Current Perspectives on Dark Matter

Zackaria Chacko

University of Maryland, College Park

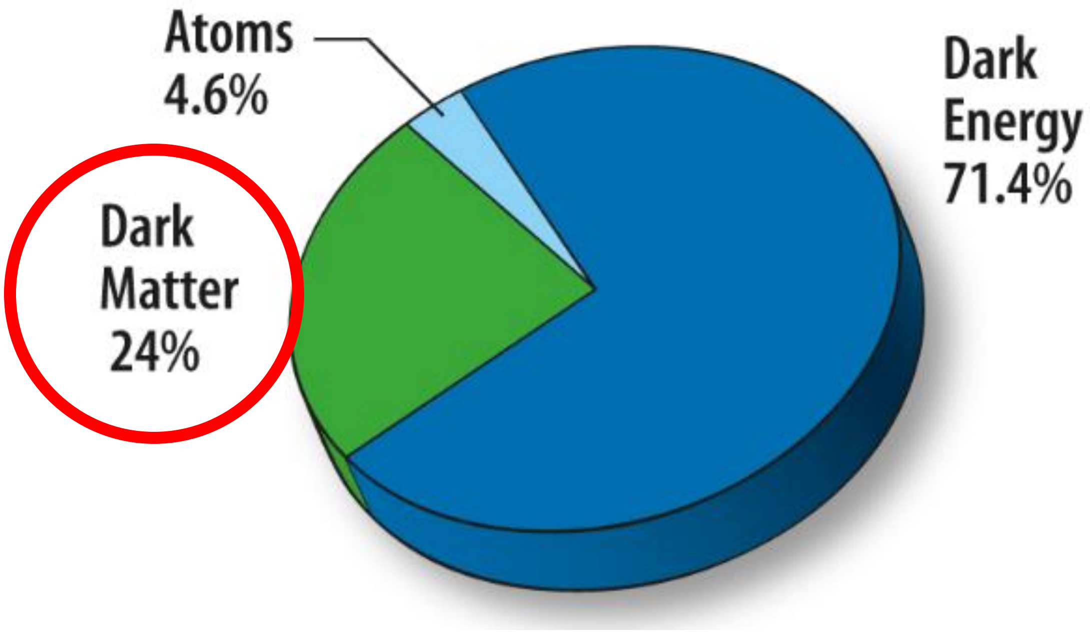
Introduction

Dark matter was proposed by Swiss astronomer Fritz Zwicky in 1933 to account for the motion of galaxies in galaxy clusters.

Zwicky was also the first to consider neutron stars and gravitational lensing. However, at the time none of these ideas was taken seriously.

Today, the situation is different.

Astrophysical and cosmological observations have led to an accurate determination of the energy budget of the universe → ΛCDM model.



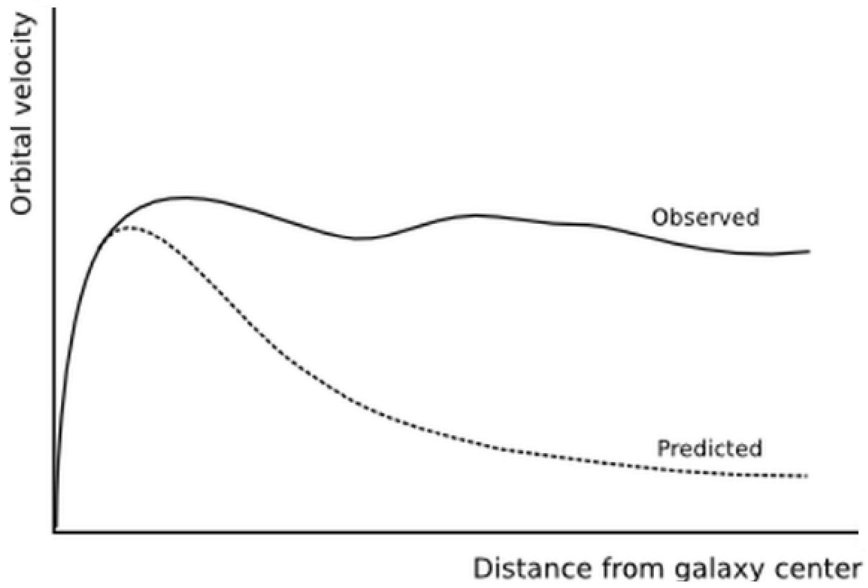
Ordinary visible matter makes up just 5% of the energy budget. Some kind of invisible dark matter makes up 25%. The rest is “dark energy”.

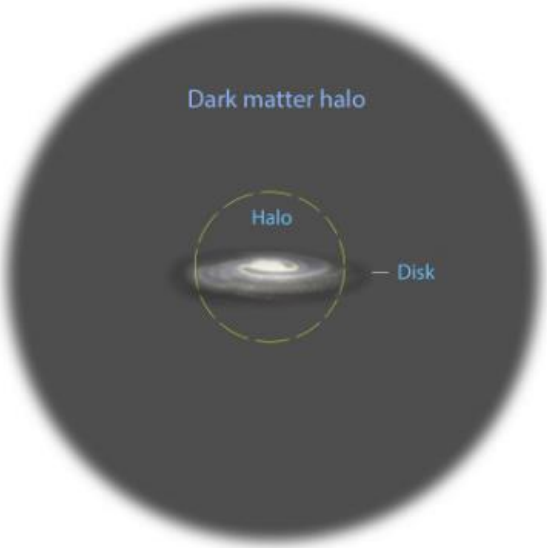
The nature of the particles of which dark matter is composed remains a complete mystery.

Observational Evidence for Dark Matter

- **Galaxy Rotation Curves**

The observed motion of stars in galaxies cannot be accounted for on the basis of the visible matter alone.





Milky Way model

The motion can be explained if the galaxy is surrounded by a nearly spherical halo of dark matter.

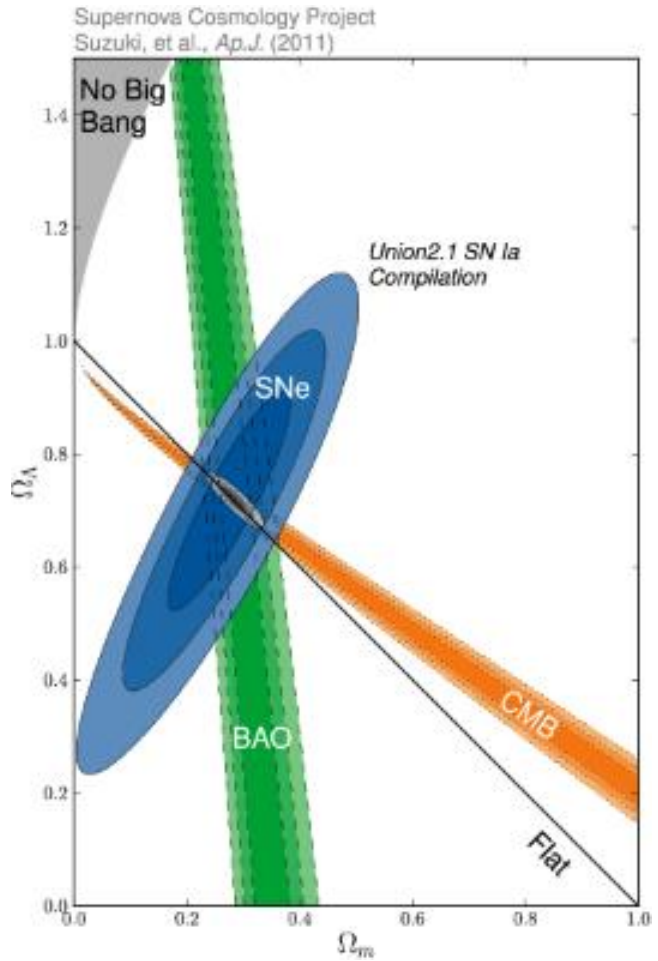
- **Galaxy Clusters**

Dark matter also provides an explanation for the motion of galaxies in galaxy clusters.

The total mass of the cluster can be independently inferred from gravitational lensing. Visible matter contribution is again too small.

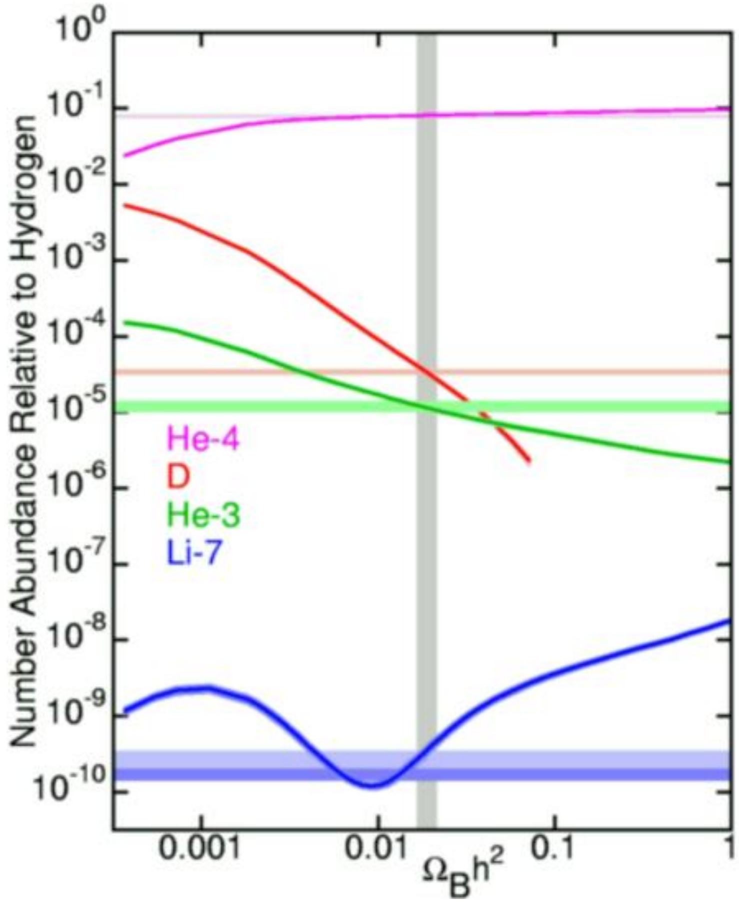
- **Cosmology**

The total matter density in the universe can be determined from the CMB, large scale structure, and supernovae independently.



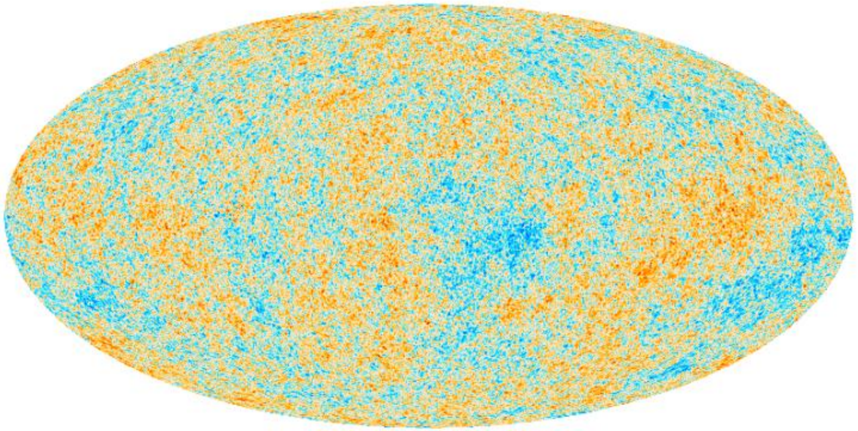
These three different measurements are consistent with each other!

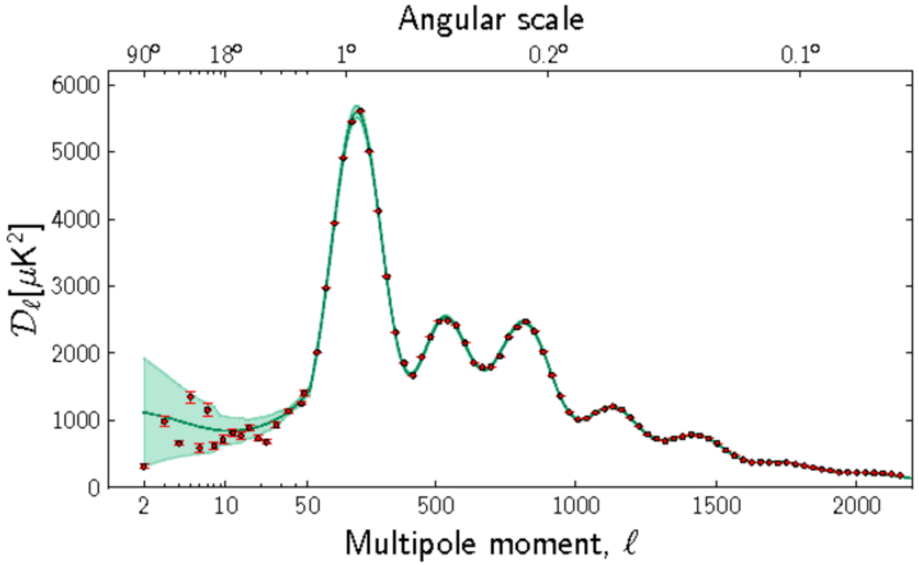
From Big Bang Nucleosynthesis (BBN), we can determine the density of free baryonic matter.



The baryonic matter density obtained is below the total matter density obtained from cosmology. An additional contribution is needed!

The anisotropies in the CMB allow us to determine the total matter density and the density of free baryonic matter independently.



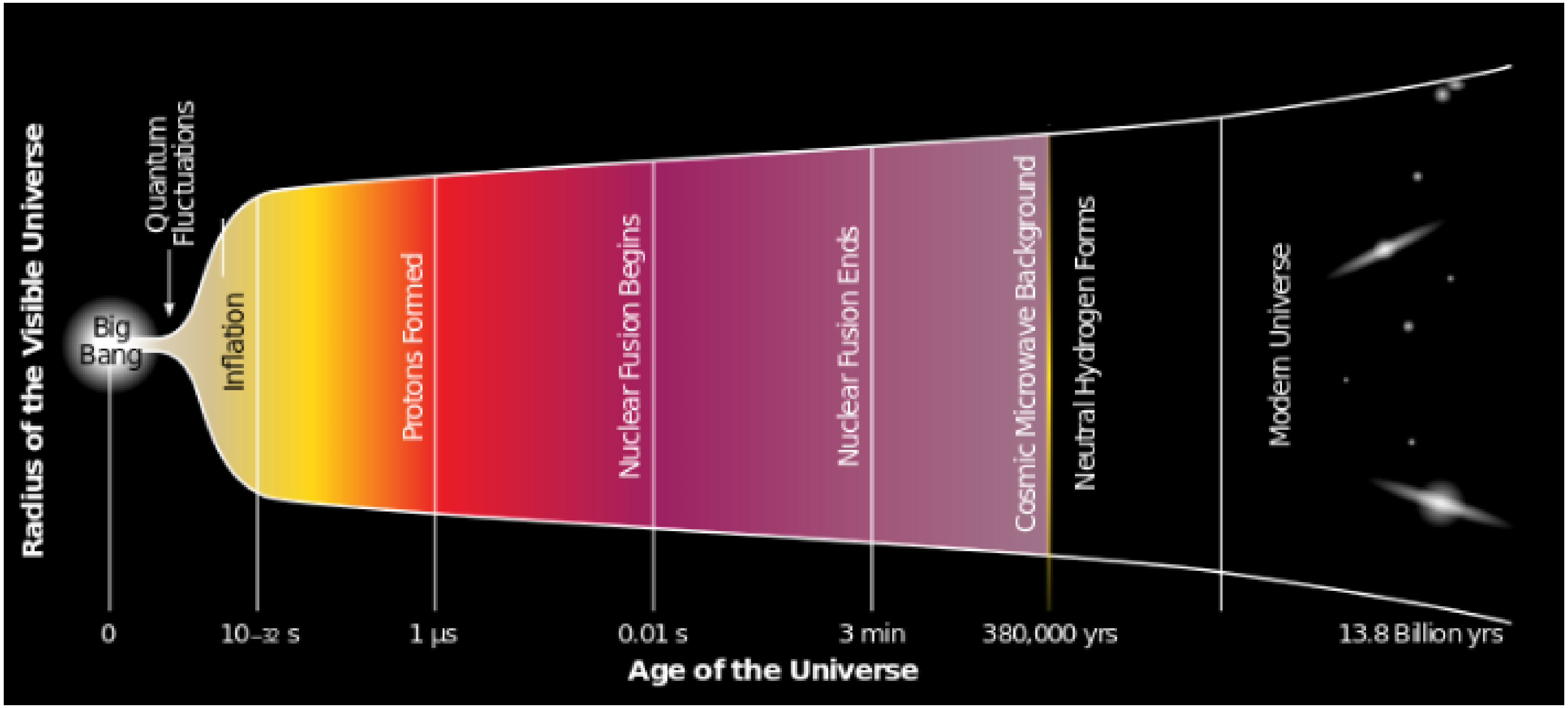


The heights of the CMB peaks depend on the total matter density.

The relative heights of the even and odd peaks depend on the density of free baryonic matter.

A consistent fit to the CMB data requires dark matter!

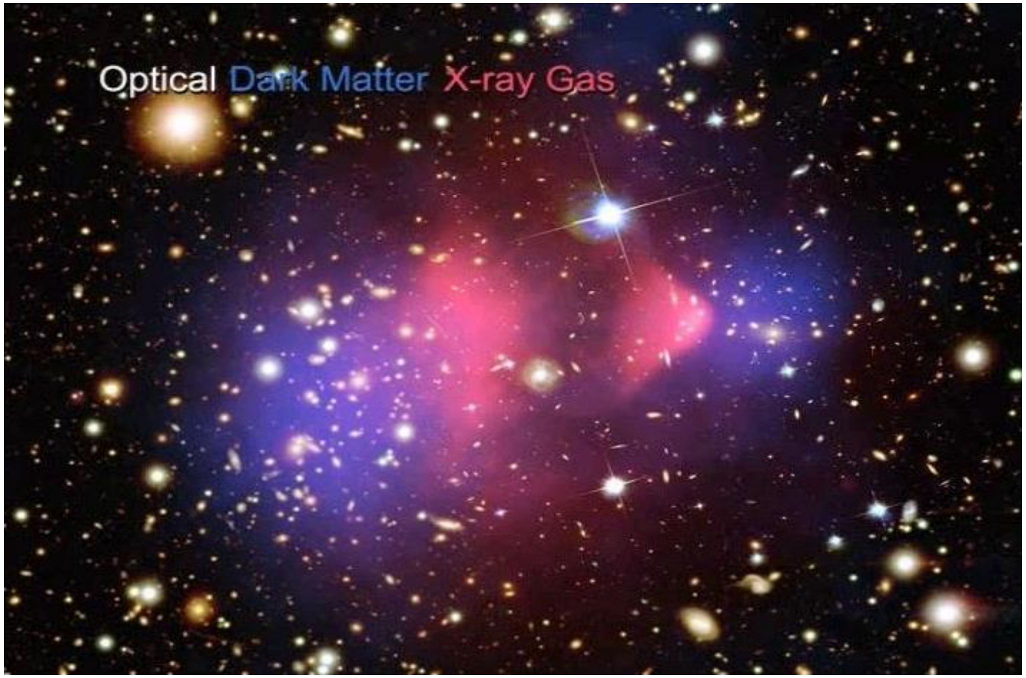
The evidence for dark matter comes from many different epochs in the history of the universe, and from many different scales.



Overall, the evidence for dark matter is overwhelming!

Could the data be explained by modifying gravity instead? No!

Gravitational lensing allows us to study the distribution of mass in galaxy clusters.



The Bullet Cluster arose from the collision of two smaller clusters.

The mass distribution is different from the distribution of visible matter. While visible matter collided, dark matter passed through!

Does dark matter have to composed of particles outside the SM?

The obvious SM candidate is the neutrino, but this is excluded. The Pauli principle prevents neutrinos from forming dwarf galaxies.

The other possibility is that dark matter is made up of bound objects composed of ordinary SM particles, such as primordial black holes.

- **must already have been bound in the early universe (CMB, BBN).**
- **bounds on clumping of dark matter rule out masses > 10^4 M_{sun} .**
- **lensing bounds rule out masses between 10^{-7} and 10^2 M_{sun} .**

There are allowed windows, but . . .

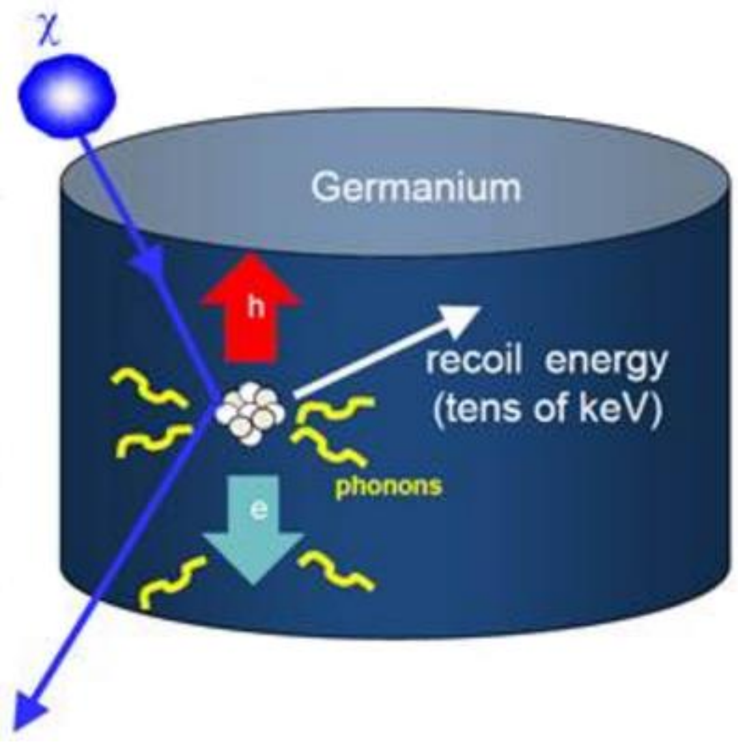
It is a challenge to explain how such objects formed, and their stability in the high temperature and pressure of the early universe.

The most likely possibility is that dark matter lies outside the SM.

Properties of Dark Matter

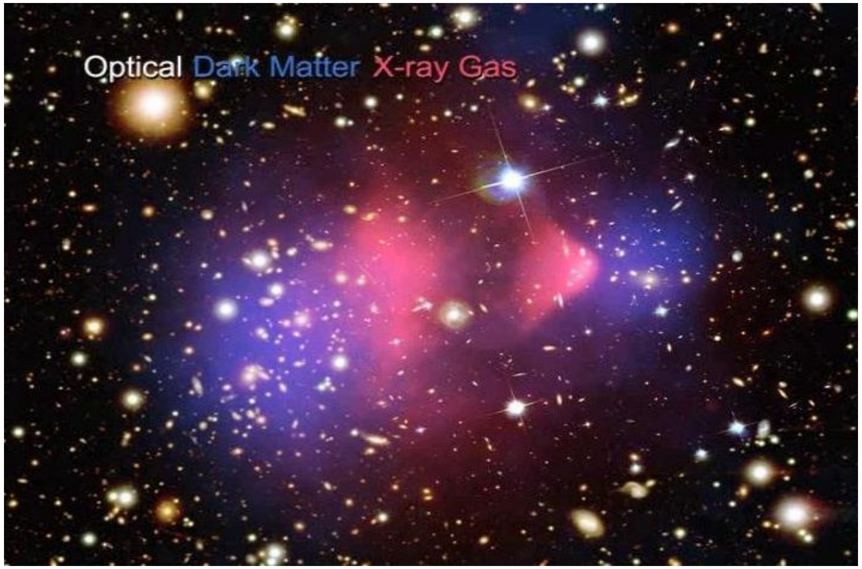
- The electric charge of dark matter is zero or vanishingly small.
- Dark matter doesn't feel the strong nuclear force.
- Whether dark matter feels the weak force is still an open question.

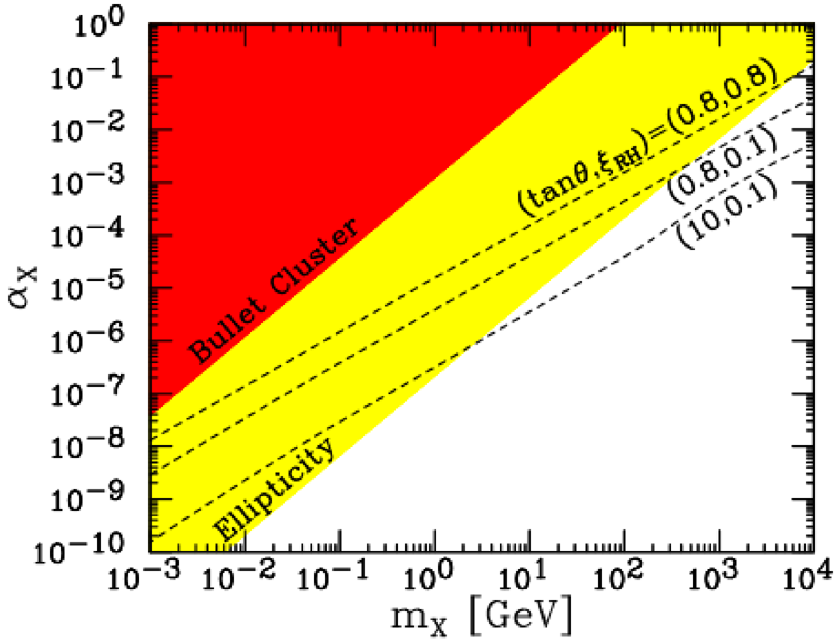
CDMS



Dark matter self-interactions are constrained by the ellipticity of the dark matter in galaxies, and by the bullet cluster.

The limits on self-interactions are weaker for heavier dark matter.





Dark matter today does not exert much pressure. It is nonrelativistic .

Almost everything we know about dark matter is through the effects of its gravitational interactions!

What could dark matter be?

Search for an analogue among the SM particles that contribute to the energy density of the universe today.

- **Neutrinos survive today as thermal relics of the Big Bang.**

Could the constituents of dark matter also arise as thermal relics? → "Weakly Interacting Massive Particle (WIMP) dark matter".

- **Protons, neutrons and electrons survive today because there were more of them in the early universe than their antiparticles.**

Could dark matter arise from an asymmetry between dark matter particles and antiparticles? → "Asymmetric Dark Matter (ADM)".

Dark matter could arise as part of solution to another problem of SM .

Strong CP Problem → "Axion dark matter".

And, of course, could be something completely different .

WIMP Dark Matter

`Natural units' $\hbar = c = 1$

- mass of the proton ~ 1 GeV
- mass of the Higgs ~ 100 GeV ⟵ weak scale
- energy of the LHC ~ 10 000 GeV

An Important Observation

If there was an extra neutrino with mass near the weak scale, it would constitute an excellent cold dark matter candidate.

Lee & Weinberg
Vysotsky, Dolgov & Zeldovich

This observation can be generalized. A neutrino has weak scale cross sections with the other SM particles.

Particles with weak scale masses and weak scale cross sections with the SM make excellent dark matter candidates!

⇩

"Weakly Interacting Massive Particle" (WIMP) dark matter

WIMPs arise naturally in many well-motivated extensions of the SM, including supersymmetry.

The WIMP framework requires dark matter to have interactions of weak scale strength with the SM!

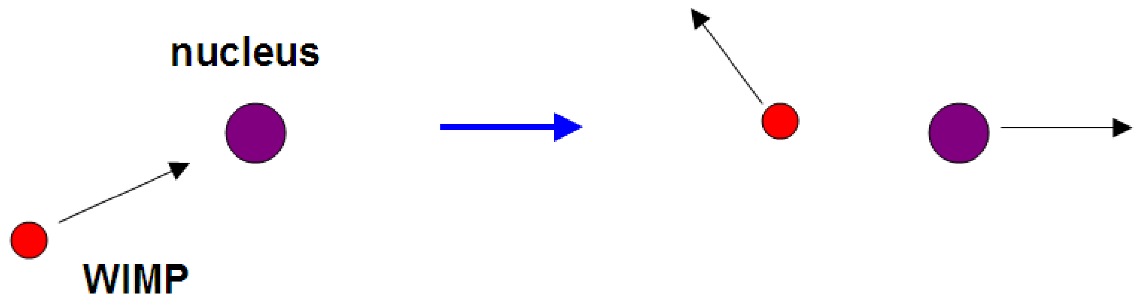
Many experiments are searching for evidence of this.

These experiments are primarily of three types.

- **Direct detection**
- **Indirect detection**
- **Collider searches**

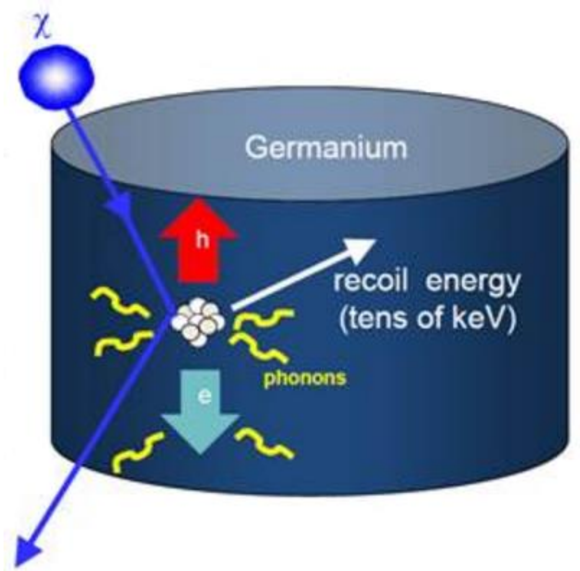
Direct Detection

Direct detection experiments search for the recoil of a nucleus after the impact of a dark matter particle.

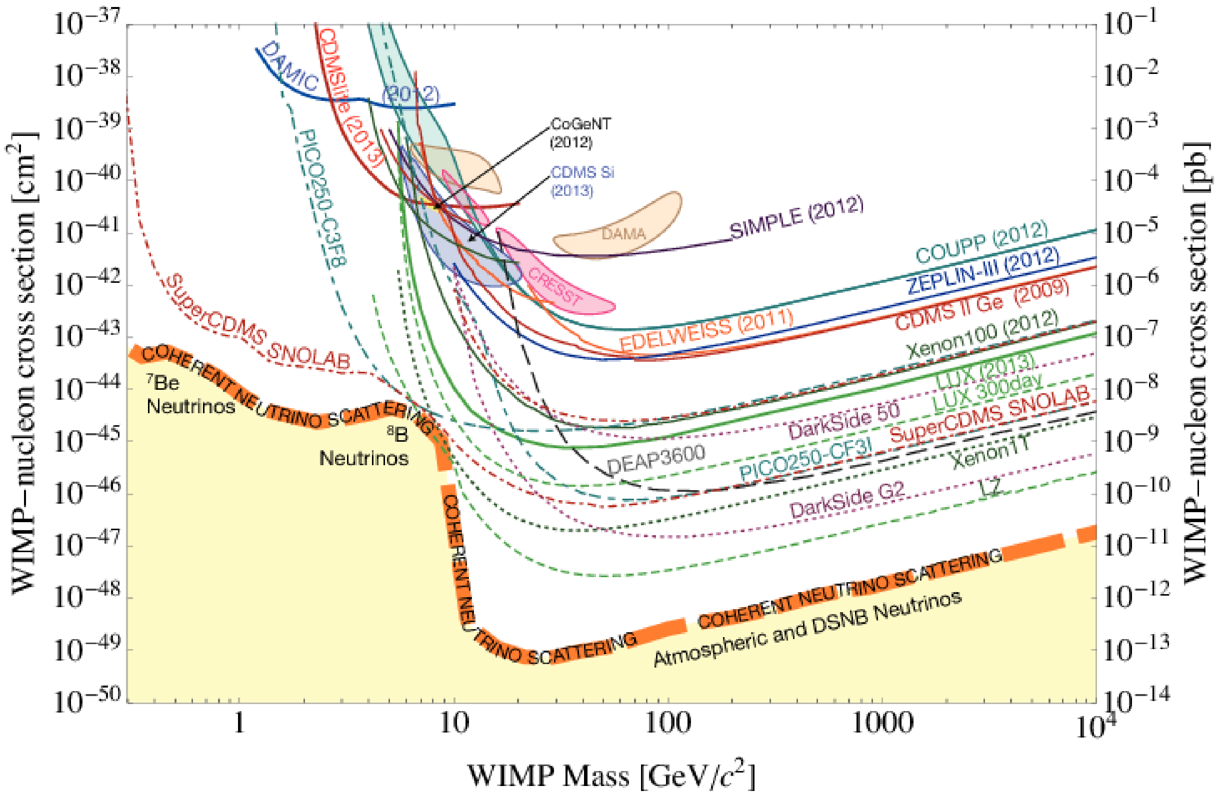


Experiments differ in their nuclear targets, and ways of measuring recoil energy.

CDMS



The current limits are very strong, and will get even better. Naively, weak scale cross sections are already excluded!



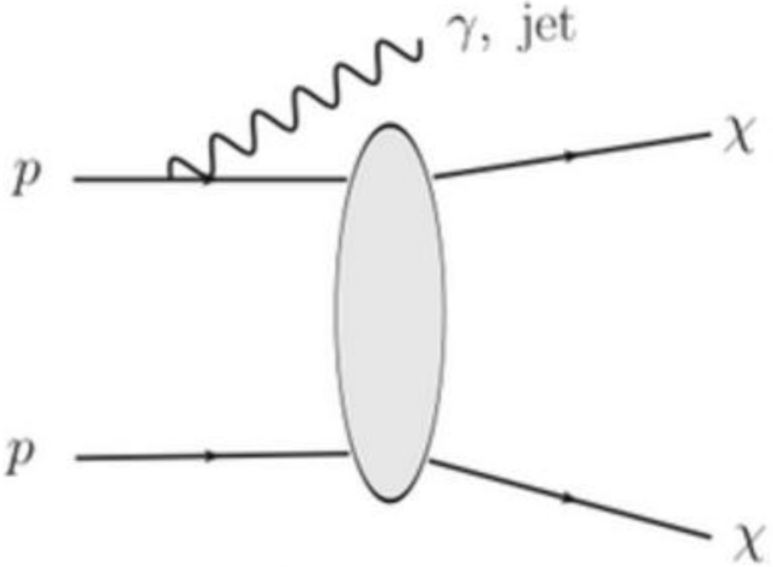
However, these limits assume weak scale coupling to light quarks.

The limits are weaker if dark matter is very light, or of it couples preferentially to heavy quarks, to leptons, or to nuclear spins.

Eventually, most of these scenarios will also be probed!

Collider Searches

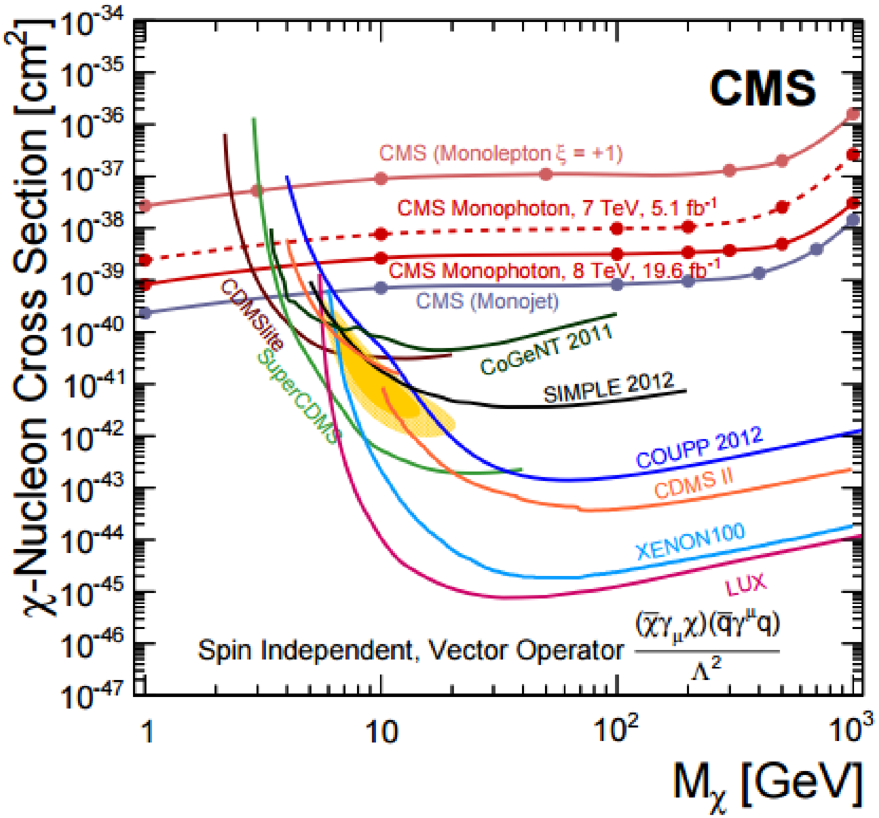
Colliders such as the LHC seek to directly produce dark matter.

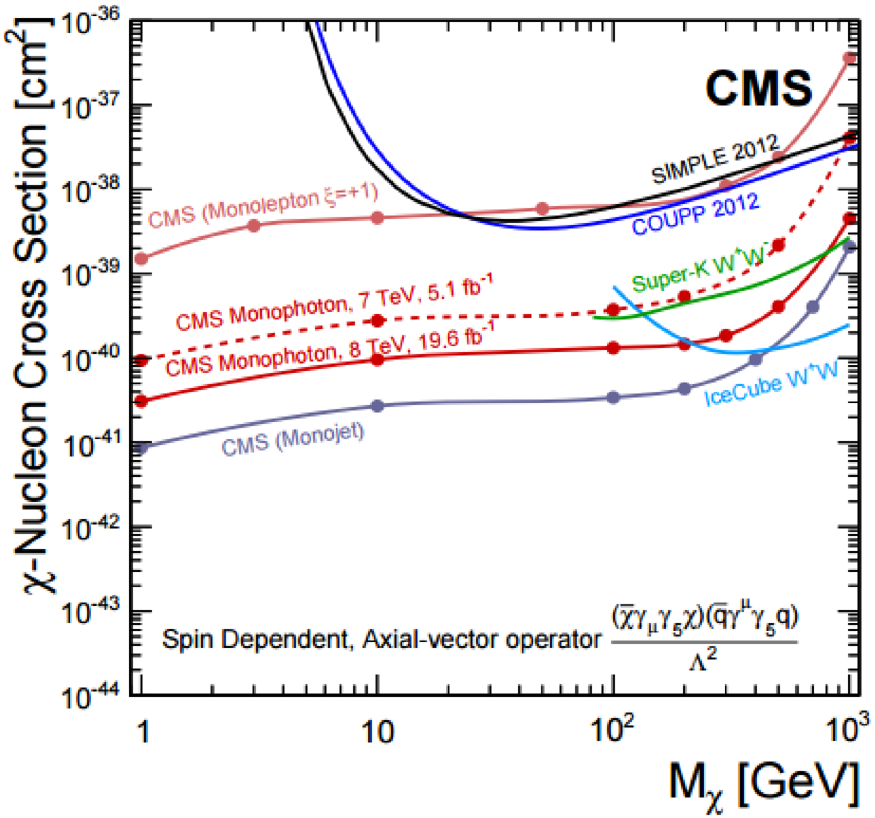


Since dark matter itself is invisible, the signal involves the recoil of SM particles, such as photons or jets, against something unseen.

The largest backgrounds involve neutrinos.

The current LHC limits are stronger than the direct detection for very light WIMPs, and for the case when dark matter couples to nuclear spin.

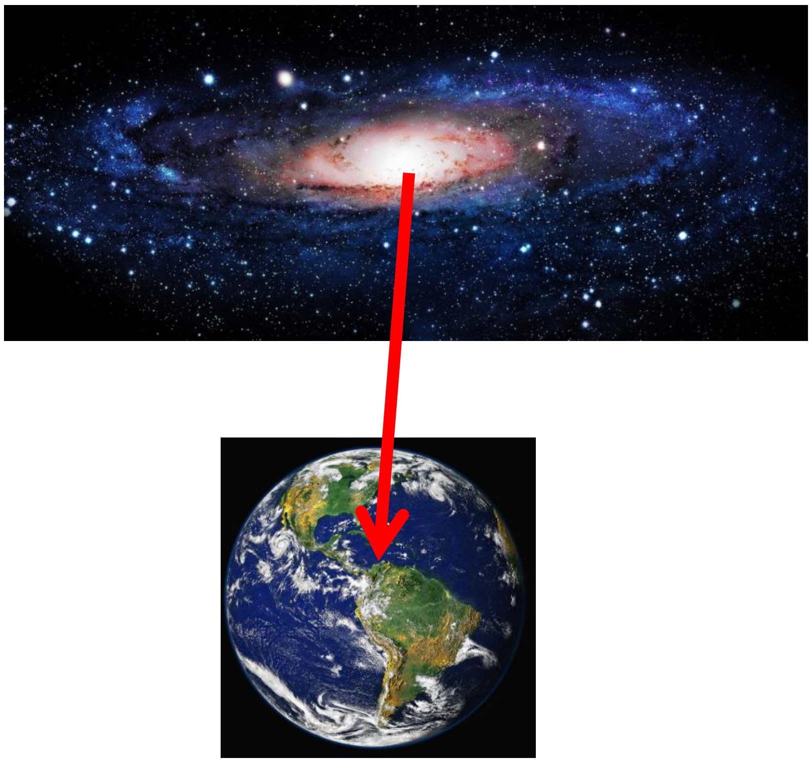


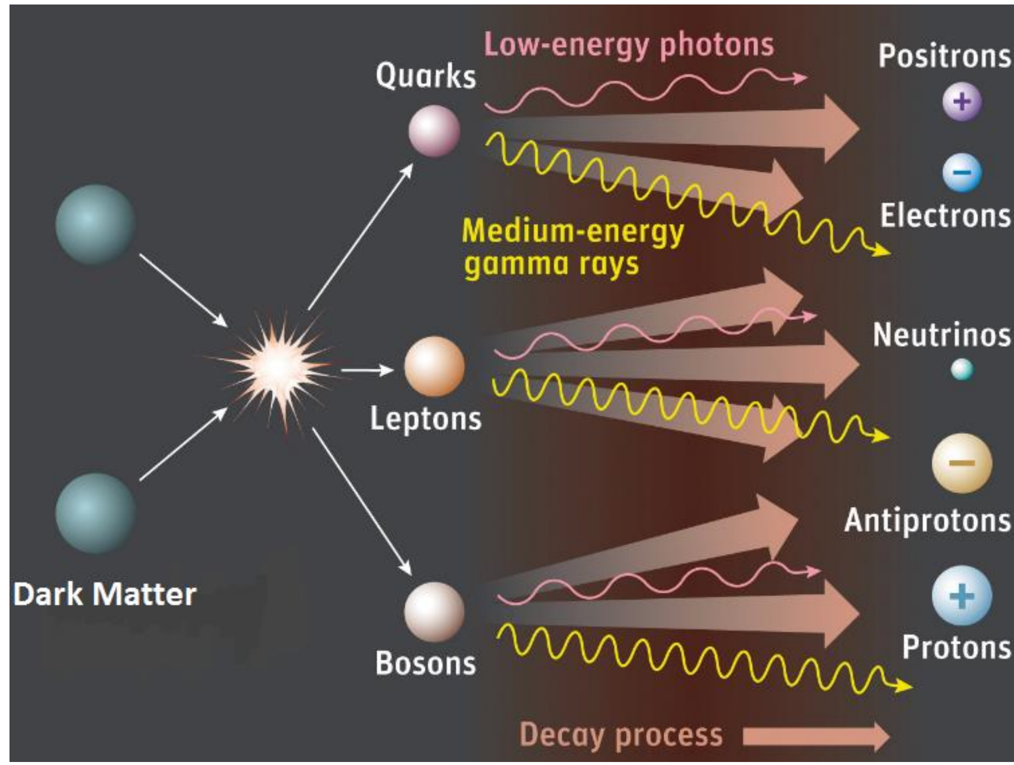


The LHC searches are complementary to direct detection.

Indirect Detection

Indirect detection involves searching for the visible products of WIMP annihilation from regions of the universe that are rich in dark matter.





The annihilation products that are being searched for include photons, neutrinos, positrons and anti-protons.

At present, there is an excess of gamma rays from the galactic center over the expected astrophysical background. **(Goodenough & Hooper)**

The signal reproduces the expected morphology of dark matter!

The Economist

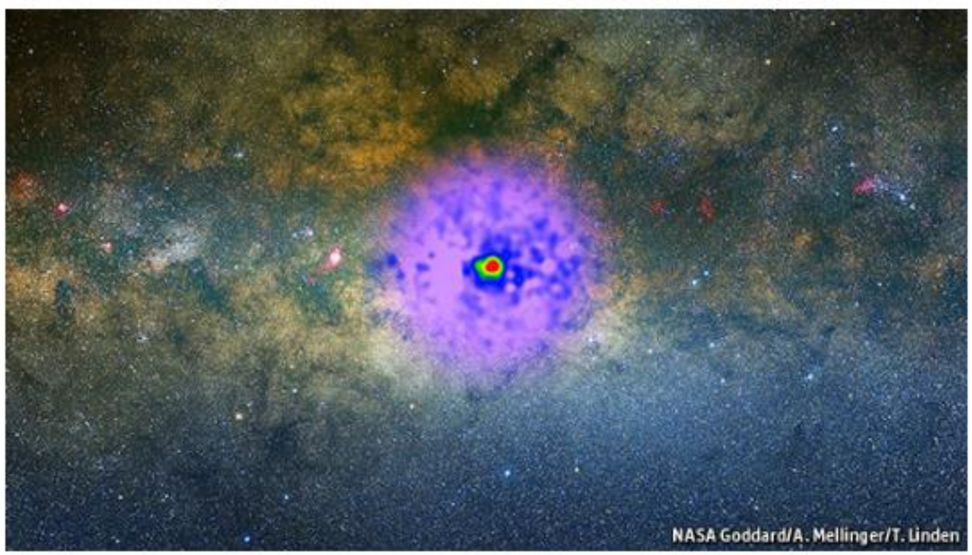
Science & technology

Dark matter

Envisaging the invisible

Powerful gamma rays from the centre of the Milky Way look ever more like signs of an elusive part of the cosmos

Nov 14th 2015 | From the print edition

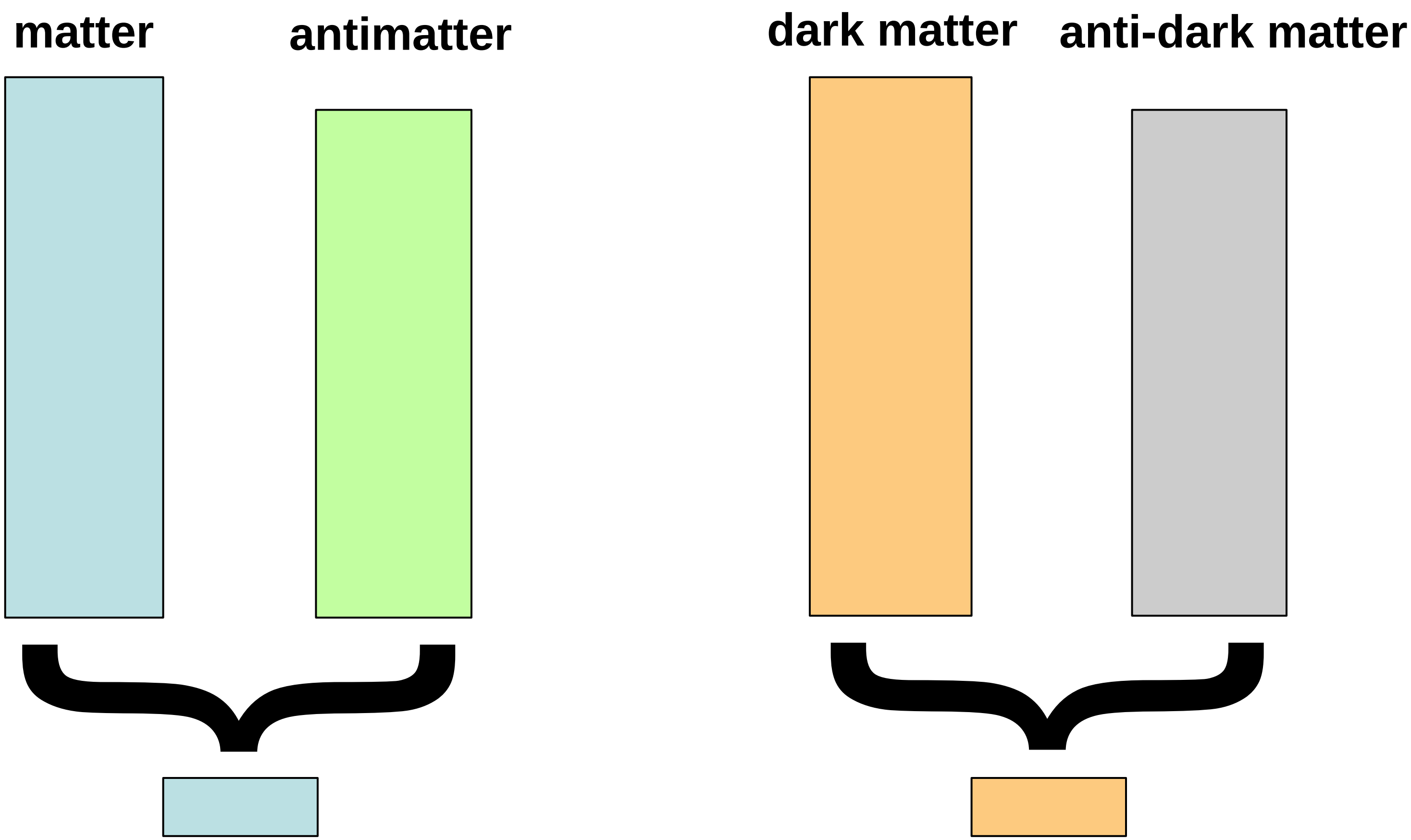


For confirmation, we would need to see the same signal elsewhere.

Asymmetric Dark Matter

The universe we see consists of matter and not antimatter.

However, this arose from a tiny (~ 1 part in 10^{10}) asymmetry between matter and antimatter in the early universe.



Something similar could have occurred with dark matter.

Nussinov;
Gelmini, Hall & Lin

The symmetric component of dark matter must have annihilated away completely.

If it annihilated into SM states, there must be sizable interactions between the visible and dark matter sectors.

- Direct detection
- Collider searches

However, indirect detection signals are often absent.

In many realizations of ADM, the asymmetry in the dark sector is closely tied to the asymmetry between matter and antimatter.

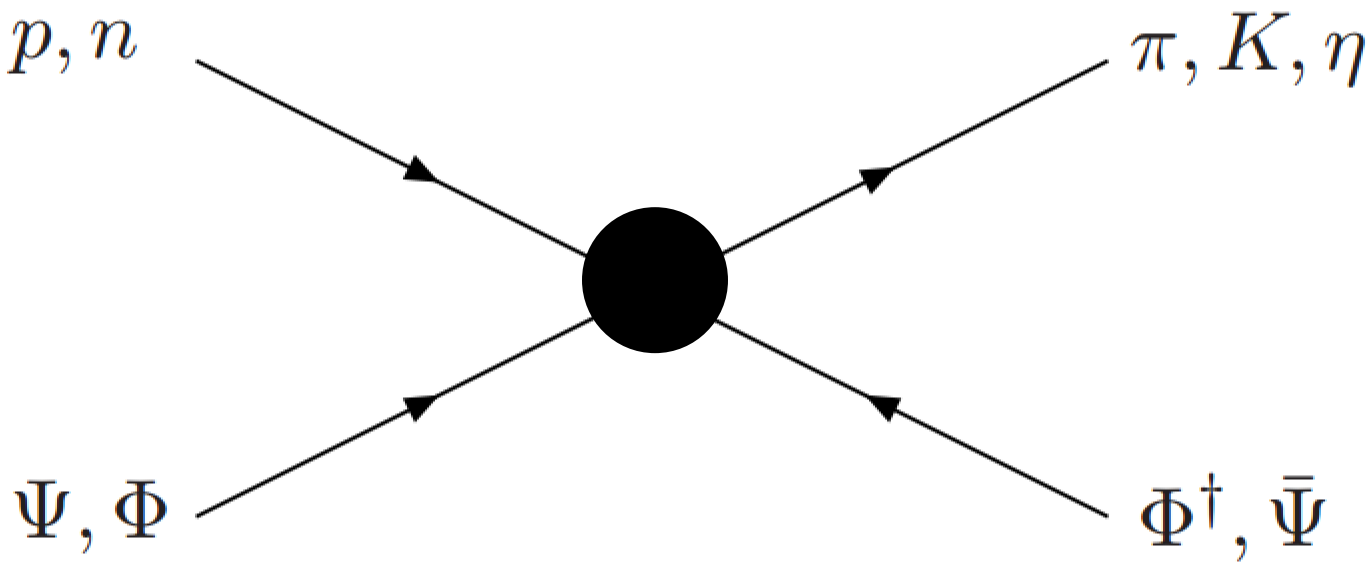
$$n_b - n_{\bar{b}} \simeq n_\chi - n_{\bar{\chi}}$$

Then the factor of 5 difference between the contributions of visible matter and dark matter to the energy of the universe can be explained if the dark matter mass is ~ 5 GeV.

ADM can give rise to some unusual signals.

If dark matter carries baryon number, "induced proton decay".

Davoudiasl. Morrissey, Sigurdson & Tulin



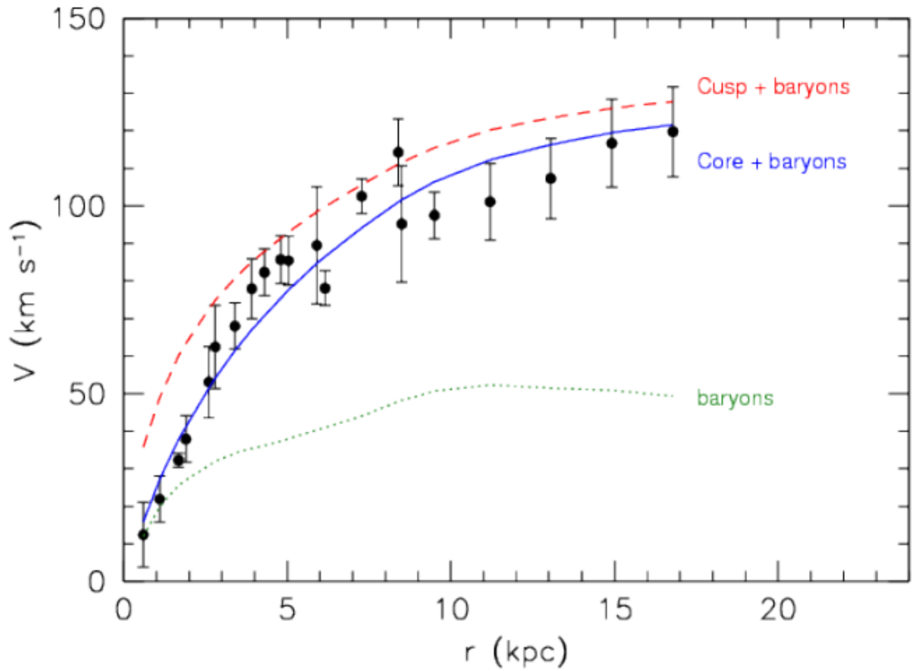
Self-Interacting Dark Matter

There are discrepancies between the predictions of collisionless cold dark matter (CDM) and the observed structure on small scales.

- **Missing Satellites** — **Weinberg, Bullock, Governato, de Naray & Peter**
- **Cusp versus Core**
- **Too Big to Fail**

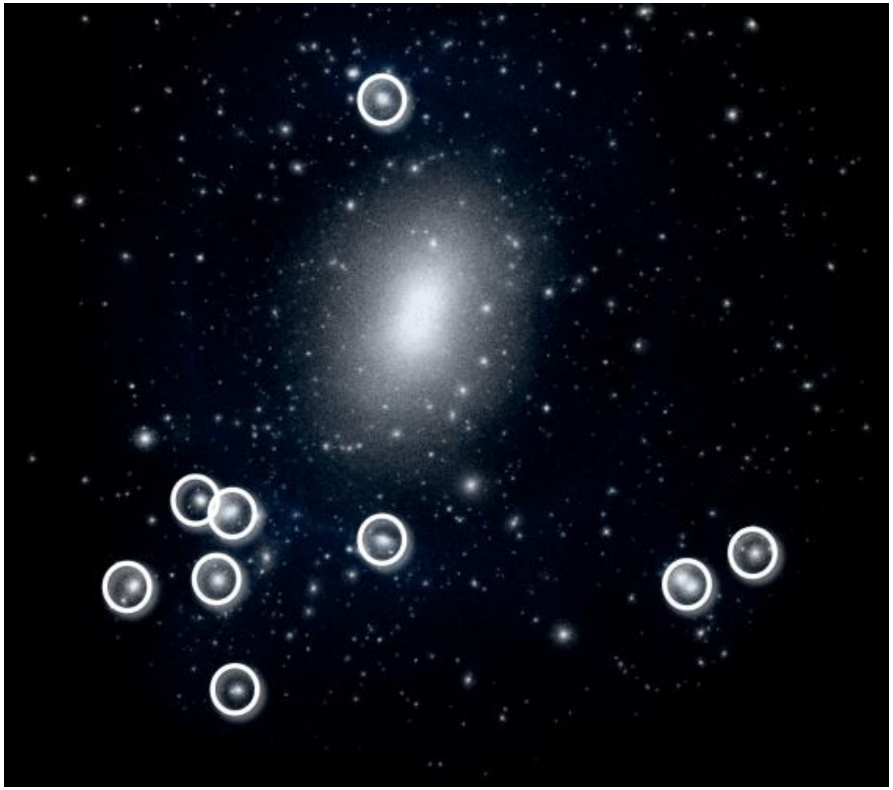
Cusp versus Core

Collisionless cold dark matter predicts cuspy halos whereas the data from galaxy rotation curves indicates constant density cores.



Missing Satellites

Collisionless cold dark matter predicts an order of magnitude more satellite galaxies of the Milky Way than are observed.



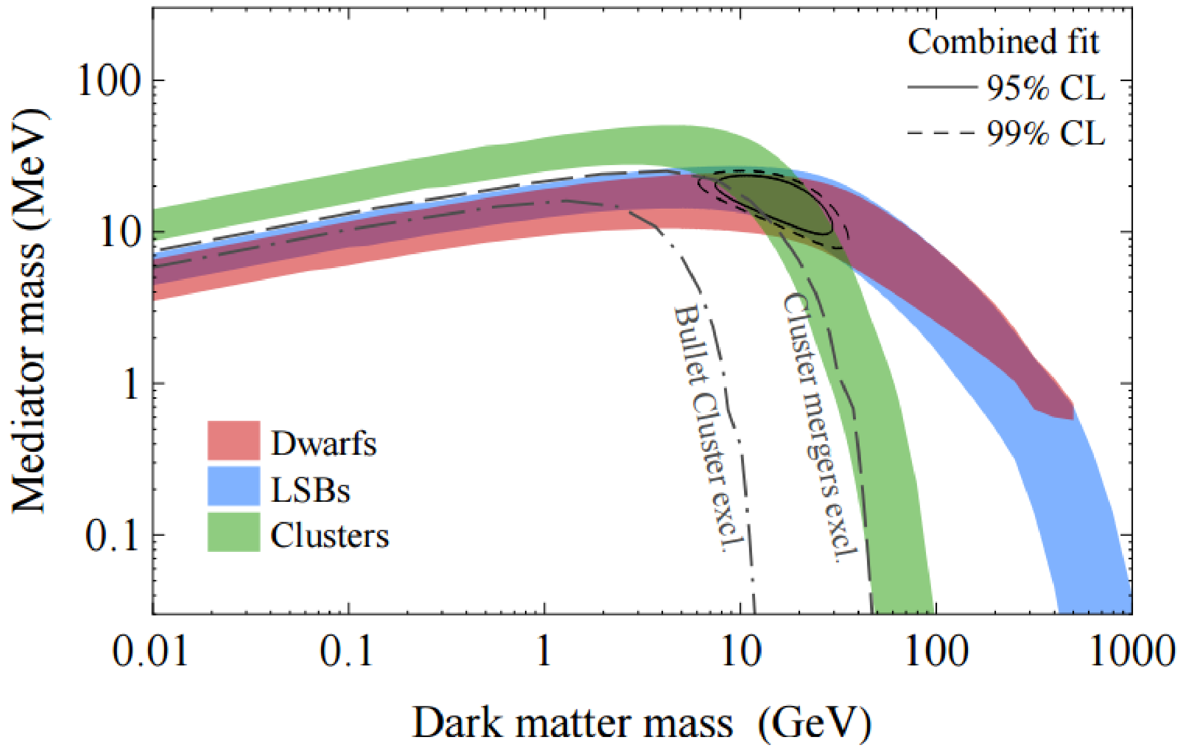
Too Big to Fail

Collisionless cold dark matter predicts larger satellite galaxies than any which have been observed in the Milky Way.

Dark matter self-interactions can solve these small scale anomalies.

To avoid constraints, the cross section must be velocity dependent.
The force is mediated by a light particle!

One possibility is dark matter carries charge under a “dark photon”.



The masses of dark matter and the dark photon can be pinned down.

Kaplinghat, Tulin & Yu

More General Dark Sectors

If dark matter is a thermal relic, we expect it to have a weak scale mass and cross section to realize the observed abundance.

However, instead of annihilating into SM states, like a conventional WIMP, it may instead annihilate into lighter states in a hidden sector.

There are then a few distinct possibilities.

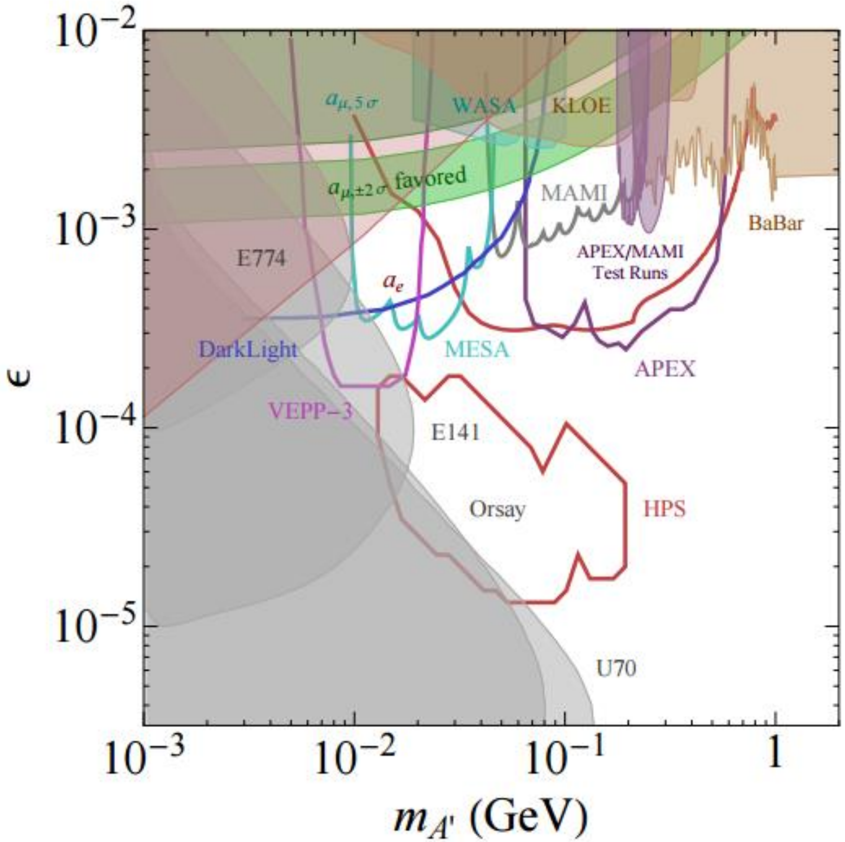
- **These lighter states decay back to the SM at later times, as in the "secluded dark matter" scenario.**
  Finkbeiner & Weiner
  Pospelov, Ritz & Voloshin
- **These lighter states survive today as dark radiation.**
  Feng & Kumar
- **These lighter states annihilate into SM or dark radiation, but a fraction survive as thermal relics – multicomponent dark matter.**

More generally, dark matter could be composed of many different components from unrelated sectors.

Secluded Dark Matter

In this scenario, dark matter annihilates into a light dark sector particle that eventually decays into the SM.

There is a light particle that couples weakly to the SM. One possibility is a "dark photon" under which the SM particles carry tiny charges.

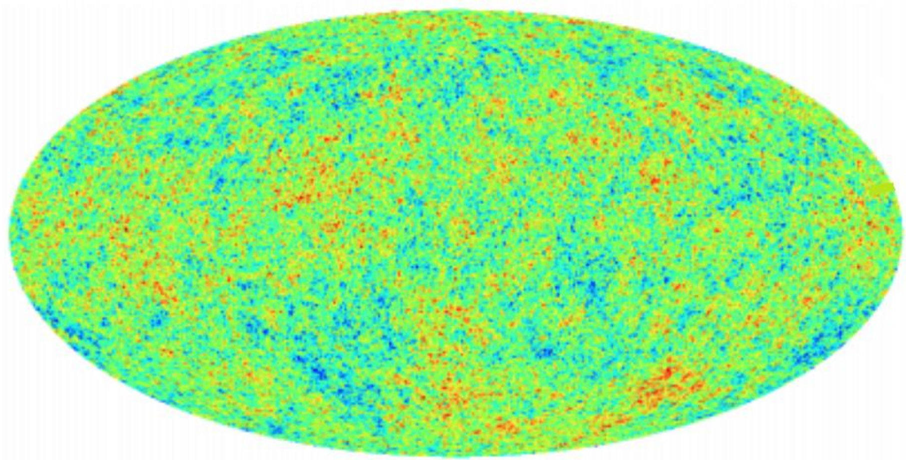


Constraints are quite tight and will improve further!

Dark Matter and Dark Radiation

If dark matter annihilates into dark radiation there is a lower bound on its contribution to the energy density $\Delta N_{eff} > 0.03$.

Current bound from the Planck CMB experiment is $\Delta N_{eff} \leq 0.6$ (2σ).



However, future CMB experiments will be sensitive to $\Delta N_{eff} \sim 0.02$.

This idea will be tested!

However, at present there is tension between the Planck bound on ΔN_{eff} and supernovae measurements, which prefer $\Delta N_{eff} \geq 0.6$.

A Possible Resolution!

The Planck bound assumes that the dark radiation is non-interacting. Does not apply if the particles in dark radiation scatter off each other.

Dark radiation affects the amplitude and locations of the CMB peaks.

The amplitude and positions of the CMB peaks are shifted in opposite directions, depending on whether the dark radiation scatters.

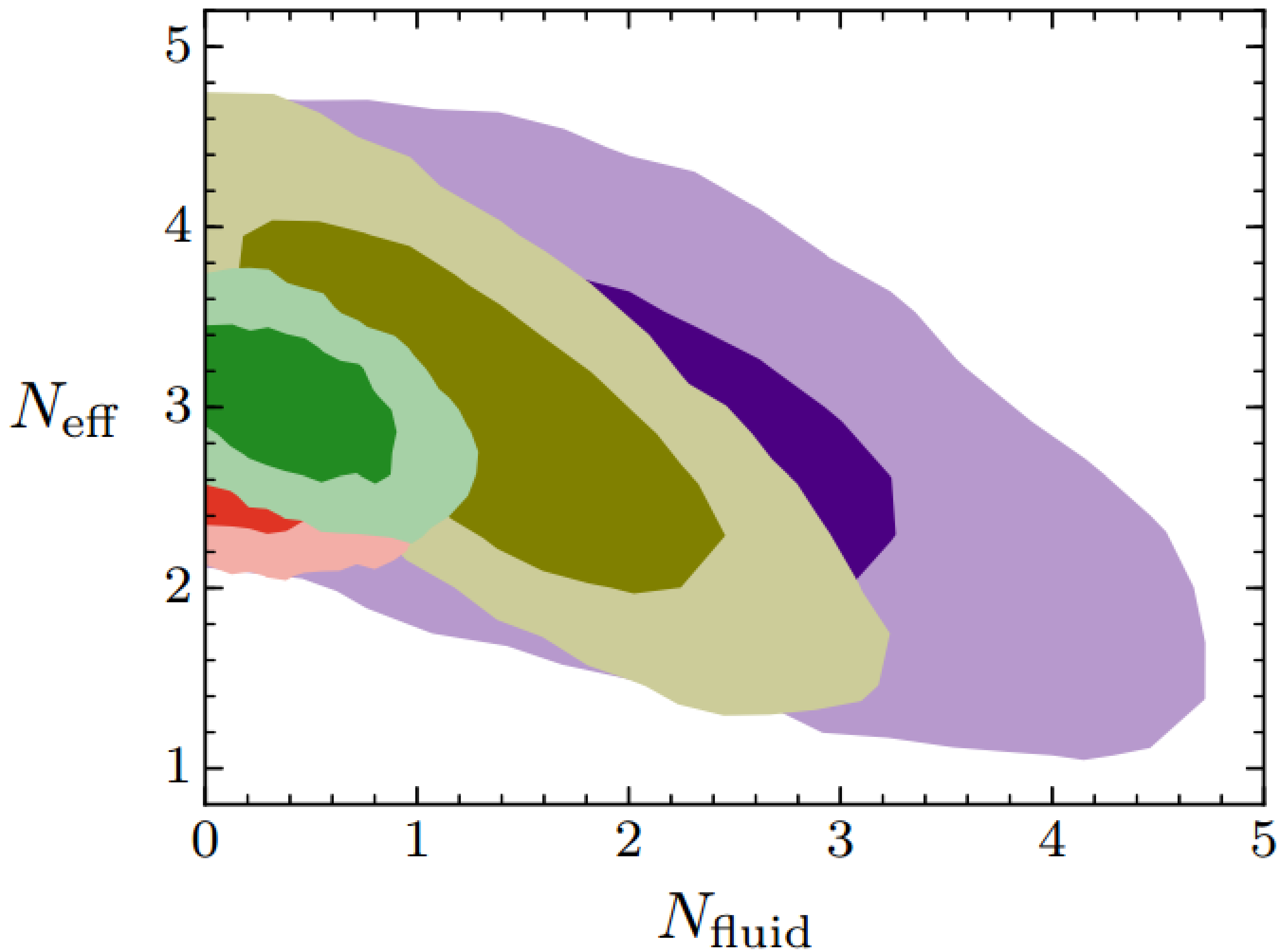
ZC, Cui, Hong & Okui

The supernovae results are not affected by dark radiation scattering.

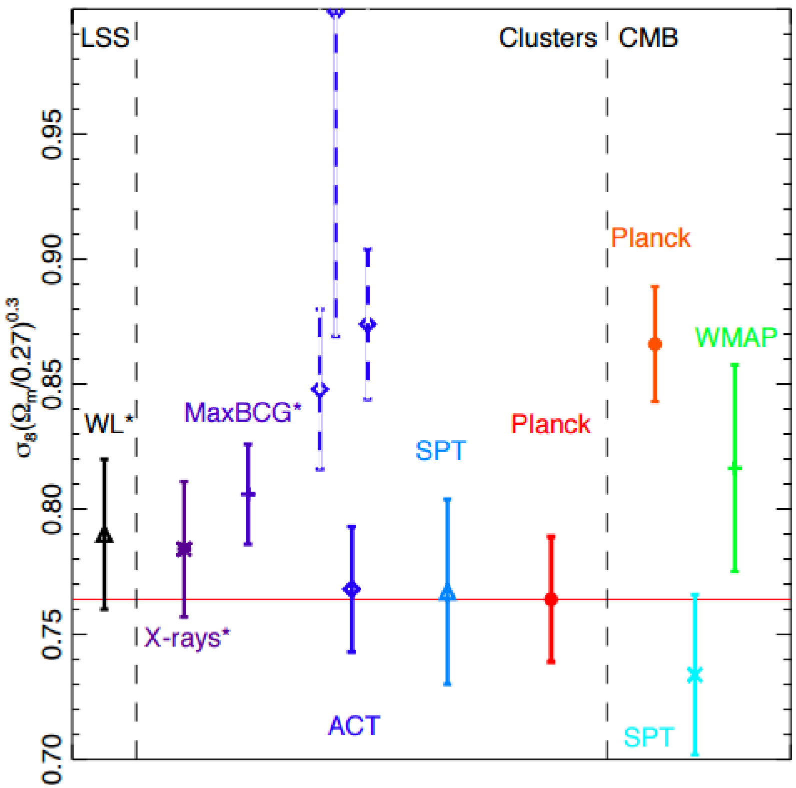
Could the scattering of dark radiation resolve the tension?

A reanalysis of Planck data, but with interacting dark radiation shows that ΔN_{eff} ~ 1 is now allowed!

Green & Baumann



There is also a discrepancy between the values of cosmological parameter σ_8 as obtained from the CMB and other measurements.



Interactions between dark radiation and dark matter, if present, can have the effect of suppressing matter power spectrum at all scales.

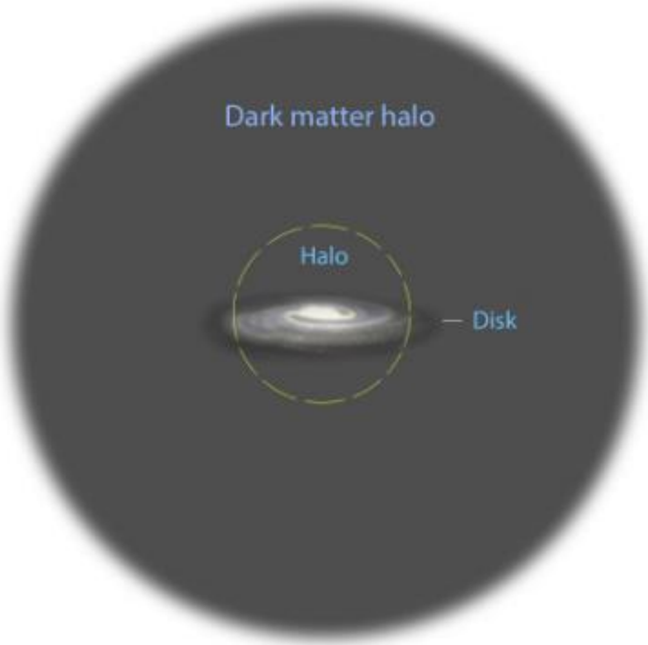
This offers a resolution to the " σ_8 problem".

Buen-Abad, Marques-Tavares & Schmaltz

Double Disk Dark Matter

Fan, Katz, Randall & Reece

The spherical distribution of dark matter in the galaxy implies that dark matter, unlike ordinary matter, is non-dissipative.



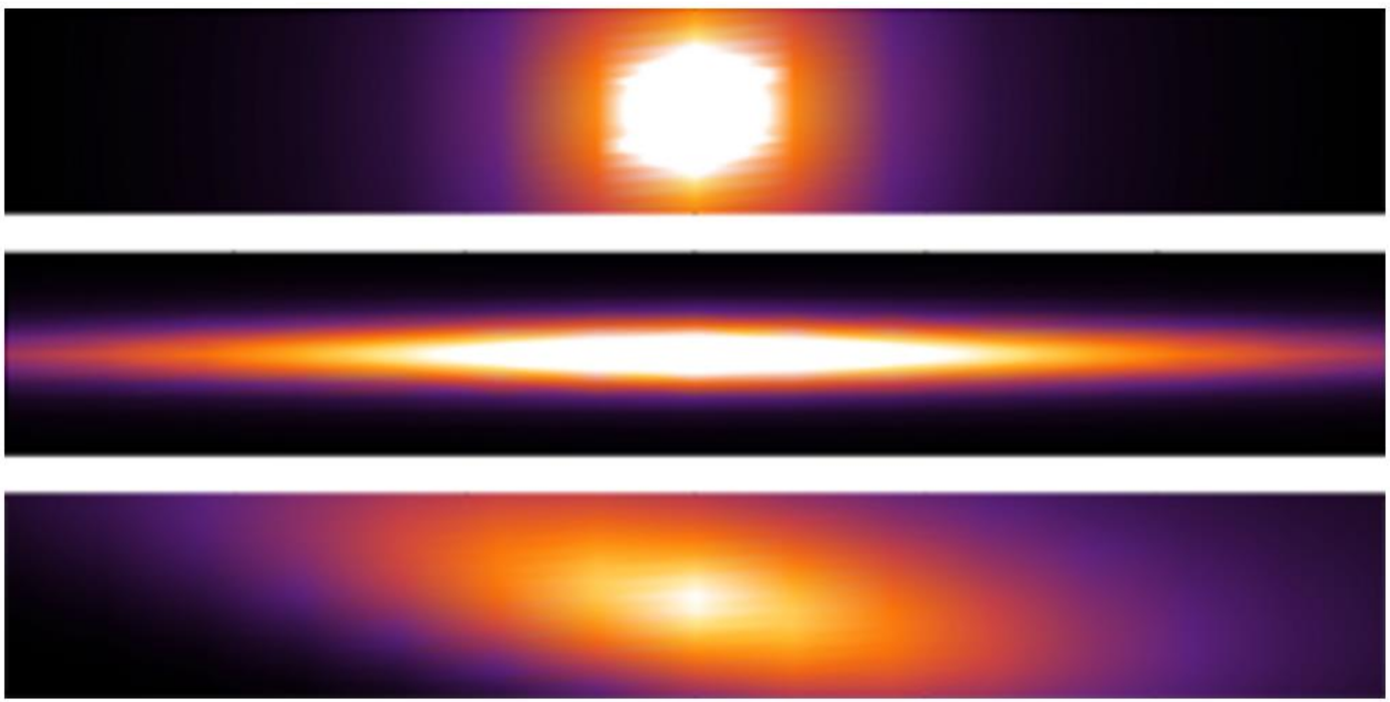
Milky Way model

However, a subcomponent of dark matter could be dissipative, and form compact objects.

As much as 5% of dark matter could have collapsed into a “dark disk”.

This second disk is expected to be somewhat, but perhaps not completely, aligned with the galactic plane.

This would lead to striking signatures in indirect detection.



conventional

aligned disk

misaligned disk

The dark disk could also be discovered through gravitational effects.

Conclusions

Although the evidence for dark matter is overwhelming, the nature of the particles of which it is composed remains a mystery.

Dark matter is most likely made up of particles outside the SM.

Although there are many competing theories, future experiments may be able to distinguish between them.

Future experiments will probe dark matter interactions with the SM, and also the nature of the dark sector itself.

- **Direct detection: XENON1T , LUX-ZEPLIN . . . .**
- **Indirect detection: Cerenkov Telescope Array (CTA) . . . .**
- **Collider searches: High Luminosity LHC, SHiP, APEX . . . .**

- **CMB Stage IV**
- **21 cm Line Cosmology**
- **GAIA Satellite**