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Compact galaxies? : ask the Illustris simulation!

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Abstract. Compact galaxies, known to be abundant in the past, some 10 billion years ago, are generally thought to be almost extinct in the present Universe. In a previous statistical study, we ratified that, instead of vanishing, the majority of them have survived, hidden by stellar disks or halos. Recent hydrodynamical cosmological simulations, like Illustris, not only produce realistic galaxies, but also enclose a sufficiently large volume to include some of the rarest specimens, like the compact galaxies. By tracking the evolution of the simulated systems we have followed the fate of the high-redshift compact galaxies. As already observed, the compact galaxies at $z = 2$ survive to $z = 0$ embedded in accreted halos or disks. We also compare two simulated galaxies hosting compact cores, yet accreting either a disk or a spheroidal halo.

Resumo. As galáxias compactas, abundantes no passado, cerca de 10 bilhões de anos atrás, encontram-se quase extintas no universo presente. Em um estudo estatístico anterior, ratificamos que, em vez de desaparecer, a maioria delas sobreviveu, escondidas por discos estelares ou halos. As recentes simulações cosmológicas hidrodinâmicas, como Illustris, não apenas produzem galáxias realistas, mas também incluem um volume suficientemente grande para incluir alguns dos espécimes mais raros, como as galáxias compactas. Neste estudo seguimos a evolução das galáxias compactas simuladas. Neste estudo confirmamos que, as galáxias compactas a redshift 2 sobrevivem na actualidade embutidas em halos ou discos. Comparamos também duas galáxias simuladas que possuem núcleos compactos, ainda que uma delas acrescentou um disco enquanto a outra um halo esferoidal.

Keywords. Galaxy: evolution – Cosmology: miscellaneous – Techniques: miscellaneous

1. Introduction

Numerical Simulations still suffer from a bad image in some observational astrophysical communities. Yet, it is worth emphasizing that numerical simulations are a must, rather than a luxury, for studying the non-linear growth of structures in the Universe. In the *pre-computer era* (1940-50), scientists and engineers commented: *God would not be so unkind as to make the equations of nature nonlinear*, frustrated after realizing that nature is essentially non-linear and, consequently out of the reach of their analitical tools. Today, numerical simulations are the theoretical tool of choice to study the formation and evolution of galaxies.

Cosmological hydrodynamic simulations, like Illustris (Vogelsberger et al. 2014; Nelson et al. 2015) or EAGLE (Schaye et al. 2015), produce a realistic morphological mixture of galaxies, which follow scaling relations not explicitly imposed by the postulated physical mechanisms. Additionally, the Illustris cosmological co-moving volume (106.5 Mpc)^3 is large enough to include rare galaxies.

Simulations allow one to track the galaxy evolution along a wide redshift range from 47 to 0 by means of the merger tree which connect galaxies at different redshifts. This makes simulations a useful tool to assist astronomers on the theoretical interpretation of their results. In the present study, we have used the Illustris simulation to shed light on the unsolved mystery of the red nugget's fate.

More than nine Gyrs ago, at $z = 1.5$, a massive galaxy census would result in roughly 40 % disks, 15 % extended spheroids, 25 % compact spheroids and some 20 % peculiars (e.g. Peth et al. 2016). A compact spheroid encloses a mass comparable to the Milky Way, within a small volume (typically the size of a bulge). At $z = 1.5$, the compact spheroids are divided into 1/4 blue (star-forming) and 3/4 red (quiescent). For short, the high-redshift massive quiescent compact galaxies have been nicknamed *red-nuggets*. On average, 200 red nuggets were found in each Illustris volume (106.5 Mpc)^3 at $z = 1.5$. In the present day universe, a similar census of massive galaxies gives 30% disks, 65% extended spheroids and 5% peculiar morphologies (Buitrago et al. 2013). Strikingly, red nuggets are virtually absent (e.g. Trujillo et al. 2009; Taylor et al. 2010).

The predominant interpretation of this extinction problem postulates that red nuggets ended up in the centres of present day massive ellipticals after the growth of an extended stellar halo through disipationless minor mergers (Hopkins et al. 2009; Bezanson et al. 2009). An alternative view links red nuggets to the bulges of the present day massive disk galaxies (e.g. Graham, Dullo & Savorgnan 2015), showing that bulges and red nuggets are structurally similar. In this scenario, red nuggets would have *survived* hidden by stellar disks. In a further study, de la Rosa et al. (2016) showed that both channels are possible and roughly 50 % of the massive galaxies hosting red nugget-like cores show disks. Additionally, the number density of red nugget-like cores hosted by present day galaxies is comparable to that of red nuggets at $z = 1.5$, giving more weight to the hypothesis of their survival.

The question we pose to the Illustris simulation is, do all individual compact cores survive from $z = 1.5$ to $z = 0.0$? By tracking the red nugget's descendants along the merger trees, the simulation allows us to watch the 2D or 3D stellar halo construction around the surviving compact core. We are particularly interested on understanding the growth of a disk around a red nugget, so we will carry out a detailed monitoring of two alternative examples, a disk and a spheroidal galaxy.

2. The Data

In de la Rosa et al. (2016), photometric bulge+disk (B+D) decomposition was used to carry out a segregated study of the bulge, herein called *core*. We use the compactness criterion devised by van Dokkum et al. (2015), $R_{eff} < 2.0$ kpc

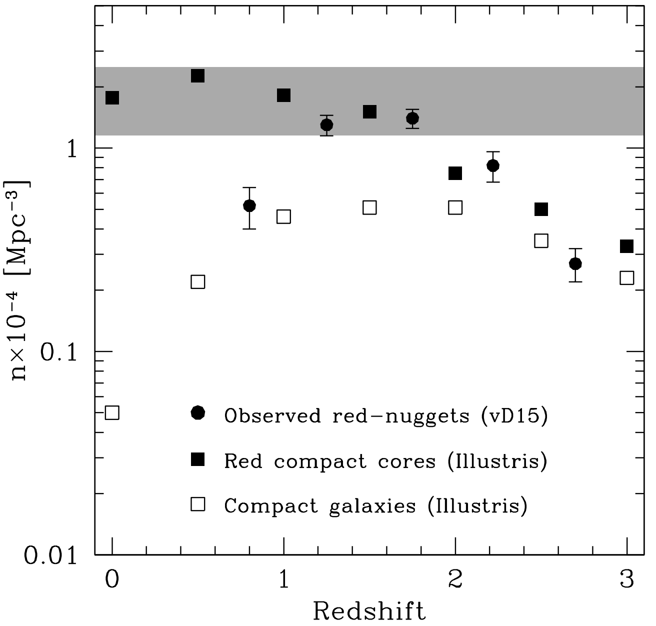

Figure 1. Number density evolution of observed red nuggets (van Dokkum et al. 2015) and Illustris red compact cores (solid circles and squares). The discrepancy between observations and simulations, at redshifts $\lesssim 1.5$, are attributed to the fact that observations compute full galaxies (instead of their cores), which are hardly compact at low redshifts, as seen by the density of Illustris compact galaxies (open squares).

$\times$ ($M_\star/10^{11}M_\odot$) to compare the number density of *compact* red nuggets at z≈1.5 with that of present day *compact* cores. A constant number density would fit the expectations of the red nugget survival hypothesis, as it was found by de la Rosa et al. (2016), using SDSS galaxies. Illustris simulation allows tracking the compact core number density along the full $z = 3$ to 0 redshift range. B+D decomposition has always been a laborious task. A kinematic, rather than photometric B+D decomposition has shown to be more suited for Illustris galaxies by Bottrell et al. (2017). Using Illustris data for 6,762 galaxies with log$M_\star$ >10 we have measured the compacity of their cores, log$(M_\star/R_{eff})_{core}$, discovering that it shows a perfect correlation with the parameter logΣ_{1kpc}, the stellar mass density in the central 1 kpc of the galaxy. This parameter, introduced by Cheung et al. (2012), is easily computable in simulated galaxies and makes a perfect proxy for the core compacity. As shown above, for van Dokkum et al. (2015) a core can be classified as compact when its compacity log$(M_\star/R_{eff})_{core}$ exceeds 10.7. Our calculations (to be published) show that this condition is equivalent to logΣ_{1kpc} > 9.15.

3. Results

In the present study, the Illustris data are used to shed light on two different controversies. On one side, the disagreement on the evolution of the number density of compact galaxies. On the other side, the poorly understood process of disk formation around a compact core.

3.1. Number density

As discussed in Section 1, red nuggets are considered as virtually extinc in the present universe (e.g. Trujillo et al. 2009; van der Wel et al. 2014; van Dokkum et al. 2015). However, other studies, using low redshift samples, disagree on that results (An updated summary in Charbonnier et al. 2017). In the present study, we test the possibility that this discrepancy could be attributable to the questionable use of compacity measurements of full galaxies. As galaxies evolve and external accretion proceeds, full galaxies see their general compacity declining to the point that, at $z = 0$ virtually no full galaxy satisfies the strict compactness criteria. Galaxy cores, on the contrary, can keep their compacity intact, despite the progressive assembly of an accreted halo.

We have carried out compacity measurements on both the core and the full galaxy of Illustris samples at redshifts ranging from 3 to 0. Following van Dokkum et al. (2015) criterion, a *compact full galaxy* must fulfil log$M_\star$ >10.6 and log$(M_\star/R_{eff})$ > 10.7. A *compact core*, as shown in Section 2, must comply with logΣ_{1kpc} > 9.15. We have used the star formation rate (SFR) Illustris information to seggregate quiescent from actively star forming galaxies. Only cores hosted by quiescent (red) galaxies are accounted. As shown in Figure 1, the number density evolution of both red compact cores and compact full galaxies are compared to van Dokkum et al. (2015) observations. Observed and simulated galaxies reasonably match down to redshift ≈ 2. There, the compact full galaxy number density declines, as expected by the accretion. The Illustris red compact core density grows along with that of the red nuggets up to a peak at redshift ≈ 1.5. At lower redshifts, when the red nuggets have likely accreted a diffuse halo, the number of both observed and simulated full compact galaxies (even those hosting a hidden red nugget) drops drastically. Oppositely, the Illustris compact core number density is kept relatively constant around the red nugget peak value, at z≈1.5, supporting the hypothesis of their survival to the present day universe.

3.2. Disk formation

We have selected examples of two simulated galaxies which host a compact core, but differ on their morphology. Galaxy id=138414 shows a disk and id=233087 (ids at $z = 0$) show a spheroidal morphology. Our purpose is to find out the processes responsible for their alternative developments. To this end, we have collected the evolution of several structural parameters, which allow us to follow the galaxy assembling. Those parameters, shown in Figures 2 and 3 include: (a) the star formation rate (SFR) and central super massive black hole (SMBH) accretion rate; (b) the gas and star masses; (c) the *in-situ* and *ex-situ* stellar masses, which refer to stars formed respectively in the present galaxy or in an external one, but later accreted; (d) bulge-to-total (B/T) ratio, where high (B/T) corresponds to spheroidal-like morphologies; (e) the stellar mass density in the central 1 kpc, the logΣ_{1kpc} parameter introduced by Cheung et al. (2012) and (f) the SMBH mass.

As seen in Figure 2, the disk galaxy exhibits two main phases: a *compact-core* phase, ranging from z ≈ 3.3 to z ≈ 2.5 and an *accretion* phase lasting to z $\lesssim$ 0.5. The *compact-core* phase is triggered by a major merger (1:1), which contributes to the formation of the bulk of the galaxy's stellar mass, with both gas and ex-situ (ready formed) stars (panel-c). Gas from the merger (panel-b) is converted into in-stu stars (panel-c) by means of the intense star formation rate, which peaks at 250 M$_\odot$/yr (panel-a). There are evidences of cold gas driven to the galaxy center, where an intense star formation burst creates a compact core and feeds the SMBH. Evidences that cold gas was driven to the galaxy center are seen in the enhanced SMBH ac-

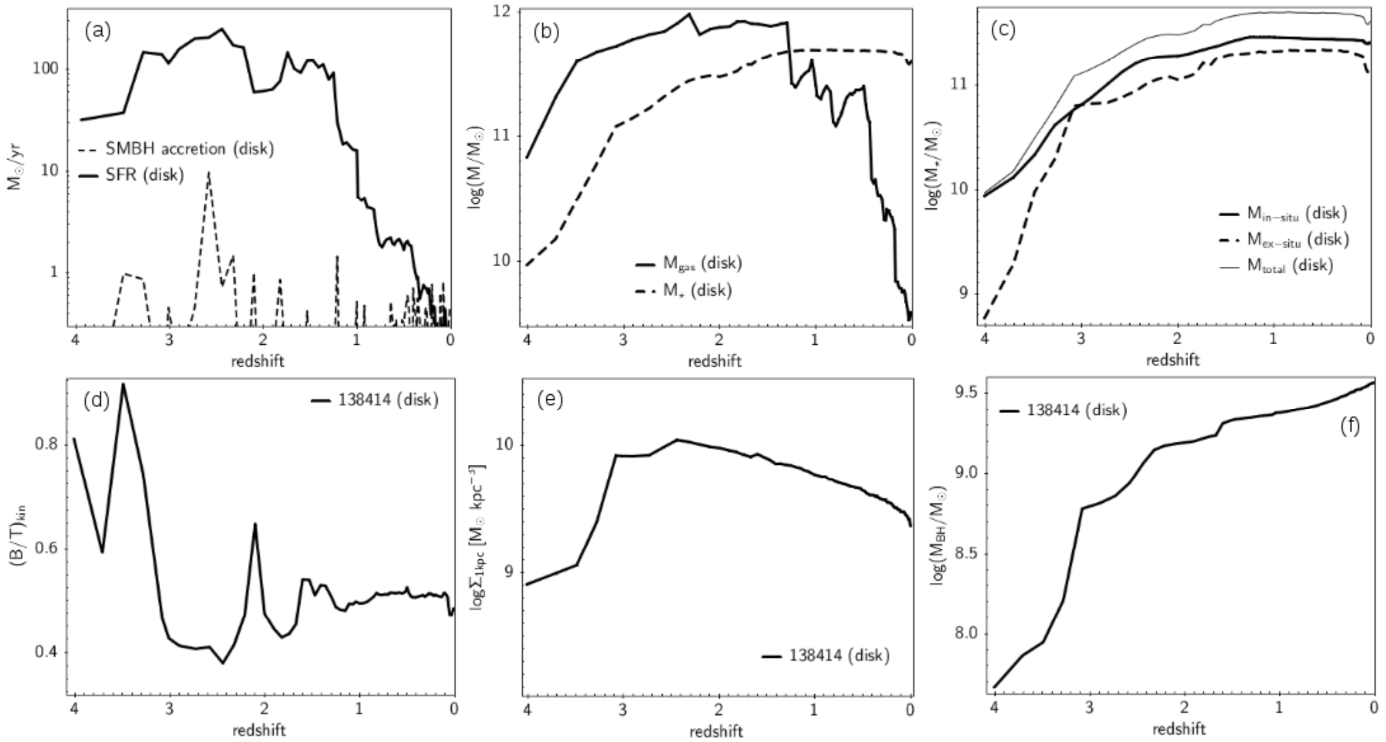

Figure 2. Parameter evolution from $z = 4$ to 0 for the simulated disk-like galaxy. See main text for parameter explanation and their evolution interpretation.

cretion (panel-a), SMBH mass increase (panel-f) and rapid central density increase (panel-e), which creates a compact core, surviving to $z = 0$, albeit with a decreasing compacity. At the beginning of this phase, the galaxy becomes morphologically very spheroidal-like (high (B/T)), although it rapidly changes to very disk-like (panel-d). This morphology is reminiscent of the high redshift disks reported by the observations (e.g. Davari et al. 2017). The subsequent accretion phase is characterized by the assembly of the external galaxy, via gas-rich mergers, generally minor, which only marginally affect the central core. Even one particular merger at $z = 1.7$, which attains a 1:4 mass ratio, equally shows mild effects on the central galaxy core.

The spheroidal galaxy, shown in Figure 3 also exhibits two main phases: a *compact-core* phase, from z≈3 to z≈2 and a subsequent *accretion* phase. A major gas-rich merger starting at z≈3 contributes few ex-situ stars (panel-c), but a large gas mass (panel-b), which is efficiently converted into in-situ stars (panel-c) via a high star formation rate, peaking at more than 350 $M_{\odot}$/yr (panel-a). As a consequence of that event, gas is funneled to the galaxy center to produce an intense star formation burst, which creates a compact core (panel-e) and feeds the SMBH (panels-a and -f). As in the disk galaxy, the compact core survives to $z = 0$, with slightly decreasing compacity. The accretion phase is characterized by gas-poor minor mergers, which are unable to replenish the depleted galaxy gas. As a result of feedback mechanisms, AGN and SN, star formation is rapidly quenched after z≈2 (panel-a) and in-situ stellar mass stops its growth (panel-c). Only a gas-rich merger at $z = 0.8$, contributes ex-situ stars (panel-c) and shows other minor effects on the external galaxy halo, but none on its central core. Along this phase, the galaxy shows an steady (B/T) growth, which changes its morphology from disk-like to the spheroidal one observed at $z = 0$. As seen above, both galaxies share a similar initial *compact-core* phase, but diverge on the *accretion* phase, key to the formation of the external galaxy parts. We can track the disk formation of the simulated galaxies and even follow the orbits of the satellites originating the minor mergers. In a preliminary study, shown in Figure 4, we follow the orbits of three satellites. Their orbits are not random, but they follow coordinated movements, which contribute to the angular momentum build-up. This observation, which deserves a deeper study, reinforces the connections found between the angular momentum of the entire DM halo and that of the baryonic component, particularly for spiral galaxies (e.g. Teklu et al. 2015).

It is worth mentioning that, although the selected Illustris disk galaxy is very massive, with $M_{\star} \approx 4.1\ 10^{11} M_{\odot}$, rather than being an eccentric simulation outcome, it is comparable to the more than fifty superluminous spiral galaxies found by Ogle et al. (2016) in the SDSS.

References

Bezanson, R., van Dokkum, P. G., Tal, T., Marchesini, D., Kriek, M., Franx, M., Coppi, P., 2009, ApJ, 697, 1290

Buitrago, F., Trujillo, I., Conselice, C. J., Häussler, B., 2013, MNRAS, 428, 1460

Bottrell, C., Torrey, P., Simard, L., Ellison, S. L., 2017, MNRAS, 467, 2879

Charbonnier, A., Huertas-Company, M., Gonçalves, T. S. et al., 2017, MNRAS, 469, 4523

Cheung, E., Faber, S. M., Koo, D. C. et al., 2012, ApJ, 760, 131

Davari, R. H., Ho, L. C., Mobasher, B., Canalizo, G., 2017, ApJ, 836, 75

de la Rosa I. G., La Barbera F., Ferreras I. et al., 2016, MNRAS, 457, 1916

Graham, A. W., Dullo, B. T., Savorgnan, G. A. D., 2015, ApJ, 804, 32

Hopkins, P. F., Bundy, K., Murray, N., Quataert, E., Lauer, T. R., Ma, C.-P., 2009, MNRAS, 398, 898

Nelson, D., Pillepich, A., Genel, S. et al., 2015, A&C, 13, 12

Peth, M. A., Lotz, J. M., Freeman, P. E. et al., 2016, MNRAS, 458, 963

Ogle, P. M., Lanz, L., Nader, C., Helou, G., 2016, ApJ, 817, 1090

Schaye, J., Crain, R.A., Bower, R.G. et al., 2015, MNRAS, 446, 521

Teklu, A. F., Remus, R-S., Dolag, K. et al., 2015, ApJ, 812, 29

Trujillo, I., Cenarro, A. J., de Lorenzo-Cáceres, A. et al., 2009, ApJ, 692, L118

Taylor, E. N., Franx, M., Glazebrook, K. et al., 2010, ApJ, 720, 723

van der Wel, A., Franx, M., van Dokkum, P. G. et al. 2014, ApJ, 788, 28

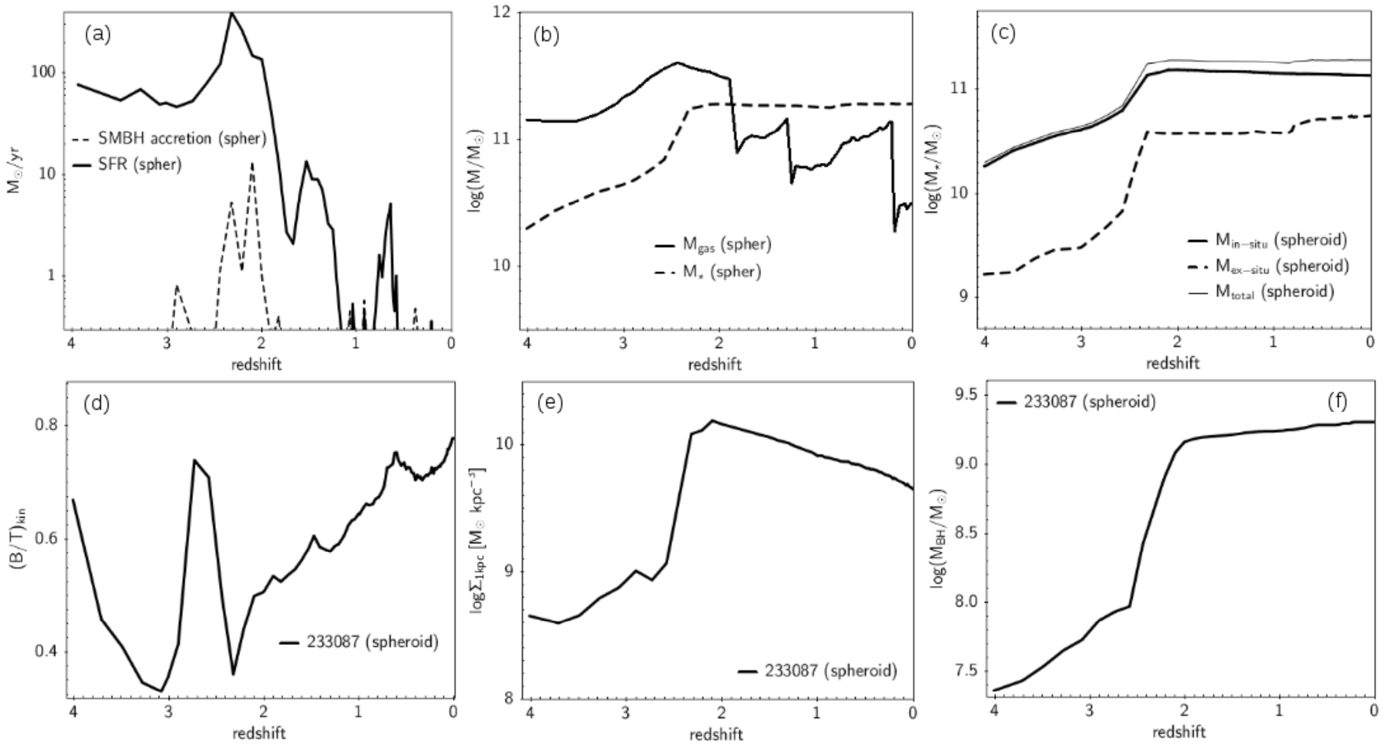

FIGURE 3. Parameter evolution from $z = 4$ to 0 for the simulated spheroidal galaxy. See main text for parameter explanation and their evolution interpretation.

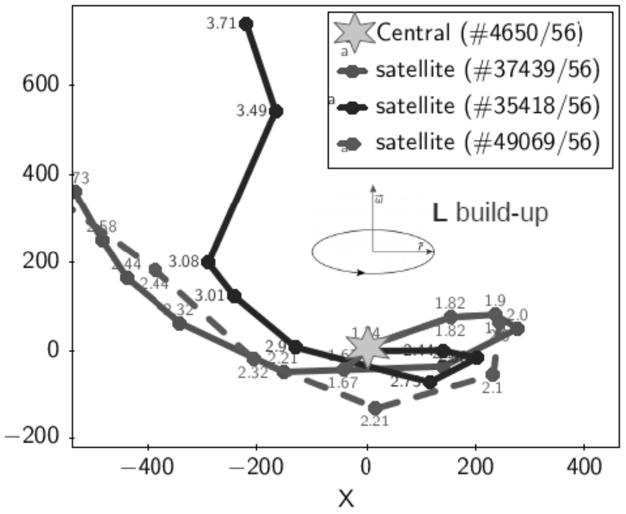

FIGURE 4. The disk construction around the central compact core results from the coordinated orbits of the accreted fragments, which contribute to the angular momentum build-up. Three fragments are shown in this figure.

van Dokkum, P. G., Nelson, E. J., Franx, M. et al., 2015, ApJ, 813, 23
Vogelsberger, M., Genel, S., Springel, V. et al., 2014, Nature, 509, 177