PROCEEDINGS OF SCIENCE

Searching for gamma-ray counterparts of FRBs with H.E.S.S.

A. Jaitly,[1,*] **H. Ashkar,**[2] **F. Bradascio,**[3] **D. Kostunin,**[1] **G. Rowell**[4] **and Fabian Schüssler**[3] on behalf of the **H.E.S.S. Collaboration**
(a complete list of authors can be found at the end of the proceedings)
[1] *Deutsches Elektronen-Synchrotron (DESY), Platanenallee 6, 15738 Zeuthen, Germany*
[2] *Laboratoire Leprince-Ringuet, École Polytechnique, CNRS, Institut Polytechnique de Paris, F-91128 Palaiseau, France*
[3] *IRFU, CEA, Université Paris-Saclay, F-91191 Gif-sur-Yvette, France*
[4] *School of Physical Sciences, University of Adelaide, Adelaide, SA 5005, Australia*

E-mail: annanay.jaitly@desy.de

Fast Radio Bursts (FRBs) are highly energetic, extremely short-lived bursts of radio flashes. Despite extensive research, the exact cause of these outbursts remains a mystery. One of the most accredited models suggests that they originate from highly magnetized and rapidly spinning neutron stars known as magnetars. The high luminosity, short duration, and high dispersion measure of these events suggest they result from extreme, high-energy astrophysical processes of extragalactic origin. The number of detected FRBs, including repeating ones, has grown rapidly in recent years. Except for FRB20200428, that is associated to the galactic magnetar SGR1925+2154, no multi-wavelength counterparts to any FRB has been detected yet. The High Energy Stereoscopic System (H.E.S.S.) telescope has developed a program to uncover the nature of these mysterious events by searching for their gamma-ray counterparts. This contribution provides an overview of the searches for FRB sources conducted by H.E.S.S., including follow-up observations and simultaneous multi-wavelength campaigns with radio and X-ray observatories.

The 38th International Cosmic Ray Conference (ICRC2023)
26 July – 3 August, 2023
Nagoya, Japan

*Speaker

© Copyright owned by the author(s) under the terms of the Creative Commons Attribution-NonCommercial-NoDerivatives 4.0 International License (CC BY-NC-ND 4.0).

PoS(ICRC2023)776

1. Introduction

Fast radio bursts (FRBs) are millisecond-long radio pulses detected around ~1 GHz. They were serendipitously discovered at the Parkes Radio Telescope [1, 2] and are now routinely detected by various facilities. Over a thousand FRB events from approximately 500 published sources have been reported (see e.g. FRB catalogs [3, 4]). Some FRBs exhibit repeating bursts, while others show periodic patterns in their activity cycle, although with limited significance. The distinction between repeating and non-repeating sources and their underlying physical differences remain unclear. Determining the distance to FRBs is challenging as they lack a direct distance indicator. Instead, the dispersion measure (DM), which tracks the amount of free electrons along the line of sight, is used to infer distance information. However, there is a degeneracy between contributions from the intergalactic medium, host galaxies, and the local environment of the FRB source. While it is widely accepted that FRBs have an extragalactic origin, estimates of their redshift (z) have large uncertainties, with most falling within the range of $0.1 \leq z \leq 1$.

Recent efforts have focused on understanding the progenitors of FRBs. Compact objects such as magnetars (strongly magnetized neutron stars) and massive black holes are favored models due to the short duration of FRBs [5]. Some magnetars may produce FRBs through interactions between strongly magnetized pulses and surrounding material, leading to synchrotron maser emission [6]. Other models suggest that repeating FRBs originate near the surface of magnetars through ultra-relativistic internal shocks and blast waves associated with flares [7].

Apart from one case associated with the galactic magnetar SGR1925+2154, no multiwavelength counterparts to FRBs have been detected. However, studying the electromagnetic emission of FRBs across different wavelengths is crucial for unraveling their nature. It allows us to understand source characteristics, explore the surrounding environment, refine emission mechanisms, search for associated phenomena, and explore cosmological and fundamental physics. The High Energy Stereoscopic System (H.E.S.S.) telescope has developed a program to search for their gamma-ray counterparts. This contribution provides an overview of the searches for FRB sources conducted by H.E.S.S. since 2015, including follow-up observations and simultaneous multi-wavelength campaigns with radio and X-ray observatories [8].

2. H.E.S.S. FRB follow-up program

H.E.S.S. is an array consisting of one 28 m and four 12 m imaging atmospheric Cherenkov telescopes (IACTs) [9]. It is situated in the Khomas Highland in Namibia at an altitude of 1835 m, and its primary function is to detect very-high-energy (VHE) gamma rays spanning energies from a few tens of GeV to 100 TeV. Since 2015, H.E.S.S. has been actively engaged in a comprehensive follow-up program for FRBs, with the aim of investigating potential correlations between these events and VHE gamma-ray emissions. The FRB searches conducted by H.E.S.S. employ two primary strategies: Target of Opportunity (ToO) alerts triggered by radio or X-ray observatories, and coordinated multi-wavelength campaigns. In the first approach, the objective is to identify the afterglow emission in VHE gamma-rays associated with FRBs. This involves promptly responding to ToO alerts from radio or X-ray observatories, enabling H.E.S.S. to capture and study any potential gamma-ray emissions that may follow the FRB events. In the second approach, the focus is on

PoS(ICRC2023)776

observing known FRB sources, whether repeating or not, to study their host galaxies and on capturing FRBs simultaneously with radio facilities. Coordinated multi-wavelength campaigns are designed to systematically observe and analyze the activity of these sources. By collecting data across different wavelengths simultaneously, H.E.S.S. aims to uncover any recurring patterns or behaviors associated with the FRB sources.

This contribution provides an overview of H.E.S.S.'s FRB searches, focusing specifically on the follow-ups of an FRB candidate triggered by UTMOST and of the magnetar SGR1830-0645m, and on the multi-wavelength campaigns conducted in collaboration with radio and X-ray observatories. For the analysis of the H.E.S.S. data presented in this contribution, the method described in [10] was employed, utilizing standard gamma-hadron separation techniques and event selection cuts. The background estimation followed the established "reflected background" technique [11], and the results were validated through cross-check analysis employing an independent event calibration and reconstruction method [12].

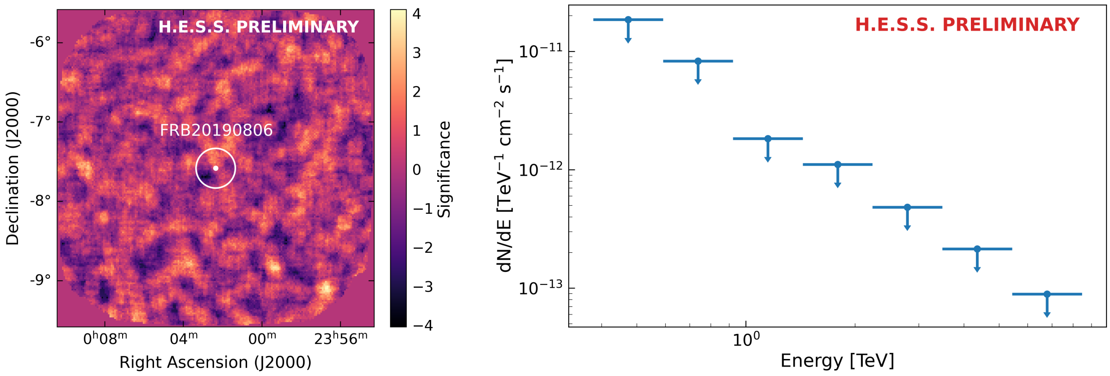
3. Follow-ups observations

A first follow-up campaign of FRBs in VHE gamma rays was conducted by H.E.S.S. in response to the detection of FRB150215 and FRB150418 [13] by the SUPERB (SUrvey for Pulsars and Extragalactic Radio Bursts) project, which utilizes the Parkes telescope. However, no gamma-ray emission was detected during the campaign. The resulting integral upper limits at 99% confidence level (C.L.) were $\Phi_\gamma(E > 1.18~\text{TeV}) < 6.5 \times 10^9~\text{m}^{-2}\text{s}^{-1}$ [14] and $\Phi_\gamma(E > 350~\text{GeV}) < 1.33 \times 10^8~\text{m}^{-2}\text{s}^{-1}$ [15], respectively, assuming an E^{-2} energy spectrum [15].

On August 6, 2019, a radio burst was detected by the Molonglo radio telescope during a blind FRB search as part of the UTMOST program [16]. The optimal DM for FRB20190806 was measured at 388.5 pc cm^{-3}, and the DM-inferred redshift was found to be $z \leq 0.32$. Subsequently, H.E.S.S. initiated observations on August 8, 2019, and collected data for ~ 2.3 hours. However, no significant gamma-ray flux was detected from the direction of FRB20190806. The distribution map of the Li&Ma [17] significance, which measures the excess of gamma-ray events over the background, is shown in Figure 1a for the full region of interest (ROI). The significance values are consistent with the background expectation. The resulting 99% C.L. differential upper limits on the gamma-ray flux, assuming an E^{-2} energy spectrum, are shown in Figure 1b.

Due to due to their similar burst characteristics and the possibility of both originating from highly magnetized compact objects, Soft Gamma Repeaters (SGRs) are considered counterparts to FRB sources. The first evidence supporting this scenario came in April 2020 when an FRB was detected from the Galactic magnetar SGR1935+2154, preceded by two gamma-ray outburst alerts by the *Swift*-Burst Alert Telescope (BAT) satellite, prompting follow-up observations by H.E.S.S.. Due to darkness and visibility constraints, follow-up observations could only commence approximately ~7.5 hours later. These observations ($\sim$ 2 hours), overlapping with X-ray bursts from the magnetar detected by INTEGRAL and *Fermi* Gamma-ray Burst Monitor (GBM) and prior to the FRB detection by STARE2 and CHIME, provided the first observations of a flaring magnetar in the very-high energy domain. While VHE gamma-ray emission was not detected from SGR1935+2154, upper limits on the flux were established, resulting in $F_\gamma(E > 600~\text{GeV}) < 2.4 \times 10^{-12}~\text{erg cm}^{-2}~\text{s}^{-1}$ assuming a spectral index of $E^{-2.5}$.

PoS(ICRC2023)776



(a) **(b)**

Figure 1: FRB20190806 triggered by UTMOST. **(a)**: Significance map computed for H.E.S.S. observational data taken on FRB20190806. **(b)**: Differential 99% C.L. upper limits derived from the H.E.S.S. observational data taken on FRB20190806 assuming a E^{-2} gamma-ray spectrum.

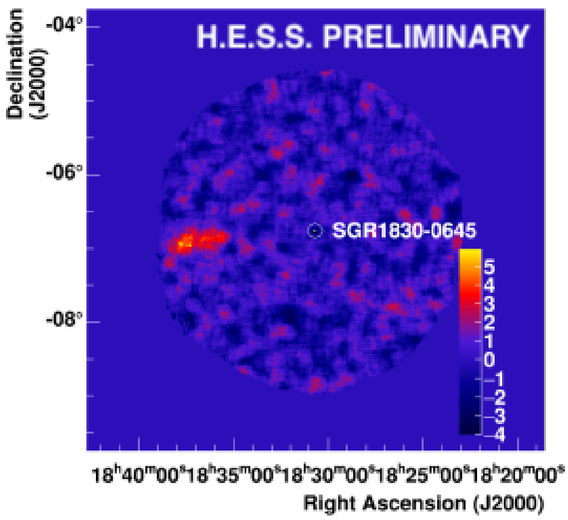
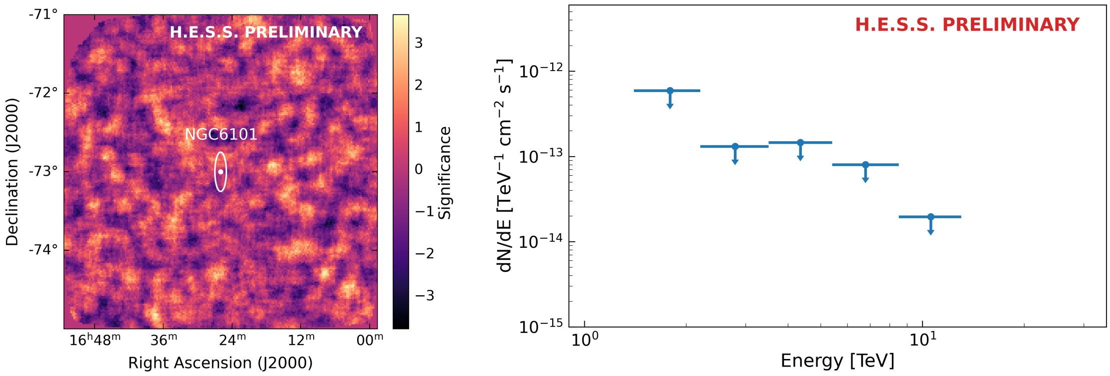


Figure 2: Significance map computed for H.E.S.S. observational data taken on SGR 1830-0645.

On October 10, 2020 H.E.S.S. conducted observations in the direction of SGR 1830-0645 following an alert from Swift-BAT [18]. The source was classified as an SGR based on its short X-ray duration (8 ms), soft spectrum (not visible above 50 keV), and its location in the Galactic bulge near the plane. No VHE gamma-ray emission was detected by H.E.S.S. during the ToO observations, as shown in the Figure 2. The Li&Ma significance map distribution obtained by excluding a circular region of 0.25° radius (red histogram) indicate compatibility with the background expectation, further supporting the absence of significant VHE gamma-ray emission.

PoS(ICRC2023)776



(a) **(b)**

Figure 3: Observations of NGC6101 as part of the MWL DWF campaign. **(a)**: Significance map computed for H.E.S.S. observational data taken on NGC6101. **(b)**: Differential 99% C.L. upper limits derived from the H.E.S.S. observational data taken on NGC6101 assuming a E^{-2} gamma-ray spectrum.

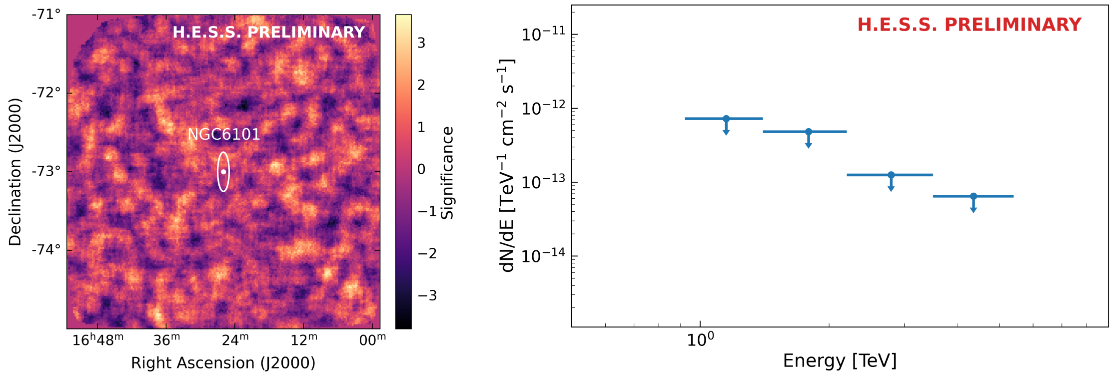
4. Multiwavelength campaigns

The Deeper Wider Faster (DWF) program [19] coordinates multi-wavelength and rapid-response follow-up for fast transient studies. Previous DWF campaigns have contributed to follow-ups of FRB and gravitational wave events in the radio and optical bands, as well as advancements in data processing and real-time pipelines. H.E.S.S. participated in the June 2019 DWF campaign, led by the MeerKAT radio telescope, for six nights from June 24 to June 29. Three fields were targeted, including galaxies NGC6101 and NGC6744, along with the single-pulse FRB20180924 [20]. Optical coverage was obtained simultaneously with DECam on the CTIO Blanco telescope in Chile, as well as from other telescopes covering X-rays (HXMT), optical, and millimeter wavelengths (AST3-2 and South Pole Telescope, Antarctica). Unfortunately, cloudy weather in Chile resulted in poor quality optical data, compromising the detailed identification of over 700 observed optical transients. Additionally, real-time analysis of MeerKAT was not functioning, leading to the unavailability of rapid FRB detection information during the observations. H.E.S.S. conducted observations during moonlight but did not detect any signals from the three targets. Consequently, 99% C.L. differential upper limits were calculated, assuming an E^{-2} spectral distribution, using ad-hoc simulations to account for moonlight conditions [21]. The resulting significance maps and upper limits are presented in Figure 3, Figure 4 and Figure 5.

In September 2017, the repeating FRB20121102 entered an active state [22], and H.E.S.S. conducted follow-up observations for a few hours. However, no gamma-ray events or concurrent radio bursts were detected during the H.E.S.S. observations. In 2019, an INTEGRAL and XMM campaign was carried out on the same source, and H.E.S.S. observed for two nights. However, due to the challenging visibility of the burst location for H.E.S.S., insufficient data were collected. Furthermore, no FRB was identified by INTEGRAL.

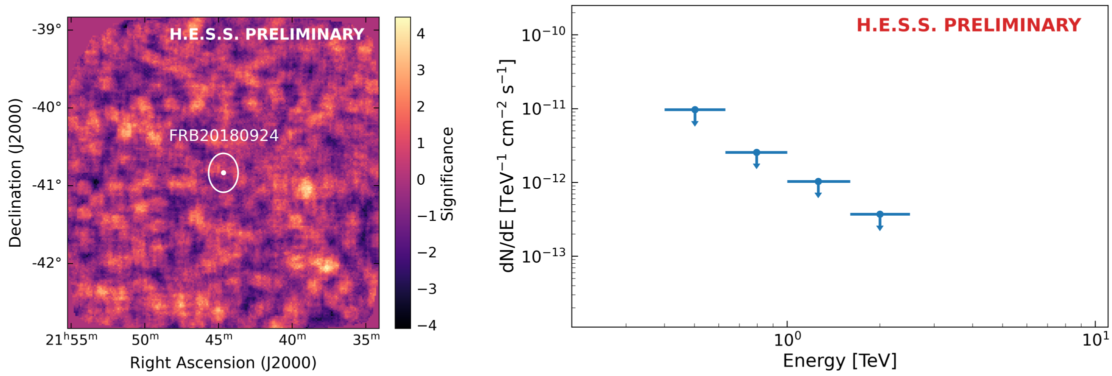
Since 2019, H.E.S.S. has been participating in FRB campaigns led by the MeerKAT radio telescope, aiming to characterize the overall properties of a sample of host galaxies, such as radio active galactic nuclei activity and star formation, and to investigate the presence of more FRBs within radio nebulae. In 2019, H.E.S.S. joined the MeerKAT campaign for the Southern

PoS(ICRC2023)776



(a) **(b)**

Figure 4: Observations of NGC6744 as part of the MWL DWF campaign. (**a**): Significance map computed for H.E.S.S. observational data taken on NGC6744. (**b**): Differential 99% C.L. upper limits derived from the H.E.S.S. observational data taken on NGC6744 assuming a E^{-2} gamma-ray spectrum.



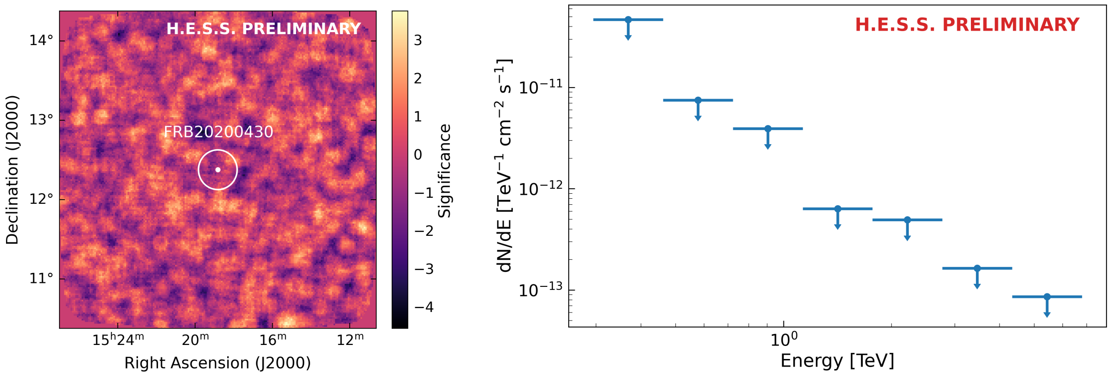
(a) **(b)**

Figure 5: Observations of FRB20180924 as part of the MWL DWF campaign. (**a**): Significance map computed for H.E.S.S. observational data taken on FRB20180924. (**b**): Differential 99% C.L. upper limits derived from the H.E.S.S. observational data taken on FRB20180924 assuming a E^{-2} gamma-ray spectrum.

repeating FRB20171019A over two nights, on September 27 and October 18. The goal was to search for variability while conducting simultaneous observations in radio, ultraviolet, optical, and X-ray wavelengths. However, H.E.S.S. was only able to observe during the first night. No significant gamma-ray excess above the expected background was detected from the direction of FRB20171019A, resulting in integral upper limits of $\Phi_\gamma(E > 120\text{ GeV}) < 2.10 \times 10^{-12}\text{ cm}^{-2}\text{s}^{-1}$ assuming an energy dependence following E^{-2} [23].

In 2021, H.E.S.S. conducted a new campaign to observe six FRBs with the objectives of obtaining detections, setting deep limits, and probing the variability of the persistent emission. The campaign, led by MeerKAT, also involved X-ray observations by Swift and optical observations by ATOM and MeerLicht. The campaign was divided into three epochs: the first epoch included observations by MeerKAT only, while the last two epochs (epoch 2A and 2B) included simultaneous observations by MeerKAT, H.E.S.S., and Swift. Epoch 2A observations were carried out on July

PoS(ICRC2023)776



(a) **(b)**

Figure 6: Observations of FRB20200430 as part of the MeerKAT campaign. **(a)**: Significance map computed for H.E.S.S. observational data taken on FRB20200430. **(b)**: Differential 99% C.L. upper limits derived from the H.E.S.S. observational data taken on FRB20200430 assuming a E^{-2} gamma-ray spectrum.

28, 2021, targeting the source FRB20200430. Epoch 2B observations took place from September 1 to September 6, 2021, with a duration of 2.5 hours each night, targeting a different source each night (FRB20190608, FRB20181112, FRB20190102, FRB20190611, and FRB20191228). The selection of these sources prioritized nearer sources and included a mix of repeating and non-repeating FRBs with well-localized positions. No gamma-ray detections were made, and only upper limits on the flux were determined. The results of the H.E.S.S. observations of FRB20200430 are shown in Figure 6.

5. Conclusions

We presented an overview of the H.E.S.S. program to search for FRB sources and summarized the results collected so far using real-time follow-up observations and simultaneous multi-wavelength campaigns with radio and X-ray observatories. While no significant gamma-ray excess was detected in the specific events studied, the program contributed valuable insights into the search for FRB sources and demonstrated the importance of multi-messenger observations in understanding high-energy astrophysical phenomena.

References

[1] D. R. Lorimer *et al.* *Science* **318** no. 5851, (Nov., 2007) 777.

[2] D. Thornton *et al.* *Science* **341** no. 6141, (July, 2013) 53–56.

[3] E. Petroff *et al.* *Publications of the Astronomical Society of Australia* **33** (Sept., 2016) e045.

[4] **CHIME/FRB** Collaboration, M. Amiri *et al.* *ApJS* **257** no. 2, (Dec., 2021) 59.

[5] J. M. Cordes and S. Chatterjee *Annual Review of Astronomy and Astrophysics* **57** (Aug., 2019) 417–465.

PoS(ICRC2023)776

[6] Y. Lyubarsky *MNRAS* **442** (July, 2014) L9–L13.

[7] A. M. Beloborodov *ApJL* **843** no. 2, (July, 2017) L26.

[8] C. Hoischen *et al.* *A&A* **666** (Oct., 2022) A119.

[9] F. Aharonian *et al.* *A&A* **457** no. 3, (2006) 899–915.

[10] M. de Naurois and L. Rolland *Astroparticle Physics* **32** no. 5, (2009) 231–252.

[11] D. Berge, Funk, S., and Hinton, J. *A&A* **466** no. 3, (2007) 1219–1229.

[12] R. Parsons and J. Hinton *Astroparticle Physics* **56** (2014) 26–34.

[13] E. F. Keane *et al.* *Nature* **530** no. 7591, (2016) 453–456.

[14] E. Petroff *et al.* *MNRAS* **469** no. 4, (Aug., 2017) 4465–4482.

[15] Abdalla, H. *et al.* *A&A* **597** (2017) A115.

[16] V. Gupta *et al.* *The Astronomer's Telegram* **12995** (Aug., 2019) 1.

[17] T. P. Li and Y. Q. Ma **272** (Sept., 1983) 317–324.

[18] K. L. Page, S. D. Barthelmy, N. J. Klingler, N. P. M. Kuin, and A. Y. Lien *The Astronomer's Telegram* **14083** (Oct., 2020) 1.

[19] I. Andreoni and J. Cooke, "The Deeper Wider Faster Programme: Chasing the Fastest Bursts in the Universe," in *Southern Horizons in Time-Domain Astronomy*, R. E. Griffin, ed., vol. 339, pp. 135–138. Aug., 2019. `arXiv:1802.01100 [astro-ph.IM]`.

[20] K. W. Bannister *et al.* *Science* **365** no. 6453, (2019) 565–570.

[21] M. Holler *et al.* *Astroparticle Physics* **123** (2020) 102491.

[22] V. Gajjar *et al.* *The Astronomer's Telegram* **10675** (Aug., 2017) 1.

[23] J. O. Chibueze *et al.* **515** no. 1, (Sept., 2022) 1365–1379.

PoS(ICRC2023)776

Full Author List: H.E.S.S. Collaboration

F. Aharonian[1,2,3], F. Ait Benkhali[4], A. Alkan[5], J. Aschersleben[6], H. Ashkar[7], M. Backes[8,9], A. Baktash[10], V. Barbosa Martins[11], A. Barnacka[12], J. Barnard[13], R. Batzofin[14], Y. Becherini[15,16], G. Beck[17], D. Berge[11,18], K. Bernlöhr[2], B. Bi[19], M. Böttcher[9], C. Boisson[20], J. Bolmont[21], M. de Bony de Lavergne[5], J. Borowska[18], M. Bouyahiaoui[2], F. Bradascio[5], M. Breuhaus[2], R. Brose[1], A. Brown[22], F. Brun[5], B. Bruno[23], T. Bulik[24], C. Burger-Scheidlin[1], T. Bylund[5], F. Cangemi[21], S. Caroff[25], S. Casanova[26], R. Cecil[10], J. Celic[23], M. Cerruti[15], P. Chambery[27], T. Chand[9], S. Chandra[9], A. Chen[17], J. Chibueze[9], O. Chibueze[9], T. Collins[28], G. Cotter[22], P. Cristofari[20], J. Damascene Mbarubucyeye[11], I.D. Davids[8], J. Davies[22], L. de Jonge[9], J. Devin[29], A. Djannati-Ataï[15], A. Dmytriiev[9], V. Doroshenko[19], L. Dreyer[9], L. Du Plessis[9], K. Egberts[14], S. Einecke[28], J.-P. Ernenwein[30], S. Fegan[7], K. Feijen[15], G. Fichet de Clairfontaine[20], G. Fontaine[7], F. Lott[8], M. Füßling[11], S. Funk[23], S. Gabici[15], Y.A. Gallant[29], S. Ghafourizadeh[4], G. Giavitto[11], L. Giunti[15,5], D. Glawion[23], J.F. Glicenstein[5], J. Glombitza[23], P. Goswami[15], G. Grolleron[21], M.-H. Grondin[27], L. Haerer[2], S. Hattingh[9], M. Haupt[11], G. Hermann[2], J.A. Hinton[2], W. Hofmann[2], T. L. Holch[11], M. Holler[31], D. Horns[10], Zhiqiu Huang[2], A. Jaitly[11], M. Jamrozy[12], F. Jankowsky[4], A. Jardin-Blicq[27], V. Joshi[23], I. Jung-Richardt[23], E. Kasai[8], K. Katarzyński[32], H. Katjaita[8], D. Khangulyan[33], R. Khatoon[9], B. Khélifi[15], S. Klepser[11], W. Kluźniak[34], Nu. Komin[17], R. Konno[11], K. Kosack[5], D. Kostunin[11], A. Kundu[9], G. Lamanna[25], R.G. Lang[23], S. Le Stum[30], V. Lefranc[5], F. Leitl[23], A. Lemière[15], M. Lemoine-Goumard[27], J.-P. Lenain[21], F. Leuschner[19], A. Luashvili[20], I. Lypova[4], J. Mackey[1], D. Malyshev[19], D. Malyshev[23], V. Marandon[5], A. Marcowith[29], P. Marinos[28], G. Martí-Devesa[31], R. Marx[4], G. Maurin[25], A. Mehta[11], P.J. Meintjes[13], M. Meyer[10], A. Mitchell[23], R. Moderski[34], L. Mohrmann[2], A. Montanari[4], C. Moore[35], E. Moulin[5], T. Murach[11], K. Nakashima[23], M. de Naurois[7], H. Ndiyavala[8,9], J. Niemiec[26], A. Priyana Noel[12], P. O'Brien[35], S. Ohm[11], L. Olivera-Nieto[2], E. de Ona Wilhelmi[11], M. Ostrowski[12], E. Oukacha[15], S. Panny[31], M. Panter[2], R.D. Parsons[18], U. Pensec[21], G. Peron[15], S. Pita[15], V. Poireau[25], D.A. Prokhorov[36], H. Prokoph[11], G. Pühlhofer[19], M. Punch[15], A. Quirrenbach[4], M. Regeard[15], P. Reichherzer[5], A. Reimer[31], O. Reimer[31], I. Reis[5], Q. Remy[2], H. Ren[2], M. Renaud[29], B. Reville[2], F. Rieger[2], G. Roellinghoff[23], E. Rol[36], G. Rowell[28], B. Rudak[34], H. Rueda Ricarte[5], E. Ruiz-Velasco[2], K. Sabri[29], V. Sahakian[3], S. Sailer[2], H. Salzmann[19], D.A. Sanchez[25], A. Santangelo[19], M. Sasaki[23], J. Schäfer[23], F. Schüssler[5], H.M. Schutte[9], M. Senniappan[16], J.N.S. Shapopi[8], S. Shilunga[8], K. Shiningayamwe[8], H. Sol[20], H. Spackman[22], A. Specovius[23], S. Spencer[23], Ł. Stawarz[12], R. Steenkamp[8], C. Stegmann[14,11], S. Steinmassl[2], C. Steppa[14], K. Streil[23], I. Sushch[9], H. Suzuki[37], T. Takahashi[38], T. Tanaka[37], T. Tavernier[5], A.M. Taylor[11], R. Terrier[15], A. Thakur[28], J. H.E. Thiersen[9], C. Thorpe-Morgan[19], M. Tluczykont[10], M. Tsirou[11], N. Tsuji[39], R. Tuffs[2], Y. Uchiyama[33], M. Ullmo[5], T. Unbehaun[23], P. van der Merwe[9], C. van Eldik[23], B. van Soelen[13], G. Vasileiadis[29], M. Vecchi[6], J. Veh[23], C. Venter[9], J. Vink[36], H.J. Völk[2], N. Vogel[23], T. Wach[23], S.J. Wagner[4], F. Werner[2], R. White[2], A. Wierzcholska[26], Yu Wun Wong[23], H. Yassin[9], M. Zacharias[4,9], D. Zargaryan[1], A.A. Zdziarski[34], A. Zech[20], S.J. Zhu[11], A. Zmija[23], S. Zouari[15] and N. Żywucka[9].

[1]Dublin Institute for Advanced Studies, 31 Fitzwilliam Place, Dublin 2, Ireland
[2]Max-Planck-Institut für Kernphysik, P.O. Box 103980, D 69029 Heidelberg, Germany
[3]Yerevan State University, 1 Alek Manukyan St, Yerevan 0025, Armenia
[4]Landessternwarte, Universität Heidelberg, Königstuhl, D 69117 Heidelberg, Germany
[5]IRFU, CEA, Université Paris-Saclay, F-91191 Gif-sur-Yvette, France
[6]Kapteyn Astronomical Institute, University of Groningen, Landleven 12, 9747 AD Groningen, The Netherlands
[7]Laboratoire Leprince-Ringuet, École Polytechnique, CNRS, Institut Polytechnique de Paris, F-91128 Palaiseau, France
[8]University of Namibia, Department of Physics, Private Bag 13301, Windhoek 10005, Namibia
[9]Centre for Space Research, North-West University, Potchefstroom 2520, South Africa
[10]Universität Hamburg, Institut für Experimentalphysik, Luruper Chaussee 149, D 22761 Hamburg, Germany
[11]DESY, D-15738 Zeuthen, Germany
[12]Obserwatorium Astronomiczne, Uniwersytet Jagielloński, ul. Orla 171, 30-244 Kraków, Poland
[13]Department of Physics, University of the Free State, PO Box 339, Bloemfontein 9300, South Africa
[14]Institut für Physik und Astronomie, Universität Potsdam, Karl-Liebknecht-Strasse 24/25, D 14476 Potsdam, Germany
[15]Université de Paris, CNRS, Astroparticule et Cosmologie, F-75013 Paris, France
[16]Department of Physics and Electrical Engineering, Linnaeus University, 351 95 Växjö, Sweden
[17]School of Physics, University of the Witwatersrand, 1 Jan Smuts Avenue, Braamfontein, Johannesburg, 2050 South Africa
[18]Institut für Physik, Humboldt-Universität zu Berlin, Newtonstr. 15, D 12489 Berlin, Germany
[19]Institut für Astronomie und Astrophysik, Universität Tübingen, Sand 1, D 72076 Tübingen, Germany
[20]Laboratoire Univers et Théories, Observatoire de Paris, Université PSL, CNRS, Université de Paris, 92190 Meudon, France
[21]Sorbonne Université, Université Paris Diderot, Sorbonne Paris Cité, CNRS/IN2P3, Laboratoire de Physique Nucléaire et de Hautes Energies, LPNHE, 4 Place Jussieu, F-75252 Paris, France
[22]University of Oxford, Department of Physics, Denys Wilkinson Building, Keble Road, Oxford OX1 3RH, UK
[23]Friedrich-Alexander-Universität Erlangen-Nürnberg, Erlangen Centre for Astroparticle Physics, Nikolaus-Fiebiger-Str. 2, D 91058 Erlangen, Germany
[24]Astronomical Observatory, The University of Warsaw, Al. Ujazdowskie 4, 00-478 Warsaw, Poland
[25]Université Savoie Mont Blanc, CNRS, Laboratoire d'Annecy de Physique des Particules - IN2P3, 74000 Annecy, France
[26]Instytut Fizyki Jądrowej PAN, ul. Radzikowskiego 152, 31-342 Kraków, Poland
[27]Université Bordeaux, CNRS, LP2I Bordeaux, UMR 5797, F-33170 Gradignan, France
[28]School of Physical Sciences, University of Adelaide, Adelaide 5005, Australia

PoS(ICRC2023)776

[29]Laboratoire Univers et Particules de Montpellier, Université Montpellier, CNRS/IN2P3, CC 72, Place Eugène Bataillon, F-34095 Montpellier Cedex 5, France
[30]Aix Marseille Université, CNRS/IN2P3, CPPM, Marseille, France
[31]Leopold-Franzens-Universität Innsbruck, Institut für Astro- und Teilchenphysik, A-6020 Innsbruck, Austria
[32]Institute of Astronomy, Faculty of Physics, Astronomy and Informatics, Nicolaus Copernicus University, Grudziadzka 5, 87-100 Torun, Poland
[33]Department of Physics, Rikkyo University, 3-34-1 Nishi-Ikebukuro, Toshima-ku, Tokyo 171-8501, Japan
[34]Nicolaus Copernicus Astronomical Center, Polish Academy of Sciences, ul. Bartycka 18, 00-716 Warsaw, Poland
[35]Department of Physics and Astronomy, The University of Leicester, University Road, Leicester, LE1 7RH, United Kingdom
[36]GRAPPA, Anton Pannekoek Institute for Astronomy, University of Amsterdam, Science Park 904, 1098 XH Amsterdam, The Netherlands
[37]Department of Physics, Konan University, 8-9-1 Okamoto, Higashinada, Kobe, Hyogo 658-8501, Japan
[38]Kavli Institute for the Physics and Mathematics of the Universe (WPI), The University of Tokyo Institutes for Advanced Study (UTIAS), The University of Tokyo, 5-1-5 Kashiwa-no-Ha, Kashiwa, Chiba, 277-8583, Japan
[39]RIKEN, 2-1 Hirosawa, Wako, Saitama 351-0198, Japan

Acknowledgements

The support of the Namibian authorities and of the University of Namibia in facilitating the construction and operation of H.E.S.S. is gratefully acknowledged, as is the support by the German Ministry for Education and Research (BMBF), the Max Planck Society, the Helmholtz Association, the French Ministry of Higher Education, Research and Innovation, the Centre National de la Recherche Scientifique (CNRS/IN2P3 and CNRS/INSU), the Commissariat à l'énergie atomique et aux énergies alternatives (CEA), the U.K. Science and Technology Facilities Council (STFC), the Irish Research Council (IRC) and the Science Foundation Ireland (SFI), the Polish Ministry of Education and Science, agreement no. 2021/WK/06, the South African Department of Science and Innovation and National Research Foundation, the University of Namibia, the National Commission on Research, Science & Technology of Namibia (NCRST), the Austrian Federal Ministry of Education, Science and Research and the Austrian Science Fund (FWF), the Australian Research Council (ARC), the Japan Society for the Promotion of Science, the University of Amsterdam and the Science Committee of Armenia grant 21AG-1C085. We appreciate the excellent work of the technical support staff in Berlin, Zeuthen, Heidelberg, Palaiseau, Paris, Saclay, Tübingen and in Namibia in the construction and operation of the equipment. This work benefited from services provided by the H.E.S.S. Virtual Organisation, supported by the national resource providers of the EGI Federation.

PoS(ICRC2023)776