General Theory of Relativity and Cosmology Report

Gravitational Lensing

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Abstract

This report is about the project topic I have chosen, Gravitational Lensing and the problem statement I have chosen under this topic. The project involved the use of dataset consisting of simulated strong lensing images with cold dark matter subhalos and the use of python along with deep learning algorithms(regression) from PyTorch library

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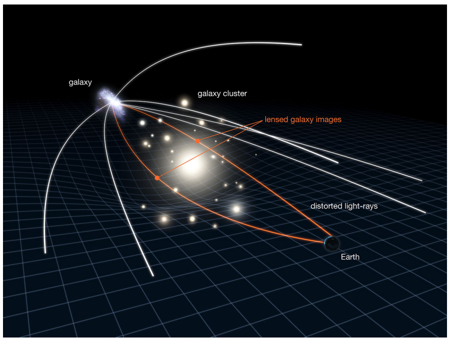
1 Introduction

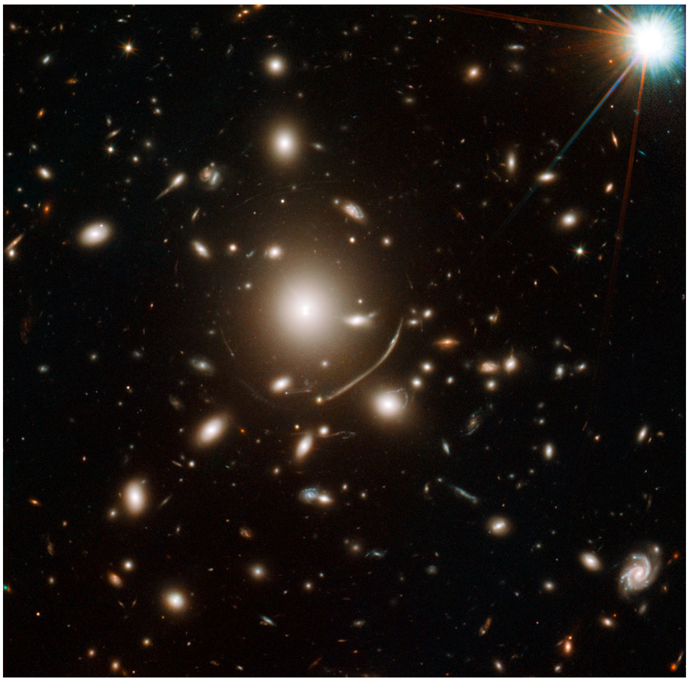
In this project, the aim is to understand The phenomenon of Gravitational Lensing and where is it used, especially in the identification of Understand Dark Matter and it's type of substructures. Dark Matter Substructure can be detercted using utilizing simulated strong lensing images with subahlo substructure Hence the total fraction of mass in substructure of a dark matter halo can be figured out by implementing regression models

2 Gravitational Lensing



(a) The mass of a galaxy cluster distorts the fabric of space, changing the path of light that passes through it.

(b) The Cosmic Horseshoe: a gravitational lens surrounding a galaxy from the group of Luminous Red Galaxies.



(c) Lensing cluster Abell 383.

According to Einstein's general theory of relativity, time and space are fused together in a quantity known as spacetime. Within this theory, massive objects cause spacetime to curve, and gravity is simply the curvature of spacetime. As light travels through spacetime, the theory predicts that the path taken by the light will also be curved by an object's mass as the gravitational pull from these objects can distort or bend the light.
Gravitational lensing occurs when a massive celestial body — such as a galaxy cluster — causes a sufficient curvature of spacetime for the path of light around it to be visibly bent, as if by a lens. The body causing the light to curve is accordingly called a gravitational lens.

An important consequence of this lensing distortion is magnification, allowing us to observe objects that would otherwise be too far away and too faint to be seen. Hubble makes use of this magnification effect to study objects that would otherwise be beyond the sensitivity of its 2.4-metre-diameter primary mirror, showing us thereby the most distant galaxies humanity has ever encountered.

Although it is difficult to measure for an individual galaxy, galaxies clustered close together will exhibit similar lensing patterns.
This effect is only visible in rare cases and only the best telescopes can observe the related phenomena.Hubble's sensitivity and high resolution allow it to see faint and distant gravitational lenses that cannot be detected with ground-based telescopes whose images are blurred by the Earth's atmosphere. The gravitational lensing results in multiple images of the original galaxy each with a characteristically distorted banana-like shape or even into rings.

The first gravitational lens was discovered in 1979, when two quasars were discovered very close to each other in the sky and with similar distances and spectra. The two quasars were actually the same object whose light had been split into two paths by the gravitational influence of an intervening galaxy.Rings or distinct multiple images of an object appear when the lens is extremely massive, and such lensing is called strong lensing, resulting in such strongly bent light . Weak gravitational lensing results in However, often the intervening lens is only strong enough to slightly stretch the background object, resulting in galaxies appearing distorted, stretched or magnified. This is known as weak lensing.

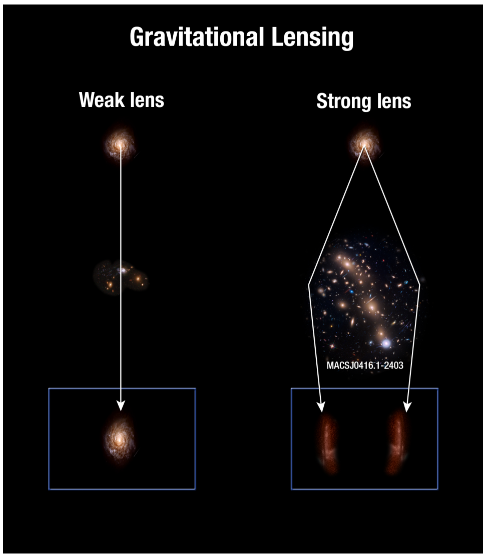


Figure 2: Strong and weak Gravitational Lensing

Hubble was the first telescope to resolve details within these multiple banana-shaped arcs. Its sharp vision can reveal the shape and internal structure of the lensed background galaxies directly and in this way one can easily match the different arcs coming from the same background object — be it a galaxy or even a supernova —by eye. Analysing the nature of gravitational lensing patterns tells astronomers about the way dark matter is distributed within galaxies and their distance from Earth. This method provides a probe for investigating both the development of structure in the universe and the expansion of the universe. Since the amount of lensing depends on the total mass of the cluster, gravitational lensing can be used to 'weigh' clusters. This has considerably improved our understanding of the distribution of the 'hidden' dark matter in galaxy clusters and hence in the Universe as a whole.

3 Dark Matter

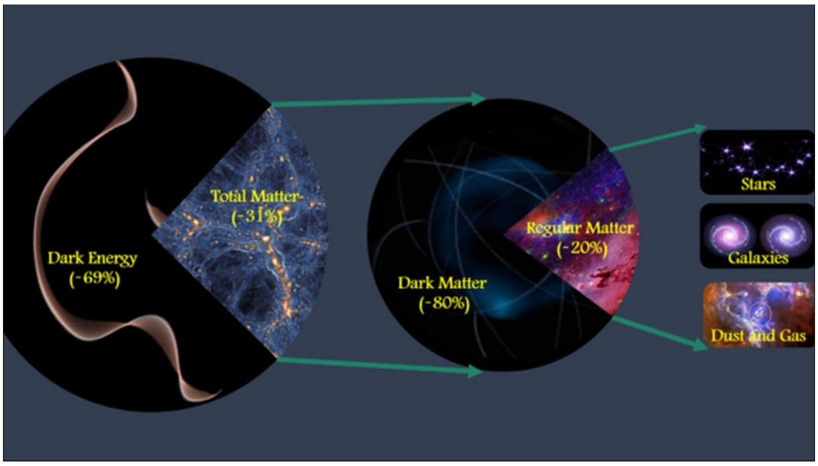


Figure 3: Most Precise Measurements of Dark Matter Ever Made

Galaxies are rotating with such speed that the gravity generated by their observable matter could not possibly hold them together. Scientists think that something is giving these galaxies extra mass, generating the extra gravity they need to stay intact. This unknown matter was called "dark matter" since it is not visible.
Dark matter is a hypothetical substance that was proposed almost a century ago to account for the clear imbalance between the amount of matter in the Universe, and the amount of gravity that holds our galaxies together.

We can't directly detect dark matter, but we can see its effects on everything around us – the way galaxies rotate and the way light bends as it travels through the Universe suggests there's far more at play than we're able to pick up.It makes up about 85 percent of the total mass of the Universe, and yet, physicists still have no idea what dark matter actually is.
Unlike normal matter, dark matter does not interact with the electromagnetic force. This means it does not absorb, reflect or emit light, making it extremely hard to spot. In fact, researchers have been able to infer the existence of dark matter only from the gravitational effect it seems to have on visible matter. Dark matter seems to outweigh visible matter roughly six to one, making up about 27 percent of the universe. Here's a sobering fact: The matter we know and that makes up all stars and galaxies only accounts for 5 pecent of the content of the universe! But what is dark matter? One idea is that it could contain "supersymmetric particles" – hypothesized particles that are partners to those already known in the Standard Model. Experiments at the Large Hadron Collider (LHC) may provide more direct clues about dark matter.

Many theories say the dark matter particles would be light enough to be produced at the LHC. If they were created at the LHC, they would escape through the detectors unnoticed. However, they would carry away energy and momentum, so physicists could infer their existence from the amount of energy and momentum "missing" after a collision. Dark matter candidates arise frequently in theories that suggest physics beyond the Standard Model, such as supersymmetry and extra dimensions. One theory suggests the existence of a "Hidden Valley", a parallel world made of dark matter having very little in common with matter we know. If one of these theories proved to be true, it could help scientists gain a better understanding of the composition of our universe and, in particular, how galaxies hold together.

4 Dark Energy

Since 1998, telescope observations have indicated that the cosmos is expanding ever-so-slightly faster all the time, implying that the vacuum of empty space must be infused with a dose of gravitationally repulsive "dark energy."

In addition, it looks like the amount of dark energy infused in empty space stays constant over time (as best anyone can tell).

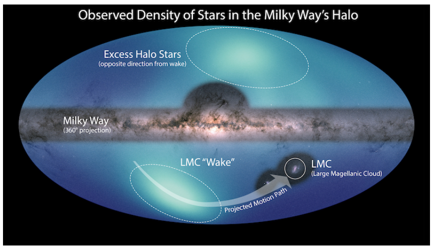
But the new conjecture asserts that the vacuum energy of the universe must be decreasing. Alan Guth and Alexei Starobinsky proposed in 1980 that a negative pressure field, similar in concept to dark energy, could drive cosmic inflation in the very early universe. Inflation postulates that some repulsive force, qualitatively similar to dark energy, resulted in an enormous and exponential expansion of the universe slightly after the Big Bang. Such expansion is an essential feature of most current models of the Big Bang. However, inflation must have occurred at a much higher energy density than the dark energy we observe today and is thought to have completely ended when the universe was just a fraction of a second old. It is unclear what relation, if any, exists between dark energy and inflation. Even after inflationary models became accepted, the cosmological constant was thought to be irrelevant to the current universe.

Dark energy makes up approximately 68 percent of the universe and appears to be associated with the vacuum in space. It is distributed evenly throughout the universe, not only in space but also in time – in other words, its effect is not diluted as the universe expands. The even distribution means that dark energy does not have any local gravitational effects, but rather a global effect on the universe as a whole. This leads to a repulsive force, which tends to accelerate the expansion of the universe. The rate of expansion and its acceleration can be measured by observations based on the Hubble law. These measurements, together with other scientific data, have confirmed the existence of dark energy and provide an estimate of just how much of this mysterious substance exists. The nature of dark energy is more hypothetical than that of dark matter, and many things about it remain in the realm of speculation. Dark energy is thought to be very homogeneous and not very dense, and is not known to interact through any of the fundamental forces other than gravity. Since it is quite rarefied and un-massive—roughly 1027 kg/m3—it is unlikely to be detectable in laboratory experiments.

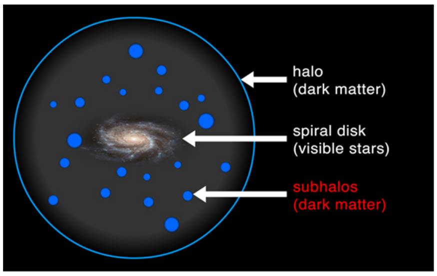
5 Dark Halo

According to modern models of physical cosmology, a dark matter halo is a basic unit of cosmological structure. It is a hypothetical region that has decoupled from cosmic expansion and contains gravitationally bound matter. A single dark matter halo may contain multiple virialized clumps of dark matter bound together by gravity, known as subhalos.[1] Modern cosmological models, such as CDM, propose that dark matter halos and subhalos may contain galaxies. The dark matter halo of a galaxy envelops the galactic disc and extends well beyond the edge of the visible galaxy. Thought to consist of dark matter, halos have not been observed directly. Their existence is inferred through observations of their effects on the motions of stars and gas in galaxies and gravitational lensing. Dark matter halos play a key role in current models of galaxy formation and evolution. Theories that attempt to explain the nature of dark matter halos with varying degrees of success include cold dark matter (CDM), warm dark matter, and massive compact halo objects

The presence of dark matter (DM) in the halo is inferred from its gravitational effect on a spiral galaxy's rotation curve. Without large amounts of mass throughout the (roughly spherical) halo, the rotational velocity of the galaxy would decrease at large distances from the galactic center, just as the orbital speeds of the outer planets decrease with distance from the Sun. However, observations of spiral galaxies, particularly radio observations of line emission from neutral atomic hydrogen (known, in astronomical parlance, as 21 cm Hydrogen line, H one, and H I line), show that the rotation curve of most spiral galaxies flattens out, meaning that rotational velocities do not decrease with distance from the galactic center. The absence of any visible matter to account for these observations implies either that unobserved (dark) matter, first proposed by Ken Freeman in 1970, exist, or that the theory of motion under gravity (general relativity) is incomplete. Freeman noticed that the expected decline in velocity was not present in NGC 300 nor M33, and considered an undetected mass to explain it. The DM Hypothesis has been reinforced by several studies.



(a) Map of Dark Matter Halo.



(b) Dark Matter Profile

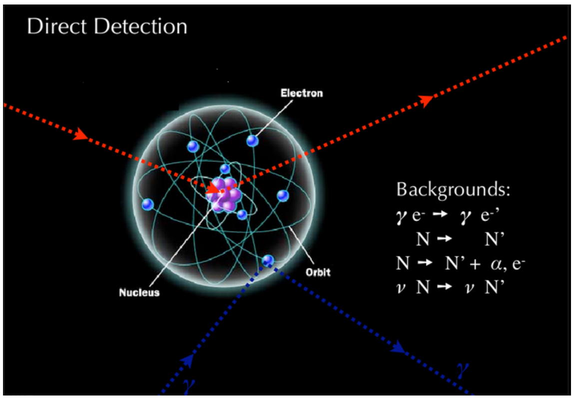
The formation of dark matter halos is believed to have played a major role in the early formation of galaxies. During initial galactic formation, the temperature of the baryonic matter should have still been much too high for it to form gravitationally self-bound objects, thus requiring the prior formation of dark matter structure to add additional gravitational interactions. The current hypothesis for this is based on cold dark matter (CDM) and its formation into structure early in the universe.

The hypothesis for CDM structure formation begins with density perturbations in the Universe that grow linearly until they reach a critical density, after which they would stop expanding and collapse to form gravitationally bound dark matter halos. These halos would continue to grow in mass (and size), either through accretion of material from their immediate neighborhood, or by merging with other halos. Numerical simulations of CDM structure formation have been found to proceed as follows: A small volume with small perturbations initially expands with the expansion of the Universe. As time proceeds, small-scale perturbations grow and collapse to form small halos. At a later stage, these small halos merge to form a single virialized dark matter halo with an ellipsoidal shape, which reveals some substructure in the form of dark matter sub-halos.

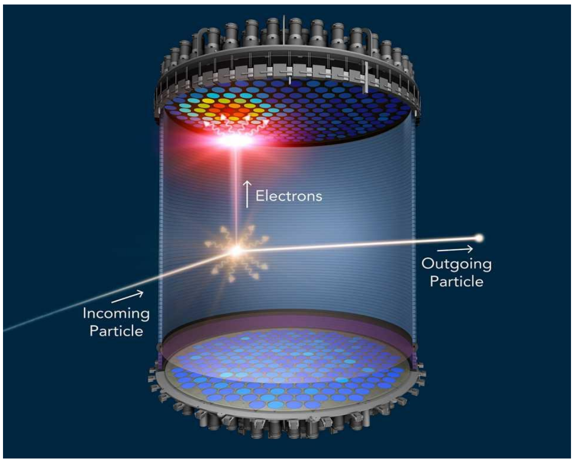
The use of CDM overcomes issues associated with the normal baryonic matter because it removes most of the thermal and radiative pressures that were preventing the collapse of the baryonic matter. The fact that the dark matter is cold compared to the baryonic matter allows the DM to form these initial, gravitationally bound clumps. Once these subhalos formed, their gravitational interaction with baryonic matter is enough to overcome the thermal energy, and allow it to collapse into the first stars and galaxies. Simulations of this early galaxy formation matches the structure observed by galactic surveys as well as observation of the Cosmic Microwave Background.

Up until the end of the 1990s, numerical simulations of halo formation revealed little substructure. With increasing computing power and better algorithms, it became possible to use greater numbers of particles and obtain better resolution. Substantial amounts of substructure are now expected. When a small halo merges with a significantly larger halo it becomes a subhalo orbiting within the potential well of its host. As it orbits, it is subjected to strong tidal forces from the host, which cause it to lose mass. In addition the orbit itself evolves as the subhalo is subjected to dynamical friction which causes it to lose energy and angular momentum to the dark matter particles of its host. Whether a subhalo survives as a self-bound entity depends on its mass, density profile, and its orbit

6 Weakly interacting massive particles (WIMPs)



(a) Detecting Dark Matter



(b) XENON10 detector

Weakly interacting massive particles (WIMPs) are hypothetical particles that are one of the proposed candidates for dark matter.The existence of WIMPs is predicted by supersymmetry theory, theories with extra spacetime dimensions, and other attempts to speculate beyond particle theory's standard model. WIMP searches are proceeding on two fronts, using the Large Hadron Collider or look for the very rare elastic collisions one expects between ambient dark-matter particles in our corner of the Milky Way and nuclei in a very sensitive detector.
Short of actually finding dark-matter WIMPs,an effecient and cost saving dectector has been dscovered which can detect the particles. XENON10 detector has an active mass of 15 kg of liquid xenon (LXe) at 180 K, just cold enough to keep the Xe from boiling.

7 Task

Since its discovery via its gravitational interactions over half a century ago, the identity of dark matter has yet to be found. This is despite countless experiments aimed at detection of the most promising dark matter candidates. An alternative to terrestrial detection (for example, with colliders or liquid xenon) for dark matter identification is unique gravitational signatures which arise from disparate substructure predictions among dark matter models. Example substructures include subhalos of WIMP-like cold dark matter and vortices of super fluid dark matter. Perhaps the most promising method to infer the unique morphology of these substructures is with strong galaxy-galaxy lensing images; an intermediate dark matter halo (which contains a visible galaxy) lenses a galaxy which is behind it.

One can use regression to measure the total fraction of mass in substructure of a dark matter halo fsub=msub/mhalo , where msub is the mass in substructure and mhalo is the mass of the dark matter halo.This can be done by simulating strong lensing images with subahlo substructure consistent with non-interacting cold dark matter models.

8 Data simulation

The dataset consists of simulated strong lensing images with cold dark matter subhalos generated by PyAutoLens. It contains 25k grayscale images with the size of 150x150 and the corresponding fsub which is known from simulations To import the dataset I used the code below

Download Dataset

```
!gdown http://drive.google.com/uc?id=1hu472ALwGPBcTCXSAM0VoCWmTktg9j-j
!tar zxvf lens_data_alt.tgz
```

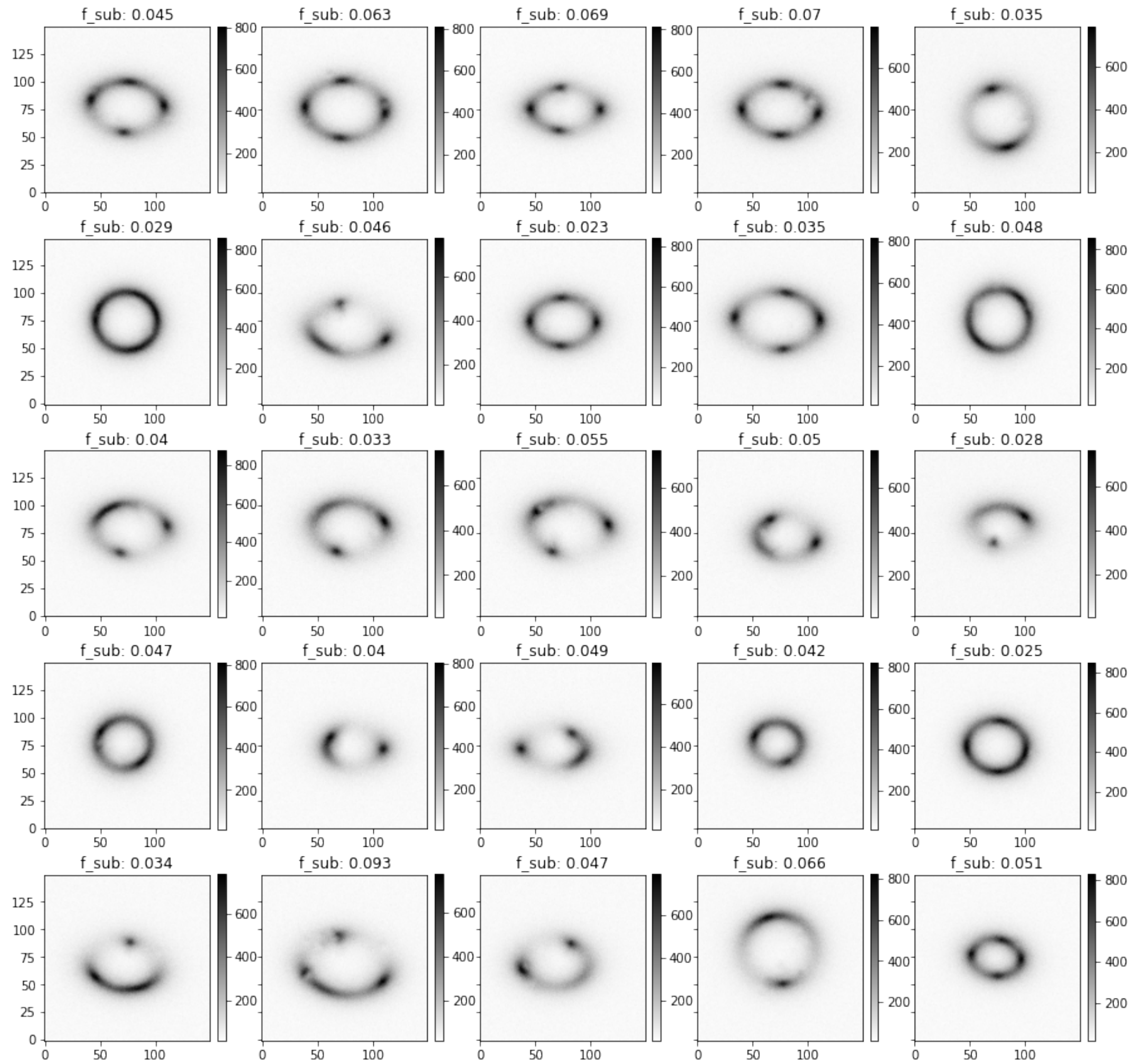
Load Dataset

```
import numpy as np
import os
import matplotlib
import matplotlib.pyplot as plt
%matplotlib inline
import torch
from torch.utils.data import Dataset, DataLoader
import torchvision
from torchvision import transforms
DATASET_PATH = './lens_data'
images = []
f_subs = [] #  mass fraction
for f_name in os.listdir(DATASET_PATH):
  img, mass = np.load(os.path.join(DATASET_PATH,f_name),allow_pickle=True)
  images.append(img.reshape(1,img.shape[0],img.shape[1]))
  f_subs.append(np.array(mass,ndmin=1))
images = np.stack(images).astype('float32')
f_subs = np.stack(f_subs).astype('float32')
```

The lensing images can be plotted to visualize the substructure halos

Plot Strong Lensing Images(first 4 lenses)

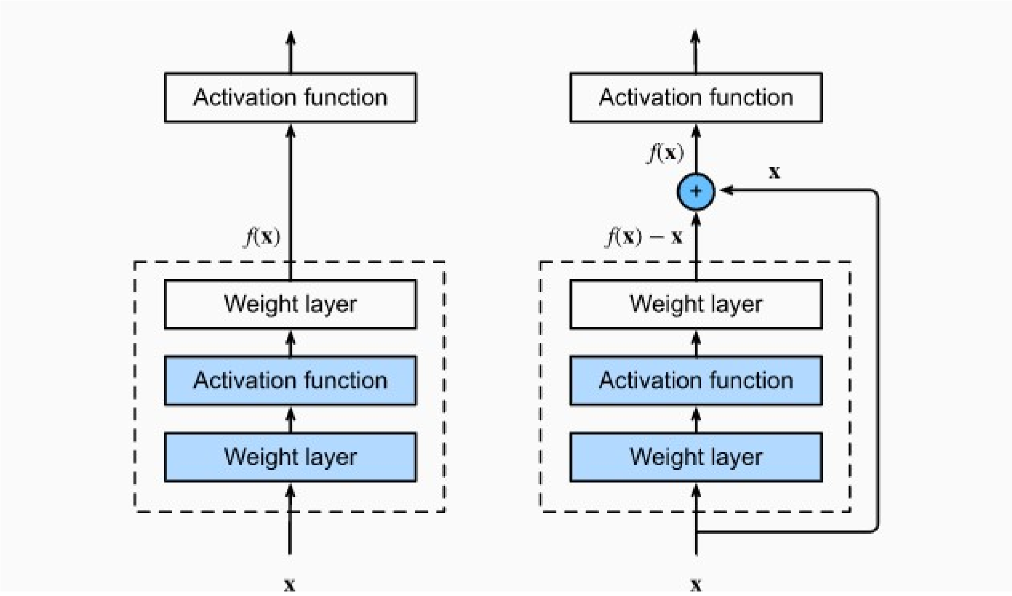
```
[ ]
grid_size = (5,5)
figure,axis = plt.subplots(grid_size[0],grid_size[1],figsize=(15,15),sharey=True)
img_indx=0

for i in range(grid_size[0]):
  for j in range(grid_size[1]):
    img = axis[i][j].imshow(images[img_indx][0], cmap='binary', origin='lower')
    axis[i][j].set_title(f'f_sub: {f_subs[img_indx][0]:.2}')
    plt.colorbar(img,ax=axis[i][j],fraction=0.046, pad=0.04)

    img_indx+=1
plt.show()
```



After importing the data, they can be standardized and separated as train and test dataset.

9 Neural network

To predict the mass of substructure, one needs to use an efficient pretrained model on images, which can predict the mass of substructure of the halos. The model that I have used is the Resnet18 Regression model with Adam optimizer.



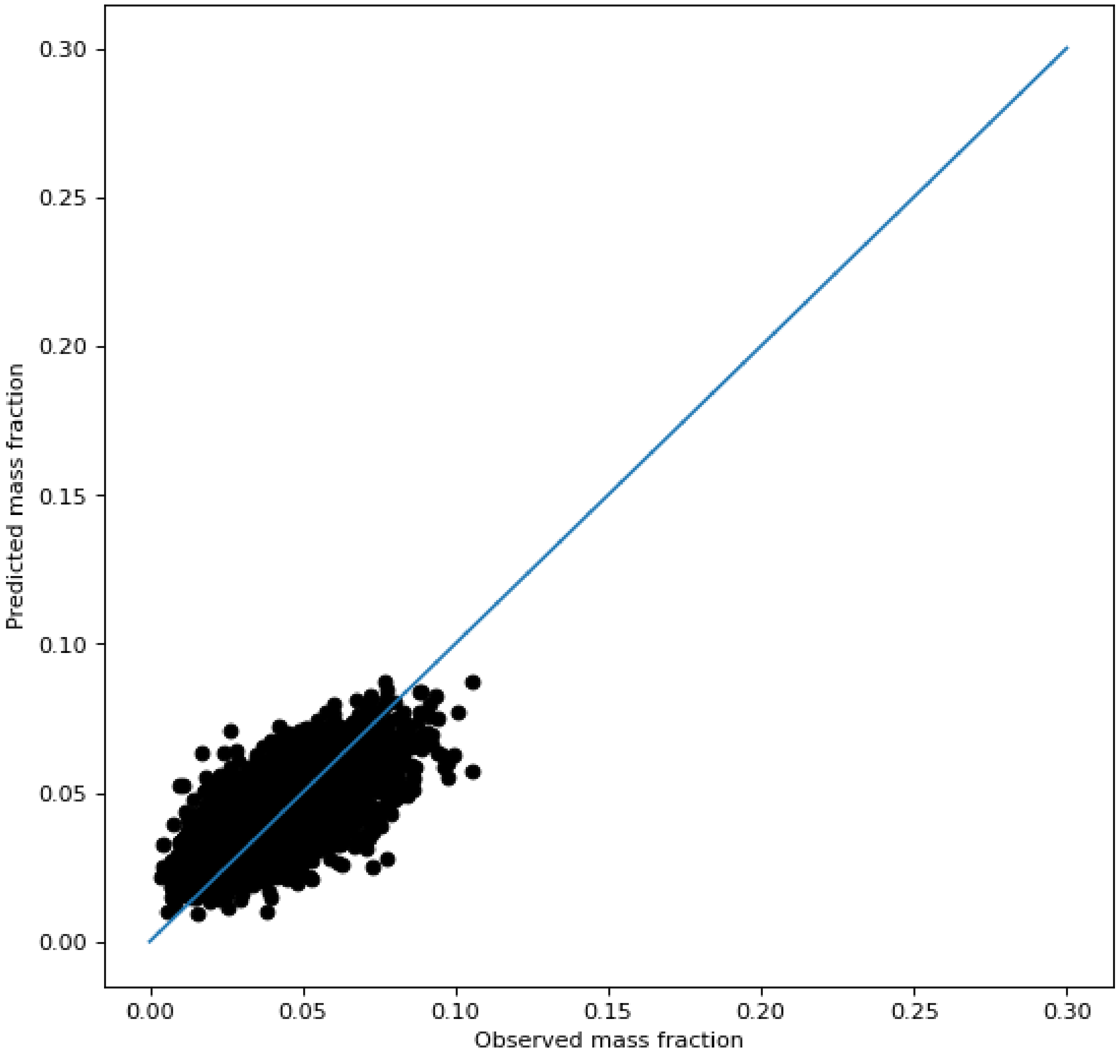

```
class Resnet18Regression(torch.nn.Module):
        def __init__(self, num_of_input_channels, output_size):
            super(Resnet18Regression, self).__init__()
            self.resnet18 = torchvision.models.resnet18()

            self.resnet18.conv1 = torch.nn.Conv2d(num_of_input_channels, 64,
            kernel_size=(7, 7), stride=(2, 2), padding=(3, 3), bias=False)

            self.resnet18.fc = torch.nn.Linear(
            in_features=512,
            out_features=output_size, bias=True)

        def forward(self, x):
            out = self.resnet18(x)
            return out
```

10 Evaluation Metric

The evaluation metric used to determine the loss(which determines how different the predicted value is from the original) is MAE (Mean Absolute Error) The formula for finding the Mean Absolute Error is
$\sum_{i=1}^{D} |x_i - y_i|$

11 Results

After training the model with the dataset and and evaluating it with the known dataset, the error comes out to be 0.0085120415315032 which is very accurate.



12 Conclusion

Apart frrom Resnet18, models such as EfficientNets , Residual Networks (WRN) and several other transfer learning models could be used for a better accuracy. Apart from that the hyperpapmeters, layers can be tuned and the optimizer can be made to function even smoother. The images could be preprocessed for training and evaluation, in by choosing a genuine image size to pick up on the distinctive features that help with image recognition, and the color channels could be reduced. Another important observation would be that colour information is very important. Even with lower noise levels, higher resolution, a simpler PSFand no masking, the lenses in the space-based set were harder to find than the lenses in the ground-based set Having multiple bands clearly makes a significant difference. The models take some time to train, but once trained they are very fast in classifying halos and predicting the mass fraction . Billions of objects can be easily handled

13 Dataset and Code

Link for the code-https://colab.research.google.com/drive/1KKnsdG2Zmcha1D8$_jB_ENCAbuIVF51r6?usp = sharing$
$Dataset - https : //drive.google.com/uc?id = 1hu472ALwGPBcTCXSAM0VoCWmTktg9j - j$

14 References

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