様　式　Ｃ－１９、Ｆ－１９－１、Ｚ－１９　（共通）

# 科学研究費助成事業　　研究成果報告書

令和　５ 年　 ６ 月　 １ 日現在

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研究種目：基盤研究(B)（一般）
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研究課題名（和文）The emergence of the supermassive black hole-galaxy mass relations at z > 1

研究課題名（英文）The emergence of the supermassive black hole-galaxy mass relations at z > 1

研究代表者
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交付決定額（研究期間全体）：（直接経費）　　11,700,000円

研究成果の概要（和文）：我々はハッブル宇宙望遠鏡とすばる望遠鏡を用いて，赤方偏移z~2までのクェーサー母銀河の恒星質量と銀河中心の超大質量ブラックホールの質量との関係を調査した．母銀河の恒星質量と銀河中心の超大質量ブラックホールの質量の比は直近80億年もであり進化していないことを発見した．さらに，質量比の分散もおおむね一定であることを初めて発見した．この結果は，クェーサーフィードバックを取り入れることで，母銀河と超大質量ブラックホール両者の質量成長の関係に制限をかけている数値シミュレーションの結果とも整合的である．銀河と超巨大ブラックホールは一緒に成長してきた，すなわち共進化してきたことが判明した．

研究成果の学術的意義や社会的意義
本課題において，国際的な論文誌にて複数の論文を出版した．また，国際学会においても研究成果の発表を行った．結果として，本研究は初期宇宙におけるクェーサー母銀河の研究に高い影響を与え，ジェームズウェッブ宇宙望遠鏡なども用いた該当分野の研究を国際的にリードしている．

研究成果の概要（英文）：We have determined the relation between black hole mass and stellar mass of quasar host galaxies out to z ~ 2 using the Hubble Space Telescope and the Subaru telescope. We find that the mass ratio is nearly constant (i.e., non-evolving) over the last 8 billion years of the universe. This is supported by the analysis of 584 quasars from the Sloan Digital Sky Survey which have their host galaxies imaged by the Hyper Suprime-Cam Subaru Strategic Program. We also found for the first time that the dispersion in the mass ratio is nearly constant and in agreement with simulations which include quasar feedback to regulate their joint mass growth. Overall, we find that supermassive black holes and their host galaxies are growing together in a co-evolutionary manner, likely by sharing a common fuel supply which simultaneously provides gas to form new stars, builds up the central stellar mass concentration, and accretes onto the central black hole.

研究分野：galaxy evolution

キーワード：supermassive black holes　near-infrared　galaxy evolution　coevolution

様　式　Ｃ－１９、Ｆ－１９－１、Ｚ－１９（共通）

１．研究開始当初の背景

The study of host galaxies of Active Galactic Nuclei (AGNs) and the more luminous quasars has been one of the pillars of Hubble Space Telescope (HST) science for over two decades now. In particular, the tight relation between the mass of supermassive black holes (SMBHs) and properties of their host galaxy (e.g., stellar mass; $M_{BH}$ vs. $M_{galaxy}$) in the local Universe has demonstrated that SMBHs play an integral role in the evolution of galaxies. The physical mechanism that can produce such a relationship between the mass of a SMBH and the stellar content of its host, that spans a vastly larger physical scale, is currently unknown. Hence, a key open question in astrophysics remains as to how galaxies and their SMBHs migrate onto the local mass relations. This requires a determination of the relation $M_{BH}$ vs. $M_{galaxy}$ as a function of cosmic time. The mass relation had been investigated up to $z \sim 1$ but not beyond that which is achievable with the near-infrared camera on HST using a well-defined statistical sample of AGN for which systematic biases and selection effects can be accounted for. These results will have a lasting impact on the field of SMBH research and plans for future studies using the James Webb Space Telescope (JWST), Prime-Focus Spectrograph (PFS) and WFIRST.

２．研究の目的

There has been much progress on understanding SMBHs and their host galaxies at $z < 1$, where the masses of SMBHs, beyond the local volume, can only be measured for AGN that exhibit broad emission lines by employing the virial method. Remarkably, an unbiased measure the mass relation of SMBHs and their host galaxies ($M_{BH}$ vs. $M_{galaxy}$) at $z > 1$ had not been accomplished even with the capabilities of the HST near-infrared (NIR) Wide-Field Camera 3 (WFC3). We plan to answer the fundamental question, “At what epoch ($z > 1$) do the masses of SMBHs and their host galaxies couple to match that in the local Universe?” This requires a detailed study of the host galaxies of distant black holes. Since these SMBHs are accreting and giving off prodigious amounts of optical and near-infrared emission, we must employ sophisticated image analysis techniques to decompose the emission into the AGN and host galaxy components separately.

３．研究の方法

To answer this key open question as described above, we were awarded 32 orbits in Cycle 25 with HST/WFC3 (PI J. Silverman) to measure the stellar masses of 32 AGN host galaxies at $1.2 < z < 1.7$. We are testing whether black holes and their host galaxies typically fall above, below, or on the local relation in the distant universe. To do so, we constructed an approach that overcomes biases from past studies: (1) use of AGNs that fall below the knee of the black hole mass function to minimize selection biases, (2) black hole masses measured using Balmer lines (i.e., H$\alpha$) with Subaru/FMOS to remove systematics with Mg II, (3) X-ray selection results in lower AGN-to-host galaxy ratios facilitating galaxy mass measurements, (4) image the host galaxy above the 4000 angstrom break and account for varying mass-to-light ratios with existing archival HST UV images, and (5) use of a significant sample of 36 AGNs (plus 4 from the HST archive). We can also measure the scatter in the relation at high-z. An increase in the scatter with redshift is expected by numerical simulations of hierarchical assembly through galaxy merging. To achieve these goals, we use a well-defined local ($z \sim 0$) AGN sample that defines our zero-point.

These analyses required us to separate the NIR (and optical in the case of HSC) emission from the AGN from that of its host galaxy using HST. This procedure requires an accurate characterization of the spatial resolution of the observations through 2D empirical modeling of the point-spread function (PSF). To achieve this, we used observations of stars in the field-of-view of each HST observation that resulted in a library of 70 stars to assess the shape of the PSF. The emission from our target galaxies was split into the unresolved emission characteristic of the AGN and the more extended emission from its underlying host galaxy through a joint modeling of their emission. Accurate uncertainties are assessed by employing different PSF models since these dominate over statistical errors.

In addition, we constructed a lower redshift quasar sample at $z < 1$ with Subaru’s Hyper Suprime-Cam (HSC) to measure the evolution in the mass ratios between black holes and their host galaxies with accuracy over cosmic time. This sample is unique since it is drawn from ~5000 quasars from the Sloan Digital Sky Survey thus enabling us to construct well-defined samples to best characterize the underlying selection function and correct for known biases. The optical imaging has been taken with the Subaru Strategic Program, a large effort to image 1000 square degrees of the extragalactic sky with HSC in five filters (grizy) down to depths of ~$26^{th}$ magnitude (Aihara et al. 2019). We utilize the characterization of the PSF as

provided by the software pipeline which greatly facilitates this study.

## ４．研究成果

We have completed our study (i.e., main aims of the program) to determine the properties of the host galaxies of quasars up to z ~ 2. This involves the analysis of the HST and Subaru imaging data using 2D image decomposition techniques (as described below) and comparisons to hydrodynamic cosmological simulations of galaxies and their SMBHs including Illustris, MassiveBlack, and Horizon-AGN. The latter requires a careful implementation of observational selection effects with the simulated samples.

Most importantly, our work determined the relation between black hole mass and the stellar mass of their host galaxies (Ding et al. 2020a) out to z ~ 2. We find that the mass ratio is nearly constant (i.e., non-evolving) over the last 8 billion years of the universe. This is supported by the analysis of 584 quasars from the Sloan Digital Sky Survey which have their host galaxies image by the Hyper Suprime-Cam Subaru Strategic Program (Li, Silverman et al. 2021a,b). We also found for the first time that the dispersion in the mass ratio is nearly constant and in agreement with most cosmological simulations (Ding et al. 2020b, 2022) which include quasar feedback to regulate their joint mass growth. As part of this work, we find that quasars tend to reside in disk-dominated galaxies thus indicating their preference for galaxies which are still forming stars. We find that the quasars are particularly found within galaxies which have smaller sizes than typical star-forming galaxies (Silverman et al. 2019) thus indicative of those which are building their central mass concentration (i.e., their bulge; Silverman, Li & Ding 2022). Overall, we find that SMBHs and their host galaxies are growing together in a co-evolutionary manner, likely by sharing a common fuel supply which simultaneously provides gas to form new stars and accrete onto the central SMBH.

The above analysis required the development of software tools (Galight) to decompose the quasar and host galaxy emission using optical and near-infrared imaging from HST and HSC. We modified tools available in the package Lenstronomy for use in the effective and highly efficient code ‘Galight’ to model the joint emission of an AGN and its host galaxy. The code fits each target with a model of the PSF and a smooth Sersic model for the host which describes its structure (i.e., compactness, light profile shape as being disk- or bulge-dominated). The choice of PSF stars are facilitated by the software along with the assessment of the uncertainties dependent on the PSF model being employed. Multiple interations allow us to infer realistic uncertainties on each parameter.

Our 2D image modeling has further allowed us to study non-axisymmetric structures (e.g., spiral arms, bars, rings) within quasar host galaxies (Nagle et al. 2023) which may play a role in fueling supermassive black holes. This work required the removal of the AGN and model host galaxy to quantify the presence of residual emission. In particular, residual images of quasar hosts are separated in a higher order dimensional space from that of a matched control sample of star-forming galaxies without quasars. The quasar hosts have more prominent substructure than seen in the non-active star-forming galaxies. This work is opening avenues for new research on fueling quasars by utilizing the potential of machine-learning techniques such as a variational autoencoder as employed in this study.

From this program, Tang et al. (2023) studied the role of mergers in triggering AGN activity by measuring the asymmetry of the SDSS/HSC quasar hosts after the AGN has been subtracted. He found that SMBHs reside in more asymmetric galaxies for those with higher black hole mass and accretion rates thus indicating that galaxy mergers do have an impact on mass accretion onto a SMBH but not at the level to be the dominant mechanism responsible for the majority of their mass.

In addition, we have studied an important population of dual quasars from the HSC-SSP survey which elucidates their frequency and galaxy properties (Silverman et al. 2020; Tang et al. 2021). Rather than having one unresolved point source, there are cases where two unresolved sources are within a close distant down to 0.6” or ~3 kpc.We find that the frequency of quasars being duals is in agreement with the Horizon-AGN cosmological simulation. Now, we are investigating the molecular gas properties based on awarded ALMA observations.

Overall, we have published numerous papers from this study as listed above which then supported an accepted program with the James Webb Space Telescope to measure the mass ratios of SMBHs and their host galaxies at z > 6 which is now currently funded as a followup Kakenhi program. In Cycle 1 JWST, observations with both the Near-Infrared Camera (NIRCam) and the Near-Infrared spectrograph (NIRSpec) have allowed us to determine the properties of their host galaxies during the first billion years of our universe.

５．主な発表論文等

〔雑誌論文〕　計11件（うち査読付論文　11件／うち国際共著　11件／うちオープンアクセス　10件）

| | |
|---|---|
| １．著者名<br>Li Junyao、Silverman John D.、Ding Xuheng、Strauss Michael A.、Goulding Andy、Birrer Simon、Yesuf Hassen M.、Xue Yongquan、Kawinwanichakij Lalitwadee、Matsuoka Yoshiki、Toba Yoshiki、Nagao Tohru、Schramm Malte、Inayoshi Kohei | ４．巻<br>918 |
| ２．論文標題<br>The Sizes of Quasar Host Galaxies in the Hyper Suprime-Cam Subaru Strategic Program | ５．発行年<br>2021年 |
| ３．雑誌名<br>The Astrophysical Journal | ６．最初と最後の頁<br>22～22 |
| 掲載論文のDOI（デジタルオブジェクト識別子）<br>10.3847/1538-4357/ac06a8 | 査読の有無<br>有 |
| オープンアクセス<br>オープンアクセスとしている（また、その予定である） | 国際共著<br>該当する |

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|---|---|
| １．著者名<br>Li Junyao、Silverman John D.、Ding Xuheng、Strauss Michael A.、Goulding Andy、Schramm Malte、Yesuf Hassen M.、Sun Mouyuan、Xue Yongquan、Birrer Simon、Shi Jingjing、Toba Yoshiki、Nagao Tohru、Imanishi Masatoshi | ４．巻<br>922 |
| ２．論文標題<br>Synchronized Coevolution between Supermassive Black Holes and Galaxies over the Last Seven Billion Years as Revealed by Hyper Suprime-Cam | ５．発行年<br>2021年 |
| ３．雑誌名<br>The Astrophysical Journal | ６．最初と最後の頁<br>142～142 |
| 掲載論文のDOI（デジタルオブジェクト識別子）<br>10.3847/1538-4357/ac2301 | 査読の有無<br>有 |
| オープンアクセス<br>オープンアクセスとしている（また、その予定である） | 国際共著<br>該当する |

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|---|---|
| １．著者名<br>Kawinwanichakij Lalitwadee、Silverman John D.、Ding Xuheng、George Angelo、Damjanov Ivana、Sawicki Marcin、Tanaka Masayuki、Taranu Dan S.、Birrer Simon、Huang Song、Li Junyao、Onodera Masato、Shibuya Takatoshi、Yasuda Naoki | ４．巻<br>921 |
| ２．論文標題<br>Hyper Suprime-Cam Subaru Strategic Program: A Mass-dependent Slope of the Galaxy Size - Mass Relation at z < 1 | ５．発行年<br>2021年 |
| ３．雑誌名<br>The Astrophysical Journal | ６．最初と最後の頁<br>38～38 |
| 掲載論文のDOI（デジタルオブジェクト識別子）<br>10.3847/1538-4357/ac1f21 | 査読の有無<br>有 |
| オープンアクセス<br>オープンアクセスとしている（また、その予定である） | 国際共著<br>該当する |

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| １．著者名<br>Tang Shenli、Silverman John D.、Ding Xuheng、Li Junyao et al. | ４．巻<br>922 |
| ２．論文標題<br>Optical Spectroscopy of Dual Quasar Candidates from the Subaru HSC-SSP program | ５．発行年<br>2021年 |
| ３．雑誌名<br>The Astrophysical Journal | ６．最初と最後の頁<br>83～83 |
| 掲載論文のDOI（デジタルオブジェクト識別子）<br>10.3847/1538-4357/ac1ff0 | 査読の有無<br>有 |
| オープンアクセス<br>オープンアクセスとしている（また、その予定である） | 国際共著<br>該当する |

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|---|---|
| 1．著者名<br>Silverman John D.、Tang Shenli et al. | 4．巻<br>899 |
| 2．論文標題<br>Dual Supermassive Black Holes at Close Separation Revealed by the Hyper Suprime-Cam Subaru Strategic Program | 5．発行年<br>2020年 |
| 3．雑誌名<br>The Astrophysical Journal | 6．最初と最後の頁<br>154～154 |
| 掲載論文のDOI（デジタルオブジェクト識別子）<br>10.3847/1538-4357/aba4a3 | 査読の有無<br>有 |
| オープンアクセス<br>オープンアクセスとしている（また、その予定である） | 国際共著<br>該当する |

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| 1．著者名<br>Ding Xuheng、Treu Tommaso、Silverman John D.、Bhowmick Aklant K.、Menci N.、Di Matteo Tiziana | 4．巻<br>896 |
| 2．論文標題<br>Testing the Fidelity of Simulations of Black Hole - Galaxy Coevolution at z ~ 1.5 with Observations | 5．発行年<br>2020年 |
| 3．雑誌名<br>The Astrophysical Journal | 6．最初と最後の頁<br>159～159 |
| 掲載論文のDOI（デジタルオブジェクト識別子）<br>10.3847/1538-4357/ab91be | 査読の有無<br>有 |
| オープンアクセス<br>オープンアクセスとしている（また、その予定である） | 国際共著<br>該当する |

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|---|---|
| 1．著者名<br>Ding Xuheng、Silverman John、Treu Tommaso、Schulze Andreas、Schramm Malte、Birrer Simon、Park Daeseong、Jahnke Knud、Bennert Vardha N.、Kartaltepe Jeyhan S.、Koekemoer Anton M.、Malkan Matthew A.、Sanders David | 4．巻<br>888 |
| 2．論文標題<br>The Mass Relations between Supermassive Black Holes and Their Host Galaxies at 1 < z < 2 with HST/WFC3 | 5．発行年<br>2020年 |
| 3．雑誌名<br>The Astrophysical Journal | 6．最初と最後の頁<br>37～37 |
| 掲載論文のDOI（デジタルオブジェクト識別子）<br>10.3847/1538-4357/ab5b90 | 査読の有無<br>有 |
| オープンアクセス<br>オープンアクセスとしている（また、その予定である） | 国際共著<br>該当する |

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|---|---|
| 1．著者名<br>Tang Shenli、Silverman John D、Yesuf Hassen M、Ding Xuheng、Li Junyao、Bottrell Connor、Goulding Andy、Omori Kiyoaki Christopher、Toba Yoshiki、Kawaguchi Toshihiro | 4．巻<br>521 |
| 2．論文標題<br>Morphological asymmetries of quasar host galaxies with Subaru Hyper Suprime-Cam | 5．発行年<br>2023年 |
| 3．雑誌名<br>Monthly Notices of the Royal Astronomical Society | 6．最初と最後の頁<br>5272～5297 |
| 掲載論文のDOI（デジタルオブジェクト識別子）<br>10.1093/mnras/stad877 | 査読の有無<br>有 |
| オープンアクセス<br>オープンアクセスではない、又はオープンアクセスが困難 | 国際共著<br>該当する |

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|---|---|
| 1．著者名<br>Nagele Chris、Silverman John D.、Hartwig Tilman、Li Junyao、Bottrell Connor、Ding Xuheng、Toba Yoshiki | 4．巻<br>947 |
| 2．論文標題<br>A Machine-learning Approach to Assessing the Presence of Substructure in Quasar-host Galaxies Using the Hyper Suprime-cam Subaru Strategic Program | 5．発行年<br>2023年 |
| 3．雑誌名<br>The Astrophysical Journal | 6．最初と最後の頁<br>30～30 |
| 掲載論文のDOI（デジタルオブジェクト識別子）<br>10.3847/1538-4357/acbd4a | 査読の有無<br>有 |
| オープンアクセス<br>オープンアクセスとしている（また、その予定である） | 国際共著<br>該当する |

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|---|---|
| 1．著者名<br>Silverman John D.、Li Junyao、Ding Xuheng | 4．巻<br>933 |
| 2．論文標題<br>Inferences on Relations between Distant Supermassive Black Holes and Their Hosts Complemented by the Galaxy Fundamental Plane | 5．発行年<br>2022年 |
| 3．雑誌名<br>The Astrophysical Journal | 6．最初と最後の頁<br>165～165 |
| 掲載論文のDOI（デジタルオブジェクト識別子）<br>10.3847/1538-4357/ac7648 | 査読の有無<br>有 |
| オープンアクセス<br>オープンアクセスとしている（また、その予定である） | 国際共著<br>該当する |

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| 1．著者名<br>Ding Xuheng、Silverman John D.、Treu Tommaso、Li Junyao、Bhowmick Aklant K.、Menci Nicola、Volonteri Marta、Blecha Laura、Matteo Tiziana Di、Dubois Yohan | 4．巻<br>933 |
| 2．論文標題<br>Concordance between Observations and Simulations in the Evolution of the Mass Relation between Supermassive Black Holes and Their Host Galaxies | 5．発行年<br>2022年 |
| 3．雑誌名<br>The Astrophysical Journal | 6．最初と最後の頁<br>132～132 |
| 掲載論文のDOI（デジタルオブジェクト識別子）<br>10.3847/1538-4357/ac714c | 査読の有無<br>有 |
| オープンアクセス<br>オープンアクセスとしている（また、その予定である） | 国際共著<br>該当する |

〔学会発表〕　計4件（うち招待講演　3件／うち国際学会　3件）

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| 1．発表者名<br>John Silverman |
| 2．発表標題<br>Quasar Host Galaxies with HSC-SSP, a precursor study for LSST |
| 3．学会等名<br>LSST AGN Workshop（招待講演）（国際学会） |
| 4．発表年<br>2021年 |

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| １．発表者名<br>John Silverman |
| ２．発表標題<br>Supermassive black holes: towards a holistic understanding in our universe |
| ３．学会等名<br>ICRR/KIPMU public lecture（招待講演） |
| ４．発表年<br>2020年 |

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| １．発表者名<br>John Silverman |
| ２．発表標題<br>Global coordination of ground and Space astrophysics: black hole science |
| ３．学会等名<br>IAU（招待講演）（国際学会） |
| ４．発表年<br>2022年 |

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|---|
| １．発表者名<br>John Silverman |
| ２．発表標題<br>Connections between supermassive black holes, host galaxies and their dark matter halos |
| ３．学会等名<br>Euclid AGN science meeting, Naples（国際学会） |
| ４．発表年<br>2022年 |

〔図書〕　計0件

〔産業財産権〕

〔その他〕

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６．研究組織

| | 氏名<br>（ローマ字氏名）<br>（研究者番号） | 所属研究機関・部局・職<br>（機関番号） | 備考 |
|---|---|---|---|

７．科研費を使用して開催した国際研究集会

〔国際研究集会〕　計0件

８．本研究に関連して実施した国際共同研究の実施状況

| 共同研究相手国 | 相手方研究機関 | | | |
|---|---|---|---|---|
| 米国 | University of California, Los Angeles | Princeton University | | |
| ドイツ | Max Planck Institute for Astronomy | | | |