Results and planned use of gravitational lensing

It was decided that the most time efficient option was to choose known lenses since an additional survey would be required to locate new lenses. Combining the constraints set out in section [observational gravitational lensing], an optimum lens redshift range **of 0.5<z<0.7** was chosen. A range of clusters lying within this redshift range were selected from the MACS **catalogue**. It was decided that lenses would be used in half of the deep field pointings in order to have a high chance of probing to the deepest redshifts while using the remaining fields without the obscuration caused by the lens. Table [potential lenses] lists the 5 chosen lenses with some of their key properties \cite{strong\_lensing\_analysis\_MACS}. The locations of these lenses are well spread out, reducing cosmic variance.

|  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- |
| **MACS Cluster** | **z** | **Α(J2000.0)**  **(h m s)** | **Δ(J2000.0)**  **(° ‘ “)** | **Mass/  1014 Msun** | **Velocity dispersion/kms-1** |
| J0744.9+3927 | 0.698 | 07:44:52.470 | +39:27:27.34 | 3.1±0.1 |  |
| J0025.4-1222 | 0.584 | 00:25:29.381 | -12:22:37.06 |  |  |
| J0257.1-2325 | 0.505 | 02:57:09.151 | -23:26:05.83 |  |  |
| J0647.7+7015 | 0.591 | 06:47:50.469 | +70:14:54.95 | 2.07±0.1 |  |
| J0911.2+1746 | 0.505 | 09:11:11.277 | +17:46:31.94 | 2.07±0.1 |  |

*Caption: List of lenses selected for the observing strategy*

It is worth noting that these lenses are all included in the HST Frontier Fields high magnification cluster candidate list, which lists massive clusters with highly efficient lensing properties increasing the likelihood of very high redshift sources being observed. \cite{HST\_strong\_magnification} The deeper the magnitude that is being observed, the longer it will take to observe the sources with a good signal to noise ratio. As a result, the depth probed will be balanced with observing time. Table[range of depths] shows a range of observing depths and the number of lensed objects that would be seen at each.

|  |  |  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- | --- | --- |
|  | **To magnitude 31.5** | | **To magnitude 31** | | **To magnitude 30.5** | | **To magnitude 30** | |
| **MACS Cluster** | **10≤z≤12** | **12≤z≤15** | **10≤z≤12** | **12≤z≤15** | **10≤z≤12** | **12≤z≤15** | **10≤z≤12** | **12≤z≤15** |
| J0025.4-1222 | 10.6 | 5.0 | 3.1 | 1.1 | 5.9 | 2.5 | 2.0 | 0.6 |
| J0257.1-2325 | 33.9 | 16.1 | 10.0 | 3.7 | 19.0 | 8.0 | 6.3 | 2.0 |
| J0647.7+7015 | 23.1 | 11.0 | 6.8 | 2.5 | 13.0 | 5.5 | 4.3 | 1.4 |
| J0744.9+3927 | 49.3 | 23.6 | 14.6 | 5.4 | 27.7 | 11.7 | 9.1 | 3.0 |
| J0911.2+1746 | 66.9 | 31.8 | 19.8 | 7.2 | 37.5 | 15.8 | 12.4 | 4.0 |

*Caption: range of observing depths and number of lensed objects observed at redshift ranges 10-12 and 12-15 for each chosen lens.*

**These results indicate a significant increase in sources observed compared to the number expected without a lens. This is largely due to the rapid increase in the number of high redshift objects at dimmer magnitudes. The total number of extra galaxies expected from lensing is 183.9 at redshifts 10-12 and 87.5 at redshifts 12-15. This increase in the number of sources observed will give a much better sample of early galaxies, allowing tighter constraint to be placed on the epoch of re-ionization.**

**While these calculations have a relatively large error due to uncertainty on the velocity dispersion, by far the dominant error affecting the number of extra galaxies seen results from cosmic variance.** This error depends on the area which is being observed so the cosmic variance should be calculated for the area corresponding to each magnification factor for every lens and combined to give an overall value. The predictions group’s programme is not sufficiently complex to complete this calculation so using an average area (13180 arcsec2) and velocity dispersion (974kms-1) from the 5 chosen lenses, the cosmic variance is, very roughly found to be 64%. This gives the total number of extra objects found to be 271±174**, indicating that** across the 5 lenses, a minimum of 97 extra galaxies should be observed, with at least 31 at redshifts greater than 12. The errors due to cosmic variance calculated for individual lenses (largely over 200%) suggest that there could be any number of galaxies between 0 and up to several times as many as calculated in table.

Once candidates have been identified behind these clusters, spectroscopy will be used to confirm the source redshift and therefore the distance to the source. The mass and redshift of the lenses are known so equation can be used to find the Einstein angle. The magnification can then be calculated from equation .The flux from the images can be obtained from observations and can be used in conjunction with the magnification factor to calculate the intrinsic brightness of the source in bands red-ward of the drop from equation . Using model galaxy spectra, the flux in the band blue-ward of the drop can be estimated. This gives a lower limit on the neutral hydrogen fraction, since there must be at least enough to absorb the flux missing in the galaxy’s spectrum. \cite{lower\_limit\_H}

From these results, it is clear that that gravitational lensing will enable this strategy to better constrain the epoch of re-ionization by increasing the number of galaxies observed and by allowing surveys to probe significantly deeper redshifts.

@article{ strong\_lensing\_analysis\_MACS,

title = { Strong-lensing analysis of a complete sample of 12 MACS clusters at z > 0.5: mass models and Einstein radii },

author = { Adi Zitrin, Tom Broadhurst, Rennan Barkana, Yoel Rephaeli

and Narciso Benítez },

journal = { Monthly Notices of the Royal Astronomical Society},

volume = {410},

issue = {3},

pages = {1939-1956},

numpages = {18},

year = {2011},

month = {Jan},

doi = { 10.1111/j.1365-2966.2010.17574.x },

url = { http://onlinelibrary.wiley.com/doi/10.1111/j.1365-2966.2010.17574.x/abstract},

publisher = {Royal Astronomical Society }

}

@misc{ HST\_strong\_magnification,

author = {Space Telescope Science Institute},

title = {{HST Frontier Fields  
High-Magnification  
Cluster Candidate List

}},

howpublished = "\url{ <http://www.stsci.edu/hst/campaigns/frontier-fields/frontier-fields-high-magnification-cluster-candidate-list/>}",

year = {2013},

}

@article{lower\_limit\_H}

title={Improved constraints on the neutral intergalactic hydrogen surrounding quasars at redshifts z> 6},

author={Wyithe, J Stuart B and Loeb, Abraham and Carilli, Chris},

journal={The Astrophysical Journal},

volume={628},

number={2},

pages={575},

year={2008},

publisher={IOP Publishing}

}