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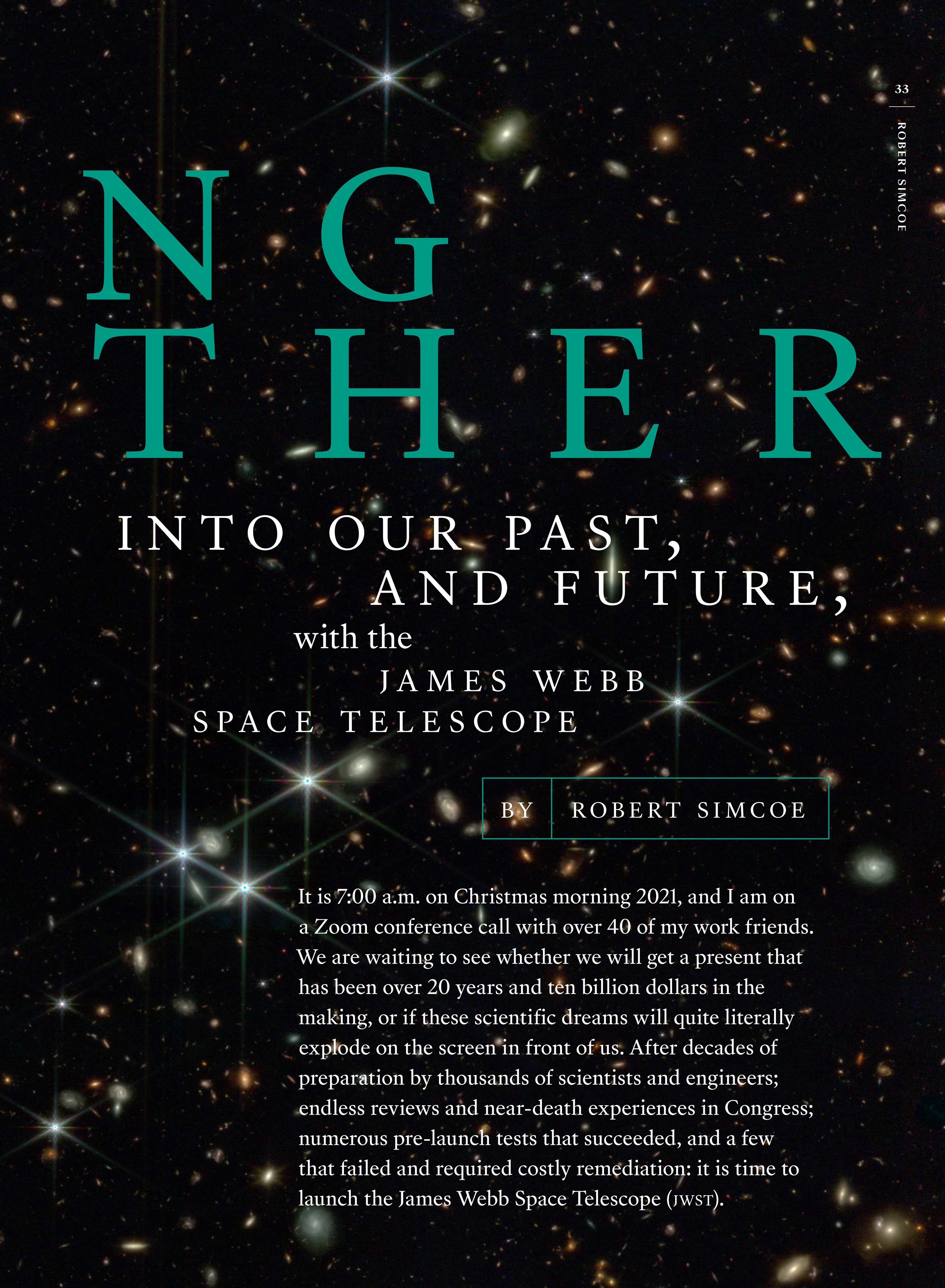

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INTO OUR PAST, AND FUTURE, with the JAMES WEBB SPACE TELESCOPE

BY ROBERT SIMCOE

It is 7:00 a.m. on Christmas morning 2021, and I am on a Zoom conference call with over 40 of my work friends. We are waiting to see whether we will get a present that has been over 20 years and ten billion dollars in the making, or if these scientific dreams will quite literally explode on the screen in front of us. After decades of preparation by thousands of scientists and engineers; endless reviews and near-death experiences in Congress; numerous pre-launch tests that succeeded, and a few that failed and required costly remediation: it is time to launch the James Webb Space Telescope (JWST).

My group at MIT has been eagerly preparing for this moment since 2016. Six years before launch, we assembled a small international team that would eventually grow to nine investigators who have planned and executed some of JWST's very first science observations. Our objective is to elucidate details about the internal physics of the first galaxies that emerged after the Big Bang, the growth of their central supermassive black holes, and how primordial stellar nurseries drew in matter from the surrounding reservoir of diffuse gas and converted it into stars.

It is now well-documented that JWST's launch, unfolding, and commissioning were a technological triumph, delivering instrument performance that exceeds nearly every pre-launch projection. The observatory's insertion into a solar parking orbit—at a saddle point in the Earth-Sun equipotential surface, about four times more distant than the Moon—was so accurate that almost no extra fuel burns were needed, doubling the Observatory's expected lifetime. Our team's early science data are consistent with all of these superlatives, delivering all that we had hoped for and more.

As we approach the one-year mark of JWST's science operations, this article offers an opportunity to explain how MIT scientists came to have coveted early access to JWST, and to report on what our group has learned already about early galaxies and intergalactic matter. It is also an occasion to reflect on important problems that JWST will not be able to solve, and opportunities on the horizon to address them in the coming decades.

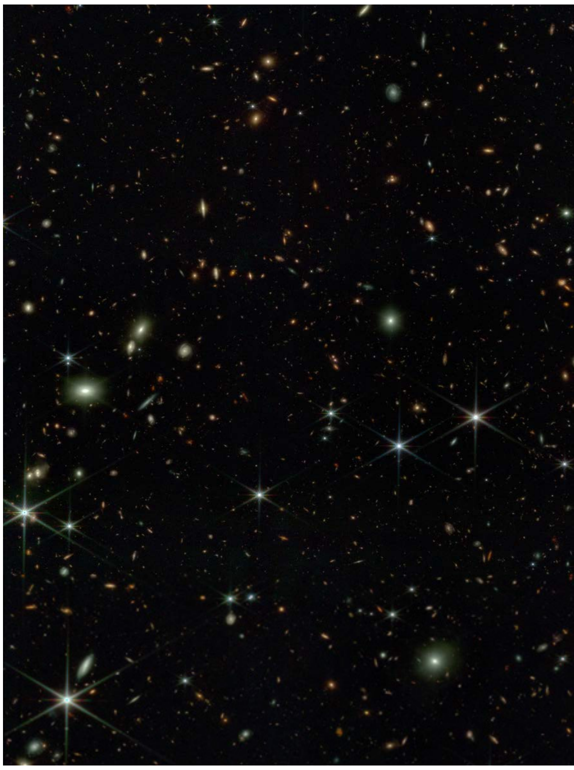
HOW MIT OBTAINED GUARANTEED TIME OBSERVATIONS IN JWST'S FIRST OBSERVING CYCLE

As with any transformational experiment, the demand for open JWST observing time greatly exceeds available supply; for the most recent proposal the success rate was 13%. The review process resembles allocation of other oversubscribed resources such as college admissions—proposal merit is the primary determining factor, but this is mixed with a significant random component that is difficult to eliminate. How did our collaboration earn the privilege of executing 120 hours of guaranteed observations within weeks of JWST's first science operations?

The story at MIT has roots dating back almost 20 years, to when I first arrived as a Pappalardo Postdoctoral Fellow in Physics. I was lured by MIT's recent investment as an institutional partner in the new Magellan Observatory—a pair of 6.5-meter diameter ground-based telescopes located under the dark skies of the Chilean Andes. I had trained during my PhD as an optical spectroscopist, but I was beginning to contemplate shifting my focus towards longer infrared wavelengths, motivated by three convergent coincidences.

First, a new generation of digital sky surveys in the early 2000s had just begun to uncover ultra-distant and ultra-bright quasars whose light was emitted less than one billion years after the Big Bang (the current age of the universe is 13.7 billion years). The redshift effect from cosmological expansion causes ultraviolet and optical light emitted by these quasars to stretch into infrared wavelengths along their journey to Earth. Second, NASA's approval of JWST in 1999 led to massive investment and a concomitant performance revolution in infrared (IR) sensors. These new detectors occupy nearly every instrument port on JWST and were also available for ground-based experimentation. Third, the Pappalardo Fellowship allowed me freedom to explore this new interest, and at MIT we were encouraged not only to observe with our new Magellan Telescopes, but also to improve them by building new and innovative instrumentation.

These factors led me to build an infrared spectrometer for Magellan named FIRE, that formed the main focus of my



pre-tenure research over a decade ago. FIRE's operational lifetime has coincided with a rapid period of discovery for new quasars in the early universe. Thanks to this instrument, my group was able to play a role in uncovering ever rarer and more distant quasars in new sky surveys. We used their spectra to probe the physics of early black hole growth, and the pollution of intergalactic gas with heavy elements fused in stars.

Access to Magellan and FIRE helped to attract prize postdoctoral fellows to MIT, and it was through these connections that our JWST program was conceived. In 2016, Rongmon Bordoloi brought a prestigious NASA Hubble Fellowship to the MIT Kavli Institute. Bordoloi is an expert in using quasars to study intervening gas, and was a student of one of JWST's "builders," who are entitled to guaranteed observing time. Their team was planning to conduct a galaxy survey in blank portions of the sky, but Bordoloi argued that the same survey would be much more valuable if it were undertaken in special fields containing bright quasars that already had exquisite FIRE observations.

The resulting survey, now named "EIGER" (Emission-line galaxies and Intergalactic Gas in the Epoch of Reionization) after the Swiss mountain, has grown to a collaboration across four countries on three continents. Bordoloi has since moved to a faculty position at North Carolina State University, but Pappalardo Fellows Anna-Christina Eilers (now on the MIT Physics faculty) and Rohan Naidu have since joined the MIT team. In this way, MIT's Magellan investment and postdoctoral fellowship programs have both facilitated early access to JWST, and also helped nurture talented young scientists.

FIRST LIGHT, AND WHAT WE ACTUALLY MEASURE

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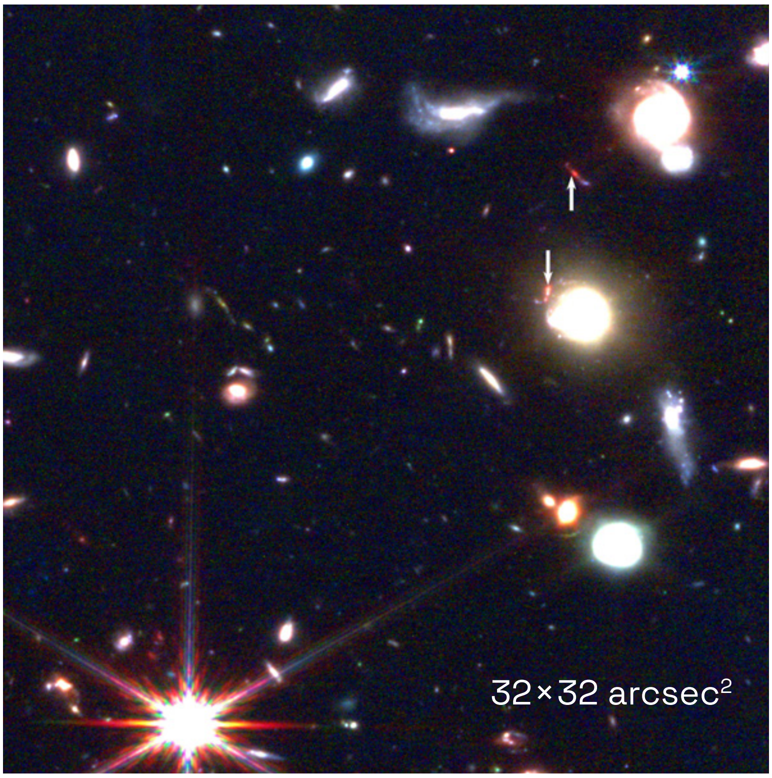
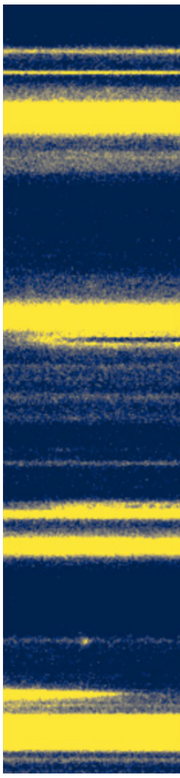
Our first tranche of EIGER data arrived in late August 2022, and comprised 20 hours of imaging and spectroscopic frames on our highest priority field. Our instructions on where to point the telescope and how to configure the instruments had been submitted over five years earlier, and the observations were at long last executed, automatically, by Mission Operations when they reached our slot in the queue. We got the news via Slack, from team members who were obsessively refreshing the webpage with JWST's real-time schedule.

The resultant image from this first visit is shown in Figure 1. It is a color composite of three monochromatic filtered images centered at wavelengths of 1.15 microns, 2.00 microns, and 3.56 microns. These wavelengths are a factor of 2–5× longer than our

FIGURE 1:
Color composite image of the first EIGER field, made from three images taken by JWST's infrared camera at wavelengths of 1.15, 2.00 and 3.56 microns. The prominent red object at the very center of the field looks like a star in this image, but spectra reveal that it is a distant quasar, whose radiation is powered by matter falling into a black hole of more than ten billion solar masses. It is located behind nearly all of the other galaxies and stars in this image, and appears red because it is rapidly receding due to cosmic expansion. This particular object is the brightest object yet discovered in the first billion years after the Big Bang, and was observed by Magellan and FIRE several years before JWST's launch. Credit: EIGER team / Ruari Mackenzie





eyes can see, as JWST is exclusively an infrared telescope and blind at optical wavelengths. Deep IR images are essential for studying the early universe, because cosmological redshifting causes optical light from these primordial objects to arrive at Earth in the infrared band. As soon as our team saw the sharp focus and depth of these images, we knew that the performance of JWST was extraordinary; indeed, we all spent many unplanned hours scanning around the images and taking in their rich detail like a child unboxing a new toy.

Even so, our official objective was to find and study objects from the early universe, and the vast majority of sources in these images are brighter foreground galaxies at lower redshift rather than the most distant objects of interest. We required additional information to screen out these interlopers, and JWST provides this in the form of infrared spectra.

You will almost never see a spectrum in a NASA press release about new discoveries, yet this is where JWST's truly transformative new powers reside. The instrument used by EIGER generates a spectrum for every object in the image shown in Figure 1 by inserting a "grism" (a diffraction grating etched onto one face of a crystalline silicon prism) into the telescope's optical path. The grism splays out each galaxy image into a linear trace on the detectors, encoding the intensity of light as a function of wavelength like a miniature rainbow. A large part of the EIGER team's effort over the past year was spent developing customized Python software to extract these spectral traces from the raw images, solve the mapping between detector pixels and position/wavelength, and calibrate the color-dependent efficiency of JWST's optics to determine fluxes of each astronomical object in physical units.

These spectra are immensely valuable because while stars emit light over a broad range of wavelengths, the emission from gaseous nebulae is driven by electron energy level transitions in atomic spectra, and is therefore discretized around specific wavelengths determined by quantum physics. These nebulae manifest as sharp spikes in a spectrum. The laboratory wavelengths of these transitions have been measured on Earth, so the spikes allow redshift measurements with 0.1% accuracy.

Redshifts are a cosmologists' Rosetta Stone, because they encode the distance to each object, historically the most difficult measurement in astronomy. Knowing the distance lets us convert photon counts per second at the Earth into a galaxy's physical energy output using the inverse square law. The total energy output is in turn proportional to the number of stars in the galaxy—its stellar mass. Likewise, we convert quantitative measurements of nebular emission line flux and image colors into estimates of each galaxy's star formation rate, because nebulae tend to be located in regions of intense star formation featuring blue-hot stars. Taken together, JWST's images and spectra can therefore help us measure physical sizes and shapes of early galaxies, the number of stars they contain, and the rate at which they are forming new stars.

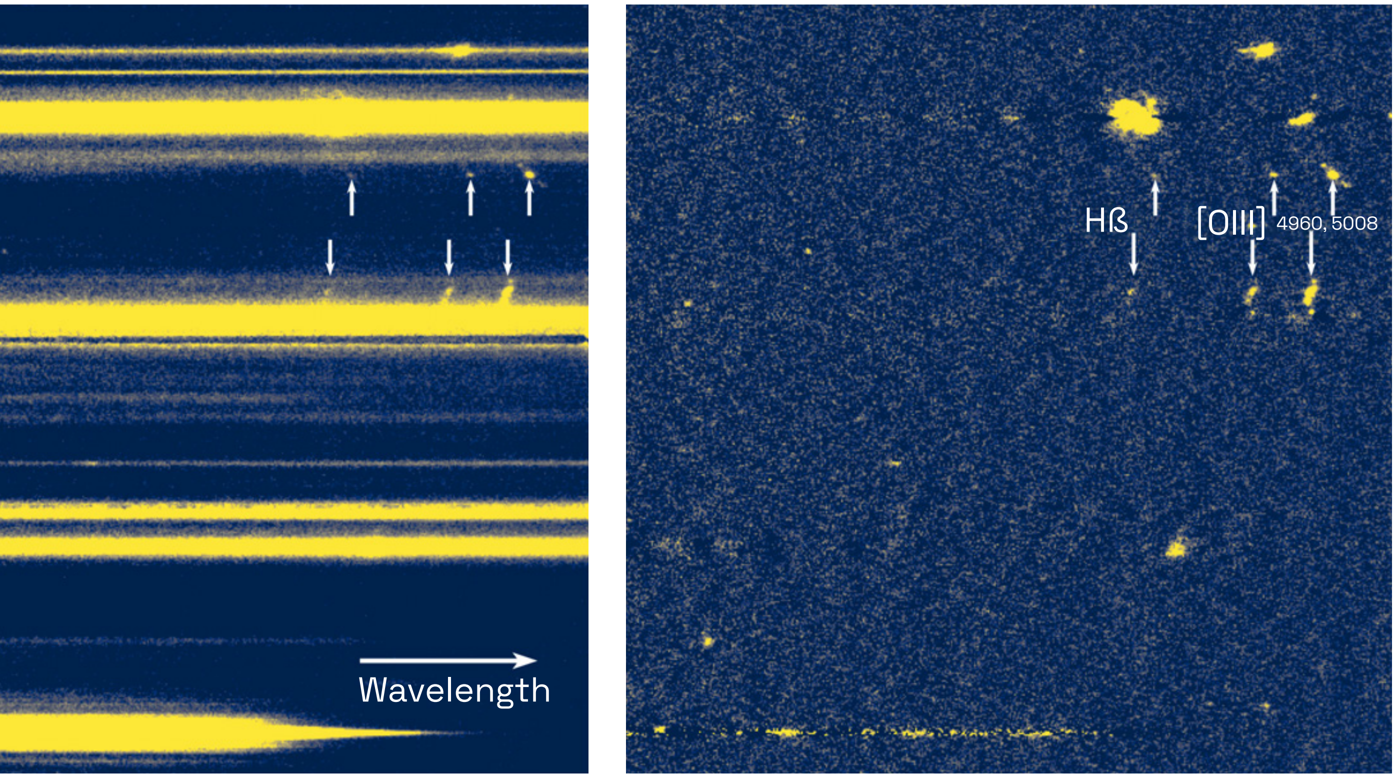


FIGURE 2:
Demonstration of grism spectroscopy with JWST. **LEFT PANEL** shows a sub-region of the image from *Figure 1*, with two galaxies in the distant universe identified with arrows (note their red colors due to redshift). All other galaxies in the cutout are in the foreground, except the quasar, which appears as a bright “star” at lower left in the image. **CENTER PANEL** shows this region of the image after insertion of the grism, which spreads the light from each object into a horizontal spectral trace where bluer light from the object is toward the left, and redder light is toward the right. Individual objects’ spectra can be identified by matching their vertical position in the center and left panels. The **RIGHT PANEL** shows the same spectral data after applying a filter to the central panel that highlights sharp spikes in the wavelength direction. Arrows indicate the locations of triplet emission lines associated with the highlighted galaxies in the left panel. These represent atomic emission from nebulae in the host galaxies, in this case from oxygen and hydrogen. The galaxy at the upper right of the image has redshift z=6.764, at which point the universe was 800 million years old. The galaxy itself is 258 million years old; it has roughly 10 billion stars, and is forming over 20 stars per year. Credit: EIGER team / Jorryt Matthee

WHAT JWST IS ALREADY REVEALING ABOUT EARLY GALAXIES

July 11, 2023, marked the one-year anniversary of JWST’s release to the science community for operations. Our team has already published our first five papers based on EIGER data, and we have concluded an exciting weeklong international conference at MIT, convening 150 of the world’s foremost JWST expert users. These groups have barely scratched the surface of what Year 1 data have to offer. Yet a preliminary consensus narrative is emerging about early galaxy formation, summarized below.

EARLY GALAXIES WERE FAR SMALLER IN SIZE AND MASS THAN THE MILKY WAY

Modern-day spiral galaxies like the Milky Way and Andromeda have 10^{10}–10^{11} stars, spread over stellar disks that are 80,000–90,000 light years in diameter. The median EIGER galaxy has just 2×10^8 solar masses of stars, and these are concentrated into irregularly-shaped morphologies of just 2,200 light years in diameter. In other words, typical galaxies seen by JWST in the first billion years are about 40× smaller than the Milky Way and have 250× fewer stars. This is consistent with the canonical theory of galaxy formation, whereby large galaxies grow over time from the mergers of smaller proto-galaxies.

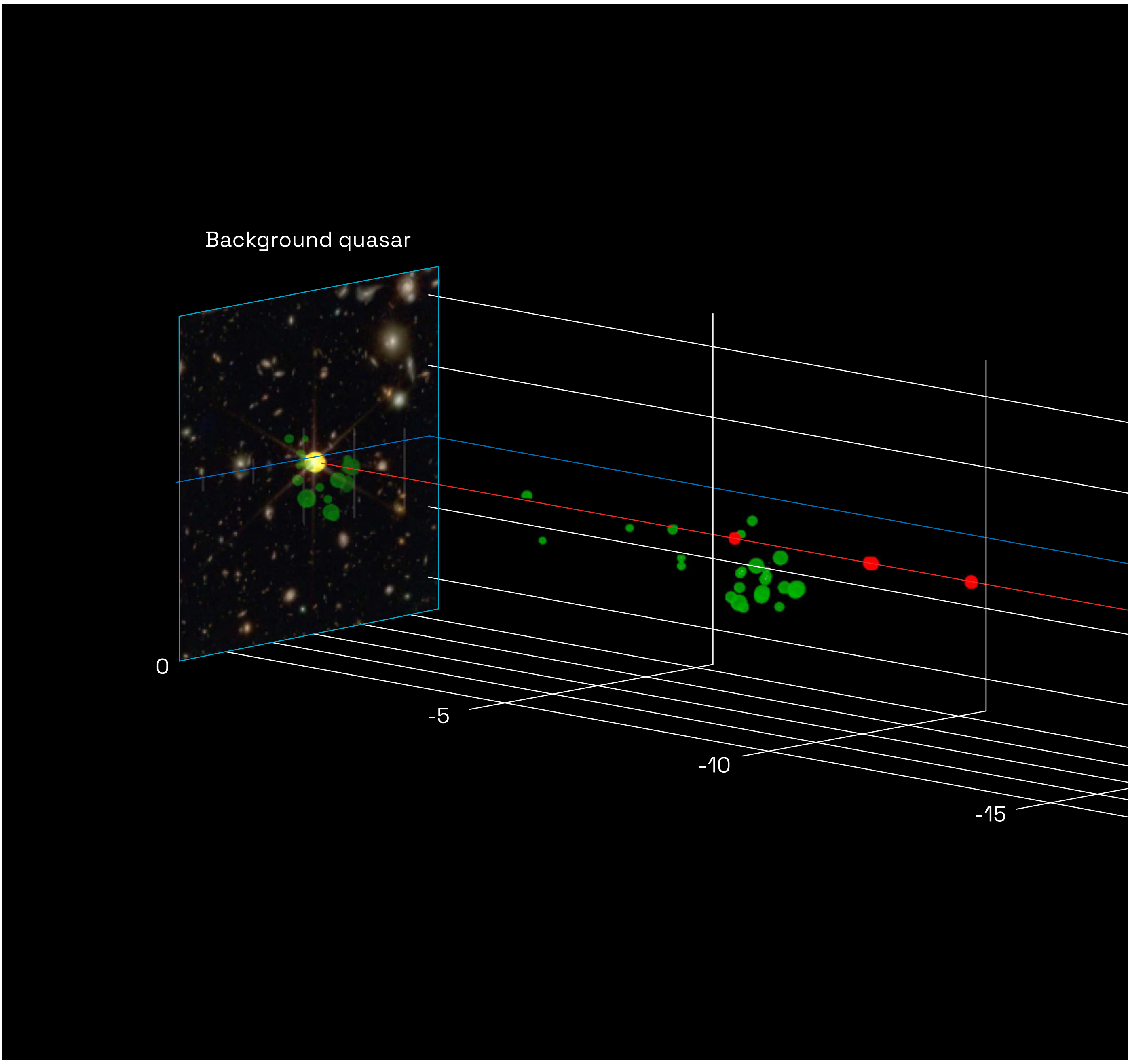
In fact, with your naked eye it is possible to see somewhat similar mini-galaxies in the local universe—these are the Magellanic Clouds, two dwarf galaxies falling into the Milky Way that are visible under a dark sky from the Southern Hemisphere. Our EIGER galaxies resemble the smaller of the two Magellanic Clouds in mass.

However, it is astounding that JWST can easily detect such tiny objects at a luminosity distance of over 200 billion light-years, which is an impressive distance even by astronomical standards!

EARLY GALAXIES EXHIBIT SPECTACULAR NEBULAE AND INTENSE STAR FORMATION

Our team was astonished when analyzing the first EIGER grism spectra at the number of galaxies whose nebular emission lines stood out clearly from the noise, exceeding our most optimistic pre-launch expectations. This is in part thanks to the superb engineering of the telescope. Yet it appears that the universe also conspires to make nebular emission much brighter in early galaxies than we see in the present day.

Emission nebulae like the famous example in Orion's sword are lit up by young, hot stars, and it appears that EIGER galaxies are forming between four and eight such new stars per year, in contrast to the Milky Way, which forms approximately one per year. Their small stellar mass and large star formation rate indicates that these galaxies can double in size every 50 million years—a blink of an eye in cosmic history. If we could somehow transport ourselves in space and time to the inside of one of these rapidly



growing infant galaxies, the sky would be spectacularly illuminated with color.

EXTREMELY MASSIVE BLACK HOLES ALREADY ANCHORED THE NUCLEI OF EARLY GALAXIES

At the center of each EIGER field, there is one very special galaxy from the early universe: the object hosting a supermassive black hole that we see as a quasar. Although the quasar just looks like a bright red star in an image, its spectrum is very distinctive, and does not at all resemble that of a normal star or galaxy. Instead, it has a series of emission lines powered by hot matter accreting onto the black hole. These lines are no longer sharp spikes, but rather are smeared by Doppler shifting of the emitting gas as it spirals in.

The Doppler broadening of these lines encodes information about orbital velocities and hence the mass of the black hole. MIT professor Anna-Christina Eilers analyzed EIGER's first observed black hole using hydrogen lines in the JWST spectrum, and found it weighed in at ten billion solar masses, consistent with other less direct measurements made from the ground. It remains a mystery how anything this enormous can be assembled less than one billion years after the Big Bang; it violates a theoretical speed limit on how fast matter can accrete onto a central body. The existence of these objects requires new theory.

One feature of many black hole growth models is that younger black holes spend some (perhaps most) of their life in a dust-enshrouded cocoon, in which they are growing but we cannot see the light that they emit. Although such veiled accretors have never been seen before, there is tantalizing evidence in data from EIGER and other surveys that JWST may be starting to find small and dusty black holes at early times, filling in a piece of this puzzle.

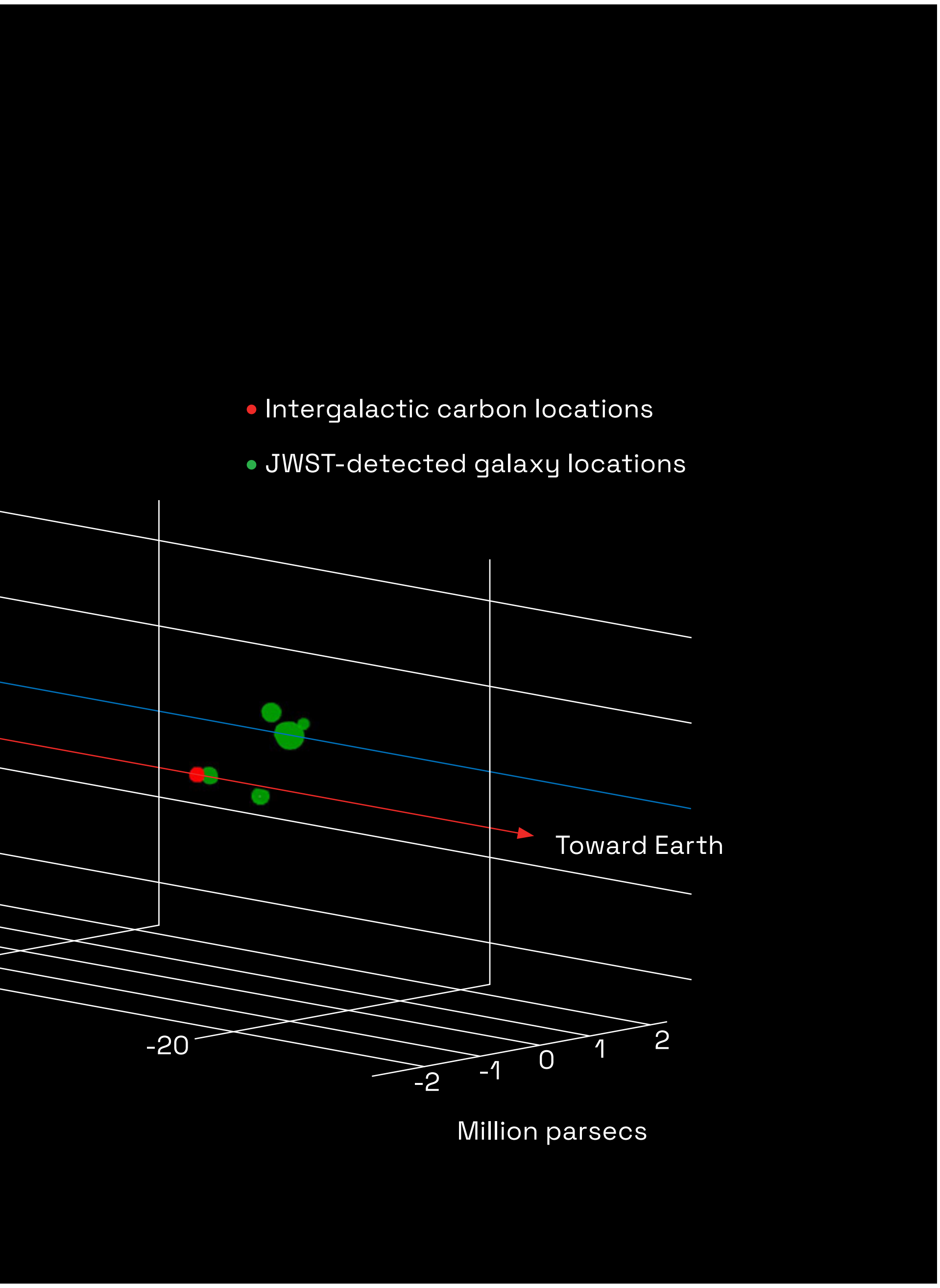


FIGURE 3: By measuring redshifts, JWST not only provides a "flat" 2D image of the sky, it also measures depth along the line of sight in 3D. This field shows the locations of galaxies (green dots) along the sightline to the quasar in *Figures 1 and 2*; the boresight is indicated by the red vector terminating with a yellow dot at the quasar's location. Red dots indicate concentrations of carbon atoms detected in the quasar's foreground, as measured with Magellan/FIRE. There is clear evidence of clustering among the galaxies interspersed with long voids. Some (but not all) carbon pollution is also occurring near galaxies detected with JWST.

EARLY GALAXIES WERE HEAVY POLLUTERS

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Quasars are useful for many things besides the study of black hole physics. As the brightest persistent sources in the universe, their spectra record a 1D density "core sample" of any intervening gas along the line of sight from Earth. This is because gaseous atoms absorb light passing through from the quasar at discrete wavelengths, according to each element's electron energy level configuration. At larger distances the observed absorption occurs at correspondingly higher redshift. All quasar spectra exhibit a menagerie of absorption lines that can be sorted by atomic element, and distance from Earth.

Our team's pre-existing spectra from FIRE and other ground-based telescopes had already revealed the presence of carbon, silicon, oxygen, iron, aluminum and magnesium at precisely determined redshifts toward these quasars. These elements are all heavier than helium and were therefore synthesized in some of the earliest stars and galaxies in the universe. EIGER's JWST observations provided the first-ever 3D map of galaxies at this same epoch, helping us locate stars that are the potential sources of these synthesized elements.

Already we have detected numerous galaxies in the neighborhood of chemically enriched gas, at epochs far earlier than we could previously access. Spatial correlations of galaxies and enriched gas are not surprising *per se*; most galaxies in the local universe have carbon, oxygen and other stellar byproducts gravitationally bound within their halos, which were deposited by supernovae in the galaxy.

The important and surprising difference is that in the early universe, the new elements are somewhat near galaxies yet still too distant to be gravitationally bound, because the galaxies are so tiny that their sphere of influence is small. Apparently, the combination of rapid star formation and small gravitational mass creates conditions where supernova energy can accelerate freshly minted elements beyond escape velocity and into intergalactic space, in an explosion of polluted matter. These free-floating elements may in time fall back into their galaxy of origin to form new stars, or they may travel over to pollute other neighboring proto-galaxies, or they may never return from intergalactic space. Theory suggests that this is an important regulating aspect of the galaxy formation process.

WHAT'S NEXT?

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In the next three years, astronomers are preparing for launch and operations of two new wide-field space telescopes: Euclid from the European Space Agency, which launched on July 1, 2023, and the Nancy Grace Roman Space Telescope from NASA, scheduled for 2026. These observatories will survey large swaths of the sky and uncover new, fainter objects suitable for detailed characterization with JWST's narrow but deep capabilities. However, after these two missions, NASA Astrophysics is not planning another flagship until the late 2040s. This is near the end of JWST's operational life, and virtually a career to wait for many young researchers.

During the 2030s, the field is instead focusing resources on a new generation of ground-based observatories to complement NASA's space-based constellation. Three new telescopes with diameters 4–5 times larger than JWST are through the design phase and into early construction, using a public-private hybrid funding model. One of these, the Giant Magellan Telescope (GMT), will be co-located with the existing Magellan Telescopes in Chile, and have 12 times their light-gathering power. Unlike JWST, which only sees infrared light, the GMT will feature a full suite of UV/optical/IR instrumentation, and it will deliver sharper images and deeper spectra in the 1–2 micron band where hydrogen transitions are redshifted in the early universe. In the same way that institutional Magellan access allowed MIT researchers to compete for scarce Hubble Space Telescope and eventually JWST time, partnership in next-generation ground based telescopes will help researchers pursue the best and most ambitious science, and capitalize on discovery opportunities for decades to come.

JWST has already revolutionized our understanding of the early universe, even though we are just one year into its projected two-decade lifetime. If past is prologue with the Hubble Space Telescope, Magellan, and indeed every world-class telescope built since Galileo, the best is yet to come as we gain a full understanding of the instrument and analysis tools, and discover new astrophysical phenomena that have yet to be imagined.

ROBERT SIMCOE is the Francis L. Friedman Professor of Physics in the MIT Department of Physics, and Director of the MIT Kavli Institute for Astrophysics and Space Research. He first acquired an interest in astronomy and telescope making as a hobby through family trips to the Stellafane convention. As an undergraduate at Princeton, he participated in development of the Sloan Digital Sky Survey camera, after which he moved to Caltech where he collaborated on a wide-field camera for the 200" Hale Telescope at Palomar Observatory and completed a thesis on chemical enrichment of the intergalactic medium using the Keck Telescopes. In 2003 he moved to MIT as a Pappalardo Postdoctoral Fellow, to make use of the newly commissioned 6.5-meter Magellan Telescopes, and joined the MIT faculty in 2006. Three years later he installed the FIRE infrared spectrometer at Magellan, which has played a key role in exploration of cool stars in the nearby universe, and the discovery and characterization of quasars in the first billion years after the Big Bang. In 2023, his research group commissioned one of the first dedicated robotic telescopes to survey the time-variable infrared sky. Later this year, his team will also commission a new hyperspectral imager for Magellan capable of taking 3D images of the astronomical sky.