CHAPTER 6. HOW DO GALAXIES EVOLVE?

This question is one of the oldest in astrophysics, dating from the very first realization a century ago that galaxies are “island universes” unto themselves. The quest to answer it has motivated some of astronomy’s brightest minds to build our most ambitious telescopes. Over decades of discovery spanning the electromagnetic spectrum, astronomers have painted a rich picture of how galaxies begin as small fluctuations in the large-scale structure that aggregate into self-bound dark matter halos where gas can pile up and stars can form. These small seeds merge and grow hierarchically into larger and larger galaxies over time. Supermassive black holes lurk in the hearts of nearly every galaxy, and for brief periods might govern their evolution.

Yet our understanding of the physics behind these emergent patterns lags behind our ability to characterize them. What sets the minimum scale for galaxy formation? Why are some massive galaxies dominated by their bulges while others have none? How do galaxies sustain their star formation for much longer than their present gas supply allows? Why do the largest and smallest galaxies cease forming stars (or “quench”), and stay that way? These questions, and many more, comprise the leading edge of galaxy formation studies today (Somerville & Davé 2015; Madau & Dickinson 2014).

LUVOIR will provide astronomers with groundbreaking increases in capability for high-resolution imaging with ultra-stable image quality, highly multiplexed UV spectroscopy, and full-time access to half the sky. It will reach the bottom end of hierarchical galaxy formation, resolve the insides of galaxies to 100 parsec or better at all redshifts, and trace the flows of gas in and out of galaxies and their AGN at all cosmic times.

This chapter will focus on Signature Science—the “Cycles of Galactic Matter” and “The Hierarchical Assembly of Galaxies”—within two broad domains of galaxy evolution that encompass a wide range of unanswered questions that will remain unanswered even in the 2030s, because they require spatial resolution, sensitivity, and wavelength coverage well beyond those of other foreseeable facilities.

To understand “The Cycles of Matter," astronomers using LUVOIR will be able to deploy multi-object spectroscopy in the ultraviolet, with 30–100 times the sensitivity of Hubble and the ability to observe more than a hundred objects at once in a highly multiplexed fashion. To map “The Multiscale Assembly of Galaxies,” astronomers using LUVOIR will employ extremely stable 10 milliarcsecond imaging with an unprecedented depth and wavelength coverage. These capabilities go far beyond those of any expected facility, including JWST, WFIRST, and the ground-based Extremely Large Telescopes. LUVOIR will perform breakthrough measurements at high redshift ($z > 2$) to see galaxies in fine detail (100 parsec scales) at critical phases of evolution, and in very nearby galaxies (< 10 Mpc) to see them resolved even star by star.

The Signature Science Cases here represent some of the most compelling types of observations that astronomers might do with LUVOIR at the limits of its performance. But, compelling as they are, they should not be taken as a complete specification of the LUVOIR program. We have developed concrete examples to ensure that the nominal design can do this compelling science, and so that the astronomical community has detailed examples they can adapt to their own interests.

State of the Field in the 2030s

Galaxy formation and evolution: We can expect that essentially the entire sky will have been surveyed at seeing-limited resolution in the optical bands. LSST's accumulated co-add will reach ~28th magnitude in the optical over 10 years, with 0.8–1″ resolution. These maps will be joined by the massive fiber-based spectroscopic surveys that started with SDSS and 2dF and will expand deeper and wider with PFS and its contemporaries. All-sky imaging provides accurate photometry, and spectroscopy provides additional physical diagnostics of galactic dust content and stellar population age and metallicity. These vast datasets support rich multivariate analyses with statistical precision and so excel at determining galaxy population statistics and galaxy/galaxy correlations in large-scale structure and halo substructure. After these surveys, there might be very little about the large-scale distribution of galaxies that remains to be learned. These massive spectroscopic surveys also detect millions of strong gas absorbers, such Mg II and Ca II lines, which probe dense interstellar medium (ISM) and CGM gas. However, they cannot access the key UV physical diagnostics over most of cosmic time.

The other major theme of the 2020s will be high-resolution imaging in the IR, sub-millimeter, and radio. JWST and WFIRST will be the prime space observatories, bringing 50–100 mas resolution to imaging and multi-object spectroscopy. WFIRST will provide Hubble-quality imaging to a large sky area, and JWST will dissect galaxies to AB ~ 32. JWST is optimized to reach "the first galaxies," seeing the first seeds of modern galaxies at $z > 15$. It will also be revolutionary in its mid-IR capability, able to observe the rise of dust, ice, and molecules in galaxies over most of cosmic time. Long-wavelength facilities such as ALMA and SKA will bring their powers to bear on the neutral and molecular gas content of galaxies at high resolution. Finally, 30-m-class telescopes on the ground will, if successful with adaptive optics, bring < 10 mas imaging and spectroscopy at IR wavelengths, in a comparable resolution and depth space as JWST.

What observational parameter space will remain unexplored after all this? Space observatories are the platform of choice for high-resolution optical imaging, UV imaging and spectroscopy, highly repeatable precision photometry, high precision astrometry, and high-performance optical coronagraphy. LUVOIR's "Signature Science" motivates and uses these capabilities, while acknowledging the areas where ground-based telescopes or space facilities at other wavelengths do their best. And in the end, complementarity and collaboration between these domains drives the science forward.

Stars, star formation, and feedback: JWST and WFIRST will have observed stellar populations down to 0.3 solar masses for all galaxies within the local 0.5 Mpc, with lower limits for nearer galaxies. This will test theories of low-mass star formation and constrain variations of the low-mass end of the stellar initial mass function in low-density environments. ALMA will have characterized the populations of gas cores in several nearby galaxies, and will have shed light on the relation between the core mass function and the stellar initial mass function around the low mass turnover. Improved models will help interpret the complex chemistry of the pre-stellar cores. In parallel, adaptive optics-assisted 30-m-class telescopes will have assembled large samples of binary stars at a range of masses out to the Magellanic Clouds, using both radial velocity (RV) and proper motion techniques. Combinations of these facilities will have increased the number of candidate galaxy hosts of very massive stars, i.e., stars with $M > 150\ M_{\odot}$, by at least tenfold, up from the current census of a handful.

Ultimately, we expect that the creativity of the community, empowered by the revolutionary capabilities of the observatory, will ask questions, acquire data, and solve problems that we cannot envision today. That is as it should be, as a flagship should always reach far beyond current capabilities and transcend the current limits of our imagination. With this in mind, let us ask the vital science questions that we believe will remain unsolved until LUVOIR, and consider how they drive the requirements for its aperture, resolution, and wavelength coverage. We hope these cases will stimulate the reader to design their own future with these tools.

6.1 Signature Science Case #10: The cycles of galactic matter

How do galaxies acquire the gas they use to form stars? How do they sustain star formation over billions of years when they appear to contain much less gas than this requires? How does feedback from star formation and active galactic nuclei (AGN) expel gas and metals, and to what extent is this feedback recycled into later star formation? What happens to a galaxy's gas when it quenches? Is it used up, ejected, or hidden? Answering these questions will go a long way toward explaining why galaxies look like they do.

Inflows and outflows of gas likely shape the evolution of star formation within a galaxy. Inflows ultimately arise from the intergalactic medium (IGM) to provide fuel for continued star formation over the lifetime of a galaxy. Outflows from the interstellar medium, driven by stellar radiation and the explosions of stars and jets from AGN, can inhibit star formation in their central regions. The balance of these flows set the rate at which galaxies accumulate heavy elements.

All these flows meet in the circumgalactic medium (CGM), a diffuse gaseous medium spanning roughly 30 times the radius and 10,000 times the volume of the visible stellar disk (**Figure 6-1**; Tumlinson, Peeples, & Werk 2017). If galaxies are the factories of creation, the CGM is their fuel tank, waste dump, and recycling center. No picture of galaxy evolution is complete without understanding the gas flows between these major components.

To organize this discussion, we will proceed into galaxies and back out again. We start with the IGM and CGM and their role as the reservoir of galactic accretion and recycling (**Section 6.1.2**). From there we will consider the flows within the CGM and how gas there is processed and recycled, and how galaxies are quenched (**Section 6.1.3**). Finally, we will consider the disk/halo interface, where accretion becomes the ISM and the ISM becomes feedback, using highly multiplexed "down-the-barrel" spectroscopy (**Section 6.1.4**). But first, we pause to reflect on why observing these processes makes LUVOIR's UV sensitivity so essential to its science case.

6.1.1 The essential ultraviolet

Because UV light damages cells and mutates DNA, life as we know it might not exist without Earth's UV-blocking ozone layer. It seems we can have life on Earth, or UV astronomy on the ground, but not both.

Figure 6-2 shows why UV coverage is essential to understanding the intrinsically "multiphase" galactic gas flows. The shaded map at lower left shows the distribution of gas in a simulated Milky-Way-like galaxy from the EAGLE project (Oppenheimer et al. 2016), which spans multiple "phases" from 10^3–10^6 K and eight orders of magnitude in density. In ionized gas like this, the quantum-mechanical rules of electron orbits dictate that the gas will emit

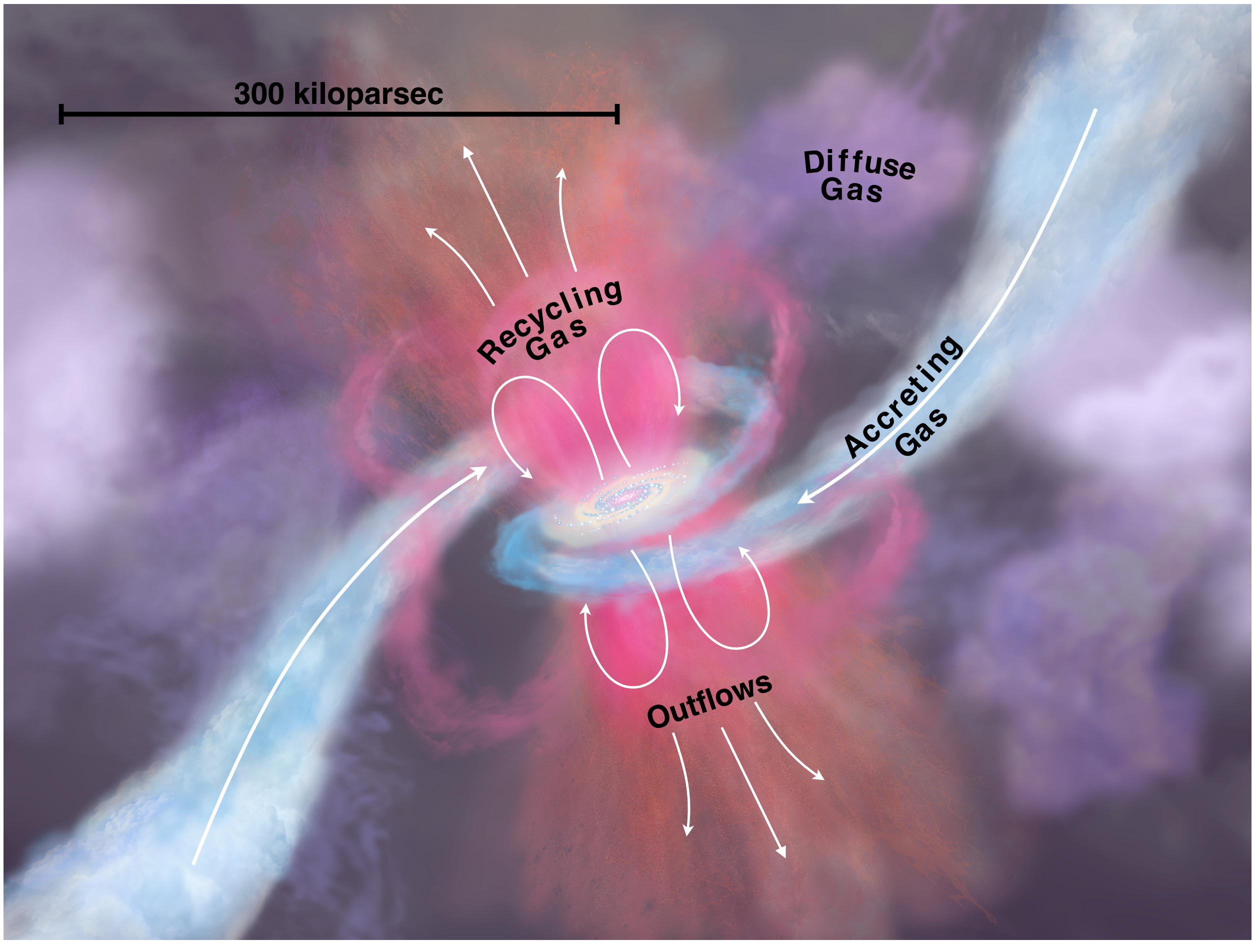


Figure 6-1. *"The Cycles of Matter" play out on scales far beyond the visible stellar disks. Normal galaxies are surrounded by a massive reservoir of diffuse gas that acts as their fuel tank, waste dump, and recycling center: the circumgalactic medium (CGM). It is fed by accretion out of the cosmic web and by outflows from the galaxy. Unraveling these gas flows is a major driving force for LUVOIR and its instruments. Adapted from Tumlinson, Peeples, & Werk (2017).*

and absorb energy predominantly at UV wavelengths, up to 80% according to detailed simulations (Bertone et al. 2013). Many of the transitions appear as strong UV absorption and emission lines (**Figure 6-2**). This inescapable physics means that access to UV wavelengths in space is essential if we are to resolve questions about how galaxies acquire, process, eject, and recycle their gas over the last 10 Gyr of cosmic time.

With LUVOIR, we have the opportunity to expand the reach of UV observations well past the range of Hubble's capabilities. Thanks to investment in technology development, new generations of high-reflectivity coatings with low contamination will be used to reach photons down to 1000 Å. With LUVOIR it will no longer be necessary to consider the UV as divided at the ~1150 Å boundary like with Hubble and FUSE. More details about this enabling technology is available in **Chapters 9** and **12**.

6.1.2 Gas flows in absorption: Accretion, feedback, and quenching

Only recently have we come to appreciate that the CGM is a major element of the mass and metal budgets of galaxies. Using Hubble's Cosmic Origins Spectrograph (COS), astronomers

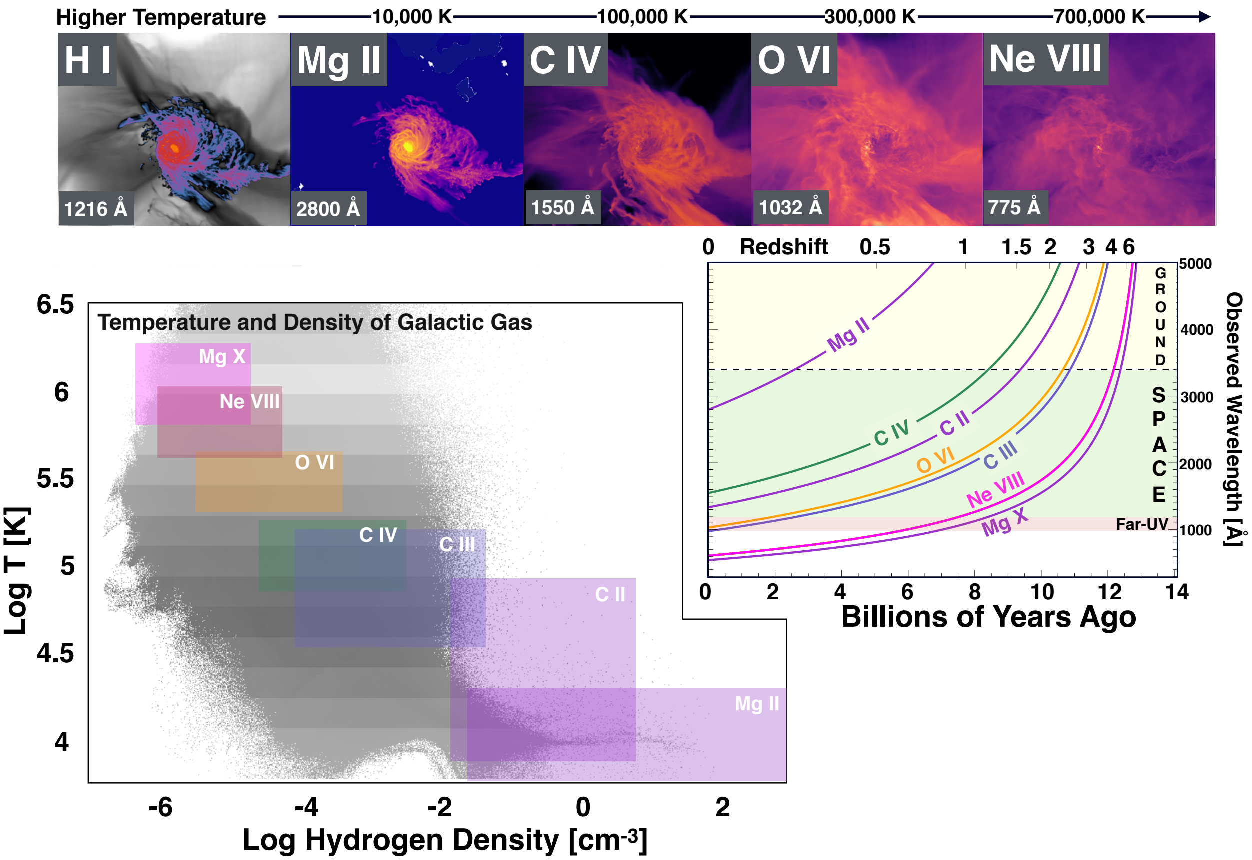


Figure 6-2. *Diffuse gas in and around galaxies requires UV capability for most of cosmic time. The top row shows a simulated galaxy at z = 0.7 from the FOGGIE suite (Peeples et al. 2019), rendered in some key diagnostic ions. The temperature and density regimes probed by these ions are marked in the "phase diagram" of this galaxy's gas (lower left). At upper right we show how these lines, ranging from Mg X at 680 Å to Mg II at 2800 Å, vary in observed wavelength with redshift. Even with redshift, most of this diffuse gas is visible only in the UV for the last 10 Gyr of cosmic time. X-ray lines such as O VII and O VIII (both around 20 Å) probe gas at ~1 million K but not the cooler phases where accretion and recycling occur. The 1000–1200 Å range marked "Far-UV" is critically important to capture O VI 1032 at z > 0.1 and the EUV ions Ne VIII and Mg X at z > 0.5 rather than z > 1.*

have found that the gaseous halos of Milky-Way-like galaxies may outweigh their disks (Werk et al. 2014), and that a large share, perhaps the majority, of all the metals ever produced by stars are outside galaxies (Peeples et al. 2014). The major strides in characterizing the CGM have left many important questions open:

1. Where are the missing baryons that are needed to fuel galaxies?
2. Where are the metals, and what do their distribution within and outside galaxies tell us about feedback?
3. How are galaxies quenched, and what happens to their CGM? Is it consumed, ejected, or heated? And how is quenching maintained?

Solving these problems requires pushing the boundaries of CGM characterization far beyond the limits of today's measurements, to $z = 1$–2, for two major reasons. First, this period

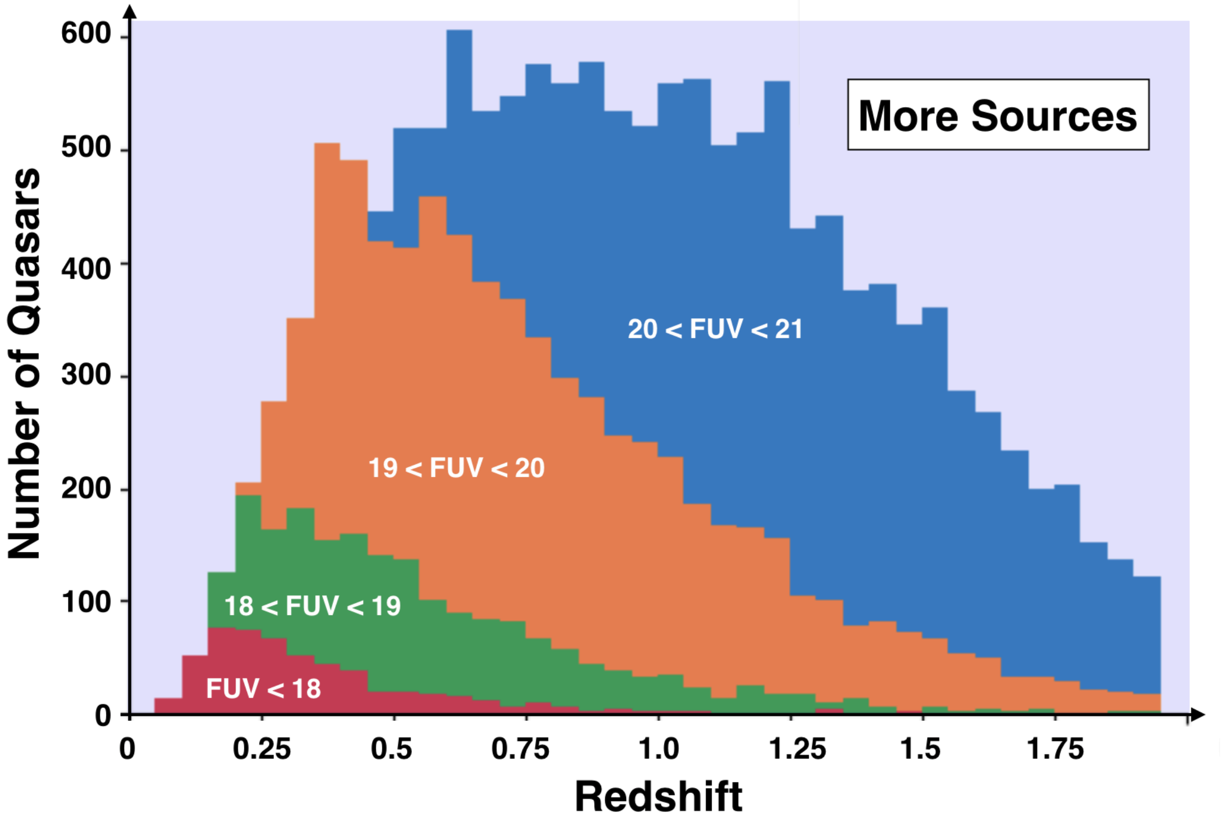


Figure 6-3. *Redshift distribution for SDSS quasars of various GALEX FUV magnitudes. For SNR = 20 spectroscopy, Hubble/COS is limited to the red wedge, which barely reaches past z ~ 0.7. With its 3 mag deeper grasp, LUMOS users will have many more QSOs to choose from, particularly in the vital z = 1–2 interval.*

7–10 Gyr ago encompasses the peak of cosmic star formation. Second, at $z > 0.5$ we gain access to a wide range of extreme UV lines, such as Ne VIII, O II to IV, and Mg X (< 800 Å in the rest frame, see **Figure 6-2**) that enable a much broader set of diagnostics of physical state and metal content that are only available with redshift.

Hubble's COS has approached the z ~ 1 frontier, but cannot advance it because it is limited to background sources of AB = 18 in the FUV (for SNR ~ 20). There are only about 1000 such QSOs on the entire sky (**Figure 6-3**), and only a handful lie at $z > 1$ where we can approach the cosmic star formation rate (SFR) peak with the optimal set of ions.

The LUVOIR Ultraviolet MultiObject Spectrograph (LUMOS) is designed for point-source spectroscopy 30–100 times more sensitive than Hubble/COS, at double its highest resolution (R ~ 40,000, or 7 km s^{-1} FWHM). LUMOS users will be able to choose from any of the quasars counted in **Figure 6-3**, including thousands of choice objects at z > 1 that are too faint for a less sensitive instrument. This is a critical time in the history of the universe: star formation rates begin declining from their z ~ 2 peak, AGN have passed their epoch of maximum activity and are turning off, the "red sequence" of passive galaxies is beginning to emerge, and the first large concentrations that we call galaxy clusters are about to form. It is thus a critical time in cosmic history of which Hubble's UV spectroscopy has given us only the slightest glimpse. LUMOS will enable great strides in depth and number of sightlines, and therefore in statistical power applied to many important problems.

Where are the missing galactic baryons? Normal galaxies appear to possess only a few percent of their expected budget of baryonic matter when only stars and ISM gas are taken into account (Fukugita, Hogan, & Peebles 1998; McGaugh 2005). We now know that a large mass fraction exists in the CGM, but this measurement has so far been performed only for galaxies around the mass of the Milky Way (or L*) and only at $z < 0.2$. (Werk et al. 2014). The large wavelength grasp of LUMOS (1000–3000 Å) provides coverage of critically important rest-frame extreme-UV ions that redshift into the FUV for $z > 0.5$ (Tripp 2013; **Figure 6-2**). This includes nearly every ionization state of the most abundant heavy element, oxygen, from O I (cold gas), though O VI (warm ionized gas), which LUMOS will cover simultaneously for sightlines at $z \sim 1$. A baryon census done with ions of a single element will eliminate the most serious systematic errors in ionization models that plague these measurements, as it is insensitive to any relative elemental abundances and only mildly sensitive to ionization corrections. The remaining oxygen ions—O VII and O VIII—absorb in the X-ray (~20 Å) and trace very low density, high temperature gas that has only been detected a few times despite investment of megaseconds of Chandra and XMM time.

Fortunately, very high ionization lines like Ne VIII (775 Å), Mg X (610 Å) and Si XII (500 Å) become available in (optically thin) IGM and CGM gas at $z > 0.5$, reaching a temperature regime ($T > 10^6$ K) that is usually thought to be the exclusive domain of X-ray telescopes. In conjunction with a sensitive X-ray facility like Lynx, which can see O VII and O VIII, LUVOIR should be able to complete a census of CGM baryons across all its phases and more than 10 Gyr of cosmic time.

Where are the metals that trace feedback? Heavy elements are "Nature's tracer particles"—the equivalent of a message in a bottle that tells us where the products of star formation have been carried over time. If we can piece together the messages from all the island universes, we could come to understand how galactic feedback works.

Hubble has extensively probed the extent of metals around galaxies, culminating in the finding that only 20% of all metals produced are still retained in the galaxies that made them (Peeples et al. 2014). The large fraction of those metals that end up in the CGM trace out a curiously bimodal metallicity distribution (Lehner et al. 2013; Wotta et al. 2016), with ~50% of the gas having metallicities around 5% solar (accretion from the IGM?), while the other half is roughly solar (metal enriched feedback?). Understanding the origins of this gas, whether it will collapse onto the galaxy or will be subsumed back into the corona, is critical to understanding how and from where galaxies replenish their fuel supply.

The same broad wavelength coverage that enables a robust baryon census will also complete a multiphase metals census over a wide range of galaxy masses, star-formation rates, and environments. By exploiting simultaneous coverage of almost every UV ion of oxygen, as shown in **Figure 6-4**, LUVOIR can avoid the systematic problems with using C, Si, O, and N variously as is done at $z < 0.2$. This is only possible with UV coverage and redshift that places EUV lines of O II, O III, and O IV into the space UV (Tripp 2013). Complementary X-ray measurements with Lynx will add in the hottest gas. Using this capability, LUVOIR's users can complete the low-z metals census, constrain the physics of feedback from galaxies, and assess the importance of galactic recycling with robust statistics.

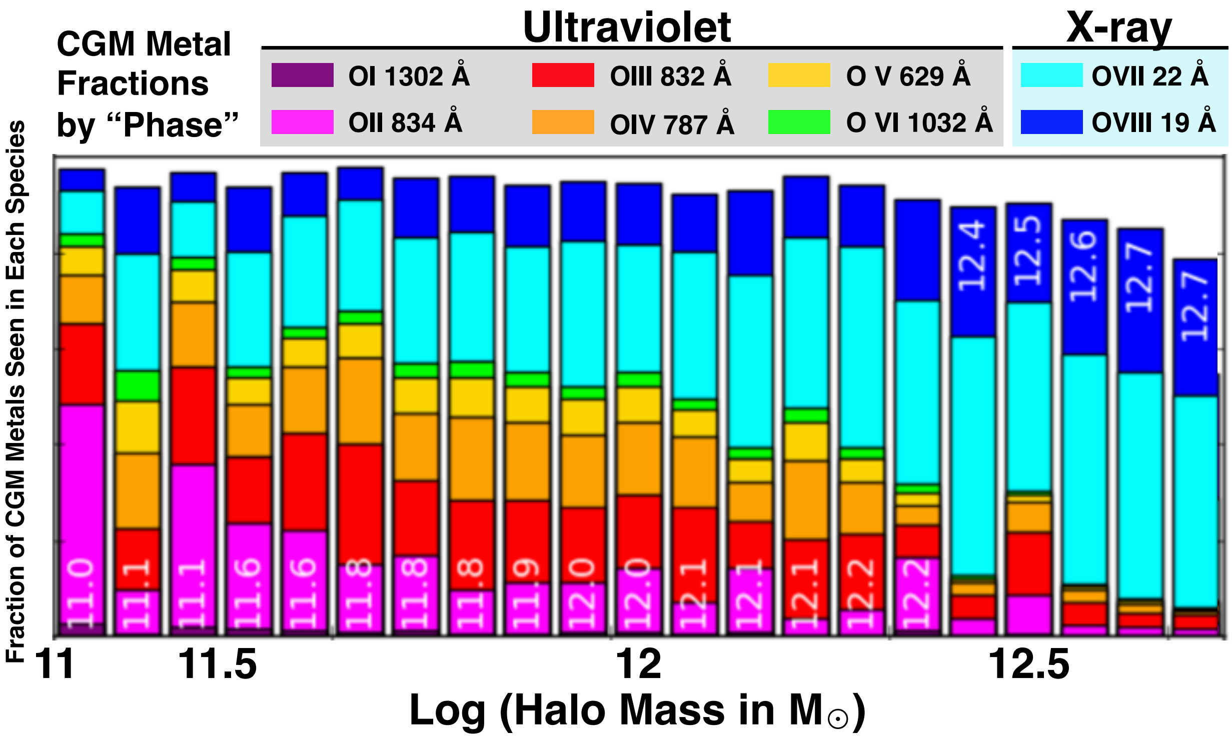


Figure 6-4. *The "metals budget" in the CGM of simulated galaxies from the EAGLE Zoom simulations (Oppenheimer et al. 2016). At low mass, halos are filled with low and intermediate ionization gas that can be detected with UV lines of the ions O I–O VI. At around the halo mass of the Milky Way (2x10^{12} $M_\odot$), the UV- and X-ray traced phases are comparable. Complementary UV and X-ray measurements are needed to perform a complete metals census and test the uncertain feedback physics in these models.*

Precision cosmology with the IGM. The IGM as traced by the Lyman alpha forest provides unique constraints on cosmological structure formation. The very high throughput of the LUMOS/G300M grating provides SNR > 30 coverage of the z ~ 1 forest in one hour. To date, less than five quasars have been observed covering the forest at SNR ~ 10 or greater at z ~ 1, at the cost of nearly 100 Hubble orbits. The baryon census and feedback studies described above obtains an unprecedented Lyman alpha forest sample with no additional exposure time. A LUVOIR program observing 100 quasar sight lines at SNR > 30 would: (1) constrain the matter power spectrum p(k) to < 5% precision on scales of 0.1 to 100 Mpc at z ~ 1; (2) measure the H I column-density distribution function $f(N_{HI})$; (3) measure the equation of state of the IGM $T=T_0(\rho/\rho_{avg})\gamma^{-1}$, to <10% precision. These measurements would constrain the formation of large-scale gaseous structure, the distribution of gas near galaxies, the radiation field produced by all sources, and the thermal history of the universe.

A comprehensive LUMOS QSOALS campaign. All of these studies of CGM missing baryons, metals, and the IGM can be carried out with a single, comprehensive QSO survey (**Appendix B.11.2**). For definiteness and scaling between architectures, we scope this to use the 100 brightest QSOs identified in the SDSS DR7+GALEX QSO catalog. We set the SNR goals such that 1 hour in each of the LUMOS M gratings will yield SNR ~ 20 for an FUV = 19 mag QSO. For brighter objects, we scale the exposures by FUV magnitude to maintain the same SNR. This survey of 100 QSOs will require 240 hours of exposures (and approximately

~350 hours with overheads). As an example of synergy between space and the ground, it is the future 20–30 m telescopes on the ground that will obtain the necessary galaxy redshifts to correlate with the detected gas along these LUVOIR sightlines. Complementary X-ray observations will, for the X-ray bright subset, constrain the hottest gas in these galaxy halos and complement LUVOIR's observations of Ne VIII and Mg X.

CGM characterization for thousands of galaxies at z~1–2 represents a fundamentally game-changing prospect for the study of the gas in, around, and between galaxies. No mission current or planned other than LUVOIR could complete such a program in a treasury scale program allocation of time. Any claim of understanding the history of baryons in the universe demands a study of this epoch of transformation in cosmic time, and LUVOIR rises to the challenge.

How is quenching done, and maintained? Galaxy quenching is a prime target for LUVOIR's unique power. How galaxies quench, and remain so, is a major open question. The number density of passive galaxies has increased 10-fold over the 10 Gyr interval since z ~ 2 (Brammer et al. 2011) at the expense of the star-forming population. Galaxies undergoing quenching are the ideal laboratories to study the feedback that all galaxies experience: the galactic superwinds driven by supernovae and stellar radiation, the hot plasma ejected by jets from black holes lurking in galactic centers, and the mergers that transform galaxy shapes while triggering the consumption or ejection of pre-existing gas.

LUVOIR's first major approach to quenching will come from the QSO absorption-line treasury program from the proceeding section. The 100 sightlines in that program should pass through the halos of hundreds of galaxies that are quenched, or even underdoing active quenching through an AGN or post-starburst phase. As most of the development of the present-day red sequence occurred since z ~ 2, and the key diagnostics are rest-frame UV lines, this critical problem is a unique and compelling driver for LUVOIR's aperture and UV sensitivity.

Another unique LUVOIR application to quenching is shown in **Figure 6-5**. AGN feedback is thought to play an important role in keeping hot halos from cooling in quiescent galaxies, though it is difficult to probe the jet and radiation interactions with the surrounding CGM gas. However, increasing the density of sources to which we have access with UV spectroscopy will allow us to probe that interaction directly. The key needs for such science are high spectral resolution and sensitivity (aperture) to provide enough source density that individual AGN hosts can be studied.

In this program, the QSO absorption-line approach is adapted to examine many sightlines behind a single galaxy, the post-starburst radio galaxy Centaurus A at 4 Mpc. Using multiple sightlines to probe halo gas is currently feasible only for M31, which subtends many square degrees, large enough to encompass 20 or so QSOs at the limits of COS. LUMOS will reach dozens of QSOs within 150 kpc of the center of Cen A, or any other nearby galaxy out to 10–20 Mpc. For each galaxy, LUMOS will access to the full suite of UV diagnostic ions (including the critical O VI 1032/1038 Å doublet) and precise kinematics to probe the gas flows associated with quenching.

Appendix B.11.3 defines a similar observing program for M51, to do the corresponding experiment for a star forming galaxy. This program observes 30 QSOs probing M51's halo out to 200 kpc, over the full wavelength range of LUMOS in a total of 117 hours of exposure time (estimated to be 146 hours with overheads). This program uses QSOs as faint as FUV

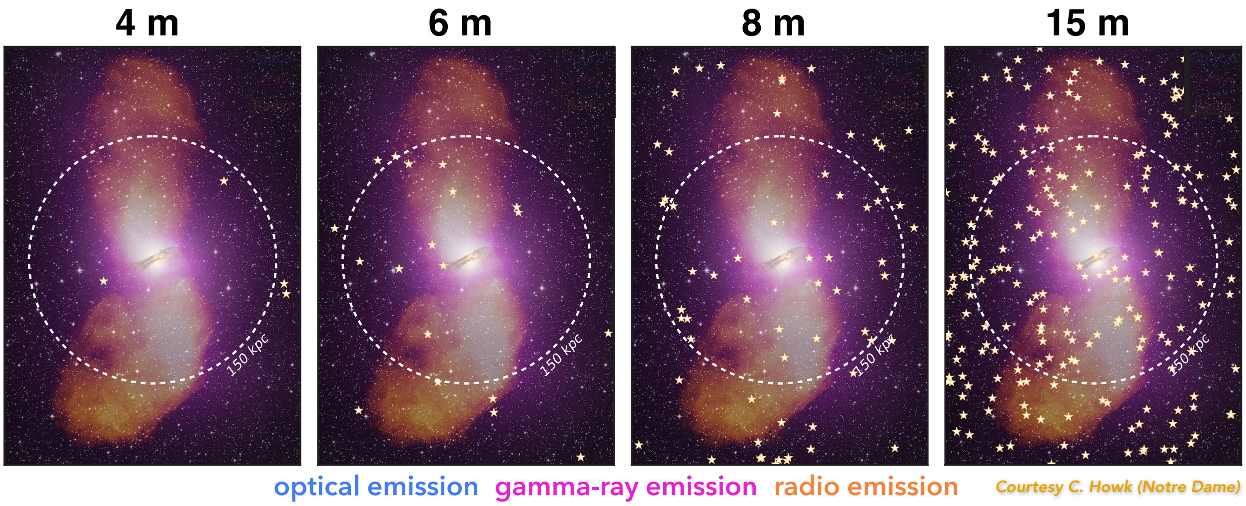


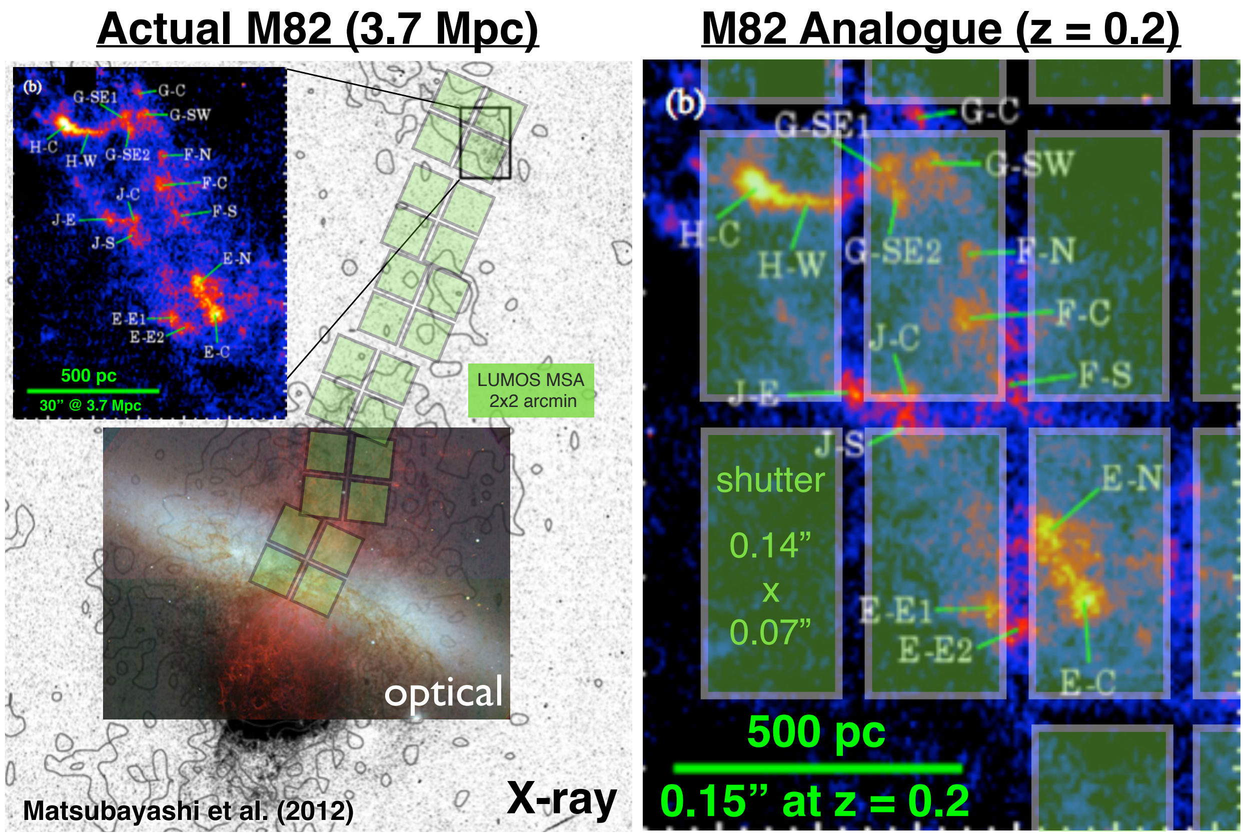
Figure 6-5. *A visualization of the sky around the radio galaxy Cen A demonstrating the density of sources available for high-resolution, high-SNR spectroscopy of background QSOs behind low-redshift galaxies. Each star represents a QSO that could be observed to SNR > 10 in ~0.5–1 hour by a telescope of the given aperture. An 8-m telescope has a source density smaller by ~5x than that of the 15-m. The nearest QSO that is reachable by Hubble/COS in <20 orbits lies at impact parameter R = 300 kpc, two times further from the core of this galaxy than the circle representing R = 150 kpc. Background galaxies, which can also be used to map the gas, are ten times more numerous.*

~21, which are far beyond present capabilities. There are hundreds of galaxies in the local Universe for which LUVOIR could perform this same experiment, mapping the CGM in many kinds of galaxies from large to small, from star forming to quenched, and in all other phases of their evolution.

6.1.3 Mapping the cycles of matter in ultraviolet emission

Quasar absorption lines can detect and characterize the IGM and CGM without regard to gas density, but they reveal little about the 3D distribution of the absorbing gas. But with its millions of ~0.1″ apertures, customizable to nearly any source, LUMOS will be able to “take a picture” of a galaxy’s gas flows in two dimensions, using emission from the gas itself that reveals its density, temperature, metallicity, and kinematics. This capability will enable LUVOIR’s users to probe physical processes—shocks, accretion, ejecta, and recycling—at scales that even simulations today can barely reach. We will consider two applications of this capability: maps of small-scale gas dynamics in nearby galaxies, and detection of the extremely diffuse gas that fills halos at higher redshift.

Galactic winds in high definition. The LUMOS microshutters map to small-scale (< 1 kpc) clouds that carry gas and metals away from the prototypical starburst galaxy, M82 (**Figure 6-6**). Tiles of the 2′ x 2′ microshutter field of view are overlaid on the galaxy and its outflow. The color zoom shows a ground-based Hα image in which small clumps appear in the flow. Did these clumps cool and form where they are? Or is this material directly ejected? If so, what does it imply about the mass ejection rate, and the mass rate of recycling? Only at UV wavelengths can we probe the relevant energy scales to see galactic feedback in action. Multiply this small region many-fold, and it becomes clear that we must be able to observe hundreds of such places in this complex flow to understand its true dynamics. Small scales are critical to study these flows: the LUMOS 0.14″ x 0.07″ shutters subtend


Actual M82 (3.7 Mpc)

M82 Analogue (z = 0.2)

Figure 6-6. *Two examples of using LUMOS to examine the small-scale physics of galactic outflows. At left, X-ray and optical images of the M82 starburst are tiled by the 2′ x 2′ MSA, and one 0.14″ x 0.086″ micro shutter matches well to the bright knots of emission. At right, the zoomed region from left has been rescaled to z = 0.2 to show how these clumps of interacting gas can be mapped at the sub-kiloparsec level of individual shutters.*

parsec-scale sizes in nearby galaxies and sub-kpc sizes at $z < 2$ (right panel of **Figure 6-6**), where the relevant diagnostics are still in the space UV. The ability to resolve gas flows at parsec to kiloparsec scales in the key UV diagnostics lines is a unique ability of a large UV-sensitive space telescope.

The resolved gas flows observing program (**Appendix B.11.4**) uses 75 hours with LUVOIR-A to map the M82 superwind as it propagates out from the galaxy at 300 (or more) different locations in the flow spread across 6 footprints of the microshutter array. At each position, LUMOS can detect emission in Lyα, O VI, C IV, or any other diagnostic line, measure the line kinematics relative to the optical lines (such as H-α) and to other UV lines, and estimate the gas mass, metallicity, and kinetic energy. Obtaining these kinds of richly detailed physical diagnostics at ~20 parsec spatial resolution is a transformative capability for the understanding of galactic winds driven by SNe and AGN.

Diffuse CGM, the faintest light in the universe. Ground-based IFU spectrographs such as VLT/MUSE and KCWI at Keck are pioneering the search for CGM gas emission at $z > 2$, where the relevant diagnostic lines pass into the visible bands (**Figure 6-2**). Gas reservoirs extending over hundreds of kpc appear to be illuminated by radiation from the stars and AGN in the galaxies (Cantalupo et al. 2014) and some large structures can be resolved (Martin et al. 2016). However, their spatial resolution corresponds to physical scales of > 10

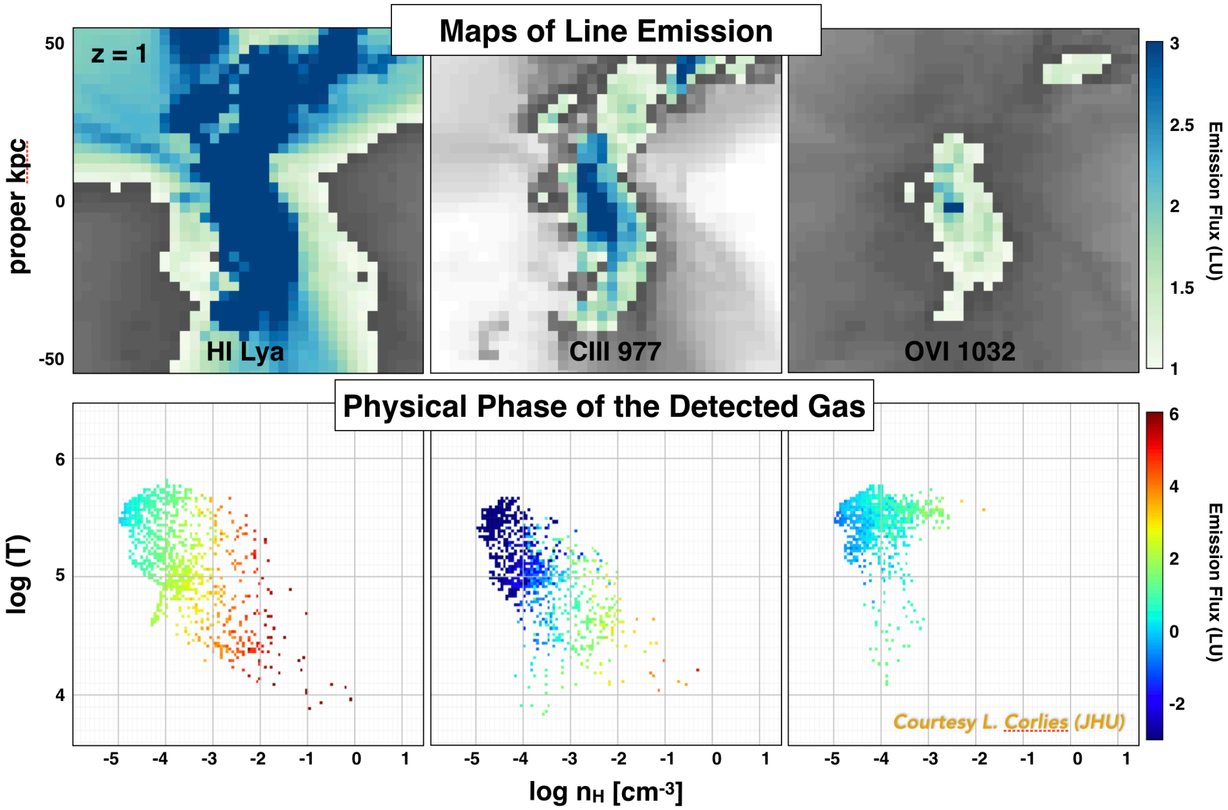


Figure 6-7. *A rendering of simulated CGM emission in three UV lines for a Milky-Way progenitor galaxy at z = 1. These lines range from 1000–1200Å in the rest frame, so they are uniquely visible in the UV at z < 2, or half of cosmic time. The 15-m LUVOIR will detect bright emission (blue/dark green regions) and resolve bright knots in the light green regions. Significantly smaller apertures will lack the sensitivity for all but the brightest knots, and will not resolve them even if they are detected. Credit: L. Corlies (LSST)*

kpc, and they are limited in sensitivity by bright and time-variable sky backgrounds that will make detection of the weaker metal lines difficult in individual halos. And most importantly, these instruments can access the most important UV diagnostic lines, usually Lyα, but only at z > 2, leaving most of cosmic time unexplored.

Using the same array of shutters binned into larger "virtual apertures," LUVOIR can also seek the extremely faint emission from the widely distributed diffuse CGM and structure within it. **Figure 6-7** shows such a hypothetical map from a new hydrodynamical simulation of a Milky Way progenitor galaxy at z = 1 (FOGGIE; Corlies et al. 2018). This diffuse gas will be challenging to detect even for LUVOIR, but appropriate integration times could be fitted in as parallels to the week-long exoplanet visits, for example. In deep LUMOS exposures, the structure of the CGM can be detected in multiple spectral lines, allowing observers to count up the heavy element content of this gas, to watch the flows as they are ejected and recycled, and to witness their fate when galaxies quench their star formation, all as a function of galaxy type and evolutionary state. LUVOIR could map galaxies in fields where deep imaging identifies filaments in the large-scale structure, and where ground-based ELTs have made deep redshift surveys to pinpoint the galactic structures and sources of metals to be seen in the CGM. Because this radiation is far weaker than local foreground radiation (S_B ~

100–1000 photons cm^{-2} s^{-1} sr^{-1}) ground-based telescopes seeking it at redshifts where it appears in the visible ($z > 2$) must perform extremely demanding sky foreground subtraction to reveal the faint underlying signal. These foregrounds are considerably lower from space (by factors of 10–100), shortening required exposure times by an equivalent factor. By binning up 0.5–1″ regions of the array (a few kpc at $z < 2$), LUMOS users can examine the large-scale distribution of the filaments and extended disks they feed, from the peak of cosmic star formation down to the present.

Galaxies undergoing quenching are the ideal laboratories to study the feedback that all galaxies experience: the galactic superwinds driven by supernovae and stellar radiation, the hot plasma ejected by black holes lurking in galactic centers, and the mergers that transform galaxy shapes while triggering the consumption or ejection of pre-existing gas. LUVOIR will have the collecting area to support deep, wide-field UV multi-object spectrograph (MOS) searches for CGM gas at the line emission fluxes that are expected, and with the spatial resolution to observe the transformation of star forming disks to passive spheroids at 50–100 pc spatial resolution and closely examine the influence of AGN on this process. For galaxies identified as quenching, emission maps of the surrounding CGM will determine the fate of the gas that galaxies must consume or eject and elucidate the physical mechanisms that trigger and then maintain quenching. Only a diffraction-limited space telescope with an aperture of at least 10–12 meters can achieve such spatial resolution in the optical and observe the rest-frame UV light necessary to witness the co-evolution of stars and gas in galaxies undergoing this transition.

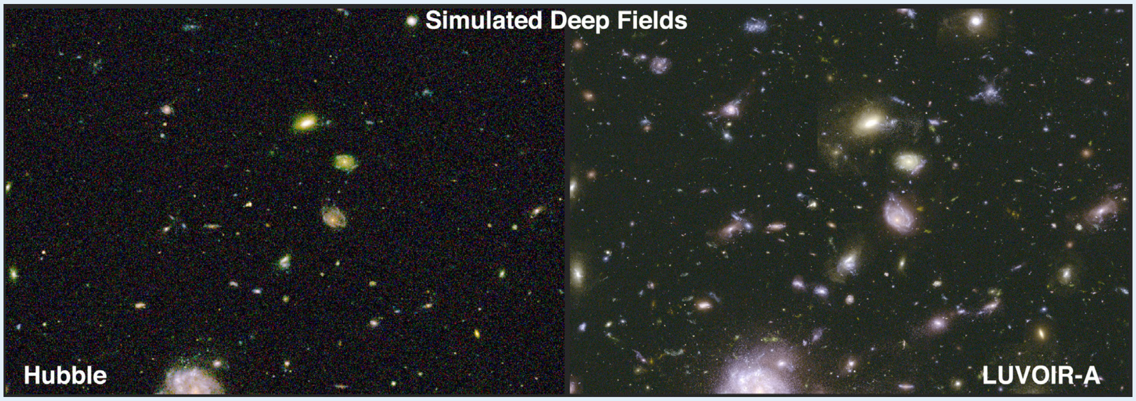
6.1.4 Gas flows with down-the-barrel spectroscopy

We can now consider the final steps in our view of galactic gas flows with LUVOIR: how CGM gas turns into ISM, and how ISM gas returns to the CGM. What drives the flows that transport mass from the CGM into galaxies, and then back? The inflows are driven primarily by gravity and cooling acting on and within gas that enters the halo in filaments, strips off satellites, or becomes thermally unstable while orbiting in the halo. Gas cooling and gravity are straightforward to implement in models and simulations, even if the emergent behavior they create is hard to simulate. “Feedback”—the general term for mass, momentum, and energy from stars and AGN that influence the course of galactic evolution—is far more complex, because the underlying physical mechanisms span a huge range of density, temperature, energy, and physical scales. “Feedback” flows such as supernovae and AGN winds originate on parsec scales, but propagate to hundreds of kiloparsecs while interacting energetically, hydrodynamically, and radiatively with everything they encounter, including current inflows and past generations of outflows.

Understanding how feedback operates physically to influence galaxies as they grow is an active and abiding challenge in the astrophysics of galaxies. Theoretical models of how flows develop and propagate for various sources and physical mechanisms, including winds and radiation pressure from main-sequence OB stars, the collective effects of correlated supernovae, and jets and winds from AGN. At their best these models make specific predictions for the mass and energy transport, velocity and acceleration profiles, and time evolution of these flows as a function of the source properties (e.g., Murray et al. 2011, Thompson et al. 2011). These trends are often then implemented as “subgrid” prescriptions in large-scale numerical simulations that attempt to recover realistic galaxy populations and internal

The LUVOIR Wide and Deep Fields

Since the original Hubble Deep Field (Williams et al. 1996), large-area surveys at the deepest limits have been a mainstay of galaxy evolution studies; the Ultra Deep Field, CANDELS, and the Frontier Fields have significantly advanced our understanding of galaxies. Much of LUVOIR's "Signature Science" will follow the same model, in which multiple scientific objectives are enabled by a single set of deep exposures over a large area.



The High Definition Imager (HDI) has a field-of view of 2 x 3 arcmin, Nyquist sampled by two focal plane arrays covering NUV/VIS and NIR wavelengths that view the same portion of the sky simultaneously. Detailed calculations show that HDI on LUVOIR-A will reach $5\text{-}\sigma$ photometric limits of AB = 33–33.5 mag for point sources in integrations of about 10 hours per band. The most basic "LUVOIR Deep Field" is a single field of view deep integration, much like Hubble's Ultra Deep Field (AB ~ 29; Beckwith et al. 2006) or Extreme Deep Field (Illingworth et al. 2013), with 10 bands taking about 100 hours of integration time to reach the limits in the table below. In the simulated view shown here, each panel (HST, LUVOIR-A) displays a field of view of 43″ x 30″. In terms of HDI's FOV, this scene shows only about 6% of a single HDI frame.

A LUVOIR "Wide" Field, inspired by Hubble's CANDELS program (Grogin et al. 2011), exploits LUVOIR's high mapping speed to cover 720 arcmin^2 in 120 tiled fields of view. If we limit this program to 1200 hours of integration time, or 10 hours per tile, 1 hour per band, the limits are AB ~ 31–32 mag, which surpasses Hubble's deepest limits by > 2 mag and matches JWST's deep limits.

These limits are unique to LUVOIR: not even 30-meter-class telescopes on the ground will reach such depths, owing to time-variable sky backgrounds. This capability enables LUVOIR to detect (1) single Sun-like stars (AB = 4.72) out to 5.5 Mpc; (2) a main sequence O star to 500 Mpc or redshift z~0.1, nearly the entire volume covered by the SDSS spectroscopic survey; and (3) a 0.001 L* galaxy at z=6, deep enough to detect the early seeds of galaxies like our own Milky Way. This is a broadly applicable capability that will advance many areas of science we contemplate as "Signature" for LUVOIR.

<table>
<tr><th colspan="11">The LUVOIR Deep Field: 6 arcmin² in 100 or 1000 hours</th></tr>
<tr><th></th><th>F225W</th><th>F275W</th><th>F336W</th><th>F475W</th><th>F606W</th><th>F775W</th><th>F850W</th><th>F125W</th><th>F160W</th><th>F220W</th></tr>
<tr><td>10 hr</td><td>33.0</td><td>33.2</td><td>33.5</td><td>33.6</td><td>33.4</td><td>33.0</td><td>32.6</td><td>33.2</td><td>33.0</td><td>29.7</td></tr>
<tr><td>100 hr</td><td>34.4</td><td>34.6</td><td>34.9</td><td>34.9</td><td>34.7</td><td>34.3</td><td>33.9</td><td>34.5</td><td>34.2</td><td>31.0</td></tr>
<tr><th colspan="11">The LUVOIR Wide Fields: 720 arcmin² in 1200 hours</th></tr>
<tr><td>10 hr</td><td>31.2</td><td>31.4</td><td>31.8</td><td>31.9</td><td>31.8</td><td>31.4</td><td>31.0</td><td>32.0</td><td>31.7</td><td>28.5</td></tr>
</table>

properties. These prescriptions are labeled "sub-grid" because they occur at sub-kiloparsec scales that cosmological simulations still cannot resolve.

Observers can test these physical models of feedback, but with a major limitation. Some bulk properties of galactic outflows can be revealed by spectroscopy that uses the driving sources themselves—whether AGN or star-forming regions—as background sources, in a so-called "down-the-barrel" spectrum. Inflow is detected as redshifted absorption and/or emission, while outflow is blueshifted. Often the observed profiles include absorption and emission from separate portions of the gas, which must be teased apart to reveal the details of the flow. The major limitation of current "down-the-barrel" measurements is that they typically cover most or all of a galaxy's disk, so the observed profiles average over a large number of individual sources, erasing the source-by-source variations in energy and mass that trace the key physical variables. Nevertheless, this technique has successfully demonstrated a correlation between gas velocity and, e.g., star formation rates (Martin 2005) and star formation surface density (Kornei et al. 2012), with galaxies with higher SFRs exhibiting higher outflow velocities. These signatures get stronger as the sightline approaches the galaxy's semi-minor axis, suggesting that the flows are biconical in shape and emerge up out of the disk (Bordoloi et al. 2014), as also seen in hydrodynamical simulations.

To resolve the physics at scales closer to the actual sources, astronomers using Hubble's COS instrument are making pioneering measurements of 16 individual clusters in the face-on nearby galaxy M83 (D = 4.6 Mpc). This program (Program 14681, PI Aloisi) is observing 16 UV-bright clusters across the face of M83, trying to map out the gas flows emerging from them individually. This program requires 40 orbits to execute, so doing 10 times as many clusters or a few galaxies would be a large or very large allocation of Hubble time.

Figure 6-8 shows the potential of the LUMOS multi-object mode to transcend these limitations and fully resolve these outflows. The resolved gas flows observing program (**Appendix B.11.4**) defines observations of 100 clusters in each of 10 nearby galaxies, obtaining a sample of 1000 different star-forming regions in a wide range of galactic environments in only 100 hours of exposure time. These observations will resolve the flows at the physical scales of individual star-forming regions (~ 100 pc), allowing us to correlate outflow properties with their driving sources in detail, rather than averaged over the whole disk. Outflows can be examined as a function of the star-formation region that produced them, as a test of specific predictions for how flow velocities and mass transfer rates depend on time and energy input (Murray et al. 2011, Thompson et al. 2005). As shown in **Figure 6-8**, each of these UV spectra will contain a wealth of information about the stellar cluster (age, metallicity, stellar winds), the absorption in the flow (mass loading rates, velocities), and emission from diffuse gas (radiative transfer, LyC escape).

Not only will LUMOS enable the dissection of flows at small scales, but the multiplexing of the microshutter arrays provides a huge efficiency gain that will enable maps of resolved flows for a wide range of galaxies in the nearby Universe. It is critical to understand the wind-expulsion history of galaxies as a function of mass, as the winds are likely critical for shaping the stellar mass-halo mass and mass-metallicity relationships of galaxies, which depend strongly on galaxy mass. This is best accomplished by high-SNR, high-resolution spectroscopy with broad UV wavelength coverage. The wavelength coverage, notably to wavelengths as short as λ~1000 Å, is critical. If we are to understand galaxy transformation

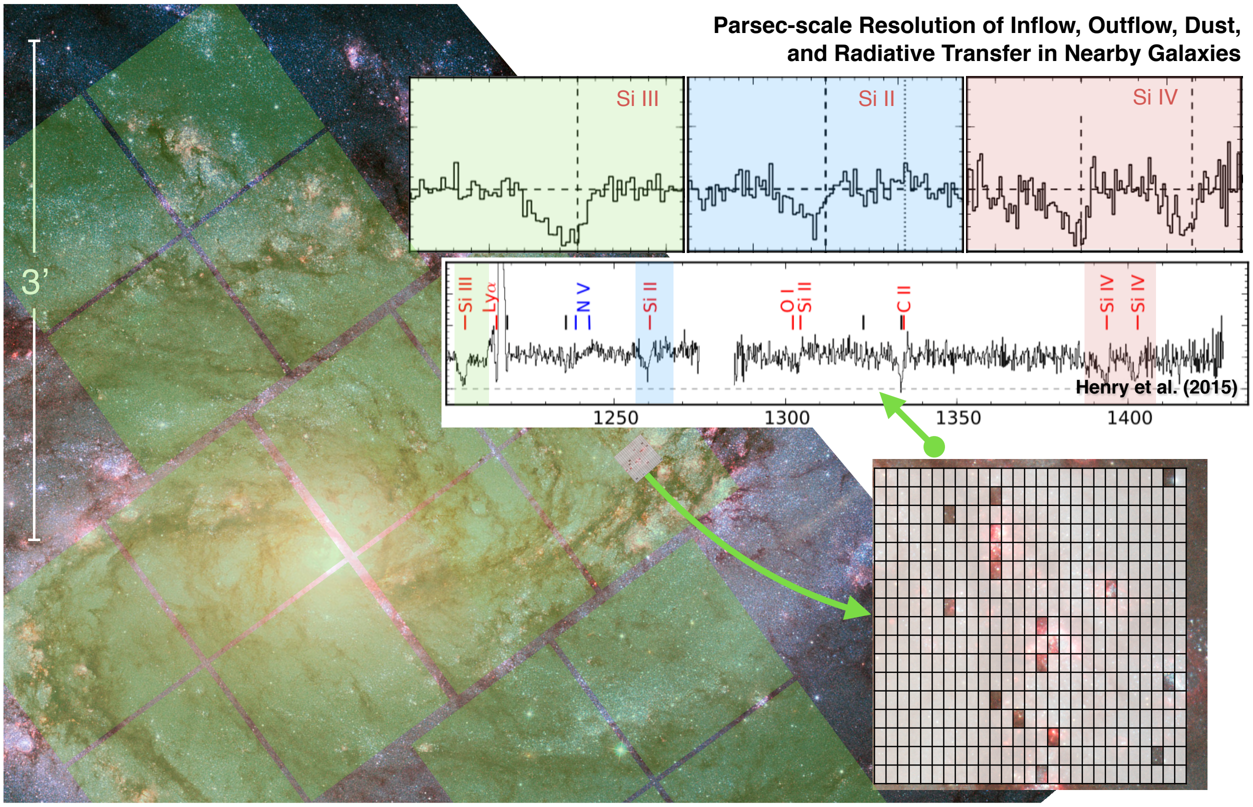


Figure 6-8. *LUMOS will perform intensive multi-object spectroscopy of star-forming regions, ISM gas, and galactic outflows in nearby galaxies. Here we have the footprint of the LUMOS multi-object mode overlaid on the nearby galaxy M83 at 4.6 Mpc. At this distance, the LUMOS micro shutters subtend 1.5–3 parsecs. At the top, we show three silicon lines that trace multiphase gas in outflows, as proxied by Hubble/COS spectra of low-z "green pea" galaxies by Henry et al. (2015). LUMOS users will be able to examine a wide range of ionization, metallicity, kinematics, and dust diagnostics down to 1–3 parsec scales at the positions of hundreds of individual stellar clusters and ISM simultaneously, and for many nearby galaxies in a single program.*

and the role that winds may play in it, the ability to observe these flows at the relevant small scales is needed.

6.2 Signature Science Case #11: The multiscale assembly of galaxies

Galaxy formation is a mutiscale process spanning at least seven orders of magnitude in mass and three in size that unfolds over the 13-billion-year sweep of cosmic time, yet galaxies follow orderly scaling relations between mass, size, star formation, and metal content. This remarkable regularity challenges our current theories and even our imaginations to understand how nature does it. Part of the story is that even the largest galaxies of today began as smaller seeds at the dawn of time, and gradually built up into massive giants by acquiring gas and merging with other galaxies. Along this "merger tree" path, galaxies grow by accreting gas and merging with their neighbors large and small. Some grow enough by forming stars and merging with their neighbors to become big galaxies with prominent bulges and massive disks hosting violently active black holes. Those that grow too big, too fast can "quench," ceasing to form stars and then evolving passively as their stars age. Other galaxies remain small, perhaps eventually merging into larger ones. Nature makes galaxies of these

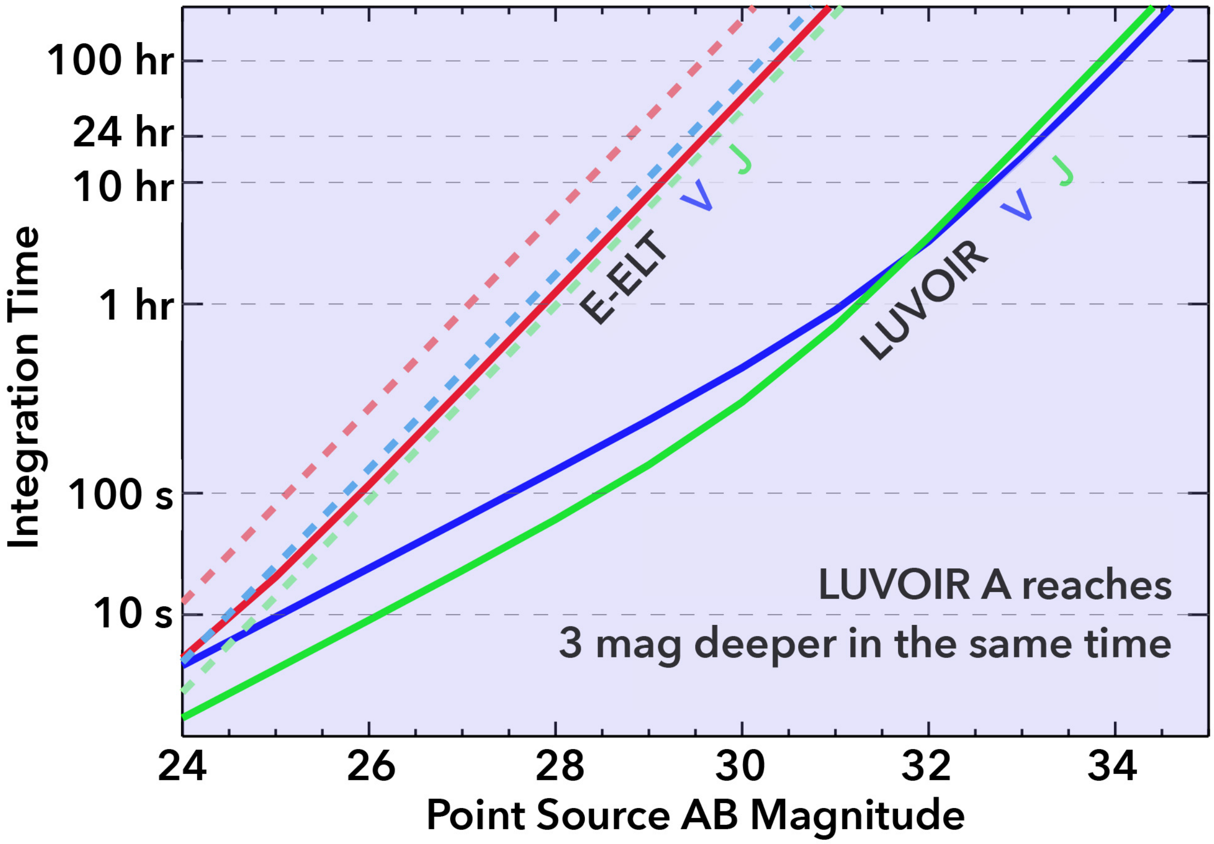


Figure 6-9. *Integration time required to achieve SNR = 10 for point-source photometry in three broad bands for the 15-m LUVOIR A (solid lines) and the 39-m E-ELT (dashed lines). If we take the 10-hour exposure as a nominal "large program" to which many nights or orbits would be devoted, LUVOIR reaches AB = 32.5 mag in V and J, 3.5 magnitudes deeper than E-ELT. The LUVOIR limits were derived from the HDI ETC available at luvoir.stsci.edu/hdi_etc.*

kinds and every type in between, and no theory of origins will be complete without a full understanding of how this happened. By reaching 33–34th magnitude, LUVOIR will detect the early building blocks of galaxies like the Milky Way and fill out the merger tree that leads to galaxies at the present time. It will also see inside galaxies to unprecedented limits, resolving their internal building blocks at < 100 pc scales to unravel the processes inside galaxies that drive their evolution.

Why will galaxy formation remain Signature Science in the era of LUVOIR, even after JWST and the ELTs? In short, none of these highly capable facilities will be able to achieve LUVOIR's unique combination of depth, resolution, and mapping efficiency. **Depth** allows us to see the smallest building blocks of galaxies (**Figure 6-9**). With enough **resolution** we can look inside galaxies at small physical scales, breaking down their formation at a level of detail that isolates the key physical processes. Finally, any observational insights must be backed by statistically significant samples collected with a high **mapping efficiency or speed**. Optimizing for these three figures of merit will enable LUVOIR's users to make revolutionary advances in the Signature Science of galaxy formation and evolution.

6.2.1 Galaxy assembly at the faint frontier

Pushing back the "faint frontier" has been a constant theme of galaxy formation from the earliest days, through the Hubble Deep Field, and into the present. LUVOIR will expand the faint frontier to the smallest relevant scales over nearly the whole of cosmic time. In the modern universe, galaxies occupy an enormous range of mass from "giant ellipticals" at $M^* > 10^{12}\ M_\odot$ to "ultra-faints" at $M^* < 10^4\ M_\odot$. In the prevailing hierarchal paradigm, all galaxies of any substantial size grow from the steady accumulation of gas and by the successive mergers of many smaller galactic components in a "merger tree." Every giant galaxy has many dwarfs in its past; our own Milky Way has evidently accumulated many such dwarfs over its history. Within the next few hundred million years, it will acquire its two Magellanic Clouds in a "minor merger" with an even more dramatic major merger with Andromeda to follow. Telling the full story of galaxy formation starts with being able to work backwards through this tree of galactic origins to see the roots, and this requires pushing back the faint frontier.

The brightest galaxies at any redshift will tend to be the seeds of the brightest galaxies at any later time. The galaxies we see at the dawn of time with Hubble, and soon with JWST, are not the earliest seeds of galaxies like our Milky Way. While we can probably reach Milky Way-like progenitors as far back as $z = 6$ with JWST (Okrochkov & Tumlinson 2010), what we see will be the main trunk of the tree, not the hundreds of other branches that existed at that time. But what is the minimum threshold for galaxy formation that LUVOIR should try to reach?

The faint frontier expanded in an unexpected direction with the discovery of "ultra-faint dwarf" (UFD) galaxies in the halo of the Milky Way. These galaxies are gravitationally bound but possess only $\sim 10^5\ M_\odot$ of stars, or even less, with characteristic radii of only 100–300 parsecs. They were detected as slight over-densities in the all-sky star map produced the Sloan Digital Sky Survey (Willman et al. 2005). The UFDs are now believed to be the ancient "fossils" of tiny galaxies that formed 80–90% of their stars before or during the epoch of reionization (Ricotti & Gnedin 2005; Brown et al. 2012; Weisz et al. 2014), like those first galaxies that preceded our own Milky Way. If so, then the ultimate "faint frontier" lies where we can detect the UFD scale over the full sweep of cosmic time.

We demonstrate the power LUVOIR will bring to such a study by deriving the plausible mass limits reached as a function of redshift in a single very deep exposure. **Figure 6-10** shows the stellar mass range that defines the "dwarf" populations of galaxies, with the UFDs at the minimum threshold (as we currently know it). The figure also shows the limits achievable by telescopes of varying size, including Hubble, JWST, and the two LUVOIR architectures. The High Definition Imager will enable LUVOIR users to reach the extreme low mass end ($M_* < 150\ M_\odot$) of the halo mass function at many redshifts in a deep survey (AB ~ 33–34) and wider surveys of 10^6–$10^7\ M_\odot$ systems in much shorter exposures.

Only LUVOIR will be able to detect galaxies at the scale of the Ultra-Faints when they are still forming stars. This capability will reveal the entire grand sweep of galaxy formation to the earliest times, permitting full reconstruction of mass functions and merger trees. LUVOIR will also be able to trace the relationships between massive galaxies and their faintest satellites, which respond to details of the gas and star formation physics in complex ways that are still poorly understood. LUVOIR can, for instance, probe the relationship between L* galaxies and their faintest satellites, looking for evidence of when and how dwarf

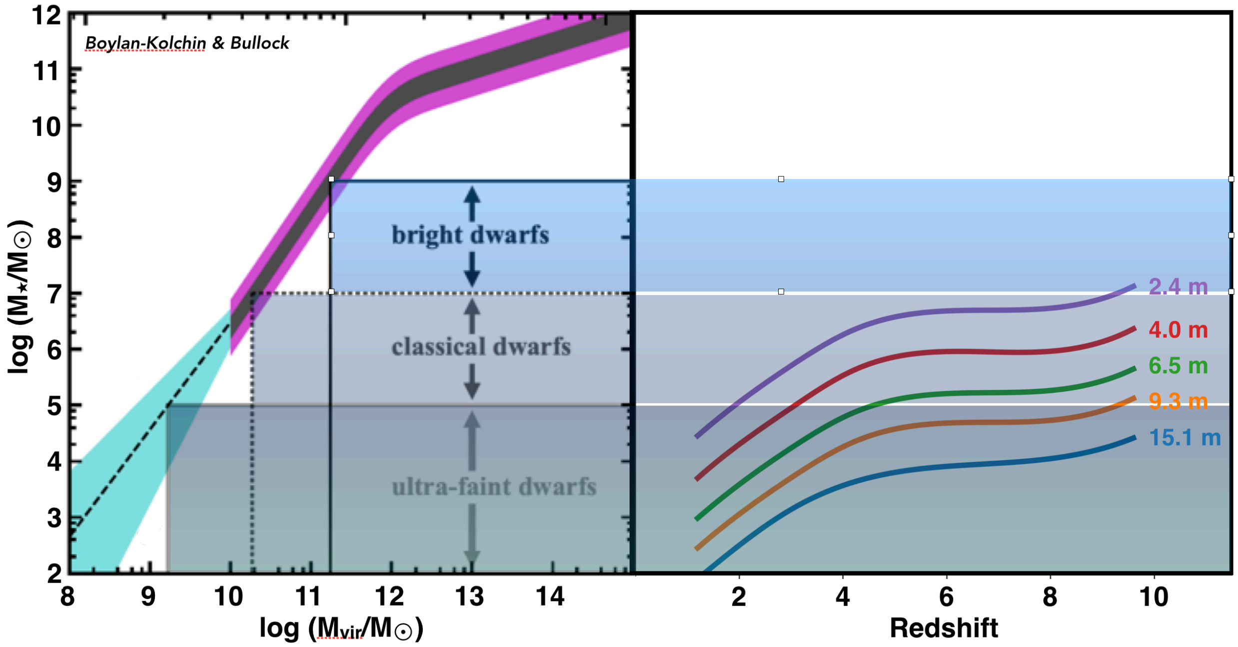


Figure 6-10. *LUVOIR pushes back the "faint frontier." At left, the stellar-to-dark matter ratio as a function of virial mass from Boylan-Kolchin & Bullock. Three stellar mass ranges for dwarf galaxies are shown. At right, the limits for detection by five observatories in a 500 ksec observations, assuming an extended source 200 pc in size and SNR = 5. LUVOIR's Architecture A can reach the UFD scale out to redshift z ~ 10.*

galaxies can be quenched by their larger, quenched neighbors ("conformal quenching") and for indications that galaxies at the UFD scale continue to form stars after reionization.

6.2.2 Seeing inside galaxies as they form and transform

Using Hubble, astronomers have surveyed large samples of galaxies during the rise and fall of cosmic star formation (Madau & Dickinson 2014). These studies have mapped out the relationship between stellar mass and star formation rate (Whitaker et al. 2012), and traced the rise of quenched galaxies on the "red sequence" almost back to its beginnings (Kriek et al. 2009). Perhaps the greatest surprise from this work is how small galaxies appear to be at early times. The red sequence is already identifiable at z ~ 2–3, but with most of its quenched galaxies occupying only a few kpc in size. Indeed, star forming galaxies at these redshifts average several times larger than passive galaxies at the same mass. How do these galaxies quench, and do they get smaller as they do?

Hubble itself has struggled to address what happens inside galaxies at these early times because its diffraction limit corresponds to physical scales of 300-400 pc at z = 2-3. Hubble images place only a few pixels across these small yet massive galaxies at high redshift. This is sufficient to marginally resolve galaxy disks, but not the smaller-scale processes at work within them. It is also sufficient to detect ~1 kpc star-forming clumps (Elmegreen et al. 2007, 2009; Forster Schreiber et al. 2011), but large clumps may be blended collections of smaller star-forming regions (Tamburello et al. 2017; Rigby et al. 2017; Bordoloi et al. 2016), even if the clumps are like the largest and brightest in our immediate neighborhood, 30 Doradus in the LMC (diameter d~200 pc) and the Carina Nebula (d~140 pc).

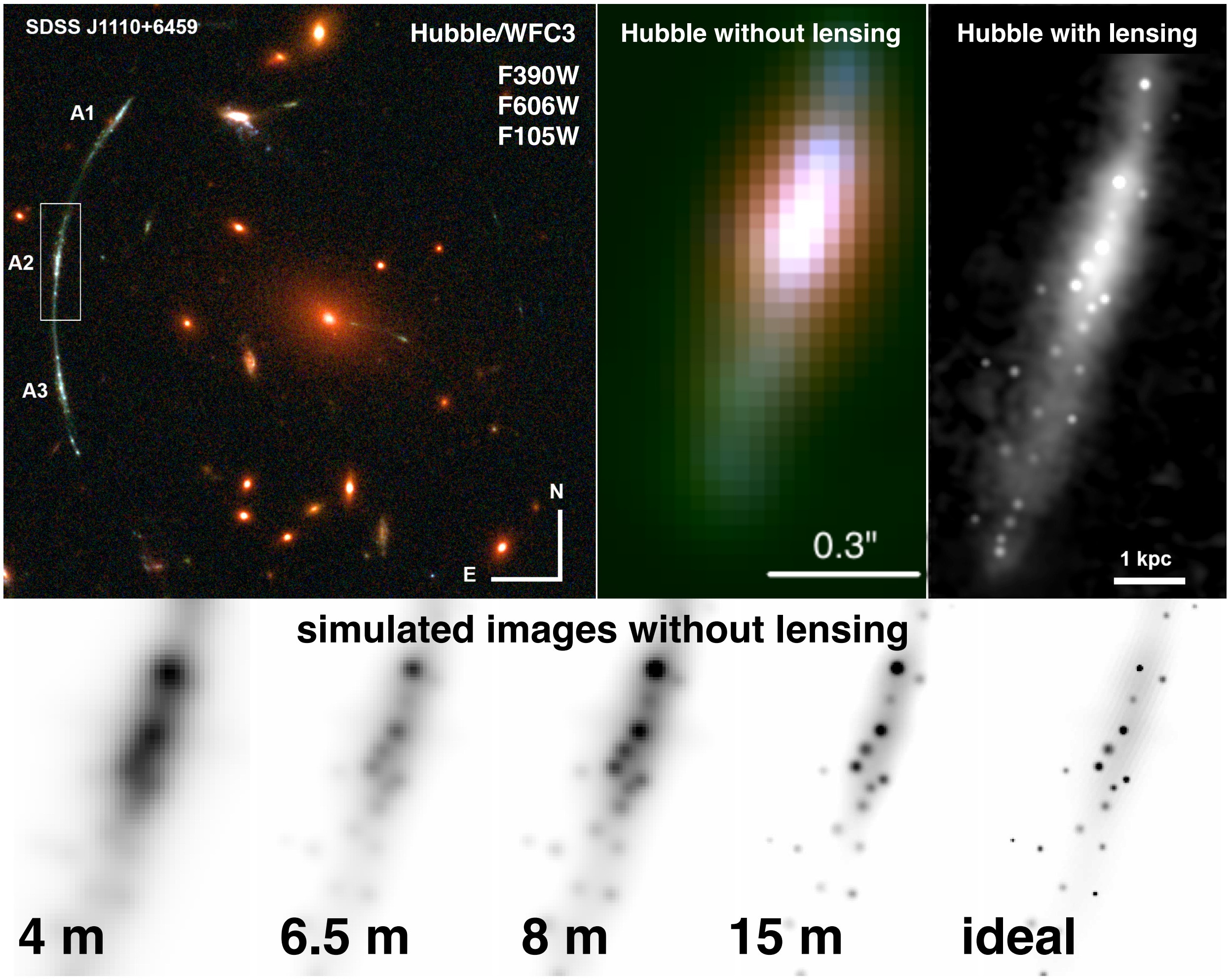


Figure 6-11. *LUVOIR would image distant galaxies with extremely high spatial resolution, in ways that at present are only available via fortuitous gravitational lensing. To LUVOIR, any distant galaxy appears as sharp as the best lensed galaxies with Hubble. A gravitationally lensed galaxy at z = 2.481 seen by Hubble/WFC3 (top left panel) reveals dozens of star-forming regions with radii of ~ 40 pc (top right panel). The top middle panel shows that Hubble could not resolve any of these clumps were this galaxy not lensed. The bottom panels simulate how this galaxy, were it not lensed, would appear to a large space telescope of varying size, scaling from the Hubble PSF. The simulated images show that an 8- to 15-m space telescope resolves, for an unlensed galaxy, all the structure that can be seen by Hubble with the benefits of magnification by lensing. Adapted from Johnson et al. (2017b) and Rigby et al. (2017).*

We know that galaxies have structure on 100 pc scales because of evidence from the few cases where natural gravitational telescopes are provided by foreground galaxy clusters. In these rare cases, Hubble probes individual star-forming regions in ways that illustrate the power of LUVOIR. **Figure 6-11** shows an example, where Hubble reveals two dozen star-forming clumps in a lensed galaxy, with radii of 30–50 pc. These clumps have the sizes and luminosities of the brightest star-forming regions in the nearby universe, and none would be resolvable with Hubble without lensing. The lensing reconstruction of this lensed galaxy provides a rare “truth image” of what distant star-forming galaxies actually look like. Convolving this truth image with the scaled empirical Hubble PSF shows which features

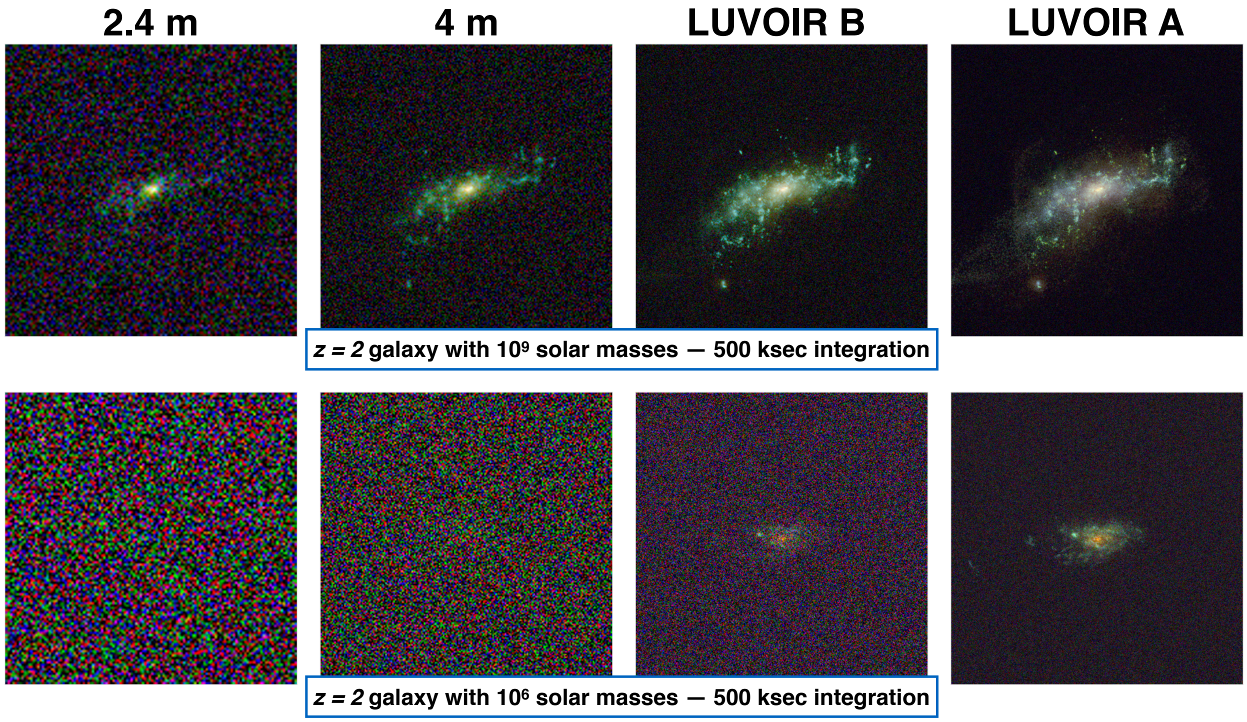


Figure 6-12. *Simulated galaxies showing the rich interior detail that is visible in deep exposures with telescopes of varying size. In all cases we assume extremely deep 500 ksec exposures of the* 10^9 $M_\odot$ *galaxy at the top and* 10^6 $M_\odot$ *galaxy at the bottom. Credit: G. Snyder and M. Postman (STScI)*

LUVOIR can recover, as a function of aperture. LUVOIR's users will be able to recover almost all the star-forming clumps in the F390W filter. This simulation shows that for a sufficiently large LUVOIR (at least ~ 8 m), any distant galaxy can be imaged with the sharpness that Hubble can now achieve for the most favorable gravitationally lensed systems, which cover only a tiny fraction of the sky. LUVOIR would therefore be able to survey star formation down to 100 pc scales for thousands of galaxies, which is terra incognita.

To illustrate the power and efficiency of LUVOIR for seeing the internal structures in galaxies at 100 pc scales, we have shown the scaling of galaxy images in LUVOIR "deep fields" as defined in **Chapter 5**. These "deep images" are seen in **Figure 6-12**, where even individual star forming regions are visible in the simulated LUVOIR-A image. These images correspond to the deep field program for Signature Science Case #9 (**Appendix B.10.2**). To illustrate the power and efficiency of LUVOIR for broader wavelength coverage, we also define a shallower addition of B and V bands to the deep I, J, H band images from Signature Science Case #9. These images will map the star-forming regions of thousands of z~2 galaxies in rest-frame UV light, for a total of only 13 additional hours with LUVOIR-A.

Galaxy death, or quenching and compactification. The mystery of how galaxies "die"—or cease to form stars at any significant level—is one of the most abiding in astrophysics. Edwin Hubble's original tuning fork (1926) captured the basic truth that some galaxies are "disky," blue, and star-forming, while others are spherical, redder, and quiescent. Numerous complex and overlapping mechanisms from stellar feedback to AGN and mergers have been proposed to turn star-forming galaxies into quenched ones, but there is still no definitive physical understanding of this basic phenomenon.

The presence of fully quenched galaxies at high redshifts $z > 2$ is surprising enough, but even more so are the extremely compact sizes of many of these galaxies. “Ultra-compact” galaxies pack a Milky Way’s worth of stars, $10^{11}\ M_\odot$ or more, into a kiloparsec or less. These galaxies are only marginally resolved by Hubble, with > 50% of their total light falling onto just one or a few pixels. Yet these galaxies are possibly the earliest progenitors of today’s massive ellipticals, and if so they are a key part of the galaxy formation puzzle.

To unravel the origins of these mysterious galaxies, we must be able to resolve their internal structures, to measure stellar content and ages of their stellar populations, to look for internal gradients in age, to follow internal dynamics, and to trace all these quantities over time as this population arises. This is Signature Science for LUVOIR owing to its exquisite spatial resolution, 100 pc or better at all redshifts, which will allow us to map the internal structures and permit age dating of stellar populations at small scales. LUVOIR’s broad UV/optical coverage and collecting area are also essential to this problem: rest-frame UV and optical colors are much more sensitive indicators of population age than are the optical / IR colors available with JWST. LUVOIR will surpass JWST in terms of both physical resolution and the diagnostics that can be applied at that resolution. The same is true of ground-based telescopes, which will exceed LUVOIR’s raw spatial resolution with extreme NIR extreme AO, but will struggle to reach the same depths and cannot see rest-UV star formation diagnostics at $z > 2$.

6.2.3 Galaxies and their black holes

Supermassive black holes (SMBHs) reside at the centers of virtually all massive galaxies. The black hole masses are well-correlated with large-scale properties of their host galaxies, indicating that the SMBHs and host galaxies co-evolve. During some phases of galaxies evolution the energy feedback from the black hole might dominate the galaxy’s gas accretion and star formation and ultimately quench both. Understanding the distribution of SMBH masses over cosmic time is thus a key to understanding the evolution of galaxies.

SMBH masses can be estimated from spectroscopy using the “reverberation mapping” technique, which requires high-SNR, multi-epoch spectroscopy and can be done only when the SMBH is in an actively accreting (AGN) state. Masses can also be obtained by observing the dynamical effects of the SMBH on stars within a few tens of parsecs, so called dynamical masses. This technique can work even in galaxies with quiescent nuclei, but it requires measuring stellar velocities dispersions in the small region of influence where stellar orbits are affected by the SMBH. This requirement for high spatial resolution has severely limited the number of galaxies for which the SMBH masses can measured.

Figure 6-13 shows SMBH masses as a function of angular size distance for both quiescent galaxies (red open circles) with SMBH masses based on stellar dynamics and other techniques, and AGNs (black filled circles) with SMBH masses from reverberation mapping. The diagonal lines indicate the minimum black hole mass for a resolvable black hole radius of influence as a function of luminosity for several telescopes, including LUVOIR-A and LUVOIR-B. The goal of this project is to use LUMOS data to model the nuclear stellar dynamics to determine the SMBH masses of both quiescent and active galaxies for which the radius of influence is resolved.

Ground-based ELTs *may* be able to measure dynamical SMBH masses in quiescent galaxies, where their high spatial resolution will allow them to work close to the nucleus.

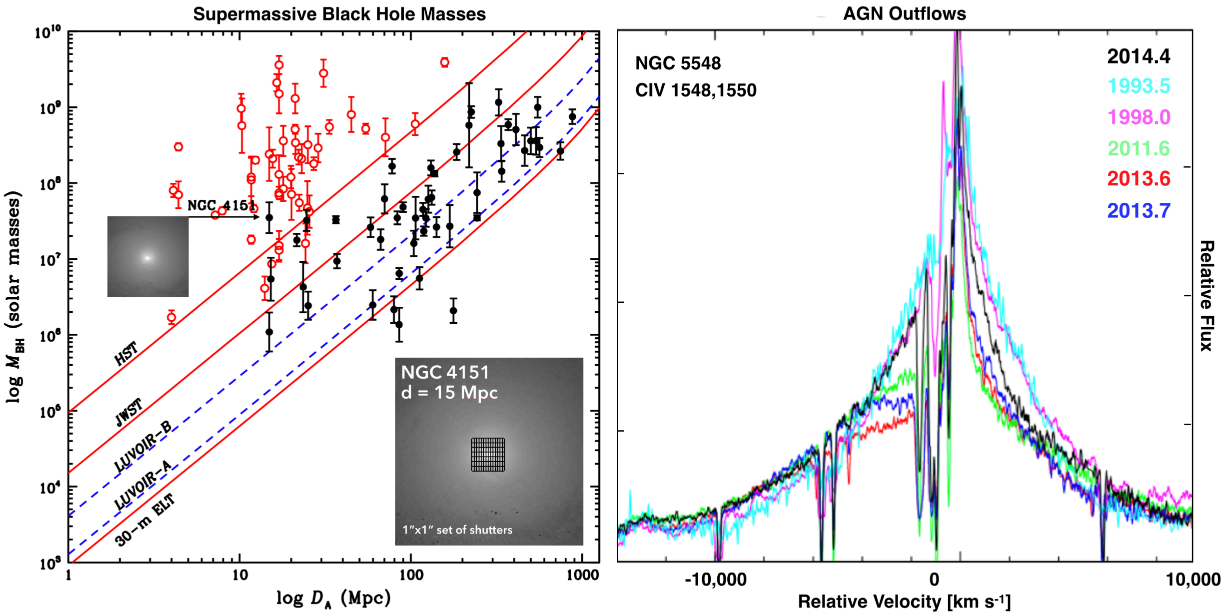


Figure 6-13. *AGN science with LUVOIR. At left, SMBH masses as a function of angular size distance for quiescent galaxies (red open circles) and AGNs (black filled circles). The minimum mass for which the black hole radius of influence is resolvable is shown for several telescopes, including LUVOIR-A and LUVOIR-B. Performing the experiment at the larger distances is required measure the stellar dynamical masses in the most massive AGNs (toward the right side). At right, time varying UV spectra from three different Hubble Space Telescope instruments that trace AGN outflows as a source of galaxy-wide feedback over 20 years. LUVOIR will expand this capability to fainter AGN and higher redshifts.*

However, this will require adaptive optics (AO) for the telescope to operate at the diffraction limit and will require guide stars in the field of view, which limits observations with the current largest ground based telescopes to about 20% of the available bright galaxies. However, it is unlikely that ELTs will be able to measure dynamical masses for SMBHs in luminous AGN, because at their expected Strehl ratios (even with AO) the scattered nuclear light will outshine the starlight.

The high angular resolution of LUVOIR/LUMOS enables measurements of the masses of both very large (more than a billion solar masses) and very low (less than a million solar masses) SMBHs in both active and quiescent galactic nuclei. LUVOIR's PSF is smaller and the LUMOS focal-plane microshutters on the nucleus can be closed, thus providing a crude coronagraph. As seen in the figure, it will be possible to measure stellar dynamical masses for the most massive (greater than 10^9 solar masses) and luminous AGN.

The spectra of active galactic nuclei (AGNs) show strong, broad absorption features in the blueshifted wings of the resonance emission lines, revealing massive, high-velocity outflows of gas. It is widely believed that these outflows, by transferring energy and momentum to the host galaxy interstellar medium (ISM), are agents in quenching star-formation by heating or completely removing the ISM. This is a favored explanation for both the steep cutoff at the bright end of the galaxy luminosity function and the tight correlation between the masses of the central black holes and larger-scale properties of the host galaxies. However, the role of AGN outflows remains largely speculative without more accurate determination of the kinetic luminosity and momentum flux of the outflows. This requires repeated measurements of the physical properties of the outflows, which requires high SNR UV spectroscopy and detailed modeling.

For local AGNs, the timescales for changes in these outflows are short, weeks to months (e.g., Kaastra et al. 2014; **Figure 6-13**. Recent observations associate these outflows with accretion disk winds that are apparently triggered by increases in the AGN luminosity which is in turn driven by an increase in the accretion rate (e.g., Kriss et al. 2019). The role of these outflows in galaxy evolution remains elusive, and the key to resolving remaining ambiguity is tracing their evolution over timescales much longer than the dynamical timescales.

Just as argued above for diffuse gas around galaxies, UV wavelengths are critical to probe these AGN outflows. The most important broad absorption features—the hydrogen Lyman series, O VI 1032, 1038 Å, N V 1239, 1243 Å, Si IV 11394, 1403 Å, and C IV 1548, 1551 Å (**Figure 6-13**)—are all in the rest-frame UV, and are currently best studied in local systems where the dynamical timescales are short and it is possible to obtain high SNR spectra in a short amount of time with LUMOS. With LUVOIR, it will be possible to obtain high-quality spectra not only of nearby AGNs, but of fainter, higher-redshift AGNs as well. Over the redshift range $0.2 < z < 2.0$, highly ionized species such as Ne VII 770, 780 Å, Mg X 610, 625 Å, and Si XII 499, 521Å become observable with LUMOS, enabling studies of gas that is currently observable only in X-rays.

6.2.4 Dissecting galaxies one star at a time

Our ability to determine when galaxies assemble their stellar populations, and how that process depends on environment is a fundamental component to any robust theory of galaxy formation. By definition, the dwarf galaxies we see today are not the same as the dwarf galaxies and proto-galaxies that were disrupted during assembly. Our only insight into those disrupted building blocks comes from sifting through the resolved field populations of the surviving giant galaxies to reconstruct the star-formation history, chemical evolution, and kinematics of their various structures (Brown et al. 2010). Resolved stellar populations are cosmic clocks and assay meters that can assess the age and metallicity of their galaxies using well-defined relationships obeyed by stellar luminosity and color. Their most direct and accurate age diagnostic comes from resolving both the dwarf and giant stars, including the main sequence turnoff. As demonstrated by the Panchromatic Hubble Andromeda Treasury program (Dalcanton et al. 2012), fitting stellar evolution models to color-magnitude diagrams (CMDs) can reveal how episodic star formation is and how it varies across the disk. (e.g., Williams et al. 2014). This work highlights both the need for the survey depth required to obtain a CMD accurate enough to differentiate between models and the ability to map across as much of a galaxy as possible.

Unfortunately, the main sequence turnoff is too faint to detect with any existing telescope for galaxies beyond the Local Group, and beyond this the increasingly severe effects of crowding become an even more fundamental limit. Both effects greatly hinder our ability to infer much about the details of galactic assembly because the galaxies in the Local Group are not representative of the galaxy population at large. LUVOIR will transform our ability to determine stellar histories by leveraging both light gathering power and spatial resolution, extending our reach beyond the Local Group to a more diverse sample of galaxies.

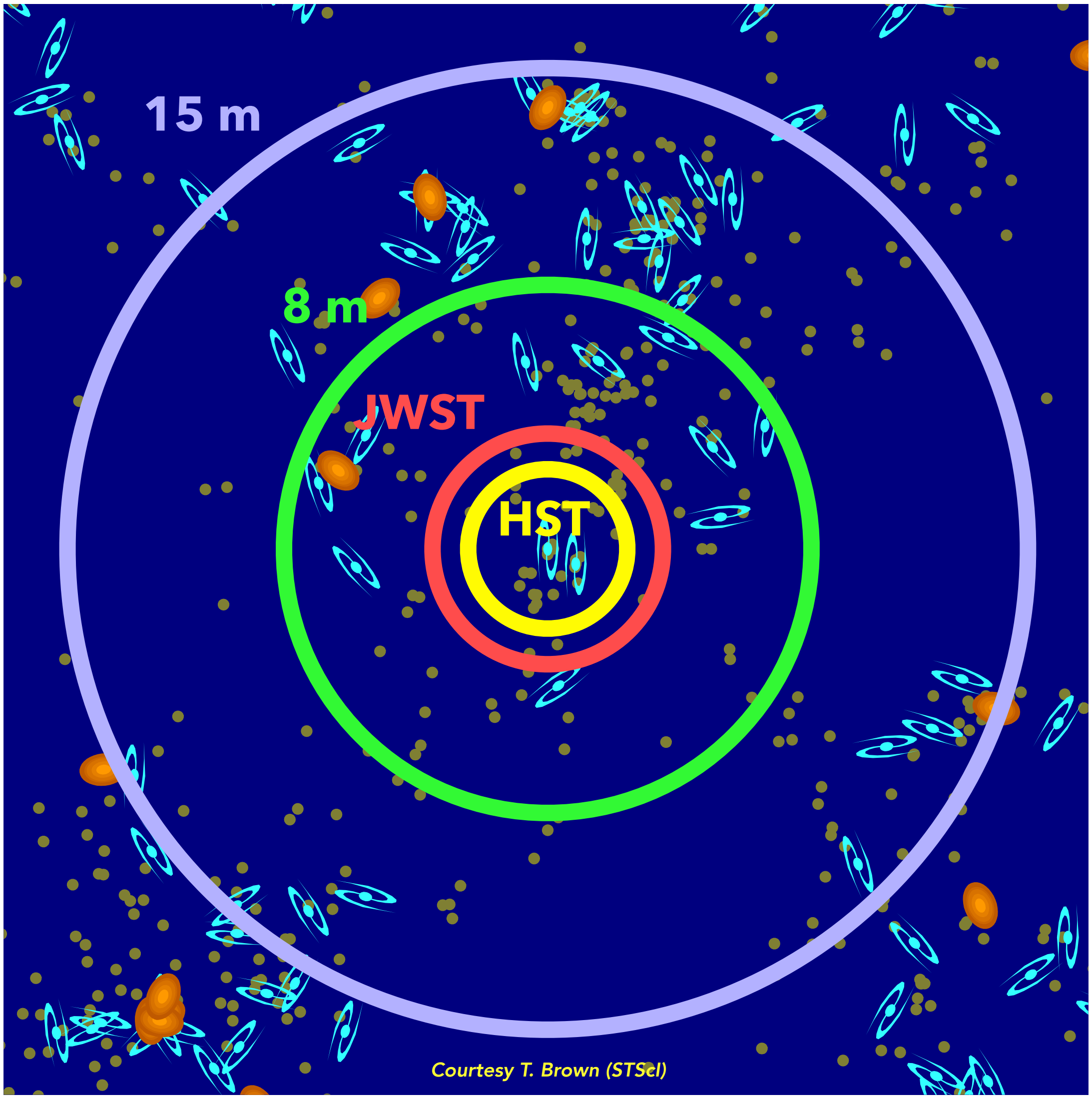


Figure 6-14. *Map of local universe (24 Mpc across) shown with the distances out to which HST (yellow), JWST (red), and LUVOIR (8-m, 15-m, green and violet), can detect the main sequence turnoff from a CMD in V and I passbands at SNR=5 in 100 hours. Giant spirals, like M31, are indicated by the blue galaxy symbols, giant ellipticals as orange blobs, and dwarf galaxies as small green dots. Derived using the HDI exposure time calculator at* luvoir.stsci.edu/hdi_etc.

We consider two types of surveys by way of example (**Appendix B.12.4**). First, we consider the distances that can be reached for characterization of diffuse (i.e., non-crowded) stellar populations in nearby galaxies. **Figure 6-14** shows a map of the local Universe with galaxies in their actual positions and marked by type. This observing program plans to reach stars at the main-sequence turnoff (MSTO) to age-date the star formation histories of eight ≥ L* galaxies in the local neighborhood. For LUVOIR-A, the sample includes six ~L* galaxies, two of which are early-type, for a total of 407 exposure hours. For LUVOIR-B we have defined a less ambitious sample of four L* galaxies, of which only one is early-type, for a total of 467 hours. LUVOIR-B would require more than 2000 hours to observe all eight of the galaxies in the LUVOIR-A sample. Both samples reach the MSTO at AB ~ 33–34, extremely deep observations beyond the reach of even JWST or 30m ground-based telescopes. For diffuse populations, this capability could also be used to probe faint dwarfs or age-date the outer regions of massive galaxies. At closer distances, these observations can be collected over time to build up the timeline of proper motion and work out galaxy motions in 3D (see **Chapter 5**).

For a second type of survey, we consider regions where crowding comes into play. LUVOIR's spatial resolution will enable usable photometry at much higher stellar densities than smaller telescopes. The PHAT program has empirically determined that usably accurate photometry can be obtained in UVOIR images up to a surface density of ~15 stars per square arcsecond with Hubble. Scaling this limit up by D^{-2}, we find that LUVOIR-A could detect the main sequence turnoff out to 5 Mpc, working with up to 400 stars per square arcsecond before crowding becomes prohibitive (**Figure 6-15**).

LUVOIR will work in concert with 30-m-class ground-based telescopes expanding our reach to other well-populated galaxy groups, with LUVOIR obtaining photometry of G dwarf stars down to V~34 mag, and the ground obtaining kinematics of much brighter giants out to the Coma Sculptor Cloud. The dwarf stars in the Coma Sculptor Cloud are effectively inaccessible from the ground, requiring gigaseconds of integration even for an isolated star. This capability for studies of resolved and semi-resolved stellar populations has a wide range of applications from mapping the history of star formation in galaxies to assessing the impact or reionization at the smallest scales.

6.3 Signature Science Case #12: Stars as the engines of galactic feedback

Finally we arrive at the most numerous sources of feedback on galaxies—the stars themselves. Stars, particularly massive stars, return energetic radiation to their environments throughout their lives, and then substantial amounts of kinetic energy and heavy elements when they explode as supernovae. With its high spatial resolution and uniquely powerful UV spectroscopy, LUVOIR will make fundamental contributions to the study of massive stars.

Stars form from the fragmentation of the dense parts of molecular clouds, in regions referred to as "cores." For all the simplicity of this description, significant challenges remain for a quantitative formulation of star formation. The relation between cores and stars is still matter of debate, as is the origin of the distribution of stellar birth masses (the stellar initial mass function, or IMF), the influence of the surrounding environment, and the effects of early dynamical evolution.

The reasons for these debates are the significant observational challenges faced by measurements of the relevant quantities (cores and stars at different stages of formation and early evolution), and the fact that *we do not have a predictive theory covering all stages of star formation*. Extant models are able to describe individual observational results, but not link them.

Without a theory, we cannot unequivocally interpret the observations of resolved or unresolved stars; and without unambiguous measurements, we cannot formulate a theory. In order to break this circular ambiguity, we need to perform unambiguous measurements of the early stages of star formation and the stellar IMF in a vast range of environments and parent galaxy properties, to guide models and finally achieve one of the key goals of modern astrophysics: a theory of "how stars form."

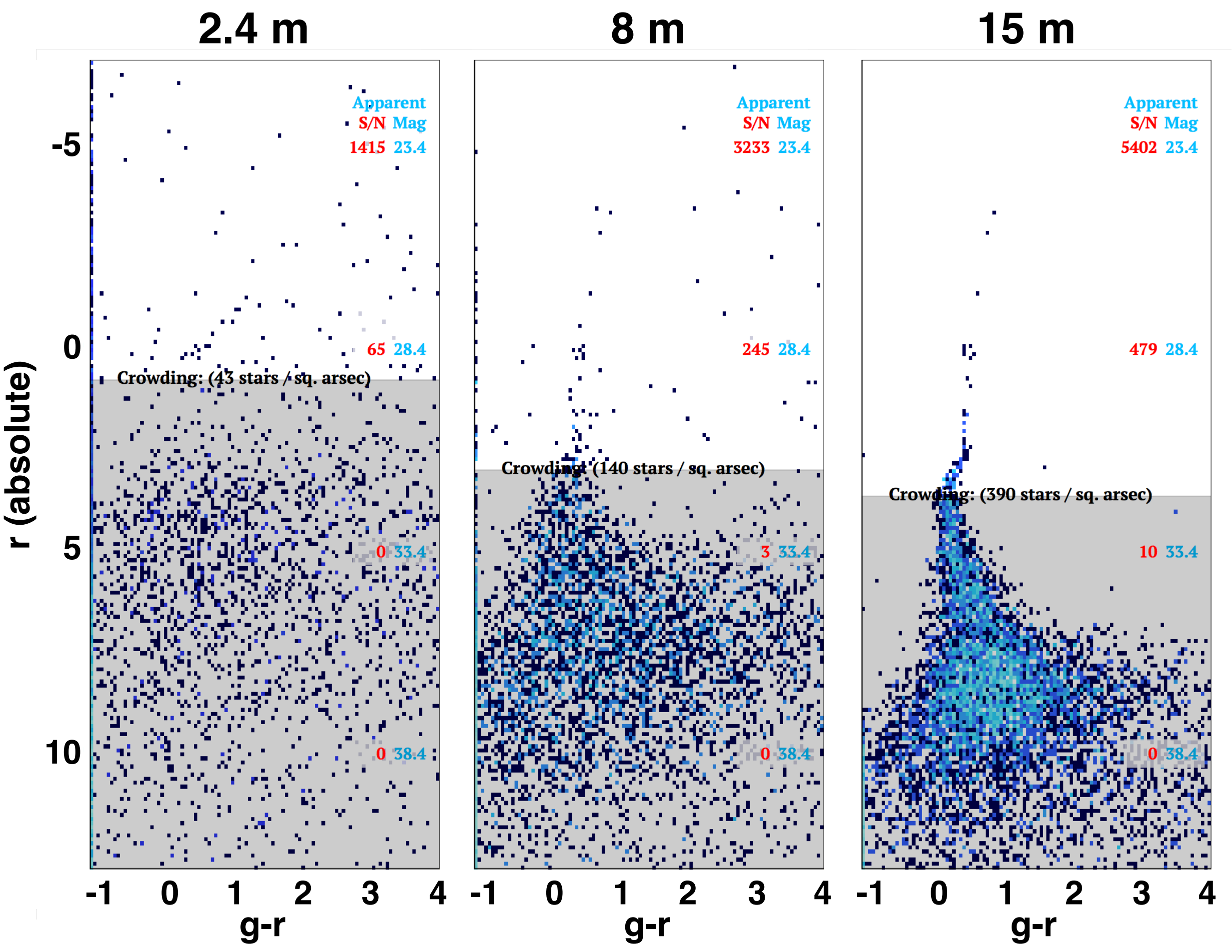


Figure 6-15. *Simulated CMDs for a single-age solar-metallicity population. The simulation uses a 10 Gyr-old isochrone from FSPS (Conroy et al.), placed at 5 Mpc and "observed" in 50 hours each in the g and r bands. To compute the crowding limit, we assume AB = 23 / arcsec^2. The Hubble / WFIRST analogue (2.4 meters) cannot overcome crowding and poor photometry. The 8-m LUVOIR can resolve the giant branch before crowding becomes too severe at the sub-giants. The 15-m LUVOIR can reach to the top of the main sequence to apply age and metallicity diagnostics. These figures were made with the LUVOIR CMD simulation tool at luvoir.stsci.edu/cmd.*

Accomplishing the characterization and quantification of star formation and the stellar IMF will require the synergistic combination of observations from a broad wavelength range, UV to millimeter. This combination is partially offered by current (Hubble, ALMA, VLT, etc.), upcoming (JWST), and planned (30m-class ground-based telescopes) facilities. Among the capabilities that are neither available nor planned, and which will be required to accomplish the overarching goal of formulating a theory of star formation, are:

1. Angular resolution for imaging: 0.007″ at 500 nm (**Figure 6-16** and **Figure 6-17**), with stable point spread function (PSF) and stable astrometry across the entire field of view (FoV).
2. UV and optical imaging spectroscopy over 1′–3′ FoV, with 0.01″–0.02″ angular resolution.

High-

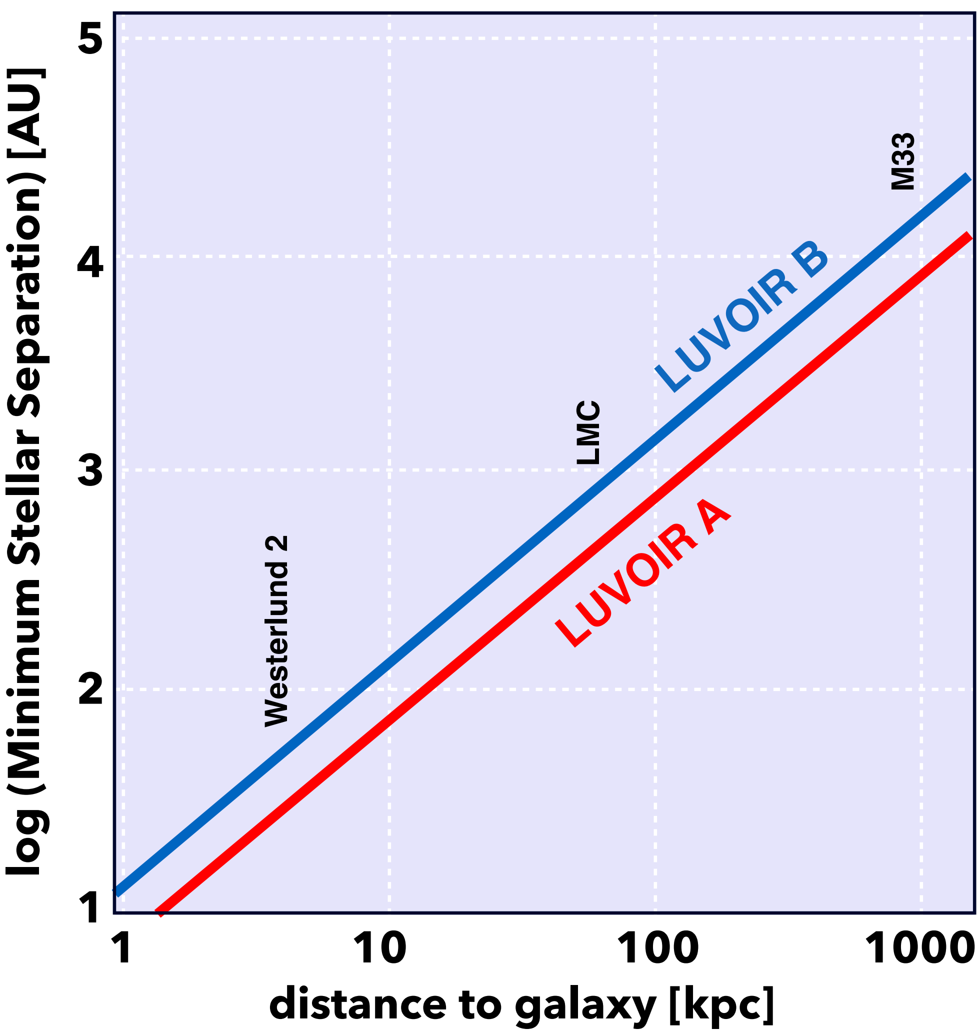


Figure 6-16. *The resolvable separation, in AU, between two stars as a function of distance of the stars from us, for both LUVOIR-A (red line) and LUVOIR-B (blue line). The distances of three representative systems: the galactic star-forming region Westerlund 2, the Large Magellanic Cloud and the galaxy M33, are marked. Binary stars at different stages of evolution will be resolvable by LUVOIR throughout most of the galaxies in the Local Group. Massive star signatures will be detectable in young star clusters resolved in galaxies out to about 150 Mpc.*

sensitivity UV spectroscopy with resolving power R > 3000, to resolve atomic and molecular lines from winds and photospheres in stellar spectra.

Determining the nature, average properties and relevant physical parameters, and potential environmental dependencies of star formation (and its corollary: the stellar IMF) across the full stellar mass range, from the high to low mass ends, will require synergy across multiple wavelength regions, from the UV to the mm. Important characteristics are poorly constrained, including merger rates, binary fractions below O stars, multiplicity, fraction of runaway stars, and whether very massive stars (VMSs, i.e., stars with masses > 150 $M_{\odot}$) exist and are common. In addition to its primary and unique role in achieving a full understanding of star formation, LUVOIR will play a complementary role in characterizing the shocks,

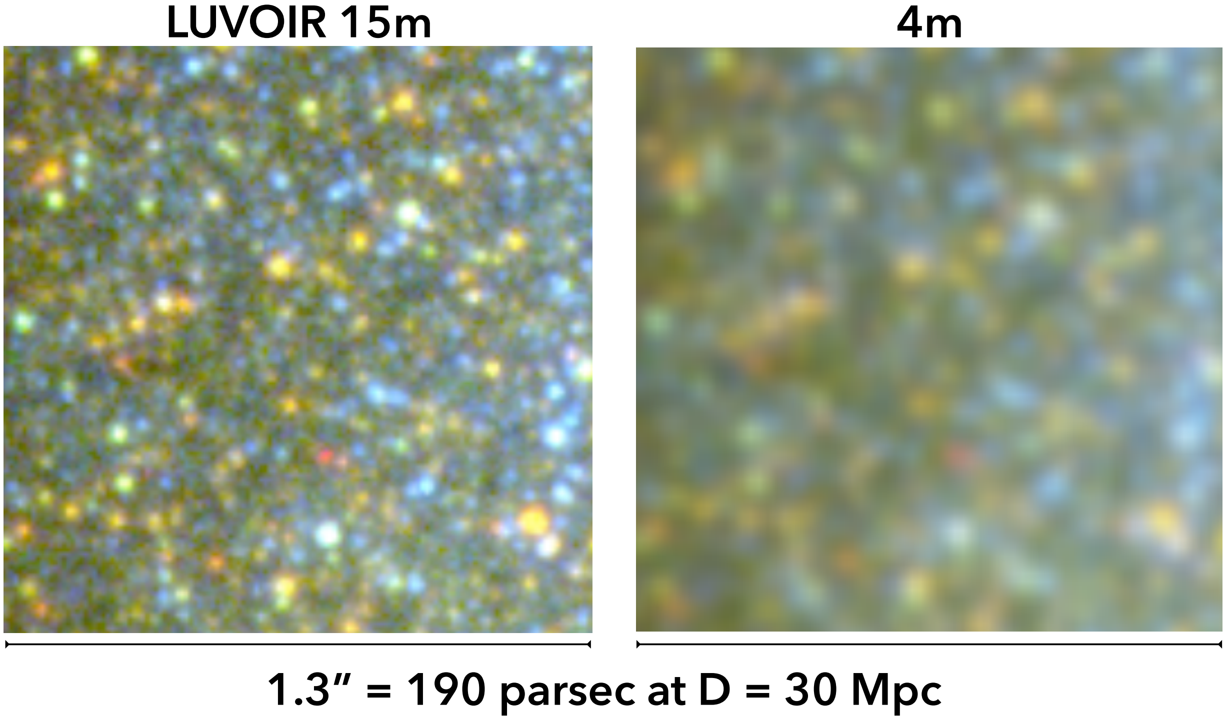


Figure 6-17. *The inner region of a dwarf galaxy as viewed by LUVOIR-A and a 4-m telescope at a distance of ~31 Mpc. Each box is 1.3" on a side, corresponding to 31 pc. The 4-m image would need ~16 times the exposure time as the LUVOIR image. The images are obtained by degrading the HST images of a region of the galaxy IC 4247, located at 4 Mpc distance (Calzetti et al. 2015).*

jets, and outflows from the individual protostars and protoclusters, and their natal cores, identified by ALMA.

Below are two example science cases that push to the limit of LUVOIR capabilities, and provide a benchmark for the large science output that LUVOIR promises in this area.

6.3.1 Very massive stars

VMSs are stars that exceed the standard limit of 150 $M_\odot$, and one needs to observe very young ($\lesssim$ 1.5 Myr), massive star clusters ($> 10^5$ $M_\odot$) in order to detect their presence, due to small number statistics at the high end of the IMF, and rapid evolutionary timescales. Yet these stars can heavily influence their surrounding environment; for instance, they can provide between 25% and 50% of the ionizing photon flux from the host cluster.

A solid case for the presence of VMSs in R136, the central cluster in 30 Dor in the Large Magellanic Cloud, has been recently made by Crowther et al. (2010, 2016). UV spectroscopy has provided evidence for the potential presence of VMSs in an additional two unresolved star clusters in NGC 3125 (Wofford et al. 2014) and NGC 5253 (**Figure 6-18**; Smith et al. 2016). Detection of supernovae that have characteristics typical of pair-instability SNe provide indirect evidence for the presence of VMSs. Whether the VMSs are the result of birth conditions or of mergers is still a matter of debate, but models can successfully reproduce many observational properties using a rotating single VMS (Yusof et al. 2013, Kohler et al. 2015). Data on the VMS numbers and frequency in young star-forming regions are lacking, due to observational limitations: they can only be recognized in the UV.

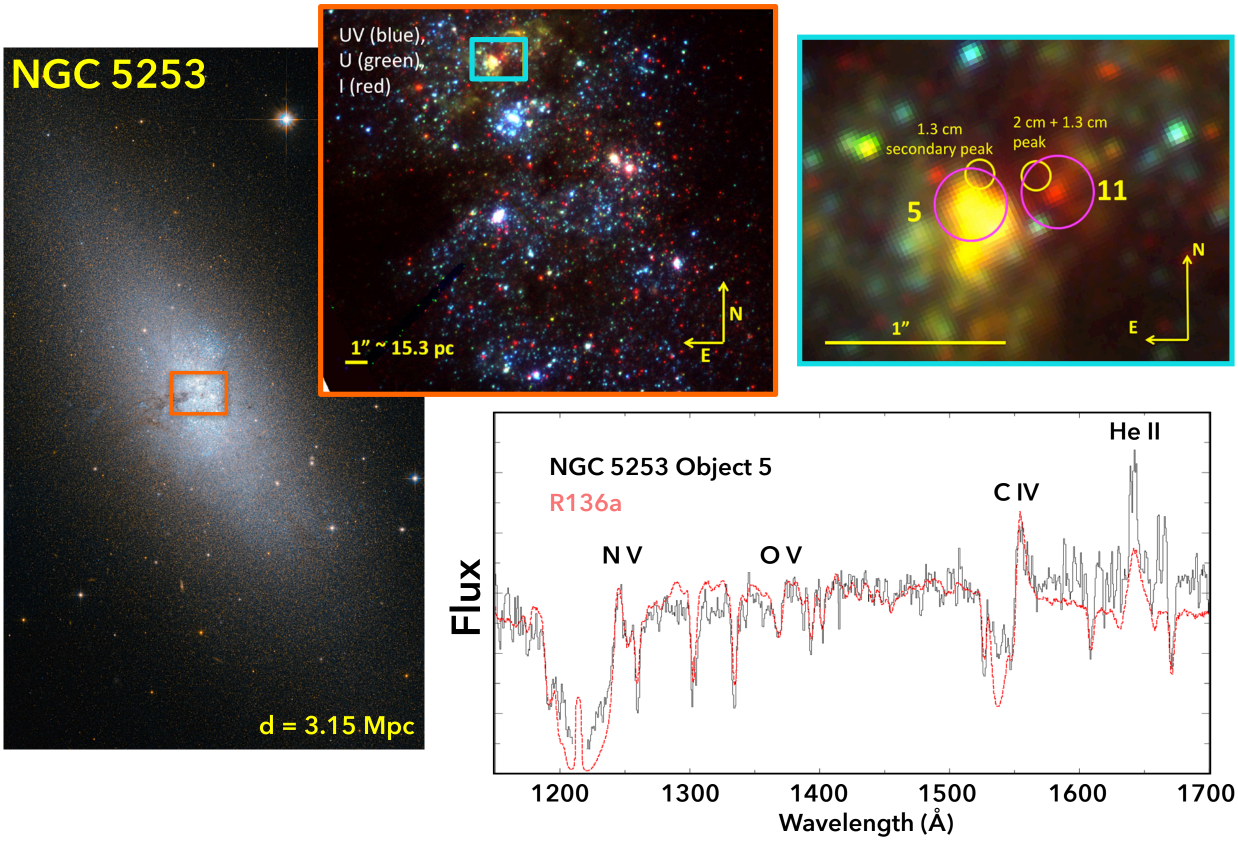


Figure 6-18. *LUVOIR will increase by at least tenfold the parameter space in distance and galactic properties (morphology, dust content, star formation rate, etc.) of the systems whose VMS content can be identified and characterized. Identifying very massive stars (VMSs) in star clusters. NGC 5253 is an amorphous dwarf hosting a starburst in its central ~250 pc. Most of the dust and molecular gas in this galaxy are concentrated in a ~20 pc region located at the north end of the starburst (right-top panel), where also the two main radio peaks are located (yellow circles in the top-right panel; Turner et al. 2000). The two radio peaks coincide with two clusters identified in the HST images (magenta circles in the top-right panel; called 5 and 11 by Calzetti et al. 2015). The two clusters are ~1 Myr old, with masses* $1–3 \times 10^5\ M_\odot$*, and with AV ~ 2–50 mag of dust. UV spectroscopy of cluster 5 further reveals the presence of VMS signatures: P Cygni N V (1240 Å) and C IV (1550 Å) profiles, broad He II (1640 Å) emission, blue-shifted O V (1371 Å) wind absorption, and absence of Si IV (1400 Å) P Cygni emission/absorption (bottom panel; Smith et al. 2016), as confirmed from the comparison with the UV spectrum of the LMC cluster R136a, also containing VMSs (Crowther et al. 2016). The HST UV spectrum of cluster 5 required 3 hours of exposure. The same amount of time with LUMOS on a 15-m will detect with SNR ~ 10 a* $10^6\ M_\odot$ *cluster with similar dust properties as cluster 5 out to a distance of 80 Mpc (25 times further away than NGC 5253). Credit: D. Calzetti (U Mass)*

A census of the frequency of VMSs across the full range of environments present in galaxies is required to gauge their overall impact on the evolution of galaxies, and to constrain models for their formation and evolution. The presence of VMSs can be inferred using unique UV spectral signatures: P Cygni N V (1240 Å) and C IV (1550 Å) profiles, broad He II (1640 Å) emission, blue-shifted O V (1371 Å) wind absorption, and an absence of Si IV (1400 Å) P Cygni profiles. In the optical, a VMS would be easily confused with WR emission from a lower mass O-star. Thus, UV spectroscopy is a key requirement for obtaining a census of VMSs and other massive stars in the nearby Universe, together with quantitative measurements of their properties.

UV multiplexing (multi-object or integral field spectrograph) to obtain spectra of resolved massive stars in clusters out to 0.7–1 Mpc and spectra of unresolved young, massive star clusters out to 150 Mpc (Arp 220, the prototype ULIRG, is at 77 Mpc distance) is a minimum requirement, and will secure about 200 LIRGs and ~20 ULIRGs, thus sampling the full range of galaxy properties. Large detector formats increase efficiency by covering entire star clusters/star-forming regions and/or entire star cluster populations in a single pointing. LUVOIR-A will ensure both enough sensitivity and angular resolution (0.01" at 80 Mpc corresponds to 4 pc, the size of star clusters, Ryon et al. 2017) for recovering individual star clusters and the signature of the massive stars they contain. As such, LUVOIR+LUMOS represents an ideal combination for VMS studies, and will provide more than a 1,000 increase in the cosmic volume that can be probed with Hubble in the UV.

6.3.2 Stellar multiplicity

Stellar multiplicity and binary frequency constrain models of star formation and the IMF (Offner et al. 2014). Hydro-dynamical simulations show that massive stars require dense and massive accretion disks to form, as these are needed to overcome the radiation pressure barrier. The disks tend to be unstable and break into complex systems. The resulting properties of the multiple systems (number of companions, distribution of separations [i.e., short vs. long orbital periods], distributions of mass ratios, and their dependence on the stellar mass) are model-dependent. Furthermore, the dynamics of binaries drive the evolution of star clusters while, simultaneously, the combination of cluster dynamics and internal stellar processes determine the internal evolution of each binary (Portegies Zwart et al. 2010), but, again, there is enormous dependency on uncertain parameters.

Short-period (spectroscopic) binaries will remain the domain of ground-based telescopes, especially the upcoming integral field spectrographs on adaptive optics-assisted (AO-assisted) 30-m+ class telescopes. Long-period binaries require high angular resolution, a very stable PSF, and high precision photometry across the entire FoV, which needs to be a few arcminutes on a side, in order to increase efficiency by targeting each cluster with as few pointings as possible. LUVOIR-A will be able to achieve accuracies as high as 0.5 μas/yr over 5 years (**Appendix B.8**), which will increase the cosmic volume over which proper motions can be measured by 8,000 times over the AO-assisted ELTs.

In addition, the physical properties of the stars need to be characterized in order to constrain models. This demands measurements of the ***resolved*** massive stars' winds and photospheric parameters (including bolometric luminosities and masses), which can be accomplished only with spectroscopy of individual stars in the 1000–2000 Angstrom range (Wofford et al. 2012). Binaries at different stages of evolution within a star cluster have mean separations that change between a few tens and a few thousand AUs (Portegies Zwart et al. 2010). Resolving binaries with UV spectroscopy *at all stages of evolution* requires resolving mean separations across a wide range from tens to hundreds of AU; probing a range of environments requires reaching at least the distance of the Magellanic Clouds. LUMOS on LUVOIR-A will resolve binary stars with separations down to ~40 AU in the iconic high-mass star cluster Westerlund 2 (~4 kpc from the Sun) and ~500 AU in the LMC.

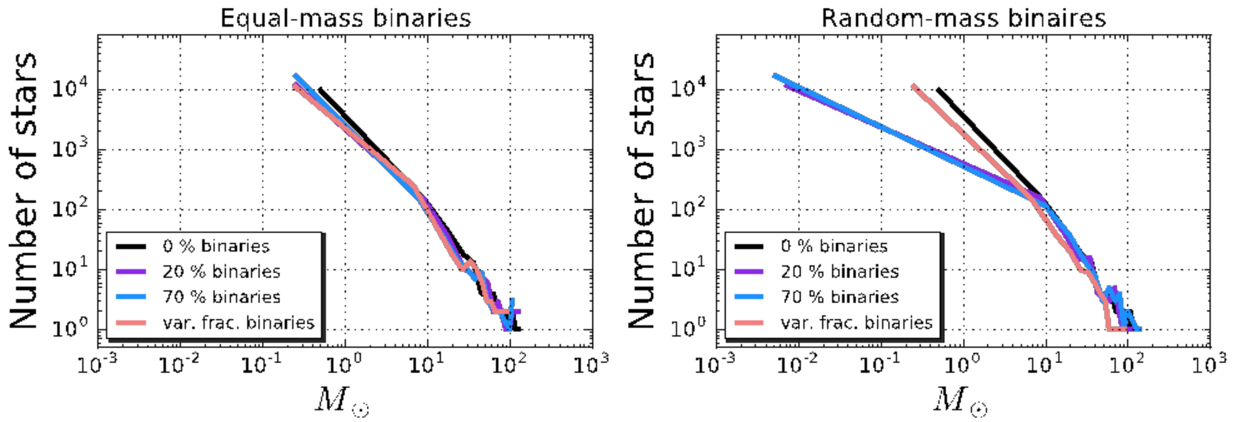


Figure 6-19. *Simulations indicate that very non-standard IMFs can nevertheless appear to be a common Salpeter IMF if binary stars are not properly resolved. These two panels show how different from Salpeter the IMFs can be and still be mistaken for this standard IMF. The effect is particularly large in the case of random-mass binaries (at right) where the high mass end can vary widely and still be "observed" as Salpeter. LUVOIR will be able to directly resolve these binary systems and measure the high-mass departures from standard IMFs.*

The diffraction-limited angular resolution of HDI on LUVOIR-A (0.007″) will resolve and image all binary stars down to ~30 AU separation in Westerlund 2 (**Figure 6-19**), and down to smaller separations in the many dozens of intervening star-forming regions spanning a wide range of densities and other properties. A 30 AU separation is found for a system of two equal-mass late-type B stars (~3 $M_\odot$ each) with a 25-year orbital period. The tens-AU regime is interesting for the investigation of the progenitors of peculiar objects and Gamma ray bursts (GRBs), as models suggest massive stars may be interacting in the post-MS phase. This will also address numerous additional related questions, including the IMF of binary stars, and the role of binary stars in determining the upper end of the IMF. As shown in **Figure 6-19** the Salpeter IMF, which is often observed in resolved star clusters, could be the result of a significantly different actual (input) IMF, if the stars in the cluster are unresolved binary stars with random mass ratios (right panel). Overall, LUVOIR will provide both the sensitivity and angular resolution to probe more widely separated binary systems throughout most of the Local Group galaxies, thus constraining models of star formation.

Table 6-1. *Chapter 6 Programs at a Glance*

Chapter 6 Programs at a Glance			
Goal	**Program Description**	**Instrument + Mode**	**Key Observation Requirements**
Signature Science Case #10: The Cycles of Galactic Matter			
Measure mass, metals, energetics, and fate of CGM gas that feeds galaxies	UV spectroscopy of 100 quasars ($z > 1$) to study absorption column densities of atoms and ions over a range of temperatures (10^4–10^7 K) and densities (10^{-6}–10^2 cm^{-3})	LUMOS NUV and FUV point-source spectroscopy	Telescope diameter $\gtrsim 8$ m Bandpass: 100–400 nm $R \gtrsim 30{,}000$ Telescope mirror reflectivity > 60% at 105 nm
Map the outflow from the starburst galaxy M82 at sub-parsec scales	Measure content and kinematics of M82 superwind at > 300 positions in flow, using emission in lines of Lyα, O VI, C IV, and Mg II	LUMOS FUV and NUV multi-object spectroscopy	Telescope diameter $\gtrsim 8$ m Bandpass: 100–400 nm $R \gtrsim 30{,}000$ Telescope mirror reflectivity > 60% at 105 nm MOS FOV $\gtrsim$ 4 sq. arcmin
Determine the spatial distribution, kinematics, metal content, and large-scale structures of the halo around a nearby galaxy	Measurements of absorption column densities and velocities for hot halo gas (Lyman-β, O VI, C IV, and Mg II) out to 200 kpc around M51 via examination of sight lines to 30 quasars through the CGM	LUMOS FUV and NUV point-source spectroscopy	Telescope diameter $\gtrsim 8$ m Bandpass: 100–400 nm $R \gtrsim 30{,}000$ Telescope mirror reflectivity > 60% at 105 nm
Resolve galactic accretion and feedback at sub-parsec scales	Measure gas absorption and emission (Lyman-β, O VI, C IV, and Mg II) from ~1000 stellar clusters in nearby spiral galaxies (< 10 Mpc)	LUMOS FUV and NUV multi-object spectroscopy	Telescope diameter $\gtrsim 8$ m Bandpass: 100–400 nm $R \gtrsim 30{,}000$ Telescope mirror reflectivity > 60% at 105 nm FOV $\gtrsim$ 4 sq. arcmin
Signature Science Case #11: The Multiscale Assembly of Galaxies			
Determine how galaxies form at early times by surveying star formation in young galaxies	Study star formation at 100 pc scales within thousands of galaxies at a range of redshifts	HDI Imaging	Telescope diameter $\gtrsim 8$ m Photometric sensitivity sufficient to reach AB = 30.5 in 1 hour
Characterize the age and metallicity of stellar populations in different types of large galaxies	Detect main sequence turnoff in galaxies beyond the Local Group, to reach the nearest giant ellipticals (8 galaxies total)	HDI Imaging	Telescope diameter $\gtrsim 8$ m Photometric sensitivity sufficient to reach AB ~ 32 in 1 hour
Signature Science Case #12: Stars as the Engines of Galactic Feedback			
Study the impact of very massive stars (VMSs) on star forming environments	Find VMSs ($M > 150\ M_\odot$, ages < 2 Myr) in luminous and ultra-luminous infrared galaxies within 150 Mpc	HDI multi-band imaging	9 broadband filters between 200–2190 nm and 3 narrow band filters (656, 1282, and 1876 nm) FOV $\gtrsim$ 6 sq. arcmin
	Measure diagnostics of these VMSs including: C IV, N V P Cygni profiles; broad He II emission; blue shifted O V wind absorption; absence of Si IV P Cygni emission / absorption	LUMOS multi-object spectroscopy	Bandpass: 120–170 nm $R > 10{,}000$ Telescope mirror reflectivity > 60% at 105 nm FOV $\gtrsim$ 4 sq. arcmin
Constrain models of star formation via knowledge of stellar multiplicity in galaxies beyond the Milky Way and Magellanic Clouds	Find long-period binaries in 7 regions of recent star formation in 5 galaxies within 1 Mpc. Measure proper motions over 5 years	HDI multi-band imaging	U, B, V, I broadband filters FOV $\gtrsim$ 6 sq. arcmin Observe each region once per year over 5 years
	Determine spectral types of these binaries with a single epoch of UV spectroscopy	LUMOS multi-object spectroscopy	Bandpass: 100–400 nm Telescope mirror reflectivity > 60% at 105 nm FOV $\gtrsim$ 4 sq. arcmin