■ Scientific Justification

1. The Regulation of the Galaxy Formation due to AGN Outflow

Fundamental relationships exist between the black hole (BH) mass and bulge stellar mass of host galaxies (e.g., Magorrian et al. 1998), and BH mass and velocity dispersion (Ferrarese et al. 2000). One possibility of the strong correlation between black hole and host galaxies is that the energy output of the black hole in its most active ("active galactic nucleus, AGN") phase may be coupled to the gas in the host galaxies.

Although the AGN outflow is often invoked to regulate massive galaxy formation (e.g., Springel et al. 2005), examples of powerful outflows are difficult to find (Green et al. 2014). While clear evidence exists that powerful radio jets bring warm gas and carry significant amounts of material out of their host galaxies (e.g., Nesvadba et al. 2006; Fu & Stockton 2009), the situation is far less clear for radio-quiet targets, which dominate the AGN population. At lower redshift of $z < 1$, people recently have identified a sample of $\gtrsim 10$ radio-quiet QSOs with high intrinsic luminosities ($M_B < -26.9$ mag) that show outflowing [O III] gas bubbles on ~ 15 kpc scales (Greene et al. 2012; Liu et al. 2013a, 2013b; Hainline et al. 2013). These observations suggest that radio-quiet AGN outflows have diverse morphology, including irregular, filamentary or bipolar structures. The progresses of direct imaging on outflow morphology at $z < 1$ beg the question whether one can use *HST* imaging to directly reveal a definitive outflow evidence in the high-redshift Universe at $z > 2$.

2. A Giant Lyα Nebula Powered by the Outflow of a Type-II, Radio-quiet AGN at $z = 2.3$, the First Definitive AGN Outflow in Emission at $z > 2$

Giant Lyα blobs (LABs) are extremely rare and strongly clustered. They live in massive dark matter halos (10^{13} $M_\odot$) and trace large-scale mass overdensities (Prescott et al. 2009). LABs provide us an unique opportunity to study the emission in the densest part of the intergalactic medium (IGM). However, physical processes generating giant LABs is poorly understood. Simulations suggest they could arise from several mechanisms, including photoionization by AGNs (e.g., Cantalupo et al. 2012) and strong outflow due to AGN feedback (e.g., Taniguchi & Shioya 2000).

Recently, we have discovered an ultraluminous, intergalactic Lyα nebula, MAMMOTH-1, in the density peak of the most massive overdensity *BOSS1441* (Fig. 1; Cai et al. 2017). Our deep KPNO-4m narrowband and broadband imaging demonstrate that MAMMOTH-1 nebula has the highest nebular luminosity of $4.7 \pm 0.4 \times 10^{44}$ erg s^{-1}, and an end-to-end spatial extent of 442 kpc (Fig.1), beyond the scale of typical galaxies. To the same depth, the linear size of MAMMOTH-1 is a factor of $1.5\times$ larger than Slug nebula, the first intergalactic nebula detected by Cantalupo et al. (2014).

Furthermore, our deep LBT/MODS spectroscopy have confirmed that MAMMOTH-1 is the first radio-quiet source to have spatially extended (~ 30 kpc) C IV, He II, and [O III] emission (Fig.2 and Fig.3). All Lyα, He II and [O III] lines show double-peaked kinematics. For Lyα emission, the blue component has a best-fit FWHM of 876 ± 120 km s^{-1} and the red component has a best-fit FWHM of 1140 ± 160 km s^{-1} (Fig.3). The rest-frame velocity offset between the two components is ≈ 700 km s^{-1}. For He II and [O III] emission, the offset between the two components is similar as that of Lyα. From the BPT diagram analysis, MAMMOTH-1 is consistent of being powered by a type-II AGN. Further, although MAMMOTH-1 only has an optically faint continuum, with $i_{\rm AB} = 24.5$, this source is detected in WISE with $m_{3.4\mu\rm m} = 16.3 \pm 0.1$, $m_{4.6\mu\rm m} = 15.5 \pm 0.1$. All these data support that MAMMOTH-1 is powered by a strongly obscured, infrared-luminous type-II AGN.

3. WFC3/F167N narrowband imaging on the [O III] emission of MAMMOTH-1.

Form our ground-based LBT/LUCI infrared spectrum (Fig.2), we detect, for the first time, a strongly extended [O III] emission at $z > 2$. As shown in Fig.2, this [O III] emission line can be fit by two velocity components. We measure that the [O III] emission has a luminosity of $4.0 \pm 0.1 \times 10^{44}$ erg s^{-1}, and a mean surface brightness (SB) of 3.0×10^{-17} erg s^{-1} cm^{-2} arcsec^{-2}. The [O III] nebula has a spatial extent of ≈ 34 kpc from ground-based observations (Fig.2). The extended [O III] nebula at $z > 2$ provide us a unique opportunity to reveal the AGN outflow at high redshift Universe. The ground-based seeing limited observations are not enough to measure the morphology and resolve filamentary structures shown in AGN outflows (~ 1 kpc) (e.g., Stockton et al. 2002; Greene et al. 2014).

Fortuitously, the HST WFC3/IR F167N filter completely covers the [O III] emission (right panel of Fig.2). Since this source is a type-II AGN, the central QSO PSF is negligibly weak compared to the extended [O III] emission. We can therefore avoid complications of PSF subtraction and fully study the [O III] morphology. **In cycle-25, we propose a deep narrowband imaging to fully map the morphology of the [O III] nebula at $z = 2.32$.** The outflow of this type-II AGN is expected to power the most luminous Lyα blob. Combined with our existing deep HST/WFC3 F160W imaging in this field, these new HST observations enable us, for the first time, to study the morphology and structure of the type-II AGN outflow at $z > 2$. The main science goals are as follows:

(a) Fully Reveal the Outflow Morphology of the [O III] Emission at $z = 2.32$ and Confirm the Most Luminous Lyα Blob can be Powered by AGN Outflow

Using HST imaging, Greene et al. (2014) present that the morphology of a low-z [OIII] nebula. This [OIII] nebula has a bipolar structure, with each [O III]-emitting bubble expanding on a scale of ~ 1 kpc $\times 10$ kpc. The velocity offset between the two components is about 1000 km s^{-1} (Sun et al. 2014). The multi-wavelength observations confirm that such luminous [O III]-emitting nebula is powered by AGN-driven hot winds. Stockton et al. (2002) also revealed that thin (1 kpc) filamentary structures exist in the extended [OIII] emission. However, at $z > 2$, clear AGN-driven outflow evidences are still ambiguous.

The MAMMOTH-1 Lyα nebula at $z = 2.32$ is the first source discovered at $z > 2$ that has strongly extended He II, C IV, [O III] on the 30 kpc scale (Fig.2 and Fig.3). The line structure (e.g., kinematics, spatial extent) of this [O III] emission is similar as the low-z AGN outflow confirmed by Greene et al. (2014) (see Fig.2). This source could be the first definitive AGN-driven outflow driven by a type-II AGN at high redshift. In cycle-25, we propose to conduct deep HST narrowband imaging on the [O III] nebula (Fig.2). The high-resolution observations will completely reveal the morphology of the [O III] bubble. The bi-polar morphology and/or filamentary structure (e.g., ionization cones) revealed by HST imaging will be used to directly compare to that of low-z AGN outflow (e.g., Liu et al. 2013; Greene et al. 2014). The confirmation of the AGN outflow (e.g., bipolar, filamentary) structure of the extended [O III] emission will provide a strong evidence that the most luminous Lyα nebula can be powered by an AGN driven outflow.

(b) Test Whether the AGN is Powered by Interactions of Multiple Components
Another alternative interpretations of the double-peaked, spatially extended emission of Lyα, C IV, He II and [O III] is that MAMMOTH-1 may consist of two or multiple components, and the type-II AGN could be powered by merging of multiple galaxies. In the type-II AGN, the optical light of central PSF is strongly obscured, making it possible for an excellent PSF subtraction and detection of host galaxies. The multiple components in merging systems at $z = 2$ have linear scale of 1 kpc ($< 0.2''$) (e.g., Bussmann et al. 2011), and thus the HST observations are needed. The HST high spatial resolution narrowband image and our existing (cycle-24) HST broadband (F160W) imaging will directly test whether this type-II AGN is powered by multiple components of star-forming ([O III]-emitting) galaxies. These multiple [O III] emitting components will be a direct test of the merger-driven evolutionary model, where quasars are triggered by interactions and mergers of gas-rich galaxies (e.g., Sanders et al. 1988; Hopkins et al. 2006).

(c) Measure the Size and Luminosity of the [O III] Nebula at $z = 2.32$.
Several recent studies have suggested that there exists a correlation between the size and luminosity of [O III] emission at $z \leq 0.5$ (e.g., Bennert et al. 2002; Schmitt et al. 2003; Greene et al. 2011; Fu et al. 2014). The [O III] size-luminosity relation provides a strong constraint to the AGN photoionization model and outflow model (Bennert et al. 2005). Comparing to the size-luminosity measurements on other sources (Fig. 6 in Fu et al. 2014), MAMMOTH-1 has the highest [O III] luminosity and the largest [O III] size. With HST narrowband imaging, we will fully reveal [O III] emission, both in size and luminosity. These measurements test whether MAMMOTH-1 nebula follows the size-luminosity relation derived from low-z AGNs. Furthermore, the size and morphology of the [O III] extended emission region can also be used to derive a dynamical timescale ($t = R_{\rm NLR}/v_{\rm outflow}$) which helps to estimate the lifetime of AGN (Fu et al. 2014; Liu et al. 2014).

Thanks to the HST WFC3/F167N filter and the most luminous Lyα nebula, providing us a unique opportunity to fully resolve and map the [O III] emission due to AGN outflow at high-redshift of $z > 2$. Since the AGN is strongly obscured in both optical and infrared, one does not need to conduct the PSF subtraction (we already have deep HST/WFC3 F160W imaging in this field). Our team has expertise on all relevant fields: giant Lyα nebula (Cai; Fan; Prochaska et al. 2017a), and AGN outflow observers: (Fu; Liu; Shen), as well as crucial theoretical models of the AGN outflow (Shen). Together, we will not only conduct a high resolution imaging on the first extended [O III] nebula at high-z, but also draw a first picture of the formation and evolution of type-II AGN and massive galaxies in the high redshift Universe. This proposed HST imaging program can also be a pilot imaging program for the future JWST integral field spectroscopy studies.

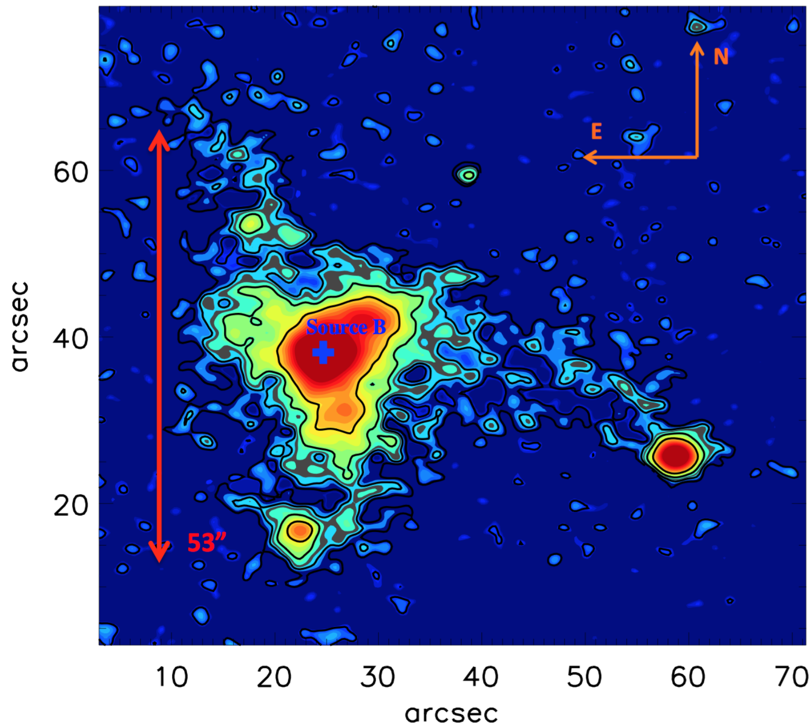

Figure 1: Continuum-subtracted narrowband image of the ultraluminous, intergalactic-scale Lyα blob (LAB): MAMMOTH-1, which is powered by a type-II AGN. This LAB is the first radio-quiet source to be associated with strongly extended ($\gtrsim$ 30 kpc) emission line region (EELR) at $z > 2$. In cycle-25, we propose a deep HST narrowband imaging on the extended [O III] emission which will directly map the morphology of outflow and test the existence of the filamentary structure (e.g., ionization cones) as shown in [O III] morphology at $z < 1$.

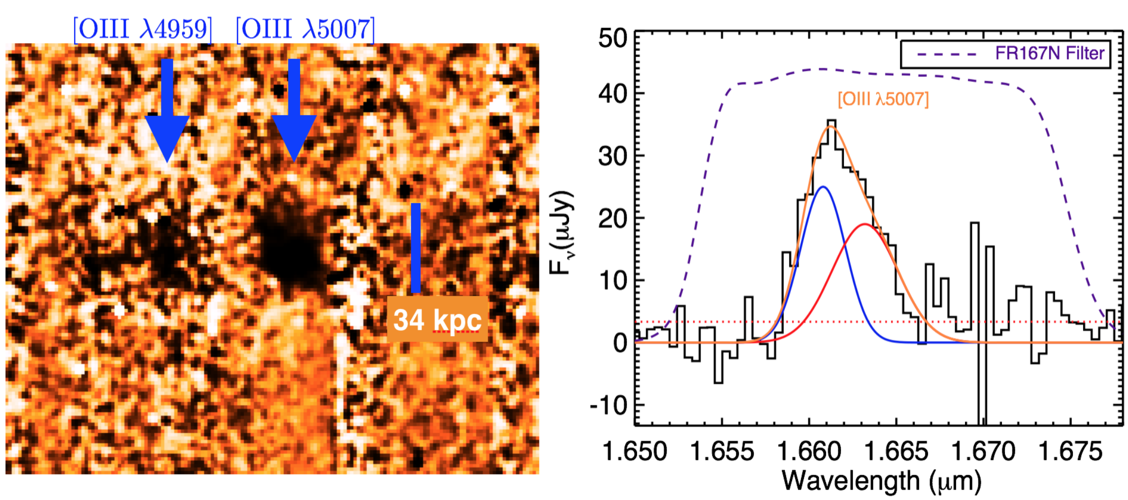

Figure 2: *Left:* The 2-D spectrum of the [O III] emission of MAMMOTH-1 Lyα blob at $z = 2.318$. *Right:* The 1-D spectrum of the [O III] emission with the filter throughput curve (purple dashed line) which covers the [O III] emission. Similar as the C IV and He II, the extended emission line region (EELR) of [O III] extends 30 physical kpc, and can be fitted by two velocity components. In Cycle-25, we will conduct the deep F167N narrowband imaging of the [O III] emission to reveal the morphology of the AGN outflow at $z = 2.32$.

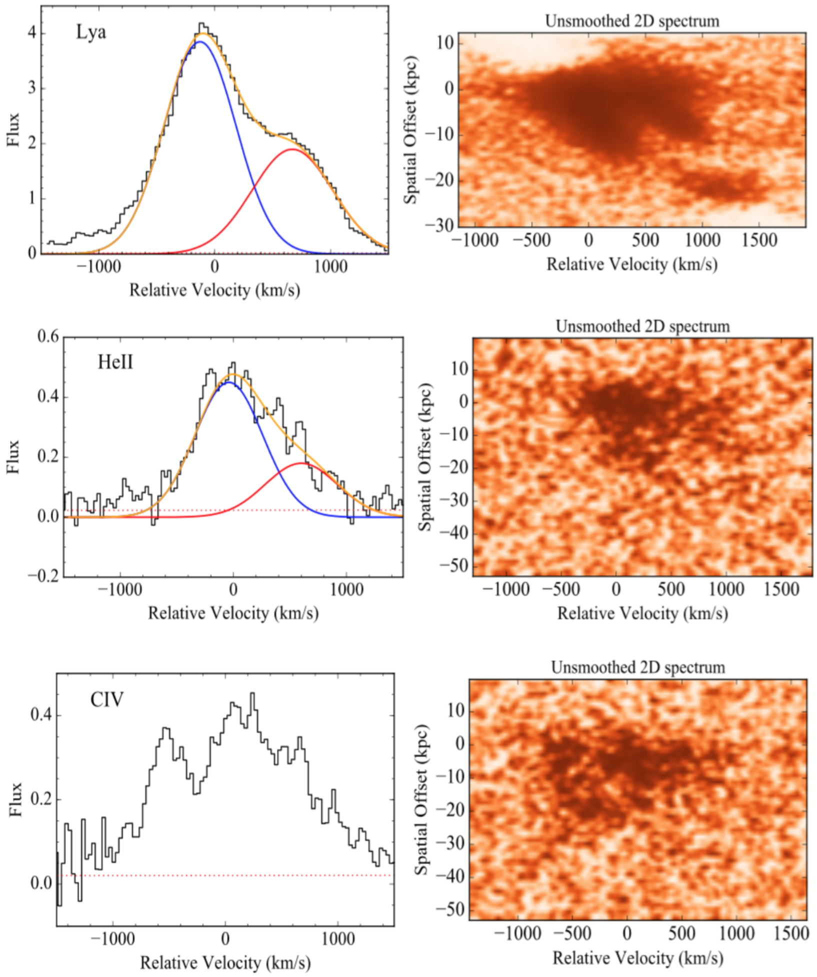

Figure 3: From top to bottm: Lyα, He II, C IV. Left column: 1-D zoom-in line profiles of Lyα, He II, C IV (from top to bottom) as a function of the rest-frame velocity centered on the redshift of the nebula. Right column: 2-D spectra of Lyα, He II, and C IV. From the spectrum, the extended Lyα emission lies the spatial direction along the slit (10"). The C IV and He II emission extend $\gtrsim$ 30 physical kpc. All these emissions strongly indicate this source is the best target to search for AGN outflow in the high-redshift Universe.

Reference: Bournaud, F. et al. 2011 ApJ, 741L, 33 Cai et al. 2016, ApJ, 833, 135C; Cai et al. 2017a, ApJ, 834, 1; Cai et al. 2017b, ApJ accepted; Croton et al. 2006 MNRAS, 369, 1808C Ferrarese & Merritt 2000 ApJ, 539L, 9 Fu & Stockton 2009 ApJ, 696, 1693F Greene, J. ApJ, 2011, 732, 9G Greene, J. ApJ, 2012, 746, 86G Hainline, L. ApJ, 2013, 774, 69H Liu, G., MNRAS, 2013, ApJ, 778L, 41L Liu, G., MNRAS, 2014, 442, 1303L Magorrian, J. et al. 1998 AJ, 115, 2285 Moe, M. et al. 2009 ApJ, 706, 525M Prescott, M. et al. 2009 ApJ, 234, 141 Steidel, C. et al. 2011, ApJ, 736, 160 Nesvadba, N. 650, 693N Springel, V. MNRAS, 361, 776S Stockton, A. ApJ, 659, 195S Stockton, A. ApJ, 600, 626S Thoul & Weinberg 1995 ApJ, 422, 480T

Description of the Observations

We propose HST F167N narrowband imaging on the extended emission of [O III] (30 kpc) associated with a radio-quiet, type-II AGN. This type-II AGN powers the most luminous Lyα nebula: MAMMOTH-1 (Fig.1). This field is already covered by our deep HST F160W observations in the previous cycle. Our proposed observations will enable us to completely map the morphology of the extended [O III] nebula, test the existence of the bi-polar, filamentary AGN outflow at $z > 2$, and search for multiple member galaxies that powering this type-II AGN. Our science requires resolution of 1 kpc ($< 0.2''$), the scale of large clumps in the outflow filamentary structure (e.g., Stockton et al. 2002) and the multiple galaxy components in merging systems, and so the *HST* observations are required. We have searched for the field and no suitable guide star in the field for laser adaptive optics (AO) imaging.

1 Target Selection

We have discovered a unique field at $z = 2.32 \pm 0.02$ in the data release of the SDSS-III over a 3000 deg^2. This field contains a rare group of deep Lyα absorbers at $z = 2.32 \pm 0.02$ projected within 20 h^{-1} Mpc. In addition, this absorption is associated with a group of seven QSOs projected within 30 h^{-1} Mpc and at the same redshifts. Both enhancement of H I and ionizing photons greatly increase the chance of detecting giant Lyα blob in the densest part of intergalactic medium (Cai et al. 2017a; 2017b).

In Cai et al. (2017a), we successfully confirm a large LAE overdensity in this field. In Cai et al. (2017b), we report a giant, the most luminous LAB in this field. This LAB, to the same surface brightness limit, is a factor of 1.5× the size of Slug nebula, first intergalactic-scale Lyα nebula discovered to date (Catalupo et al. 2014). Our deep LBT/LUCI infrared spectrosocopy revealed strongly extended [O III] on $\gtrsim$ 30 kpc scale (Fig.2) and confirmed that MAMMOTH-1 is powered by a type-II AGN. In cycle-25, we propose to use HST F167N narrowband, combined with our existing deep WFC3 H-band imaging in this field to fully probe the morphology of the extended [O III] nebula at $z > 2$, and test if the type-II AGN is powered by merging of multiple member galaxies.

2 Filter Selections

We present the 2-D and 1-D spectra of the extended [O III] in Fig.2. In Fig.2, we also plot the WFC3/IR filter F167N (λ_c = 16670Å, with FWHM=207Å, purple dotted line in right panel). The narrowband filter is chosen because the sensitive wavelength range of F167N completely covers the extended [O III] emission. Because it is a type-II AGN, only a tiny fraction of the flux coming from quasar continuum which makes the PSF subtraction to be straightforward. With this HST WFC3/IR F167N narrowband imaging, we can completely map and measure the morphology and physical properties of the AGN outflow from inner kpc scale up to a few tens of kpc scale.

3 Exposure time

From our LBT/LUCI spectroscopy, we measured that our [O III] has an average surface brightness (SB) of 3.0×10^{-17} erg s^{-1} cm^{-2} arcsec^{-2}, and the surface brightness (SB) $\propto r^{-1.1}$, with the SB peak of 5.0×10^{-17} erg s^{-1} cm^{-2} arcsec^{-2}.

For completely mapping the outflow, fully measuring the morphology, and resolving the individual galaxy components, we plan to use 0.1" × 0.1" box as the aperture to carry out this morphological analysis and examine the deep narrowband image. Our depth needs to reach the surface brightness on the edge of 30 kpc extended region in 5-σ. The measured SB on the edge of 30 kpc is 2.0×10^{-17} erg s^{-1} cm^{-2} arcsec^{-2}. This depth will enable us to fully map the [O III] flux and size and measure the possible filamentary morphology of [O III] nebula. Using the WFC3 Exposure Time Calculator, we find that with a 10-orbit ($\approx 30,000$

sec) integration, we will be able to detect the flux at a 5-σ level down to 2.0×10^{-17} erg s^{-1} cm^{-2} $arcsec^{-2}$ in an aperture of $0.1'' \times 0.1''$ box using the HST/WFC3 F167N filter. In Cycle-24, we already mapped this field with deep F160W (2-orbit) broadband imaging, which depth is sufficient for our science goal. Therefore, no continuum imaging is needed in this cycle.

We request a total of 10 orbits for these proposed HST observations to meet our science goals. No special calibration is needed. The field does not have bright stars, so saturation is not an issue. We will split each orbit into two exposures with a slight offset for cosmic ray and detector defect rejections.

Special Requirements

Coordinated Observations

Justify Duplications

Analysis Plan

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