Constraining Primordial Black Hole Dark Matter with CHIME Fast Radio Bursts

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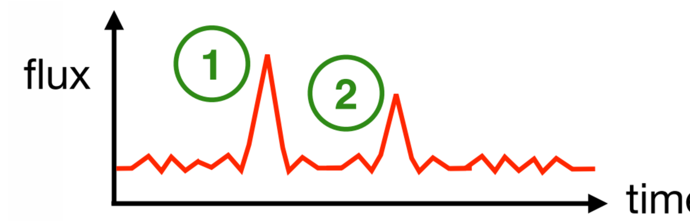
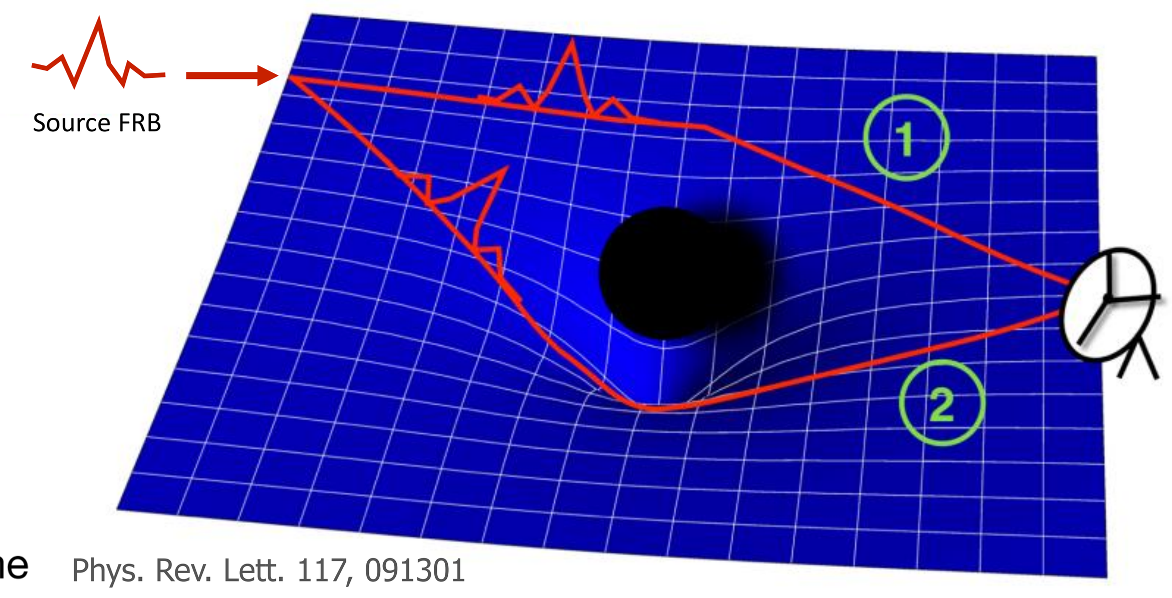
Keren Krochek & Ely D. Kovetz, Phys. Rev. D 105, 103528

We use gravitational lensing of fast radio bursts (FRB) to try to constrain primordial black hole dark matter with the latest CHIME catalog and make a forecast for future results.

- **Using the intrinsic burst width and a calibrated flux-ratio threshold per FRB.**
- **Taking into account the uncertainty in dispersion measure and redshift relation.**
- **We outline an algorithm to detect lensed FRBs and to validate the possibility of detection.**
- **We demonstrate how stacking repeating FRBs can improve the constraints, especially for lower masses.**
- **We Identified one FRB with a double peak as a candidate for strong gravitational lensing.**





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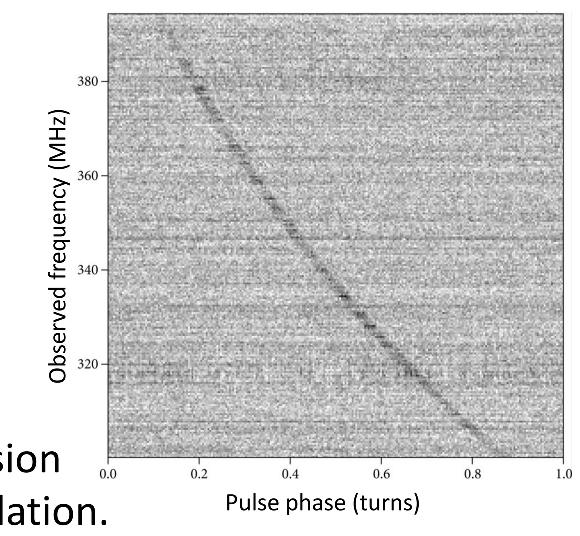
Introduction

FRBs are bursts of millisecond duration in radio frequencies. As the light interacts with charged particles as it propagates through the universe, the more energetic photons can push through the free electrons with little effect on their speed. This results in dispersion of the burst as seen in the figure to the Right [1]. Since the dispersion measure (DM) is proportional to the distance traveled, it can be used to estimate that distance and the redshift of the source z_S. We use the *Macquart relation* [2] to estimate z_S from the dispersion measure while taking into account the uncertainty in their relation.



We model the DM as consisting of:

$$DM = DM_{MW} + DM_{EG}$$

Where DM_{MW} is the total Milky-Way contribution and the extra-galactic DM contribution is

$$DM_{EG} = DM_{cosmic} + \frac{DM_{host} + DM_{src}}{1+z}$$

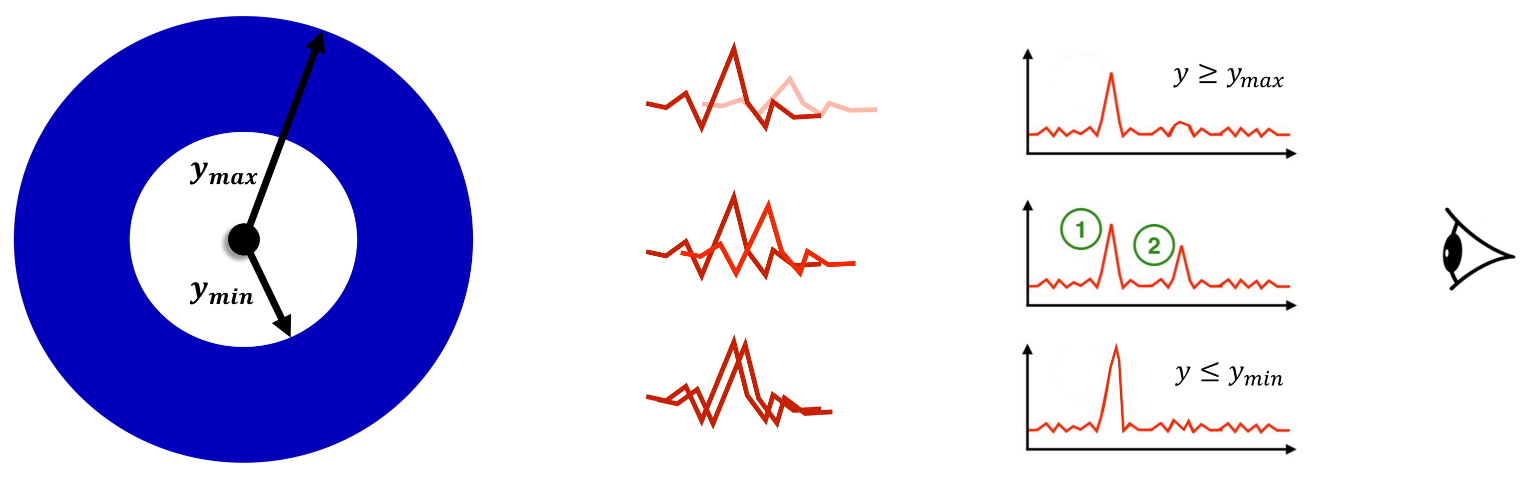
DM_{cosmic} is the contribution of the intergalactic medium (IGM), and DM_{host} and DM_{src} result from the FRB host galaxy and source environment.

The probability that an FRB is lensed is approximately the lensing optical depth.

$$\tau(M_L, z_S) = \int_0^{z_S} d\chi(z_L)(1+z_L)^2 n_L \sigma(M_L, z_L)$$

Where $\chi(z)$ is the comoving distance at redshift z and n_L is the comoving number density of the lens. $\sigma(M_L, z_L)$ is the effective cross section for lensing, it is an anulus defined by two requirements:

- The first is that the two images are completely separated, for this we require that the separation is greater than the width of the FRB. This gives us the minimal normalized impact parameter for lensing y_{min}.
- The second is that the second image is strong enough to detect, this gives a maximal flux ratio between the two images R_f, we find it through our algorithm by simulating the bursts as lensed and finding the maximal R_f that enables detecting the lensing, $\bar{R}_f$. From this we get the maximal normalized impact parameter for lensing y_{max}.



Summing over every source's lensing optical depth gives the total optical depth of a lens with mass M_L, $\bar{\tau}(M_L)$.

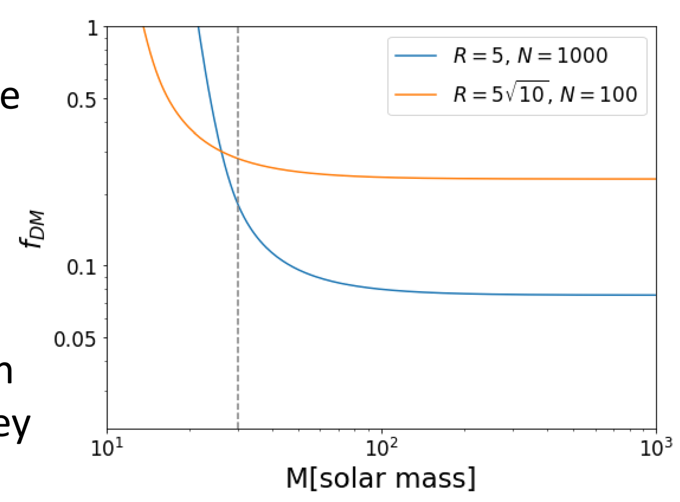
$$\bar{\tau}(M_L) = \sum_i \tau(z_{S,i}, M_L, w_i, \bar{R}_{f,i})$$

The sum is over all FRBs that pass our validation process and their optical depths are a function of their redshift, lens mass, intrinsic width and $\bar{R}_f$ that we find for each FRB.

If none of the events are lensed the bound we can place on the fraction f_{DM} of dark matter allowed in the form of PBHs is $f_{DM} < 1/\bar{\tau}$.

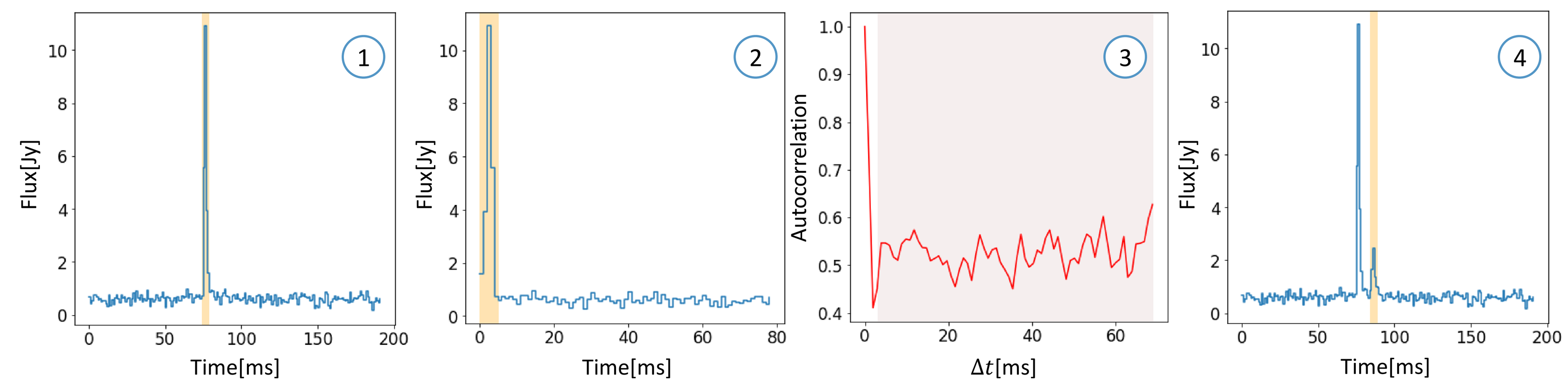
Repeaters

For repeating FRBs we can stack their N repetitions, so that the signal gets magnified by a factor of N, while the noise only gets magnified by a factor of $\sqrt{N}$, therefore allowing to increase $\bar{R}_f$ by a factor of $\sqrt{N}$ and improve the sensitivity to strong lensing by PBHs. This relies on two assumptions: (i) one and all FRB repetitions are lensed by the intervening PBH; (ii) a meaningful fraction of the repetitions have small intrinsic widths so that they can be efficiently stacked together.

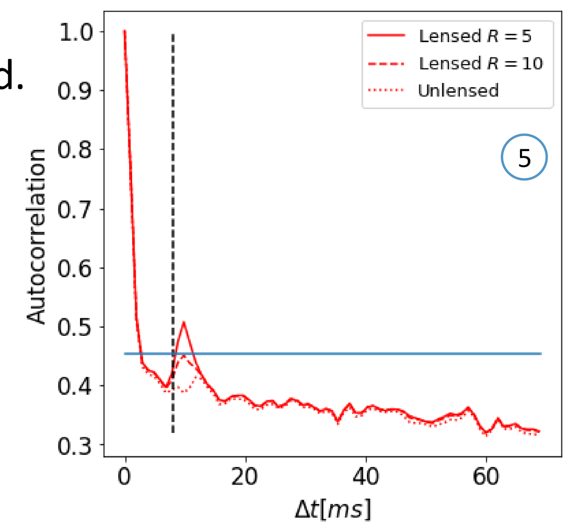


This figure shows f_{DM} for: 1000 non-repeating events (blue), 100 events that repeat 10 times (orange). We simplified and assumed all FRBs can be detected as lensed with $R_f = 5$, in reality this is not the case. The full details of these calculations can be found in our paper. The dashed line is $30M_\odot$, as you can see, fewer repeating events can constrain f_{DM} in low masses where many non-repeating events fail to give a constraint.

Algorithm



Before ruling out FRBs as lensed, we want to see for what $\bar{R}_f$ they can be detected es lensed if they can indeed be detected. To do this, we simulate the events as lensed with different R_f and find the maximal one that allows detection.



The lensing detection is done through autocorrelation. First we define a threshold based on the autocorrelation of unlensed burst. For the unlesed burst we take the burst (highlighted in orange in the Fig. 1) and its preceding section of noise where we can be sure there is no echo from lensing. We then flip it to place the burst in the beginning (Fig. 2) and calculate its autocorrelation. Image 3 shows this autocorrelation. The beginning of the autocorrelation is high because of the burst overlapping with itself, we discard this part and only use the rest (the shaded part of Fig. 3) to calculate the mean μ and the standard deviation σ of the autocorrelation. We set the threshold at $\mu + 2.325\sigma$ (corresponding to a detection of an outliner at $99\% - C.L$).

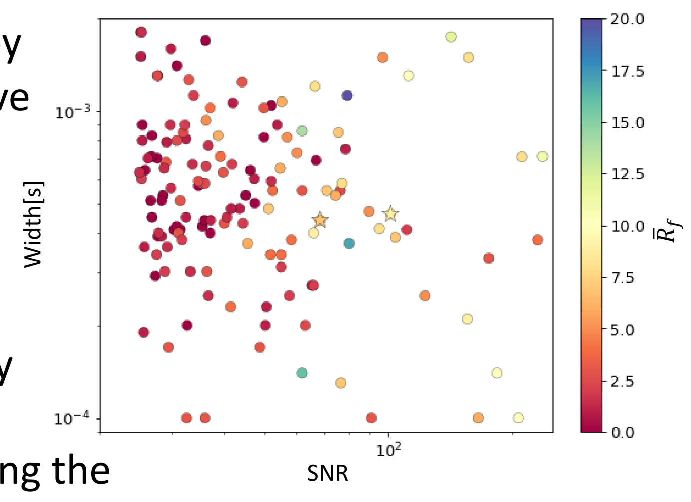
To simulate the lensing add the echo as follows: we subtract the mean of the noise from the burst, divide it by R_f and shift it forward in time enough to ensure a full separation between the burst and the echo. The lensed signal is shown in Fig. 4 with the echo highlighted in orange. Fig. 5 shows the autocorrelations of the FRB in three cases: lensed with $R_f = 5$, lensed with $R_f = 10$, and unlensed. For an FRB to be considered valid at a certain R_f we require the autocorrelation to pass the threshold (blue line in Fig.5) in the place we added the echo.

An FRB is considered as a candidate for lensing if the autocorrelation of the original signal passes the threshold past the dashed line. This line marks the beginning of the lensing search, to its left the autocorrelation is high due to the burst overlapping with itself.

Results

We focus on the range $10 - 100M_\odot$ as it is motivated by LIGO and as there already are sufficient constraints above $100M_\odot$.

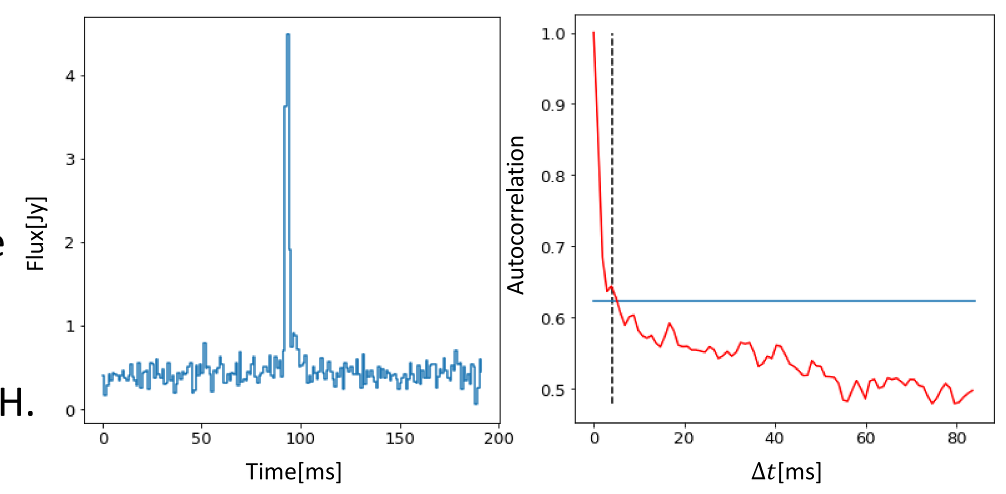
We first make two gross cuts to the CHIME FRB data. We filter out FRBs with widths $\geq$ 6ms which are too wide to constrain PBHs in the desired mass range, and FRBs with $SNR < 25$ as the noise in these FRBs is simply too large to allow a detection of a lensed echo.



This cut leaves us with only 143 FRBs to be validated using the process described above. The 114 FRBs that pass our validation process are shown in the figure above with their width, SNR and $\bar{R}_f$.

Lensing candidate

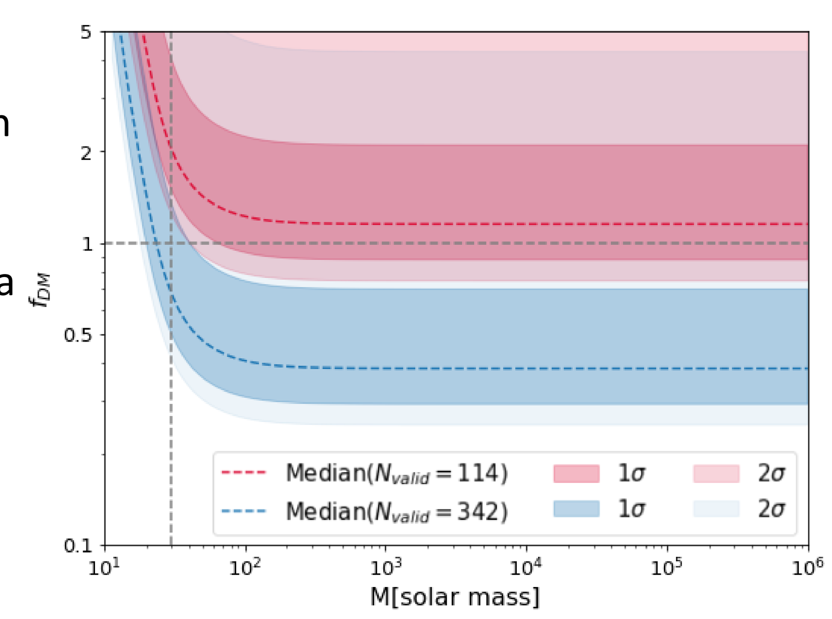
We found two candidates for lensing and were able to rule one out due to different peak structure. The second candidate is FRB20190627B, here are Its light curve and autocorrelation. This double burst could be explained via strong lensing by a $\mathcal{O}(10M_\odot)$ PBH.



Forecast

With 1 FRB at most being lensed the 114 FRBs that pass the validation process are not enough to place a bound on f_{DM}, as you can see in this figure, it results in $f_{DM} > 1$ (red).

However with only three times the current data we can constrain f_{DM} even at low masses (blue). The dashed line at $30M_\odot$ is shown for orientation.



[1] Image from: Essential Radio Astronomy James J. Condon and Scott M. Ransom
[2] *Monthly Notices of the Royal Astronomical Society*, Volume 509, Issue 4, February 2022, Pages 4775–4802