PXT992 Research Project Plan

Research project plan title: **Modelling of galaxies acting as a strong gravitational lens: a useful tool for the study of high *z* submillimetre-bright galaxies**

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1 Purpose (motivation)

In recent decades, there has been a marked increase in the number of observed gravitational lensing events, dominated by observations of lensed galaxies.[1,2,3] Gravitational lensing of a distant object occurs when light from that object, known as the source, is refracted by a sufficiently massive body, such as a galaxy,[a] which sits along the line of sight between Earth and the source. In such circumstances, the foreground galaxy is referred to as the lens. Such lensing can produce one or more offset and distorted images of the source, which appear in the plane of the lens. When the refraction caused by the lens is of sufficient strength to produce *multiple* images of the source, the lensing is referred to as strong lensing.[1] Gravitational lensing is responsible for some of the more exotic astronomical features which appear in the universe, including so-called Einstein Rings and Einstein Crosses, the latter being a clear example of strong lensing.[1] For a more detailed explanation of strong lensing, the reader is referred to section 2.2.

Needless to say, successful analysis of images of lensed galaxies requires careful planning and attention to detail. By using specialized software programs along with appropriate statistical techniques, the spectral contribution of the lens can first be accurately modelled and then subtracted from the original image, leaving only an image of the background source. Once such an image is obtained, it can then be analysed using standard astrophysical methods to extract important information about the source. Critically, in cases where the source is a galaxy, key attributes of the galaxy such as the star formation rate (SFR) and red shift, *z*, can generally be determined. As the source galaxies in such cases are, by definition, at a higher red shift than the lens, analysis of strongly lensed galaxies allows astrophysicists to study high red shift galaxies which often would not be readily observable with current telescopes as they are simply too far away. Thus, the study of strongly lensed galaxies provides cosmologists with critical information about galaxy formation in the early universe. As will be explained below, lensing can be particularly useful in the study of high *z* galaxies which exhibit strong features in the infrared (IR).

Pursuant to this, the purpose of this project is to model the spectral contribution of the foreground galaxy (the lens) for two different probable[b] strong lensing events, SPT0418-47 and SPT2147-50 (also referred to as the targets and hereafter denoted SPT0418 and SPT2147, respectively). For each of the targets, the spectral contribution of the lens will then be subtracted from the original image to obtain an image of the source galaxy, as described above. This process will then be repeated using multiple images of each respective target, each image having been obtained in a different photometric band. If the resulting set of images of the source are of sufficient quality and resolution, the SED of the source galaxy can then be analysed in order to obtain significant information about the source. In particular, if the stellar mass and SFR of the source galaxy can be established, important information about the evolutionary mechanisms which drove the formation of the source can then be determined. Such insights will add to the continually growing body of information on high redshift galaxies. A thorough understanding of high *z* galaxies requires a large dataset from which accurate statistics can be extracted. Thus, as previously suggested, this project will ultimately play a very small role in increasing our understanding of galaxy formation in the early universe – information which is critical to have in order to constrain existing cosmological models or to advance new ones.

1.1 Aims and objectives

In accordance with the above description, the explicit aims and objectives of this project are shown below. The aims of the project are denoted by a capital letter while the more specific objectives are indicated by a

[a] Or a group of bodies i.e., a galaxy cluster.

[b] For more information on how the targets were selected, see section 3.1.

lower-case Roman numeral. Note that, by design, this project has a dual purpose – namely, the project has a technical purpose (briefly outlined above and further explained in subsequent sections) and an additional *educational* purpose. Broadly speaking, the educational aims of the project are for the student to gain experience with astrophysical research methods, to acquire more in-depth insight into a topic of current interest in the astrophysical research community, and to develop their project management and writing skills. The aims and objectives listed below are reflective of both the technical purpose of the project and of its educational purpose.

A. Become proficient at using Aladin[4] (a free software package used for viewing and manipulating astronomical data).
    i. Be able to view and manipulate fits files (including overlaying images, obtaining pixel level data from a given image and extracting meta-data from a file).
B. Become proficient at using Galfit[5,6] (a free software package used primarily for fitting an appropriate model of a galaxy to raw spectral data contained in an image).[7,8]
    i. Successfully run the Galfit example file (available at [5]) with no error codes. Obtain a reasonable chi-square statistic.
C. Generate a noise map[9] and point spread function[10] (PSF) for each target.
    i. Generate a noise map for SPT0418.
    ii. Generate a noise map for SPT2147.
    iii. Generate a PSF for SPT0418.
    iv. Generate a PSF for SPT2147.
D. For each target, successfully model the foreground galaxy using the noise map and PSF and then subtract the spectral contribution of the lens from the original raw image.
    i. Successfully use Galfit to model the foreground galaxy for SPT0418. Obtain a reasonable chi-square statistic (chi-square less than 2).
    ii. Successfully use Galfit to model the foreground galaxy for SPT2147. Obtain a reasonable chi-square statistic (chi-square less than 2).
E. For each target, extract photometry of the source from the lens subtracted image and plot the SED.
    i. For SPT0418, fit a function to the source using Galfit (obtain a reduced chi square statistic of less than 2), and then extract the photometry of the source.
    ii. For SPT2147, fit a function to the source using Galfit (obtain a reduced chi square statistic of less than 2), and then extract the photometry of the source.
F. Using the photometric data obtained, determine key parameters including the SFR, infrared (IR) luminosity (L_{IR}) and stellar mass for each target. Correctly propagate error for these values.
    i. Determine key parameters for SPT0418
    ii. Determine key parameters for SPT2147
G. Compare results obtained to relevant literature
H. (stretch goal) As time permits, use MAGPHYS to refine and better understand obtained SED for each target.

1.1.1 Explanatory notes on aims and objectives

When reviewing the aims and objectives, it is important to note that each target has multiple images associated with it. This is due to the fact that data for each target were collected in a range of photometric bands. Aims C through F, and the associated objectives, therefore pertain to multiple images for each target. Note that while all available images of sufficient quality will be analysed using the above methodologies, it is impossible to know ahead of time exactly how many images this will turn out to be for each target. As such, none of the objectives listed in C through F is predicated on a goal of analysing a certain number of images.

The aims and objectives listed above were developed in cooperation with Dr. Mattia Negrello, the project supervisor, and Ruthvik Joshi, a fellow MSc student who is also working on the project. Of note, it was critical to develop the aims and objectives in conjunction with Ruthvik given that it was decided mid-way through the Spring Term that there would be a high degree of teamwork between the author and Ruthvik on most aspects of the project. Where possible, the objectives were designed to be SMART objectives. In some cases, however, this was hampered by the fact that deciding on a specific, measurable goal was not straightforward given the author's lack of background knowledge on the topic. That said, after some discussion with Dr. Negrello (private communication), it was decided that specifying a measurable outcome for objectives D.i. and D.ii. made the most sense. This is because obtaining a reasonable reduced chi-square statistic for this step essentially means that it is highly likely that one was successful in prior steps. Note also that, for the sake of brevity, the aims and objectives as listed above do not include dates for completion. These dates can be found in section 3 in the Gantt chart, which was explicitly constructed using the aims and objectives shown above.

Finally, while it may seem redundant to list identical objectives for each target, it is entirely possible that the approach outlined in this report could be successful with one target but not with the other. This could happen, for example, if one of the targets has poor quality data or if one of the targets exhibits unusual (and therefore difficult to model) galactic morphology. It therefore made sense to list separate objectives for each target.

2 Literature review

In support of this project, a wide-ranging review of the relevant literature was conducted. The review, presented in the following sections, has been organized as follows: first, a brief review of the major historical milestones in the field of gravitational lens studies is given. This is followed by a more focused review of the history of strong lensing. Next, a review of analytical methods and approaches for detecting and analysing strong lensing events is presented. This is followed by a discussion of strong lensing of SMGs. The literature review then concludes with a discussion of prospects for further developments in the field.

To aid the reader, a Glossary of terms used in the text is provided in section 5.1.

2.1 Gravitational lensing: a brief historical perspective

In a seminal paper published in 1936, Albert Einstein described how, according to his theory of General Relativity, a suitably massive body could distort space-time to such a degree that the body would act as a lens which could amplify and focus nearby rays of light.[11] Interestingly, Einstein remarked in this paper that this predicted bending of light rays would be virtually impossible to observe and, as such, that it was mostly a curiosity. It is important to note that recent scholarship[12] has strongly suggested that not only did Einstein realize this effect could occur much earlier than 1936, but also that other key contributions to the field prior to this time, notably those of Eddington and Chwolson, may have been overlooked.[13,14,15]

Indeed, it had been recognized for some time prior to 1936 that light rays could be appreciably deflected by a strong enough gravitational field. Perhaps the most well-known example of this was Einstein's paper on the theory of relativity that was published in 1911.[16] In this landmark paper, he predicted that light rays would be slightly bent when passing near enough to a star. Amazingly, this same prediction had in fact first been made more than a century earlier by von Soldner.[17,18,19] After experimental confirmation[c] of the prediction by Dyson, Eddington and Davidson in 1919,[20] the idea that a gravitational field could deflect a ray of light gained far wider acceptance in the scientific community. Theories concerning the existence of gravitational lensing were thus a logical extension of this same key idea.

After the publication of Einstein's 1936 paper, the astronomer Fred Zwicky noted in a 1937 article that nebulae should be able to act as gravitational lenses.[21] Importantly, Zwicky made an argument (bolstered with calculations) that nebulae acting as gravitational lenses would be far easier to resolve spectroscopically than smaller bodies like stars. This, he pointed out, was due simply to the fact that nebulae were far more massive and much larger in volume than stars. Crucially, Zwicky also identified three key reasons why observations of gravitational lensing would be of interest to the astronomical community. As these insights continue to be primary motivations for astrophysicists to study gravitational lensing, it is worth explicitly highlighting them here.

- First, such observations would serve as further empirical confirmation of the theory of relativity.

[c] At the time, empirical confirmation of Einstein's prediction was only able to be obtained during a suitable eclipse. Such an eclipse took place in 1919.

- Second, lensing would enable astronomers to see objects at much greater redshifts than they otherwise would be able to when using instrumentation alone.
- Finally, under the right circumstances, observation of gravitational lensing would allow astronomers to determine the mass of the *lens*.[d] This is because the strength of the lens is dependent only on the mass-energy confined within a given region.[1]

As noted above, Zwicky's last two motives for studying lensing continue to motivate the field to the present day. In particular, in recent years there has been considerable interest in how the study of lensed systems can be used to probe the presence and distribution of dark matter.[1,22] That said, it is Zwicky's second point, that lensing permits astronomers to increase the range and resolving power of their telescopes, that is essentially the focus of this project.

In spite of astronomers' obvious interest in the topic, it would not be until 1979 that the first actual observation of gravitational lensing (involving a quasar) took place.[23] Even then, the authors were not entirely certain that they had detected a gravitational lensing event, as evidenced by the title of their publication (see [[23]], below). In the years that followed, however, further observations were made[24] and interest in the topic grew considerably. Indeed, as shown below in Figure 1, there was a marked increase in the number of papers published on gravitational lensing after the first observation in 1979.[25]

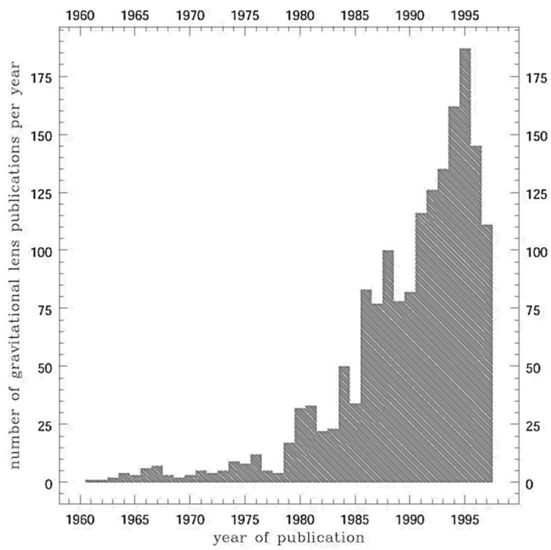

Figure 1: A bar graph of the number of publications on gravitational lensing per year for the years ~1960 to 1997. Note the sharp increase in the annual number of papers after 1979. Reproduced from Figure 1 in [[25]] with slight modifications.

Over time, researchers studying lensed systems began to sub-divide such systems into various categories. These categories have generally been based on the strength of the lens, on the nature of the body acting as the lens or on the nature of the source.[25,26] To date, strong lensing by galaxies (i.e. when a galaxy or galaxy cluster is serving as the lens) has been observed acting on quasars,[27] galaxies,[1] and supernovae.[28] Irrespective of the source, strong lensing events can also be further classified as macrolensing, millilensing or microlensing events. Macrolensing occurs when multiple images with separations on the order of arcseconds are produced, millilensing occurs when the images are separated by only milliarcseconds and microlensing occurs when the images are separated by only microarcseconds.[1] In addition to strong lensing there is also weak lensing (when a single deformed image of the source, only slightly shifted in space, is visible).[1,29] Given the nature of this work, however, the remainder of this literature review is focused on strong lensing.

2.2 Galaxies as strong lenses: a brief overview

Galaxies (or galaxy clusters) can act as strong lenses for point source objects like quasars or for larger bodies i.e. other galaxies.[1] In order for this to occur, however, the conditions must be near optimal. In particular, the deflector and the source must be in excellent alignment (as viewed from Earth) and the deflector must be of sufficient mass density to act as a lens.[1] This begs the question, however, of how often

[d] Zwicky's actual statement in the 1937 paper applied specifically to nebulae, but is applicable to all lensed systems.

these two conditions coincide. As is the case with most astronomical phenomena, a proper understanding of gravitational lensing necessarily requires a large dataset of observations of lensed systems. Thus, the determination of exactly *how* rare lensing events truly are has long been recognized to be of critical importance for the field. Indeed, this fact was recognized quite early on and methods for detecting lensed systems continue to be put forth in recent publications.[30]

Shortly after publishing his 1937 paper on nebulae as gravitational lenses, Zwicky published a brief note on the likelihood of *actually observing* such a system.[31] He concluded that it was virtually certain that such systems would be found. Several decades later, in 1967, Wagoner attempted to quantify the number of lensed systems which could theoretically be observed. In this paper, he estimated that the number of galaxies in optimal *alignment*, as viewed from Earth, should be on the order of $\sim 10^8$.[32] Further work in 1967 was carried out by Sadeh.[33] Barnothy and Barnothy followed up on this paper in 1968 with a work that extended on Wagoner's by taking into consideration the mass density and size of the lens.[34] While this work was heavily focused on the observation of quasars, it was nonetheless of importance to the wider field.

Today, the conditions under which a galaxy can act as a strong lens are generally well understood.[1] Even so, there does continue to be debate about the nature of the role that dark matter plays in certain cases.[1,35] This is because the (presumed) distribution of dark matter within a galaxy acting as a deflector would have a marked effect on its mass density and therefore on its ability to act as a lens. Irrespective of the exact reasons for a particular galaxy's variation in mass density, the relationship between variation in mass density and a galaxy's velocity dispersion is well understood (as expressed in the Faber-Jackson and Tully-Fisher relationships). Thus, it can be shown that for a galaxy to act as an efficient lens, its velocity dispersion should generally be less than ~300 km s^{-1}.[1,36]

Figure 2, below, contains a simple diagram illustrating the geometry of lensed systems. Note that the gray arrow in the source plane is magnified and shifted in the image plane. Here, the image plane is coincident with the plane of the lens.

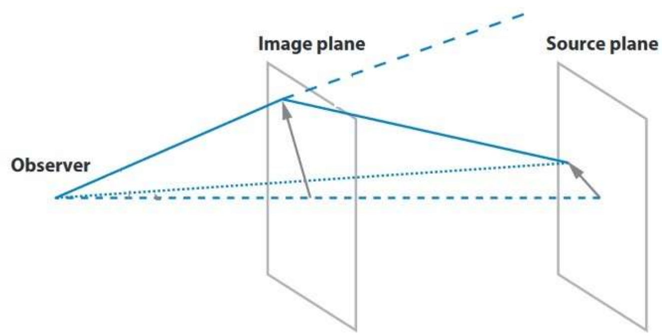

Figure 2: A simple diagram illustrating gravitational lensing. Reproduced from [1] and slightly modified.

2.3 Modern analytical methods used in the study of lensed systems

2.3.1 Finding lensed systems

One of the biggest difficulties encountered when attempting to study strongly lensed systems is a rather prosaic one: locating them. Indeed, while gravitational lensing as a phenomenon is somewhat rare to observe (though is still to be expected, as explained above), *strong* lensing is rarer still as it requires a more precise set of conditions to occur. Even prior to the observation of the first lensed system, methods to locate lensed systems were being proposed. In particular, Sadeh, using data from Sandage, had employed a so-called "2 color" search technique to search for lensed quasars.[33,37] This technique relied on the difference in colour between bluer, high energy quasars and redder galaxies which were acting as a lens. As such, it is not well suited for the identification of lensed galaxies.

In the decades since the observation of the first lensed system, various additional methods for locating lensed systems have been proposed. Many of these methods, like Sadeh's, rely on colour discrimination; the other primary methods that have been used are based on luminosity.[30] In effect, one can search images collected from photometric surveys for regions of unexpectedly bright luminosity (in a chosen photometric band) around the edges of a galaxy. Such searching can be done manually or with the aid of a computer. A detailed review of such methods is given in [30] and the references therein. For the purposes of this review, it is sufficient to note that as computing power has increased in recent decades, the task of locating strongly lensed systems has become much easier (though it is still not trivial). Indeed, according to the authors of [30], there are several promising methods available. This will be important in the future, as with the recent deployment of JWST (and the planned deployments of other new telescopes), it is expected that the number of datasets suitable for analysis will greatly increase.

In section 2.4, below, a method for locating a particular type of strongly lensed system is reviewed. This method, well suited for the detection of sub-millimetre bright galaxies, is of key relevance to this project given the nature of the targets.

2.3.2 Analysing lensed systems: competing methods

A proper analysis of strongly lensed systems requires a detailed model of the foreground galaxy so that it can be subtracted from an image, leaving only a model of the source. At the instruction of the project supervisor, the author will be using Galfit for this purpose. However, there are other software packages. Perhaps the most well-known is GIM2D.[38] This software package is functionally quite similar to Galfit. However, according to the creators of Galfit, GIM2D is significantly slower.[39] This assertion is supported by at least one peer reviewed publication.[40] Additionally, over the years, a number of freely available 3rd party add-ons to Galfit have been developed.[41] This demonstrates that it is a popular choice of software package for astrophysicists. Additional software packages for modelling/fitting images of galaxies do exist[42] but given the short timeline of this project, it was deemed safest to use Galfit, as recommended by the project supervisor.

It is important to note that each distinct software package is likely to give a slightly different fit for a given image of a galaxy. This is expected and is due to the use of different underlying statistical equations employed by each piece of software. In light of this, it should be pointed out that while careful selection of an appropriate software package for modelling is clearly important, it is even more important to accurately record and report which piece(s) of software were used in an analysis. This ensures that other scientists can easily reproduce (or critique) a given result.

2.4 Strong lensing of submillimetre-bright galaxies

As previously noted, a major challenge to studying strong lensing by galaxies is locating suitable systems for analysis. Of relevance to this work, in 2010, Negrello and co-workers published a method for detecting strongly lensed sub-millimetre bright galaxies.[43] This method, which relies on flux selection, is well suited for detection of this class of galaxy. Detection of these kinds of galaxies is otherwise challenging. This is due to the inherent instrument limitations of suitable telescopes (i.e., the fact that the resolving ability of a telescope scales with wavelength) and due to interference from galactic dust in this region of the electromagnetic spectrum. Additionally, as with all shared scientific instrumentation around the world, there is a high degree of competition for telescope time (and such time is expensive). Therefore, it is often the case that astrophysicists searching for lensing events are working with relatively shallow surveys (i.e., short exposure times), further increasing the difficulty of locating strongly lensed systems.

In a series of follow up papers,[2,44,3,45] it was convincingly demonstrated that this method was remarkably effective at detecting these dust obscured, high redshift galaxies. This provided the scientific community with a wealth of data on high red shift galaxies which would have been otherwise difficult or impossible to obtain. On a more practical note, this method will be especially useful going forward as it can be used with images obtained from JWST surveys.

Lastly, it is important to note that this is the method which was used to select the two targets of this project. Obviously, no method for detecting strongly lensed systems will have a 100% success rate. It is therefore necessary to perform follow-up analysis on any identified candidates. Such follow-up analysis is the focus of this project.

2.5 Avenues for further research

As mentioned in the aims and objectives, one possible extension of this work would be to analyze any results obtained using MAGPHYS. The goal of using MAGPHYS would be to more effectively compare the results of this work (i.e., the SED of the source) to a relevant population of similar galaxies. This approach has been used by other groups[46] and would likely be successful using the results of this project. Other possible extensions of this work would be to use a software package other than Galfit for modelling the lens, to attempt to extend this methodology to weakly lensed systems or to attempt to extend this methodology to lensed compact objects like quasars or supernovae (*vide supra*).

More broadly, the future of gravitational lens studies is bright. Its relevance to fields as diverse as galaxy formation and evolution, the study of dark matter, and cosmology clearly demonstrates that it is a powerful tool for astronomers and astrophysicists. Recent scholarship even suggests that the study and analysis of lensed systems could play a role in settling ongoing debates about the value of the Hubble Constant, one of the key unsettled issues in the field of cosmology today.[47]

3 Research project structure

As with many research projects focused on astrophysics, this project will be carried out entirely on a computer. As detailed in subsequent sections, the images being utilized for the project have already been collected and are available online. Accordingly, no further astronomical observations are needed in order to complete the project.

Given the relatively small size of the datasets being worked with, the author's personal computer has enough computing power and memory to successfully carry out the project.

This section of the plan lists software, raw data and other resources needed in order to complete the project. Following this, a timeline of the project is given along with brief comments on work which has already been commenced. Next, more detail is given on key selected steps of the project. The section concludes with a discussion of potential obstacles to completing the project and how such risks will be mitigated.

Note that a thorough review of certain topics (e.g. how to use Galfit) is beyond the scope (and indeed, the page limit) of this report. As such, the author has elected to highlight items of key importance to the project's success below. Additionally, some explanation of terms likely to be unfamiliar to readers (e.g., PSF, noise map) is also provided.

3.1 Software needed

The project will make use of the following software packages, plug-ins and coding languages:

Aladin[4] – a free software package which enables users to view and manipulate astronomical images.[48] The version being used for this work is the desktop version 12.0. A screen capture from Aladin desktop is shown below in Figure 3.

Galfit[5] – a free software package which is used in the modelling of galaxies. The version being used for this work is version 3.05. A screen capture from Galfit, which is a text based program, is shown below in Figure 4.

Windows Subsystem for Linux (WSL)[49] – a free addition to Windows 10 (or higher) which allows the user to run Linux based software. Galfit does not run on Windows and so WSL is needed.

Ubuntu[50] – a free, open source Linux operating system.

Python[51] – a coding language widely used by astronomers and astrophysicists. Python scripts can be created, edited and run online or can be created offline using a range of free programs.

PSF Simulation Tool for JWST[52] – a free online tool which can be used to obtain a suitable PSF for JWST data.

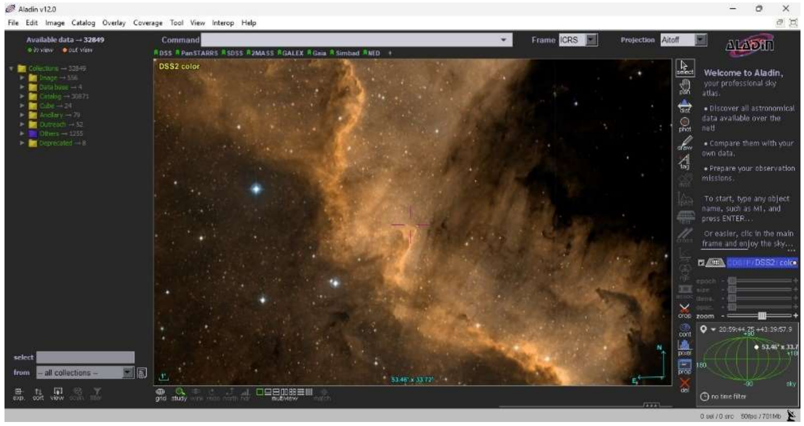

Figure 3: A screen capture of Aladin, taken from Aladin Desktop. Note the toolbar on the right, which allows the user to easily manipulate images.

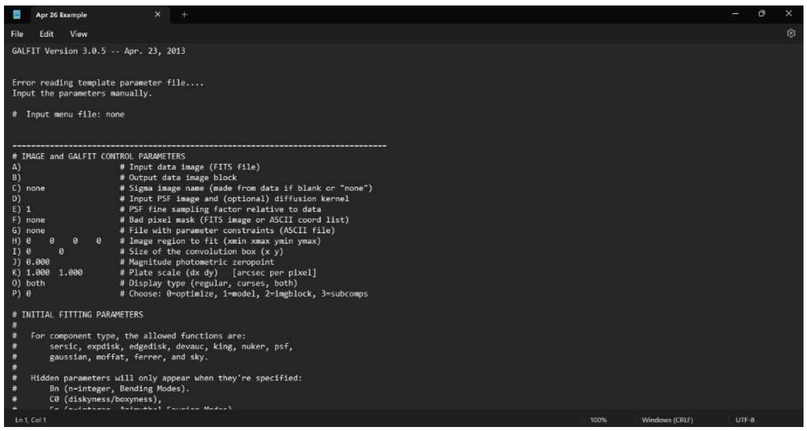

Figure 4: A screen capture from Galfit v. 3.0.5. Note the control parameters A through P, which can be modified using text commands entered directly into the command line.

3.2 Raw data needed

In order to complete this project, data from a variety of telescopes (and their associated instruments) will be needed. These include the James Webb Space Telescope (JWST),[53] the Hubble Space Telescope (HST),[54] the South Pole Telescope (SPT),[55] the Herschel Space Observatory (HSO),[56] the Large Apex Bolometer Camera (LABOCA)[57] and the Atacama Large Millimeter Array (ALMA).[58]

These data are needed because photometry of the targets at different wavelengths is needed in order to completely reconstruct the SED. Per the project supervisor, most of the data needed are available from [[59]] or from other readily accessible websites.[60] Any ancillary or supplementary data needed will be obtained from an appropriate database[61] or directly from the entity which manages each particular instrument (see References).

For reference, the author notes that the targets, SPT0418 and SPT2147, are located at the following coordinates (private communication from Dr. Negrello):

SPT0418-47: RA 04:18:39 Dec -47:51:50

SPT2147-50: RA 21:47:19 Dec -50:35:59

3.3 Other inputs and resources needed

The three primary inputs which Galfit needs in order to attempt to fit a function to a galaxy are an appropriate image of the galaxy, a suitable noise map and an appropriate PSF. As noted above, the raw images are readily available and, as noted in section 3.1, software which can be used for obtaining a suitable PSF is also available. Further details on how to obtain a noise map are given in subsequent sections below.

Once Galfit has been used to successfully create lens subtracted images of the target in various photometric bands, the SED of the source must be extracted. To facilitate this, the author will make use of "templates" which have been published for this purpose.[62] During this stage of the project, it is also possible that the author will make use of open source Python code available on GitHub or from other code repositories. For example, code used for error propagation or for obtaining more detailed statistics about the final modelled SED would be desirable.

3.4 *Proposed project timeline*

Shown below in Figure 5 is a Gantt chart which illustrates the proposed timeline for the project. This chart was developed in conjunction with the project supervisor, Dr. Negrello, and the author's project partner, Ruthvik Joshi. Explanatory notes about key milestones and possible branching points are given below. Due to space limitations, the font on the Gantt chart is somewhat small and the reader is invited to zoom in to the chart if they need to.

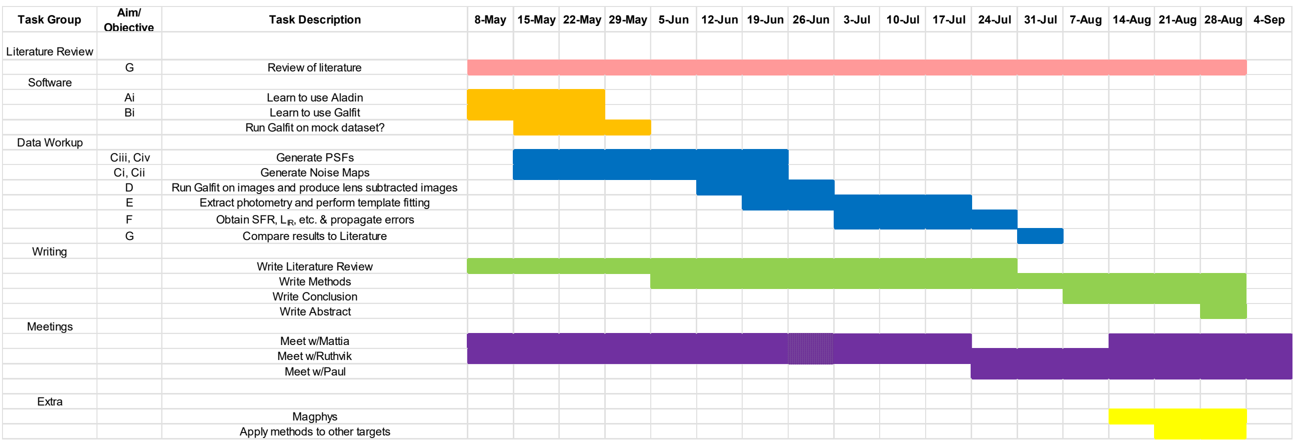

Figure 5: A Gantt chart which explains the project timeline.

3.4.1 *Key milestones and important dates*

Obviously, the success of the entire project is dependent on the author learning to use both Galfit and Aladin. To accomplish these tasks, the author intends to make used of a variety of resources.

For Galfit, there is an extensive user manual available along with a dummy file which can be used to learn how to correctly enter commands in the Galfit interface.[5] Additionally, the creators of Galfit maintain a webpage with a wealth of practical information provided in plain English[39] and, critically, detailed explanations of key inputs like the noise map.[9] There are also tutorials available on YouTube.[63] Lastly, the project supervisor is very familiar with Galfit and time can be set aside during weekly meetings with him to discuss and troubleshoot any issues encountered. The situation is similar for Aladin, which also has a user manual[48] and YouTube tutorials.[64]

As the success of the project is also dependent on the author's ability to successfully generate both a PSF and a noise map for each target, it is worth explaining these concepts in more detail.

Point spread functions are widely encountered in astronomy and detailed explanations of them have been given elsewhere.[10] They are inherent to the use of digital technology with telescopes as all digital images are, by definition, made up of individual pixels. In a "perfect" image, each individual pixel would not be in any way influenced or affected by spectral data associated with its neighbouring pixels. In reality, however, it will always be the case that information from neighbouring pixels bleeds into adjacent pixels. As the name suggests, the degree to which this occurs can be quantified using a PSF – the PSF provides a researcher with a quantitative measure of exactly how much spectral information from an individual pixel "spreads out" to its neighbouring pixels. Unsurprisingly, a PSF is generally associated with not only particular instrument e.g., JWST,[52] but also with a particular set of conditions under which an image was acquired.

Clearly, selection of an appropriate PSF is critical if one wishes to accurately analyze an image. As such, this is a gating factor which, if not completed, effectively holds up the entire project. To that end, and per the project supervisor's instruction (private communication), the author intends to use the JWST PSF tool[52] for generation of an appropriate PSF. As shown above, over a month has been allocated to this task.

An accurate noise map[e] is another key input for Galfit. The noise map accounts for the fact that not only does information in a given pixel influence its neighbours, but information in any given pixel has some inherent error (i.e., noise) associated with it. The total noise includes contributions from random sources (often assumed to be either Gaussian or Poissonian in nature) and from sources inherent to the instrument and acquisition conditions. Crucially, the noise is not uniform across an image – in particular, the signal to noise ratio (SNR) will vary considerably. This is because while each pixel will of course have a different degree of brightness (i.e., flux), not all the sources of noise scale equally with brightness.

Again, generation of an accurate noise map is a task that is critical to the success of this project. The author intends to use the guidance provided by the creators of Galfit[9] along with regular input from the project supervisor to successfully achieve this task in a timely manner.

It should be noted that while in principle generation of the first PSF and first noise map (for one of the targets) should take the longest (due to the author's own learning curve), this may not end up being the case. It could be, for example, that one target has a distinctly more complex noise map. Contingency plans for what to do if this occurs are outlined in the next section.

Additional key dates/weeks to note in the Gantt chart are as follows:

- the week of June 26th, when the author has a prior personal engagement and work on the project is likely to be impacted significantly,
- the last week of July and the first two weeks of August, when the project supervisor will be out of the office and have limited availability. It is critical that work on the PSF and noise map be completed by this time. These tasks are scheduled to be completed by third week of June. In effect, therefore, the author has allowed for up to a one-month delay in completion of these tasks. This was intentional but it does mean that a significant amount of work will need to be completed in June to keep the project on track (i.e., the project is somewhat front loaded). Note also that while the project supervisor will be out of town beginning late July, the author intends to begin meetings with Dr. Paul Roche during this time. While Dr. Roche cannot provide technical support for the project, he can serve as an additional resource or "sounding board" if problems with the project arise. Crucially, he can also provide general guidance on how to approach writing up the results of the project.
- The final key time period to note is the second week of August. This is when the project supervisor will return from being out of the office. As shown in the Gantt chart, this is when the decision on whether or not to pursue the extended objectives of the project (i.e., using MAGPHYS to further analyse the results) will be made. This decision will ultimately be based on consultation with the project supervisor, Dr. Roche and the author's research project partner. Note that making this decision so late in the project lifecycle does not afford the author a significant amount of time to work on this task. As such, it is unlikely that the author will achieve the extended objectives of the project.

3.4.2 Branching points and contingency plans

By prior agreement, the author will be focusing his efforts on the target SPT2147 while the author's lab partner will focus his efforts on SPT0418.

Critically, it was also decided that if either the author or his project partner encounters insurmountable difficulties in their attempted modelling of either target, then both researchers will continue work on the remaining viable target. Per the project supervisor, this is most likely to occur if significant issues arise when attempting to generate a suitable PSF or noise map. Consistent with this observation, if the author has been unable to generate a suitable PSF and noise map by the third week of July (when the supervisor departs for three weeks), the author will abandon his efforts to model SPT2147 and commence work on modelling SPT0418.

[e] Also referred to as a "sigma image" by the creators of Galfit.

3.5 Work already commenced or completed

While the project is formally set to begin the week of May 8th, a significant amount of work has already been completed by the author. This has been facilitated by the project supervisor and by the author's project partner. More specifically, once the author had been assigned to the project,

- the project supervisor provided the author with a list of key papers to read and links to key software and datasets. These were all uploaded to a dedicated, private folder on OneDrive.
- the author and his project partner (after exploring various options) were able to successfully install WSL, Ubuntu and Galfit on their respective personal computers.
- the author and his project partner began holding bi-weekly meetings with the project supervisor. These meetings have enabled the author to acquire knowledge about key concepts fundamental to the project's success (e.g., the PSF, the noise map, lensing, etc.) and have paved the way for an efficient start to the project.

3.6 Obstacles to success and risk analysis

As with any project, perhaps the greatest obstacles to success of this project would be a lack of organization or poor project planning. These risks have both been sufficiently mitigated by the creation of this report. Other risks remain, however, and to this end the author conducted a risk analysis for the project. The results of the risk analysis are shown below in Figure 6.

Event	**Likelihood**	**Impact**	**Risk**
Pandemic resurgence	1	4	4
Computer breakdown	1	4	4
Major life event	1	5	5
Loss of data	2	5	10
Key			
Likelihood	Definition	Impact	Definition
1	1/100 chance (or less)	1	Negligible impact
2	~5/100 chance	2	Minor impact
3	~10/100 chance	3	Moderate impact
4	~25/100 chance	4	Significant impact
5	50/100 chance or greater	5	Major impact

Figure 6: A risk analysis for the project. See text for full explanation.

It is worth pointing out that no risk analysis can plan for all possibilities and indeed, putting an excessive amount of effort into planning for very low likelihood events can hamper the progress of a project. To that end, the above chart only contains events which the author deemed would have a *roughly* 1/100 chance or greater of occurring. Using the key above, the author assigned a likelihood score and an impact score to each event. The product of these two numbers represents the risk. Events with a risk score of 10 or greater were deemed to be risks which required further mitigation. Note that this method is a rough adaptation of a similar method used by the United States Antarctic Program.[65] A brief explanation of the ratings in the chart is given below.

A major resurgence of the Covid 19 pandemic was deemed unlikely given that

a) the project was taking place over the summer,
b) due to vaccination and herd immunity, a significant level of resistance to the virus is now present in the global population and
c) governments around the world now have tools and methods at their disposal for dealing with the pandemic that were not available to them 3 years ago.

Even if such a resurgence did occur, this project is well suited for a pivot to remote work and so the impact to the project, while significant, would not be catastrophic.

If the author's personal computer were to break, the author could use university computers to complete most aspects of the project or could simply purchase a new computer. Further, the author could use his project partner's computer to run Galfit. As an additional contingency plan, the author discussed the possibility of borrowing a Macintosh computer (which can run Galfit) from Dr. Amy Morreau.

If a major life event were to occur for the author (sudden illness or injury, death in the family, etc.), there are a number of ways in which this could be effectively dealt with. As stated before, the project is well suited for remote work. Thus, even if the author was not mobile (due, for example, to an injury) work on the project could continue. In an extreme situation, the author could also take advantage of the university's Extenuating Circumstances policy.

The biggest identified impediment to completing the project would be a loss of key data or results. For example, if the author generated a quality noise map but then lost it (for whatever reason) this could severely hamper the progress of the project. While this is *related* to the possibility of a computer breakdown, it is a distinctly different risk. To mitigate this risk, the author intends to perform a backup of all data/results generated during the project at least weekly. The author will do this by uploading the data to OneDrive.

4 List of references

(1) Treu, T. Strong Lensing by Galaxies. *Annu. Rev. Astron. Astrophys.* **2010**, *48* (1), 87–125. https://doi.org/10.1146/annurev-astro-081309-130924.
(2) Vieira, J. D.; Marrone, D. P.; Chapman, S. C.; De Breuck, C.; Hezaveh, Y. D.; Weiβ, A.; Aguirre, J. E.; Aird, K. A.; Aravena, M.; Ashby, M. L. N.; Bayliss, M.; Benson, B. A.; Biggs, A. D.; Bleem, L. E.; Bock, J. J.; Bothwell, M.; Bradford, C. M.; Brodwin, M.; Carlstrom, J. E.; Chang, C. L.; Crawford, T. M.; Crites, A. T.; de Haan, T.; Dobbs, M. A.; Fomalont, E. B.; Fassnacht, C. D.; George, E. M.; Gladders, M. D.; Gonzalez, A. H.; Greve, T. R.; Gullberg, B.; Halverson, N. W.; High, F. W.; Holder, G. P.; Holzapfel, W. L.; Hoover, S.; Hrubes, J. D.; Hunter, T. R.; Keisler, R.; Lee, A. T.; Leitch, E. M.; Lueker, M.; Luong-Van, D.; Malkan, M.; McIntyre, V.; McMahon, J. J.; Mehl, J.; Menten, K. M.; Meyer, S. S.; Mocanu, L. M.; Murphy, E. J.; Natoli, T.; Padin, S.; Plagge, T.; Reichardt, C. L.; Rest, A.; Ruel, J.; Ruhl, J. E.; Sharon, K.; Schaffer, K. K.; Shaw, L.; Shirokoff, E.; Spilker, J. S.; Stalder, B.; Staniszewski, Z.; Stark, A. A.; Story, K.; Vanderlinde, K.; Welikala, N.; Williamson, R. Dusty Starburst Galaxies in the Early Universe as Revealed by Gravitational Lensing. *Nature* **2013**, *495* (7441), 344–347. https://doi.org/10.1038/nature12001.
(3) *Herschel-ATLAS: a sample of 500 μm-selected lensed galaxies over 600 deg2 | Monthly Notices of the Royal Astronomical Society | Oxford Academic*. https://academic.oup.com/mnras/article/465/3/3558/2454768 (accessed 2023-04-30).
(4). https://aladin.cds.unistra.fr/java/nph-aladin.pl?frame=downloading (Accessed 2023-05-01).
(5) *GALFIT Home Page*. https://users.obs.carnegiescience.edu/peng/work/galfit/galfit.html (accessed 2023-05-01).
(6) Peng, C. Y. GALFIT USER'S MANUAL.
(7) Peng, C. Y.; Ho, L. C.; Impey, C. D.; Rix, H.-W. Detailed Structural Decomposition of Galaxy Images. *Astron. J.* **2002**, *124*, 266–293. https://doi.org/10.1086/340952.
(8) Peng, C. Y.; Ho, L. C.; Impey, C. D.; Rix, H.-W. Detailed Decomposition of Galaxy Images. II. Beyond Axisymmetric Models. *Astron. J.* **2010**, *139*, 2097–2129. https://doi.org/10.1088/0004-6256/139/6/2097.
(9) *WHAT ONE SHOULD KNOW ABOUT Chi^2/NU and SIGMA IMAGE IN GALFIT*. https://users.obs.carnegiescience.edu/peng/work/galfit/CHI2.html (accessed 2023-05-03).
(10) Racine, R. THE TELESCOPE POINT SPREAD FUNCTION. *Publ. Astron. Soc. Pac.* **1996**, *108* (726), 699. https://doi.org/10.1086/133788.
(11) Einstein, A. Lens-Like Action of a Star by the Deviation of Light in the Gravitational Field. *Science* **1936**, *84* (2188), 506–507. https://doi.org/10.1126/science.84.2188.506.
(12) Renn, J.; Sauer, T.; Stachel, J. The Origin of Gravitational Lensing: A Postscript to Einstein's 1936 Science Paper. *Science* **1997**, *275* (5297), 184–186. https://doi.org/10.1126/science.275.5297.184.
(13) Schneider, P.; Ehlers, J.; Falco, E. E. Gravitational Lenses as Astrophysical Tools. In *Gravitational Lenses*; Schneider, P., Ehlers, J., Falco, E. E., Eds.; Astronomy and Astrophysics Library; Springer: Berlin, Heidelberg, 1992; pp 467–515. https://doi.org/10.1007/978-3-662-03758-4_13.
(14) Eddington, A. *Space, Time and Gravitation*; Cambridge University Press: Cambridge, 1920.
(15) Chwolson, O. Uber eine mogliche Form fiktiver Doppelsterne. *Astron. Nachrichten* **1924**, *221*, 329.
(16) Einstein, A. Über den Einfluß der Schwerkraft auf die Ausbreitung des Lichtes. *Ann. Phys.* **1911**, *340* (10), 898–908. https://doi.org/10.1002/andp.19113401005.
(17) vol Soldner, J. G. *Astron. Jahrb. Für Jahr 1804 Nebst Einer Samml. Neuesten Astron. Wiss. Einschlagenden Abh. Beob. Nachrichten* **1801**, *29*, 161.
(18) Sauer, T. Soldner, Einstein, Gravitational Light Deflection and Factors of Two. *Ann. Phys.* **2021**, *533* (8), 2100203. https://doi.org/10.1002/andp.202100203.

(19) Jaki, S. L. Johann Georg von Soldner and the Gravitational Bending of Light, with an English Translation of His Essay on It Published in 1801. *Found. Phys.* **1978**, *8* (11), 927–950. https://doi.org/10.1007/BF00715064.
(20) Dyson, F. W.; Eddington, A. S.; Davidson, C. A Determination of the Deflection of Light by the Sun's Gravitational Field, from Observations Made at the Total Eclipse of May 29, 1919. *Philos. Trans. R. Soc. Lond. Ser. A* **1920**, *220*, 291–333. https://doi.org/10.1098/rsta.1920.0009.
(21) Zwicky, F. Nebulae as Gravitational Lenses. *Phys. Rev.* **1937**, *51* (4), 290–290. https://doi.org/10.1103/PhysRev.51.290.
(22) Ellis, R. S. Gravitational Lensing: A Unique Probe of Dark Matter and Dark Energy. *Philos. Trans. R. Soc. Math. Phys. Eng. Sci.* **2010**, *368* (1914), 967–987. https://doi.org/10.1098/rsta.2009.0209.
(23) Walsh∗, D.; Carswell†, R. F.; Weymann‡, R. J. 0957 + 561 A, B: Twin Quasistellar Objects or Gravitational Lens? *Nature* **1979**, *279* (5712), 381–384. https://doi.org/10.1038/279381a0.
(24) Kochanek, C. S.; Falco, E. E.; Impey, C.; Lehar, J.; McLeod, B.; Rix, H.-W. *Gravitational Lens Data Base*. https://lweb.cfa.harvard.edu/castles/ (accessed 2023-05-02).
(25) Wambsganss, J. Gravitational Lensing in Astronomy. *Living Rev. Relativ.* **1998**, *1* (1), 12. https://doi.org/10.12942/lrr-1998-12.
(26) Blandford, R. D.; Narayan, R. Cosmological Applications of Gravitational Lensing. *Annu. Rev. Astron. Astrophys.* **1992**, *30* (1), 311–358. https://doi.org/10.1146/annurev.aa.30.090192.001523.
(27) Wang, L.; Shu, Y.; Li, R.; Zheng, Z.; Wen, Z.; Liu, G. SDSS J1640+1932: A Spectacular Galaxy-Quasar Strong Lens System. *Mon. Not. R. Astron. Soc.* **2017**, *468* (3), 3757–3763. https://doi.org/10.1093/mnras/stx733.
(28) Oguri, M. Strong Gravitational Lensing of Explosive Transients. *Rep. Prog. Phys.* **2019**, *82* (12), 126901. https://doi.org/10.1088/1361-6633/ab4fc5.
(29) Hoekstra, H.; Jain, B. Weak Gravitational Lensing and Its Cosmological Applications. *Annu. Rev. Nucl. Part. Sci.* **2008**, *58* (1), 99–123. https://doi.org/10.1146/annurev.nucl.58.110707.171151.
(30) Metcalf, R. B.; Meneghetti, M.; Avestruz, C.; Bellagamba, F.; Bom, C. R.; Bertin, E.; Cabanac, R.; Courbin, F.; Davies, A.; Decencière, E.; Flamary, R.; Gavazzi, R.; Geiger, M.; Hartley, P.; Huertas-Company, M.; Jackson, N.; Jacobs, C.; Jullo, E.; Kneib, J.-P.; Koopmans, L. V. E.; Lanusse, F.; Li, C.-L.; Ma, Q.; Makler, M.; Li, N.; Lightman, M.; Petrillo, C. E.; Serjeant, S.; Schäfer, C.; Sonnenfeld, A.; Tagore, A.; Tortora, C.; Tuccillo, D.; Valentín, M. B.; Velasco-Forero, S.; Kleijn, G. A. V.; Vernardos, G. The Strong Gravitational Lens Finding Challenge. *Astron. Astrophys.* **2019**, *625*, A119. https://doi.org/10.1051/0004-6361/201832797.
(31) Zwicky, F. On the Probability of Detecting Nebulae Which Act as Gravitational Lenses. *Phys. Rev.* **1937**, *51* (8), 679–679. https://doi.org/10.1103/PhysRev.51.679.
(32) Wagoner, R. V. Some Effects of an Intervening Galaxy on the Radiation from Very Distant Objects. *Astrophys. J.* **1967**, *149*, 465. https://doi.org/10.1086/149278.
(33) Sadeh, D. Galaxies as Gravitational Lenses. *Science* **1967**, *158* (3805), 1176–1178. https://doi.org/10.1126/science.158.3805.1176.
(34) Barnothy, J.; Barnothy, M. F. Galaxies as Gravitational Lenses. *Science* **1968**, *162* (3851), 348–352. https://doi.org/10.1126/science.162.3851.348.
(35) Meneghetti, M.; Davoli, G.; Bergamini, P.; Rosati, P.; Natarajan, P.; Giocoli, C.; Caminha, G. B.; Metcalf, R. B.; Rasia, E.; Borgani, S.; Calura, F.; Grillo, C.; Mercurio, A.; Vanzella, E. An Excess of Small-Scale Gravitational Lenses Observed in Galaxy Clusters. *Science* **2020**, *369* (6509), 1347–1351. https://doi.org/10.1126/science.aax5164.
(36) Schneider, P.; Kochanek, C. S.; Wambsganss, J. *Gravitational Lensing: Strong, Weak and Micro*; Meylan, G., Jetzer, P., Series Eds.; Saas-Fee Advanced Courses; Springer: Berlin, Heidelberg, 2006; Vol. 33. https://doi.org/10.1007/978-3-540-30310-7.
(37) Sandage, A. The Ability of the 200-INCH Telescope to Discriminate Between Selected World Models. *Astrophys. J.* **1961**, *133*, 355. https://doi.org/10.1086/147041.
(38) *GIM2D Home Page*. https://www.astro.uvic.ca/~simard/GIM2D/ (accessed 2023-05-04).
(39) *GENERAL GALFIT FAQ*. https://users.obs.carnegiescience.edu/peng/work/galfit/GFAQ.html (accessed 2023-05-04).
(40) Häussler, B.; McIntosh, D. H.; Barden, M.; Bell, E. F.; Rix, H.-W.; Borch, A.; Beckwith, S. V. W.; Caldwell, J. A. R.; Heymans, C.; Jahnke, K.; Jogee, S.; Koposov, S. E.; Meisenheimer, K.; Sánchez, S. F.; Somerville, R. S.; Wisotzki, L.; Wolf, C. GEMS: Galaxy Fitting Catalogs and Testing Parametric Galaxy Fitting Codes: GALFIT and GIM2D. *Astrophys. J. Suppl. Ser.* **2007**, *172* (2), 615. https://doi.org/10.1086/518836.

(41) Ryan Jr, R. E. IGalFit: An Interactive Tool for GalFit. arXiv October 5, 2011. https://doi.org/10.48550/arXiv.1110.1090.
(42) Erwin, P. IMFIT: A FAST, FLEXIBLE NEW PROGRAM FOR ASTRONOMICAL IMAGE FITTING. *Astrophys. J.* **2015**, *799* (2), 226. https://doi.org/10.1088/0004-637X/799/2/226.
(43) *The Detection of a Population of Submillimeter-Bright, Strongly Lensed Galaxies | Science*. https://www.science.org/doi/10.1126/science.1193420 (accessed 2023-05-04).
(44) Negrello, M.; Hopwood, R.; Dye, S.; Cunha, E. da; Serjeant, S.; Fritz, J.; Rowlands, K.; Fleuren, S.; Bussmann, R. S.; Cooray, A.; Dannerbauer, H.; Gonzalez-Nuevo, J.; Lapi, A.; Omont, A.; Amber, S.; Auld, R.; Baes, M.; Buttiglione, S.; Cava, A.; Danese, L.; Dariush, A.; De Zotti, G.; Dunne, L.; Eales, S.; Ibar, E.; Ivison, R. J.; Kim, S.; Leeuw, L.; Maddox, S.; Michałowski, M. J.; Massardi, M.; Pascale, E.; Pohlen, M.; Rigby, E.; Smith, D. J. B.; Sutherland, W.; Temi, P.; Wardlow, J. Herschel*-ATLAS: Deep HST/WFC3 Imaging of Strongly Lensed Submillimetre Galaxies. *Mon. Not. R. Astron. Soc.* **2014**, *440* (3), 1999–2012. https://doi.org/10.1093/mnras/stu413.
(45) *Herschel-ATLAS: magnifications and physical sizes of 500-μm-selected strongly lensed galaxies | Monthly Notices of the Royal Astronomical Society | Oxford Academic*. https://academic.oup.com/mnras/article/475/3/3467/4795318 (accessed 2023-05-04).
(46) Díaz-Sánchez, A.; Dannerbauer, H.; Sulzenauer, N.; Iglesias-Groth, S.; Rebolo, R. The Einstein Ring GAL-CLUS-022058s: A Lensed Ultrabright Submillimeter Galaxy at z = 1.4796. *Astrophys. J.* **2021**, *919* (1), 48. https://doi.org/10.3847/1538-4357/ac0f75.
(47) Jee, I.; Suyu, S. H.; Komatsu, E.; Fassnacht, C. D.; Hilbert, S.; Koopmans, L. V. E. A Measurement of the Hubble Constant from Angular Diameter Distances to Two Gravitational Lenses. *Science* **2019**, *365* (6458), 1134–1138. https://doi.org/10.1126/science.aat7371.
(48) *Aladin Sky Atlas*. https://aladin.cds.unistra.fr/ (accessed 2023-05-03).
(49) craigloewen-msft. *Install WSL*. https://learn.microsoft.com/en-us/windows/wsl/install (accessed 2023-05-03).
(50) *Enterprise Open Source and Linux*. Ubuntu. https://ubuntu.com/ (accessed 2023-05-03).
(51) *Welcome to Python.org*. Python.org. https://www.python.org/ (accessed 2023-05-03).
(52) *WebbPSF*. STScI.edu. https://www.stsci.edu/home/jwst/science-planning/proposal-planning-toolbox/psf-simulation-tool (accessed 2023-05-04).
(53) *Webb Image Release- Webb Space Telescope GSFC/NASA*. https://webb.nasa.gov/ (accessed 2023-05-03).
(54) Belleville, M. *Hubble Space Telescope*. NASA. http://www.nasa.gov/mission_pages/hubble/main/index.html (accessed 2023-05-03).
(55) *South Pole Telescope, Antarctica | Center for Astrophysics*. https://www.cfa.harvard.edu/facilities-technology/telescopes-instruments/south-pole-telescope-antarctica (accessed 2023-05-03).
(56) *ESA Science & Technology - Fact Sheet*. https://sci.esa.int/web/herschel/-/47356-fact-sheet (accessed 2023-05-03).
(57) information@eso.org. *LABOCA*. https://www.eso.org/public/teles-instr/apex/laboca/ (accessed 2023-05-03).
(58) *ALMA Observatory*. https://almaobservatory.org/en/home (accessed 2023-05-03).
(59) Weiß, A.; Breuck, C. D.; Marrone, D. P.; Vieira, J. D.; Aguirre, J. E.; Aird, K. A.; Aravena, M.; Ashby, M. L. N.; Bayliss, M.; Benson, B. A.; Béthermin, M.; Biggs, A. D.; Bleem, L. E.; Bock, J. J.; Bothwell, M.; Bradford, C. M.; Brodwin, M.; Carlstrom, J. E.; Chang, C. L.; Chapman, S. C.; Crawford, T. M.; Crites, A. T.; Haan, T. de; Dobbs, M. A.; Downes, T. P.; Fassnacht, C. D.; George, E. M.; Gladders, M. D.; Gonzalez, A. H.; Greve, T. R.; Halverson, N. W.; Hezaveh, Y. D.; High, F. W.; Holder, G. P.; Holzapfel, W. L.; Hoover, S.; Hrubes, J. D.; Husband, K.; Keisler, R.; Lee, A. T.; Leitch, E. M.; Lueker, M.; Luong-Van, D.; Malkan, M.; McIntyre, V.; McMahon, J. J.; Mehl, J.; Menten, K. M.; Meyer, S. S.; Murphy, E. J.; Padin, S.; Plagge, T.; Reichardt, C. L.; Rest, A.; Rosenman, M.; Ruel, J.; Ruhl, J. E.; Schaffer, K. K.; Shirokoff, E.; Spilker, J. S.; Stalder, B.; Staniszewski, Z.; Stark, A. A.; Story, K.; Vanderlinde, K.; Welikala, N.; Williamson, R. ALMA REDSHIFTS OF MILLIMETER-SELECTED GALAXIES FROM THE SPT SURVEY: THE REDSHIFT DISTRIBUTION OF DUSTY STAR-FORMING GALAXIES. *Astrophys. J.* **2013**, *767* (1), 88. https://doi.org/10.1088/0004-637X/767/1/88.
(60) *Mikulski Archive for Space Telescopes (MAST) Portal*. https://mast.stsci.edu/portal/Mashup/Clients/Mast/Portal.html (accessed 2023-05-04).
(61) *Home | NASA/IPAC Extragalactic Database*. https://ned.ipac.caltech.edu/ (accessed 2023-05-03).
(62) Berta, S.; Lutz, D.; Santini, P.; Wuyts, S.; Rosario, D.; Brisbin, D.; Cooray, A.; Franceschini, A.; Gruppioni, C.; Hatziminaoglou, E.; Hwang, H. S.; Floc'h, E. L.; Magnelli, B.; Nordon, R.; Oliver, S.; Page, M. J.; Popesso, P.; Pozzetti, L.; Pozzi, F.; Riguccini, L.; Rodighiero, G.; Roseboom, I.; Scott, D.;

Symeonidis, M.; Valtchanov, I.; Viero, M.; Wang, L. Panchromatic Spectral Energy Distributions of Herschel Sources. *Astron. Astrophys.* **2013**, *551*, A100. https://doi.org/10.1051/0004-6361/201220859.
(63) *GALFIT Tutorial: S N Hasan*; 2021. https://www.youtube.com/watch?v=-nUe4YXTJ2Y (accessed 2023-05-04).
(64) *Aladin for Dummies*; 2015. https://www.youtube.com/watch?v=lKC71ylv1Eg (accessed 2023-05-04).
(65) ASC-18-026a.Pdf. https://www.usap.gov/usapgov/travelAndDeployment/documents/ASC-18-026a.pdf (accessed 2023-05-04).

5 Appendices

5.1 Glossary

ALMA – Atacama Large Millimetre Array

Dec - declination

Deflector – another term for lens

HSO – Herschel Space Observatory

HST – Hubble Space Telescope

IR - Infrared

JWST – James Webb Space Telescope

LABOCA – Large Apex Bolometer Camera

lens – any sufficiently massive body which sits on the line of sight between an observer and a source and which sufficiently distorts passing light rays so as to act as a “lens”

L_{IR} – the luminosity in the IR band, generally from ~10’s to ~1000 microns in wavelength

noise map – an input for Galfit. See explanation in section 3

PSF – point spread function. A mathematical function which describes the inherent “blurring” of images acquired with a telescope.

RA – right ascension

SED – spectral energy distribution

SFR – star formation rate

SMG – submillimetre galaxy

SNR – signal to noise ratio

source – an object or body in space (i.e. a star or galaxy) that, when viewed from Earth, is experiencing gravitational lensing

SPT – South Pole Telescope

target – an object of study for this research project

WSL – Windows Subsystem for Linux

z – the red shift

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