Roman CCS White Paper

Low-mass SMBH at High Redshift: Deepest variability search for low-luminosity AGN

Roman Core Community Survey: *High Latitude Time Domain Survey*

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Abstract:

We discuss the strategy of the systematic variability search for low-luminosity Active Galactic Nuclei (AGN) by utilizing the Roman High Latitude Time Domain Survey in order to study low-mass (~$10^6 M_{sun}$) BH at intermediate and high redshift.

I.Low-mass Super Massive Black Holes *(Science Importance and Open Questions)*

Super Massive Black Holes (SMBH) locate in the most of elliptical galaxies and (classical) bulges in the local universe and the tight correlation between the black hole mass (M_{BH}) and the central velocity dispersion or stellar mass of the host spheroids is observed, over the wide range of BH mass (e.g., Kormendy and Ho 2013). A crucial question is how SMBHs formed and evolved in the hierarchical growth of galaxies in the universe and how the AGN activities affects evolution of their host galaxies. Unveiling the population of low-mass SMBH (~$10^6 M_{sun}$) at intermediate or high redshift is essential to answer the questions observationally. The evolution of the BH mass function, their ANG activities (distribution of Eddington ratio λ_{edd}), the absorption fraction, and the relationship between BH mass and the bulge mass (or the related quantities) toward high redshift down to such low-mass range is necessary to understand how SMBH grows in the history of the universe. It is most interesting to characterize these low-mass SMBH and to reveal the properties of their host galaxies; identifying the very young BHs, close to the seeds with further low mass, in the early phase of massive galaxy formation, BHs formed in the 'building blocks' of ~10^9 M_{sun} galaxies to be merged/assembled to massive galaxies, BHs of the bulges such as the one in our Milky Way galaxy (M_{BH}~$4\times10^6 M_{sun}$) related to the formation of those spheroids in disk galaxies, and BHs in the dwarf elliptical galaxies.

It is not easy, however, to systematically search for such very low-mass SMBH at intermediate or high redshift. While searching for low-luminosity AGN (LL-AGN, here we consider AGN with $L_{bol}<10^{45}$ ergs^{-1}) is an obvious direction, the deep observations with current X-ray facilities marginally reaches L_{bol}~$10^{43.5}$ergs^{-1} or M_{BH}~$10^{6.5}$ M_{sun} for λ_{edd}~0.1 at z~1 to cover ~1 deg^2 (Marchesi et al. 2016) and the future more powerful facilities will be realized only in the middle of 2030's. The method using MIR excess, optical emission line diagnostics, and UVoptical-NIR colors suffer from the contamination by the radiation from the star-formation components in the hosts which easily overwhelm the AGN light (e.g., Kimura et al. 2020), and not very much efficient to detect AGN with L_{bol}~10^{43-44} erg/s or fainter. Deep spectroscopic observations to detect wings of broad emission in the lines is an interesting method to detect low-mass BH (e.g., Harikane et al. 2023, Hatano et al. 2023) but it is expensive in observational time and separation from the larger-scale gas motion such as wind requires very high S/N ratio. In order to measure BH mass of LL-AGN, with the efficient method such as single-epoch virial mass, it is also important to identify their type-1 nature to measure the velocity width of their broad emission lines from the BLR.

II.Deep Variability Search for Low-Luminosity AGN

(How the capabilities of a Roman Core Community Survey will uniquely enable the investigation)

Variability selection is a very powerful tool to detect 'type-1' AGN as the most of the observed AGN continuum show significant variability if not obscured. Since little variability is expected for the host galaxies, even LL-AGN can be detected if the enough photometric accuracy is achieved. For example, Kimura et al. (2020) demonstrated, by using one of the deepest multicolor multi-epoch dataset covering ~2 deg^2 in the Subaru HSC-SSP Survey Ultradeep Layer (with the typical limiting magnitude i~25-25.5 at each epoch), reaches 10^{44} $ergs^{-1}$ at z~2 and can detect the AGN as faint as, or even fainter than those detected in the deep X-ray observations. Follow-up spectroscopic analysis revealed the sample contains a dozen of AGN at z=0.5-3 with BH mass below x $10^7 M_{sun}$. Kimura et al. (2020) also found that the variability structure function of LL-AGN can be represented by the similar shape as the luminous ones (i.e., power-low function with the index 0.4-0.5 over the 10-300 days) and that the intrinsic variability is larger in the LL-AGN while the apparent variability strength has turn-off at around due to the host galaxy light. Fig.1 shows the obtained structure function of the Subaru HSC-SSP variability-selected AGN in Kimura et al. (2020) and the dependence of the amplitude on luminosity and the rest-frame wavelength.

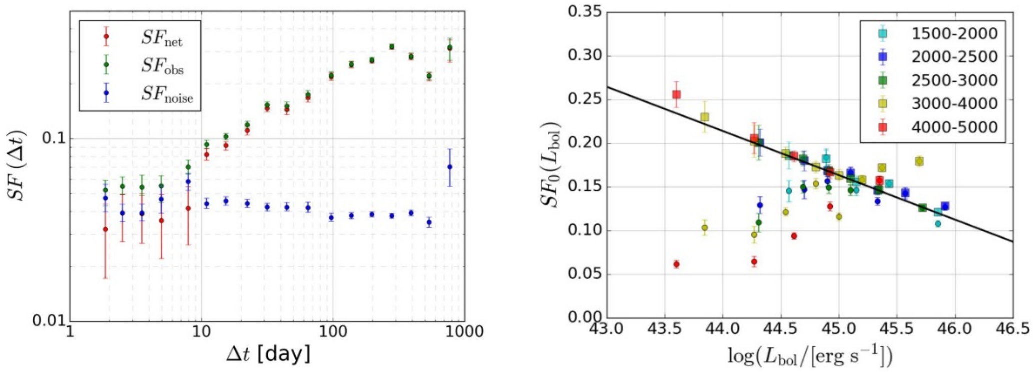

Fig.1 Structure function of the variability selected AGN in Kimura et al. (2020) using the dataset of Subaru HSC-SSP Ultradeep Layer at the COSMOS field. The right panel shows the dependence of the amplitude (at Δt=100days) on the AGN bolometric luminosity and the rest-frame wavelength.

Previous deepest multi-color dataset is, however, still not deep enough and not well designed to conduct the systematic variability search for BH down to ~10^6 M_{sun} at z>1. It is found inevitably difficult to achieve homogeneous detection limit over the epochs and also for multi-band filters even with the largest ground-based telescopes. **Roman High-Latitude Time Domain Survey (HLTDS) can provide an ideal, very powerful dataset for the systematic variability search for very low-luminosity AGN.** In the HLTDS reference survey plan (Rose et al. 2021) every piece of the sky in the HLTDS filed is observed by ~125 shots, either Wide (19.04 deg^2) or Deep (4.2 deg^2) surveys, over the two years and the total depth reaches ~28 and 29 mag (S/N=5 for point sources), respectively. This allows to obtain the *binned* light curves with ~10 separate epochs in multi filter bands which can be utilized to identify faint AGN population separated from SNe and other variable objects or transient, and photometric spurious. Figure 2 shows the expected magnitude of the AGN with M_{BH} ~10^6 M_{sun}

and Eddington ratio λ_{edd}=1 and 0.1. Assuming higher Eddington ratio is reasonable for the population of young active AGN.

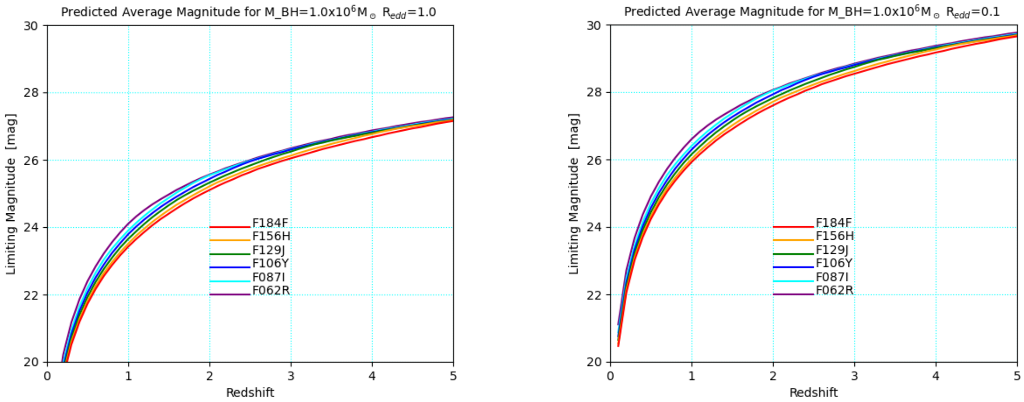

Fig.2 Predicted apparent magnitude of AGN with the BH mass of 10^6 M_{sun} and Eddington ratio λ_{edd}=1 (left) and 0.1 (right) in the Roman WFI filters. We adopted the wavelength-depended bolometric correction factor from Runnoe et al. 2012a,b.

III. Optimal Survey Strategy *(The minimal and optimal observational strategies)*

An optimal observational strategy for the variability survey for LL-AGN at intermediate/high redshift requires,

(i) Sufficient depth at each 'epoch', which consists of a certain number of visits. For example, to detect ~10% variability for AGN components with M_{BH} ~10^6 M_{sun} and Eddington ratio λ_{edd}=1 and 0.1 at z=2, S/N>10 for ~25.5 and 28.0 mag objects is required. Note that the depth is not deep enough to detect the significant variability in a single pair of two epochs but by using cross correlation between the flux values in different filter bands over ~10 epochs such AGN variability can be significantly detected (Kimura et al. 2020).

(ii) To obtain the multi-color photometry of a given patch of the sky as close as possible at each 'epoch'.

(iii) To obtain the similar depth in multi band at given 'epoch'

(iv) To cover the cadence from 10 days to 300 days (Fig.1 structure function)

(v) Survey area larger than 10 deg^2. Previous empirical BH mass function guessed from the spheroidal galaxy mass function gives the number density of BH with M_{BH} ~10^6 M_{sun} as 10^{-3} Mpc^{-3} (e.g., Kelly and Merloni 2011). However, it is also known that the type-1 fraction of AGN changes along the AGN luminosity and ~1-10% at L_{bol}~10^{43-44} ergs^{-1} (Ricci et al. 2017, Kimura et al. 2020). Taking the unknown distribution of Eddington ratio for such low-mass BH at high redshift also into account, we need to observe the volume at least 10^8Mpc^3 per unit-redshift to detect more than 100-1000 LL-AGN by their variability per unit-redshift.

In the reference plan of HLTDS (Rose et al. 2021), these requirements can be mostly achieved but the sky mapping strategy limits the minimum interval to get the photometric datapoint at one 'epoch' (summing up the data over a certain number of visits) with enough depth at a patch of the sky. For example, if a patch of the sky is visited once in 1.5 days (assuming ~60 visits e.g., in three months in a year), 15days is needed to sum up 10 visits data to obtain the deeper image for a 'epoch'. In the reference plan the depth per visit in Wide and Deep surveys are 26.4-25.4 mag and 26.7-26.5 mag (S/N=5) respectively (Table 2 in Rose et al.), so summing up ~10 visits may achieve 27.1-25.9 mag and 27.3-27.1 mag (S/N=10) for one 'epoch' photometric data. The depth in the Deep survey appears to deep enough to detect BH with M_{BH} ~10^6 M_{sun} at z~1.5 for the Eddington ratio λ_{edd}=0.1 and z~4 for λ_{edd}=1.0. The obtained sample may contains further less massive BH (~$10^5$$M_{sun}$) at the lower redshift at z~0.5. This magnitude range is also reachable by the deep spectroscopy with ELTs to obtain the velocity width of the broad emission lines to estimate their BH mass (TMT Detailed Science Case Book 2015).

We mat obtain light curves with ~12 'epochs' over the whole period of the 125 visits. As the AGN structure function shows the larger variation in the longer time interval up to Δt=300 days, it requires to have the baseline of >2 years for the survey. More randomized distribution of the intervals of 'epochs' are preferred.

In summary, LL-AGN variability survey requires the mapping strategy and cadence to obtain ~10 visits with 300sec exposure in ~10 days, with multifilters (~3-4 bands) at the shortest intervals, and in total ~125 visits over three years at a given patch of the sky, and the total survey area of ~10deg^2. This can be reasonably achieved in the reference plan (Rose et al. 2021) but tuning of the mapping strategy such as the timing to obtain the multi band data at a sky and the total time baseline can be considered to maximize the survey output.

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