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Crystal Eye: a wide sight on the Universe for X and gamma-ray detection

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Crystal Eye is a new concept of space-based all sky monitor for the observation of 10 keV-30 MeV photons exploiting a new detection technique, which foresees enhanced localization capability with respect to current instruments. This is now possible thanks to the use of new materials and sensors. The primary scientific goal is the detection of the electromagnetic signal of extreme phenomena in the Universe. In order to enhance their study with many messengers, the satellite will provide an alert to both space and ground based experiments. A full scale model of the Crystal Eye detector is now under design and construction. Moreover, a smaller prototype has been set up to fly aboard of the Space Rider (ESA) on a LEO orbit (400 km, 5.3° of inclination) for two months in 2025. We present here the Crystal Eye mission concept and performance.

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1. Introduction

Gamma and X-ray astronomy is destined to play a crucial role in the exploration of non-thermal phenomena in the Universe in their most extreme and violent forms.
Fermi Gamma-ray space telescope has revolutionized our awareness of the γ-Universe in the energy range from 8 keV to 100 GeV (Fermi-GBM: 8 keV-40 MeV; Fermi-LAT: 50 MeV-100 GeV) collecting many breakthrough discoveries in the last 15 years. In 2008, Fermi detected the first gamma-ray pulsar [1]. It also detected the GRB 080916C, known as the most powerful Gamma-ray Burst (GRB) ever detected with power of about 9000 ordinary supernovae [2]. This record was then overcome by a successive observation: GRB130427A, three times more powerful [3]. In November 2010, it was announced the discovery of Fermi bubbles, two gamma-ray and X-ray emitting bubbles, extending about 25 thousand light-years distant above and below the galactic center [4, 5].
The hard X-ray energy range (up to few tens of keV) has been well covered by the observations made by the NASA Swift satellite, that discovered the most distant object in the Universe [6], the previously-unknown class of long-soft GRBs without an associated supernova [7] and X-ray flares in GRBs finding that in some cases the X-ray afterglow decays very slowly. This suggests that the central engine remains active for minutes to hours after the burst [8]. Last but not least, AGILE observed an X-ray burst from a magnetar, enlightening the mechanism of fast radio bursts [9].
Both Fermi and Swift also contributed to the GW170817/GRB170817A multimessenger observation, where the gravitational wave and the gamma ray burst have been observed in coincidence and followed from gamma to radio frequencies [10]. Moreover, together with others, they also pointed out that most of the observed sources present an output power peak in the medium energy range. Therefore, to progress in understanding the mechanism powering extreme phenomena in the Universe, it is necessary to study the medium energy range, where there is a lack of observations as shown in figure 1. Moreover, in few years, new instruments for the X and γ-sky observations will be needed as the current observatories will no longer be in operation.
Crystal Eye [11], an innovative space-based X and γ-ray all-sky monitor which will be active in the energy range 10 keV-30 MeV, perfectly fits these requests. Crystal Eye aims at playing a key role in high-energy and multimessenger astronomy, by observing the prompt and afterglow emission of long and short GRBs, and by following-up and observing electromagnetic counterparts of gravitational wave signals detected by ground-based interferometers. Thanks to its crossover technology, it combines a wide Field Of View (FOV), a good sky localization capability and a large effective area. An innovative instrument such as Crystal Eye is the perfect instrument for the study of a plethora of different sources and emission mechanisms: short and long GRBs as main goal, but also magnetars, shock breakouts and lines from supernovae, and AGNs.
Crystal Eye will fly on a Low Earth Orbits (LEO). This open the possibility of Earth observations and will allow us to study also the Terrestrial Gamma-ray Flashes (TGFs), millisecond pulses of γ rays produced in coincidence with lightning and initially detected by BATSE [12].

2. The Crystal Eye concept

Crystal Eye design consists of a 14 cm radius hemisphere, made of 112 pixels with a total weight of about 50 kg (see the top panel of figure 2). This compact design eases its installation

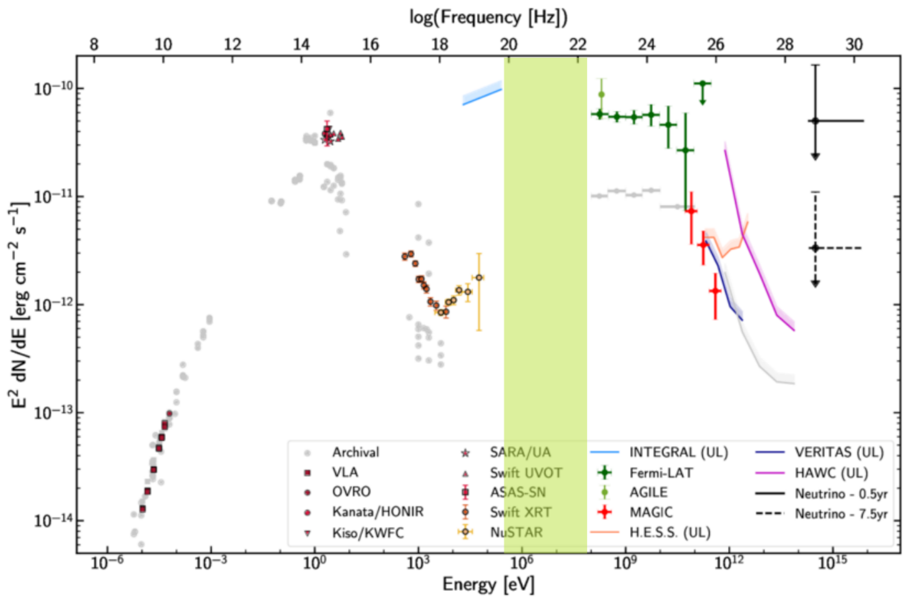

Figure 1: Broadband spectral energy distribution for the blazar TXS 0506+056. It is based on observations obtained within 14 days from the detection of the IceCube-170922A event from all the available sources. In the Crystal Eye energy range (green band), there is a lack of observations.

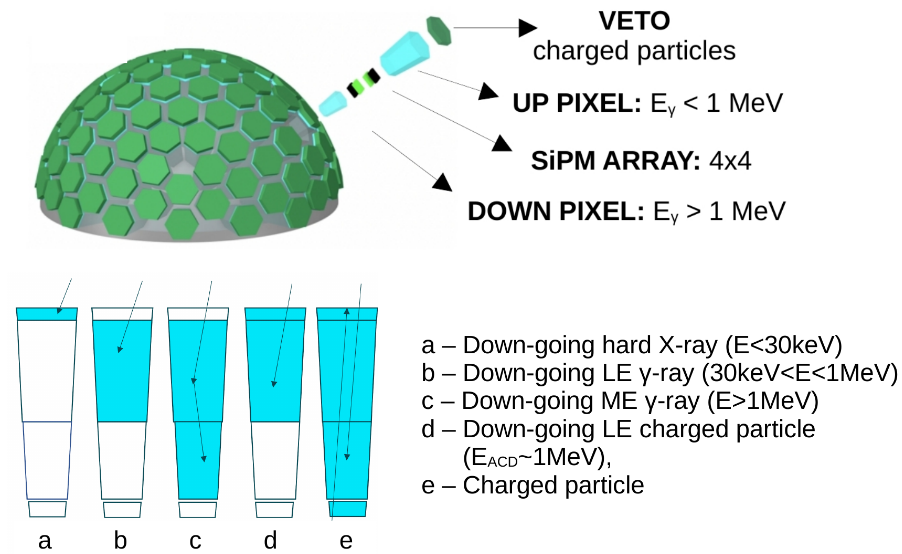

Figure 2: Top: Exploded model of the baseline configuration of the Crystal Eye detector. In cyan, the UP and DOWN LYSO pixels. In green, the anticoincidence layer. It will be optimized to improve the hermeticity. Bottom: The trigger concept. In cyan, the fired parts. E_{ACD} means the energy deposited in the external veto layer.

either on free-flyer satellites or on-board space stations. The pixels are composed by two layers of LYSO crystal scintillators read by SiPMs arranged between the layers. On the top of the upper (UP) crystal, there is an anticoincidence or veto layer (BC408 plastic scintillator) for photon tagging and charged CR rejection. There is also an unsegmented anticoincidence layer in the internal

part, below the DOWN pixels. In the past, it was impossible to realize such a design due to size and weight of photodetectors (mainly photomultipliers) and the consequent high costs; today this innovative observation technique is feasible thanks to the use of new sensors and materials allowing the realization of a highly efficient, low cost, compact device. Among new technologies, SiPM underwent impressive improvements during the last decade. Enabling them to space environment is a challenge that creates new scientific perspectives.
Thanks to its 112 pixels shaped as hexagonal pyramids pointing in different directions (see the top panel of figure 2), Crystal Eye will have a 2π FOV. In addition, its design also guarantees:

- *symmetry*: the positioning of the crystals has been studied in order to achieve a uniform coverage of the whole hemisphere, so that all the directions in the FOV will be equally monitored.
- *thermal protection*: the SiPMs are shielded from the external environment by the LYSO crystals ensuring the thermal stabilization in the SiPM housing layer.
- *radiation hardness*: the SiPM housing layer is shielded by 4 cm of LYSO on the top and 3 cm of LYSO on the bottom, strongly reducing the radiation damage of the sensors. Preliminary tests show that the dose received by a naked SiPM in 5 years is equivalent to those received in 20 years by a SiPM shielded with 3 cm of LYSO.

Crystal Eye will perform a full scan of the sky in the motion along its equatorial LEO orbit with a period of about 90 minutes. The full scale mission foresees a constellation of at least two Crystal Eyes, ensuring constantly the full sky coverage and avoiding any Earth occultation issue. In

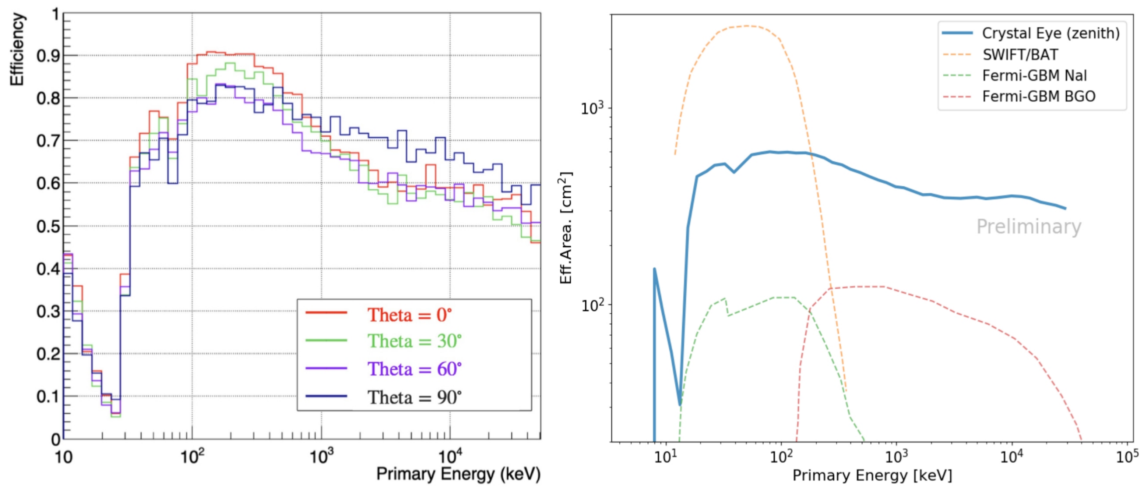

Figure 3: Left: Crystal Eye efficiency as function of energy for different zenith angles. Right: Crystal Eye effective area compared with the one of Swift and Fermi-GBM. The decrease at 30 keV represents the transition between the veto and UP crystal events. With the current electronics, there is a pedestal that prevents the detection of events with an energy lower than 30 keV in the UP crystal. An electronics optimization is requested to reduce this effect.

figure 3, first simulation results about one Crystal Eye module are shown. On the left, the Crystal Eye efficiency is shown as a function of the energy, which is almost independent of the zenith angle as expected thanks to the symmetry of the detector. On the right, we can see that the Crystal Eye

effective area at 1 MeV is about five times higher than the one of Fermi-GBM.
The particle identification and energy measurement rely on the topology of the event, as shown in the bottom panel of figure 2. The trigger concept is based on the readout of the signal distribution in the pixels. The double layer structure and the anticoincidence module are necessary to allow particle identification. The size of the LYSO pyramids is optimized to absorb γ-rays with energy below 1 MeV in the UP pixel with a probability higher than 85%. Some possible trigger configurations are shown in figure 2. The (a), (b) and (c) configurations are considered good photon triggers. Implementing them in a GEANT-4 based simulations, we found that Crystal Eye has improved localization capabilities with respect to current all-sky monitors. The localization algorithm is based on a minimization process that compares a simulated signal in a particular direction, with a template map containing expected counts with multiple directions in the sky. The method would work in real time, and allows to reconstruct the direction and localization error of the event. We can reach an angular resolution of few degrees.

3. WINK: the Crystal Eye pathfinder

A Crystal Eye prototype, WINK, is being developed for a pathfinder mission onboard the ESA Space Rider vehicle. It is an uncrewed robotic laboratory with pointing capabilities and its maiden flight will be in 2025. After launch on Vega-C, it will stay in low orbit for about two months and then will return to Earth with its payloads and land on a runway to be unloaded and refurbished for another flight.
WINK will be made of 3 full scale Crystal Eye pixels and their anticoincidence, to enable technologies for a future full scale mission while observing deep space and Earth, hunting respectively for GRBs and TGFs. The position requested for WINK in the Multy Purpouse Cargo Bay (MPCB) of Space Rider will ensure a 30° of FOV. Space Rider and a mechanical scheme of WINK are shown in figure 4. Three operation modes are envisaged:

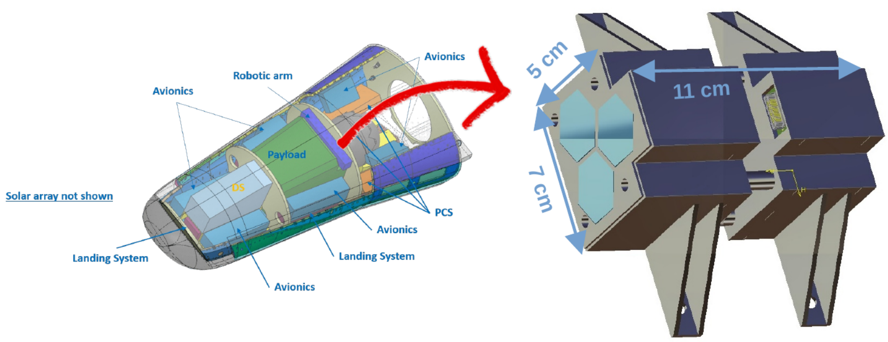

Figure 4: Left: The Space Rider vehicle by ESA which will host WINK in its MPCB (green) whose dimension are 1x1x1 meters. WINK will be installed on a thermal plate (purple) to ensure power dissipation. Right: A CAD model of WINK, where the three pixel are highlighted.

Space Observation Mode: WINK shall be exposed to deep space. In this phase we will characterize the cosmic background at the orbit and hunt for GRBs;
Calibration Mode: after each relevant event WINK will start 1 minute of calibration based on the

detection of the emission spectrum of each crystal. In absence of relevant event it will be done each 30 minutes;

Earth Observation Mode: WINK shall point at the Earth hunting for TGFs.

Thanks to a breadboard prototype and an Engineering Model (EM) with a temporary mechanical structure hosting three pixels (see the upper panel on the left of figure 6), preliminary studies about the materials to be used and the DAQ concept has been made. The choice of LYSO as the scintillation material used for pixels has been mainly driven by the following reasons:

- the photon absorption probability is higher in LYSO compared with other materials;
- the time response of LYSO is very fast (about 40ns decay time, e.g a factor 7 faster than NaI(Tl));
- the light yield is very high (about 30000 scintillation photons/MeV);
- the emission spectrum (due to the ^{176}Lu radioactivity) can be used as self-calibration source of the SiPMs;
- the intrinsic noise rate is relatively low for such small pixels (order of kHz) and can be easily killed by setting a majority trigger logic.

Moreover, LYSO crystals by different manufacturers were tested concluding that those made by EPIC Crystals have a better energy resolution with respect to others (see figure 6) [13]. For the full scale mission, the possibility of using GAGG crystals in substitution or in combination with LYSO crystals is being investigated. GAGG crystals haven't self emission and their use can improve Crystal Eye sensitivity allowing to detect also a single photon.

As readout photosensor for each LYSO crystal, the idea is to use a 4x4 SiPM-array in order to

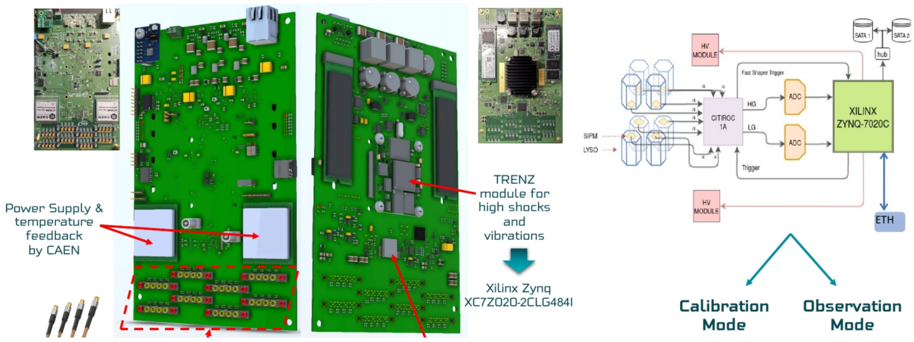

Figure 5: Left: first prototype of a custom DAQ developed with INFN-NA and Nuclear Instruments. Right: DAQ modes.

ensure redundancy and high scintillation light collection. WINK detection method is based on the readout of the signal distribution in the pixels. A versatile DAQ electronics able to set different triggers is necessary. The idea is to design an improved custom board based on a CITIROC 1A ASIC, housing both frontend and DAQ features. CITIROC 1A is a 32-channel frontend ASIC designed to readout SiPM. It allows to set both coincidence triggering and a threshold triggering. Once triggered, it provides the signal measurement with a good noise rejection. Moreover, it

collects signals with a high resolution timing. A custom board to test the triggering and detection capability of the EM with multipurpose connections and features was designed in collaboration with INFN-Napoli and Nuclear Instruments (see figure 5). At that time, no specifications about Space Rider electronics interfaces and data exchange protocols were available, therefore it is necessary to redesign the board to fulfill the requests. The core of this board will be the TE0720-03, a rugged module for high shocks and vibrations produced by Trenz Electronic which houses a Xilinx Zynq XC7Z020-2CLG484I FPGA, a Cortex-A9 MPCore dual-core ARM microcontroller with 1 GByte (32-bit) of DDR3 SDRAM memory, high efficiency on-board dc-dc converters with related system management and power sequencing. On the host card, we will also have: the Gigabit Ethernet 10/100/1000 tri-speed transceiver service, an isolated serial port for receiving the GPS signal from remote systems and a channel consisting of LVDS transceivers to use the SpaceWire communication protocol. The software process running in the board will also provide data treatment and finally transmission to ground. Local storage will also be provided with a given latency.
Since each LYSO crystal is read by a 4x4 SiPM-array, reading the 16 SiPMs singularly is unreasonable. We need a front-end electronic board to reduce the number of readout channels. The idea is to sum up the signals coming from the SiPMs in the same array by using different configurations in order to obtain two readout channels, one for the low gain and the other for the high gain. A temperature probe will be mounted on each frontend board to stabilize the gain with the temperature feedback circuit on the DAQ board. With this front end board we meet several requirements: reduction of the readout channels, use of the SiPMs in the array as redundancy (if one is damaged we don't lose the whole pixel but we can renormalize the array sum), avoid any saturation of the CITIROC channels. The proposed solution for this issue is to divide the SiPM-arrays which read the crystals in 4 quadrants, each of them will fit a CITIROC channel (see the right panel of figure 6). Each anticoincidence tile instead will be read with 2 CITIROC channels, leaving two empty channels on the ASIC.
Measurements have been performed to test the calibration procedure and, after that, also measurements with different radioactive sources (^{137}Cs,^{60}Co, ^{22}Na) have been made in observation mode. The right panel of figure 6 shows the measurements performed with the ^{22}Na source oriented toward the UP pixel manufactured by Epic Crystal (first panel). ^{22}Na decays, emitting a positron, into an excited state of ^{22}Ne, that passes into the ground state whereby a 1275 keV γ is emitted. While, the emitted positrons react with the electrons of the surrounding matter and lead to a characteristic annihilation radiation at 511 keV. We can see that the calibration procedure was successful, and the ^{22}Na photopeaks at 511 keV and 1275 keV are reconstructed with a good precision ($\sim$ 5 - 6%).

Conclusions

Crystal Eye will play a key role in high-energy and multimessenger astrophysics, and it will make possible to increase the knowledge of the mechanisms powering extreme phenomena of the Universe studying γ rays in the MeV energy range, where there is a lack of observations and where the sources have their peak of power output. The pioneering design, possible thanks to new materials and photosensors, will allow us to achieve optimized observations in terms of localization of the source, timing and energy coverage. Two pathfinder missions are foreseen for Crystal Eye. The NUSES mission with its payload Zirè [14] and WINK, that has been selected for the ESA

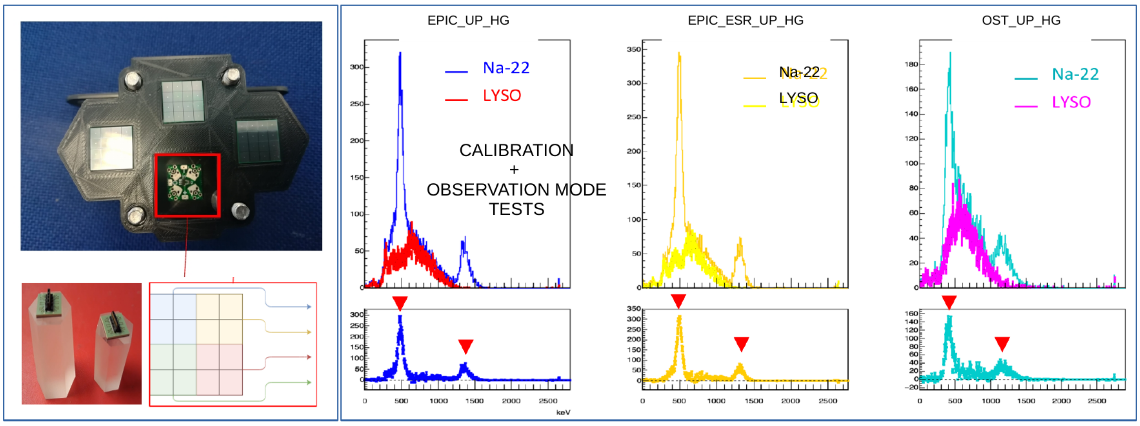

Figure 6: Left - The Crystal Eye Engineering Model (EM) and LYSO crystals, read by a 4x4 SiPM-array. Each array is divided in four quadrants to ensure double redundancy. Each quadrant represents one channel of the DAQ. Right - Response to ^{22}Na of three different crystals (left panel: pixel with ground surfaces made by Epic Crystals; center: with polished surfaces and Enhanced Specular Reflector (ESR) made by Epic Crystals; right: pixel with ground surfaces made by OST PHOTONICS). The source is oriented towards the UP pixel by Epic Crystal. Top: total spectra (blue) and LYSO emission spectrum (red); bottom: source spectra after subtraction of LYSO emission spectrum. Acquisition time set at 60 s.

Space Rider maiden flight in 2025. The Zirè calorimeter is segmented to work as calorimeter and to allow the implementation of Crystal Eye-like detection concept for gammas. WINK will flight 8 weeks on equatorial LEO orbit. This will enable Crystal Eye technology to the space environment and will allow us to characterize the background at the orbit while hunting for GRBs and TGFs.

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