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研究課題名（和文）The identification and distribution of warm dark matter subhalos

研究課題名（英文）The identification and distribution of warm dark matter subhalos

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研究成果の概要（和文）：宇宙を構成する暗黒物質は、重力によって宇宙の構造形成に寄与する。コンピュータを用いた大規模シミュレーションにより、ハローと呼ばれる暗黒物質が空間的に密集している領域を形成することが明らかになった。ハローの内部には、さらにサブハローと呼ばれる小質量塊が形成され、銀河をホストするとされている。この研究の目的は、ハローの内部構造やサブハローの分布を調べることにより暗黒物質の性質をより詳細に明らかにすることである。そのためにまずサブハローを同定する新しいアルゴリズムを開発し、その後ハローやサブハローの詳細について統計的な研究を行い、ハローの分布とその内部構造は複雑に関わりあっていることが明らかにした。

研究成果の学術的意義や社会的意義
本研究で開発したサブハローを同定するアルゴリズムは、この種のアルゴリズムの中で最も信頼性の高いアルゴリズムの一つであり、重力レンズ効果を用いた観測結果と数値シミュレーションにおけるサブハローの分布に関しての相違を明らかにした。また、機械学習を用いることで、本研究で初めてハローの内部構造と大規模構造の相関関係が、従来考えられていたよりも複雑であることも明らかにした。それ以外にもハローの中のサブハローの分布を詳細に調べることで、サテライト銀河を用いたハロー質量の計測手法を開発し、ミルキーウェイの質量を計測する新しい手法の開発に成功した。この手法は、従来の手法に比べてより精度の高い測定を可能にした。

研究成果の概要（英文）：The main matter content of the Universe is in the form of the so-called dark matter, that is invisible to us but affects the structure of the Universe through its gravitational effect. Although the nature of dark matter is still unknown, computer simulations can tell us that dark matter in the Universe tend to exist in dense clumps called dark matter halos, that contain plenty of subclumps called subhalos. This project aims at studying the distribution of dark matter on these halo and subhalo scales, to shed light on the nature of dark matter. We first develop a novel computer program to extract subhalos from simulations, and then study various statistical properties of these halos and subhalos. We have found the largescale distribution of halos cares about their internal structures in a complex way, while the distribution and motion of subhalos inside each halo follow universal profiles. We have used these universal profiles to accurately map out the dark matter mass in our galaxy.

研究分野：distribution of dark matter around halo scales

キーワード：dark matter halo　subhalo　numerical simulation　dynamical model

１．研究開始当初の背景

Figure 1. The projected density image of a Milky Way sized halo (from the Aquarius simulations) simulated with cold (left) and warm dark matter (right).

Recent progresses in high resolution numerical simulation and near field cosmological observations have posted a few serious challenges to the standard cosmological model, commonly known as the “small scale crisis”. Among these, both the “missing satellite” problem and the “too big to fail” problem concern the over-abundance of subhalos produced in simulations compared to the observed population of satellites. Solving these problems require better numerical and analytical understandings of the dark matter distribution around subhalo scale. One promising way to resolve these problems is by replacing cold dark matter (CDM) with warm dark matter (WDM) in the standard model. Due to the suppressed small scale power in the WDM universe, a WDM halo harbors much fewer substructures than its CDM counterpart (Figure 1), automatically avoiding the small-scale problems.

Despite this, numerical problems are preventing simulations from efficiently resolving the small-scale structure of the WDM universe. The most well-known problem is the production of “spurious halos”—objects that form inside filaments and halos due to numerical noise. A method to efficiently remove these spurious objects from the halo catalogue has become a major technical barrier in the field.

On the other hand, the interpretation of these small-scale crises rely heavily on our knowledge of the total dark matter distribution in the Milky Way halo. Existing results in the literature differ from each other by a typical factor of two. A significant part of these differences can be attributed to systematic uncertainties among different methods. Accurate methods with small systematic biases are needed to better estimate the dark matter distribution in our Galaxy.

２．研究の目的

The purpose of this research is to study the formation and distribution of dark matter subhalos. I expect to develop a new technique to find subhalos that can be applied to warm dark matter simulations while avoiding contamination from “spurious halos”. I will also build analytical models for the mass, spatial and velocity distribution of halos and subhalos, which will be subsequently applied to interpret small scale observations of the universe to shed light on the particle properties of dark matter.

３．研究の方法

The new method of finding subhalos proposed in this research is to track the hierarchical formation of halos and subhalos. As shown in Figure 2, subhalos form through hierarchical merger of their progenitor halos. By tracking the remnants of halos after merger events and postprocessing the remnants to keep only self-bound particles, we can easily identify both the subhalos and their formation histories. This method can be applied to warm dark matter simulations to potentially avoid the spurious halo contamination. Because spurious halos and subhalos form through fragmentation rather than hierarchical growth, in most cases they do not appear in the output of tracked merger events. In more complicated situations, the parameters of the halo-finding and subhalo tracking can be fine tuned to minimize or eliminate the influence of spurious objects.

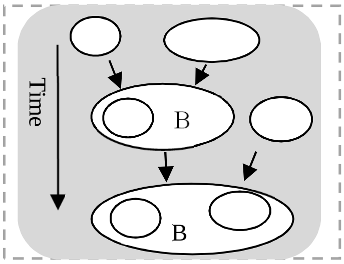

Figure 2. By tracking the progenitor halos A, B and C in time, descendant subhalos A and C at later times can be identified together with their merger history.

After subhalos are identified, we will model their distribution in mass, position and velocity. The distribution of subhalos in their properties at infall time can be compared with the distribution of properties at present day, to extract physical descriptions of the evolution of subhalos. The spatial and kinematic distribution of subhalos can also be modelled assuming subhalos form a steady-state system in the gravitational potential of the host halo.

４．研究成果

As a first step, we have developed a much improved subhalo finder based on the tracking algorithm, HBT+, which is much faster, more user friendly, and more complete in physics than our previous implementation. We have also built a FoF halo finder into HBT+, in order to explore halo finding in warm dark matter simulations with varying linking length. We have applied HBT+ to the Millennium-II simulation and the Aquarius simulation, and have obtained much improved results in the halo merger-tree as well as the subhalo mass function. In particular, we have shown that HBT+ finds a more abundant population of massive subhaloes in the center of host haloes, and the spatial and mass distribution of these subhaloes deviate from the universal distribution for low mass ones, reflecting that the massive subhaloes are more resilient to tidal stripping. These results are in contrast to the subhalo distribution found by conventional subhalo finders that work in configuration space, and are in better agreement with recent gravitational lensing observations of the subhalo population in galaxy clusters.

After developing the HBT+ code for subhalo finding, we have applied the code to simulations to study the properties and distributions of halos and subhalos, as well as carrying out some observational studies of matter distribution around halos.

On large scale, we carried out a multi-dimensional analysis of the clustering of central subhalos, to shed light on the origin of their assembly bias. For the first time, we are able to explicitly show that the dependences of bias on halo mass, concentration (or formation history), spin and shape are non-redundant with respect to each other, indicating their different physical origins. We also find that an environmental density is able to largely account for all the bias dependences. This reveals a new way to understand and model the large scale clustering of halos and subhalos. We have further used the subhalo catalog to develop a new algorithm for correcting for the fibre-collision effect in observational measurements of galaxy/halo clustering, and to study the lensing signal around low density regions in different cosmological models. These results are important progressess towards precision cosmological analysis using the large scale distribution of galaxies and halos.

On small scales, starting from simulated mergers of galaxies and subhalos, we developed a new code (StarGO) to identify substructures in the stellar halo around galaxies using a

technique called self-organizing map. It can be applied to real observations such as the GAIA survey to study the small scale matter distribution and potentially constrain the property of dark matter.
Starting from the subhalo catalogue extracted from large simulations, we have also built a new universal model for the phasespace distribution of satellite subhalos and satellite galaxies, and developed a new method to infer the dark matter halo mass profile from satellite dynamics, which is subsequently applied to measure the MW halo mass. The halo mass of the Milky Way is a fundamental quantity that is crucial for the cosmological interpretation of many near field observations. Existing measurements on this quantity, however, have shown a very large discrepancy up to a factor of ~2 among different works. We have shown that this uncertainty is related to the intrinsic dynamical state of tracers in the halo. In particular, most recently we have found that this uncertainty can be reduced using satellite galaxies instead of halo stars due to the closer-to-equilibrium distribution of satellites. Starting from this we have further developed a universal model for the phasespace distribution of satellites from a large sample of simulated halos. Fitting this new model to a most recent sample of satellite galaxies with GAIA proper motions, we are able to get the most accurate measurement of the Milky Way halo mass to date.

We have also carried out an extensive review on the Milky Way mass measurements in the literature, providing a consistent and up-to-date view of the subject. These progresses can provide a good foundation for further near field cosmological studies on the property of dark matter and their small scale distributions.

５．主な発表論文等

〔雑誌論文〕　計8件（うち査読付論文　8件／うち国際共著　8件／うちオープンアクセス　0件）

１．著者名 Yang Lei、Jing Yipeng、Yang Xiaohu、Han Jiaxin	４．巻 872
２．論文標題 Using the Modified Nearest Neighbor Method to Correct Fiber-collision Effects on Galaxy Clustering	５．発行年 2019年
３．雑誌名 The Astrophysical Journal	６．最初と最後の頁 26～26
掲載論文のDOI（デジタルオブジェクト識別子） 10.3847/1538-4357/aafc22	査読の有無 有
オープンアクセス 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 該当する

１．著者名 Dong Fuyu、Zhang Jun、Yu Yu、Yang Xiaohu、Li HeKun、Han Jiaxin、Luo Wentao、Zhang Jiajun、Fu Liping	４．巻 874
２．論文標題 Constraining Dark Energy with Stacked Concave Lenses	５．発行年 2019年
３．雑誌名 The Astrophysical Journal	６．最初と最後の頁 7～7
掲載論文のDOI（デジタルオブジェクト識別子） 10.3847/1538-4357/ab0648	査読の有無 有
オープンアクセス 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 該当する

１．著者名 Han Jiaxin、Li Yin、Jing Yipeng、Nishimichi Takahiro、Wang Wenting、Jiang Chunyan	４．巻 482
２．論文標題 The multidimensional dependence of halo bias in the eye of a machine: a tale of halo structure, assembly, and environment	５．発行年 2018年
３．雑誌名 Monthly Notices of the Royal Astronomical Society	６．最初と最後の頁 1900～1919
掲載論文のDOI（デジタルオブジェクト識別子） 10.1093/mnras/sty2822	査読の有無 有
オープンアクセス 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 該当する

１．著者名 Wang Wenting、Han Jiaxin、Cole Shaun、More Surhud、Frenk Carlos、Schaller Matthieu	４．巻 476
２．論文標題 What to expect from dynamical modelling of galactic haloes - II. The spherical Jeans equation	５．発行年 2018年
３．雑誌名 Monthly Notices of the Royal Astronomical Society	６．最初と最後の頁 5669～5680
掲載論文のDOI（デジタルオブジェクト識別子） 10.1093/mnras/sty706	査読の有無 有
オープンアクセス 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 該当する

1．著者名 Yuan Zhen、Chang Jiang、Banerjee Projjwal、Han Jiaxin、Kang Xi、Smith M. C.	4．巻 863
2．論文標題 StarGO: A New Method to Identify the Galactic Origins of Halo Stars	5．発行年 2018年
3．雑誌名 The Astrophysical Journal	6．最初と最後の頁 26～26
掲載論文のDOI（デジタルオブジェクト識別子） 10.3847/1538-4357/aacd0d	査読の有無 有
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1．著者名 Han Jiaxin、Cole Shaun、Frenk Carlos S.、Benitez-Llambay Alejandro、Helly John	4．巻 474
2．論文標題 hbt+: an improved code for finding subhaloes and building merger trees in cosmological simulations	5．発行年 2017年
3．雑誌名 Monthly Notices of the Royal Astronomical Society	6．最初と最後の頁 604～617
掲載論文のDOI（デジタルオブジェクト識別子） 10.1093/mnras/stx2792	査読の有無 有
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1．著者名 Wang Wenting、Han Jiaxin、Cole Shaun、More Surhud、Frenk Carlos、Schaller Matthieu	4．巻 476
2．論文標題 What to expect from dynamical modelling of galactic haloes II: the spherical Jeans equation	5．発行年 2018年
3．雑誌名 Monthly Notices of the Royal Astronomical Society	6．最初と最後の頁 5669-5680
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1．著者名 Wang Wenting、Han Jiaxin、Cole Shaun、Frenk Carlos、Sawala Till	4．巻 470
2．論文標題 What to expect from dynamical modelling of galactic haloes	5．発行年 2017年
3．雑誌名 Monthly Notices of the Royal Astronomical Society	6．最初と最後の頁 2351～2366
掲載論文のDOI（デジタルオブジェクト識別子） 10.1093/mnras/stx1334	査読の有無 有
オープンアクセス 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 該当する

〔学会発表〕　計2件（うち招待講演　0件／うち国際学会　2件）

1．発表者名 Jiaxin Han
2．発表標題 A multidimensional view of halo bias in simulations
3．学会等名 Studying the Universe with Galaxy Surveys--Revealing the Unlimited in Shanghai（国際学会）
4．発表年 2018年

1．発表者名 Jiaxin Han
2．発表標題 Can we measure the halo mass of the Milky Way accurately?
3．学会等名 2017 Asia-Pacific Regional IAU Meeting (APRIM 2017)（国際学会）
4．発表年 2017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 （ローマ字氏名） （研究者番号）	所属研究機関・部局・職 （機関番号）	備考