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# 科学研究費助成事業　　研究成果報告書

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研究課題名（和文）An Independent Test of the Hubble Constant Tension with Time-Delay Cosmography

研究課題名（英文）An Independent Test of the Hubble Constant Tension with Time-Delay Cosmography

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研究成果の概要（和文）：私の研究は強重力レンズ(重力による光線の偏向)を使用して宇宙の物理的特性を研究することに焦点を当てています。遠いクェーサーのレンズイメージを観測して、宇宙の膨張率を測ります。「ハッブル定数」と呼ばれるこの値は、物理学の理解に重要な意味を持ち、様々な議論が成されています。私はTDCOSMOの一環として働いて、今までに重力レンズを使用したハッブル定数の最も正確な測定を行いました。さらに、私はすばるHSCサーベイの強重力レンズワーキンググループのリーダーを務めています。このサーベイでは、私は従来の方法と機械学習の両方を使用し、すでに何百もの新たな重力レンズ天体を発見し、さらなる発見が期待されます。

研究成果の学術的意義や社会的意義
The expansion rate of the Universe has major implications for its age, energy content, and future. My research using gravitational lensing to calculate the expansion rate provides a key independent measurement to check for error in other methods, which have been in tension with each other.

研究成果の概要（英文）：My research primarily focuses on using strong gravitational lensing (the deflection of light rays by gravity) to study the physical properties of our Universe.  By using strongly-lensed images of distant quasars, I worked to constrain the expansion rate of the Universe.  This value, called the "Hubble constant", is highly debated, and has important implications for our understanding of physics.  I have been working as part of the TDCOSMO collaboration, which has provided the most precise measurement of the Hubble constant using strong gravitational lensing to date.  In addition, I have been a leader of the strong lensing working group for the Subaru Hyper Suprime-Cam survey.  This large imaging survey provides a great opportunity to search for new strong lenses for a variety of science goals.  I have worked on lens searches in the HSC survey using both traditional algorithms and new machine-learning approaches, helping to discover hundreds of new gravitational lenses.

研究分野：cosmology; astronomy

キーワード：cosmology　gravitational lensing　extragalactic astronomy

## １．研究開始当初の背景

(1) Our best current cosmological model is consistent with many observational probes. Recently however, a >5σ tension has emerged in measurements of the expansion rate of the Universe (the “Hubble constant”, $H_0$) inferred from observations of the cosmic microwave background (CMB) compared to that inferred from the “distance ladder” in the local Universe. If unresolved, this tension may lead to a rejection of our cosmological model (the so-called “flat $\Lambda$CDM” model) in favor of new physics. Strong gravitational lensing of a background quasar by an intervening galaxy allows us to measure the “time delay”between the multiple images. By measuring the time delay and accurately modeling the mass distribution of the lens galaxy, we can determine $H_0$ independent of the CMB and the distance ladder. This technique, called “time-delay cosmography”, can provide a key independent constraint to test for systematic uncertainties in the other methods.

(2) Strong gravitational lenses are useful not just for cosmology but for a variety of science goals including studies of galaxies, dark matter, and the evolution of structure. However, strong lenses are rare, requiring a chance alignment of a massive galaxy with a bright background source. The best datasets to search for lenses are deep, wide, multiband imaging surveys. The Hyper Suprime-Cam Subaru Strategic Program (HSC SSP) is an ideal dataset for this purpose, as it covers a large area (>1000 $deg^2$) of the sky with five filters (*grizy*-bands) to very faint depths. However, searching such large datasets manually is unfeasible, so various search methods need to be developed. Increasing the overall sample size will have benefits for all of the above science goals.

## ２．研究の目的

(1) As part of the TDCOSMO collaboration, I have worked to construct mass models of several lensed quasars to determine $H_0$. These mass models are constrained by high-resolution imaging data, as well as spectroscopy to characterize the kinematics of the galaxy and an estimate of the mass along the line of sight to the lens. Our goal is to obtain a precise constraint on $H_0$ that is competitive with probes such as the CMB and distance ladder. Our most recent results can constrain $H_0$ to ~2% assuming certain parameterized lensed mass profiles, or a maximally conservative ~8% constraint if we relax this assumption. Reaching ~1% precision from a sample of ~40 time delay lenses is the long-term goal, putting this method at a similar precision to the best other methods.

(2) I have been working as part of the HSC SSP Strong Lensing Working Group to search for new gravitational lenses. We use a variety of search methods, including automated algorithms, citizen science, and machine learning. Since strong lenses are rare, discovering them in large imaging surveys is the most efficient way to increase the sample size for a variety of science goals. We expect to discover several hundred lensed galaxies, at both the galaxy- and group/cluster-scale, as well as ~tens of lensed quasars. The lensed quasars we discover in the HSC SSP could potentially be used for time-delay cosmography with future follow-up observations.

## ３．研究の方法

(1) I have used high-resolution imaging from the *Hubble Space Telescope* (*HST*) to constrain the mass models of lensing galaxies in the TDCOSMO sample. Such imaging is required to accurately constrain the slope of the mass profile of the lens, and to separate out the bright quasar light from the underlying host galaxy. I used the lens modeling code “GLEE” (Suyu & Halkola 2010; Suyu et al. 2012) to model the lens system WGD 2038-4008. I am also working on modeling of three additional systems that will be published in the future. I also use the Subaru telescope to obtain spectroscopy on future lens systems that may be added to the TDCOSMO sample.

(2) To discover new lenses in the HSC SSP, I have used both automated arc-finding algorithms and machine learning techniques. I have run the arc-finding algorithm “YattaLens” (Sonnenfeld et al. 2018) on the latest data release to find new lens candidates and classify them. I also use machine learning tools such as TensorFlow to develop a convolutional neural network (CNN) for lens finding.

## ４．研究成果

(1) As part of TDCOSMO, I was one of the primary authors on a lens model comparison of the lensed quasar WGD 2038-4008 (Shajib et al. 2022). I led one of two independent teams to predict the time delay of this lens (which had not yet been measured at the time) using both a power-law and composite (stars+dark matter) model. The purpose of having two independent teams model this system was to evaluate systematic uncertainties associated with the choice of lens modeling codes and assumptions. At the moment, systematic uncertainties are the primary limitation, and this was a key test of one of the most important parts of the analysis. Our results show that the predicted time delays (and therefore, cosmological constraints) between the two teams agree to within ~1σ.

(2) Following a new measurement of the time delay for the WGD 2038-4008 system, I am leading a

cosmological inference from this lens using the models previously developed. The analysis is complete, and the paper has been submitted for publication (Wong et al. 2024, submitted). I performed the inference on the time-delay distance and $H_0$ for this paper, and we obtain a constraint of $H_0$ = 65.6 +22.6/-13.8 km/s/Mpc (Figure 1) in a flat $\Lambda$CDM cosmology. The uncertainty is dominated by the time delay measurement uncertainty due to the low variability of the source quasar. Nevertheless, this lens will contribute to an upcoming TDCOSMO hierarchical analysis of the entire lens sample that will provide the most robust constraint to date on $H_0$ from time-delay cosmography.

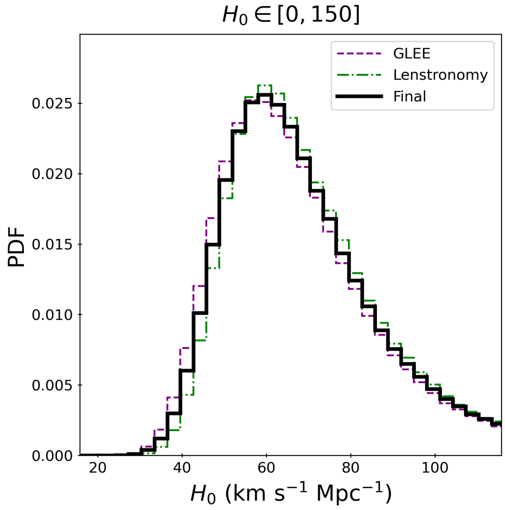


**Figure 1:** Constraint on $H_0$ from the lensed quasar WGD 2038-4008 (Wong et al. 2024, submitted). We find $H_0$ = 65.6 +22.6/-13.8 km/s/Mpc in a flat $\Lambda$CDM cosmology.

(3) I proposed for and was awarded observing time on the Subaru telescope to use the FOCAS instrument to obtain spectroscopy of several lenses that will be added to the TDCOSMO sample. These lensed quasars lack redshifts for the lens galaxy, which is crucial for converting angular quantities from lens modeling to physical quantities. Although I was awarded four separate observing nights, one of them was lost due to weather, and two others were lost due to technical problems at Subaru. Despite only getting a fraction of the time I had been awarded, I was able to measure new redshifts for four lensed quasars. These lenses already have all of the other necessary data to be analyzed, and will be a part of the TDCOSMO cosmological sample in the future.

(4) As a leader in the HSC SSP Strong Lensing Working Group, I have been involved in several recent papers with hundreds of newly-discovered strong lens candidates from the survey (Chan et al. 2020, 2024; Jaelani et al. 2020, 2024 submitted; Sonnenfeld et al. 2020). I personally led one of these lens searches using the arc-finding algorithm YattaLens, which resulted in the discovery of tens of new galaxy-scale lens candidates (Wong et al. 2022).

(5) I mentored an undergraduate student, Yuichiro Ishida (now a graduate student at the University of Tokyo), on a project to develop a machine-learning based lens search in the HSC SSP. He worked to develop a CNN (Figure 2) that has already been included as part of a comparison of various lens search algorithms (Holloway et al. 2024) and will also be included in an upcoming comparison of lens-finding CNNs (More et al. 2024, submitted). Under my supervision, he also developed a new technique to subtract the central galaxy light from the input imaging sample before training. The purpose of this is to enhance the contrast between any lensed images and the background. By combining this galaxy-subtracted images with the original fiducial images, he found that the performance of his CNN could be improved compared to training on just the original data. This technique can be applied to future lens searches using CNNs to improve classification performance. He led a paper on this project that has been submitted for publication (Ishida et al. 2024, submitted).

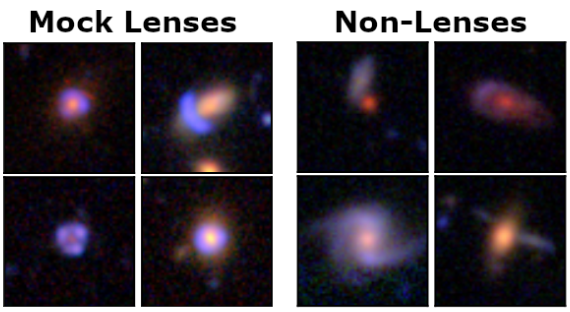


**Figure 2**: Sample mock lenses (*left*) and non-lenses (*right*) constructed using HSC SSP imaging data that has been used to train CNNs that have discovered hundreds of new lenses in the dataset (Jaelani et al. 2024, submitted). These objects are also used as part of the training sample for a lens-finding CNN being developed by Ishida et al. (2024, submitted).

５．主な発表論文等

〔雑誌論文〕　計16件（うち査読付論文　15件／うち国際共著　16件／うちオープンアクセス　1件）

| | |
|---|---|
| １．著者名<br>Wong Kenneth C、Chan James H H、Chao Dani C-Y、Jaelani Anton T、Kayo Issha、Lee Chien-Hsiu、More Anupreeta、Oguri Masamune | ４．巻<br>74 |
| ２．論文標題<br>Survey of Gravitationally lensed objects in HSC Imaging (SuGOHI). VIII. New galaxy-scale lenses from the HSC-SSP | ５．発行年<br>2022年 |
| ３．雑誌名<br>Publications of the Astronomical Society of Japan | ６．最初と最後の頁<br>1209～1219 |
| 掲載論文のDOI（デジタルオブジェクト識別子）<br>10.1093/pasj/psac065 | 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>Shajib A. J.、Wong K. C.、Birrer S.、Suyu S. H.、Treu T.、Buckley-Geer E. J.、Lin H.、Rusu C. E.、Poh J.、Palmese A.、Agnello A.、Auger-Williams M. W.、Galan A.、Schuldt S.、Sluse D.、Courbin F.、Frieman J.、Millon M. | ４．巻<br>667 |
| ２．論文標題<br>TDCOSMO. IX. Systematic comparison between lens modelling software programs: time delay prediction for WGD 2038-4008 | ５．発行年<br>2022年 |
| ３．雑誌名<br>Astronomy & Astrophysics | ６．最初と最後の頁<br>A123～A123 |
| 掲載論文のDOI（デジタルオブジェクト識別子）<br>10.1051/0004-6361/202243401 | 査読の有無<br>有 |
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| １．著者名<br>Wong Kenneth C. | ４．巻<br>6 |
| ２．論文標題<br>A star from the dawn of the Universe | ５．発行年<br>2022年 |
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| 掲載論文のDOI（デジタルオブジェクト識別子）<br>10.1038/s41550-022-01674-3 | 査読の有無<br>無 |
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| １．著者名<br>Chan James H. H.、Suyu Sherry H.、Sonnenfeld Alessandro、Jaelani Anton T.、More Anupreeta、Yonehara Atsunori、Kubota Yuriko、Coupon Jean、Lee Chien-Hsiu、Oguri Masamune、Rusu Cristian E.、Wong Kenneth C. | ４．巻<br>636 |
| ２．論文標題<br>Survey of Gravitationally lensed Objects in HSC Imaging (SuGOHI). IV. Lensed quasar search in the HSC survey | ５．発行年<br>2020年 |
| ３．雑誌名<br>Astronomy & Astrophysics | ６．最初と最後の頁<br>A87～A87 |
| 掲載論文のDOI（デジタルオブジェクト識別子）<br>10.1051/0004-6361/201937030 | 査読の有無<br>有 |
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| 1．著者名<br>Jaelani Anton T、More Anupreeta、Sonnenfeld Alessandro、Oguri Masamune、Rusu Cristian E、Wong Kenneth C、Chan James H H、Suyu Sherry H、Kayo Issha、Lee Chien-Hsiu、Inoue Kaiki T | 4．巻<br>494 |
| 2．論文標題<br>Discovery of an unusually compact lensed Lyman-break galaxy from the Hyper Suprime-Cam Survey | 5．発行年<br>2020年 |
| 3．雑誌名<br>Monthly Notices of the Royal Astronomical Society | 6．最初と最後の頁<br>3156～3165 |
| 掲載論文のDOI（デジタルオブジェクト識別子）<br>10.1093/mnras/staa583 | 査読の有無<br>有 |
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| 1．著者名<br>Shajib A J, et al. (incl. Wong Kenneth C) | 4．巻<br>494 |
| 2．論文標題<br>STRIDES: a 3.9 per cent measurement of the Hubble constant from the strong lens system DES J0408-5354 | 5．発行年<br>2020年 |
| 3．雑誌名<br>Monthly Notices of the Royal Astronomical Society | 6．最初と最後の頁<br>6072～6102 |
| 掲載論文のDOI（デジタルオブジェクト識別子）<br>10.1093/mnras/staa828 | 査読の有無<br>有 |
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| 1．著者名<br>Jaelani Anton T、More Anupreeta、Oguri Masamune、Sonnenfeld Alessandro、Suyu Sherry H、Rusu Cristian E、Wong Kenneth C、Chan James H H、Kayo Issha、Lee Chien-Hsiu、Chao Dani C-Y、Coupon Jean、Inoue Kaiki T、Futamase Toshifumi | 4．巻<br>495 |
| 2．論文標題<br>Survey of Gravitationally lensed Objects in HSC Imaging (SuGOHI) - V. Group-to-cluster scale lens search from the HSC-SSP Survey | 5．発行年<br>2020年 |
| 3．雑誌名<br>Monthly Notices of the Royal Astronomical Society | 6．最初と最後の頁<br>1291～1310 |
| 掲載論文のDOI（デジタルオブジェクト識別子）<br>10.1093/mnras/staa1062 | 査読の有無<br>有 |
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|---|---|
| 1．著者名<br>Arendse Nikki、Wojtak Radoslaw J.、Agnello Adriano、Chen Geoff C.-F.、Fassnacht Christopher D.、Sluse Dominique、Hilbert Stefan、Millon Martin、Bonvin Vivien、Wong Kenneth C.、Courbin Frederic、Suyu Sherry H.、Birrer Simon、Treu Tommaso、Koopmans Leon V. E. | 4．巻<br>639 |
| 2．論文標題<br>Cosmic dissonance: are new physics or systematics behind a short sound horizon? | 5．発行年<br>2020年 |
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| 掲載論文のDOI（デジタルオブジェクト識別子）<br>10.1051/0004-6361/201936720 | 査読の有無<br>有 |
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| １．著者名<br>Millon M., et al. (incl. Wong Kenneth C) | ４．巻<br>639 |
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| ３．雑誌名<br>Astronomy & Astrophysics | ６．最初と最後の頁<br>A101～A101 |
| 掲載論文のDOI（デジタルオブジェクト識別子）<br>10.1051/0004-6361/201937351 | 査読の有無<br>有 |
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| １．著者名<br>Sonnenfeld Alessandro, et al. (incl. Wong Kenneth C) | ４．巻<br>642 |
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| ２．論文標題<br>Survey of Gravitationally-lensed Objects in HSC Imaging (SuGOHI). VI. Crowdsourced lens finding with Space Warps | ５．発行年<br>2020年 |
| ３．雑誌名<br>Astronomy & Astrophysics | ６．最初と最後の頁<br>A148～A148 |
| 掲載論文のDOI（デジタルオブジェクト識別子）<br>10.1051/0004-6361/202038067 | 査読の有無<br>有 |
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| １．著者名<br>Tihhonova O、Courbin F、Harvey D、Hilbert S、Peel A、Rusu C E、Fassnacht C D、Bonvin V、Marshall P J、Meylan G、Sluse D、Suyu S H、Treu T、Wong K C | ４．巻<br>498 |
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| ２．論文標題<br>HOLiCOW - XI. A weak lensing measurement of the external convergence in the field of the lensed quasar B1608+656 using HST and Subaru deep imaging | ５．発行年<br>2020年 |
| ３．雑誌名<br>Monthly Notices of the Royal Astronomical Society | ６．最初と最後の頁<br>1406～1419 |
| 掲載論文のDOI（デジタルオブジェクト識別子）<br>10.1093/mnras/staa1436 | 査読の有無<br>有 |
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| １．著者名<br>Rusu Cristian E、Wong Kenneth C、Bonvin Vivien、Sluse Dominique、Suyu Sherry H、Fassnacht Christopher D、Chan James H H、Hilbert Stefan、Auger Matthew W、Sonnenfeld Alessandro、Birrer Simon、Courbin Frederic、Treu Tommaso、Chen Geoff C-F、Halkola Aleksi、Koopmans Leon V E、Marshall Philip J、Shajib Anowar J | ４．巻<br>498 |
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| ３．雑誌名<br>Monthly Notices of the Royal Astronomical Society | ６．最初と最後の頁<br>1440～1468 |
| 掲載論文のDOI（デジタルオブジェクト識別子）<br>10.1093/mnras/stz3451 | 査読の有無<br>有 |
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| 1．著者名<br>Birrer S., et al. (incl. Wong Kenneth C) | 4．巻<br>643 |
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| 2．論文標題<br>TDCOSMO. IV. Hierarchical time-delay cosmography - joint inference of the Hubble constant and galaxy density profiles | 5．発行年<br>2020年 |
| 3．雑誌名<br>Astronomy & Astrophysics | 6．最初と最後の頁<br>A165～A165 |
| 掲載論文のDOI（デジタルオブジェクト識別子）<br>10.1051/0004-6361/202038861 | 査読の有無<br>有 |
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| 1．著者名<br>Buckley-Geer E J、et al. (incl. Wong Kenneth C) | 4．巻<br>498 |
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| 2．論文標題<br>STRIDES: Spectroscopic and photometric characterization of the environment and effects of mass along the line of sight to the gravitational lenses DES J0408-5354 and WGD 2038-4008 | 5．発行年<br>2020年 |
| 3．雑誌名<br>Monthly Notices of the Royal Astronomical Society | 6．最初と最後の頁<br>3241～3274 |
| 掲載論文のDOI（デジタルオブジェクト識別子）<br>10.1093/mnras/staa2563 | 査読の有無<br>有 |
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| 1．著者名<br>Ding Xuheng、Treu Tommaso、Birrer Simon、Agnello Adriano、Sluse Dominique、Fassnacht Chris、Auger Matthew W、Wong Kenneth C、Suyu Sherry H、Morishita Takahiro、Rusu Cristian E、Galan Aymeric | 4．巻<br>501 |
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| 2．論文標題<br>Testing the evolution of correlations between supermassive black holes and their host galaxies using eight strongly lensed quasars | 5．発行年<br>2020年 |
| 3．雑誌名<br>Monthly Notices of the Royal Astronomical Society | 6．最初と最後の頁<br>269～280 |
| 掲載論文のDOI（デジタルオブジェクト識別子）<br>10.1093/mnras/staa2992 | 査読の有無<br>有 |
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| 1．著者名<br>Jaelani Anton T、Rusu Cristian E、Kayo Issha、More Anupreeta、Sonnenfeld Alessandro、Silverman John D、Schramm Malte、Anguita Timo、Inada Naohisa、Kondo Daichi、Schechter Paul L、Lee Khee-Gan、Oguri Masamune、Chan James H H、Wong Kenneth C、Inoue Kaiki T | 4．巻<br>502 |
|---|---|
| 2．論文標題<br>Survey of Gravitationally Lensed Objects in HSC Imaging (SuGOHI) - VII. Discovery and confirmation of three strongly lensed quasars | 5．発行年<br>2021年 |
| 3．雑誌名<br>Monthly Notices of the Royal Astronomical Society | 6．最初と最後の頁<br>1487～1493 |
| 掲載論文のDOI（デジタルオブジェクト識別子）<br>10.1093/mnras/stab145 | 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 |

〔学会発表〕　計7件（うち招待講演　6件／うち国際学会　7件）

| | |
|---|---|
| 1．発表者名<br>Kenneth Wong | |
| 2．発表標題<br>An Independent Measurement of H0 from Lensed Quasars | |
| 3．学会等名<br>Exploring the Dark Universe（招待講演）（国際学会） | |
| 4．発表年<br>2022年 | |

| | |
|---|---|
| 1．発表者名<br>Kenneth Wong | |
| 2．発表標題<br>An Independent Measurement of the Hubble Constant from Lensed Quasars | |
| 3．学会等名<br>Gravity: Current challenges in black hole physics and cosmology（招待講演）（国際学会） | |
| 4．発表年<br>2022年 | |

| | |
|---|---|
| 1．発表者名<br>Kenneth Wong | |
| 2．発表標題<br>TDCOSMO: Lens modelling software comparison and time delay prediction for WGD 2038-4008 | |
| 3．学会等名<br>International Astronomical Union XXXIst General Assembly（国際学会） | |
| 4．発表年<br>2022年 | |

| | |
|---|---|
| 1．発表者名<br>Kenneth Wong | |
| 2．発表標題<br>Measurement of the Hubble Constant from Lensed Quasars | |
| 3．学会等名<br>Astronomical Society of Japan Spring 2022 Annual Meeting（招待講演）（国際学会） | |
| 4．発表年<br>2022年 | |

| |
|---|
| **1．発表者名**<br>Kenneth Wong |
| **2．発表標題**<br>Measurement of the Hubble Constant from Lensed Quasars |
| **3．学会等名**<br>Exploring the Dark Universe（招待講演）（国際学会） |
| **4．発表年**<br>2022年 |

| |
|---|
| **1．発表者名**<br>Kenneth Wong |
| **2．発表標題**<br>An Independent Measurement of H0 from Lensed Quasars |
| **3．学会等名**<br>American Physical Society Virtual Meeting April 2020（招待講演）（国際学会） |
| **4．発表年**<br>2020年 |

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|---|
| **1．発表者名**<br>Kenneth Wong |
| **2．発表標題**<br>An Independent Measurement of H0 from Lensed Quasars |
| **3．学会等名**<br>Assessing uncertainties in Hubble ’ s constant across the Universe（招待講演）（国際学会） |
| **4．発表年**<br>2020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 | UCLA | UC Davis | University of Chicago | 他3機関 |
| ドイツ | Max Planck Institute for Astrophysics | Techinical University of Munich | | |
| ベルギー | University of Liege | | | |
| スイス | EPFL | | | |
| インド | IUCAA | | | |
| インドネシア | Institut Teknologi Bandung | | | |
| チリ | European Southern Observatory | | | |
| イタリア | INAF - Milan | | | |