the reverse shock. However, because stars in early-universe galaxies form in substantially denser regions than those in local galaxies [(*41*) and references therein], the dust mass–survival rate is probably greater than that which we infer. Additionally, if each SNe produced as much dust as observed in the ejecta of SN1987A (~0.5 $M_\odot$) (*42*, *43*), SNe could reasonably account for the dust production. These findings are consistent with SNe being a dominant dust-production mechanism in galaxies of the early universe (*7*).

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SUPPLEMENTARY MATERIALS

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REPORTS

GALAXY EVOLUTION

Isolated compact elliptical galaxies: Stellar systems that ran away

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Compact elliptical galaxies form a rare class of stellar system (~30 presently known) characterized by high stellar densities and small sizes and often harboring metal-rich stars. They were thought to form through tidal stripping of massive progenitors, until two isolated objects were discovered where massive galaxies performing the stripping could not be identified. By mining astronomical survey data, we have now found 195 compact elliptical galaxies in all types of environment. They all share similar dynamical and stellar population properties. Dynamical analysis for nonisolated galaxies demonstrates the feasibility of their ejection from host clusters and groups by three-body encounters, which is in agreement with numerical simulations. Hence, isolated compact elliptical and isolated quiescent dwarf galaxies are tidally stripped systems that ran away from their hosts.

Galaxies are thought to form through the hierarchical merging of smaller building blocks into larger systems (*1*, *2*), and the history of these interactions is imprinted in their observable properties. Some galaxies, such as ultra-compact dwarfs (*3*) and compact ellipticals (cEs) (*4*–*7*), show evidence of strong tidal interactions with massive neighboring galaxies (*8*) that stripped most of the stars from the compact galaxies' progenitors. cEs are rare galaxies with high stellar densities that resemble centers of giant ellipticals but have masses that are about two orders of magnitude smaller [M ~ 10^9 solar mass ($M_\odot$)]. They are found mostly in the cores of galaxy clusters next to massive central galaxies, which is in alignment with the above hypothesis for their evolution.

The recent discoveries of isolated cE galaxies (*9*, *10*) that do not belong to any galaxy cluster or group raised another round of debate about cE formation: whether they all formed through the tidal stripping, or through a different mechanism of formation, such as mergers of dwarf galaxies with specific morphologies and configurations (*10*). Dwarf-dwarf galaxy mergers do happen in vicinities of massive galaixes (*11*, *12*). However, neither have they been observed in low-density environments, nor do any of the remnants resemble properties of cE galaxies. The existence of a substantial number of isolated cEs will hence imply notably higher dwarf-dwarf merger rates than predicted by numerical simulations (*13*) and challenge the currently accepted hierarchical structure formation paradigm.

We demonstrated that all known cE galaxies are outliers from the universal optical-ultraviolet color-color-magnitude relation of galaxies (*14*). We could therefore perform a search for cE galaxies not only in the centers of rich clusters and groups as has been done before (*5*), but across all environments using data from wide-field imaging surveys, the optical ground-based Sloan Digital Sky Survey [SDSS, (*15*)] and the ultraviolet all-sky survey carried out by the GALaxy Evolution eXplorer [GALEX, (*16*)] spacecraft, which are all publicly available in the Virtual Observatory.

First, we created an initial list of candidates (supplementary materials) from the sample of galaxies having spectra in the SDSS and, hence, known distances by selecting outliers above +0.035 mag in the optical ($g - r$) color from the

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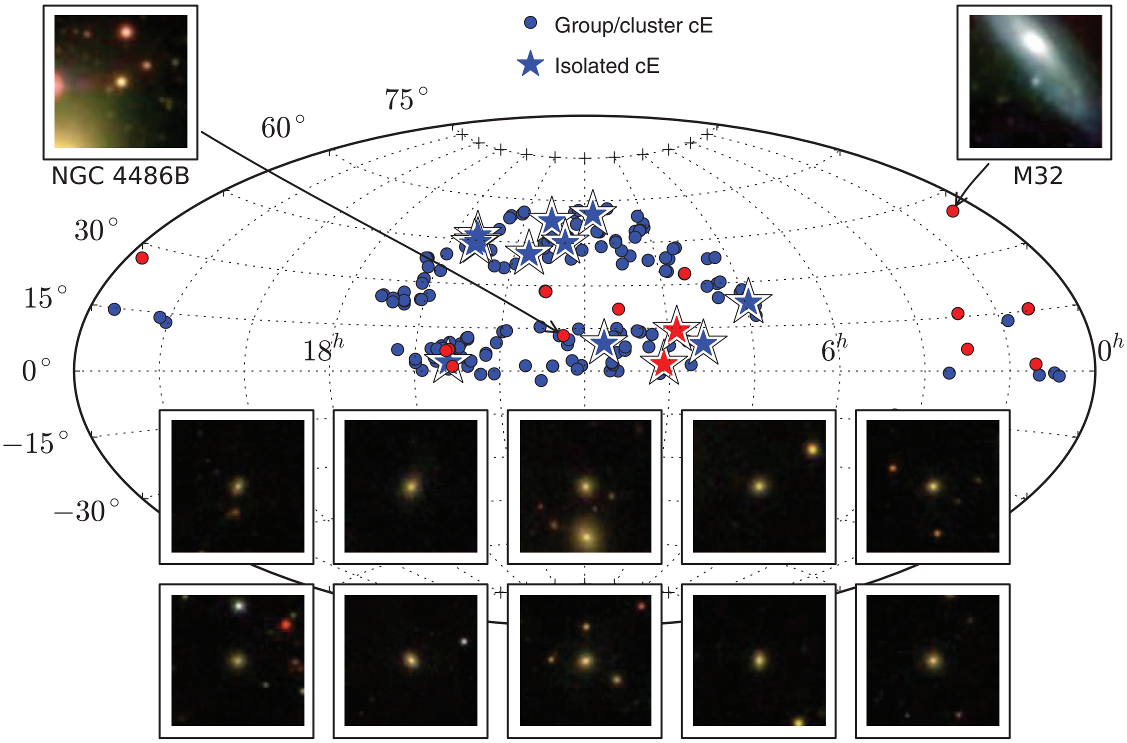

Fig. 1. A sample of compact elliptical galaxies in all types of environment. Our current sample of compact elliptical galaxies (blue symbols) is compared with a data set compiled from the literature (red symbols). Dots and stars denote group/cluster and isolated compact elliptical galaxies, respectively. Square panels in the bottom part of the figure show representatives of the current sample, and top corner insets display Messier 32 and NGC 4486, prototypical cEs in the local universe, as they would look with the SDSS telescope at a 130 Mpc distance (z = 0.03). Each inset panel covers a 20 by 20 kpc region centered on a cE.

universal relation (*14*). We chose low-luminosity galaxies [$L < 4 \times 10^9$ solar luminosity ($L_\odot$) or absolute magnitude (M_g) > –18.7 mag] that had small half-light radii (R_e < 0.6 kpc) or were spatially unresolved in SDSS images; did not show substantial ellipticity, which was essential for removing edge-on spiral galaxies; had the redshifts in the range of $0.007 < z < 0.08$ (distances between 30 and 340 Mpc); and either possessed red near-ultraviolet colors [$(NUV - r) > 4$ mag] or remained undetected in the *NUV* band. We constrained by color and also removed objects that have emission lines in their spectra in order to exclude any objects with recent or ongoing star formation.

We then fitted their SDSS spectra against a grid of stellar population models using the "NBursts" code (*17*) and obtained mean ages, metallicities, and velocity dispersions of their stars. We rejected candidates with stellar ages younger than 4 billion years and introduced an additional constraint based on stellar velocity dispersions (σ > 60 km/s). Stellar systems in equilibrium that are dynamically supported by random motions of stars, as most elliptical galaxies are, have their dynamical masses (M_{vir}), half-mass radii (R_e), and global velocity dispersions (σ_v) connected by the simple virial relation $M_{vir} = 9.96\ R_e\ \sigma_v^2/G$ (*18*, *19*). Therefore, for a galaxy with known velocity dispersion and a stellar mass (M_*) derived from its luminosity and stellar population parameters, we can estimate the lower limit for the half-light radius (if a galaxy contains dark matter, its real half-light radius will be larger because $M_{vir} > M_*$). Hence, we can firmly reject physically extended objects such as "normal" dwarf elliptical galaxies that are unresolved in SDSS images because of their large distances by selecting only objects with high velocity dispersions.

In this fashion, we constructed a sample of 195 galaxies (Fig. 1 and supplementary materials). We then cross-matched this list against the SDSS Galaxy Groups catalog (*20*) and established their group/cluster membership. For seven objects without counterparts in the Galaxy Groups catalog, we identified possible host galaxies (in most cases, group centers) located between 750 kpc and 3.3 Mpc in projection. Because some bright and extended galaxies were missing from the SDSS

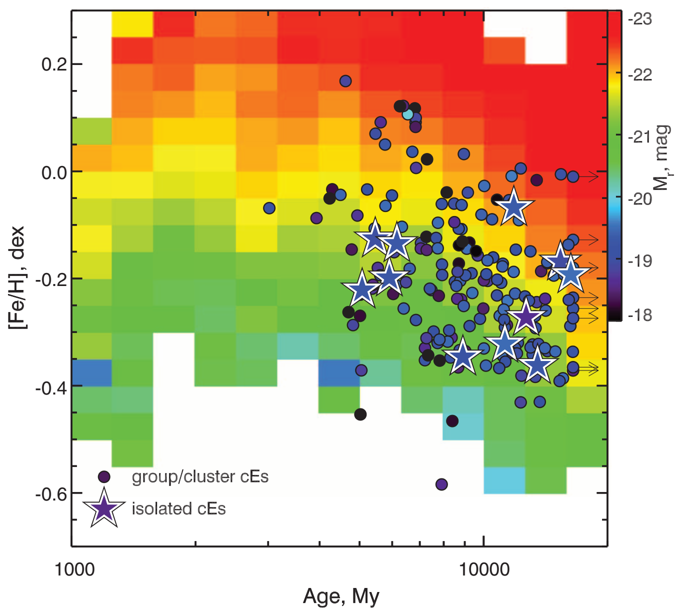

Fig. 2. Comparison of stellar population properties of isolated and nonisolated compact elliptical galaxies to a reference sample of elliptical galaxies from the SDSS. Mean stellar ages and metallicities of cE galaxies hosted by groups and clusters (round symbols) and isolated cEs (stars) were determined from the modeling of their SDSS spectra by using the NBursts full-spectrum fitting. The plotting symbols are color-coded according to the r-band absolute magnitudes derived from the SDSS photometry. We also computed ages and metallicities for a reference sample of 82,500 elliptical galaxies from SDSS DR7 in the same fashion, along with the median r-band absolute magnitude for every bin of age-metallicity parameter space. These magnitudes are shown as a background map, with the colors on the same scale as cE galaxies. This figure demonstrates that (i) stellar populations of isolated and group/cluster cEs do not differ statistically and (ii) cEs are on average much fainter than are normal elliptical galaxies of the same stellar age/metallicity.

spectroscopic sample, and therefore also from the Galaxy Groups catalog, we used NASA/Infrared Processing and Analysis Center (IPAC) Extragalactic Database (NED) for the identification of host galaxies for 45 cEs. Our final sample contains 56 galaxies in clusters, 128 in groups, and 11 isolated or field cE galaxies. Eight galaxies (supplementary materials) exhibit prominent tidal streams similar to the two known cEs (*8*).

Ages and metallicities (Fig. 2 and supplementary materials), colors, and luminosities of 11 isolated cE galaxies do not show a statistically significant difference from those of galaxies being members of clusters and groups. The Kolmogorov-Smirnov (KS) probabilities of these properties for isolated and nonisolated subsamples to be derived from the same underlying distribution range from 30 (for luminosities) to 80% (metallicities). Our cE sample does not show any correlation between the metallicity and the stellar mass, conversely to normal elliptical galaxies, which exhibit a rather tight mass-metallicity relation (Fig. 2).

For rich groups and clusters hosting cE galaxies, we built caustic diagrams (*21*–*23*) that present differences of radial velocities of cluster members from the cluster center versus projected distances. A galaxy position on such a diagram reflects its dynamical status: objects sitting deep inside the cluster potential well are located inside the distribution, whereas galaxies near the edges are barely gravitationally bound to the host cluster or infalling onto it for the first time.

We constructed an ensemble cluster by normalizing individual cluster and group data by their velocity dispersions and sizes for 33 structures from our sample, each of which included over 20 member galaxies (*24*, *25*). Then, we computed its caustic diagram in order to visualize the phase space pattern of the infalling galaxy population and overplotted our cE galaxies on it (Fig. 3). The cE population strongly differs from other cluster members. The KS tests for projected distance and radial velocity distributions reject the hypothesis of cE and cluster member samples being derived from the same parent population at the 97 and 98% levels. Numerical simulations of tidal stripping (*5*, *26*) suggest that a progenitor galaxy, even if it approaches a cluster center on a very extended radial orbit, will lose a major fraction of its orbital energy because of dynamical friction, become gravitationally locked in the inner region of a cluster on a tightly bound orbit, and will finally be accreted by the host galaxy after a few billion years. Many cEs from our sample exhibit this behavior (Fig. 3 and supplementary materials). However, we see a number of cE galaxies close to the edges of the caustics, suggesting that they are barely gravitationally bound to the cluster potential because they do not belong to the infalling population, as we demonstrated. This looks completely unrealistic in the case of a one-to-one galaxy encounter resulting in tidal stripping, but in the case of a three- or multiple-body encounter, this situation becomes significantly more likely.

An interaction of binary stars with the central supermassive black hole is one accepted scenario for the creation of hypervelocity stars (*27*) in our Galaxy: One of the binary components is ejected, whereas the other one falls onto the black hole. Numerical simulations suggest (*28*) that three-body encounters are responsible for putting Milky Way satellites on extreme orbits, going as far as 3 Mpc away. Even though typical galaxy clusters have much wider and deeper potential wells than that of the Local Group, three- and even multiple-body encounters must happen much more frequently in those dense environments. Therefore, a certain probability exists that some of them will lead to the gravitational ejection of galaxies participating in the interaction to extreme radial orbits with the apocentric distances of a few megaparsecs (*29*). A three-body encounter that might eject a cE galaxy from its host cluster or group does not have to happen during the cE formation through tidal stripping; that is, two galaxies do not have to fall onto the cluster/group center at the same time. When a cE progenitor is tidally stripped, it quickly settles on a tightly bound, rapidly decaying orbit (*5*), and if another galaxy infalls later, but before a newly formed cE has been accreted (hundreds of millions to a couple of billion years), the three-body encounter becomes possible.

We estimate the probability of a close three-body encounter geometrically. Numerical simulations suggest (*30*) that over a typical cE lifetime of 2 billion years (*5*), an average brightest cluster galaxy (BCG) must have experienced three or four mergers with massive ($M_* >\sim 10^{10}\ M_\odot$) galaxies. We assume that (i) a typical cE resides on a quasicircular orbit within r_{cE} ~ 120 kpc from a host BCG galaxy after correction for projection effects (fig. S4), (ii) galaxies infall on a BCG on radial orbits from random directions, and (iii) a three-body encounter will be sufficiently close if a cE passes within $r_{3b} \approx 20$ kpc from a massive infalling galaxy. Hence, the probability is as a volume ratio of a cylinder of radius r_{3b}, height r_{cE}, and a

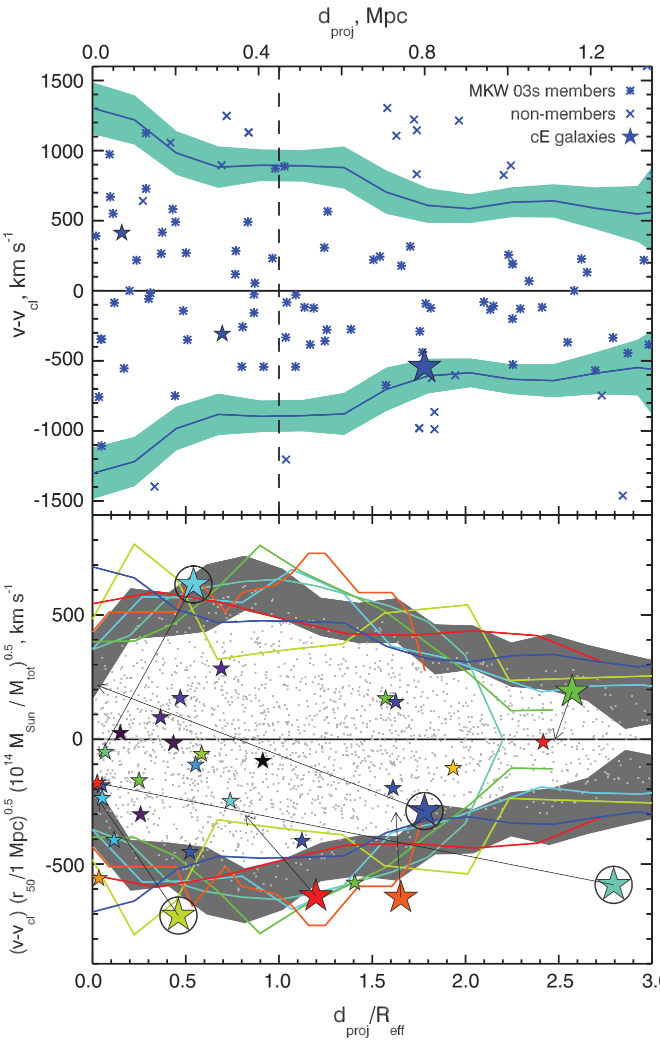

Fig. 3. Positions of cE galaxies identified on caustic diagrams in galaxy clusters and rich groups with more than 20 members in the SDSS. (**Top**) An example of a caustic diagram showing projected distances and radial velocity differences of the members of the cluster MKW 03s that includes cE galaxies shown as stars. The derived caustics shown as solid blue lines roughly correspond to the escape velocity for a galaxy at a given distance from the cluster center. Shaded areas show statistical 1σ uncertainties of the caustic line computation. (**Bottom**) The caustic lines for an ensemble cluster of 2592 individual members are shown as gray shaded areas and light gray dots, respectively. The caustic lines normalized by corresponding velocity dispersions and half-mass radii (R_{eff}) are shown for six individual clusters as colored solid lines. Small stars denote cEs located deeply inside the potential wells of these six clusters, and large stars (with same colors as caustic lines) indicate cEs that have projected radial velocities of at least 85% of the caustic amplitude. Vectors point to the location of identified host galaxies for corresponding cEs. Three of them are different than the cluster of central galaxies, indicating that these cEs belong to subgroups inside clusters and that the caustic diagnostic is irrelevant for them. However, the four circled cEs are examples of galaxies barely gravitationally bound to their host clusters.

sphere of radius r_{cE}, $P_{3b} = 3/4\,(r_{3b}/r_{cE})^2 \approx 0.02$, or ~6 to 8% for three or four merger events.

In our sample of cluster and group cE galaxies, we indeed see numerous examples in which a cE resides only 20 to 80 kpc in projection from an ongoing major merger scene or several other massive cluster members are visible in the cE vicinity apart from the massive central cluster/group galaxy. Also, there is a known example of a globular cluster in the Virgo cluster (*31*) that was likely ejected at the speed of 2500 km/s and became gravitationally unbound to the cluster and its central galaxy, Messier 87.

We conclude that the tidal stripping process can explain all observational manifestations of compact elliptical galaxies, including the formation of isolated cEs whose existence was suggested as a strong counter-argument for tidal stripping (*9*). The ejection of cEs from central regions of galaxy clusters by three-body encounters is a channel for these galaxies to survive for an extended period of time in the violent cluster environment, where they would otherwise be accreted by massive hosts on a time scale of 2 billion to 3 billion years. The 11 isolated cEs probably represent a population of runaway galaxies that received sufficient kick velocities to leave their host clusters or groups forever.

The gravitational ejection mechanism may also explain the very existance of extremely rare isolated quiescent dwarf galaxies (*32*), where the star formation quenching is usually explained by environmental effects. These systems are more spatially extended than cEs and do not exhibit substantial tidal stripping footprints. This suggests that they never came very close to cluster/group centers, and therefore, the three-body encounter probability for them should be lower than that for cEs, although still nonnegligible.

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SUPPLEMENTARY MATERIALS

www.sciencemag.org/content/348/6233/418/suppl/DC1
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ORGANIC CHEMISTRY

A rhodium catalyst for single-step styrene production from benzene and ethylene

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Rising global demand for fossil resources has prompted a renewed interest in catalyst technologies that increase the efficiency of conversion of hydrocarbons from petroleum and natural gas to higher-value materials. Styrene is currently produced from benzene and ethylene through the intermediacy of ethylbenzene, which must be dehydrogenated in a separate step. The direct oxidative conversion of benzene and ethylene to styrene could provide a more efficient route, but achieving high selectivity and yield for this reaction has been challenging. Here, we report that the Rh catalyst (^{FI}DAB)Rh(TFA)(η^2–C_2H_4) [^{FI}DAB is *N,N'*-bis(pentafluorophenyl)-2,3-dimethyl-1,4-diaza-1,3-butadiene; TFA is trifluoroacetate] converts benzene, ethylene, and Cu(II) acetate to styrene, Cu(I) acetate, and acetic acid with 100% selectivity and yields ≥95%. Turnover numbers >800 have been demonstrated, with catalyst stability up to 96 hours.

Vinyl arenes are important precursors for fine chemical synthesis, as well as for the preparation of plastics and elastomers (*1–5*). For example, styrene is produced globally on a scale of ~18.5 million tons (*2*). Current methods for the large-scale production of vinyl arenes involve multiple steps, typically beginning with arene alkylation using a Friedel-Crafts (e.g., $AlCl_3$ with HF) or zeolite catalyst followed by energy-intensive dehydrogenation of the alkyl group (Fig. 1) (*1–6*). Friedel-Crafts catalysis suffers from the use of harsh acids, including HF, low selectivity for the monoalkylated product (polyalkylation is inherent to the mechanism), and the generation of stoichiometric waste (*2*). Zeolite catalysts have improved the process for benzene alkylation, yet these catalysts still require high temperatures (generally 350° to 450°C) and give polyalkylated products (*2, 7–10*).

An alternative method for the production of vinyl arenes is a direct and single-step oxidative arene vinylation (Fig. 1). If the terminal oxidant is oxygen from air (either introduced in situ or used to recycle a different in situ oxidant), the net reaction is the conversion of benzene, ethylene, and oxidant to styrene and water (*11*). Acid-based (i.e., Friedel-Crafts or zeolite catalysts) catalysis occurs by electrophilic aromatic substitution and does not offer a viable pathway to directly generate vinyl arenes. Transition metal complexes that catalyze ethylene hydrophenylation by benzene

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Science

Isolated compact elliptical galaxies: Stellar systems that ran away

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Galaxies stripped down and evicted

It is easy to imagine that the relatively small and dense compact elliptical galaxies once had more to them. Especially when massive galactic neighbors are seen nearby that may have robbed them of their matter, but sometimes there are no such neighbors. Chilingarian and Zolotukhin have mined survey data to show that stripped-down galaxies are found in varied environments, with and without obvious disruptive companions. These isolated galaxies may still have been tidally stripped and then ejected from more crowded neighborhoods.

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