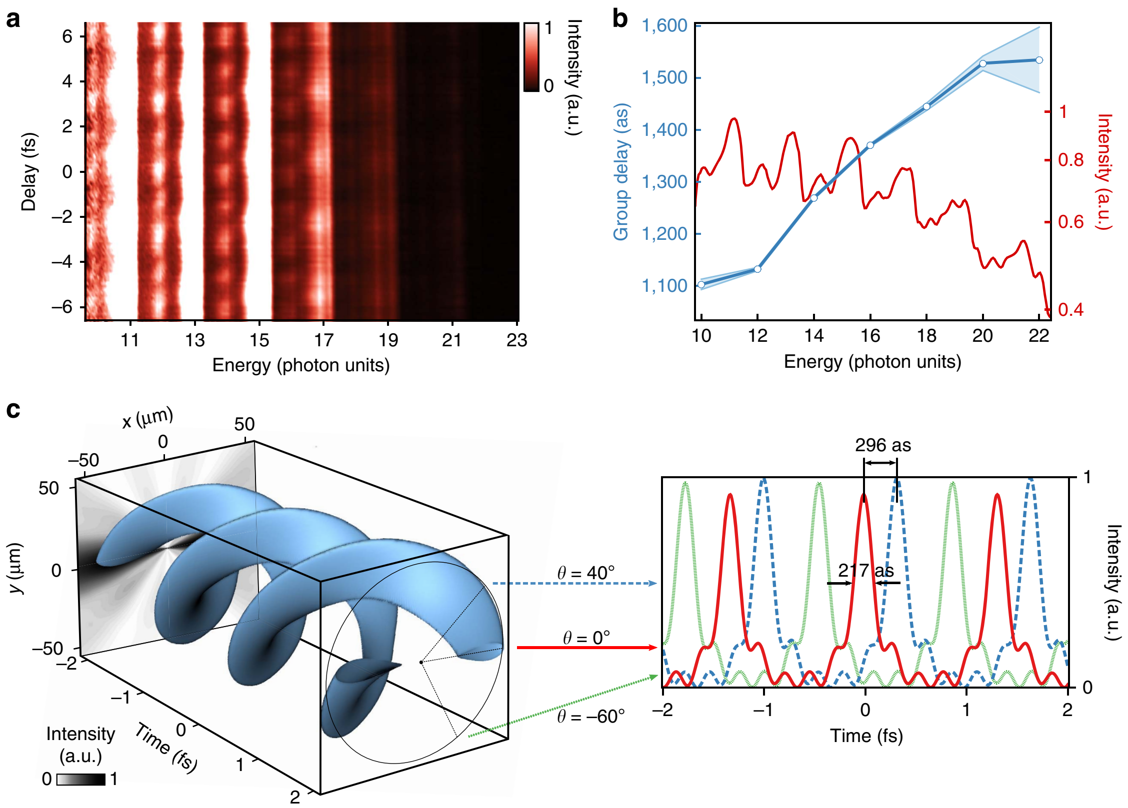

Figure 3 | Attosecond electronic beams carrying OAM. (**a**) Two-colour XUV + infrared two-photon photoionization spectrogram of argon for a driving field with $\ell_1 = 1$. The main lines correspond to odd harmonics, while the weaker oscillating ones, showing a double periodicity of $T = 1.33$ and 2.7 fs, are SBs. The collection efficiency of our spectrometer limits the number of measurable SBs even if the harmonic cutoff lies higher. (**b**) Delay-averaged spectrum in log scale (red) and group delay of the photoionized EWP (blue circles, the light blue strip about the curve represents the numerical analysis error bar at 3σ). (**c**) Spatiotemporal shape of the photoelectrons emitted in the forward direction using the intensity profiles from Fig. 2c, the group delays from **b**, and assuming a flat cross-section for argon in this energy range. The 3D surface is a contour at 80% of the maximum intensity. The black and white back panel is a projection of this intensity in the $t = -2$ fs plane. (**d**) Temporal cuts at three different azimuthal angles in the electron beam $\theta = 0°$ (red), 40° (dashed blue) and $-60°$ (green).

us to reach an OAM $\ell_{41} = 41$ with $\ell_1 = 1$ while keeping a clean spatial profile (see Supplementary Fig. 3). Combined with the spectral phase locking inherent to the HHG process, this opens a way of synthesizing attosecond light pulses carrying extremely high mean values of OAM. In the next section, we demonstrate that the harmonics generated with a helically phased infrared beam are phase-locked and use the resulting attosecond 'light spring' to shape electron wave packets (EWP) through photoionization.

Attosecond electron vortices. Since the early days of attophysics it has been recognized that attosecond XUV pulses could tailor EWP through photoionization[17,30]. Applications of such attosecond EWP were proposed, for instance, as a quantum stroboscope[31], or as tools to localize EWP in space and time around atoms and molecules[32]. In the present context, we propose to increase the tailoring knobs by transferring the OAM carried by the harmonics on photoionized electrons, resulting into electron bursts carrying OAM. We demonstrate the synthesis of such helically shaped electron beams through an interferometric measurement based on the well-established XUV–infrared cross-correlation technique called RABBIT[33] (reconstruction of attosecond beating by interference of two-photon transitions), in which synchronized XUV harmonics and infrared beams ionize a target gas. Thus, an electron can be promoted to a given final state called sideband (SB) through two quantum paths involving the absorption of one photon coming from consecutive harmonic orders and the absorption/emission of one infrared photon. The resulting quantum interference leads to oscillations of the SB yield as a function of the XUV/infrared delay at twice the infrared laser period and its phase is the sum of the total relative phase of the harmonic orders involved plus that of the two-photon dipole transitions at play, denoted by $\Delta\varphi_q$.

Most importantly, for the interference to be observed, a constant phase relation between the XUV and infrared fields across the gas jet is required. Using a twisted XUV beam (see Supplementary Note 4), this condition is met with a dressing infrared beam carrying the OAM ℓ_1, but not with a standard Gaussian dressing beam (see Methods).

Our experimental test is based on a Mach–Zehnder interferometer sketched in Fig. 2a. Scanning the XUV–infrared delay, we observe the expected 2ω oscillations of the SBs' intensity (Fig. 3a). We also see some ω oscillations, which are due to a modulation of HHG by the second infrared field but do not hinder the 2ω SB analysis[33]. As in standard RABBIT measurements, the phase of the 2ω oscillation is directly linked to the group delay ($\mathrm{GD} \simeq \Delta\varphi_q/2\omega$, with $\omega = 2\pi/\lambda$) of the EWP generated at the atomic level by the harmonic comb. This GD exhibits a linear dependence, with an increase of $\Delta t_e = 103 \pm 9$ as between consecutive odd harmonic orders, which is consistent with the reported values using a Gaussian beam with the same driving wavelength and peak intensity[33]. The presence of the 2ω oscillations demonstrates that the azimuthally spinning infrared intensity is matched with the XUV light spring on the subcycle