PROCEEDINGS OF SCIENCE

Multifrequency and multimessenger observations of short GRBs and kilonovae

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Binary mergers involving a binary neutron stars system can result in 3 kind of astrophysical source: a gravitational wave signal (GW), a gamma-ray burst (GRB), and a kilonova. The first and only (to date) optical counterpart of a gravitational wave source AT2017gfo is the first kilonova (KN) that could be extensively monitored in time both photometrically and spectroscopically. In contrast, approximately 10 KN have been identified in association to short GRBs, although none spectroscopically and with various degree of evidence. Here I present the current status of our understanding of the kilonovae associated to short GRBs, the current and future improvements in the field to best separate GRB and kilonova, also in light recent peculiar recent events. Moreover, I discuss the advantages of a dedicated GRB mission for the study of KN events.

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1. Introduction

The gravitational wave (GW) event GW170817 at 40 Mpc [1] was the first BNS detected by aLIGO/AdVirgo [2, 3]. It was accompanied by an optical counterpart named AT2017gfo [e.g., 4–6]. This showed to be a "kilonova" (KN), i.e., a thermal emission powered by the radioactive decay of heavy elements formed via r-process nucleosynthesis in the ejecta of the BNS merger [7]. GW 170817 was accompanied by the simultaneous detection of the short gamma-ray burst GRB 170817A [4, 8, 9]. This has provided the first direct confirmation that at least a fraction of short GRBs is associated with the merging of two neutron stars.

Up to now, AT2017gfo is the only case detected thanks to the follow-up of a GW signal. In fact, the BNS horizon of 2nd generation GW interferometers (LIGO, VIRGO, KAGRA, or LVK) was limited to the few cases we can detect within 150 Mpc during the LVK runs ($\sim$200 for the 04 run which will start in few months). Consequently, as of today, evidence for the majority of the known KNe was found in the light curves of the optical counterparts of 10 short GRBs, including the most recent GRB 230307A [10].

While the analysis of the BNS-ejecta composition is only possible for high-S/N spectra of the closest events associated with GW signals, nonetheless the study of GRB-KNe allows us to first characterize the general properties of the KN population like the luminosity peak time ranges. Secondly, thanks to this knowledge, we can estimate our chances to detect the future KNe, especially when the 3rd generation of gravitational waves interferometers with become available in the late 30s. Finally, in the the cases with the best data-set, is possible to model the GRB and KN components, thus constraining ejecta properties of the KNe as e.g. masses and velocities, and understanding the contribution of enrichment of r-process heavy-metals in the universe.

2. The classification of GRBs

The afterglows of GRBs are multi-wavelength non-thermal synchrotron sources that fade with a power-law decay. They are collimated events, thus they can be observed only when pointing in the direction of the observer (on-axis). Observational and theoretical studies has identified two different origins for the GRBs: the death of very massive stars (collapsar model) or the merger of compact objects like BNS systems. The collapsar model has been confirmed by the observed association of GRBs longer than 2s with type Ic broad line supernovae. Therefore, the classification as long or short GRBs is commonly interpreted as synonym of a collapsar or merger origin. However, this simple division has been recently jeopardized by the discovery of the short GRB 200826A associated with a SN [11, 12] and the discovery of a population of short GRBs with an extended gamma-ray emission. These bursts have a total duration similar to long GRBs of collapsar origin but have gamma-ray spectra, afterglow luminosity and a host galaxy more similar to short GRBs.

3. Kilonovae known to date

Although AT2017gfo is the most outstanding and clear demonstration of the existence of kilonovae, the majority of the known kilonovae are associated to sGRBs, although often the association is not very strong. Among those, the strongest indication was found in the optical

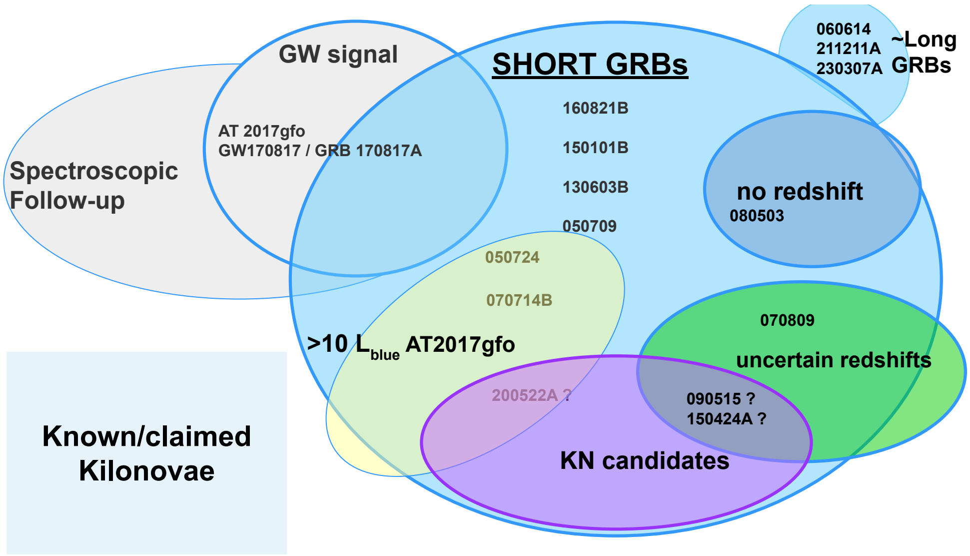

Figure 1: The KNe known up to date. AT2017gfo is the only KN detected after a GW signal. In contrast to this, most of the known KN are associated to GRBs, though without spectroscopic follow-up, except for the very recent case of 230307A, where a late spectra was obtained thanks to the JWST. Highlighted, are the cases with no or uncertain redshift, due to an uncertain association with a host galaxy, 3 non-confirmed KN (due to their low S/N and/or uncertain behavior), and the special case of the 3 KN associated long GRBs, or better short GRBs with extended emission.

counterparts of 9 sGRBs: 050709A [13], 060614A [14, 15], 070809 [16], 080503 [17, 18], 130603B[19, 20], 150101B [21], 160821B [22–24], 211211A [25–27]. More recently, the signature of a KN have been found in the light curve and spectra of the afterglow of GRB 230307A [10], which is also the second KN with available spectroscopy (thanks to observations with the *James Webb Space Telescope*). Noticably, the KNe of GRBs 060614, 211211A and 230307A are associated to long GRBs. We note that in case of GRB 060614, the presence of the KN component is not indicated by the shallower decay at ∼ 4 hours [e.g., 28, 29], but instead the KN dominates over the afterglow much later (at more than ∼ 3 days) as shown by [e.g., 14]. In addition to those, there are the extremely luminous kilonovae identified by [18] (GRBs 050724, 070714B), which are explained as powered by a magnetar (magnetar-powered kilonovae). Unfortunately, in the case of GRB 080503 the redshift could not be measured either via spectroscopy of the afterglow or of the host galaxy; in the case of GRB 070809 the redshift is not well defined. A KN candidate has been found associated to GRBs 090515 and 150424A [29], and GRB 200222A [30, 31], although these claims are not secure. Recently, Ferro et al. [32] could exclude a KN emission in the optical and NIR light curves of the afterglow of GRBs 211006A and 211227A, likely due to high local extinction for the first one and a peculiarly faint kilonova for the second one. We further note that all these kilonovae are associated to a bright GRB afterglow indicating an on-axis configuration, but also that the kilonova emission may after some time (hours–days) exceed the afterglow luminosity even for on-axis GRBs.

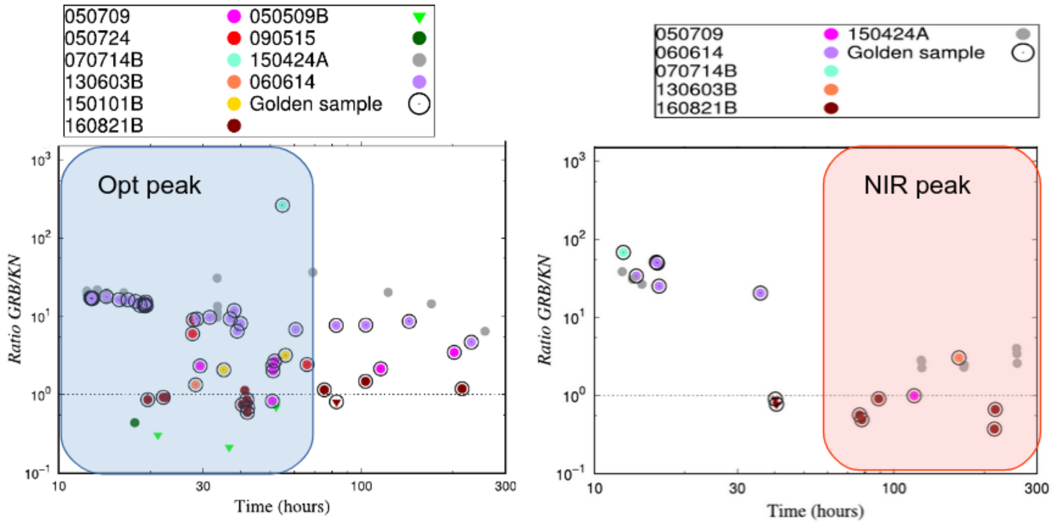

Figure 2: Luminosity ratios of GRB and AT2017gfo versus time from merger for the blue (*left*) and red (*right*) spectral bands (blue: <9000 Å, red: >9000 Å). Upper limits are indicated as downward triangles and only when below AT2017gfo luminosity. Bursts with confirmed KN component (in the literature) are highlighted with a black circle. The large blue- ad red-areas indicate where the peak of the light curve is expected for an AT2017gfo-like KN.

4. GRBs originated from compact-binary mergers

To build a sample of GRBs that originated from a merger of compact objects, for example with the final goal to look for the signal of a KN, is not an easy task. To avoid the sample of GRBs originated from a merger events to be biased by collapsar events erroneously classified as mergers because of their short duration, the most recent studies do not just consider the duration to identify mergers, but also other methods, like the position in the energy-hardness-duration (EHD) plane (a combination of $E_{\mathrm{p,i}}$ and E_{iso} used in the Amati relation of long GRBs with the T90 distribution [33, 34]. Another approach is to study the minimum variability timescale (MVT), i.e. the shortest duration of individual gamma-ray pulses. Camisasca et al. [35] showed that short GRBs have shorter MVTs than long GRBs, but correctly classify events with extended emission, as likely merger events. These results show that the only way to unambiguously determine the origin of a short GRB is via the observation of at least one of the other two counterparts of a merger: the GW signal and the KN.

5. Constraints to the kilonovae luminosity

In [29] we searched for the fingerprints of AT2017gfo-like KN emissions in the optical/NIR light curves of 39 short GRBs with known redshift. We have also used these GRBs to constrain the range of optical and NIR luminosity of KNe. To do so we compared their optical and NIR observations to the light curve of AT 2017gfo, shifted to the observer-frame of the GRB. We could distinguish between the *blue* and *red* components, depending on whether the rest-frame effective wavelength was below or above 9000 Å, respectively. Doing so we have found that all KNe have similar luminosity in the NIR in contrast to a significant KN luminosity gradient for the blue component. The most outstanding cases are GRBs 050724, 060614, 070714B, and 150424A, which are more than 10 times brighter than AT2017gfo. Note that in the case of GRBs 150423A and 150424A the optical and X-ray light curves are very similar to those of GRB 050724 and GRB 060614, which optical re-brightening is interpreted as magnetar-powered kilonova emission by [18]. In this case, the additional source of energy would explain why they are all much brighter than AT2017gfo. The different luminosity range is not completely unexpected. Specifically, it is thought that, if an NS remnant is formed after the merger, the blue component is emitted from regions closer to the merger event, and have lower opacity [e.g., 36, 37]. Instead, the regions immediately ejected during the merger (tidal ejecta), and thus with higher velocity and far from the merger, can keep a lower electron fraction and are the cradle for heavy elements and responsible for the red component. In this scenario, it is not unexpected that the small range of luminosity of the red component is simply the result of the limited amount of matter that goes in the tidal ejecta.

Recently, the sample of merger-GRBs with redshift has been recently doubled thanks to the studies of [38, 39], and consists of ~80 events. With a larger sample, we will be able to better investigate the luminosity range of KNe and the physics involved.

5.1 Additional components

A large fraction of GRBs of all kind shows a plateau phase during the X-ray and sometimes optical afterglow emission, whose physical origin is still debated. Recent studies found that that ~40% of these GRBs may be produced by two cooperating processes in order to explain the broad band spectral behavior [40]. One of the main scenarios commonly invoked to explain the plateau feature is energy injection from a spin-down magnetar. Alternatives have been proposed like energy injection from a stratified emission from a collapsing black hole, or the high latitude emission from a structured jet. This additional mechanism can enhance the afterglow emission, i.e. injecting energy in the external shocks in the ejecta. Separating additional processes is important to understand the physical mechanism powering the KN emission. For example, energy injection from a spinning-down magnetar can also enhance the luminosity of a KN component in case of merger events. Energy injection could also explain the late time flattening in the decay of the X-ray afterglow, like the one observed after 1 day GRB 130603B [41].

5.2 Separate different components by modelling

For on-axis events like those associated to GRBs, the optical signal is dominated by the GRB afterglow emission and the KN emission is subdominant on the first day after explosion. Evidence of KN in GRB optical afterglows has been found by searching for the characteristic late (>1 day) flattening or even a bump, an approach that is similar to the case of SNe associated with collapsar (long) GRBs but for a bump that peaks earlier (within 1 week) and is 10 times fainter. Indeed, within the standard afterglow theory (and slow cooling regime) a decay is anomalously shallow when the power-law temporal slope is larger than $\alpha = -0.75$ [e.g., 42]. Please note that reality can be more complex that this simple scenario, and this shallower decay does not unambiguously identify an additional component (SN or KN). In some cases, can be the result of a change in the spectra, like the passage in the optical bands of the cooling frequency of the synchrotron emission (e.g., GRB 060614, [28]). Or, as shown above (§5.1), shallow decays like those observed during plateaus can be cause by an additional mechanism powering only the afterglow, without necessarily involving the KN, because the mechanism usually stops in the early phase ($\lesssim$ 1day). In the KN scenario, the shallow decay can simply be the result of an additional thermal component powered by the radioactive decay of newly formed heavy elements.

Separating between GRB afterglows and KNe is easier when considering that the majority of GRBs are well followed up in X-rays where the KN does not emit. Moreover, the non-thermal afterglow component fades following a power-law decay, thus markedly different from the thermal emission of KNe. Therefore, it is possible to separate the KN and afterglow components by modeling together X-rays and optical/NIR data (and radio, when available, which also is free of KN emission). This can be useful also to identify plateaus due to energy injection because this mechanism enhances the afterglow emission at all frequencies, and thus the plateau can be observed also in e.g., X-rays. In contrast, additional thermal components can be observed only in optical and NIR. For the afterglow, several modeling tools have been developed that make use of the most advanced afterglow characterization, like the widely used *afterglowpy* [43], which however do not consider energy injection like others [e.g. 44]. The last is of particular interest for those cases powered by a spin-down magnetar. For the KN models, one can use models for EM counterparts from NSBH or BNS events, going from simple analytical models to more sophisticated but accurate Monte Carlo radiative transfer ones. The field is in rapid development, and several alternatives exist, with different attention to different aspects, like different opacities, progenitors, geometry, numerical relativity outflows, components and the computational effort necessary. Among others, we cite only the most recent, including 3D models [45, 46], the 1D and 2D models developed by different authors [47, 48, e.g.,] or semi-analytical models [e.g., 49–51].

By matching KN observations to models, is possible to infer the properties of the ejecta components powering the KN emission. KN emission properties encode a wealth of information that goes from the opacity of freshly synthesized heavy elements as lanthanides and actinides, to the progenitor system and the equation of state of neutron stars. Different compact binary system properties, such as the binary component mass ratio, the NS mass and radius, etc. are expected to produce different values of ejected mass and velocities [e.g., 52]. As a consequence, KN modeling provides useful insights on the still unknown equation of state (EOS) regulating supra-nuclear matter densities as the one in the innermost regions of NSs. In particular, even if in most of the cases only upper-limits to the KN emission are found, these can be used to put constraints on the ejecta masses and thus to reject some BNS merger models based on a particular equation of state (EOS) which predicts very large ejecta masses and thus bright KNe [37].

6. The importance of a Space GRB Observatory

The results presented in [29] permitted for the first time to study the range of luminosity of KN in short GRBs, and to understand the maximum redshift at which a KN can be followed with the current and future observatories. In the top panel of Fig. 3 we show the maximum brightness of AT2017gfo in the observed r-band (at 12 hours in the rest frame) up to the redshift $z = 0.6$. In light of the luminosity constrain results from [29], we constrain the range of the peak brightness of a putative blue kilonova to be between 0.8 and 10 times that of AT2017gfo. These constrain identify blue colored regions in the figure. We put a lower limit to the 3-σ detection with the

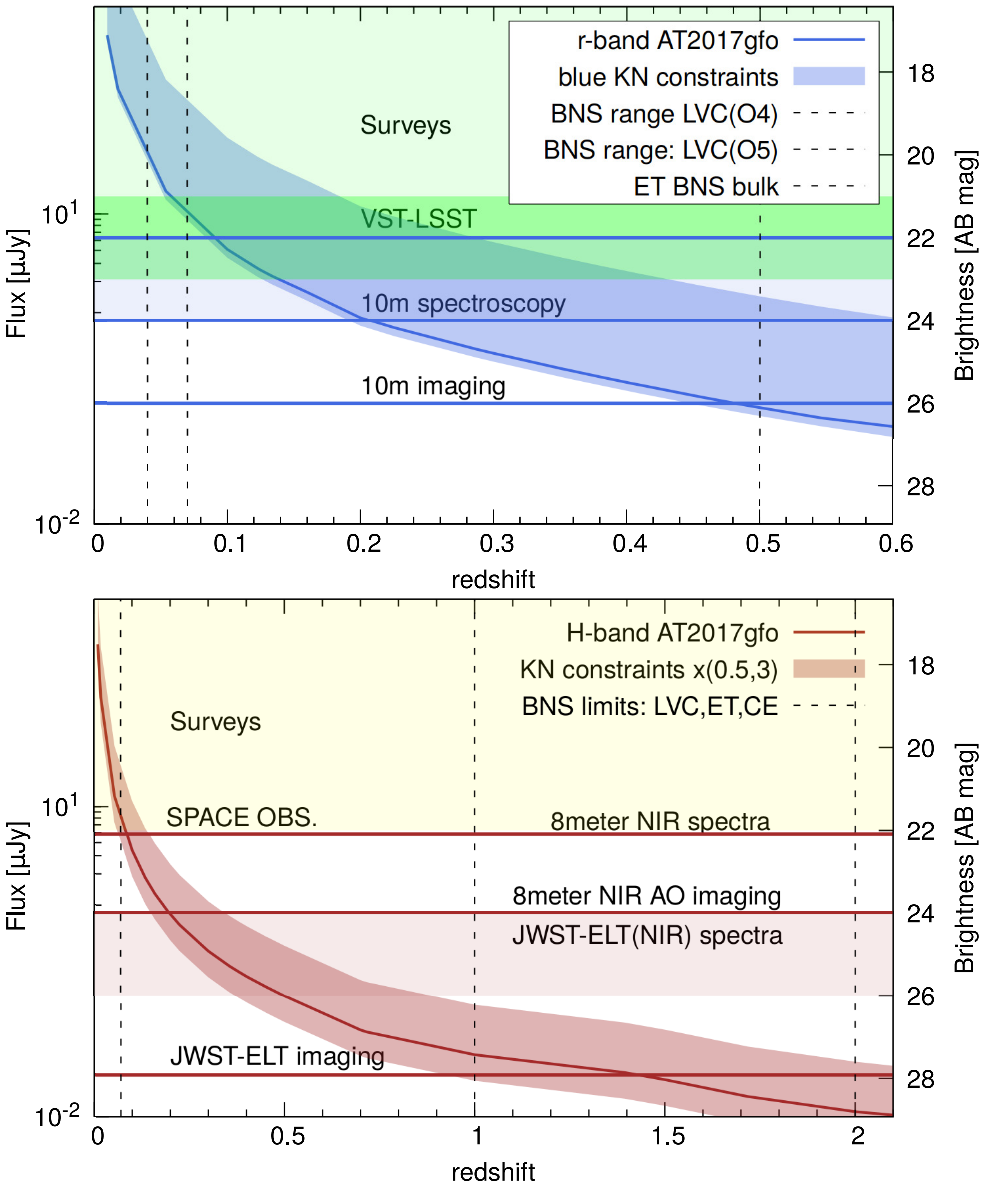

Figure 3: Peak brightness of AT2017gfo in the *H* (red) band at different redshifts, within the constraints we derived for an AT2017gfo-like kilonova in [29]. The vertical lines are the detection limits for a GW signal from a BNS event detected by aLigo/AVirgo in O4 and O5 (∼150 and ∼300 Mpc [1]), Einstein Telescope ($z \lesssim 0.5$) and Cosmic Explorer ($z \lesssim 2$). The horizontal lines are different detection limits for different class of telescopes with an exposure time of 10 minutes. A Space GRB Observatory will allow us to localize the EM counterpart down to sub-arcsec precision, thus permitting the follow-up with the larger telescopes like ELT or the space telescope JWST.

current largest ground-based and orbiting telescopes dedicated to the characterization of the source: e.g., VLT, LBT, along with the forthcoming LSST [53] assuming 10 min exposure time. The peak of an AT2017gfo-like kilonova would be always detectable up to redshift 0.5 in the optical. For this reason, the KN emission is much easy to be found only in GRBs below this redshift. To date, considering the updated GRBs with redshifts [38, 39] only ∼ 30 bursts are within this redshift.

Following a similar approach, in Fig. 3 we show the maximum brightness of AT2017gfo in the H-band (at 58 hours in the rest frame) up to the redshift at which the future Einstein Telescope [ET 54]) and Cosmic Explorer [55] will be able to observe a GW signal from a merging BNS ($z \lesssim 1$ and $z \lesssim 2$, respectively). Similar to above, and following the results in [29], we can constrain the peak luminosity of the red kilonova component between 0.5 and 3 times that of AT2017gfo. These constrain identify a red-colored region in figure 3. Also in this case we indicate lower limits for 3-σ detections. In particular, we indicate those with the future ELT [56] and the JWST [57] space telescope (H ∼ 28 mag, AB system) assuming 10 min exposure time [see also 58]. The peak of an AT2017gfo-like kilonova would be detectable up to redshift 0.2 in the NIR by ground-based very large telescopes. The situation will improve when, thanks to JWST and ELT, we will be able to detect a kilonova up to $z \sim 1-2$. There are, however, two important caveats: i) in most cases it can be difficult to distinguish the GRB afterglow from the kilonova component (see above); ii) the real challenge will be to search and identify a kilonova within the error boxes given by the GW detectors. Distant GW sources ($z > 0.5$) will be discovered only with interferometers of third generation as ET and will be localized within several thousands square degrees with a single interferometer and within few tens of square degrees with three detector network [e.g. 59]. Therefore, only the association with a GRB will permit to localize compact-merger events which may also be followed by a kilonova with enough accuracy. This can be provided by future space-based GRB dedicated missions as for example the proposed THESEUS mission [60, 61].

7. Summary

To date, AT2017gfo is still the only case detected thanks to the follow-up of a GW signal, and the majority of the known KNe was found in the optical light curves of 10 short GRBs. In fact, KN emission may after some time (hours–days) exceed the afterglow luminosity even for on-axis GRBs. The number is increasing, also thanks also to the new JWST, which allowed us to obtain the second spectra of a KN, i.e., the one associated to GRB 230307A. Intriguingly, this is not a classical short-duration GRB, but a particular class of short GRBs with an extended gamma-ray emission that can be confused with long GRBs in some cases. Indeed, there is evidence of a population of short GRBs with extended gamma-ray emission and an associated KN, whose progenitors are the merger of two compact objects. In fact, the only way to unambiguously determine the origin of a GRB is via the observation of at least one of the other two counterparts of a merger: the GW signal and the KN.

Studying the KN associated to GRBs, we have found that all KNe have similar luminosity in the NIR in contrast to a significant KN luminosity gradient for the blue component. Recently, the sample of merger-GRBs with redshift has been recently doubled and we will be able to better study the luminosity range of KNe. But not only, thanks to more recent advancement in modeling, it is possible to separate the KN and afterglow components also considering additional processes, like energy injection. Separating all components is important to understand the physical mechanism powering the KN emission.

Finally, the future space-based GRB dedicated missions will allow us to promptly localize compact-merger events and observe the following KN with space and ground-based facilities which lack a large field-of-view but can observe more far away.

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