SORBONNE UNIVERSITY

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INTERNSHIP REPORT

Theoretical Study and Modeling of Background Radiation from Dark Matter by Simulation

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ABSTRACT

There is strong and convincing evidence that most of the mass in the observable universe is not composed of known particles. Indeed, numerous independent tracers of the gravitational potential demonstrate that the dynamics of galaxies and galaxy clusters cannot be explained by the Newtonian potential created by visible matter only. Here we review sterile neutrinos as possible Dark Matter candidates. After a short summary on the role of neutrinos in cosmology and particle physics, we give a comprehensive overview of the current status of the research on sterile neutrino Dark Matter. Then after reviewing the role of active neutrinos in particle physics, astrophysics, and cosmology, we focus on sterile neutrinos in the context of the Dark Matter puzzle. Here, we first review the physics motivation for sterile neutrino Dark Matter, based on challenges and tensions in purely cold Dark Matter scenarios. We then round out the discussion by critically summarizing all known constraints on sterile neutrino Dark Matter arising from astrophysical observations, laboratory experiments, and theoretical considerations. In this context, we provide a balanced discourse on the possibly positive signal from X-ray observations, and the missions done to study it. Another focus of the paper concerns reexamining this model by simulating the radiation intensity coming from the decay of the assumed sterile neutrinos to provide the dark matter sky map (on demand) so that it can be used to test different dark matter models with different telescopes.

CHAPTER I

INTRODUCTION

I.1 Dark Matter in the Universe

There is a body of strong and convincing evidence that most of the mass in the observable universe is not composed of known particles. Indeed, numerous independent tracers of the gravitational potential (observations of the motion of stars in galaxies and galaxies in clusters; emissions from hot ionized gas in galaxy groups and clusters) demonstrate that the dynamics of galaxies and galaxy clusters cannot be explained by the Newtonian potential created by visible matter only. Moreover, cosmological data (analysis of the cosmic microwave background anisotropies) show that the cosmic large scale structure started to develop long before decoupling of photons due to the recombination of hydrogen in the early Universe and, therefore, long before ordinary matter could start clustering. This evidence points at the existence of a new substance, universally distributed in objects of all scales and providing a contribution to the total energy density of the Universe at the level of about 27%. This hypothetical new substance is commonly known as "Dark Matter" (DM). The DM abundance is often expressed in terms of the density parameter $\Omega_{\rm DM}$ = $\rho_{\rm DM}$ /ρ_0, where $\rho_{\rm DM}$ is the comoving DM density and ρ_0 = $3H^2 m_{\rm Pl}^2$ /(8π) is the critical density of the universe, with H the Hubble parameter and $m_{\rm Pl}$ the Planck mass.

Various attempts to explain this phenomenon by the presence of macroscopic compact objects (such as, for example, old stars) or by modifications of the laws of gravity failed to provide a consistent description of all the above phenomena. Therefore, a microscopic origin of DM phenomenon, i.e., a new particle or particles, remains the most plausible hypothesis.

Explaining DM in terms of a new elementary particle clearly requires physics beyond the standard model (SM). There are multiple suggested extensions to the SM, providing a variety of suitable DM candidates, but to date there is no clear evidence telling us which of these is correct. Typically, extensions of the SM are sought at high energies, resulting in DM candidates with masses above the electroweak scale.

I.2 Standard Model Neutrino as Dark Matter Candidate?

The only electrically neutral and long-lived particles in the Standard Model (SM) of particle physics are the neutrinos. As experiments show that neutrinos have mass, they could in principle play the role of DM particles. Neutrinos are involved in weak interactions that keep them in thermal equilibrium in the early Universe down to the temperatures of few MeV. At smaller temperatures, the interaction rate of weak reactions drops below the expansion rate of the Universe and neutrinos "freeze out" from the equilibrium. Therefore, a background of relic neutrinos was created just before primordial nucleosynthesis.

Neutrinos are the most elusive known particles. Their weak interactions make it very difficult to study their properties. At the same time, there are good reasons to believe that neutrinos may hold a key to resolve several mysteries in particle physics and cosmology. Neutrinos are unique in several different ways.

- Neutrinos are the only fermions that appear only with left handed (LH) helicity in the SM.
- In the minimal SM, neutrinos are massless. The observed neutrino flavour oscillations clearly indicate that at least two neutrinos have non-vanishing mass. In the framework of quantum field theory, the existence of neutrino masses definitely implies that some new states exist. This is why neutrino masses are often referred to as the only sign of New Physics that has been found in the laboratory.
- The neutrino masses are much smaller than all other fermion masses in the SM. The reason for this separation of scales is unclear. This is often referred to as the mass puzzle.

- The reason why neutrinos oscillate is that the quantum states in which they are produced by the weak interaction (interaction eigenstates) are not quantum states with a well defined energy (mass eigenstates). The misalignment between both sets of states can be described by a flavour mixing.

I.3 Heavy "Sterile" Neutrinos as Dark Matter

As we saw above, neutrinos in principle are a very natural DM candidate. The reasons why the known neutrinos cannot compose all of the observed DM are the smallness of their mass and the magnitude of their coupling to other particles. Hence, one obvious solution is to postulate the existence of heavier "sterile" neutrinos with weaker interactions that fulfill the constraints from cosmic structure formation. Indeed, the existence of heavy neutrinos is predicted by many theories of particle physics, and they would provide a very simple explanation for the observed neutrino oscillations via the seesaw mechanism.

The implications of the existence of heavy neutrinos strongly depend on the magnitude of their mass, see. For masses of a few keV, they are a viable DM candidate. Sterile neutrino DM interacts much weaker than ordinary neutrinos. These particles can leave imprints in X-ray spectra of galaxies and galaxy clusters. Moreover, they decay and X-ray observations provide bounds on their parameters. There exist a larger number of models that accommodate this possibility.

I.3.1 The seesaw mechanism

It may seem unusual to have such low values for masses of neutrinos, when all other particles like electrons, quarks, etc are much heavier, with their masses relatively closely grouped. Given that particles get mass via the Higgs mechanism, why, for example, should the electron neutrino be 10^5 times or more lighter than the electron, up and down quarks. That is, why would the coupling to the Higgs field be so many orders of magnitude less?

One might not be too surprised if the Higgs coupling were zero, giving rise to zero mass. One might likewise not be too surprised if the coupling resulted in masses on the order of the Higgs.

Consider the quite reasonable possibility that after symmetry breaking, two types of neutrino exist, with one having zero mass (no Higgs coupling) and the other having (large) mass of the symmetry breaking scale. As we will see, it turns out that reasonable superpositions of these fields can result in light neutrinos (like those observed) and a very heavy neutrino (of symmetry breaking scale, and unobserved).

I.3.2 Properties of Sterile Neutrino Dark Matter

As originally suggested in, sterile neutrinos with the mass in the keV range can play the role of DM. Indeed, these particles are neutral, massive and, while unstable, can have their lifetime longer than the age of the Universe (controlled by the active-sterile mixing parameter θ). Such sterile neutrinos are produced in the early Universe at high temperatures.

Unlike other cosmic relic particles (e.g. photons, neutrinos or hypothetical WIMPs) the feeble interaction strength of sterile neutrinos means that they were never in thermal equilibrium in the early Universe and that their exact production mechanism is model-dependent. In the following we discuss the most important observational constraints on these particles as DM candidates. These can broadly be classified into three main categories,

- the phase space density in DM dense objects
- indirect detection through emission from the decay of sterile neutrino DM
- the effect of their free streaming on the formation of structures in the universe

Here we will be interested in the decay of sterile neutrino.

I.3.3 Decaying Dark Matter

For sterile neutrino masses below twice the value of the electron mass the dominant decay channel is N → $\nu_\alpha \nu_\beta \overline{\nu_\beta}$.

From now on we will discuss the total mixing angle and use the simplified notation.

$$\theta^2 = \sum_{\alpha=e,\mu,\tau} |\theta_\alpha|^2$$

If one requires that the lifetime should be (much) longer than the age of the Universe, $t_{\text{Universe}} = 4.4 \times 10^{17}$ sec the bound on the sum of the mixing angles θ^2 becomes

$$\theta^2 < 3.3 \times 10^{-4} \left(\frac{10\text{ keV}}{m_s}\right)^5 \quad \text{(lifetime longer than the age of the Universe)}$$

Along with the dominant decay channel, N → 3ν sterile neutrino also possesses a loop mediated radiative decay N → ν + γ, The decay width of this process is

$$\Gamma_{N\to\gamma\nu} = \frac{9\,\alpha\,G_F^2}{256\pi^4}\theta^2 M^5 = 5.5 \times 10^{-22}\theta^2 \left[\frac{M}{1\,\text{keV}}\right]^5 \text{sec}^{-1}$$

$$\Gamma = 5.6 \text{ x } 10^{-22}\, \theta^2 \left(\frac{m_S}{1kev}\right)^5 [s^{-1}]$$

While it is suppressed by $\frac{27\alpha}{8\pi} \sim \frac{1}{128}$ as compared to the main decay channel, such a decay produces a photon with energy $E_\gamma = \frac{m_s}{2}$. If the sterile neutrino is a main ingredient of the DM, then such a mono-chromatic signal is potentially detectable from spots on the sky with large DM overdensities. This opens an exciting possibility of astrophysical searches of sterile neutrino DM.

The number of photons from DM decay is proportional to the DM column density – integral of the DM distribution along the line of sight (l.o.s.):

$$S = \int_{l.o.s.} \rho_{DM}(r)dr$$

Averaged over a sufficiently large field-of-view (of the order of 100 or more) this integral becomes only weakly sensitive to the underlying DM distributions. As a result a vast variety of astrophysical objects of different nature would produce a comparable decay signal. Therefore,

- one has a freedom of choosing the observational targets, avoiding complicated astrophysical backgrounds;

- If a candidate line is found, its surface brightness profile may be measured, distinguished from astrophysical lines and compared among several objects with the same expected signal.

In this way one can efficiently distinguish the decaying DM line from astrophysical backgrounds.

Searches of this decaying DM signal in the keV–MeV mass range have been conducted using a wide range of X-ray telescopes: XMM-Newton, Chandra, Suzaku, Swift, INTEGRAL, HEAO-1 and Fermi/GBM, as well as a rocket-borne X-ray microcalorimeter, NuStar.

CHAPTER II

METHOD AND USE

II.1 Method

We extract data from a file (in a form of a data cube) which represents the density contrast of dark matter $\frac{\rho}{\rho_0}$ (where ρ_0 is the cosmological average matter density) distributed on each coordinate in the space (where we are located in the center),

$$\rho_0 = 10^{-26}\,\frac{kg}{m^3}$$

Our objective is to calculate the intensity of radiation (number of photons) coming from each direction of space using the formula below [1]

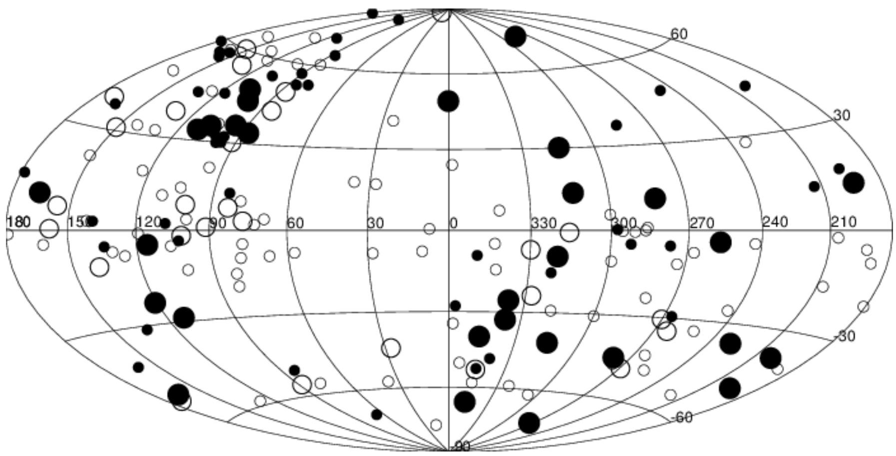
$$\frac{d^2N}{d\Omega\,\mathrm{dE}} = \frac{\Gamma\,\mathrm{n}_{\mathrm{DM}}^{0}}{2\pi\,\mathrm{H}_0}\,\frac{(2E)^{\frac{1}{2}}}{\sqrt{8E^3\Omega_\Lambda+\Omega_{\mathrm{matter}}\mathrm{m}_{\mathrm{s}}^{3}}} \qquad \text{Eq(1)}$$

Where N is the number of photons coming from a certain direction (at a dΩ differential solid angle) from space with certain energy (E). n_{DM}^{0} is the DM number density at the present time(the data we have extracted after multiplying by ρ_0).

Using the method of sightlines, we will be interested to integrate this variable (determined by the dark matter column density) along these lines.

II.2 Sightlines

In this method, we treat each simulation particle as a point source of X-ray photons. We randomly select positions on the surface of a sphere of some radius and place the observers (ourselves) at the center. We then define a cone with an opening angle and calculate the total flux of all simulation particles found within that cone: this is our 'sightline' measurement.



Here, we smear out each simulation particle into a spherical shell around the halo centre. We then calculate the flux from the shell surface area that intersects the line-of-sight cone as described above and as it will be described in more details below, then forming a sky map (which is our goal).

II.3 Code

Using of sightlines the method previously mentioned we will try to integrate along the LOS at different directions of space to get a sky-map. We use python 3 to implement it.
We will try to explain the steps simply by order:

- We start by 3-d rendering of a modeled distribution of dark matter within some 300 Mpc or so from the Milky Way galaxy stored in a data cube in a file, Each 3d pixel (voxel) of the cube stores the value of “density contrast”.

- Build the mesh grid to find the location of the different voxels by repeating it in three matrices (X, Y, Z) (each represents a coordinate).

- Start building the function that returns 2d matrices with each element representing the integrated number of photons along the line of sight of that we can plot in a picture after.

- Here we get into a problem were we know according to Hubble’s law that the universe is expanding

$$v = \mathrm{H_0 R} \qquad \text{Eq(@)}$$

$$\mathrm{H_0} = 70\,\frac{km}{s.Mpc}$$

where v is speed of the celestial object at a distance R from us

This will lead to a redshift in the radiation coming to us as we go further in space, as to a change in the energy of this radiation, this prevents us from integrating along the whole LOS and we will not have a monochromatic sky-map

$$E = \frac{m_S}{2(z+1)}$$

$$z = \frac{v}{c} \qquad \text{Eq(\#)}$$

z is the redshift (Doppler effect)

Then substituting Eq(@) in Eq(#)

$$z = \frac{v}{c} = \frac{\mathrm{H_0 R}}{c}$$

then,

$$E = \frac{m_S}{2(\frac{H_0 R}{c}+1)}$$

- Instead we will divide each LOS into different red shifts and integrate over each piece independently.
- We first create a gridded array of distances over 300 Mpc (equal in size to the length of that data cube we have).
- Then using the last formula, we compute the of energy E and energy difference dE (that we'll use it after) at each distance and store them in 2 arrays.
- We take in all directions in a certain region in space by the use of a double 'for loop' that goes in two orthogonal angular directions (Ra and Dec astronomical directions) ~8° x 8° moving 0.1° step in each direction after one turn. We determine the density contrast at each distance ($\mathbf{n_{DM}^0} / \boldsymbol{\rho_0}$) along the line of sight of each step using the regular grid interpolation function between the given data cube and array of distances previously done.

- Then calculating the variable 'dNph' in the Eq(1) (3d matrix with each axis representing Ra, Dec and distance)along LOS using the interpolated data and making $\mathbf{m_s}$ and $\boldsymbol{\theta^2}$ parameters of this function that represent different models.
- To integrate along each column R partially, we create a function that takes the cube 'dNph' and an array dE (the variable we will integrate over) as an input and returns a shorter /integrated cube 'Nph' (number of photons coming from each shell) as an output doing a partial integration along the LOS. We integrate simply by summing 4 vertical consecutive elements then multiplying by Energy difference dE.

$$\frac{\mathbf{d}N_{ph}}{d\Omega} = \int \frac{\mathbf{d}^2 N_{ph}}{\mathbf{d\Omega\ dE}}\ \mathbf{dE}$$

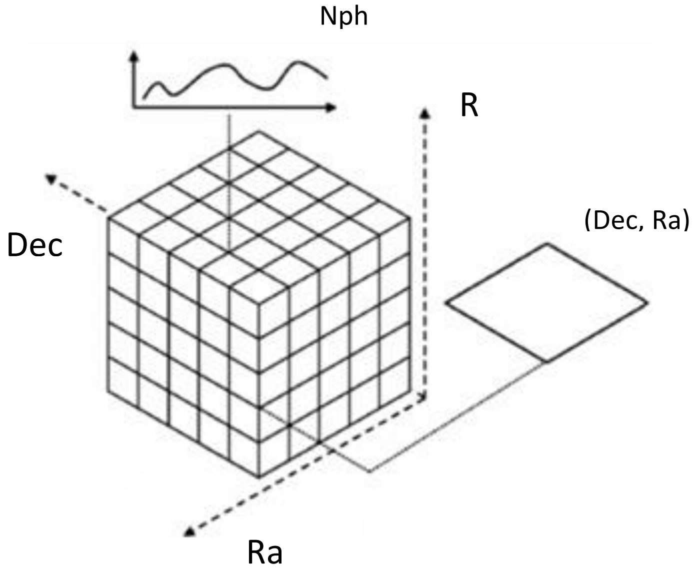
$$\equiv$$

$$\text{Nph[Ra][Dec][i]} = \sum_{j=4i}^{4i+4} \mathbf{dNph[Ra][Dec][j]\ x\ dE}[j]$$

Nph[Ra][Dec][i] : number of photons coming from i^{th} shell at direction (Ra, Dec)

- We will remain with a 3d matrix Nph, and then slice it horizontally at each shell, so we get a group of 2d matrices that can be plotted representing the sky map at different redshifts in different directions.

(A simple sketch will show some of that done in the code)



II.3 XRISM Mission

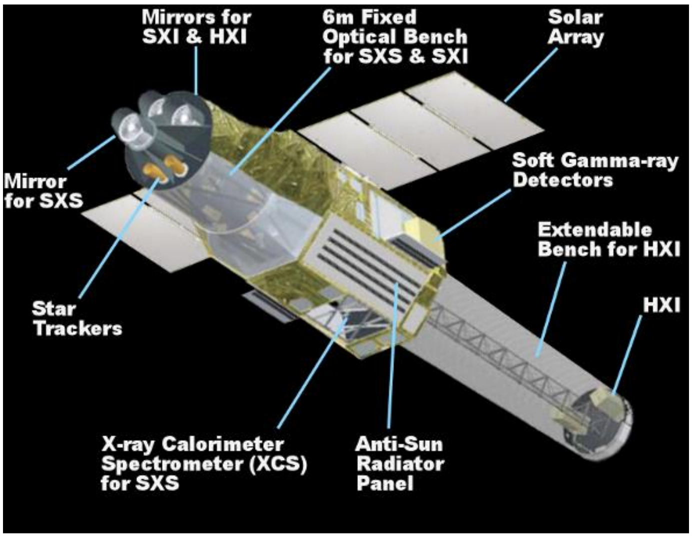
Also known as “X-Ray Imaging and Spectroscopy Mission” formerly known as the X-ray Astronomy Recovery Mission (XARM), is a JAXA-NASA collaborative mission with ESA participation. XRISM will offer non-dispersive, high-resolution X-ray spectroscopy in the soft X-ray bandpass ($\sim 0.3 - 12$ keV), while offering complementary CCD imaging resolution over a wide field of view. It represents a revolutionary leap forward in X-ray spectroscopy. With a spectral resolution 20-40 times better than the CCD instruments that are used on Chandra, XMM-Newton, and Suzaku, as well as a substantially increased collecting area and bandpass over the grating instruments on those missions.

XRISM will do this using two instruments:

- Resolve, a soft X-ray spectrometer with a constant < 7 eV spectral resolution over the entire bandpass. Resolve has a field of view of 2.9′ ×2.9′ over an array consisting of a 6×6 pixel X-ray microcalorimeter (pixels are 30” in size). The array has an operating temperature of 50 mK, and must be cooled by a multi-stage adiabatic demagnetization refrigerator.

- Xtend, a soft X-ray imager providing simultaneous coverage of the Resolve field and the surroundings over a 38′ × 38′ field of view. Xtend will provide CCD-quality imaging spectroscopy similar to that available on Suzaku (energy resolution < 250 eV at 6 keV), with $\sim$ 1′ spatial resolution.

The results (slice images) which give the sky map at different energy radiation can be compared to the observations that this mission will do a significant high energy-resolution spectroscopy E/ΔE ~1200 (ΔE~5eV).



CHAPTER III

RESULTS AND CONCLUSION

III.1 Result

After debugging the code, we choose a specific direction where we wish to simulate the radiation (sky-map). So we add the angles of direction as parameters in the main function and tried out to direct it to several galaxy clusters to maybe see some of the dark matter.

Let’s try mapping some galaxy clusters by simply putting their coordinates using this code.

Galaxy Cluster	Right ascension ~ [°]	Declination ~ [°]	Distance ~ [Mpc]
Coma cluster	195	28	103
Virgo cluster	187	13	20
Centaurus	192	-41	52

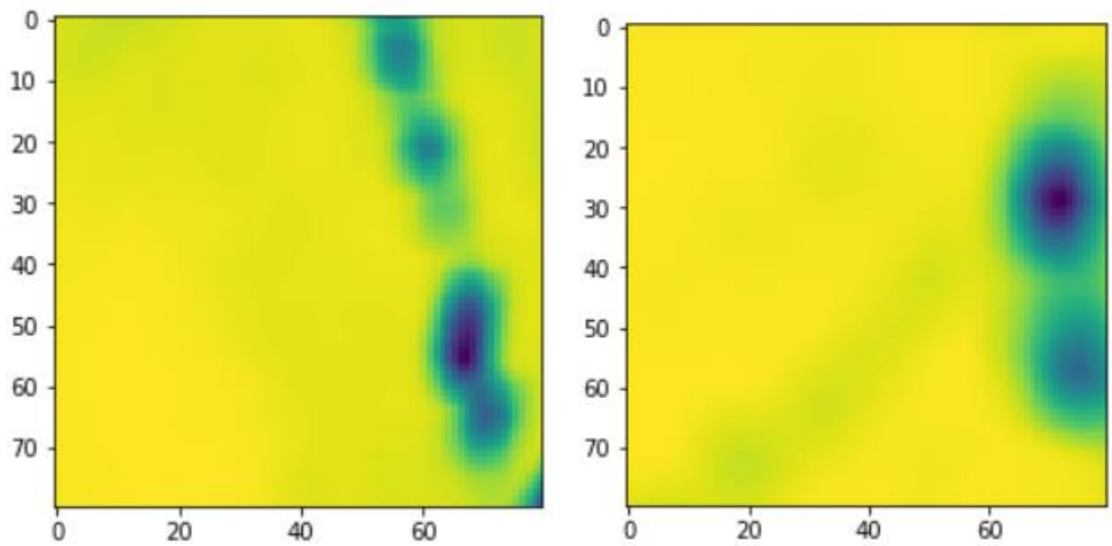
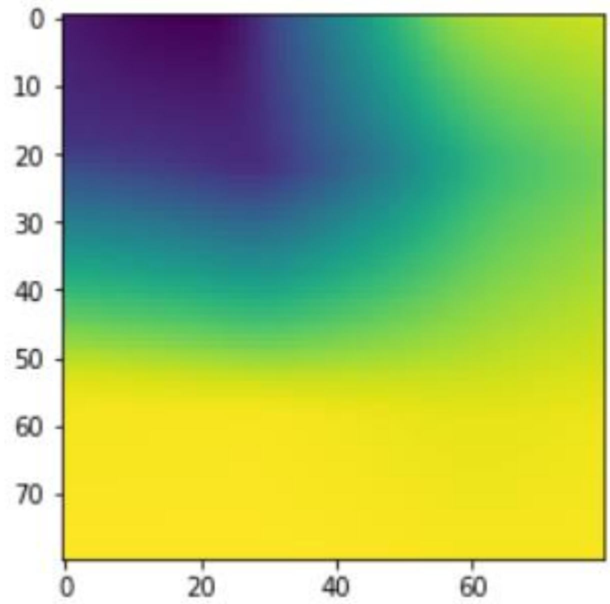


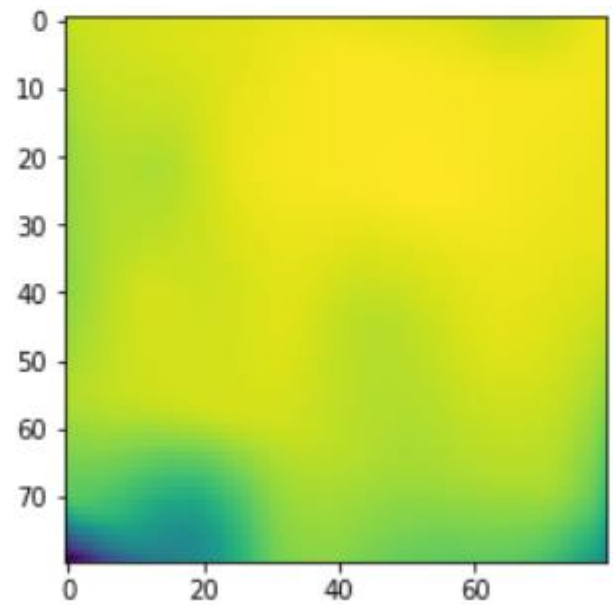
Image of Coma cluster(on the right)

And image on the same direction of coma cluster

but different distance



Virgo cluster



Centaurus

10 pixels = 1°

The strength of the radiation depends on the color of each pixel (blue/strongest → yellow /weakest)

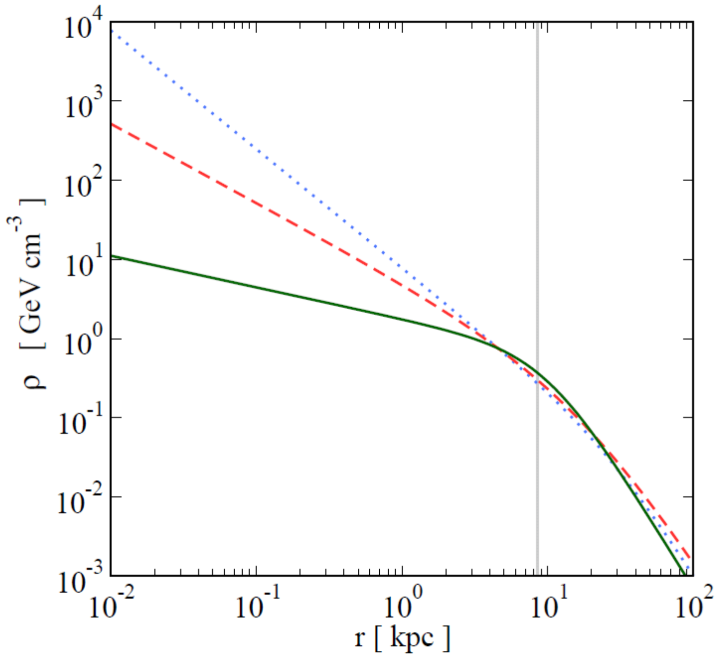
III.2 Discussion

Each image is represented in different radiation energy (color) due to the different redshifts the objects are in.

We can clearly see in the first picture as we take different distance the picture changes , that is because we face different celestial objects at each one.

And we can see in the figures that the virgo cluster is more detailed and spread angularly than other two galaxies, we can explain that because it is nearer to us than those.

By observing virgo we can predict that the density of dark matter in the center is higher than at the edges of it by the difference in the radiation density, same as predicted theoretically in the figure bellow.



Dark matter density as a function of the distance to the Galactic Center for three halo profiles [3]. From top to bottom, the Moore (blue-dotted), NFW (red-dashed) and Kravtsov (green-solid) profiles are shown. The vertical line marks the orbital radius of the solar system

Let's compare the observed angular size of virgo and the one by our simulation.

Theoretical angular size = 7° almost the same as in the figure (observe it)

All of these results show that this code for a good approximation works well, it can be modified to give a better images with greater resolution.

This code also can help to discard the background radiation when one studies a dark matter radiation coming from a certain galaxy.

III.3 Conclusion

Heavy sterile neutrinos are a very well motivated DM candidate. They overcome the shortcomings that exclude the SM neutrinos as viable DM candidates and appear in seesaw models that explain the light neutrino masses. In practice there are, however, many constraints on the properties of sterile neutrinos as DM candidates. In this article, we had simulated theoretically the radiation coming from a specific direction of space(Solid angle) from far galaxy clusters at a different conditions/models (depend on the mass of this sterile neutrino and the mixing angle), and showing the 1-D velocity dispersion of the dark matter as measured within the Hitomi/XRISM field-of-view (FoV) .

This code can help studying dark matter there by comparing it to the observations done by missions (XRISM, *ATHENA*) that investigate similar radiation

This radiation maps can also be taken out as a background radiation in researches about the radiation of dark matter in near galaxies.

After observing the figures above, the Virgo galaxy cluster is an excellent target for which to collect data suitable for detection of DM radiation.

In a more advanced detailed researches we can study the formation of sterile neutrinos in the early universe and their evolution (although they must be too stable) and maybe their density distribution over galaxy clusters that can be compared to our simulation.

References

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Science with the X-ray Imaging and Spectroscopy Mission https://arxiv.org/pdf/2003.04962.pdf