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GAIA'S CONSTRAINTS ON THE ~150 $M_{\odot}$ RUNAWAY STAR CANDIDATE VFTS682

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ABSTRACT

How very massive stars form is still among the most intriguing open questions in stellar astrophysics. VFTS 682 is among the most extreme massive stars known, with an inferred initial mass of about 150 $M_{\odot}$. It is located in 30 Doradus at a projected distance of 29 pc from the central cluster R136. The absence of other massive stars in its immediate vicinity lead to two intriguing possible hypotheses posed in earlier work. Either it formed in relative isolation through a new mode of star formation or it was ejected dynamically from the central cluster.

Aiming to shine light on this debate, we investigate the kinematics of VFTS 682 as obtained by *Gaia* and a *Hubble Space Telescope* proper motion campaign. We derive a projected velocity relative of to the cluster of $\sim 30 \pm 20\,\mathrm{km\,s^{-1}}$. The direction and magnitude of the proper motion are consistent with ejection from the central cluster considering its inferred age. However, the error bars and spread in proper motions derived for other sources in the region are substantial, which makes us cautious to derive hard conclusions.

If future data confirms the runaway nature, this would make the VFTS682 the most massive runaway star known to date. While we cannot prove this solidly from the current data, we do consider this hypothesis plausible. The central cluster is known to harbor several other stars more massive than 150 $M_{\odot}$ similar in spectral type. Moreover, the current record holders are O type stars including VFTS 16 which provides direct evidence that R136 is indeed capable of ejecting some of its most massive members.

Subject headings: stars: kinematics, stars: runaways, stars: individual: VFTS 682

1. INTRODUCTION

How massive stars form is one of the major longstanding questions in astrophysics (e.g., Zinnecker & Yorke 2007). Improving our understanding of massive star formation, and its possible dependence on environment and metallicity, is crucial for understanding the role massive stars play within their host galaxies, but also for understanding the transients that mark their death and the compact remnants they leave behind. Obtaining clues from observations has been challenging, because massive stars are intrinsically rare, evolve fast, typically reside in dense groups and remain enshrouded in their parent cloud during the entirety of their formation process. Important progress has been made on the theoretical side, (e.g. Bate 2009; Kuiper et al. 2015; Rosen et al. 2016), but the simulations of this multi-scale and multi-physics problem are computationally very expensive and therefore remain challenging.

In has been proposed that most, if not all, stars form in clusters (Lada & Lada 2003), where massive stars are thought to reside in the innermost cores. In this picture, field stars are primarily the result of the dissolution of dense groups. However, a significant population of massive stars exists in relative isolation, far from dense clusters or OB associations and their origin remains matter of debate (Gvaramadze et al. 2012; Lamb et al. 2016; Ward & Kruijssen 2018). One hypothesis to explain the population of relatively isolated massive stars is that they formed in the field. The alternative hypothesis is that these massive stars were ejected from the clusters in which they formed. Such ejections may result from dynamical interactions (e.g., Poveda et al. 1967) or from the disruption of binary systems at the death of the companion star (e.g., Zwicky 1957; Blaauw 1961; Renzo et al. 2018).

One of the most extreme examples that has been considered in this debate is the very massive star VFTS682 (Bestenlehner et al. 2011; Bressert et al. 2012). This star is located in the field of the 30 Doradus region in the Large Magellanic Cloud (LMC) and was studied as part of the multi-epoch spectroscopic VLT-FLAMES Tarantula Survey (VFTS, Evans et al. 2011). It is a hydrogen-rich Wolf-Rayet star of spectral type WNh5. Spectral analysis and comparison with evolutionary models lead to an inferred present-day mass of $\sim 140^{+30}_{-16}\,M_{\odot}$ corresponding to an initial mass of $\sim 150^{+30}_{-17}\,M_{\odot}$ (Schneider et al. 2018). This makes VFTS682 one of the most massive stars known and one of the most extreme objects in the region. From the spectral point of view, it is reminiscent of the

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very massive stars in the core of the R136 cluster (de Koter et al. 1997; Crowther et al. 2010, 2016). In particular, a remarkable similarity exist between the spectrum of VFTS682 and R136a3 for which Crowther et al. (2016) report a current mass estimate of $180^{+30}_{-30}\,M_\odot$. R136 hosts at least two more very massive WN5h stars, R136a1 and R136a2, whose estimated current masses are even higher.

VFTS682 stands out by its relative isolation at a projected distance of 119.4 arcseconds, corresponding to ~29 pc, from the star cluster R136. Bestenlehner et al. (2011) considered two possible explanation for the offset: either the star formed in situ as an isolated massive star, or it was ejected from R136. N-body simulations indicate that the ejection of very massive stars like VFTS682 is expected (e.g. Fujii & Portegies Zwart 2011; Banerjee et al. 2012). This is supported by the recent findings of other massive runaway stars in the region based on proper motion studies. Platais et al. (2015, 2018) analyze multi-epoch *Hubble Space Telescope* (HST) photometry and identify 10 stars, which appear to be ejected from R136. Lennon et al. (2018) investigate the kinematics of isolated O-type stars in the region using the second *Gaia* data release (DR2, Gaia Collaboration et al. 2016, 2018) and show that the proper motion, postion and direction of the $\sim 100\,M_\odot$ star VFTS16 is consistent with a runaway origin from R136.

In this paper we present an analysis of the new kinematical constraints for VFTS682 provided by *Gaia* DR2 and constraints from HST proper data by Platais et al. (2018). We discuss the implications for the hypothesis that VFTS682 is a slow runaway star ejected from R136.

2. OBSERVATIONS

2.1. *Overview of VFTS682 from previous studies*

The star VFTS682, located at right ascension (RA) $05^h38^m55.510^s$ and declination (DEC) -69°04'26.72" J2000 (Evans et al. 2011) was originally classified as a young stellar object based on its mid-infrared excess (Gruendl & Chu 2009). Evans et al. (2011) reclassified the object as Wolf-Rayet star of spectral type WNh5 using multi-epoch spectra covering λ4000–7000 from the VFTS survey.

Using the same dataset, Bestenlehner et al. (2011) excluded the presence of a close companion with high confidence from the absence of radial velocity variations. Bestenlehner et al. (2011) also derived stellar parameters and surface abundances. They inferred an extinction of $A_V = 4.45 \pm 0.12$, leading to the high luminosity $\log_{10}(L/L_\odot) = 6.5 \pm 0.2$. Schneider et al. (2018) estimated a present-day mass for VFTS682 of $137.8^{+27.5}_{-15.9}\,M_\odot$, an apparent age of $1.0^{+0.2}_{-0.2}$ Myr and an inferred initial mass of $150.0^{+28.7}_{-17.4}\,M_\odot$.

Bestenlehner et al. (2011) reported for VFTS682 a wind mass loss rate of $10^{-4.1\pm0.2}\,M_\odot\,\mathrm{yr}^{-1}$, not accounting for clumping. The present-day surface helium mass fraction is $Y = 0.45\,(0.49)$ from the spectral analysis of Bestenlehner et al. (2011) (Rubio-Díez et al. 2017). This value can be used to constrain the age of the star and its past evolution.

Further worth noticing is the variability of the star. Parker (1993) reported B and V magnitudes roughly 0.5 magnitude lower than found by Evans et al. (2011). Bestenlehner et al. (2011) discuss the Optical Gravitational Lensing Experiment (OGLE-III) light curves (Udalski et al. 2008) and show a variability in the V-band at ~10% level on a timescale of years. They commented that this is unusual for Wolf-Rayet stars and more reminiscent of Luminous Blue Variable (LBV) stars.

Bressert et al. (2012) note that VFTS682 shows a significant radial velocity offset compared to the nebular lines from the gas surrounding it, suggesting peculiar motion in the line of sight direction. Bestenlehner et al. (2011) quote a radial velocity measured from the Nv λ4944 of $300 \pm 10\,\mathrm{km\,s^{-1}}$. The average radial velocity of the 30 Doradus region is $270\pm10\,\mathrm{km\,s^{-1}}$. Whether this measurement truly reflects a peculiar radial velocity is debated. The determination of radial velocities for emission-lines stars is difficult because of the presence of an optically thick, non-homogeneous, and variable wind obscuring the photosphere. The radial velocity errors quoted above are only statistical, and do not quantify the (possibly larger) systematic errors. ■ **[Possibly mention and cite paper in prep by Paco and student on Xshooter data? Possibly mention (or even use) on their measurement for the RV?]** ■

For simplicity, throughout this study, we assume the same distance of 50 kpc to the star (Pietrzyński et al. 2013), and to the 30 Doradus region as a whole. We do not consider the error on the distance determination ($\lesssim 2\%$) when converting proper motions into physical velocities.

TABLE 1
ASTROMETRIC PARAMETERS FOR VFTS682.

Parameter	Value	Source
RA [degree]	84.73	Evans et al. (2011)
DEC [degree]	-69.07	
$\delta\mu^{Gaia}_{\mathrm{RA}}$ [mas yr^{-1}]	0.10±0.07	*Gaia* DR2
$\delta\mu^{Gaia}_{\mathrm{DEC}}$ [mas yr^{-1}]	0.08±0.09	
$\delta\mu^{HST}_{\mathrm{RA}}$ [mas yr^{-1}]	0.01±0.13	Platais et al. (2018)
$\delta\mu^{HST}_{\mathrm{DEC}}$ [mas yr^{-1}]	0.2±0.1	
δv_{rad} [km s^{-1}]	30±20	Bestenlehner et al. (2011)

NOTE. — The error on the RA and DEC positions, are of order $\sim10^{-2}$ mas yr^{-1} in *Gaia* DR2.

2.2. *HST astrometry for VFTS682*

For large distances ($\gtrsim$ 50 kpc), HST astrometry can compete or even exceed *Gaia* DR2 data in quality.

Recently, Platais et al. (2018) presented HST astrometry and proper motions in the 30 Doradus region (GO-12499; P.I.: D. J. Lennon). The brightest stars (V<14) are missing from the catalogue because of saturation, but the high extinction towards VFTS682 makes is faint enough to be included. The proper motions are listed in Table 2.3.

The catalog from Platais et al. (2018) lists the proper motion components of VFTS682 relative to the field, providing a measure of the motion of this star completely independent from *Gaia*. They found proper motion components relative to the field $\delta\mu^{\mathrm{HST}}_{\mathrm{RA}} = 0.01 \pm 0.13\,\mathrm{mas\,yr^{-1}}$ and $\delta\mu^{\mathrm{HST}}_{\mathrm{DEC}} = 0.2 \pm 0.1\,\mathrm{mas\,yr^{-1}}$, which added in quadrature give a relative proper motion of $\delta\mu^{HST} = 0.20 \pm 0.15\,\mathrm{mas\,yr^{-1}}$.

These proper motion components can also be converted into projected velocities assuming a distance of 50 kpc, obtaining $\delta v^{HST}_{\mathrm{RA}} = 2 \pm 31\,\mathrm{km\,s^{-1}}$ and $\delta v^{HST}_{\mathrm{RA}} = 47 \pm 24\,\mathrm{km\,s^{-1}}$. Adding them in quadrature to the radial velocity measured by Bestenlehner et al. (2011) we obtain a three-dimensional velocity of $v^{HST}_{\mathrm{pec}} = 56 \pm 23\,\mathrm{km\,s^{-1}}$.

2.3. *New data from* Gaia *DR2*

The second *Gaia* Data Release (DR2) provides positions, parallaxes, and proper motion components for more than a billion sources (Gaia Collaboration et al. 2018). VFTS682 is identified with the source id 4657685637907503744 in the *Gaia* DR2 catalog[1]. Its G-band magnitude from *Gaia* is 15.65. The star has a `visibility_period` = 17, which counts how many observations have been used to reconstruct its astrometric solution (Lindegren et al. 2018), and the reported `astrometric_excess_noise` = 0. These values suggest that the *Gaia* data for VFTS682 are reliable.

While *Gaia* DR2 data can be correlated, this is not an issue for VFTS682, and we treat the proper motion components ($\mu_{\rm RA}$, and $\mu_{\rm DEC}$, respectively) of the star as uncorrelated for simplicity. For the radial velocity of VFTS682 and of the 30 Doradus region as a whole, we instead use the VFTS data as quoted in Bestenlehner et al. (2011). Table 2.3 lists the values adopted throughout this work for each of these quantities.

We follow Lennon et al. (2018) to define a local frame of reference and derive the peculiar velocity of VFTS682 with respect to the cluster R136. Their selection (see their Sec. 2.1) of 153 bright ($G < 17$) stars around R136 with reliable astrometric data from *Gaia* DR2 yields $\langle\mu_{\rm RA}\rangle = 1.74 \pm 0.01$ mas yr^{-1} and $\langle\mu_{\rm DEC}\rangle = 0.70 \pm 0.02$ mas yr^{-1} for the components of the mean motion of the region projected on the sky.

3. THE KINEMATICS OF VFTS682

3.1. *Is it a runaway star?*

We first address the question of whether VFTS682 is a typical star from the kinematic point of view, or whether it is a runaway star with a significantly large peculiar velocity compared to its surrounding population. The former is what should be expected if it formed in the relative isolation that we observe today.

Subtracting the mean proper motion components given by Lennon et al. (2018) from the proper motion of VFTS682 (see Table 2.3), we obtain the components of proper motion of the star relative to the surrounding region $\delta\mu_{\rm RA}^{Gaia} = 0.10 \pm 0.07$ mas yr^{-1} and $\delta\mu_{\rm DEC}^{Gaia} = 0.08 \pm 0.09$ mas yr^{-1}. These components result in a two-dimensional relative proper motion of $\delta\mu^{Gaia} = 0.13 \pm 0.09$ mas yr^{-1}.

The proper motion components can be converted into the components of the relative transverse velocity $\delta v_{\rm RA}^{Gaia} = 24 \pm 19$ km s^{-1}, $\delta v_{\rm DEC}^{Gaia} = 20 \pm 23$ km s^{-1}, assuming a distance of 50 kpc. These can be combined obtaining a projected two-dimensional velocity of 31 ± 21 km s^{-1}. The radial velocity from Bestenlehner et al. (2011) then gives the third component along the line of sight, which added in quadrature to the transverse components results in a three-dimensional velocity of 44 ± 21 km s^{-1}.

Therefore, two completely independent measures of the proper motion of VFTS682 relative to the surrounding field, one from HST and one from *Gaia* DR2, yield values of the peculiar three-dimensional velocity of VFTS682 which would make it the most massive runaway star known to date. However, the large errors on both the proper motion measures require confirmation with future astrometric data.

3.2. *Does it come from the R136 cluster?*

Assuming that the best estimate of the peculiar velocity of VFTS682 are reliable, we now address the question of its likely origin.

Figure 1 shows the distribution in proper motion relative to R136 of OB type and Wolf-Rayet stars included both in the VFTS survey and *Gaia DR2* with reliable astrometric solutions. VFTS682 is not an extreme outlier compared to the two O-type runaways (re-)identified by Lennon et al. (2018). VFTS682 was expected to be a "slow runaway" by Bestenlehner et al. (2011) in the dynamical ejection scenario. The green shade in Fig. 1 shows the range of relative proper motions within the uncertainties on the apparent age of the star, assuming it was ejected from R136 very early in its life. The proper motion measurements from *Gaia* DR2 are consistent with the hypothesis of dynamical ejection.

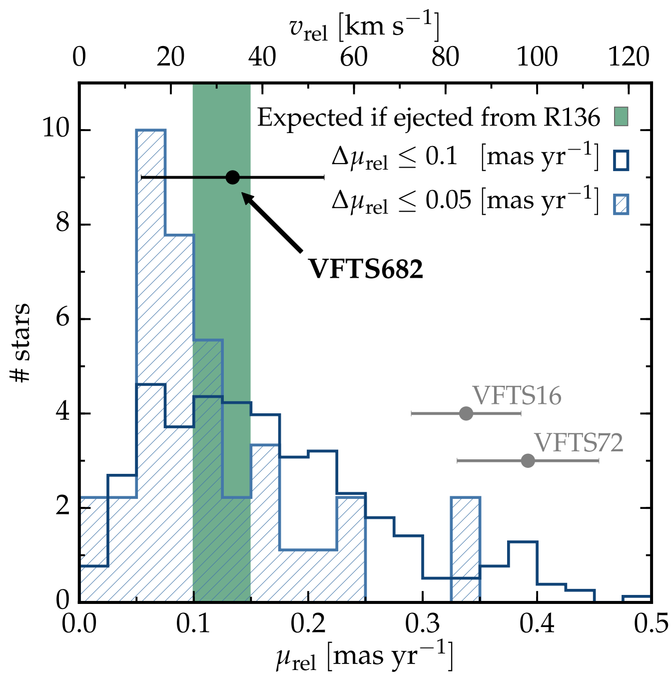

FIG. 1.— Distribution of OB-type and Wolf-Rayet stars in proper motion relative to R136. VFTS682 is not an extreme outlier, but its relative proper motion matches the expected value if it were indeed ejected from R136 assuming an age of 1.0 ± 0.2 Myr. The dark blue histogram contains 317 stars with error smaller than 0.1 mas yr^{-1} $\simeq$ 25 km s^{-1} at 50 kpc, the lighter blue histogram contains 36 stars with errors smaller than 0.05 mas yr^{-1}. The top axis shows the conversion to physical units assuming a distance of 50 kpc.

The red arrow in Fig. 2 shows the direction of relative proper motion of VFTS682 from *Gaia* DR2, and the yellow arrows illustrate the uncertainty. These arrows cross at the present-day location of VFTS682 and are prolonged in the direction opposite to the motion to illustrate the possible range of origins.

Although the large uncertainties on the relative proper motion components results in a wide range of possible directions,we argue that the most likely origin of the star is R136.

The kinematic age of this star, assuming it originates from the cluster, is

$$\tau_{\rm kin} = \frac{d_{\parallel}}{\delta\mu^{\rm Gaia}} \simeq \frac{119.4\,{\rm arcsec}}{0.13\,{\rm mas\,yr^{-1}}} \simeq 0.9 \pm 0.6\,{\rm Myr}\ , \quad (1)$$

where $d_{\parallel} = 119.4$ arcsec is the angular distance from

[1] https://vizier.u-strasbg.fr/viz-bin/VizieR-3?-source=I/345/gaia2

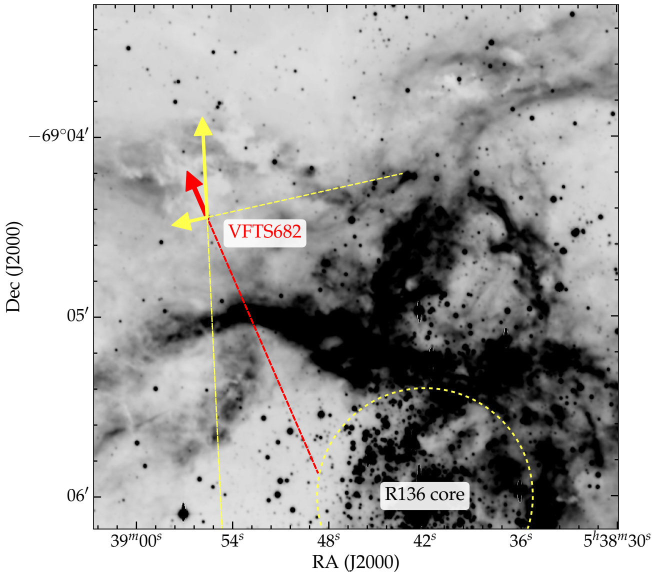

FIG. 2.— The red solid arrow indicates the proper motion of VFTS682 relative to the region from *Gaia* DR2, starting from the present day position of the star. The yellow arrows indicate the possible directions of projected motion within the *Gaia* DR2 errors, and are extended backwards (dashed) to illustrate the uncertainty on the origin of the star. The length of the prolongations is proportional to the relative proper motion times the age of VFTS682 (1.0 ± 0.2 Myr, Schneider et al. 2018).

VFTS682 to the core of R136 (corresponding to ~29 pc at LMC distance, Bestenlehner et al. 2011). As in the rest of this study, we neglect for simplicity the error on the distance estimates, because it is negligible compared to other uncertainties.

The kinematic age $\tau_{\rm kin}$ is compatible with a very early ejection from the cluster, given is apparent age of 1.0 ± 0.2 Myr (Schneider et al. 2018). Note that the present-day surface helium abundance ($Y \simeq 0.5$, Bestenlehner et al. 2011; Rubio-Díez et al. 2017) puts a lower limit on the age of the star of ~0.9 Myr, corresponding to the time needed to synthesize this amount of helium in the models from Köhler et al. (2015).

4. DISCUSSION

Based on our results, we tentatively claim that VFTS682 is the most massive runaway known to date, with a peculiar three-dimensional speed of 44 ± 21 km s^{-1}. Due to the large error bars, this result will need to be revisited with future astrometric data. If confirmed, it means that isolated star formation is *not* required to explain the isolation of VFTS682. Its proper motion suggests that it was ejected from the cluster R136 0.9 ± 0.6 Myr ago. Because of the exceptionally large mass of this star, this raises the question of which stars must populate the core of the cluster.

Dynamical ejections due to N-body interactions typically (although, not necessarily) eject the least massive star among those interacting (e.g., Banerjee et al. 2012). This means that, just based on the kinematic properties of VFTS682, we would expect several stars with initial masses larger than $\sim 150\,M_\odot$ in the cluster R136. This is consistent with the detection of extremely massive stars in the core of the cluster.

The spectral type of VFTS682 (WNh5, Bestenlehner et al. 2011) is the same as R136a1-a3, i.e. the three most massive stars detected in the core of the cluster, with an astonishing similarity in particular with the spectrum of R136a3. Therefore, the isolation of VFTS682 makes it an ideal target to constrain the stellar physics of stars with masses well above $\sim 100\,M_\odot$ while avoiding crowding issues.

Banerjee et al. (2012) used N-body simulations of fully segregated clusters with all massive stars in binaries to suggest that VFTS682 was ejected from R136. They demonstrated that the cluster potential does not significantly change the velocity of the star after the ejection. In their model, they relied on (dynamically driven) stellar mergers to explain the high masses of VFTS682 and the massive members of R136.

To eject such a massive object, the cluster is expected to have produced a large number of massive runaways. Indeed, several isolated massive stars are observed in the region, some with known large radial velocities and/or proper motion. A comprehensive study of the kinematic properties of all the massive stars surrounding R136 might shed light on whether some can be unequivocally identified as merger products. It is also possible that the star or binary that caused the ejection of VFTS682 might have been ejected in the opposite direction, and is also isolated at present day. If the ejection was caused by an interaction with a binary, however, it is likely that the binary scattered in the opposite direction will experience further dynamical interactions on its way, modifying its trajectory and making it difficult to find.

The similarities between VFTS682 and the WNh5 stars in the core of R136 are also in agreement with the "bully binary" model of Fujii & Portegies Zwart (2011). Based on their numerical results, they suggested that early in the evolution of a cluster, dynamical interactions form an extremely massive binary, which then tightens its orbit by ejecting other stars passing by. Interpreting our results for VFTS682 through the lens of their simulations suggests the presence of a close binary with total mass $M_1 + M_2 \gtrsim 300\,M_\odot$ in the core of the cluster. Such bully binary could be R145 according to Fujii & Portegies Zwart (2011), and it might be an ideal observational candidate for a dynamically formed progenitor system of a binary black-hole, provided that stars this massive can avoid a pair-instability supernova (e.g., Rakavy & Shaviv 1967) at LMC metallicity (see also Langer et al. 2007). Similarly, the final fate of VFTS682 could be either a pair-instability supernova without compact remnant formation, or possibly direct collapse to a black hole above the 2$^{\rm nd}$ mass gap. The amount of mass loss of these stars will determine their final core mass and thus their final fate.

The kinematic age of VFTS682 puts an upper limit to the timescale to form the "bully binary" in R136. The cluster must have been at the very beginning of its evolution, given the age estimate of $\lesssim 2$ Myr (Crowther et al. 2010; Sabbi et al. 2012) and the kinematic age of VFTS682. If the cluster is indeed younger than the shortest stellar lifetime (~3 Myr, e.g., Brott et al. 2011; Zapartas et al. 2017), then the alternative explanation for ejection of VFTS682 from the disruption of a binary by a core-collapse event is excluded since the region is too young for stars to have experienced core-collapse already.

The variability of VFTS682, reminiscent of LBV stars, suggests that VFTS682 (and therefore its analogs in the core of R136) might experience enhanced mass loss episodes in LBV eruptions. Smith & Tombleson (2015) made the highly debated[2] claim that LBV stars are typically isolated form O-type stars. The fact that VFTS682 is a dynamically ejected runaway which might evolve into an LBV star suggests that N-body interactions also play a role in explaining the apparent isolation of at least some LBV stars.

■ **[maybe move around fig. 1]** ■ Lennon et al.

[2] See, e.g., Humphreys et al. (2016); Davidson et al. (2016); Smith (2016).

(2018) carried out a study similar to ours on the fast moving O-type stars in the region, and found two massive runaway stars (~90 $M_{\odot}$) in the 30 Doradus region. One of them (VFTS 16) was previously known as a runaway star from its line of sight velocity (Evans et al. 2010). Lennon et al. (2018) also concluded that VFTS16 is the result of a dynamical ejection from the R136 cluster, while the origin of the other star (VFTS 72) is less clear given its direction of motion. The value of $\tau_{\rm kin} \simeq 0.9$ Myr we find for VFTS682 (see Sec. 3.2) is smaller than the corresponding value for VFTS16: Lennon et al. (2018) inferred a kinematic age of ~1.5 Myr, possibly in tension with the apparent age of that star. This means that the more massive VFTS682 was ejected later than VFTS16 from the same cluster.

The numerical simulations from Oh & Kroupa (2016) suggest that dynamical interaction eject the majority of the stars during or shortly after the cluster core-collapse. The large number of isolated massive stars around it suggest that R136 has already evolved past the time of maximum stellar density. This might have implications for the question of whether the cluster formed via a monolithic collapse, or as a (potentially ongoing) merger of several sub-structures (e.g., Sabbi et al. 2012).

Oh & Kroupa (2016) also showed that the mass and velocity distribution of the ejected star depends on the cluster initial conditions (whether it is segregated, its primordial binary fraction and initial period distribution of the binary population), therefore studies on the population of isolated massive stars in the surroundings of R136 might shed light on its initial stellar population and dynamical state.

VFTS682 is potentially the most massive runaway known to date, and its ejection from the cluster R136 likely implies that it is only the "tip of the iceberg" of possibly extremely massive runaways in the region. Studies of this population, enabled by recent HST and *Gaia* observations will put constraints on the evolution of these extreme stars, together with the formation and evolution of the central cluster itself.

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