On the impact of runaway stars on dwarf galaxies with resolved interstellar medium

Ulrich P. Steinwandel,1,★ Greg L. Bryan,2,1 Rachel S. Somerville,1 Christopher C. Hayward1 and Blakesley Burkhart1,3

1Center for Computational Astrophysics, Flatiron Institute, 162 5th Avenue, New York, NY 10010
2Department of Astronomy, Columbia University, 550 West 120th Street, New York, NY 10027, USA
3Department of Physics and Astronomy, Rutgers University, 136 Frelinghuysen Road, Piscataway, NJ 08854, USA

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ABSTRACT

About ten to 20 percent of massive stars may be kicked out of their natal clusters before exploding as supernovae. These “runaway stars” might play a crucial role in driving galactic outflows and enriching the circumgalactic medium with metals. To study this effect, we carry out high resolution dwarf galaxy simulations that include velocity kicks to massive stars above 8 M⊙. We consider two scenarios, one that adopts a power law velocity distribution for kick velocities, resulting in more stars with high velocity kicks, and a more moderate scenario with a Maxwellian velocity distribution. We explicitly resolve the multi-phase interstellar medium (ISM), and include non-equilibrium cooling and chemistry. We adopt a resolved feedback scheme (GRAFFIN) where we sample individual massive stars from an IMF and follow their radiation input as well as their SN feedback (core-collapse) channel at the end of their lifetime. In the simulations with runaway stars, we add additional (natal) velocity kicks that mimic two and three body interactions that cannot be fully resolved in our simulations. We find that the inclusion of runaway or walkaway star scenarios has an impact on mass, metal, momentum and energy outflows as well as the respective loading factors. We find an increase in mass, metal and momentum loading by a factor of 2-3, whereas we find an increase in the mean energy loading by a factor of 5 in the runaway case and a factor of 3 in the walkaway case. We conclude that the inclusion of runaway stars could have a significant impact on the global outflow properties of dwarf galaxies.

Key words: methods: numerical – galaxies: dwarf – galaxies: formation – galaxies: evolution – galaxies: ISM – ISM: jets & outflows

1 INTRODUCTION

The ΛCDM paradigm has been extremely successful at predicting and reproducing observations of structure formation on large scales (greater than a few Mpc). However, since the first attempts to model galaxy formation within this paradigm, it has been clear that feedback from massive stars, supernovae, and active black holes is critical for reproducing many observed properties of galaxies within this paradigm (e.g. Somerville & Davé 2015; Naab & Ostriker 2017, for reviews). There has been great progress recently in developing large scale simulations that reproduce many key observations of galaxy populations (e.g. Hirschmann et al. 2014; Schaye et al. 2015; Vogelsberger et al. 2014; Pillepich et al. 2018; Nelson et al. 2018). In addition, in the past decade, numerical simulations finally succeeded in producing thin, rotation dominated disks with rather inefficient baryon-to-star conversion (e.g. Guedes et al. 2011; Agertz et al. 2013; Marinacci et al. 2014; Hopkins et al. 2014, 2018).

However, all of these simulations to one degree or another achieve this success by implementing somewhat ad hoc or phenomenological “sub-grid” recipes, as they are not able to explicitly resolve many of the physical processes that actually drive feedback. For example, large-volume simulations typically have a spatial resolution of a few hundred parsecs or larger, and baryonic mass resolution of 10^5 M⊙ or greater (see figure 1 of Nelson et al. 2019 for a recent summary). Thus these simulations typically do not resolve the multi-phase interstellar medium (ISM), nor blastwaves from (individual) supernova explosions, among many other relevant processes. One of the biggest open questions in galaxy formation theory currently is how “small scale” processes (that occur below the explicit resolution of the simulation) may impact larger scale and global properties of galaxies.

A new generation of simulations are achieving parsec to sub-parsec spatial resolution and mass resolution comparable to that of single stars. These simulations can explicitly resolve the multiphase ISM, the Sedov-Taylor phase of individual supernova explosions, and the multiphase character of outflows, and are therefore able to implement the physics of star formation and stellar feedback in a more explicit manner. Several groups have carried out such simulations for sub-galactic regions (Kim & Ostriker 2015; Kim et al. 2017, 2020; Walch et al. 2015), typically representative of Solar Neighborhood or Milky Way conditions. Recently, a few groups have been able to achieve this “individual star” resolution and implement these more explicit feedback approaches within simulations of entire dwarf galaxies with accurate non-equilibrium heating and cooling (Hu et al. 2017; Emeric et al. 2019; Lahén et al. 2019b; Smith et al. 2021), which is a
significant step forward. In this work, we leverage this relatively new capability to study a process that is unresolved in galaxy scale simulations, but may play an important role in shaping “macroscopic” galaxy properties: runaway stars.

Massive stars are predominantly born in clusters. Simulations of individual star clusters (e.g. Oh & Kroupa 2016) have shown that some fraction of massive stars can receive kicks large enough to move them out of their natal clouds before exploding as supernovae. These kicks can be imparted by gravitational interactions within a binary star system (sometimes involving a third star), or when one of the stars in a binary explodes as a SNae. In both cases, one of the massive stars can be accelerated above the escape velocity of the binary system (or even the star cluster itself). These unbound stars can easily travel at velocities > 30 km s$^{-1}$ and can thus travel the typical length scale of a GMC of a few 10 pc in as little as a few 10 Myr. However, we note that it is not clear yet which of the scenarios for the formation of runaway stars is favoured (Renzo et al. 2019; Fuji & Portegies Zwart 2011).

It is extremely challenging to include these processes in a galaxy scale simulation, for several reasons. First, one would have to model the binary stellar initial mass function (IMF), which has significant uncertainties (e.g. Kroupa 1995; Makhó & Zinnecker 2001). Second, and perhaps more challenging, one would have to model two and three body interactions of single stars. Galaxy formation simulations are not well equipped to carry out orbital integration of multiple stellar systems, due to the nature of the gravity calculation which is often performed with a tree or particle mesh. Hence, the gravity solvers of many astrophysical simulation codes operate in the limit of a collisionless system, while this is no longer a good description of few body interactions in star clusters. At the cloud scale, there are attempts to circumvent this weakness (e.g. Hirai et al. 2021; Fuji & Ostriker 2021; Grudic et al. 2022; Guszejnov et al. 2022). However, it has also been pointed out recently that there might be an issue with the underlying Schmidt-type star formation recipes often applied in galaxy scale simulations which makes it intrinsically hard to disperse star clusters on the correct timescales (e.g. Smith et al. 2021; Hislop et al. 2022), a problem which would likely become worse when orbits are integrated using direct summation algorithms.

Why might we expect that runaway stars could have a significant effect on galaxy scale properties? Supernova (SNe) feedback is believed to have the strongest impact on providing the necessary mid-plane pressure to drive a galactic outflow. (Martizi et al. 2015; Kim & Ostriker 2015; Walch et al. 2015; Gatto et al. 2017; Naab & Ostriker 2017; Steinwandel et al. 2020). However, recently several groups have put forward the idea of galactic winds that are driven by cosmic-rays (e.g. Buck et al. 2020; Girichidis et al. 2016, 2022; Hopkins et al. 2021a,b,c,d,e). For SN-feedback, the crucial condition to drive outflows is the formation of a hot volume filling ISM phase (e.g. Naab & Ostriker 2017; Steinwandel et al. 2020). An important factor in this picture is the host environment of the SNe (e.g. Hu et al. 2016, 2017, 2019; Lahén et al. 2019a,b; Gutcke et al. 2021; Smith et al. 2021; Hislop et al. 2022). SNe that explode in the cold neutral medium (CNM) or the cold molecular medium are inefficient in establishing the hot phase of the ISM as cooling times are short (a few 100 years) and the remnants remain small (~ 10 pc) while in the energy conserving Sedov-Taylor phase. This makes it relatively unlikely that subsequent supernovae will explode in the bubble of previous SNe, so that no efficient outflows can be launched from the cold ISM due to the formation of superbubbles (e.g. Fielding et al. 2017; Orr et al. 2021, 2022). However, the situation is different in the diffuse ISM at lower densities and higher temperatures, where SNe remnants occupy a larger volume fraction. Cooling times are much longer, and a hot phase is naturally established, due to the larger occupation fraction of the remnants which makes superbubble formation and subsequent breakout much easier. There are a limited number of physical processes that can lead to lower ambient media preceding a SN-event, of which some are driven by the host star itself (e.g. Forbes et al. 2016; Haid et al. 2016; Hu et al. 2017; Haid et al. 2018; Emerick et al. 2019; Kim et al. 2019; Smith et al. 2021; Lancaster et al. 2021a,b,c, for an overview of main and post main sequence stellar winds, photo-ionisation, photoelectric heating). As discussed above, runaway stars are another mechanism that could potentially allow massive stars to travel out of their dense natal gas clouds, such that the SNe potentially explode in a warmer, lower density environment, enhancing their ability to drive large scale outflows (e.g. Naab & Ostriker 2017).

The impact of runaway stars has recently been studied in conditions similar to the Milky Way in Kim & Ostriker (2018) and Andersson et al. (2020). However, there has been no detailed study of this issue in the context of dwarf galaxies, which is the goal of this paper. In this paper, we create 4 simulations of isolated dwarf galaxies similar to the observed Wolff-Lundmark-Meynet (WLM) system at the outer edge of the Local Group (baryon mass of $2 \cdot 10^7$ M$_\odot$ and dark matter mass of $2 \cdot 10^7$ M$_\odot$). We use the Griffin(Galaxy Realizations with the feedback from individual massive stars) model for single star formation and resolved feedback (e.g. Lahén et al. 2019a,b; Steinwandel et al. 2020; Hislop et al. 2022). We include a sub-grid treatment for runaway stars based on existing results for the runaway population from simulations and observations (e.g. Eldridge et al. 2011; Oh & Kroupa 2016). We note that our approach includes only the natal kicks, neglecting the gravitational interaction of the star with the environment over its lifetime, and therefore may represent an upper limit on the effects of including such stars in galaxy simulations. The remainder of the paper is structured as follows: In Section 2 we introduce the code, present the Griffin model for single star formation and resolved feedback, and explain in detail how we incorporate runaway stars into our model. In Section 3 we discuss the results with a specific focus on how runaway stars may alter outflow properties of dwarf galaxy systems and impact the ISM and CGM-ISM interface. In Section 4 we discuss our results and compare to previous simulations in the literature. In Section 5 we summarise our results.

2 NUMERICAL METHODS
In this section we discuss the details of our numerical modelling and present the initial conditions of our simulations. The results are part of the Griffin project 1.

2.1 Simulation Code
For all simulations presented we use the Tree-SPH code P-Gadget3 (Springel 2005; Hu et al. 2014) to carry out the gravity and hydrodynamics calculations. However, we made significant improvements by updating the baseline SPH solver to incorporate the meshless finite mass (MFM) method for solving the fluid flow following the methods discussed in Hopkins (2015) and Gaburov & Nitadori (2011), using the MFM implementation of Steinwandel et al. (2020). MFM represents a fully consistent second order method in space and time and

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1 https://wwwmpa.mpa-garching.mpg.de/~naab/griffin-project/
we compute fluid fluxes by solving the one-dimensional Riemann-problem between single fluid tracers by adopting an HLLC-Riemann solver that accounts for the appropriate reconstruction of the contact wave. The face area is defined over the smoothing-length weighted quadrature point between the single fluid tracers (Steinwandel in prep.). The code is then coupled to the cooling and feedback network, utilised in the Griffin-framework (e.g. Hu et al. 2016, 2017, 2019; Lahén et al. 2019b,a; Steinwandel et al. 2020; Hislop et al. 2022).

2.2 Cooling, heating and star formation

To model the multiphase ISM, we self-consistently model the non-equilibrium formation and destruction of molecular hydrogen and CO, following the cooling and chemistry networks developed in Glover & Mac Low (2007) and Glover & Clark (2012), where we also account for the self-shielding of molecular gas based on a column density computation on a healpix sphere. In earlier versions of our code this was achieved by the TreeCol method. In the latest version this is done with a healpix expansion using the c library CHEALPIX. The details of the cooling and chemistry network can be found in Hu et al. (2017) and Steinwandel et al. (2020).

Star formation is modelled by utilising an IMF-sampling approach where we sample all the stars more massive than 4 $M_\odot$ (base resolution of the simulation) as single stars. The details of the method can be found in Hu et al. (e.g. 2017); we have adopted minor updates here that will be presented in greater detail in Steinwandel (in prep.).

2.3 Stellar feedback

We follow several feedback channels for the massive stars that form within the simulation, including the photoelectric heating, the UV-radiation and the photoionising radiation, as well as the metal enrichment from AGB and subgrid stellar winds. However, the core of the stellar feedback scheme is the resolved SN-feedback mechanism developed by Hu et al. (2017) and Steinwandel et al. (2020), that allows for a self consistent build-up of the hot phase and the momentum of individual SN-events in a resolved Sedov-Taylor phase (see Hu et al. 2021, 2022). Hence, all the outflow properties in these simulations are self-consistently driven from the hot phase of the ISM without the need for any “ad-hoc” tuning of mass loading factors as adopted in lower resolution galaxy formation simulations. Therefore, our simulations allow for a detailed study of the origin and driving of large scale galactic winds.

We include the UV radiation of single stars following the implementation of Hu et al. (2017). This implementation makes the assumption of a (locally) optically thin medium, which is a good approximation for dwarf galaxies. Hence, we can simply sum over the radiation field for each star using an inverse square law. The lifetime approximation for dwarf galaxies. Hence, we can simply sum over the implementation of Hu et al. (2017). This implementation makes the detailed study of the origin and driving of large scale galactic winds.


deviation of the tree. This can be straightforwardly improved in future implementations by either including higher order moments in the tree or modifying the tree’s opening angle (i.e. running a separate gravity tree for the gravity force and UV-radiation computation) (e.g. Grond et al. 2019, for one approach to improve our method).

We follow photoelectric heating rates from Bakes & Tielens (1994); Wolfire et al. (2003) and Bergin et al. (2004) at the rate:

$$\Gamma_{pe} = 1.3 \cdot 10^{-24} e D G_{eff} n \text{erg s}^{-1}\text{cm}^{-3}$$

(1)

with the hydrogen number density $n$, the effective attenuation radiation field $G_{eff} = G_0 \exp^{-1.33 \cdot 10^{-21} D N_{H,tot}}$, the dust-to-gas ratio $D$, the total hydrogen column density $N_{H,\text{tot}}$ and the photoelectric heating rate $\epsilon$ that can be determined via:

$$\epsilon = \frac{0.049}{1 + 0.004\psi^{0.7}} + \frac{0.037(T/10000)^{0.7}}{1 + 2 \cdot 10^{-4}\psi}$$

(2)

where $\psi$ is denoted as $\psi = G_{eff} \sqrt{T}/n^3$, with the electron number density $n^-$ and the gas temperature $T$.

We include a treatment for photoionising radiation since previous work (e.g. Hu et al. 2017; Emerick et al. 2019; Steinwandel et al. 2020; Smith et al. 2021), has revealed that photoionisation feedback can have a significant impact on ISM properties and star formation rates. Ideally, we would utilize a proper radiative transfer scheme for this purpose, but this is prohibitively computationally expensive. Thus we model the photoionising feedback via a Strömgren approximation locally around each photoionising source in the simulation, similar to the approach used in Hopkins et al. (2012) and later improved by Hu et al. (2017).

Every star particle that fulfils the criterion of having one or more constituent stars with mass $m_{\text{BBF}} > 8 M_\odot$ is treated as a photoionising source in our simulations. Thus all of the neighbouring gas particles are labelled as photoionised within the radius $R_S$ around the star and all of the surrounding molecular and neutral hydrogen is destroyed and transferred to $H^+$ (we set the ionising fraction to 0.9995 in our chemical model). Alongside this procedure we heat the surrounding gas within $R_S$ to $10^4 K$, which is the temperature in HII-regions, by providing the necessary energy input from the ionising source. This procedure is straightforward if $R_S$ is known (i.e. as long as the gas density is more less constant). However, in practice this will rarely be the case, and we obtain $R_S$ iteratively, where we use the classic Strömgren-radius as an “educated guess”.

We include the feedback from Type II (CCSN) supernovae in our simulations. The supernova feedback routines presented in this section are the core feedback mechanism in our current galaxy formation and evolution framework. Every supernova distributes $10^{51}$ erg into the nearest 32 neighbours. We follow metal enrichment using the yields of Chieffi & Limongi (2004), who present stellar yields for stars from zero metallicity to solar metallicity for progenitors ranging from 13 $M_\odot$ to 35 $M_\odot$, from which we interpolate our metal enrichment routines. When a star explodes in a CCSN the mass is added to the surrounding 32 (one kernel) gas particles with the respective metal mixture that is expected from the above yields. It is important to include the correct metal yields in order to obtain the correct cooling properties of the ambient medium and thus in the end the correct density and phase structure of the ISM. However, as the amount of metal mass that is distributed into the neighbours of the star particle can be much larger than the mass of one gas particle, we split the gas particles after the enrichment has taken place if the mass exceeds the initial particle mass resolution of the simulation by a factor of two, to avoid numerical artefacts. The split particles inherit all the physical properties that were present in the parent particle including specific internal energy, kinetic energy, metallicity and chemical abundances. The particle mass is split by a factor of two and the position is offset by one fifth of the parent particle smoothing
length in a random (isotropic) direction to avoid the overlap of the
two newly spawned particles. The spawning process requires a new
domain decomposition and a re-build of the gravity tree which makes
the code somewhat slower.

2.4 Treatment of Runaway stars

While the spatial and mass resolution of our simulation is relatively
high by current standards, we are not yet capable of accurate modeling
of two, three and few-body interactions needed to self-consistently ac-
count for the velocity offset from which runaway O/B stars originate.
We note that attempts can be made to self-consistently model these
phenomena in the near future in galaxy scale simulations employing
the methods presented in Rantala et al. (2017) and Rantala et al.
(2020) (higher order symplectic), and there are recent demonstra-
tions of similar methods on the cloud scale for higher order hermite
integration of star clusters (e.g. Grudić et al. 2022; Guszejnov et al.
2022). However, currently it is not possible to accurately compute
the forces for two or three body encounters in a galaxy scale simulation
that also takes a detailed ISM model into account. A first order ap-
proximation for the effect of runaway stars can be obtained by
constructing a “subgrid” model for the velocity kicks for the massive
O/B stars that become runaway stars. In the following we present two
models, one motivated by simulations for a strong runaway case and
another one which represents a weaker walkway case.

2.4.1 The Runaway Case: Power law velocity distribution

In the strong runaway model we assume that the velocity distribution
follows a simple power law

\[ f_{vel} \propto v^{-\beta}, \]  

(3)

with the velocity power law slope \( \beta \), which is dependent on several
factors. One popular scenario for runaway star formation occurs when a
binary system undergoes gravitational scattering processes with a
third star. Thus it is straightforward to assume that \( \beta \) is mainly driven
by the number of binary systems in the star cluster and the relaxation
time of the star cluster itself. Moreover, in reality, star clusters can be
interrupted (e.g. due to internal supernova events or tidal interactions
with other star clusters) which is also important for setting \( \beta \). All
these processes can lead to velocity kicks following the distribution
of equation 3. However, there would be a time delay that comes from
the direct N-body interactions which is not captured by our approach.
This is a clear limitation of applying random (isotropic) velocity
kicks. To accurately model star cluster formation and evolution it is
necessary to solve the direct N-body system, which would give a
reliable estimate for \( \beta \) (Eldridge et al. 2011; Perets & Šubr 2012; Oh
\& Kroupa 2016; Renzo et al. 2019). In detail, the velocity distribution
may depend on the mass of the star as well as the properties of the
star cluster. Alternatively, one could follow an empirically motivated
approach and adopt an estimate for \( \beta \) directly from observations (e.g.
Blaauw 1961; Comerón & Pasquili 2007; Gies 1987; Hoogerwerf
et al. 2000, 2001). In our first runaway model we will follow a
theoretically motivated approach by adopting estimates from Oh
\& Kroupa (2016). This will allow for a direct comparison to Andersson
et al. (2020), who investigated the effects of runaway stars in galaxy
simulations of the Milky Way.

We start our modelling by building a subgrid model for runaway stars
in which we adopt a power law velocity distribution following eq. 3
with a slope \( \beta = 1.8 \). To do so we slightly modify our IMF-sampling
approach and add velocity kicks to stars that are more massive than
8\( M_\odot \). First, we have to sample the velocity distribution of equation
3. This can be accomplished by drawing a random number \( p \) and
obtaining the absolute value for the velocity kick of particle \( i \) in the
following manner:

\[ v_i = v_{\text{min}} \cdot (1 - p)^{-\frac{1}{\beta}}. \]  

(4)

We adopt a minimum value \( v_{\text{min}} = 3 \text{ km s}^{-1} \) for direct comparison
with Andersson et al. (2020). We truncate the distribution at 385 km
s\(^{-1}\). However, this truncation process introduces a complication. If
we draw a random number between zero and one and we calculate \( v_i \) following equation 4, then it can happen that we naturally sample
values above 385 km s\(^{-1}\). We want to truncate the sampling because
this will give as a distribution where 14 percent of the stars obtain a
velocity kick of more than 30 km s\(^{-1}\), which is in good agreement
with observations. The sampling of values above 385 km s\(^{-1}\) can be
related to a certain upper limit \( p_{\text{max}} \) for the random number \( p \), which is
given by

\[ p_{\text{max}} = 1 - \left( \frac{3}{385} \right)^{\frac{1}{\beta}} \approx 0.9744. \]  

(5)

We thus only accept the random number \( p \) if it is smaller or equal than
\( p_{\text{max}} \). This ensures that we obtain a velocity power law distribution
with a slope of \( \beta = 1.8 \) and a 14 percent fraction of stars with velocity
kicks of more than 30 km s\(^{-1}\).

2.4.2 The Walkaway Case: Maxwellian velocity distribution

The second scenario that we adopt for velocity kicks is designed to
mimic the more conservative case of so called walkaway stars,
where the bulk of the stars in the velocity distribution is moving at
a speed lower than 10 km s\(^{-1}\), following a velocity distribution that is
consistent with a Maxwell-Boltzmann distribution:

\[ p(v) \propto v^2 \exp \left( \frac{-v^2}{2\sigma^2} \right). \]  

(6)

where \( \sigma \) is the width of the distribution. This is motivated based
on previous work, both observational and theoretical, that shows
some indication for a Maxwellian distribution (e.g. Eldridge et al.
2011; Silva & Napiwotzki 2011). However, we note that we take
a rather conservative approach that is more consistent with previ-
ous research such as Renzo et al. (2019) which is suggesting that
the bulk of runaway stars can actually be classified as walkaway
stars. While such a distribution is a little harder to sample than
the power law from the previous section, it becomes almost trivial
when considering that the distribution of equation 6 is the three
dimensional representation of the Maxwell-Boltzmann distribution
integrated over solid angle in spherical coordinates. Hence, this
distribution in Cartesian coordinates consists of three (independent)
Gaussian distributions. The latter can be straightforwardly sampled
by a Gaussian random number generator, which is available in the gsl
package as the Ziggurat-algorithm, and is the fastest way of sampling
the distribution of equation 6. We note that we explored different op-
tions to sample this distribution such as the Box-Muller method that
can obtain Gaussian random numbers by utilising a linear combina-
tion of four uniform random numbers. In practice the difference is
marginal, but the Ziggurat-algorithm is much faster. We note that for
this model we also adopt a probability for a star to get any velocity
kick. This is motivated by the fact a fraction of stars will be born as
single stars and a fraction will be born as binary stars. In this model
we assume that only binary stars can receive a velocity kick and we
The choice of 50 per cent is rather ad-hoc since most the exact fraction of runaway/walkaway stars is not exact. We note that we did not assume this in the first model, to have a model close to the results of Oh & Kroupa (2016) and the implementation of Andersson et al. (2020). Note that we do not explicitly sample the binary IMF, which is a clear limitation of this model. Since this model is supposed to represent the more conservative walkaway case we adopt a relatively low value of $\sigma = 32 \text{ km s}^{-1}$.

### 2.5 Initial conditions and simulations

In our set of simulations we use the initial conditions of an isolated dwarf galaxy with a baryon mass of $2 \times 10^7 \, M_\odot$ and a dark matter mass of $2 \cdot 10^{10} \, M_\odot$, which is an analogue of a classic Wolff-Lundmark-Moyette (WLM) system. The mass resolution is set to 4 $M_\odot$. The force softening for this system is 0.1 pc. Our choice for the gravitational softening is rather aggressive we note that extensive testing of different values of this parameter has little effect on global galactic properties such as morphology, star formation, and outflow rates. However, we note that a smaller choice of the softening-length than 0.1 leads to sub-optimal gravity time stepping behaviour due to runaway star formation in dense regions that result in the gravitational ejection of single stars to arbitrarily large velocity. This effect is mainly significant in runs without PI-radiation (not presented here). The softening is roughly comparable to the size of the kernel that we observe in the dense regions of the ISM during the simulation. The initial conditions are generated with the code presented in Springel et al. (2005) often referred to as “MakeDiskGal” or “Makegalaxy”. In total we carry out four simulations WLM-fiducial, WLM-RunP (power law runaway stars), WLM-RunM (Maxwellian runaways), and WLM-inplane (runaways only in xy plane) summarised in Table 1. The first case WLM-fiducial represents a baseline case without runaway stars. The second case WLM-RunP represents a strong runaway case. The third case WLM-RunM represents a weaker runaway scenario, in which stars do not receive such high velocity kicks as in the WLM-RunP scenario. The final case WLM-inplane samples the same power-law velocity distribution as WLM-RunP, but kicks are only imparted in the x-y plane. This allows us to test the impact of runaways migrating within the plane of the galaxy versus escaping above or below the disk.

### 2.6 Definitions for outflow rates, inflow rates, loading factors and metal enrichment factors

We follow the definitions for outflow rate, inflow rate, mass loading and enrichment factors of previous work, specifically, the definitions presented in Hu et al. (2019). Generally, galactic wind quantities can be split into mass-flux ($m$), momentum-flux ($p$) and energy-flux ($E$) defined via:

$$\mathcal{T}_m = \rho \nu,$$  \hspace{1cm} (7)

$$\mathcal{T}_p = \rho \nu \cdot \nu + P,$$  \hspace{1cm} (8)

$$\mathcal{T}_E = (\rho \varepsilon_{\text{tot}} + P) \nu,$$  \hspace{1cm} (9)

with $\rho$, $\nu$ and $P$ given as the fundamental fluid variables density, velocity and pressure. At all times $\varepsilon_{\text{tot}}$ is defined as the total energy per unit mass $e_{\text{tot}} = 0.5 \, \nu^2 + u$, where $u$ is the internal energy per unit mass. In standard cgs units $u$ takes the units $\text{km s}^{-2}$. We note this to avoid confusion with converting these units to proper cgs units in the sections below.

In this work, if not stated otherwise, all the flow rates are measured at a height of 1 kpc above the midplane of the galaxies in a plane-parallel patch with thickness $dr$, where $dr = 0.1 \, \text{kpc}$. We will adopt the following definitions for in and outflows rates, with the total flow rates defined via $\dot{M} = \dot{M}_{\text{in}} - \dot{M}_{\text{out}}$, $\dot{P} = \dot{P}_{\text{out}} - \dot{P}_{\text{in}}$ and $\dot{E} = \dot{E}_{\text{out}} - \dot{E}_{\text{in}}$. Outflow is defined by a positive value of the radial velocity given via $\nu \cdot \hat{n} = v_r > 0$, and inflow is defined as the material in the patch with negative radial velocity $v_r < 0$. Hence, we can write down the discrete inflow and outflow rates for mass, momentum and energy:

$$\dot{M}_{\text{out}} = \sum_{i, v_r > 0} \frac{m_i v_{i,r}}{dr},$$  \hspace{1cm} (10)

$$\dot{M}_{\text{in}} = - \sum_{i, v_r < 0} \frac{m_i v_{i,r}}{dr},$$  \hspace{1cm} (11)

$$\dot{P}_{\text{out}} = \sum_{i, v_r > 0} \frac{m_i \nu^2_{i,r} + (y - 1) u_i}{dr},$$  \hspace{1cm} (12)

$$\dot{P}_{\text{in}} = - \sum_{i, v_r < 0} \frac{m_i \nu^2_{i,r} + (y - 1) u_i}{dr},$$  \hspace{1cm} (13)

$$\dot{E}_{\text{out}} = \sum_{i, v_r > 0} \frac{m_i (\nu^2_{i,r} + y u_i) v_{i,r}}{dr},$$  \hspace{1cm} (14)

$$\dot{E}_{\text{in}} = - \sum_{i, v_r < 0} \frac{m_i (\nu^2_{i,r} + y u_i) v_{i,r}}{dr},$$  \hspace{1cm} (15)

where we use $P = \rho u (y - 1)$ as an equation of state. Furthermore, we will compute metal outflow rates via:

$$\dot{M}_Z = \sum_{i, v_r > 0} \frac{Z_i m_i v_{i,r}}{dr},$$  \hspace{1cm} (16)

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### Table 1. Overview of the physics variations adopted in our different simulations. For convenience we follow similar naming conventions as those adopted in Hu et al. (2017).

| Name         | Core Collapse Supernovae | Photoionising radiation | Photoelectric heating | runaway stars |
|--------------|--------------------------|-------------------------|-----------------------|---------------|
| WLM-fiducial | ✓                        | ✓                       | ✓                     | X             |
| WLM-RunP     | ✓                        | ✓                       | ✓                     | power law distribution |
| WLM-RunM     | ✓                        | ✓                       | ✓                     | Maxwellian distribution |
| WLM-inplane  | ✓                        | ✓                       | ✓                     | maxwellian (sampling only for $v_x$ and $v_y$) |
\[ M_{\text{in}} = - \sum_{i, v_i > 0} Z_i m_i v_i r \frac{d}{dr}, \]  
\( (17) \)

where \( Z_i \) is the metallicity of particle \( i \). It is useful to investigate these parameters normalised to a set of reference quantities, defined as the so-called loading factors for mass \( (\eta_m) \), metals \( (\eta_Z) \), momentum \( (\eta_p) \) and energy \( (\eta_e) \) and given by:

(i) outflow mass loading factor: \( \eta_m^{\text{out}} = M_{\text{out}} / \text{SFR} \),
(ii) inflow mass loading factor: \( \eta_m^{\text{in}} = M_{\text{in}} / \text{SFR} \),
(iii) momentum outflow loading factor: \( \eta_p^{\text{out}} = p_{\text{out}} / (p_{\text{SN}} R_{\text{SN}}) \),
(iv) momentum inflow loading factor: \( \eta_p^{\text{in}} = p_{\text{in}} / (p_{\text{SN}} R_{\text{SN}}) \),
(v) energy outflow loading factor: \( \eta_e^{\text{out}} = E_{\text{out}} / (E_{\text{SN}} R_{\text{SN}}) \),
(vi) energy inflow loading factor: \( \eta_e^{\text{in}} = E_{\text{in}} / (E_{\text{SN}} R_{\text{SN}}) \),
(vii) outflow metal loading factor: \( \eta_Z^{\text{out}} = M_{Z, \text{out}} / (m_Z R_{\text{SN}}) \),
(viii) inflow metal loading factor: \( \eta_Z^{\text{in}} = M_{Z, \text{in}} / (m_Z R_{\text{SN}}) \).

where we adopt \( E_{\text{SN}} = 10^{51} \) erg, \( p_{\text{SN}} = 3 \cdot 10^4 M_\odot \) km s\(^{-1}\), the supernova rate \( R_{\text{SN}} = \text{SFR} / (100 M_\odot) \) and the metal mass (IMF-averaged) \( m_Z = 2.5 M_\odot \) which we take for best comparison with previous dwarf galaxy studies from Hu et al. (2019). We compute the mean star formation rate \( \text{SFR} \) over the time span of one Gyr, which is the total run time of the simulation. Additionally, we define metal-enrichment factors that not only quantify the amount of metals transported in the outflows, but can quantify to what degree metals are over- or under-abundant in galaxy outflows relative to the ISM. This can be achieved by normalising the metal outflow rate to the mass outflow rate, weighted by the background metallicity of the galactic ISM, \( Z_{\text{gal}} = 0.1 Z_\odot \).

(i) outflow enrichment factor: \( \gamma^{\text{out}} = M_{Z, \text{out}} / (M_{\text{out}} Z_{\text{gal}}) \),
(ii) inflow enrichment factor: \( \gamma^{\text{in}} = M_{Z, \text{in}} / (M_{\text{in}} Z_{\text{gal}}) \).

3 RESULTS

In this section we will study the outflow properties of all of our dwarf galaxy simulations with a specific focus on the time evolution of the outflow rates and wind loading factors.

3.1 Morphology

We start the discussion of our results with a brief comparison of the morphological structure of the resolved ISM in the simulations with and without runaway stars. As summarized in Table 1 the models WLM-RunP, WLM-RunM and WLM-inplane include a treatment for runaway stars, while the simulation WLM-fiducial is a control run that includes the feedback from massive stars (supernovae, photoionisation and photo heating), as described in Section 2.

In Fig. 1 we show face-on projections of the stellar surface density (left), the gas surface density (center) and the thermal pressure (right) for the runs WLM-fiducial (first row), WLM-RunP (second row), WLM-RunM (third row) and WLM-inplane (fourth row). Qualitatively, the runs look very similar and there are only marginal differences in the global evolution of the stellar and the ISM-structure of the simulated systems. This trend is generally true over the full duration of the simulation. In the simulations that include a treatment of runaway stars, the stellar structure appears to be less clustered than in the cases without runaway stars and the regular stellar tails that are clearly visible in the run WLM-fiducial appear to be less prominent in the simulations WLM-RunP, WLM-RunM and WLM-inplane. However, the effect is marginal.

In Fig. 2 we show the same results for the simulations WLM-fiducial (first row), WLM-RunP (second row), WLM-RunM (third row) and WLM-inplane (fourth row) for the edge-on perspective. One can easily identify the thin stellar disk. Again we note that the overall morphology is similar in all four cases, but one can see a slightly “puffed up” stellar disc in the runs WLM-RunP and WLM-RunM, which include a treatment for runaway stars. This effect is not present in the model WLM-inplane, in which velocity kicks are only applied in directions parallel to the galactic plane. We note that the runaway stars have a minor impact on the morphological structure of the stars and the turbulent, supernova driven ISM, relative to the variations expected just due to the stochastic nature of the underlying star formation and feedback prescription.

3.2 Star formation rate

In the top panel of Fig. 3 we show the time evolution of the star formation rate (SFR) for all four simulations WLM-fiducial (black), WLM-RunP (blue), WLM-RunM, and WLM-inplane (orange). Comparable to similar simulations of the WLM system in previous work, the SFR in our fiducial run is settling around \( 2 \times 10^{-4} M_\odot \) yr\(^{-1}\), where we note that the star formation rate drops by roughly a factor of two due to the presence of photoionising radiation, compared to runs that only include the feedback from SNe alone (e.g. Hu et al. 2017; Smith et al. 2021). Generally, the star formation rate in the two runaway models WLM-RunP and RunM do not differ significantly from the star formation rate in both the fiducial run WLM-fiducial and the run WLM-inplane, in which we only consider velocity kicks in the x and y plane, with the maxwellian velocity kick model. However, there are some differences that we would like to point out in greater detail. First, there is a difference in the strong runaway model WLM-RunP compared to the other three runs, namely the height of the peaks in SFR which can be larger by more than a factor of two for specific selected times. Thus the overall structure of the star formation history in the strong runaway model appears to be more bursty. The most likely reason for this is that the velocity kicks that we apply in this particular case can easily drive some of the photoionising sources out of the natal clouds. Since the molecular clouds in our WLM analogues are rather small (a few times \( 10^3 M_\odot \) up to around a maximum of \( 10^4 M_\odot \)) they are easily dispersed by the effect of photoionisation. However, if a large fraction of massive stars are quickly removed from their natal clouds, PI-radiation will not be able to locally quench star formation as strongly as in the reference run WLM-fiducial. This leads to a more bursty behaviour as shown in the studies of Hu et al. (2017) and Smith et al. (2021). This is not seen to the same degree in the simulations WLM-RunM and WLM-inplane, which adopt the more moderate “walkaway” case with a Maxwellean velocity distribution, where the bulk of stars (80 per cent) receive rather small velocity kicks (\( \sim 10 \) km s\(^{-1}\)) consistent with the “walkaway” picture.

In the bottom panel of Fig. 3 we show the integrated star formation rate for all four runs, adopting the same colour scheme for the lines. While the build up of the total stellar mass of the system is similar, the final masses (at \( t=1 \) Gyr) are slightly different between the runs. Generally, we find that there can be a deviation of the total mass and average star formation rate of up to a few per cent due to model stochasticity. This is very apparent for the runs WLM-fiducial and WLM-inplane where we find agreement on the per cent level. However, in the runaway models WLM-RunM and WLM-RunP we find a significant increase of the total stellar mass by 35 and 85 per cent respectively which is a significant increase compared to model scatter of around a few per cent. We note that we use reproducible random numbers based on Gadget’s random number generator for the
Figure 1. Visualisation of the the face-on stellar surface density (left), the gas surface density (center) and the pressure (right), for our isolated dwarf galaxy simulations, for the runs WLM-fiducial (first row), WLM-RunP (second row), WLM-RunM (third row) and WLM-inplane (fourth row). We find only very minor differences between the different runs in terms of the morphology of the stellar structure and the ISM.
Figure 2. We visualise the edge-on stellar surface density (left), the gas surface density (center) and the temperature (right), for our isolated dwarf galaxy simulations, for the runs WLM-fiducial (first row), WLM-RunP (second row), WLM-RunM (third row) and WLM-inplane (fourth row). We find only very minor differences between the different runs in terms of the morphology of the stellar structure and the ISM. However, the stellar disc seems to be slightly “puffed up” in the runs WLM-RunP and WLM-RunM compared to the runs WLM-fiducial and WLM-inplane.
Figure 3. We show the star formation rate for the runs WLM-fiducial (black), WLM-RunP (blue), WLM-RunM (red) and WLM-inplane (orange) in the top panel, as well as the total stellar mass of the systems in the bottom panel as a function of time. We find a slight boost of the star formation rate in the runaway star models. This may be due to the reduction of feedback from PI-radiation as some massive stars quickly leave their natal clouds. However, the time averaged star formation rate is only weakly influenced by this effect due to the self-regulating nature of the star formation and feedback cycle.

Figure 4. Distribution of the density of the gas in which SNe explode, for all runs WLM-fiducial (black), WLM-RunP (blue), WLM-RunM (red) and WLM-inplane (orange). For all runs we took a statistically large enough sample of 3000 SNe explosions to allow for direct comparison. The data are binned in 128 equally spaced logarithmic bins in the range from $10^{-3}$ to $10^3$ cm$^{-3}$. Runaway stars have only a weak effect on the distribution function but in the run WLM-RunP there is a slight excess of stars exploding in lower density environments. However, this is within the model scatter, which implies that major changes in global properties are driven by the altitude above or below the disc at which the SNe explode and not the redistribution of the SNe in the galactic plane.

IMF sampling routine as well as the sampling routine for the runaway stars’ velocities, our simulations are prone to the “butterfly-effect” recently reported on in cosmological zoom simulations (e.g. Genel et al. 2019) and molecular cloud simulations (e.g. Keller et al. 2019). Hence our results are only strictly reproducible on the same machine for the same number of MPI ranks and OPENMP threads. The results of the runs WLM-fiducial and WLM-inplane are consistent with one another within this model stochasticity, but this is not the case for the run WLM-RunP and WLM-RunM which both show a significant boost in the integrated star formation history.

In Fig. 4 we show the supernova environmental density for all four runs, ranging from a density of $10^{-4}$ cm$^{-3}$ to $10^4$ cm$^{-3}$. The environmental density is computed in SPH-like fashion as a kernel weighted sum over all the neighbours of a star particle is flagged as experiencing a SN. The sum is computed before the ejecta are distributed. For all runs we plot a total of 3000 supernova explosions. However, due to the slight differences in the models there is roughly a 50 Myr range in the time where the simulations reach that value, i.e. these distributions are not plotted at the exact same time. The distribution of the environmental density of core collapse supernovae explosions is very similar between the different runs. There appears to be a slight increase in the number of SN explosions in low density environments in the model WLM-RunP compared to the other three models. Furthermore, it is interesting to point out that the distribution of densities for the control run WLM-inplane is very similar to the other models. From this we can directly deduce that in the following, all major changes that we report on are driven by “high altitude supernovae”, that explode in gas with similar density but above or below the plane of the disk.

3.3 Phase structure and volume filling fraction

Next, we investigate the changes in the density-temperature phase space and the hot volume filling fraction of the gas. In Fig. 5, we show the time averaged density-temperature phase space diagrams over a time span of 500 Myr, which is equivalent to 500 snapshots and around $5 \times 10^9$ particles, for the model WLM-fiducial(top), WLM-RunP(centre) and WLM-RunM(bottom). A more continuously populated hot phase can be seen in both runaway models. Additionally, we note that in both runaway cases, there is significantly more mass in the diffuse hot phase around $10^5$ K. Gas in HII regions is clearly apparent as a horizontal line at $10^4$ K.

In Fig 6 we show the same phase diagrams, also averaged over 500 Myrs, in a volume weighted fashion (actually we weight by effective cell size which is $\sqrt[3]{V}$), which clearly reveals the volume filling nature of the hot phase of the ISM.

In Fig. 7, we show the time evolution of the hot volume filling fraction for all models as a function of time. To define the hot phase, we choose a cut of $3 \times 10^4$ K, which has two motivations. The first one is numerical, as this is the temperature where we transit from a non-equilibrium cooling prescription to an equilibrium cooling prescription. The second is chosen to be comparable with previous results of Hu et al. (2017). However, we note that this differs from the
Figure 5. We show the time averaged mass weighted density-temperature phase space for the runs WLM-fiducial (top), WLM-RunP (centre) and WLM-RunM (bottom). All plots are averaged over a time scale of 500 Myr. The runs WLM-RunP and WLM-RunM show excess mass in the hot phase of the ISM. However, since the hot phase typically does not contain most of the mass, the trend is more apparent in the volume weighted version of this figure (Fig. 6).

Figure 6. We show the time averaged volume weighted density-temperature phase space for the runs WLM-fiducial (top), WLM-RunP (centre) and WLM-RunM (bottom). All plots are averaged over a time scale of 500 Myr. It is apparent that the inclusion of runaway stars can have a significant effect on establishing the hot, volume filling phase of the ISM.

The definition of the hot phase in Steinwandel et al. (2020). We compute the hot volume filling factor as the sum over the volume stored in the hot phase above $3 \times 10^4$, divided by the total volume of the simulation. The volume is computed as:

$$V = \frac{4}{3} \pi h_i^3,$$

where $h_i$ is the smoothing length of particle $i$. Alternatively, one can compute the volume as $m_i / \rho_i$. We tested both methods and note that there is only a minor difference between the two, which typically remains below the per cent level.

We can see from Fig 7 that the volume filling fraction of hot gas in the WLM-RunP (strong runaway) model is significantly higher than...
in the other models. The weaker runaway model \textit{WLM-RunM} has a slightly higher hot gas volume filling fraction than the \textit{WLM-fiducial} and \textit{WLM-inplane} models, especially at late times. We note that the exact value for the hot phase filling fraction is very sensitive to the exact value of the temperature cut, and can change by a factor of five when the cut is varied within the range of \(3 \times 10^3\) K and \(3 \times 10^5\) K. Nevertheless, we find a consistently larger volume filling factor for the hot phase independent of which temperature cut we adopt.

Since runaway stars induce a more efficient coupling of feedback to diffuse gas, we might expect their inclusion to affect the cold dense ISM. We do note a substantial difference in the dense cold gas between our runs in Fig 6. In particular, the run \textit{WLM-RunP} has a noticeable dearth of volume-weighted gas above \(n = 10^3\) cm\(^{-3}\). This run also has a slightly higher star formation rate overall (as seen in Fig. 3), which suggests that the depletion time of the cold star forming gas is shorter when runaway stars are included. In this run, massive stars are more often ejected out of the natal cold dense gas into warmer and diffuse regions of the ISM. Thus, the CNM and star forming gas will be less disturbed and more likely to continue its star forming state (e.g. can continue to be Toomre/Jeans unstable).

We now turn to a quantification of the outflow properties and loading factors. In Fig. 8 we show the logarithm of the outflow properties and loading factors. In Fig. 8, we plot the main outflow diagnostics for all four simulations in logarithmic space for the models \textit{WLM-fiducial} (top) and \textit{WLM-RunP} (bottom). The colour code indicates the averaged outflow mass flux rate over a time span of 500 Myr. While these indicate that the bulk of the mass in the outflow is transported by the cold phase, we find a significant increase in mass transport in the hot phase of the wind, that extends to higher outflow velocities and sound speed for the simulation \textit{WLM-RunP} (bottom).

### 3.4 Outflow rate and outflow mass loading

In Fig. 9 we show the same plots for the energy outflow rate, for \textit{WLM-fiducial} on the top and \textit{WLM-RunP} on the bottom, indicating that while there is a cold energy transporting phase in our dwarf galaxy simulation, there is a tail that extends to higher specific energy. This is even more true in the bottom panel for strong runaway case \textit{WLM-RunP}, where we find a tail that not only extends to higher sound speed but also to higher outflow velocity, which is direct evidence that runaway stars can not only boost the mass flux but can additionally increase the specific energy loading as well as the total energy loading of the wind significantly.

### Figure 7. Volume filling factor for different models.

\textbf{Figure 7.} We show the volume filling factor of the hot gas (above a temperature of \(3 \times 10^4\) K) as a function of time for all four models \textit{WLM-fiducial} (black), \textit{WLM-RunP} (blue), \textit{WLM-RunM} (red), and \textit{WLM-inplane} (orange). One can clearly see that the runaway models show an increase in the volume filling factor of the hot phase. As pointed out in previous studies of Hu et al. (2017) and Steinwandel et al. (2020), the volume filling factor is critical for driving outflows in galaxies.

\textbf{Figure 8. Outflow velocity as a function of the sound speed.}

\textbf{Figure 8.} We show the outflow velocity as a function of the sound speed in logarithmic space for the models \textit{WLM-fiducial} (top) and \textit{WLM-RunP}. The colour code indicates the averaged outflow mass flux rate over a time span of 500 Myr. While these indicate that the bulk of the mass in the outflow is transported by the cold phase, we find a significant increase in mass transport in the hot phase of the wind, that extends to higher outflow velocities and sound speed for the simulation \textit{WLM-RunP} (bottom).
RunM and energy (bottom right) loading for all four simulations in logarithmic space for the models WLM-RunM (top) and WLM-RunP (bottom). The colour code indicates the averaged outflow energy flux rate over a time span of 500 Myr. The energy flux carried by the phase at high velocities and high sound speeds is significantly increased when runaway stars are included in the runs WLM RunP (bottom).

We show the outflow velocity as a function of the sound speed in Fig. 9. We show the outflow velocity as a function of the sound speed in logarithmic space for the models WLM-fiducial (top) and WLM-RunP. The colour code indicates the averaged outflow energy flux rate over a time span of 500 Myr. The energy flux carried by the phase at high velocities and high sound speeds is significantly increased when runaway stars are included in the run WLM-RunP (bottom).

In Fig. 11 we show the mass (top left), metal (top right), momentum (bottom left) and energy (bottom right) loading for all four simulations considered in this paper. While we see similar trends for the loading factors, we note that the trend in the mass loading is slightly suppressed compared to the boost we find in the mass outflow rate.

### 3.5 Inflow rates

In Fig. 12 we show the inflow rate for mass (top left), metals (top right), momentum (bottom left) and energy (bottom right) for the simulations WLM-fiducial (black), WLM-RunP (blue), WLM-RunM, and WLM-inplane (orange). We measure the inflow rate in the same 100 pc thick patch located at 1 kpc above/below the midplane. Generally, one can see that in all the models, the inflow rates decrease with time, then increase slightly after about 500 Myr. This increase is more pronounced in the models with runaway stars. In the models with runaway stars, the mass, metal and momentum inflow rates show a similar degree of increase as the increase in outflow rates. However, the energy inflow rate decreases by only a factor of 2-3, not a factor of ~ 10 as was seen in the energy outflow rate for the strong runaway model. This implies that the SN-feedback energy of “high altitude supernovae” is either efficiently kept in the CGM due to mixing with lower specific energy gas, or lost to cooling in the highly metal rich outflowing material. The latter case seems unlikely when we consider the phase-structure of the mass and volume weighted density-temperature diagrams. These reveal more mass in the diffuse $10^5$ K regime at low densities, indicating that there is an slight increase in the virial temperature of the system when runaway stars are included. We note that inflow rates are slightly larger in the runs that include a runaway/walkaway model. This can be understood in combination with the slightly increased mass outflow rates we observe in the runaway models. We find that the peaks in outflow and inflow rate are shifted by roughly 150-200 Myr, indicating that some fraction of the gas is actually “recycled” over a few dynamical times of our simulated dwarf.

### 3.6 Metal enrichment factor

Finally, we discuss the metal outflow enrichment factor $\gamma_{Z, out}$ and the metal inflow enrichment factor $\gamma_{Z, in}$, which we show for all simulations in Fig. 13 on the top and the bottom respectively. There is a striking increase of the metal outflow enrichment factor when runaway star modelling is included in the simulations. Generally we find a boost of around 15 to 20 percent in the metal outflow enrichment factor compared to the fiducial run and the run where we only apply the velocity kicks in the x- and y-plane. We note that while the metal inflow enrichment factor is also boosted compared to the reference simulations the effect is not as strong as for the outflow enrichment factor. This indicates that runaway stars can significantly contribute to the metal enrichment of the CGM and can boost its metallicity by about 15 percent. Since metals are the most important coolant in the low density regime, this might have crucial consequences for mixing properties in the CGM. However, since we do not explicitly model the CGM in our simulation by including a hot cooling halo, we postpone a detailed study of CGM cooling, heating and mixing rates alongside with a detailed analysis of metal emission line properties to future work.

### 4 DISCUSSION

#### 4.1 Interpretation and comparison to previous work

We start our discussion by briefly comparing to previous results of similar WLM systems without the inclusion of runaway star model-
ing, which has been used in several studies throughout the literature (Hu et al. 2016, 2017; Emerick et al. 2019; Hu et al. 2019; Gutcke et al. 2021; Smith et al. 2021; Hislop et al. 2022). The most appropriate of these to compare to are the simulations by Hu et al. (2017) and Smith et al. (2021) since the implemented physics modules cover the same range from the cooling and SN-feedback routines to the prescription for photo-electric heating and photoionisation. This is important since Hu et al. (2017) used a pressure-energy SPH formalism with 100 neighbours and Smith et al. (2021) adopted the moving mesh code moving for their simulations which employs a second order Riemann-method on an unstaggered moving mesh. The latter is numerically more similar to our MFM approach. Generally, all codes agree quite well for our fiducial model when compared to the appropriate runs of Hu et al. (2017) (PI-SN-PE) and Smith et al. (2021) (lowΣ in their Appendix A). This is true across star formation histories and loading factors. A more detailed study on the subtle differences between SPH and MFM on identical setups will be investigated in future work.

Our results indicate that even conservative modelling of runaway stars in galaxy simulations with a resolved treatment of the ISM and stellar feedback can have a significant impact on the properties of large scale stellar driven winds. This most apparent in the energy outflow and energy loading factors, which we show in our respective Fig. 10 and Fig. 11. It is remarkable to point out that the inclusion of runaway stars can boost the energy loading factor by up to an order of magnitude, up to a value of ~ 0.1 in the peak values. On average, we still find an increase by roughly a factor of 5 in the model WLM-runP and a factor of 3 in the model WLM-runM. We note that previous work, such as from the rorss suite (e.g. Kim & Ostriker 2015, 2018; Kim et al. 2020) or from (e.g. Li et al. 2017), typically find a value of the energy loading of around ~ 0.1 for Milky Way like conditions. Our results suggest that similarly high values of the energy loading might also be found in dwarf galaxies. The imprints of the runaway star process are not very clear in the mass and temporal weighted density-temperature phase space diagrams that we show in Fig.5, but become more apparent in the volume weighted phase-space diagrams shown in Fig.6. There we can clearly see that the volume of the hot phase significantly increases when any runaway modelling is included. This can be quantified not only as an increase in the specific energy loading but also in the total energy loading, as we can see in Fig.9. While the effect on the mass loading is somewhat weaker, we still see a significant increase in the mass flux rates when runaway stars are included (Fig. 8).

In this context it is interesting to point out that while we do not explicitly include a CGM around our dwarf galaxy simulation, it is not

Figure 10. We show the mass outflow rate (top left), the metal outflow rate (top right), the momentum outflow rate (bottom left) and the energy outflow rate (bottom right) as a function of time for all four simulated models, where black indicates the fiducial model WLM-fiducial, blue represents the power law model WLM-RunP and red the Maxwellian runaway model WLM-RunM. The orange line shows the runaway model WLM-inplane in which we apply the velocity kicks only along the v_x and v_y directions. The impact of runaway stars can be clearly seen in a boost of the mass, the metal and the momentum outflow rate by a factor of around two (comparing blue lines to black lines). In the case of the energy outflow rate the boost is even more significant, around a factor seven to eight.
that case that there is no pristine low density gas around the dwarf due to the 500 Myr of initial evolution with turbulent SN-driving that we apply before examining any science results. This can be clearly deduced from Fig. 4 where we find little difference in the SN-environmental distribution between the fiducial run WLM-fiducial and the run WLM-inplane where the runaway kicks are only applied in the plane of the galaxy. The similar shape of these implies two things directly. First, the increase in the specific energy of the wind is not driven by the re-positioning of the SNe in the disc due to the presence of the runaway stars but rather stems from the “high-altitude” SNe, introduced by the presence of the runaway star modelling. That this effect is still present in the weaker walkaway case is a rather promising result as it indicates that the re-positioning of SNe in the vertical direction is more important at constant environmental SN-density. Second, the fact that the low density distribution of SN explosion environment is only weakly affected by the presence of any runaway modelling indicates that the SNe have to explode around the disc scale height in gas that is still mostly resolved even without an additional CGM that would provide an external pressure. If this were not the case, the distribution of environmental SN-densities would be significantly altered and shift to an overabundance in events in unresolved low density gas.

Finally, it is important to point out that we find a significant increase in the metal mass loading, by around 20 per cent in both runaway models as we show in 13. This can have crucial consequences for the cooling behaviour around dwarf galaxy systems and observational properties of the CGM.

We can compare our results with two notable studies concerning runaway stars. One was presented by Andersson et al. (2020), and was carried out with the adaptive mesh refinement code Ramses (Teyssier 2002) for a global MW-simulation. Another was carried out by Kim & Ostriker (2018) within the TGRASS framework of local stratified environments. At face value, these studies seem to disagree with one another, as Kim & Ostriker (2018) reports that runaways have a very weak effect, while Andersson et al. (2020) reports a significant boost in the wind outflow rates when runaway modeling is included. However, the comparison is tricky due to the different setup choices. Furthermore, both studies are evolved for a short amount of time compared to any global MW-scale. The comparison to our work is even more complicated since our simulations are designed to study very low mass dwarf galaxies at very high resolution. However, Andersson et al. (2020) state that they find that runaway stars do not have any effect in dwarf galaxies, which they discuss very briefly without showing the details of the dwarf simulations. These appear to be centered around very low mass cosmological dwarf galaxy simulations taken from the edge sample (Agertz et al. 2020). Indeed, we also find
that if we apply the runaway modelling in lower mass isolated discs we do not see a strong effect on any of the properties, which may be because these do not form a thin disc due to the strong impact of SN-feedback. Hence our results are not necessarily in disagreement with what Andersson et al. (2020) report, but we represent difference in the galaxy properties between our study and theirs. Furthermore, we note that some of the dwarf galaxy simulations that are carried out with RAMSES by now do not see an effect of runaway stars when only SN-feedback is employed (Andersson p.c. and Andersson et al. in prep.) The same can be said about a comparison with Kim & Ostriker (2018), where again, the results are very hard to compare since we are in very different outflow regime, as can be seen from the shape of our Fig. 8 and Fig. 9 compared to their results as shown in Kim et al. (2020). For now we can only conclude that our results seem to be somewhere in between the studies of Andersson et al. (2020) and Kim & Ostriker (2018), with runaways having a weaker impact than in the Milky Way simulations of Andersson et al. (2020), but stronger than in the work of Kim & Ostriker (2018). However, differently from both studies we find a significant increase in the appearance of high specific energy outflows although we note that while Kim & Ostriker (2018) is investigating energy loading as well, this is not put forward in Andersson et al. (2020). Nevertheless, we recommend that future resolved simulations include some treatment of runaways to capture this effect. However, we note that even with the runaway star modelling we do not achieve the high loading factors observed in the supernova only case (e.g. Hu et al. 2016, 2017). The lower loading factors in out case are mostly driven by the inclusion of photoionising radiation and the runaway star implementation seem to be able to counterbalance that effect on the loading factors.

4.2 Model limitations

In this sub-section, we briefly discuss some caveats and model limitations of our simulations. First, our two presented runaway models strictly only represent a natal kicks in a binary star formation scenario. However, we note that we only sample a single star IMF that strictly speaking does not account for a fraction of the stars to be formed in binary or few body systems. The latter would allow us to study more complex runaway scenarios like ejection of massive stars due to few body interactions or ejection of B stars in a OB binary due to supernova kicks when the O-star explodes. However, this could be realised by adding a time delay to the kick, which is straightforward to implement in our code. It is not very likely that this will have a major impact on the conclusions of our study.

Additionally, we do not include an explicit pre-existing CGM around our dwarf galaxy, which could result in an overestimate of the boost in the outflow rates and loading factors. However, there are a few arguments that support our picture even without the explicit inclusion of a low density CGM around the dwarf. First, dwarfs have a very low virial temperature of \( \sim 10^5 \) K. In combination with the assumption...
We carried out high resolution numerical simulations of isolated dwarf galaxies. The effect of this process on galactic outflows and related galaxy and ISM properties. We showed that the effect of runaway stars is weak with respect to the resulting structure of the multiphase ISM. Furthermore, we showed that there is an impact on the global star formation rate and the build up of the total stellar mass of the system as a function of time for all simulations that include runaway stars compared to the fiducial run. While this results in very similar distributions for the PDFs of the environmental density where SNe explode, the run WLM-RunP shows a slight excess of supernovae in lower density environments, which is beyond the intrinsic model scatter. However, the fact that all the models, including the run WLM-inplane, show similar SN density distributions is clear evidence that the main changes in global outflow evolution due to runaways stars is caused by the stars that explode at higher altitude around the midplane. The fact that this trend remains for the weaker runaway model WLM-RunM indicates that runaway stars can heat the gas at the important boundary between galactic disc and CGM. This can be quantified by investigating the hot phase of the ISM in density-temperature phase space in the cases with and without runaway stars. Averaging over about half of the simulation run time, we find an excess in the mass of hot gas in the diffuse low density ISM in the simulations with runaway stars.

Figure 13. We show the outflow metal enrichment factor $y_{Z_{out}}^*$ (top) and the inflow metal enrichment factor $y_{Z_{in}}^*$ for the runs WLM-fiducial (black), WLM-RunP (blue), WLM-RunM (red) and WLM-inplane (orange). We find a significant boost in the outflow metal enrichment factor in the runs that include runaway stars. Naturally, the inflowing gas is more metal enriched as well compared to the background ISM metallicity.

of a very low density in the CGM compared to the galactic disc, it is rather unlikely that the CGM of dwarf galaxies is heavily supported by thermal pressure which would work against the thermal pressure provided by high altitude SNe due to the presence of runaway stars. Second, we note that the SN-environmental density distributions in all runs are very similar and there is no excess of SNe in lower density regions. This directly indicates that even above the disc scale height the resolution seems still to be sufficient to model the evolution of regions. This directly indicates that even above the disc scale height the resolution seems still to be sufficient to model the evolution of regions. This directly indicates that even above the disc scale height the resolution seems still to be sufficient to model the evolution of regions. This directly indicates that even above the disc scale height the resolution seems still to be sufficient to model the evolution of regions. This directly indicates that even above the disc scale height the resolution seems still to be sufficient to model the evolution of regions.

5 CONCLUSIONS AND OUTLOOK

5.1 Summary

We carried out high resolution numerical simulations of isolated dwarf galaxies with and without a treatment for runaway stars to probe the effect of this process on galactic outflows and related galaxy and ISM properties. We showed that the effect of runaway stars is weak with respect to the resulting structure of the multiphase ISM. Furthermore, we showed that there is an impact on the global star formation rate and the build up of the total stellar mass of the system as a function of time for all simulations that include runaway stars compared to the fiducial run. While this results in very similar distributions for the PDFs of the environmental density where SNe explode, the run WLM-RunP shows a slight excess of supernovae in lower density environments, which is beyond the intrinsic model scatter. However, the fact that all the models, including the run WLM-inplane, show similar SN density distributions is clear evidence that the main changes in global outflow evolution due to runaways stars is caused by the stars that explode at higher altitude around the midplane. The fact that this trend remains for the weaker runaway model WLM-RunM indicates that runaway stars can heat the gas at the important boundary between galactic disc and CGM. This can be quantified by investigating the hot phase of the ISM in density-temperature phase space in the cases with and without runaway stars. Averaging over about half of the simulation run time, we find an excess in the mass of hot gas in the diffuse low density ISM in the simulations with runaway stars. In Fig. 10 we show the mass, metal, momentum and energy outflow rates as a function of time. All quantities are measured at a height of 1 kpc above the midplane in a thin slice with thickness 0.1 kpc. We find a slight boost in the overall mass outflow rate which is slightly more dominant when only the metal mass is considered, showing first evidence that runaway stars can lead to an excess of metals in the outflowing gas. The more dominant effect of the runaway stars can be seen in the momentum and energy outflow rates, where the momentum outflow rate is boosted by at least a factor of two in the models WLM-RunP and WLM-RunM. The effect is even more dramatic for the energy outflow rate where in the model WLM-RunP it is boosted by almost one order of magnitude and in the model WLM-RunM it increases by roughly a factor of 7. As this increase is not seen in the fiducial run WLM-fiducial and the run WLM-inplane in which we apply the natal kicks only in the midplane of the galaxy, this provides clear evidence that runaway stars could contribute to the driving of high specific energy winds. We note that while these trends are also seen in the momentum and energy loading they are somewhat reduced for the mass and metal outflow loading. There is a clear trend of stronger metal enrichment in the models that include a treatment of runaway stars. We summarise the mean outflow parameters after saturation in Table 2 and the mean outflow loading factors in Table 3. The key findings of this paper can be summarised as follows

(i) Runaway stars affect the structure of the multiphase turbulent ISM and can lead to a slightly “puffier” stellar disc.
(ii) The global star formation rate and the distribution of SN-environmental densities is increasing in the simulations with runaway stars.
(iii) The cold ISM gas is less disturbed when runaways are included. This leads to enhanced star formation as the cold gas can continue to be gravitationally unstable.
(iv) Runaways stars can contribute to the build-up of the hot phase of the ISM and promote outflow launching.
(v) Runway stars can boost the mass outflow rate and metal outflow rate while keeping mass outflow and metal outflow loading roughly constant compared to the fiducial run WLM-fiducial.
(vi) Runways stars can boost the momentum outflow rate by around a factor of at least 2, a trend that remains for the momentum outflow loading.
(vii) Runways stars can boost the energy outflow rate by around a factor of 7-10 in the peaks and around 3-5 in the mean, a trend that remains for the momentum outflow loading. Therefore, they can potentially contribute to the origin of high specific energy winds in dwarf galaxies.

Figure 13. We show the outflow metal enrichment factor $y_{Z_{out}}^*$ (top) and the inflow metal enrichment factor $y_{Z_{in}}^*$ for the runs WLM-fiducial (black), WLM-RunP (blue), WLM-RunM (red) and WLM-inplane (orange). We find a significant boost in the outflow metal enrichment factor in the runs that include runaway stars. Naturally, the inflowing gas is more metal enriched as well compared to the background ISM metallicity.

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5.2 Outlook and future work

We close by briefly discussing a few interesting ideas and implications for future work. While we find a rather weak impact of runaway stars on the mass outflow rate and specifically the outflow mass loading, runaway stars could have implications beyond what is represented in our study. Recently, some groups have explored cosmic ray (CRs) driven winds (e.g. Pakmor et al. 2016; Buck et al. 2020; Hopkins et al. 2020, 2021, 2022; Hopkins 2022). In particular, Quataert et al. (2022b) and Quataert et al. (2022a) study in detail CR wind driving scenarios for CR-streaming and CR-diffusion. The outcome of this extensive analytic study is that winds by CR-streaming require a significant Alfvén velocity $v_A$ and thus magnetic field strength. This is intrinsically hard to obtain in dwarf galaxies as the ISM turbulence is rather weak due to low SN-rates, which limits small-scale turbulent dynamo action. Furthermore, since dwarfs are often only weakly rotationally supported, there is no large scale dynamo possible. On the other hand, the diffusion driven winds require a large diffusion coefficient in order to obtain consistency with gamma-ray observations from pion decays that originate from cosmic ray protons, which puts rather tight constraints on the exact value of this coefficient. An interesting direction to explore in future work (both numerically and analytically) would be to constrain the effect of cosmic rays seeded by runaway stars at or above the wind launching scale which could significantly contribute to outflows driven by cosmic rays above the midplane. Hence, one could imagine runaways stars as an external boost for the cosmic ray diffusion coefficient. This could be explored with future simulations and improved analytic modelling.

DATA AVAILABILITY STATEMENT

The data used in this article will be made available based on reasonable request to the corresponding author.

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Table 2. Summary of the mean outflow diagnostics once the system has reached a quasi-self-regulating state

| Name        | SFR [M$_\odot$ yr$^{-1}$] | $M_{\text{out}}$ [M$_\odot$ yr$^{-1}$] | $M_{\text{Z,out}}$ [M$_\odot$ yr$^{-1}$] | $\rho_{\text{out}}$ [M$_\odot$ km s$^{-1}$ yr$^{-1}$] | $E_{\text{out}}$ [10$^{43}$ erg yr$^{-1}$] |
|-------------|--------------------------|--------------------------------------|--------------------------------------|--------------------------------------|--------------------------------------|
| WLM-fiducial| 0.00023                  | 0.00632                              | 0.00068                              | 0.194                                | 2.225                                |
| WLM-RunP    | 0.00021                  | 0.00816                              | 0.00100                              | 0.291                                | 15.298                               |
| WLM-RunM    | 0.00029                  | 0.00757                              | 0.00087                              | 0.243                                | 8.512                                |
| WLM-inplane | 0.00024                  | 0.00686                              | 0.00074                              | 0.200                                | 3.085                                |

Table 3. Summary of the mean loading factors once the system has reached a quasi-self-regulating state

| Name        | $\eta_{\text{M, out}}^\text{WLM-fiducial}$ | $\eta_{\text{L, out}}^\text{WLM-fiducial}$ | $\eta_{\text{P, out}}^\text{WLM-fiducial}$ | $\eta_{\text{E, out}}^\text{WLM-fiducial}$ | $\eta_{\text{Z, out}}^\text{WLM-fiducial}$ |
|-------------|-------------------------------------------|-------------------------------------------|-------------------------------------------|-------------------------------------------|-------------------------------------------|
| WLM-fiducial| 31.4                                      | 125.2                                     | 2.93                                      | 0.11                                      | 1.089                                      |
| WLM-RunP    | 45.7                                      | 136.4                                     | 3.28                                      | 0.5                                       | 1.23                                       |
| WLM-RunM    | 39.0                                      | 143.5                                     | 3.34                                      | 0.35                                      | 1.15                                       |
| WLM-inplane | 34.0                                      | 133.0                                     | 2.97                                      | 0.13                                      | 1.088                                      |
