

FRAMEWORK TECHNICAL -SCIENTIFIC REPORT OF THE IMPLEMENTING ENTITY



Funded by the
European Union
NextGenerationEU



Ministero
dell'Università
e della Ricerca



Italiadomani
PIANO NAZIONALE
DI RIPRESA E RESILIENZA

**NATIONAL RECOVERY AND RESILIENCE PLAN (NRRP) – MISSION 4
COMPONENT 2 INVESTMENT 1.1 – “Fund for the National Research Program and
for Projects of National Interest (NRP)”**

INTRODUCTION

The Technical-Scientific Report is produced by the *Principal Investigator*, on the basis of a discussion with each local manager for the purposes of collecting data and documenting the progress of each operational unit. It is then submitted according to deadlines envisaged in the related notification.

The Report is composed of the following sections:

SECTION 1 – GENERAL TRENDS OF THE PROJECT, where information on the general trends of the projects are included by making reference to the achievement of intermediate and long-term goals, to the compliance with the project activities, to the *DNSH* and *Open Access* principles as per the approved project.

SECTION 2 – PROGRESS OF ACTIVITIES, which entails the description of carried out activities based on the details provided by the operational units involved in the implementation of the project during the collaboration period. It also includes the description of future activities, potential publications and challenges encountered as well as actions for improvement. This, in order to guarantee the achievement of goals that have been established when the financed project was presented.

SECTION 3 – COMMON INDICATORS, where EU common indicators connected to the specific investment should be enhanced.

SECTION 4 – PREDICTIVE ANALYSIS AND FINAL COMMENTS, regards the forecast scenario on the development of the project and final comments.

The hereby provided scheme will also be used when presenting the final results of the implemented activities within the project financed by the Ministry.

SECTION 1 – GENERAL TRENDS OF THE PROJECT

With regard to the **full duration of the project (month-1 to month-27)**, it is below provided:

a) a brief summary of the project;

Our project proposes to employ next-generation high-performance computing and advanced algorithms for data analysis, including machine learning (ML) tools, to investigate the unknown metal distributions around galaxies in the early Universe.

One objective (OBJ 1) is the development of HPC codes, execution of cosmological hydrodynamical simulations, the generation and analysis of large statistical samples of simulated data; finally the comparison with astronomical observational data and infer scientific conclusions.

The other objective (OBJ 2) is to develop new toolkits for fast and reliable analysis of big data from absorption spectroscopy. One set of tools will rely on advanced ML techniques to process spectral data, extract and classify absorption features. The other set of tools will build on the “Astrocook” software for spectral analysis to implement spectro-perfectionism techniques of data treatment and the Bayesian information criterion for accurate modeling of the spectral features.

Our simulations and analysis tools were applied to the investigation of the metal distribution around galaxies in the Circumgalactic and Intergalactic Medium (CGM and IGM) at redshifts $z \sim 2-4$, or $\sim 10-12$ Gyr ago. We shed some light on the multiple baryonic feedback processes that distribute energy/metals in the CGM/IGM which are still poorly understood and debated, in particular the feedback from early supermassive black holes in high-redshift quasars.

b) names of the operational units involved in the implementation of the project;

1. Istituto Nazionale di Astrofisica - Osservatorio Astronomico di Trieste (INAF-OATs)
2. Università degli Studi di MILANO-BICOCCA (UNIMIB)

c) description of the achievement of the objectives connected to the project and related outcomes;

A concise list of the final results of the project: the full publication list and github links to code websites can be found in pages 18 and 19; the details of which are described in the text of this report.

OBJ 1

WP1:

We have included the sub-resolution recipes of kinetic AGN feedback from the older version P-GADGET3 to the newer version of our code OpenGADGET3. We have also incorporated an unified AGN feedback numerical scheme in OpenGADGET3, which includes both thermal and kinetic feedback depending on the central black hole accretion

rate (**Deliverable D1.1**), together with heating and cooling from a BH corona (**Activity 1.1**). Thus there is an updated version of the OpenGADGET3 code with the new physics included. We have written proposals within the USC VIII - Call for Computing of the INAF and have obtained HPC resources in the INAF supercomputer Pleiadi (**Activity 1.2**).

We have executed 11 cosmological hydrodynamical simulations of $(50 \text{ Mpc})^3$ periodic boxes (**Deliverable D1.2**) with 256^3 dark-matter and 256^3 gas particles, by varying a few numerical model parameters: BH seed mass, AGN feedback efficiency, kinetic feedback wind velocity, supernova feedback wind velocity of 700 km/s, AGN thermal feedback, a control run of SF only with no SN or AGN feedback, and another run with full physics of SN feedback + unified AGN feedback model with thermal feedback in the quasar-mode of AGN and kinetic feedback in the radio mode of AGN (**Activity 1.3**). The numerical simulations were carried out at the supercomputing cluster GAPAE of IAG-USP, Brazil and at the INAF supercomputer Pleiadi.

We also performed 2 cosmological hydrodynamical simulations with a larger particle number, which were stopped at an earlier cosmic epoch $z=2$, because of the higher computational resources required: one of $(100 \text{ Mpc})^3$ periodic-box (**Deliverable D1.3**) with 512^3 dark-matter and 512^3 gas particles to probe a larger population of massive galaxies, and another of $(50 \text{ Mpc})^3$ box with 512^3 dark-matter and 512^3 gas particles to study the effects of numerical resolution.

The paper presenting the simulations and investigating the science case of gas accretion versus BH merger driven growth modes of central SMBHs in galaxies has been accepted for publication in the *A&A journal* (*proofs attached*, [Barai 2026](#), **Deliverable D1.5**). Here we investigate the black growth, Eddington ratio trends and central black hole-host galaxy coevolution properties. Based on our results, we suggest a growth scenario of high- z Little Red Dots recently observed by JWST: the normal-mass SMBHs had predominantly undergone BH merger driven evolution, whereas the overmassive BHs underwent periods of Eddington-limited or super-Eddington bursts of gas accretion.

Additional Scientific Objective (*change described in Section 2, item (b), implemented during the execution of the project from 01 February 2025 up to 13 December 2025.*)

Rationale: This objective was not planned in our original proposal; the goals achieved in this context replaces one of the original objective “*Emission line diagnostics in quasar spectra: Observations compared to Zoom-in Galaxy Simulations*” in the proposal. This change led to the development of a semi-analytical model of dust evolution to be included in cosmological hydrodynamical simulations. It will allow us to perform zoom-in simulations with the dust model included, *in the near future*, and then do a more realistic comparison with observations because dust plays a crucial role for high- z quasars.

We have implemented a new dust growth model, adopting the framework of Zhukovska et al. (2008), where the dust grain composition and the recycling of the ISM between the

different phases are taken into account. The dust scaling relations involving metallicity are well reproduced with this new improved switch. We ran the new dust growth model on the Millennium II (Boylan-Kolchin et al. 2009) merger trees, which allowed us to extend the range of the simulation predictions down to galaxies with stellar masses of $10^7 M_{\odot}$.

We have developed a novel self-consistent model of dust formation by stars, destruction by supernova shocks and hot gas, and growth within the dense interstellar medium (**Deliverable D2.1**) integrated in the GAEA semi-analytical modeling of galaxy formation. The model was applied to merger trees extracted from the Millennium and Millennium-II simulations, and the dust properties in galaxies were studied; all the results are written in the submitted publication [Osman et al. \(2026\)](#).

WP2:

We have been analyzing the $(50 \text{ Mpc})^3$ and $(100 \text{ Mpc})^3$ cosmological hydrodynamical simulations done in WP1 to extract in postprocessing the simulated spectra of the ionized metal specie CIV. We have generated the ionization correction tables for a range of densities and temperatures for redshifts $z=2-6$ using the photoionization code CLOUDY. We have examined the simulation snapshots to understand the effect of feedback processes on the distribution of CGM and IGM gas (**Activity 2.1**). Comparing the phase space plots of three simulations (i) no Black Hole (ii) with BH but no AGN feedback and (iii) with 100% kinetic feedback efficiency from the AGN feedback, we conclude that the phase space distribution of gas and metal enriched particles are similar for the simulations (i) and (ii), and the gas fraction in the WHIM phase increases significantly when AGN kinetic feedback is included. Comparing 2 simulations with seed BH masses $10^4 M_{\odot}$ and $10^6 M_{\odot}$, we find that BHs grow faster in the case of higher seed mass, resulting in higher energy imparted as AGN kinetic feedback. Hence a higher gas fraction is shock-heated and pushed to the high-temperature WHIM phase.

We have generated mock observations along randomly shot sightlines in the different simulation boxes. We extracted the SPH smoothed quantities along the grids of these sightlines, and applied the ionization correction using the tables generated from CLOUDY (**Activity 2.2**). We have fitted the absorption line profiles with Voigt profiles to estimate the column density and the velocity spread given by the Doppler parameter. A simulated observable was generated: quasar spectra of the CIV absorption line (**Deliverable D2.2**), by projecting random sightlines tracing the IGM gas in the simulation boxes.

WP5:

We have carried out the identification and fit of metal absorption lines in a new sample of 23 quasar spectra obtained in an ESO large program with the ESPRESSO spectrograph (**Activity 5.1**). The quasars in the sample have emission redshifts in the range $z \sim 3.3-4.3$ and have been observed with a resolving power $R \sim 130,000$.

We have analyzed quasar spectra both at high-resolution and $z \sim 3$ (ESPRESSO EQUALS sample) and intermediate resolution and $z \sim 5$ (X-Shooter sample) with the identification of

metal absorption lines (**Activity 5.3**). We continued the analysis of archival ALMA data on [CII] halos and [CII] outflows in high-redshift quasars (**Activity 5.5**). A paper presenting the results for a particularly notable object has been published in *The Astrophysical Journal* ([Bischetti et al. 2025](#), **Deliverable D5.4**). We also completed the study of outflows in both emission and absorption in a sample of quasars at $z \sim 5$, which is now published in the *Astronomy & Astrophysics journal* ([Brazzini et al. 2025](#), **Deliverable D5.1**).

The simulated spectra of CIV absorption lines generated in WP2 were used to compute the CIV correlations which were then compared to observational studies, in particular the XQR-30 quasar sample ([D'Odorico et al. 2023](#)). We are checking if the cosmological simulations are able to reproduce the observed CIV absorption line correlations; and how the SN/AGN feedback processes in the simulations impact the metal absorber statistics (**Deliverable D5.1**, *in preparation*).

The objective of WP5 involving the extraction of emission-line spectra from zoom-in simulations has been replaced with the additional scientific objective of dust model development in WP1, as described in Section 2, item (b).

OBJ 2

WP3:

We have generated mock catalogs containing half a million spectra of quasars. We started using the PCA method to input eigenvectors that allows random generation of spectral shapes. The intrinsic characteristics (luminosity and redshift distributions) of the mock spectra follow the distributions of the target from the WEAVE survey. Then, we added the absorption features due to the metals using the Non-negative matrix factorization (NMF) absorption maker. Finally, the Lyman- α forest is imprinted on the spectra following the distribution of absorbers from the Sherwood simulation.

We tested the performances of three different neural networks (an autoencoder, a convolutional neural network, and a U-Net) in fitting the continua of quasar spectra (**Activity 3.1**). Thereby we optimized these architectures using a subsample of previously developed quasar mock spectra. A mock making code for large datasets was developed along the way (**Deliverable D3.1**). We compared the performances of the optimized architectures with neural networks used in the literature. We found that the autoencoder has performances comparable to more complex architecture for much less computational time (~ 100 times lower). Finally, we tested the autoencoder on the DESI early data release data for a more physical test (**Activity 3.2**). We estimated the evolution of the optical depth in the Lyman- α forest and found agreement with the results in the literature.

The paper on continuum fitting was published in the *Astronomy & Astrophysics journal* ([Pistis et al. 2025](#), **Deliverables D3.1 and D3.2**).

We developed tools for the identification and classification of absorption lines via deep learning. We built a U-net to identify absorption features in the quasar spectra. We focused on using the U-Net for a binary classification (continuum-absorption line) for the identification of the features of interest. Such a model reaches a completeness of 95% at S/N of the lines of ~ 5 with a purity of $\sim 100\%$ at the same S/N level. We performed a deeper optimization of the model on a larger sample. We also built a different model for the multiclassification of the lines. Taking as input the position of the lines, this model will classify the ion that produces each line (**Activity 3.3**).

We generated a new set of mock spectra, increasing the number of transitions producing absorption lines from 30 to 46 transitions. We trained various U-Net models for the multi-classification of absorption lines, also incorporating residual and attention blocks, or both. We decided to use nested sampling for fitting absorption lines templates to simultaneously fit multiple transitions of a given ion. The work on the publication draft for the detection of absorption lines is continuing (**Deliverable D3.3**).

We finally fallback to a more physical algorithm that classifies the absorption lines from a set of centroids, because of the extensive computational resources needed by the nested sampling for classifying and measuring absorption lines. The algorithm works by searching for absorbing systems using doublets and then verifying if the missing lines can be classified by ions corresponding to the same systems.

Regarding the measurement of such absorption lines, a working extension of the code MC-ALF ([Github](#)) for using GPUs instead of CPUs (**Deliverable D3.4**) was developed.

WP4:

We have reorganized the existing Astrocook fitting procedures. We evaluated several strategies to implement spectro-perfectionism. The development of Astrocook-2 has continued in the form of bug fixing, based on user reports (**Activity 4.1**). We implemented a refined technique for continuum fitting.

The development of Astrocook+ has focused on an architectural redesign to enhance stability and for integration with emerging technologies. We have implemented a clean, standardized API across the core codebase. We have completed the integration of improved algorithms for key tasks, including continuum normalization and Voigt profile fitting (**Deliverable D4.1**). We are developing proof-of-concept interfaces to enable human-in-the-loop analysis. These efforts progress toward making Astrocook+ a next-generation and scalable package (**Activity 4.2**).

The core framework of Astrocook+ software has been heavily upgraded to include an advanced MCMC (Markov chain Monte Carlo) Bayesian fitting module. The resulting package Astrocook v2.0 has been recently released ([Cupani 2026](#), **Deliverable D4.2**).

- d) description of the carried out activities which are in compliance with the *DNSH*, *Open Access* principles as well as with *gender*, *generational* principles and with those of *Equal opportunities*

All our activities carried out were in compliance with the DNSH.

The selection processes for hiring the new postdocs at each of the operational units INAF-OATs and UNIMIB were performed by adhering to gender equality and Equal opportunities.

Our submitted and future publications of research articles have been in peer-reviewed Open Access journals.

- e) description of the actions aimed at informing and disseminating knowledge

The results of the project have been presented at the following national and international conferences/meetings and seminars.

- 1) 2nd International Workshop on Machine Learning and Quantum Computing Applications in Medicine and Physics held in Warsaw - Poland, during 4-7 June 2024 (<https://events.ncbj.gov.pl/event/314>): TALK by Francesco Pistis
- 2) European Astronomical Society (EAS) Annual Meeting 2024 held in Padova - Italy, during 1-5 July 2024 (<https://eas.unige.ch/EAS2024/>): POSTERS & Flash Talk by Paramita Barai
- 3) OpenGADGET3 User Meeting 2024 held in Ljubljana - Slovenia, during 29 July - 1 August 2024 (<https://indico.ict.inaf.it/event/2850>): TALK by Paramita Barai
- 4) Conference “Physics in the AI era” held in Pisa - Italy, during 24-27 September 2024 (<https://agenda.infn.it/event/40134>): TALK by Francesco Pistis
- 5) Conference “The Ecosystem of Gas and Dust in Galaxies Near and Far” held in Chiang Mai - Thailand, during 10-15 December 2024 (<https://indico.narit.or.th/event/211/page/846-programme>): TALK by Paramita Barai
- 6) Conference “Exploring the Enigma of First Stars and Galaxies in the era of JWST” held in Sesto - Italy, during 27-31 January 2025 (<https://www.sexten-cfa.eu/event/jwst25>): TALK by Chiara Feruglio
- 7) Meeting of Research Line “Galaxies in the cosmic web” at the Institute for Fundamental Physics of the Universe - IFPU in Trieste - Italy, 27 February 2025: TALK by Sukanya Mallik
- 8) Conference “WST - the Wide-field Spectroscopic Telescope: surveying the Universe in the 2040’s and beyond – Italian Workshop” held in Naples - Italy, during 10-12 March 2025 (<https://indico.ict.inaf.it/event/3071/page/1486-home>): POSTER by Sukanya Mallik

- 9) Conference “Galaxy Origins in the JWST era: a ‘CRISTOL’ of stars, ISM, and super massive black holes in the City of the Three Cultures” held in Toledo - Spain, during 12-16 May 2025 (<https://galaxy-crisol25.github.io/website>): POSTER & Flash Talk by Sukanya Mallik
- 10) Conference “International Workshop on Galaxy Formation + AGORA in Asia 2025” held in Osaka - Japan, during 26-30 May 2025 (<https://sites.google.com/view/galaxy-formation-adora-2025>): TALK by Paramita Barai
- 11) Conference “UniversAI: Exploring the Universe with Artificial Intelligence” held in Athens - Greece, during 02-06 June 2025 (<https://universai2025.hua.gr/programme/>): TALK by Francesco Pistis
- 12) “ICGAC2025: International Conference on Gravitation, Astrophysics and Cosmology” - CONPLUS meeting held in Amsterdam - Netherlands, during 9 June 2025 (<https://astrophysics.conplusmeeting.com>): TALK by Paramita Barai
- 13) Conference “42. Zjazd Polskiego Towarzystwa Astronomicznego (PTA)” held in Warsaw - Poland, during 8-12 September 2025 (<https://zjazd42.pta.edu.pl/event/1>): POSTER by Francesco Pistis
- 14) Conference “MMC2025: Multi-phase, Multi-temperature and Complex” held in Olbia (Sardinia) - Italy, during 6-10 October 2025 (<https://galaxylifecycle.wixsite.com/mmc2025/program>): TALK by Paramita Barai, and POSTER by Sukanya Mallik
- 15) IFPU Focus Week “Unraveling Little Red Dots: Linking JWST Discoveries with Simulations” held at the Institute for Fundamental Physics of the Universe (IFPU), Trieste - Italy, during 27-31 October 2025 (<https://sites.google.com/inaf.it/lrdsifpu/schedule>): TALK by Paramita Barai
- 16) ESO Workshop “Highly Accreting Supermassive Black Holes Across all Cosmic Times: from the Local Universe to Cosmic Dawn” held at the ESO headquarters in Santiago - Chile during 1-5 December 2025 (https://www.eso.org/sci/meetings/2025/highlyaccreting/ESO_workshop_high_accretion_programme_new.pdf): TALK by Paramita Barai
- 17) SOTU Invited Seminar (<https://theory.tifr.res.in/~sotu/previous.php>) at the Tata Institute of Fundamental Research (TIFR), Mumbai - India by Sukanya Mallik on 9 January 2026

Any relevant attached document which includes the above mentioned details:

- PDF of the slides of the talks (2 page per presentation) and posters listed above.

Because of the maximum file size limit of 40 MB for all the scientific attachments; we are only attaching 2 pages (first page + last page) per talk presentation given at conferences.

The complete versions of all the above PDF presentations were already submitted during the 1st, 2nd, 3rd, 4th, 5th and 6th Quadrimestre reports that we have transmitted before.

SECTION 2 – PROGRESS OF ACTIVITIES

With regard to the **full duration of the project (month-1 to month-27)**, it is below provided:

- a) detailed description of activities carried out by each operational unit with a focus on the timeframe for their implementation

Unit INAF-OATs

WP1:

- **Month 1-2:** We have incorporated the numerical sub-resolution prescriptions of kinetic AGN feedback from the older version of the code P-GADGET3 to the newer version of the code OpenGADGET3. The feedback energy from a central supermassive black hole in a galaxy is distributed to the surrounding gas in the kinetic form, where velocity is increased.
- **Month 3:** We have written a proposal within the INAF USC VIII - Call for Computing for obtaining HPC resources in the INAF supercomputer Pleiadi.
- **Month 3-4:** We have generated initial conditions to execute cosmological hydrodynamical simulations of $(50 \text{ Mpc})^3$ periodic boxes with 256^3 dark matter and 256^3 gas particles.
- **Month 1-4:** The procedures for opening a competition (bando) for hiring a new postdoc at INAF-OATs were started and completed. The postdoc is to begin in July-2024.
- **Month 5-6:** We have developed and incorporated an unified AGN feedback numerical scheme in our code OpenGADGET3; which includes both thermal and kinetic feedback depending on the central black hole accretion rate, together with heating and cooling from a BH corona (**Deliverable D1.1, Activity 1.1**).
- **Month 6-8:** We are executing cosmological hydrodynamical simulations of $(50 \text{ Mpc})^3$ periodic boxes with 256^3 dark-matter and 256^3 gas particles (**Activity 1.3**). We plan a total of 8 simulations by varying the numerical parameters of the AGN feedback model: the BH seed mass, AGN feedback efficiency, kinetic feedback wind velocity.
- **Month 8:** We are preparing a proposal for obtaining HPC resources in the ISCRA Class C project scheme (**Activity 1.2**).
- **Month 9-12:** We have started to execute one new cosmological hydrodynamical simulation of $(100 \text{ Mpc})^3$ periodic box with 512^3 dark-matter and 512^3 gas particles, which would allow us to investigate the effect of the boxsize. We have also started one new simulation of $(50 \text{ Mpc})^3$ box with 512^3 dark-matter and 512^3 gas particles; which has the same boxsize as our previous simulations but a higher numerical resolution.
- **Month 13-16:** Both the cosmological hydrodynamical simulations of $(100 \text{ Mpc})^3$ and $(50 \text{ Mpc})^3$ box, each with 512^3 dark-matter and 512^3 gas particles have reached up to $z=2$. The execution of the following more simulations of $(50 \text{ Mpc})^3$ boxes with 256^3 dark-matter and 256^3 gas particles have started (**Activity 1.3**): one new run with a Supernova feedback Wind velocity of 700 km/s, one new run with AGN thermal feedback only.
- **Month 17-20:** All the planned periodic-box cosmological hydrodynamical simulations of $(50 \text{ Mpc})^3$ and $(100 \text{ Mpc})^3$ comoving volumes have finished executing starting from

$z=100$, and have reached up to $z=0$, and $z=2$ for the two larger particle number runs (**Activity 1.3**). In these simulations we have implemented different configurations of supermassive Black Hole feedback parameters: seed BH mass, BH feedback efficiency, BH kinetic feedback kick velocity, as well as a comparison between thermal and kinetic forms of BH feedback.

A publication presenting the simulations and analyzing the gas accretion versus BH merger driven growth modes of central SMBHs in galaxies has been completed and submitted in *the Astronomy & Astrophysics journal*. We find that, starting as $10^5 M_{\odot}$ seeds, the BHs grow initially via BH mergers to $\sim 10^7 M_{\odot}$. Gas accretion onto the BHs increases with time, and reaches the Eddington rate after 7 – 9 Gyrs. The BHs then undergo very fast growth via efficient gas accretion over a period of 600 – 700 Myr, causing their predominant growth from $10^7 M_{\odot}$ to $(10^9 - 10^{10})M_{\odot}$.

- **Month 21-27:** The submitted publication presenting our cosmological hydrodynamical simulations (**Deliverables D1.2 and D1.3**) has undergone referee review. According to the referee's suggestions, we have performed two new periodic-box $(50 \text{ Mpc})^3$ cosmological simulations, with 2×256^3 dark-matter+gas particles: one run is a control case of SF only with no SN or AGN feedback, and another run with full physics of SN feedback + unified AGN feedback model which implements thermal feedback in the quasar-mode of AGN and kinetic feedback in the radio mode of AGN. The manuscript is currently accepted for publication (*A&A proofs attached*, [Barai 2026](#), **Deliverable D1.5**).

Additional Scientific Objective (*change described in item (b) of this section, implemented during the execution of the project from 01 February 2025 up to 13 December 2025.*):

- **Month 15-18:** We had progress toward the development of a semi-analytical model of dust evolution to be included in cosmological hydrodynamical simulations. We completed the development of a new dust growth model, adopting the framework of Zhukovska et al. (2008). Here the dust grain composition and the recycling of the ISM between the different phases are taken into account. The advantage of adopting this model over the classical Dwek (1998) formulation is that Oxygen depletion is kept at low levels consistent with those adopted in emission-line modelling (e.g. Groves et al. 2004; Gutkin et al. 2016). This new switch (improvement from Dwek 1998) also allowed our scheme to reproduce well the dust scaling relations involving metallicity.
- **Month 19-20:** We ran the new dust growth model on the Millennium II (MSII, Boylan-Kolchin et al. 2009) merger trees, which allowed us to extend the range of the simulation predictions down to galaxies with stellar masses of $10^7 M_{\odot}$. We performed all the standard analyses to assess the model's success in reproducing several observational constraints with a large collection of data for each constraint. The model reproduces reasonably well all the constraints and is often consistent with predictions of models from other groups, adopting the same theoretical framework.
- **Month 21-25:** A novel self-consistent model of dust formation by stars, destruction by supernova shocks and hot gas, and growth within the dense interstellar medium was developed (**Deliverable D2.1**) integrated in the GAEA semi-analytical modeling of galaxy

formation. Extending the chemical evolution prescription ([De Lucia et al. 2014](#)), an explicit model for the formation and evolution of dust was implemented. This consists of physical processes which are the main drivers of dust mass evolution: (i) dust formation in stellar winds of AGB stars, SNIa, and SNII, (ii) accretion of the ISM gas-phase metals on dust grains, i.e. dust growth, and (iii) dust destruction by SN remnants and sputtering in the hot gas. This dust model was applied to merger trees extracted from the Millennium and Millennium-II simulations, which are dark-matter-only N-body cosmological simulations of volumes $(500 \text{ Mpc})^3$ and $(100 \text{ Mpc})^3$, respectively. The resulting dust properties in galaxies were studied: dust buildup as a function of stellar mass, the dust-to-gas/dust-to-metal ratio scaling relations, and the dust mass function; all of which are written in the submitted publication [Osman et al. \(2026\)](#).

WP2:

- **Month 7-8:** We have started to analyze the $(50 \text{ Mpc})^3$ cosmological hydrodynamical simulations. We identify galaxies using subhalo finder code, and post-process the gas particles to compute radial profiles of gas properties around the galaxies ([Activity 2.1](#)).
- **Month 9-12:** We compute the stellar mass of the simulated halos and the star formation rate densities over redshifts $z=0-8$. We compare these quantities for different simulations and also with the various observations reported in the literature. For our next step to extract the spectra of metal ions from these simulations, we generated the ionization correction tables for a range of densities and temperatures for redshifts $z=2-6$ using the photoionization code CLOUDY.
- **Month 13-16:** We made plots to understand the effect of feedback processes on the distribution of gas and metals in the simulations. Considering the gas temperature (T) versus overdensity (Δ) plane as a diagnostic, we divide the phase-space into four phases: *Diffuse* ($T < 10^5 \text{ K}$ and $\Delta < 120$), *Warm Hot Ionized Medium* (WHIM: $T > 10^5 \text{ K}$ and $\Delta < 120$), *Hot halo* ($T > 10^5 \text{ K}$ and $\Delta > 120$), and *Condensed* ($T < 10^5 \text{ K}$ and $\Delta > 120$).
 - Comparing 3 simulations with (i) no Black Hole (BH), (ii) with BH but no AGN feedback, and (iii) with 100% kinetic AGN feedback efficiency; we conclude that the fraction of gas in the WHIM phase increases significantly when AGN kinetic feedback is included. In the 3rd simulation, a significant fraction of high-metallicity gas ($Z > Z_\odot$) is shock-heated to $T > 10^{6.5} \text{ K}$.
 - Comparing the simulations with AGN wind velocities of 1000 km/s, 5000 km/s and 10000 km/s, we find that more metals are distributed in lower-density and higher-temperature phases with higher AGN wind velocities. Comparing two simulations of seed BH masses $10^4 M_\odot$ and $10^6 M_\odot$, we find that more gas is shock heated and pushed to the high-temperature WHIM phase with a higher seed mass.
- **Month 17-20:** We extract mock observations along randomly shot sightlines in the different simulation boxes ([Activity 2.2](#)). We generated the SPH smoothed quantities along the grids of these sightlines, and applied the ionization correction using the tables from CLOUDY. We are currently fitting the absorption line profiles with Voigt profiles to

estimate the column density and the velocity spread given by the Doppler parameter.

- **Month 21-27:** The $(50 \text{ Mpc})^3$ cosmological hydrodynamical simulations done in WP1 are being analyzed to extract quasar spectra for the ionized metal species CIV. We generated a simulated observable: quasar spectra of the CIV absorption line (**Deliverable D2.2**), by drawing random sightlines tracing the IGM gas in each of the simulation boxes. We convolved the spectra with a gaussian profile mimicking the observational instrumental line spread function. For $z < 4$, we use a gaussian profile with FWHM of 6.6 km/s and SNR of 50 per pixel. For $z > 4$, we use gaussian profiles with variable FWHM and variable SNR, uniformly sampled from the observed spectra along different quasar sightlines.

WP4:

- **Month 1-4:** We performed the first task which was the reorganization of the existing Astrocook fitting procedures, to improve the flexibility of the code before new additions are done. The resulting package will be soon released as Astrocook v2.0. Meanwhile, several strategies to implement spectro-perfectionism have been evaluated.
- **Month 5-8:** We have continued working on Astrocook-2, according to the following steps:
 - The merging of existing tools into specific numerical recipes to model the Lyman-alpha forest, thereby detect and model the metal absorbers outside and within the forest.
 - The improvement and testing of the numerical recipes to model the emission continuum, now employing a more refined smoothing and the possible use of a template to correctly reproduce the shape of the Lyman-alpha emission line.
- **Month 9-12:** The development of Astrocook-2 has continued primarily in the form of bug fixing, based on user reports (**Activity 4.1**). A refined technique for continuum fitting has been implemented. Concurrently, we have started a re-assessment of the activities and originally proposed deliverables based on the currently acquired results.
- **Month 13-16:** Development of Astrocook+ has focused on a foundational architectural redesign to enhance stability and prepare the package for integration with emerging technologies. To date, we have been implementing a clean, standardized API across the core codebase. We have also completed the integration of improved algorithms for key tasks, including continuum normalization and Voigt profile fitting (**Deliverable D4.1**).
- **Month 17-20:** The architectural choices implemented so far are specifically designed to pave the way for a new generation of analysis workflows. Our immediate future work is centered on leveraging the standardized API to explore integration with Large Language Models (LLMs) and intelligent agents. We are actively developing proof-of-concept interfaces to enable human-in-the-loop analysis, allowing researchers to guide complex spectral tasks using natural language prompts. These efforts re-oriented our purpose towards position Astrocook+ as a modern, reliable, and scalable framework (**Activity 4.2**).
- **Month 21-27:** The core framework of Astrocook+ software has been heavily upgraded to

include an advanced MCMC (Markov chain Monte Carlo) Bayesian fitting module. This has drastically improved the statistical robustness of parameter estimations for complex systems. The Astrocook-V2 has been recently released ([Cupani 2026](#), **Deliverable D4.2**). This has progressed the existing Astrocook package to a precision-oriented, highly-scalable environment for the analysis of massive catalogs of spectroscopic data from large surveys of QSOs.

WP5:

- **Month 1-4:** We are assembling a sample of quasars at $z > 4$ from ALMA and NOEMA archives and proprietary data, which will be used to derive the properties of the [CII] line.
- **Month 9-12:** We are carrying out the identification and fit of metal absorption lines in a new sample of 23 quasar spectra obtained in an ESO large program with the ESPRESSO spectrograph (**Activity 5.1**). The quasars in the sample have emission redshifts in the range $z \sim 3.3-4.3$ and have been observed with a resolving power $R \sim 130,000$. Part of the activity of this WP has also consisted of discussions on the best strategy to compare simulations with observations. We have developed and validated a comprehensive quasar catalog and created a database that incorporates quasar properties, detailed characteristics of the identified emission lines, including the profiles of [CII] and/or CO emission lines.
- **Month 13-16:** We continued the analysis of archival ALMA data on [CII] halos and [CII] outflows in high-redshift quasars (**Activity 5.5**). A paper presenting results for a particularly notable object has been submitted to *The Astrophysical Journal Letters* ([Bischetti et al. 2025](#), including Feruglio and D’Odorico, **Deliverable D5.4**), and published. The analysis of a larger sample is currently underway. We also completed the study of outflows in both emission and absorption in the sample of quasars at $z \sim 5$, and submitted a paper to *Astronomy & Astrophysics* ([Brazzini et al. 2025](#), including D’Odorico and Feruglio, **Deliverable D5.1**).
- **Month 17-27:** The simulated spectra of CIV absorption lines generated in WP2 were used to compute the CIV absorber statistics which were then compared to observational studies, in particular the XQR-30 quasar sample (obtained by the X-Shooter spectrograph, [D’Odorico et al. 2023](#)). The goals are to firstly check if the cosmological simulations are able to reproduce the CIV absorption line statistical correlations; and thereby examine how the SN/AGN feedback processes in the simulations impact the metal absorber statistics (*Mallik et al. in preparation*).

The objective of WP5 involving the extraction of emission-line spectra from simulations has been replaced with the additional scientific objective of dust model development in WP1, as described earlier.

Unit UNIMIB

WP3:

- **Month 1-2:** We have implemented the spectra generation of quasars following the PCA method. We have done imprinting of the absorption features due to the metals with the NMF method.
- **Month 3-4:** We have done imprinting of the Lyman- α forest following the Sherwood simulation. Then we did imprinting of the observational characteristics (e.g., signal to noise of the spectra) of WEAVE using the code WEAVEify (WEAVE survey simulation). We have generated the mock catalog containing 500,000 spectra.
- **Month 1-4:** The procedures for opening a call for hiring a new postdoc at UNIMIB were also started and completed during this period. The postdoc began in March-2024.
- **Month 5-7:** We optimized three neural networks, such as an autoencoder, a convolutional neural network, and a U-Net using the previously developed quasar mock spectra. We compared the performances with neural networks found in the literature. Finally, we performed physical test over spectra from the DESI early data release with the autoencoder, that results having comparable performances with more complex architectures for much less computational time (~ 100 times).
- **Month 8:** We wrote the draft of a paper showing our results with the intention to submit to *Astronomy & Astrophysics*. The draft is currently awaiting the approval of the editorial board of the WEAVE consortium.
- **Month 9-12:** The manuscript about the tools for continuum fitting (**Deliverable D3.2**) based on WEAVE mock data (**Deliverable D3.1**) has been *submitted to the journal Astronomy & Astrophysics*, which was eventually published ([Pistis et al. 2025](#)). We started the work on deep learning tools for the identification and classification of absorption lines focusing on the identification problem.
- **Month 13-16:** We fixed the issues of blended lines in the mock spectra. After fixing such problems, we built a U-net to identify absorption features in the quasar spectra. Such a model reaches a completeness of 95% at S/N of the lines of ~ 5 with a purity of $\sim 100\%$ at the same S/N level. We are currently performing a deeper optimization of the model on a higher number of spectra. Meanwhile, we started to build a different model for the multiclassification of the lines. Taking as input the position of the lines, this model will classify the ion that produce each line. (**Activity 3.3**)
- **Month 17-20:** We produced a new set of mock spectra, increasing the number of transitions producing absorption lines from 30 to 46 transitions. We trained various U-Net models for the multi-classification of absorption lines, also incorporating residual and attention blocks, or both (**Activity 3.3**). All models do not exceed 60% purity. For this reason, we opted to adapt the WP3 by joining the classification with the measurements of the lines. We decided to use nested sampling for fitting absorption lines templates to simultaneously fit multiple transitions of a given ion. This is a work in progress, and we

are missing the measurements of integrated metrics such as completeness and purity. At the same time, the work on the draft for the detection of absorption lines is continuing (**Deliverable D3.3**, *in attachment*).

- **Month 21-27:** Because of the extensive computational resources needed by the nested sampling for classifying and measuring absorption lines, we fallback to a more physical algorithm that classifies the absorption lines from a set of centroids. The algorithm works by searching for absorbing systems using doublets and then verifying if the missing lines can be classified by ions corresponding to the same systems.

Regarding the measurement of such absorption lines, we have a working extension of the code MC-ALF ([Github](#)) for using GPUs instead of CPUs (**Deliverable D3.4**).

- b) description of potential changes to what has been originally approved mentioning the impacts on the aim of the intervention, on the achievement of intermediate and long-term goals, on the proposed actions for improvement;

Delay of hiring postdoc for WP2:

The postdoc (external personnel hired with MUR funding) at INAF-OATs started working only from July-2024, as it took some months for the recognition of the qualifications obtained abroad as well as for the application of a work Visa for Italy of the successful candidate, who is a non-Italian citizen. This delay brought in by the administrative recruiting procedure led to the fact that we were able to start working on WP2 (Simulation output analysis) only from month-8 (instead of the originally planned month-1 or month-2). This forced us to request an extension of the project up to February-2026, in order to obtain the scientific objectives of WP2.

Boxsize of Simulations in WP1 (because of Computational Resources):

For some of our new cosmological hydrodynamical simulations, we had to downsize the periodic boxsize from $(100 \text{ Mpc})^3$ with 2×512^3 particles to $(50 \text{ Mpc})^3$ with 2×256^3 particles. This was a measure to execute the runs faster, and explore a larger parameter space of the new AGN feedback models. The gas particle mass resolution of 4.6×10^7 solar masses remains the same in both the cases. The only difference being the masses of the galaxies produced in the simulations; in the $(50 \text{ Mpc})^3$ box the galaxies are about 4-5 times smaller than that would have been generated in the $(100 \text{ Mpc})^3$ box. Thus in these $(50 \text{ Mpc})^3$ simulations we will probe the circumgalactic and intergalactic medium of slightly lower-mass galaxies. We performed only one $(100 \text{ Mpc})^3$ simulation from $z=100$ continued up to $z=2$.

Additional Scientific Objective:

We have included an additional scientific objective within the ambience of WP1 of the project. The practical implementation has involved an addendum to the contract of *assegno di ricerca* “*The critical role of DUST in the cosmic barYon cycle*” of postdoc *Omima Osman Mohammed Osman* (external personnel supported with MUR funding to work on the objective), executed from 01 February 2025 up to 13 December 2025. It was done for an optimal utilization of the personnel hiring funds by the project deadline of 28 February 2026.

This postdoc support for 10.5 months has been on the scientific topic of “**Building a New Semi-Analytical Model of Dust Evolution**”, which is within the context of refining the sub-resolution models in our WP1, in particular the development of a semi-analytical model of dust evolution to be included in cosmological hydrodynamical simulations. The relevant activities carried out are described before in Section 2 – item (a), second and third paragraphs, and the goals reached ([Osman et al. 2026](#)) are described in Section 1 – item (c).

The prospect of this additional objective has made us dedicate time and resources on it during the last year of the execution of the project, which was not planned in our original proposal. This objective has thereby replaced one of the original objectives of the proposal in WP5 “*Emission line diagnostics in quasar spectra: Observations compared to Zoom-in Galaxy Simulations*”. The goals achieved in this context ([Osman et al. 2026](#)) has led to the development of a new sub-resolution model of dust evolution. It will allow us to perform zoomed-in cosmological simulations with the new dust model included, *as a long- term goal*, and then do a more realistic comparison with observations because dust plays a crucial role for high-*z* quasars.

- c) description of potential challenges encountered and of the proposed actions for improvement;

As described in the *item (b)* above, the delay of the postdoc hiring at INAF-OATs brought in a delay of starting the activities of our WP2.

Also as described in item (b) of this section, the inclusion of an additional scientific objective within the ambience of WP1 was implemented during the execution of the project. This has made us dedicate time and resources on its achievement during the last year of the project, which was not planned in our original proposal. This new objective has thereby replaced one of the original objectives of the proposal in WP5, namely “*Emission line diagnostics in quasar spectra: Observations compared to Zoom-in Galaxy Simulations*”.

The goals accomplished in the context of the new objective ([Osman et al. 2026](#)) has led to the development of a new sub-resolution model of dust evolution. It will allow us to perform zoom-in galaxy simulations with the new dust model included, *as a long- term goal*, and then do a more realistic comparison with observations because dust plays a crucial role for high-*z* quasars.

d) brief description of potential publications.

The following publications have acknowledged funding from MUR for this PRIN 2022 PNRR project.

- Publication “Exploring the Evolution of a Dwarf Spheroidal Galaxy with SPH Simulations. II. AGN Feedback” – R. Hazenfratz, P. Barai, G. A. Lanfranchi & A. Caproni, 2025, The Astrophysical Journal, Volume 979, Issue 2, id.238, 26 pp. <https://ui.adsabs.harvard.edu/abs/2025ApJ...979..238H> (work mostly done before the project)
1. Publication “ALMA Reveals Bright Circumgalactic Emission and a Biconical Outflow in $z \sim 6.4$ Quasar PSOJ183+05” – M. Bischetti, C. Feruglio, S. Carniani, V. D’Odorico, F. Salvestrini & F. Fiore, 2025, The Astrophysical Journal Letters, Volume 990, Issue 2, id.L31, 8 pp. <https://ui.adsabs.harvard.edu/abs/2025ApJ...990L..31B> (**Deliverable D5.4**)
 2. Publication “Automated quasar continuum estimation using neural networks: A comparative study of deep-learning architectures” – F. Pistis, M. Fumagalli, M. Fossati et al., 2025, Astronomy & Astrophysics, Volume 698, id.A292, 21 pp. <https://ui.adsabs.harvard.edu/abs/2025A%26A...698A.292P> (**Deliverables D3.1 and D3.2**)
 3. Publication “Multi-phase investigation of outflows in the circumgalactic and interstellar media of luminous quasars at $z \sim 5$ ” – M. Brazzini, V. D’Odorico, M. Bischetti, C. Feruglio, G. Cupani, G. Becker & R. Tripodi, 2025, Astronomy & Astrophysics, Volume 698, id.A145, 19 pp. <https://ui.adsabs.harvard.edu/abs/2025A%26A...698A.145B> (**Deliverable D5.1**)
 4. Publication “Gas accretion versus black-hole-merger-driven growth modes of supermassive black holes and implications for the little red dots” – P. Barai 2026, A&A in press <https://ui.adsabs.harvard.edu/abs/2026arXiv260215952B> (**Deliverables D1.2 and D1.5**)
 5. Publication Manuscript “Dust evolution across cosmic times as seen through DUSTY-GAEA” – O. Osman, G. De Lucia, F. Fontanot, L. Xie, M. Hirschmann, 2026, accepted for publication in A&A <https://arxiv.org/abs/2512.15902> (**New Deliverable of additional scientific objective**)
 6. Publication Draft “A physically motivated classifier for metal lines in quasar spectra. Accurate ion and transition classification using synthetic WEAVE spectra” – F. Pistis, M. Fumagalli, M. Fossati et al. in preparation (**Deliverable D3.3**)
 7. Publication Draft “Detection of metal absorption lines in quasar spectra. A neural network approach using U-Net” – E. S. Mangola, F. Pistis, M. Fumagalli, M. Fossati et al. in preparation (**Deliverable D3.3**)

8. Publication Draft “Origin and Evolution of CIV absorbing systems in the Intergalactic Medium from the reionization epoch up to cosmic noon at $2 \leq z \leq 5$ ” – S. Mallik, P. Barai, V. D’Odorico et al. in preparation **(Deliverable D2.2)**
9. Publication Draft “Enabling AI-Driven Spectral Discovery: The Astrocook v2 Decoupled Architecture for Quasar Analysis” – G. Cupani et al. in preparation (conference abstract) **(Deliverable D4.1)**
10. Publication Draft “Astrocook v2: LLM-Ready Foundation for Autonomous Analysis of Quasar Spectra” – G. Cupani et al. in preparation <https://spie.org/astronomical-telescopes-instrumentation/presentation/Astrocook-v2--LLM-Ready-Foundation-for-Autonomous-Analysis-of/14155-74> **(Deliverable D4.2)**

The following webpages list our results of software publication.

Public webpage of project (to highlight the progress of activities, present and future publications) : <https://adlibitum.oats.inaf.it/paramita.barai/Grants/PRIN-2022-PNRR>

- 1) OpenGADGET3 code websites **(Deliverables D1.1 and D2.1)**

Public version: <https://gitlab.lrz.de/MAGNETICUM/Hydro-OpenGadget3>

Developmental version: <https://gitlab.lrz.de/KlausDolag/OpenGadget3>

- 2) Astrocook website **(Deliverables D4.1 and D4.2)**

Public version: <https://github.com/DAS-OATs/astrocook>

Documentation: <https://das-oats.github.io/astrocook/>

- 3) Code MC-ALF for using GPUs in our ML pipeline for the measurement of absorption lines **(Deliverable D3.4)**: <https://github.com/matteofox/MC-ALF>

Any relevant attached document which includes the above mentioned details

- PDF of the above publications

SECTION 3 – COMMON INDICATORS

Below the updates on the indicator RRFCI 8 – “*Number of researchers who work in research centres which are recipients of financial support (women; men; non-binary)*” – as per the description in the guidelines included in the n.34 MEF notification from the 17th of October 2022.

Istituto Nazionale di Astrofisica - Osservatorio Astronomico di Trieste (INAF)
CUP C53D23010020001

Common indicators RRFCI 8	Planned value	Implemented value
Researchers who work in research centers which are recipients of financial support (women)	1.4	1.26
Researchers who work in research centers which are recipients of financial support (men)	0.04	0.04
Researchers who work in research centers which are recipients of financial support (non-binary)	0	0

Università degli Studi di MILANO-BICOCCA (UNIMIB)
CUP H53D23011030001

Common indicators RRFCI 8	Planned value	Implemented value
Researchers who work in research centers which are recipients of financial support (women)	0	0
Researchers who work in research centers which are recipients of financial support (men)	1.16	1.04
Researchers who work in research centers which are recipients of financial support (non-binary)	0	0

Errata correction: An inadvertent error occurred in filling out this table for the unit UNIMIB in Q5. The values reported correspond to the row “men”, while they were mistakenly filled in the row “women”. The above show the total planned data compared with the actual data obtained after a 3-month extension.

SECTION 4 – PREDICTIVE ANALYSIS AND FINAL COMMENTS

Below it is provided a description of the forecast scenario on the development of the project, any potential change which is deemed necessary for the future as well as comments on the document.

1) Predictive analysis

The activities carried out have opened avenues for future studies. The $(50 \text{ Mpc})^3$ cosmological simulations can be analyzed to investigate multiple galaxy properties, e.g., the stellar mass function, SMBH mass density, mass-metallicity relation of galaxies, etc. The new dust evolution model would allow a more realistic comparison with observations. On the observational side, the analysis of quasar spectra at high-resolution and $z \sim 3$ (ESPRESSO EQUALS sample), and intermediate-resolution and $z \sim 5$ (X-Shooter sample); together with a larger sample of archival ALMA data on [CII] halos in high- z quasars. The QSO spectral analysis software Astrocook+ can be expanded toward a fully automated architecture. Another goal would be to integrate the separate elements of the spectral analysis ML codes into an end-to-end full Machine-Learning pipeline that can be deployed on very large catalogs of observed or simulated spectra.

2) Final comments

The project has concluded satisfactorily. We have obtained scientific/technical results in all the work packages as elaborated earlier, with 10 publications (5 papers already published and 5 manuscripts in preparation) and 3 github links reported in total.

*Delegate of the Legal Representative of the
implementing entity*

Director of

*Astronomical Observatory of Trieste
of the National Institute for Astrophysics*

Power of Attorney n. 1265 of 12.6.24

Emended by note n. 15891 of 26.11.25

Fabrizio Fiore

 Paramita
Barai
23.04.2026
00:02:42
GMT+02:00

Paramita Barai

Principal Investigator

PRIN 2022 PNRR project

code n° P2022ZLW4T



ATTACHMENTS

The below documents are also attached to the technical – scientific report:

Att.1 – Declaration of compliance with DNSH principle and compliance with other principles as per the Environment code

Because of the maximum file size limit of 40 MB for all the scientific attachments over 27 months; we had to heavily compress a few of the publication PDFs and we are only attaching 2 pages (first page + last page) per talk presentation given at conferences.

The original resolution and full versions of all these documents were already submitted during the 6 Quadrimestre reports we have uploaded before.

Att.2 – Publication “Exploring the Evolution of a Dwarf Spheroidal Galaxy with SPH Simulations. II. AGN Feedback” – R. Hazenfratz, P. Barai, G. A. Lanfranchi & A. Caproni, 2025, The Astrophysical Journal, Volume 979, Issue 2, id.238, 26 pp. <https://ui.adsabs.harvard.edu/abs/2025ApJ...979..238H>

Att.3 – Publication “ALMA Reveals Bright Circumgalactic Emission and a Biconical Outflow in $z \sim 6.4$ Quasar PSOJ183+05” – M. Bischetti, C. Feruglio, S. Carniani, V. D’Odorico, F. Salvestrini & F. Fiore, 2025, The Astrophysical Journal Letters, Volume 990, Issue 2, id.L31, 8 pp. <https://ui.adsabs.harvard.edu/abs/2025ApJ...990L...31B>

Att.4 – Publication “Automated quasar continuum estimation using neural networks: A comparative study of deep-learning architectures” – F. Pistis, M. Fumagalli, M. Fossati et al., 2025, Astronomy & Astrophysics, Volume 698, id.A292, 21 pp. <https://ui.adsabs.harvard.edu/abs/2025A%26A...698A.292P>

Att.5 – Publication “Multi-phase investigation of outflows in the circumgalactic and interstellar media of luminous quasars at $z \sim 5$ ” – M. Brazzini, V. D’Odorico, M. Bischetti, C. Feruglio, G. Cupani, G. Becker & R. Tripodi, 2025, Astronomy & Astrophysics, Volume 698, id.A145, 19 pp. <https://ui.adsabs.harvard.edu/abs/2025A%26A...698A.145B>

Att.6 – Publication “Gas accretion versus black-hole-merger-driven growth modes of supermassive black holes and implications for the little red dots” – P. Barai 2026, A&A in press <https://ui.adsabs.harvard.edu/abs/2026arXiv260215952B>

Att.7 – Publication Manuscript “Dust evolution across cosmic times as seen through DUSTY-GAEA” – O. Osman, G. De Lucia, F. Fontanot, L. Xie, M. Hirschmann, 2026, accepted for publication in A&A <https://arxiv.org/abs/2512.15902>

Att.8 – Publication Draft “A physically motivated classifier for metal lines in quasar spectra. Accurate ion and transition classification using synthetic WEAVE spectra” – F. Pistis, M. Fumagalli, M. Fossati et al. in preparation

- Att.9* – Publication Draft “Detection of metal absorption lines in quasar spectra. A neural network approach using U-Net” – E. S. Mangola, F. Pistis, M. Fumagalli, M. Fossati et al. in preparation
- Att.10* – Publication Draft “Origin and Evolution of CIV absorbing systems in the Intergalactic Medium from the reionization epoch up to cosmic noon at $2 \leq z \leq 5$ ” – S. Mallik, P. Barai, V. D’Odorico et al. in preparation
- Att.11* – Deliverable D1.1: Print out of one subroutine of the Black Hole physics in the OpenGADGET3 code (part of the gitlab repository). This subroutine includes the relevant numerical parts developed within this PRIN 2022 PNRR project.
- Att.12* – Deliverable D3.1: Print out of the private gitlab page containing the mock making code for large datasets.
- Att.13* – PDF slides 2 pages each of the 17 talks listed below presented at national and international conferences/meetings and seminars (*reported in Section 1, item (e) before*):
- A. 2nd International Workshop on Machine Learning and Quantum Computing Applications in Medicine and Physics held in Warsaw - Poland, during 4-7 June 2024 (<https://events.ncbj.gov.pl/event/314>): TALK by Francesco Pistis
 - B. European Astronomical Society (EAS) Annual Meeting 2024 held in Padova - Italy, during 1-5 July 2024 (<https://eas.unige.ch/EAS2024/>): POSTERS & Flash Talk by Paramita Barai
 - C. OpenGADGET3 User Meeting 2024 held in Ljubljana - Slovenia, during 29 July - 1 August 2024 (<https://indico.ict.inaf.it/event/2850>): TALK by Paramita Barai
 - D. Conference “Physics in the AI era” held in Pisa - Italy, during 24-27 September 2024 (<https://agenda.infn.it/event/40134>): TALK by Francesco Pistis
 - E. Conference “The Ecosystem of Gas and Dust in Galaxies Near and Far” held in Chiang Mai - Thailand, during 10-15 December 2024 (<https://indico.narit.or.th/event/211/page/846-programme>): TALK by Paramita Barai
 - F. Conference “Exploring the Enigma of First Stars and Galaxies in the era of JWST” held in Sesto - Italy, during 27-31 January 2025 (<https://www.sexten-cfa.eu/event/jwst25>): TALK by Chiara Feruglio
 - G. Meeting of Research Line “Galaxies in the cosmic web” at the Institute for Fundamental Physics of the Universe - IFPU in Trieste - Italy, 27 February 2025: TALK by Sukanya Mallik
 - H. Conference “WST - the Wide-field Spectroscopic Telescope: surveying the Universe in the 2040’s and beyond – Italian Workshop” held in Naples - Italy, during 10-12 March 2025 (<https://indico.ict.inaf.it/event/3071/page/1486-home>): POSTER by Sukanya Mallik
 - I. Conference “Galaxy Origins in the JWST era: a ‘CRISTOL’ of stars, ISM, and super massive black holes in the City of the Three Cultures” held in Toledo - Spain, during 12-16 May 2025 (<https://galaxy-crisol25.github.io/website>): POSTER & Flash Talk by Sukanya Mallik
 - J. Conference “International Workshop on Galaxy Formation + AGORA in Asia 2025” held in Osaka - Japan, during 26-30 May 2025 (<https://sites.google.com/view/galaxy-formation-adora-2025>): TALK by Paramita Barai
 - K. Conference “UniversAI: Exploring the Universe with Artificial Intelligence” held in Athens - Greece, during 02-06 June 2025 (<https://universai2025.hua.gr/programme/>): TALK by Francesco Pistis

- L. “ICGAC2025: International Conference on Gravitation, Astrophysics and Cosmology” - CONPLUS meeting held in Amsterdam - Netherlands, during 9 June 2025 (<https://astrophysics.conplusmeeting.com>): TALK by Paramita Barai
- M. Conference “42. Zjazd Polskiego Towarzystwa Astronomicznego (PTA)” held in Warsaw - Poland, during 8-12 September 2025 (<https://zjazd42.pta.edu.pl/event/1>): POSTER by Francesco Pistis
- N. Conference “MMC2025: Multi-phase, Multi-temperature and Complex” held in Olbia (Sardinia) - Italy, during 6-10 October 2025 (<https://galaxylifecycle.wixsite.com/mmc2025/program>): TALK by Paramita Barai, and POSTER by Sukanya Mallik
- O. IFPU Focus Week “Unraveling Little Red Dots: Linking JWST Discoveries with Simulations” held at the Institute for Fundamental Physics of the Universe (IFPU), Trieste - Italy, during 27-31 October 2025 (<https://sites.google.com/inaf.it/lrdsifpu/schedule>): TALK by Paramita Barai
- P. ESO Workshop “Highly Accreting Supermassive Black Holes Across all Cosmic Times: from the Local Universe to Cosmic Dawn” held at the ESO headquarters in Santiago - Chile during 1-5 December 2025 (https://www.eso.org/sci/meetings/2025/highlyaccreting/ESO_workshop_high_accretion_programme_new.pdf): TALK by Paramita Barai
- Q. SOTU Invited Seminar (<https://theory.tifr.res.in/~sotu/previous.php>) at the Tata Institute of Fundamental Research (TIFR), Mumbai - India by Sukanya Mallik on 9 January 2026