# Follow-up of high-z GLIMPSE candidates

**None Assigned**


**ABSTRACT**

We propose to use ALMA's Band 7 receiver to spectroscopically confirm and characterize five candidate galaxies at redshifts z>16, recently identified by the GLIMPSE survey using JWST observations of the strongly lensed cluster Abell S1063. By targeting key far-infrared cooling lines, [CII] 158 um and [OIII] 52 um, we aim to resolve photometric degeneracies of these observations, measure precise redshifts and asses the prexence of thermal dust emission. These observations will constrain star formation rates, metallicities, and the dust and gas dynamics of these sources, possibly providing critical insights into the nature of galaxies in the reionization era.


| | | | | | |
|---|---|---|---|---|---|
| **SCIENCE CATEGORY:** | Cosmology and the High Redshift Universe | | | | |
| **ESTIMATED 12-M TIME:** | **11.2 h** | **ESTIMATED 7-M TIME:** | **9.4 h** | **ESTIMATED TP TIME:** | **18.8 h** |
| **DUPLICATE OBSERVATION JUSTIFICATION:** | | | | | |

**REPRESENTATIVE SCIENCE GOALS (UP TO FIRST 30)**

| SCIENCE GOAL | CLUSTER | POSITION (ICRS) | BAND | ANG.RES.(") | LAS.(") | 12m time (hrs) | 7m time (hrs) | TP time (hrs) | Number of sources |
|---|---|---|---|---|---|---|---|---|---|
| Abell S1063 | Abell S1063 | 22:48:56, -44:34:16 | 7 | 0.200 | 24.000 | 11.2 | 9.4 | 18.8 | 5 |
| Total # Science Goals : 1 | | | | | | | | | |

| | | | | | |
|---|---|---|---|---|---|
| **SCHEDULING TIME CONSTRAINTS** | NONE | **TIME ESTIMATES OVERRIDDEN ?** | No | **JOINT PROPOSAL?** | No |

# 1 Scientific justification

## 1.1 High-Redshift JWST Galaxies

The launch of the James Webb Space Telescope (JWST) has spearheaded a great scientific effort to discover and study the Universe's earliest galaxies. However, within its first months of operation, JWST photometrically detected dozens of $z > 10$ galaxy candidates, suggesting an overabundance of UV-bright galaxies in the early Universe than was previously predicted. These results placed significant stress on our understanding of galaxy formation in the standard cosmological model ($\Lambda$CDM), suggesting the possibility of negligible dust attenuation at very high redshifts (Ferrara+2023, Mason+2023) or a greater efficiency of converting gas into stars in the early Universe. These initial photometric results could also predict a shift toward the formation of more massive stars in the early Universe, resulting in a "top-heavy" initial mass function (IMF) (Bromm+2001, Sharda+2022, Larson 1998). Conversely, this overabundance could also suggest that there exists an unmitigated foreground contaminant resulting in a larger-than-expected sample of high-z JWST galaxies (Finkelstein+2023). Given the consequences of these results, it is important to ensure the robustness of these high-z measurements before invoking new physics.

Over the next year, multiple follow-up efforts were launched to spectroscopically confirm the redshifts suggested via JWST photometry. Careful analysis revealed that many of these high redshift galaxies are actually dusty, low redshift interlopers (Arrabal+2023, Zavala+2023). This confusion results from a degeneracy of the observed colors of high-redshift galaxies and their lower-redshift counterparts. Dust glows brightly in the IR and therefore reddens the spectral energy distribution of galaxies sufficiently enough that they may be falsely characterized as an older stellar population (Steidel+1996a). In particular, a Lyman-$\alpha$ (Ly$\alpha$) break, as is common for $z > 12$ galaxies, could also be interpreted as the Balmer and 4000Å breaks of lower-z galaxies combined with dust attenuation and/or strong nebular emission (Zavala+2023). In other words, dusty star-forming galaxies (DSFGs) at $z \lesssim 6-7$ can mimic the JWST NIRCam colors of $z > 10$ Lyman-break galaxies (LBGs). This effect is most pronounced in NIRCam's shorter wavelength filters.

As stated above, DSFGs masquerading as LBGs has non-negligible effects on our understanding of stellar and galactic formation, and places significant strain on $\Lambda$CDM. However, this confusion can be eased via spectroscopic observations of high-z candidates. Spectroscopic measurements break photometric degeneracies and allow us to precisely measure the redshifts of observed galaxies while also providing characterizing information about the galaxy, such as it's metallicity and star formation rate. Furthermore, the mere detection of thermal dust emission in the spectroscopic continuum can serve as a secondary confirmation of the redshift, as we expect galaxies of $z \gtrsim 6$ to have little to no dust signatures (Gall+2011, Mancini+2015). In other words, we do not expect to see old stellar characteristics in early-type galaxies.

## 1.2 FIR Fine-Structure Emission

Atomic fine structure emission has proven to be a valuable tool in spectroscopic confirmation of sources as well as a powerful probe of the ISM. Most notably, [CII] 158$\mu$m is typically the dominant cooling line seen in the far-infrared (FIR) (Malhotra+2011), making it useful in the study of high-redshift galaxies. [CII] 158$\mu$m has been used as a tracer of star formation rates (SFR) in these high-z galaxies, and more recently of cold gas reservoirs (Zanella+2018, Vizgan+2022a, 2022b, Gurman+2024). Doubly ionized oxygen [OIII] 88$\mu$m is typically the third brightest cooling line in the FIR, following [OI] 63$\mu$m, and has proven to be an excellent probe of gas phase metallicity and density of HII regions within high-redshift galaxies (Brauher+2008, Ferkinhoff+2010). The line intensity of [OIII] 88$\mu$m has been found to be larger than that of [CII] at times, particularly at high

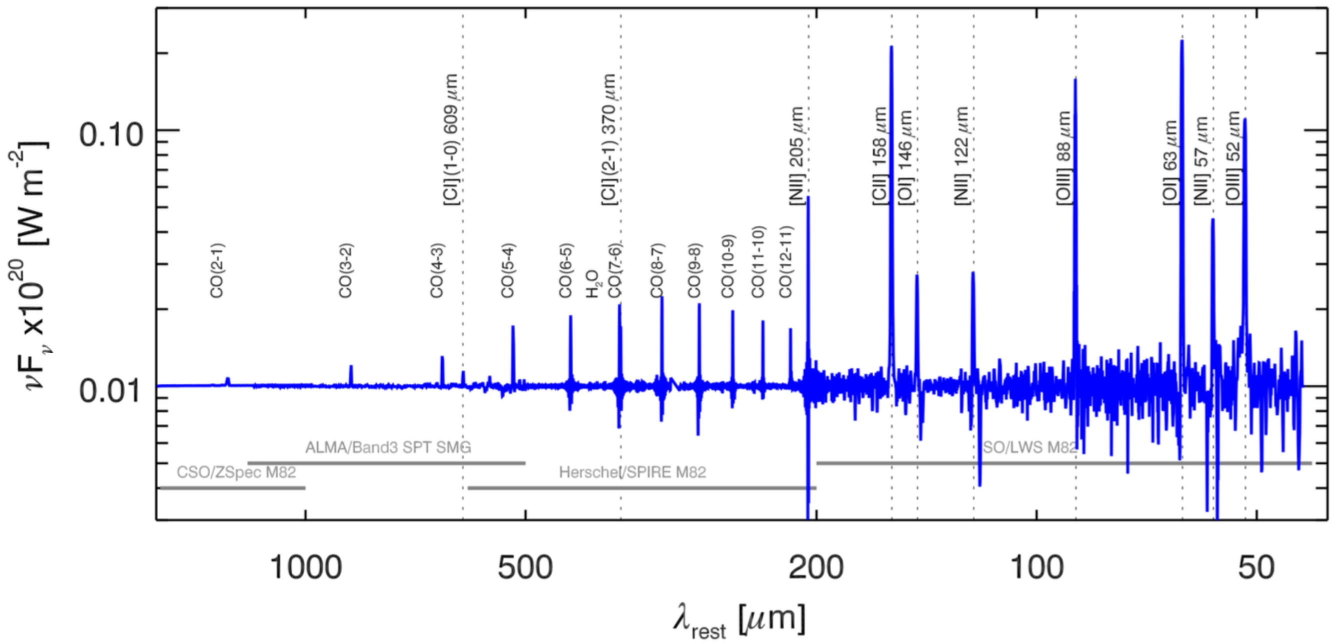


Figure 1: The far-infrared spectrum of the local starburst galaxy M82. The brightest emission features belong to [CII] 158$\mu$m, [OI] 63$\mu$m, and the doublet [OIII] lines at 88$\mu$m and 52$\mu$m, respectively. The [CII] 158$\mu$m and [OIII] 52$\mu$m lines are the central targets of this proposal. Other notatble features include the triplet [NII] 205$\mu$m, 122$\mu$m, and 57$\mu$m lines. *(Credit: Joaquin Vieira.)*

redshifts, making [OIII] a bright and promising tracer of reionization-era galaxies (Harikane+2020b). Unfortunately, at high densities ($n_H \geq 10^2 - 10^3 \mathrm{cm}^{-3}$) collisional de-excitations become important and a degeneracy arises between the observed luminosity drop could result from either an increase in density or a decrease in metallicity (Yang+2021). However, the [OIII] 52 $\mu$m line has the potential to break these degeneracies (Jones+2020, Yang & Lidz 2020). The ratio of the luminosities of the 52 and 88$\mu$m lines ($L_{52}/L_{88}$) depends on collision de-excitations, making [OIII] 52 $\mu$m a powerful density diagnostic (Draine 2011) and probe of the high-redshift ISM. Additionally, [OIII] 52 $\mu$m is the fourth brightest FIR cooling line, making it a very detectable line in spectroscopic follow-ups.

## 1.3 Goals of this project

With an increase it photometric detections of potential $z > 10$ galaxies comes the increasing need to spectroscopically confirm and characterize these galaxies given their impact on theoretical predictions on galactic formation in the early Universe. This can easily be done through short follow-up observations of these sources, looking for the presence of these bright FIR cooling lines as a means to spectroscopically confirm their redshifts while also gathering useful information about their metallicity, gas and dust reservoirs, and star-formation rates.

We propose follow-up observations of the five, recently discovered, high-redshift galaxy candidates ($15.9 < z < 18.6$) detected by JWST observations from the GLIMPSE survey (Korkorev+2024). These sources originate from the strongly gravitational lensed galaxy cluster Abell S1063 (AS1063). These candidates experience moderate magnification ($\mu \sim 2$). We aim to spectroscopically confirm these sources using a detection of either the [CII] 158$\mu$m (at low redshift) or [OIII] 58$\mu$m (at high redshift) line and the detection of dust within the measured continuum. The presence of a thermal dust continuum will place significant constraints on the likelihood of these candidates being true high-z galaxies, which will then inform our conclusions on their identification as either DSFGs or LBGs and place constraints on the gas and dust dynamics within these galaxies.

## 2 Description of observations

We make the assumption that the five $z \gtrsim 16$ galaxy candidates described in (Korkorev+2024) are actually dusty $z \sim 5$ galaxies. Their photometric detection in JWST signals the confirmed presence of a galaxy. We therefore expect to observe some emission line(s). The question becomes its characterization. This characterization hinges upon the detection (or lack there of) of a dust continuum and the identification of FIR cooling emission lines.

The assumption that the candidates are dusty, low-z interlopers informs our observing strategy. Typical star forming galaxies at redshifts $z \approx 4-6$ are observed with [CII] 158$\mu$m line flux densities of $0.1-1$mJy (Le Fèvre+2020, Béthermin+2020, Lagache+2018, Capak+2015). Therefore, a sensitivity (RMS) of 50$\mu$Jy would easily yield a $5\sigma$ [CII] detection of 0.25mJy, which fits nicely at the lower end of the expected line strength spectrum for similar DSFGs. This would give us significant confidence in a single line detection should the candidates experience larger dust attention.

The [CII] 158$\mu$m line at $z \sim 5$ could also appear to be the [OIII] 52$\mu$m line at $z \sim 17$. At these redshifts, either line would be clearly visible in ALMA's Band 7 receiver with an RMS of 50$\mu$Jy. We will observe over $\sim 334 - 358$GHz, with a bandwidth of approximately 24GHz. Given a sensitivity of 50$\mu$Jy across 24GHz, we require an estimated total observing time 1.25 days (including overhead). We chose a 24GHz bandwidth to ensure we cover as much of the high-z SED fit error as possible from Korkorev+2024, so that if the line truely is high-z [OIII] then we should be able to detect it roughly according to it's photo-z measured error. Furthermore, 24GHz was chosen to ensure enough of the continuum is captured to make scientific arguments on dust properties of these candidates.

ALMA data will be reduced and calibrated using the Common Astronomy Software Applications package (CASA; CASA Team 2022) in the standard manner. Continuum maps will be generated down to the $2\sigma$ level and scrutinized for the presence of thermal dust emission. Should a dust continuum be detected we will make the more realistic conclusion that the measured line is from [CII] 158$\mu$m and compute a spectroscopic redshift under this assumption. However, should no continuum be detected then we make the converse assumption that the measured line is the highly redshifted [OIII] 52 $\mu$m line. These lines and the strength of the dust continuum will then be used to constrain star formation rates, metallicity, and the dust and gas dynamics within their respective galaxies.

• Arrabal *et al.* 2023, Nature 622, 707-711 • Brauher *et al.* 2008, ApJS 178, 280-301 • Béthermin *et al.* 2020, A&A 643, A2 • Bromm *et al.* 2001, ApJ 552, 464-472 • Capak *et al.* 2015, A&A 609, A130 • CASA Team 2022, PASP 134, 114501 • Draine 2011, Princeton University Press • Ferkinhoff *et al.* 2010, ApJL 714, L147-L151 • Finkelstein *et al.* 2023, ApJ Letters 946, L13 • Ferrara *et al.* 2023, MNRAS 522, 3986-3991 • Gall *et al.* 2011, Astronomy and Astrophysics Reviews 19, 43 • Gurman *et al.* 2024, ApJ 965, 179 • Harikane *et al.* 2020b, ApJ 896, 93 • Jones *et al.* 2020, ApJ 903, 150 • Korkorev *et al.* 2024, *arXiv:2411.13640* • Lagache *et al.* 2018, A&A 609, A130 • Larson 1998, MNRAS 301, 569-581 • Le Fèvre *et al.* 2020, A&A 643, A1 • Malhorta *et al.* 2001, ApJ 561, 766-786 • Mancini *et al.* 2015 MNRAS 451, L70-L74 • Mason *et al.* 2023, MNRAS 521, 497-503 • Sharda *et al.* 2022, MNRAS 509, 1959-1984 • Steidel *et al.* 1996a, ApJ Letters 462, L17 • Vizgan *et al.* 2022a, ApJ 929, 92 • Vizgan *et al.* 2022b, ApJL, 939, L1 • Yang *et al.* 2021, MNRAS 504, 723-730 • Yang & Lidz 2020, MNRAS 499, 3417 • Zanella *et al.* 2018, MNRAS 481, 1976-1999 • Zavala *et al.* 2023, ApJ Letters, 943 L9

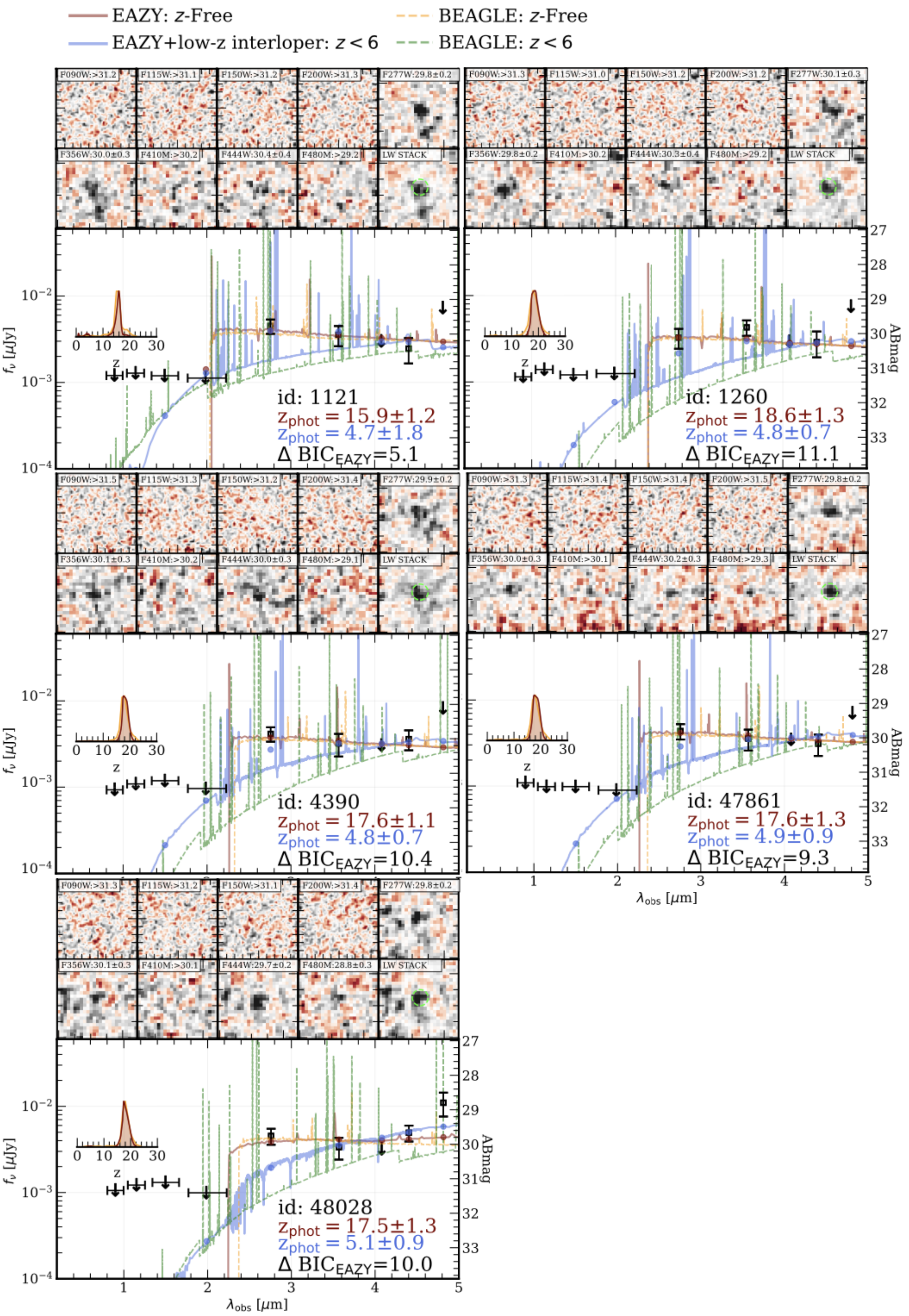


Figure 2: *(Figure 2 from Korkorev+2024.)* The five $z \geq 16$ candidate galaxies discovered by GLIMPSE proposed for follow-up observation using ALMA in this proposal. For each source, the top panels display a $1''.0$ cutout of the NIRCam filters used and a detection (F277W+F365W+F444W) LW stack with a $D = 0''.2$ aperture overlaid in lime green. The bottom panel of each source contains high and low-z SED fits. Two SED models are compared here: EASY and BEAGLE. The insert panel shows the $p(z)$ for both EAZY and BEAGLE fits given a free redshift parameter space.

# None Assigned

SG : 1 of 1 Abell S1063 Band 7

Science Goal Parameters

| Ang.Res. | LAS | Requested RMS | RMS Bandwidth | Rep.Freq. | Cont. RMS | Cont. Bandwidth | Poln.Prod. |
|---|---|---|---|---|---|---|---|
| 0.2000" | 24.0" | 50 µJy, 12.7 mK | 20741.022 km/s, 24 GHz | 346.898000 GHz | 47.905 µJy, 12.2 mK | 25.797 GHz | XX |

Use of 12m Array (43 antennas)

| t_total(all configs) | t_science(C-5) | t_total(C-2) | Imaged area | #12m pointing | 12m Mosaic spacing | HPBW | t_per_point | Data Vol | Avg. Data Rate |
|---|---|---|---|---|---|---|---|---|---|
| 11.2 h | 3.1 h | 2.3 h | 5.6 " | 5 | offset | 16.8 " | 574.1 s | 53.5 GB | 1.9 MB/s |

Use of ACA 7m Array (10 antennas) and TP Array

| t_total(ACA) | t_total(7m) | t_total(TP) | Imaged area | #7m pointing | 7m Mosaic spacing | HPBW | t_per_point | Data Vol | Avg. Data Rate |
|---|---|---|---|---|---|---|---|---|---|
| 18.8 h | 9.4 h | 18.8 h | 9.6 " | 5 | offset | 28.8 " | 705.1 s | 7.2 GB | 0.2 MB/s |

Spectral Scan Setup

| Start Frequency | END Frequency | Bandwidth | Resolution | Vel. Bandwidth | Vel. Resolution | Res. El. per FWHM | RMS |
|---|---|---|---|---|---|---|---|
| 334.000 GHz | 358.000 GHz | 1.875 GHz | 15.625 MHz | 1620 km/s | 13.503 km/s | 14.8 | 49.67 µJy, 12.6 mK |

5 Targets

| No. | Target | Ra,Dec ( ICRS ) | V,def,frame --OR--z |
|---|---|---|---|
| 1 | 1-ID1121 | 22:48:56, -44:34:16 | 0.00 km/s,lsrk,RADIO |
| 2 | 2-ID1260 | 22:48:56, -44:34:14 | 0.00 km/s,lsrk,RADIO |
| 3 | 3-ID4390 | 22:48:51, -44:33:47 | 0.00 km/s,lsrk,RADIO |
| 4 | 4-ID47861 | 22:48:45, -44:33:09 | 0.00 km/s,lsrk,RADIO |
| 5 | 5-ID48028 | 22:48:46, -44:33:10 | 0.00 km/s,lsrk,RADIO |

Expected Source Properties

| | Peak Flux | SNR | Linewidth | RMS (over 1/3 linewidth) | linewidth / bandwidth used for sensitivity | Pol. | Pol. SNR |
|---|---|---|---|---|---|---|---|
| Line | 25.00 mJy | 28.5 | 200 km/s | 876.03 µJy, 222.... | 0.01 | 0.0% | 0.0 |
| Continuum | 50.00 uJy | 1.0 | | | | 0.0% | 0.0 |

Dynamic range (cont flux/line rms): 0.1

Spectral scan tunings (frequencies on Sky)

| Tuning | Spw1(GHz) | Spw2(GHz) | Spw3(GHz) | Spw4(GHz) |
|---|---|---|---|---|
| 1 | 334.937500 | 336.640625 | 346.937500 | 348.640625 |
| 2 | 338.343750 | 340.046875 | 350.343750 | 352.046875 |
| 3 | 341.750000 | 343.453125 | 353.750000 | 355.453125 |
| 4 | 345.156250 | 346.859375 | 357.156250 | 358.859375 |

## Sensitivity Comments

Note that one or more of the S/N estimates are < 3. Please double-check the RMS and/or line fluxes entered and/or address the issue belo
Note that the bandwidth used for sensitivity is larger than 1/3 of the linewidth.
The S/N achieved for a resolution element that allows the line to be resolved will be lower than that reported.

## Justification for requested RMS and resulting S/N (and for spectral lines the bandwidth selected) for the sensitivity calculation.

We opperate under the assumption that these high-z candidates are actually dusty star-forming interlopers. We therefore assume that we will see a [CII] 158um line at low-z rather than a highly redshifted [OIII] 52um. Typical flux densities of [CII] 158um for standard star-forming galaxies of redshifts z=4-6 are 0.1-1mJy. Setting our RMS to 50uJy across the band will yeild a 5-sigma detection of [CII] at ~250uJy, which is in line with lower abundances for these types of galaxies, so that even if the galaxy has relatively little [CII] we should be able to make a confident detection regardless. 50uJy also provides ample sensitivity to any thermal dust emission.

## Justification of the chosen angular resolution and largest angular scale for the source(s) in this Science Goal.

The largest angular size is taken from Korkorev+2024, where they measure an effective radius of each source to be ~0.1-0.2 arcmin. We set it to the largest here. The requested angular resolution corresponds roughly to the lowest angular resolution possible with the Band 7 receiver.

## Justification of the correlator set-up with particular reference to the number of spectral resolution elements per line width.

The expected line-widths are ~200km/s for [CII] detection. We therefore select 1.875 GHz bandwidth (~1800 km/s at the requisite frequency range) and select the lowest possible spectral resolution for the corresponding bandwidth.

## Justification for single polarisation.

We are interested in total intensities for the lines measured and the continuum. We wish to spectroscopically identify and characterize these galaxies, rather than make polarization arguments about their contents. Our science, therefore, can be done using single polarization.