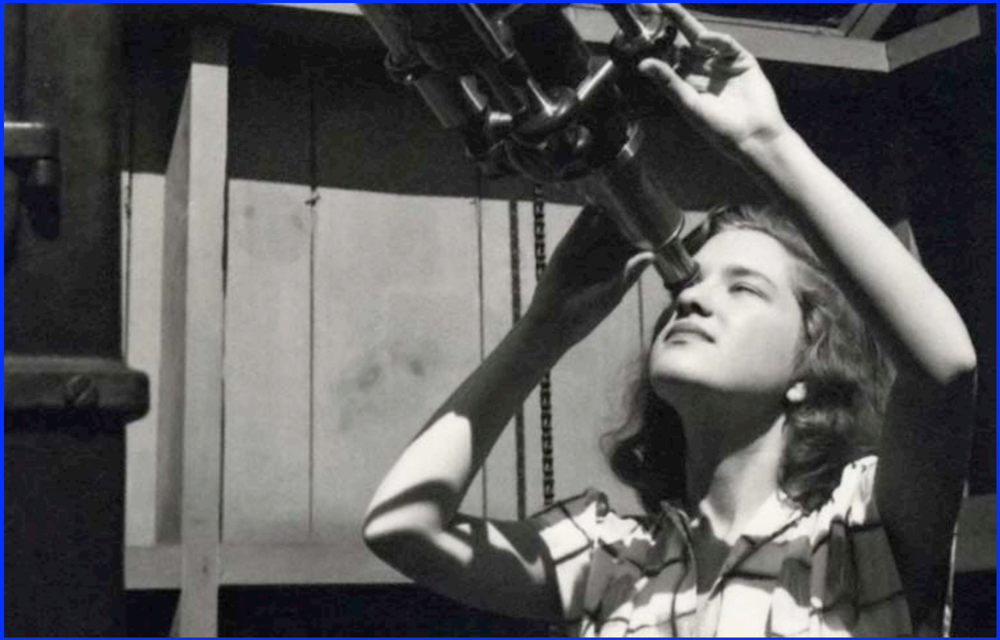
A multicomponent dark matter scenario consistent with experiment

Reagan Thornberry, Caden LaFontaine, Steven Sellers, Bailey Tallman, Matthew Sadler, Alex Behne, Gabe Frohaug, and Roland E. Allen

Physics and Astronomy, Texas A&M University



Fritz Zwicky – 1930s

Credit: http://www.astro.caltech.edu/palomar/about/timeline.html

Vera Rubin – 1970s

Credit: Archives and Special Collections, Vassar College Library

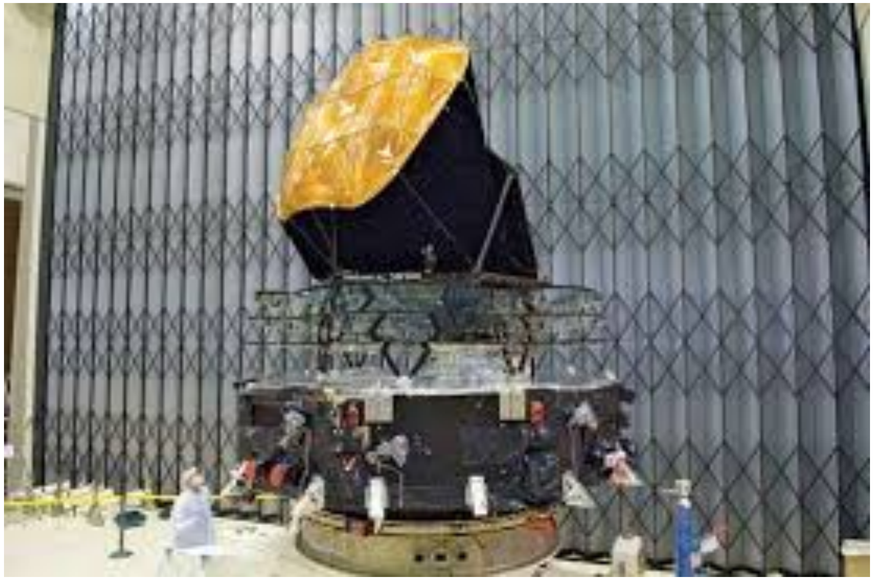
Three space-based experiments relevant to indirect detection.

Fermi-LAT

Image credits: Fermi-LAT, AMS-02, Planck
(NASA, ESA)

AMS-02

Planck



In the present scenario, there are two stable spin 1/2 WIMPs (weakly interacting massive particles) -- a high-mass neutralino and a more abundant "Higgson" with a mass of $\leq$ 125 GeV/c^2.

Recent (and earlier) analyses of the data from Planck, Fermi-LAT, AMS-02, and other experiments indicate that:

(i) the positron excess at ~ 800 GeV or above observed by AMS is not evidence of dominant high-mass dark matter particles (which would have disconfirmed the present theory with a rigorous upper limit of 125 GeV),

(ii) the Galactic center excess of gamma rays observed by Fermi-LAT may be evidence for dark matter particles with a mass below or near 100 GeV/c^2,

(iii) the gamma-ray excess from Omega Centauri (also observed by Fermi-LAT) also may be evidence of annihilation of such relatively low-mass particles,

(iv) the antiproton excess observed by AMS may yet again be evidence of roughly 100 GeV dark matter particles, and

(v) the Planck results are consistent with a dark matter particle which is thermally produced (in the early universe) and has a mass near or somewhat below 100 GeV/c^2.

A fundamental principle (Karl Popper):

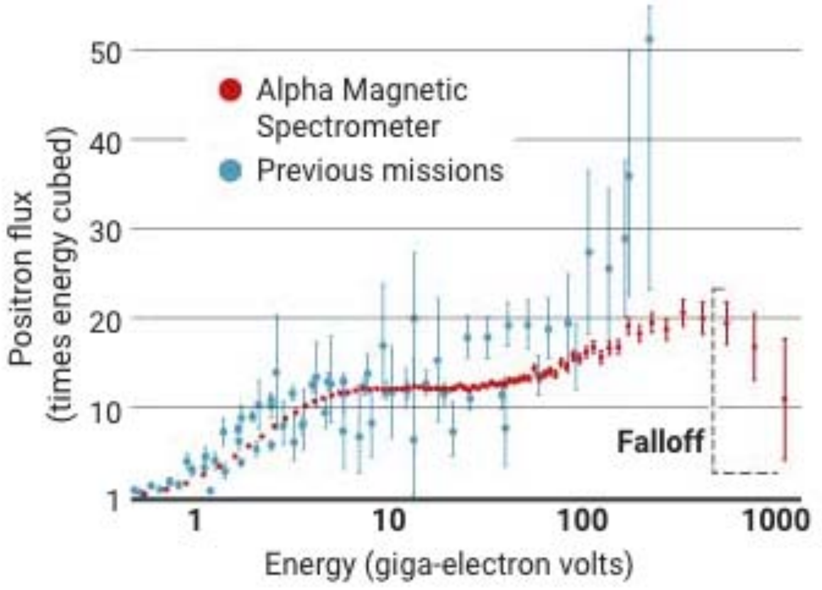
Any real theory should contain a specific prediction that can be disconfirmed by experiment within the foreseeable future!

The present theory is disconfirmed if the dominant dark matter particle is found to have a mass greater than 125 GeV/c^2.

It is rendered unlikely if the mass is far below 125 GeV/c^2.

Rigorous theorem: the mass of the present dark matter candidate is $\leq$ 125 GeV/c^2 [1].

[1] R. E. Allen, "Saving supersymmetry and dark matter WIMPs —a new kind of dark matter candidate with well-defined mass and couplings", Phys. Scripta 94, 014010 (2019), arXiv:1811.00670 [hep-ph].

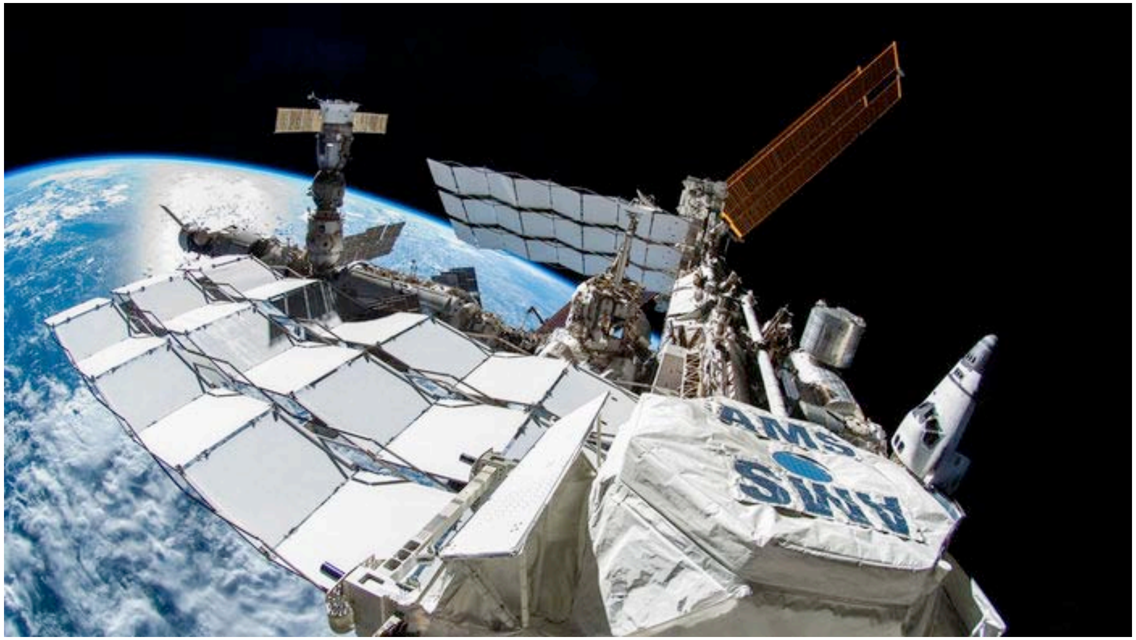


M. AGUILAR *ET AL.*, *PHYS. REV. LETT.* 122, 041102, (2019), ADAPTED BY C. BICKEL/*SCIENCE*

← If this positron excess demonstrated a dominant dark matter particle at about 800 GeV, our theory would be disconfirmed, because of our upper limit of 125 GeV.

But such an interpretation is ruled out By the Planck observations.

On the other hand, the AMS-02 and Fermi-LAT evidence favoring our lower-mass particle is consistent with the Planck data.



Multicomponent picture of Baer, Barger, Sengupta, and Tata:

These authors have pointed out that a multicomponent dark matter scenario, with a significant admixture of neutralinos but some other particle dominating, relieves the tension between susy dark matter and the observed dark matter abundance:

Here the additional dark matter particle results from an extended Higgs sector:

1. R. Thornberry, M. Throm, J. Killough, D. Blend, M. Erickson, B. Sun, B. Bays, G. Frohaug, and R. E. Allen, "A natural dark matter scenario with two coexisting stable WIMPs: neutralinos and Higgsons", submitted.

2. M. Throm, R. Thornberry, J. Killough, B. Sun, G. Abdulla, and R. E. Allen. "Two natural scenarios for dark matter particles coexisting with supersymmetry", Mod. Phys. Lett. A 34, 1930001 (2019), arXiv: 1901.02781 [hep-ph].

3. R. E. Allen, "Saving supersymmetry and dark matter WIMPs—a new kind of dark matter candidate with well-defined mass and couplings", Phys. Scripta 94, 014010 (2019), arXiv:1811.00670 [hep-ph].

4. R. E. Allen and A. Saha, "Dark matter candidate with well-defined mass and couplings", Mod. Phys. Lett. A 32, 1730022 (2017), arXiv:1706.00882 [hep-ph].

5. Reagan Thornberry, Alejandro Arroyo, Caden LaFontaine, Gabriel Frohaug, Dylan Blend, and Roland E. Allen, "Gauge couplings in a multicomponent dark matter scenario", eConf: The SLAC Electronic Conference Proceedings Archive, arXiv:1910.09950.

6. Dylan Blend, Reagan Thornberry, Alejandro Arroyo, Gabriel Frohaug, Caden LaFontaine, and Roland E. Allen, "A multicomponent dark matter scenario and the experimental evidence supporting it", Proceedings of Science [proceedings of European Physical Society High Energy Physics conference].

In the present theory the lowest-energy neutralino is a stable dark matter particle, but so is the new particle predicted here (also with spin ½ and R-parity = -1). In the present theory, Higgs bosons are amplitude modes in an extended sector with spin ½ particles.

They are somewhat analogous to the Higgs/amplitude modes observed in superconductors: P. B. Littlewood and C. M. Varma, "Amplitude collective modes in superconductors and their coupling to charge density waves", Phys. Rev. B. 26, 4883 (1982).

In Mod. Phys. Lett. A 34, 1930001 (2019) we have called the new spin ½ particles (both neutral and charged) "Higgsons" *H*, to be distinguished from Higgs bosons *h* and the higgsinos of susy.

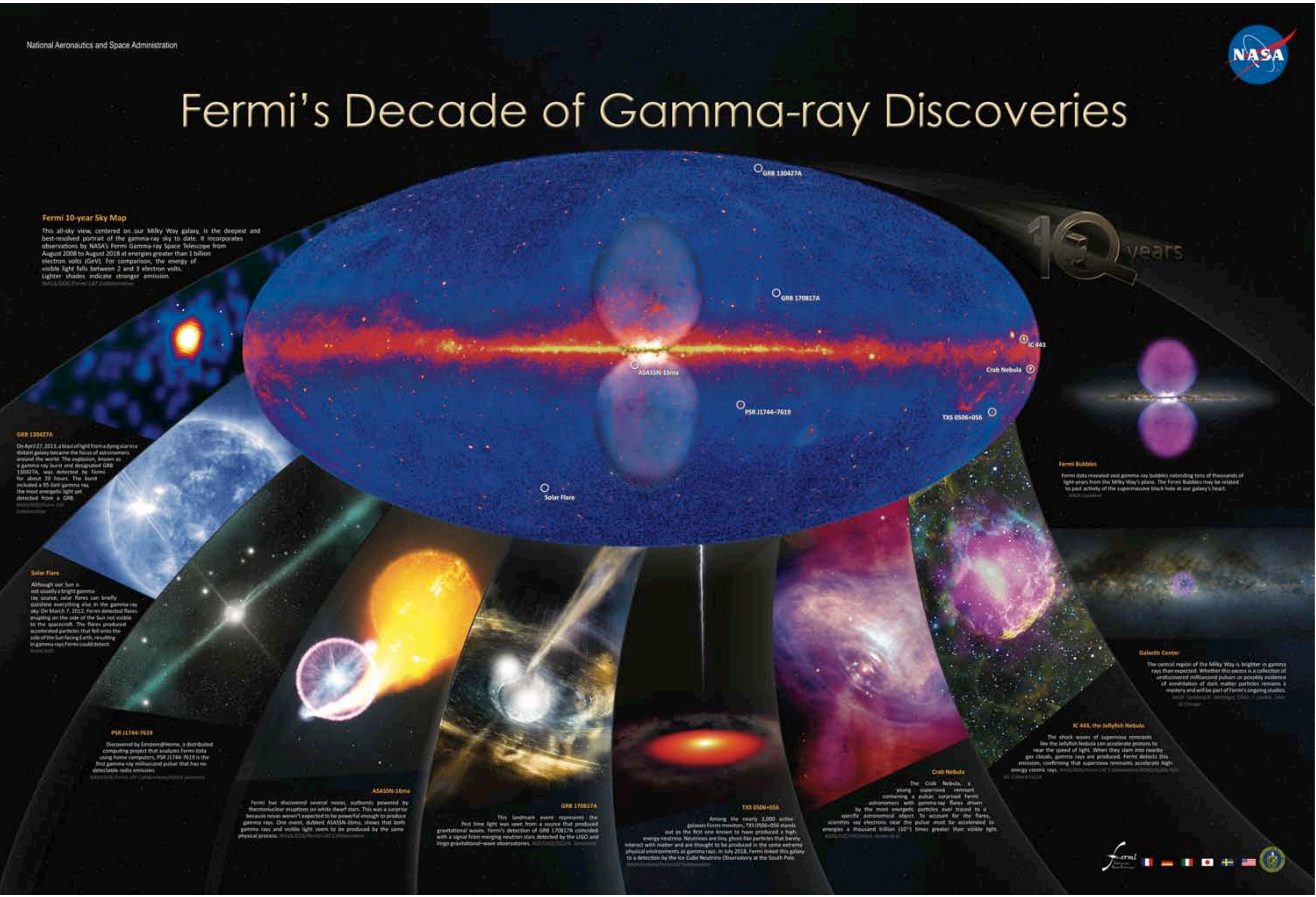
Their coupling to the Z^0 is comparable to that of a neutralino, but the nonrelativistic cross-section is lower by a factor of about 1/8:

$$\frac{\sigma_H}{\sigma_\chi} \approx \frac{1}{8}\frac{g_H^2}{g_\chi^2} \text{ as calculated, and explained by a simple counting argument.}$$

This appears to imply consistency with the observed abundance of dark matter and the limits imposed by direct, indirect, and collider detection.

The coupling to Higgs bosons, and thus the cross-section for spin-independent direct detection, is not determined by the theory.

The International Space Station, photographed by a crew member while space shuttle Endeavour was docked with the station, on May 20, 2013. The newly installed Alpha Magnetic Spectrometer-2 (AMS) is visible at center left. The Earth's horizon can be seen below. AMS, like the Fermi and PAMELA experiments, is looking for evidence of particles created through dark matter annihilation.



National Aeronautics and Space Administration

Fermi's Decade of Gamma-ray Discoveries

Fermi 10-year Sky Map

This all-sky view, centered on our Milky Way galaxy, is the deepest and best-resolved portrait of the gamma-ray sky to date. It incorporates observations by NASA's Fermi Gamma-ray Space Telescope from August 2008 to August 2018 at energies greater than 1 billion electron volts (GeV). For comparison, the energy of visible light falls between 2 and 3 electron volts. Lighter shades indicate stronger emission. NASA/DOE/Fermi LAT Collaboration

GRB 130427A

On April 27, 2013, a blast of light from a dying star in a distant galaxy became the focus of astronomers around the world. The explosion, known as a gamma-ray burst and designated GRB 130427A, was detected by Fermi for about 20 hours. The burst included a 95 GeV gamma ray, the most energetic light yet detected from a GRB. [illegible]

Solar Flare

Although our Sun is not usually a bright gamma-ray source, solar flares can briefly outshine everything else in the gamma-ray sky. On March 7, 2012, Fermi detected flares erupting on the side of the Sun not visible to the spacecraft. The flares produced accelerated particles that fell onto the side of the Sun facing Earth, resulting in gamma rays Fermi could detect. NASA/SDO

PSR J1744-7619

Discovered by Einstein@Home, a distributed computing project that analyzes Fermi data using home computers, PSR J1744-7619 is the first gamma-ray millisecond pulsar that has no detectable radio emission. [illegible]

ASASSN-16ma

Fermi has discovered several novae, outbursts powered by thermonuclear eruptions on white dwarf stars. This was a surprise because novas weren't expected to be powerful enough to produce gamma rays. One event, dubbed ASASSN-16ma, shows that both gamma rays and visible light seem to be produced by the same physical process. [illegible]

GRB 170817A

This landmark event represents the first time light was seen from a source that produced gravitational waves. Fermi's detection of GRB 170817A coincided with a signal from merging neutron stars detected by the LIGO and Virgo gravitational-wave observatories. [illegible]

TXS 0506+056

Among the nearly 2,000 active galaxies Fermi monitors, TXS 0506+056 stands out as the first one known to have produced a high-energy neutrino. Neutrinos are tiny, ghost-like particles that barely interact with matter and are thought to be produced in the same extreme physical environments as gamma rays. In July 2018, Fermi linked this galaxy to a detection by the Ice Cube Neutrino Observatory at the South Pole. [illegible]

Crab Nebula

The Crab Nebula, a young supernova remnant containing a pulsar, surprised Fermi astronomers with gamma-ray flares driven by the most energetic particles ever traced to a specific astronomical object. To account for the flares, scientists say electrons near the pulsar must be accelerated to energies a thousand trillion (10^{15}) times greater than visible light. [illegible]

IC 443, the Jellyfish Nebula

The shock waves of supernova remnants like the Jellyfish Nebula can accelerate protons to near the speed of light. When they slam into nearby gas clouds, gamma rays are produced. Fermi detects this emission, confirming that supernova remnants accelerate high-energy cosmic rays. [illegible]

Galactic Center

The central region of the Milky Way is brighter in gamma rays than expected. Whether this excess is a collection of undiscovered millisecond pulsars or possibly evidence of annihilation of dark matter particles remains a mystery and will be part of Fermi's ongoing studies. [illegible]

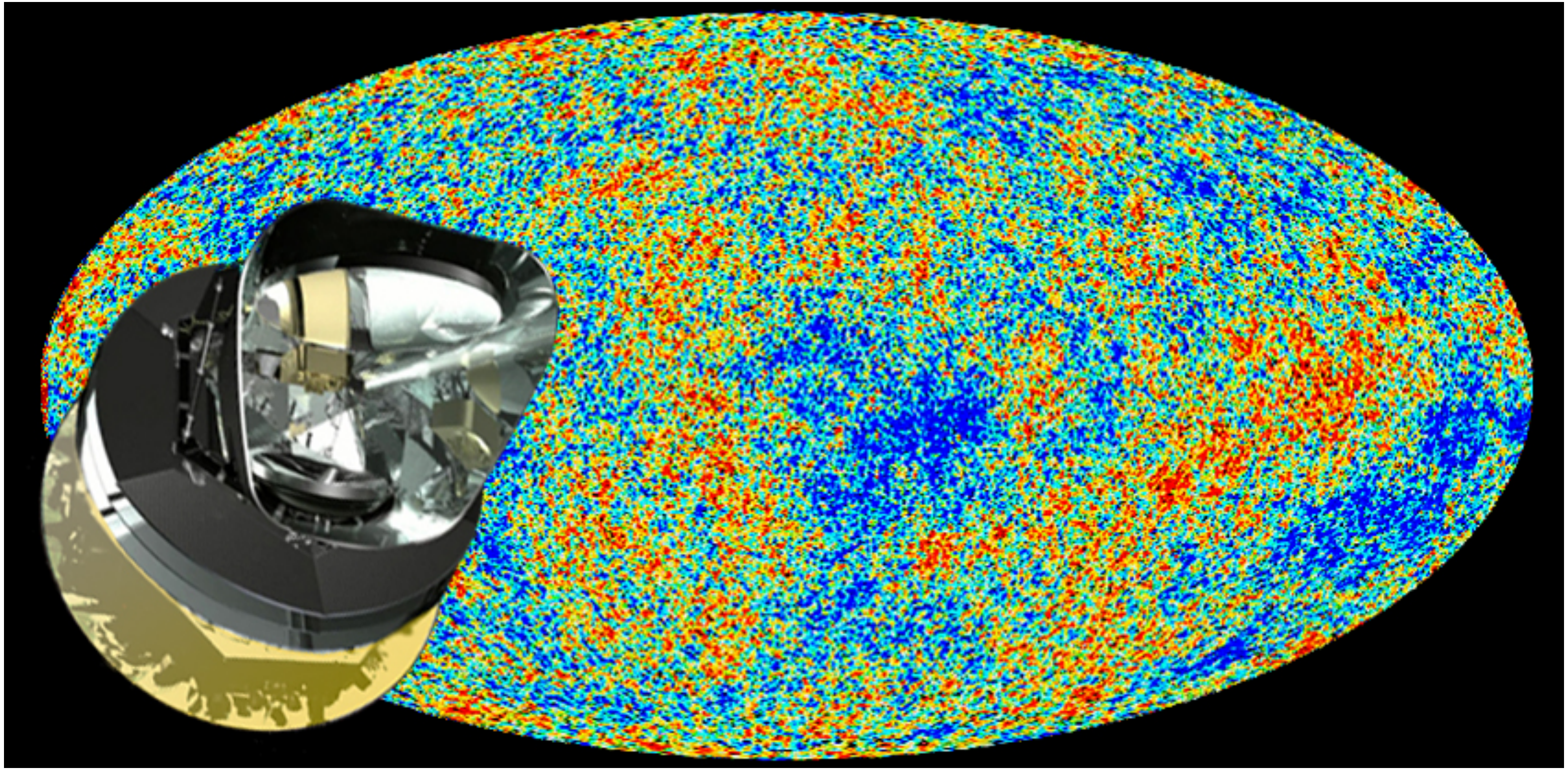
Fermi Bubbles

Fermi data revealed vast gamma-ray bubbles extending tens of thousands of light-years from the Milky Way's plane. The Fermi Bubbles may be related to past activity of the supermassive black hole at our galaxy's heart. [illegible]

Galactic Center

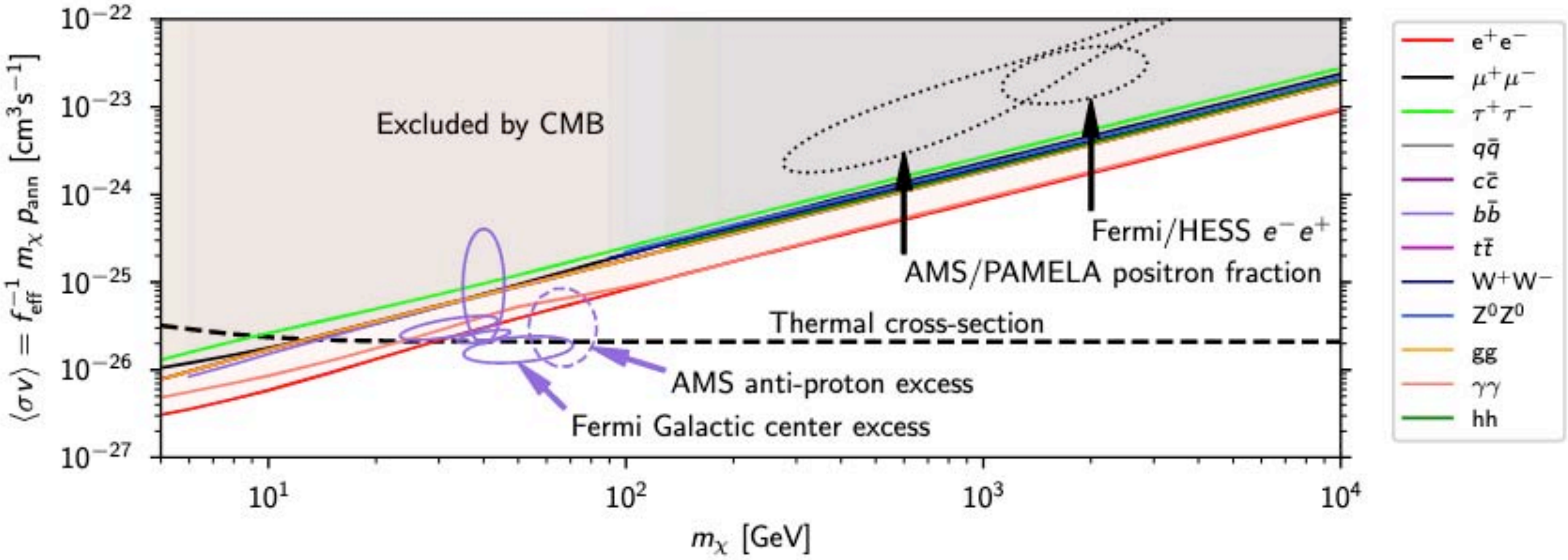
The central region of the Milky Way is brighter in gamma rays than expected. Whether this excess is a collection of undiscovered millisecond pulsars or possibly evidence of annihilation of dark matter particles remains a mystery and will be part of Fermi's ongoing studies.

NASA Goddard/A. Mellinger, CMU; T. Linden, Univ. of Chicago



The Planck satellite experiment

Credits: https://newscenter.lbl.gov/ and https://www.britannica.com/topic/Planck.



“*Planck* 2018 constraints on DM mass and annihilation cross-section. Solid straight lines show joint CMB constraints on several annihilation channels (plotted using different colours) … We also show the 2σ preferred region suggested by the AMS proton excess (dashed ellipse) and the Fermi Galactic centre excess according to four possible models with references given in the text (solid ellipses) … We additionally show the 2σ preferred region suggested by the AMS/ PAMELA positron fraction and Fermi/H.E.S.S. electron and positron fluxes … Assuming a standard WIMP-decoupling scenario, the correct value of the relic DM abundance is obtained for a ‘thermal cross-section’ given as a function of the mass by the black dashed line.”

“CMB anisotropies are sensitive to energy injection in the intergalactic medium that could be a consequence, for example, of dark-matter (DM) annihilation … The current CMB sensitivity to the annihilation cross section of weakly-interactive massive particles (WIMPs) is competitive with and complementary to that of indirect DM search experiments.”

Planck Collaboration, “Planck 2018 results. VI. Cosmological parameters”, arXiv:1807.06209 [astro-ph.CO].

Intriguing results from two careful analyses of AMS-02 observations of antiprotons and Fermi-LAT observations of gamma rays from the Galactic Center

Ilias Cholis, Tim Linden, and Dan Hooper, "A Robust Excess in the Cosmic-Ray Antiproton Spectrum: Implications for Annihilating Dark Matter", Phys. Rev. D 99, 103026 (2019); arXiv:1903.02549 [astro-ph.HE]:

"This excess is well fit by annihilating dark matter particles, with a mass and cross section in the range of $m_\chi \approx$ 46-94 GeV ..."

"… it is particularly intriguing that the range of dark matter models that can accommodate the antiproton excess is very similar to those which could generate the excess of GeV-scale gamma rays observed from the Galactic Center…"

Alessandro Cuoco, Jan Heisig, Lukas Klamt, Michael Korsmeier, and Michael Krämer, "Scrutinizing the evidence for dark matter in cosmic-ray antiprotons", Phys. Rev. D 99, 103026 (2019); arXiv:1903.01472 [astro-ph.HE]:

"… strong limits on heavy DM have been derived from global CR fits. At the same time, the data have also revealed a tentative signal of DM, corresponding to a DM mass of around 40–130 GeV …"

"This signal, if confirmed, is compatible with a DM interpretation of the Galactic center γ-ray excess …"

A mass of $\leq$ 125 GeV is required of the present dark matter candidate, whereas susy particles are commonly expected to have significantly larger masses.

Christopher Karwin, Simona Murgia, Tim M. P. Tait, Troy A. Porter, and Philip Tanedo, "Dark matter interpretation of the Fermi-LAT observation toward the Galactic Center", Phys. Rev. D 95, 103005 (2017), arXiv:1612.05687 [hep-ph]:

"The excess persists and its spectral characteristics favor a dark matter particle with a mass in the range approximately from 50 to 190 (10 to 90) GeV … for pseudoscalar (vector) interactions."

Rebecca K. Leane and Tracy R. Slatyer, "Dark Matter Strikes Back at the Galactic Center", arXiv:1904.08430 [astro-ph.HE]:

"… we conclude that dark matter may provide a dominant contribution to the GCE after all."

Anthony M. Brown, Richard Massey, Thomas Lacroix, Louis E. Strigari, Azadeh Fattahi, and Céline Boehm, "The glow of annihilating dark matter in Omega Centauri", arXiv:1907.08564 [astro-ph.HE]:

"[Omega Centauri contains] DM with density as high as compact dwarf galaxies, [and] emits gamma-rays with an energy spectrum matching that expected from the annihilation of DM particles with mass 31±4 GeV (68% confidence limit)."

Note: The quantitative values of the inferred masses are highly model dependent.

In collider experiments, a *real* (on-shell) Higgs could decay into a pair of neutralinos or Higgsons, if each particle had a mass $\leq 125/2 \approx$ 60 GeV/c^2.

CMS and ATLAS [1,2] have independently placed upper limits on the branching ratio for such decays, at roughly 20 % with the full data sets -- imposing a constraint on either the mass or the Higgs coupling of H^0 (and the lowest-mass neutralino).

In the upper range of masses for the present candidate, creation will require a *virtual* Higgs or virtual gauge bosons.

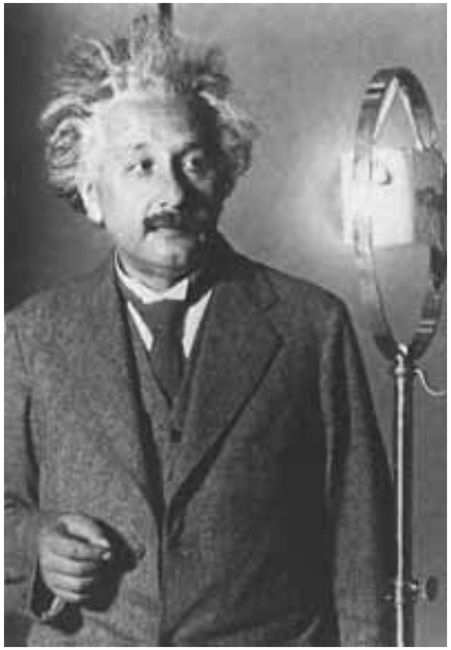
But the coupling to the Higgs is not quantitatively determined in the present theory, so creation through a virtual Z^0 appears more likely.

1. CMS Collaboration, ``Search for invisible decays of a Higgs boson produced through vector boson fusion in proton-proton collisions at $\sqrt{s} = 13$ TeV", Phys. Lett. B 793, 520 (2019), arXiv:1809.05937 [hep-ex].
2. M. Aaboud et al. (ATLAS Collaboration), ``Combination of Searches for Invisible Higgs Boson Decays with the ATLAS Experiment", Phys. Rev. Lett. 122, 231801 (2019), arXiv:1904.05105 [hep-ex].

The history of spin 1/2 fermions begins with the discovery of the electron in 1897 by J. J. Thomson.

The history of spin 1 gauge bosons begins with the 1905 paper of Einstein which introduced the photon.

A spin 0 boson is something new (2012), and surprises may *again* lie ahead!



Picture credits: phy.cam.ac.uk/history/electron, spaceandmotion.com, CERN

There is a mild breaking of Lorentz invariance for these new particles, but the most familiar features of classical Einstein relativity still hold: They satisfy a relativistic equation of motion, $E = mc^2$, etc.

As discussed in our papers, there is only one deviation from complete Lorentz invariance in the present theory -- in an interaction term involving new particles that can be created only at high energy. For this one unconventional term there is a preferred frame with respect to boosts -- the cosmological frame.

The present theory has exact rotational and gauge invariance in all sectors, and also has exact Lorentz symmetry for all fields except the Higgson fields. But as indicated above, even these fields are in accord with the most familiar results of Einstein relativity.

We recall that P, CP, and T violation were respectively observed in 1956, 1964, and 2012; that there have recently been many experimental efforts to test for Lorentz violation; and that the mild violation here is not ruled out by these tests (since radiative effects on Standard Model particles will be extremely small).

In summary, with an R-parity of -1 (providing stability), a mass that is ≤ 125 GeV/c^2 , and precisely defined weak-interaction couplings, the particle predicted here is in many respects an ideal dark matter candidate.

The theory that predicts these new particles -- which are associated with an extended version of the Higgs sector -- also unambiguously predicts supersymmetry.

The fact that susy has also not yet been observed is then attributed to a higher energy scale for superpartners than has been explored so far.

And the neutralino of susy remains a quite likely secondary component of the dark matter.

(There may be other constituents, such as axions, but these other candidates remain poorly characterized with respect to mass and abundance.)

Perhaps most important, the present theory predicts many new neutral and charged particles, and new physics, to be discovered at collider energies that could be available in the foreseeable future – in addition to the dark matter WIMP.

Thanks for your attention!