The environment of early supermassive black holes: ALMA observations of a flagship field

2017.1.01606.S

ABSTRACT

Theory predicts that supermassive black holes at z>6 should form and evolve within the densest environments at that time. These environments are expected to be traced by large galaxy overdensities whose observational evidence is still controversial.
We propose a 7-pointing ALMA mosaic at 1.2mm around the z=6.31 QSO SDSS J1030+0524, complemented by another deep pointing centered on the QSO. Among all the ~200 QSO known at z~6, the field around SDSS J1030+0524 shows the most convincing evidence for both a large- and small-scale galaxy overdensity aroud it, and features the best multi-band coverage for a prompt identification and physical characterization of the companion galaxies.
Our goals are: i) detect [CII]-emitting companions at the QSO redshift and determine their physical properties; ii) determine the physical properties of the QSO host. Depending on the detected number of companion galaxies, our observations will eventually reveal one of these long-sought overdensities or highlight a major problem in our understanding of early BH (and structure) formation.
Finally, the proposed observations will constitute "per se" a deep ALMA legacy survey.

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ESTIMATED 12M TIME:	**11.8 h**	**ESTIMATED ACA TIME:**	**0.0 h**	**ESTIMATED NON-STANDARD MODE TIME (12-M):**	**0.0 h**
CO-PI NAME(S): (Large & VLBI Proposals only)					
CO-INVESTIGATOR NAME(S):	Simona Gallerani; Marco Mignoli; Barbara Balmaverde; Paramita Barai; Andrea Comastri; Cristian Vignali; Marcella Brusa; Livia Vallini; Eros Vanzella; Andrea Pallottini; Andrea Ferrara; Marcella Massardi; Rosita Paladino; Nico Cappelluti; Colin Norman; Giorgio Lanzuisi; Riccardo Nanni; Giovanni Zamorani				
DUPLICATE OBSERVATION JUSTIFICATION:	The z=6.31 QSO SDSS~J1030+0524 has been already observed by ALMA in band 6 (program 2015.1.0111.S, PI F. Walter). The data became public on 14/04/2016. We retrieved the archival data and verified that the angular resolution (1" FWHM) and sensitivity (continuum rms ~50 uJy/beam, [CII]-line rms ~680 uJy/beam over a 40 km/s bandwidth) are not sufficient to our goals, as we need angular resolution as good as 0.3" to separate companion galaxies from the QSO emission, and a factor of ~4 better sensitivity to detect companion objects down to L_[CII]~1e8 L_sun and detect the host of the QSO itself (only a marginal detection in the continuum is visible in the archival data).				

REPRESENTATIVE SCIENCE GOALS (UP TO FIRST 30)

SCIENCE GOAL	POSITION	BAND	ANG.RES.(")	LAS.(")	ACA?	NON-STANDARD MODE
mosaic	ICRS 10:30:27.1019, 05:24:54.955	6	0.400 - 0.200	1.000	N	N
QSO	ICRS 10:30:27.1019, 05:24:54.955	6	0.400 - 0.200	1.000	N	N
Total # Science Goals : 2						

SCHEDULING TIME CONSTRAINTS	NONE	**TIME ESTIMATES OVERRIDDEN ?**	No

1 Scientific justification

1.1 Rationale.
The existence of supermassive black holes (SMBHs) with $M_{BH} \sim 10^9 M_\odot$ powering luminous QSOs at $z \sim 6$ and beyond, represents a persistent challenge for extragalactic astronomy. Theory strongly argues that these objects must have formed within the most massive dark matter halos ($M_{halo} \sim 10^{12-13}\ M_\odot$) situated in the most overdense regions of the early Universe, where the amount of gas available and fueling efficiency are highest (Koushiappas+04, Di Matteo+17, Barai+17). Within these environments, high accretion rates can indeed be triggered and sustained by both frequent mergers of proto-galaxies and possibly by the steady flows of cold gas from which proto-galaxies can form. Such early large scale structures (LSSs), whose cores would eventually evolve into local massive galaxy clusters (Overzier+09, Angulo+12), are expected to be traced by significant galaxy overdensities, that may extend up to 10 physical Mpc (pMpc) from the QSO (Overzier+09, Di Matteo+11). The entity and observability of these overdensities, however, may be affected by the negative feedback produced either by SNe winds (Costa+14) or by the QSO itself (Maiolino+12, Cicone+15). *Currently, observations lag behind theoretical modeling, and there is still no direct measurement of the environment around early SMBHs.* The attempts to directly measure these overdensities have started since the discovery of high-z QSOs, mainly by selecting Lyman Break Galaxy (LBG) and Lyman Alpha Emitter (LAE) candidates at the QSO redshift. Yet, these heroic efforts did not produce any conclusive results (Kim+09, Husband+13,+15, Banados+13, Simpson+14, Mazzucchelli+17)

Recently, we found evidence for large-scale (up to $\sim$ 4 projected pMpc) overdensities of LBG candidates around four luminous $z \sim 6$ QSOs (at 3.7σ significance level for the four fields combined), that we selected through wide-field (25'x25') deep ($z_{AB} \sim 25$) optical imaging at the Large Binocular Telescope (Morselli+14). The field around the $z = 6.31$ QSO SDSS J1030+0524 (hereafter J1030), was found to be the most overdense, reinforcing the results of previous small-scale studies with ACS/HST (Stiavelli+05, Kim+09). In 2016 we obtained deep (Y_{AB}=24.5, J_{AB}=24) near-IR imaging of the J1030 field with WIRCAM ($21' \times 21'$ FoV) at the CFHT. Using these new observations plus archival Spitzer/IRAC data, we pushed the selection of $z\sim6$ galaxy candidates to fainter fluxes, measured photometric redshifts for high-z sources, and improved the rejection of contaminants, reinforcing the large scale overdensity estimate (now $>4\sigma$; Balmaverde+17). Finally, we were also able to investigate smaller scales around the QSO through a 6.4hr MUSE (1'x1' FoV) archival pointing: we measured the redshifts of more than 100 objects and discovered two faint LAEs ($L_{Ly\alpha}\sim 1.5-2\times10^{42} erg\, s^{-1} \rightarrow SFR \sim 1.4-1.8\ M_\odot/yr$; Kennicutt98) at z=6.219 and z=6.335 – i.e. at 5 and 2.5 pMpc from the QSO, respectively – that likely reside in its LSS and are invisible at any other wavelength (see Fig.1 *left*). This *spectroscopic* result is very promising and again points towards a galaxy overdensity around SDSS J1030[1].

A new and major result on the environment of high-z SMBHs was obtained by Decarli+17, who observed a sample of 25 QSOs at $z \sim 6$ with ALMA (at a resolution of ∼0.4”-1” at 1.2mm) and, for four of them, discovered a [CII]158μm-emitting companion at the same redshift ($\Delta z < 0.01$) and with projected separations < 70 kpc. At least some of these companions are not detected at any other wavelength (likely because of heavy dust extinction and low luminosity), so that only ALMA could discover them. The companion abundance greatly exceeds (by >2 dex) what is expected from the average density of [CII] emitters at $z > 6$ (e.g. Aravena+16a). This is strong evidence for galaxy overdensities around high-z QSOs, as expected from theoretical models.

We recently performed a cosmological simulation to follow the growth of a $10^9 M_\odot$ BH powering a $z \sim 6$ QSO and considered different physical prescriptions of AGN feedback on its environment (Barai+17). One of the main results of this work is that we expect the central QSO to be surrounded

[1] albeit with low significance: we submitted a proposal to ESO P100 to add four MUSE pointings on J1030.

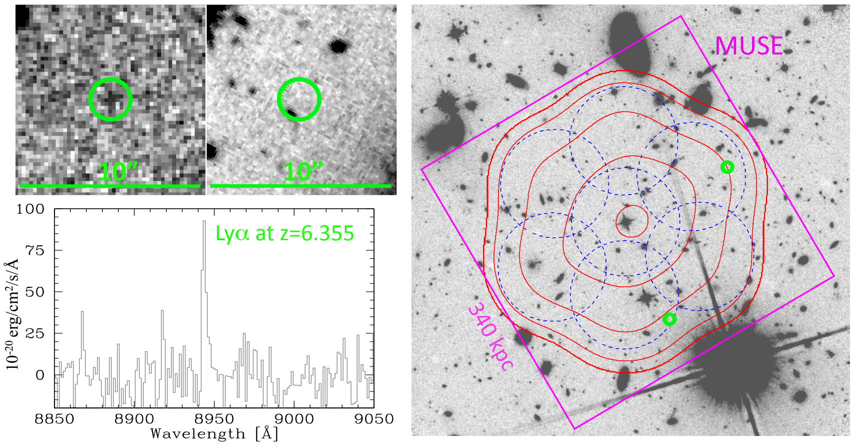

Figure 1: *Left.* Cutouts and spectrum of one of the two $z\sim6.3$ LAEs discovered by MUSE. The cutouts show the MUSE image sliced around the $Ly\alpha$ emission and the HST F160W image, respectively. *Right:* Layout of the proposed ALMA pointings (blue dashed circles; diameter=beam FWHM) and [CII]-sensitivity map (red contours) overplotted to the HST F160W image. The contours (from inside out) correspond to an rms of 0.17, 0.25, 0.4, 0.75 and 1.2 mJy/beam per 40 km/s bandwidth. The magenta square shows the 1'x1' MUSE FoV. The two LAEs associated to the QSO LSS are shown in green.

by $\sim$ 1-10 star-forming (SFR$\sim 10^{-1} - 10^{2} M_{\odot} yr^{-1}$), metal-rich (0.1-0.5 $Z_{\odot}$) galaxies, depending on the AGN-feedback prescription adopted. Given the physical properties of these galaxy (SFR, Z), we have computed their expected [CII] luminosity (L_{CII}) according to eq. 1 in Yue+15, based on the modeling developed within our group (Vallini +13,+15, Pallottini+17). This can be seen in Fig. 2 ($left$), where we show the galaxy companions [CII] luminosity vs projected separation from the QSO. Our simulations predict that, at the angular resolution and line sensitivity of Decarli+17, many nearby companions are blended with the QSO, and only $\lesssim 1$ well-separated companion per field is expected (vs 0.16 observed). The comparison with current data is therefore encouraging, and we expect that, with a 4-5 times higher sensitivity and larger area, more [CII] emitting galaxies would emerge out of the noise.

1.2 Why observing the J1030 field?

Among the $\sim$200 QSOs discovered at $z > 5.7$[2] ($\sim$ 60% observable with ALMA), we consider SDSSJ1030+0524 the best target to perform a deep ALMA observation and search for [CII] emitters around it. The reasons are as follows: i) it shows the most promising overdensity of LBG *candidates* among *all* $z \sim 6$ QSO fields, both on large (4 pMpc, our LBT+CFHT data) and small (<600 kpc, HST/ACS; Stiavelli+05, Kim+09) projected scales. On even smaller scales, further indications of a galaxy overdensity, come from the MUSE spectroscopic detection of two LAEs at < 5 radial pMpc from the QSO. ii) it features the best multi-band coverage of *all* $z \sim 6$ QSO fields, spanning from radio to X-ray data, and allowing for a prompt identification and physical characterization of any detected source. In fact, it is the only one observed by MUSE and features the deepest available optical and near-IR imaging (HST ACS+WFC3; public data, see Table 2). Furthermore, it is the $z > 6$ QSO with deepest X-ray coverage, based on our 500ks Chandra Large Program (PI Gilli; 4th deepest X-ray survey field to date; observations in progress, preliminary data analysis ongoing).

1.3 Proposed observations and immediate objectives.

We propose a 7-pointing mosaic to cover the entire $\sim$arcmin^2 around the QSO, i.e. the field observed by MUSE, down to 1.2mJy/beam rms over a 40 km/s bandwith for [CII] detection. The pointing layout is similar to what has been used by Walter+16 and Aravena+16b to observe the HUDF with ALMA in band 6. We will also add a deeper single pointing centered on the QSO, to reach a sensitivity of < 0.17 mJy/beam rms per 40 km/s bandwidth in the inner few square arcsecs. The rms contours of the proposed observations are shown in Fig.1 ($right$). They will allow detection of [CII] at z=6.31 down to $L_{[CII]} = (1.4, 2, 10) \times 10^{8}\ L_{\odot}$ within radii of 18, 80 and 170 kpc from the QSO, respectively. With the adopted resolution of $\sim 0.3''$, we will be able to separate sources on the sky with projected distances down to 1 kpc, which is not possible with the existing ALMA archival data

[2]See https://users.obs.carnegiescience.edu/~ebanados/high-z-qsos.html for an updated compilation.

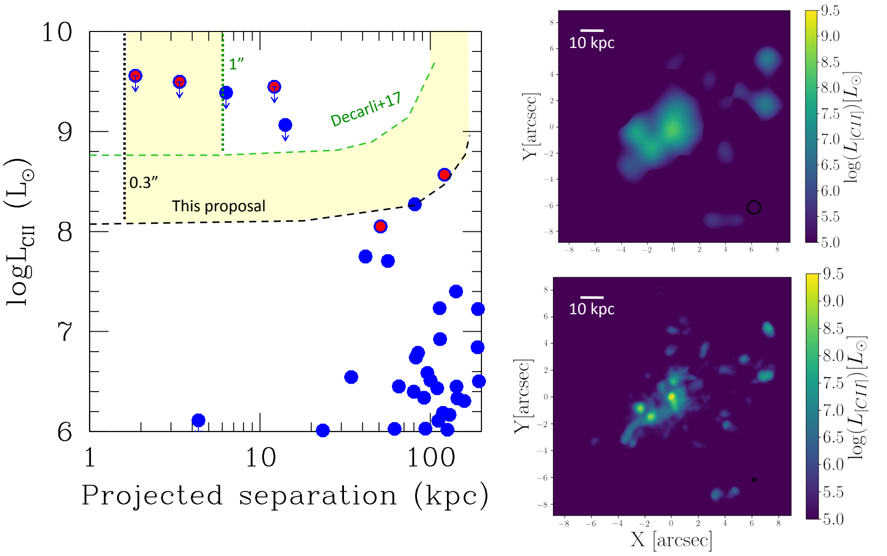

Figure 2: *Left:* [CII] luminosity vs projected separation from the QSO for the SF galaxies in our simulation box (blue dots). Red dots mark active BHs with $L_X > 5 \times 10^{43}$ erg/s detectable by our 500ks deep Chandra observation. The green and black curves show the 5σ detection limit for [CII] emission at z=6.3 and angular resolution of the archival data and of our proposed mosaic, as labeled. The yellow area shows the region of gain in angular resolution and *rms* wrt archival data. *Right:* Simulated [CII] luminosity maps around a z=6.3 QSO, smoothed at 1” (top) and 0.3” (bottom) resolution. SF companion galaxies and gas clumps at < 5.7 projected kpc from the QSO are all blended at 1” resolution.

(1″ FWHM = 5.7 kpc; see Fig. 2). Our main science goals are: i) detect [CII]-emitting companions at the QSO redshift and study their physical properties, and ii) investigate the physical properties of the QSO host. The proposed observations will also represent *per se* a legacy mm survey to investigate galaxy evolution over cosmic time. The immediate objectives associated to these science goals are as follows:

Galaxy overdensity. We will identify galaxies associated to the QSO LSS through [CII] detection and probe the overdensity around the QSO. Given the chosen spectral setup and mosaic FoV we will be able to identify objects within $\Delta z = \pm 0.05$ (± 2.8 pMpc radial) from the QSO. Based on the requested sensitivity, (see Fig.2 $left$) we expect to find up to $\sim$7 companions around J1030. Since the number and physical properties of the companions depend on the adopted AGN feedback prescriptions, especially at $\lesssim$20 kpc separations from the QSO (these objects are indeed plotted as upper limits in Fig.2 $left$), ALMA data will provide the first indications ever on how early SMBHs affect their environment. Should we detect NO companions, this would mean that either some form of extreme AGN feedback is at play, or that we are still far from understanding early BH formation.

If detected, we will also measure the physical properties of the companion galaxies. The [CII]-line and continuum detections will be used to estimate SFR and dust masses. The deep optical-through mid-IR coverage available in the field will allow us to perform SED fitting and get stellar masses. The combination of ALMA, sensitive to metals- and dust-rich systems, and MUSE, sensitive to dust-poor LAEs, will provide a complete census of companion galaxies around the QSO. Thanks to our deep X-ray imaging we will search for the presence of companions hosting moderately-luminous AGN down to $L_X = 5 \times 10^{43}$ erg/s (see Fig.2 $left$). Our simulation predicts that $\approx 3-4$ galaxy companions should contain BHs with $M_{BH} \sim 10^7$ $M_\odot$ nearly accreting at the Eddington limit, hence powering AGNs with $L_X \sim 10^{44}$ erg/s. The combined detection of [CII] and X-ray emission from even a single source would represent a real breakthrough for our understanding of the SMBH formation process, as it would be the first discovery of a $\sim 10^7$ $M_\odot$ BH at $z > 6$.

QSO host. We will measure the dust content, SFR and [CII] emission of the host. Our observations have best sensitivity at the QSO position, where they reach 0.16 mJy/beam rms over a 40 km/s bandwidth for the [CII] line and 11.2 μJy/beam rms in the continuum. These values are a factor of > 4 better than what is available from the archival band 6 observation (~ 8 min on-source time). The archival data went public a week before this deadline: we downloaded and analyzed the data, and found that the QSO is only marginally detected at $\approx 3\sigma$, i.e. $f_{QSO} \approx 150\mu$Jy in the continuum. Should this be the true flux density, we will detect the QSO continuum emission at $> 13\sigma$ (we do not expect significant flux losses because of the increased resolution since $z > 6$ QSO hosts have

Proj.dist[a] (kpc)	Area (arcmin^2)	Line sensitivity $rms^b_{[CII]}$	$L^c_{[CII]}$	Continuum sens. $rms^d_{1.2}$	L^e_{FIR}
18	0.009	0.17	1.4	11	1.3
80	0.17	0.25	2.0	17	2.0
120	0.39	0.40	3.2	27	3.1
160	0.69	0.75	6.4	48	5.5
170	0.78	1.20	10.0	78	9.0

Table 1: Summary of the proposed observations. Notes: [a]Projected distance from the QSO. [b]In mJy/beam over a 40 km/s bandwidth. [c]5σ luminosity limit for [CII] detection at z=6.3 (assuming a line FWHM of 200 km/s) in units of 10^8 $L_\odot$. [d]In μJy/beam. [e]5σ limit on FIR luminosity derived from $rms_{1.2}$ following Eq.1 of Omont+13. In units of 10^{11} $L_\odot$.

sizes comparable with the requested beam of 0.3"; Venemans+16,+17). We will also investigate the presence of extended emission on scales <5.7 kpc (i.e. <1") that could not be seen in the archival data. For instance, we will search for outflow signatures, similar to those found in the well known z=6.42 QSO SDSS J1148+5251 (Maiolino+12, Cicone+15) and for [CII] emission from large gas clumps irradiated by the QSO that are merging with its host, as the ones in Fig.2 (*right*).

Survey science. Based on the 1.2mm source counts (Carniani+15, Fujimoto+16) and HUDF results (Aravena+16b; continuum rms of 13 μJy/beam), we expect to detect $\sim$ 10 continuum sources at $> 4\sigma$ in our survey (continuum rms = 17μJy/beam within 14" from the QSO). The counterparts of the mm sources in Aravena+16b have $m_{850LP} < 25.8$ and $m_{F160W} < 23.6$, well within the sensitivity range of our multi-band coverage. We will then perform SED fitting to get the physical parameters of these objects (e.g. stellar masses), check for AGN presence through our deep Chandra data, and get an immediate redshift determination with MUSE. This will represent a legacy sample for galaxy evolution studies.

Band	Instrument	Area[a]	Depth[b]	Ref.
Radio - 1.4GHz	VLA	120	100 μJy	Petric+03
FIR - 1.2mm [CII]	ALMA	0.5	0.73	Decarli+17
FIR - 1.2mm cont.	ALMA	0.5	48	Decarli+17
MIR - 3.5÷24μm	Spitzer	310	2 μJy	archive
NIR - Y,J	CFHT	625	m_{AB}=24	Balmaverde+17
NIR - H_{160}	HST	4.4	m_{AB}=27.5	archive
Opt. Phot. - i_{775},z_{850}	HST	11	m_{AB}=27	Kim+09
Opt. Phot. - r,i,z	LBT	625	m_{AB} ~25-26	Morselli+14
Opt. Phot - r,i,z	Subaru	810	m_{AB} ~26	Diaz+14
Opt. Spec. - em. lines	MUSE	1	2×10^{-18}	archive
X-ray - 0.5-2 keV	Chandra	289	9×10^{-17}	our program

Table 2: Multiband coverage around SDSS J1030+0524. Notes: [a]In arcmin^2. [b]All quoted values refer to the 5σ best sensitivity over the covered area, except for the ALMA observations of Decarli+17 where we quote the best $rms_{[CII]}$ and $rms_{1.2}$ values for comparison with Table 1 (same units). Flux units for MUSE line detections and Chandra detections are $erg/cm^2/s/\AA$ and $erg/cm^2/s$, respectively.

2 Feasibility of the program

We used the `simobs` tool within CASA to simulate a 7-pointing mosaic at 1.2mm to cover an ~arcmin^2 region around the QSO ($\sim$ 9.4hrs in total with overheads), plus a deeper pointing centered at the QSO position ($\sim$ 2.4hrs with overheads). The total exposure time of this program is therefore 11.8hrs. With the adopted spectral setup we will detect the [CII] line in galaxies within $\Delta z = \pm 0.05$ ($\pm$2.8 radial pMpc) from the QSO. The expected rms for [CII] detection are reported in Table 1. By assuming $FWHM_{[CII]}$ =200 km/s, a typical value for the companion galaxies in Decarli+17 and for other high-z galaxies (e.g. Capak+15), we expect to detect the [CII] line in z=6.31 galaxies down to 5σ luminosity limits ranging from $L_{[CII]} = 1.4 \times 10^8$ $L_\odot$ within 18 projected kpc from the QSO, to $L_{[CII]} = 10^9$ $L_\odot$ over the whole mosaic (see Fig. 1 *right* and Table 1).

References. Angulo+12,MNRAS,425,2722 • Aravena+16a,ApJ,833,71 • Aravena+16b,ApJ,833,68 • Balmaverde+17,A&A,submitted: http://oabo.inaf.it/~gilli/balma17.pdf • Banados+13, ApJ, 773, 178 • Barai+17,MNRAS,subm.: http://www.astro.iag.usp.br/~barai/Talks-Posters/Papers_Thesis/Quasar_Outflow_Sim.pdf • Capak+15,Nature,522,455 • Carniani+15A&A,584,A78 • Cicone+15,A&A,575,A14 • Costa+14,439,2146 • Decarli+17,Nature,in press • Diaz+14,MNRAS,442,946 • Di Matteo+17,MNRAS,467,4243 • Fujimoto+16,ApJS,222,1 • Husband+13,MNRAS,432,2869 • Kim+09,ApJ,695,809 • Koushiappas+04,MNRAS,354,292 • Maiolino+12,MNRAS,425,L66 • Mazzucchelli+17,ApJ,834,83 • Morselli+14,A&A,568,A1 • Omont+13, A&A,662,A43 • Overzier+09,MNRAS,394,577 • Pallottini+17,MNRAS,465,2540 • Petric+03,AJ,126,15 • Simpson+14,MNRAS,442,345 • Stiavelli+05,ApJ,622,L1 • Vallini+13,MNRAS,433,1567 • Venemans+16,ApJ,816,37 • Venemans+17,ApJ,837,146 • Walter+16,ApJ,833,67 • Yue+15,MNRAS,450,3829

None Assigned

SG : 1 of 2 mosaic Band 6

Science Goal Parameters

Ang.Res.	LAS	Requested RMS	RMS Bandwidth	Rep.Freq.	Cont. RMS	Cont. Bandwidth	Poln.Prod.	Non-standard mode
0.4000" - 0.2000"	1.0"	250 µJy, 28.4 mK-113.7 mK	40 km/s, 34.6 MHz	1895.376750 G...	16.954 µJy, 1.9 mK-7.7 mK	7.425 GHz	XX,YY	No

Use of 12m Array (43 antennas)

t_total(all configs)	t_science(C43-4,C...	t_total()	Imaged area	#12m pointing	12m Mosaic spacing	HPBW	t_per_point	Data Vol	Avg. Data Rate
9.4 h	5.7 h	0.0 h	28" x 28"	7	15.7 arcsec	22.5 "	2963.4 s	487.2 GB	14.8 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

Spectral Setup : Spectral Line

BB	Center Freq Rest GHz	spw name	Eff #Ch p.p.	Bandwidth	Resolution	Vel. Bandwidth	Vel. Res.	Res. El. per FWHM
1	1895.376750	CII 2P3/2-2P1/2	3840	1875.00 MHz	1.129 MHz	2168.2 km/s	1.305 km/s	153
2	1908.536550	continuum	3840	1875.00 MHz	1.129 MHz	2153.3 km/s	1.296 km/s	154
3	1803.623700	continuum	3840	1875.00 MHz	1.129 MHz	2278.5 km/s	1.372 km/s	146
4	1789.001700	continuum	3840	1875.00 MHz	1128.906 kHz	2297.1 km/s	1.383 km/s	145

1 Target

No.	Target	Ra,Dec (ICRS)	V,def,frame --OR--z
1	1-SDSSJ1030+0524	10:30:27, 05:24:54	288780.94 km/s,hel,RELATIVIS...

Expected Source Properties

	Peak Flux	SNR	Pol.	Pol. SNR	Linewidth	RMS (over 1/3 linewidth)	linewidth / bandwidth used for sensitivity
Line	800.00 uJy	4.2	0.0%	0.0	200 km/s	192.41 µJy, 87.5 mK	5.00
Continuum	0.00 uJy	0.0	0.0%	0.0			

Dynamic range (cont flux/line rms): N/A

1 Tuning

Tuning	Target	Rep. Freq. Sky GHz	RMS (Rep. Freq.)	RMS Achieved
1	1	259.250000	248.4 µJy, 113.0 mK	233.76 uJy - 248.40 uJy

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

[CII]158um line:

We aim at detecting [CII] emission from the star forming (SFR~0.1-100 Msun/yr), metal-rich (0.1-0.5 solar) galaxies that are expected to surround the central z=6.31 QSO. To predict their [CII] luminosity we used Eq.1 in Yue+15(MNRAS,450,3829) based on the modeling developed by Vallini+13(MNRAS,433,1567) and Pallottini+17(MNRAS,465,2540), which combines SFR and metallicity to predict the [CII] emission. Based on our simulations, up to 7 objects within 170 projected kpc from the QSO are expected to have L_[CII]>2e8 Lsun. By assuming a line width of 200 km/s (similar to what is observed for other galaxies at z~5-6 (e.g. Capak+15,Nature,522,455), we expect a [CII] peak flux density of 0.8 mJy for a galaxy at z=6.31 with L_CII=2e8 L_sun.
We then request a sensitivity of 0.25 mJy over a 40 km/s bandwidth to detect the peak line emission at S/N~3.2 and detect the whole line at S/N > 6. Based on the adopted geometry of our 7-pointing mosaic, the on-source time to achieve this sensitivity over a region of 28"x28", is ~49min per pointing. Including overheads, this corresponds to ~9.4hr in total.

Continuum

We will use the spectral regions free from the [CII] line emission to detect the continuum emission of our sources, by integrating over a spectral range of ~7.4 GHz. With the adopted geometry for our mosaic and based on the exposure per pointing needed to achive the requested sensitivity for [CII] detection, we reach a sensitivity of 17 uJy/beam over the inner 28"x28" portion of the mosaic.

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

We require a synthesized beam FWHM of ~0.3 arcsec. This will allow us to separate objects down to 1.8 projected kpc. Significantly poorer resolutions, e.g. FWHM=1" as in the existing archival data of this field, would completely blend the numerous objects expected at <5.7 projected kpc from the QSO. Significantly smaller resolutions will likely resolve out the flux of the QSO host itself, which we aim to detect. Indeed, typical FHWM sizes measured for z~6 QSOs are 0.2-0.4" (Venemans+16,ApJ,816,37, +17,ApJ,837,146).
We note that any resolution in the range 0.2-0.4" is fully acceptable for our goals, which is achievable with a standard array configuration.

Justification for use of Non-nyquist sampling.

We have chosen a 7-pointing mosaic pattern with a spacing equal to 70% of the antenna beamsize since this extends the covered area up to ~1arcmin2, similar to the field covered by MUSE that we want to observe. This non-Nyquist sampling is fine for our goals, since we are not searching for extended structures that need a uniform background sensitivity. We are indeed interested in likely-pointlike sources distributed across our mosaic. A similar, 7-pointing mosaic with spacing equal to 70-75% of the antenna beamsize, has been also used by Walter+16(ApJ,833,67) and Aravena+16(ApJ,833,68) to perform a band6 deep survey in the Hubble Ultra Deep Field.

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

We will use 4 basebands in FDM with a bandwidth of 1.875 GHz and a spectral resolution averaged to 2 km/s. This avoids exceeding the maximum allowed datarate and guarantees an excellent sampling of the line profile (e.g. over ~100 channels) for the brightest lines.

The [CII] 2P3/2-2P1/2 transition will fall in baseband 1.
The other basebands will be used for continuum observations.

None Assigned

SG : 2 of 2 QSO Band 6

Science Goal Parameters

Ang.Res.	LAS	Requested RMS	RMS Bandwidth	Rep.Freq.	Cont. RMS	Cont. Bandwidth	Poln.Prod.	Non-standard mode
0.4000" - 0.2000"	1.0"	220 µJy, 25 mK-100.1 mK	40 km/s, 34.6 MHz	1895.376750 G...	14.95 µJy, 1.7 mK-6.8 mK	7.425 GHz	XX,YY	No

Use of 12m Array (43 antennas)

t_total(all configs)	t_science(C43-4,C...	t_total()	Imaged area	#12m pointing	12m Mosaic spacing	HPBW	t_per_point	Data Vol	Avg. Data Rate
2.5 h	1.5 h	0.0 h	7.5 "	1	offset	22.5 "	5322.0 s	127.8 GB	14.7 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

Spectral Setup : Spectral Line

BB	Center Freq Rest GHz	spw name	Eff #Ch p.p.	Bandwidth	Resolution	Vel. Bandwidth	Vel. Res.	Res. El. per FWHM
1	1895.376750	CII 2P3/2-2P1/2	3840	1875.00 MHz	1.129 MHz	2168.2 km/s	1.305 km/s	153
2	1908.536550	continuum	3840	1875.00 MHz	1.129 MHz	2153.3 km/s	1.296 km/s	154
3	1803.623700	continuum	3840	1875.00 MHz	1.129 MHz	2278.5 km/s	1.372 km/s	146
4	1789.001700	continuum	3840	1875.00 MHz	1128.906 kHz	2297.1 km/s	1.383 km/s	145

1 Target

No.	Target	Ra,Dec (ICRS)	V,def,frame --OR--z
1	1-SDSSJ1030+0524	10:30:27, 05:24:54	288780.94 km/s,hel,RELATIVIS...

Expected Source Properties

	Peak Flux	SNR	Pol.	Pol. SNR	Linewidth	RMS (over 1/3 linewidth)	linewidth / bandwidth used for sensitivity
Line	800.00 uJy	4.7	0.0%	0.0	200 km/s	169.66 µJy, 77.2 mK	5.00
Continuum	0.00 uJy	0.0	0.0%	0.0			

Dynamic range (cont flux/line rms): N/A

1 Tuning

Tuning	Target	Rep. Freq. Sky GHz	RMS (Rep. Freq.)	RMS Achieved
1	1	259.250000	219.03 µJy, 99.6 mK	206.12 uJy - 219.03 uJy

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

In the previous science goal we justified the request of obtaining a mosaic with a sensitivity of 0.25 mJy over a 40 km/s bandwidth to detect the peak emission of the [CII]158um line at S/N~3.2 and detect the whole line at S/N > 6 for galaxies with L_CII>2e8 Lsun at z=6.31. Here we focus on fainter objects and on the detection of the QSO itself, which went undetected in [CII] in the archival pointing and was only marginally detected (at ~3sigma) in the continuum. In order to detect the QSO with high significance we aim at going at least a factor of four deeper than archival data. By adding a pointing with rms=0.22 mJy/beam over a 40 km/s bandwidth, we will get a final sensitivity at the center of the mosaic of ~0.16 mJy/beam over a 40 km/s, which will allow detection of L_CII=1.3 Lsun at z=6.3 (assuming again FWHM=200 km/s).
We used the "simobs" tool in CASA to simulate the response of the mosaic and of the individual pointing, combine them, and get a final rms map. The final, combined rms of the continuum, computed over a 7.4 GHz band, will be 11 uJy/beam, which will allow detection of the QSO host dust continuum with S/N>13 if the tentative archival detection is real.
This additional pointing requires an exposure of 2.5hrs including overheads, bringing the total time request to 11.8hrs.

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

We require a synthesized beam FWHM of ~0.3 arcsec. This will allow us to separate objects down to 1.8 projected kpc. Significantly poorer resolutions, e.g. FWHM=1" as in the existing archival data of this field, would completely blend the numerous objects expected at <5.7 projected kpc from the QSO. Significantly smaller resolutions will likely resolve out the flux of the QSO host itself, which we aim to detect. Indeed, typical FHWM sizes measured for z~6 QSOs are 0.2-0.4"(Venemans+16,+17).
We note that any resolution in the range 0.2-0.4" is fully acceptable for our goals, which is achievable with a standard array configuration.

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

We will use 4 basebands in FDM with a bandwidth of 1.875 GHz and a spectral resolution averaged to 2 km/s. This avoids exceeding the maximum allowed datarate and guarantees an excellent sampling of the line profile (e.g. over ~100 channels) for the brightest lines.

The [CII] 2P3/2-2P1/2 transition will fall in baseband 1.
The other basebands will be used for continuum observations.