Cosmic opacity: cosmological-model-independent tests from gravitational waves and Type Ia Supernova

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In this paper, we present a scheme to investigate the opacity of the Universe in a cosmological-model-independent way, with the combination of current and future available data in gravitational wave (GW) and electromagnetic (EM) domain. In the FLRW metric, GWs propagate freely through a perfect fluid without any absorption and dissipation, which provides a distance measurement unaffected by the cosmic opacity. Focusing on the simulated data of gravitational waves from the third-generation gravitational wave detector (the Einstein Telescope, ET), as well as the newly-compiled SNe Ia data (JLA and Pantheon sample), we find an almost transparent universe is strongly favored at much higher redshifts ($z \sim 2.26$). Our results suggest that, although the tests of cosmic opacity are not significantly sensitive to its parametrization, a strong degeneracy between the cosmic opacity parameter and the absolute $B$-band magnitude of SNe Ia is revealed in this analysis. More importantly, we obtain that future measurements of the luminosity distances of gravitational waves sources will be much more competitive than the current analyses, which makes it expectable more vigorous and convincing constraints on the cosmic opacity (and consequently on background physical mechanisms) and a deeper understanding of the intrinsic properties of type Ia supernovae in a cosmological-model-independent way.

I. INTRODUCTION

One of the most important issues of the modern cosmology lies in the discovery that our universe is undergoing an accelerated expansion at the present stage, through the observations of unexpected dimming of type Ia supernovae (SNe Ia)\textsuperscript{1}. In the framework of general relativity (GR), a mysterious substance with negative pressure, dubbed as dark energy, was proposed to explain this acceleration [2][4]. However, another mechanism attempts to explain this observed SNe Ia dimming, i.e., whether the light intensity of a supernova is diminished because of the photon absorption or scattering of dust in Milky Way, intervening galaxies or the host galaxy [8]. Although subsequent observations such as large-scale structure [9], baryon acoustic oscillation (BAO) [10] and cosmic microwave background (CMB) anisotropy [11] independently confirmed the accelerating expansion of the Universe, the question of whether the universe is transparent still needs to be confronted, as the acceleration rate and the cosmological parameters determined by SNe Ia observations are highly dependent on the dimming effect. For instance, a recent analysis [12] seems to imply only a marginal evidence for this widely accepted claim, if rigorous statistical tests are performed on these standardizable candles with the varying shape of the light curve and extinction by dust. This motivates the need to probe other plausible mechanisms for this observed SNe Ia dimming.

The general methodology of testing the cosmic opacity focuses on the distance duality relation (DDR), which connects the luminosity distance $D_L$ and angular diameter distance (ADD) $D_A$ at the same redshift, $\frac{D_L(z)}{D_A(z)} (1 + z)^{-2} = 1$. Having been derived from the reciprocity law, the DDR holds in whatever cosmology provided the space-time is Riemannian and that the number of photons is conserved. The former condition, which is related to the foundations of the gravity theory, could be used to probe the possible existence of exotic physics in the theory of gravity. Meanwhile, if one can take it for granted, a more interesting possibility is to test whether there are sources of attenuation (like gray dust) or brightening (as gravitational lensing) along the light path [13].

From the observational point of view, the measurement of the luminosity distance will be affected when the Universe is opaque. In recent works, there are many papers [14][19] devoted to investigating the cosmic opacity under the assumption that the violation of DDR is generated by the non-conservation of the photon number, in which type Ia supernovae are the ideal tool to estimate the luminosity distances, while the angular diameter distances are derived from various astrophysical probes. Although ADDs are much more difficult to measure, some significant steps forward have been progressed recently based on the Sunyaev-Zel’dovich effect together with X-ray emission of galaxy clusters, estimates of the cosmic expansion $H(z)$ from cosmic chronometers, measurements of the gas mass fraction in galaxy clusters and observations of strong gravitational lensing systems. Reference [14] made a joint ADD analysis with two galaxy cluster samples compiled by [20][21] and performed cosmological-model-independent tests for the cosmic opacity. The final results showed that a transparent universe is ruled out by the Bonamente et al. [21] sample at 68.3% confidence level (C.L.), which demonstrated the importance of considering the dimming effect of SNe Ia, given the compatibility of results derived by using angular diame-
ter distances and luminosity distances, respectively [22]. Further papers [15,17] have also noticed this disagreement in cosmographic studies using BAO as a source of angular diameter distances. More recently, some substantial progress has been made in the measurements of the Hubble parameter $H(z)$, which are combined with different sub-samples of SNe Ia observations to quantify the cosmic opacity [23,24]. However, it is worth noting that $H(z)$ describes the expansion rate of the universe rather than the distance, i.e., the angular diameter distance obtained by integrating these scattered points will inevitably lead to large uncertainties, which indicated the importance of taking the correlations between different redshifts into account [23]. More importantly, considering the limited sample size of $H(z)$ measurements, one has also to take care of the errors due to the mismatch between the $H(z)$ redshift and the closest SNe Ia in the companion SNe Ia sample adopted. The cosmological constraining power of these ADD measurements, derived in the electromagnetic (EM) domain, could be significantly affected by large observational uncertainties.

An alternative opacity-free distance indicator is represented by the standard sirens, i.e., the gravitational wave signal from an inspiraling binary system to determine the absolute value of its luminosity distances. Such original proposal, especially focusing on inspiraling binary black holes (BH) and neutron stars (NS) can be traced back to the paper of [20]. The breakthrough took place with the first direct detection of the gravitational wave (GW) source GW150914 [27], as well as GW170817 [28] with an electromagnetic counterpart, which has opened an era of gravitational wave astronomy and added a new dimension to the multi-messenger astrophysics. Since then, extensive efforts have been made to use simulated GW data to constrain cosmological parameters, which showed that the constraint ability of GWs is comparable or better than the traditional probes, if hundreds of GW events have been observed [29]. Compared with the observations of SNe Ia in the EM domain, the self-calibrating GW signals could provide the effective information of luminosity distances, independent of any other distance ladders. More importantly, the greatest advantages of GW lies in its ability to propagate freely through a perfect fluid without any absorption and dissipation [30-32], in the Friedmann-Lemaître-Robertson-Walker metric. Therefore, when confronting the luminosity distance derived from SNe Ia with that directly measured from GW sources, we may naturally propose a scheme to investigate the opacity of the Universe, given the wealth of current and future available data in gravitational wave (GW) and electromagnetic (EM) domain. If the universe is opaque, the flux from SNe Ia received by the observer will be reduced, and we may characterize this effect with a factor $e^{-\tau(z)}$, where $\tau(z)$ is the optical depth related to the cosmic absorption. As is discussed above, since the GWs travel in the Universe without any absorption and scattering with dust, the observed luminosity distance from SNe Ia is related to the true luminosity distance from GW as

$$D_{L,SN} = D_{L,GW}e^{\tau(z)/2},$$  \hspace{1cm} (1)

More specifically, we will consider the simulated data of gravitational waves from the third-generation gravitational wave detector (the Einstein Telescope, ET), as well as the newly-compiled type Ia supernovae (SNe Ia) data from Joint Light-curve Analysis (JLA) sample and the Pantheon sample, in order to, compare opacity-free distance from GW data and opacity-dependent distance from SNe Ia.

This paper is organized as follows. The simulated GW data and the current SNe Ia sample used in our work are presented in Section II. Section III investigates the constraints these data put on two different parameterizations of cosmic opacity. Finally, the conclusions and discussions are presented in Section IV.

II. DATA

A. Gravitational waves detected by ET

First of all, we will briefly introduce the simulated observations of GWs from the third generation of the ground-based GW detector, Einstein Telescope (ET) [63], which would be ten times more sensitive than current advanced ground-based detectors covering the frequency range of $1-10^4$ Hz. Theoretically, ET could detect GW signals up to redshift $z \sim 2$ for the neutron star-neutron star (NS-NS) mergers and $z \sim 5$ for black hole-neutron star (BH-NS) mergers systems [29]. These two GW sources are of concern to our investigation in this paper, as the electromagnetic (EM) signals are emitted during the merger processes, allowing us to determine the
the luminosity distance, and the chirp mass can be measured from the GW signal’s phasing, we can extract luminosity distance from the amplitude. Note that the GW sources used in this work are caused by binary merger of a neutron star with either a neutron star or black hole, which can generate an intense burst of γ-rays (SGRB) with measurable redshift. More importantly, from observational point of view, the SGRB is emitted in a narrow cone, which indicates that one specific gravitational wave event should be detected within the total beaming angle (e.g., $\iota < 20^\circ$) \cite{34}. In the following simulations, we adopt the flat ΛCDM with $H_0 = 67.8$ km s$^{-1}$ Mpc$^{-1}$ and $\Omega_m = 0.308$ as the fiducial cosmological model, following the most recent Planck results \cite{34}.

Given a waveform of GW, the signal-to-noise ratio (SNR) of a detector can be written as

$$\rho = \sqrt{\langle H, H \rangle},$$

where the inner product is defined as

$$\langle a, b \rangle = 4 \int_{f_{\text{lower}}}^{f_{\text{upper}}} \tilde{a}(f) \tilde{b}^\ast(f) + \tilde{a}^\ast(f) \tilde{b}(f) \frac{df}{2 S_b(f)},$$

and $S_b(f)$ represents the one-side noise power spectral density (PSD) characterizing the performance of a GW detector \cite{33}. The lower cutoff frequency $f_{\text{lower}}$ is fixed to be 1 Hz, while the upper cutoff frequency, $f_{\text{upper}}$, is decided by the last stable orbit (LSO), $f_{\text{upper}} = 2 f_{\text{LSO}}$, where $f_{\text{LSO}} = 1/(6^{1/2} \pi M_{\text{obs}})$ is the orbit frequency at the LSO. For the network of three independent interferometers in ET, the combined SNR can be calculated as

$$\rho = \sqrt{\sum_{i=1}^{3} \rho_i^2}.$$  

III. According the Fisher information matrix, the instrumental uncertainty of the measurement of $D_{L,GW}$ can be estimated. In this analysis, we take the simplified case where the binary’s orbital plane is nearly face on and then the Fourier amplitude $A$ will be independent of the polarization angle $\psi$. From theoretical point of view, the distance of source $D_L$ is correlated with other parameters, especially the inclination angle with possible values of $\iota = [0, 180^\circ]$. However, recent analysis \cite{31, 33} indicated that SGRBs, the electromagnetic counterparts of GWs, are likely to be strongly beamed phenomena, which allow one to constrain the inclination of the compact binary system and furthermore breaking the distance-inclination degeneracy. More specifically, averaging the Fisher matrix over the inclination $\iota$ with the limit $\iota < 20^\circ$ is approximately equivalent to taking $\iota = 0$. Therefore, we suppose that the luminosity distance $D_L$ is independent of other GW parameters, and double its uncertainty calculated from the Fisher matrix as the upper limit of the instrumental error

$$\sigma_{\text{inst}}^2 D_{L,GW} \simeq \frac{2 D_L}{\rho}.$$
Moreover, following the uncertainty budget described by Cai and Yang [29], the lensing uncertainty caused by the weak lensing is modeled as $\sigma_{\text{lens}}^{D_{L,GW}} / D_L = 0.05z$. Therefore, the distance precision per GW is taken as

$$\sigma_{D_{L,GW}} = \sqrt{(\sigma_{\text{inst}}^{D_{L,GW}})^2 + (\sigma_{\text{lens}}^{D_{L,GW}})^2} \approx \sqrt{\left(\frac{2D_{L,GW}}{\rho}\right)^2 + (0.05zD_{L,GW})^2}. \quad (10)$$

Let us clarify some simplified assumptions underlying our error strategy listed above. In this paper, we consider only instrumental and lensing uncertainties to derive the information of GW luminosity distances. Note that the precise measurement of the chirp mass and the redshift could constitute the biggest challenge using GWs as the standard sirens. On the one hand, as can be clearly seen from Eq. (5), the uncertainty related to the measurement of chirp mass will contributes to the scatter of luminosity distances at high redshifts and might reveal as a systematic effect at low redshifts. On the other hand, with present sensitivity (of the advanced LIGO and Virgo detectors), the localization accuracy is far from accurate enough to identify the host galaxy and provide accurate measurement of redshift. Therefore, the redshift inferred at the current observational level will adds additional uncertainty to our cosmological constraints. However, in the framework of the Einstein Telescope, the third-generation detector with higher sensitivity, one could expect the chirp mass to be accurately measured from the GW signal’s phasing, while the host galaxy can be identified from the electromagnetic counterpart of GW (such as SGRB), the redshift of which can be determined accurately by the follow-up observations. Specially, following the recent analysis given the observations of host galaxies, the peculiar velocity is typically set at 150-250 km/s and the corresponding redshift uncertainty is estimated to be $\Delta z = 0.001$ [37]. Therefore, in our approach this the redshift determination does not significantly contribute to the scatter in the simulation results.

IV. We have simulated many catalogues of NS-NS and BH-NS systems, with the masses of NS and BH sampled by uniform distribution in the intervals [1,2] $M_\odot$ and [3,10] $M_\odot$. The ratio of the possibility to detect the BHNS and BNS events is set to be $\sim 0.03$ [29]. The sky position of GW source is sampled from the uniform distribution on 2-dimensional sphere [38]. In addition, the signal is identified as a GW event only if the ET interferometers have a network SNR of $\rho > 8.0$, the SNR threshold currently used by LIGO/Virgo network [38]. Finally, the redshift distribution of these GW sources are taken as [39]

$$P(z) \propto 4\pi d_C^2(z) R(z) / H(z)(1+z), \quad (11)$$

where $H(z)$ is the Hubble parameter of the fiducial $\Lambda$CDM, $d_C = \int_0^z 1/H(z)dz$ is co-moving distance, and $R(z)$ represents the time evolution of the burst rate (see [40,41] for details). Denoting with $D_{L,GW}(z)$ the predicted value from our fiducial cosmological model, we then assign to each GW, an opacity-free luminosity distance randomly generated from a Gaussian distribution centered on $D_{L,GW}(z)$ and $\sigma_{D_{L,GW}}$ from Eq. (10). The simulated 1000 GW samples are shown in Fig. 3.

B. Latest Supernovae Ia observations

Concerning the opacity-dependent distance modulus, we will turn to the joint light-curve analysis (JLA) sample with 740 SNe Ia data compiled by the SDSS-II and SNLS collaborations [42], as well as the Pantheon sample consisting of 1048 SN Ia recently released by Pan-STARRS1 (PS1) Medium Deep Survey [43,44].

SNe Ia are used as “standard candles” to provide the most direct indication of the accelerated expansion of the universe. The recent discovery of a new gravitationally lensed SNe Ia from the intermediate Palomar Transient Factory (iPTF) has also opened up a wide range of possibilities of using strong lensing systems in cosmology and astrophysics [43,45]. Apart from developing a precise model able to determine the standardization parameters directly from the physics of the SNe Ia thermonuclear explosions, the only way to evaluate these parameters is through the Hubble diagram. Indeed, one can express the distance modulus of each SN Ia as a difference between its apparent and absolute magnitude. For the JLA sample, the observed distance modulus is

$$\mu_{SN} = m_B^n + \alpha \cdot X_1 - \beta \cdot C - M_B, \quad (12)$$

where $m_B^n$ is the rest frame $B$-band peak magnitude, $X_1$ and $C$ describe the time stretch of light curve and the supernova color at maximum brightness, respectively. Moreover, the parameter $M_B$ is the absolute $B$-band magnitude, whose value is determined by the host stellar mass $M_{\text{stellar}}$ by a step function

$$M_B = \begin{cases} M_B^1 & \text{for } M_{\text{stellar}} < 10^{10} M_\odot \\ M_B^1 + \Delta_M & \text{otherwise.} \end{cases} \quad (13)$$

Thus, there are four nuisance parameters ($\alpha, \beta, M_B^1$ and $\Delta_M$) to be fitted, along with the parameters characterizing the opacity of the universe. Recently, the Pan-STARRS1 (PS1) Medium Deep Survey has released their Pantheon compilation which consists of 1048 SNe Ia, which have been extensively used to constrain cosmological models in Park and Ratra [46], L’Huillier et al. [47], Qi et al. [48]. For the Pantheon sample, the stretch-luminosity parameter $\alpha$ and the color-luminosity parameter $\beta$ should be set to zero, and the observed distance module is simply reduced to $\mu_{SN} = m_B^n - M_B$ [43].

It should be noted that the distance modulus of the compiled SNe Ia could provide the opacity-dependent luminosity distance as $D_{\text{L,SN}}(z) = 10^{\mu(z)/5-5}$. If the observed luminosity distance from SNe Ia is related to
FIG. 2: The one-dimensional and two-dimensional distributions of cosmic opacity parameter $\epsilon$ and SNe Ia nuisance parameters ($\alpha$, $\beta$, $M_B^1$ and $\Delta_M$) constrained from the JLA sample in the P1 (left) and P2 (right) model, respectively.

FIG. 3: The two-dimensional distributions of cosmic opacity parameter $\epsilon$ and SNe Ia nuisance parameters ($M_B^1$) constrained from the Pantheon sample in the P1 (left) and P2 (right) model, respectively.

|               | JLA+ET           | Pantheon+ET  |
|---------------|------------------|--------------|
|               | $\epsilon$      | $\alpha$    | $\beta$    | $M_B^1$         | $\Delta_M$       |
| P1            | 0.007 ± 0.038    | 0.138 ± 0.023 | 2.33 ± 0.28 | $-19.149 ± 0.044$ | $-0.028 ± 0.043$ |
| P2            | 0.005 ± 0.055    | 0.137 ± 0.023 | 2.31 ± 0.27 | $-19.149 ± 0.050$ | $-0.028 ± 0.042$ |
|               | $MB = -19.415 ± 0.016$ |             |             | $MB = -19.417 ± 0.019$ |

TABLE I: Best-fit values with 1σ standard error for the cosmic opacity $\epsilon$ and SNe Ia nuisance parameters.
the true luminosity distance from GWs by  

\[ D_{L,\text{SN}}^2 = D_{L,GW}^2 \exp(\Delta(z)) \]

the theoretical distance modulus of a SNe Ia can be obtained as

\[ \mu_{th}(z) = 5 \log D_{L,GW} + 25 + 2.5(\log_{10} c)\tau(z). \quad (14) \]

For a given SNe Ia data point, theoretically, we should select an associated GW data point at the same redshift. In order to avoid any bias of redshift differences between SNe Ia and GW, we adopt a selection criterion that bins \( D_{L,GW} \) measurements within the redshift range \( \Delta z = |z_{SN} - z_{GW}| \leq 0.005 \). One should note that the redshifts of observations are not determined with infinite accuracy, which indicates that it is unrealistic to decrease \( \Delta z \) below the total 1σ error of observational redshifts \( \sigma_{z,tot} = \sigma_{z,SN} + \sigma_{z,GW} \). For the observations of SNe Ia, the uncertainty of peculiar velocity is set at the level of 300-400 km/s and the corresponding redshift uncertainty is \( \sigma_{z,SN} = 0.001 \). For the observations of GW host galaxies, the three-dimensional rms velocity (150-250 km/s) corresponds to the redshift uncertainty of \( \sigma_{z,GW} = 0.001 \). Therefore, in principle, \( \Delta z = \sigma_{z,tot} = 0.002 \) should be considered in our work. However, considering the observational difficulties in precisely identifying the host galaxy and measuring GW redshift, it is not appropriate to use a smaller window constraint. Thus we increase such uncertainty by a factor and 2 (as the upper limit) and choose the SNe Ia points which have the minimum acceptable redshift difference of the GW sample \( \Delta z \leq 0.005 \). Such selection criterion has been widely used in the recent works, which tested the potentials of future GW sources to impose limit on possible departures of the distance-duality relation with current strong lensing observations.

The likelihood estimator is determined by \( \chi^2 \) statistics

\[ \chi^2 = (\mu_{th} - \mu_{SN}) \cdot \text{Cov}^{-1} \cdot (\mu_{th} - \mu_{SN}), \quad (15) \]

where Cov is the covariance matrix. For robustness and simplicity, we only consider the statistical uncertainty, and it defined by

\[ \text{Cov} = D_{\text{stat}}^2 + \sigma_{GW}^2, \]

where \( \sigma_{GW} \) is the uncertainty of \( D_{L,GW} \), and \( D_{\text{stat}} \) is the diagonal part of the statistical uncertainty, whose expression is

\[ (D_{\text{stat}})_{ii} = \sigma_{mB,i}^2 + \alpha^2 \sigma_{X1,i}^2 + \beta^2 \sigma_{C,i}^2 + 2\alpha C_{mB,X1,i} \]

\[ -2\beta C_{mB,C,i} - 2\alpha \beta C_{X1,C,i}, \quad (17) \]

where \( \sigma_{mB,i} \), \( \sigma_{X1,i} \), \( \sigma_{C,i} \) denote the errors of the peak magnitude and light curve parameters of the ith SN Ia. \( C_{mB,X1,i} \), \( C_{mB,C,i} \) and \( C_{X1,C,i} \) represent the covariances of \( m_B \), \( X1 \), \( C \) for the ith SN Ia. For the Pantheon sample, however, the stretch-luminosity parameter \( \alpha \) and the color-luminosity parameter \( \beta \) are set to zero, whose statistical uncertainty simplifies to \( D_{\text{stat}} = \sigma_{mB}^2 \).

In this work, we directly adopt the observational quantities \( (m_B, X1, C) \) from the JLA sample and Pantheon sample to constrain the cosmic opacity \( \tau(z) \). By marginalizing the nuisance parameters \( (\alpha, \beta, M_B^1 (M_B), \Delta M) \), one can obtain a cosmology-independent constraint on the opacity and justify whether the cosmic opacity has a dependence on the nuisance parameters. The constraints on the parameter are derived by evaluating the likelihood distribution function, \( L \propto \exp(-\chi^2/2) \), with the corresponding \( \chi^2 \) defined in Eq. (15). We choose to determine the best-fit values and the marginalized errors of each model parameter through the Markov chain Monte Carlo (MCMC) method, which has been extensively applied in cosmological studies. The advantage of the MCMC method is that it allows for a simple inclusion of priors and a comprehensive study of the effects of systematic uncertainties. Our code is based on the publicly available emcee Python module.

### III. Cosmic opacity

#### PARAMETERIZATIONS AND CONSTRAINTS

Regarding the parametrization of the opacity of the Universe, a model-independent test has been extensively discussed in the above quoted papers. In general, \( \tau \) can be treated as parameterized functions of the redshift,

\[ P1. \quad \tau(z) = 2z; \quad (18) \]

\[ P2. \quad \tau(z) = (1+z)^{2\epsilon} - 1. \]

which are not strongly wavelength dependent on the optical band. The former linear parametrization is inspired on similar expressions for DDR, which can be derived from the parameterization \( D_L(z) = D_A(z)(1+z)^{2+\epsilon} \) for small \( \epsilon \) and redshift. The latter parametrization, which is basically similar to the former one for \( z \ll 1 \) but could differ when \( z \) is not very small. For the two models, one should expect the likelihood of \( \epsilon \) to peak at \( \epsilon = 0 \), if it is consistent with photon conservation and there is no visible violation of the transparency of the Universe. The graphic representations of the probability distribution of the opacity parameter are presented in Fig. and . We give the 1-D distributions for each parameter \( (\epsilon; \alpha, \beta, M_B^1 (M_B), \Delta M) \) and 1σ, 2σ contours for the joint distributions of any two parameters. The corresponding best-fit parameters are summarized in Table along with the 1σ standard deviations for each.

As one may see, the analyses are consistent with zero cosmic opacity within 68.3% confidence level for both of SNe Ia samples, implying that there is no significant deviation from the transparency of the Universe at the current observational data level. Similar to the results obtained by examining the cosmic opacity in a particularly low redshift range \( (z < 0.890) \), we find that an almost transparent universe is also favored by the
JLA sample at higher redshifts ($z < 1.30$): the best-fit $\epsilon$ parameter with $1\sigma$ confidence level is $0.007 \pm 0.038$ for P1 function. Therefore, the upper limit for the optical depth related to the cosmic absorption per Mpc is about $10^{-5}$ Mpc$^{-1}$ at 68.3% C.L. More interestingly, we find that our constraints on the nuisance parameters (see Table I) are very different from those results of Betoule et al. [12]: $\alpha = 0.140 \pm 0.006$, $\beta = 3.101 \pm 0.072$ and $M_B = -19.04 \pm 0.01$, which are derived from a fit to the flat LCDM cosmology. Therefore, the consideration of cosmic opacity might effectively affect the values of SNe Ia nuisance parameters, which can be particularly seen from the constraints in $(\epsilon, M_B^l)$ plane. We still find strong degeneracies between $\epsilon$ and $M_B^l$, i.e., a lower absolute $B$-band magnitude of SNe Ia will lead to a larger value of the cosmic opacity, which not only attests to the reliability of our calculation, but also confirms that the cosmic opacity parameter is not independent of the nuisance parameters. Working on the Pantheon sample, one can clearly see that the currently larger data improves the constraints on model parameters significantly. From the above results, the parameter $\epsilon$ capturing the transparency of the Universe seems to be vanishing: $\epsilon = 0.009 \pm 0.018$ for P1 function. Compared with the JLA SNe Ia standard candles, the advantage of the Pantheon sample is that SNe Ia are observed at much higher redshifts ($z \sim 2.26$), which motivate us to investigate the cosmic opacity in the early universe. The strong degeneracies between the cosmic opacity parameter $\epsilon$ and the intrinsic brightness parameter $M_B$ is also illustrated in Fig. 3.

It is worth investigating how the constraints depend on the assumed $\tau(z)$ parameterization. For the P2 parameterization, the results derived from the JLA sample and Pantheon sample are shown in Fig. 2 and Table I. The best-fit cosmic-opacity parameters with $1\sigma$ confidence level are $\epsilon = 0.005 \pm 0.055$ and $\epsilon = 0.013 \pm 0.027$, respectively. Comparing the constraints on the two $\tau(z)$ parameterizations in Table I, we can see that the dependence of test results on the above-chosen parameterizations for $\tau(z)$ is relatively weak. Indeed, the 68% confidence ranges are well overlapped for the two $\tau(z)$ functions so that one could draw conclusions on cosmic opacity in a roughly model independent way. However, it should be noted that P2 function may be reconciled with the data only if smaller $\epsilon$ values are used, i.e., a smaller $\epsilon$ partially compensates for the different scalings with $z$ of the two cases considered, which highlights the importance of choosing a reliable parameterization for $\tau(z)$ in order to better check the cosmic opacity validity at any redshift.

Now it is worthwhile to compare our forecast results with some actual tests involving the angular diameter distances from various astrophysical probes in the EM window. The recent determinations of the cosmic-opacity parameters from different independent cosmological observations are also listed in Table I. Li et al. [14] combined two galaxy cluster samples with luminosity distances from the largest Union 2.1 type Ia supernova sample. The analysis results show that an almost transparent universe is favored by Filippis et al. sample but it is only marginally accommodated by Bonomette et al. samples at 95.4% confidence level. Another analysis was also performed in Liao et al. [24], by fitting the luminosity distance of Union 2.1 SNe Ia with the newly published 28 observational Hubble parameter data. The results, in the framework of three model-independent methods (nearby SNe Ia method, interpolation method and smoothing method), converged to a point that the effects of cosmic opacity are vanished. Such methodology was recently extended by Liao et al. [23], who examined the residuals between the constructed opacity-free luminosity distances from $H(z)$ determinations and distance estimation in type Ia supernovae observations with variable light-curve fitting parameters. A transparent universe is currently consistent with the current EM data. By comparing the results at $1\sigma$ C. L., we obtain the error bar 65% smaller than that from [23], when the P1 parametrization is considered. By considering our results and those from Liao et al. [24], we obtain that our error bars are 60% and 55% smaller when the P1 and P2 functions are considered. Finally, focusing on the Pantheon compilation which consists of more SNe Ia, one could expect much smaller error bars when the P1 and P2 functions are considered, more precisely, 80% and 75%, respectively [23]. Therefore, given the wealth of future available data in both EM and GW domain, our results show that strong constraints on cosmic opacity (and consequently on background physical mechanisms) can be obtained in a cosmological-model-independent fashion.

### IV. CONCLUSIONS AND DISCUSSIONS

The first direct detection of the gravitational wave (GW) source with an electromagnetic counterpart has opened an era of gravitational wave astronomy and added a new dimension to the multi-messenger astrophysics. Compared with the observations of SNe Ia in the EM domain, the greatest advantages of GW signals lies in its ability to propagate freely through a perfect fluid without any absorption and dissipation in the FLRW metric. Therefore, one can be confident that, future GW data will make it possible not only to improve the precision of the

| Data                          | $\epsilon$ (P1) | $\epsilon$ (P2) |
|-------------------------------|-----------------|-----------------|
| JLA + ET                      | 0.007 ± 0.038   | 0.005 ± 0.055   |
| Pantheon + ET                 | 0.009 ± 0.018   | 0.013 ± 0.027   |
| Union2.1 + Cluster            | 0.009 ± 0.005   | 0.014 ± 0.007   |
| Union2.1 + H(z) [23]          | -0.01 ± 0.10    | -0.01 ± 0.12    |
| JLA + H(z) [25]               | 0.07 ± 0.107    | 0.12 ± 0.12     |

**TABLE II:** Summary of the best-fit value for the cosmic opacity parameter obtained from different observations.
constraints on cosmological models, but also, test the cornerstones of observational cosmology. More specifically, the cosmic opacity, the importance of which is usually underrated, stands out as one of the fundamental pillars our interpretation of astrophysical data.

In this paper, we propose a scheme to investigate the opacity of the Universe in a cosmological-model-independent way, with the combination of current and future available data in gravitational wave (GW) and electromagnetic (EM) domain. More specifically, we consider the simulated data of gravitational waves from the third-generation gravitational wave detector (the Einstein Telescope, ET), as well as the newly-compiled type Ia supernovae (SNe Ia) data from Joint Light-curve Analysis (JLA) sample and the Pantheon sample, in order to compare the opacity-free distance from GW data and opacity-dependent distance from SNe Ia. Two redshift-dependent parametric expressions: \( \tau(z) = 2\epsilon z \) and \( \tau(z) = (1+z)^{2\epsilon} - 1 \) are considered to describe the optical depth associated with the cosmic absorption. Here we summarize our main conclusions in more detail:

- We find that the optimized cosmic-opacity parameters change quantitatively, though the qualitative results and conclusions remain the same, independent of which kind of the sample is used, i.e., there is no significant deviation from the transparency of the Universe at the current observational data level. Similar to the previous results obtained by examining the cosmic opacity in a particularly low redshift range \((z < 0.890)\), an almost transparent universe is strongly favored by the JLA sample and the Pantheon sample at much higher redshifts \((z \sim 1.30 \text{ and } z \sim 2.26)\). However, we still find strong degeneracies between the cosmic opacity parameter \(\epsilon\) and the intrinsic brightness parameter \(M_B\), i.e., a lower absolute \(B\)-band magnitude of SNe Ia will lead to a larger value of the cosmic opacity, which confirms that the cosmic opacity parameter is not independent of the nuisance parameters. As a consequence, this source of systematic error should be fully taken into account with future data.

- The tests suggest that the tests of cosmic opacity are not significantly sensitive to the parametrization for \(\tau(z)\). Indeed, the 68% confidence ranges are well overlapped for the two \(\tau(z)\) functions so that one could draw conclusions on cosmic opacity in a roughly model independent way. However, it should be noted that \(P_2\) function may be reconciled with the data only if smaller \(\epsilon\) values are used, i.e., a smaller \(\epsilon\) partially compensates for the different scalings with \(z\) of the two cases considered, which highlights the importance of choosing a reliable parameterization for \(\tau(z)\) in order to better check the cosmic opacity validity at any redshift.

- Comparing our forecast results with some actual tests involving the angular diameter distances from various astrophysical probes in the EM window, we obtain that future measurements of the luminosity distances of gravitational waves sources will be much more competitive than the current analyses. Therefore, given the wealth of more precise data, especially the GW data in the coming years, we may expect more vigorous and convincing constraints on the cosmic opacity (and consequently on background physical mechanisms) and a deeper understanding of intrinsic properties of type Ia supernovae in a cosmological-model-independent way.

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