Multi-directional, non-steady mass-accretion onto high-mass protostars

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Understanding the formation of massive stars with more than ten times the mass of the Sun is one of the unsolved problems in modern astronomy\textsuperscript{39}. The main difficulty is that the intense radiation from the high-luminosity stars and the thermal pressure from the resulting ionized gas (both insignificant for low-mass stars) may be able to reverse the accretion flow and prevent the star from accreting fresh material. Such feedback effects can naturally be mitigated if accretion proceeds through discs, which is the established mechanism to form sun-like stars\textsuperscript{37}. However, recent 3D (magneto)hydrodynamic simulations\textsuperscript{5,26,35} have shown that accretion on 1000 au scales is through filaments rather than a large disc. This mechanism allows the star to sustain high average accretion rates (of order of $10^{-3}$ solar masses per year) while mitigating the effects of stellar feedback. This theoretical prediction has
never been confirmed via observations owing to the poor linear resolution of previous studies ($\geq 1000$ au). Here we present the first observational evidence that mass assembly in young high-mass stars forming in protoclusters is predominantly asymmetric and disordered. In particular, we observed the innermost regions around three deeply embedded high-mass protostars with very high spatial resolution ($\sim 100$ astronomical units). We identified multiple massive (several solar masses), warm (50-150 Kelvin) filamentary streamers pointing onto the central sources, which we interpret as multi-directional accretion channels. These structures inhibit the formation of a large, steady disc. Nevertheless, the identification of fast collimated outflows in the three observed systems indicates that (non-steady) compact discs may be present (we measure upper limits on their radii of $<80$ for one object and $<350$ astronomical units for the remaining two objects). Our finding contrasts with the simplified classic paradigm of an ordered (and stable) disc/jet system and provides an experimental confirmation of a multi-directional and unsteady accretion model for massive star formation supported by recent 3D (magneto)hydrodynamic simulations.

We used the Atacama Large Millimetre Array (ALMA) to observe at millimetre-wavelengths the high-mass star forming complex W51 located at a distance of about 5.4 kiloparsecs (kpc)\textsuperscript{32}. This region is forming a luminous and rich protocluster (with at least fifty protostellar sources detected\textsuperscript{18}), which contains both exposed O-type stars and deeply-embedded high-mass young stellar objects (HMYSOs), and as such it is a powerful laboratory for studying the high-mass star formation process. Here, we focus on three HMYSOs: W51e2e, W51e8, and W51north, which are distributed across a $\sim 3$ pc region. Previous observational studies using the Jansky Very Large
Array (JVLA\cite{11} and ALMA cycle 2\cite{10} have provided kinematic and physical properties of these HMXYSOs on angular scales of 0.2–1" (corresponding to 1000-5000 au). Based on this previous work, we know that these objects must be in the earliest stages of their evolution, whereas the lack of an observable ionized (HII) region indicates that the central sources have not yet started ionising their surroundings via ultraviolet radiation (they may be bloated due to their high accretion rates and therefore have surface temperatures too low to produce ionizing radiation\cite{15}).

The ALMA observations (see Methods) were taken with the longest baselines of 16 km, which allowed us to achieve the unprecedented angular resolution of 20 milli-arcseconds, which corresponds to a spatial resolution of about 100 astronomical units (au) at the distance of W51. We produced a set of high-spatial resolution images of both the λ1.3mm continuum emission and a selected set of molecular lines at different excitation energies (see Methods for a summary of the imaging parameters).

We display some of these images in Figures 1, 2 and 3, which yield four main findings. (1) There are warm (∼ 50 − 150 K) dusty streamers converging onto compact cores that we conclude are accreting filaments (Fig. 1 and Supplementary Figs. 6 and 7). (2) We find no hints of rotation towards these cores (Fig. 2), suggesting that they do not host large discs (radii < 80 to < 350 au). (3) The central sources in the cores drive young (∼ 100 years), compact (∼ 1000 au), fast (∼ 100 km s\(^{-1}\)) collimated outflows (Fig. 1 and Supplementary Fig. 5), indicating that the driving protostars are vigorously accreting. (4) The outflow from W51north has a different axis (projected onto the plane of the sky) as a function of distance from the protostar, hinting at a change of
Finding 1. Figure 1 showcases the complex structures in the circumstellar material within 2000 au of the central protostar in W51e2e, W51e8, and W51north, respectively. The three-color composite shows the λ1.3mm continuum emission (in green), which traces dust in the cores, and the redshifted and blueshifted emission of the SiO J = 5-4 line (in red and blue), which traces outflowing gas from those cores. Remarkably, the dust emission does not show a simple flattened structure at the center of the outflows, as one would expect if there is a large accretion disc, but instead the emission is resolved into multiple streamers (or “dust lanes”) that converge onto the central cores. These dust lanes appear elongated in several directions, both perpendicular and parallel, relative to the SiO outflows in all three sources. They extend typically across 0′′1-0′′4 (∼500-2000 AU) from the compact sources, have relatively high temperatures (∼ 50 – 150 K; see Supplementary Figs. 6 and 7), and carry a significant amount of mass (several solar masses; see Methods). We suggest that these dust lanes represent the dominant accretion flows onto each source (we rule out alternative explanations like outflows; see Methods).

Finding 2. Having identified these flows, we attempted to determine their kinematic structure in order to infer an accretion rate. Velocity gradients perpendicular to outflow axes are usually interpreted as gas rotation in a disc\textsuperscript{4}, while redshifted absorption is usually considered a signature of gas infall\textsuperscript{11}. In Figure 2 and Supplementary Figure 4, we display velocity field maps (see...
Methods) for selected lines of CH$_3$CN (a typical dense gas tracer$^5$) for W51e2e, W51e8, and W51north, respectively. A remarkable feature seen in these velocity maps is the nearly perfectly flat velocity field in all three sources near their systemic velocity (shown in green). In particular, the lack of rotational velocity gradients towards the compact cores (i.e. the dust continuum peaks) is surprising, because there one would expect to see rotation if accretion discs were present. This property is best seen towards W51north, where different CH$_3$CN lines from the K-ladder (with lower energy levels between 133 K and 638 K), show exactly the same remarkably flat velocity profile regardless of their excitation (Supplementary Fig. 4, bottom row). Higher excitation lines should supposedly probe warmer gas closer to the protostar, and therefore be redshifted compared to lower-excitation lines, as the gas should be moving with higher velocities toward the center (the bottom of the gravitational potential well). This is not seen in our velocity field maps. Since the geometry of the sources is different, it is unlikely that the true velocity field is similarly flat in all three sources. We conclude that the lack of velocity structure is an observational effect caused by the high optical depth in the dust continuum$^{18}$ (towards the cores, we only detect molecular lines in absorption against the continuum; see Methods). The only exception is W51e2e (Fig. 2, left panel), which shows red-shifted velocities along the northwest dust lane. Since these lines are seen in absorption against the dust continuum, one would be prompted to conclude that they probe dense gas infalling toward the compact core. However, the redshifted velocities are observed away from the dust continuum peak and only along the redshifted lobe of the SiO outflow, which is pointing away from us, suggesting that this material may actually be entrained by the outflow. In this scenario, the lower opacity expected along the outflow cavity may explain why dense gas tracers
like CH$_3$CN display kinematics only along that specific line-of-sight. Lacking a clear signature of accretion (rotation or infall), we cannot directly measure the mass accretion rate (but see Finding 3 below) nor the disc size in these protostars. We can however measure upper limits on the potentially disc-containing regions based on the observed extent of the dust emission, which yields 160 au for W51e8 and 700 au for W51e2e and W51north, respectively (indicated with black arrows in Fig. 1 and Supplementary Fig. 5).

Finding 3. Despite the lack of (large) discs, we identify fast ($\sim \pm 100 \text{ km s}^{-1}$), collimated bipolar outflows in SiO emission (Fig. 1 and Supplementary Fig. 5), which provide a clear indication of ongoing accretion onto the three HMYSOs. Lower resolution ALMA images of the $^{12}$CO J=2-1 line emission\textsuperscript{[10]} identified bipolar outflows stemming from W51e2e and W51north on scales from 1000 AU up to 30000 AU, which have dynamical ages of roughly 1000 years. The SiO thermal emission displayed in Figure 1 traces shocked gas at the root of these larger-scale CO outflows, within roughly one thousand au of the protostars, i.e., on scales that were previously unresolved. In Methods, we estimate dynamical ages of about 50-100 years for the SiO outflows, which are among the youngest known outflows driven by high-mass protostars. We conclude that the CO emission probes the oldest component of the outflow, while the innermost compact component traced by SiO represents the latest outflowing event. We measure a mass ejection rate from the SiO emission (see Methods), which provides a lower limit on the infall rate in the core and a proxy for the accretion rate onto the protostar. We infer accretion rates of $1.5 \times 10^{-3}$ and $3.3 \times 10^{-3} \text{ M}_\odot \text{ yr}^{-1}$ onto the W51north and W51e2e protostars, respectively (the outflow in W51e8 appears to be
nearly in the plane of the sky, making estimates of the accretion rate less reliable; see Methods).

**Finding 4.** While the SiO outflows from W51e2e and W51north are both clearly bipolar, an analysis of their spatial and velocity structure reveals an important difference. While W51e2 appears to be continuously driving an outflow with a steady orientation, W51north shows a 'multi-component' outflow structure (best displayed in Figure\textsuperscript{3} and Supplementary Fig.\textsuperscript{9}). In particular, the SiO emission traces a prominent fast jet (up to 95 km s\textsuperscript{−1}) along a northwest-southeast direction (at a P.A. of −70°) close to the driving protostar (within roughly 1300 au in the redshifted lobe and 1600 au in the blueshifted lobe). Slightly before the outflow endpoints (at radii of 800 au in redshifted side and 1200 au in the blueshifted side), it makes what appears to be a sharp turn of 80°(at P.A.\sim10°), and curves until it settles at P.A. 0°, along the edges of the larger scale CO flow\textsuperscript{9} (the sharp turn is more prominent in the redshifted lobe, but is clearly discernible also in the blueshifted lobe). The overall SiO emission appears to trace a single outflow that has changed direction on the sky.

This peculiar morphological structure is best explained as a single protostellar outflow that changes direction over time (see Methods). The prominent and compact northeast-southwest faster component represents the latest powerful outflow event, while the faint and diffuse north-south slower component represents a fossil outflow from an older event. In particular, the ‘young’ outflow has an age of about 80 years, the ‘old’ outflow has an age of about 420 years, while the ‘transition’ between the two (i.e. the sharp turn) is completed in about 160 years (the three events are sketched in the Supplementary Fig.\textsuperscript{9}). The dramatic change of direction over a fairly short
period indicates a substantial change in the orientation of the outflow-launching region of the disc over that same timescale.

The observational findings described above support a scenario where *accretion filaments are feeding very compact (unsteady) discs, which drive collimated outflows and can change orientation over time*. Such a scenario has three main implications on our understanding of the high-mass star formation process, which we detail below.

**Implication 1.** Our findings contrast with a simple picture of an ordered and stable disc/jet protostellar system, which is the standard model for low-mass star formation[^37] and support an alternative mechanism of multi-directional accretion that may be the default mode of high-mass star formation. In fact, our observations provide an experimental confirmation to recent 3D (magneto)hydrodynamic simulations[^5][^7][^26][^33][^34][^35] in which accretion onto cores proceeds highly asymmetrically along filaments on scales greater than about 100 AU. The multi-directional nature of the accretion flows implies that the dominant angular momentum direction does not remain constant over the course of the mass assembly process.

**Implication 2.** Even with our unprecedented high-angular resolution observations, we do not detect discs in our protostellar sources, mainly because of high optical depth of the dust continuum emission. Nevertheless, we believe discs (with radii <80 au and <350 au) are present based on the presence of collimated SiO outflows. Some simulations, such as those with asymmetric accretion flows, suggest that the discs should only form on scales less than about 100 au[^5][^26][^33][^34][^35]. However, other simulations that have more ordered initial conditions and do not produce asymmet-
ric flows\textsuperscript{17,19,20} often produce much larger (\(\sim\) 500 AU) discs. The smaller discs predicted by the simulations with more turbulent initial conditions suggest that even ALMA’s longest baseline configurations should be unable to resolve Keplerian discs around distant high-mass forming stars\textsuperscript{36}. This observation suggests that direct detection of massive discs and dynamical mass measurement of high-mass protostars will require (optically-thin) low-frequency molecular line observations.

**Implication 3.** A natural consequence of asymmetric accretion on a thousand au scales is the occurrence of unsteady, episodic accretion events onto the disc and subsequently onto the protostar itself. If the parent core feeding the central disc has a distribution of angular momentum vectors at different radii from the protostar, the central disc will accrete gas with time-dependent directions of the mean gas angular momentum vector. The buildup of a steady protostellar disc can occur only during periods when the accreting filaments do not significantly change their orientation relative to the disc. In W51north, a dramatic structural change in the orientation of the accretion channels may have resulted in a sudden change of orientation of the accretion disc. Given the presence of a substantial reservoir of surrounding material distributed asymmetrically around the source, we argue that accretion onto the disk is a likely cause for the change of outflow direction. From the ejection/accretion rate analysis (see Methods), we infer that a large amount of mass, 0.8 \(M_\odot\), was deposited in a recent accretion event (over the course of just \(\sim\) 160 years). The sudden deposit of a large amount of mass, nearly orthogonal to the disk’s original direction, can readily explain the substantial modification (\(\gtrsim\) 60°) in its spatial orientation.

In the low-mass regime, evidence of episodic accretion is observed in FU Ori objects\textsuperscript{37}, which
exhibit sudden increases in the accretion rates (and therefore luminosities) of a few orders of magnitude that last from a few tens of years to a few centuries. Recently, a few outbursts in the high-mass regime have also been reported in the literature. These events are marked by substantial increases in maser and dust emission both at mm-waves and/or infrared. In this context, the rapid and substantial change in the disc orientation observed in W51north provides an indirect observational evidence of a significant recent accretion burst in the growth of a massive protostar.

We conclude that accreting cores within a thousand au of forming massive stars have a much more complex structure than observed in low-mass pre-main-sequence stars. The complex filamentary structures revealed by ALMA on scales of 100–1000 AU represent multidirectional accretion channels that inhibit the formation of large, steady discs (at least in the early stage of formation). These filaments feed central compact discs, whose presence is inferred from the existence of massive and collimated SiO outflows. These discs are not the classic smooth, steady discs seen around low-mass stars and in rotating core simulations, but instead are truncated and change orientation over time. These observations provide critical constraints on the small-scale conditions in high-mass star forming regions and will aid the development of a much needed general theory of massive star formation.
**Methods**

**ALMA Observations, data processing, and imaging.** As part of ALMA Cycle 3 program 2015.1.01596.S, we observed two fields centered on W51north ($\alpha(J2000) = 19^h23^m40^s.05, \delta(J2000) = +14^\circ31'05''.5$) and W51e2/e8 ($\alpha(J2000) = 19^h23^m43^s.91, \delta(J2000) = +14^\circ30'34''.6$) with long baselines in Band 6 (216–237 GHz). The project was carried out in three executions on 2015 October 27 and 30. Between 37 and 42 antennas in the 12-m array were employed and provided baselines ranging from 85 m to 16,196 m. The precipitable water vapour was between 0.85 and 1.98 mm for the observations and there was reasonable phase stability (see below). We employed the band 6 sideband-separating receivers in dual polarization mode to record nine spectral windows (spw): seven spws with a $\sim$234 MHz bandwidth were recorded in 960 channels and were Hanning smoothed by a factor of 2, achieving a frequency resolution of 564 kHz (corresponding to $\sim$0.75 km s$^{-1}$ at band 6), which enabled us to cover a large number of spectral lines from different molecular species; the remaining two spws had a broader bandwidth of 1.8 GHz and 1.13 MHz frequency resolution (corresponding to $\sim$1.5 km s$^{-1}$) to obtain sensitive continuum measurements at 217 GHz and 235 GHz as well as to cover additional spectral lines. We spent 2.2 hours on-source during a total observing time of 5.3 hours.

The data calibration and imaging was carried out in the Common Astronomy Software Applications (CASA) package (version 4.5.1) and followed standard procedure. Fast referencing was used for these long baseline observations: the phase calibrator was observed every $\sim$70 s. The phase calibrator to target field separation angle was small at $<1.2^\circ$. The combination of fast switching times and a close phase calibrator is imperative for accurate phase calibration in-
terpolation for these long baselines. Additionally, the water-vapour radiometer (WVR) scaling algorithm\textsuperscript{24} was implemented to improve the short term (3-6 sec) phase stability. This is a stand-alone modular package that runs inside the CASA environment and provides a user with the optimal value to scale the water vapour corrections in the \texttt{WVRGCAL} task within CASA. The phase calibration of the data was then further improved by phase self-calibrating on the continuum emission down to an integration timescale of 50 sec (using the CASA tasks \texttt{tclean} and \texttt{gaincal}). The combined effect of WVR scaling and phase self-calibration improved the dynamic range of the final continuum maps by about 35%. The phase and amplitude solutions from the continuum self-calibration were also applied to the full spectral dataset (using the CASA task \texttt{applycal}) in order to improve the signal-to-noise ratio of line cubes.

The calibrated visibilities were transformed from the Fourier plane (\textit{uv} domain) into the image domain using the \texttt{clean} and \texttt{tclean} algorithms (which provided images of comparable quality and fidelity). Three sets of images were produced in the data analysis using uniform, Briggs (robust parameter R=0.5), and natural weighting schemes which achieved the angular resolution of 19, 28, and 35 milli-arcseconds, respectively. Since interferometric observations lead to spatial filtering of large-scale structures, the maximum recoverable scale in our images is $0''.4$ (about 2000 au at a distance of 5.4 kpc). This implies that we do not detect any emission that is extended over scales larger than 2000 au. Within the \texttt{clean} and \texttt{tclean} tasks, we only include data from baselines longer than 300 meters to mitigate striping in the images from large-scale emission detected on the shortest baseline that could not be properly imaged.

Continuum images were produced by selecting line-free channels in each spw and then com-
bining all spw, and have a resulting central frequency of about 226 GHz assuming a flat spectrum source. Channel selection was accomplished in the $uv$ domain using the shorter baselines $<1000$ m where emission is seen, and line-free regions can be discerned. Approximately 5 percent of the total bandwidth was assessed to be ‘line-free’ and was selected to establish the continuum level. The final images were cleaned to a threshold of 0.3 mJy and then corrected for the primary beam response. The lowest noise level in the images, away from bright sources, is typically $\sim 0.1$ mJy beam$^{-1}$, near the thermal noise level, as expected from the ALMA sensitivity calculator (near the brightest sources W51e2e and W51north, the noise can be two to three times higher). Continuum images were produced with both uniform weighting ($\theta \sim 19$ milli-arcseconds) and Briggs weighting with a robust parameter $R = 0.5$ ($\theta \sim 28$ milli-arcseconds). The former provides the highest angular resolution to identify compact components, while the latter provides sufficient signal-to-noise ratio to recover the continuous filamentary structure around the dusty peaks.

For the line emission data analysis, we used natural weighting (also excluding baselines shorter than 300 m) in order to provide the highest signal-to-noise ratio, providing a typical angular resolution of 35 milli-arcseconds. Images were also produced with Briggs (Robust=0.5) weighting ($\theta \sim 28$ milli-arcseconds) which were useful in identifying compact components. From the nine spw, we identified a large number of lines ($> 130$) from about 20 different chemical species (a full description will be reported elsewhere). We then identified a subset of lines which are unblended and strong enough to be used for kinematic analysis. For these lines, we created and inspected integrated intensity ($0^{th}$ moment), velocity ($1^{st}$ moment), and velocity dispersion ($2^{nd}$ moment) maps. The $1^{st}$ and $2^{nd}$ moment maps were constructed using an intensity threshold of 7 mJy ($\sim 3 - 4\sigma$,
depending on spectral channel/source), and the velocity extent was chosen to avoid contamination from nearby lines where possible. For this kinematic and moment analysis, the median value over the full spw was used to estimate and subtract the local continuum. The resulting maps allowed us to study the structure, the kinematics, and the velocity dispersion of the circumstellar gas with a spatial resolution of about 150-200 AU. We also note that the molecular lines observed toward the dust structures are only seen in absorption (except for SiO, which is only seen in the outflow).

**Analysis of the continuum emission: temperature, mass, and luminosity estimates.** The temperature is a critical ingredient for determining the total mass (or luminosity) of each continuum source. Assuming that at least the central beam of the mm continuum emission is optically thick, we can use its Planck brightness temperature as a proxy of the dust temperature. The peak intensities of the three sources in the robust 0.5 map are $S_{227\text{ GHz}(e2e)} = 19.4$ mJy beam$^{-1}$, $S_{227\text{ GHz}(e8)} = 14.7$ mJy beam$^{-1}$, and $S_{227\text{ GHz(north)}} = 13.2$ mJy beam$^{-1}$ in 0.033 × 0.024 $''$ beams. These values correspond to brightness temperatures of $T_{B,max} = 575$ K, 435 K, and 390 K, respectively, which can serve as lower limits on the dust temperature. LTE modeling of CH$_3$OH lines imaged with the ALMA cycle 2 program measured temperatures in the range 200-600 K inside 5000 AU, therefore we assume $T = T_{gas,min} = 200$ K as a lower limit on the dust temperature. Assuming optically thin emission away from the peak positions, we can use these dust temperatures estimates to compute lower limits to the gas masses from the flux density measurements using the following equation:

$$M = \frac{S_\nu d^2}{\kappa_\nu B_\nu(T_d)},$$
where $S_\nu$ is the source flux density, $B_\nu(T_d)$ is the Planck function for a blackbody at dust temperature $T_d$, $d$ is the distance to the source, and $\kappa_\nu$ is the dust opacity coefficient (which includes already the gas-to-dust ratio of 100); we use the same coefficient $\kappa_{227 \text{ GHz}} = 0.0083 \text{ cm}^2\text{g}^{-1}$ as in the ALMA cycle 2 program.\(^{10}\)

For the highest column density regions toward the source centers, we assume that the source is just barely optically thick, with $\tau = 1$ and therefore $N(\text{H}_2) = 1/\kappa_\nu = 2.6 \times 10^{25} \text{ cm}^{-2}$ (using the same calculation as Ginsburg et al.\(^{10}\)), which yields dust masses for the central beam of each source $M = 0.36 \text{ M}_\odot$. In these small beams, the gas mass required to reach high optical depth is quite small. We use this same approach to obtain mass estimates of the spatially resolved cores. In W51e2e, there is a clear central core object that is round and extended from the brightest central beam (captured in the yellow contour in Supplementary Fig. 6). This source spans 27 beam areas (radius $r \approx 500$ AU), implying a mass $M_{e2e,\text{core}} = 9.7 \text{ M}_\odot$ if it is entirely optically thick. If it is optically thin on average, using the expression above for $T = T_{B,\text{max}} = 575 \text{ K}$, the total is 4 $\text{ M}_\odot$, while for $T = T_{\text{gas,\text{min}}} = 200 \text{ K}$, the total is 12 $\text{ M}_\odot$. In the larger area around W51e2e, there are four main filamentary accretion structures that extend out to $r \sim 2500$ AU (captured in the red contour in Supplementary Fig. 6). We estimate the mass of these assuming $T = 200 \text{ K}$ and obtain $M_{e2e,\text{filaments}} = 25 \text{ M}_\odot$ (this estimate does not include the inner core). In W51e8, as in W51e2e, there is a bright central source, but the structure surrounding the W51e8 point source is less symmetric. A filament extends to 1400 au from W51e8 along northwest (captured in the yellow contour in Supplementary Fig. 6), for which we measure a mass of $M(T_{B,\text{max}} = 435 \text{ K}) = 4 \text{ M}_\odot$ and $M(T = 200 \text{ K}) = 9 \text{ M}_\odot$. There is also a more extended structure toward the southwest,
covering approximately a semicircle centered on W51e8 out to a maximum radius of 2600 AU (see the red contour in Supplementary Fig. 6). This structure has $M(200 K) = 16 M_\odot$. Finally, in W51north, there is no central point source. However, there is a slightly elongated peanut-shaped structure (shown in yellow contour in Supplementary Fig. 6), with long axis $r \sim 350$ au. This source occupies 14 beams, implying a lower-limit mass $M > 5.2 M_\odot$ if it is optically thick or $M(T_{B,max} = 390 K) > 4.2 M_\odot$ if it is thin and isothermal at the peak observed temperature. For the larger surrounding structure (captured in the red contour in Supplementary Fig. 6), we obtain a mass range $M(T_{B,max} = 390 K) = 14 M_\odot$ and $M(200 K) = 28 M_\odot$. This mass is contained within a 1200 AU radius, though it is primarily in a structure that is elongated northeast/southwest.

We compare the recovered flux in the long-baseline maps to that in the ALMA cycle 2 maps at the same frequency. In the robust 0.5 maps, in W51e2e, 13% of the flux is recovered, in W51e8, 12%, and in W51north, 23%. These low recovery fractions indicate that most of the dust emission is smooth on $\gtrsim 2000$ AU scales. It is therefore likely that the cores contain up to five to ten times as much mass within $r \lesssim 2000$ AU as we have estimated above.

The peak brightness temperatures are a lower limit to the surface brightness of the millimeter core, since an optical depth $\tau < 1$ or a filling factor of the emission $f f < 1$ (in the case of W51e2e and W51e8 which have a central unresolved component) would both imply higher intrinsic temperatures. One can use these temperatures to estimate lower limits on the source luminosities. Assuming blackbody emission from a spherical beam-filling source, the luminosity can be calculated as $L = 4\pi r^2 \sigma_{sb} T^4$, where $\sigma_{sb} = 5.670373 \times 10^{-5} g s^{-3} K^{-4}$ is the Stefan-Boltzmann constant. This provides lower limits of $8.2 \times 10^3 L_\odot$, $7.5 \times 10^3 L_\odot$, and $2.8 \times 10^3 L_\odot$ on the luminosity of
W51e2e, W51e8, and W51north, respectively. Such luminosities correspond to B1-B1.5V mainsequence stars with masses $M \sim 8 - 11 \, M_\odot$ and effective temperatures of 24000-26000 K\cite{10}. However, coarser-resolution observations with ALMA in cycle 2 yielded lower luminosity limits that are slightly higher than these, $L \gtrsim 10^4 \, L_\odot$, implying masses $M \gtrsim 10 - 15 \, M_\odot$\cite{10}.

**Ages of the outflows.** To estimate the dynamical age of the outflows, $T_{\text{dyn}}$, we take the ratio of the projected length (measured from the protostar), $R_{\text{max}}$, to the the maximum speed of the outflow, $V_{\text{max}}$, corrected for the inclination $i$: $T_{\text{dyn}}(V_{\text{max}}) = (R_{\text{max}}/V_{\text{max}})/\tan (i)$.

Toward W51e2e, the outflow is clearly bipolar and fairly symmetric, though the redshifted side is partly obscured by the dust continuum, therefore in the following we use the blue lobe in our estimates. We observe a maximum velocity of 105 km s$^{-1}$ ($v_{\text{lsr}} = -50$ km s$^{-1}$) at a separation of 0.47″ or about 2500 au, which gives a dynamical age $T_{\text{dyn}}(V_{\text{max}}) = 115 \times (\tan (45^\circ)/\tan (i))$ years, where the inclination $i$ is expressed in units of $^\circ$.

In W51e8, the highest observed outflow velocity is 42 km s$^{-1}$, at a separation of about 390 au, which corresponds to $T_{\text{dyn}}(V_{\text{max}}) = 44/\tan (i/45^\circ)$ years. We however warn the reader that the outflow appears to be nearly in the plane of the sky, therefore estimates of its age are less reliable.

Toward W51north, the SiO outflow breaks in three major components, representing three consecutive events (these are labeled as ‘young’, ‘transition’, and ‘old’ in the Supplementary Fig.\cite{9}). The first ‘young’ component of the flow close to the protostar has an observed velocity of $v_{\text{lsr}} = -35$ km s$^{-1}$ or an outflow velocity of 95 km s$^{-1}$, for a maximum length of about 1600 au,
which corresponds to $T_{\text{dyn}}(V_{\text{max}}) = 82 \times (\tan (45^\circ)/ \tan (i))$ years. The second component, which identifies the 'transition' between the young northwest-southeast component and the old north-south component, has a maximum velocity of $30 \text{ km s}^{-1}$ at a separation of about $1500 \text{ au}$, which gives a dynamical age $T_{\text{dyn}}(V_{\text{max}}) = 245 \times (\tan (45^\circ)/ \tan (i))$ years. The third component is the larger-scale 'old' north-south outflow, which has a maximum velocity of $50 \text{ km s}^{-1}$ at a separation of $0.8''$ or about $4300 \text{ au}$, which gives a dynamical age $T_{\text{dyn}}(V_{\text{max}}) = 420 \times (\tan (45^\circ)/ \tan (i))$ years, where the inclination $i$ is expressed in units of $^\circ$. An even older component of the outflow is traced by $^{12}\text{CO}$, which has a maximum expansion speed of $100 \text{ km s}^{-1}$ and a length of about $4 \text{ or } 22000 \text{ au}$, yielding a dynamical age of about 1000 years.

**Mass accretion rate estimates.** Lacking a clear signature of accretion, we use ejection rates as a proxy for the infall/accretion rates. Here, we use the term ”infall rate” to describe gas in the core infalling onto the disc/protostar system, and the term ”accretion rate” to describe gas accreting onto the protostar itself. To this end, we use the SiO emission structure to estimate the mass-loss rate in the outflows. One straightforward method would be to determine the mass of the outflowing gas from SiO emission and divide it by the outflow dynamical age. While this may provide the correct order-of-magnitude answer in some cases, molecular outflows, such as those seen in CO and SiO emission, are driven by an underlying primary wind/jet and probe mostly entrained ambient gas moving at lower velocity (this applies especially to CO). In fact, the linear correlation between accretion and ejection rates strictly holds only for either the primary (stellar- or disc-)wind and/or jet from the protostar, not for the entrained material. Since in protostellar jet/outflow systems momentum is conserved (and one speaks of momentum-driven as opposed to
energy-driven outflows\cite{22}, one can set a tight constraint on the mass accretion rate using \( \dot{m}_j v_j = \dot{m}_o v_o = \dot{P}_o \), where \( \dot{m} \) is the mass-loss rate, \( v \) is the speed and \( \dot{P} \) is the momentum rate (\( j \) and \( o \) stand for the primary jet and molecular outflow, respectively).

In order to determine the momentum of the outflowing gas, we compute its total mass from the SiO emission integrated in the full velocity range. We follow a standard approach in two steps. As a first step, we measure the number of SiO molecules per unit area along the line of sight, a quantity called the ”column density”. We first calculate the column density of SiO in the energy level corresponding to the observed transition J=5-4, using the measured intensity of that transition (channel by channel) and the Boltzmann equation for statistical equilibrium coupled with the standard radiative transfer equation (e.g. the optically thin version of Eq. (30) in\cite{22}). Then we relate the number of molecules in the given energy level, to the total population of all energy levels in the molecule assuming that they are populated according to a Boltzmann distribution: we use the “rotational partition function”, a quantity that represents a statistical sum over all rotational energy levels in the molecule, and we assume a constant temperature defined by the excitation temperature \( T_{ex} \) (e.g. Eq. (31) in\cite{22}). We adopt \( T_{ex} = 250 \) K (note that the partition function is approximately linear with \( T_{ex} \) in this regime, so if the molecules are twice as hot, the column estimate should be halved). In the second step, we use the SiO column density to compute the total mass of the molecular gas. This requires to convert the number density of SiO into number density of molecular hydrogen, H\(_2\) (which is the most abundant molecule). For this conversion, we assume a conservatively high abundance of SiO, \( N(SiO)/N(H_2) = 10^{-7} \)\cite{21} obtain \( 0.7 - 4.8 \times 10^{-8} \) for a sample of high-mass star forming regions, while\cite{20} measure \( 1 \times 10^{-9} \) to \( 3 \times 10^{-8} \). Note that a
high abundance of SiO implies lower mass and momentum. From the knowledge of the mass of the H$_2$ molecule, it is then straightforward to convert the number density of H$_2$ into a molecular gas mass. The total momentum is then obtained by integrating over the full velocity range of SiO emission: $P_o = \sum v m_v v$. We thus derive: $P_o = (\cos (45^\circ)/\cos (i)) \times 383 \text{ km s}^{-1} \text{ M}_\odot$ in W51e2e, 117 km s$^{-1}$ M$_\odot$ in W51north, 32 km s$^{-1}$ M$_\odot$ in W51e8, respectively, where $i$ is the inclination.

In our analysis, we treated independently the redshifted and the blueshifted lobes, which yielded similar order-of-magnitude estimates. However, in W51e2e, the redshifted lobe is partly obscured by the dust continuum, whereas in W51north the redshifted side shows a more complex structure than the blueshifted side, yielding more uncertain estimates. Owing to these observational biases, we used the blue flows alone in our estimates.

At this point we convert the computed momenta of the molecular outflows into ejection rates of the primary winds/jets. This requires the knowledge of their speed, which however we do not measure. Jet speeds measured in low-mass outflows via spectroscopy of atomic lines in the optical and near-infrared wavelengths are typically a few hundred kilometers per second$^8$. For massive outflows, there are fewer measurements of jet velocities, but a handful of proper-motion studies of the radio continuum jets provide speeds of about 500 km s$^{-1}$ (see HH 80/81$^{23}$). Using the total momentum computed above and the ages determined in previous section, we derive the following mass ejection rates for the primary jet: $\dot{m}_j = (500 \text{ km s}^{-1}/v_j \text{ km s}^{-1}) \times (\cos (45^\circ)/\cos (i)) \times 6.6 \times 10^{-3} \text{ M}_\odot \text{ yr}^{-1}$ in W51e2e, $3.1 \times 10^{-3} \text{ M}_\odot \text{ yr}^{-1}$ in W51north, $1.5 \times 10^{-3} \text{ M}_\odot \text{ yr}^{-1}$ in W51e8, where $i$ is expressed in units of $^\circ$ and $v_j$ is the jet speed in km s$^{-1}$ (Note that the same concerns apply also here on the reliability of the estimates in W51e8 due to its high inclination).
A comparison of the prestellar core mass function with the stellar initial mass function suggests that only 1/3 of the core mass is accreted onto the star\textsuperscript{[20]}. To explain this low “core-to-star” efficiency, it has been suggested that a significant fraction of the infalling gas is actually re-ejected via protostellar winds/jets\textsuperscript{[3]}. Assuming a 1/3 core accretion efficiency, corresponding to a 2/3 mass outflow efficiency, we can now convert the ejection rate into an infall rate using \( \dot{m}_{\text{inf}} = 1.5 \times \dot{m}_j \). Therefore, our analysis indicates mass-infall rates in the range of \( 1 \times 10^{-2} - 1.5 \times 10^{-3} \, M_\odot \, \text{yr}^{-1} \) for the high-mass cores in W51 (the mass-accretion rate onto the protostar itself will be a factor of 1/3 lower).

Under the assumption that the present (young) outflow is the result of a single major accretion event and that the infall rate remained constant over the transition period (\( \sim 160 \) years), we infer that a mass of about 0.8 \( M_\odot \) was dumped onto the protostar/disc system in such accretion event.

**On the lack of kinematical signatures of accretion.** We have looked for expected signatures of accretion onto a high-mass, high-luminosity protostar embedded in a core that is optically thick in the continuum, in particular: a) higher excitation lines should be redshifted compared to lower-excitation lines (the gas should be moving with higher velocities toward the center), b) the spectral profiles should be moderately asymmetric (skewed toward the blueshifted component\textsuperscript{[13]}). The velocity field appears however to be approximately flat across the core for the three sources, in both absorption lines toward the continuum and emission lines in the continuum-free regions (as seen in the lower-resolution data\textsuperscript{[10]}). While some lines show some signs of different-velocity absorption features, these are all low-excitation lines (e.g., \(^{13}\)CO, H\(_2\)CO) that demonstrably trace the broader molecular cloud, not the core.
If there are genuinely massive, accreting cores in these objects, as demonstrated by the presence of powerful outflows, some infall must be occurring. A few solutions are possible for its non-detection: 1) All gas is accreting in the plane of the sky. Since we see three sources, none of which have clear kinematic accretion signatures, and all of which have detectable outflow kinematic signatures, this possibility is implausible. 2) Radiative transfer effects are hiding the kinematic signatures. In low-mass cores, (double-peaked) symmetric line profiles are expected in optically thin tracers because the velocity of the flow increases toward the star, and inverse P Cygni profiles in optically thick lines. However, in low-mass cores, the continuum is almost always optically thin and relatively low brightness temperature. In the high-mass cores we observe, the continuum brightness temperature is very high, leading us to infer that the optical depth is similarly high. As we probe closer to the star (where the velocities are expected to be higher), the gas temperature rises and approaches equilibrium with the dust. If $T_{\text{gas}} = T_{\text{dust}}$, as $\tau_{\text{dust}} \to 1$, any absorption signature from the molecular line approaches zero. This means we should not expect to see the highest velocities in absorption at all, but we should see very strong absorption from cooler gas further in front of the core. The point at which we begin to detect molecular absorption indicates the approximate location of the $\tau_{\text{dust}} = 1$ surface, but it is not a very strong probe since what we observe is a mass-weighted profile of the foreground gas. This mechanism readily explains the lack of signatures in the absorption lines toward each source. 3) A purely observational effect hides the emission. When lines appear as absorption features toward the continuum source and emission features off of the source, the average surface brightness in a given velocity channel approaches a smooth, constant value. Because we are observing with an interferometer with low spatial dynamic
range, these smoother features are suppressed. It is likely that this effect is sufficient to push any emission signatures below the noise of our current data set.

We regard explanation (2) above as the most relevant. It implies that longer-wavelength observations, where the dust may be optically thin, are necessary to detect infall kinematics. We note that our finding that that dust opacity prevents kinematic measurements on small scales in high-mass protostellar disks using dense gas molecular lines was explicitly predicted in 18.

**Are the dust lanes outflow rather than accretion flows?** In the main text we mention that in W51e2e one of the filament along the redshifted lobe shows redshifted absorption and may arise along the outflow cavity. This finding raises the question whether the multidirectional dust lanes are actually probing warm dust heated by the outflows (e.g. by shocks), rather than accretion filaments. In W51e2e, there are at least four dust lanes with similar sizes (0.01-0.04 or ∼500-2000 AU) and brightness (50–150 K), which appear elongated in several random directions relative to the SiO outflows, therefore it is unlikely that they all identify dust in the outflow cavities. Similar arguments apply to W51north, where there are three different lanes with no common point of symmetry. If the outflow were responsible for the observed dust emission, the lack of bright emission toward the blueshifted lobe in the southeast would imply a much lower density of material in that direction, yet the blue lobe truncates sharply at a distance of only 1600 au at a point where no hot dust emission is observed. The hot dust emission is therefore almost certainly driven by (1) the presence of (much) more gas+dust toward the northwest than the southeast and (2) proximity of that gas+dust to the central star. Even if the outflow is interacting with this material, it is clear that there is a major asymmetry in the total mass.
Outflow structure in W51-north. The W51north outflow appears to be a single outflow that has changed direction substantially (from -10° to -70°) over a short period (a few hundreds years). In this section, we describe the structure of the outflow in detail, then assess alternative models that might explain the observed structure, then conclude that a single outflow is the best explanation of the observational data.

We focus the description on the redshifted lobe, since it is more prominent and more prominently displays relevant features. As best shown in Fig. 3 and Supplementary Fig. 9, close to the central protostar, the flow has an orientation consistent with that of the blueshifted lobe at a position angle (P.A.) ∼ −70°, up to a radius of 0′′24 (1300 au). Starting at about 0′′15 (800 au) from the center, it suddenly turns by 80° (at P.A. ∼ 10°) and curves until it settles at P.A. 0° along the base of the redshifted lobe of the 12CO outflow, which has P.A. ∼ −13°. The high-velocity portions of the flow (up to ∼70 km s\(^{-1}\) from the systemic velocity) are found closer to the protostar, while the material in the ‘transition’ region has lower-velocity (65 < \(V_{LSR}\) < 90 km s\(^{-1}\), i.e. within 30 km s\(^{-1}\) from the stellar systemic velocity). Some high-velocity material (up to 50 km s\(^{-1}\) from the systemic velocity) is also observed at the northern end of the SiO emission (see Supplementary Fig. 5). The large-scale red lobe shows contiguous structure tracing onto the small-scale, with the change in direction starting at around 0′′35 (1900 au) and completing by about 0′′15 (800 au). Assuming a constant velocity of 30 km s\(^{-1}\), the outflow turn occurred over just 165 years. The general structure, including the sharp turn, seen in the redshifted lobe is reflected in the blueshifted lobe, which shows a southward ‘protrusion’ starting at about 0′′22 (1200 au) from the protostar. Although much less prominent, this southern component in the blueshifted SiO lobe provides a
(weaker and more compact) counterpart to the redshifted northern component. In both SiO and CO emission, the blueshifted lobe is barely detected beyond about 0′′30 or 1600 au (perhaps it breaks out of the cloud if the source is located at the front of it).

The peculiar structure of the outflow revealed by ALMA images of SiO emission is also tracked by the H$_2$O masers 3-D velocities$^{18}$, shown in Supplementary Fig. 8. The H$_2$O masers reside in two complexes separated by ∼3000 au at the front edges of the compact SiO outflow lobes and are moving away from each other in ballistic motions at about 200 km s$^{-1}$ and at a position angle of −72°, consistent in both P.A. and velocity with the SiO compact outflow. In particular, the H$_2$O masers detected in the southeast appear to trace a bow shock at the tip of the blueshifted SiO lobe, while the H$_2$O maser complex in the opposite side traces both the high-velocity northwest redshifted lobe as well as the base of the northern outflow component. In the redshifted part of the outflow, the measured proper motions appear to smoothly rotate from northwest to north moving away from the tip of the SiO lobe, following closely the SiO emission.

Several scenarios can be envisioned to explain the structure of the SiO outflow from W51-North, with an emphasis on the sudden change of orientation:

1. The outflow hits an “obstacle” in the surrounding dense clump and gets deflected in another direction.

2. There are multiple independent outflows driven by different protostars.

3. There is a single unique outflow from the same protostar which changes direction over time.
Scenario 1) requires the presence of two obstacles located at approximately the same distance from the central source along the axis of the outflow, and these obstacles must be angled such that the redshifted flow is deflected to the northeast and the blue flow to the southwest. Such a contrived scenario is implausible, since it requires a unique and unlikely set of conditions with no known analogs in the observational or theoretical literature.

Similarly, scenario 2) requires at least two undetected YSOs to be symmetrically offset from the central source and be precisely at the locations of the intersections between the SiO and CO outflows. Each of these YSOs would have to drive a single-lobe outflow\footnote{Single-lobe outflows have been observed, and can be explained with inclination effects and/or with different densities of ambient material around the source.} in the blueshifted (southeast) and redshifted (northwest) direction. These single-lobe flows must also have velocities consistent with the brighter SiO outflow from the central source (redshifted for the northern MYSO and blueshifted in the southern YSO). The detection of the W51north, e2e, and e8 outflows in SiO, but nondetection of other SiO outflows in the field that contains dozens of candidate YSOs confirms that such high-brightness SiO outflows are very rare, so that even if there were two perfectly positioned YSOs, they are each unlikely to drive an SiO outflow. Combined, the various restrictions imposed by this model make it highly improbable.

Scenario 3) is a straightforward explanation of the observations. In this scenario, some process has caused the outflow to change direction over the course of just 150–200 years. Any change in the disk’s preferred direction would result in a change in the outflow direction, though the large change in angle ($\gtrsim 60^\circ$) suggests that small perturbations (e.g., an instability in the disk resulting
in warp) are inadequate.

Outflows that change direction have been observed. For example, the Cepheus A outflow shows evidence of steady precession over several thousand years possibly driven by a binary orbit that affects the disk. Qualitatively, the existence of this precessing outflow confirms that a single-source outflow changing direction over time is possible. The W51north outflow is somewhat different from the Cepheus A outflow, however, as it exhibits a single shift in direction that occurred on a shorter timescale, suggesting that a steady binary interaction is not the driver.

Given the presence of a substantial reservoir of surrounding material distributed asymmetrically around the source, we argue that accretion onto the disk is a likely cause for the change of outflow direction. There are three distinct time periods in this scenario (sketched in the Supplementary Fig.): the ‘old’ outflow, $t \gtrsim 240$ yr, the ‘transition’ period, with a total duration of about 160 years, and the ‘young’, bright outflow, $t \lesssim 80$ yr. This implies that, over the course of those $\sim 160$ years, a significant amount of mass was accreted nearly orthogonal to the disk’s original direction. The outflow morphology fits this scenario: there is emission detected in both the red and blue lobes at intermediate position angles ($-10^\circ > PA > -70^\circ$). This emission is not as cleanly symmetric as the more linear ‘old’ and ‘young’ outflows, which may be caused either by asymmetries in the surrounding medium or by changing speed of the outflow launch.

A final point in favor of this scenario is the lack of detected outflow emission in either CO or SiO at greater distances along the current southeast-northwest outflow axis. If the W51north outflow has not changed directions in the last $\sim 100$ years, the lack of observed outflow tracers
at greater distances along southeast-northwest implies that accretion onto this source only began in the last 100 years. Given the high luminosity of the source ($L \gtrsim 10^4 \, L_\odot$), such an age is implausible.

This final scenario does not suffer from any of the improbability of the others, and it is consistent with the observed morphology in several unique ways. We therefore conclude that a substantial accretion event changing the disk’s direction is the best explanation for the W51north outflow.
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Acknowledgements This paper makes use of the following ALMA data: 2015.1.01596.S. ALMA is a partnership of ESO (representing its member states), NSF (USA) and NINS (Japan), together with NRC (Canada), NSC and ASIAA (Taiwan), and KASI (Republic of Korea), in cooperation with the Republic of Chile. The Joint ALMA Observatory is operated by ESO, AUI/NRAO and NAOJ.

Author Contributions C.G. and A.G. led the project, analysis, and discussion. C.G. drafted the manuscript. L. M. led the data calibration and imaging of the ALMA data. Q. Z. and L. Z. commented on the manuscript and participated in the discussion.

Data Availability Statement This letter makes use of the following ALMA data: 2015.1.01596.S. The data that support the plots within this paper and other findings of this study are available upon reasonable request to the corresponding author.

Competing interests The authors declare no competing financial interests.
Supplementary: Multi-directional, non-steady mass-accretion onto high-mass protostars

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Figure 1: Overlays showing the complex structures in the circumstellar material within 2000 au from the central protostar in W51e2e, W51e8, and W51north, respectively. The three-colors overlay shows the dust continuum emission at $\lambda 1.3$mm (in green), tracing warm dust (50-400 K) in the (accreting) cores, and the redshifted and blueshifted emission of the SiO $J = 5-4$ line (in red and blue), tracing fast gas ($\pm 100$ km s$^{-1}$) outflowing from the same cores. The black arrows indicate the orientation and the upper limits to the size of putative underlying discs. The angular resolution of the continuum emission data is given by the ellipse drawn in the lower left corners: 0.$''033 \times 0.$''024 or 178 au $\times$ 130 au (green image). The SiO emission data has slightly worse resolution: 0.$''041 \times 0.$''031 or 221 au $\times$ 167 au (blue and red images). The highest resolution maps in this study achieve 0.$''022 \times 0.$''014 or 119 au $\times$ 76 au (not shown here). The SiO emission is integrated over $V_{\text{LSR}} = [-56,53]$ km s$^{-1}$ and [71,159] km s$^{-1}$ (W51e2e), [0,60] km s$^{-1}$ and [60,120] km s$^{-1}$ (W51e8), [-36,56] km s$^{-1}$ and [66,126] km s$^{-1}$ (W51north), for the blueshifted and redshifted maps, respectively. These corresponds to $V_{\text{outflow}} = [-112,-3]$ km s$^{-1}$ and [15,103] km s$^{-1}$ for $V_{\text{SYS}} = 56$ km s$^{-1}$ (W51e2e), [-60,0] km s$^{-1}$ and [0,60] km s$^{-1}$ for $V_{\text{SYS}} = 60$ km s$^{-1}$ (W51e8), [-96,-4] km s$^{-1}$ and [6,66] km s$^{-1}$ for $V_{\text{SYS}} = 60$ km s$^{-1}$ (W51north), for the blueshifted and redshifted SiO emission, respectively ($V_{\text{SYS}}$ were measured from ammonia inversion lines$^{12,13}$).
Figure 2: Velocity fields of the circumstellar molecular gas in W51e2e (left panel), W51e8 (middle panel), and W51north (right panel). The colors in each panel display the first-moment maps of the CH$_3$CN J=12-11 K=4 transition ($\nu_{\text{rest}} = 220.67929$ GHz) seen in absorption against the λ1.3mm continuum emission (shown in black contours). Contours indicate flux density levels of (0.0005,0.002,0.005,0.01) Jy beam$^{-1}$ for the three sources. The LSR velocity scale is drawn on the right-hand side. The angular resolution of the velocity maps is given by the filled ellipse drawn in the lower left corners: 0″041 × 0″031 or 221 au × 167 au (the displayed continuum maps achieve a better resolution: 0″033 × 0″024 or 178 au × 130 au). The selected molecular transition is representative of the velocity field of the circumstellar molecular gas (see Supplementary Figure 2). Note the flat velocity profile, especially towards the center of each molecular core, indicating the lack of kinematics in our molecular data. The redshifted velocities observed in W51e2e are probably associated with the outflow (see text).
Figure 3: SiO outflow from W51north. The blueshifted and redshifted emission of the SiO $J = 5-4$ line (in red and blue) is integrated over $V_{\text{LSR}} = [-36, 56]$ km s$^{-1}$ and $[66, 126]$ km s$^{-1}$ or $V_{\text{outflow}} = [-96, -4]$ km s$^{-1}$ and $[6, 66]$ km s$^{-1}$ for $V_{\text{SYS}} = 60$ km s$^{-1}$, respectively. The green colour displays the dust continuum emission at 1.3mm, already shown in Figure [1] here a different 'stretch' of the intensity brightness ($\text{arcsinh}$ function in the $\text{matplotlib}$ Python plotting library) is employed to highlight the central core (and filter out the complex filamentary structure). The black arrow indicates the orientation and the upper limit to the size (350 au radius) of the putative underlying disc. The angular resolution of these data is given by the ellipse drawn in the lower left corners (same as figure 1 in the main text).
Figure 4: Velocity fields of the circumstellar molecular gas in W51e2e (top panels), W51e8 (middle panels), and W51north (bottom panels). Each row displays the first-moment maps of the CH$_3$CN J=12-11 K=3 ($E_l=122$ K), K=6 ($E_l=315$ K), K=8 ($E_l=515$ K) transitions (colors) seen in absorption against the 1.3mm continuum emission (shown in black contours). The LSR velocity scale is drawn on the right-hand side. The angular resolution of the velocity maps is given by the filled ellipse drawn in the lower left corners: 0.041 x 0.031 or 221 au x 167 au (the continuum maps achieve a better resolution: 0.033 x 0.024 or 178 au x 130 au). Note how the different CH$_3$CN lines from the K-ladder, show exactly the same remarkably flat velocity profile regardless of their excitation (in the presence of either rotation or infall/accretion, the velocity is expected to increase with the energy level). This result confirms the lack of kinematics shown in Figure 2 in the main text. Transitions from other molecular species show similar flat profiles.
Figure 5: Structure of massive protostellar outflows as a function of velocity within 2000 au from the central protostars W51e2e (top two rows) and W51north (bottom two rows), respectively. The red and blue colors indicate redshifted and blueshifted emission of the SiO J = 5−4 line. The emission is integrated over different velocity ranges (indicated in brackets in the figure). In W51e2e the high velocities trace preferentially the central parts (i.e., primary wind) and the low-velocities the limb-brightened edges (i.e. entrained gas) of the outflow, a phenomenon often observed in low-mass protostellar outflows. In W51north the high velocities trace material at larger radii from the protostar both in the compact northwest-southeast outflow and the larger scale north-south outflow, reminiscent of the ‘Hubble flows’ observed in low-mass protostellar outflows. It is also interesting to note that the bulk of the compact northwest-southeast outflow expands at high velocities while the bulk of the larger scale north-south outflow expands at low velocities, in agreement with the scenario where the former represents the latest outflow event and the latter is a fossil outflow. The green color displays the dust continuum emission at 1.3 mm, already shown in Figure 1 in the main text; here a different ‘stretch’ of the intensity brightness (arcmin^2 function in the astropy package) Python plotting library) is employed to highlight the central core (and filter out the complex filamentary structure). The black arrow in each panel indicates the upper limit to the size of putative underlying disks. The angular resolution of these data is given by the ellipse drawn in the lower left corners (same as figure 1 in the main text).
Figure 6: The greyscale shows the dust continuum emission, tracing warm dust in the W51e2e, W51e8, and W51north hot-cores, respectively. The contours enclose the regions where we compute the mass values quoted in the paper, for both the central cores (yellow contours) as well as the full extent of the continuum (red contours). In particular, the red and orange contours trace the 23% and 3% (131 and 15 K), 35% and 3% (15 and 152 K), 62% and 10% (245 and 39 K) levels from the continuum flux density peaks of 19, 14, and 13 mJy/beam, for W51e2e, W51e8, and W51north, respectively. The brightness temperature $T_b$ scale is on the right-hand side in each panel.
Figure 7: The greyscale shows the dust continuum emission, tracing warm dust in the W51e2 core. The dusty hot core e2e is to the left, and the hyper-compact HII region e2w (not discussed in this article) is to the right. The contours enclose the regions with different brightness temperatures $T_b$ (scale on the right-hand side). While the highest temperatures in e2e are measured towards the central core, the dusty streamers are also significantly warm with 50–150 K.
Figure 8: Outflow from W51north as traced by SiO emission and H$_2$O masers. The H$_2$O masers 3-D velocities measured with the VLBA are overplotted onto the total intensity of the redshifted (red contours) and blueshifted (blue contours) emission of the SiO J = 5-4 line and the 1.3mm continuum emission (white contours and greyscale image). Colors denote l.o.s. velocity (color scales on the right-hand side) and the scale for the proper motion amplitude is given in the lower right corner (both in km s$^{-1}$). The H$_2$O masers reside in two complexes separated by $\sim$3000 AU at the front edges of the compact SiO outflow lobes and are moving away from each other in ballistic motions at about 200 km s$^{-1}$ and at a position angle of $-72^{\circ}$, consistent in both P.A. and velocity with the SiO northwest-southeast outflow. The H$_2$O masers detected in the southeast appear to trace a bow shock at the tip of the blueshifted SiO lobe, while the H$_2$O maser complex in the opposite side traces both the high-velocity northwest redshifted lobe as well as the base of the northern outflow component. In the redshifted part of the outflow, the measured proper motions appear to smoothly rotate from northwest to north moving away from the tip of the SiO lobe. The expansion velocity of the outflow decreases from 90 km s$^{-1}$ to 50 km s$^{-1}$ at radii $0.75'$ to $0.5'$ mas from the outflow origin, consistent with the SiO redshifted emission. We registered the H$_2$O masers positions and our ALMA maps under the assumption that the H$_2$O maser outflow origin (estimated with a least-squares fitting analysis of the measured maser 3-D motion) coincides with the peak of the dust continuum and/or the origin of the SiO outflow imaged with ALMA. We assume that this is the putative location of the driving protostar.
Figure 9: Sketch of the three-component structure of the outflow from W51north. The H₂O masers positions (white circles) measured with the VLBA are overplotted onto the total intensity of the redshifted (red contours) and blueshifted (blue contours) emission of the SiO J = 5-4 line and the λ1.3mm continuum emission (white contours and greyscale image). The color ellipses identify three outflow components, resulting from three consecutive events: the 'old' outflow (t > 240 yr) shows a fossil redshifted lobe (and a now invisible blueshifted lobe) along north-south (indicated by the dark red and blue ellipses), the 'young', bright outflow (t ≲ 80 yr) is the present outflow with an axis along southeast-northwest (indicated by the red and blue ellipses), while the 'transition' period (with a total duration of about 160 years) represents material ejected in between events (identified by light red and blue ellipses). The lack of the 'old' blueshifted counterpart to the 'old' redshifted lobe may be due either to some sort of localized blockage (so the outflow never blew out) or to the lack of material to be entrained (e.g., the outflow breaks out of the cloud if the source is located at the front of it). It is worth noting that even in the lower-resolution maps of the CO 2-1 emission, the blueshifted lobe is barely detected beyond about 0.′′30 or 1600 au CO emission.