Cosmic Deconstructionism

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Dark Matter that is composed of WIMP remnants of incomplete particle-antiparticle annihilation in the early universe experiences ongoing annihilation in gravitationally bound large scale structure. This annihilation will have important consequences in the perhaps distant cosmic future, as the annihilation time-scale becomes comparable to the age of the universe. Much of large scale structure, from galaxy satellites to galaxy clusters will disappear.

I. INTRODUCTION

As demonstrated over 25 years ago by Lee and Weinberg [1], and also by Dicus and collaborators [2], there is a remarkable connection between heavy particles at the electroweak scale and the possibility that these particles might be the dark matter that dominates galaxies and clusters today. In particular, the annihilation cross sections for these particles can be such that particle-antiparticle annihilations freeze out in the early universe at a temperature somewhat below the mass of the particles. Annihilation terminates while still incomplete. A remnant abundance results which, depending upon the mass of the particles, can provide a substantial contribution to the present mass density of the universe.

While freeze-out occurs when the universe is a fraction of a second old for these particles, annihilations can once again be important at late times. For example, as these particles collapse into systems like small satellites of galaxies, their density can become sufficiently great so that a small fraction will annihilate, producing possible indirect signatures for dark matter which are currently be ing searched for.

In this letter, we demonstrate that on time-scales much longer than the current age of the universe, annihilation will once again come into equilibrium in the cores of bound structures. Dark matter residing in these structures will disappear while matter outside them will dilute with the expansion of the universe. We outline here the general expected effects of this annihilation on the future disappearance of large scale structure.

II. ESCHATOLOGICAL ANNIHILATION ESTIMATES

The remnant density of Dark Matter determined by freeze-out following annihilations in the early universe is determined by the canonical freezeout condition:

$$n(T)\langle\sigma v\rangle = H(T) \tag{1}$$

where $n(T)$ is the particle number density at temperature T, $H(T)$ is the expansion rate at this temperature, σ is the annihilation cross section, v is the relative velocity of the particle-antiparticle pair, and the average is a thermal average at temperature T.

Since $n \propto T^3$, while $H \propto T^2$ at early times, for most annihilation cross sections, which themselves fall as a positive power of the mean thermal energy at temperature T, annihilations will fall out of equilibrium in an expanding universe as the temperature decreases.

The formation of large scale bound structures with a time-independent density profile adds a new wrinkle to this situation. Annihilations become significant on time scales

$$t \gtrsim t_A \equiv \left(n\langle\sigma v\rangle\right)^{-1}. \tag{2}$$

Since n is larger in more tightly bound systems, t_A is smaller there. As we shall describe in the next section, this implies a future history of the universe in which structures at increasingly large scales begin to unravel – a process we term Cosmic Deconstruction.

We first estimate the approximate times for the deconstruction of a variety of cosmic structures – galaxy satellites, galaxies, and galaxy clusters. We make these estimates this for realistic SUSY WIMP candidates, for which freezeout occurs near the electroweak scale,

For s-wave annihilations, σv is a constant at low energies. For particles of mass m, annihilating via exchange of a particle of comparable mass M, $\sigma v \approx \alpha^2 m^2 M^{-4}$. Here α represents some effective fine-structure constant appropriate

to the interaction in question. Assuming $\alpha \approx 10^{-2}$, and $M \approx 100\text{GeV}$, one finds

$$\sigma v \approx \left(\frac{m}{M}\right)^2 \times 10^{-26} \text{cm}^3 \sec^{-1} \tag{3}$$

Taking as a fiducial estimate the average galactic density $\rho_0 \approx 1\text{GeV/cm}^3$ (and assuming that $m \approx M \approx 100\text{GeV}$), we find an annihilation time

$$t_A \approx 10^{11} \frac{n}{n_0} t_0 \tag{4}$$

where t_0 is the present age of the universe.

Clearly, the effect of annihilation on large scale structure is an eschatological issue.

We next estimate what the impact of such annihilations will be on the evolution of structure. Not surprisingly, the effects vary depending upon scale.

III.   THE DISAPPEARANCE OF LARGE SCALE STRUCTURE?

Large scale structure formation in a ΛCDM universe is hierarchical, with smaller structures decoupling from the background distribution when the universe was at a higher density. Numerical simulations suggest a general NFW [3] form for the dark matter density inside these structures:

$$\rho(r = xr_s) = \rho_s x^{-1}(1+x)^{-2} \tag{5}$$

at the time the halo first decoupled from the cosmic expansion and began to collapse. The inner parts of the distribution can be even more strongly clumped with $\rho \approx r^{-1.5}$. Ultimately this behavior flattens out in some dense inner core.

It is predicted that dark matter halos contain many smaller sub-clumps of higher density[4]. The number of clumps with mass greater than or equal to M relative to the mass of the host galaxy is [5]

$$N_{\text{clump}}(\leq M) \approx 10^2 \left(\frac{M_{\text{host}}}{M}\right)^2. \tag{6}$$

Fitting to numerical simulations from the galaxy size downward to clumps as small as $10^{-6}M_{\text{solar}}$ one finds central densities that go roughly as $\rho \simeq M^{1/4}$, where M is the mass of the clump. Few such clumps are observed in luminous matter, in particular, far fewer satellite galaxies are observed than are predicted in N-body simulations. This could be because small subclumps are almost entirely dark matter, or because they may not survive tidal interactions. Diemand et $al.$[5] have argued that at least the cores of such clumps survive tidal interactions over long times.

It has not gone unnoticed that dark matter annihilation provides one way of explaining the absence of these sub-clumps [6]; however, t_A is far too long for generic WIMP dark matter to have played any significant role to-date in the evolution of dark matter clumps. Moreover, good constraints exist on this possibility if the annihilation products include (as they almost always do) photons or standard model antiparticles (for example [7]).) We also note that, when it was first claimed that observed density profiles in galactic cores were less steep than those predicted in N-body simulations, it was proposed that enhanced dark-matter particle-antiparticle annihilation cross sections might smooth out galaxy halo cores (see, e.g., Ref. [8]). The cross sections required for this to occur by the present time are again far larger than those discussed in the last section. However, it has been noted that, for sufficiently high densities, even the small rate of dark matter annihilations predicted for realistic annihilation cross sections of WIMPs might provide observable signatures in indirect detection experiments [7, 9, 10, 11, 12, 13].

We sketch out below the general features that will affect the evolution of structure as dark matter annihilation begins to become significant. The details will, as we shall describe, depend upon the dark matter to baryon content in the system.

We shall approximate dark matter halos as thermal distributions, with particles distributed in velocity space with a roughly Maxwell-Boltzmann distribution $N(x) \approx x^{1/2} \exp{-x}$, where $x = v^2/v_0^2$, and v_0 is the mean velocity dispersion in the system.

As dark matter begins to annihilate in the dense inner core, there will be three major effects:

- Flattening of Cusps: Dark matter annihilation will maintain the central core density at $n_0 \approx 1/\sigma vt$. Hence, over time, core densities will decrease. We can use this relation to estimate the rate of mass loss from the core (see next item)

- Adiabatic Expansion: Because the timescale for annihilation will far exceed the dynamical relaxation time of galactic systems, the mass loss due to annihilation will result in adiabatic expansion of the core, so that the quantity $M(r_0)r_0$ remains constant as the mass decreases in the core [14]. This adiabatic expansion will supplement annihilation in reducing the density in the core. As a result, the mass loss due to annihilation will be less than it would otherwise be. If we require that the core density fall inversely with time, as given above, and use the adiabaticity constraint, then we derive a simple approximate mass loss rate from the expanding core, given by $\dot{M} = M(t)/4t$, instead of $\dot{M} = M(t)/t$, as it would otherwise be. Thus, the mass in the core falls as $M = M_0/t^{1/4}$ rather than as t^{-1} as it would do otherwise.

- Evaporation: As mass is lost, the gravitational potential will decrease outside of the core, and particles (both dark matter and baryons) whose velocities were close to the escape velocity before will now escape. We estimate this effect below, which could be the most significant factor affecting structure deconstruction, depending upon the extent to which dark matter, rather than baryons, dominates the potential in the core evaporating region, as we describe below

To get an estimate of the total mass lost due to evaporation for a dark matter dominated system we consider the magnitude shift of the gravitational potential from the time that dark matter begins to annihilate until it completely disappears from in the system via a combination of annihilation and evaporation. Assuming that particles with velocity squared $v^2 2v_0^2$ will initially escape the system, if the potential after annihilation is $|V| = p|V_0|$, where $p < 1$, then the fraction of particles that will escape will be roughly the fraction in the initial distribution with initial velocity-squared exceeding $2pv_0^2$ This is given by

$$F = \frac{\int_{2p}^2 x^{1/2}e^{-x}dx}{\int_0^2 x^{1/2}e^{-x}dx} \tag{7}$$

Note that this approximation assumes that non-annihilating particles like baryons do not contribute significantly to the gravitational potential themselves until late times. For example, if we consider the dark halos, where the integrated baryon mass is perhaps 10% of the total mass in the core, so that if a significant fraction of the dark matter were to annihilate, then $p = 0.1$, and F =.92, and most of the baryons and the remaining dark matter will also evaporate.

Once enough dark matter has annihilated in cores, however, so that baryons begin to dominate, the future evolution will change. The core size will be fixed, determined by the baryon dynamics. Those baryons in the core that do not evaporate during the annihilation process will leave a bound stable remnant.

As annihilation proceeds, the core radius will not grow significantly because the core mass will now be dominated by baryons and thus the variation in $M(r)$ will reduced. We then expect that the outer halo halo will puff up slightly in response to the reduced mass in the core. Eventually this will stabilize as the dark matter mass in the core continues to reduce, at which point annihilation in the outer halo should begin to become significant. As this process proceeds, from the inside outward, much of the rest of the halo will continue to grow in size, and decrease in density. This will result in mass loss due to a combination of annihilation and evaporation of the dark matter and baryon particles outside this core, as given by eq. 7. This halo should then dissipate completely by this combination. A significant fraction of the dark matter will evaporate rather than annihilate, and over 90 % of the halo baryons will evaporate, assuming that the dark-matter-to-baryon mass ratio outside the core is larger than a factor of 10 .

In some cases, the residual baryons left after the dark matter abundance in the core annihilates down will come to dominate the entire potential of the system. In this case, the dark matter halo dynamics will be determined by the remnant baryonic core, and its distribution will be determined by the baryon potential. Dark matter halos will then continue to annihilate, with minimal evaporation, because the dominant potential will not be changing .

Galaxy clusters are simpler to consider. While the mean density in their inner cores is smaller than for galaxies, and thus annihilation will take longer to become significant, the gravitational potential wells in these systems is dominated by dark matter throughout. As a result, after most of the dark matter in the core annihilates, we expect $p << 1$, so that F will be large. In this case, F can roughly be interpreted as the probability for a cluster galaxy to become unbound. Assuming that the dark matter continues to dominate the potential, the system will continue to puff up in size, with core density, and halo density decreasing over time, and with dark matter continuing to evaporate from the system.

There is, of course, an important caveat in all of our discussions. The time scales we are considering are *very long*, in excess of perhaps 10^{10} times the current age of the universe. The extent to which dynamical friction will have caused most of the baryons to have settled in the central region of the galaxy or galaxy cluster by the point at which annihilation will be significant will dramatically affect whether or not the baryons evaporate following dark matter annihilation and evaporation. Eventually of course, as has been noted in the past, possible black hole evaporation and proton decay may drive a much later period of evaporation of any such residual structures [15].

IV. CONCLUSIONS

Annihilating dark matter, which froze out early in the history of the universe will, because of the formation of bound large scales structures, ultimately disappear from large scale structure via annihilation and subsequent evaporation, which become significant in a sufficiently old universe. We have estimated here that as a result most clusters will disintegrate, and galactic systems will be largely dissipated, although dense baryon cores can remain. In order to explore in more detail the role of annihilation versus evaporation vs gravitational settling over the incredibly long dynamical timescales we have described here, we plan to carry out numerical simulations It is also worth pointing out the recent result that regardless of how efficient annihilation is at removing dark matter from large scale structures in the future, nevertheless matter will continue to dominate over the possible relativistic products of this annihilation for all times [16].

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