Constraining violations of the Weak Equivalence Principle Using CHIME FRBs

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ABSTRACT

Einstein’s General Relativity (GR) is the basis of modern astronomy and astrophysics. Testing the validity of basic assumptions of GR is important. In this work, we test a possible violation of the Weak Equivalence Principle (WEP), i.e., there might be a time-lag between photons of different frequencies caused by the effect of gravitational fields if the speeds of photons are slightly different at different frequencies. We use Fast Radio Bursts (FRBs), which are astronomical transients with millisecond timescales detected in the radio frequency range. Being at cosmological distances, accumulated time delay of FRBs can be caused by the plasma in between an FRB source and an observer, and by gravitational fields in the path of the signal. We segregate the delay due to dispersion and gravitational field using the post-Newtonian formalism (PPN) parameter $\Delta \gamma$, which defines the space-curvature due to gravity by a unit test mass. We did not detect any time-delay from FRBs but obtained tight constraints on the upper limit of $\Delta \gamma$. For FRB20181117C with $z = 1.83 \pm 0.28$ and $\nu_{\text{obs}} = 676.5$ MHz, the best possible constraint is obtained at $\log(\Delta \gamma) = -21.58^{+0.10}_{-0.12}$ and $\log(\Delta \gamma/r_\odot) = -21.75^{+0.10}_{-0.14}$, respectively, where $r_\odot$ is the energy ratio of two photons of the same FRB signal. This constraint is about one order of magnitude better than the previous constraint obtained with FRBs, and five orders tighter than any constraint obtained using other cosmological sources.

Key words: Gravitation – Radio continuum: transients – transients: Fast Radio Bursts – Galaxies: distances and redshifts – Catalogues

1 INTRODUCTION

Fast Radio Bursts (FRBs) are astronomical transient signals or millisecond time scales occurring at cosmological distances (Thornton et al. 2013; Petroff et al. 2016a). Since the first discovery in 2007 from the Parkes Data taken by Manchester (2008), FRBs have been an interesting subject and many detections have been successfully made with Parkes (Yang et al. 2021; Tang et al. 2021), Molonglo Observatory Synthesis Telescope (MOST) (Gupta et al. 2019), The Canadian Hydrogen Intensity Mapping Experiment (CHIME) (Masui & Collaboration 2021), and other observatories (Shannon et al. 2019; Fedorova & Rodin 2019; Pilia et al. 2020; Kohler 2020). However, an important question that remains is “What is the origin of FRBs?”. There have been numerous theories regarding their origins (Burke Spolaor 2015; Katz 2016; Mejia et al. 2021; Bhardwaj et al. 2021) although none of those have been fully confirmed. Even though we do not understand their origins, FRBs can be used for many cosmological experiments - one of which is to test the famous Equivalence Principle of Einstein, which is the starting point of General Theory of Relativity (Einstein 1908). The equivalence principle is a hypothesis which states - if some persons are free-falling, their experience of weightlessness will be the same as their experience in a space without gravity. This idea is referred to as Weak Equivalence Principle (WEP). While the weak principle only focuses on the free-falling aspect of gravity (Will 2006, 2009, 2014), the "strong equivalence principle" (Bertotti & Grishchuk 1990) is a more generalized statement. It states that the effect of acceleration and that of an equivalent gravitational field would always be the same. In this study, we would be focused on testing the WEP using the latest CHIME FRB data (Masui & Collaboration 2021).
FRBs are generally classified into two types - repeating and non-repeating FRBs. The repeating signals are observed to repeat after certain intervals (the intervals might vary from hours to days and the repetitions are not necessarily periodic) while the non-repeaters are single pulses. The classification is simply observational and certain non-repeaters can turn out to be repeaters in the future. A necessary reason for the existence of two kinds of FRBs is probably associated with their origins according to studies by Hashimoto et al. (2020a); Pleunis et al. (2021); CHIME/FRB Collaboration et al. (2020); Kirsten et al. (2021); Bochenek et al. (2020); Pleunis & Chime/FRb Collaboration (2021). These studies suggest that there is a possibility that the non-repeating FRBs are mostly originated from astronomical objects like Black Holes, White Dwarfs and Neutron Stars while repeating FRBs originated from supernova remnants, young pulsars and magnetars. Certain more interesting properties of FRBs are their emission frequencies which lie mostly in the 400 MHz to 1 GHz range. FRBs are presumed to have powerful engines, as the amount of energy release in a few milliseconds can be equivalent to the energy released by the Sun in a few days (Petroff et al. 2021). The latest data released by CHIME is a catalogue consisting of 535 FRB sources in the frequency range of 400 MHz to 1 GHz, approximately.

The test of WEP is based on the “Shapiro Time Delay” method which is considered to be the fourth test of GR (Shapiro 1964b). The other three tests were defined by Einstein himself as follows - (1) The precision of perihelion of Mercury’s orbit, (2) The gravitational redshift of light and (3) The light-deflection by the Sun as observed during eclipses (Abbott et al. 2016; Ferreira 2019; Abbott et al. 2019). In simple words, the Shapiro Time Delay test uses the idea that when a ray of light passes through a gravitating object, its path will be slightly deflected according to the geodesic or the curvature of the space. This leads to a small delay in its arrival in comparison to an unperturbed path if no gravitational field is present. The amount of curvature of space is defined in the Parameterized Post Newtonian (PPN) formalism using the gamma parameter (γ). γ defines how much curvature is produced by a unit test mass (Misner et al. 1973). The test mass particle can be a massless particle like a photon, or the hypothetical graviton, or the neutrino. In our study, the test particles are the FRB photons (Wei et al. 2015). In the case of general relativity, γ = 1. A slight deviation thus indicates that a photon is not following the space-time geodesic, violating the WEP.

In this study, we considered many cosmological models to verify our results. All these models are fiducial Λ Cold Dark Matter (LambdaCDM) model with the cosmological parameters \((Ω_m, Ω_Λ, Ω_b, H_0)\). The model parameters in our study are Planck 13 (0.307, 0.693, 0.0486, 67.8) (Planck Collaboration et al. 2014), Planck15 (0.307, 0.693, 0.0486, 67.7) (Planck Collaboration et al. 2016), and WMAP9 (0.287, 0.713, 0.02256, 69.3) (Hinshaw et al. 2013).

The paper is arranged in the following way. We discuss the theoretical considerations behind our analysis in Section 2. We discuss the FRB dataset that we have used in Section 3. In Section 4, the results related to the study can be found, followed by a discussion comparing to previous studies in Section 5. The conclusions are in Section 6.

2 THEORETICAL MODEL

For any transient beam observed from a cosmic distance with \(z > 1\), like FRBs, we are required to consider the following reasons for time-delay. The time-delay can be expressed in terms of the following equation (Wang et al. 2020a) under the observation by a telescope:

\[
\Delta_{\text{obs}} = \Delta_{\text{DM}} + \Delta_{\text{ini}} + \Delta_{\text{LIV}} + \Delta_{\text{gra}},
\]

where \(\Delta_{\text{obs}}\) denotes the total possible time-delay of a particular FRB transient between different frequencies, \(\Delta_{\text{DM}}\) is the time-delay between different frequencies of light calculated from the dispersion due to the ionised medium between the source and the observer. This dispersion measure (DM) may be caused by the interaction of photons with the host galactic medium, the intergalactic medium, and the Milky Way. \(\Delta_{\text{ini}}\) is the initial time-delay of emission between two photons which is an intrinsic property of the source. \(\Delta_{\text{LIV}}\) is the time-delay due to different time-dilation of photons with different non-zero rest mass which is a rather negligible special relativistic effect. \(\Delta_{\text{gra}}\) is the time-delay due to Lorentz Invariance Violation.

\[
\Delta_{\text{gra}} = \frac{2\gamma_2 - \gamma_1}{c^3} \int_{r_0}^{r_1} V(r) \, dx,
\]

where \(c\) is the speed of light, \(r_0\) and \(r_1\) are positions of source and observer, and \(\gamma_1\) and \(\gamma_2\) are parameterized post-Newtonian formalism of two photons of an FRB. In general, for all metric theories, WEP remains valid i.e. any test particle independent of energy should follow the space-time geodesic and hence \(\gamma_2 = \gamma_1 = 1\). Now, in Eq. 1, according to the approximation of Wang et al. (2020a); Wang et al. (2020b), the terms \(\Delta_{\text{LIV}}\) and \(\Delta_{\text{gra}}\) are negligible in comparison to the other time-delays, and \(\Delta_{\text{ini}} > 0\) is considered. Thus, Eq. 1 changes to the following inequality:

\[
\Delta_{\text{obs}} = \Delta_{\text{DM}} > \Delta_{\text{gra}}
\]

This inequality explains that by subtracting the effect of dispersion measure (DM) from the total time delay, we can clearly observe the time-delay caused by the Shapiro effect. In many of the earlier papers like Nusser (2016), the Shapiro time delay is calculated based on local universe models like the Large Scale Structure models (like the Laniakea Super-cluster) or considering a host galaxy as the reasons. However, for huge cosmological distances where \(z \geq 1\), it is not the proper calculation. In fact, for cosmological sources, \(\Delta_{\text{gra}}\) and \(\Delta_{\text{gra}}\) do not have a monotonic increment, as shown in Minazzoli et al. (2019a). Thus, to calculate \(\Delta_{\text{gra}}\), we have to consider all the gravitational sources in the path of the radiation. This is rather difficult and impractical, considering the fact that we do not have enough knowledge and the calculations become more complicated at \(z \geq 1\). Therefore, we consider an analytic model-based solution where we consider the average matter distribution. In this way, the average Shapiro time delay \(t_{\text{gra,avg}}\) can be expressed as a summation of the following two terms:

\[
t_{\text{gra,avg}} = t_{\Lambda} + t_{\text{matter}},
\]

where,

\[
t_{\Lambda} = \frac{\Omega_{\Lambda} H_0^2}{12c^3} \int_0^d \rho \, ds,
\]

and

\[
t_{\text{matter}} = \frac{\Omega_m H_0^2}{6c^3} \int_0^d \rho \, ds,
\]

where \(d_s\) is the co-moving distance of the cosmological source. The co-moving distance is defined as the distance between any two cosmological objects after factoring out the expansion of the universe, so as to take note of any other variation that can lead to
a change of distance. Eq. 6 is consistent (Minazzoli et al. 2019b) up to at least ~ 400 Mpc (z ~ 0.1) when Shapiro Time Delay is calculated from observed galaxy clusters.

Now, in this paper, we focus on a time lag under gravity between two photons with different energies. Because, we focus on the time-lag due to the gravitational effect, we assume that the $f_{\Lambda}$ term is cancelled out between different frequencies while calculating $\Delta_{\text{gra}}$. The time delay for the first and second photon can thus be expressed as -

$$t_{\text{matter}, \gamma_1} = \frac{\Omega_m H_0^2}{6c^3} d_s^3$$

and

$$t_{\text{matter}, \gamma_2} = \frac{\Omega_m H_0^2}{6c^3} d_s^3$$

respectively. Thus, we express $\Delta_{\text{gra}}$ in terms of $t_{\text{matter}}$ and the PPN parameters in the following form:

$$\Delta_{\text{gra}} = t_{\text{matter}, \gamma_2} - t_{\text{matter}, \gamma_1} = (\gamma_2 - \gamma_1) \frac{\Omega_m H_0^2}{6c^3} d_s^3,$$  

where, $\gamma_1$ and $\gamma_2$ are the PPN parameter values of photon-1 and photon-2 respectively. From Eq. 3 and 9, we obtain,

$$\Delta \gamma := \gamma_2 - \gamma_1 < (\Delta_{\text{obs}} - \Delta_{\text{DM}}) \frac{6c^3}{\Omega_m H_0^2 d_s^3}.$$  

In the case of FRB data, the deviation of WEP can be observed in the uncertainties of the observed Dispersion Measure ($\Delta_{\text{DM}}$) i.e. $\delta \Delta_{\text{DM}}$. Therefore, evidence might exist where the value of observed frequency ($\nu_{\text{obs}}$) should effect the violation of WEP. It is because $t_{\text{obs}}$ can be represented by $\Delta_{\text{DM}}$ and also $\nu_{\text{obs}}$. If both the violation of WEP and $\Delta_{\text{DM}}$ show an equivalent dependence on $\nu_{\text{obs}}$, the two effects are not distinguishable (Ioka 2003; Macquart et al. 2020; Inoue 2004). Until now, current studies of FRBs or any other sources have not found any such violation due to frequency (Einstein 1908; Tingay & Kaplan 2016; Nusser 2016; Minazzoli et al. 2019a; Xing et al. 2019).

The time lag due to the observed dispersion measure can be expressed using the following inequality as

$$\Delta_{\text{DM}} \approx 4.15 \left( \frac{\nu_{\text{obs}}}{1 \ GHz} \right)^{-2} \frac{\delta \Delta_{\text{DM}}}{1 \ \text{pc cm}^{-3}} \ s,$$  

The uncertainty of $\Delta_{\text{DM}}$ ($\delta \Delta_{\text{DM}}$) is proportional to $\delta \Delta_{\text{DM}}$ as

$$\delta \Delta_{\text{DM}} \approx 4.15 \left( \frac{\nu_{\text{obs}}}{1 \ GHz} \right)^{-2} \frac{\delta \Delta_{\text{DM}}}{1 \ \text{pc cm}^{-3}} \ s.$$  

The limit of $\delta \Delta_{\text{DM}}$ defines an upper limit constraint on WEP violation. Thus, $\delta \Delta_{\text{DM}}$ puts an upper limit on $\Delta \gamma$. Here, we have considered $\Delta_{\text{DM}}$ as the upper limit of $\Delta_{\text{obs}}$ - $\Delta_{\text{DM}}$ as in eqn 10:

$$\Delta_{\text{obs}} - \Delta_{\text{DM}} < \delta \Delta_{\text{DM}}.$$  

3 DATA

We adopt the latest FRB catalogue released by Canadian Hydrogen Intensity Mapping Experiment (CHIME) as of April, 2021 (Masui & Collaboration 2021). Here, we use classification in the catalogue to separate the repeating and non-repeating cases. However, see Chen et al. (2021 submitted) for a more efficient classification using Machine Learning. We use redshift and its uncertainty of each FRB calculated from the observed dispersion measure ($\Delta_{\text{DM}}$) by Hashimoto et al. (2021 submitted). Here, we consider the redshift, redshift uncertainty, $\Delta_{\text{DM}}$, $\delta \Delta_{\text{DM}}$, $\nu_{\text{obs}}$, and observed bandwidth for our analysis. The observed frequency $\nu_{\text{obs}}$ is the peak-frequency for each FRB sub-burst in our study. The peak-frequency is the frequency value at which the amplitude of the signal is highest.

In the Fig 1, we show the ratio of $\delta \Delta_{\text{DM}}$ for non-repeating and repeating FRBs. For the non-repeating FRBs, $\log(\delta \Delta_{\text{DM}}/\Delta_{\text{DM}})$ ~ -6.3 while in the case of repeating FRBs, the value is around ~-6. Non-repeaters show slightly lower values because their brightnesses are higher compared to the repeaters. On average, therefore, $\delta \Delta_{\text{DM}}$ is slightly smaller for non-repeating FRBs with higher signal-to-noise ratios. In comparison to an earlier study by Hashimoto et al. (submitted) using earlier FRBCAT data where the non-repeaters lower limit of $\log(\delta \Delta_{\text{DM}}/\Delta_{\text{DM}})$ was around -5, this result is around one order of magnitude lower, which implies the CHIME dataset provides a more accurate $\Delta_{\text{DM}}$. Thus, we can provide a tighter constraint on the time lag between different photon energies (having different energies and frequencies).

4 RESULTS

We aim to find the constraint on $\Delta \gamma$. According to our understanding from various previous studies (Tingay & Kaplan 2016; Nusser 2016; Xing et al. 2019; Bartlett et al. 2021; Li et al. 2021; Yang et al. 2020; Tangmatitham & Nemiroff 2019), we can only consider the upper limit of $\Delta \gamma$ value to mark a constraint which essentially indicates an upper limit of the violation of WEP. According to our calculation from Eqs. 10,12 and 13 we find a limit on $\Delta \gamma$ as a function of the observed frequency. In Fig 2, the lowest upper limit of $\Delta \gamma$ of the distribution is approximately around ~-21 in the logarithmic scale. The most stringent constraint in our work is shown by FRB20181117C as $\Delta \gamma = -21.58_{-0.12}$. For FRB20181117C, the value of $z = 1.83 \pm 0.28$, $\Delta_{\text{DM}} = 1773.739 \ \text{pc cm}^{-3}$, $\delta \Delta_{\text{DM}} = 0.001 \ \text{pc cm}^{-3}$ and $\nu_{\text{obs}} = 676.5 \ MHz$. Interestingly, this constraint is so far the best possible constraint we have been able to obtain using FRB data. The most recent constraint as described by Hashimoto.
et. al. using the FRBCAT data (Petroff et al. 2016b; Hashimoto et al. 2020b) also showed rather promising results for FRBs as they have shown a limit of ~20 which is a tighter constraint than that from neutrinos, gamma-ray bursts (GRBs), and gravitational waves (GWs). A comparison between the FRBCAT data (Petroff et al. 2016b; Hashimoto et al. 2020b) and the current CHIME FRB data (Masui & Collaboration 2021) is shown in Fig. 3. Both these results give us an insight into the FRBs that they can act an effective probe to test the WEP.

The average energy difference between the photons is around ~20% (Einstein 1908; Tingay & Kaplan 2016; Nusser 2016; Xing et al. 2019). This is comparatively a lower energy variation with respect to that obtained from strong GRBs and X-ray Pulsar radiation. Hence, the deviation of WEP becomes more prominent due to high energy difference if the value of y depends on energy. In that case, we might not obtain a resolute evidence regarding whether WEP is violated or not. Therefore, Tingay & Kaplan (2016) has introduced a new representation where log(Δγ/E_\text{F}) should be a function of the observed frequency (ν_\text{obs}). Here, E_\text{F} is the ratio of the higher and lower energy of a signal. Thus, E_\text{F} := E_{\text{high}}/E_{\text{low}} = y_{\text{high}}/y_{\text{low}}. From our sample we obtain that for FRB20181117C, the value of log(Δγ/E_\text{F}) = -21.75\pm0.14 gives a stringent constraint. This result is about one order of magnitude lower than the previous result obtained from FRBCAT data developed by Petroff et al. (2016b); Hashimoto et al. (2020b). We have considered a number of cosmological models as given in Section 1 to check any variation in our results. Through analysis, we find that the variations are negligible in terms of the cosmology parameters.

5 Discussion

Constraining the PPN parameter Δγ using FRBs has been done in many previous studies like Tingay & Kaplan (2016); Nusser (2016); Xing et al. (2019). According to Wei et al. (2015), considering FRB 110220 having frequencies between 1.18 to 1.52 GHz, they have obtained log Δγ < -7.6. In their formulation, Δ_t_\text{obs} is primarily dominated by WEP violation rather than dispersion measure. However, according to our formulation, for same FRB110220, the log Δγ < -19.87. Tingay & Kaplan (2016) used FRB150418 in the frequency range 1.2 to 1.5 GHz, yielding a lower limit of log Δγ < -7.7. They also calculated the limit to be lower up to -9 based on the assumption that the WEP is 5% masked by the uncertainty of DM_\text{obs}. Using the same FRB data, Nusser (2016) suggested using the gravitational field of large-scale structures like the Laniakea Supercluster Tully et al. (2014) rather than the Milky Way to measure the WEP constraint. They have obtained a lower limit of log Δγ < -12. In our calculation, the limit of log Δγ for FRB150418 is < -18.05. Using the Nusser (2016) model as described above, Xing et al. (2019) studied the repeated burst of FRB121102 in the frequency range of 1.344 to 1.374 GHz. The time lag of their sub-burst samples were around Δ_\text{t}_\text{obs} = 0.4 ms, which provides log Δγ < -15.6. However, using the similar sample for FRB121102, our formulations have obtained a log Δγ < -16.5. Again, an extended sub-burst set of FRB121102 in the frequency range of 4 to 6 GHz yields a limit of log Δγ < -18.39. All the previous measurements have used the approximation of the Minkowski metric with linear perturbation. However, Minazzoli et al. (2019a) reconsidered the fact and concluded that such an assumption is not applicable for cosmological sources like FRBs. All the previous measurements were based on z < 1, whereas we have tried to consider FRB sources to be originated from cosmological distances where z ≥ 1. Our approach follows the argument where the exact value of 6DM_\text{obs} is considered instead of assuming the 5% typical uncertainty of DM_\text{obs} is assumed (Tingay & Kaplan 2016). However, we have used the latest FRB data obtained by CHIME as of April 2021. In our study, we have obtained the lowest possible value of both log Δγ and log (Δγ/E_\text{F}) cases, considering same particles with different energies.

6 Conclusion

Fast Radio Bursts (FRBs) are radio bursts coming from yet unknown sources at cosmological distances. The time-lag between different energies of FRB signals depends on the dispersion measure. However, they are also hypothesized to be dependent on the frequency following the inverse square law (ν^2). Thus, we have tested the Weak Equivalence Principle (WEP) using FRB data. WEP is the hypothetical time-lag between photons with different frequencies caused by a gravitational field. Hence, the violation of WEP, if it exists, can be detected in the observational uncertainties of the Dispersion Measures of FRBs. Note that it is our assumption that the frequency dependence of WEP violation does not mimic that of dispersion.

We have used the concept of "Shapiro Time Delay" using the
Δ increment in the order of magnitude of the log(Δ) between FRBCAT and CHIME data. The CHIME data clearly shows an increment in the order of magnitude of the log(Δ) mentioned in Section 5 are included in the FRBCAT data (b) Comparison CHIME data. Here post-Newtonian parameter γ which explains how much gravitational curvature is caused by unit mass. Measuring the variation curvature is caused by unit mass. Measuring the variation of observed frequency, we have derived the strictest constraint of log(Δ) as a function of observed frequency between FRBCAT and CHIME data. Here γ is the ratio of energy i.e. $\gamma = E_{\text{high}}/E_{\text{low}}$. The CHIME data clearly shows an increment in the order of magnitude of the log(Δ) value. The other FRB data mentioned in Section 5 are included in the FRBCAT data.

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DATA AVAILABILITY

The data underlying this article are available at https://www.chime-frb.ca/catalog. The redshifts and their uncertainties of FRBs will be available at the article online supplementary material after the publication of Hashimoto et al. 2021 in prep.

REFERENCES

Abbott B. P., et al., 2016, Phys. Rev. Lett., 116, 221101
Abbott B. P., et al., 2019, Phys. Rev. D, 100, 104036
Bartlett D. J., Bergsdal D., Desmond H., Ferreira P. G., Jasche J., 2021, Phys. Rev. D, 104, 084025
Berti O., Grishchuk L. P., 1990, Classical and Quantum Gravity, 7, 1733
Bhardwaj M., et al., 2021, ApJ, 910, L18
Bochenek C. D., Ravi V., Belov K. V., Hallinan G., Kocz J., Kulkarni S. R., McKenna D. L., 2020, Nature, 587, 59
Burke Spolaor S., 2015, in IAU General Assembly. p. 2228939
CHIME/FRB Collaboration et al., 2020, Nature, 587, 54
Einstein A., 1908, Jahrbuch der Radioaktivität und Elektronik, 4, 411
Fedora A. V., Rodin A. E., 2019, Astronomy Reports, 63, 39
Ferreira P. G., 2019, Annual Review of Astronomy and Astrophysics, 57, 335
Gupta V., et al., 2019, The Astronomer’s Telegram, 13363, 1
Hashimoto T., Goto T., Wang T.-W., Kim S. J., Ho S. C. C., On A. Y. L., Lu T.-Y., Santos D. J. D., 2020a, MNRAS, 494, 2886
Hashimoto T., et al., 2020b, Monthly Notices of the Royal Astronomical Society, 498, 3927–3945
Hinshaw G., et al., 2013, ApJS, 208, 19
Inoue S., 2004, Monthly Notices of the Royal Astronomical Society, 348, 999–1008
Joca K., 2003, The Astrophysical Journal, 598, L79-L82
Katz J. I., 2016, Modern Physics Letters A, 31, 1630013
Kirsten F., Snelders M. P., Jenkins M., Nimmo K., van den Eijnden J., Hessels J. W. T., G awroński M. P., Yang J., 2021, Nature Astronomy, 5, 414
Kohler S., 2020, An Update on the Mysterious Flashes of FRB 180916, AAS Nova Highlights
Li C., Zhao H., Cai Y.-F., 2021, Physical Review D, 104
Macquart J.-P., et al., 2020, Nature, 581, 391–395
Manchester R. N., 2008, in Bassa C., Wang Z., Cumming A., Kaspi V. M., eds, American Institute of Physics Conference Series Vol. 983, 40 Years of Pulsars: Millisecond Pulsars, Magnets and More, pp 584–592 (arXiv:0710.5026, doi:10.1063/1.2900303)
Masui K., Collaboration C., 2021, Bulletin of the AAS, 53
Meja A., Jorgenson R., Chintiki J., Stolle-McAllister G., 2021, in American Astronomical Society Meeting Abstracts, p. 328.04
Minazzoli O., Johnson-McDaniel N. K., Sakellariadou M., 2019a, Physical Review D, 100
Minazzoli O., Johnson-McDaniel N. K., Sakellariadou M., 2019b, Phys. Rev. D, 100, 104047
Misser C. W., Thorne K. S., Wheeler J. A., 1973, Gravitation. W. H. Freeman, San Francisco
Nusser A., 2016, The Astrophysical Journal, 821, L2
Petroff E., et al., 2016a, Publications of the Astronomical Society of Australia, 33
Petroff E., et al., 2016b, Publ. Astron. Soc. Australia, 33, e045
Petroff E., Hessels J. W. T., Lorimer D. R., 2021, arXiv e-prints, p. arXiv:2107.10113
Pilia M., et al., 2020, ApJ, 896, L40

Figure 3. (a) Comparison of log(Δ) as a function of observed frequency between FRBCAT and CHIME data. The CHIME data clearly shows an increment in the order of magnitude of the log(Δ) value. The other FRB data mentioned in Section 5 are included in the FRBCAT data. (b) Comparison of log($\gamma_r$) as a function of observed frequency between FRBCAT and CHIME data. Here $\gamma_r$ is the ratio of energy i.e. $\gamma_r = E_{\text{high}}/E_{\text{low}}$. The CHIME data clearly shows an increment in the order of magnitude of the log($\gamma_r$) value. The other FRB data mentioned in Section 5 are included in the FRBCAT data.
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Planck Collaboration et al., 2014, A&A, 571, A16
Planck Collaboration et al., 2016, A&A, 594, A13
Pleunis Z., Chime/Frb Collaboration 2021, in American Astronomical Society Meeting Abstracts. p. 236.03
Pleunis Z., et al., 2021, arXiv e-prints, p. arXiv:2106.04356
Shannon R. M., Day C., Kumar P., Askap-Craft Collaboration 2019, The Astronomer’s Telegram, 13376, 1
Shapiro I. I., 1964a, Phys. Rev. Lett., 13, 789
Shapiro I. I., 1964b, Phys. Rev. Lett., 13, 789
Tang Z., Zhang S., Dai S., Li Y., Wu X., 2021, arXiv e-prints, p. arXiv:2106.04821
Tangmatitham M., Nemiroff R. J., 2019, Testing the Weak Equivalence Principle with Cosmological Gamma Ray Bursts (arXiv:1903.05688)
Thornton D., et al., 2013, Science, 341, 53–56
Tingay S. J., Kaplan D. L., 2016, The Astrophysical Journal, 820, L31
Tully R. B., Courtois H., Hoffman Y., Pomarède D., 2014, Nature, 513, 71–73
Wang D., Li Z., Zhang J., 2020a, Physics of the Dark Universe, 29, 100571
Wang D., Li Z., Zhang J., 2020b, Physics of the Dark Universe, 29, 100571
Wei J.-J., Gao H., Wu X.-F., Mészáros P., 2015, Phys. Rev. Lett., 115, 261101
Will C. M., 2006, Living Reviews in Relativity, 9, 3
Will C. M., 2009, in IAU Symposium #261, American Astronomical Society. p. 886
Will C. M., 2014, Living Reviews in Relativity, 17, 4
Xing N., Gao H., Wei J.-J., Li Z., Wang W., Zhang B., Wu X.-F., Mészáros P., 2019, The Astrophysical Journal, 882, L13
Yang S.-C., Han W.-B., Wang G., 2020, Monthly Notices of the Royal Astronomical Society: Letters, 499, L53–L57
Yang X., et al., 2021, MNRAS, 507, 3238

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