Are We Close to Unraveling Dark Matter ?

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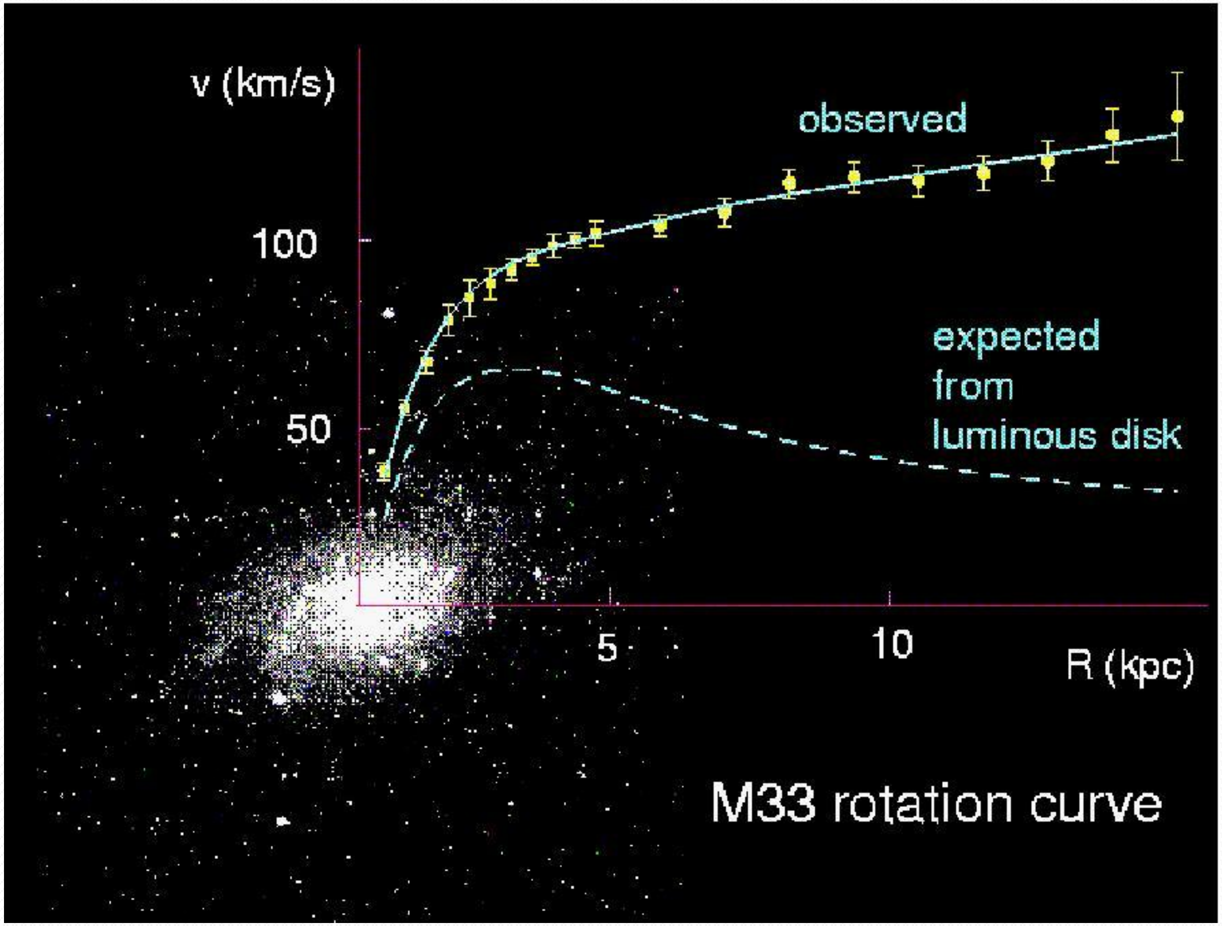
First Discovery of Dark Matter

- As you get farther away from the main central mass of a galaxy, the acceleration from that mass becomes weaker, and less velocity is needed for a star to stay in a circular orbit.
- However, Fritz Zwicky discovered in 1933 that as he observed stars farther out from a galaxy, their velocities were roughly constant. This means that more diffuse and dark matter was now included inside the star's orbit that was not visible as galactic stars or gas.
- Zwicky also predicted neutron stars and supernovas.

Galactic Rotation Curve and Dark Matter Halo



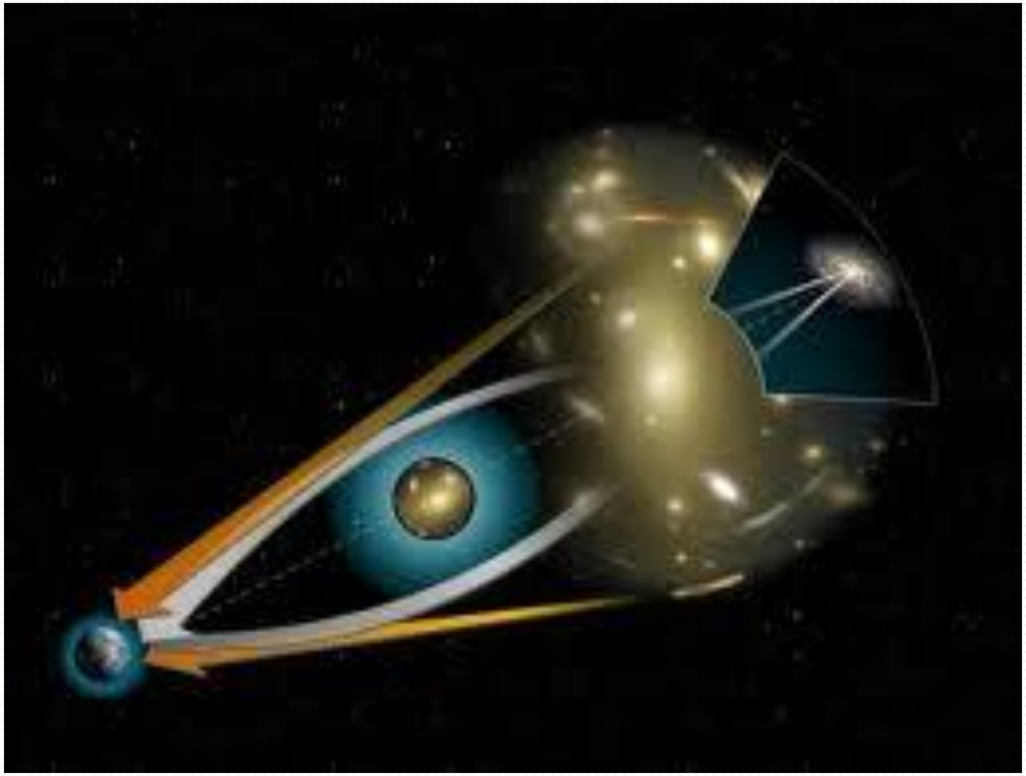
Gravitational Lensing

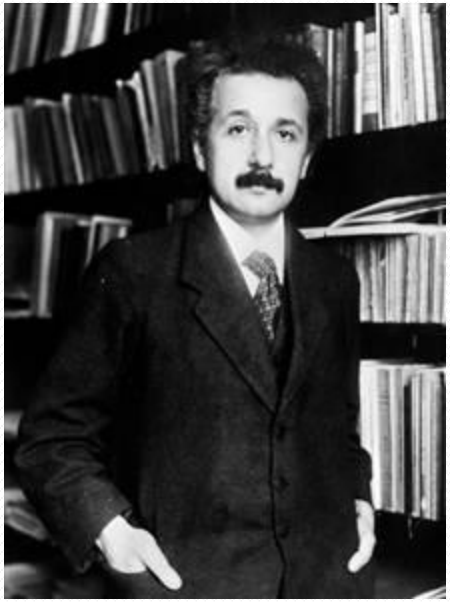
Dark matter does not condense and form stars because it is electrically neutral, and cannot shed energy by radiation.

It does have mass though, and deflects light from stars behind it.

This "gravitational lensing" allows us to detect its presence around a star or galaxy.

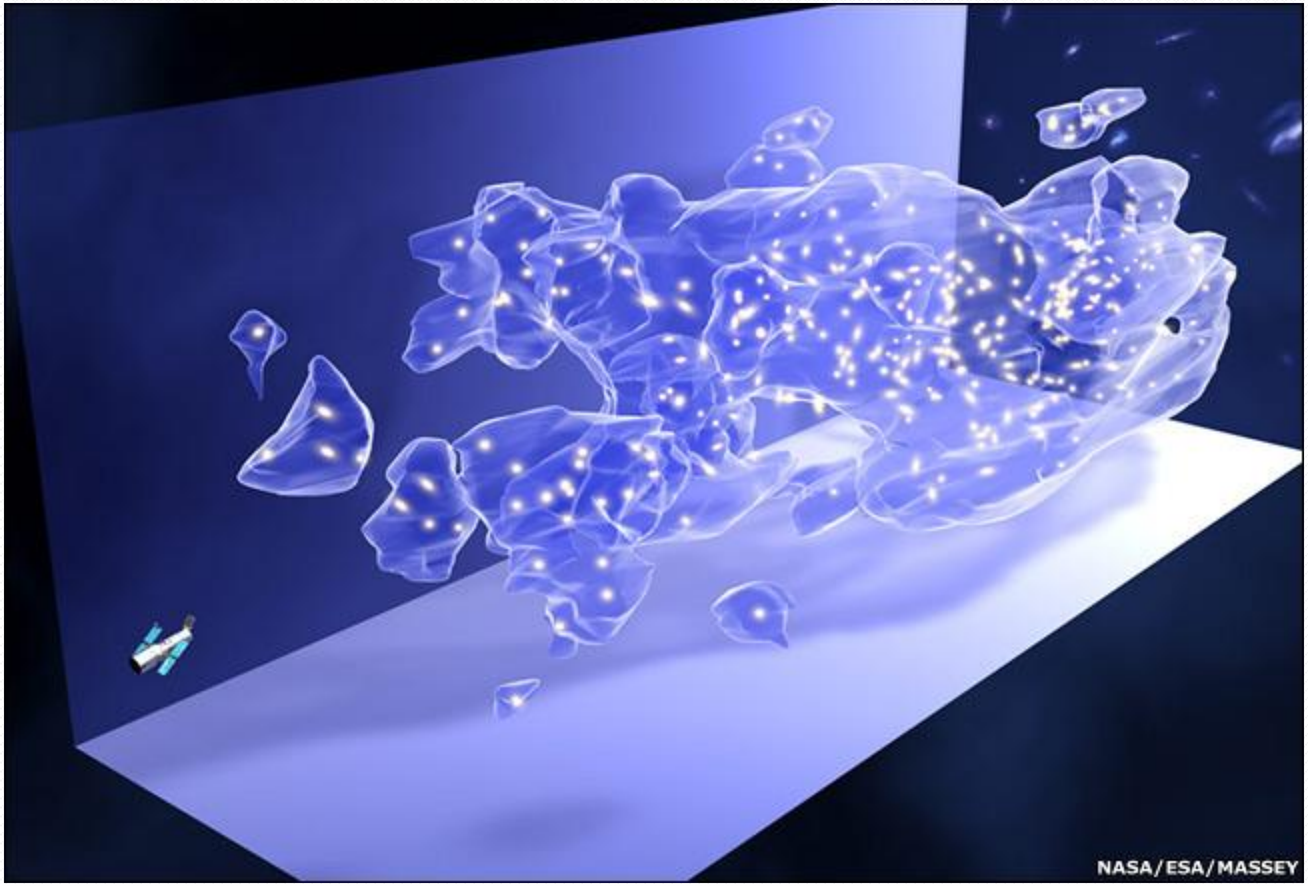
The lensing makes multiple images of the farther galaxy, and/or makes arcs, or spread out images.





Dark Matter on a Universal Scale

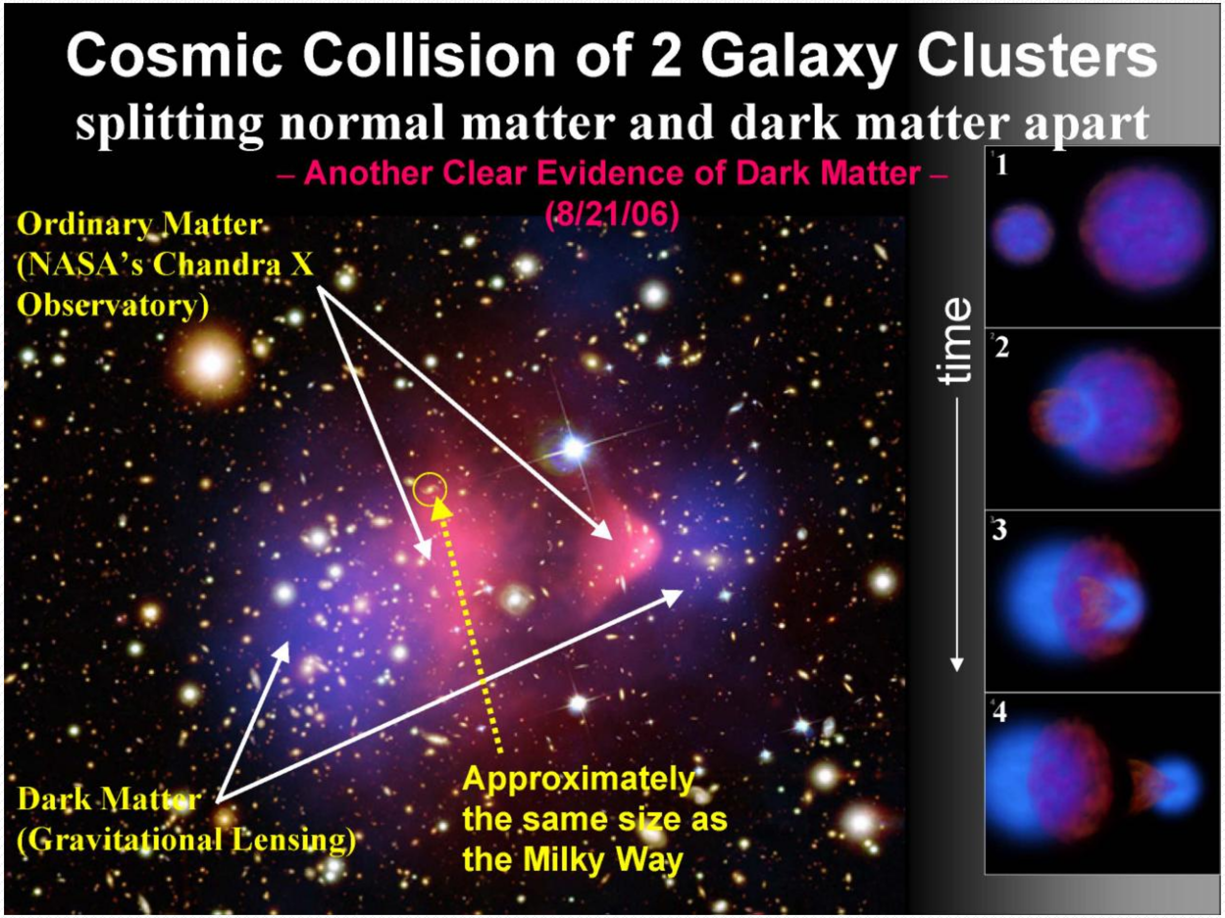
This maps the dark matter distribution by a thousand hours of the Hubble space telescope. Closer matter is on the left out to 6.5 billion years earlier on the right. The older closer matter is more gravitationally clumped.



Dark Matter on a Galactic Cluster Scale

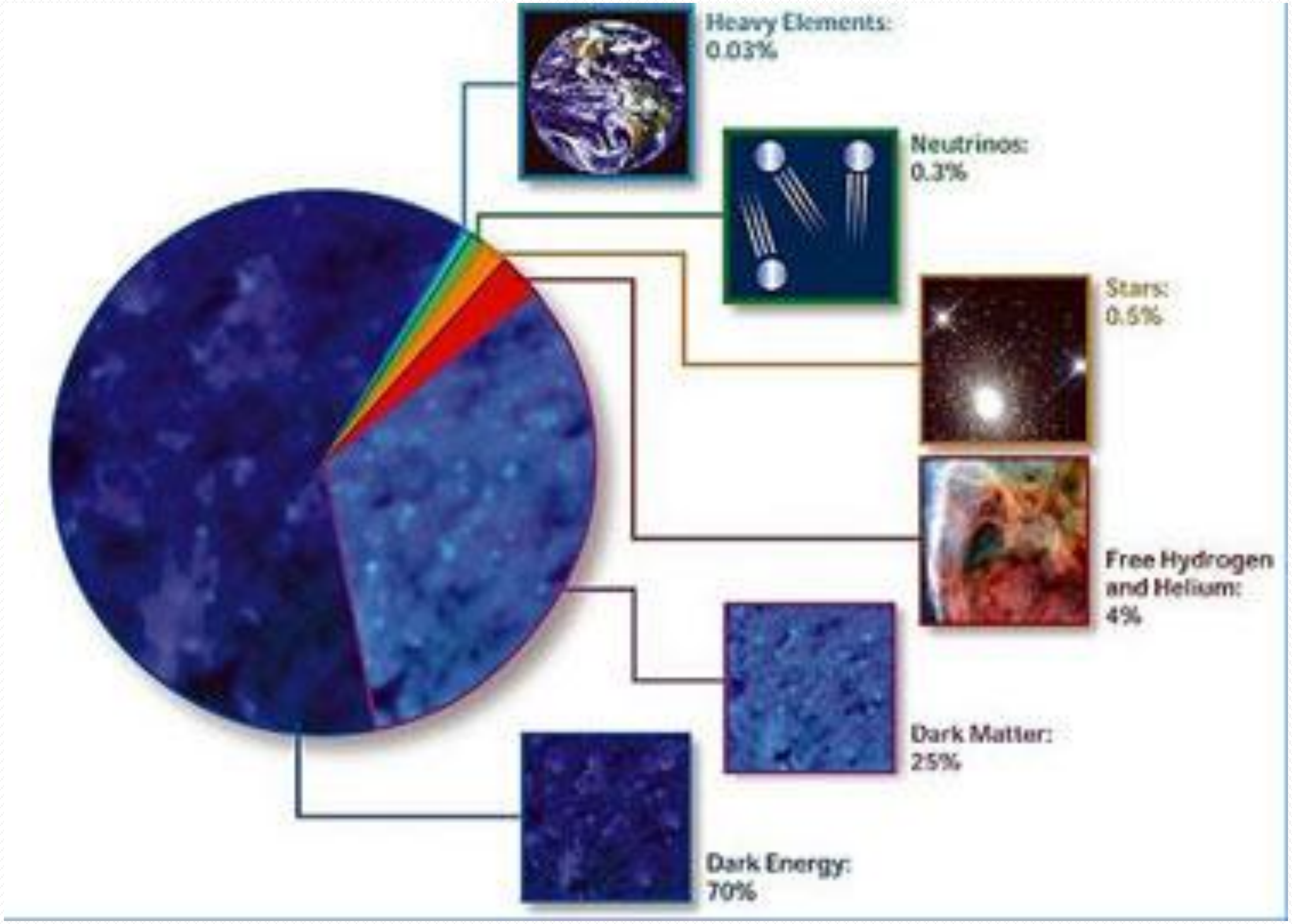
The dark matter is inferred by gravitational lensing and painted in in blue.

Dark Matter inferred in a collision of galaxy clusters and painted in as blue.
The hot gas gives off X rays and is painted in as red.
The dark matter hardly interacts and continues at a high speed away from the collision, whereas the gas collides and slows.
This is called the Bullet Cluster.



Dark Matter in the Universe

From many cosmic experiments, astronomers found that dark energy is about 70% of total energy, dark matter is about 25%, ordinary matter is about 5%, and stars are about 0.5%.



Properties of Dark Matter

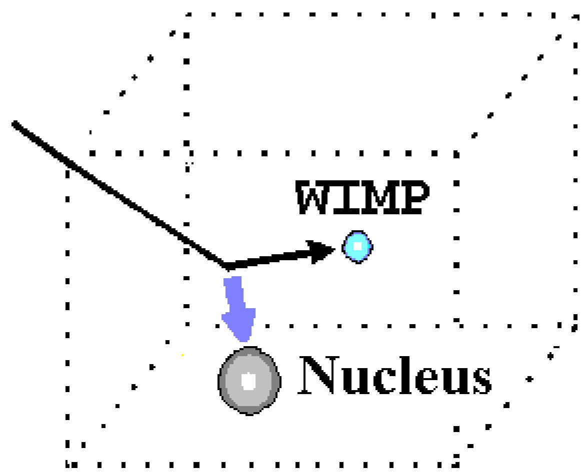
- Dark matter has mass and gravitational interactions
- Dark matter is neutral since it is slow to radiate and condense.
- Dark matter is not an atomic like composite, since it does break apart and condense.
- Dark matter is stable on the timescale of the universe.
- It is not the Higgs, which would decay instantly to massive particles.
- Dark matter does not have ordinary strong interactions, since it would then bind to charged protons or nuclei and condense.
- There is some evidence that it does not have any other new type of strong interactions.
- It could be weakly interacting on a short range, and collisions would then be rare, and it would not condense much because of this. Weakly interacting massive particles are given the acronym **WIMPs**.

Ways to search for Dark Matter

- Let's call the dark matter particle X.
- Since it is neutral it could be its own antiparticle like a neutral pion or photon, and annihilate to form particle-antiparticle pairs. Detecting these created pairs, or their decay particles would be called **indirect detection**.
  - The X particles may be mildly condensed by weak collisions or gravitational collisions into the centers of galaxies or of the sun. Neutrinos from annihilations can escape from the sun and be detected.
- X particles might be **directly detected** by collisions with charged nuclei or electrons that would leave tracks in an experiment.
- The X particles might be **created** in pairs in high energy collisions such as at the new Large Hadron Collider.

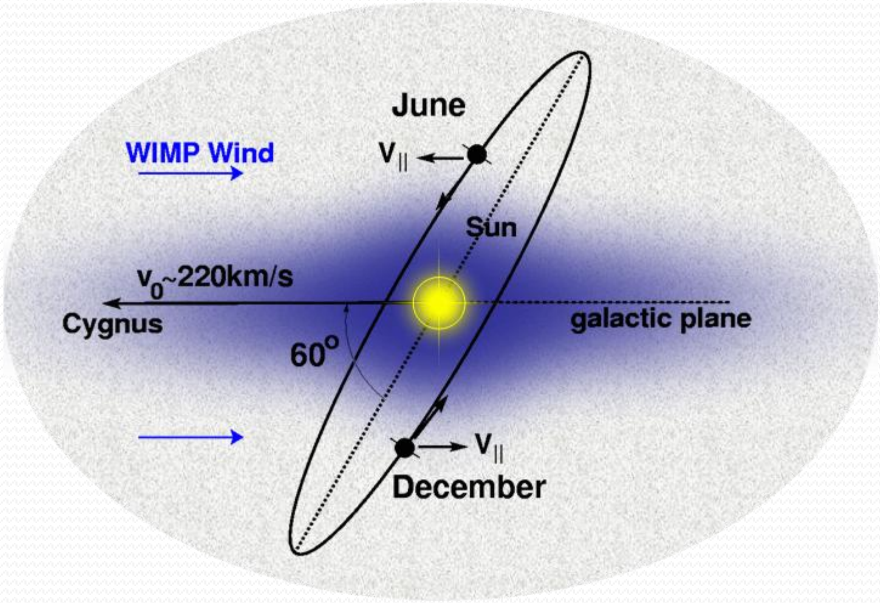
Direct Detection Experiments

These are usually deep underground to get rid of cosmic rays, and at supercooled temperatures, so that the only signal comes from the nucleus which is deflected by the weak interaction. The weak interaction range is only 1/100th the size of the proton. Typically, 100 billion WIMPs cross the detector each second, and one might be detected per day, if at all.



Yearly oscillations in collision rate

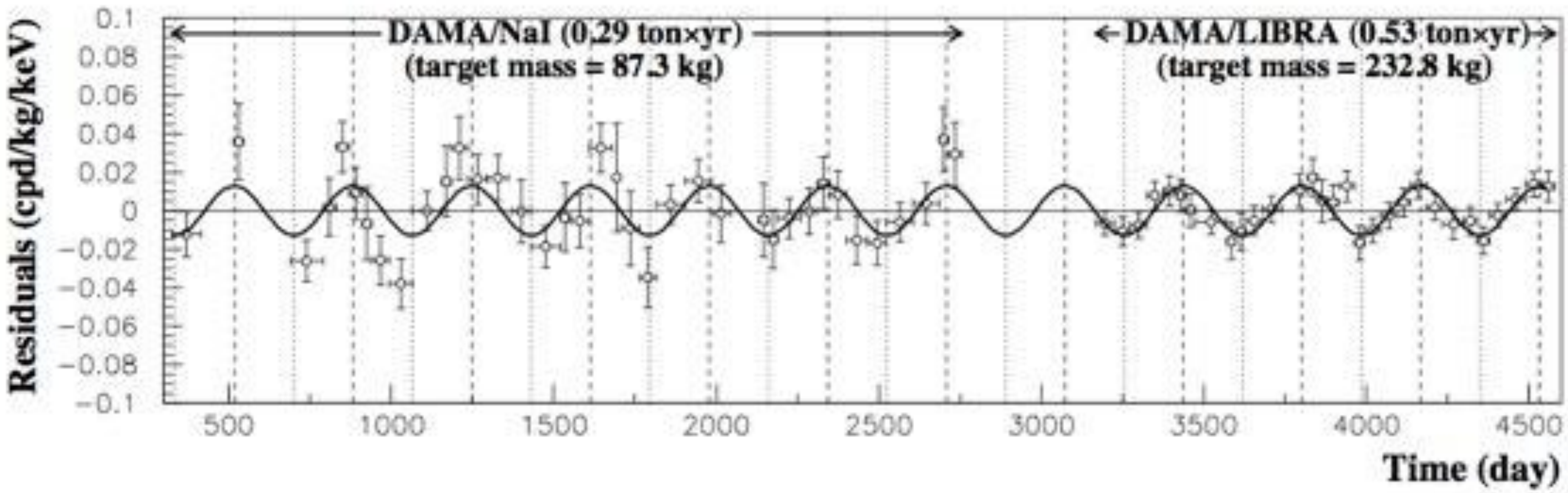
Supposedly the dark matter is relatively at rest in the galaxy, and the earth is moving through the galaxy at about 1/1,500 the speed of light. Thus we are relatively in a **wimp wind** at that speed. But as the earth circles the sun, in June we are moving relatively slower with respect to the wind, and in December we are moving relatively faster into the wind by 30 km/sec. The changing relative velocity causes the probability of interaction to also oscillate on a yearly basis.



DAMA Oscillation Detections

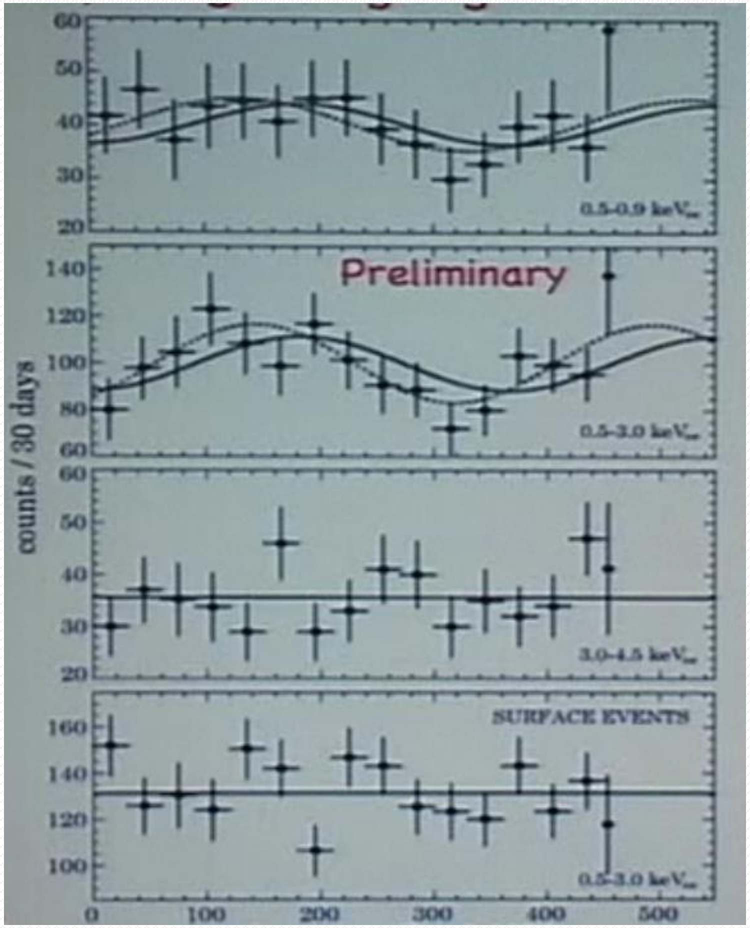
Two experiments have now detected oscillations.

DAMA/NaI and DAMA/LIBRA (250 kg Thallium doped NaI) in the Gran Sasso lab in Italy has detected an oscillating signal for many years, and now has a bigger detector that also detects them. The two detectors signals are in phase.



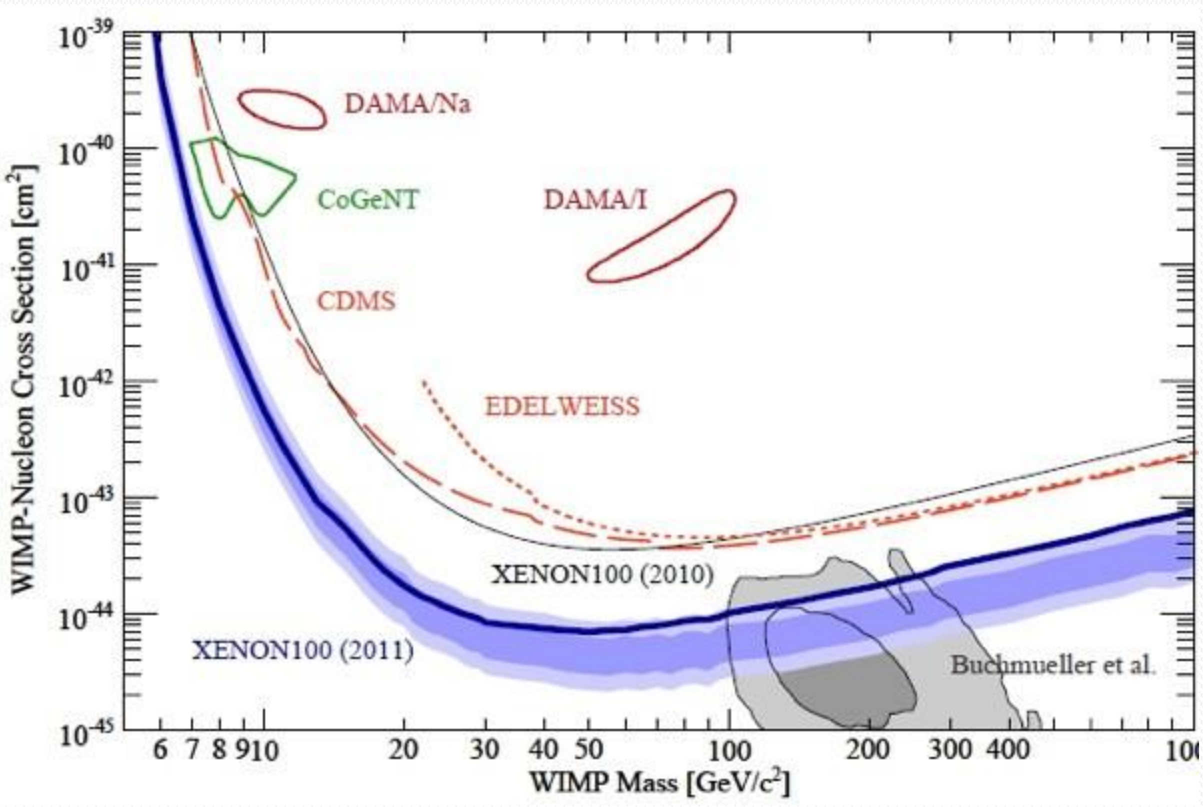
CoGeNT detection of oscillations

Last week at the APS meeting in Anaheim, CoGeNT (0.44 kg of Germanium) in the Soudan mine in Minnesota announced their detection of oscillations. They had 440 days of data. I am told that the CoGeNT peaks and the DAMA peaks are within the experimental error of a month.



Direct Conflict of Direct Detection Experiments

Xenon100 has a target of about 60 kg of Xenon, and sets a better limit. It detects no signal of WIMPs. The "cross section" is a measure of the strength or probability of interaction. The gray blob at the right is the prediction of a range of supersymmetry theories, which is now being probed. The next experiment of Xenon1000 of a 1000 kg of Xenon by 2015, will have a limit that touches the bottom of the graph and covers the whole main part of the supersymmetry region shown. (For metric aficionados, the bottom cross section is a zeptobarn or 10^{-21} the size of a large nucleus.)



Evolution of WIMPs

- In the big bang, at the earliest and hottest time, all particles are produced because the thermal energy is enough to provide the $E=mc^2$ to create the particles:

  $X + X \leftrightarrow q + \text{anti-}q$
- As the universe cools, it is no longer able to make the heavier WIMPs X, but they can still annihilate:
  - $X + X \rightarrow q + \text{anti-}q$
- As the universe expands farther, the short range weak interacting WIMPs can no longer interact, and their number stays constant, i. e. they “freeze out”.

The WIMP “Miracle”

- Using the known weak interaction strength, if the WIMP mass is between 100 GeV and 1,000 GeV (where the proton mass is about 1 GeV), the right amount of dark matter is formed. This is called the WIMP miracle.
- This makes them the right mass to create and search for in the Large Hadron Collider.
- It also means that WIMPs might be supersymmetric particle doubles of the regular force or interacting particles of the standard model.

Supersymmetric Particles

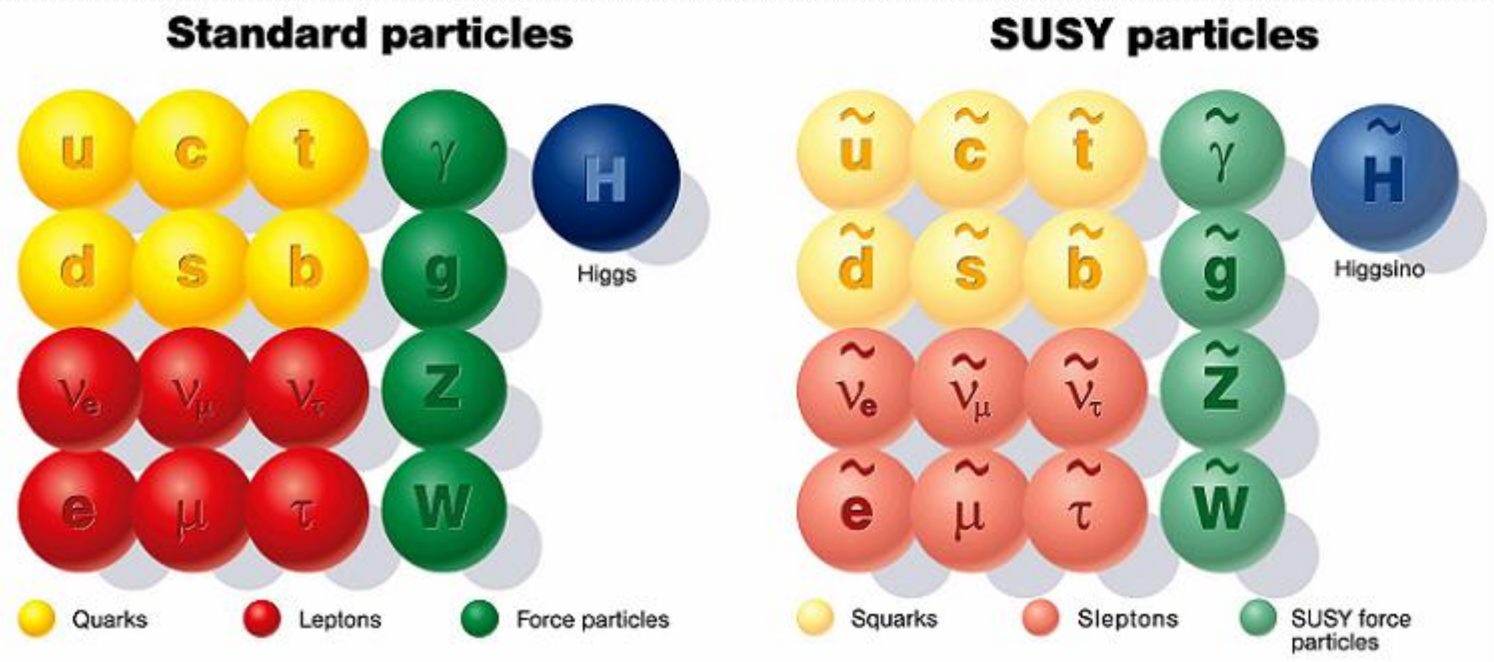
- In quantum mechanics, angular momentum of 1 or 2, etc. is understood to be due to orbital motion.
- Spin ½ arises from relativistic quantum mechanics, and is an intrinsic property of a quark or electron. (The proton's or neutron's spin ½ arises from coupling the spins of their three quarks.)
- Given the mystery of what the spin ½ is, we might ask if there is a supersymmetry made of adding or subtracting a spin ½ to or from each of the standard model elementary particles.

Supersymmetric Particles

- The charges and interactions of the new “supersymmetric particles” would be the same as their original particles, but their masses are expected to be hundreds of GeV.
- For neutral “force” particles, the spin zero Higgs would become the spin ½ higgsino. The supersymmetric spin 1/2 partners of the W^0 would be the Wino, of the Z^0 would be the Zino, and of the photon would be the photino, all marked with tildes.

Supersymmetric Partners and WIMPs

The WIMP could be a spin ½ Wino, Zino, Higgsino, or photino, or a linear superposition of them. The lightest of the above is assumed to be the only stable one, due to an imposed symmetry called R symmetry which requires them to be created or destroyed in pairs. It also requires that in the decay of each there is another supersymmetric particle. The lightest and therefore stable one is called the LSP and would be the dark matter WIMP.

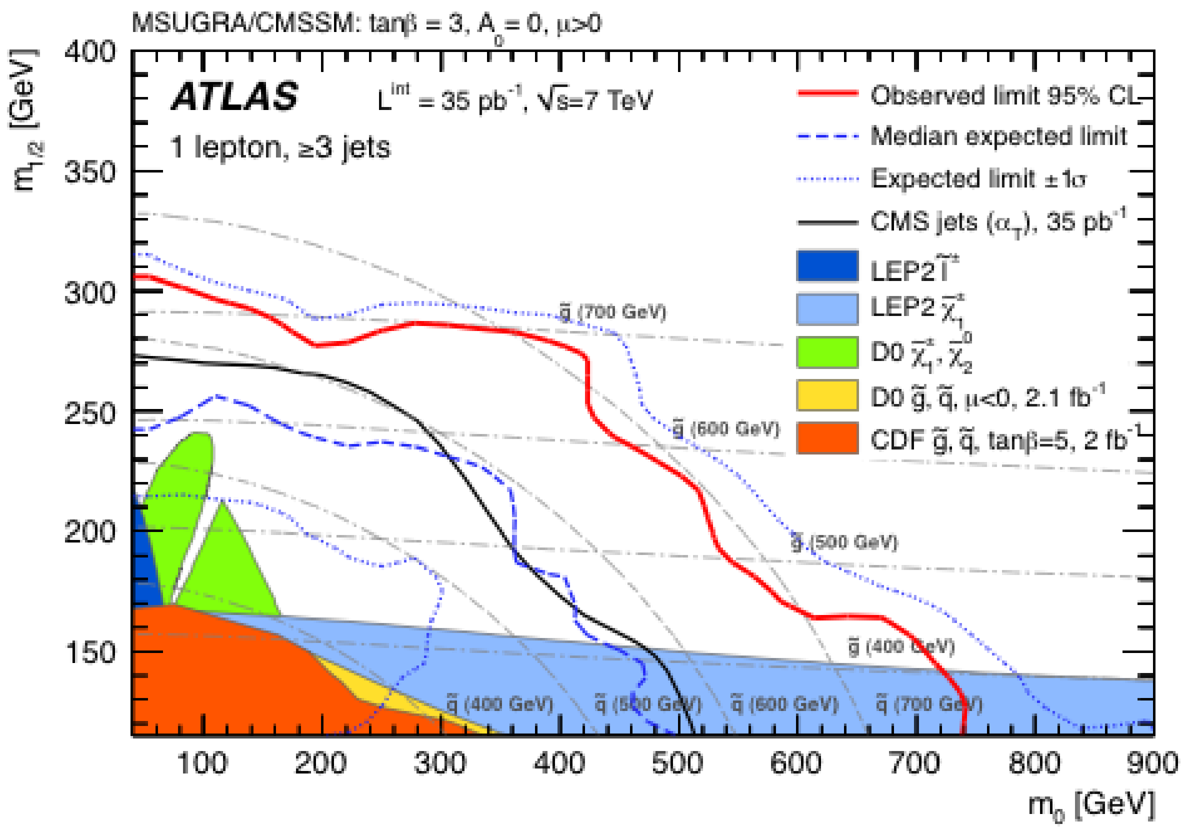


Large Hadron Collider Very Early Limits

Much more data (x60) is expected before the next shutdown at the end of 2012 in ATLAS (red limit) and CMS (black limit) experiments.

The Higgs will be discovered by then or something is wrong.

The graph shows excluded regions with a supersymmetry model where $m_{1/2}$ is around the WIMP mass, and m_0 is around the squark masses.



Future Reaches of the LHC for SUSY particles

For various processes and models we see that final results could find spin ½ “inos” to 1400 GeV, and squarks or sleptons to 5,000 GeV

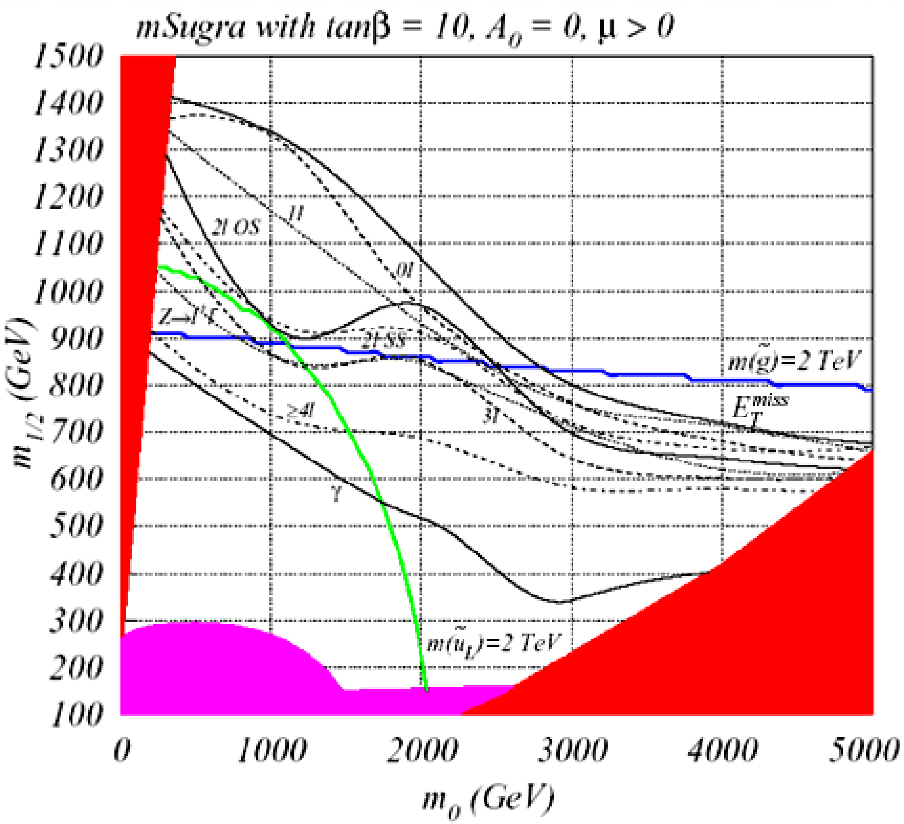
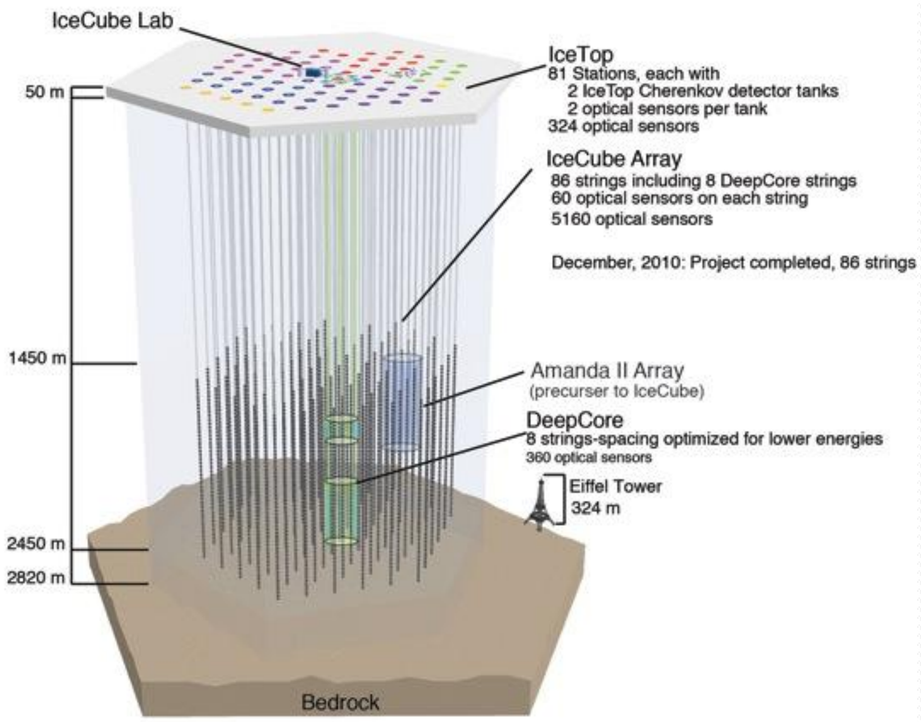


Figure 3. LHC reach for several channels extract from ref. [11]. The E_T missing inclusive channel is the upper solid line. Also shown is gluino mass contour of 2 TeV.

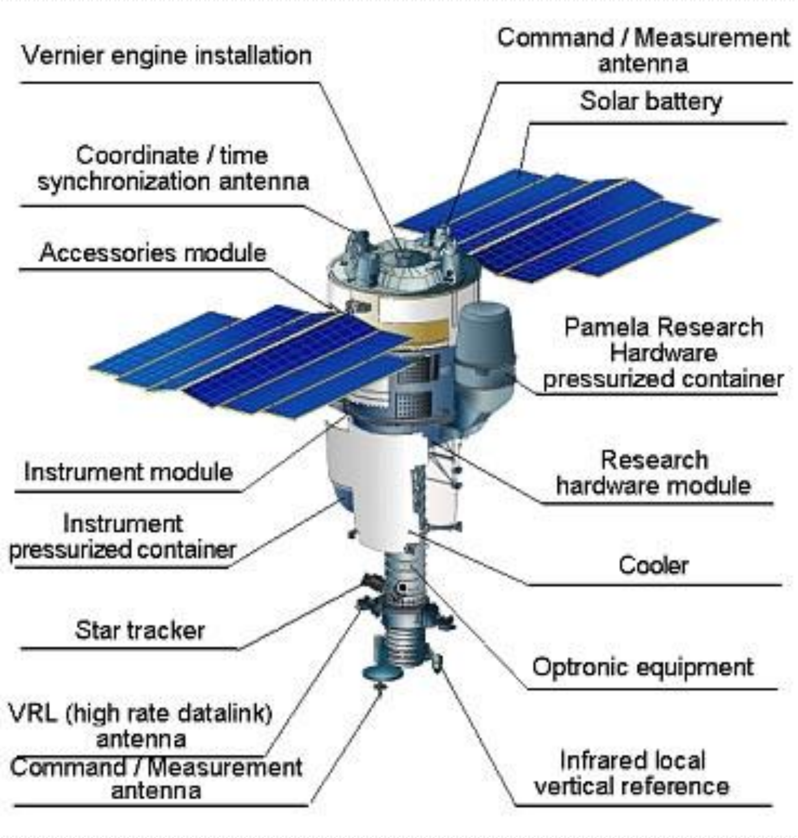
IceCube at the South Pole for Indirect WIMP Detection
Depth of the photocell strings is from 1.45 km to 2.45 km. The array has 5,160 optical sensors.



- Also called the cubic kilometer array, the upcoming neutrinos make muons that leave long tracks and indicate the direction of their source.
- The sources of those neutrinos coming "up" from below could be black holes, gamma ray bursters, or supernova remnants. The data that IceCube will collect will also contribute to our understanding of cosmic rays, supersymmetry, weakly interacting massive particles (WIMPS), and other aspects of nuclear and particle physics.

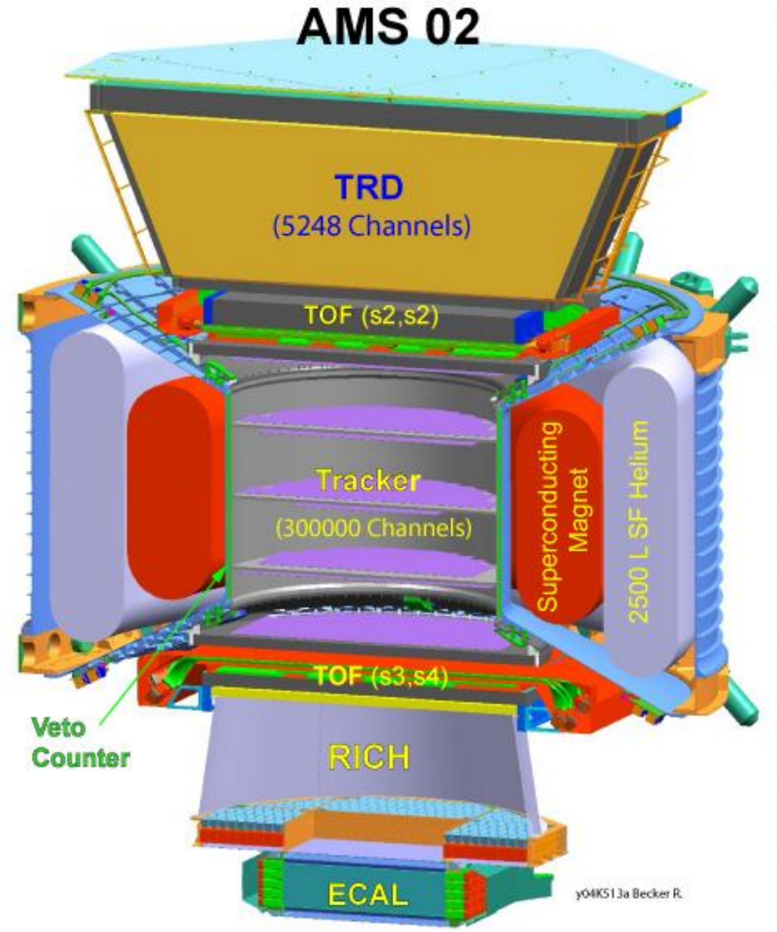
Indirect WIMP Detection Satellites

Fermi, to the left detects gamma rays (photons) that might come from positron annihilation, where the positrons were created in dark matter annihilations. PAMELA, to the right, detects cosmic ray positrons, antiprotons, and light nuclei. New phenomena have been detected, but are they astrophysical or dark matter in origin?



Alpha Magnetic Spectrometer

This is about to be launched by the Endeavor Space Shuttle.
The spectrometer has about 100 times the area of PAMELA to detect positrons, antiprotons, and antinuclei, if they exist.



Are We There Yet?

- It seems that within the next 5 years, we will indirectly or directly detect dark matter, if our ideas of a WIMP are correct.
- We should also produce them in the LHC.
- The final identification and establishment of the properties of dark matter will require agreement of several experiments of each type.