




A-SLOTH: Ancient Stars and Local Observables by Tracing Halos

Mattis Magg ^{1,2}, Tilman Hartwig ^{3,4,5}, Li-Hsin Chen^{1,2}, and Yuta Tarumi ⁴

1 Institut für Theoretische Astrophysik, Universität Heidelberg, Germany **2** International Max Planck Research School for Astronomy and Cosmic Physics, University of Heidelberg (IMPRS-HD), Germany **3** Institute for Physics of Intelligence, The University of Tokyo, Japan **4** Department of Physics, The University of Tokyo, Japan **5** Kavli Institute for the Physics and Mathematics of the Universe (WPI), The University of Tokyo, Japan

DOI: [10.21105/joss.04417](https://doi.org/10.21105/joss.04417)

Software

- [Review](#) 
- [Repository](#) 
- [Archive](#) 

Editor: [Dan Foreman-Mackey](#) 

Reviewers:

- [@gregbryan](#)
- [@kaleybrauer](#)

Submitted: 06 April 2022

Published: 26 June 2022

License

Authors of papers retain copyright and release the work under a Creative Commons Attribution 4.0 International License ([CC BY 4.0](#)).

In partnership with



This article and software are linked with research article DOI [10.3847/1538-4357/ac7150](https://doi.org/10.3847/1538-4357/ac7150), published in the *Astrophysical Journal*.

Summary

Galaxies are thought to reside inside of large gravitationally bound structures of dark matter, so-called haloes. While the smallest of these haloes host no or only a few stars, the biggest host entire clusters of galaxies. Over cosmic history, haloes often collided and merged, forming bigger and bigger structures. Merger trees, i.e., catalogues of haloes evolving and connections between them as they grow and merge, have become a vital tool in describing and understanding the history of cosmological objects such as our Galaxy. Semi-analytical models, built on top of such merger trees, are a common approach for theoretical studies in cosmology. The semi-analytical nature of such models is especially beneficial when the dynamic range in spatial and time scales that need to be considered becomes too large for numerical simulations.

Ancient Stars and Local Observables by Tracing Halos (A-SLOTH) is such a semi-analytical model and it is designed to simulate star formation in the early Universe in a fast and accessible way. It uses merger trees, either from numerical simulations or generated by statistical algorithms to describe the history of galaxies. The processes of baryonic physics, in particular gas cooling, star formation and stellar feedback are described with approximations and statistical models. The range of applications for this model is extensive and we, therefore, make it available to the scientific community. We also provide [full documentation](#).

Statement of need

Attempts to model the early Universe are notorious for the wide range in spatial and time scales that they need to consider ([Greif, 2015](#)). Therefore, a wide range of authors has resorted to developing semi-analytical models for investigating the high-redshift Universe ([Brauer et al., 2019](#); [de Bannassuti et al., 2017](#); [Ishiyama et al., 2016](#); [Visbal et al., 2018](#)). These models differ widely in their scope, and often they are specifically geared towards addressing a specific issue or question. With A-SLOTH, we offer a highly capable semi-analytical model that can make predictions in numerous areas, ranging from 21-cm cosmology to metal-poor stars in the Milky-Way ([Chen et al., 2022](#); [Hartwig et al., 2015, 2018](#); [Hartwig, Volonteri, et al., 2016](#); [Hartwig, Latif, et al., 2016](#); [M. Magg et al., 2018, 2016](#); [Mattis Magg et al., 2022](#); [Tarumi et al., 2020](#)). This model was originally based on the Extended-Press-Schechter algorithm and more specifically the GALFORM code ([Parkinson et al., 2008](#)) but has since evolved to use merger trees from numerical simulation. A-SLOTH has the primary purpose of quickly simulating star formation in the early Universe and connecting it to present-day and high-redshift observables, such as the metallicity distribution function of the Milky Way or the ionization history of the Universe. By modifying the parameters of the models governing

the high-redshift processes and repeated comparison of the results, a user can investigate the relationship between assumptions about poorly understood processes in the high-redshift Universe and astrophysical observations. Because the model is highly optimized, A-SLOTH can build up a Milky-Way-like galaxy star by star in only a few minutes. The code is written in a modular way, such that users can add new physics and go from an idea to a set of predictions in a short time and without developing a completely new model of high-redshift star formation.

Acknowledgements

We appreciate the thorough testing and constructive feedback from Kaley Brauer and Greg Bryan during code review. We thank Britton Smith for very helpful advice with regards to the publication of open-source software. We acknowledge funding from JSPS KAKENHI Grant Numbers 19K23437 and 20K14464, from Deutsche Forschungsgemeinschaft (DFG) via the Collaborative Research Center (SFB 881, Project-ID 138713538) “The Milky Way System” (sub-project A1), and from the Max-Planck-Gesellschaft via the fellowship of the International Max Planck Research School for Astronomy and Cosmic Physics at the University of Heidelberg (IMPRS-HD).

References

- Brauer, K., Ji, A. P., Frebel, A., Dooley, G. A., Gómez, F. A., & O’Shea, B. W. (2019). The Origin of r-process Enhanced Metal-poor Halo Stars In Now-destroyed Ultra-faint Dwarf Galaxies. *Astrophysical Journal*, 871(2), 247. <https://doi.org/10.3847/1538-4357/aafafb>
- Chen, L.-H., Magg, M., Hartwig, T., Glover, S. C. O., Ji, A. P., & Klessen, R. S. (2022). Tracing stars in Milky Way satellites with A-SLOTH. *arXiv e-Prints*, arXiv:2202.01220. <https://arxiv.org/abs/2202.01220>
- de Bannassuti, M., Salvadori, S., Schneider, R., Valiante, R., & Omukai, K. (2017). Limits on Population III star formation with the most iron-poor stars. *Monthly Notices of the Royal Astronomical Society*, 465, 926–940. <https://doi.org/10.1093/mnras/stw2687>
- Greif, T. H. (2015). The numerical frontier of the high-redshift Universe. *Computational Astrophysics and Cosmology*, 2, 3. <https://doi.org/10.1186/s40668-014-0006-2>
- Hartwig, T., Bromm, V., Klessen, R. S., & Glover, S. C. O. (2015). Constraining the primordial initial mass function with stellar archaeology. *Monthly Notices of the Royal Astronomical Society*, 447, 3892–3908. <https://doi.org/10.1093/mnras/stu2740>
- Hartwig, T., Latif, M. A., Magg, M., Bromm, V., Klessen, R. S., Glover, S. C. O., Whalen, D. J., Pellegrini, E. W., & Volonteri, M. (2016). Exploring the nature of the Lyman- α emitter CR7. *Monthly Notices of the Royal Astronomical Society*, 462, 2184–2202. <https://doi.org/10.1093/mnras/stw1775>
- Hartwig, T., Volonteri, M., Bromm, V., Klessen, R. S., Barausse, E., Magg, M., & Stacy, A. (2016). Gravitational waves from the remnants of the first stars. *Monthly Notices of the Royal Astronomical Society*, 460, L74–L78. <https://doi.org/10.1093/mnrasl/slw074>
- Hartwig, T., Yoshida, N., Magg, M., Frebel, A., Glover, S. C. O., Gómez, F. A., Griffen, B., Ishigaki, M. N., Ji, A. P., Klessen, R. S., O’Shea, B. W., & Tominaga, N. (2018). Descendants of the first stars: the distinct chemical signature of second generation stars. *Monthly Notices of the Royal Astronomical Society*. <https://doi.org/10.1093/mnras/sty1176>
- Ishiyama, T., Sudo, K., Yokoi, S., Hasegawa, K., Tominaga, N., & Susa, H. (2016). Where are the Low-mass Population III Stars? *Astrophysical Journal*, 826, 9. <https://doi.org/10.3847/0004-637X/826/1/9>

- Magg, M., Hartwig, T., Agarwal, B., Frebel, A., Glover, S. C. O., Griffen, B. F., & Klessen, R. S. (2018). Predicting the locations of possible long-lived low-mass first stars: importance of satellite dwarf galaxies. *Monthly Notices of the Royal Astronomical Society*, 473, 5308–5323. <https://doi.org/10.1093/mnras/stx2729>
- Magg, M., Hartwig, T., Glover, S. C. O., Klessen, R. S., & Whalen, D. J. (2016). A new statistical model for Population III supernova rates: discriminating between Λ CDM and WDM cosmologies. *Monthly Notices of the Royal Astronomical Society*, 462, 3591–3601. <https://doi.org/10.1093/mnras/stw1882>
- Magg, Mattis, Reis, I., Fialkov, A., Barkana, R., Klessen, R. S., Glover, S. C. O., Chen, L.-H., Hartwig, T., & Schauer, A. T. P. (2022). Effect of the cosmological transition to metal-enriched star-formation on the hydrogen 21-cm signal. *Monthly Notices of the Royal Astronomical Society*. <https://doi.org/10.1093/mnras/stac1664>
- Parkinson, H., Cole, S., & Helly, J. (2008). Generating dark matter halo merger trees. *Monthly Notices of the Royal Astronomical Society*, 383, 557–564. <https://doi.org/10.1111/j.1365-2966.2007.12517.x>
- Tarumi, Y., Hartwig, T., & Magg, M. (2020). Implications of Inhomogeneous Metal Mixing for Stellar Archaeology. *Astrophysical Journal*, 897(1), 58. <https://doi.org/10.3847/1538-4357/ab960d>
- Visbal, E., Haiman, Z., & Bryan, G. L. (2018). Self-consistent semi-analytic models of the first stars. *Monthly Notices of the Royal Astronomical Society*, 475(4), 5246–5256. <https://doi.org/10.1093/mnras/sty142>