Specific angular momentum of disc merger remnants and the $\lambda_R$-parameter

Roland Jesseit,1* Michele Cappellari,2 Thorsten Naab,1 Eric Emsellem3 and Andreas Burkert1

1Universitätssternwarte München, Scheinerstr. 1, 81679 München, Germany
2Sub-department of Astrophysics, University of Oxford, Denys Wilkinson Building, Keble Road, Oxford OX1 3RH
3Université de Lyon, Lyon, F-69003, France; Université Lyon 1, Observatoire de Lyon, 9 avenue Charles André, Saint-Genis Laval, F-69230, France; CNRS, UMR 5574, Centre de Recherche Astrophysique de Lyon; École Normale Supérieure de Lyon, Lyon, F-69007, France

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ABSTRACT

We use two-dimensional kinematic maps of simulated binary disc mergers to investigate the $\lambda_R$-parameter, which is a luminosity-weighted measure of projected angular momentum per unit mass. This parameter was introduced to subdivide the SAURON sample of early-type galaxies in so-called fast $\lambda_R > 0.1$ and slow rotators $\lambda_R < 0.1$. Tests on merger remnants reveal that $\lambda_R$ is a robust indicator of the true angular momentum content in elliptical galaxies. We find the same range of $\lambda_R$ values in our merger remnants as in the SAURON galaxies. The merger mass ratio is decisive in transforming fast rotators into slow rotators in a single binary merger, the latter being created mostly in an equal-mass merger. Slow rotators have a $\lambda_R$ which does not vary with projection. The confusion rate with face-on fast rotators is very small. Mergers with a gas component form slow rotators with smaller ellipticities than collisionless merger remnants have, and are in much better agreement with the SAURON slow rotators. Remergers of merger remnants are slow rotators, but tend to have too high ellipticities. Fast rotators maintain the angular momentum content from the progenitor disc galaxy if merger mass ratio is high. Some SAURON galaxies have values of $\lambda_R$ as high as our progenitor disc galaxies.

Key words: methods: N-body simulations – galaxies: elliptical and lenticular, cD – galaxies: evolution – galaxies: formation – galaxies: fundamental parameters – galaxies: kinematics and dynamics.

1 INTRODUCTION

The connection between projected and the intrinsic properties of elliptical galaxies is a notorious problem. The Hubble classification of early-type galaxies is based on their elliptical shape, which was the natural observable distinctive feature. It was already pointed out by Hubble that this sequence is only a sequence of apparent shape depending on the inclination under which we observe a galaxy. When kinematic observations of ellipticals became available, they showed that some of them rotate too slowly to be shaped by rotation alone (Bertola & Capaccioli 1975; Illingworth 1977). Binney (1978) proposed that these systems are probably shaped to a large extent by anisotropic pressure. This is best seen when the apparent flattening is plotted versus the balance between ordered and unordered motions ($v/\sigma, \epsilon$) using the relation of these observables for an isotropic rotator as a reference point. Observations also showed that the amount of rotation varies with luminosity (Davies et al. 1983) and isophotal shape (Bender 1988). Isophotal shapes as measured by the $\alpha_4$-parameter can appear either boxy ($\alpha_4 < 0$) or discy ($\alpha_4 > 0$). Boxy and discy galaxies seem to form a true dichotomy as the isophotal shape correlates with on first sight unconnected observational properties like X-ray luminosity (Bender et al. 1989) and central surface density slope (Ferrarese et al. 1994; Lauer et al. 1995; Faber et al. 1997). This led Kormendy & Bender (1996) to propose a revision of the Hubble sequence using the isophotal shape to cast elliptical galaxies into boxy and discy ellipticals, which might be a classification more closely connected to their formation history than apparent ellipticities (Naab & Burkert 2003, hereafter NB03).

Kinematic properties are normally measured from long-slit data at the major axis (for $v$) and at a central aperture (for $\sigma$). But these are very special positions, which might or might not be representative for the overall structure of the galaxy. It is now possible to extract the line-of-sight velocity distributions (LOSVDs) from the full two-dimensional (2D) field of a galaxy with modern integral-field instruments. The SAURON survey pioneered the first comprehensive...
sample of nearby E/S0 galaxies (de Zeeuw et al. 2002) with 2D kinematic data. Some of these galaxies exhibit very complex velocity or velocity dispersion fields which are not easily captured by the usual \( v/\sigma, \epsilon \) parametrization (Emsellem et al. 2004). It can happen that two galaxies with similar long-slit measurements of ellipticity and \( v/\sigma \) have morphologically different kinematic fields, e.g. one galaxy has a kinematically decoupled component (KDC) and the other a regular velocity field. Emsellem et al. (2007, hereafter EM07) therefore introduced a luminosity-weighted measure of the specific line-of-sight angular momentum

\[
\lambda_R = \frac{\langle R|V| \rangle}{\langle R/\sqrt{V^2 + \sigma^2} \rangle},
\]

where the pointed brackets are luminosity averages. \( \lambda_R \) is designed to account for radial changes of angular momentum content in kinematic fields. This is different to the measure \( \langle V \rangle/\langle \sigma \rangle \) proposed by Binney (2005) to exploit integral-field kinematic data. However, Binney (2005) also stressed that with integral-field data available, the connection between internal and projected structures of a galaxy is much less ambiguous.

The E/S0 galaxies are cast into the category of slow or fast rotator according to their measured \( \lambda_R \) (EM07): slow rotators have \( \lambda_R < 0.1 \) and fast rotators have \( \lambda_R > 0.1 \). Cappellari et al. (2007) showed that the slow- and fast-rotating galaxies of the SAURON sample populate distinct regions in the \( (v/\sigma, \epsilon) \) diagram, even if their inclination is taken into account, which means that those galaxies are also intrinsically fast or slowly rotating. Slow rotators tend to be more massive, have lower ellipticities and exhibit faster rotating, kpc-sized, old KDCs, while fast rotators have lower luminosities and can also have central KDCs, which are however small and often consist of young stellar populations (McDermid et al. 2006). Slow rotators also have strong kinematic twists and kinematic misalignments, while photometry and velocity contours are almost always aligned in fast rotators. In addition, a correlation between anisotropy and ellipticity has been detected for slow and fast rotators with slow rotators being more isotropic and fast rotators being anisotropic (Cappellari et al. 2017; Burkert et al. 2008).

In this paper, we want to connect the findings of the SAURON galaxies with their formation history. Ever since the work of Toomre & Toomre (1972), the merger of two late-type galaxies has been so far the most appealing and the best tested theoretical model for the formation of an elliptical galaxy (Barnes 1992; Barnes & Hernquist 1996; NB03; Cox et al. 2006; Naab, Jesseit & Burkert 2006, hereafter NJB06; Robertson et al. 2006 and references therein).

The full 2D kinematic field of merger remnants has scarcely been studied. Following the pioneering work of Bendo & Barnes (2000), Jesseit et al. (2007, hereafter J07) analyzed kinematic maps of \( N \)-body merger remnants with kinematic methods, introduced by Krajnović et al. (2006). They quantified the presence of counter-rotating cores, the flattening of isovelocity contours, counter-rotating discs and other peculiar features which are also observed in the SAURON galaxies. In general, maps of slow rotators resembled more equal-mass mergers, while fast rotators show kinematical fields similar to unequal-mass mergers. However, with the introduction of \( \lambda_R \), we can quantify the line-of-sight angular momentum content of \( N \)-body merger remnants in the same way as has been done with observed galaxies. Ideally, we can connect merger remnants which appear as a slow or fast rotator with a certain formation mechanism. Beyond that we know the true angular momentum content of a simulated \( N \)-body merger remnant and can therefore determine whether the remnant is indeed intrinsically a slow (fast) rotator or not.

The aim of this work is two-fold: we want to study how much can be learned from the intrinsic structure of a galaxy by calculating its line-of-sight angular momentum parameter \( \lambda_R \). In addition, we want to clarify whether remnants of binary mergers follow the slow–fast rotator division of the red sequence as found in the SAURON sample. This paper is organized as follows: we describe the simulations in Section 2; give details about how we calculate the maps and determine \( \lambda_R \) (Section 2.2) and examine the connection between line-of-sight angular momentum and intrinsic angular momentum (Section 3); show the projectional behaviour of \( \lambda_R \) for merger remnants with varying orbital content (Section 4); classify the maps derived from the merger remnants as fast or slow rotator and investigate the influence of various formation mechanisms (Section 5) and finally discuss the results in Section 6.

2 SIMULATIONS

2.1 The merger models

The model parameters of the sample of 1:1 and 3:1 disc mergers we are studying in this paper are identical to the sample presented in NJB06, except that we include star formation and stellar feedback in the modelling of the dissipative component. Here we give a brief review of the setup.

The disc galaxies were constructed in dynamical equilibrium using the method described by Hernquist (1993) with the following system of units: gravitational constant \( G = 1 \), exponential scale-length of the larger progenitor disc \( h_d = 1 \) (the scaleheight was \( h_z = 0.2 \)) and mass of the larger disc \( M_d = 1 \). The discs were exponential with an additional spherical, non-rotating bulge with mass \( M_b = 1/3 \), a Hernquist density profile (Hernquist 1990) and a scalelength \( r_s = 0.2h_d \) and a pseudo-isothermal halo with a mass \( M_d = 5.8 \), cut-off radius \( r_c = 10h_d \) and core radius \( r_c = 1h_d \). The parameters for the individual components were the same as for the collisionless mergers presented in NB03 and NJB06. We replaced 10 per cent of the stellar disc by gas with the same scalelength and an initial scaleheight of \( h_{\text{gas}} = 0.1h_z \).

Whereas the NB03 and NJB06 simulations had been performed with the \( N \)-body smoothed particle hydrodynamic (SPH) code \textsc{v}in\textsc{e} (Nelson, Wetzstein & Naab 2008; Wetzstein et al. 2008), we used the parallel \textsc{treepsh} code \textsc{gadget}-2 (Springel 2005) to follow radiative cooling (Katz, Weinberg & Hernquist 1996) for a primordial mixture of hydrogen and helium together with a spatially uniform time-independent local ultraviolet background (Haardt & Madau 1996). In addition, we include star formation and the associated supernova feedback following the subresolution multiphase model developed by Springel & Hernquist (2003) using the same implementation as in Johansson, Naab & Burkert (2009), but without feedback from black holes.

We followed mergers of discs with mass ratios of 1:1 and 3:1. The equal-mass mergers were calculated using in total 440 000 particles with each galaxy consisting of 20 000 bulge particles, 60 000 stellar disc particles, 20 000 SPH particles representing the gas component in the disc and 120 000 halo particles. Twice as many halo particles than disc particles were used to reduce heating and instability effects in the disc components (Naab, Burkert & Hernquist 1999) by encounters between halo and disc particles. For 3:1 mergers, the parameters of the more massive galaxy were as described above. The low-mass companion contained a third the mass and the number of particles in each component, with a disc scalelength (stars and gas) of \( h = \sqrt{T/3} \).
The gravitational forces were softened with a spline kernel of \( h_{\text{grw}} = 0.05 \). The minimal size of the spline kernel used for computing the SPH properties, \( h_{\text{SPH}} \), was fixed to the same value. Implicitly, this procedure suppressed gas collapse on scales smaller than the softening scale and prevents numerical instabilities (Bate & Burkert 1997). The initial discs were run in isolation for two dynamical times to allow the systems to finally settle into an equilibrium state. The galaxies merged on parabolic orbits, which is the most probable configuration as found in cosmological simulations (Khochfar & Burkert 2006), with a pericentre distance of two disc scalelengths. The initial geometries are identical to NB03 (see also Table A2) and NB06. The merger remnants were allowed to settle into dynamical equilibrium for approximately 30 dynamical timescales after the merger was complete. Then, their equilibrium state was analyzed. All simulations have been run on an SGI Altix at the University Observatory in Munich.

### 2.2 Determination of \( \lambda_R \)

The 2D maps examined in this article are identically determined as laid out in J07. We briefly repeat here the most important steps: for the 2D analysis, we binned particles within the central 6 length units (21 kpc) on a grid of \( 48 \times 48 \) cells. This corresponds typically to two-three effective radii depending on projection (see Naab & Trujillo 2006 for the exact determination of \( r_e \)). To include seeing effects, we created for every luminous particle \( 10 \times 10 \) pseudo-particles with identical velocities on a regular grid with a total size of 0.125 unit lengths (0.44 kpc) centred on the original particle position. The mass of the original particle was then distributed to the pseudo-particles weighted by a Gaussian with a standard deviation of 0.1625 unit lengths (0.56 kpc). Thereafter, the pseudo-particles were binned on a \( 48 \times 48 \) grid. For the kinematic analysis, we binned (mass-weighted) all pseudo-particles falling within each grid cell in velocity along the line of sight. The width of the velocity bins was set to a value of \( 0.1 \) (26.2 km s\(^{-1}\)) for line-of-sight velocities \( v_{\text{los}} \) in the range \(-4 \leq v_{\text{los}} \leq 4 \) (corresponding to \( \pm 1048 \) km s\(^{-1}\)). This resulted in 80 velocity bins over the whole velocity interval. Using the binned velocity data, we constructed line-of-sight velocity profiles (LOSVD) for each bin of the 2D grid. Subsequently, we parametrized deviations from the Gaussian shape of the velocity profile using Gauss–Hermite basis functions (Gerhard 1993; van der Marel & Franx 1993). The kinematic parameters of each profile \((\sigma_{\text{app}}, v_{\text{app}}, h_3, h_4)\) were then determined by least-squares fitting.

\( \lambda_R \) can be calculated from integrated field data via the formula given in EM07

\[
\lambda_R = \frac{\sum_{i=1}^{N} V_i \sqrt{F_i R_i}}{\Sigma_{i=1}^{N} F_i R_i \sqrt{V_i^2 + \sigma_i^2}},
\]

where \( F_i \) is the flux, \( R_i \) is the projected radius, \( V_i \) is the line-of-sight velocity and \( \sigma_i \) is the line-of-sight velocity dispersion of each grid cell. We determined these properties as explained in the previous section, and can therefore calculate \( \lambda_R \) directly from our 2D data. As galaxies are projected randomly on the sky, we project each remnant 200 times randomly on the sphere of viewing directions. This gives us a sample of 20,000 2D maps. SAURON has a finite field of view which extends to one effective radius, which we need to take into account as \( \lambda_R \) can vary strongly with \( R \). We determine for each projection the effective radius and sum only over the grid cells inside one effective radius. Thus, we ensure a fair comparison to the SAURON data.

### 3 THE INTRINSIC SPECIFIC ANGULAR MOMENTUM AND \( \lambda_R \)

#### 3.1 Intrinsic angular momentum

The total intrinsic specific angular momentum \( J_{\text{intr}} \) of a galaxy (or \( N \)-body merger remnant) can be calculated from the discrete stellar (particle) distribution. The components of \( J \) in Cartesian coordinates are

\[
J_x = \sum_i y_i v_{x,i} - z_i v_{y,i},
\]

\[
J_y = \sum_i z_i v_{x,i} - x_i v_{z,i},
\]

\[
J_z = \sum_i x_i v_{y,i} - y_i v_{x,i},
\]

and \( J_{\text{intr}} \) is the norm of that vector. For simplicity, we implied here that all particles (stars) have the same mass and do not write the sums over masses explicitly. The angular momentum vector can be projected to the plane of the sky, defining the *projected* intrinsic angular momentum vector \( J_{\text{proj}} \) with components

\[
J_x = \sum_i y_i v_{x,i} - z_i v_{y,i},
\]

\[
J_y = 0,
\]

\[
J_z = \sum_i x_i v_{y,i} - y_i v_{x,i},
\]

where we define the \( y \)-direction arbitrarily as perpendicular to the plane of the sky. As our line of sight is along the \( y \)-direction, we cannot observe transversal motions, i.e. in \( x \)- and \( z \)-direction. We can now define an apparent angular momentum vector \( J_{\text{app}} \) with the components

\[
J_x = \sum_i z_i v_{x,i},
\]

\[
J_y = 0,
\]

\[
J_z = \sum_i x_i v_{y,i},
\]

It has been show by Franx (1988) that for triaxial galaxies the apparent angular momentum amounts to half the intrinsic angular momentum, which we rewrite as

\[
J_{\text{app}} = 0.5 J_p + 1_{\text{proj}} \omega_{\text{proj}},
\]

where \( 1_{\text{proj}} \) and \( \omega_{\text{proj}} \) are the inertial moment tensor and the angular velocity of the projected density distribution, respectively. Indeed figure rotation is present in about 15 per cent of the merger remnants, but we do not try here to disentangle the relative contributions of figure rotation and streaming motion. Although such a decomposition would be possible, in principle, for the \( N \)-body remnants, such an analysis would be beyond the scope of this paper.
3.2 Angular momentum in observations

We cannot directly access the apparent angular momentum of a galaxy observationally. The closest proxy to the apparent angular momentum which we can calculate from the 2D velocity field is \( \langle R|V| \rangle \), where \( R \) is the projected radius, \( V \) is the line-of-sight velocity and brackets denote luminosity averages (see also appendix A of EM07 for a discussion). It is straightforward to calculate \( J_{\text{app}} \) from the \( N \)-body simulation and \( \langle R|V| \rangle \) from mock observations of the same remnants and same aperture. In Fig. 1, we show that agreement is very good and verifies that the mapping of the velocity fields gives a close account of the intrinsic structure.

The inclination of a galaxy is, in general, not known and dynamical modelling or other observational clues are needed to infer its projection (Cappellari 2008). We can choose the projection of an \( N \)-body remnant at will and can calculate \( J_{\text{app}} \) and \( J_p \) for each projection. The ratio of these two values should be equal to two, if and only if we have the information over the whole field of the galaxy. This is, in general, not the case, as the field of view is limited by the instrument we are using. We are calculating therefore \( J_{\text{app}} \) and \( J_p \) for two different apertures, one which encloses the whole remnant and one which extends only to one effective radius. This is illustrated in the right-hand plot of Fig. 2 where we highlighted the aperture at one effective radius.

It is instructive to examine first a test model, for which we chose the progenitor disc galaxy, which is by construction axisymmetric and fast rotating. For almost all projections, we find that \( \kappa_j \) (Fig. 2, left-hand panel) is very close to the theoretical value of 2, if calculated over the whole remnant. If we determine \( J_p \) and \( J_{\text{app}} \) inside one \( R_e \), we tend to get a spread of higher values for \( \kappa_j \). This is not too surprising, as we catch the particles only on part of their trajectory (close to pericentre) and line-of-sight velocities are not representative of their total angular momentum content. This will depend on the detailed orbit structure of the remnant, i.e. how much angular momentum sits at large radii. In the same Fig. 2, we illustrate the spread for the whole remnant sample, which is somewhat larger than for our axisymmetric test models, but with the same tendency to underestimate \( J_p \). Again using the information on the full remnants shows that the apparent angular momentum and the projected intrinsic angular momentum are on average connected by a factor of 2.

The quantity \( \lambda_R \), as defined by EM07, has been proposed as a proxy for the intrinsic specific angular momentum of a galaxy within the radial range over which \( \lambda_R \) is determined. In the last test, we want to see how closely \( \lambda_R \) and the angular momentum content are connected for a random projection. We discussed before that \( \langle R|V| \rangle \), as a proxy for \( J_{\text{app}} \), is closely connected to the projected intrinsic angular momentum, \( \lambda_R \) is in contrast to \( \langle R|V| \rangle \), a normalized quantity. Therefore, we scale both quantities to their maximal values in order to compare the effect of inclination. We use again the progenitor disc galaxy as a test model for which ellipticity maps inclination accurately. We see in Fig. 3 that \( \lambda_R \) decreases much less rapidly with inclination than \( \langle R|V| \rangle \) does, which is also shown by the histograms of the deviations from their maximal values (in this case scaled to one). The reason is that \( \langle v \rangle \) and \( \langle \sigma \rangle \) decrease simultaneously and their ratio stays roughly constant until we reach inclinations close to face-on. The true angular momentum content is of course most closely related to the maximum value of \( \lambda_R \) or \( \langle R|V| \rangle \), which in many cases, at least for fast rotators, is a projection close to edge-on. In summary, even if there is a close connection between \( \langle R|V| \rangle \) and the projected intrinsic angular momentum \( J_p \), the projectional behaviour of \( \lambda_R \) is more robust and will stay closer to its maximal value for a higher fraction of all possible viewing angles.

4 INTRINSIC SHAPE VARIATIONS: EXAMPLE REMNANTS

Before we examine the properties of the merger remnant sample as a whole, it is instructive to assess the variety of remnant properties present in the sample. The remnants in our sample have very
different orbital makeups and intrinsic shapes. They can be dominated by major axis tubes, minor axis tubes and box orbits, and have prolate, oblate or triaxial shapes, respectively (Jesseit, Naab & Burkert 2005). Their projected properties must correlate with their intrinsic shape, and it is interesting to study how $\lambda_R$ is varying with inclination. In Thomas et al. (2007), we selected merger remnants at the extreme ends of the shape distribution, and we want to study the projected 2D properties of three of them to elucidate systematic kinematical trends with intrinsic shape.

Our test remnants are the OBLATE, PROLATE and TRIAXIAL remnants from Thomas et al. (2007). We are plotting the ellipticity, $\lambda_R$ and the isophotal shape parameter $a_4$ in Fig. 4 to illustrate the variation with projection. The OBLATE remnant (red symbols) is the result of a 4:1 merger, which is dominated by minor axis tubes. It

![Figure 3](image1.png)

Figure 3. Left-hand panel: $\lambda_R$, $\langle R(V)\rangle$ and $J_{app}$ for random projections of the progenitor galaxy. All quantities are normalized to their maximum value. Right-hand panel: Distribution of absolute deviation of the same quantities from their (normalized) maximum values.

![Figure 4](image2.png)

Figure 4. Left-hand panels: case study of projectional relation between $\lambda_R$ and photometric properties, i.e. ellipticity and isophotal shape parameter for an oblate (red), prolate (black) and triaxial remnant (blue). The triaxial remnant has $\lambda_R \approx 0$ not varying with projection. Ellipticity and $\lambda_R$ are good proxies for inclination angle for the oblate remnant, which is nearly axisymmetric. The prolate remnant can have more than one $\lambda_R$ value for a given ellipticity owing to a complicated orbital structure. Right-hand panels: histogram of ellipticities and $\lambda_R$ of the projectional study. The oblate remnant is a fast rotator for almost all viewing angles, while the triaxial remnant is a slow rotator for all viewing angles. The prolate remnant is equally probable to be observed as a fast or slow rotator.

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is classified as a fast rotator from almost any viewing angle, although a dependence on inclination is visible. The TRIAXIAL remnant is a 1:1 merger remnant which is dominated by box and boxlet orbits. Interestingly, the remnant has a $\lambda_R$ consistent with zero from all viewing angles. The PROLATE remnant (black symbols) has the most complex dependency on inclination angle. This is so because it contains a significant amount of both minor and major axis tube orbits. Therefore, we almost always see some rotation, originating from different kinds of orbit classes (for the detailed description of the orbit classification in $N$-body remnants, see Jesseit et al. 2005). However, as this is also a 1:1 merger remnant, it does not rotate very fast and reaches a maximum $\lambda_R$ of 0.18.

The statistical distribution of $\lambda_R$ and $\epsilon$ is better seen in the right-hand column of Fig. 4. The $\lambda_r$ of the TRIAXIAL remnant has a delta-function like distribution at $\lambda_R = 0$ that means it is a slow rotator under any viewing angle, while the OBLATE remnant is a fast rotator for almost all projections except for three inclinations close to face-on. This results in a probability of $\approx$1 per cent to misclassify the OBLATE remnant as a slow rotator. The PROLATE remnant is one of the few remnants which could be classified as a fast or a slow rotator with equal likelihood, because both tube orbit classes seem to carry an equal amount of rotation and move along the line of sight for different viewing angles. The PROLATE remnant is rather round for almost all projections, while the TRIAXIAL and the OBLATE remnants are quite flattened, albeit the flattening is caused by different orbit classes, i.e. box orbits in the case of the TRIAXIAL remnant. Flattened slow rotators are observed in the SAURON sample only in exceptional cases (see also Section 5).

4.1 Kinematical misalignment

Another discriminatory property of slow and fast rotators is the kinematical misalignment. The misalignment angle $\Psi$ is defined as the angle difference between the global photometric and the kinematic position angle

$$\Psi = |PA_{\text{phot}} - PA_{\text{kin}}|,$$

where $PA_{\text{kin}}$ is defined as the angle $0^\circ < PA_{\text{kin}} < 180^\circ$ along which $|V|$ is maximal (see appendix C of Krajnović et al. 2006). Triaxial systems can have complicated velocity fields, because of the possible superposition of orbits with angular momenta with respect to the minor and major axes (van den Bosch et al. 2008). In a perfect axisymmetric galaxy, there can be no kinematic misalignment. Indeed all fast rotators in the SAURON sample have misalignments $\Psi < 5^\circ$, whereas slow rotators can have any kinematic misalignment up to $90^\circ$. Measuring $\Psi$ with identical technique on the data and the simulations, we find that our example remnants are also quite diverse in their behaviour of kinematic misalignment with projection angle (Fig. 5). The oblate remnant as it is dominated by minor axis tubes has very few projections where $\Psi \neq 0$. The triaxial remnant has a much broader distribution, which peaks at low misalignments, but the maps of this remnant show little rotation, such that the misalignment has larger error bars and is not so meaningful. The prolate remnant, however, clearly shows a strong misalignment, i.e. $\Psi > 20$, for most of the projections, as both tube orbit classes revolving around the major and the minor axes are present in this remnant.

5 SLOW AND FAST ROTATORS

The determination of the $\lambda$-parameter is important insofar as ellipticals can be divided into two broad subclasses, so-called slow and fast rotators (EM07). The (empirical) cut which separates these classes has been made at $\lambda_R = 0.1$. These seem to be genuinely intrinsically different galaxy types with little overlap through projection effects. Many slow rotators exhibit for example large, old and fast-rotating KDCs, which however are not affecting the overall angular momentum balance too much, as the stars which move on high-angular-momentum orbits are not located in the centre, such that the $\lambda_R$ as determined from the map is rather low. In general, maps of slow rotators resemble more the kinematic maps derived from equal-mass merger remnants. The formation of KDCs requires the inclusion of a gaseous component in the simulation. Fast rotators are, on the other hand, more likely to be unequal-mass mergers. For a detailed discussion on the origin of kinematic features in 2D LOSVD maps, we refer the reader to J07.

5.1 The role of merger mass ratios

The most fundamental parameter which influences the outcome of a merging event is the amplitude of the fluctuations of the gravitational potential during the merger. How strongly the phase space is rearranged after a merger will be mainly determined by the ratio of the masses of the merging objects (NB03). An equal-mass merger will be more effective in redistributing the energies of the stars in the progenitor galaxies than an unequal-mass merger. It is true that secondary factors like infall velocity and merging geometry also have an impact on the final shape of the remnant, but the mass ratio of the merger is the dominant factor. We want to quantify when
a given projection of a given remnant is classified as a slow or a fast rotator, and we use collisionless disc–disc merger remnants of mergers with mass ratios of 1:1, 2:1, 3:1 and 4:1 from NB03. In Fig. 6, the $\lambda_R$ distribution is shown for each of these merger sub-samples. We see, as expected, that the fraction of slow rotators for a given merger mass ratio is decreasing with increasing mass ratio (see Table 1). $\lambda_R$ peaks at 0, 0.1, 0.27 and 0.4 for the mass ratios 1:1 to 4:1. If one would assume that binary disc merging is the main formation channel of elliptical galaxies, then only equal or near equal-mass merger could produce them. However, this picture is probably too simple as elliptical galaxies can have more complicated merger histories in a cosmological context (Meza et al. 2003; Khochfar & Silk 2006; Naab et al. 2007). Multiple minor mergers, for example three 3:1 mergers, might also be a viable way to form slowly rotating ellipticals, which closely resemble the outcome of a single equal-mass merger, as was shown recently by Bournaud, Jog & Combes (2007). All the results (except for Section 5.5) we present in this paper are valid for one generation of merging only. The examination of the impact of complex hierarchical merging histories is beyond the scope of this paper.

### Table 1. Dependence of the slow rotator fraction on the merger mass ratio. Only equal-mass merger are very effective in removing angular momentum in a single merging event.

| Merger mass ratio | Slow rotator fraction |
|-------------------|-----------------------|
| 1:1               | 0.75                  |
| 2:1               | 0.10                  |
| 3:1               | 0.03                  |
| 4:1               | 0.02                  |

5.2 Confusion rate

Cappellari et al. (2007) showed that slow and fast rotators are indeed intrinsic fast and slow rotators and not randomly projected fast-rotating galaxies which happen to appear non-rotating. We address this question in Fig. 7, where we examine the fraction of projections for each of the collisionless remnants which have $\lambda_R < 0.1$. There is an isolated sample of remnants which have a probability of greater than 90 per cent to be classified as slow rotators. The remaining remnants have a probability of less than 40 per cent to be identified as slow rotators. The mergers which are located at the extreme ends of the distribution are the unambiguous cases they are (almost) always either fast or slow rotators. There is however a small population of remnants which have a reasonable probability to be identified as slow rotators although they have a non-zero angular momentum content (shaded zone in Fig. 7, left-hand panel). These are on average the most prolate of all remnants (same figure, right-hand plot).

The confusion arises from the presence of major and minor axis tubes in the remnants, i.e. there are two face-on projections under which the angular momentum content is perpendicular to the line of sight and cannot be observed. But there are also remnants which are mildly to strongly triaxial ($\sim 0.3 < T < 0.5$), which are hot but regularly rotating systems, i.e. with low kinematic misalignment. Almost all of these systems resulted from 2:1 mergers. We can now calculate the global probability to falsely classify a rotating galaxy...
as a slow rotator in our sample and find $P_{\text{confuse}} = 0.046$. This is probably an upper limit as prolate remnants are overabundant in our sample, and are suppressed if a significant amount of gas is included in the simulations (NJB06). This is consistent with the SAURON sample where not a single galaxy has been observed with rotational patterns as, for example our PROLATE model, which we presented in Section 4. We further note that the maximal $\lambda_R$ is a good tracer for the triaxiality of our remnants (Fig. 7, right-hand panel), albeit with an increasing spread towards lower $\lambda_R$. Particular spin alignments of the progenitor discs can find a slow rotator with $T_0 = 0$. This merger remnant originated from a planar merger of discs with anti-aligned spins. The counter-rotation of both disc components cause a net zero rotation. While this is a possible formation scenario, most slow rotators are triaxial box-dominated remnants.

5.3 The influence of dissipation

Late-type spiral galaxies are normally not purely collisionless systems, but have a sizable fraction of gas. We therefore compare two sets of mergers: disc–disc mergers with gas and star formation, and collisionless disc–disc mergers. Each set consists of 16 1:1 and 32 3:1 mergers, which formed on identical merging geometries. As mentioned before, we take 200 observations of each remnant at random viewing angles, which results in 9600 maps for each set of simulations. We determine for each set the fraction of slow and fast rotators, as well as standard photometric parameters such as ellipticity and the isophotal shape parameter $a_4$. In Fig. 8, we show the distributions of ellipticities and $a_4$ for slow and fast rotators from mergers which formed with and without gas. Maps classified as slow and fast rotators show distinct photometric properties. Slow rotators, in general, have smaller ellipticities and have smaller $a_4$ values, while fast rotators are more elliptical and discy. It is apparent that the fast rotator population hardly changes its photometric properties when gas is included in the simulation. The impact on slow rotators, however, is more visible as the ellipticity distribution is now more skewed towards $\epsilon = 0$, while the $a_4$ distribution peaks now at zero (Cox et al. 2006; NJB06). The mean slow rotator properties are summarized in Table 2, which also confirm that most slow rotators originate from equal-mass mergers. The results from the SAURON survey showed that slow- and fast-rotating ellipticals are located at certain positions in the $\lambda - \epsilon$ and $\lambda - a_4$ planes. For a better comparison, we also show the distribution of merger remnants in those parameter spaces (Fig. 9). In general, the parameter space bracketed by the SAURON observations is reproduced well by the merger remnants. There are, however, some differences. For example, we see that the collisionless mergers have too high $\epsilon$ for a given $\lambda_R$ which is alleviated, especially for slow rotators, by the inclusion of gas. We also indicated the progenitor galaxy in Fig. 9. We already showed in Section 5.1 that the amount of rotational support always decreases after a merger event. Very high merger mass ratios will lead to merger remnants which would lie closer to the progenitor limit, but we have not performed 10:1 or even higher mass ratios. Therefore, we do not find projections of merger remnants with $\lambda_R > 0.6$. It is remarkable though that some of the SAURON fast rotators have $(\lambda_R, \epsilon)$ values very close to the progenitor galaxy and are, at least in this sense, hardly distinguishable from early-type spiral galaxies.

The situation is different in the $a_4 - \lambda_R$ plane where the merger remnants are only partly located in the parameter space occupied by the SAURON galaxies. Collisionless slow rotators are too boxy, while fast rotators are on average too discy compared to SAURON galaxies. While gas removes the boxy projections of slow rotators, it does not help to create, as expected, boxy projections in fast rotators. Probably the origin of boxiness in the fast-rotating SAURON galaxies is different from the source of boxiness in our remnants, for example bars.

As we discussed earlier, kinematical misalignment is also a distinguishing feature between fast and slow rotators. Again we divide up the simulation sample into fast and slow rotators and measure the angle $\Psi$ between kinematic and photometric position angles. The observational trends are reproduced remarkably well: fast rotators are very unlikely to show kinematic misalignment, while slow rotators show a flat distribution of misalignment angles, in other words there is no preferred alignment angle for slow rotators (see Fig. 10). The low misalignment angles for fast rotators are not very surprising, because we already start out with a perfectly aligned system. Unequal-mass merger simply do not destroy the initial alignment. Indeed observed fast rotators are also remarkably aligned. Only two out of 50 fast rotators have $\Psi > 5^\circ$ (see Cappellari et al. 2007; Fig. 12). The crucial question to explain the origin of fast rotators

| Table 2. Slow rotator properties. Main results of the classification according to the $\lambda_R$-parameter. Every projection which has a $\lambda < 0.1$ is classified as a slow rotator. Dissipation mainly influences the ellipticity, while the slow rotator fraction is almost unaffected. |
|--------------------|--------------------|--------------------|
| Collisionless      | Gas + SF            |
| Slow rotator fraction | 0.26               | 0.28               |
| Slow rotator $\langle \epsilon \rangle_{\text{med}}$ | 0.28               | 0.18               |
| Slow rotator $\epsilon < 0.3$ | 0.55               | 0.81               |
| Slow rotators from 1:1 merger | 0.95               | 0.94               |

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Figure 9. Left-hand column: 2D probability contours of collisionless 1:1 and 3:1 remnants in $\lambda_R-a_4$, respectively in the $\lambda_R-\epsilon$ plane. The SAURON galaxies are indicated by black stars. High-$\lambda_R$ galaxies are resembling more the progenitor galaxy than 3:1 merger remnants. Boxy fast rotators are not formed in mergers, but are probably barred galaxies. Right-hand column: the same plots, but this time with merger remnants which formed with gas. The photometric properties are stronger affected than $\lambda_R$. Slow-rotating remnants agree well with SAURON galaxies.

Figure 10. Histograms of kinematic misalignment angle $\Psi$ measured from 2D kinematical maps of the merger remnants. The overwhelming majority of maps identified as fast rotators have no kinematic misalignment, while slow rotators have no preferred misalignment angle. Dissipation changes the results only slightly, i.e. on average slightly lower values of $\Psi$ are measured.

is rather how the axisymmetric progenitor systems are produced in the first place, rather than the subsequent merging. Gas changes the picture only slightly. There are somewhat fewer projections with high misalignment angles for fast rotators, and velocity fields of slow rotators are slightly better aligned. In general, the inclusion of only 10 per cent of gas in the merging process is not necessary to explain the kinematic misalignment of slow and fast rotators. However, the inclusion of high fractions of gas would probably change this picture.

5.4 Young stellar populations

We have so far assumed a constant stellar mass-to-light ratio (M/L), which is identical for the old stellar population (OSP) originating from the progenitor galaxies and the newly formed stars. This assumption is of course too simple as a relatively small number of young stars can be able to dominate the light in certain parts of a galaxy. Kuntschner et al. (2006) measured the 2D metallicity distribution for a large sample of nearby early-type galaxies including the SAURON sample. They find, for example, interesting deviations between the isophotal shape of a galaxy and isoindex contours of Mg$b$. Metal-rich subcomponents seem to be more flattened and could hint to a higher rotational support of a distinct stellar population. The centre of some of their galaxies shows strong peaks in H$\beta$ line strength indicating recent star formation activity. In merger simulations, the gas looses angular momentum through torques which depend on the particularities of the merging geometry, merger mass fraction and other details of the interaction. Such young central stellar population has first been found in merger remnants by Mihos & Hernquist (1994), and further studied in other work (see recently
Hopkins et al. 2009 on central extra light in merger remnants). However, we cannot reproduce line strength maps as shown by Kuntschner et al. (2006), because we are not following the chemical evolution in our simulations. If we want to produce more realistic kinematic maps of the merger remnants which included star formation, we need to assume an ad hoc metallicity. For simplicity, we assume \( Z = 0.02 \) (solar) as a global metallicity. As we know the ages of the newly formed stars in the simulation, we can calculate the fluxes from the single stellar population models of Bruzual & Charlot (2003) in the \( B \) band and assume an age of 6 Gyr for the OSP. Finally our measurements of \( \lambda_R \) will also depend on when after the merger event we observe the remnant to take into account the dimming of the young stellar populations.

We chose two 3:1 remnants which have a different radial distribution of new stars. In one remnant (merging geometry 5; see A1), most of the gas lost its angular momentum and formed stars predominantly in the centre, while in the other remnant (merging geometry 11) the stars formed in a large-scale disc. We observe the remnants in the \( B \) band at the end of the simulation (the new stars have a maximal age of 2.6 Gyr) and 1, 2, 3 and 4 Gyr later. Also, we constrain ourselves to edge-on observations where we would expect to see the biggest absolute differences for \( \lambda_{Re} \). The results are summarized in Table 3. The remnant 3:1 G5 has immediately at the end of the simulation a \( \lambda_{Re} \) which is about 0.1 lower than if we use a constant M/L (marked with no ages). Also as we mentioned earlier, the new stars are located mainly in the centre and the effective radius is therefore significantly smaller. Interestingly, 3:1 G11 has a slightly higher \( \lambda_{Re} \) than in the standard case, because there are enough young stars at large radii and with high angular momentum. However, in both simulations effects of a young stellar population are difficult to detect in \( \lambda_R \) measurements (and photometry) after 1–2 Gyr. Indeed the shape of the \( \lambda_R \) profile hardly changes at all as can be seen in Fig. 11. We plot the radial profiles of 3:1 G5 observed after different time-spans normalized to the effective radius.

### Table 3. List of values for the effective radius \( r_{eff} \), \( \lambda_{Re} \) and ellipticities observed at different times after the merger to take into account fading stellar populations. The OSP has an age of 6 Gyr at the end of the simulation. The rows titled no ages assume no age distribution. Results are shown for a merger remnant with a young population at the centre (3:1 G5) and a merger remnant with a young stellar disc (3:1 G11).

| 3:1 GEOM 5 | Age OSP (Gyr) | \( r_{eff} \) | \( \lambda_{Re} \) | \( \epsilon \) |
|------------|----------------|----------------|----------------|---------|
| 6          | 0.55           | 0.25           | 0.31           |
| 7          | 0.71           | 0.30           | 0.42           |
| 8          | 0.75           | 0.32           | 0.41           |
| 9          | 0.77           | 0.32           | 0.41           |
| 10         | 0.78           | 0.32           | 0.4            |
| No ages    | 0.83           | 0.34           | 0.43           |

| 3:1 GEOM 11 | Age OSP (Gyr) | \( r_{eff} \) | \( \lambda_{Re} \) | \( \epsilon \) |
|------------|----------------|----------------|----------------|---------|
| 6          | 0.56           | 0.49           | 0.36           |
| 7          | 0.80           | 0.45           | 0.4            |
| 8          | 0.84           | 0.46           | 0.42           |
| 9          | 0.85           | 0.46           | 0.42           |
| 10         | 0.86           | 0.47           | 0.44           |
| No ages    | 0.89           | 0.47           | 0.43           |

Figure 11. Radial profiles of the specific angular momentum parameter \( \lambda_R \) for remnant 3:1 G5 \( B \)-band flux (top panels) and \( R \)-band flux (bottom panels) are calculated at different times after the completion of the merger assuming an OSP with a minimum age of 6 Gyr. The shape of the \( \lambda_R \) profiles is hardly changed (right-hand panels), but effective radii are consistently smaller and therefore \( \lambda_{Re} \) is smaller as long as the young stars are still bright (left-hand panels). The effect is stronger in \( B \) band than in \( R \) band.
radius (left-hand panels) and not normalized (right-hand panels). That underscores that the young stellar population influences more at which radius $\lambda_{R,e}$ is determined than having clearly distinct kinematics.

This is hardly an exhaustive investigation into the impact of varying stellar mass-to-light ratios, but it illustrates that notable observational consequences would vanish in a short time-span after the merging event. Mergers with higher gas fractions, chemical evolution and different modes of feedback, for example AGN feedback, must be addressed in the future.

5.5 Dry mergers

The most massive galaxies in the Universe are probably not formed from a single generation of binary spiral–spiral mergers (Naab & Ostriker 2009), because there are simply not enough massive late-type galaxies to account for the stellar mass of galaxies with luminosities, for example, of $4 \, L^*$. Their merging history included probably more than one major merger, and semi-analytic modelling showed that the last major merger was probably dry (Khochfar & Burkert 2003; Hopkins et al. 2007; Khochfar & Silk 2008). We have a small sample of remergers of collisionless merger remnants to test the assumption if slow rotators are the end product of dry merging. We analyzed six equal-mass mergers of discy remnants and six equal-mass mergers of boxy remnants. The majority of the maps (about 68 per cent) of the dry mergers are indeed slow rotators. As we have a very limited sample of merger remnants, we compare them only with the slow rotators which originated from 1:1 collisionless disc mergers, which is admittedly the overwhelming majority. In Fig. 12, we show that the ellipticity distribution from elliptical–elliptical mergers is hardly distinguishable from equal-mass disc–disc mergers. However, they are on average more boxy than remnants of disc mergers in agreement with Naab, Khochfar & Burkert (2006). The slow rotators in the SAURON sample are indeed hardly boxy. As mentioned before, the SAURON sample is not representative of the shape distribution of all elliptical galaxies due to the selection procedure of galaxies. There is especially a dearth of triaxial, boxy galaxies which makes it difficult to exclude or confirm the dry merging origin of massive ellipticals with the present sample (see also Burkert et al. 2008 for a more detailed discussion of the origin of the slowly rotating SAURON ellipticals).

6 DISCUSSION AND CONCLUSIONS

We calculated the $\lambda_R$-parameter from line-of-sight velocity maps of 48 remnants of collisionless disc mergers, 48 remnants of disc mergers with a dissipative component and 12 remergers of collisionless remnants, according to the procedure laid out in EM07. Every remnant is projected 200 times randomly and then treated as a mock galaxy. We first investigated how the intrinsic properties of the merger remnants manifest itself in the maps, and how much can be deduced of the intrinsic structure by calculating $\lambda_R$. We then identified a mock galaxy as a fast or slow rotator and compare their photometric and kinematic properties like $a_{\epsilon}, \epsilon$ and kinematic misalignment $\Psi$ to the properties of SAURON galaxies. We examined the influence of gas and merging mass ratio on the statistical properties of slow and fast rotators. We report the following findings.

(i) The line-of-sight angular momentum parameter $\lambda_R$ is a rather robust indicator of the intrinsic angular momentum content of a galaxy. $\lambda_R$ stays close to its maximum value for a wide range of viewing angles as it captures the balance between ordered (line-of-sight velocity) and unordered motion (line-of-sight velocity dispersion) well. In principle, the projected angular momentum content could also be deduced from the 2D velocity field alone, but information over the entire field of the galaxy would be needed, which is normally not available. We conducted therefore tests to explore the deviation from the intrinsic angular momentum, observing galaxies with apertures of limited size.

(ii) The projectional behaviour of $\lambda_R$ is determined by the intrinsic orbital structure. Most fast rotators consist of disc-like minor axis tubes and have $\lambda_R > 0.1$ for almost all projections. Likewise, slow rotators consist of box orbits and have $\lambda_R < 0.1$ for all projections. Prolate remnants have a more complicated projectional behaviour as they consist of major and minor axis tubes. There is however not a single galaxy in the SAURON survey with significant rotation around the major axis, and we slightly overproduce these systems in our merger sample. Even so we determine the misclassification probability for the whole collisionless merger sample to only 4.6 per cent. We therefore confirm the robustness of the slow/fast rotator classification scheme for binary disc merger remnants.

(iii) The spread of $\lambda_R$ is naturally reproduced in the binary merger scenario. However, their photometric properties have some important differences. Slow rotators from collisionless mergers have too high ellipticities. The problem is alleviated by the inclusion of a modest fraction of gas, which does not modify the slow rotator fraction but produces remnants with lower ellipticities. Therefore gas, maybe counterintuitively, can be important for the formation of slow rotators.

(iv) The destruction of ordered rotation is only effective in equal-mass mergers. The violence of the merger seems to be the decisive factor, i.e. with increasing mass ratio the percentage of formed slow rotators drops very rapidly. This trend has already been seen in earlier studies of equal and unequal-mass merger remnants (see e.g. Naab et al. 1999; Bendo & Barnes 2000; NB03). More complex formation mechanisms, like very large gas fractions and multiple mergers, will complicate this picture.

(v) The impact of young stellar populations in our particular models is notable only a few Gyr after the merger and even then the absolute change in $\lambda_R$ amounts to about 0.1 or less. The remnants, however, would appear significantly more concentrated, owing to the fact that during the merging the gas quickly falls to the centre, where it forms stars.

(vi) We tested the amount of kinematic misalignment for slow and fast rotators separately. Again the agreement with observations is very good. Slow rotators can have any misalignment with equal probability, while fast rotators show kinematical alignment for almost all projections. The picture changes with the inclusion of gas only insofar as the strongest misalignments vanish for slow
rotators. Higher gas fraction will probably lead to a further decrease in observed misalignments.

(vii) Slow rotators in the SAURON sample are not strongly boxy and rather round, therefore the dry mergers are a poor fit to them. This is somewhat surprising, as the projection and mass ratio independence of boxiness were seen as an asset of this formation mechanism (Naab et al. 2006). To assess the role of dry mergers adequately probably a larger sample of ellipticals, like ATLAS$^3D$, is needed.

(viii) Fast rotators with boxy isophotes are absent from our sample. Some early-type S0s in the SAURON are barred galaxies, and such strong bars seem not to be formed in our particular merger sample. Our sample of course has its limits, and it is possible that the bulge-to-disc ratio of our progenitor galaxies is too high or the initial bulges are not rotating or probably both to compare to this particular property of the SAURON galaxies.

(ix) The fast rotators with the highest $\lambda_R$ values in the SAURON sample resemble our progenitor galaxy more than a merger remnant, which leads to the question, if major merging played a significant role in their formation at all.

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APPENDIX A: DETAILS OF THE MERGER SAMPLE

We have used a large sample of 172 distinct binary mergers, including mergers with and without a dissipative component. The different analyses presented in this work were often carried out on subsets of mergers taken from the larger merger sample. For clarity, we summarize in Table A1 the exact number and general properties of the mergers used for a specific figure, where appropriate. The merging geometries, which are identical for all merger sets, are explicitly stated in Table A2.
Table A1. Description of merger sets used in this work.

| Figure | $N_{\text{Colles}}$ | $N_{\text{SF}}$ | $N_{\text{Total}}$ | Published in | Comment |
|--------|---------------------|-----------------|-------------------|--------------|---------|
| 1      | 112                 | 0               | 112               | NB03         | Disc merger (1:1,2:1,3:1,4:1) |
| 6      | 112                 | 0               | 112               | NB03         | Disc merger (1:1,2:1,3:1,4:1) |
| 7      | 112                 | 0               | 112               | NB03         | Disc merger (1:1,2:1,3:1,4:1) |
| 8      | 48                  | 48              | 96                | NB03, this work | Disc merger (1:1,3:1) |
| 9      | 48                  | 48              | 96                | NB03, this work | Disc merger (1:1,3:1) |
| 10     | 48                  | 48              | 96                | NB03, this work | Disc merger (1:1,3:1) |
| 12     | 28                  | 0               | 28                | NB03, NBK    | 16 discs and 12 elliptical mergers (1:1) |

Note. $N_{\text{Colles}}$ is the number of collisionless remnants and $N_{\text{SF}}$ is the number of remnant with gas and star formation. NB03 stands for Naab & Burkert (2003) and NBK for Naab et al. (2006).

Table A2. Full list of merging geometries.

| Geometry | $i_1$ | $i_2$ | $\omega_1$ | $\omega_2$ |
|----------|-------|-------|-------------|-------------|
| 1/17     | 0     | 0     | 180         | 0           |
| 2/18     | 0     | 0     | 71          | 30          |
| 3/19     | 0     | 0     | 71          | -30         |
| 4/20     | 0     | 0     | 71          | 90          |
| 5/21     | -109  | -60   | 180         | 0           |
| 6/22     | -109  | -60   | 71          | 30          |
| 7/23     | -109  | -60   | 71          | -30         |
| 8/24     | -109  | -60   | 71          | 90          |
| 9/25     | -109  | 0     | 180         | 0           |
| 10/26    | -109  | 0     | 71          | 30          |
| 11/27    | -109  | 0     | 71          | -30         |
| 12/28    | -109  | 0     | 71          | 90          |
| 13/29    | -109  | 60    | 180         | 0           |
| 14/30    | -109  | 60    | 71          | 30          |
| 15/31    | -109  | 60    | 71          | -30         |
| 16/32    | -109  | 60    | 71          | 90          |

Note. For unequal-mass mergers, the first number indicates the orientation of the more massive galaxy as $i_1$ and $\omega_1$, the second number indicates the orientation of the more massive galaxy as $i_2$ and $\omega_2$.

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