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研究課題名（和文）An Open Source Code to Simulate the First Galaxies

研究課題名（英文）An Open Source Code to Simulate the First Galaxies

研究代表者
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研究成果の概要（和文）：我々は準解析的モデルコードA-SLOTHを11人の国際コラボレーションで開発した。本コードは初代星・初代銀河の形成と観測量を繋ぐ公開コードとしては世界初である。我々はこのコードを一般公開し、世界中の研究者たちに利用可能にした。
A-SLOTHはダークマターのマージャーツリー上でバリオンの物理過程を解析的手法でモデル化し、初代星の形成を予言する。個々の星を分解し、輻射的、化学的、力学的フィードバックを考慮する。モデルパラメーターは六種の観測量で較正する。A-SLOTHは中程度の計算リソースで広い対象に利用可能であり、科学コミュニティに属する人々が利用可能である。

研究成果の学術的意義や社会的意義
A-SLOTH is the first public semi-analytical model that connects the formation of the first stars and galaxies to observables. The code release paper has 11 co-authors from 5 countries, which demonstrates the international support and interest in this project.

研究成果の概要（英文）：With a team of 11 international scientists, we have developed the semi-analytical model A-SLOTH (Ancient Stars and Local Observables by Tracing Halos). It is the first public code that connects the formation of the first stars and galaxies to observables. We now publish the source code to make it accessible to the public.
On top of dark matter merger trees, A-SLOTH applies analytical recipes for baryonic physics to model the formation of the first generations of stars with unprecedented precision and fidelity. It samples individual stars and includes radiative, chemical, and mechanical feedback. It is calibrated based on six observables. A-SLOTH has versatile applications with moderate computational requirements and can now be used by the scientific community.

研究分野：Astrophysics

キーワード：Public Software　Star Formation　Frst Stars　Milky Way　Semi-analytical Model

1. 研究開始当初の背景 / **Initial Research Background**

There is a gap in observational astronomy. The last observational imprint of the Big Bang is the cosmic microwave background, 380,000 years after the Big Bang. The oldest galaxies that we see date back around 1 billion years after the Big Bang. The time in between is invisible to current instruments.

This observational gap is the time when the first galaxies formed. They are the building blocks of our present-day Universe and most questions of galaxy formation, stellar evolution, and the chemical composition of the Universe are causally connected to the first galaxies. However, only a handful of galaxies have been observed at redshift $z>10$ (Bowens et al., 2011, Nature, 469, 504), due to their intrinsic faintness. Therefore, many fundamental questions related to the first galaxies remain open: their contribution to reionisation (Robertson et al., 2015, ApJ, 802, 19), the production sites of metals (Nomoto et al., 2013, ARA&A, 51, 457) and especially of r-process elements (Ji et al., 2016, Nature, 531, 610), the origin of supermassive black holes (Volonteri, 2010, A&Arv, 18, 279), and the UV luminosity function (Bowens et al., 2015, ApJ, 803, 34). Finding answers to these questions is crucial to understand the Universe: When do the first stars form? Where are elements synthesized that are the building blocks of life? What do black hole mergers reveal about structure formation?

Since direct observations of the first galaxies are challenging, we had proposed the development and public release of the first semi-analytical model (SAM) to simulate the formation of the first galaxies. This SAM will guide and optimize upcoming observations to eventually fill this observational gap at cosmic dawn.

2. 研究の目的 / **Purpose of Research**

We have developed the astrophysical simulation software A-SLOTH (Ancient Stars and Local Observables by Tracing Halos) and made the source code public.

This tool can be used by the community for various tasks: to predict initial conditions for other simulations, such as the stellar-to-halo mass or the star formation rate in unresolved halos (Magg et al. submitted), to simulate satellite galaxies of the Milky Way (Chen et al. 2022, MNRAS, 513, 934), to select promising candidates of old halo stars (Ishigaki et al. 2021, MNRAS, 506, 5410), or to calculate reliable rates of gamma ray bursts, supernovae, and black hole mergers to unprecedented redshifts. Moreover, the code will help to plan, optimize, and analyze future observations by providing a flexible framework of forward modeling to predict and interpret observations, a crucial task in the era of data-driven astronomy. The modular approach in Fortran with preprocessing flags and optimized memory allocation makes A-SLOTH more versatile than 3D simulations. This allows for the first time to explore sufficiently large volumes and to perform parameter studies of the underlying cosmology or nature of dark matter.

3. 研究の方法 / Research Method

A-SLOTH is a semi-analytical model (SAM), which makes it very versatile and computationally efficient compared to hydrodynamical simulations. We build upon seven years of experience in the development of A-SLOTH. The primary input is a dark matter (DM) halo merger tree describing the merger history of the DM halos whose stellar and gas content we wish to model. These merger trees can be generated using the Extended Press-Schechter formalism or extracted from cosmological simulations. On top of this skeleton, we model the formation of stars and their radiative, chemical, and mechanical feedback.

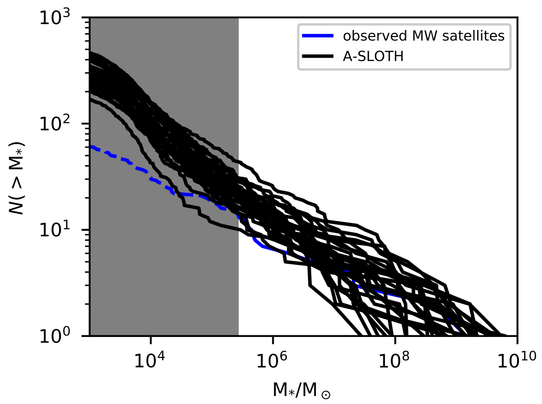
We have included and optimized various aspects, which makes the public version of A-SLOTH more powerful than its predecessors and more accurate and versatile than other models in the literature:

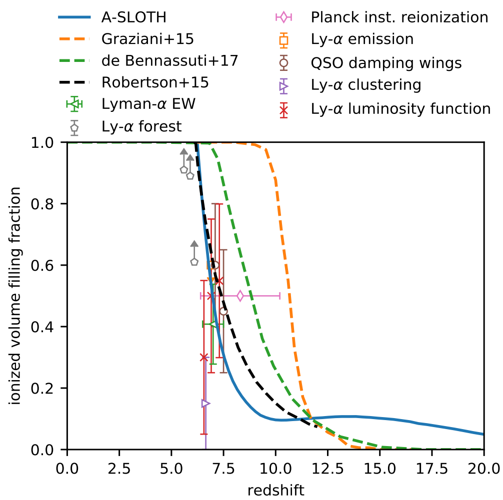
1. A-SLOTH is the first public SAM that models the formation of the first stars and galaxies and connects those to local observables. It is calibrated transparently, which guarantees reproducibility and has several advantages over existing SAMs.
2. A-SLOTH uses both EPS-based merger trees and merger trees extracted from N-body simulations as input. We provide instructions to obtain spatially resolved merger trees, or users can input their own data. Currently, A-SLOTH supports trees in the format of *consistent-trees*, but the input routine can be modified easily. Other SAMs that use only EPS-generated merger trees lack spatial information for the feedback model.
3. A-SLOTH is highly efficient and parallelized. We have implemented a tree-based lookup for external feedback and minimized the memory requirements as much as practically possible.
4. A-SLOTH is the only SAM that samples and traces individual PopIII and PopII stars, which is essential to correctly model feedback in the first galaxies, and the tracking of individual PopII stars allows us to directly compare our results to metal-poor stars in the MW.
5. A-SLOTH tracks individual elements. In the current version, we track carbon and iron explicitly, which allows us to apply a more sophisticated, observationally-motivated criterion to distinguish between PopIII and PopII star formation.
6. A-SLOTH is calibrated to reproduce observables from both the local and high-redshift Universe simultaneously, and we show that this calibration also reproduces additional constraints that we did not actively aim for, such as the metal-enriched volume fraction, the recovery time distribution from simulations, or the observed stellar-mass-to-halo-mass relation. Our calibration procedure is robust and transparent.
7. A-SLOTH models the recovery time between PopIII and PopII star formation self-consistently by following the baryonic contents over time. Most models assume a constant recovery time, which defines the time between the last PopIII SN explosion and the first PopII star formation. We solve the differential equations that govern the heating and cooling of gas inside minihalos in order to calculate when there is enough gas re-accreted after the first SNe to trigger second-generation star formation.
8. A-SLOTH includes a subgrid recipe for inhomogeneous metal mixing inside the first galaxies, which is crucial to correctly model the metallicity of second-generation stars.

4. 研究成果 / Research results

Once we have developed and optimized the source code of A-SLOTH, we had to calibrate its input parameters to demonstrate the we can reproduce existing observations. We use six different observables to calibrate the input parameters of A-SLOTH: the optical depth to Thomson scattering, the stellar mass of the MW, the cumulative distribution of stellar masses of MW satellite galaxies, the fraction of EMP stars in the MW halo, the ratio of UMP ([Fe/H] <-4) to EMP ([Fe/H] <-3) stars, and the cosmic star formation rate density at high redshift. For each of these observables, we calculate a goodness-of-fit parameter, which quantifies how consistent the output of A-SLOTH is with observations. Eventually, we multiply these six individual parameters to obtain our final goodness-of-fit measure. Maximizing it during the calibration guarantees that all six observables are reproduced simultaneously in the final model.

Testing one new combination of parameters requires about 1h wallclock time on a supercomputer. Exploring the entire high-dimensional parameter space to obtain the full posterior distribution is prohibitively expensive for this optimization problem. Therefore, we have developed a new optimization technique ("Quadient Descent", QD), which combines quadratic fits with gradient descent. After several loops over all input parameters, the QD chains converged to a local optimum and we cannot find any combination of input parameters that provides a significantly better fit. This calibration, reproduces all observables sufficiently well, two of which are illustrated in these plots:





The source code of A-SLOTH is made public:
https://gitlab.com/thartwig/asloth
We also provide a documentation for users:
https://a-sloth.readthedocs.io/en/latest/index.html

During the duration of this grant, we have also published various results based on A-SLOTH:
In Chen et al. 2022, we study the stellar-mass-to-halo-mass relation in MW-like systems and how it is influenced by stellar feedback. In Magg et al. 2022, we investigate the effect of the cosmological transition to metal-enriched star-formation on the hydrogen 21-cm signal. In Ishigaki et al. 2021, we use A-SLOTH to estimate how age-cuts can optimize the selection of old metal-poor halo stars. In Tarumi et al. 2020, we study inhomogeneous metal mixing after the first supernovae and have developed a new subgrid model for A-SLOTH.

５．主な発表論文等

〔雑誌論文〕　計9件（うち査読付論文　7件／うち国際共著　9件／うちオープンアクセス　7件）

１．著者名 Rasmussen Kaitlin C.、Zepeda Joseph、Beers Timothy C.、Placco Vinicius M.、Depagne Eric、Frebel Anna、Dietz Sarah、Hartwig Tilman	４．巻 905
２．論文標題 Metal-poor Stars Observed with the Southern African Large Telescope	５．発行年 2020年
３．雑誌名 The Astrophysical Journal	６．最初と最後の頁 20～20
掲載論文のDOI（デジタルオブジェクト識別子） 10.3847/1538-4357/abc005	査読の有無 有
オープンアクセス 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 該当する

１．著者名 Silverman John D.、Tang Shenli、Lee Khee-Gan、Hartwig Tilman、et al.	４．巻 899
２．論文標題 Dual Supermassive Black Holes at Close Separation Revealed by the Hyper Suprime-Cam Subaru Strategic Program	５．発行年 2020年
３．雑誌名 The Astrophysical Journal	６．最初と最後の頁 154～154
掲載論文のDOI（デジタルオブジェクト識別子） 10.3847/1538-4357/aba4a3	査読の有無 有
オープンアクセス 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 該当する

１．著者名 Tarumi Yuta、Hartwig Tilman、Magg Mattis	４．巻 897
２．論文標題 Implications of Inhomogeneous Metal Mixing for Stellar Archaeology	５．発行年 2020年
３．雑誌名 The Astrophysical Journal	６．最初と最後の頁 58～58
掲載論文のDOI（デジタルオブジェクト識別子） 10.3847/1538-4357/ab960d	査読の有無 有
オープンアクセス 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 該当する

１．著者名 Whalen Daniel J.、Mezcua Mar、Meiksin Avery、Hartwig Tilman、Latif Muhammad A.	４．巻 896
２．論文標題 Radio Power from a Direct-collapse Black Hole in CR7	５．発行年 2020年
３．雑誌名 The Astrophysical Journal	６．最初と最後の頁 L45～L45
掲載論文のDOI（デジタルオブジェクト識別子） 10.3847/2041-8213/ab9a30	査読の有無 有
オープンアクセス 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 該当する

１．著者名 Chen Li-Hsin、Magg Mattis、Hartwig Tilman、Glover Simon C O、Ji Alexander P、Klessen Ralf S	４．巻 513
２．論文標題 Tracing stars in Milky Way satellites with <scp>a-sloth</scp>	５．発行年 2022年
３．雑誌名 Monthly Notices of the Royal Astronomical Society	６．最初と最後の頁 934～950
掲載論文のDOI（デジタルオブジェクト識別子） 10.1093/mnras/stac933	査読の有無 有
オープンアクセス 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 該当する

１．著者名 Ishigaki Miho N、Hartwig Tilman、Tarumi Yuta、Leung Shing-Chi、Tominaga Nozomu、Kobayashi Chiaki、Magg Mattis、Simionescu Aurora、Nomoto Ken’ichi	４．巻 506
２．論文標題 Origin of metals in old Milky Way halo stars based on GALAH and Gaia	５．発行年 2021年
３．雑誌名 Monthly Notices of the Royal Astronomical Society	６．最初と最後の頁 5410～5429
掲載論文のDOI（デジタルオブジェクト識別子） 10.1093/mnras/stab1982	査読の有無 有
オープンアクセス 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 該当する

１．著者名 Magg, Mattis ; Reis, Itamar ; Fialkov, Anastasia ; Barkana, Rennan ; Klessen, Ralf S. ; Glover, Simon C. O. ; Chen, Li-Hsin ; Hartwig, Tilman ; Schauer, Anna T. P.	４．巻 N/A
２．論文標題 Effect of the cosmological transition to metal-enriched star-formation on the hydrogen 21-cm signal	５．発行年 2022年
３．雑誌名 submitted to MNRAS	６．最初と最後の頁 0~0
掲載論文のDOI（デジタルオブジェクト識別子） なし	査読の有無 無
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 Tilman Hartwig、Mattis Magg、Li-Hsin Chen、Yuta Tarumi、Volker Bromm、Simon C. O. Glover、Alexander P. Ji、Ralf S. Klessen、Muhammad A. Latif、Marta Volonteri、Naoki Yoshida	４．巻 N/A
２．論文標題 Public Release of A-SLOTH: Ancient Stars and Local Observables by Tracing Halos	５．発行年 2022年
３．雑誌名 accepted in ApJ	６．最初と最後の頁 0~0
掲載論文のDOI（デジタルオブジェクト識別子） なし	査読の有無 有
オープンアクセス 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 該当する

1．著者名 Mattis Magg、Tilman Hartwig、Li-Hsin Chen、Yuta Tarumi	4．巻 N/A
2．論文標題 A-SLOTH: Ancient Stars and Local Observables by Tracing Haloes	5．発行年 2022年
3．雑誌名 submitted to JOSS	6．最初と最後の頁 0~0
掲載論文のDOI（デジタルオブジェクト識別子） なし	査読の有無 無
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10件（うち招待講演　3件／うち国際学会　5件）

1．発表者名 Tilman Hartwig
2．発表標題 The First Stars
3．学会等名 SAZERAC (online)（招待講演）（国際学会）
4．発表年 2020年～2021年

1．発表者名 Tilman Hartwig
2．発表標題 AI-Based Constraint on the Multiplicity of the First Stars
3．学会等名 初代星・初代銀河研究会2020
4．発表年 2020年～2021年

1．発表者名 Tilman Hartwig
2．発表標題 Public Release of A-SLOTH: Ancient Stars and Local Observables by Tracing Haloes
3．学会等名 ASJ Fall Meeting
4．発表年 2020年～2021年

１．発表者名
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２．発表標題
News from the Past: 2019 Updates on Metal-Poor Stars

３．学会等名
初代星・初代銀河研究会2019（招待講演）

４．発表年
2019年

１．発表者名
Tilman Hartwig

２．発表標題
Teaching the Teachers: Astronomy as Gateway to Scientific Literacy in Liberia

３．学会等名
IAU Symposium 358

４．発表年
2019年

１．発表者名
Tilman Hartwig

２．発表標題
Exploring new Frontiers with Gravitational Waves from Massive Black Holes

３．学会等名
First Stars VI (Chile)（招待講演）（国際学会）

４．発表年
2019年～2020年

１．発表者名
Li-Hsin Chen

２．発表標題
Interpreting The Abundance Patterns Of Metal-poor Stars With A SLOTH

３．学会等名
First Stars VI (Chile)（国際学会）

４．発表年
2019年～2020年

１．発表者名 Li-Hsin Chen
２．発表標題 Interpreting The Abundance Patterns Of Metal-poor Stars With A SLOTH
３．学会等名 IMPRS Seminar I, Heidelberg (Germany)（国際学会）
４．発表年 2020年～2021年

１．発表者名 Li-Hsin Chen
２．発表標題 Stellar mass-halo mass relation of the Milky Way satellites down to the ultra-faint regime with A-SLOTH
３．学会等名 FB 881 Seminar, Heidelberg (Germany)（国際学会）
４．発表年 2021年～2022年

１．発表者名 Tilman Hartwig
２．発表標題 Public Release of A-SLOTH
３．学会等名 初代星・初代銀河研究会2020
４．発表年 2021年～2022年

〔図書〕　計0件

〔産業財産権〕

〔その他〕

A-SLOTH source code: https://gitlab.com/thartwig/asloth

First poster price for A-SLOTH at the conference "First Stars VI" in Chile (2020).

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
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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