The Star Formation History of The Milky Way and M31 Bulges

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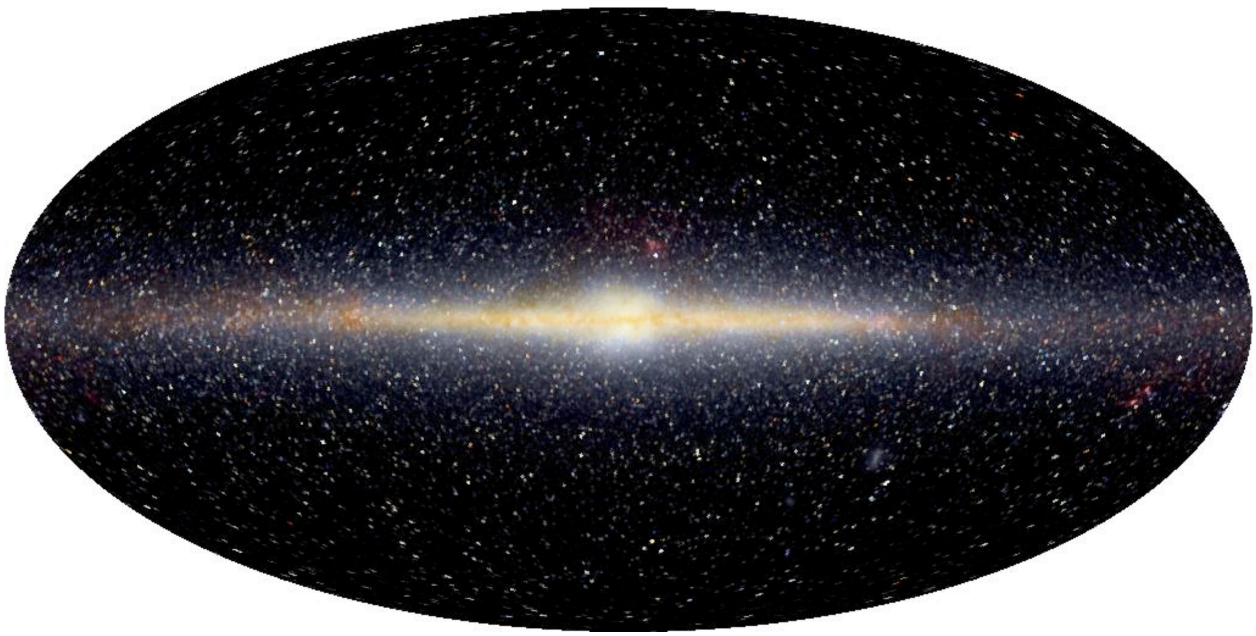

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1.1 Perspective: Galaxy bulges and the formation of structure in the Universe

Galaxy bulges are roughly spheroidal components in disk galaxies that account for 50-70\% of the stellar mass of the local universe (Fukugita et al. 1998). Their importance to galaxy formation and evolution is now well-established by a number of correlations with host galaxy properties. For example, the velocity dispersion of galaxy bulges correlates strongly with the mass of the supermassive black hole at the galactic center (Ferrarese & Merritt 2000; Gebhardt et al. 2000; Tremaine et al. 2002) and the dark matter halo mass (e.g. Courteau et al. 2007).

Bulges are a heterogeneous class, which may be sub-divided by apparent formation scenario. *Classical* bulges are observationally distinguished by spheroidal morphology and low rotational support, and are thought to form and grow by mergers (e.g. Eggen, Lynden-Bell, & Sandage 1962; Conselice 2006). Conversely, *pseudobulges* are flatter and show a higher degree of rotation support, and are reproduced in simulations through dynamical instabilities associated with bars in spirals (e.g. Kormendy & Kennicutt 2004). The demographics of bulge types through cosmic time tests the relative importance of galaxy mergers and secular evolution to observed structure in the Universe, and is thus a critical test of the currently dominant ΛCDM paradigm (e.g. Tegmark et al. 2004).

ΛCDM models predict that largely old, spheroidal bulges should *dominate* the light from disk galaxies (Figure 1) as mergers build up galaxies which then attract more mergers (e.g. Abadi et al. 2003). However, mid-late type spirals are *observed* to show mostly secularly-grown pseudobulges, as was first suggested from a number of test cases (see e.g. Drory & Fisher 2008) and now confirmed with a sample of thousands from the Sloan Digital Sky Survey (e.g. Gadotti 2009).

Constraints on the age distribution of the stars in bulges, and their formation timescales, are thus important tests for theories of galaxy formation. While the broad picture of merger-grown classical bulges in early types vs secularly-grown pseudobulges in late-type spirals is probably correct, a number of testable mechanisms must be explored. Episodes of gas accretion and exhaustion in the disk may create a bar that experiences more than one episode of destruction and reformation (Figure 1, bottom, from Combes 2009; note that proper integration of gas into Bulge simulations is a relatively recent innovation). A complex formation history involving an early major merger (Immelli et al. 2004; Elmegreen et al. 2008) may leave populations with distinct chemical signatures.

From an observational perspective, we are presented with three cases that are amenable to study: the Milky Way bulge and nucleus, at 8kpc. The M31 bulge and nucleus, at 770 kpc (roughly 100 times the distance of the Galactic bulge, and more distant systems like M81 and NGC 5128, at 2-4 Mpc.

1.2 The bulges of the Milky Way and M31

Nearly all studies agree that the stars in the Milky Way bulge are mostly old (~10Gyr), and formed rather rapidly (e.g. McWilliam & Rich 1994; Zoccali et al. 2006; Ballero et al. 2007), suggesting a merger-grown classical bulge. However, the *arrangement* of these stars suggests a secularly-grown pseudobulge (Dwek et al. 1995; Launhardt et al. 2002), as do their kinematics outside ~200pc from the galactic center (Rich et al. 2007a; Howard et al. 2008; Clarkson et al. 2008). In addition, while the first generation of the oldest, most metal-poor stars are thought to reside in the bulge (e.g. Scannapieco et al. 2006), its stellar population also spans an abundance range that is among the greatest of any known stellar population, -2 < [Fe/H] < +0.6; (e.g. Rich 1988; Santiago, Javiel & Porto de Mello 2006). However the distribution within this envelope is controversial. Studies of the giants (e.g. Fulbright, McWilliam & Rich 2006) find the mean metallicity to be slightly subsolar, while high resolution spectroscopic analysis of 7 microlensed dwarfs finds 6 showing [Fe/H]>+0.3. The question has been raised (Cohen et al. 2008) whether there is a fundamental problem with the bulge abundance scale for giants. When spectroscopic gravity and temperature are used to place the bulge dwarfs in the HR diagram, their ages are found to be younger by several Gyr than is derived from the isochrone fitting to the bulge CMD (Johnson et al. 2008).

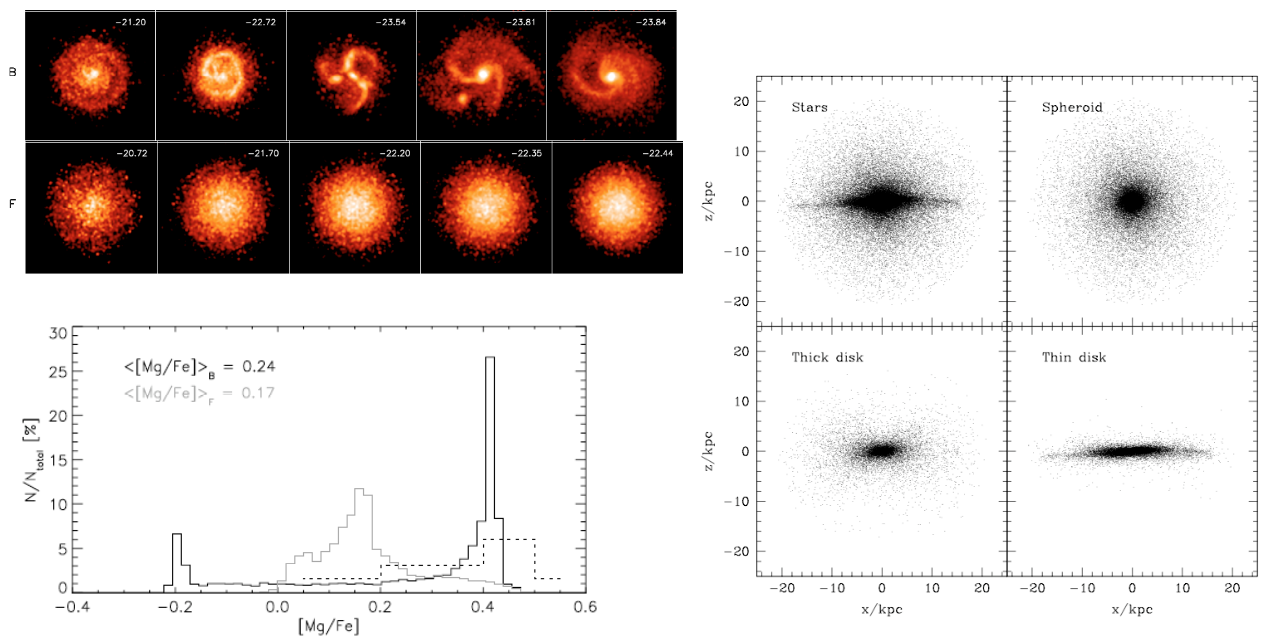
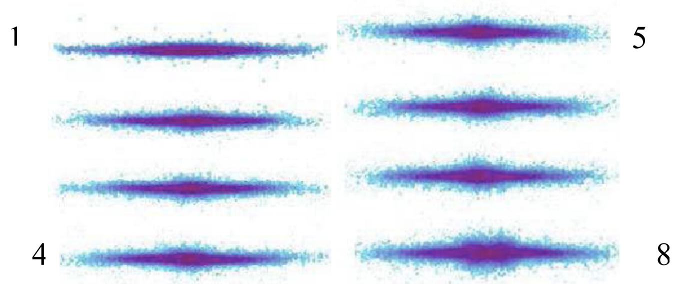


Fig. 1- A range of bulge formation scenarios, with observable consequences. *Upper Left:* The upper panel (corresponding to the bimodal [Mg/Fe] distribution below) considers bulge formation via a merger of clumps (Immeli et al. 2004); lighter (single mode) histogram corresponds to standard scenario shown in lower panel. *(Upper Right):* LCDM model of Abadi et al. (2003) produces an old, spheroidal bulge population, but predicts little or no abundance gradient or rotation. *(Below):* According to Combes et al. (2009) the accretion of gas may promote the regeneration of a bar (peanut bulge) perhaps resulting in population subgroups exhibiting discrete ages and kinematics.



N-body model including gas accretion by Combes (2009). Numbers indicate the sequence of time steps, with time starting at upper left and proceeding down to step 4, with model continuing at step 5. Gas infall has regenerated the bar, which then thickens vertically into an x-shaped bulge.

For the bulge of M31, we have no secure measurements of composition for any individual stars. Since the M31 bulge is well placed in integrated light to share the properties of the classical elliptical galaxy populations in the Virgo cluster, we would be most interested in measuring the characteristics of its individual stars. Placing these abundance and age measurements in the context of kinematics, measured from radial velocities and proper motions, might give insight into the origin and evolution of the Galaxy's central bar population.

Modern facilties (space-based, AO, near-IR) are required to study the bulge populations of the Milky Way, M31 and more distant spheroids in detail. The two key questions here are:

2.1. What is the formation history of the Milky Way bulge?

From an observational perspective, we are presented with two cases that are amenable to study: the Milky Way bulge and nucleus, at 8kpc. The M31 bulge and nucleus, at 770 kpc (roughly 100 times the distance of the Galactic bulge. Each is crucial to understanding structure growth in the universe, but presents its own set of challenges. The Milky Way bulge is obscured by high and variable extinction (e.g. Sumi 2004), and where not highly obscured, is mixed in the field of view with the foreground and background disk, and possibly spatially intertwined with the stellar halo and thick disk. Spatial crowding below the main sequence will defeat small-aperture facilities like GAIA, and is a challenge for HST. AO-enabled imagers on 30m-class apertures (for example IRIS on TMT) will be capable of providing relative astrometric precision on the order of 50μas for well-exposed stars for several fields within a night, dramatically improving the survey efficiency over the only facility that can currently kinematically separate the bulge down to the lower main sequence (HST).

Studies of the Milky Way bulge have so far been limited to any two of {depth, wide area, high stellar density}, but not all three. This has allowed general trends across the Bulge to be discerned (e.g. Sumi et al. 2004), or a detailed picture of bulge kinematics along a single sight-line (e.g. Clarkson et al. 2008), yet a question as fundamental as how many bulge components are even present (is there a superposition of classical *and* pseudobulge?) are not answered by current data.

Addressing this problem requires a deep photometric and spectroscopic census of the Milky Way bulge stellar population, to sample sight lines all along the bulge and bar, with depth sufficient to sample main sequence objects to the far side of the bulge and with multiple epochs (several years separating each epoch). The observations are:

1. Multi-epoch photometry will be crucial to attach proper motions to main sequence objects to the far side of the bulge. The primary aim is to kinematically separate bulge stars from the foreground and background disk on a star-by-star basis, producing a very clean bulge sample. This has been shown to work well for a 2.4m mirror from space in the visible (Kuijken & Rich 2002; Clarkson et al. 2008), but in the near-IR is apparently limited by stellar crowding (e.g. Zoccali et al. 2000). AO facilities on moderate-large aperture facilities will enable this technique to be pushed to the hydrogen-burning limit for the inner Bulge. (Figs 2 & 3)

2. The pure-bulge sample extracted in this way will be the target for spectroscopic investigation, to robustly determine the true abundances of bulge stars at the main sequence, without recourse to evolved objects that might show metallicity bias due to metallicity-dependence of mass loss (see Cohen et al. 2008). This will complement multi-filter metallicity estimates.
3. Photometric distances will allow stellar properties to be probed as a function of distance. This has been demonstrated from HST photometry (e.g. Clarkson et al. 2008) but will be far cleaner when metallicities are used to improve photometric parallax.
4. Photometry of this pure-bulge sample will establish the IMF of the Bulge down to the H-burning limit for a number of sight-lines within the Bulge.
5. For a few sight-lines, deep, contiguous observation-sets will allow transient events to be detected.

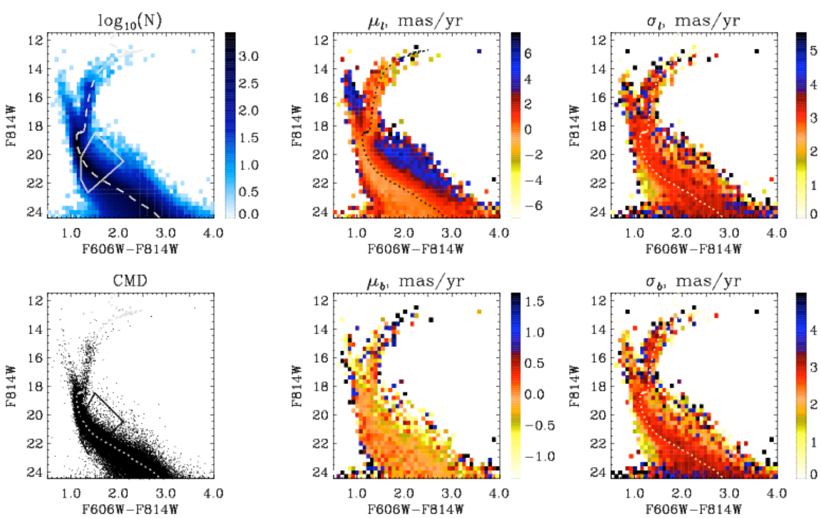


Fig 2-Proper motions may be used to separate the foreground disk (in blue, upper middle panel) from the bulge (orange). This separation is accomplished by segregating the population according to the proper motion parallel to Galactic latitude, μ_l<-2 is assigned to the bulge (not following foreground disk). Notice that the orange population has the appearance of an old globular cluster turnoff. Figure from Clarkson et al. (2008) using the method first employed by Kuijken & Rich 2002.

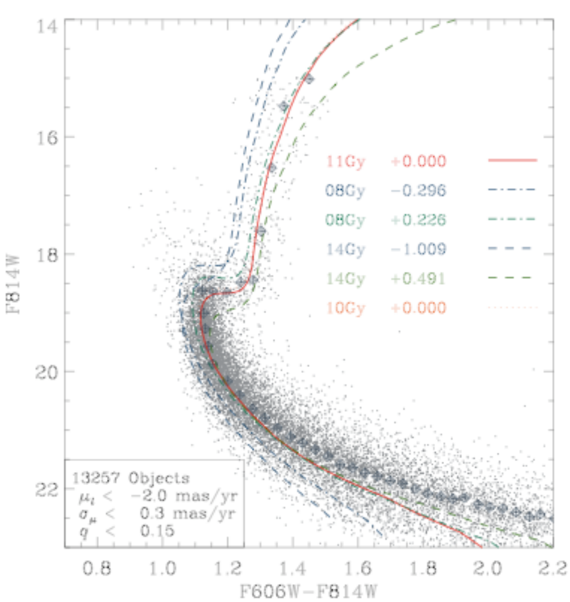


Fig 3- Color-magnitude diagram for a low-latitude field in the Galactic bulge, designed to isolate a pure bulge population using the method given in Figure 2 (Clarkson et al. 2008). The turnoff population is clearly complicated, with the possibility of some age range and even a relatively young (few Gyr) subpopulation. Isochrones presently favor the bulk of the population to be 11 Gyr and Solar metallicity. An IFU on a giant segmented telescope would be capable of measuring radial velocities and compositions for the stars as faint as 1 mag below the turnoff in this plot.

This will enable the formation history of the bulge to be uncovered. The critical issues along the process of explaining the Milky Way bulge, and the observables, are:

- What is the balance of bulge components? Is a small, merger-built classical bulge observable in addition to a secularly-grown pseudobulge? {Metallicities, kinematics}
- What is the range of ages of Bulge stars near the main-sequence turnoff? Did the MW stars form within 10 ± 2.5 Gy or 10 ± 0.5 Gy? {distances, abundances}
- Do kinematics vary as a function of age? {distances, abundances, kinematics}
- Did the bulge form in an outside-in or inside-out manner? {Abundances, kinematics, spatially-resolved IMF}
- Are N-body models (without dark matter and only limited integration of gas, the IGM; Binney 2008) really sufficient to reproduce the existing Milky Way bulge? {metallicities, kinematics}
- What is the true shape of the Bulge potential? How does this integrate with the halo? {3D Kinematics vs distance}
- What is the incidence of planetary systems within the Bulge? How do the results of Sahu et al. (2006) scale to the wider Bulge? Is high metallicity alone a sufficient condition to increase planetary incidence (e.g. Valenti & Fisher 2005) or are additional factors required? {Photometry (transit and/or microlensing), abundances, kinematics}

Current AO-fed imagers on 8-10 m class telescopes can measure proper motions over a small ~20" FOV, and kinematics but not abundances are possible for a brighter subset of that population. Space-based measurements can deliver proper motions but not spectroscopic abundances and radial velocities over a wider field, but may just be capable of reaching the hydrogen burning limit.

An AO-fed integral field unit on a giant segmented telescope would yield spectra of sufficient quality to derive not only radial velocities, but also abundance information well below the main sequence turn-off, and do so for many fields over the whole of the bulge. Combining the abundance and 3D kinematics would provide the spatially resolved formation history of the bulge.

2.2 What are the abundances and kinematics of the M31 bulge and nucleus?

At 770 kpc distant, the M31 bulge and nucleus hosts a black hole two orders of magnitude more massive than that in our Galactic nucleus (Bender et al. 2005), and is observable without significant foreground reddening. Along with M32 and M33, these represent the nearest galactic nuclei available for study, other than that of the Milky Way. The star formation history and composition of stars in these systems would be of great interest, as the alpha enhancement would reveal much about the formation timescale, and the abundance distribution would help to constrain the chemical evolution history. The nucleus of M31 hosts a pc scale disk of A stars (Bender et al. 2005), and with higher spatial resolution, one might be able to ask whether the kinematics and abundances of the stars reveal multiple formation epochs as they appear to do in the Galactic Center. Although the main sequence turnoff is unlikely to be reachable, even with a 30m class telescope, spectroscopy can identify red supergiants that trace Gyr old populations. At R~4,000, (expected for, e.g. IRIS on TMT), it is possible to constrain [α/Fe] and [Fe/H] from spectrum synthesis (Fig 4) for thousands of M31 nucleus and bulge stars (Fig 5). The [α/Fe] constrains the formation timescale for the bulge of M31 and can be compared with the Milky Way bulge. If period distributions can be measured for the Mira variables in the bulges of M31, M81, and in NGC 5128 (already done; Rejkuba et al. 2003) it would be possible to tie kinematics to inferred ages (the longest period Miras are ~few Gyr old). For the first time, it would be possible to compare the detailed formation history of the Milky Way bulge with that of M31, gaining insight into the spheroidal populations that comprise much of the baryonic content of the local Universe.

We do not understand how stars might form in the vicinity of a black hole's strong tidal field. This is also a major problem in the case of the Galactic center, and instrumental capabilities we mention, brought to bear on the M31 bulge, might provide additional answers.

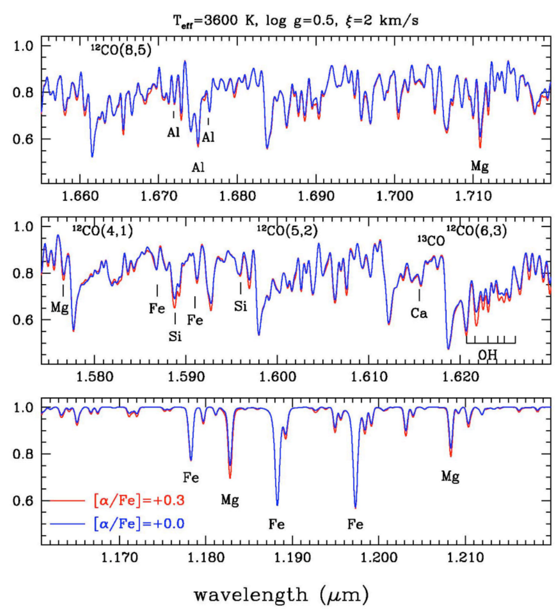


Fig 4- Synthesis of spectrum of an M giant with Solar metallicity and [α/Fe]=0.0 and +0.3, R=3800 (approximate expected resolution of IRIS). It would be straightforward to detect the lower surface gravities of intermediate-age AGB stars, enabling a description of the kinematics as a function of population age and composition. The high S/N required for these anlyses can only be obtained with a giant segmented mirror telescope. Spectrum is courtesy of L. Origlia; see also Rich et al. (2007b). Spectra of this quality in the bulges of M31 (and M32) might be possible, in long integrations, with Keck NGAO. Large samples could be obtained only with an AO-fed integral field unit behind a thirty-meter aperture.

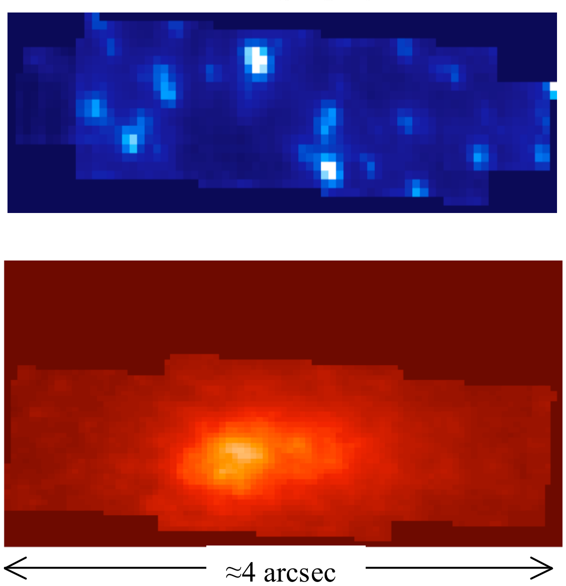


Fig 5- Top: Resolved giants in the bulge of M31, obtained with Keck and the AO-fed integral field spectrograph OSIRIS (field is roughly 1' from the nucleus). The broadband H filter was used. It is not feasible to obtain the S/N ~ 70 spectra required for abundance; the extracted spectra of these stars have S/N~3 in a 1 hour exposure. Bottom: Nucleus of M31 imaged at Keck with AO (OSIRIS). A 30m telescope would resolve the population and permit abundance and gravity measurements for individual stars. Like the Galactic Center, M31 has a massive black hole with star formation in its vicinity. AO-fed spectroscopy with a 30m telescope would enable the construction of detailed velocity maps. The separation between the two nuclei in the bottom figure is ~0.5" ~2 pc (from Rich et al. 2007c).

3.1 References

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