A possible subclassification of fast radio bursts

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Abstract. Although fast radio bursts (FRBs) have been an active field in astronomy and cosmology, their origin is still unknown to date. One of the interesting topics is the classification of FRBs, which is closely related to the origin of FRBs. Different physical mechanisms are required by different classes of FRBs. In the literature, they usually could be classified into non-repeating and repeating FRBs. Well motivated by the observations, here we are interested in the possible subclassification of FRBs. By using the first CHIME/FRB catalog, we propose to subclassify non-repeating (type I) FRBs into type Ia and Ib FRBs. The distribution of type Ia FRBs is delayed with respect to the cosmic star formation history (SFH), and hence they are probably associated with old stellar populations, while the distribution of type Ib FRBs tracks SFH, and hence they are probably associated with young stellar populations. Accordingly, the physical criteria for this subclassification of type I FRBs have been clearly determined. We find that there are some tight empirical correlations for type Ia FRBs but not for type Ib FRBs, and vice versa. These make them different in physical properties. Similarly, we suggest that repeating (type II) FRBs could also be subclassified into type IIa and IIb FRBs. A universal subclassification scheme is given at the end. This subclassification of FRBs might help us to reveal quite different physical mechanisms behind them, and improve their applications in astronomy and cosmology.

Keywords: cosmological simulations, intergalactic media, neutron stars, star formation

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1 Introduction

Although fast radio bursts (FRBs) have been an active field in astronomy and cosmology, their origin is still unknown to date. FRBs are mysterious transient radio sources of millisecond duration [1–15]. Most of them are at extragalactic/cosmological distances, as suggested by their large dispersion measures (DMs) well in excess of the Galactic values, and hence FRBs are a promising probe to study cosmology and the intergalactic medium (see e.g. [56–63] and also [1–15]).

To reveal the possible origins of FRBs, various topics are extensively debated in the literature [1–15], such as the engine, radiation mechanism, distribution, classification, propagation effect, and cosmological application of FRBs. Many theoretical models have been proposed to this end, and we refer to e.g. [6–13] for comprehensive reviews and [16] for the up-to-date online catalogue of FRB theories. On the other hand, the observational data were rapidly accumulated in the recent years [10–14, 18, 21]. Therefore, many impressive progresses have been made in the field of FRBs.

One of the interesting topics is the classification of FRBs [4, 6–8, 10]. How many different populations of FRBs exist? In the actual observations, many FRBs were found to be (apparently) one-off, while some FRBs are repeating. So, it is natural to classify them into two populations: non-repeating FRBs and repeating FRBs. This classification is closely related to the origin of FRBs. Obviously, the repeaters rule out the cataclysmic engines for these sources. However, the question is whether the apparently non-repeating FRBs are genuinely one-off or not. In fact, some apparently non-repeating FRBs were found to be repeaters in the follow-up observations. It is possible that all FRBs repeat, and the non-detection of repetition might be due to the long waiting time or low flux of the repeating bursts (see e.g. [23–25]), or an unknown selection effect [26]. Some unified models for repeating and non-repeating FRBs were proposed in the literature (see e.g. [27–30]). Recently, some works have tried to address this question. In [24], the number fraction of repeating FRBs

\footnote{The up-to-date FRB theory catalogue is available at ref. [17].}

\footnote{The up-to-date FRB Catalogue is available at refs. [19, 20].}

\footnote{The up-to-date compilation of all known FRB host galaxies is available at ref. [22].}
was predicted to peak at a value less than 100% in the future if non-repeating FRBs are
genuinely one-off, otherwise it will increase to 100% eventually. In [31], it was found that the
time-integrated-luminosity functions and volumetric occurrence rates of non-repeating and
repeating FRBs against redshift are significantly different. In [32], it was claimed that the
discriminant properties in FRBs is difficult to be explained by a single population. In [33],
an observed difference in the burst morphologies of one-off FRBs and repeater bursts was
found. The above works indicate that it is reasonable to classify them into repeating and
non-repeating FRBs.

Another natural question is whether there are other classifications of FRBs different
from repeating and non-repeating FRBs. Recently, several efforts were made in the literature.
In [34], similar to gamma-ray bursts (GRBs), it was proposed to classify FRBs into short
(< 100 ms) and long (> 100 ms) FRBs. A tight power-law correlation between fluence and
peak flux density was found for them. Long FRBs are more energetic than short FRBs
in the fluence versus extragalactic DM plane. In [35], it was argued that the brightness
temperature $T_B$ might be used to classify the repeating bursts into classical ($T_B \geq 10^{33} K$)
and atypical ($T_B < 10^{33} K$) ones in the light of the well-known repeating FRB 20121102A. A
tight power-law correlation between pulse width and fluence was found for classical bursts.
In [36], using cross-correlation and clustering algorithms applied to one-dimensional intensity
profiles of the bursts, two major classes of FRBs featuring different waveform morphologies
and simultaneously different distributions of brightness temperature were identified. These
efforts might shed new light on the nature of FRBs.

In the present work, we are interested in the possible subclassification of FRBs. There
are two main motivations for doing this. The first one comes from the neighboring fields
of supernovae and GRBs. As is well known, there are two major classes of supernovae:
type I and II [37]. Then, type I supernovae are subclassified into type Ia, Ib and Ic, while
type II supernovae are subclassified into type II-P, II-L, IIn and IIb. Only the well-known
type Ia supernovae could be used as standard candles, which led to the great discovery of
cosmic acceleration (and Nobel prize in physics 2011). This highlights the importance of
the subclassification. On the other hand, GRBs are usually classified into long and short
ones. However, the existence of temporally long events showing signatures of short GRBs
led to introduce an alternative classification: type I (typically short and associated with old
populations) and type II (typically long and associated with young populations) [38, 39].
Similarly, our second motivation is related to FRBs associated with young or old
populations. For a long time, it was speculated that the FRB distribution tracks the cosmic star
formation history (SFH) [1–15]. The landmark Galactic FRB 200428 associated with the
young magnetar SGR 1935+2154 [40–43] confirmed that at least some (if not all) FRBs
originate from young magnetars. So, it is reasonable to expect that the FRB distribution
is closely correlated with star-forming activities, as observed for the repeating FRB 121102 [44],
FRB 180916.J0158+65 [45], FRB 20190520B [46], FRB 20181030A [47], and
FRB 20201124A [48, 82]. But it was argued in [49] that FRB 20201124A is located at an
inter-arm region of a barred-spiral galaxy, namely an environment not directly expected for
young populations. On the other hand, the recently discovered repeating FRB 20200120E in
a globular cluster of the nearby galaxy M81 [50–52] suggested that some FRBs are associated
with old stellar populations. In [53], it was claimed that the bursts of the first CHIME/FRB
catalog [54]4 as a whole do not track SFH. In [56], it was independently confirmed that the

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4The data for CHIME/FRB Catalog 1 in machine-readable format can be found via their public webpage
at ref. [55].
FRB distribution model tracking SFH can be rejected at high confidence, and a suppressed evolution (delay) with respect to SFH was found. Putting the above facts together, it is reasonable to speculate that some FRBs are associated with young populations and hence they track SFH, while the other FRBs are associated with old populations and hence they do not track SFH. So, a possible subclassification of FRBs is required.

This paper is organized as followings. In section 2, we briefly introduce the observational data of FRBs, namely the first CHIME/FRB catalog [54, 55]. In section 3, we show that the distributions of non-repeating and repeating FRBs are significantly different. For convenience, we suggest calling them type I and II FRBs, respectively. Then, we propose to subclassify non-repeating (type I) FRBs into type Ia and Ib FRBs. The distribution of type Ia FRBs is delayed with respect to SFH, and hence they are probably associated with old stellar populations, while the distribution of type Ib FRBs tracks SFH, and hence they are probably associated with young stellar populations. Accordingly, the physical criteria for this subclassification have been clearly determined. In section 4, we find that there are some tight empirical correlations for type Ia FRBs but not for type Ib FRBs, and vice versa. These empirical correlations make them different in physical properties. Clearly, type Ia and Ib FRBs require quite different physical mechanisms. In section 5, we turn to repeating (type II) FRBs. In section 6, some brief concluding remarks and a universal subclassification scheme are given.

2 The observational data

As is well known, one of the key observational quantities of FRBs is the dispersion measure DM, namely the column density of the free electrons, due to the ionized medium (plasma) along the path. Clearly, the observed DM of FRB can be separated into

\[ DM_{\text{obs}} = DM_{\text{MW}} + DM_{\text{halo}} + DM_{\text{IGM}} + DM_{\text{host}}/(1+z), \] (2.1)

where \( z \) is the redshift, and \( DM_{\text{MW}}, DM_{\text{halo}}, DM_{\text{IGM}}, DM_{\text{host}} \) are the contributions from the Milky Way, the Milky Way halo, the intergalactic medium (IGM), the host galaxy (including interstellar medium of the host galaxy and the near-source plasma), respectively. For convenience, one could introduce the extragalactic DM [56–63], namely

\[ DM_{E} = DM_{\text{obs}} - DM_{\text{MW}} - DM_{\text{halo}} = DM_{\text{IGM}} + DM_{\text{host}}/(1+z). \] (2.2)

Here, we adopt \( DM_{\text{halo}} = 30 \text{ pc cm}^{-3} \) (see e.g. [64, 65]), and \( DM_{\text{host}} = 50 \text{ pc cm}^{-3} \) (see e.g. [66–68]). In fact, they are the ones used in the literature for our Milky Way at high Galactic latitude. We can obtain \( DM_{\text{MW}} \) by using NE2001 [69–71] up to 30 kpc. \( DM_{\text{IGM}} \) is given by [56–63]

\[ DM_{\text{IGM}} = \frac{3cH_0\Omega_b}{8\pi Gm_p} \int_{0}^{z} \frac{f_{\text{IGM}}(\tilde{z}) f_\epsilon(\tilde{z}) (1 + \tilde{z}) d\tilde{z}}{h(\tilde{z})}, \] (2.3)

where \( c \) is the speed of light, \( H_0 \) is the Hubble constant, \( \Omega_b \) is the present fractional density of baryons, \( G \) is the gravitational constant, \( m_p \) is the mass of proton, \( h(z) \equiv H(z)/H_0 \) is the dimensionless Hubble parameter, \( f_{\text{IGM}}(z) \) is the fraction of baryon mass in IGM, and \( f_\epsilon(z) \) is the ionized electron number fraction per baryon. The latter two are functions of redshift \( z \) in principle. Following e.g. [31, 53, 56, 60], we use the fiducial values \( f_\epsilon = 7/8 \) and \( f_{\text{IGM}} = 0.82 \) in this work. Note that it is very safe to adopt \( f_\epsilon = (3/4) \chi_{\epsilon, H}(z) + (1/4) \chi_{\epsilon, He}(z) = 7/8 \) for \( \chi_{\epsilon, H}(z) = \chi_{\epsilon, He}(z) = 1 \), since hydrogen and helium are both fully ionized at \( z \leq 3 \) for almost
all observed FRBs [56–63]. Actually, the variation of $f_{\text{IGM}}(z)$ is fairly small as it could be constrained by using other cosmological observations such as cosmic microwave background (see e.g. [57]), and hence it is also reasonable to adopt a constant $f_{\text{IGM}}$ at low redshifts $z \leq 3$. On the other hand, we consider the fiducial cosmology in this work, namely the well-known flat $\Lambda$CDM model, and hence

$$h(z) = \left[ \Omega_m (1 + z)^3 + (1 - \Omega_m) \right]^{1/2}, \quad d_L = (1 + z)d_C = c(1 + z) \int_0^z \frac{dz}{H(z)},$$

(2.4)

where $d_L$ and $d_C$ are the luminosity distance and the comoving distance, respectively. In this work, we adopt $\Omega_m = 0.3153$, $\Omega_b = 0.0493$, and $H_0 = 67.36$ km/s/Mpc from the Planck 2018 results [72].

The first CHIME/FRB catalog [54, 55] of 536 events (including 474 one-off bursts and 62 repeat bursts from 18 repeaters) was released in June 2021. Such a large uniform sample detected by a single telescope is very valuable to study FRBs. We preliminarily deal with it following [56]. At first, we exclude the bursts with zero fluences and the bursts labeled with excluded_flag = 1. Following e.g. [53, 56], we only use the first detected burst of each FRB source. In practice, we identify the non-repeaters labeled with repeater_name = -9999 and then only take the ones labeled with sub_num = 0 (434 bursts in total). We identify the repeaters labeled with repeater_name ≠ -9999 and only take the ones labeled with sub_num = 0, and then from them we adopt the first ones in each group with the same repeater_name (18 bursts in total). For each burst, its “observed” $\text{DM}_E = \text{DM}_{\text{obs}} - \text{DM}_{\text{MW}} - \text{DM}_{\text{halo}}$, where $\text{DM}_{\text{obs}}$ is given by the column labeled with “bonsai_dm” in the data table. Then, its inferred redshift $z$ is obtained by numerically solving $\text{DM}_E = \text{DM}_{\text{IGM}} + \text{DM}_{\text{host}}/(1 + z)$ with $\text{DM}_{\text{IGM}}$ given by eq. (2.3). In this work, we require a very conservative criterion $\text{DM}_{\text{IGM}} \geq \text{DM}_{\text{obs}}/10$ to exclude the bursts very close to us. After this robust cut, we have 430 one-off FRBs and 17 repeaters.

For each burst, its observed specific fluence $F_\nu$ is given by the column labeled with “fluence” in the data table. Assuming a flat radio spectrum, the specific fluence is related with isotropic energy $E$ according to [53, 56, 73, 74]

$$F_\nu = \frac{(1 + z)E}{4\pi d_L^2 \nu_c},$$

(2.5)

where $\nu_c$ is the central observing frequency. For CHIME, $\nu_c = 600$ MHz [54, 55]. Thus, the “observed” isotropic energy $E$ can be inferred from eq. (2.5) with the observed $F_\nu$ and the luminosity distance $d_L$ given by eq. (2.4). So far, the observational data of 430 one-off FRBs and 17 repeaters are ready.

3 Subclassification of non-repeating FRBs

3.1 Type I and II FRBs

In the radio sky, there are many known transients besides FRBs, such as pulsars, solar bursts, rotating radio transients (RRATs), nano-shots, flare stars/brown dwarves, X-ray binaries, RSCVn/Algols, novae, supernovae, AGN/blazar/QSO, giant radio pulses (GRPs), and GRBs. We refer to e.g. figure 1 of [3] for details. As is well known, they could be well distinguished in the transient duration $\nu W$ versus spectral luminosity $L_\nu$ phase plane, with the help of brightness temperature $T_B$ which relates to the radiation mechanism (see e.g. figure 1 of [3], figure 5 of [75], figure 3 of [52], figure 7 of [7], and figure 4 of [76]).
Since the $\nu W - L_\nu$ phase plane is very useful to distinguish radio transients, we might also use it to subclassify FRBs. In figure 1, we plot 430 one-off FRBs and 17 repeaters from the CHIME/FRB catalog in the $\nu W - L_\nu$ plane, with some isothermal lines of $T_B$. For each burst, we take the frequency $\nu$ and the pulse width $W$ from the columns labeled with “peak.freq” and “bc.width” in the CHIME/FRB data table, respectively. We calculate the spectral luminosity $L_\nu$ according to (e.g. [75, 76])

$$L_\nu = 4\pi d_L^2 S_\nu,$$

(3.1)

where the luminosity distance $d_L$ is given by eq. (2.4), and the flux $S_\nu$ is given by the column labeled with “flux” in the CHIME/FRB data table. The brightness temperature $T_B$ is given by (e.g. [35, 75, 76])

$$T_B = \frac{S_\nu d_L^2}{2\pi \kappa_B (\nu W)^2} = 1.1 \times 10^{35} \text{K} \left(\frac{S_\nu}{\text{Jy}}\right) \left(\frac{d_L}{\text{Gpc}}\right)^2 \left(\frac{\nu}{\text{GHz}}\right)^{-2} \left(\frac{W}{\text{ms}}\right)^{-2},$$

(3.2)

which can be expressed in terms of $\nu W$ and $L_\nu$. $\kappa_B$ is the Boltzmann constant. It is worth noting that the above quantities might be slightly different in the literature (for example, in some works, the angular diameter distance $d_A$ might be used instead of $d_L$, the central frequency $\nu_c$ might be used instead of the peak frequency, $\pi$ might be removed, the redshift might be introduced, and so on). We intentionally use them as the ones mentioned above, because they work well for our purpose in the present forms.

From figure 1, it is easy to see that the distributions of non-repeating and repeating FRBs are different in the $\nu W - L_\nu$ phase plane. Clearly, most of the repeaters are located in the bottom-right region, where the transient duration $\nu W$ is relatively large, the spectral luminosity $L_\nu$ is relatively low, and the brightness temperature $T_B$ is also relatively low. In figure 2, we present the normalized $\nu W$, $L_\nu$, and $T_B$ distributions of non-repeating and repeating FRBs, respectively. Again, we find that these distributions are clearly different for non-repeaters and repeaters (note that the number of repeaters is only 17, and hence they do not form a good enough statistics). Thus, its is reasonable to classify FRBs into two types as usual. For convenience, we suggest calling non-repeating/repeating FRBs type I/II FRBs, respectively.

3.2 Type Ia and Ib FRBs

At first, we consider the possible subclassification of non-repeating (type I) FRBs. By definition, the subclasses should be significantly different. As is well known, the Kolmogorov-Smirnov (KS) test is one of the useful tools to compare two samples [77]. One can perform the KS test by using `scipy.stats.kstest` in Python [78], which returns the KS statistic and the corresponding p-value. For convenience, we use the p-value ($p_{KS}$) in the two-sample case as in [54–56, 79], rather than the KS statistic ($D_{KS}$). The null hypothesis (namely two samples are drawn from the same distribution) can be rejected at 90% (95%) confidence if $p_{KS} < 0.1$ (0.05), respectively. Otherwise, two samples can be consistent with each other if $p_{KS} > 0.1$ (or 0.05). $p_{KS}$ is higher for two closer samples (and $p_{KS} = 1$ for two identical samples), while $p_{KS} \to 0$ for two completely different samples.

There are three candidates ($\nu W$, $L_\nu$, and $T_B$) in the $\nu W - L_\nu$ phase plane for the possible criteria of subclassification. For a given critical value (say, $\nu W_{\text{crit}}$), 430 non-repeating FRBs can be divided into two samples (say, $\nu W \geq \nu W_{\text{crit}}$ and $\nu W < \nu W_{\text{crit}}$), and then we compare the redshift distributions of these two samples by using the KS test. So, the p-values $p_{KS}$
Transient duration $\nu W$ versus spectral luminosity $L_\nu$ plane, with some isothermal lines of brightness temperature $T_B$ (chocolate dashed lines). The green solid lines $\nu W = 10^{-3} \text{GHz s}$, $L_\nu = 10^{34} \text{erg/s/Hz}$ and $T_B = 2 \times 10^{35} \text{K}$ are used to divide this $\nu W - L_\nu$ phase plane into various regions. See section 3 and figure 3 for details.

Figure 1. 430 one-off FRBs (blue points) and 17 repeaters (red points) from the first CHIME/FRB catalog in the transient duration $\nu W$ versus spectral luminosity $L_\nu$ plane, with some isothermal lines of brightness temperature $T_B$ (chocolate dashed lines). The green solid lines $\nu W = 10^{-3} \text{GHz s}$, $L_\nu = 10^{34} \text{erg/s/Hz}$ and $T_B = 2 \times 10^{35} \text{K}$ are used to divide this $\nu W - L_\nu$ phase plane into various regions. See section 3 and figure 3 for details.

As mentioned above, we speculate that some FRBs track SFH and the others do not. Their distributions should be significantly different. So far, we have divided the $\nu W - L_\nu$ phase plane into 7 regions as above. For a given region, 430 non-repeating (type I) FRBs inside/outside this region form two samples. One can compare them by using the KS test. But now it is more important to see whether one of these two samples tracks SFH. Fortunately, a suitable method for this purpose was proposed in [53] and then has been extended in [56].
Figure 2. Normalized $\nu W$, $L_\nu$ and $T_B$ distributions of 430 non-repeaters (blue histograms) and 17 repeaters (red histograms), respectively. See section 3.1 for details.

Figure 3. The p-values $p_{KS}$ are shown as functions of $\nu W_{\text{crit}}$ (a), $L_{\nu,\text{crit}}$ (b) and $T_{B,\text{crit}}$ (c). $p_{KS} = 0.05$ is indicated by the red dashed lines. In panel (d), the $\nu W - L_\nu$ phase plane is divided into seven regions by the green solid lines $\nu W = 10^{-3}$ GHz s, $L_\nu = 10^{34}$ erg/s/Hz and $T_B = 2 \times 10^{35}$ K. These 7 regions are labeled with the numbers (1) $\sim$ (7). In addition, region (8) = regions (1) + (3), region (9) = regions (4) + (5), region (10) = regions (2) + (7). Panel (d) should be viewed together with figure 1. See section 3.2 for details.
Here, we closely follow the method used in [56]. The key idea is to confront the Monte Carlo simulations with the observational data. If the simulations are rejected by the observational data, the assumed FRB distribution models generating these simulations could be ruled out. Otherwise, they survive. In the present work, we generate the simulations assuming SFH, namely the mock observed FRB redshift rate distribution is given by \[ dN/dt dV \propto (1+z)^{2.6} \] (3.4)

Note that eq. (3.4) is the best-fit SFH density from the latest observational data of ultraviolet and infrared surveys (see eq. (1) of [80]), which characterizes the real SFH of our universe. On the other hand, we generate the isotropic energy \( E \) for the mock FRBs with [53, 56]

\[ dN/dE \propto (E/E_c)^{-\alpha} \exp\left(-E/E_c\right), \] (3.5)

where \( \alpha = 1.9 \) and \( \log (E_c/\text{erg}) = 41 \) are fixed as in [56], while “log” gives the logarithm to base 10. Note that eq. (3.5) corresponds to the Schechter luminosity function of FRBs [84, 85]. Actually, the isotropic energy distribution in eq. (3.5) is characterized by a simple power law \( \propto E^{-\alpha} \) with a sharp exponential cutoff around the energy scale \( E_c \). In the literature, \( \alpha \) and \( E_c \) could be constrained by the observations, i.e. \( 1.8 \lesssim \alpha \lesssim 2 \) roughly [74, 84, 86, 87] and \( E_c \sim 3 \times 10^{41} \) erg loosely [74, 84]. So, \( \alpha = 1.9 \) and \( \log (E_c/\text{erg}) = 41 \) are well consistent with the observations. One can generate \( N_{\text{sim}} \) mock FRBs tracking SFH as follows: (i) randomly assign a mock redshift \( z_i \) to the \( i \)-th mock FRB from the redshift distribution in eq. (3.3) with eq. (3.4); (ii) generate a mock energy \( E_i \) randomly from the distribution in eq. (3.5) for

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**Figure 4.** Left panel: the redshift distributions of type I FRBs inside (blue) and outside (red) region (3). The numbers of these two samples are given, respectively. We also present the p-value \( p_{\text{KS}} \) of the KS test for these two redshift distributions. Right panel: the same as in left panel, but for region (8). See section 3.2 for details.
Table 1. Some examples of the acceptable SFH models with the sensitivity model parameter \( \log F_{\nu, \text{th}} \), and three \( p_{KS} \) for the \( \log F_\nu \), \( \log E \) and \( \text{DM}_E \) criteria against the CHIME/FRB data for 390 type I FRBs outside regions (3). The boldfaced ones are also presented in the accompanying plots. See section 3.2 for details.

| \( \log F_{\nu, \text{th}} \) | \( p_{KS} \) for \( \log F_\nu \) | \( p_{KS} \) for \( \log E \) | \( p_{KS} \) for \( \text{DM}_E \) |
|----------------|----------------|----------------|----------------|
| 0.77           | 0.2750         | 0.2859         | 0.4575         |
| 0.78           | 0.3234         | 0.2530         | 0.3963         |
| 0.76           | 0.2266         | 0.2653         | 0.3944         |
| 0.84           | 0.8382         | 0.1714         | 0.6506         |

Figure 5. The simulated SFH model with \( \log F_{\nu, \text{th}} = 0.77 \) (magenta lines) against the CHIME/FRB data for 390 type I FRBs outside regions (3) (dodgerblue lines), with respect to the \( \log F_\nu \), \( \log E \) and \( \text{DM}_E \) criteria. Note that the simulations are all scaled to the CHIME/FRB data. The p-values \( p_{KS} \) of the KS tests are given, respectively. See section 3.2 for details.

This mock FRB; (iii) derive the specific fluence \( F_{\nu, i} \) by using eq. (2.5) with \( z_i \) and \( E_i \) for this mock FRB; (iv) derive \( \text{DM}_{E, i} \) at redshift \( z_i \) by using eq. (2.2) with eq. (2.3) for this mock FRB; (v) repeat the above steps for \( N_{\text{sim}} \) times. Finally, \( N_{\text{sim}} \) mock FRBs are on hand. However, these \( N_{\text{sim}} \) mock FRBs intrinsically generated above are not the ones “detected” by the telescope, due to the telescope’s sensitivity threshold and instrumental selection effects near the threshold. Therefore, the next step is to filter them by using the telescope’s sensitivity model, which is difficult to characterize in fact. Here, we consider the simplified sensitivity model for CHIME following [53, 56], in which the sensitivity threshold is about 0.3 Jy ms for CHIME, or equivalently \( \log F_{\nu, \text{min}} = -0.5 \), where the specific fluence is in units of Jy ms. Due to the direction-dependent sensitivity of the telescope, there is a “gray zone” in the \( \log F_\nu \) distribution, within which CHIME has not reached full sensitivity to all sources [53, 56]. The detection efficiency parameter in the “gray zone” is given by \( \eta_{\text{det}} = \mathcal{R}^3 \), where \( \mathcal{R} = (\log F_{\nu, \text{th}} - \log F_{\nu, \text{min}})/(\log F_{\nu, \text{max}} - \log F_{\nu, \text{th}}) \), such that \( \eta_{\text{det}} \to 0 \) at \( \log F_{\nu, \text{th}} = -0.5 \) and \( \eta_{\text{det}} \to 1 \) at \( \log F_{\nu, \text{max}} \). Outside the “gray zone”, \( \eta_{\text{det}} = 1 \). The filtered mock sample of FRBs will be confronted with the observational data, by using the KS tests with respect to the \( \log F_\nu \), \( \log E \) and \( \text{DM}_E \) distributions. In our case of SFH, the only free parameter is \( \log F_{\nu, \text{th}} \), which should be adjusted to match the observation. Notice that there
Table 2. The same as in table 1, but for 365 type I FRBs outside regions (8).

| $\log F_{\nu, \text{th}}^{\max}$ | $p_{\text{KS}}$ for $\log F_{\nu}$ | $p_{\text{KS}}$ for $\log E$ | $p_{\text{KS}}$ for DM$_E$ |
|-----------------------------|-----------------|-----------------|-----------------|
| 0.91 | 0.9621 | 0.5015 | 0.6550 |
| 0.96 | 0.7832 | 0.5050 | 0.5656 |
| 0.94 | 0.8742 | 0.4341 | 0.7663 |
| 0.87 | 0.7526 | 0.4238 | 0.7071 |

are a few minor differences between the present work and [56]. Here, we use slightly different DM$_{\text{host}}$ and $f_{\text{IGM}}$, while we have required the very conservative cut DM$_{\text{IGM}} \geq \text{DM}_{\text{obs}}/10$ to exclude the actual bursts very close to us in the first CHIME/FRB data table, as in section 2. In practice, most of these $N_{\text{sim}}$ mock FRBs cannot pass the filter of sensitivity threshold and instrumental selection effects. To ensure that there are still enough mock FRBs ($\sim \mathcal{O}(10^2)$, comparable with the number of observed FRBs) after the filter of sensitivity threshold and instrumental selection effects, we generate $N_{\text{sim}} = 4,000,000$ mock FRBs in the simulation for our case of SFH. We strongly refer to [56] for the technical details.

Now, we test regions (1) $\sim$ (7) in the $\nu W - L_{\nu}$ phase plane one by one. For each region, 430 type I FRBs are divided into two samples inside or outside this region. We compare their redshift distributions by using KS test, and also check whether one of these two sample tracks SFH by using the above method closely following [56]. For 6 of these 7 regions, although their redshift distributions are fairly different, both samples of type I FRBs inside/outside the given region do not track SFH. The only survivor is region (3), which is not so bad in some sense. It is defined by three physical conditions simultaneously

Region (3) : \( \nu W \leq 10^{-3} \, \text{GHz s} \quad \& \quad L_{\nu} \leq 10^{34} \, \text{erg/s/Hz} \quad \& \quad T_B \geq 2 \times 10^{35} \, \text{K} \). \hspace{1cm} (3.6)

As shown in left panel of figure 4, there are 40 (390) type I FRBs inside (outside) region (3), and their redshift distributions are significantly different, with a $p$-value $p_{\text{KS}} = 1.51 \times 10^{-8} \ll 0.05$. We find that the 40 type I FRBs inside region (3) do not track SFH. However, the 390 type I FRBs outside region (3) can be consistent with SFH. In table 1, we show some examples of the acceptable SFH models with the sensitivity model parameter $\log F_{\nu, \text{th}}^{\max}$, and three $p_{\text{KS}}$ for the $\log F_{\nu}$, $\log E$ and DM$_E$ criteria against the CHIME/FRB data for 390 type I FRBs outside regions (3). For some suitable $\log F_{\nu, \text{th}}^{\max}$, three $p_{\text{KS}} > 0.25$ simultaneously. We present an explicit example with $\log F_{\nu, \text{th}}^{\max} = 0.77$ in figure 5, whose three p-values $p_{\text{KS}} > 0.27$ simultaneously. So, SFH cannot be rejected at high confidence by the CHIME/FRB data for 390 type I FRBs outside regions (3), although three p-values are not fairly high.

Could we improve these results? The answer is a loud yes. Let us come back to figure 3. From its panels (a), (b) and (c), we easily find that the $p$-value for the dividing line with respect to $\nu W$ ($\sim 2 \times 10^{-5}$) is much larger than the ones with respect to $L_{\nu}$ ($\sim 4 \times 10^{-59}$) and $T_B$ ($\sim 10^{-15}$). Thus, it is reasonable to discard the dividing line $\nu W = 10^{-3} \, \text{GHz s}$ from the $\nu W - L_{\nu}$ phase plane to improve the situation. In this case, the $\nu W - L_{\nu}$ phase plane is divided into 4 regions as shown in panel (d) of figure 3, namely region (8) = regions (1) + (3), region (9) = regions (4) + (5), region (10) = regions (2) + (7), and region (6). Again, we test these 4 regions one by one. We find that the last three regions fail. However, region (8) is...
very successful, which is defined by two physical conditions simultaneously

\[ \text{Region (8)} : \quad L_{\nu} \leq 10^{34} \text{erg/s/Hz} \quad \& \quad T_B \geq 2 \times 10^{35} \text{K}. \]  

(3.7)

As shown in right panel of figure 4, there are 65 (365) type I FRBs inside (outside) region (8), and their redshift distributions are significantly different, with a p-value \( p_{\text{KS}} = 5.13 \times 10^{-12} \ll 0.05 \) (note that this \( p_{\text{KS}} \) is also much smaller than the one for region (3), namely \( 1.51 \times 10^{-8} \)). We find that the 65 type I FRBs inside region (8) do not track SFH. But the 365 type I FRBs outside region (8) do track SFH at high confidence. In table 2, we show some examples of the acceptable SFH models with the sensitivity model parameter \( \log F_{\nu, \text{th}}^{\text{max}} \), and three \( p_{\text{KS}} \) for the \( \log F_{\nu} \), \( \log E \) and \( \text{DM}_E \) criteria against the CHIME/FRB data for 365 type I FRBs outside regions (8). Clearly, for some suitable \( \log F_{\nu, \text{th}}^{\text{max}} \), three \( p_{\text{KS}} > 0.5 \) simultaneously. We present an explicit example with \( \log F_{\nu, \text{th}}^{\text{max}} = 0.91 \) in figure 6. Thus, SFH can be fully consistent with the CHIME/FRB data for 365 type I FRBs outside regions (8).

So far, we have identified a special region (8) in the \( \nu W - L_{\nu} \) phase plane, which is defined by two physical conditions in eq. (3.7) simultaneously. 430 type I FRBs are divided into two distinct samples. The 65 type I FRBs inside region (8) do not track SFH, and hence they are probably associated with old stellar populations. We suggest calling them type Ia FRBs. On the other hand, the 365 type I FRBs outside region (8) do track SFH, and hence they are probably associated with young stellar populations. We suggest calling them type Ib FRBs. In this way, we have achieved a physical subclassification of type I FRBs. From right panel of figure 4, it is easy to see that type Ib FRBs can appear at very high redshifts up to \( z \sim 3.7 \), but type Ia FRBs can only be triggered at fairly low redshifts \( z \lesssim 0.7 \). A delay is required for type Ia FRBs with respect to type Ib FRBs (which track SFH). Quite different physical mechanisms are necessary for type Ia and Ib FRBs, respectively.

4 Discriminating properties

After the subclassification of type I FRBs, we would like to see their discriminating physical properties. It is worth noting that the only consideration in the previous section is whether one subclass of type I FRBs tracks SFH while the other subclass does not, namely we completely have not taken their physical properties into account when we made this subclassification. We identified type Ia and Ib FRBs only in the light of SFH. Logically, if they
Figure 7. Type Ia FRBs (blue points) and type Ib FRBs (red points) are located in distinct regions of 3-D spaces $\text{DM}_E - \log E - \log T_B$ (left panel) or $\text{DM}_E - \log E - \log \nu W$ (right panel). See section 4 for details.

Figure 8. The empirical correlations (blue lines) between fluence $F_\nu$, flux $S_\nu$ and $\text{DM}_E$ for 65 type Ia FRBs (blue points), but no such correlations for 365 type Ib FRBs (red points). See section 4 for details.

do come from different physical mechanisms, their physical properties might be also different in some aspects.

In figure 1 and panel (d) of figure 3, by definition, type Ia and Ib FRBs are clearly separated in the $\nu W - L_\nu$ phase plane. Type Ia FRBs have relatively high brightness temperatures $T_B$ and low spectral luminosities $L_\nu$, as required by eq. (3.7). It is worth noting that we do not take transient duration $\nu W$ into account when the physical conditions in eq. (3.7) are determined. However, an upper boundary in $\nu W$ naturally emerges for type Ia FRBs, namely $\nu W \lesssim 2 \times 10^{-3}$ GHz s, which is determined by the right vertex of region (8) in figure 1 and panel (d) of figure 3. So, type Ia FRBs have also relatively short transient durations $\nu W$. Type Ib FRBs are the rest outside region (8). These two subclasses are clearly separated in this 2-D phase plane. Although they overlap each other in the $\text{DM}_E - \log E$
Figure 9. Left panel: the 3-D empirical correlation (blue meshed plane) between fluence $F_\nu$, flux $S_\nu$ and DM$_E$ given in eq. (4.4) for 65 type Ia FRBs (blue points), but no such correlation for 365 type Ib FRBs (red points). Right panel: the 3-D empirical correlation (red meshed plane) between spectral luminosity $L_\nu$, isotropic energy $E$ and DM$_E$ given in eq. (4.15) for 365 type Ib FRBs (red points). The ones for 65 type Ia FRBs (blue points) and 430 type I FRBs (all points) are given in eqs. (4.14) and (4.16), respectively. See section 4 for details.

Figure 10. The empirical correlations (blue/red/black lines) between spectral luminosity $L_\nu$, isotropic energy $E$ and DM$_E$ for 65 type Ia FRBs (blue points), 365 type Ib FRBs (red points), and 430 type I FRBs (all points), respectively. See section 4 for details.

plane, we find that type Ia and Ib FRBs are located in distinct regions if the third dimension log $T_B$ or log $\nu W$ is added, as shown in figure 7. Their separation in 3-D spaces also hints different physical mechanisms.

We try to find some empirical correlations for type Ia and Ib FRBs through trial and error. At first, we present the empirical correlations between fluence $F_\nu$, flux $S_\nu$ and DM$_E$. In figure 8, we show the 2-D plots for these empirical correlations. Since our main purpose is to find the discriminating physical properties for type Ia and Ib FRBs, it is enough to fit the data without error bars (and we will take errors into account in the future works). This can be done by using sklearn.linear_model.LinearRegression in Python [81]. The
score (coefficient of determination) is given by \( R^2 \equiv 1 - \sum_k (y_k - \hat{y}_k)^2 / \sum_k (y_k - \bar{y})^2 \), where \( y_k, \hat{y}_k \) and \( \bar{y} \) are the observed values, regressed values and mean of observed values \([35, 81]\), respectively. The higher \( R \) indicates the better fit, and \( R = 1 \) at best. As shown in figure 8, we find tight 2-D empirical correlations for 65 type Ia FRBs, namely

\[
\log F_\nu = 0.7709 \log S_\nu + 0.3150 , \quad \text{with} \quad R = 0.9119 , \quad (4.1)
\]

\[
\log \text{DM}_E = -0.3987 \log S_\nu + 2.5402 , \quad \text{with} \quad R = 0.8626 , \quad (4.2)
\]

\[
\log F_\nu = -1.2873 \log \text{DM}_E + 3.6139 , \quad \text{with} \quad R = 0.7038 . \quad (4.3)
\]

On the contrary, there are no such correlations for 365 type Ib FRBs (since the corresponding \( R^2 < 0 \)), as expected by eyes. Putting eqs. (4.1)–(4.3) together, it is anticipated that there is a tight 3-D empirical correlation between fluence \( F_\nu \), flux \( S_\nu \) and \( \text{DM}_E \) for 65 type Ia FRBs. Fitting to the data, we find

\[
\log S_\nu = -0.9468 \log \text{DM}_E + 0.7143 \log F_\nu + 2.1880 , \quad \text{with} \quad R = 0.9634 , \quad (4.4)
\]

which is a 2-D plane in the 3-D plot as shown in left panel of figure 9. Noting that its \( R \) is much higher than the ones of 2-D empirical correlations given in eqs. (4.1)–(4.3), we recommend preferably using the tight 3-D empirical correlation given in eq. (4.4). No such 3-D correlation for 365 type Ib FRBs.

On the other hand, we also find some empirical correlations between spectral luminosity \( L_\nu \), isotropic energy \( E \) and \( \text{DM}_E \). As shown by the blue lines in figure 10, we find the 2-D empirical correlations for 65 type Ia FRBs, namely

\[
\log E = 1.1446 \log L_\nu + 1.0720 , \quad \text{with} \quad R = 0.9081 , \quad (4.5)
\]

\[
\log L_\nu = 0.8470 \log \text{DM}_E + 31.5430 , \quad \text{with} \quad R = 0.6112 , \quad (4.6)
\]

\[
\log E = 1.1698 \log \text{DM}_E + 36.6770 , \quad \text{with} \quad R = 0.6697 . \quad (4.7)
\]

There are similar 2-D empirical correlations for 365 type Ib FRBs as shown by the red lines in figure 10, but with quite different slopes and intercepts, namely

\[
\log E = 0.8862 \log L_\nu + 10.0664 , \quad \text{with} \quad R = 0.9285 , \quad (4.8)
\]

\[
\log L_\nu = 2.4707 \log \text{DM}_E + 27.3976 , \quad \text{with} \quad R = 0.9065 , \quad (4.9)
\]

\[
\log E = 2.2345 \log \text{DM}_E + 34.2238 , \quad \text{with} \quad R = 0.8590 . \quad (4.10)
\]

Obviously, these fits are much better than the ones for 65 type Ia FRBs, since they have much higher \( R \). If we instead consider all 430 type I FRBs as a whole, these 2-D empirical correlations become

\[
\log E = 0.9106 \log L_\nu + 9.1906 , \quad \text{with} \quad R = 0.9249 , \quad (4.11)
\]

\[
\log L_\nu = 2.3656 \log \text{DM}_E + 27.6917 , \quad \text{with} \quad R = 0.8952 , \quad (4.12)
\]

\[
\log E = 2.2309 \log \text{DM}_E + 34.2027 , \quad \text{with} \quad R = 0.8575 . \quad (4.13)
\]

as shown by the black lines in figure 10. Obviously, they are very close to the ones for 365 type Ib FRBs. It is not surprising since 365 type Ib FRBs dominate the whole type I sample.
| \( \log F_{\nu, \text{th}}^{\text{max}} \) | \( p_{\text{KS}} \) for \( \log F_{\nu} \) | \( p_{\text{KS}} \) for \( \log E \) | \( p_{\text{KS}} \) for \( \text{DM}_E \) |
|---|---|---|---|
| 0.95 | 0.9180 | 0.3951 | 0.7758 |
| 0.96 | 0.8801 | 0.3928 | 0.7769 |
| 0.97 | 0.8504 | 0.3911 | 0.7120 |
| 0.99 | 0.7631 | 0.3868 | 0.6610 |
| 1.0 | 0.7036 | 0.3841 | 0.6185 |

Table 3. The same as in table 1, but for 365 type Ib FRBs + 17 repeaters.

In the light of the 2-D empirical correlations in eqs. (4.5)–(4.13), it is anticipated that there is a tight 3-D empirical correlation between spectral luminosity \( L_{\nu} \), isotropic energy \( E \) and \( \text{DM}_E \). Fitting to the data, we find

Type Ia: \( \log L_{\nu} = 0.0079 \log \text{DM}_E + 0.7174 \log E + 5.2316 \), with \( R = 0.9081 \), (4.14)

Type Ib: \( \log L_{\nu} = 1.1330 \log \text{DM}_E + 0.5986 \log E + 6.0909 \), with \( R = 0.9525 \), (4.15)

Type I: \( \log L_{\nu} = 1.0196 \log \text{DM}_E + 0.6033 \log E + 7.0561 \), with \( R = 0.9460 \), (4.16)

for 65 type Ia, 365 type Ib and all 430 type I FRBs, respectively. They are much better than the ones of 2-D empirical correlations in eqs. (4.5)–(4.13), since they have much higher \( R \). We recommend preferably using the tight 3-D empirical correlations given in eqs. (4.14)–(4.16). In right panel of figure 9, we present the 2-D plane corresponding to eq. (4.15) in the 3-D plot. Although they have similar empirical correlations, type Ia and Ib FRBs are still distinguishable, due to their quite different slopes and intercepts.

So far, we show that type Ia and Ib FRBs have some discriminating physical properties. They can be clearly separated in the \( \nu W - L_{\nu} \) phase plane and some 3-D spaces. We find some tight empirical correlations for them, which can also be used to distinguish between type Ia and Ib FRBs. These results hint that they do come from different physical mechanisms.
5 Repeating FRBs

Let us turn to repeating (type II) FRBs. It is reasonable to also consider a similar subclassification of type II FRBs. As mentioned in section 2, there are only 17 repeaters after the robust cut, which are too few to form a good enough sample in statistics. But this does not prevent us from some exploratory studies.

The first question is whether there are subclasses of repeating (type II) FRBs? The answer is a clear yes. In the recent observations, some extragalactic repeaters were located in the star-forming environments, as mentioned in section 1. The Galactic repeater FRB 200428 has been firmly associated with the young magnetar SGR 1935+2154. On the other hand, the well-known repeating FRB 20200120E in a globular cluster is clearly associated with old stellar populations. These observations strongly suggest a similar subclassification of repeating (type II) FRBs: type IIa FRBs (e.g. FRB 20200120E) are associated with old stellar populations and hence do not track SFH, while type IIb FRBs (e.g. FRB 180916.J0158+65, FRB 121102, FRB 20190520B, FRB 20181030A, FRB 200428) are associated with young stellar populations and hence track SFH. Different physical mechanisms are required by type IIa and IIb FRBs.

The second question is whether there are two subclasses in the 17 repeaters of the first CHIME/FRB catalog? The answer might be not. It is reasonable to speculate that they are all type IIb FRBs, because (a) the known type IIa repeater associated with old stellar populations (i.e. FRB 20200120E) is not in the first CHIME/FRB catalog. (b) at least 16 of these 17 repeaters are clearly outside region (8) in the $\nu W - L_\nu$ phase plane as shown in figure 1, while the only one just at the right vertex of region (8) can also be excluded due to the uncertainty of the exact boundaries of region (8). (c) at least two of the known type IIb repeaters associated with young stellar populations (i.e. FRB 20121102A and FRB 20180916B (FRB 180916.J0158+65)) are in the first CHIME/FRB catalog, namely they are 2 of the 17 repeaters under discussion. (d) if these 17 repeaters are all type IIb FRBs, we could check this speculation by combining them with 365 type Ib FRBs and see whether these 382 FRBs track SFH (n.b. 17 repeaters are too few to do this alone since they cannot form a good enough sample in statistics). This can be tested by using the method mentioned in section 3.2, and we present the results in table 3 and figure 11. Clearly, these 382 FRBs can be fully consistent with SFH since three p-values $p_{K3} > 0.39$ simultaneously for some suitable log $F_\nu,\text{th}$. So, the possibility that these 17 repeaters are all type IIb FRBs (associated with young stellar populations and hence track SFH) cannot be excluded by now.

The third question is that could we speculate the physical criteria for the subclassification of type II FRBs? Let us try. It is natural to also subclassify type II FRBs in the $\nu W - L_\nu$ phase plane, and the conservative physical criteria might be similar to the ones of type I FRBs, namely they might also be the dividing lines of $L_\nu$ and $T_B$ (and $\nu W$). But it is reasonable that the dividing lines of $L_\nu$ and $T_B$ (and $\nu W$) might be quite different from the ones of type I FRBs (namely $L_{\nu,\text{crit}} = 10^{34}\text{erg/s/Hz}$ and $T_{B,\text{crit}} = 2 \times 10^{35}\text{K}$). For instance, a much lower $T_{B,\text{crit}} = 10^{33}\text{K}$ was proposed for FRB 20121102A in [35], although their main purpose is somewhat different from ours. Here, we would like to make a bold but not too bold speculation. We strongly refer to figure 3 of [52] or figure 7 of [7], where the known repeater associated with old stellar populations (type IIa), i.e. FRB 20200120E, is plotted in the $\nu W - L_\nu$ phase plane, together with the known repeaters associated with young stellar populations (type IIb), i.e. FRB 20180916B (FRB 180916.J0158+65), FRB 20121102A, FRB 20190711A, and the Galactic FRB 200428 (SGR 1935+2154). Thus, figure 3 of [52] or figure 7 of [7] are ideal test ground for the subclassification of type II FRBs. Similar to region (8)
defined by eq. (3.7) for type I FRBs, we speculate that the possible physical criteria for the subclassification of type II FRBs might be given by

\begin{align}
\text{Type IIa :} & \quad L_\nu \lesssim 10^{29} \text{ erg/s/Hz} \quad \& \quad T_B \gtrsim 10^{30} \text{ K}, \\
\text{Type IIb :} & \quad \text{otherwise}.
\end{align}

(5.1) (5.2)

Note that they are roughly estimated by eyes from figure 3 of [52] or figure 7 of [7], and hence they are not the exact ones. In this way, FRB 20200120E, the known type IIa repeater associated with old stellar populations, could be roughly separated from the known type IIb repeaters associated with young stellar populations mentioned above. If these physical criteria for the subclassification of type II FRBs given by eqs. (5.1) and (5.2) are roughly correct, it is easy to see from figure 1 that the 17 CHIME repeaters are all type IIb FRBs, coincident with our discussions about the second question.

Although the number of repeaters under consideration is too few to go further, we have tried our best to subclassify the repeaters into type IIa and IIb FRBs, with good enough reasonings based on the observational facts. We stress that they are highly speculative. Since the data of repeaters will be rapidly accumulated in the future, we hope this subclassification of type II FRBs could be refined.

6 Concluding remarks

Although FRBs have been an active field in astronomy and cosmology, their origin is still unknown to date. One of the interesting topics is the classification of FRBs, which is closely related to the origin of FRBs. Different physical mechanisms are required by different classes of FRBs. In the literature, they usually could be classified into non-repeating and repeating FRBs. Well motivated by the observations, here we are interested in the possible subclassification of FRBs. By using the first CHIME/FRB catalog, we propose to subclassify non-repeating (type I) FRBs into type Ia and Ib FRBs. The distribution of type Ia FRBs is delayed with respect to SFH, and hence they are probably associated with old stellar populations, while the distribution of type Ib FRBs tracks SFH, and hence they are probably associated with young stellar populations. Accordingly, the physical criteria for this subclassification of type I FRBs have been clearly determined. We find that there are some tight empirical correlations for type Ia FRBs but not for type Ib FRBs, and vice versa. These make them different in physical properties. Similarly, we suggest that repeating (type II) FRBs could also be subclassified into type IIa and IIb FRBs. This subclassification of FRBs might help us to reveal quite different physical mechanisms behind them, and improve their applications in astronomy and cosmology.

In history, the subclassifications have made many important progresses in various fields. For example, the subclassification of supernovae is well known, as mentioned in section 1. The famous subclass of type Ia supernovae was identified in this way. Only they can be used as standard candles, which led to the great discovery of cosmic acceleration (and Nobel prize in physics 2011). This highlights the importance of the subclassifications. It might happen again in the field of FRBs. For instance, FRBs can be used to study cosmology, but the constraints on the cosmological parameters are usually loose (see e.g. [57–63]). If one of the subclasses of FRBs could be used as standard candles, rulers, or sirens (say, by the help of some unknown empirical correlations for this subclass of FRBs), we might remarkably improve the cosmological constraints in the future. Let us keep an open mind to this possibility.
Class (a) : associated with old stellar populations
Class (b) : associated with young stellar populations

| FRBs       | Type Ia : Non-repeating FRBs associated with old stellar populations and hence delayed with respect to SFH | Type Ib : Non-repeating FRBs associated with young stellar populations and hence track SFH |
|------------|--------------------------------------------------------------------------------------------------|--------------------------------------------------------------------------------------------------|
| Type I :   | Non-repeating                                                                                   | Repeating                                                                                     |
|            | Type IIa : Repeating FRBs associated with old stellar populations and hence delayed with respect to SFH | Type IIb : Repeating FRBs associated with young stellar populations and hence track SFH |
| Type II :  | Repeating                                                                                       |                                                                                                 |

Table 4. A brief summary of the universal subclassification scheme of FRBs.

In this work, we have identified 65 type Ia FRBs in the first CHIME/FRB catalog. They have relatively high brightness temperatures $T_B$ and low spectral luminosities $L_\nu$, as required by eq. (3.7). As shown in right panel of figure 4, type Ia FRBs can only be triggered at fairly low redshifts $z \lesssim 0.7$. A delay is required for type Ia FRBs with respect to type Ib FRBs (which track SFH). They are probably associated with old stellar populations. On the other hand, as mentioned at the beginning of section 4, an upper boundary in $\nu W$ naturally emerges for type Ia FRBs, namely $\nu W \lesssim 2 \times 10^{-3}$ GHz s. So, type Ia FRBs have also relatively short transient durations $\nu W$. These properties might help us to reveal the physical mechanism for type Ia FRBs. For instance, the compact binary merger model in a rapid process might be one of the candidates. Gravitational waves (GWs) are usually expected in such a merger. Thus, we might witness type Ia FRBs as electromagnetic counterparts of GW events in the future. This might be a good chance to study gravity, cosmology and IGM.

As found in [53, 56], all FRBs in the first CHIME/FRB catalog as a whole do not track SFH. In this work, we have identified the main cause, namely 65 type Ia FRBs. If they are removed, the rest (mainly type Ib FRBs) do track SFH. In the future, numerous type I FRBs could be well located in their host galaxies, and hence they could be easily subclassified: the ones associated with old/young stellar populations are type Ia/Ib FRBs, respectively. So, one might only use type Ib FRBs to study cosmology and IGM. Thus, it is justified that today one can generate the mock sample of type Ib FRBs by simply assuming a redshift distribution tracking SFH, and use these mock type Ib FRBs to study cosmology and IGM. In this way, one might avoid to consider the complicated redshift distribution models, and hence the simulations could be significantly simplified.

Currently, many of well located FRBs are repeaters [21, 22], thanks to their repeating behaviors. So, it is reasonable to expect that there will be many observational data for repeating (type II) FRBs well located in their host galaxies in the near future, and hence they could be easily subclassified: the ones associated with old/young stellar populations are type IIa/IIb FRBs, respectively. At that time, the physical criteria (in terms of e.g. $L_\nu$, $T_B$, $\nu W$) for the subclassification of type II FRBs could be clearly determined. In turn, they could be used to subclassify the repeaters without well located host galaxies. This virtuous cycle will benefit the studies on repeating (type II) FRBs.

In table 4, we present a brief summary of the universal subclassification scheme of FRBs. As in the literature, type I/II FRBs are non-repeating/repeating, respectively.
Class (a)/(b) FRBs are associated with old/young stellar populations, respectively. Their combinations result in four subclasses: Ia, Ib, IIa, IIb, as shown in table 4. The physical criteria for this subclassification given in eqs. (3.7) and (5.1) are inferred by using the first CHIME/FRB catalog and figure 3 of [52] or figure 7 of [7], respectively. We stress that the physical criteria in eqs. (3.7) and (5.1) might be changed for the larger and better FRB datasets in the future, but the universal subclassification scheme given in table 4 will always hold. Different physical mechanisms for FRBs are required by these subclasses. Note that the key improvement of the universal subclassification scheme given in table 4 is that it works even for a single FRB. A sample of FRBs is needed to see whether their distribution tracks SFH, while one cannot determine whether a single FRB tracks SFH or not. But even for a single FRB, its host galaxy and local environment can be precisely determined. If this FRB has been localized in a star-forming environment, it is a class (b) FRB. Otherwise, it is a class (a) FRB. Combining with whether it repeats, we can then determine its subclass to be one of Ia, Ib, IIa, IIb. In this way, no other criteria are needed (on the other hand, for a single FRB without identified host galaxy, we could instead subclassify it by using the physical criteria given in eq. (3.7) or eq. (5.1)).

It is of interest to speculate the possible progenitor theories for these four subclasses of FRBs. We refer to [16, 17] for the up-to-date FRB theory catalogue. In general, since class (a) FRBs are associated with old stellar populations and hence delayed with respect to SFH, their progenitors might be formed via the compact binary merger which needs to undergo a long inspiral phase before the final coalescence, or the accretion-induced collapse of a white dwarf (WD) which also needs a long time to accrete before the final collapse. On the other hand, since class (b) FRBs are associated with young stellar populations and hence track SFH, their progenitors might be formed directly via the collapse of a massive star. Therefore, we speculate that type Ia FRB comes from the merger of neutron star (NS) — black hole (BH) binary or NS-NS binary (see section 4.1 of [16, 17]), and the final remnant of this merger is a black hole so that the resulted FRB is one-off. The progenitor of type IIa FRB might be the magnetar formed via the merger of WD-WD binary or the accretion-induced collapse of WD (see e.g. [51, 83]), while the magnetars similar to the well-known SGR 1935+2154 are the leading progenitors for the repeating FRBs. Similarly, the progenitor of type IIb FRB might be the young magnetar formed directly via the collapse of a massive star. The progenitor of type Ib FRB might be the supramassive NS formed via the collapse of a massive star, and it quickly collapses into a black hole or a quark star to produce a one-off FRB (see section 4.2 of [16, 17]). Of course, the above speculations are proposed just for examples. The other novel progenitor theories for these four subclasses of FRBs are all desirable.

We would like to briefly discuss the possible systematic errors. In generating the mock FRBs, the main systematic errors come from DM\textsubscript{IGM}. In principle, DM\textsubscript{IGM} should deviate from the mean given in eq. (2.3) if the plasma density fluctuations are taken into account [88–90]. In the literature, the typical error in DM\textsubscript{IGM} is \( \sigma_{\text{IGM}} \sim 100 \text{pc cm}^{-3} [56–63, 88–90] \). However, we stress that it is not a serious problem in the present work, because we are simulating a very large sample of mock FRBs (\( N_{\text{sim}} = 4,000,000 \)) and hence DM\textsubscript{IGM} should heavily concentrate on the mean given in eq. (2.3) [53]. Similarly, if we take the error of DM\textsubscript{host} into account, it is also not a serious problem when we generate DM\textsubscript{L} for a very large sample of mock FRBs (\( N_{\text{sim}} = 4,000,000 \)) [53]. On the other hand, our main goal is to subclassify FRBs, while the physical criteria given in eq. (3.7) or eq. (5.1) are very rough in fact. Some uncertainties in the boundaries of e.g. region (8) in the \( \nu W - L_\nu \) phase plane (see figure 1) only affect a few observed FRBs, and hence cannot significantly change the subclassification of FRBs. Of course, they should be carefully considered in the future works.
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