Scientific annual report

The Cosmic Dawn Center

2023

2.1.1 Annual highlights

The brightest galaxies at cosmic dawn

Last year, the astronomical community found itself in a bit of a crisis, after the James Webb Space Telescope almost immediately had revealed a large number of galaxies that were seemingly too big, bright, and abundant than virtually all cosmological models predicted. How these early galaxies were able to form such an enormous amount of stars in so little time is not only puzzling, but had people doubt everything from instruments, to observational techniques, to analyses, and even the "standard" model of structure formation in the Universe.

Rather than overthrowing the fundamentals of cosmology, the solution to the puzzle is likely a combination of several mechanisms. But a crucial factor was shown by Mason et al. (2023a) from "first principles", i.e. as a theoretical calculation with few assumptions beyond what is well-established:

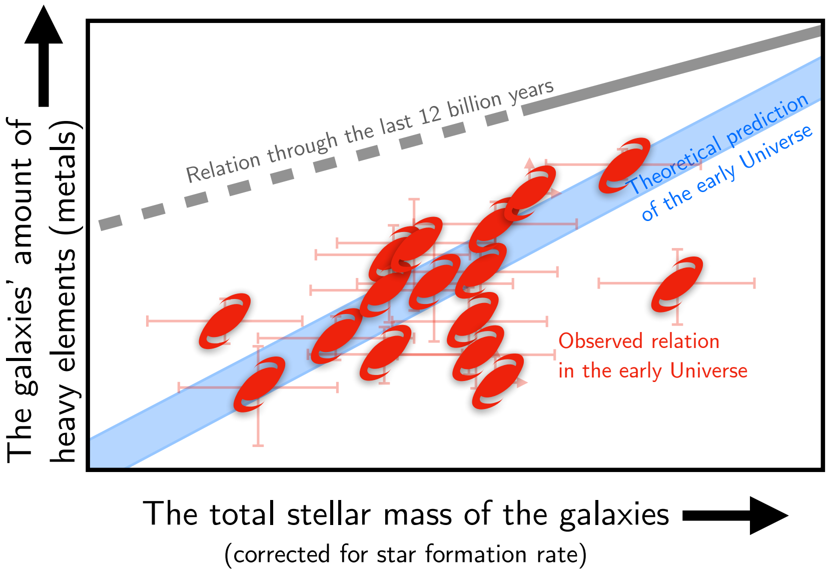
During their very first epochs of star formation, galaxies form stars in rapid bursts and undergo particularly bright phases as the most massive and luminous stars are still alive and the galaxies are unobscured by the dust that is formed later. For a brief period, only a few percent of the age of the Universe at that time, galaxies therefore appear extraordinarily bright. And it is these galaxies that we now see.

Before there were building blocks

Of all the elements that comprise the visible world, only the three lightest were present when the Universe was born. All heavier elements — from the carbon that comprises all known life, to the oxygen you breathe, to the gold ring on your finger — were created by stars much later.

Throughout most of the history of the Universe, galaxies apparently have quickly reached an equilibrium between their amount and production of stars, and their content of heavy elements. But galaxies don't form instantaneously, and if we look far enough back in time, we should theoretically be able to see more "pristine" galaxies, before they were polluted by heavy elements.

This theory was confirmed last year when Heintz et al. (2023d) examined the chemical composition of 16 galaxies, seen 500–800 million years after the Big Bang, finding them all to be significantly poorer in heavy elements than later galaxies. This discovery, which would have been impossible before we had James Webb, confirms our understanding of the early formation and evolution of galaxies.



This diagram shows the relation between galaxies' production of stars, and their amount of heavy elements. Whereas the gray line shows the relation throughout most of the history of the Universe, the red points shows the recent observation of the early Universe. They fit nicely with theoretical predictions from computer simulations (the blue band).

Årets højdepunkter

De klareste galakser ved kosmisk daggry

Sidste år fandt astronomien sig i lidt af en krise, efter at rumteleskopet James Webb næsten øjeblikkeligt gav os et stort antal galakser, som tilsyneladende var for store, for lysstærke, og for mange, i forhold til hvad stort set alle kosmologiske modeller forudsagde. Hvordan disse galakser var i stand til at danne en så enorm mængde stjerner på så kort tid, er ikke blot mystisk, men fik folk til at betvivle alt fra instrumenter, over observationsteknikker og analysemetoder, til selve "standardmodellen" for strukturdannelse i Universet.

I stedet for at forkaste kosmologiens fundament, er løsningen på mysteriet nok en kombination af flere mekanismer. Men en afgørende faktor blev påvist af Mason et al. (2023a) fra "første principper", dvs. som en teoretisk beregning med kun få antagelser ud over, hvad der er veletableret:

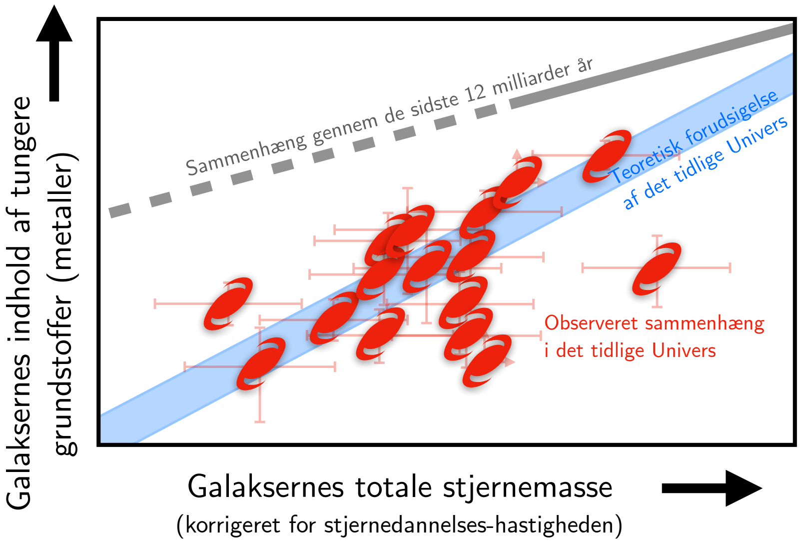
I løbet af deres allerførste epoker af stjernedannelse danner galakserne stjerner i kortvarige udbrud og gennemgår særligt klare faser, mens de tungeste og klareste stjerner stadig er i live, og galakserne er utilslørede af det støv, der dannes senere. For en kort stund, blot et par procent af Universets alder på denne tid, fremstår galakserne derfor ekstraordinært lysstærke. Og det er disse galakser, som vi nu ser.

Før der var byggesten

Af alle de grundstoffer, der udgør den synlige verden, var kun de tre letteste til stede da Universet blev født. Alle tungere grundstoffer — fra kulstoffet der findes i alt kendt liv, over ilten du indånder, til guldringen på din finger — blev skabt af stjernerne langt senere.

Gennem størstedelen af Universets historie har galakser tilsyneladende hurtigt opnået en ligevægt mellem deres mængde og produktion af stjerner, og deres indhold af tunge grundstoffer. Men galakser dannes ikke fra det ene øjeblik til det andet, og kigger vi langt nok tilbage i tiden, burde vi teoretisk set se "renere" galakser, før de blev forurenet af tunge grundstoffer.

Denne teori blev bekræftet sidste år, da Heintz et al. (2023d) undersøgte den kemiske sammensætning af 16 galakser, set 500–800 millioner år efter Big Bang, og fandt, at de alle havde et væsentligt lavere indhold af tunge grundstoffer end senere galakser. Denne opdagelse, som ikke ville have været mulig før vi havde James Webb, bekræfter vores forståelse af galaksernes tidlige dannelse og udvikling.



Dette diagram viser sammenhængen mellem galaksernes stjerneindhold og -dannelse, og deres indhold af tunge grundstoffer. Hvor den grå linje viser sammenhængen gennem det meste af Universets historie, viser de røde punkter de nylige observationer af det tidlige Univers. Det passer smukt sammen med teoretiske forudsigelser fra computersimuleringer (det blå bånd).

2.1.2. Organization

Professor Darach Watson and Associate Professor Charlotte Mason have taken over the roles as head and deputy head of the DAWN section at the NBI.

To support openness and communication in DAWNs growing organization, we have included representatives for early career researchers in the DAWN board. The elected representatives are Simone Vejlgaard Nielsen (alternate Kimi Cardoso Kreilgaard) for the PhD students, and Marko Shuntov (alternate Anne Hutter) for the postdocs.

2.1.3. Recruitment and gender strategy

DAWN’s recruitment strategy continues to uphold simplicity while focusing on attracting and recruiting the top candidates from around the globe regardless of gender, ethnicity or cultural background. Postdoc and PhD positions are offered yearly through wide, open international calls. All deadlines are individual for applications, rounds of interviews, offers and acceptances, while following the international academic hiring cycle. We continue to organize a summer research program which attracts some of the most talented undergraduate researchers from the United States and Denmark. This year seven international and three Danish students participated in the program. Three of the students were female, and seven were male.

In 2023 we recruited three new postdoctoral fellows, one female and two males, who are nationals of Italy and Japan, and arrived from institutes in Italy, the Netherlands and the United States.

Through our PhD fellowship program we hired six PhD students, three female and three male, who are nationals of Denmark and India. One PhD student graduated and continued on to a postdoctoral fellowship in Chile.

2.1.4. Outreach

From its inception, DAWN has valued the significance of disseminating its discoveries and other aspects of astronomy to the public. In 2023 we issued 10 press releases which all caught the media's attention, resulting in numerous reports in various Danish and foreign media, interviews in TV news & shows, radio programs, and podcasts.

Additionally, several members from DAWN are active in giving talks to the public — in particular high-schools but also FolkeUniversitetet, amateur astronomy associations, and the industry — and in writing popular science articles in real and online magazines. We frequently receive inquiries from laypersons and journalists about various astronomical phenomena, and act as consultants on various projects on the border between the arts and sciences.

2.1.5. Research integrity and data management

In astrophysics we are adhering fully to the guiding principles of FAIR (Findability, Accessibility, Interoperability, and Reuse of digital assets) concerning the management of scientific data. In all of these four categories we have practices in astronomy tuned to meet these principles. All data is automatically stored in searchable archives. The data format is FITS (Flexible Image Transport System). Fits-files have two components: 1) a binary data file and 2) a so-called header, which contains all the meta-data required for understanding the data. Typically, principal investigators have one year of proprietary access to data resulting from their accepted observing proposal. After this proprietary period, everybody can access the data both in its raw form or as calibrated and reduced data.

While the raw astronomical data is available, at DAWN we have taken democratization of science a step further with our DAWN JWST Archive[1]. This major initiative processes all public data in the James Webb and Hubble Space Telescope archives and makes the science-ready reduced data products and derived properties available in a database at our website. We have recently added spectroscopic data to the database. This has already had a large impact in the community as such data requires significant technical skills to process.

Furthermore we strive to make major codes and analysis tools developed at DAWN available to the public (e.g. Grizzly, Eazy, Stardust, Farmer, 21CMFISH).

Concerning the wider context of research integrity, we also do what we can to follow guidelines and regulations. All scientists, including PhD students, are receiving training in the rules and principles behind the proper conduct of research.

2.1.6. Research plan

Major meetings and grants

DAWN hosted the Euclid Consortium meeting on June 19–23 in CPH Conference, Copenhagen. A major and exciting event with almost 600 participants (440 in person) from Europe, USA and Japan. The meeting took place just a week before Euclid's successful launch from Cape Canaveral, Florida. Euclid has now arrived safely at its new home in Lagrange point 2, close to the James Webb Space telescope. It has passed all tests and has recently started its six year survey of 1/3 of the extragalactic sky[2]. This is a major milestone for DAWN who are heavily invested in the mission through the center's leadership in its deep field observations (the Cosmic Dawn Survey).

DAWN CoI Darach Watson leads the new ERC Synergy project HEAVYMETAL which aims to shed light on the origin of the heaviest two thirds of all elements in the periodic table, believed to originate in enigmatic events following mergers between neutron stars.

Science progress

The Cosmic Dawn Center derives its name from our greatest passion: the epoch in the history of the Universe where light from the first luminous sources broke through the darkness that had pervaded space throughout the first few hundred million years after the Big Bang. These luminous sources were initially stars, conglomerating to form galaxies. But also the gas between the stars may glow, in particular if it happens to fall into a supermassive black hole in the center of a galaxy. The most energetic luminous sources then started to alter the state of the Universe as a whole, splitting atoms apart in the event known as *reionization*. Later — but apparently not much later — some galaxies were *quenched*, losing their ability to create new stars.

These are the physical processes that we aim to understand and describe. The following sections report on the advances that we made during 2023, the first full year with James Webb, and it is evident that we are now fully capable of achieving the goals we set out at our inception.

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[1] See https://cosmicdawn.dk/dja

[2] Since we reside inside the plane of the Milky Way, a large chunk of the sky is obstructed from our view by local stars, gas, and dust. To gaze really deep into the early Universe, we are therefore restricted to looking in the directions away from this plane.

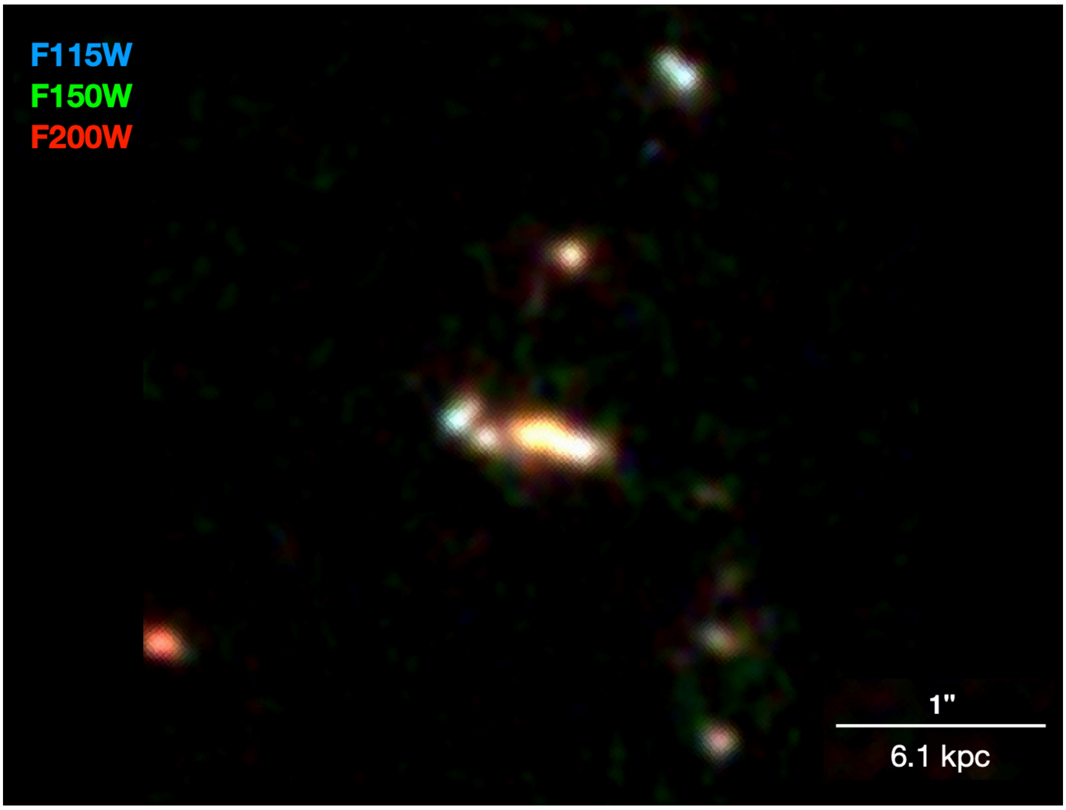
The first galaxies

As described in the annual highlights, a breakthrough was made by Heintz et al. (2023d; top 10$^{\mathrm{II}}$) who showed that some of the most distant, and hence earliest, galaxies were caught in the process of forming. Meanwhile, on the theoretical side Mason et al. (2023a; top 10$^{\mathrm{I}}$) gave a plausible explanation of why these first galaxies appear extraordinarily bright.

The James Webb Space Telescope intriguingly revealed a hitherto unknown population of galaxies which were dubbed "little red dots" due to their compactness and red appearance. Their exact nature is still a mystery, but could form a link between early supermassive black holes and the extremely luminous quasars. Several of these objects, including one seen only 600 million years after the Big Bang (Kokorev et al. 2023; top 10$^{\mathrm{VII}}$), showed clear signs of an "active galactic nucleus"; gas falling into a black hole. This discovery was part of an observational program called *Ultra-deep NIRCam and NIRSpec Observations Before the Epoch of Reionization*, or UNCOVER for short, in which DAWN is involved. Several other interesting results concerning the first galaxies emanated from this survey, e.g. a black hole-to-galaxy mass fraction which is 100 to 1000 times higher than today (Goulding et al. 2023)

Aided by the gravitationally magnifying power of a foreground galaxy cluster, Wang et al. (2023) were able to study the details of two of the very first galaxies, only 350 million years after the Big Bang, down to scales of 1000 lightyears. While this may sound like a lot, since the galaxies are a whopping 33 billion lightyears away this resolution corresponds to being able to read the headline of a newspaper in Oslo, standing in Copenhagen. Utilizing the same technique, Atek et al. (2023) showed how various properties of these very early galaxies, e.g. their color and the relation between mass and luminosity, evolve very fast.

Interestingly, not all galaxy formation happens during the first few hundred million years; some form during later epochs, as found by Jin et al. (2023).



A group of small galaxies, seen almost 13 billion years back in time, likely in the process of forming a massive galaxy. The colors are composed from three different infrared colors, specifically 1.15, 1.5, and 2 nanometers represented by blue, red, and green, respectively. The white, horizontal bar shows the scale of approximately 20,000 lightyears. Credit: Shown et al. (2023).

Galaxy evolution

One of the most wonderful aspects of astronomy is that, as we gaze through the vast depths of space, we also look through time. More than just a curiosity of physics, this phenomenon allows us to study the evolution of galaxies, if only in a statistical sense, through cosmic history. With James Webb, however, we are entering a hitherto unexplored epoch, and interpreting these observations inevitably relies on our knowledge from later epochs in the more nearby Universe. Striving to improve the standard techniques, Steinhardt et al. (2023; top 10^{X}) developed a new framework for the interpretation of observations of the very earliest galaxies, including taking into account the higher temperature in the early Universe and younger stellar populations.

Interpreting observations

One of the fundamental metrics used to describe a galaxy is its stellar mass, i.e. the total mass of all its stars. Since individual stars can only be seen in the most nearby galaxies, we instead measure their emitted stellar *light*, and "translate" it to a stellar *mass*.

The standard procedure is to use a library of "synthetic" spectra templates from a theoretical population of stars, then determining which population fits the observed one the best.

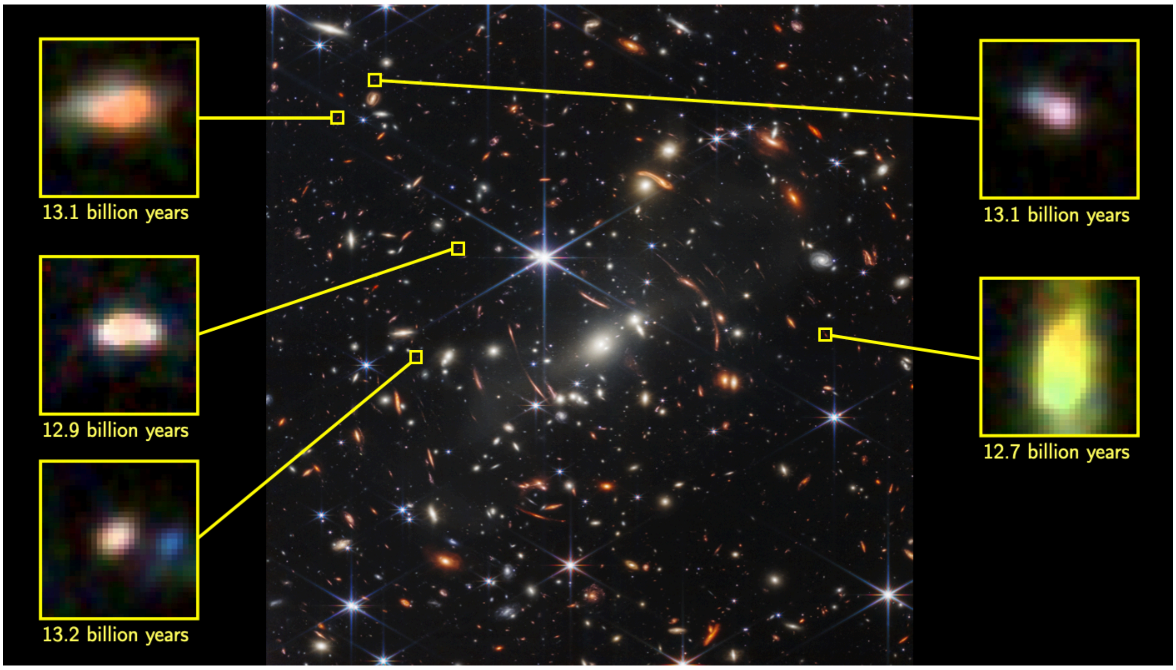
Another software package, designed in particular for interpreting galaxies in the COSMOS2020 catalog, was presented by Weaver et al. (2023b). This catalog of more than one million galaxies, described in last year's report, has already led to hundreds of publications, including the identification of the early progenitor of a galaxy cluster (Brinch et al. 2023), a look into the effect of considering the fact that stars are born from gas that was hotter in the past (Rusakov et al. 2023), an account of how stellar mass is distributed among galaxies across 90% of the history of the Universe (Weaver et al. 2023a; top 10^{VIII}), as well as a novel method for finding non-star-forming ("quiescent") galaxies (Gould et al. 2023; top 10^{IX}). Two surveys which have similarly proved a treasure trove of new discoveries are the COSMOS-Web (Casey et al. 2023; top 10^{V}) and FRESCO (Oesch et al. 2023; top 10^{VI}).

The gravitational lensing mentioned above, together with James Webb's unprecedented resolving power, enables us to really, for the first time, study the internal structure of the earliest galaxies. In this way, Matharu et al. (2023) was able to study how dust is distributed throughout galaxies, while Giménez-Arteaga et al. (2023) studied how star formation varies at different locations in early galaxies. Being able to resolve galaxies' star formation enables us to characterize different stellar populations. This is of course easier for more nearby galaxies, as in the case of Gillman et al. (2023).

Galaxy quenching

After an initial burst of star formation, some galaxies continue to form new stars at a lower rate. But others cease to form stars, and recently it has become apparent that in some cases this happens quite early on. Thus, Strait et al. (2023) discovered a galaxy just after the epoch of reionization which is apparently already on its way to being quenched. With James Webb, we can now probe not only earlier epochs but also smaller galaxies, as explored in a systematic search by Valentino et al. (2023, top 10^{III}) who highlighted the fact that considerable variation prevails between observations of different fields on the sky.

While different mechanisms may lead to the quenching of a galaxy, they all have to do with the galaxies' gas, the fuel for stars. Since interstellar gas is mixed with dust, quiescent galaxies can also be studied by observing the dust which glows in infrared, as done by Blánquez-Sesé et al. (2023a). To better understand *early* quenching, Blánquez-Sesé et al. (2023b) carried out a search for quiescent galaxies in the SMACS 0723 field (seen in the figure above). Meanwhile, Kokorev et al. (2023b) used Webb's outstanding resolving power to study a very dusty galaxy — so dusty that it was virtually invisible to the Hubble Space Telescope — lying close to to a massive, quiescent galaxy. The two galaxies, respectively dubbed "Hyde" and "Jekyll", are likely undergoing a collision, a process which is known to be able to eject most of the gas, thereby quenching the resulting merged galaxy completely.



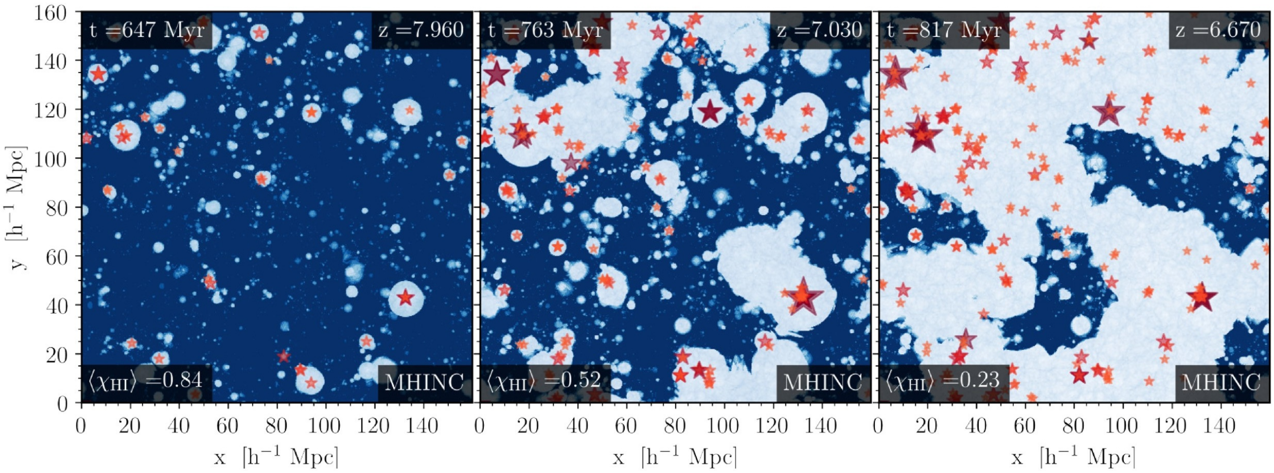
This image of galaxy cluster SMACS 0723 and its surroundings was the first image released from the James Webb Space Telescope in July 2023. The five zoom-ins are each roughly 19,000 lightyears across, and show galaxies seen some 13 billion years back in time. Careful analysis of these galaxies reveals that if we cannot resolve a galaxy, we may severely underestimate the total mass of its stars. Image credit: NASA, ESA, CSA, STScI / Giménez-Arteaga et al. (2023), Peter Laursen.

The interstellar medium

The evolution of a galaxy is intricately intertwined with the gas lying between the stars — the so-called *interstellar medium*, or ISM. Stars are born from gas — originally only hydrogen and helium — but their properties depend on the state of gas, and when they die they return the gas to the ISM, now enriched with heavier elements and dust. Studying how galaxies evolve therefore necessitates a deep understanding of the ISM. Knowing the typical fraction of the ISM that consists of heavy elements (or *metals*, as astronomers like to call them), and of dust, gives us an idea about all ingredients of the ISM, even if only one ingredient can be observed, and for the first time, we are now able to constrain these fractions in the very early Universe (Heintz et al. 2023a,b,c). With metals being produced by stars, galaxies have, in general, low metallicities in the early Universe. It was therefore a surprise when Killi et al. (2023) discovered a galaxy as metal-rich as our own today, but seen 13 billion years ago.

Whereas most galaxies are discovered and investigated through the light they *emit*, a complementary method is to look for absorption in the light from distant sources, created by chance foreground galaxies. This method, especially useful for studying the ISM of small and intrinsically faint galaxies, was used by Christensen et al. (2023) to investigate the metal contents of a large sample of intervening galaxies. Using the same technique, Fynbo et al. (2023) discovered a group of galaxies, seen almost 11 billion years back in time, curiously resembling a progenitor of our own Local Group.

While some metals are formed by dying stars when they run out of fuel, many — in particular precious metals like gold, silver, and platinum — are created long after the stars have died, if there happens to be *two* dead stars orbiting each other and eventually colliding and exploding. Such an event is called a *kilonova*, and several theoretical advances were made in this field last year concerning the physical properties of the explosion (Sneppen et al. 2023a,b,c,d). Also on the theoretical side, Narayanan et al. (2023) developed a framework for modeling so-called polycyclic aromatic hydrocarbons — large, complex, soot-like molecules — in simulations of galaxies, investigating e.g. how their size distribution is affected by UV radiation from stars.



Three snapshots from the ASTREAUS cosmological reionization simulation, showing a box roughly 750 million lightyears across when the Universe was 647, 763, and 817 million years old, respectively. The red stars indicate the position of galaxies. Dark blue colors show neutral gas while light blue show the growing, ionized bubbles around the galaxies. Credit: Hutter et al. (2023a).

The epoch of reionization

As the first stars appeared, their intense UV radiation began splitting apart the hydrogen atoms that enshrouded the galaxies. This process, known as *ionization* — or, in this particular case, *re*-ionization, because the atoms had all previously been ionized shortly after the Big Bang — altered the state of the entire Universe over a short period. The exact progress of this epoch — when, for how long, which sources were responsible, and what was the shape and size of the ionized, expanding "bubbles" — is a matter of intense study.

Because the ionizing photons are absorbed in the process, they are almost always unobservable. Fortunately, there are alternative ways to study this epoch. Arguably, the most popular probe is a type of light known as "Lyman alpha" that, while also ultraviolet, does not have quite enough energy to ionize hydrogen, but is still able to interact with it. Using this tool requires knowledge of the correlation between the ionizing radiation and the Lyman alpha radiation from later epochs, where it is more easily studied; a comprehensive study of this was therefore provided by Prieto-Lyon et al. (2023). Observations of Lyman alpha-emitting galaxies well into the epoch of reionization *is* possible, albeit challenging, but if such galaxies have managed to ionize a sufficiently large bubble around themselves, it can be done, as shown by Tang et al. (2023) who was able able to measure their metallicity, something which would not have been possible before James Webb.

Interpreting observations requires a good theoretical understanding of the physics that may or may not be at play. In a large cosmological simulation, Hutter et al. (2023a) therefore explored how the visibility and distribution of Lyman alpha-emitting galaxies depend on the fraction of ionizing photons that escape galaxies of different masses. The simulation (which also provided the theoretical prediction matching the observations of Heintz et al. (2023d), represented by a blue band in the figure in the annual highlight), also served as the basis for analyzing the expected signal from another type of light, also emitted from hydrogen but at a much longer wavelength of 21 cm (Hutter et al. 2023b). This wavelength region was also studied by Mason et al. (2023b) who published a new code that can help produce fast forecasts for the 21 cm emission during the epoch of reionization.