Phenomenology of Decaying Dark Matter

Ana Fernanda San Juan Villegas
Universidad Autónoma del Estado de Hidalgo

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Instituto de Ciencias Básicas e Ingeniería

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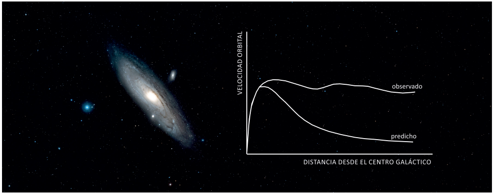
Dark Matter

The problem of dark matter (DM) arose while studying galaxy clusters, a difference was noticed between the behavior that should occur according to theoretical knowledge and what was observed.



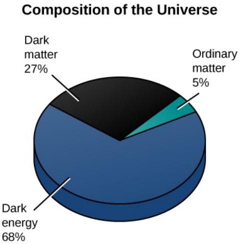


Figure: Rotation speed of stars in galaxies (left). Composition of the universe (right). [1] Torres, M. RIAA, 2016

Dark Matter Characteristics

So far, we don't know what dark matter is, but we do know some of its characteristics:

- Massive.
- Stable: at least the age of the Universe, otherwise its effects would already have been detected.
- It interacts mainly with gravity.
- Mostly cold, it moves at non-relativistic speeds. If dark matter were hot, due to the high speed of its components, it would cause structures to be different from what is currently observed. [2] Arbey, arXiv:2104.11488 [hep-ph]
- Others...

Detection Methods

Observational evidence of the existence of MD has prompted its search using different methods:

1. Direct detection.
2. Search by colliders.
3. Indirect detection.

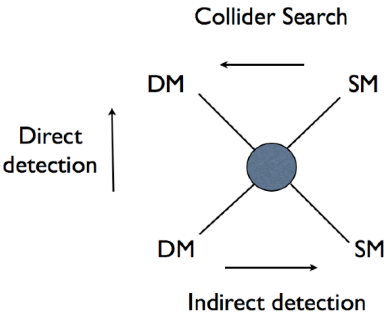


Figure: Detection methods of Dark Matter

Detection methods

1. Direct detection.
2. Search by colliders.
3. **Indirect detection.** When DM decays/annihilates, it produces gamma rays, neutrinos, cosmic rays, etc.

Figure: Experiments for the indirect detection of dark matter.

Introduction to the model

- This model is motivated by the fact that we know that DM only interacts gravitationally.
- Gravitational portals induce the decay of DM.
- BRs depend only on the mass of the DM.
- It considers as a DM candidate a scalar singlet that decays when considering a curved spacetime due to a non-minimal coupling with gravity breaking the Z_2 symmetry.

Model: Dark Matter Decays from Nonminimal Coupling to Gravity.

In general, the operator that allows the DM to decay can be written as:

$$\mathcal{L}_\xi = -\xi R F(\phi, X), \tag{1}$$

where ξ is a coupling parameter, R is the Ricci scalar, and $F(\phi, X)$ is a real function of the DM field. For this model, equation (1) is rewritten as:

$$\mathcal{L}_\xi = -\xi M R \phi, \tag{2}$$

where M is a mass parameter, performing a Weyl transformation and expanding the SM Lagrangian yields terms that induce DM to decay into SM particles. [3] Cata, et al. PhysRevLett. arXiv: 1611.00725v2

Lifetime

The lifetime is calculated as the inverse of the Γ function.

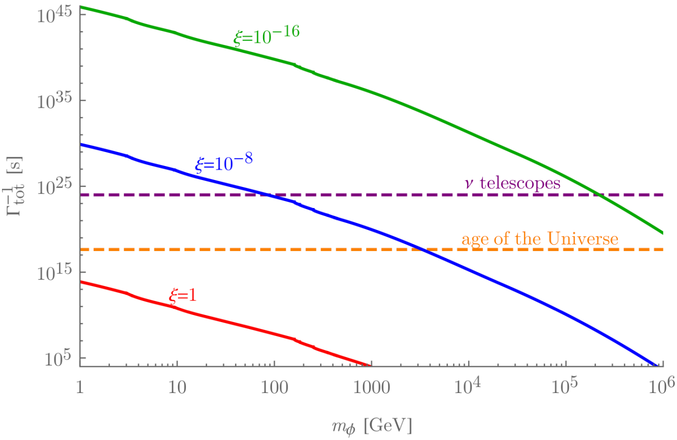


Figure: Lifetime vs. mass of the candidate. [4] Cata, et al. arXiv:1311.5477v1

Gamma ray and neutrinos

When DM decays, it can produce high-energy gamma rays or neutrinos that inherit information from their parent particles and could help us determine the nature and properties of DM. The gamma flux is obtained from:

$$\frac{d\Phi_\gamma}{d\Omega dE} = \frac{r_s}{4\pi}\frac{\rho_0}{M_{DM}} D \sum_f \Gamma_f \frac{dN^f_\gamma}{dE}, \tag{3}$$

where dN^f_γ/dE is the energy spectrum of particles produced by decay, Γ_f is the decay rate, and D is the factor calculated as:

$$D = \int_{l.o.s} \frac{ds}{r_s}\left(\frac{\rho(r(s,\theta))}{\rho_0}\right), \tag{4}$$

where the coordinate r is the distance to the center of the Galaxy and θ is the opening angle. [5] Cirelli, et al. arXiv:1012.4515v4

Dwarf Spheroidal Galaxies (dSph)

The distribution of DM in a galaxy depends on the kinematics of its luminosity and the stars that compose it, due to their low luminosity and mass dSph's are good candidates. [6] Strigari arXiv:1805.05883v1

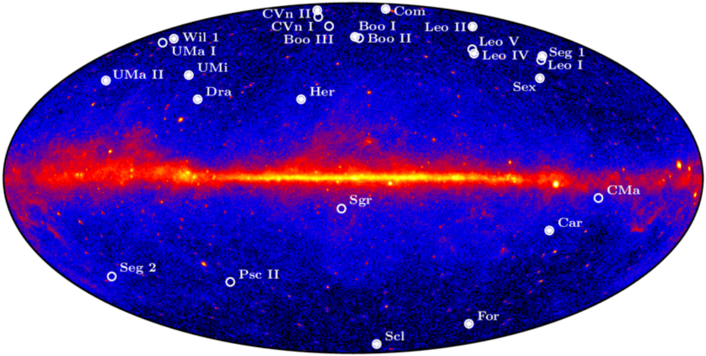


Figure: Distribution of some dwarf spheroidal galaxies on a gamma-ray sky map (galactic coordinates).

Dwarf Spheroidal Galaxies (dSph)

Name	l (°)	b (°)	d (kpc)	Rdelta (kpc)	ρ_s ($M_\odot/kpc^3$)	rs (kpc)
Bootes I	358.08	69.62	66	0.541	18197008	6.309
Canes Venatici I	74.31	79.82	218	2.016	13489628	2.290
Canes Venatici II	113.58	82.70	160	0.363	34673685	8.128
Coma Berenice	241.89	83.61	44	0.238	10232929	5.128
Draco	86.37	37.42	76	1.724	18197008	3.715
Hercules	28.73	36.87	132	0.645	23988329	0.851
Leo I	225.99	49.11	254	1.994	6606934	6.309
Leo II	220.17	67.23	233	0.935	120226443	0.776
Leo IV	265.44	56.51	154	0.430	15848931	0.870
Segue I	220.48	50.43	23	0.140	87096358	1.819
Sextans	243.50	42.27	86	2.551	4073802	6.165
Ursa Major I	159.43	54.41	97	0.897	14454397	3.162
Ursa Major II	152.46	37.44	32	0.240	74131024	4.265
Triangulum II	33.32	36.18	30	10	30052000	0.1

Table: Information about the dSph Galaxies studied for this work. Columns 2 and 3 corresponding to the galactic coordinates, *d* is the distance of the object, Rdelta is the outer bound of the halo and rhos, rs are parameters for the density profile. [7, 8] DOI 10.3847/1538-4357/aaa6d8, arXiv:2508.20229

CLUMPY

The CLUMPY software allows the calculation of gamma ray and neutrino fluxes as indirect signals of dark matter annihilation or decay.

It consists of different “modules” that allow the analysis of mass profiles, density, fluxes, and intensity of different dark matter sources.

To process the data obtained and generate graphs, other programs such as Mathematica and Python are required.

Gamma ray flux

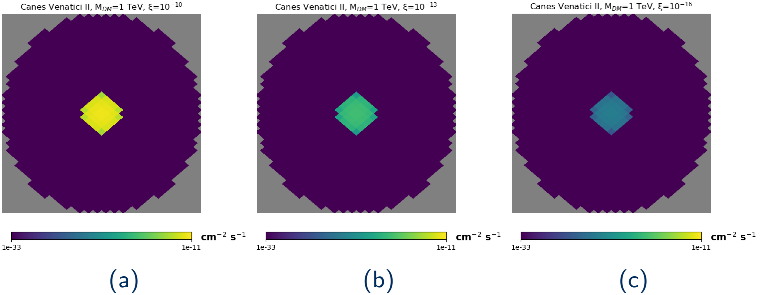


Figure: Gamma ray flux produced in the Canes Venatici II galaxy with a mass of 1 TeV and varying the coupling parameter.

Gamma ray flux

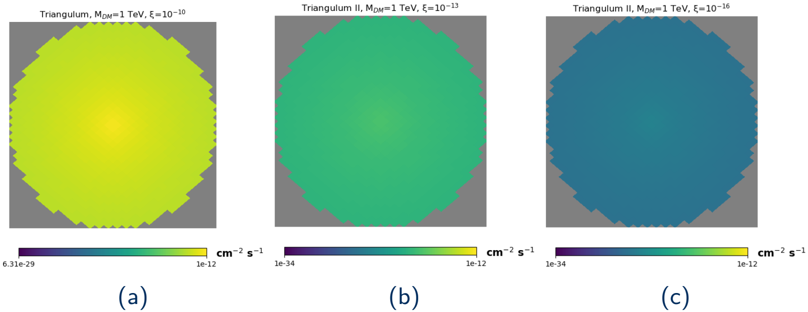


Figure: Gamma ray flux produced in the Triangulum galaxy with a mass of 1 TeV and varying the coupling parameter.

Gamma ray flux

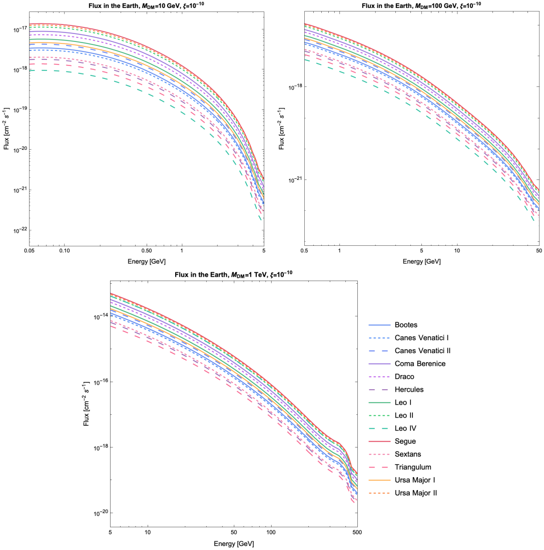


Figure: Gamma ray flux produced varying the mass and with coupling parameter 10^{-10}.

Gamma ray events

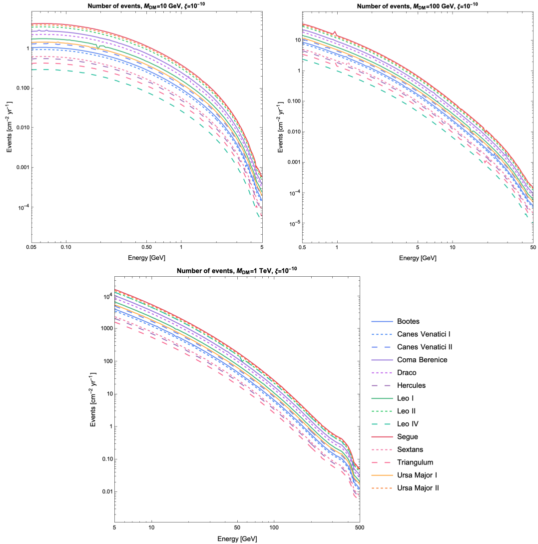
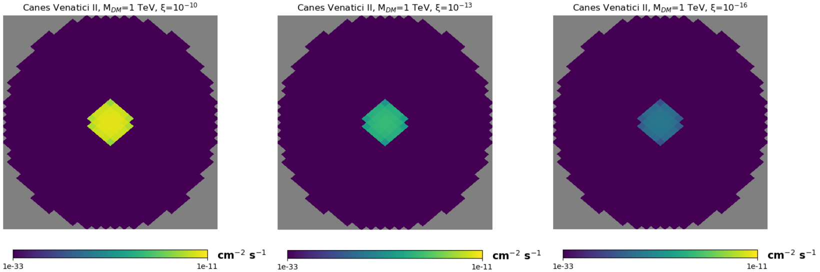


Figure: Number of events of gamma ray produced varying the mass and with coupling parameter 10^{-10}.

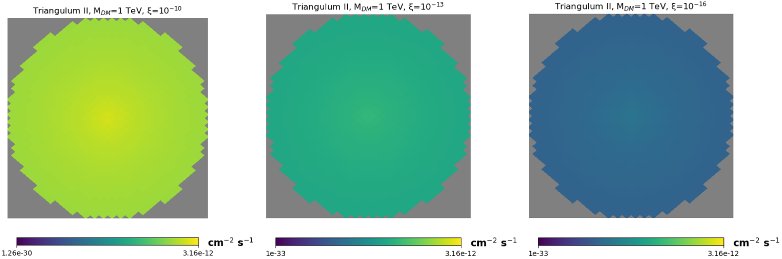
Neutrino flux



(a) (b) (c)

Figure: Muon neutrino flux produced in the Canes Venatici II galaxy with a mass of 1 TeV and varying coupling parameter.

Neutrino flux



(a) (b) (c)

Figure: Muon neutrino flux produced in the Triangulum galaxy with a mass of 1 TeV and varying the coupling parameter.

Neutrino flux

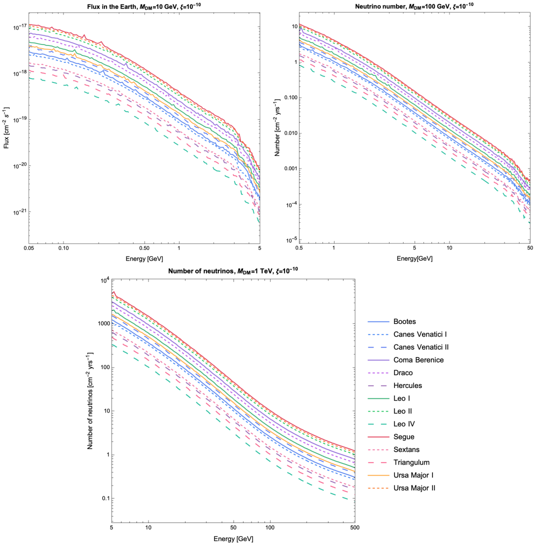


Figure: Muon neutrino flux produced varying the mass with coupling parameter 10^{-10}.

Number of neutrinos produced

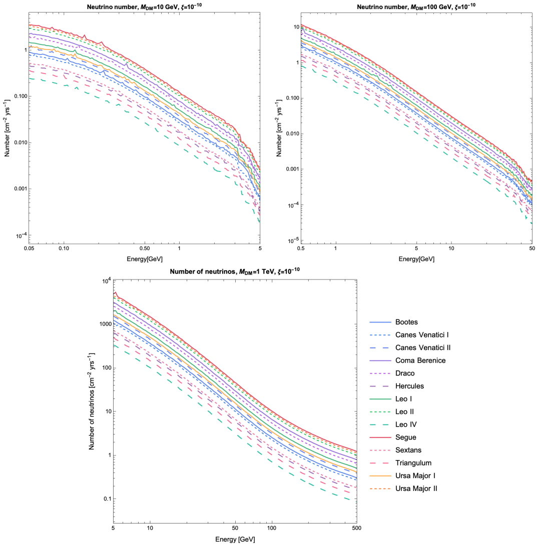


Figure: Number of muon neutrino produced varying the mass and with coupling parameter 10^{-10}.

Conclusions

- Although decaying dark matter requires very long lifetimes, its phenomenology can be studied today because observing phenomena such as the generation of gamma rays or neutrinos with particular energies in regions where they did not previously occur allows the presence of DM to be detected.
- Software such as `CLUMPY` is useful for calculating the spectrum produced by DM decay and can be used for different objects such as dSphs.
- The search for dark matter continues to be one of the great problems in physics that allows us to better understand our universe.

Thank you!

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