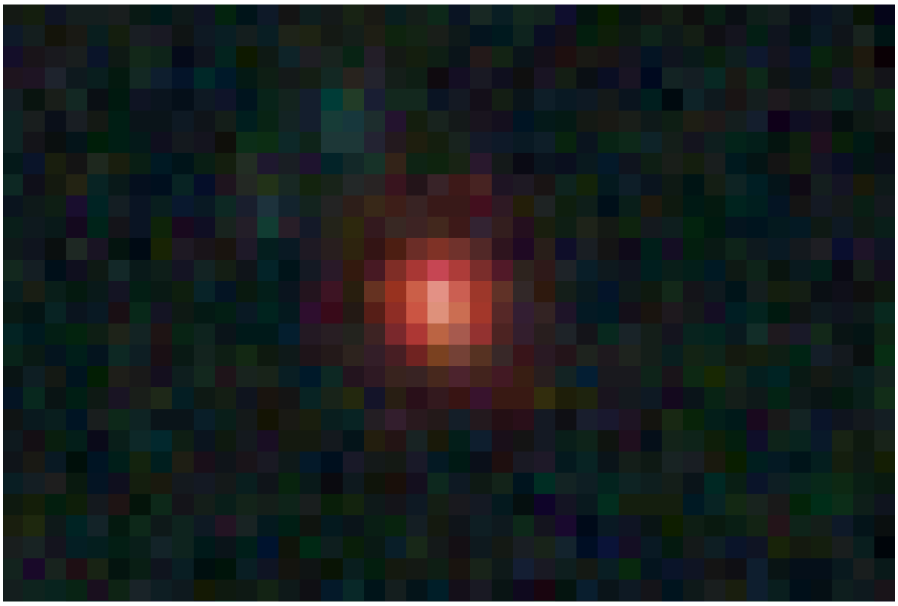
Scientific annual report 2024

Cosmic Dawn Center



Everyone knows how a pretty Webb galaxy looks, so here is instead something slightly less pretty, but no less interesting: a so-called "little red dot", a member of a new, puzzling population of galaxies recently discovered by Webb. From Killi et al. (2024).

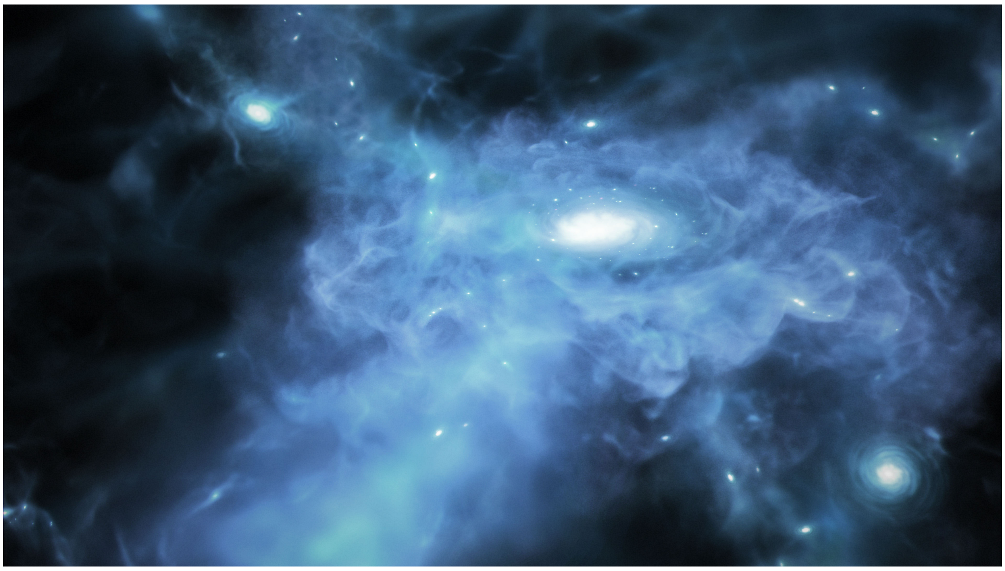
Annual highlights

Galaxy formation caught in the act

Galaxies are made of stars, and stars are made of gas. To form a galaxy, an immense cloud of gas therefore must overcome the expansion of the Universe and collapse. This picture is the theoretical prediction, but with the study by Heintz et al. (2024; Top 10[1]) it is now also observationally verified.

Using the James Webb Space Telescope, we detected eleven galaxies so distant that we see them more than 13 billion years back in time. At this time, the neutral gas between the galaxies was beginning to be turned into ionized plasma due to the energetic light emitted from the very first stars formed even earlier.

Interestingly, three of the eleven galaxies are seen to be enshrouded in ten times as much gas as the average intergalactic medium would have, even if the Universe were *fully* neutral. The gas is plummeting down toward the central galaxies, destined to fuel later star formation. In other words, we are seeing the galaxies as they form.



Artist's conception of the gas enshrouding a galaxy. Exactly how the gas is distributed is still an open question. Illustration: Joseph Olmsted (STScI, from NASA's press release about the study).

The DAWN JWST Archive

After processing the spectra used in the study above, the authors uploaded it to the “DAWN JWST Archive”, or DJA for short, a new, public repository of James Webb data initiated by researchers at DAWN.

Data from James Webb (and any other telescope) is not ready-to-use, but requires a certain amount of processing. This procedure is often done on an individual basis, which will in general affect the final result to some extent.

The purpose of DJA is to offer easy access to all spectroscopic Webb data, processed in a consistent manner, to be used by the whole astronomical community. The initiative has been very well received – as of March 2025, over 50 scientific studies led by researchers *not* at DAWN have made use of DJA.

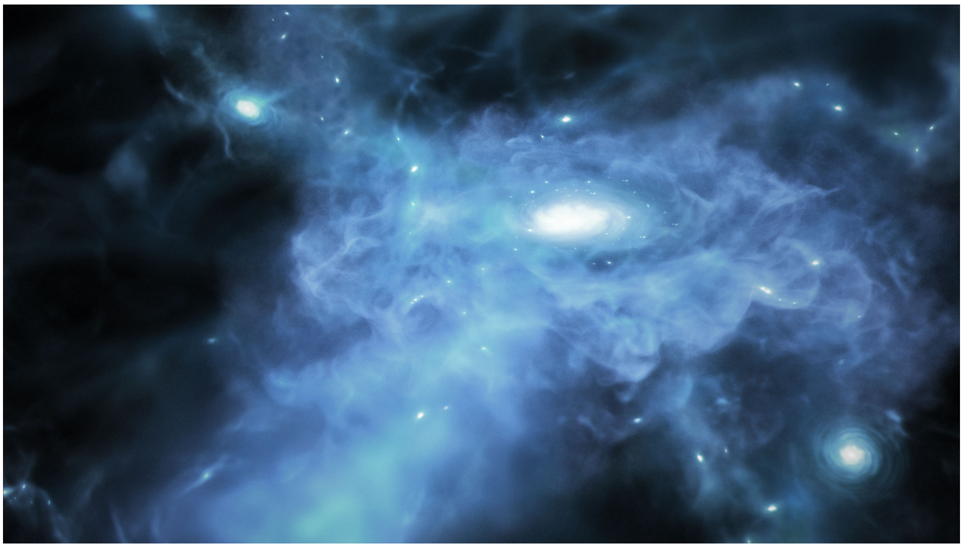
Årets højdepunkter

Galaksedannelse taget på fersk gerning

Galakser er lavet af stjerner, og stjerner er lavet af gas. For at skabe en galakse må en enorm gassky derfor overvinde Universets udvidelse og kollapse. Dette billede er den teoretiske forudsigelse, men med undersøgelsen af Heintz et al. (2024; Top 10[1]) er det nu også observationelt verificeret.

Ved hjælp af rumteleskopet James Webb opdagede vi elleve galakser så fjerne, at vi ser dem mere end 13 milliarder år tilbage i tiden. På dette tidspunkt begyndte den neutrale gas mellem galakserne at blive omdannet til ioniseret plasma på grund af det energirige lys, der blev udsendt fra de allerførste stjerner, dannet endnu tidligere.

Interessant nok ses tre af de elleve galakser at være indhyllet i ti gange så meget gas, som det gennemsnitlige intergalaktiske medium ville have haft, selv hvis Universet var fuldstændig neutralt. Gassen vælter ned mod de centrale galakser, destineret til at give brændstof til senere stjernedannelse. Med andre ord ser vi galakserne i gang med at blive dannet.



Kunstnerisk opfattelse af gas, som indhyller en galakse. Præcis hvordan gassen er fordelt er stadig et åbent spørgsmål. Illustration: Joseph Olmsted (STScI, fra NASA's pressemeddelelse om studiet).

DAWN JWST Archive

Efter at have processeret de spektre, der blev brugt i undersøgelsen beskrevet ovenfor, uploadede forfatterne det til "DAWN JWST Archive", forkortet DJA – en ny, offentlig database af James Webb-data iværksat af forskere ved DAWN.

Data fra James Webb (og ethvert andet teleskop) ankommer ikke fra teleskoperne klar til brug, men kræver en vis behandling. Denne procedure udføres ofte individuelt, hvilket generelt vil påvirke det endelige resultat til en vis grad.

Formålet med DJA er at tilbyde nem adgang til alle spektroskopiske Webb-data, processeret på en konsistent måde, og til brug for hele det astronomiske samfund. Initiativet er blevet utrolig godt modtaget – i marts 2025 har over 50 videnskabelige undersøgelser ledet af forskere *udenfor* DAWN gjort brug af DJA.

Organization

Charles Steinhardt, CoI and founding member of DAWN, returned to the United States to take up a tenure track faculty position at the University of Missouri. DAWN postdoctoral fellow Francesca Rizzo moved to University of Groningen to take up a tenure track position.

DAWN's coordinator Guarn Nissen retired at the end of DAWNs first round, and was replaced by Peter Laursen.

Caitlin Casey, Professor at University of California, Santa Barbara, a long-time collaborator of DAWN, has officially joined the center as a new international associate. Caitlin is co-lead of the COSMOS collaboration and principal investigator of the COSMOS-Web JWST program.

To further the integration of DAWN's two institutes, we have started a new concept called “DAWN Days”. Once per month the whole center meets physically for a half-day team meeting. The venue alternates between NBI and DTU, and the program is a mix of science talks, discussions, information-sharing and social activities. The meeting is organized by a committee of postdocs and students in collaboration with admin staff.

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.

This hiring strategy secures 100+ international applications for every call, including the best of the generation. Our hiring committees include a broad representation across career levels and genders, which helps both to ensure that a diverse group of candidates makes the shortlist, but also that underrepresented candidates end up accepting our offers because they can see themselves represented during the interviews.

Outreach

Through frequent press releases, social media posting, interviews, popular science articles, podcasts, videos, and public talks, we disseminate the insight we acquire about the Universe. We seek to promote especially young researchers and students. The aim of these outreach activities is not only to advertise our own research, but also to attract and inspire the future generation of scientists.

In 2024, Peter Laursen agreed to serve as the editor of the Niels Bohr Institute's Q&A “Spørg om Fysik”, where anyone can ask any physics-related question. The Q&A's webpage is the university's most popular page, with tens of thousands of visitors per month.

Research integrity and data management

In astrophysics, we prioritize responsible data management by adhering to the FAIR principles, which emphasize making scientific data Findable, Accessible, Interoperable, and Reusable. Astronomy has long-established methods designed to uphold these standards, ensuring that data is well-documented and easily retrievable.

Observational data are systematically archived in searchable databases, allowing researchers to locate and access them efficiently. The standard file format used is FITS (Flexible Image Transport System), which consists of a binary data section and a detailed header containing essential metadata. Typically, researchers leading an approved observation project are granted exclusive access to their data for the first year. After this period, the data – both in its original and processed forms – become publicly available for the broader scientific community. In astronomy it is also becoming increasingly more common to share the software (e.g. Python scripts and notebooks) that was developed as part of the data reduction and analysis. This is typically shared via online repositories such as Github, with the intent of others to download and use it and even contribute to the further development of the software.

Beyond data accessibility, astrophysics also maintains high standards of research integrity. Scientists at all levels, including PhD students, receive training on ethical research practices to ensure compliance with established guidelines and promote transparency in scientific work.

Research plan

While interests at the Cosmic Dawn Center are broad and encompassing, we adhere to our main pillars of research, all revolving around the birth, life, and death of galaxies, how these beautiful structure are organized internally and together, and how they influence not only each other, but also the Universe as a whole. In 2024 we published over 300 articles which have so far been cited more than 7000 times in the literature, demonstrating that our ambition is proceeding according to plan. In the following we will describe a few highlights of our discoveries.

First galaxies

One swallow does not a summer make. Similarly a galaxy needs a certain amount of stars in order to be considered a galaxy. As there is absolutely no consensus on the exact number, nor should there be, we will never be able to firmly say that we have discovered *the* first galaxy.

The quest for the first galaxies is therefore not a hope of one day being able to say "We found it! The very first galaxy." Rather, we are investigating the very early Universe in order to find and, importantly, characterize *some* of the very first galaxies.

The James Webb Space Telescope was built for this exact purpose, and because its data are typically released immediately, galaxies are studied by multiple groups in various ways. This community-minded approach led Heintz et al. (2024; Top 10[1]) to the discovery of the galaxies seen in the process of forming, described in the Annual Highlight above.

Other galaxies are discovered as a result of a dedicated effort, as in the case of the COSMOS-Web survey, a 255 hour program charting galaxies in a large area on the sky throughout cosmic history. DAWN's new affiliated scientist, Caitlin Casey, who is also the leader of COSMOS-Web, used these data to discover and investigate 12 exceptionally bright galaxies in the very early Universe (Casey et al. 2024; Top 10[v]). Another sample of 15 luminous galaxies was identified in COSMOS-Web by Franco et al. (2024). The unexpected brightness of the earliest galaxies continues to be a bit of a mystery, so these two, as well as other studies such as Castellano et al. (2024), aimed specifically at investigating various reasons for this.

While the most distant galaxy will never be found, each time a more distant galaxy is discovered and the old record is broken, is indeed remarkable, because it tells us that galaxies existed this early. In 2024, we pushed the limits back further, as we discovered galaxies less than 300 million years after the Big Bang (Carniani et al. 2024).

Reionization

The first galaxies transformed the Universe as a whole, from opaque to transparent. This so-called epoch of reionization is a subject of intense research in astronomy: When did it start, how long did it take, how did it proceed, and which sources were responsible?

In general, the primary source of the UV radiation reionizing the Universe is thought to be hot, massive stars. However, a non-negligible contribution could come from gas around supermassive black holes, being heated to millions of degrees before it plunges into nothingness, as found by Fujimoto et al. (2024c).

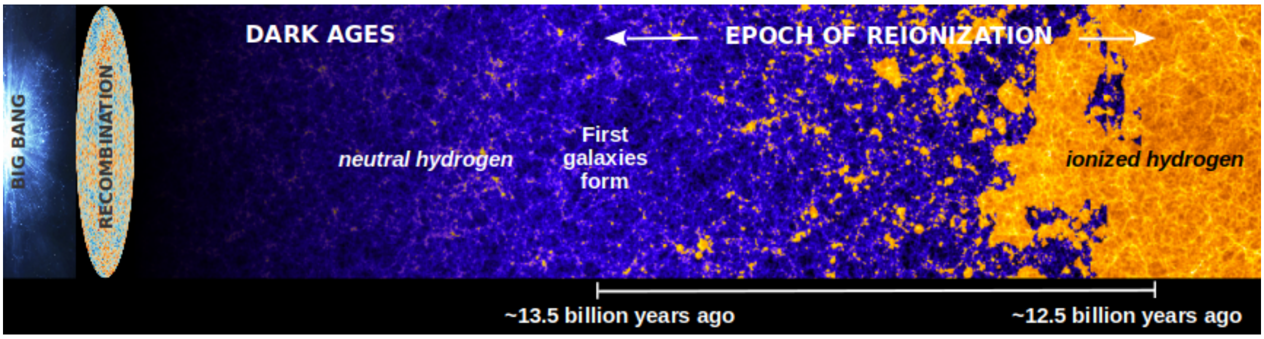
The Epoch of Reionization

The first galaxies formed in a *neutral* Universe; atoms were combined in protons and electrons. Because young galaxies shine most brightly with energetic UV light, and because neutral gas is very efficient at absorbing UV, only their faint, less energetic light can escape, making these galaxies very hard to detect.

With time, the UV light splits apart the atoms of the circumgalactic gas, forming ionized bubbles around the galaxies that spread out and eventually render the Universe transparent. This important period in the history of the Universe is known as the Epoch of Reionization.

The physics governing the epoch of reionization will affect the shape, size, and evolution of the ionized bubbles emanating from the galaxies, i.e. things that can be observed. Through computer simulations Lu et al. (2024; Top 10[IX]) investigated the size of ionized bubbles around galaxies, while Cueto et al. (2024) found that assuming a higher fraction of massive stars will not result in observable changes, at least not in small galaxies.

One of the big uncertainties in calculations of the progress of reionization is the fraction of UV photons that escape from the galaxies so they are able to ionize the surroundings. In general, the escape fraction is very small and hence difficult to observe. To understand this better, Kreilgaard et al. (2024) analyzed how the fraction depends on galaxy size. Meanwhile, Vijayan et al. (2024) investigated how dust attenuates the UV luminosity of computer-simulated galaxies in this epoch.



This timeline of roughly the first billion year of the Universe shows, with time progressing from left to right, how the Universe transitioned during the "epoch of reionization" from mostly neutral (purple) to mostly ionized (orange). The ionized regions percolated intergalactic space, spreading as bubbles from galaxies, eventually overlapping (credit: Anne Hutter).

Another factor that seems to be of importance are random sudden bursts of star formation, both in the beginning (Gelli et al. 2024) and the end (Caputi et al. 2024) of the epoch of reionization.

Galaxy evolution

Galaxies mature and evolve throughout their lives, but like humans, most of the interesting development takes place during their young ages. As galaxies age, they not only grow but also produce heavy elements and dust, modify their stellar population, nurture their supermassive black holes, alter their looks a.k.a. *morphology*, merge with other galaxies, and much more.

Because the typical timescale for such changes is measured in hundreds of millions of years, we cannot hope to observe how any individual galaxy evolves. Instead we utilize the ability of a telescope to function as a time machine; a single image can contain galaxies at all distances and – because of the time it takes light to reach us – therefore seen at various epochs throughout the history of the Universe. With large samples of galaxies we can then infer statistically how galaxies in general evolve.

With its unprecedented sensitivity, as well as its ability to see infrared light which more easily penetrates clouds of cosmic dust, and is emitted from dust, James Webb has revealed a whole new population of galaxies (Gottumukkala et al. 2024; Top 10[VII]; Weibel et al. 2024). These galaxies simply were not visible prior to Webb, even with Hubble. In fact, Fujimoto et al. (2024); Top 10[III] estimate that the total amount of stars during the first 1.5 billion years was 60% higher than previously thought, while Gillman et al. (2024) show how the presence of dust can change the galaxies' apparent morphology.

Not only its sensitivity is remarkable; Webb's ability to resolve its targets in fine details is also unparalleled. Galaxies seen as tiny blobs in the pre-Webb era can now be resolved into their components, an important element when deducing properties such as star formation (Matharu et al. 2024) and stellar masses (Giménez-Arteaga et al. 2024; Top 10[VI]).

Galaxies tend to build up in a hierarchical manner, with small star clusters forming first, later merging to increasingly larger galaxies. Even later, galaxies form first small groups, and then large clusters, as investigated by Sillassen et al. (2024; Top 10[VIII]). At the end of reionization, clusters had not formed yet, but Brinch et al. (2024) discovered an overdensity of galaxies in this epoch – a *proto*-cluster – that they show will later evolve into a massive cluster of galaxies.

Little red dots

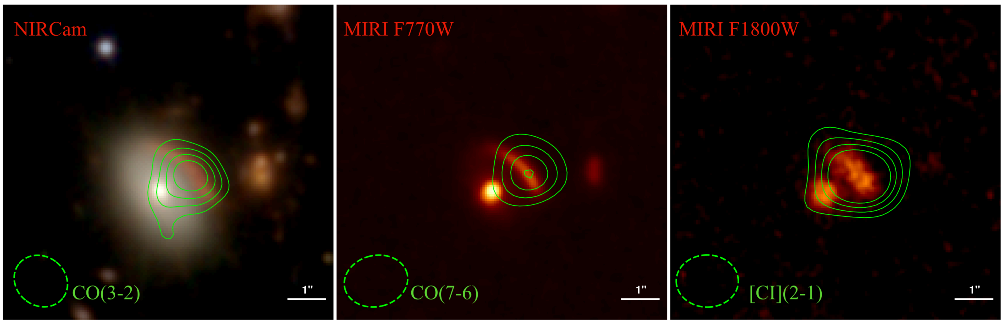
Recently James Webb presented yet another conundrum that we had not anticipated: the existence of a whole new population of galaxies. Due to their color and compact sizes, following a long tradition of three-letter acronyms in astronomy, they were dubbed “little red dots”, or LRDs. They seem to have existed in the post-reionization Universe for a rather short time, but their nature has puzzled the astronomical community. Whereas most astronomical objects tend to emit light that increases either toward longer (infrared) or toward shorter (UV) wavelengths, LRDs seem to do both.

A likely explanation is that LRDs consist of two components; a highly obscured and hence reddened, central object, probably a supermassive black hole, and a slightly more extended, star-forming and hence UV-emitting region (Killi et al. 2024; Top 10[ii], adorning the front page of this report). That the central object is a dust-enshrouded black hole is supported by Greene et al. (2024), and by Furtak et al. (2024) who found that black holes comprise at least 3% of the total mass of the galaxies, a factor of 100 more than in local galaxies. It seems that LRDs are an important factor in an evolutionary scenario where, as black holes grow, the dusty gas around them eventually outshines stars (Matthee et al. 2024), possibly later becoming compact elliptical galaxies (Kokorev et al. 2024; Top 10[x]).

The interstellar medium

Most of the observations and physical processes described above involve light emitted from *stars*. While stars are arguably the most prominent part of a galaxy, the space between the stars – the *interstellar medium*, or ISM – plays a crucial role in the evolution of galaxies, in addition to being interesting in itself. Indeed, to astronomers, “space" is not empty at all, but filled with *gas* at all temperatures, densities, ionization states, etc., whirling around and coalescing to form molecules, dust grains, stars and planets.

In order for the atoms to stick together, the gas must be *cold*, typically around 100 K, meaning that the light it emits is often in the very low-energy regime, observed at sub-millimeter wavelengths and microwaves. To complement the observations of starlight probed by James Webb with observations that allow us to study the nature of the interstellar medium we make extensive use of the *Atacama Large Millimeter Array*. With this array of more than 50 radio dishes, located in the Chilean desert at an altitude of 5000 meters, Jin et al. (2024) observed the radiation of large, organic dust grains and molecules such as carbon monoxide, establishing the need for such observations when inferring distances to galaxies. Observing the ratio between the amount of ionized carbon and ionized oxygen, Fujimoto et al. (2024a) demonstrated the presence of strong galactic outflows which may have helped ionizing radiation escape, and hence contribute to the epoch of reionization. The ISM also holds the answer to many physical key quantities that characterize a galaxy; Valentino et al. (2024), targeting a small galaxy seen at the end of reionization, measure the mass and temperature of its dust, the amount of gas, and as well the rate at which it forms new stars.



These three images show, in the background, the galaxy "COSBO-7" as observed by James Webb at different infrared wavelengths. On top of this, in green contours, is seen the galaxy as observed by ALMA in three different radio wave regimes that reveal the presence of carbon monoxide (left and mid) and ionized carbon (right). These observations allowed Jin et al. (2024) to establish that the galaxy was not, as previously thought, seen 700 million years after the Big Bang, but at a much later 2.5 billion years. The white bar shows a distance of roughly 30,000 lightyears.

Before the advent of stars, the Universe consisted only of hydrogen, helium, and trace amounts of lithium. Dying stars eventually enriched the ISM with heavier elements. Roughly a decade ago, it was realized that the majority of the heaviest half of the elements in the periodic table are produced in *kilonovae*, the violent collision between two neutron stars, or between a neutron star and a black hole. While all the physical processes described above occur on timescales of millions or billions of years, research in this field – appropriately is called *transient astronomy* – requires astronomers to act fast. Sneppen et al. (2024a) and Sneppen et al. (2024b) highlighted the importance of observing and modeling a kilonova explosion with short time intervals, while Sneppen et al. (2024c) settled a debate on the origin of a special feature in a kilonova's spectrum, establishing that it is indeed the first direct evidence of freshly synthesized heavy elements.

Quenching

While the majority of galaxies continue to form stars, some galaxies seem to be "quenched" at some point in their life. Because the massive, luminous, hot and hence bluish-white stars burn out fast, only the smaller, fainter, cooler and hence orange-reddish stars are left, giving these quiescent galaxies their distinctive color.

What is the physical mechanism that makes some, but not all, galaxies "resign"? Unveiling the answer to this question is one of DAWN's core scientific goals. It is clear that there is not one, but multiple mechanisms, including "self-quenching" where a galaxy stabilizes itself against fragmentation of gas clouds, so that they cannot collapse to form stars (Lee et al. 2024), and "induced quenching" where merging with other galaxies triggers starbursts which blow away and heat the gas needed to form new stars (Jin et al. 2024). These stellar winds may be caused by exploding stars, but Gelli et al. (2024) show that, at least in some cases, the wind is dominated by the mere pressure of the light being emitted from massive stars.

In a more systematic study with JWST, Ito et al. (2024; Top 10[IV]) was able to, for the first time, probe quiescent galaxies during the first 1-2 billion years after the Big Bang, establishing a relation between their stellar mass and size. To help interpret these and other observations, Lagos et al. (2024) investigated quenched galaxies in the semi-analytical code SHARK, finding excellent agreement between simulated and observed galaxies.