Encoding of the infrared excess in the NUVrK color diagram for star-forming galaxies
S. Arnouts, E. Le Floc’h, J. Chevallard, B. D. Johnson, O. Ilbert, M. Treyer, H. Aussel, P. Capak, D. B. Sanders, N. Scoville, et al.

To cite this version:
S. Arnouts, E. Le Floc’h, J. Chevallard, B. D. Johnson, O. Ilbert, et al.. Encoding of the infrared excess in the NUVrK color diagram for star-forming galaxies. Astronomy and Astrophysics - A&A, 2013, 558, pp.A67. 10.1051/0004-6361/201321768. cea-01135438

HAL Id: cea-01135438
https://cea.hal.science/cea-01135438
Submitted on 25 Mar 2015

HAL is a multi-disciplinary open access archive for the deposit and dissemination of scientific research documents, whether they are published or not. The documents may come from teaching and research institutions in France or abroad, or from public or private research centers.

L’archive ouverte pluridisciplinaire HAL, est destinée au dépôt et à la diffusion de documents scientifiques de niveau recherche, publiés ou non, émanant des établissements d’enseignement et de recherche français ou étrangers, des laboratoires publics ou privés.
Encoding of the infrared excess in the NUVrK color diagram for star-forming galaxies

S. Arnouts1,4, E. Le Floc’h2, J. Chevallard3, B. D. Johnson3, O. Ilbert4, M. Treyer4, H. Aussel2, P. Capak5, D. B. Sanders6, N. Scoville7, H. J. McCracken3, B. Milliard4, L. Pozzetti3, and M. Salvato8,9,10

1 Canada-France-Hawaii Telescope Corporation, 65-1238 Mamalahoa Hwy, Kamuela, HI 96743, USA
e-mail: arnouts@cftl.hawaii.edu
2 Laboratoire AIM, CEA/DSM-CNRS-Université Paris Diderot, IFRU/Service d’Astrophysique, Bât. 709, CEA-Saclay, 91191 Gif-sur-Yvette Cedex, France
3 UPMC-CNRS, UMR7095, Institut d’Astrophysique de Paris, 75014 Paris, France
4 Aix-Marseille Université, CNRS, Laboratoire d’Astrophysique de Marseille, UMR 7326, 13388 Marseille, France
5 Spitzer Science Center, MS 314-6, California Institute of Technology, Pasadena, CA 91125, USA
6 Institute for Astronomy, 2680 Woodlawn Dr., University of Hawaii, Honolulu, HI 96822, USA
7 California Institute of Technology, MC 249-17, 1200 East California Boulevard, Pasadena, CA 91125, USA
8 INAF – Osservatorio Astronomico di Bologna, via Ranzani 1, 40127 Bologna, Italy
9 MPE, Giessenbachstrasse 1, 85748 Garching, Germany
10 Excellence Cluster, Boltzmann Strasse 2, 85748 Garching, Germany

Received 25 April 2013 / Accepted 25 July 2013

ABSTRACT

We present an empirical method of assessing the star formation rate (SFR) of star-forming galaxies based on their locations in the rest-frame color–color diagram (NUV – r) vs. (r – K). By using the Spitzer 24 μm sample in the COSMOS field (~16 400 galaxies with 0 ≤ z ≤ 1.3) and a local GALEX-SDSS-SWIRE sample (~700 galaxies with z ≤ 0.2), we show that the mean infrared excess (IRX) = (LIR/LNUV) can be described by a single vector, NRK, that combines the two colors. The calibration between (IRX) and NRK allows us to recover the IR luminosity, LIR, with an accuracy of σ ~ 0.21 for the COSMOS sample and 0.27 dex for the local one. The SFRs derived with this method agree with the ones based on the observed (UV+IR) luminosities and on the spectral energy distribution (SED) fitting for the vast majority (~85%) of the star-forming population. Thanks to a library of model galaxy SEDs with realistic prescriptions for the star formation history, we show that we need to include a two-component dust model (i.e., birth clouds and diffuse ISM) and a full distribution of galaxy inclinations in order to reproduce the behavior of the (IRX) stripes in the NUVrK diagram. In conclusion, the NRK method, based only on the rest-frame UV/optical colors available in most of the extragalactic fields, offers a simple alternative of assessing the SFR of star-forming galaxies in the absence of far-IR or spectral diagnostic observations.

Key words. infrared: galaxies – ultraviolet: galaxies – galaxies: evolution

1. Introduction

Star formation activity is a key observable for understanding the physical processes in the build up of galaxies. The SFR in galaxies depends on the physics of star-forming regions, merger history, gas inflow and outflows and on stellar and AGN feedbacks. The SFR distribution and its evolution therefore offer a crucial test for any model of galaxy evolution. There are different indicators of the ongoing star formation (e.g., Kennicutt 1998), such as ultraviolet continuum (λ ~ 912–3000 Å) produced by massive, young stars (t ~ 10^6 yr, Martin et al. 2005); nebular recombination lines from gas ionized by the hot radiation from early-type stars (λ ~ 912 Å, t ~ 10^7 yr); far-infrared (FIR) emission from dust heated by UV light; and non-thermal radio emission, such as synchrotron radiation from supernova remnants (see Kennicutt 1983, 1998 for their respective calibrations with SFR).

Recently, measurements of SFRs in large samples of galaxies based on the above indicators have provided interesting insights in the dominant mode of baryon accretion for star-forming galaxies: the tight correlation, with small scatter, between stellar mass and SFR observed up to z ~ 2 (e.g., Salim et al. 2007; Noeske et al. 2007b; Daddi et al. 2007; Wuyts et al. 2012) suggests that a secular, smooth process, such as gas accretion, rather than merger-induced starbursts, may be the dominant mechanism governing star formation in galaxies. Also, the relation between specific SFR and stellar mass (e.g., Brinchmann et al. 2004; Salim et al. 2007; Noeske et al. 2007a) reveals that less massive galaxies have their onset of star formation occurring later than more massive ones (e.g., Cowie et al. 1996), and that a simple mass-dependent gas exhaustion model can reproduce the observed decline of the cosmic SFR since z ~ 1–1.5 (e.g., Lilly et al. 1996; Schiminovich et al. 2005; Le Floc’h et al. 2005). Such a scenario is also consistent with recent evidence of a higher fraction of molecular gas in massive star-forming galaxies at z ≥ 1 with respect to nearby galaxies (e.g., Erb et al. 2006; Daddi et al. 2008, 2010; Tacconi et al. 2010).

Extending such measurements to high redshift for large samples of galaxies poses several challenges: optical recombination lines are often too weak and are shifted to near-IR wavelengths, where current spectroscopic capabilities are limited.

Appendices are available in electronic form at http://www.aanda.org
Far-IR indicators are also of limited use at high redshift, since the modest sensitivity and resolution of infrared telescopes make these observations sparse and restricted to the most massive galaxies, unless stacking techniques are used (e.g., Zheng et al. 2007; Pannella et al. 2009; Karim et al. 2011; Lee et al. 2010; Heinis et al. 2013). On the other hand, with increasing redshift, the ultraviolet continuum emission is progressively shifted to optical and near-IR bands, making it easily accessible with the largest ground-based telescopes (e.g., Burgarella et al. 2007; Daddi et al. 2007; Reddy et al. 2006; Steidel et al. 1996; Bouwens et al. 2011).

In this work, we analyze the behavior of the IRX within the frame of the steepness of the ultraviolet spectral region, providing a way to quantify the amount of attenuation of UV starlight (i.e., infrared excess, \( \frac{L_{\text{IR}}}{L_{\text{UV}}} \)) reprocessed from the star-burst IRX-β relation. This new diagnostic provides an effective way to assess the total IR luminosity \( L_{\text{IR}} \) and then the SFR for individual galaxies with photometric information widely available in large surveys, and does not require complex modeling such as SED fitting techniques. The (NUV – r) vs. \((r-K)\) color diagram adopted in this work is similar to the \((U-V)\) vs. \((V-J)\) diagram proposed by Williams et al. (2009) to separate passive or quiescent from star-forming galaxies, but better leverages the role of SFH and dust by extending into the extreme wavelengths of the SED. Total infrared luminosities were estimated from the deep MIPS-24 \( \mu \)m observations of the COSMOS field, with standard technics extrapolating mid-IR flux densities with luminosity-dependent IR galaxy SED templates as described in e.g., Le Floc’h et al. (2005). Our approach is motivated by the tight correlations that exist between mid-IR and total IR luminosities, both at low redshifts (Chary & Elbaz 2001; Takeuchi et al. 2003) and in the more distant Universe (Bavouzet et al. 2008). In fact, stacking analysis and direct individual identifications of distant sources in the far-IR with facilities like Spitzer and Herschel (e.g., Lee et al. 2010; Elbaz et al. 2010) have shown that these extrapolations from mid-IR photometry provide reliable estimates of total IR luminosities up to \( z \approx 1.3 \) (dispersion of \(-0.25\) dex, no systematic offset), at least for star-forming galaxies initially selected at 24 \( \mu \)m. Also, given the relative depths of the different IR and submillimeter observations carried out in the COSMOS field with e.g., Spitzer, Herschel or JCMT, we note that the deep 24 \( \mu \)m data in COSMOS provide the largest sample of star-forming galaxies with measurable IR luminosities. We thus decide to limit our analysis to massive (\( M \geq 10^8 \, M_\odot \)) star-forming sources first selected at 24 \( \mu \)m and lying at \( z \leq 1.3 \) so as to obtain reliable \( L_{\text{IR}} \) estimates. In a companion paper Le Floc’h et al. (in prep.), we will extend our analysis to higher redshifts and lower masses by stacking along the NRK vector the MIPS and Herschel data available in the COSMOS field.

The paper is organized as follows. In Sect. 2 we describe the dataset, the sample selection and the estimates of physical parameters. In Sect. 3 we discuss the behavior of the mean IRX (i.e., (IRX)) in the (NUV – r) vs. \((r-K)\) diagram and the calibration of the (IRX) vs. NRK relation. In Sect. 4, we compare our predicted IR luminosities with the ones based on the 24 \( \mu \)m observations and SED fitting technique. We also investigate the dependence with galaxy physical parameters and apply our method to the well established SFR-mass relation. In Sect. 5 we discuss the method, the possible origin of the relation with a complete library of model galaxy SEDs and dust models. We draw the conclusions in Sect. 6.

Throughout the paper we adopt the following cosmology: \( H_0 = 70 \, \text{km s}^{-1} \, \text{Mpc}^{-1} \) and \( \Omega_m = 0.3, \Omega_\Lambda = 0.7 \). We adopt the initial mass function of Chabrier (2003), truncated at 0.1 and 100 \( M_\odot \). All magnitudes are given in the AB system (Oke 1974).

2. The dataset

2.1. Observations

2.1.1. The Spitzer-MIPS 24 \( \mu \)m observations and COSMOS catalog

The region of the sky covered by the Cosmic Evolution Survey (i.e., COSMOS Scoville et al. 2007) is observed by Spitzer-MIPS (Multi Imaging Photometer) at 24, 70 and 160 \( \mu \)m over a 2 deg\(^2\) area (Sanders et al. 2007). In this work, we use the deep 24 \( \mu \)m observations and the catalogue of sources extracted by Le Floc’h et al. (2009). This catalog is 90% complete down to the flux limit density \( S_{24} \approx 80 \, \mu \text{Jy} \). The sources are cross-
matched with the multi-wavelength photometric COSMOS cat-
alog. This includes deep ultraviolet GALEX imaging (Zamojski et al. 2007), ground based optical observations with interme-
diate and broad band filters, near IR photometry (Capak et al. 2007; McCracken et al. 2010; Taniguchi et al. 2007) and deep IRAC photometry (Sanders et al. 2007; Ilbert et al. 2010) for a total of 31 filter passbands. The combined photometry, as well as accurate photometric redshifts, are available from the catalog of Ilbert et al. (2010, version 1.8). The typical depths at 5σ are 25.2, 26.5, 26.0, 25.0, 23.5 and 24.0 in the NUV, u, g, r, i, and K, and 3.6 μm pass-bands, respectively. A vast majority of 24 μm sources is also detected in the optical bands (∼95% with u ≤ 26.5 and iAB ≤ 24.5).

We adopt spectroscopic redshifts from the bright and faint zCOSMOS sample (Lilly et al. 2009), when available, otherwise we use the photometric redshifts computed by Ilbert et al. (2009). The photo-z accuracy for the 24 μm sample is σ = 0.009 at iAB ≤ 22.5 (with 5700 zspec) and 0.022 for the fainter sample (with 470 zspec)1).

We limit our analysis to a maximum redshift z ≤ 1.3 in order to derive reliable IR luminosities from the 24 μm flux density (see next section). We reject AGN dominated sources according to their mid-IR properties based on the diagnostic of Stern et al. (2007). The selected sample consist of ∼16500 star-forming galaxies and ∼400 evolved/passive galaxies, with S24 ≥ 80 μJy and z ≤ 1.3. The separation between star-forming and passive galaxies is based on the position of the galaxies in the rest-frame (NUV - r) versus (r - K) diagram as discussed in Sect. 2.3 and Appendix B.

2.2. Rest-frame quantities and physical parameters

2.2.1. The infrared luminosity

The total Infrared luminosity (LIR) refers to the luminosity integrated from 8 to 1000 μm and is derived by using the code “Le Phare”2 (Arnouts et al. 1999; Ilbert et al. 2006) combined with infrared SED templates of Dale & Helou (2002). For the low-z sample, the IR luminosity is estimated by fitting the 8, 24, 70 and 160 μm bands with a free scaling of the SEDs (see Goto et al. 2011, for details). For the COSMOS sample, the LIR is derived by extrapolating the 24 μm observed flux density with the star-forming galaxy templates of Dale & Helou (2002). While such SEDs are provided as a function of 60/100 μm luminosities ratio, we rescale the templates following the locally-observed dust temperature-luminosity relationship, so as to mimic a lum-

1) The accuracy of the photometric redshifts is based on the normalized median absolute deviation (Hoaglin et al. 1983): 1.48 × Median(|zspec - ztrue|)/0.74, where zspec and ztrue are the spectroscopic and photometric redshifts, respectively.

2) http://www.cfht.hawaii.edu/~arnouts/lephare.html

osity dependence similar to the SEDs of the libraries proposed by Chary & Elbaz (2001) and Lagache et al. (2004). In this scheme, the monochromatic luminosity at any given IR wave-
length is linked to LIR by a monotonically relation, similar to the correlations that have been observed between the mid-IR emission and the total IR luminosity of galaxies in the local Universe (e.g., Spinoglio et al. 1995; Chary & Elbaz 2001; Takeuchi et al. 2003; Treyer et al. 2010; Goto et al. 2011). In this way, a 24 μm flux density observed at a given redshift is associated to a unique LIR. Note that we did not consider any AGN SEDs in this work, since AGN-dominated sources were removed from our initial sample (see Sect. 2.1.1).

Such extrapolations from mid-IR photometry have been widely used in the past, especially for the interpretation of the mid-IR deep field observations carried out with the infrared Space Observatory and the Spitzer Space Telescope. Given the large spectral energy distribution (SED) variations between the rest-frame emission probed at 24 μm and the peak of the IR SED where the bulk of the galaxy luminosity is produced, the estimate of LIR with this method yet depends on the assumed SED library. To quantify this effect, we use different IR star-forming galaxy templates of the literature, finding systematic differences of only ±0.2 dex up to z ∼ 1 (e.g., see Fig. 7 of Le Floc’h et al. 2005). Furthermore, stacking analysis of mid-IR selected sources with MIPS-70 μm and MIPS-160 μm data in COSMOS (Lee et al. 2010) and other fields (e.g., Bavaouet et al. 2008) has allowed accurate determinations of average IR luminosities for galaxies stacked by bin of 24 μm flux. These studies have shown very good agreement with the 24 μm extrapolated luminosities of star-forming galaxies up to z ∼ 1.5, thus confirming the robustness of the technique. Even more convincingly, direct far-IR measurements of the total IR luminosities for a 24 μm flux-limited sample of star-forming galaxies at z ≤ 1.5 with the Herschel Space Observatory have recently revealed a tight correlation with the luminosities extrapolated from 24 μm photometry and star-forming SED templates (Elbaz et al. 2010). The comparison between the two estimates shows a dispersion less than 0.15 dex at z ≤ 1, demonstrating again the relevance of the method at least for mid-IR selected sources at low and intermediate redshifts, such as in our current study. For these reasons we restrict our analysis to redshifts lower than z ∼ 1.3, where the method discussed above to derive the LIR is widely tested and robust.

2.2.2. The other physical parameters and luminosities

We use the code “Le Phare” combined with the population synthesis code of Bruzual & Charlot (2003, hereafter BC03) to derive the physical parameters for each galaxy. Details regarding the SED fitting are given in Appendix A. We perform a maximum likelihood analysis, assuming independent Gaussian distributed errors, including all the available photometric bands from 0.15 to 4.5 μm. The physical parameters are derived by considering the median value of the likelihood marginalized over each parameter, while errors correspond to the 68% credible region.

We adopt the same approach as Ilbert et al. (2006) to derive the rest-frame luminosities (or absolute magnitudes). We use the photometry in the nearest rest-frame broadband filter to minimize the dependency to the k-correction. These luminosities are consistent within 10% with those derived according to the best fit template (smallest χ²) or those provided by Ilbert et al. (2009)
based on a smaller set of empirical SEDs. Our results are not significantly affected by the adopted choices of luminosities.

We note also that the great accuracy of the COSMOS photometric redshifts in our redshift domain allows us to neglect the impact of the photo-z errors in the quantities discussed here. However, we adopt spectroscopic redshifts when available.

Throughout this paper, the stellar masses always refer to the estimates from the SED fitting technique, assuming a Chabrier IMF truncated at 0.1 and 100 \( M_\odot \), while the total SFR is defined as the sum of the unobscured ultraviolet and total IR luminosities. For the latter, we adopt a relation similar to that proposed by Bell et al. (2005) and adjusted for a Chabrier (2003) IMF:

\[
SFR_{24}[M_\odot yr^{-1}] = 8.6 \times 10^{-11} \times (L_{IR} + 2.3 \times L_{NUV}),
\]

where the total IR luminosity is defined as \( L_{IR}/L_\odot \equiv \int_0^{1000} \nu dL(\nu) \) and \( L_{NUV} \) is the monochromatic NUV luminosity:\( L_{NUV}/L_\odot = \nu L_\nu(2300 \text{ Å}) \). We adopt a factor of \( \sim 2.3 \) instead of 1.9 as proposed by Bell et al. (2005) who uses the FUV luminosity. According to stellar population models, our factor is more appropriate to correct the \( L(2300 \text{ Å}) \) in total UV luminosity. The use of the FUV luminosity better traces the emission of short-lived, massive stars, while in this work we use the NUV luminosity. The reason is that we can obtain a more accurate rest-frame NUV than FUV luminosity, thanks to the GALEX NUV and CFHT \( u \)-band observations at different redshifts. As shown by Hao et al. (2011), this choice does not impact the reliability of the SFR estimates.

It is worth noting that, as shown in Appendix A, the instantaneous SFR derived from the SED fitting is consistent within less than a factor of two with the SFR estimated with Eq. (1). Considering that the SED fitting relies only on the 0.15–4.5 \( \mu \)m bands, this agreement between the different SFR estimates over at least 2 orders of magnitudes is remarkable.

Figure 1 shows the SFR (top panel; as estimated with Eq. (1)) and stellar mass (bottom panel) as a function of redshift for the 24 \( \mu \)m star-forming galaxies. As already shown by Le Floc’h et al. (2005), below \( z \leq 0.5 \) the population is composed of moderately star-forming galaxies with \( SFR \lesssim 10 M_\odot \) yr\(^{-1} \). The fraction of luminous IR galaxies (LIRGs) gradually increases from \( z = 0.5 \) to \( z = 1 \) and becomes dominant at \( z \gtrsim 1 \) in our sample. At all redshift, the fraction of ultra luminous IR galaxies (ULIRGs) is negligible.

Our sample is dominated by galaxies with \( \log (M/M_\odot) \gtrsim 9.5 \). To characterize how representative the 24 \( \mu \)m population is with respect to the entire star-forming (hereafter SF) population at a given mass and redshift, we define a 50\% completeness mass limit \( (M_{50\%}(z)) \) as the stellar mass where the ratio \( \Phi^{24\mu}_{\text{SF}}(M,z) dM/\Phi^{24\mu}_{\text{SF}}(M), dM \sim 0.5 \); where \( \Phi^{24\mu}_{\text{SF}}(M) \) and \( \Phi^{24\mu}_{\text{SF}}(M) \) are the \( V_{\text{max}} \)-weighted comoving volume densities of 24 \( \mu \)m- and \( K \)-selected \( (K \leq 23.5) \) samples of star-forming galaxies respectively. Above this limit (~10\(^{-10} \) [10\(^{10.5} \) \( M_\odot \) at \( z \sim 1 \) [1,3]), we consider the physical properties of the 24 \( \mu \)m population to be representative of the whole SF sample.

\( 3 \) We remind the readers that systematic shifts in photometric passbands can propagate into the absolute magnitudes and then in the Eqs. (2) and (3) of this work. A change in calibration of the IRAC 3.6 \( \mu \)m of \( \sim 0.1 \) mag will affect \( K_{\text{ABS}} \) by the same amount and the SFR by \( \sim 0.06 \) dex.

Fig. 1. Star formation rate (top panel) and stellar mass distribution (bottom panel) as function of redshift for the 24 \( \mu \)m-selected star-forming population. The horizontal gray lines in the top panel indicate the SFR thresholds corresponding to luminous and ultra-luminous infrared galaxies (i.e., LIRGs and ULIRGs). The solid red line in the bottom panel indicates the 50\% completeness limit (i.e., \( M_{50\%}(z) \), see Sect. 2.2.2).

2.3. The \((NUV-r)\) versus \((r-K)\) color–color diagram

Recently, Williams et al. (2009) have shown that quiescent and star-forming galaxies occupy two distinct regions in the rest-frame \((U-V)\) versus \((V-J)\) color–color diagram (i.e., \( UJV \)) and validated their separation scheme with a morphological analysis (Patel et al. 2011). In the present work, we adopt the \((NUV-r)\) versus \((r-K)\) color–color diagram to increase the wavelength leverage between current star formation activity and dust reddening. The \( NUVrK \) diagram provides also an efficient way to separate passive and star-forming galaxies. In Fig. 2, we show the mean sSFR derived from the SED fitting for the entire COSMOS spectroscopic sample with \( 0 \leq z \leq 1.3 \). The density contour levels (black solid lines) reveal the presence in the top left part of the diagram of a population with low specific SFR \([\log (sSFR_{\text{SED}}/\text{yr}^{-1}) \lesssim -10.5]\), well separated from the rest of the sample. We define this region with the following criteria: \((NUV-r) > 3.75\) and \((NUV-r) > 1.37 \times (r-K) + 3.2\). In Appendix B we discuss further the star-forming and passive galaxy separation based on the morphological information from HST imaging of the COSMOS field.

In Fig. 3, we show the density distribution of the 24 \( \mu \)m sample in this \( NUVrK \) diagram and the color tracks for five models with exponentially declining star formation histories. The colors indicate models with different e-folding times \( \tau = 0.1, 1, 3, 5, 30 \) Gyr (red, purple, orange, green, blue lines respectively), while the filled and open squares mark different ages \((\tau = 0.1, 0.5, 1, 3, 5\) and \(\tau = 6.5, 9.0, 12\) Gyr respectively). The \((NUV-r)\) is a good tracer of the specific SFR, since the NUV band is sensitive to recent (i.e., \( t \leq 10^{10.5} \) yr) star formation and the \( r \)-band to old stellar populations (e.g., Salim et al. 2005). Models with short star formation timescales quickly move to the top side of the diagram, since star formation ceases early...
We now explore the behavior of the infrared excess in the NUVrK diagram. We define the infrared excess as $\text{IRX} = L_{\text{IR}} / L_{\text{NUV}}$, where $L_{\text{IR}}$ and $L_{\text{NUV}}$ are defined in Sect. 2.2.2. This ratio is weakly dependent on the age of the stellar population, dust geometry and nature of the extinction law (Witt & Gordon 2000).

Figure 4 shows on the left, the volume weighted mean IRX ([IRX], color-coded in a logarithmic scale shown in the top right panel), and, on the right, the dispersion around the mean ($\sigma(\text{IRX})$) in the NUVrK diagram in four redshift bins. At any redshift, (IRX) increases by $\sim 1.5$–2 dex from the blue side (bottom-left) to the red side (top-right) of the diagram, while the dispersion around the mean remains small and constant ($\lesssim 0.3$ dex). We note also the presence of stripes of constant IRX values, which we discuss in Sect. 5. The presence of such stripes allows us to describe the variation of (IRX) in the NUVrK diagram with a single vector perpendicular to those stripes. This vector, hereafter called $\text{NRK}$, can be defined as a linear combination of rest-frame colors $\text{NRK}(\phi) = \sin(\phi) \times (\text{NUV} - r) + \cos(\phi) \times (r - K)$, where $\phi$ is an adjustable parameter which we require to be perpendicular to the (IRX) stripes. We empirically estimate $\phi$ in each redshift bin ($\Delta z = 0.1$) by performing a linear least square fit: $\text{IRX} = f(\text{NRK}(\phi))$ (the linear approximation is justified in the next section). Since the dispersion $\sigma(\text{IRX}(\phi))$ reaches a minimum when the vector $\text{NRK}(\phi)$ is perpendicular to the stripes, we minimize $\sigma(\text{IRX}(\phi))$ to find the best-fit angle, $\phi_0$. We find $15^\circ \leq \phi_0 \leq 25^\circ$ in all redshift bins, with a median and semi-quartile range $\phi_0 = 18^\circ \pm 4^\circ$. Given the narrow distribution of $\phi_0$ and the fact that a change up to $\Delta \phi \pm 7^\circ$ does not affect our

3. Infrared excess of star-forming galaxies in the NUVrK diagram

3.1. Definition of the IRX and NRK parameters

We now explore the behavior of the infrared excess in the NUVrK diagram. We define the infrared excess as $\text{IRX} = L_{\text{IR}} / L_{\text{NUV}}$, where $L_{\text{IR}}$ and $L_{\text{NUV}}$ are defined in Sect. 2.2.2. This
increases in both of the low-redshift sample from Johnson et al. (2007a) ($\langle IRX \rangle \sim 0.3$) compared to the evolution of $\langle IRX \rangle$ with NRK. We bin the data in redshift ($\Delta z = 0.1$) and NRK ($\Delta NRK = 0.5$) and perform a linear least square fit to derive the five free parameters. We obtain for the redshift evolution $f(z) = a_0 + a_1 z + a_2 z^2 + a_3 z^3$ with $a_0 = -0.69 \pm 0.06$; $a_1 = 3.43 \pm 0.33$; $a_2 = -3.49 \pm 0.55$; $a_3 = 1.22 \pm 0.28$, and for the dependence on NRK $a_N = 0.63 \pm 0.01$.

The resulting fits from this calibration are shown in Fig. 5 (solid red lines). We show, in the top panel of Fig. 6, the linear fit of $IRX$ as a function of NRK after rescaling all the $IRX$ values at $z = 0$ and in the bottom panel, the polynomial fit of $IRX$ vs. $z$ after rescaling all the $IRX$ values at NRK = 0. The small uncertainty in the slope parameter $a_N$ supports our initial choice of a linear function to describe the relation between $IRX$ and NRK.
and NRK. We note that due to adoption of a polynomial function, the redshift evolution is only valid in the range well constrained by the data (0.1 ≤ z ≤ 1.3) and should not be extrapolated outside this range.

A simple interpretation of the redshift evolution of (IRX), at fixed NRK, is the aging of the stellar populations. In fact, Fig. 3 shows that, at a fixed position in the NUVrK diagram (or NRK value), a galaxy at higher redshift, which has a younger stellar population, needs a larger dust reddening than a galaxy at lower redshift, which hosts older, intrinsically redder stars.

This effect being more pronounced between 0 ≤ z ≤ 0.5 where the universe ages by ∆T ∼ 5 Gyr, compared to 4 Gyr in between 0.5 ≤ z ≤ 1.3, and which is also enhanced by the global decline of the SF activity in galaxies with cosmic time.

4. The infrared luminosity and SFR estimated from NRK vector

The relationship between IRX and the vector NRK allows us to predict the IR luminosity for each galaxy according to its NUV, r, K luminosities and redshift as follows $L_{IR}^{NRK} = L_{NUV} \times (IRX)(z, NRK)$, where NRK and (IRX) are estimated from Eqs. (2) and (3), respectively.

4.1. Comparison with the reference LIR

In Fig. 7 (left and middle panels) we compare the IR luminosity predicted with the NRK method ($L_{IR}^{NRK}$) with our reference IR luminosity derived from the mid/Far-IR bands ($L_{IR}$, see Sect. 2.2.1). The IR luminosities estimated with the two methods for the ~16 500 star-forming galaxies in the COSMOS 24 µm sample (left panel) agrees with almost no bias and a dispersion of ~0.2 dex over the entire luminosity range. Less than 1% of the galaxies shows a difference larger than a factor of 3. The prediction of the IR luminosity for the LIRG population, which dominates the COSMOS sample (the 24 µm population peaks at $L_{IR} \sim 2 \times 10^{11} L_{\odot}$), is excellent, considering the small number of parameters involved in the NRK method.

At low redshift, the prediction of the IR luminosity for the SWIRE galaxies (middle panel), which are 10 times less luminous than the 24 µm COSMOS population ($L_{IR} \sim 2 \times 10^{10} L_{\odot}$), shows a larger scatter ($\sigma \sim 0.27$ dex). This reflects the larger dispersion observed in Fig. 5 which is likely related to the wider range of galaxy properties at low z. Johnson et al. (2007b) have also modeled the IRX as a function of different rest-frame colors and $D_{L0}(4000)$ break for the SWIRE galaxies (see their Table 2 and Eq. (2)). The fit residuals for their predictions of IRX vary.

Fig. 5. Volume weighted mean IRX (⟨IRX⟩), on a logarithmic scale) as a function of NRK in five redshift bins. The COSMOS sample based on photometric redshifts is shown as solid black circles, gray squares and yellow shaded area indicate the mean IRX and dispersion for the spectroscopic sample of local galaxies of Johnson et al. (2007a) (left-most panel) and the COSMOS spectroscopic sample (four right-most panels).

The solid red line indicates the predictions of Eq. (3) for (IRX) as a function of NRK at the mean redshift of the bin, while the dashed line refers to $z = 0.11$ the mean redshift of the Johnson et al. (2007a) sample. We overplot the different mass selected samples: $9.5 \leq \log (M/M_{\odot}) \leq 10.0$ (open triangles); $10.0 \leq \log (M/M_{\odot}) \leq 10.5$ (open squares); $10.5 \leq \log (M/M_{\odot}) \leq 11.5$ (open stars). The distributions of NRK for the total (solid lines) and spectroscopic samples (shaded histograms) are shown in the bottom part of each panel.

Fig. 6. Illustration of the analytical parametrization of the relation $\log (\langle IRX \rangle) = f(NRK, z)$. Top panel: linear fit as a function of NRK after rescaling (IRX) at $z = 0$. Bottom panel: polynomial fit as a function of redshift, after rescaling (IRX) at NRK = 0.
Fig. 7. Comparison of the infrared luminosity $L_{\text{IR}}$ estimated from the 24 $\mu$m luminosity (COSMOS sample) or 8, 24, 70 and 160 $\mu$m luminosities (local sample) with that estimated with NRK ($L_{\text{NRK}}$), for the COSMOS (left panel) and SWIRE (middle panel) samples. We also compare with the one estimated from the SED fitting ($L_{\text{SED}}$, right panel). In each panel, the dashed and dotted lines refer to a factor ratio of 2 and 5 respectively. The distributions of $L_{\text{IR}}$ are shown in the bottom part of each panel. The numbers in each panel refer to the logarithm of the mean and dispersion of the luminosity ratio for the star-forming galaxies. From $\sigma(\text{IRX}) \sim 0.27$ to 0.36, depending on the adopted colors. Even with the use of the $D_n(4000)$ break as a dust-free indicator of star formation history, they do not achieve a better accuracy than that obtained with the method presented in this work.

Finally, our method provides a smaller dispersion in the prediction of the IR luminosity than the dust luminosity obtained from the SED fitting (Fig. 7 right panel), where we obtain a dispersion of $\sim 0.26$ dex and a bias of $\Delta \sim -0.13$. We note that the $L_{\text{IR}}$ derived from SED fitting is computed by integrating all the stellar photons absorbed by dust according to the adopted attenuation law and reddening excess (see Appendix A), while the reference $L_{\text{IR}}$ is based on the extrapolation of the 24 $\mu$m luminosity. Both measurements suffer from independent source of uncertainties, thus the bias in the IR luminosity may be related to either methods. However, the small scatter (less than a factor 2) and bias show that the SED fitting is a robust and reliable method to estimate the total IR luminosity, when accurate observations on a wide enough wavelength are available (e.g., Salim et al. 2009). This is indeed the case for the COSMOS dataset used here (i.e., 31 passbands from Far-UV to Mid-IR: $0.15 \leq \lambda \leq 4.5 \mu$m).

4.2. Dependence of the predicted IR luminosity with physical galaxy properties

Despite the use of a single vector, NRK, and the absence of mass dependency, our recipe provides a reasonable estimate of the total IR luminosity $L_{\text{IR}}$. However, galaxies with physical properties that deviate from the bulk of the 24 $\mu$m population may be less accurately described in this framework. To test this issue and determine the range of validity of the method, we show in Fig. 8 the residuals (i.e., the difference) between the reference (i.e., $L_{\text{IR}}^{24 \mu m}$) and predicted IR luminosity as a function of redshift (top-left panel), total SFR (top-right), stellar mass (bottom-left) and specific SFR (bottom-right). The total SFR refers to the (UV+IR) SFR (see Eq. (1)), while the stellar mass is obtained with the SED fitting (see Sect. 2.2.2). We perform this comparison for the $L_{\text{IR}}$ predicted with both the NRK and SED fitting methods.

Fig. 8. Median and dispersion of the difference (i.e., residuals) between the IR luminosity based on the 24 $\mu$m flux (i.e., $L_{\text{IR}}^{24 \mu m}$) and that predicted with different methods, as a function of different galaxy physical parameters. In each panel red-filled circles refer to the NRK method, green squares to the NRK sSFR-corrected and open-blue triangles to the SED fitting (open-blue triangles). Top-left panel shows the residuals as function of redshift, top-right of total SFR, bottom-left of stellar mass and bottom-right of specific SFR. The number distribution for each physical parameter is shown as an histogram in the lower part of each panel.

Top-left panel of Fig. 8 does not reveal any bias with redshift in the IR luminosity predicted with both methods. This is expected by construction for the NRK method, while it confirms the good performance of the SED fitting technique despite the larger scatter than the one obtained with the NRK method.
Top-right panel of Fig. 8 shows that the residuals as a function of the total SFR are relatively stable, with an almost zero bias and a dispersion of $\sim 0.2$ dex for $SFR \leq 100 M_\odot yr^{-1}$. At higher SFR, where galaxies approach the ULIRG regime, the residuals start to deviate from zero, indicating that both the NRK and SED fitting methods under-predict the reference IR luminosity. The difference with the NRK predictions is likely to be caused by the rarity of these highly star-forming objects in our redshift range ($0 \leq z \leq 1.3$, see also Le Floc’h et al. 2005), which makes these objects under-represented in the NRK calibration. The disagreement with the prediction of the SED fitting may have a different origin. As shown in Appendix A, the starburst attenuation law is favored at high SFR, however ULIRGs are found to deviate from Meurer’s relation (Reddy 2009; Reddy et al. 2012) and exhibit a higher IRX at a given UV-slope. This effect has been observed at higher redshift ($z \geq 1.5$), but it could also be the reason of the under-estimate of $L_{IR}$ by the SED fitting technique at lower redshift. We also note that our e-folding SF history models used in the SED fitting may be too simplistic and models including burst episodes would be more appropriate for these actively star-forming galaxies. Finally, we also note that the reference $L_{IR}$, based on the extrapolation of the $24 \mu m$ luminosity, may reach its limit of validity in this regime. Indeed, the conversion of the $24 \mu m$ luminosity to total IR luminosity becomes uncertain for ULIRGs (i.e., for $L_{IR} \geq 10^{12} L_\odot$, see Bavaouzet et al. 2008; Goto et al. 2011). Also, the merger nature of ULIRGs at low $z$ (Kartaltepe et al. 2010) makes predictions inaccurate in absence of a complete set of far-IR observations.

Bottom-left panel of Fig. 8 does not reveal any bias with stellar mass for the IR luminosity predicted with the SED fitting technique, while the dispersion increases at the extreme sides. On the other hand, the NRK method under-estimates $L_{IR}$ for stellar mass $\log (M/M_\odot) \geq 9.3$. As shown in Le Floc’h et al. (in prep.) from the analysis of a mass-complete sample obtained with stacking techniques of Herschel/SPIRE data at 250/350/500 $\mu m$, the NRK calibration presented in this work needs to be modified for galaxies with $M \lesssim 10^{9.5} M_\odot$. At high stellar mass (i.e., $\log (M/M_\odot) \geq 11$) the NRK method over-estimates $L_{IR}$. This reflects the correlation between stellar mass and sSFR, where quiescent galaxies become the dominant population at high stellar masses (see below).

Bottom-right panel of Fig. 8 shows that the NRK method systematically (as reflected by the small scatter) over-estimates $L_{IR}$ at low sSFR (i.e., $\log (sSFR/yr^{-1}) \leq -10$). We investigate this bias in more details in Appendix D and find that the sSFR derived with NRK saturates at such low sSFR, while the reference sSFR keeps decreasing. We therefore propose a simple analytical correction for this bias in order to reconcile the two sSFR estimates, which can then be used to correct $L_{IR}^{NRK}$. The results for this $L_{IR}^{NRK}$ sSFR-corrected are shown in Fig. 8 as filled green squares. The correction provides a better match to the $24 \mu m$ parent distribution across the entire range of stellar mass and sSFR, but at the cost of a larger dispersion for the global sample (i.e., from $\sigma = 0.21$ to $\sigma = 0.24$). It is worth noting that the reference sSFR for quiescent galaxies might also suffer from systematic error. In fact, recent analysis with Herschel data have reported evidences for a warmer dust temperature in early- than in late-type galaxies (Skibba et al. 2011; Smith et al. 2012). This will result in an over-estimation of $L_{IR}$ as derived from the $24 \mu m$ luminosity (by adopting a too high $L_{IR}/L_{24\mu m}$ ratio). Combined with the UV luminosity partially produced by evolved stars, these two effects can lead to an over-estimate of our reference SFR (based on UV+IR). As shown in Fig. 8, the $L_{IR}$ comparison with the SED fitting method shows a large dispersion at low sSFR. The reason is illustrated in Appendix A (Fig. A.1), where a significative fraction of the galaxies with $\log (sSFR_{bol}/yr^{-1}) \leq -10$ shows a much lower sSFR with the SED fitting method, leading to a lower $L_{IR}$.

In conclusion, the NRK and SED fitting methods provide two independent and reliable estimates of $L_{IR}$ over a large range of redshift and galaxy physical parameters for the vast majority ($\sim 90\%$) of the $24 \mu m$ star-forming sample. However, differences arise when considering the extreme sides of the population, such as highly star-forming (i.e., $SFR_{bol} \geq 100 M_\odot yr^{-1}$) or quiescent galaxies (i.e., $\log (sSFR_{bol}/yr^{-1}) \leq -10$), which represent $\lesssim 1\%$ and $7\%$ of the whole sample, respectively. While the NRK method suffers from a bias at low sSFR, it is not clear the amplitude of this effect, since there is no robust indicators of SFR in the low activity regime. In the next section, we obtain an independent estimate of this bias for the quiescent population by directly comparing the SFRs estimated with the NRK and SED fitting methods.

### 4.3. Comparison of SFR estimates with NRK and SED fitting techniques

Once calibrated with a Far-IR sample, the NRK technique can be applied to any sample of galaxies. In this section we compare the SFRs derived with the SED fitting and NRK methods for two samples of galaxies, the $24 \mu m$ and a K-selected (down to $K \leq 23.5$) samples. We restrict the analysis to galaxies with stellar masses $M \geq 2 \times 10^9 M_\odot$, and redshift 0.05 $\leq z \leq 1.3$. The SFR$^{NRK}$ is estimated by means of Eqs. (1)–(3). As discussed above, we found that this technique is better suited for active star-forming galaxies than the less active population (low sSFR). As shown in Fig. 2, we exploit the capability of the NUVrK diagram to separate galaxies with different SFRs and we define a new vector $\text{NRK}_{sfr}$, perpendicular to the starburst attenuation vector ($\text{NRK}_{sfr} = \cos(54^\circ) \times (NUV - r) - \sin(54^\circ) \times (r - K)$). In Fig. 2, we show constant values of $\text{NRK}_{sfr}$ (i.e., the norm of the $\text{NRK}_{sfr}$ vector), corresponding to the range $\sim 2 \leq \text{NRK}_{sfr} \leq 3$ as gray lines, which is a good proxy to follow the variation of the mean sSFR. The limit adopted to define the passive population corresponds to $\text{NRK}_{sfr} \geq 1.9$.

The ratios $(SFR^{NRK}/SFR^{SED})$ for the $24 \mu m$ (top panel) and the K (bottom panel) selected samples are shown in Fig. 9 for different intervals of $\text{NRK}_{sfr}$. In each panel, we report for each bin of $\text{NRK}_{sfr}$ the percentage of objects in this bin, the percentage of catastrophic objects (estimated as ABS($\Delta > 3\sigma$), the median ($\Delta$) and scatter ($\sigma$). For $\sim 85\%$ of the sample, with $\text{NRK}_{sfr} \leq 1.3$, the two SFRs are in excellent agreement, with small biases, scatter and catastrophic fraction for both the $24 \mu m$ and K-selected samples. For $1.3 \leq \text{NRK}_{sfr} \leq 1.5$ ($6$–$7\%$ of the two samples), the fraction of catastrophic objects sharply increases to $\sim 10\%$, the dispersion also increases and the median starts to deviate from zero, with $SFR^{SED}$ being higher than $SFR^{NRK}$. This trend becomes more severe for $1.5 \leq \text{NRK}_{sfr} \leq 1.9$ (the remaining $7$ to $9\%$ of the samples). The two SFRs disagree, with a large fraction of catastrophic objects ($\sim 25\%$), a significant non-zero median and large dispersion, with some slight differences between the two samples. This region with inconsistent SFR estimates is shown in Fig. 2 as a shaded area.

This comparison shows that the NRK method can be successfully applied to a sample of galaxies larger than the $24 \mu m$ sample, since it provides SFR estimates in good agreement with the SED fitting for the vast majority (i.e., $\sim 85$–$90\%$) of the
star-forming population. However, the methods diverge when including low-activity (low-sSFR) galaxies (see also Johnson et al. 2007a; Treyer et al. 2007). To alleviate this limitation, we show that the population with discording results (≤10% of the whole sample) can be easily isolated in the NUVrK diagram.

### 4.4. Application to the SFR vs. stellar mass relationship

A correlation between SFR and stellar mass in star-forming galaxies is observed both at low (Salim et al. 2007) and high redshift (Nobeske et al. 2007b; Elbaz et al. 2007). This relation is surprisingly tight, with an intrinsic scatter of ~0.3 dex. We can therefore exploit the presence of this correlation and test the ability of the NRK method to reproduce the slope and amplitude of this relation at different redshifts.

In Fig. 10 we show the $V_{\text{max}}$ weighted mean of SFR in bins of stellar mass for different samples of star-forming galaxies: the COSMOS 24 μm sample, a flux limited K-selected sample (K ≤ 23.5) and, in the lowest redshift bin, the local GALEX-SWIRE sample. Symbols indicate SFR estimated with different methods: ($L_{\text{IR}} + L_{\text{UV}}$) from Eq. (1) (black stars), NRK method (red filled circles and open blue squares), NRK method corrected for the sSFR bias (green-filled squares); the local GALEX-SDSS-SWIRE sample (blue open squares). We compare with the local estimate from Salim et al. (2007) (red lines) and the radio stacking analysis by Karim et al. (2011) (heavy dark-blue lines). The region where the NRK method becomes less reliable is shown as light shaded area.

In the previous section we have shown that galaxies with different ultraviolet-to-infrared luminosity ratios (IRX) are well separated in the NUVrK diagram. To confirm the validity of this approach, and to explain the physical origin of the observed trends, we appeal to a library of galaxy SEDs computed with the BC03 spectral evolution model. We follow the approach of Pacifici et al. (2012) and extract a set of star formation and chemical
enrichment histories from the semi-analytic post-treatment of De Lucia & Blaizot (2007) of the Millennium cosmological simulation (Springel et al. 2005). The star formation and chemical enrichment histories computed in this way reproduce the mean properties of nearby SDSS galaxies. Thus, they span only limited ranges in sSFR, around $10^{-10}\text{yr}^{-1}$, and in the fraction of the current stellar mass formed in the last 2.5 Gyrs at $z = 0$. Following Pacifici et al. (2012), to account for the broader range of spectral properties of the galaxies in our sample with respect to the SDSS, we re-draw the evolutionary stage at which a galaxy is looked at in the library of star formation and chemical enrichment histories (we do this uniformly in redshift between 0.2 and 1.5). We also resample the current (i.e., averaged over the last 30 Myr) SFR from a Gaussian distribution centered on $\log(sSFR) = -9.1$, with a dispersion of 0.6. This choice of parameters reproduces the observed global distribution of sSFR (i.e., summed over all redshift bins) and the distribution of galaxies in the $NUV$-$r$ diagram, after accounting for dust attenuation as described in the next section. We adopt the Chabrier (2003) IMF.

5.1. Dust attenuation model

To include the effect of dust attenuation, we adopt the dust prescription of Chevallard et al. (2013). This extends the two-components, angle-average dust model of Charlot & Fall (2000) to include the effect of galaxy inclination and different spatial distributions of dust and stars on the observed SEDs of galaxies. Chevallard et al. (2013) combine the radiative transfer model of Tuffs et al. (2004), hereafter T04 with the BC03 spectral evolution model. To accomplish this, they relate the different geometric components of the T04 model (a thick and thin stellar disk, and a bulge, attenuated by two dust disks) to stars in different age ranges. Here, for the sake of simplicity and to limit the number of adjustable parameters, we describe attenuation in the diffuse ISM using only the thin stellar disk model of Tuffs et al. (2004). This is supported by the finding by Chevallard et al. (2013) that, in a large sample of nearby star-forming galaxies, the thin stellar disk component of the T04 model accounts for $\approx 80$ percent of the attenuation in the diffuse ISM. Also, we note that adding the T04 thick disk component has a weak effect on the results. The dust content of the diffuse ISM in the T04 model is parametrized by means of the $B$-band central face-on optical depth of the dust disks $\tau_{B,L}$. This determines, at fixed inclination, the attenuation of starlight by dust at any galaxy inclination $\theta$, which measures the angle between the observer line-of-sight and the normal to the equatorial plane of a galaxy. At fixed $\tau_{B,L}$, the integration over the solid angle of the attenuation curve $\hat{\tau}^{ISM}_\lambda(\theta)$ in the T04 model yields the angle-average attenuation curve $\hat{\tau}^{ISM}_\lambda(\theta)$ (see Sect. 2 of Chevallard et al. 2013). As in Charlot & Fall (2000), we couple the attenuation in the diffuse ISM described by the T04 model with a component describing the enhanced attenuation of newly born stars ($t < 10$ Myr) in their parent molecular clouds. Following Charlot & Fall (2000), we parametrize this enhanced attenuation by means of the fraction 1-$\mu$ of the total attenuation that arises from dust in stellar birth clouds, in the angle-average case.

The attenuation of the radiation emitted by a stellar generation of age $t$ at inclination $\theta$ can therefore be written as

$$\hat{\tau}^{ISM}_\lambda(\theta,t) = \begin{cases} \hat{\tau}^{BC}_\lambda(\theta,t) + \hat{\tau}^{ISM}_\lambda(\theta) & \text{for } t \leq 10 \text{ Myr}, \\ \hat{\tau}^{ISM}_\lambda(\theta) & \text{for } t > 10 \text{ Myr}, \end{cases}$$

where the superscripts “BC” and “ISM” refer to attenuation in the birth clouds (assumed isotropic) and the diffuse ISM, respectively. In this expression the attenuation curve for the diffuse ISM $\hat{\tau}^{ISM}_\lambda(\theta)$ is taken from the T04 thin stellar disk model, and following Wild et al. (2007, see also da Cunha et al. 2008), we compute the attenuation curve in the birth clouds as

$$\hat{\tau}^{BC}_\lambda = \hat{\tau}^{BC}_V (\lambda/0.55 \text{ mm})^{-1.3},$$

where the $V$-band optical depth of the birth clouds $\hat{\tau}^{BC}_V$ is related to the angle-average optical depth of the diffuse ISM $\hat{\tau}^{ISM}_V$ as

$$\hat{\tau}^{BC}_V = (1 - \mu) / \mu \hat{\tau}^{ISM}_V.$$  

To compute the ratio of the infrared-to-ultraviolet luminosities $IRX$ in this model, we take the IR luminosity to be equal to the fraction of all photons emitted in the range $912 \AA \leq \lambda \leq 3 \mu m$ in any direction that are absorbed by dust (dust is almost transparent at $\lambda > 3 \mu m$). Assuming that photons at IR wavelengths emerge isotropically from a galaxy, we write the IR luminosity $L_{IR}$ as

$$L_{IR} = \frac{1}{4\pi} \int_{0}^{1} \sin \theta d\Theta \int_{0.0012}^{3} \sin \theta d\lambda (1 - \exp(-\hat{\tau}_{\lambda}(\theta))) L_{\lambda}^0(\theta)$$

where $L_{\lambda}^0(\theta)$ is the unattenuated luminosity emitted by stars (assumed isotropic), $\Theta$ is the solid angle, and $\hat{\tau}_{\lambda}(\theta)$ is the integral of Eq. (4) over the star formation history of the galaxy. We compute the monochromatic ultraviolet luminosity at the frequency $\nu$ corresponding to $\lambda = 2300$ Å as $L_{NUV}(\nu) = \nu L_\nu(\theta)$, where $L_\nu(\theta)$ is given by

$$L_\nu(\theta) = [\exp(-\hat{\tau}_{\nu}(\theta))] L_{\nu}^0(\theta) \frac{\lambda^2}{c},$$

and $L_{\nu}^0(\theta)$ if the luminosity emitted by all stars at $\lambda = 2300$ Å in the direction $\theta$, and $c$ is the speed of light.

5.2. Model library

We use this model to compute a library of 20000 SEDs of dusty star-forming galaxies, which we divide in bins of constant $(NUV - r)$ and $(r - K)$. We compute the mean sSFR and $\langle IRX \rangle$ in each bin and explore their distribution in the $NUV$-$r$-$K$ diagram. After some experimentation, we find that a Gaussian distribution of $\tau_{B,L}$ centered at 7, with a dispersion of 3, truncated at the maximum value of available models $\tau_{B,L} = 8$, and a Gaussian distribution of $\mu$ centered at 0.3, with a dispersion of 0.2, and truncated at $\mu = 0$ and $\mu = 1$, allow us to well reproduce the data, as shown in the top-left panel of Fig. 11. We note that a uniform distribution of galaxy inclinations would produce a large tail of highly attenuated galaxies, which is not observed in the data (at $(r - K) > 2.5$). Hence, in Fig. 11 we have adopted the observed distribution of axis ratios, converted to inclinations using the standard formula for an oblate spheroid (e.g., Guthrie 1992)

$$\cos \theta = \frac{(b/a)^2 - q_0^2}{1 - q_0^2};$$

where $q_0$ is the intrinsic axis ratio of the ellipsoid representing the galaxy, which we fix to $q_0 = 0.15$.

A comparison between top-left and bottom-right panels of Fig. 11 shows that the models reproduce, at least qualitatively, the distribution of $\langle IRX \rangle$ in the color–color plane. The reddest
near-IR colors, \((r - K) > 1.4\), correspond to galaxies seen at large inclination. This is consistent with Fig. B.2, which shows that the galaxies with reddest \((r - K)\) colors have the largest measured ellipticities, i.e., they are more inclined. A large inclination makes the disk appear more opaque, since photons have to cross a larger section of the dust disk before they escape toward the observer.

The location and shape of the IRX stripes in the theoretical \(NUV/VK\) diagram depend on several galaxy physical parameters, namely evolutionary stage, current SFR, dust content and distribution. The evolutionary stage and current SFR determine the relative amount of young and old stars in the galaxy, which controls the ratio of unattenuated ultraviolet to optical and near-IR luminosity of the galaxy. The global dust content, \(\tau_{V,\text{dust}} + \tau_{V,\text{ISM}}(\theta)\), and the distribution of dust between ambient ISM and birth clouds affect the \((NUV - r)\) and the \((r - K)\) colors in different ways. For galaxies with a non-negligible fraction of young stars (i.e., \(\log(\text{sSFR}) \lesssim -9\)), the \((NUV - r)\) color is mainly driven by the stellar birth clouds optical depth \(\tau_{V,\text{BC}}\), and the \((r - K)\) color by the optical depth of the diffuse ISM \(\tau_{V,\text{ISM}}(\theta)\).

We test the effect of varying the optical depth of stellar birth clouds by computing the same library of 20 000 SEDs as described above, but fixing \(\tau_{V,\text{BC}} = 0\). Top-right panel of Fig. 11 shows that neglecting birth clouds attenuation prevents us from reproducing the reddest \((NUV - r)\) color observed in the data. The stripes appear almost perpendicular to the \((r - K)\) color driven primarily by the diffuse ISM. Also, this model predicts smaller values of (IRX) at a fixed position in the \((NUV - r)\) vs. \((r - K)\) diagram, since the UV photons emitted by young stars do not suffer enhanced attenuation by the dusty birth cloud environment, which would be re-emitted at IR wavelengths increasing the overall IR luminosity.

We also study the effect of neglecting the dependance of dust attenuation on galaxy inclination. To achieve this, we compute the same library of 20 000 SEDs as above, but we fix the attenuation curve to the angle-averaged curve \(\langle \tau_{V,\text{ISM}}(\theta) \rangle\). Bottom-left panel of Fig. 11 shows that this prevents us from reproducing the reddest \((r - K)\) colors of the observed galaxies, which correspond to highly inclined objects (see top-left panel of Figs. 12 and B.2).

We have shown in Fig. 11 that to reproduce qualitatively the observed distribution of galaxies and the value and orientation of the (IRX) stripes in the \((NUV - r)\) vs. \((r - K)\) plane we need a prescription for dust attenuation which includes both a two-component medium (i.e., ISM + birth clouds) and the effect of galaxy inclination. We can now consider the “Full model” shown in the top-left panel of Fig. 11 and study how different dust properties vary in the \((NUV - r)\) vs. \((r - K)\) plane. Figure 12 shows the same library of SEDs as in the top-left panel of Fig. 11. As for Fig. 11, we divide the galaxy SEDs in bins of constant \((NUV - r)\) and \((r - K)\), and compute in each bin the mean value of galaxy inclination 1 – \(\cos\theta\), V-band attenuation optical depth seen by stars younger [older] than 10\(^7\) yr \(\tau_{V,\text{young}}(\theta)\) [\(\tau_{V,\text{old}}(\theta)\)], and slope of the optical attenuation curve in the diffuse ISM \(n_{V,\text{ISM}}(\theta)\).

The top-left panel of Fig. 12 shows that the galaxy inclination systematically increases as \((r - K)\) increases, with a weaker dependence on the \((NUV - r)\) color. This can be understood in terms of the attenuation optical depth in the diffuse ISM, which increases with increasing galaxy inclination, hence making \((r - K)\) redder. The \((NUV - r)\) color is also influenced by the variation of galaxy inclination, but to a much less extent since it also depends on the birth clouds attenuation optical depth (see Eq. (4)). The variation of the mean galaxy inclination shown in the top-left panel of Fig. 12 is also in qualitative agreement with Fig. B.2, which shows that the mean observed ellipticity of the galaxies in our sample increases from the bottom-left to the top-right side of the \((NUV - r)\) vs. \((r - K)\) plane.

The top-right panel of Fig. 12 shows the variation of the V-band attenuation optical depth suffered by stars younger than 10\(^7\) yr (i.e., \(\tau_{V,\text{young}}(\theta)\), see Eq. (4)). At small \((r - K)\) the stripes of
constant \( \tau_{V}^{\text{young}}(\theta) \) are more parallel to the (NUV - \( r \)) color, while they become more and more inclined as (NUV - \( r \)) and (r - K) increase. This behavior can be understood in terms of the different fraction of light emitted by young stars attenuated by dust in the birth clouds and in the diffuse ISM. At small (i.e., blue) (r - K), young stars are mostly attenuated by the birth clouds component, which makes the (NUV - \( r \)) larger (i.e., redder, by decreasing NUV, at fixed \( r \)) without affecting (r - K). As (r - K) increases, the attenuation in the diffuse ISM increases, because galaxies are more inclined or have a larger dust content, and so the fraction of light emitted by young stars attenuated by this component raises too. As a consequence, the (NUV - \( r \)) color is determined by attenuation in both components, and the stripes of constant \( \tau_{V}^{\text{young}}(\theta) \) change orientation.

The variation of the V-band attenuation optical depth suffered by stars older than 10^7 yr (i.e., \( \tau_{V}^{\text{old}}(\theta) \)) shown in the bottom-left panel of Fig. 12 follow that of the (r - K) color, as indicated by the orientation of the stripes of constant \( \tau_{V}^{\text{old}}(\theta) \) almost perpendicular to (r - K). This is not surprising, since (r - K) traces stars older than 10^7 yr, which are attenuated by dust in diffuse ISM. When moving from left to right on the (r - K) axis, \( \tau_{V}^{\text{old}}(\theta) \) increases from 0 to 2.5, indicating that the amount of attenuation suffered by stars in galaxies with very large (i.e., red) (r - K) is substantial.

The bottom-right panel of Fig. 12 shows the slope of the optical attenuation curve in the diffuse ISM \( n_{V}^{\text{ISM}}(\theta) \), obtained by fitting a power law to the model attenuation curves in the range 0.4 \( \leq \theta \leq 0.7 \) \( \mu \)m. The slope \( n_{V}^{\text{ISM}}(\theta) \) becomes smaller (i.e., the attenuation curve becomes flatter) when moving from the bottom-left to the top-right side of the diagram. This effect, as described in Chevallard et al. (2013), see their Fig 4), is a general prediction of radiative transfer models which consider disk galaxies with a mixed distribution of dust and stars. The variation of the slope of the attenuation curve in the (NUV - \( r \)) vs. (r - K) plane can account for the fact that the observed stripes of constant IRX are not perpendicular to the SMC and Calzetti attenuation vectors (see Fig. 4) and that the SED fitting predicts a systematic variation of the slope of the attenuation curve as a function of sSFR (see Fig. A.2).

With this analysis we have shown that we must account for the effect of geometry (i.e., of the spatial distribution of dust and stars) and galaxy inclination to reproduce the attenuation of starlight by the diffuse ISM, which mainly affects the (r - K) color. We have also shown the importance of accounting for the enhanced attenuation of newly born stars by their birth clouds to reproduce the reddest (NUV - \( r \)) colors and to match the observed values of (IRX). In the end, the good qualitative agreement between the “fully model” galaxies and the data (i.e., top-left and bottom-right panels of Fig. 11) confirms that the NUVrK diagram encodes valuable information about the global energy transfer between starlight and dust and galaxy inclination. We defer to a future work a more detailed and quantitative analysis of the data presented here, which would help us to better constrain the global amount, distribution and redshift evolution of the dust in star-forming galaxies.

6. Conclusion

We present a new method to compute the SFR of individual star-forming galaxies based on their location in the (NUV - \( r \)) versus (r - K) color–color diagram. We show that the NUVrK diagram provides an efficient way to separate quiescent and star-forming galaxies, an alternative to the UVJ diagram proposed by Williams et al. (2009). For the star-forming galaxies, the UV/optical luminosities in this diagram are highly sensitive to the shape of the dust attenuation laws. On the other hand, the infrared excess, IRX = \( L_{\text{IR}}/L_{\text{UV}} \), as the net budget of the absorbed versus unabsorbed UV light, is weakly dependent on these effects. We combine the two dust diagnostics by analyzing the distribution of the mean infrared excess (i.e., (IRX)) in the NUVrK diagram for a large sample of star-forming galaxies at redshift 0 \( \leq z \leq 1.3 \) selected from the COSMOS 24 \( \mu \)m and low-z GALEX-SDSS-SWIRE (Johnson et al. 2007a) samples. We observe the presence of stripes with constant (IRX), associated with a small dispersion around the mean, which allows us to describe (IRX) with a unique vector (i.e., \( \text{NRK} \), a combination of (NUV - \( r \)) and (r - K) colors). We derive a simple relation between (IRX) and NRK, the norm of the vector \( \text{NRK} \), and redshift, valid for star-forming galaxies with \( M \geq 2 \times 10^{9} M_{\odot} \) and 0.05 - 0.1 \( \leq z \leq 1.3 \). This relation allows us to predict the IR luminosity of individual galaxies with an accuracy of \( \approx 0.2 \) dex (up to 0.27 dex for the local sample), which is better than the accuracy obtained with the SED fitting method based on 31 COSMOS pass-bands for the same galaxies.

We perform extensive comparisons of the L\( _{\text{IR}} \) and SFRs derived with the 24 \( \mu \)m, NRK and SED fitting methods. We find that the three methods provide consistent results for the vast majority of star-forming galaxies (\( \approx 85 - 90\% \)). The methods diverge for highly star-forming galaxies (SFR \( \geq 100 M_{\odot} \text{yr}^{-1} \)), which remain a negligible population at \( z \leq 1.3 \), and for more evolved galaxies (sSFR \( \leq 10^{-11} \text{yr}^{-1} \)). For the latter, we describe a sSFR-, redshift-dependent limit below which the NRK method becomes unreliable and we also show that this population with inconsistent SFR estimates can be easily isolated and discarded in the NUVrK diagram.

By using the NRK method, we reconstruct the relation between SFR and stellar mass for a K-selected sample of star-forming galaxies and find an excellent agreement with previous results over the entire redshift range.

Finally, we investigate the physical origin of the (IRX) stripes in the NUVrK diagram by appealing to a library of model SEDs based on the population synthesis code of Bruzual & Charlot (2003). We find that this library of models is able to qualitatively reproduce the location and shape of (IRX) stripes in the NUVrK diagram if we adopt a realistic prescription for dust attenuation (Chevallard et al. 2013). We show that to reproduce the observed stripes of (IRX) we must appeal to a two-component (i.e., birth clouds + diffuse ISM) dust model, which must account also for the effect on dust attenuation of galaxy inclination and geometry (i.e., the spatial distribution of dust and stars).

The method discussed in this work offers a simple alternative to assess the total SFR of star-forming galaxies in the absence of Far-IR observations or spectroscopic diagnostics. Because it directly predicts the infrared excess, no assumption on the dust attenuation curves is required to derive the SFR, in contrast to other methods such as the \( \beta \)-slope or SED fitting.

In a companion paper Le Floc’h et al. (in prep.), we extend our analysis toward lower stellar mass and higher redshifts based on the stacking technique of the Far-IR emission using the complete dataset available from Spitzer/MIPS at 24 \( \mu \)m to Herschel/SPire at 250, 350 and 500 \( \mu \)m.

Acknowledgements. We thank the anonymous referee for his useful comments. This work has been partially supported by the CNRS-INSU and the Programme National de Cosmologie et Galaxies. J.C. acknowledges the support of the European Commission through the Marie Curie Initial Training Network ELIXIR under contract PITN-GA-2008-214227.
Appendix A: The SED fitting technique

The broad band SED fitting technique is a simple approach to infer the physical properties of a galaxy, such as stellar mass, SFR, amount of dust, age of stellar populations, by statistically comparing model and observed SED. The constraints on the physical parameters depend on the wavelength range spanned by the data and their quality. The COSMOS field, for which a wealth of multi-wavelength, high signal-to-noise ratio observations exist, is thus well suited for such modeling.

To derive the physical parameters, we adopt a library of SEDs based on the synthetic stellar population code from Bruzual & Charlot (2003, hereafter BC03). We describe the star formation history either with an exponentially declining function, with e-folding time \( 0.01 \leq \tau \leq 15 \) Gyr, or with a constant. We adopt two metallicities, subsolar and solar (i.e., \( Z_{\odot} \), 0.2 \( Z_{\odot} \)), and the IMF of Chabrier (2003), truncated at 0.1 and 100 \( M_{\odot} \). Since the maximum redshift of the galaxies in our sample is \( z \sim 1.3 \), we force the age of galaxies to be larger than 100 Myr, computed from the onset of SF which, in our case, corresponds to the initial burst. We also constrain the age of the galaxies not to exceed the age of the universe at any redshift.

We do not adopt rising star formation histories, since these were developed to improve the SED fitting at high redshift (\( z \geq 2 \), see Maraston et al. 2010). The prescriptions for TP-AGB stars adopted in BC03 produces a lower near-IR luminosity for intermediate age stellar populations with respect to the prescriptions of Maraston (2005). This affects the galaxy mass-to-light ratio, and produces a difference in the stellar mass estimated with Maraston et al. (2010) of \( \sim 0.15 \) dex. The dust attenuation curve encodes informations about the nature of the dust grains (sizes, chemical compositions) and the spatial distributions of dust and stars. Boquien et al. (2009) have shown the necessity of adopting a range of attenuation laws to reproduce the observed scatter in the IRX vs. \( \beta \) relation. In particular, they show that a gray (i.e., shallow) attenuation curve, such as the starburst curve of Calzetti et al. (2000), and a steeper curve, such the SMC extinction curve of Prevot et al. (1984), are required to span the observed distribution in the IRX versus \( \beta \) diagram of the starbursting and normal star-forming galaxies. Similar conclusions are reached by Ilbert et al. (2009), who find that a range of attenuation curves is required to improve the photometric redshift accuracy via the SED fitting method. For these reasons, we adopt three different attenuation curves: a starburst, SMC-like laws and a curve with a slope in between them (\( \lambda^{-0.9} \)). We then consider reddening excess in the range \( 0 \leq E(B-V) \leq 0.6 \), which allows us to explore the observed color distribution of our sample (see Fig. 3).

We use LePhare code (Arnouts et al. 1999; Ilbert et al. 2006) to compute the \( \chi^2 \) for each observed galaxy and the entire model library, with all the photometric passbands from 0.15 \( \mu m \) to 4.5 \( \mu m \). The physical parameters are derived by computing the median of the marginalized likelihood for each parameter and the errors corresponding to the 68% credible region.

In Fig. A.1, we compare the instantaneous SFR and sSFR derived with the SED fitting with the "total" SFR and sSFR derived from the observed IR and UV luminosities (i.e., Eq. (1)). The mean errors (based on 68% errors) for the SED parameters vary between 0.2 to 0.4, as shown by the gray region on the right side of the figures.

For the bulk of the 24 \( \mu m \) population the SFRs are in good agreement over ~3 order of magnitude, with a dispersion lower than a factor of two. The vast majority of sources with large discrepancies is located in the region occupied by passive galaxies (red triangles) or next to it, in the "intermediate" zone (green dots) as defined in Fig. 2. For those galaxies, the SED fitting predicts a low specific SFR (i.e., sSFR \( \leq 10^{-10.5} \) yr\(^{-1}\)). The origin of this difference may have multiple causes: an inadequate description of dust attenuation may cause the SED fitting to reject highly attenuated models and prefers models with low or no dust content and a low specific SFR. Alternatively the adopted definition of the total SFR in Eq. (1) may over-estimate the SFR, since we neglect the contribution of old stars to the
Our results agree with Wuyts et al. (2011) with a transition for the SED fitting technique are in good agreement with those derived from the UV∗IR contributions consistent with a simple dust screen model. See Sect. 5 for the SMC-like extinction law is favored for galaxies with low specific SFR, while “normal” star-forming galaxies prefer the SMC-like attenuation laws, corresponding to the best-fit templates, as a function of the SFR and specific SFR. As mentioned above, a good measure of the SFR is possible because of the presence of a larger population of old stars or the inadequate conversion of L24 to LIR. While this problem cannot be easily solved, in this paper we show that we can isolate in the NUVrK diagram the region occupied by galaxies for which we obtain inconsistent SFR estimates with the different methods.

Appendix B: Separation between passive and active

As the UVJ diagram proposed by Williams et al. (2009), in Sect. 2.3 and in Fig. 2, we define a criterion based on the NUVrK diagram to separate the passive and star-forming galaxies. To test the validity of the above color criterion, we show the distribution in the NUVrK diagram of galaxies with morphological information provided by the Zurich estimator of structural type (ZEST) catalog (Scarlata et al. 2007). The ZEST classification uses three morphological classes: Early type, Disk and Irregular, with subclasses describing the degree of “irregularity” in the early-type class (i.e., 0 for regular, 1 for irregular), and the contribution of the bulge for disk galaxies (i.e., from 0 for bulge dominated galaxies, to 3 for pure, bulge-less disks). We also consider the ellipticity class for the galaxies classified as disks. This traces the galaxy inclination with an ellipticity of 0 corresponding to a face-on galaxy and up to 3 for an edge-on galaxy. The ZEST catalog includes galaxies down to Ib ≲ 24 and we restrict the sample to galaxies with good flags. The distributions of the different morphological classes in the NUVrK diagram are shown in Fig. B.1 for the whole ZEST sample (as density contours) and for the 24 μm-selected subsample (small dots). We detect a clear evolutionary sequence in this diagram, with the Irregular (IRR) and Spiral-disk dominated (Sp-3, and Sp-2) galaxies showing only blue colors, typical of active star-forming galaxies. The Spirals with a growing contribution of bulge (Sp-1 and Sp-0) and the early-types (ELL) show an increasing fraction of their population to lie in the passive region (i.e., top-left
Fig. B.2. Mean value of the ellipticities (color coded) in the NUVrK diagram for the morphological sample from Scarlata et al. (2007).

side) of the diagram. The 24 µm sample tends to lie in the blue plums of the early type (ELL) and bulge dominated spiral (Sp-0) samples. The blue plum in the early type class could be due to some residual of star formation activities (the plum is present in the two subclasses based on the regularity criterion: ELL-0 and ELL-1).

The Spiral disk-dominated population (Sp-3, and Sp-2) extend to relatively red colors in (NUV − r) and (r − K) (top-right part of the diagram), where high values of IRX are also observed. As discussed by Patel et al. (2011), in the UVJ diagram, the disk inclination can be indeed responsible for this extreme reddening. This is indeed supported by Fig. B.2, where we show the mean values of the ellipticity parameter for the disk population, in different redshift bins (see also the discussion in Sect. 5).

Appendix C: The average spectral energy distributions along the vector NRK

The evolution of ⟨IRX⟩ with NRK vector should be reflected in the shape of the galaxy SEDs when moving from low to high value of NRK. In Fig. C.1, we have reconstructed the averaged rest-frame SEDs in different bins of NRK, redshift and stellar mass, by using the 31 broad and medium bands available in the COSMOS catalog. They are reconstructed in logarithmic wavelength bins (Δlog(λ) = 0.15). Before computing the average and the dispersion in each wavelength bin, the low resolution spectrum of all the galaxies was first normalized at λ ∼ 0.5 µm (dashed lines). In each panel, we show the number of galaxies used to reconstruct the averaged SEDs and as an indicative value of the IRX, we show the ratio log(FIR/FNUV), where the FIR is the redshift corrected 24 µm flux of the averaged SED (F24 µm/(1+z)) and FNUV the rest-frame flux at 0.23 µm (F0.23µm). As a reference, we overplot the template of a young star-forming galaxy (SB24 from Ilbert et al. 2009).

For the first bin 0.5 ≤ NRK ≤ 1, corresponding to the bluest population in our sample, no attenuation is applied to the template. For the three other bins of NRK, we increase the amount of dust reddening to E(B−V) = 0.2, 0.4, 0.6, assuming a starburst attenuation law (solid black lines) and a SMC extinction law (gray dashed lines).

A strong evolution of the SED shape is observed with increasing NRK. We can quantitatively reproduce this evolution by increasing the reddening excess applied to our SB2 star-forming template. On the other hand, redshift and stellar mass appear to play a secondary role in shaping the SED properties. This provides an additional evidence that NRK is sensitive to the global budget between UV and Far-IR emission in galaxies, regardless of other properties. It also supports our choice of neglecting the dependence on the stellar mass in Eq. (3). However, in Le Floc’h et al. (in prep.) we extend our analysis to a complete mass selected sample using the stacking technique at 24, 220, 350 and 500 µm and we show that the ⟨IRX⟩ vs. NRK relation should include a corrective term based on stellar mass when considering galaxies with stellar masses M⋆ ≤ 10^9.3 M_☉.

A67, page 17 of 18
Fig. C.1. Evolution of the average rest-frame SEDs with NRK for the 24 µm-selected sample. Each SED is reconstructed by using all the available COSMOS pass-bands. Galaxies are divided in bins of NRK (columns of the figure), redshift (rows) and stellar mass (blue, green and red symbols in each panel). The number of galaxies for each sample is shown in each panel. We also report the logarithm of the mean ratio $F_{\text{IR}}/F_{\text{UV}}$ as an indicative value of the IRX. In the first bin of NRK (i.e., first column of the figure) we overplot the dust-free template of young star-forming galaxy. In the other three bins of NRK (i.e., three right-most columns) we overplot the same template, but with increasing reddening excess ($E(B-V)=0.2, 0.4, 0.6$, respectively), assuming the Calzetti et al. (2000) attenuation law (solid, black line) and the SMC extinction law (dashed, gray line). The three vertical bands refer to the bandwidths of the NUV, $r$ and $K$ filters.

Appendix D: Dependence with sSFR

As observed in Fig. 8, the difference between the IR luminosity derived from the 24 µm observations and the NRK method varies with the specific SFR. In particular, we have shown that the NRK method over-estimates $L_{\text{IR}}$ for galaxies with low sSFR. In Fig. D.1 we compare, in different redshift bins, the predicted specific SFR ($sSFR_{\text{NRK}}$) with the reference sSFR (derived with the 24 µm, $sSFR_{\text{tot}}$), with both sSFR estimated with Eq. (1). The $sSFR_{\text{NRK}}$ tends to saturate while the true sSFR keeps declining toward galaxies with low star formation activity, and this deviation varies with redshift. We propose an analytical fit which allows us to reproduce this deviation over the entire redshift range:

$$\log(sSFR_{\text{NRK COR}}) = -9.5 + 1.1 \left[ \log \left( \frac{10^{y_0}}{10^{a(z)} - 10^{b(z)}} \right) - b(z) \right]$$

(D.1)

where, $y_0 = \log(sSFR_{\text{NRK}}) + 9.5$, $a(z) = -1.4 + 0.8 \, z$ and $b(z) = -0.1 \, (1 - z)$ and $z$ is the redshift. By mean of this equation, we can define a sSFR threshold below which the NRK method over-estimates the SFR by a given factor. By choosing a factor 2, the redshift evolution of this threshold can be simply described by $sSFR_{\text{lim}}(z) = -10.6 + 0.8 \, z$. These thresholds are shown as shaded yellow regions in Fig. D.1.

Fig. D.1. The predicted specific SFR ($sSFR_{\text{NRK}}$) vs. the reference sSFR ($sSFR_{\text{tot}}$) for the star-forming population in the local SWIRE (top left panel) and COSMOS (other panels) samples. The mean and the sigma per bin of $sSFR_{\text{tot}}$ are shown as blue symbols and the solid lines show the analytical fit described in the text. The yellow area corresponds to the limit where $sSFR_{\text{NRK}} > 2 \times sSFR_{\text{tot}}$. 