FACULTAD DE CIENCIAS FÍSICAS

MÁSTER EN ASTROFÍSICA



Cosmology from space:
Design of the observational strategies for the DUNES space mission

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TRABAJO DE FIN DE MÁSTER

Madrid, Septiembre de 2021

Abstract

The Standard Model of Cosmology assumes that the nature of the dark matter is cold (ΛCMD). However, this cosmological model does not solve all question about the Universe. One of the problems that appears when assuming this model is the so called "*missing satellites*" problem. This problem is solved applying other models, such as the one based on Warm Dark Matter (WDM). The detailed study of ultra-low surface brightness, like stellar tidal streams, could reveal which is the nature of the dark matter. The DUNES space mission has the purpose of restricting the cosmological model of the universe by studying the stellar tidal streams in galaxies of the Local Universe, up to 30 Mpc, using a small telescope (with 1500 mm of focal lenght and 150 mm of aperture) on board a microsatellite in Low Earth Orbit (LEO). This instrument has been developed by the SATLANTIS company: the iSIM camera.

This work focuses on creating a software that is capable of simulating, as realistic as possible, how these galaxies would be observed through iSIM in order to study the viability of the mission. To simulate the observations, cosmological simulations are used, which provide the galaxies with their structures, and the most relevant effects, both observational and optoelectronic, that affect the detection of these objects are applied. These cosmological simulations predict that the stellar tidal streams can have a surface brightness up to $\sim$ 32 mags/arcsec^2 in the VNIR spectral range. In this Master Thesis, in addition to presenting a fully functional tool which simulates a realistic observation, it is demonstrated that, in the absence of considering more effects, a limit surface brightness of 33 mag/arcsec^2 can be reached.

Resumen

El Modelo Cosmológico Estándar asume que la naturaleza de la materia oscura es fría (ΛCDM). Sin embargo, este modelo cosmológico no resuelve todas las preguntas sobre el Universo. Uno de los problemas que aparece al asumir este modelo, es el problema de los "*satélites desaparecidos*". Este problema sí se resuelve al aplicar otros modelos, como el de materia oscura templada (WDM). El estudio detallado de estructuras de ultra bajo brillo superficial, como las corrientes estelares de marea, podría indicarnos cuál es la naturaleza de la materia oscura. La misión espacial DUNES tiene el fin de restringir el modelo cosmológico del universo estudiando las corrientes estelares de marea en galaxias del Universo Local, hasta 30 Mpc, utilizando un telescopio pequeño (de 1500 mm de distancia focal y 150 mm de apertura) a borde de un microsatélite en una órbita baja terrestre (LEO). Este instrumento ha sido desarrollado por la empresa SATLANTIS: la cámara iSIM.

Este trabajo se centra en crear un software que sea capaz de simular de la forma más realista posible cómo se observarían estas galaxias a través de iSIM con el fin de estudiar la viabilidad de la misión. Para simular las observaciones, se utilizan simulaciones cosmológicas, que proporcionan las galaxias con sus estructuras, y se aplican los efectos más relevantes, tanto observacionales como optoelectrónicos, que afectan a la detección de estos objetos. Estas simulaciones cosmológicas indican que las corrientes estelares de marea tienen brillos superficiales de hasta $\sim$ 32 mags/arcsec^2 en el rango espectral de VNIR. En este trabajo, además de presentar una herramienta completamente funcional que simula una observación realista, se demuestra que, a falta de considerar más efectos, se podría alcanzar un brillo superficial límite de hasta 33 mag/arcsec^2.

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1. Introduction

The hierarchical model of galaxy formation and evolution predicts that the stellar halos of massive galaxies are formed and evolved primarily by low-mass mergers, fundamentally, due to satellite galaxies formed by stars, gas and dark matter. The Lambda-Cold Dark Matter (ΛCDM) simulations predicts that satellite galaxies decay over time on every massive galaxy. As a consequence, nowadays, stellar halos of massive galaxies should show diffuse remains of these satellite galaxies, such as stellar streams and shells. Observations of the Milky Way and M31 support the simulation's predictions about this stellar streams formation on spiral galaxies of the Local Group. However, the 'cosmic variance' limits the comparison between observations and simulations (very different assembly histories).

The main observational limitation of these structures of the stellar halo is due to its ultra-low surface brightness. These tidal streams should be fainter than $\sim$32 mag/arcsec^2 in visible wavelengths and $\sim$30 mag/arcsec^2 in infrared wavelengths. The Stellar Tidal Stream Survey (STSS) (Martinez-Delgado 2018) has revealed a huge structure variety whose characteristic morphological agree with the predictions of the N-body simulations.

DUNES space mission ("Dark matter Unveiled with Nanosatellite Exploration of Space") is focused on the study of Stellar Tidal Streams (STS) formed from the accretion of a dwarf galaxy on a massive host galaxy.

A detailed study of STS will allow us to restrict the cosmological model because the morphology of STS varies for different cosmologies.

The sub-halo mass function of the Cold Dark Matter (CDM) and Warm Dark Matter (WDM) models differs in masses below the mass of satellite galaxies.

- **WDM**: Exists a cut-off on the low-masses halos because the velocity dispersion of the dark matter particles suppresses the primordial density fluctuations of small scale (Peebles 1982).
- **CDM**: This cut-off does not exist, so it is expected to find a large number of DM halos orbiting the host galaxy (Diemand et al. 2008).

Although the CDM framework allows us to explain structure formation on large scales, N-body simulations predict an order of magnitude more of DM sub-halos within the halo galaxies than the number satellite galaxies observed around the Milky Way. This is the so-called "missing satellites" problem (Klypin et al. 1999; Moore et al. 1999). Fig. 1 shows this difference between both cosmological models. Thus, the best way to do detect the presence or not of these satellites is to look for gravitational effects in the environment. For this reason, good candidates to observe these effects are cold stellar streams. In a universe dominated by WDM, they should be characterized by being thin and continuous, covering large distance around the host galaxy. Whereas, if the universe were dominated by CDM, the presence of many DM halos should break the stellar streams (due to gravitational interaction), developing gaps along the stream that would increase with time (Yoon et al. 2011).

Throughout the last decade, two methods have been developed to optimize the efficiency of the ultra-deep universe surveys from the ground. Both involves small telescopes with apertures from 10 cm to 80 cm. One is a sophisticated system of refraction telephoto lenses ("Dragonfly Telescope Array", Abraham & van Dokkum (2014)), and the other is a citizen scientific project (Martínez-Delgado et al. 2010). The latter consists of coordinated observations from small, high-quality

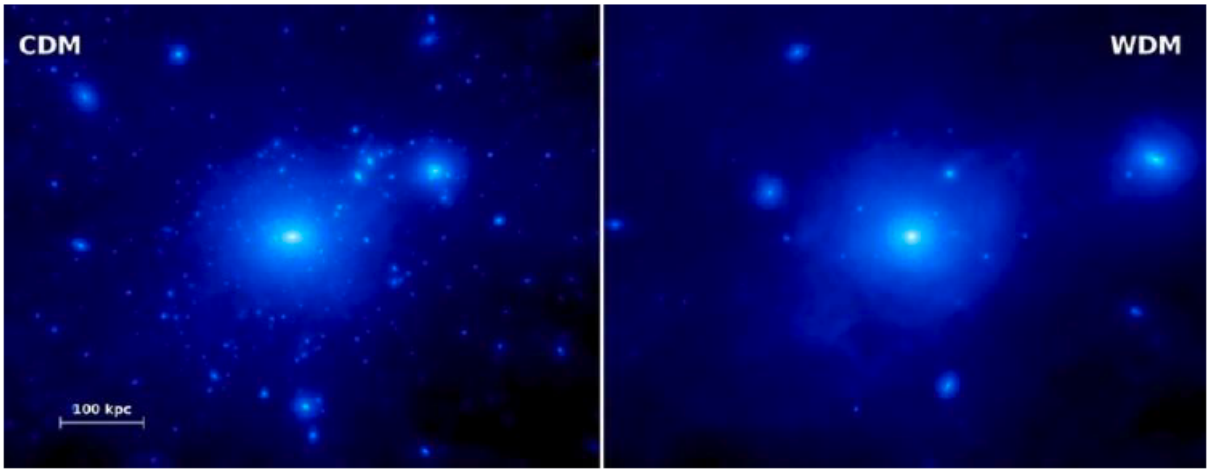


Figure 1. Example of the differences of the number of sub-halos and galactic structure in the stellar halos of a typical Milky Way-like galaxy as predicted by cosmological simulations (Bœhm et al. 2014). Left: CDM model, there are a large number of sub-halos and well-defined stellar streams. Right: WDM model, there are a fewer sub-halos and more diffuse stellar streams.

amateur reflector telescopes.

However, with these observations it is only possible to study optical surface brightness levels of ∼28 mag/arcsec^2. To obtain a good comparison between models and data, it is crucial to have a huge sample of galaxies. To observe SB fainter than ∼28-29 mag/arcsec^2 in the visible range wavelength is totally challenging. The first obstacle that we find out is the sky background noise, which is about 21.8 mag/arcsec^2 in the V band. Although this is bigger in the infrared, reaching the 14.4 mag/arcsec^2 in the H band. Nowadays, the observation of fainter SB from the ground is almost science-fiction.

As an alternative, small telescopes (apertures ∼150 mm) with large fields of view (∼1°) can be used on-board a micro-satellite orbiting on a Low Earth Orbit (LEO). This is the main technological proposal of DUNES space mission. DUNES pretends to observe ∼200 galaxy halos simultaneously over the visible and over the IR wavelengths, reaching a SB of ∼32-30 mag/arcsec^2, respectively. The key technology is iSIM camera (integrated Standard Image systeM), a camera developed by the leading technology company, SATLANTIS (Guzmán et al. 2020).

iSIM consist of a binocular telescope based on a modified Maksutov-Cassegrain design. It has a focal distance of 1500 mm and an effective aperture of 150 mm. It offers imaging from 450 nm to 1700 nm thanks to its binocular system of a FOV of 1°. It can also work simultaneously in the optical and the IR ranges. This sophisticated imaging system has three key innovations:

- **Super-resolution**: the spatial resolution is limited by the optics size, while in traditional systems it is limited by the pixel size of the detector. This spatial resolution can be also improved with later AI algorithms.
- **Multi-spectroscopy**: the spatial resolution is independent of the number of spectral bands, while in traditional systems it decays proportionally to the number of bands.
- **Agility**: iSIM can take images while the satellite moves along and across its orbit, whereas the traditional systems can do it only along its orbit.

The camera model iSIM-170 FM, launched in May 25th 2020 to the ISS, in order to be tested. The results of this mission, such as the one presented on Fig. 2, demonstrate the potential of this instrument. Using super-resolution algorithms, processed images, taken with iSIM on board the ISS, can achieve sub-meter resolutions.

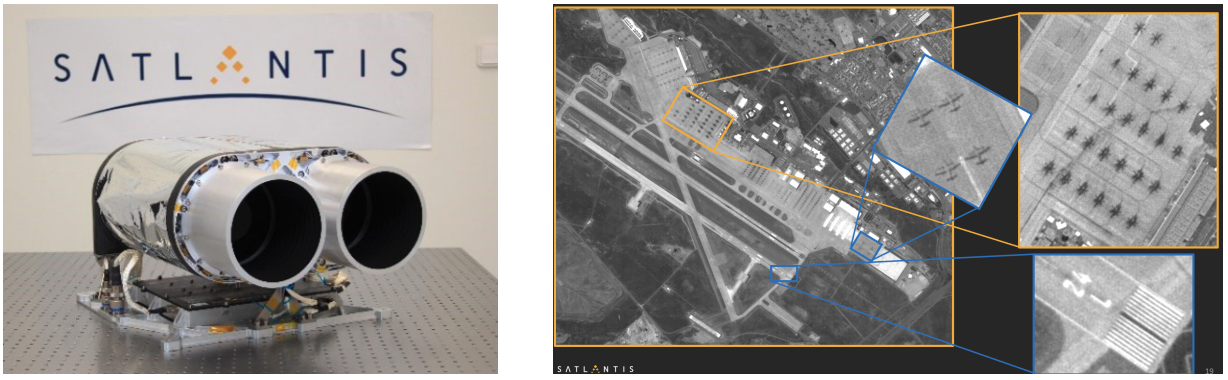


Figure 2. Left: The Flight Model of iSIM-170 payload, which launched to the ISS. Right: Example of processed iSIM-170 images. Note that one can distinguish the blades of the helicopter, which are typically 0.5 m wide approximately (Guzmán et al. 2020).

To ensure the success of DUNES space mission, it is crucial to design the best observation strategy. With this propose, it has been developed a realistic simulation to estimate the expected results of the observations. This is the main goal of this project. This simulation must take into account certain input information, such as the location in the sky, the distance to the galaxy or the characteristics of the detector.

GARROTXA DM+hydro simulations has been used to simulate these galaxies observations (Roca-Fàbrega et al. 2016). These simulations reproduce realistic high resolution Milky-Way-like galaxies and their satellites and stellar streams. The simulations provide, not only the surface density of the tidal streams, but also their metallicity and their age so that we can obtain the color of these streams.

The crucial point that this project faces is the transformation of the mass stellar particles into luminosity particles which is discussed at the beginning of Section 2. In this section, it is also discussed the simulation of the other effects involved: in Section 2.2, the observational effects such as the distance, the dust extinction and the zodiacal light; in Section 2.3, the noise taken into account and a detailed description of the iSIM camera simulation developed with all its features (flat field, Point Spread Function (PSF), detector characteristics and bandpass), and at the end, in Section 2.4, the cosmological corrections (K-correction, decreased flux due to cosmology...).

In Section 3, a detailed explanation of the program developed is given, whilst in Section 4 the main results of this Master Thesis are presented. In the last section, Section 5, the conclusions and a brief notion of the future work that could be done to improve the work are presented.

2. Simulation of the observation

2.1. Mass to luminosity transformation

The main goal of the simulation is to obtain the Spectra Energy Distribution (SED) of the galaxy, in order to be able to integrate any wavelength range, allowing to study which is the best filter to observe stellar tidal streams. For this reason the simulation is based on the black body approximation to calculate the number of photons emitted by every star of the galaxy as a function of the wavelength. Thus, it is crucial to obtain the temperature and the luminosities of stellar particles.

The first step on the simulation is to transform mass particles into luminosity particles. The starting point is a Milky Way-like galaxy, provided by GARROTXA (Roca-Fàbrega et al. 2016), composed by mass particles of at least 10^3 $M_\odot$, with very different ages and metallicities. To obtain the luminosity of these particles, it is necessary to use adequate isochrones from Color Magnitude Diagrams.

In this case, 65 isochrones of different ages with 4 different metallicities ($[M/H]$ = -2, -1, 0, 0.68) have been selected, making a total of 260 different isochrones with approximately 280 mass points that covers the entire mass spectrum. To simplify the conversion, the mass spectrum has been reduced to 18 mass bins, taking their luminosity and temperature mean values. These bins can be seen in Fig. 3.

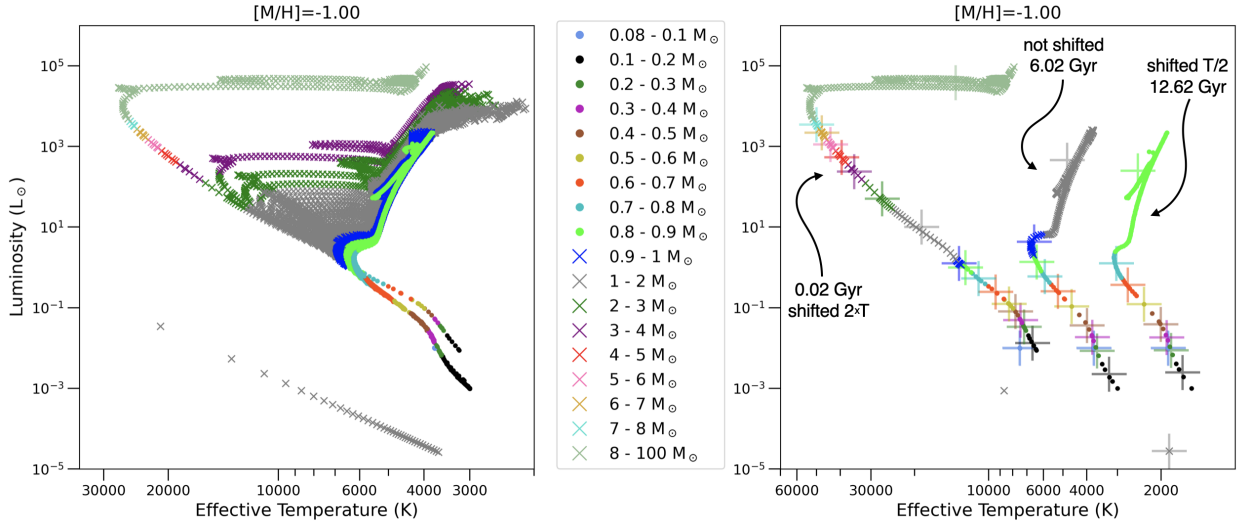


Figure 3. **Left**: Original isochrones for a metallicity $[M/H] = -1$. The different colors represent the 7 mass bins selected. **Right**: Three specific isochrones with metallicity $[M/H] = -1$ and ages: 0.02, 6.02, 12.62 Gyr respectively (shifted in temperature for better viewing: $\times 2$, $\times 1$, $\times 0.5$, respectively). The crosses show the mean position of the mass bins on the H-R diagram.

Once the mass spectrum is reduced to 18 mass bins, it is necessary to assume an Initial Mass Function (IMF) to determinate the number of stars expected from each mass bin. In this project, the IMF selected is obtained from Salpeter (1955), but it can be applied other IMF, such as from Kroupa (2002), Chabrier (2001), Chabrier (2003), and from a power law. In Fig. 4, is shown the different IMF that can be applied, although Salpeter's has been chosen.

The next step is to find the isochrone that best represents each particle in the simulated galaxy. With this goal, each stellar particle has been analysed, finding the most similar values to its metallicy and age in the isochrones. Once the isochrone is identified, the appropriate temperature and

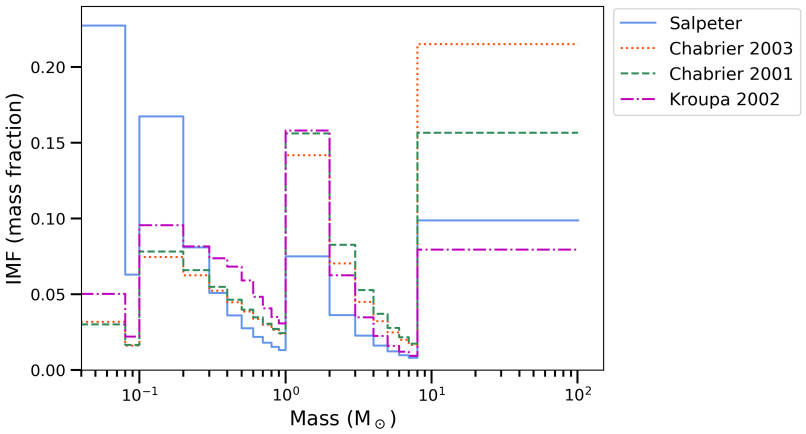


Figure 4. Different IMF in the mass bins shown in Fig. 3, which can be applied in this transformation. Solid blue line refers to Salpeter (1955), dotted red line to Chabrier (2003), dashed green line to Chabrier (2001) and dashed-dotted purple line to Kroupa (2002).

a luminosity are automatically assigned to each mass bin of the mass particle. With this method, a stellar particle of a certain mass is transformed into a several stars with different temperatures and luminosities along the isochrone defined by their age and metallicity, therefore, their black body function is also known and, consequently, the total galaxy SED.

This SED of a stellar particles will be the sum of the different contributions of each black body:

$$B_\lambda^{\text{total}}(M) = \sum_i N_i(M) \cdot B_\lambda(T_i) \qquad i = \text{mass bins of the stellar particle}$$
$$\text{with} \quad B_\lambda^{\text{total}}(M) \equiv [\text{erg s}^{-1}\text{cm}^{-2}\text{str}^{-1}\text{Å}^{-1}] \tag{1}$$

However, since a Super Giant star does not emit the same photon flux as a Main Sequence star, it is necessary to weight its luminosity. For this purpose, a factor is added in order to take this fact into account.

$$B_\lambda^{\text{total}}(M) = \sum_i N_i(M) \frac{L_i}{\sigma T_i^4} \cdot B_\lambda(T_i) \qquad i = \text{mass bins of the stellar particle}$$
$$\text{with} \quad \frac{L_i}{\sigma T_i^4} = 4\pi R_i^2 = [\text{cm}^2\text{str}] \quad \text{and} \quad B_\lambda^{\text{total}}(M) \equiv [\text{erg s}^{-1}\text{Å}^{-1}] \tag{2}$$

To check the approximation, a stellar particle with the following characteristics has been taken:

$$M = 10^6\ M_\odot \qquad \text{Age} = 7.0\ \text{Gyr} \qquad [M/H] = -1.0 \tag{3}$$

The result of integrating (2) over the entire wavelength spectrum can be compared with the total sum of its intrinsic luminosity obtained by the isochrones:

$$L_{\text{total}} = \int_0^\infty B_\lambda^{\text{total}} d\lambda \simeq 5.7140 \times 10^6 L_\odot$$
$$L_{\text{total}} = \sum_i N_i \cdot L_i \simeq 5.7142 \times 10^6 L_\odot \tag{4}$$

which means a relative error of $\sim 0.002\%$. This exercise can be done with different age and metallicity stars of the same mass (10^6 $M_\odot$), verifying that this error is systematic. This is shown in Fig.5.

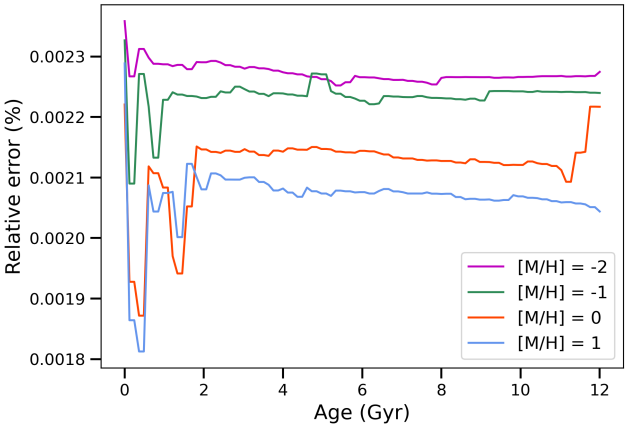


Figure 5. Relative error between the black body approximation and the isochrones data along stars of different ages. Different color lines denote different metallicity of these stars

Thus, if B_λ^{total} convolves with a wavelength range, the result is the total luminosity of the stellar particle in that range. Therefore, to simulate SED of the galaxy, it is crucial to obtain the factor $N_i L_i/\sigma T_i^4$ for each star type. However, the dominant term of this function will depend on the super-giant stars.

On the other hand, a second test has been carried out to confirm that this transformation from stellar particles to luminosity particles is correct: the simulated galaxy has been integrated over the V-band (450-750 nm) and it has been calculated its surface brightness profile. This profile, shown in Fig. 6, is very similar to the expected one, reaching Surface Brightness (SB) of $\sim$ 16 mag/arcsec^2 at the center of the galaxy and $>$ 28 mag/arcsec^2 at the outskirts. At the center of the galaxy the SB decreases exponentially, while at the outskirts the decrease is smoother. There are also some peaks of SB due to satellite galaxies that orbit the MW-like galaxy.

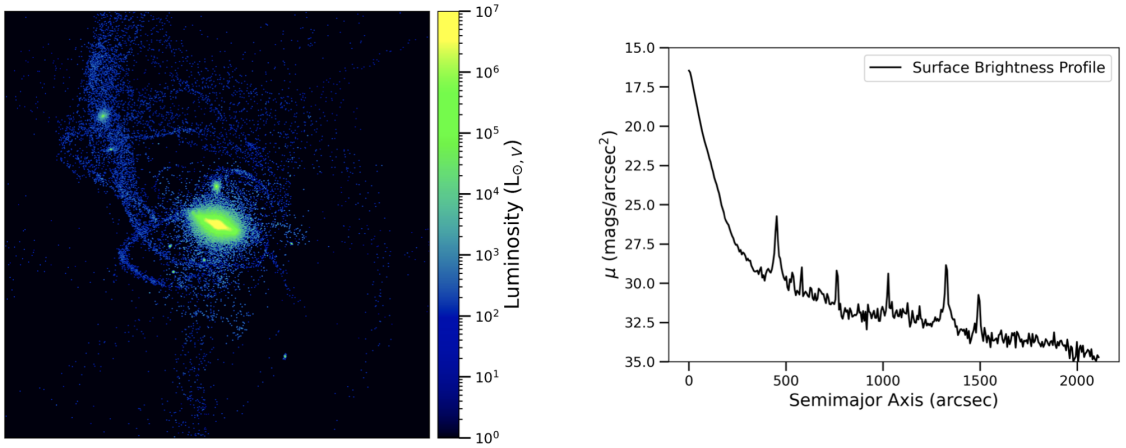


Figure 6. **Left**: Image of the simulated galaxy in Solar Luminosities in the V-band ($L_{\odot,V}$). The center of the galaxy reaches 10^7 $L_{\odot,V}$, while the tidal stream in blue, is $\sim 10^3$ $L_{\odot,V}$. **Right**: Surface Brightness profile of the simulated galaxy from the right side. The profile goes from $\mu \sim 16$ mag/arcsec^2 (at the center) to ~ 28 mag/arcsec^2 (at the outskirts).

However, telescopes do not measure luminosities, but measure counts (photons transformed in electrons). Thus, the last step is to divide the function B_λ^{total} by the energy of a photon with

wavelength λ:

$$B^{\text{total}}_{\text{photons}} = \frac{hc}{\lambda} B^{\text{total}}_{\lambda} \equiv [\text{photons s}^{-1}\ \text{Å}^{-1}] \qquad L_{\text{total}} = \int B^{\text{total}}_{\text{photons}} d\lambda \equiv [\text{photons s}^{-1}] \quad (5)$$

Despite how essential the transformation between mass and luminosity is, there are other effects (both observational and optoelectronic) that must be included in a simulation of a real observation.

2.2. Simulation of observational effects

There are different effects involved in the observation of the tidal streams, mainly the distance to the galaxy, the orientation of these structures, the extinction by the dust of the Milky Way, and the sky background noise due to the zodiacal light.

- **Distance:** Only the distance will determine a limit in the observation. The flux from a source at a distance d is well known:

$$F_{\text{photons}} = \frac{L_{\text{photons}}}{4\pi d^2} \equiv [\text{photons s}^{-1}\ \text{cm}^{-2}] \quad (6)$$

  In the case of DUNES mission, the target source are between 10 to 30 Mpc away. This distance is short enough to ignore cosmological effects such as the K-correction and the redshift effect on the flux (will be discussed later in Section 2.4). However, the number of photons that would arrive from a source at 30 Mpc is 0.88 times smaller than those arriving from the same source at 10 Mpc. This is why the effect of the distance is important.

- **Orientation:** The orientation of the stellar tidal stream with respect to the line of sight will also play an important role. Since the numerical simulations provides the coordinates of the stellar particles (with the reference system at the center of the galaxy), it is trivial to rotate the coordinate system multiplying the appropriate matrix of the Euler angles.

$$R_{\text{total}}(\alpha, \beta, \gamma) = R_x(\alpha) R_y(\beta) R_z(\gamma) \quad (7)$$

- **Dust extinction:** Dust from the Milky Way extincts some of the light that comes from external galaxies. For this reason, it is necessary to properly simulate this decrease in the incoming photons. In order to do this, the Python package sfdmap has been used. It uses the E(B-V) skymap provided by Schlegel et al. (1998) in RA and DEC of the whole sky. Thus, with a pair of coordinates and the extinction coefficient of the common band passes (in this Master Thesis, the Johnson-Cousins UBVRI photometric system, including JHK bands, have been used with the extinction coefficients of Table 6 from Schlafly & Finkbeiner (2011)), the percentage of photons that pass through by the dust of the Milky Way can be estimated in an efficient and simple way. Fig. 7 shows a map of this percentage at the V-band. This map determines the regions where it is appropriate to observe, avoiding the opaque areas of dust. In Fig. 7, it is also provided an estimation of the paths of the planets of the Solar System, the moon and the sun (green dots); and the approximate regions of interest (blue regions).

- **Zodiacal light:** Finally, the sky background noise due to the zodiacal light has been calculated using gunagala. This package provides an efficient estimation of the zodiacal light surface brightness at the ecliptic pole as a function of the wavelength (in photon spectral flux density units) and the surface brightness relative to that at the ecliptic poles for a given sky position and observing time. Fig. 8 shows different maps with the number of photons per cm^2, second and arcsec^2 corresponding to several days throughout the year. The maximum

incoming photons of the zodiacal light varies with the epoch, so this will restrict the area of observation based on time and date.

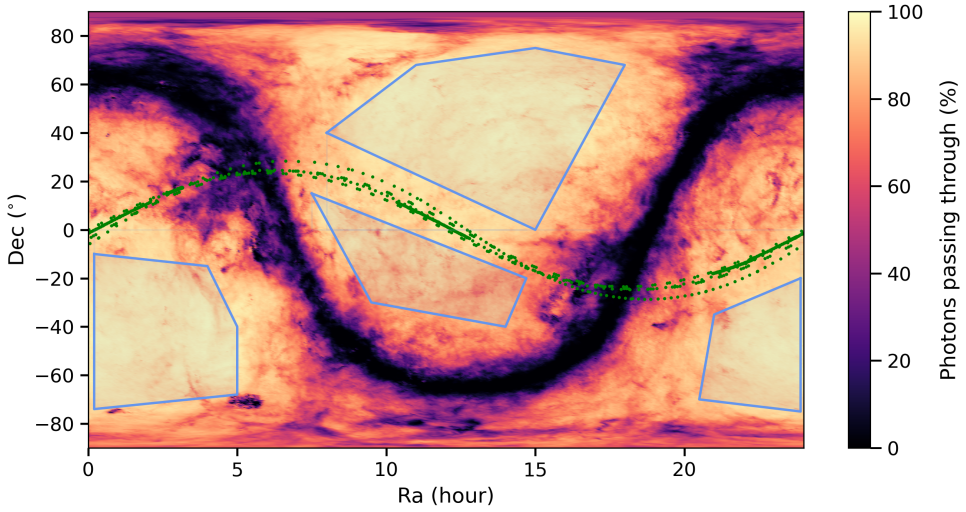


Figure 7. Dust extinction skymap used in the simulations. The color-code shows the percentage of photons that pass through the Milky Way's dust. The green dots represent the orbits of the planets of the Solar System, the Moon and the Sun (near the plane of the ecliptic). The approximate regions of interest are highlighted in blue.

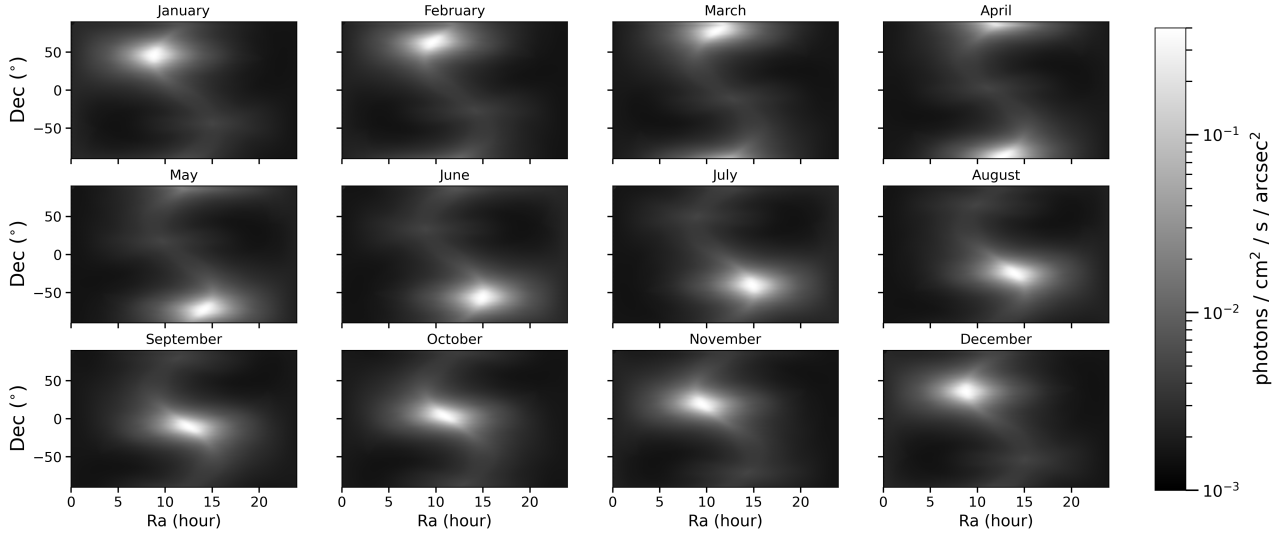


Figure 8. Skymaps of the photons per cm^2, second and $arcsec^2$ incoming of the zodiacal light throughout the year 2022. The color-code shows the maximum and the minimum regions of this light, and its dependence with the epoch of the year.

2.3. Simulation of optoelectronic effects

In addition to the observational effects, there are also other effects related with the telescope, the detector and the filter that must be taken into account.

- **Detector characteristics:** For DUNES mission (as in other mission or telescope) a detector with specific characteristics, such as a low read-out-noise and dark current, is required to avoid

the dominance of electronic noise that will limit the surface brightness observable by iSIM. To evaluate this limit, a realistic simulation of the noise and the efficiency of a detector is crucial. The simulation uses different detectors (both optic and IR) well characterized by the manufacturer or by SATLANTIS. The noise of these detectors will be composed by the read-out-noise, the bias and the dark current (that depends on the exposure time). Therefore, the total dark signal noise is calculated as:

$$\text{Dark}_{\text{noise}} = \sqrt{t_{\text{exp}} \cdot \text{Dark}_{\text{current}}} \tag{8}$$

and the total sensor noise:

$$\text{Det}_{\text{noise}} = g \cdot \sqrt{\text{Dark}_{\text{noise}}^2 + \text{Read-out-Noise}^2} \tag{9}$$

where g is the gain of the detector. The bias will not be simulated because it will not affect significantly at the calculation of the surface brightness limit. However, in the real future observation with iSIM, the master-bias will be obtained using the pixels outside the FOV. On the other hand, the detector is not equally sensitive at all pixels, so a well characterized Flat Field is required. In case of not having a flat field of the selected detector, it can be simulated. Also, both the gain and the quantum efficiency of the detector are necessary because not all incoming photons produce an electron.

- **Filter characteristics:** The filter is an important part of the simulation because it restricts the range of the spectrum that is observed. Stellar tidal streams are characterized by being composed of old, red stars. This is why the mission is interested in both optical and infrared bands. Thus, a detailed description of the efficiency and the wavelengths of the filters is required. It is also necessary to know the extinction coefficient due to the Milky Way's dust in the selected filter. Any filter, whose characteristics are known, can be applied in the simulation.

- **Telescope characteristics:** From the telescope, in this case iSIM, it is necessary to know the aperture, the focal length and the PSF. These data have been provided by SATLANTIS. In the pursuit of ultra-low brightness structures, a good knowledge of the PSF is important so as not to confuse these structures with very low diffraction orders due to the aperture of the camera. The aperture (a) determines the number of photons that the detector collects:

$$N_{\text{photons}}/s = F_{\text{photons}} \cdot \pi a^2 \tag{10}$$

and the focal length (f), the plate scale of the telescope, which is useful for transforming the physical units of the simulated galaxy (in Mpc from its center) to the detector units (pixels at the detector). In this step it is necessary to know the number of pixels and their size because (with the distance) this will determine the part of the galaxy observed in the detector.

$$\text{"/mm} = \frac{1\text{"}}{f(\text{mm})} = \frac{206265}{f(\text{mm})} \qquad \text{"/pix} = \text{"/mm} \cdot s_{\text{pix}}(\text{mm}) = \frac{206265}{f(\text{mm})} \cdot s_{\text{pix}}(\text{mm}) \tag{11}$$

With the distance, the angular position in arcseconds can be calculated:

$$r(\text{"}) = \frac{r(\text{Mpc})}{d(\text{Mpc})} \cdot 206265 \tag{12}$$

At the end, using both equations, the position of the galaxy in pixel units is obtained:

$$r(\text{pix}) = \frac{r(\text{"})}{\text{"/pix}} = \frac{r(\text{Mpc})}{d(\text{Mpc})} \cdot \frac{f(\text{mm})}{s_{\text{pix}}(\text{mm})} \tag{13}$$

The effective aperture of iSIM is 150 mm and a focal length of 1500 mm.

- **Exposures parameters:** Finally, it is necessary to select an exposure time and integrate (10) over it. This will provide the number of photons that arrive at a pixel of the camera. Other terms that have to be added to this signal are: the sky background noise, the extinction percentage, both explained in Section 2.2, the efficiency of the sensor and the detector quantum efficiency gain and noise (read-out-noise and dark current).
- **Orbit effect:** Another noteworthy point is that iSIM is planned to be on-board a microsatellite orbiting on a LEO. So, in order to do a realistic simulation, in this Master Thesis, the rotation of the camera during the observation has been simulated between different exposures.

2.4. Cosmological Corrections

The cosmological effects can be perceived in the observations of the deep sky. However, the importance of this effect depends on the distance in which the observation is taking place (previously commented in Section 2.2). The cosmological observation of galaxies at high redshift has an intrinsic decrease on the luminosity of the source which depends on the cosmological model used and, therefore, on the reduced Hubble constant, $h_0 = H_0/(100 \text{ km s}^{-1}\text{Mpc}^{-1})$, where H_0 is the Hubble constant (Hubble parameter at the present age) (Hogg 1999).

However, as the main goal of DUNES space mission is to observe nearby galaxies (up to $\sim$ 30 Mpc) some cosmological effects such as the K-correction (because of the bandpass selected for the observation and the redshift) and the redshift effect on the flux will be low enough to be considered negligible.

In cosmology, a comoving system of coordinates which change as the universe is expanding is defined. These comoving distances are defined from the Hubble parameter and the redshift as:

$$d_C(z) = c\int_0^z \frac{1}{H(z')}dz' = \frac{c}{H_0}\int_0^z \frac{1}{\sqrt{\Omega_{m,0}(1+z')^3+\Omega_{\Lambda,0}}}dz' \tag{14}$$

where $H(z)$ is the Hubble parameter at a certain redshift, z:

$$H(z) = H_0\sqrt{\Omega_{m,0}(1+z)^3+\Omega_{\Lambda,0}} \tag{15}$$

This comoving distance can not be directly measured, but can be estimated from the luminosity of the objects. The distance calculated by the luminosity and the flux of cosmological objects is called luminosity distance:

$$d_L^2(z) = \frac{L}{4\pi F} \tag{16}$$

Since the luminosity and the comoving distances are related as:

$$d_L(z) = d_C(z)(1+z) = \frac{c(1+z)}{H_0}\int_0^z \frac{1}{\sqrt{\Omega_{m,0}(1+z')^3+\Omega_{\Lambda,0}}}dz' \tag{17}$$

the decreased flux from a cosmological source with redshift is calculated as:

$$\frac{F_{\text{obs}}}{F_{\text{emi}}} = \frac{1}{(1+z)^2} \tag{18}$$

The decreased percentage with the distance is shown in Fig. 9, for example, at 50 Mpc, the flux is reduced by approximately 2%.

On the other hand, the K-correction is an effect produced by the change with the redshift of the same spectrum ($f(\lambda)$) observed with the same filter $R(\lambda)$. This is because the spectrum becomes redder at greater distances (as $\lambda(1+z)$) and the bandpass used for observation does not change. The K-correction can be calculated as:

$$K = -2.5\log\left[\frac{\int_0^\infty f_\lambda(\frac{\lambda}{1+z})R(\lambda)\frac{\lambda}{1+z}d\lambda}{\int_0^\infty f_\lambda(\lambda)R(\lambda)d\lambda}\right] \tag{19}$$

Fig. 9 shows the variation of the K-correction with the distance and the redshift for different type of stars (different $V-R$ color) in the V-band. The maximum value of the K-correction is ~ 0.1 magnitudes when the source is at 50 Mpc (with $V-R=1$). However, this effect is always bound to the filter and the spectrum of the observed object.

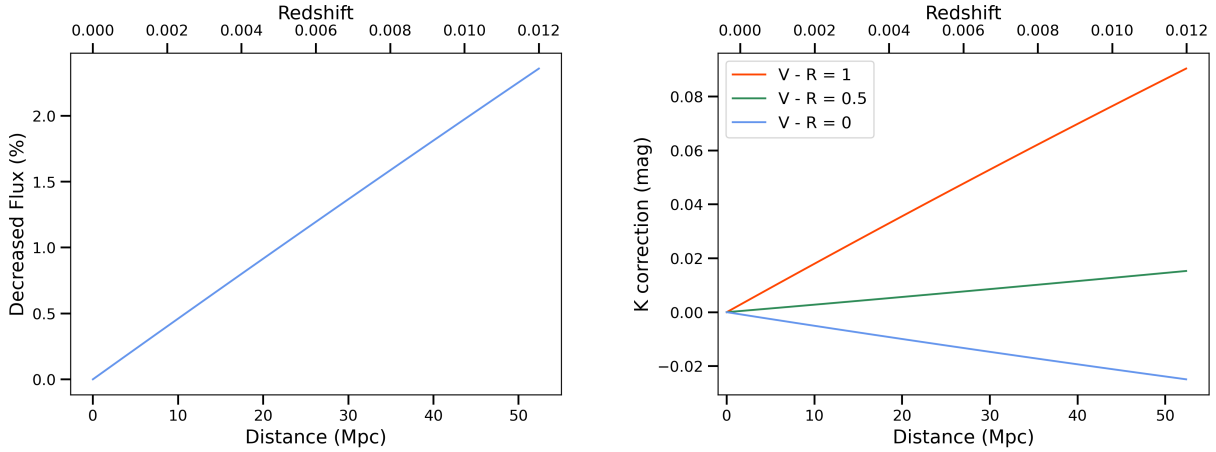


Figure 9. **Left**: Decreased percentage of flux due to the redshift as a function of the distance (bottom x-axis) and the redshift itself (top x-axis). It shows that the flux lost by neglecting this effect is very small at a distance of ~ 30 Mpc ($\sim 1.3\%$) **Right**: K-correction of the V band in magnitudes for sources with colors $V-R=0$ (blue), 0.5 (green), 1 (red) at different distances (bottom x-axis) and redshifts (top x-axis). The correction at a distance of ~ 30 Mpc is approximately 0.05 mags, which is small enough to ignore this effect.

Another source of noise that is not accounted in this simulation is the cosmological background galaxies. This will be improved in the future, but to consider a more realistic simulation it is crucial to take this into account. Both this future improvement and others will be discussed in Section 5.2.

3. iSIM Dark Matter Halo Simulations

iSIM Dark Matter Halo Simulations is a program with a Graphical User Interface where the user can select different options in order to make a complete study of a real survey. This program takes into account every parameter, both optoelectronic and observational, explained in Section 2. The goal of this simulator is not only to check the viability of the DUNES mission, but also to provide a preliminary study of the best conditions of the observations. This section focuses on explaining the Graphical User Interface (GUI) and the code itself.

3.1. The Graphical User Interface (GUI)

The Graphical User Interface (GUI) has been constructed from python package tkinter. It basically consists on a window with options, text spaces and buttons where the user can select, fill and press

in order to combine the different effects from Sections 2.2 and 2.3. The GUI is shown in Fig. 10.

The simulator provides different galaxies to be simulated: 2 Andromeda-type galaxies and 4 Milky Way type galaxies and the user can select any of them. It also offer all type of sensors for the user to decide which one they want to use. There are sensors both in the optical and in the IR, with all kind of sizes, number of pixels, read-out-noise and dark current parameters. In addition, there is also an option to select the bandpass, where Johnson-Cousins UBVRI and JHK filters are offered. However, this options can be modified at any time, so that the simulation can be always updated with new information.

The interface also have some blanks, where the user can text on them (or not) the conditions of the simulation. Most of the fields have a default value in case the user do not mind the value of the parameter. There is an option for the indicator of distance, where the user can indistinctly use redshift or distance because the code can do the appropriated calculations in both cases to transform the input value into the luminosity distance (which is the value used in the program). The default value is the indicator of luminosity distance at 12 Mpc. To change the orientation of the galaxy, there are three fields created to customize the Euler angles of the rotation matrix (7). If there is no angle selected, the orientation will depend on the output coordinates of the cosmological simulation.

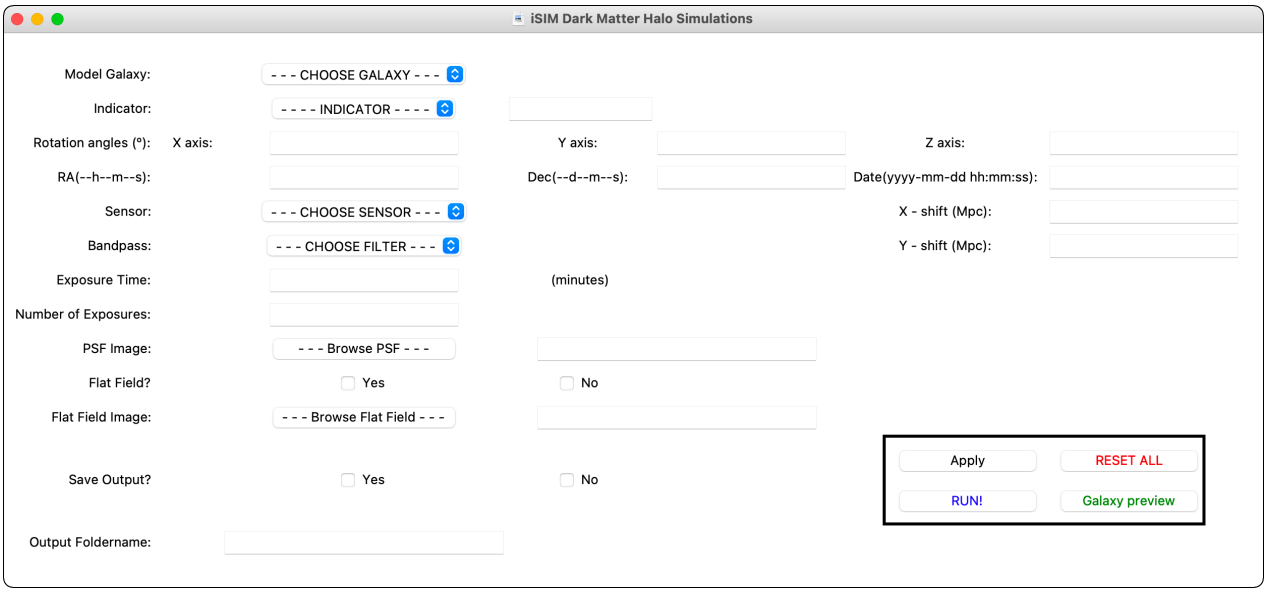


Figure 10. Appearance of the GUI of iSIM Dark Matter Halo Simulations.

As it has been explained in Section 2.2, the pointing coordinates are going to make the difference between avoiding the extinction of the Milky Way's dust and the photon pollution of the zodiacal light or not. Thus, there are two more fields responsible of collect the Right Ascension (--h--m--s) and Declination (--d--m--s) coordinates. As the zodiacal light changes throughout the year (Fig. 8), there is also a field to write the date and time (yyyy-mm-dd hh:mm:ss) of the future observation. The default values are: RA = "09h21m06s", DEC = "41d38m53s" and DATE = "2022-04-01 00:00:00".

As most of the stellar tidal streams are at a few kpc distance from the center of the galaxy, the GUI has an option to move the camera to the sides of the galaxy to provide another degree of freedom in the simulation. To improve the signal-to-noise ratio of the observation, there is a field

to fill with the duration of the exposures and another for the number of exposures that the user wants to simulate. The default values are 20 minutes per exposure and 300 exposures, for a total of 100 hours of exposure.

Afterwards, there is a browser option to find the PSF file of the telescope. This file must be a FITS file and must be given by the user because there is not a default file. There is also the possibility of ignoring the flat field of the filter, the GUI asks about it and the user can select "*yes*" or "*no*". If the answer is "*no*", then the program will not apply any flat field. But if the answer is "*yes*", then the user can provide a flat field file of the sensor (created at the laboratory) or, in case that no file is provided, the program itself will simulate one. If the user wants to simulate the Flat Field of the sensor, it is not even necessary to answer the question because the program will do it by default.

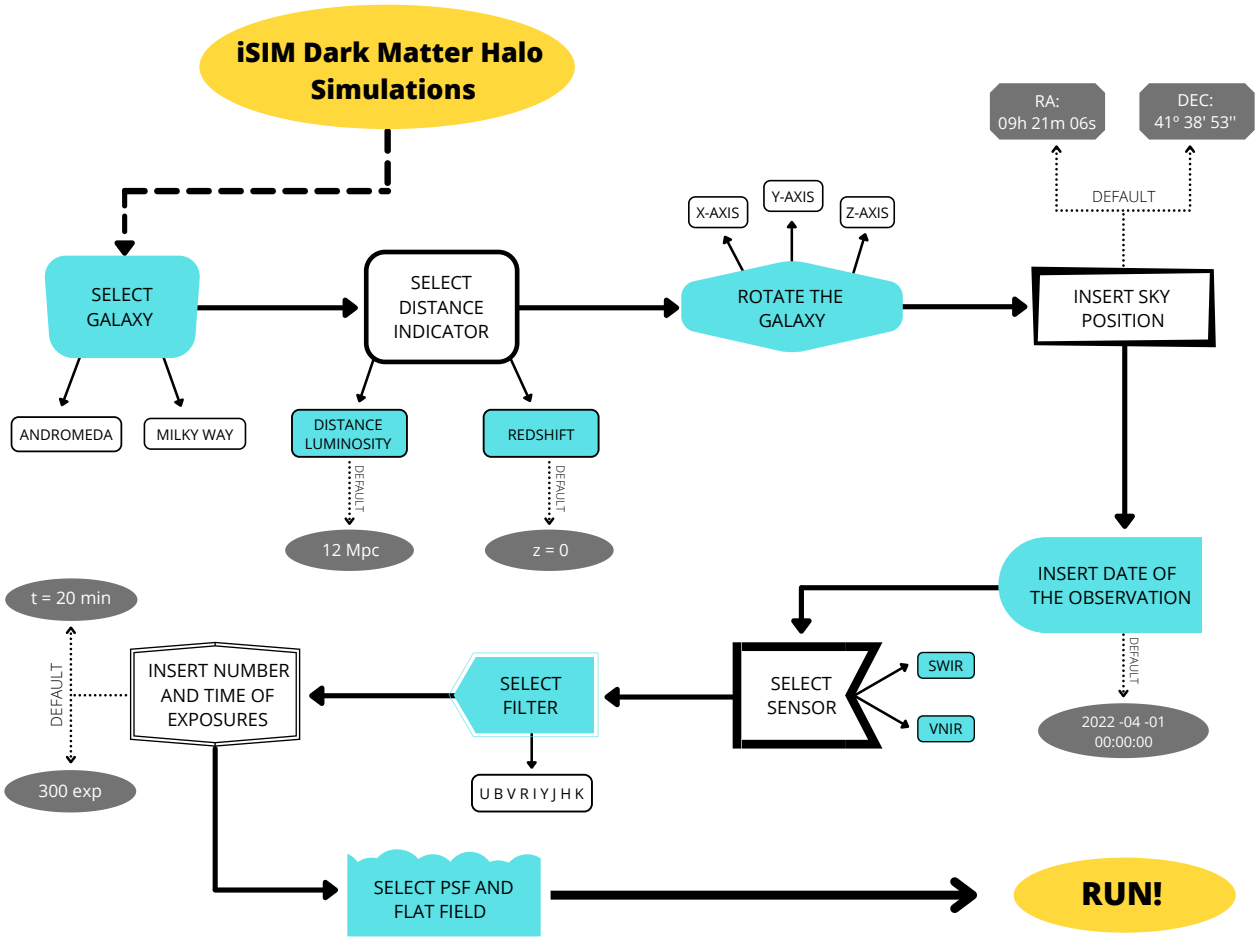


Figure 11. DUNES Simulator GUI input parameters flow chart.

Finally, there are some options related to the output results. There is an option that asks if the user want to save the output files. By default, the output files will be saved in a folder named as the selected properties, explained above (in the folder of outputs). However, there is another option where the user can type the path of the folder where they want to save these files.

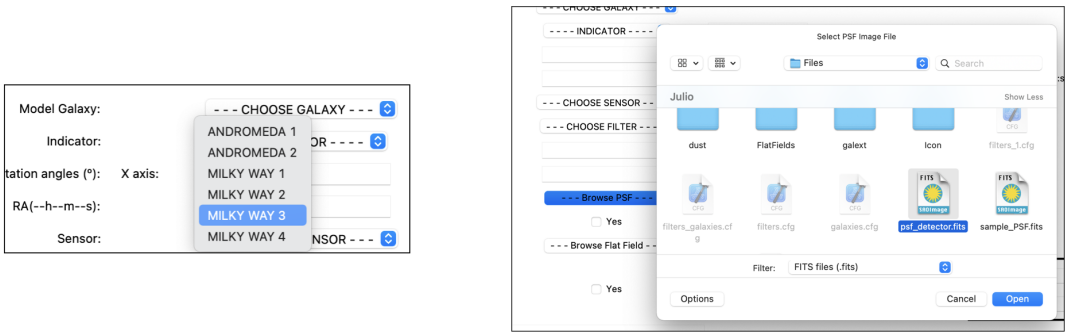


Figure 12. **Left:** Scroll bar with the different options of the galaxy's model: two Andromeda-type and three Milky Way-type. A similar scroll bar is used to display the sensor and the bandpass options. **Right:** Browser window to select the PSF file. It is only allowed to select FITS type files. A similar window is opened to select the Flat Field.

Apart from the options that the GUI offers, there are four buttons with different assigned functions. The "*Apply*" button will check that every field is correctly filled. In case that there is a wrong value on the input information, a warning message will appear in the screen. Next one is the "*RESET ALL*" button, which will clear all the fields and return to the initial values (as when the program was opened for the first time). The "*Galaxy preview*" button will provide a pop-up window with a quick view of the region of the simulated galaxy that will be pointing the telescope (an image of the entire simulated galaxy from the cosmological simulation and another one of how the region of the galaxy would look like from the telescope, without any effect) as well as the region of the sky (with maps of the zodiacal light and the extinction of the MW's dust marked with an arrow where the user is pointing). Fig. 14 shows this pop-up window.

Eventually, the "*RUN!*" button will start the simulation. When this button is pressed, a pop-up emerges where the different steps of the simulation and a progress bar will appear (see figure of the left side in Fig. 13).

Once the simulation is finished, a message appears asking if the user want to see the result, if the answer is yes, the file will be opened with the default program to read FITS files (SAOImageDS9, fv, etc) (see figure on the right side in Fig. 13).



Figure 13. **Left:** pop-up window that appears after pressing the "*RUN!*" bottom, which indicates the progress of the simulation. **Right:** message that appears when the simulation has finished, asking if the user want to open the result image.

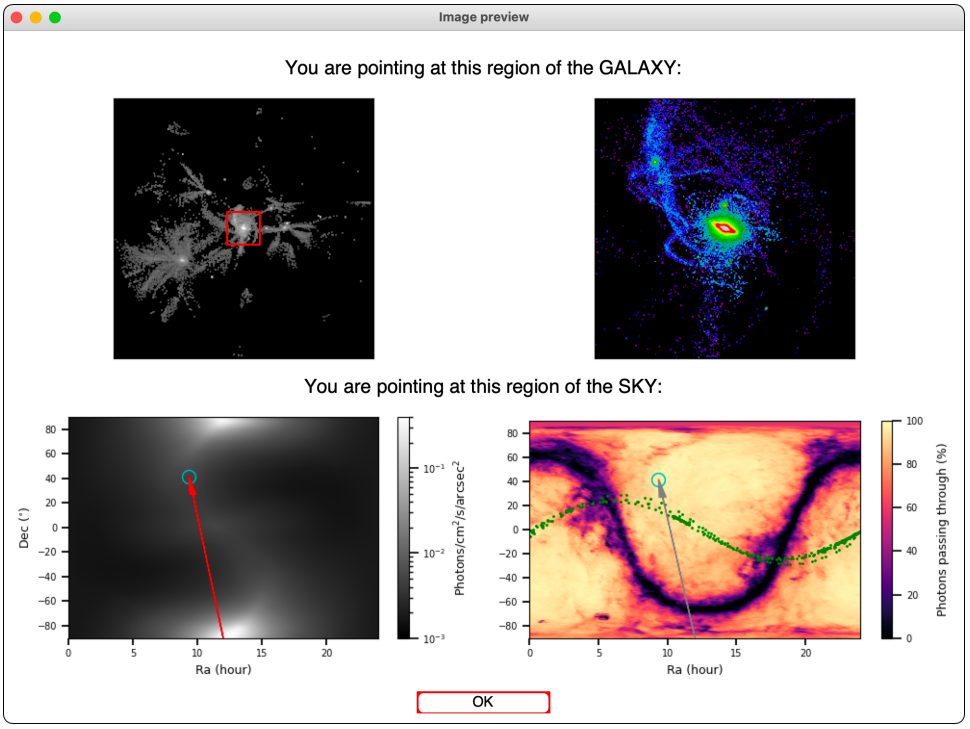


Figure 14. Pop-up window of the "*Galaxy preview*" button. It shows where the user is pointing at the galaxy and at the sky. **Top-left** is the entire galaxy from the cosmological simulation, where the red square is the region observed. **Top-right** is an enlargement of this region and the color code shows the density of photons per second. **Bottom-left** is a zodiacal light map like the ones in Fig. 8. The green circle and the red arrow shows where is the user pointing. **Bottom-right** is an extinction map like Fig. 7. The green circle and the gray arrow shows where the user is pointing.

3.2. The code

Although the iSIM Dark Matter Halo Simulations code has more than 2000 lines, it can be separated in several moduli and functions. The main code is helped by some auxiliary functions that are in external files. These external files have the functions related to the calculation of the galactic extinction, the zodiacal light, the image rotation and the transformation from mass to luminosities (in case that it has not already been calculated for the selected bandpass). As it has been explained in the previous section, the main code has 4 functions, which can be executed pressing the buttons (a reset function, an apply function, a preview function and the main function). The simulator also uses python package such as numpy, for the numerical calculations and astropy to manage the FITS files and the convolution with the PSF. This section will go through the procedure of the "*RUN!*" function:

- It is checked whether all the fields are correctly filled by running the "*Apply*" function. Once it finishes, the galaxy model and the filter fields are read. If the black bodies are already calculated in the bandpass selected, the code just read the data file, but if they are not calculated, it will ask the user if they want to proceed. Thus, the code will reuse the calculations at the different bandpasses for future simulations. At this point, the luminosity of every stellar particle at the selected filter is calculated (5).
- The effect of the distance (6) and the change in the orientation with respect to the line of sight (7) are applied.
- The sensor data is read and the coordinates of the galaxy model are converted from Mpc

(with the center of the galaxy as reference system) to pixels (with the sensor's bottom-left corner as new reference system). The pixels outside the size of the detector will be removed. Then, the image of the galaxy is created.

- The coordinates in the sky of the observation are read and a map of the dust extinction of the size the detector is obtained and apply to the galaxy image (using the skymap explained in Section 2.2, see Fig. 7).

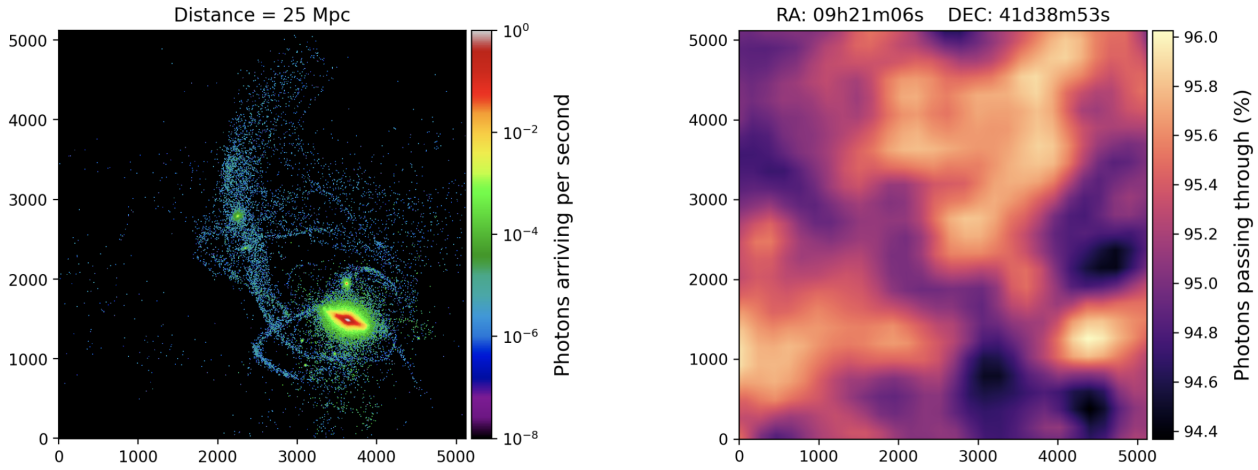


Figure 15. **Left:** Galaxy image with the photons per second that arrive to the telescope at a distance of 25 Mpc. **Right:** Dust extinction map of the FOV of the telescope at coordinates RA: 09h21m06s and DEC: 41d38m53s.

- The date of the observation is read and the zodiacal light value is calculated (using the skymap explained in Section 2.2, see Fig. 8).
- The duration of the observation is read and, using the aperture of the telescope, the galaxy image is integrated in time and in collecting surface (10).
- The sensor noise, both read-out-noise and dark current, are read and the total noise is calculated (8), (9).
- The PSF file selected is read and it is convolved with a small jitter adding some noise to this function.
- The Flat Field is read or simulated. The simulation of this layer is, essentially, a map of ones with a little random variation.
- The galaxy image is convolved with the PSF.

One of the most delicate parts is the simulation of the number of exposures selected by the user with the rotation of the telescope due to the orbit. This is explained in detail below. At the present, it is impossible to calculate a realistic and precised orbit because there is not any information about the micro-satellite and the platform where iSIM will be placed. However, it is well known that satellites in lower orbits travel at high velocities, so the telescope will rotate many times. In the simulation, we decided to assume a period of 30 different angles (from 0° to 360°) along its orbit in a regular time. This means that if the user select 300 exposures, the telescope will take 10 images in each angle. Fig. 17 shows a diagram to help the reader in the development of following explanation.

Just after convolving the photon image with PSF, the simulation opens two files to calculate the master dark and a master flat. Later, a double-loop starts:

- One for each angle in the rotation of the orbit.
- Another one for each exposure in the corresponding angle.

The images are simulated inside the second loop, see Fig. 16. The procedure is the next:

- First, the photon image is rotated the appropriate angle with a random error.
- Afterwards, the detector and sky noise background is calculated as a Poisson distribution in an image of the size of the detector.
- It is also assumed that the flat field has a small variation with respect to that obtained in the laboratory.
- The photon image is also convolved with a Poisson distribution and it is added the sky noise.
- This photon + sky image is multiplied by the efficiency (a multiplication of the different efficiencies of the telescope, detector, filter, detector's gain, etc) and by the flat field and it is added the detector noise.

In order to calculate both master flat and master dark, the simulation calculates the mean value with the flat and dark images already calculated. In a real observation, both master flat and master dark are calculated apart of the science observation but this will save calculation time in the simulation. Every exposure is saved in a temporary folder created in the directory of the simulator, so as not to consume RAM memory. These files will be updated while the scientific images are reduced in the next steps.

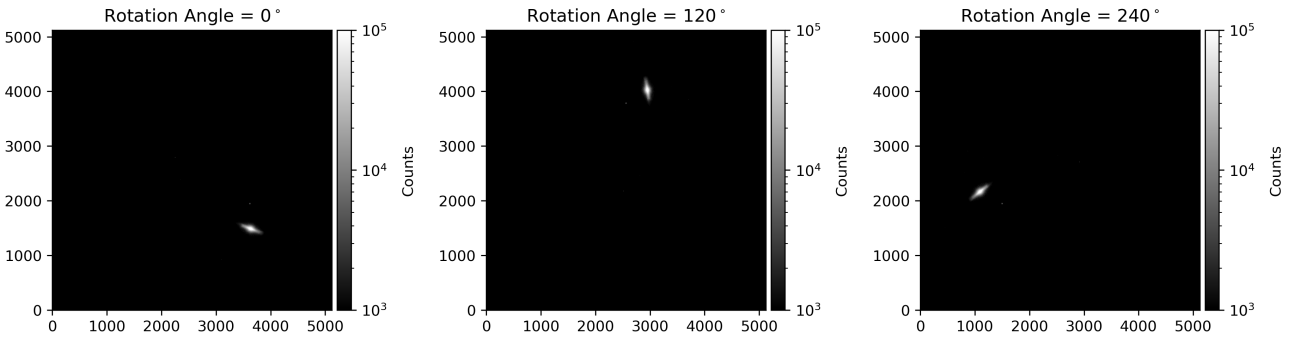


Figure 16. Three outputs of the effect of the rotation along the orbit. Left image is the first image taken, rotated 0° , the middle image has been rotated 120° and the one on the right, 240°. These images are too noisy to see the same structures that appear in Fig. 15 (so, many more need to be taken). These are the "*raw*" images.

The next step is to subtract a master sky. To obtain this, the simulation is helped by the software of GNU (Akhlaghi & Ichikawa 2015; Akhlaghi 2019), specially by the *astnoisechisel* function which subtract the background level of noise of a FITS file, masking the galaxy and interpolating. In this loop the program saves a file with the value of the image but without both master dark and master flat and an image of the output sky of *astnoisechisel*. With the value of every sky file, a master sky can be done doing the median (or the mean, as it is a Poisson distribution they must converge on the same value). This is done in the next loop.

Finally, the code arrives at its last loop where it is subtracted the master sky to every image. Then the rotation is undone to align the images (without the random error that is given at the initial rotation) and it is calculated a median (or mean) of all science reduced images.

This is the final result that will be analyzed in next Section. This part of the code can be found in Appendix A.

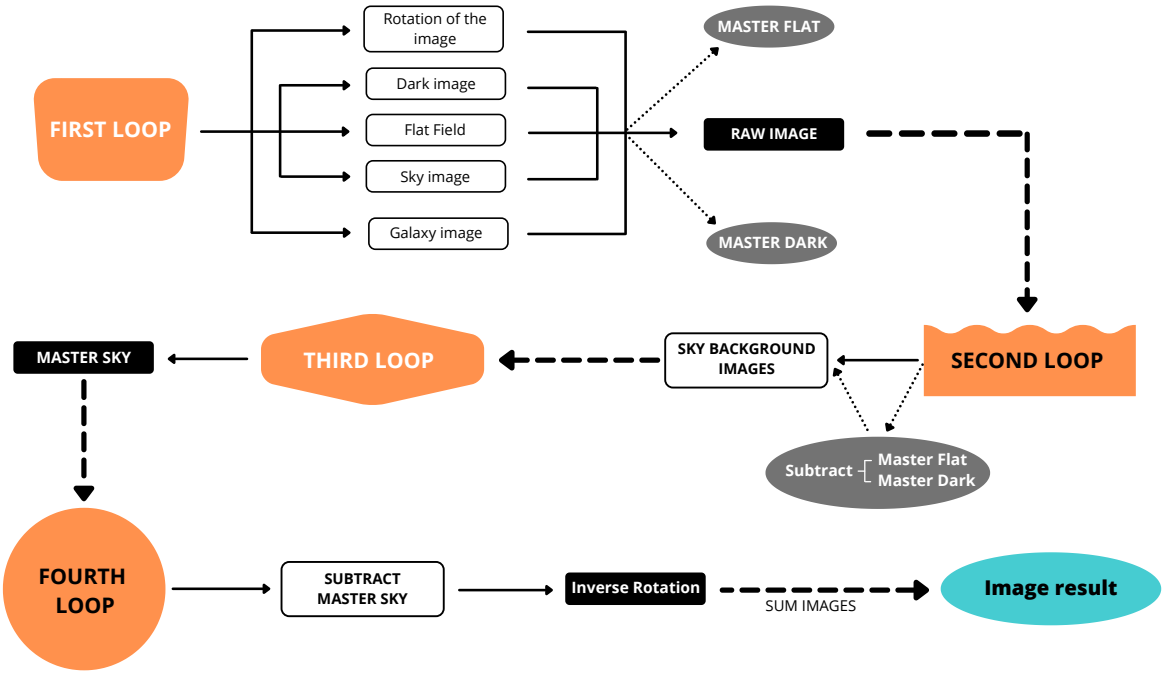


Figure 17. Orbit simulation and image reduction flow chart.

4. Results

The output image of the iSIM Dark Matter Halo Simulation has to be analysed to estimate the limit of the surface brightness. Although there are different definitions of this limit, in this Master Thesis, the limit value is sought above 5 times the standard deviation, σ, of the background. This σ is obtained measuring the full width at the half maximum (FWHM) of the histogram from a sky region of the final image. The distribution of this histogram (shown in Fig. 18) has a Gaussian profile, which means that the image is dominated by Poisson noise.

Due to the FWHM and the standard deviation in a gaussian distribution are related, σ can be calculated as:

$$\sigma = \frac{\mathrm{FWHM}}{\sqrt{8\ \ln 2}} \tag{20}$$

Now, it is necessary to convert those counts in flux units using the gain of the detector, the energy of the photons at the peak wavelength of the band and the time of exposure of each image. In addition, the standard deviation calculated in (20) has been measured per pixel and must be transformed into units of arcsec^2:

$$\mu_{\mathrm{lim}} = -2.5\ \log_{10}\left(\frac{\mathrm{E_V}\cdot 5\sigma}{\mathrm{pix}^2\cdot \mathrm{gain}\cdot t_{\mathrm{exp}}}\right) \tag{21}$$

where "*pix*" is the scale of the pixel in arcseconds. Equation (21) is not complete because the telescope must be calibrated in the desired filter, but it is enough to estimate the limiting surface brightness.

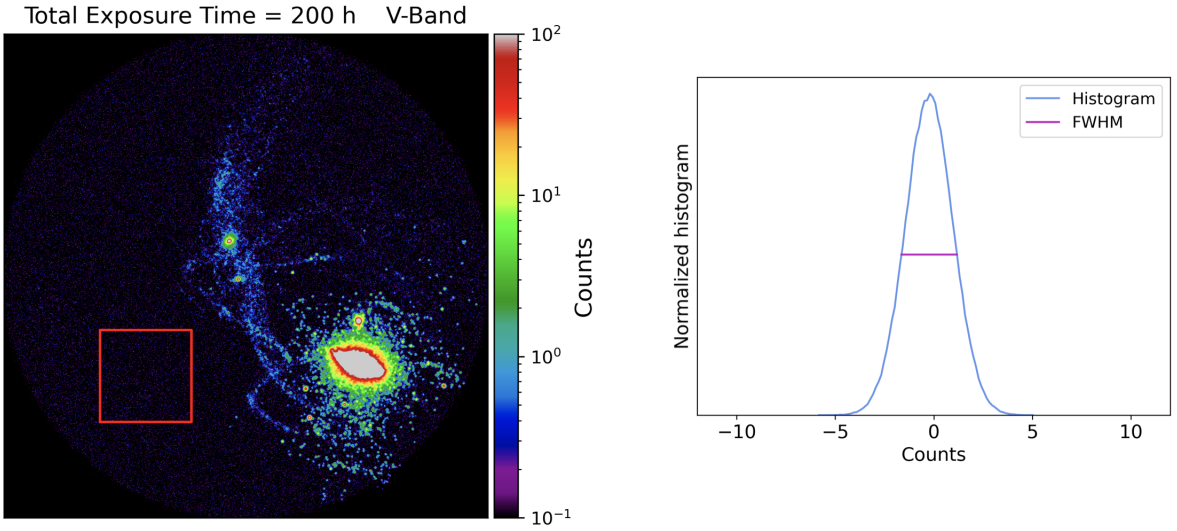


Figure 18. **Left:** Result image of the simulation of 600 exposures of 20 minutes each in the Johnson-Cousins V band. The host galaxy has is in color white, while the stellar tidal streams are in color blue. The red square is the sky region where the histogram is calculated. **Right:** Histogram of the red region of the left figure. Purple line shows the FWHM of the gaussian.

In the simulation shown in Fig. 18, with 600 exposures of 20 minutes each, making a total of 200 hours of exposure in the V band, this limit value is $\mu_{\text{lim}} \sim 33$ mag/arcsec^2. In a real observation, this value will be lower, because there are other source of noise that this simulation does not consider yet, see Section 5.2 and possible systematic errors or degradations are not taken into account either.

The program itself is a result of this work. The development of a complete software, which transforms mass stellar particles from a cosmological simulation into a realistic observation of them, can have multiple applications apart from studying viability of the DUNES space mission. Specially, iSIM Dark Matter Halo Simulations will be used, in collaboration with the observational astronomer Dr. Martinez-Delgado (from IAA-CSIC), to compare the characteristics of the Stellar Tidal Streams observed from earth (such as their color,their morphology, their sizes, etc) with the simulated ones, in order to create a mock catalogue of these structures.

5. Conclusions and future work

5.1. Conclusions

The main goal of this Master Thesis is to simulate an observation as realistic as possible starting from data of the mass stellar particle of the cosmological simulations, using the black body approximation and taking into account the most relevant effects such as the distance, Milky Way's dust extinction, noise of the zodiacal light, the noise of the detector, the Flat Field, the PSF, etc (see Section 2.2 and 2.3). iSIM Dark Matter Halo Simulations, not only offer the possibility of studying viability of the DUNES space mission, but also offer a realistic simulation of any observation with any instrument only by changing the characteristics of these.

In addition, this work has achieved a complete transformation of mass stellar particles, with a determined mass, age, metallicity and coordinates in physical units from the center of the galaxy, first into photons across the entire spectrum and then into counts at a sensor.

Regarding to the DUNES space mission, the simulation probes the possibility of studying the structures of the stellar tidal streams in galaxies located up to distances of 25 Mpc using the iSIM camera of SATLANTIS in the VNIR wavelengths because it is possible to reach ~ 33 mag/arcsec^2 of surface brightness when the theory predicts that these structures should be fainter than ~ 32 mag/arcsec^2 in this wavelengths.

Another statement that can be made is the fact that placing iSIM into orbit means an improvement in the limit surface brightness up to 4 magnitudes respect to the values obtained by Martinez-Delgado et al. (2021) who reaches values of ~ 29 mag/arcsec^2 respect to the value presented in this work of ~ 33 mag/arcsec^2.

5.2. Future work

In spite of the fact that this simulation takes into account the main factors of a real simulation, there are four important points to bear in mind.

One of the points is that it is necessary to find a way to eliminate the higher diffraction orders because they can be confused with structures of the stellar tidal streams. In order to do this, there are two possibilities that must be explored. On the one hand, it can be used the Richardson-Lucy iterative algorithm (Richardson 1972; Lucy 1974) to deconvolve the PSF on the final image (or any similar iterative algorithm). However, this technique increases the noise of the image making more difficult the study of the structures of ultra-low surface brightness. On the other hand, it is possible to subtract the PSF as it were another type of "master sky". The procedure would be to compare the real galaxy with similar simulated galaxies and using the minimum square method or residues subtract the PSF. This last method would be more complex but would not increase the noise.

Another point is to create a realistic background of cosmological galaxies at a different redshift. This could be done from images of different surveys of the sky. A good approximation would be to take real data from surveys such as the Hubble Ultra-Deep Field and make a mosaic with a randomized rotation and overlapping to cover 1° of the sky, which is the iSIM FOV. However, the repetition of the same field would add another error source. Other possibility could be to acquire a cosmological simulation where different snapshots at different redshifts have been added. However, this method would be less realistic than using real data and, as before, the volume of data simulated wouldn't be large enough to cover the entire FOV.

The following point is to obtain a flat field using the zodiacal light. This has been proposed because space missions can have any unexpected event. Flat fields are not stable in time, they can change due to many different reasons. An advantage of iSIM respect with other missions is that the researchers have all the controls of the telescope. So pointing to different regions of the sky, where the zodiacal light is more intense, it could be possible to reconstruct the flat field of the detector throughout taking several images (Borlaff et al. 2019).

The last point is to study and simulate the stray light incoming from stars, moon, planets close to the FOV. Because iSIM will be placed in a low orbit, it is important to understand how is the earth

effect in the detector. Although the LEO orbit is thought to point in the opposite direction of the sun, the moonlight reflected in the earth reaches surface brightness of ~ 17.5 mag/arcsec^2 at full moon. The stray light transmission can be measured knowing its normalized detector irradiance (NDI) function, which is defined as the ratio of stray light irradiance (power per unit area) on the detector to the source irradiance at the entrance to the telescope (Bely 2003). The NDI of a telescope can be measured in a laboratory.

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A. Code scripts

```
#loop over different rotation of the telescope's FOV with some uncertainties
#in pointing
for j in range(0, int(n_angle)):
    for k in range(0, int(n_exp_per_ang)):
        rot_angle[k] = angle[j] + angle_err*np.random.randn()
        model_conv_rot = imrot(model_obs_conv, rot_angle[k])
        for m in range(0, s_size_y):
            for n in range(0, s_size_x):
                if model_conv_rot[m,n] < 0:
                    model_conv_rot[m,n] = 0

        read_dark_background = np.random.poisson(lam = (adu_detnoise**2.0),
                               size = (s_size_y, s_size_x))
        sky_zod_background = np.random.poisson(lam = sky_signal, size = (s_size_y,
                               s_size_x))
        model_conv_derot_with_sky = sky_zod_background + np.random.poisson(lam =
                               model_conv_rot, size = (s_size_y, s_size_x))
        flat = flat_sim_conv*(1.0+0.0000001*np.random.randn(s_size_y, s_size_x))
        flat0 = flat0 + flat
        read_dark_background0 = read_dark_background0 + read_dark_background
        name_image = "".join(["/image_set_\%d_"% int(j+1), "exposure_%d" %
                      int((j*int(n_exp_per_ang)+k+1)), ".fits"])
        fits.writeto(path + name_image, eff_tot*flat*model_conv_derot_with_sky +
                     read_dark_background, overwrite=True)

# substracting sky
for j in range(0, int(n_angle)):
    for k in range(0, int(n_exp_per_ang)):
        name_image = "".join(["/image_set_%d_"% int(j+1), "exposure_%d" %
                       int(j*int(n_exp_per_ang)+k+1), ".fits"])
        name_image_reduced = "".join(["/image_set_%d_"% int(j+1), "exposure_%d" %
                       int(j*int(n_exp_per_ang)+k+1), "_reducted", ".fits"])
        name_image_sky = "".join(["/image_set_%d_"% int(j+1), "exposure_%d" %
                       int(j*int(n_exp_per_ang)+k+1), "_sky", ".fits"])
        image = fits.getdata(path + name_image)
        image_reducted = (image - master_dark)/master_flat
        os.remove(path + name_image)
        fits.writeto(path + name_image, image_reducted, overwrite=True)
        subprocess.run(["astnoisechisel", path + name_image_reduced, "-h0",
                     "--rawoutput", "".join(["--output=", path, name_image_sky])])
        os.remove(path + name_image_reduced)
        sky_image = fits.getdata(path + name_image_sky, 2)
        list_hdu = fits.HDUList([fits.PrimaryHDU(image_reducted), fits.ImageHDU(
                                                    sky_image)])
        os.remove(path + name_image_sky)
        list_hdu.writeto(path + name_image_reduced)

# master sky
sky_median0 = np.zeros((s_size_y, s_size_x, int(n_exp_per_ang)))
sky_median1 = np.zeros((s_size_y, s_size_x, int(n_angle)))
for j in range(0, int(n_angle)):
    for k in range(0, int(n_exp_per_ang)):
        name_image_sky = "".join(["/image_set_%d_"% int(j+1), "exposure_%d" %
        int(j*int(n_exp_per_ang)+k+1), "_reduced", ".fits"])
        sky_median0[:,:,k] = fits.getdata(path + name_image_sky, 1)
    sky_median1[:,:,j] = np.nanmedian(sky_median0, axis=2)

master_sky = np.nanmedian(sky_median1, axis=2)
```

```
master_sky_value = np.nanmedian(master_sky.flatten())

# science image reduction
image_reduct_flat_dark_derot0 = np.zeros((s_size_y, s_size_x, int(n_exp_per_ang)))
image_reduct_flat_dark_derot1 = np.zeros((s_size_y, s_size_x, int(n_angle)))
for j in range(0, int(n_angle)):
    for k in range(0, int(n_exp_per_ang)):
        name_image_reduced = "".join(["/image_set_%d_"% int(j+1), "exposure_%d" %
                        int(j*int(n_exp_per_ang)+k+1), "_reducted", ".fits"])
        image_reducted = fits.getdata(path + name_image_reduced, 0)
        image_reducted_sky = image_reducted - master_sky_value
        image_reduct_flat_dark_derot0[:, :, k] =
                    imrot(image_reducted_sky, (-1.0)*angle[j])
        os.remove(path + name_image_reduced)

    image_reduct_flat_dark_derot1[:, :, j] =
                np.median( image_reduct_flat_dark_derot0, axis=2)

model_reducted = np.median(image_reduct_flat_dark_derot1, axis=2)
```