This parametrization has the great advantage of being linear. A simpler version, fixing $f_{\rm VSAC}$, has been implemented in CIGALE by Nersesian et al. (2019). A more physical way to vary the size distribution would be to vary the minimum cut-off size and the index of the power-law size distribution (cf. Jones et al. 2013, for the description of the size distribution of THEMIS). However, this alternate parametrization would be CPU time consuming, and would not produce noticeable differences in the resulting broadband SED (cf. Appendix C).

3.1.2. The mixing of physical conditions

A model, such as THEMIS, is not directly applicable to observations of galaxies. Indeed, the monochromatic flux of a whole galaxy comes from the superposition of grains exposed to a range of physical conditions. This well-known problem can be addressed assuming a distribution of starlight intensity inside each galaxy. We adopt the prescription proposed by Dale et al. (2001), where the dust mass, $M_{\rm dust}$, follows a power-law distribution, as a function of the starlight intensity, U:

$$\mathrm{d}M_{\rm dust} \propto U^{-\alpha}\,\mathrm{d}U \quad \text{for} \quad U_{\rm min} < U < U_{\rm min} + \Delta U. \tag{2}$$

The parameter U is the frequency-integrated monochromatic mean intensity of the Mathis et al. (1983) diffuse ISRF. It is normalized so that $U = 1$ in the solar neighborhood (e.g., Eq. (2) of Galliano et al. 2011). This phenomenological composite SED is the *powerU* model component of G18 (Sect. 2.2.5). We add to the emission the *starBB* component of G18 (Sect. 2.2.6), in order to account for the residual diffuse stellar emission at short wavelengths.

The list of free SED model parameters, that HerBIE infers, is thus the following. Similarly to the ancillary parameters (Table 2), we use the natural logarithm of quantities varying over more than an order of magnitude.

1. $\ln M_{\rm dust}$, the dust mass, scales with the whole dust SED.
2. $\ln U_{\rm min} \in [\ln 0.01, \ln 10^3]$ is the minimum cut-off in Eq. (2).
3. $\ln \Delta U \in [\ln 1, \ln 10^7]$ controls the range in Eq. (2).
4. $\alpha \in [1, 2.5]$ is the power-law index in Eq. (2).
5. $\ln q_{\rm AF} \in [\ln 10^{-5}, \ln 0.9]$ is defined in Sect. 3.1.1.
6. $f_{\rm VSAC} \in [0, 1]$ is defined in Sect. 3.1.1.
7. $\ln L_\star$ is the luminosity of the residual stellar emission (cf. G18, Sect. 2.2.6).

These parameters are however not the most physically relevant. In the rest of the present article, we focus our discussion on the following three parameters, marginalizing over the other ones: (i) $M_{\rm dust}$; (ii) $\langle U\rangle$; and (iii) $q_{\rm AF}$, where $\langle U\rangle$ (Eq. (9) of G18) is the mean of the distribution in Eq. (2). It quantifies the mass-averaged starlight intensity illuminating the grains. It is a function of the three parameters $U_{\rm min}$, ΔU, and α (Eq. (10) of G18). It can be related to an equivalent large grain equilibrium temperature, $T_{\rm eq}$, through: $\langle U\rangle \simeq (T_{\rm eq}/18\,\mathrm{K})^{5.8}$ (e.g., Nersesian et al. 2019).

3.1.3. Questionable assumptions and residual contaminations

In our experience, the model of Sect. 3.1.2 is the most appropriate for galaxies observed with the typical spectral coverage of Table 1. It presents however the following limitations.

Shape of the ISRF. We assume that dust is heated by the Mathis et al. (1983) ISRF, scaled by a factor U. We assume in the model that the shape of this ISRF does not vary between galaxies nor within regions inside galaxies. It is obvious that this assumption is not correct. However, its consequences are minimal on the parameters we are interested in, for the following reasons. Firstly, $M_{\rm dust}$ and $\langle U\rangle$ depend mainly on the far-IR peak emission, which is dominated by large grains. These grains are at thermal equilibrium. Their emission therefore does not depend on the shape of the ISRF, only on the absorbed power. Secondly, $q_{\rm AF}$ controls the fraction of small, stochastically-heated grains. The emission from these grains depends on the shape of the ISRF (e.g., Camps et al. 2015). However, since small a-C(:H) are destroyed in H II regions (cf. Sect. 4.2.3 of Galliano et al. 2018, and Sect. 4.2), they are effectively heated by a rather narrow spectral range ($4\,\mathrm{eV} \lesssim h\nu < 13.6\,\mathrm{eV}$), where they exist. This effect is demonstrated on Fig. 7 of Draine (2011), with PAHs. We thus do not expect that actual variations of the ISRF shape will significantly bias our estimate of $q_{\rm AF}$.

Evolution of small a-C(:H). The abundance of small a-C(:H) and their properties evolve with the ISRF and the gas density. These grains are dehydrogenated and destroyed by intense ISRFs; they are also accreted onto large grains, in dense regions (e.g., Jones et al. 2013; Köhler et al. 2015). Our parametrization (Sect. 3.1.1) allows us to explore variations of $q_{\rm AF}$ between galaxies, but we assume that $q_{\rm AF}$ is constant, for all U, within each galaxy. However, this assumption will not bias our global estimate of $q_{\rm AF}$, as this parameter is merely a way to give a physical meaning to the observed $L_{\rm AF}$/TIR ratio ($L_{\rm AF}$ denoting the power emitted by the aromatic features). This assumption would only be problematic if we were trying to estimate the local value of $q_{\rm AF}$ in PDRs, for instance. Indeed, we would, in this case, underestimate $q_{\rm AF}$, by assuming that a fraction of the aromatic feature emission comes from H II regions, which are generally hotter than PDRs, and thus more emissive.

Grain opacity. We assume that the grain opacity does not vary between galaxies, nor within regions inside galaxies. There are several indications that this hypothesis is not correct (e.g., Sect. 4.2.1 of Galliano et al. 2018). In particular, the far-IR opacity can typically vary by a factor of $\simeq 3$ with the accretion or removal of mantles and grain-grain coagulation (Köhler et al. 2015). Such variations will bias our estimate of the dust mass. In addition, the submm and mm silicate emissivity implemented in THEMIS has an unphysical power-law dependence at long wavelengths. Accounting for a more realistic opacity, based on laboratory measurements such as those of Demyk et al. (2017a,b), will likely affect our dust mass estimates. This is an important effect that we can not avoid. We discuss its consequences in Sect. 4.1.3, when interpreting our results.

Residual contaminations. The following emission processes, not accounted for in our model, could be present in our observations.

Several gas lines contribute to the emission in the photometric bands of Table 1. The brightest are: $[\mathrm{O\,I}]_{63\,\mu\mathrm{m}}$, $[\mathrm{O\,III}]_{88\,\mu\mathrm{m}}$, $[\mathrm{C\,II}]_{158\,\mu\mathrm{m}}$, $[\mathrm{O\,I}]_{145\,\mu\mathrm{m}}$, and $^{12}\mathrm{CO}(J=3\to2)_{867\,\mu\mathrm{m}}$. Without dedicated spectroscopic observations, the subtraction of these lines is hazardous. Luckily enough, their intensities are, to first order, proportional to TIR (e.g., Cormier et al. 2015). They constitute therefore a bias proportional to the flux, that can be taken into account together with the calibration bias, as we show in Sect. 3.2.

The submm excess is an excess emission of debated origin, appearing longward 500 µm (cf. Sect. 3.5.5 of Galliano et al. 2018, for a review). Since it is not accounted for in our model, it could bias our submm SED. This effect is however probably negligible in our sample, for the following reasons. Firstly, this