

# Characterizing the FRB host galaxy population and its connection to transients in the local and extragalactic Universe

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## ABSTRACT

We present the localization and host galaxies of one repeating and two apparently non-repeating Fast Radio Bursts. FRB 20180301A was detected and localized with the Karl G. Jansky Very Large Array to a star-forming galaxy at  $z = 0.3304$ . FRB20191228A, and FRB20200906A were detected and localized by the Australian Square Kilometre Array Pathfinder to host galaxies at  $z = 0.2430$  and  $z = 0.3688$ , respectively. We combine these with 13 other well-localised FRBs in the literature, and analyse the host galaxy properties. We find no significant differences in the host properties of repeating and apparently non-repeating FRBs. FRB hosts are moderately star-forming, with masses slightly offset from the star-forming main-sequence. Star formation and low-ionization nuclear emission-line region (LINER)

emission are major sources of ionization in FRB host galaxies, with the former dominant in repeating FRB hosts. FRB hosts do not track stellar mass and star formation as seen in field galaxies (95% confidence). FRBs are rare in massive red galaxies, suggesting that progenitor formation channels are not solely dominated by delayed channels which lag star formation by gigayears. The global properties of FRB hosts are indistinguishable from core-collapse supernovae (CCSNe) and short gamma-ray bursts (SGRBs) hosts (95% confidence), and the spatial offset (from galaxy centers) of FRBs is consistent with that of Galactic neutron star population. The spatial offsets of FRBs (normalised to the galaxy effective radius) mostly differs from that of globular clusters (GCs) in late- and early-type galaxies with 95% confidence.

*Keywords:* radio continuum: general, instrumentation: interferometers, galaxies: star formation

## 1. INTRODUCTION

The physical mechanism and the source population(s) powering the energetic ( $10^{-2}$  to  $\sim 400$  Jy ms) and  $\mu$ s duration fast radio bursts (FRBs) are currently two of the biggest mysteries of modern astrophysics. Significant progress has been made in the last two years, with (sub-)arcsecond localization of FRBs using radio interferometers such as the Karl G. Jansky Very Large Array (VLA), the Australian Square Kilometre Array Pathfinder (ASKAP), the Deep Synoptic Array (DSA-10), and the European VLBI Network (EVN) (Chatterjee et al. 2017; Bannister et al. 2019b; Ravi et al. 2019; Marcote et al. 2020; Law et al. 2020). These FRB localizations have enabled the identification of FRB host galaxies, and in some cases the location of the FRBs within the galaxies, which has provided the clues to the progenitor channels of these enigmatic sources. While the nature of FRBs remains uncertain, the redshifts for localized FRBs still permit us to probe the baryonic content of the Universe (Macquart et al. 2020), through measurements of the ionised baryon density in the intergalactic medium (IGM). FRBs are thus excellent probes of cosmology and the structure of the Universe (Bhandari & Flynn 2021).

Recently, the Canadian Hydrogen Intensity Mapping Experiment Fast Radio Burst (CHIME/FRB) Project published a catalog of 535 FRBs detected during their first year of operations and observed in the range 400 – 800 MHz (The CHIME/FRB Collaboration et al. 2021). The catalog represents the first large sample ( $\gg 10^2$ ) of FRBs detected in a well-controlled experiment. It includes bursts from repeating and non-repeating FRB sources, and facilitates a comparative study of the FRB population. The CHIME/FRB sample reveals that while the sky locations and dispersion measures (DMs) of the two FRB populations are consistent with being drawn from the same distribution, the bursts from repeating sources have wider pulse widths and narrower bandwidths compared to apparent non-repeaters (Fonseca et al. 2020; Pleunis et al. 2021). Thus, these obser-

vational differences in the bursts themselves hint at different propagation or emission mechanisms for the two FRB sub-populations. Whether all FRBs repeat is still an outstanding question in the field (Palaniswamy et al. 2018; James 2019; Caleb et al. 2019; Ravi 2019; Ai et al. 2021).

In addition to the properties of the bursts, analyses of their host galaxy environments may provide more clues to disentangle the two FRB populations and their progenitor sources (Chittidi et al. 2020; Tendulkar et al. 2021). Currently, 15 FRBs (including repeating and non-repeating) have been localized to host galaxies at redshifts in the range  $z = 0.03 - 0.66$  (Heintz et al. 2020)<sup>1</sup>. This preliminary sample shows that FRB host galaxies overall exhibit a broad range of color ( $u - r = 0.9 - 2.0$ ), stellar mass ( $M_\star = 10^8 - 10^{10} M_\odot$ ), and star-formation rates ( $SFR = 0.05 - 10 M_\odot \text{ yr}^{-1}$ ). Moreover, the burst sites are in most cases significantly offset from the host-galaxy centers. A high spatial resolution analysis of a subset of FRB hosts found that most FRBs are not located in regions of elevated local star formation and stellar mass surface densities in comparison to the mean global values of their hosts (Mannings et al. 2020). Also, the majority of hosts in Mannings et al. (2020) show clear spiral arm features in the infrared (IR), with the positions of the bursts found to be consistent with an origin in the spiral arms. An analysis of the host-burst offset distribution and other host properties rule out long gamma-ray bursts (LGRBs) and super-luminous supernovae (SLSNe) as FRB production channels and favor compact merger events (double white dwarf (WD) and double neutron star (NS) mergers), accretion-induced collapse (AIC) of a white dwarf and core-collapse supernovae (CCSNe) to be plausible mechanisms for non-repeating ASKAP-localized bursts (Bhandari et al. 2020; Heintz et al. 2020; Li & Zhang 2020).

<sup>1</sup> <http://frbhosts.org>

In this first, relatively small host galaxy sample, tentative evidence was found for the hosts of the repeating FRBs to be less massive and less luminous on average, compared to the hosts of the apparently non-repeating FRBs. Even within the specific sub-population of repeating FRB hosts, though, a very diverse nature is apparent; FRB20121102A originates in a highly magnetized environment (Michilli et al. 2018) co-located with a radio nebula in a low-metallicity, highly star-forming dwarf galaxy at  $z = 0.1927$  (Chatterjee et al. 2017; Tendulkar et al. 2016). The immediate environment and host galaxy properties of the FRB20121102A source led to a concordant model for FRBs in which bursts are produced by young magnetars, remnants from SLSNe or LGRBs (Margalit & Metzger 2018). In contrast, FRB20180916B originates close to a star-forming region in a massive nearby ( $z = 0.03$ ) spiral galaxy (Marcote et al. 2020) lacking an extreme magneto-ionic environment and radio nebula. Observations with the *Hubble Space Telescope* (HST) established a small but significant offset of FRB20180916B from the nearest knot of active star formation in the host galaxy. This suggests that the age of the progenitor is inconsistent with that of a young magnetar but compatible with the ages of high-mass X-ray binaries and gamma-ray binaries (Tendulkar et al. 2021). Another repeating source, FRB20200120E is localized to a globular cluster system in the nearby spiral galaxy M81, suggesting that if the progenitor is a young neutron star, it must have been formed via an alternative pathway, such as accretion-induced collapse of a white dwarf, or the merger of compact stars in a binary system (Bhardwaj et al. 2021; Kirsten et al. 2021). Finally, the repeating FRBs 20190711A and 20201124A are observed to originate in typical star-forming galaxies at their respective redshifts (Heintz et al. 2020; Ravi et al. 2021; Fong et al. 2021).

In this paper, we introduce three additional bursts and their host galaxies to the existing sample and conduct a differential study of the host population of one-off and repeating FRBs using an updated sample of 16 FRB hosts (containing 6 repeating and 10 non-repeating FRBs). The paper is laid out as follows: Section 2 presents the discovery of a new burst from the repeating FRB20180301A source (Luo et al. 2020) and resulting localization using the REALFAST system at the VLA. We also describe the radio and optical properties of the host galaxy of FRB20180301A. Section 3 presents the discovery and localization of two new (apparently) non-repeating FRBs, namely FRB20191228A and FRB20200906A, found in the Commensal Real-time ASKAP Fast Transients (CRAFT) Survey (Macquart et al. 2010). We also describe the follow-up observa-

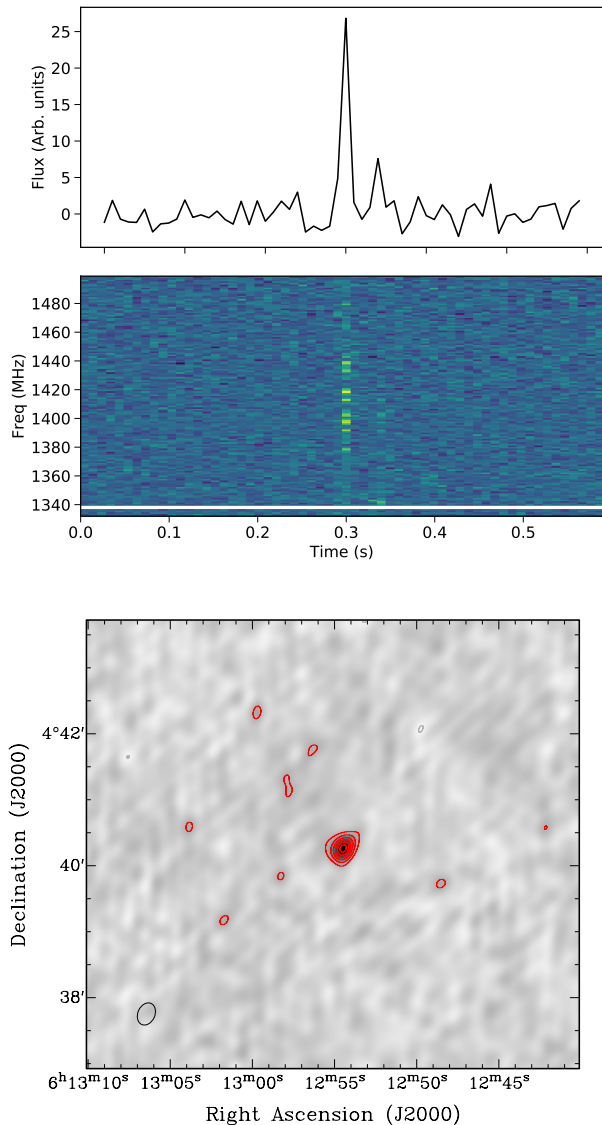
tions and identification of their host galaxies. In Section 4, we compare the overall population of FRB hosts with field galaxies at similar redshifts, based on the largest sample to date. In Section 5, we differentiate the hosts and compare the properties of the two sub-populations; repeating and one-off bursts. In Section 6, we compare the global properties and the projected physical offsets of FRBs to a range of both extragalactic transients and the projected source population of Galactic objects. Additionally, we compare the host-normalized offset distributions of FRBs with that of globular clusters associated with different galaxy types. We summarise our results in Section 7.

## 2. LOCALIZATION OF THE REPEATING FRB20180301A

### 2.1. Detection of a repeating burst

FRB20180301A, a burst originally detected in the Breakthrough Listen project at the Parkes radio telescope (Price et al. 2019), was observed to emit repeating radio pulses in sensitive follow-up observations with the FAST telescope using the 19-beam receiver centered at 1.25 GHz (Luo et al. 2020). Fifteen repeating bursts with fluences ranging from 0.03 Jy ms to 0.4 Jy ms, were detected from the source of FRB20180301A in a total effective observation time of  $\sim 12$  hrs at FAST.

We performed follow-up observations of FRB20180301A using Director’s Discretionary Time (DDT) with 40 hrs scheduled under VLA/19B-351, using the VLA in C array configuration at L-band, spanning 1-2 GHz. We used the L16f5DC-realfast correlator mode, which enables a fast sampling time of 10 ms. We observed the field of FRB20180301A centered at RA(J2000): 06:12:54.96 and Dec(J2000): +04:38:43.60 covering a localization uncertainty region of  $2.6'$  at 1.25 GHz obtained from detection at FAST. The source was observed at 9 epochs, each with an observation time of 2 hr in the period Feb–May 2020. Each observation had an on-source time of  $\sim 1.5$  hrs and was searched for fast transients by the REALFAST system. The details of the REALFAST search procedure can be found in Law et al. (2018, 2020). We detected a repeat burst from FRB20180301A on 2020 May 28 at UTC 19:14:47.310 in the last epoch. It was detected in the real-time system with an image S/N of 10.8 at a DM of  $517.45 \text{ pc cm}^{-3}$ . The Deep Learning based classifier *fetch* (Agarwal et al. 2020) reported an astrophysical probability of 99% for this burst. We used the recorded visibilities of the burst data to refine our estimate of the burst properties in an offline reprocessing. We re-ran the search with a finer DM grid at 0.1 percent fractional sensitivity loss on a sub-band of the data. This sub-band was manually identified to



**Figure 1.** REALFAST detection of FRB20180301A. Top and middle panels show the dispersion-corrected frequency integrated profile and spectrum of FRB20180301A. Bottom panel shows the fast sampled (10 ms) calibrated radio image of FRB20180301A. The red contour levels are placed at  $11.2 \text{ mJy beam}^{-1}$  times factors of  $[-3, 3, 6, 9, 12, 15, 18]$ . The synthesised beam in the burst image is  $20.9'' \times 15.5''$  at a position angle of  $-24.1^\circ$ .

consist of burst signal. The refined search led to an improvement in detection significance to  $\sim 19$  at the DM of  $536 \text{ pc cm}^{-3}$ . The top panel of Fig. 1 shows the burst profile and dedispersed spectrogram. This figure also shows a weaker component  $\sim 50 \text{ ms}$  after the burst that is present in the lower part of the band. This could either be a component of the main burst, or another burst from this FRB. We used the visibilities from the

main component to determine the localization of this FRB.

We used BURSTFIT<sup>2</sup> (Aggarwal et al. 2021a) to model the spectro-temporal properties of FRB20180301A using its spectrogram. Following Aggarwal et al. (2021a), we modelled the spectrum and the pulse using a Gaussian, and fit for the following parameters simultaneously: arrival time of peak, Gaussian FWHM of pulse, peak of the spectrum, FWHM of the spectrum, fluence and DM. We used SCIPY.CURVE\_FIT followed by Markov-Chain Monte-Carlo methods to obtain the posterior distribution of all the fit parameters. The resulting burst properties are presented in Table 1.

### 2.1.1. Spatial localization

The images generated by the REALFAST search pipeline make several assumptions (coarse DM grid, non-optimal image size, simpler calibration algorithm, etc) during calibration and imaging. To address these, we used the raw, de-dispersed burst visibilities to form the burst image using CASA (McMullin et al. 2007). We ran the full CASA pipeline to generate VLA calibration tables for this observation. We then used the CASA task `applycal` to apply those calibration and flagging table to the burst data. Observations of calibrator 3C147 were used to calibrate the flux density scale, bandpass and delays. The nearby source J0632+1022 was used to calibrate the complex gain fluctuations over time, by observing it every 20 minutes. We then used CASA tasks `tclean` and `imfit` to generate a radio image and fit an ellipse to the burst position. The initial burst position was found to be RA(J2000):  $06^{\text{h}}12^{\text{m}}54.47^{\text{s}}$  and Dec(J2000):  $+04^{\circ}40'15.6''$  with a statistical uncertainty of  $0.008''$  in RA and  $0.01''$  in Dec (see bottom panel of Fig. 1).

### 2.1.2. VLA Radio Continuum Image

In addition to the fast-sampled data with an integration time on order of a few milliseconds generated by REALFAST, the VLA correlator creates slow-sampled data with an integration time of 5 s. This slow sampled data will average out any fast-varying signal (like FRBs) but is suitable for finding any persistent radio source near the burst location. We made separate images for each epoch to search for any persistent or slowly varying emission from the FRB location. As each individual epoch reached very close to the confusion limit for the VLA in that observing configuration (the confusion limit is around  $18 \mu\text{Jy beam}^{-1}$ ), we did not combine the epochs to improve sensitivity.

<sup>2</sup> <https://github.com/thepetabyteproject/burstfit>



Properties	FRB20180301A	FRB20191228A	FRB20200906A
Arrival time <sup>a</sup> (UT)	2020-05-28 19:14:47.310	2019-12-28 09:16:16.444	2020-09-06 21:40:50.923
S/N	19.0 <sup>b</sup>	22.9	19.2
DM (pc cm <sup>-3</sup> )	536 <sup>+8</sup> <sub>-13</sub>	297.5 ± 0.05	577.8 ± 0.02
DM <sub>ISM</sub> NE2001 (pc cm <sup>-3</sup> )	152	33	36
DM <sub>ISM</sub> YMW16 (pc cm <sup>-3</sup> )	254	20	38
DM <sub>cosmic</sub> <sup>c</sup> (pc cm <sup>-3</sup> )	289	210	324
RA (J2000)	06h12m54.42(4)s	22h57m43.30(7)s	03h33m59.08(2)s
Dec (J2000)	+04d40'15.9(6)''	-29d35'38.7(9)''	-14d04'59.5(6)''
Fluence (Jy ms)	4.9 <sup>+0.5</sup> <sub>-0.4</sub>	40 <sup>+100</sup> <sub>-40</sub>	59 <sup>+25</sup> <sub>-10</sub>
Pulse width (ms)	7 <sup>+2</sup> <sub>-3</sub>	2.3 ± 0.6 <sup>d</sup>	6.0 ± 0.6
Spectral energy density <sup>e</sup> (erg Hz <sup>-1</sup> )	6.9 × 10 <sup>30</sup>	6.4 × 10 <sup>31</sup>	1.1 × 10 <sup>32</sup>
Persistent source, radio luminosity (W Hz <sup>-1</sup> )	< 2.0 × 10 <sup>22</sup> 1.5 GHz	< 3.4 × 10 <sup>21</sup> 6.5 GHz	< 4.3 × 10 <sup>21</sup> 6 GHz
<b>Host galaxy</b>			
Redshift <sup>*</sup>	0.3304	0.2432	0.3688
$u - r^{\dagger}$ (restframe)	0.90 ± 0.11	2.13 ± 0.74	1.22 ± 0.11
$M_r^{\dagger}$ (restframe)	-20.18 ± 0.07	-18.26 ± 0.05	-21.49 ± 0.05
Galactic $E(B - V)^{\dagger}$	0.46	0.02	0.05
$M_{*}^{\dagger}$ (10 <sup>10</sup> $M_{\odot}$ )	0.23 ± 0.06	0.54 ± 0.60	1.33 ± 0.37
SFR <sup>*</sup> ( $M_{\odot}$ yr <sup>-1</sup> )	1.93 ± 0.58	0.03 ± 0.01	0.48 ± 0.14
log(sSFR) (yr <sup>-1</sup> )	-9.08	-11.28	-10.44
Metallicity <sup>f*</sup>	8.70	8.48	8.76
Projected offset from galaxy center (kpc)	10.8 ± 3.0	5.7 ± 3.3	5.9 ± 2.0
Effective radius (kpc)	5.80 ± 0.20	1.78 ± 0.06	7.58 ± 0.06

**Table 1.** Measured and derived properties of the new FRBs presented in this work.<sup>a</sup> Arrival time of a repeating burst from FRB20180301A source and one-off ASKAP/CRAFT FRBs.<sup>b</sup> This is the coherent S/N of the FRB detected in the VLA image.<sup>c</sup> Estimated using the Macquart-relation.<sup>d</sup> FRB20191228A shows a scattering tail of 6.1(6) ms. The deconvolved width is 2.3(6) ms.<sup>e</sup> The energies are derived assuming a flat spectrum for FRBs ( $\alpha = 0$ ) and zero k-correction.<sup>f</sup> In units of  $12 + \log[\text{O}/\text{H}]$ .<sup>\*</sup> These measurements are derived from spectroscopy.<sup>†</sup> These properties are derived using **CIGALE** SED fitting. $1\sigma$  uncertainties are quoted for these measurements.

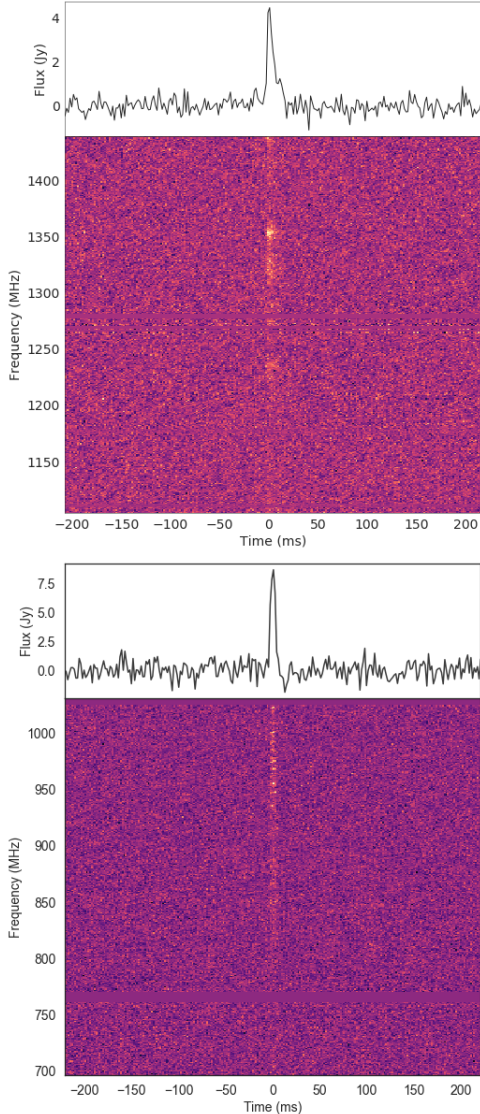
The slow-sampled data was calibrated using the standard VLA calibration pipeline, followed by manual data inspection and further flagging. We used **tclean** to produce images. Manual flagging of the dataset was done to allow for much finer and in-depth RFI flagging than autoflagging algorithms. The inputs of **tclean** used the gridded **wproject** with 128 wprojplanes. The deconvolver was set to **mtmfs** and **Briggs** weighting was used with a robustness parameter of 0. These parameters were chosen to help reduce noise from sources outside the primary beam as well as suppressing minor baseline-dependent errors. The full field of view was also imaged to allow cleaning on these bright sources, specifically

sources  $\sim 42$  and  $\sim 30$  arcminutes away from the phase center.

Once **tclean** was run, the RMS near the center of the primary beam was found to be in the range 23 – 26  $\mu\text{Jy beam}^{-1}$  for all epochs. In the best VLA epoch image, we find no persistent radio source above a  $3\sigma$  flux density of 70  $\mu\text{Jy beam}^{-1}$  yielding a luminosity of  $2.0 \times 10^{22}$  W Hz<sup>-1</sup> at 1.5 GHz.

### 2.1.3. Astrometry

We tested our astrometric precision by associating radio sources in the FRB-epoch VLA image with the Karl G. Jansky Very Large Array Sky Survey (Lacy et al. 2020, VLASS) Epoch 1 Quick Look catalog (Gordon et al. 2020). We re-imaged the FRB epoch, select-



**Figure 2.** Pulse profile and dynamic spectrum for FRB20191228A (top) and FRB20200906A (bottom). FRB signals are de-dispersed at the S/N maximised DM of  $297.5 \text{ pc cm}^{-3}$  and  $577.8 \text{ pc cm}^{-3}$  for FRB20191228A and FRB20200906A respectively.

ing an interval of 30 s centered on the FRB for investigating astrometric accuracy. We ran the PYSE source finding package (Spreeuw et al. 2018) on this 30 s image and identified six radio sources above a significance level of  $15\sigma$ . All these sources had VLASS counterparts within a  $2''$  search radius. We measured the weighted mean and associated uncertainty of the offsets between these six sources in the 30 s snapshot image and their VLASS catalog positions, measuring  $156 \pm 330 \text{ mas}$  and  $-197 \pm 223 \text{ mas}$  in RA and Dec respectively. However, the scatter in the measured offsets is clearly not due solely to the statistical (signal-to-noise limited) mea-

surement uncertainty, with the  $\chi^2$  of the weighted mean fit being 50.40 for 10 degrees of freedom. This is not unexpected, given the potential for systematic differences in centroid position due to, e.g., the different frequency and resolution of our 30 s image vs the VLASS catalog. Previous studies using ASKAP (Day et al. 2021) have examined a large number of fields to estimate a scaling factor that can be applied to the weighted mean uncertainty to correct (on average) for these contributions, but the value of the scaling factor should depend on the telescope and reference catalogs used. Here, we instead take an unweighted mean of the six source offsets, which effectively assumes that the signal-to-noise limited contribution to each measured offset is small, and yields a more conservative estimation of the mean offset and uncertainty of  $556 \pm 619 \text{ mas}$  and  $-297 \pm 603 \text{ mas}$  in RA and Dec respectively. We note that the astrometric accuracy of the VLASS Epoch 1 is well characterized, with a mean offset of the order  $0.2''$  in RA and  $0.0''$  in Dec<sup>3</sup>. We corrected for this positional offset in the reference VLASS positions, and obtain a final offset correction of  $0.75''$  in RA and  $-0.30''$  in Dec. The final position of FRB20180301A after correcting for positional offsets is RA(J2000): 06h12m54.42(4)s and Dec(J2000): +04d40'15.9(6)'', where final uncertainties are the quadrature sum of statistical and systematic uncertainties. These are also listed in Table 1.

We conducted additional tests on the FRB-epoch data to investigate the astrometric stability on  $\sim$  minute scales across the entire observation duration, generating a set of images with spacing 3 minutes. The mean offset varied by up to half an arcsecond between adjacent 3 min images, consistent with our previous experience of L-band observations and implying a potential gradient in the observed positional offsets of up to  $\sim 0.2$  arcseconds/minute. We noted, however, that the average offset derived from the 30 s image centered on FRB does not lie on an interpolation between those derived from adjacent 3 min images, suggesting some structure on  $< 3 \text{ min}$  timescales. We note that any remaining variability on  $< 30 \text{ s}$  timescales could lead to a small, uncorrected positional bias.

#### 2.1.4. Optical follow-up

In archival Pan-STARRS images we identify a faint galaxy, PSO J093.2268+04.6703, as the putative host of FRB20180301A. We acquired deep (0.5 – 0.7 hrs in each band) follow-up imaging of the FRB field with the Nordic Optical Telescope (NOT) using the Sloan

<sup>3</sup> [https://library.nrao.edu/public/memos/vla/vlass/VLASS\\_013.pdf](https://library.nrao.edu/public/memos/vla/vlass/VLASS_013.pdf)

filters  $u, g, r, i$ , and  $z$  on nights between UT 2021 October 26 to December 14, followed by additional deep ( $36 \times 100$  s) Gemini  $r$ -band observations on UT 2021 January 25. The Gemini image was astrometrically calibrated to match the Gaia DR2 catalog (Gaia Collaboration et al. 2018; Lindegren et al. 2018), with a relative accuracy of  $0.2''$ . We note that there is an additional nearby source to the south of the identified host galaxy in the field of FRB20180301A. The morphology of this source is consistent with being point-like, so we classify it as a Galactic foreground star.

Observations of the host with the Keck/DEIMOS spectrograph on UT 2020 September 17 determined the galaxy’s redshift  $z = 0.3304$  based on nebular emission lines such as [N II] and H $\alpha$ . The measured redshift was found to be consistent with the redshift range ( $z = 0.13 - 0.35$ ) estimated by extragalactic DM in Luo et al. (2020). We also performed NIR observations of the galaxy in  $JHK$ -bands using the MMT telescope on UT 2021 February 27 & 28. The photometric measurements derived from MMT imaging, along with those from NOT, were used by CIGALE (Noll et al. 2009) for SED fitting to estimate the stellar mass of the galaxy (see Appendix for details). The deep  $r$ -band Gemini imaging was used for the probabilistic host galaxy association analysis. We find a Probabilistic Association of Transients to their Hosts (PATH) (Aggarwal et al. 2021b) probability of 99.9% for the association of FRB20180301A with the given galaxy. The host is presented in Fig. 3 and properties are listed in Table 1.

### 3. ASKAP LOCALIZATION OF APPARENTLY NON-REPEATING FRBS

Here we report the discoveries of the single bursts from two new FRB sources, FRBs 20191228A and 20200906A, discovered in the CRAFT incoherent-summed (ICS) searches with ASKAP (Bannister et al. 2019a). The burst pulse profiles and dynamic spectra are shown in Figure 2.

#### 3.1. FRB20191228A

FRB20191228A was detected on 2019 December 28 at UT 09:16:16.44440 during CRAFT observations conducted with ASKAP, with 28 antennas in a 336 MHz band centered on 1271.5 MHz. The burst had a detection S/N of 23 at a DM =  $297.5(5)$  pc cm $^{-3}$ . The real-time detection in online incoherent-sum data triggered a download of 3.1 s of voltages around the FRB. The offline correlation of voltages across 28 antennas and their interferometric analysis led to an initial localization of FRB20191228A.

On 2020 January 31, we used the Australia Telescope Compact Array (ATCA) in the frequency range

of 1.1 – 3.1 GHz to perform astrometric observations of background sources near the position of FRB20191228A, to refine the position of the burst. In addition to four target background sources in the field of FRB20191228A (J2258–2929, J2255–2937, J2258–2955 and J2259–2957), we observed three gain calibrators (PKS2254–367, PKS2337–334, and PKS2255–282). For each target background source, we obtained three position estimates – one for each gain calibrator, by applying phase calibration solutions derived from that calibrator. We observed a scatter of  $\sim 80$  mas in RA and  $\sim 200$  mas in Dec in the position of the background sources depending on which gain calibrator was used. To account for this systematic uncertainty to the ATCA positions, for each background source we took a weighted mean of the three positions to estimate the probable location, and added the average residual offset from this mean position in quadrature to our estimate of the absolute positional uncertainty for the source.

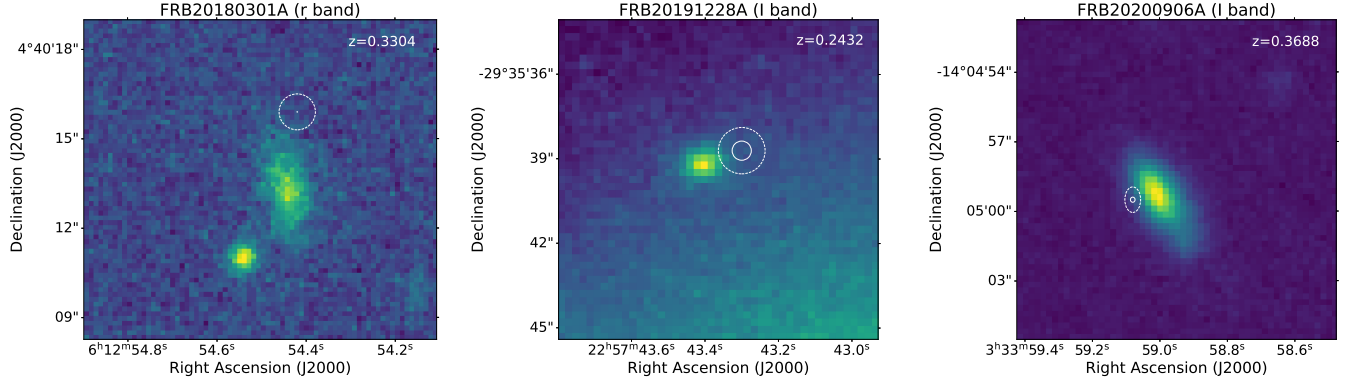
The positions of target sources obtained from the ATCA radio image were compared with those obtained from the 3.1 s ASKAP data, following the method described in Day et al. (2020), to astrometrically register the FRB image frame to that of the International Celestial Reference Frame (ICRF3, Gordon 2018) and estimate the accuracy of this registration. J2258–2929 and J2259–2957 were excluded from the field source comparison due to low S/N in the ASKAP image for the latter, and the former being resolved.

Finally, we computed a weighted mean systematic image frame offset using the method described in Day et al. (2021). We found positional offsets of  $0.410 \pm 0.830''$  and  $-0.856 \pm 0.823''$  in RA and Dec., respectively. The final FRB position after correcting for the astrometric shifts in the image frame and summing the statistical ( $\pm 0.34''$  in RA and Dec.) and systematic uncertainties in quadrature is RA(J2000): 22h57m43.30(7)s and Dec(J2000):  $-29^{\circ}35'38.7(9)''$ .

#### 3.1.1. Follow-up observations

The burst position is 1.8 arcmin from the first-magnitude star Fomalhaut ( $\alpha$  PsA), which severely complicated identification and characterisation of the optical counterpart.

Deep imaging with FORS2 instrument at the European Southern Observatory’s (ESO) Very Large Telescope (VLT) was performed in the  $g$ -band ( $5 \times 90$  s) and  $I$ -band ( $20 \times 100$  s) on 2020 September 21 UT, while using the movable slitlets normally employed for multi-object spectroscopy to completely mask the lower of the 2 CCDs to protect the detector from saturation by Fo-



**Figure 3.**  $r$ -band Gemini image of the host of repeating FRB20180301A and  $I$ -band FORS2 images of the hosts of FRB20191228A and FRB20200906A, overplotted with the positions of each FRB. The white solid and dashed circle/ellipse represents the  $1\sigma$  statistical and systematic uncertainty respectively in the FRB position.

malhaut. The seeing ranged between  $0.6'' - 0.9''$  during the observations.

The individual frames were bias-subtracted and flat-fielded using the ESOReflex package (Freudling et al. 2013). To overcome the glare produced by Fomalhaut, a two-dimensional polynomial was fit to a patch of sky centered on the burst position in each individual frame, after masking sources. This model was then subtracted from the patch. The glare-subtracted images were coadded with the Montage package (Berriman & Good 2017). A candidate host galaxy was identified with centroid approximately  $1.5''$  from the burst coordinates with a 100% PATH association probability (see Fig. 3). Photometry of the identified galaxy was performed with Source-Extractor (Bertin & Arnouts 1996) using a circular aperture with a  $5''$  diameter. The effect of the glare subtraction on the photometry was investigated, and the uncertainty introduced by the procedure quantified, using injected synthetic sources of known magnitude (making use of Astropy, Robitaille et al. 2013).

On UT 2020 November 08, the Keck/LRIS spectrograph was used to perform spectroscopic observations in order to determine the galaxy redshift. The nebular emissions such as  $H\alpha$ ,  $[O III]$  established the redshift of the host to be  $z = 0.243$ .

We also performed observations of the host of FRB20191228A using the ATCA at center frequencies of 5.5 and 7.5 GHz to search for a compact and persistent radio emission. We did not detect any radio emission above  $22 \mu\text{Jy beam}^{-1}$  ( $3\sigma$ ) constraining the luminosity of the source to be  $< 3.4 \times 10^{21} \text{ W Hz}^{-1}$  at 6.5 GHz.

### 3.2. FRB20200906A

FRB20200906A was discovered in the incoherent sum of 7 ASKAP antennas on 2020 September 06 UT 21:40:50.923 during CRAFT observations at 864.5 MHz. The burst had an optimal S/N of 19.2 at a DM of

$577.8(2) \text{ pc cm}^{-3}$  in the low time resolution search data stream. Voltages spanning 3.1 s around the FRB were downloaded, cross-correlated and imaged offline to obtain a preliminary position of the burst. The astrometric registration was performed by comparing background sources in the 3.1 s ASKAP image with their NRAO VLA Sky Survey (NVSS) radio source catalog (Condon et al. 1998) counterparts. We cross-matched seven sources and computed a weighted mean systematic image frame offset using the method described in Day et al. (2021). We found positional offsets of  $2.05 \pm 0.34''$  and  $0.51 \pm 0.55''$  in RA and Dec., respectively. The final burst position after correcting for the astrometric shifts in the image frame and summing the statistical ( $\pm 0.10''$  in RA and  $\pm 0.11''$  in Dec.) and systematic uncertainties in quadrature is RA(J2000): 03h33m59.08(2)s and Dec(J2000):  $-14^{\circ}04'59.5(6)''$ .

#### 3.2.1. Follow-up observations

A candidate host galaxy for FRB20200906A was identified in the DES, Pan-STARRS and AllWISE database as DES J033358.99-140459.2, PSO J033358.994-140459.287 and J033358.99-140459.1 respectively, with 100% PATH association probability (see Fig. 3). On UT 2020 December 20 & 22, we performed follow-up observations using VLT/FORS2 in  $g$ - and  $I$ -band following a similar strategy as for FRB20191228A (Sec. 3.1.1) but without the need to mask the lower CCD. On UT 2020 September 17, we also triggered Keck/DEIMOS for spectroscopic observations and found the redshift of the putative host to be  $z = 0.3688$ . The photometric measurements from Pan-STARRS and those from the VLT were used to model the SED of the host galaxy. The derived properties are presented in Table 1.

We triggered the VLA (project code: VLA/20A-157) on UT 2020 September 22 to observe the host galaxy of FRB20200906A in the frequency range 4 – 8 GHz. We



found no radio emission from the host galaxy above a  $3\sigma$  flux density of  $12 \mu\text{Jy beam}^{-1}$ , implying an upper-limit on the source’s luminosity to be  $< 4.3 \times 10^{21} \text{ W Hz}^{-1}$  at 6 GHz.

#### 4. COMPARING FRB HOST GALAXIES TO THE UNDERLYING FIELD GALAXY POPULATION

In this section, we place the overall population of FRB hosts in context with the field galaxy population, expanding on our earlier work (Bhandari et al. 2020; Heintz et al. 2020). We use the data published in Heintz et al. (2020), Mannings et al. (2020) and measurements derived for the hosts in this work. We also update the measurements published for a subset of FRB hosts (see Appendix). For FRB20171020A, FRB20201124A and FRB20200120E, we use the data published in Mahony et al. (2018), Fong et al. (2021) and Bhardwaj et al. (2021) respectively.

We considered only the FRB host galaxies for which the PATH posterior probability is greater than 90% (see last column of Table A2). This includes all 3 of the new FRBs presented here which have posterior probability  $P(O|x) > 0.999$ . The host of FRB20190614D (Law et al. 2020), FRB20181112A (Prochaska et al. 2019) and FRB20190523A (Ravi et al. 2019) have low probabilities of  $P(O|x)$  of 0.58, 0.67 and 0.82 respectively and, are therefore excluded. Also, FRB20191001A has two nearby candidate hosts at a common redshift (Bhandari et al. 2020), that yield PATH posterior probabilities  $P(O|x) = 0.6$  and  $0.4$ . We proceeded by adopting the galaxy with smaller angular separation from the FRB as the host which is akin to adopting a stronger prior on the projected offset than adopted by Aggarwal et al. (2021b). Future associations will refine this assumption. We also included the host of FRB20200120E (Bhardwaj et al. 2021; Kirsten et al. 2021) and the candidate host for FRB20171020A, because of their low probability of chance association (North-Hickey et al. in prep). Thus, we obtained a sample of 16 confident host associations for our analysis, of which 10 are hosts of apparently non-repeating FRBs and six host repeating FRBs (see Table A3).

Figure 4 shows our comparison of the color–magnitude and star-formation rate (SFR)–stellar mass ( $M_*$ ) distributions of the FRB host galaxies with those of the general population of galaxies at redshift  $< 0.5$  from the PRIMUS survey (Moustakas et al. 2013). The left panel of Fig. 4 presents the current SFR as a function of  $M_*$ . The hosts of repeating and one-off bursts are distinguished by symbol color and shape. Most of the FRB hosts lie in or around the star-forming cloud of galaxies, but are offset from the star-forming main sequence for

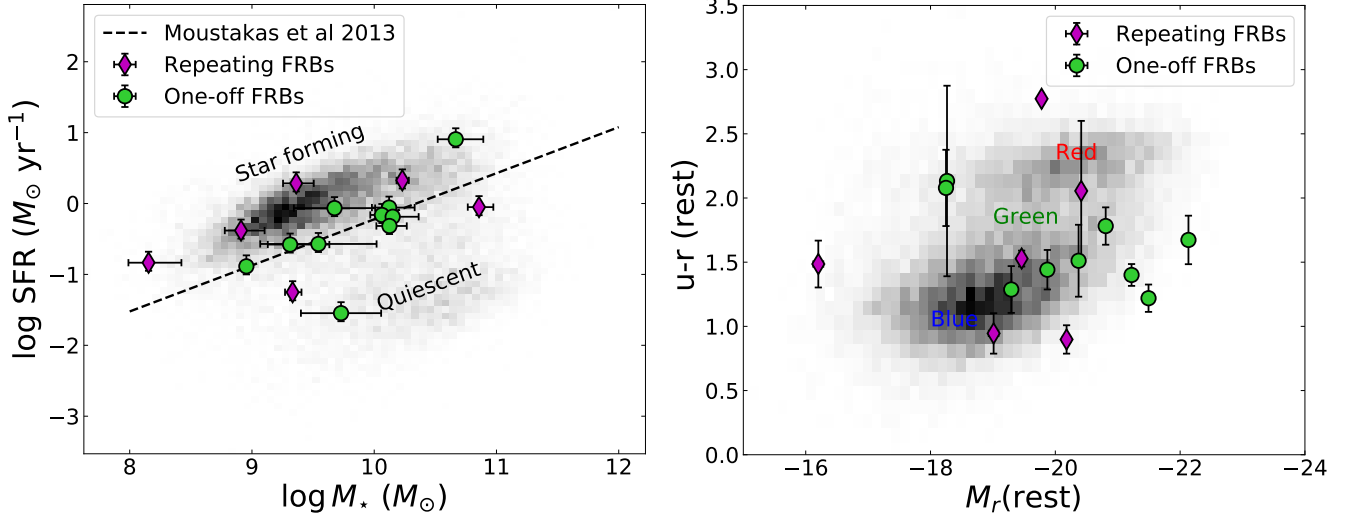
galaxies with similar stellar masses. We note that only 2 of the 16 hosts lie in the region occupied by quiescent galaxies.

The right panel of Fig. 4 shows a color magnitude diagram and provides information about the overall stellar populations in these galaxies. The late-type galaxies with ongoing star formation and therefore, young stellar populations lie in the ‘blue cloud’, i.e., blue galaxies (Strateva et al. 2001), while massive early-type galaxies live in the ‘red and dead’ zone characterized by very low star formation and hence older stellar populations, i.e., red galaxies. The host galaxies of the FRBs appear to lie on the luminous side of the absolute magnitude distribution, mainly near the ‘blue cloud’ and ‘green valley’ region, where galaxies are expected to be transitioning between star-forming and quiescent systems (Martin et al. 2007). We observe a dearth of red galaxies in our current sample of FRB host galaxies.

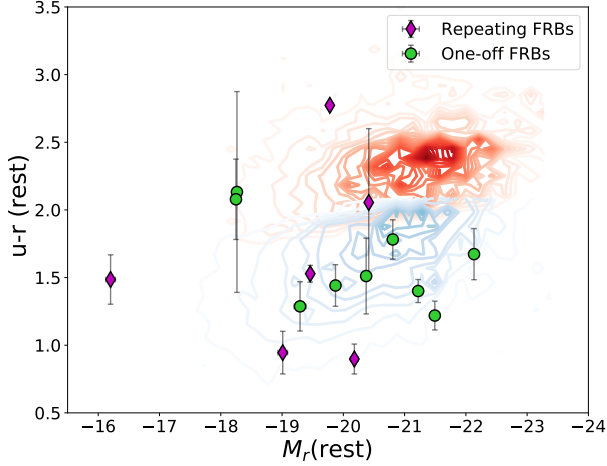
##### 4.1. Do FRB hosts track stellar mass and star formation rates?

In Fig. 5 we again present the color-magnitude diagram, but with the background PRIMUS galaxy sample weighted by their stellar masses. This is a good approximation of where most stars are in the local Universe. We show that the majority of FRB hosts do not trace massive red galaxies and also do not seem to align with the color-magnitude diagram space of the peak of stellar mass-weighted blue galaxies which tend to redder color. To quantify this trend, we examined the null hypothesis that FRB hosts track stellar mass. The galaxy stellar mass function (GSMF) of low- $z$  galaxies,  $\Phi(M_*)\Delta M$ , was weighted by stellar mass and compared to the observed FRB host mass distribution. We used the double Schechter function to model GSMF for all, star-forming and passive galaxies in the redshift range  $0.2 < z < 0.5$  in the COSMOS field (Davidzon et al. 2017). Our KS tests comparing the cumulative mass distributions of all FRB hosts with the mass-weighted stellar mass distribution of all field galaxies yielded a p-value  $P_{KS} < 0.05$  (see top panel of Fig. 6). Therefore, these results reject the null hypothesis that FRB hosts directly track stellar mass with 95% confidence, consistent with the findings of Heintz et al. (2020).

Furthermore, we tested the null hypothesis that FRB hosts track star formation rates. We used the star formation rate distribution function derived from the UV and IR luminosity Schechter functions for the local Universe using GALEX data (Bothwell et al. 2011). We then computed the star formation rate volume density distribution function, which is given by  $\Phi(\Psi) \times \Psi$ , where  $\Psi$  is the star formation rate in  $\text{M}_\odot \text{ yr}^{-1}$ . The KS test



**Figure 4.** Left: Star-formation rate and stellar mass distributions of the host galaxies of 6 repeating and 10 one-off FRBs compared against a population of galaxies at  $z < 0.5$  taken from the PRIMUS survey (Moustakas et al. 2013). The dashed line is the line of constant specific SFR separating the primary sequences of star-forming and quiescent galaxies. Right: Rest-frame color-magnitude diagram of the host galaxies of a sample of 6 repeating and 9 one-off FRBs compared to the population of PRIMUS galaxies at  $z < 0.5$ . FRB20171020A is not included due to lack of  $u-r$  measurement. We also note that the observed magnitudes for FRB20201124A and FRB20200120E are approximated as rest-frame magnitudes because of their low redshifts and thus, small k-correction.



**Figure 5.** Approximation of the stellar density in blue and red galaxies as presented by blue and red contours respectively and derived from the PRIMUS galaxies in the color-magnitude diagram. The shading from white to respective color represent outer to inner contour levels. The contour levels are set same for blue and red galaxies. The bright red region shows that most of the stars in the local Universe are concentrated in massive red galaxies. Green and magenta data points are the sample of one-off and repeating FRB hosts respectively. We observe that FRBs are distributed in normal blue galaxies.

between the cumulative star formation rate volume density distribution function and the star formation rates of FRB hosts in our sample resulted in a p-value of the

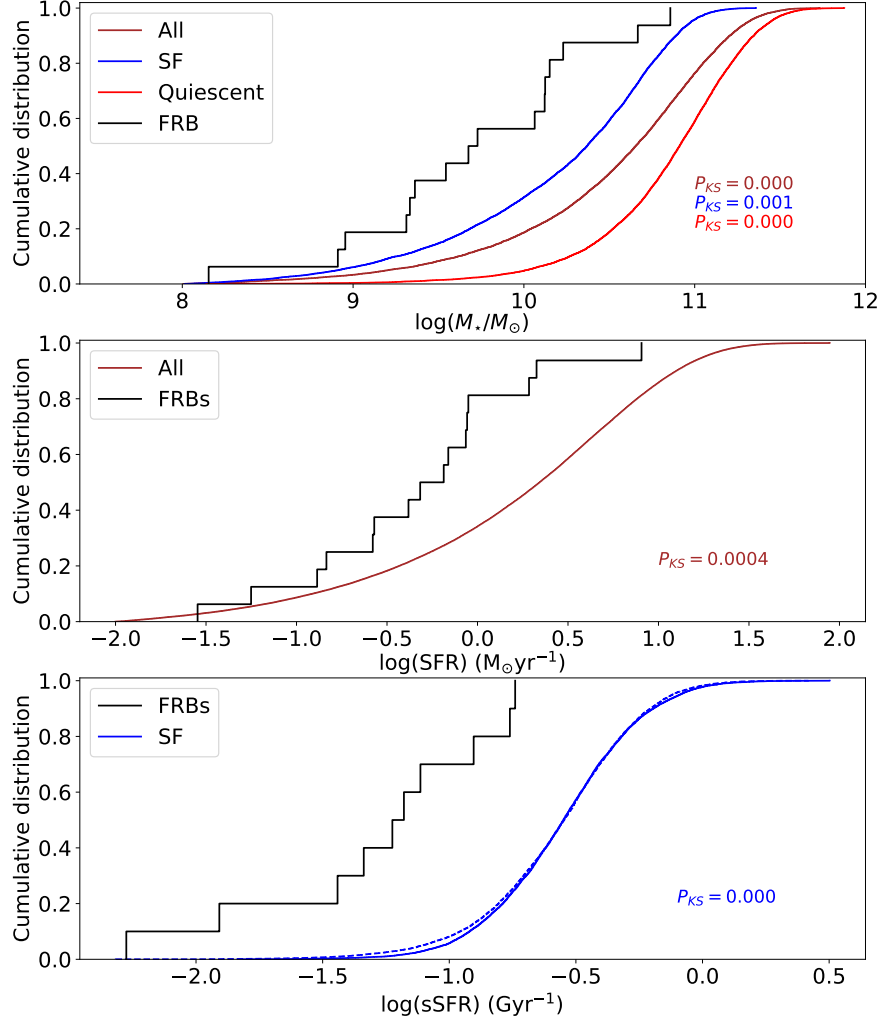
order of  $10^{-4}$  (middle panel of Fig. 6). Thus, we reject the null hypothesis that the host galaxies of FRBs track star formation rates of field galaxies with 95% confidence level.

Finally, we investigated the specific star formation rates (sSFRs) of FRB hosts in our sample with that of sSFR functions derived from the star-forming sample of galaxies defined by a main sequence using a color-color selection in COSMOS and GOODS survey in the redshift range  $0.2 - 0.4$  (Ilbert et al. 2015). The sSFR function can be modelled as a log-normal or a double exponential profile for a given stellar mass bin range (Eq. 2 and 3 of Ilbert et al. (2015)). We computed the function over four mass bins ranging from  $9.5 < \log(M) < 11.5$  and combined them together. The weighted cumulative sum of this sSFR function is compared to the cumulative distribution of sSFRs of FRB hosts in the same mass range. The results are presented in the bottom panel of Fig. 6. We observed that FRB hosts do not follow the sSFRs of star-forming galaxies and thus reject the null hypothesis with 95% confidence.

Thus, we conclude that FRB hosts have lower  $M_{*}$ , SFR and sSFR than randomly selected field galaxies weighted by  $M_{*}$ , SFR or sSFR.

#### 4.2. BPT diagram

To identify the dominant source of ionization in FRB host galaxies, we plot their nebular emission line ratios namely,  $[\text{N II}]/\text{H}\alpha$  and  $[\text{O III}]/\text{H}\beta$  in a Baldwin-



**Figure 6.** Top: Comparison of FRB cumulative mass distribution with mass-weighted stellar mass distribution for all field galaxies (brown), star-forming galaxies (blue) and quiescent galaxies (red). Middle: Comparison of FRB host cumulative SFR distributions (black) with the star formation rate volume density distribution function for all field galaxies in the local Universe (brown). Bottom: Comparison of sSFRs for FRBs in the mass range  $9.5 < \log(M) < 11.5$  with the log-normal (solid) and double exponential functions (dashed) for sSFRs of main-sequence star-forming galaxies.

Phillips-Terlevich (BPT) diagram (Baldwin et al. 1981) in Fig. 7. This diagram can also be used to distinguish between star-forming (SF) galaxies, low-ionization nuclear emission-line region (LINER) galaxies, and Active Galactic Nuclei (AGN) (see Kewley et al. (2001) for more details). For comparison, we show the distribution of nearby ( $0.02 < z < 0.4$ ) emission-line ( $> 5\sigma$  significance) galaxies from the Sloan Digital Sky Survey (SDSS) including the standard demarcation lines between SF, AGN, and LINER galaxies (Kauffmann et al. 2003; Cid Fernandes et al. 2010). We performed a 2D KS-test to compare the host population of FRBs with that of underlying SF, AGN and LINER galaxies and found that they are not drawn from a specific class ( $P_{KS} < 10^{-3}$ ), which remains consistent with the findings of Heintz et al. (2020). The majority of FRB hosts

occupy the star-forming and LINER region of the BPT diagram and are offset from the main star-forming sequence. We note that all three hosts of repeating FRBs lie in the star-forming region and the host of repeating FRB20121102A remains an outlier as compared to the hosts of other FRBs (Li et al. 2019).

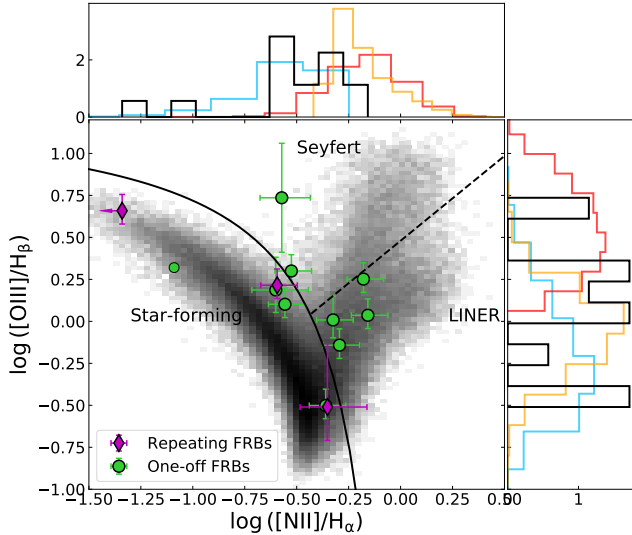
##### 5. DISENTANGLING THE HOST GALAXIES OF REPEATING AND NON-REPEATING FRBS

The progenitors of FRBs are linked to the specific stellar population and environments of their host galaxies. Based on the larger set of FRBs and their hosts presented here, in combination with previous literature identifications, we leverage this larger sample to further constrain the likely progenitor channels of FRBs. More specifically, we aim to quantify whether the repeating

Transient type	Literature reference
ULXs <sup>a</sup>	Kovlakas et al. (2020)
SGRBs	Leibler & Berger (2010); Fong et al. (2010); Fong & Berger (2013); Berger (2014)
LGRBs	Blanchard et al. (2016); Taggart & Perley (2021)
CCSNe	Schulze et al. (2020)
SLSNe	Schulze et al. (2020); Taggart & Perley (2021)
Type Ia SNe	Lampeitl et al. (2010); Uddin et al. (2020)

**Table 2.** Literature references of the data used for various transients in this work.

<sup>a</sup> Excluding unreliable data, nuclear sources and sources with X-ray luminosities  $< 10^{39} \text{ erg s}^{-1}$ .



**Figure 7.** BPT classification diagram for FRB hosts. The gray-scale background shows the density distribution of SDSS galaxies with redshifts  $0.02 < z < 0.4$ . The dashed and dotted black lines represent the demarcation line between SF galaxies and AGNs (Kauffmann et al. 2003) and AGN and LINERs (Cid Fernandes et al. 2010), respectively. The majority of FRB hosts are SF and LINER galaxies. Top and sideways inset present the histograms of the ratio of  $[N II]/H\alpha$  and  $[O III]/H\beta$  respectively for FRBs (black), AGNs (red), SF (light blue) and LINER (orange) galaxies. We note that a smaller sample of FRBs is shown in this plot, due to either lack of available spectral line data or the non-detection of required emission lines.

and apparently non-repeating bursts are hosted by distinct galaxy environments. This might provide further clues to whether their progenitor channels are physically distinct.

Initially, Heintz et al. (2020) found that FRB hosts seem to show an overall broad, continuous range of physical properties. They noted that the hosts of repeating FRBs generally occupied the faint, low-mass end of the FRB galaxy distribution. Here, we performed a differential analysis of the properties of the larger sample of FRB hosts. In Fig. 8 we compared the projected physical offsets, SFR, stellar mass, metallicities,  $r$ -band lu-

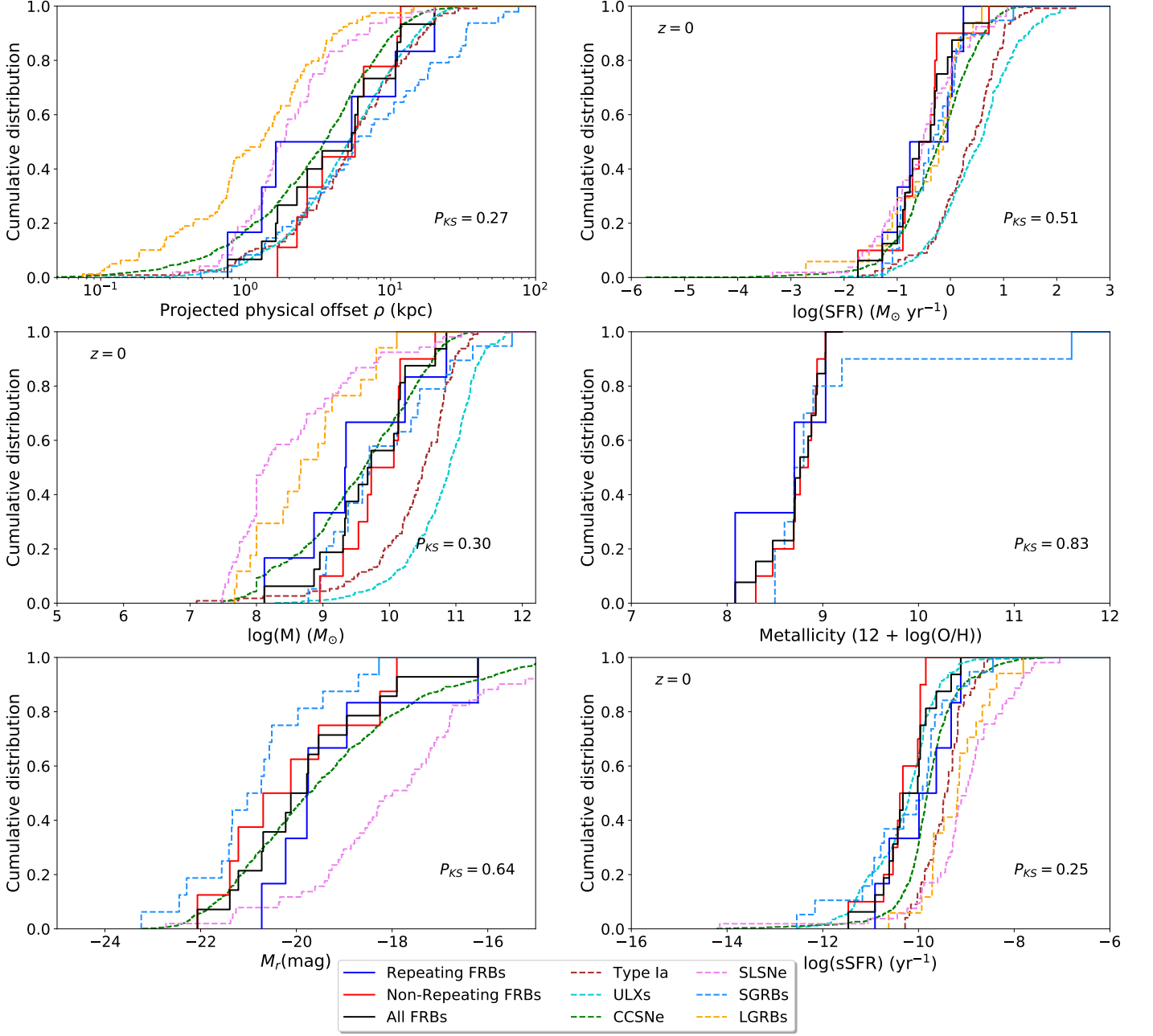
minosities and specific star formation rates of repeating and non-repeating FRB host population. We found the KS test p-values to be greater than our threshold statistical significance level ( $\alpha = 0.05$ ). Thus, the null-hypothesis that these distributions are drawn from the same underlying distribution cannot be rejected. The present sample of FRB hosts thus do not indicate strong physical distinctions between the two apparent source populations.

## 6. COMPARISON OF THE FRB HOST GALAXY PROPERTIES WITH OTHER TRANSIENTS

### 6.1. Extragalactic transients

Studies of extragalactic transients often use their physical offsets from the center of their hosts, and locations within their host galaxies, to aid in inferring the nature of their progenitors. In the past, such investigations including other global properties for a small sample of FRB hosts have been conducted (Bhandari et al. 2020; Heintz et al. 2020; Mannings et al. 2020; Li & Zhang 2020; Safarzadeh et al. 2020; Bochenek et al. 2021). The majority of them suggest that galaxies hosting gamma-ray bursts (SGRBs) and CCSNe are similar to galaxies hosting FRBs. Additionally, the progenitor scenarios of LGRBs and SLSNe have been disfavored for the majority of FRBs. Recently, ultra-luminous X-ray sources (ULX)-like binaries were proposed as a possible progenitor for periodically active FRBs (Sridhar et al. 2021). Motivated by such studies, we performed two sample 1D-KS tests comparing the distributions of various global host properties of the most updated sample of FRBs together and separated into two populations (repeating and non-repeating) with the host galaxy properties of other transients (see Fig. 8). We also included Type Ia supernovae – a proxy for the accretion-induced collapse of white dwarf stars, which have been suggested as possible FRB progenitors (Margalit et al. 2019; Kirsten et al. 2021). Table 2 represents the data from the literature that has been used in this study for all these transients. We used the method described in Bochenek et al. (2020) to correct for redshift evolution

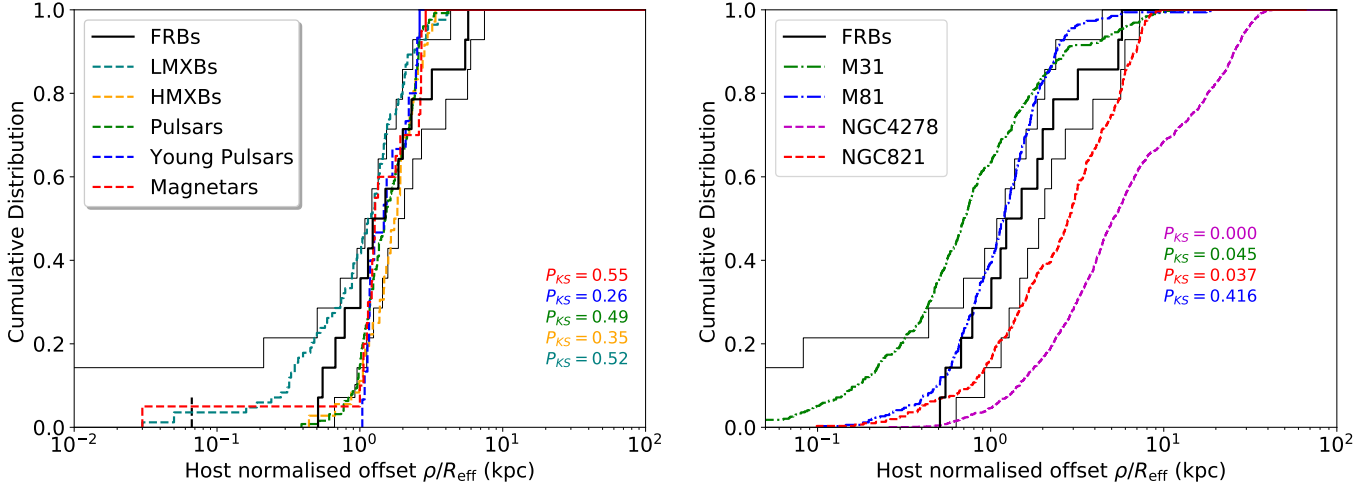




**Figure 8.** Cumulative distributions of the projected physical offsets, SFR, stellar mass, metallicity, absolute  $r$ -band magnitudes and specific SFR for repeating (blue), non-repeating (red) and combined (black) FRB host population compared with ultra-luminous X-ray (ULX) sources (cyan), short (lightblue) and long (orange) gamma-ray bursts and core-collapse (CC)(green), superluminous (SL)(magenta) and Type Ia (brown) supernovae (SNe). The data for these transients are taken from literature listed in Table 2. The p-values for KS-test between the repeating and non-repeating population is listed on the right side of each plot. We also summarize the p-values for KS-tests between FRB populations and respective transients in Table 3.

**Table 3.** P-values for two-sample 1D-KS after comparing the distributions of various properties (column 1) of the hosts of FRBs (all together and separated by repeating and on-off host population) with that of galaxies hosting ULXs, SGRBs, LGRBs, SLSNe, CCSNe and Type Ia SN. Highlighted cells shows the p-values ( $> 0.05$ ) for which the null hypothesis cannot be rejected. SGRBs and CCSNe remain as the allowed dominant channels for producing FRBs.

Property	FRB Type	Transients					
		ULXs	SGRBs	LGRBs	SLSNe	CCSNe	Type Ia
Offset	Rep	0.28	0.44	0.18	0.37	0.82	0.28
	Non-rep	0.88	0.24	0.00	0.03	0.44	0.77
	All	0.82	0.25	0.00	0.03	0.46	0.83
SFR	Rep	0.01	0.93	0.96	0.86	0.65	0.03
	Non-rep	0.00	0.26	0.07	0.54	0.04	0.00
	All	0.00	0.68	0.23	0.80	0.1	0.00
log(M)	Rep	0.00	0.36	0.29	0.06	0.73	0.02
	Non-rep	0.00	0.64	0.00	0.00	0.33	0.00
	All	0.00	0.59	0.00	0.00	0.50	0.00
Z	Rep	-	0.91	-	-	-	-
	Non-rep	-	0.99	-	-	-	-
	All	-	0.84	-	-	-	-
$M_r$	Rep	-	0.07	-	0.06	0.60	-
	Non-rep	-	0.89	-	0.01	0.80	-
	All	-	0.15	-	0.00	0.73	-
sSFR	Rep	0.32	0.75	0.25	0.05	0.70	0.34
	Non-rep	0.57	0.08	0.00	0.00	0.00	0.00
	All	0.82	0.39	0.00	0.00	0.01	0.00



**Figure 9.** Left: Cumulative distributions of the host-normalized offsets for FRBs compared with that of Galactic objects in the Milky Way galaxy. The data for various Galactic sources has been taken from [Chrimes et al. \(2021\)](#). The gray-shaded region represents the  $1\sigma$  uncertainty on the CDF, accounting for uncertainties due to individual measurements and sample size. The p-values for a KS-test between Galactic sources and all FRBs are listed on the right side of the plot. Right: Cumulative distributions of the host-normalized offsets for FRBs compared with offset distributions of globular clusters associated with M81, M31 (spiral late-type galaxies), NGC821 (isolated elliptical galaxy) and NGC4278 (L\* elliptical galaxy). The effective radius used for these galaxies are  $R_{\text{eff}}(\text{M81}) = 3.5$  kpc ([Bhardwaj et al. 2021](#)),  $R_{\text{eff}}(\text{M31}) = 7.2$  kpc ([Savorgnan & Graham 2016](#)),  $R_{\text{eff}}(\text{NGC821}) = 5.1$  kpc ([Pellegrini et al. 2007](#)) and  $R_{\text{eff}}(\text{NGC4278}) = 2.4$  kpc ([Usher et al. 2013](#)). The p-values for KS-test between globular clusters and all FRBs are listed on the right side of the plot.

by scaling the stellar masses and star-formation rates of host galaxies of FRBs and other transients to be statistically representative of  $z = 0$  galaxies.

While the distribution of projected physical offsets for ULXs and Type Ia supernovae are statistically consistent with that of FRBs, their host galaxies are often more massive and star-forming, i.e., a mean of  $\log(M_*) = 10.4 M_\odot$  and  $10.8 M_\odot$ ,  $\text{SFR} = 6.2 M_\odot \text{yr}^{-1}$  and  $11.7 M_\odot \text{yr}^{-1}$  for the hosts of Type Ia SN and ULXs, respectively. However, we observe the specific SFR for ULX hosts to be similar to that of FRB hosts. Also, the majority of properties of the hosts of SGRBs and CCSNe are very similar to FRB hosts suggesting that the host population of FRB progenitors shares the same/similar characteristics to those of these transients. A KS test shows that the SFR distribution of LGRB hosts and SLSNe hosts are consistent with FRB hosts. However, we note that such events are common in dwarf galaxies with high specific SFRs as evident from the left middle and right bottom panel of Fig. 8, which is not consistent with the overall FRB-host population. Interestingly, while the results of our KS-tests allow us to statistically rule out LGRB scenarios for all FRBs combined ( $P_{\text{KS}} < 0.05$ ), we are unable to reject the hypothesis that the repeating FRB and LGRB hosts are drawn from the same continuous distribution. When comparing with SLSNe hosts, we found the physical off-

sets of the repeating FRBs ( $P_{\text{KSR}} = 0.37$ ) and  $r$ -band magnitude ( $P_{\text{KSR}} = 0.06$ ) of their hosts to agree with that of SLSNe hosts. The p-values from our KS-tests are presented in Table 3.

## 6.2. Comparison to the Galactic source population and globular clusters

The prevailing view currently associates FRBs with magnetars, whose extreme magnetic fields provide a reservoir of energy to produce FRBs ([Metzger 2018](#); [Lyutikov & Rafat 2019](#)). With the detection of an FRB-like burst from SGR1935+2154, the association of some (low-luminosity) FRBs with magnetars has been observationally confirmed ([CHIME/FRB Collaboration et al. 2020](#); [Bochenek et al. 2020](#)). Following the analysis of [Chrimes et al. \(2021\)](#), we compared the host-normalized offset distributions of low-mass X-ray binaries (LMXBs), high-mass X-ray binaries (HMXBs), pulsars, young pulsars and magnetars in the Milky Way with the updated FRB host sample — including all repeating and non-repeating FRBs in the left panel of Fig. 9. Based on our KS-test, the offset distribution of the neutron star population in the Milky Way is consistent with that observed for FRBs in their host galaxies.

Recently, a repeating FRB20200120E originally associated with the galaxy M81 ([Bhardwaj et al. 2021](#)) has been precisely localized, by the EVN network, to a glob-

ular cluster (GC) system [PR95] 30244 in M81 (Kirsten et al. 2021). Motivated by this finding, we compared the host-normalized offset distributions of FRBs in our sample with globular clusters in late-type spirals and early-type elliptical galaxies in the right panel of Fig. 9.

For the GCs in late-type galaxies, we used a sample of 340 high quality GC candidates (of which 74 were confirmed using spectroscopy) associated with M81, identified in HST imaging (Nantais et al. 2010; Nantais & Huchra 2010). We note that the available data is dominated by a GC disk population with the majority of GCs within 10 kpc from the center of M81. We also used a sample of 390 GCs associated with the galaxy M31 (both disk and halo population) identified in images from the Wide Field Camera (WFCAM) on the United Kingdom Infrared Telescope and from the Sloan Digital Sky Survey (SDSS) (Peacock et al. 2010). For early-type galaxies, we used the available GC data associated with an isolated elliptical galaxy NGC821, extending up to 50 kpc from the center of the galaxy (Spitler et al. 2008). The sample consist of 306 GCs identified in the new imaging from the 3.5-m Wisconsin Indiana Yale NOAO (WIYN) Mini-Mosaic imager, supplemented with the HST WFPC2 images. We also used a sample of 1828 GC candidates (of which 270 are confirmed using spectroscopy from Keck/DEIMOS) associated with the  $L_*$  elliptical galaxy NGC4278, identified in HST/ACS and wide-field Subaru/Suprime-Cam imaging (Usher et al. 2013).

Our KS-test shows that the host-normalized offset distribution of FRBs in their hosts are not consistent with being drawn from the same continuous distribution as that of the halo and disk population of GCs associated with late-type (M31) and early-type galaxies in our sample ( $P_{KS} < 0.05$ ). We were unable to rule out globular cluster in M81 ( $P_{KS} = 0.262$ ) which may be because the data is incomplete and mostly dominated by GC disk population. We also note possible caveats in our analysis such as the number of GCs scale with galaxy stellar mass and our FRB host population spans three orders of magnitude in the stellar mass, i.e.  $M_* = 10^8 - 10^{10} M_\odot$  and our FRB host sample shows a deficiency of elliptical galaxies. A subset of FRBs in our sample were found to originate from or near the spiral arms of their hosts. Whether they are linked to the disk population of GCs is presently unknown and we are limited by the sensitivity of current telescopes. A much larger sample of precisely localized FRBs with high spatial observations of nearby hosts are needed to pursue this further.

We have presented the localization of the sixth repeating FRB20180301A using the REALFAST system at the VLA and two apparently non-repeating FRBs (FRB20191228A and FRB20200906A) discovered by ASKAP. With an updated sample of 6 repeating and 10 non-repeating FRB host galaxies, we have conducted a differential analysis of global properties of the FRB host population. While the latest observations of FRBs from the CHIME/FRB project strongly suggest that repeaters and single-burst sources arise from separate mechanisms and astrophysical sources (Pleunis et al. 2021), we did not find significant differences in their host populations. We observed FRB hosts to be moderately star-forming galaxies ( $0.03 - 8 M_\odot \text{ yr}^{-1}$ ), with masses offset from the star-forming main-sequence. The majority of FRB hosts lie in the star-forming and LINER region of the BPT diagram. As a low metallicity dwarf galaxy, the host of FRB20121102A continues to be an outlier in the sample.

We find that FRBs in our sample do not track the stellar mass and in general are not hosted in old, red and dead galaxies which have old stellar population. The dearth of FRBs in the massive red galaxies suggest that FRBs are not solely produced in channels with a large average delay between star formation and the FRB source formation such as magnetars formed via compact object-related systems, including neutron star mergers, or the AIC of a white dwarf to a neutron star. Current data supports a mix of prompt (core-collapse SNe) and delayed channels for producing FRB progenitors, suggesting that they are drawn from the general stellar population rather than an exotic and rare sub-population. Furthermore, FRB hosts do not follow the specific SFRs of star-forming galaxies, nor do they track the star formation rates of field galaxies in the nearby Universe.

When comparing the properties of FRB host galaxies with that of other transients, we find the host galaxies of ULXs and Type Ia supernovae to be more massive and star-forming than FRBs. The hosts of CCSNe and SGRBs are similar to FRB hosts in terms of their stellar masses, star-formation rates, projected physical offsets, absolute  $r$ -band magnitudes, and specific SFRs. While from the host galaxy considerations, we could statistically rule out LGRBs and SLSNe as progenitor scenarios for all FRBs combined, we found some similarities between the repeating FRB host population and hosts of LGRBs and SLSNe. These may be attributed to either the small sample size or the effect of the outlier FRB20121102A host galaxy on the overall repeating FRB host population. We also note that one is more

## 7. SUMMARY AND FUTURE WORK



likely to find an extreme value under the null hypothesis with more KS-tests.

Driven by the studies and findings of [Chrimes et al. \(2021\)](#) and [Kirsten et al. \(2021\)](#), we compared the physical offsets of FRBs in their hosts with that of Galactic sources such as pulsars, magnetars, X-ray binaries in the Milky Way, and globular clusters in the late- and early-type galaxies. According to our KS test, the Galactic source offset distributions resemble the observed FRB offset distribution. We also show that FRBs are positioned in their host galaxies in a way that is mostly not comparable to globular clusters found in late-type spiral and early-type elliptical galaxies.

Lastly, in the future, observations of a much larger sample of nearby FRB hosts will be ideal for progenitor model studies as these will allow the high spatial resolution analysis of FRB environments in their host galaxies.

All of the data and the majority of the software used for the host analysis is available at <https://github.com/FRBs/FRB>.

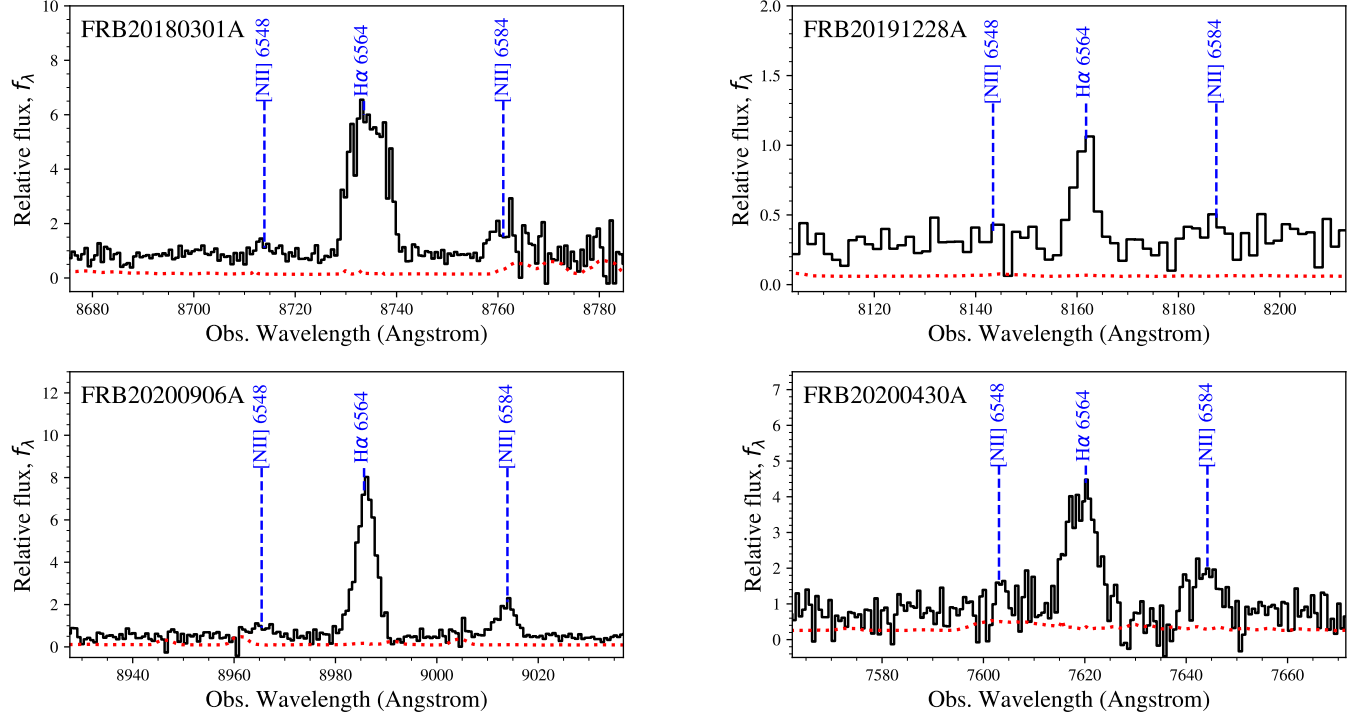
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Based on observations obtained at the international Gemini Observatory, a program of NSF’s NOIRLab, which is managed by the Association of Universities for Research in Astronomy (AURA) under a cooperative agreement with the National Science Foundation on behalf of the Gemini Observatory partnership: the National Science Foundation (United States), National Research Council (Canada), Agencia Nacional de Investigación y Desarrollo (Chile), Ministerio de Ciencia, Tecnología e Innovación (Argentina), Ministério da Ciência, Tecnologia, Inovações e Comunicações (Brazil), and Korea Astronomy and Space Science Institute (Republic of Korea). The Gemini data were obtained from program GS- 2020B-Q-138, and were processed using the DRAGONS (Data Reduction for Astronomy from Gemini Observatory North and South) package.



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<https://doi.org/10.1093/mnras/stt1637>



**Figure A1.** A zoomed in version of the optical spectrum of the host of FRB20180301A, FRB20191228A, FRB20200906A and FRB20200430A.

## APPENDIX

The spectrum of the new FRB hosts in this paper and newly obtained data for FRB20200430A are shown in Fig. A1. Table A1 lists the nebular line measurements of FRB hosts that are used in the BPT diagram. We have also updated the previously reported Pan-STARRS photometric measurements (PSFMag) for hosts of FRB20190714A, FRB20190611B and FRB20200430A to Kron Mag and re-did the SED fitting in CIGALE using the method described in Heintz et al. (2020). The best fitting models for these hosts and new FRBs introduced in this work are presented in Fig. A2 and the updated measurements are shown in Table A3.



**Table A1.** Nebular line emission measurements in units of  $10^{-16} \text{ erg s}^{-1} \text{ cm}^{-2}$ . New FRB hosts presented in this paper are highlighted in cyan and old FRB hosts with new data are highlighted in gray. The data for FRB20171020A and FRB20201124A is taken from Mahony et al. (2018) and Fong et al. (2021) respectively.

FRB	$H\alpha$	$H\beta$	N II	O III
FRB20121102A	$2.61 \pm 0.04$	$0.96 \pm 0.09$	$< 0.12$	$4.38 \pm 0.08$
FRB20180301A	$16.97 \pm 0.18$	$7.77 \pm 0.61$	$4.32 \pm 0.32$	$12.75 \pm 0.65$
FRB20180916B	$40.27 \pm 0.25$	-	$15.24 \pm 0.24$	$71.62 \pm 0.60$
FRB20180924B	$2.79 \pm 0.03$	$0.72 \pm 0.02$	$1.94 \pm 0.03$	$0.79 \pm 0.02$
FRB20190102C	$5.66 \pm 0.17$	$1.90 \pm 0.17$	$1.69 \pm 0.19$	$3.80 \pm 0.27$
FRB20190608B	$27.65 \pm 0.41$	$8.37 \pm 0.33$	$18.32 \pm 0.38$	$14.95 \pm 0.44$
FRB20190611B	$0.49 \pm 0.05$	$0.12 \pm 0.03$	$0.12 \pm 0.04$	$0.18 \pm 0.04$
FRB20190711A	-	$0.26 \pm 0.05$	-	-
FRB20190714A	$3.89 \pm 0.03$	$0.97 \pm 0.03$	$1.70 \pm 0.03$	$0.31 \pm 0.03$
FRB20191001A	$27.38 \pm 0.26$	$5.01 \pm 0.30$	$13.91 \pm 0.19$	$3.62 \pm 0.35$
FRB20191228A	$0.30 \pm 0.02$	$0.02 \pm 0.02$	$0.08 \pm 0.02$	$0.13 \pm 0.03$
FRB20200430A	$4.27 \pm 0.15$	$1.15 \pm 0.21$	$2.02 \pm 0.20$	$1.17 \pm 0.25$
FRB20200906A	$6.49 \pm 0.07$	$4.25 \pm 0.14$	$1.80 \pm 0.06$	$5.38 \pm 0.17$
FRB20201124A	$56.9^{+14.9}_{-9.9}$	$12.3^{+3.0}_{-2.3}$	$25.3^{+6.0}_{-4.7}$	$3.8^{+2.1}_{-1.1}$

**Table A2.** Results for FRB Associations

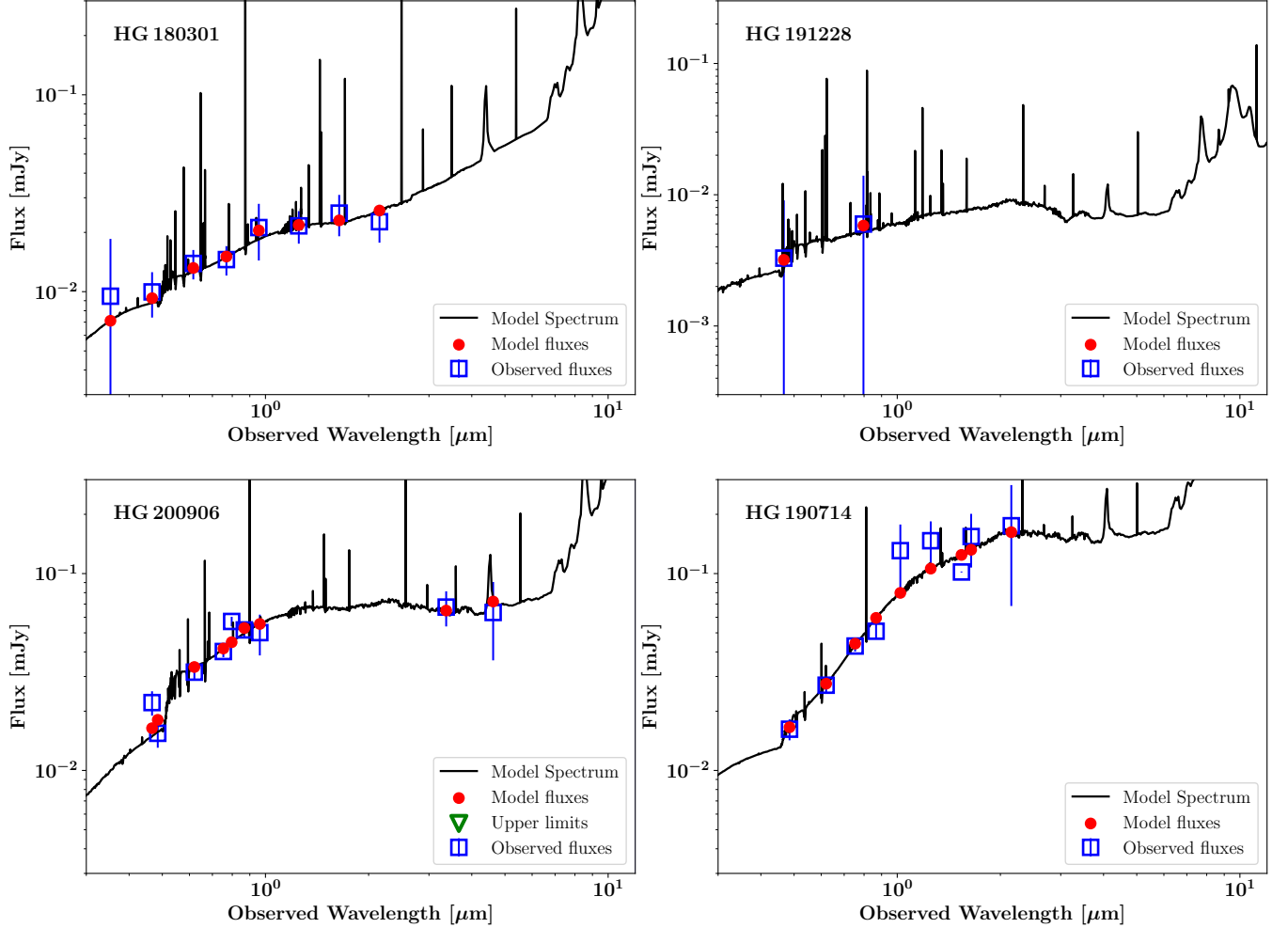
FRB	RA <sub>cand</sub>	Dec <sub>cand</sub>	$\theta$	$\phi$	$m$	Filter	$P^c$	$P(O)$	$P(O x)$
FRB20121102A	82.9945	33.1479	0.2	0.28	23.52	GMOS_N_i	0.0039	0.0245	1.0000
FRB20180916A	29.5012	65.7148	7.7	3.03	16.16	GMOS_N_r	0.0005	0.8200	1.0000
FRB20180924B	326.1054	-40.9002	0.8	1.31	21.32	VLT_FORS2_g	0.0119	0.8723	0.9894
FRB20181112A	327.3486	-52.9709	0.4	0.67	21.49	VLT_FORS2_I	0.0622	0.0784	0.6678
FRB20190102C	322.4149	-79.4756	0.5	0.86	20.73	VLT_FORS2_I	0.0056	0.8425	1.0000
FRB20190523A	207.0642	72.4706	3.4	0.71	22.13	LRIS_R	0.1158	0.1974	0.8154
FRB20190608B	334.0203	-7.8988	2.5	1.66	17.60	VLT_FORS2_I	0.0005	0.9930	1.0000
FRB20190611B	320.7429	-79.3973	2.0	0.50	22.35	GMOS_S_i	0.0407	0.3322	0.9741
FRB20190614D	65.0743	73.7068	1.3	0.41	24.01	LRIS_I	0.0552	0.1944	0.5825
FRB20190711A	329.4194	-80.3581	0.5	0.46	22.93	GMOS_S_i	0.0172	0.4782	0.9937
FRB20190714A	183.9795	-13.0212	1.2	0.95	19.48	VLT_FORS2_I	0.0014	0.7993	1.0000
FRB20191001A	323.3525	-54.7487	4.2	1.36	17.82	VLT_FORS2_I	0.0010	0.5075	0.5980
FRB20200430A	229.7064	12.3766	0.4	0.72	21.18	LRIS_I	0.0047	0.9379	1.0000
FRB20191228A	344.4307	-29.5940	2.1	0.49	21.92	VLT_FORS2_I	0.0251	0.5596	1.0000
FRB20200906A	53.4958	-14.0833	1.6	1.51	20.70	VLT_FORS2_g	0.0106	0.8997	1.0000
FRB20180301A	93.2269	4.6704	2.3	0.92	22.07	GMOS_S_r	0.0387	0.7154	0.9993

**Table A3.** Host galaxies of six repeating and ten non-repeating FRBs used in this work, for which PATH posterior probability is  $> 90\%$ . Derived measurements for new FRB hosts are highlighted in cyan. Updated measurement of previously reported hosts in Heintz et al. (2020) are highlighted in gray. We have also added most probable host of FRB20171020A (Mahony et al. 2018) in our sample including the published host of repeating FRB20200120E (Bhardwaj et al. 2021) and FRB20201124A (Fong et al. 2021).

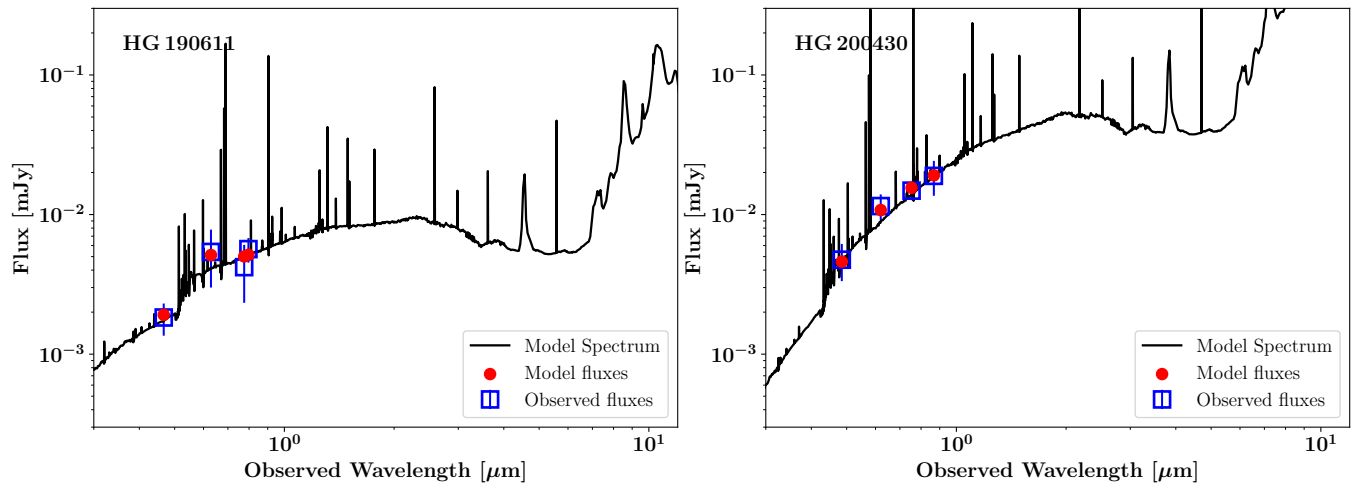
S.No	FRB	$z$	Rep	Offset (kpc)	$R_{\text{eff}}^a$ (kpc)	Mass ( $10^{10} M_{\odot}$ )	SFR ( $M_{\odot} \text{ yr}^{-1}$ )	$\log(\text{sSFR})$ ( $\text{yr}^{-1}$ )	$M_r$	$u - r$	$Z$
1	FRB20121102A	0.1927	y	$0.8 \pm 0.1$	$0.66 \pm 0.03$	$0.01 \pm 0.01$	$0.15 \pm 0.04$	-8.99	$-16.20 \pm 0.08$	$1.49 \pm 0.18$	8.08
2	FRB20180301A	0.3304	y	$10.8 \pm 3$	$5.80 \pm 0.20$	$0.23 \pm 0.06$	$1.93 \pm 0.58$	-9.08	$-20.18 \pm 0.07$	$0.90 \pm 0.11$	8.70
3	FRB20180916B	0.0337	y	$5.4 \pm 0.0$	$3.57 \pm 0.36$	$0.22 \pm 0.03$	$0.06 \pm 0.02$	-10.58	$-19.46 \pm 0.05$	$1.53 \pm 0.06$	-
4	FRB20180924B	0.3212	n	$3.4 \pm 0.8$	$2.75 \pm 0.10$	$1.32 \pm 0.51$	$0.88 \pm 0.26$	-10.18	$-20.81 \pm 0.05$	$1.78 \pm 0.15$	8.93
5	FRB20190102C	0.2912	n	$2.3 \pm 4.2$	$4.43 \pm 0.51$	$0.47 \pm 0.54$	$0.86 \pm 0.26$	-9.74	$-19.87 \pm 0.06$	$1.44 \pm 0.15$	8.70
6	FRB20190608B	0.1178	n	$6.5 \pm 0.8$	$2.84 \pm 0.23$	$1.16 \pm 0.28$	$0.69 \pm 0.21$	-10.22	$-21.22 \pm 0.05$	$1.40 \pm 0.09$	8.85
7	FRB20190611B	0.3778	n	$11.7 \pm 5.8$	$2.15 \pm 0.11$	$0.35 \pm 0.70$	$0.27 \pm 0.08$	-10.11	$-19.29 \pm 0.10$	$1.29 \pm 0.18$	8.71
8	FRB20190711A	0.5220	y	$1.6 \pm 4.5$	$2.94 \pm 0.17$	$0.08 \pm 0.03$	$0.42 \pm 0.12$	-9.29	$-19.01 \pm 0.08$	$0.95 \pm 0.16$	-
9	FRB20190714A	0.2365	n	$2.7 \pm 1.8$	$3.94 \pm 0.05$	$1.42 \pm 0.55$	$0.65 \pm 0.20$	-10.34	$-20.37 \pm 0.05$	$1.51 \pm 0.28$	9.03
10	FRB20191001A	0.2340	n	$11.1 \pm 0.8$	$5.55 \pm 0.03$	$4.64 \pm 1.88$	$8.06 \pm 2.42$	-9.76	$-22.13 \pm 0.05$	$1.67 \pm 0.19$	8.94
11	FRB20191228A	0.2432	n	$5.7 \pm 3.3$	$1.78 \pm 0.06$	$0.54 \pm 0.60$	$0.03 \pm 0.01$	-11.28	$-18.26 \pm 0.05$	$2.13 \pm 0.74$	8.48
12	FRB20200430A	0.1608	n	$1.7 \pm 2.2$	$1.64 \pm 0.53$	$0.21 \pm 0.11$	$0.26 \pm 0.08$	-9.89	$-18.25 \pm 0.05$	$2.08 \pm 0.30$	8.88
13	FRB20200906A	0.3688	n	$5.9 \pm 2.0$	$7.58 \pm 0.06$	$1.33 \pm 0.37$	$0.48 \pm 0.14$	-10.44	$-21.49 \pm 0.05$	$1.22 \pm 0.11$	8.76
14	FRB20171020A*	0.0087	n	-	-	0.09	0.13	-9.84	-17.9	-	8.30
15	FRB20200120E*	0.0008	y	$20.1 \pm 3$	3.5	$7.20 \pm 1.70$	$0.89 \pm 0.27$	-10.91	-19.78	$2.77 \pm 0.00$	-
16	FRB20201124A*	0.0980	y	$1.3 \pm 0.1$	-	$1.70^{+0.08}_{-0.11}$	$2.12^{+0.69}_{-0.28}$	-9.90	$-20.41 \pm 0.03$	$2.06 \pm 0.55$	9.03

<sup>a</sup>Isophotal effective half-light radius are used for a sample of FRB host published in Mannings et al. (2020). For remaining hosts, effective radius derived from GALFIT are used.

\*Host properties are taken from Mahony et al. (2018); Bhardwaj et al. (2021); Fong et al. (2021). The observed magnitudes for FRB20171020A, FRB20200120E and FRB20201124A are approximated as rest-frame magnitudes because of their low redshifts.



**Figure A2.** SED models for the host galaxies of FRB20180301A, FRB20191228A, FRB20200906A, FRB20190714A. The best-fit SED models from CIGALE are shown as solid black lines, the observed magnitudes (corrected for Galactic extinction and converted into fluxes) as blue squares, and the model fluxes as red dots. In all models, the redshift has been fixed to the redshift of respective host galaxies.



**Figure A2.** SED models for the host galaxies of FRB20190611B and FRB20200430A.