VHE Gamma-Ray Future Project: Beyond CANGAROO

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We have started discussions on beyond-CANGAROO projects among the Very High Energy (VHE) gamma-ray community in Japan. Three straightforward directions using the imaging atmospheric Cherenkov technique have been considered: 1) telescopes of a large aperture or at a high altitude to explore the so-called unopened window between 10 and 100 GeV, 2) telescopes of a large effective area to obtain better sensitivity or explore the higher energy region around 100 TeV, and 3) telescopes of a wide field of view to discover transient sources and obtain better survey ability. The considerations are summarized together with physics cases favored by each direction.

1 Introduction

In the series of the international workshops, "Towards a Major Atmospheric Cherenkov Detector", we have extensively discussed options for a major atmospheric Cherenkov telescope for ground-based gamma-ray observations. One of the best solutions to this question is likely to be a stereoscopic system of Imaging Atmospheric Cherenkov Telescopes (IACTs) of a large aperture (10 m class), with which we aim to explore the so-called unopened window between 10 and 100 GeV, rejecting the major background due to single muons. This design has been taken by the CANGAROO-III [1], H.E.S.S. [2] and VERITAS [3] groups. In addition, the MAGIC group has recently decided to do stereoscopic observations building a second 17 m telescope [4]. Successful results have already come from the H.E.S.S. group [5, 6, 7] and obtaining more important results by these groups in the near future looks promising. However, it is only 15 years from the first 9 σ detection of the Crab Nebula by the Whipple Observatory using the imaging atmospheric Cherenkov technique [8], which can be deemed to be the breakthrough in this field, and there are still many interesting applications using IACTs that have not been tried or implemented.

The CANGAROO-III stereoscopic IACT system was completed in 2004 near Woomera, South Australia [1] and we have started considering our future plan among the Very High Energy (VHE) gamma-ray community in Japan. In the near future, we intend to improve the current CANGAROO-III system, especially the first telescope

(T1), which has been used as the CANGAROO-II telescope for five years and has deteriorated significantly compared to the other three telescopes. As for the longer time scale of 10 or 20 years, we do not have a unified plan yet, however our considerations so far are summarized here.

2 Current Situation and Future Directions

The sensitivity and energy coverage of the current IACT systems described above are shown in Figure 1 [3]. In spite of many efforts, the unopened window has not been explored completely yet. However, the sensitivity to gamma rays has successfully been improved down to the % Crab level. Where should we go from here, looking 10 or 20 years into the future? There are three straightforward directions indicated by

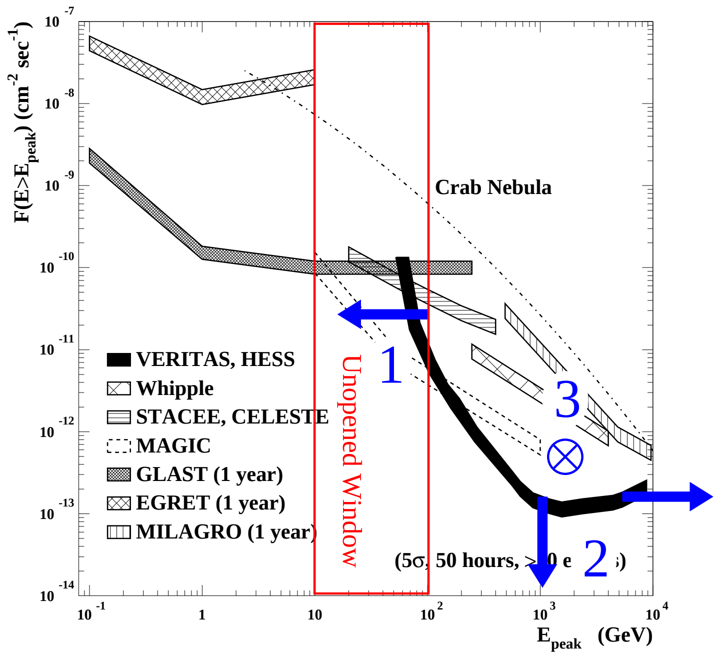

Figure 1: Sensitivity of current gamma-ray telescopes [3]. Straightforward future directions utilizing IACTs are indicated by the blue arrows. Imagine that the time axis is taken perpendicularly to the figure. Each direction numbered is discussed in detail in the text.

the arrows in Figure 1:

1. low energy extension using *a telescope of a large aperture or at a high altitude* to further explore the unopened window,

2. higher sensitivity or high energy extension using *a telescope of a large effective area* to get more statistics,

3. better time coverage using *a telescope of a wide field of view* to observe transient sources.

In the following sections, each direction is discussed from physical and technical aspects.

3 Physics Considerations

Physics targets favorable to each direction described above are summarized in Table 1 on the basis of author's arbitrary view. The low energy extension has an advantage

Source/Physics	Large D/High Altitude	Large $A_{\rm eff}$	Wide FOV
AGN and EBL	○		○
Pulsar	○		
EGRET Source	○		
Dark Matter	○	○	
Galactic Origin of CRs	○	○	
GRB			○
Unknown Source		○	○

Table 1: Physics targets favorable to the future directions.

over the other directions if we aim to find more sources since the high energy tails of ~ 300 EGRET sources are expected to be observed and we will have more GeV sources during the GLAST era. Any target is interesting to be observed by a high sensitivity telescope having a large effective area, but in particular, this direction is important to investigate the Galactic origin of cosmic rays, which is a long-standing enigma. We are getting closer to a solution considering the recent observational progress of supernova remnants (SNRs) [5, 9, 10]. One of the keys to a full solution is clear separation of the electron and proton origins of gamma rays, and the low energy extension of the TeV spectra of the SNRs may play an important role on this point. However, the low energy extension cannot answer the origin up to the "knee" energy and a telescope of a large effective area can play a unique role at high energies. The wide field of view telescope has an advantage also in survey ability finding unknown sources, and that is discussed later comparing with the system of a large effective area.

4 Technical Considerations of Future Directions

4.1 Large Aperture or High Altitude

A major problem in implementing a very large aperture telescope is its huge cost. Optical astronomers have an empirical "cost paradigm" in which the traditional cost scaling law is expressed as follows [11]:

$$\text{Cost} \propto D^{2.7}, \tag{1}$$

where D is the diameter of the telescope. As described in the reference, this cost curve may not be very firm and there are some successful examples in which the cost was significantly reduced by "innovation factors". Also, there is no guarantee that this law is directly applicable to atmospheric Cherenkov telescopes. However, if we assume the law and that a 30 m diameter is necessary to cover the unopened window down to 10 GeV, the cost will be ~ 20 times more than that of the 10 m diameter. Therefore, cost reduction is essential in this direction.

One possible idea to reduce the cost is to utilize multiple reflection optics. With this option, the telescope will be shorter than that of the conventional prime focus optics, and then its torque will be smaller, the support structure can be less rigid, and finally the total weight will be reduced. Let us take a very simple model of a Cassegrain type telescope shown in Figure 2, to see if the telescope torque is really reduced. This model is compared to a prime focus optics of the focal length F and the diameter of the primary reflector D. The Cassegrain telescope has the same primary reflector and its camera is set at the center of the primary reflector or on the rotation axes to minimize its torque. The secondary reflector of the diameter d is located at the distance from the primary reflector r. In this configuration, d is automatically decided as a function of r so as to collect all of the photons reflected by the primary reflector and to minimize the dead area of the primary reflector shaded by the secondary reflector. The masses of the primary reflector and the camera are M and m, respectively. Their area densities are assumed to be the same.

With the above configuration, the moments of inertia of the primary reflector, the secondary reflector and the camera at the prime focus are approximately given as:

$$I_{\text{primary}} \sim \frac{1}{8}MD^2, \tag{2}$$

$$I_{\text{secondary}} \sim MD^2t^2(1-t)^2, \tag{3}$$

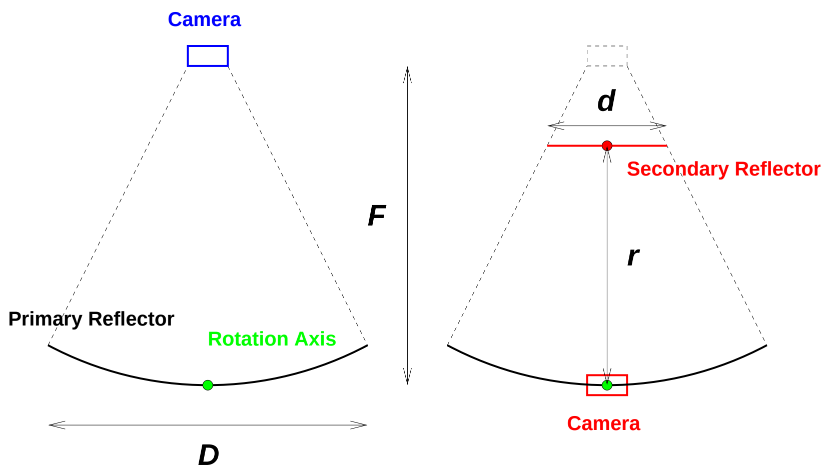

Figure 2: Simple prime focus (left) and Cassegrain (right) optics to define parameters used in the discussion on the telescope torque. See the text in detail.

$$I_{\rm camera} \sim mD^2, \tag{4}$$

where $t = r/F$ is the fractional distance of the secondary reflector from the primary reflector. Total moments of inertia of the Cassegrain and prime focus optics are $I_{\rm primary} + I_{\rm secondary}$ and $I_{\rm primary} + I_{\rm camera}$, respectively. Figure 3 shows the total moment of inertia normalized by $I_{\rm primary}$ as a function of the fractional distance t. Better solutions using the multiple reflection optics than the prime focus optics exist if $I_{\rm secondary} < I_{\rm camera}$, which corresponds to the right side of Figure 3, and the multiple reflection optics is effective if the camera is relatively heavy compared to the primary reflector.

The above discussion is for a very simple case and a better solution may be found by utilizing more degrees of freedom of the multiple reflection optics. Also, only the telescope torque has been considered above but the critical disadvantage of the multiple reflection optics is significant loss of the light due to more number of reflections and a dead area shaded by the secondary reflector. We should consider its gain and loss in a comprehensive way and a detailed study is now underway.

The alternative way to reduce the energy threshold is to observe gamma rays at a very high altitude, around 4 km, where the density of Cherenkov photons on the ground is much higher and therefore a very large aperture is not necessary. The group from the Kyoto University has an experience of gamma-ray observations at a high mountain with the CheSS Experiment [12], in which they put an imaging camera at the prime focus of the Subaru Telescope. The system must remotely be controlled at

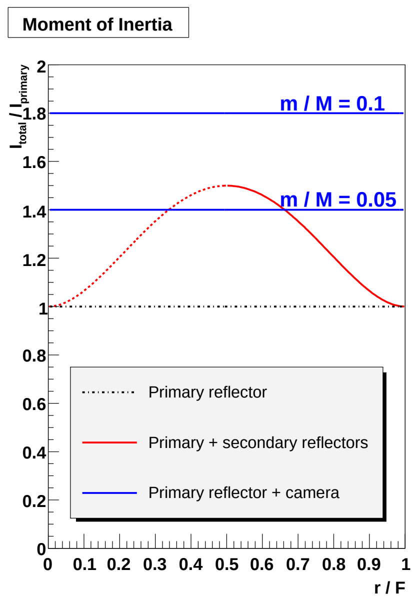

Figure 3: Total moments of inertia of the prime focus and Cassegrain telescopes normalized by the moment of inertia of the primary reflector, plotted as a function of the fractional distance of the secondary reflector from the primary reflector.

the base camp and this technology will be important at a high altitude because human activity is limited there.

4.2 Large Effective Area

In this direction, the design concept is relatively unique: we must have an array of many IACTs to get more statistics, but the stereoscopic observation is also necessary to achieve better sensitivity. The more telescopes we have, the better the sensitivity to gamma rays, but at the same time, the more cost we need. We should select the best telescope span and the best telescope aperture to maximize the effective area with a low cost.

Let us think about a telescope array shown in Figure 4. If we put many telescopes like that, the total effective area of the array $A_{\mathrm{eff}}(\mathrm{total})$ is approximately expressed as:

$$A_{\mathrm{eff}}(\mathrm{total}) \sim A_{\mathrm{eff}}(\mathrm{unit\ square}) \times N, \tag{5}$$

where $A_{\mathrm{eff}}(\mathrm{unit\ square})$ is the effective area for gamma rays arriving inside of the unit square shown in Figure 4 and N is the number of telescopes. This approximation is not correct for gamma rays falling outside the array, but here we are interested only in an array of quite many telescopes to improve the sensitivity dramatically, in which the approximation is almost valid. Then, we can concentrate to investigate performance of the unit square hereafter.

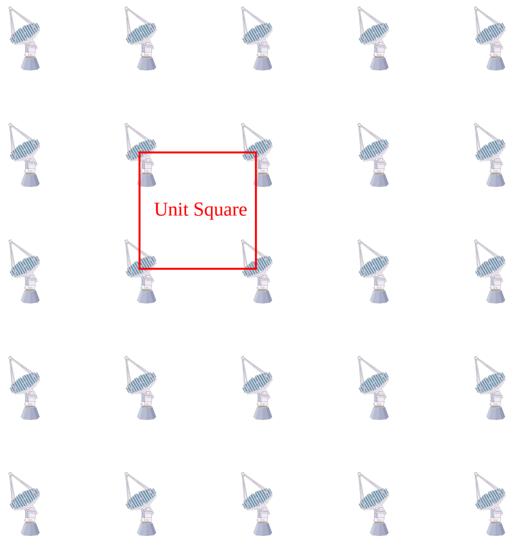

Figure 4: Example of the IACT array to achieve a large effective area. The array can be split into the unit squares of approximately the same response, which is investigated using Monte Carlo simulations.

One may think that the telescope span is not an important parameter because the lateral distribution of Cherenkov photons is almost flat up to the core distance of about 150 m and the density of Cherenkov photons quickly drops outside of that radius. That is demonstrated in Figure 5. However, the tail of the lateral distribution can be detected if the telescope aperture and field of view are large enough, and as a result, the effective detection area quickly increases following the function of (core distance)^2. Therefore, the combination of a large aperture, a large field of view and a large span can reduce the number of telescopes to get the same total effective area. However, the cost of one telescope also quickly increases as a function of aperture as described before. This is the key issue when looking for the best cost performance of the array.

Monte Carlo simulations have been done to investigate how the effective area of the unit square changes as a function of the telescope aperture and span. CORSIKA 6.20 was used to generate gamma-ray showers, of which the source is located at

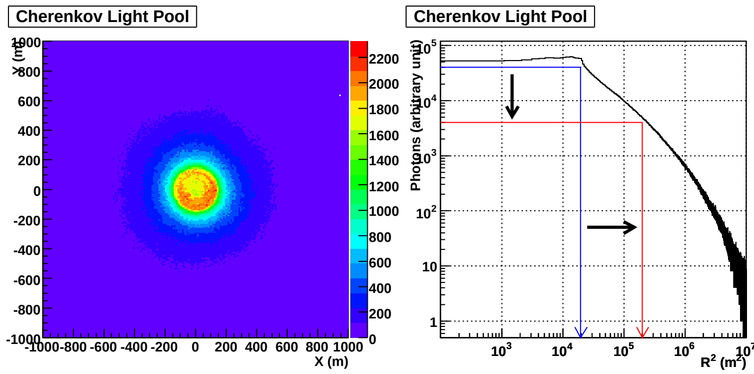

Figure 5: Typical lateral distribution of Cherenkov photons radiated from a gamma-ray shower. The tail of the distribution at large core distances can be detected if the telescope aperture and field of view are large enough, where the threshold to photon densities is reduced and the detection area expands as demonstrated in the right.

zenith. Environmental parameters such as the geomagnetic field and altitude are taken from those in Woomera. The parabolic reflector of $f = 1$ was used and the imaging camera has a hexagonal alignment with the pixel size $0^\circ.17$. No blurring and no night sky background have been added. The trigger requirement is at least 5 photoelectrons $\times$ 3 adjacent pixels $\times$ any 2 telescopes. Note that these are very simple and optimistic conditions and probably somewhat overestimate effective areas. The left in Figure 6 shows examples of the results for the 20 hexagonal ring camera corresponding to the field of view $\sim 6^\circ$. The effective area of 100 % efficiency is represented by the dotted curves, which are quadratic because the injected area has a square shape of the side corresponding to the telescope span. Note that the span at the maximum effective area is significantly longer than 150 m when the primary energy is high and the telescope aperture is large as pointed out above. A similar calculation has also been done by Plyasheshnikov, Aharonian and Völk [13].

To optimize the array configuration in terms of the cost, the traditional cost scaling law of Equation 1 is assumed here again. Then, the total cost of the array is proportional to $D^{2.7} \times N$. Eliminating N with Equation 5, we get

$$A_{\rm eff}(\text{total}) \propto A_{\rm eff}(\text{unit square}) \times \text{Cost}/D^{2.7}. \qquad (6)$$

Therefore, the maximum effective area with a fixed cost is obtained maximizing $A_{\rm eff}(\text{unit square})/D^{2.7}$. The right in Figure 6 shows example distributions of this value as a function of the telescope aperture and span, obtained using the simulation data described above. Again, the examples are for the 20 hexagonal ring camera.

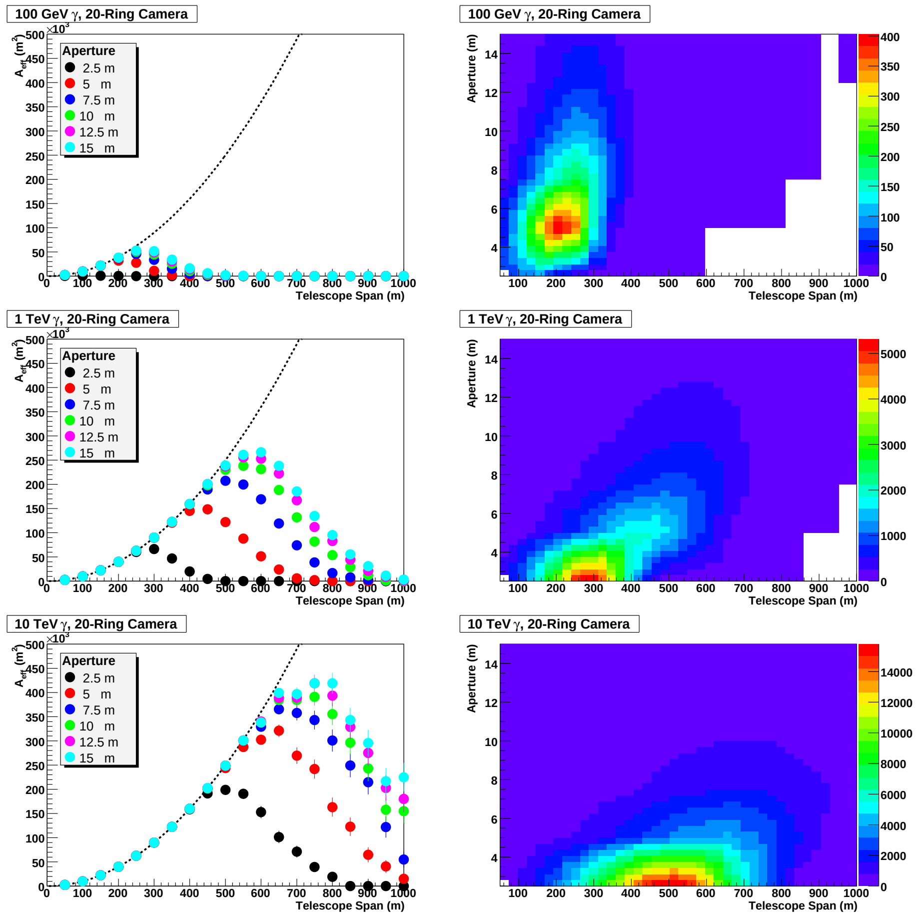

Figure 6: Effective area of the unit square as a function of the telescope aperture and span (left). Assuming the traditional cost scaling law of Equation 1, the best combination of aperture and span is searched for maximizing the total effective area with a fixed cost (right). Simulated gamma-ray energies are 100 GeV, 1 TeV and 10 TeV from the top.

The most important conclusion from the figures is that the maximum effective area is given by using relatively small aperture and span, rather than larger values. However, it looks too optimistic that the best telescope aperture is about 5 m for 100 GeV gamma rays and more realistic simulation study is necessary. Note also that the distributions are elongated toward the top right of the figures, where we can efficiently detect the tail of the lateral distribution of Cherenkov photons with a smaller number of telescopes as described above.

4.3 Wide Field of View

If we think about the telescope of a very wide field of view of about 60° diameter, reflecting optics cannot be used and instead refracting optics are necessary. We could learn many important technologies on this type of telescope from EUSO [14]: using Fresnel lenses is quite effective to reduce the weight of the telescope and make enlargement of the telescope easier, to correct aberration effects in the wide field of view, and so on. The idea utilizing this type of telescope as an IACT was originally proposed by Kifune and Takahashi [15]. Figure 7 is a schematic view of an example for the telescope of a wide field of view. To cover the field of view with fine pixels, many photodetectors of about 100,000 channels must be used, and handling such large number of channels with fast response will be a technical challenge.

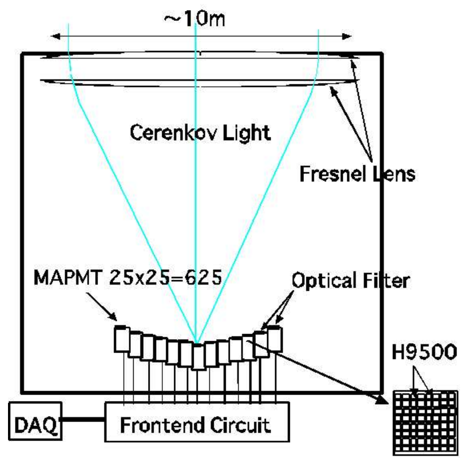

Figure 7: Schematic view of an example for the telescope of a wide fi eld of view.

The wide field of view also has an advantage in surveying for unknown sources. However, the survey ability of the telescope is also dependent on the effective area and represented as:

$$\text{Survey ability} \propto (A_{\rm eff} \times \Omega)^{1/2}. \tag{7}$$

Therefore, the large effective area is also useful for surveying. Then, which type of telescope is better? By definition, their survey abilities are the same if the gross field of view is the same. However in this case, the number of telescopes is N times greater in the large effective area. Therefore, the total cost of the wide field of view is much cheaper than that of the large effective area if N is large and the cost per telescope is comparable. In fact, however, we cannot state that the wide field of view is better only by this point since the cost for large Fresnel lenses is difficult to estimate now and also they have different characteristics depending on the science targets.

Figure 8 shows histories of the number of sources found in X-ray, gamma-ray and VHE gamma-ray energy bands summarized by Kifune [16]. In 2005, the number of VHE gamma-ray sources is about 30 and a new point is plotted on the right in the figure. The new point is still close to the extrapolation of the red line and this trend suggest about 1000 sources will have been discovered in 10 or 20 years. A survey ability will be a more important characteristic in the future.

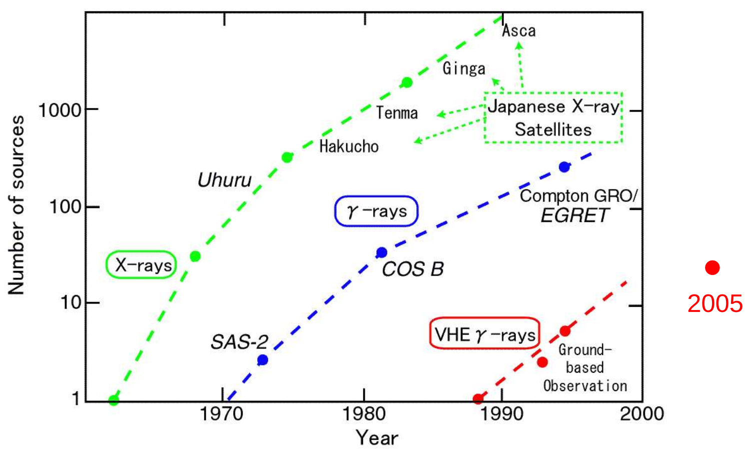

Figure 8: Histories of the number of sources found in X-ray (green), gamma-ray (blue) and VHE gamma-ray (red) energy bands [16].

5 Summary

We have considered our future plan in Japan for a next generation VHE gamma-ray observatory. The following three directions are under investigation: 1) telescopes of a large aperture or at a high altitude, 2) telescopes of a large effective area and 3) telescopes of a wide field of view. Although there are still many interesting applications using IACTs, the experimental scale has inevitably been getting bigger to improve the performance significantly. The cost reduction will be an essential factor in the future, or a bigger international collaboration may be necessary.

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