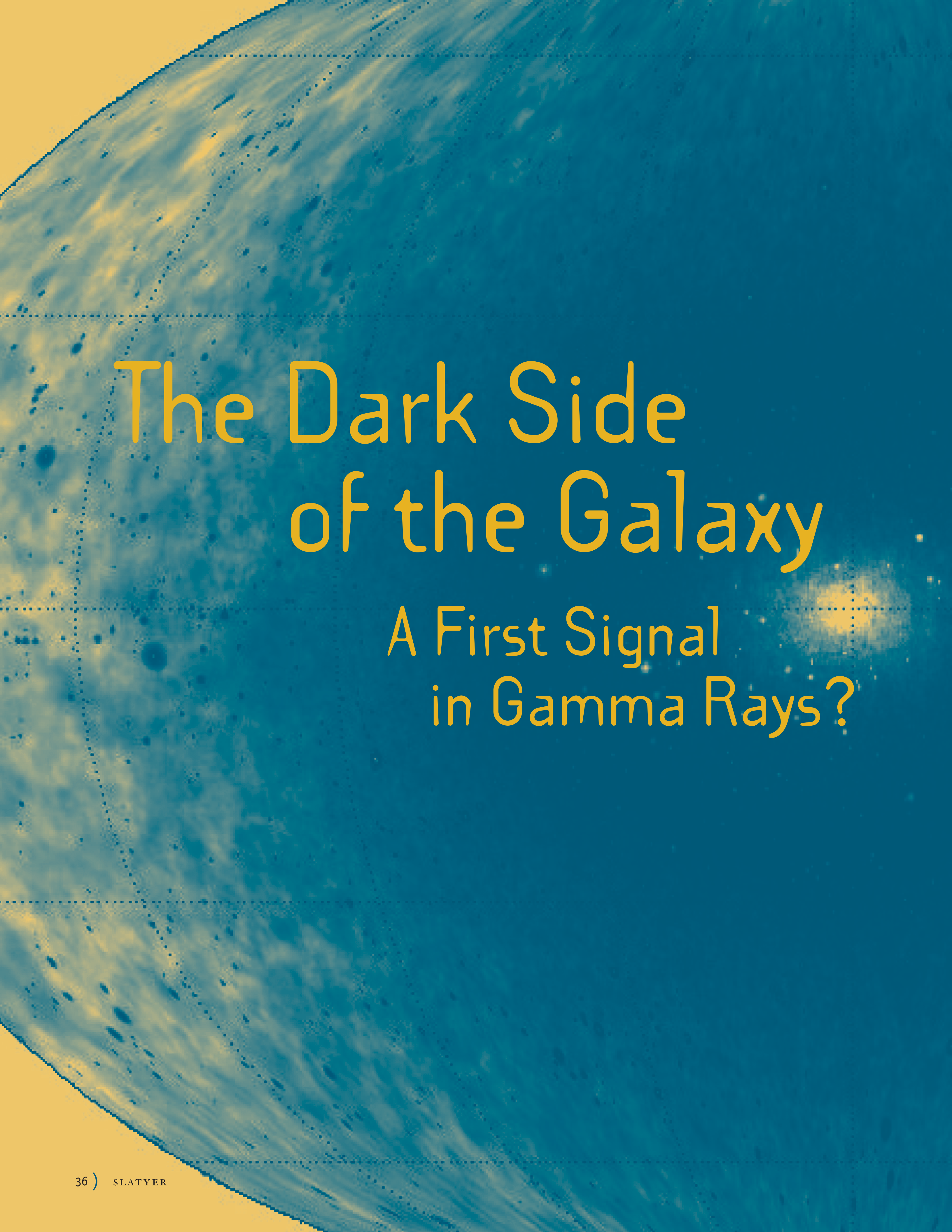


The Dark Side of the Galaxy

A First Signal in Gamma Rays?

by Tracy Slatyer

We inhabit a universe rich in mysteries. Measurements of the cosmic microwave background radiation—the afterglow of the Big Bang—have painted a picture of a surprisingly simple cosmos, but one that is characterized by large amounts of "dark matter" and "dark energy."

THESE PHENOMENA HAVE NO EASY EXPLANATION within known physics. Dark energy drives the accelerating expansion of the universe, while the gravitational pull of dark matter holds galaxies together. Dark matter particles are invisible to normal telescopes, but may collide with each other and radiate gamma-ray photons a billion times more energetic than visible light. The detection of this glow from regions where the dark matter is abundant would illuminate, for the first time, the connections between the hidden and visible constituents of the cosmos. Using data from the Fermi Gamma-Ray Space Telescope, we have identified such a gamma-ray glow in the heart of our Milky Way Galaxy, although its origins have not yet been confirmed.

FIGURE 1

A sketch of the structure of the Milky Way Galaxy. *The bright visible disk of stars and gas is embedded in a large, roughly spherical halo of dark matter. Densities of both visible and dark matter rise toward the Galactic Center, where there is also an extended bulge of gas and old stars.*

Light from dark matter

More than eighty percent of the matter in the universe is comprised of an unknown substance. Unlike most ordinary matter, it is *dark*, interacting, at most, very weakly with light and all other known particles. Neutrinos share this property, but unlike neutrinos, the bulk of the dark matter must have been slow-moving (relative to the speed of light) at the time when galaxies were beginning to form. Regions where the dark matter was dense collapsed into even denser structures due to gravitational attraction, forming a complex cosmic web of dark matter clumps—called "halos"—and filaments stretching between them. This web seeded the formation of galaxies: ordinary visible gas was drawn to the filaments and clumps by gravity, where it formed the galaxies and galaxy clusters we see today [1].

Early hints of the existence of dark matter came through studies of the motions of galaxies, stars, and gas clouds, revealing the presence of far more mass in galaxy clusters and galaxies than could be accounted for by the visible matter. More recently, observations of colliding galaxy clusters have shown that the dark matter behaves quite differently to the ordinary matter: when galaxy clusters collide, their gas clouds ram into each other and heat up under the resulting pressure, but their dark matter halos pass directly through each other. Likewise, the halos of dark matter around galaxies do not appear to collapse down into compact disks in the same way as the stars and gas. They remain as large, diffuse halos, shaped more like footballs, rather than the spiraling disk of the Milky Way (*Figure 1*). These differences imply that dark matter interacts only very feebly with *other* dark matter particles, as well as with light and visible matter.

Dark matter annihilation

The non-gravitational interactions of dark matter, however tiny, could play a very important role in its genesis. If the dark matter *does* interact with the visible matter by any means other than gravity, then collisions between dark matter particles could convert the mass of the dark matter into visible particles—this process is referred to as *dark matter annihilation* [2].

In a popular class of models, dark matter was far more abundant in the early universe—when the cosmos was less than a microsecond old—than in the present day. Dark matter annihilation destroyed the vast bulk of this original dark matter.

In this picture, the amount of dark matter in the present day is set precisely by the rate of annihilation in the early universe. A higher rate of annihilation would result in less dark matter in the present day; less annihilation would leave a larger residue of dark matter at late times. Observations of the cosmic microwave background radiation have measured the dark matter abundance to percent-level precision, from which we can infer the annihilation rate required to generate that abundance.

We can then ask: what signatures of dark matter annihilation could we see in the present day? *Figure 2* shows how we assemble these ingredients—knowledge of the annihilation rate required to generate the observed abundance of dark matter, and predictions for how the dark matter should form clumps and streams—to calculate a predicted signal. The brightest source of dark matter annihilation in the sky is expected to be the center of the Milky Way, where both dark matter and ordinary matter have collected at the lowest point of the gravitational potential.

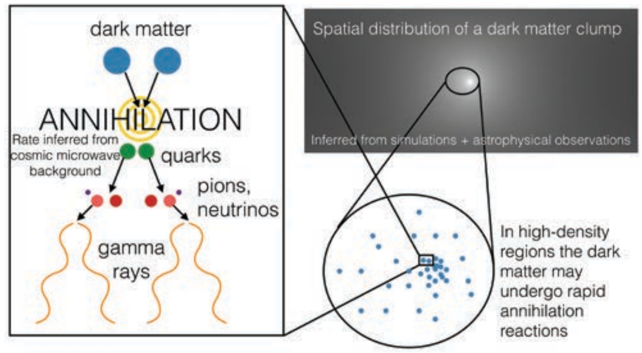


FIGURE 2

Predicting a signal from dark matter annihilation. *The signal is brightest in regions of high dark matter density, where particles collide more frequently. As described in the text, we know the annihilation rate required to give the measured amount of dark matter in the universe. The final ingredient, the particles to which the dark matter annihilates—quarks, in this example—depends on the particle nature of the dark matter: given a signal, we can infer the intermediate steps by looking at the final products, such as gamma rays.*

There are, however, other unknown factors that go into calculating the signal. We do not know the mass of individual dark matter particles, or what visible particles they would produce through annihilation. Finding an annihilation signal could provide answers to these questions; measure the distribution of dark matter with unprecedented precision; and constitute the first discovery of a non-gravitational link between the dark matter and the rest of the universe.

Why light?

The dark matter could annihilate to almost any known particle. However, most known particles are *unstable*—they quickly decay into protons, electrons, neutrinos and photons, as shown schematically in *Figure 2*. By measuring the final decay products we can narrow down the properties of the original particles.

The AMS-02 experiment at MIT, led by Prof. Sam Ting, is searching for electrons and protons (and their antimatter counterparts) from dark matter annihilation, and has indeed identified a possible signal [3]. But charged particles do not travel in straight lines through the Milky Way, due to interstellar magnetic fields, so it is not usually possible to determine where these particles originated.

In contrast, since photons do travel in straight lines, they can be traced back to their sources—presumably regions where the dark matter density is high. In searching for the *photons* from dark matter annihilation, we can use this spatial information to separate signals from backgrounds.

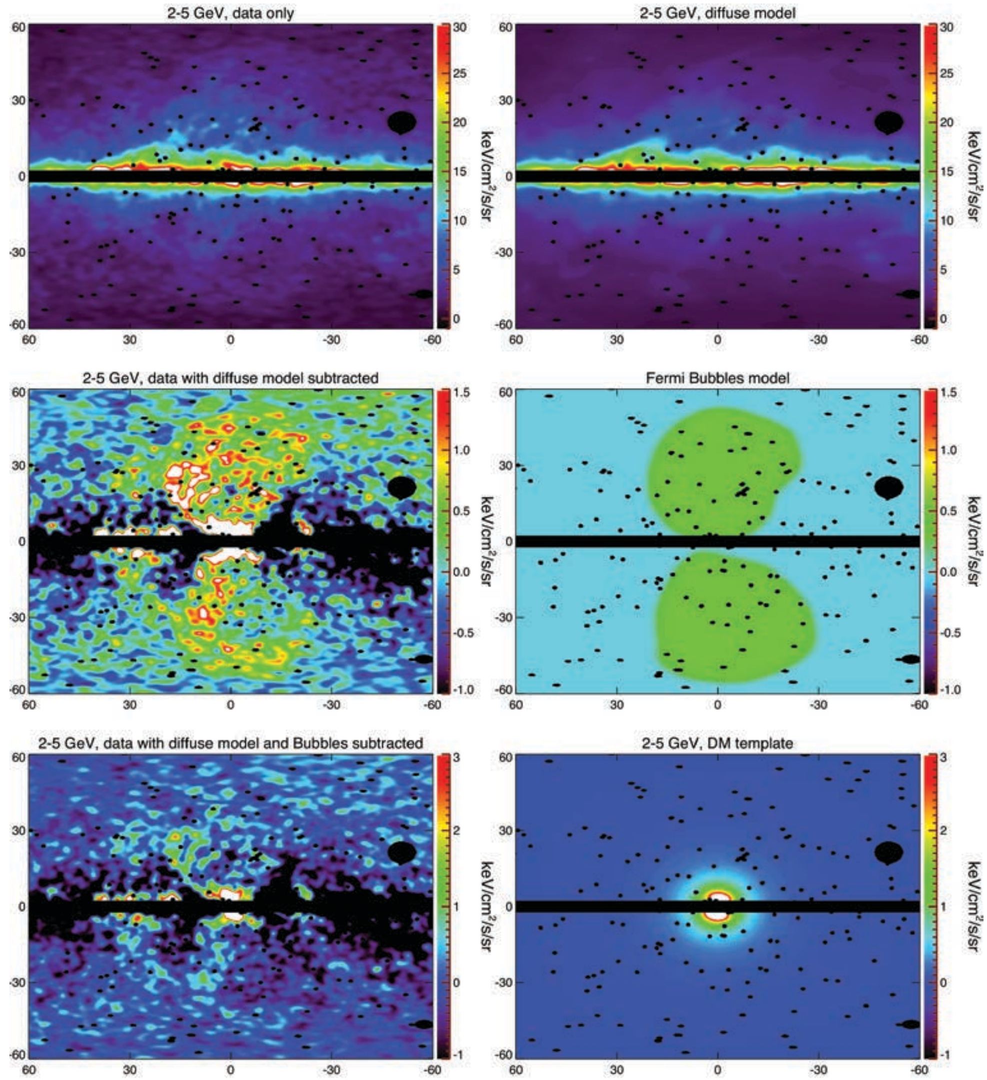
A sea of cosmic rays: Where's Waldo?

For there are indeed backgrounds, which threaten to overwhelm any signal from dark matter annihilation. The center of the Milky Way may be rich in dark matter, but it is also rich in stars and gas clouds. When cosmic rays—very high-energy charged particles—strike the gas clouds, or interact with the visible light from the stars, they produce a sea of high-energy photons.

The physical mechanisms at work here are well understood; the difficulty is that we do not know the exact distribution of gas, starlight and cosmic rays in the Milky Way. However, using a wide range of clues from observations of the sky at

FIGURE 3

Subtraction of foregrounds to reveal the Fermi Bubbles and a potential dark matter signal. *The bright horizontal line of emission in the center of each panel corresponds to the disk of the Milky Way, and each panel is centered on the Galactic Center. The inner part of the disk, and the brightest point sources, are "masked" out of the figure. The right panels show the contributions to the best-fit model from the photon sea of diffuse emission, the Fermi Bubbles, and the dark-matter-like signal. The left panels show, from top to bottom, the raw data, the data with the diffuse model subtracted (leaving the Bubbles and the dark-matter-like signal), and the data with the diffuse model and Bubbles subtracted (leaving only the dark-matter-like signal and residuals not accounted for in the model). There are other regions of residual emission, but they are fainter and have a different spectrum compared to the bright signal centered on the Galactic Center.*



different energies, astrophysicists have built up a model for these quantities. The brightness of the photon sea can be predicted from this model, and it explains the data well—over *most* of the sky (*Figure 3*).

Before 2008, we had little direct data on gamma rays with energies between a few GeV and 100 GeV. (GeV—gigaelectronvolts—measure energy; 1 GeV is roughly a billion times the energy of visible light. By the famous relation $E=mc^2$, 1 GeV also corresponds roughly to the mass of one proton.) That changed with the launch of the Fermi Gamma-Ray Space Telescope (hereafter *Fermi*), which was launched in June 2008 and is still in operation. *Fermi* provides our clearest view ever of the gamma-ray sky at energies between a tenth of a GeV and hundreds of GeV. All of the data from the telescope are now public, and can be used by researchers outside the experimental collaboration.

Since the public data release in late 2009, several discrepancies have been identified between the Milky Way as seen by *Fermi* and the photon-sea model just described.

These discrepancies could be the first signals of dark matter annihilation, or hint at surprising features of the Milky Way. (See “Coming Full Circle: Fermi Bubbles and the Galactic Center,” pages 40–41).

Bringing a signal into focus

By mid-2013, it was clear that there were at least two striking signals from the inner part of the Milky Way, not explained by any model for the known sources of gamma rays. The *Fermi* Bubbles extend far to the north and south of the Galactic Center; are visible in gamma rays up to energies of roughly 100 GeV; and their striking sharp edges mean they are almost certainly associated with some novel high-energy astrophysics rather than dark matter annihilation.

The signal originally identified in the Galactic Center, and later in the region further from the Galactic disk, looks much more like a candidate dark matter signal. If interpreted as dark matter annihilation, the inferred annihilation rate is consistent with the prediction from the observed dark matter abundance (recall *Figure 2*), and the mass of the dark matter needs to be somewhere in the 10-50 GeV range (about 10-50 times heavier than the proton)—somewhat lighter than the Higgs boson.

One early concern was that this signal might be coming purely from the supermassive black hole at the center of the Milky Way. The reconstruction of the origin point of photons is not perfect: even if a string of photons all originate from exactly the same point in reality, they will appear to come from slightly different locations. This blurs any image, like an unfocused photograph. In the case of the *Fermi* telescope, the blurring is on a scale of about one degree (roughly the size the Sun and Moon appear in the sky). By 2013, however, it was clear that blurring of photons from the black hole could not be responsible, as the signal had been detected more than *five* degrees away from the Galactic Center.

However, the limited resolution of the telescope does make it more difficult to separate any potential signal from the background photon sea. This problem is more severe close to the disk of the Milky Way, where the stars and gas are concentrated and the background is very bright. In 2013, my collaborators and I had found that the apparent properties of the signal changed when we looked at regions closer to the Galactic disk, and this left us with a puzzle [4].

This might have been a real indication that the signal was *not* coming from dark matter annihilation, but had something to do with the stars or clouds of interstellar gas. But it might also have simply reflected blurring between the signal and the background, making it difficult to tell them apart and causing some of the background to be attributed to the signal.

How could we tell the difference? We realized that we had an additional piece of information—the *Fermi* Collaboration had recently provided an event quality ranking for the individual photons in the dataset. High-quality photons took a long, well-measured path through the detector, allowing the Collaboration to accurately reconstruct their original direction. Low-quality photons might only have

(continued on page 42)

Coming Full Circle

The Fermi Bubbles and the Galactic Center

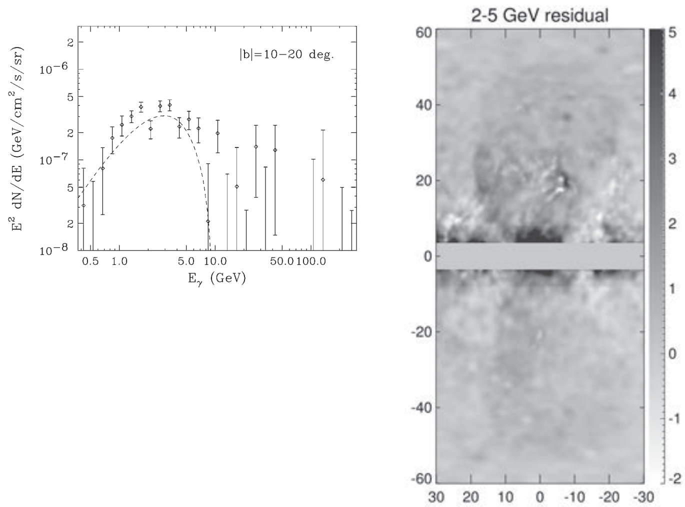
FEBRUARY 2013

Full Circle

5

While studying the spectrum of the Fermi Bubbles, Hooper & Slatyer discovered a signal very similar to the Galactic Center excess. Far from the Galactic disk, the Bubbles have the expected spectrum with power at high energies, but closer to the disk, there are excess photons at energies of a few GeV. The left panel plots the power in these extra photons; the dashed line shows the expected signal from a particular dark matter model.

The excess can now be seen even when all photons within five degrees of the Galactic disk are removed: it is not coming from bright sources at the Galactic Center. The excess photons are distributed roughly symmetrically around the Galactic Center (right panel).



OCTOBER 2009 – MAY 2010

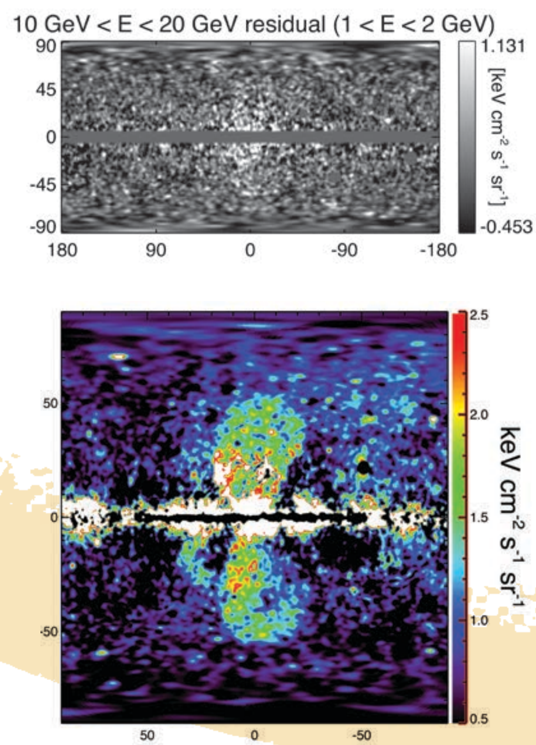
The Fermi Haze

Dobler, Finkbeiner, Cholis, Slatyer & Weiner isolated a gamma-ray counterpart to the microwave haze in public Fermi data. The signal appeared as a dim fog of gamma rays in the inner Galaxy (shown in the upper panel), hypothesized to come from the same energetic electrons as the microwave haze, now scattering starlight to gamma-ray energies.

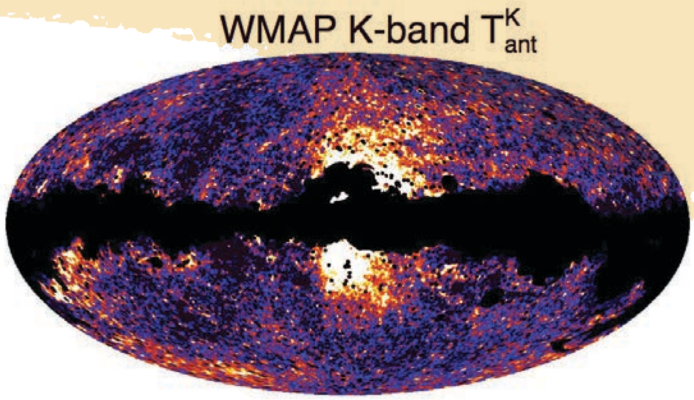
But in subsequent work, Su, Slatyer & Finkbeiner showed that the gamma-ray haze could be resolved into sharp-edged "bubble" structures, centered on the Galactic Center, as shown in the lower panel.

Instead of dark matter annihilation, we had found a clue to new Galactic astrophysics. One widely discussed possibility is that the bubbles are driven by the black hole at the center of the Milky Way.

4



1



2003

The WMAP Haze

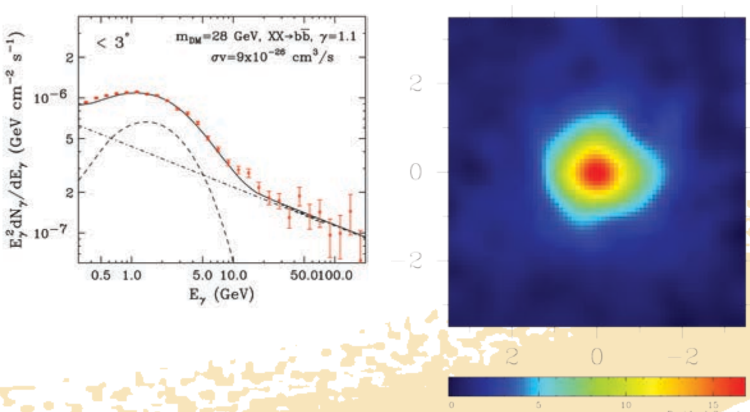
Doug Finkbeiner, then a postdoc at Princeton, identified an excess of microwave photons in the inner Milky Way, using data from the Wilkinson Microwave Anisotropy Probe. These photons could be produced by energetic electrons accelerating in the magnetic fields of the inner Galaxy—but they require a peculiar spectrum for the electrons, with more power at high energies than expected from ordinary cosmic rays. Could the electrons be coming from dark matter annihilation? [Figure reproduced by permission of Greg Dobler, *ApJ* 760 L8, (2012)]

2

JUNE 2008

Launch of Fermi

The *Fermi* Gamma-Ray Space Telescope was launched into low-Earth orbit. Circling the Earth every ninety minutes and mapping the full sky every three hours, *Fermi* has provided the first clear view of the sky in 1-100 GeV gamma rays. Slightly more than one year later, *Fermi* data was made available to researchers outside the collaboration. [Figure courtesy NASA]



3

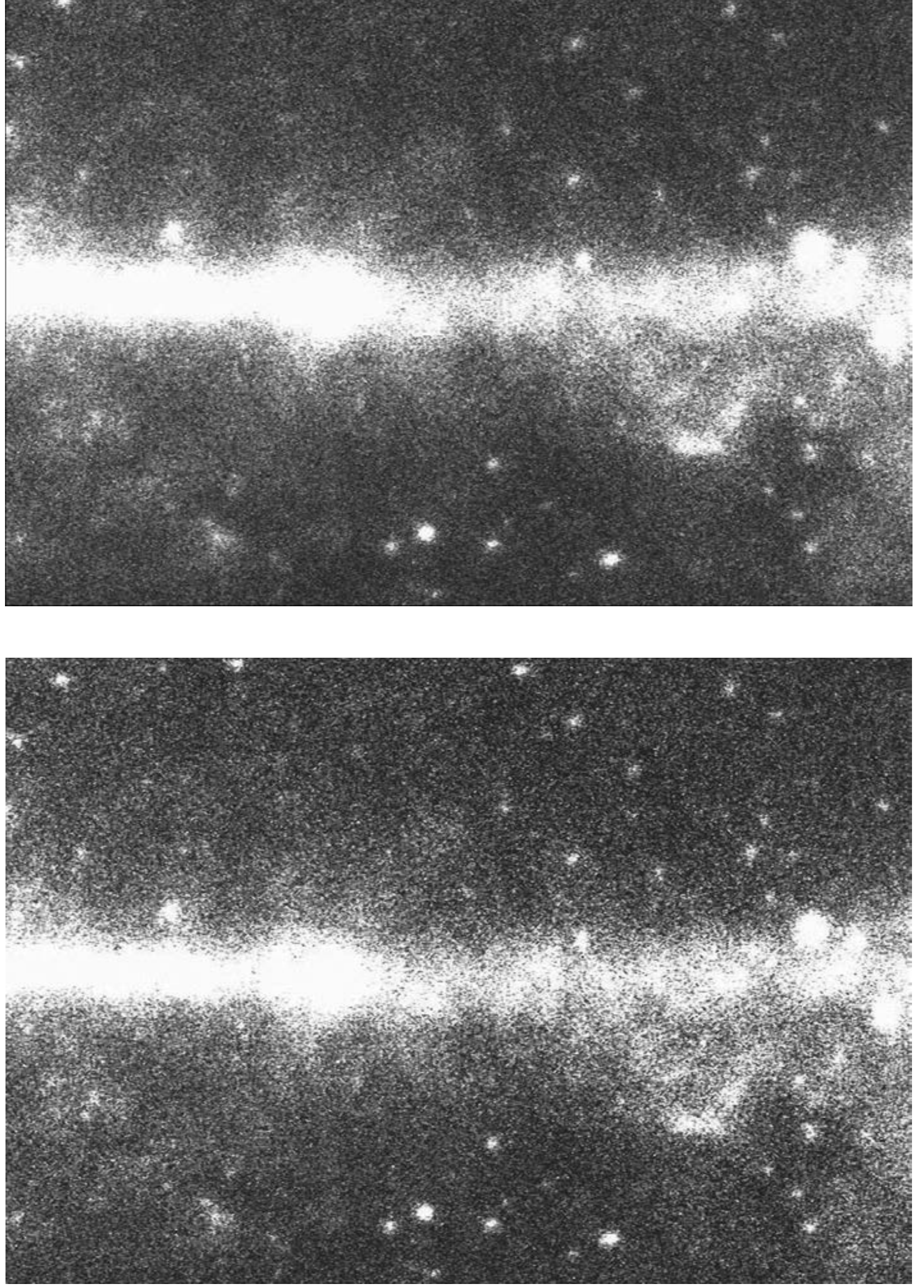
OCTOBER 2009

The Galactic Center

Goodenough & Hooper claimed detection of a possible dark matter annihilation signal in the Galactic Center, consistent with 25-30 GeV dark matter. The signal was characterized by a "bump" of extra photons at energies of a few GeV; the left panel shows the power in excess photons as a function of energy. [Figure courtesy Dan Hooper, Fermilab] The signal was found to be brightest at the Galactic Center: the right panel shows a false-color image of the area near the Galactic Center in gamma rays, after subtraction of the backgrounds. [Figure courtesy Kevork Abazajian, University of California, Irvine]

FIGURE 4

Improving angular resolution. *We show a portion of the gamma-ray sky before and after discarding the poorly reconstructed events. The lower panel has better angular resolution; it is less blurry. (This is easiest to see from looking at the clusters of photons on the right-hand side of the figure.) [Figure courtesy Stephen Portillo, Harvard University]*



(continued from page 39)

hit an edge or corner of the detector, or might have scattered several times inside the detector, making it difficult to reconstruct their point of origin. By throwing out the low-quality photons and constructing images purely from high-quality photons, we could take a less blurry "photograph" of the sky. *Figure 4* shows the impact visually: in the lower (and sharper) image, bright sources of photons are more distinct.

Once we discarded the lower-quality half of our photon sample, the properties of the signal became much more consistent when we looked at regions close to, and far from, the Galactic disk, supporting the hypothesis that the apparent discrepancies had come from the bright photon sea blurring into our signal. Previously we had not been able to directly test whether the signal was present outside the *Fermi* Bubbles, as the bright background of the Galactic disk heavily contaminated the area outside the Bubbles yet still close to the Galactic Center. With the low-quality photons gone, this problem was also resolved, with the signal appearing clearly outside the Bubbles.

The shape of the signal

Recall from *Figure 1* that a dark matter signal is expected to be roughly spherical or football-shaped, in contrast to the disk of stars and gas. The Milky Way has a central "bulge" of old stars, but while this bulge is more spherical than the disk, it is still roughly twice as wide as it is tall. To pick out the signal from the photon sea in the first place, we had assumed it was symmetrically surrounding the Galactic Center—but how good was this assumption? A signal shaped like the bulge might not be *too* badly fitted by our spherically symmetric model, but would most likely originate from the bulge rather than from dark matter annihilation.

We found that when we tested models elongated along the direction of the disk, or perpendicular to it, the best fit occurred for spherical symmetry, or a slight stretch (by less than 20%) along the Galactic disk. It proved impossible to distinguish these two cases with the available data. When we allowed the signal to be stretched along an arbitrary direction—not necessarily the Galactic disk—we found a slight preference for a tilt of about 35 degrees from the Galactic disk, with a stretch factor of about 30%. This direction is not aligned with any known astrophysical object. If the signal *is* coming from dark matter annihilation, this might be a first clue to the shape and orientation of the dark matter halo.

By throwing out the low-quality photons and constructing images purely from high-quality photons, we could take a less blurry "photograph" of the sky.

Pulsars

What could the signal be, if not dark matter? The leading alternate explanation is that we are seeing the aggregate emission from a large number of faint *millisecond pulsars*. These rapidly rotating dense neutron stars are known to emit gamma rays in the right energy range (up to 10 GeV), and the high-energy part of their spectrum (the number of photons produced as a function of energy) matches the spectrum of the signal quite well.

But there are several potential problems with the pulsar interpretation. To generate this signal, thousands of faint millisecond pulsars would be required, each too faint to be detected as an individual source by *Fermi*. This is reasonable in the crowded environs of the Galactic Center, but more challenging five or ten degrees away from the center.

A *new*, previously unmeasured population of faint millisecond pulsars, extending a significant distance from the Galactic Center, might be able to generate the signal—although it would need to have a very low ratio of bright to faint pulsars, relative to pulsar populations observed elsewhere in the Milky Way. Whether such a pulsar population could exist, and naturally be distributed symmetrically around

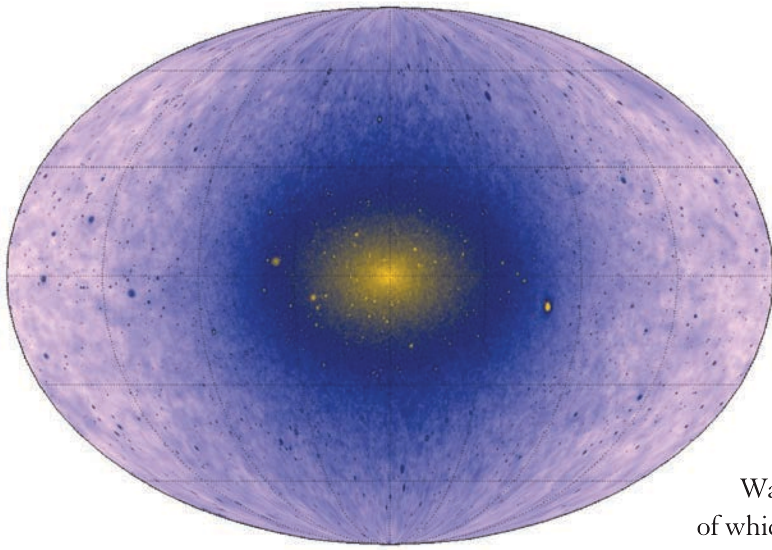


FIGURE 5

The distribution of photons from dark matter annihilation in the Milky Way, *as predicted by simulations of structure formation. The signal is brightest in the Galactic Center, but the halo contains many smaller clumps of dark matter. The most massive of these are associated with the dwarf galaxies of the Milky Way. Seeing a counterpart of the signal in these clumps would be a smoking gun for dark matter annihilation, as the astrophysical backgrounds are much fainter than those near the Galactic Center. [Figure reproduced by permission from Kuhlen, Diemand & Madau, AIP Conf. Proc. 921:135-138, 2007.]*

the Galactic Center, is an open question. Such a population was not expected from any current datasets or theoretical models—but perhaps this is its discovery.

Where to search next?

The best way to exclude astrophysical explanations, and confirm a dark matter origin for the signal, would be to see a corresponding signal elsewhere. The Milky Way hosts numerous small satellite "dwarf galaxies," each of which is thought to have its own dark matter halo (*Figure 5*). The annihilation signal from these much smaller halos is expected to be very faint compared to the Galactic Center, but on the other hand, the dwarf galaxies have few stars and little gas, and the expected astrophysical backgrounds are correspondingly faint.

The *Fermi* Collaboration has performed a search for dark matter annihilation in dwarf galaxies [5]. This search could test the possibility that the signal from the inner Milky Way arises from dark matter annihilation: if the Collaboration had not measured gamma rays from the dwarfs, that would have largely falsified the dark matter hypothesis. Instead, they saw a small signal in gamma rays. It may still only be a statistical fluctuation of the background, but could also be the first hint of a corresponding signal. A firm detection of a corresponding signal in the dwarf galaxies would be a smoking gun for dark matter annihilation, and may be possible with further data from *Fermi* and improvements in the analysis. Together with Dr. Gilly Elor and my graduate student Nick Rodd, I am currently applying our techniques to improve angular resolution (reducing blurriness) to the search for dark matter in dwarf galaxies.

The simple dark matter models that provide a good fit to the signal require relatively light dark matter, with masses in the 10-50 GeV range. My collaborators and I have previously shown that at the lower end of this mass range, dark matter annihilation in the early universe could ionize the gas and create a detectable signal in the cosmic microwave background radiation. The release of polarization data from the *Planck* experiment—expected later this year—will test this hypothesis, albeit only for masses around 10 GeV. The AMS-02 experiment [3] may be able to probe the heavier end of the mass range, via measurements of antiprotons.

The relatively low mass of the dark matter also means it could plausibly be detected at the Large Hadron Collider or in direct detection experiments. The absence of a detection in those channels already excludes a significant fraction of models that could otherwise fit the signal. The prediction in these cases is not so clear-cut, as the signal in these experiments cannot be directly inferred from knowledge of the annihilation rate. However, a firm detection at the correct mass would be a spectacular confirmation of the gamma-ray signal.

REFERENCES

[1] This process can be described by the "Press-Schechter" formalism, developed by Prof. Paul Schechter of MIT together with William Press (Press & Schechter, *ApJ* 187, 425-438 (1974)). Here at MIT, Profs. Anna Frebel and Mark Vogelsberger are actively studying dark matter structure formation.

[2] One way to search for dark matter in the present day is by *reversing* this annihilation process, converting matter and radiation into dark matter, in high-energy collisions at experiments like the Large Hadron Collider. For a recent review article, see Mitsou, *Int. J. Mod. Phys.* A28 (2013) 1330052.

[3] The AMS-02 experiment released its first results last year (Aguilar et al., *Phys. Rev. Lett.* 110, 141102 (2013)), and the scientific community is eagerly awaiting further data. You can read about the experiment at *http://ams.nasa.gov/*.

[4] For further information on Prof. Slatyer's research on the potential dark matter signal in the inner Galaxy, visit *http://arxiv.org/abs/1402.6703*. This work was completed in collaboration with Tansu Daylan, Douglas Finkbeiner and Stephen Portillo (Harvard); Dan Hooper and Tim Linden (University of Chicago); and Nicholas Rodd (MIT), Slatyer's graduate student.

[5] The *Fermi* Collaboration dwarf search is detailed in Ackermann et al., *Phys. Rev. D* 89, 042001 (2014). You can learn more about the Fermi Gamma-Ray Space Telescope at *http://fermi.gsfc.nasa.gov*.

TRACY SLATYER *is a theoretical physicist who works on particle physics, cosmology and astrophysics. Her research interests are motivated by key particle physics questions, such as the search for new particles and forces and a microscopic description of dark matter, but she seeks answers to these questions by analyzing astrophysical data, including gamma-rays, X-rays, radio and the cosmic microwave background (CMB). Professor Slatyer has proposed a new kind of dark matter particle that accounts for the measured excess of cosmic ray positrons that could be due to dark matter annihilation. She has demonstrated strong skills in particle physics beyond the Standard Model, but also has done significant and highly cited work in astrophysics and cosmology. Included in this work was a major contribution to high-energy astrophysics that showed that the gamma ray "haze" seen by the Fermi Gamma Ray Space Telescope is, in fact, emission from two hot bubbles of relativistic plasma emanating from the Galactic Center. Slatyer and colleagues Meng Su and Douglas Finkbeiner were awarded the 2014 Bruno Rossi Prize of the AAS for this discovery. She has done similarly creative work combining particle physics modeling with cosmological N-body simulations and calculations of ionization during the cosmic dark ages, and its effects on the CMB.*

Tracy Slatyer joined the MIT Physics Department in July 2013, after completing a three-year postdoctoral fellowship at the Institute for Advanced Study at Princeton. Slatyer completed her undergraduate work with honors in theoretical physics at the Australian National University in 2005 and her doctoral work in physics at Harvard in 2010 under the direction of Douglas Finkbeiner.