Near-Field Cosmology with the Lowest-Mass Galaxies

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ABSTRACT

The term "near-field cosmology" broadly describes connections between the low- and high-redshift Universe. Resolved studies of $z = 0$ galaxies less massive than the LMC ($M_\star \lesssim 10^9$ $M_\odot$) provide access to (i) small scales of the matter power spectrum that are challenging to study otherwise and (ii) the galaxy population that is fainter than high-redshift direct detection limits. **The study of nearby low-mass galaxies has implications that extend far beyond the local Universe and include the nature of dark matter, cosmic reionization, and galaxy formation across cosmic time.**

Dark Matter: The only evidence for dark matter's existence comes from its inferred gravitational influence on galactic and cosmological scales. Near-field cosmology provides our best evidence for the amplitude of density fluctuations on sub-galactic scales: so long as ultra-faint galaxies are hosted by dark matter halos, their existence and inferred abundance require the matter power spectrum to extend down to mass scales of $M \sim 10^9$ $M_\odot$. Kinematic information from large samples of individual line-of-sight and transverse velocities of stars and from spatially resolved gas kinematics in nearby dwarf galaxies directly informs our understanding of dark matter interactions in the deeply nonlinear regime.

Galaxy and Stellar Astrophysics: Resolved stars in low-mass galaxies serve as crucial and unique foundations for interpreting the light of galaxies at all cosmic epochs, including faint galaxies in the distant Universe. Fundamental measurements include star formation histories (SFHs) from color-magnitude diagrams, chemical abundance patterns from stellar spectroscopy, and stellar and galaxy velocities from spectroscopy and proper motions. Observations of resolved low-metallicity massive stars and HII regions are central to interpreting faint galaxies at all earlier epochs.

Outlook: In the 2020s, hundreds of new low-mass galaxies will be discovered and characterized with LSST, HST, JWST, WFIRST, and the ELTs. In the longer term, fully realizing the promise of near-field cosmology with low-mass galaxies requires: (i) a large aperture ($\gtrsim 9$m) UV/optical space telescope. This is the only way to measure SFHs and proper motions, as well as acquire invaluable UV spectroscopy of stars and star-forming regions, to several Mpc; (ii) a two-fold community investment in ground-based optical spectroscopy: ELTs, which enable high-fidelity spectroscopy of faint and/or crowded stars; and a dedicated wide-field spectroscopic survey on a 10m class telescope. Combined, they will uncover primordial enrichment events and signatures of the first stars, provide unique insight into dark matter, and anchor our interpretation of the faint galaxy frontier at high redshifts; (iii) radio facilities that can measure high-precision, resolved rotation curves in order to shed light into the nature of dark matter.

HST: Finally, we suggest that **a servicing mission to extend the life of HST beyond 2025 should be seriously explored**. This may be a cost-effective way to bridge the looming gap in space-based UV/optical capabilities during development of a next-generation space telescope. Its high over-subscription rate suggests that HST can continue to enable ground-breaking science across all of astrophysics for quite some time.

1 Dark Matter

1.1 Matter Power Spectrum

The matter power spectrum – essentially, the contribution to the variance in the smoothed initial dark matter density field as a function of comoving smoothing scale – contains information about the nature of dark matter: any property of dark matter that reduces power on a particular scale will be reflected in the abundance and structure of dark matter halos at a corresponding mass[1,2]. On scales comparable to the LMC and above (dark matter masses of $\gtrsim 10^{11}$ M$_\odot$ or comoving sizes of $\gtrsim 1$ Mpc), the power spectrum is strongly constrained to be virtually indistinguishable from the baseline ΛCDM model. Tests on smaller scales are much more difficult. **The near field provides our best evidence for the amplitude of density fluctuations on sub-galactic scales:** the number of known ultra-faint dwarf galaxies (UFDs) requires the power spectrum to extend to mass scales of $\sim 10^9$ M$_\odot$[1,3]. The total count of M$_\star \lesssim 10^5$ M$_\odot$ dwarf galaxies within the virial volume of the Milky Way (MW) is highly uncertain (at the factor of 10 level[4–6]) owing to spatial clustering of satellites, incomplete sky coverage, and luminosity bias. Even with a complete, stellar-mass-limited census of MW satellite galaxies, the matter power spectrum may be impossible to accurately measure because of the uncertainties related to the disruptive effects of the Galaxy's disk[7,8]. Observations of regions where such effects are irrelevant is therefore a high priority. **An accurate and complete census of very faint galaxies** $\sim 500 - 1000$ **kpc from the MW, which is achievable with LSST, has the potential to constrain the dark matter power spectrum on mass scales of** $M \sim 10^7 - 10^8$ M$_\odot$**.**

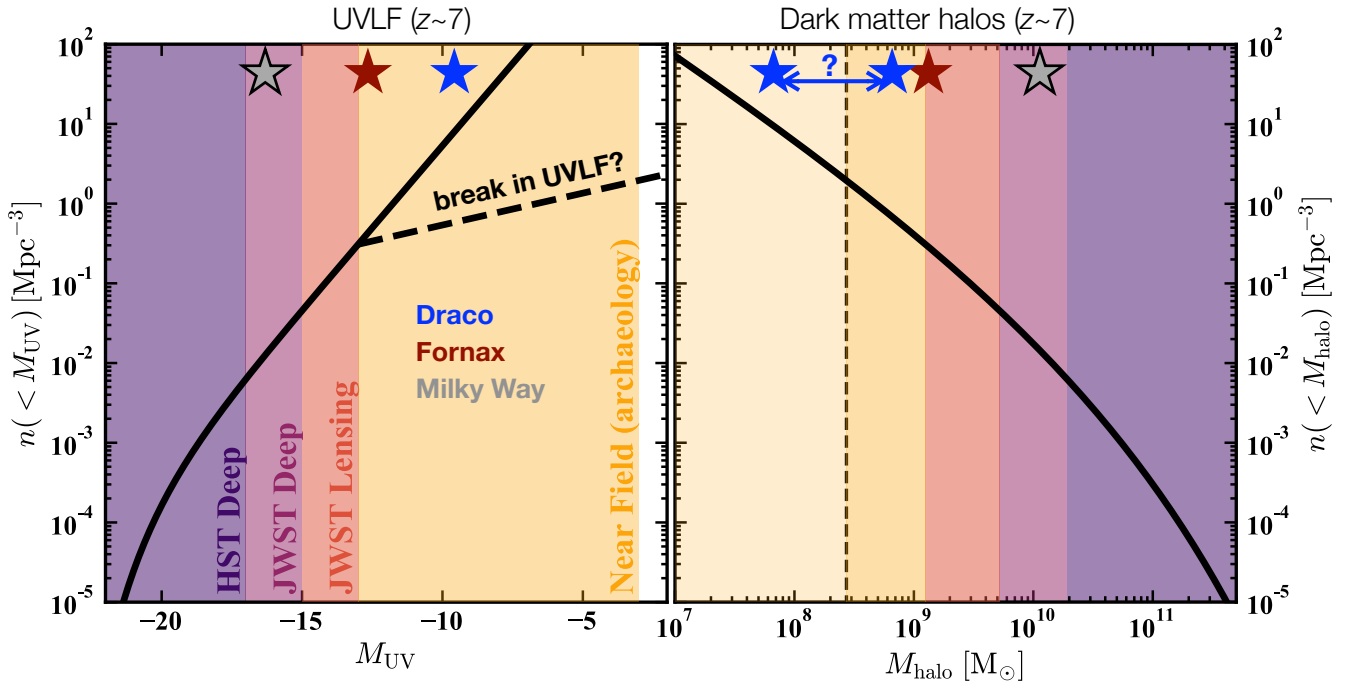Any test of the dark matter power spectrum on even smaller mass scales requires the detection of

FIGURE 1: The cumulative abundance n of rest-frame-UV-selected objects (*left*) and dark matter halos (*right*) at $z \sim 7$. Matching objects at fixed n provides an association between galaxies and their host dark matter halos, linking galaxy observations with structure formation and dark matter physics. In this view, current blank field HST surveys are sensitive to dark matter halos with $M(z \sim 7) \gtrsim 10^{10}$ M$_\odot$, while JWST+lensing will probe masses an order of magnitude lower. Archaeological reconstructions based on near-field data provide a window to substantially lower-mass dark halos at high redshifts that may *never* be accessible through direct observation. In particular, the possibility of a turn-over or break in the UV luminosity function (UVLF) will be very difficult to detect robustly even with JWST lensing fields. A census of galaxies like Draco in the near field would differentiate between the two, as an unbroken UVLF would result in an order of magnitude more local descendants than a broken UVLF.

perturbations or virialized halos that will never host a galaxy. This is highly challenging, as CDM halos have densities that are extremely low relative to the typical densities of astrophysical objects: a virialized halo at $z = 0$ with a mass of $M \sim 10^5$ M$_\odot$ has a virial radius of ~ 1 kpc, while a typical globular cluster has a similar mass but a size of $\lesssim 10$ pc. Nevertheless, multiple lines of inquiry in the near field may be sensitive to the power spectrum at scales below the threshold of galaxy formation. Precision measurements of density variations in globular cluster streams may reveal the presence of low-mass substructure[9,10], while the detection of wide stellar binaries at very large separations may rule out its existence[11]. These measurements must be complemented with other techniques far outside of the MW (e.g., gravitational lensing[12,13]), where environmental and baryonic effects will be diminished and systematic uncertainties will be different. **Given the complete absence of non-gravitational detections of dark matter, all possible astrophysical lines of inquiry that can confirm or exclude the existence of dark matter structure below the scale of (the smallest) galaxies are essential and should be pursued vigorously.**

1.2 Properties of Individual Halos

While the matter power spectrum is sensitive to dark matter physics operating in the linear regime of density perturbations, the structure of collapsed dark matter halos can be sensitive to dark matter interactions that occur when densities are high. The low baryonic content of dwarf galaxies makes them an important testing ground for CDM and its alternatives; however, results from the past several years have made it clear that comparisons between observations and CDM predictions must take into account the impact of baryonic physics on the distribution of dark matter within dwarf galaxies[7,14–16]. These effects can be grouped into two classes: "environmental", involving any dwarf galaxies that interact with a larger system (such as the inner MW satellites interacting tidally with the MW disk and moving through its gaseous halo) and "internal", involving energy and momentum input from star formation and stellar evolution[17] (with other sources such as black holes also being potentially important).

Theoretical and computational models indicate that certain systems are preferred candidates for testing the nature of dark matter. UFDs are expected to have fewer stars per unit dark matter halo mass, meaning stellar feedback should be relatively less important[18,19]. Low-mass galaxies that formed all of their stars early (before $z \sim 2$) retain their primordial dark matter density profiles in CDM+baryon simulations[20]. Those that have never come within ~ 50 kpc of the MW are likely to have avoided strong environmental effects[8]. **These conditions point to faint ($M_\star \lesssim 10^6$ M$_\odot$), distant ($\gtrsim 500$ kpc), isolated dwarf galaxies in the Local Group (LG) as ideal probes of dark matter density profiles (and therefore, of the nature of dark matter).** While only a handful of such galaxies are known, all current evidence points to the existence of a large population lurking just below current detection thresholds[21]. It will be crucial to have multiple kinematic tracers in these systems – HI rotation curves and line-of-sight (LOS) velocities of individual stars – to mitigate uncertainties.

2 Extra-Galactic Archaeology with Resolved Stars

2.1 Star Formation Histories

The colors and absolute magnitudes of resolved stars, along with their relative densities on various parts of a color-magnitude diagram (CMD), encode a galaxy's star formation history (SFH; which includes its age-metallicity relationship). Techniques to recover SFHs from CMDs require minimal assumptions about the functional form of the SFH and been extensively vetted over the past few decades[22–28].

CMDs that reach the oldest main sequence turnoff (MSTO) with a SNR$\gtrsim 5 - 10$ per star provide the most secure SFHs[29,30]. However, even HST cannot produce CMDs that reach the oMSTO beyond the LG due to its faintness ($M_V \sim +4$) and crowding; SFHs from shallower CMDs are less certain[31,32] (Figure 2).
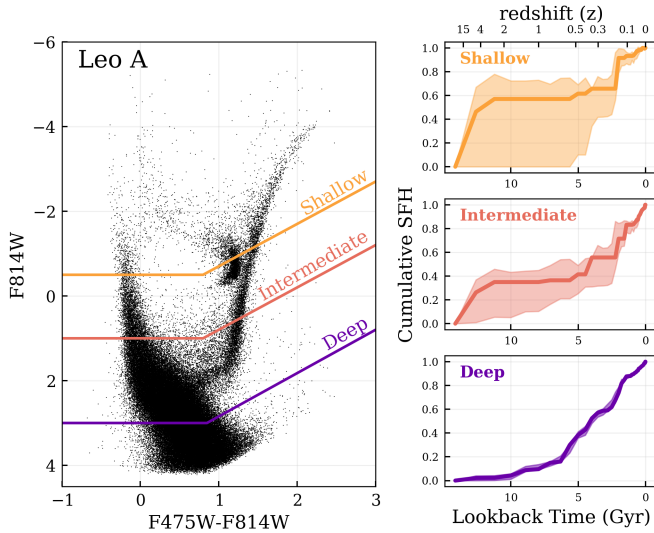
FIGURE 2: **Left:** The HST-based CMD of LG dwarf irregular Leo A[43] ($D \sim 800$ kpc, $\log(M_\star/M_\odot) \sim 6.8$, $\log(Z_\star/Z_\odot) \sim 10\%$)[44]. The colored lines represent the variety of CMD depths that are typical of archival HST data in and beyond the LG. HST can only reach the oldest MSTO within the LG due to sensitivity and crowding limitations. **Right:** The cumulative SFHs (fraction of stellar mass formed prior to a given epoch) of Leo A measured from the CMD (at different depths) in the left panel. Uncertainties include contributions from random (e.g., number of stars[45]) and systematic components (e.g., from variations in stellar models[31,32]). CMDs that include the oldest MSTO provide a precise SFH measurement at all epochs, while SFHs measured from shallower CMDs are uncertain at older ages.

Oldest MSTO-based SFHs exist for a few dozen dwarf galaxies in the LG. Among MW satellites, the lowest-mass systems generally stop forming stars in the very early Universe[33], while more luminous systems continue forming stars until later times[34]. However, it remains unclear if this trend also exists among M31 satellites[35]. Isolated dwarfs exhibit diverse SFHs at fixed present-day properties.[30,36]. **Dozens to hundreds of oMSTO-based SFHs of isolated dwarfs are needed to fully determine the variance and identify trends. Achieving such sample sizes requires a $\gtrsim$9m optical space telescope (Figure 3).**

Proper motion measurements are essential to our understanding of SFHs in satellite galaxies. For example, the HST-based proper motion measurement for Leo I[37] demonstrated that Leo I quenched at a time coincident with its pericentric passage of the MW, consistent with efficient ram pressure stripping[38,39].

Between HST, Gaia, WFIRST, and JWST, proper motions measurements, and similarly detailed insight into quenching, are possible for all low-mass galaxies in the LG[40–42]. **Proper motions outside the LG require facilities with better angular resolution than JWST and decade-plus time baselines.**

2.2 Reionization

The lowest mass galaxies in the high-redshift Universe are beyond the direct detection limits of our most powerful telescopes, including JWST (Figure 1). **The study of resolved dwarf galaxies may be the only way to observationally link the faintest galaxies to reionization.** This topic is of the utmost importance for both cosmology and galaxy formation modeling[46–48].

The main progenitors of classical LG dwarf galaxies such as Draco and Leo A had UV luminosities consistent with the faint galaxy population thought to drive reionization[49,50]. Moreover, UFDs around the MW require that the high-redshift UVLF extends as faint as $M_{\rm UV}(z = 7) \sim -3$[51]. A break in the high-redshift galaxy UVLF appears necessary to match LG dwarf galaxy number counts[21,50]. This break may be impossible to observe directly at high redshifts, even with gravitational lensing (Figure 1). **An accurate census of nearby dwarfs along with their oMSTO-based SFHs may be the only way to constrain shape of the faint UVLF in the early Universe.**

The relatively small number of low-mass satellite galaxies around the MW can be understood naturally if cosmic reionization sets a lower mass limit on galaxy formation: halos below the atomic cooling limit of $T_{\rm vir} \approx 10^4$ K were unable to form stars once hydrogen was reionized[52,53]. The discovery of UFDs and the revelation that their stellar populations are generally consistent with no star formation since the reionization era[33,34] helped to solidify the idea that the "missing satellites problem"[54,55] might not be fatal for CDM. SFHs of some low-mass dwarf galaxies, along with cosmological simulations, now suggest

that reionization may not quench all of the lowest-mass galaxies simultaneously due to inhomogeneities in reionization and/or self-shielding[19,56–58]. **Measuring the oMSTO-based SFHs for a large number of UFDs, particularly those that are not satellites, provides a unique test of reionization scenarios.**

2.3 Chemical Enrichment and the First Stars

The low metallicities of resolved stars in dwarf galaxies imply they have been subjected to relatively little enrichment, thus providing a plausible pathway for identifying individual enrichment events. For example, the enhancement of r-process elements such as Ba and Eu in some UFDs suggests that these systems hosted singular neutron capture events (e.g., neutron star mergers) in the early Universe[59–61]. Measurements of just a handful of elements, such as Fe or a few α-elements, can be used to distinguish between leaky and closed box chemical evolution or constrain the relative timing of supernovae-based enrichment[62,63]. In galaxies with purely ancient populations, such as UFDs, the abundance patterns can provide important insight into the lives and deaths of the first stars[64].

The number and quality of abundance determinations scales with distance, resolution, and SNR. Medium resolution ($R \sim 6000$) spectroscopy can provide several elements in MW satellites[65], and $[\langle\alpha\rangle/\text{Fe}]$ with $10+$ hour times at the edge of the LG[66]. High resolution ($R \gtrsim 10,000 - 20,000$) spectroscopy provides dozens of elements[67], and is particularly information rich at UV wavelengths[68]. New spectral fitting techniques can recover 10-20 elements from low resolution ($R \sim 2000$) spectra[69,70]. **Substantially improved knowledge of abundance patterns and enrichment processes requires a combination of wide-field narrow-band photometric[71,72] and/or modest resolution spectroscopic surveys[73,74] with higher resolution follow-up in the optical/UV, either from ELTs[21] or space-based observatories.**

2.4 Resolved Low Metallicity Calibrators for the High-Redshift Universe

Interpreting the spectral energy distributions and emission lines of faint, metal-poor, star-forming galaxies requires knowledge of low-metallicity massive stars and HII regions. For massive stars, resolved observations of the SMC ($Z \sim 20\%\ Z_\odot$) have long served as the metal-poor empirical anchor[75]. However, it may not be a sufficiently metal-poor proxy for the faintest systems at high redshifts[76–80]. At lower metallicities, massive stars have different rotation rates, wind strengths, surface chemistry, and intrinsic binarity, which affects properties such as lifetimes and the output of ionizing photons[81–83]. Nebular emission in HII regions is also highly sensitive to metallicity and massive stars properties[84–87].

Expanding local calibrations of low-metallicity massive stars and HII regions is challenging. Most sub-SMC metallicity star-forming regions are located at the periphery of the LG or beyond. Acquiring high SNR spectroscopy of massive stars at such distances, particularly in the UV, requires large integration times with our most powerful telescopes[88–90]. Comparatively more progress has been made on low-metallicity HII regions at optical wavelengths[91]. Rest-frame far-UV spectra of HII regions (especially $\sim$900-1200 Å) are particularly feature-rich[85,92] but are not easily observed. **Improving local calibrations of low-metallicity massive stars and HII regions, particularly at UV wavelengths, is imperative for accurately interpreting the light of faint, star-forming galaxies in the high-redshift Universe.**

3 Future Prospects

Spectroscopy: Substantial progress in understanding the nature of dark matter, the first stars, and enrichment mechanisms in the early Universe requires a three-fold investment in spectroscopy. First, medium and high-resolution spectroscopy are needed to measure LOS velocities and abundance patterns of faint stars in, for example, UFDs (e.g., discovered by LSST, WFIRST), as well as to improve our knowledge of low-metallicity massive stars and HII regions. This requires a 30m class ground-based
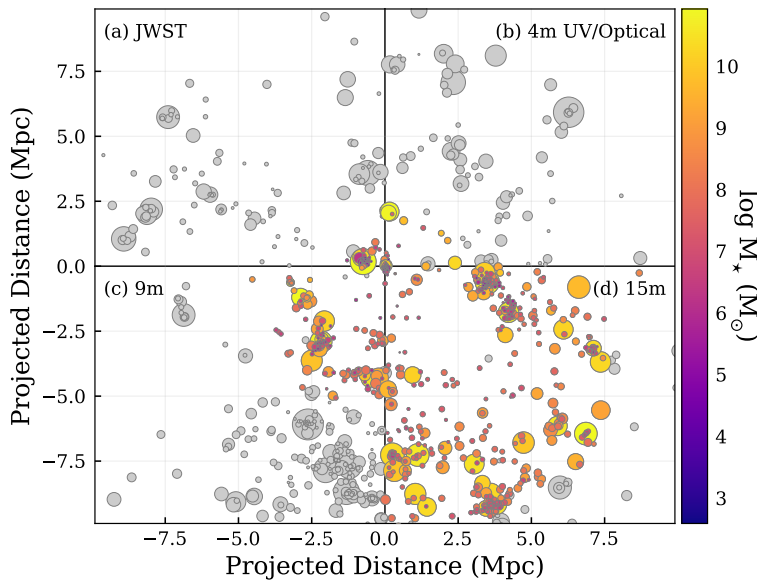
FIGURE 3: A projected 2D map of known Local Volume galaxies[93] centered on the MW. Point sizes are proportional to half-light radii. In each quadrant, a galaxy for which a given facility can reach the oMSTO in $\lesssim$100 hours of integration time, assuming negligible crowding effects, is colored-coded by $M_\star$. JWST is limited mainly by its poor blue sensitivity. Projections for the 4, 9, and 15-m UV/optical options are adopted from the LUVOIR STDT[94]. In total, the 4, 9, and 15m UV/optical telescopes can reach the oldest MSTO in $\sim$150 ($\sim$2.5 Mpc), $\sim$500 ($\sim$5 Mpc), and $\sim$1000 ($\sim$10 Mpc) known galaxies. Reaching the oldest MSTO is the most demanding observation, and thus enables a range of other science (e.g., proper motions).

facility. Second, it is important to collect large samples of stars in order to establish broad trends (e.g., kinematics vs. abundances), identify rare populations (e.g., extremely metal-poor star), characterize resolved ultra-diffuse dwarf galaxies[95,96], and improve the efficiency of follow-up with 30m telescopes (e.g., membership identification). This can be achieved to moderately faint limits with a wide-field, highly multiplexed optical spectrograph on a dedicated 10m class telescope[97]. Finally, UV spectroscopy from a $\sim$9-15m class space telescope is necessary to reveal detailed abundances of ancient stars and characterize the information rich UV spectra of low-metallicity massive stars and HII regions. *If* the HST "UV Legacy Initiative" proposed by STScI includes a substantial number of targets at sub-SMC metallicities, it may help to address some of the current observational shortcomings of low-metallicity massive stars.

Imaging: Connecting local low-mass galaxies to cosmic reionization and high-redshift galaxy studies requires imaging the oldest MSTO for hundreds of nearby dwarf galaxies. As shown in Figure 3, JWST and a 4m UV/optical space telescope will provide our first observations of the oldest MSTO outside the LG to $\sim$2-3 Mpc. However, truly transformative science requires the angular resolution, sensitivity, and stability of a $\sim$9-15m optical space telescope. Observations of the oldest MSTO will also enable precise transverse motions for resolved stars in and around the LG and for bulk motions of galaxies out to several Mpc, given sufficient time baselines.

HST: HST-based science remains at the forefront of astrophysics, including near-field cosmology. Without HST, US astronomy will lack a UV/optical observatory in space for the 15-20 years it will take to develop and launch a next-generation facility. We strongly advocate for serious exploration of a servicing mission (public or private) to extend the lifetime of HST beyond 2025. Such a mission may prove to be a cost effective way to mitigate $\sim$ 15 years or more of no high-angular resolution UV/optical space-based capabilities between the planned decommissioning of HST and the launch of a potential replacement.

Further Scientific Synergy: Though this white paper is broad, it is not an exhaustive exploration of near-field cosmology. For example, precise spatially resolved HI rotation curves of dwarf galaxies would provide deep insight into the nature of dark matter. A space-based UV spectrograph would revolutionize our knowledge of the circumgalactic medium and baryon cycle of low-mass galaxies[98], while study of the hot interstellar and circumgalactic medium via X-rays is critical to understanding stellar feedback[99].

High resolution and alternative versions of the figures can be found `here`.

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