

A Pearl in the Shell: an ultra-compact dwarf within the tidal debris surrounding spiral galaxy NGC 7531

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ABSTRACT

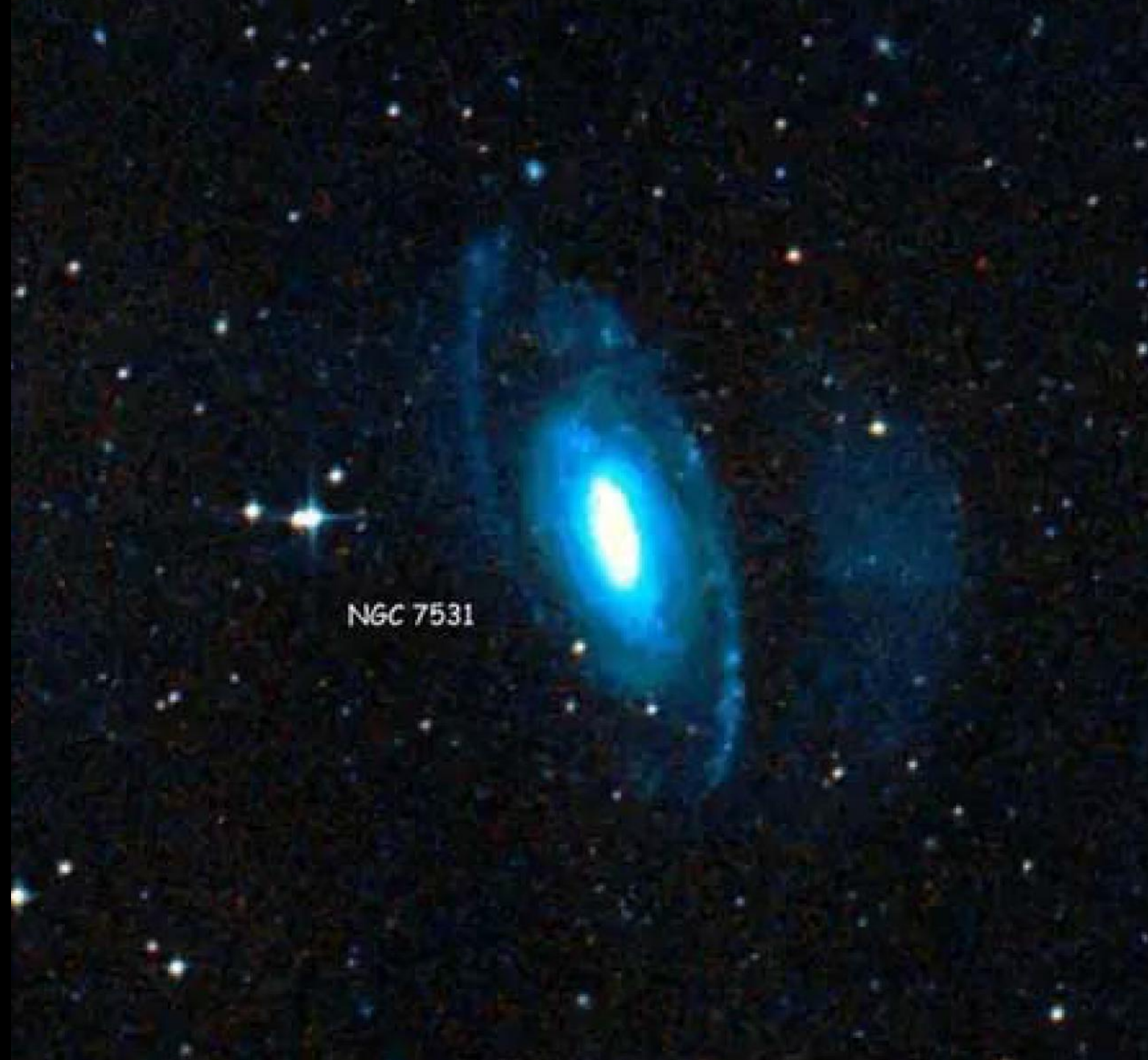
Context. Stellar substructures within tidal debris preserve information about their progenitor galaxies' properties, offering insights into hierarchical mass assembly processes.

Aims. We examine a compact stellar system (CSS) around the nearby spiral galaxy NGC 7531, including the shell-like tidal debris it is embedded within. Our goals are to determine the nature of the CSS, reconstruct its accretion history, and understand how the large, diffuse shell-like structure formed.

Methods. We present photometric measurements of the shell-like debris and CSS using DESI Legacy Imaging Survey (LS) data. We obtained Keck/LRIS spectroscopic data for the CSS to confirm its association with NGC 7531 and to derive its star formation history through spectral energy distribution fitting. Deep (~ 27.9 mag/arcsec²) amateur telescope images of NGC 7531 enabled complete characterization of the tidal debris structure. We constructed tailored N-body simulations to reproduce the observed morphology.

Results. We confirm the CSS is associated with NGC 7531. We rename it as NGC 7531-UCD1, since our estimates for its stellar mass ($3.7_{-0.7}^{+1.0} \times 10^6 M_{\odot}$), half-light radius ($R_h = 0.13 \pm 0.05$ arcsec) and extended star formation history place it in the ultra-compact dwarf galaxy (UCD) category. We find NGC 7531-UCD1 experienced a star formation burst ~ 1 Gyr ago. NGC 7531-UCD1 was likely a nuclear star cluster (NSC) that experienced (and may still be experiencing) tidal stripping which transformed it into a UCD – which is further supported by the presence of tidal tails. We quantify the shell-like debris' mass as $M_{\star} \sim 3\text{--}11 \times 10^8 M_{\odot}$, implying a merger mass ratio of $\sim 300:1$ to $10:1$. Our amateur telescope follow-up images confirm new pieces of tidal debris, previously unclear in the DESI LS images. N-body simulations successfully reproduce these tidal features, requiring a near radial orbit of the progenitor dwarf galaxy with two pericentric passages. The timing of the first pericentre passage coincides with the measured star formation enhancement ~ 1 Gyr ago.

Conclusions. Our findings agree with theoretical predictions about the NSC to UCD formation pathway via tidal stripping, and further confirm the presence of these objects outside of our Milky Way.



NGC 7531

Постановка задачи

Many of the disrupted satellite dwarf galaxies once harbored nuclear star clusters within their cores (NSCs). Thanks to their high densities and stellar masses ($M_{\star} \sim 10^5\text{--}10^8 M_{\odot}$), NSCs tend to survive the tidal disruption of their host galaxy and morphologically evolve into a different object class, such as GCs or ultra-compact dwarf galaxies (UCDs). We examine a stellar system (CSS) around the nearby spiral galaxy NGC 7531, including the shell-like tidal debris. **Our goals** are to determine the nature of the CSS, reconstruct the accretion history, and understand how the large, diffuse shell-like structure formed.



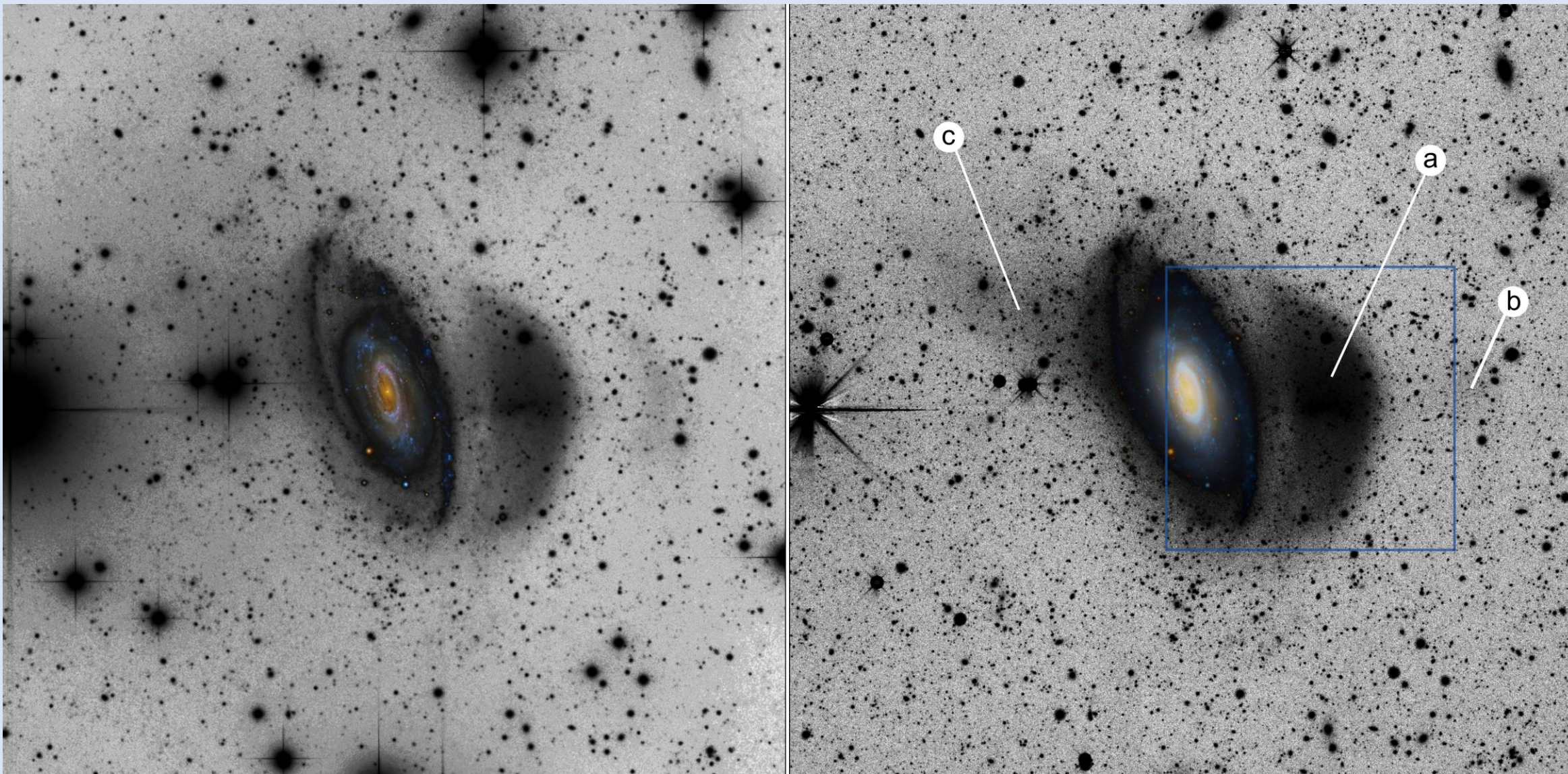


Fig. 1. Amateur image of NGC 7531 (*left*). DESI Legacy Imaging Survey image of NGC 7531 (*right*). Sky-subtracted image of NGC 7531 as processed by Gnuastro’s *NoiseChisel* program was used as a basis for photometry measurements. Features are labelled: (a): main shell; (b): faint outer shell; c: counter plume.

- DESI Legacy survey: Пределы (3 sigma от темного фона) 29.3, 29.0, 27.8 (g,r,z)
- Amateur telescope 60 cm, luminance filter, 126x900s (более 30 час)
- Keck spectroscopy



Fig. 2. Identification chart of the compact stellar system potentially embedded within the giant tidal debris cloud in the halo of NGC 7531. The background image used is from the DESI Legacy Imaging Survey.

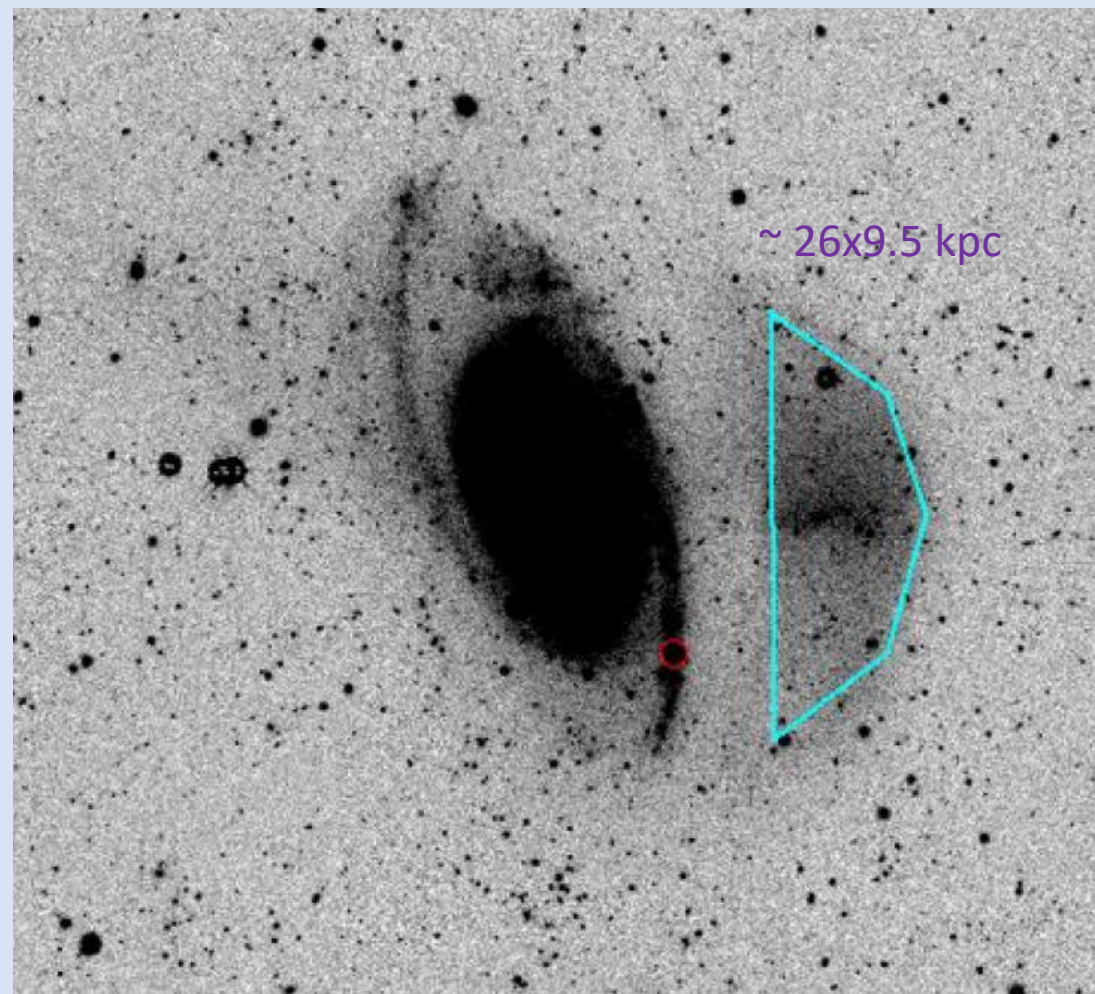


Fig. 3. Photometric measurement method for the shell around NGC 7531. The polygonal aperture (*blue*) indicates the part of the image where the magnitude, surface brightness and colour of the shell were measured. For comparison, the surface brightness and colours were measured in a circular aperture (*red*) placed on the NGC 7531 spiral arm.

- Грубая оценка светимости “shell feature” - $\sim$ неск. $10^8 L_s$.
Соответствующая начальная масса разрушившегося спутника $\sim 10^9 M_s$.

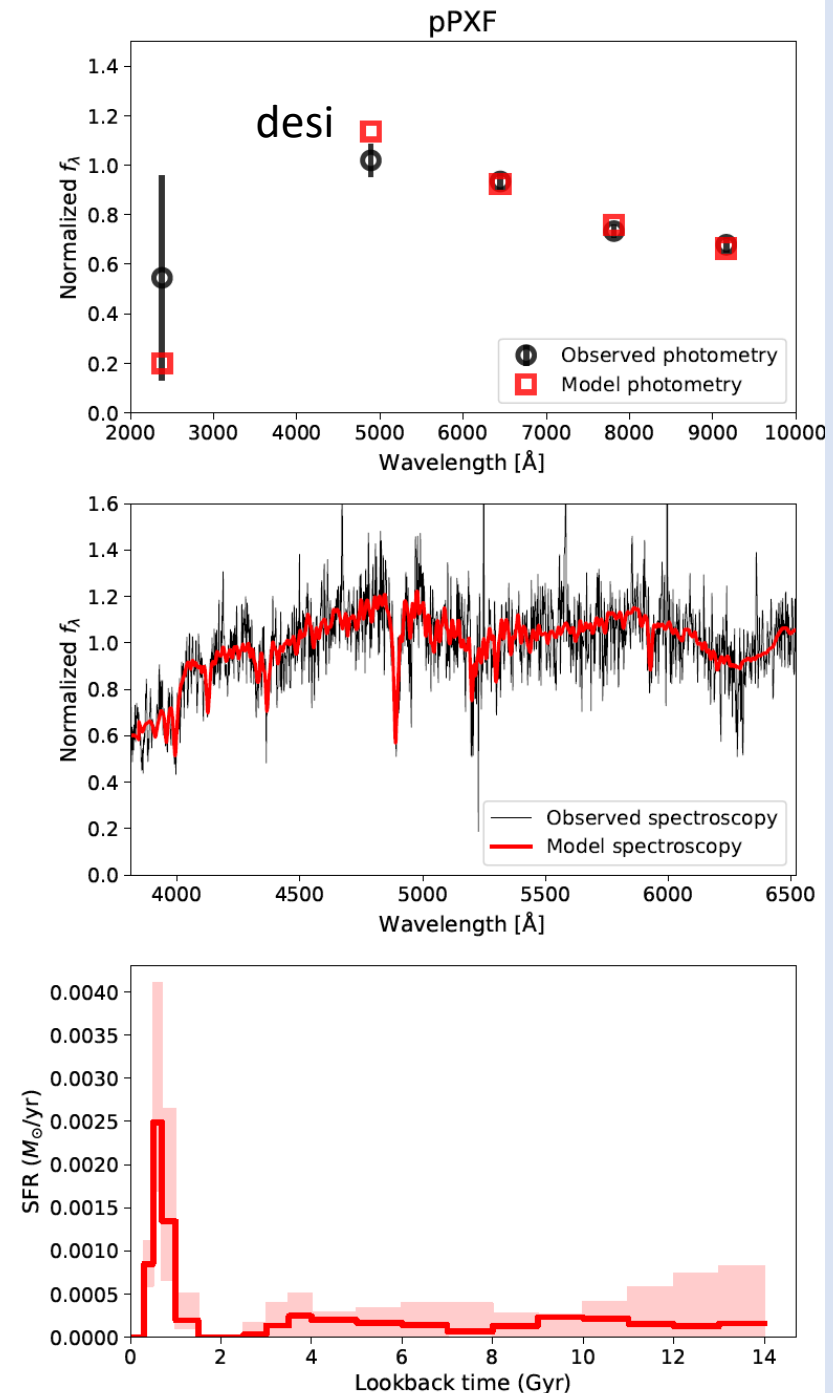
Масса NGC7531 – порядка $3 \cdot 10^{10} M_{\odot}$

Table 1. Surface brightnesses and colors for the shell-like debris feature around NGC 7531 (top row) and for an aperture placed on the arm of NGC 7531 (bottom row).

	$\langle \mu_g \rangle$ [mag arcsec ⁻²]	$\langle \mu_r \rangle$ [mag arcsec ⁻²]	$\langle \mu_z \rangle$ [mag arcsec ⁻²]	$\langle g-r \rangle$ [mag]	$\langle g-z \rangle$ [mag]	$\langle r-z \rangle$ [mag]
Shell	25.43 ± 0.0019	24.85 ± 0.0017	24.50 ± 0.0012	0.57 ± 0.003	0.90 ± 0.002	0.34 ± 0.002
NGC 7531	23.79 ± 0.008	23.60 ± 0.007	23.53 ± 0.007	0.18 ± 0.009	0.24 ± 0.009	0.06 ± 0.009

Моделирование спектра “compact stellar system” (CSS) (по характеристикам – это UCD)

- To obtain a non-parametric SFH, we set the time bins to $[0, 0.1]$, $[0.1, 0.2]$, $[0.2, 0.5]$, $[0.5, 1.0]$, $[1.0, 2.0]$, $[2.0, 5.0]$, $[5.0, 10.0]$, $[10.0, 14.0]$, including stellar mass ($6.0 < \log M^*/M_\odot < 7.5$), metallicity ($-2.0 < [M/H] < +0.2$), and dust ($0 < A_V < 2.0$).
- We do not attempt to model the stellar populations of the diffuse substructure, given the lack of either spectroscopy or near infrared photometry. However, we can make a qualitative conclusion that it is older than the CSS, given the redder color and implausibility of the metallicity being higher.



Compact stellar system

R_G	15.2	kpc
g_0	20.69 ± 0.07	mag
$M_{g,0}$	-11.02 ± 0.07	mag
$(NUV - g)_0$	2.29 ± 0.60	mag
$(g - r)_0$	0.54 ± 0.06	mag
$(g - i)_0$	0.72 ± 0.06	mag
$(g - z)_0$	0.82 ± 0.07	mag
R_h	0.13 ± 0.05	arcsec
R_h	14 ± 5	pc
P.A.	18.07 ± 25.73	degree
b/a	0.96 ± 0.02	
$M_\star$	$3.7^{+1.0}_{-0.7} \times 10^6$	$M_\odot$
Age (SSP MODEL)	$3.7^{+2.0}_{-1.3}$	Gyr
[M/H]	$+0.13^{+0.02}_{-0.03}$	dex

Age = mass-weighted

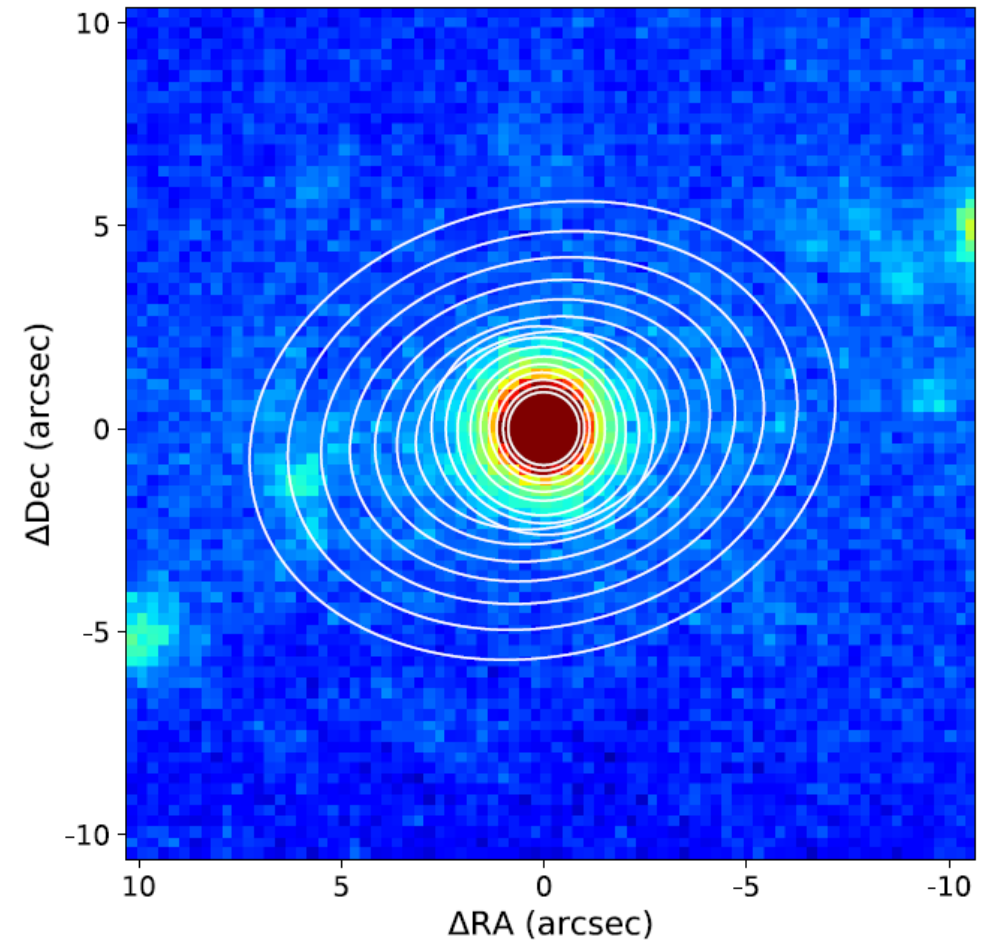


Fig. 4. DESI Legacy Survey image of the compact stellar system and surroundings, with elliptical isophote contours overlaid. North is up and East is left. The compact, round star cluster transitions to a flattened structure at $\sim 2\text{--}3$ arcsec that likely represents tidal tails (also visible in Figure 2).

- В процессе эволюции UCD1 вполне может переместиться к ω Cen.

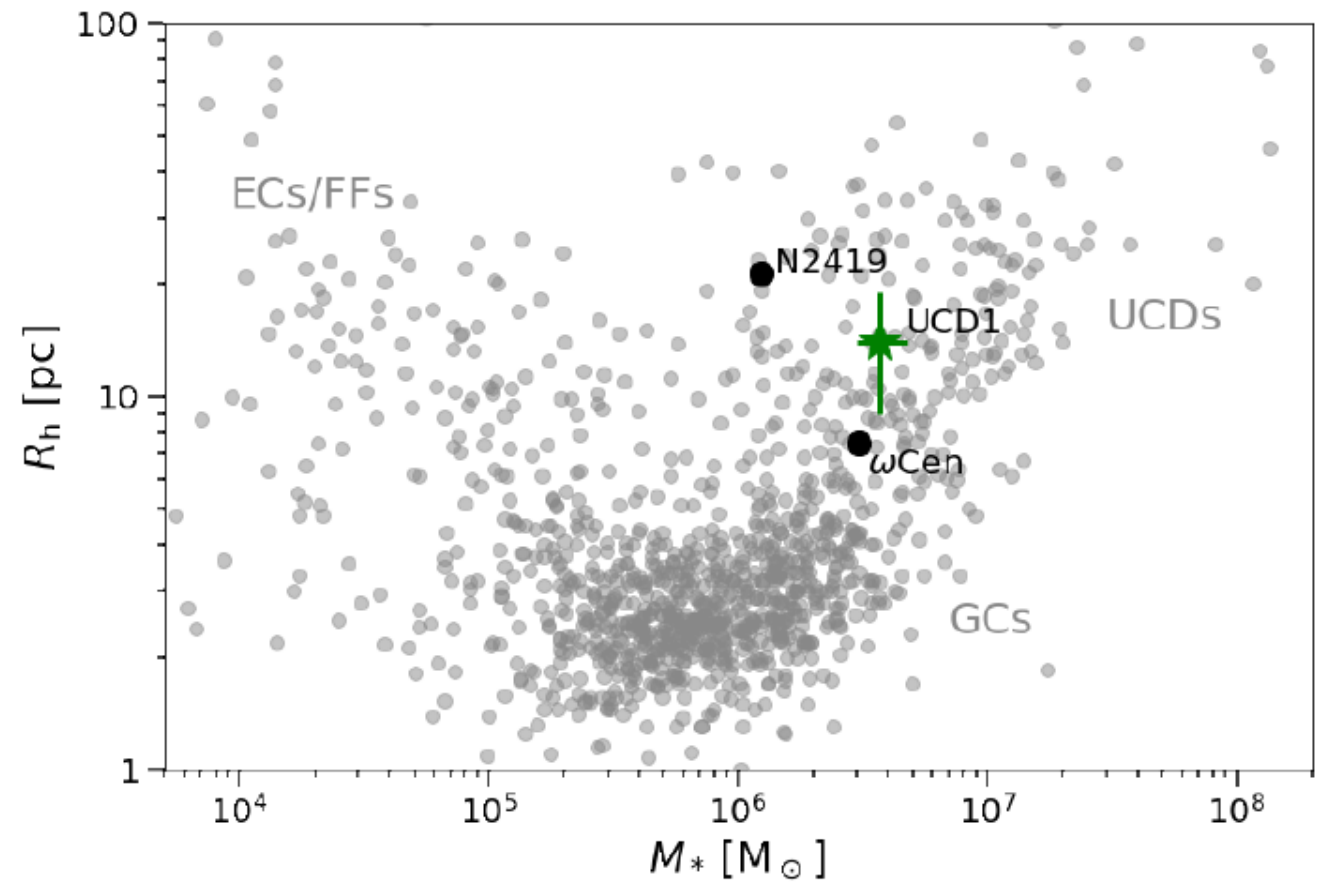


Fig. 6. Half-light radius vs. stellar mass for the compact stellar systems. The object lies in the ultra-compact dwarf galaxy (UCD) range, we thereby denote it as UCD1 (green star). For reference, we mark the location of the massive MW star clusters ω Cen and NGC 2419. We also denote the approximate locations of globular clusters (GCs), extended clusters (ECs) and faint fuzzies.

ЧИСЛЕННАЯ МОДЕЛЬ

NGC 7531:

- NFW dark halo with $M = 3.32 \cdot 10^{11} M_{\odot}$, Scale radius 11.93 kpc
- Disc with a mass of $2.82 \times 10^{10} M_{\odot}$, a scale radius of 2.24 kpc and a scale height of 0.21 kpc.

The stellar component:

- stellar mass of $3 \times 10^8 M_{\odot}$,
- half-light radius 1.5 kpc.
- A virial mass $M_{200} = 3 \times 10^{10} M_{\odot}$
- Near-radial motion

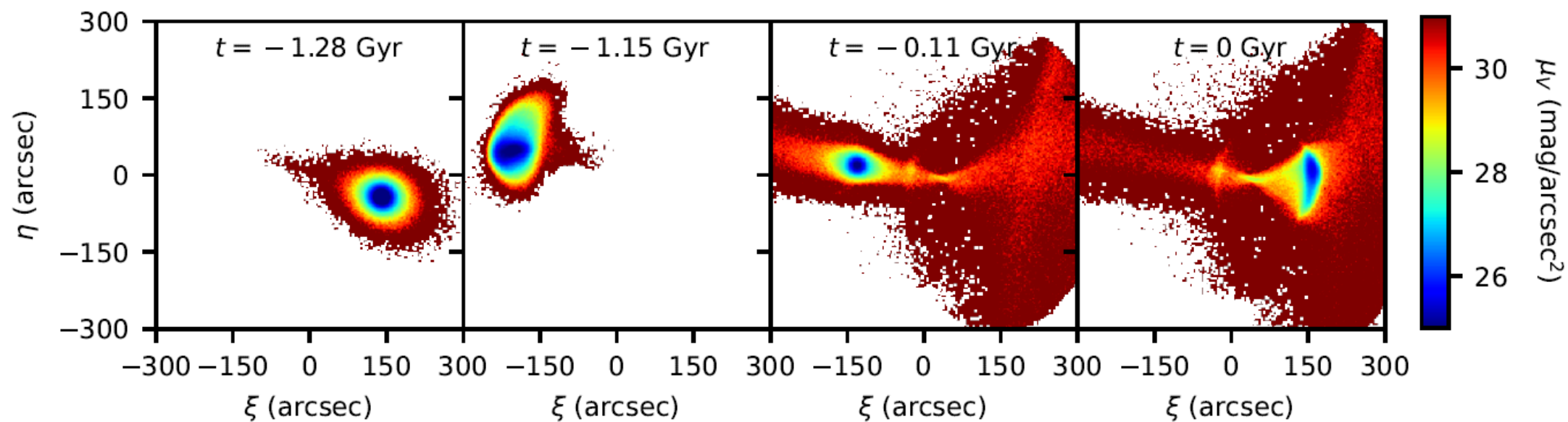


Fig. 8. Evolution of the N -body simulation which produces a shell similar to what is observed in NGC 7531. From left to right, the panels show the simulated dwarf 50 Myr before the first pericenter ($t = -1.28$ Gyr), 70 Myr after the first pericenter ($t = -1.15$ Gyr), 50 Myr before the second pericenter ($t = -0.11$ Gyr), and 60 Myr after the second pericenter (present day).

The present day: a vibrant shell, a trailing stream on the left, and an additional shell-like low surface brightness structure to the right.

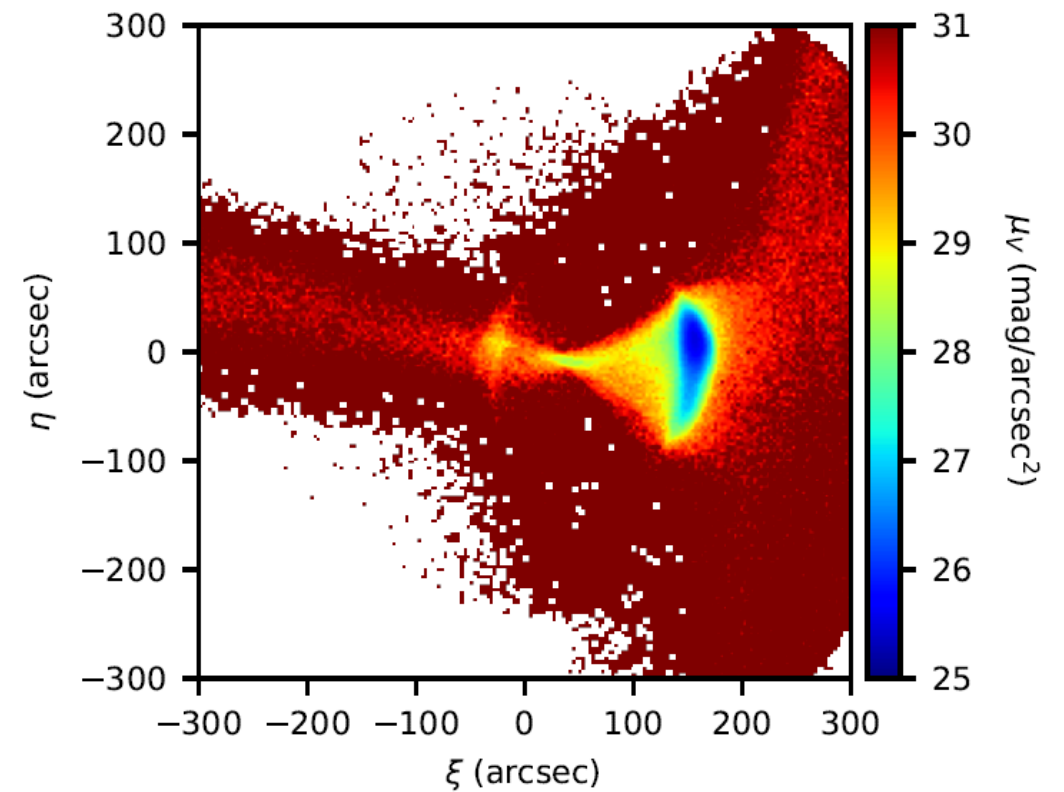
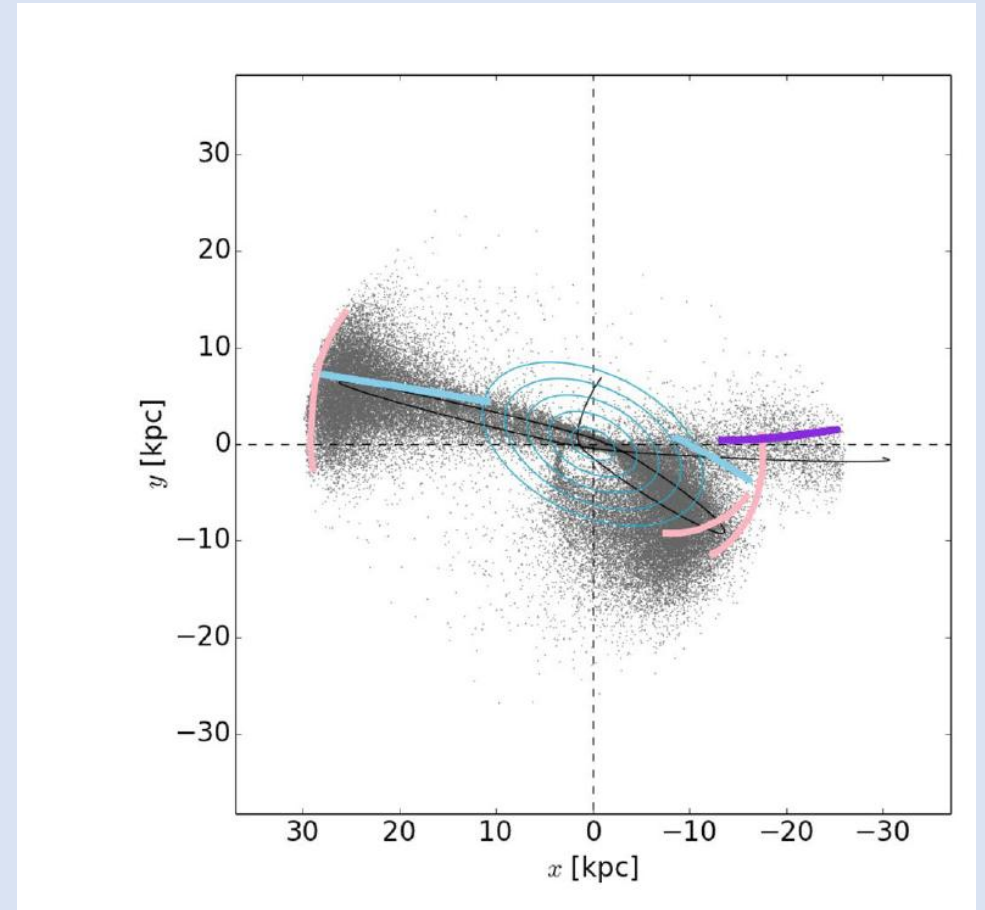
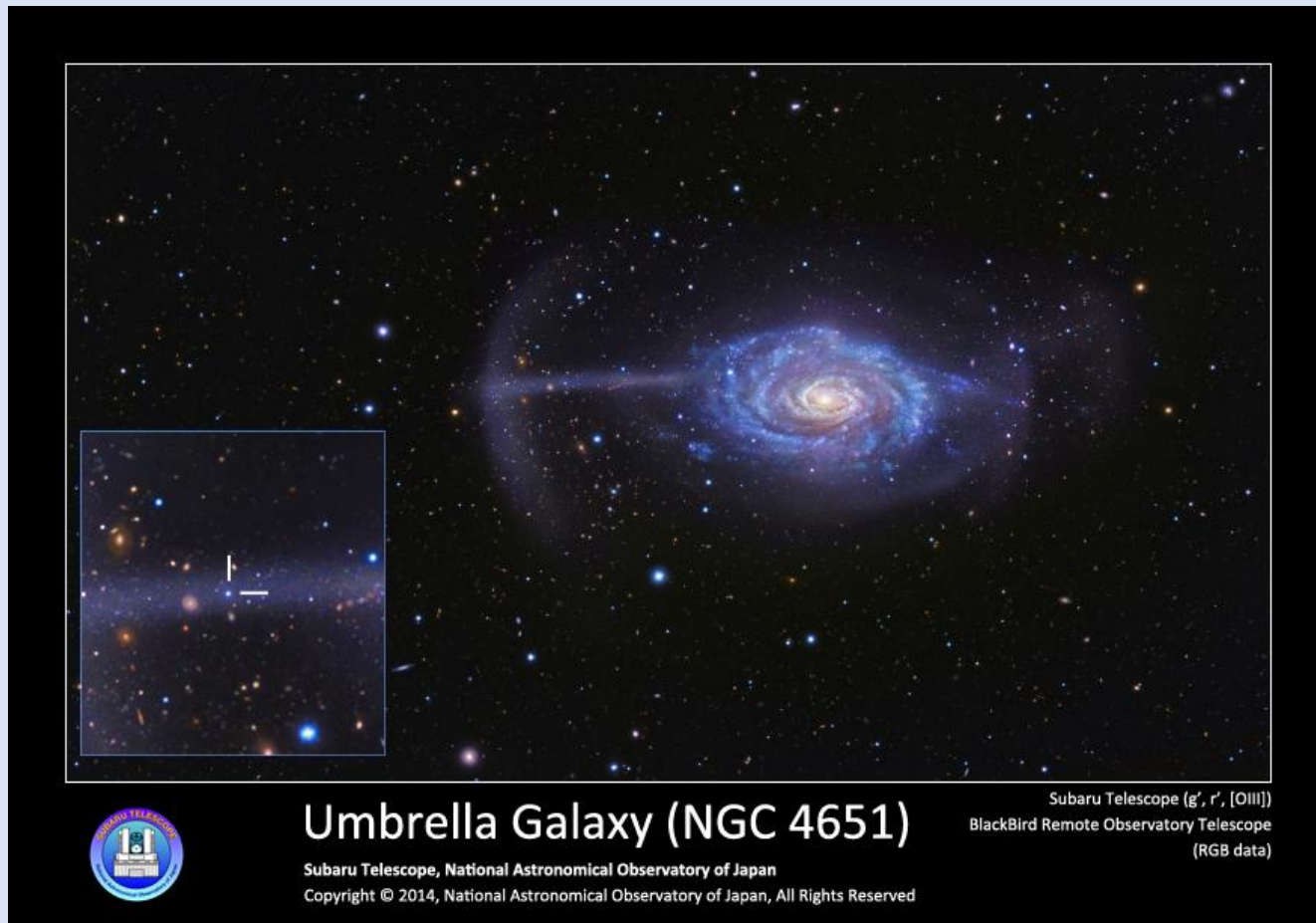


Fig. 7. Surface brightness map of the simulated dwarf debris around NGC 7531 which qualitatively matches the observations. This snapshot occurs 60 Myr after the most recent pericentric passage and 1.23 Gyr after the first pericenter.

- This conclusion matches up well with the recent burst in star formation ~ 1 Gyr ago

Сходный случай: NGC4651



The Umbrella Galaxy system may provide an example of dwarf quenching during infall to a larger galaxy (Foster et al., 2014)