Constraining Dark-Matter Ensembles with Supernova Data

Aditi Desai[1], Keith Dienes[2], Brooks Thomas[1]

[1] Department of Physics, Lafayette College, Easton, PA 18042 USA

[2] Department of Physics, University of Arizona, Tucson, AZ 85721 USA

Introduction

A variety of dark-matter theories exist today, the majority of which involve either stable particles or decaying particles. Within the realm of decaying dark-matter theories, there exists the theory of Dynamical Dark Matter. Rather than dark matter consisting of a single type of particle that decays over its lifetime, the Dynamical Dark Matter theory proposes that dark matter is comprised of an ensemble of particles, all of which have different lifetimes and as a result, decay at different rates.[1,2] The number of particle species in these ensembles can range all the way up to infinity.

If these particles decay into visible particles, there are constraints that can be placed on those decays due to astrophysics. The question that then arises is whether decays that yield invisible particles can also be constrained.

The purpose of this project was to determine what constraints can be placed on these types of decays based on their effect on the rate of expansion of the universe. The project used observed supernova data in order to determine what combinations of parameters yield consistent ensembles. In doing this, the possibilities of what constitutes a plausible dark-matter ensemble can be narrowed down.

In this project, supernova data in the Union 2.1 catalog[3] was used to determine which theoretical models yield results that match measured data.

Background

$$H^2(z) = H_0^2\left[\sum_{n=0}^{N-1}\widetilde{\Omega}_n(z) + \widetilde{\Omega}_{\rho_1}(z) + \widetilde{\Omega}_b(z) + \widetilde{\Omega}_\gamma(z) + \widetilde{\Omega}_\nu(z) + \widetilde{\Omega}_\Lambda\right]$$

Hubble parameter

$$\Omega_i(z) = \frac{\rho_i(z)}{\rho_{\rm crit}(z)}$$

abundance of a particle *i*

The Hubble parameter is a measure of the rate of expansion of the universe. The parameter depends on what the universe is made up of and how much of each type of particle exists at any given time. The decaying of dark matter will affect the Hubble parameter's value, so if any given model of Dynamical Dark Matter is to be viable, these ensembles must be constrained so that *H* is consistent with its known present-day value.

In their 2014 paper, Blackadder and Koushiappas presented an approach to modeling and constraining one-particle decays of dark matter.[4] Using their work as the basis for this research, the equations and methods proposed by Blackadder and Koushiappas were modified and applied to many-particle-decay situations.

$$\rho_{\rm cdm} = \mathcal{A}e^{-\Gamma t(z)}(1+z)^3$$

energy density of parent particle

$$\mathcal{A} = \rho_{{\rm cdm},0}e^{\Gamma t(z_{\rm LS})} \qquad \epsilon = 1/2$$

$$\rho_1 = \epsilon\,\mathcal{A}(1+z)^4 \times \int_{a_{\rm LS}}^{a} e^{-\Gamma t(a')}da' - \frac{e^{-\Gamma t(z)}}{1+z} + \frac{e^{-\Gamma t(z_{\rm LS})}}{1+z_{\rm LS}}$$

energy density of daughter particle

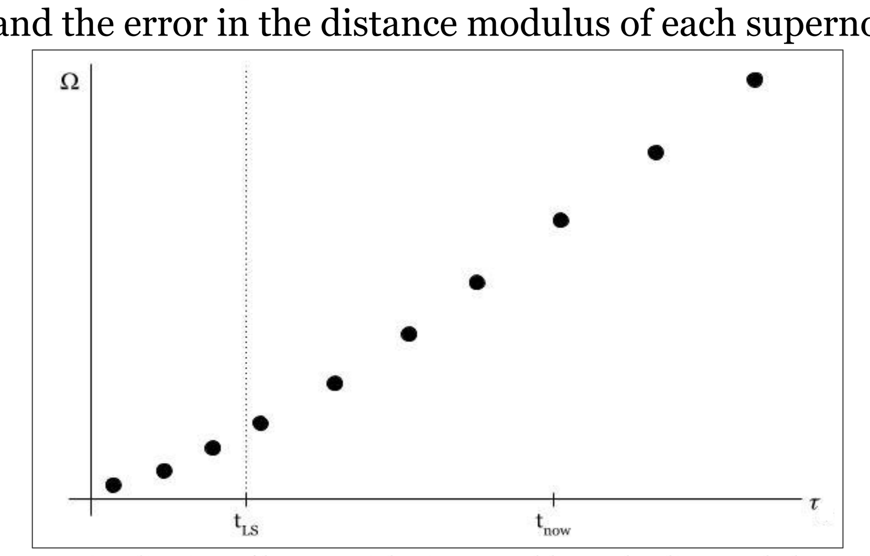
$$d_{\rm L}(z) = \frac{c(1+z)}{H_0}\int_0^z \mathcal{F}^{-1/2}(z')dz'$$

luminosity distance

$$\mu_0 = 5\log_{10}\left(\frac{d_L}{\rm Mpc}\right) + 25$$

distance modulus

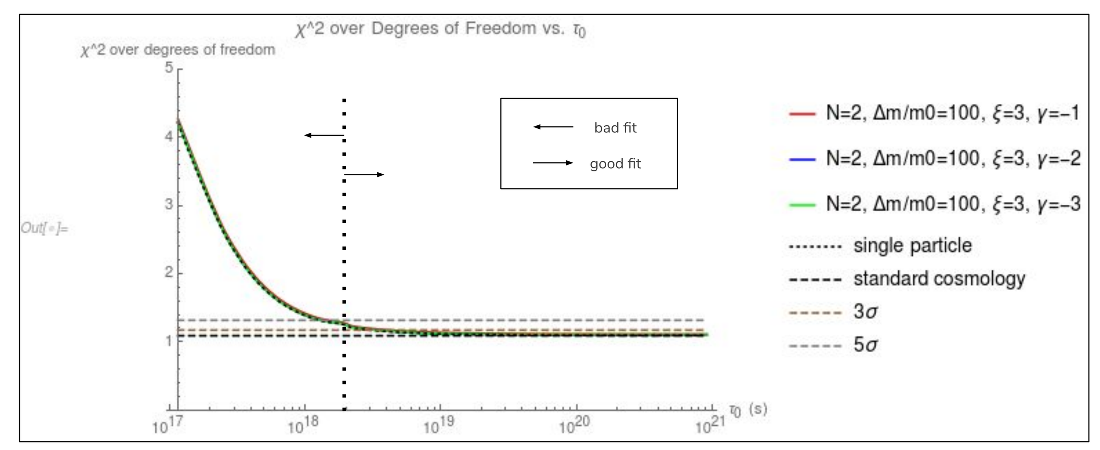
The Union 2.1 catalog provided information for 580 supernovae at varying redshifts.[3] The information provided included the measured distance modulus, the redshift, and the error in the distance modulus of each supernovae.

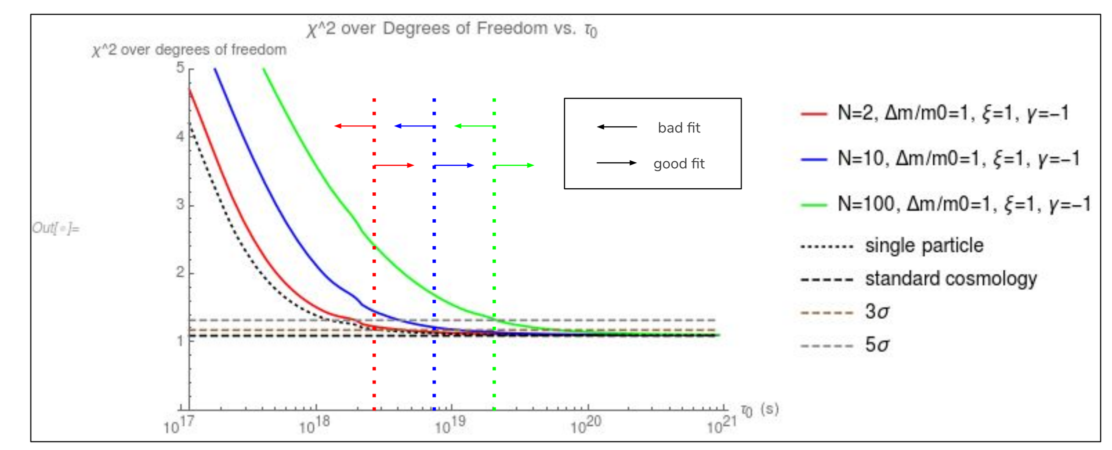


visualization of how particles in ensemble can be disregarded based on lifetime and abundance

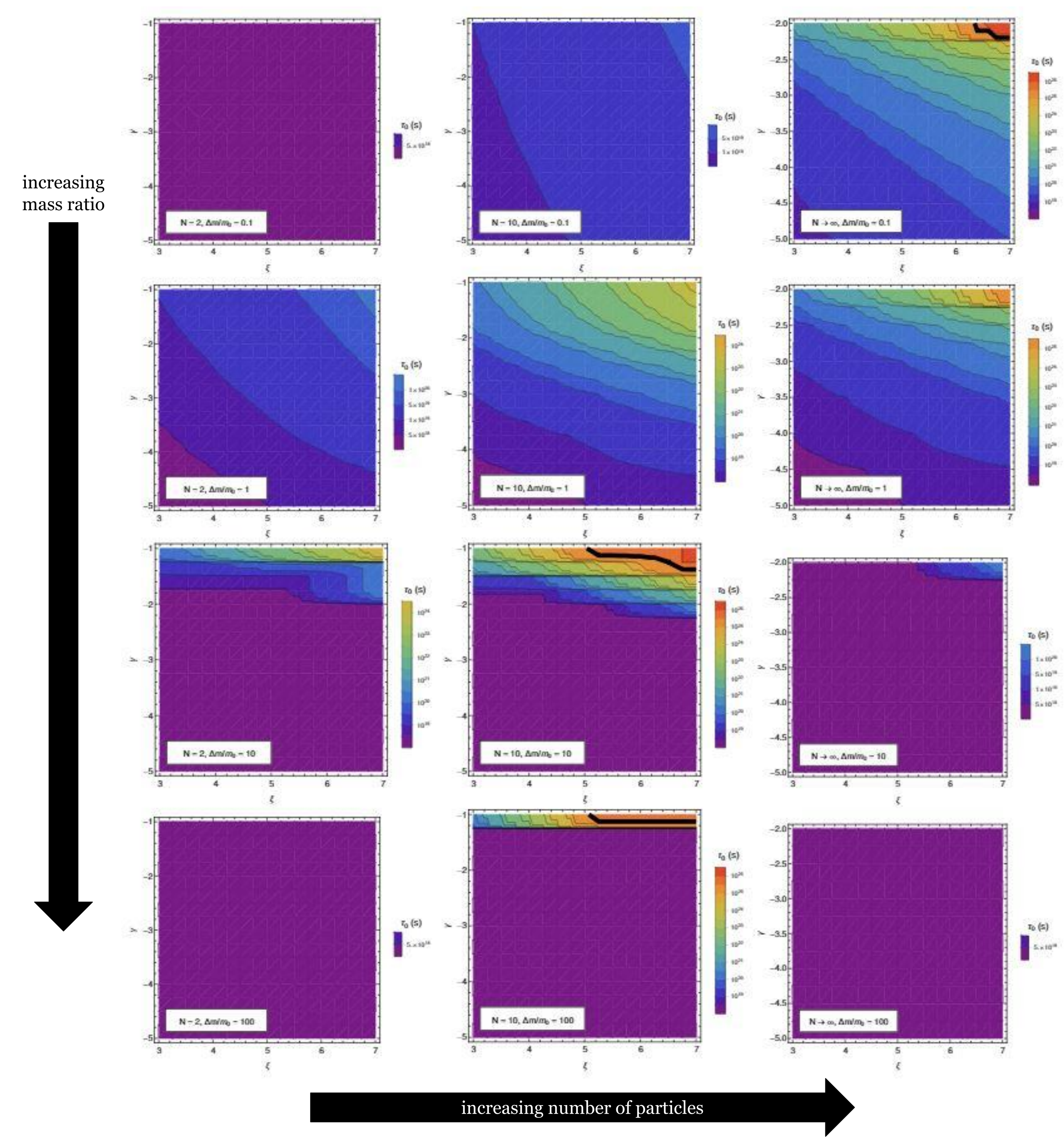
In this graph, the abundances of particles with lifetimes less than the initial condition, t_{LS}, are summed, and if they comprise less than 1% of the total abundance, they can be disregarded.

Results





Goodness-of-fit plots allow for the determination of which combinations of parameters are most useful to explore further. This data was useful in determining which parameters to vary and which to hold constant for the next step of the project.



The contours on these plots represent the smallest possible lifetime of the heaviest particle in the ensemble while keeping the ensemble consistent. Each plot depicts the results for a different number of particles in the ensemble and a different mass ratio. The variables that are not kept constant within each plot are the scaling factors for the scaling relations between particles in the ensemble.

Methods

$$m_n = m_0 + n^\delta \Delta m \qquad \Gamma_n = \Gamma_0\left(\frac{m_n}{m_0}\right)^\xi \qquad \widetilde{\Omega}_n = \widetilde{\Omega}_0\left(\frac{m_n}{m_0}\right)^\gamma$$

scaling relations used for masses, lifetimes, and abundances of particles in ensemble

Using Mathematica, a code was written to compare the supernova distance moduli to theoretical values of Dynamical Dark Matter ensembles using the Hubble parameter, the energy density equations, the distance modulus calculations, and the scaling relations. This code could then be adapted to apply to ensembles involving any combination of parameters.

$$\chi^2 = \sum_{i=1}^{N}\frac{[\mu_{0i}^{\rm meas} - \mu_0^{\rm calc}(z_i)]^2}{(\Delta\mu_i)^2}$$

formula to calculate chi squared values

In order to determine goodness of fit, a chi-squared analysis was performed, comparing the measured distance moduli to theoretical values based on different cosmologies.

Once these analyses were performed, the next step was to create a second code that could determine the minimum lifetime of the heaviest particle in the ensemble, while ensuring that the ensemble yielded a cosmology with values that agreed with the measured data. In doing this this, particles in the ensemble with small enough abundances and lifetimes that were too short could be disregarded.

Conclusions and Future Work

This research allows for constraints to be placed on Dynamical Dark Matter ensembles and has provided a flexible code that can be used to determine the shortest possible lifetime of the heaviest particle for any set of parameters. As of now, only the case where dark matter particles decay into two massless particles has been explored.

In the future, this code can be adapted to model the cases who particles decay into one massless and one massive particle, as well as other decay scenarios. Additionally, new supernova data has recently been made available,[5] which can be used in the future to improve the goodness of fit measures.

References

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