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研究課題名（英文）The evolution of the stellar IMF with HSC strong lenses

研究代表者
Ｓｏｎｎｅｎｆｅｌｄ　Ａｌｅｘ（Sonnenfeld, Alex）

東京大学・カブリ数物連携宇宙研究機構・特任研究員

研究者番号：４０７７２８２７

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研究成果の概要（和文）：銀河の恒星質量は、通常光度を測定し恒星集団モデルより導出される質量対光比率を掛けて得られる。この比率の最も大きな系統誤差の1つは恒星初期質量関数（IMF）である。強いレンズ重力効果の測定により銀河の内部領域の総質量が得られる。慎重に全質量から暗黒物質の寄与を差引くと、恒星質量を得ることができ、恒星集団モデルと比較して恒星IMFを制約することができる。Hyper Suprime-Camのサーベイデータを使って23個の強い重力レンズ効果のサンプルを研究した。まず超大型望遠鏡の分光測定結果を得て、次にサンプルの恒星IMFの統計的研究を行ったことで巨大銀河の恒星IMFは以前ほど重くないことが判明した。

研究成果の学術的意義や社会的意義
恒星IMFは一般に銀河質量測定における系統誤差の最も重要な要因の1つと見なされている。これにより、銀河進化や宇宙論研究での理論モデルと数値シミュレーションの比較の精度が制約される。過去10年間で、理論的および観測的側面で恒星IMFに関する研究が数多く行われてきた。これらの努力にもかかわらず、真の恒星IMFとは何か、そしてそれがどのように銀河間で異なるのかについて合意には至っていない。この課題では以前と比較してより少ない仮定で確実な巨大銀河の恒星IMFの新しい測定を提供した。私たちは、新しい観測施設が利用可能になるまでの今後数年間、強い重力レンズ効果による恒星IMFが基準測定値になると期待する。

研究成果の概要（英文）：Galaxy stellar masses are typically obtained by measuring their luminosity and multiplying it by a mass-to-light ratio derived from a model of their stellar population.One of the biggest systematic uncertainties in the determination of this mass-to-light ratio is the stellar initial mass function (IMF).
The stellar IMF can be constrained using strong gravitational lensing. A strong lensing measurement provides the total mass enclosed within the inner regions of a galaxy. By carefully subtracting the dark matter contribution from the total mass, we can obtain the stellar mass,which can then be compared to stellar population models to constrain the IMF.
We studied a sample of 23 strong lenses with data from the Hyper Suprime-Cam survey. We first obtained spectroscopic measurements from the Very Large Telescope, then carried out a statistical study of the stellar IMF of the sample. Our measurement show that the stellar IMF of massive galaxies is not as heavy as previously thought.

研究分野：Formation and evolution of massive galaxies

キーワード：Galaxies　Strong lensing　Stellar populations

１．研究開始当初の背景

Galaxy stellar masses are typically obtained by measuring their luminosity and multiplying it by a mass-to-light ratio derived from a model of their stellar population.One of the biggest systematic uncertainties in the determination of this mass-to-light ratio is the stellar initial mass function (IMF), which sets the relative abundance of stars of different mass.While in the Milky Way the stellar IMF is observed to be more or less universal, measurements in massive elliptical galaxies seem to indicate how the stellar IMF in these objects is significantly heavier compared to our galaxy, leading to differences in mass-to-light ratio of a factor of two.However, some observational studies show contrasting results: the true stellar IMF in galaxies other than the Milky Way is still highly uncertain.

２．研究の目的

The main goal of the project is to obtain an accurate measurement of the stellar IMF of massive elliptical galaxies from strong gravitational lensing.A strong lensing measurement provides the total mass enclosed within the inner regions of a galaxy. By carefully subtracting the dark matter contribution from this total mass, we can obtain the stellar mass, which can then be compared to stellar population models to constrain the IMF.

３．研究の方法

The main requirements for carrying out this project are 1) a statistically large sample of strong lenses, 2) spectroscopic measurements of the lenses in the sample, 3) a method and data that can be used to separate the contribution of luminous and dark matter to the total mass obtained from strong lensing.

We obtained our strong lenses from the Survey of Gravitationally-lensed Objects in HSC Imaging (SuGOHI, Sonnenfeld et al. 2018, see Figure 1). We carried out spectroscopic follow-up observations of 9 such lenses with the X-Shooter spectrograph on the Very Large Telescope (ESO Program 099.A-0220, PI Suyu). Combining this data with measurements from the literature, we had a sample of 23 lenses with spectroscopic data necessary for a strong lensing study. For each lens, we measured the stellar mass and the Einstein radius of the lens galaxy, which provides the total projected mass within the area enclosed by the multiple images of the strongly lensed source.

In parallel, we carried out a weak lensing study to infer the distribution of dark matter halo mass of massive elliptical galaxies, as a function of stellar mass. This measurement was needed to remove the contribution of dark matter from the total mass in the inner region of a galaxy measured from strong lensing.

Finally, we statistically combined the stellar mass and Einstein radius measurements of the strong lenses in our sample to infer the distribution in the stellar IMF mismatch parameter,defined as the ratio between the true stellar mass of a galaxy and that obtained assuming a reference IMF, of the population of massive elliptical galaxies. We used our weak lensing constraints to put a prior on the dark matter mass of each lens.

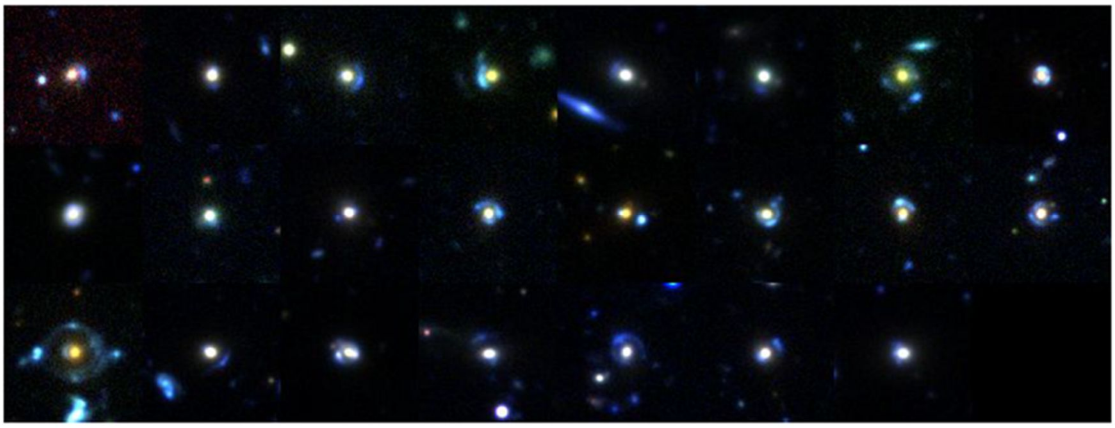
Figure 1: color-composite images of the 23 strong lenses used for the main study of the project.

４．研究成果

We inferred the posterior probability distribution of the average IMF mismatch parameter of the population of massive galaxies. This is shown in Figure 2.

After accounting for strong lensing selection effects, our analysis reveals that the stellar IMF of the population of elliptical galaxies is consistent with that of a Chabrier IMF, commonly used to describe the IMF of the Milky Way, and in tension with a Salpeter IMF, which was favored by previous strong lensing studies.

This apparent discrepancy between our study and previous measurements from the literature is due to the type of data used for the analysis. Our measurement is based on a combination of strong and weak gravitational lensing, while previous measurements used strong lensing and stellar kinematics. Stellar kinematics is particularly sensitive to the presence of gradients in the stellar mass-to-light ratio of the galaxy, which can bias the IMF mismatch parameter towards larger values if not accounted for. Strong and weak lensing are not sensitive to mass-to-light ratio gradients, therefore we consider our measurement to be more robust.

The statistical methods used for the analysis were developed specifically for this project. These include innovative elements, such as the use of a Bayesian hierarchical approach for the weak lensing part of the project and the use of posterior predictive tests as a way of checking the goodness-of-fit and improving the model. The impact of these methods will go beyond the scope of this project, as they will serve as the basis for more complex analyses with future datasets, such as lens samples from the LSST and Euclid.

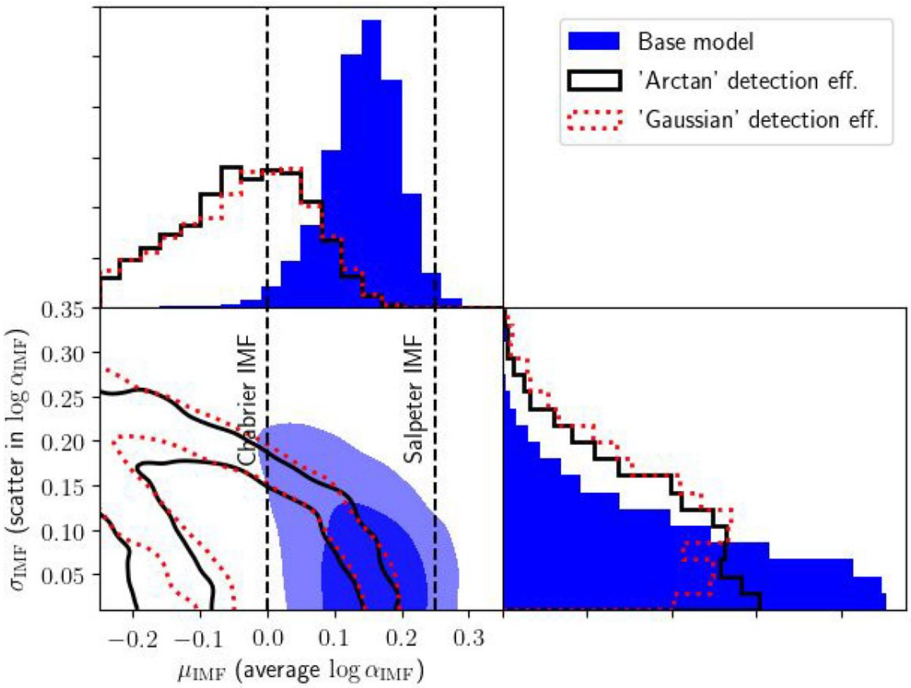

Figure 2: posterior probability distribution of the parameters describing the stellar IMF mismatch parameter of massive elliptical galaxies. Filled contours: base (simplified) model. Solid lines and red-dotted lines: final model, obtained with two different choices of the model used to describe the strong lens detection efficiency of our lensing survey. Contour levels mark the 68% and 95% enclosed probability regions.

５．主な発表論文等

〔雑誌論文〕（計５件）

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○ Wong, Kenneth C.; Sonnenfeld, Alessandro; Chan, James H. H.; Rusu, Cristian E.; Tanaka, Masayuki; Jaelani, Anton T.; Lee, Chien-Hsiu; More, Anupreeta; Oguri, Masamune; Suyu, Sherry H.; Komiyama, Yutaka: “Survey of Gravitationally Lensed Objects in HSC Imaging (SuGOHI). II. Environments and Line-of-Sight Structure of Strong Gravitational Lens Galaxies to z~0.8”, The Astrophysical Journal, 2018, 867:107, doi:10.3847/1538-4357/aae381, Refereed

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〔学会発表〕（計４件）

◯ Sonnenfeld Alessandro, “HSC view of the CMASS galaxy sample”, Australia-ESO 2019 conference “Linking galaxies” (Sydney, Australia), 2019

○ Sonnenfeld Alessandro, “Accurate dark matter halo masses in the precision cosmology era”, Sugarrush (Shanghai Jiao Tong University, China), 2018
○ Sonnenfeld Alessandro, “Luminous and dark matter in massive galaxies with strong and weak gravitational lensing”, Rencontres du Vietnam (Phu-Quoc, Vietnam), 2018
○ Sonnenfeld Alessandro, “Revisiting the dark matter halo-stellar IMF degeneracy”, East Asian Young Astronomers Meeting (Ishigaki, Japan), 2017

〔図書〕（計 0 件）

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○出願状況（計 0 件）

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番号：
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国内外の別：

○取得状況（計　　件）

名称：
発明者：
権利者：
種類：
番号：
取得年：
国内外の別：

〔その他〕
ホームページ等

６．研究組織

(1)研究分担者
研究分担者氏名：

ローマ字氏名：

所属研究機関名：

部局名：

職名：
研究者番号（8 桁）：

(2)研究協力者
研究協力者氏名：
ローマ字氏名：

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