



Size of shell universe in light of *Fermi* GBM transient associated with GW150914



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ARTICLE INFO

Article history:

Received 21 February 2016

Received in revised form 1 August 2016

Accepted 21 October 2016

Available online 31 October 2016

Editor: S. Dodelson

Keywords:

Gravitational waves

Gamma ray burst

Extra dimensions

ABSTRACT

The possible burst occurred in location and temporal consistence with gravitational wave event GW150914, as reported by *Fermi* GBM, offers a new way of constraining models with extra dimensions. Using the time delay in arrival of the gamma ray transient observed by *Fermi* Gamma-ray Burst Monitor (GMB) relative to the gravitational waves event triggered by the LIGO detectors we investigate the size of the spherical brane-universe expanding in multi-dimensional space–time. It is shown that a joint observation of gravitational waves in association with gamma ray burst can provide a very stringent bound on the spatial curvature of the brain.

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Recently, the team of the Laser Interferometer Gravitational-Wave Observatory (LIGO) has reported on simultaneously detected identical chirp like signals in their both detectors [1]. This historical event, which became world wide known as GW150914, has been interpreted as the first detection of gravitational waves, predicted by the general relativity, from inspiral and merger of a pair of black holes (BHs) at a luminosity distance of about 0.4 Gpc. The inferred merger of the BH binary whose components have masses $M_1 = 36_{-4}^{+5} M_\odot$ and $M_2 = 29_{-4}^{+4} M_\odot$ has formed the final BH of mass $M = 62_{-4}^{+4} M_\odot$ releasing $E_{\text{gw}} = 3.0_{-0.5}^{+0.5} M_\odot / c^2 \simeq 5.4 \cdot 10^{54}$ erg in gravitational waves.

The *Fermi* Gamma-ray Burst Monitor (GBM), being exposed consistently with the direction of GW150914, revealed, at about 3σ -level, the presence of a weak hard X-ray transient signal of luminosity $E_\gamma \simeq 10^{-49}$ erg at photon energies 10 and 1000 keV over 1 s that appeared 0.4 seconds after the gravitational wave event [2]. Although having ill-constrained localization, because of nonoptimal pointing of the GBM detector, it was suggested to associate this short lasted about 1 second transient with GW150914.

The properties of this *Fermi* GBM transient are broadly consistent with a short gamma ray burst (SGRB), apart the fact that it would be significantly harder than the typical $E_{\text{peak}} - E_{\text{iso}}$ relation for SGRBs [3]. We notice that so far no other instrument could report on detection of an electromagnetic transient counterpart or an afterglow [4–10]. Also, no success has been achieved in high energy neutrino follow-up of GW150914 [10,11]. In addition, later on, two other gravitational waves event candidates from compact object mergers have been reported by LIGO, namely GW151226 and the subthreshold LIGO-Virgo Trigger LVT151012. Eventually, GW151226 has been confirmed to occur due to the inspiral and merger binary black holes system, consisting of $14.2_{-3.7}^{+8.3} M_\odot$ and $7.5_{-2.3}^{+2.3} M_\odot$ components at the luminosity distance of 0.4 Gpc [12]. The subthreshold trigger has not been confirmed as being associated with a real astrophysical event. No electromagnetic counterpart of GW151226 has been revealed either by gamma ray observations performed by *Fermi* GBM and LAT [13] or optical follow up campaigns [14,15]. With many more LIGO events expected in the future, it would be straightforward to test whether GRBs are a common byproduct of BHs mergers.

Right after the discovery of the gravitational wave signal, some tests on general relativity have been performed [16,17], including measurements of the velocity and mass of the graviton as well as violations of Shapiro delay and Einstein's equivalence principle

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between the gravitons at different frequencies [18]. It has been also understood that the putative association of the *Fermi* GBM transient with GW150914 can be compiled in spectacularly useful results on general relativity, quantum gravity and astrophysics. In particular, time lag between arrival of GW150914 event and the *Fermi* GBM transient has been used in [3,19] to obtain the most stringent constraints on the velocity of the graviton.

Before detection of GW150914 putatively followed by the X-ray transient there was no specific astrophysical analysis on the electromagnetic radiation counterparts from the merger of binary stellar BHs. However, provided that the BHs have spin, as seems inevitable, and there are relic magnetic fields and disk debris remaining from the formation of the BHs or from their accretion history, one can substantiate that merging BHs potentially provide an environment for gamma rays emission [20,21] and even for accelerating cosmic rays to ultrahigh energies [20]. Indeed, simulations of gas and magnetic fields around the merging systems suggest that the motion of two BHs in a magnetically dominated plasma could generate a magnetosphere and nebular structure similar to those inferred in pulsars, as well as collimated jets [22–29].

The power of the gamma emission generated is however quite uncertain, and in general depends on parameters and unknown structural details of the system. Most models [23–29] are in line with the so called Blandford–Znajek (BZ) process [30] that extracts the space–time rotational energy of the BHs to generate a powerful electromagnetic outflow in externally supported magnetic field. On the cost of rescaling the BH mass and the magnetic field, it seems that the same mechanism can be applied to stellar BHs. Poynting flux for such kind of emission has been estimated in [31] and reads

$$L_{\text{BZ}} = \frac{(GM)^3 B^2}{c^5 R} \simeq 3.2 \cdot 10^{46} \text{ erg s}^{-1} \left(\frac{M}{100 M_{\odot}} \right)^3 \left(\frac{B}{10^{11} \text{ G}} \right)^2 \left(\frac{R_S}{R} \right), \quad (1)$$

where M is the final BH mass and B is the strength of the external magnetic field. The orbital radius R can be taken to be equal to the Schwarzschild radius $R_S = 2GM/c^2 \simeq 3 \cdot 10^5 (M/M_{\odot})$ cm.

Thus, if an external magnetic field of the order of $\gtrsim 5 \cdot 10^{12}$ G could be generated, equation (1) implies that the BZ process would extract enough electromagnetic luminosity to account for the level of emission of the transient reported by *Fermi* GMB. Although a magnetic field of such strength can be easily accounted for pulsars and magnetars, there is a certain concern on an ability of ambient plasma surrounding a BH to anchor the magnetic field of such strength [32]. Mostly, the concern is related to the fact that plasma in a close vicinity of the horizon of a resulting BH is expected to be diluted, since a BHs binary hollows out from material the inner few hundreds of Schwarzschild radius before the merger [22]. However, as pointed out in [33], a small disk or celestial body may be involved in the binary of two BHs. In this case, magnetic field of required level would be supplied by the mini-disk via magnetohydrodynamic instabilities such as the magneto-rotational instability [33]. Also, as argued in [34] it would take infinite time, as measured by an external observer, for infalling matter to arrive at the horizon of a BH. Therefore, at the time of merger the accreted matter should be accumulated in the vicinity of the horizon forming so called “frozen” or “black” star [35]. Thus, due to presence of significant amount of matter directly at the horizon which has been accreted with an angular momentum the magnetic field may be compressed in the shell of the “black” star and amplified up to the level of neutron star or magnetar making the BZ mechanism working effectively [36]. A generic version of BZ mechanism with respect to the association of the *Fermi* GBM transient and GW150914 is discussed in [37]. Other models, outside the lore of

the BZ process, are also discussed in the literature. In [38], it has been suggested that the merging BHs might have been generated in course of a collapse of a rapidly rotating massive star, that at the end a GRB occurs from a jet that originated in the accretion flow around the remnant BH. Another possibility of having in a binary system two gravitationally collapsing objects with non-vanishing electric charge has been discussed in [39]. In this case, the co-penetration of the two magnetospheres occurring during the coalescence, through turbulent magnetic reconnection, produces a highly collimated relativistic outflow that becomes optically thin and can power a SGRB. More exotic possibility of generation of an electromagnetic counterpart of the GW150914 due to the appearance of a short living naked singularity during the merger has been discussed in [40].

Future gravitation wave observations with larger coverage from *Fermi* GMB or other gamma ray bursts orbiters should settle if the binary BHs mergers indeed are accompanied by a gamma ray emission. However, it might happen that due to observer angle effects, the association of gravitational waves events from BHs mergers will only be confirmed once a reasonably large sample of gravitational waves and gamma ray observations has collected. Indeed, as one can see from the above discussion, GRB models usually invoke jets emitted along the rotation axis of their progenitor BH. Thus, we can assume, due to Doppler boosting, that our viewing angle is within the opening angle of the jet, otherwise the electromagnetic emission would be substantially suppressed bellow the limit of detectability. Therefore, the most favorable situation for both gravitational waves detection and collimated electromagnetic emission is in case we view the binary system, perpendicular to the rotation plane. It is clear, that the gravitational waves signal should not have a strong dependence on the viewing angle. The difference in gravitational waves signal to noise ration between on face and on edge line of sight to the rotation plane of the binary system can be accounted by factor $\sqrt{8} \approx 2.8$ [1]. Due to a known degeneracy between the inclination angle of the line of sight and distance, in general all the inclination angles are allowed by gravitational waves data [1]. The observed gamma rays however suggest that we see the system close to on face to the rotation plane line of sight. The latter might not be the case in the observational configuration of GW151226 and thus caused negative results of its electromagnetic follow up campaigns [13–15].

In this note, we exploit the relative timing of GW150914 and *Fermi* GBM events to bound the spatial curvature in a class of models with large extra dimensions, where matter particles and radiation are localized on a brane while the gravity can propagate in the bulk outside the brane.

The main virtue in warped extra dimensional models is their ability to solve many long standing problems in particle physics, for instance, the hierarchy problem [41,42]. A particular class of the brane scenario is the shall-universe model, where the universe is represented as a 3-shell expanding in a higher dimensional hyper-universe [43–45]. Interestingly, the hyper-sphere is a simple space possessing a positive curvature. Recent analysis of CBM data, combined with other astronomical observations, suggests that the universe is nearly flat, but possibly with small positive curvature, i.e. finite. Moreover, some observational data such as the isotropic runaway of galaxies, the deficiency in the first modes of the angular power spectrum and an existence of the preferred frame in the universe support this model. The shell-universe model also predicts a correct value of the redshift parameter that corresponds to the transition from cosmic deceleration to acceleration without introduction of dark energy on the brane [44] and provides a natural mechanism for the local increment of the brane tension, leading to the modified Newton’s law at galaxy scales, alternative to galactic dark matter [45].

Since within the shell-universe scenario, the Standard Model particles are localized on the 3D spherical brane, the propagation of a radiation probe (light) between two points should be affected by the curvature of the universe. The graviton being able to propagate outside the brane, can make a shortcut between these points, what would look like if in our 3D world the graviton was traveling faster than light. In the simplest case of a spherically symmetric 3D shell, the distance covered by a radiation probe propagated between two points on the sphere should be represented by an arc distance L between the source and the observer. In the same time, the bulk shortcut of the graviton would connect these points simply via span of the arc. Thus, measuring an extent d of the shortcut (span) one can calculate the distance excess Δx accumulated due to the curvature of the brane,

$$\Delta x = L - d \approx R\alpha - 2R \sin \frac{\alpha}{2} \approx R \frac{\alpha^3}{24}. \quad (2)$$

Here,

$$R \propto a(t) \quad (3)$$

is the bulk radial coordinate of the expanding brane, which serves as the dimensional cosmological scale factor for the brane (shell) observer, and

$$\alpha = \frac{d}{R} \quad (4)$$

is the central angle subtended by an arc on the 3-shell between the points of the source and the observer. Therefore, as soon we get in our disposal a gravitational wave signal along with an electromagnetic counterpart associated with it, the size of the expanding shell (3) and hence the curvature of the observable universe for the brane observer can be measured.

In the case of the *Fermi* GBM transient arrived 0.4 seconds later in coincidence with GW150914, one can constrain the distance excess accumulated during the propagation of the radiation probe,

$$\Delta x \lesssim 10^5 \text{ km}. \quad (5)$$

Then using the estimation for the distance to the source of GWs given by LIGO [1]

$$d \sim 10^{22} \text{ km} \gg \Delta x, \quad (6)$$

from (2) and (4) we estimate the curvature radius of the shell-universe:

$$R = \sqrt{\frac{d^3}{24\Delta x}} \gtrsim 10^{30} \text{ km}. \quad (7)$$

Note that this value is much larger than the radius of the observable universe (Hubble sphere),

$$RH \gtrsim 10^7, \quad (8)$$

where the Hubble constant is expressed as $H = \dot{R}/R$, according to relation (3).

One can write down the expression for spatial curvature density of the universe,

$$\Omega_K = 1 - \Omega_M - \Omega_\Lambda = -\frac{1}{R^2 H^2}, \quad (9)$$

where Ω_M represents the sum of the density fractions of baryons and the dark matter, while Ω_Λ stands for the density fraction of the dark energy. Using Eq. (8) one arrives to the constraint:

$$|\Omega_K| \lesssim 10^{-14}. \quad (10)$$

The bound (10) is much stringent than the one deduced by *Planck*, $|\Omega_K| < 0.005$ [46]. Of course, the constraint obtained here to be considered a definitive as much as the *Fermi* GBM transient can be regarded a firm observation of a photon flash in coincidence with GW150914. Moreover, in light of negative results of the electromagnetic follow up campaigns of another, more recent, LIGO's gravitational waves event GW151226 performed by *Fermi* GRB and LAT as well as by other instruments [13–15], the bound (10) to be treated as a prospective one requiring an accumulation of a much more sizeable sample of confirming observations. Indeed, provided that gravitational waves signals from compact mergers are not strongly dependent on the orientation of the rotation plane of the binary while prompt gamma rays are essentially not expected if we are not inside the jet opening angle one may not expect that only few gravitational waves signals followed up by electromagnetic observations can confirm or falsify the association of the *Fermi* GBM transient with GW150914.

Acknowledgements

Merab Gogberashvili acknowledges the hospitality of CERN TH Department, where this work has been done. The work of Alexander Sakharov is partially supported by the US National Science Foundation under Grants No. PHY-1505463 and No. PHY-1402964.

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