The Journal of Open Source Software

Generating synthetic star catalogs from simulated data for next-gen observatories with py-ananke

Adrien C. R. Thob[1¶], **Robyn E. Sanderson**[1], **Andrew P. Eden**[2], **Farnik Nikakhtar**[3], **Nondh Panithanpaisal**[1,4,5], **Nicolás Garavito-Camargo**[6], and **Sanjib Sharma**[7]

1 Department of Physics & Astronomy, University of Pennsylvania, 209 S 33rd Street, Philadelphia, PA 19104, USA **2** Department of Aerospace, Physics and Space Sciences, Florida Institute of Technology, Melbourne, FL 32901, USA **3** Department of Physics, Yale University, New Haven, CT 06511, USA **4** The Observatories of the Carnegie Institution for Science, 813 Santa Barbara Street, Pasadena, CA 91101, USA **5** TAPIR, Mailcode 350-17, California Institute of Technology, Pasadena, CA 91125, USA **6** Center for Computational Astrophysics, Flatiron Institute, Simons Foundation, 162 Fifth Avenue, New York, NY 10010, USA **7** Space Telescope Science Institute, 3700 San Martin Drive, Baltimore, MD 21218, USA ¶ Corresponding author

DOI: 10.xxxxxx/draft

Software

- Review
- Repository
- Archive

Editor: Warrick Ball

Reviewers:

- @rrjbca
- @lheckmann

Submitted: 23 November 2023
Published: unpublished

Summary

We find ourselves on the brink of an exciting era in observational astrophysics, driven by groundbreaking facilities like JWST, Euclid, Rubin, Roman, SKA, or ELT. Simultaneously, computational astrophysics has shown significant strides, yielding highly realistic galaxy formation simulations, thanks to both hardware and software enhancements. Bridging the gap between simulations and observations has become paramount for meaningful comparisons.

We introduce py-ananke, a Python pipeline designed to generate synthetic resolved stellar surveys from cosmological simulations, adaptable to various instruments. Building upon its predecessor, ananke by Sanderson et al. (2020), which produced Gaia DR2 mock star surveys, the py-ananke package offers a user-friendly "plug & play" experience. The pipeline employs cutting-edge phase-space density estimation and initial mass function sampling to convert particle data into synthetic stars, while interpolating pre-computed stellar isochrone tracks for photometry. Additionally, it includes modules for estimating interstellar reddening, dust-induced extinctions, and for quantifying errors through dedicated modeling approaches. py-ananke promises to serve as a vital bridge between computational astrophysics and observational astronomy, facilitating preparations and making scientific predictions for the next generation of telescopes.

Statement of need

The upcoming decade holds promise for groundbreaking discoveries, thanks to a multitude of recent and forthcoming observational facilities. The James Webb Space Telescope (Gardner et al., 2006), for instance, with its exceptional specifications, has already delved into early universe galaxies with unprecedented detail, revealing their rich diversity (Adams et al., 2023; Casey et al., 2023; Eisenstein et al., 2023; Ferreira et al., 2022, 2023; Finkelstein et al., 2023; Harikane et al., 2023; Hsiao et al., 2023; Kartaltepe et al., 2023; Kocevski et al., 2023; Pérez-González et al., 2023; Trussler et al., 2023). The recently launched Euclid Telescope (Laureijs et al., 2011) promises to shed light on the universe's accelerating expansion by surveying an immense number of galaxies (Euclid Collaboration et al., 2022). The Vera Rubin Observatory (Ivezić et al., 2019), with first light expected soon, will precisely map the Milky Way (MW) up to the virial radius and nearby galaxies, providing exceptional stellar astrometry data. Furthermore, the Nancy Grace Roman Space Telescope (Akeson et al., 2019), set to launch in the next couple of years, will offer a wide field of view for deep-sky near-infrared exploration, facilitating the study of resolved stellar populations in nearby galaxies (Dey et al., 2023; Han et al., 2023). However, these observatories will generate an unprecedented amount of raw data, necessitating community preparedness.

In parallel, a number of projects have emerged over the last decade in computational astrophysics, continuously surpassing hardware and software limits to simulate galaxy formation in a cosmological context realistically (Agertz et al., 2021; Applebaum et al., 2021; Bastian et al., 2020; Crain et al., 2015; Davé et al., 2016, 2019; Dolag et al., 2015, 2016; Y. Dubois et al., 2014; Yohan Dubois et al., 2021; Feldmann et al., 2023; Feng et al., 2016; Henden et al., 2018; Hirschmann et al., 2014; Hopkins et al., 2014, 2018, 2023; Khandai et al., 2015; Kruijssen et al., 2019; Nelson et al., 2018; Pakmor et al., 2023; Peeples et al., 2019; Pfeffer et al., 2018; Pillepich et al., 2018; Rey et al., 2023; Schaye et al., 2015, 2023; Springel et al., 2018; Stinson et al., 2010, 2013; Tremmel et al., 2017; Vogelsberger et al., 2014; Wang et al., 2015). These simulations serve as invaluable test beds for tools developed in anticipation of the next-generation telescope era, but also for our own models. However, translating these simulations into mock observables is challenging due to the representation of stellar populations as star particles, with each particle representing a total stellar mass between 10^3 and 10^8 times the mass of the Sun. To compare simulations with real data, one must break down these particles into individual stars consistently. Since the simulation resolution is not "one star particle per star" in the vast majority of these simulations, producing mock observables necessarily requires a series of assumptions that can have different effects on the final prediction.

This challenge was addressed by Sanderson et al. (2020) when producing a mock Gaia DR2 catalog from Milky-Way-mass simulated galaxies in the latte suite of FIRE simulations (Wetzel et al., 2016) using the so-called ananke pipeline. They used phase-space density estimation and initial mass function sampling to transform particle data into individual synthetic stars, retaining parent particle age and metallicity. Photometry was determined by interpolating pre-computed stellar isochrone tracks from the Padova database (Paola Marigo et al., 2017) based on star mass, age, and metallicity. Additional post-processing included estimating interstellar reddening, per-band dust extinctions using metal-enriched gas distribution, and error quantification based on a model described by functions calibrated to (Gaia Collaboration et al., 2018) characterizations. Each different step of the process, and its associated assumptions, was modularized and its assumptions documented, both to understand and isolate the effect of each assumption on the final product and to retain enough information at each step that a change to one assumption did not necessarily require re-producing the predictions from scratch.

The ananke pipeline by Sanderson et al. (2020), though powerful, lacks user-friendliness and flexibility. It is challenging to integrate into other pipelines and expand beyond the Gaia photometric system. The development of `py-ananke` aims to make this framework more accessible to a wider community. By providing a self-contained and easily installable `Python` package, it streamlines the ananke pipeline, automating tasks previously requiring manual intervention. `py-ananke` also expands ananke's photometric system support and employs a modular implementation for future enhancements, promising a smoother upgrade path for users.

Overview of py-ananke's framework and infrastructure

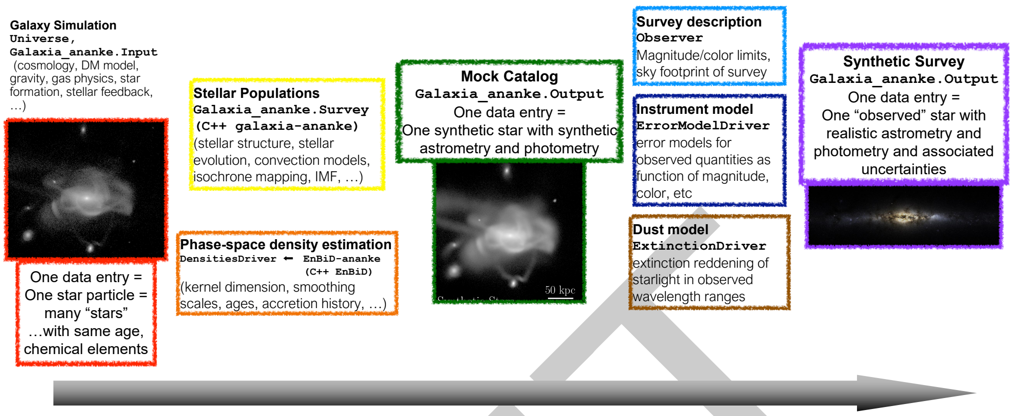

Figure 1: Schematic illustrating the inner framework of the py-ananke pipeline. The modules py-EnBiD-ananke and py-Galaxia-ananke are referred to by their import names EnBiD_ananke and Galaxia_ananke, with their respective C++ backend softwares EnBiD and galaxia-ananke. The pipeline framework is illustrated from input to final output from left to right, showcasing the different objects and their purposes.

The implementation of py-ananke is designed to streamline the ananke pipeline, and to prevent the need for the user to manually handle the interface between Python and the C++ backend software. It notably introduces dedicated wrapper submodules (hosted in repositories that are separate from that of py-ananke, but linked as git submodules), namely py-EnBiD-ananke and py-Galaxia-ananke, specifically developed to handle the installation and utilization of these C++ subroutines, namely EnBiD (Sharma & Steinmetz, 2006, 2011) and a modified version of Galaxia (Sharma et al., 2011a, 2011b) called galaxia-ananke. These submodules relieve users from the need to directly manage the C++ software while isolating the C++ wrapping process. This allows py-ananke to focus on processing inputs and outputs using pure Python. Figure 1 illustrates the inner framework process of the full pipeline, showcasing the various module and submodule classes and where they are used in an input to output fashion from left to right.

py-EnBiD-ananke

The full description of EnBiD is detailed in Sharma & Steinmetz (2006), but to summarize, EnBiD uses a binary space partitioning tree to estimate the space density of a discrete data sample of particles given their coordinates in that space. The tree is recursively built by successively splitting spatial volumes in equally sample-populated volumic tree-nodes until each leaf node contains one single particle. The densities at the location of each particle are estimated using the volume of the leaf node that contains that particle and smoothed using kernel smoothing methods.

The py-EnBiD-ananke submodule handles the installation of EnBiD and interfaces with its pipeline. The installation pulls the archived source code of EnBiD from its SourceForge repository and builds its executable which gets added to the packaged data. Note that for this version of py-ananke, the EnBiD pipeline is configured to determine 3D space densities for a set of particles, which py-ananke uses twice to get separate estimates of the position and velocity densities. In this situation, py-ananke combines both densities into a 6D phase space density, but future versions will consider the native implementation for determining true 6D phase space densities.

py-EnBiD-ananke consists of a collection of functions that are combined into the pipeline-function enbid that takes particles 3D coordinates as input and returns their densities. The role of each sub-function is to write the files that are given as input to the EnBiD pipeline, to run the EnBiD pipeline and to read the pipeline's output files, for which various operational constants and templates are defined in a dedicated module file.

py-Galaxia-ananke

The full description of Galaxia is detailed in Sharma et al. (2011b), but to summarize, Galaxia uses a given galactic model to generate a population of synthetic stars that composes it, with its associated astrometric and photometric catalog. The original pipeline had a more general purpose as the input galactic model can be generated via an N-Body simulation as much as it can be specified as a set of density distributions. However, for our purpose with our modified version galaxia-ananke, the pipeline uses cosmological simulation star particle data provided by the user, specifically the mass, position, velocity, age, metallicity & abundances, as well as phase space densities for each star particle.

galaxia-ananke generates the synthetic stars by sampling phase space to reproduce the distribution representing overlapping phase space kernels centered at each particle, invertly scaled with the particle density, and by sampling mass to reproduce a Kroupa (2001) initial mass function. Each synthetic star carries the other properties of the parent particle such as age and metallicity, with which the masses are used to interpolate photometry from pre-computed isochrone tracks (details on those are described in section Dependencies). Finally, astrometry is determined by converting the phase space coordinates to celestial coordinates given a user-specified observer phase space position.

The py-Galaxia-ananke submodule handles the installation of galaxia-ananke, a modified version of Galaxia, and interfaces with its pipeline. The galaxia-ananke source code lives in a separate repository which is linked as a git submodule in the repository of py-Galaxia-ananke. At installation, py-Galaxia-ananke builds and packages the executable of galaxia-ananke from its source code directly from its git submodule, as well as the operational data for galaxia-ananke which includes the collections of isochrones sets. All the resulting galaxia-ananke packaged data is eventually placed in a dedicated cache folder that is created in the site-specific directory of the running Python installation.

py-Galaxia-ananke consists of mainly three classes, with one function utilizing them to run the galaxia-ananke pipeline. It also includes a submodule that interfaces via dedicated objects with the data from the collection of isochrones sets/photometric systems. The three classes of py-Galaxia-ananke serve the following roles:

- Input objects are used to store the input star particles data, and have methods that write the input files that galaxia-ananke requires
- Survey objects receive Input objects and the selection of photometric systems to simulate, and have methods that run the galaxia-ananke pipeline and return Output objects
- Output objects serve as the main interface with galaxia-ananke's output files, and have methods that turn them into HDF5 files and associated vaex dataframes

py-ananke

The implementation of py-ananke involves six classes, with only one - Ananke - being relevant to the end user:

- Ananke objects serve as the user interface, connecting all of py-ananke's classes and the py-Galaxia-ananke classes (described in the previous subsection) to execute the full pipeline via its method run
- Universe objects store the particle data and various parameters provided to Ananke
- Observer objects store the observing configuration, including the position in space
- DensitiesDriver objects utilize the particle data from the Universe class to compute and store phase space densities, employing py-EnBiD-ananke

- `ExtinctionDriver` objects are utilized by `Ananke` objects for post-processing to estimate and append extinctions in the output catalogs of `py-Galaxia-ananke`, only if the user specified dust column densities per star particle
- `ErrorModelDriver` objects are utilized by `Ananke` objects for post-processing to determine and append errors on the quantities in the output catalogs of `py-Galaxia-ananke`

The latter two driver classes require respectively extinction coefficients and error models that are photometric-system-dependents and can be specified by the user. Also, `py-ananke` is designed with dedicated source files to contain default implementations, which currently only hold default for the Gaia photometric system. Future updates will continue to expand this further.

Dependencies

`py-ananke` makes use of the following `Python` packages:

- `astropy` (Astropy Collaboration et al., 2013, 2018, 2022)
- `ebfpy` (Sharma, 2020)
- `h5py` (Collette, 2013)
- `numpy` (Harris et al., 2020)
- `pandas` (The pandas development team, 2023)
- `pytest` (Pajankar, 2017)
- `scipy` (Virtanen et al., 2020)
- `vaex` (Breddels & Veljanoski, 2018)

It also uses adapted versions of the `C++` packages:

- `EnBiD` (Sharma & Steinmetz, 2006, 2011) integrated in `py-EnBiD-ananke`
- `Galaxia` (Sharma et al., 2011a, 2011b) integrated as `galaxia-ananke` in `py-Galaxia-ananke`

Lastly, the `galaxia-ananke` `C++` submodule uses sets of pre-computed stellar isochrones generated by the Padova database[1], using:

- PARSEC version 1.2S (Bressan et al., 2012; Chen et al., 2014, 2015; Tang et al., 2014) and COLIBRI PR16 (Paola Marigo et al., 2013; Rosenfield et al., 2016) evolutionary tracks as in Paola Marigo et al. (2017) (the solar metallicity is assumed to be 0.0152), with the mass-loss on the red giant branch using the Reimers formula with $\eta_{Reimers} = 0.2$, and $\eta_{inTPC} = 10$ for the resolution of the thermal pulse cycles in the COLIBRI section,
- specific choices of photometric systems for the corresponding instrument[2] with OBC bolometric corrections as described in L. Girardi et al. (2002), Léo Girardi et al. (2008) and P. Marigo et al. (2008),
- circumstellar dust compositions with a combination of 60% Silicate + 40% AlOx around O-rich M stars, and a combination of 85% AMC + 15% SiC around C-rich C stars, as in Groenewegen (2006),
- periods from Trabucchi et al. (2019) and Trabucchi et al. (2021) for long-period variability during the red and asymptotic giant branch phases.

Past and Ongoing Applications

Sanderson et al. (2020)'s data have now been in public use for 5 years and have delivered on the promise of this technique, leading to the discovery of a new stellar stream (Necib et al., 2020), the development and validation of new machine learning methods for inferring the origins of stars (Ostdiek et al., 2020), insights into the formation history of the MW (Nikakhtar

[1] http://stev.oapd.inaf.it/cgi-bin/cmd
[2] further described in http://stev.oapd.inaf.it/cmd/photsys.html

et al., 2021), searches for dark matter subhalos (Bazarov et al., 2022), and inference of the MW's interstellar dust distribution (Miller et al., 2022).

In addition, a number of studies have also made use of the existing ananke pipeline that generated Sanderson et al. (2020)'s data, often through the extensive effort to adapt it to other photometric systems:

- Shipp et al. (2023) investigated the detectability of MW stellar streams in the Dark Energy Survey (Abbott et al., 2018, 2021; Flaugher et al., 2015), for which they produced mock star catalogs mimicking DECam photometry from disrupted star clusters identified around simulated MW-mass galaxies
- Nguyen et al. (2023) produced a synthetic survey mimicking the third data release of Gaia (Gaia Collaboration et al., 2021, 2023), similar to how Sanderson et al. (2020) produced a synthetic survey of the second data release of Gaia (Gaia Collaboration et al., 2018)

These studies required significant effort caused by the challenges of using ananke, which py-ananke is designed to alleviate. Current ongoing projects are already using the new py-ananke package, and are benefiting significantly from his ergonomicity.

Author Contributions

As the lead developer on py-ananke, ACRT adapted ananke by integrating its routines into a self-contained fully installable Python package, and implemented the new modular and object-oriented infrastructure py-ananke relies on, including the submodule py-EnBiD-ananke and py-Galaxia-ananke submodules, preparing all the associated repository overarching organization. RES, ananke's original developer, supervised ACRT throughout py-ananke's development and helped to disseminate early in-development versions of the software to collaborators. SS is the original developer of the C++ softwares EnBiD and Galaxia which ananke relies heavily upon. APE tested the package for their own projects under the supervision of NGC. FN also tested the package for their projects and implemented fixes to the source code during testing. ACRT, NP and NGC added sets of isochrones to those in the galaxia-ananke C++ submodule that had previously been assembled by RES.

Acknowledgements

ACRT and RES acknowledge support from the Research Corporation through the Scialog Fellows program on Time Domain Astronomy, from NSF grant AST-2007232, from NASA grant 19-ATP19-0068, and from HST-AR-15809 from the Space Telescope Science Institute (STScI), which is operated by AURA, Inc., under NASA contract NAS5-26555.

Development of this code package made use of resources provided by the Frontera computing project at the Texas Advanced Computing Center (TACC). Frontera is made possible by National Science Foundation award OAC-1818253. Simulations used as test data for the package, and which form part of the example suite, were run using Early Science Allocation 1923870 and analyzed using computing resources supported by the Scientific Computing Core at the Flatiron Institute. This work used additional computational resources from the University of Texas at Austin and TACC, the NASA Advanced Supercomputing (NAS) Division and the NASA Center for Climate Simulation (NCCS), and the Extreme Science and Engineering Discovery Environment (XSEDE), which was supported by National Science Foundation grant number OCI-1053575.

Package development and testing was performed in part at the Aspen Center for Physics, which is supported by National Science Foundation grant PHY-1607611, and at the Kavli Insitute for Theoretical Physics workshop "Dynamical Models for Stars and Gas in Galaxies in the

Gaia Era" and the 2019 Santa Barbara Gaia Sprint, supported in part by the National Science Foundation under Grant No. NSF PHY-1748958 and by the Heising-Simons Foundation.

The authors are grateful to Anthony Brown and Jos de Bruijne for their cooperation in building the Gaia error models encoded in this package. We also gratefully acknowledge the input and encouragement of the many participants of the Gaia Sprints (2017–2019), and of the Gaia Challenge series (2012-2019).

The authors thank the extended Galaxy Dynamics @ UPenn group and the attendees of the "anankethon" workshops for the valuable feedback and suggestions they provided which have contributed to the refinement and enhancement of the package.

References

Abbott, T. M. C., Abdalla, F. B., Allam, S., Amara, A., Annis, J., Asorey, J., Avila, S., Ballester, O., Banerji, M., Barkhouse, W., Baruah, L., Baumer, M., Bechtol, K., Becker, M. R., Benoit-Lévy, A., Bernstein, G. M., Bertin, E., Blazek, J., Bocquet, S., … NOAO Data Lab. (2018). The Dark Energy Survey: Data Release 1. *239*(2), 18. https://doi.org/10.3847/1538-4365/aae9f0

Abbott, T. M. C., Adamów, M., Aguena, M., Allam, S., Amon, A., Annis, J., Avila, S., Bacon, D., Banerji, M., Bechtol, K., Becker, M. R., Bernstein, G. M., Bertin, E., Bhargava, S., Bridle, S. L., Brooks, D., Burke, D. L., Carnero Rosell, A., Carrasco Kind, M., … Linea Science Server. (2021). The Dark Energy Survey Data Release 2. *255*(2), 20. https://doi.org/10.3847/1538-4365/ac00b3

Adams, N. J., Conselice, C. J., Ferreira, L., Austin, D., Trussler, J. A. A., Juodžbalis, I., Wilkins, S. M., Caruana, J., Dayal, P., Verma, A., & Vijayan, A. P. (2023). Discovery and properties of ultra-high redshift galaxies ($9 < z < 12$) in the JWST ERO SMACS 0723 Field. *518*(3), 4755–4766. https://doi.org/10.1093/mnras/stac3347

Agertz, O., Renaud, F., Feltzing, S., Read, J. I., Ryde, N., Andersson, E. P., Rey, M. P., Bensby, T., & Feuillet, D. K. (2021). VINTERGATAN - I. The origins of chemically, kinematically, and structurally distinct discs in a simulated Milky Way-mass galaxy. *503*(4), 5826–5845. https://doi.org/10.1093/mnras/stab322

Akeson, R., Armus, L., Bachelet, E., Bailey, V., Bartusek, L., Bellini, A., Benford, D., Bennett, D., Bhattacharya, A., Bohlin, R., Boyer, M., Bozza, V., Bryden, G., Calchi Novati, S., Carpenter, K., Casertano, S., Choi, A., Content, D., Dayal, P., … Zimmerman, N. (2019). The Wide Field Infrared Survey Telescope: 100 Hubbles for the 2020s. *arXiv e-Prints*, arXiv:1902.05569. https://doi.org/10.48550/arXiv.1902.05569

Applebaum, E., Brooks, A. M., Christensen, C. R., Munshi, F., Quinn, T. R., Shen, S., & Tremmel, M. (2021). Ultrafaint Dwarfs in a Milky Way Context: Introducing the Mint Condition DC Justice League Simulations. *906*(2), 96. https://doi.org/10.3847/1538-4357/abcafa

Astropy Collaboration, Price-Whelan, A. M., Lim, P. L., Earl, N., Starkman, N., Bradley, L., Shupe, D. L., Patil, A. A., Corrales, L., Brasseur, C. E., Nöthe, M., Donath, A., Tollerud, E., Morris, B. M., Ginsburg, A., Vaher, E., Weaver, B. A., Tocknell, J., Jamieson, W., … Astropy Project Contributors. (2022). The Astropy Project: Sustaining and Growing a Community-oriented Open-source Project and the Latest Major Release (v5.0) of the Core Package. *935*(2), 167. https://doi.org/10.3847/1538-4357/ac7c74

Astropy Collaboration, Price-Whelan, A. M., Sipőcz, B. M., Günther, H. M., Lim, P. L., Crawford, S. M., Conseil, S., Shupe, D. L., Craig, M. W., Dencheva, N., Ginsburg, A., VanderPlas, J. T., Bradley, L. D., Pérez-Suárez, D., de Val-Borro, M., Aldcroft, T. L., Cruz, K. L., Robitaille, T. P., Tollerud, E. J., … Astropy Contributors. (2018). The Astropy

Project: Building an Open-science Project and Status of the v2.0 Core Package. *156*(3), 123. https://doi.org/10.3847/1538-3881/aabc4f

Astropy Collaboration, Robitaille, T. P., Tollerud, E. J., Greenfield, P., Droettboom, M., Bray, E., Aldcroft, T., Davis, M., Ginsburg, A., Price-Whelan, A. M., Kerzendorf, W. E., Conley, A., Crighton, N., Barbary, K., Muna, D., Ferguson, H., Grollier, F., Parikh, M. M., Nair, P. H., … Streicher, O. (2013). Astropy: A community Python package for astronomy. *558*, A33. https://doi.org/10.1051/0004-6361/201322068

Bastian, N., Pfeffer, J., Kruijssen, J. M. D., Crain, R. A., Trujillo-Gomez, S., & Reina-Campos, M. (2020). The globular cluster system mass-halo mass relation in the E-MOSAICS simulations. *498*(1), 1050–1061. https://doi.org/10.1093/mnras/staa2453

Bazarov, A., Benito, M., Hütsi, G., Kipper, R., Pata, J., & Põder, S. (2022). Sensitivity estimation for dark matter subhalos in synthetic Gaia DR2 using deep learning. *Astronomy and Computing*, *41*, 100667. https://doi.org/10.1016/j.ascom.2022.100667

Breddels, M. A., & Veljanoski, J. (2018). Vaex: big data exploration in the era of Gaia. *618*, A13. https://doi.org/10.1051/0004-6361/201732493

Bressan, A., Marigo, P., Girardi, Léo., Salasnich, B., Dal Cero, C., Rubele, S., & Nanni, A. (2012). PARSEC: stellar tracks and isochrones with the PAdova and TRieste Stellar Evolution Code. *427*(1), 127–145. https://doi.org/10.1111/j.1365-2966.2012.21948.x

Casey, C. M., Kartaltepe, J. S., Drakos, N. E., Franco, M., Harish, S., Paquereau, L., Ilbert, O., Rose, C., Cox, I. G., Nightingale, J. W., Robertson, B. E., Silverman, J. D., Koekemoer, A. M., Massey, R., McCracken, H. J., Rhodes, J., Akins, H. B., Allen, N., Amvrosiadis, A., … Zavala, J. A. (2023). COSMOS-Web: An Overview of the JWST Cosmic Origins Survey. *954*(1), 31. https://doi.org/10.3847/1538-4357/acc2bc

Chen, Y., Bressan, A., Girardi, L., Marigo, P., Kong, X., & Lanza, A. (2015). PARSEC evolutionary tracks of massive stars up to 350 $M_\odot$ at metallicities $0.0001 \leq Z \leq 0.04$. *452*(1), 1068–1080. https://doi.org/10.1093/mnras/stv1281

Chen, Y., Girardi, L., Bressan, A., Marigo, P., Barbieri, M., & Kong, X. (2014). Improving PARSEC models for very low mass stars. *444*(3), 2525–2543. https://doi.org/10.1093/mnras/stu1605

Collette, A. (2013). *Python and HDF5*. O'Reilly.

Crain, R. A., Schaye, J., Bower, R. G., Furlong, M., Schaller, M., Theuns, T., Dalla Vecchia, C., Frenk, C. S., McCarthy, I. G., Helly, J. C., Jenkins, A., Rosas-Guevara, Y. M., White, S. D. M., & Trayford, J. W. (2015). The EAGLE simulations of galaxy formation: calibration of subgrid physics and model variations. *450*(2), 1937–1961. https://doi.org/10.1093/mnras/stv725

Davé, R., Anglés-Alcázar, D., Narayanan, D., Li, Q., Rafieferantsoa, M. H., & Appleby, S. (2019). SIMBA: Cosmological simulations with black hole growth and feedback. *486*(2), 2827–2849. https://doi.org/10.1093/mnras/stz937

Davé, R., Thompson, R., & Hopkins, P. F. (2016). MUFASA: galaxy formation simulations with meshless hydrodynamics. *462*(3), 3265–3284. https://doi.org/10.1093/mnras/stw1862

Dey, A., Najita, J., Filion, C., Han, J. J., Pearson, S., Wyse, R., Thob, A. C. R., Anguiano, B., Apfel, M., Arnaboldi, M., Bell, E. F., Beraldo e Silva, L., Besla, G., Bhattacharya, A., Bhattacharya, S., Chandra, V., Choi, Y., Collins, M. L. M., Cunningham, E. C., … Wojno, J. L. (2023). RomAndromeda: The Roman Survey of the Andromeda Halo. *arXiv e-Prints*, arXiv:2306.12302. https://doi.org/10.48550/arXiv.2306.12302

Dolag, K., Gaensler, B. M., Beck, A. M., & Beck, M. C. (2015). Constraints on the distribution and energetics of fast radio bursts using cosmological hydrodynamic simulations. *451*(4), 4277–4289. https://doi.org/10.1093/mnras/stv1190

Dolag, K., Komatsu, E., & Sunyaev, R. (2016). SZ effects in the Magneticum Pathfinder simulation: comparison with the Planck, SPT, and ACT results. *463*(2), 1797–1811. https://doi.org/10.1093/mnras/stw2035

Dubois, Yohan, Beckmann, R., Bournaud, F., Choi, H., Devriendt, J., Jackson, R., Kaviraj, S., Kimm, T., Kraljic, K., Laigle, C., Martin, G., Park, M.-J., Peirani, S., Pichon, C., Volonteri, M., & Yi, S. K. (2021). Introducing the NEWHORIZON simulation: Galaxy properties with resolved internal dynamics across cosmic time. *651*, A109. https://doi.org/10.1051/0004-6361/202039429

Dubois, Y., Pichon, C., Welker, C., Le Borgne, D., Devriendt, J., Laigle, C., Codis, S., Pogosyan, D., Arnouts, S., Benabed, K., Bertin, E., Blaizot, J., Bouchet, F., Cardoso, J.-F., Colombi, S., de Lapparent, V., Desjacques, V., Gavazzi, R., Kassin, S., … Volonteri, M. (2014). Dancing in the dark: galactic properties trace spin swings along the cosmic web. *444*(2), 1453–1468. https://doi.org/10.1093/mnras/stu1227

Eisenstein, D. J., Willott, C., Alberts, S., Arribas, S., Bonaventura, N., Bunker, A. J., Cameron, A. J., Carniani, S., Charlot, S., Curtis-Lake, E., D'Eugenio, F., Endsley, R., Ferruit, P., Giardino, G., Hainline, K., Hausen, R., Jakobsen, P., Johnson, B. D., Maiolino, R., … Woodrum, C. (2023). Overview of the JWST Advanced Deep Extragalactic Survey (JADES). *arXiv e-Prints*, arXiv:2306.02465. https://doi.org/10.48550/arXiv.2306.02465

Euclid Collaboration, Scaramella, R., Amiaux, J., Mellier, Y., Burigana, C., Carvalho, C. S., Cuillandre, J.-C., Da Silva, A., Derosa, A., Dinis, J., Maiorano, E., Maris, M., Tereno, I., Laureijs, R., Boenke, T., Buenadicha, G., Dupac, X., Gaspar Venancio, L. M., Gómez-Álvarez, P., … Whittaker, L. (2022). Euclid preparation. I. The Euclid Wide Survey. *662*, A112. https://doi.org/10.1051/0004-6361/202141938

Feldmann, R., Quataert, E., Faucher-Giguère, C.-A., Hopkins, P. F., Çatmabacak, O., Kereš, D., Bassini, L., Bernardini, M., Bullock, J. S., Cenci, E., Gensior, J., Liang, L., Moreno, J., & Wetzel, A. (2023). FIREbox: simulating galaxies at high dynamic range in a cosmological volume. *522*(3), 3831–3860. https://doi.org/10.1093/mnras/stad1205

Feng, Y., Di-Matteo, T., Croft, R. A., Bird, S., Battaglia, N., & Wilkins, S. (2016). The BlueTides simulation: first galaxies and reionization. *455*(3), 2778–2791. https://doi.org/10.1093/mnras/stv2484

Ferreira, L., Adams, N., Conselice, C. J., Sazonova, E., Austin, D., Caruana, J., Ferrari, F., Verma, A., Trussler, J., Broadhurst, T., Diego, J., Frye, B. L., Pascale, M., Wilkins, S. M., Windhorst, R. A., & Zitrin, A. (2022). Panic! at the Disks: First Rest-frame Optical Observations of Galaxy Structure at z > 3 with JWST in the SMACS 0723 Field. *938*(1), L2. https://doi.org/10.3847/2041-8213/ac947c

Ferreira, L., Conselice, C. J., Sazonova, E., Ferrari, F., Caruana, J., Tohill, C.-B., Lucatelli, G., Adams, N., Irodotou, D., Marshall, M. A., Roper, W. J., Lovell, C. C., Verma, A., Austin, D., Trussler, J., & Wilkins, S. M. (2023). The JWST Hubble Sequence: The Rest-Frame Optical Evolution of Galaxy Structure at $1.5 < z < 8$. *955*(2), L2. https://doi.org/10.3847/1538-4357/acec76

Finkelstein, S. L., Bagley, M. B., Ferguson, H. C., Wilkins, S. M., Kartaltepe, J. S., Papovich, C., Yung, L. Y. A., Haro, P. A., Behroozi, P., Dickinson, M., Kocevski, D. D., Koekemoer, A. M., Larson, R. L., Le Bail, A., Morales, A. M., Pérez-González, P. G., Burgarella, D., Davé, R., Hirschmann, M., … Zavala, J. A. (2023). CEERS Key Paper. I. An Early Look into the First 500 Myr of Galaxy Formation with JWST. *946*(1), L13. https://doi.org/10.3847/2041-8213/acade4

Flaugher, B., Diehl, H. T., Honscheid, K., Abbott, T. M. C., Alvarez, O., Angstadt, R., Annis, J. T., Antonik, M., Ballester, O., Beaufore, L., Bernstein, G. M., Bernstein, R. A., Bigelow, B., Bonati, M., Boprie, D., Brooks, D., Buckley-Geer, E. J., Campa, J., Cardiel-Sas, L., … DES Collaboration. (2015). The Dark Energy Camera. *150*(5), 150. https://doi.org/10.1088/0004-6256/150/5/150

Gaia Collaboration, Brown, A. G. A., Vallenari, A., Prusti, T., de Bruijne, J. H. J., Babusiaux, C., Bailer-Jones, C. A. L., Biermann, M., Evans, D. W., Eyer, L., Jansen, F., Jordi, C., Klioner, S. A., Lammers, U., Lindegren, L., Luri, X., Mignard, F., Panem, C., Pourbaix, D., … Zwitter, T. (2018). Gaia Data Release 2. Summary of the contents and survey properties. *616*, A1. https://doi.org/10.1051/0004-6361/201833051

Gaia Collaboration, Brown, A. G. A., Vallenari, A., Prusti, T., de Bruijne, J. H. J., Babusiaux, C., Biermann, M., Creevey, O. L., Evans, D. W., Eyer, L., Hutton, A., Jansen, F., Jordi, C., Klioner, S. A., Lammers, U., Lindegren, L., Luri, X., Mignard, F., Panem, C., … Zwitter, T. (2021). Gaia Early Data Release 3. Summary of the contents and survey properties. *649*, A1. https://doi.org/10.1051/0004-6361/202039657

Gaia Collaboration, Vallenari, A., Brown, A. G. A., Prusti, T., de Bruijne, J. H. J., Arenou, F., Babusiaux, C., Biermann, M., Creevey, O. L., Ducourant, C., Evans, D. W., Eyer, L., Guerra, R., Hutton, A., Jordi, C., Klioner, S. A., Lammers, U. L., Lindegren, L., Luri, X., … Zwitter, T. (2023). Gaia Data Release 3. Summary of the content and survey properties. *674*, A1. https://doi.org/10.1051/0004-6361/202243940

Gardner, J. P., Mather, J. C., Clampin, M., Doyon, R., Greenhouse, M. A., Hammel, H. B., Hutchings, J. B., Jakobsen, P., Lilly, S. J., Long, K. S., Lunine, J. I., McCaughrean, M. J., Mountain, M., Nella, J., Rieke, G. H., Rieke, M. J., Rix, H.-W., Smith, E. P., Sonneborn, G., … Wright, G. S. (2006). The James Webb Space Telescope. *123*(4), 485–606. https://doi.org/10.1007/s11214-006-8315-7

Girardi, L., Bertelli, G., Bressan, A., Chiosi, C., Groenewegen, M. A. T., Marigo, P., Salasnich, B., & Weiss, A. (2002). Theoretical isochrones in several photometric systems. I. Johnson-Cousins-Glass, HST/WFPC2, HST/NICMOS, Washington, and ESO Imaging Survey filter sets. *391*, 195–212. https://doi.org/10.1051/0004-6361:20020612

Girardi, Léo, Dalcanton, J., Williams, B., de Jong, R., Gallart, C., Monelli, M., Groenewegen, M. A. T., Holtzman, J. A., Olsen, K. A. G., Seth, A. C., Weisz, D. R., & ANGST/ANGRRR Collaboration. (2008). Revised Bolometric Corrections and Interstellar Extinction Coefficients for the ACS and WFPC2 Photometric Systems. *120*(867), 583. https://doi.org/10.1086/588526

Groenewegen, M. A. T. (2006). The mid- and far-infrared colours of AGB and post-AGB stars. *448*(1), 181–187. https://doi.org/10.1051/0004-6361:20054163

Han, J. J., Dey, A., Price-Whelan, A. M., Najita, J., Schlafly, E. F., Saydjari, A., Wechsler, R. H., Bonaca, A., Schlegel, D. J., Conroy, C., Raichoor, A., Drlica-Wagner, A., Kollmeier, J. A., Koposov, S. E., Besla, G., Rix, H.-W., Goodman, A., Finkbeiner, D., Anand, A., … Zucker, C. (2023). NANCY: Next-generation All-sky Near-infrared Community surveY. *arXiv e-Prints*, arXiv:2306.11784. https://doi.org/10.48550/arXiv.2306.11784

Harikane, Y., Ouchi, M., Oguri, M., Ono, Y., Nakajima, K., Isobe, Y., Umeda, H., Mawatari, K., & Zhang, Y. (2023). A Comprehensive Study of Galaxies at z 9-16 Found in the Early JWST Data: Ultraviolet Luminosity Functions and Cosmic Star Formation History at the Pre-reionization Epoch. *265*(1), 5. https://doi.org/10.3847/1538-4365/acaaa9

Harris, C. R., Millman, K. J., van der Walt, S. J., Gommers, R., Virtanen, P., Cournapeau, D., Wieser, E., Taylor, J., Berg, S., Smith, N. J., Kern, R., Picus, M., Hoyer, S., van Kerkwijk, M. H., Brett, M., Haldane, A., del Río, J. F., Wiebe, M., Peterson, P., … Oliphant, T. E. (2020). Array programming with NumPy. *585*(7825), 357–362. https://doi.org/10.1038/s41586-020-2649-2

Henden, N. A., Puchwein, E., Shen, S., & Sijacki, D. (2018). The FABLE simulations: a feedback model for galaxies, groups, and clusters. *479*(4), 5385–5412. https://doi.org/10.

1093/mnras/sty1780

Hirschmann, M., Dolag, K., Saro, A., Bachmann, L., Borgani, S., & Burkert, A. (2014). Cosmological simulations of black hole growth: AGN luminosities and downsizing. *442*(3), 2304–2324. https://doi.org/10.1093/mnras/stu1023

Hopkins, P. F., Kereš, D., Oñorbe, J., Faucher-Giguère, C.-A., Quataert, E., Murray, N., & Bullock, J. S. (2014). Galaxies on FIRE (Feedback In Realistic Environments): stellar feedback explains cosmologically inefficient star formation. *445*(1), 581–603. https://doi.org/10.1093/mnras/stu1738

Hopkins, P. F., Wetzel, A., Kereš, D., Faucher-Giguère, C.-A., Quataert, E., Boylan-Kolchin, M., Murray, N., Hayward, C. C., Garrison-Kimmel, S., Hummels, C., Feldmann, R., Torrey, P., Ma, X., Anglés-Alcázar, D., Su, K.-Y., Orr, M., Schmitz, D., Escala, I., Sanderson, R., … Narayanan, D. (2018). FIRE-2 simulations: physics versus numerics in galaxy formation. *480*(1), 800–863. https://doi.org/10.1093/mnras/sty1690

Hopkins, P. F., Wetzel, A., Wheeler, C., Sanderson, R., Grudić, M. Y., Sameie, O., Boylan-Kolchin, M., Orr, M., Ma, X., Faucher-Giguère, C.-A., Kereš, D., Quataert, E., Su, K.-Y., Moreno, J., Feldmann, R., Bullock, J. S., Loebman, S. R., Anglés-Alcázar, D., Stern, J., … Hayward, C. C. (2023). FIRE-3: updated stellar evolution models, yields, and microphysics and fitting functions for applications in galaxy simulations. *519*(2), 3154–3181. https://doi.org/10.1093/mnras/stac3489

Hsiao, T. Y.-Y., Coe, D., Abdurro'uf, Whitler, L., Jung, I., Khullar, G., Meena, A. K., Dayal, P., Barrow, K. S. S., Santos-Olmsted, L., Casselman, A., Vanzella, E., Nonino, M., Jiménez-Teja, Y., Oguri, M., Stark, D. P., Furtak, L. J., Zitrin, A., Adamo, A., … Welch, B. (2023). JWST Reveals a Possible z 11 Galaxy Merger in Triply Lensed MACS0647-JD. *949*(2), L34. https://doi.org/10.3847/2041-8213/acc94b

Ivezić, Ž., Kahn, S. M., Tyson, J. A., Abel, B., Acosta, E., Allsman, R., Alonso, D., AlSayyad, Y., Anderson, S. F., Andrew, J., Angel, J. R. P., Angeli, G. Z., Ansari, R., Antilogus, P., Araujo, C., Armstrong, R., Arndt, K. T., Astier, P., Aubourg, É., … Zhan, H. (2019). LSST: From Science Drivers to Reference Design and Anticipated Data Products. *873*(2), 111. https://doi.org/10.3847/1538-4357/ab042c

Kartaltepe, J. S., Rose, C., Vanderhoof, B. N., McGrath, E. J., Costantin, L., Cox, I. G., Yung, L. Y. A., Kocevski, D. D., Wuyts, S., Ferguson, H. C., Bagley, M. B., Finkelstein, S. L., Amorín, R. O., Andrews, B. H., Haro, P. A., Backhaus, B. E., Behroozi, P., Bisigello, L., Calabrò, A., … Zavala, J. A. (2023). CEERS Key Paper. III. The Diversity of Galaxy Structure and Morphology at z = 3-9 with JWST. *946*(1), L15. https://doi.org/10.3847/2041-8213/acad01

Khandai, N., Di Matteo, T., Croft, R., Wilkins, S., Feng, Y., Tucker, E., DeGraf, C., & Liu, M.-S. (2015). The MassiveBlack-II simulation: the evolution of haloes and galaxies to $z \sim 0$. *450*(2), 1349–1374. https://doi.org/10.1093/mnras/stv627

Kocevski, D. D., Barro, G., McGrath, E. J., Finkelstein, S. L., Bagley, M. B., Ferguson, H. C., Jogee, S., Yang, G., Dickinson, M., Hathi, N. P., Backhaus, B. E., Bell, E. F., Bisigello, L., Buat, V., Burgarella, D., Casey, C. M., Cleri, N. J., Cooper, M. C., Costantin, L., … Zavala, J. A. (2023). CEERS Key Paper. II. A First Look at the Resolved Host Properties of AGN at $3 < z < 5$ with JWST. *946*(1), L14. https://doi.org/10.3847/2041-8213/acad00

Kroupa, P. (2001). On the variation of the initial mass function. *322*(2), 231–246. https://doi.org/10.1046/j.1365-8711.2001.04022.x

Kruijssen, J. M. D., Pfeffer, J. L., Crain, R. A., & Bastian, N. (2019). The E-MOSAICS project: tracing galaxy formation and assembly with the age-metallicity distribution of globular clusters. *486*(3), 3134–3179. https://doi.org/10.1093/mnras/stz968

Laureijs, R., Amiaux, J., Arduini, S., Augueres, J.-L., Brinchmann, J., Cole, R., Cropper, M., Dabin, C., Duvet, L., Ealet, A., Garilli, B., Gondoin, P., Guzzo, L., Hoar, J., Hoekstra, H., Holmes, R., Kitching, T., Maciaszek, T., Mellier, Y., … Zucca, E. (2011). Euclid Definition Study Report. *arXiv e-Prints*, arXiv:1110.3193. https://doi.org/10.48550/arXiv.1110.3193

Marigo, Paola, Bressan, A., Nanni, A., Girardi, L., & Pumo, M. L. (2013). Evolution of thermally pulsing asymptotic giant branch stars - I. The COLIBRI code. *434*(1), 488–526. https://doi.org/10.1093/mnras/stt1034

Marigo, P., Girardi, L., Bressan, A., Groenewegen, M. A. T., Silva, L., & Granato, G. L. (2008). Evolution of asymptotic giant branch stars. II. Optical to far-infrared isochrones with improved TP-AGB models. *482*(3), 883–905. https://doi.org/10.1051/0004-6361:20078467

Marigo, Paola, Girardi, L., Bressan, A., Rosenfield, P., Aringer, B., Chen, Y., Dussin, M., Nanni, A., Pastorelli, G., Rodrigues, T. S., Trabucchi, M., Bladh, S., Dalcanton, J., Groenewegen, M. A. T., Montalbán, J., & Wood, P. R. (2017). A New Generation of PARSEC-COLIBRI Stellar Isochrones Including the TP-AGB Phase. *835*(1), 77. https://doi.org/10.3847/1538-4357/835/1/77

Miller, A. C., Anderson, L., Leistedt, B., Cunningham, J. P., Hogg, D. W., & Blei, D. M. (2022). Mapping Interstellar Dust with Gaussian Processes. *arXiv e-Prints*, arXiv:2202.06797. https://doi.org/10.48550/arXiv.2202.06797

Necib, L., Ostdiek, B., Lisanti, M., Cohen, T., Freytsis, M., Garrison-Kimmel, S., Hopkins, P. F., Wetzel, A., & Sanderson, R. (2020). Evidence for a vast prograde stellar stream in the solar vicinity. *Nature Astronomy*, *4*, 1078–1083. https://doi.org/10.1038/s41550-020-1131-2

Nelson, D., Pillepich, A., Springel, V., Weinberger, R., Hernquist, L., Pakmor, R., Genel, S., Torrey, P., Vogelsberger, M., Kauffmann, G., Marinacci, F., & Naiman, J. (2018). First results from the IllustrisTNG simulations: the galaxy colour bimodality. *475*(1), 624–647. https://doi.org/10.1093/mnras/stx3040

Nguyen, T., Ou, X., Panithanpaisal, N., Shipp, N., Necib, L., Sanderson, R., & Wetzel, A. (2023). Synthetic Gaia DR3 surveys from the FIRE cosmological simulations of Milky-Way-mass galaxies. *arXiv e-Prints*, arXiv:2306.16475. https://doi.org/10.48550/arXiv.2306.16475

Nikakhtar, F., Sheth, R. K., & Zehavi, I. (2021). Laguerre reconstruction of the correlation function on baryon acoustic oscillation scales. *104*(4), 043530. https://doi.org/10.1103/PhysRevD.104.043530

Ostdiek, B., Necib, L., Cohen, T., Freytsis, M., Lisanti, M., Garrison-Kimmmel, S., Wetzel, A., Sanderson, R. E., & Hopkins, P. F. (2020). Cataloging accreted stars within Gaia DR2 using deep learning. *636*, A75. https://doi.org/10.1051/0004-6361/201936866

Pajankar, A. (2017). pytest. In *Python unit test automation : Practical techniques for python developers and testers* (pp. 87–100). Apress. https://doi.org/10.1007/978-1-4842-2677-3_5

Pakmor, R., Springel, V., Coles, J. P., Guillet, T., Pfrommer, C., Bose, S., Barrera, M., Delgado, A. M., Ferlito, F., Frenk, C., Hadzhiyska, B., Hernández-Aguayo, C., Hernquist, L., Kannan, R., & White, S. D. M. (2023). The MillenniumTNG Project: the hydrodynamical full physics simulation and a first look at its galaxy clusters. *524*(2), 2539–2555. https://doi.org/10.1093/mnras/stac3620

Peeples, M. S., Corlies, L., Tumlinson, J., O'Shea, B. W., Lehner, N., O'Meara, J. M., Howk, J. C., Earl, N., Smith, B. D., Wise, J. H., & Hummels, C. B. (2019). Figuring Out Gas & Galaxies in Enzo (FOGGIE). I. Resolving Simulated Circumgalactic Absorption at $2 \leq z \leq 2.5$. *873*(2), 129. https://doi.org/10.3847/1538-4357/ab0654

Pérez-González, P. G., Barro, G., Annunziatella, M., Costantin, L., García-Argumánez, Á., McGrath, E. J., Mérida, R. M., Zavala, J. A., Haro, P. A., Bagley, M. B., Backhaus, B. E., Behroozi, P., Bell, E. F., Bisigello, L., Buat, V., Calabrò, A., Casey, C. M., Cleri, N. J., Coogan, R. T., … Yung, L. Y. A. (2023). CEERS Key Paper. IV. A Triality in the Nature of HST-dark Galaxies. *946*(1), L16. https://doi.org/10.3847/2041-8213/acb3a5

Pfeffer, J., Kruijssen, J. M. D., Crain, R. A., & Bastian, N. (2018). The E-MOSAICS project: simulating the formation and co-evolution of galaxies and their star cluster populations. *475*(4), 4309–4346. https://doi.org/10.1093/mnras/stx3124

Pillepich, A., Nelson, D., Hernquist, L., Springel, V., Pakmor, R., Torrey, P., Weinberger, R., Genel, S., Naiman, J. P., Marinacci, F., & Vogelsberger, M. (2018). First results from the IllustrisTNG simulations: the stellar mass content of groups and clusters of galaxies. *475*(1), 648–675. https://doi.org/10.1093/mnras/stx3112

Rey, M. P., Agertz, O., Starkenburg, T. K., Renaud, F., Joshi, G. D., Pontzen, A., Martin, N. F., Feuillet, D. K., & Read, J. I. (2023). VINTERGATAN-GM: The cosmological imprints of early mergers on Milky-Way-mass galaxies. *521*(1), 995–1012. https://doi.org/10.1093/mnras/stad513

Rosenfield, P., Marigo, P., Girardi, L., Dalcanton, J. J., Bressan, A., Williams, B. F., & Dolphin, A. (2016). Evolution of Thermally Pulsing Asymptotic Giant Branch Stars. V. Constraining the Mass Loss and Lifetimes of Intermediate-mass, Low-metallicity AGB Stars. *822*(2), 73. https://doi.org/10.3847/0004-637X/822/2/73

Sanderson, R. E., Wetzel, A., Loebman, S., Sharma, S., Hopkins, P. F., Garrison-Kimmel, S., Faucher-Giguère, C.-A., Kereš, D., & Quataert, E. (2020). Synthetic Gaia Surveys from the FIRE Cosmological Simulations of Milky Way-mass Galaxies. *246*(1), 6. https://doi.org/10.3847/1538-4365/ab5b9d

Schaye, J., Crain, R. A., Bower, R. G., Furlong, M., Schaller, M., Theuns, T., Dalla Vecchia, C., Frenk, C. S., McCarthy, I. G., Helly, J. C., Jenkins, A., Rosas-Guevara, Y. M., White, S. D. M., Baes, M., Booth, C. M., Camps, P., Navarro, J. F., Qu, Y., Rahmati, A., … Trayford, J. (2015). The EAGLE project: simulating the evolution and assembly of galaxies and their environments. *446*(1), 521–554. https://doi.org/10.1093/mnras/stu2058

Schaye, J., Kugel, R., Schaller, M., Helly, J. C., Braspenning, J., Elbers, W., McCarthy, I. G., van Daalen, M. P., Vandenbroucke, B., Frenk, C. S., Kwan, J., Salcido, J., Bahé, Y. M., Borrow, J., Chaikin, E., Hahn, O., Huško, F., Jenkins, A., Lacey, C. G., & Nobels, F. S. J. (2023). The FLAMINGO project: cosmological hydrodynamical simulations for large-scale structure and galaxy cluster surveys. https://doi.org/10.1093/mnras/stad2419

Sharma, S. (2020). *Ebfpy 0.0.20*. Online; Python Package Index. https://pypi.org/project/ebfpy/0.0.20

Sharma, S., Bland-Hawthorn, J., Johnston, K. V., & Binney, J. (2011a). *Galaxia: A Code to Generate a Synthetic Survey of the Milky Way* (p. ascl:1101.007). Astrophysics Source Code Library, record ascl:1101.007.

Sharma, S., Bland-Hawthorn, J., Johnston, K. V., & Binney, J. (2011b). Galaxia: A Code to Generate a Synthetic Survey of the Milky Way. *730*(1), 3. https://doi.org/10.1088/0004-637X/730/1/3

Sharma, S., & Steinmetz, M. (2006). Multidimensional density estimation and phase-space structure of dark matter haloes. *373*(4), 1293–1307. https://doi.org/10.1111/j.1365-2966.2006.11043.x

Sharma, S., & Steinmetz, M. (2011). *EnBiD: Fast Multi-dimensional Density Estimation* (p. ascl:1109.012). Astrophysics Source Code Library, record ascl:1109.012.

Shipp, N., Panithanpaisal, N., Necib, L., Sanderson, R., Erkal, D., Li, T. S., Santistevan, I. B., Wetzel, A., Cullinane, L. R., Ji, A. P., Koposov, S. E., Kuehn, K., Lewis, G. F., Pace, A. B., Zucker, D. B., Bland-Hawthorn, J., Cunningham, E. C., Kim, S. Y., Lilleengen, S., … FIRE Collaboration. (2023). Streams on FIRE: Populations of Detectable Stellar Streams in the Milky Way and FIRE. *949*(2), 44. https://doi.org/10.3847/1538-4357/acc582

Springel, V., Pakmor, R., Pillepich, A., Weinberger, R., Nelson, D., Hernquist, L., Vogelsberger, M., Genel, S., Torrey, P., Marinacci, F., & Naiman, J. (2018). First results from the IllustrisTNG simulations: matter and galaxy clustering. *475*(1), 676–698. https://doi.org/10.1093/mnras/stx3304

Stinson, G. S., Bailin, J., Couchman, H., Wadsley, J., Shen, S., Nickerson, S., Brook, C., & Quinn, T. (2010). Cosmological galaxy formation simulations using smoothed particle hydrodynamics. *408*(2), 812–826. https://doi.org/10.1111/j.1365-2966.2010.17187.x

Stinson, G. S., Brook, C., Macciò, A. V., Wadsley, J., Quinn, T. R., & Couchman, H. M. P. (2013). Making Galaxies In a Cosmological Context: the need for early stellar feedback. *428*(1), 129–140. https://doi.org/10.1093/mnras/sts028

Tang, J., Bressan, A., Rosenfield, P., Slemer, A., Marigo, P., Girardi, L., & Bianchi, L. (2014). New PARSEC evolutionary tracks of massive stars at low metallicity: testing canonical stellar evolution in nearby star-forming dwarf galaxies. *445*(4), 4287–4305. https://doi.org/10.1093/mnras/stu2029

The pandas development team. (2023). *Pandas-dev/pandas: pandas* (Version v2.1.1). Zenodo. https://doi.org/10.5281/zenodo.8364959

Trabucchi, M., Wood, P. R., Montalbán, J., Marigo, P., Pastorelli, G., & Girardi, L. (2019). Modelling long-period variables - I. A new grid of O-rich and C-rich pulsation models. *482*(1), 929–949. https://doi.org/10.1093/mnras/sty2745

Trabucchi, M., Wood, P. R., Mowlavi, N., Pastorelli, G., Marigo, P., Girardi, L., & Lebzelter, T. (2021). Modelling long-period variables - II. Fundamental mode pulsation in the non-linear regime. *500*(2), 1575–1591. https://doi.org/10.1093/mnras/staa3356

Tremmel, M., Karcher, M., Governato, F., Volonteri, M., Quinn, T. R., Pontzen, A., Anderson, L., & Bellovary, J. (2017). The Romulus cosmological simulations: a physical approach to the formation, dynamics and accretion models of SMBHs. *470*(1), 1121–1139. https://doi.org/10.1093/mnras/stx1160

Trussler, J. A. A., Adams, N. J., Conselice, C. J., Ferreira, L., Austin, D., Bhatawdekar, R., Caruana, J., Frye, B. L., Harvey, T., Lovell, C. C., Pascale, M., Roper, W. J., Verma, A., Vijayan, A. P., & Wilkins, S. M. (2023). Seeing sharper and deeper: JWST's first glimpse of the photometric and spectroscopic properties of galaxies in the epoch of reionization. *523*(3), 3423–3440. https://doi.org/10.1093/mnras/stad1629

Virtanen, P., Gommers, R., Oliphant, T. E., Haberland, M., Reddy, T., Cournapeau, D., Burovski, E., Peterson, P., Weckesser, W., Bright, J., van der Walt, S. J., Brett, M., Wilson, J., Millman, K. J., Mayorov, N., Nelson, A. R. J., Jones, E., Kern, R., Larson, E., … SciPy 1. 0 Contributors. (2020). SciPy 1.0: fundamental algorithms for scientific computing in Python. *Nature Methods*, *17*, 261–272. https://doi.org/10.1038/s41592-019-0686-2

Vogelsberger, M., Genel, S., Springel, V., Torrey, P., Sijacki, D., Xu, D., Snyder, G., Nelson, D., & Hernquist, L. (2014). Introducing the Illustris Project: simulating the coevolution of dark and visible matter in the Universe. *444*(2), 1518–1547. https://doi.org/10.1093/mnras/stu1536

Wang, L., Dutton, A. A., Stinson, G. S., Macciò, A. V., Penzo, C., Kang, X., Keller, B. W., & Wadsley, J. (2015). NIHAO project - I. Reproducing the inefficiency of galaxy formation across cosmic time with a large sample of cosmological hydrodynamical simulations. *454*(1), 83–94. https://doi.org/10.1093/mnras/stv1937

Wetzel, A. R., Hopkins, P. F., Kim, J., Faucher-Giguère, C.-A., Kereš, D., & Quataert, E. (2016). Reconciling Dwarf Galaxies with ΛCDM Cosmology: Simulating a Realistic Population of Satellites around a Milky Way-mass Galaxy. *827*(2), L23. https://doi.org/10.3847/2041-8205/827/2/L23