Some post-starburst E+A galaxies are not truly post starburst

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ABSTRACT

Post-starburst E+A galaxies are believed to be systems in a rapid transition between major merger starbursts and quiescent ellipticals. Their optical spectrum is dominated by A-type stars, suggesting a significant starburst that was quenched recently. While optical observations of post-starburst galaxies suggest little ongoing star formation, they have been shown to host significant molecular gas reservoirs. This led to the suggestion that gas consumption or expulsion are not required to end the starburst, and that star formation is suppressed by turbulent heating of the molecular gas. We present NOEMA continuum and CO(1-0) observations of 15 post-starburst galaxies, and collect CO measurements in post-starburst galaxies from the literature. Using archival far-infrared observations, we show that the majority of these systems host obscured star formation, with some showing far-infrared emission that is comparable to those of luminous and ultraluminous infrared galaxies. Once far-infrared star formation rates are used, these systems show similar SFR-$\mathcal{M}_{\text{H}_2}$ and Kennicutt-Schmidt relations to those observed in star-forming and starburst galaxies. In particular, there is no need to hypothesize star formation quenching by processes other than the consumption of molecular gas by star formation. The combination of optical, far-infrared, and CO observations indicates that some regions within these galaxies have been recently quenched, while others are still forming stars at a high rate. We find little connection between the post-burst age of the optically-thin quenched regions and the star formation rate in the obscured regions. All this calls into question the traditional classification of E+A galaxies.

Key words: galaxies: general – galaxies: interactions – galaxies: evolution – galaxies: active – galaxies: supermassive black holes – galaxies: star formation

1 INTRODUCTION

Observations of the local galaxy population reveal a bimodal distribution in their properties, suggesting two broad classes of galaxies: star-forming and quiescent. These two classes differ in their morphology, color, stellar kinematics, star formation, and gas properties (see e.g., Baldry et al.\textsuperscript{2006} and references therein). Post-starburst galaxies (also called E+A or K+A) are rare objects that are located in the “green valley” of the galaxy color-magnitude diagram (Wong et al.\textsuperscript{2012}). They are believed to represent a rapid transition between the star-forming and quiescent classes (see French\textsuperscript{2021} for a review). Their optical spectra are dominated by A-type stars, suggesting a recent burst of star formation.

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that was terminated abruptly ~1 Gyr ago (Dressler & Gunn 1983; Couch & Sharples 1987). Stellar population synthesis modeling of their ultraviolet-optical spectral energy distributions (SEDs) suggest peak star formation rates (SFRs) in the range 10–300 M\(_{\odot}\)/yr (Kaviraj et al. 2007; French et al. 2018), with 10%–80% of their total stellar mass forming in the most recent burst (Liu & Green 1996; Norton et al. 2001; Yang et al. 2004; Kaviraj et al. 2007; French et al. 2018). Many E+A galaxies show disturbed morphologies with tidal features, suggesting that they are merger remnants (Zabludoff et al. 1996; Canalizo et al. 2000; Yang et al. 2004; Goto 2004; Cales et al. 2011).

Post-starburst galaxies are believed to be the evolutionary link between major merger ultra luminous infrared galaxies and quiescent ellipticals (e.g., Yang et al. 2004, 2006; Kaviraj et al. 2007; Wild et al. 2009; Yesuf et al. 2014; Cales & Brotherton 2015; Wild et al. 2016; Almaini et al. 2017; Baron et al. 2017, 2018; French et al. 2018). According to the current paradigm, a major merger between gas-rich spirals triggers a starburst (Mihos & Hernquist 1994, 1996; Barnes & Hernquist 1996) which is highly-obscured by dust and is primarily visible in infrared and mm wavelengths. Soon after, gas in funneled to the vicinity of the supermassive black hole, triggering an Active Galactic Nucleus (AGN; e.g., Sanders et al. 1988; Springel, Di Matteo & Hernquist 2005; Hopkins et al. 2006). The molecular gas reservoir is then quickly depleted by the starburst and by stellar and AGN feedback, terminating additional star formation and black hole accretion (e.g., Tremonti, Moustakas & Diamond-Stanic 2007; Coli et al. 2011; Diamond-Stanic et al. 2012; Rowlands et al. 2015; Baron et al. 2017, 2018; Maiolino et al. 2019; Baron et al. 2020). The regions undergoing rapid quenching become optically-thin, and their observed spectrum is dominated by A-type stars (E+A spectrum). Having their molecular gas reservoirs exhausted, they are expected to transition into red and dead ellipticals in a few hundreds Myrs.

Several studies challenged this simple picture, by finding significant molecular gas reservoirs in optically-selected post-starburst galaxies (French et al. 2015; Rowlands et al. 2015; Alatalo et al. 2016b; Yesuf et al. 2017; Li et al. 2019; Yesuf & Ho 2020; Smercina et al. 2022). This led to the suggestion that complete gas consumption or expulsion are not required to end the starburst in these systems. In addition, post-starbursts were found to be offset from the Kennicutt–Schmidt (KS) relation (Kennicutt 1998) observed in normal star-forming and starburst galaxies (French et al. 2015; Smercina et al. 2018; Li et al. 2019; Smercina et al. 2022), with SFRs that are suppressed by a factor of ~10 compared to galaxies with similar molecular gas surface densities. Smercina et al. (2022) suggested that the star formation in these systems is suppressed by significant turbulent heating of the molecular gas.

The traditional selection and classification scheme of post-starburst galaxies relies on their optical spectra (see review by French 2021). As a result, the star formation properties of post-starburst galaxies have been typically derived from optical observations, using for example, the H\(_{\alpha}\) emission line or the Dn4000˚A index. The optically-derived SFRs place most of these systems on or below the star-forming main sequence, consistent with the idea that they are completely quenched or transitioning to quiescence. However, using infrared and radio observations, several studies found significant obscured star formation in systems showing post-starburst signatures in their optical spectrum (Smail et al. 1999; Poggianti & Wu 2000; Smercina et al. 2018; Baron et al. 2022). In particular, in Baron et al. (2022) we used far-infrared observations and found that many systems selected to have post starburst signatures in their optical spectrum ("post-starburst candidates" hereafter) are in fact obscured starbursts.

In this paper we combine far-infrared and Carbon Monoxide (CO) observations to study the star formation and molecular gas properties of post-starburst galaxy candidates. We present new CO observations for a sample of 15 galaxies selected from our parent sample of post-starburst candidates with AGN and ionized outflows from Baron et al. (2022). We combine this sample with several other samples of post-starburst candidates with available CO observations. This allows us to study the molecular gas properties of post-starburst candidates with different emission line properties. The paper is organized as follows. In section 2 we describe our observations and data analysis, and describe the other samples we consider. We present our results in section 3, discuss their implications in section 4, and summarize in section 5. We provide a description of the data availability in section 6. Throughout this paper we use a Chabrier initial mass function (IMF; Chabrier 2003), and assume a standard ΛCDM cosmology with Ω\(_{M}\) = 0.3, Ω\(_{\Lambda}\) = 0.7, and h = 0.7.

## 2 Observations and Data Analysis

### 2.1 Sample Selection

Our parent sample of post-starburst galaxy candidates with AGN and ionized outflows was drawn from the Sloan Digital Sky Survey (SDSS; York et al. 2000), and is described in detail in Baron et al. (2022). We fitted stellar population synthesis models to all the galaxies at z < 3, and measured the equivalent width (EW) of the H\(_{\alpha}\) absorption line. We define post-starburst galaxy candidates as systems for which EW(H\(_{\alpha}\)) > 5 Å. We performed line profile decomposition into narrow and broad kinematic components, where the former traces stationary gas, while the latter originates from outflowing gas. We selected systems with narrow line ratios that are consistent with AGN photoionization (including LINERs). Systems with detected broad components in both Balmer and forbidden lines were defined as post-starburst galaxies hosting AGN and ionized outflows.

We found a total of 215 post-starburst candidates with AGN and ionized outflows, out of which 144 show evidence for an ionized outflow in multiple lines: [OII] \(\lambda\lambda 3725,3727\) Å, H\(_{\beta}\) \(\lambda 4861\) Å, and [SII] \(\lambda\lambda 6717,6731\) Å.
Table 1. The NOEMA sample.

| Object ID | RA (J2000) | Dec. (J2000) | z | t_{obs} (hr) |
|-----------|------------|-------------|---|-------------|
| 0626-52057-0460 | 16:27:38.07 | 44:53:42.12 | 0.179 | 3.00 |
| 1008-52707-0017 | 10:28:37.36 | 50:23:50.93 | 0.092 | 2.13 |
| 1463-53063-0262 | 13:24:01.63 | 45:46:20.69 | 0.125 | 3.00 |
| 1605-53062-0122 | 11:19:43.84 | 10:50:37.17 | 0.177 | 3.50 |
| 1609-53142-0564 | 11:52:59.31 | 13:07:18.76 | 0.104 | 2.49 |
| 1646-53498-0129 | 14:46:39.62 | 33:21:29.32 | 0.070 | 2.10 |
| 1686-53472-0386 | 16:36:14.09 | 29:16:12.73 | 0.136 | 2.10 |
| 1766-53468-0172 | 12:16:22.73 | 14:17:53.02 | 0.082 | 2.16 |
| 1773-53112-0588 | 13:21:11.30 | 14:54:52.13 | 0.103 | 4.50 |
| 1870-53383-0446 | 07:59:27.49 | 53:37:48.23 | 0.084 | 2.10 |
| 2026-53711-0219 | 10:50:41.50 | 31:19:50.38 | 0.115 | 2.31 |
| 2268-53682-0278 | 08:04:27.84 | 13:29:30.73 | 0.134 | 2.46 |
| 2345-53757-0457 | 10:03:34.27 | 28:50:31.53 | 0.138 | 2.60 |
| 2494-54174-0129 | 11:20:23.91 | 15:43:54.63 | 0.159 | 2.46 |
| 6281-56295-0012 | 00:34:43.68 | 25:10:20.96 | 0.118 | 2.25 |

(1): SDSS identifier PLATE-MJD-FIBER. (2) and (3): SDSS right ascension and declination. (4): SDSS redshift. (5): NOEMA integration time.

Using the ionized outflow properties, we selected a subset of 32 systems for follow-up observations. These galaxies show the highest signal-to-noise ratios (SNRs) in the broad kinematic components of the [OII] and Hα emission lines. Such a selection is biased towards objects with more luminous emission lines, and since emission line luminosity is correlated with AGN bolometric luminosity and SFRs. Roughly half of the objects can be observed from the Northern hemisphere.

2.2 NOEMA observations

We used the Northern Extended Millimeter Array (NOEMA) of the Institute of Radioastronomy in the Millimeter (IRAM)1 to observe the CO(1-0) line in 15 galaxies (project W19BS). The observations were carried out with 10 antennas in C or D configurations under good weather conditions. The NOEMA receivers provide two orthogonal linear polarizations, each delivering a bandwidth of 7.744GHz. The observations were calibrated using the task *go clean*, and show in figure A1 in the appendix the integrated spectra around the CO(1-0) transition. The CO line intensity was estimated by integrating over these spectra. The statistical uncertainty in the line intensity is defined as 

$$\sigma_L = \Delta v \sigma_\text{rms} N_s \left(1 + N_s / N_b \right),$$

where $\Delta v$ is the channel velocity width, $\sigma$ is the channel RMS noise, $N_s$ is the number of channels used to integrate over the line, and $N_b$ is the number of channels used for the baseline fitting.1

We identified the emission line channels in each USB uv-table and used the task *uv baseline* to fit and subtract a constant baseline. We produced clean images using the task *go clean*, and show in figure A1 in the appendix the integrated spectra around the CO(1-0) transition. The CO line intensity was estimated by integrating over these spectra. The statistical uncertainty in the line intensity is defined as 

$$\sigma_L = \Delta v \sigma_\text{rms} N_s \left(1 + N_s / N_b \right),$$

where $\Delta v$ is the channel velocity width, $\sigma$ is the channel RMS noise, $N_s$ is the number of channels used to integrate over the line, and $N_b$ is the number of channels used for the baseline fitting.1

The CO line luminosity in K km/sec pc² is given by

$$L'_\text{CO} = 3.25 \times 10^7 S_{\text{CO}} \Delta v \nu_{\text{obs}}^2 D_l^2 (1 + z)^{-3},$$

where $S_{\text{CO}} \Delta v$ is the velocity-integrated flux in Jy km/sec, $\nu_{\text{obs}}$ is the observed frequency in GHz, $D_l$ is the luminosity distance in Mpc, and $z$ is the redshift. The molecular gas mass is given by $M_H = \alpha_{\text{CO}} L'_\text{CO}$, where $\alpha_{\text{CO}}$ is the CO conversion factor. We assume a constant conversion factor similar to the Milky Way disc, $\alpha_{\text{CO}} = 4.3 M_\odot$ (K km/sec pc²)⁻¹ (Bolatto, Wolfire & Leroy 2013). We verified that other definitions for the conversion factor (bimodal or CO intensity-weighted $\alpha_{\text{CO}}$; e.g., Narayanan et al. 2012) do not affect our conclusions.

To study the spatial extent of the CO line emission we combined the baseline-subtracted line channels in each USB with the task *uv continuum*. Using the graphical interface of MAPPING, we fitted each object with a point source and a circular Gaussian in the uv-plane. For the point source fits, we inspected the clean images of the residuals and found significant residuals in most of our sources, suggesting that the emission is spatially-resolved. For the circular Gaussian fits, the residuals in the clean images are consistent with those of the background. We verified that the integrated CO fluxes from the circular Gaussian fits are consistent with the fluxes estimated from the spatially-integrated CO spectra. We consider the CO emission as spatially-resolved if the best-fitting full width at half maximum (FWHM) of the circular Gaussian fit is larger than three times its uncertainty. Out of 14 objects with detected CO lines, we spatially-resolve the emission in 13.

To estimate the mm continuum flux, we combined all the non-line channels in the LSB and USB separately. For each object in each sideband (LSB/USB), we defined a polygon around the source to estimate the flux, and a polygon outside the source to estimate the RMS, which we defined.
as the flux uncertainty. To study the spatial extent of the continuum emission we combined the LSB and USB channels and fitted each object with a point source and a circular Gaussian in the uv-plane. We detect mm continuum emission in 11 sources, and spatially-resolve it in the three brightest objects. For these three sources, the derived extents are close to the extents derived from the CO emission. In section 2.3 below, we combine the mm fluxes with archival far-infrared observations to estimate the SFR or its upper limit for every object in our sample. Table 2 summarizes the CO and mm continuum emission properties for our systems, and table 3 the measured molecular masses.

2.3 IRAS far-infrared data

We make use of publicly-available far infrared photometry from the Infrared Astronomical Satellite (IRAS; Neugebauer et al. 1984). IRAS provides a full-sky coverage in four bands centered around 12, 15, 60, and 100 µm, including several scans of individual fields. Our method to extract the 60 µm fluxes follows the approach described in Baron et al. (2022) which we briefly summarize here. We used SCANPI (Helou & Walker 1985) to stack the calibrated surveys scans around the SDSS coordinates of our objects. We used the default settings of SCANPI, with ‘Source Fitting Range’=3.2, ‘Local Background Fitting Range’=30’, and ‘Source Exclusion Range for Local Background Fitting’=4’, and used median stacks since the IRAS data has non-Gaussian noise. The SCANPI output includes the best-fitting flux density ($f_v$), the RMS deviation of the residuals after the subtraction of the best-fitting template ($\sigma$), the offset of the peak of the best-fitting template from the galaxy coordinates ($\Delta$), and the correlation coefficient between the best-fitting template and the data ($\rho$). To avoid contamination by false matches and noise fluctuations, we consider a source detected if the following requirements are met: $\rho > 0.8$, $\Delta < 0.4'$, and $f_v/\sigma > 3$ (see details in Baron et al. 2022). We defined the flux uncertainty of the detected sources to be $\sigma$. For undetected sources, we defined their flux upper limit to be $3\sigma$. Out of 15 objects, 5 are detected in 60 µm and the rest are considered upper limits.

To estimate the SFR in each source, we combined the mm continuum fluxes (LSB and USB) from NOEMA and the 60 µm flux by IRAS. We used the Chary & Elbaz (2001) templates to search for the template that best fits the far-infrared and mm flux measurements or upper limits. Each CE01 template corresponds to a different star formation luminosity, $L_{SF}$, allowing us to estimate $L_{SF}$ in sources where at least one of the three flux measurements is available (60 µm, LSB, and USB). For objects where both far-infrared and mm fluxes are measured, we found a good correspondence between the three flux measurements and the best-fitting template. For objects where only upper limits are available, we placed an upper limit on $L_{SF}$. Following Baron et al. (2022), we adopted a conservative uncertainty on $L_{SF}$ of 0.2 dex. In figure 2 in the appendix we show the far-infrared and mm luminosities, along with the best-fitting star formation templates. We estimated the SFR from $L_{SF}$ assuming a Chabrier initial mass function (IMF; Chabrier 2003) which we rounded off slightly to give SFR = $L_{SF}/10^{10} L_{\odot} [M_{\odot}/yr]$. Out of the 15 objects in our sample, we estimated the SFR in 12 systems, and placed upper limits on the remaining 3. We list the SFRs in table 4.

2.4 Galaxy properties from optical and ultraviolet observations

We use several properties derived from the SDSS optical spectra and photometry. We use the Petrosian radius measured in r-band from the SDSS photometric catalogs (Petrosian 1976). We use the stellar masses and the Dn4000A-
Table 3. Integrated galaxy properties.

| Object ID | $r_{25}$ | log SFR(Dn4000A) | log $M_*$ | $t_{fibr}$ | log $M_{H_2}$ | log SFR(FIR + mm) | $r_{CO}$ | log $\Sigma_{gas}$ | log $\Sigma_{SFR}$ |
|-----------|---------|----------------|----------|-----------|----------------|------------------|--------|----------------|----------------|
| 0626-52057-0490 | 5.89 | -0.89 | 10.35 | 90 | | | | | |
| 1008-52070-0017 | 6.47 | 0.17 | 10.50 | 79 | | | | | |
| 1463-53063-0262 | 8.65 | 0.56 | 10.49 | - | | | | | |
| 1605-53062-0122 | 8.17 | 0.81 | 10.70 | -88 | | | | | |
| 1609-53142-0564 | 4.63 | 0.13 | 10.47 | 69 | | | | | |
| 1644-53498-0129 | 4.81 | -1.19 | 10.62 | 279 | | | | | |
| 1686-53472-0386 | 14.35 | 0.95 | 11.09 | 57 | | | | | |
| 1776-53468-0172 | 3.22 | 0.03 | 10.36 | 20 | | | | | |
| 1773-53112-0588 | 4.77 | 0.64 | 10.20 | - | | | | | |
| 1870-53383-0446 | 3.99 | -0.88 | 10.67 | 104 | | | | | |
| 2026-53711-0219 | 7.50 | -0.04 | 10.53 | 121 | | | | | |
| 2268-53682-0278 | 6.44 | 0.00 | 10.00 | 63 | | | | | |
| 2345-53757-0457 | 5.01 | -1.00 | 10.40 | 8 | | | | | |
| 2494-54174-0129 | 10.73 | 1.14 | 10.89 | 68 | | | | | |
| 6281-56295-0012 | 10.19 | 0.00 | 11.05 | - | | | | | |

**Columns.** (1): SDSS identifier PLATE-MJD-FIBER. (2): Petrosian radius measured in $r$-band from the SDSS. (3) Dn4000A-based SFR from the MPA-JHU catalog. (4) Stellar mass from the MPA-JHU catalog. (5) Post-burst age: the time elapsed since 90% of the stars were formed in the more recent burst(s). (6) Molecular gas mass from CO emission. (7) SFR derived from fitting the far-infrared fluxes by IRAS and mm fluxes by NOEMA. (8) Half-light radius of the CO emission. (9) Gas surface density. (10) SFR surface density.

**Notes.** †: a negative post-burst age, suggesting that 90% of the population has not yet been formed.

The objects in our sample were selected to have strong Hδ absorption (EW(Hδ) > 5Å), suggesting a recent starburst that was quenched abruptly. To derive their star formation history (SFH), we performed the stellar population synthesis modeling described in French et al. [2018], Tremonti et al. [2004], Salim et al. [2007]. All these properties are listed in table [3].

The French et al. [2018] SFH model has several free parameters. The first is the time elapsed since the first starburst began. In the case of a single recent burst, the burst duration is a free parameter of the model. In the case of two recent bursts, the burst duration is set to a characteristic timescale of 25 Myrs, while the time separation between the bursts is a free parameter of the model. In both cases, the mass fraction of the young stellar population with respect to the total stellar mass is a free parameter of the model (see additional details there).

Using the modeled SFH, French et al. [2018] constructed model template spectra using the stellar population synthesis models by Conroy, Gunn & White [2009] and Conroy & Gunn [2010]. By fitting the templates to the GALEX and SDSS observations, they derived the best SFH model parameters. They also defined the "post-burst age" as the time elapsed since 90% of the stars were formed in the more recent burst(s). Therefore, the "post-burst age" represents the age of the recently-quenched starburst, as seen in ultraviolet and optical wavelengths.

We applied the above age-dating technique to the objects in our sample. For three of the sources we found non-physical SFHs, where the mass fractions of the young stellar populations are 1, suggesting that all stars in these galaxies were formed in the recent burst(s). The derived peak SFRs during the burst exceed 100 $M_\odot$/yr, comparable to those observed in the most extreme ULIRGs in the local universe. The ultraviolet and optical observations of these sources are completely dominated by the young stellar population, resulting in a young stellar mass fraction of 1. Near-infrared photometry (e.g., 2MASS J, H, and K bands: Skrutskie et al. [2006]) is required to constrain the old stellar population in these sources, thus obtaining physical mass fractions. We therefore omit these three sources from further optical age-dating analysis. For one object, we obtained a negative post-burst age, suggesting ongoing star formation. We list the post-burst ages in table [3] and the best-fitting SFH parameters are given in table [A1] in the appendix.

2.5 Statistical methods

Our sample includes a number of upper limits on both SFR and $M_{H_2}$. To perform linear regression in the case of upper limits only in the dependent variable, we used the Python implementation of LINMIX (Kelly 2007). LINMIX is a
Table 4. Properties of post-starburst candidates from the literature.

| Sample                  | Post-starburst selection | Emission line properties | $N_{obj}$ | $M_H^*$ detections | SFR(FIR) detections |
|-------------------------|--------------------------|--------------------------|-----------|-------------------|-------------------|
| French et al. (2015)    | H$_\delta$ - $e$(H$_\delta$) > 4Å | EW(H$\alpha$) < 3Å | 32        | 17 (53%)          | 32 (100%)         |
| Rowlands et al. (2015)  | PCA on 3175–4150Å: selection according to H$\delta$ and Dn4000Å | SF/AGN/composites | 11        | 10 (90%)          | 9 (81%)           |
| Alatalo et al. (2016b)  | H$_\delta$ > 5Å          | SF/AGN/composites        | 52        | 47 (90%)          | 35 (67%)          |
| Yesuf et al. (2017)     | H$\delta$P $\geq$ 3Å & cuts on (NUV-g)  | Seyferts                | 24        | 6 (25%)           | 12 (50%)          |

Bayesian method that accounts for measurement uncertainties in both the dependent ($y$) and independent ($x$) variables, but it is only suitable for datasets with upper limits on $y$. To perform linear regression in the case of upper limits in both $x$ and $y$, we used the analytic likelihoods derived by [1] (2017). These likelihoods take into account both measurement uncertainties and upper limits in both of the variables. Using these likelihoods, we derived posterior probability distributions of our model parameters using the nested sampling Monte Carlo algorithm MLFRIENDS [Buchner 2014, 2017] with the ULTRANEST package [Buchner 2021]. For the cases where the upper limits are only on $y$, we applied both methods and found consistent results.

2.6 Post-starburst candidate samples from the literature

To obtain a more global view, we collected additional published information about post-starburst galaxies with CO measurements. We used the samples presented by [French et al. (2015), Rowlands et al. (2015), Alatalo et al. (2016b), and Yesuf et al. (2017)] All these studies selected post-starburst candidates using their optical spectra, in particular using the H$\alpha$ absorption and/or the Dn4000Å index. The objects in the different samples differ in their emission line properties, since some of the samples were selected to have weak emission lines, while others were selected according to their emission line ratios. We used the molecular gas masses reported by the different studies, and scaled them so that $\alpha_{CO} = 4.3 M_\odot (K \text{ km/sec } pc^2)^{-1}$. The properties of the different samples are summarized in table 4.

To estimate the far-infrared-based SFR in these sources, we used SCANPI to extract their 60μm fluxes and the [Baron et al. (2022)] method assuming $L_{SF} = 1.716 \times \nu L_{\nu}(60\mu m)$, which we then converted into SFRs using the expression given in section 2.3. The objects from [French et al. (2015)] were followed up with far-infrared Herschel observations [Smercina et al. (2018)]. Since these are deeper than the archival IRAS scans, we used the total infrared luminosities reported in [Smercina et al. (2018)], and converted them to star formation luminosities (8–1000 μm) using $L_{SF} = L_{TIR}/1.06$, where $L_{TIR}$ is the total infrared luminosity (3–1100 μm). For the [French et al. (2015)] sources that were detected in 60μm by IRAS, we verified that the IRAS-based SFRs are consistent with those obtained with Herschel. In table 4 we list the detection fractions of SFR(far-infrared).

We also collected the stellar masses and Dn4000Å-based SFRs reported in the MPA-JHU catalog for these sources. [French et al. (2018)] applied their age-dating technique to the objects of [French et al. (2015), Rowlands et al. (2015), and Alatalo et al. (2016b)]. We used the best-fitting SFH parameters presented there. We applied the age-dating technique to the objects of [Yesuf et al. (2017)], and list the best-fitting SFH parameters in table A2 in the appendix.

3 RESULTS

3.1 Obscured star formation

Post-starburst galaxy candidates are usually selected by optical spectra, with their star formation properties derived from optical observations. According to the traditional selection scheme, galaxies with strong H$\alpha$ absorption are classified as post-starburst candidates. Post-starburst galaxy candidates with weak emission lines have been classified as quenched, and those with emission lines as transitioning to quiescence (e.g., [Yesuf et al. (2014), Alatalo et al. (2016a), French et al. (2018) and references therein]). A major assumption of this scheme is that optically-derived properties, such as the H$\alpha$ emission, H$\delta$ absorption, and the Dn4000Å index, can be used to infer the star formation properties of these systems. Therefore, a key component unaccounted for by the scheme is the presence of obscured star formation. For example, [Poggiotti & Wu (2000)] found that ~50% of their very luminous infrared galaxies show strong H$\alpha$ absorption and weak line emission. Using this scheme, such sources would have been classified as quenched post-starburst galaxies (see also [Tremonti, Moustakas & Diamond-Stanic 2007, Diamond-Stanic et al. 2012]).

In [Baron et al. (2022)] we used IRAS far-infrared observations to study the star formation properties of several large samples of post-starburst candidates. We found that many of these systems host obscured starbursts, and that optically-derived properties, such as the H$\alpha$ emission or the Dn4000Å index, do not represent their intrinsic star-forming
Post-starburst galaxies are not truly post starburst

nature. Here we repeat part of the analysis presented in Baron et al. (2022), concentrating on post-starburst candidates with available $M_{\text{H}_2}$ measurements. We also perform a more general comparison of the optical and far-infrared information, and examine whether the optically-derived SFH can account for the observed far-infrared emission.

In figure 1 we compare between the SFRs derived from far-infrared observations and the Dn4000Å index. We present the 15 sources we observed with NOEMA, and the post-starburst galaxy candidates described in section 2.6. For comparison, we also present the far-infrared and optical SFRs derived for the xCOLD GASS survey (Saintonge et al. 2017). The full xCOLD GASS sample includes 532 galaxies with CO(1-0) measurements from the IRAM 30 m telescope. The galaxies in this sample were mass-selected in $0.01 < z < 0.05$ to be representative of the local galaxy population with $M_*>10^9 M_\odot$. We used scanpi to extract their 60 μm fluxes and estimated their far-infrared-based SFRs. We show the best-fitting linear relation between SFR(far-infrared) and SFR(Dn4000Å) obtained with linmix for the xCOLD GASS emission-line galaxies. The best-fitting relation is very close to a one-to-one relation for SFR $\lesssim 0.3 M_\odot/yr$, suggesting that for this sample, SFRs derived from far-infrared and optical observations are consistent with each other. On the other hand, most of the post-starburst galaxy candidates are above the one-to-one relation, with some sources showing SFR(far-infrared) which is two orders of magnitude larger than that derived using the Dn4000Å index.

In figure 2 we show SFR versus stellar mass for post-starburst galaxy candidates, where the left panel shows the optical SFR and the right panel the far-infrared SFR. For comparison, we present the xCOLD GASS emission line galaxies, where we use the SFRs reported in their catalog, which are based on a combination of ultraviolet and mid-infrared photometry (Janowiecki et al. 2017). We verified that the reported SFRs are consistent with those we obtained using IRAS far-infrared observations. We also present the sample of luminous and ultraluminous infrared galaxies by U et al. (2012), where the SFRs and stellar masses were estimated using radio to X-ray SED fits. According to figure 2, the optically-based SFRs place most of the post-starburst candidates on or below the star-forming main sequence, with roughly half of the sources being one order of magnitude below it. However, the far-infrared observations place many of the galaxies above the star-forming main sequence, with some of the systems showing SFRs which are comparable to those of (ultra)luminous infrared galaxies. Figure 2 also suggests that the galaxies in the different post-starburst samples have different SFR properties, with the objects from Alatalo et al. (2016a) showing the largest SFRs, followed by our sources, the Yesuf et al. (2017) sources, and finally the French et al. (2015) sources. This is in line with Baron et al. (2022), where we found that post-starburst candidates with more luminous emission lines are more likely to be found above the main sequence (see additional details there).

In figure 3 we show the location of the galaxy with respect to the star-forming main sequence, $\Delta$(MS), as a function of the optical post-burst age, $\Delta$(MS) was estimated using far-infrared SFRs, assuming the Whitaker et al. (2012) star-forming main sequence. The post-burst age was estimated from stellar population synthesis modeling of the optical spectra. Figure 3 shows a significant scatter, with, for example, systems with post-burst ages of 200 Myrs showing SFRs 1 dex above and 1 dex below the main sequence. This suggests that the optical post-burst age does not trace the obscured star formation in the system, and cannot be used to accurately determine the age of the starburst.

Several studies suggested that far-infrared emission may overestimate the true SFR in post-starburst galaxies (e.g., French et al. 2015; Smercina et al. 2018; Li et al. 2019). These suggestions are based on the recent work by Hay...
To test the possibility that the far-infrared emission is powered by the recently-quenched starburst seen in the optical (i.e., the A-type stars), we followed the same approach we presented in Baron et al. (2022). We used the optically-derived best-fitting SFHs of the post-starburst candidates, and estimated the expected far-infrared emission which is unrelated to ongoing star formation. However, Hayward et al. (2014) found a significant boost of $\sim 2$ dex to the far-infrared emission only for systems with SFR(far-infrared)$\gtrsim 1 M_\odot$/yr, while figure 2 shows that many of the post-starburst candidates we consider have SFR(far-infrared)$>1 M_\odot$/yr.

To estimate the far-infrared emission driven by the post-burst population, we used the formalism presented in Hirashita, Buat & Inoue (2003). In the most extreme case of dust-obscured starbursts, dust covers the stellar population entirely and absorbs all its radiation. In this case, the dust far-infrared emission will be equal to the total bolometric luminosity. In the more realistic case of partial obscuration, the far-infrared emission will be some fraction of the total bolometric luminosity: $L_{\text{FIR}} = k \times L_{\text{bol}}$. Hirashita, Buat & Inoue (2003) showed that $k \sim 0.5$ in star-forming galaxies. We examine a broader range of $k \sim 0.3$ to $k = 1$, where the latter describes dust-obscured starbursts.

In figure 4 we compare between the observed far-infrared emission and that expected from the recently-quenched starburst. Here we use Padova tracks with solar metallicity, and use $k = 0.5$. Most of the galaxies are above the one-to-one line, suggesting that the observed far-infrared emission is larger than that expected from the post-burst population observed in optical wavelengths. Excluding the sources by French et al. (2015), figure 4 shows that the observed far-infrared emission is 10–100 times brighter than that expected from the optical information. This suggests that the observed far-infrared emission is not powered by the remaining A-type stars, but instead is powered by ongoing obscured star formation. We reach similar conclusions when using Padova tracks with 0.4 or 2.5 solar metallicity, and for the entire range of $k$ observed in star-forming galaxies, from roughly 0.3 to 1. Figure 4 shows that roughly half of the French et al. (2015) sources lie on or below the one-to-one line. These galaxies also have SFR(far-infrared)
Post-starburst galaxies are not truly post starburst

3.2 SFR versus $M_{H_2}$

Standard galaxy evolution scenario suggests that the termination of star formation is the result of the exhaustion of the molecular gas reservoir, which can be depleted by star formation, stellar feedback, or AGN feedback (e.g., Hopkins et al. 2006). Recent studies challenged this picture, by finding significant molecular gas reservoirs in systems that were selected to have post-starburst signatures in optical wavelengths (e.g., French et al. 2015, Rowlands et al. 2015, Alatalo et al. 2016b, Yesuf et al. 2017, Yesuf & Ho 2020). For example, French et al. (2015) detected CO emission in 53% of their post-starburst galaxies, finding molecular gas fractions that are consistent with star-forming galaxies. Alatalo et al. (2016b) detected CO emission in 90% of their post-starbursts, and found molecular gas fractions that are even larger than those found by French et al. (2015). More recent studies combined the molecular gas measurements with optically-derived SFHs to study the evolution of the molecular gas reservoir as the starburst ages. In particular, French et al. (2018) found a significant decline in the molecular gas fraction as a function of the post-burst age, which they attributed to AGN feedback. Li et al. (2019) found a significant decline in the star formation efficiency (SFR/$M_{H_2}$) as a function of the post-burst age, suggesting that SFR is decoupled from $M_{H_2}$ and declines faster, possibly also due to AGN feedback.

In this section we use the far-infrared SFRs to show that the molecular gas mass in post-starburst candidates is consistent with their SFR, and that systems that were reported to have large molecular gas reservoirs with respect to their (optical) SFR host in fact obscured star-forming regions. We then show that the recently discovered trends between SFR, $M_{H_2}$ and the post-burst age are the direct result of the SFR(far-infrared)-$M_{H_2}$ correlation and the usage of inaccurate optical SFRs. Therefore, these trends do not trace the true evolution of the molecular gas reservoir with the starburst age. The results presented in this section are
Figure 5. SFR versus \( M_{\text{H}_2} \) using optical and far-infrared-based SFRs. The points represent measurements and arrows represent upper limits, where arrows pointing down are upper limits on SFR, arrows to the left on \( M_{\text{H}_2} \), and diagonal arrows to the bottom left on both SFR and \( M_{\text{H}_2} \). Each color corresponds to a different sample, as indicated in the legend on the right. For the post-starburst galaxy candidates, the left panel shows the optical SFR derived from the Dn4000 Å index, and the right panel shows the far-infrared SFR derived from 60 \( \mu \)m IRAS observations. For the comparison galaxies, the left and right panels show the SFRs reported by the different surveys, and thus are identical in both panels. The figure shows that once far-infrared SFRs are used, post-starburst candidates do no longer show exceptionally large molecular gas reservoirs.

Figure 6. Comparison of best-fitting SFR-\( M_{\text{H}_2} \) relations in post-starbursts and comparison galaxies. Points and arrows represent measurements and upper limits respectively. The solid lines represent the best-fitting SFR-\( M_{\text{H}_2} \) relations, including upper limits and uncertainties in both variables. The insert at the top left shows the stellar mass distributions of post-starburst galaxies (red) and galaxies from the comparison sample (grey). To match the stellar mass distributions, only \( \log M_*/M_\odot > 10 \) galaxies were selected for comparison.

consistent with the common galaxy evolution picture, where the decrease in SFR is due to the consumption of molecular gas by the starburst (e.g., Rowlands et al. 2015).

In figure 5 we show SFR versus \( M_{\text{H}_2} \) for the post-starburst galaxy candidates, where the left panel shows the optical SFR and the right panel the far-infrared SFR. For comparison, we also show the xCOLD GASS emission line galaxies and the (ultra)luminous infrared galaxies by Gao & Solomon (2004). In both cases we rescaled the molecular gas masses so that \( \alpha_{\text{CO}} = 4.3 \, M_\odot (K \text{ km/sec pc}^2)^{-1} \). According to the left panel of figure 5 when using optically-derived SFRs, many post-starburst candidates deviate from the SFR-\( M_{\text{H}_2} \) relation observed in other galaxies, showing significantly larger molecular gas masses. However, the right panel of the figure shows that if far-infrared SFRs are used instead, then post-starburst candidates show a similar SFR-\( M_{\text{H}_2} \) relation to that observed in other galaxies. That is, post-starburst galaxies that were reported to have significant molecular gas reservoirs also have high SFR.

In figure 6 we compare between SFR-\( M_{\text{H}_2} \) relations obtained for post-starbursts and for non-post-starburst galaxies. Our comparison sample includes all the galaxies with \( \log M_*/M_\odot > 10 \) from the xCOLD GASS survey or from Gao & Solomon (2004). We chose this stellar mass cut to ensure that the stellar mass distribution of the galaxies in the comparison sample matches the distribution in the post-starbursts samples. The best-fitting relations were estimated using the methods described in section 2.5 which take into account both uncertainties and upper limits in both variables. The diagram shows that the best-fitting SFR-\( M_{\text{H}_2} \) relation in post-starburst candidates is consistent with that...
Figures 7 and 8 present the derived molecular gas masses for $\alpha_{\text{CO}} = 4.3 \text{M}_\odot (\text{K km sec}^{-1} \text{pc}^{-2})^{-1}$. However, some of the sources in the different samples are (ultra)luminous infrared galaxies, for which lower conversion factors are more appropriate (e.g., Narayanan et al. 2012; Tacconi, Genzel & Sternberg 2020 and references therein). Here and in section 3.3 below, we verified that other definitions for the conversion factor (bimodal or CO intensity-weighted) do not affect our conclusions.

Finally, we revisit the recently-discovered trends between SFR, $M_{\text{H}_2}$ and post-burst age (French et al. 2018; Smercina et al. 2022), which they attributed to depletion of molecular gas by AGN feedback. We suggest that the decline is driven by the tight correlation between SFR(far-infrared) and $M_{\text{H}_2}$, and the weak decline of SFR(far-infrared) as a function of post-burst age. Indeed, the ratio of the SFR to $M_{\text{H}_2}$ is nearly constant with the post-burst age, suggesting that the reported decline in $M_{\text{H}_2}$ is due to depletion of molecular gas by the starburst. The resulting depletion times, around $10^9$ yrs, are consistent with those observed in other non E+A galaxies.

Li et al. (2019) found a significant decline in star formation efficiency as a function of post-burst age, where the star formation efficiency drops from log SFE $\sim -8$ at post-burst age of $\sim 0$ Myrs to log SFE $\sim -12$ at 500 Myrs. In contrast, figure 8 shows a nearly constant star formation efficiency, with log SFE $\sim -9$ for post-burst ages 0–750 Myrs. In appendix B we repeat the analysis presented in Li et al. (2019) and show that the significant decline they detect is due to their use of optical SFRs. Once far-infrared SFRs are used, we find that the star formation efficiency does not evolve with the post-burst age, consistent with figure 7.

### 3.3 The Kennicutt–Schmidt relation

Previous studies found that post-starburst galaxy candidates are offset from the Kennicutt–Schmidt (KS) relation (Kennicutt 1998), with SFRs that are suppressed by a factor of $\sim 10$ compared to galaxies with similar gas surface densities (French et al. 2015; Smercina et al. 2018; Li et al. 2019; Smercina et al. 2022). The earlier works by French et al. (2015) and Li et al. (2019) were based on unresolved infrared/CO observations. Thus, they used the SDSS Petrosian radii to convert the SFR and $M_{\text{H}_2}$ to surface densities. However, Smercina et al. (2018) used resolved infrared observations to show that the half-light mid-infrared radii, which are expected to better trace the star formation and molecular gas regions, are 3–4 times smaller than the optical sizes of those systems. Smercina et al. (2022) used ALMA observations to resolve the star formation and CO emitting regions in six post-starburst candidates, finding highly compact molecular gas regions, and an offset of $\sim 0.3$ dex from the KS relation.

In figure 8 we show the KS relation for the post-starburst candidates in our NOEMA sample. We used the CO half-light radii to convert the SFR and $M_{\text{H}_2}$ to surface densities (see table 3). Similarly to Smercina et al. (2018, 2022), our inferred CO half-light radii are 2.5–4 times smaller than the optical radii of the galaxies. As a comparison, we show the dwarfs, spirals, circumnuclear disks, and...
Figure 8. Kennicutt–Schmidt relation of post-starburst galaxy candidates. The points represent measurements and triangles represent upper limits, where each color corresponds to a different post-starburst sample, as indicated in the legend at the top. The comparison galaxies include the dwarfs, spirals, circum-nuclear disks, and luminous infrared galaxies from de los Reyes & Kennicutt (2019) and Kennicutt & De Los Reyes (2021), and are marked with black empty symbols. For the dwarfs and spirals, $\Sigma(\mathrm{HI} + \mathrm{H}_2)$ is plotted, while for the infrared luminous galaxies, $\Sigma(\mathrm{H}_2)$ is plotted. The SFRs were estimated assuming a uniform conversion from total infrared luminosity, and the molecular gas masses were estimated assuming a similar CO conversion factor (see text for additional details). The figure shows that once far-infrared SFRs are used, post-starburst candidates are not offset from the KS relation as previously argued.

luminous infrared galaxies from de los Reyes & Kennicutt (2019) and Kennicutt & De Los Reyes (2021), assuming a constant $\alpha_{\mathrm{CO}} = 4.3 \, M_\odot / (\mathrm{K} \, \mathrm{km} / \mathrm{s} \, \mathrm{pc}^2)$ for all systems. We rescale their reported SFRs to match our conversion from far-infrared luminosity to SFR described in section 2.6.

We also include in the figure the six post-starburst galaxies presented in Smercina et al. (2022). We used their total infrared luminosities, which we converted to SFRs using the expressions given in section 2.6. For the gas surface densities, we used their CO luminosities and sizes, and estimated the gas surface density assuming $\alpha_{\mathrm{CO}} = 4.3 \, M_\odot / (\mathrm{K} \, \mathrm{km} / \mathrm{s} \, \mathrm{pc}^2)$. While Smercina et al. (2022) suggest that their sources are offset from the KS relation, using the far-infrared SFRs, we find no offset from the KS relation. The Smercina et al. (2022) objects appear to be offset only when Neon- and [CII]-based SFR estimators are used. While Smercina et al. (2018) suggest that far-infrared emission may overestimate the true SFR, and advocate using Neon and [CII]-based SFRs, the offset reported in Smercina et al. (2022) is with respect to comparison galaxies for which the SFR was estimated using far-infrared information, rather than Neon or Carbon emission lines. Therefore, it is not clear whether an offset will still be observed once consistent SFR estimators are used for both E+A and comparison galaxies.

Figure 8 shows that the post-starburst galaxies we consider are not offset from the KS relation of other galaxies. The figure does not include the systems from Li et al. (2019) since they used optical radii to convert SFR and $M_{\mathrm{H}_2}$ to surface densities. However, in appendix B, we examine the KS relation of the Li et al. (2019) post-starbursts, and show that once far-infrared SFRs are used, these objects are no longer offset from the KS relation of other galaxies. The three samples combined (this work, Li et al. 2019 and Smercina et al. 2022) constitute the majority of post-starburst candidates with available CO measurements. Our results therefore suggest that once far-infrared information is taken into account, post-starburst candidates are not offset from the KS relation and their SFRs are not suppressed as previously claimed.

4 DISCUSSION

The combination of optical, infrared, and mm observations leads to the following emerging picture of post-starburst galaxy candidates, which is shown in figure 8. In an optically-selected post-starburst galaxy, some of the regions have experienced a recent and abrupt quenching of their star formation. As a result, these regions became optically-thin, and their observed optical spectrum is dominated by A-type stars. The optical emission lines trace the warm ionized gas within these quenched regions, with $\mathrm{H}_\alpha$ emission that suggests little ongoing star formation. These regions are dust and molecular gas poor, resulting in low SFR. Other regions within the galaxy host significant star formation which is obscured in optical wavelengths. The dust in these regions emits in infrared wavelengths, and their far-infrared SFRs place them on or above the star-forming main sequence. These regions have significant molecular gas reservoirs, and their star formation efficiencies are similar to those observed in star-forming and starburst systems. These regions are

2.5–4 times more compact than the optically-thin quenched regions.

Previous studies of post-starburst candidates suggested that they are offset from the SFR-$M_{\mathrm{H}_2}$ and Kennicutt–Schmidt relations of other types of galaxies, with star formation that is suppressed compared to galaxies with similar amount of molecular gas. Our analysis shows that those results were driven by the combination of observables originating from different regions within the galaxies. While the CO emission originates from the obscured star-forming regions, previous studies estimated the SFR using optical observations that trace the quenched optically-thin regions. Once far-infrared SFRs are used, post-starburst galaxy candidates show similar SFR-$M_{\mathrm{H}_2}$ and Kennicutt–Schmidt relations to those observed in other star-forming and star-bursting systems.

The weak correlation between the far-infrared SFR and the optically-derived post-burst age (figure 8) suggests little connection between the obscured star-forming regions...
Post-starburst galaxies are not truly post starburst

Quenched optically-thin regions:
- Little star formation and molecular gas.
- Traced by optical E+A-like spectrum and optical emission lines.

Obscured star-forming regions:
- Significant star formation and molecular gas.
- Traced by infrared and CO emission.
- 2.5-4 times more compact than the optically-thin regions.

Figure 9. Emerging picture of optically-selected post-starburst candidates. Such galaxies consist of two types of regions. Some regions have experienced a recent quenching of star formation, they are optically-thin, and emit an E+A-like optical spectrum. Their Hα emission suggests little ongoing star formation. Other regions host significant obscured star formation, and emit primarily at mm and far-infrared wavelengths. Their far-infrared SFRs place them on or above the star-forming main sequence, and their CO emission is consistent with this SFR.

and the quenched optically-thin ones. Galaxies with a post-burst age of 200 Myrs in the quenched optically-thin regions are found between 1 dex above and 1 dex below the star-forming main sequence when considering their far-infrared SFR. This calls into question the traditional classification of these sources as transitioning to quiescence. Although some regions within these galaxies have experienced a recent quenching of their star formation, we find no evidence of a global quenching taking place throughout these.

In Baron et al. (2022) we studied the far-infrared SFRs of post-starburst candidates with different emission line properties, and found that systems with more luminous emission lines tend to be above the star-forming main sequence when considering their far-infrared SFR. This calls into question the traditional classification of these sources as transitioning to quiescence. Although some regions within these galaxies have experienced a recent quenching of their star formation, we find no evidence of a global quenching taking place throughout these.

In this work we concentrated on a subset of the systems for which molecular gas measurements are available. The IRAS far-infrared detection fractions in this subset are larger than those we found in Baron et al. (2022), since most studies selected mid-infrared-bright galaxies for their followup CO observations. As a result, we found that even galaxies with weak emission lines show significant obscured star formation. Combining the results from Baron et al. (2022) and this work, we conclude that Hδ-strong, mid-infrared-faint galaxies with weak emission lines are the best candidates for truly-quenched post-starburst galaxies.

While figure 9 shows the quenched optically-thin and obscured star-forming regions as physically-distinct regions, the current observations do not allow us to constrain their geometry. Another option, suggested by Smercina et al. (2018), is of a "skin" effect, where significant obscured star formation is buried behind an optically-thin post-starburst skin. Spatially-resolved optical and mm observations are required to verify, or put constraints on such ideas.

5 SUMMARY AND CONCLUSIONS
We used NOEMA to observe the CO(1-0) line in 15 galaxies selected from our parent sample of post-starburst candidates with AGN and ionized outflows (Baron et al. 2022). We also collected all previous samples of post-starburst candidates with available CO observations. Combining the CO with archival far-infrared observations, we studied the star formation and molecular gas in post-starburst galaxy candidates with different emission line properties. Our main results are as follows.

(i) The derived far-infrared SFRs are significantly larger than the optical, Dn4000Å-based, SFRs for most of the post-starburst candidates we consider. While the optical SFRs place many of the systems on or below the star-forming main sequence, far-infrared observations place them above the main sequence, with some showing SFRs which are comparable to those of (ultra)luminous infrared galaxies. We rule out the possibility that the far-infrared emission is driven by the post-burst population (e.g., A-type stars), and instead argue that it is powered by significant obscured star formation (consistent with Baron et al. 2022).

(ii) Using stellar population synthesis modeling, we de-
derive the age of the recently-quenched starburst seen in optical, the “post-burst age” (French et al. 2018). The relation between the far-infrared SFR and the post-burst age shows significant scatter, suggesting little or no connection between the far-infrared and optically emitting regions (the obscured and optically-thin respectively).

(iii) Using far-infrared SFRs, post-starburst galaxy candidates show similar SFR-$M_{\text{H}_2}$ relation to that observed in star-forming and starburst galaxies. In particular, systems reported to have exceptionally large molecular gas reservoirs host in fact significant obscured star formation. We show that the recently-discovered trends between SFR, $M_{\text{H}_2}$, and the optical post-burst age (French et al. 2018; Li et al. 2019) are the result of the tight SFR(far-infrared)-$M_{\text{H}_2}$ correlation and the usage of the inaccurate optical SFRs. Once far-infrared SFRs are used, the star formation efficiency observed in post-starburst candidates does not evolve with the post-burst age, and is consistent with the efficiency observed in star-forming and starburst galaxies. Our results are consistent with the common galaxy evolution picture, where the decrease in SFR is due to the consumption of molecular gas by the starburst.

(iv) We argue that previous results claiming that post-starburst candidates are offset from the Kennicutt–Schmidt relation are due to the usage of inaccurate optical SFRs. Once far-infrared SFRs are used, post-starburst galaxy candidates show a similar Kennicutt–Schmidt relation to that observed in star-forming and starburst galaxies. Thus, the star formation in such systems is not suppressed as previously suggested.

The combination of optical, infrared, and mm observations suggests that optically-selected post-starburst galaxies are not necessarily post starburst. While some regions within these galaxies experienced a recent quenching of their star formation, other regions contain active star forming regions. These regions also contain significant amounts of molecular gas. All the above is in contradiction with the traditional classification of these sources as a single class of objects that are rapidly transitioning to quiescence. Spatially-resolved optical and mm observations are required to better constrain the geometry and physical properties of these systems.

6 DATA AVAILABILITY

The properties of the 15 sources observed with NOEMA are given in tables 2 and 3. The best-fitting SFH parameters for our sources are given in table A1. The best-fitting SFH parameters for the Rowlands et al. (2016b) samples are given in French et al. (2018), while the parameters for the Yesuf et al. (2017) sample are given in table A2. The optical and far-infrared data were extracted from public catalogs by the SDSS and IRAS.

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REFERENCES

Alatalo K. et al., 2016a, ApJS, 224, 38
Alatalo K. et al., 2016b, ApJ, 827, 106
Almaini O. et al., 2017, MNRAS, 472, 1401
Astropy Collaboration et al., 2018, AJ, 156, 123
Astropy Collaboration et al., 2013, A&A, 558, A33
Baldry I. K., Balogh M. L., Bower R. G., Glazebrook K., Nichol R. C., Bamford S. P., Budavari T., 2006, MNRAS, 373, 469
Barnes J. E., Hernquist L., 1996, ApJ, 471, 115
Baron D., Netzer H., Davies R. I., Xavier Prochaska J., 2020, MNRAS, 494, 5396
Baron D., Netzer H., Lutz D., Prochaska J. X., Davies R. I., 2022, MNRAS, 509, 4457
Baron D., Netzer H., Poznanski D., Prochaska J. X., Förster Schreiber N. M., 2017, MNRAS, 470, 1687
Baron D. et al., 2018, MNRAS, 480, 3993
Bolatto A. D., Wolfire M., Leroy A. K., 2013, ARA&A, 51, 207
Brinchmann J., Charlot S., White S. D. M., Tremonti C., Kauffmann G., Heckman T., Brinkmann J., 2004, MNRAS, 351, 1151

6 http://www.astropy.org
7 www.sdss3.org
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Buchner J., 2014, arXiv e-prints, arXiv:1407.5459
Buchner J., 2017, arXiv e-prints, arXiv:1707.04476
Buchner J., 2021, The Journal of Open Source Software, 6, 3001
Cales S. L., Brotherton M. S., 2015, MNRAS, 449, 2374
Cales S. L. et al., 2011, ApJ, 741, 106
Canalizo G., Stockton A., Brotherton M. S., van Breugel W., 2000, AJ, 119, 59
Chabrier G., 2003, PASP, 115, 763
Coil A. L., Weiner B. J., Holz D. E., Cooper M. C., Yan R., Aird J., 2011, ApJ, 743, 46
Conroy C., Gunn J. E., 2010, ApJ, 712, 833
Conroy C., Gunn J. E., White M., 2009, ApJ, 699, 486
Couch W. J., Sharples R. M., 1987, MNRAS, 229, 423
Chabrier G., 2003, PASP, 115, 763
Chary R., Elbaz D., 2001, ApJ, 556, 562
Coil A. L., Weiner B. J., Holz D. E., Cooper M. C., Yan R., Aird J., 2011, ApJ, 743, 46
Conroy C., Gunn J. E., 2010, ApJ, 712, 833
Conroy C., Gunn J. E., White M., 2009, ApJ, 699, 486
Couch W. J., Sharples R. M., 1987, MNRAS, 229, 423
de los Reyes M. A. C., Kennicutt, Robert C. J., 2019, ApJ, 872, 16
Diamond-Stanic A. M., Moustakas J., Tremonti C. A., Coil A. L., Hickox R. C., Robaina A. R., Rudnick G. H., Sell P. H., 2012, ApJ, 755, L26
Dressler A., Gunn J. E., 1983, ApJ, 270, 7
French K. D., 2021, PASP, 133, 072001
French K. D., Yang Y., Zabludoff A. I., Tremonti C. A., 2015, ApJ, 801, 1
French K. D., Yang Y., Zabludoff A. I., Tremonti C. A., 2018, ApJ, 862, 2
Gao Y., Solomon P. M., 2004, ApJS, 152, 63
Girardi L., Bressan A., Bertelli G., Chiosi C., 2000, A&AS, 141, 371
Goto T., 2004, A&A, 427, 125
Hayward C. C. et al., 2014, MNRAS, 445, 1598
Helen G., Walker D. W., 1988, Infrared Astronomical Satellite (IRAS) Catalogs and Atlases. Volume 7: The Small Scale Structure Catalog. Tech. rep.
Hirashita H., Buat V., Inoue A. K., 2003, A&A, 410, 83
Hopkins P. F., Hernquist L., Cox T. J., Di Matteo T., Robertson B., Springel V., 2006, ApJS, 163, 1
Janowiecki S., Catinella B., Cortese L., Saintonge A., Brown T., Wang J., 2017, MNRAS, 466, 4795
Kauffmann G. et al., 2003, MNRAS, 341, 33
Kaviraj S., Kirkby L. A., Silk J., Sarzi M., 2007, MNRAS, 382, 960
Kelly B. C., 2007, ApJ, 665, 1489
Kennicutt, Robert C. J., 1998, ApJ, 508, 541
Kennicutt, Robert C. J., De Los Reyes M. A. C., 2021, ApJ, 908, 61
Kroupa P., 2001, MNRAS, 322, 231
Leitherer C. et al., 1999, ApJS, 123, 3
Li Z., French K. D., Zabludoff A. I., Ho L. C., 2019, ApJ, 879, 131
Liu C. T., Green R. F., 1996, ApJ, 458, L63
Maltby D. T. et al., 2019, MNRAS, 489, 1139
Martín D. C. et al., 2005, ApJ, 619, L1
Mihos J. C., Hernquist L., 1994, ApJ, 431, L9
Mihos J. C., Hernquist L., 1996, ApJ, 464, 641
Narayan D., Krumholz M. R., Ostriker E. C., Hernquist L., 2012, MNRAS, 421, 3127
Neugebauer G. et al., 1984, ApJ, 278, L1
Norton S. A., Gebhardt K., Zabludoff A. I., Zaritsky D., 2001, ApJ, 557, 150
Petrosian V., 1976, ApJ, 210, L53
Pihajoki P., 2017, MNRAS, 472, 3407
Poggiotti B. M., Wu H., 2000, ApJ, 529, 157
Rowlands K., Wild V., Nesvadba N., Sibthorpe B., Mortier A., Lehner M., da Cunha E., 2015, MNRAS, 448, 258
Sage L. J., Welch G. A., Young L. M., 2007, ApJ, 657, 232
Saintonge A. et al., 2017, ApJS, 233, 22
Salim S. et al., 2007, ApJS, 173, 267
Sanders D. B., Soifer B. T., Elias J. H., Madore B. F., Matthews K., Neugebauer G., Scoville N. Z., 1988, ApJ, 325, 74
Skrutskie M. F. et al., 2006, AJ, 131, 1163
Small I., Morrison G., Gray M. E., Owen F. N., Ivison R. J., Kneib J. P., Ellis R. S., 1999, ApJ, 525, 609
Smercina A. et al., 2018, ApJ, 855, 51
Smercina A. et al., 2022, arXiv e-prints, arXiv:2108.03231
Solomon P. M., Downes, D., Radford S. J. E., Barrett J. W., 1997, ApJ, 478, 144
Springel V., Di Matteo T., Hernquist L., 2005, ApJ, 620, L79
Tacconi L. J., Genzel R., Sternberg A., 2020, ARA&A, 58, 157
Tremonti C. A. et al., 2004, ApJ, 613, 898
Tremonti C. A., Moustakas J., Diamond-Stanic A. M., 2007, ApJ, 663, L77
U V. et al., 2012, ApJS, 203, 9
Whitaker K. E., van Dokkum P. G., Brammer G., Franx M., 2012, ApJ, 754, L29
Wild V., Almaini O., Dunlop J., Simpson C., Rowlands K., Bowler R., Maltby D., McLure R., 2016, MNRAS, 463, 832
Wild V., Walcher C. J., Johansson P. H., Tresse L., Charlot S., Pollo A., Le Fèvre O., de Ravel L., 2009, MNRAS, 395, 144
Wong O. I. et al., 2012, MNRAS, 420, 1684
Yang Y., Tremonti C. A., Zabludoff A. I., Zaritsky D., 2006, ApJ, 646, L33
Yang Y., Zabludoff A. I., Zaritsky D., Lauer T. R., Mihos J. C., 2004, ApJ, 607, 258
Yesuf H. M., Faber S. M., Trump J. R., Koo D. C., Fang J. J., Liu F. S., Wild V., Hayward C. C., 2014, ApJ, 792, 84
Yesuf H. M., French K. D., Faber S. M., Koo D. C., 2017, MNRAS, 469, 3015
Yesuf H. M., Ho L. C., 2020, ApJ, 901, 42
York D. G. et al., 2000, AJ, 120, 1579
Young L. M. et al., 2011, MNRAS, 414, 940
Zabludoff A. I., Zaritsky D., Lin H., Tucker D., Hashimoto Y., Shectman S. A., Oemler A., Kirshner R. P., 1996, ApJ, 466, 104
Figure A1. Integrated CO(1-0) spectra obtained from our NOEMA observations. The SDSS IDs (PLATE-MJD-FIBER) are indicated at the top of each plot.

APPENDIX A: NOEMA AND IRAS DATA
Figure A2. Star formation template fits of the far-infrared and mm continuum emission. The SDSS IDs (PLATE-MJD-FIBER) are indicated at the top. The black circles represent measurements and triangles represent upper limits. The solid lines represent the Chary & Elbaz (2001) star formation templates, color-coded by the star formation luminosity. The best-fitting star formation template is marked with a thicker line.
### Table A1. Age-dating best-fitting parameters: this work.

| Object ID | SFH | Post-burst Age (Myr) (16%) | Age since Burst Start (Myr) (16%) | τ or Δt (Myr) (16%) | Burst Light Fraction (16%) | Burst Mass Fraction (84%) | mburst (mag) | A_V |
|-----------|-----|-----------------------------|-----------------------------------|----------------------|---------------------------|--------------------------|-------------|-----|
|           | 2   | 118                         | 142                               | 230                  | 258                       | 282                      | 100         | 0.29|
| 1008-52707-0017 | 2 | 79                           | 118                               | 219                  | 258                       | 287                      | 100         | 0.28|
| 1463-53063-0292 | 2 | -88                         | -18                               | 7                   | 141                       | 211                      | 237         | 0.79|
| 1605-53062-0122 | 2 | 69                           | 93                               | 113                 | 209                       | 233                      | 253         | 0.28|
| 1659-53142-0564 | 2 | 279                         | 335                               | 388                 | 619                       | 675                      | 728         | 0.29|
| 1665-53498-0129 | 2 | 57                           | 78                               | 106                 | 197                       | 218                      | 246         | 0.27|
| 1766-53466-0172 | 2 | 20                           | 30                               | 40                  | 160                       | 170                      | 180         | 0.18|
| 1771-53112-0588 | 2 | 104                         | 127                               | 167                 | 244                       | 267                      | 307         | 0.21|
| 1870-53383-0446 | 2 | 121                         | 154                               | 197                 | 252                       | 286                      | 314         | 0.25|
| 2026-53711-0219 | 2 | 63                           | 115                               | 155                 | 223                       | 253                      | 282         | 0.20|
| 2226-56882-0278 | 2 | 8                            | 85                               | 122                 | 148                       | 185                      | 225         | 0.26|
| 2345-53757-0457 | 2 | 68                           | 85                               | 103                 | 208                       | 225                      | 243         | 0.30|

Due to unphysical SFHs, we omit these three sources from the analysis: a: Number of recent bursts. b: If SFH = 1, burst duration (τ). If SFH = 2, separation between bursts (Δt). c: If SFH = 2, light fraction for each burst is shown (burst mass fractions are the same for each burst, so the light fractions will be different). d: If SFH = 2 recent bursts, burst mass fraction shown is combined from both recent bursts. e: Includes Galactic foreground extinction.

### Table A2. Age-dating best-fitting parameters: Yesuf et al. (2017).

| RA (deg) | DEC (deg) | SFH | Post-burst Age (Myr) (16%) | Age since Burst Start (Myr) (16%) | τ or Δt (Myr) (16%) | Burst Light Fraction (16%) | Burst Mass Fraction (84%) | mburst (mag) | A_V |
|----------|-----------|-----|-----------------------------|-----------------------------------|----------------------|---------------------------|--------------------------|-------------|-----|
| 126.01530 | 51.903355 | 2   | 109                       | 186                               | 223                  | 249                       | 326                      | 100         | 0.15|
| 134.61916 | 0.023468  | 2   | 322                        | 381                               | 440                 | 1361                      | 1421                     | 1480         | 0.28|
| 139.49937 | 0.002183  | 2   | 285                        | 276                               | 390                 | 1225                      | 1316                     | 1430         | 0.14|
| 173.41284 | 52.74111  | 2   | 211                        | 241                               | 349                 | 713                       | 751                      | 880         | 0.11|
| 173.16760 | 52.953075 | 2   | 273                        | 318                               | 363                 | 331                       | 375                      | 420         | 0.32|
| 179.02847 | 59.43297  | 1   | 1760                      | 2045                               | 2051                | 2102                      | 255                     | 290         | 0.79|
| 182.01942 | 55.407072 | 1   | 136                        | 183                               | 217                 | 1171                      | 1223                     | 1257         | 0.15|
| 236.93394 | 41.402300 | 1   | 96                         | 118                               | 140                 | 236                       | 258                     | 280         | 0.14|
| 247.63060 | 39.384201 | 1   | 241                        | 281                               | 1239               | 1281                      | 1321                     | 1360         | 0.15|
| 240.65805 | 41.293433 | 1   | 366                        | 433                               | 499                 | 14067                     | 1473                    | 1539         | 0.17|
| 200.95188 | 43.301187 | 1   | 152                        | 183                               | 215                 | 392                       | 323                     | 355         | 0.24|
| 178.62255 | 48.920193 | 1   | 163                        | 197                               | 233                 | 1203                      | 1237                     | 1273         | 0.29|
| 189.51730 | 48.345096 | 1   | 249                        | 709                               | 1743               | 1754                      | 1749                     | 2783         | 0.20|
| 190.45028 | 47.708848 | 1   | 1403                      | 1638                               | 1950              | 1543                       | 1778                     | 2090         | 0.45|
| 198.74930 | 51.275282 | 1   | 36                         | 49                                | 61                 | 176                       | 189                     | 201         | 0.20|
| 212.01668 | 7.327645  | 1   | 112                        | 137                               | 162                | 257                       | 277                     | 302         | 0.13|
| 117.96029 | 51.814318 | 1   | 366                        | 433                               | 499                 | 14067                     | 1473                    | 1539         | 0.29|
| 203.56170 | 54.191446 | 1   | 450                        | 555                               | 639                 | 9900                      | 10955                    | 1179         | 0.24|
| 180.519230 | 35.326181 | 1   | 161                        | 258                               | 313                | 301                       | 398                     | 453         | 0.11|
| 179.454910 | 35.424038 | 1   | 208                        | 225                               | 243                | 100                       | 100                    | 100         | 0.18|
| 222.657720 | 22.734337 | 1   | -9                        | -4                                | 0                  | 130                       | 135                    | 140         | 0.52|

For additional details about the best-fitting parameters, see description in [French et al., 2018]. a: Due to unphysical SFHs, we omit these three sources from the analysis (see section 2.4 for details). b: Number of recent bursts. c: If SFH = 1, burst duration (τ). If SFH = 2, separation between bursts (Δt). d: If SFH = 2, light fraction for each burst is shown (burst mass fractions are the same for each burst, so the light fractions will be different). e: If SFH = 2 recent bursts, burst mass fraction shown is combined from both recent bursts. f: Includes Galactic foreground extinction.
Post-starburst galaxies are not truly post starburst

APPENDIX B: RE-ANALYSIS OF THE LI ET AL. (2019) SAMPLE

Li et al. (2019) combined the post-starburst galaxies from Rowlands et al. (2015), Alatalo et al. (2016a), and French et al. (2018) for which Herschel observations were publicly-available. They used the dust-corrected Hα emission line to estimate the SFR in their sources. Some of the objects in their combined sample were observed in mm wavelengths, and their CO emission lines were used to estimate the molecular gas masses. For the rest, Li et al. (2019) used SED-based dust masses to estimate $M_{H_2}$. We collected the Hα-based SFRs and $M_{H_2}$ measurements of the objects in their sample. We used scanpi to extract their 60 μm fluxes, and estimated their far-infrared SFRs.

Figure B1 shows the SFR and $M_{H_2}$ versus the post-burst age for the Li et al. (2019) sample. First column: $M_{H_2}$ versus the post-burst age, where measurements are marked with points and upper limits with arrows. The solid line represents the best-fitting relation obtained with linmix, and the lighter bands represent the uncertainty of the best fit. Second column: optical (top) and far-infrared (bottom) SFR versus the post-burst age. Third column: optical (top) and far-infrared (bottom) star formation efficiency. Only galaxies with measured SFR and $M_{H_2}$ are shown.

Figure B1 shows the SFR and $M_{H_2}$ versus the post-burst age for the Li et al. (2019) sample, where the top row shows optical SFRs and the bottom row far-infrared SFRs. Using the optical SFRs, we reproduce the declining trend of the star formation efficiency as a function of the post-burst age reported by Li et al. (2019). However, when using far-infrared SFRs, the resulting star formation efficiency is practically independent of the post-burst age. The figure therefore suggests that the trend reported by Li et al. (2019) is driven by the inaccurate optical SFRs, and that there is no significant evolution of the star formation efficiency as the starburst ages.

Figure B2 shows the location of the Li et al. (2019) post-starburst galaxies in the Kennicutt–Schmidt (KS) plane. To reproduce their results, we used the SDSS Petrosian radii to convert the SFR and $M_{H_2}$ into surface densities. Using optical SFRs, we reproduce their main result that post-starbursts are offset from the KS relation of other galaxies. When far-infrared SFRs are used instead, post-starburst galaxies lie on the same KS relation as other types of galaxies. This suggests that the offset reported by Li et al. (2019) is due to their usage of optical SFRs.

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Figure B2. Location of the Li et al. (2019) post-starbursts in the Kennicutt–Schmidt plane. The SFR surface density versus the molecular gas surface density, using optical (left) and far-infrared (right) SFRs. The Li et al. (2019) galaxies are color-coded according to their post-burst age, similarly to their color-coding in Li et al. (2019). The comparison galaxies include the dwarfs, spirals, circumnuclear disks, and luminous infrared galaxies from de los Reyes & Kennicutt (2019) and Kennicutt & De Los Reyes (2021), and are marked with black empty symbols.