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INTEGRAL UPPER LIMITS ON GAMMA-RAY EMISSION ASSOCIATED WITH THE GRAVITATIONAL WAVE EVENT GW150914

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ABSTRACT

Using observations of the INTErnational Gamma-Ray Astrophysics Laboratory (INTEGRAL), we put upper limits on the gamma-ray and hard X-ray prompt emission associated with the gravitational wave event GW150914, discovered by the LIGO/Virgo collaboration. The omni-directional view of the INTEGRAL/SPI-ACS has allowed us to constrain the fraction of energy emitted in the hard X-ray electromagnetic component for the full high-probability sky region of LIGO trigger. Our upper limits on the hard X-ray fluence at the time of the event range from $F_\gamma = 2 \times 10^{-8}$ erg cm⁻² to $F_\gamma = 10^{-6}$ erg cm⁻² in the 75 keV - 2 MeV energy range for typical spectral models. Our results constrain the ratio of the energy promptly released in gamma-rays in the direction of the observer to the gravitational wave energy $E_\gamma/E_{\text{GW}} < 10^{-6}$. We discuss the implication of gamma-ray limits on the characteristics of the gravitational wave source, based on the available predictions for prompt electromagnetic emission.

1. INTRODUCTION

Gravitational waves were predicted nearly one hundred years ago as a natural consequence of general relativity (Einstein 1916), but up to now only indirect evidence of their existence has been found by measuring the time evolution of orbital parameters of binary pulsars (Hulse & Taylor 1975; Kramer et al. 2006). The direct detection of gravitational waves is challenging since it relies on measurements of the relative change in distance of the order of 10^{-22} . This will be achieved, for low frequency signals (10^{-4} –1 Hz), with the space-based eLISA mission to be launched after 2030 (Amaro-Seoane et al. 2012), while it is currently possible at higher frequency (10 – 10^4 Hz), thanks to the ground-based advanced LIGO (LIGO Scientific Collaboration et al. 2015) and Virgo (Acernese et al. 2015) detectors. Advanced LIGO has been in operation since September 2015 with the first science run extending to January 2016 and a sensitivity enabling routine detection of gravitational waves from merging compact binaries. Once a possible trigger has been recorded, it is vital to conduct multiwavelength observations to search for additional information about this event. The LIGO/Virgo collaboration recently reported the first gravitational-wave event, GW150914, detected on 2015-09-14 at 09:50:45 UTC, with a false alarm probability of

less than one event per 203 000 years (Abbott et al. 2016; The LIGO Scientific Collaboration & the Virgo Collaboration 2016). Here, we exploit the data obtained by the INTEGRAL satellite (Winkler et al. 2003), which was fully operational at the time of the gravitational-wave trigger, to derive limits on the hard X-ray and gamma-ray emission associated with this event.

2. INTEGRAL/SPI-ACS

The SPI instrument onboard INTEGRAL (Vedrenne et al. 2003) comprises an active anti-coincidence shield (ACS, von Kienlin et al. 2003) made of 91 BGO (Bismuth Germanate, Bi₄Ge₃O₁₂) scintillator crystals¹. Besides its main function of shielding the SPI germanium detectors, the ACS is also used as a nearly omnidirectional detector of transient events with a large effective area (up to 1 m²) at energies above ~ 75 keV (von Kienlin et al. 2003). The ACS data consist of event rates integrated over all the scintillator crystals with a time resolution of 50 ms. The typical number of counts per 50 ms time bin ranges from about 3000 to 6000 (or more during periods of high Solar activity). Since only a single integrated rate is recorded for the whole instrument, no spectral and directional

¹ only 89 are currently functional

information is available. Contrary to most instruments for the detection of GRBs, the ACS read-out does not rely on any trigger. Thus a complete time history of the detector count rate is continuously recorded for $\sim 90\%$ of the time² and simultaneously covering nearly the whole sky.

SPI is partially surrounded by the satellite structure and by the other INTEGRAL instruments, which, by shielding the incoming photons, affect the response of the ACS in the different directions. Therefore, the ACS response must be determined through detailed simulations which take into account the whole satellite structure. We developed a *GEANT3* Monte-Carlo model based on the INTEGRAL mass model (Sturmer et al. 2003) and simulated the propagation of monochromatic parallel beams of photons in the 50 keV to 100 MeV range. For each energy we simulated 3072 sky positions (16-side *HEALPix*³ grid). This enables us to generate an instrumental response function for any sky position, which can then be used to compute the expected number of counts for a given intrinsic source spectrum. We have verified that the response produces valid results for the bursts detected simultaneously by SPI-ACS and other detectors, primarily Fermi/GBM, with an accuracy better than 20%.

3. RESULTS

SPI-ACS was operating nominally at the time of the LIGO trigger on 2015-09-14 at 09:50:45 UTC, yielding an uninterrupted count rate from 33 hours before to 19 hours after the event. The background was relatively stable and low, with a rate of $\sim 7 \times 10^4$ counts/s. The main limit to the sensitivity is set by the Poisson noise in the background rate. In addition to the high-count rate approximation of the Poisson process, there is an excess variance which changes from 3% to 10% on a time scale of the order of one year, and increases in case of strong solar activity. This excess noise is related to multiple events in the detector and to the solar activity. The total noise at every time scale can still be well-described by a gaussian process (Savchenko et al. 2012). We measure the average background and its variance in the vicinity of the region of interest, from -1000 s to $+1000$ s from the trigger and use it in the computation of significance and upper limits.

We investigated the light curve at -30 to $+30$ s from the trigger time on 5 time scales from 0.05 to 10 s. These time scales correspond to the expected accretion time scales in the compact binary coalescence (Lee & Ramirez-Ruiz 2007). We do not detect any obvious signal coincident with the GW trigger. We derived a maximum post-trial peak significance of $\sim 0.5\sigma$ with a time scale of 1 s, at 26.4 s after the GW trigger. Such an excess is clearly not significant.

A zoom on the light curve from -10 to $+10$ s around the trigger time is shown in Figure 1. The excess at $T_0 - 3$ s, where T_0 is the GW trigger time, is compatible with regular background variability. A similar, but negative, deviation can be seen at $T_0 + 7$ s.

² instruments are switched-off near perigee of every revolution; until January 2015, the INTEGRAL orbit lasted three sidereal days. Afterwards, it was reduced to 2.7 sidereal days to allow for a safe satellite disposal in 2029.

³ <http://healpix.sourceforge.net>

The upper limit on the total number of observed photons depends on the assumed duration of the event. The results for different search time scales are summarized in Table 1. The dependence of the upper limit on the burst duration remains the same for any sky position or burst spectrum. In what follows we assume a typical duration for a short GRB, 1 s.

TABLE 1
THREE SIGMA UPPER LIMIT ON THE POSSIBLE GAMMA-RAY
COUNTERPART FLUENCE

Time scale (seconds)	total counts	fluence (erg cm ⁻²)	
		best 95%	worst 5%
10	4319	$3.5 - 4.5 \times 10^{-7}$	$1.1 - 1.4 \times 10^{-6}$
1	1410	$1.3 - 1.5 \times 10^{-7}$	$3.7 - 4.7 \times 10^{-7}$
0.25	727	$5.8 - 7.6 \times 10^{-8}$	$1.9 - 2.4 \times 10^{-7}$
0.1	200	$1.6 - 2.1 \times 10^{-8}$	$5.2 - 6.6 \times 10^{-8}$
0.05	220	$1.8 - 2.3 \times 10^{-8}$	$5.7 - 7.3 \times 10^{-8}$

NOTE. — The fluence range is calculated in the 75-2000 keV range, assuming two standard hard and soft GRB spectra, characterized by smoothly broken power law (Band model; Band et al. 1993) with parameters $\alpha = -0.5$, $\beta = -1.5$, $E_{peak} = 1000$ keV and $\alpha = -1.5$, $\beta = -2.5$, $E_{peak} = 500$ keV. Best sensitivity applies to 95% of the trigger localization region, for the remaining 5% we provide a less constraining limit.

In order to put an upper limit on the signal fluence, we have to investigate the different assumptions on the spectrum and sky coordinates. Figure 2 shows the upper limit on the 75–2000 keV fluence in 1 second for a typical short hard GRB spectrum: smoothly broken power law (Band model) with parameters $\alpha = -0.5$, $\beta = -2.5$, $E_{peak} = 1000$ keV (Ghirlanda et al. 2009). SPI-ACS observed the full sky and in particular covered about 95% of the GW150914 localization confidence area with a sensitivity at most 20% lower than that reached in the most favorable position. The weighted average of the limiting fluence in this region is 4% higher than that of the best, while it is a factor 3 less favorable over the remaining 5% of the localization region. The reduced sensitivity is caused by the opacity of the satellite structure and the other INTEGRAL instruments. The limit depends, however, on the incident spectrum: for harder spectra the low-sensitivity regions are less pronounced. Figure 3 illustrates the energy dependency of the SPI-ACS sensitivity for two sky regions. The low energy threshold of ACS around 75 keV limits our low-energy sensitivity. At high energy, the effective area is approximately constant, slowly increasing above 1 MeV. A spectrum typical for a hard gamma-ray burst (Band model with parameters $\alpha = -0.5$, $\beta = -2.5$, $E_{peak} = 1000$ keV) is scaled to reproduce different values of the total energy release in the 75-2000 keV band, assuming a distance of 410 Mpc.

3.1. IBIS results

The IBIS instrument (Ubertini et al. 2003) is composed of two detectors, ISGRI (20-1000 keV; Lebrun et al. 2003) and PICsIT (175 keV–10 MeV; Di Cocco et al. 2003), which using a coded mask provide images over a field of view of $30^\circ \times 30^\circ$. The ISGRI data are used to automatically search and localize in real

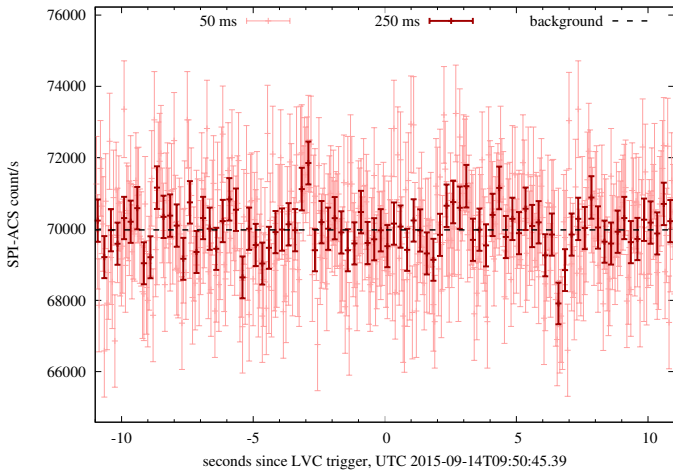


FIG. 1.— INTEGRAL/SPI-ACS lightcurve in ± 10 s around GW150914 trigger time. Light red symbols represent the measurements at the natural instrument time resolution of 50 ms; dark red points are rebinned to 250 ms. The dashed black curve is the background level estimated from a long-term average.

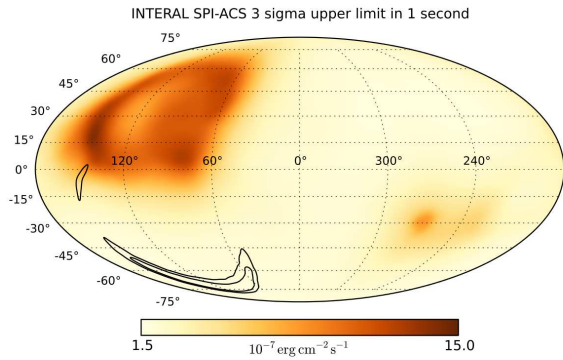


FIG. 2.— INTEGRAL/SPI-ACS 3 sigma upper limit in 1 second for a characteristic short hard GRB spectrum: Band model with parameters $\alpha = -0.5$, $\beta = -2.5$, $E_{peak} = 1000$ keV. In black contours regions (50% and 90%) we show the most accurate GW150914 trigger localization from the LALInference (LIGO/Virgo scientific collaboration 2016).

time GRBs and other transient through the INTEGRAL Burst Alert System (IBAS; Mereghetti et al. 2003). IBAS did not reveal any new transient in the IBIS field of view at the time of the LIGO trigger, down to a peak flux sensitivity of ~ 0.1 ph $\text{cm}^{-2} \text{s}^{-1}$ (20–200 keV, 1 s integration time). We also carried out an off-line search in the time interval 09:28 – 10:00 UT, again with negative results. Note, however, that the instruments of INTEGRAL were pointed at a position (R.A.=271°, Dec.=−31°) outside the high-probability region of the gravitational signal. This prevented also the X-ray monitor instrument JEM-X (Lund et al. 2003) to collect constraining data.

IBIS can also provide response to photons outside the field of view, due to high-energy photons passing through the passive and active shields of the instrument, allowing the detection of transient events. Indeed, most of the shielding of IBIS is passive and relatively thin, be-

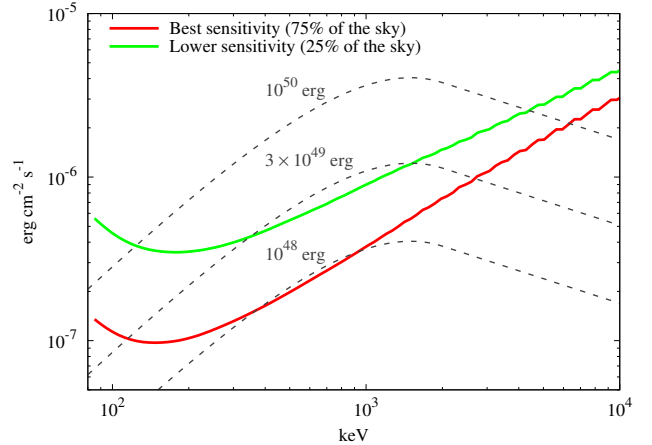


FIG. 3.— INTEGRAL/SPI-ACS 3-sigma sensitivity as function of energy averaged over each of the two sky regions, corresponding to optimal orthogonal orientation and the least favorable directions shaded by heavy satellite material. Dashed curves correspond to the hard GRB spectrum used in Fig. 2, scaled to reproduce several values of the total energy released in the 75-2000 keV band, assuming a distance to the source of 410 Mpc.

coming transparent to photons above ~ 200 keV. For high energy events, ratemeters of the PICsIT detector are available in 8 energy bands in the range 210 keV - 2600 keV. We investigated the count rate light curve in ± 10 s around the GW150914 for possible excesses on time scales from 0.016 s to 10 s, but found no positive signal. We set 3-sigma upper limits to fluences in the 570 keV - 1200 keV energy range of 2.5×10^{-7} erg cm^{-2} and 6.5×10^{-7} erg cm^{-2} assuming durations of 1 s and 10 s, respectively. These values apply to a fully exposed detector area. The detection efficiency is highly dependent on the source position and it is considerably reduced for sources located at large angles with respect to the instrument pointing direction, owing to the lower exposed area and the presence of the 2 cm thick BGO antiscatter shield. The localization region of GW150914 is positioned at large offset (~ 80 to 140 degrees) from the telescope axis. This implies that the sensitivity is decreased and is strongly dependent on the source position in the sky. Nevertheless, the PICsIT observation provides an important independent limit on gamma-ray emission above 500 keV associated with the GW150914.

3.2. On the Fermi/GBM candidate

The Fermi/GBM team reported a possible hard X-ray transient on 2015-09-14 at 09:50:45.8 UTC, about 0.4 s after the reported LIGO burst trigger time, and lasting for about one second (Blackburn et al. 2015; Connaughton et al. 2016). The light travel time can introduce a time difference between INTEGRAL and Fermi detections of up to ± 0.5 s, depending on the source position within the LVC error region. We do not observe any excess within a -0.5 s to +0.5 s window around the Fermi/GBM trigger (Figure 1), and set a 3-sigma upper limit of 1.5×10^{-7} erg cm^{-2} for one-second integration time, assuming a typical short hard GRB, characterized by Band model with parameters $\alpha = -0.5$, $\beta = -2.5$, $E_{peak} = 1000$ keV. A substantial part of the candidate event in the GBM comes from the high-energy BGO detector, above 100 keV (Blackburn et al. 2015), where the Fermi/GBM effective area is about a factor 30-40 smaller

than that of the INTEGRAL/SPI-ACS.

Connaughton et al. (2016) find that preferable localization of their candidate is in the direction of the Earth, or close to it, limited to the southern, dominant, arc of the GW150914 localization. Assuming the preferred localization, they conclude that the spectrum can be best fit by a hard powerlaw with a slope of -1.4 and 10 – 1000 keV fluence of $2.4_{-1.0}^{+1.7} \times 10^{-7}$ erg cm $^{-2}$. Extrapolating this spectrum to the full 75 keV– 100 MeV energy range accessible to the SPI-ACS without a cutoff is clearly unphysical and incompatible with the SPI-ACS upper limit. However, no best fit parameters for a model comprising a cutoff powerlaw are reported. On the other hand, Connaughton et al. (2016) found a best fit to the Comptonized model in the north-eastern tip of the southern arc, with a powerlaw index $\alpha^{\text{COMP}} = -0.16$ and $E_{\text{peak}}^{\text{COMP}} = 3500$ keV, harder than a typical Fermi/GBM spectrum. We assume this spectral model to compute the expected signal in the SPI-ACS: for the southern (northern) arc, SPI-ACS would detect 4740 (1650) counts, with a signal significance of 15 (5) sigma above the background. It should be noticed that the northern arc is disfavored by both the GBM and the LIGO localizations.

We stress that to compare the GBM and SPI-ACS sensitivities, it is inappropriate to use a soft spectral model as in the computation of our early fluence upper limits (Ferrigno et al. 2015), since the spectral properties of the GBM candidate are very different.

Considering the reported hardness of the GBM candidate, and the favorable orientation of the SPI-ACS with respect to the GW150914 localization, we are inclined to claim that the non-detection by SPI-ACS disfavors a cosmic origin of the Fermi/GBM excess. If the origin of the event was near the Earth, INTEGRAL would not detect it, due to the large INTEGRAL - Earth distance at the time of GW150914 ($140\,000$ km). Connaughton et al. (2016) discussed a possible terrestrial origin of the GBM excess, and came to the conclusion that it is not compatible with the characteristics of a terrestrial gamma-ray flash. However, they do not exclude a possibility that the event had a magnetospheric origin. Eventually, considering that the false alarm probability of the GBM association relatively high (0.2% ; Connaughton et al. 2016) and SPI-ACS does not detect it, it is likely that the GBM excess is a random background fluctuation.

4. DISCUSSION

4.1. Model-independent limit

INTEGRAL/SPI-ACS is the only instrument covering the whole GW150914 position error region at the time of the GW trigger. The limit depends on the position, burst duration, and the assumed spectral model, and ranges from $F_\gamma = 2 \times 10^{-8}$ erg cm $^{-2}$ to $F_\gamma = 10^{-6}$ erg cm $^{-2}$ in the 75 keV - 2 MeV energy range for a typical range of GRB models and sky positions (see Figure 3). Assuming the reference distance to the event of $D = 410$ Mpc (Abbott et al. 2016) this implies an upper limit on the isotropic equivalent luminosity of $E_\gamma < 2 \times 10^{48}$ erg $\left(\frac{F_\gamma}{10^{-7} \text{ erg cm}^{-2}}\right) \left(\frac{D}{410 \text{ Mpc}}\right)^2$. The LIGO observation corresponds to the energy emitted in gravitational waves $E_{\text{GW}} = 1.8 \pm 0.3 \times 10^{54}$ erg. Our SPI-ACS upper limit constrains the fraction of energy

emitted in gamma-rays in the direction of the observer $f_\gamma < 10^{-6} \left(\frac{F_\gamma}{10^{-7} \text{ erg cm}^{-2}}\right) \left(\frac{E_{\text{GW}}}{1.8 \times 10^{54} \text{ erg}}\right)^{-1} \left(\frac{D}{410 \text{ Mpc}}\right)^2$.

4.2. BH+BH and circumbinary environment

The analysis of the gravitational wave signal indicates that it was produced by the coalescence of two black holes (Abbott et al. 2016). If at least one of the merging black holes was charged, following the Reissner-Nordstrom formulation, up to 25% of the gravitational energy could have been converted into electromagnetic radiation (Zilhão et al. 2012). However, it is expected that the charge of the black hole is spontaneously dissipated and is not significant for astrophysical applications. There is no theoretical work to date predicting electromagnetic emission from the coalescence of two non-charged black holes in vacuum. Indeed, it is not possible to create photons in a system with no matter outside of the gravitational horizon and only gravitational interaction involved, without invoking effects of quantum gravity, a theory which has not been developed, yet.

The coalescing black holes may be surrounded by matter, in a form of spherically symmetric inflow or/and an accretion disk, which can form if the inflow possesses sufficient angular momentum. The accretion disk can have high density and large potential energy. Rapid changes in the accretion dynamics during binary coalescence may lead to bright observational signatures (Farris et al. 2012). Magnetic fields, anchored in the accretion disk, can cause bright radio emission simultaneous with the gravitational waves (Mösta et al. 2010).

While supermassive black holes are often accompanied by substantial disks, black holes of stellar mass lose the disk created during the progenitor star collapse on a time scale of the order of $\tau_{\text{disk}} \sim 100$ s (Woosley 1993). Sustainable accretion disks can be expected when a constant inflow of matter is provided by a companion star: in these cases, the black hole - star binary can be a bright and variable X-ray and gamma-ray source. However, it remains to be established how likely it is to find a dynamically stable triple system composed of a binary black hole and an additional companion star.

Isolated stellar-mass black holes or binary black holes are bound to accrete from the interstellar medium (ISM). This process can be described as quasi-spherical Bondi-Hoyle accretion (Bondi & Hoyle 1944), characterized by very low accretion rates $\dot{M} \sim 10^{15}$ g s $^{-1}$ $\left(\frac{M_H}{65 M_\odot}\right)^2 \left(\frac{\rho_\infty}{10^{-24} \text{ g cm}^{-3}}\right) \left(\frac{c_s}{10 \text{ km s}^{-1}}\right)^{-3}$. In the case of a merger the accretion rate may be enhanced by up to two orders of magnitude on a one-second time scale (Farris et al. 2010), but in the case of a stellar black hole binary accreting from the ISM, the isotropic peak luminosity can not exceed $L_{\text{iso}} = 100 \times 0.3 \times \dot{M} c^2 = 2.5 \times 10^{37}$ erg s $^{-1}$ $\left(\frac{M_H}{65 M_\odot}\right)^2 \left(\frac{\rho_\infty}{10^{-24} \text{ g cm}^{-3}}\right) \left(\frac{c_s}{10 \text{ km s}^{-1}}\right)^{-3}$. This luminosity is almost 17 orders of magnitude lower than the GW luminosity and more than ~ 11 orders of magnitude below the current gamma-ray upper limits. Agol & Kamionkowski (2002) calculated a possible range of Bondi-Hoyle accretion rates in a Milky Way-like galaxy, yielding in very rare cases $\dot{M} \sim 10^{17}$ g s $^{-1}$ or peak luminosity $L_{\text{iso}} = 3 \times 10^{39}$ erg s $^{-1}$, still a factor 10^9 below

what is observable. The conditions necessary to produce observable emission may be reached in dense molecular clouds, where $\left(\frac{\rho_\infty}{10^{-16} \text{ g cm}^{-3}}\right) \left(\frac{c_s}{1 \text{ km s}^{-1}}\right)^{-3} > 1$. Therefore, our upper limit on the hard X-ray burst associated with the merger disfavors a possibility that the binary was embedded in such a cloud, unless the emission was very anisotropic.

Recently, different mechanisms to produce the gamma-ray emission in a black hole binary merger were suggested. For example, a binary black hole with a very small separation could be formed immediately after the collapse of a massive star, resulting in a gamma-ray burst produced nearly simultaneously with a gravitational wave signal (Loeb 2016). Alternatively, if an unusually long-lived disk is present around the black hole binary it could produce bright gamma-ray signature at the time of the coalescence (Perna et al. 2016).

4.3. Alternative possibilities

Abbott et al. (2016) were able to make use of the gravitational wave data to constrain the compactness of the merging objects, excluding a possibility that either of them is a neutron star.

Strange stars are more compact than neutron stars, and their coalescence can have different gravitational wave signatures (Moraes & Miranda 2014). Very exotic equation of states for strange quark stars would allow them to reach $6 M_\odot$ (Kovács et al. 2009, not considering rotation). This is well below the 90% lower limit inferred for this event ($25 M_\odot$).

Boson Stars (see Schunck & Mielke 2003 for a review) might reach arbitrarily high masses, while being only slightly bigger than their gravitational radius. The existence of these objects requires an extension of the minimal standard model with a new fundamental scalar field, responsible for a stable particle. The properties of this field would determine the macroscopic properties of boson stars. This field has to be compatible with the non-detection by particle physics experiments on Earth, cosmological simulations, and models of stellar evolution. Because of these limitations, the preferred model is generally a field with minimal coupling to standard model fields. A boson star consisting of non-charged scalar field can not be directly involved in any electromagnetic radiation, even in the case of an energetic coalescence event. On the other hand, the coalescence of boson stars might have distinct gravitational wave signatures (Palenzuela et al. 2007).

Another exotic star kind, Q-stars (Bahcall et al. 1989, 1990; Miller et al. 1998) (where Q here does not stand for quark) can reach 10 or even 100 solar masses. The

existence of these objects was suggested based on finding a possibility of a peculiar barionic state of matter, without introducing new matter fields. No predictions on their coalescence exist to the best of our knowledge.

5. CONCLUSIONS

We have derived an upper limit on the gamma-ray emission associated with the gravitational wave event GW150914 for the whole localization region with INTEGRAL. This sets an upper limit on the ratio of the energy directly released in gamma-rays in the direction of the observer to the gravitational wave energy $E_\gamma/E_{\text{GW}} < 10^{-6}$ (E_γ in 75-2000 keV). This limit excludes the possibility that the event is associated with substantial gamma-ray radiation, directed towards the observer.

The LIGO trigger reconstruction favors a binary black hole scenario. In this case, almost no detectable gamma-ray emission is expected, unless the binary is surrounded by a very dense gas cloud, and the emission caused by the enhancement of the accretion rate during the coalescence is directed towards the observer.

If at least one of the objects is an exotic star (unusually massive quark star, boson star, Q-star, etc), some electromagnetic emission can not be excluded. Unfortunately, very little predictions for electromagnetic signatures of exotic star coalescence are available so far, and our upper limit provides a constraint for future modeling.

For the first time we have set an upper limit on the gamma-ray emission associated with a binary black hole merger. This is the tightest limit that can be set on GW150914 with any modern instrument in the gamma-ray energy range. The emerging possibility of combining observations of gravitational waves and electromagnetic radiation sets the beginning of a new era in multi messenger astrophysics.

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